Scientific Exploitation of MICADO with Pure PSF Reconstruction

Science with MAVIS 2021 - 5-7/07/2021

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& MICADO PSF-Reconstruction Team:

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OSSERVATORIO ASTRONOMICO DI PADOVA

MICADO

MAVIS

Deeper than HST, sharper than JWST

Simioni+2020 - Micado PSF-R WP description

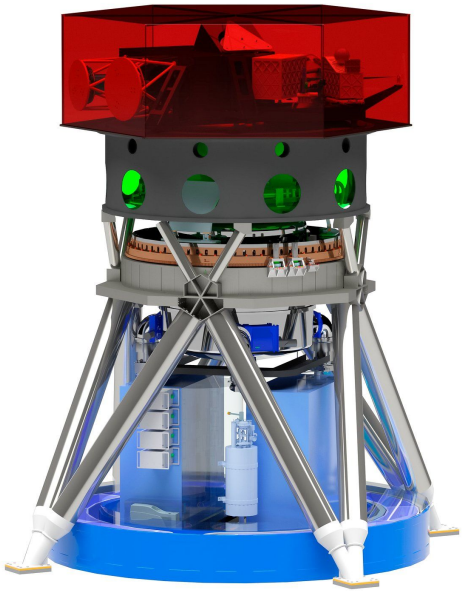
MICADO/MAORY in a nutshell

- MICADO will be a first light instrument for the ELT
- It will work with the MAORY adaptive optics system.
- It'll do imaging at 6-12mas resolution over a 50" field to J/H/K ~ 29 mag AB,

  R~20000 spectroscopy covering H & K simultaneously,

  (also astrometric & high contrast imaging).
- It'll use SCAO for initial operations, &

  MCAO, providing uniform correction over the field.
- It'll provide the user with a reconstructed PSF reference.



MICADO Science Cases

- Dynamics of dense stellar systems (3D kinematics)
- Black Hole at the center of the Milky Way (SgrA*)
- Super Massive Black Holes in local galaxies
- Resolved stellar populations of local galaxies (up to Virgo and Fornax)
- Exoplanets discovery and characterization
- Solar System
- Star Forming Clumps in high-z galaxies
- Formation and evolution of high-z galaxies in the early Universe

-> A detailed knowledge of the PSF is required and the PSF-R service is a deliverable of MICADO

Synergies between MICADO and MAVIS (Eline talk)

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PURE PSF-R approach is currently pursued

done without recourse to the science data, using telemetry data only:

- weather conditions: (wind, atm turbulence - Cn2 profiles etc)
- “telescope+instrument”: or non-AO components
- AO: all infos coming from the system

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Science case	*Observation mode*	*PSF-R type*	*Strehl ratio ΔS/S*	*FWHM ΔFWHM any axis*
Dynamics of Dense Stellar Systems including the Galactic Center	imaging	hybrid	0.002	0.01 mas
Resolved Stellar Populations	Imaging	hybrid	0.01	1 mas
Galaxy Evolution: Detailed Properties of Distant galaxies	Imaging	pure	0.1	1 mas
Galaxy Evolution: Detailed Properties of Distant galaxies	Spectroscopy	pure	0.1	1 mas
Planets & Planet Formation	Imaging	none	-	-
The Solar System	Imaging	adaptive	0.15	0.5 mas
Black Holes in Galaxies	Imaging	pure	0.1	1 mas
Black Holes in Galaxies	Spectroscopy	pure	0.1	0.5 mas

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An Astrophysical Context for PSF Reconstruction (ESO doc. Ric Davies)

Why Pure PSF-R ?

35-40% of extragalactic target, a MICADO science frame is void of point sources suitable for standard PSF characterization

[**An Astrophysical Context for PSF Reconstruction** (ESO doc. Ric. Davies)]

GOODS field South ~180 sq.arcmin [l,b= 223.6, -54.4]

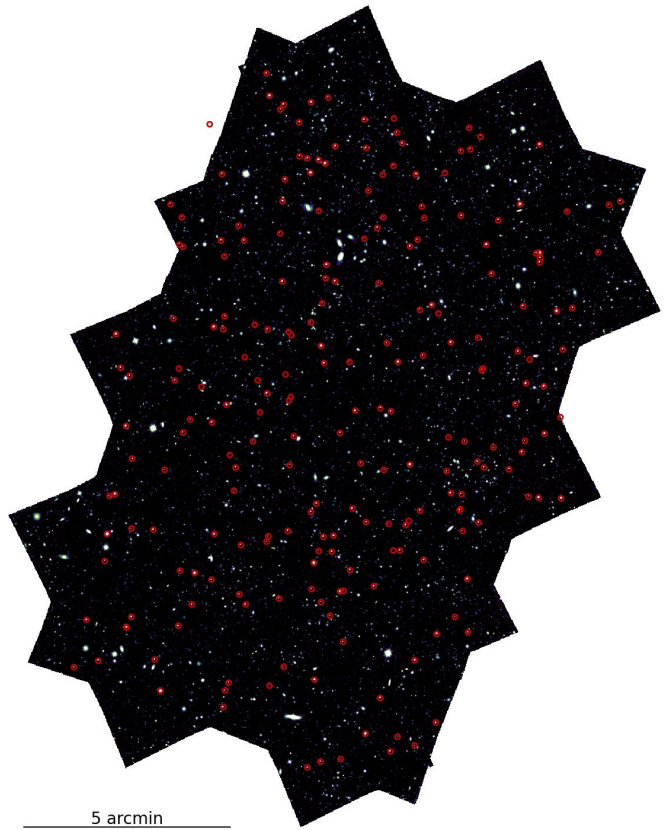
~220 stars (J≲23mag) ➞ 1.2 star/sq. arcmin

*all stars detected in HST images

J<32mag ➞ 3.5 star/sq. arcmin (3x; with most of sources populating the faint end of the mass function)

*TRILEGAL simulation [http://stev.oapd.inaf.it/cgi-bin/trilegal]

with no lower limit on initial stellar mass



MICADO Science Cases II

Structure of high-z Galaxies

Key science drivers at z > 1

- Resolving disks, bulges, clumps.
- Characterising SSCs.
- Resolving compact galaxies at z>
- Massive ETG progenitors in dens
- QSO host properties.
- Structure of lensed galaxies on <
- The first galaxies.
- Substructure of DM halos to ~10 M_{sun}.

SimCADO simulations
https://simcado.readthedocs.io

Based on HUDF source catalog with additional clump and cluster populations.
MICADO, 10hrs each on IJH bands.

Structure of high-z Galaxies

Spatial resolution

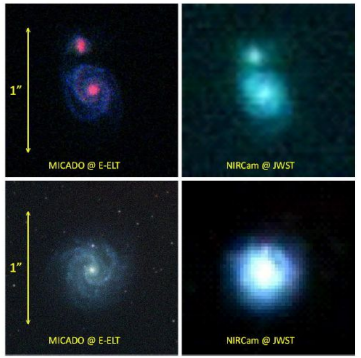
Order of magnitude gain in resolution from 1 kpc- to 100 pc-scale at z>1.

6-12 mas ~ 50-100 pc matches seeing limited scale for Virgo cluster galaxies.

JWST will select samples & measure basic galaxy properties.

MICADO will trace stellar continuum & provide detailed structure.

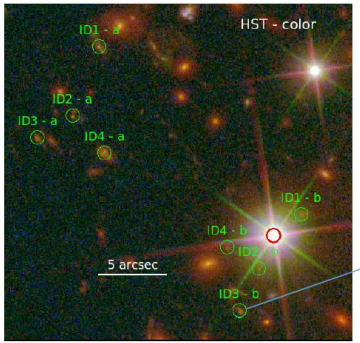
Synergies with ALMA, HARMONI, etc.



combined JHK images of local templates (BVR bands) shifted to z=2 (top) and z=1 (bottom), with R_{eff}=0.5" and M_V=-21; 5hrs integration.

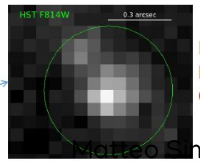
SCAO for initial operations - an example

The structure of lensed Lyman-α absorbers/emitters at 4 < z < 5
(courtesy of G. Caminha & K. Caputi)



Cluster CL0102 (El Gordo):

- 4 spectroscopically confirmed Lyα emitters/absorbers at z=4.3, within ~8" of a star with H_{AB} = 15.6 mag & Gaia G =15.9 mag. (Caminha et al. 2019)
- Even with lensing magnification, HST resolution of 90mas is insufficient to resolve morphology.



ID3-b
Highest magnification of 10
Observed magnitude H_{AB} = 23.6

SCAO for initial operations - an example

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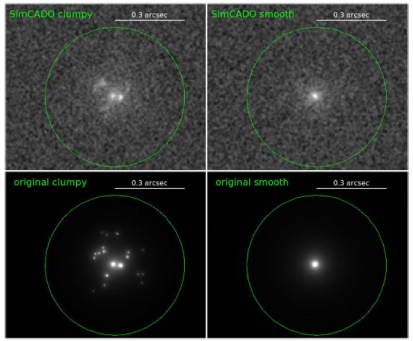
Question: can clumpy star-forming regions be resolved in ID3-b?

- SimCADO simulations: 2-hr integration of sources based on size & total flux in ID3-b.
- MICADO can easily distinguish clumpy and smooth distributions.
- Clumps with K_{AB} < 29.5 can be detected for all sizes considered in range 3-600pc; small fainter clumps can also be detected.
- Lensing in ID3-b allows one to detect structures to 10-20pc scales in K-band.



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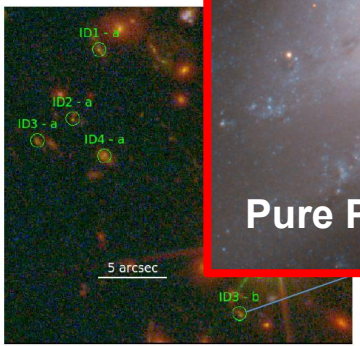
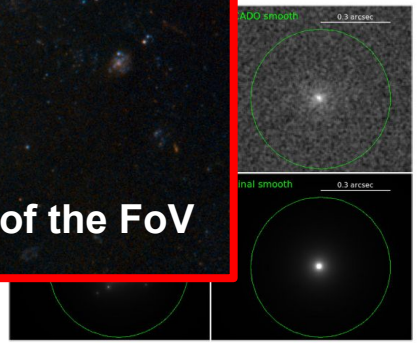


Pure PSF-R is required when extended targets cover most of the FoV

Structure of high-z Galaxies

R bands) shifted to z=2
$_V$=-21; 5hrs integration.



PSF-R Scientific Evaluation

Goal: develop a work-flow (simulations and analysis) to:

- Evaluate the impact of the uncertainties of the reconstructed PSFs on the scientific output
- Given the maximum acceptable uncertainties on the scientific measurements, estimate the maximum uncertainties on the reconstructed PSFs

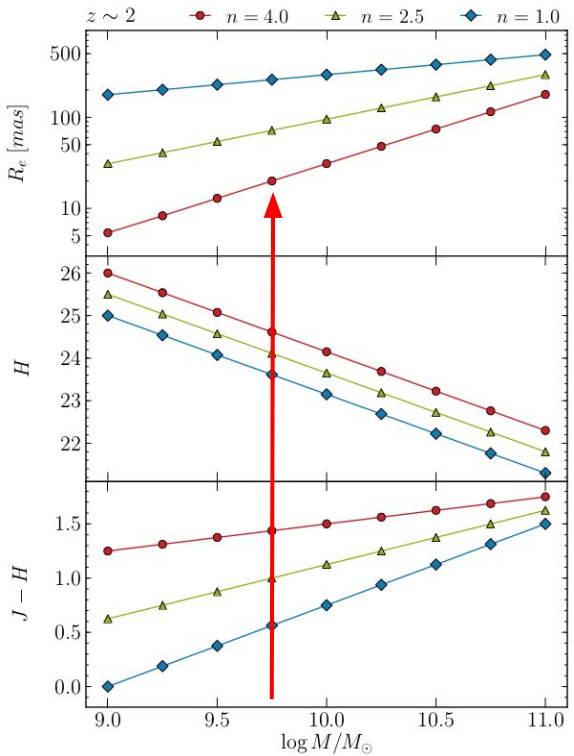
What is the effect of using a PSF that is not the "real" one on the scientific measurements?

Test case: Detailed Properties of Distant Galaxies

Method: Simulate pure-Sersic sources and fit Sersic profiles using different PSFs.

- Sersic profiles with size (Re) typical of early type galaxies at z~2
- High-SNR simulations [do not evaluate effects due to SNR]

Gullieuszik+2016, derived from van Der Wel+2014



PSF-R Scientific Evaluation II

Analysis scheme:

Software: GALFIT. Fit Sersic profiles convolved with an input PSF

1. GALFIT + **PSF model** vs inputs -> uncertainties (systematics + random noise) on the measurement process
2. GALFIT + **PSF-R** vs inputs -> uncertainties + systematics introduced by using a PSF different from the "real" one

*By comparing the output of **1** and **2**, we can isolate the effects of the PSF-R on the measured parameters*

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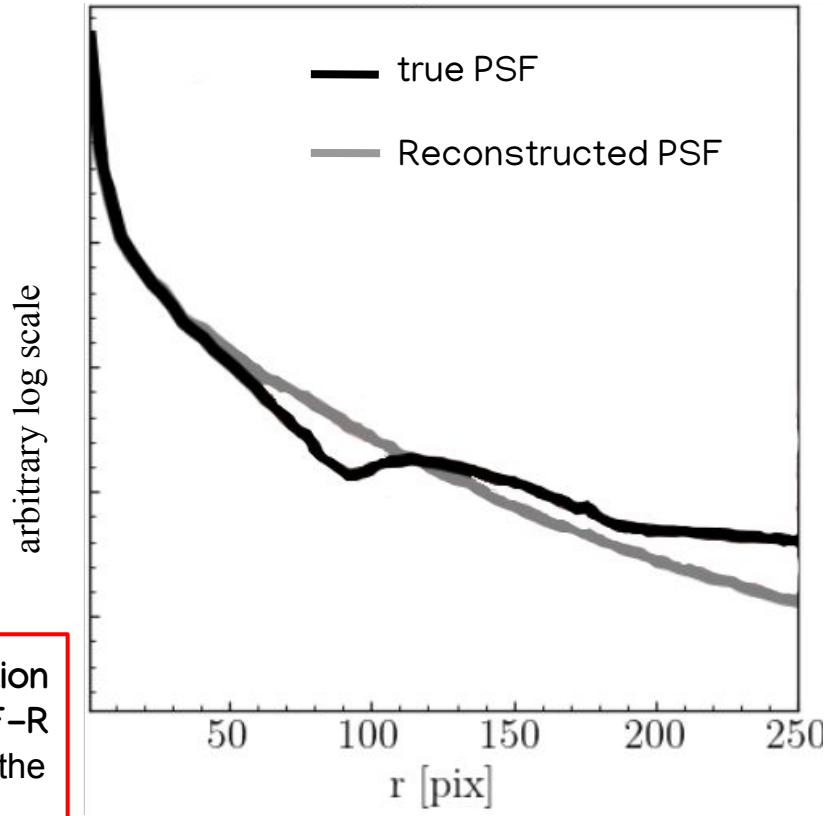
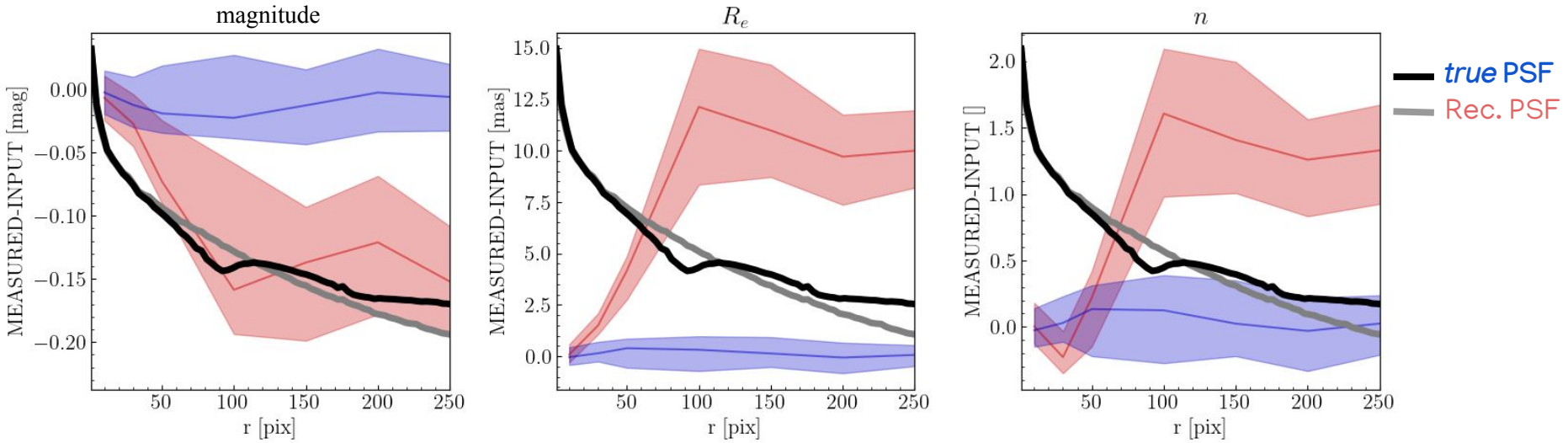


"true" PSF model is obtained using ESO's Octopus simulation tool; not 100% same assumptions underlying our PSF-R procedure → SR is overestimated by 8%; the outer regions of the PSF are not reconstructed with extreme accuracy

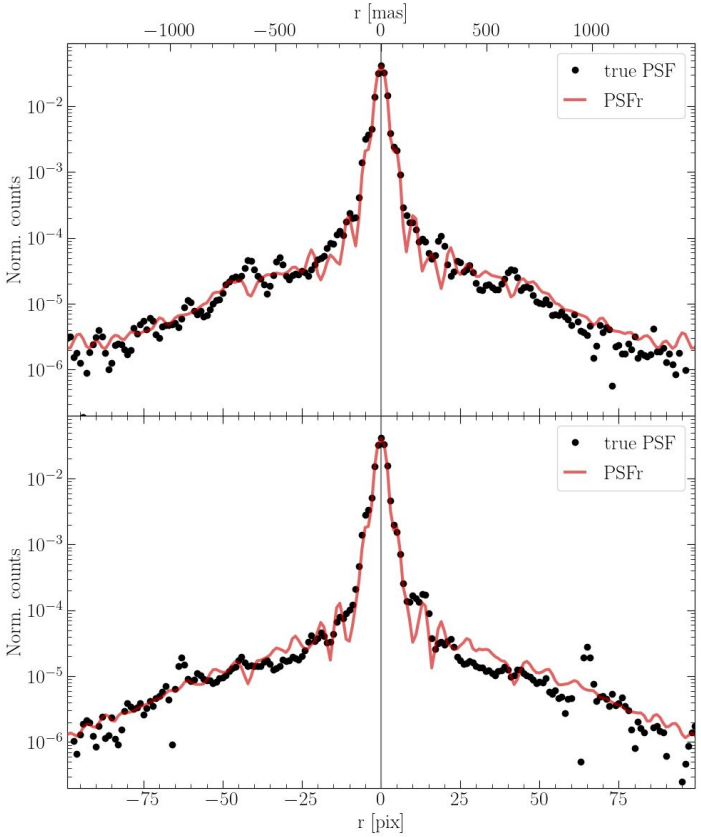
PSF-R Scientific Evaluation III

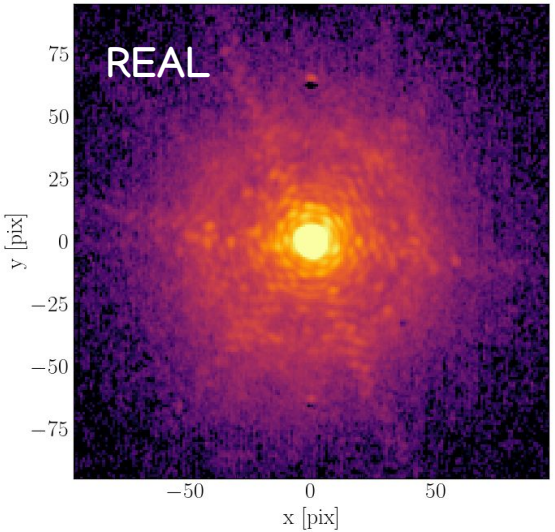


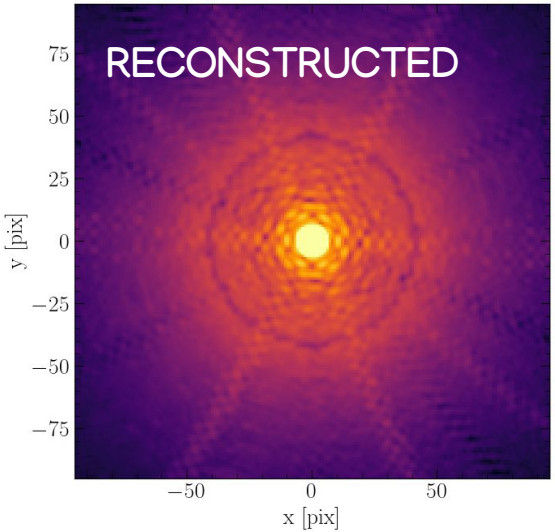
- Non-negligible systematics on the recovered values of the galaxy's structural parameters. Re is 10 mas (50%) larger

- Reliable values are retrieved if we exclude the outer regions of the PSF. The PSF core is OK

LUCI+SOUL@LBT PSF-R







Summary

- MICADO will be a first light instrument of the EELT
- Detailed PSF knowledge is required for a substantial number of MICADO science cases
- PSF-R is a deliverable of MICADO and our WG is in charge of its development
- A pure PSF-R approach is pursued:
  - PSF is reconstructed from AO and non-AO telemetry data, with no use of science data
  - a user-friendly software will be provided; it will take as input position of the object, filter, observing mode, exposure time, telemetry and calibration data; the output will likely be a FITS image with the reconstructed PSF, or a cube of reconstructed PSF at different wavelengths
- We are currently at Final Design Review level, with positive feedback received from ESO
- Preliminary results are extremely promising, the method has also been adapted to real data
- We have also developed tools and a pipeline to evaluate how uncertainties on the reconstructed PSF translate into uncertainties on scientific measurements (and viceversa)