MICADO and MAORY:
Science with MCAO on the E-ELT

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on behalf of

MICADO

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NOVA Leiden, Gronigen, Dwingeloo (ASTRON), Netherlands
LESIA Paris Observatory, France

MAORY

INAF + University of Bologna
ONERA
ESO

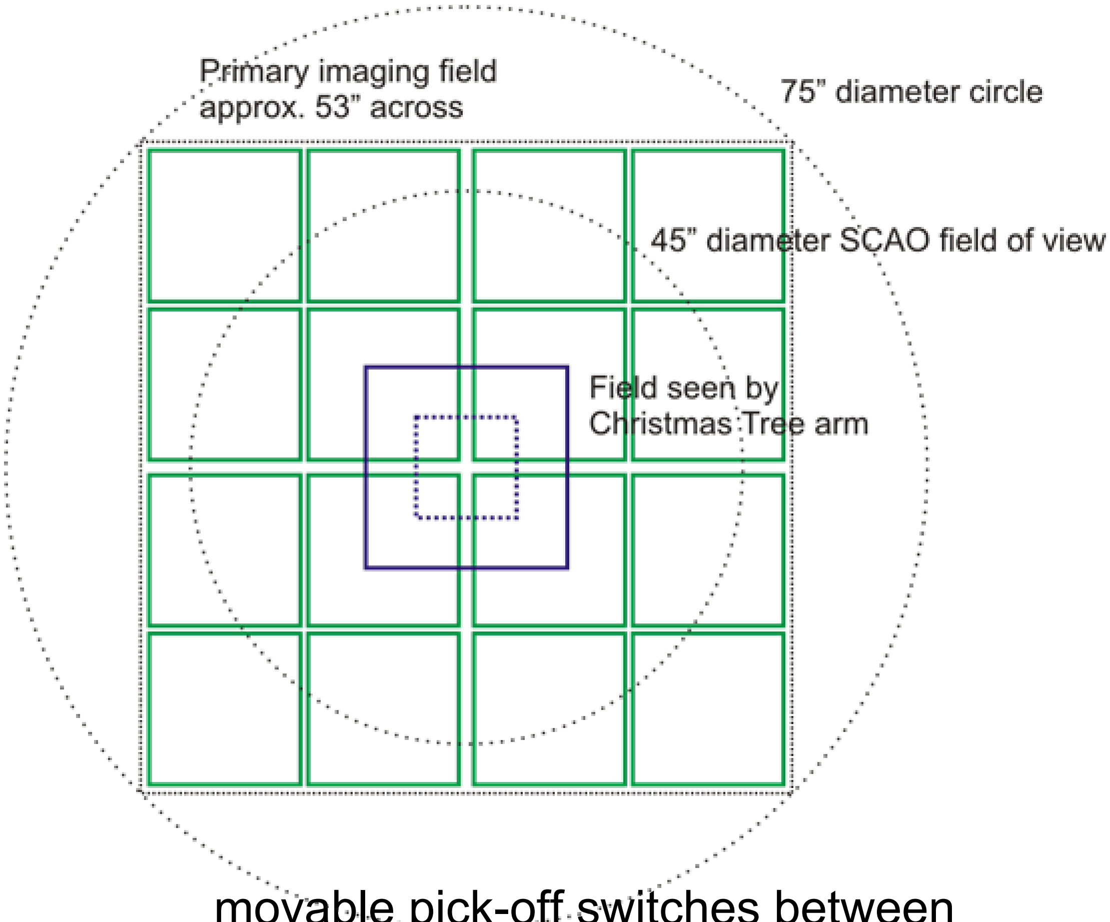
MICADO: Multi-AO Imaging Camera for Deep Observations

Primary Imaging Field

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

Xmas Tree Arm

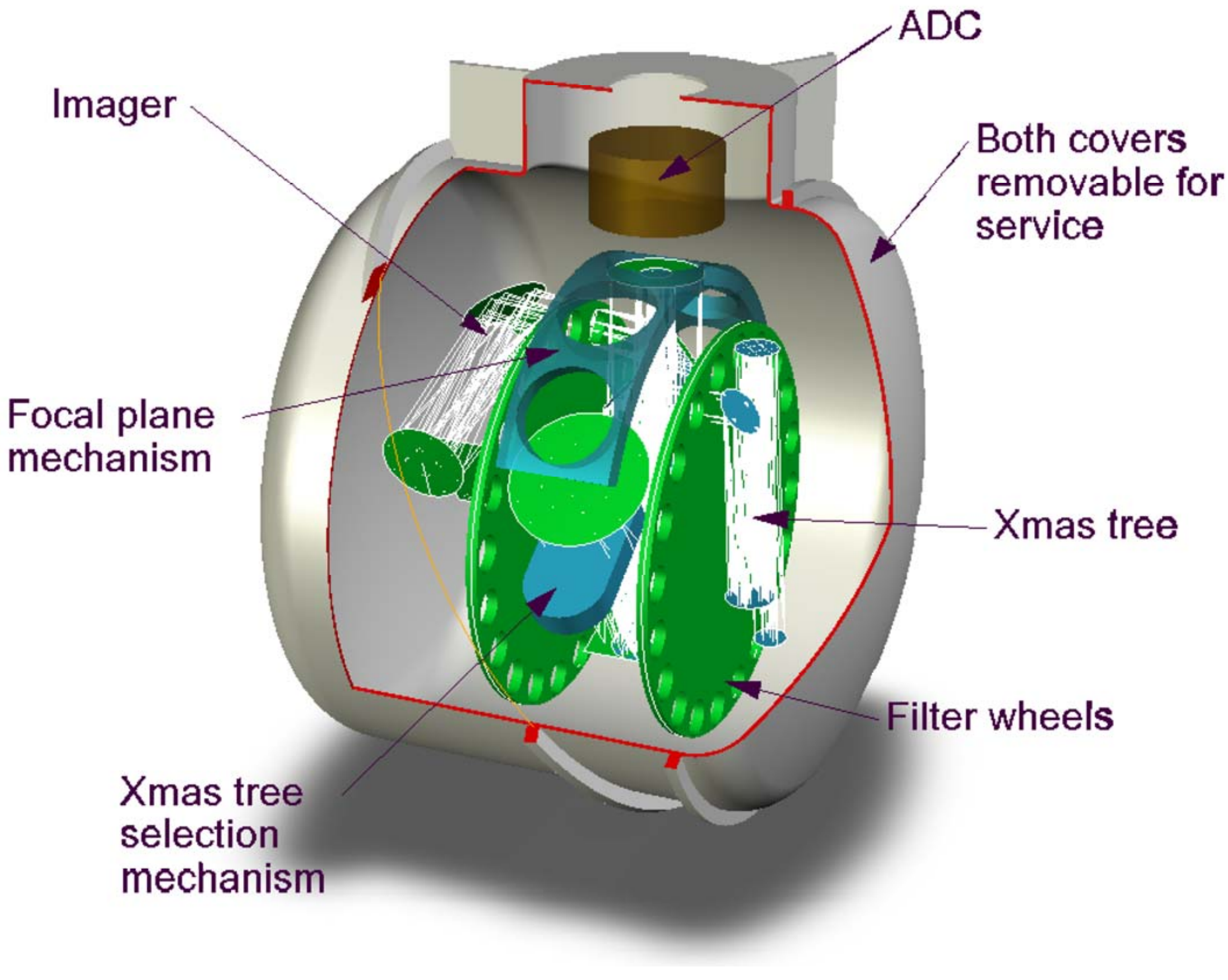
- 1.5mas & 4mas pixels
- imaging & spectroscopy
- ~20 filter slots
- [polarimetry]
- [tunable filter (dual imager)]
- [high time resolution]



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



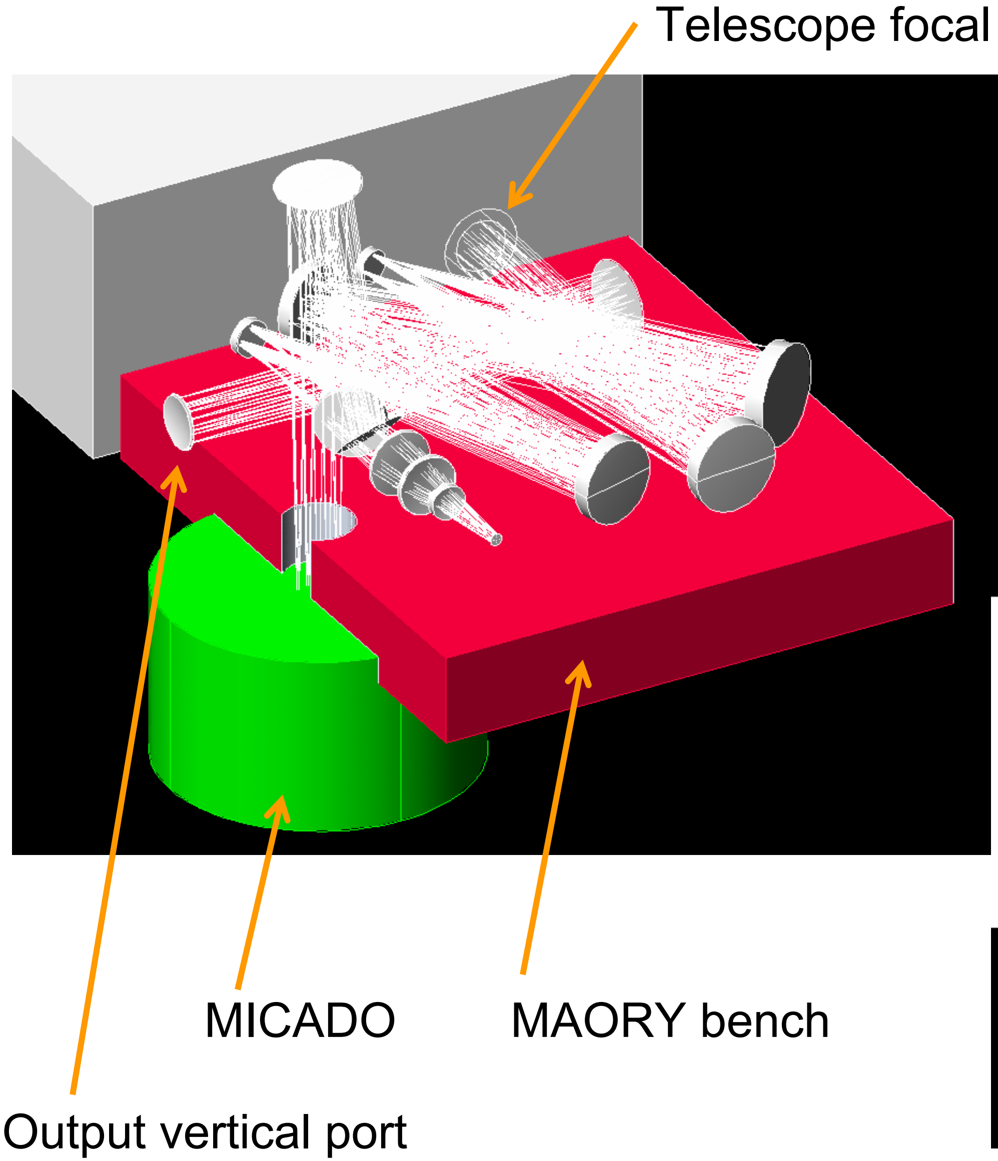
MAORY: Multi-conjugate Adaptive Optics RelaY

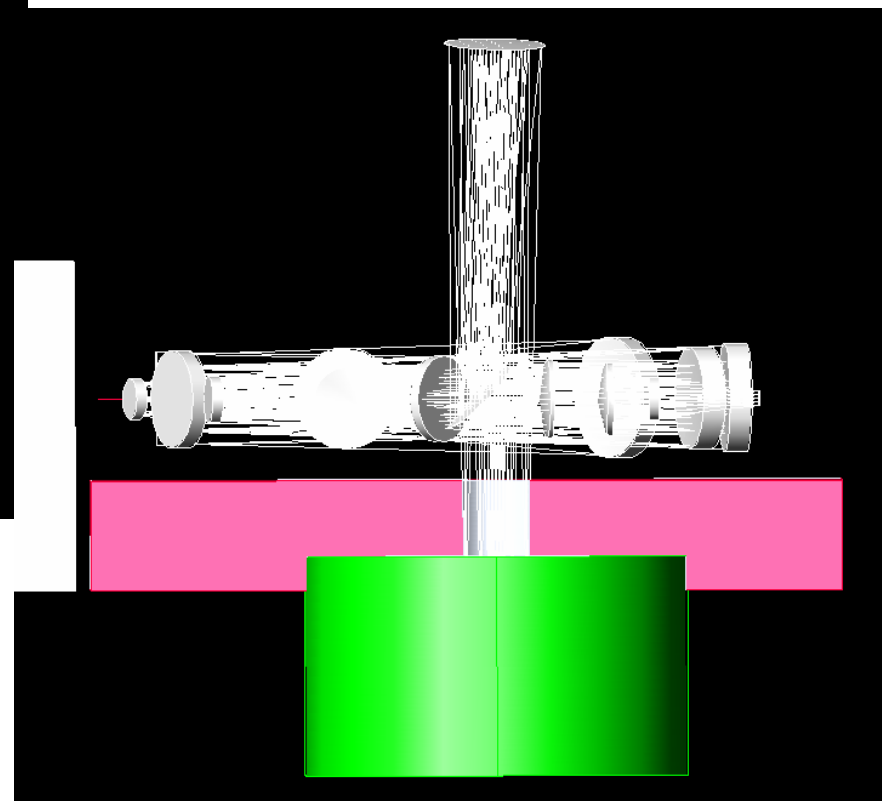
http://www.bo.astro.it/~maory

- MCAO module overview
  - Corrected field of view
    - Central 53"x53" unvignetted for MICADO
    - Outer field Ø=2.6' for Natural Guide Star search and other instruments
  - Wavefront sensing
    - 6 Sodium Laser Guide Stars for high-order wavefront measurement
    - 3 Natural Guide Stars for low-order and windshake measurement
    - 1 Natural Guide Star used as high-order reference WFS
  - Wavefront correction
    - Telescope M4 + M5
    - 2 post-focal deformable mirrors
    - Simplified option with 1 post-focal DM and reduced outer field under study

MAORY opto-mechanical layout

- background <50% sky + telescope: cooling not needed





Front view

MAORY performance

Nominal average performance over MICADO field of view (53"×53")

Seeing @0.5 μm	Strehl Ratio %				
	K_s (2.16 μm)	H (1.65 μm)	J (1.215 μm)	Y (1.021 μm)	I (0.9 μm)
0.8"	53.1	33.8	13.6	6.0	2.7
0.6"	60.7	42.5	20.7	10.7	5.7

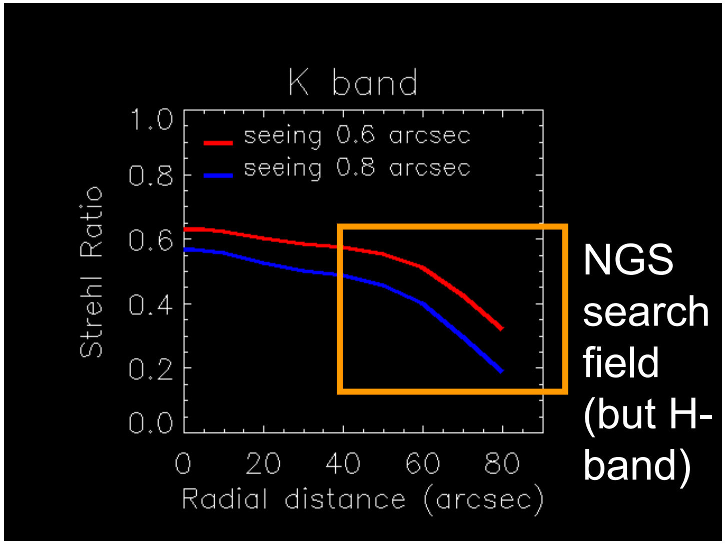
Sky coverage at North Galactic Pole

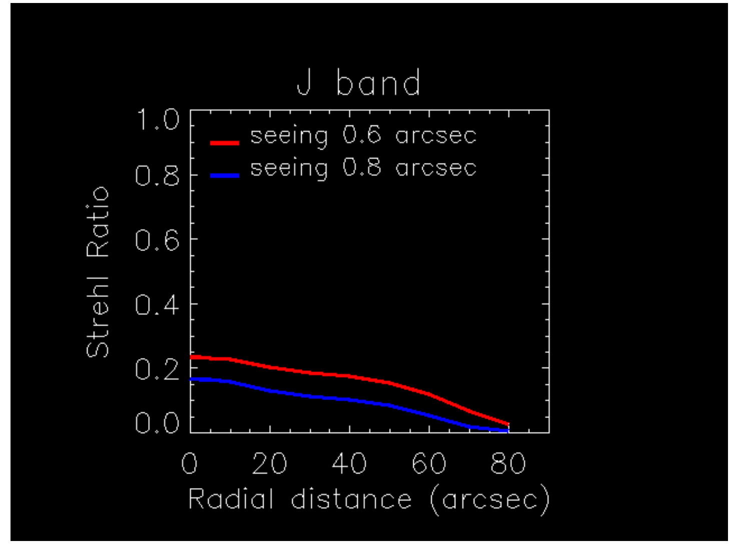
3 NGS (2 Tip-Tilt, 1 Tip-Tilt & Focus) measured at H band, NGS search field Ø = 2.6'

Seeing @0.5 μm	Minimum field-averaged Strehl Ratio					Probability
	K_s (2.16 μm)	H (1.65 μm)	J (1.215 μm)	Y (1.021 μm)	I (0.9 μm)	
0.8"	53.1	33.8	13.6	6.0	2.7	26%
	47.8	28.2	9.7	3.7	1.5	38%
	41.2	21.9	6.1	1.9	0.6	48%
0.6"	60.7	42.5	20.7	10.7	5.7	33%
	54.6	35.4	14.8	6.6	3.1	48%
	47.1	27.5	9.3	3.4	1.3	57%

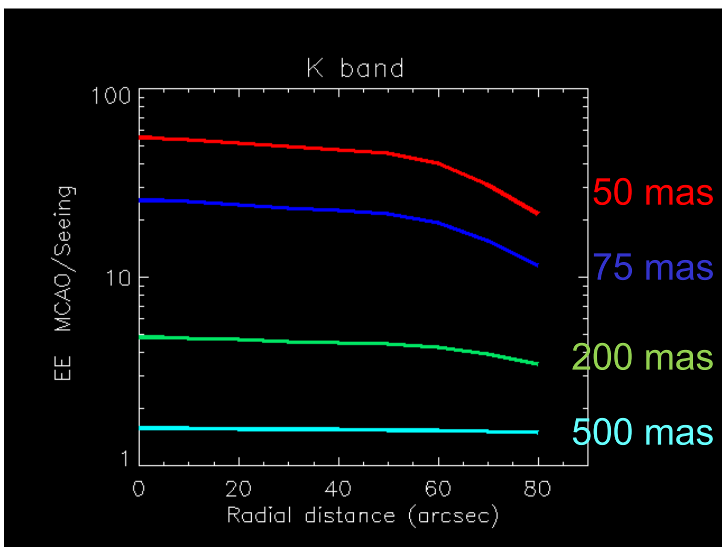
MAORY performance

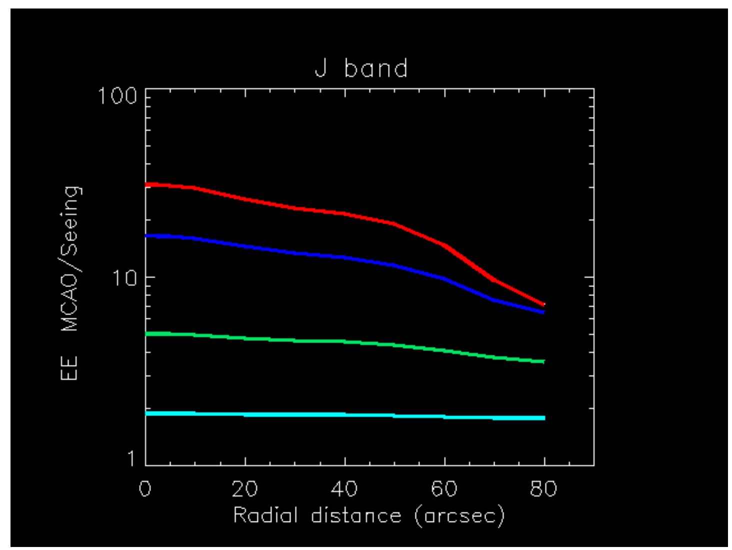
strehl ratio





encircled energy





Approximate EE values. Seeing = 0.8".
Seeing EE from http://www.eso.org/observing/etc/doc/elt/etc_spec_model.pdf

MICADO-MAORY 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

Science:

- star formation history via resolved stellar populations, out to Virgo cluster
- structure of high-z galaxies on 100pc scales: galaxy formation & evolution
- environment of galaxies & QSOs at high-z
- nuclei of nearby galaxies (stellar cusps, star formation, black holes, …)

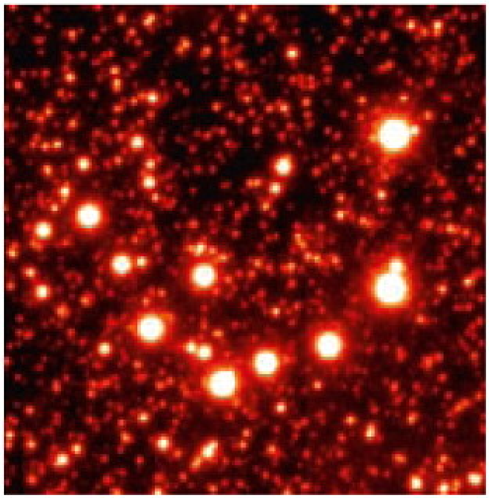
Crowded Field Photometry: MICADO-MAORY vs JWST

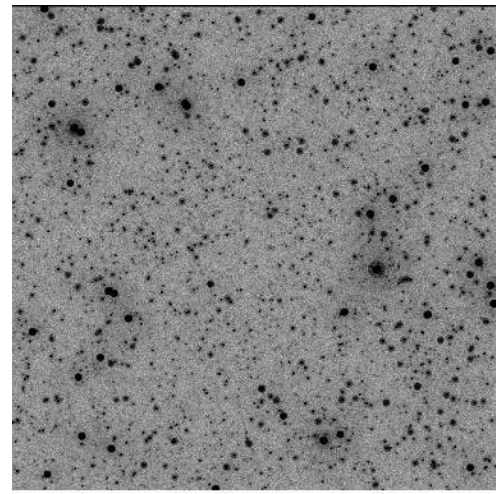
Resolution gives an effective sensitivity gain – cf. 3mag for MAD vs ISAAC

Omega-Cen

5-hr K-band simulated exposure

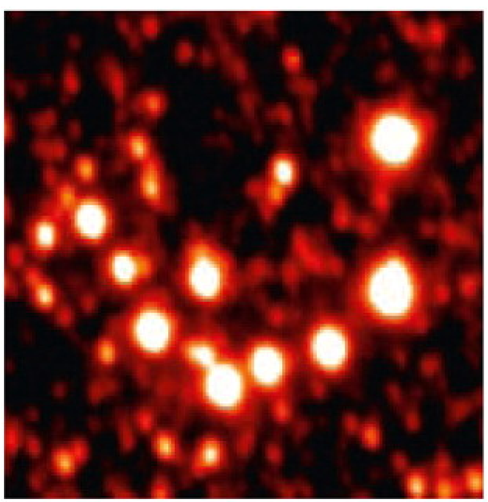
MAD

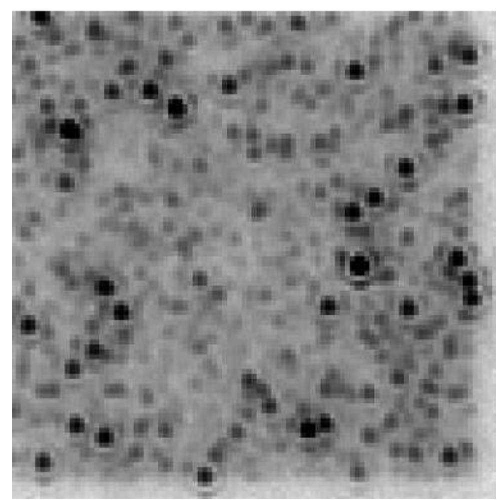




MICADO

ISAAC





JWST

MICADO-MAORY 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, 10μas/yr after a few years
• multiple measurements leads to higher precision
• many systematic effects to correct but necessary SW is available
• bring precision astrometry into the mainstream & open a new field

Science:
• stellar motions to within light hours of the Galaxy's black hole
• intermediate mass black holes
• globular cluster motions probe the formation & evolution of the Galaxy
• dwarf spheroidal motions test dark matter & structure formation

MICADO-MAORY 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

Science:
• Galactic Centre: stellar types, & 3D orbits from velocities
• velocities of stars in nearby galaxies: M_{BH}, extended mass distributions, …
• absorption lines: ages, metallicites of first red sequence galaxies at z=2-3
• spectra of first supernovae at z=1-6
• emission lines: redshifts, velocities, metallcities of starburst galaxies at z=4-6

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

Science with MICADO & Requirements on AO

a few examples to illustrate what is possible

- ***Astrometry***
  - Galactic Centre & supermassive black holes
  - Globular Clusters:
    - intermediate mass black holes
    - proper motions
- ***PSF & Photometry***
  - QSO hosts
  - resolved stellar populations

Astrometry - systematic & statistical effects

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 warping → coordinate transform
Atmosphere	
Achromatic differential refraction	low order warping → coordinate transform
Chromatic differential refraction	tunable ADC (10-20µas) or multi-colours
AO	
Differential Tilt Jitter	270µas/ $T^{½}$ [Ellerbroek 07] → ‘integrate it out’ statistically [cf Cameron+ 08]
NGS instrumental effects	low order warping? → coordinate transform
NGS atmospheric effects	low order warping? → 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

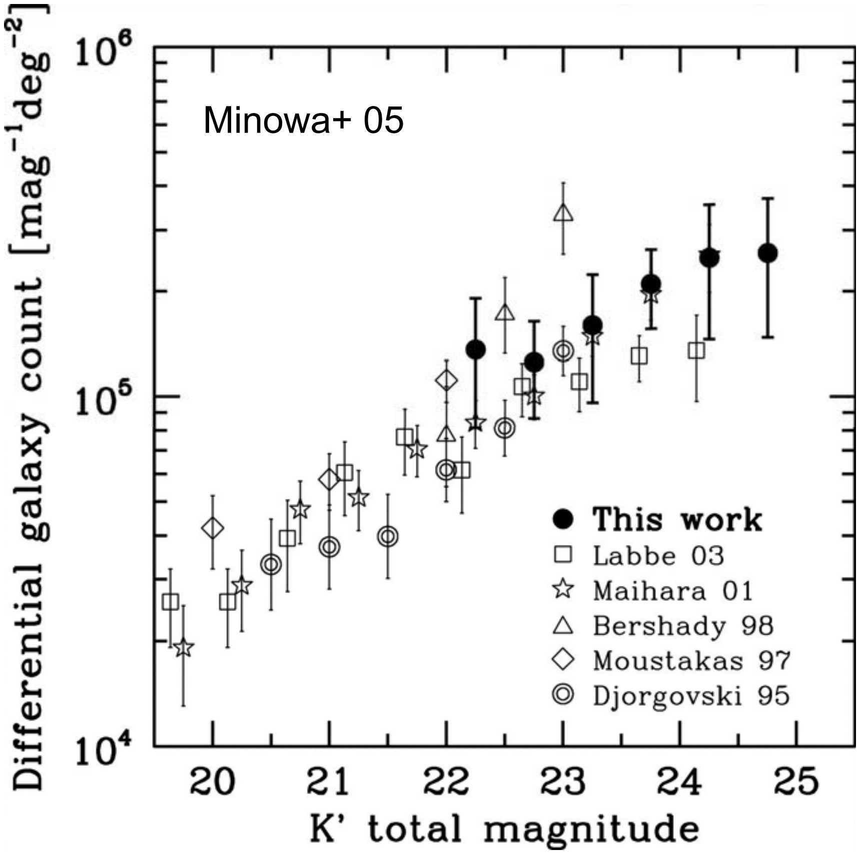
single epoch

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

inter epoch
(for absolute reference because stars move)

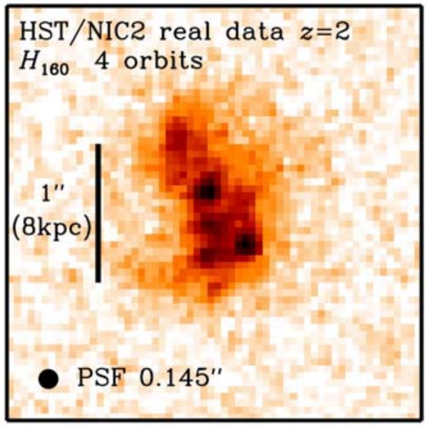
- high-z galaxies — polynomial fit on deep combined single epoch data sets to remove low order effects

High-z galaxies as Astrometric References

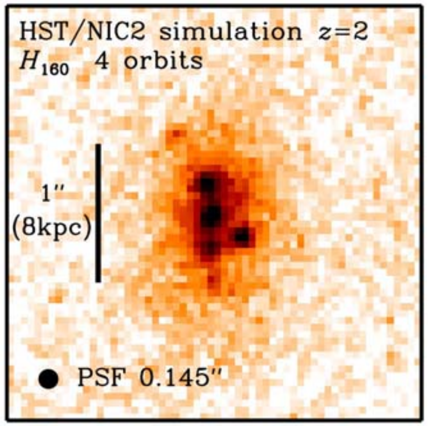


- ~25 galaxies to K<21.5 in MICADO field
- each galaxy has many clumps
- tests yield 60-80μas precision for a 10hr integration on a K=21.4 simulated galaxy
- with several galaxies, precision improves

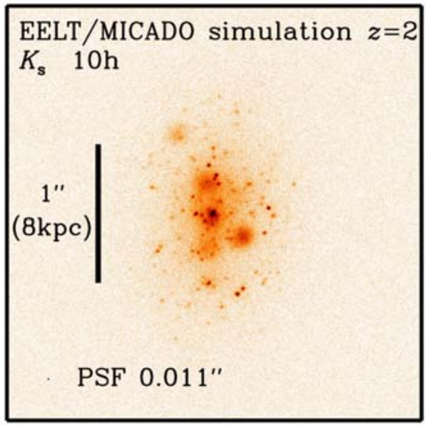
HST image of a z=2 galaxy



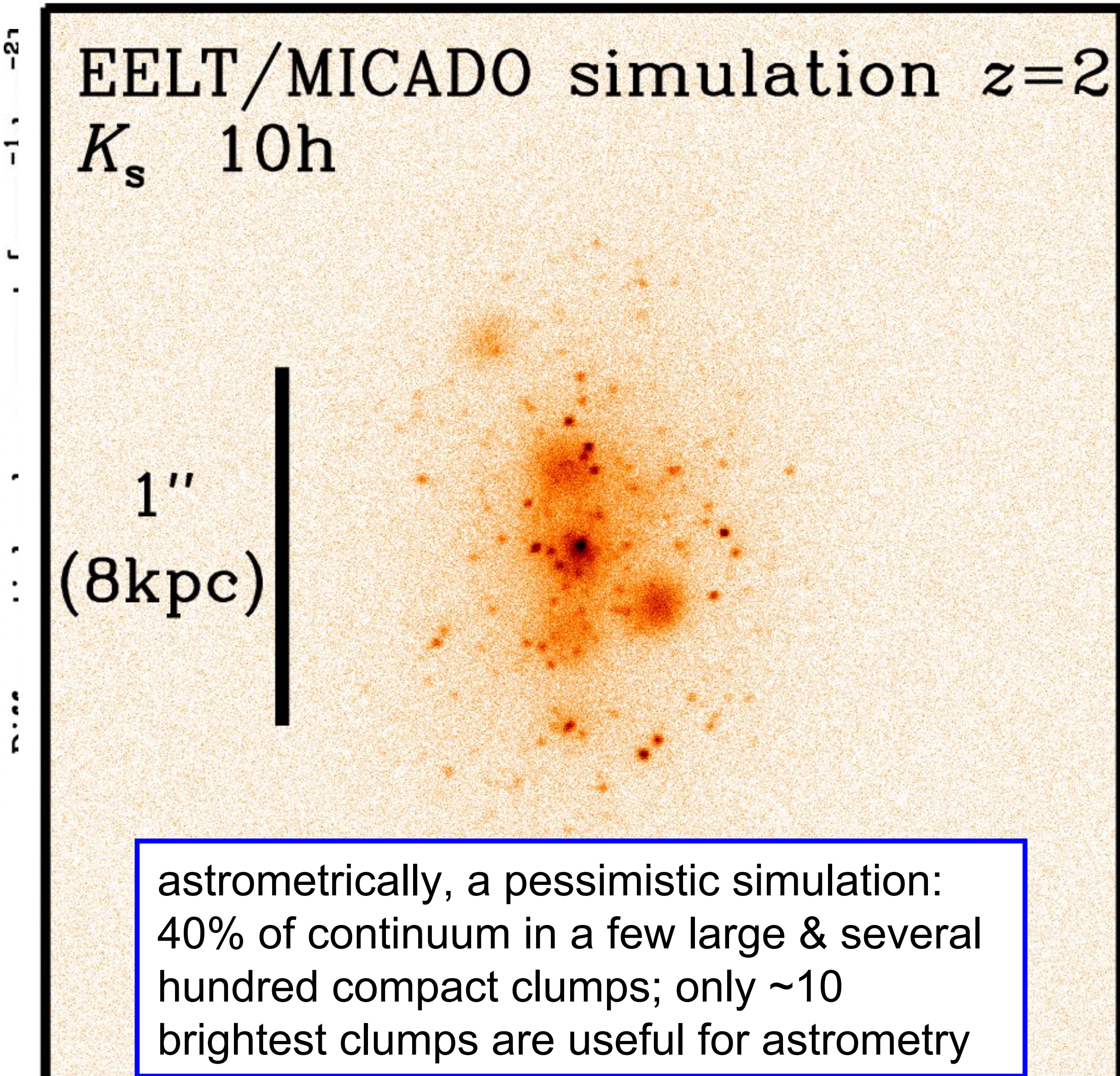
simulation at HST resolution

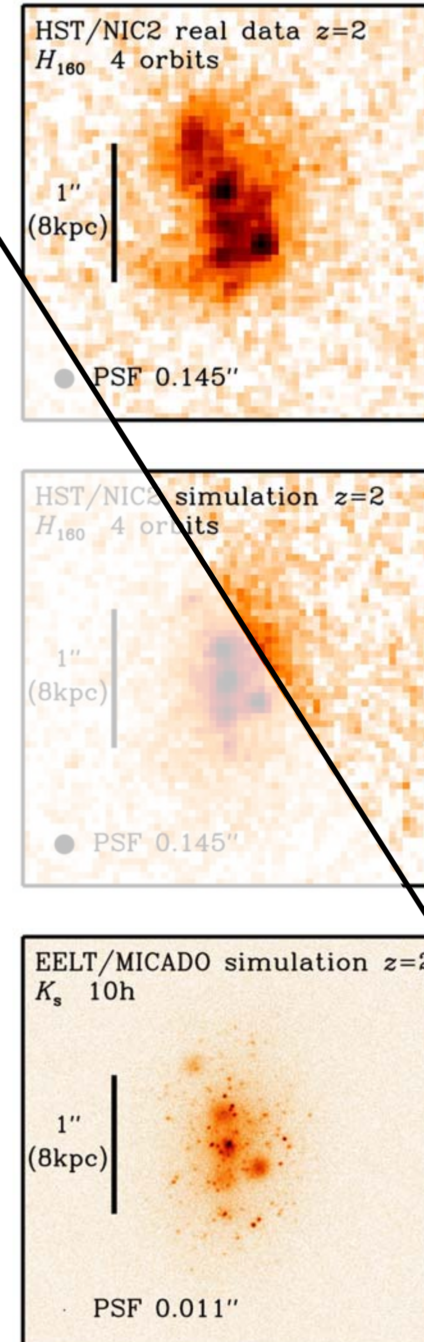


MICADO's view



High-z galaxies as Astrometric References

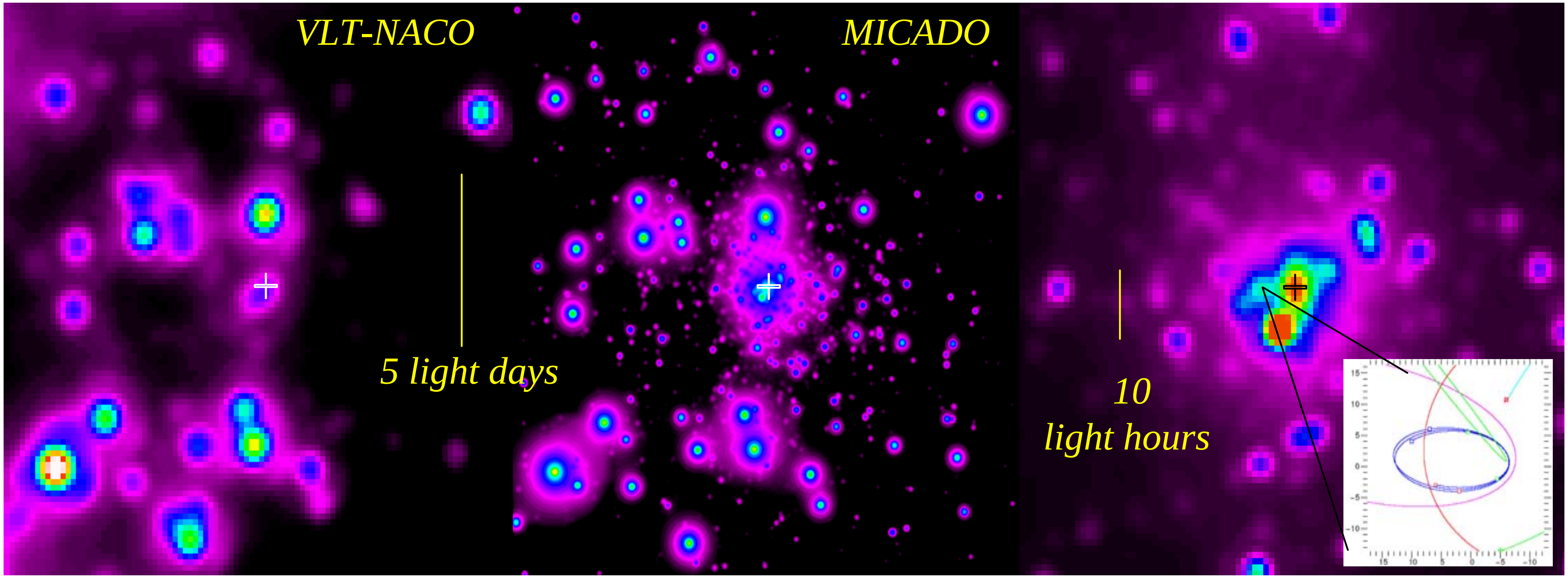




- with several galaxies, precision improves

Galactic Center

- A unique laboratory for exploring strong gravity around the closest massive black hole
- A crucial guide for: - accretion onto black holes
  - co-evolution of dense star clusters and AGN
- also applicable to M31, Cen A, …



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

A simulation showing what one can expect to see with MICADO

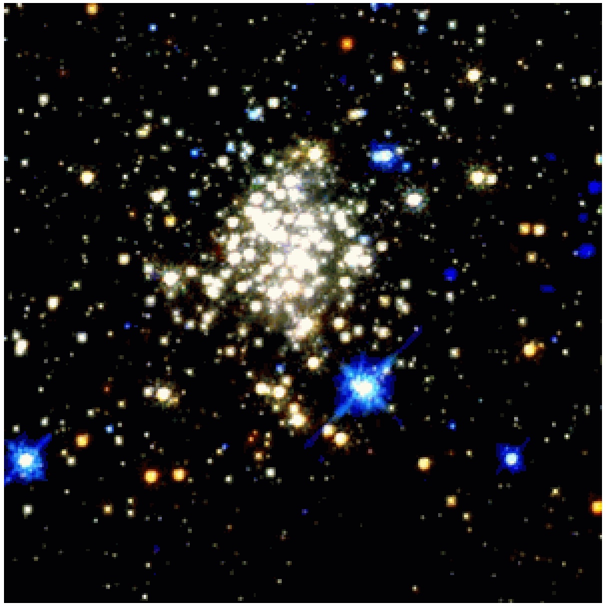
The central 0.1” will reveal many stars in close, fast orbits around the central black hole with measurable precession

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

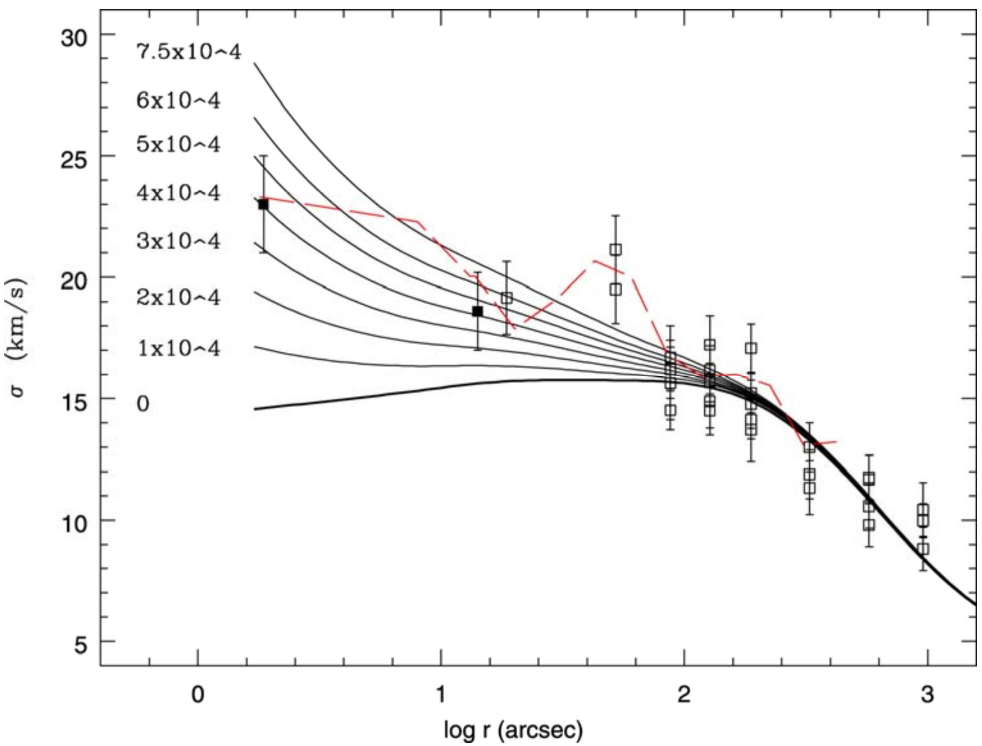
M_{BH}~$1300M_{sun}$? (Maillard et al. 04)

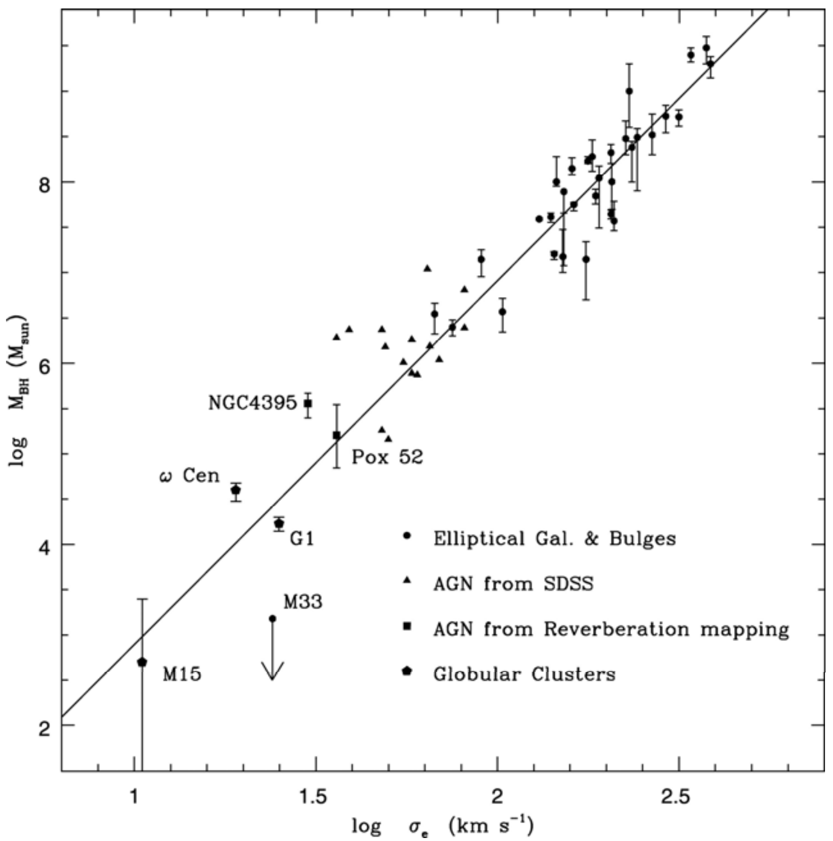
Omega Cen: M_{BH}~$10000M_{sun}$?

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 $\sigma_t/\sigma_r<0.67$





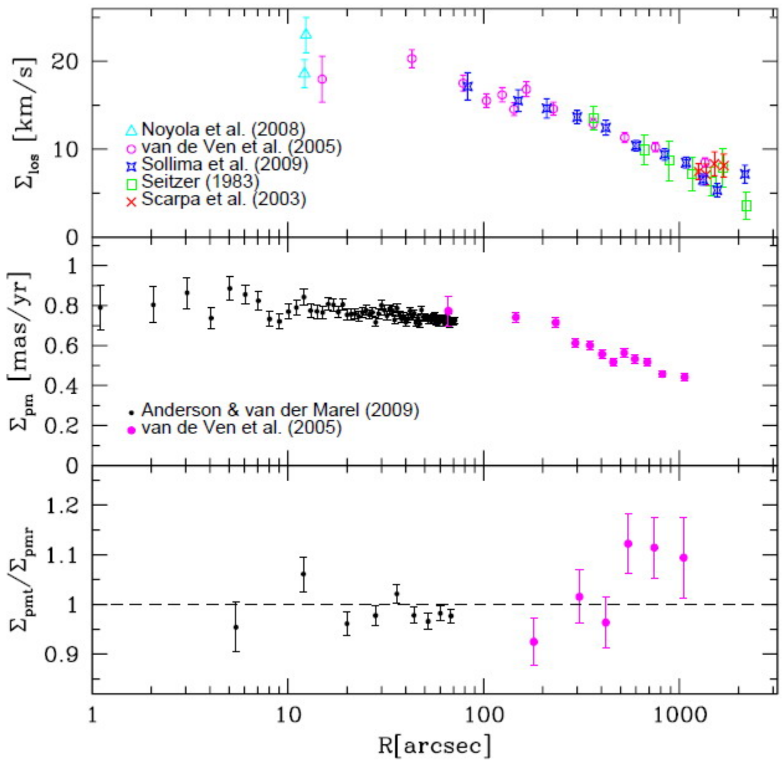
Omega Cen: does it have a black hole?

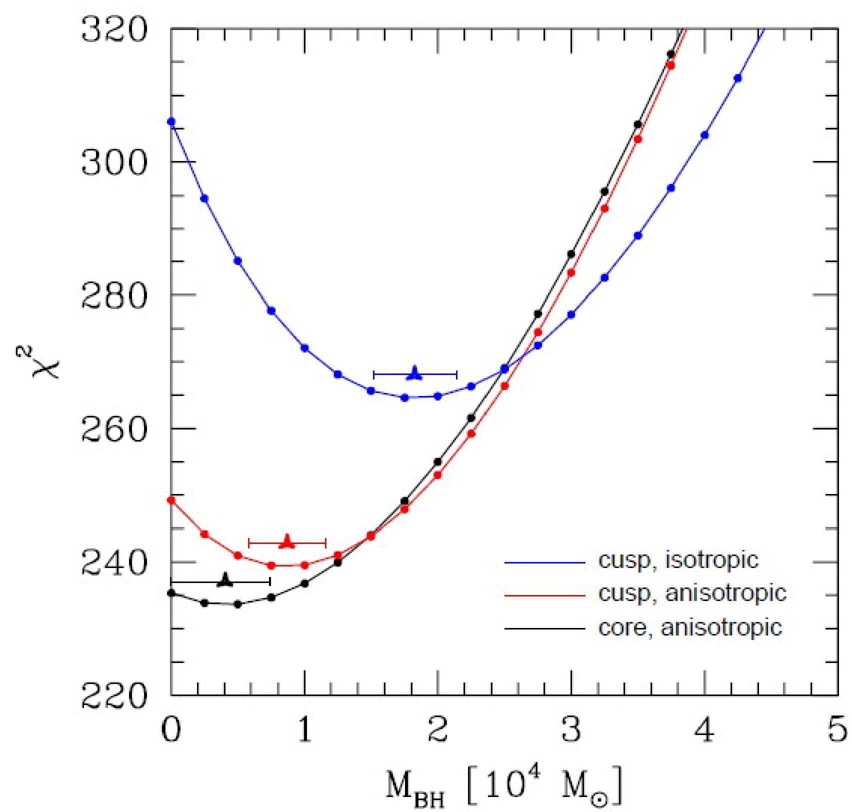
Andersen+ 09, van der Marel+ 09

- 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×$10^3 M_{sun}$

➢ 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

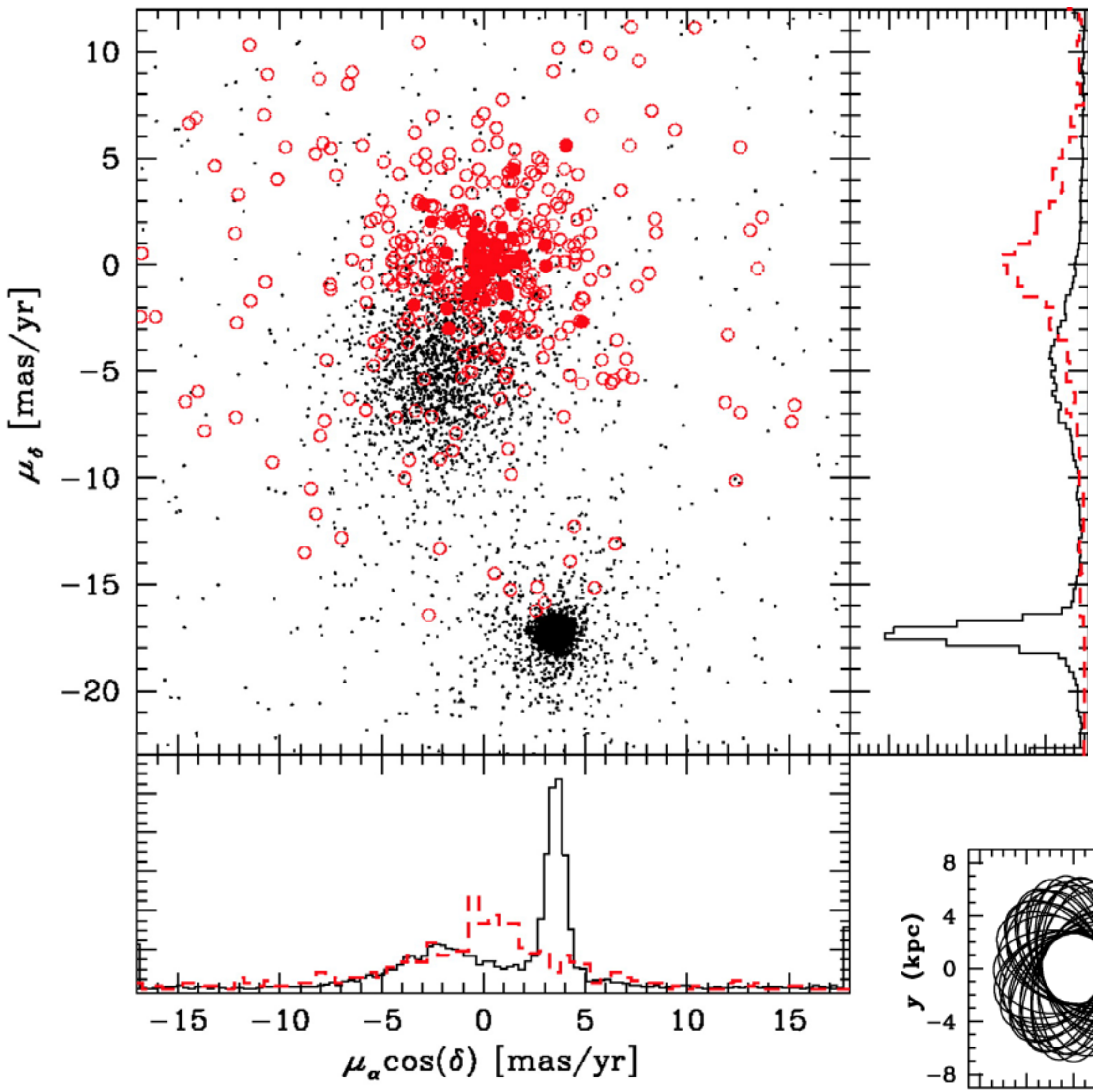
in a few years we can constrain masses of BHs at centres of GCs

- ➢ 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

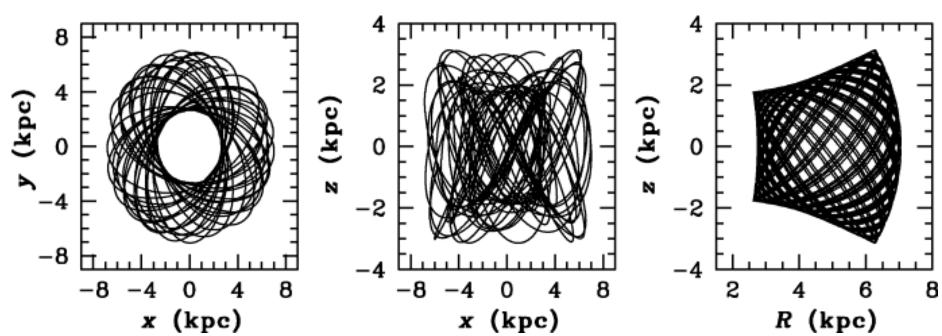
black: field stars & cluster members

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

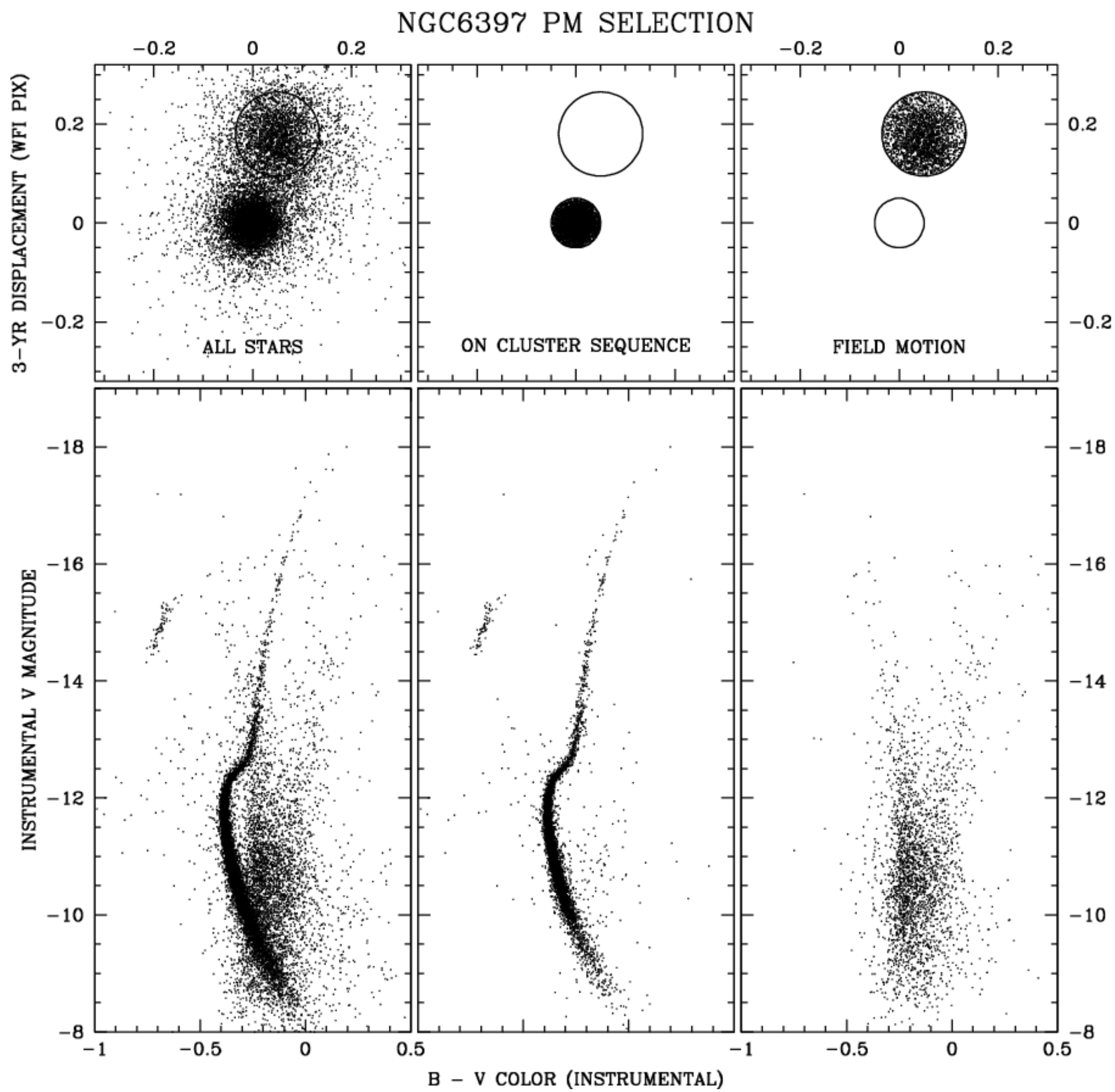


Globular Cluster Proper Motions

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.

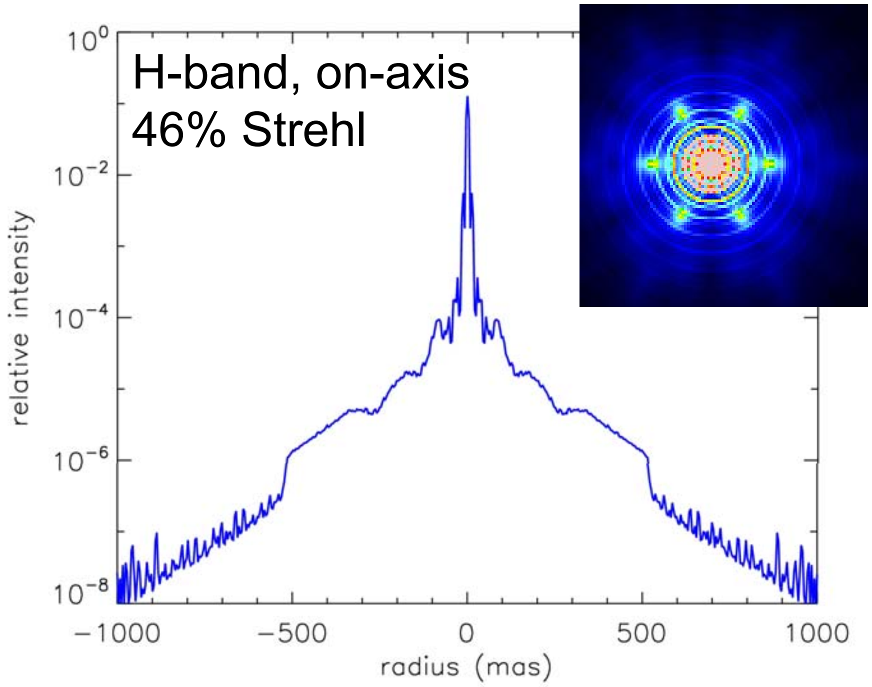
kinematic families:
if GCs belong to several kinematic groups, this would imply that they were created during different events and at different times

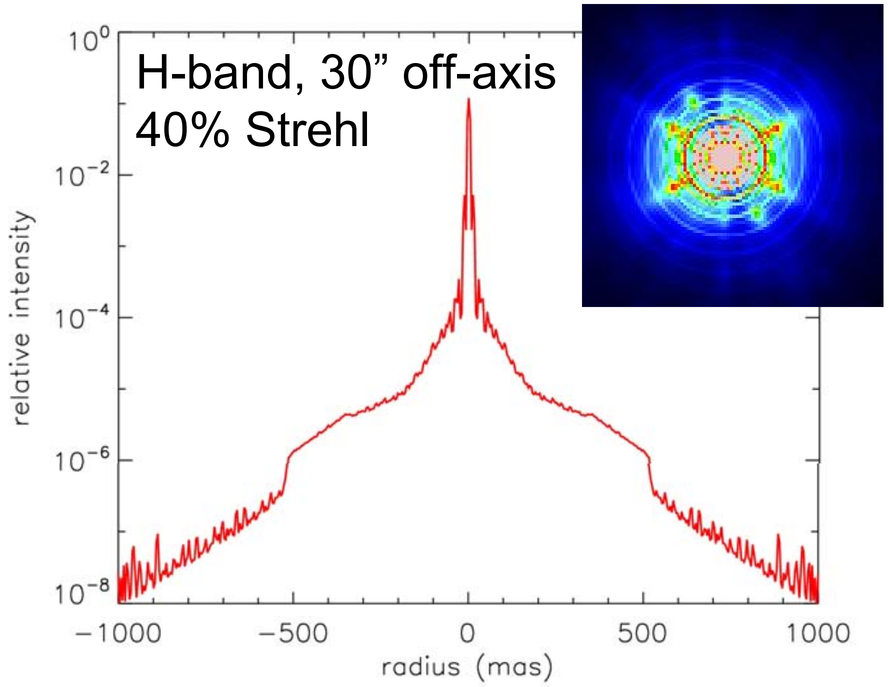
stellar populations:
proper motions provide a clean way of separating cluster members from field stars & interlopers

Photometry & the MAORY PSF

PSF variations much less

H-band
- 50% of flux within radius ~10mas
- photometry to 0.03mag (3%): profile fitting
- profile has to be accurate to large radius

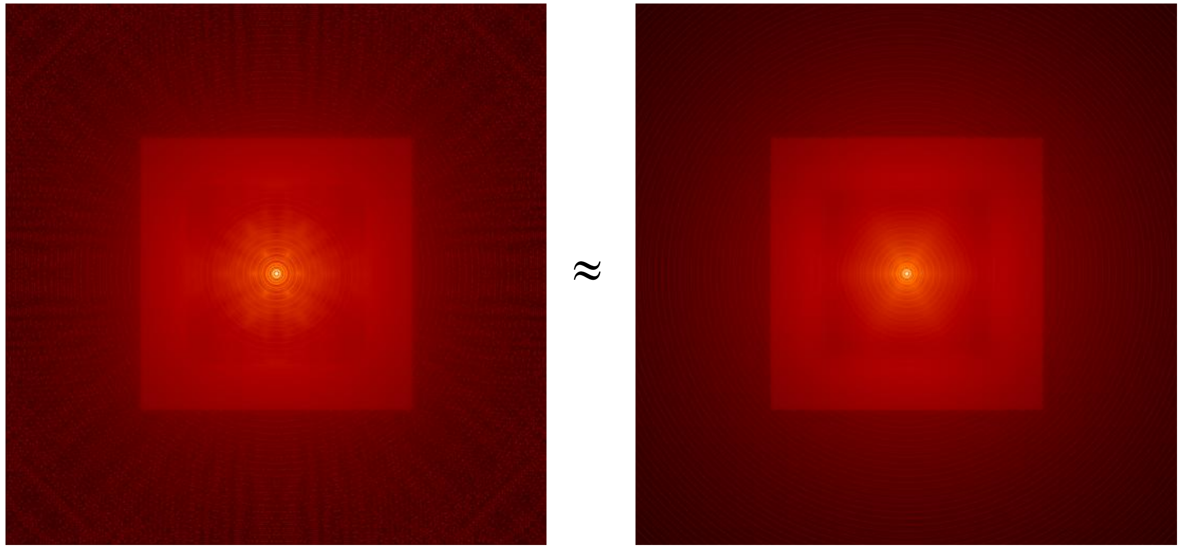




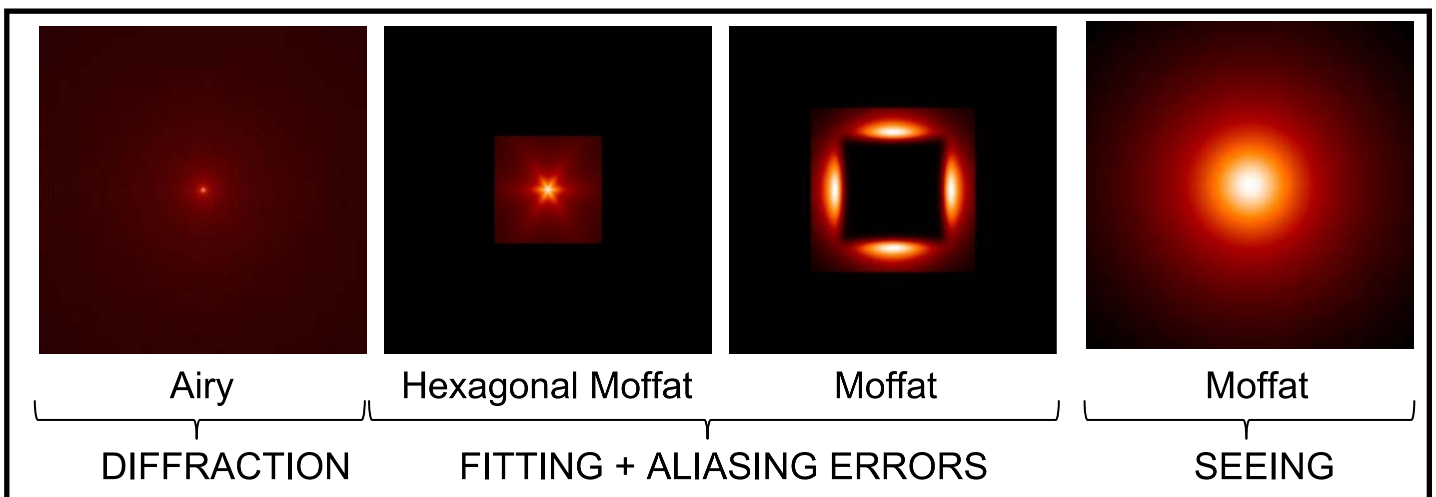
MAORY PSF

Simulated PSF **PSF model**

Strehl Ratio ≈ 0.6
Image size = 2.7"

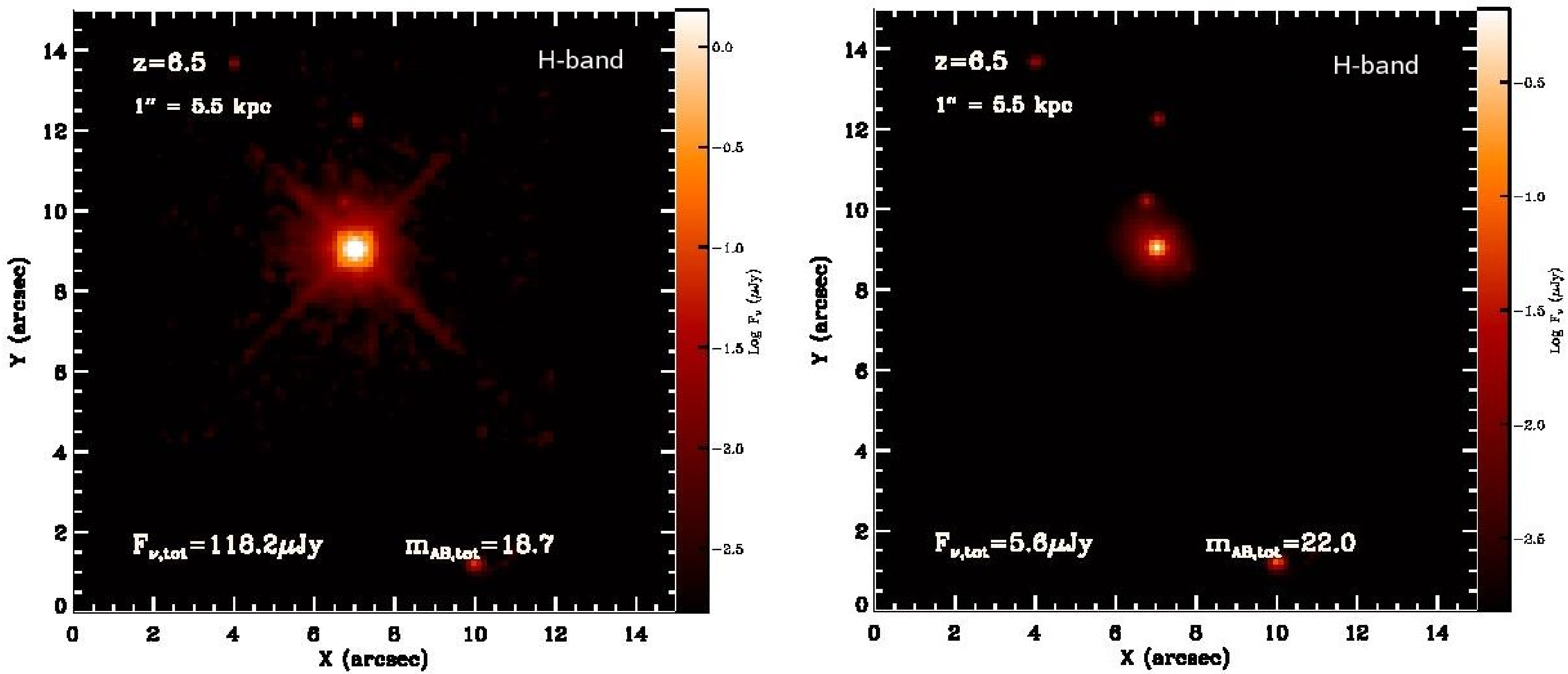


Model components



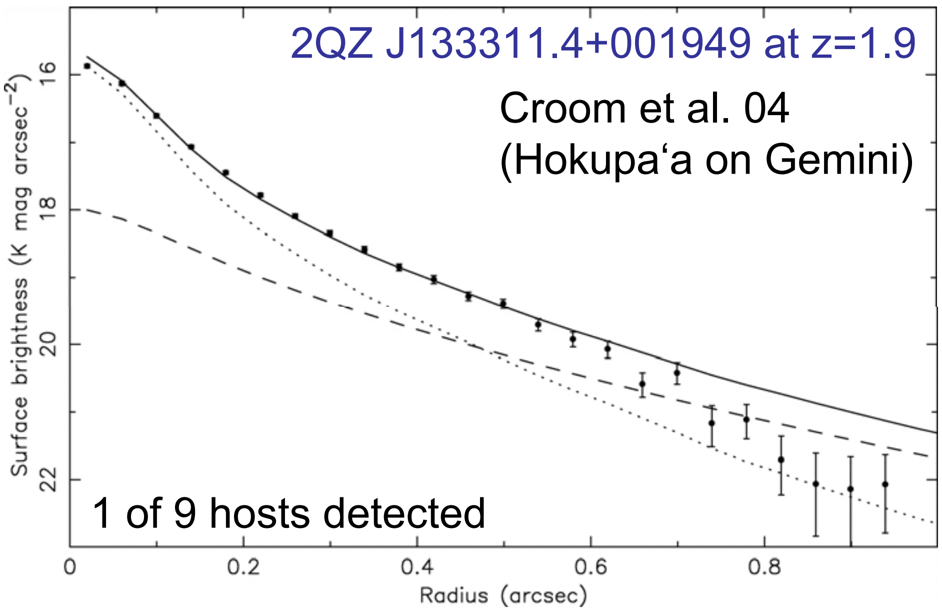
QSO hosts

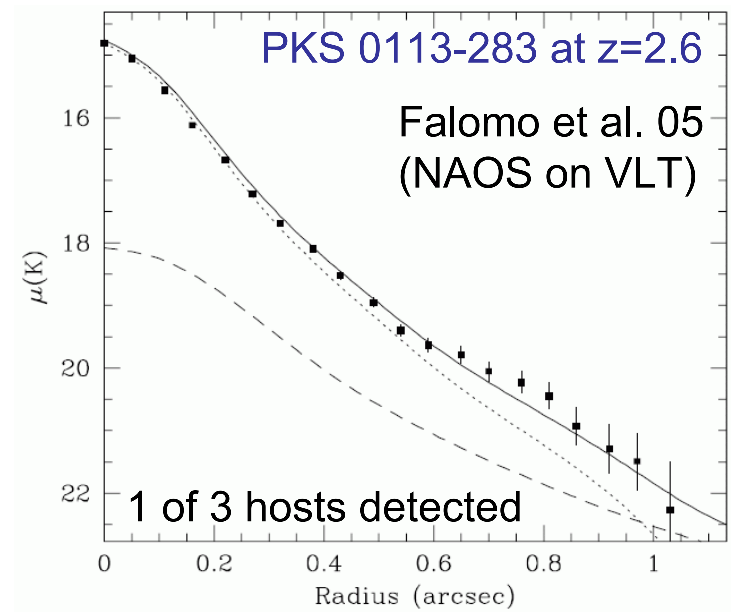
- Black hole – bulge mass relation @z=3, 4
- Luminosities, colours, structure of active galaxies @ 3<z<7
  - Luminosity function of host galaxies over cosmic time
  - masses/SF, trace co-eval BH and galaxy evolution
  - drivers of AGN activity, trace galaxy formation in DM density peaks

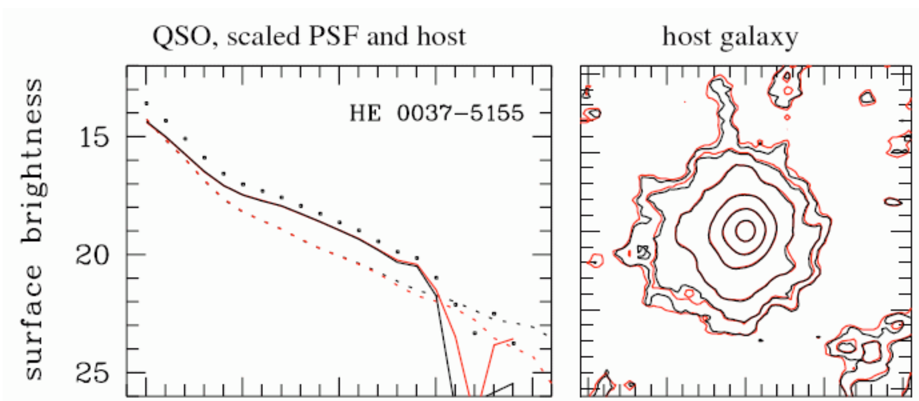


Yuexing Li: sim QSO+host @ z=6.5 (priv. com.)

Detecting QSO hosts







HE 0037-5155 at z=2.2

Kuhlbrodt et al. 05 (ADONIS on ESO 3.6m)

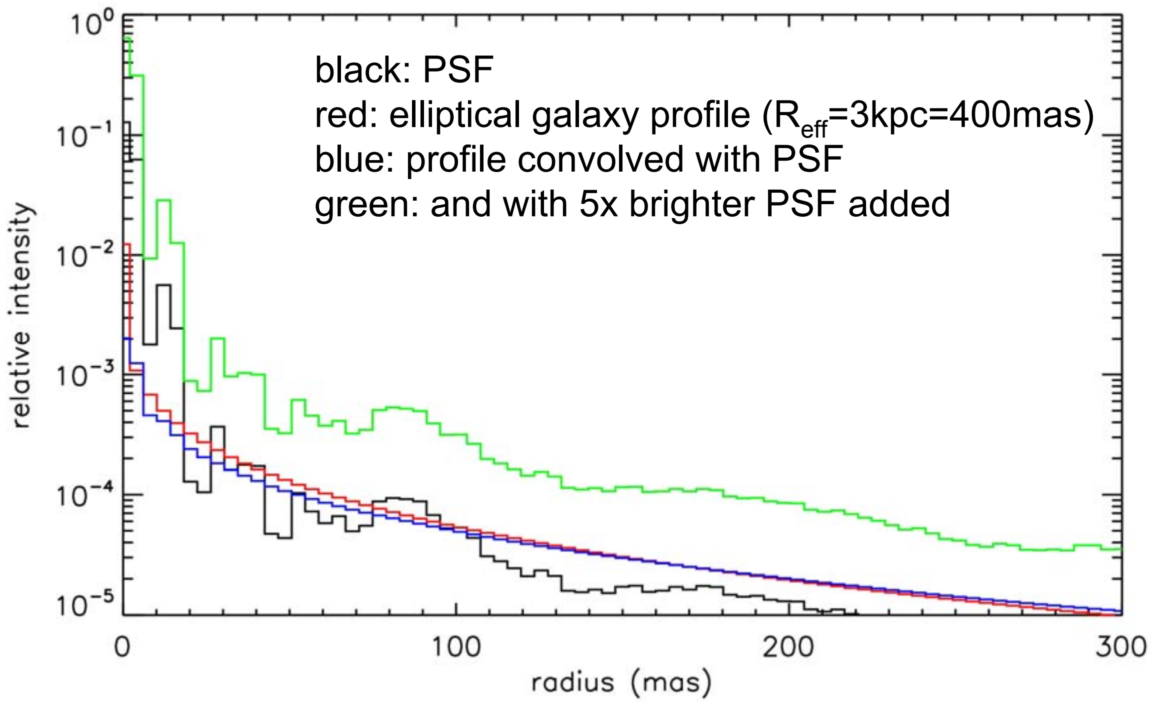
3 of 3 hosts detected: rather luminous due to recent star formation

Detecting QSO hosts with MICADO

MAORY PSF & elliptical galaxy profile

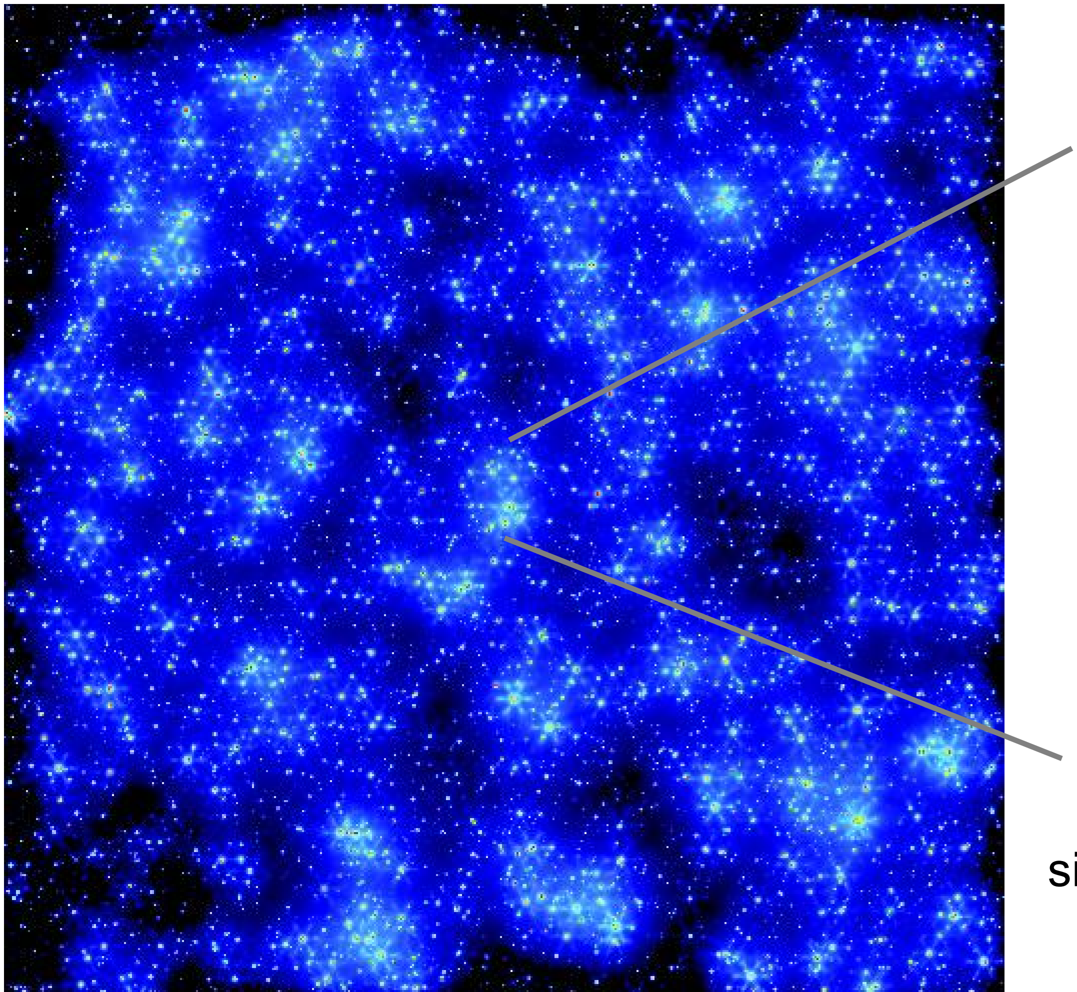
Strong requirement on accurate knowledge of PSF (Strehl & shape)

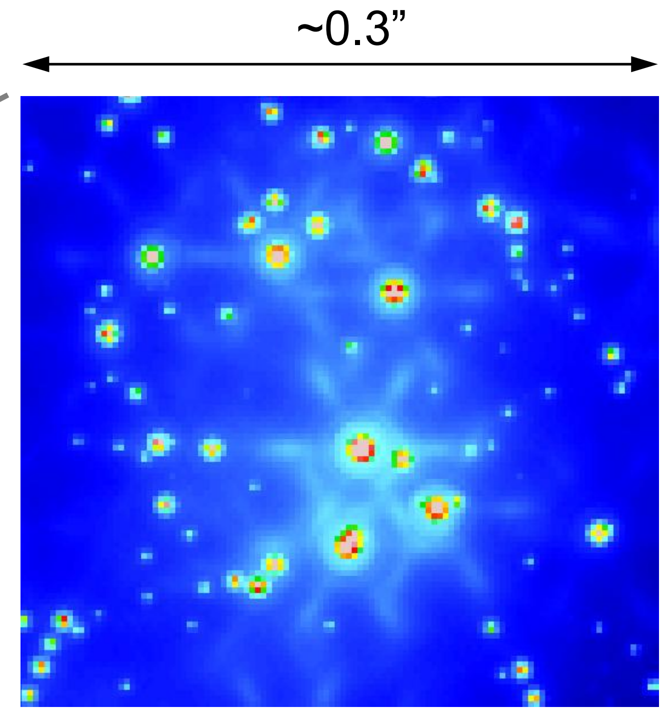
Strehl error 2%, → scaling error 8%,
5% 18%



Resolved Stellar Populations

simulation of 3” stellar field in young & old galaxies at 3 & 18 Mpc
contain 10000 & 25000 stars for $\mu_B \sim 18$ & $\mu_B \sim 22$
I, J, & K bands; MAORY PSFs; 1 hr exp. with MICADO
photometry performed with StarFinder using PSF derived from data





simulation by A. Deep & E. Tolstoy

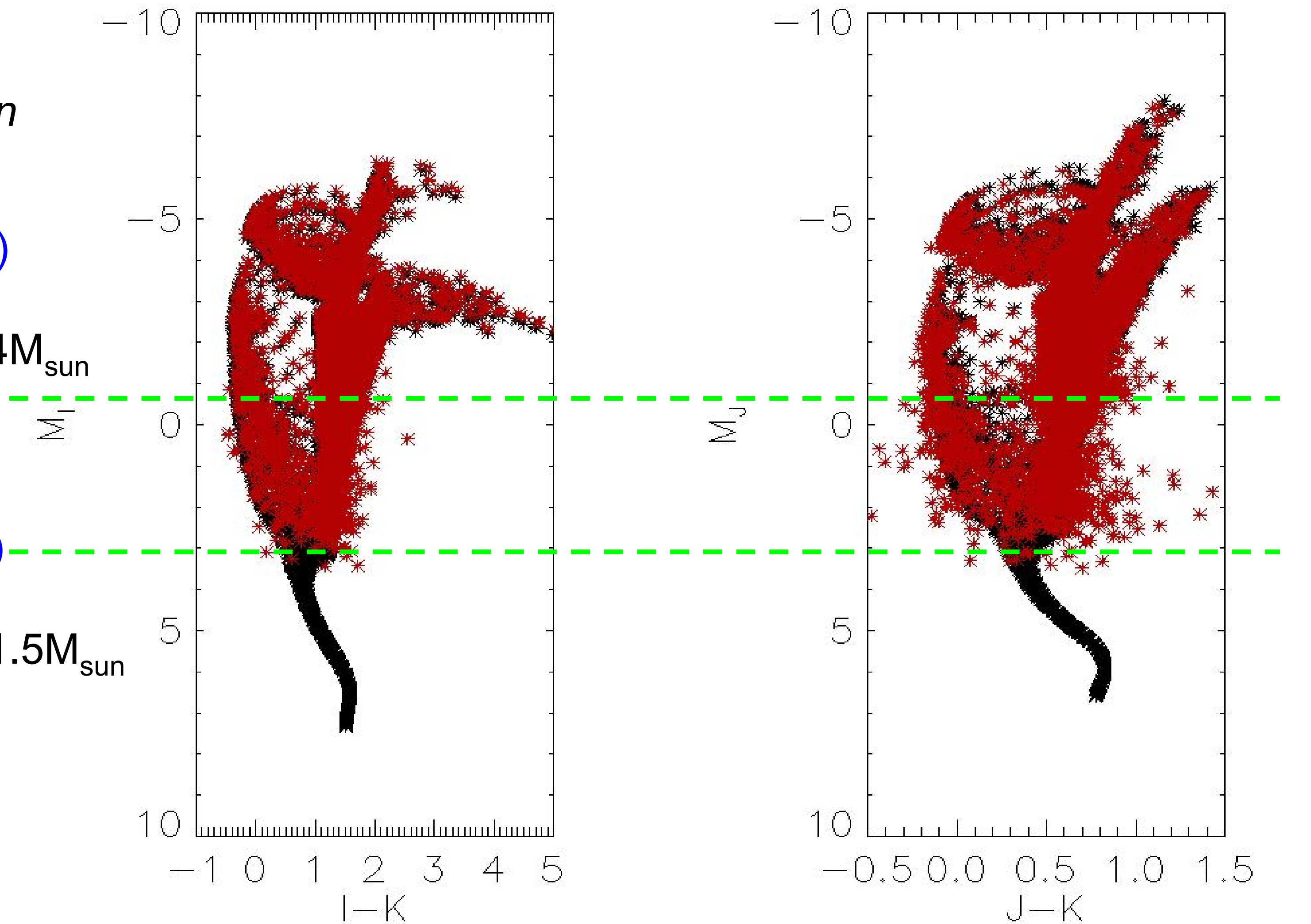
Resolved Stellar Populations to Virgo

- young galaxy
- aim: break age-metallicity degeneracy

1 hr integration

~18Mpc (Virgo)
giants & main
sequence to ~4M_{sun}

~3Mpc (Cen A)
giants & main
sequence to ~1.5M_{sun}



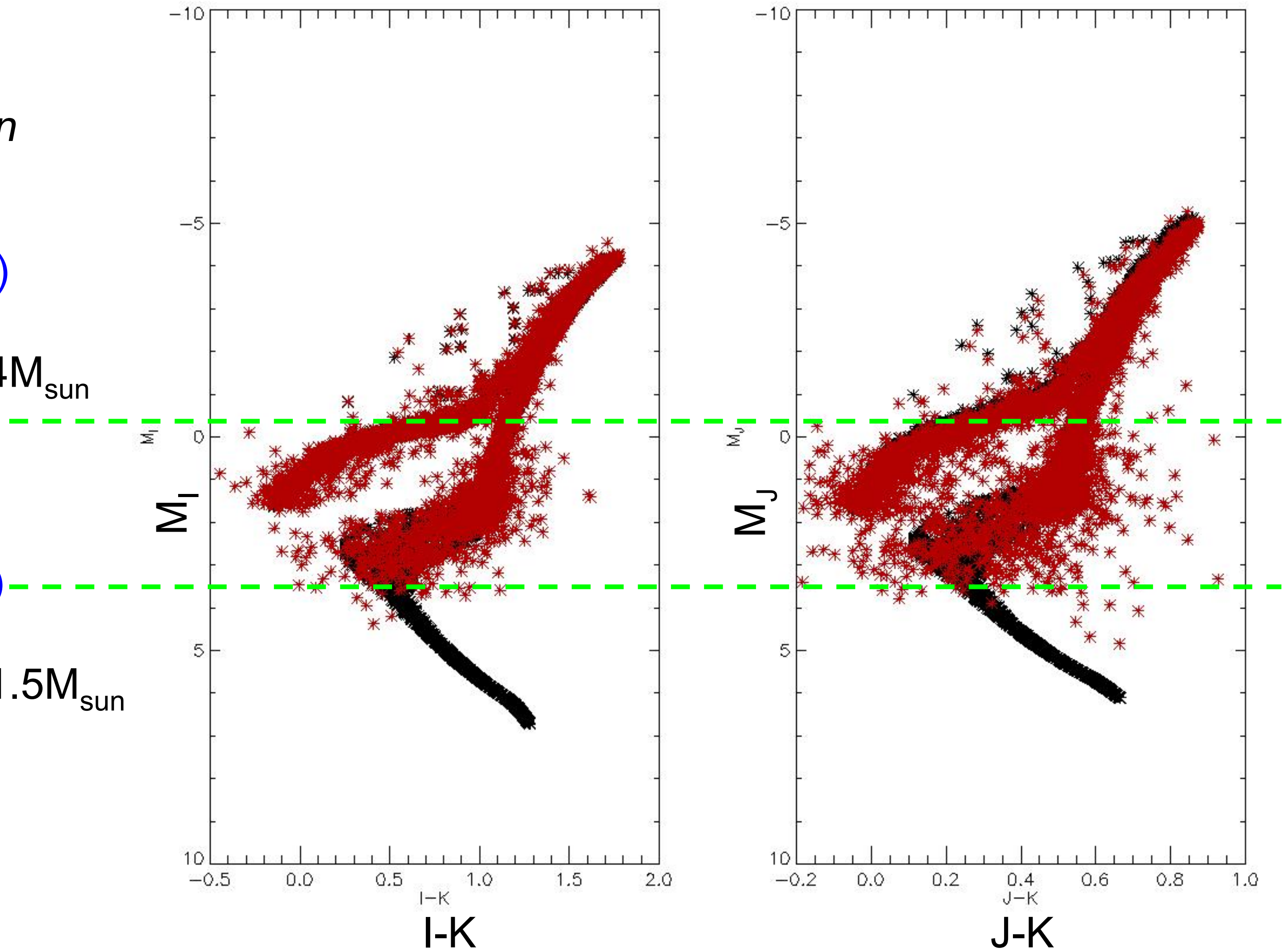
Resolved Stellar Populations to Virgo

- elliptical galaxy
- aim: probe star formation history with cosmic time (i.e. oldest stars)

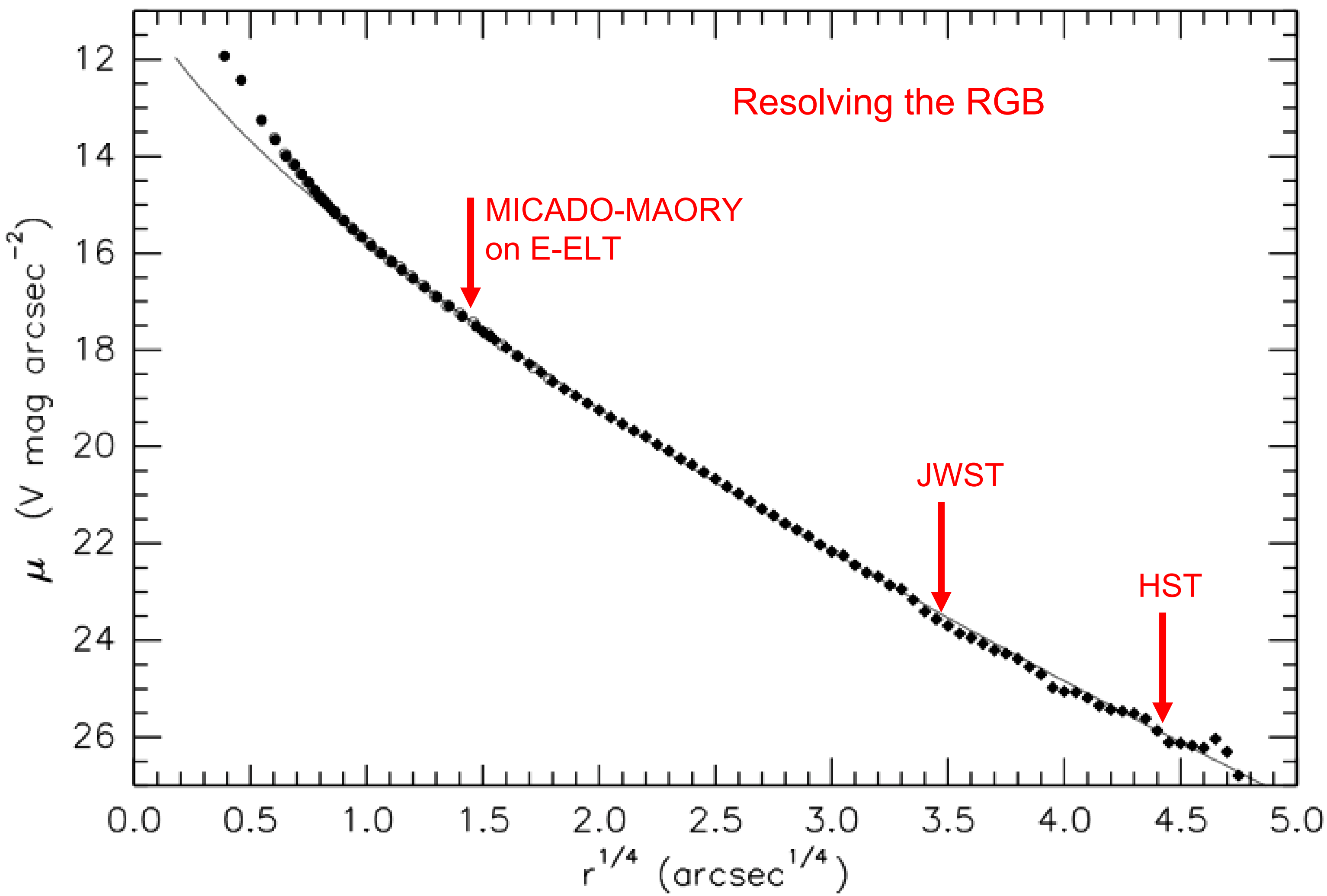
1 hr integration

~18Mpc (Virgo)
giants & main sequence to ~4M_{sun}

~3Mpc (Cen A)
giants & main sequence to ~1.5M_{sun}



Resolution & Crowding



MICADO and MAORY:
Science with MCAO on the E-ELT

- MICADO is the adaptive optics imaging camera for the EELT
  & makes use of the MCAO system MAORY
- sensitivity is comparable to JWST and resolution is 6 times better
- astrometric accuracy will be better than 50μas across the 1’ field
- AO effects on astrometry & knowledge of PSF are important factors
- numerous science cases can make use of the unique capabilities of
  MICADO-MAORY
- write a science case in the DRSP (deadline 30 June):
  http://www.eso.org/sci/facilities/eelt/science/drsp