AO data analysis challenge

How PSF shape relates to the technique used, vs. the field, vs. wavelength, vs. turbulence profile, and many more

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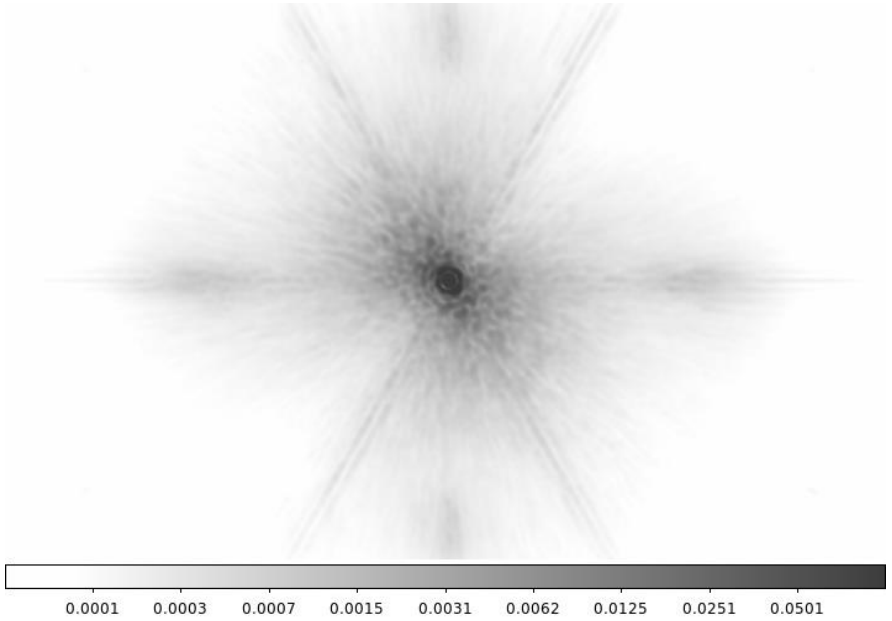
General context

- The Point Spread Function (PSF) ignorance can lead to significant systematic errors for science data extraction.
- The PSF estimation technique is one of the key ingredients for the analysis of the observations.
- The actual PSF is not a priori fully determined, since the degree of Adaptive Optics (AO) correction is sensitive to the observing conditions: seeing, wind speed, the brightness of the reference stars, etc.
- Each AO technique produces PSF with specific morphology and field variation.

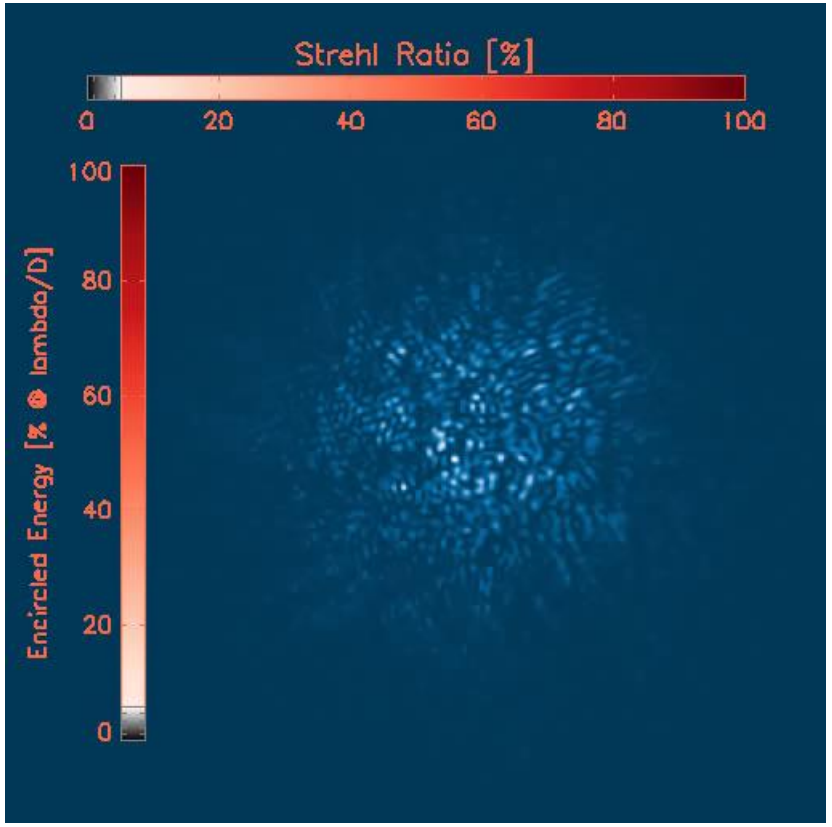


PSF formation and AO effects

The PSF is the result of the integration along the time of consecutive instantaneous PSF and across the wavelengths within the filter used for the observations.

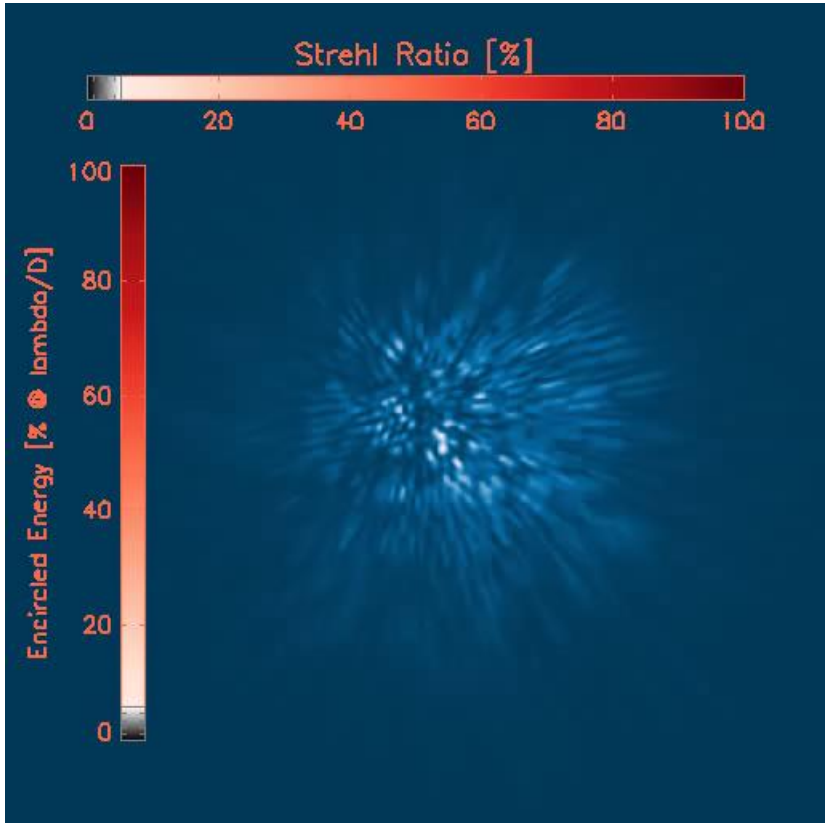
Example: 20 sec, 1.2” seeing in V
X bar: SR Ratio
Y bar: EE in the diffraction limited core

Open Loop Sequence **monochromatic**



Linear Scale

Open Loop Sequence **polychromatic**



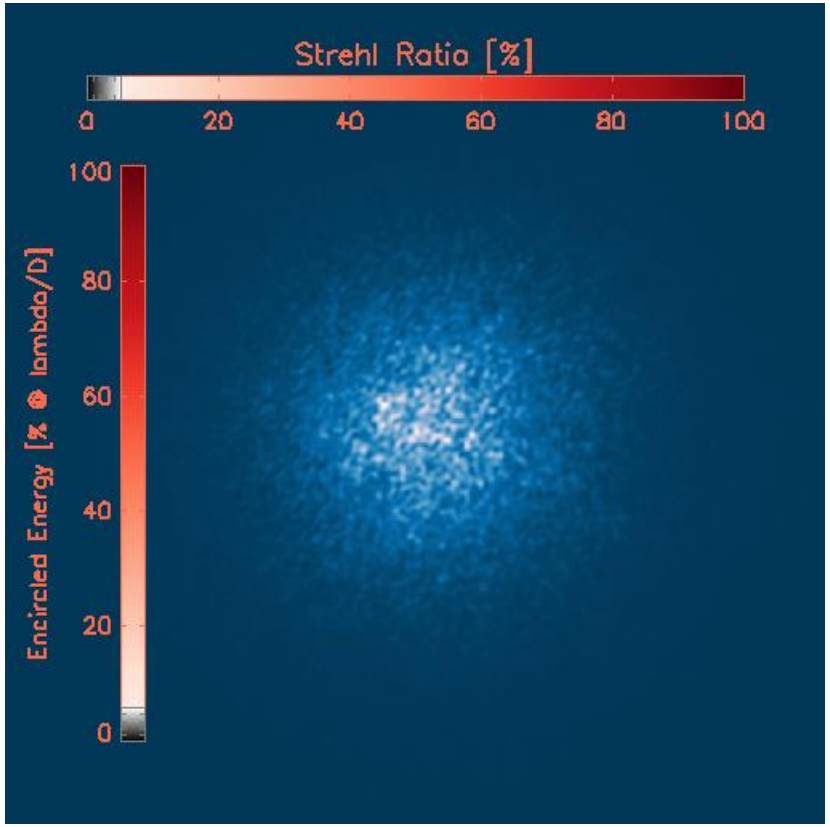
Linear Scale

PSF formation and AO effects

The speckles, dancing on the focal plane of ground-based telescopes, produce the seeing disk.

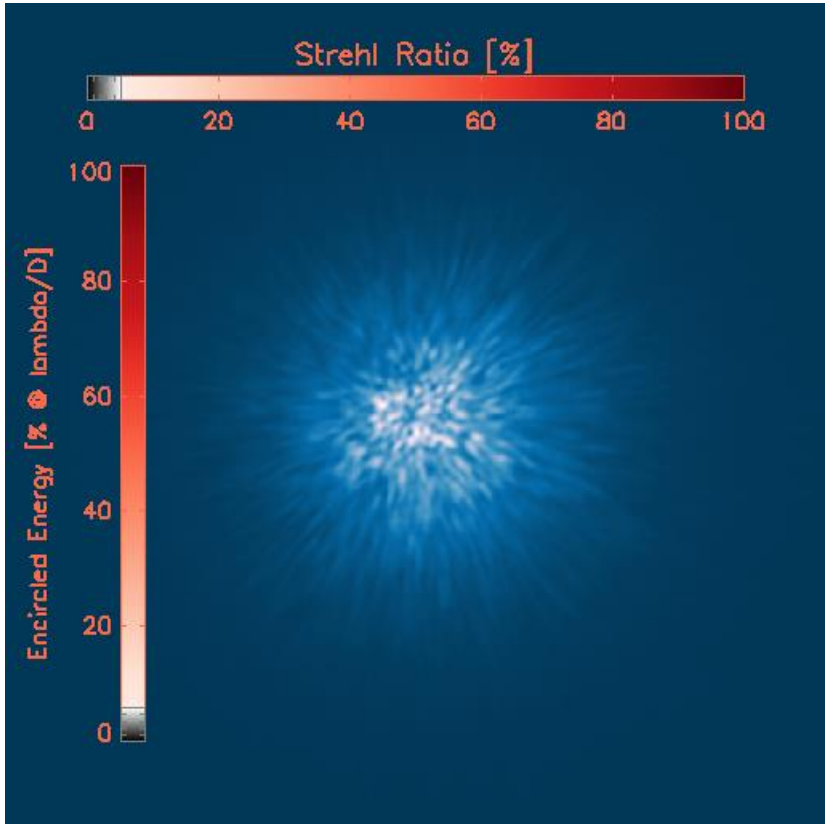
Example: 20 sec, 1.2” seeing in V
X bar: SR Ratio
Y bar: EE in the diffraction limited core

Open Loop Sequence **monochromatic**



Linear Scale

Open Loop Sequence **polychromatic**



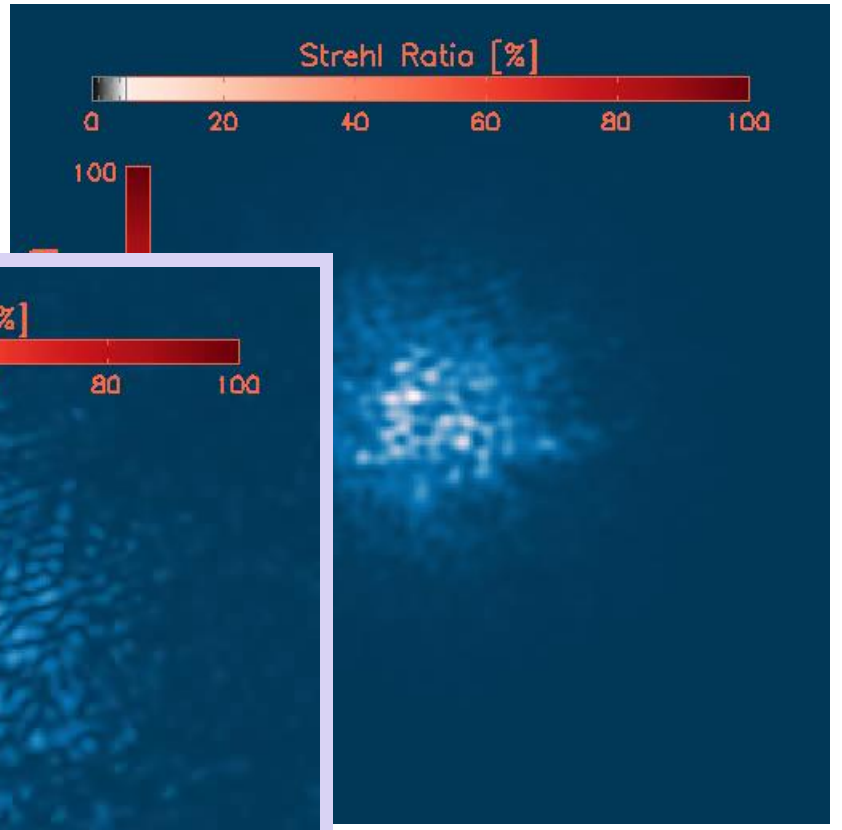
Linear Scale

PSF formation and AO effects

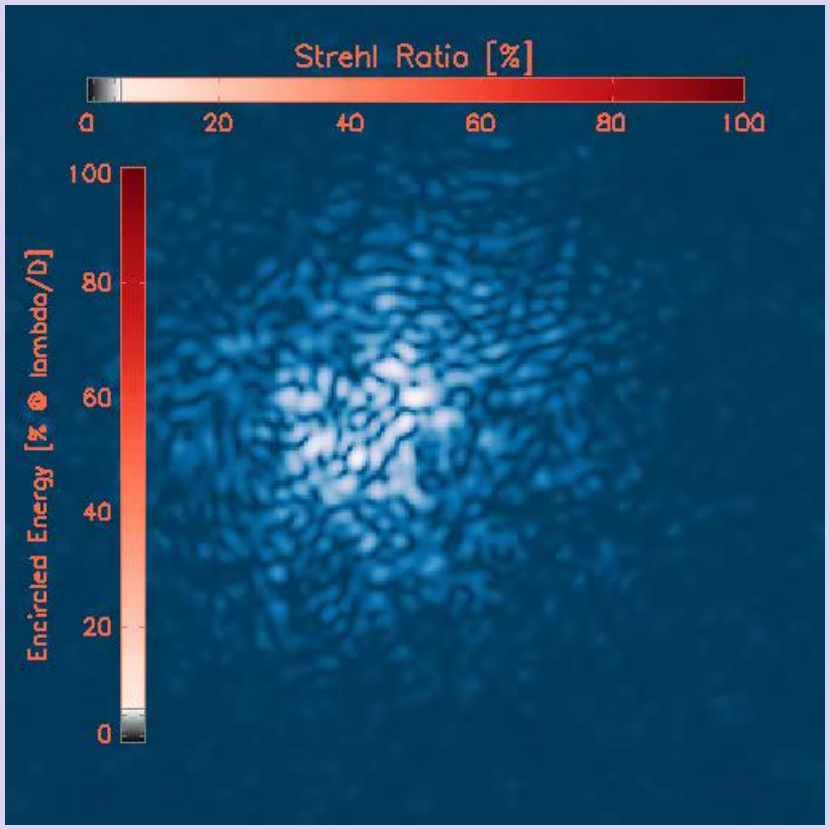
- $\iint dt\mathrm{d}\lambda$ of the instant PSF
- AO flattens the incoming WF and acts moving speckles from the seeing halo to the Airy diffraction pattern

Example: 20 sec, 0.9” seeing in V,
X bar: SR Ratio
Y bar: EE in the diffraction limited core

Linear Scale



Log Scale

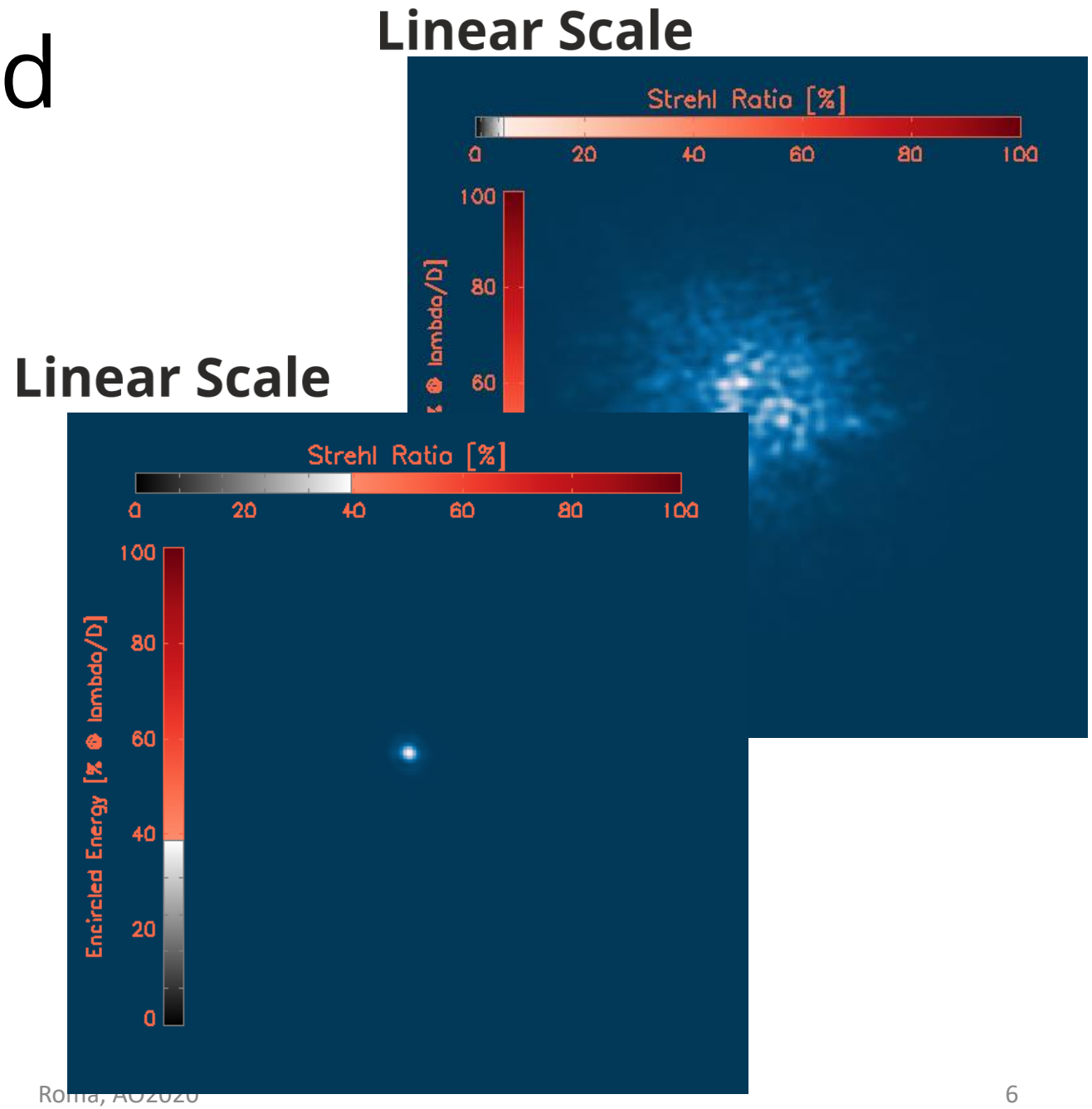


Closing Loop Sequence

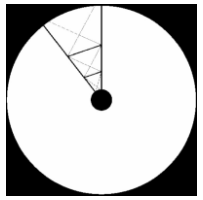
3,50"

PSF formation and AO effects

- PSF is the result of the integration in time of the instantaneous PSF
- The speckles, dancing on the focal plane of ground-based telescopes, produce the seeing disk.
- AO flattens the incoming WF and acts moving speckles from the seeing halo to the Airy diffraction pattern
- AO retrieves a FWHM gain of the order $\frac{\lambda/r_0}{\lambda/D} = D/r_0$

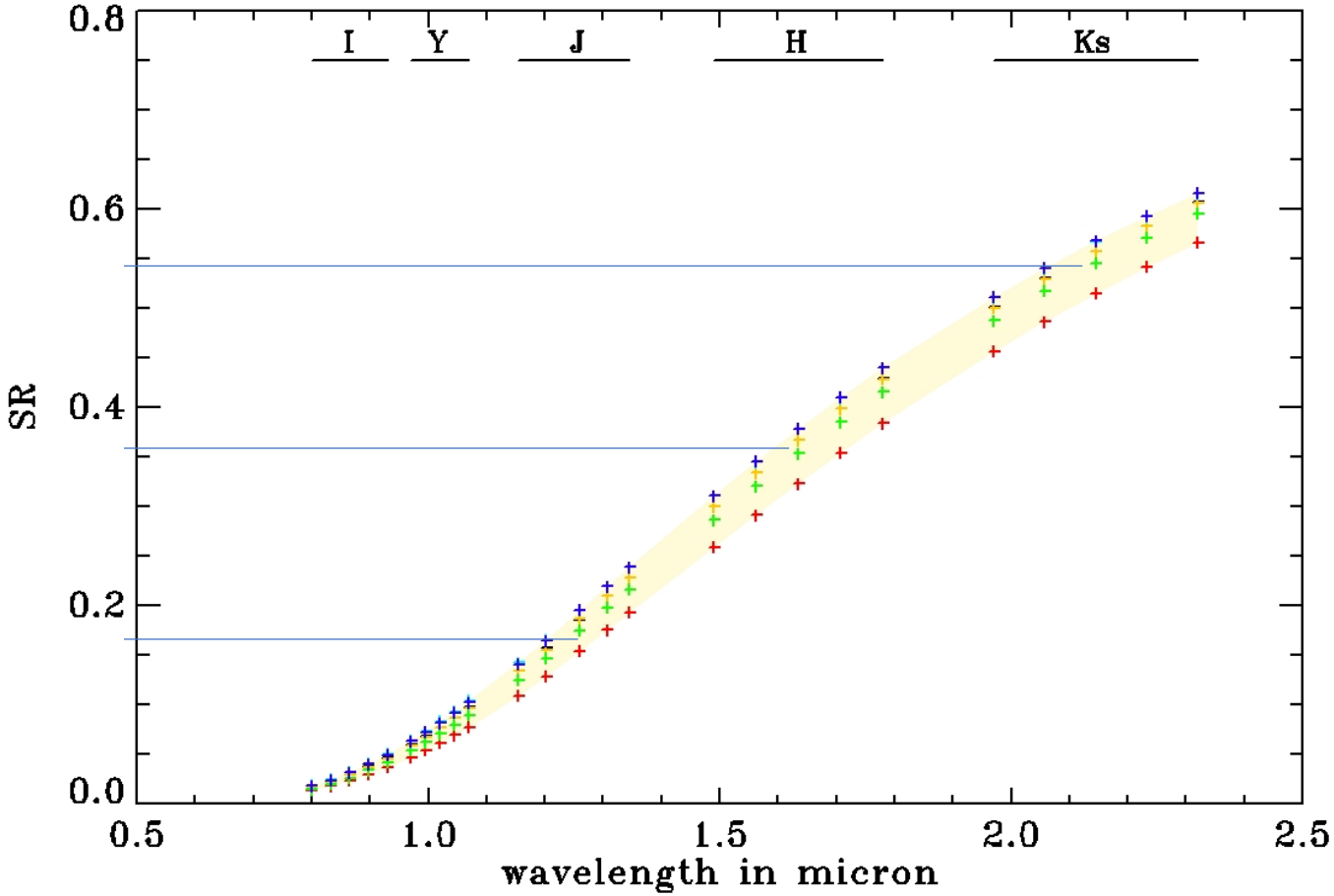


PSF vs Wavelength [λ]

$A(x,y)$ 

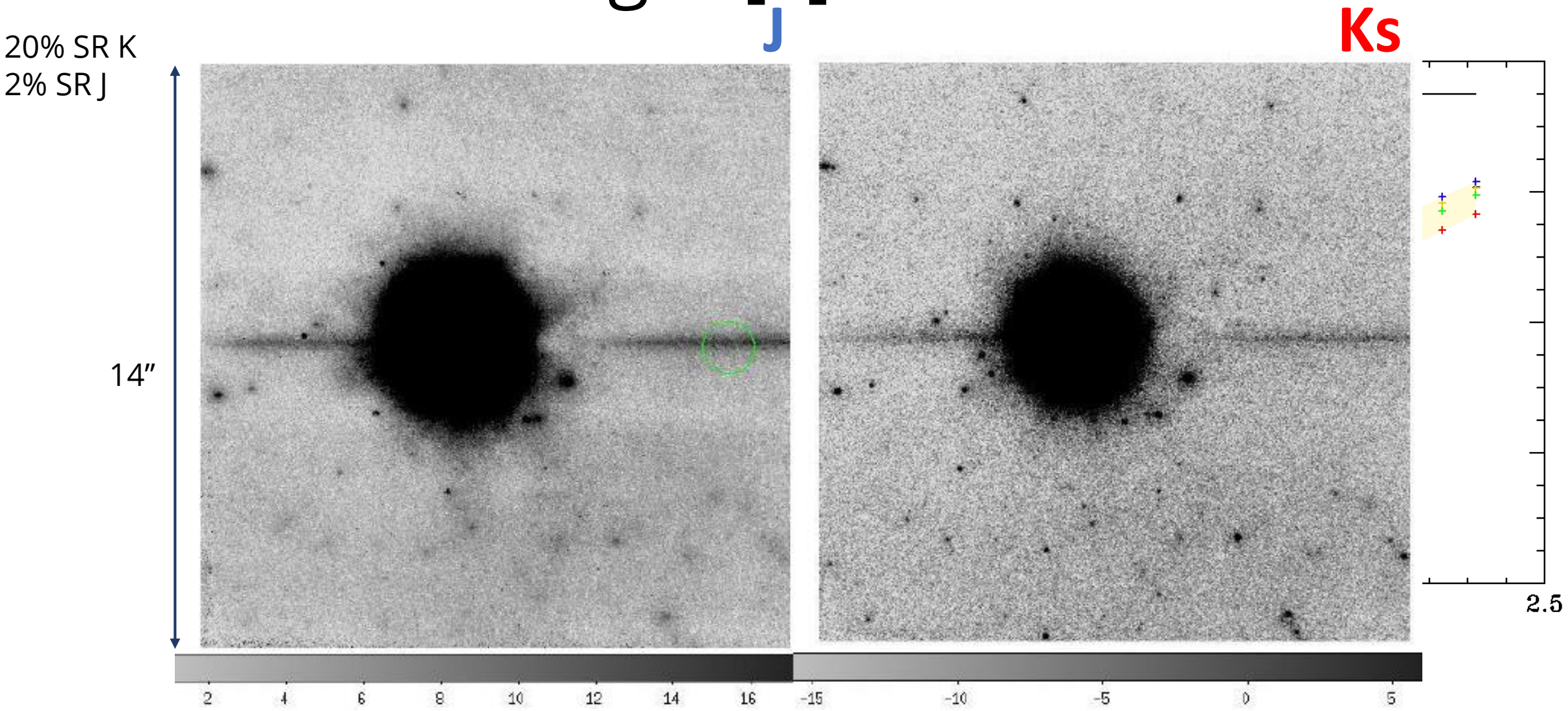
From a MAORY Case

- The PSF can be computed as the square of the Fourier transform of the complex amplitude $A(x,y)e^{i\varphi(x,y)}$
- the (residual) phase is proportional to λ^{-1}.
  - identical correction residuals are more effective in **K** than in **H** or **J**
  - r_0 to $\lambda^{6/5}$ -> Seeing FWHM is prop.to $\lambda^{-1/5}$



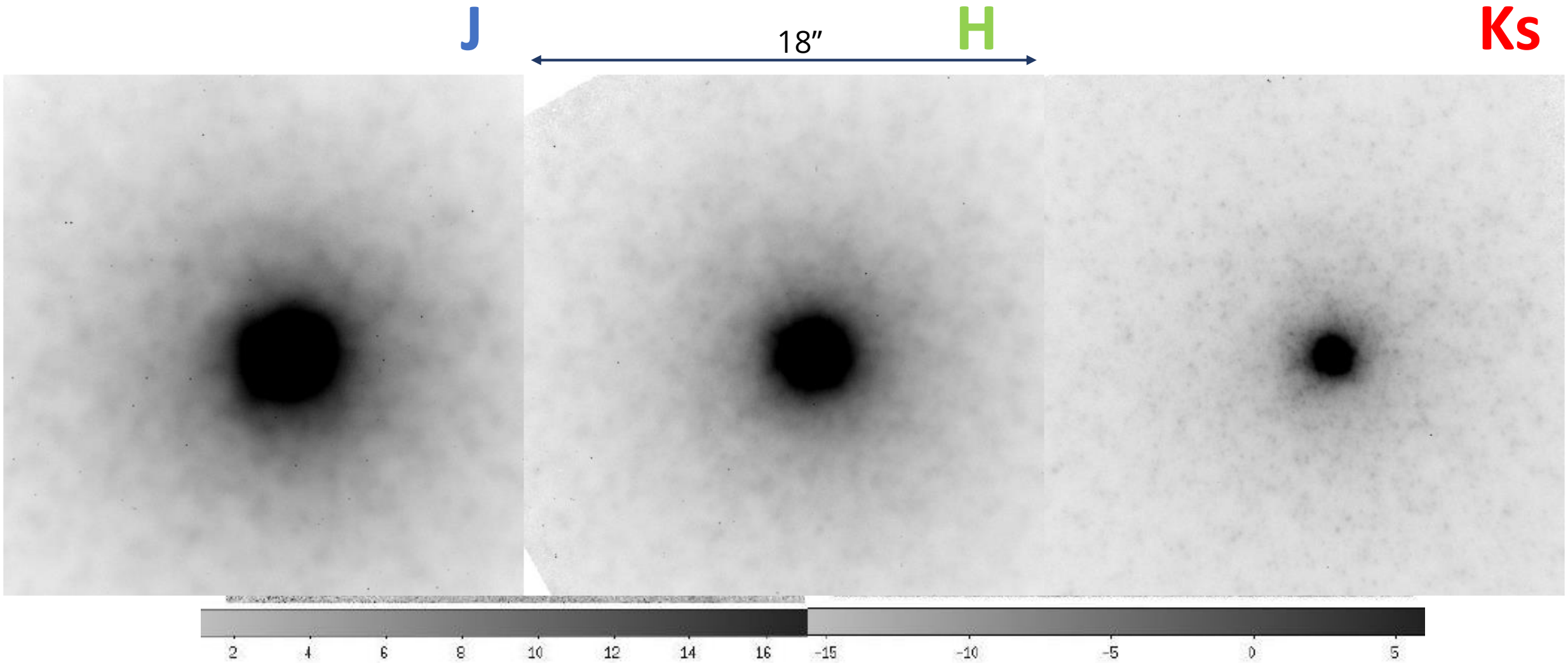
PSF vs Wavelength [λ]

Resolving stars in NGC 1560
FLAO + PISCES, Closed loop
on foreground local star



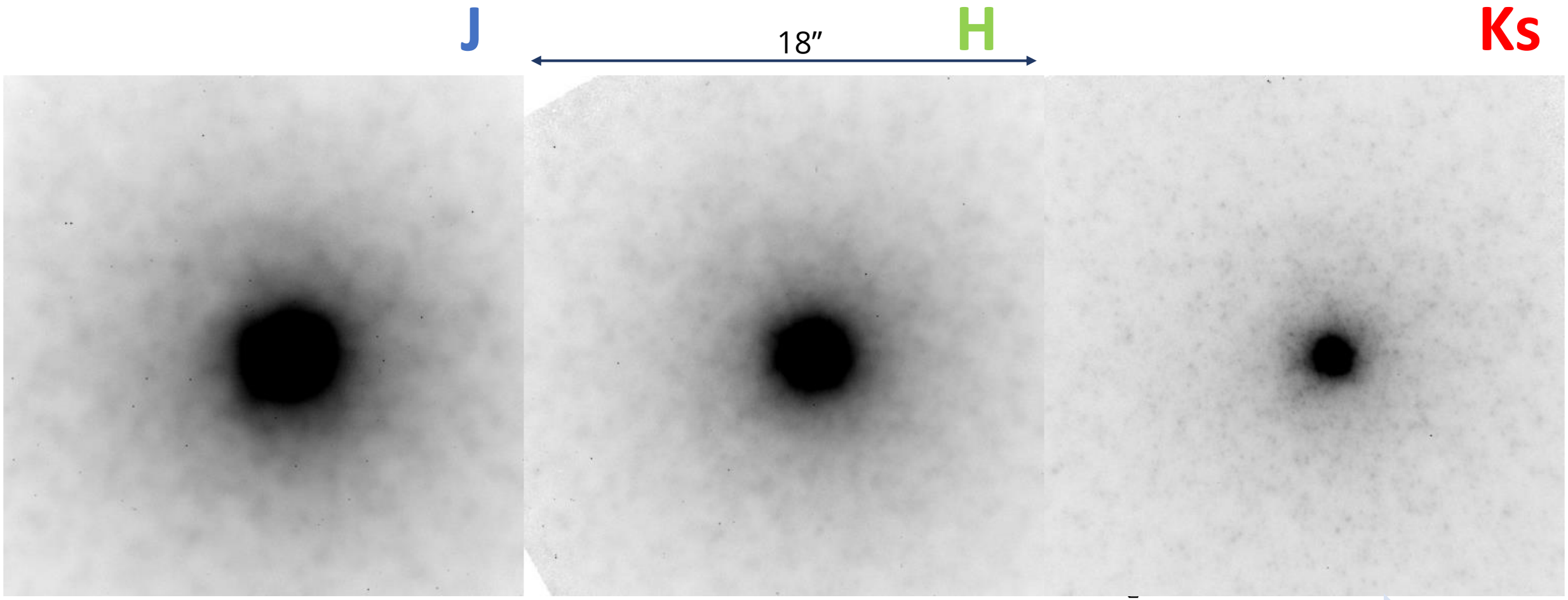
PSF vs Wavelength

NGC 404, FLAO + PISCES, Closing Loop on the core of the galaxy.



PSF vs Wavelength

Better performance toward the red.
Narrower peak: More Resolution
Lower Halo: More Contrast

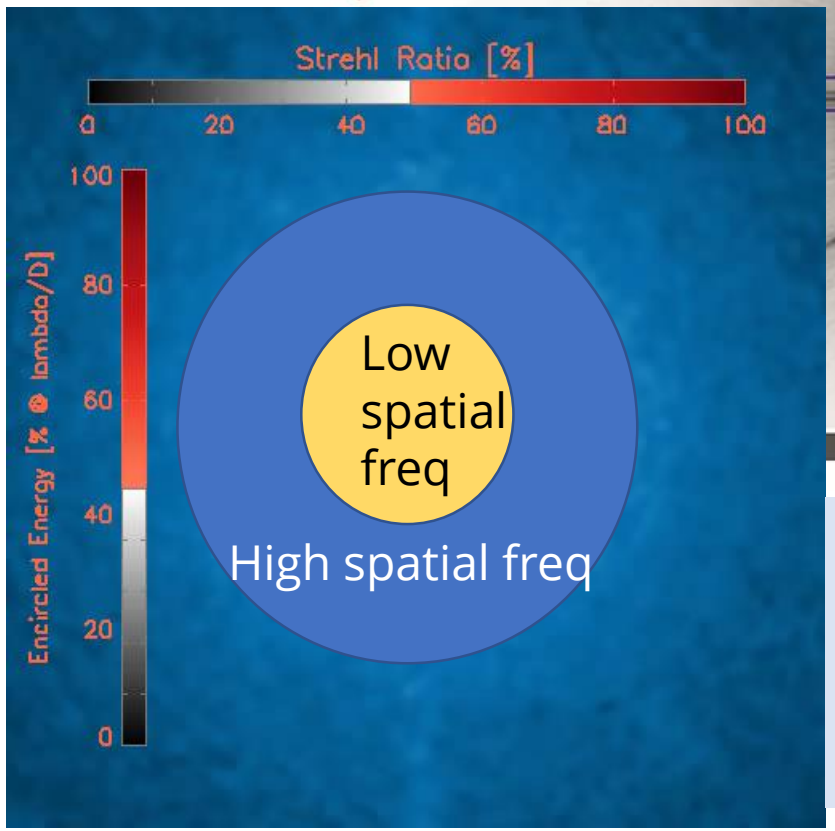


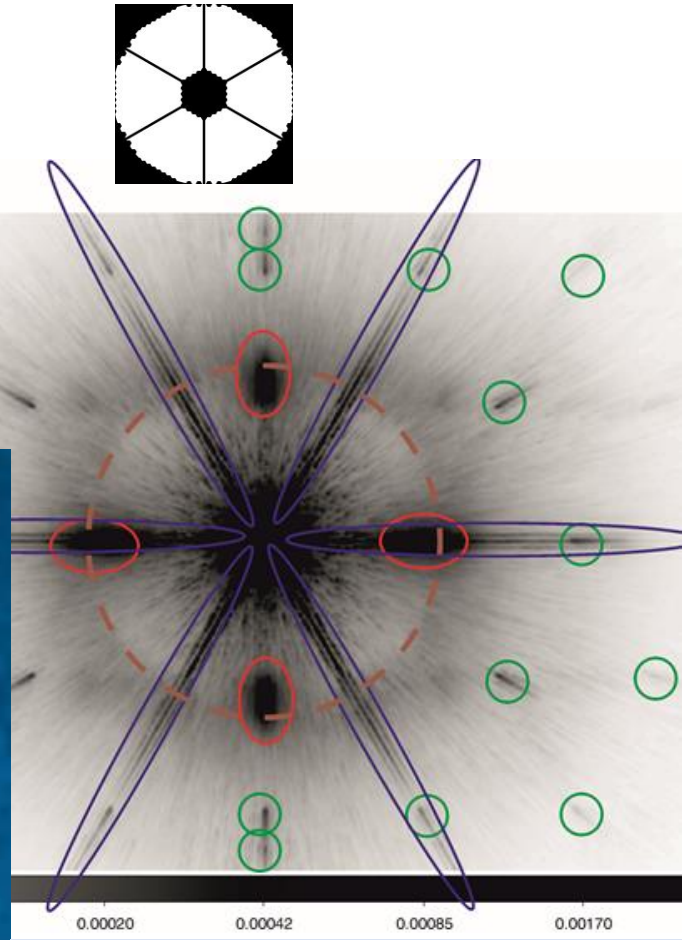
Resolution, Contrast, Wavelength

Quasi Diffr.-Lim. PSFs have Structures

The number of DM modes used fixes the highest frequency corrected

- It is ultimately limited by the number of actuators
- It appears in the PSF fixing the so-called control radius (Perrin+2003), well visible in SCAO mode
- Control Radius is at $(\lambda/2d)$ where d, is the dimension of the smallest correction patch on the DM



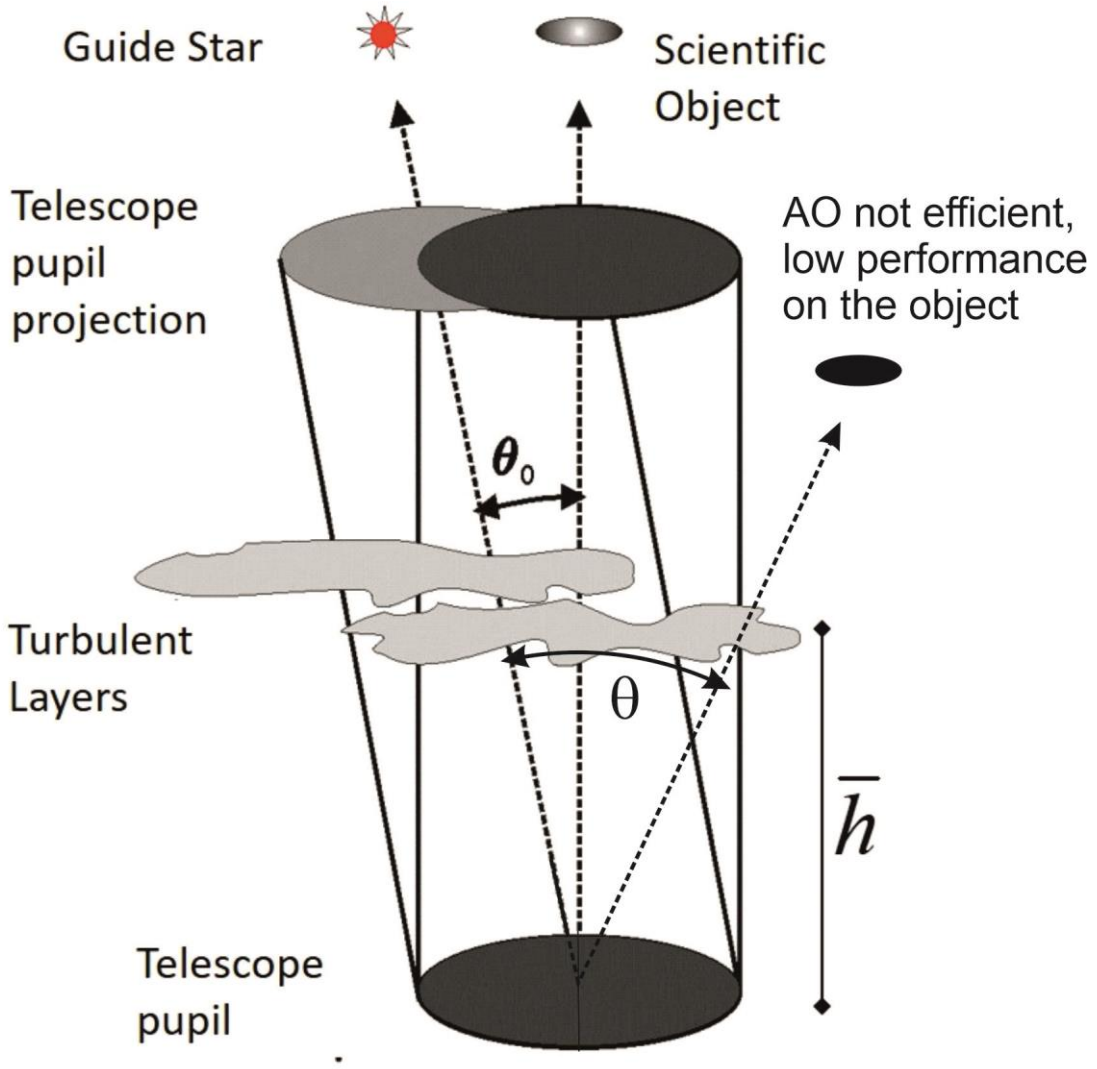


i.e., the c. radius follows the maximum frequency controlled by the AO, accordingly to the mode number, here fixing the rms of the corrected WF.

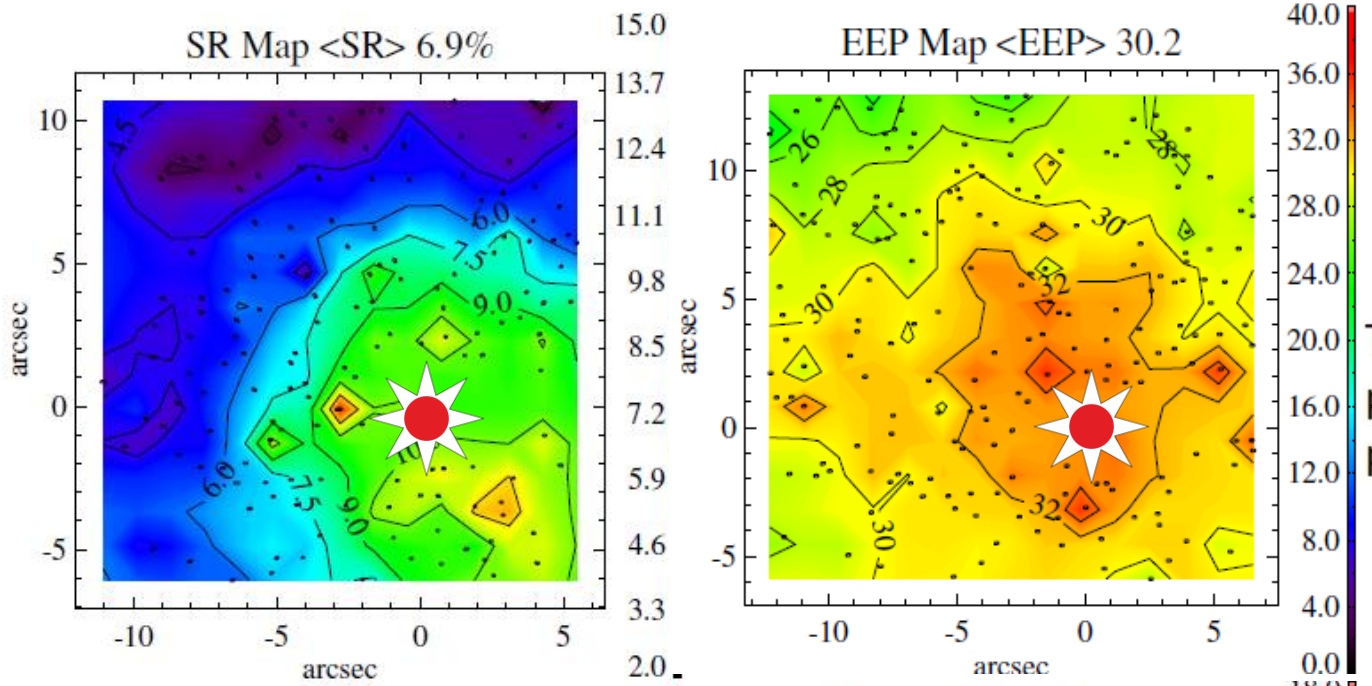
Space variant PSF

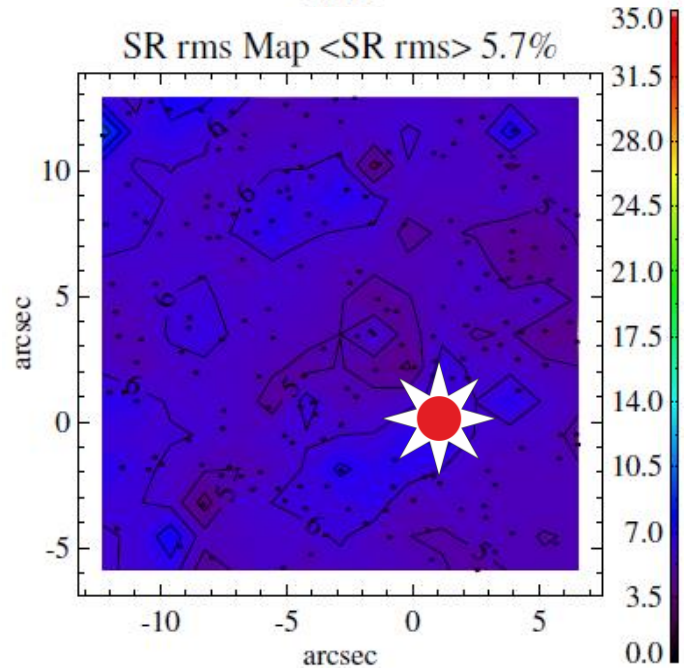
SCAO efficiency is limited to the region within the isoplanatic angle, $\theta < \theta_0$.

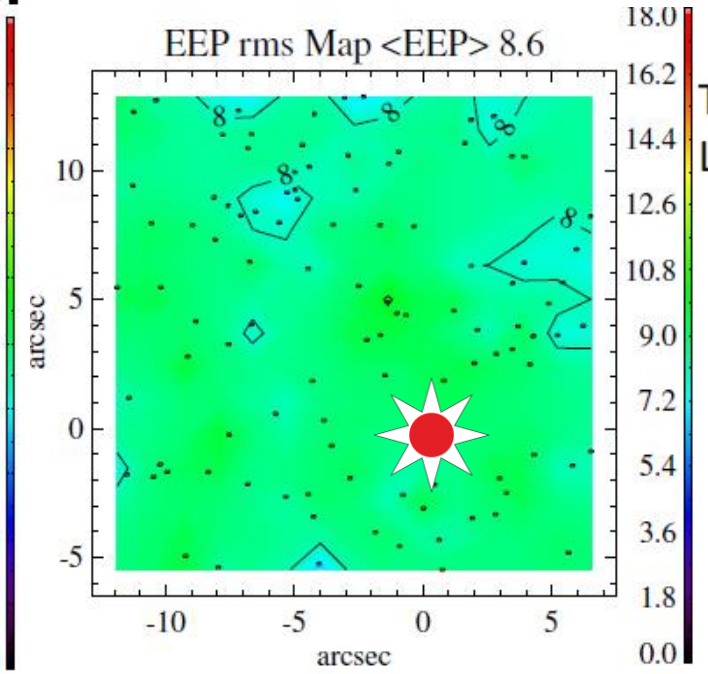
The θ_0 depends on the turbulence vertical profile (i.e., $\bar{h}$) and this makes it very variable, intranight and even in short timescale (min-hour).

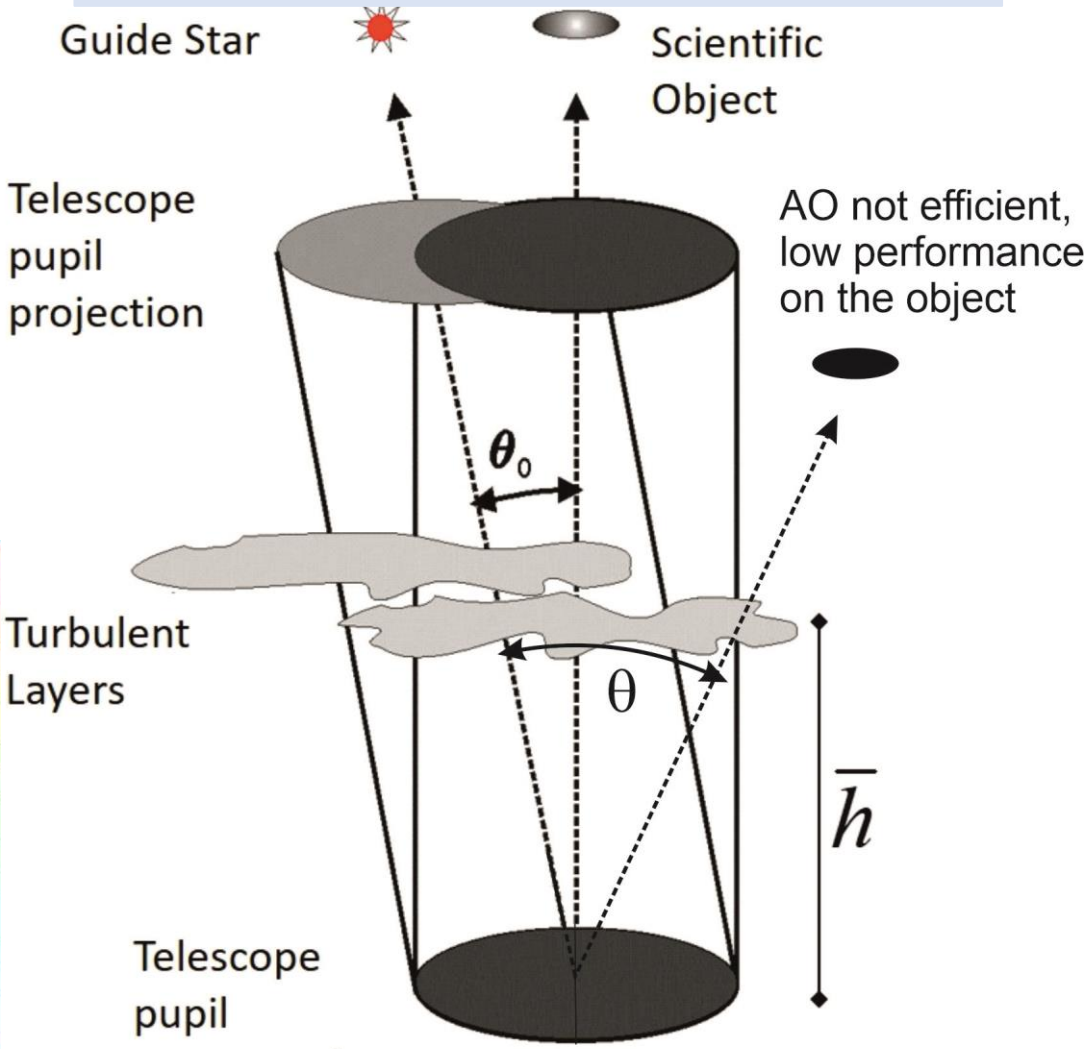


Example: M15 J band data
20”x20”, PISCES+FLAO, SR_J & $EE_{0''.1}$
Measured values and temporal rms









Seeing

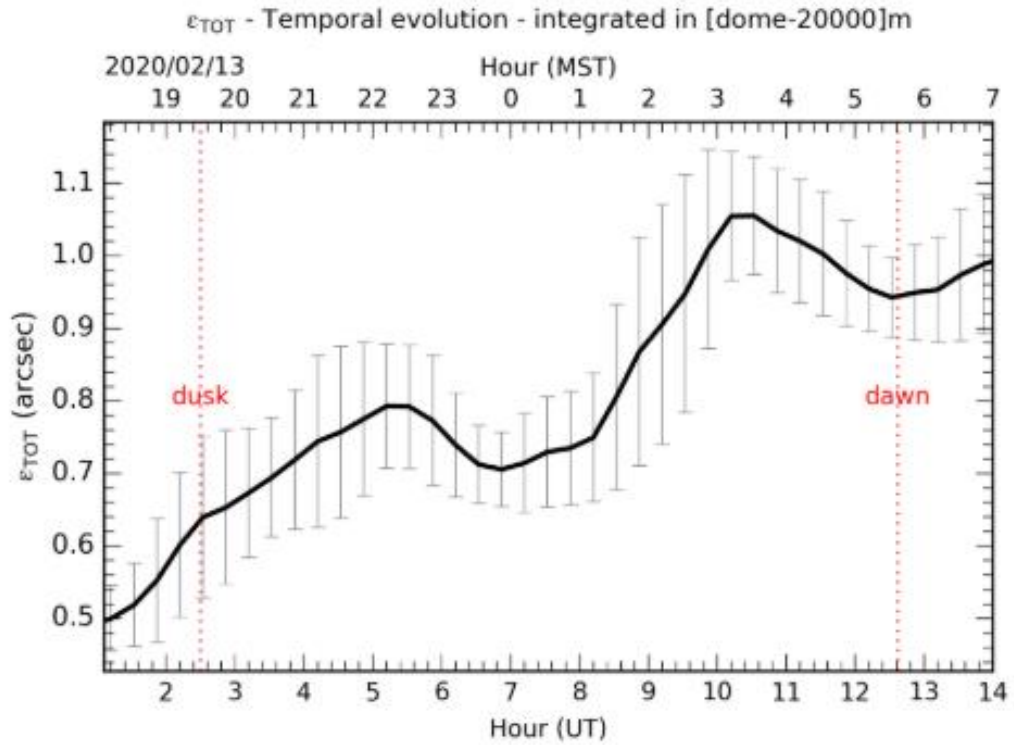


Fig. 1: Temporal evolution of ε_{TOT} ([dome-20km]) between the sunset and the sunrise.

Isoplanatic Angle

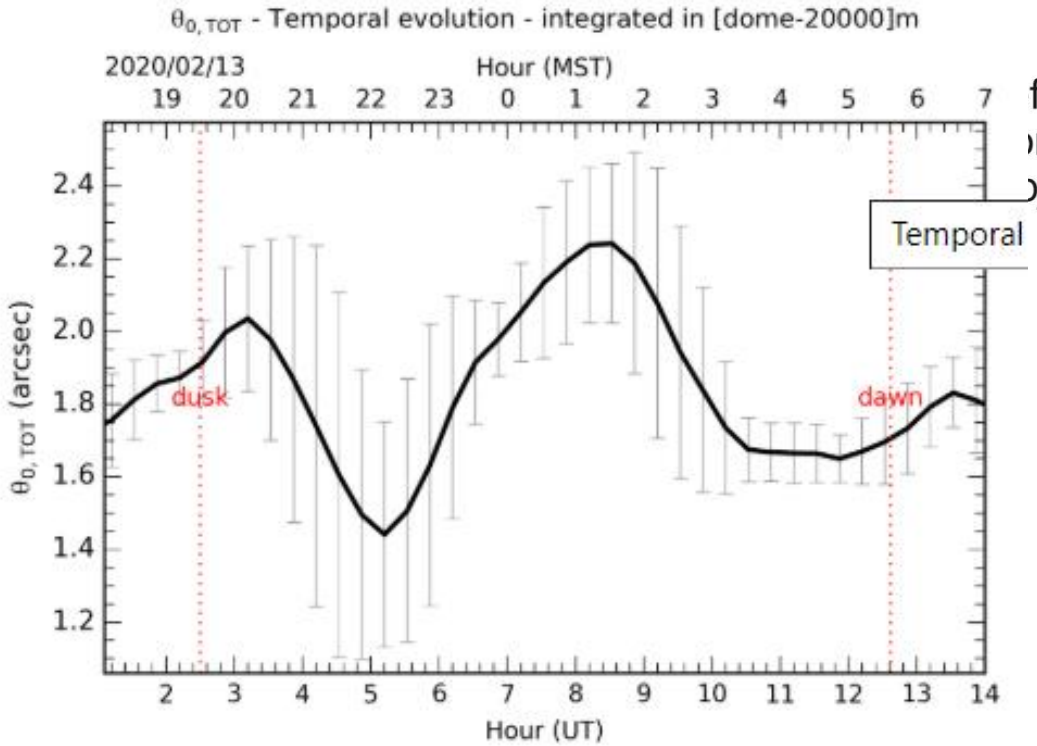
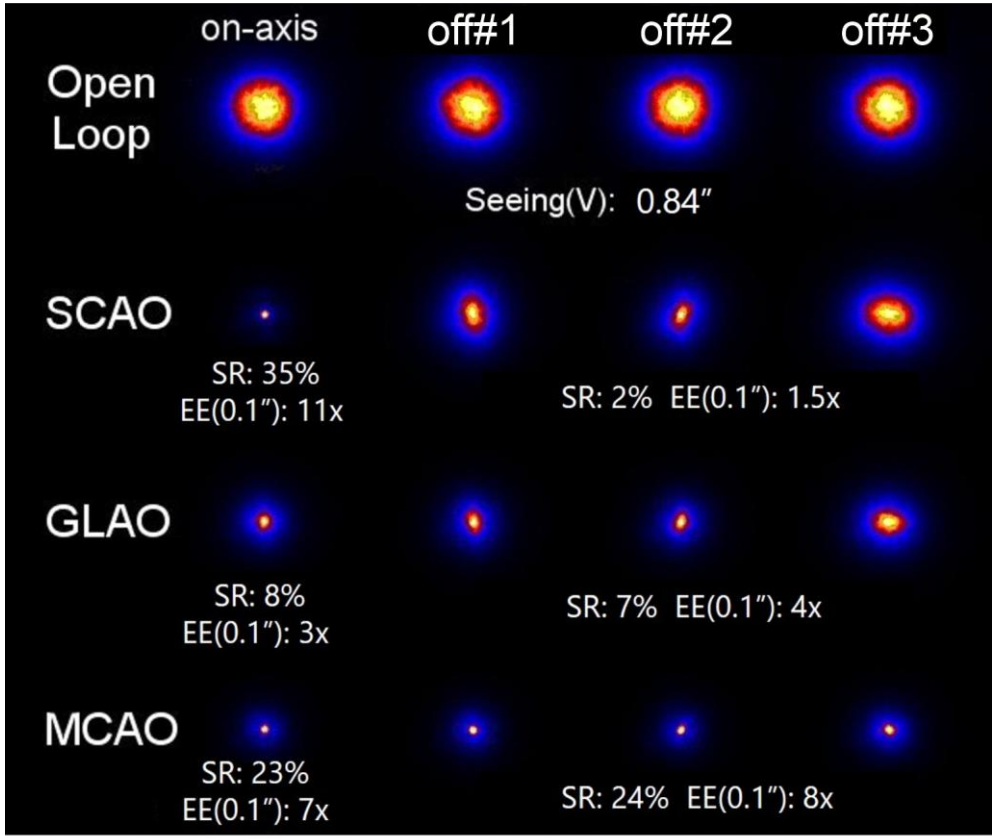


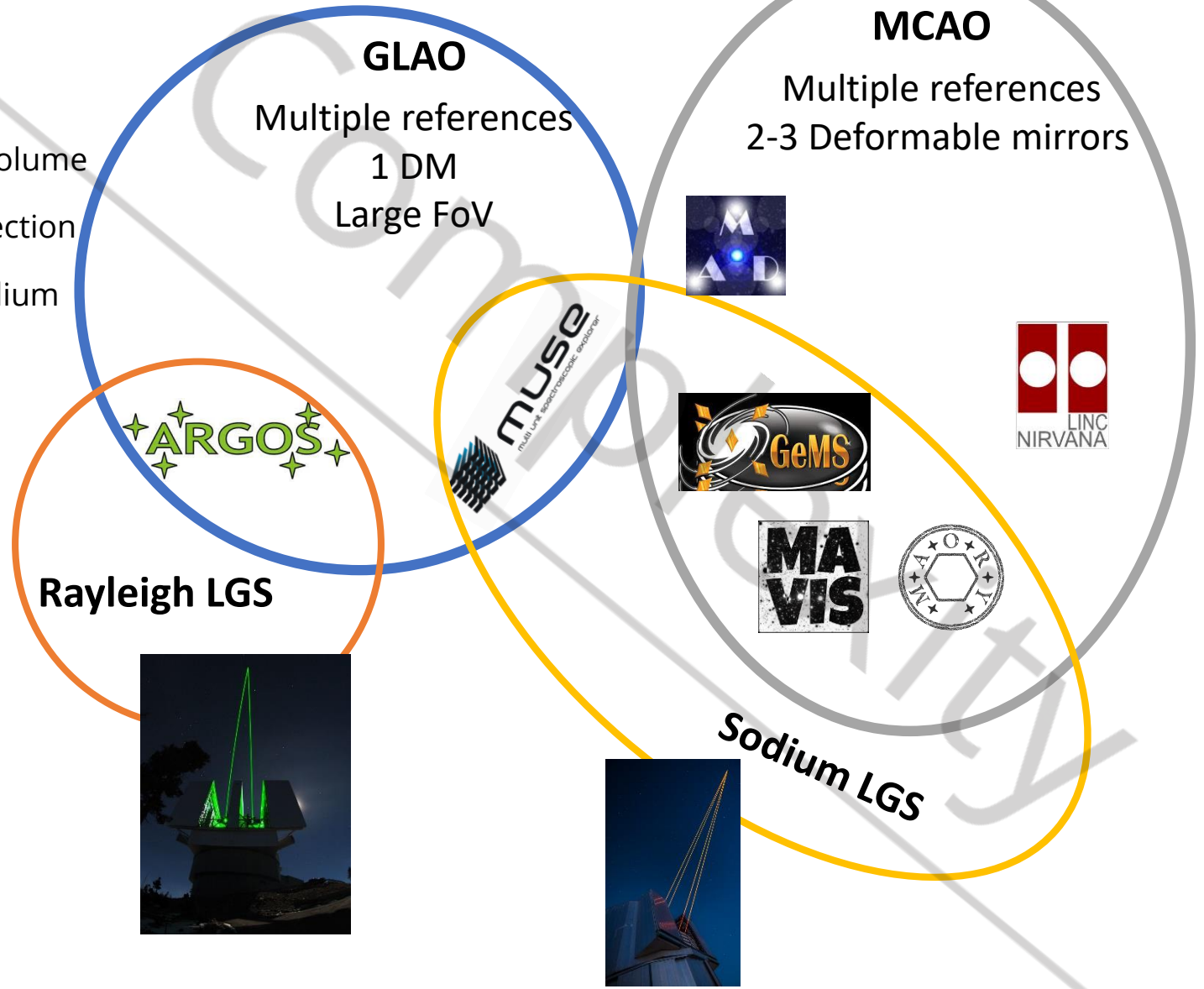
Fig. 2: Temporal evolution of $\theta_{0,TOT}$ ([dome-20km]) between the sunset and the sunrise.

ALTA PREDICTIONS FOR THE 13th Feb

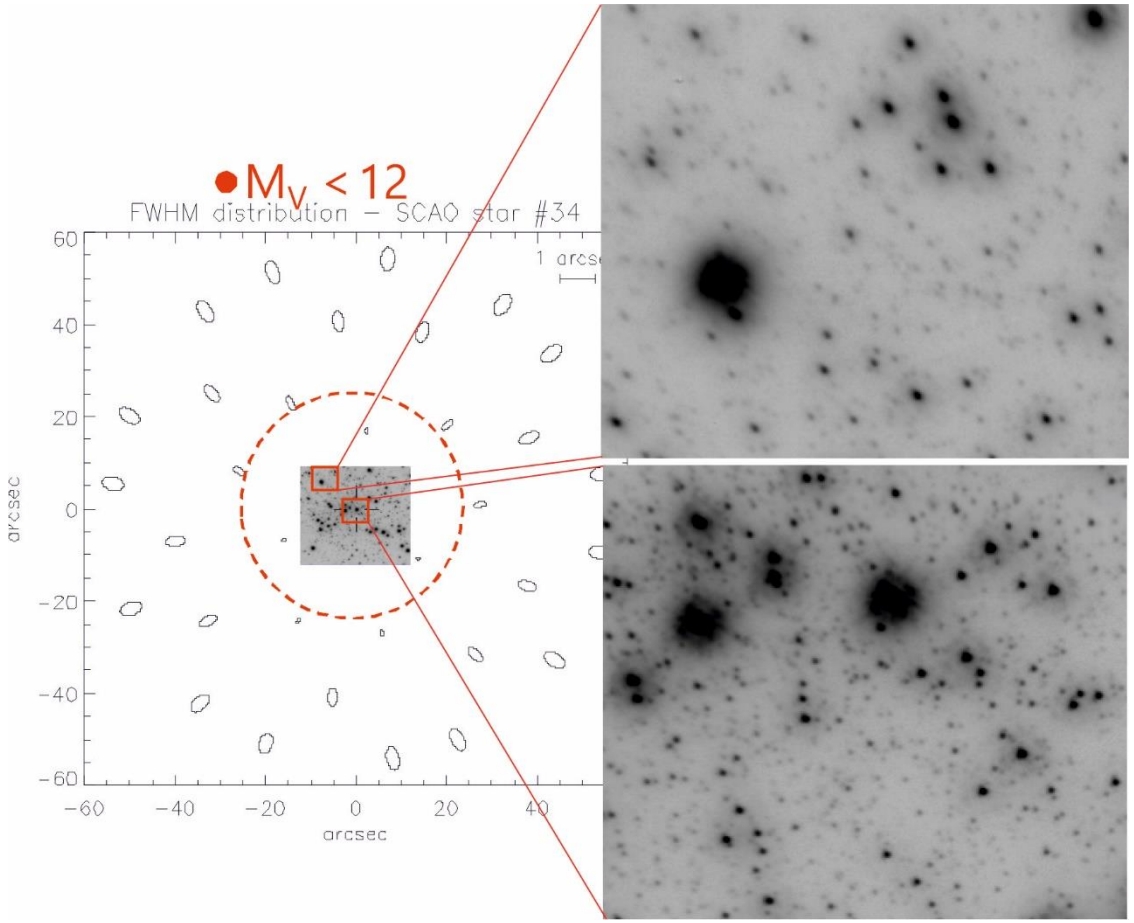
Adding complexity

- Adding References to sense the atmospheric turbulence volume
- Adding Deformable Mirrors to apply field dependant correction
- Firing lasers to generate low (Rayleigh <10km) or high (Sodium 90km) artificial stars for sky coverage.



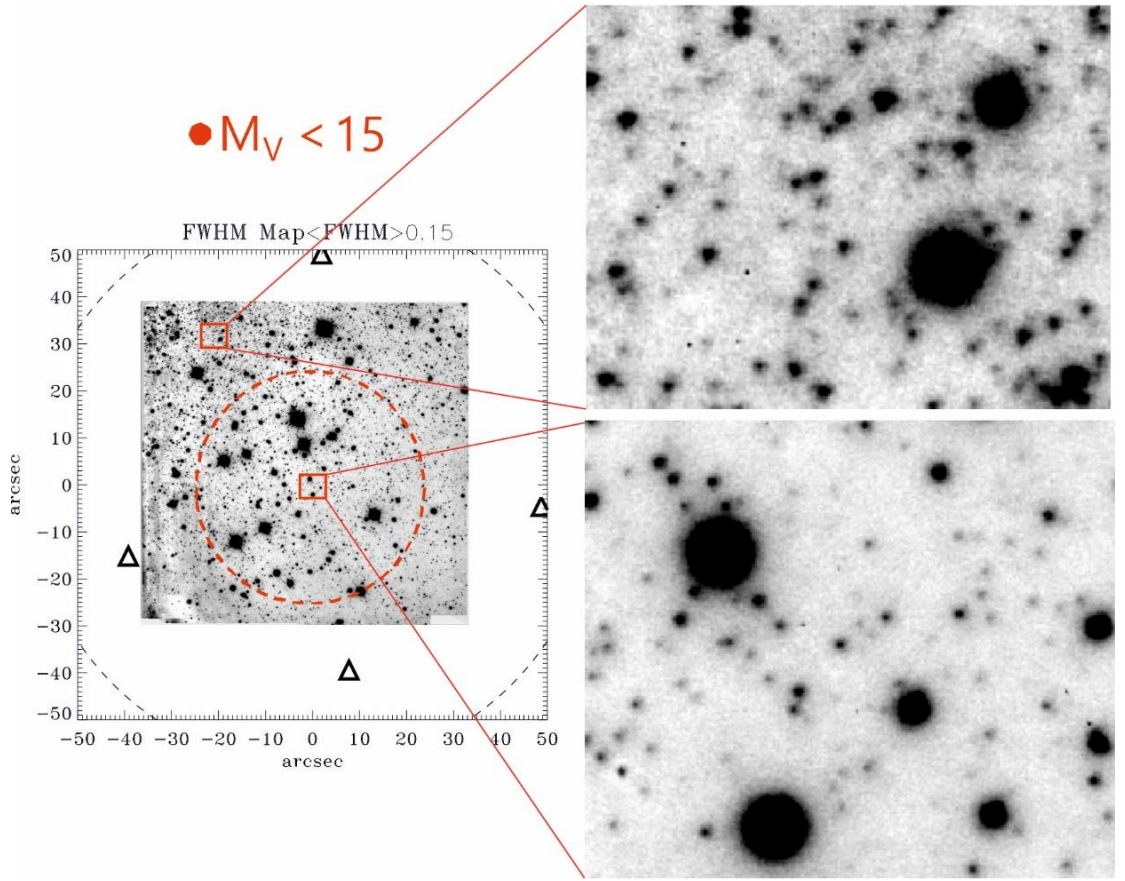


SCAO



*M15 core, 23”x23” data J band PISCES+FLAO @ LBT, inset 6 ”x5”

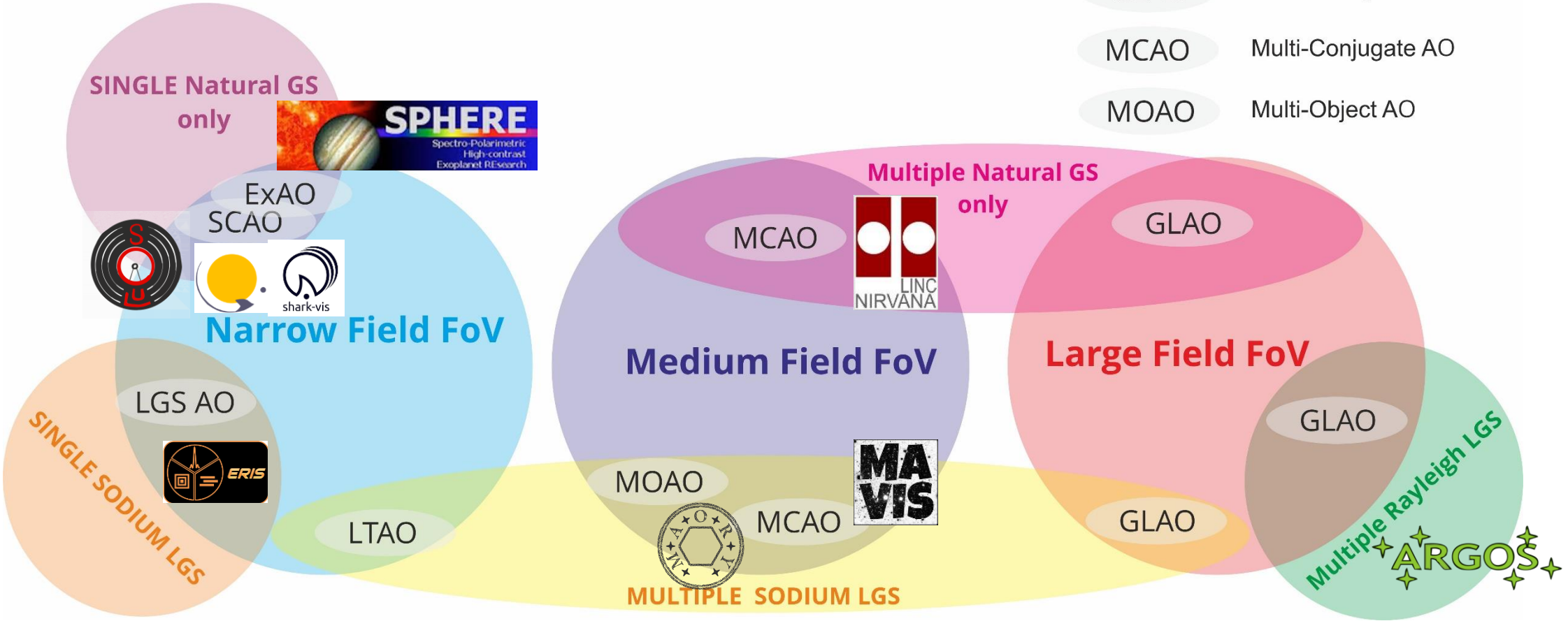
MCAO



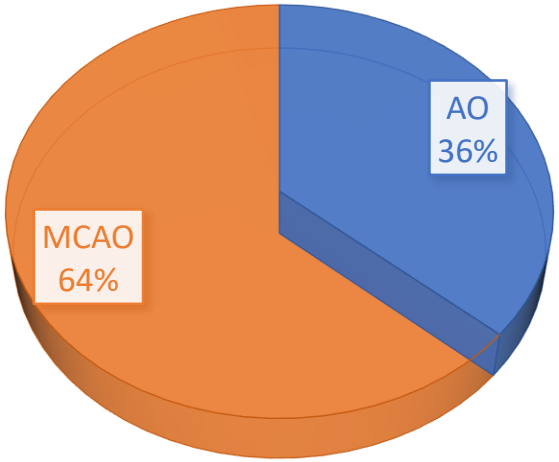
*NGC 6388 halo,65”x63”, Ks band, MAD @ VLT, inset 6 ”x5”

Adaptive Optics Zoo

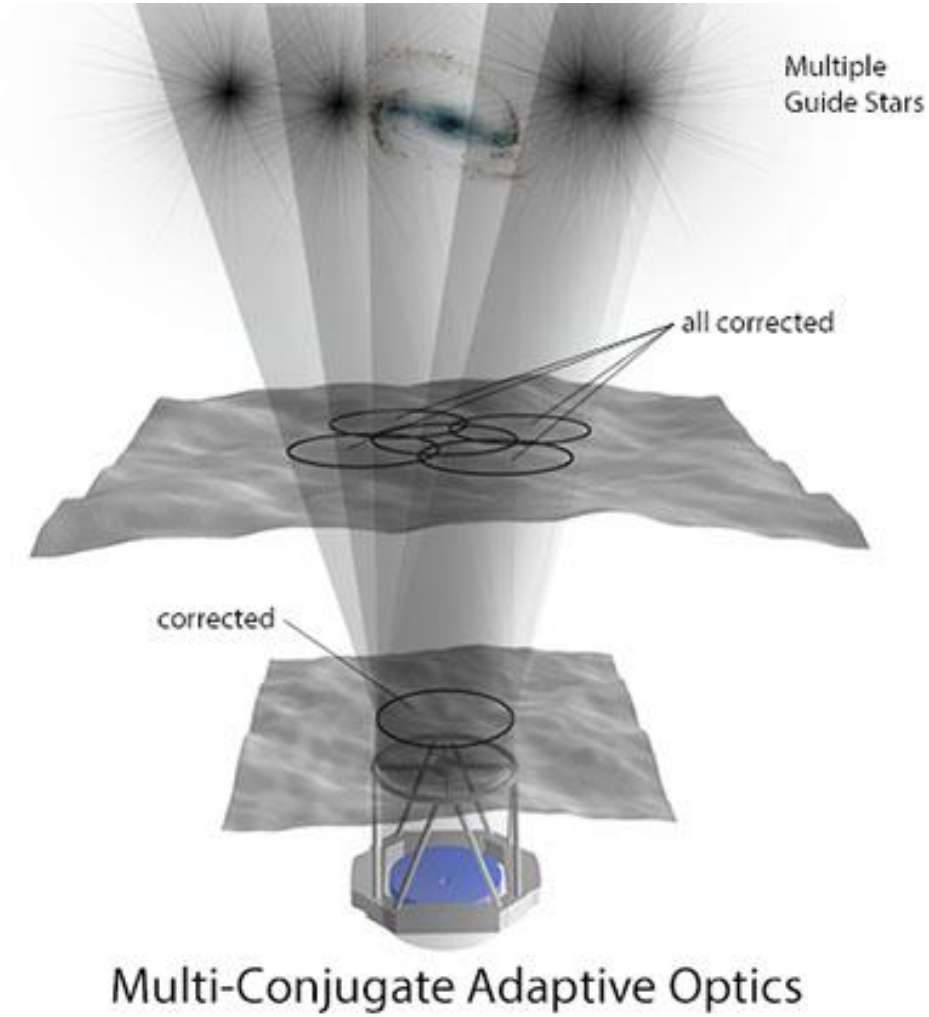
SCAO	Single Conjugate AO
ExAO	Extreme AO
LTAO	Laser Tomography AO
LGS AO	Laser Assisted AO
GLAO	Ground Layer AO
MCAO	Multi-Conjugate AO
MOAO	Multi-Object AO



- In MCAO mode we get a uniform PSF over the field by correcting the turbulence volume using multiple reference and multiple deformable mirrors
- Data reduction software can deal with the residual field aberration, enabling accurate photometry



*Refereed GC Papers by AO mode, MCAO exceeds SCAO by a factor 2



MCAO vs SCAO PSF

SCAO removes:

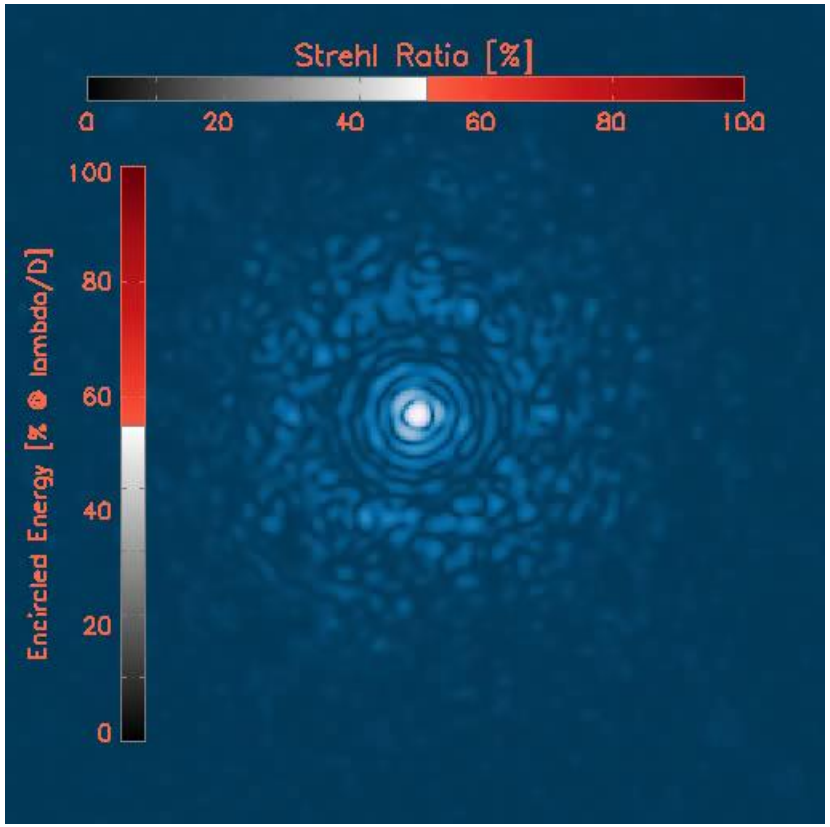
higher and higher spatial frequencies correcting the turbulence in the direction of the ref.

The MCAO removes:

higher and higher spatial freq from conjugated layers,

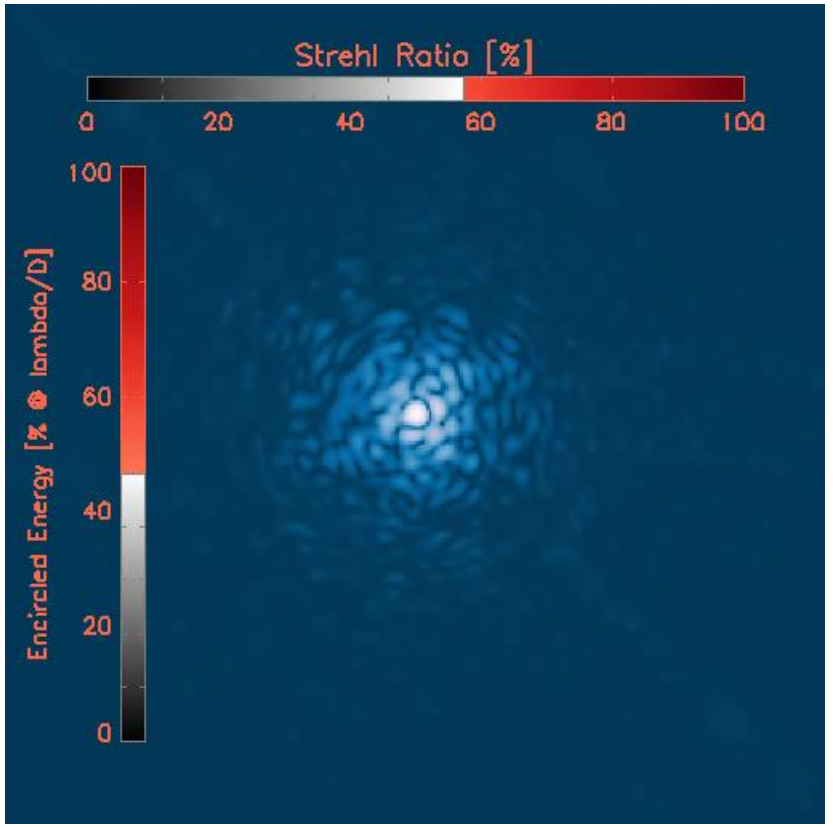
Limited to lower freq. proportionally to the distance of the layer from the conjugation plane.

Log Scale



SCAO ev. 20sec, K
SR 50%

Log Scale



MCAO ev. 20sec, K
SR 50%

MCAO vs SCAO PSF

SCAO removes:

higher and higher spatial frequencies correcting the turbulence in the direction of the ref.

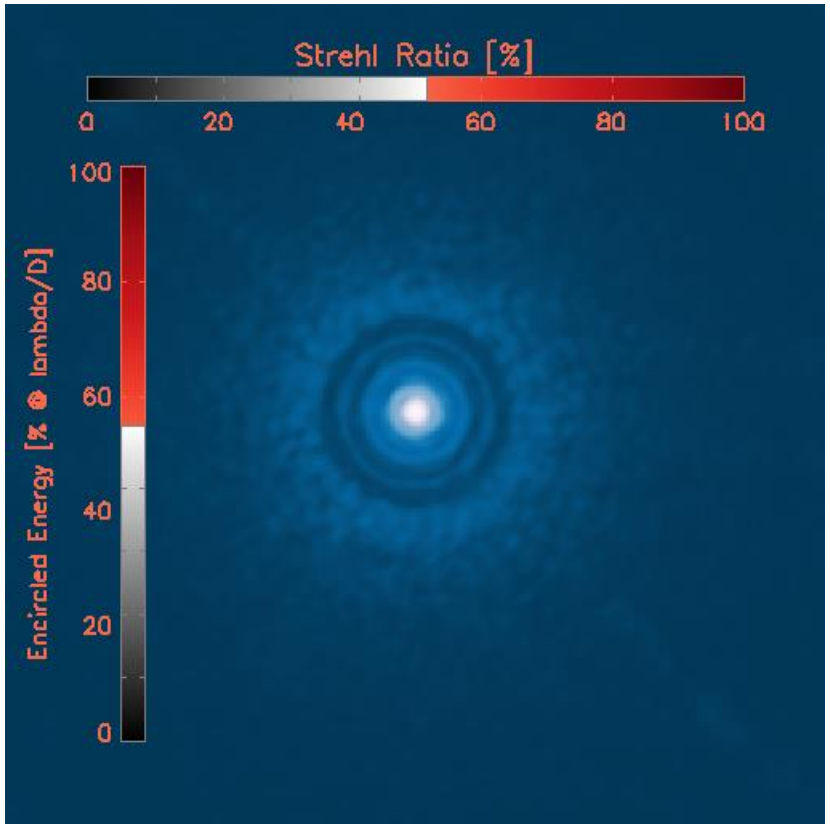
The MCAO removes:

higher and higher spatial freq from conjugated layers,

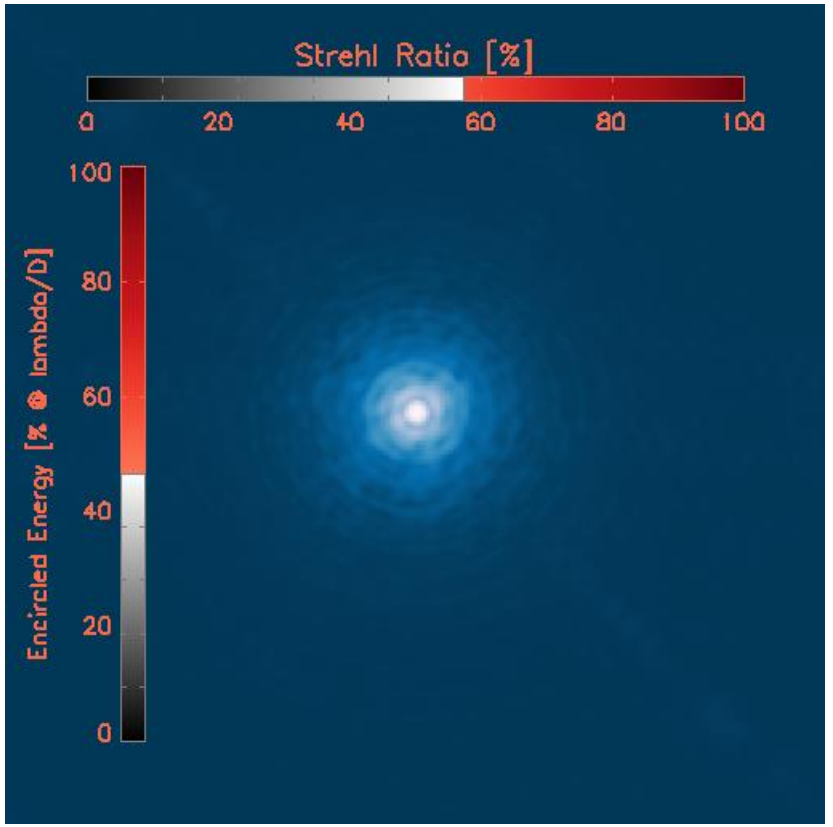
Limited to lower freq. proportionally to the distance of the layer from the conjugation plane.

It's much challenging to obtain 50% on MCAO than in SCAO!

Log Scale



Log Scale



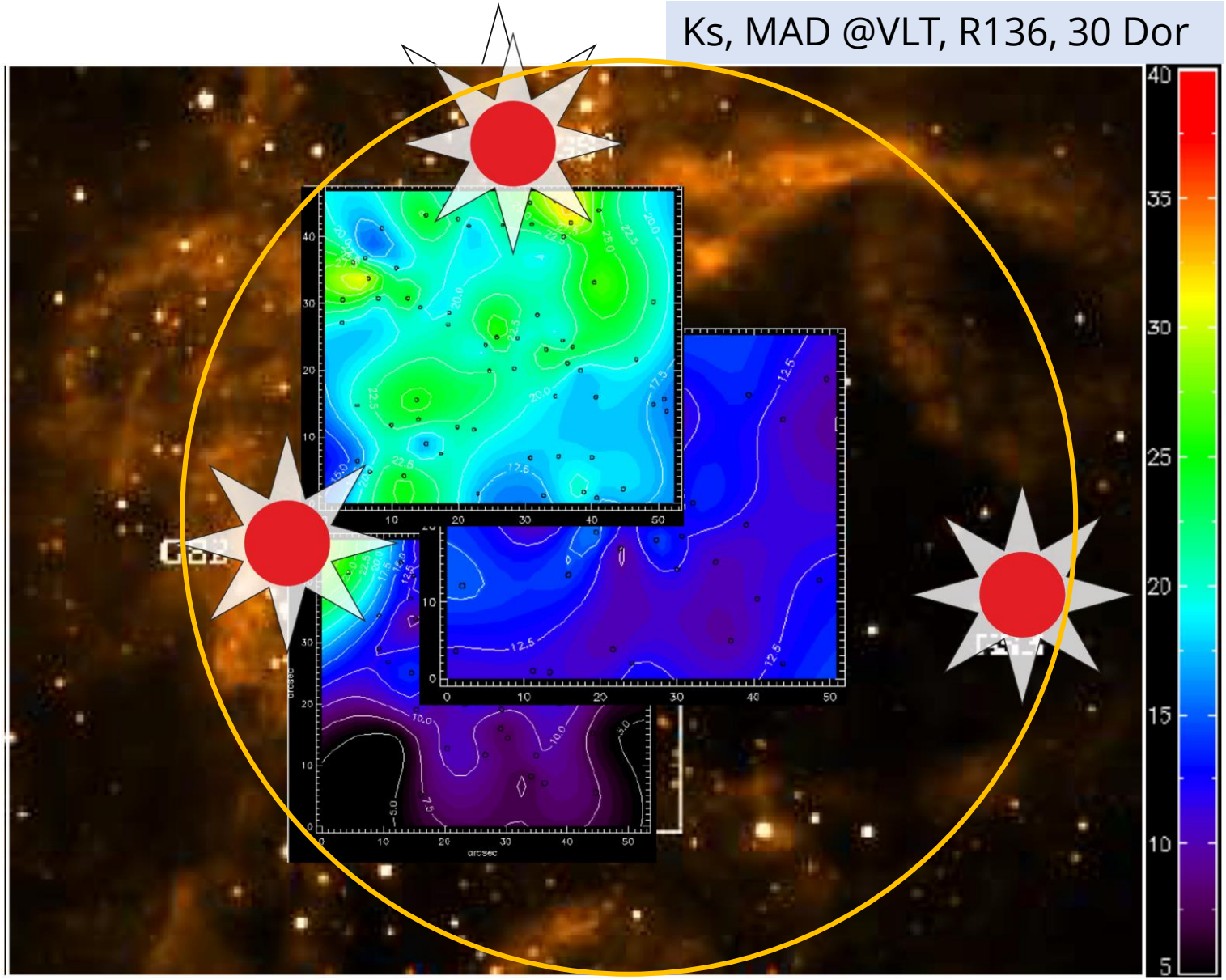
Typically, in MCAO the correction radius is almost invisible. **The uncorrected layers far from the conjugated planes introduce residuals including the lowest spatial frequencies filling the area included in the control radius**

MCAO limitations

MCAO peforms turbulence volume correction, still, the correction is not exactly uniform, depending on Guide Stars magnitude and spatial configuration.

It can be uniform within the area inscribed by the Guide Stars

MCAO does not provide extreme peak performance as the SCAO may do, leading to important difference within different filters.



The role of PSF

The main methods of PSF-dependent post-processing can be broadly grouped into four classes:

- Image Deconvolution;
- Model convolution;
- Photometry and astrometry [Marasco A, Schreiber L];
- Speckle suppression [Li Causi G].

If you know the PSF over the field, PSF should not be a limitation for photometry-astrometry.

However, PSF field variation introduces spatial dependent errors because of the **field varying SNR.**
This may be source of systematic errors:
regions of the observed field have different depth;

PSF and PSF-R

The PSF-Reconstruction is a method for retrieving the PSF shape(s) from the focal plane data, the telescope and WFS telemetry, or both (aka hybrid), it is even possible to develop ad hoc numerical simulations for that.

- Refer to Grazian A., about *MICADO PSF-R*, later today
- Massari D., Marasco A., Beltramo-Martin O., Milli J., Fiorentino G., Tolstoy E., Kerber F., 2020, A&A, 634, L5
- PSF-R, Beltramo-Martin O., Correia C.M., Ragland S., Jolissaint L., Neichel B., Fusco T., Wizinowich P.L., 2019, MNRAS, 487, 5450
- Sphere Simulation, Fètick R.J.L., et al., 2019, A&A, 628, A99

Math, ASTronomy and Research (MAST&R)

- An INAF group working on mathematical methods for high-resolution imaging
- It supports several current mainstream AO projects as MAORY, MICADO, ERIS, SHARK, MAVIS
- Focus on PSF- Reconstruction activities
- Looking for beneficial return for other large project as Gaia and Euclid

COORDINATION

PERMANENT COORDINATION ACTIVITIES TO SHARE METHODS AND HUMAN SKILLS

ADONI: ADAPTIVE OPTICS

TETIS: CONTROL SOFTWARE

SPELAB: TOOLS FOR MOS DATA ANALYSIS & SCIENCE

MAST&R: PSF RECONSTRUCTION

M³ projects

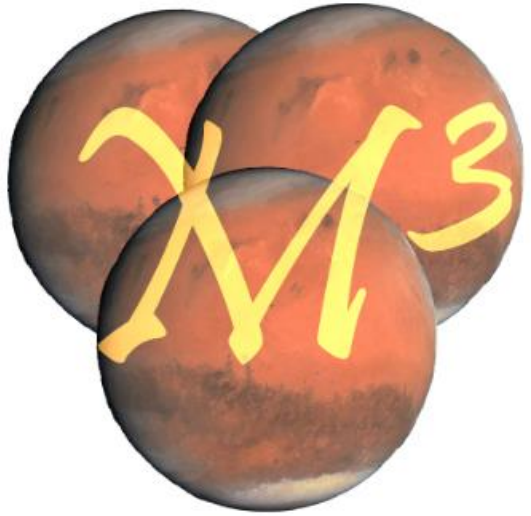
In the framework of the science related activities of MAORY, MICADO and MAVIS, we built a collaboration devoted to the scientific exploitation of the unique combination of:

- Large Spectral Coverage V to K;
- similar spatial resolution ~10mas;
- “Large” FoV ~30”-50”;
- High-SR > 15%V - 50% K;
- High-sky coverage > 50%;
- almost parallel schedule, operative 2026-2027.

INAF PRIN PROPOSAL

M³ARS - MICADO MAORY MAVIS:

Advancing the Research of Synergies



And that’s all, thanks