The Messenger

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ESO–SKAO Synergies
GRAVITY+ Project Updates
Introducing Yearly Call and Fast Track Channel at ESO

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Front Cover: Located in the constellation of the Centaur (Centaurus), the Running Chicken Nebula is a labyrinth of gas, dust and young stars whose highly intense radiation erodes away the surrounding material. The gas cloud IC2948 is the brightest region of the nebula. Obtaining such a detailed snippet of the nebula was possible thanks to a 1.5-billion-pixel image taken by the VLT Survey Telescope (VST), hosted and operated by ESO. Credit: ESO/VPHAS+ team. Acknowledgement: CASU

Häußler/ESO

In this image, taken in September 2024, the Sun is lighting up the ELT construction site, almost like a shadow theatre. The steel dome, in which the telescope will be encased to protect it from the harsh desert weather, is steadily taking shape. Once it’s finished, more than 600 pieces of thermally insulated aluminium will cover the structure.

ESO–SKAO Synergies

SKAO/Cassandra Cavallaro

The historic Lovell Telescope sits behind the SKAO Global Headquarters, UK.

Roland Halbe/ESO

The buildings of the ESO Headquarters in Garching, Germany.

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SKAO, SKA Precursors/pathfinders and ESO Facilities

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In The Messenger 192 a short report was published on the ESO–SKAO workshop Coordinated Surveys of the Southern Sky, which was held at ESO in Garching in early 2023. An important goal of this workshop was to publish a collection of articles that describe in some detail what existing synergetic science would be possible with well-planned coordinated surveys using ESO and SKAO facilities. The other four articles in this edition of The Messenger, covering respectively the Galaxy, galaxy formation and evolution, cosmology, and the epoch of reionisation and cosmic dawn, present such synergies and promising ways forward, and serve as references for ESO–SKAO coordinated surveys. By way of introduction, this article describes the SKAO and SKA precursor/pathfinder facilities and also briefly highlights the current and future ESO instrumentation that will be of particular importance for such coordinated surveys of the southern sky.

The Square Kilometre Array Observatory

The Square Kilometre Array Observatory (SKAO), currently under construction, will comprise two instruments: SKA-Low, consisting of stations each of 256 log-periodic antennas to observe in the 50–350 MHz frequency range (Labate et al., 2022), and SKA-Mid, consisting of dishes to observe in five frequency bands in the 350 MHz – 15.4 GHz range (Swart, Dewdney & Cremonini, 2022).

The SKA-Low site is located at Inyarrimanha Ilgari Bundara, CSIRO's Murchison Radio-astronomy Observatory in Western Australia, on the lands of the Wajarri Yamaji, who are the Traditional Owners and native title holders of the observatory site. The SKA-Mid site is located in South Africa's semi-desert Karoo region.

The '*baseline*' design for SKA (see Table 1), also referred to in the literature as SKA Phase 1, consists of 512 SKA-Low stations and 197 SKA-Mid dishes (64 of which will be integrated from the currently operating MeerKAT telescope). Only SKA-Mid Band 1 (0.35–1.05 GHz), Band 2 (0.95–1.76 GHz) and Band 5 (4.6–15.4 GHz) receivers will be initially deployed, with the others to be added at a later date.

The SKAO is scheduled to begin science operations after the end of construction, towards the end of the decade. While SKAO is committed to delivering the design baseline, funding to meet this goal has not been fully secured yet. With the funding currently secured, SKAO is working towards delivering an intermediate stage called AA*, which will consist of 144 Mid dishes (including the 64 MeerKAT dishes) and 307 Low stations. As more funding becomes available, the gap between AA* and the design baseline will be bridged while maintaining a continuously working and expanding facility. More information on the different array assemblies can be found on SKAO's website[2].

The science programme for the SKAO will be determined through competitive calls for proposals from the scientific community. It is foreseen that the majority of the telescope time will go towards Key Science Projects (KSPs), large observational programmes, running for several years, to explore new frontiers in, for example, galaxy evolution and cosmology, cosmic magnetism, the laws of gravity, time-domain astrophysics, extraterrestrial life and the unknown (see the SKA Science Book[3] for a comprehensive description of the SKA science cases). The science community behind the SKA is organised in science working groups[4] (SWGs).

Nominal Frequency (GHz)	0.11	0.3	0.77	1.4	6.7	12.5
Frequency range (GHz)	0.05–0.35	0.05–0.35	0.35–1.05	0.95–1.76	4.6–8.5	8.3–15.4
Telescope	Low	Low	Mid	Mid	Mid	Mid
Maximum baseline length (km)	73.4	159.6				
FoV at nominal frequency (arcmin)[a]	277	101	102	57	12	6
Max bandwidth (MHz)	300	300	700	810	3900	2 × 2500
Continuum channel width (kHz)	5.4	5.4	13.4	13.4	13.4	13.4
Finest zoom channel width (Hz)	14.1	14.1	210	210	210	210
Width of a single tuneable spectral window at narrowest zoom channel width (MHz)	0.024	0.024	3.1	3.1	3.1	3.1
Continuum RMS (μJy/beam)[b]	9	8.2	2.6	1.4	1	1.2
Line RMS (μJy/beam)[c]	407	410	140	78	56	69

Table 1. Anticipated performance of the SKA baseline design. The sensitivities listed here are indicative values. Accurate sensitivity values for different observational setups can be estimated using the SKA sensitivity calculators[1].

Of the science cases that are being developed, several either rely on or would benefit from synergy with instruments operating at different wavelengths. Some examples include Target of Opportunity, where an observation is triggered by an external event, such as a detection by another facility, and Coordinated Projects, where observations are carried out on multiple facilities.

Several currently operational SKA precursors and pathfinder facilities[5] are producing state-of-the-art radio science. Below we describe in particular the facilities that were mentioned at the workshop and in the articles in this issue of The Messenger.

CSIRO's ASKAP radio telescope

The Australian SKA Pathfinder (ASKAP) radio telescope is owned and operated by CSIRO, Australia's national science agency. It is located at Inyarrimanha Ilgari Bundara, the CSIRO's Murchison Radio-astronomy Observatory in Western Australia, on the lands of the Wajarri Yamaji, who are the Traditional Owners and native title holders of the observatory site. The array comprises 36 dish antennas, 12 metres in diameter, and operates across the frequency range of 700 MHz to 1.8 GHz with a contiguous bandwidth of up to 288 MHz. Spectral-line observations can span this entire bandwidth with a channel size of 18.5 kHz, or in zoom modes for finer resolution (up to 0.58 kHz) with a tradeoff in bandwidth.
A more detailed description of the technical design and capabilities of ASKAP is given by Hotan et al. (2021).

A defining characteristic of ASKAP is its phased-array feed technology, which forms 36 beams on the sky to give an instantaneous field of view of 6 × 6 degrees in the lowest frequency band. This wide-field capability makes ASKAP particularly adept at swiftly mapping large areas of the sky. ASKAP observations are autonomously scheduled and processed using a specialised data reduction pipeline written in ASKAPsoft. After processing, science-ready data products are uploaded to CSIRO's Astronomy Science Data Archives[6] (CASDA) where, after a short validation period, they are publicly available.

Reflecting ASKAP's unique surveying capability, the majority of the available observing time is dedicated to a set of nine Survey Science Projects (SSPs) which are being conducted over a five-year period. Under the guest science scheme, about 10% of the observing time is open to all astronomers. These large surveys[7] cover a wide range of science topics, including studies of neutral hydrogen from the Milky Way out to a redshift of one (GASKAP, WALLABY, DINGO, FLASH) mapping the continuum and polarisation properties of galaxies (EMU, POSSUM) and studying radio transients (VAST) and fast radio bursts (CRAFT). This is in addition to observatory-led projects such as the Rapid ASKAP Continuum Survey (Hale et al., 2021; Duchesne et al., 2021) which provides a rich legacy dataset of radio continuum sources across the entire southern hemisphere.

The Low Frequency Array

The Low Frequency Array (LOFAR; van Haarlem et al., 2013) is an innovative low-frequency radio telescope, composed of antenna 'stations' across Europe. Each LOFAR station contains both Low Band Antennas (LBA), operating between about 10 and 90 MHz, and High Band Antennas (HBA), operating between 110 and 240 MHz. LOFAR stations have no moving parts: the signals from the antennas are combined at station level using advanced beam-forming technologies to enable the station to steer and track across the sky, resulting in a highly flexible system.

LOFAR has a dense core in the north of the Netherlands, with 24 antenna stations within a 2-kilometre radius; this is complemented by a further 14 'remote' Dutch stations with baselines out to around 100 kilometres and an increasing number of international stations (14, as of early 2024) with baselines out to 2000 kilometres. At 150 MHz, the international stations allow the angular resolution to improve from 6 arcseconds using only the Dutch stations to 0.3 arcseconds with the full international array.

With a sensitivity more than 100 times better than any previous telescope at these low frequencies, (sub-)arcsecond angular resolution, an enormous field of view, and an agile system, LOFAR supports an extremely broad and diverse science case, from cosmology to Solar System studies. Major projects include its unique low-frequency surveys, such as the LOFAR Two-Metre Sky Survey (LoTSS; Shimwell et al., 2022), the LoTSS Deep Fields (Best et al., 2023), the LOFAR LBA Sky Survey (LoLSS; de Gasperin et al., 2023) and the LOFAR Tied-Array All Sky Survey (LOTASS; Sanidas et al., 2019).

While LOFAR's northern location (and poorer sensitivity at equatorial declinations) restricts potential overlap with ESO facilities, there has been considerable effort to combine LOFAR data with multi-wavelength northern hemisphere surveys (for example, Williams et al., 2019; Hardcastle et al., 2023), and future projects build further upon this (for example, WEAVE-LOFAR; Smith et al., 2016). The vast array of science that this work has enabled clearly showcases the opportunities for synergies between future SKA and ESO surveys, as well as developing many of the required tools and techniques.

MeerKAT

Located in the semi-desert region in the Northern Cape, South Africa, the MeerKAT radio telescope consists of 64 offset-Gregorian dishes 13.5 metres in diameter. Table 2 gives the basic telescope specifications and Table 3 gives the available correlator channelisation modes. Further information can be found on the MeerKAT knowledge base[8].

Number of antennas	64 (offset Gregorian)
Dish diameter (nominal)	13.5 m
Minimum baseline	29 m
Maximum baseline	7 700 m
Frequency range (UHF)	580–1015 MHz (544–1088 MHz digitised)
Frequency range (L)	900–1670 MHz (856–1712 MHz digitised)
Frequency ranges (S)	S0: 1750–2625 MHz S1: 1968–2843 MHz S2: 2187–3062 MHz S3: 2406–3281 MHz S4: 2625–3500 MHz

Table 2. MeerKAT basic telescope specifications.

Mode	Channels	L-band channel width	UHF-band channel width	S-band channel width
Wideband coarse	4096 (4k)	208.984 kHz	132.812 kHz	213.623 kHz
Wideband fine	32768 (32k)	26.123 kHz	16.602 kHz	26.703 kHz
Narrowband extended (107 MHz bandwidth)[d]	32768 (32k)	3.3 kHz	–	
Narrowband extended (54 MHz bandwidth)[d]	32768 (32k)	1.633 kHz	–	

Table 3. Available correlator channelisation modes.

MeerKAT's wide field of view and sensitivity make it an excellent survey instrument, but it is also excellent for deep follow-up observations.

Many datasets are no longer proprietary and visibilities are available through the archive interface[9]. In addition, the SARAO Science Verification Legacy Surveys (among other data products of interest) are available as fully calibrated Stokes I image cubes from the SARAO data repository[10]. This includes the 1.28-GHz Galactic Centre Mosaic (Heywood et al., 2022), the 1.3-GHz Survey of the Small Magellanic Cloud (Cotton et al., 2024) and the 1.3-GHz Galactic Plane Survey (Goedhart et al., 2024). These datasets open up a large discovery space for multi-wavelength astronomy.

The Murchison Widefield Array

The Murchison Widefield Array[11] (MWA; Tingay et al., 2013; Wayth et al., 2018) is an SKA-Low precursor. The telescope is located at CSIRO's Murchison Radio-astronomy Observatory in Western Australia, on the lands of the Wajarri Yamaji, who are the Traditional Owners and native title holders of the observatory site. An international project, the MWA collaboration comprises 28 partner institutions from Australia, Japan, China, Canada, the United States and Switzerland.

The telescope consists of 256 'tiles', each with 4 × 4 dual-polarisation dipole antennas. The effective width of each tile is about 4 metres. Currently, the telescope operates in two configurations of 128 tiles each. The compact configuration includes two 36-tile hexagonal sub-arrays and is particularly suitable for epoch of reionisation observations thanks to its surface brightness sensitivity and calibratability. The extended configuration, comprising the remaining 128 tiles, has a maximum baseline of approximately 5.3 kilometres.

With its combination of very wide bandwidth (70–300 MHz; instantaneous bandwidth 30.72 MHz), huge field of view (for example, approximately 600 square degrees at 150 MHz), excellent *u*, *v* coverage, high time and frequency resolutions (for example, as good as 250 ms or 200 Hz when correlating), and agile, advanced beamforming capabilities, the MWA is a very powerful low-frequency facility for conducting arcminute-resolution studies of the sky below a declination of about +30 degrees.

In full science operation since 2013, the MWA has facilitated transformational low-frequency science across five key themes: the epoch of reionisation, Galactic science, time-domain, space weather, and pulsars and fast transients (see, for example, Beardsley et al., 2019 for an overview of results). An example of a major survey project well-matched with potential ESO synergies, and that has achieved significant impact in the literature, is the 70–230 MHz GaLactic and Extragalactic All-sky MWA survey (GLEAM; for example, Wayth et al., 2015; Hurley-Walker et al., 2017): over 300 000 extragalactic radio sources were catalogued with broadband low-frequency spectral information.

The MWA long-term archive is hosted at the Pawsey Supercomputing Research Centre[12] and has over 45 PB of data at the time of writing. Data can be downloaded using the MWA node of the All-Sky Virtual Observatory[13].

'Phase III' of MWA science operations has recently commenced, during which it will be possible to conduct imaging and high-time-resolution beamforming with all 256 tiles, allowing improved sensitivity and *u*, *v* coverage. Such functionality will be enabled by a new, next-generation, flexible correlator (MWAX; Morrison et al., 2023), as well as a new receiver suite that is expected to be in place during 2025. MWA operations have also significantly influenced the designs of the SKA-Low prototypes (for example, Wayth et al., 2017; Benthem et al., 2021; Wayth et al., 2022; Macario et al., 2022), as well as the design of SKA-Low itself.

ESO facilities

The purpose of this section is to briefly highlight the current and planned instrumentation on ESO facilities that is of direct relevance to coordinated ESO–SKAO surveys. In particular we highlight four instruments/facilities that were mentioned frequently at the workshop, and which feature most prominently in the four science-focused articles in this Messenger issue. As these instruments are all introduced in much more detail in dedicated articles in previous Messenger editions, we describe them in much less detail than the SKA facilities.

Among the ESO instruments most referred to in the context of ESO–SKAO coordinated surveys, the 4-metre Multi-Object Spectroscopic Telescope (4MOST; de Jong et al., 2019) is one of the most conspicuous. 4MOST is a wide-field spectroscopic survey facility that is under development for the Visible and Infrared Survey Telescope for Astronomy (VISTA) and which will be able to simultaneously obtain spectra of around 2400 objects distributed over a field of view of 4.2 square degrees (see The Messenger 175 and 190 for descriptions of the planned surveys with this facility).

A future facility that is very frequently mentioned in this context is the new Multi-Object Optical and Near-infrared Spectrograph (MOONS; Cirasuolo et al., 2020) currently under construction for the Very Large Telescope (VLT), which will provide exquisite spectroscopic capabilities across the 0.65–1.8 μm wavelength range. Using ~1000 fibres across a field 25 arcminutes in diameter, it offers a spectroscopic resolving power between $R \sim 4000$ and $R \sim 18\,000$.

As for ESO’s Extremely Large Telescope[14] (ELT) instruments, MOSAIC (Hammer et al., 2021) is particularly important. This multi-object spectrograph will use the widest possible field of view provided by the ELT, and will operate in the visible and near-infrared, covering 0.47–1.80 µm with R between 5000 and 20 000, over a field of view of 40 square arcminutes.

Another important facility for possible SKA synergies is the Atacama Large Millimeter/submillimeter Array[14] (ALMA), which, despite its limited field of view, provides a unique view of gas and dust across the Universe, fitting quite naturally alongside deep radio observations. ALMA currently provides continuum and spectral-line capabilities for wavelengths from 0.32 mm to 8.5 mm, and angular resolutions from 0.0048 arcseconds to 8.5 arcseconds on the array of 50 12-metre dishes. ALMA’s field of view ranges from ~ 2.5 arcminutes at the lowest frequencies to 0.1 arcminutes in the highest frequency band. The Wideband Sensitivity Upgrade (WSU), which is currently in the planning phase, will improve ALMA’s imaging speed by up to a factor of six, and increase the spectral grasp for high-spectral-resolution observations by one to two orders of magnitude.

Although these four instruments and facilities stand out as being crucially important for future synergetic surveys, it should be noted that many other VLT and ELT instruments are referred to as well in the context of ESO–SKAO joint observations. ESO’s widefield multi-band imaging capabilities, as well as its optical/NIR spectroscopic and integral-field instruments, will all play a key role in maximising the science impact of coordinated surveys.

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Links

[1] SKA sensitivity calculators: https://www.skao.int/en/science-users/ska-tools/493/ska-sensitivity-calculators
[2] SKA array assemblies: https://www.skao.int/en/science-users/ska-tools/494/ska-staged-delivery-array-assemblies-and-subarrays
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[11] MWA telescope: https://www.mwatelescope.org/
[12] Pawsey Supercomputing Research Centre: https://pawsey.org.au/
[13] MWA virtual observatory: https://asvo.mwatelescope.org/
[14] ESO’s ELT: https://elt.eso.org
[15] ALMA: https://almascience.eso.org/

Notes

[a] Field of view is estimated using the relation FoV [deg] ~ 66 × (λ/D) where λ is the wavelength in metres and D is the diameter in metres. For SKA-Low, the station diameter is set to 39 m. For SKA-Mid, the dish diameter is set to 15 m.
[b] Naturally-weighted continuum sensitivity at Nominal Frequency for 1 hr assuming fractional bandwidth of 0.3.
[c] Naturally-weighted line sensitivity at Nominal Frequency for 1 hr, assuming fractional bandwidth per channel of 0.0001.
[d] The ‘zoom’ or narrowband modes run in parallel with the wideband coarse (4k) mode, i.e. you will receive two datasets, enabling continuum as well as spectral-line science.


SKAO

The ‘big lift’ of the main reflector onto the pedestal of the first SKA-Mid production dish on site in South Africa. The lift took place on 4 July 2024, and was carried out by a team from the SKAO, South African Radio Astronomy Observatory (SARAO) and China’s CETC54.

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ESO–SKAO Coordinated Surveys: the Galaxy

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Our Galaxy occupies a special place in astrophysics, because it allows us to observe fundamental phenomena at least four orders of magnitude fainter and at physical scales at least 100 times smaller than in any other comparable galaxy. Observations of the Milky Way therefore provide the fundamental data for our understanding of processes such as star and planet formation, the physics of accretion and ejection, interstellar chemistry or the interaction of the interstellar medium, stars and a massive black hole as it occurs in galaxy nuclei. In this article we discuss accretion and ejection in star formation, carbon chemistry, unidentified radio sources in the Milky Way, Galactic structure, and stellar remnants in the Galactic centre as exemplary science cases where multiwavelength observations with the SKAO and ESO facilities can make a profound impact. We also briefly discuss the nature of the coordinated observations and any requirements that we consider necessary to carry them out successfully.

Studying the accretion-ejection link in a young cluster deep field

The accretion and ejection of material are key processes that shape star and planet formation. Accretion impacts protostellar development and the pre-main-sequence phase, determining stellar masses and protoplanetary disc lifespans. The ejection of material (via outflows, winds and jets) influences the final stellar mass, the conditions in the planet-forming discs, and the wider star- and planet-forming environment. Despite this importance, our understanding of the link between accretion and ejection is limited. The upcoming joint operation of the SKAO and ESO facilities presents a unique opportunity to study the accretion-ejection link in unprecedented detail.

A proposed key science project for the SKAO involves observations of a nearby young stellar cluster to investigate many aspects of star and planet formation (see Hoare et al., 2015). The large field of view of SKA-Mid (between 6.7 and 60 arcminutes at 12.5–1.4 GHz) would enable contemporaneous 'one-shot' observations of many tens to hundreds of young stellar objects spanning a range of evolutionary stages in nearby star-forming regions (see Figure 1a). By performing repeated observations of these fields, it would be possible to i) build up deep observations, and ii) investigate temporal phenomena across the various epochs. The extremely sensitive observations will reveal both dust continuum and radio recombination lines throughout the star-forming region. Comparison of epoch-to-epoch data (with careful choice of cadence) will allow us to characterise any changes in the morphology and kinematics of thermal emission from protostellar jets and non-thermal emission from magnetic flaring activity, both of which are closely linked to accretion and ejection processes. An example of a radio jet observed in the transitional disc GM Aur using the

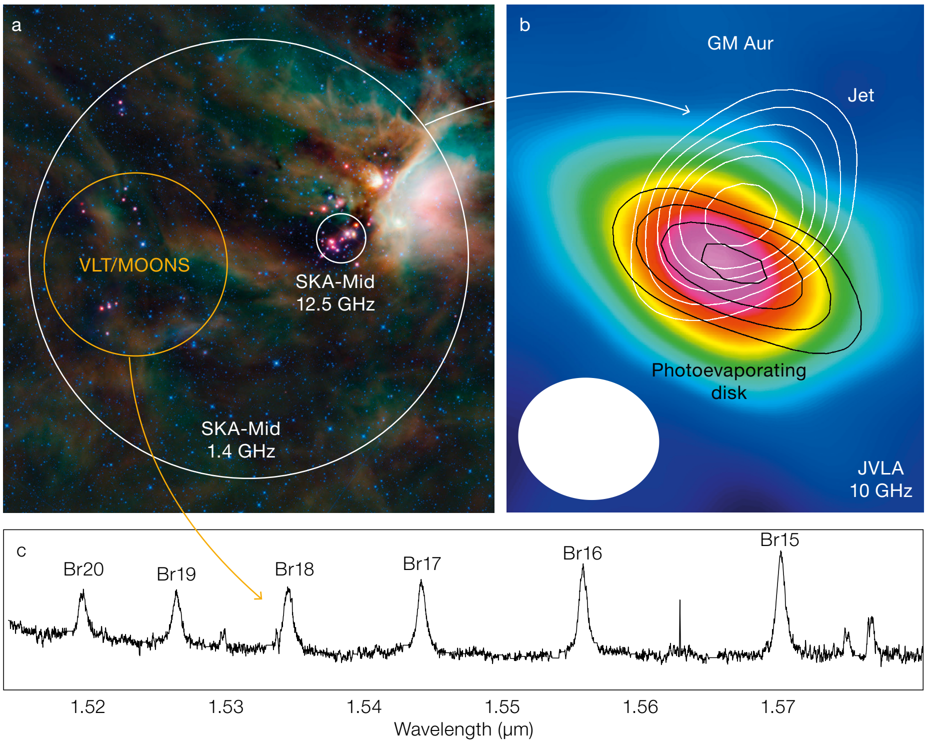

Figure 1. a) Comparison of the fields of view between MOONS/VLT and SKA-Mid between 1.4–12.5 GHz (Bands 2–5b) overlaid on a Wide-field Infrared Survey Explorer (WISE) image of ρ Oph (NASA/JPL-Caltech). b) JVLA observations of the photoevaporating disc and radio jet in GM Aur (10 GHz at ~ 0.5 arcseconds resolution; Macias et al., 2016). c) Brackett series of emission lines from a strongly accreting young stellar object identified in the Apache Point Observatory Galactic Evolution Experiment (APOGEE) survey (*H* band, *R* ~ 22 500; Campbell et al., 2023).

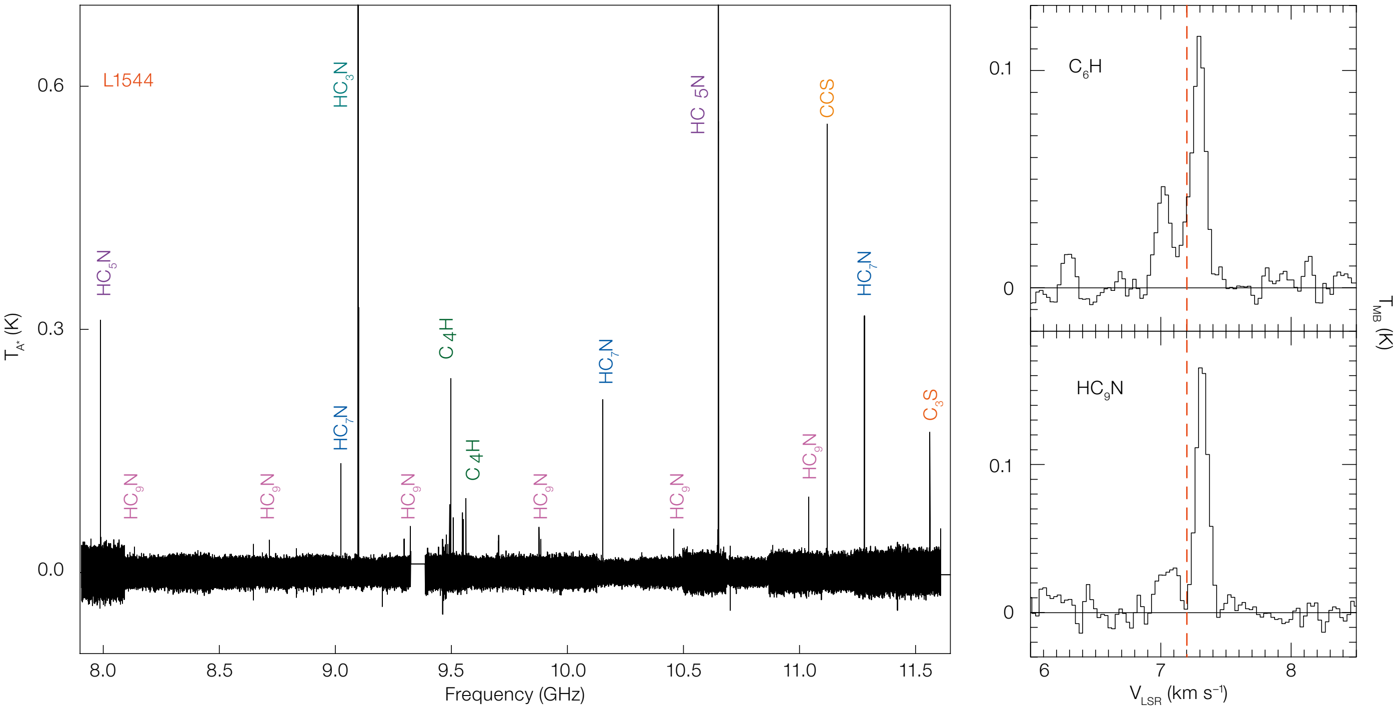

Figure 2. Complex carbon species observed towards the prestellar core L1544 using the GBT single-dish telescope (Bianchi et al., 2023). These observations have been acquired in the context of pilot projects aimed at preparing the scientific cases on C-bearing complex species observable in the frequency window of the SKA1-Mid Band 5.

Janksy Very Large Array (JVLA) is shown in Figure 1b (Macias et al., 2016). SKA-Mid will achieve an angular resolution more than 10 times smaller than these observations (0.034 arcseconds at 12.5 GHz). This, combined with sensitivities more than four or five times higher than what is currently possible, will enable a precise decomposition of the various processes occurring in young stellar objects that emit at these frequencies.

A natural synergy to this comes with ESO's Multi-Object Optical and Near-infrared Spectrograph (MOONS) instrument at the Very Large Telescope (VLT). MOONS will have the ability to simultaneously obtain one thousand multiplex spectra in the *H* band across a 25-arcminute field of view (see Figure 1a). This wavelength range (0.65–1.8 microns) covers a variety of diagnostic emission lines that can reveal much about the accretion processes in young stellar objects. Line luminosities can be converted to stellar mass accretion rates using well-calibrated scaling relations (for example, Fairlamb et al., 2017), spectrally resolved emission lines give clues to the morphology and kinematics (disc, jet, infall; for example, Chojnowski et al., 2017), and relative intensities can be used to derive physical conditions of the emitting material (for example, temperatures and densities, Campbell et al., 2023, and see Figure 1c).

SKA-Mid and MOONS/VLT will open a new window to understanding accretion and ejection in young stars. Owing to the highly variable nature of emission mechanisms in both the infrared and radio regimes (for example, Wolk et al., 2018; Curone et al., 2023), closely coordinated observations will be required (within days to hours). Such contemporaneous observations will reveal links between stellar accretion rates and outflow momentum rates, allowing us to understand the efficiency of star formation itself for the first time. The wide fields of view of both instruments will enable these studies to be performed on statistically significant numbers of young stars covering all evolutionary stages. For instance, the nearest star-forming region in ρ Oph contains many hundreds of Class 0–III YSOs (see Figure 1a). Combining these multiwavelength results will allow us to piece together the most detailed picture yet of how young stars and planets grow while interacting with their natal environment.

Complex carbon chemistry in Solar System analogues with the SKAO

Life on Earth is carbon-based, and carbon serves as the primary structural component, or 'backbone', of prebiotic species. Despite their crucial role in synthesising prebiotic compounds, complex carbon chains and rings (molecules containing more than five carbon atoms) remain relatively unexplored in astrochemical studies. This is primarily due to the faintness of spectral lines associated with complex carbon chains and rings at millimetre wavelengths, necessitating observations at radio wavelengths for their exploration.

Surveys conducted at radio frequencies using the Green Bank Telescope (GBT) and the Yebes 40-metre telescope have led to the detection of numerous complex carbon species in a few prestellar cores (McGuire et al., 2020; Cernicharo et al., 2021; Bianchi et al., 2023). These findings confirm the existence of complex carbon chemistry during the early stages of Solar System precursor formation (see Figure 1). If these species are stored within icy grain mantles and subsequently integrated into the disc, they will contribute to the organic material transported from the pre- and proto-stellar phases to newly formed planetary system objects such as asteroids and comets (Mumma & Charnley, 2011; Sakay & Yamamoto, 2013; Ceccarelli et al., 2023).

The unique synergy between SKAO and ESO facilities will provide us with the opportunity to explore, for the first time, the complete chemical composition of planet formation regions. On the one hand, the new Atacama Large Millimeter/submillimeter Array (ALMA) Band 1 and Band 2, along with the ALMA Wideband Sensitivity Upgrade (WSU), will allow us to study emissions from interstellar complex organic molecules. These molecules are species with more than six atoms, containing oxygen and/or nitrogen, and are considered the precursors of more complex prebiotic species. On the other hand, SKA-Mid will give us the unique possibility of exploring complex carbon species below 20 GHz in planet-forming discs.

The combination of the ALMA WSU and SKA-Mid will provide us with large spectral coverage, allowing us to have, for the first time, a complete view of the physics and chemistry of planet-forming discs, including the mid-plane region that is deeply obscured by dust opacity at high frequencies. Moreover, the large spectral coverage will ensure that we can observe several transitions and obtain the gas physical parameters via radiative transfer analysis or detect weak species via stacking techniques. We developed an SKA-Mid Scientific use case[1], in the framework of the Cradle Of Life working group, to observe the Orion molecular cloud 2 (OMC-2) region. This active star-forming filament hosts a diverse population of both low- and high-mass stars and discs (López-Sepulcre et al., 2013; Tobin et al., 2019), making it ideal for single-pointing observation within the large SKA field of view. Among these, the FIR 4 region is of particular interest because of its exposure to a flux of high-energy cosmic-ray-like particles (Fontani et al., 2017; Favre et al., 2018). This heightened exposure closely mirrors the conditions experienced by the young Solar System, which formed within a dense cluster of stars (Lichtenberg et al., 2019). Consequently, OMC-2 FIR4 is considered one of the closest analogues to the environment in which our Sun may have formed, making it an ideal location for studying chemistry reminiscent of our early Solar System. We propose to image the spatial distribution of complex carbon species in SKA-Mid Band 5 at angular scales of 0.5 arcseconds (corresponding to ~ 200 au at the source distance). This will perfectly complement surveys dedicated to the ongoing chemical exploration of the region at (sub-)millimetre wavelengths with ALMA and dedicated to the detection of interstellar complex organic molecules (for example, the ORion ALMA New GEneration Survey [ORANGES]; Bouvier et al., 2022).

Blind surveys of the Galactic plane and Galactic structure

Large-scale surveys of the Galactic plane at radio wavelengths can be used to study a very broad range of astrophysical phenomena (for example, Beuther et al., 2016; Brunthaler et al., 2021; Goedhart et al., 2024). With observations of the radio continuum one can observe various stages during the life cycle of stars and their interaction with the interstellar medium, from tell-tale tracers of star formation including compact, ultra- and hyper-compact HII regions, to radio continuum emission from active radio stars, to the graveyards of stars in the form of planetary nebulae and supernova remnants, as well as X-ray binaries and pulsars. Observations of polarised emission and spectral index information can be used to separate thermal from non-thermal emissions which will give important insights into the emission mechanisms of sources. On the other hand, observations of spectral lines give access to the gas in the Milky Way. Spectral-line observations give also access to kinematic information about the neutral atomic gas (for example, HI), the ionised gas (for example, radio recombination lines), and the molecular gas (for example, hydroxyl, methanol, formaldehyde).

Galactic plane surveys with SKA-Mid will deliver an unprecedented view of our Galaxy. Pushing sensitivity down to tens of microjansky, about 1000 point sources and 30 extended sources per square degree will be detected, enriching the census of Galactic objects and even allowing the discovery of new source types (for example, the 'Odd Radio Circles' described by Norris et al., 2021). In the Galactic plane, roughly a quarter of the point sources are likely Galactic (for example, Cavallaro et al., 2018). This result is usually derived from a statistical comparison with extragalactic fields and does not provide any useful information on single sources.

Radio spectral indices can help distinguish thermal and non-thermal sources, but degeneracy (when different kinds of sources share the same spectral index) and mimics (sources whose class has a typical spectral index may have a different one) strongly limit this method. In-band spectral indices are possible only for very bright sources and multi-epoch observations at different wavelengths are not capable of providing spectral information for variable sources.

In principle, cross-matching with optical and infrared surveys can provide a huge quantity of complementary data that can almost unambiguously classify a source. However, the mere positional cross-matching has proven unfeasible in many circumstances. On the one hand, at the typical resolution of current radio surveys (a few arcseconds, for example the South African Radio Astronomy Observatory's MeerKAT Galactic Plane Survey), a single radio source may 'cover' several optical or near-infrared sources. On the other hand, surveys like the 2-Micron All Sky Survey are close to the confusion limit. Spurious matches are therefore very likely (for example, Umana et al., 2015).

The improvement in resolution and imaging fidelity (extended also to polarisation and time-domain) offered by SKA-Mid will certainly mitigate this problem. An SKA-Mid Band 5 survey of the Galactic plane, with a resolution better than 0.5 arcseconds, will represent a major step forward. This resolution is similar to that of the Visible and Infrared Survey Telescope (VISTA) and VLT Survey Telescope (VST).

After a first tentative classification, follow-up spectroscopic studies may be proposed in both the radio and optical/infrared. Both radio recombination lines and infrared lines can strongly constrain the nature of the source, supporting or discarding the cross-identification. Instruments like the Enhanced Resolution Imager and Spectrograph adaptive optics instrument at the Very Large Telescope (ERIS/VLT) will be perfectly suitable for near- and mid-infrared observations.

Depending on the nature of the source, simultaneous observations are usually not required. Variable sources (active stars, star-planet interaction) can instead benefit from simultaneity, even if, limiting to the simple classification, not strictly necessary. For certain science cases (such as luminous blue variable binaries), coordinated observations can be exploited to correlate the presence of infrared spectral features with the radio variability, further constraining the nature of the sources.

The interpretation of observations of Galactic sources depends critically on our knowledge of the distance to the object. Kinematic distances and luminosity distances can have very large systemic biases. Since many radio sources are located in the highly obscured spiral arms of the Milky Way, the Gaia space observatory is not able to see them and measure accurate parallaxes. However, radio waves are not affected by extinction, and using SKA-Mid in VLBI mode one can measure highly accurate parallaxes of radio continuum sources as well as maser sources in high-mass star-forming regions, which trace these spiral arms (Reid et al., 2019).

The Galactic centre

Embedded deep inside the Milky Way's bar, at 8.25 kpc from Earth, we can find the central components of the Milky Way: the four million solar mass black hole Sagittarius A* (Sgr A*), arguably the best studied object of its kind (GRAVITY Collaboration, 2020); the nuclear star cluster (~ 3 pc half-light radius and stellar mass ~ $2.5 \times 10^7\ M_\odot$; Schödel et al., 2014); and the so-called nuclear stellar disc (vertical and radial scale heights ~ 30 and ~ 100 pc, respectively; stellar mass ~ $1.0 \times 10^9\ M_\odot$; Launhardt, Zylka & Mezger, 2002). The Galactic centre (GC) thus contains the typical building blocks of a barred spiral galaxy. It is the only galactic nucleus that can be observationally resolved down to scales of milliparsecs (1 arcsecond corresponds to 40 milliparsecs at the distance of the GC).

On average, the GC is the most extreme astrophysical environment in the Milky Way. Its star formation rate, normalised by volume, is about two orders of magnitude greater than in the Galactic disc (Henshaw et al., 2023). The stellar density, the magnetic field and the properties of the interstellar medium in the GC make this region a nearby analogue to high-redshift star-forming regions (Kruijssen & Longmore, 2013). Because of its properties and nearness, the GC plays a unique role in astrophysics as a template for understanding the structure and kinematics of the stars and interstellar medium in a spiral galaxy nucleus and how those components interact with the massive central black hole. It is also an excellent proxy for the conditions in high-redshift star-forming galaxies.

As a result of this exceptional relevance, the GC has been extensively studied with all major observatories, such as the Atacama Large Millimeter/submillimeter Array (ALMA), the W. M. Keck Telescopes, the Hubble and James Webb space telescopes and ESO's VLT and VLT Interferometer. The high angular resolution and sensitivity of SKA-Mid, combined with its large field of view, will allow us to explore the radio emission from stellar and gas sources at the GC with unprecedented quality.

Much potential GC science with SKA-Mid does not necessarily require coordinated or quasi-simultaneous observations with ESO facilities. However, the study of neutron star and black-hole X-ray binaries (XBs) could receive a significant boost from a coordinated approach. The stellar density at the GC is extremely high, which may favour the dynamical formation of XBs (for example, Generozov et al., 2018). XBs have been reported to show a tight correlation between their radio and infrared luminosities when they undergo an outburst and enter the so-called hard state that is dominated by jet emission (see Russell et al., 2006 and Figure 3).

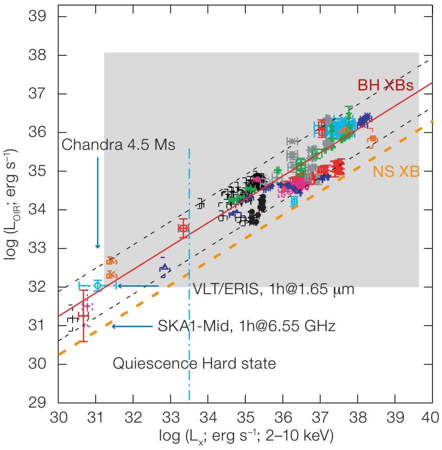

Figure 3. Radio–optical/infrared–X-ray correlation of XBs (Figure from Russell et al., 2006; different colours and symbols indicate different sources measured in different states). The flux densities are scaled to a distance of 8 kpc, closely corresponding to the distance of the GC. An extinction of 4.5 mag is applied to the near-infrared *H*-band fluxes. The continuous red line indicates the relation for black hole XBs and the dashed orange one for neutron star XBs. The blue, annotated arrows indicate, approximately, the detection limit of the 4.5 Ms deep Chandra field reported by Zhu, Li & Morris (2018), the one-sigma detection limit of SKA1-Mid imaging in one hour on source (using the SKAO sensitivity calculator[2]), and the detection limit of ERIS/VLT in the *H* band in a one-hour observation (several tens of sigma detection; the limiting factor is the stellar crowding in the GC).

This relation has been established only with a handful of sources at relatively uncertain distances. As shown in Figure 4, the GC can provide us with the opportunity to investigate these sources in large numbers and at a well-defined distance to constrain their radio–infrared correlation over more than six orders of magnitude in brightness. The observations will also serve to study their still poorly constrained recurrence times and to better understand the properties of the dark cusp of stellar black holes around Sgr A* (Hailey et al., 2018). Some pulsars/magnetars at the GC may also be detectable at infrared wavelengths, thus helping us to gain deeper insights into this population.

Based on our current knowledge of the star formation history in the nuclear star cluster (for example, Schödel et al., 2020), we estimate that the primary beam of SKA-Mid in Band 5b (central frequency 11.85 GHz) will contain ~ 10^5 neutron stars and a few times 10^4 stellar black holes when pointed at Sgr A* (Figure 2). If only

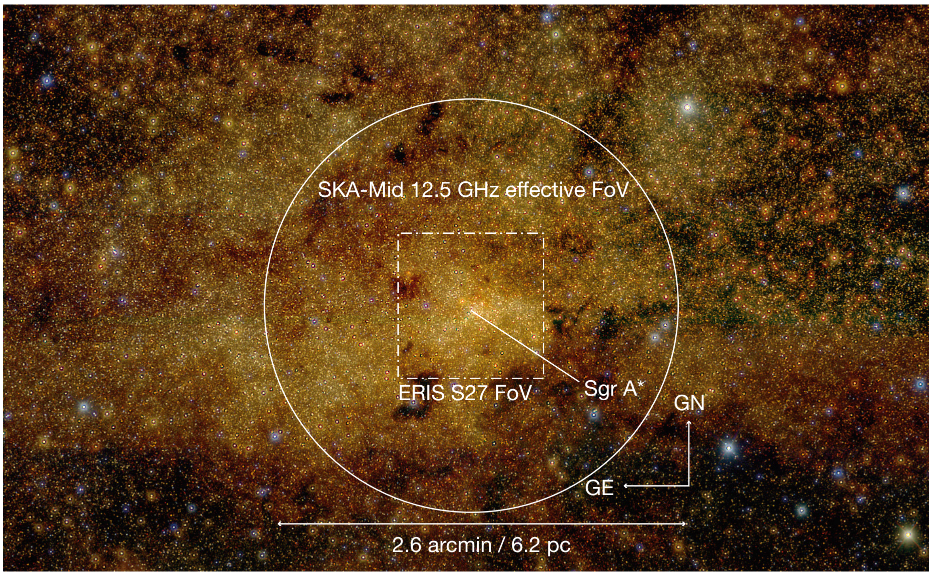

Figure 4. *JHK*s near-infrared image of the nuclear star cluster of the Milky Way. The circle indicates effective beam of SKA-Mid in Band 5a (central frequency 6.7 GHz). About 10^4 stellar black holes (and one supermassive black hole) and 10^5 neutron stars are located within this beam. The dashed square indicates the field of view of the near-infrared camera ERIS/VLT. The field of view of the future Multi-AO Imaging Camera for Deep Observations (MICADO) at ESO's Extremely Large Telescope will only be about 10% smaller.

a small fraction of them are contained in binaries, it is plausible that at any given time SKA-Mid will pick up an XB in a state bright enough that it may be detected by infrared imaging. The latter should be performed quasi-simultaneously with the radio imaging (within a few days). The angular resolution of SKA-Mid at band 5 (FWHM ~ 0.07 arcseconds) is an excellent match to that provided by ERIS/VLT. This high angular resolution is necessary to disentangle the crowded stellar field at the GC. The SKA-Mid observations can be used to trigger those by ERIS/VLT, which has a significantly smaller field of view. The GC contains a significant number of massive post-main-sequence stars (for example, Feldmeier-Krause et al., 2015) which will be picked up by the SKA1-Mid because of the thermal radio emission from their winds (for example, Yusef-Zadeh et al., 2015). These stars can therefore be used to cross-register radio and infrared imaging.

In order to reach down to almost quiescent black hole XBs and to constrain the recurrence time of these sources, repeated multi-epoch pointings towards Sgr A* over several years are required, with a total observing time of at least 100 hours per band. Quasi-simultaneous imaging with ERIS/VLT should be carried out in the *H*, and *K*s bands. One-hour observations, including overheads, will be sufficient. Two filters are required to confirm the location of the sources at the GC via their reddening. Observations in the *J* band would suffer from > 8 mag of extinction.

Owing to our limited knowledge about the target population (number of XBs, recurrence times, brightness range), it is currently hard to provide an estimate of the required time with ERIS. SKA observations should be followed up by infrared imaging within not more than a few days if changes are detected in the radio images. Only a fraction of the radio observations will require ERIS/VLT follow-up with a pointing towards the target of interest. If we assume that 30% of all SKA observations should be followed up, then an upper limit of 200 hours may be required with ERIS.

Summary

Combining observations using SKA-Mid in the radio regime with data in the millimetre, infrared and optical regimes is decisive for all the science cases described above. The multiwavelength data will allow us to identify reliably the types of observed objects and provide us with key information about the accretion/emission state of protostars and stellar remnants as well as about the interstellar medium. The necessary ESO facilities are primarily ALMA, VISTA, MOONS and ERIS on the VLT, and the VST. Quasi-simultaneous observations will be required for the young cluster field and stellar remnants at the Galactic centre, owing to the variability of the targets.

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Links

[1] SKA scientific use cases: https://www.skao.int/sites/default/files/documents/d35-SKA-TEL-SKO-0000015-04_Science_UseCases-signed.pdf
[2] https://www.skao.int/en/science-users/ska-tools/493/ska-sensitivity-calculators

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An ESO–SKAO Synergistic Approach to Galaxy Formation and Evolution Studies

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We highlight the potential benefits of a synergistic use of SKAO and ESO facilities for galaxy evolution studies, focusing on the role that ESO spectroscopic surveys can play in supporting next-generation radio continuum and atomic hydrogen (HI) surveys. More specifically we illustrate the role that currently available or soon to be operational ESO multiplex spectrographs can play for three classes of projects: large/deep redshift survey campaigns, integral field unit/Atacama Large Millimeter/submillimeter Array (IFU/ALMA) surveys of selected regions of sky, and IFU/ALMA follow-ups of selected samples. We conclude with some general recommendations for an efficient joint exploitation of ESO–SKAO surveys.

Introduction

A panchromatic approach is essential for a comprehensive understanding of the complex process of galaxy formation and evolution, and of the concurrent growth of supermassive black holes (SMBH) at galaxy centres. Only through observations along the entire range of the electromagnetic spectrum it is possible to get a full census of the physical (thermal and non-thermal) processes regulating star formation and nuclear activities in galaxies, as well as of the various galaxy components (stars, multi-phase gas, dust, relativistic plasma; see, for example, Figure 1), and link these to the evolutionary properties of galaxies as a whole.

No less important is the role of multi-wavelength follow-ups of given samples to identify wavelength-dependent systematics and/or selection biases, that may hinder a full understanding of the underlying physics (see, for example, Stark et al., 2021; Catinella et al., 2023).

The astronomical community has a long track record of jointly exploiting combinations of observations at many wavelengths. Obvious examples are i) the COSMOS[1] and GOODS[2] fields, which have been targeted by virtually all telescopes from ground and space, and can count on deep photometry over a wide range of wavelengths, as well as sensitive spectroscopy, and ii) the WEAVE-LOFAR[3] project, which represents a very good example of a spectroscopic follow-up campaign of a wide-area radio-continuum survey.

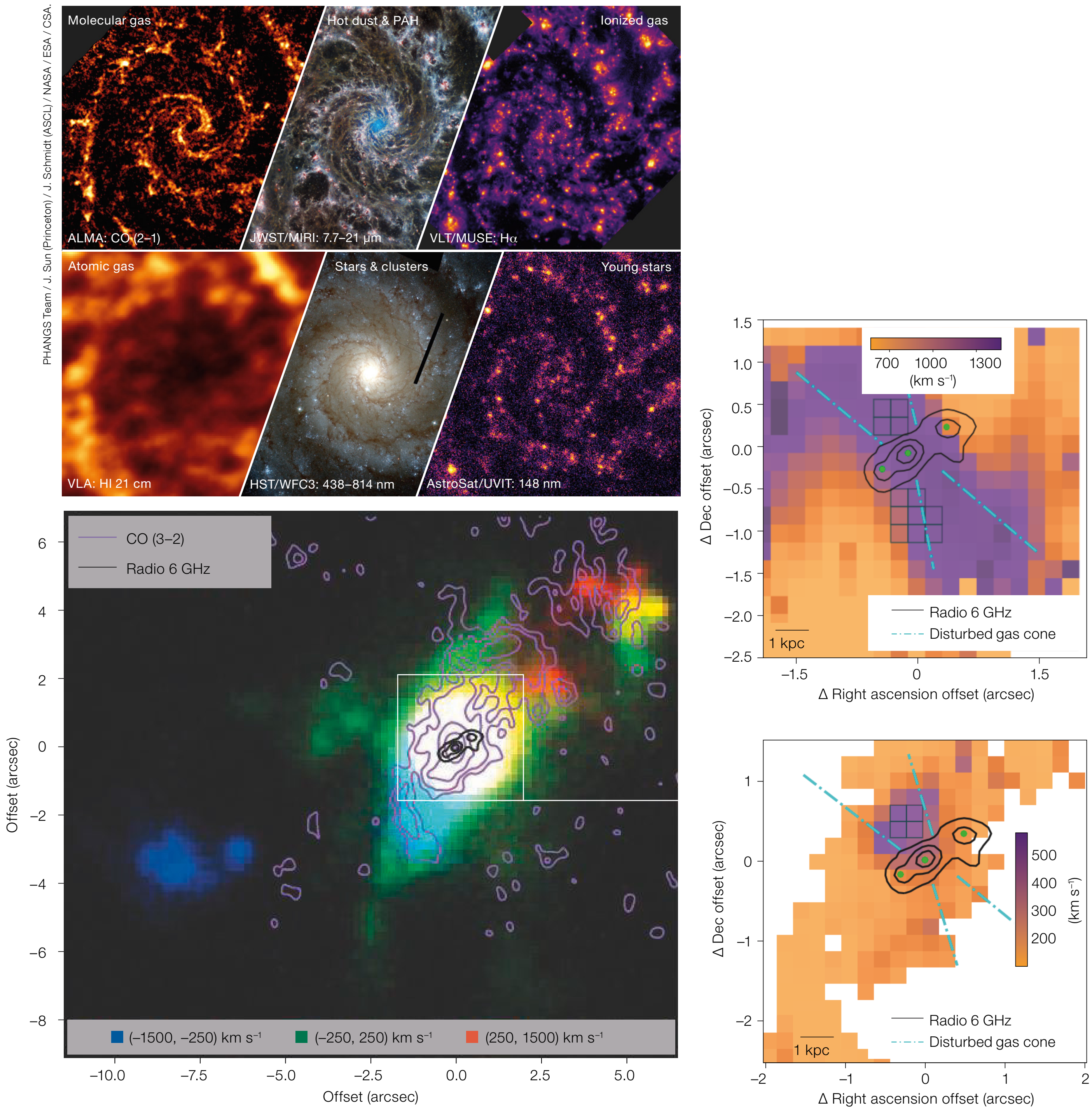
In this paper we briefly review the role that ESO facilities can play in supporting galaxy-evolution studies, building on radio continuum and 21-cm line surveys from SKA and its precursors, and make some general recommendations that could render joint SKAO–ESO projects more effective (for a description of SKAO, SKA precursors and ESO facilities we refer to Bonaldi et al., on page 5 of this edition). The content of this paper is mostly (but not only) based on dedicated discussions at the Coordinated Surveys of the Southern Sky workshop[4], held in 2023 at ESO headquarters.

SKAO and ESO working together

SKA radio continuum (Prandoni & Seymour, 2015) and 21-cm line (Staveley-Smith & Oosterloo, 2015) surveys will have a transformational impact on galaxy formation and evolution studies, as SKA precursors are already demonstrating to some extent. The former will provide an unbiased view of star formation across the Universe, and will probe jetted active galactic nuclei (AGN) down to the lowest radio powers, offering unique insights into the role of jet-induced AGN feedback. The latter will be able to detect neutral hydrogen (HI) emission from individual galaxies up to redshift $z \sim 1$ for the first time, as well as HI absorption to higher z, hence uncovering the role of HI in galaxy assembly and evolution.

SKAO surveys will need to be complemented by observations at shorter wavelengths to fully unlock their scientific potential, and ESO will play a key role in this respect. ESO can provide access to multi-band photometry and to optical/near-infrared (NIR) spectroscopy, through multi-object spectrographs (MOS). Both are essential for: i) properly identifying radio sources and deriving source distances (through spectroscopic or photometric redshifts); ii) classifying radio sources into AGN and star-forming galaxies (SFG); and iii) inferring important physical characteristics (for example, bolometric luminosities, stellar masses, star formation rates [SFR], metallicities, environment, etc.), and linking these to the radio-derived galaxy properties, such as, for example, SFR, AGN radio power, HI mass and kinematics, etc. Comparing radio SFR to SFR indicators derived at other wavelengths can provide useful information on selection effects due to dust attenuation. Optical/NIR spectroscopy can also play a key role in addressing galaxy/AGN HI properties beyond HI detection limits, enabling HI stacking experiments (see, for example, Brown et al., 2017; Chowdhury, Nissim & Chengalur, 2022; Sinigaglia et al., 2022).

No less important is integral field spectroscopy (IFS) and the leading role that



PHANGS Team / J. Sun (Princeton) / J. Schmidt (ASCL) / NASA / ESA / CSA.

Figure 1. Top: A collection of images of the nearby disc galaxy NGC 628. Each panel highlights a different galactic constituent, obtained through observations with different instruments, over a range of wavelengths (as indicated in the panels), namely: Physics at High Angular resolution in Nearby Galaxies (PHANGS)-ALMA (Leroy et al., 2021), PHANGS-JWST (Lee et al., 2023), PHANGS-MUSE (Emsellem et al., 2022), The HI Nearby Galaxy Survey (THINGS; Walter et al., 2008), PHANGS-HST (Lee et al., 2022), and PHANGS-AstroSat (Hassani et al., 2024). Bottom left: Multi-wavelength images of a $z = 0.15$, type-2 quasar, showing the impact of small-scale jets on the interstellar medium. The background image shows three velocity slices of [OIII] λ5007 emission (ionised gas), traced by MUSE. The radio jet is shown as black contours. The right pannels show velocity dispersion of ionised gas ([OIII], top) and cold molecular gas (CO (3-2), bottom) traced by ALMA. Regions with high dispersion (purple spaxels) are orthogonal to the jet axis and different gas phases are affected on different spatial scales. Adapted from Girdhar et al. (2022).

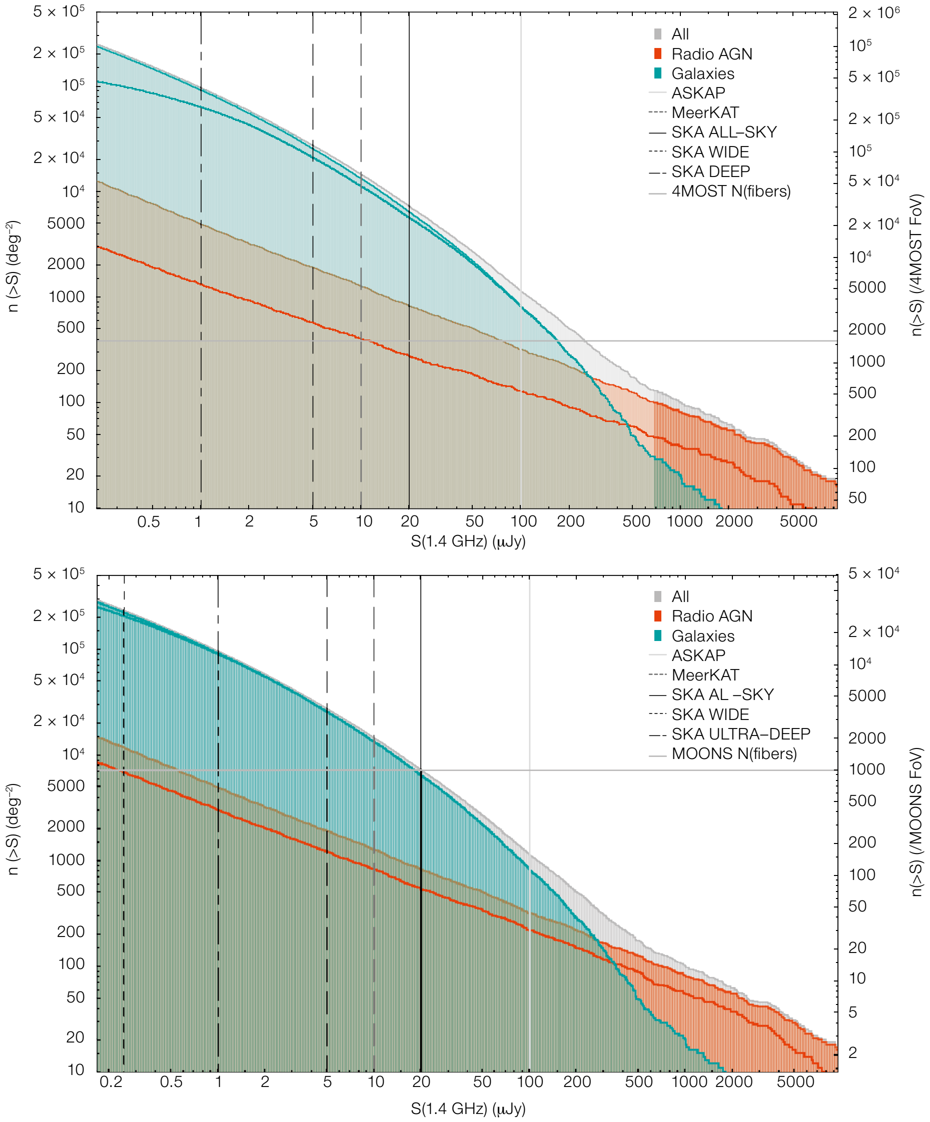


Figure 2. Radio continuum source cumulative number density predictions from T-RECS (Bonaldi et al., 2023) for different classes of sources, compared with 4MOST (top) and MOONS (bottom) capabilities. The y-axis on the left indicates the number of sources in a 1-deg^2 field. The y-axis on the right shows the number of sources in the 4MOST (top) and in the MOONS (bottom) field of view. The grey horizontal lines indicate the number of fibres available for 4MOST (2 × 812 for low-resolution spectroscopy; top) and MOONS (1000; bottom). The filled histograms in both panels represent radio source populations: galaxies (cyan), radio AGN (red) and the sum of the two (light grey). The thick lines of the same colours correspond to sources from the aforementioned populations that can be detected by 4MOST in two hours of exposure (i.e. with $r_{AB} < 22.5$; de Jong et al., 2019; top) or MOONS in one hour (i.e. with $H_{AB} < 22$; Cirasuolo et al., 2020; bottom). The vertical lines indicate expected radio continuum survey depths for SKA-Mid (Prandoni & Seymour, 2015) and its precursors (EMU at ASKAP and MIGHTEE at MeerKAT). In the top panel only surveys covering sky areas larger than the 4MOST field of view are shown.

ESO's suite of integral field units (IFU) can play in combination with Atacama Large Millimeter/submillimeter Array (ALMA) and SKAO observations. Together, they can provide a resolved view of the various components (stars, dust, molecular, ionised, atomic gas) and related processes involved in galaxy assembly and evolution. In this respect, particularly interesting is the possibility of using different tracers to probe different scales, thereby linking the internal galaxy properties with the circumgalactic medium and ultimately the cosmic web (see, for example, gas spin-filament alignments: Welker et al., 2020; Tudorache et al., 2022; Barsanti et al., 2022, 2023). Detailed investigations of the AGN fuelling/feedback cycle would also benefit greatly from resolved multi-line observations, providing 3D snapshots of inflows and outflows for the various gas phases involved in these processes. While the HI 21-cm line can be observed by the SKAO, molecular and ionised gas phases require observations at shorter wavelengths, from (sub-)mm to NIR/optical/ultraviolet bands.

Establishing joint SKAO–ESO partnerships in a timely fashion is especially important when it comes to exploiting ESO's facilities for follow-up spectroscopic campaigns, which are usually the observational bottleneck that prevents a prompt scientific exploitation of radio surveys.

We identify three main classes of spectroscopic surveys needed to support new-generation radio surveys:

- Redshift survey campaigns with medium to large field of view (FoV) multiplexed spectrographs (for example, the 4-metre Multi-Object Spectrograph Telescope [4MOST] and the Multi-Object Optical and Near-infrared Spectrograph [MOONS]), supporting wide-area and (degree-scale) deep radio continuum surveys;
- IFU (for example, the Multi Unit Spectroscopic Explorer [MUSE], BlueMUSE, the *K*-band Multi Object Spectrograph [KMOS], and the MOSAIC spectrograph at ESO's Extremely Large Telescope [ELT]) and ALMA surveys of selected regions of sky, to gather spatially resolved spectroscopy on sizeable samples of galaxies and AGN for multi-phase studies on kpc/sub-kpc scales over a wide range of redshifts.
- IFU and ALMA targeted surveys (at both low and high redshift), including small FoV IFUs, such as, for example, the Enhanced Resolution Imager and Spectrograph (ERIS), the NIRSpec IFU, the Mid InfraRed Instrument's medium resolution spectroscopy mode (MIRI/MRS), and the Multi-conjugate-adaptive-optics-Assisted Visible Imager and Spectrograph (MAVIS), which trace ionised/warm molecular gas.

In addition we identify two main time scales for joint SKAO–ESO projects:

- Short- to medium-term, linked to several upcoming opportunities such as, for example, KMOS public surveys, MOONS open time operations and second-generation 4MOST ESO community surveys (likely starting around 2030). Over this timescale the first stages of the ALMA wideband sensitivy upgrade (Carpenter et al., 2022) should also be completed;

- Long-term (> 2035), when ESO facilities will directly support SKAO surveys (and vice versa). At this point, ELT instrumentations such as MOSAIC will likely be available, perhaps further supported by a wide-field spectroscopy-dedicated telescope (like the proposed concept for the Wide-field Spectroscopic Telescope[5]; see also Mainieri et al., 2024; Bacon et al., 2024).

In the following we focus on short- to medium-term projects, that should be defined in the near future. Before the end of the current decade, spectroscopy targets will necessarily have to be selected from currently ongoing radio surveys with SKA precursors. Particularly relevant for galaxy evolution studies are ongoing surveys with SKA-Mid precursors, for example the EMU[6] and WALLABY[7] wide-area surveys at the Australian SKA Pathfinder (ASKAP), or the MIGHTEE[8] and LADUMA[9] surveys with MeerKAT.

The role of MOS: 4MOST and MOONS

ESO's new-generation multi-fibre spectrographs 4MOST and MOONS can be effectively used for complementary spectroscopic follow-up campaigns of radio sources, targeting different redshift ranges.

Thanks to its large FoV (4.2 square degrees) and large number of fibres (1624 for low-resolution spectroscopy), 4MOST is ideally suited to follow-up spectroscopy of relatively shallow large-area radio surveys. Figure 2 shows the redshift –1.4 GHz flux density distribution of radio sources from the Tiered Radio Extragalactic Continuum Simulation (T-RECS; Bonaldi et al 2023). All radio-selected galaxies from, for example, the EMU ASKAP survey ($S_{1.4GHz}$ > 100 μJy), and from the planned all-sky SKA-Mid survey ($S_{1.4GHz}$ > 20 μJy), are detectable by 4MOST in two hours of exposure (de Jong et al., 2019; see thick cyan line in

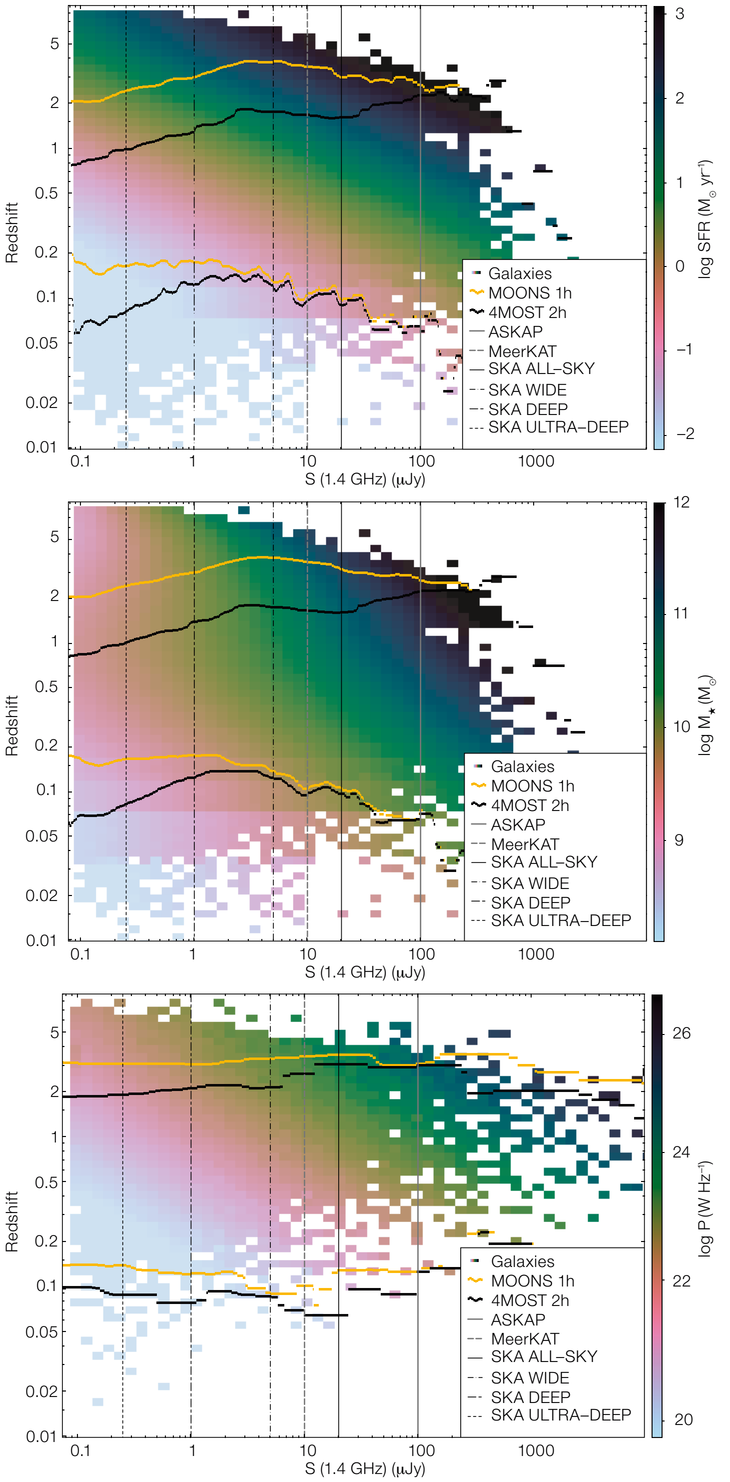


Figure 3. 1.4 GHz flux (in μJy) vs redshift distribution of simulated radio continuum sources from T-RECS (Bonaldi et al., 2023) for galaxies (top and middle panels) and radio-loud AGN (bottom panel) in a 1-deg^2 field of view. The colour grid shows variations of a third parameter, namely star formation rate and stellar mass (top and middle panels), and radio power (bottom panel). The overplotted lower and upper curves in all panels show respectively the 1% and 99% quantiles of the flux–redshift distribution for sources that can be detected by 4MOST (black curves) and MOONS (yellow curves) in the given exposure times (see legend in each panel). Vertical lines as in Figure 2.

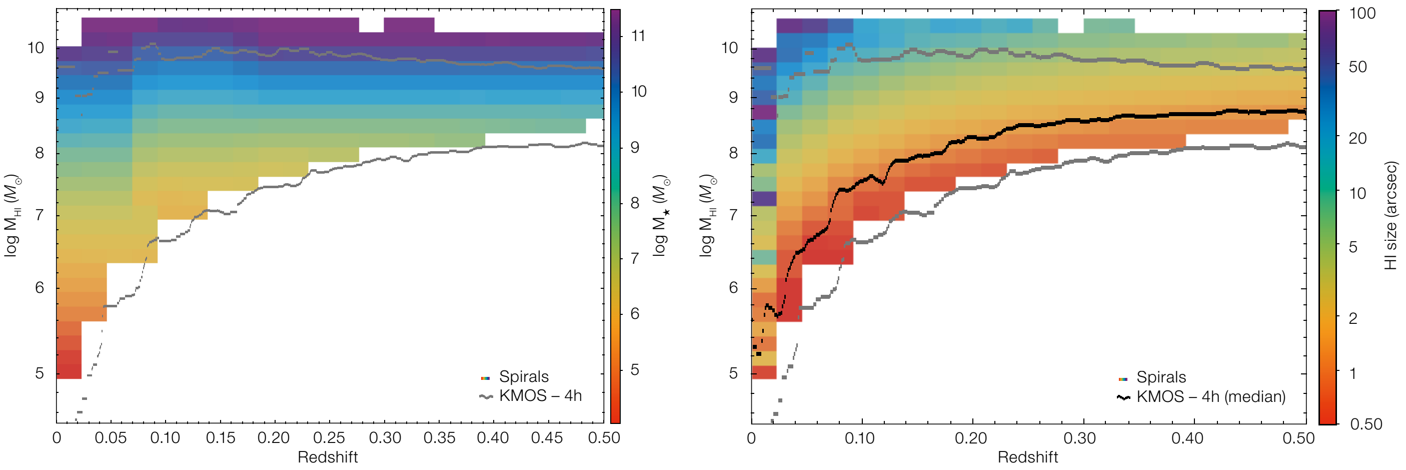


Figure 4. HI mass vs redshift distribution of late-type galaxies from T-RECS simulations (Bonaldi et al., 2023). The T-RECS HI simulation is limited to z ~ 0.5. The colour grid shows variations in stellar mass (left) and HI size (right). The overplotted grey curves show the 1% (lower) and 99% (upper) quantiles of the M(HI)–redshift distribution for sources that can be detected by KMOS with a four-hour exposure (i.e. with $K_{AB} < 22.5$; Birkin et al., 2024). The black curve in the right panel indicates the median of the distribution.

the top panel). In addition, the 4MOST fibre density (horizontal grey line) provides a good match to the cumulative number density of detectable galaxies at the EMU limit. On the other hand, in two hours 4MOST can detect only about 25–30% of the radio AGN population at all fluxes (thick red line), but provides a good match in terms of detectable radio AGN number density down to $S_{1.4GHz}$ ~ 5–10 µJy, i.e. down to the MeerKAT MIGHTEE and the planned SKA-Mid WIDE survey limits. As shown in Figure 3 (black curves), 4MOST mainly samples galaxies at $z < 1$ (top), and radio AGN at $z < 2$ (bottom). A first notable example of a synergistic MeerKAT/4MOST project is the Optical, Radio Continuum and HI Deep Spectroscopic Survey (ORCHIDSS; Duncan et al., 2023), approved for the first round of 4MOST community surveys, which pre-selected radio sources from the MeerKAT MIGHTEE, LADUMA and Fornax[10] surveys.

Extending to the NIR, MOONS (1000 fibres over a 500-square-arcminute field) is particularly well suited to following up radio sources across the redshift range $1.5 < z < 2.5$, where major spectral features are redshifted out of the optical range. This redshift range is crucial for galaxy evolution studies, as it encompasses the peak of star formation and nuclear activity, and is the main target of deep, degree-scale, radio surveys with SKAO and its precursors (for example, MIGHTEE). As shown in Figure 2 (bottom), in one hour MOONS is able to detect all radio sources associated with galaxies (Cirasuolo et al., 2020; cyan line), as well as ~ 50% of the radio AGN populations (red line) down to the deepest fluxes probed by SKA-Mid radio continuum surveys ($S_{1.4GHz}$ > 0.25 µJy). The radio source cumulative number density approximately matches the MOONS fibre number density (horizontal grey line) at $S_{1.4GHz}$ ~ 10–20 µJy for galaxies and $S_{1.4GHz}$ ~ 0.2 µJy for radio AGN. It is also interesting to note that 4MOST and MOONS, combined with SKA-Mid and precursors, will be able to probe galaxies with $M_\star \sim 10^9\ M_\odot$ out to $z \sim 0.5$ and galaxies with $M_\star \sim 10^{10}\ M_\odot$ out to $z \sim 2$ (Figure 3, middle panel).

The role of IFS and ALMA

Understanding the interplay of galaxies' physical processes requires large-area surveys and/or targeted campaigns of multi-phase gas and stellar tracers, which can be obtained through coordinated spatially resolved studies with IFUs, ALMA and SKAO. The call for KMOS public surveys[11] could be exploited to trigger joint SKAO–ESO IFS projects. With its 24 independent arms each covering a 2.8 × 2.8 arcsec^2 FoV, a source with major axis greater than twice the point spread function, or > 1.2 arcsec, can be considered resolved (assuming a seeing of ~ 0.6 arcsec; Birkin et al., 2024). A possible synergistic use of SKA-Mid and KMOS is illustrated in Figure 4, which shows the HI mass distribution of T-RECS simulated spirals up to redshift $z \sim 0.5$ (Bonaldi et al., 2023). All of them are detectable (Birkin et al., 2024; see grey curves), with only about half being suitable for co-spatial resolved HI-IFU studies. KMOS could thus be exploited to follow up complete HI mass-selected samples with $M(\mathrm{HI}) > 10^{7.5\text{-}8}\ M_\odot$ up to $z \sim 0.5$, with ALMA providing the coverage of the molecular gas component of the interstellar medium at similar resolutions.

The need to cover more extended sky areas and perform blind sky integrations, for specific cases like for example, deep fields, intermediate redshift galaxy clusters or the nearby star-forming galaxy population, could be supported by dedicated campaigns with monolithic wide-field IFUs such as MUSE at the Very Large Telescope (VLT) (for example, Epinat et al., 2024, Della Bruna et al., 2022). The synergistic use of blue/optical (MUSE and later BlueMUSE), sub-mm (ALMA) and radio (SKAO) facilities represents a key leverage to reveal the full complexity and multi-phase nature of the baryon cycle in galaxies.

Summary and final considerations

As briefly discussed, ESO's MOS and IFUs can be exploited to complement new-generation galaxy-evolution-driven radio surveys. Timely radio source optical/NIR spectroscopy follow-up campaigns will ensure a prompt scientific exploitation of SKA-related surveys by, for example: i) easing the host galaxy identification and classification process; ii) enabling immediate measurements of the source physical parameters; and iii) providing prompt information on the wider environment in which the radio sources are located. IFUs and ALMA combined with SKAO will enable spatially resolved multi-scale and multiphase studies of the various processes and components involved in galaxy assembly and evolution.

In the short–medium term (≤ 2030), joint SKAO–ESO projects could exploit existing ESO instrumentation such as KMOS, MUSE and ALMA, as well as soon to be operational multi-fibre spectrographs like MOONS and 4MOST, and follow-up campaigns will have to be based on currently ongoing surveys with SKA precusors. Naturally, any planning of joint SKAO–ESO projects should bear in mind that over the next decade the optical/NIR spectroscopic survey landscape will change dramatically — not only as a consequence of 4MOST community surveys and MOONS guaranteed-time programmes, but also as a result of major non-ESO surveys such as those undertaken by ESA's Euclid mission. In the longer term, new VLT instruments like BlueMUSE, and the ELT will enable novel high-resolution and/or medium-multiplex spectroscopic studies. For specific radio source populations (for example, optically faint radio-loud objects) the ELT with MOSAIC can reveal the presence of outflow components and characteristics, and targeted IFU observations with the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI) will permit fine-grained studies of the astrophysics of stellar and AGN feedback processes within galaxies. A future facility like the WST has the potential to provide optical counterparts for the SKAO over large (~ 3 deg^2) MOS survey areas, and to study the gaseous and stellar emission in the environment of, for example, AGN at cosmic noon (z ~ 1–3) thanks to its IFU, opening new scientific opportunities and synergies.

As a final remark, we note that a prompt scientific exploitation of joint ESO–SKAO surveys will likely require an efficient use of the available infrastructures. From an operational point of view, we therefore encourage SKAO–ESO coordinated efforts towards joint proposal schemes, shared archival capabilities and joint virtual observing platforms, possibly building on the work already done by ESO and SKAO/SKA-precursors teams.

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Links

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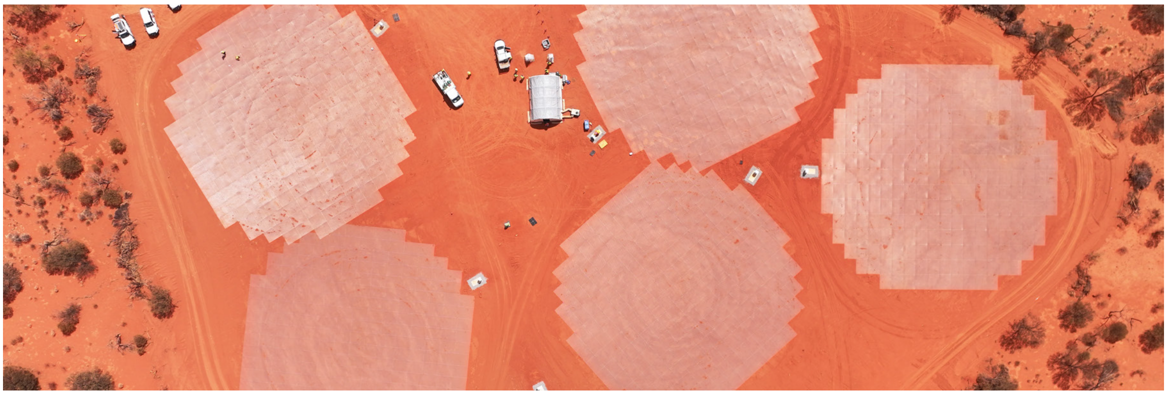
[2] GOODS: https://www.stsci.edu/science/goods/
[3] WEAVE-LOFAR: https://arxiv.org/abs/1611.02706
[4] Coordinated Surveys of the Southern Sky workshop: https://www.eso.org/sci/meetings/2023/CSSS.html
[5] WST: https://www.wstelescope.com/
[6] EMU: http://emu-survey.org/
[7] WALLABY: https://wallaby-survey.org
[8] MIGHTEE: https://www.mighteesurvey.org/
[9] LADUMA: https://science.uct.ac.za/laduma
[10] MeerKAT Fornax Survey: https://sites.google.com/inaf.it/meerkatfornaxsurvey
[11] KMOS public survey call: https://www.eso.org/sci/observing/PublicSurveys/KMOSloicall.html



SKAO

Bird's eye view of S8, a cluster of SKA-Low antenna stations. Image taken in March 2024.

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Cosmology with ESO–SKAO Synergies

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We discuss the possible synergies for cosmology between SKAO and ESO facilities, focusing on the combinations SKA-Mid with the Multi-Object Spectrograph Telescope (4MOST) instrument built for ESO's Visible and Infrared Survey Telescope for Astronomy (VISTA) and SKA-Low with ESO's Extremely Large Telescope (ELT) multi-object spectrograph MOSAIC. Combining multiple tracers allows for tackling systematics and lifting parameter degeneracies. It will play a crucial role in the pursuit of precision cosmology.

Introduction

The next decade will be dominated by large-sky surveys trying to improve on, and even provide a paradigm shift in, our understanding of the Universe. Such a change could manifest in clues about how to extend current theories of fundamental physics and combine the two pillars of quantum mechanics and general relativity. The standard model of cosmology — the so-called Λ-Cold Dark Matter model (ΛCDM) — with about six parameters, has been able to successfully describe almost all the measurements made so far. It assumes a universe with zero curvature, pressureless dark matter, and a cosmological constant, Λ, driving the observed accelerated expansion in recent times. In the recent past, observations using the cosmic microwave background (CMB) achieved unprecedented sub-percent errors on the parameters of this model (Planck Collaboration, 2020). This has been further confirmed through surveys of the large-scale cosmic structure, with the most recent examples being the Dark Energy Spectroscopic Instrument (DESI; DESI Collaboration, 2024) survey — a spectroscopic galaxy survey providing clustering statistics and constraints on baryon acoustic oscillations — and the Dark Energy Survey (DES; DES Collaboration, 2022) — a photometric galaxy survey capable of probing the matter distribution in the cosmos through weak gravitational lensing measurements.

There are, however, some tensions in the model (Di Valentino, Saridakis & Riess, 2022), in particular with the measured current expansion rate and the amplitude of cosmological fluctuations. Moreover, there is no theoretical reason to stick to the minimal ΛCDM model, and several extensions have been considered: a universe with non-zero curvature; dynamical dark energy models to account for the current accelerated expansion; interacting dark matter, including different scenarios for the neutrino species; modifications to general relativity; or changes in the nature of primordial fluctuations. Exploring possible inconsistencies in the standard cosmological model and constraining extensions to it is the main focus of upcoming cosmological surveys. Some examples are the Euclid satellite mission (Euclid Collaboration, 2024), or Vera C. Rubin Observatory (Izević et al., 2019). They will rely on a combination of probes, from galaxy clustering and weak lensing to Type Ia supernovae (SNIa). At the same time, the CMB is expected to continue to bring improvements and eventually detect primordial gravitational waves, providing insights into the physics of the early Universe.

As we enter the regime of high-precision cosmology, systematic errors are becoming the limiting factor in constraining cosmological parameters. Combining different experiments will help reduce such systematics and bring more confidence to any discovery while also lifting parameter degeneracies. Here we explore the synergy gains in combining data from the wide-area cosmology surveys planned with the SKAO and ESO facilities. For a description of what these surveys can do individually, please see SKA Cosmology Science Working Group (2020), and the 4MOST Cosmology Redshift Survey (CRS; Richard et al., 2019). Our focus is on clustering statistics using different tracers provided by these surveys. In particular, we shall consider the neutral hydrogen (HI) intensity mapping surveys planned for SKA-Mid/Low, the continuum galaxy surveys with SKA-Mid/Low, the 4MOST CRS and ELT-MOSAIC (Japelj et al., 2019).

SKA-Mid HI intensity mapping and 4MOST CRS

Intensity mapping has been hailed as a highly efficient method to probe the large-scale cosmic structure (Santos et al., 2015). Instead of requiring the detection of single galaxies and the measurement of their redshift from their spectra, it looks for the total intensity from a given line, corresponding to the combined emission from all galaxies in a voxel. This is particularly useful for the HI line which is quite weak, allowing SKA-Mid to achieve high survey speeds in single-dish mode, while maintaining high spectral resolution. The MeerKAT telescope, a percursor to SKA-Mid, has already showcased the enormous potential of this technique (Wang et al., 2021, Cunnington et al., 2023, MeerKLASS Collaboration et al., 2024). The challenge is that excellent control of systematics is required, particularly those related to bright foreground emission. Cross-correlations with galaxy surveys can therefore be extremely useful in terms of dealing with these systematics, while at the same time improving the overall constraining power on cosmological parameters. Furthermore, using multiple tracers will improve constraints on primordial non-Gaussianity that cannot be obtained independently (Fonseca et al., 2015).

In the southern sky, one of the few wide spectroscopic surveys planned is the 4MOST CRS survey, in particular for $z < 1.0$, since at higher redshifts we expect Euclid to cover a large fraction of the southern sky. Therefore, we consider

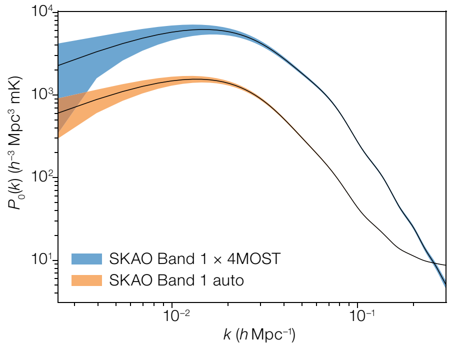

Figure 1. Constraints on the spherically averaged power spectrum for SKA-Mid and the cross-correlation with 4MOST.

here a joint analysis between SKA-Mid HI intensity mapping and the 4MOST CRS luminous red galaxies (LRG) sample with a density of 400 galaxies per square degree. Given 4MOST's redshift coverage and area, we consider a large bin centred on $z = 0.55$ with width $\Delta z = 0.3$ and covering 7500 square degrees with complete overlap. For SKA-Mid, we assume a 20 000-square-degree survey, covering $0.3 < z < 3$ with 10 000 hours of total integration. Figure 1 shows the expected constraints on the spherical averaged power spectra and Figure 2 shows the resulting cosmological constraints. Although constraints from SKA alone are forecasted to be better, this assumes a control on systematics that might be too optimistic. A multi-tracer analysis on the overlapping area can provide similar constraints while being more robust in dealing with such systematics. This approach also helps to reduce cosmic variance on very large scales, achieving a 1-σ error of 7 on the primordial non-Gaussianity parameter f_{NL}.

SKA-Mid continuum galaxy survey and 4MOST CRS

Catalogues of galaxies detected in the radio continuum typically extend to much higher redshifts than those detected at optical/near-infrared wavelengths, thanks to the fact that observations in the radio are not affected by dust obscuration. This translates into a long redshift tail, which can be exploited to track the evolution of critical cosmological quantities over cosmic time. However, redshift information is usually unavailable for continuum galaxies (see also Harrison, Lochner & Brown, 2017). For this reason, synergistic analyses with optical galaxy surveys have an enormous potential. For instance, by cross-identifying low-redshift radio-continuum galaxies with their optical counterparts, we can bin them tomographically, leaving the unmatched ones as an additional, mostly high-redshift, tomographic bin — an approach that has been suggested to deliver a large improvement on the Figure-of-merit (FoM) of the equation of state of dark energy (Camera et al., 2012).

Moreover, continuum galaxy surveys can cover up to three quarters of the sky, allowing one to probe huge swathes of cosmic volume. This is especially relevant in searches for primordial non-Gaussianity (Celoria & Matarrese, 2018) or for tests of general relativity on cosmological scales. In both cases, smoking-gun signatures appear only on the largest cosmic scales, making it paramount to be able to access the largest possible volumes. This can be achieved with an SKA-Mid continuum survey that is commensal with the planned intensity mapping survey by using the on-the-fly mapping technique. The synergy with area-overlapping spectroscopic galaxy surveys like 4MOST will be particularly important for going after such feeble signals (Raccanelli et al., 2012). Moreover, multi-wavelength data will unlock the possibility of performing a 'multi-tracer' analysis (Seljak, 2009), thanks to which the poor statistical sampling that plagues the largest scales can be alleviated. This approach has been investigated theoretically in the past in the context of continuum galaxy surveys with redshift/morphological cross-matching provided by optical/near-infrared spectroscopy. It has been suggested that it can

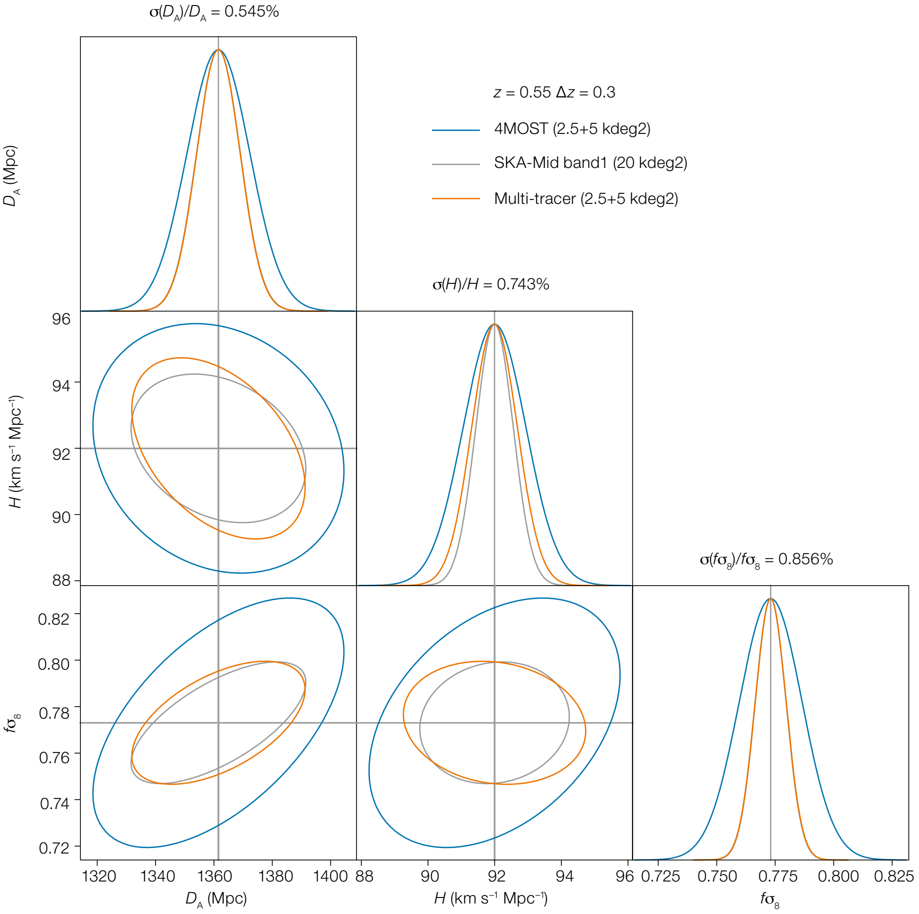

Figure 2. Constraints on the angular-diameter distance, Hubble rate and the growth rate using the 4MOST CRS LRG sample and SKA-Mid Band-1 HI intensity mapping, and their multi-tracer analysis in the overlapping sky area. The quoted relative errors refer to the multi-tracer analysis. Only one large redshift bin was assumed, and all the bias parameters were marginalised over.

SKA-Low	Frequency	Redshift	Survey Area	δf	A_{eff}/T_{sys}	Integration Time
	272-320 MHz	3.4-4.2	1 deg^2	250 kHz	1.289 m^2/K	1000 hrs
ELT MOSAIC	<F>	NDIT	Total throughput	N_{forest}	R	
	0.44	10	13%	720	5000	

Table 1. The survey specifications of SKA-Low and ELT MOSAIC assumed in this work. From left to right, the top row lists the frequency range of the survey, the corresponding redshift, the effective survey area, the frequency resolution, the natural sensitivity of one station A_{eff}/T_{sys}, and the total integration time. The bottom row lists the mean transmitted fraction of the flux <F>, the number of integration times per field with each integration time lasting 1 h (NDIT), the total throughput, the number of forests observed, and the spectral resolution.

provide one to two orders of magnitude better constraints on the amplitude of primordial non-Gaussianity, $f_{\rm NL}$ (Ferramacho et al., 2014; Gomes et al., 2020).

SKA-Low HI intensity mapping and ELT-MOSAIC

The overlapping redshift range and survey area make the 21-cm signal and measurement of the Lyman-α forest ideal candidates for cross-correlations (Carucci, Villaescusa-Navarro & Viel, 2017). Cross-correlations are highly desirable to reduce the systematic effects in both probes and to produce tighter constraints on cosmological parameters, such as the growth rate, which can directly constrain theories of gravity. To forecast the detectability of the Lyman-α forest, we follow McQuinn & White (2011) to estimate the noise power spectrum. We assume the observations from the ELT MOSAIC instrument (Japelj et al., 2019). For the HI power spectrum, we simulate baseline distributions of SKA-Low for a tracking observation and calculate the corresponding thermal noise power spectrum according to Chen & Pourtsidou (2024). The specifications of the surveys are listed in Table 1. The redshift range of the cross-correlation is chosen to be 272–320 MHz, where observations of SKA-Low have low levels of radio frequency interference.

For the auto- and cross-power spectra, we adapt the modelling of Carucci, Villaescusa-Navarro & Viel (2017) with four fitting parameters: the HI bias b_{HI}, the HI redshift distortion parameter β_{HI}, the Lyman-α forest bias b_F, and the Lyman-α forest redshift distortion parameter β_F. The fiducials values are listed in Table 2.

To capture the anisotropy of the power spectrum in redshift space, it is desirable to split the k-space into clustering wedges of different $\mu = k_{||}/k$, where $k_{||}$ is the line-of-sight mode component. We choose the number of wedges $n_{wedge} = 5$ in this work. Furthermore, for the HI auto-power spectrum and the cross-power spectrum, we assume that the first wedge $\mu < 0.2$ is dominated by foregrounds and can not be used for parameter fitting. The resulting forecasts for the detectability of the power spectra are shown in Figure 3.

Using the forecasts of the power spectrum measurements, we perform MCMC parameter fitting to the model parameters. The 1-σ confidence intervals of the model parameters are listed in Table 2. Instead of β_{HI}, we present the results in terms of the growth function $f = b_{HI}\,\beta_{HI}$, which is what we are interested in.

Including the cross-power spectrum helps to obtain better constraints on the HI parameters. Comparing the results to using auto-power only, they improve by ~ 30% the HI model parameters. These parameters are slightly biassed when cross-power is included. This is due to the fact that we assume a non-uniform cross-correlation coefficient and do not model it in the parameter fitting. Nevertheless, the fiducial values are within the 1-σ confidence interval of the posterior. Cross-correlating HI and Lyman-α forests allow us to constrain the growth function $f = b_{HI}\,\beta_{HI}$ at $z \sim 4$, providing a novel probe of cosmological expansion at high redshifts.

Summary

Near-term wide surveys in cosmology promise to bring the field to sub-percent accuracy and possibly unravel the nature of some of the most pressing open questions in cosmology, for example, the nature of dark matter and dark energy, and Inflation. In order to achieve this, we need to deal with complex systematics and break parameter degeneracies. Both issues can be addressed by combining different surveys with multiple probes. Focusing on SKAO and ESO instruments, we identified the combination SKA-Mid plus 4MOST CRS at $z < 1$ and SKA-Low plus ELT-MOSAIC at higher z to be the most interesting for cosmology. Correlations with 4MOST will constrain the standard cosmological parameters through clustering statistics that should be more robust to systematics and help us characterise the nature of dark energy and primordial fluctuations. Correlations between SKA-Low and MOSAIC will improve our knowledge of the HI content of the Universe at $z \sim 4$ and provide a novel probe of cosmological expansion at high redshifts. Other possibilities not explored here are, for instance, the measurement of the redshift drift of objects following the cosmological expansion using the ArmazoNes high Dispersion Echelle Spectrograph (ANDES) at the ELT and an SKAO HI galaxy survey, albeit this would require much more collecting area than the current SKA-Mid setup (Rocha and Martins, 2023). Another interesting prospect would be the use of a single-dish telescope with spectroscopic capabilities in the submillimetre (like the proposed concept for the Atacama Large Aperture Submillimeter Telescope [AtLAST; Mroczkowski et al., 2024]). Combining CO and CII intensity mapping surveys

Parameter	$b_{\rm HI}$	$f = b_{\rm HI}\,\beta_{\rm HI}$	b_F	β_F
Fiducial	2.50	0.986	−0.156	1.39
Auto	$2.45^{+0.26}_{-0.27}$	$1.053^{+0.504}_{-0.482}$	$-0.156^{+0.002}_{-0.002}$	$1.39^{+0.04}_{-0.04}$
Auto+Cross	$2.51^{+0.19}_{-0.21}$	$0.755^{+0.369}_{-0.354}$	$-0.156^{+0.002}_{-0.002}$	$1.39^{+0.04}_{-0.04}$

Table 2. The forecast constraints on the Lyman-α forest and 21-cm intensity mapping power spectra parameters using the assumed ELT-MOSAIC and SKA-Low surveys. The third row lists the results from using only the auto-power spectra signal while the last row includes cross-correlations.

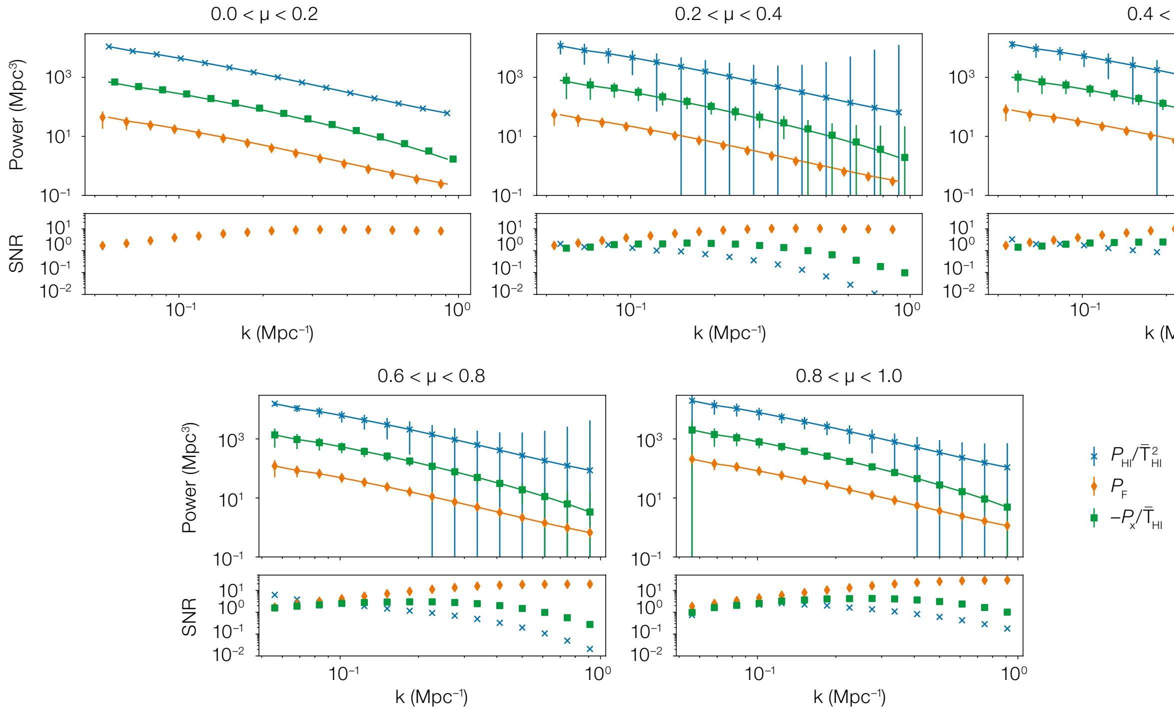

Figure 3. Forecasts for the 1D power spectrum measurements from Lyman-α forests using ELT MOSAIC and the 21-cm line using SKA-Low. The title of each panel shows the clustering wedge in which the power spectrum is averaged. The upper part of each panel shows the fiducial power spectrum for the 21-cm line, the Lyman-α forest and their cross-correlation. Note that the cross-power spectrum is negative, and its absolute values are shown. The centres of the k-bins for the Lyman-α forest and cross-power are misplaced by 5% for better visualisation. The error bar denotes the 1-σ of the measurement error. The lower part of each panel shows the signal-to-noise ratio of the measurements. We assume that the 21-cm power spectrum and the cross-power are dominated by foregrounds in the first wedge $0 < \mu < 0.2$.

from such a facility with SKA-Mid and Low will allow us to probe baryon acoustic oscillations and redshift-space distortions in the rather unexplored redshift regime between two and seven. One concerning conclusion from our analysis is the lack of spectroscopic coverage of the southern sky at $z < 1$. ESA's Euclid mission should be able to cover about 10 000 square degrees but mostly at $z > 1$ and Vera C. Rubin Observatory's Legacy Survey of Space and Time will only provide photometric redshifts. With the Extended Baryon Oscillation Spectroscopic Survey (eBOSS) and now DESI covering mostly the northern sky, the planned 4MOST CRS survey looks to be quite crucial for multi-wavelength cosmology in the southern hemisphere. In fact, it would be extremely powerful if such a survey could be expanded in the coming years in order to achieve number densities of at least 1000 per square degree in the redshift range $0.2 < z < 1.0$ over areas close to 10 000 square degrees. Although several competitive large-scale surveys will be coming online in the near future, it is becoming clear that combining these datasets will provide more than just the sum of its individual constraints and help us build robust measurements in our goal to narrow down the cosmological model.

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ESO–SKAO Synergies for the Epoch of Reionisation and Cosmic Dawn

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Mapping out the first billion years using the 21-cm line with the Square Kilometre Array (SKA) will revolutionise our understanding of the cosmic dawn, reionisation and the galaxies that drove these milestones. However, synergies with other telescopes in the form of cross-correlations will be fundamental in making and confirming initial, low signal-to-noise claims of a detection. Participants in the 2023 ESO–SKAO workshop discussed such synergies for Epoch of Reionisation (EoR) and Cosmic Dawn (CD) science. Here we highlight some of the most promising candidates for cross-correlating SKA EoR/CD observations with ESO instruments such as the Multi-Object Optical and Near-infrared Spectrograph (MOONS), the MOSAIC multi-object spectrograph, and the ArmazoNes high Dispersion Echelle Spectrograph (ANDES).

Introduction

The final phase-change of our Universe, the so-called Epoch of Reionisation (EoR), remains at the forefront of modern cosmology. After decades of studies, we are starting to home-in on the timing of the bulk of reionisation (for example, Qin et al., 2021; Bosman et al., 2022). However, we still do not really know how to connect this final phase-change of our Universe to the populations of stars and black holes that drive it.

The ultimate probe of this fundamental milestone is arguably the 21-cm line of neutral hydrogen, which is sensitive to the ionisation, temperature and density fluctuations of the intergalactic medium (IGM). Current 21-cm interferometers are aiming for a statistical detection of the 21-cm power spectrum (for example, Mertens et al., 2020; Trott et al., 2020; Abdurashidova et al., 2022). However, over the next decade(s), the Square Kilometre Array being built in Australia (SKA-Low) should provide the ultimate dataset: a 3D map of the barely-explored first half of our observable Universe. Such a worthy dataset contains precious insights into the astrophysics of galaxies and the IGM, as well as physical cosmology (see, for example, the review by Mesinger, 2020).

However, it will be a long time until we have a high-signal-to-noise (S/N) map of the EoR and the preceding Cosmic Dawn (CD). Initial claims of a detection will come from a handful of power-spectrum wave modes with low S/N. Given the novel, ground-breaking nature of the observation, it will be challenging to convince ourselves and the broader community that these preliminary 'detections' are genuinely cosmological. The best way of doing this is to cross-correlate the 21-cm signal with another signal of known cosmic origin.

In addition to providing an invaluable sanity check on preliminary claims of a 21-cm detection, cross-correlations can also improve the S/N. The cross power spectrum could provide a cleaner probe of the cosmological signal, since the foregrounds and systematics of different datasets are typically not correlated (for example, Amiri et al., 2024). Eventually, with SKA phase 2 we should be able to correlate images (i.e. including phases) of different datasets. This would allow us to study individual ionised or heated regions, comparing their tomography (obtained with SKA) to the brightest galaxies they contain (obtained with optical/IR telescopes like JWST).

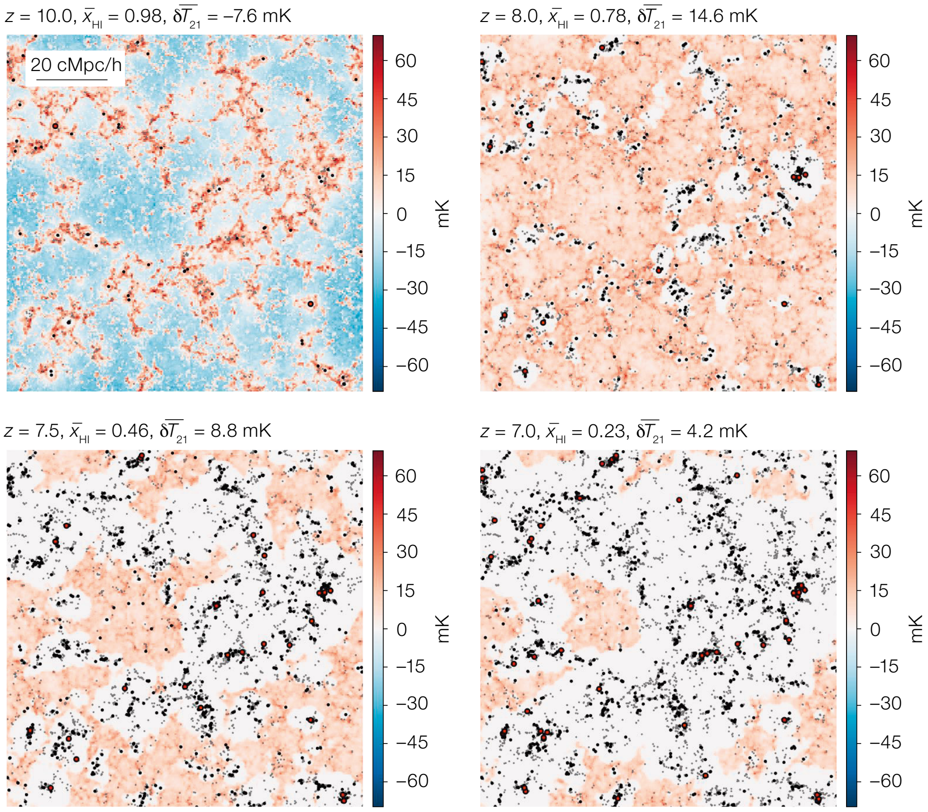

Figure 1. An example 21-cm brightness temperature map (see colour bar) and corresponding galaxy map at z = 10, 8, 7.5 and 7, obtained from a 3D multi-frequency radiative transfer code (Eide et al., 2020). The black and red points represent galaxies with [OIII] luminosity $L_{OIII} > 10^{41}$ erg s^{-1} and $L_{OIII} > 10^{42}$ erg s^{-1}, respectively, while grey points denote all galaxies within the slice. Galaxy locations are clearly seen to correlate with the 21-cm brightness temperature, since their radiation ionises and heats the surrounding IGM. Figure from Moriwaki et al. (2019).

EoR signals that can be cross-correlated with the 21-cm line

The 21-cm signal from the EoR/CD is determined by the IGM density, temperature, and ionised fraction. During the dark ages, it is a fairly clean probe of density fluctuations. After the CD, radiation from the first galaxies heats and ionises the IGM, effectively coupling modes over a range of scales. However, galaxies themselves are biased tracers of the matter field. Therefore any tracer of the large-scale matter field should in principle correlate with the 21-cm signal from the EoR/CD. The quantitative details of this correlation encode a wealth of information about the first galaxies (see references below).

In practice, however, it is difficult to cross-correlate signals because we need to match the ‘footprints’ of different probes. Foregrounds for 21-cm interferometry live in a ‘wedge’ region in Fourier space (for example, Morales et al., 2012). As such, large-scale and transverse (on-sky) modes might either be lost during foreground cleaning or be subject to a very large cosmic variance in the cross-correlation (i.e. uncorrelated cross terms only vanish in the limit of infinite samples). Therefore, the ideal candidates for cross-correlation with 21-cm interferometry are large-volume surveys with good redshift localisation.

We list some potential candidates here, briefly mentioning their pros and cons.

1. Cosmic backgrounds: (integral) radiation backgrounds like the cosmic microwave background (CMB; for example, Ma et al., 2018a; La Plante, Sipple & Lidz, 2022), near-infrared background (NIR; for example, Mao, 2014), and the X-ray background (XRB; Ma et al., 2018b), contain a contribution from $z > 5.5$, which should correlate with the EoR/CD 21-cm signal. Some radiation background analyses, like those for the CMB, are very mature. However, the overlap with the 21-cm signal is small, given that backgrounds are integrated over all redshifts, while the 21-cm signal loses many on-sky modes to foregrounds.
2. Resolved galaxies: as shown in Figure 1, galaxy maps would be obvious choices for cross-correlation with the 21-cm signal. Mapping galaxies, at least at lower redshifts, is also a mature field. However, the need for accurate redshift determinations, a reasonably wide field of view, and a sufficient number density of $z > 5.5$ objects, makes it challenging to design wide and deep surveys. Narrowband dropouts, grism, or spectroscopic follow-up are the most promising options (for example, Wiersma et al., 2013; Vrbanec et al., 2020; Sobacchi, Mesinger & Greig, 2016; Hutter et al., 2017; Moriwaki et al., 2019; Kubota et al., 2020; Heneka & Mesinger, 2020; Hutter et al., 2023; La Plante et al., 2023).
3. Intensity mapping (i.e. unresolved galaxies): other lines such as [CII], [OIII], CO, Lyman-α are mostly sourced by the combined emission from unresolved galaxies. In principle, line intensity maps (LIMs) could have wide fields and good redshift localisation, thus providing an excellent complementary probe to 21-cm observations (for example, Kovetz et al., 2017). However, LIMs have not yet been made at high redshifts, and many line luminosities are expected to be faint (for example, Crites et al., 2014; Yue et al., 2015; Lagache, Cousin & Chatzikos, 2018; Heneka & Cooray, 2021). A reported cross-correlation between two untested probes might be met with skepticism. However, credible detections of (sub)millimetre lines from high-z galaxies with the Atacama Large Millimeter/submillimeter Array (ALMA) should help demonstrate the viability of LIM at higher redshifts in the near future.
4. Quasar spectra: the Lyman-α forest in quasar spectra provides a 1D skewer through the IGM which could be cross-correlated with the corresponding 21-cm forest. These UV and radio absorption lines in the same background object would provide complimentary information about the intervening IGM. Such a study requires the presence of radio-loud quasars at high redshifts, as well as a sufficiently cold IGM so as to detect the 21-cm forest (Bhagwat et al., 2022).

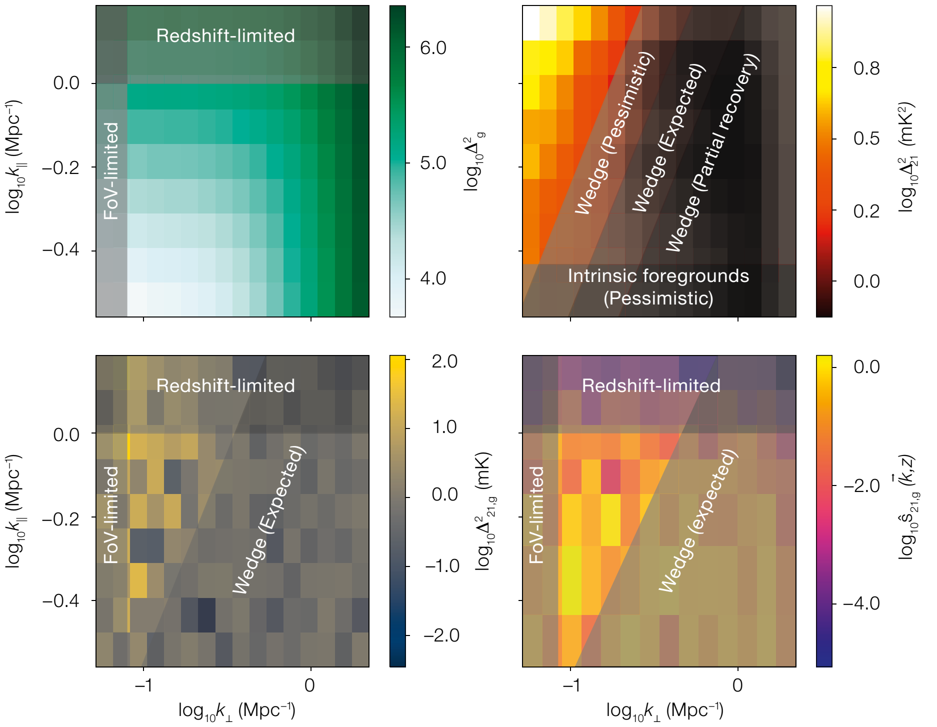

Figure 2. Cylindrical power spectra (PS) of various fields used in the calculation of the galaxy–21-cm cross-power spectrum S/N ratio. Clockwise from top left: galaxy auto PS, 21-cm brightness temperature auto PS, S/N ratio in each bin of the cross-power spectrum, galaxy–21-cm cross-power spectrum. The total S/N of the cross-power spectrum shown in Figure 3 is computed by summing the S/N of each wave-mode bin in quadrature. Figure from Gagnon-Hartman et al. (in preparation).

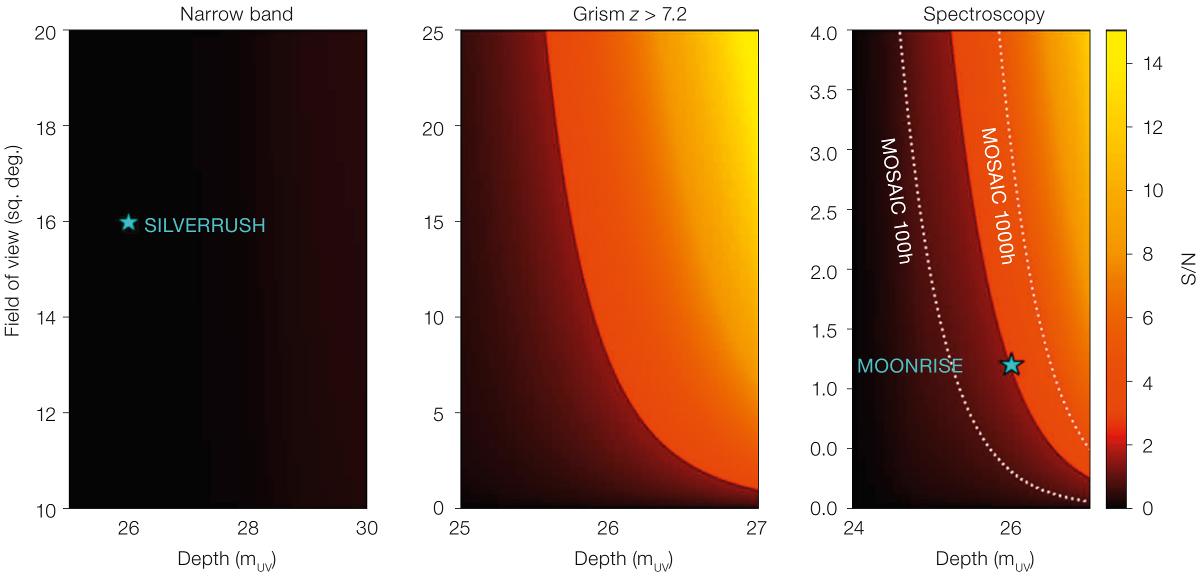

Figure 3. Signal-to-noise ratio of the galaxy – 21-cm cross-power spectrum as a function of Lyman-α galaxy survey FoV and apparent UV magnitude limit. Narrow-band dropout, grism, and spectroscopy are shown left to right. The ESO instruments MOSAIC and MOONS have the potential to provide a high-S/N measurement targeting a ~ 1.5-square degree patch of sky. The MOONRISE survey, which targets ~ 1100 sources at $z > 5.5$, will provide a galaxy map sufficient for a S/N ~ 3 detection of the galaxy-21-cm cross-power spectrum. Narrow-band dropout photometry does not provide sufficient redshift precision to allow for a significant detection of the cross-power spectrum. Figure from Gagnon-Hartman et al. (in preparation).

In the following, we focus on specific ESO instruments that have arguably the most potential for a cross-correlation with an EoR/CD observation with SKA-Low. For 21-cm interferometry forecasts with SKA-Low we assume a fiducial, deep (1000-hour) survey and moderate foreground wedge excision from Prelogovic & Mesinger (2023). For 21-cm forest forecasts with SKA-Low, we assume an observation time of 1000 hours and a bandwidth of 10 kHz (see Bhagwat et al., 2022).

SKAO synergies with ESO facilities

MOSAIC/MOONS (galaxy Lyman-α) — SKA (21-cm intensity mapping)

The Multi-Object Optical and Near-infrared Spectrograph (MOONS) and MOSAIC are multi-object spectrographs currently in development for deployment at the Very Large Telescope (VLT) and ESO's Extremely Large Telescope (ELT), respectively. Both instruments are expected to yield high-precision redshift estimates for thousands of Lyman-α emitters (LAEs) from the EoR. They will cover similar wavelength ranges of 0.76–1.35 and 0.45–1.8 μm, respectively, both at a spectral resolving power *R* ~ 4000. MOSAIC is expected to have much greater sensitivity since it benefits from the larger dish of the ELT; however, it has a smaller field of view (FoV) and its deployment is delayed relative to that of MOONS. Furthermore, the MOONRISE survey (Maiolino et al., 2020) already has guaranteed observing time on the MOONS instrument to measure the redshifts of about a thousand LAEs at $z > 5.5$. Candidates for future surveys using MOONS or MOSAIC may be provided by photometric or grism surveys with the Nancy Grace Roman Space Telescope or the James Webb Space Telescope.

To measure a cross-correlation of galaxy and 21-cm maps, their effective footprints should overlap. As seen in Figure 2, the FoV of the galaxy survey sets the largest observable on-sky mode in the cross-power spectrum (i.e. the smallest $k_\perp$), and its redshift uncertainty sets the smallest observable line-of-sight mode (i.e. the largest $k_\parallel$). The 21-cm foreground 'wedge' limits observability in the small $k_\parallel$ – large $k_\perp$ corner of cylindrical k-space. The amplitude of the cross-power is determined mostly by the depth of the galaxy survey (see La Plante et al., 2023 for a recent forecast for the SKA precursor, Hydrogen Epoch of Reionization Array).

Gagnon-Hartman et al. (in preparation) forecast the potential for cross-correlation between MOONS/MOSAIC galaxy fields and a prospective 21-cm field detected by SKA-Low. They find that a survey comprising roughly 1000 hours of observation time with MOSAIC covering ~ 2 square degrees can detect the 21-cm signal in cross-correlation at a significance level of ~ 6σ. They also find that the planned MOONRISE survey covering 1.2 square degrees should yield a ~3σ detection of the galaxy–21-cm cross-power spectrum.

ANDES (quasar metal lines) — SKA (21-cm forest)

The ArmazoNes high Dispersion Echelle Spectrograph (ANDES) is the high-resolution spectrograph foreseen for the ELT, whose design phase is ongoing. It will cover the wavelength range 0.4–1.8 μm simultaneously at a resolving power *R* ~ 100 000, making it ideal for the study of the EoR with quasar absorption spectra (among many other science cases), and in particular using absorption lines from chemical elements heavier than helium (generally called 'metals') which will be fully resolved at this resolution.

Bhagwat et al. (2022) have used hydrodynamic cosmological simulations to test how simultaneous absorption from metals (observed with ANDES) and HI 21-cm (with SKA) in the spectrum of a bright, radio-loud background quasar can complement each other as probes of the underlying gas properties. In Figure 4 we show maps of HI column density overlaid with 21-cm optical depth $\tau_{21\text{cm}}$, OI, CII, SiII and FeII column density at various redshifts, resulting from post-processing of the radiation hydrodynamic simulation Aurora (Pawlik et al., 2017). From the figure, the correspondence between a high HI and metal column density is clear.

Such correspondence is better quantified in Figure 5, where we show synthetic spectra from ANDES and SKA-Low. Here we assume a background source with flux of 10 mJy at 150 MHz and a power law index of –1.31. The shaded regions highlight the locations of aligned and cospatial absorbers (ACA), i.e. those in which 21-cm and metal absorption fall in the same window in velocity space and absorption originates from the same underlying gas, while for non-cospatial systems the absorption appears aligned only because of peculiar velocity effects and thus does not effectively probe the same region in space. These observations would probe the physical state of the IGM, including its temperature, metallicity and ionisation state, as well as the nature of nearby sources.

Conclusions

The first, low-S/N 21-cm EoR detection should come in the near future. The best way of convincing ourselves and the community that this detection is genuine would be to cross-correlate it with a known $z > 5$ signal (that has completely different foregrounds and systematics).

All high-redshift probes ultimately correlate with the matter field, albeit non-trivially in the case of 21 cm owing to its sensitivity to large-scale radiation fields. Thus, there are many candidates for cross-correlations, including: (i) cosmic radiation backgrounds (CMB, CXB, CIB); (ii) (resolved) galaxy maps; (iii) line-intensity maps; and (iv) quasar spectra.

Here we identify promising ESO instruments that will synergise well with SKA-Low EoR surveys: (i) MOONS on the VLT; (ii) MOSAIC on the ELT; (iii) ANDES on the ELT. We show that a Lyman-α galaxy map obtained with MOONS or MOSAIC can be used together with the 21-cm interferometric signal to detect the cross-power spectrum at high S/N. Line-intensity maps obtained with a single-dish telescope with spectroscopic capabilities in the submillimetre (like the

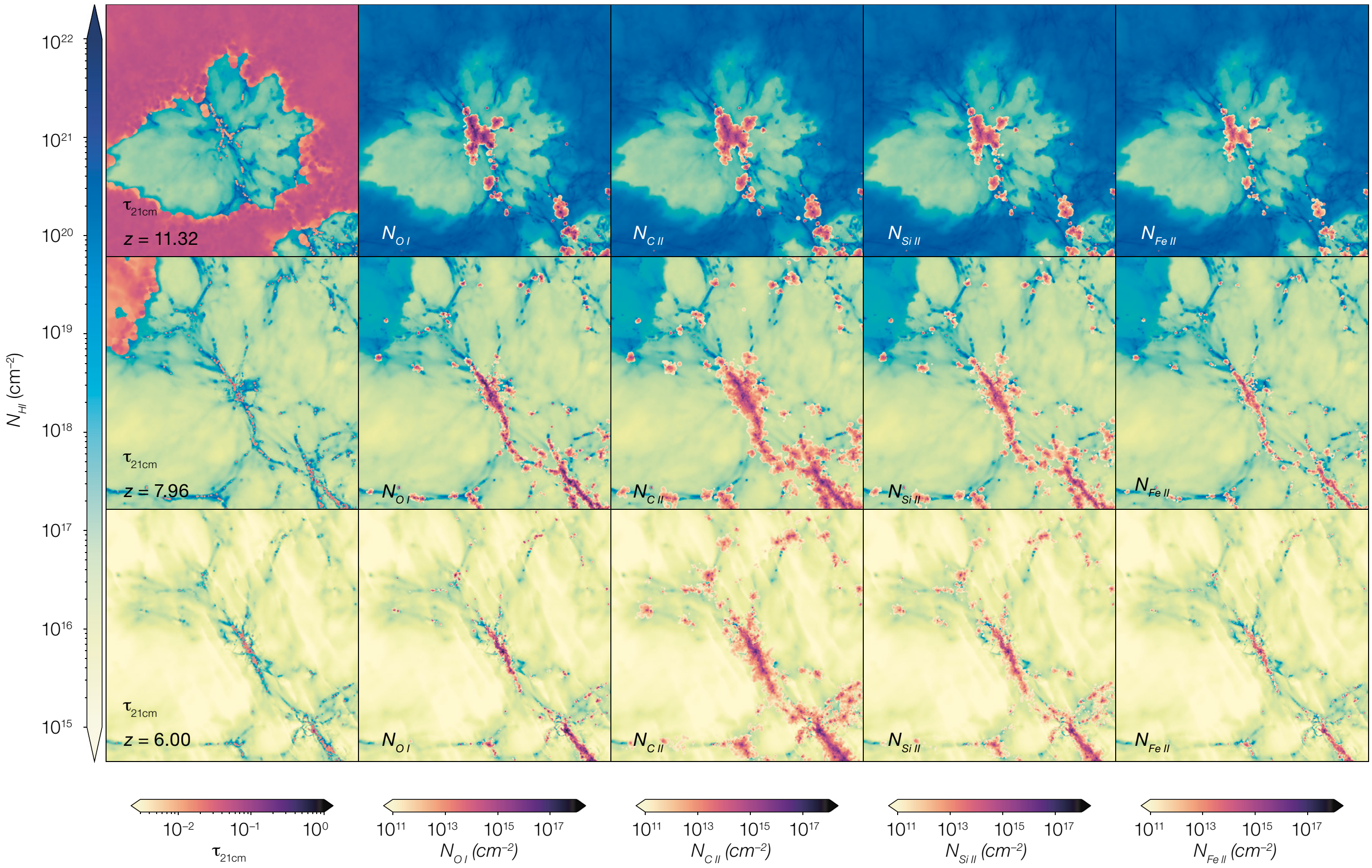

Figure 4. Maps of HI column density overlaid with (from left to right): 21-cm optical depth $\tau_{21\text{cm}}$, OI, CII, SiII and FeII column density at z = 11.32 (top panels), 7.96 (middle) and 6 (bottom). Each projection is 3 h^{-1} c Mpc on a side and 1 h^{-1} c Mpc deep. Figure from Bhagwat et al. (2022).

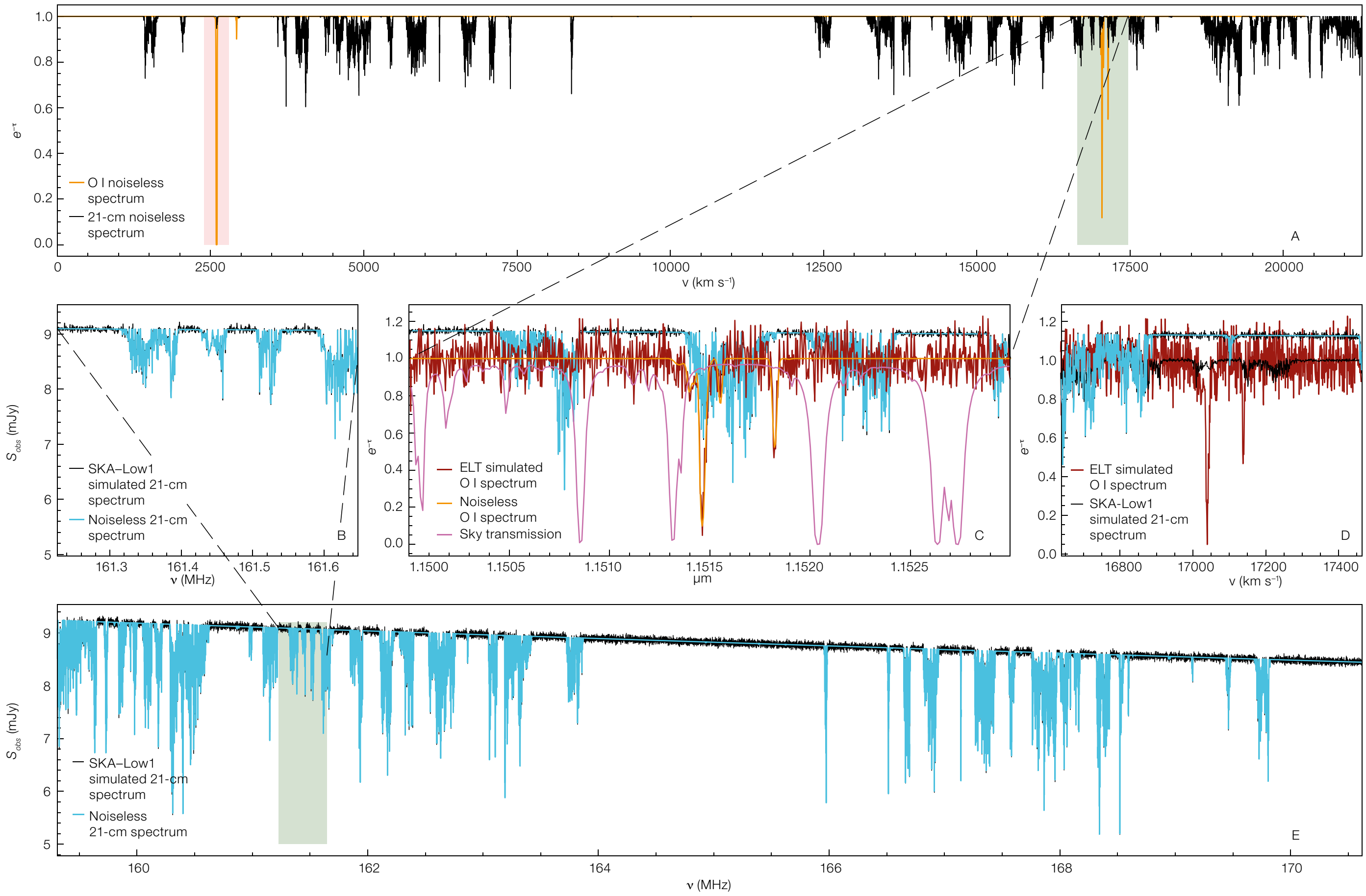

Figure 5. Panel A: synthetic (noiseless) spectra at z = 7.96 showing the 21-cm forest (black lines) and the O I λ1302 absorption spectra (orange). Shaded regions (pink and green) highlight the location of ACA, but their extent does not coincide with that of the corresponding absorber. The green shaded regions correspond to the same absorber in panels A and E. Panel B: zoom into the portion of the 21-cm forest spectrum with the ACA shown in panels A and E. The blue line is the noiseless spectrum ($e^{-\tau_{21\mathrm{cm}}}$), while the black one is the simulated spectrum ($S_{\mathrm{obs}} = S_0\, e^{-\tau_{21\mathrm{cm}}}$) for a background radio-loud source of flux (S_0) of 10 mJy at 150 MHz. Panel C: zoom into the portion of the O I spectrum of Panel A with the ACA. The orange line shows the noiseless spectrum, while the red one shows the simulated spectrum as observed by the ELT–ANDES instrument assuming an exposure time of 10 hours, two readouts per hour and spectral resolution $R = 10^5$ for a m_{AB} = 21.0 mag source. The purple line shows sky transmission at these wavelengths. Panel D: simulated normalised spectra as observed by the ELT and SKA-Low for O I and 21 cm overlayed in velocity space showing the green shaded region from Panel A. Panel E: full extent of the simulated 21-cm forest. The blue line shows the noiseless spectrum (as in panel A) multiplied with the radio continuum of the background source, while the black line shows the simulated spectrum as observed by SKA-Low. Figure from Bhagwat et al. (2022).

proposed concept for the Atacama Large Aperture Submillimeter Telescope [AtLAST; see Klaassen et al., 2020; Mroczkowski et al., 2024]) could also contribute to this. We also demonstrate that correlating Lyman-α and 21-cm absorption as seen in the spectrum of a putative radio-loud high-z quasar can provide complimentary information about the physical state of the IGM.

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SKAO

An SKA-Low antenna at the site of the SKA-Low telescope in Western Australia.

Astronomical Science

Zdeněk Bardon/ESO

With advanced instruments designed to catch the light from extrasolar worlds and the Universe's most distant stars and galaxies, crystal clear images are a must. To achieve this, the Unit Telescope 4 of ESO's Very Large Telescope (VLT) in Chile has an adaptive optics facility equipped with four sodium lasers, aimed towards the sky. When the laser beams reach about 90 kilometres into the atmosphere, they excite sodium atoms that start to glow, creating artificial stars in the sky.

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VST-SMASH: the VST Survey of Mass Assembly and Structural Hierarchy

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The VLT Survey Telescope Survey of Mass Assembly and Structural Hierarchy (VST-SMASH) aims to detect tidal features and remnants around very nearby galaxies, a unique and essential diagnostic of the hierarchical nature of galaxy formation. Leveraging optimal sky conditions at ESO's Paranal Observatory, combined with the VST's multi-band optical filters, VST-SMASH aims to be the definitive survey of stellar streams and tidal remnants in the Local Volume, targeting a low surface-brightness limit of $\mu \sim 30$ mag arcsec^{-2} in the *g* and *r* bands, and $\mu \sim 28$ mag arcsec^{-2} in the *i* band, in a volume-limited sample of local galaxies within 11 Mpc and the Euclid footprint.

The low-surface-brightness realm

According to our current understanding of galaxy formation, cosmic structures form hierarchically. During the very early epochs, gas condenses, and the first stars are formed within the primordial dark matter perturbations (Blumenthal et al., 1984; White & Frenk, 1991). These first galaxies then merge, resulting in larger and larger galaxies, which in turn undergo physical transformations governed by the wide range of different environments they live in. Major mergers (for example involving galaxies of equal mass) are the most spectacular manifestation of hierarchical assembly, but only a small fraction of galaxies are involved in such catastrophic events that are expected to destroy pre-existing discs. Instead, minor mergers (for example involving galaxies having a 1:10 ratio of mass) are expected to be more common (see, for example, Cole et al., 2000). If satellite galaxies, orbiting the stellar body of the massive central companion, are tidally disrupted, a variety of tidal structures, such as shells, streams and plumes, which are a direct 'smoking gun' of hierarchical assembly, should emerge (see, for example, Cooper et al., 2010). Within the standard ΛCDM cosmological model (Springel et al., 2008), such features can provide important constraints on the formation of the stellar halo (Bell et al., 2008), gravitational potential (Bovy et al., 2016) and dark matter substructures (Sandford et al., 2017). To better understand the hierarchical structural assembly, it is necessary to systematically study the remnants of such interactions. This can be achieved via deep imaging of nearby galaxies and their surroundings to address the following still-open questions: What is the frequency of tidal interactions and galaxy accretion via minor mergers in the very Local Universe? What are the properties of their stellar populations? Are observations consistent with numerical simulations and the current paradigm for galaxy formation?

The state of the art

Tidal structures are extremely faint, with very low surface brightness (LSB; $\mu_V \geq$ 27 mag arcsec^{-2}; Johnston et al., 2001), and therefore have been historically difficult to observe. With Gaia and the Dark Energy Survey, the study of stellar streams has entered a golden age (see, for example, Belokurov et al., 2017; Shipp et al., 2018). Nevertheless, the challenge now is to go deeper and beyond the Local Group (LG). The Milky Way and its companions by themselves cannot provide a representative picture of the hierarchical structure assembly of the Universe. Outside the LG, the first systematic ground-based searches have so far been limited to only a few galaxies, relying on wide-band photometry and therefore lacking the colour information needed for a characterisation of the stellar populations (see, for example, Martinez-Delgado et al., 2010). Space-based HST observations (for example, Radburn-Smith et al., 2011) incorporate different broad-band filters, providing excellent spatial resolution but with a very limited field of view (FoV). Neither type of approach can provide a complete picture of the overall statistics of such features. The limitation of the FoV has been overcome in the last 10 years, mainly in the northern cap, by the surveys MATLAS (Bílek et al., 2020), ELVES (Carlsten et al., 2022), SSH (Annibali et al., 2020) and LIGHTS (Trujillo et al., 2021).

The VST: a seeker of faint structures

Next-generation facilities, such as Vera C. Rubin Observatory or ESA's Euclid mission, thanks to their large FoV and superb spatial resolution, will improve our understanding of galaxy assembly in the local Universe. Unfortunately, Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) will reach the required surface brightness (SB) limits only after about 10 years of observations and Euclid will observe in three near-infrared (NIR) bands and mounts only a single broad-band optical filter. A mission planned to achieve these scientific goals, reaching an unprecedentedly ultra-low SB, known as ARRAKIHS[1], will only be launched in the early 2030s. Therefore, the VLT Survey Telescope (VST) is currently the ideal instrument with which to study tidal features and hierarchical structuring. Thanks to the unique combination of exquisite seeing and dark skies at the Paranal site and OmegaCam's FoV of 1 square degree, the VST can reveal the very faint structures around galaxies in the Local Volume. It has already proven its ability to study such structures within the VST Early-type GAlaxy Survey (VEGAS; Capaccioli et al., 2015; Iodice et al., 2021) and the Fornax Deep Survey (FDS; Iodice et al., 2019; Spavone et al., 2020), which obtained maps of the SB of early- and late-type galaxies, detecting the signatures of diffuse stellar components with azimuthally averaged SB depths of ~ 29–30 mag arcsec^{-2} in the *g* band (see also Iodice et al., 2019; Ragusa et al., 2021, 2022).

VST-SMASH: a game changer in the Local Volume

Until now a systematic, homogeneous census of features reaching μ_g ~ 29–30 mag arcsec^{-2} around very nearby galaxies in the southern sky was missing. The VST Survey of Mass Assembly and Structural Hierarchy (VST-SMASH) will fill this gap, by observing, in the *g*, *r* and *i* bands, a sample of 27 local galaxies within the Euclid footprint in a distance-limited (< 11 Mpc) sample (Karachentsev, Makarov & Kaisina, 2013). These data will provide an unprecedented look at the hierarchical galaxy assembly, complementing the VEGAS and FDS datasets with a wide range of galaxy types (from dwarfs to massive spirals). Comparing the specifics of VST-SMASH with past surveys, we find that with the exception of SSH, which explores the same volume but focuses on dwarf galaxies, and ELVES, the previous surveys have observed galaxy samples at greater distances than ours. VST-SMASH is observing a sample as large as that observed by ELVES, including less massive systems.

The survey objectives

To obtain the most complete characterisation of the mass assembly at D < 11 Mpc, we select a volume-limited galaxy sample, which includes objects of different types, masses and sizes, exploiting the VST and OmegaCAM characteristics. We reach an SB of about 30, 30 and 28 mag arcsec^{-2}, in the *g*, *r* and *i* bands respectively, with an exposure time of 2.5 hours in *g* and *r* and of 2 hours in *i*, and azimuthally averaged profiles. Observing both the fields around the target and a contiguous one for a proper background subtraction (Spavone et al., 2018), we can probe their halos, depending on their distances, up to about 250 kpc.

Sample selection and data reduction

From the 869 galaxies in the distance-limited (< 11 Mpc) Updated Nearby Galaxy Catalogue (Karachentsev, Makarov & Kaisina, 2013), we have selected all the galaxies at declinations ≤ 5 deg, with a Holmberg diameter a_{26} ≥ 5 arcmin and within the Euclid wide-survey footprint. We have purposely excluded: i) the largest galaxies (LMC, SMC, Sag DSph) and the Milky Way companions because they have already been extensively studied; ii) NGC 3115 since it is already observed by the VST; and iii) galaxies with overlapping and overwhelmingly bright stars. We end up with 27 galaxies. The sample spans a wide range of mass (10^9 – 2 × 10^{11} $M_\odot$), HI gas mass (10^8 – 10^{10} $M_\odot$), types, orientations and environments. The target galaxies are also characterised by a wide range of apparent sizes: a_{26} in the range of 5–40 arcminutes. The VST, with its wide FoV, is the perfect facility to efficiently observe such extended galaxies and their surroundings. Data are reduced with the AstroWISE pipeline (McFarland et al., 2013), which performs instrumental corrections, background subtraction and calibrations, and creates the final mosaics. Table 1 presents the galaxy sample.

Table 1. Data sample. Data on Coordinates, distance, Holmberg diameter and mass are extracted from Karachentsev, Makarov & Kaisina (2013). In the last column, we show the sky area observed around galaxies with complete VST-SMASH data in all the bands.

Galaxy	R. A. (deg)	Dec. (deg)	Distance (Mpc)	a_{26} (arcmin)	log($M/M_\odot$)	Area (sq. deg.)
NGC 0024	2.485	−24.963333	9.9	7.24	10.32	0
NGC 0045	3.51625	−23.182222	9.2	8.51	10.45	0
NGC 0055	3.785417	−39.220278	2.13	37.15	10.15	0
NGC 0247	11.784583	−20.76	3.65	25.12	10.44	0
NGC 0253	11.892917	−25.292222	3.94	37.15	11.24	0
NGC 0300	13.722917	−37.6825	2.15	25.7	10.18	0
NGC 0625	23.770833	−41.436389	3.89	7.08	9.01	0
ESO 115-021	39.4375	−61.341111	4.99	7.24	9.5	0
ESO 154-023	44.21	−54.573056	5.55	8.32	9.62	0
ESO 300-014	47.4075	−41.030556	9.8	7.08	10.0	0
NGC 1291	49.3275	−41.108056	8.8	14.45	9.77	0
NGC 1313	49.564167	−66.4975	4.07	12.59	10.44	0
NGC 1744	74.9925	−26.026667	10.0	6.92	10.38	2
NGC 3109	150.78	−26.16	1.32	19.95	9.37	2
Sextans A	152.753333	−4.692778	1.32	5.89	8.4	1
NGC 3621	169.567083	−32.811667	6.7	12.3	10.73	2
NGC 5068	199.730417	−21.039167	5.45	10.0	9.94	2
NGC 5236	204.250417	−29.867778	4.92	18.62	11.32	2
NGC 5253	204.9825	−31.64	3.56	6.92	8.91	1
IC 5052	313.025833	−69.203889	6.03	8.13	9.97	0
NGC 7090	324.119167	−54.557222	6.7	10.23	10.26	0
IC 5152	330.674583	−51.295278	1.97	7.08	8.94	0
NGC 7462	345.696667	−40.835	10.1	5.5	10.06	0
IC 5332	353.614583	−36.101667	7.8	8.32	10.24	2
NGC 7713	354.0625	−37.938889	7.8	6.76	10.11	1
UGCA 442	355.941667	−31.959167	4.27	6.31	9.16	0
NGC 7793	359.455833	−32.59	3.91	14.13	10.28	0

Figure 1. VST *gri* composite images of NGC 3109, Sextans A (top), NGC 5236, NGC 5253, IC 5332 (bottom).

Scientific objectives

The main aims of the survey are the following:

1. Detection and statistics of tidal features, LSB galaxies and star clusters in the outskirts of galaxies, up to galactocentric distances of about 50–250 kpc, based on their distance. 1D and 2D models of the light distribution are derived by fitting the isophotes and the latter are then subtracted from the parent images. This will allow us to detect any asymmetry in the galaxy's outskirts and the remnants of past accretion/merging events. Using multiple analytical profiles, we can then set the scales of the different components in the light distribution, identifying the regions where the diffuse stellar envelope plus LSB features dominate over the in-situ populations. For the two closest galaxies (NGC 3109 and Sextans A), the analysis is performed via resolved star counts (for example, Annibali et al., 2020).
2. Determination of colour maps and a probe of the stellar halo populations by tracing galaxy SB to the outskirts. Colour profiles and possible break radii provide unique information about the interplay between internal galaxy processes and the assembly in the outskirts. In-situ processes vs ex-situ accretion leave a signature in the colour gradients, interpreted via hydrodynamical simulations (for example, Cook et al., 2016).
3. Characterisation of the stellar populations using *g*, *r*, *i* photometry of the main galaxy body and of the galaxy peripheries, to disentangle accreted stars from the in-situ populations. More precise stellar parameters, primarily stellar mass, will be constrained by fitting the spectral energy distribution (Abdurro'uf et al., 2021). Euclid will provide deep NIR bands. Meanwhile, we will complement our optical data with literature photometry in the ultraviolet and NIR, using the extended wavelength range to constrain stellar populations in the main galaxy bodies.
4. Inventories of star clusters and dwarf companions following the methodology described by Cantiello et al. (2020) and Venhola et al. (2018), respectively, which relies on automatic detection tools that take into account background/foreground contamination and are used to map their number density, structural properties and stellar population properties. These small stellar systems are the main contributors of extended stellar halos and the 2D density map of star clusters can provide hints about the galaxy mass assembly. For example, the adopted observing strategy will enable the detection and analysis of the old halo globular cluster (GC) populations in all targets, extending well beyond the peak of the GC luminosity function. Detection of satellites in both dwarfs and massive spirals would observationally test the self-similarity of the hierarchical formation process at all scales.
5. Comparison with mock galaxies. Large-volume hydrodynamical simulations (for example, TNG50 or NewHorizon; Pillepich et al., 2019; Dubois et al., 2021), including not only gravity but also stellar and gas physics and feedback from supernovae and AGN, provide the most efficient way to quantitatively interpret the statistics of tidal features and companions, and their properties (see, for example, Martìnez-Delgado et al., 2023), exploring the galaxy-halo connection and putting under a magnifying glass our understanding of the cosmological model and the galaxy mass assembly. In turn, such deep data can constrain the 'subgrid' models implemented in the simulations. Synthetic multi-band images of mock galaxies will be generated using the SKIRT radiative transfer code, which takes into account stellar emission by various stellar populations, absorption and scattering by interstellar dust (Baes et al., 2024). Such mock observations with realistic and physically motivated structures, stellar populations and statistics of LSB features will provide a sensitive testbed for galaxy evolution studies.
6. Complementary archival WISE, GALEX, H_2, ALMA, SPITZER/IRAC, HI, JWST data, which probe wide spectral and resolution ranges, can be used to determine star formation rates, stellar masses, rotational velocities, and HI and H_2 gas masses. Comparing our deep optical observations with such data (in particular the high-resolution ones from ALMA, JWST and HST), will allow us to constrain the interplay between the small-scale physics

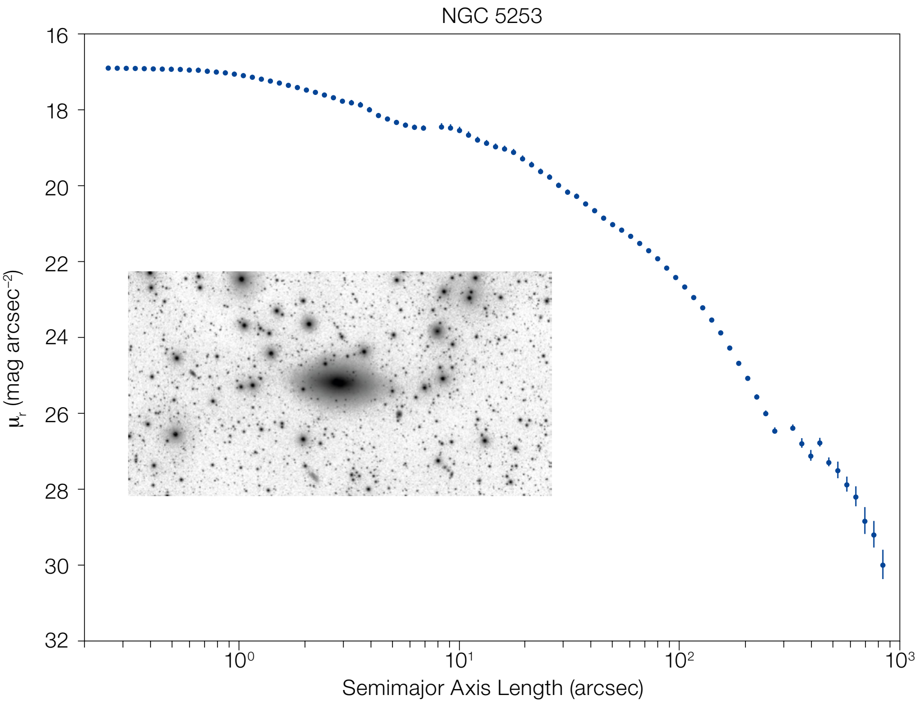

Figure 2. *r*-band azimuthally averaged surface brightness profile of NGC 5253. Surface brightness is plotted against the semimajor axis length in arcseconds. Our *r*-band photometry reaches a depth of 30 mag arcsec^{-2}. Inset: A cutout of the r-band image of the galaxy, aligned along the semimajor axis, is displayed. The size of the cutout matches the major-axis length corresponding to the outermost point in the SB profile.

of gas and star formation and galaxy-scale properties, like galaxy morphology and stellar populations in the local volume.

7. As a byproduct, the large FoV will also enable the studies of stellar and structural parameters of the background galaxies in terms of mass, redshift and environment, leading to the discovery of gravitational lenses, quasars, and clusters.

Status of the survey and first observations

At the time of writing, observations for the VST-SMASH programmes have run for two semesters, and observations for a third semester have been granted. Nine out of 27 targets have complete observations in the *g*, *r* and *i* bands, and are listed in Table 1, with their coordinates, distances, Holmberg radii, total masses and the sky area observed around that specific target. Figure 1 shows a montage of the colour composite images for: the two irregular galaxies NGC 3109 and Sextans A, the only two galaxies resolved in stars among our targets, respectively on the top left and top right panels; the face-on barred spiral galaxy NGC 5236 (the well-known Southern Pinwheel galaxy) with the companion starburst galaxy NGC 5253, on the bottom left and bottom central sides; and the intermediate spiral galaxy IC 5332 on the bottom right panel. The first data analysis has confirmed that our observing strategy, under the required seeing and sky conditions, has reached the requested depths. In particular, our SB azimuthally averaged profiles reach depths of around 29.5–30 mag arcsec^{-2} in the *g* and *r* bands. In Figure 2 we show, as an example, the *r*-band surface brightness profile of NGC 5253. During the current semester, we are planning to finish the incomplete galaxies and add more observations for some other targets, aiming at completing the programme in the next few semesters.

Conclusions

Thanks to the VST's capabilities, and the good sky conditions at ESO's Paranal Observatory, VST-SMASH is collecting exceptional data in the *g*, *r* and *i* bands, providing the most homogeneous legacy survey of stellar streams and tidal remnants in the very Local Volume for years to come, observing a volume-limited sample of galaxies at $D \lesssim 11$ Mpc. VST-SMASH is obtaining an image depth that LSST will reach only close to the end of its operations, owing to its observing strategy, and will contribute to the science that will be performed with the NIR Euclid imaging, providing the deep optical counterpart for this set of galaxies. Our dataset and the analysis we are performing will represent a fundamental benchmark for simulations and our understanding of hierarchical mass assembly.

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Links

[1] ARRAKIHS: https://www.cosmos.esa.int/web/call-for-missions-2021/selection-of-f2

A dark cloud of cosmic dust snakes across this spectacular image, illuminated by the brilliant light of new stars. This dense cloud is a star-forming region called Lupus 3, where dazzlingly hot stars are born from collapsing masses of gas and dust. This image was created from images taken using the VLT Survey Telescope and the MPG/ESO 2.2-metre telescope.

ESO/R. Colombari

Telescopes and Instrumentation

A. Ghizzi Panizza/ESO

Pictured here is one of the four Auxiliary Telescopes (AT) of ESO's Very Large Telescope (VLT) sitting under the magnificent arc of our galaxy, the Milky Way. The excellent viewing conditions at the Paranal Observatory, home of the VLT, combined with the VLT's sophisticated technology allow astronomers to study the Universe in detail and advance our understanding of it.

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The GRAVITY+ Project: GRAVITY-Wide and the Beam Compressor Differential Delay Lines

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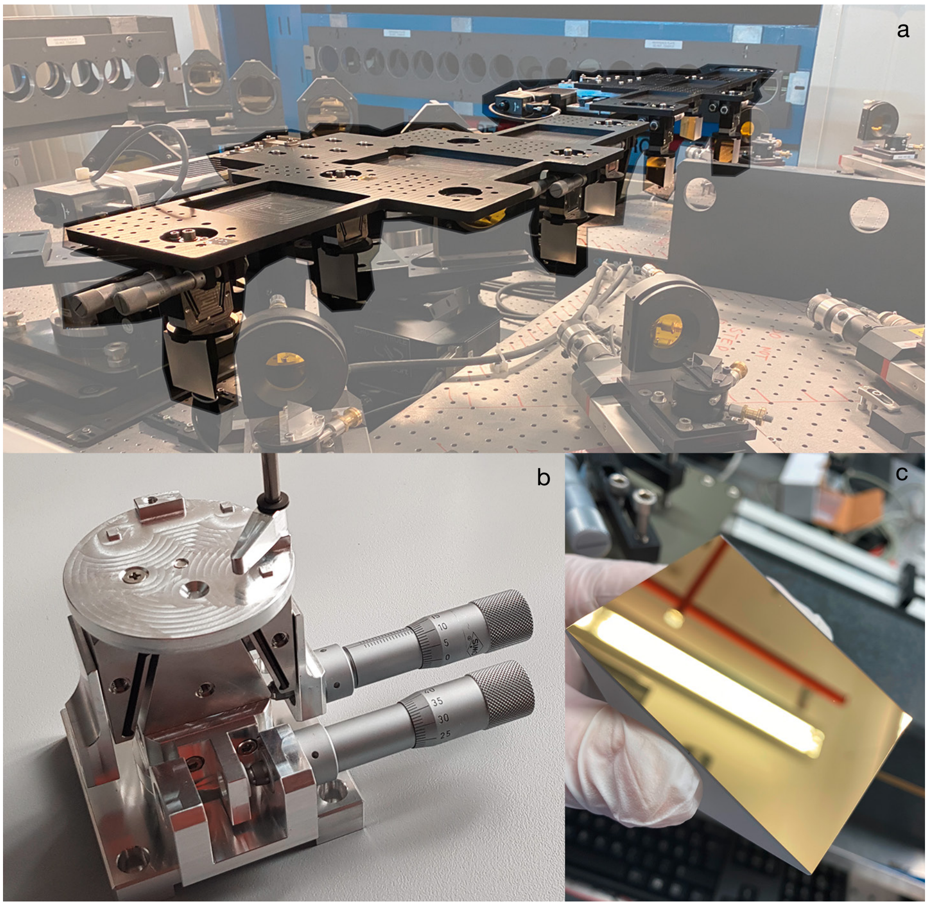
One of the primary goals of the GRAVITY+ upgrade is to significantly improve the sky coverage of GRAVITY and the Very Large Telescope Interferometer. With the successful commissioning and start of operations of the GRAVITY-Wide mode and the new Beam Compressor Differential Delay Lines, GRAVITY+ has opened up the sky to deep interferometric observations. These include the first dynamical black hole mass measurements at cosmic noon, vastly increased observable samples of microlensing events, and a step towards the first detection of an intermediate-mass black hole through stellar orbits.

Introduction

The GRAVITY+ project will bring the next revolution in near-infrared interferometry through a phased upgrade of both the GRAVITY beam combiner instrument and the Very Large Telescope Interferometer (VLTI) infrastructure itself. A unique feature of GRAVITY is its dual-field mode, which allows for simultaneous observations of a faint science target and a nearby bright star. The star is then used to correct for the fast-changing optical paths of each telescope induced by the atmosphere during long exposures of the science target. A critical limitation of GRAVITY and the VLTI was the requirement that the fringe-tracking star and science target be within 2 arcseconds of each other for the Unit Telescopes (UTs). This severely constrained the sky coverage, especially for faint extragalactic targets that are primarily located away from the Galactic plane. To improve the sky coverage, the first phase of GRAVITY+ was to implement wide-angle off-axis fringe tracking and allow for separations between the fringe-tracking star and the science target out to the atmospheric limit (~ 30 arcseconds) as well as to upgrade the beam compressors (BCs) and differential delay lines (DDLs). The GRAVITY-Wide upgrade was carried out in two steps: first with the activation of wide-angle off-axis fringe tracking using the pre-existing PRIMA DDLs and second with the installation and commissioning of a new combined system (BCDDL). Both steps have now been completed with the successful commissioning of the BCDDL system at the end of April 2024.



Phase 1: GRAVITY-Wide

The light from the 8-metre UTs or the 1.8-metre Auxillary Telescopes (ATs) is routed via a long optical train down to the VLTI laboratory. In fact, the light undergoes more than 20 reflections before even entering the instrument. Within this chain are the VLTI main delay lines that compensate for Earth's rotation and, as a result, the optical path between the observed science object and the telescope changes with time. Mirrors mounted on carts travel along some 100-metre-long rails constantly and very precisely throughout each observation. Bringing the full field of view of the telescopes down to the laboratory would have required prohibitively large optics. Instead, a 2-arcsecond cutout is picked up at the telescopes and propagated along the long delay lines under the VLT platform until they finally are directed to the VLTI laboratory. The beam diameter is about 80 millimetres, and the first optical system encountered by this light in the VLTI Lab comprises the beam compressors, which turn those into 18-millimetre beams with a three-mirror system. After two more reflections, the light enters, for instance, GRAVITY. GRAVITY was built with a dual feed capability. So instead of observing just one object through four telescopes, it is able to observe two objects simultaneously. A brighter object (star) is used to track the motions of the fringe pattern inside GRAVITY. Fast piezo-driven mirrors inside the instrument then allow for the stabilisation of the pattern, such that the second, much fainter, object can be observed with long exposure times.

Unfortunately, nature was not kind enough to place sufficiently bright fringe-tracking stars in the vicinity of all interesting science objects. This severely limits the ability of GRAVITY to observe, for example, faint and highly redshifted active galactic nuclei (AGN) or microlensing targets. This limitation was, however,

Figure 1. The four-fold periscope that overlaps the beams of the fringe tracking object with those of the science object (a). As the optical bench was already quite crowded, the prism-based mirrors (b) from two motorised bridges that allow the periscope to be moved in and out of the beams to switch automatically between on-axis and off-axis operation (c) were suspended hanging upside down.

Figure 2. The left panel shows the enclosure of the beam compressor delay line optical bench; the right panel shows a bird's-eye view with the protective panels removed. The eight newly activated beam compressors can be seen towards the right of the images; they stretch, however, the entire length of the bench. The two grey laser heads on the top feed the laser distance metrology system that monitors the optical path length to better than 2 nm precision at all times.

foreseen since the early days of the VLTI, which was designed to bring two 2-arcsecond field cutouts per telescope to the interferometric laboratory. This capability was implemented under the umbrella of the Phase-Referenced Imaging and Micro-arcsecond Astrometry (PRIMA) project which delivered star separators (STS) and DDLs to the VLTI. Although this dual-field capability never succeeded in transitioning to science operations, the DDLs and STSs remained in place, largely unused.

To implement the first phase of GRAVITY-Wide, in a close collaboration between ESO, the Max Planck Institute for Extraterrestrial Physics (MPE), and the University of Cologne, our team first reactivated the PRIMA dual-field infrastructure. A minor optical modification had to be carried out on the DDLs to project the optical pupil at the correct location for GRAVITY. Secondly, periscopes were installed (see Figure 1) on the optical bench of the VLTI switchyard to merge the two beams of each of the respective four telescopes and feed the GRAVITY instrument. The STSs can pick up two targets more or less arbitrarily inside a 2-arcminute field of view. But atmospheric turbulence sets a limit on the separation to around 30 arcseconds when operating in the *K* band. This is 15 times larger than the 2 arcseconds of an individual beam and consequently increases the probability of finding a sufficiently bright fringe-tracking star by a factor of 225. In return, the number of observable targets multiplies by the same factor, significantly increasing the science grasp of GRAVITY.

GRAVITY-Wide was commissioned in December 2021 and, since period P110, has been offered to the community. A full description of phase 1 of GRAVITY-Wide was given by GRAVITY+ Collaboration et al. (2022a).

Phase 2: BCDDL

We mentioned above the large number of reflections that the light path undergoes before entering the science instruments. Reintroducing the PRIMA DDLs added five further reflections to the beam path. Any such reflection inevitably results in the loss of light. Also, while the optical path length between telescopes and the science object varies very slowly and smoothly with time, the VLTI optical train is subject to a number of different sources of vibration such as compressors from other cryogenic instruments. These vibrations ultimately affect the fringe contrast. The vibrations from the telescopes' primary, secondary and tertiary mirrors are measured with accelerometers and then partially compensated in open-loop by forwarding appropriate correction signals to fast actuators in the main delay lines. This MANHATTAN vibration control system is upgraded as part of the GRAVITY+ project with additional vibration sensors on the other mirrors of the coudé train, and with improved control algorithms that compensate for these vibrations in a very similar fashion as noise-cancelling headphones. But this requires fast actuators that can be driven directly by MANHATTAN.

The second phase of GRAVITY-Wide (see Figure 2) removed the PRIMA DDLs entirely and instead moved their functionality directly to the aforementioned beam compressors. These formerly statically mounted three-mirror systems were placed on 2-metre-long rails that ride on top of high-precision, directly driven linear stages for low frequency but larger stroke corrections (+/– 35 millimetres, which corresponds to the maximum differential optical path length difference over a 24-hour period). The secondary mirror of the system is now mounted on a piezoelectric stage that we took over from the PRIMA DDL system. We also transferred and augmented the laser metrology system from the PRIMA DDLs to these newly activated beam compressors, called BCDDLs, which provides a very precise feedback signal for the closed-loop control of the optical path length.

Figure 3. Left: The installation of the new BCDDLs was completed on 16 April by the combined team from ESO, MPE and the University of Cologne. Right: The occasion of first light on 17 April.

A direct bypass feed from MANHATTAN to the BCDDLs allows us to take advantage of the full bandwidth of the piezo system and to correct for vibrations.

The new BCDDLs were commissioned in April 2024 by a collaboration of ESO, MPE, and the University of Cologne (see Figure 3). They saw first light on the ATs on 17 April and then on the UT on 22 April. The change to this new system is entirely transparent to the user and available to the community immediately.

Exploring black holes across cosmic time and mass range

Quasars at cosmic noon

One of the first science cases achievable with GRAVITY-Wide involved deep observations of quasars at high redshift. Direct measurements of the broad line region (BLR) and ultimately the supermassive black hole (SMBH) mass are impossible with single-dish facilities, but the VLTI with GRAVITY+ can achieve the necessary spatial and astrometric accuracy for these unique observations. Black hole mass measurements at cosmic noon ($z \sim 1–3$) are particularly important for tracking and testing the co-evolution of SMBHs and their host galaxies, as suggested by the strong correlations between SMBH mass and host galaxy properties in the local Universe.

GRAVITY+ Collaboration et al. (2022a, 2022b) showed the potential of GRAVITY-Wide observations to measure the SMBH mass at $z = 2$ with the first observations of a cosmic noon quasar and a clear detection of the coherent flux and differential phase across the redshifted H-alpha line. Since then, the GRAVITY+ AGN team has published the first $z = 2$ dynamical SMBH mass measurement of the quasar J0920 (Abuter et al., 2024). Combined with complementary measurements of the host galaxy mass from the Northern Extended Millimeter Array (NOEMA) interferometer, J0920's SMBH was found to be undermassive compared to the expectation from the $z = 0$ $M_{BH}–M_{stellar}$ relationship.

Following the first successful detection, the team has been using the GRAVITY-Wide mode and the BCDDL as a workhorse for building a sizable sample of $z = 2$ quasars with combined high-precision SMBH masses and host galaxy masses. Two more BLR signals have now been detected (Figure 4) and deep observations have been completed on a total of five quasars. This allows both for testing the use of local scaling relations (i.e., the BLR radius–luminosity relation) for quick SMBH masses and for establishing a dynamically based $M_{BH}–M_{stellar}$ relationship at $z = 2$.

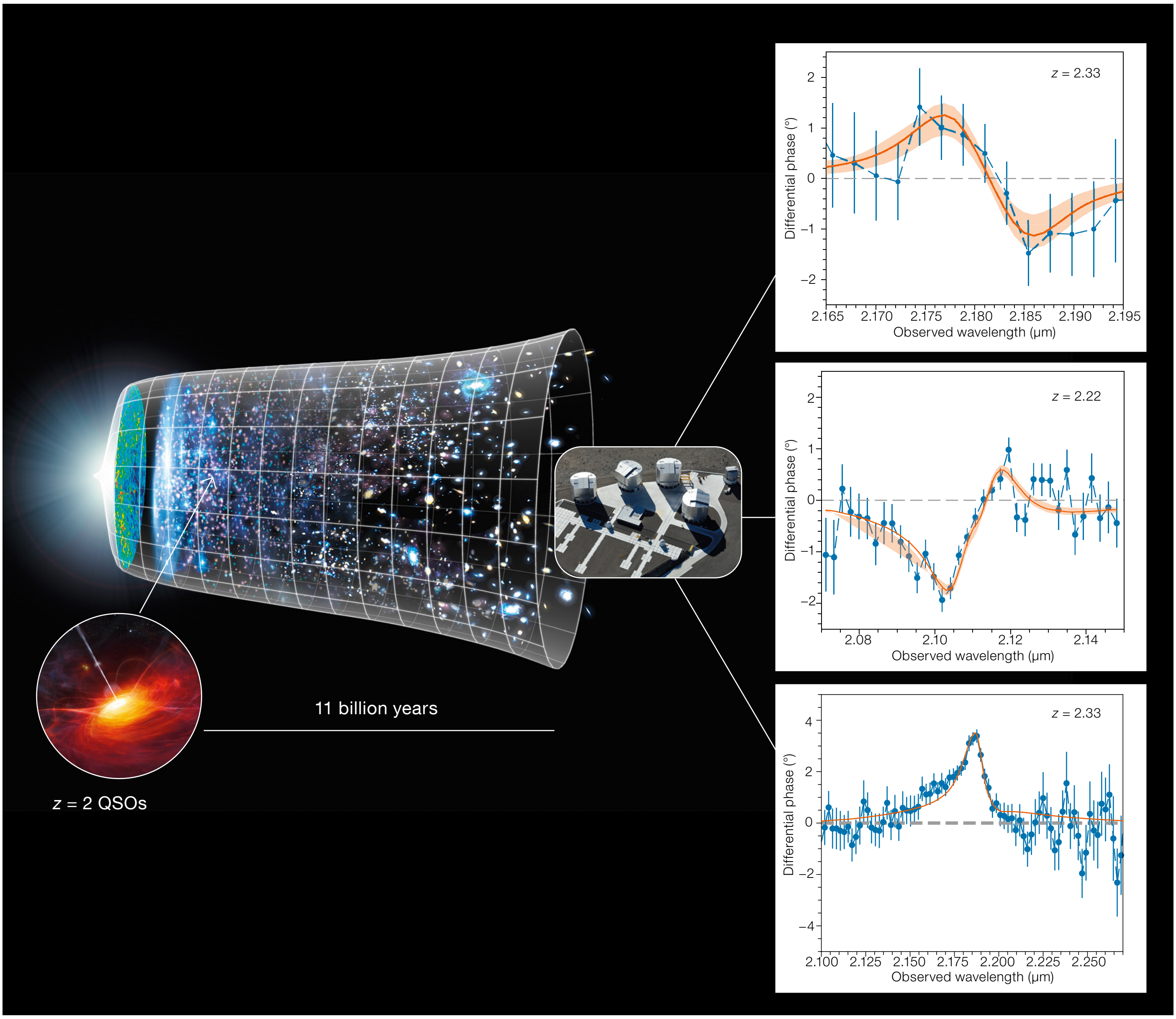
Gravitational Microlensing

Isolated dark objects such as stellar-mass black holes or free-floating planets are thought to be abundant throughout the Galaxy. Detecting and measuring their masses is critical for understanding the formation mechanisms, mass functions, and evolution of their full population. Because they are isolated, however, the only way to find them is through gravitational microlensing when a foreground object (star, planet, black hole, etc.) passes in front of a more distant star. Lensing due to the gravitational potential of the foreground object then magnifies the star and causes a rapid brightening of its light. These microlensing events are therefore found through constant, wide-field monitoring of Milky Way stars.

However, the light curve by itself does not measure the mass of the lens because it is also dependent on the lens–source relative parallax and proper motion. One method to recover these parameters is to spatially resolve the two microlensed images of the source star and measure the Einstein radius. For Galactic microlensing events, the Einstein radius is on the order of a milliarcsecond and therefore only interferometry has the power to resolve the microlensed images. Dong et al. (2019) showed the power of GRAVITY and near-infrared interferometry by measuring the Einstein radius of a bright and nearby microlensing event for the first time using the single-field on-axis mode (see Figure 5, left panel).

The majority of microlensing events, though, are much fainter and require off-axis fringe tracking and increased sensitivity. GRAVITY-Wide has therefore provided a revolution in the number of microlensing events that can be followed up with interferometry, from a few per year to several dozen per year (see Figure 5, middle panel). Taking advantage of target-of-opportunity observations, the GRAVITY microlensing team, a collaboration between astronomers primarily at ESO, Peking University, and the University of Warsaw, have already observed four microlensing events with GRAVITY-Wide. The first GRAVITY-Wide event measured a lens mass of ~ 0.5 $M_\odot$ (i.e., likely a main sequence star) with an unprecedented precision of 2.5% (see Figure 5, right panel). It is therefore only a matter of time before the first black holes are discovered.

Figure 4. GRAVITY-Wide has now been used to detect the broad-line region differential phase signal in three $z > 2$ quasars. This allows us to measure the supermassive black hole mass with unprecedented precision and helps to disentangle the coevolution of black holes and the galaxies they live in at a time when the Universe was only two billion years old.



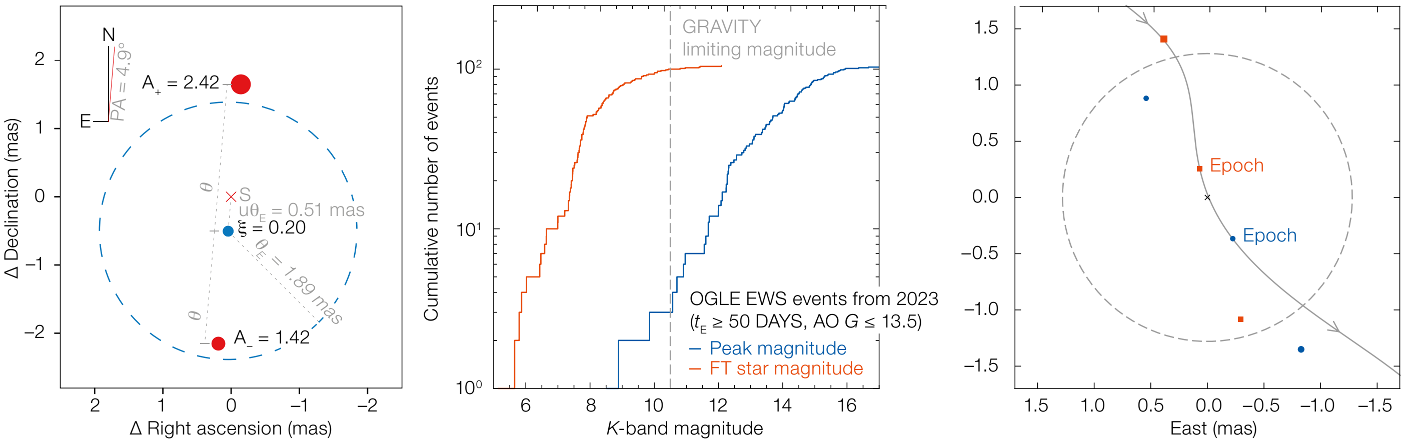


Figure 5. Left: First resolved microlensed images from Dong et al. (2019). Middle: Cumulative distribution of microlensing events in 2023 as a function of *K*-band magnitude (blue curve) along with their potential fringe-tracking stars (red curve). With GRAVITY-Wide, ~ 100 events were available to be followed up, compared to only a few in the single-field on-axis mode. Right: First resolved microlensed images using GRAVITY-Wide. This event was observed in two epochs showing the motion of the images.

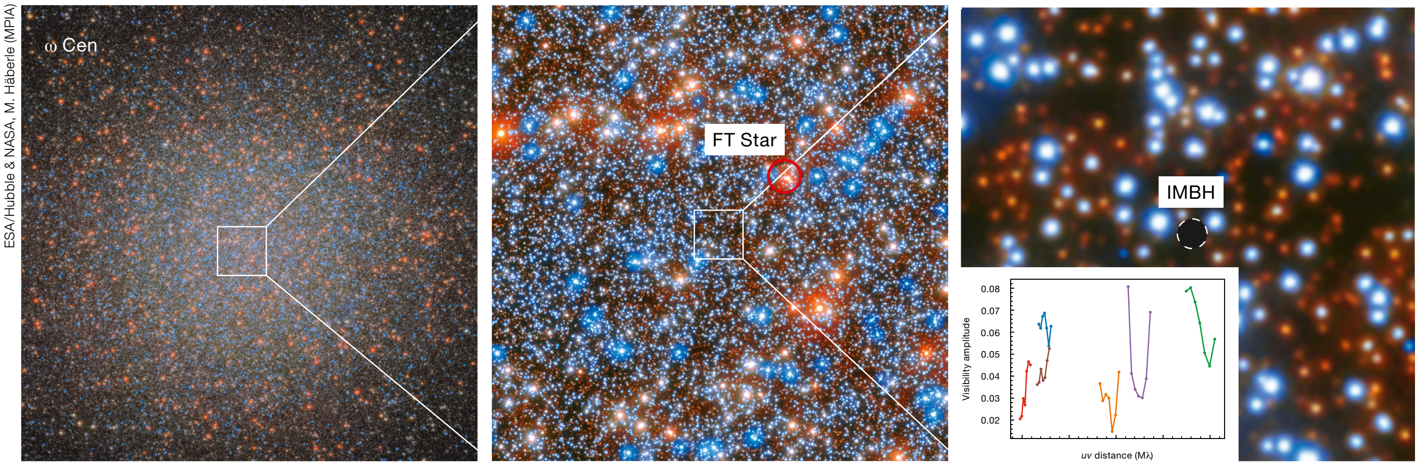
ω Cen and the search for IMBHs

While many black holes in the stellar and supermassive black hole mass ranges have been discovered, only a few candidates in the so-called 'intermediate-mass' range (10^2 – 10^5 $M_\odot$) exist. Finding intermediate mass black holes (IMBHs) would provide strong constraints on the seeding and formation of SMBHs. Extrapolating from the well-studied black hole mass – bulge mass relation, one possible location of IMBHs is at the centres of stellar clusters. Recently, Häberle et al. (2024) discovered fast-moving stars at the centre of the globular cluster ω Cen that provide strong evidence for an IMBH with a mass of at least 8200 $M_\odot$. Definitive proof of an IMBH and a precise measurement of its mass would come from astrometric monitoring of these fast stars to determine their orbits, similarly to what has been done for the Galactic centre.

However, no bright stars are available for fringe tracking within 2 arcseconds of the centre of ω Cen — but there are several brighter than $K = 11$ within 11 arcseconds. During the commissioning of the BCDDLs, we tested the performance and sensitivity of GRAVITY-Wide by observing several stars within 1 arcsecond of the proposed location of the IMBH including the brightest fast-moving star ($K = 18.1$ mag) from Häberle et al. (2024). We could for the first time detect interferometric fringes from the star and measure the visibility (see Figure 6). Absolute astrometry is currently not possible with GRAVITY-Wide owing to the lack of a metrology system but will be investigated in the near future to permit the measurement of the acceleration of the central fast-moving stars of ω Cen and other globular clusters similarly to the discovery and characterisation of the Galactic centre SMBH.

With the next phases of GRAVITY+ that include the adaptive optics systems and laser guide stars, the sensitivity will be

Figure 6. Hubble Space Telescope images of the nearby globular cluster ω Cen showing successively zoomed-in views of the central region. The middle panel highlights the fringe-tracking star used for the GRAVITY-Wide observations during BCDDL commissioning. The right panel highlights the expected location of the IMBH with an inset showing the detected fringes and visibility amplitude of one of the fast-moving stars discovered by Häberle et al. (2024).


ESA/Hubble & NASA, M. Häberle (MPIA)

greatly improved and it will be possible to rapidly assemble fainter and larger samples for all three science cases presented. Even higher redshift quasars will be accessible (out to $z \sim 7$ with the MgII line), the first isolated stellar-mass black hole through microlensing will be detected, and more IMBH detections will become possible in the local Universe. This is an exciting time for GRAVITY+ and the VLTI and we look forward to the unexpected science that will be done once GRAVITY+ is completed.

Acknowledgements

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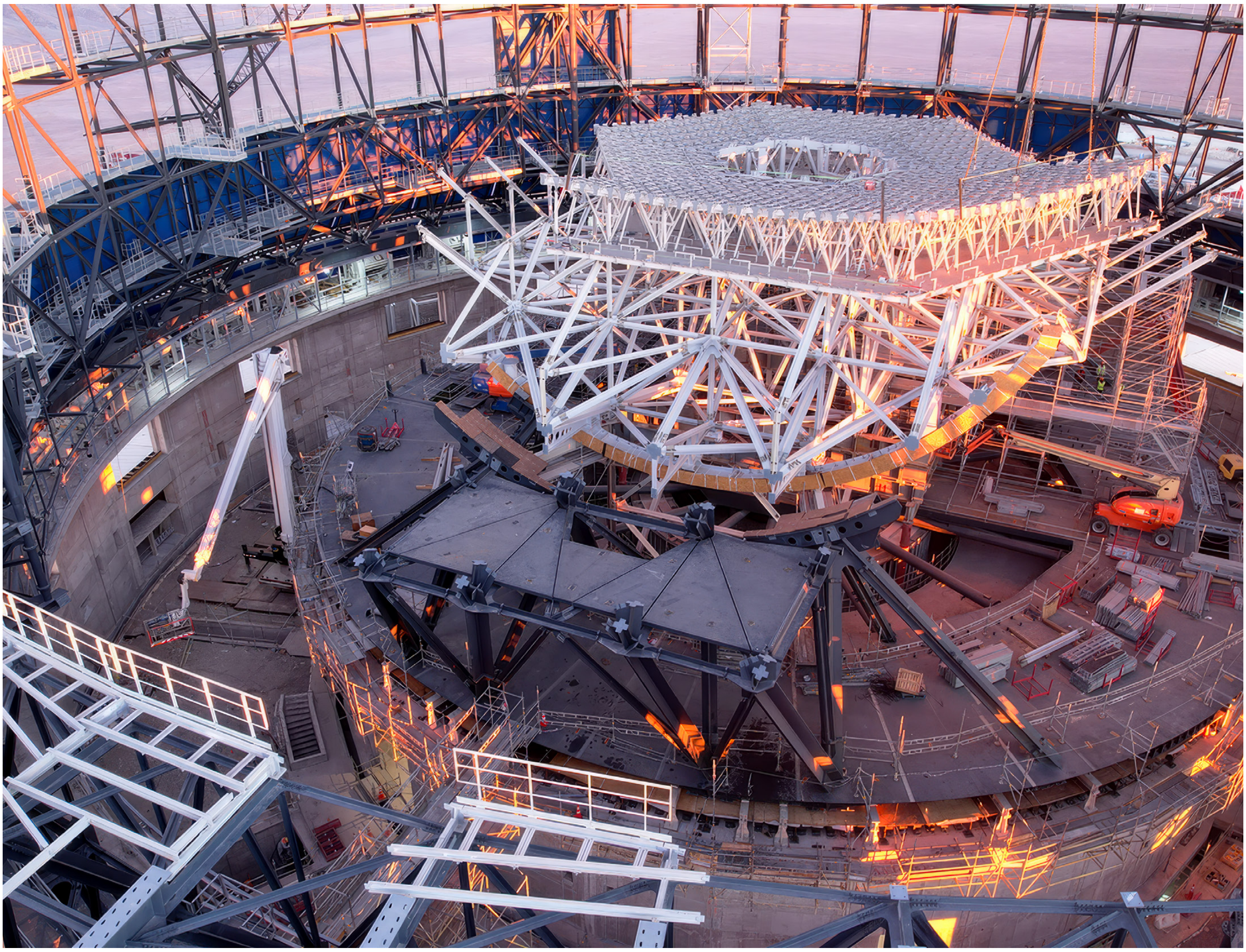

This drone image from June 2024 shows progress in the construction of ESO's Extremely Large Telescope (ELT), located on Cerro Armazones in the Atacama Desert, Chile. The white lattice structure under construction is a support structure that will eventually hold the ELT's primary mirror, M1. Notice the cranes and vehicles at the bottom, which illustrate just how enormous the ELT is!

S. Otarola/ESO

This picture shows six of ALMA's sixty-six antennas, located on the Chajnantor Plateau in the Chilean Atacama desert. But why are they pointed at the Sun? This photograph was taken in March 2023 after a snowfall, and some snow had accumulated on the antennas. Aiming them at the Sun helps to melt the snow.

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Yearly Call and Fast Track Channel at ESO

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The Time Allocation Working Group (TAWG), formed in 2015 as one of the actions generated by the ESO 2020 prioritisation initiative, was tasked with reviewing the telescope time allocation process at ESO. The TAWG report outlined key recommendations aimed at enhancing the efficiency and effectiveness of proposal handling and telescope scheduling at ESO. Among these, the transition to a yearly cycle for the Call for Proposals and the introduction of a Fast Track Channel were highlighted as significant steps forward. This paper outlines the background, rationale, and next steps for these upcoming changes, made possible thanks to recent improvements in software and scheduling tools.

Introduction

The ESO 2020 prioritisation initiative (Primas et al., 2015) generated a number of actions. One of them was the formation of a Time Allocation Working Group (TAWG), which was charged with the task of reviewing the telescope time allocation process at ESO. The working group, constituted in 2015 and composed of leading experts in the field of resource allocation, submitted a report[1] to the Director for Science in 2016, including a set of recommendations and suggestions for an implementation plan. A summary of the report is given by Patat (2018). After presenting it to the ESO advisory committees, and following their feedback and internal discussions on the operational aspects, ESO decided to proceed with the implementation of the recommendations in a gradual way.

The TAWG report formulated ten recommendations. Most of them have been, or are in the course of being, implemented. The two major recommendations, concerning the change of the frequency of the Call for Proposals (CfP) from a semester-based cycle (SC) to a yearly cycle (YC), and the parallel introduction of a Fast Track Channel (FTC) to compensate for the increased length of the time between call for proposals, are still pending. These two recommendations were included in the report of an earlier Observing Programmes Committee Working Group (OPCWG), which was convened in 2010 (Brinks, Leibundgut & Mathys, 2012). At that time, the two recommendations were internally assessed by the Observing Programmes Office (OPO), the User Support Department (USD) and Paranal Science Operation (PSO). Given the status of the proposal handling system, the limitations of the telescope scheduling tool and the related database infrastructure, it was decided not to proceed with the proposed changes.

The rationale for and advantages of a change of the CfP frequency to a YC along with the FTC have been presented and discussed with the OPC, the Users Committee (UC) and the Scientific Technical Committee (STC) over the past years. The list includes the following advantages: decreasing the total number of proposals to be reviewed in one year; removing the need for submitting and reviewing identical proposals to cover the full RA range with possible disparate outcomes; increasing the number of larger time requests per submission, given that there is more time available at any given call; removing the artificial pressure at the edges of the semesters; removing the unnecessary pressure on the applicants, given the very little time left between receiving the results and the next submission deadline; relaxing the timelines of proposal selection and long-term scheduling processes, so that they can be conducted in a more thorough way; allowing for a better-optimised scheduling; increasing the flexibility for programmes requiring a faster duty-cycle; aligning with other large, ground-based and space-borne facilities (e.g. ALMA, HST, JWST, and other ESA and NASA facilities).

Status and next steps

Both the new proposal submission and handling software and Distributed Peer Review (DPR), which is a crucial ingredient for the deployment of the FTC, are now in place. In addition, ESO has formed a dedicated scheduling group specifically designed to cope with the increasing operational demands and the requirements dictated by dynamic scheduling. This is fully in line with the TAWG report, which mentioned the need for a dedicated operational unit.

In parallel, a new scheduling tool is being finalised. This software (Rejkuba et al., 2024) features a more sophisticated scheduling algorithm, and it was designed to enable dynamical scheduling, as opposed to the monolithic and static semester schedule implemented previously. The newly developed scheduling software has been successfully applied to prepare the P113 and P114 schedules.

The actions required for the implementation and deployment of the YC and the FTC can be divided into two groups: operational and procedural.

From the operational point of view, the YC will be treated in the same way as the current CfP, with the exception of the frequency. There will be one single deadline per year and the proposals will be assigned to the Expert Panels/OPC or to DPR, based on the amount of time requested, similarly to what is done currently. The yearly telescope schedules will be produced after the scientific proposal review is completed and will include a provision for inserting the FTC runs approved between the yearly calls. The FTC proposals will be solicited at fixed deadlines, called with an initial cadence of 3–4 months[a]. The FTC calls may be adjusted (in terms of offered instruments/modes, RA ranges, observing constraints) in a dynamic way, considering the prevailing situation of the observing queues. The successful proposals will be inserted in the schedule and queued for execution with a validity period which may depend on the science case and its urgency[b]. As regards the procedural aspects, no significant policy or procedural changes are expected. Large Programmes are already called on a yearly basis and the introduction of the YC will not change the cadence of their current calls. Public Surveys will also not be affected by the change, as they are offered only occasionally and via dedicated calls.

The FTC proposals will have to obey certain criteria to qualify. They are meant to not lose the opportunity of important or even major breakthroughs because of the increased reaction time introduced by the YC. They must not be resubmissions of regular proposals. The possibility of this type of proposals was included in the ESO Optical/Infrared Telescope Science Operations Policies approved by Council in 2020[2].

To this end a set of criteria are being discussed with the governing and advisory bodies and will be clearly spelled out in the FTC Calls. These will likely include a maximum amount of requested time per proposal and a cap on the time fraction allocated via the FTC. The criteria will be finalised by the end of 2024.

A deployment and information plan has been prepared by OPO in consultation with USD and PSO for the operational aspects, which include CfP for the YC and FTC, telescope scheduling, phase 2 and observation execution. A preliminary version was presented to the OPC, UC and STC in the course of 2023 and 2024. Following the proposed plan, and as announced in the June Science Newsletter[3], ESO intends to move to the YC in the course of 2025, contingent upon a final readiness review that year. The community will be regularly informed about the implementation through news in the regular CfP, newsletter posts and direct emails to active Principal Investigators.

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Links

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[3] ESO Science Newsletter Announcement June 2024: https://www.eso.org/sci/publications/announcements/sciann17641.html

Notes

[a] The frequency of the FTC call may be adjusted depending on the response from the community.

[b] The urgency of an FTC proposal will be dictated by the need of covering a given science case which cannot wait for the next regular CfP with a short response time. This does not include unforeseeable time-critical proposals related to transient phenomena, which should continue to be requested through Director's General Discretionary Time.

S. Lowery/ESO

At first glance, this image might appear to be straight out of the 'Dune' films, but this spectacular sunset scene is actually in the Atacama Desert in northern Chile, where the air is so dry and clean that colours shine through more vividly. This desert's rocky and sandy landscape may not hide mind-bending 'spice' or giant worms, but it holds something arguably as precious — can you see its silhouette in the distance?

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Scientific Visits to Chile — Numerous Opportunities

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[1] ESO

ESO operates its observatories in the Chilean Atacama Desert, far from large light-polluting cities. At the same time, there is a rich scientific life on the ESO campus in Santiago de Chile, with more than 30 faculty astronomers, two dozen postdoctoral fellows and around 10 PhD students. This makes ESO's hub in Chile an excellent location to foster scientific collaborations, and a natural starting point to interact with the Chilean astronomical community. Here we summarise the numerous opportunities for astronomers to visit ESO in Chile and connect with its scientific ecosystem.

Observing at an ESO telescope

The classic way of connecting to ESO's Santiago campus (Figure 1) is to combine a visitor mode (VM) observing run on La Silla or Paranal with a scientific talk on the Vitacura campus. ESO organises regular weekly Thirty Minutes Talks, colloquia, and lectures to aid in promoting scientific interactions between ESO staff and the wider community. In 2023 ESO welcomed around 110 visiting astronomers to La Silla, and 70 to Paranal. About 15% of those visiting astronomers gave a talk about their research at the ESO campus in Santiago, Chile. Extensions of observing trips for a couple of days in Santiago to enable such a talk are funded by ESO.

As shown in Figure 2, VM on Paranal is equally as effective as service mode for completing observing runs: 70% of the runs get completed, and 85–90% of the runs get at least 50% of their data. Therefore, VM is still an attractive scientific option, in addition to the advantages outlined by, for example, Rejkuba et al. (2018). Combining the observing trip with a stay at ESO's Santiago Office[1] can further enhance this experience and in particular help younger astronomers to build their collaboration networks.

Not all VM runs require astronomers to travel to Chile. ESO schedules short VM runs (less than about one or two nights) in designated VM, where users join the observing activities remotely from their home or institute[2]. Within the overall VM allocation since the pandemic restrictions were relaxed (the last three observing semesters, P111–P113), about 40% of the time and 50% of the runs have been scheduled in designated VM.


ESO/J. Girard (djulik.com)

Figure 1. Roof-top view of ESO's campus in Santiago de Chile[3]. In the foreground is the roof of the ESO building and in the left background are the offices of the Joint Alma Observatory (JAO).

Programmes for scientific visits

ESO's Office for Science in Chile offers various programmes designed to host scientific visitors and facilitate interactions between ESO staff and its community. Tailored to suit scientists at various career stages, these programmes vary in length and purpose, offering a competitive set of opportunities to visit the Santiago campus. In 2023 the Office hosted 40 short- to long-term visitors[4]. Below we briefly describe these various programmes.

ESO scientific visitor programme

The ESO scientific visitor programme[5] facilitates visits by distinguished senior scientists, with the goal of nurturing scientific collaboration between ESO and its community, and reinforcing ESO's standing as an astronomical centre of excellence. Applications for the scientific visitor programme in Chile are welcome throughout the year, without specific deadlines. The duration of a visit can range from a few days to a year, with an average duration of two to three months.

ESO early-career scientific visitor programme

This programme supports short-term visits[6] by PhD students and postdoctoral researchers within three years of completing their PhD in astronomy or related fields. It offers them the opportunity to promote their research experience, connect with potential collaborators, and enhance their professional experience by interacting with ESO experts involved in developing and operating ESO facilities. Applications are accepted at any time, with visits typically lasting between one and four months.

Short-term internships

The science internship programme in Chile is designed for students in the final stage of their undergraduate studies or enrolled in a master's programme in astronomy or a related discipline. It serves as an excellent platform for students to gain first-hand experience of conducting scientific or operations-related research projects in an international observatory within a culturally diverse environment. Experience has shown that these internships can help to direct students towards making a decisive choice for their future education and career. Interested students are encouraged to connect with potential supervisors (ESO staff astronomers and/or ESO

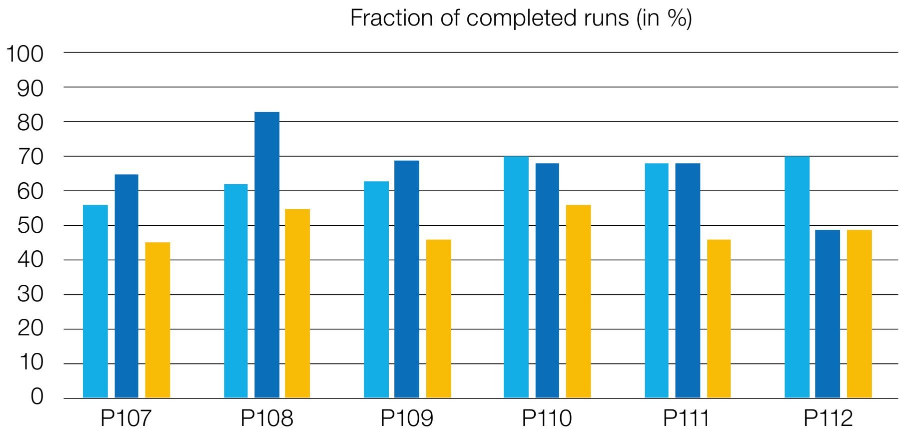

Figure 2. Completion fraction for visitor mode (VM, light blue) and A-ranked service mode (SM, dark blue) runs at Paranal, and VM at La Silla (there is no SM at La Silla, yellow). The bars indicate the fraction of observing runs that are completed to 100%, for runs that are scheduled in the given semester. For Paranal, the completion fraction is remarkably similar between VM and SM runs, at around 70%. The SM completion for P112 will still increase because some A-ranked P112 runs will be carried over to subsequent semesters. Runs that have only partial completion are not included in this Figure. For example, 85–90% of VM runs for both sites get at least 50% of their data.

Fellows)[7] to discuss science projects. The selection process takes place through an annual internal call, with the deadline typically falling in the third quarter of the year.

ESO PhD studentships

Students enrolled in a PhD programme, preferentially in an ESO Member or Partner State, or a Chilean university, can apply for ESO studentships[8] with a duration of between six months and two years. The ESO Chile studentships provide excellent training opportunities for the upcoming generations of astronomers and ESO telescope users. Additionally, they facilitate connections between students, their host university supervisors, and ESO scientific personnel. In Chile, students have the chance to visit the observatory and engage in self-contained technical projects. Two applications per year are announced on the ESO recruitment portal[9] with deadlines in April and October.

Agreements with specific ESO Member States

Acknowledging the importance of training the next generation of astronomers at the most productive ground-based astronomical observatory in the world, several Member States have signed dedicated agreements with ESO to fund early-career scientists for long-term visits to the observatory. With this goal in mind, the Ministry of Education, Youth, and Sports (MEYS) of the Czech Republic sponsors an on-the-job training programme for Czech students and interns at ESO[10]. Similarly, the Irish Research Council has signed a partnership agreement with ESO to fund studentships of one or two years duration[11].

La Silla Observing School

The La Silla Observing School[12] is organised every one to two years, targeting PhD students in astronomy or MSc students in their final year. During two weeks of intense work the participants obtain hands-on real-life experience of the full cycle of activities, including observation planning, observing with professional 2–4-metre telescopes and the data reduction & analysis afterwards. All this is done with the help of experienced tutors who also provide lectures on the basics of observing techniques (Figure 3). The school is free for the students, and ESO covers lodging in Santiago and at La Silla plus travel to/from Santiago/La Silla. After a very successful, and highly oversubscribed, school in February 2024, ESO will organise another La Silla Observing School in 2025.

In summary, the ESO office in Santiago in Chile provides a unique environment for scientific collaboration and professional development. Through observing runs,

Figure 3. Right: Introductory lecture to the La Silla Observing School 2024, in the main lecture hall of the ESO Chile premises. Left: A talk in the ESO Chile library.

scientific talks, and various visitor programmes, astronomers can enhance their research and connect with ESO's dynamic scientific ecosystem.

Acknowledgements

We would like to thank the ESO visiting astronomers' travel office and the ESO Chile colloquia organisers for help with deriving the statistics of visiting astronomers who gave a talk in Vitacura.

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[12] La Silla observing school: https://www.eso.org/sci/meetings/2024/lasilla_school2024.html

ESO/VPHAS+ team. Acknowledgement: CASU

The Running Chicken Nebula comprises several clouds, all of which we can see in this vast image from the VLT Survey Telescope (VST), hosted at ESO's Paranal site. This 1.5-billion-pixel image spans an area in the sky of about 25 full Moons. The clouds, with their wispy pink plumes, are full of gas and dust, illuminated by the young and hot stars within them.

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Report on the

La Silla Observing School 2024

held at ESO Santiago office and La Silla observatory, Chile, 12–23 February 2024

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The La Silla Observing School is a series of training workshops in the use of telescopes and astronomical instruments for students and early-career researchers in astronomy. Following schools in 2016, 2018 and 2020, the fourth La Silla Observing School was held over two weeks in February 2024 and was hosted by ESO's Office for Science and the La Silla Observatory. A total of 20 MSc students, PhD students and postdoctoral researchers from South and North America, Europe and Australia participated. They attended lectures on various observing strategies and astronomical instrumentation, on diversity, equity and inclusion in astronomy, as well as soft skills. For the hands-on part at the observatory, the students were supervised by five tutors. Four small research projects were offered, using three telescopes and four instruments. The students in each research group went through the full process of defining and discussing the observing strategies, conducting the observations, reducing and analysing the data and finally presenting the results to the scientific community at the ESO Vitacura offices. Given the high demand from the astronomical community for such educational programs, ESO is currently exploring the possibility of offering the La Silla Observing School on a yearly basis. Accordingly, the next school is foreseen for February 2025.

Introduction

First held in 2016, ESO has hosted four observing schools at La Silla during the summer break in the southern hemisphere, aimed at senior master's students and early doctorate students. The main goal of these observing schools is to give the participants the opportunity to gain experience of observations, instrumentation background, and the entire cycle from planning observations, carrying them out, data reduction and analysis to the presentation of the results. This is becoming increasingly important given the increasing use of remote and service mode observations, which denies many students the possibility of having hands-on experience with large, modern observing facilities.

The La Silla Observing School 2024[1] (Figure 1) was open to students worldwide; the students were asked to pay for their travel to Santiago themselves, while lodging and transport in Chile were covered by ESO. They were housed in shared flats in the lively district of Providencia, which allowed them to get to know each other in a relaxed environment. The La Silla Observing School started on Monday

Figure 1. The enthusiastic participants at the fourth La Silla Observing School.

12 February with a four-day workshop at the ESO premises in Vitacura. The lectures covered ESO in general, astronomical instrumentation, observing preparation and strategies, and a discussion of diversity, equity and inclusion in astronomy. In addition, on three afternoons the tutors introduced the students to the research projects and prepared the upcoming observations with them. On the Thursday evening, we celebrated the end of the workshop with a barbeque in the garden of the ESO premises.

On Friday 16 February the students and tutors travelled to La Silla by bus, and arrived there just in time for the wonderful sunset (Figure 2). During the night the students visited the control room of the 3.6-metre telescope, the New Technology Telescope (NTT) and the 2.2-metre ESO/MPG telescope and got acquainted with the southern night sky, which most of the students had never seen before. Saturday was reserved for a visit to the 2.2-metre ESO/MPG telescope and final observation preparations, and a small group of students and tutors hiked to the ancient petroglyphs in the valley behind the 3.6-metre telescope (Figure 4). On Sunday afternoon the students visited the NTT and the 3.6-metre telescope (Figure 3), and after sunset they began the observations using the High Accuracy Radial velocity Planet Searcher and the Near InfraRed Planet Searcher (HARPS+NIRPS; Mayor et al., 2003; Bouchy et al., 2017) on the 3.6-metre telescope, the ESO Faint Object Spectrograph and Camera 2 (EFOSC2; Buzzoni et al., 1984) on the New Technology Telescope (NTT) and the Fiber-fed Extended Range Optical Spectrograph (FEROS; Kaufer at al., 1999) on the 2.2-metre ESO/MPG telescope. During the first day and a half the weather conditions were good; however, the last night was mostly lost because of clouds.

On Wednesday 21 February, the students returned to Santiago with happy memories and data in hand. The last days in Santiago were dedicated to data analysis and lectures on career prospects and soft skills, before the students presented their scientific results to the public on Friday 23 February (Figure 5). The successful conclusion of the school was celebrated with wine & cheese in the ESO garden.

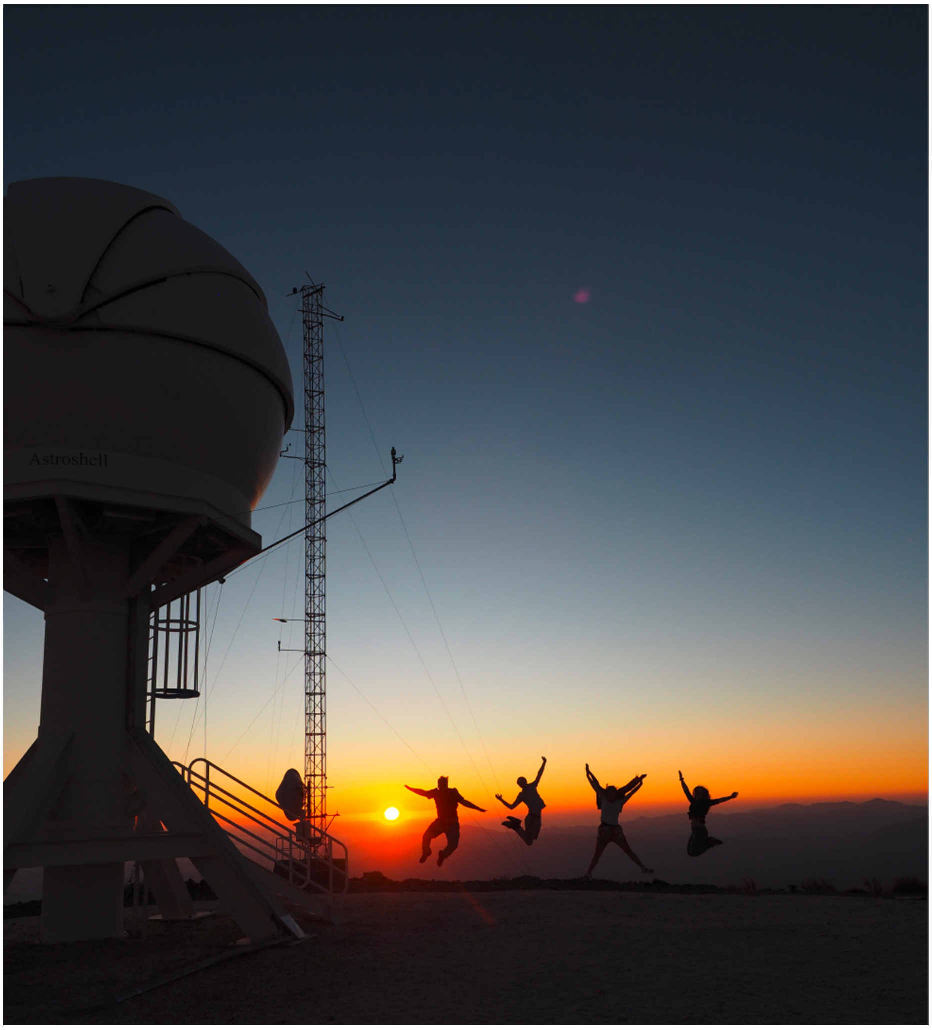

Figure 2. Happy students on La Silla!

The two weeks of the school were intense for both the tutors and students — and immensely rewarding. The amount of work carried out over the two weeks was impressive and the organisers were pleased to receive very positive feedback from the students.

The working groups

Four small research projects were developed by five experienced astronomers working at ESO and at Universidad Diego Portales.

The goal of the project led by ESO staff astronomer Robert J. De Rosa was to measure the light curves and radial velocities of a small number of short-period eclipsing binaries (EBs) using EFOSC2 on the NTT and FEROS on the 2.2-metre telescope. The participants filtered a large catalogue of EBs using the orbital ephemerides to predict the times of primary and secondary eclipse, and the time when the velocity difference is highest. The observations were prepared using the Exposure Time Calculator for both instruments, and an observing plan was drawn up given their time-critical nature. In parallel to taking the observations with EFOSC2 and FEROS, the students developed a pipeline to perform differential photometry on the EFOSC2 data and were easily able to detect the primary and secondary eclipses of the four EBs. Their light curves were then combined with literature data to model the geometry of the systems using the PHOEBE eclipsing binary modelling software. Unfortunately, the four systems

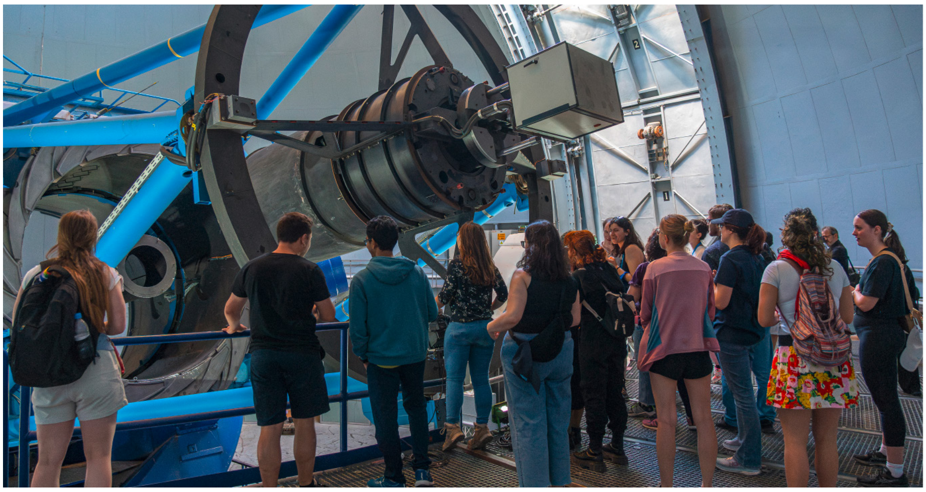

Figure 3. The participants on a tour of the La Silla 3.6-metre telescope.

were very chromospherically active given their short orbital period and it was not possible in the short timeframe available for the analysis to determine their spectroscopic orbits. However, in one system a third component on a long orbital period was discovered thanks to the linear variation of some sharp specral lines evidently not caused by either of the eclipsing components.

The project led by Evelyn Johnston, a professor at Diego Portales University, aimed to explore the properties of galaxies along the Hubble Sequence. The students selected five galaxies with elliptical, lenticular and spiral morphologies, and observed these galaxies with long-slit spectroscopy and multi-waveband imaging using EFOSC2 on the NTT. Once reduced, they binned the spectra and measured the kinematics along the major axes of each galaxy. They saw that the spiral and lenticular galaxies showed clear rotation curves while the elliptical galaxies had little or no rotation, as expected. This result then led to discussions of the dark matter content within galaxies to explain the rotation curves. With the imaging data they saw how the galaxies change in different filters, such that the bulges of spirals and lenticulars are more prominent in the redder filters while the discs and spiral arms dominate in the blue. This finding led to discussions of the stellar populations in different galaxies and their components.

The project led by ESO fellow Francesca Lucertini and ESO staff astronomer Luca Sbordone aimed at deriving stellar atmospheric parameters and detailed abundances in FGK stars from high-resolution spectra. The targets were selected from Gaia photometry. The two groups of four students determined the best exposure times, and prepared and executed the observations with HARPS/NIRPS and FEROS. Fourteen targets were observed with both instruments with a typical signal-to-noise ratio between 50 and 100. Owing to an issue with the FEROS pipeline, only the HARPS spectra were used in the data

Figure 4. One of the highlights was a hike to the ancient petroglyphs of La Silla.

Figure 5. On the last day the different groups presented their work to the audience at ESO Vitacura.

analysis. The students then derived atmospheric parameters and detailed abundances using the MyGIsFOS code. The targets turned out to be mostly moderately metal-poor ([Fe/H] ~ –0.5) K giants, with a few G dwarfs. The most metal-poor star had [Fe/H] = –1.4. All primary nucleosynthetic channels were represented with abundances for about 30 ions. The students then compared the derived abundances with available literature trends for the different elements, and discussed the implications of their findings.

In the exoplanet atmospheres project group led by ESO staff astronomer Elyar Sedaghati, the participants first searched for extra-solar planets with primary transits occurring on either of the two observing nights allocated on the 3.6-metre telescope. Of all the possible candidates two systems were deemed to possess atmospheres extended enough to be detectable. The transit events on the two nights were observed with the HARPS and NIRPS high-resolution echelle spectrographs. The data were reduced using the dedicated ESO pipeline recipes, run on the esoreflex platform. After correction for the radial velocity variations in the stellar spectra due to the reflex motion of the star around the centre of mass of the system, the out-of-transit spectra were combined to create a stellar template. This was used to remove the stellar signature, and then the residuals were shifted to the planetary restframe. These were then combined to create the planetary transmission spectrum. The group inspected this spectrum, cross-matching any possible absorption lines with atomic and molecular databases. They also detected a surprisingly polar orbit for one of the systems, via the modelling of the Rossiter-McLaughlin effect.

Demographics

The school was open to students and early-career postdocs worldwide. We received a total of 140 applications evenly distributed between male and female applicants, of whom nine were MSc students, 114 PhD students and 17 postdoctoral researchers. Students applied from institutes based in Argentina, Australia, Austria, Belgium, Brazil, Bulgaria, Chile, Czechia, Denmark, Estonia, France, Germany, India, Iran, Italy, Kazakhstan, the Netherlands, Poland, Spain, Sweden, the UK, and the USA. As part of the application, the students were asked to provide a summary of their background in astronomy, their motivation to participate in the school, and a reference letter from their supervisor.

The selection committee did not have personal information about the applicants, such as gender, nationality, etc., and the applications were evaluated purely on the basis of the students' background in astronomy, their motivation to participate in the school, their potential career gain from participating in the school, and in a later step, on the reference letters provided by their supervisors. Individual requests for financial travel support did not have any influence on the selection process. The final selection resulted in 18 female and two male students based at institutes in South America, Europe and Australia; one of the students was a senior MSc student, 18 were PhD students and one was a young postdoctoral researcher who had just defended their thesis.

Acknowledgements

We thank the Max-Planck-Gesellschaft (MPG) for awarding three nights of the La Silla MPG/ESO 2.2-metre Telescope to the La Silla Observing School, the ESO Office for Science for their financial help and the La Silla Observatory for their kind hospitality and generous support. The logistical aspects of the school were handled by Paulina Jirón, Leslie Kiefer and Francisco Tapia, to whom we extend our deep gratitude. We would also like to thank the invited speakers at the school: Belén Alcalde, Magda Arnaboldi, Marco Berton, Roland Gredel, Itziar de Gregorio Monsalvo, Nicolas Haddad, Boris Häußler, Gaspare LoCurto, Michaël Marsset, Faviola Molina, Claudia Paladini, Maria Jose Rain, Eleonora Sani, Linda Schmidtobreick and Jonathan Smoker.

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Links

[1] Workshop programme: https://www.eso.org/sci/meetings/2024/lasilla_school2024.html

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Report on the ESO workshop

A Decade of ESO Wide-field Imaging Surveys

held at ESO Headquarters, Garching, Germany, 16–20 October 2023

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A decade of targeted wide-field imaging at ESO was coming to an end in early 2023, when the near-infrared imager VIRCAM at the Visible and Infrared Survey Telescope for Astronomy was decommissioned. Shortly before, in October 2022, the optical wide-field imager OmegaCAM at the VLT Survey Telescope had become a hosted telescope after many years of being an ESO-operated optical survey machine. The two instruments were largely dedicated to public imaging surveys, which have amassed a total of nearly 60 000 hours of telescope time. To commemorate these milestones, ESO organised a five-day workshop in October 2023 to review the legacy left by these instruments, to summarise the variety of scientific impacts that the imaging surveys have had on a wide range of research topics in astronomy, and to encourage new ideas from/within the community to enlarge the exploitation of the high-quality VIRCAM and OmegaCAM survey data.

Introduction

The Visible and Infrared Survey Telescope for Astronomy (VISTA; Emerson et al., 2004) and the VLT Survey Telescope (VST; Arnaboldi et al., 1998), were designed to host wide-field imagers enabling efficient observations of large portions of the southern sky with high sensitivity and sub-arcsecond spatial resolution. VIRCAM, the infrared camera installed on VISTA, was mostly dedicated to 13 public surveys[1], and has amassed over 40 000 hours of science data over 13 years. Similarly, the optical imager OmegaCam on the VST spent about 15 000 hours acquiring data for three public surveys[2] and Guaranteed Time Observations for large programmes between 2011 and 2022. Large collaborative survey teams stood behind each of the public surveys, that targeted many of the fundamental questions in contemporaneous astrophysics, ranging from the nature of dark energy to the universality of the stellar initial mass function. ESO, for its part, had set in place mechanisms and procedures to manage these public surveys and to ensure their legacy value and their usefulness to the astronomical community at large. All raw data from these surveys became public in the ESO Science Archive immediately and processed data and catalogues provided by each survey team are available via the ESO Science Archive Facility. The main goals of the workshop were to further advance science cases, create international collaborations among research groups and encourage new ideas from/within the community to enlarge the exploitation of the high-quality VIRCAM and OmegaCAM survey data and, last but not least, to promote the usage of the archival data from these facilities.

The programme

Approximately 110 participants (around 65% attended in person) gathered during the week in October 2023 to listen to inspiring talks and to engage in lively discussions (Figure 1). The workshop programme[3] was split into Galactic and extragalactic scientific fields between the morning and afternoon sessions of each day of the workshop. The topics ranged from Galactic star formation, the structure of the Milky Way, stellar populations of the Galactic plane, transient and variable objects and exploring stellar populations in the Magellanic Clouds to studying dark energy, investigating galaxy evolution and the evolution of galaxy clusters, baryonic

Figure 1. Conference photo.

acoustic oscillations, and mass assembly in the very first galaxies. Sessions were introduced by one or two invited overview talks describing a public survey connected to each specific research topic. Contributed talks were intertwined with the overview talks, spanning a near-complete range of science cases and environments. The legacy value of several public surveys was showcased through many scientific findings presented in various contributed talks.

On the third day of the workshop the programme featured invited and contributed talks that outlined the synergy of the VIRCAM/OmegaCAM legacy with the new generation of wide-field imaging and spectroscopic facilities and missions, for example, Euclid, the 4-metre Multi-Object Spectrograph Telescope (4MOST), the Wide-field Spectroscopic Telescope (WST) and the Multi-Object Optical and Near-infrared Spectrograph (MOONS). In addition, ESO's plans for future surveys were presented, which are largely focused on spectroscopic public surveys carried out, for example, with exisiting Very Large Telescope (VLT) instruments such as the *K*-band Multi-Object Spectrograph (KMOS) — see the recent Call for Letters of Intent[4]. The 'future surveys' session was followed by a Wednesday afternoon session that concentrated on how to potentially exploit the VIRCAM and OmegaCAM survey data and to promote the usage of the archival data from these facilities. Specific talks were given to explain the content and use of the Cambridge Astronomical Survey Unit / Wide-Field Astronomy Unit and ESO science archives that encouraged the attendees and others to download the data from the public surveys (especially Phase 3 data) for their own science. In addition, a hands-on presentation showed how to navigate step-by-step through the ESO Science Archive. This and most of the talks during the week were recorded and are available in a special YouTube Channel[5]. The interested reader may also view the slides made available by the workshop participants on Zenodo[6].

An important part of the workshop during the week was the ESO Archive Booth. This was a 'helpdesk' stand in the auditorum foyer set up by the ESO archive science group for public survey team

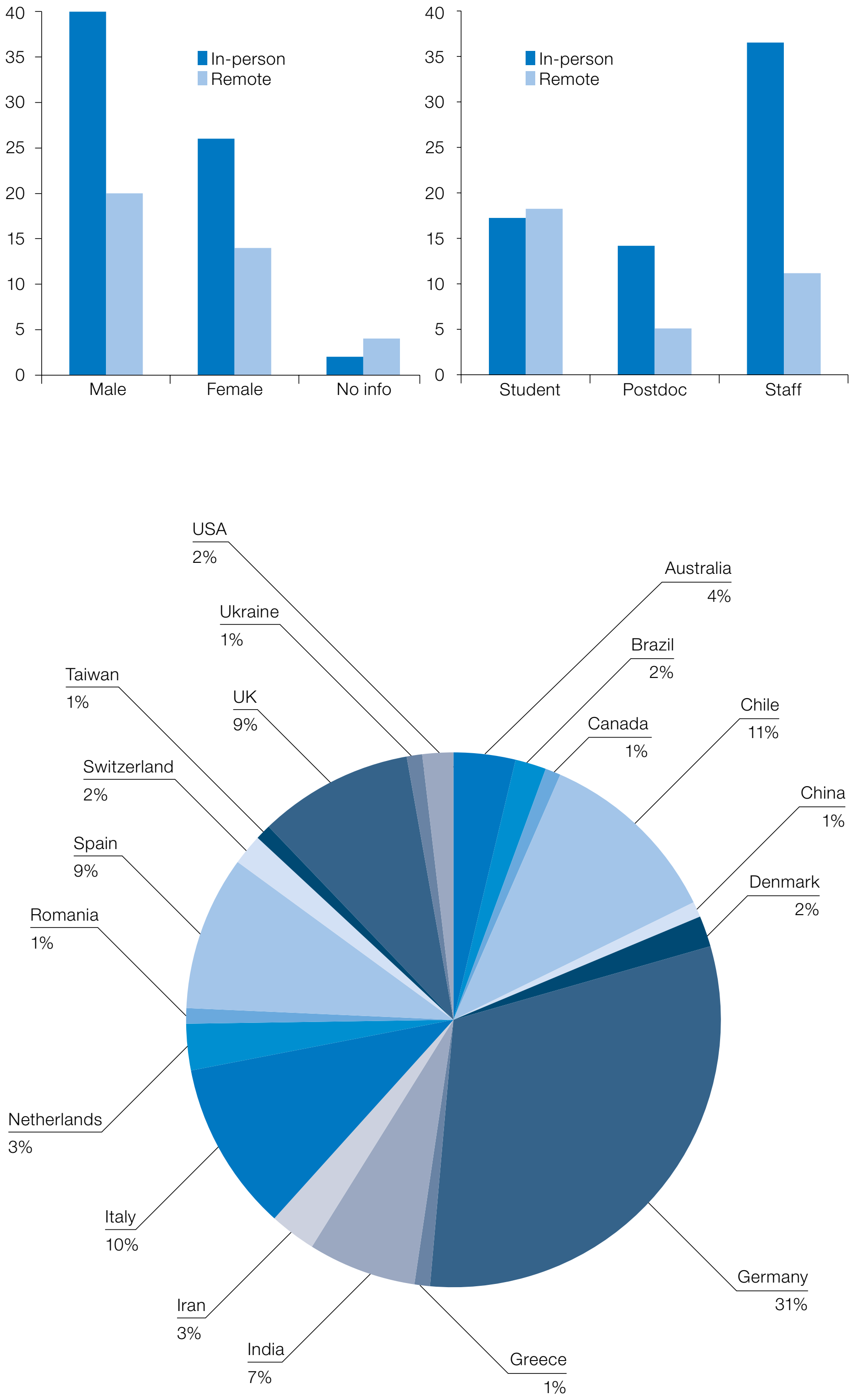

Figure 2. Top: Demographic distributions of the gender (left) and career stage (right) of the participants, split up into in-person (blue) and remote (light blue) participants. Bottom: Overview of the home countries of all participants.

members and users in the community who were interested in publishing/using data to/from the ESO Science Archive. It turned out that this service was extremely well received, in particular among the public survey team members who could use this opportunity to effectively discuss in person outstanding matters and issues with the publication of survey data. Also, after the hands-on talk on Wednesday afternoon there was an increased interest from the workshop participants in the activities at the archive booth. Moreover, for those colleagues who prefered specific help in hands-on tutorials or had specific questions, for example about accessing data from a specific public survey, arrangements for one-to-one sessions in the week(s) following the workshop could be made.

Demographics

The workshop had a good number of participants, with 69 in-person and 38 remote attendees. The Scientific Organising Committee (SOC) agreed that each public survey PI would be invited to nominate a person from their team to give an overview talk of their public survey. In doing so the PIs were encouraged to nominate a young researcher and/or female speaker. This worked out for roughly 30% of the surveys. Once all the workshop registrations were received, there was a perfect match between requested talks and available talk slots, such that the SOC happily agreed to accept all the contributed talks and asked the one student who had only registered for a poster to convert their poster into a short talk. The resulting representation from the community in terms of gender was 40/60 (female/male), which is a bit higher than the female/male distribution among the invited speakers (around 33% female), and also higher than the ratio for the contributed talks (around 35% female).

Attendees came from all over the world, with the following percentages (see also Figure 2):
- 68% Europe (Germany, Italy, UK, Switzerland, Ukraine, Spain, the Netherlands, Greece, Romania, Denmark);
- 3% North America (US, Canada);
- 12% Asia (India, China, Taiwan, Iran);
- 13% South America (Chile, Brazil);
- 4% Australia.

Thanks to the well-balanced budget, it was also possible to provide generous financial support to a few young researchers and students.

Concluding remarks

As the workshop was intented to emphasise the legacy of a decade of ESO wide-field imaging surveys and to promote the ongoing scientific exploitation of these surveys, we wish to highlight once again that the main access point to the data products is the ESO Science Archive[7]. As demonstrated by the interest in the workshop and the activities within the community, survey data are rich and have enormous potential for discoveries in every niche of astronomical research.

Acknowledgements

We would like to thank the SOC and Local Organising Committee for all their fantastic support work, before, during and after the conference. We also thank colleagues from the ESO facility management for their help with logistics and making sure coffee/tea and snacks were arranged in time for the numerous breaks. A special thanks goes to Denisa Tako for her patient help and support with the organisational aspects of the conference.

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Emerson, J. P. et al. 2004, The Messenger, 117, 27
Arnaboldi, M. et al. 1998, The Messenger, 93, 30

Links

[1] VISTA surveys: https://www.eso.org/sci/observing/PublicSurveys/sciencePublicSurveys.html#VISTA
[2] VST surveys: https://www.eso.org/sci/observing/PublicSurveys/sciencePublicSurveys.html#VST
[3] Workshop programme: https://www.eso.org/sci/meetings/2023/surveys
[4] KMOS Call for Letters of Intent: https://www.eso.org/sci/observing/PublicSurveys/KMOSloicall.html
[5] Workshop YouTube channel: https://www.youtube.com/@WFIS_at_ESO
[6] Workshop slides on Zenodo: https://zenodo.org/communities/surveys2023/
[7] ESO Science Archive: http://archive.eso.org/cms.html

ESO Acknowledgements: Flickr user hdahle70

This image from the Wide-Field Imager on the MPG/ESO 2.2-metre telescope shows the starry skies around a galaxy cluster named PLCKESZ G286.6-31.3. The cluster itself is difficult to spot initially, but shows up as a subtle clustering of yellowish galaxies near the centre of the frame.

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ALMA at Ten Years: Past, Present and Future

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In December 2012 the first results from Early Science observations by the ALMA Observatory were discussed at a workshop held in Puerto Varas, Chile. In 2013 ALMA was inaugurated and only ten years later it has revolutionised our view of the Universe, both near and far. In December 2023 the scientific community returned to Puerto Varas to attend the conference ALMA at ten years: Past, Present and Future, celebrating ten years of ALMA operations. In this article, we report on the outcome of this conference.

Introduction

The conference was structured around five main scientific categories, from the high-redshift Universe to the Solar System and the Sun. In addition, observatory-specific topics were presented, from ALMA's history and current status to technical developments in the near and far future. The conference included in-person and online talks. Posters were displayed online and at the conference venue and highlighted in poster-flash sessions interleaved with the oral contributions throughout the conference.

An important goal of the conference was to showcase the success of ALMA, both in terms of its scientific reach and its diverse community. This was amply achieved with an attendance of more than 300 participants, of whom nearly 55% attended in person (Figure 1). Figure 2 shows the distribution of participants by career stage, region and science category. The ALMA reach is reflected in all and each one of such distributions, from the more than 20% of Chilean participants to the nearly 50% of young astronomers and the multiple science topics. ALMA is clearly attracting astronomers from a wide range of areas, well beyond traditional areas of millimetre/submillimetre astronomy and it keeps on renewing its community with young astronomers.

Scientific highlights

High-redshift galaxies

ALMA has opened the study of the interstellar medium (ISM) in high-redshift galaxies thanks to increased sensitivity, better angular resolution, access to submillimetre bands (> 300 GHz) and new observing modes, such as frequency scans, compared to previous facilities. ALMA has detected and imaged emission from a galaxy at $z = 9.119$ (Hashimoto et al., 2018), but more importantly it has

Figure 1. In-person participants.

C. Gutierrez (Soluciones Digitales)

increased the sample from ~ 200 galaxies known at $z > 1$ before ALMA to thousands now, with a significant fraction above $z > 4$ found by the Large Programmes[1] (LPs) ALPINE and REBELS.

High angular resolution has enabled the discovery of dense, highly star-forming protocluster systems at $z > 3$. The break-up of previously known submillimetre galaxies in multiple galaxies also showed that many of them were main-sequence galaxies rather than starburst ones. ALMA has also imaged the kinematics of discs at high redshifts, showing that rotation-dominated discs are already present at early times, in contrast to previous trends observed in warm gas (Hα) and simulations, which indicated clumpy, thick discs, dominated by turbulence. Using [CII] and dust in addition to CO, the field is further progressing by performing a census of stars, gas and dust for main sequence galaxies at $z \sim 4$–6 at 1–2.5 kpc resolution (for example, with the LP CRISTAL).

Another significant achievement of ALMA has been to demonstrate that the star formation rate density in the Universe is driven by gas mass rather than by star formation efficiency at $z \sim$ 1-4. While a significant number of obscured star-forming galaxies have been unveiled at $z \sim 4$–7, demonstrating that the Universe was already dusty at < 1 Gyr of age, efforts are now ongoing to find the first massive quiescent galaxies at such redshifts and thus shed light on the question of why galaxies quench star formation. Importantly, many of the results in this field have not yet pushed ALMA to the highest angular resolutions or frequencies, and advances are already foreseen, for example by using the highest frequencies to constrain dust masses and temperatures.

Nearby galaxies and galactic nuclei

In more nearby galaxies, ALMA is being exploited to investigate star formation over cosmic time (LP PHANGS) or the origin and role of feedback in galaxy evolution.

Observations of galaxy bars at 0.5-parsec resolution show super star clusters hosting more than 1000 O-type stars. In these clusters, spherical outflows are found to be expelling a large fraction of molecular gas that may have an origin in winds from the O-type stars and/or dust-reprocessed radiation pressure. Feedback from outflows of active galactic nuclei (AGN) at the core of galaxies is also being searched for, although so far no clear depletion or enhancement of the molecular gas content of galaxies with AGN and the control samples of pure star-forming galaxies has been found.

As part of the Event Horizon Telescope, ALMA provided the crucial sensitivity needed to obtain the first image of a black hole via very long baseline interferometry (Event Horizon Telescope Collaboration, 2019). The image shows the shadow of the supermassive black hole at the centre of the galaxy Messier 87 (M87) and obtained more than 4.5 billion image views shortly after being released!

ALMA's sensitivity can probe how these supermassive black holes are fed by stars, by monitoring the nonthermal emission from the so-called tidal disruption events that result from such feeding, and investigate the potential role of black hole spin to form jets in these events. ALMA's exquisite angular resolution has been used to identify the host galaxies of other transient events such as gamma-ray bursts or fast radio bursts and to characterise their environment, indicating, for example, that the latter can arise in a wide range of environments, from star-forming regions to old populations within a galaxy.

Star formation and the ISM

Following the discovery of the prebiotic molecule glycolaldehyde towards a solar-type star with ALMA Early Science Verification data, astrochemistry has become a key scientific tool of the ALMA community, especially but not only in the fields of star formation and the ISM. More than 100 different species were identified towards a protostar in just one programme (PILS; Jørgensen et al., 2016) and studies are now attempting to establish how the environment impacts chemistry, including not only protostars but also comets (LP COMPASS). The earlier stages of star formation, such as core collapse, are being investigated via deuterated species that can trace the densest gas, and the core mass function of young massive protoclusters has been revealed as top-heavy by the LP ALMA-IMF, which has also found a correlation between the power-law index of the core mass function high-mass end and the cloud properties and evolutionary stage.

The access to diverse spatial scales has also allowed the characterisation of as many as a thousand clumps by the LP ALMAGAL and the ability to follow individual stars as they form in our own Milky Way, including the discovery of protostellar multiplicity requiring disc and turbulent fragmentation.

Polarisation observations have further looked at which stage discs form around protostars and the role of magnetic fields in such formation, seeming to indicate that external irradiation by cosmic rays is not sufficient to ionise the gas so that it can couple to the magnetic field that is thought to regulate disc formation via extraction of angular momentum.

Finally, ALMA is also looking at the diffuse ISM in absorption to find the earliest stages of molecule formation, and has already revealed puzzlingly high abundances of SiO in low-density, non-star-forming diffuse gas and shown that photodissociation regions cannot explain the high HCO+ column densities observed in directions in which HI has a temperature higher than 40 K and non-equilibrium chemistry may be required.

Circumstellar discs

ALMA revolutionised the study of circumstellar discs with its iconic image of the protoplanetary disc around the young star HL Tau, where the network of rings in the disc demonstrates that planet formation is under way at stellar ages of 1 Myr (ALMA Partnership, 2015). Current studies are moving towards characterising precisely the moment at which rings appear by imaging protoplanetary discs around protostars at even younger ages and characterising such discs via detailed maps of dust and gas, the latter being enabled by the detection of numerous molecules that trace different densities,

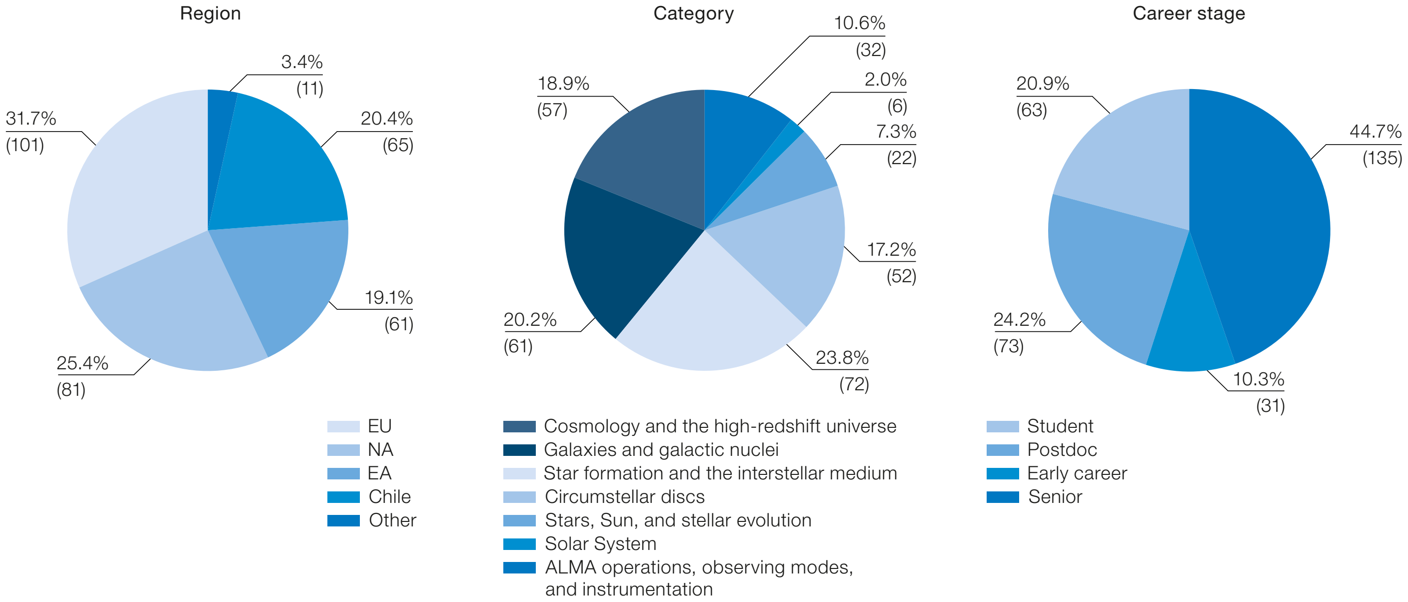

Figure 2. Demographic distributions of the conference participants by geographical region, scientific category and career stage of conference participants.

temperatures and environments (for example the LP MAPS).

An important new aspect of these studies is how the chemistry in discs is affected by X-ray flares from the protostar, thus bringing protoplanetary studies into the realm of time-domain astronomy. A significant advance has also been provided by precision kinematic studies that have detected distortions in the velocity structure in discs that suggest the presence of embedded planets (LP exoALMA). Finally, polarisation observations are exploring the importance of magnetic fields in the alignment of dust grains. Observers in this field, however, have emphasised the need for long (including LPs) multi-wavelength observations to disentangle the effect of magnetic fields from that of self-scattering in aligning the grains.

Closely related to these studies are those of debris discs. ALMA's resolution and sensitivity have revealed that belts are morphologically diverse, and have radial and vertical substructures possibly caused by planets, and cold gas with an uncertain origin, either exocometary or remnants from the protoplanetary phase (for example the LP ARKS).

Stars and stellar evolution

In the field of evolved stars, ALMA has been key in demonstrating that stellar winds have 3D inhomogeneities that were much more pronounced than ever thought. ALMA has seen the impact of a binary companion shaping the winds at thousands of stellar radii, indicating that mass loss rates have been long overestimated by being based on single-star evolution models. Observations are also now being pushed to the limits of angular resolution (as far as 8 milliarcseconds for observations of the red supergiant Betelgeuse!) to study the distribution of molecular gas and dust down to the stellar atmosphere, based on which the presence of convective cells in the photosphere has been already revealed in an asymptotic giant branch star (Velilla-Prieto et al., 2023). But ALMA has also investigated how dust forms from oxydes and hydroxides (LP ATOMIUM), thus indirectly providing information about what is happening at scales as small as nanometres.

Further down the path of stellar evolution, ALMA is now providing new insights into explosive events related to stellar death, such as supernovae and the remnants of those explosions. Explosive events involve blast waves, which expand in the circumstellar medium and beyond, creating shocks. The evolution of the synchrotron emission at millimetre/submillimetre wavelengths provides information about the properties of the ejecta and the surrounding medium and allows a unique look at the earliest times since the millimetre/submillimetre emission peaks before emission at longer wavelengths.

Surprises are also arising in the study of remnants such as rotating neutron stars or pulsars. While pulsars have a very steep spectrum at radio frequencies and were therefore not expected to show significant emission in the ALMA bands, the phased-mode of ALMA has already enabled it to detect an emission component at 100 GHz in the Vela pulsar, distinct from the component peaking at 1.4 GHz. Further community efforts are now being targeted on the search for pulsars at the Galactic centre, which would enable high-precision tests of strong gravity around the supermassive black hole at the centre, Sgr A* (Torne et al., 2023).

The Solar System and the Sun

Closest to home, ALMA has also opened a new discovery space in the area of planets and their moons or comets, as spacecrafts are not typically equipped with millimetre–wavelength instruments. ALMA has mapped the chemistry, derived the temperature structure and studied the kinematics of atmospheres, mapped zonal winds and identified volcanoes in planets and their moons. ALMA has also been highly synergetic with space missions in the Solar System, for example by observing nitriles in Saturn's moon Titan and complementing the hydrocarbon measurements from Cassini's flyby. Remarkably, some of the results have been derived from the use of Titan as a calibrator for other ALMA observations, highlighting that new species can be detected in only a few minutes of observations. In comets, ALMA has allowed for the first time tracing molecular species to the coma, helping to link interstellar and planetary ice and gas reservoirs (see also LP COMA).

Finally, ALMA has observed the Sun at various frequencies that are sensitive to different levels of the chromosphere, allowing a map to be built of its temperature structure and making progress towards answering the fundamental question of how the chromosphere is heated. As Stephen White said in his talk, *"ALMA solar observations provide tests that establish the physics needed to understand the solar atmosphere and by extension the atmospheres of all stars."*

ALMA development

The ALMA Programme Scientists gave an overview of the development projects and studies that are taking place at the ALMA regions. Such development is the key pillar of the Wideband Sensitivity Upgrade (WSU), presented by the Observatory Scientist. ALMA will rejuvenate as it approaches 20 years of operations by undergoing an upgrade of the full signal chain, from the receivers and digitisers, all the way to the correlator, which will result in increases in sensitivity for all observations. This is fundamental to taking advantage of the planned upgrade of the receivers to increase their instantaneous spectral bandwidth by as much as a factor of four. Observations at full spectral resolution over the entire bandwidth will result in increases of the spectral scan speed of up to a factor of 50 for the highest spectral resolution, and make ALMA an even more powerful tool to explore the Universe. Discussions in this session touched on how to best access and prepare for data analysis and exploitation of the massive sets that will be obtained. Beyond the WSU, former ALMA Director Pierre Cox encouraged the scientific community to start thinking about the key scientific questions of the 2040s and the relevant capabilities that ALMA needs to solve them.

Outlook

ALMA has opened a new window onto the millimetre Universe and revolutionised our understanding in areas as diverse as the high-redshift Universe and star and planet formation. However, the conference has made clear that ALMA's capabilities have not yet been fully exploited. For example, high-frequency observations are necessary to unequivocally determine the dust temperature or to measure far-infrared probes of gas and dust at the peak of cosmic star formation. Further, a combination of capabilities such as multi-wavelength polarisation and high angular resolution are 'a must' for advancement, as demonstrated by the maps of the protoplanetary disc around HL Tau with ALMA (Stephens et al., 2023) or the supermassive black holes M87* and Sgr A* with the EHT (Event Horizon Telescope Collaboration, 2024) that are required to disentangle the signatures of magnetic fields and scattering.

ALMA is now embarking on an upgrade that will further broaden the receiver bandwidth, increase the sensitivity, and deploy a vastly more powerful correlator, enabling wideband scans at high spectral resolution. Further advances are therefore expected in all fields in the next decade. With a steadily increasing community and the ongoing upgrades, the future is bright for ALMA.

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Links

[1] ALMA Large Programs: https://almascience.org/alma-data/lp

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Report on the ESO workshop

What was that? — Planning ESO follow-up for transients, variables, and Solar System objects in the era of LSST

held at ESO Headquarters, Garching, Germany, 22–26 January 2024

Colin Snodgrass[1]

[1] Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh, UK

This workshop aimed to bring together the various communities of astronomers who observe the changing night sky, from studies of nearby moving targets to the most distant transient sources. All of these fields will soon enter a new era of discovery with the beginning of the LSST, and many of the most exciting science cases will need detailed follow-up observations (for example spectroscopic characterisation), which will place significant demands on ESO's facilities. Participants at the workshop discussed the how, why, and when of obtaining ESO observations to find out 'what was that?', in the era of millions of alerts per night.

Introduction

Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST; Ivezić et al., 2019) is expected to begin in 2025. This survey will yield a revolutionary view of the changing night sky, with deep images of almost the entire sky visible from Chile every few nights. With individual images reaching a depth of around 24th magnitude in broad SDSS-like *ugrizy* band-passes, and high-cadence monitoring over a vast area of sky, the LSST will discover an unparalleled number of variable, transient, or moving objects. Real-time processing of the data will lead to millions of public alerts, indicating that something changed or moved, every night. Response to these alerts, for example obtaining follow-up spectroscopy of interesting targets, will be a significant scientific and logistical challenge. It is clear that ESO's facilities in Chile will be perfectly positioned and often uniquely capable of providing such follow-up observations — the purpose of this workshop was to bring together the LSST and ESO communities to discuss how best to coordinate such efforts.

The scientific topics covered by the workshop[1] were very broad — everything from the smallest near-Earth asteroids to the highest-energy high-redshift explosions. To cover such a range, the meeting was arranged around common topics of interest, on LSST and ESO capabilities, software, and lessons learned from previous large surveys. Scientific topics, and the motivations for follow-up observations to LSST discoveries that they provide, were introduced in a series of invited review talks. These were grouped into Solar System, Galactic, and Extragalactic sessions. The invited reviews were complemented by contributed presentations, which were mostly given as virtual posters and pre-recorded 'lightning' introductions to them, which were played in blocks within relevant sessions, providing a wide selection of topics as food for thought. As the workshop was intended to enable real organisation and consortium building, a significant part of it was dedicated to breakout sessions in smaller groups.

The meeting began with introductory talks on the LSST and what the community can expect from it, and on the outlook for ESO facilities over the next decade, which includes the beginning of ESO's Extremely Large Telescope (ELT) operations, as well as next generation Very Large Telescope (VLT) instruments and relevant projects like Son Of X-Shooter (SOXS; Schipani et al., 2018) at the New Technology Telescope (NTT). Future facilities that are of particular relevance, including SOXS, the 4-metre Multi-Object Spectroscopic Telescope (4MOST; de Jong et al., 2019), and the proposed Wide-field Spectroscopic Telescope (WST; Mainieri et al., 2024) were described in greater detail in the Thursday morning session. The sessions dedicated to the science drivers for LSST follow-up observations began with the most distant, and showed the significant contributions the LSST is expected to make to studying variable (for example, active galactic

nuclei) and transient (for example, supernovae) extragalactic sources, and the importance to these of rapid-response spectroscopy to measure redshifts and understand the underlying physics. In the session on Galactic science we discussed variable, pulsating and accreting stars, and related novae. The discussion here focused on the vast numbers (~ 10^8) of variable stars that the LSST will follow, and how to optimise and prioritise spectroscopic follow-up. Finally, we learned in the Solar System session that the LSST will be a discovery machine, providing an approximately order of magnitude increase in the known numbers of all small body populations, and that follow-up observations will be critical to understanding the things which are both moving and transient, such as the evolving debris from asteroid collisions or outbursts from comets.

Given the large number of discoveries that will flow from the survey every night, an essential part of the LSST ecosystem is the collection of software Brokers that will filter and distribute alerts. All six of the community Brokers that are being developed for the LSST were presented by their respective teams, and there was productive discussion of how these will serve different science goals throughout the week; getting these software teams in the same room as astronomers from such a wide range of science communities proved to be a very useful part of the workshop. There were also presentations on how software systems can further automate rapid response follow-up observations, in particular the Astrophysical Events Observatories Network (AEON) system (Street et al., 2020), which is used for automated observation scheduling in various US telescope facilities (Las Cumbres Observatory, NOIRLab, Gemini), and discussion on how such systems could work within ESO operations.

As we looked towards how best to coordinate ESO follow-up observations, we made a concious effort to do so in an equitable way, and dedicated a session to equality, diversity and inclusion (EDI), with presentations on how both ESO and the LSST are working to improve this, and a panel discussion on best practices. We also had invited talks on lessons learned from current/past surveys and alert follow-ups, from the highly successful Gaia Alerts (Hodgkin et al., 2021) and PESSTO/ePESSTO+ (Smartt et al., 2013) projects. Finally, the workshop concluded with short contributed talks on a diverse range of interesting topics related to follow-up of alerts in the era of the LSST, covering multi-messenger astronomy, machine learning tools for alert characterisation and follow-up prioritisation, and the future of smaller telescopes at the La Silla site for dedicated alert follow-up.

The topics for the small group breakout discussions were decided on during the workshop using a virtual noticeboard and voting system that allowed attendees to suggest and select relevant discussions. These were then organised into similar topics, broadly following the Solar System, Galactic, and Extragalactic science themes, and the general topics of Communication, Policies, and Brokers. Discussions included how best to rapidly share information, including between communities — where ‘my junk is your data’ means we can help each other out, and make more efficient use of precious follow-up opportunites, by efficiently communicating what we find. There was quite a lot of discussion on how best to approach applying for ESO time for follow-up — whether or not the best approach for such proposals would be large public surveys with no proprietary time, and how ‘data driven’ proposals covering a wide range of scientific topics can be proposed through the Observing Programmes Committee.

With the start of LSST operations expected in 2025, this meeting was a timely opportunity to bring together the communities who study the changing sky. Across Europe and beyond, these astronomers will look to ESO’s unique facilities to study the targets that the LSST finds; this will be an exciting era of discovery, and it will begin very soon. The conclusion of the community members present at the workshop was clear: we need to be ready for the coming step-change in the discovery rate of transient, variable and moving objects, and it is in the best interests of ESO and ESO’s user community to be organised in the way that observations are proposed, carried out, and analysed. The workshop recommended that ESO consider a call for (a) specific large and/or public survey type programme(s) dedicated to LSST follow-up, to which these communities could respond in an organised way, rather than dealing with many competing urgent requests following discoveries. If ESO decides to follow this recommendation, it should do so soon — the era of million-alert nights is just around the corner.

Demographics

In order to have a balanced programme across diverse scientific fields, and to have significant time for discussion and collaboration building, the Science Organising Committee (SOC) decided to have most of the schedule based on invited talks. In so doing the committee paid careful attention to having a balance of invited speakers between scientific topics, career stage, geographical distribution, and gender. The final list had 16 men and 14 women, with 19 speakers from Europe, nine from North America, two from South America, and none from other continents. Most contributed presentations were given as virtual posters, with a short pre-recorded ‘lighting talk’ to introduce each one, although six contributed talks were selected on the basis of their expected broad general interest to the workshop attendees. These speakers were all from Europe, and had a 50/50 gender split, although no particular effort was made to enforce balance here; the decision on which contributed talks to select was made entirely based on the perceived quality of the abstract and appeal to a broad audience, using a scoring system with the contributions anonymised. The workshop had a high level of participation, with approximately 100 participants in person and another 50 online. Of the total around 60 were early career researchers (~ 20 students and 40 postdocs).

Acknowledgements

This workshop would not have been possible without the generous support of ESO, including the financial and logistical support for the meeting itself and the engagement of ESO staff astronomers in helpful discussions throughout the week. The enthusiastic participation of the teams responsible for the hardware and software that will enable the LSST was also a big part of the success of this workshop. We are grateful to everyone who gave their time generously to take part. As the SOC chair, I also want to thank the members of the SOC (Joe Anderson, Amelia Bayo, Rosaria Bonito, Benoit Carry, Jesus Corral-Santana, Alessandro Ederoclite, Markus Hundertmark, Laura Inno, Valentin Ivanov, Rosita Kokotanekova, Michaël Marsset, Cyrielle Opitom, Paula Sanchez Saez, Linda Schmidtobreick, Meg Schwamb, Mark Sullivan, Rachel Street) and the Local Organising Committee (Matej Barta, Jesus Corral-Santana, Valentin Ivanov, Daniel Jadlovsky, Rosita Kokotanekova, Michaël Marsset, Nicolás Monsalves, Amanda Rubio, Paula Sanchez Saez, Felipe Schmidt, Linda Schmidtobreick, Denisa Tako, Sebastian Zuniga Fernandez), who put together an excellent programme and ensured that it would all run smoothly. The Local Organising Committee chair, Paula Sanchez Saez, and ESO workshop organiser extrordinaire Denisa Tako also deserve particular recognition for their efforts.

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Links

[1] Workshop programme: https://www.eso.org/sci/meetings/2024/lsst

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ESO Acknowledgements: Flickr user hdahle70

Astronomers are well-known for naming objects with odd conventions, and the cometary globule GN 16.43.7.01 is no exception. Cometary globules have nothing to do with comets aside from appearance: they are named for their dusty head and elongated, dark tail, as seen in this image taken with the VLT Survey Telescope (VST) hosted at ESO's Paranal Observatory in Chile. This globule, dubbed the Dark Tower — astronomers compensate with obvious names — lies about 5000 light-years away from Earth in the southern constellation Scorpius (the Scorpion). It contains dense clumps of collapsing gas and dust out of which stars will be born.

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Fellows at ESO

Michaël Marsset

I come from a family of scientists: both my parents were ocean geologists. When I was a kid, they were spending a lot of time on oceanographic boats in various parts of the world, such as the delta of the Congo River, the coast of Djibouti, and the Black Sea near Romania. I was amazed that someone could be paid to travel to such fascinating places around the globe. This undoubtedly fueled my desire to become a scientist too.

My grandmother, 'Babouchka', also played an important role in my early life by giving me books on astronomy. She was a big fan of Hubert Reeves, our 'French-speaking Carl Sagan', who sadly passed away recently. In a beautiful coincidence, years later, I won a grant created by this great man while doing my Master's studies in astronomy at the University of Montreal. This award contributed significantly to launching my career, as I used the funds to attend my first international conference on astronomy.

At university, I chose to study physics and then astronomy, trying to carve out my own path separate from my parents' field of geology. Ironically, I now study meteorites and asteroids, essentially space rocks! These ancient 'fossils' from the early Solar System are truly fascinating, offering insights into our young protosolar disc and the early migrations of the giant planets. They are also intimately linked to the history of life on Earth. For example, I recently had a paper accepted in Nature, in which we demonstrate that a very peculiar collisional cluster of asteroids in the main belt — the so-called Massalia family — was responsible for the mid-Ordovician ice age, and the major biodiversification event that followed.

But let's take a step back in time. My first contact with ESO happened during my PhD when I was fortunate enough to be selected for a two-year studentship in Chile. During those two years, I fell in love twice: first with the country, and second with someone who would later become my wife. After the studentship, I moved back to France — my home country — to finish my PhD and then took on a postdoc at Queen's University in Belfast, Northern Ireland. There, I studied the Kuiper belt, the ring of small bodies beyond Neptune's orbit, through multi-band photometry obtained at the Gemini Observatory on Maunakea — a breathtaking astronomical site I was lucky to visit twice!

Two years later, following the path of Irish immigrants from a couple of centuries ago, I moved from Ireland to the east coast of the U.S., settling in Boston. There, I worked for three years at MIT on two parallel projects: a spectroscopic survey of near-Earth asteroids and an imaging programme of large main-belt asteroids using SPHERE on the VLT. This next-generation instrument, providing diffraction-limited observations at optical wavelengths, is quite amazing. It enables us to see asteroids from Earth in unprecedented detail, offering insights into their… geology! (Ironic, isn't it?)

After MIT, I returned to my first loves — ESO and Chile — working as a fellow at Paranal and Vitacura. I had the chance to be assigned to a brand-new instrument, ERIS, which offered me the incredible experience of participating in its commissioning and science verification. Later, I joined the Paranal team responsible for developing and maintaining our homemade set of software tools for first-level quality control. During my shifts at the observatory, I alternate between core operations and software development, ensuring I never get bored. While at Vitacura, I thoroughly enjoy the scientific environment and continue working on my various projects.

The life of an observational astronomer can be a true adventure, offering many opportunities to travel the world and work in remarkable places like the Maunakea and Paranal observatories. In my case, the most surreal destination this journey took me to was undoubtedly the film set of the movie Don't Look Up, where I served as a hand double for Leonardo DiCaprio, writing the comet's equations on-screen. It was an incredible experience working alongside renowned actors and blending science with cinema.

Looking back, my journey has been a mix of opportunities, passion, and a bit of irony. From a kid avoiding geology to an astrophysicist studying space rocks, it's been (and still is) a fascinating ride. And through it all, my goal has always remained the same: to understand the universe a little better and inspire others to look up at the stars (and space rocks) with wonder. Finally, I want to thank all the people who have helped me along the way: my family, my friends, colleagues, and importantly, my scientific mentors over the years: Doctors Pierre Vernazza, Christophe Dumas, Audrey Delsanti, Wesley Fraser, Francesca DeMeo, and the great Professor Richard Binzel.

Ashley Barnes

To start with, I must say that I truly love my work in astronomy, the amazing people I collaborate with, and the day-to-day discoveries that keep my passion for the cosmos alive. However, my path to this stellar career wasn't something I envisioned from a young age.

Like many young boys, my first scientific love was not the stars, but dinosaurs. I was utterly captivated by them and could spend hours on end learning everything about all these ancient creatures (I think I saw them as something like real-life pokemon!). But around the age of 10, coinciding perhaps with the release of the prequel Star Wars films (and, probably, how the era of the dinosaurs ended), my fascination shifted upwards to the cosmos. I became engrossed in everything space-related, watching countless programmes on the Discovery Channel.

Yet, despite this growing interest, I didn't initially see a career in astronomy as something achievable. With no academics in my immediate environment, the concept of being a scientist was somewhat abstract and distant.

During my school years, I pursued a different path entirely. I aspired to become a chef, dreaming of emulating culinary stars like Jamie Oliver and such. My school required a work placement in our chosen field, so I spent a week in a small kitchen. It was a wake-up call. The professional cooking environment, with its intense heat, pressure, stress, and long, unsocial hours, was far from what I had imagined. It was a sobering experience that prompted me to reconsider my future.

After this pivotal moment, I shifted gear and focused on studying maths and science in college, subjects I found far more enjoyable and rewarding than during my earlier school years. Doing relatively well in these areas, I went on to study Physics with Astronomy at the University of Leeds. There, I had the opportunity to undertake two summer student projects, delving into astrochemistry within star-forming molecular clouds. This experience gave me my first real taste of a career in academia and cemented my interest in pursuing this path further.

My academic journey continued with a PhD jointly at Liverpool John Moores University in the UK and the Max Planck Institute for Extraterrestrial Physics (MPE) in Munich, Germany. My research focused on understanding star formation across the Milky Way, from the galaxy's disc to its very heart in the Galactic centre. I was incredibly fortunate to be working at a time when the Atacama Large Millimeter/submillimeter Array (ALMA) was providing cutting-edge, high-resolution observations of star-forming regions. This led to my involvement in the ALMA CMZ Exploration Survey (ACES) ALMA large programme, where I am now a lead co-PI, and currently pushing on ground-breaking science.

Following my PhD, I moved into a postdoctoral position at the University of Bonn's Argelander-Institut für Astronomie (AIfA), where my research extended beyond the Milky Way to nearby galaxies. This work primarily utilised the multiwavelength database from the PHANGS consortium, incorporating observations from ALMA, the Very Large Telescope (VLT) MUSE instrument, the Hubble Space Telescope (HST), and most recently, the James Webb Space Telescope (JWST). During this time, it became apparent that to fully understand star formation, we must also consider the effects of the stars themselves, a process known as stellar feedback. In addition to my research, I found teaching and supervising students to be very rewarding. Many of these students have gone on to do great science themselves, and I am immensely proud of their achievements!

Now, as an ESO Fellow, I am focused on combining my work on external galaxies from the PHANGS project with my studies of the Milky Way (from e.g. ACES). My goal is to understand the high-mass star formation and stellar feedback cycle and how these processes drive the evolution of galaxies. I am currently conducting my fellow duties in the ALMA ARC at ESO, which I very much enjoy. Seeing the inner workings of a telescope I have used throughout my astronomy career has been incredibly insightful and rewarding. Overall, I am extremely grateful for my current position, which allows me to work with state-of-the-art observations and push the boundaries of our knowledge of the Universe.

Through my winding journey, I hope to inspire the next generation of young scientists to pursue their passions, no matter how unconventional their paths might seem!

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External Fellows at ESO

In addition to the ESO fellowships, external postdoctoral researchers are hosted at ESO. Here one of them presents herself.

Karina Mauco Coronado

For as long as I can remember I have been passionate about the night sky. Something about those little lights on the dark background amazed me. Growing up I was always the ‘smart’ kid who did all her homework and got good grades in maths and physics. But it was more the result of curiosity than being really smart. I’ve always been eager to learn everything I can about the world, so if ‘doing my homework’ was the way to do it, I was willing to pay the price. But although I was passionate about the stars, I never considered making a career out of them, simply because I never thought it was possible.

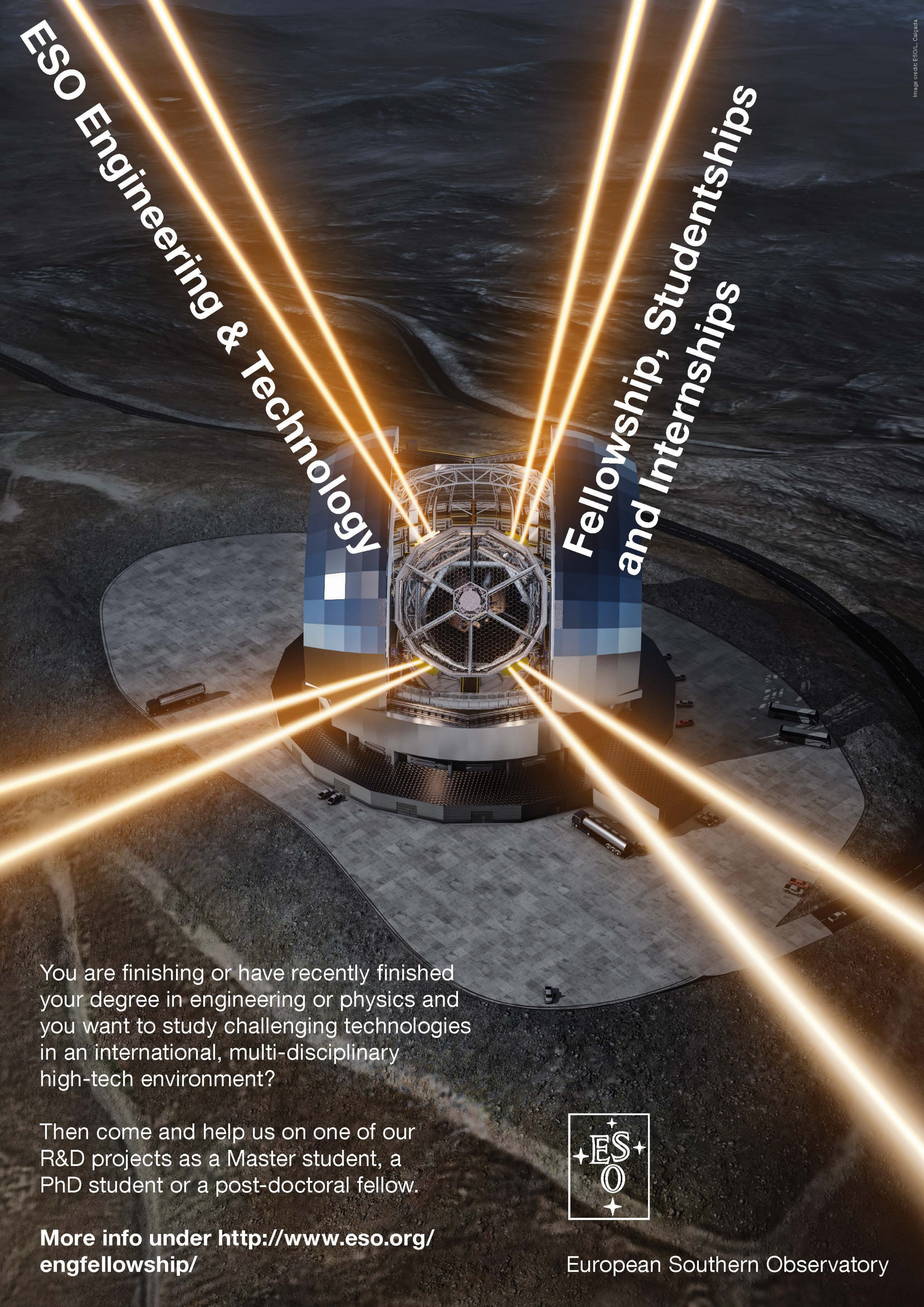
I was born in Caracas, Venezuela, and although there were very good universities there at that time, there was no astrophysics major in the capital. I knew I wanted to study something related to physics but also something that would teach me about natural phenomena. So I chose my second favourite subject (besides stars, of course), volcanoes and hurricanes. So I went for Geophysics Engineering. Something I loved when I was a teenager buying National Geographic magazines with impressive images of volcanoes and tornadoes. My naïve young self thought that, as a geophysicist, I would end up chasing tornadoes (like Helen Hunt in Twister) and entering the threatening craters of volcanoes. To my surprise, geophysics in Venezuela is nothing about that and all about oil. So after finishing my engineering studies, I started working at the main oil company in Venezuela. It lasted just one year — I hated it completely. Don’t get me wrong, I really enjoyed the career. In fact, it was during my undergrad that I realised that I really loved physics, especially that related to radiation and light. But the oil business just wasn’t my thing. It was at that moment when everything in my life began to change very quickly. I needed to make a big decision, one that would mark my life forever. Fortunately for me, it was the right one, but it took a good dose of courage and a lot more of hope.

Feeling miserable in my oil-related job, I decided to look for opportunities to study my true passion, astronomy. At that point, I already knew that the ‘conventional path’ to astrophysics was to first study physics and then pursue a PhD in astrophysics. OK, that was no longer possible for me, but I didn’t let that discourage me. I found that many PhD programmes, particularly one in Mexico, allow students other than physicists to enter; I just needed to pass their three-month training first. So, with a backpack full of dreams and hopes, I quit my job and flew abroad to pursue my dream of becoming an astronomer. Little did I know what I was getting into. It hasn’t been easy, but it’s definitely been worth it.

I did my Master’s and PhD studies in Morelia, Mexico — a beautiful historic city in the central part of Mexico. I was blessed to have amazing supervisors who supported me throughout and gave me the means to go to various observatories around the world for regular observing runs which I completely fell in love with. I still remember the first time I observed completely alone and felt like a real astronomer. I knew then that I had made the right decision. However, the hardest part of my entire PhD was the first three months of training! Learning all the physics necessary for a career in astrophysics, but irrelevant in engineering, in such a short time was more than a challenge, but if you have the passion and determination, anything is possible.

After my PhD, I found a three-year postdoctoral position in Valparaíso, Chile. There I had the opportunity to visit the most important observatories in the world: Paranal and ALMA. I can’t describe the joy and privilege I felt being in these incredible places and making science from them. Getting to know a completely new astronomical community and having a fantastic boss really made my years in Chile very pleasant, despite COVID of course. My mom used to say *“every sacrifice brings its reward,”* so with that in mind, I was ready to dream big again. This time, my goal was a postdoctoral position at ESO. I saw the opportunity and was lucky enough to be considered for the job. I have been an ESO postdoc for a year and a half and it has exceeded all my expectations. I never imagined that I could get such a wonderful position, being from Venezuela, from a non-scientific family. Reflecting on it now, I recognise that the most important part of my journey was the support of the people around me who always believed in me and inspired me to reach for the stars, literally.

At ESO, I am part of the WANDA ERC hosted by Carlo Manara. I’ve been lucky enough to continue working on the same topic since my PhD: star and planet formation. The main goal of my research at ESO is to study how discs of gas and dust around baby stars evolve in highly irradiated environments to form planetary systems. I make use of spectroscopic observations to characterise the low-mass stars hosting the protoplanetary discs, as well as the winds coming from the disc surface as the result of the ionising radiation from nearby massive OB stars in the region. ALMA observations also hold a very special place in my heart, and I am leading a continuum analysis of a sample of 80 stars in different star-forming regions as part of the ALMA DECO Large Programme aiming at characterising the dust disc radii and morphology. In addition to the amazing science I have the privilege of doing at ESO, the scientific environment and friendly community definitely add invaluable value to my journey, which I can now share with others, especially young kids who dream of the night sky.



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