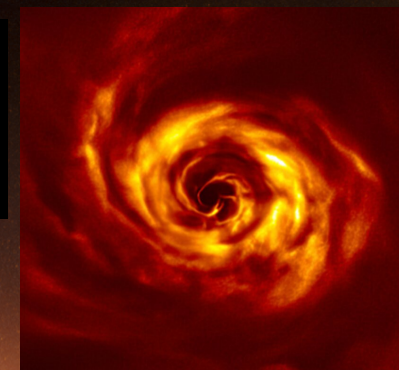




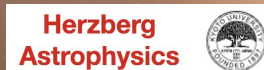
SCIENCE WITH MORFEO@ELT

Francesca Annibali (INAF-OAS)

*C. Arcidiacono (INAF-OAPd), E. Vanzella (INAF-OAS),
G. Duchene (IPAG), S. Douté (IPAG),
and the MORFEO science team*



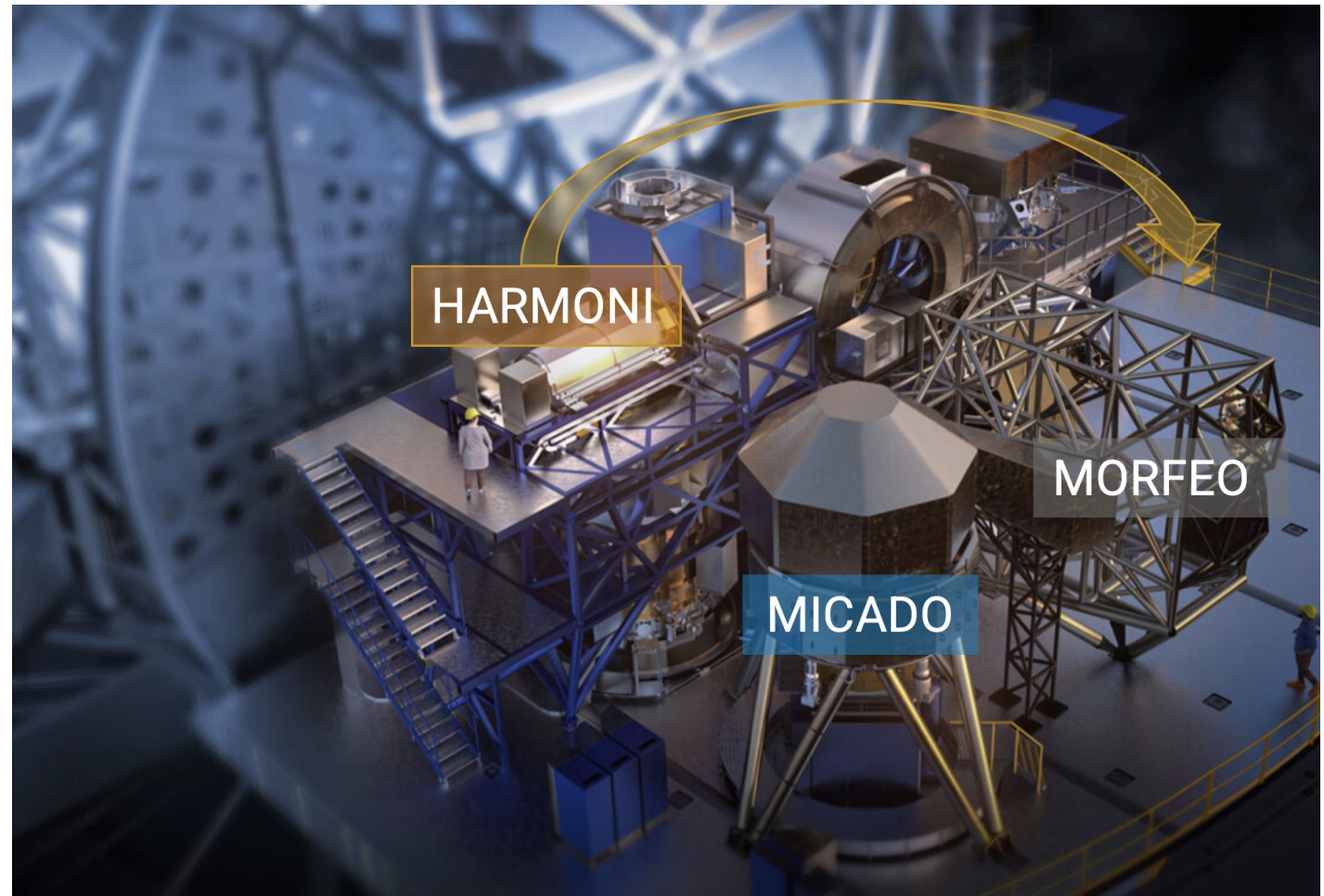
*Meeting della strumentazione ELT a guida italiana (MORFEO e ANDES)
May 12-15, 2026 - Napoli*





MORFEO – MICADO – HARMONI

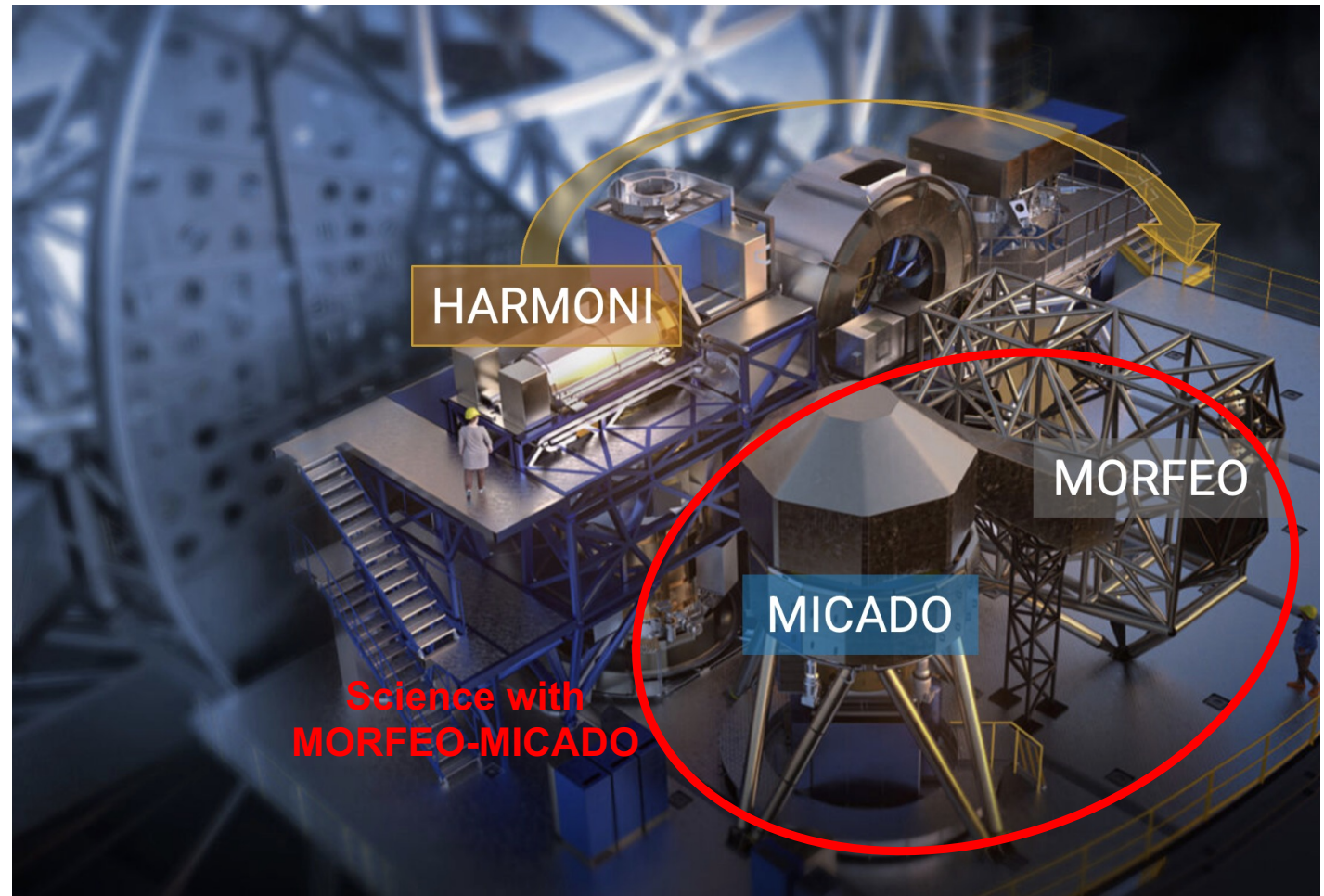
- **MORFEO** is the MCAO instrument for the ELT (serving MICADO and HARMONI)
- First technical light: end of 2032
- One of the largest projects with INAF leadership





MORFEO – MICADO – HARMONI

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MICADO: Multi-AO Imaging Camera for Deep Observations

(PI R. Davies)

- First light instrument for the ELT
- Will operate in stand-alone mode (SCAO) until MORFEO will arrive at ELT a couple years later
- Key capabilities:

- ❖ 0.8-2.4 μ m with 27 broad/narrow filters
- ❖ 1.5 & 4mas pixels for 19" & 51" FoV at 6-12mas
- ❖ Similar sensitivity to JWST, and 6 $\times$ better resolution

- ❖ 10-50 μ as precision anywhere in the field
- ❖ 10 μ as/yr = 5km/s at 100 kpc after only a few years

- ❖ focal & pupil plane coronagraphs
- ❖ angular differential imaging
- ❖ small inner working angle

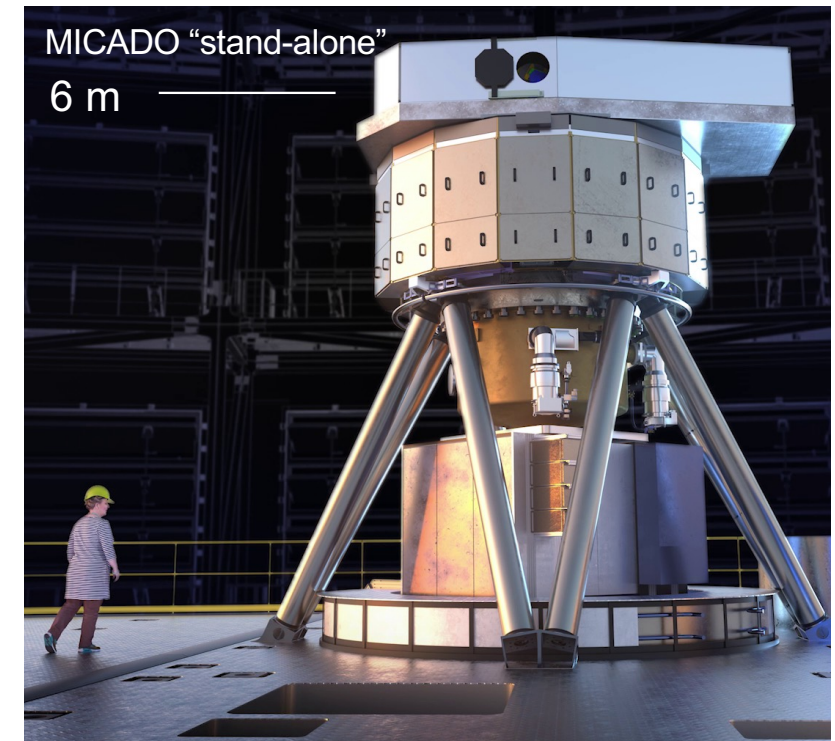
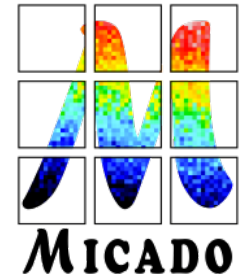
- ❖ Longslit, 16 mas width
- ❖ fixed configuration for 0.83-1.57 μ m & 1.50-2.46 μ m
- ❖ $R \sim 20000$ for point sources ($R \sim 10000$ across slit)
- ❖ IFU?

IMAGING

ASTROMETRIC
IMAGING

HIGH
CONTRAST
IMAGING

SPECTROSCOPY

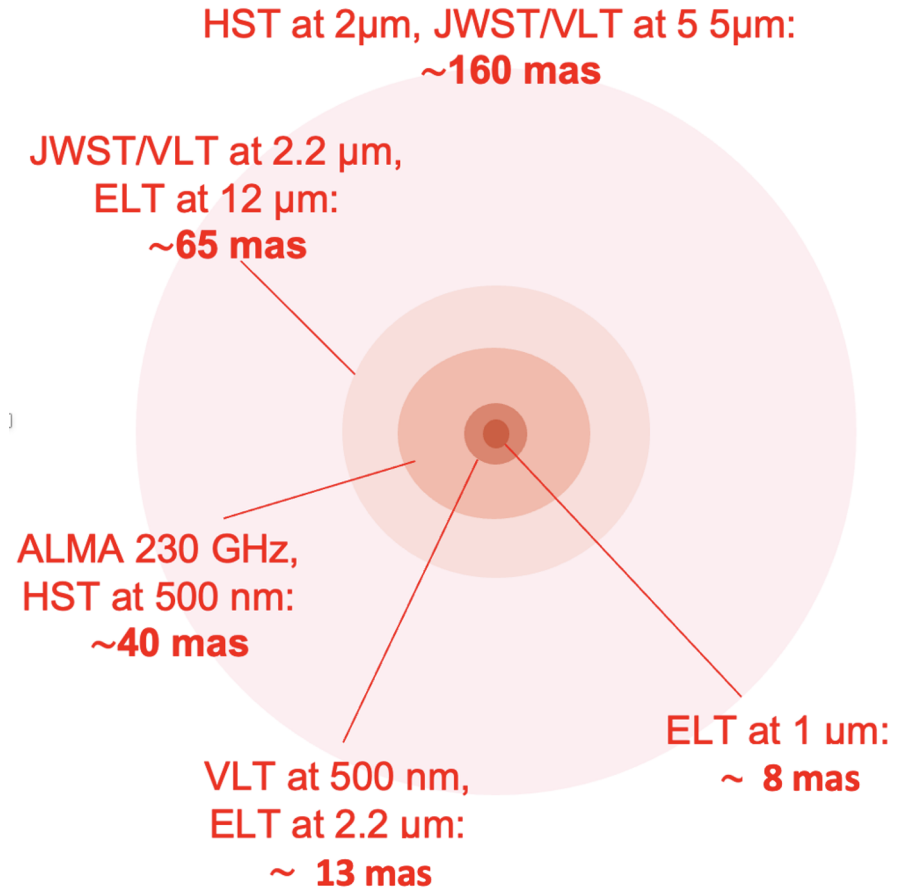




MICADO resolution in context



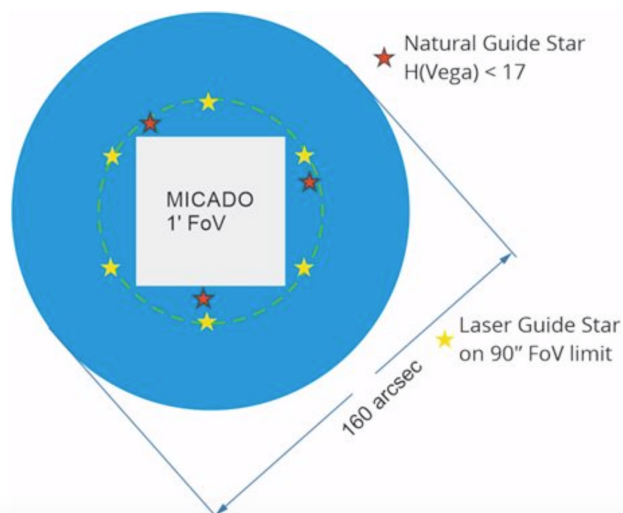
10 mas at:		
Galactic Center	8 kpc	0.4 mpc
Cen A	4 Mpc	0.2 pc
Virgo Cluster	18 Mpc	1 pc
Cosmic Noon	$z \sim 2$	80 pc





The MORFEO + MICADO system

- ✓ MORFEO will provide **uniform PSF** (Strehl ratio and FWHM) over the entire ~ 1 arcmin² MICADO field of view plus **large sky coverage** (MCAO mode)
- ✓ MORFEO will also support **SCAO mode** over a smaller $\sim 10''$ field of view



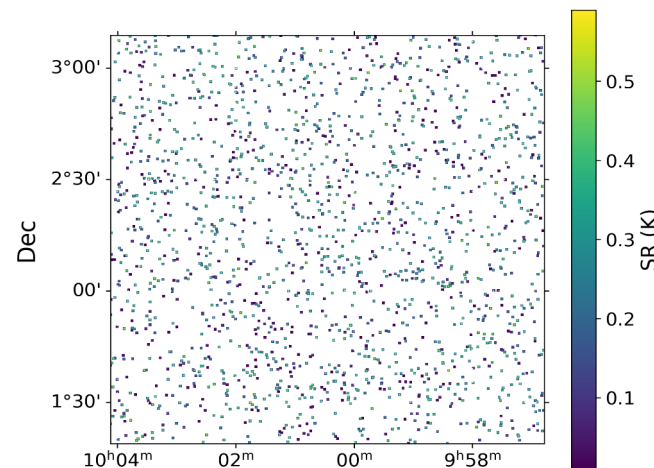
SCAO

1 NGS (R<16)

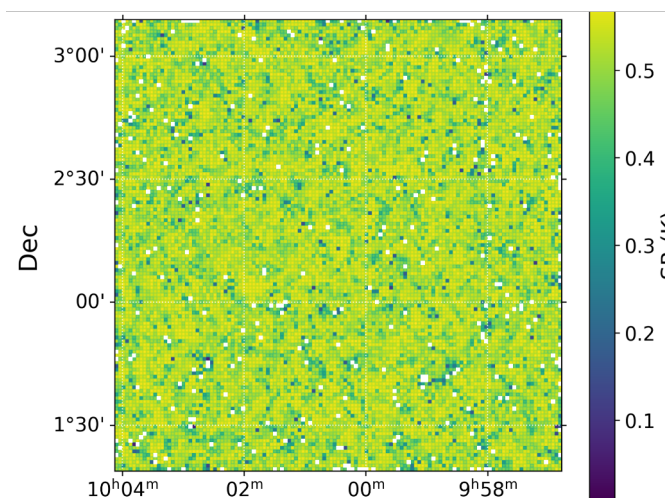
MCAO

3 NGSs (R<24, H<21)
6 LGSs

- COSMOS field – sky coverage



SCAO

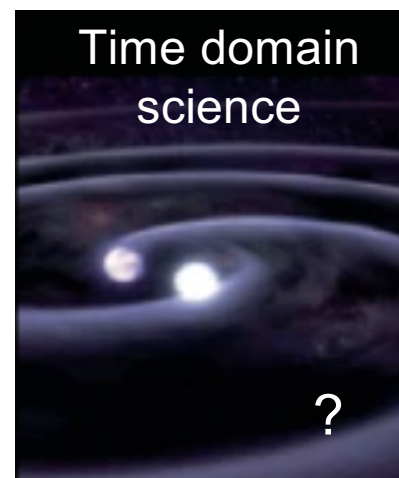
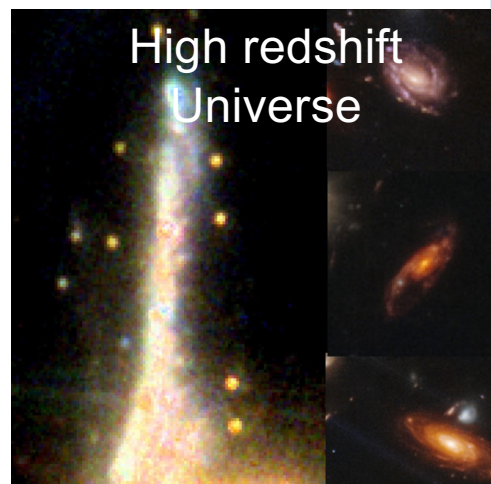
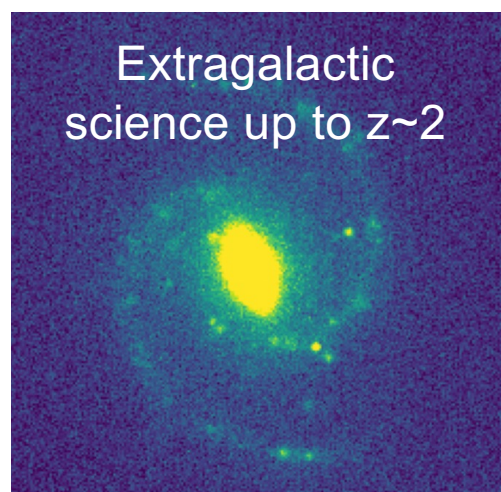
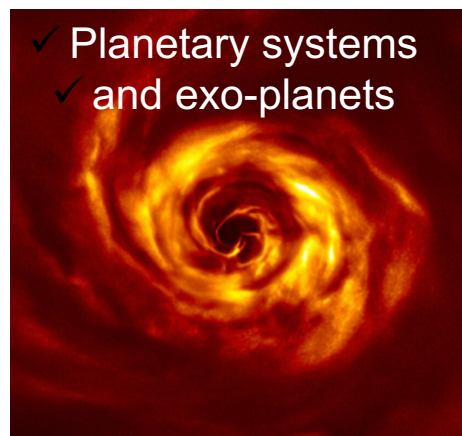


MCAO

Courtesy: E. Valenti



MORFEO will allow MICADO (and HARMONI) to address a large variety of science cases!



MORFEO science team working groups



The Solar System

Three main topics:

- Origins, geology, activity and evolution of **icy worlds** (i.e. satellites of giant planets and icy dwarf planets);
- **Small bodies** (e.g. asteroids, Trojans, Centaurs, **TNOs** and comets) as witnesses to the formation and dynamics of the early Solar System;
- **Giant planet atmospheres** as laboratories for investigating large-scale fluid dynamics and physicochemical phenomena.





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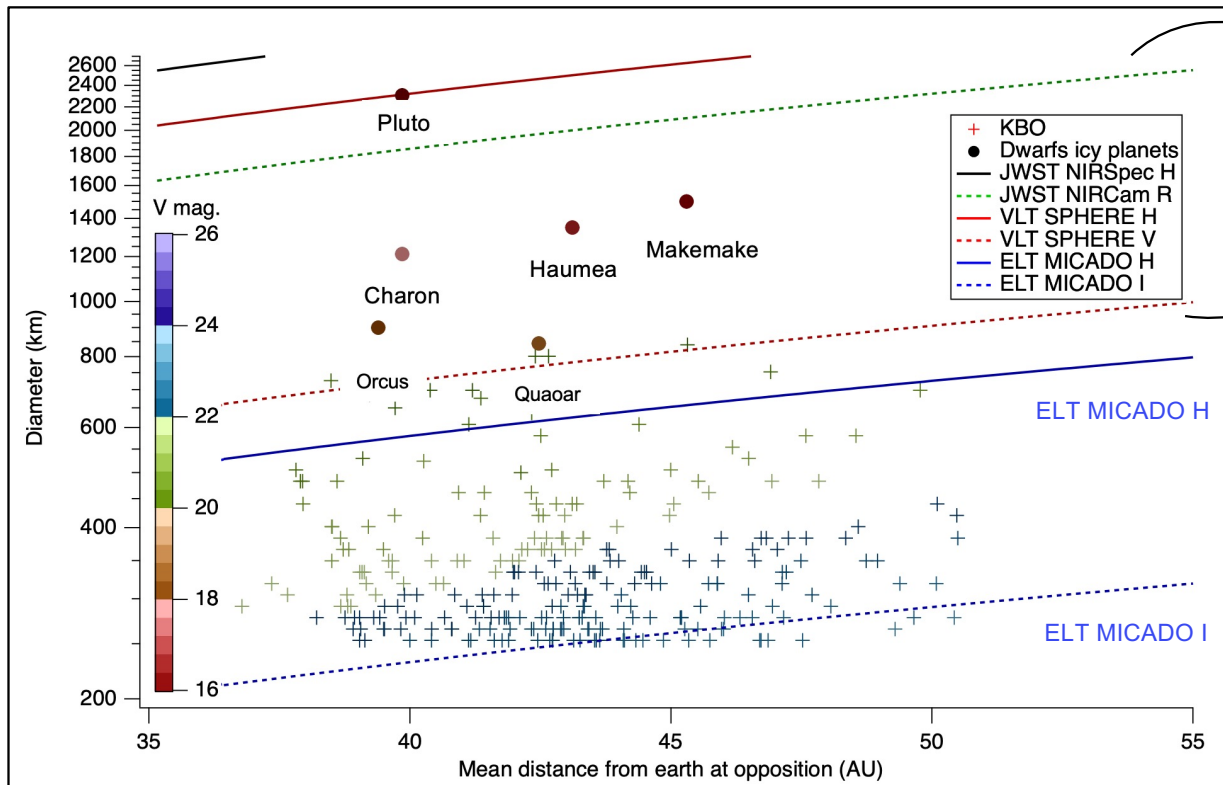
TNOs: Icy remnants of the disk that formed the Solar System, among the least altered material → provide constraints on the timing and scenario of formation of the early Solar System





The Solar System

Trans Neptunian objects



~20 objects resolved
in MICADO H

Dwarf planet	M_V [mag]	Apparent D ["]	Spatial Res. [km]	N_{pix} (D)
Pluto	14	0.104	230	20
Eris	18.7	0.038	400	8
Makemake	16.9	0.04	263	12
Haumea	17.1	0.037	250	10
Sedna	21	0.025	250	6
Quaoar	18.8	0.028	250	6

Credit: S. Douté



The Solar System

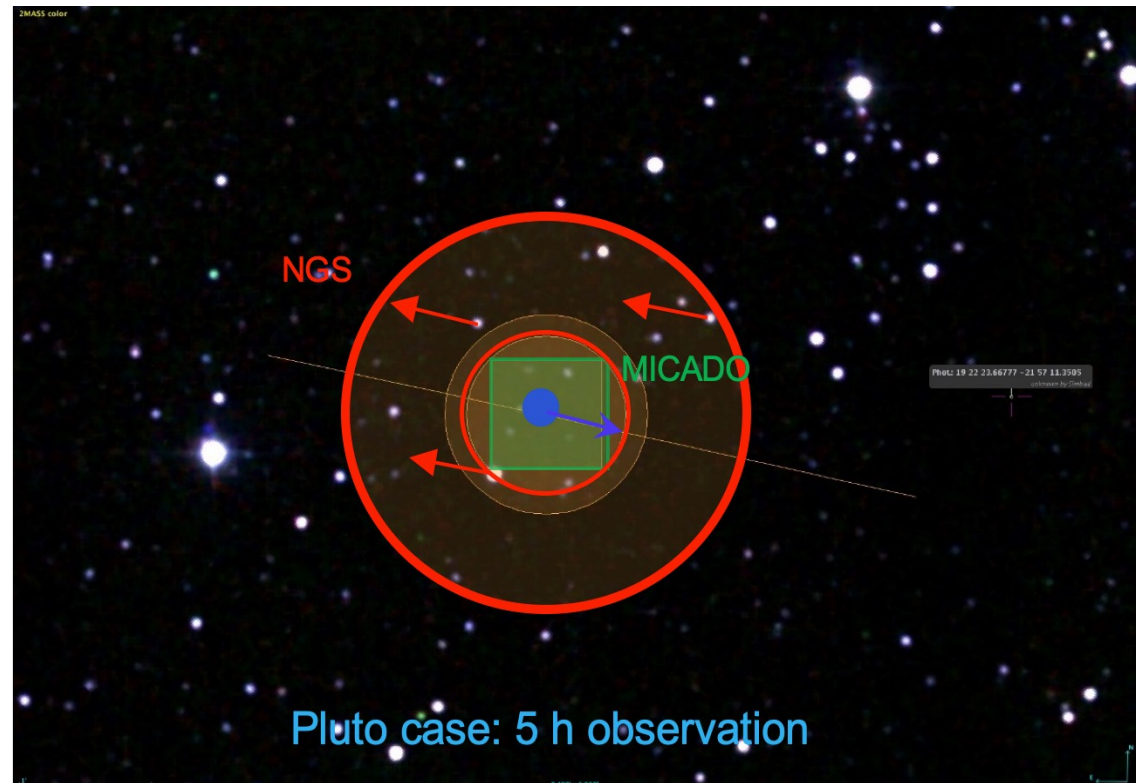
Trans Neptunian objects

- ✓ Are typically faint ($24 < \text{mag} < 16$)
- ✓ Move fast on sky ($> 0.3 \text{ mas/sec}$)



- ✓ **non-sideral tracking** required (telescope tracks the target while moving wrt NGSs)
- ✓ Need to compute target **ephemerides** and searching for 3 NGS in NIR star catalogs
- ✓ Reduced performance (depending on target velocity)

non-sideral tracking
MCAO mode





The Solar System

Trans Neptunian objects – M&M performances:

non-sidereal tracking
MCAO mode

Haumea icy dwarf planet
($D=32$ mas, $V=19.1$, $PM=0.4$ mas s $^{-1}$)

Model:
shape, topography,
reflectance
properties, etc...

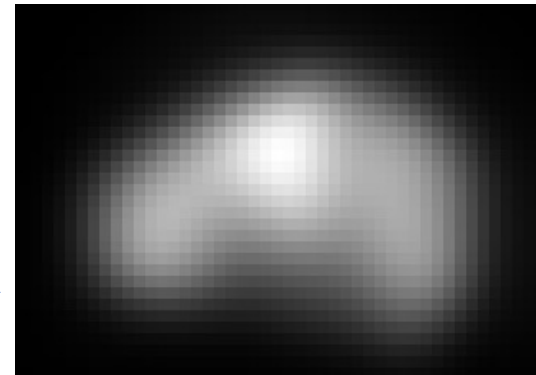
radiative transfer
model (HYPsim)

Raw source image:

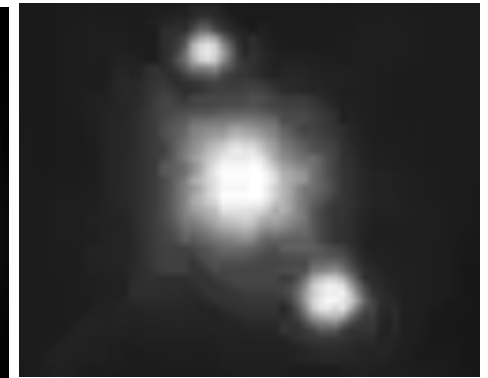


Simcado

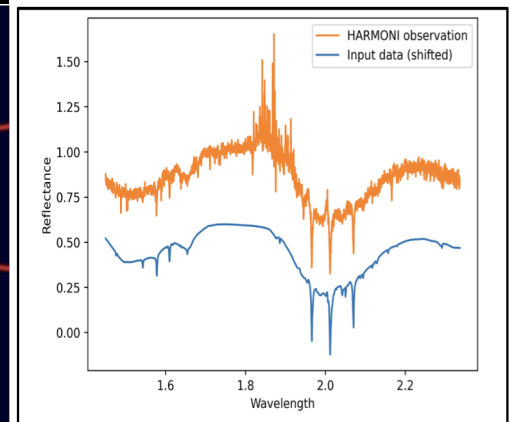
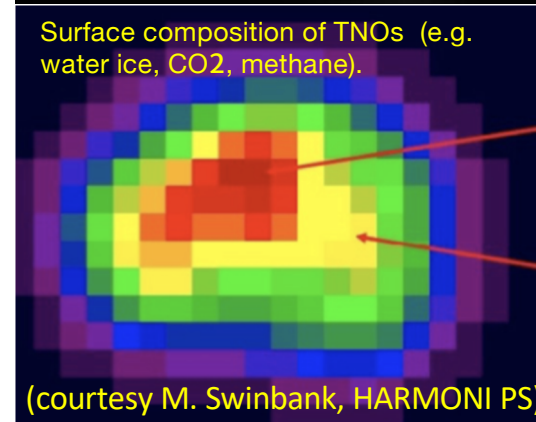
MORFEO/MICADO
simulated image



HST WFC3 image



Surface composition of TNOs (e.g.
water ice, CO₂, methane).



Ephemerides +
NIR star catalog

NGS asterism

PSF

Credit: S. Douté



Proto-planetary disks and exoplanets

AB Aurigae

Solar System



10''

SPHERE/IRDIS (H-band)
Boccaletti et al. 20

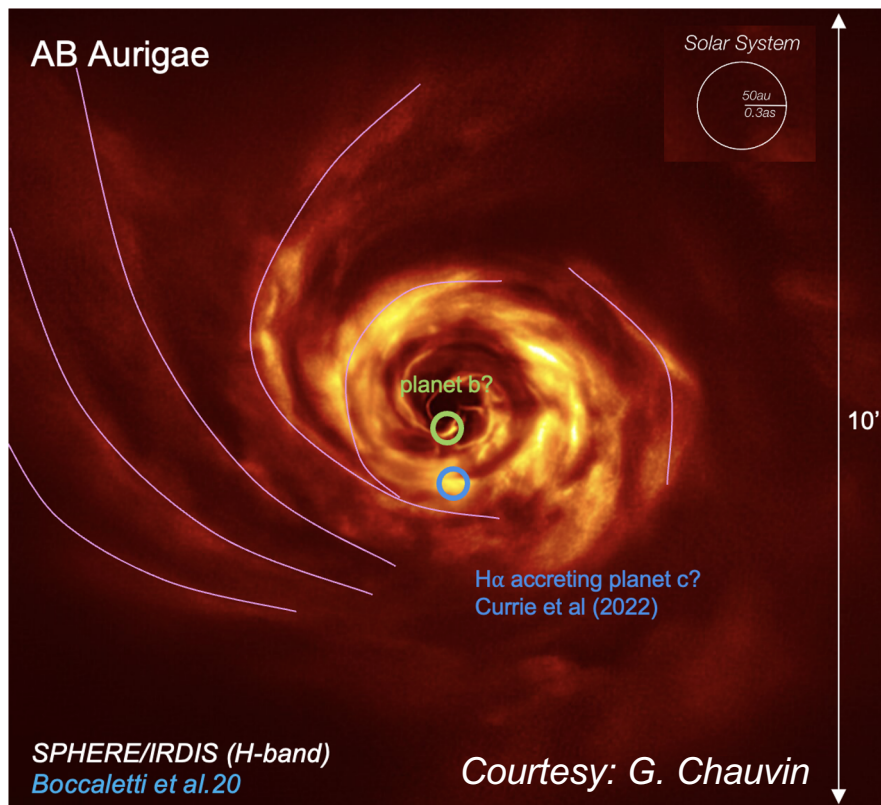
Courtesy: G. Chauvin

AB Aurigae:

- ❖ Herbig A0V star
- ❖ $2.4 M_{\odot}$
- ❖ 162.9 pc
- ❖ 2 Myr



Proto-planetary disks and exoplanets

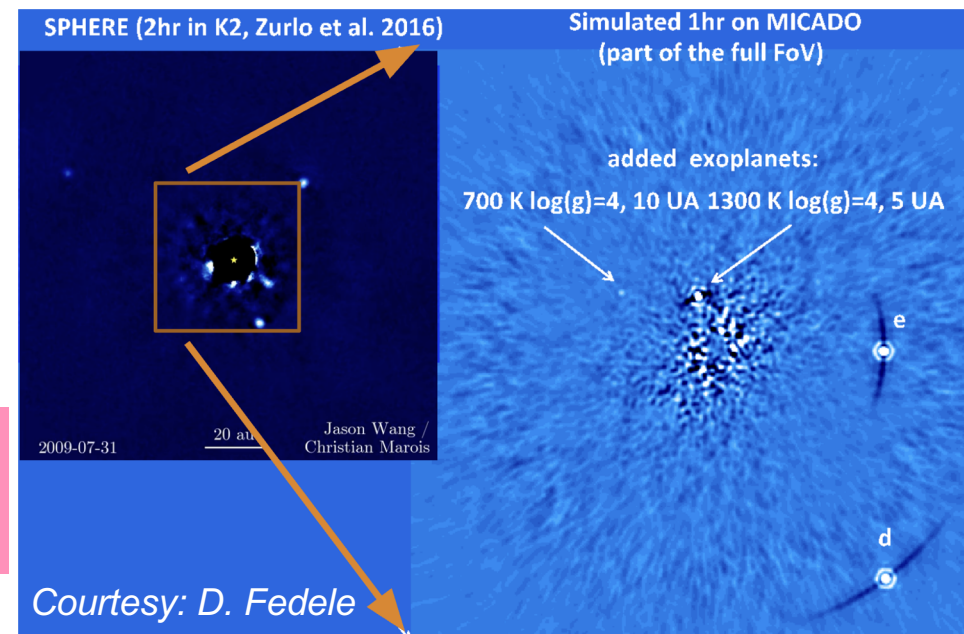


AB Aurigae:

- ❖ Herbig A0V star
- ❖ 2.4 $M_{\odot}$
- ❖ 162.9 pc
- ❖ 2 Myr

5 times better resolution with M&M@ELT !

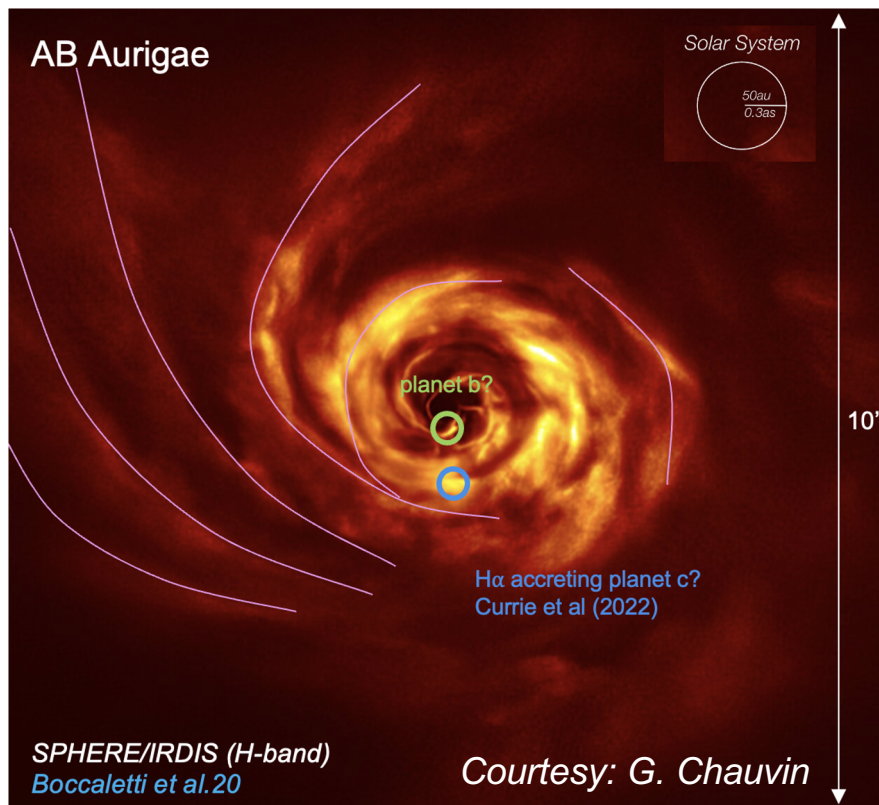
Baudoz+19



First instrument capable of direct observations of giant planets within 0.15"



Proto-planetary disks and exoplanets



AB Aurigae:

- ❖ Herbig A0V star
- ❖ 2 planets
- ❖ 16 AU
- ❖ 2 AU

5 times
resolution
M&M@ELT !

See talks by **Linda Podio**
and **Antonio Garufi** today
afternoon and by **Davide**
Fedele on Wed.

Baudoz+19

SPHERE (2hr in K2, Zurlo et al. 2016)

Simulated 1hr on MICADO
(part of the full FoV)

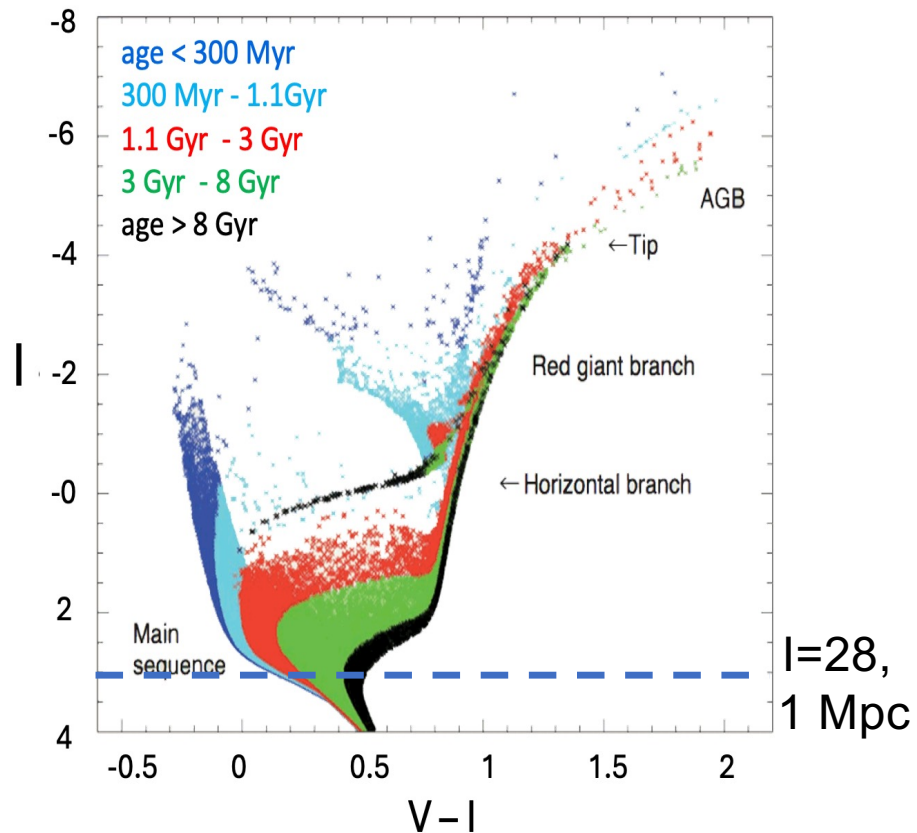
exoplanets:
1300 K $\log(g)=4$, 5 UA

Courtesy: D. Fedele

First instrument capable of direct observations of giant
planets within 0.15"

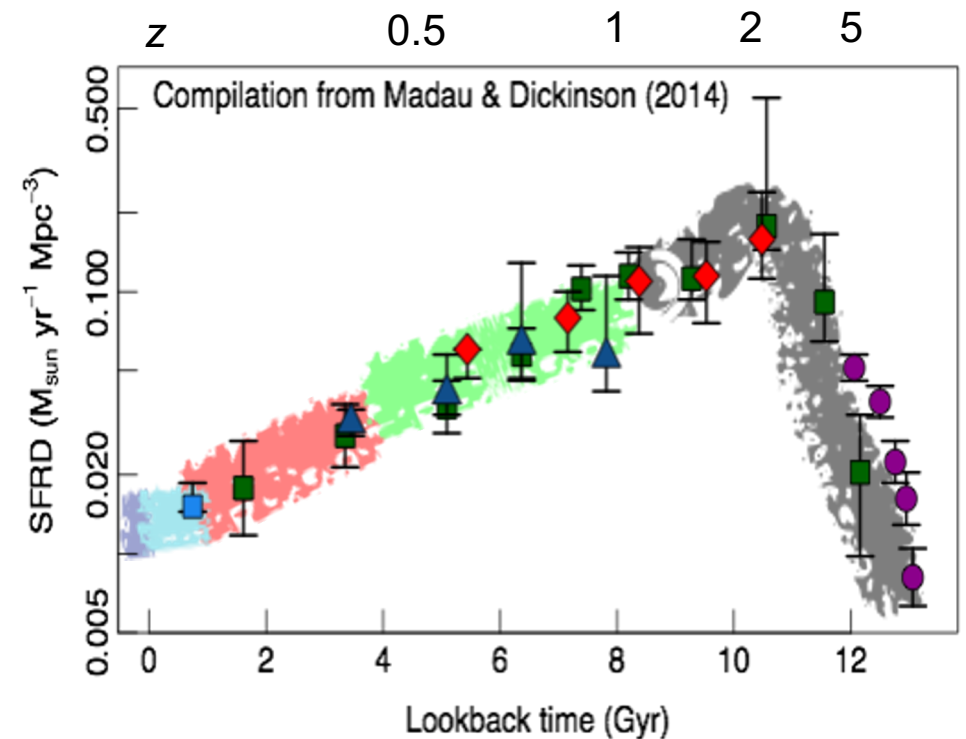
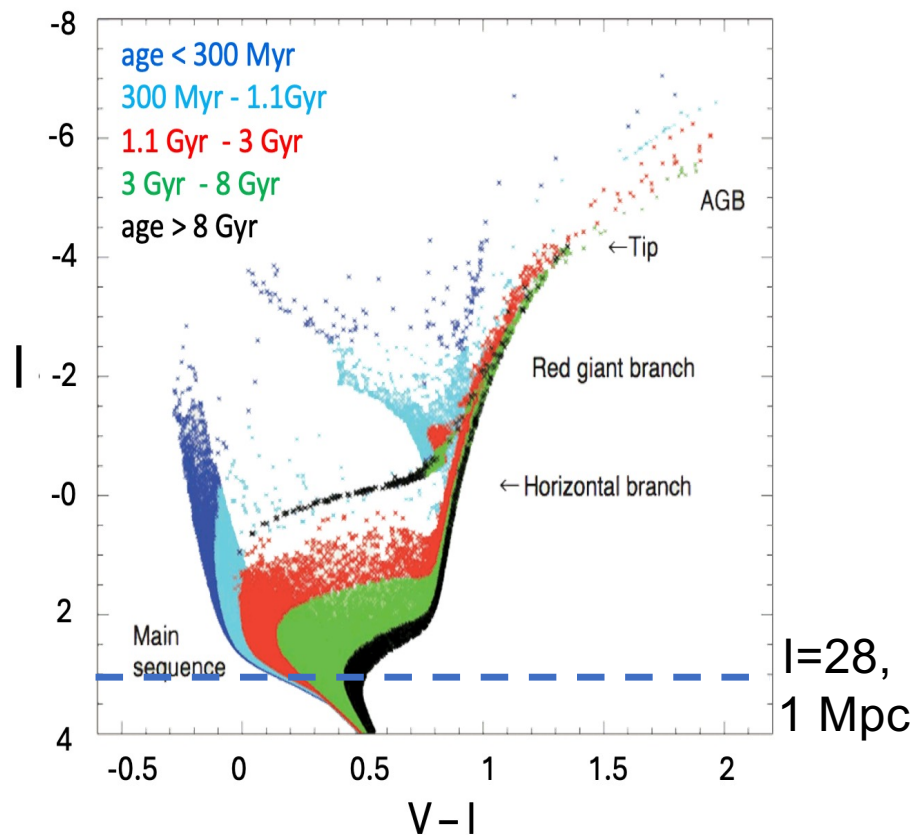
Tracing galaxy evolution with resolved stars

Color-magnitude diagrams are powerful tools to age-date stars



Tracing galaxy evolution with resolved stars

Color-magnitude diagrams are powerful tools to age-date stars

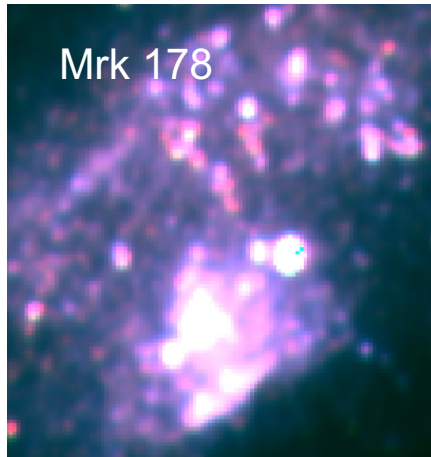


The deeper the CMD,
the higher the z we can probe

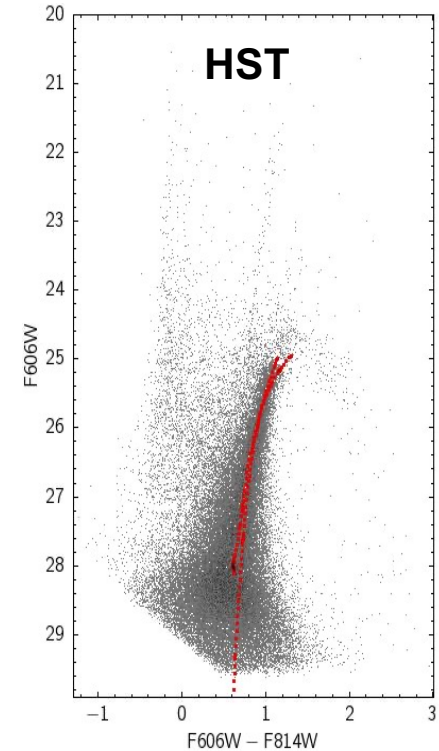
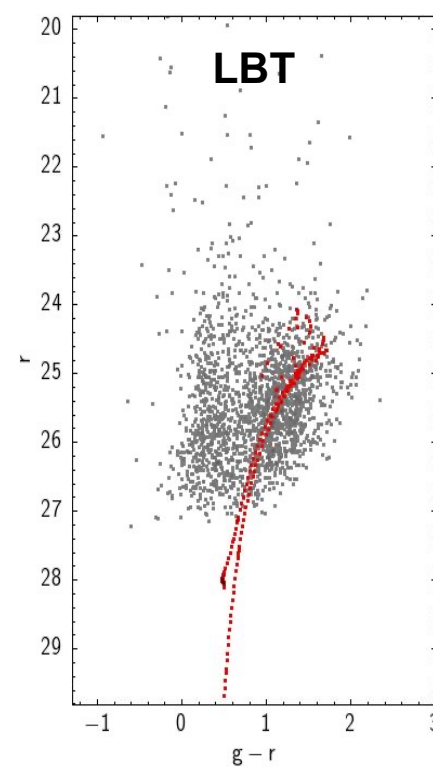
Tracing galaxy evolution with resolved stars

The importance of spatial resolution

LBT (8.4 m)
seeing limited



HST (2.4 m)
diffraction limited



Resolving individual stars to deep magnitudes requires
high angular resolution in crowded fields!

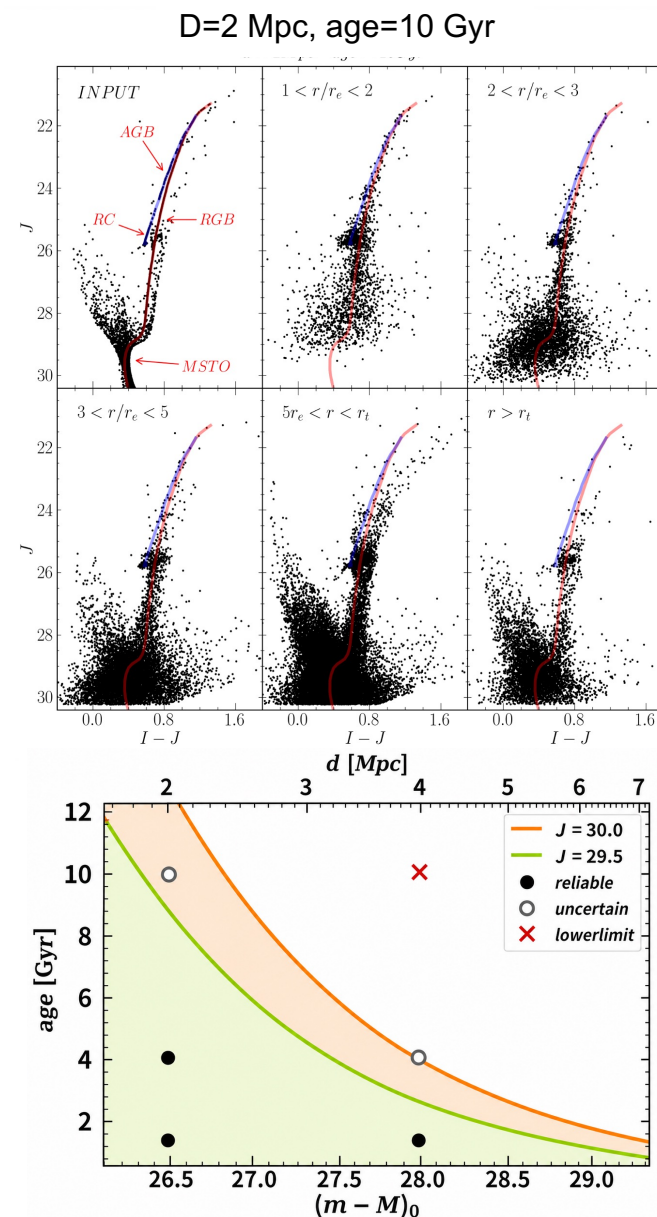
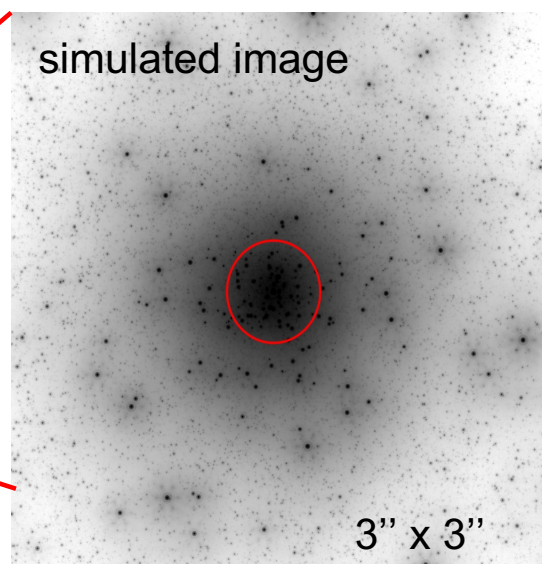
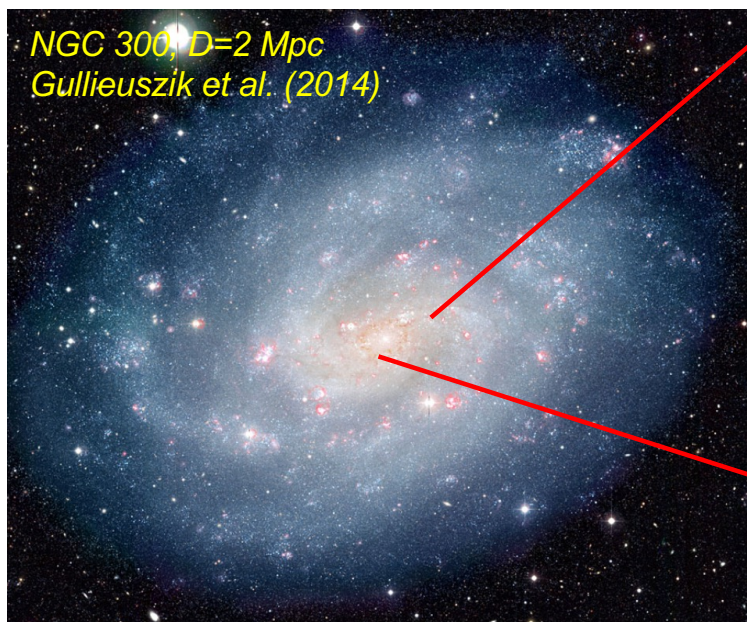


Resolving stars in Nuclear Star Clusters

Model:

NSC: King profile, $r_e = 0.27''$, $\sim 10^6 M_\odot$, (1-4-10) Gyr

NGC 300: disk, $\mu_c(H) \sim 17.3$ mag arcsec $^{-2}$, const. SF since 12 Gyr ago



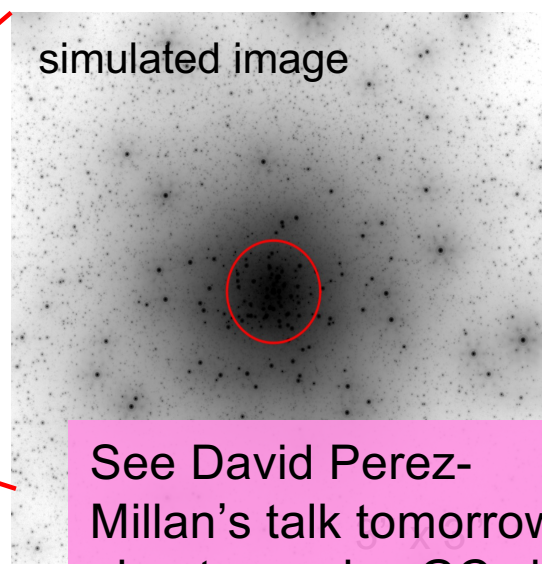
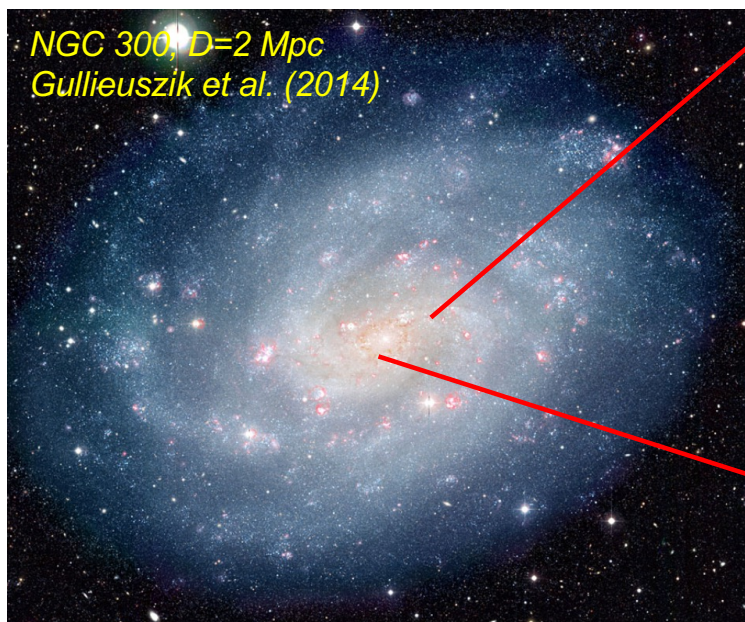


Resolving stars in Nuclear Star Clusters

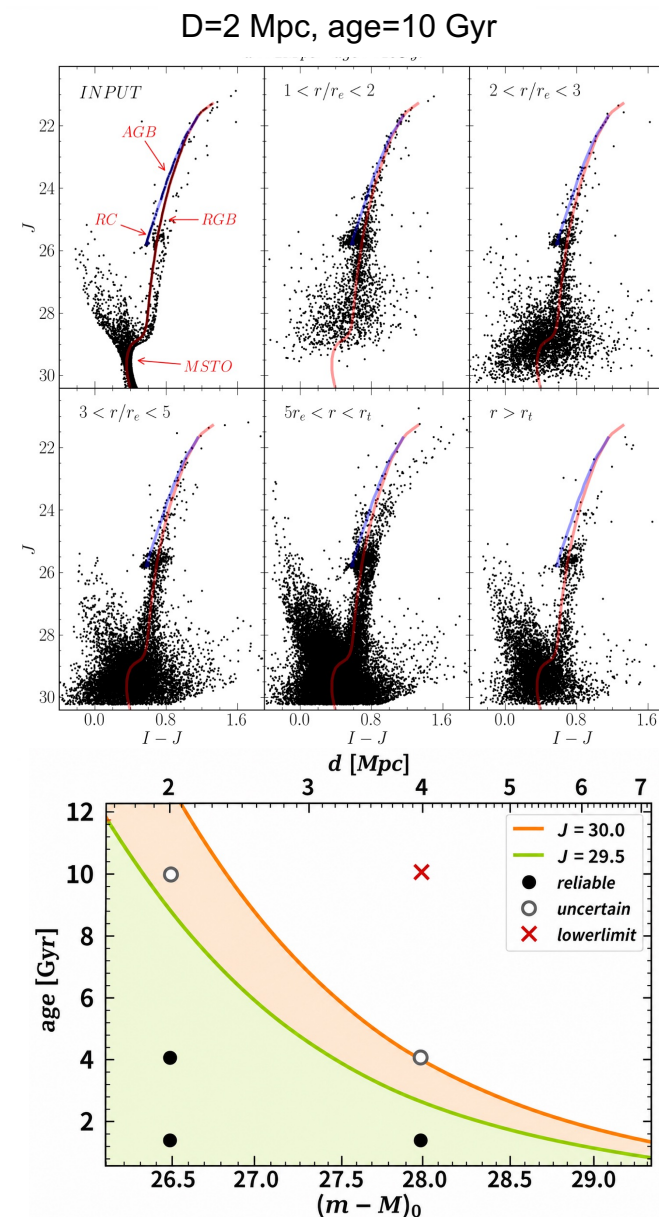
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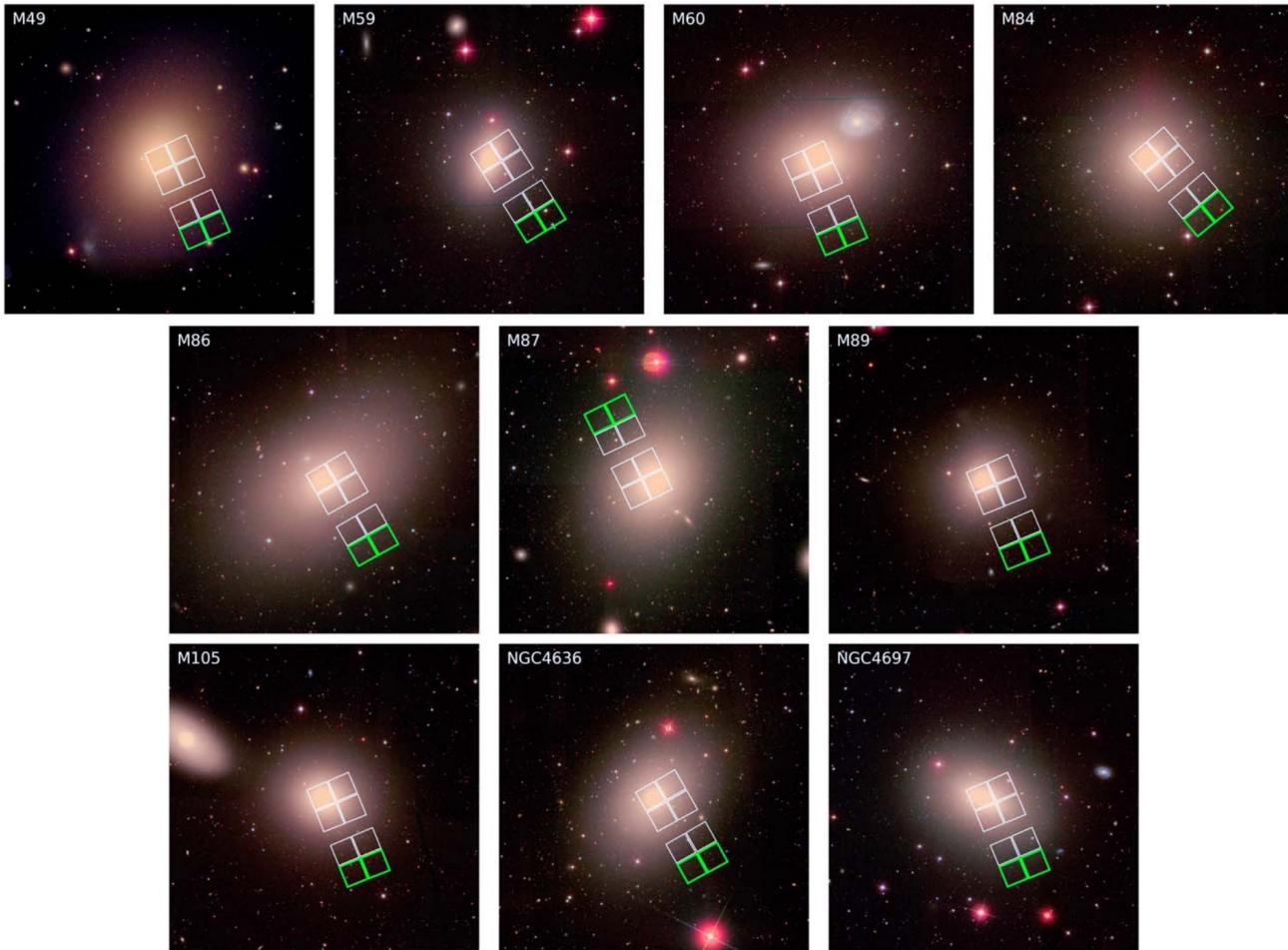
See David Perez-Millan's talk tomorrow about massive GCs in Cen A



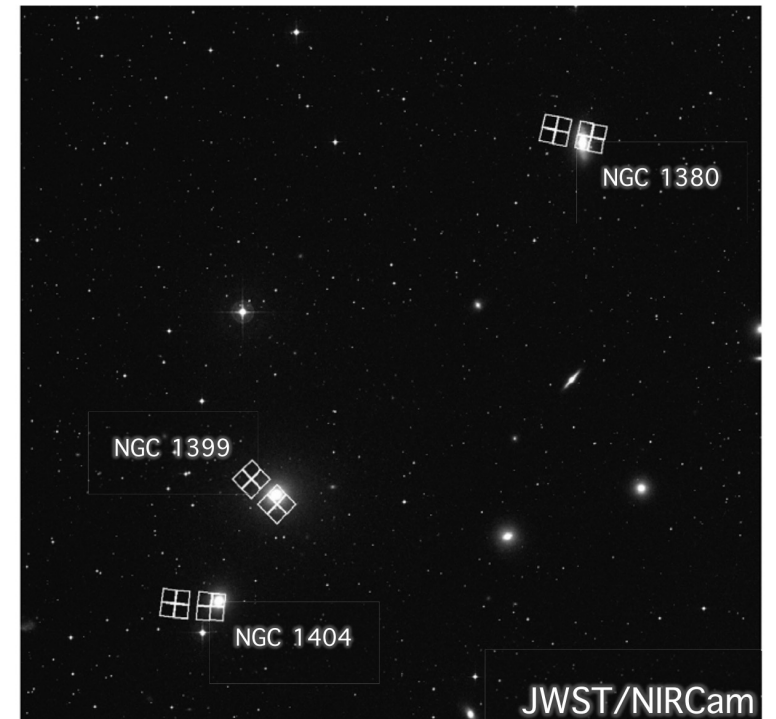


Cluster ellipticals with JWST

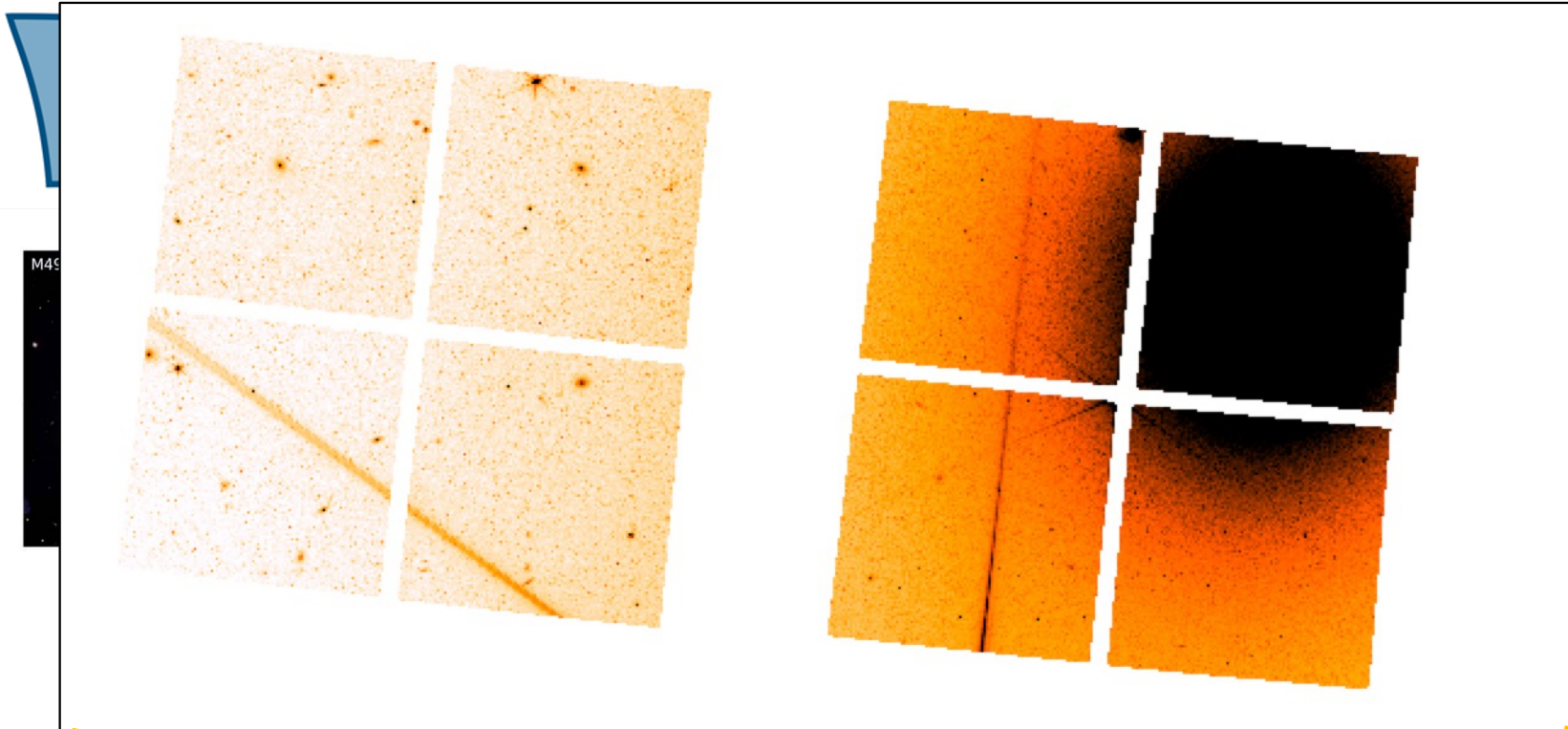
10 E galaxies in **Virgo** (Anand et al. 2025)



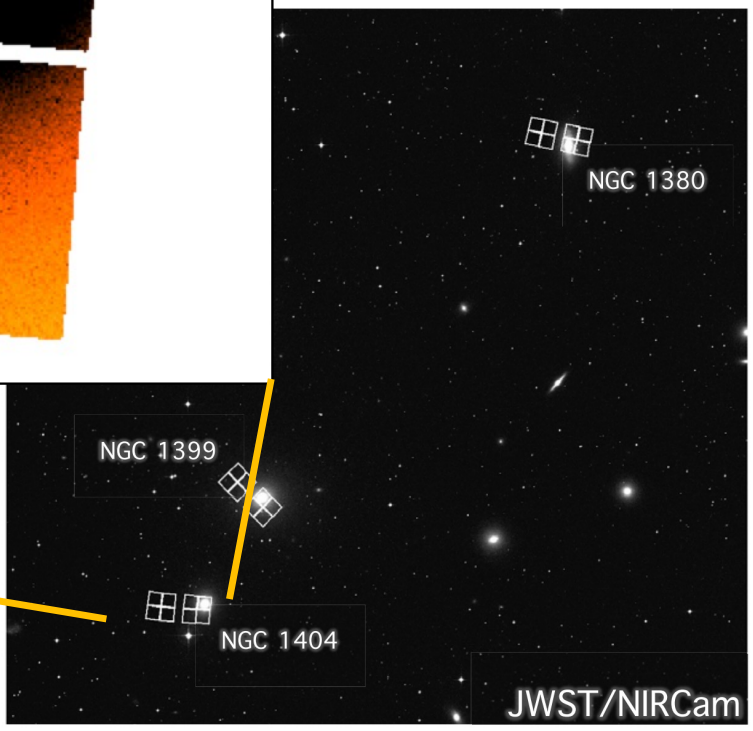
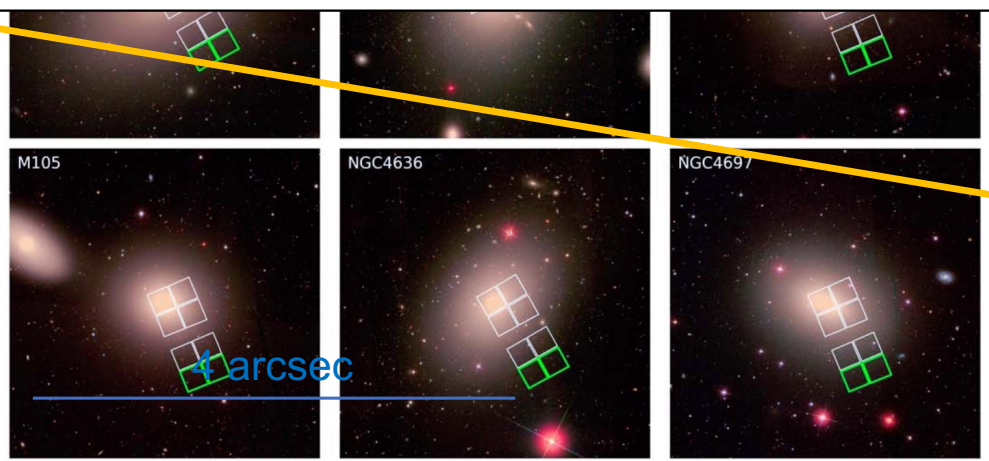
3 E galaxies in **Fornax** (Anand et al. 2024)



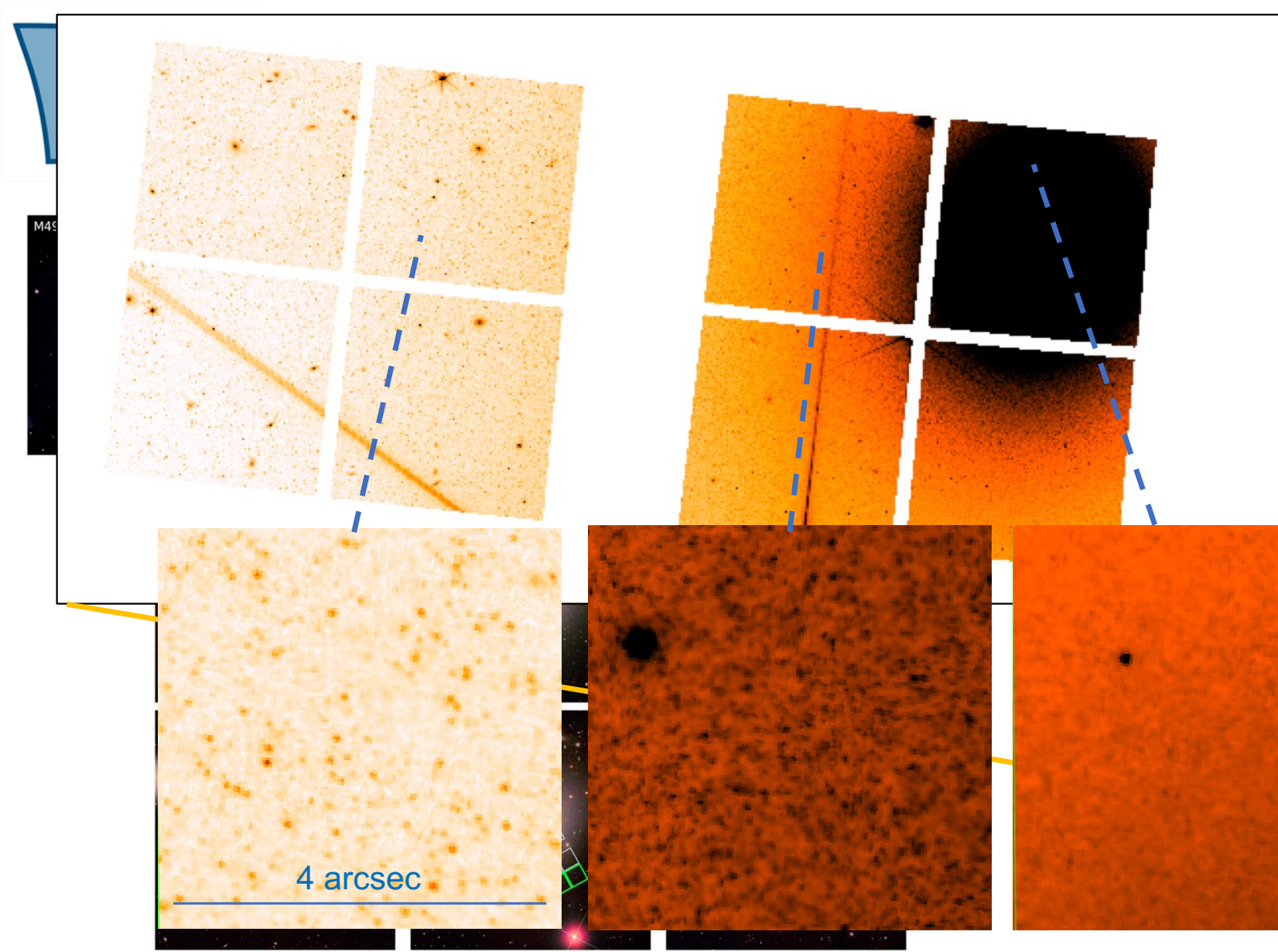
Anand et al. 2025



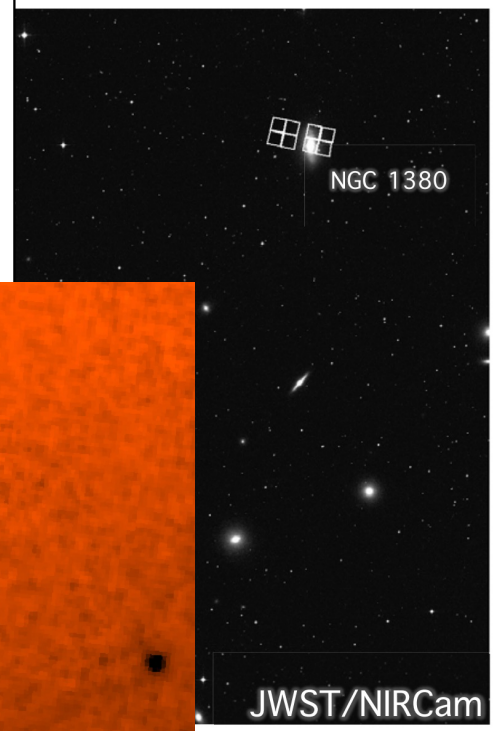
Fornax (Anand et al. 2024)



Anand et al. 2025



Fornax (Anand et al. 2024)

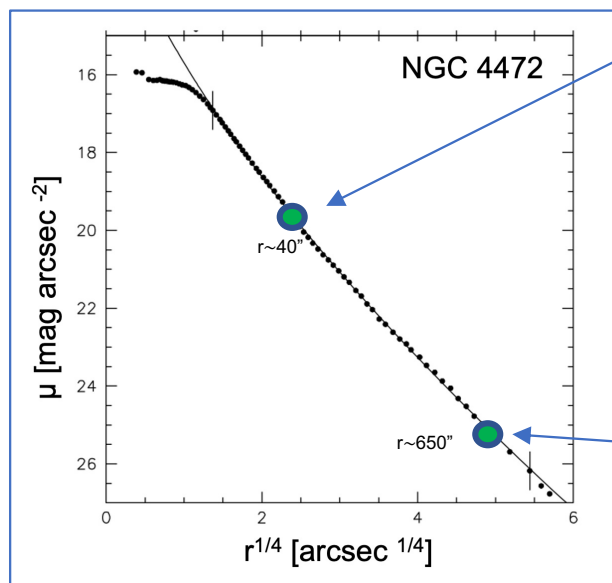
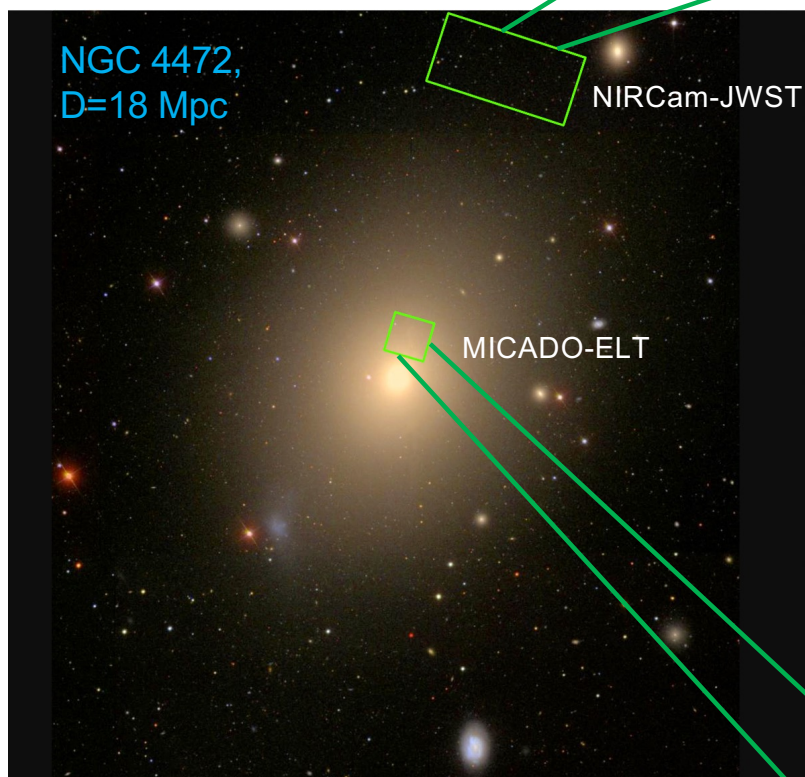


Anand et al. 2025

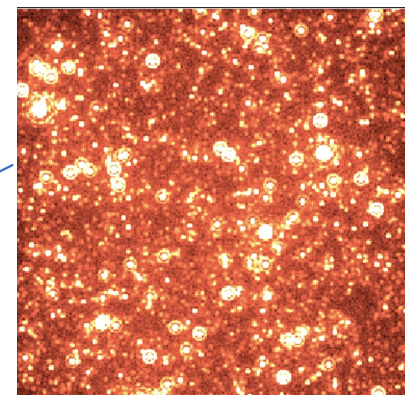


Accessing inner regions of Virgo Ellipticals

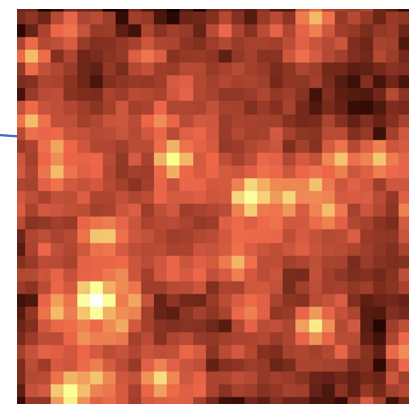
Large FoV,
outer, low-crowding regions



Simulated images



$\mu = 19.6$
MICADO-ELT



$\mu = 25.2$
NIRCam-JWST

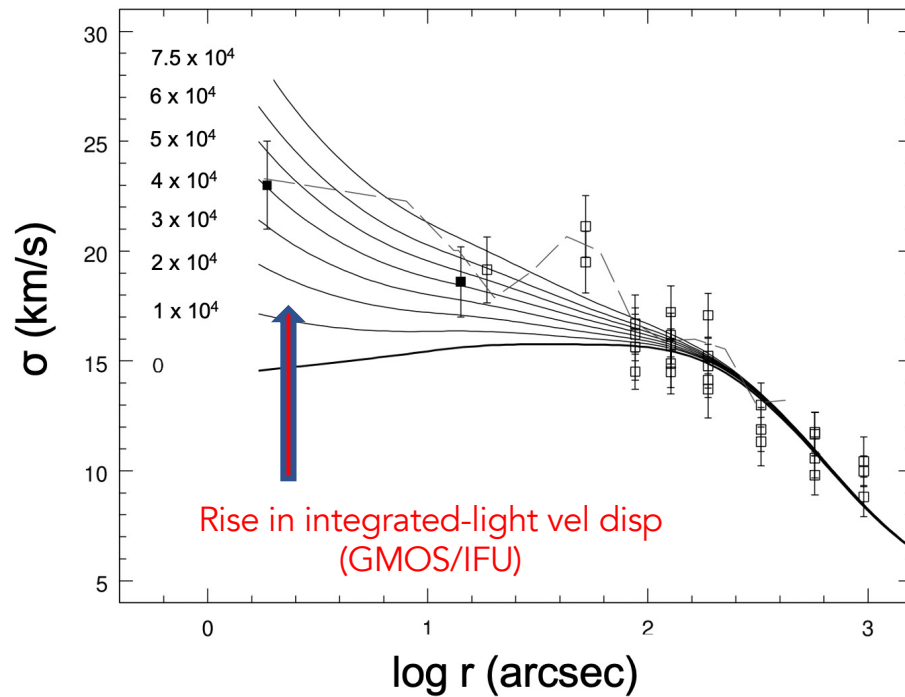
Small FoV,
inner, high-crowding regions

See also Schreiber et al. 2014



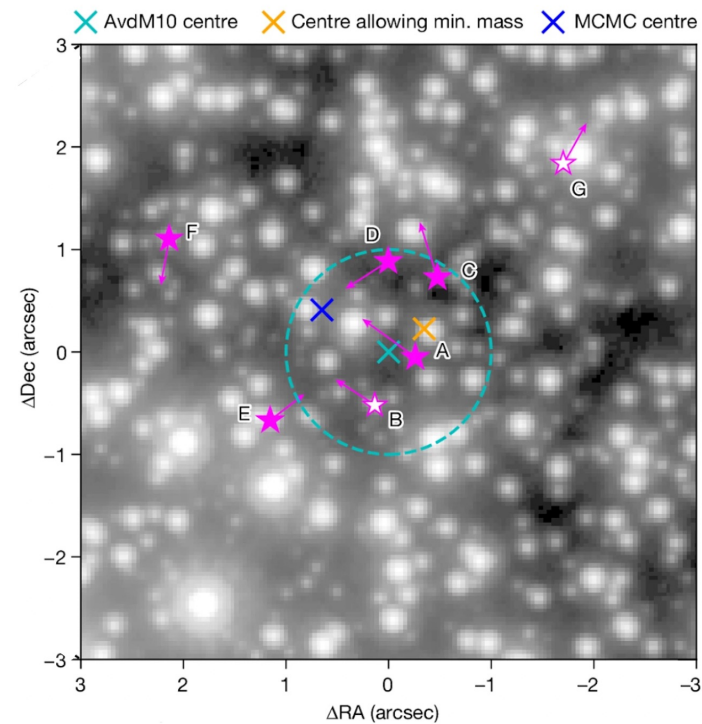
Dynamics of dense stellar systems with high-precision astrometry: searching for IMBH in star clusters

Claim for $4 \times 10^4 M_{\odot}$ IMBH in ω Cen (~ 5 kpc)



Noyola+2008

From HST PMs, $M_{\text{BH}} > 8200 M_{\odot}$



Haberle+2024

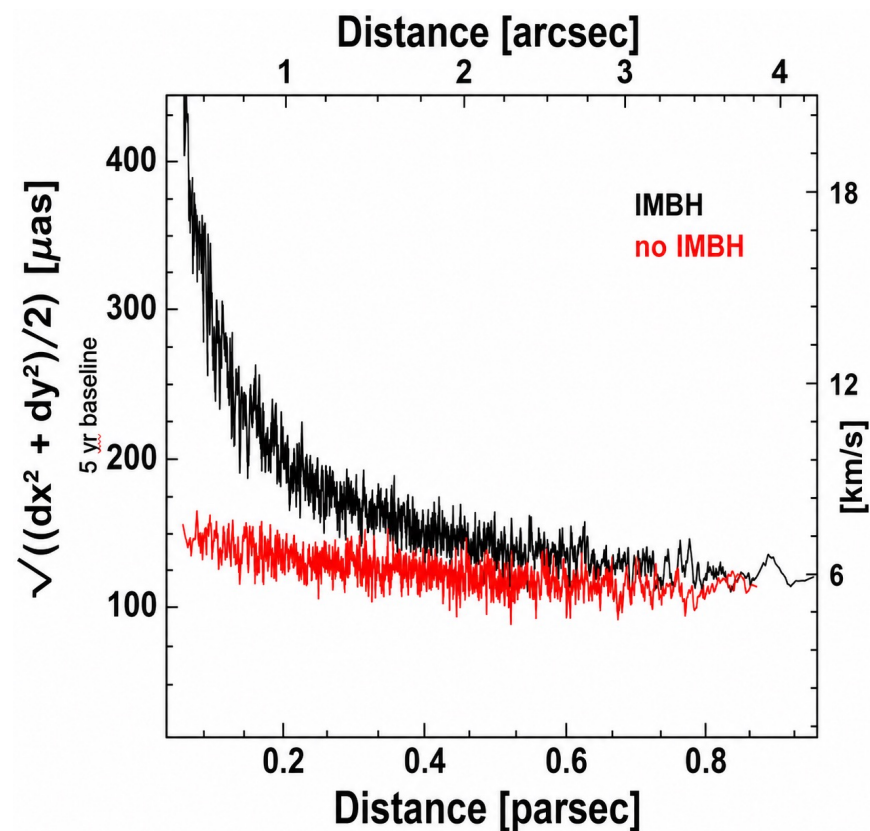
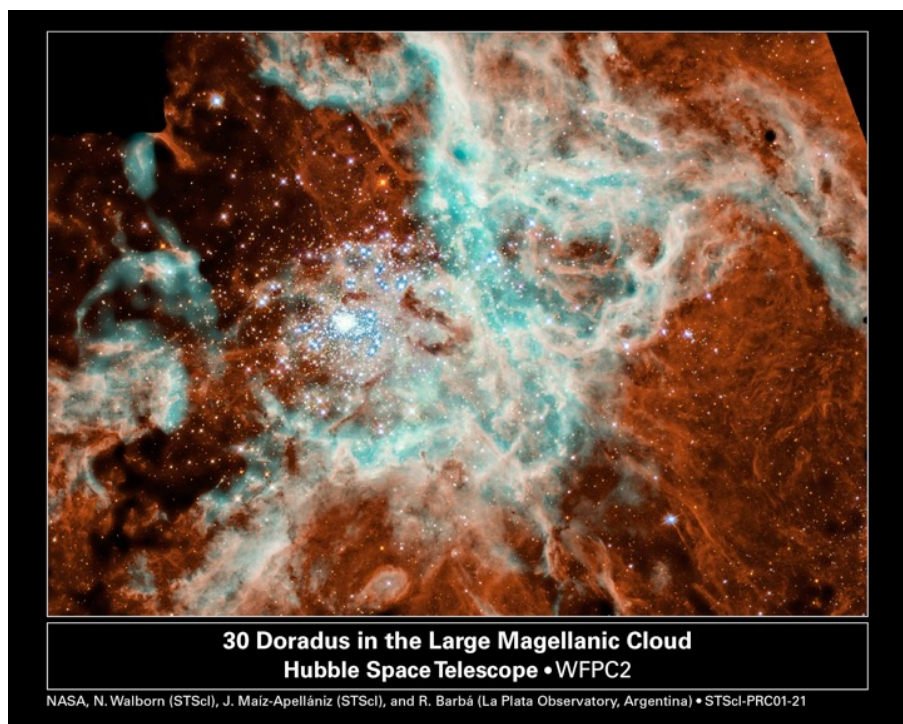
- 20 yr time- baseline
- $\sim 7 \mu\text{as/yr}$ precision
- 7 fast-moving stars ($\geq 100 \text{ km/s}$) at $r < 3''$



Dynamics of dense stellar systems with high-precision astrometry: searching for IMBH in star clusters

Fiorentino et al. (2020)

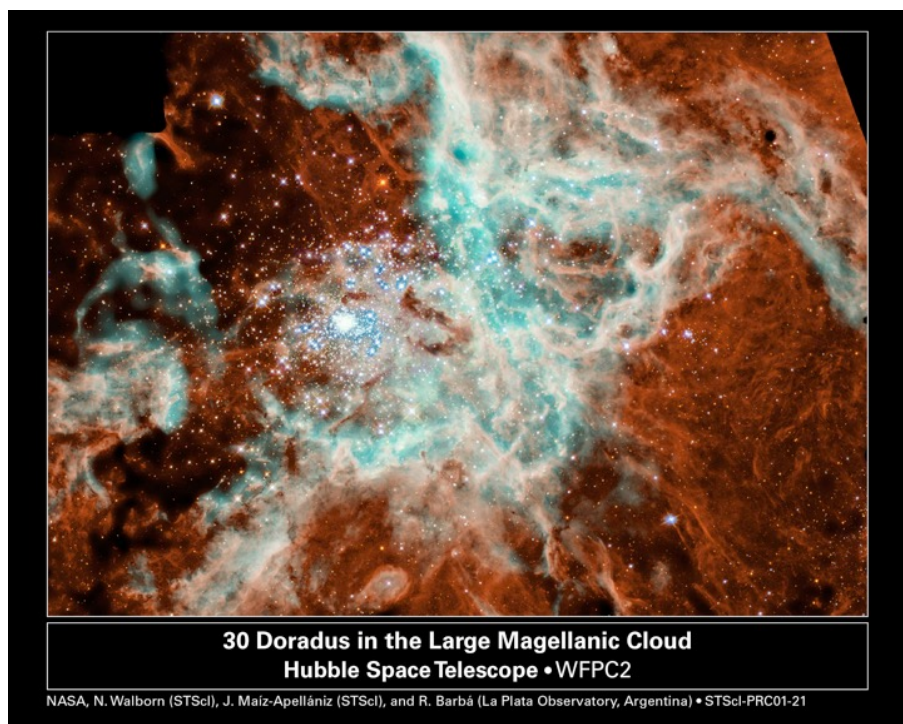
30 Doradus, LMC (~50 kpc)



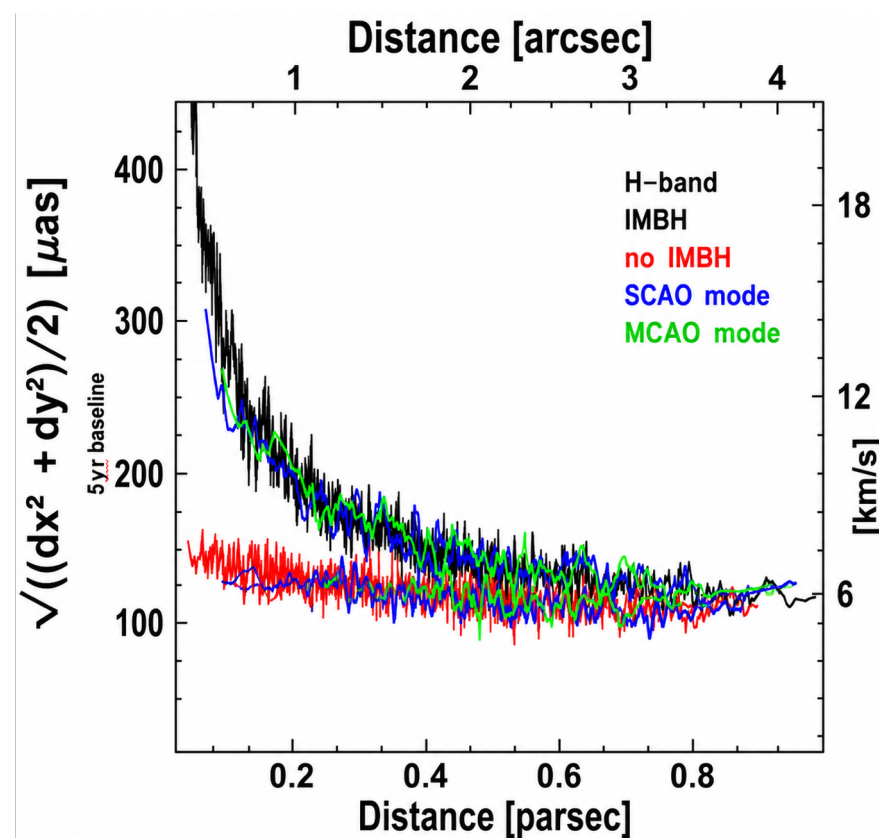


Dynamics of dense stellar systems with high-precision astrometry: searching for IMBH in star clusters

30 Doradus, LMC (~50 kpc)



Fiorentino et al. (2020)

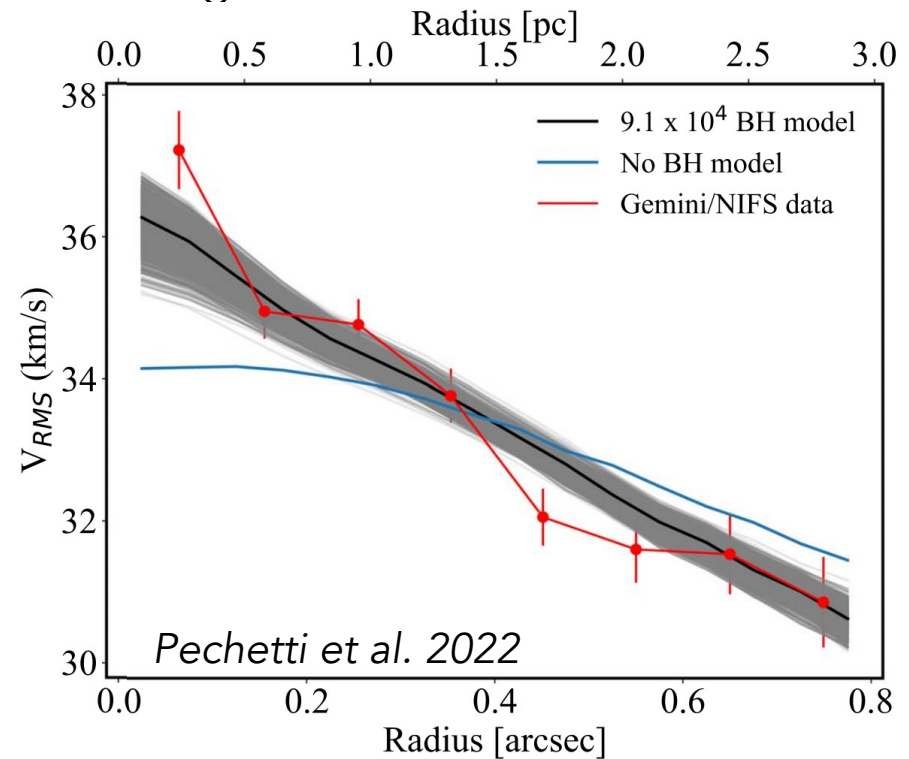
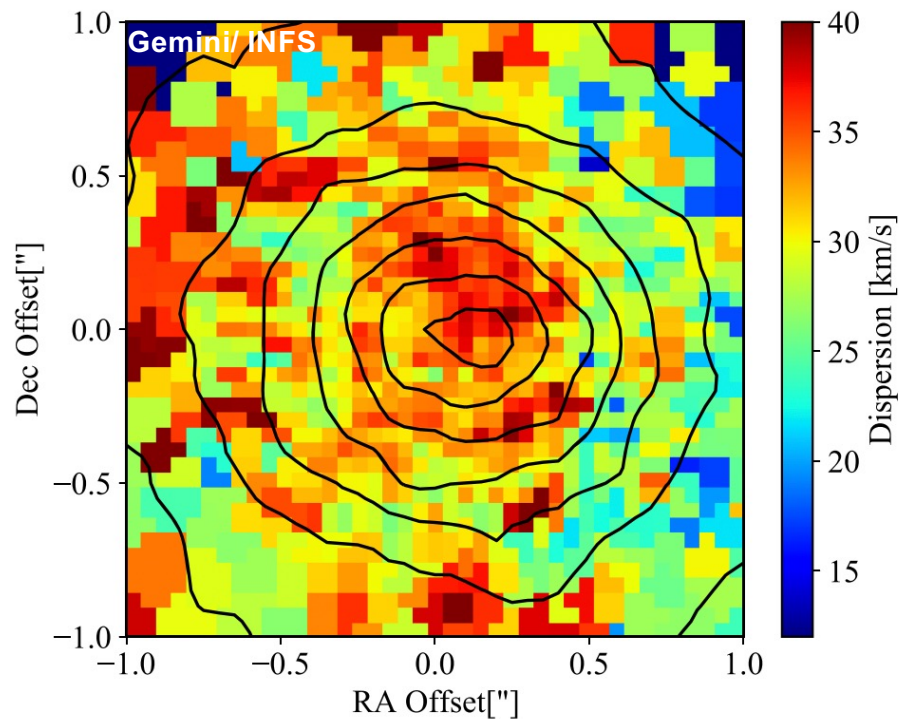




Searching for IMBH with integrated light spectroscopy

At larger distances, IMBHs can be detected through kinematics of star and gas in the dense central regions: both spatial and spectral resolution are critical!

GC B023-G078 in M31, $M_{\star} \sim 6 \times 10^6 M_{\odot}$, $M_{\text{BH}} \sim 9 \times 10^4 M_{\odot}$

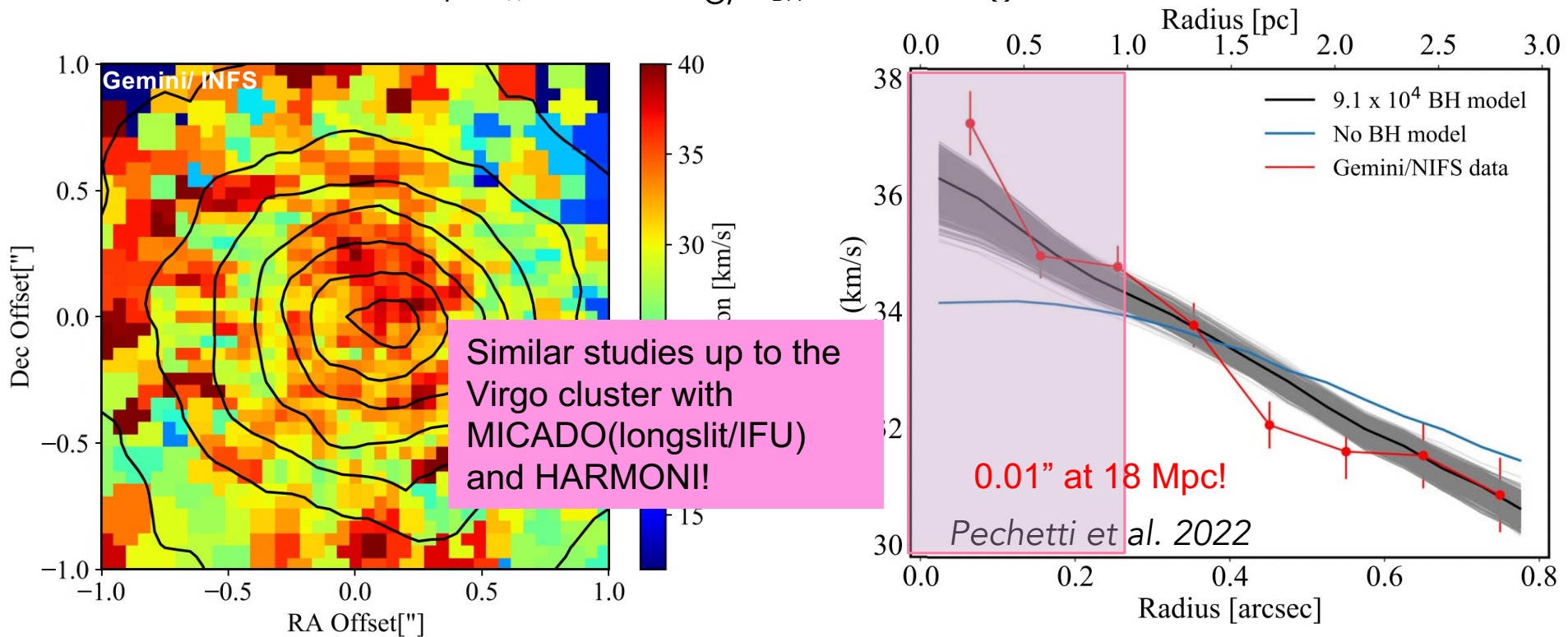




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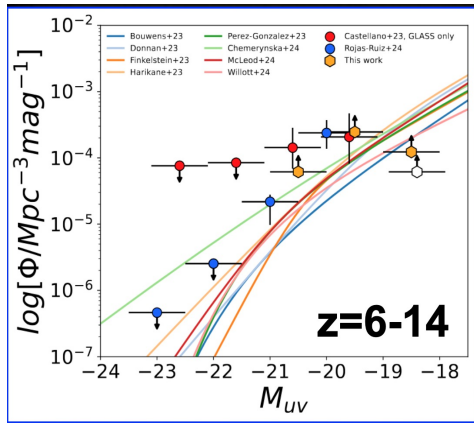




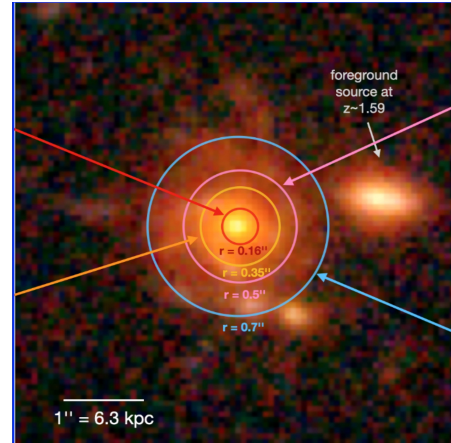
JWST revolution for high z Universe

Grand-design spiral galaxies up to $z \sim 5$

Overabundance of bright galaxies at $z > 9$

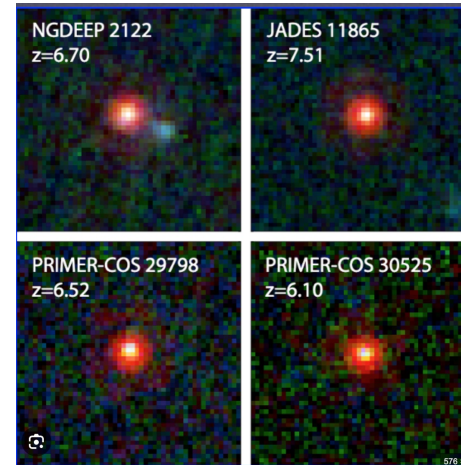


e.g., Castellano +24, Napolitano + 25,
Finkelstein + 24, Dekel+23...



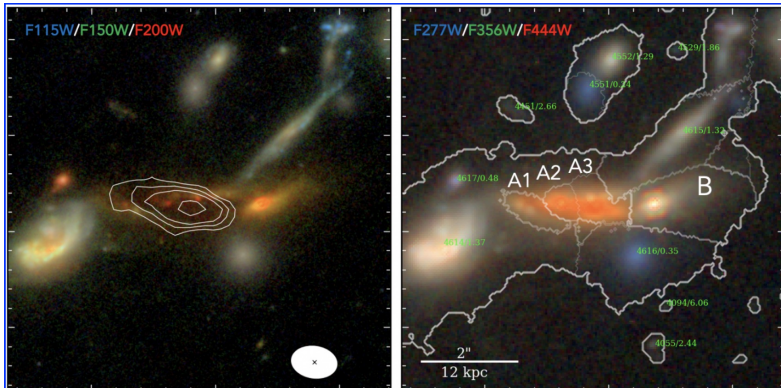
Mengyuan Xiao + 24

Little Red Dots

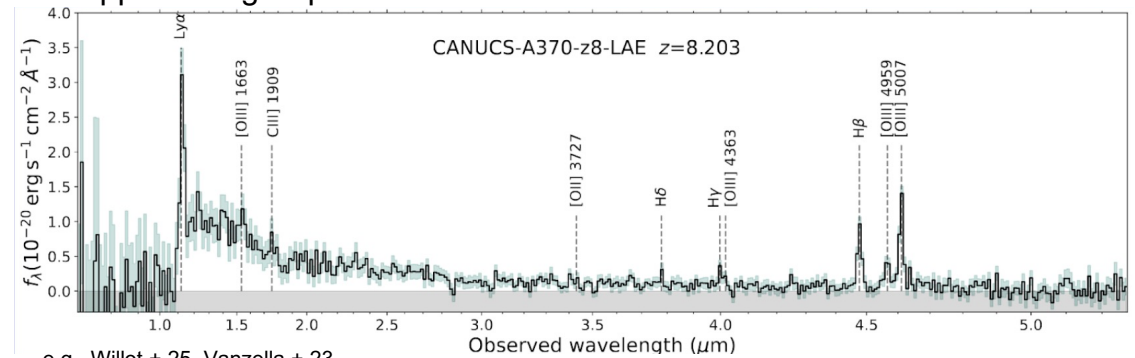


e.g., Furtak + 25

HST dark galaxies



Approaching Pop III stars

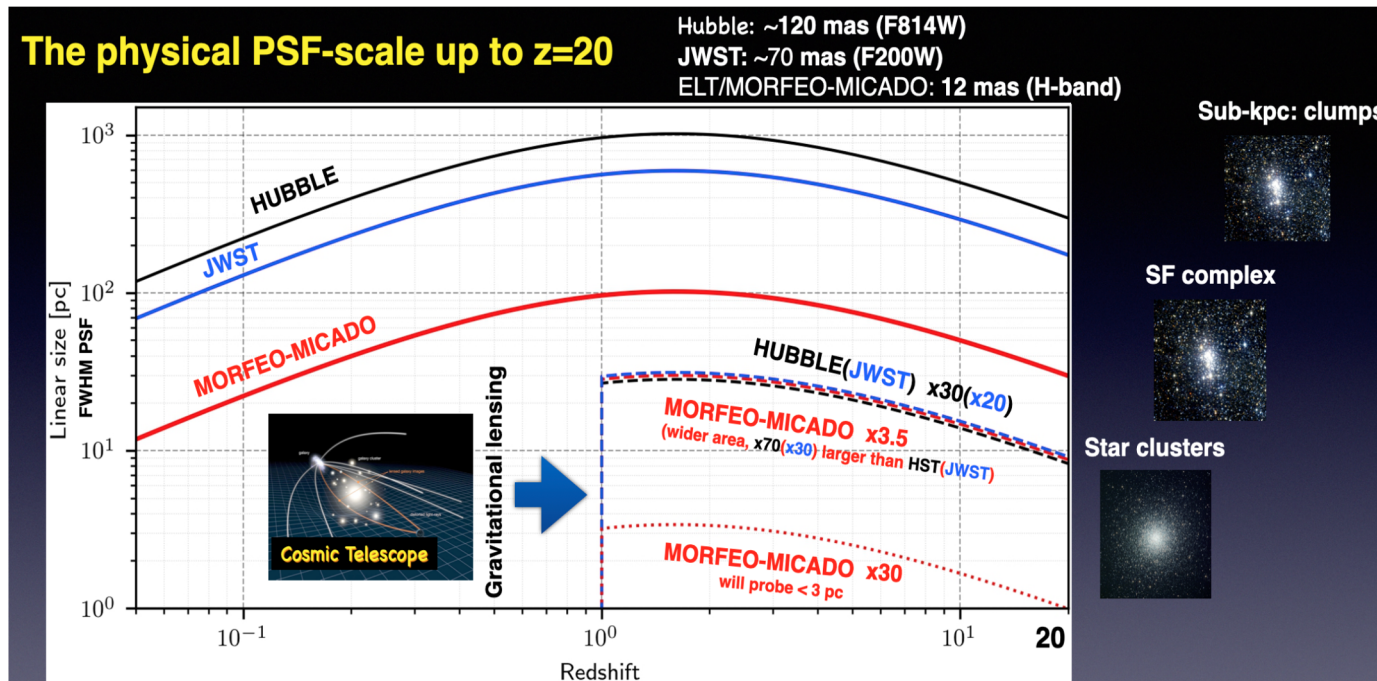


e.g., Willot + 25, Vanzella + 23,
Fujimoto + 24, Maiolino +24



High z Universe with ELT

Probing physical scales <100 pc everywhere in the Universe



Courtesy E. Vanzella



High z Universe with ELT

Probing physical scales < 100 pc everywhere in the Universe

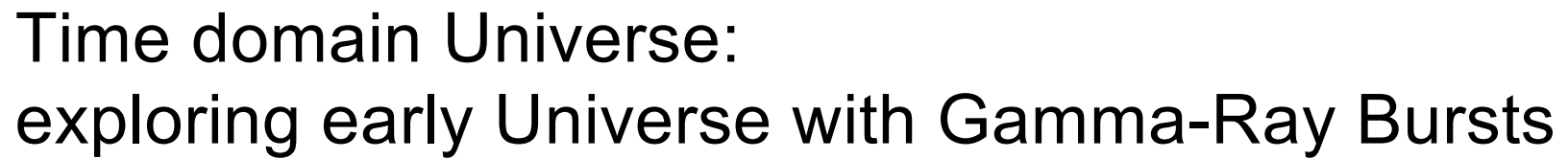
- Recovery of galaxy morphologies (bulges, bars, spiral arms, SF clumps) up to $z \sim 2$ → see **Letizia Scaloni's** talk

- Studying massive, compact, old galaxies at high z → see **Crescenzo Tortora's** talk

- Star forming clumps in high- z galaxies → see **Eros Vanzella's** talk

- High – z star forming galaxies → see **Anita Zanella's** talk

Courtesy E. Vanzella

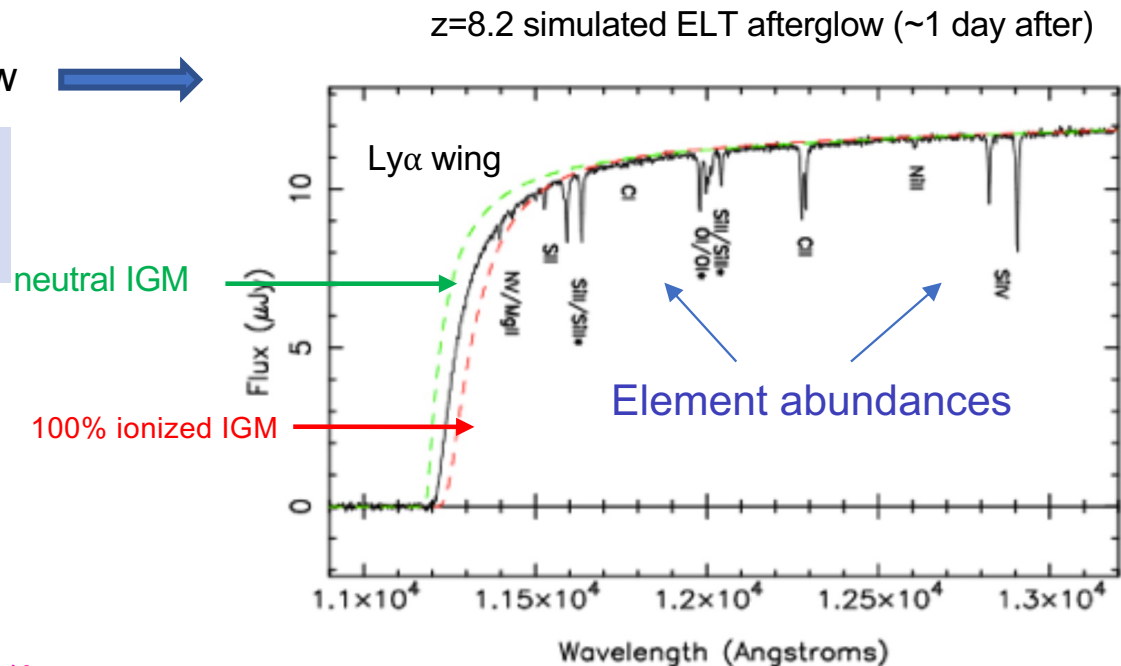


- With MORFEO/MICADO/HARMONI@ELT:

Cosmic chemical evolution: AGs provide high-S/N spectra enabling study of abundances in host and intervening absorbers.

Reionization: AGs provide info on column density of HI $\rightarrow$ constrain on f_{esc}

Detection of $z>6$ GRB is $\lesssim 1/\text{yr}$, but increased rate of discovery with future facilities (SVOM, THESEUS, etc)!





Characterization of electromagnetic counterparts of compact binary coalescence systems

- Electromagnetic counterpart of NS-NS and NS-BH mergers
- Studying host galaxy + kilonova



By resolving in detail the host's stellar population, we could get insights on the age of the progenitor



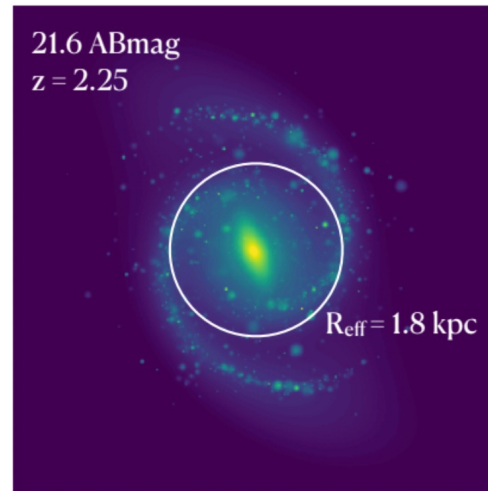
Characterization of electromagnetic counterparts of compact binary coalescence systems

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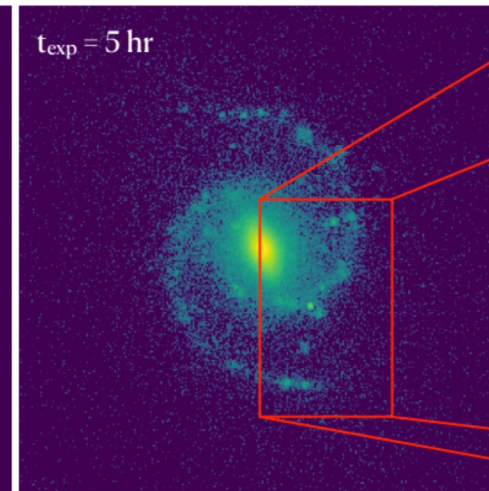


By resolving in detail the host's stellar population, we could get insights on the age of the progenitor

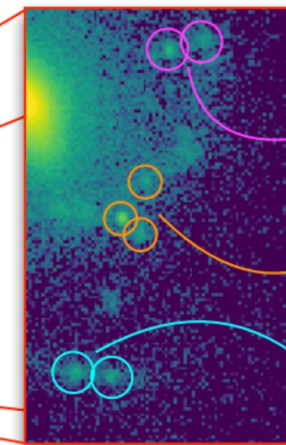
MORFEO/MICADO Simulations by Letizia Scaloni,



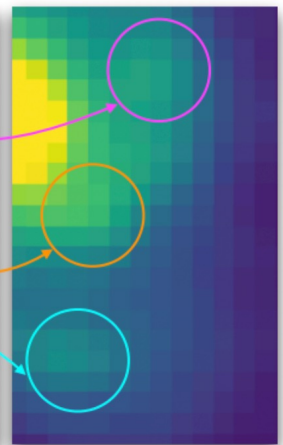
GALFIT model



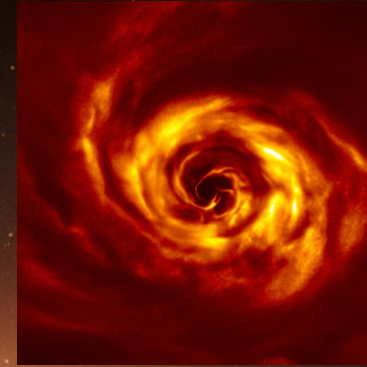
ScopeSim output



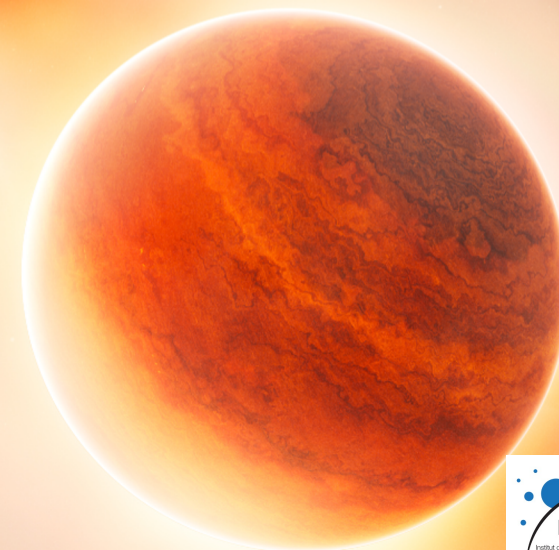
M&M K-band
PSF FWHM = 12 mas



JWST F200W
PSF FWHM = 66 mas



Thanks!







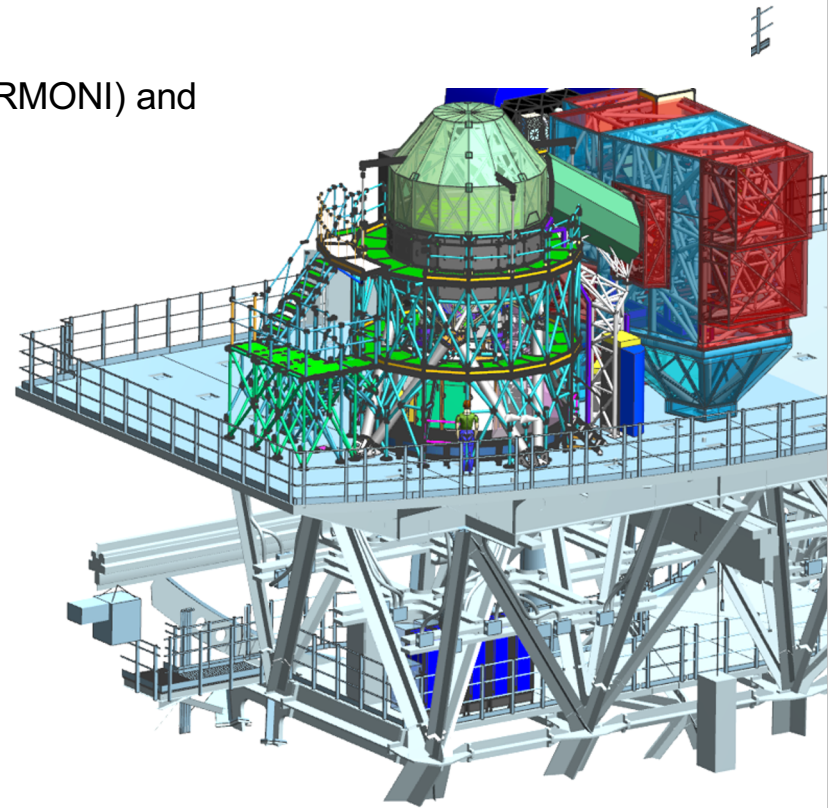
Additional slides

MORFEO: Multiconjugate adaptive Optics Relay For ELT Observations (PI P. Ciliegi, INAF)

- **MORFEO** is the AO instrument for the ELT (serving MICADO and HARMONI) and will provide MCAO correction
- First Technical light end of 2031, commissioning in 2031-2032
- One of the largest projects with INAF leadership:
 - ❖ INAF: leader institute, 85% of FTE
 - ❖ CNRS, France : LGS WFS module
 - ❖ University of Galway, Ireland : Test Unit
 - ❖ NRC, Canada : Real Time Computer
 - ❖ Three Japanese Institutes (NAOJ, University of Kyoto, University of Osaka): two Optical elements

GTO (105 NIGHTS IN TOTAL)

INAF	80.3
CNRS	9.2
UoG	2.5
NRC	6.0
JPI	7.0

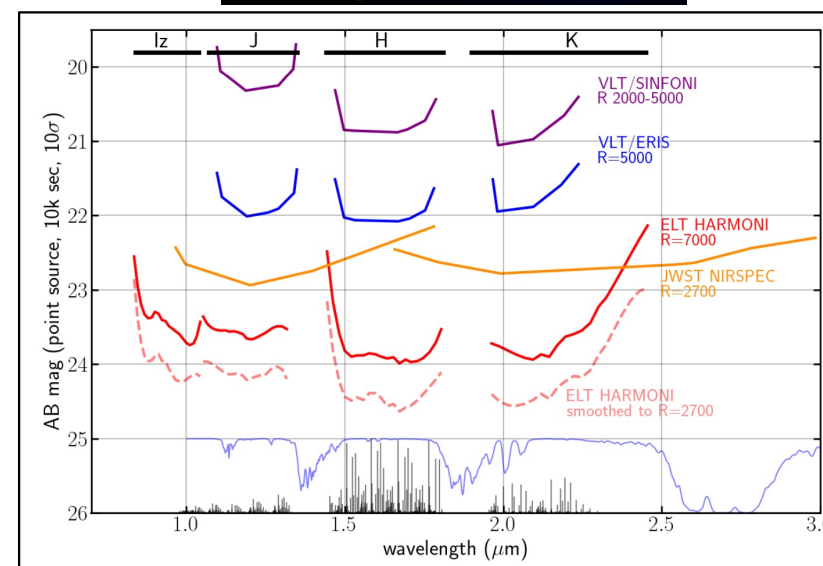
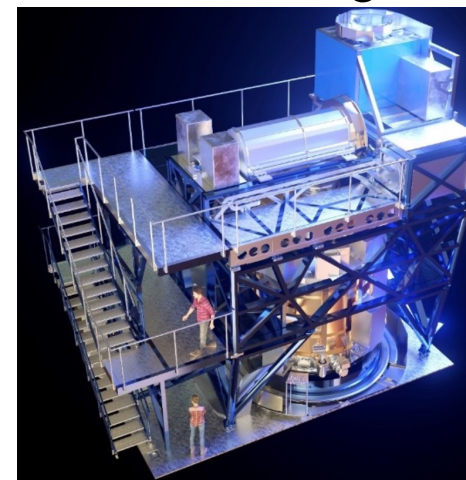




HARMONI: High Angular Resolution Monolithic Optical and NIR Integral field spectrograph (PI J. Dunlop, Univ. of Edinburgh, UK))

- **HARMONI** recently rescoped (MORFEO will provide AO correction)

Simplified HARMONI		
Spatial pixel scale	6x6 mas	25x25 mas
FoV	1.2"x 0.9"	3.8" x 5.1"
Wavelength range	0.8 – 2.4 μm	
Spectral resolution	R=7000 (Iz, J, H, K) R=3000 (Iz+J, H+K)	
SCAO	4x4 mas sampling	
MCAO		



- Courtesy Mark Swinbank (HARMONI PS)



MORFEO updated performance in context

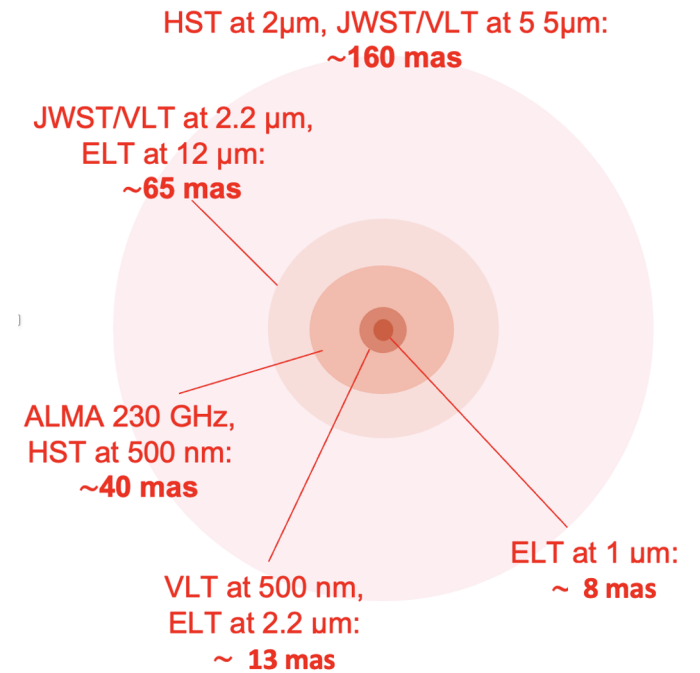
$\geq 50\%$ sky coverage

Band	SR	FWHM [mas]
K	0.6	13
J	0.2	9
I	0.05	8
K	0.44	13.5
J	0.08	9

10 mas at:		
Galactic Center	8 kpc	0.4 mpc
Cen A	4 Mpc	0.2 pc
Virgo Cluster	18 Mpc	1 pc
Cosmic Noon	$z \sim 2$	80 pc

Best atmo conditions, 20" Fov diameter

Avg. atmo conditions, 60" Fov diameter



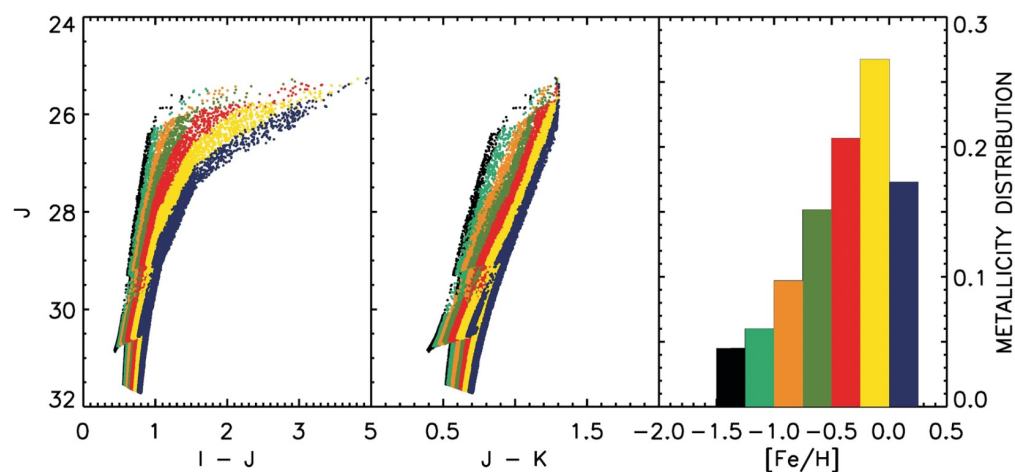


Accessing inner regions of Virgo Ellipticals

Schreiber et al. 2014

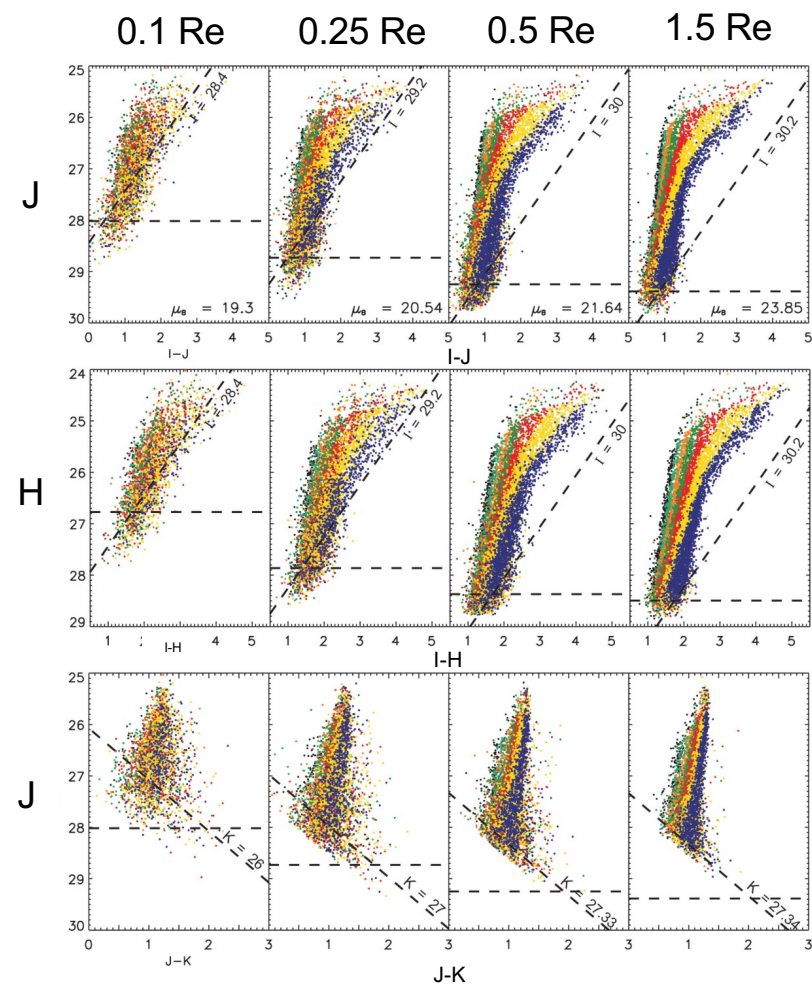
ASSUMPTIONS:

- ✓ flat age distribution between 10-12 Gyr
- ✓ wide metallicity distribution



RESULTS:

- ✓ Metallicity distribution is better recovered in lower SB regions
- ✓ Metallicity bins are well separated at $R > 0.5$ Re
- ✓ (I-J) and (I-H) diagrams more effective than (J-K)

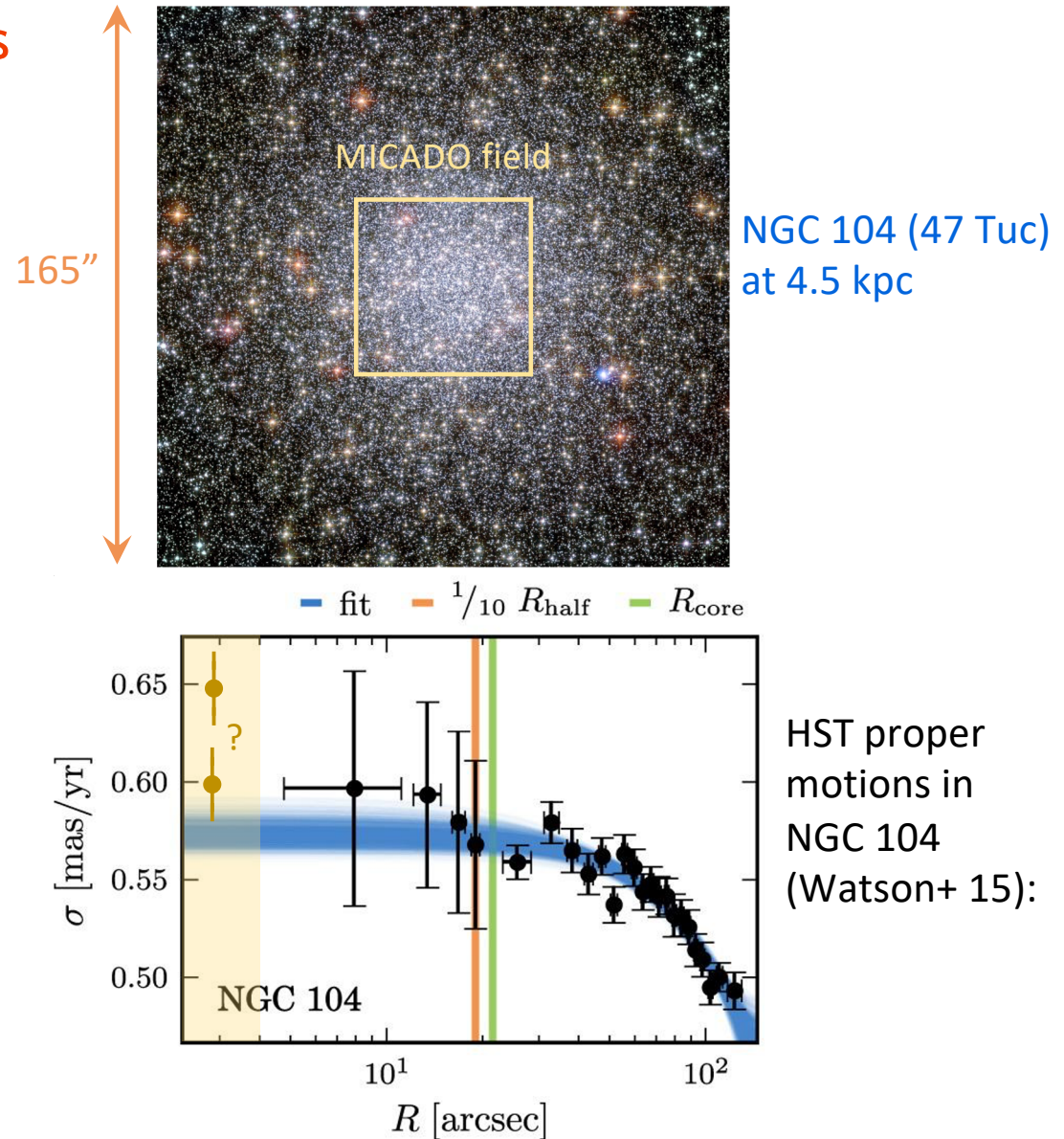


Measuring Black Holes in Globular Clusters

- Almost no robust IMBHs in globular clusters.
- Mass of IMBH uncertain to orders of magnitude.
- Location of IMBH uncertain to arcsec scales.
- Even existence uncertain
(& stellar mass BH cluster is an alternative).

MICADO's role:

- Image wide field at high resolution.
- Overcome extreme crowding in central region: probe dispersion to subarcsec scales.
- Uncertainties from simulations show MICADO can distinguish whether there is a BH.





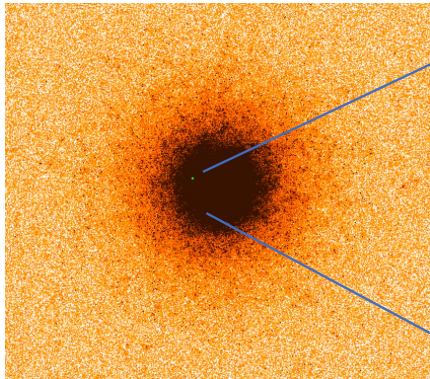
Old stellar populations outside the LG

M&M simulated dwarf

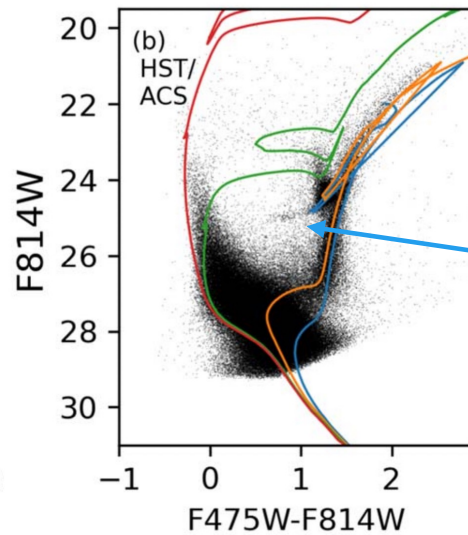
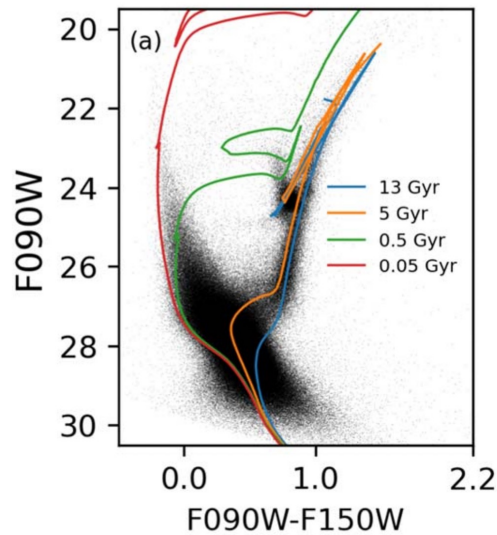
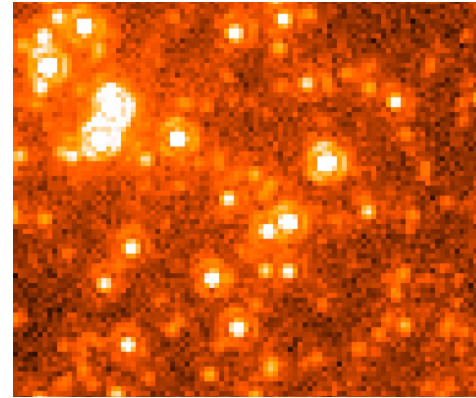
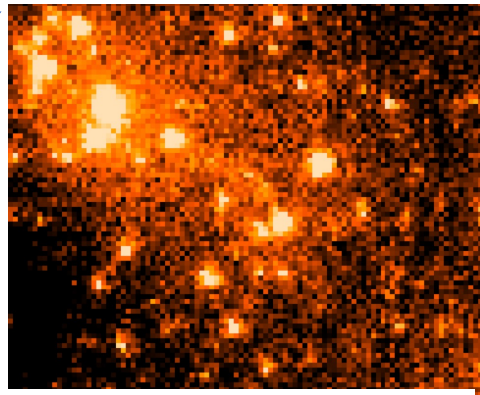
Dwarf galaxy at 5 Mpc, $M_{\star} = 2 \times 10^7 M_{\odot}$

I band

H band

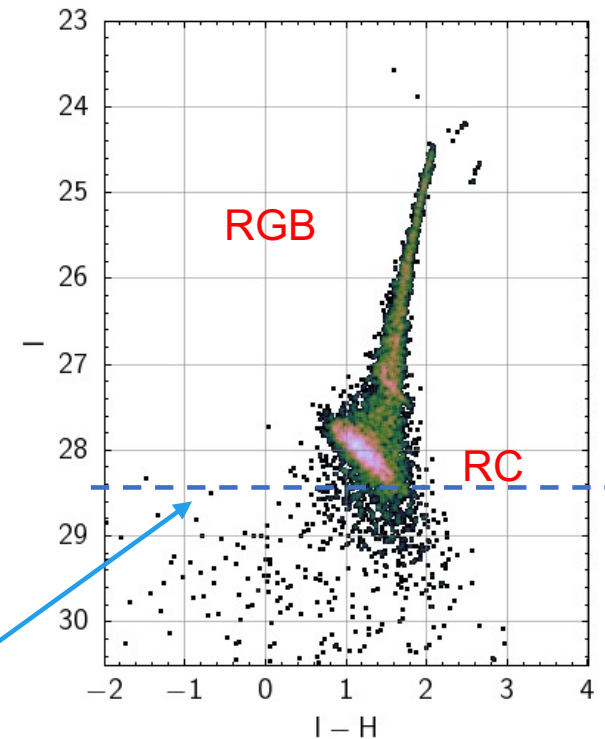


0.4 arcsec



Old, HB stars
detected in all
studied nearby
systems

Parsec iso, 10 Gyr, $[Fe/H] = -1.65$

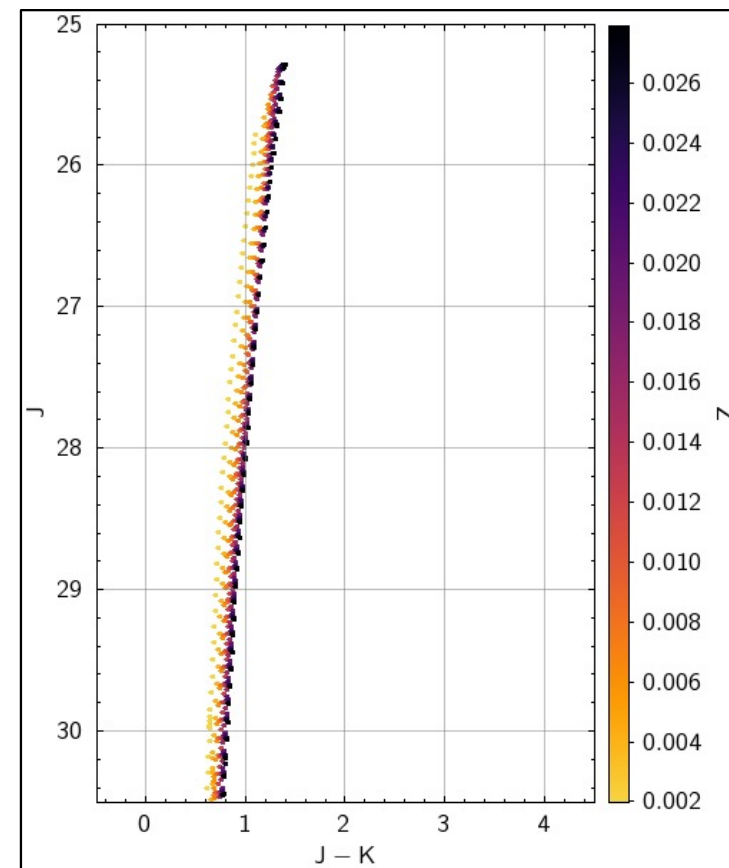
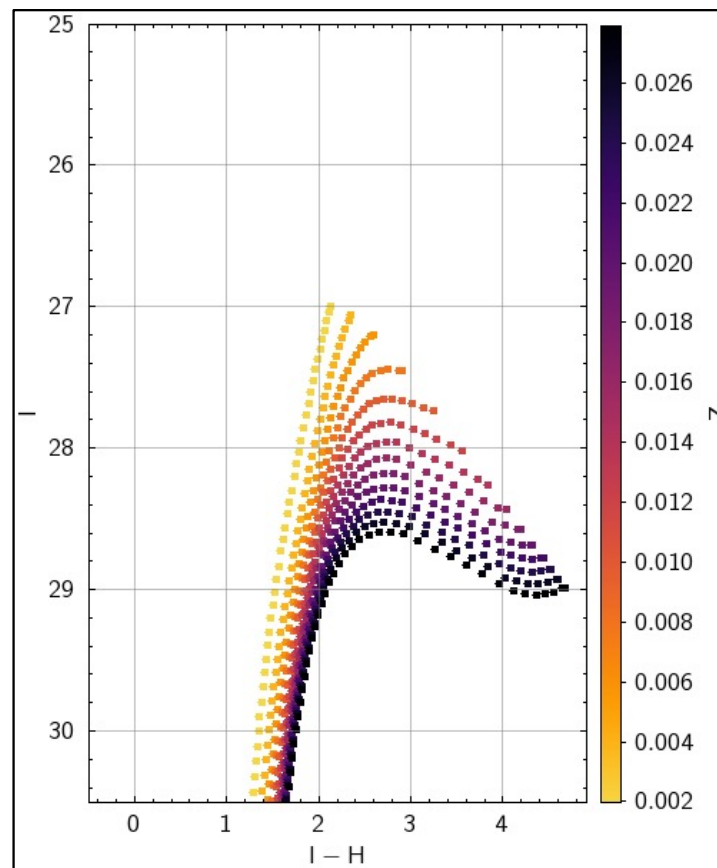
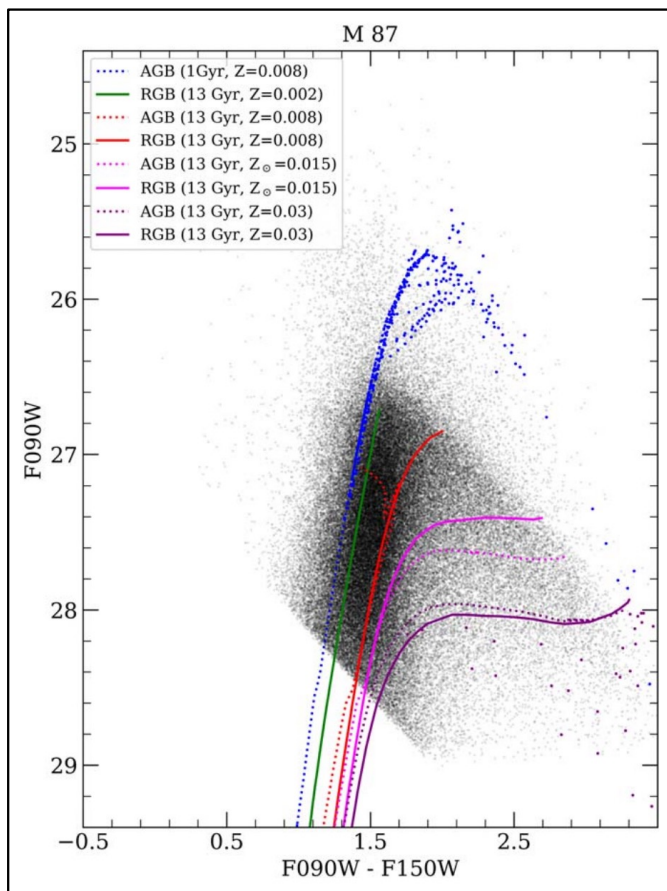




Anand et al. 2025

The importance of color baseline

I, J, H, K filters available with M&M

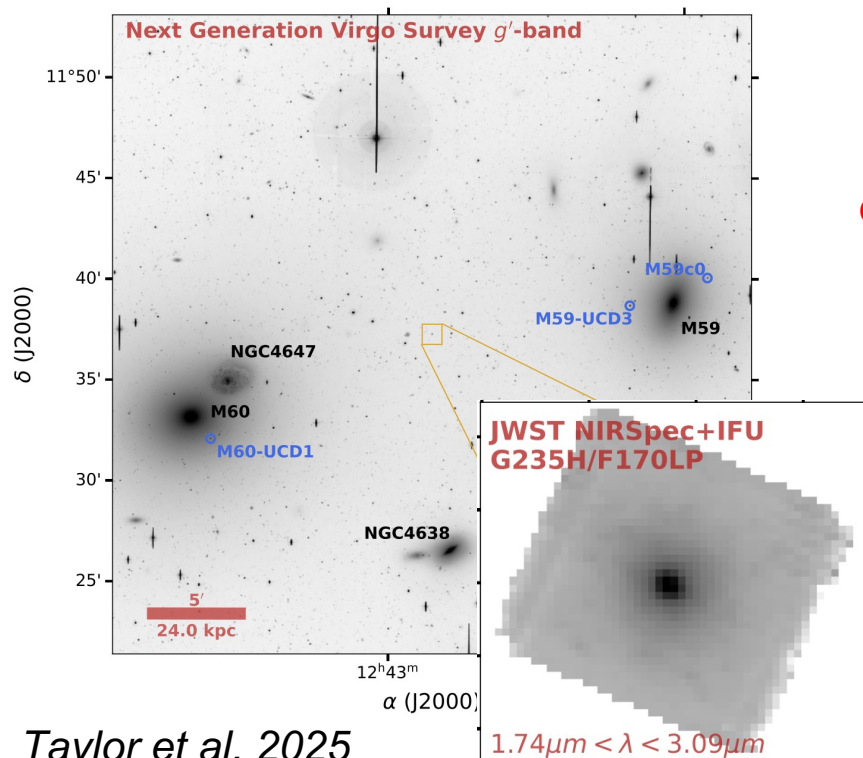




IMBH search in less nearby galaxies

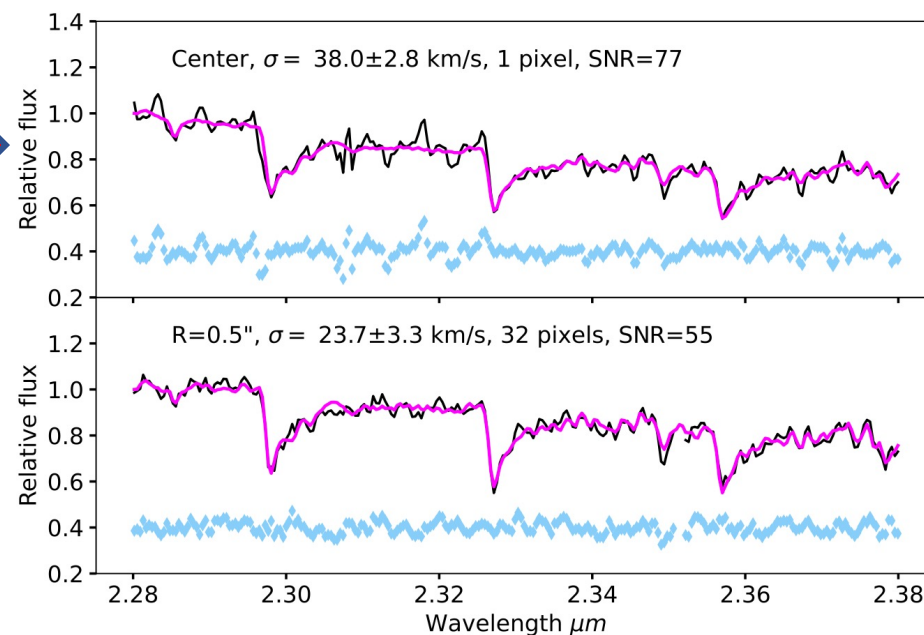
For more distant stellar systems, IMBHs can be detected through **kinematics of star and gas** in the dense central regions: **both spatial and spectral resolution are critical!**

UCD736 in Virgo $M_{\star} = 2 \times 10^7 M_{\odot}$, $M_{\text{BH}} = 2 \times 10^6 M_{\odot}$



Taylor et al. 2025

JWST NIRSpec IFU, $R \sim 2700$, FWHM $\Delta v_r \sim 47$ km/s



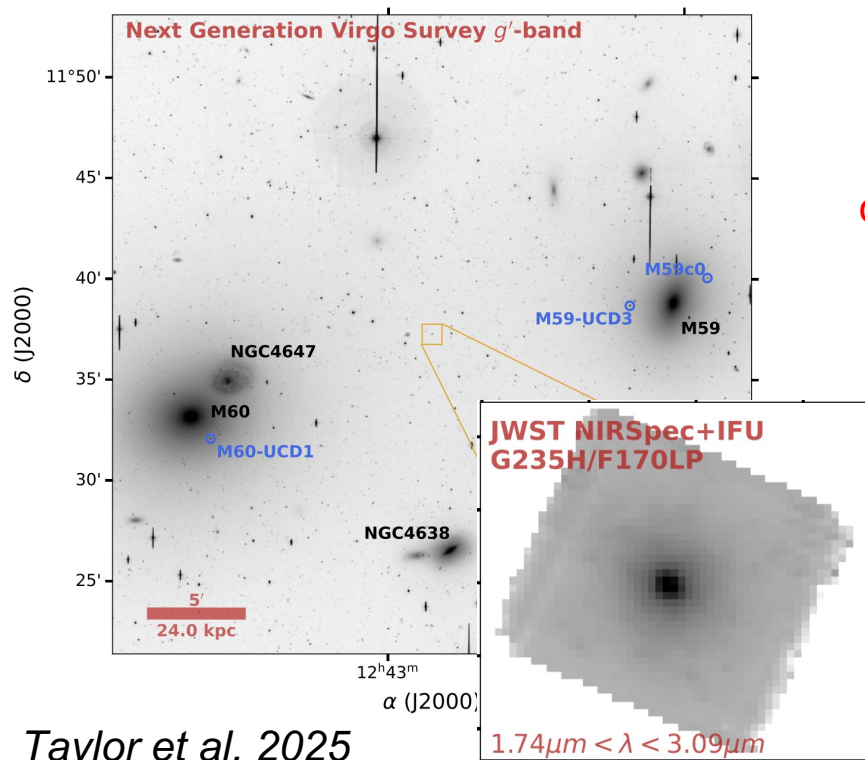


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MICADO long slit: 16 mas width, $R \sim 20,000$

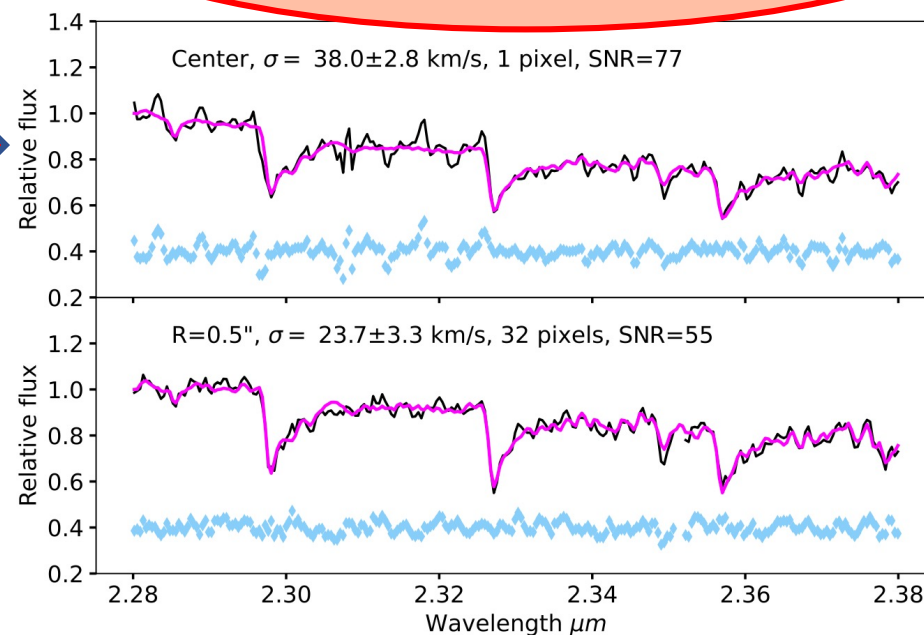


Taylor et al. 2025

central
pixel



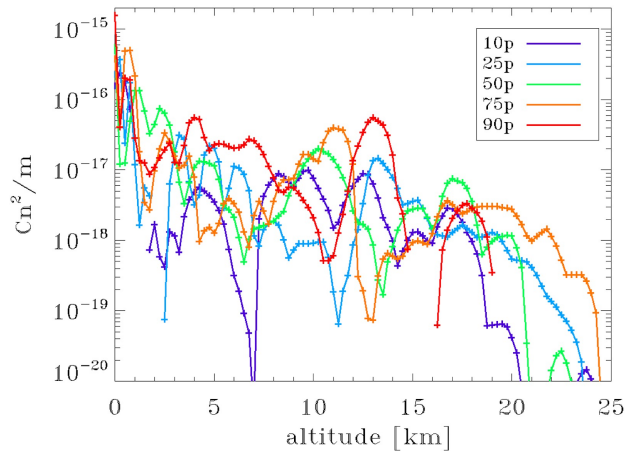
JWST NIRSpec





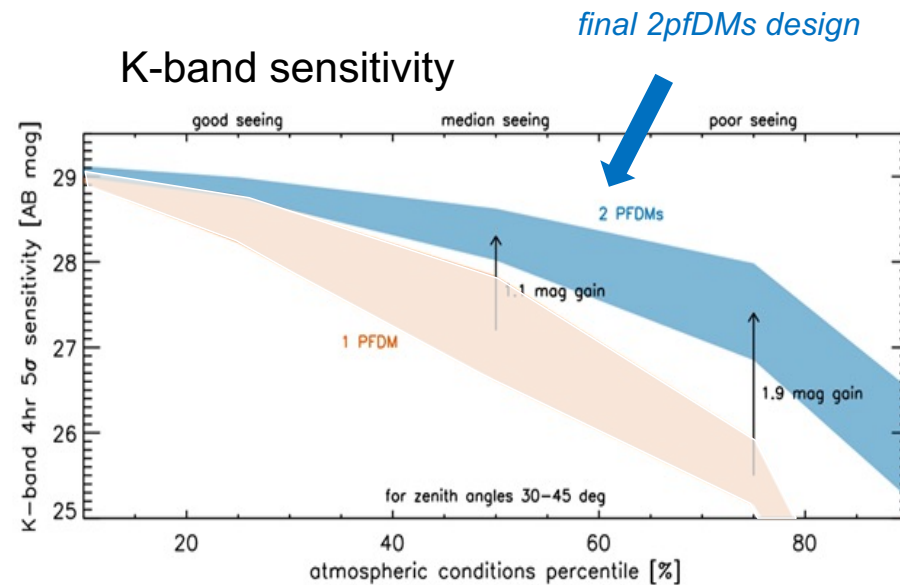
Performance – Strehl Ratios and Sensitivity

- Exhaustive analysis of the expected performance under a variety of observing conditions, based on **representative atmospheric profiles** (Q1 to Q4, or P10 to P90, from very good to very bad conditions)



P10 to P90 profiles from SCIDAR database (20,000 in tot) corresponding to 10th, 25th, 50th, 75th and 90th percentiles of observing conditions)

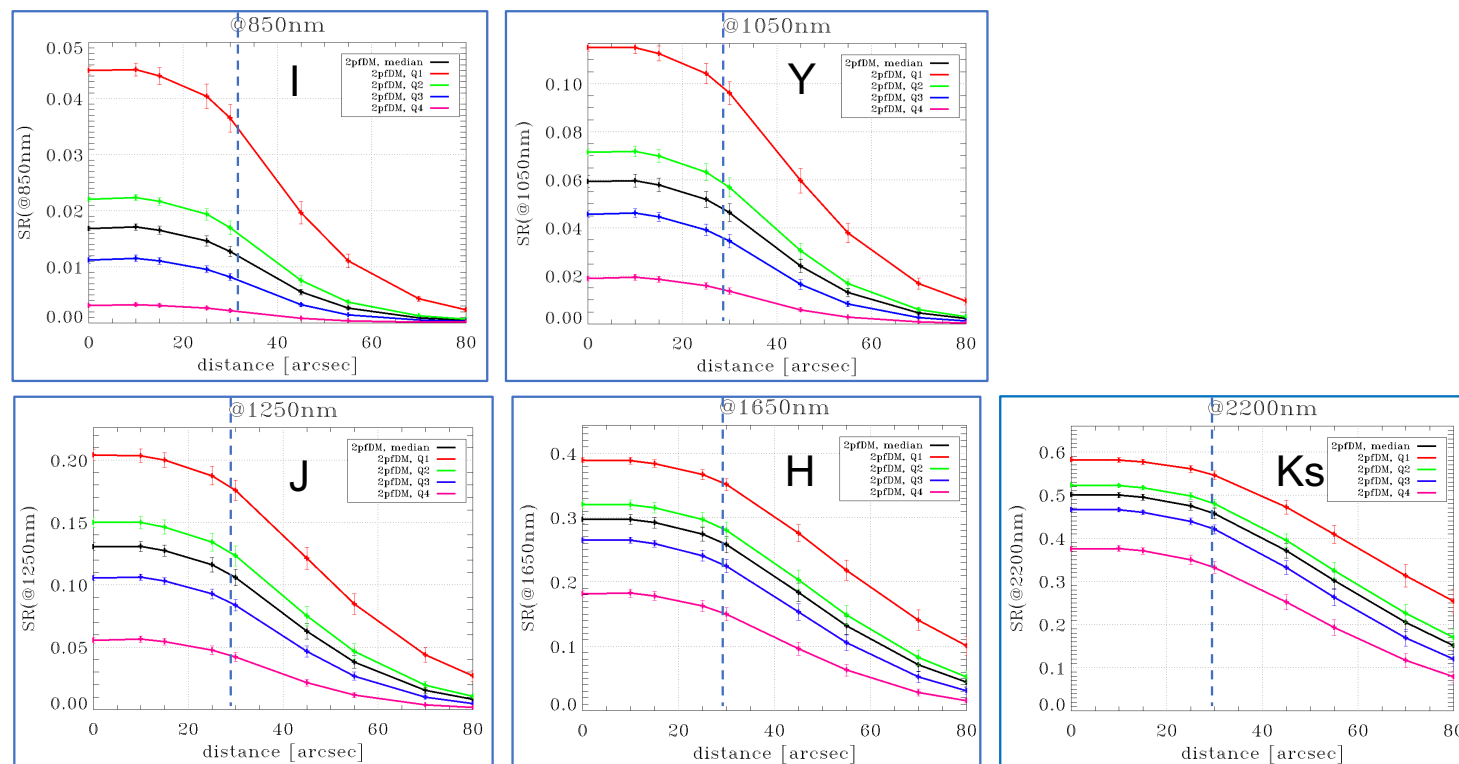
SR%	P10	P25	P50	P75	P90
I	13.4	7.5	2.5	0.8	0.1
Ks	71.4	64.9	53.5	43.2	30.6





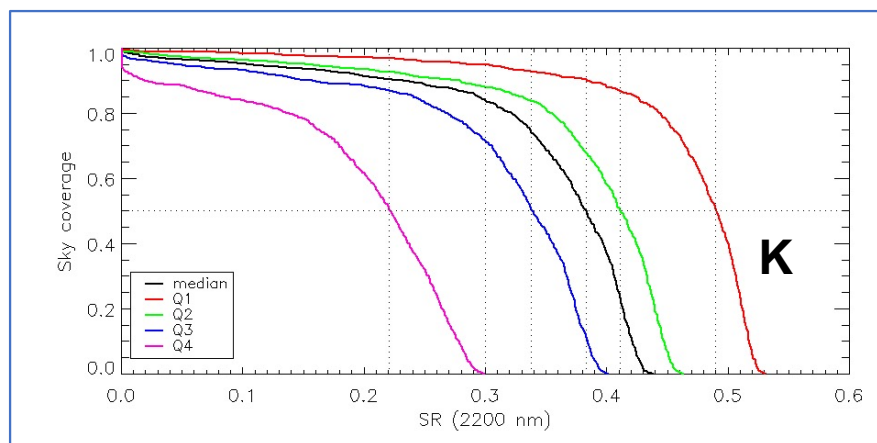
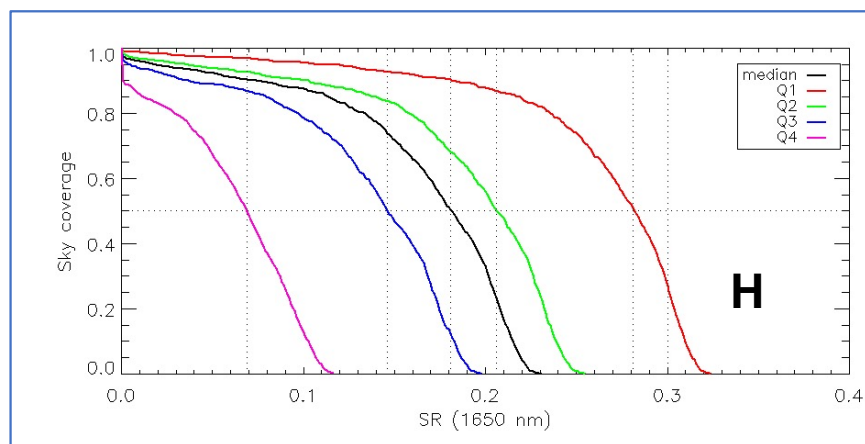
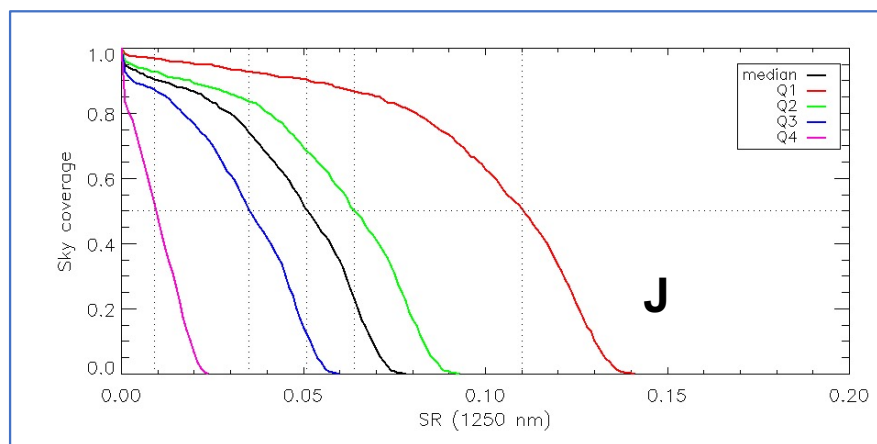
Performance – SRs radial trends

- SRs derived for a good NGS asterism and computed starting from PSFs (no Marechal approximation)
- Results: larger spatial variation of SR at shorter wavelength – SR quite uniform over MICADO FoV in Ks





Performance – Sky Coverage (60" FoV)

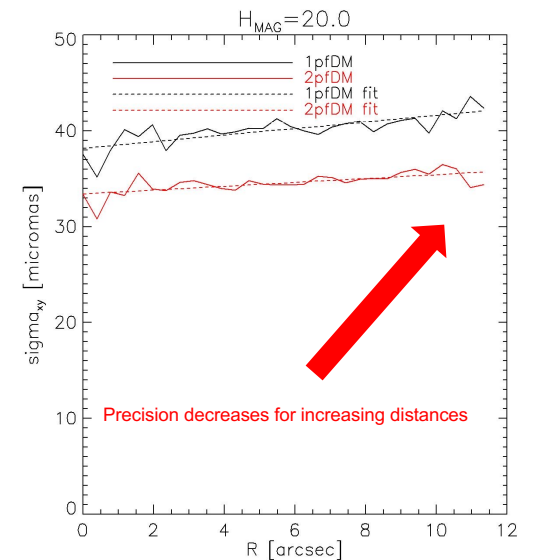
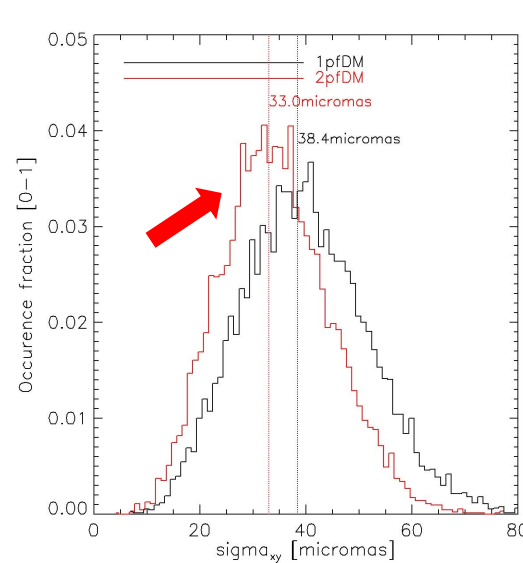


SR from Marechàl



Performance – Astrometric Accuracy

- MICADO zoom-in mode, 1.5mas/pixel
 - Simulation of $\sim 10,000$ stars ($H=20$) uniformly distributed over a MICADO FoV of $16'' \times 16''$
 - Spatially variable PSF
 - Photometric reduction (DAOPHOT) of the simulated images, see how well centroids are recovered
- this provides a **relative** astrometric precision of ~ 30 microarcsec

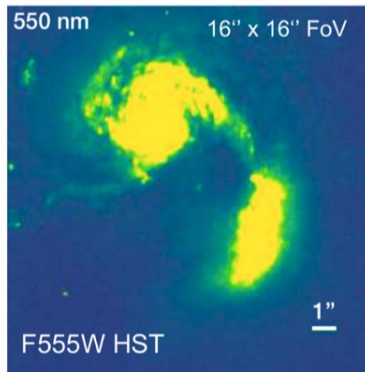




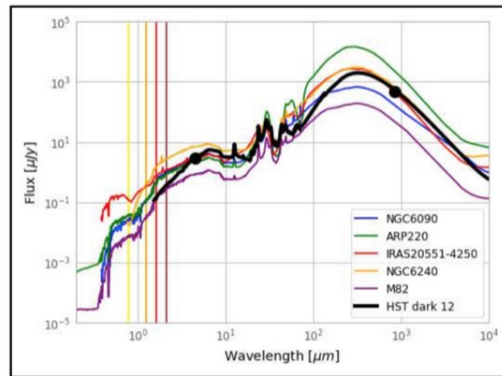
HST dark galaxies – obscured star formation

Assumptions:

1) Local template: ULIRG NGC 6090

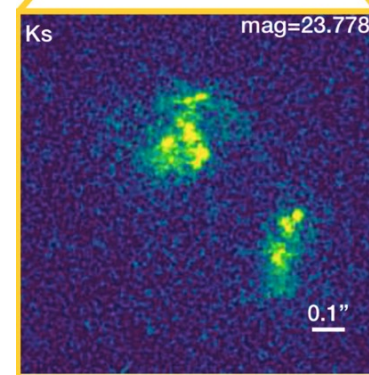
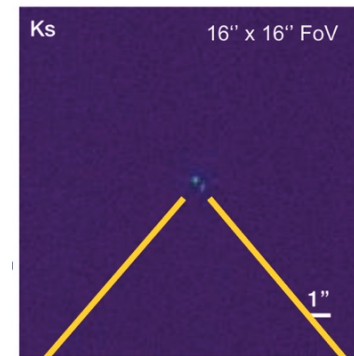


2) HST- dark SED ($z=2.85$)

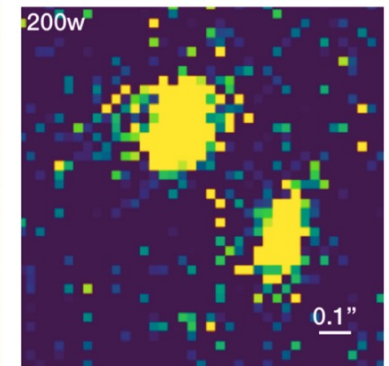


Simcado

Simulated M&M images



≥ 10 h exposure time

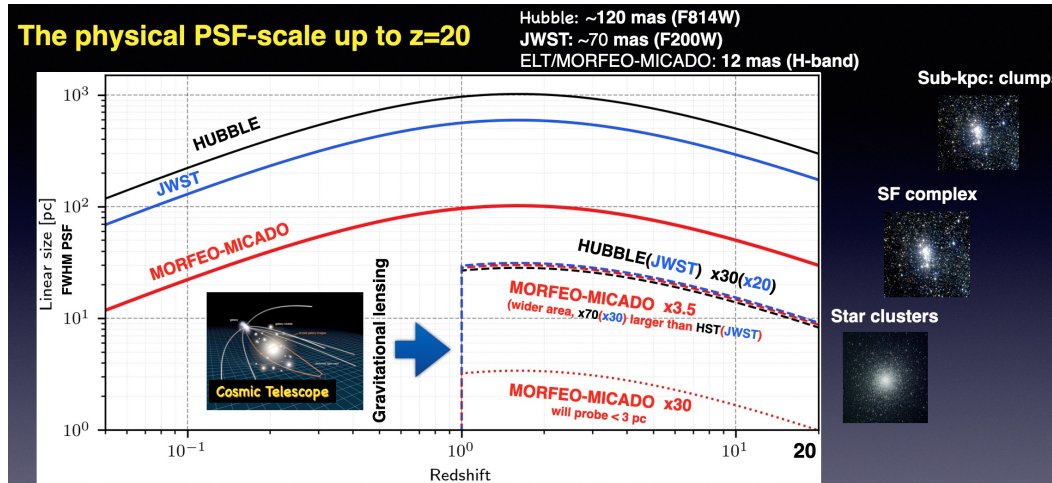


JWST simulation

L. Pasquale Ms. thesis at Bologna
(supervisors F. Annibali & C. Gruppioni,
MORFEO ST member)



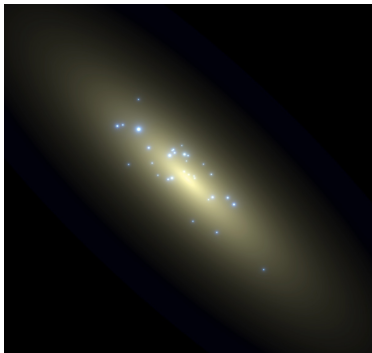
MORFEO+MICADO simulations of high-z sources with strong gravitational lensing



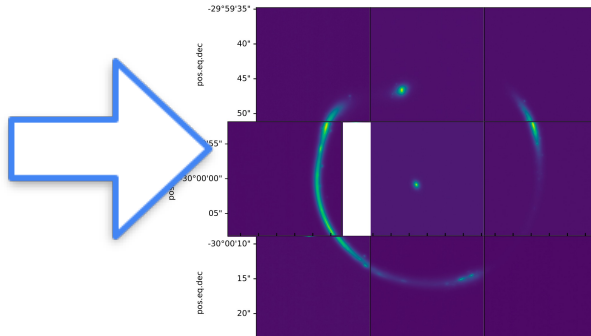
Gravitational Lensing as a
cosmic telescope

From Irene Mini's Ms. thesis (INAF-OAS Bologna).
 Supervisor: M. Meneghetti (MORFEO ST member)

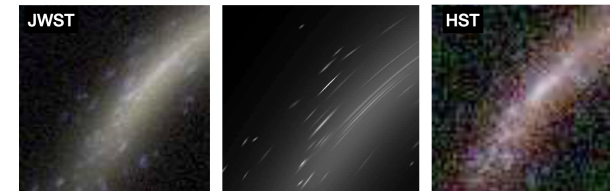
Populating an host galaxy with
 star clusters...



...and moving it to high- z ($z=1$)
 behind a cluster ($z=0.44$)



I band, 500 s exposure time



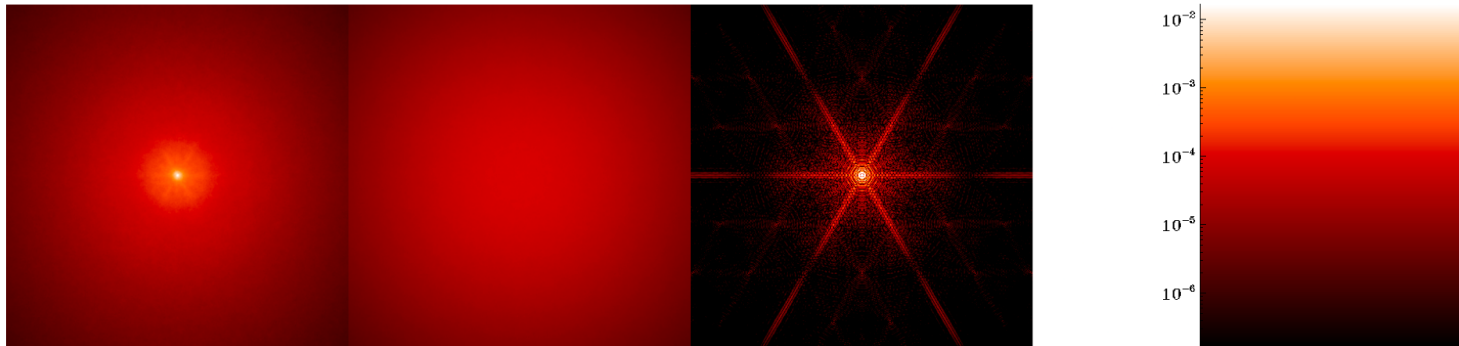


CL VS seeing – I band (850nm)

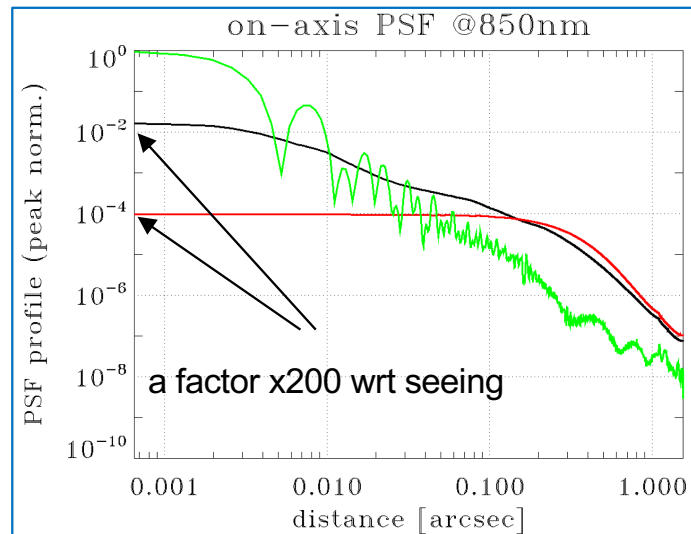
Closed loop

Seeing limited

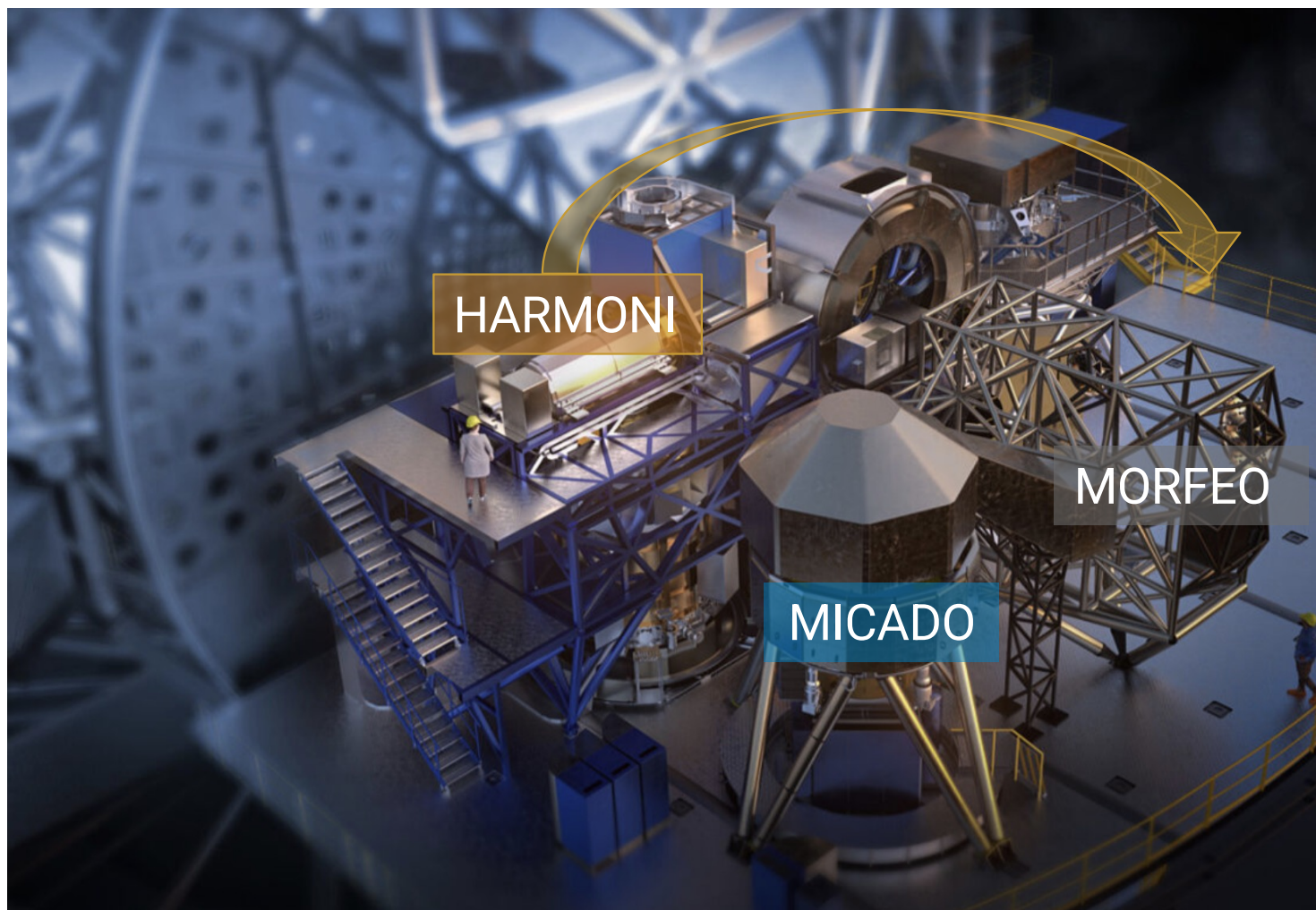
DL



- median atmo (seeing 0.65")
- $z=30$ deg
- on-axis PSF
- NGS@55", $H=10$



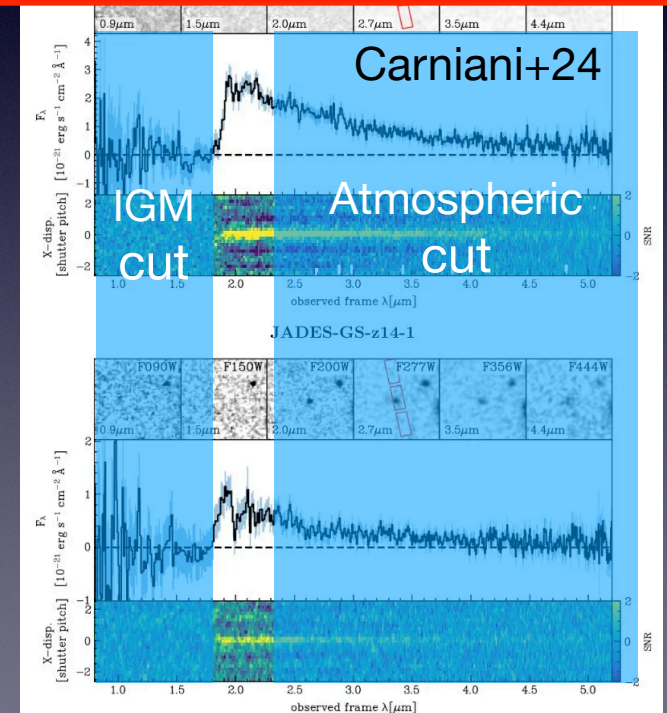
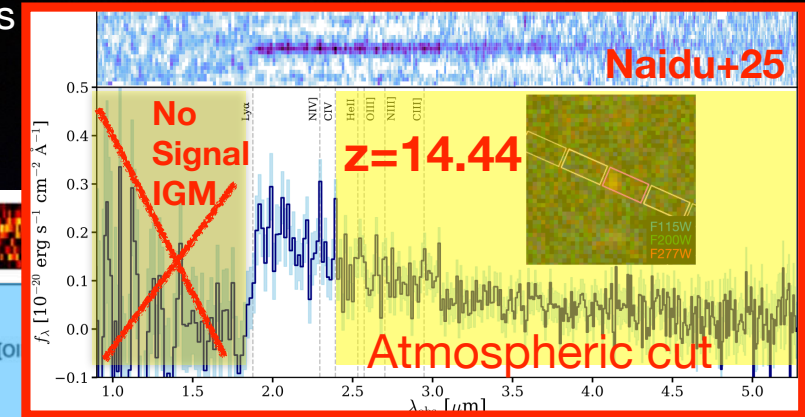
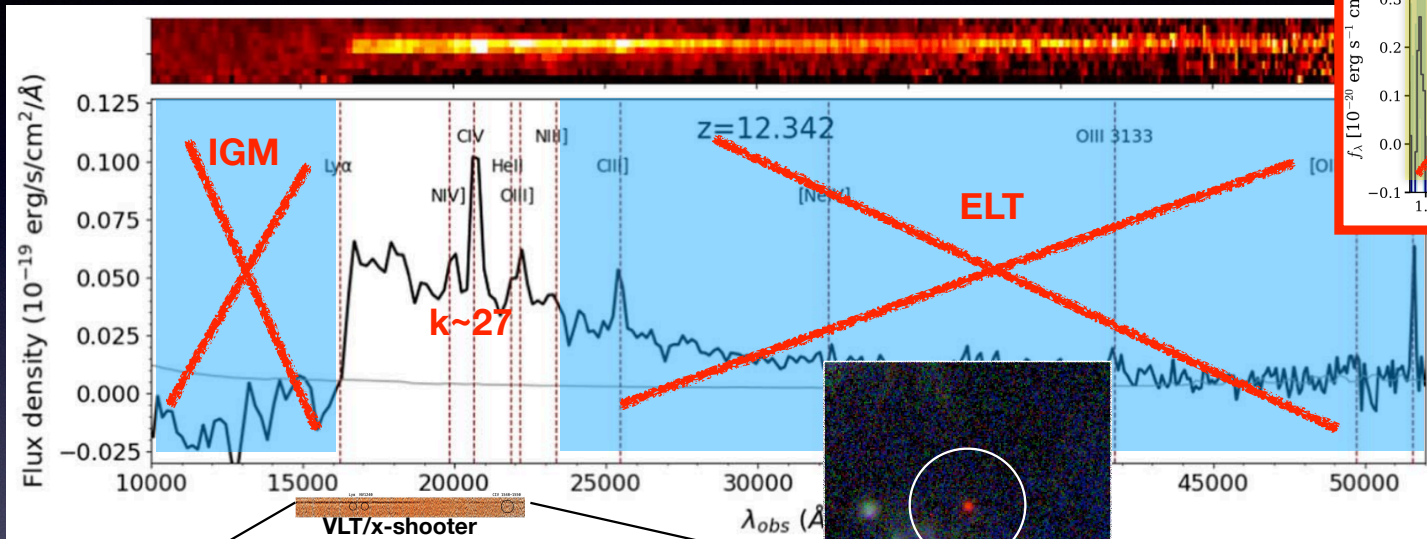
- $SR(I)$ is $\sim 2\%$
- ratio with seeing is $\sim 200\times$



Present(II): Early Universe, the ongoing revolution JWST

- As redshift increases the observable spectral range drastically decreases
- The best high- z targets will be JWST-based

Castellano+24 - JWST/NIRSpec - prism an example at $z=12.34$



VLT/X-Shooter (30h, PI Vanzella)

The deepest and highest redshift spectrum from ground-based telescope in the NIR