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

*SHARPER THAN JWST, DEEPER THAN HST*

RICHARD MCDERMID, MACQUARIE UNIVERSITY
ON BEHALF OF THE MAVIS CONSORTIUM

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

LAM LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

ESO

# ESO STRATEGIC PARTNERSHIP – AN IMPORTANT OPPORTUNITY

- Australia joined ESO as **strategic partner, July 2017**
- Opened opportunities for leading instrumentation projects
- Instrumentation opportunities for Australia limited to La Silla and Paranal, but **Adaptive Optics Facility (AOF)** newly commissioned
- Key technical components of AOF:
  - **Four laser guide stars**, 20W each, operating above specifications
  - **Deformable secondary mirror** with high actuator density
- Currently mainly ground-layer AO (wide field, low Strehl)
- MUSE Narrow Field Mode approaches diffraction limit, but only for bright on-axis guide stars
- **Full AOF science potential not being realized**
- **Led to Phase A call for optical AO imager/spectrograph**

Australia Enters Strategic Partnership with ESO

11 July 2017

# SOME REASONS TO UNLOCK THE VISIBLE WITH AO

- Optical wavelengths are **information-rich**, with many well-understood astrophysical diagnostics
- **Sky background** is x1,000-10,000 times fainter than IR - possible to **compete with space** facilities
- **Detectors** are larger, lower noise, faster frame rates, and cheaper
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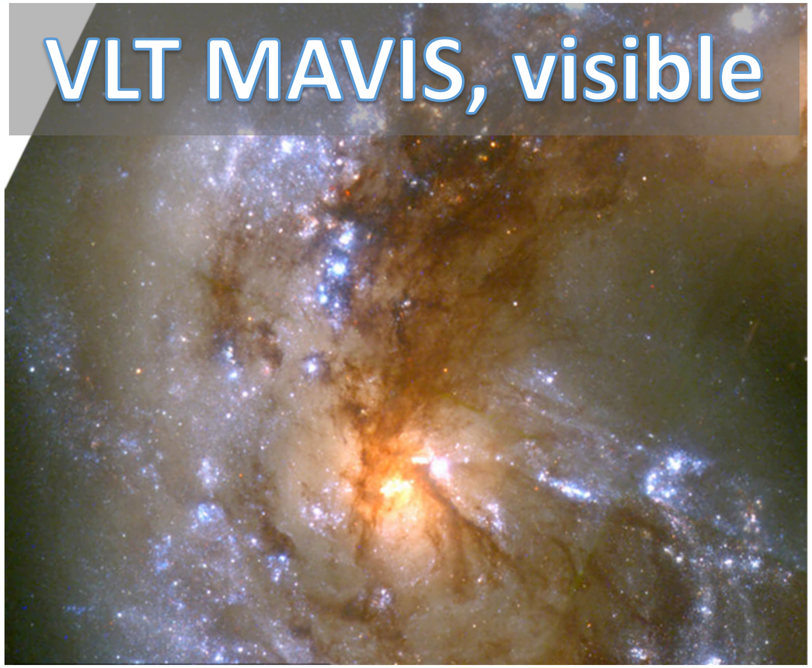
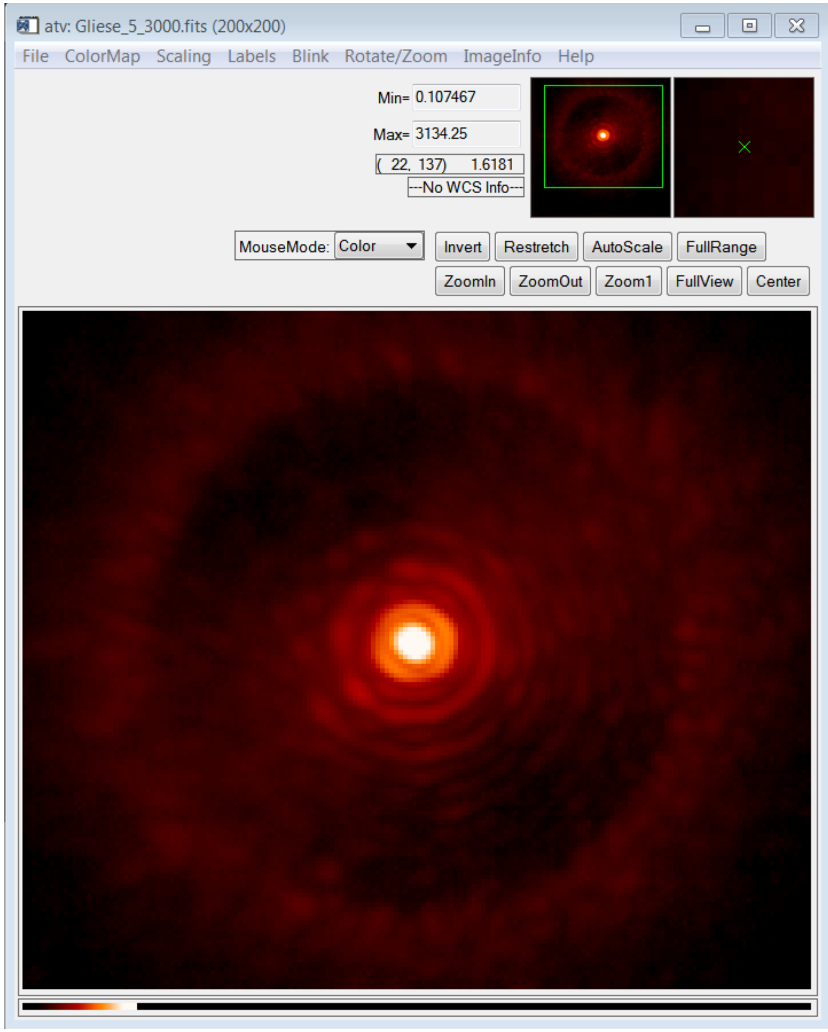


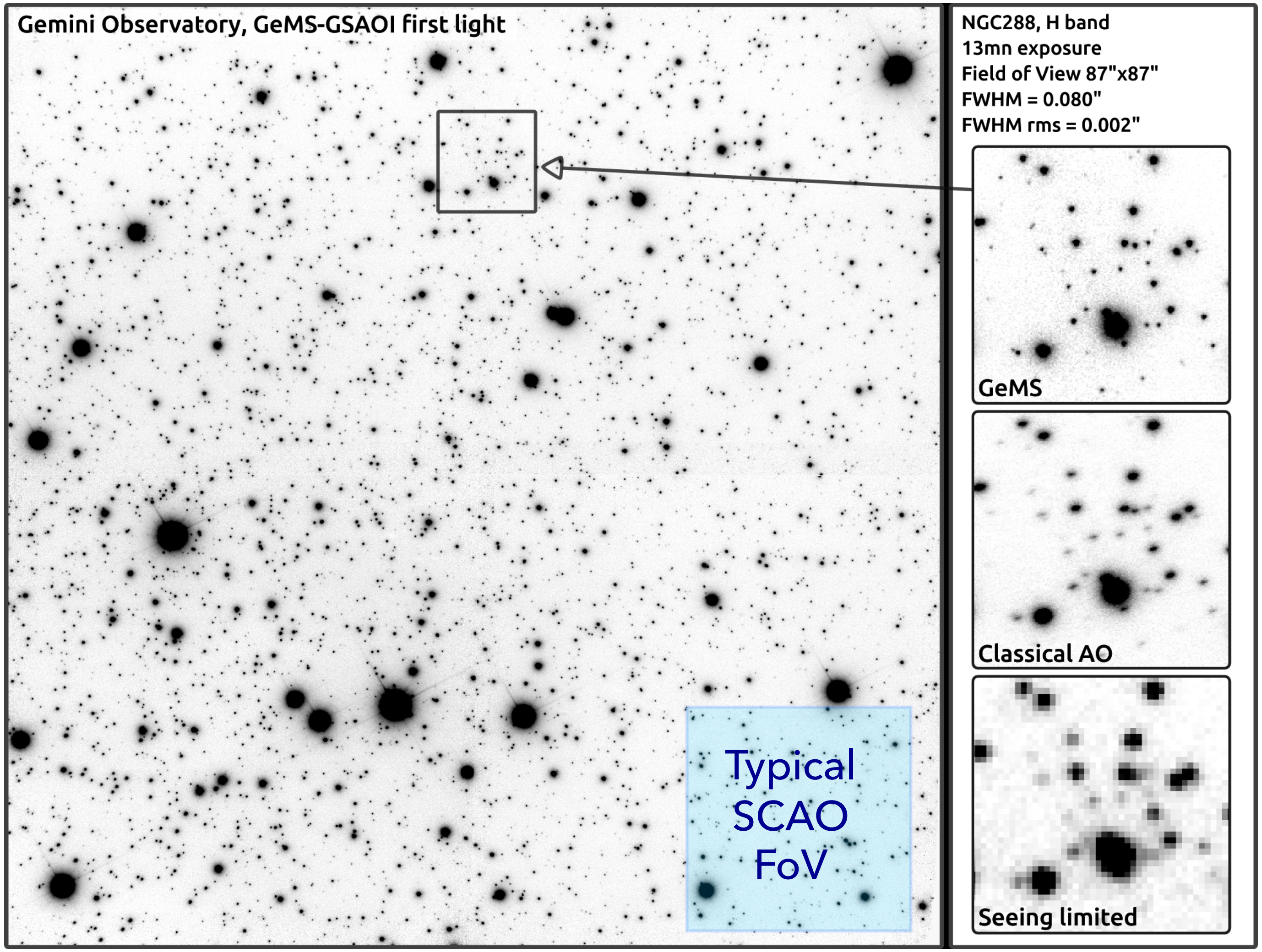

# SINGLE CONJUGATE AO IN THE VISIBLE

- 650nm images from ForRunner @LBT
  - 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!**



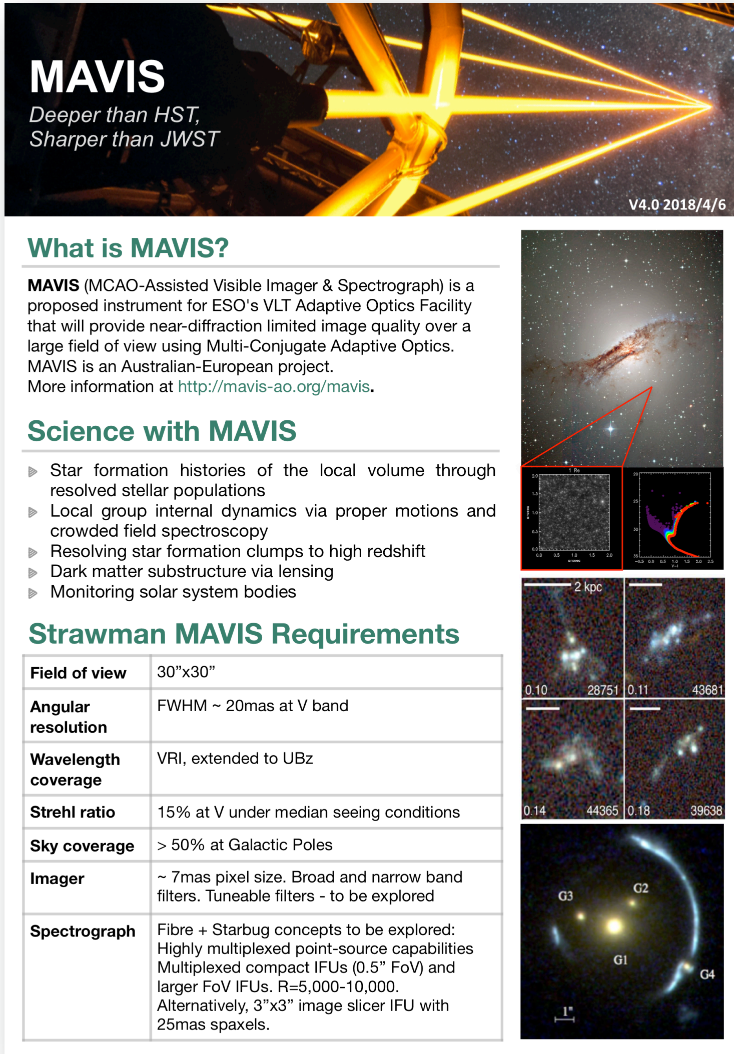
# MCAO IN THE NIR: GEMS @ GEMINI

- Facility instrument using MCAO is demonstrated
- MCAO in the optical – is it doable?



# WHAT IS MAVIS?

- Blog: www.mavis-ao.org



# MAVIS

*Deeper than HST,*
*Sharper than JWST*

V4.0 2018/4/6

## What is MAVIS?

**MAVIS** (MCAO-Assisted Visible Imager & Spectrograph) is a proposed instrument for ESO's VLT Adaptive Optics Facility that will provide near-diffraction limited image quality over a large field of view using Multi-Conjugate Adaptive Optics. MAVIS is an Australian-European project.
More information at http://mavis-ao.org/mavis.

## Science with MAVIS

- Star formation histories of the local volume through resolved stellar populations
- Local group internal dynamics via proper motions and crowded field spectroscopy
- Resolving star formation clumps to high redshift
- Dark matter substructure via lensing
- Monitoring solar system bodies

## Strawman MAVIS Requirements

| | |
|---|---|
| **Field of view** | 30”x30” |
| **Angular resolution** | FWHM ~ 20mas at V band |
| **Wavelength coverage** | VRI, extended to UBz |
| **Strehl ratio** | 15% at V under median seeing conditions |
| **Sky coverage** | > 50% at Galactic Poles |
| **Imager** | ~ 7mas pixel size. Broad and narrow band filters. Tuneable filters - to be explored |
| **Spectrograph** | Fibre + Starbug concepts to be explored: Highly multiplexed point-source capabilities Multiplexed compact IFUs (0.5” FoV) and larger FoV IFUs. R=5,000-10,000. Alternatively, 3”x3” image slicer IFU with 25mas spaxels. |

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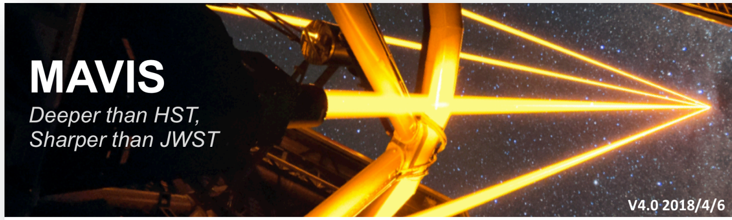


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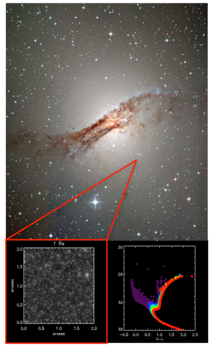

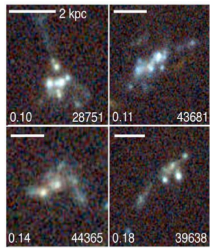


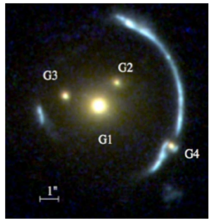

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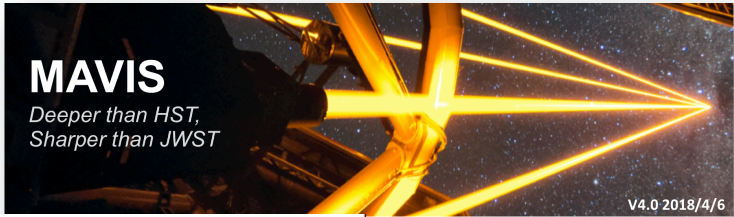


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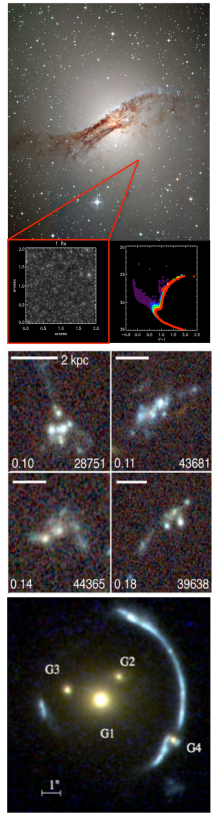
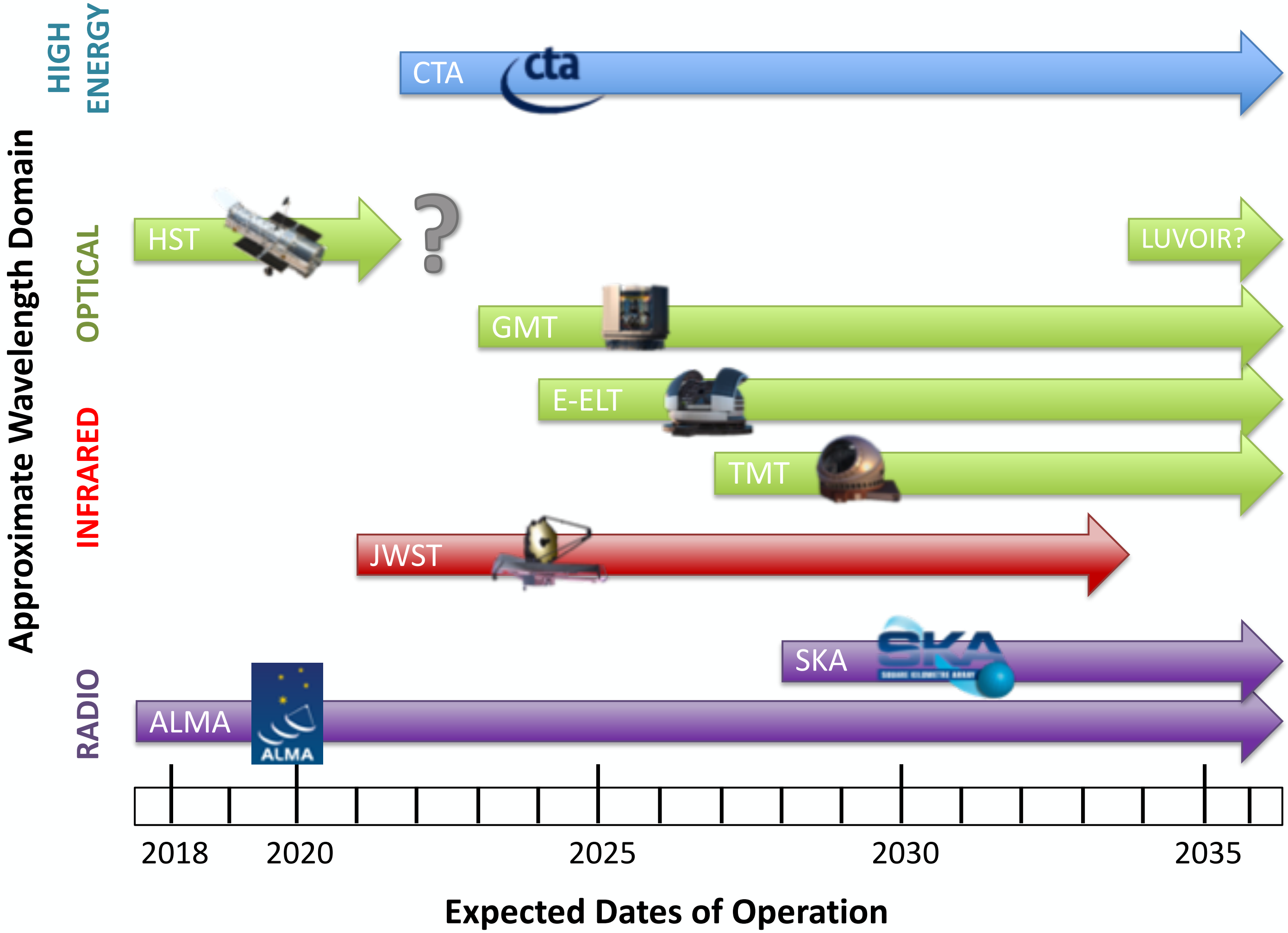


# FUTURE FACILITIES

- MAVIS operations overlaps well with ELT era
- Overlaps with JWST core (5yr) and goal (10yr) mission
- Will fill the gap left at optical wavelengths in the post-HST era



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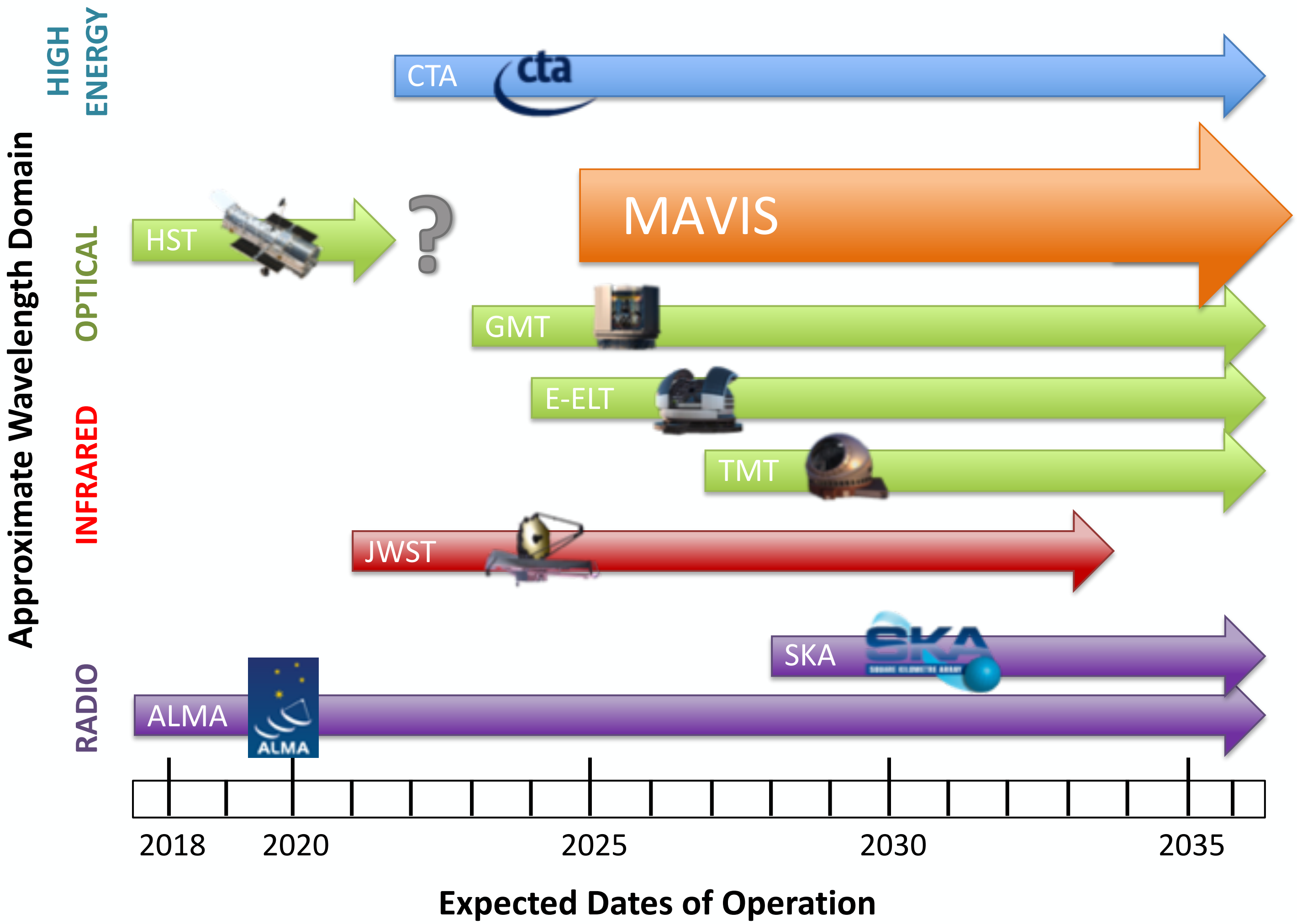

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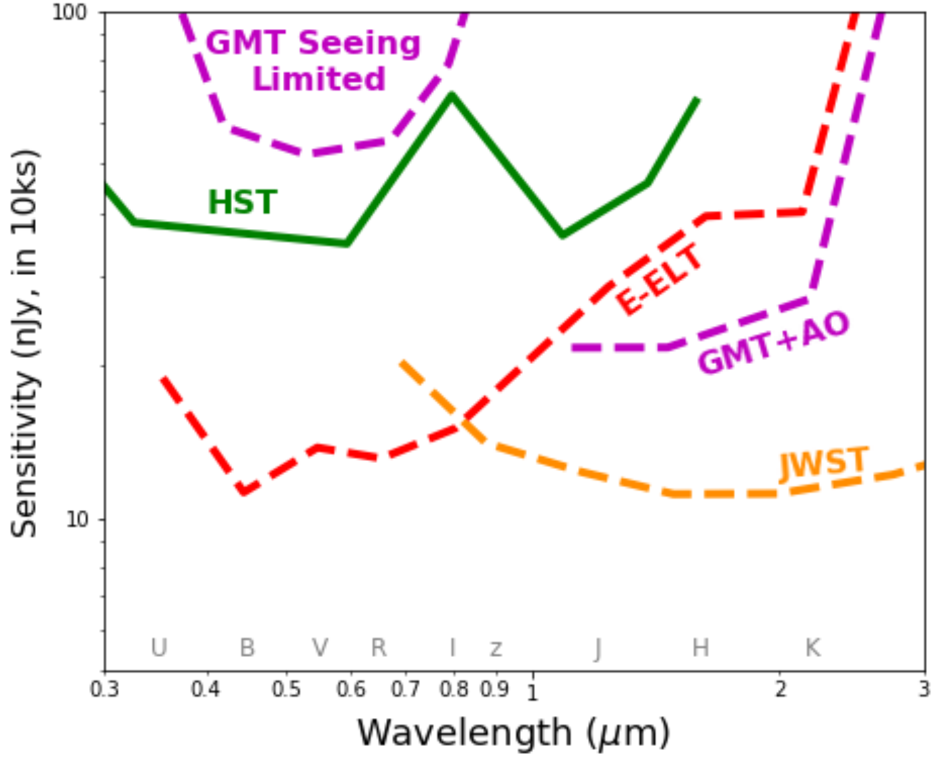


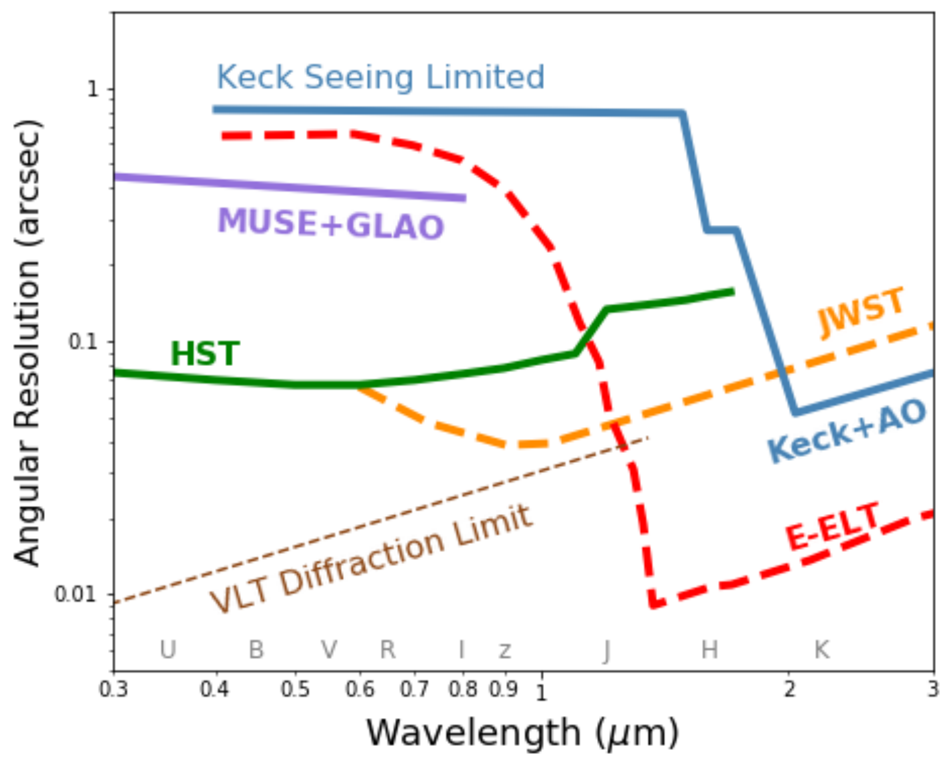


- MAVIS will provide comparable sensitivity to JWST and ELTs, but with higher angular resolution

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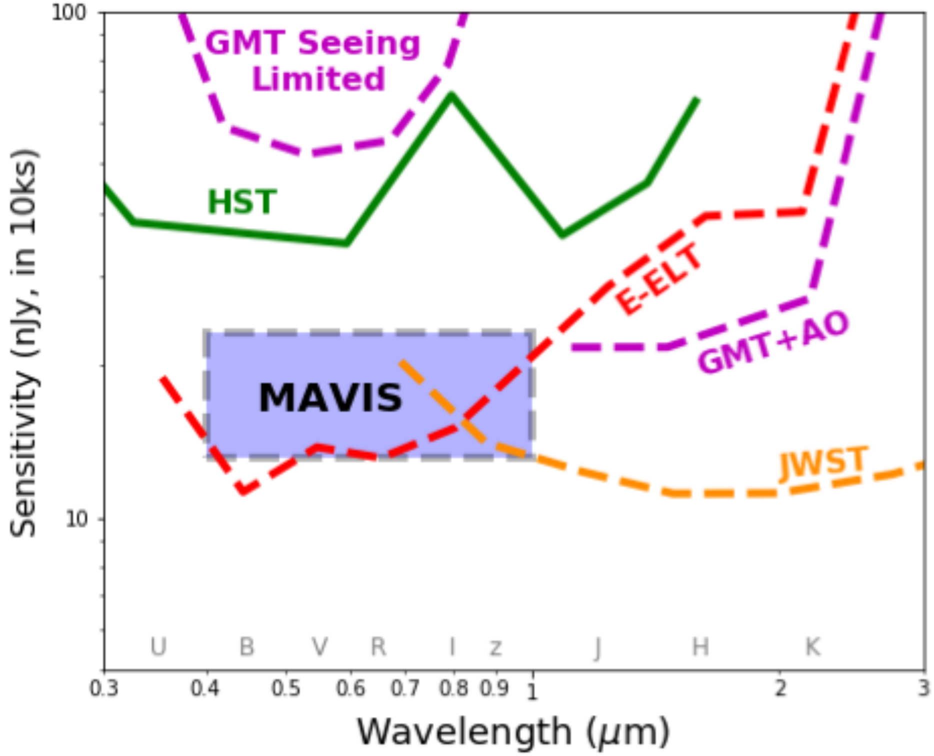


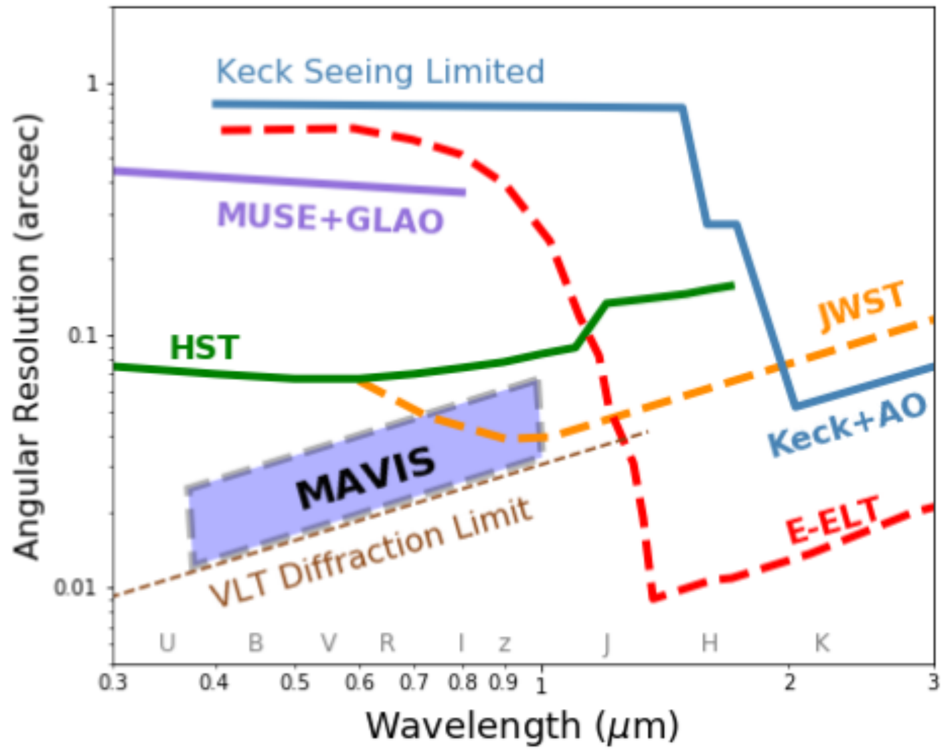


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# MAVIS CONSORTIUM

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

AO system engineering
Opto-mechanics
Instrument Software
NGS WFS

National Optical Astronomical Instrumentation Capability

AAO
Australian National University
MACQUARIE University

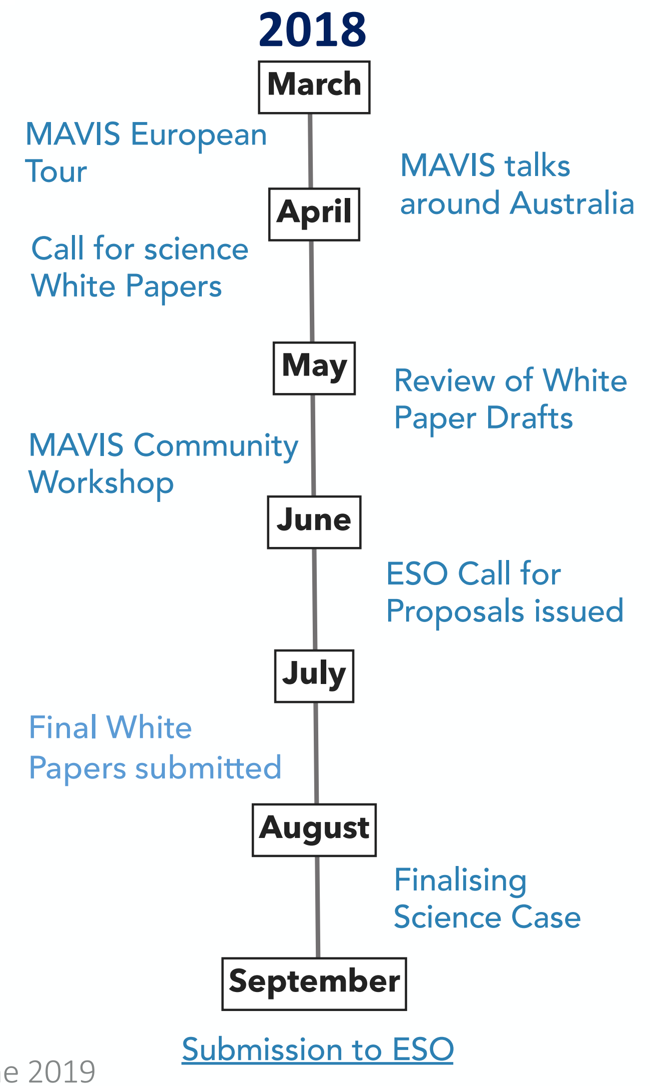
Post-focal instrumentation:
Imager, spectrograph,
IFU front-end
Management
LGS WFS
RTC, AO expertise

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

Simulations
Post-processing
AO Control

# PROCESS OF BUILDING THE PRE-PHASE A SCIENCE CASE

- March: Consolidate consortium partners in Europe; visited ESO
- April 2018: issued public call for **MAVIS White Papers**
- Series of MAVIS talks around Australian institutions
- **Workshop May 2018** to discuss meshing of science and instrument designs and documentation
- **Final White Papers** submitted July 2018



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**White Paper Template**

1. *Key Questions*
2. *Open Problems*
3. *Observational Needs*
4. *Instrument Requirements (value and reason)*
   - *Field of View*
   - *Image Quality*
   - *Spectral Range*
   - *Spectral Resolution*
   - *Multiplexing Needs*

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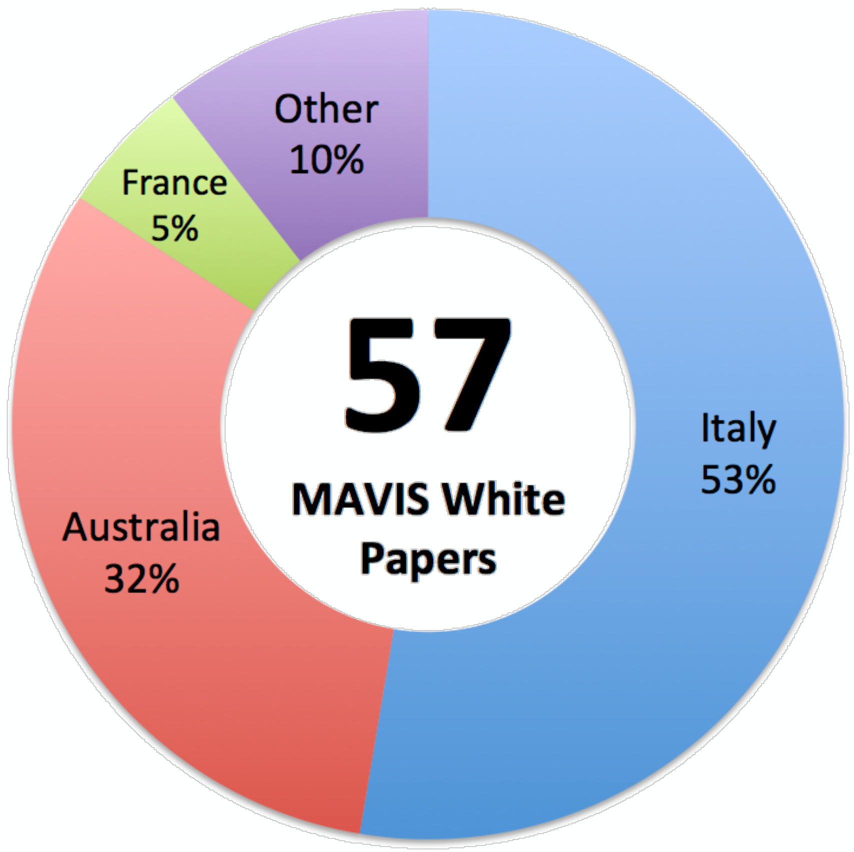
**Lead Author Affiliations by Country**



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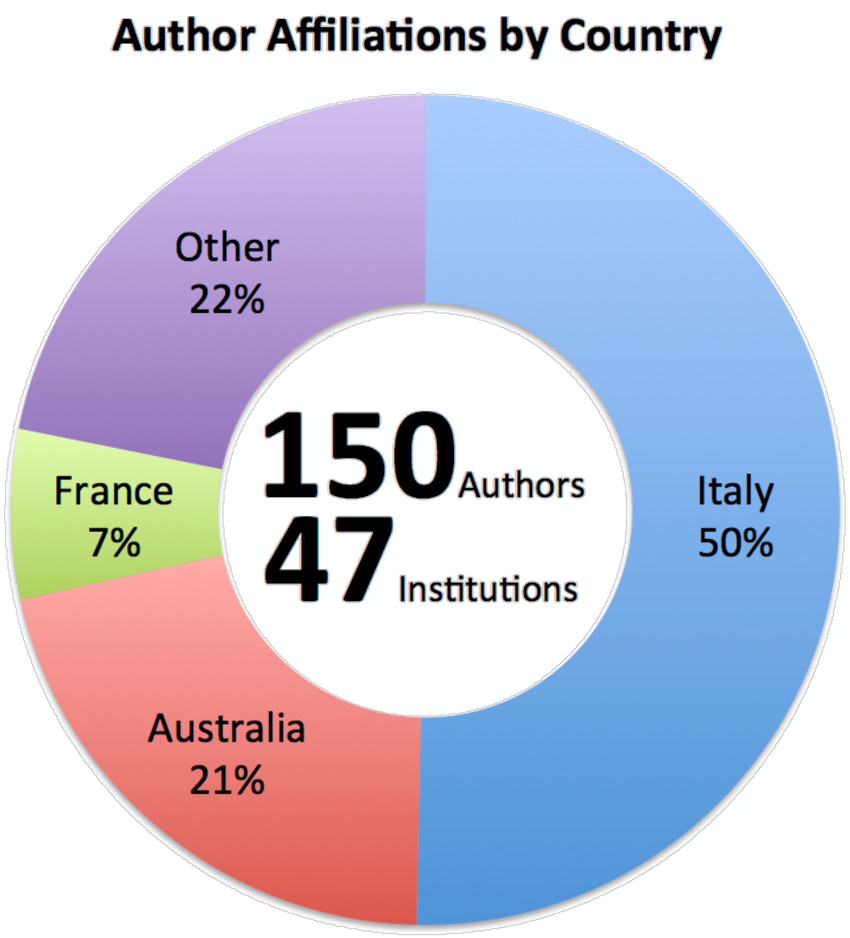

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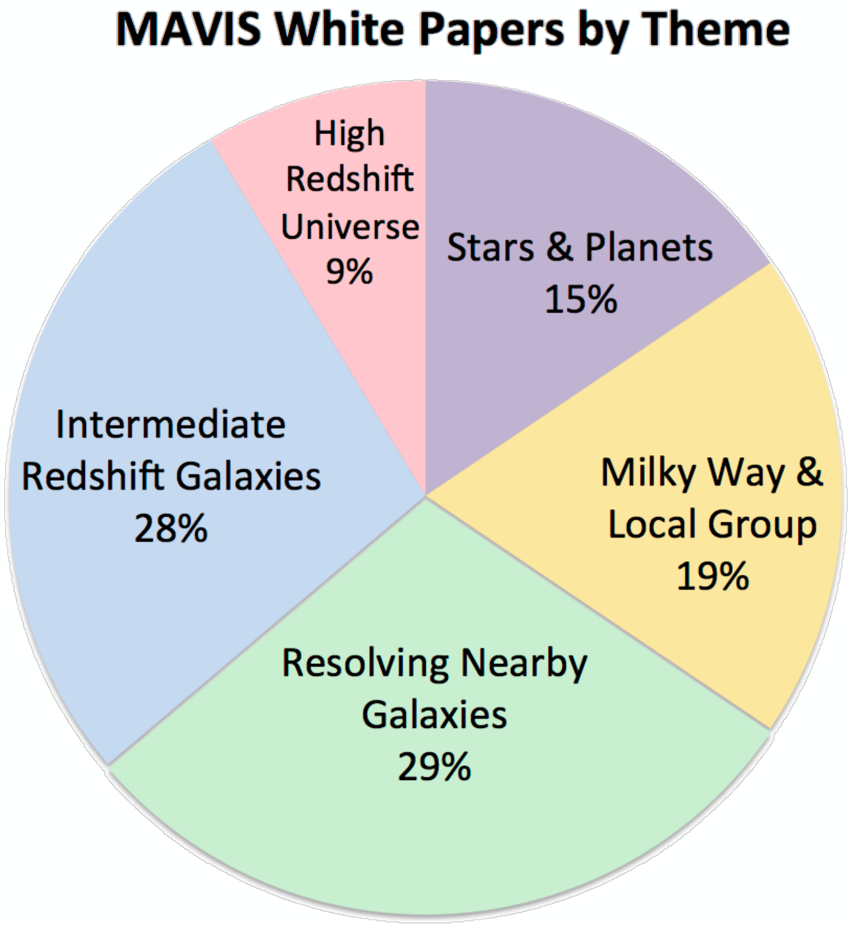

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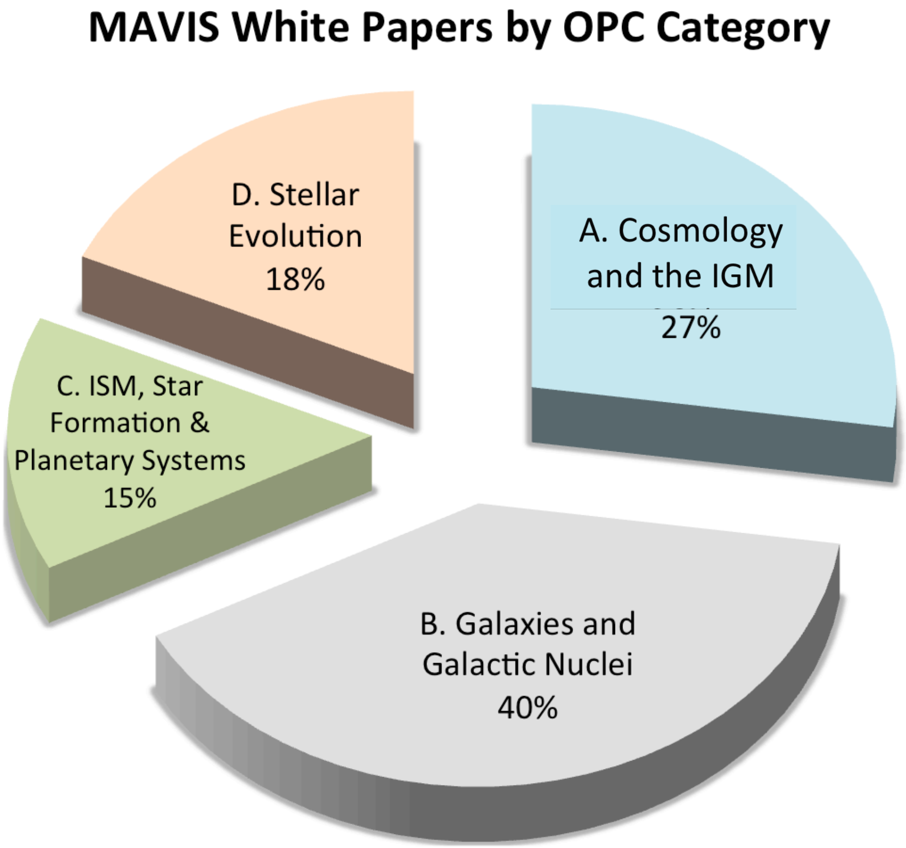

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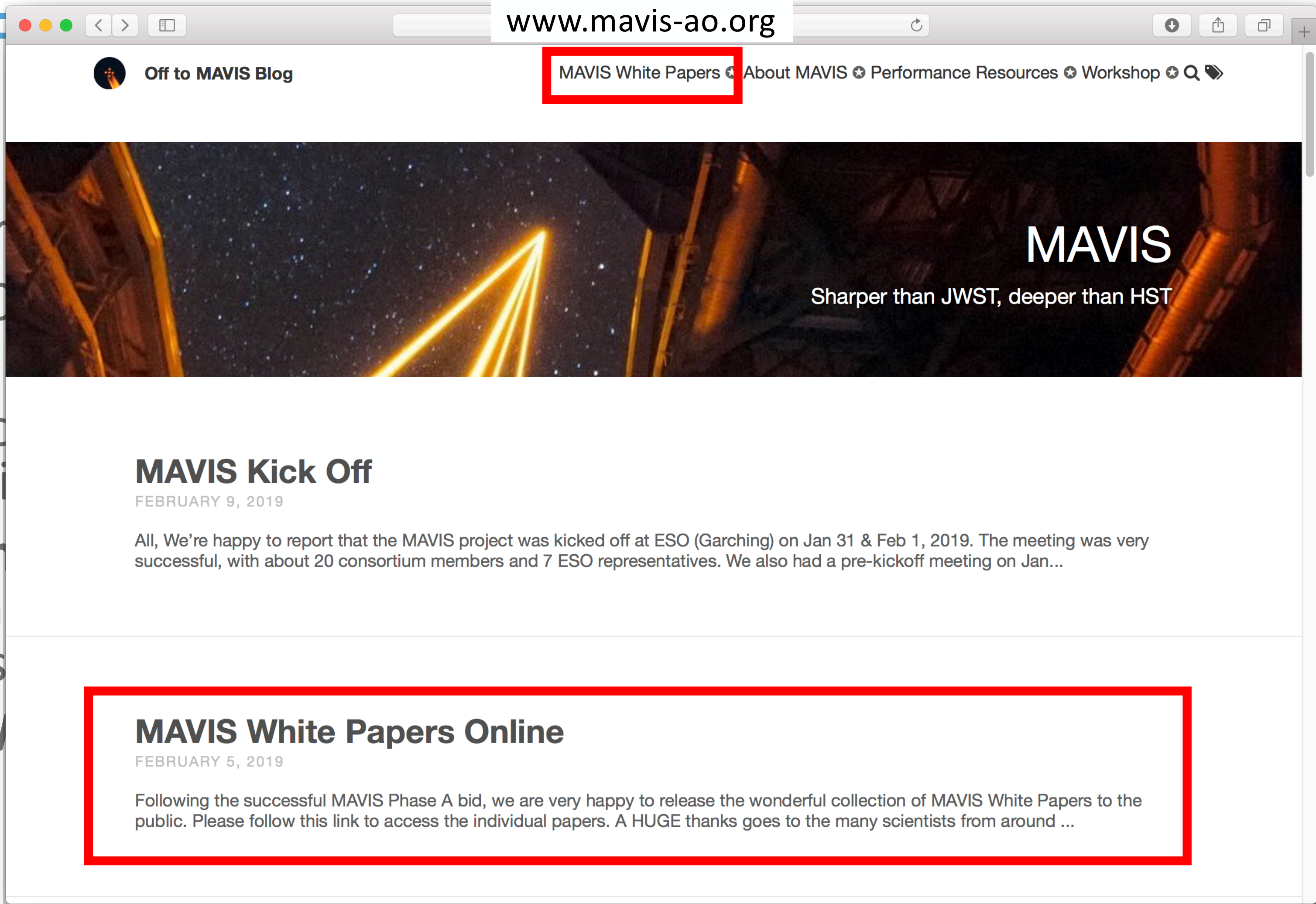


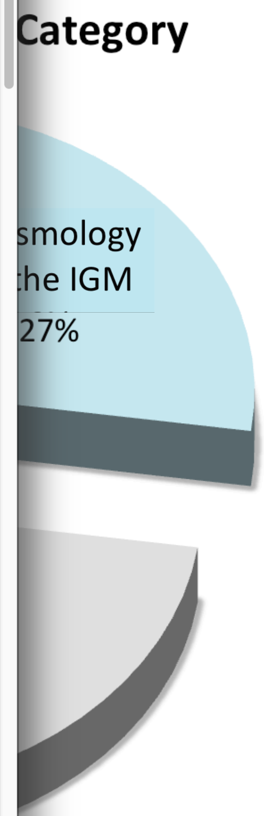

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## Download MAVIS White Papers

| The Birth, Life, and Death of Stars and Their Planets | | | | |
|---|---|---|---|---|
| **Lead Author** | **Institute** | **Co-Authors** | **Title** | **PDF** |
| Antoniucci, Simone | INAF-Roma | J.M. Alcalà, K. Biazzo, B. Nisini, T. Giannini, L. Podio, and F. Bacciotti | Mass accretion in low-metallicity environments of the outer Galaxy | pdf |
| Antoniucci, Simone | INAF-Roma | B. Nisini, K. Biazzo, J.M. Alcalá, T. Giannini, L. Podio, and F. Bacciotti | Frequency of accreting sub-stellar companions of low-mass stars | pdf |
| Bacciotti, Francesca | INAF-Arcetri | L. Podio, S. Antoniucci, B. Nisini, C. Codella, T. Giannini and J. Alcalá | Jets from young stars at high angular resolution: the launching mechanism as a solution to the angular momentum problem | pdf |
| Filacchione, Gianrico | INAF-IAPS | Capria M.T., De Sanctis M.C., and Capaccioni, F | Comets science with MAVIS | pdf |
| Filacchione, Gianrico | INAF-IAPS | Capaccioni, F | Observations of planetary rings with MAVIS | pdf |
| Grassi, Davide | INAF-IAPS | Piccioni G., and Adriani A. | The outer Solar System: Icy Giants | pdf |
| Ireland, Michael | Australian National University | | High Dispersion Coronagrapy for Exoplanet Characterization | pdf |
| Kamath, Devika | Macquarie University | Hans Van Winckel, Jacques Kluska, Steve Ertel, Dylan Bollen and Orsola De Marco | Revealing the structure and evolution of the second generation protoplanetary disks around evolved stars with MAVIS | pdf |
| Maoz, Dan | Tel-Aviv University | Mannucci, F. | White Dwarf Binaries with MAVIS | pdf |
| Migliorini, Alessandra | INAF-IAPS | Capria M.T., De Sanctis M.C., and Capaccioni F. | The outer Solar System: KBO and Comets | pdf |
| Sacco, Germano | INAF-Arcetri | Massi F., Fedele D., Franciosini E., Randich, S., Roccatagliata V., and Sanna, N. | Star and planet formation at low metallicities | pdf |

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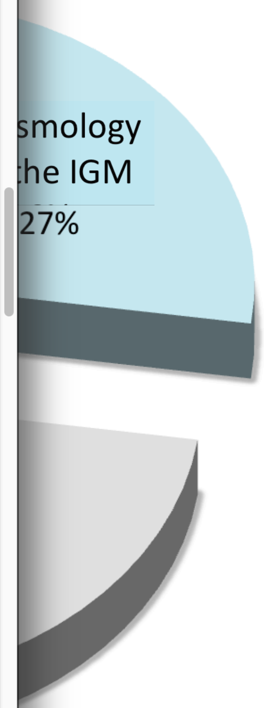
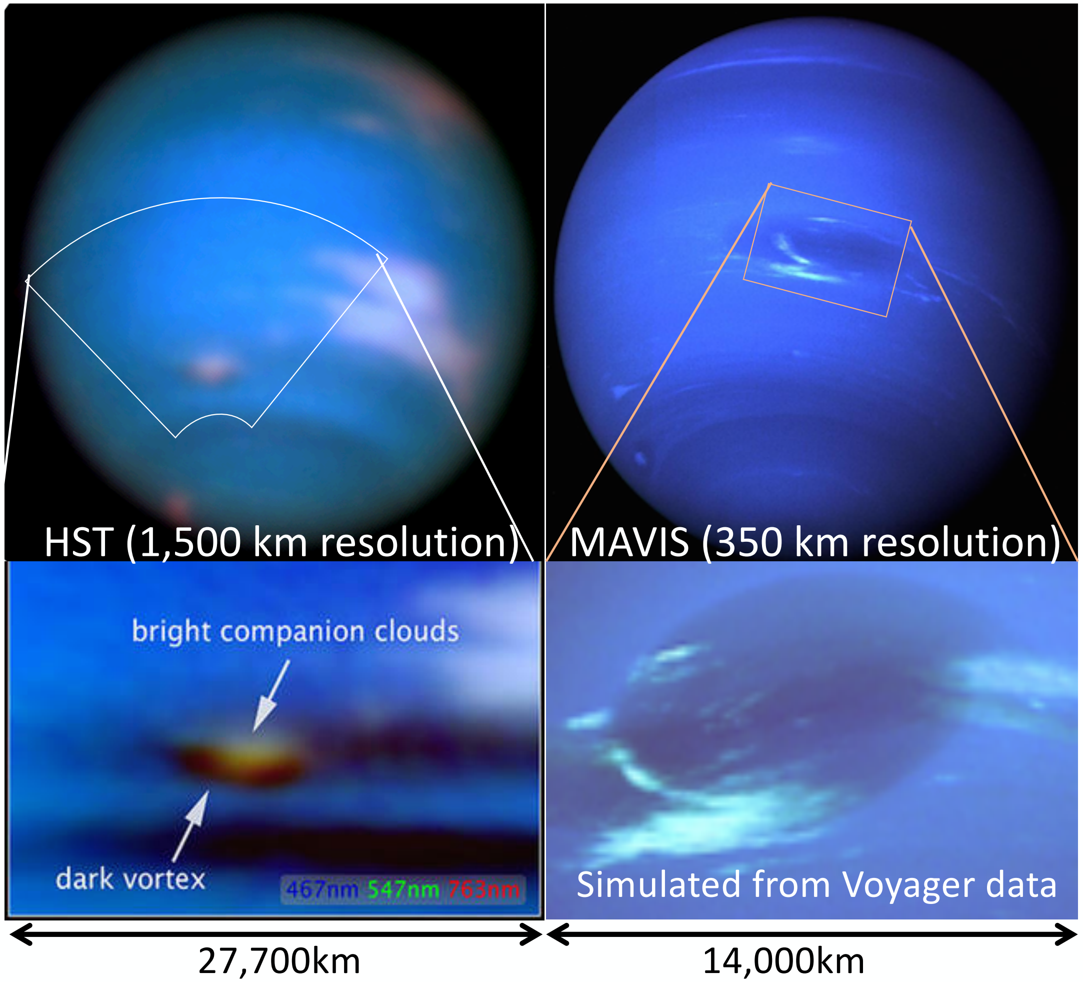
| Star Clusters as Tracers of Galaxy Processes Within the Local Group | | | | |
|---|---|---|---|---|
| **Lead Author** | **Institute** | **Co-Authors** | **Title** | **PDF** |
| Bono, Giuseppe | INAF-Roma | M. Latour, C. Arcidiacono, V. F. Braga, A. Calamida, V. D'Orazi, G. Fiorentino, D. Magurno, S. Moehler, M. Nonino, S. Randall, M. Salaris , and M. Torelli | CNO abundances of Extreme Horizontal Branch stars in globular clusters | pdf |
| | | A. Calamida, V. F. Braga, G. Fiorentino, V. D'Orazi, M. Latour | | |

Category



# SOLAR SYSTEM

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




WP Grassi et al.

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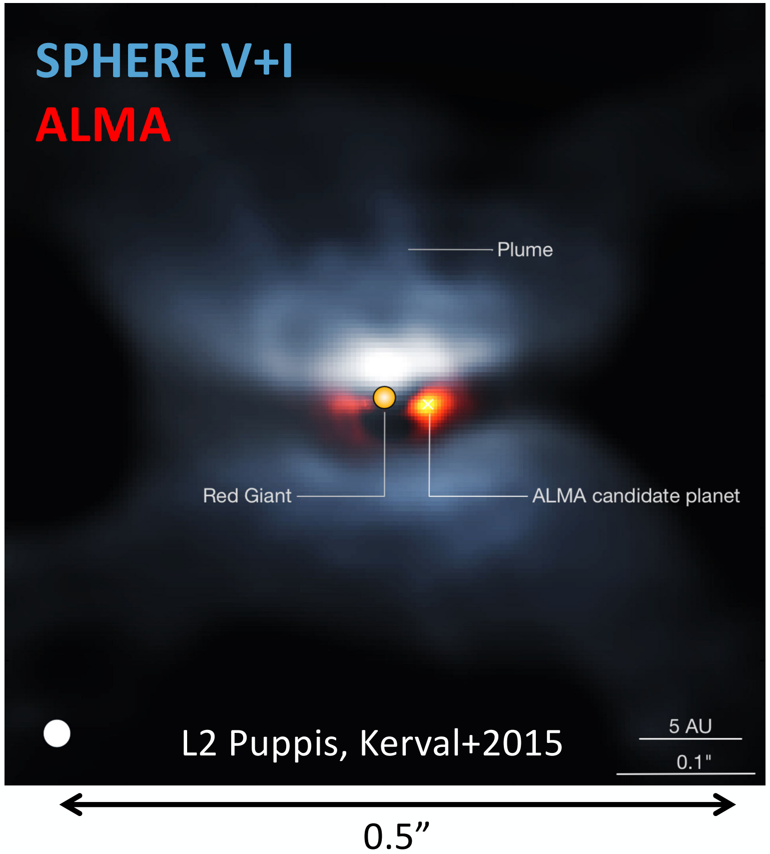
eso1910 — Organisation Release

## ESO contributes to protecting Earth from dangerous asteroids

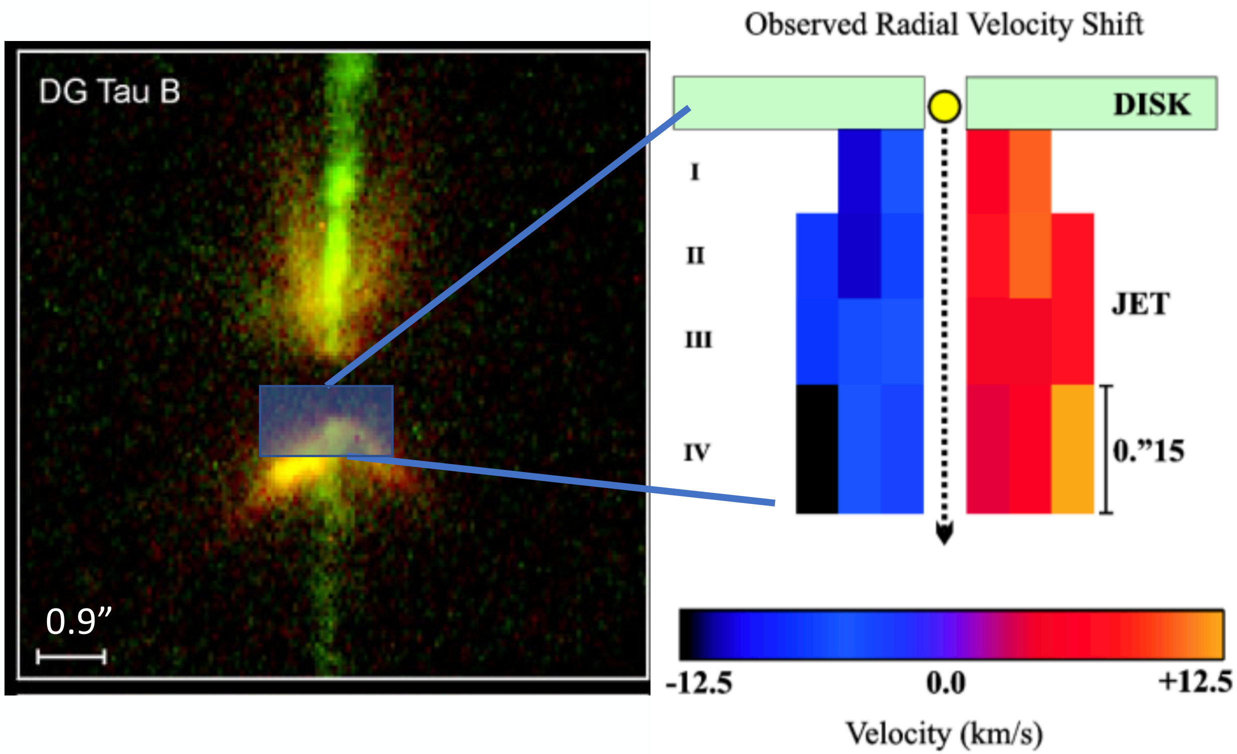
VLT observes a passing double asteroid hurtling by Earth at 70 000 km/h

3 June 2019

# CIRCUMSTELLAR ENVIRONMENTS



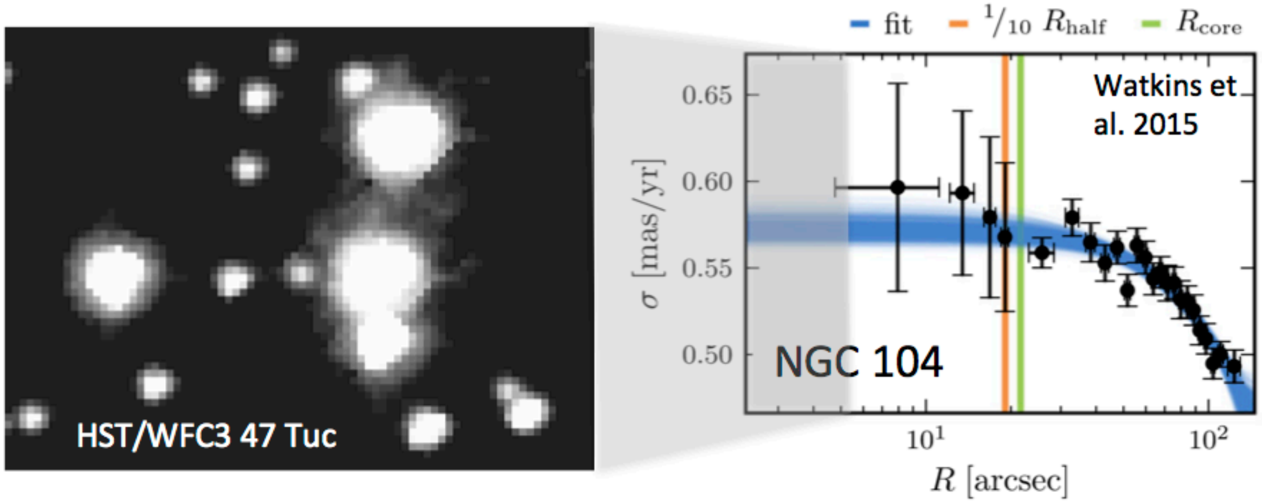

WP Kamath et al.

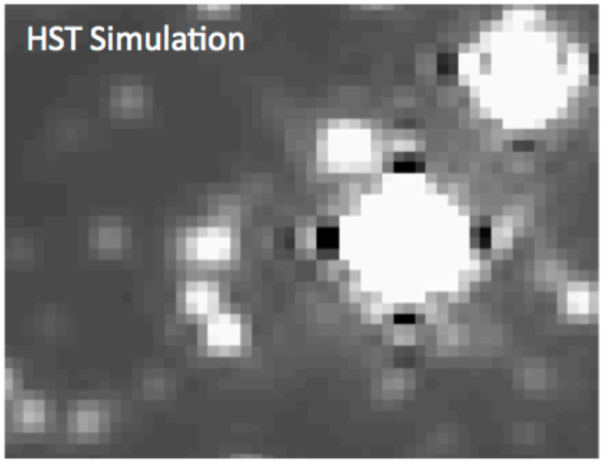


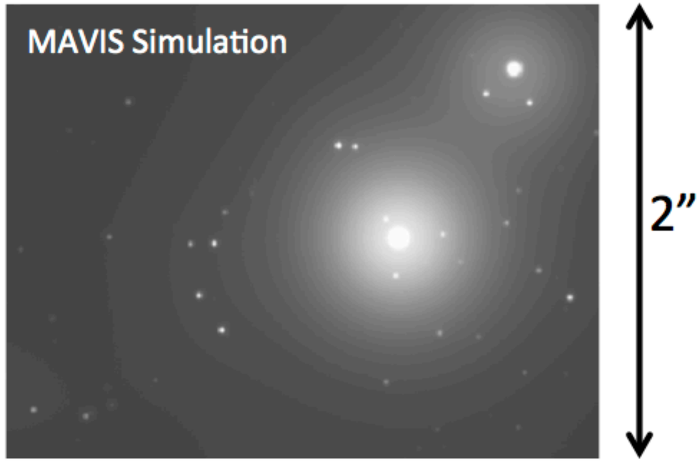

WP Bacciotti et al.

# 6D PHASE SPACE OF NEARBY DWARFS AND CLUSTERS

- Combined proper motions and radial velocities in regimes too faint for GAIA, and too crowded for HST
- Intermediate mass black hole detection
- Dark matter constraints



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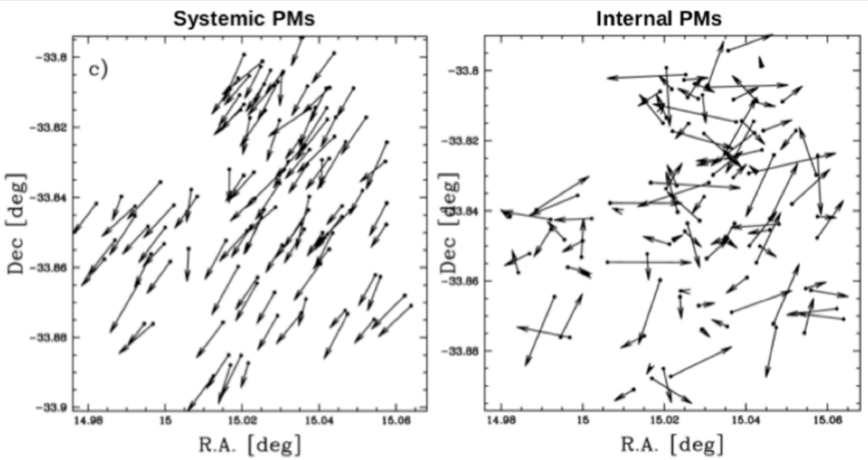
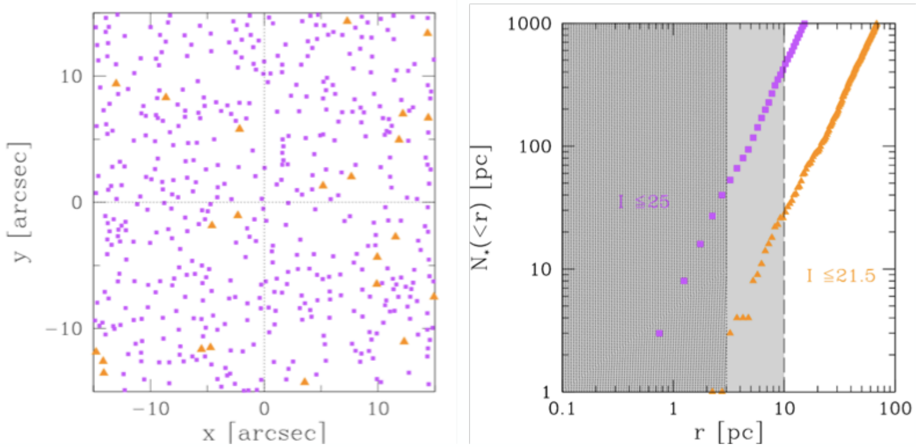
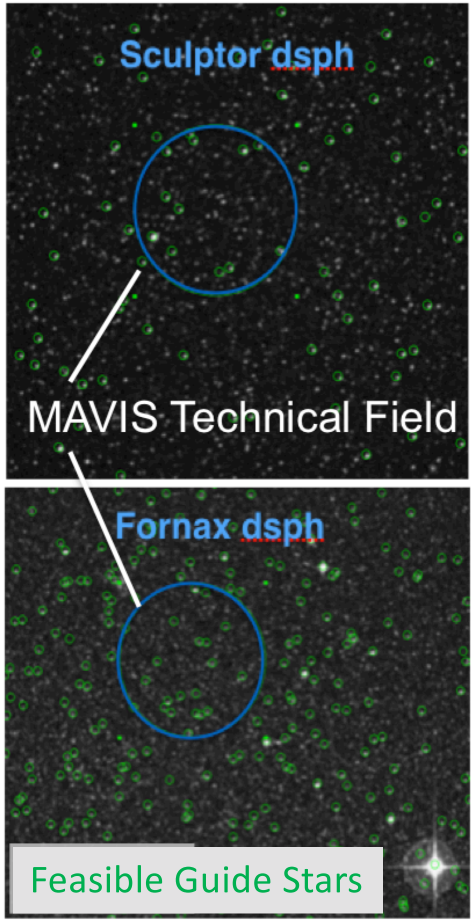
## Proper Motions



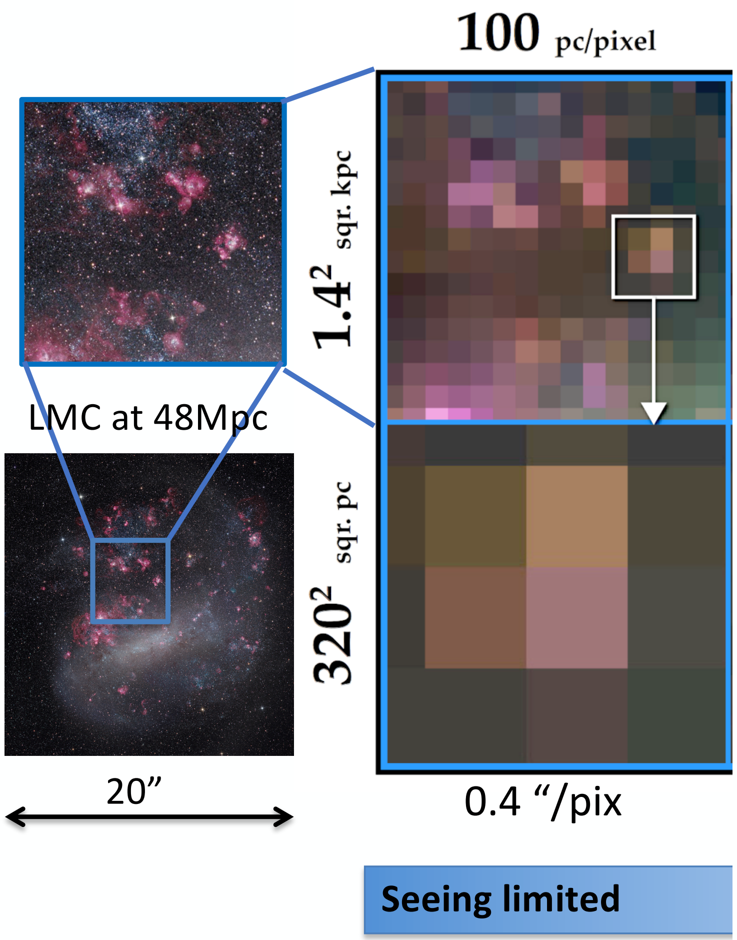

## Radial Velocities




WP Pancino et al.
WP Salvadori et al.

# RESOLVING COMPLEXITY IN GALAXIES BEYOND THE LOCAL GROUP



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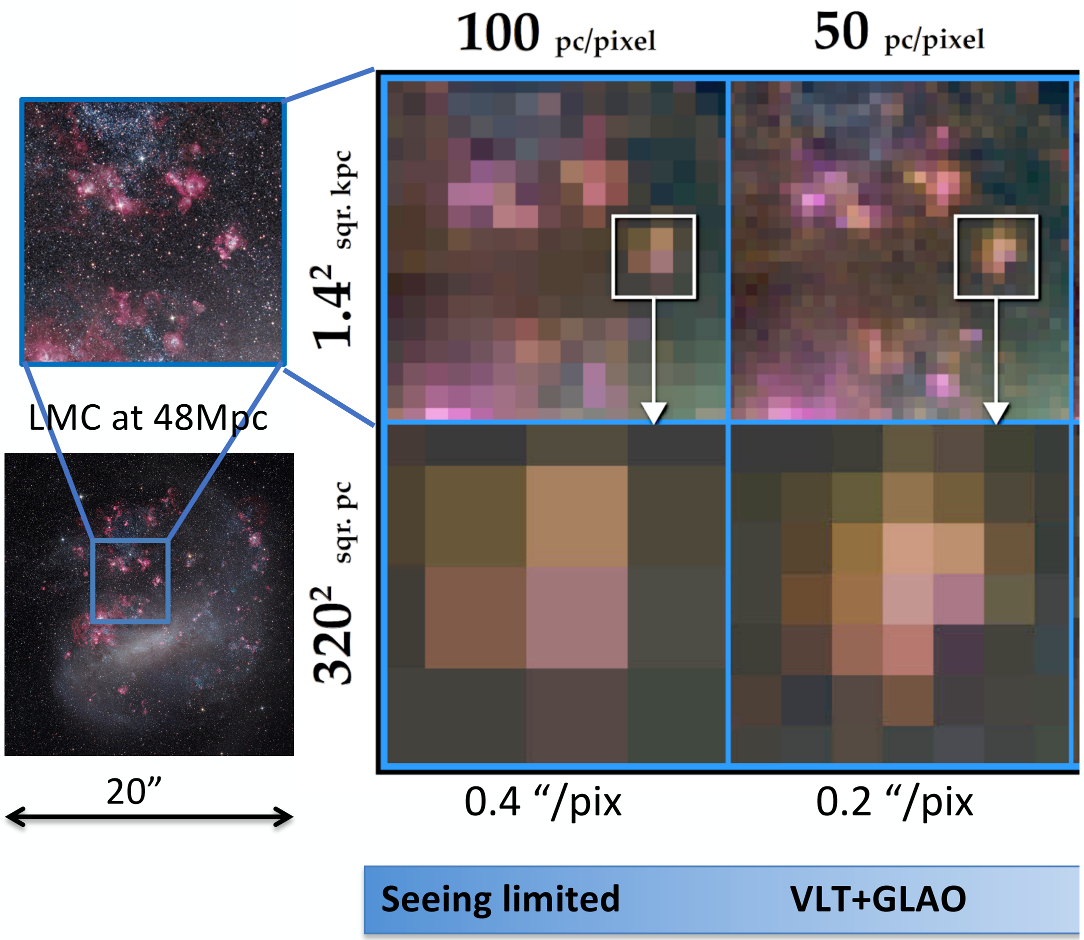

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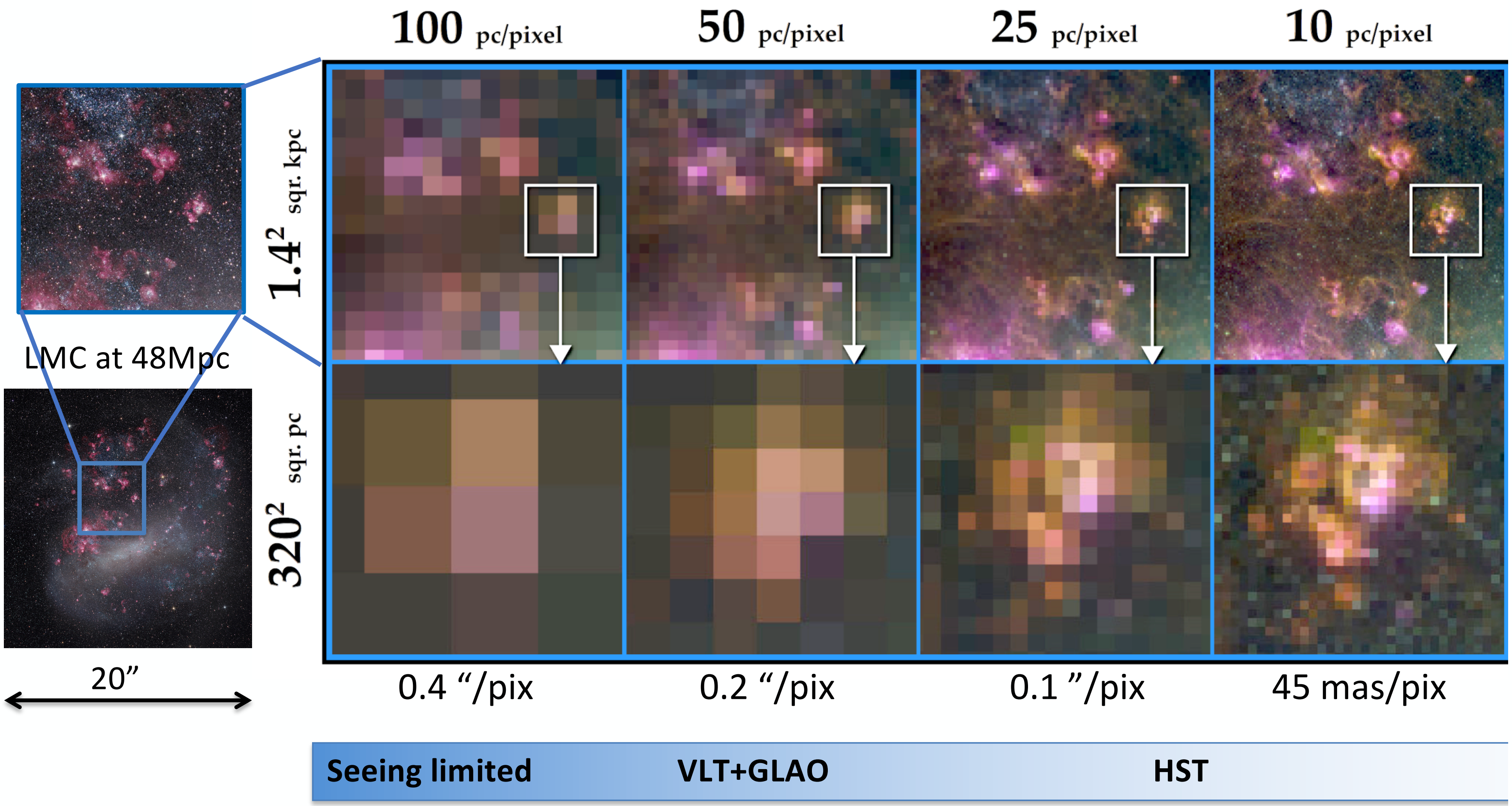

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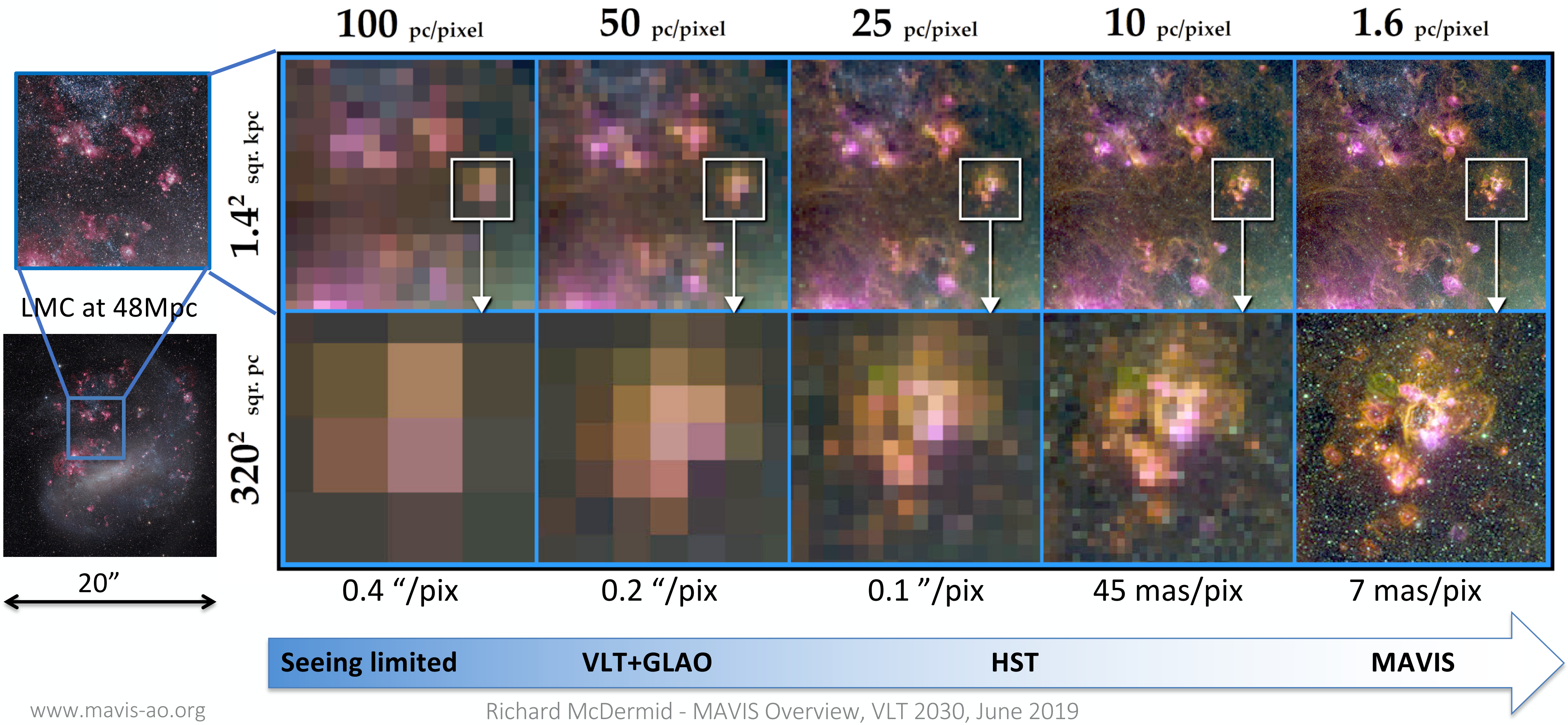
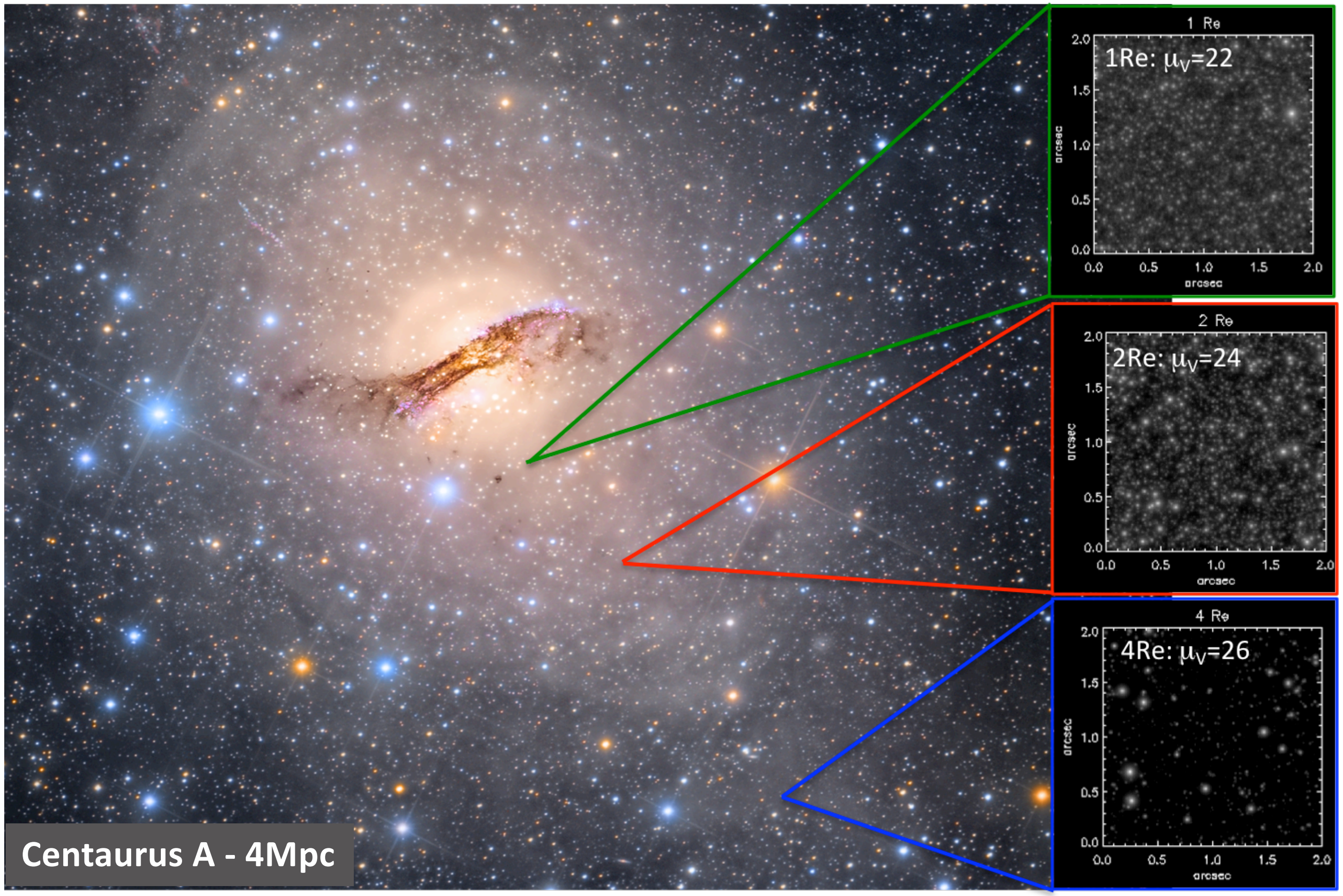
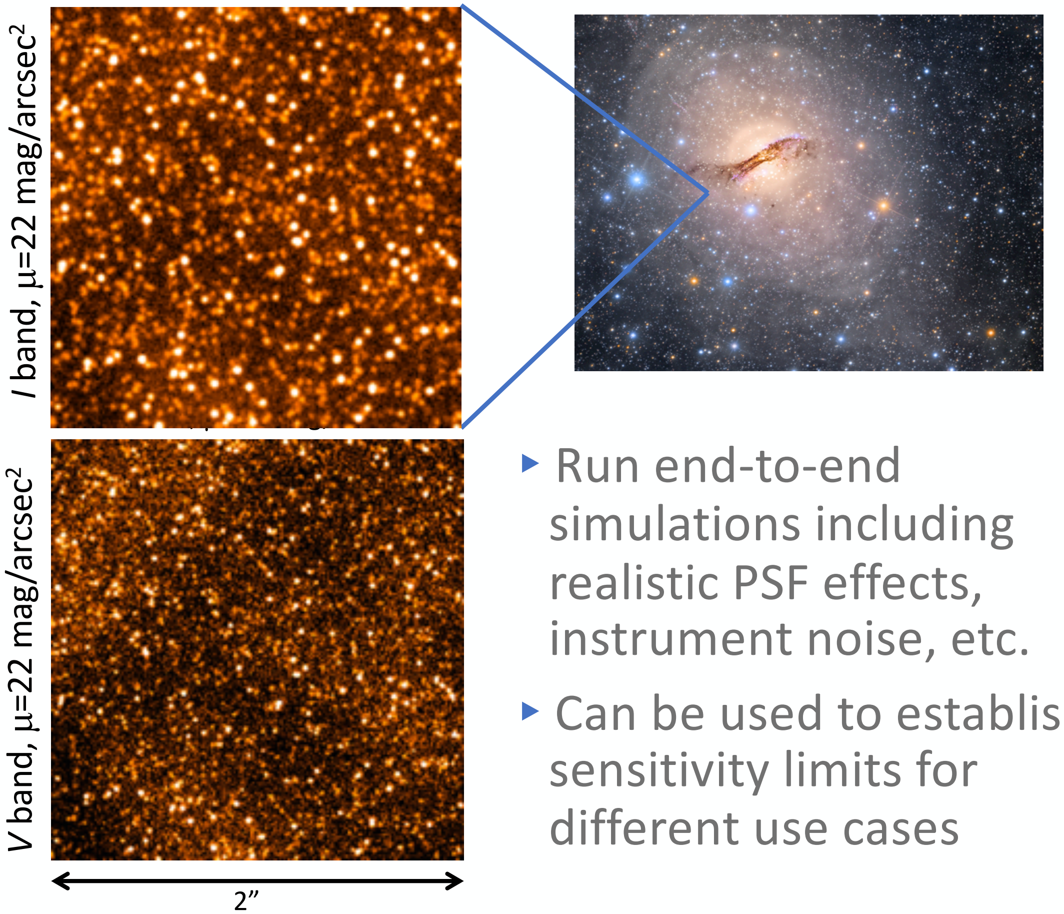


# RESOLVING STELLAR POPULATIONS IN GALAXIES BEYOND THE LOCAL GROUP

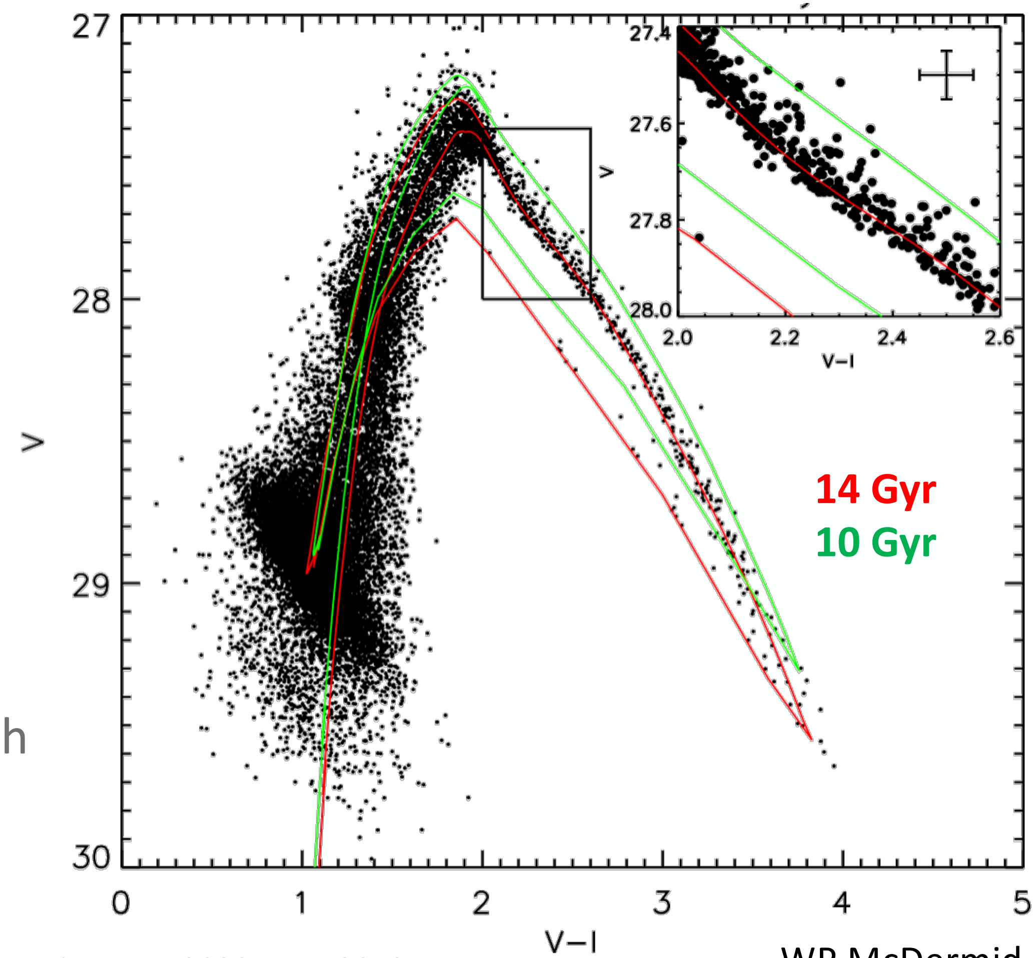



WP Magrini et al.
WP McDermid
WP Tosi et al.

# KEY SCIENCE SIMULATIONS: RESOLVED STELLAR POPULATIONS

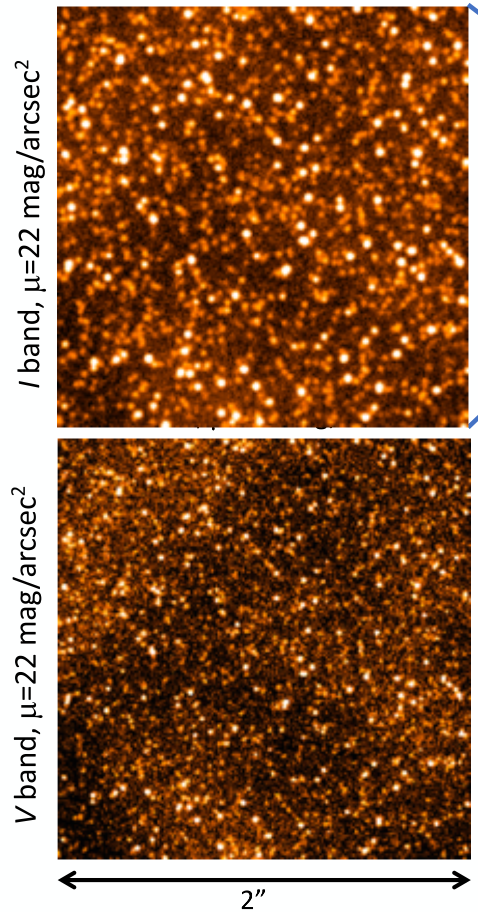


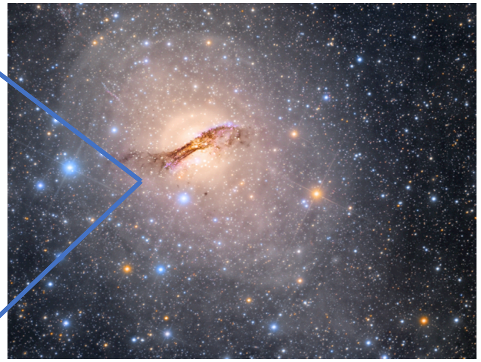

- Run end-to-end simulations including realistic PSF effects, instrument noise, etc.
- Can be used to establish sensitivity limits for different use cases



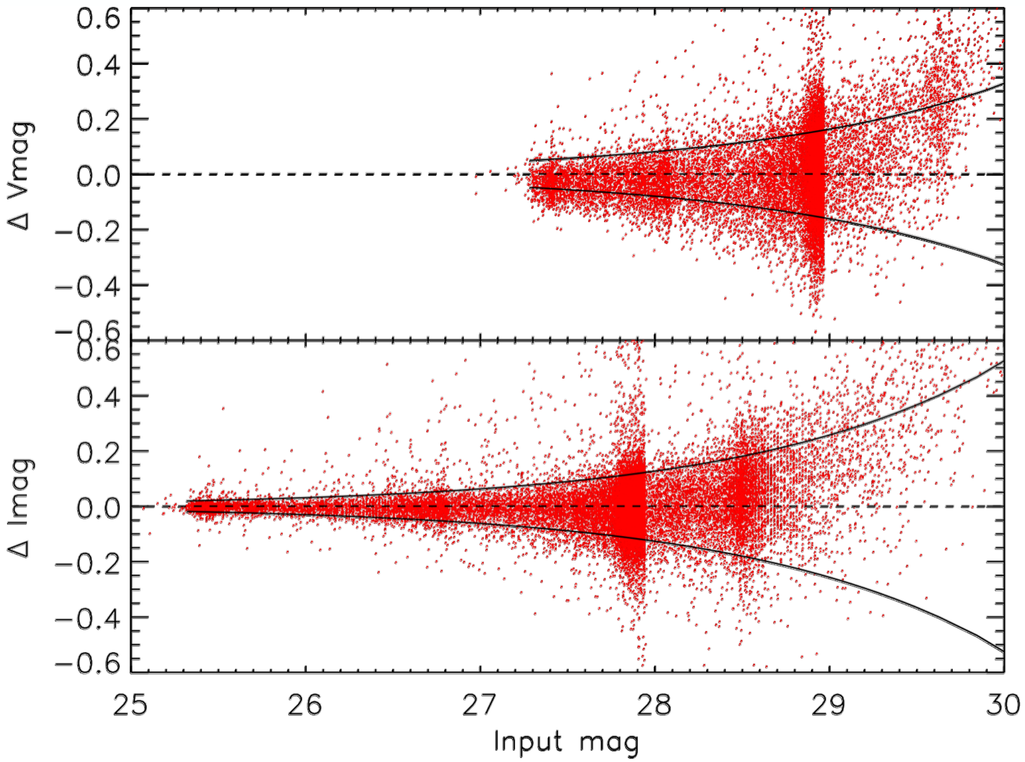

WP McDermid

# KEY SCIENCE SIMULATIONS: RESOLVED STELLAR POPULATIONS



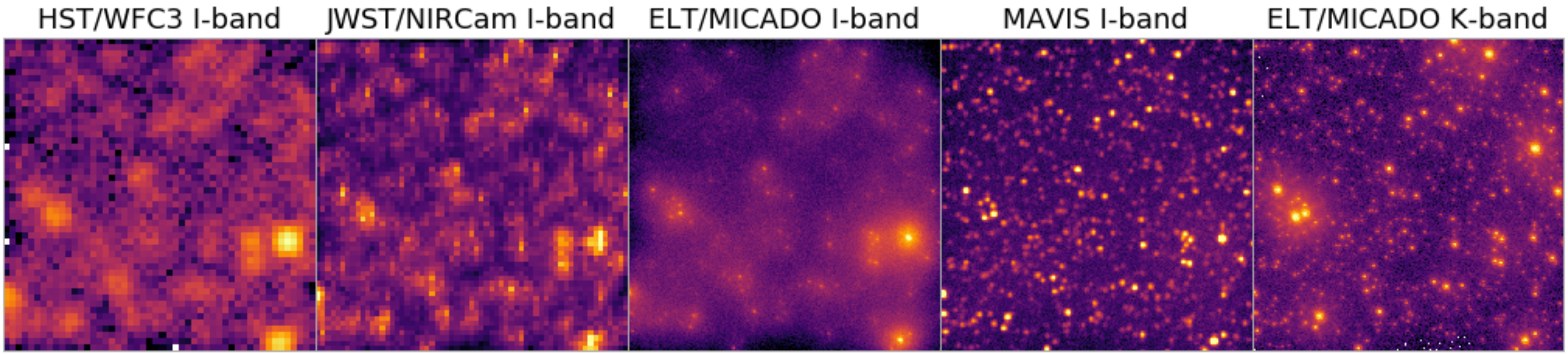



- Run end-to-end simulations including realistic PSF effects, instrument noise, etc.
- Can be used to establish sensitivity limits for different use cases




WP McDermid

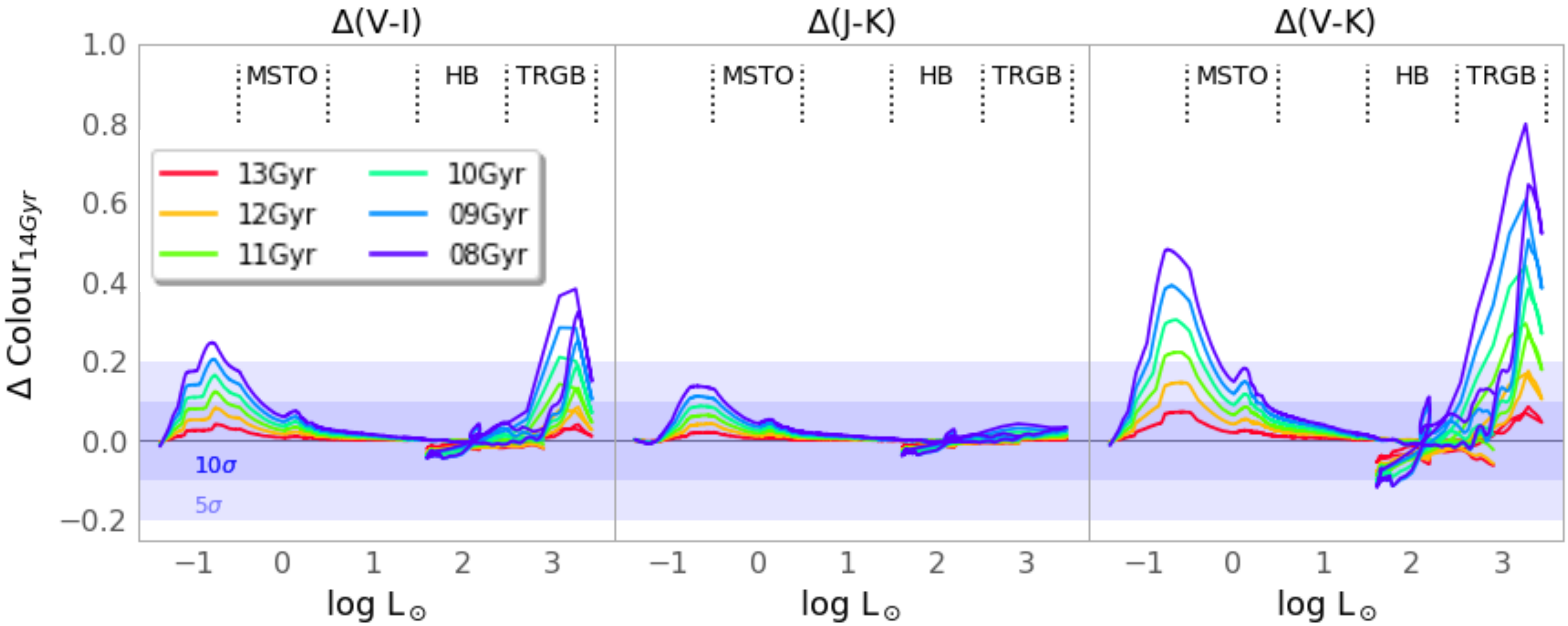
# KEY SCIENCE SIMULATIONS: RESOLVED STELLAR POPULATIONS




- 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

Generated using the Advanced Exposure Time Calculator (AETC) http://geode.oapd.inaf.it (Falomo et al. 2011)

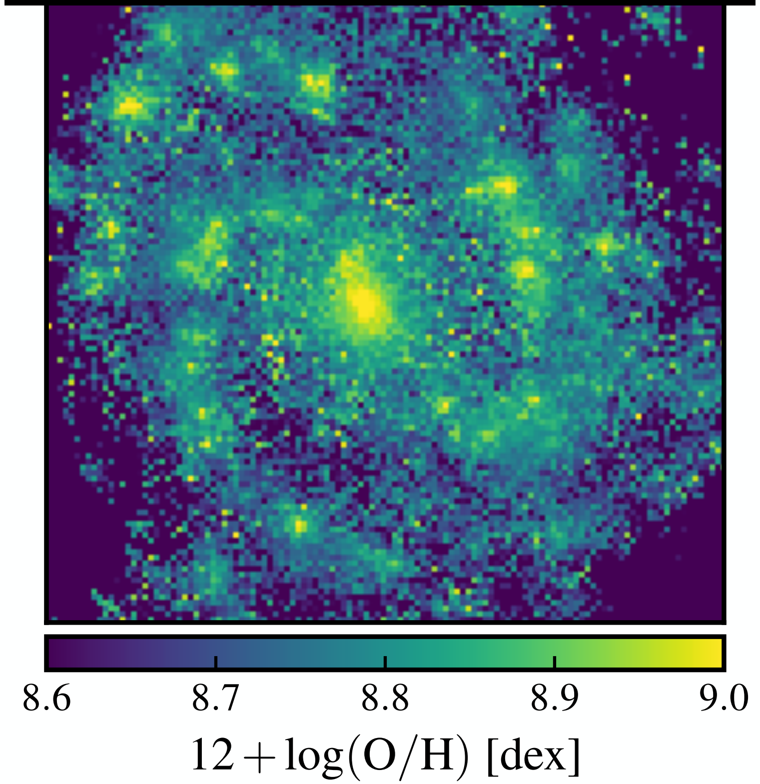
# KEY SCIENCE SIMULATIONS: RESOLVED STELLAR POPULATIONS

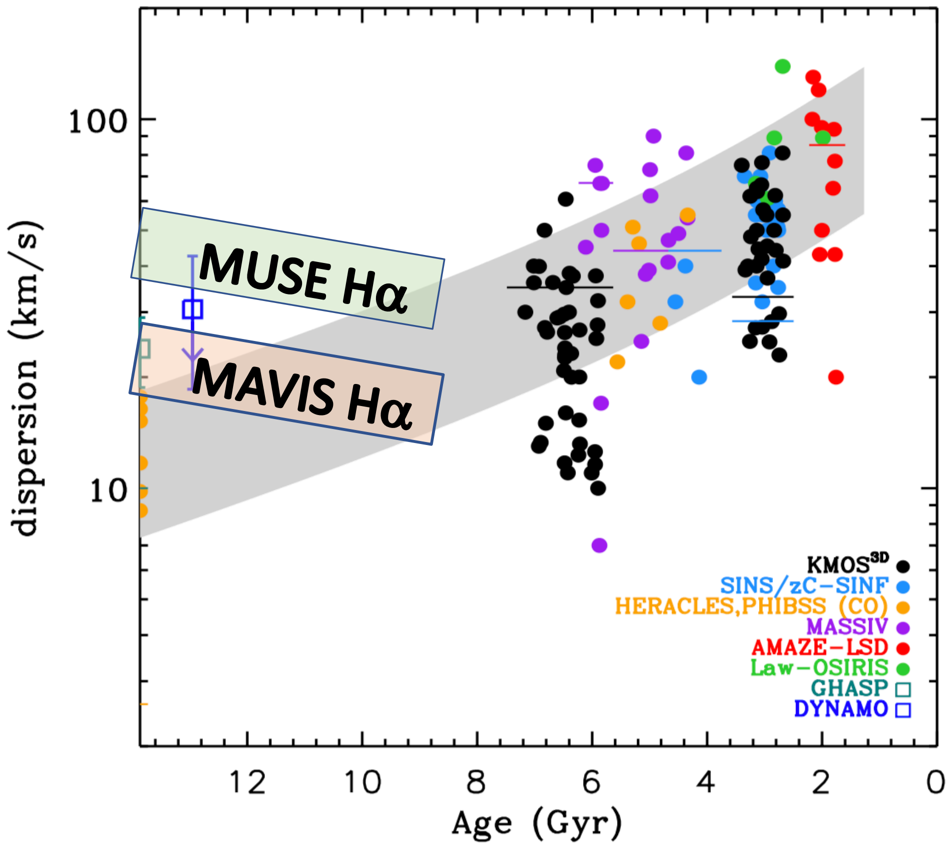



MAVIS only MICADO only MAVIS + MICADO

# ACCURATE PROPERTIES OF STAR FORMATION CLUMPS IN DISKS

M83 datacube @ z=0.05, WP Mendel et al.

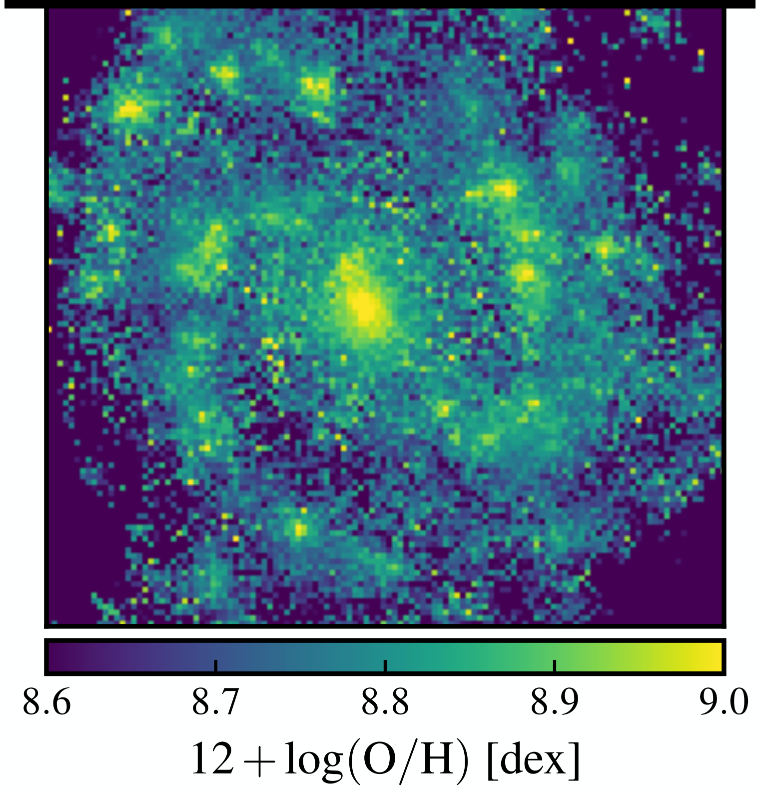


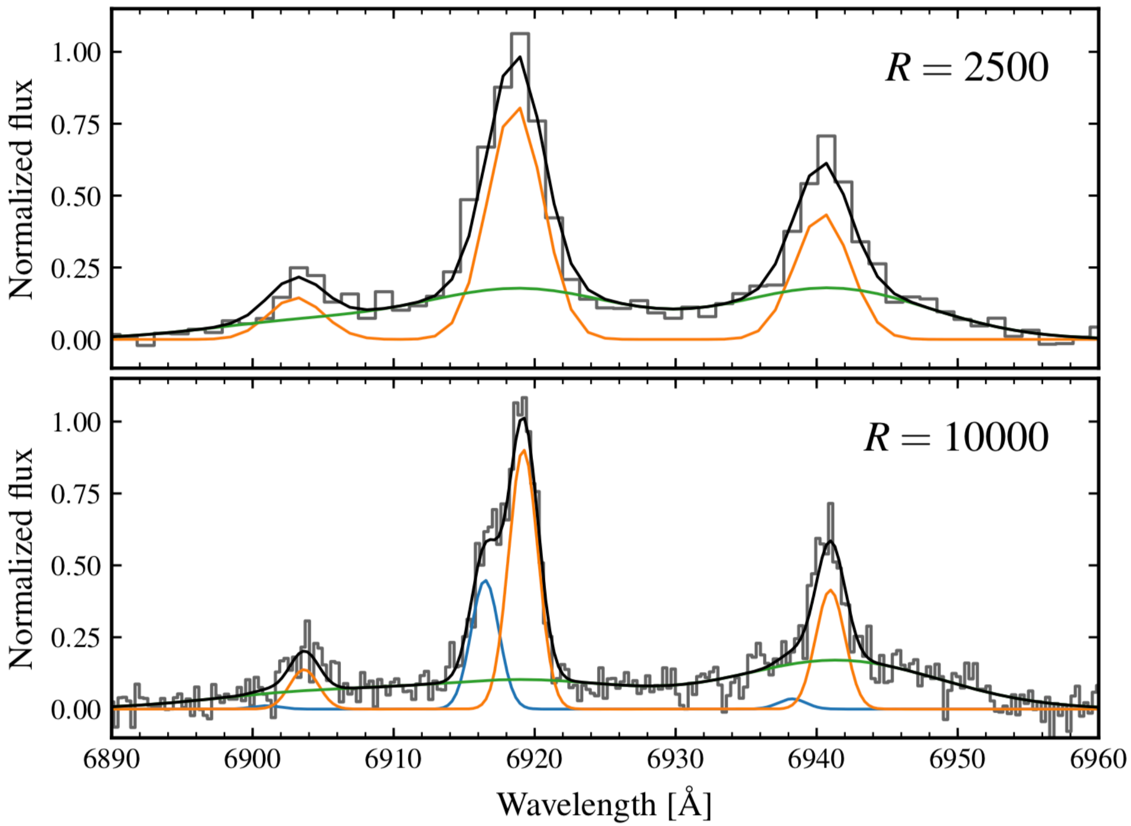




- Disks are much more ‘turbulent’ at early times
- Turbulence? Outflows/winds? Beam smearing?

# ACCURATE PROPERTIES OF STAR FORMATION CLUMPS IN DISKS

M83 datacube @ z=0.05, WP Mendel et al.

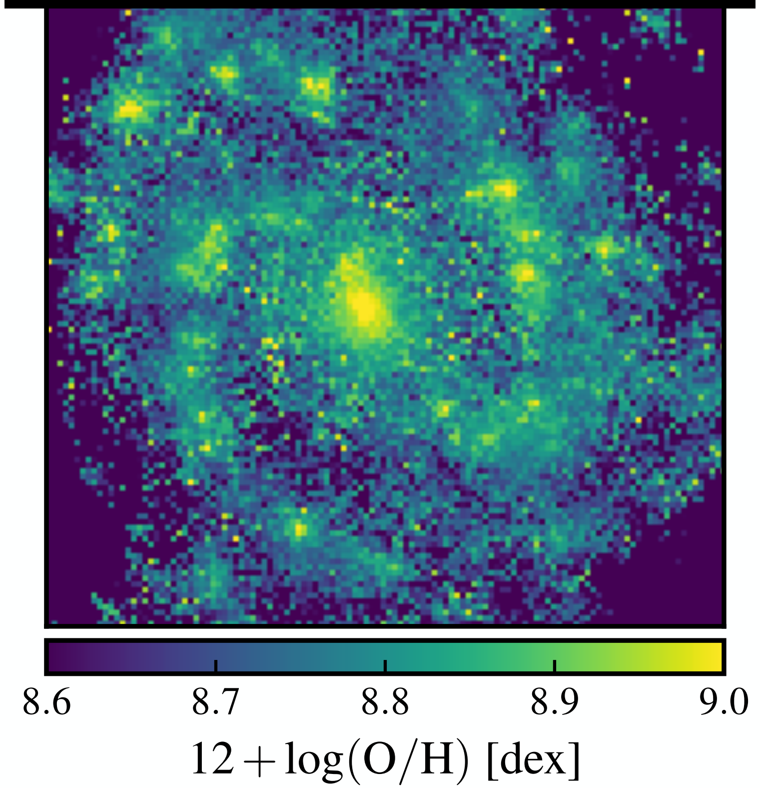


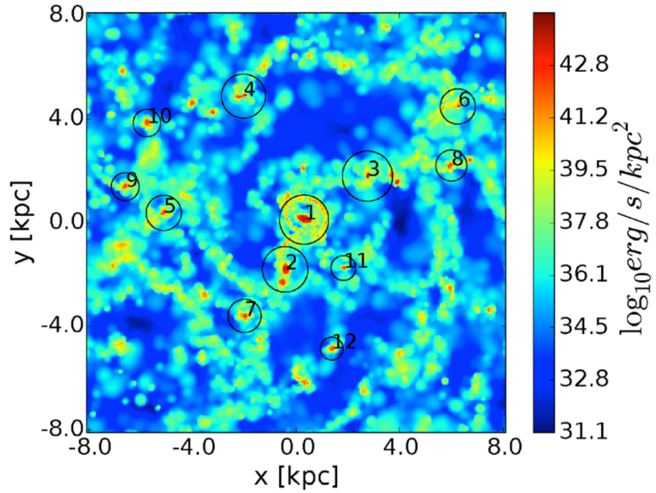




- Separating gravitational motion from winds, outflows, shocks, etc. requires moderately high resolution

# ACCURATE PROPERTIES OF STAR FORMATION CLUMPS IN DISKS

M83 datacube @ z=0.05, WP Mendel et al.

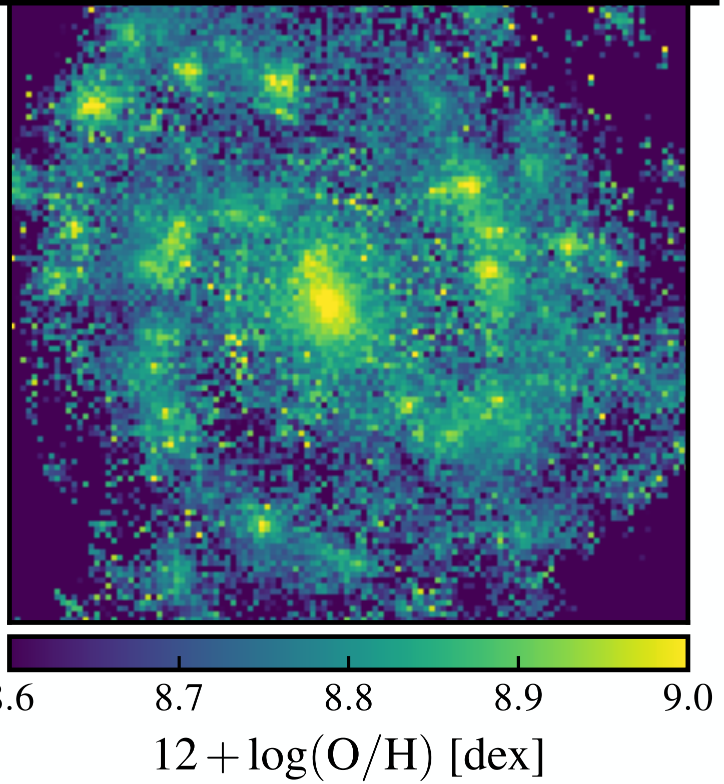


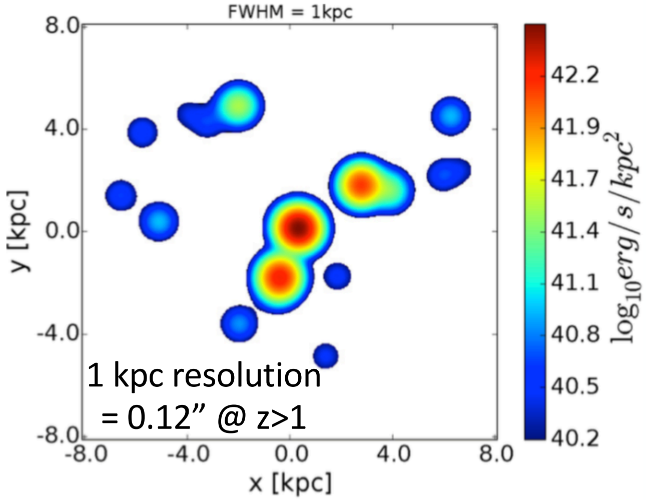



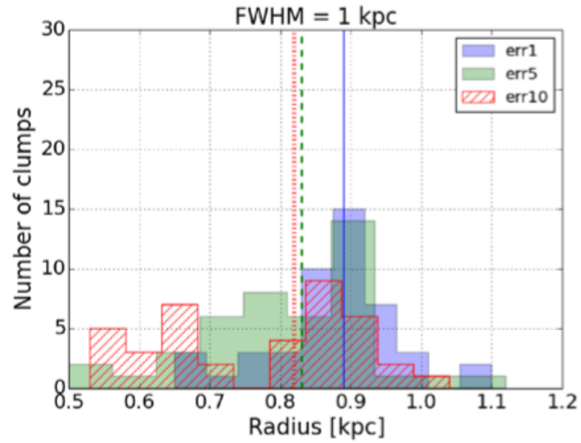

Tamburello+17, WP Fisher, WP Gullieuszik et al.

# ACCURATE PROPERTIES OF STAR FORMATION CLUMPS IN DISKS

M83 datacube @ z=0.05, WP Mendel et al.




Tamburello+17, WP Fisher, WP Gullieuszik et al.

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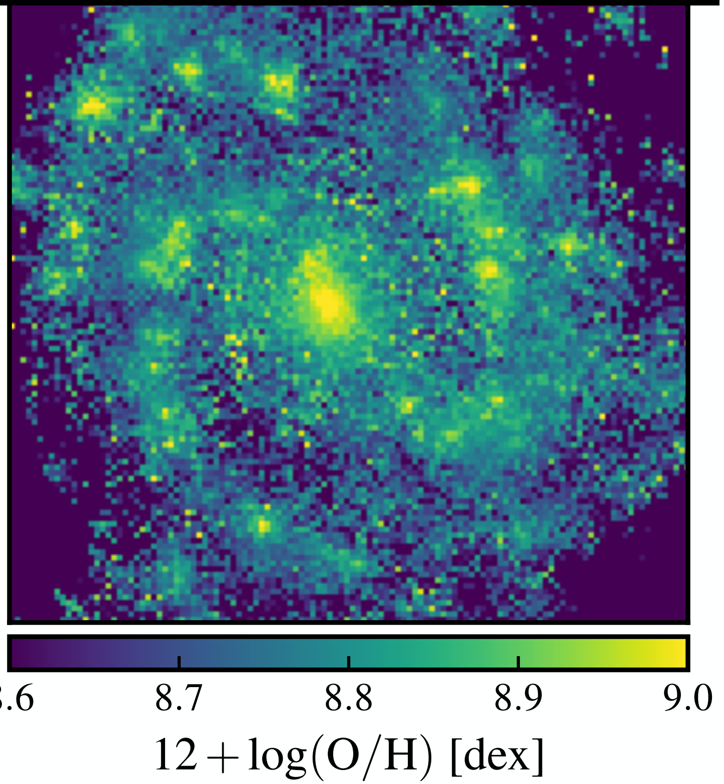
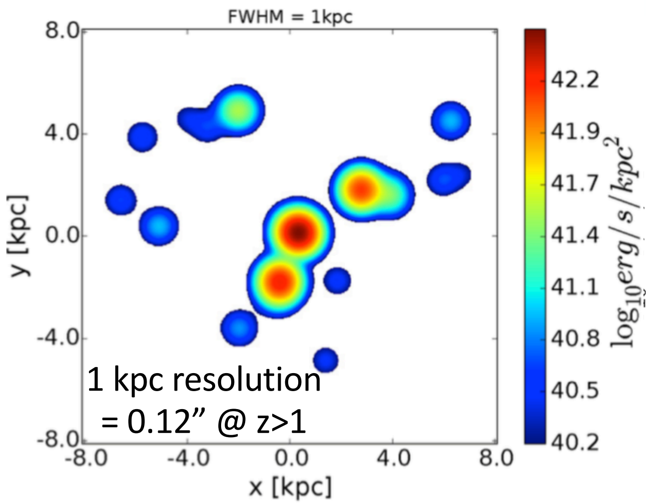
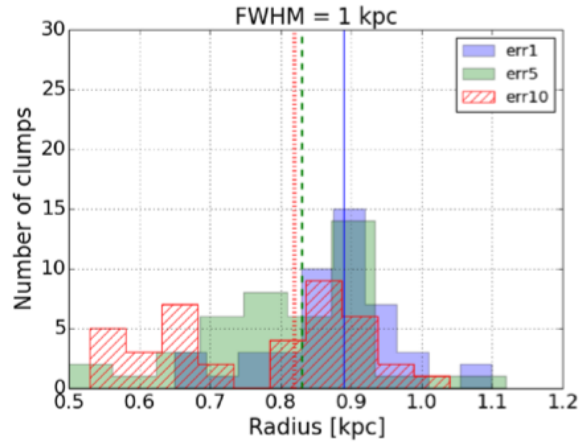
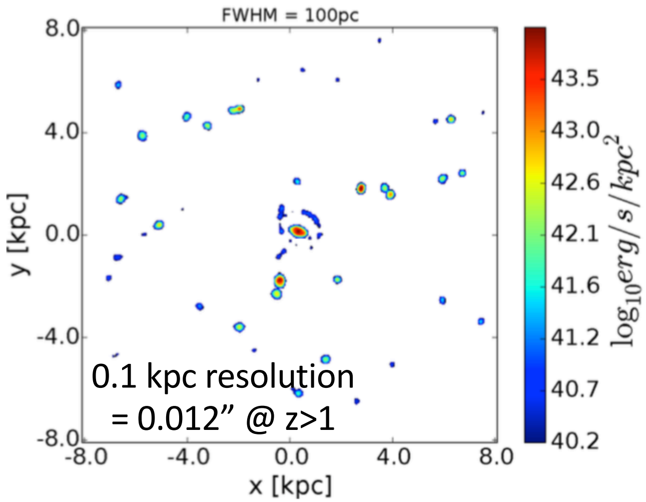
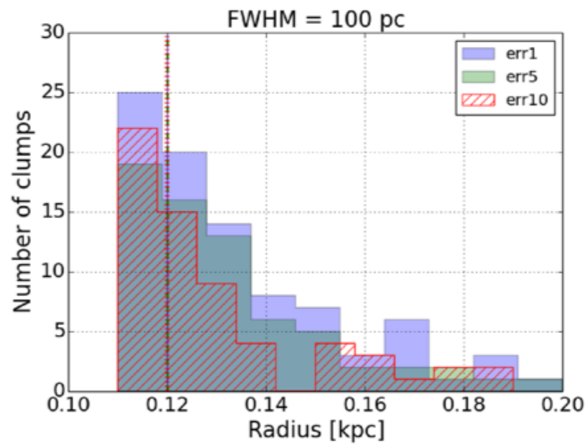


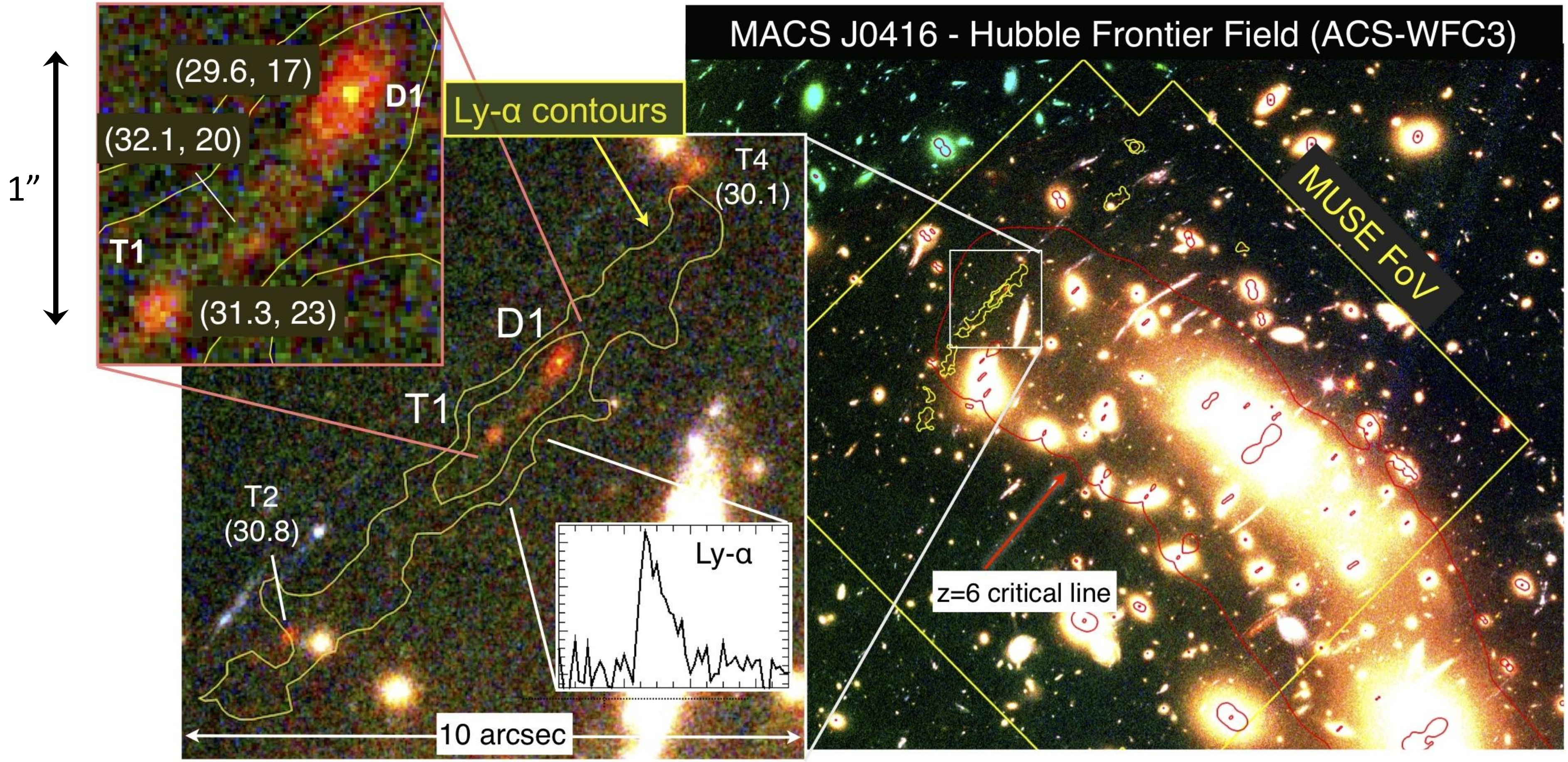



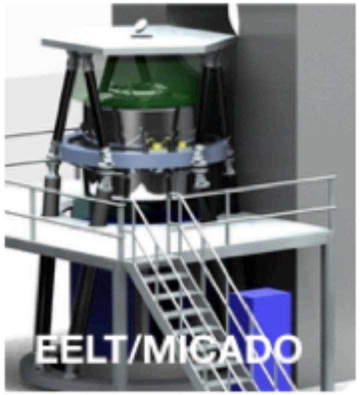

Tamburello+17, WP Fisher, WP Gullieuszik et al.

# DETECTING FIRST STAR CLUSTERS AND SPECTRALLY RESOLVING Z>6 GALAXIES VIA LENSING




WP Rosati et al.

# KEY SCIENCE SIMULATIONS: HIGH-Z GALAXIES







SIMCADO:

- official parameters

Official simulator

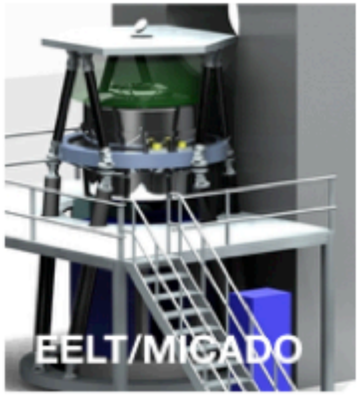
SIMCADO:

- parameters: PSF, mirrors, filters, pixels scale, QE ....
- calibrated on background and SNR for ETCs

- First zero-order simulations in progress
- Based on rough guesses of instrument parameters and throughputs

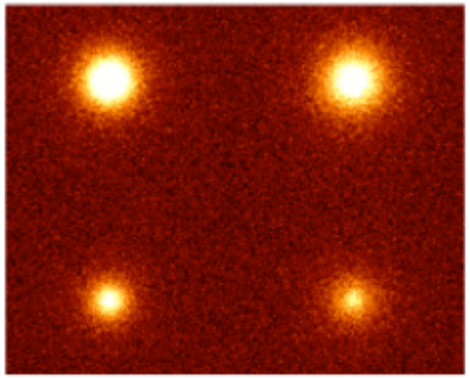
WP Mannucci et al.

# KEY SCIENCE SIMULATIONS: HIGH-Z GALAXIES

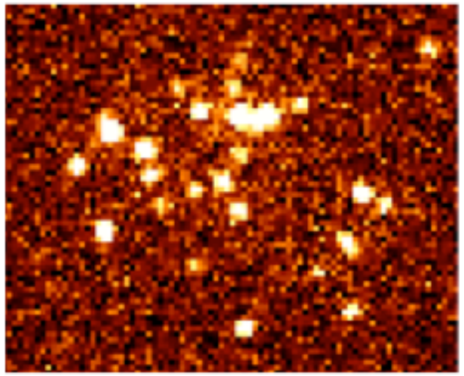




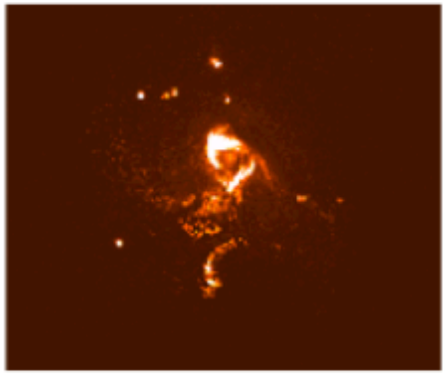




**Sersic profiles**



**Clumpy galaxies**



**Galaxy models**

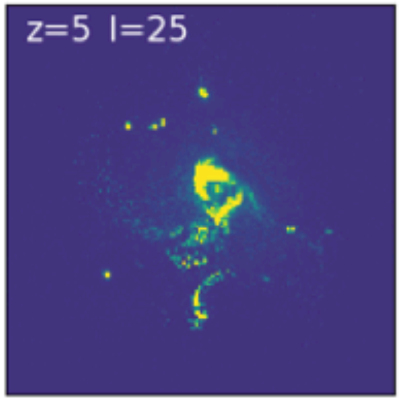
WP Mannucci et al.

# KEY SCIENCE SIMULATIONS: HIGH-Z GALAXIES – IMAGING

Pallottini et al 2017:

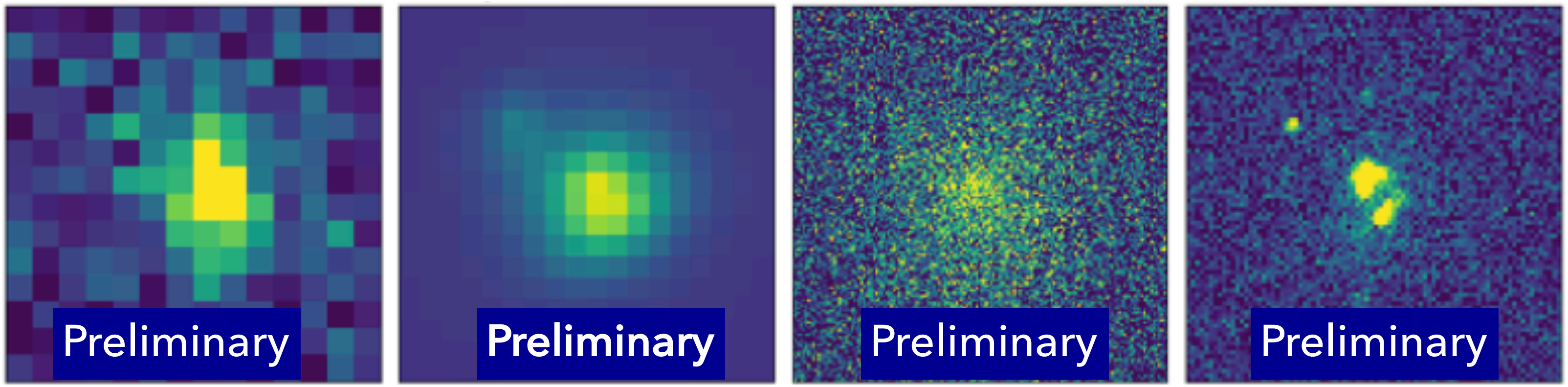
- M~ 1.6 · $10^{10}$ M⊙
- Re ~ 0.6 kpc ~ 100mas at z=5
- high resolution: ~30pc

600mas




**$T_{exp}$= 1h**

HST/WFC3/F814W JWST/NIRCAM/F090W ELT/MICADO/I VLT/MAVIS/F090W

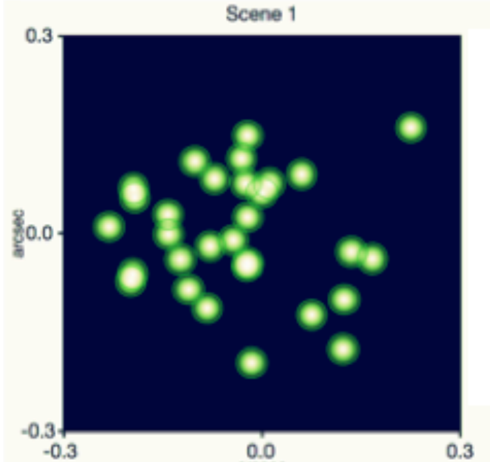


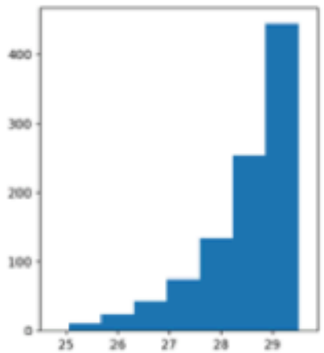

WP Mannucci et al.

# KEY SCIENCE SIMULATIONS: HIGH-Z GALAXIES – IMAGING

Clumpy galaxies

- 30 point sources
- 25.5<mag<29.5
- mag=25

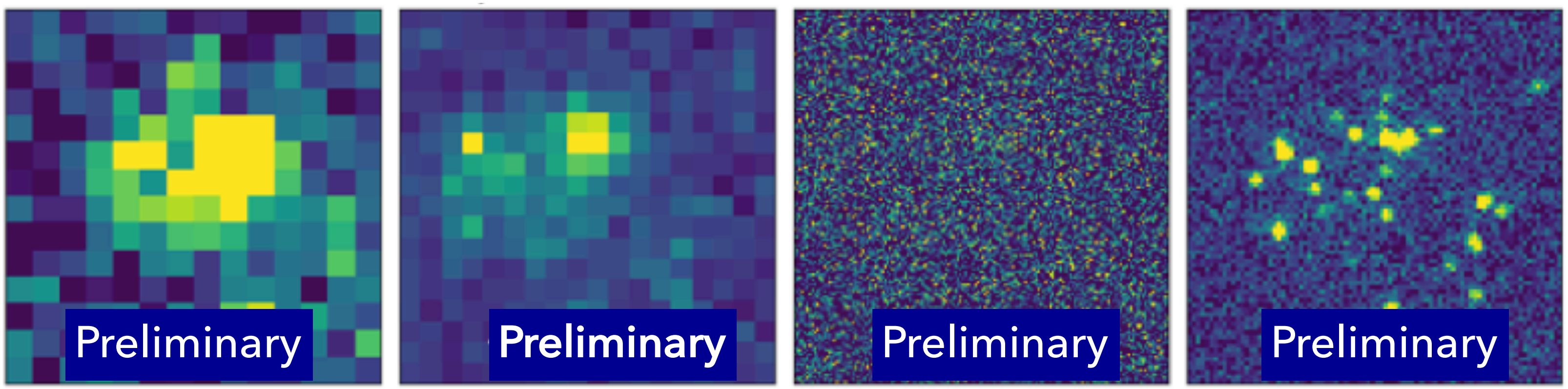



To do:

1. compare input and output luminosity distribution

HST/WFC3/F814W JWST/NIRCAM/F090W ELT/MICADO/I VLT/MAVIS/F090W




WP Mannucci et al.

# KEY SCIENCE SIMULATIONS: HIGH-Z GALAXIES – SPECTROSCOPY

Assuming:
- flat sky spectrum
- RON=2, $\varepsilon_{spec}$=0.7
- R=2500, pix/resol=2
- various spaxel scales

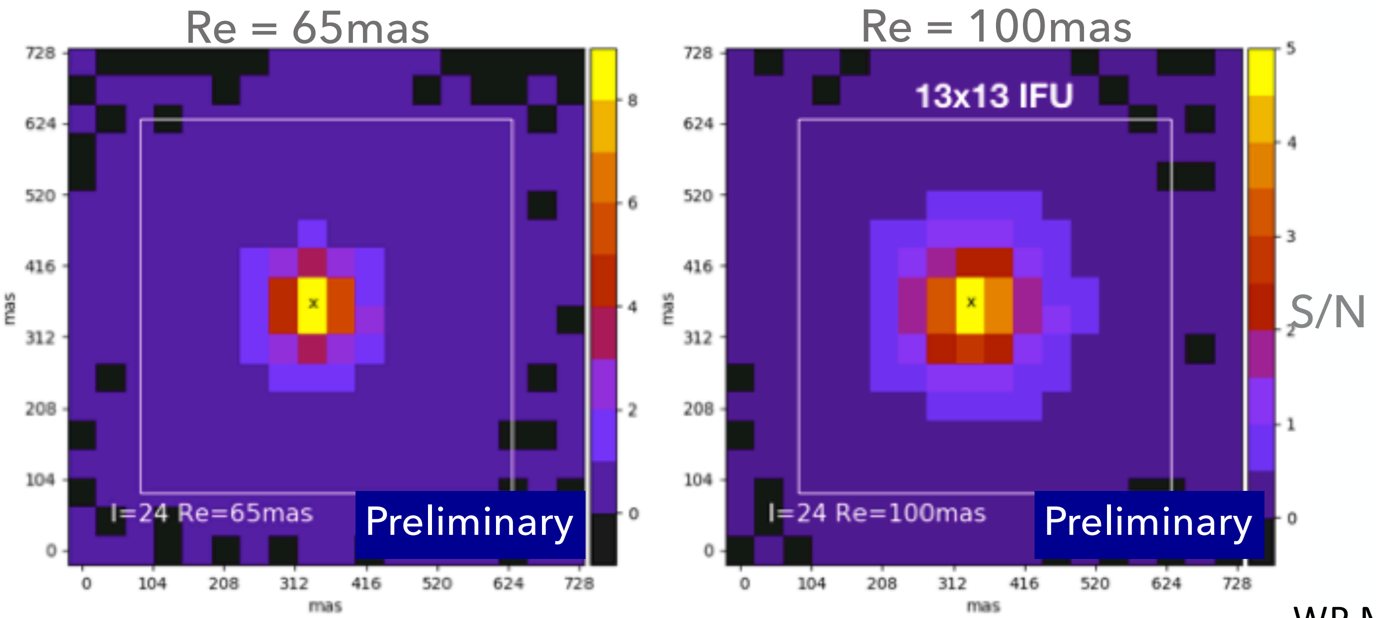
Background limited in 1hr → 30x30mas (larger in the real case)

SNR maps, 10hrs

42.0 x 42.0 mas spaxels

Long exposures – potentially large multiplex benefit

Sersic n=1
I=24
$R_e$ = 65mas
100mas

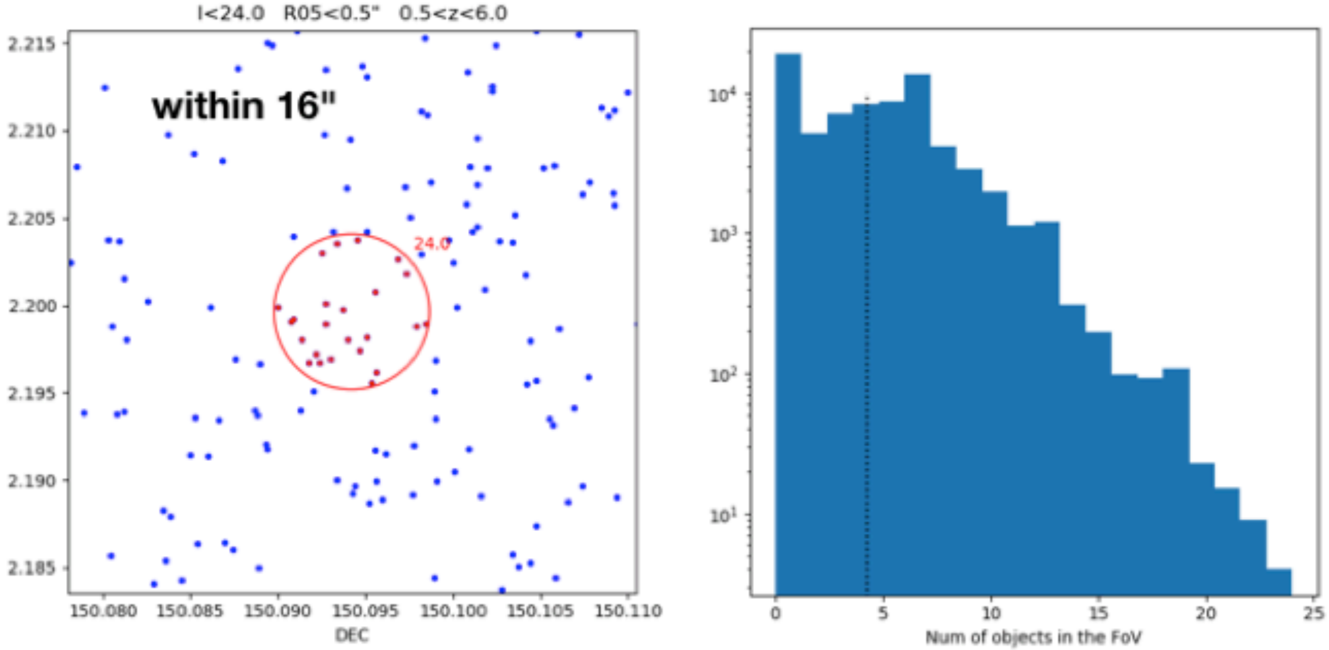



WP Mannucci et al.

# KEY SCIENCE SIMULATIONS: HIGH-Z GALAXIES – TARGET DENSITY

COSMOS,
Nayyeri+17
216 sq.arcmin

- I<24
- 0.5<z<6.0
- $R_{1/2}$<0.5"

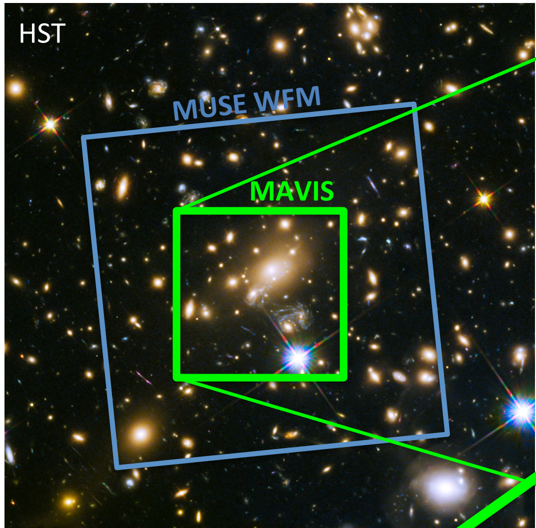


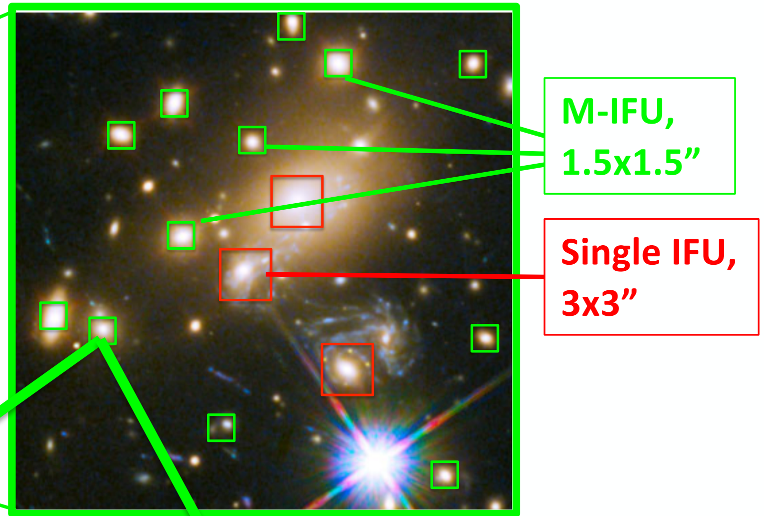

- Can derive spatial info for *I*<24 – use this as limiting magnitude
- Typical target density in COSMOS field is ~5 per MAVIS field

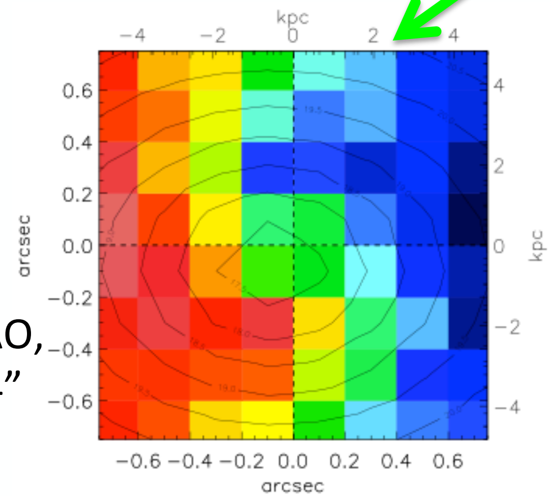
WP Mannucci et al.

# KEY SCIENCE SIMULATIONS: BENEFIT OF MULTI-IFU

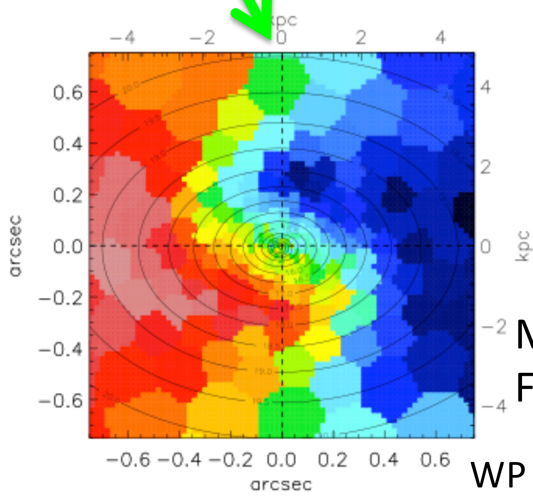
- M-IFU takes full advantage of the large corrected field
- Unique hi-res follow-up machine for e.g. blind MUSE+GLAO surveys




MUSE+GLAO, FWHM=0.4”




5hr expsure, photometric model from Tortorelli+18

MAVIS, FWHM=30mas

WP McDermid
WP Moretti et al.

# SUMMARY OF REQUIREMENTS – IMAGER

- Similar number of spectroscopy & imaging cases (>50% use both)
- U+B bands useful
- 30” FoV adequate

| | | Science Theme: The Birth, Life, and Death of Stars and Their Planets | Star Clusters as Tracers of Galaxy Processes Within the Local Group | Directly Resolving Galaxy Contents Beyond the Local Group | The Evolving Complexity of Galaxy Structure Over 10 Billion Years | Probing the Edge of Reionization | All Science Cases | ESO TLRs |
|---|---|---|---|---|---|---|---|---|
| MAVIS Mode | Imaging | 82% | 56% | 81% | 75% | 60% | 79% | TLR-1 (Requirement) |
| MAVIS Mode | Spectroscopy | 100% | 78% | 75% | 69% | 60% | 83% | TLR-1 (Requirement) |
| Imager – Photometric Bands | U | 64% | 11% | 19% | 25% | 0% | 28% | TLR-19 (Goal) |
| Imager – Photometric Bands | B | 82% | 11% | 50% | 38% | 0% | 45% | TLR-19 (Goal) |
| Imager – Photometric Bands | V | 82% | 56% | 75% | 63% | 40% | 72% | TLR-19 (Requirement) |
| Imager – Photometric Bands | R | 82% | 44% | 69% | 69% | 60% | 72% | TLR-19 (Requirement) |
| Imager – Photometric Bands | I | 82% | 56% | 75% | 63% | 60% | 74% | TLR-19 (Requirement) |
| Imager – Photometric Bands | z | 9% | 11% | 19% | 38% | 20% | 23% | TLR-19 (Requirement) |
| Imager – Photometric Bands | NB | 9% | 33% | 6% | 19% | 0% | 15% | TLR-19 (Requirement) |
| Imager – Field of View | <30" | 55% | 0% | 19% | 19% | 20% | 25% | TLR-31b |
| Imager – Field of View | 30" | 45% | 56% | 75% | 50% | 40% | 60% | TLR-31b |
| Imager – Field of View | >30" | 0% | 0% | 0% | 13% | 0% | 4% | TLR-31b (Requirement) |

Legend: Requirement / Goal

# SUMMARY OF REQUIREMENTS – IFU TYPE

- Monolithic IFU
- Multiplex desirable
- 3” FoV seems adequate

| Integral Field Unit | | | The Birth, Life, and Death of Stars and Their Planets | Star Clusters as Tracers of Galaxy Processes Within the Local Group | Directly Resolving Galaxy Contents Beyond the Local Group | The Evolving Complexity of Galaxy Structure Over 10 Billion Years | Probing the Edge of Reionization | All Science Cases | ESO TLRs |
|---|---|---|---|---|---|---|---|---|---|
| | Multiplex | 1 | 64% | 11% | 56% | 44% | 40% | 49% | Requirement |
| | | 2-10 | 9% | 11% | 0% | 38% | 20% | 17% | |
| | | 10+ | 27% | 56% | 19% | 25% | 20% | 30% | |
| | Field of View | <3" | 55% | 44% | 25% | 25% | 40% | 38% | |
| | | 3" | 18% | 22% | 44% | 50% | 20% | 38% | Requirement |
| | | >3" | 27% | 33% | 31% | 19% | 0% | 26% | |
| | IFU Type | IFU | 100% | 44% | 63% | 56% | 40% | 68% | Requirement |
| | | Multi-IFU | 36% | 44% | 38% | 38% | 40% | 42% | |
| | | MOS | 0% | 33% | 13% | 0% | 0% | 9% | |

Science Theme

Requirement
Goal

TLR-41

# SUMMARY OF REQUIREMENTS – SPECTROGRAPH

- Key range: 400-900nm
- R=5,000 satisfies most, but options for 1,000-10,000 desirable

| Spectrograph | | The Birth, Life, and Death of Stars and Their Planets | Star Clusters as Tracers of Galaxy Processes Within the Local Group | Directly Resolving Galaxy Contents Beyond the Local Group | The Evolving Complexity of Galaxy Structure Over 10 Billion Years | Probing the Edge of Reionization | All Science Cases | ESO TLRs |
|---|---|---|---|---|---|---|---|---|
| Wavelength (nm) | <400 | 36% | 11% | 31% | 25% | 0% | 26% | TLR-40 |
| | 400-500 | 73% | 44% | 50% | 44% | 20% | 53% | |
| | 500-600 | 82% | 22% | 75% | 63% | 40% | 66% | |
| | 600-700 | 100% | 33% | 75% | 69% | 40% | 74% | |
| | 700-800 | 91% | 33% | 63% | 69% | 60% | 70% | |
| | 800-900 | 91% | 33% | 56% | 69% | 60% | 68% | |
| | 900-1000 | 36% | 11% | 25% | 44% | 60% | 36% | |
| | 1000+ | 0% | 0% | 0% | 6% | 20% | 4% | |
| Resolution | <1000 | 55% | 0% | 0% | 6% | 0% | 13% | TLR-39 |
| | 1,000-4,999 | 36% | 22% | 6% | 38% | 40% | 28% | |
| | 5,000 | 55% | 44% | 50% | 50% | 20% | 51% | |
| | 5,001-10,000 | 27% | 44% | 31% | 25% | 0% | 30% | |
| | >10,000 | 36% | 33% | 13% | 0% | 0% | 17% | |

Science Theme

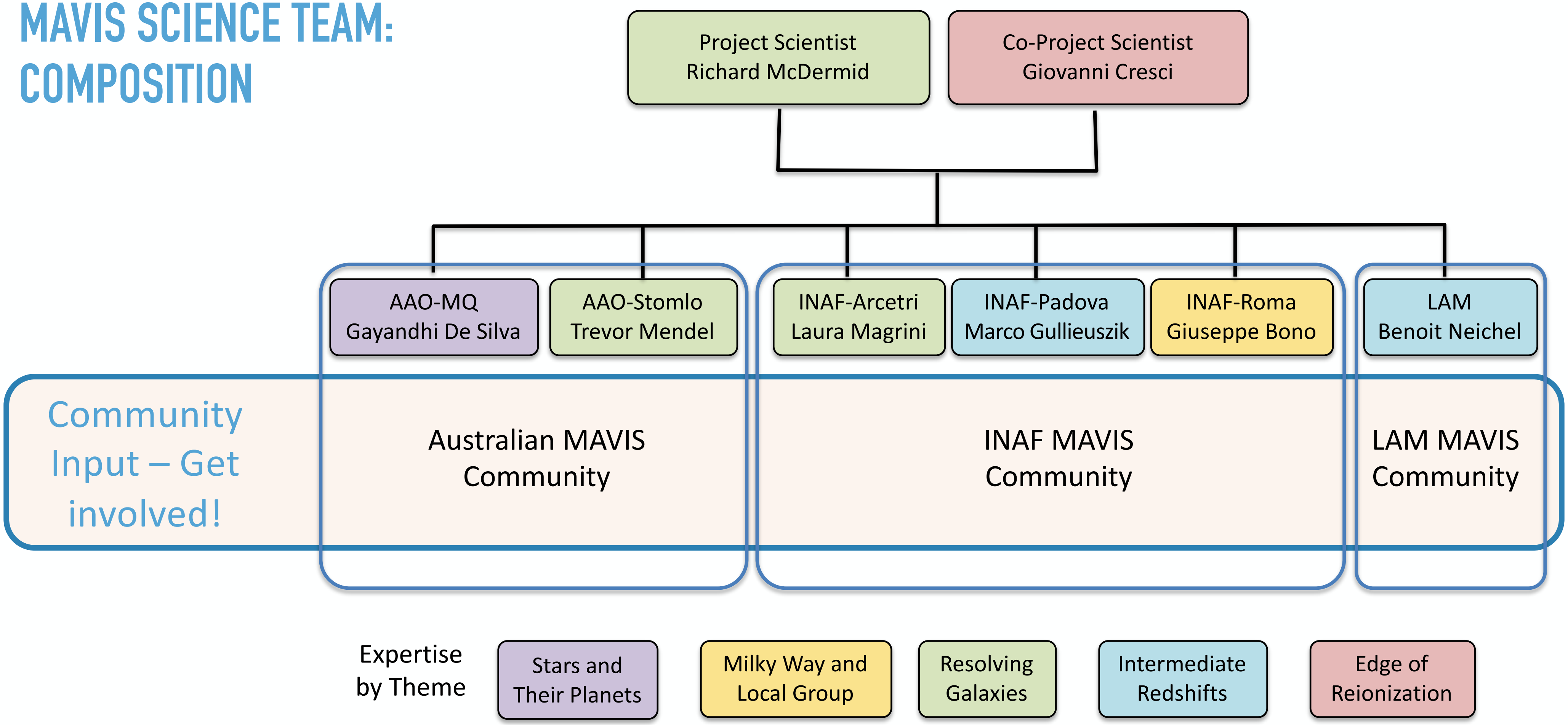
Requirement

Goal

# CHALLENGES TO BE SOLVED IN PHASE-A

- White Papers demand broad range of requirements – **need to down-select**
  - **Scientific Impact:** Addressing important and timely science questions?
  - **Detailed Feasibility**: Is the S/N, target density, sky coverage, etc. sufficient?
  - **Competitiveness**: Compare with existing/planned facilities
- MCAO in optical has never been done before – **need to establish feasibility**
  - **Sky coverage -** No compromise approach, test against ‘real life’ use cases
  - **Number of LGS sources** – May need more than 4 to meet requirements
- MAVIS will be a facility instrument, and so must be:
  - ***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 SCIENCE TEAM: COMPOSITION



NEXT STEPS

# MAVIS SCIENCE TEAM: COMPOSITION

Project Scientist
Richard McDermid

Co-Project Scientist
Giovanni Cresci

LAM
Benoit Neichel

Sign up for MAVIS emails:
http://bitly.com/join_mavis_list

Community Input – Get involved!

Community

Community

LAM MAVIS Community

Expertise by Theme

Stars and Their Planets

Milky Way and Local Group

Resolving Galaxies

Intermediate Redshifts

Edge of Reionization

# MAVIS PHASE-A SCHEDULE

**Phase-A Kick Off**

**Progress Meeting**

**Mid-Term Review**

**Progress Meeting**

**Team Busy Week**

**Documents Delivered to ESO**

**Phase-A Review**

2019

Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

2020

Jan Feb Mar Apr

**Engage Science Team**

- Release White Papers
- Review requirements
- Establish key work packages

**Team Busy Week**

- Down-selection of instrument baseline
- Update on PSF & sky coverage performance

**Science Meeting**

- Arcetri Workshop, November 4-8th
- Finalizing Science Case
- Build key Science projects

**Publish Science Case**

# MAVIS

**Blog:** www.mavis-ao.org

**Email List Signup:** bitly.com/join_mavis_list

**Contact:** project-scientist@mavis-ao.org