Precision Astrometry with MICADO

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on behalf of

MPE	Garching, Germany
MPIA	Heidelberg, Germany
USM	Munich, Germany
OAPD	Padova (INAF), Italy
NOVA	Leiden, Gronigen, Dwingeloo (ASTRON), Netherlands
LESIA	Paris Observatory, France

MICADO: Multi-AO Imaging Camera for Deep Observations

Primary Imaging Field

- 53” across, 3mas pixels
- high throughput
- 4x4 HAWAII 4RG detectors
- ~20 filter slots

Xmas Tree Arm

- 1.5mas & 4mas pixels
- imaging & spectroscopy
- ~20 filter slots
- polarimetry
- [tunable filter (dual imager)]

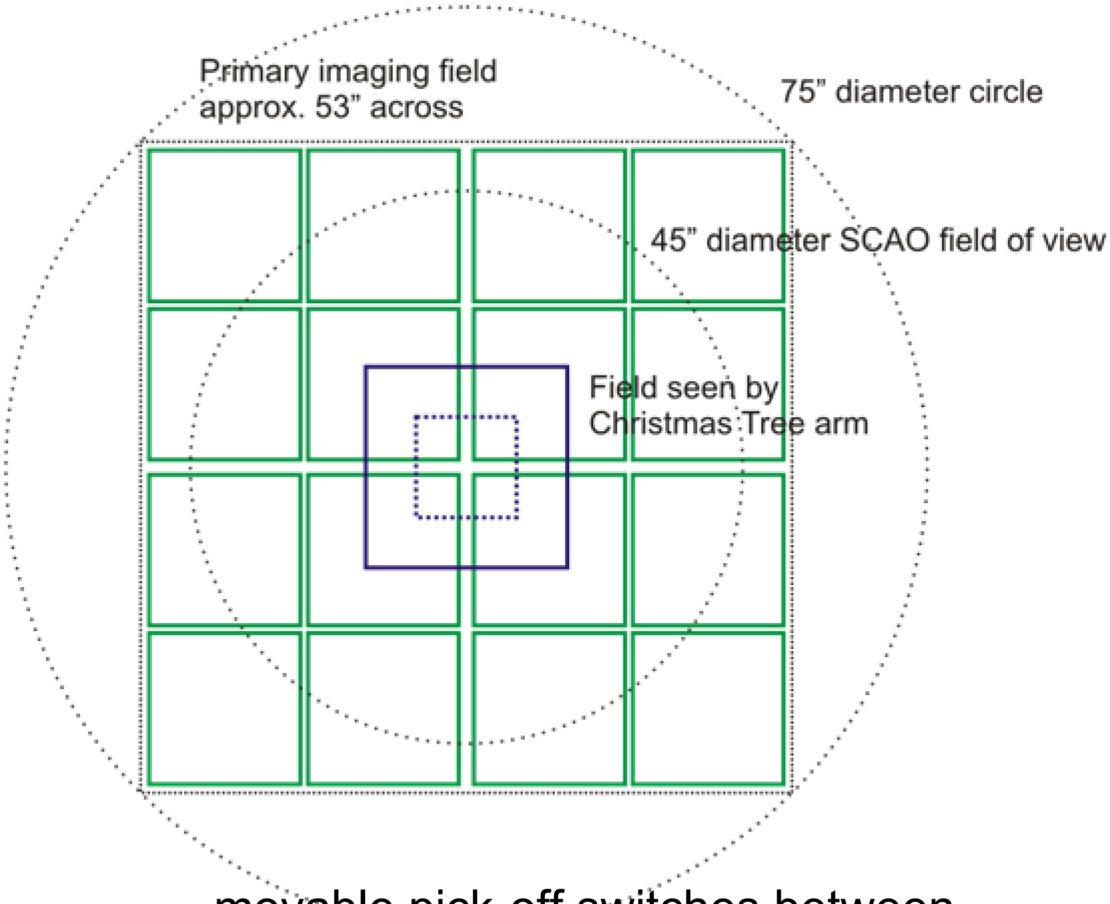
Adaptive Optics Compatability

SCAO: yes, own module

GLAO: yes, but not optimised

LTAO: TBC

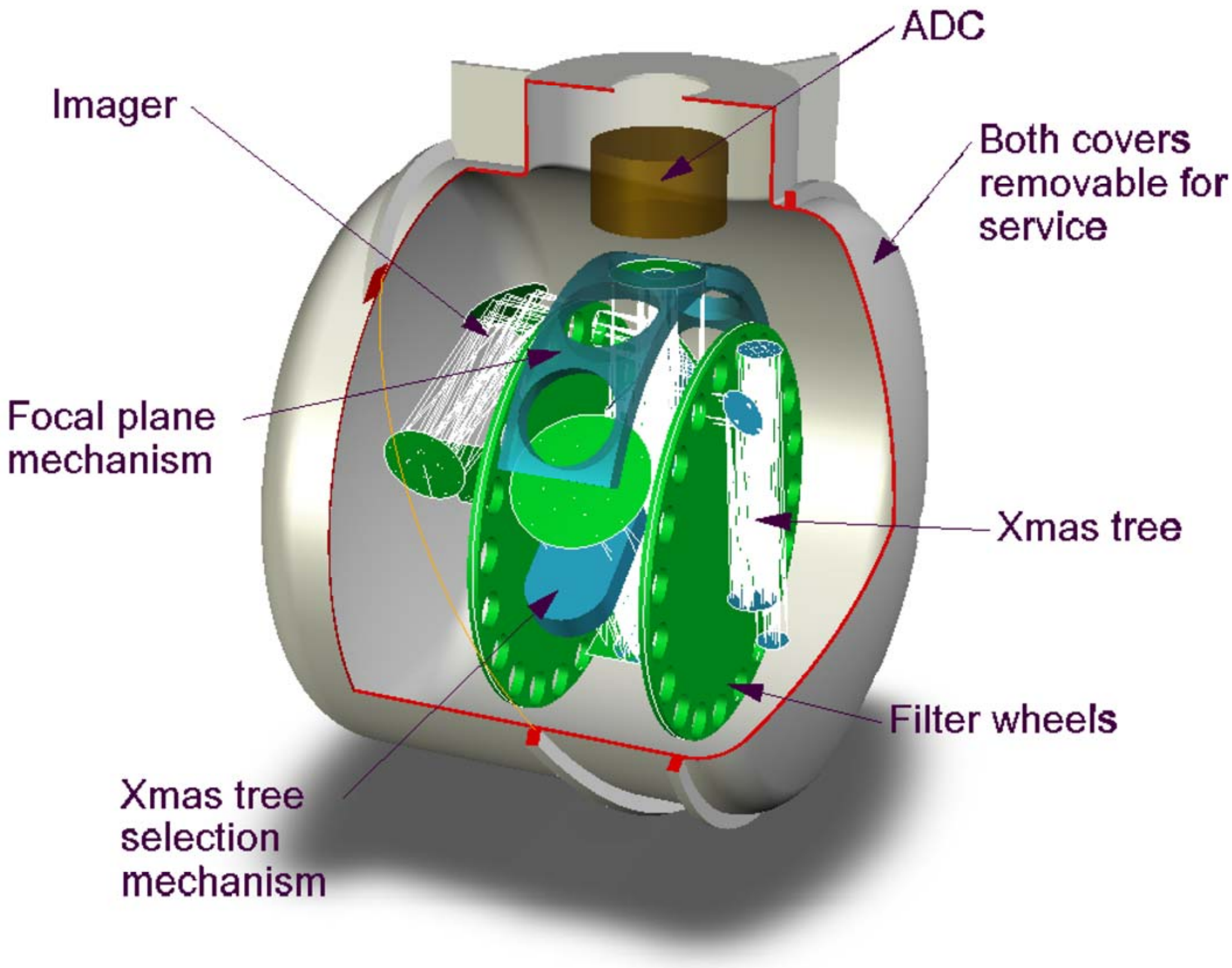
MCAO: yes, optimised



movable pick-off switches between Primary field & Xmas Tree

Opto-Mechanics Overview

- imager: simple high-throughput reflective design using only fixed mirrors; optimised for photometric & astrometric precision
- cryostat 1.7m×1.9m, rotating diameter 2.3m; mounts underneath SCAO & MAORY



MICADO Key Capabilities

- **Sensitivity & Resolution**
- Precision Astrometry
- High throughput Spectroscopy
- Simple, Robust, Available early

- MICADO is optimized for imaging at the diffraction limit
- JHK sensitivity comparable to JWST
- may be improved by OH suppression (R&D effort)
- resolution of 6-10mas over 1arcmin field is unique (cf IRIS on TMT)
- photometry in crowded fields

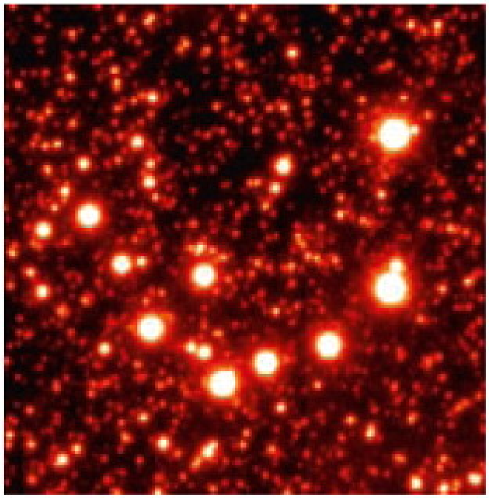
Crowded Field Photometry: MICADO vs JWST

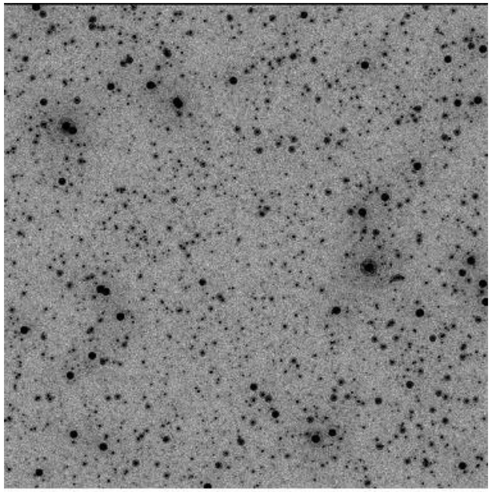
Resolution gives an effective sensitivity gain – cf. 3mag for MAD vs ISAAC

Omega-Cen

5-hr K-band simulated exposure

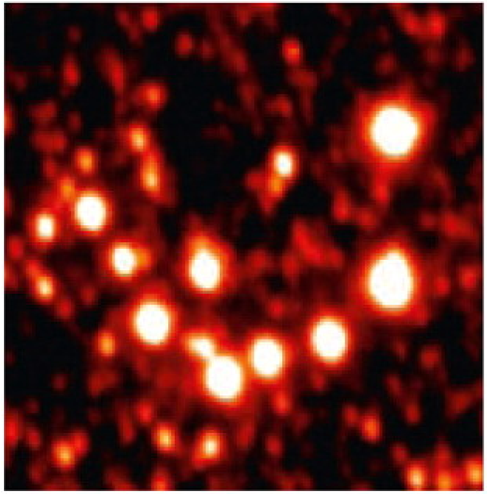
MAD

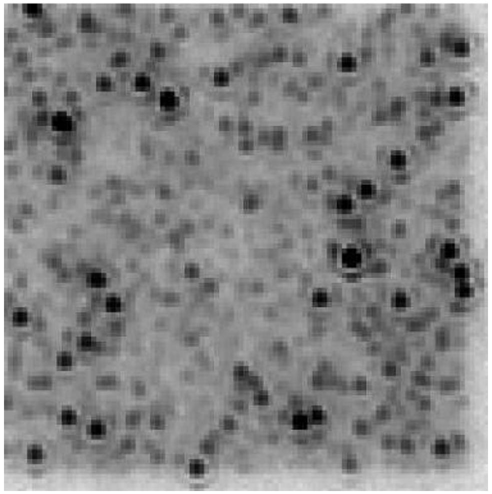




MICADO

ISAAC





JWST

MICADO Key Capabilities

- Sensitivity & Resolution
- **Precision Astrometry**
- High throughput Spectroscopy
- Simple, Robust, Available early

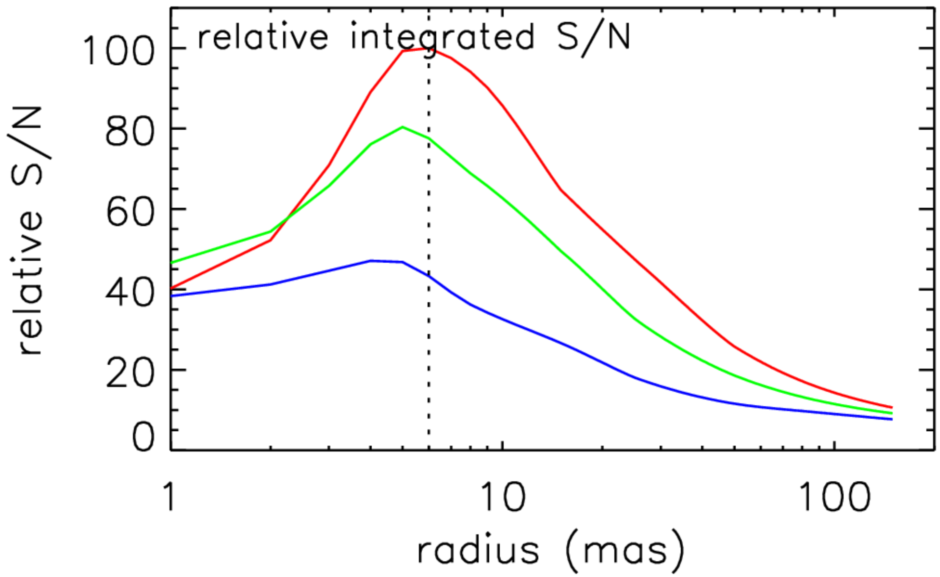
- to <50µas over full 1arcmin field
- 50µas/yr = 10km/s at 40kpc
- multiple measurements leads to higher precision
- many systematic effects to correct but necessary SW is available
- bring precision astrometry into the mainstream
- effectively open up a new field of astrophysics

MICADO Key Capabilities

- ➢ Sensitivity & Resolution
- ➢ Precision Astrometry
- ➢ **High throughput Spectroscopy**
- ➢ Simple, Robust, Available early

- simple high-throughput slit spectroscopy
- ideal for compact sources
- 12mas (& 48mas) slits, R~3000
- reaches ABmag~24.5 (10σ) in 1 hr across JHK

for point sources:



MICADO Key Capabilities

- Sensitivity & Resolution
- Precision Astrometry
- High throughput Spectroscopy
- **Simple, Robust, Available early**

- MICADO philosophy is optical & mechanical simplicity
- leads directly to stability needed for astrometry & photometry
- exemplifies most unique features of E-ELT: resolution & sensitivity
- flexibility to work with different AO systems

Precision Astrometry with MICADO

with NACO we reach precision of ~0.5% of FWHM

- **Can we achieve this for MICADO ?**
- **What is the science ?**

Systematics

Fundamental Limit	34μas for S/N=100 (measurement noise)
Goal	50μas over 50” field: 1/1000000 precision
Sources of error	*Requirement*
Instrument	
Sampling	pixel scale 3mas (less in crowded fields)
Instrument Distortions	careful calibration to 0.01pix (30μas) using a calibration mask
Plate scale & derotation	low order → coordinate transform
Atmosphere	
Achromatic differential refraction	low order → coordinate transform
Chromatic differential refraction	tunable ADC (10-20μas) or multi-colours
AO	
Differential Tilt Jitter	270μas/ $T^{1/2}$ [Ellerbroek 07] → ‘integrate it out’ statistically [cf Cameron+ 08]
NGS atmospheric effects	low order → coordinate transform
PSF variations & asymmetries	minimal PSF variation & good PSF model

Calibration Scheme

basic

- calibration mask	- polynomial + lookup table to remove stable high order effects & discontinuities

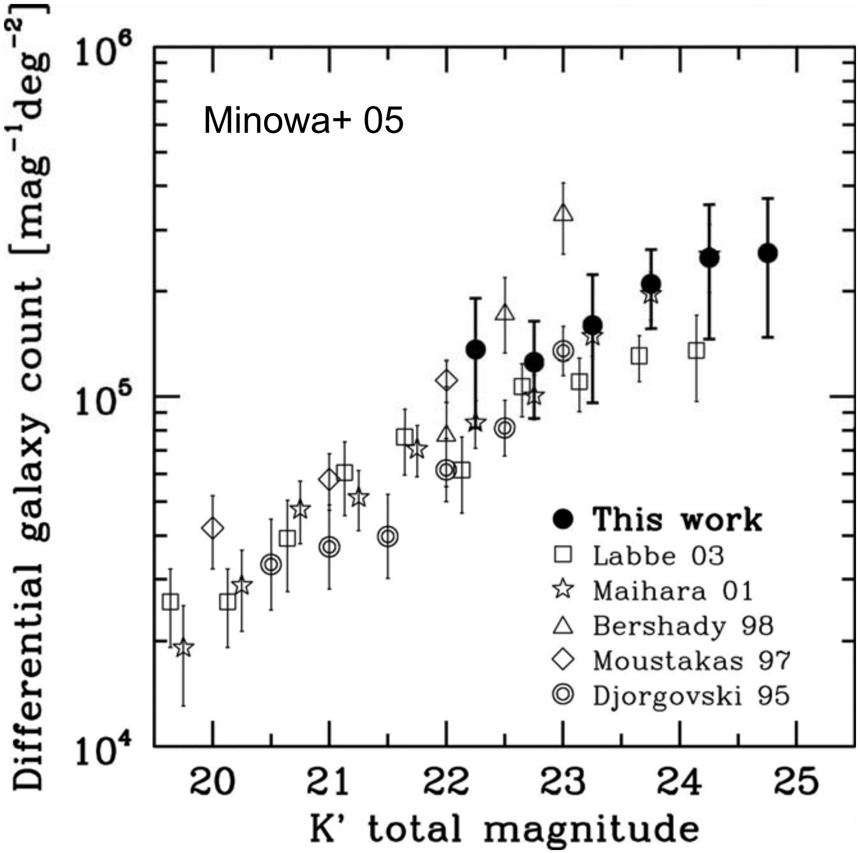
single epoch

- stars	- polynomial fit to remove low/mid-order effects that change during a sequence of observations

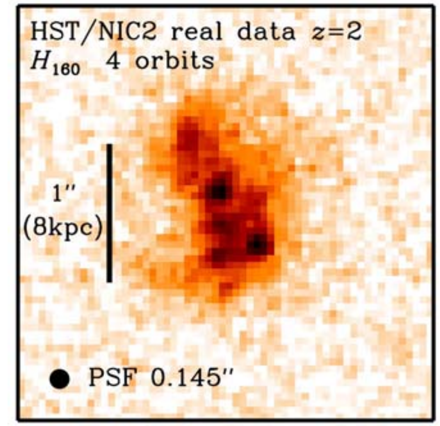
inter epoch
(for absolute reference because stars move)

- high-z galaxies	- polynomial fit on deep combined single epoch data sets to remove low order effects

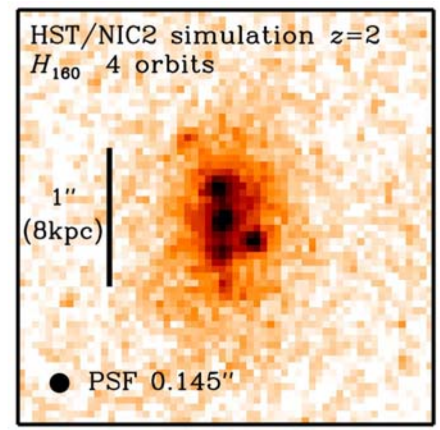
High-z galaxies as Astrometric References



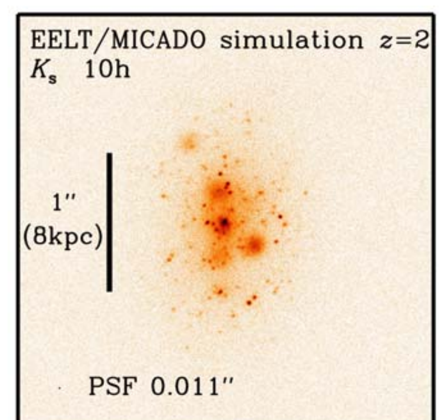
HST image of a z=2 galaxy



simulation at HST resolution

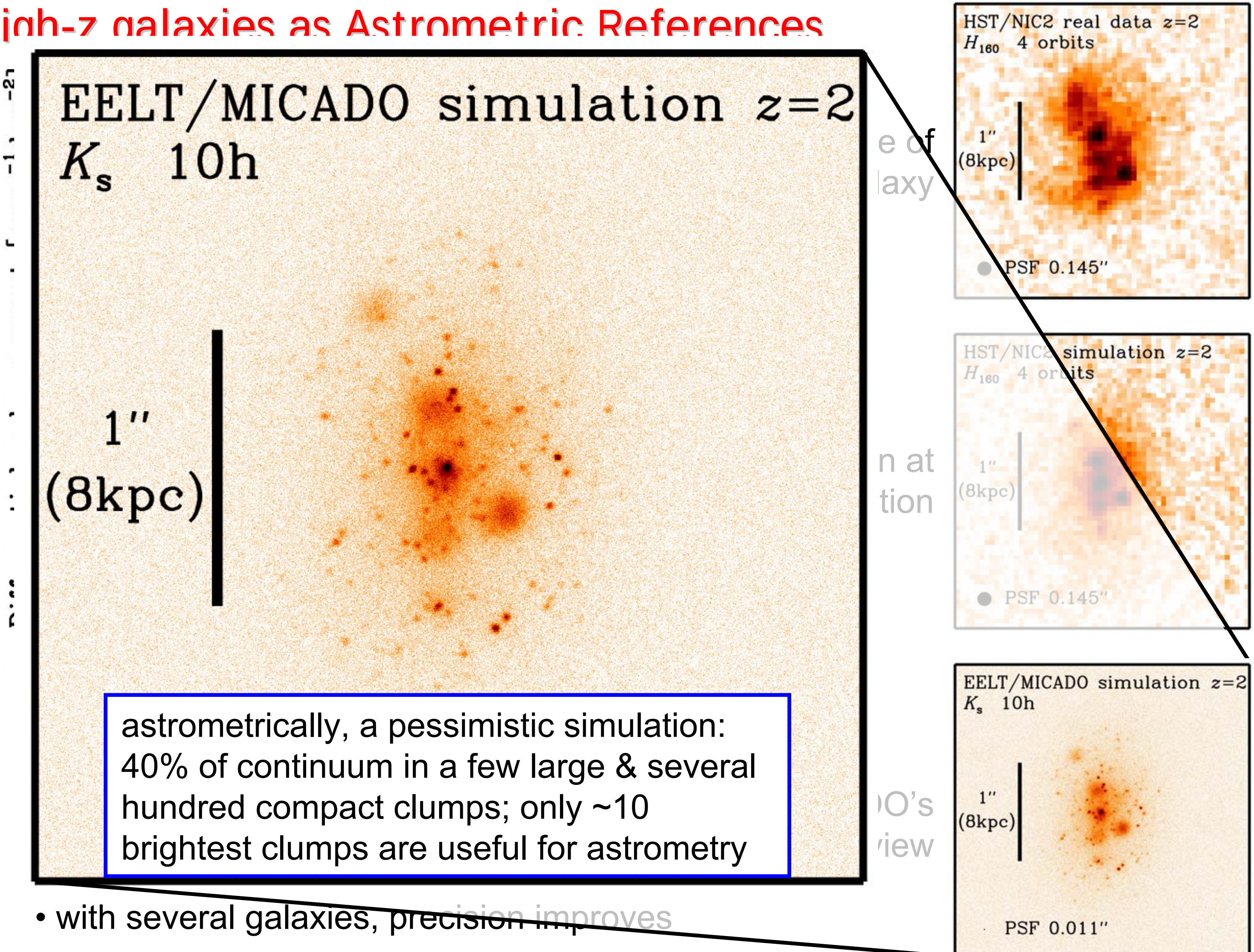


MICADO's view



- ~25 galaxies to K<21.5 in MICADO field
- each galaxy has many clumps
- tests yield 60-80μas precision for a 10hr integration on a K=21.4 simulated galaxy
- with several galaxies, precision improves

High-z galaxies as Astrometric References



astrometrically, a pessimistic simulation: 40% of continuum in a few large & several hundred compact clumps; only ~10 brightest clumps are useful for astrometry

- with several galaxies, precision improves

Astrometric Data Processing

Astro-WISE - the Astronomical Widefield Imaging System for Europe
see http://www.astro-wise.org/

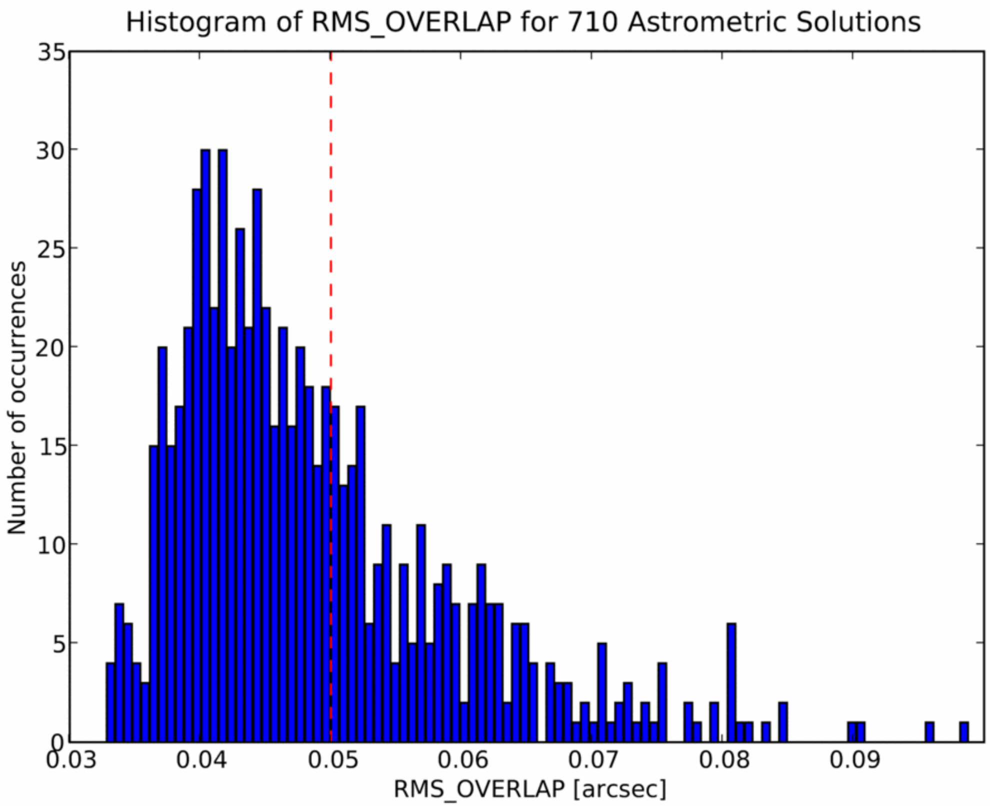
Astrometry SW has been tested and works

WFI tests

- accuracy of USNO reference catalogue 0.3” rms
- local solution (2nd order) performs astrometric correction on individual detectors
- global solution (3rd order) minimises differences between detectors
- final accuracy <0.05” rms

MICADO

- needs 1000x better precision
- but has 100x better resolution
- only relative astrometry
- higher order correction



McFarland, Deul, Valentijn, Verdoes, 08

Precision Astrometry: science

A few examples

Binary stars, planets, asteroids
orbits & dynamical masses

Black Hole masses & the M_{BH}-σ_* relation
galaxy nuclei: Galactic Center, M31, …
star clusters: intermediate mass black holes

Mass Distribution & Formation History of the Galaxy
globular cluster motions
motions of local group galaxies

Dark Matter & Structure Formation
motions of dwarf spheroidals

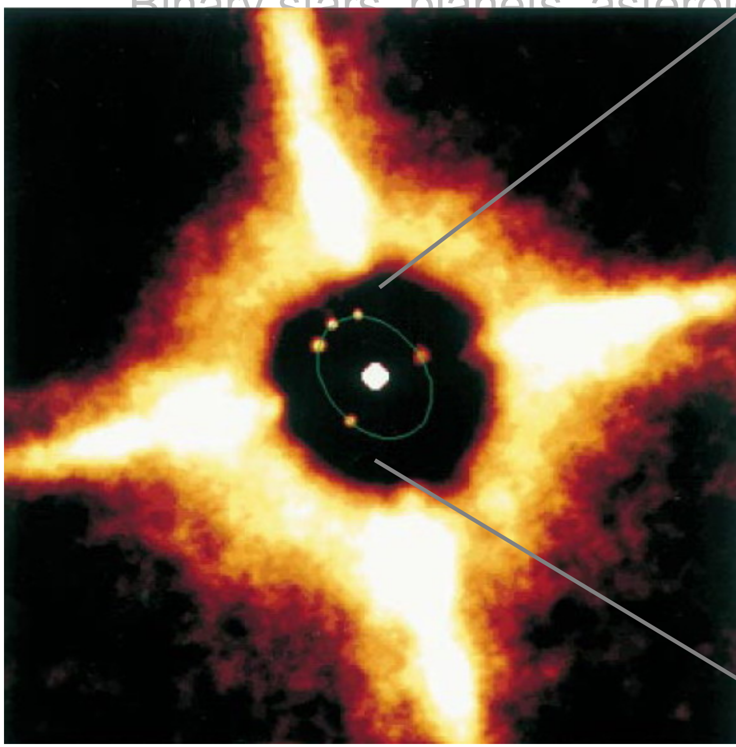
narrow angle astrometry (EPICS)

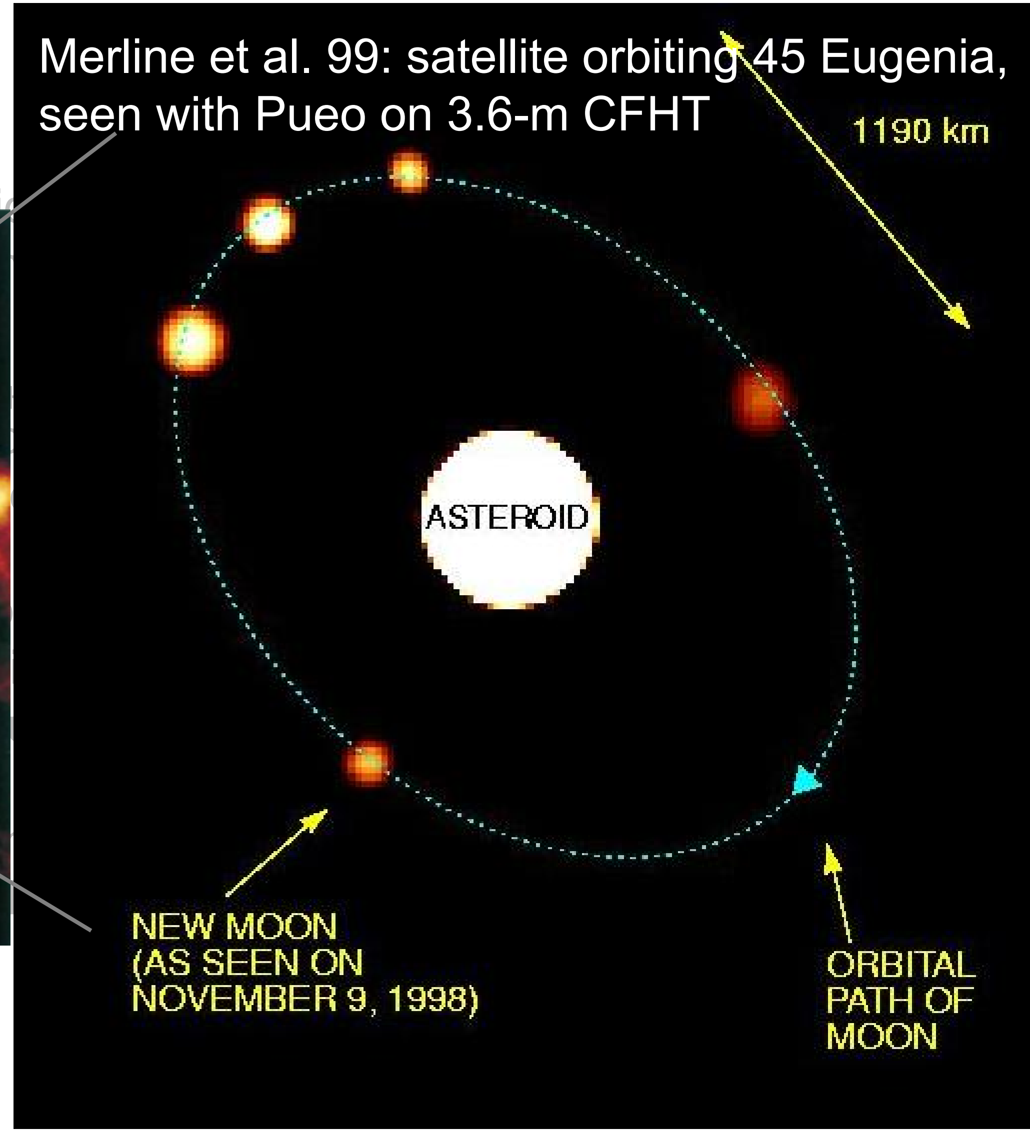
wide angle astrometry (MICADO)

Precision Astrometry: science

A few examples

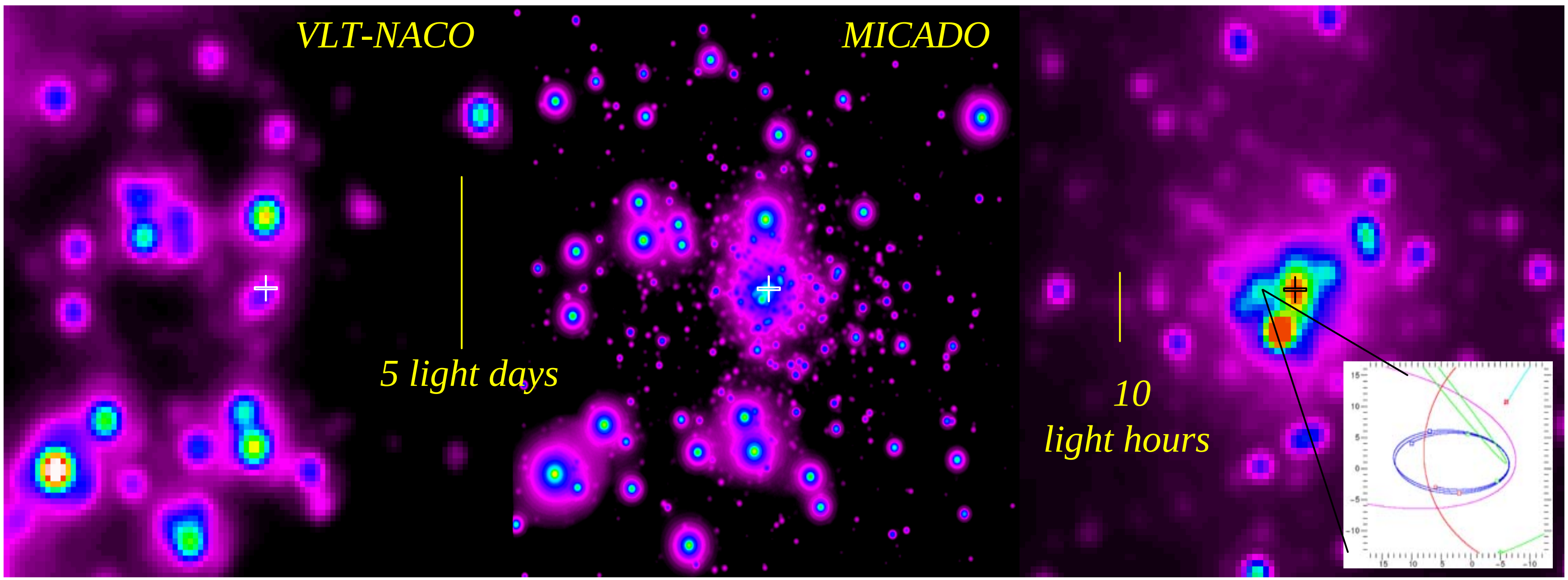
Binary stars, planets, asteroi





Galactic Center

- A unique laboratory for exploring strong gravity around the closest massive black hole
- A crucial guide for: - accretion onto black holes and
  - co-evolution of dense stars cluster and AGN



Observations at the diffraction limit of the VLT: the central 0.4”

A simulation showing what one can expect to see with MICADO

The central 0.1” will reveal many stars in close, fast orbits around the central black hole with measurable precession

Galactic Center

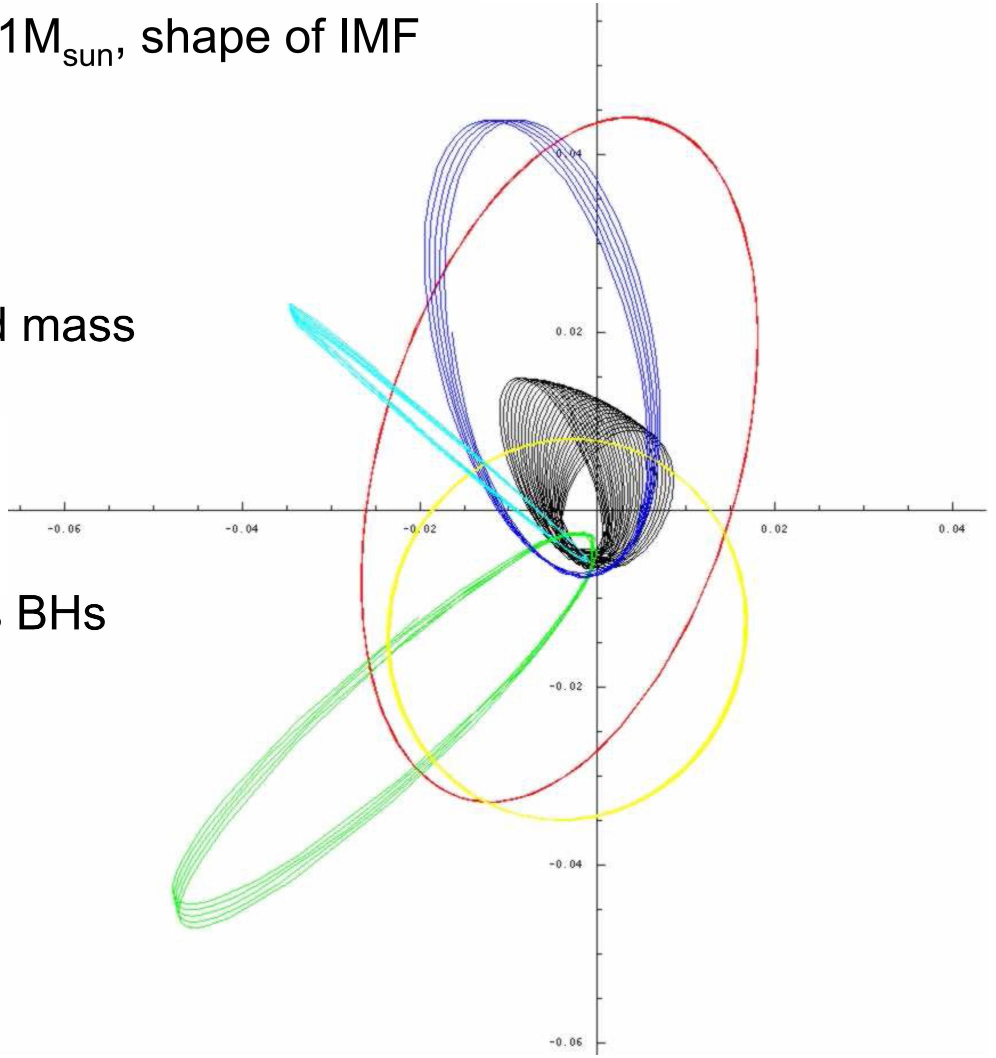
MICADO on E-ELT

sensitivity >5mag fainter, resolution & astrometry 5x better than NACO on VLT

- density profile, luminosity function to $<1M_{sun}$, shape of IMF

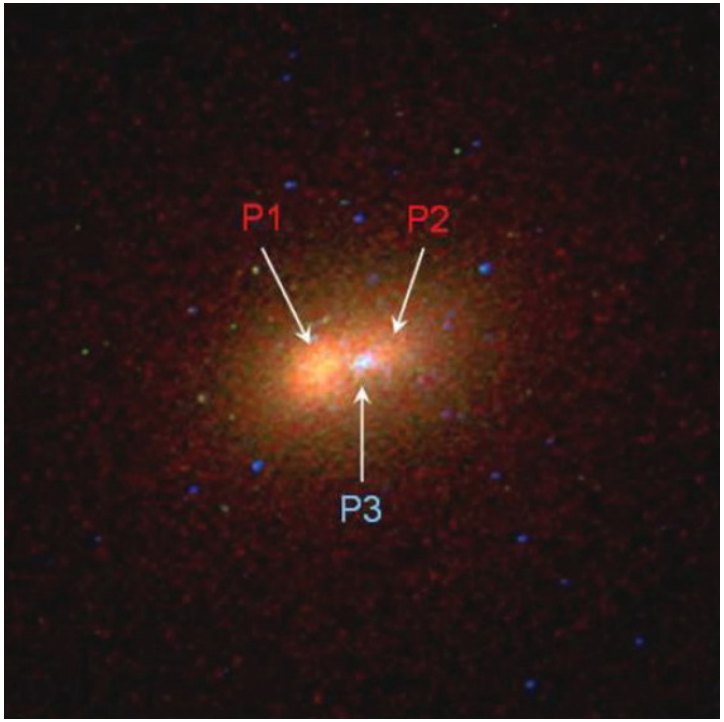
- orbits of stars closest to BH
- relativistic (v^2/c^2) prograde precession

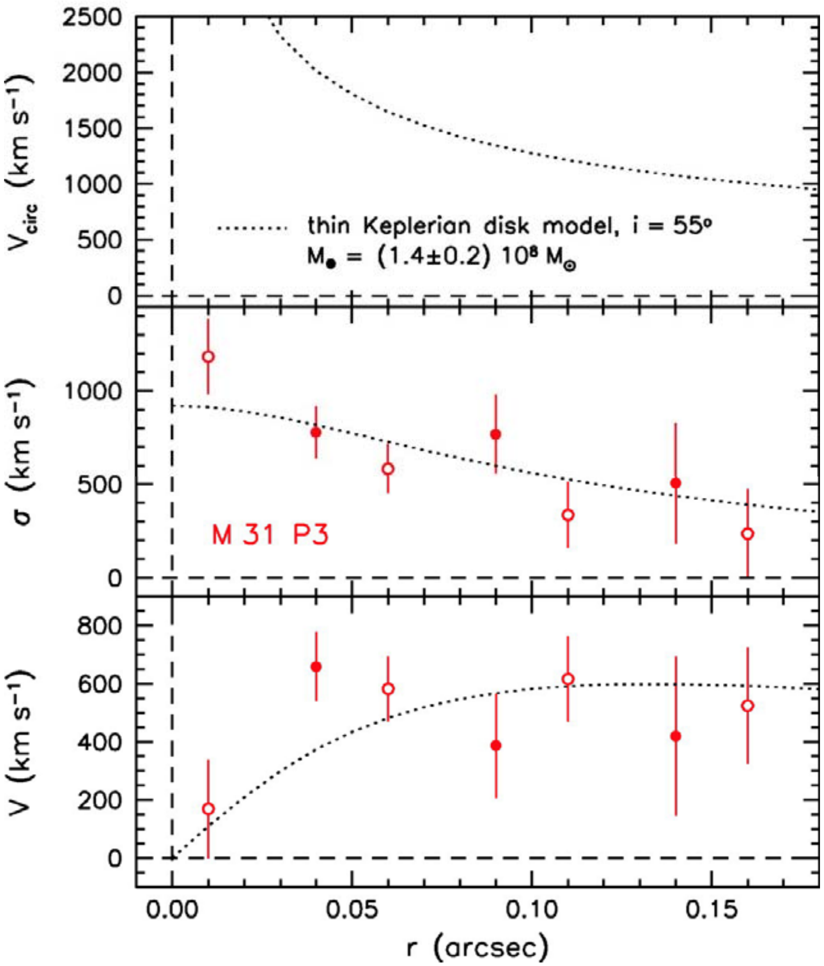
- retrograde precession due to extended mass
- proper motions of ~1000 stars
  - accurate distance to GC
  - phase-space clumping (disks)
  - binary fraction
  - presence of intermediate mass BHs



The core of M31

- P1 & P2: apo- and peri- center of disk of old red stars
- P3: cluster of young stars, scale length 0.1"
- thin disk Keplerian models provide best fit; $M_{BH} = 1.4\times10^8 M_{sun}$





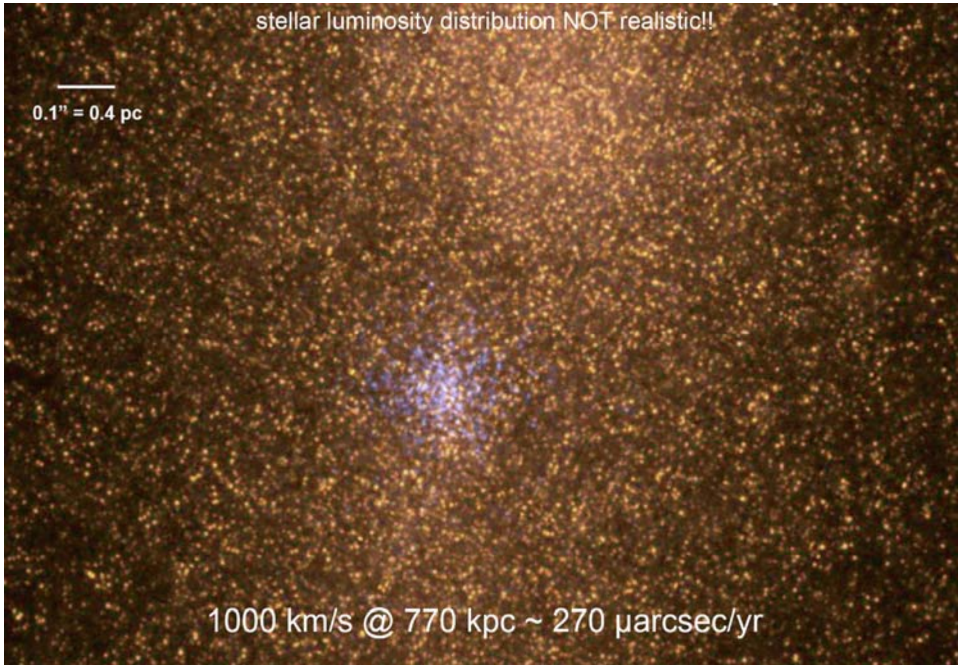
Bender et al. 05

The core of M31... and beyond

• distance ~100x GC, but BH mass ~35x more: proper motions similar magnitude

Keck's view

MICADO's view

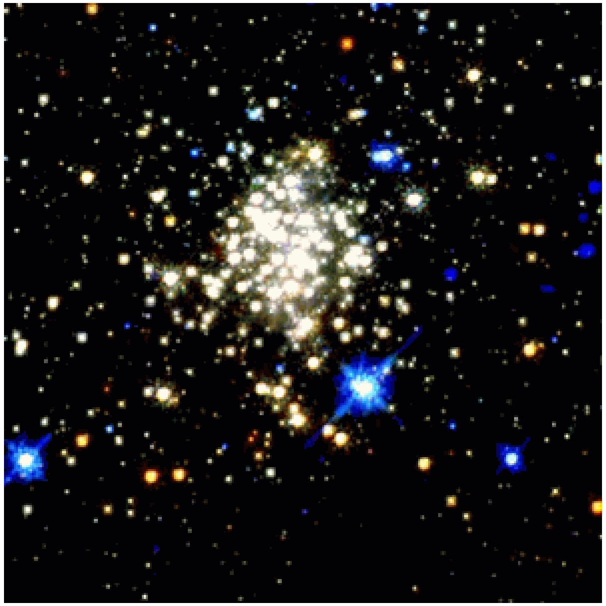


- determine the mass & location of black hole
- understand the kinematics & origin of eccentric disk of stars

- other galaxies also possible: Cen A, $M_{BH}=5\times10^7 M_{sun}$,
  - expect stellar velocities 1000km/s = 50μas/yr
  - can measure proper motions

Intermediate Mass Black Holes

Arches
M_{BH}~$1000M_{sun}$? (Portegies Zwart et al. 06)
proper motion: 5.6mas/yr (Stolte et al. 08)



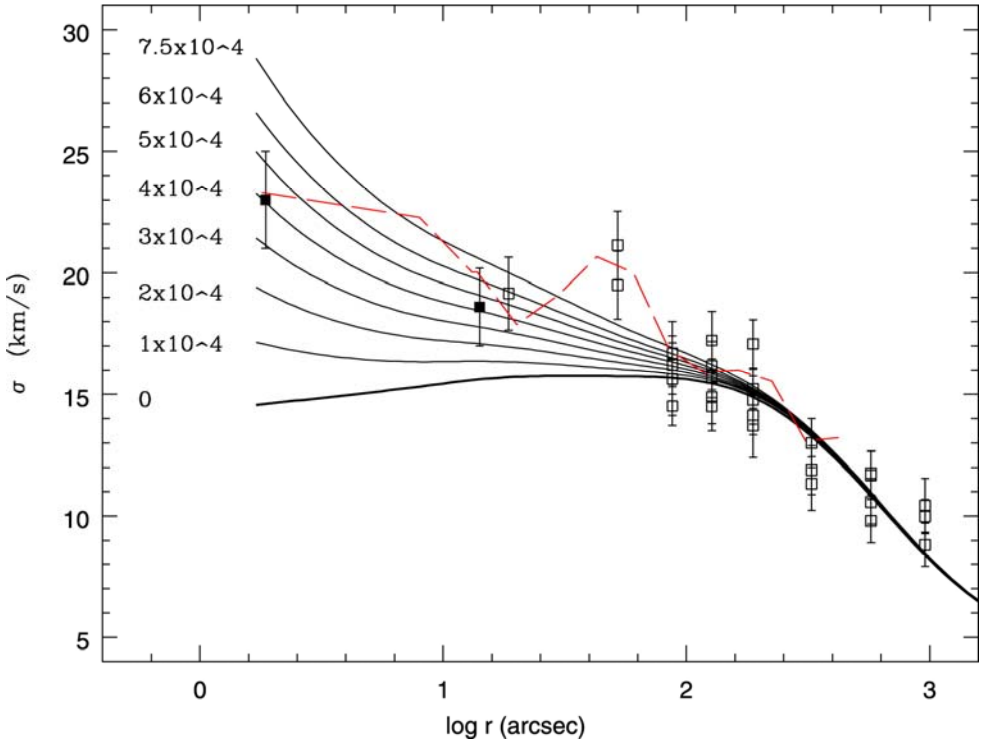
IRS 13
M_{BH}~$1300M_{sun}$? (Maillard et al. 04)

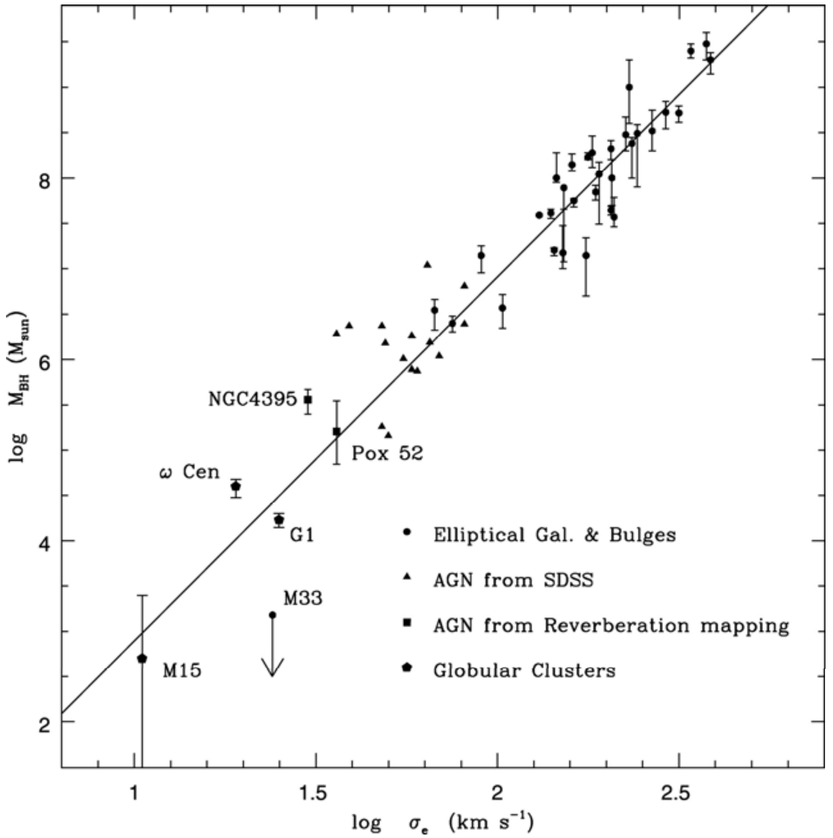
Omega Cen: M_{BH}~$10000M_{sun}$?

Omega Cen: does it have a black hole?

Noyola+ 08

- used luminosity profile & l.o.s. dispersion
- isotropic spherical model yielded $M_{BH}=4\times10^4 M_{sun}$
- considered radial anisotropy, but argued against it since model without BH required $\sigma_t/\sigma_r<0.67$





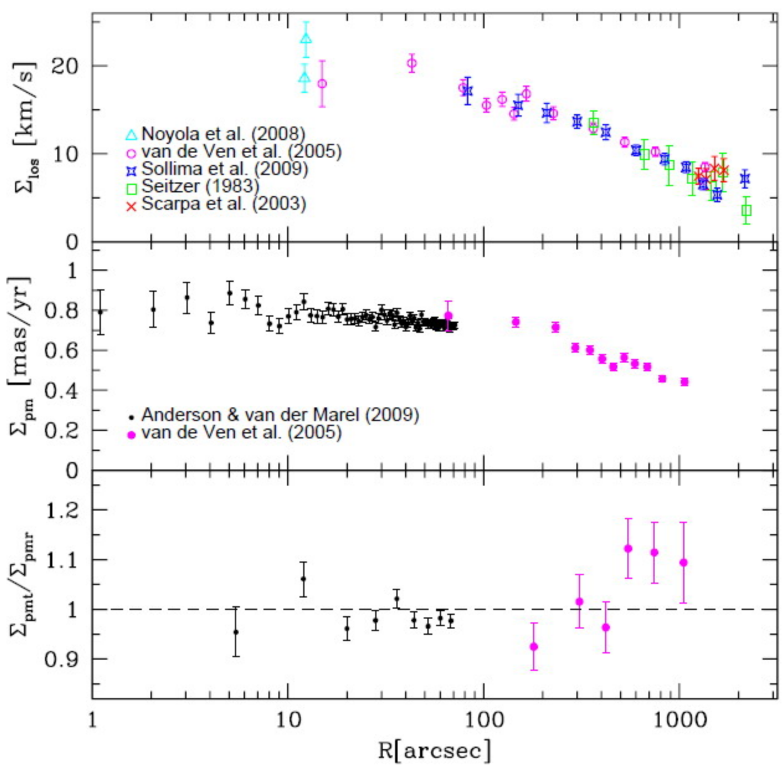
Omega Cen: does it have a black hole?

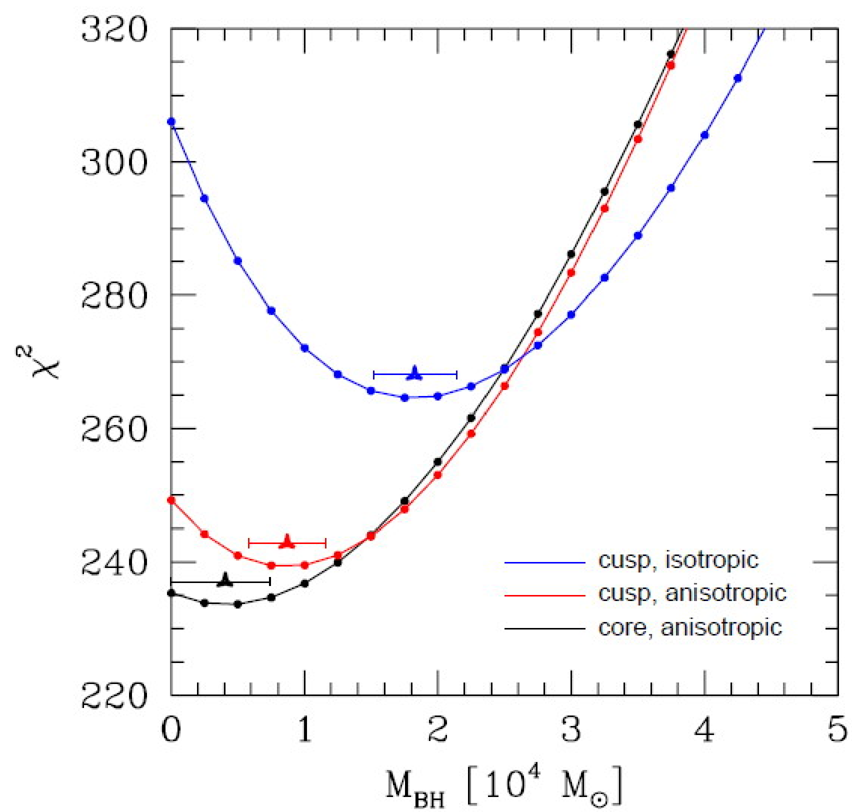
Andersen+ 09, van der Marel+ 09

- used >50000 (faint) stars, 4-yr baseline, individual errors ~100µas/yr
- proper motion dispersions along tangential & radial directions
- models account for small but significant anisotropy (pm_t/pm_r=0.983±.006) since isotropic models overpredict M_{BH}

➢ models with shallow cusp require M_{BH}~$9\times10^3 M_{sun}$

➢ models with core profile (formally the best fit) require no central dark mass !





Intermediate Mass Black Holes with MICADO

Arches, Quintuplet, open clusters, globular clusters, etc.

- Milky Way has ~150 GCs
- Typical GC has central dispersion ~10km/s
- 10km/s is 50μas/yr at a distance of 40kpc
- This is ~10x distance to Omega Cen & covers large part of GC system
- Can measure proper motions on relatively short timescale

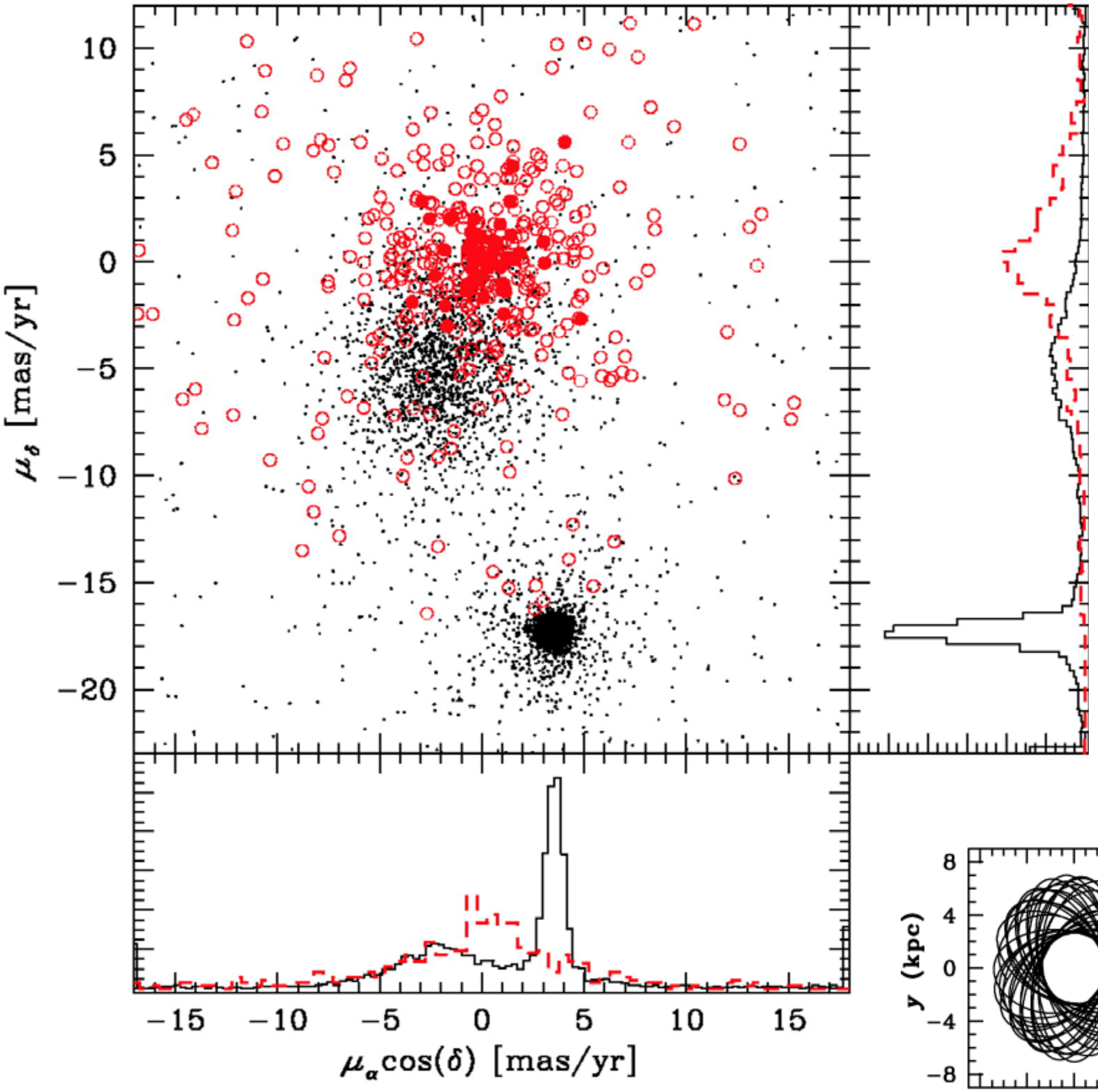
in a few years we can constrain masses of BHs at centres of GCs

- impact on M_{BH}-σ_* relation
- dynamical evolution of GCs

internal proper motions:

- rotation, flattening and internal structure of GCs
- binary fraction: 50μas is sufficient to measure wobble for stars with a dark companion >0.5M_{sun} and separation >0.5AU out to 10kpc

Globular Cluster Proper Motions



Kalirai+ 07

NGC6397

red: galaxies

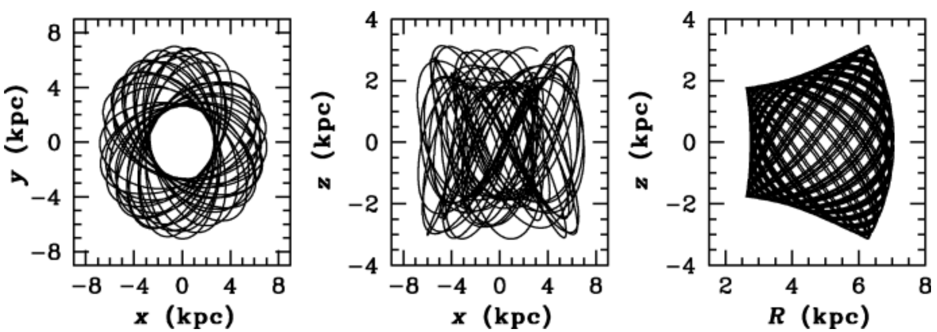
black: field stars & cluster members

10 years of HST data:

$\mu_\alpha \cos\delta = 3.56 \pm 0.04$ mas yr^{-1}

$\mu_\delta = -17.34 \pm 0.04$ mas yr^{-1}

- provides orbit around Milky Way
- frequent passages through the disk

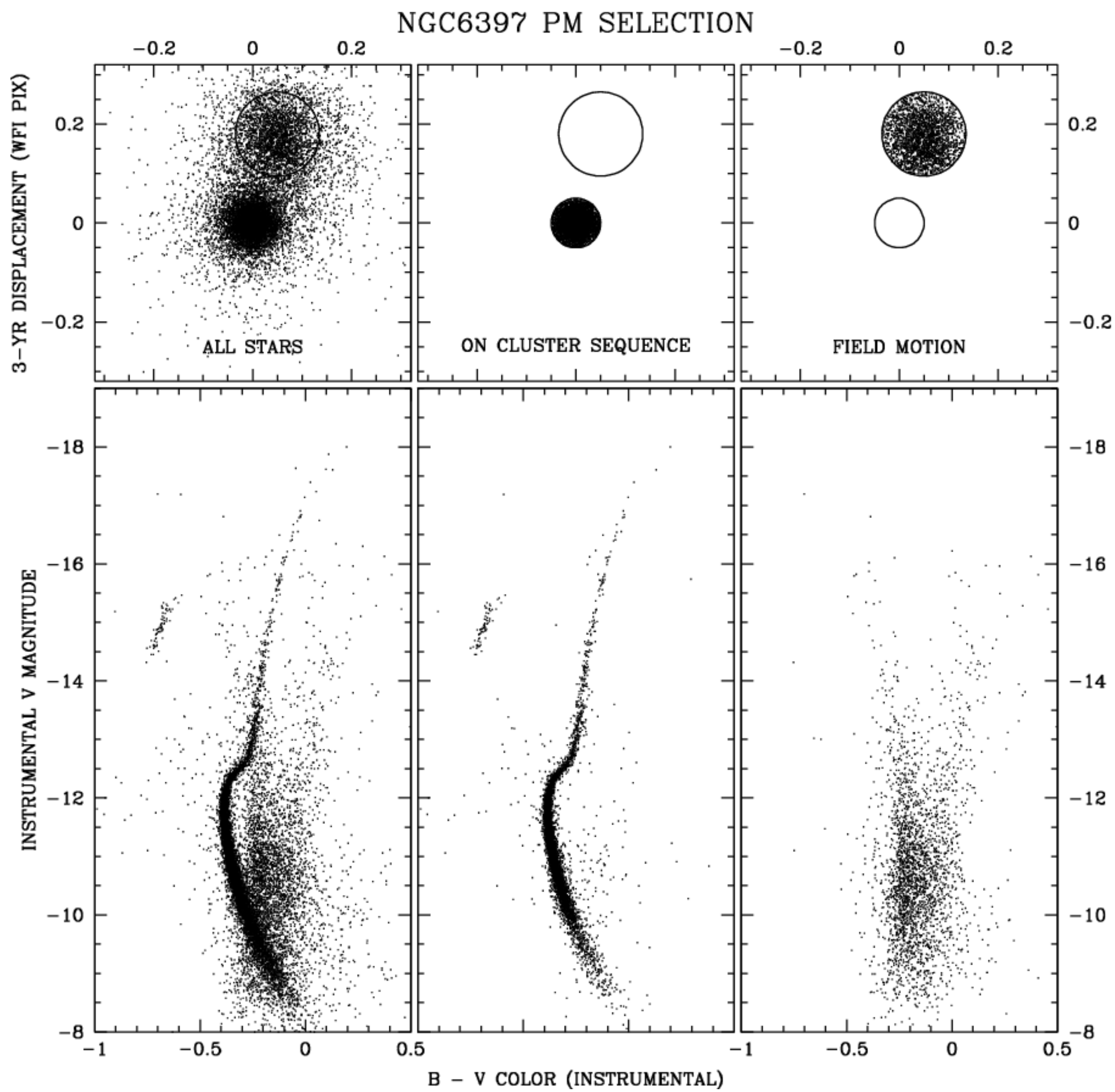


Globular Cluster Proper Motions

Decontamination for studying stellar populations

separating cluster members from field stars
e.g. NGC6397

Andersen+ 06:
“Observations just a few years apart allow decontamination of field objects from members in two globular clusters”



Globular Cluster Proper Motions with MICADO

cluster distances:
at 40kpc, full parallax displacement is 50μas
cluster parallax can be measured directly (wrt background galaxies/QSOs)

cluster structure & evolution:
past & future orbit for GCs can be traced; passages through the disk or near to the Galactic Center will affect GC evolution & structure.

kinematic families:
if GCs belong to several kinematic groups, this would imply that they were created during different events and at different times

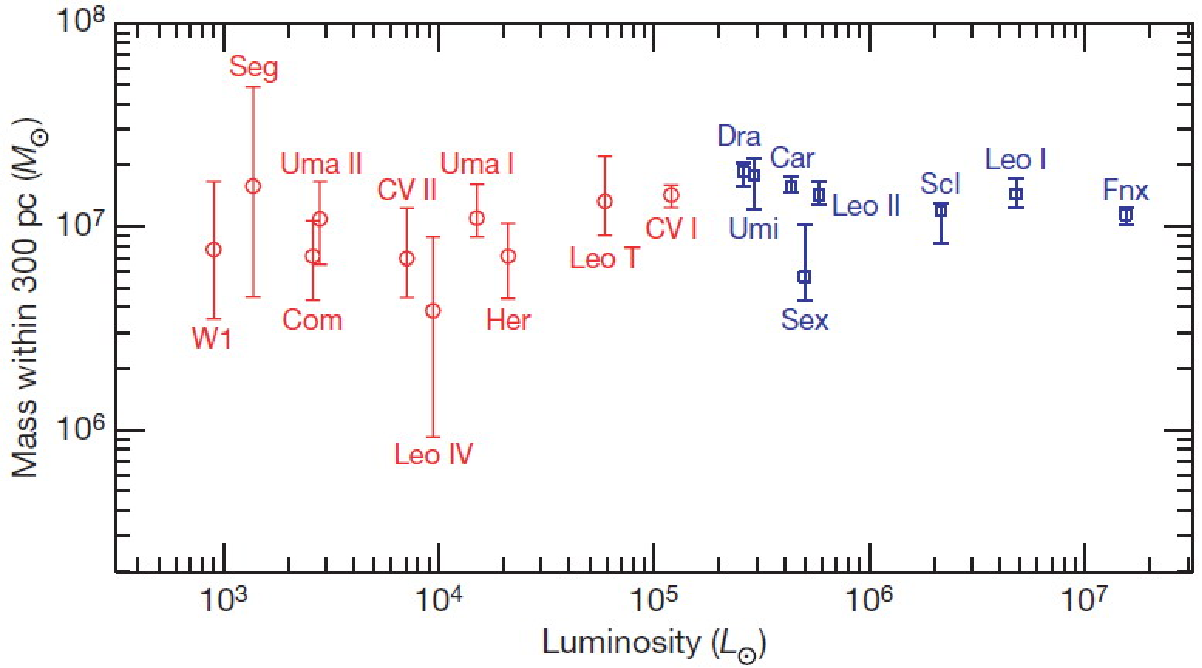
stellar populations:
proper motions provide a clean way of separating cluster members from field stars & interlopers

Dwarf Spheroidal Internal Kinematics

- CDM predicts halos should be clumpy, with cuspy central density profiles;
- Dwarf spheroidal & clump mass functions should be similar;
- if observations do not uphold this, CDM structure formation would need to be modified, e.g. halo disruption by star formation & mass loss, WDM, etc.

Strigari+ 08: constant mass scale over 5 orders of magnitude in luminosity

- ➢ faintest dSph are the most dark matter dominated galaxies;
- ➢ is the lack of halos $<10^7 M_{sun}$ within 300pc due to star formation feedback or suppression, or a lower limit to halo mass (dark matter candidates)?



Dwarf Spheroidal Internal Kinematics with MICADO

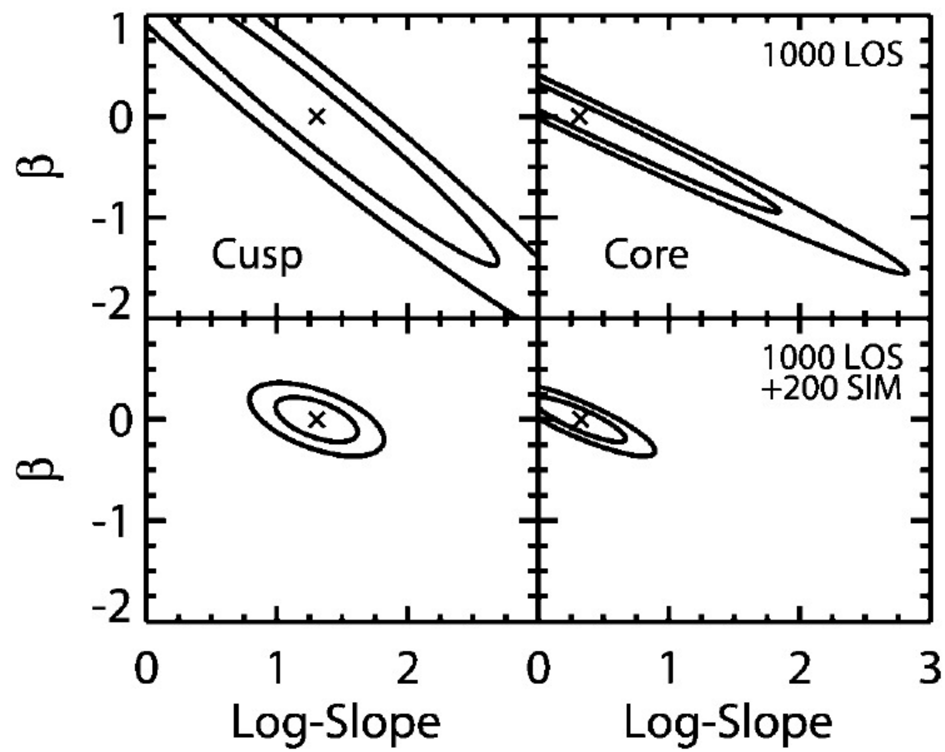
need to measure mass function of clumps,
density profiles (core vs cuspy), &
ansiotropy

- l.o.s. motions alone are not sufficient
- need proper motions to measure radial/tangential anisotropy & break degeneracy with mass scaling

Strigari+ 07:
5× accuracy by adding proper motions of 200 stars to 5km/s accuracy

this is possible with MICADO:

- ➢ RGB stars in dSPh have K~18-19
- ➢ one can achieve 5km/s out to 100kpc within a few years



Precision Astrometry with MICADO

- MICADO is the adaptive optics imaging camera for the EELT
- sensitivity is comparable to JWST and resolution is 6 times better
- astrometric accuracy will be better than 50μas across the 1’ field
- numerous science cases can make use of this capability, including:
  - black hole masses & M_{BH}-σ_* relation
  - formation & evolution of the Galaxy
  - dark matter & structure formation