Introduction to telescopes
and types of instruments III

the Very Large Telescope Interferometer
-VLTI-

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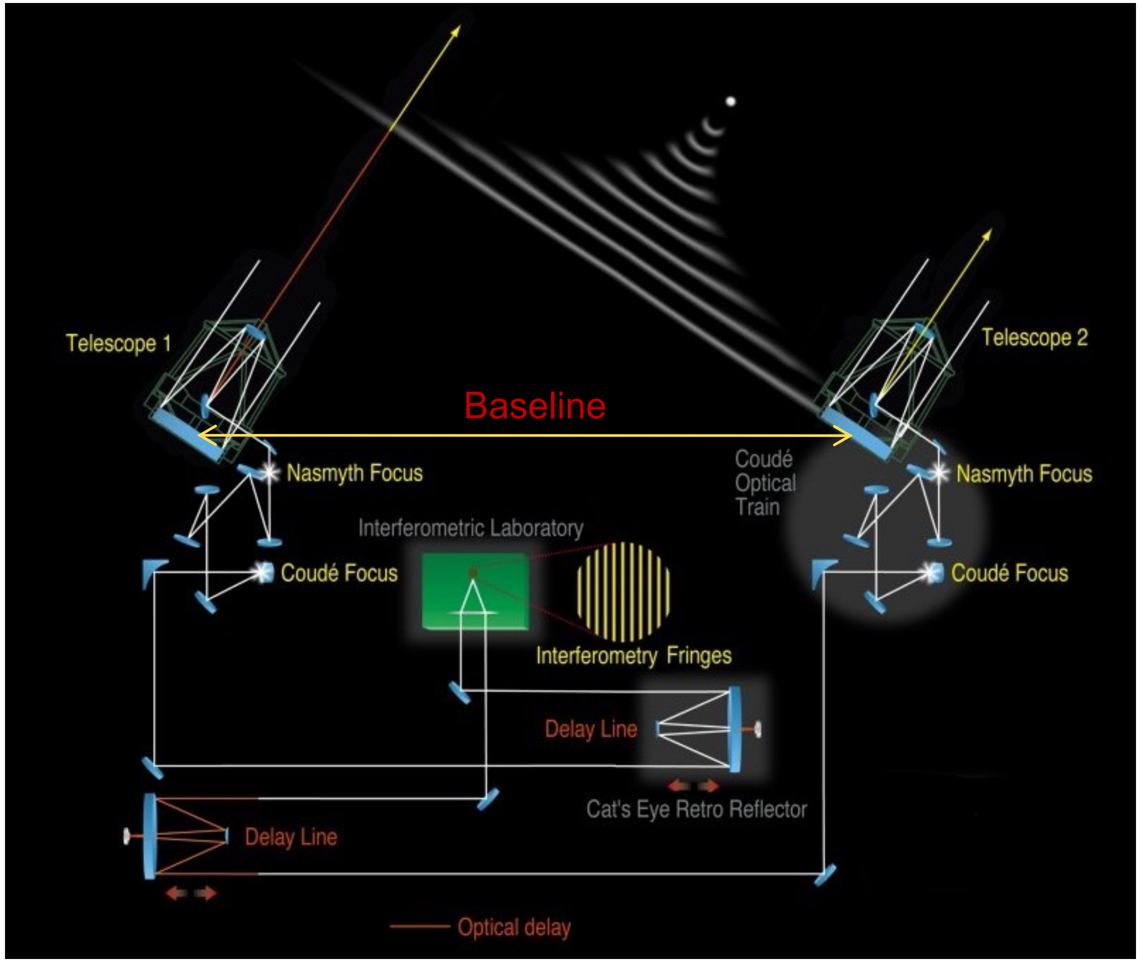
Why Interferometry?

Objects	Wavelength	Diameter	Telescope diameter
Circumstellar envelope around evolved star	11 µm	50 mas	45 m (more than the ELT!)
Vulcan on a Jupiter satellite	5 µm	10 mas	100 m
Nucleus of AGN	2.2 µm	< 1 mas	> 400 m
Spot on the photosphere of a solar-type star	0.5 µm	0.07 mas	1500 m

Principles of Interferometry

- Not a single dish, but light combined from 2,3,4… telescopes
- **Gain**: angular resolution
- **Cost**: sensitivity



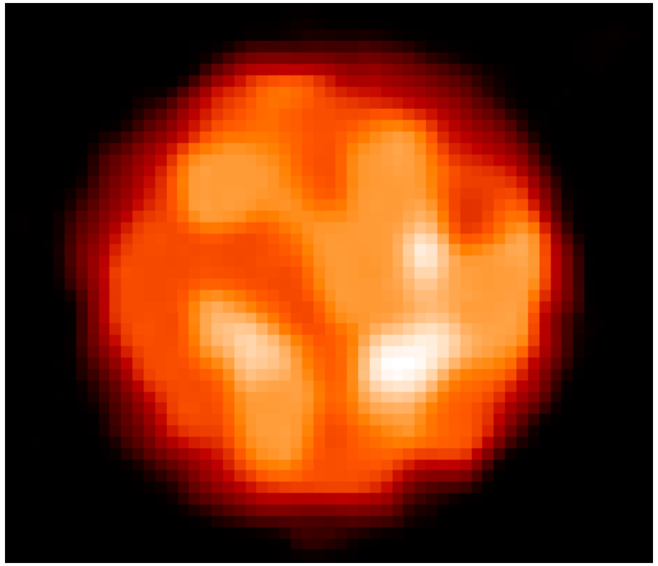
«The complex visibility is the Fourier transform of the source intensity distribution on the sky at the spatial frequencies corresponding to the projected baseline on the sky per observing wavelength.»

Van-Cittert-Zernicke theorem

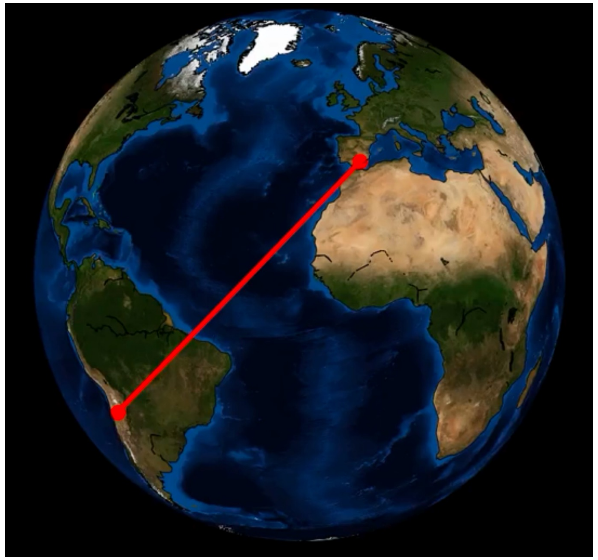
Linking the complex visibility

to the intensity distribution of the object in the sky

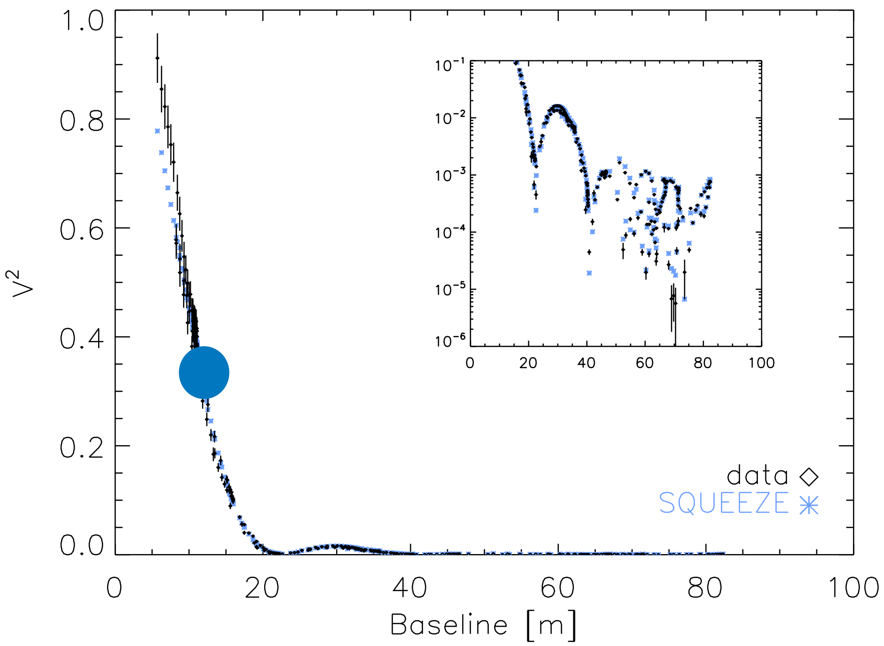
Van-Cittert-Zernicke theorem



Choose your preferred object



Project the baseline on your object and collapse the intensity in that direction

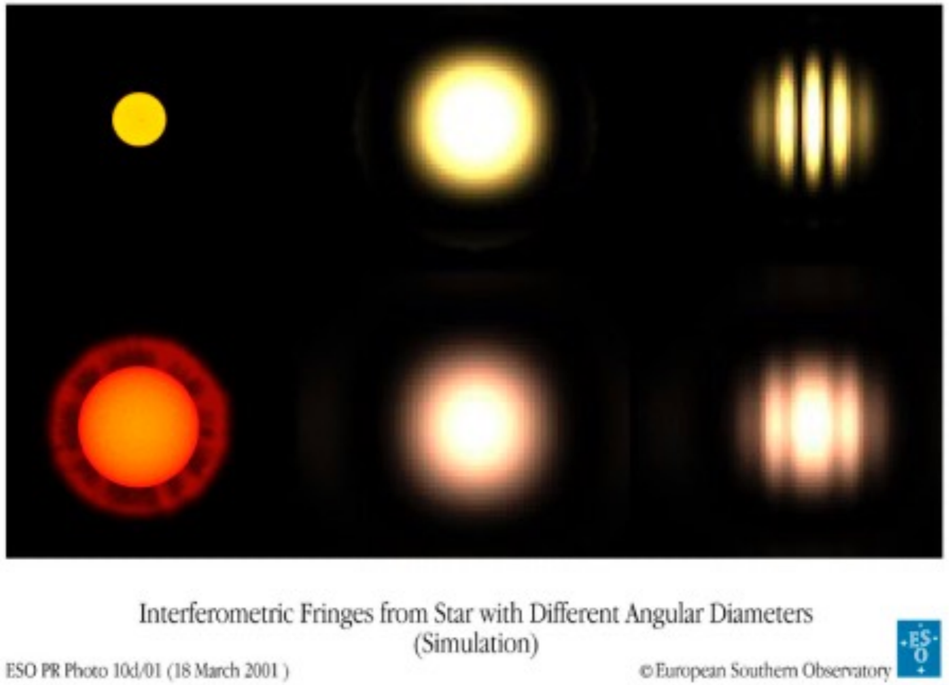


Take 1-D Fourier Transform

What is the observable?

We observe FRINGES and we measure a complex quantity called VISIBILITY

- fringe visibility is the contrast between fringes => Angular dimension of the object.
- fringe phase related to the location of fringes. => Symmetry of the object



left: "real star"

center: star observed by single dish

right: star observed by interferometer

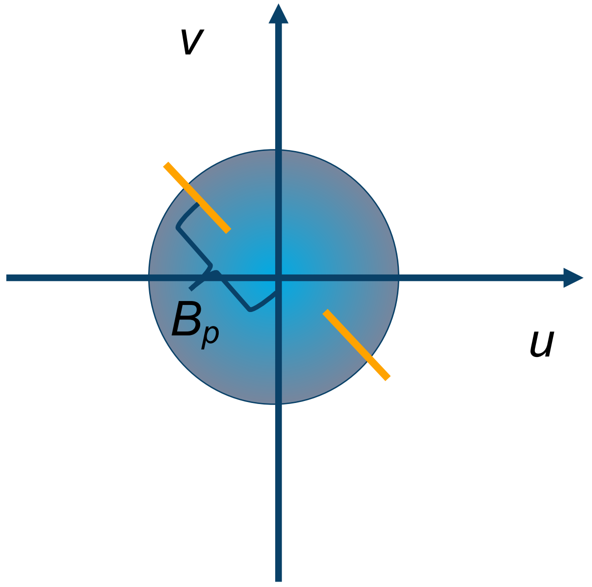
The u-v plane

The **complex visibility** is a function of the ***spatial frequencies or u-v coordinates***

$$u = \frac{B_x}{\lambda}$$

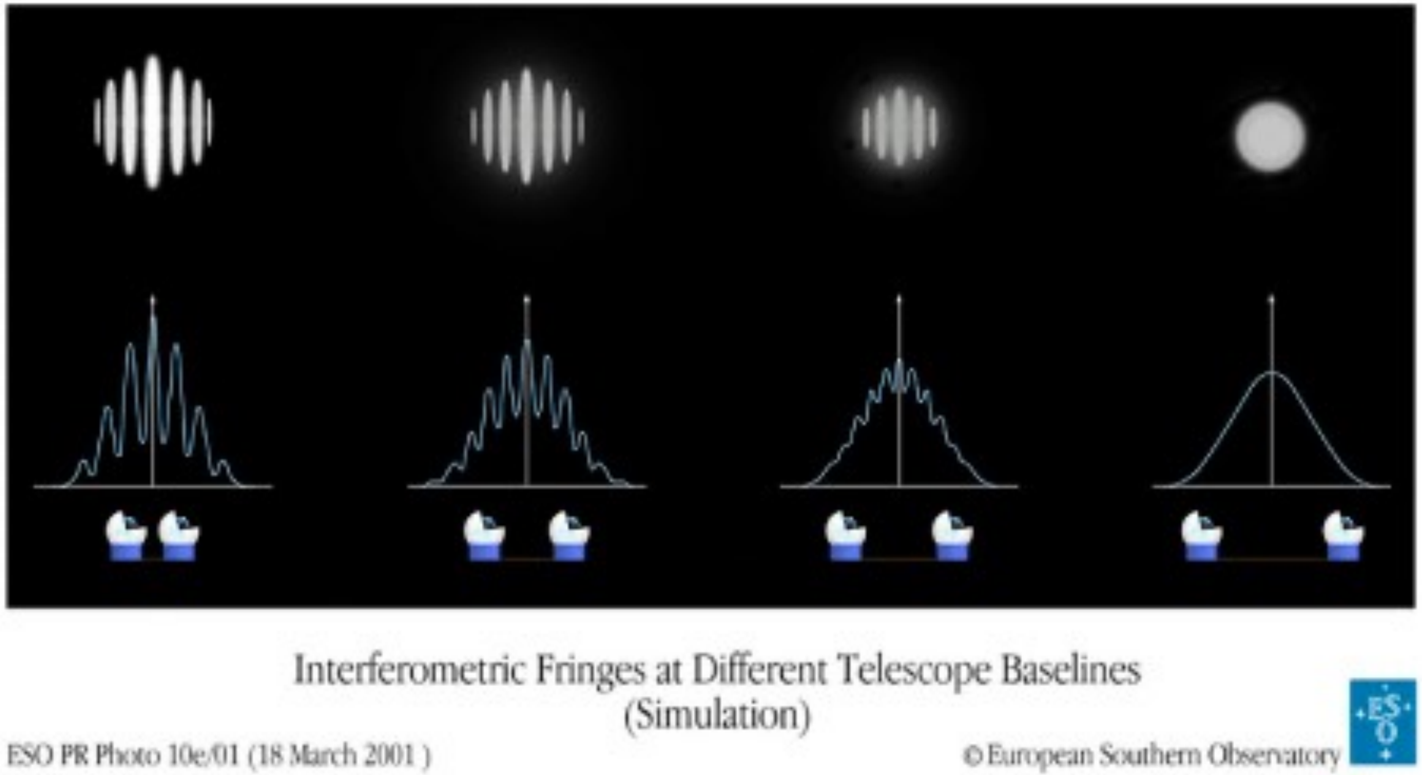
$$v = \frac{B_y}{\lambda}$$

$$\frac{B_p}{\lambda} = \sqrt{u^2 + v^2}$$



- Projected baseline (baseline as seen from the star) is what matters
- Sidereal motion changes this projection
- Changing the wavelength also changes the spatial frequency

Baseline effect



Short baseline → higher contrast
Long baseline → smaller contrast (V~0)

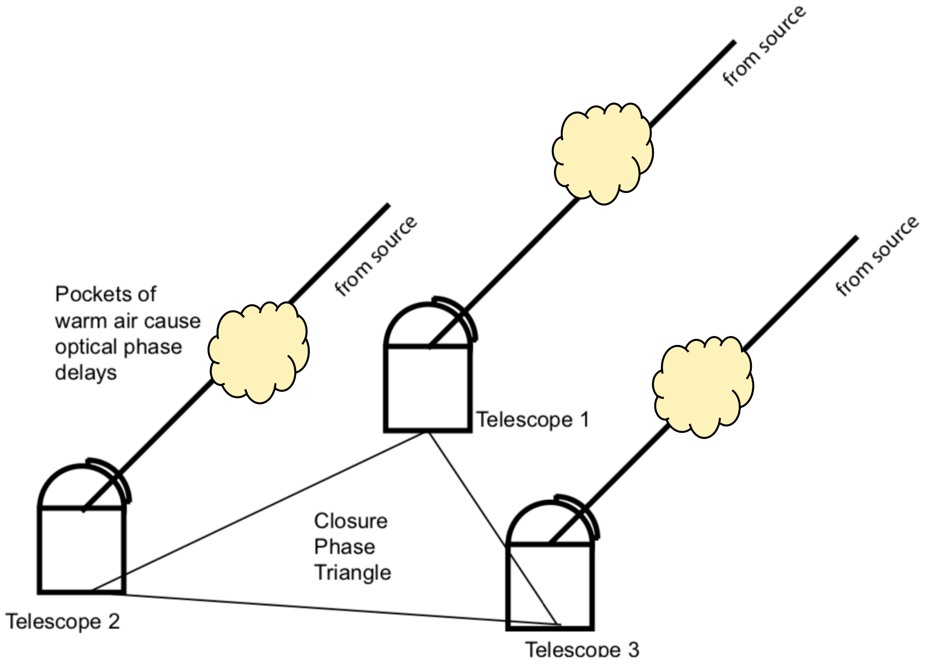
About the phase: closure phase

- In visible & infrared we cannot measure the "pure" phase because of the atmosphere variation

$$\begin{aligned}\Phi_{1,2} &= \phi_{1,2}^{\rm obj} + \phi_2^{\rm atm} - \phi_1^{\rm atm}\\ \Phi_{2,3} &= \phi_{2,3}^{\rm obj} + \phi_3^{\rm atm} - \phi_2^{\rm atm}\\ \Phi_{3,1} &= \phi_{3,1}^{\rm obj} + \phi_3^{\rm atm} - \phi_1^{\rm atm}\end{aligned}$$

- In optical near-infrared interferometry we use the "**closure phase**"

Credit: Monnier+2006



$$\Psi_{1,2,3} = \phi_{1,2}^{\rm obj} + \phi_{2,3}^{\rm obj} + \phi_{3,1}^{\rm obj}$$

About the Phase: differential phase

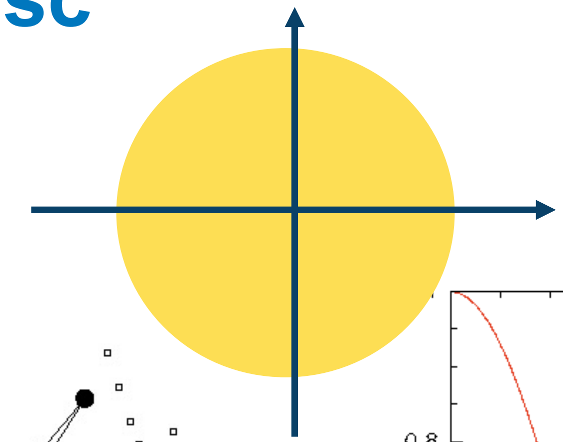
Definition*:*

Choose a reference spectral channel.
The differential phase is the phase difference between different spectral channels.

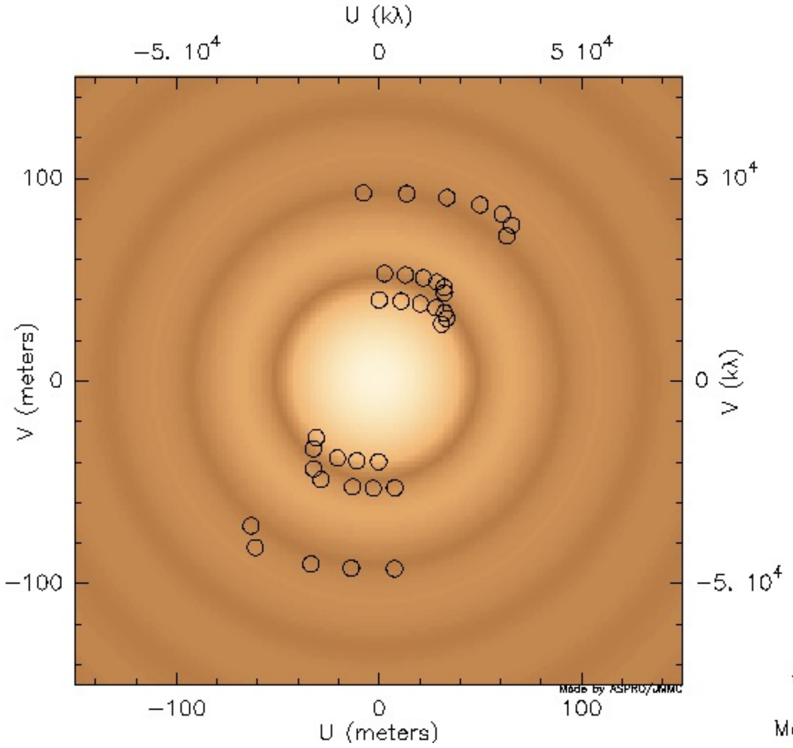
If you have only 2 telescopes and few wavelength channels: **differential phase.**

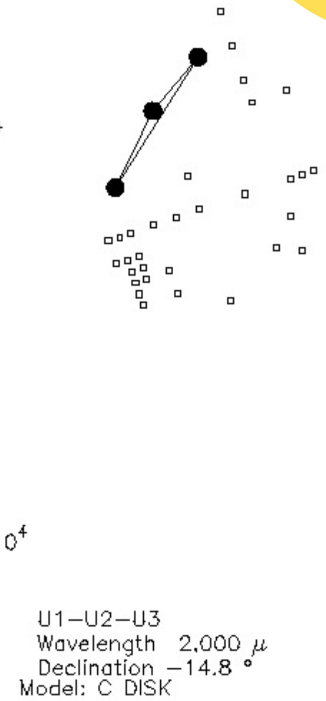
The differential phase is sensitive to the astrometric position

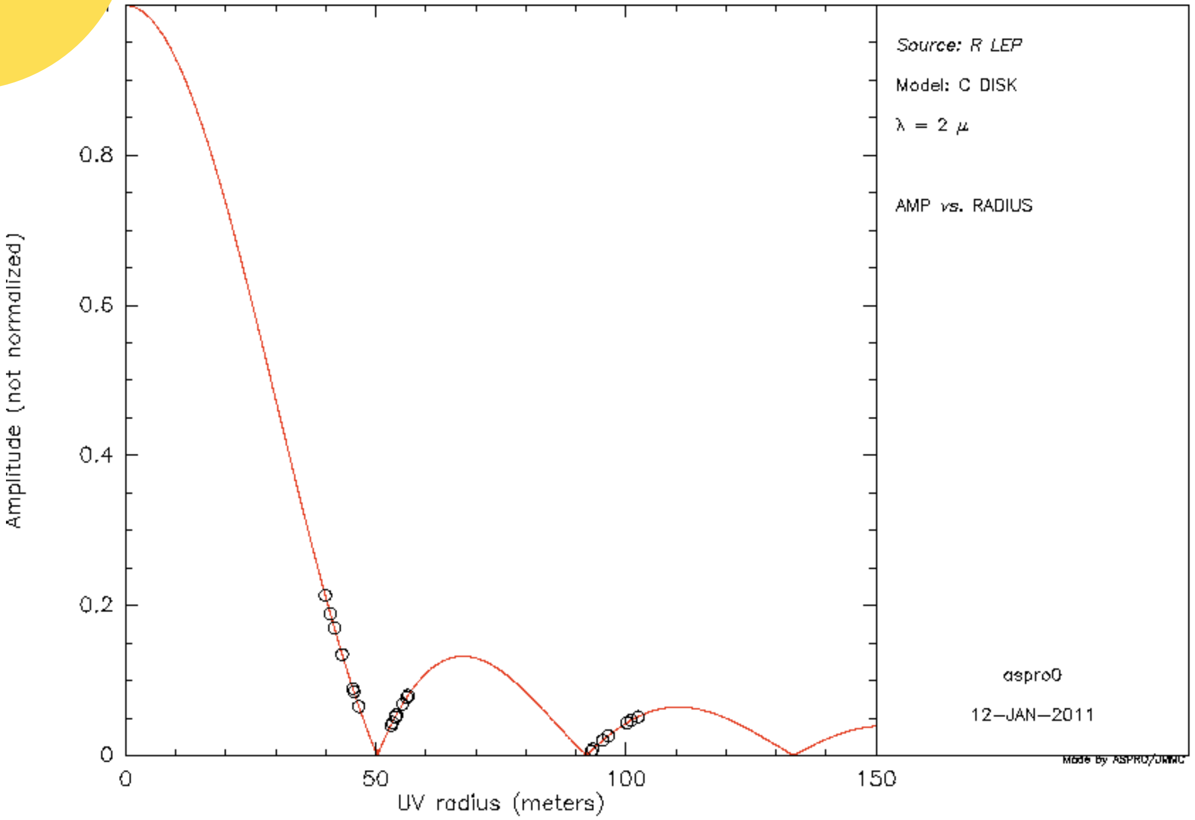
Modeling: Uniform disc



Software: ASPRO

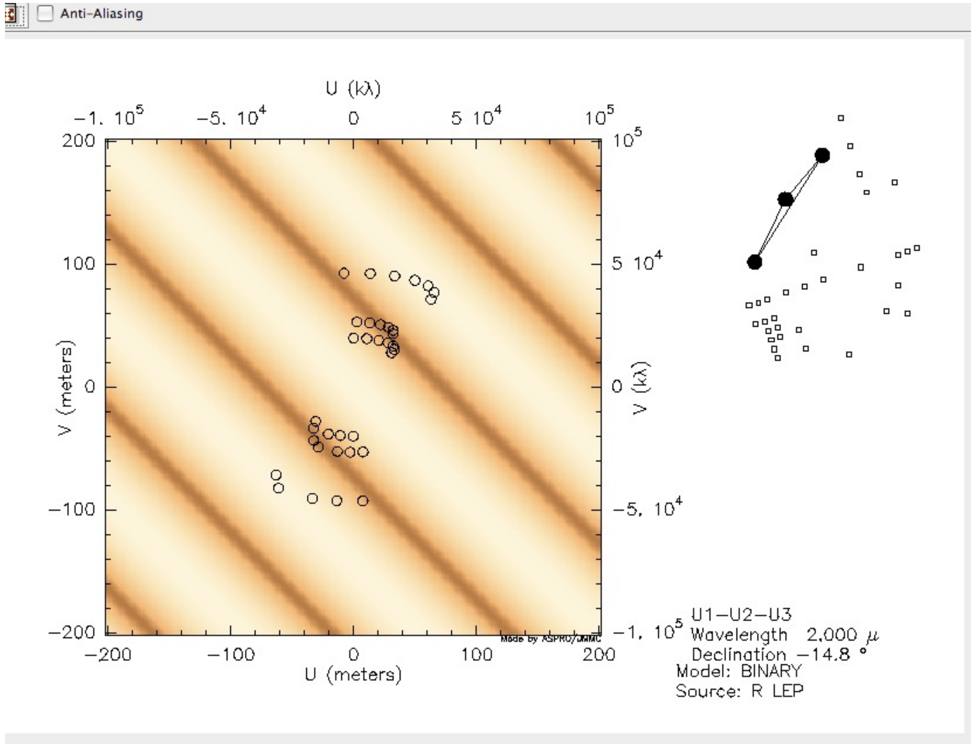


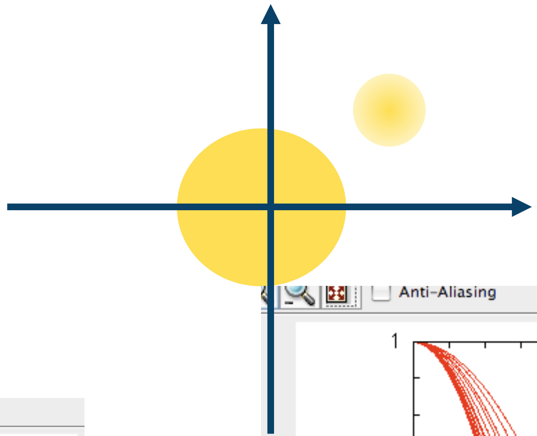




Modeling: binary

Binary stars:
diameter of the primary resolved star 10 mas
Flux ratio = 0.8
θ = 45 degree





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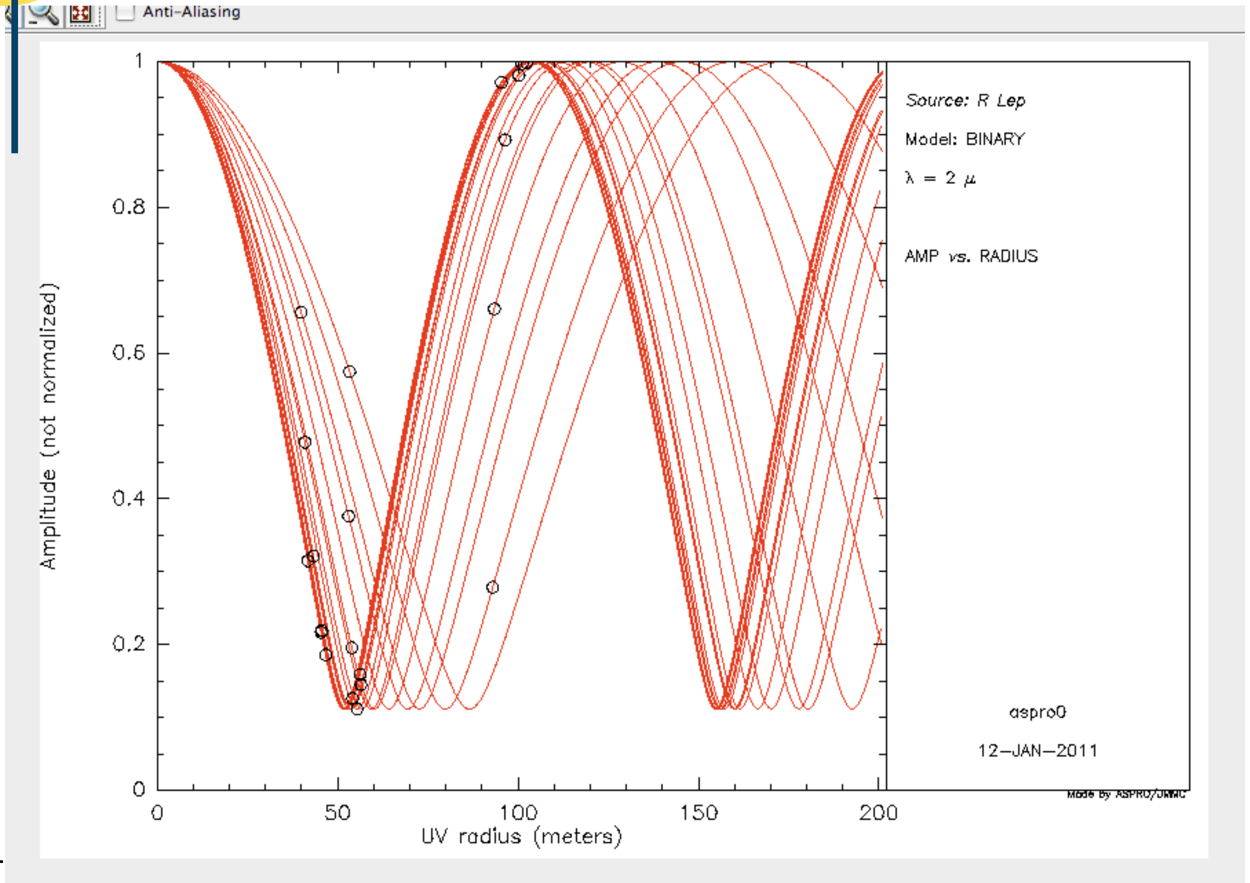
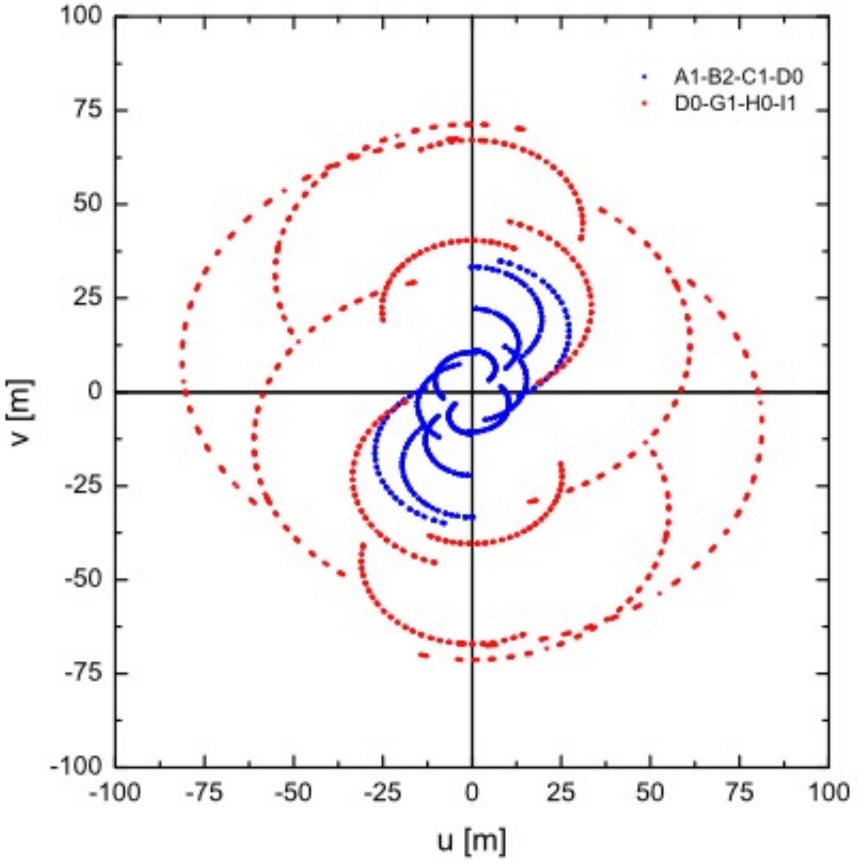
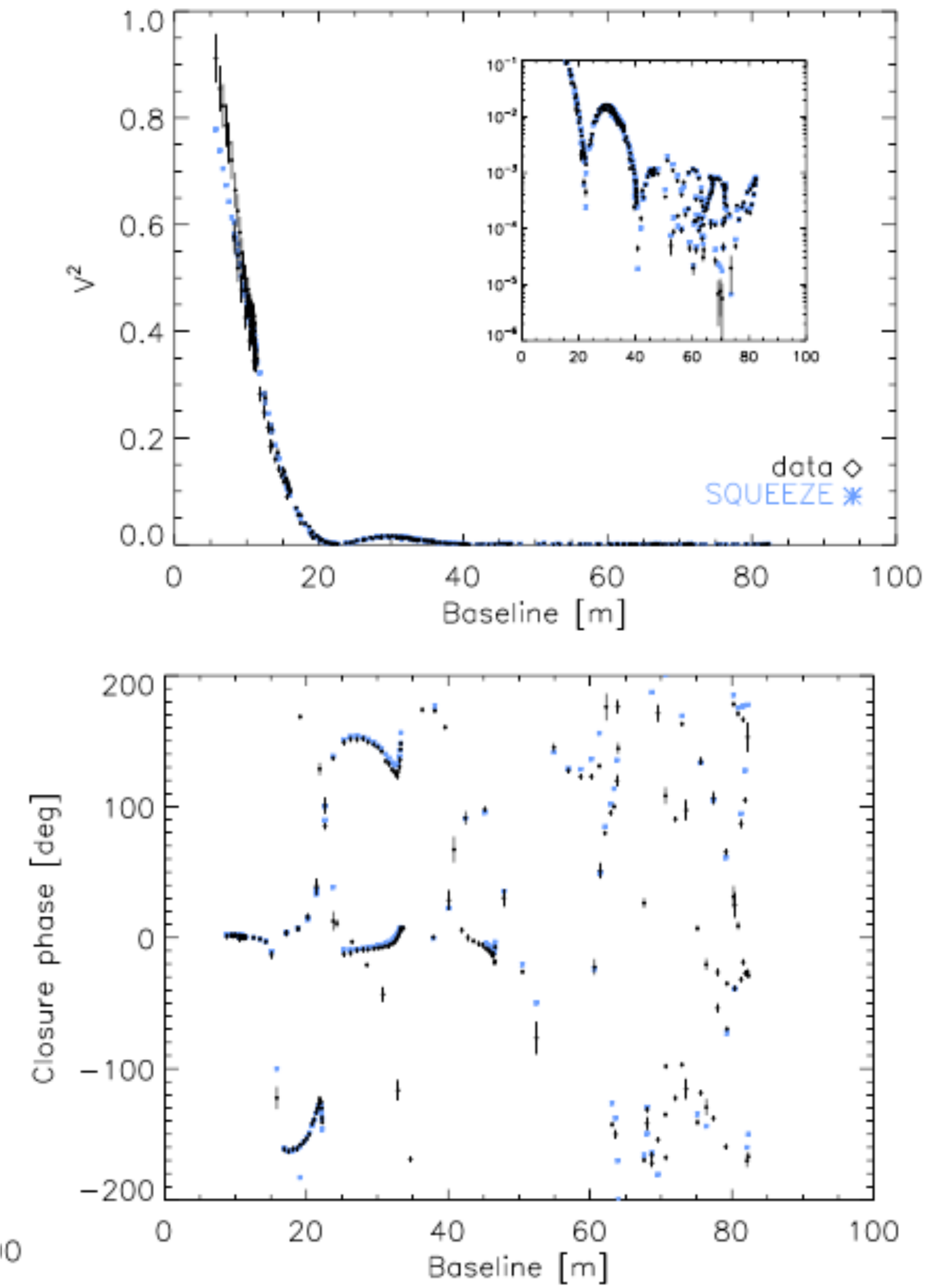


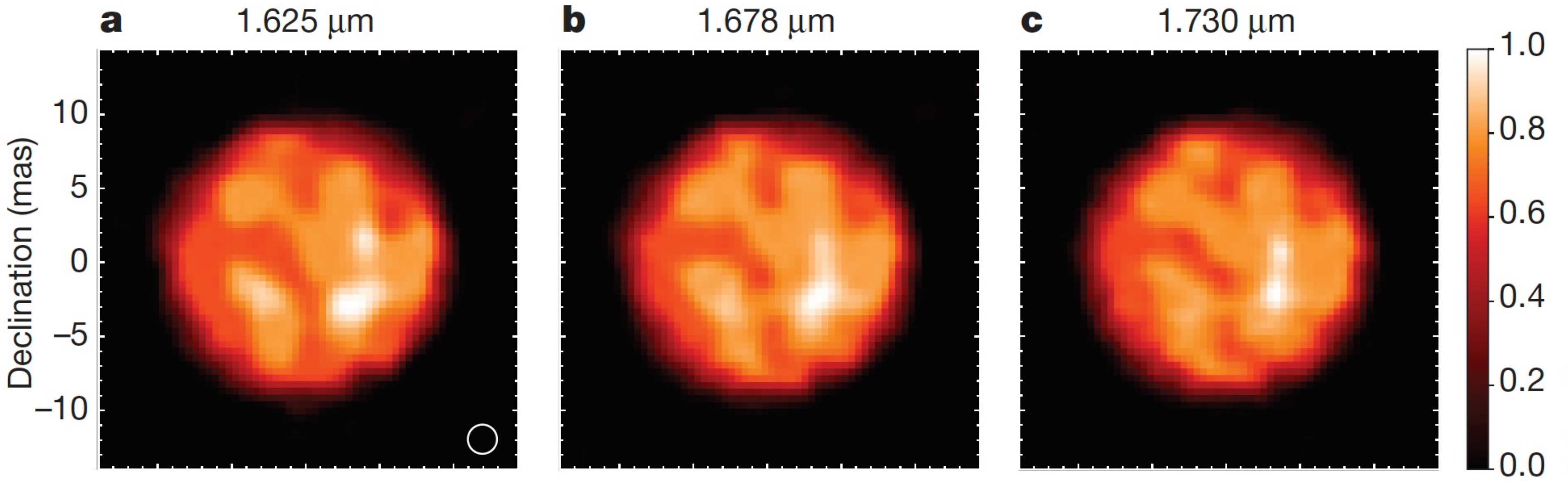
Imaging



Credit: Paladini++2018

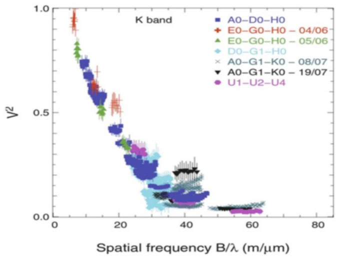
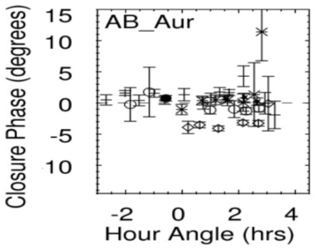
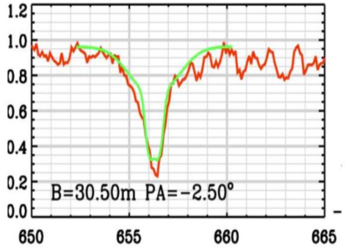
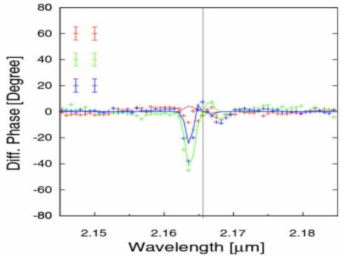
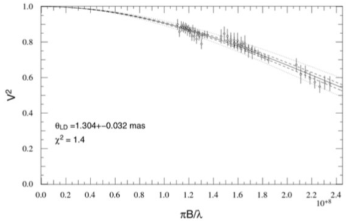
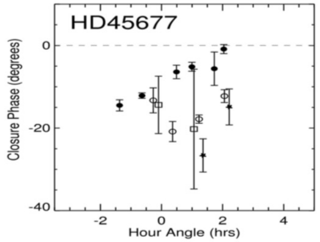
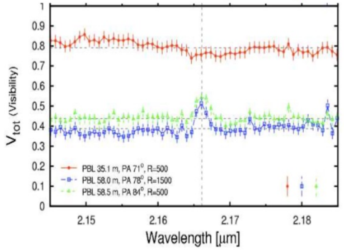
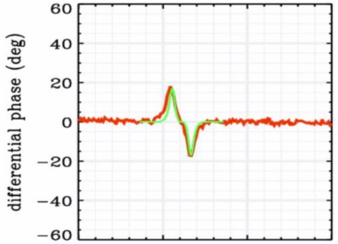
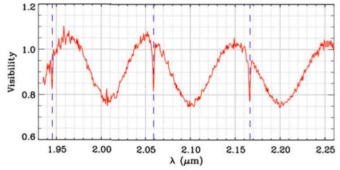
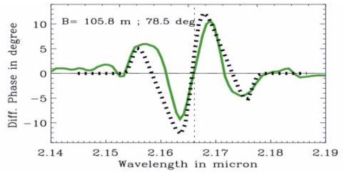
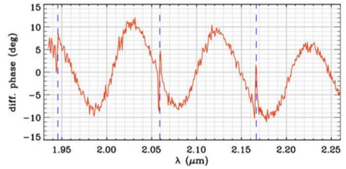


Imaging



Credit: Paladini++2018

Some applications

Visibility	Closure phase	Diff. Vis.	Diff. Phase
(a) Resolved source Benisty *et al.* (2010)	(b) Zero Monnier *et al.* (2006)	(c) ↘ in emission line Stee *et al.* (2012)	(d) “V” shape Weigelt *et al.* (2007)
			
(e) Unresolved source Demory *et al.* (2009)	(f) Non-zero Monnier *et al.* (2006)	(g) ↗ in emission line Kraus *et al.* (2008)	(h) “S” shape Meilland *et al.* (2012)
			
(i) Cosine shape Meilland *et al.* (2011)		(j) “W” shape Chesneau *et al.* (2011)	(k) Sine shape Meilland *et al.* (2011)
			

Observations in practice

Between us and the star there is atmosphere and the instrument

We measure visibility as well as instrumental effect & atmosphere (transfer function TF)

Intrinsic contrast of the object

$$\mu^2_{obs} = \frac{V^2_{intrinsic}}{T^2}$$

Observed contrast

Transfer function

Calibration of the visibility

To correct for these effects, we observe a source with a known diameter θ , the calibrator

(1) $$\mu^2_{obs} = \frac{V^2_{intrinsic}}{T^2}$$

For the calibrator, assuming a Uniform disk distribution:

(2) $$V_{intrinsic}(u,v) = 2\frac{J_1(\pi\theta r)}{\pi\theta r}$$

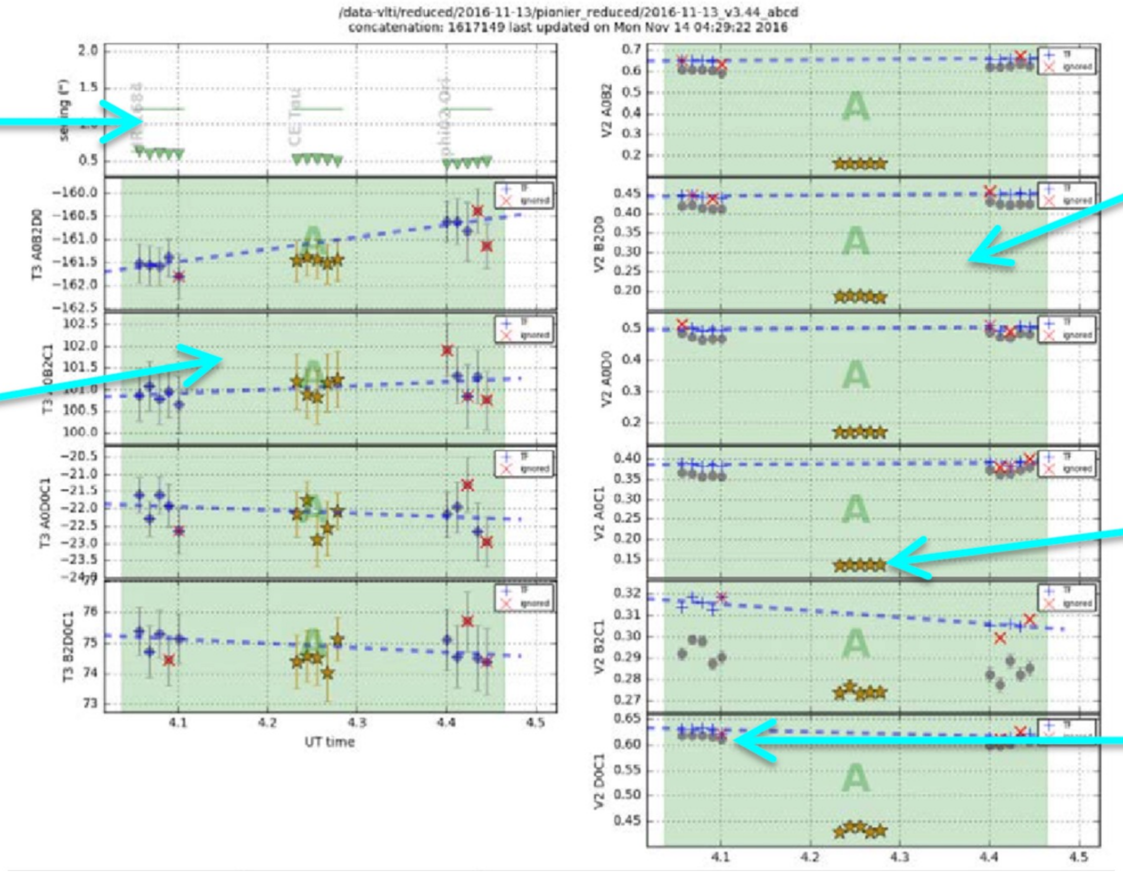
Combining (1) and (2) one can derive the transfer function T and calibrate the intrinsic visibility of the SCIENCE

Example of calibration at VLTI

PIONIER calibration sequences are CAL-SCI-CAL or CAL-SCI-CAL-SCI-CAL

Seeing: ASM
vs. constraints

Closure phases



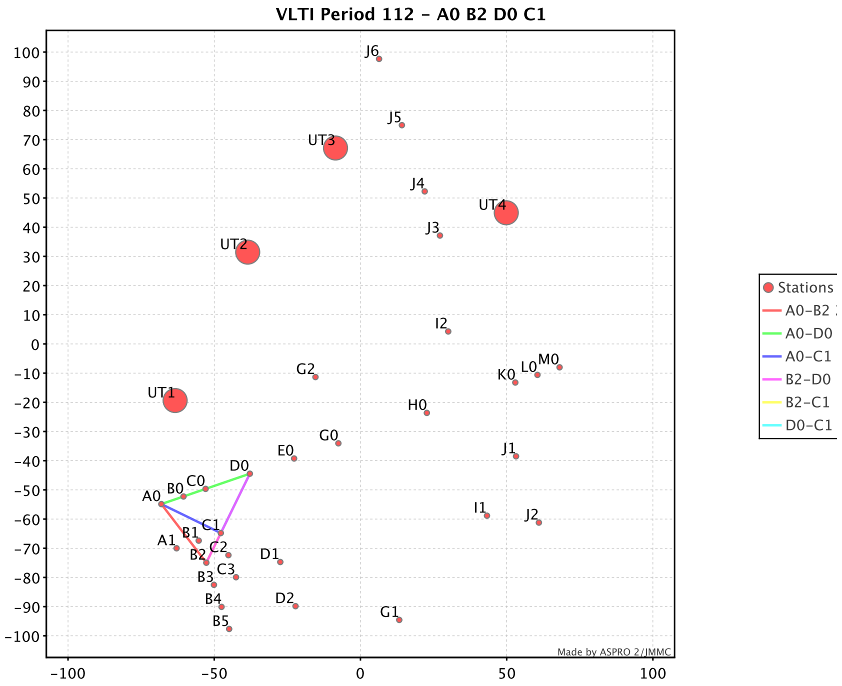
Visibilities

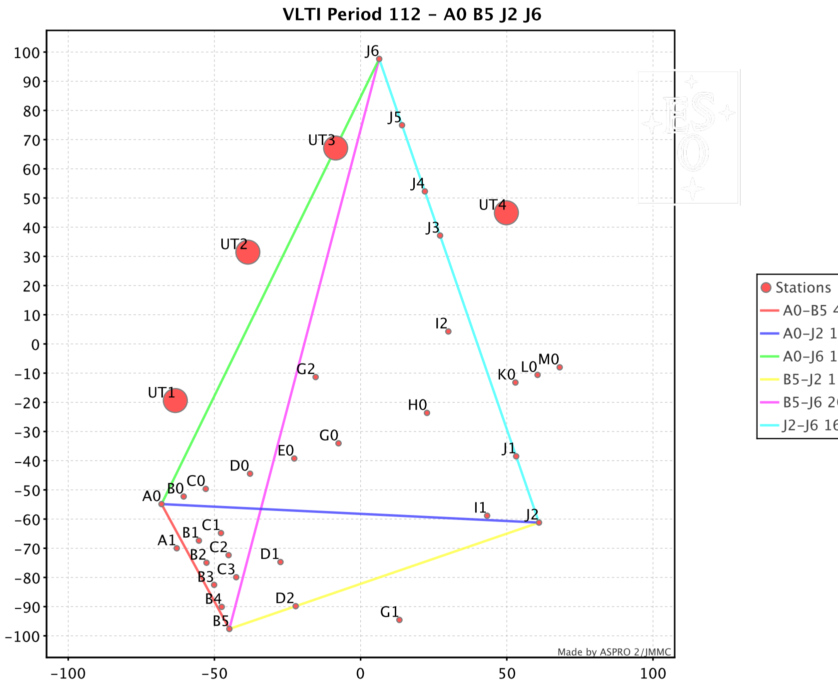
Science target:
orange star

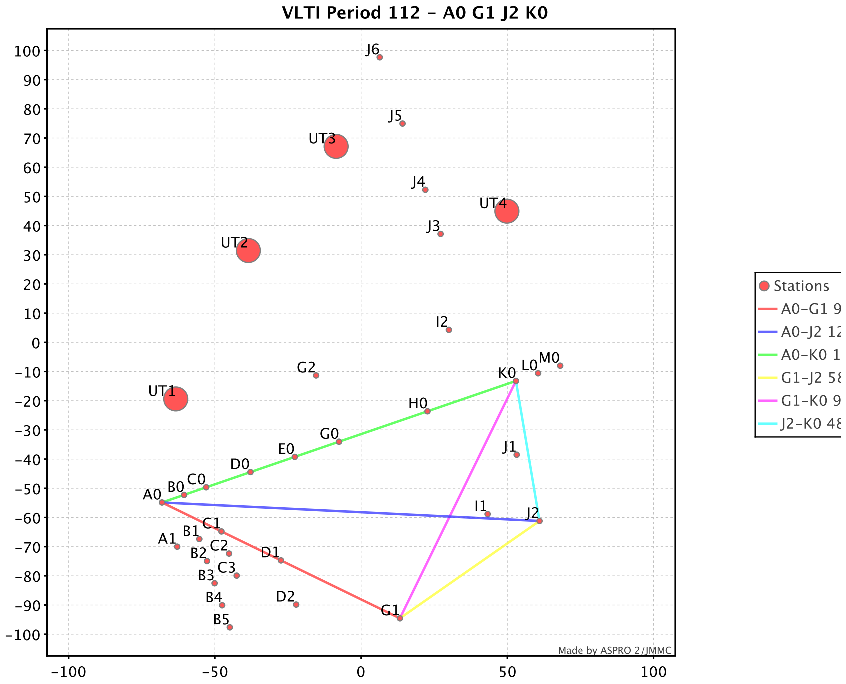
Calibrator:
gray dot &
blue cross

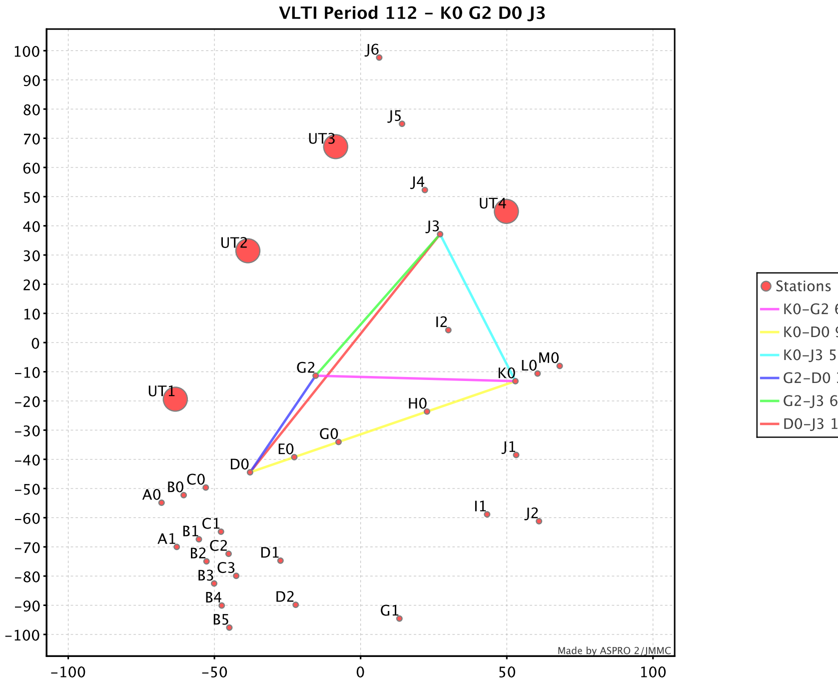
VLTI acts like a virtual 200 m telescope

- Combining 4UTs (8m telescope), maximum baseline 130 m, resolution ~2 mas at 2 micron
- Combining 4ATs (1.8m telescope), maximum baseline 200 m *(from October 2023), resolution ~0.8 mas at 1.5 micron*

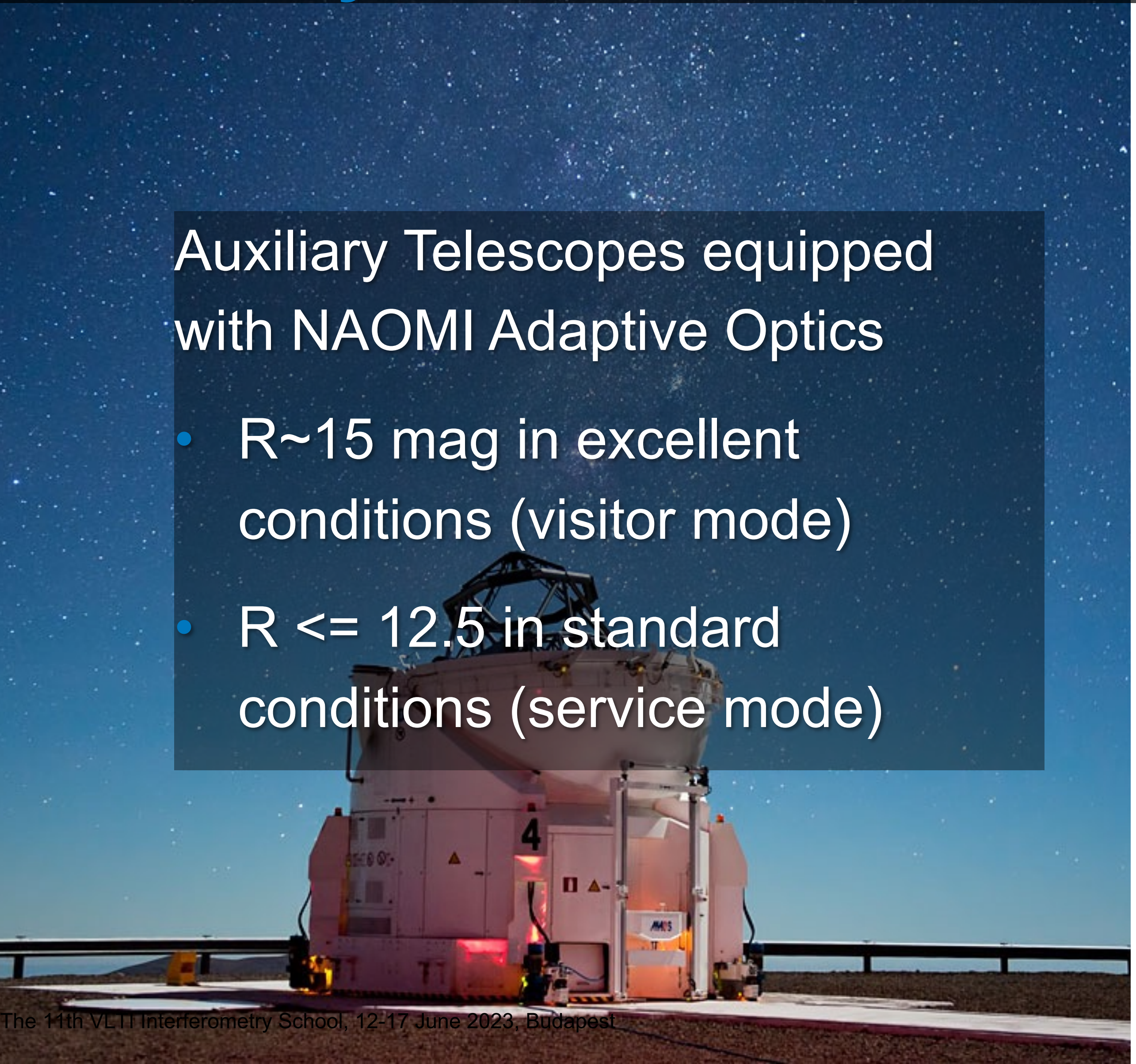

VLTI Period 112 – A0 B2 D0 C1
Stations
A0–B2
A0–D0
A0–C1
B2–D0
B2–C1
D0–C1
Made by ASPRO 2/JMMC


VLTI Period 112 – A0 B5 J2 J6
Stations
A0–B5
A0–J2
A0–J6
B5–J2
B5–J6
J2–J6
Made by ASPRO 2/JMMC


VLTI Period 112 – A0 G1 J2 K0
Stations
A0–G1
A0–J2
A0–K0
G1–J2
G1–K0
J2–K0
Made by ASPRO 2/JMMC

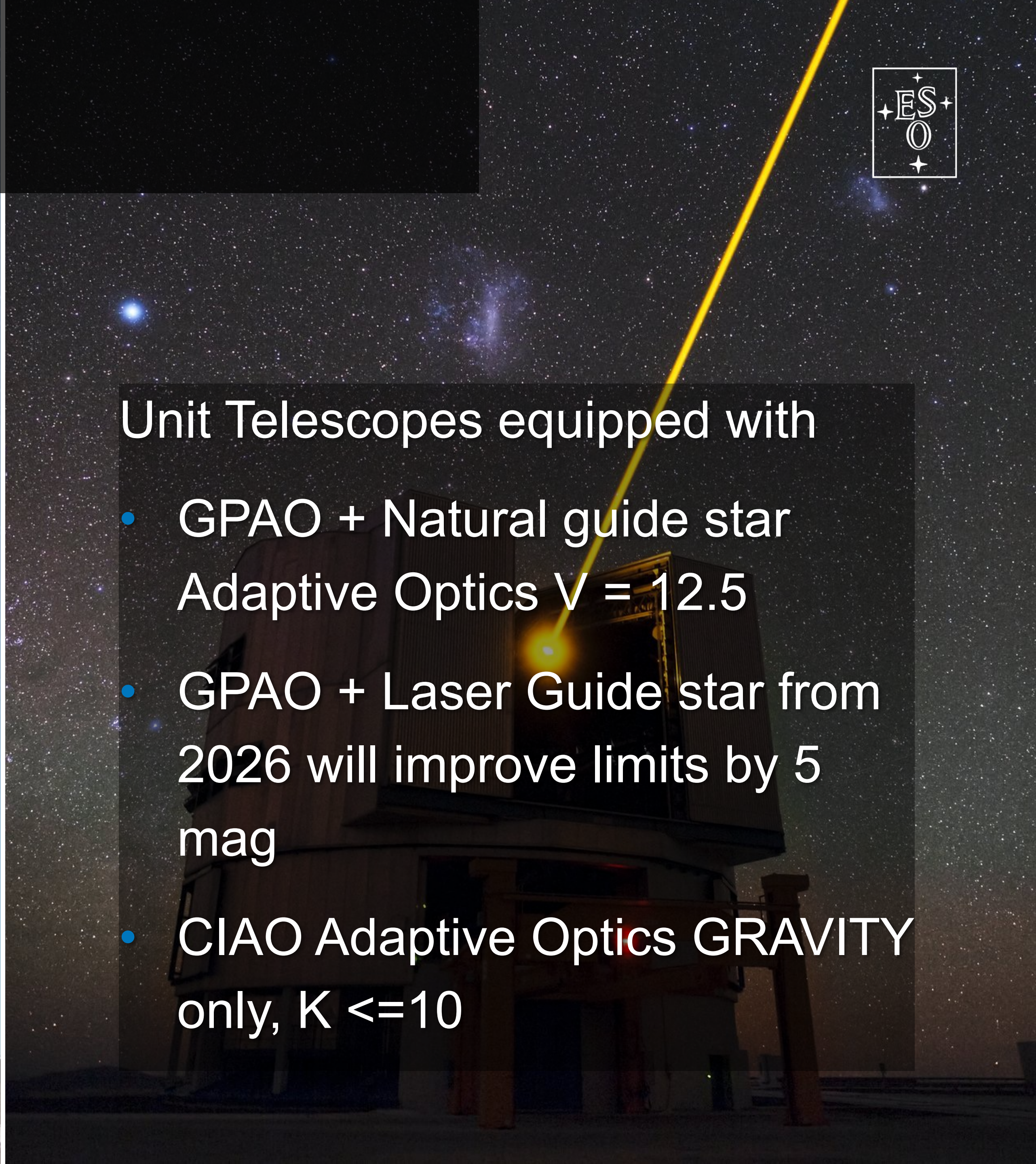

VLTI Period 112 – K0 G2 D0 J3
Stations
K0–G2
K0–D0
K0–J3
G2–D0
G2–J3
D0–J3
Made by ASPRO 2/JMMC

VLTI today



Auxiliary Telescopes equipped with NAOMI Adaptive Optics

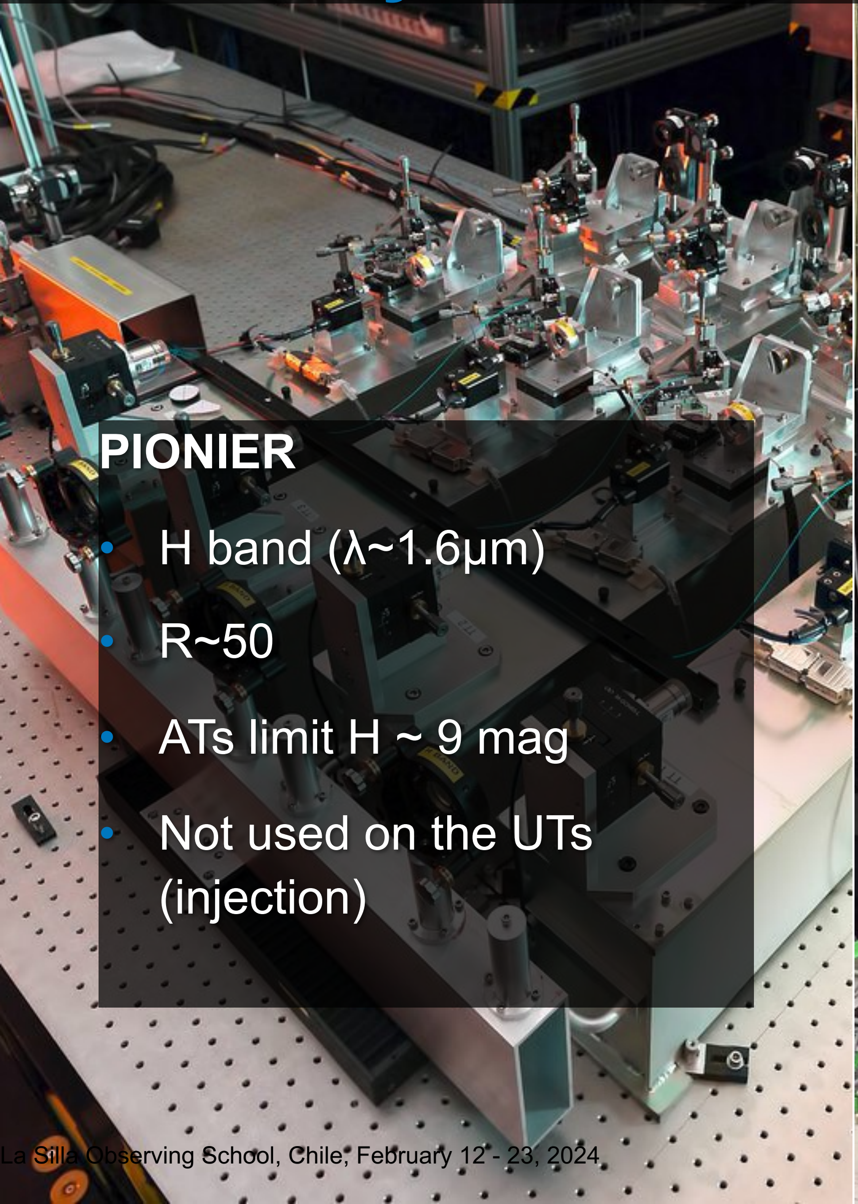
- R~15 mag in excellent conditions (visitor mode)
- R <= 12.5 in standard conditions (service mode)



Unit Telescopes equipped with

- GPAO + Natural guide star Adaptive Optics V = 12.5
- GPAO + Laser Guide star from 2026 will improve limits by 5 mag
- CIAO Adaptive Optics GRAVITY only, K <=10

VLTI today

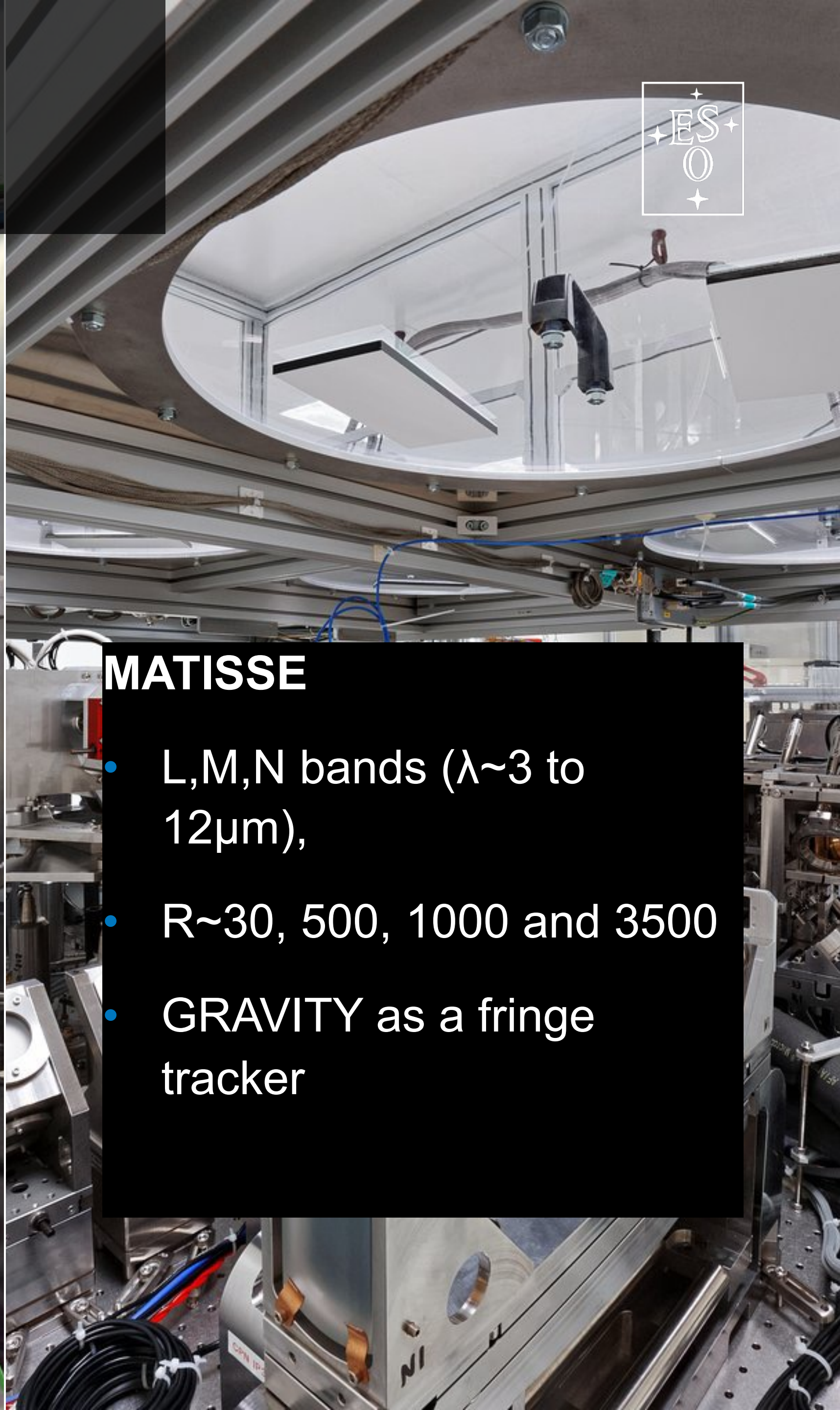


PIONIER

- H band (λ~1.6μm)
- R~50
- ATs limit H ~ 9 mag
- Not used on the UTs (injection)

GRAVITY

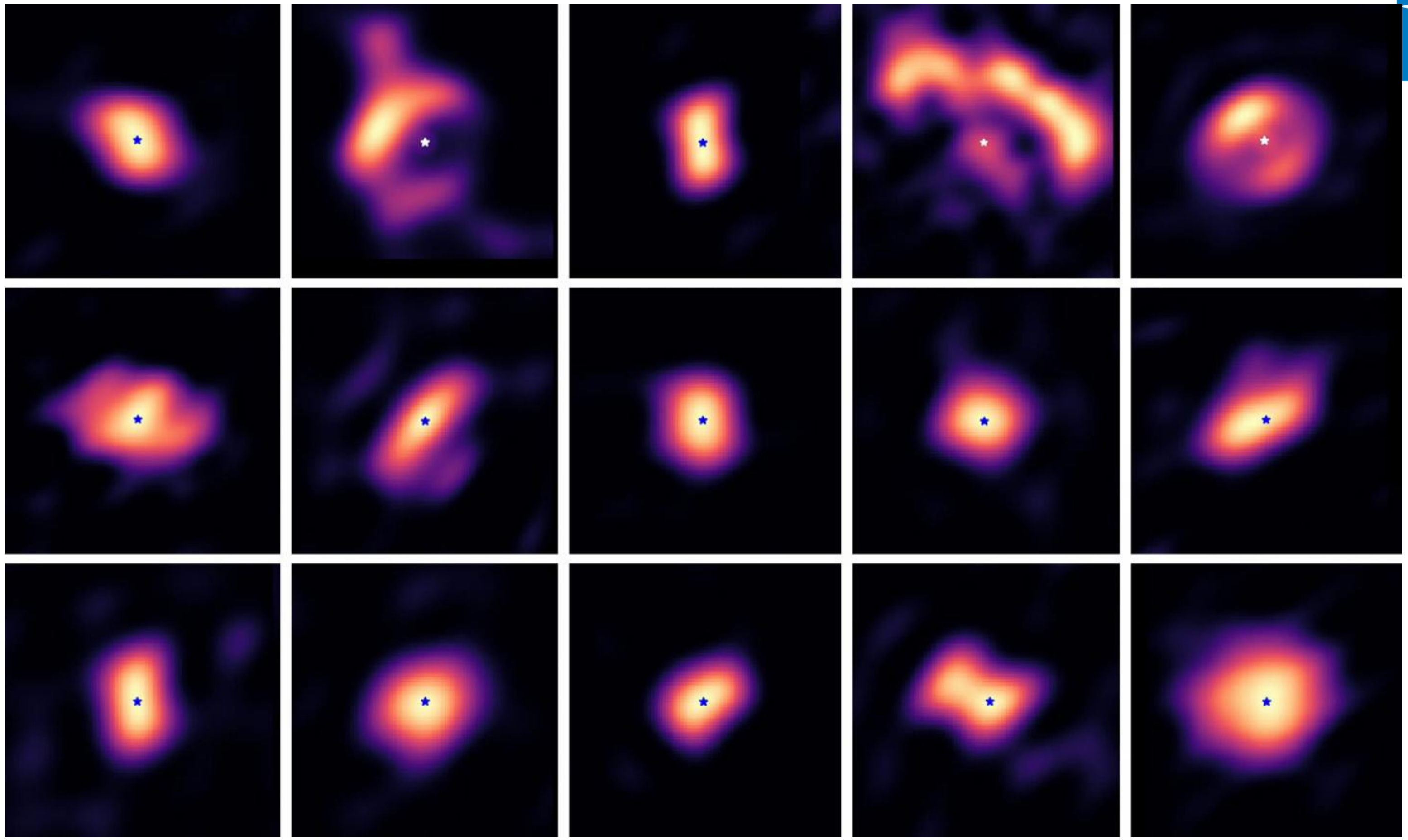
- K band (λ~2.2μm),
- R~20, 500 and 4000
- Fringe tracker (up to 2” off-axis)

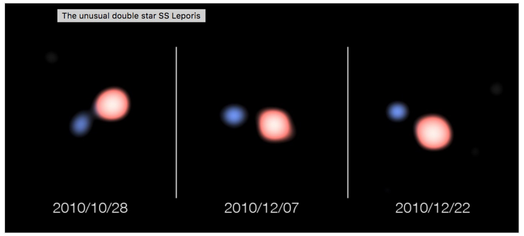


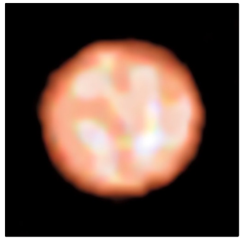
MATISSE

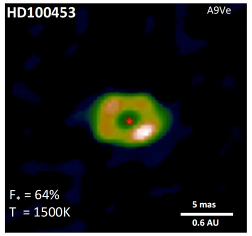
- L,M,N bands (λ~3 to 12μm),
- R~30, 500, 1000 and 3500
- GRAVITY as a fringe tracker

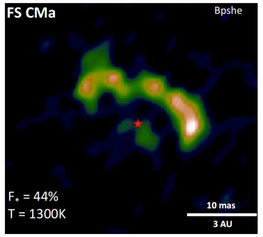
KEEP
CALM
AND
OBSERVE
WITH
PIONIER











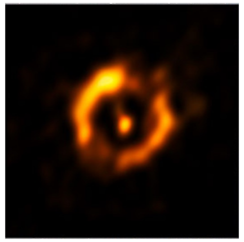
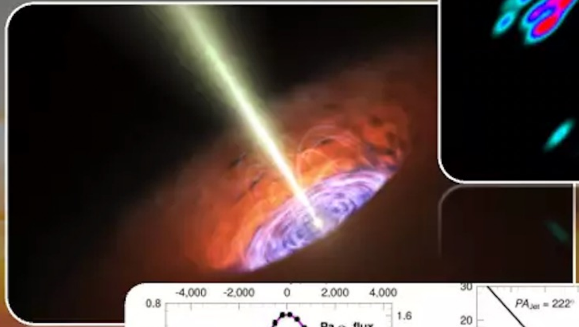
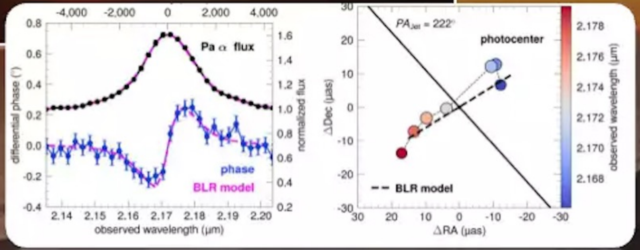


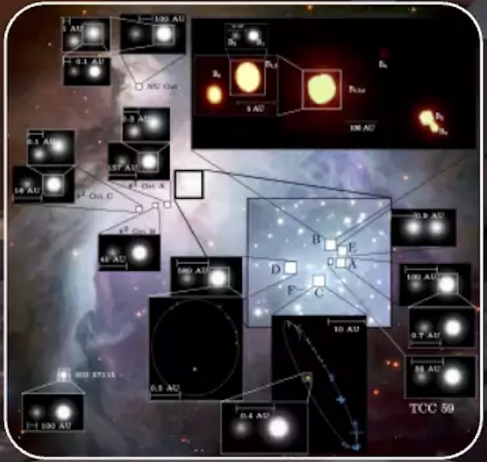
Image credit: GRAVITY consortium

Observing the Universe in Motion: 5 years of GRAVITY



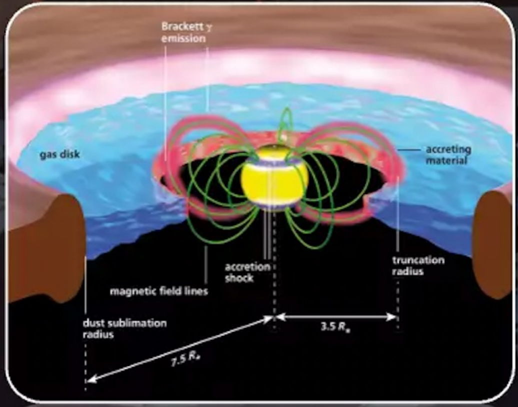


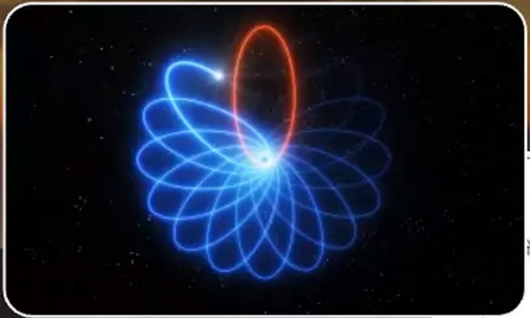
19+ mag limiting magnitude & polarimetry

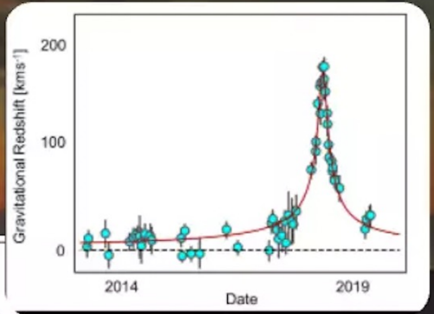


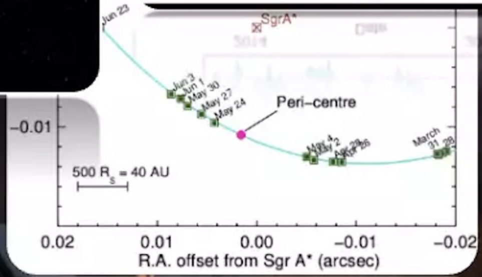
2 x 4 milli-arcsec resolution imaging

Micro-arcsec spectral differential astrometry



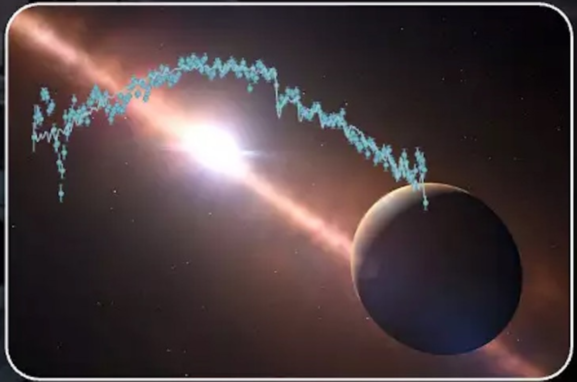


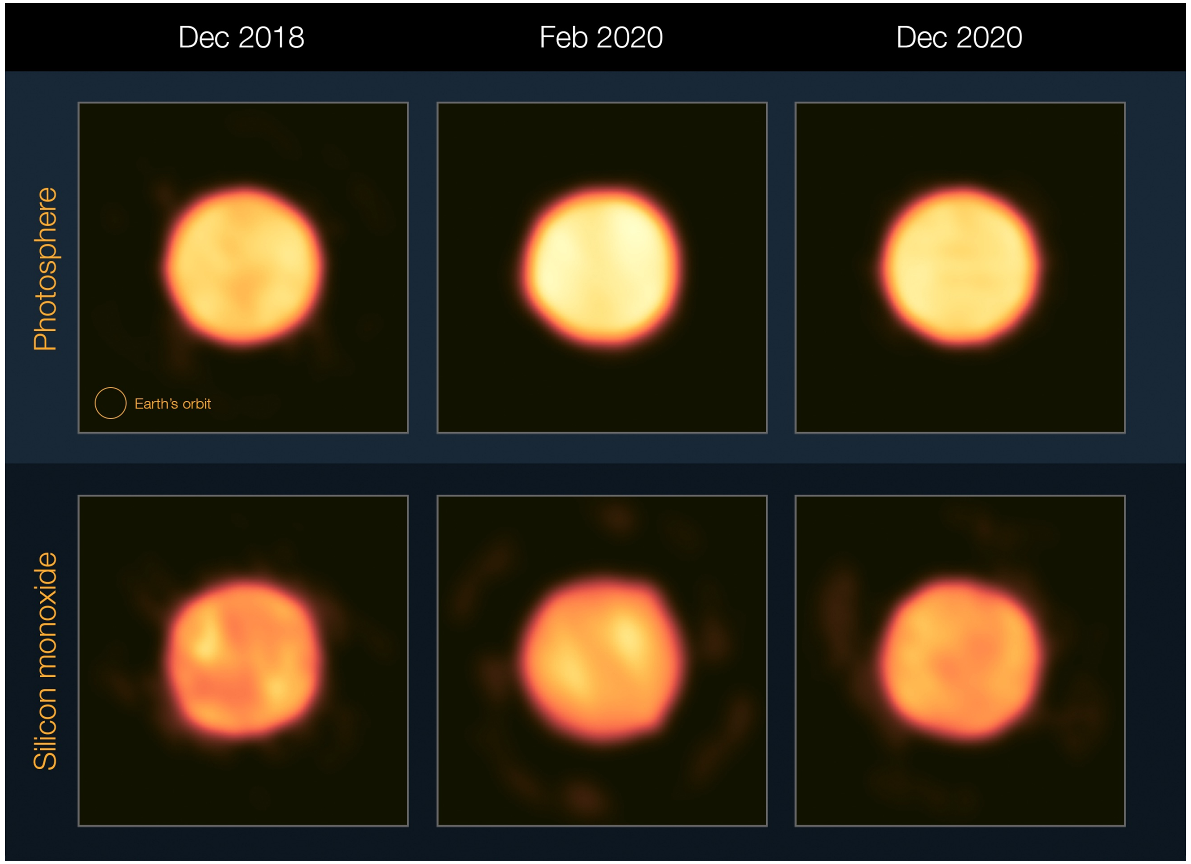




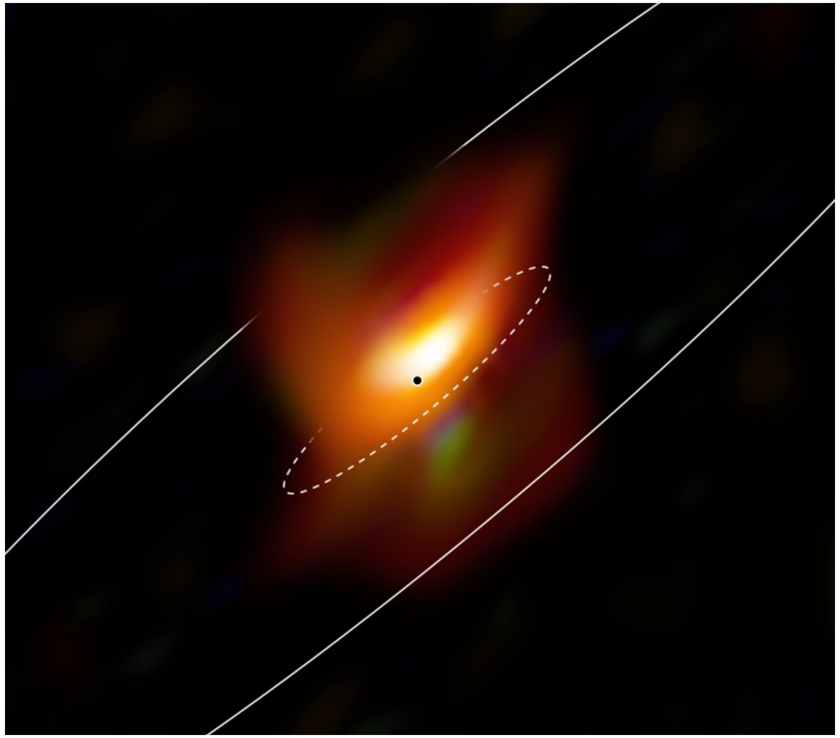
High resolution spectroscopy

<50 μas imaging astrometry





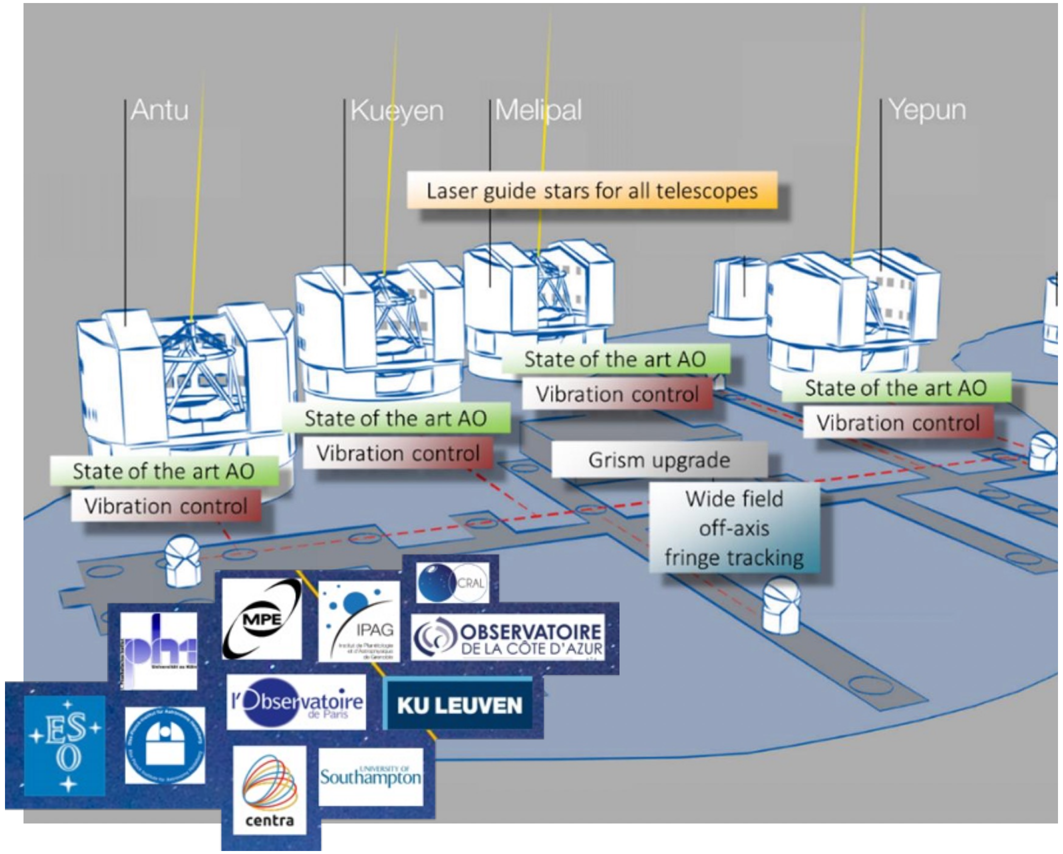
Betelgeuse's Great Dimming Event in high resolution
Drevon et al. 2023



A close-up view of Messier 77's active galactic nucleus
Gámez-Rosas et al. 2022

MATISSE

VLTI tomorrow: going faint with GRAVITY+

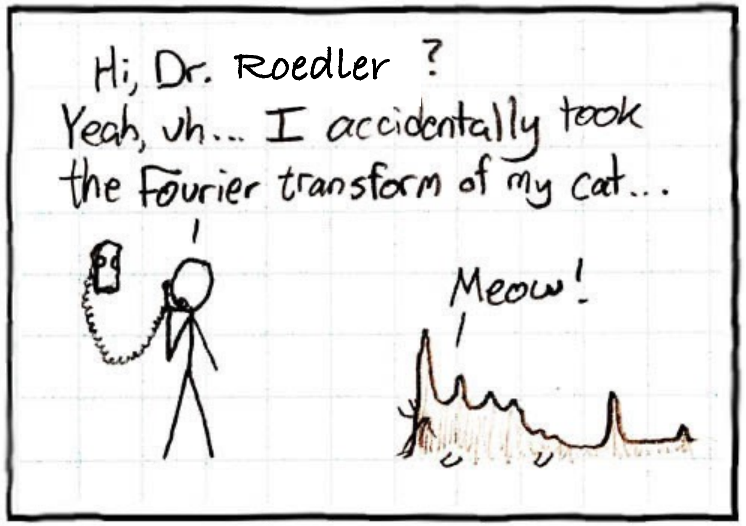


+5mag and better sky coverage:

- off-axis fringe tracking (2”→ 30”)
- Laser Guide Star on every UT
- Higher performance Adaptive Optics
- Better vibration control

Science Cases (Kmag~22):

- The Galactic Centre
- Galaxy AGN coevolution and the masses of supermassive Black Holes (up to z~2.5)
- Characterization of exoplanets
- Young suns and their planet-forming disks



Thank you!

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