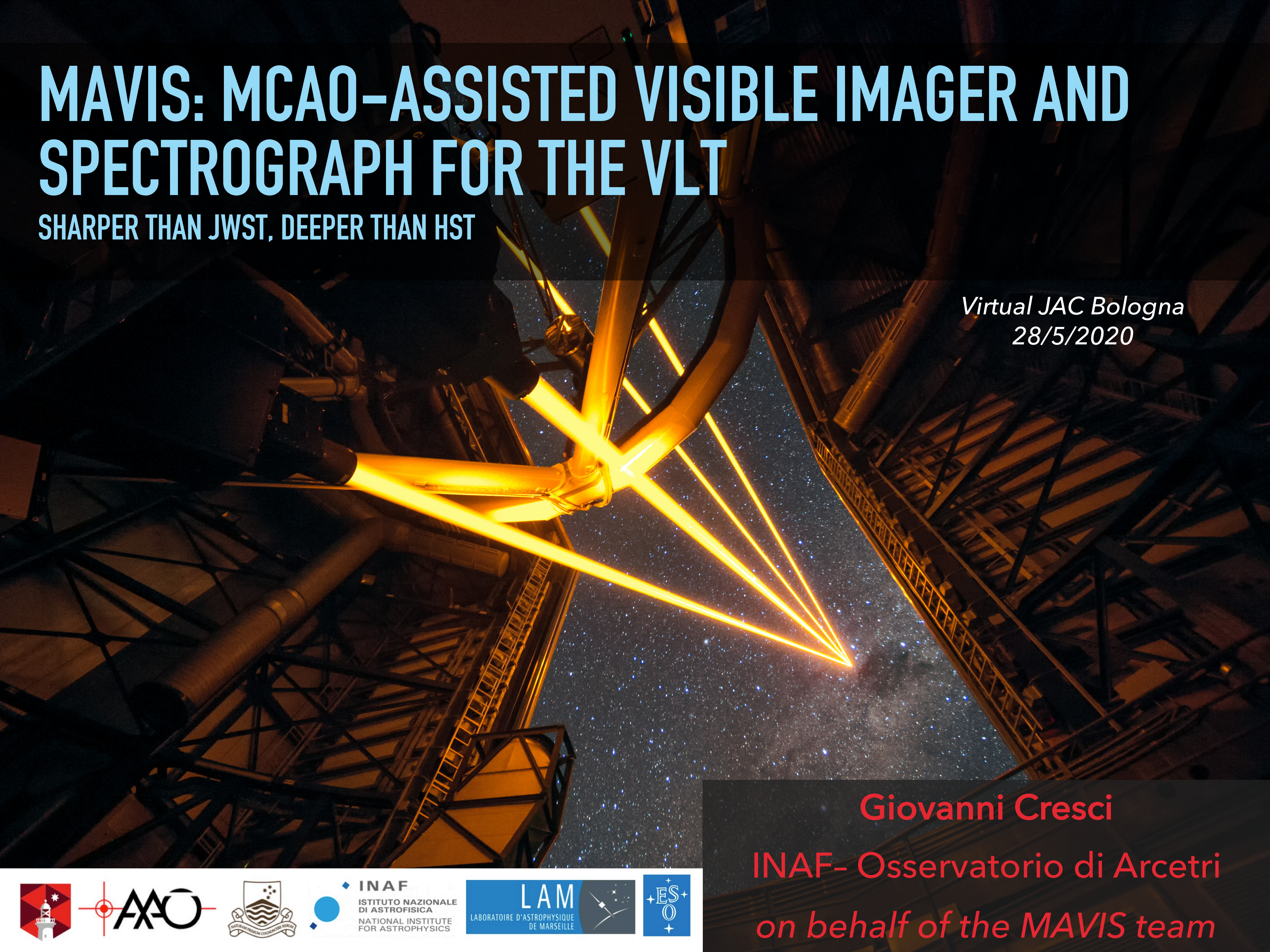


MAVIS: MCAO-ASSISTED VISIBLE IMAGER AND SPECTROGRAPH FOR THE VLT

SHARPER THAN JWST, DEEPER THAN HST

Virtual JAC Bologna
28/5/2020

Giovanni Cresci

INAF– Osservatorio di Arcetri

on behalf of the MAVIS team

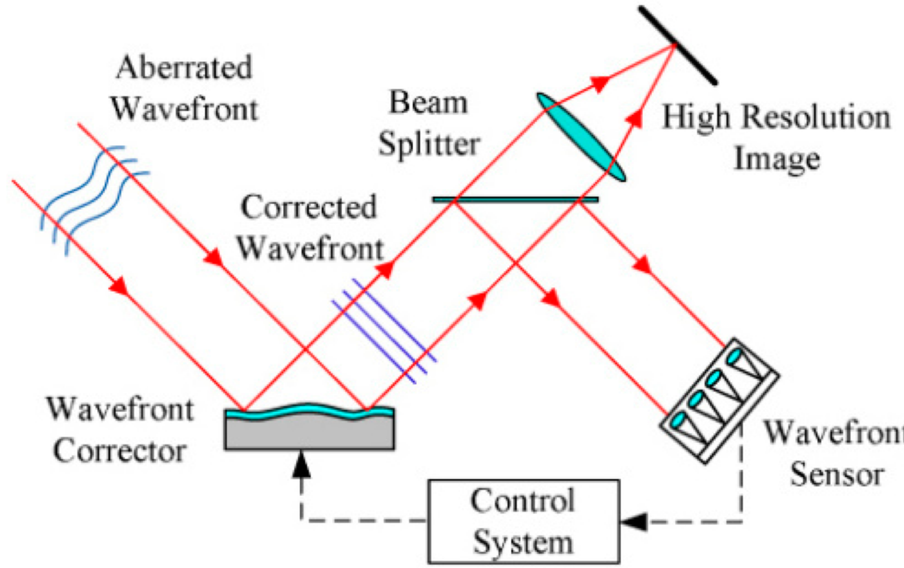
A BRIEF HISTORY

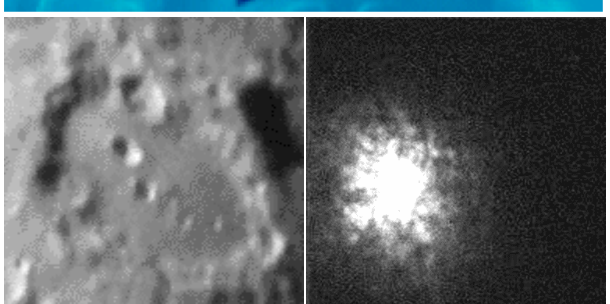
- "ESO Community Days" annual workshop to discuss future instrumentation and upgrades:
  - 2015+2016, a visible MCAO capability gathered most interest
  - Concept initially presented by Simone Esposito (INAF Arcetri)
- July 2017: Australia joined ESO as strategic partner
- October 2017: consortium formed to address ESO phase A call, with INAF (Arcetri, Padova & Roma), Laboratoire d'Astrophysique de Marseille (LAM), and Australian Astronomical Optics (AAO, including ANU, MQ & UniSyd)
- Initial science workshop November 2017 in Sidney
- October 2018: Phase A proposal submitted to ESO
- November 2018: MAVIS awarded agreement for phase A conceptual design study by ESO
- May 2020: Phase A review

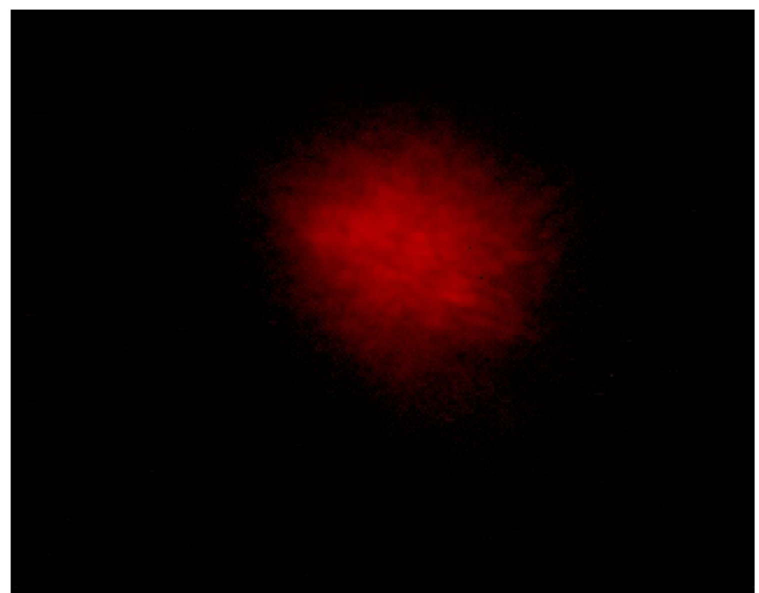
ADAPTIVE OPTICS

An Adaptive Optics system uses the light from a bright (R<~15) natural or artificial laser star to counteract these aberrations using a deformable mirror (frequency up to kHz)

Observing from ground is like looking through a pool full of water:
the atmosphere refracts starlight in random directions → seeing: the resolution of a 8m telescope is the same of a ~30 cm one!



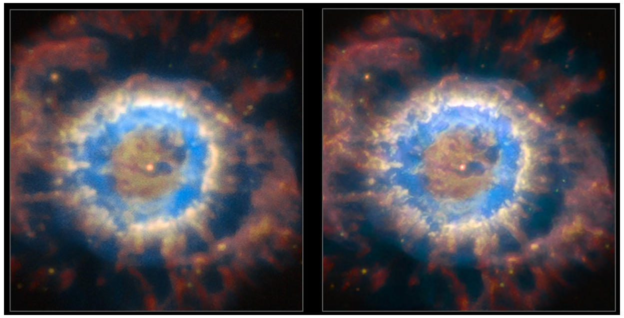




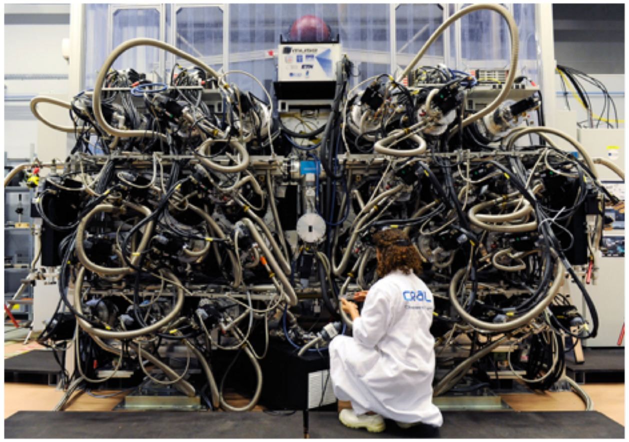
ADAPTIVE OPTICS FACILITY (AOF)

- Upgrade of VLT UT4 since 2016 with AO fully integrated into the telescope
- Key technical components:
  - **Deformable secondary mirror** with high actuator density (1170 actuators)
  - **Four laser guide stars**, 20W each, operating above specifications with high photon return
  - Both key for high performance in the optical

Full AOF science potential not being realized yet



AOF INSTRUMENTATION



MUSE @ Obs LYON, France

- HAWK-I, a wide FoV NIR imager (Nasmyth)
  - 0.9-2.5μm
  - 7′x7′ FoV, 0.1″ pixel size
  - Served by GLAO mode
  - AOF Req. gain of x2 in EE in 0.1″
- MUSE, a visible 3D spectrograph (Nasmyth)
  - Wide Field Mode (with GLAO)
    - 1′x1′, 0.2″ spaxels
    - Served by narrow field GLAO, req gain x2 in 0.2″ spaxel
  - Narrow Field Mode (with LTAO), being commissioned
    - 7.5″x7.5″, 0.025″ spaxel
    - AOF requirement: 5 to 10% Strehl at 650nm under 0.6″ seeing
- SINFONI, 1-2.5 μm IFS - decommisioned

  → ERIS from 2021, 1-5 μm imager and IFU spectrograph

Mainly InfraRed and/or ground-layer AO (wide field, low Strehl)

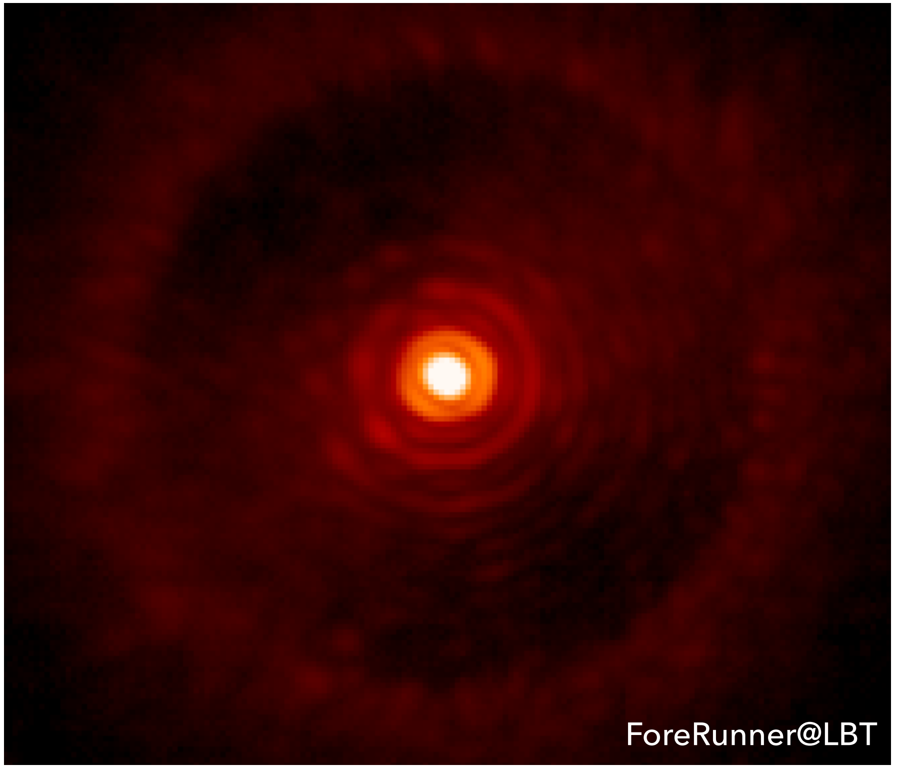
MUSE narrow field mode gives diffraction limit in optical, but only bright guide stars (<14 J-H mag, within 3.75″) and limited performances (Strehl~5%, FWHM~50 mas)

IN THE VISIBLE WITH AO

- Optical wavelengths are information-rich, with many well-understood astrophysical diagnostics
- Sky background is x1,000-10,000 times lower than infrared, possible to compete with space facilities
- Detectors are larger, lower noise, faster frame rates, and cheaper
- 500nm on an 8m gives same angular resolution as 2mm on an ELT

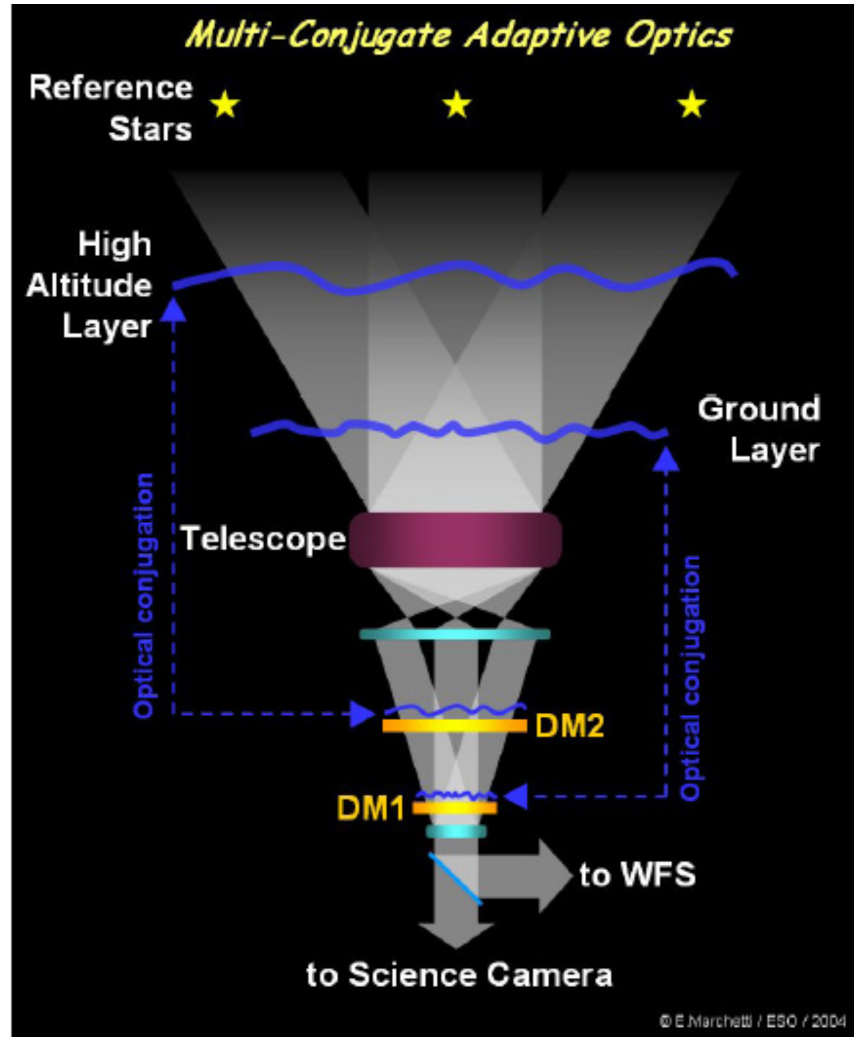
SINGLE CONJUGATE AO IN THE VISIBLE

- 650nm images from SHARK-VIS ForeRunner@LBT+FLAO
  - Adaptive secondary
  - 0.8″ seeing
  - 50% Strehl ratio!
  - 18 milliarcsec FWHM
- Similar examples from:
  - SPHERE @VLT
  - MAG-AO @Magellan
  - MUSE Narrow Field Mode
- **Visible AO is feasible!**

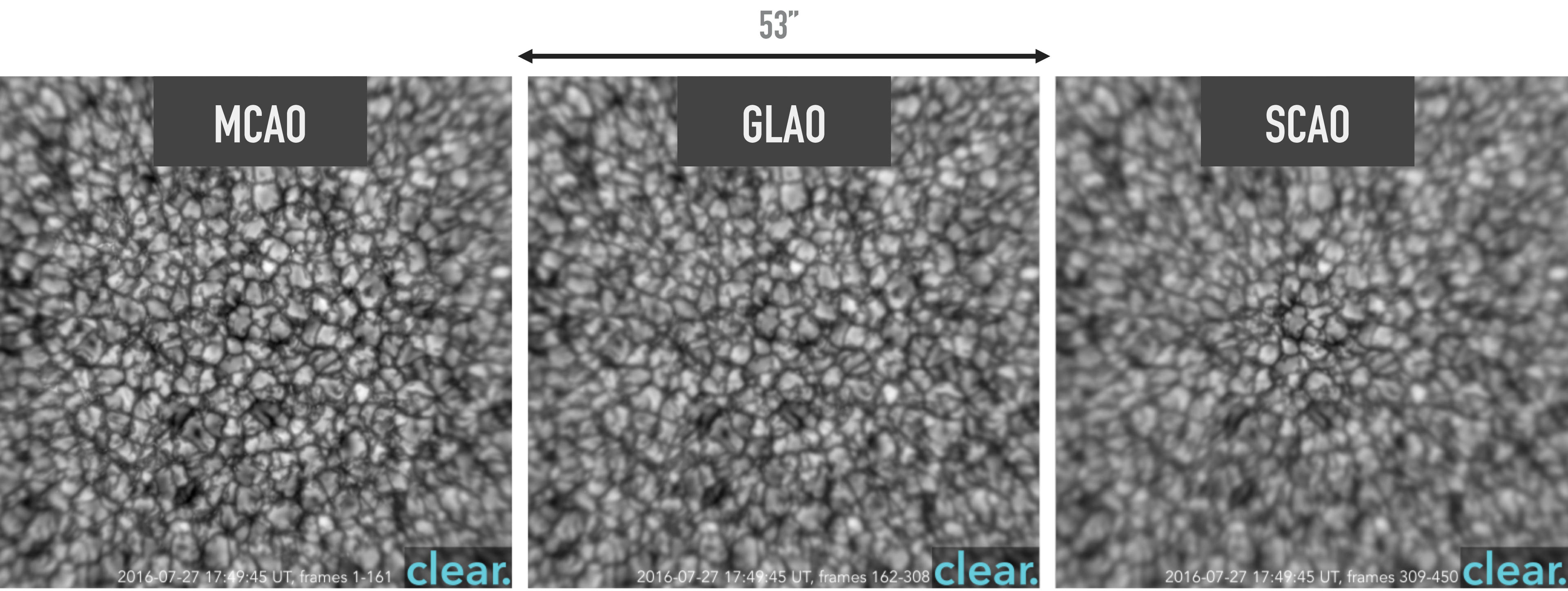


MULTI CONJUGATE AO

- Classical SCAO has limited corrected field of view and heavy PSF variations
- MCAO uses multi deformable mirrors, optically conjugated to different distances from the telescope, to correct aberrations produced by different layers
- Each mirror is driven by several wavefront sensors using different stars or LGS in the field, to reconstruct the 3D structure of the atmosphere



AN AO ZOO: SCAO VS GLAO VS MCAO



GST solar telescope

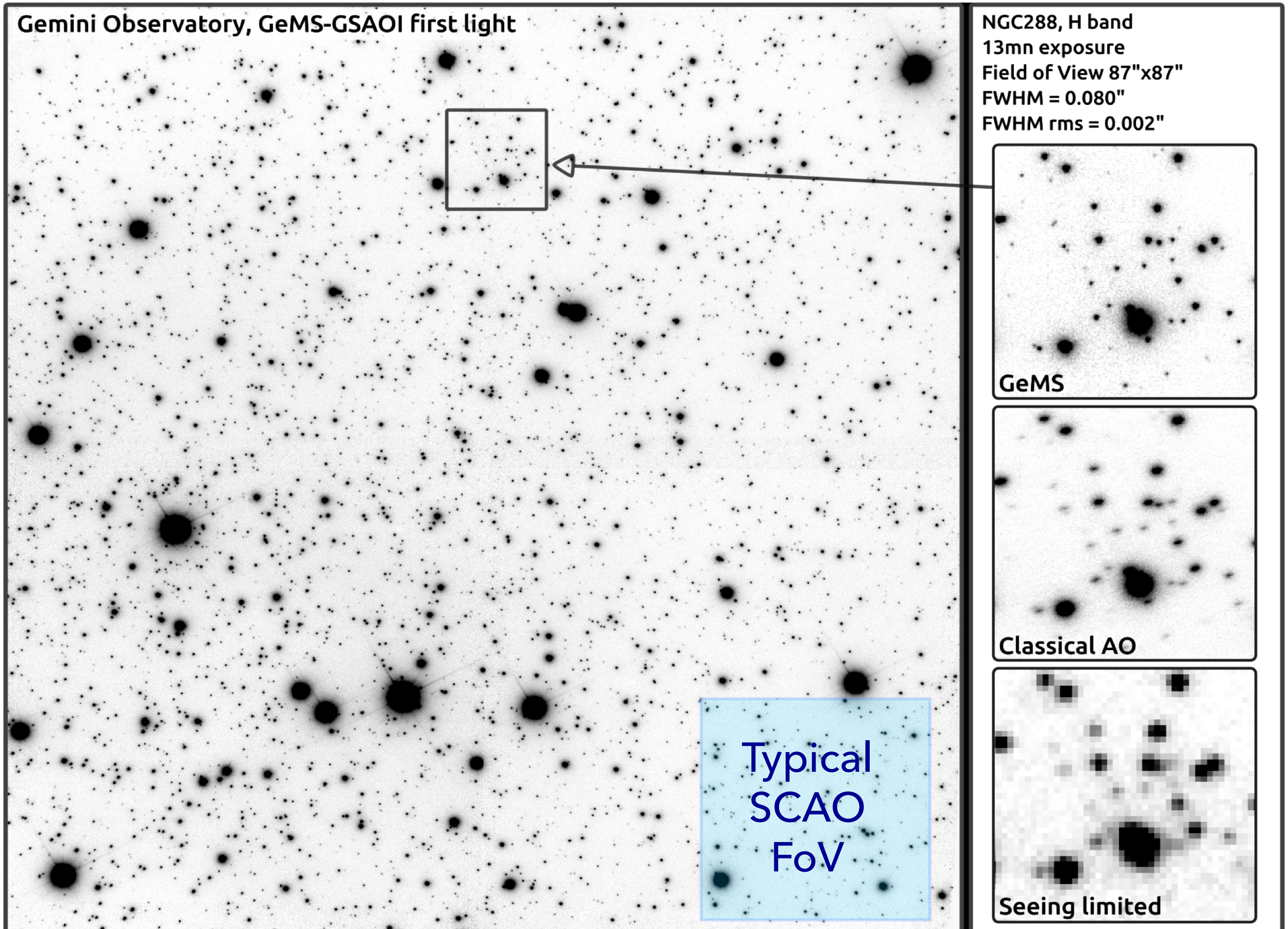
MCAO = Multi-Conjugate Adaptive Optics

GLAO = Ground Layer Adaptive Optics

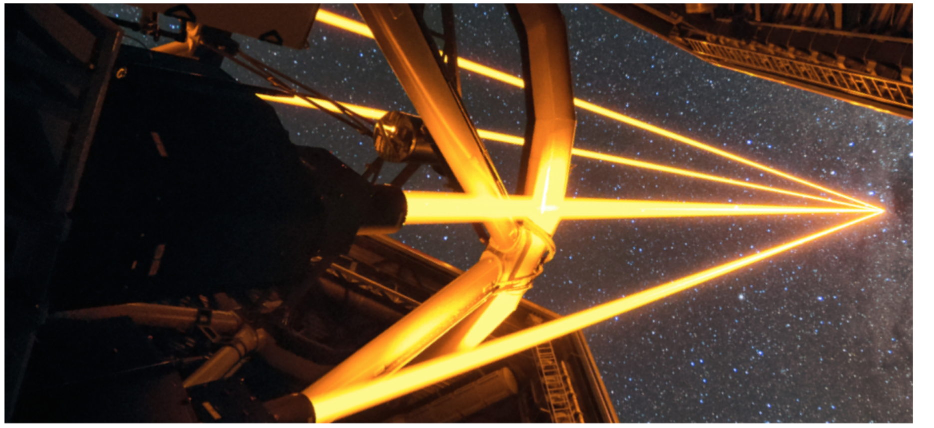
SCAO = Single Conjugate Adaptive Optics (Classical)

MCAO IN THE NIR

see also MAD@VLT



WHAT IS MAVIS?



An adaptive optics facility, diffraction-limited in the visible (~380-950nm), complete with a 4kx4k imager and an IFU spectrograph.

Uses VTL UT4 AO Facility

- Existing deformable secondary
- Existing laser guide star facility

AO Module

- **Visible** (VRI, UB goal)
- **30″x30″** field of view corrected
- FWHM ≈ **20mas** (V band)
- Strehl ratio ≈ **15%** (V band)
- Sky coverage ≈ **50%** @ Gal. pole

Imager

- 30″x30″ FoV, 7mas pixel
- Diffraction limited imaging V-z
- 4Kx4K pixels
- Wide + narrow band filters

IFU Spectrograph

- **image slicer IFU**
- **25 mas and 50 mas spaxels**
    - 3.5″ and 7″ FoV respectively
- **~5000 and ~12000** spectral resolution modes
- 4 interchangeable VPH gratings

MAVIS - *MCAO-Assisted Visible Imager & Spectrograph*

MAVIS CONSORTIUM

PI: F. Rigaut
(AAO-STROMLO)

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

AO system engineering
& numerical simulations
Opto-mechanics
Instrument Software
NGS WFS

AAO
Australian National University
MACQUARIE University

Project Office (Stromlo)
LGS WFS, AO expertise
RTC & AO control
Post-focal instrumentation:
Imager, spectrograph,
IFU front-end

LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE
ONERA
THE FRENCH AEROSPACE LAB

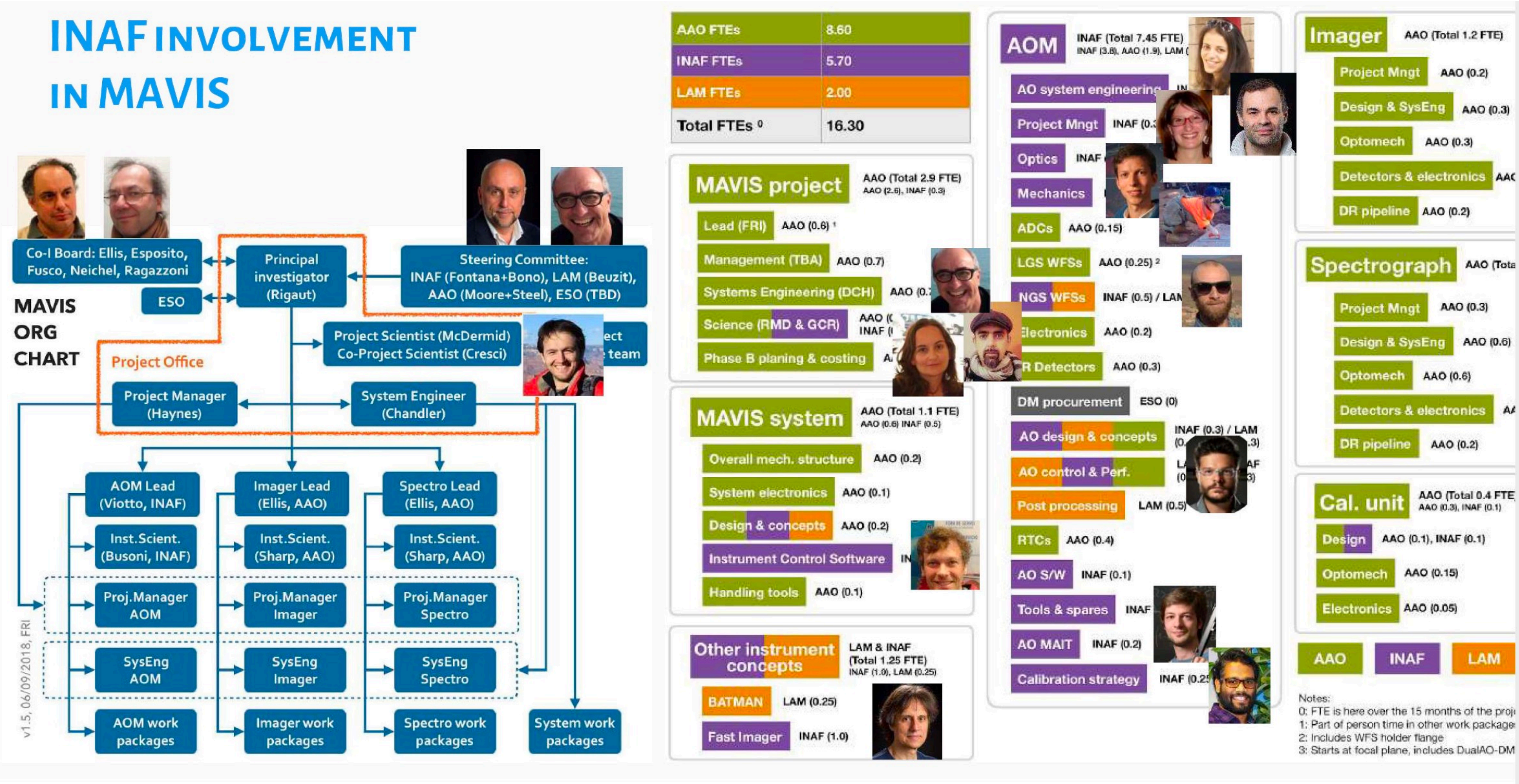
Post-processing
AO expertise

ESO

Observatory
interfaces, LGSF,
Deformable Mirrors

GTO: ~150 nights

INAF involvement in MAVIS



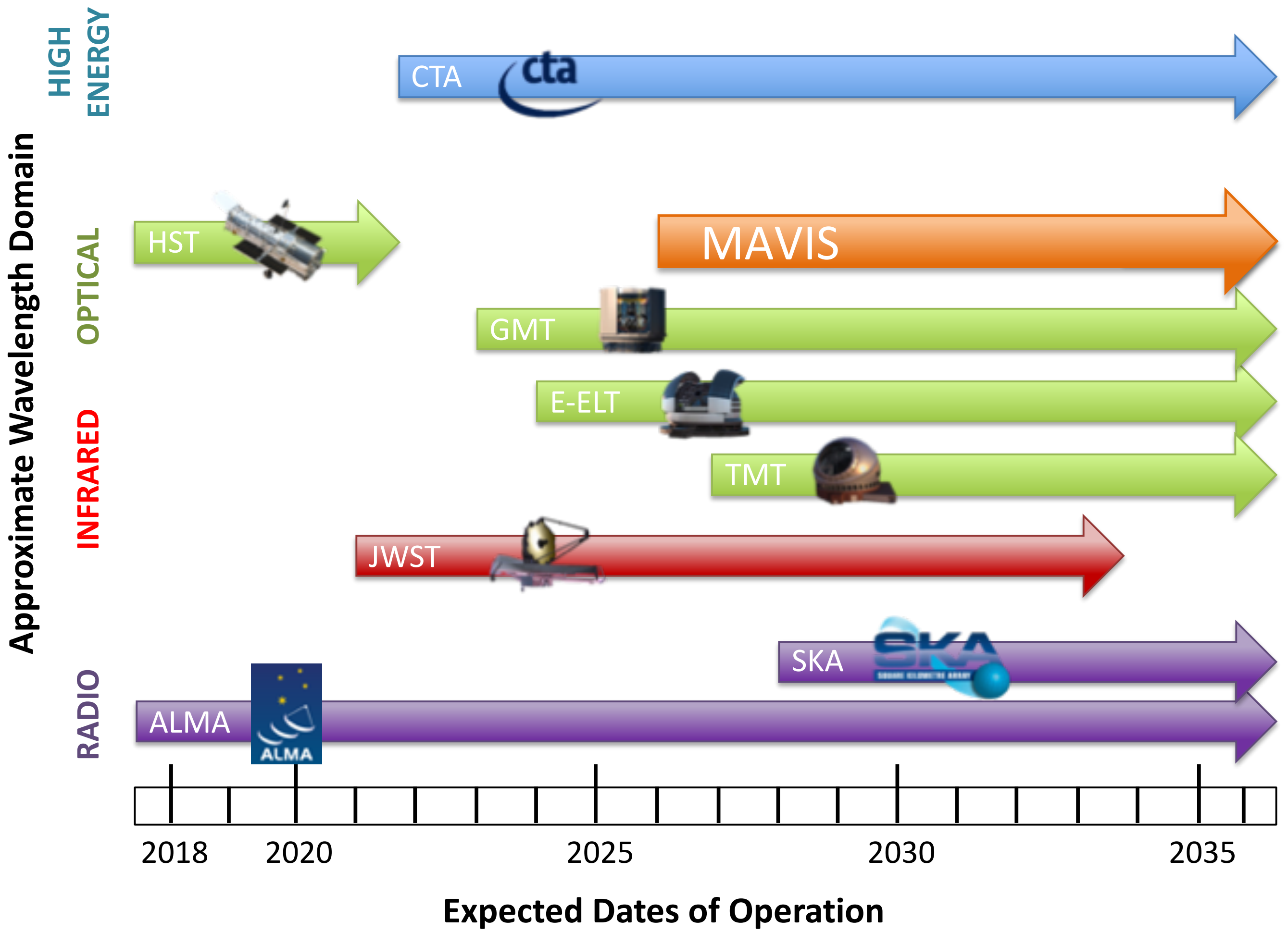
Courtesy: V. Viotto

MAVIS TEAM

MAVIS IN CONTEXT

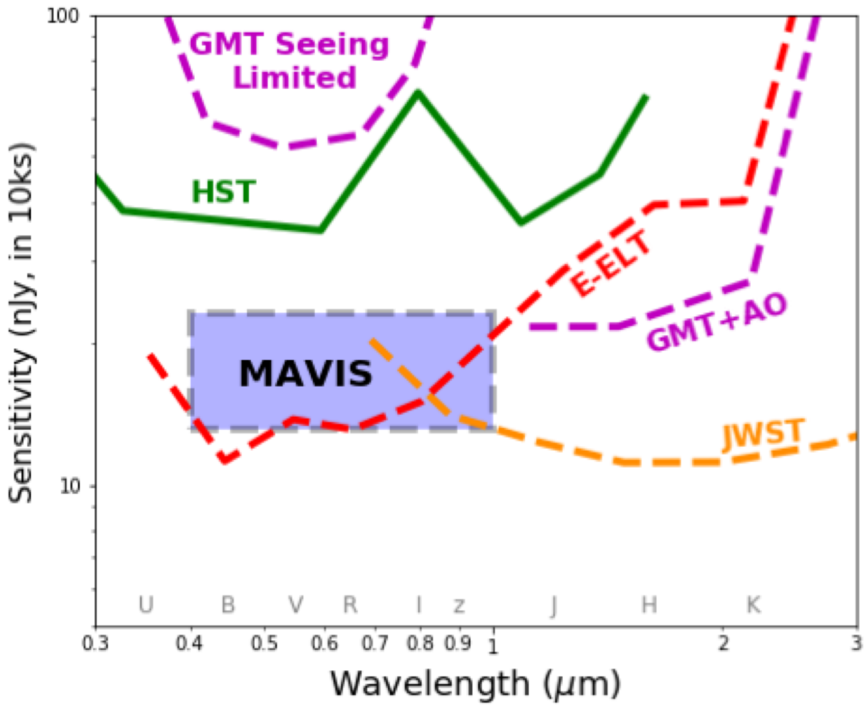
MAVIS operations overlap with forthcoming era of high sensitivity, high resolution astronomy with large telescopes

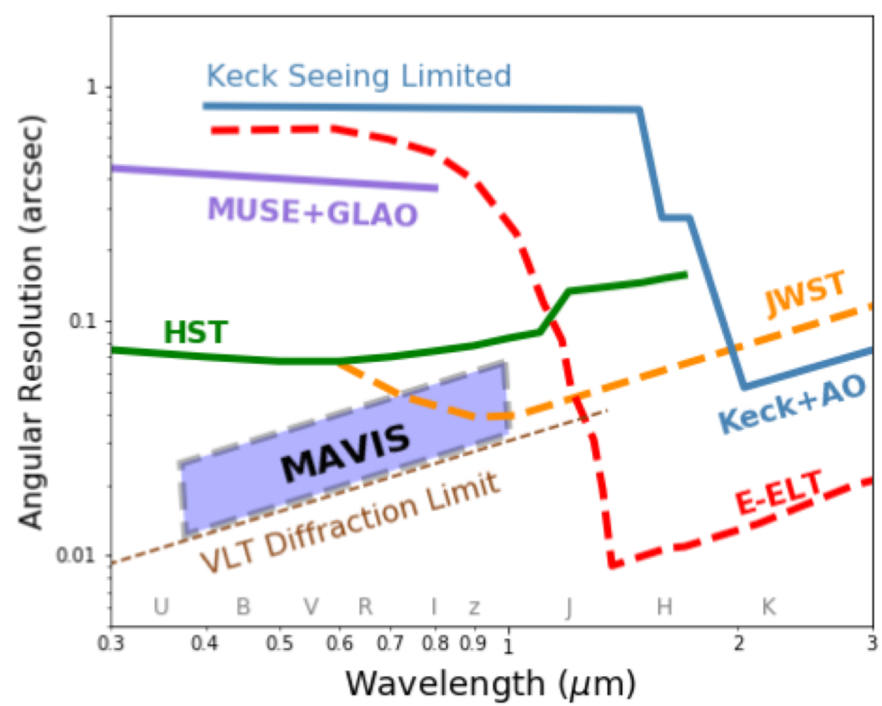
MAVIS will fill the gap at optical wavelengths in the post-HST era



MAVIS IN CONTEXT: DEEPER THAN HST, SHARPER THAN JWST

Improvement in resolution from future facilities limited to $\lambda > 1\ \mu m$





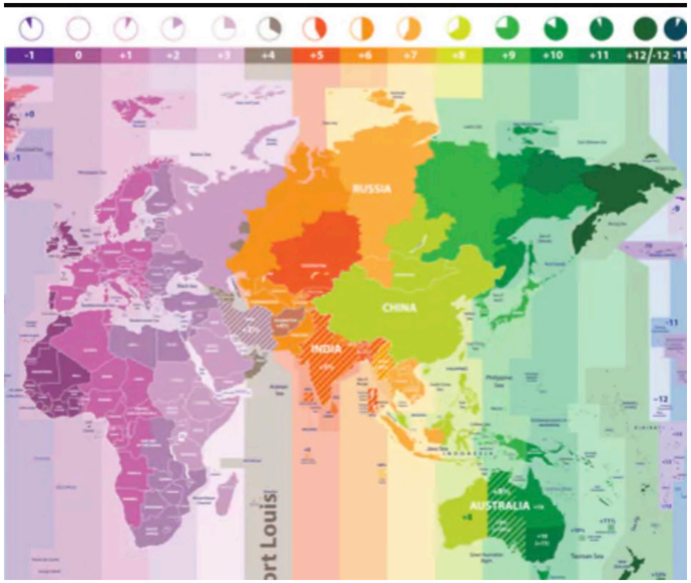
MAVIS in the optical will provide comparable sensitivity to JWST and ELTs, but with higher angular resolution

• 10 hours time

- *Versatile* – *Maximise sky coverage, rich discovery space, multiple use-cases*
- *Sensitive* – *Maximise throughput and sensitivity*
- *Stable* – *Allow deep-exposures, high repeatability, high-quality astrometry*
- *Robust* – *Push-button operations, high up-time, minimal modes*

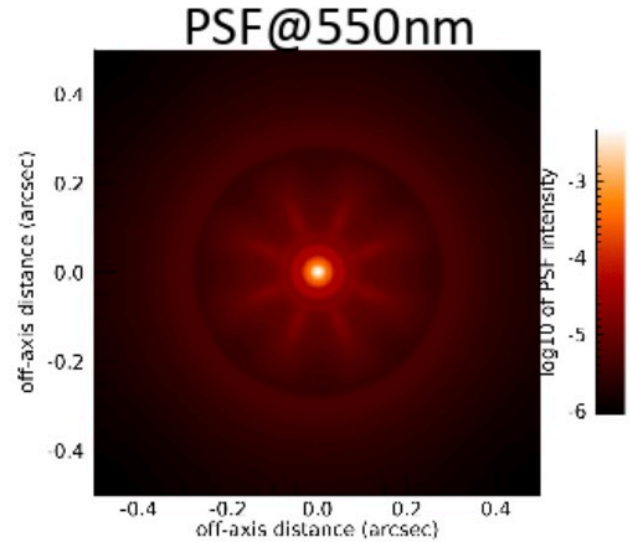
MAVIS NUMBERS

- 8 laser guide stars
- 3 Deformable mirrors with 5000 actuators
- 2 spectrographs with 9k x 9x detectors
- 1 imager 4k x 4k
- 178 M pixels
- 12 MEuro hardware
- ~200 FTE
- 8 years from kickoff to first light
- 10 hours time difference !

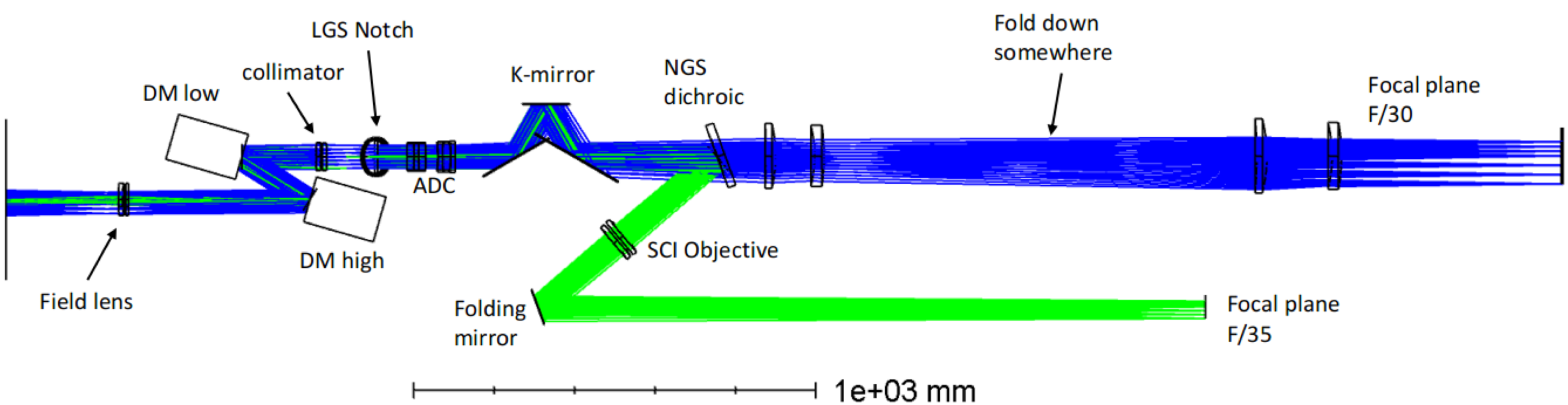


MAVIS: AO MODULE

- Working in the visible VRIz (UB goal)
- 30" ⦰ fov corrected
- FWHM ~ 20 mas (V band)
- Strehl ratio >10% in V
- Sky coverage ~50% at galactic pole!!



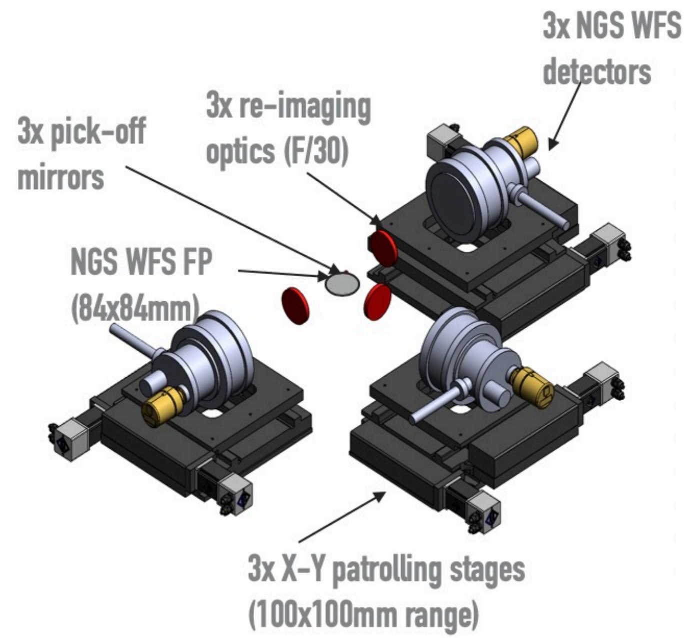
- Innovative Optical design (D.Greggio)
- 2 DMs @ ~ 6 & 15km
- One single ADC across 450-1700nm!
- Excellent Science IQ (>90% everywhere) + distortion (<0.0021%)

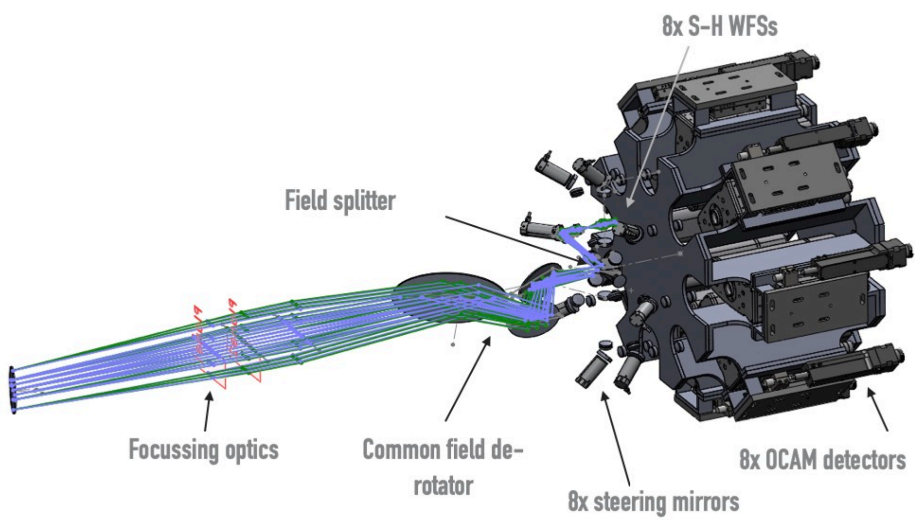


MAVIS: AO MODULE

NGS Wavefront Sensors

- Up to 3 NGS sensed in J+H band
- H≲18.5 in 2 arcmin patrol field
- Tomographic truth sensing



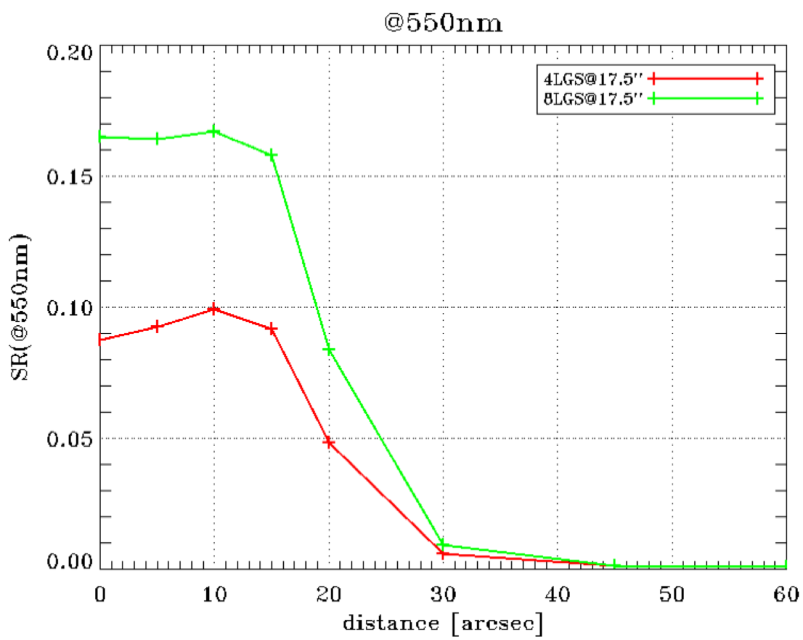


LGS Wavefront Sensors

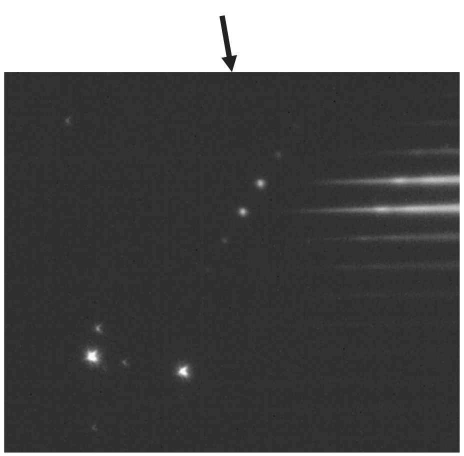
- 8 LGS S-H WFS
- 17.5" radius circular asterism
- including FP steering mirrors and FoV derotation

LGSF SPLITTING

- AO simulations showed that at least 6 (baseline is for 8) LGSs are needed to reach the performances over the FoV.
- Trade-off on solutions concluded that only a static splitting, i.e. the 2 LGS are created at the same time, is viable. Adding additional GSLs costly/complex.
- Possible technical solutions: Wollaston prism, wedged beam-splitter, diffractive optical element (DOE).
- DOE is the most promising one and can be implemented in 4LGSF.

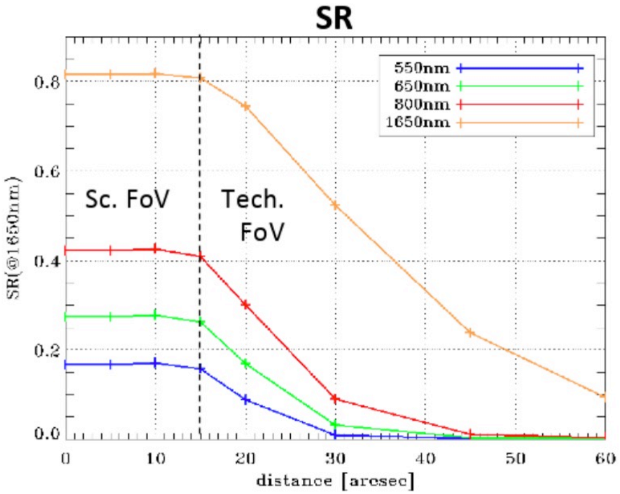


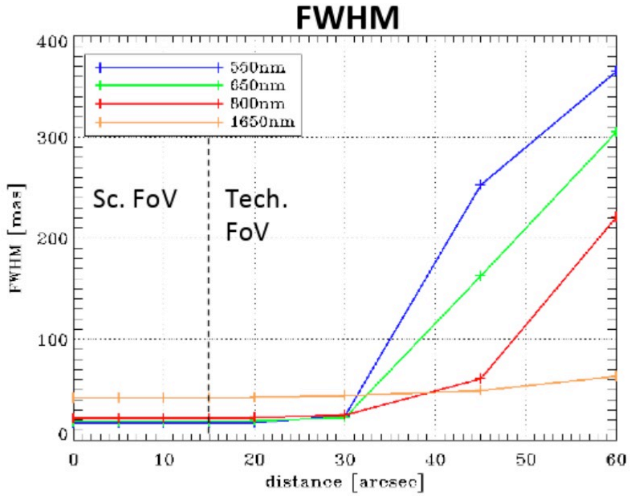
On-Sky demonstration
(September 2019)

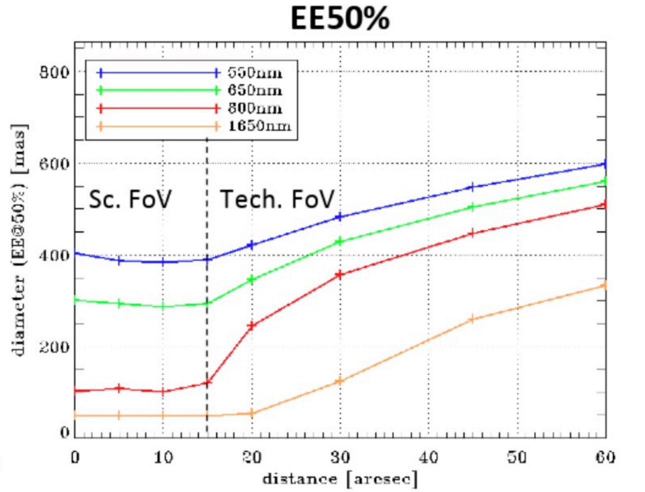


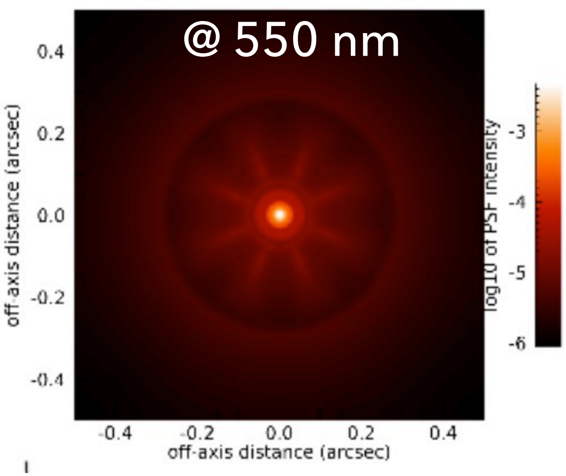
MAVIS PSF

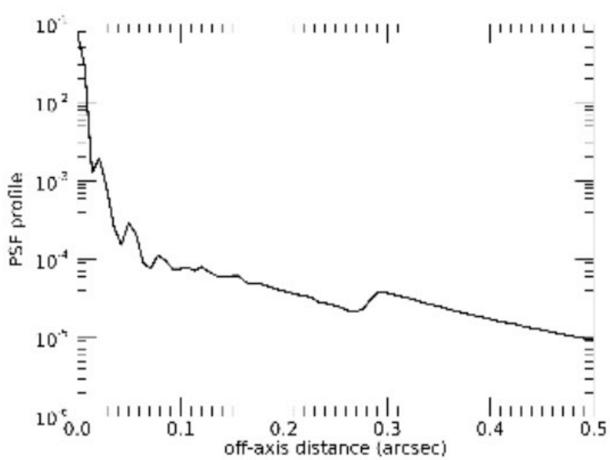
"Good" NGS asterism:
H=12, d=20", angles=[0,120,240]deg

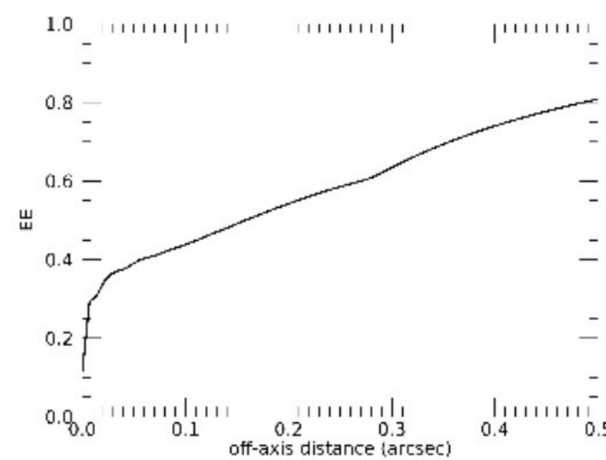






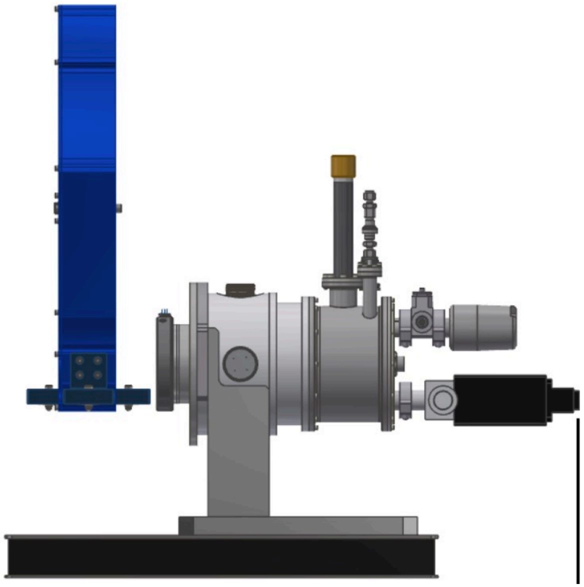




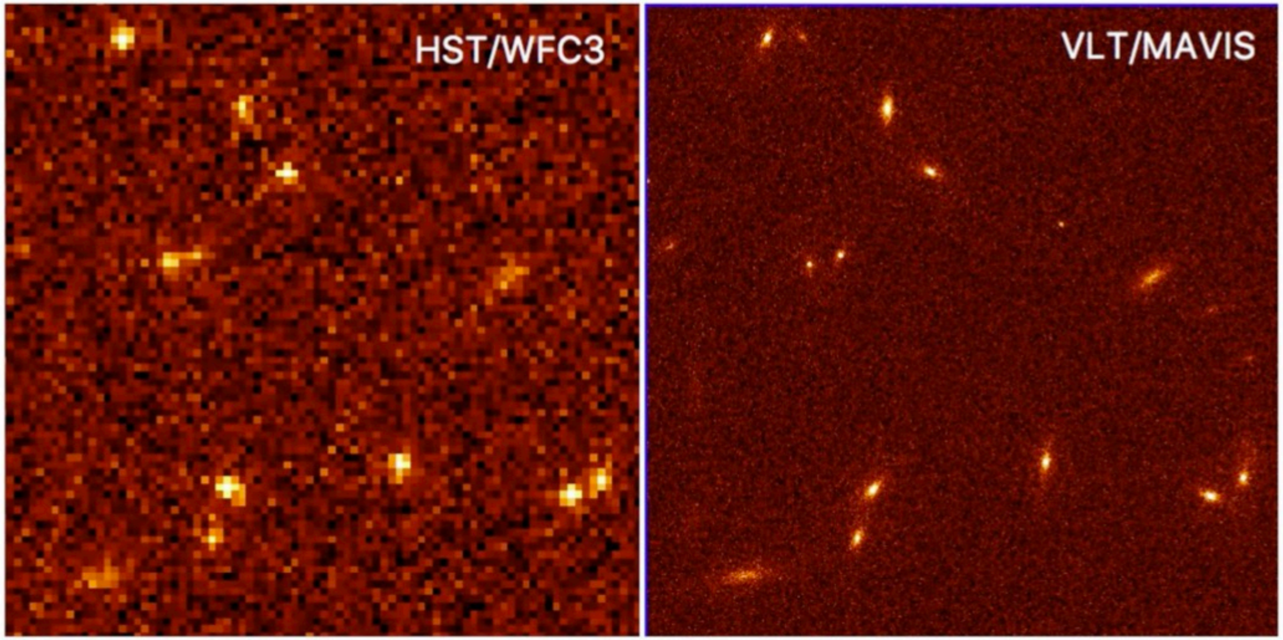


MAVIS: IMAGER

- 30″x30″ FoV
- 7mas pixel
- Diffraction limited imaging V-z
- 4Kx4K detector pixels
- Wide + narrow band filters
- Sensitivity > 29mag (5σ) in 1hr



A MAVIS Deep Field



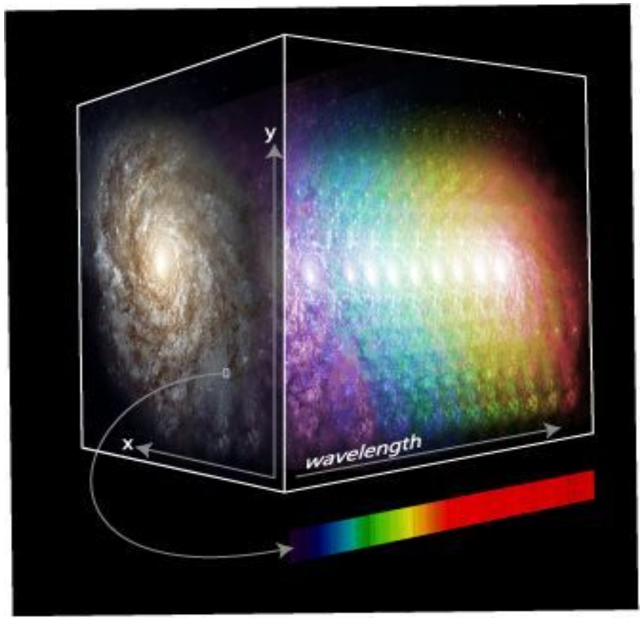
In 10 hours, MAVIS can reach a 5σ limiting mag of 30.4 AB in the I band.

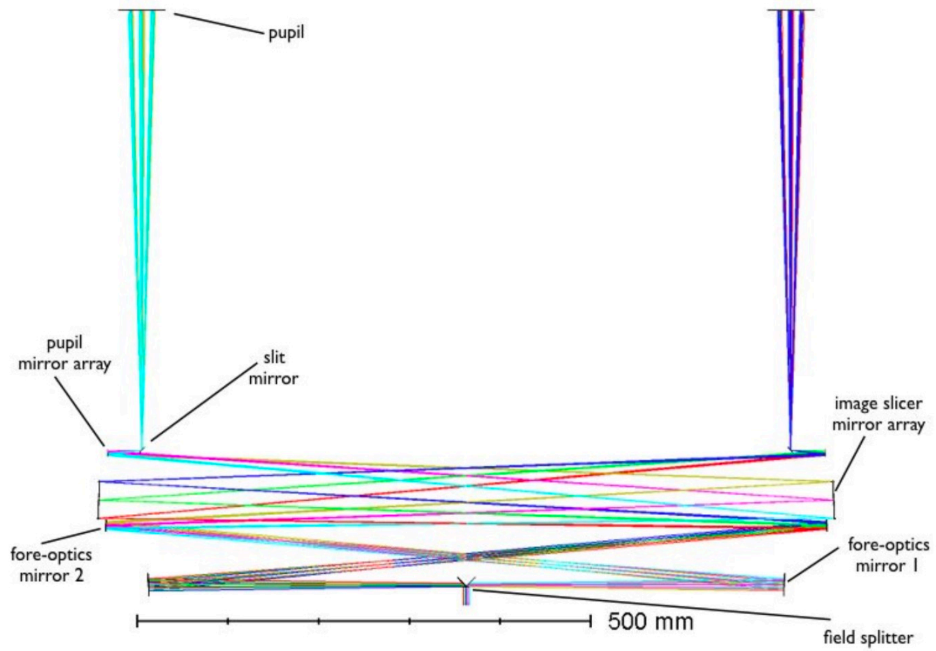
This is about 1 mag deeper than the HST UDF in i775 (96h)

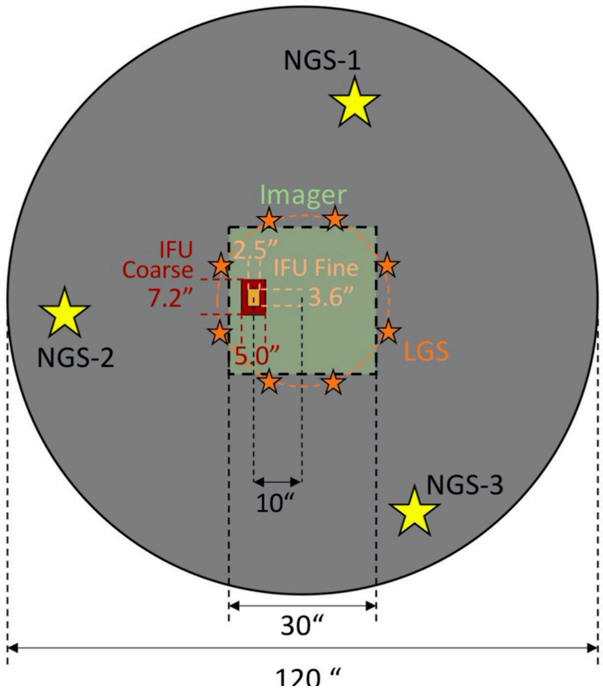
MAVIS: SPECTROGRAPH

Monolitic image slicer IFU

- Two spectrographs with 9k x 9k detectors
- R band diffraction limit = 19 mas
- spaxel ~25 mas: fov ~3.6″x2.5″
- spaxel ~50 mas: fov ~7.2″x5″
- R~4000-15000
- $\lambda \sim 370 - 1000$ nm

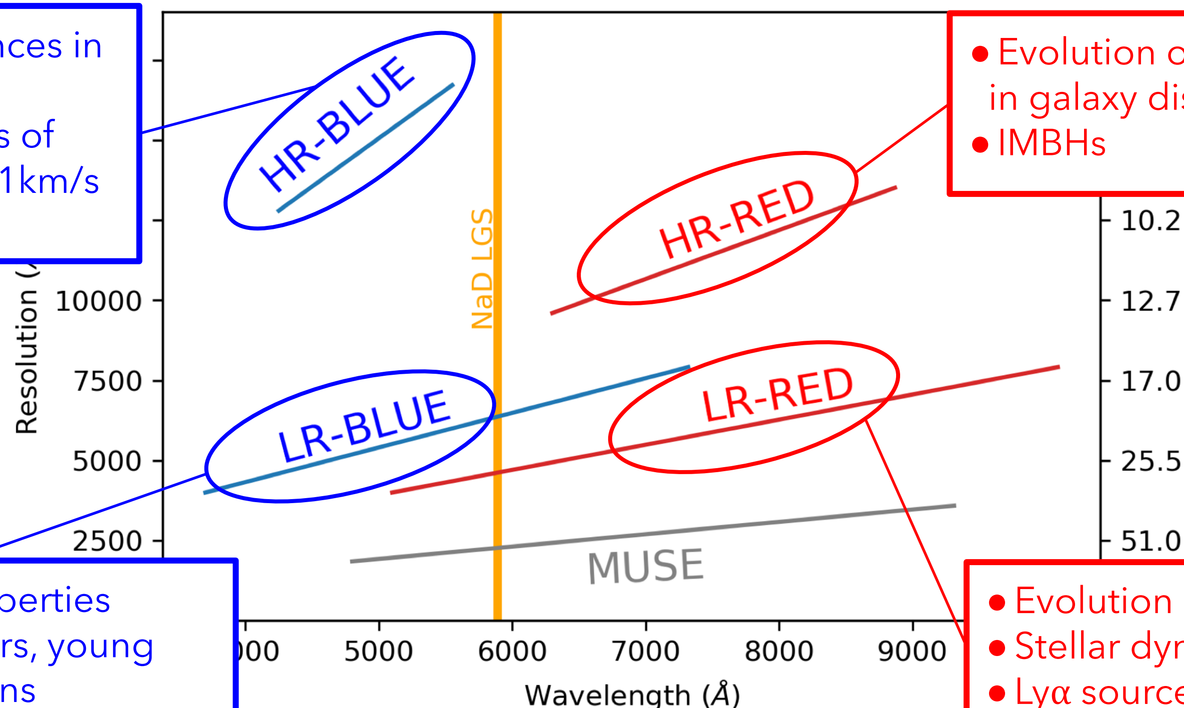




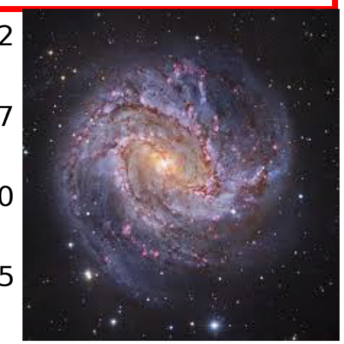


MAVIS: SPECTROGRAPH

- Stellar abundances in crowded fields
- Radial velocities of stars and gas < 1km/s

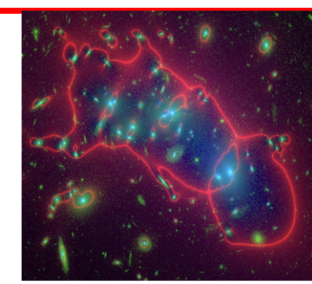


- Evolution of ISM turbulence in galaxy disks
- IMBHs



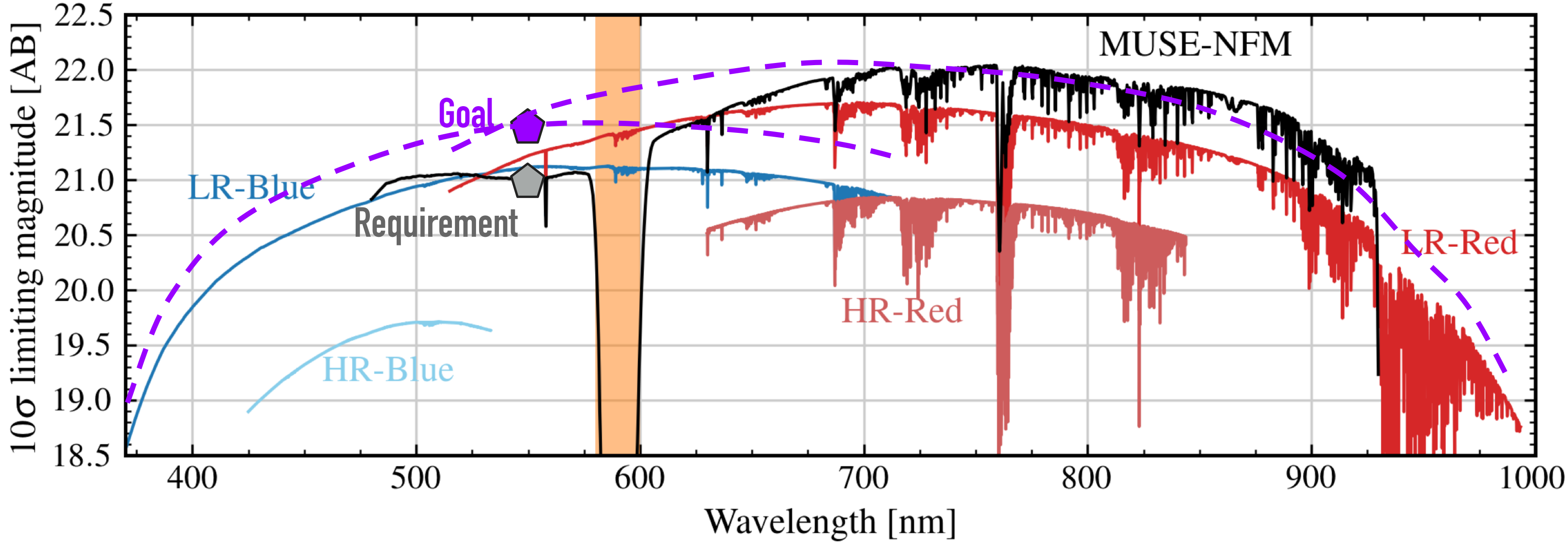
- Ionised gas properties
- Hot/Massive stars, young stellar populations
- Extreme Metal Poor stars

- Evolution of ISM chemistry
- Stellar dynamics z<1
- Lyα sources at z>6.6



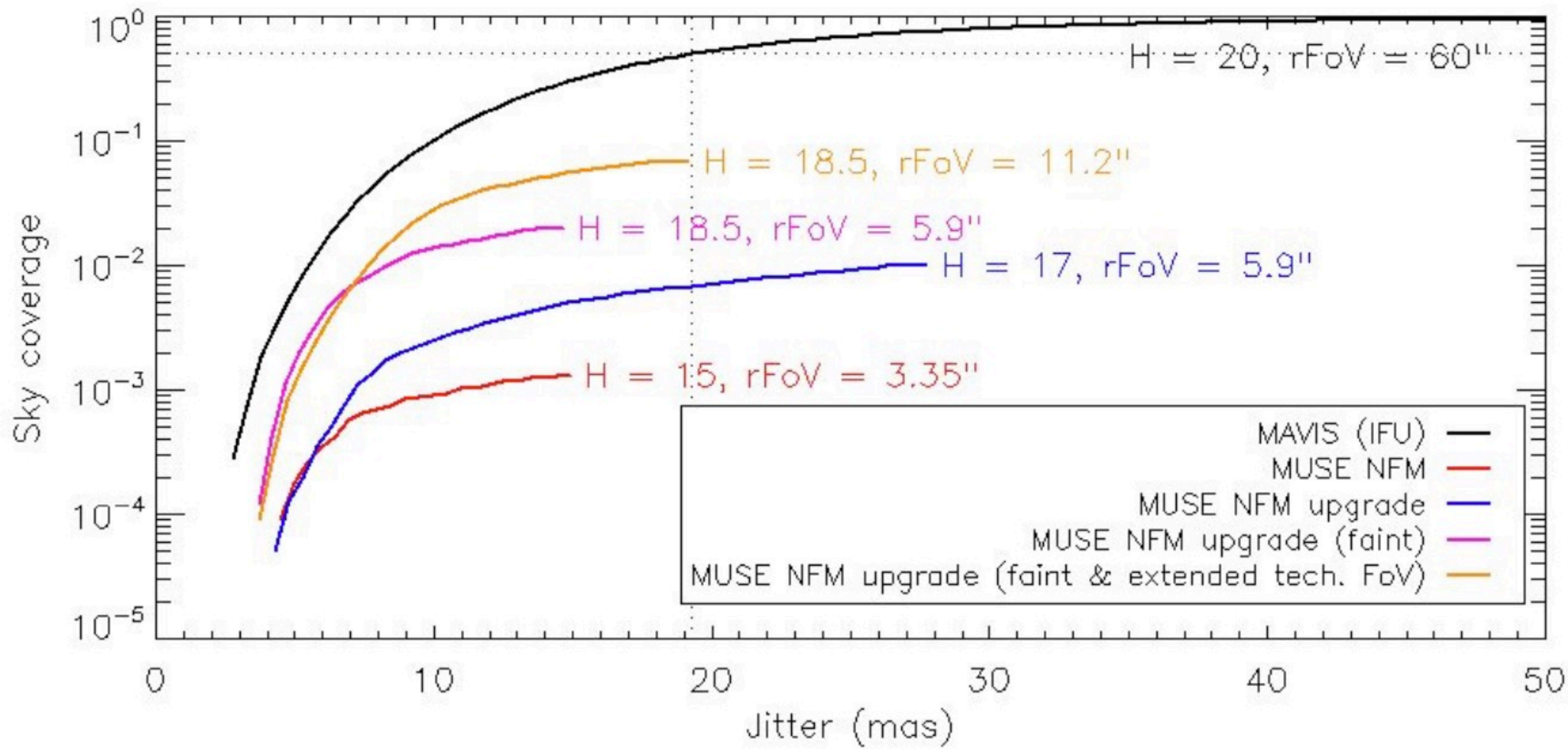
4 different gratings to cover the whole
3700-10000 Å band
optimized for different science requirements

MAVIS: SPECTROGRAPH



- Comparison with MUSE-NFM, which has half the spectral resolution of MAVIS LR modes
- **Requirement** based on conservative assumptions on throughput and ensquared energy
- **Goal** relaxes these assumptions to be closer to current design estimates

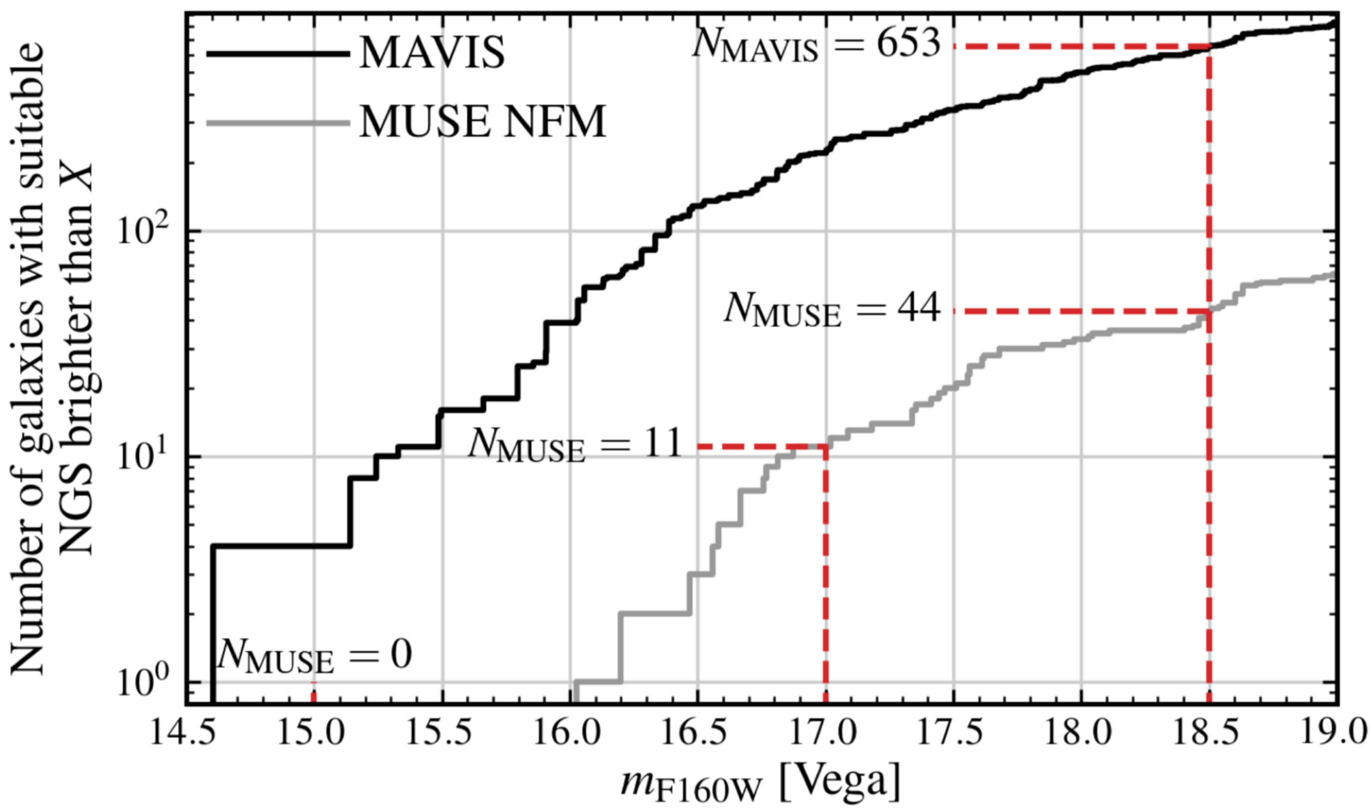
MAVIS VS MUSE-NFM: SUPERIOR SKY COVERAGE



- **Statistical assessment** of sky coverage, in terms of % of sky for a given AO performances at Galactic Pole
- Can compare sky coverage for comparable residual jitter

⇒ MUSE-NFM out of stars ~5-6%; MAVIS hits ~50%

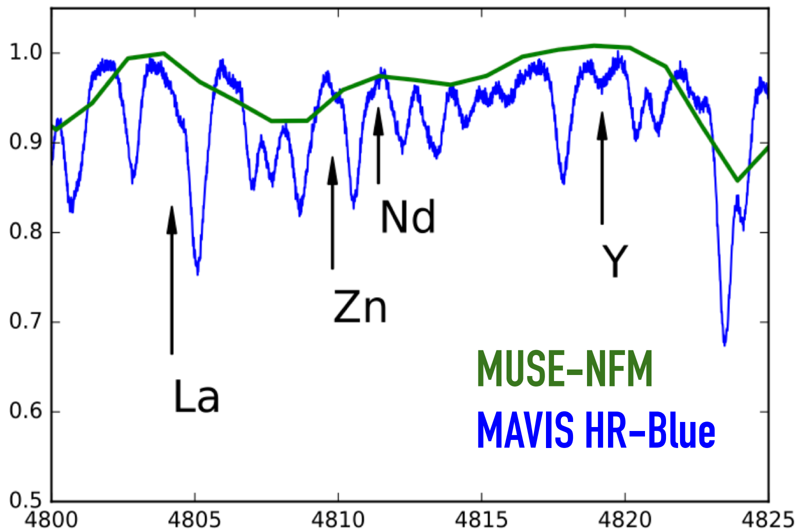
MAVIS VS MUSE-NFM: SUPERIOR SKY COVERAGE

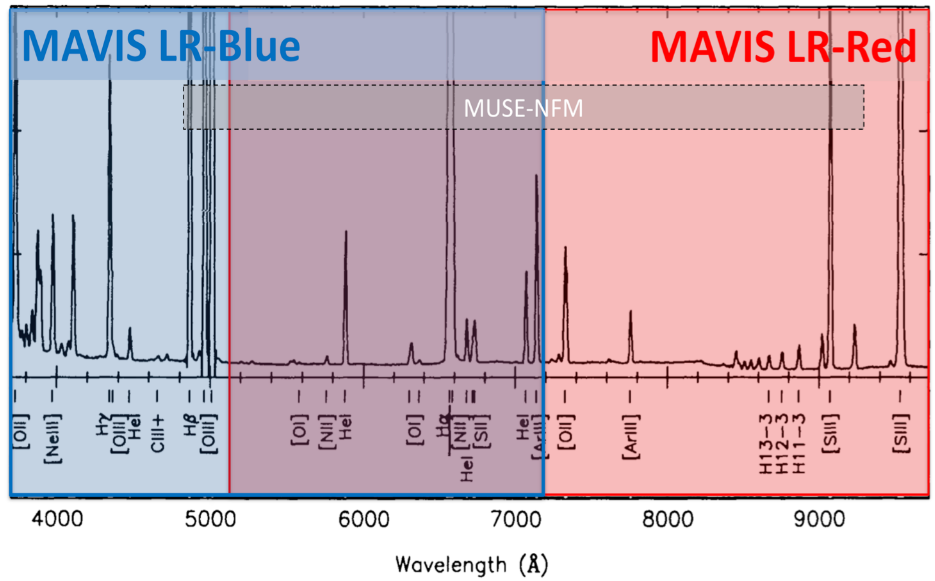


- **Use Case:** No. of observable intermediate-z galaxies in GOODS-S, COSMOS and UDS with MAVIS and MUSE-NFM as a function of (faintest) NGS magnitude
- MAVIS sky coverage gives > 1 order of magnitude more targets

⇒ MAVIS makes statistical samples possible

MAVIS VS MUSE-NFM: WAVELENGTH RANGE AND RESOLUTION





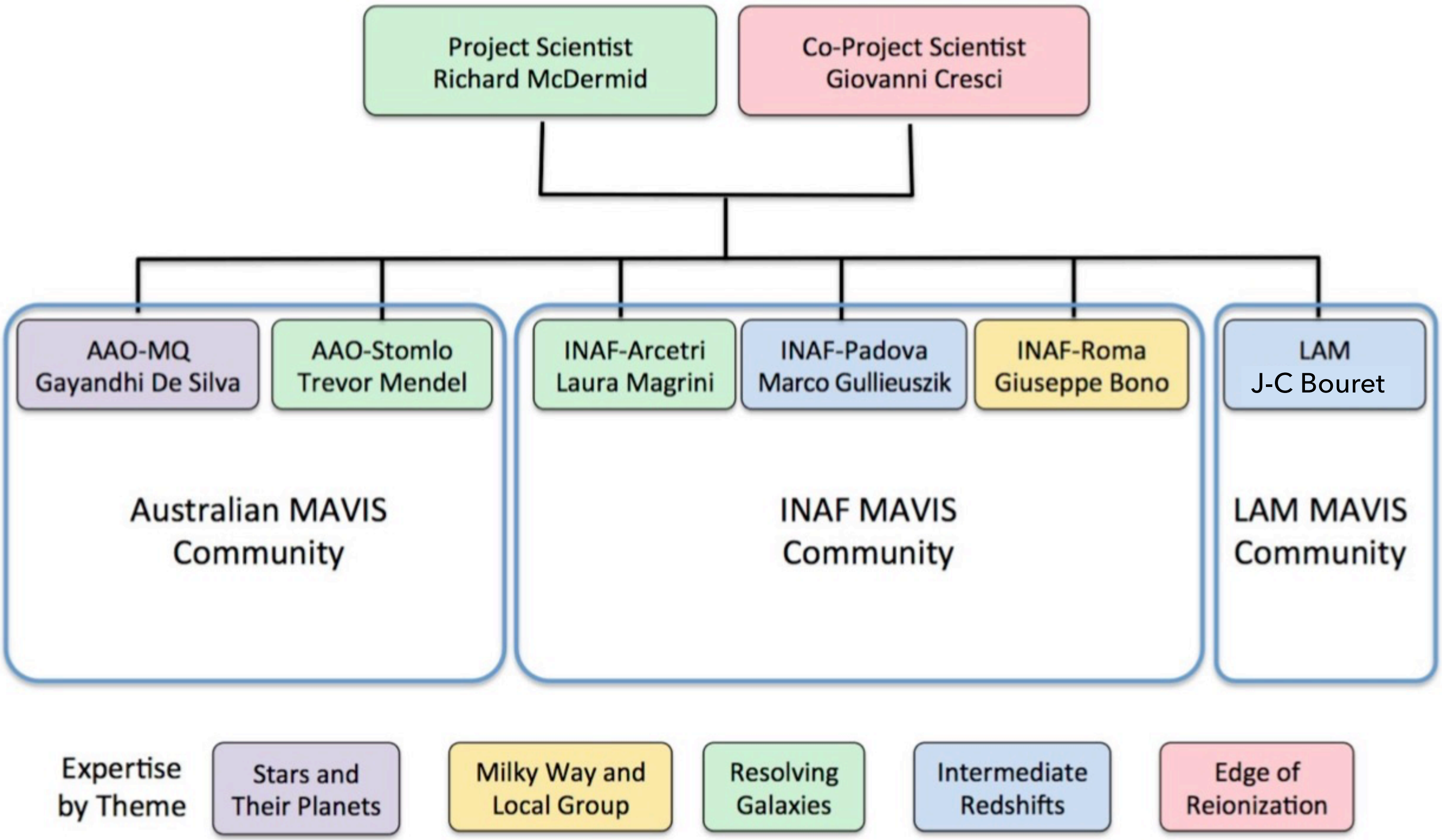
R=5000-12000 vs R=2000 for MUSE:

- MAVIS HR-Blue will measure **first element abundances in globular cluster cores**
- Wavelength range tuned to cover key diagnostic species
- Also gives high precision radial velocities (IMBHs, binary fractions, circumstellar disks and jets, etc.)

Larger wavelength coverage of MAVIS covers key line diagnostics:

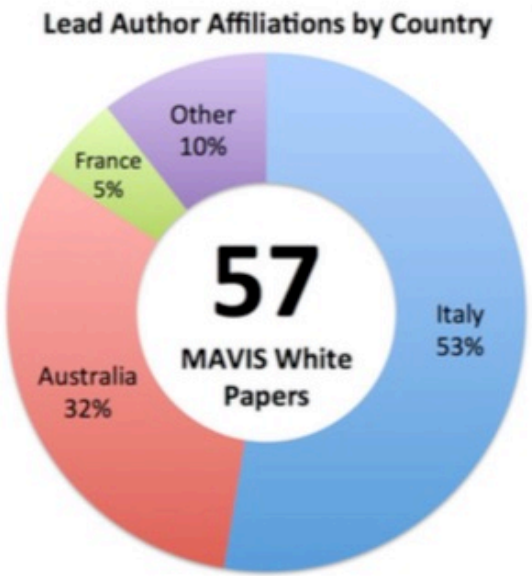
- [OII] λ3727 doublet is key ISM diagnostic
- [OIII]l λ4363 auroral line -> 'direct' metallicity
- HeII λ4686 -> Important massive star indicator
- ISM diagnostics with S32 via [SIII] λ9351
- **Powerful ISM diagnostic machine**
- Extends Lyα to z=7.23 vs. 6.6 = 100Myr, **additional 12% of the Universe's age at z~7**

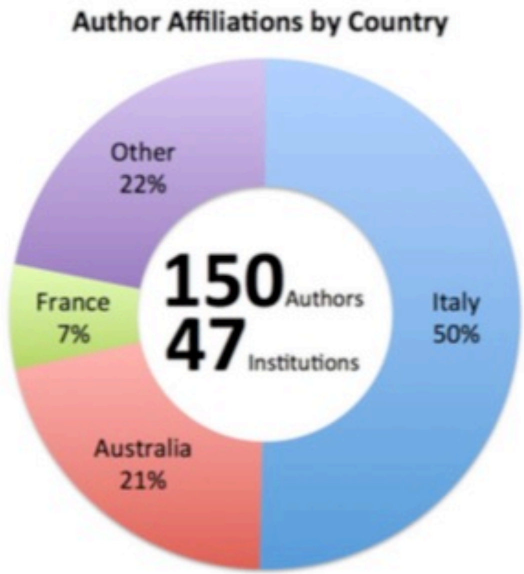
MAVIS CORE SCIENCE TEAM

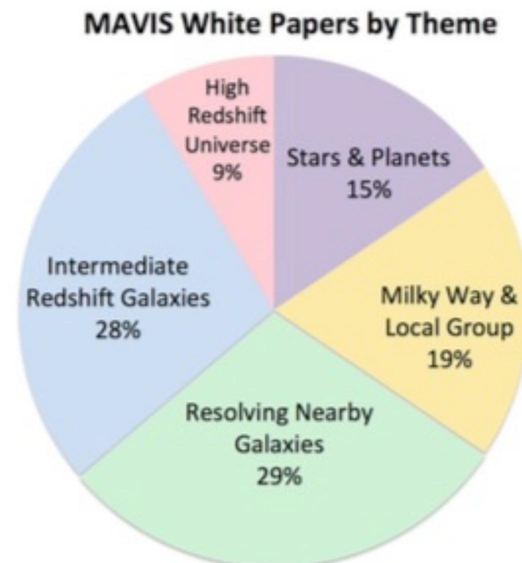


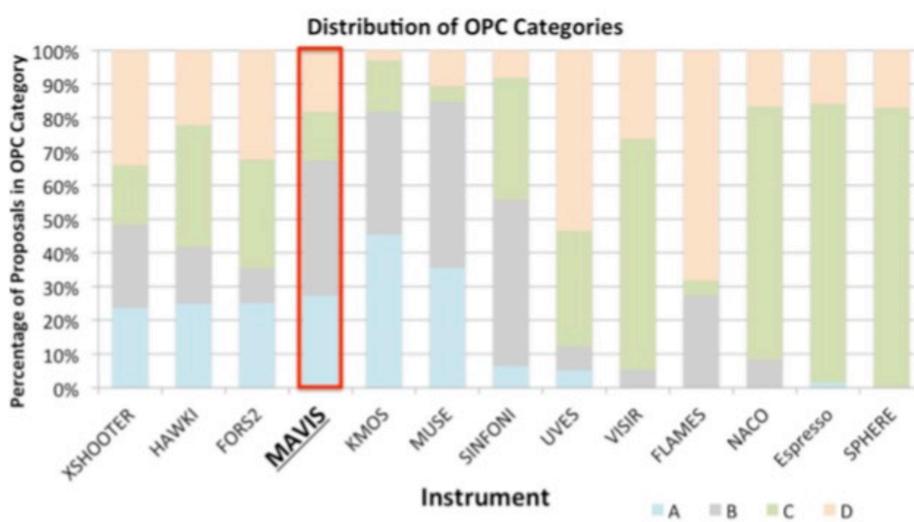
SCIENCE WITH MAVIS: WHITE PAPERS

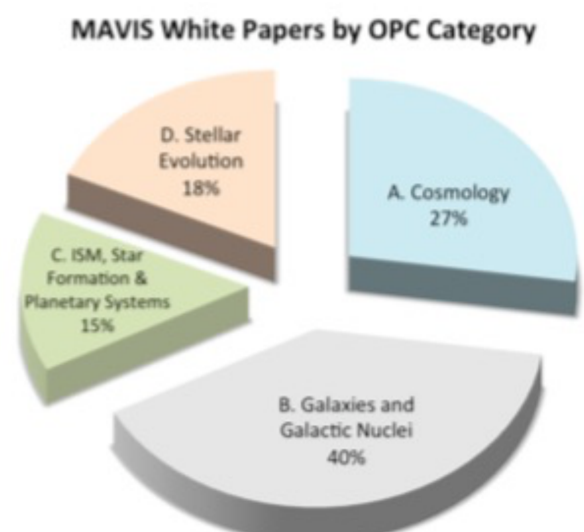
Call in July 2018





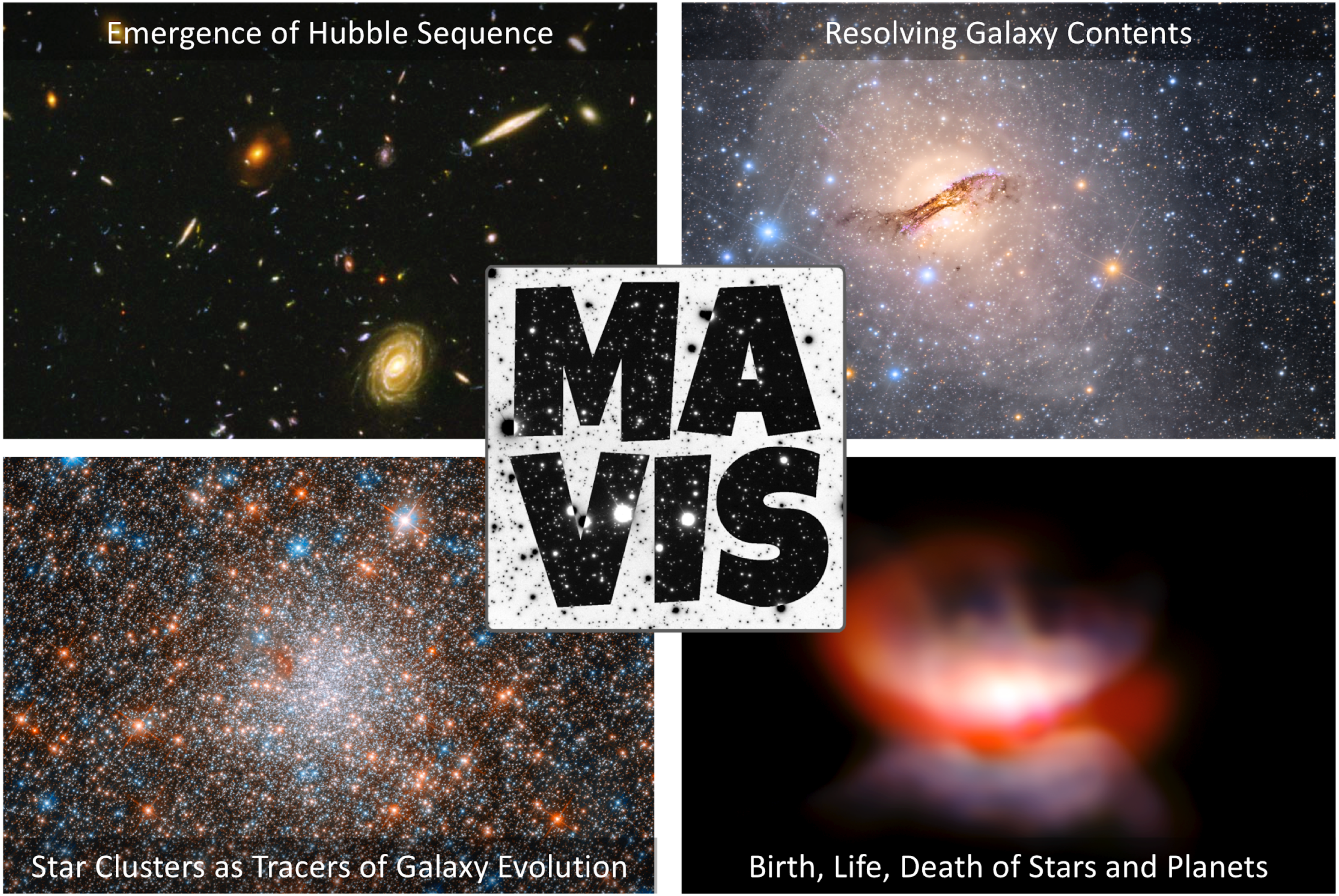




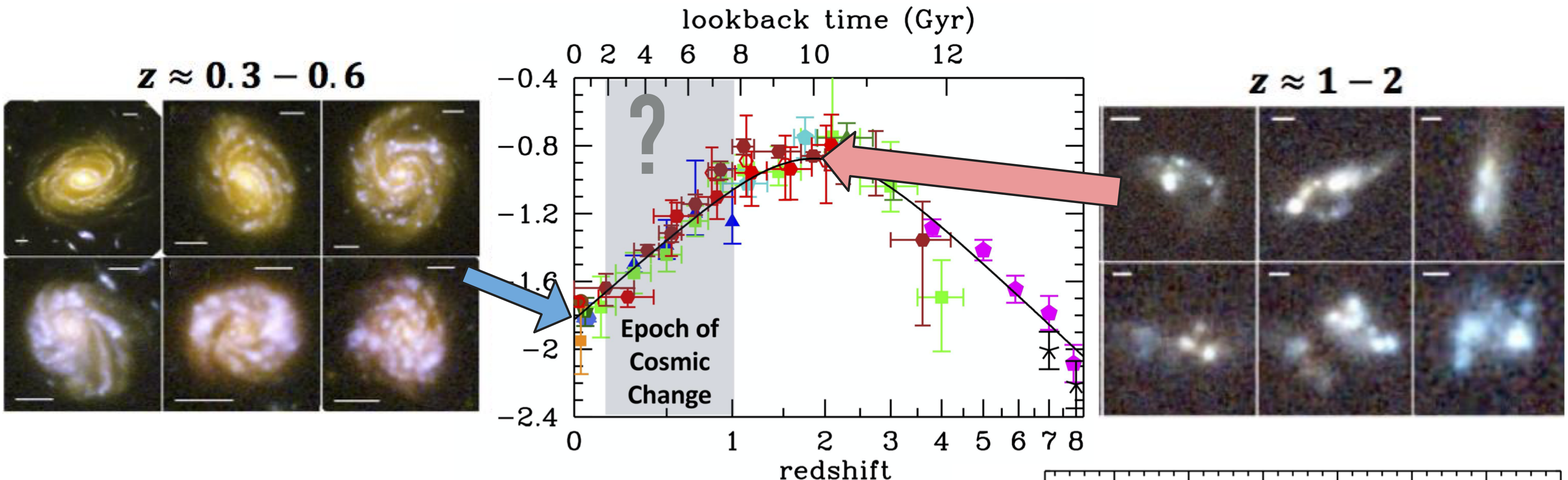


A general purpose instrument!

SCIENCE WITH MAVIS

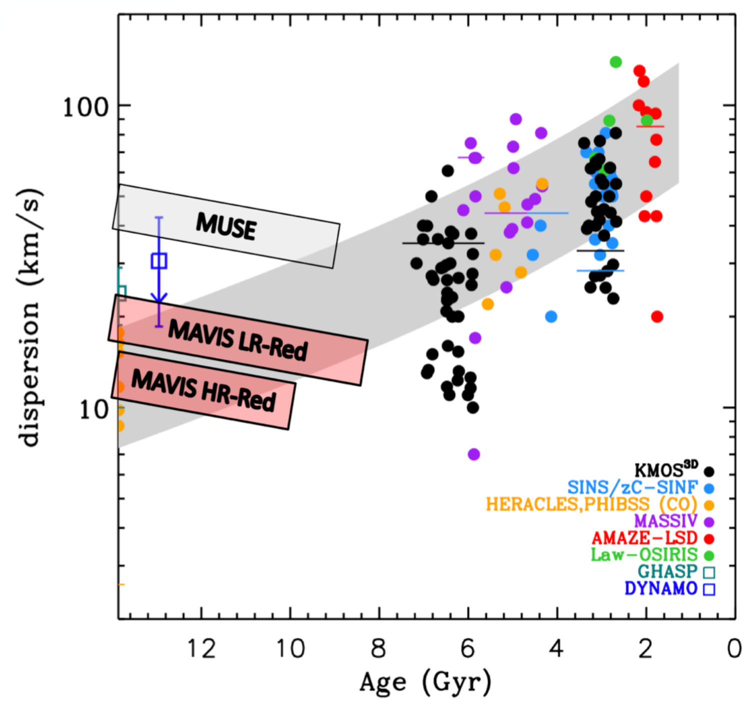


EMERGENCE OF THE HUBBLE SEQUENCE



- The Hubble Sequence becomes established between z=1 and today
- Galaxies change from turbulent and clumpy to regular and dynamically cold
- Change in feedback processes? Bulge formation and disk growth?

⇒ Only MAVIS has sufficient spectral and spatial resolution to disentangle gravitational and non-gravitational processes



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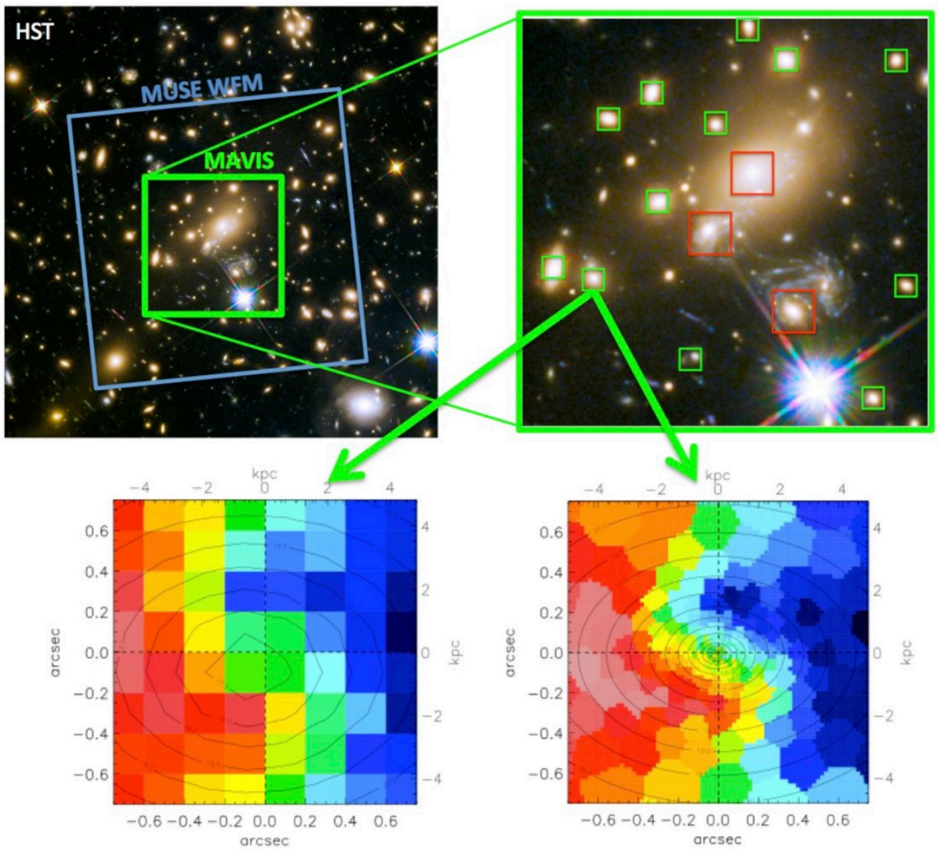
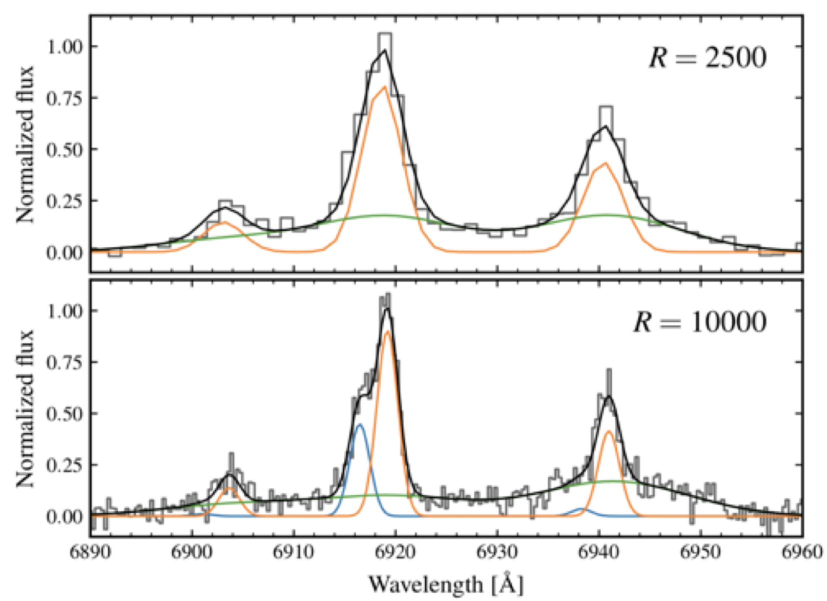


MUSE+GLAO, FWHM=0.4”

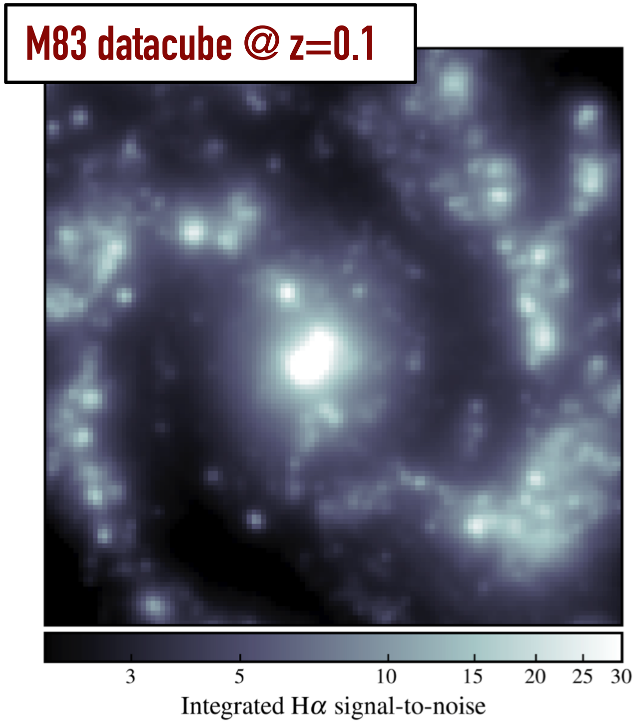
MAVIS, FWHM=30mas

Kinematics on Sub-Kiloparsec Scales at z~0.5:

- High spatial resolution <0.1’’ required for precise kinematic classification
- High spectral resolution needed to pin down cold disk dispersion and identify additional components

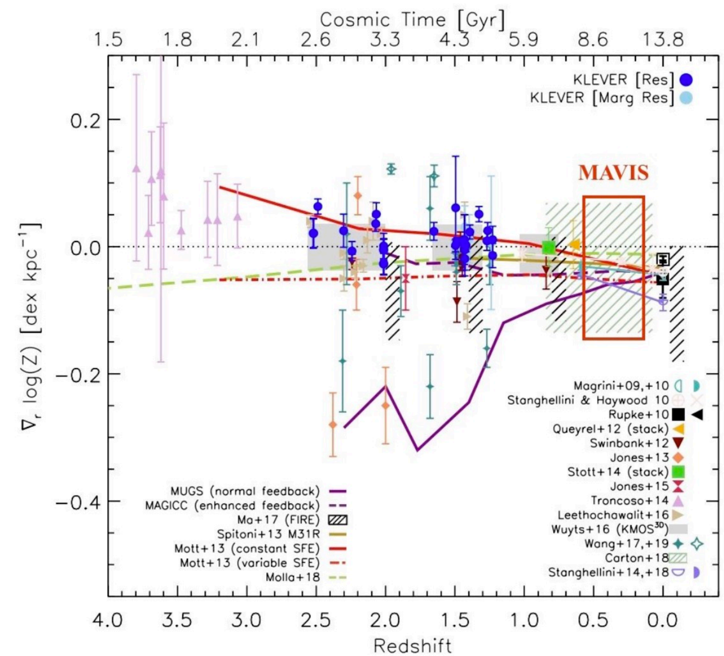


EMERGENCE OF THE HUBBLE SEQUENCE

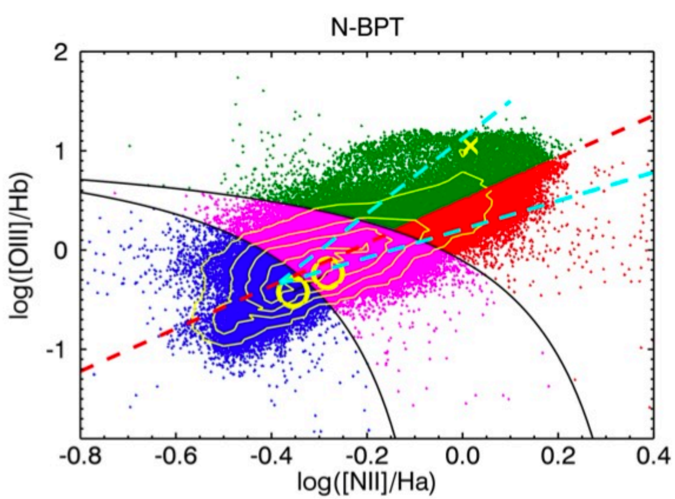


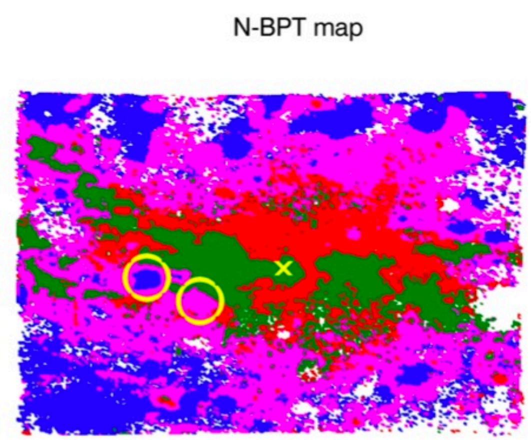
Resolved chemical
and
physical properties
of the ISM (e.g.
metallicity,
ionisation,
densities etc)

on scales <100 pc
up to z~0.15!



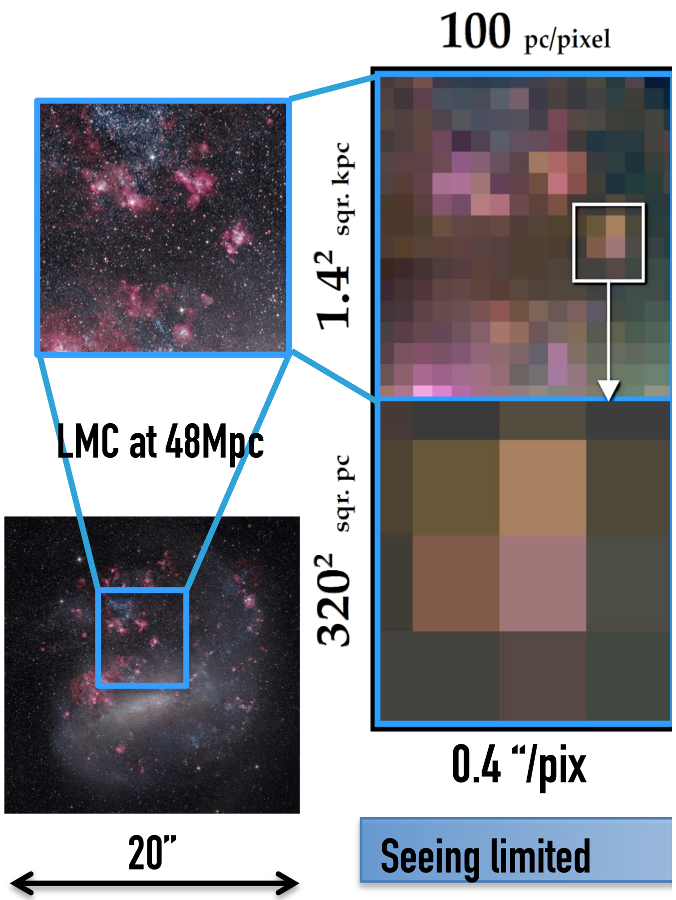
Curti et al. 2019





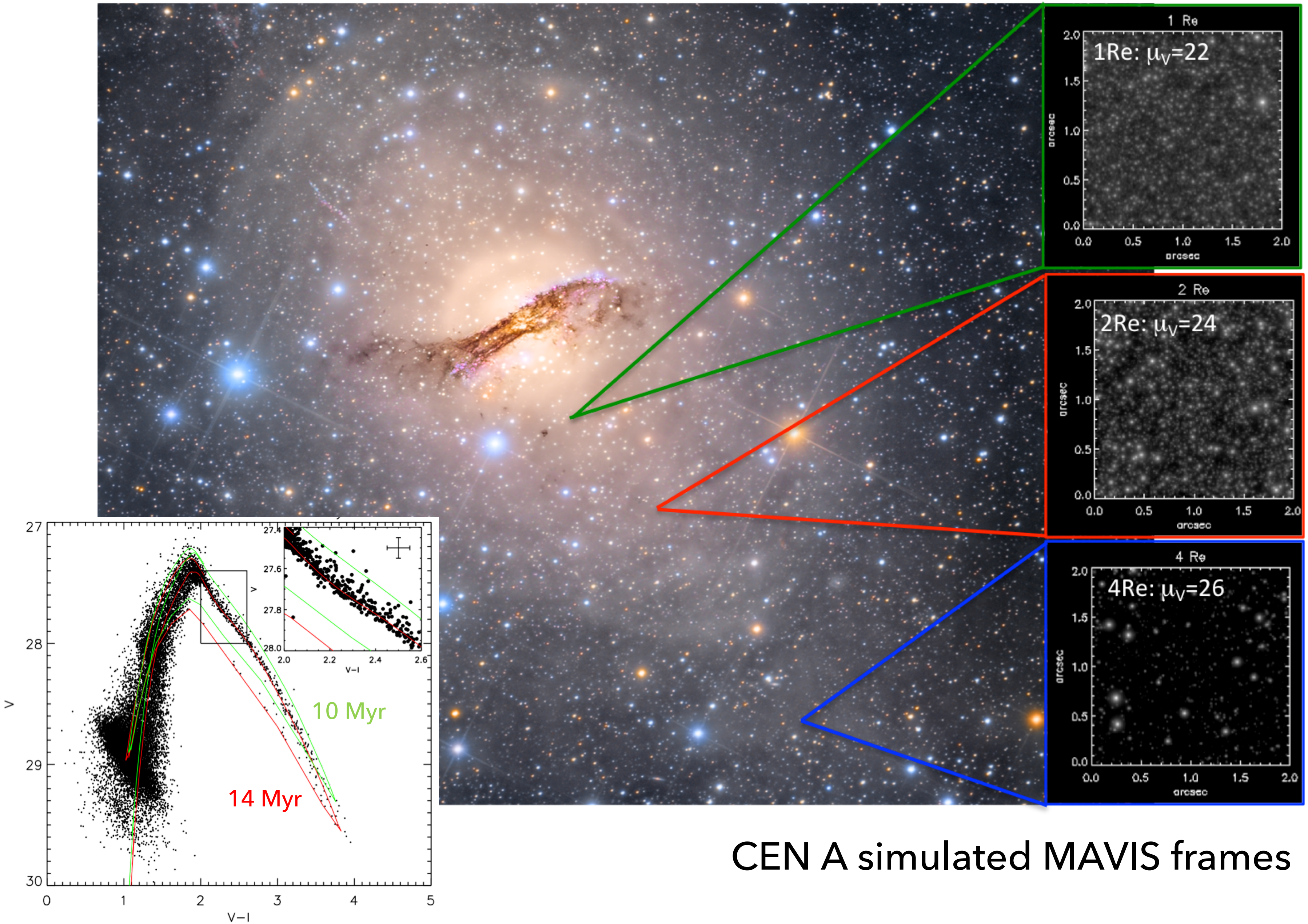
Cresci et al. 2015

RESOLVING GALAXY CONTENTS



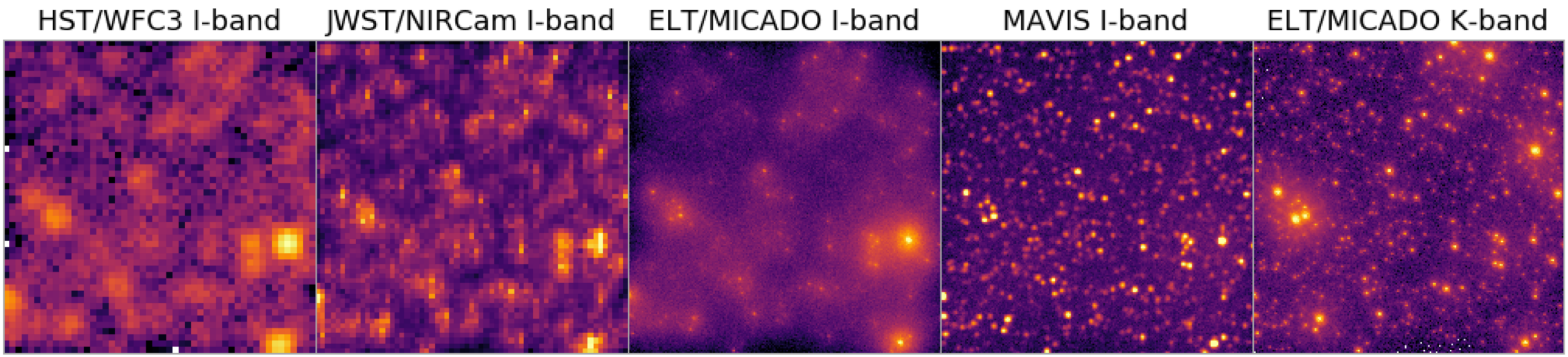
Resolving complexity in galaxies beyond the local group

RESOLVING GALAXY CONTENTS: BEYOND LOCAL GROUP

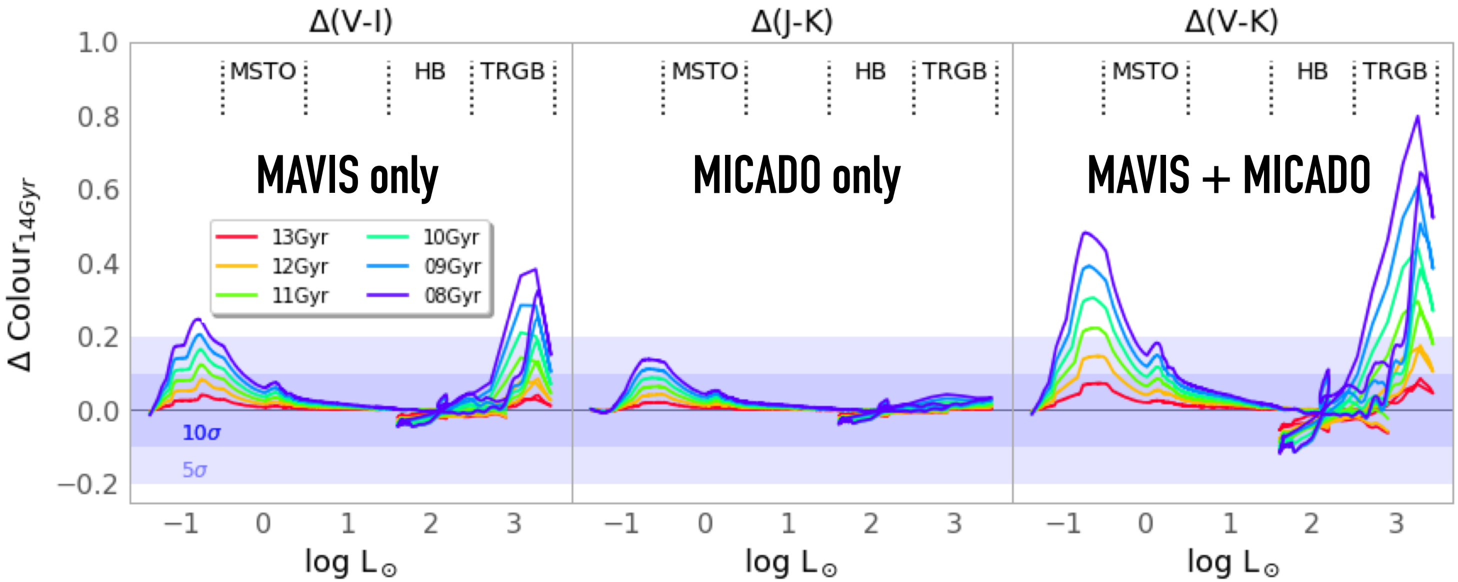


CEN A simulated MAVIS frames

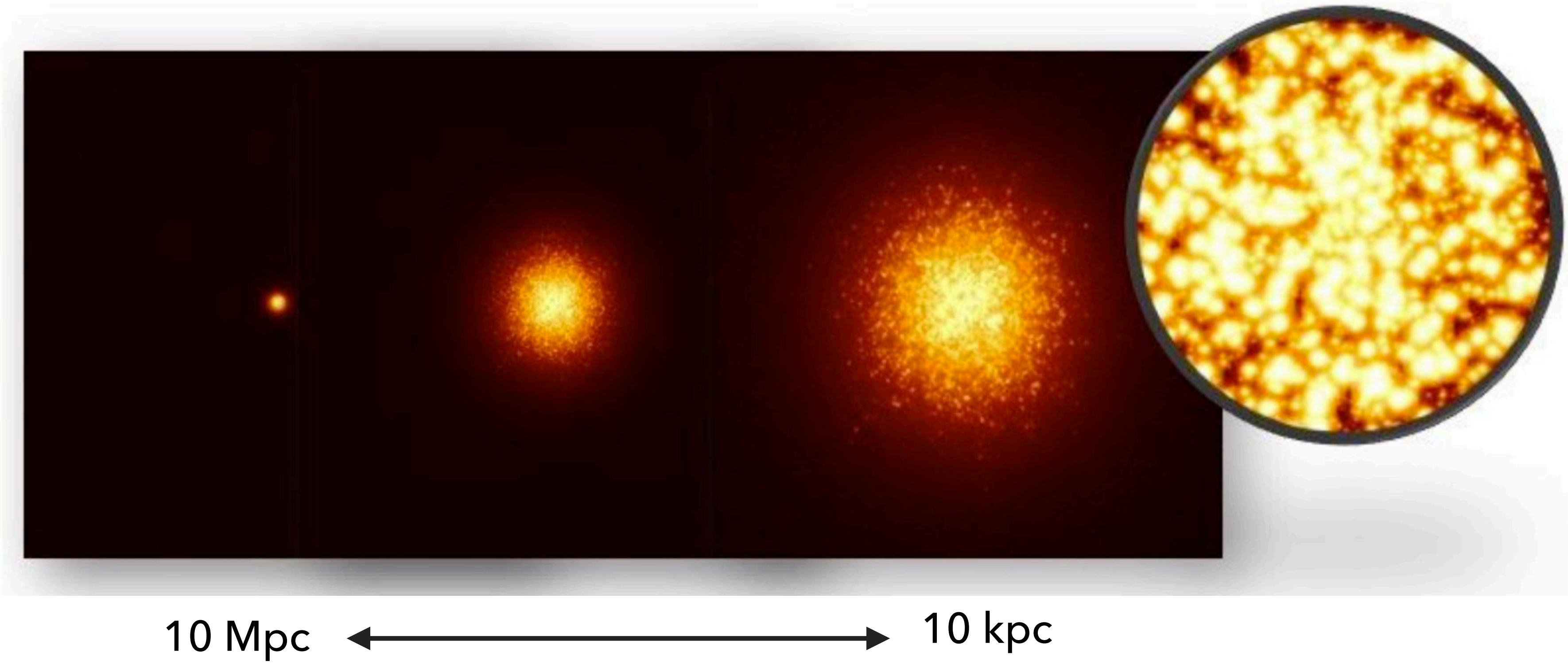
RESOLVING GALAXY CONTENTS: BEYOND LOCAL GROUP



- Key future facilities JWST and ELT are not well-optimized for <1μm
- MAVIS is <u>crucial</u> to provide optical coverage at matched angular resolution to ELT in the IR

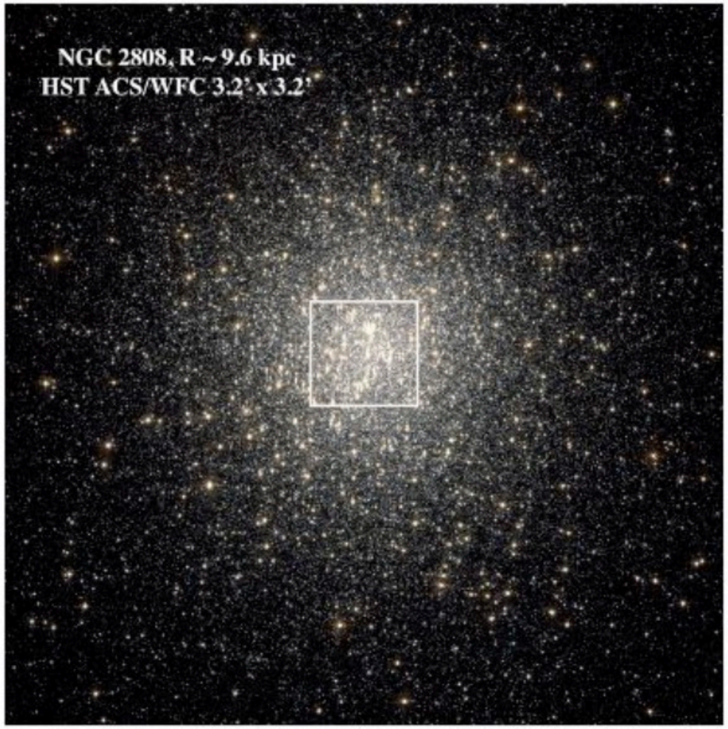


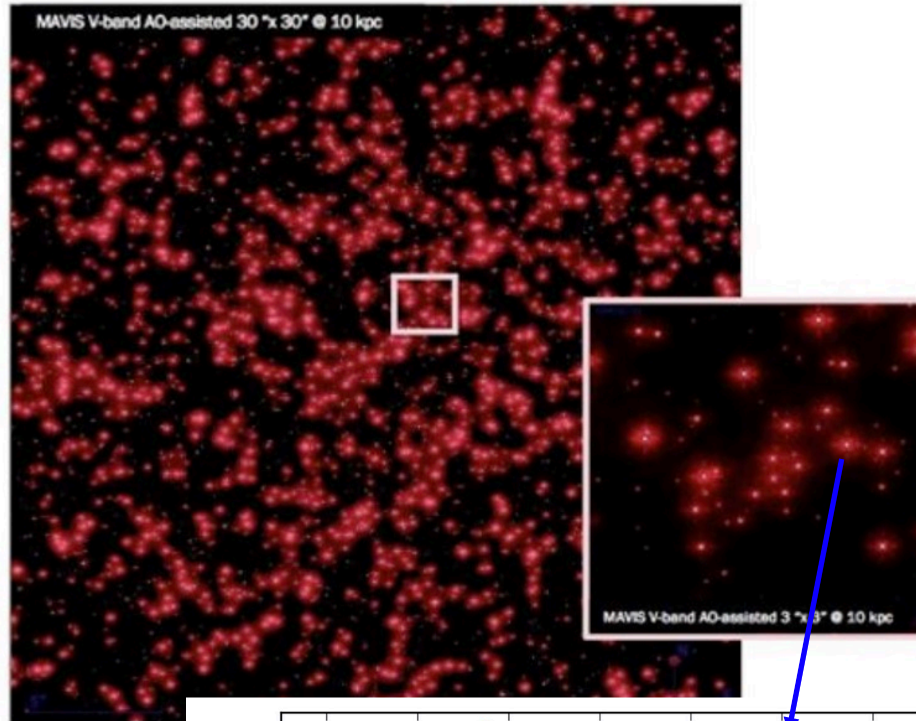
STAR CLUSTERS AS TRACERS OF GALAXY EVOLUTION

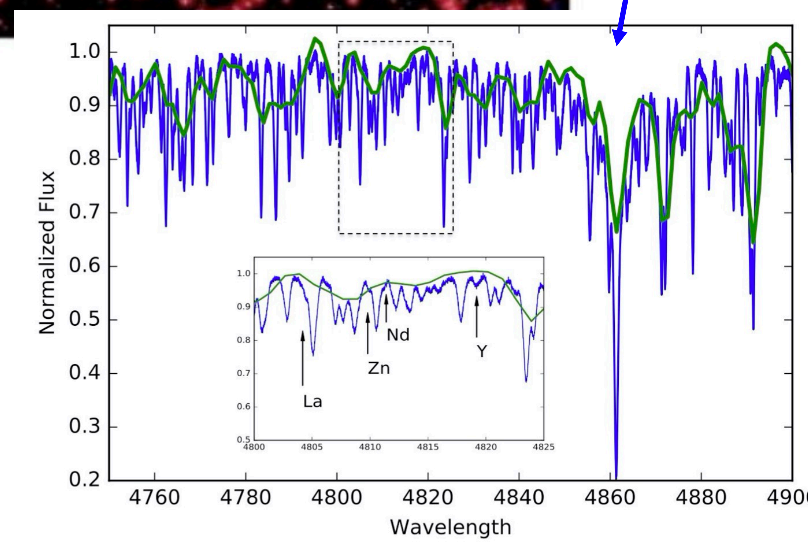


MAVIS offers exciting opportunities to study star clusters at different time and spatial scales. The combined capabilities of photometry at very high spatial resolution with low- and high-resolution spectroscopy opens possibilities to explore parameters previously not possible

STAR CLUSTERS AS TRACERS OF GALAXY EVOLUTION

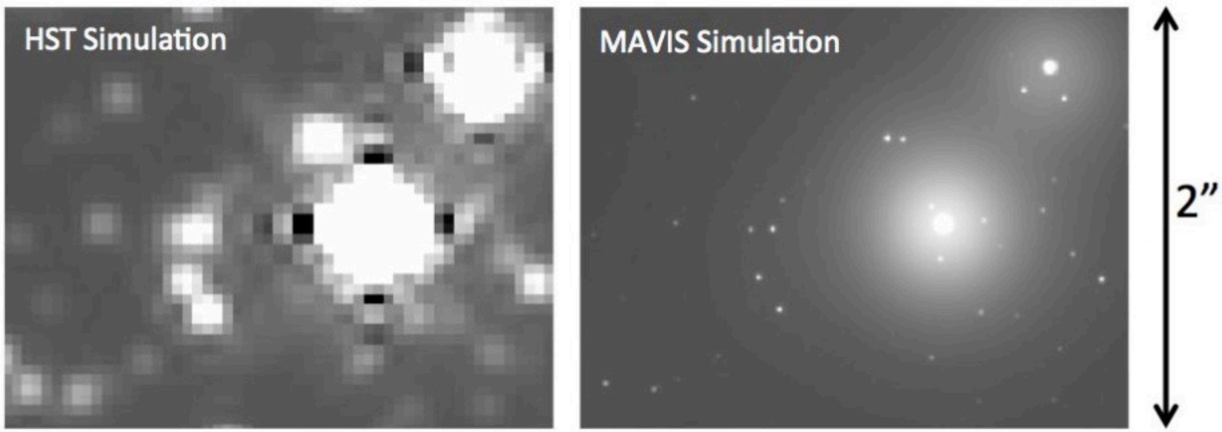






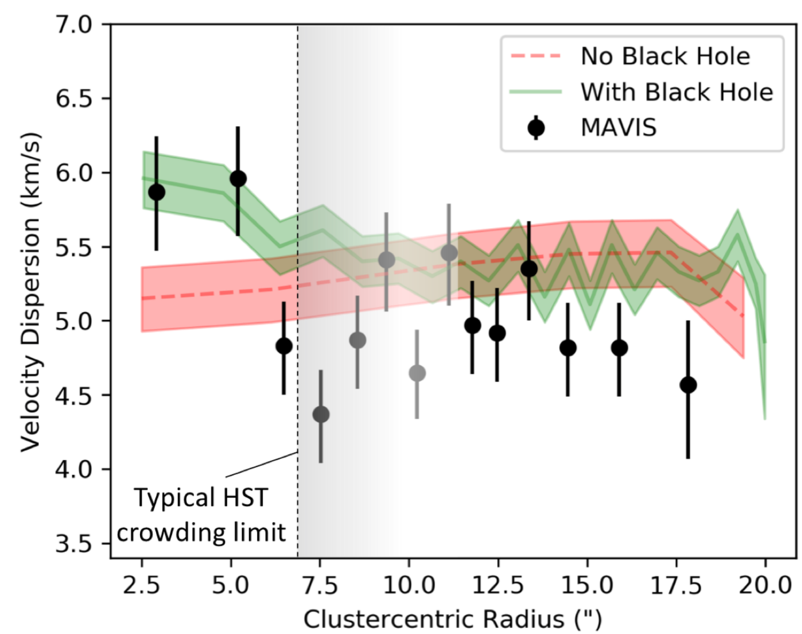
Detect individual stars in Galactic Globular Clusters and measure their chemical abundances

STAR CLUSTERS AS TRACERS OF GALAXY EVOLUTION



Search for intermediate mass BH in globular clusters

Combining precision astrometry and spectroscopy in crowded fields below HST limit with unprecedented resolution



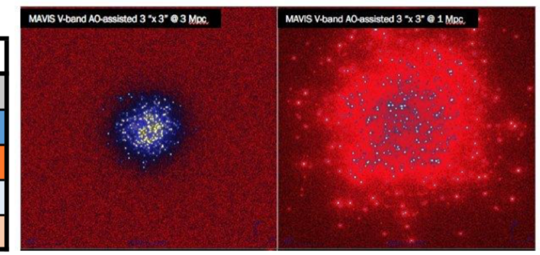
STAR CLUSTERS AS TRACERS OF GALAXY EVOLUTION

Photometry + spectroscopy of stars in extragalactic star clusters possible with MAVIS!

	Nearby Galaxies	distance (kpc)	distance modulus	G5III-K0III (clump old clusters)	O5V (MS young clusters)	B0V (MS young clusters)	B5V (MS young clusters)	angular size"
Local Group	Sagittarius	30	17.39	17.89	11.59	13.29	16.29	68.76
Local Group	LMC	50	18.49	18.99	12.69	14.39	17.39	41.25
Local Group	SMC	60	18.89	19.39	13.09	14.79	17.79	34.38
Local Group	Sculptor	90	19.77	20.27	13.97	15.67	18.67	22.92
Local Group	Sextans	90	19.77	20.27	13.97	15.67	18.67	22.92
Local Group	Carina	100	20.00	20.50	14.20	15.90	18.90	20.63
Local Group	Fornax	140	20.73	21.23	14.93	16.63	19.63	14.73
Local Group	Phoenix	400	23.01	23.51	17.21	18.91	21.91	5.16
Local Group	NGC6822	500	23.49	23.99	17.69	19.39	22.39	4.13
Local Group	IC1613	720	24.29	24.79	18.49	20.19	23.19	2.86
Local Group	Tucana	870	24.70	25.20	18.90	20.60	23.60	2.37
Local Group	WLM	930	24.84	25.34	19.04	20.74	23.74	2.22
Local Group	Aquarius	1020	25.04	25.54	19.24	20.94	23.94	2.02
Sextans group	Sextans A	1500	25.88	26.38	20.08	21.78	24.78	1.38
Sextans group	Sextans B	1500	25.88	26.38	20.08	21.78	24.78	1.38
Sextans group	NGC3109	1500	25.88	26.38	20.08	21.78	24.78	1.38
Local Uni	NGC5253	3150	27.49	27.99	21.69	23.39	26.39	0.65
Local Uni	NGC7793	3440	27.68	28.18	21.88	23.58	26.58	0.60
Local Uni	NGC1313	4390	28.21	28.71	22.41	24.11	27.11	0.47
Local Uni	NGC1705	5100	28.54	29.04	22.74	24.44	27.44	0.40
Local Uni	IC4247	5110	28.54	29.04	22.74	24.44	27.44	0.40
Local Uni	NGC1433	8300	29.60	30.10	23.80	25.50	28.50	0.25
Local Uni	NGC1291	10400	30.09	30.59	24.29	25.99	28.99	0.20

MAVIS Mode
Imaging
HR-Blue
HR-Red
LR-Blue
LR Red

3 Mpc 1 Mpc

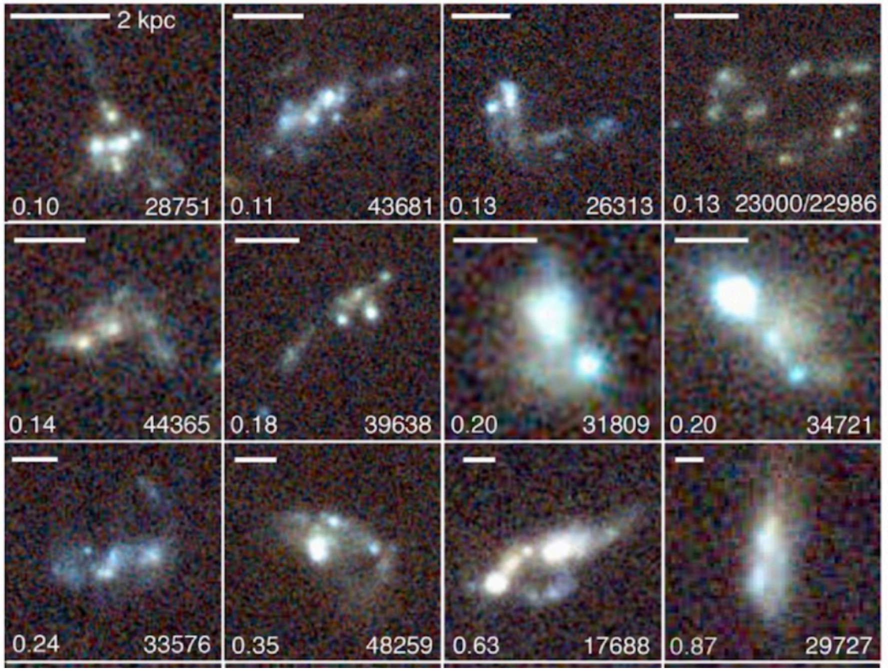


- Tiered approach based on cluster age and host distance
- Single stars of full cluster population resolved up to 100 kpc
- R>12,000 possible to 1Mpc
- R>5,000 possible to 3Mpc
- Explore IMF, chemical enrichment, time scales…

STAR CLUSTERS AS TRACERS OF GALAXY EVOLUTION

The majority of galaxies at z>1 – 2 are dominated by bright star-forming "clumps":

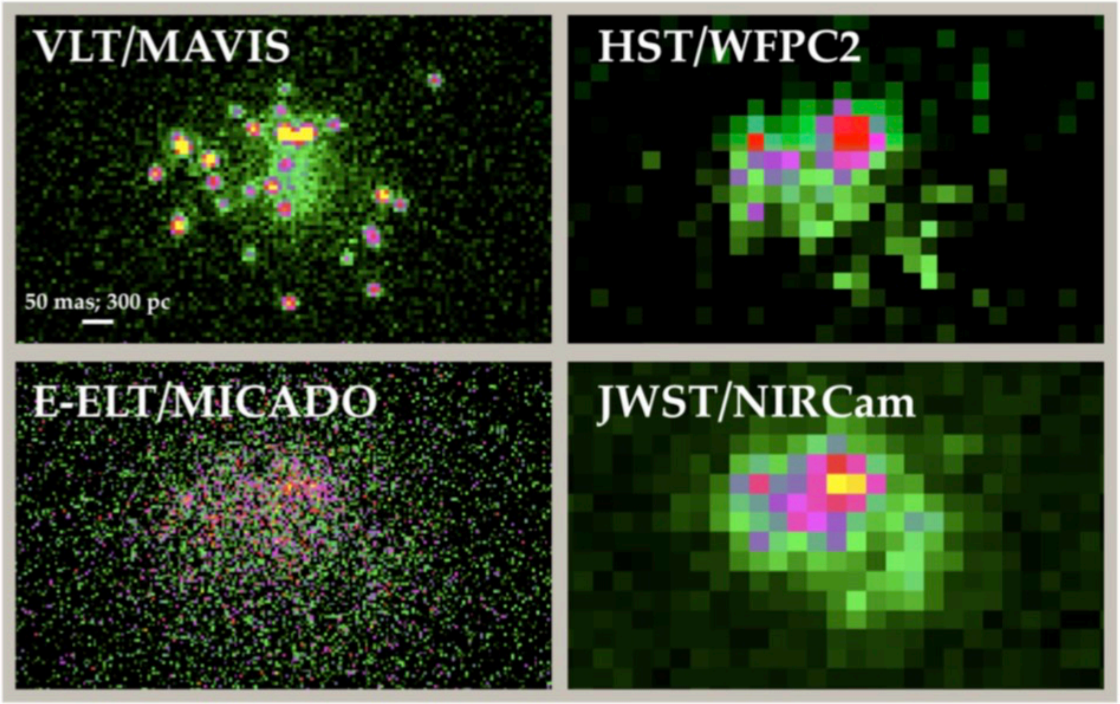
- stellar masses ~10^9 M_{sun}
- typical sizes ≤1 kpc (≤0.1″ at z ~2) but unresolved



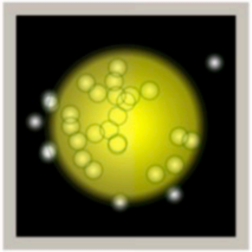
UV spectroscopy:

Lyα, CIII]λ1909, HeIIλ1640, Mg IIλ2798 …

- dynamics
- outflows
- IMF
- escape fraction
- …



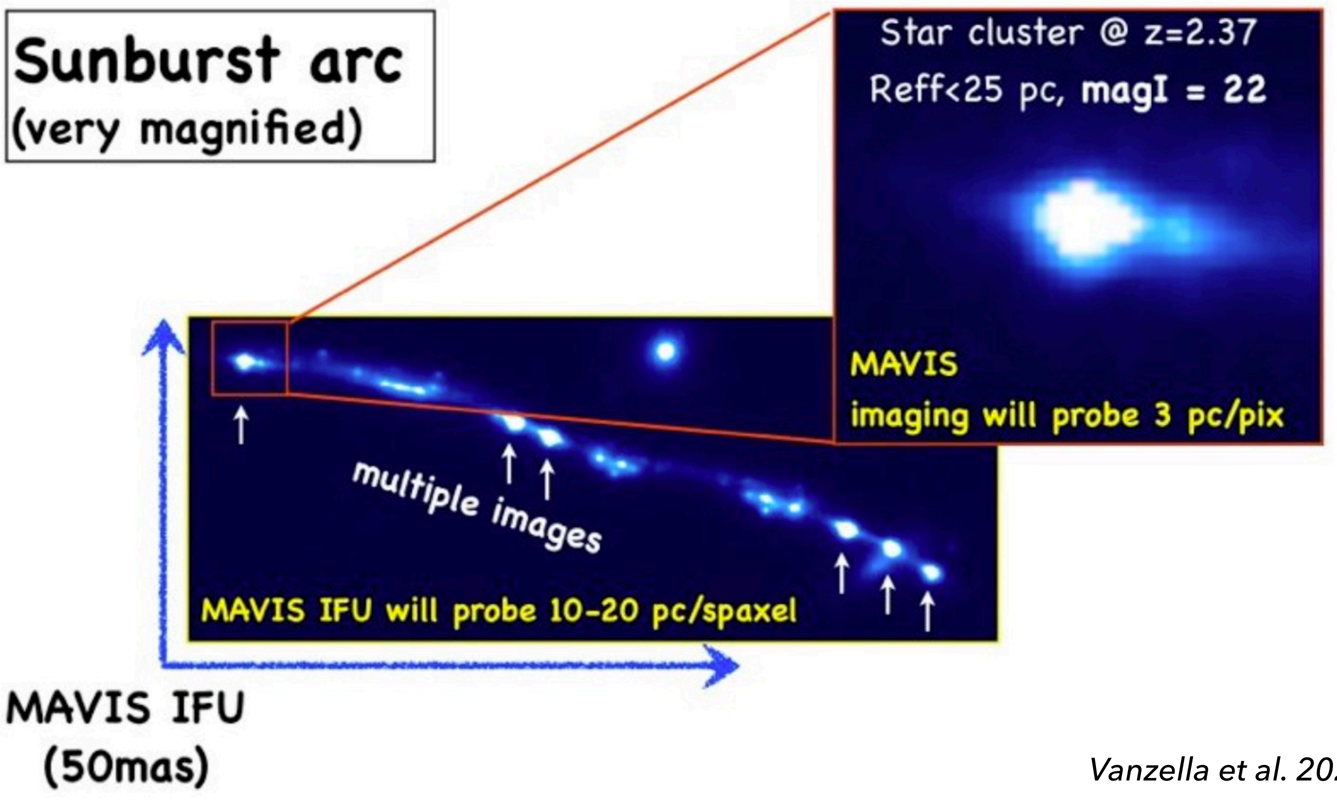
MODEL



I band simulations ($\sigma = 0.1''$ 0.6 kpc at z=5)

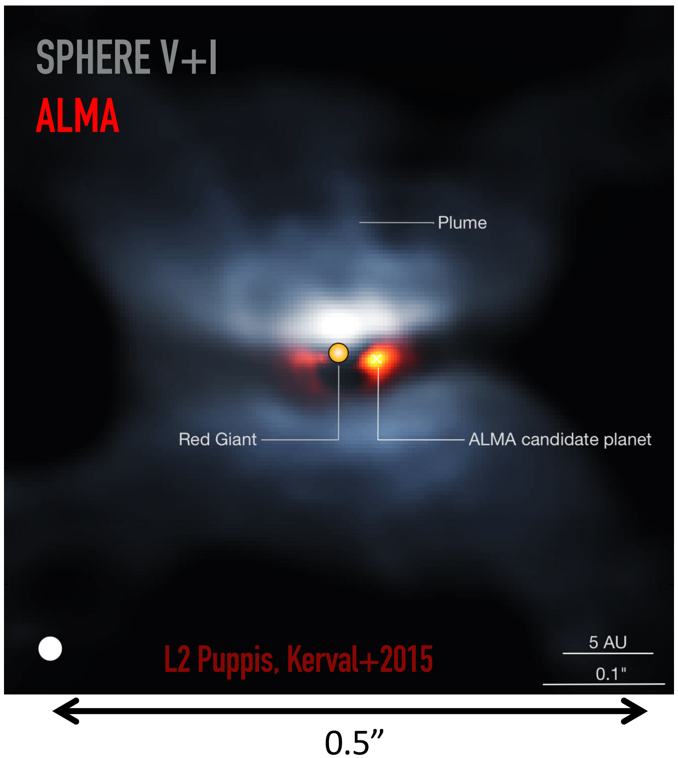
STAR CLUSTERS AS TRACERS OF GALAXY EVOLUTION: FORMING GC AT HIGH Z

MAVIS will identify **globular cluster precursors** up to the reionization epoch and quantify their ionizing photon production efficiency.



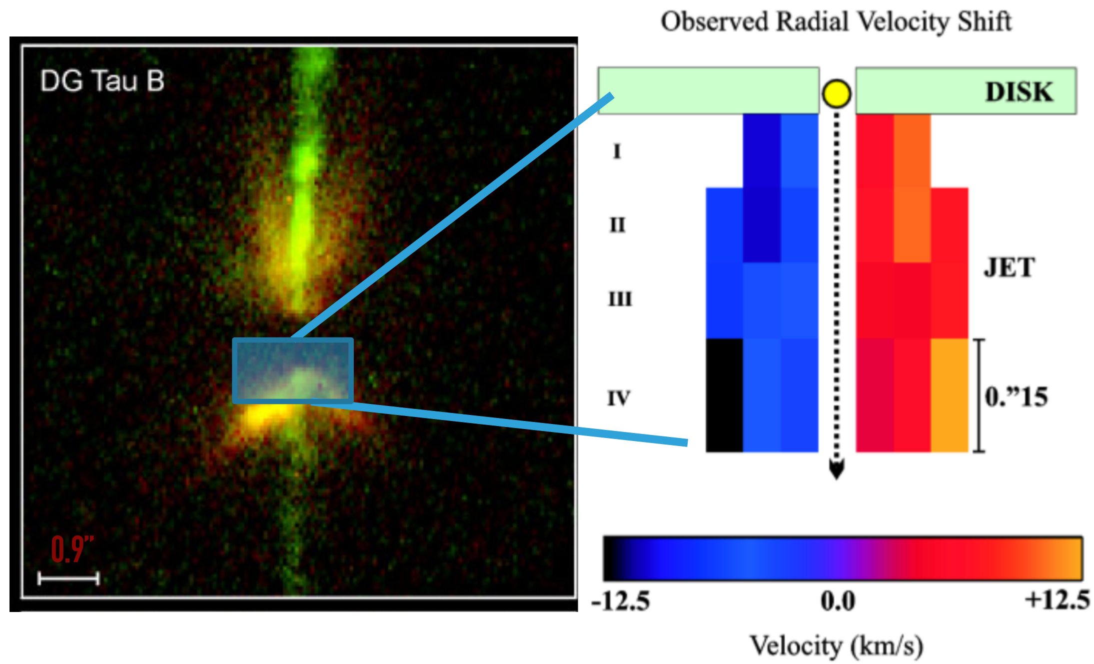
Vanzella et al. 2020

BIRTH, LIFE, DEATH OF STARS AND PLANETS



Protoplanetary disks around evolved stars

optical needed to probe the external parts



Bacciotti et al. 2002

Jets from young stars

Jet precession observed from HST spectra

BIRTH, LIFE, DEATH OF STARS AND PLANETS

SOLAR SYSTEM

- Ground-based campaigns may play an important role in solar system science:
  - Monitoring programs
  - Unexpected events
  - Coordination with ESA
- MAVIS sky coverage and large field of view well suited to flexible observations of non-sidereal targets

SPHERE@VLT + AO

eso1910 — Organisation Release

ESO contributes to protecting Earth from dangerous asteroids

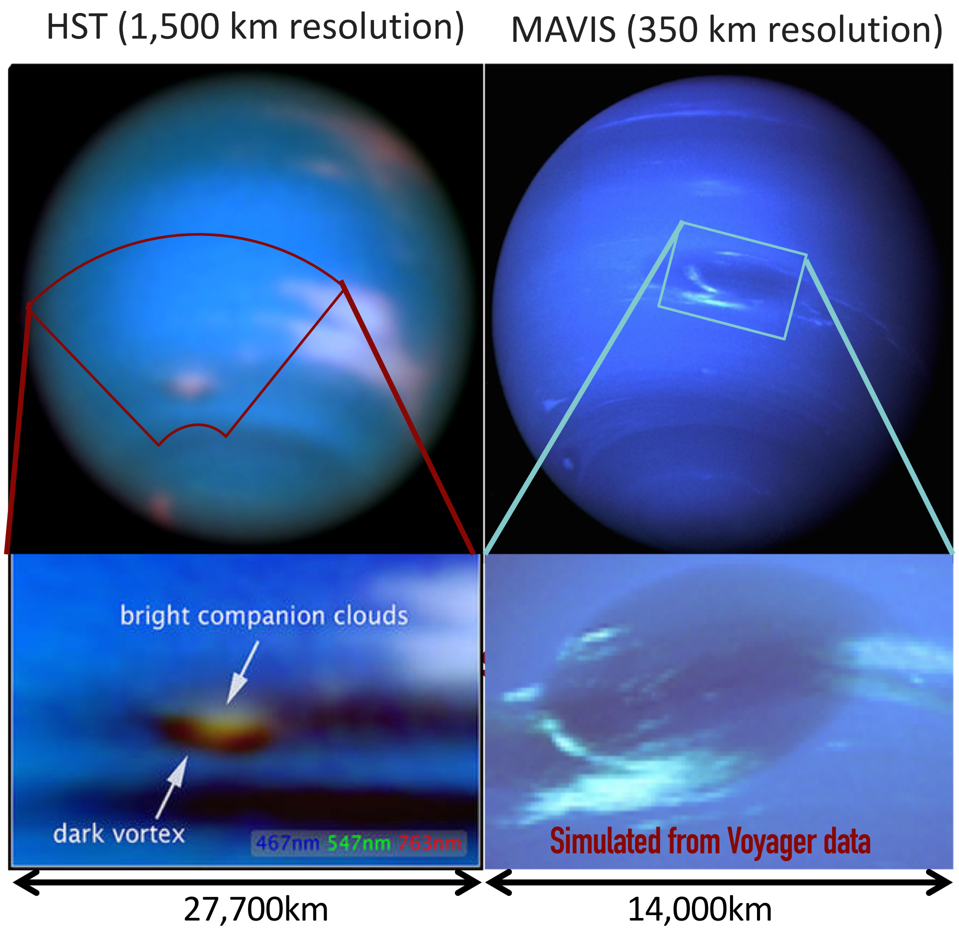
VLT observes a passing double asteroid hurtling by Earth at 70 000 km/h

3 June 2019

A double asteroid with separation 2.6 km
(but SPHERE limited to targets with R~9-11)

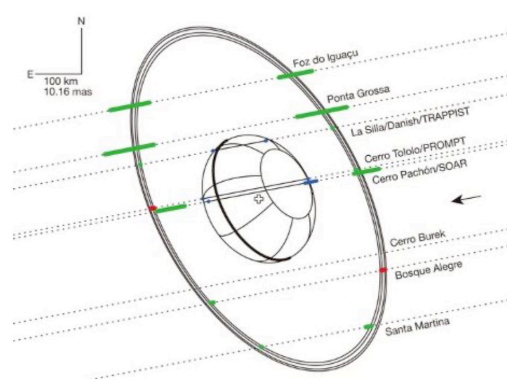
BIRTH, LIFE, DEATH OF STARS AND PLANETS

Giant planets



Comets & Kuiper Belt Objects

- high resolution imaging and spectroscopy:
    - dust and coma morphology
    - surface composition
    - planetary rings
    - …



Braga-Ribas et al. 2014

MAVIS: WHERE ARE WE?

- Phase A went **very well**:
  - Lots of interest from science community (you)
  - 2 participated Science Meetings in Arcetri and Australia
  - Project running on time
  - Most manpower founds secured
  - Successfully passed **mid-term review (MTR) October 24-25** with very good feedback from ESO:

> *"ESO wishes to command the consortium for the terrific work and progress accomplished so far by the MAVIS consortium.*
>
> *ESO is impressed by the amount of work completed until now, and by the maturity of the conceptual design; this has been made possible by the skills of the people involved in this project and the efficient organization. Indeed, in spite of the multi-institutes status and remote geographic locations, a successful collaborative spirit and efficient coordination has been setup. ESO can observe the concrete benefits and perceive the positive team spirit that has been established;* ***whatever it is that the consortium is doing, keep doing it*** *!"*

MAVIS: WHERE ARE WE?

- **Final phase A review yesterday!**

ACKNOWL

- The Board commends the MAVIS Consortium for the substantial effort, cohesion and enthusiasm
- Science cases extremely well worked out
- Well prepared review, with a well developed documentation package, highly consistent
- Effective Systems Engineering across the members of the Consortium

- Main concern is cost: 8 ME allocated for hardware vs ~12 ME needed (including 20% contingency)
- Phase B to start in early 2021
- Current schedule calls for **first light end of 2026**, in line with ELT (…)

CONCLUSIONS

MAVIS

- Diffraction limit optical imaging and spectroscopy is coming
- Just passed through Phase A review, very good initial outcome
- A joined Australian, Italian and French effort in technology and science
- A new discovery window: *sharper than JWST, deeper than HST*
- An unique, multipurpose instrument, complementary with existing and forthcoming facilities
- Expected first light ~**2026,** GTO~150 nights

Interested? Want more info?
Follow the blog: www.mavis-ao.org
Subscribe to the mailing list: http://eepurl.com/ghyq35
email: project-scientist@mavis-ao.org
giovanni.cresci@inaf.it

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