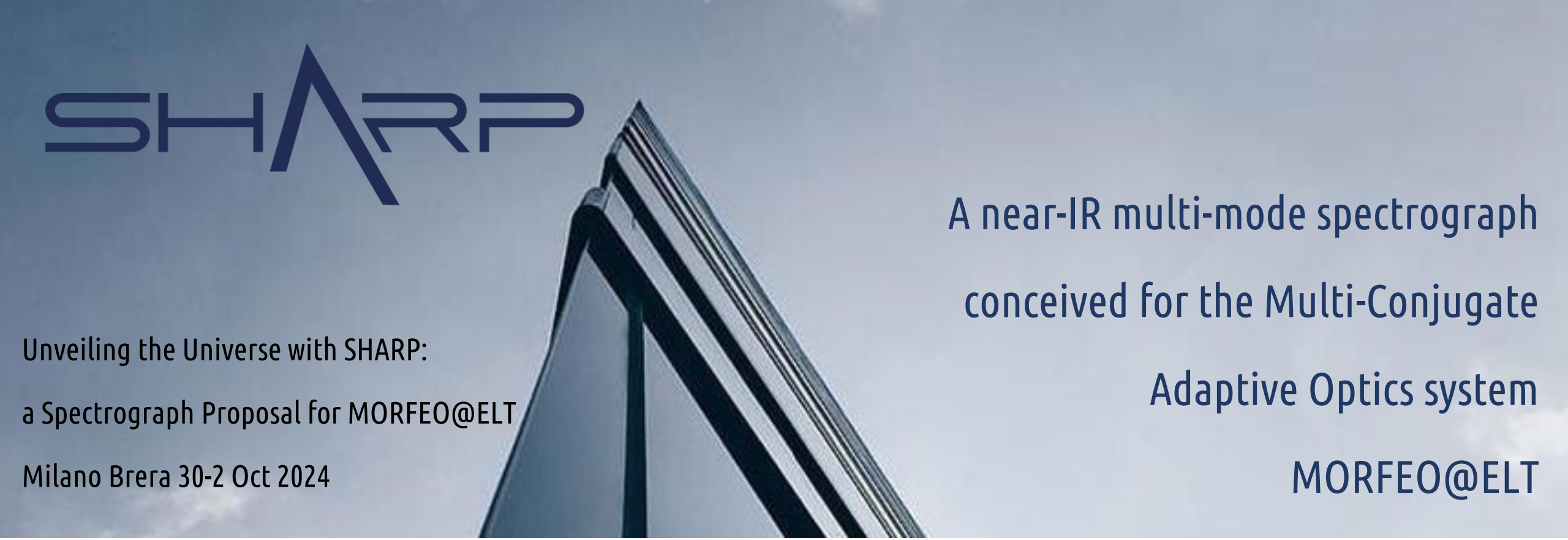


SHARP

A near-IR multi-mode spectrograph conceived for the Multi-Conjugate Adaptive Optics system MORFEO@ELT

Unveiling the Universe with SHARP:

a Spectrograph Proposal for MORFEO@ELT

Milano Brera 30-2 Oct 2024

Adaptive Optics for the Extremely Large Telescope: Overcoming PSF Challenges with MORFEO

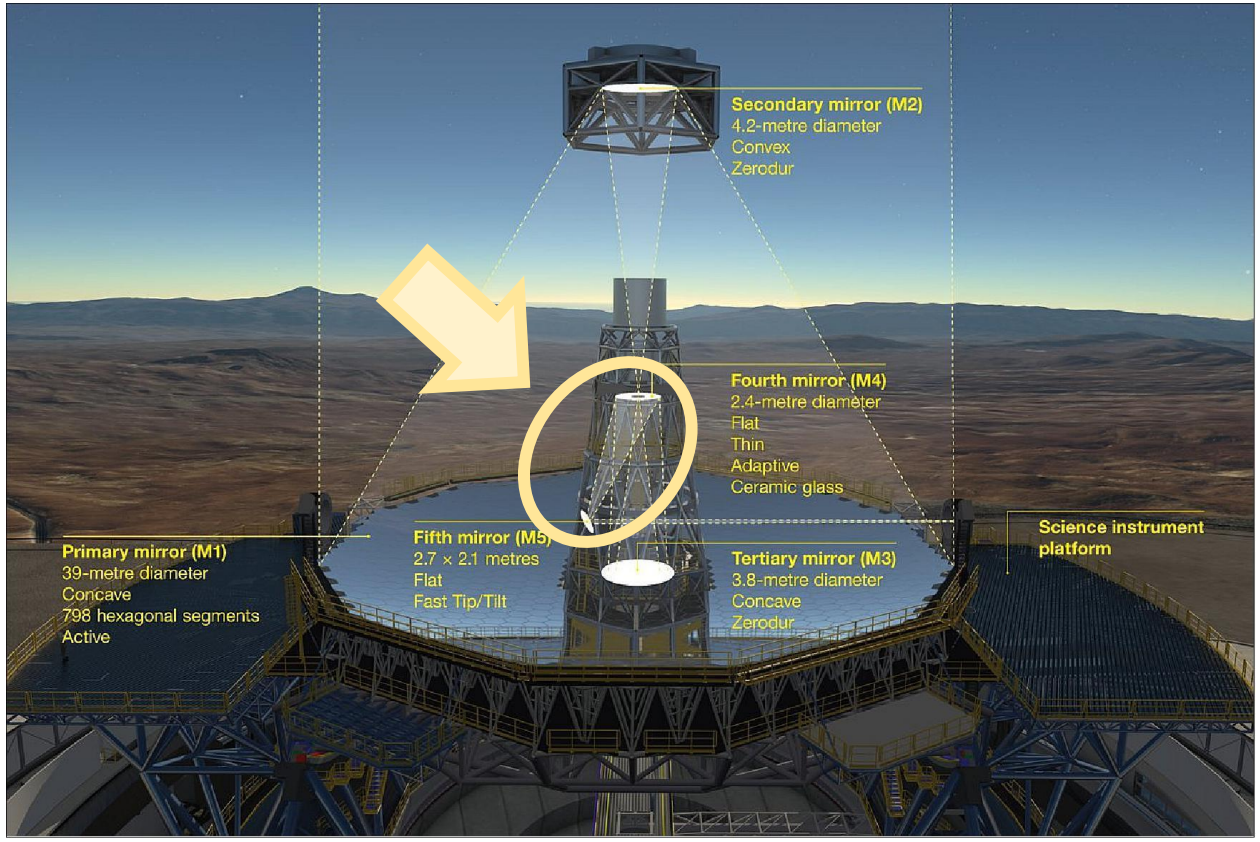
Carmelo Arcidiacono – INAF

Multiconjugate adaptive Optics Relay For ELT Observations

ELT is an adaptive telescope

All the ELT instruments on take advantage of the M4 adaptive mirror and M5 flat tip-tilt mirror.
These two mirrors are essential for delivering both spatial resolution and sensitivity.
These two mirrors, possibly assisted by the artificial laser stars facility, can support different AO mode, SCAO/GLAO/LTAO in a continuous trade-off of optical performance vs sky coverage and field of view.

NO MORFEO	Adaptive Optics Mode	Spectroscopic Spatial FoV	Optical Performance	Sky Coverage
MICADO	**SCAO**	**16-48 mas x 15”**	**SR_K 30%-80%**	**Limited, R < 16**
HARMONI	**SCAO**	**< 3” x 4”**	**SR_K -80%**	**Limited, V < 17**
	LTAO		**SR_K 30%-40%**	**High, J < 19**
METIS	**SCAO**	**< 1”**	**SR_K 20%-90%**	**Limited, K < 11**
MOSAIC	**GLAO → MOAO***	**MOS/mIFU 0”.7 – 2”.5 over ~7’**	**low? >25% EE_H within 160mas**	**Potentially high**
ANDES	**SCAO**	**Point sources**	**Diffr. Lim.**	**Limited**



Limited or Small

Large or High

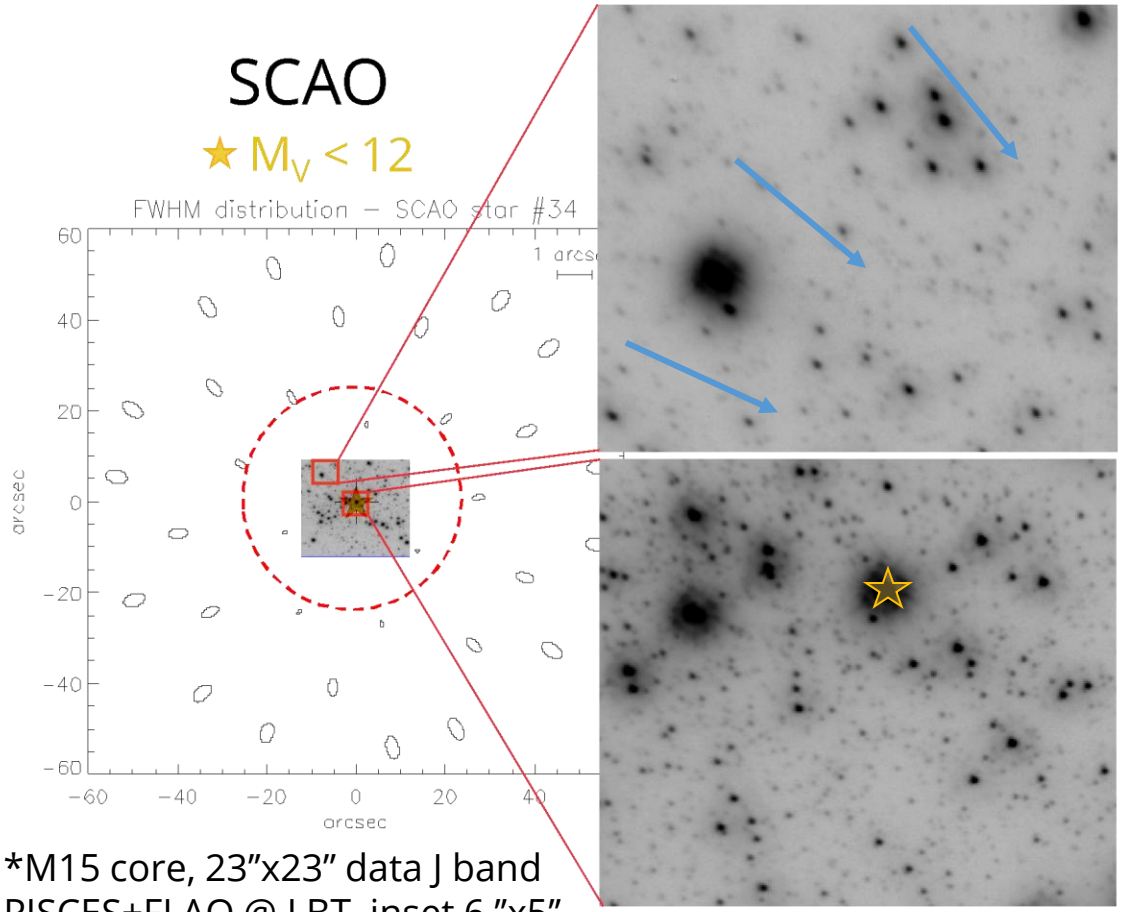
**MOSAIC uses additional 10 deformable mirrors for MOAO.*

The MCAO step

Multi-Conjugate Adaptive Optics requires multiple deformable mirrors and multiple guide stars/WFSs
Uniform and effective correction over several arcmin FoV.

SCAO

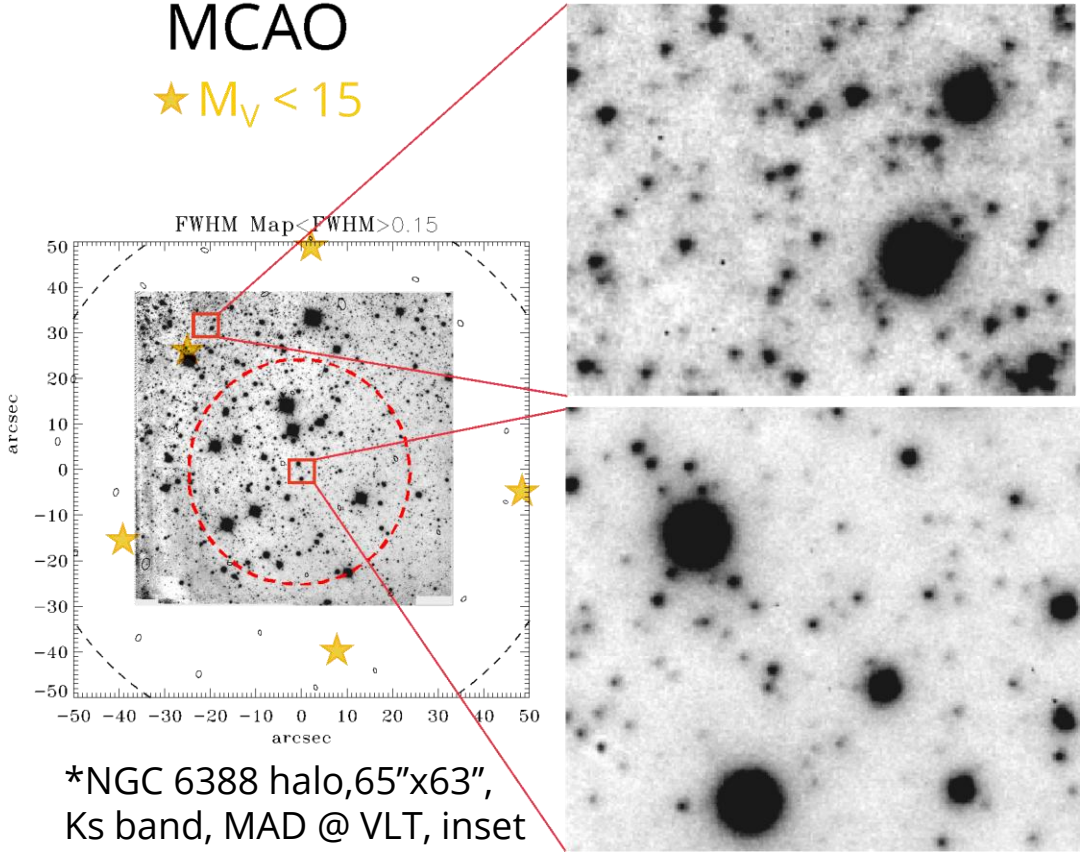
★ $M_V < 12$



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

MCAO

★ $M_V < 15$



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

MORFEO solution

MORFEO MCAO breaks the trade-off of optical performance vs sky coverage and FoV at the ELT providing:

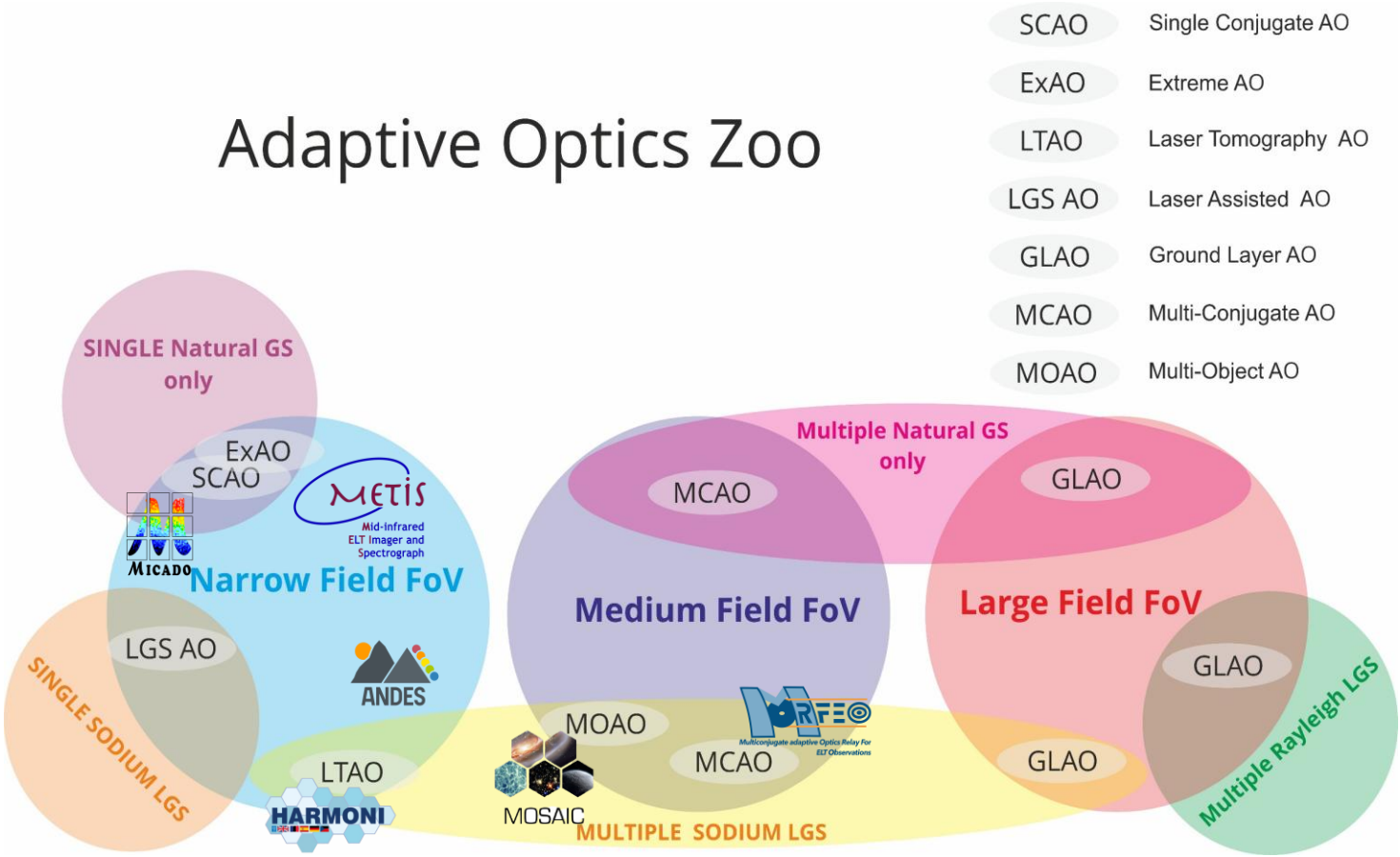
- High Sky Coverage > 50% even at high gal. latitudes
- Diffraction limited resolution from I to Ks
- On a remarkable FoV of up to ~2,5arcmin

Moreover, solving other issues that has a crucial role on a scientific perspective:

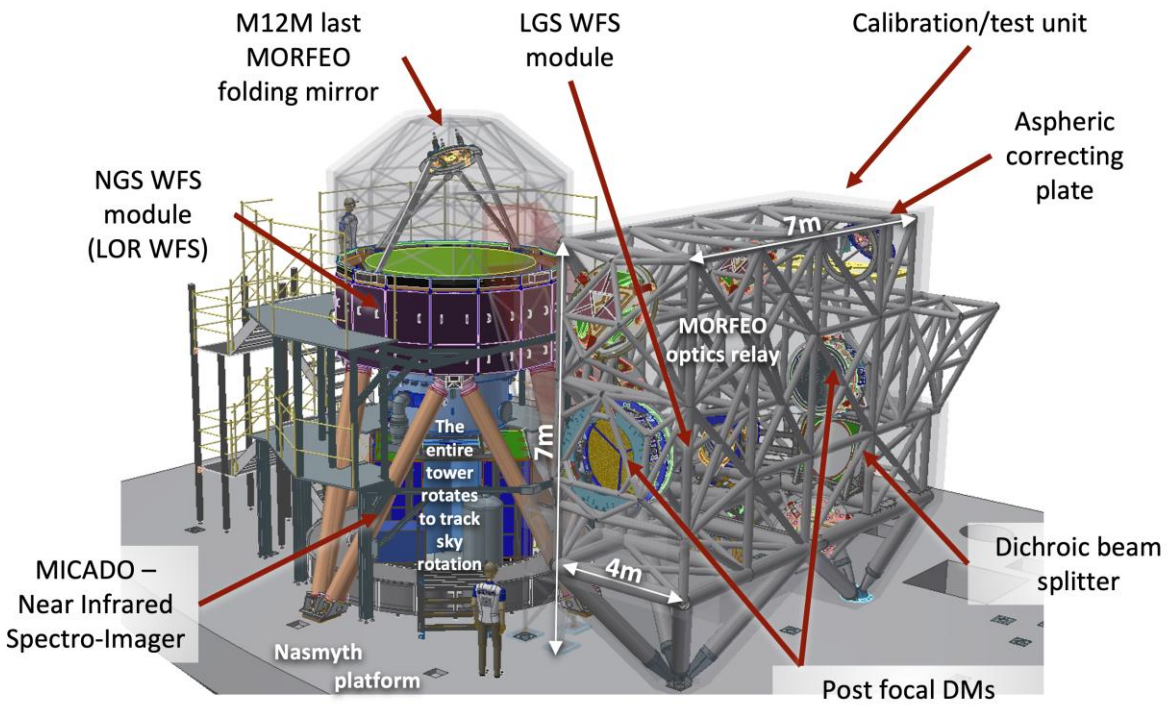
- PSF uniformity across the Field of View

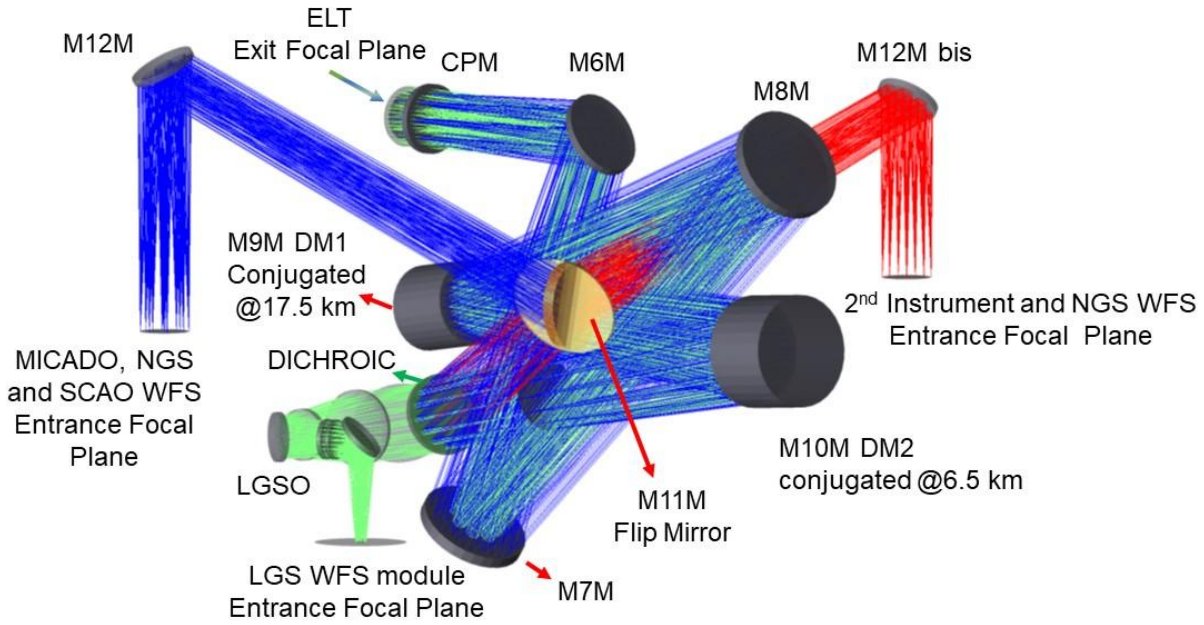
- Performance and robustness w.r.t. atmospheric conditions through multiple DMs

MORFEO pays the improvement in both sky coverage and FoV in term of budgets (complexity, size, mass, …) saving diffraction limited spatial resolution



MORFEO Implementation



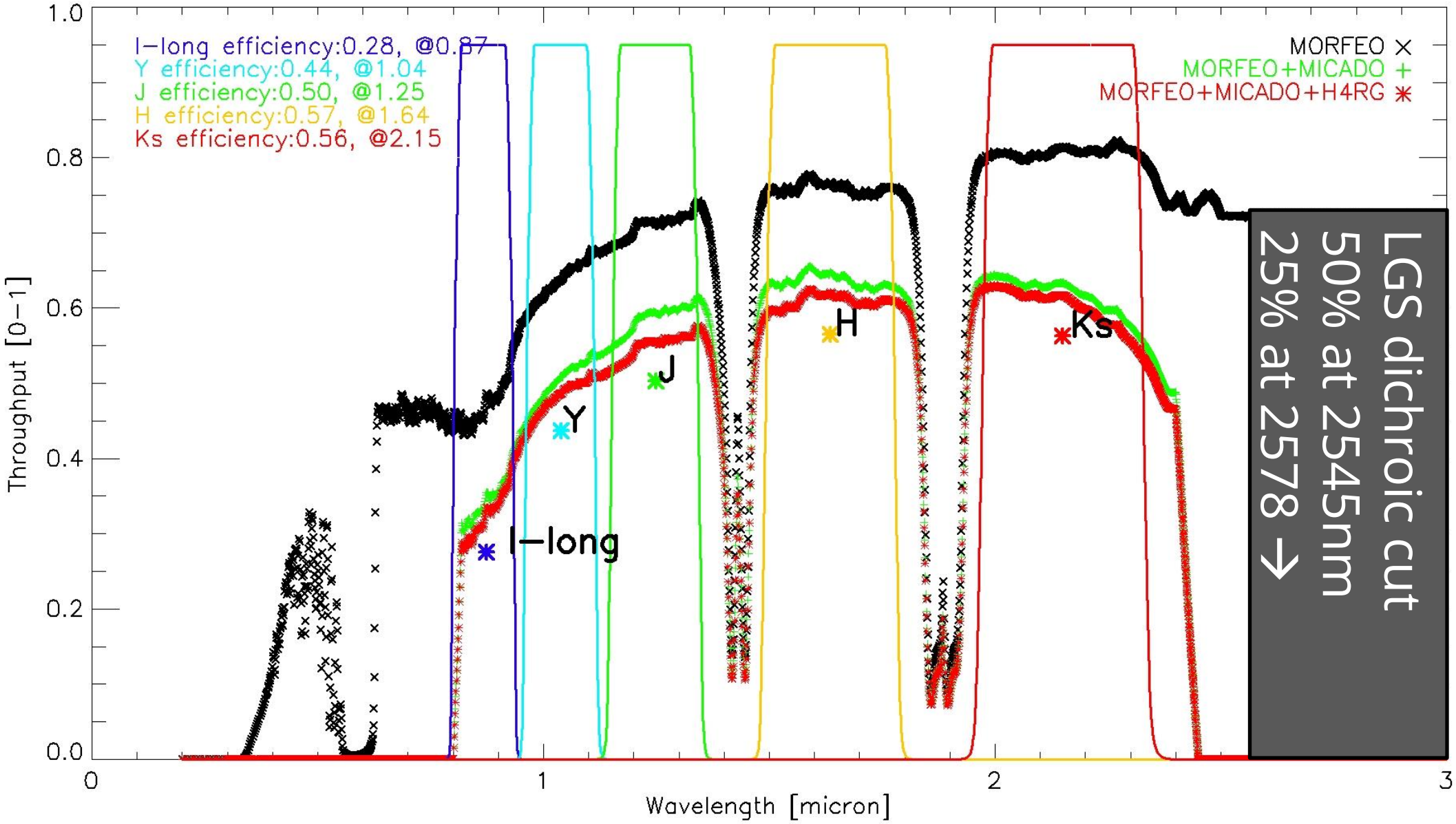


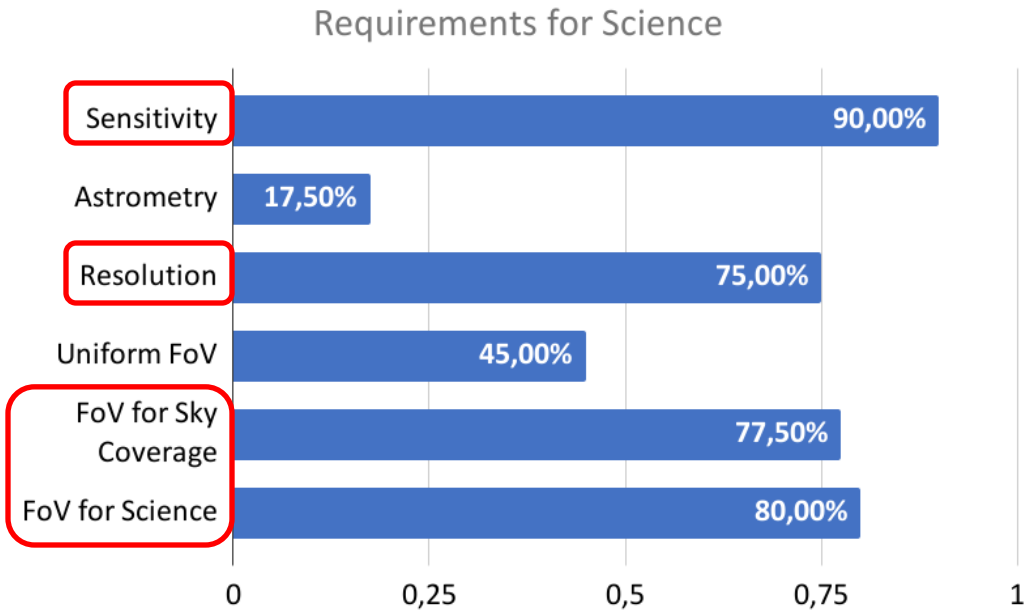
The two post-focal Deformable Mirrors (M9, M10) conjugated at 6,5km and 17,5km provide the field position dependent wavefront correction over 160” FoV.

M11 redirects the reflected beam towards MICADO or the 2nd port.

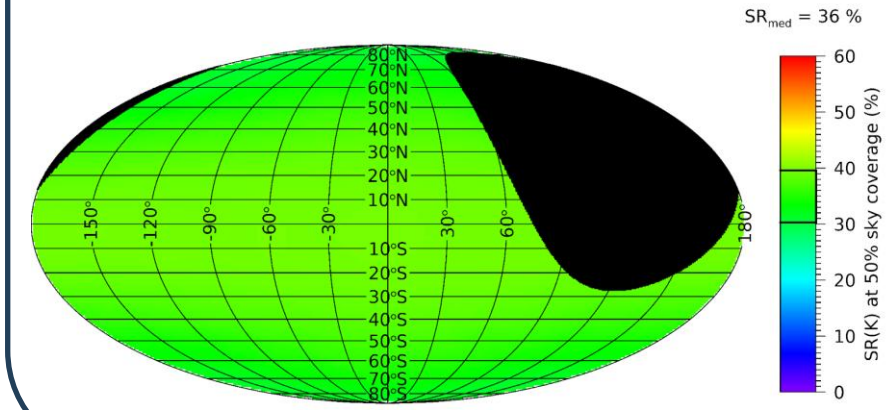
Three NGS WFS on board of the instruments provide vibration and atmospheric jitter and plate-scale real time measurement

MORFEO Transmissivity





Map of the median K band Strehl Ratio reached on different sky directions. Galactic Coordinates, median atmospheric conditions, MORFEO PDR.



1. MORFEO restores the **sensitivity** that it is possible to expect by an ELT by the concentration of the energy on the diffraction limited peak area of the PSF.

2. The astronomical science benefits by the large **fraction of the sky** that can be reached with this sensitivity, **science driven observations.**

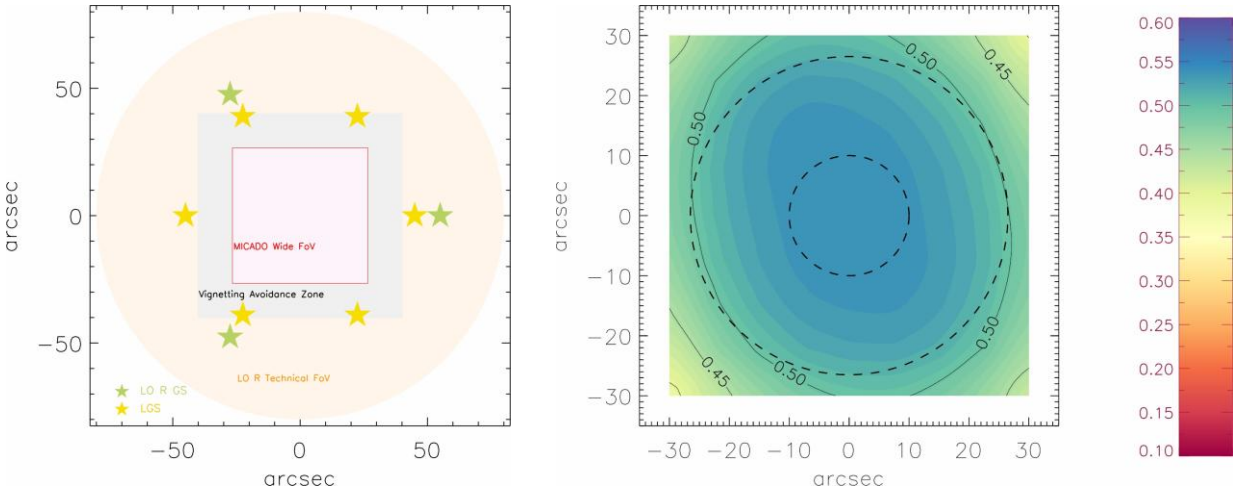
3. The relatively **small PSF spatial variability** within 10% Strehl Ratio is beneficial for photometrical and morphological analysis. i.e. the energy distribution on the multiplexed areas is ~constant.

MORFEO scientific requirements as from science drivers / white book

The (relatively) large FoV is requested in most of the proposed science for MAORY/MORFEO.

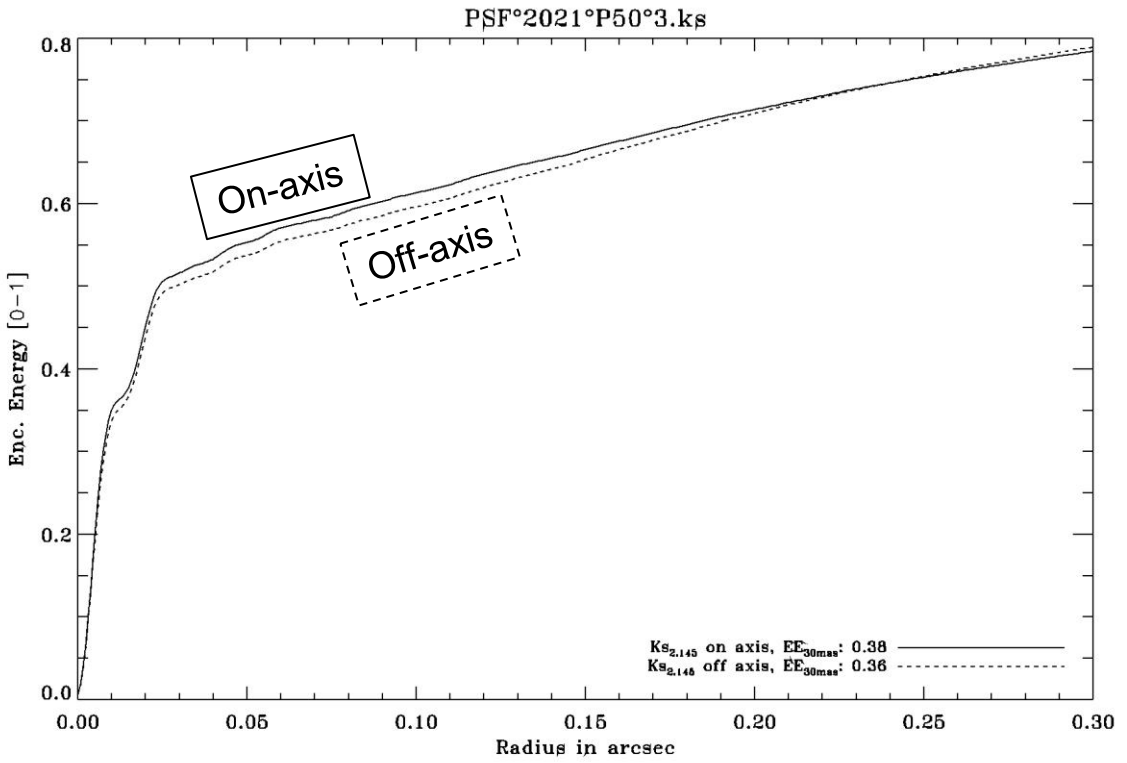
MORFEO Performance K band

- Strehl Ratio vs field→ is uniform
- EE energy plot → is uniform
- Resolution diffraction limited → wherever

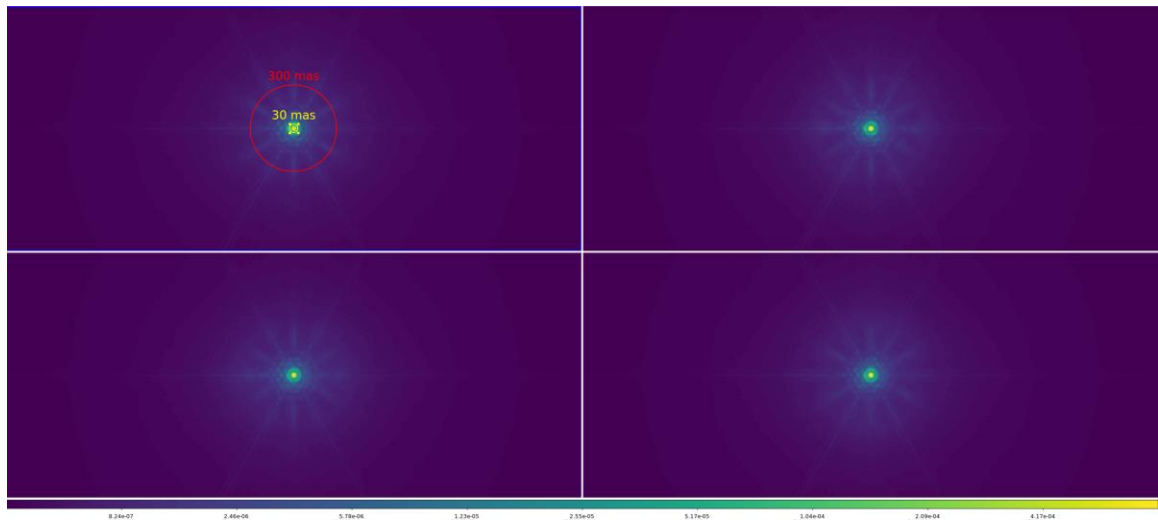


Over the top: SR in K map, for Q1 profile and optimal NGS configuration

WFE 105nm, PDR	**Median SR SR [0%-100%]**	**EE in 30 mas**
SRK (2200 nm) @50% 2PDM	33.7	36%-38%



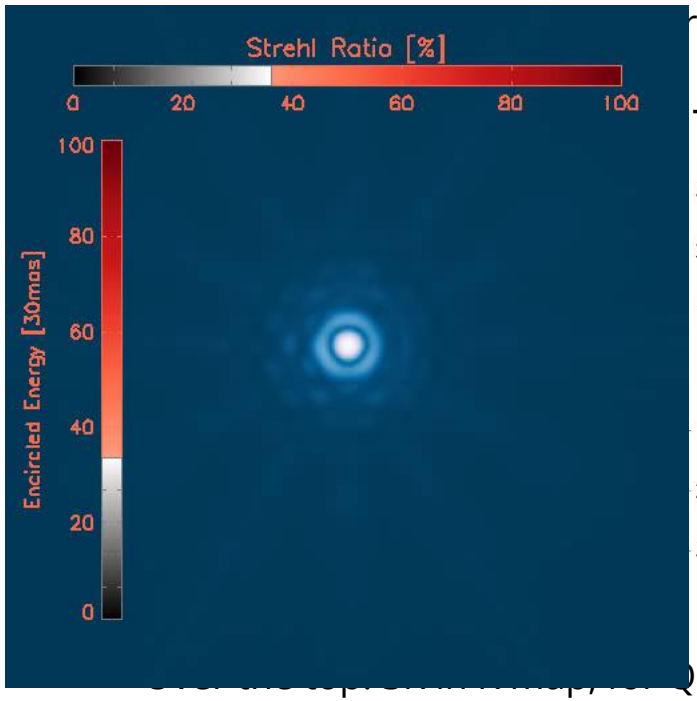
Four different directions at the center and edge of 1’ square FoV, median

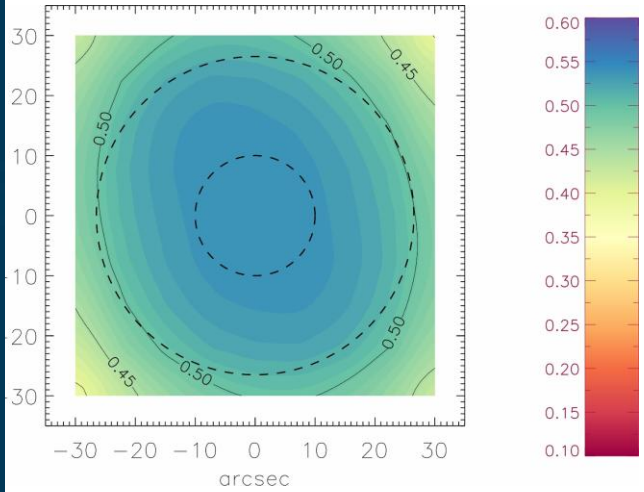


MORFEO Performance K band

rm

→ wherever





1 profile and optimal NGS configuration

WFE 105nm, PDR	**Median SR SR [0%-100%]**	**EE in 30 mas**
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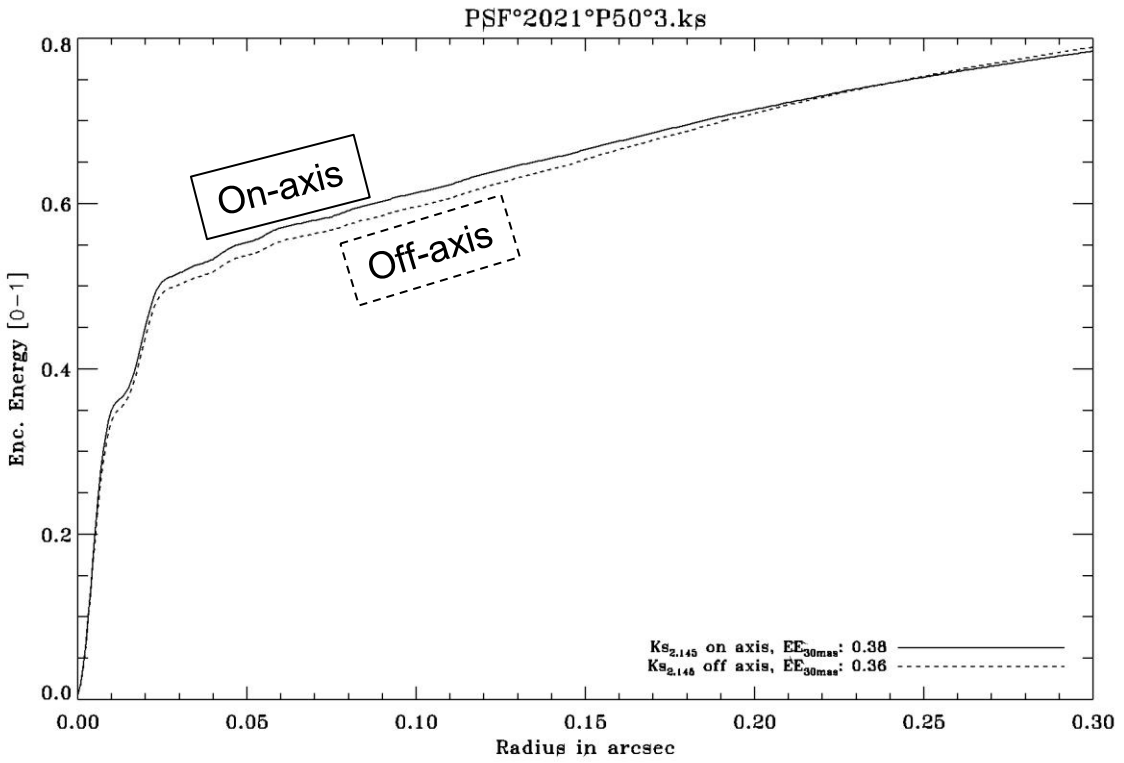
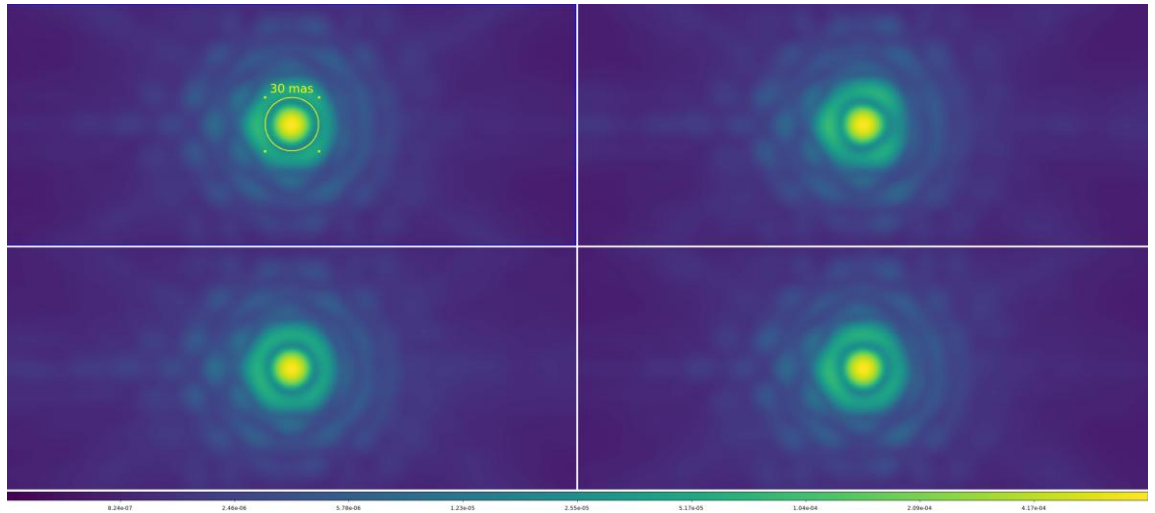


Four different directions at the centre and edge of 1’ square FoV, median



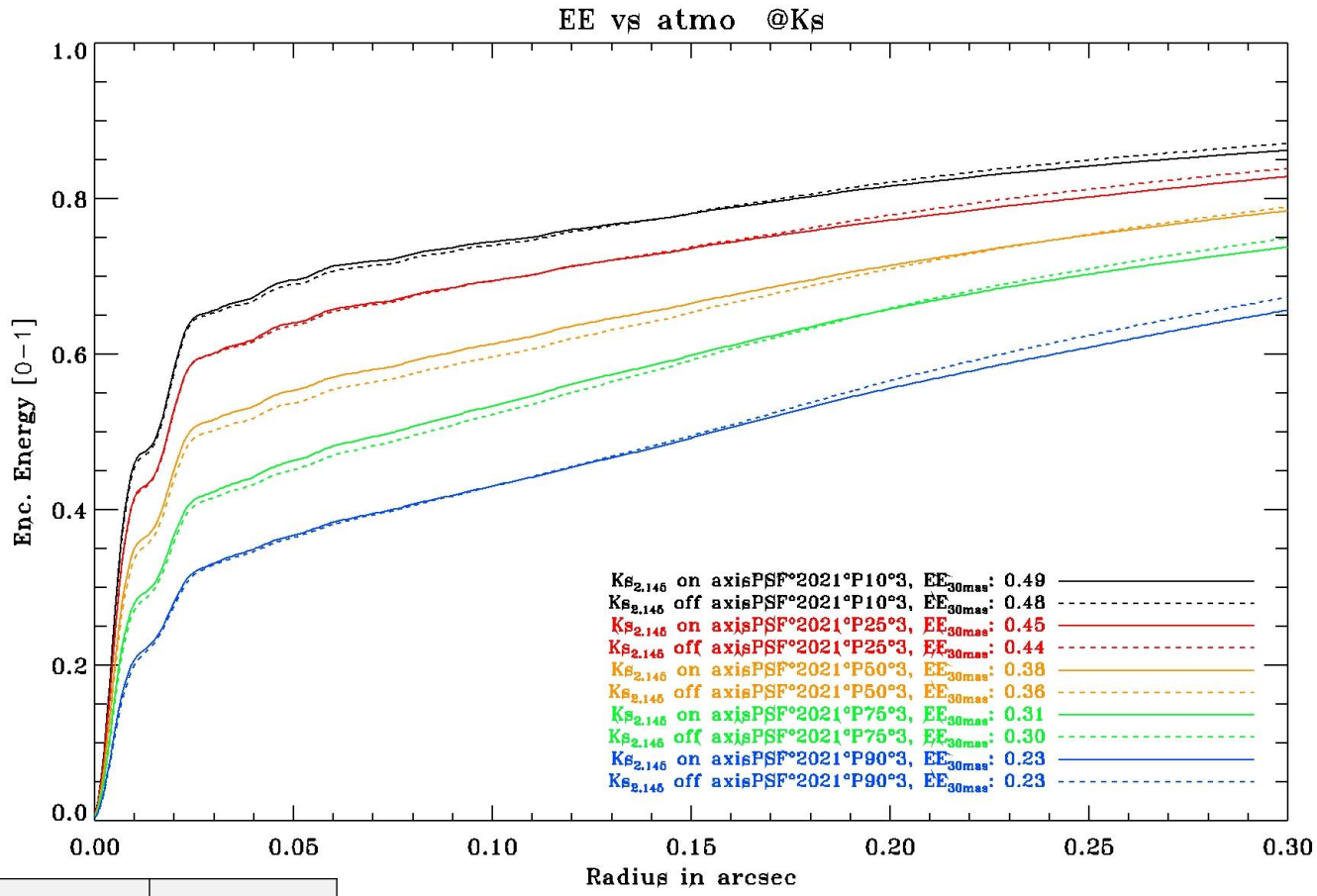
MORFEO Performance dependencies

- Wavelength
- Atmospheric Optical Turbulence statistics
- Vibration
- Guide stars Constellation

The original amount of optical disturbance is the dominant factor for the residual phase value after Adaptive Optics correction.

Final optical performance is a non-linear function of the original atmospheric parameters:

- Seeing vertical distribution
- Wind vertical profile
- Power spectrum



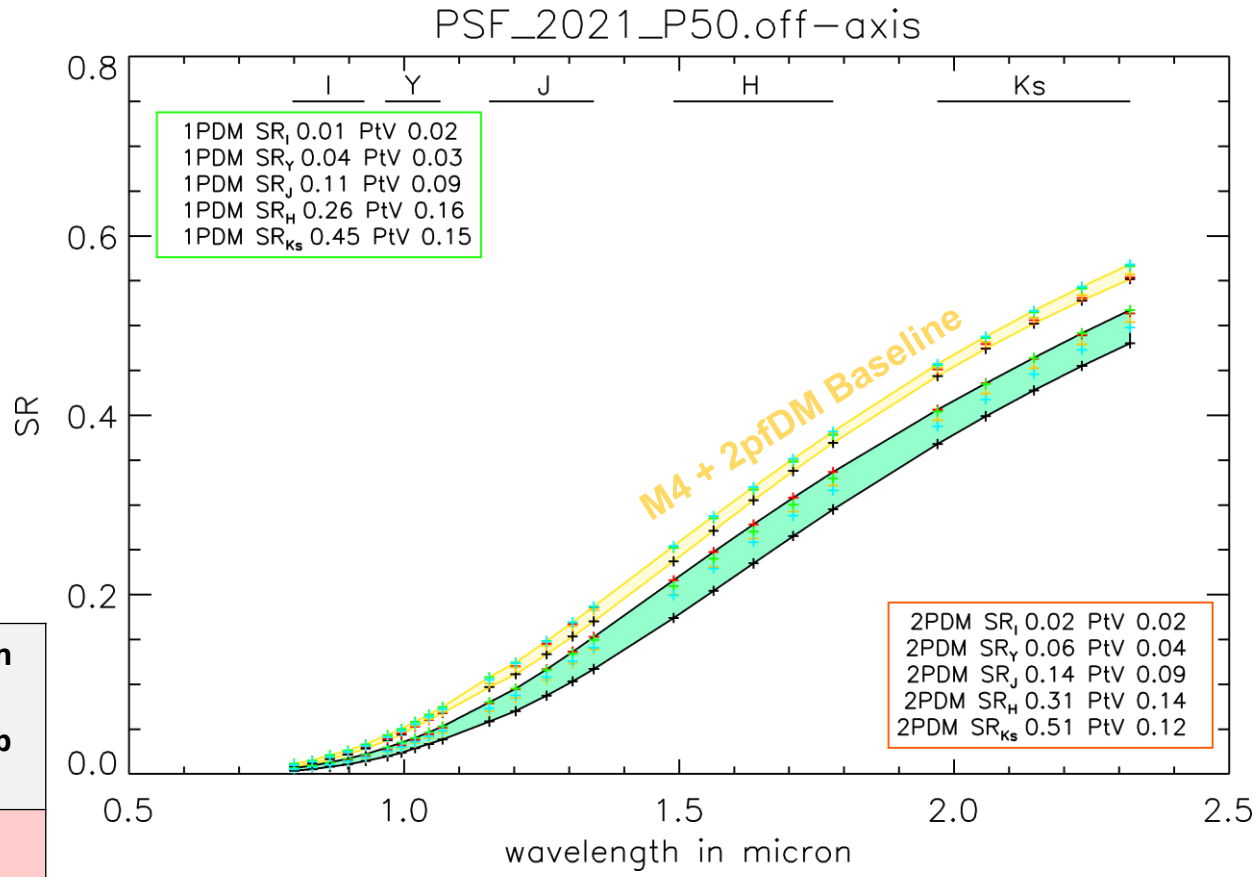
WFE 105nm, PDR SR [0%-100%]	Percentile of the SR Performance					Median 0,64" 60°eleb
	P10 Super	P25 Good	P50 Median	P75 Poor	P90 Why???	
SR@K (2200 nm) @50% 2PDM	54.5	41.9	33.7	20.2	5.8	46.5

MORFEO Performance dependencies

- Wavelength
- Atmospheric Optical Turbulence statistics
- Vibration

- Guide stars Constellation

The guide star brightness strongly affects vibration/optical jitter suppression



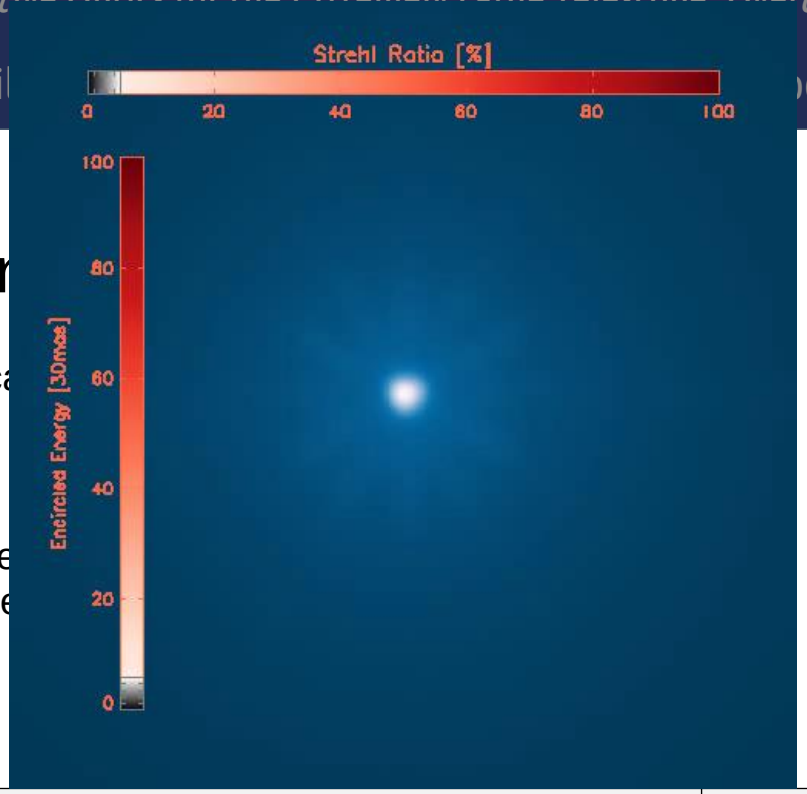
WFE 105nm, PDR SR [0%-100%]	**Percentile of the SR Performance**					**Median 0,64" 60°eleb**
	P10 Super	**P25 Good**	**P50 Median**	**P75 Poor**	**P90 Why???**	
SR@K (2200 nm) @50% 2PDM	54.5	41.9	33.7	20.2	5.8	46.5
SR@H (1650 nm) @50% 2PDM	33.9	27.6	14.5	5.8	0.6	25.6
SR@J (1250 nm) @50% 2PDM	15.2	10.6	3.5	0.7	0	9.3

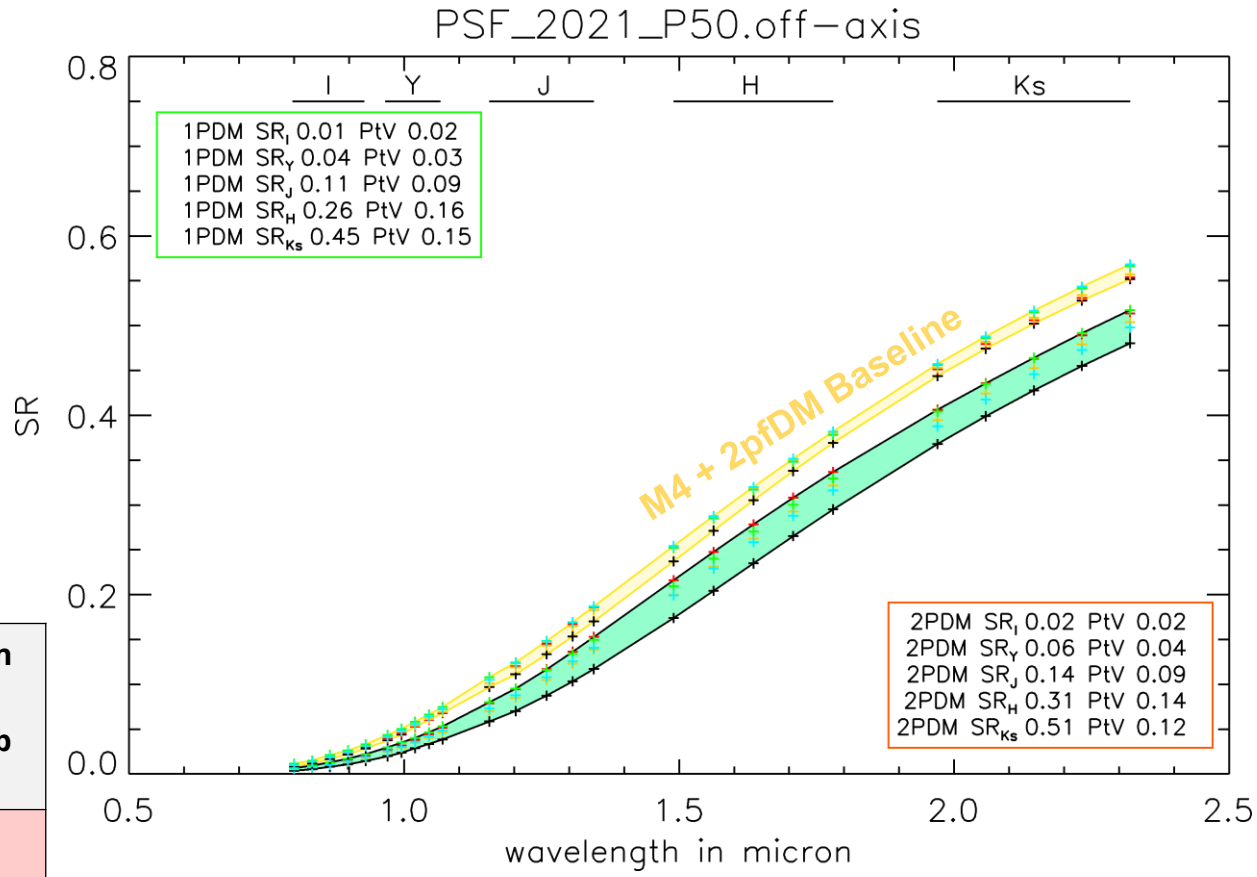
MORFEO Per…

- Wavelength
- Atmospheric Optica…
- Vibration

- Guide stars Conste…

The guide star brightne… suppression





WFE 105nm, PDR SR [0%-100%]	**Percentile of the SR Performance**					**Median 0,64" 60°eleb**
	P10 Super	**P25 Good**	**P50 Median**	**P75 Poor**	**P90 Very bad**	
SR@K (2200 nm) @50%	54.5	41.9	33.7	20.2	5.8	46.5
SR@H (1650 nm) @50%	33.9	27.6	14.5	5.8	0.6	25.6
SR@J (1250 nm) @50%	15.2	10.6	3.5	0.7	0	9.3

MORFEO Performance dependencies

- Wavelength
- Atmospheric Optical Turbulence statistics
- Vibration

Guide stars Constellation

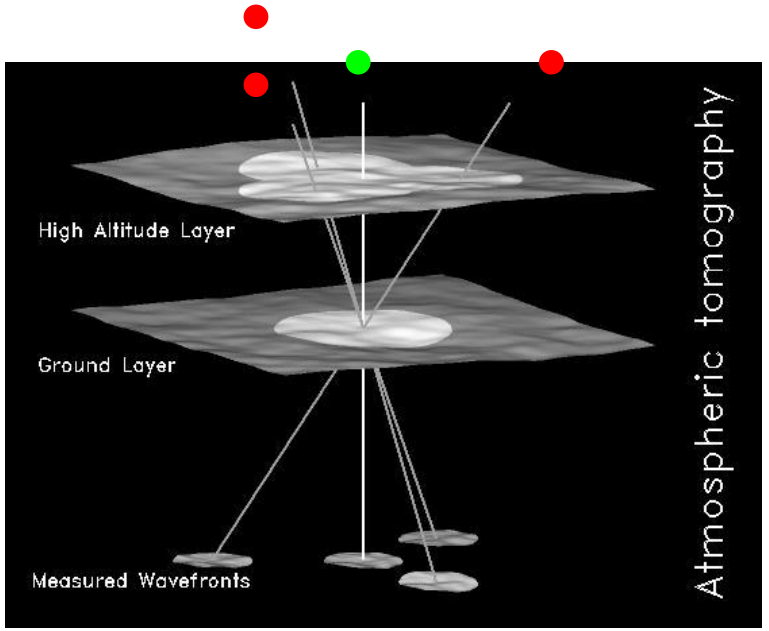
- MORFEO can use 1 to 3 natural guide stars with magnitude up to H≈21selected within a 160” FoV.

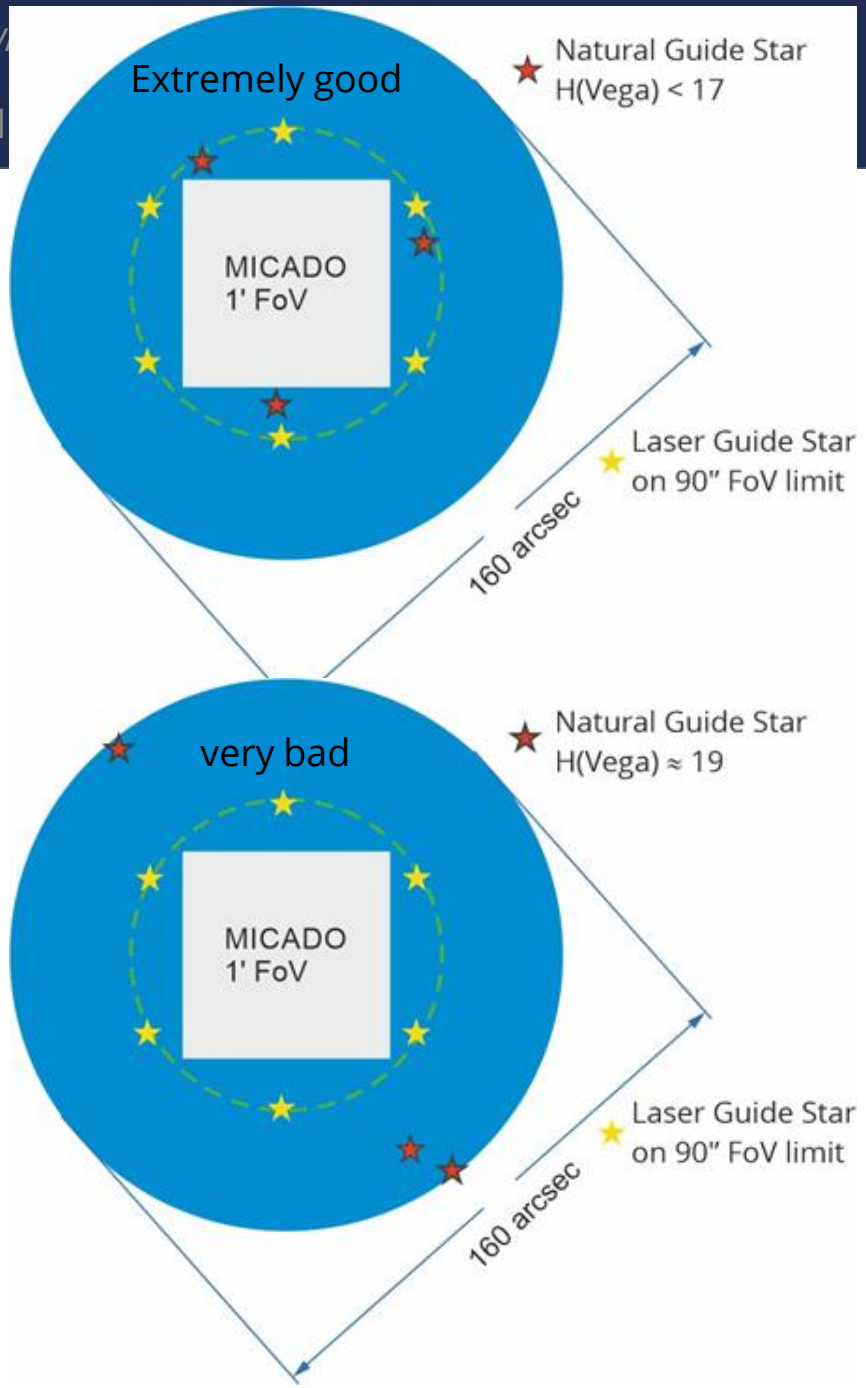
The guide stars brightness strongly affects vibration/atmospheric jitter suppression and platescale control.

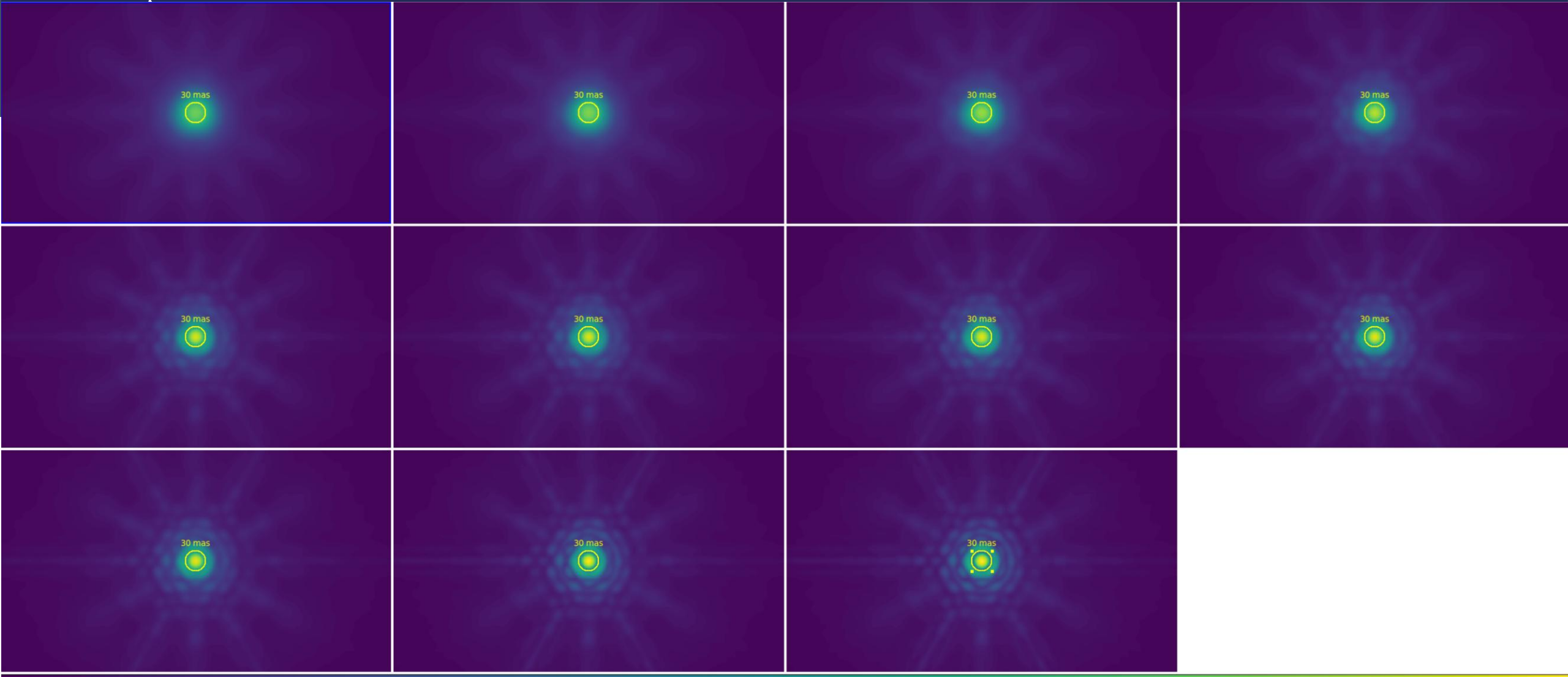
The guide star geometry fixes how well tomography can work.

The distribution of the reference starlight can introduce:

- resolution loss by jitter residual
- PSF Spatial variability because of non optimal tomographic solution







The distribution of the reference starlight can introduce:

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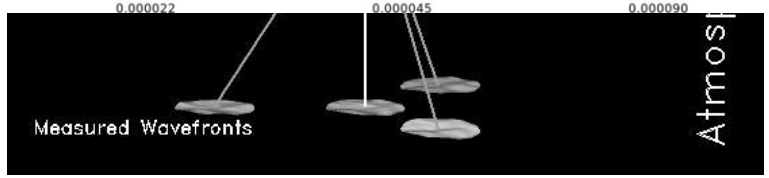
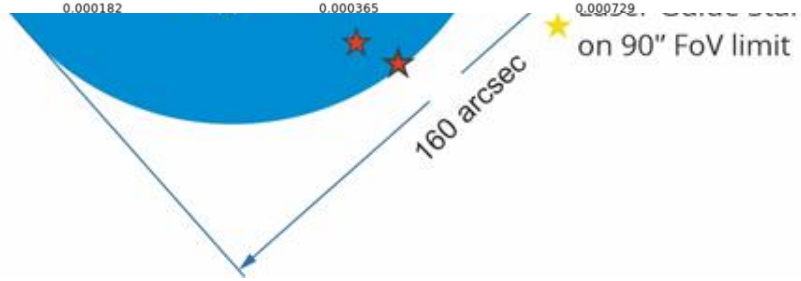
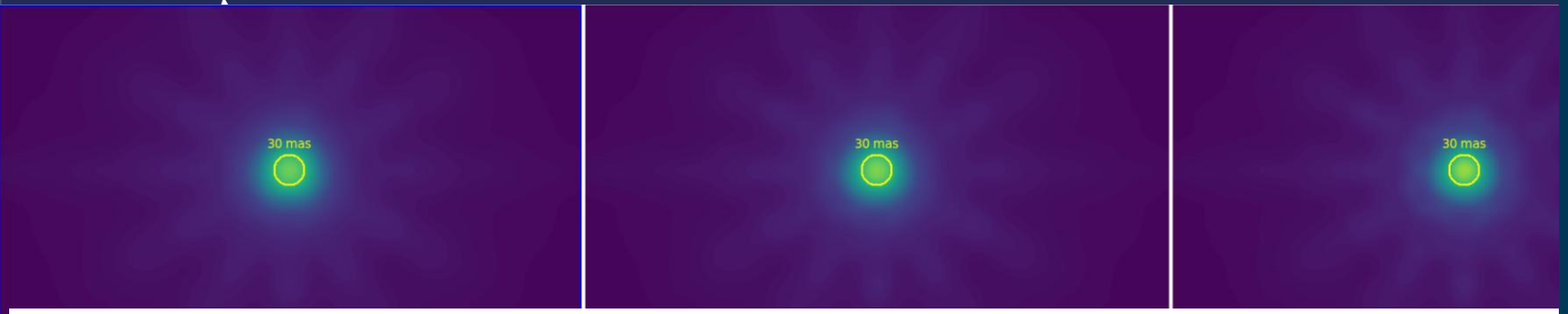
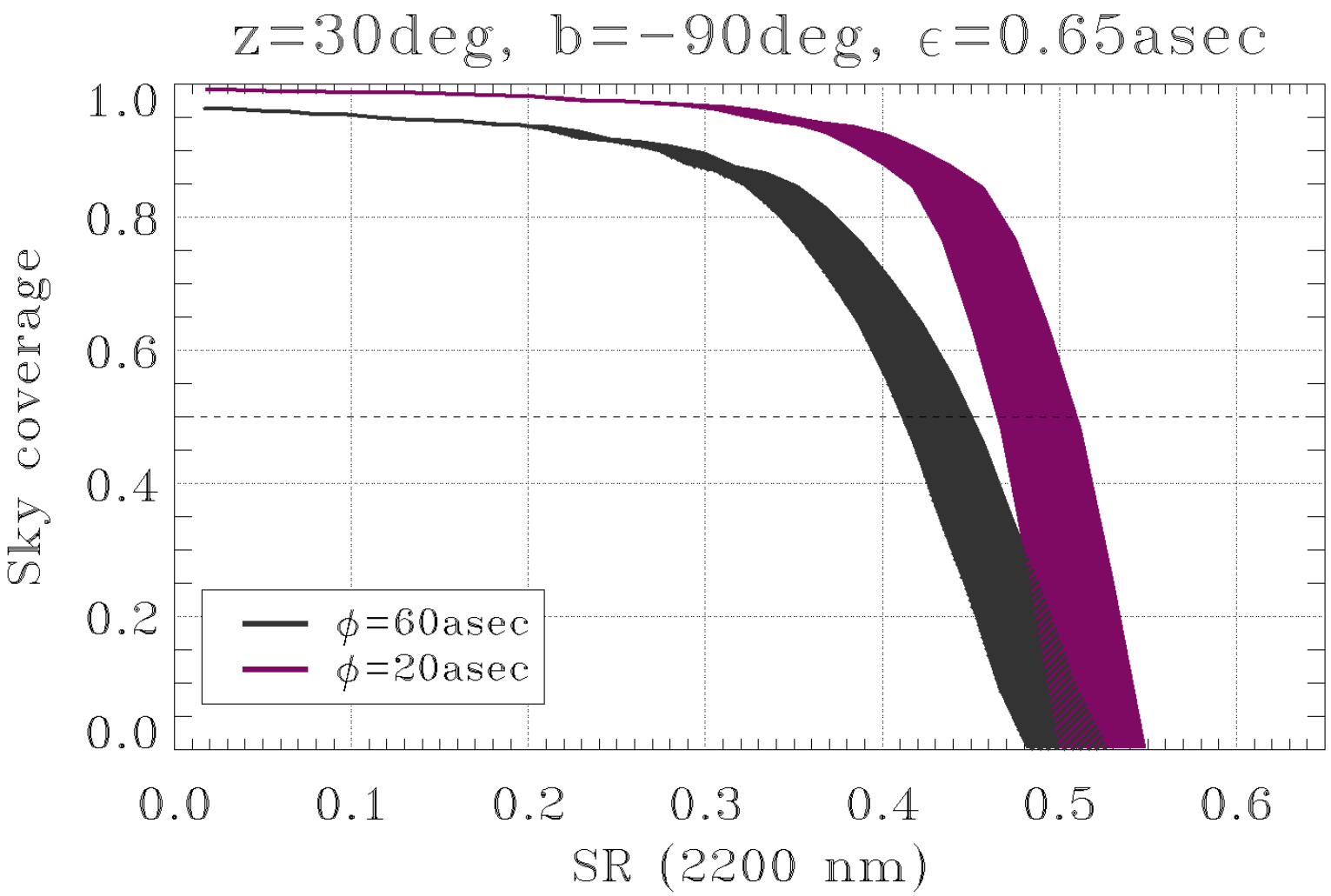
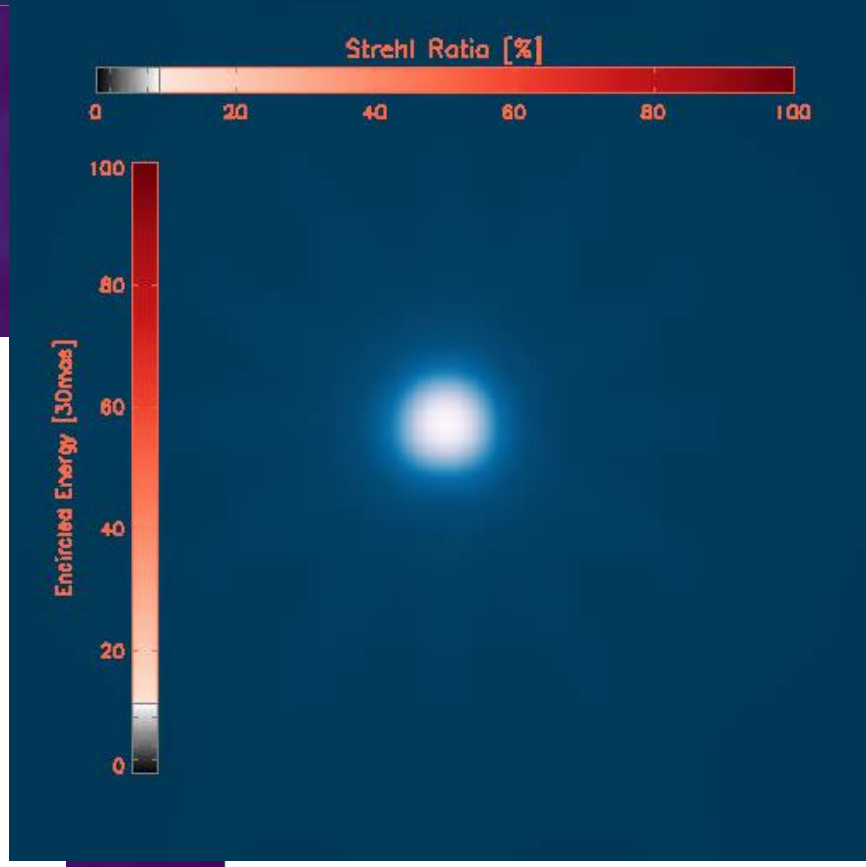
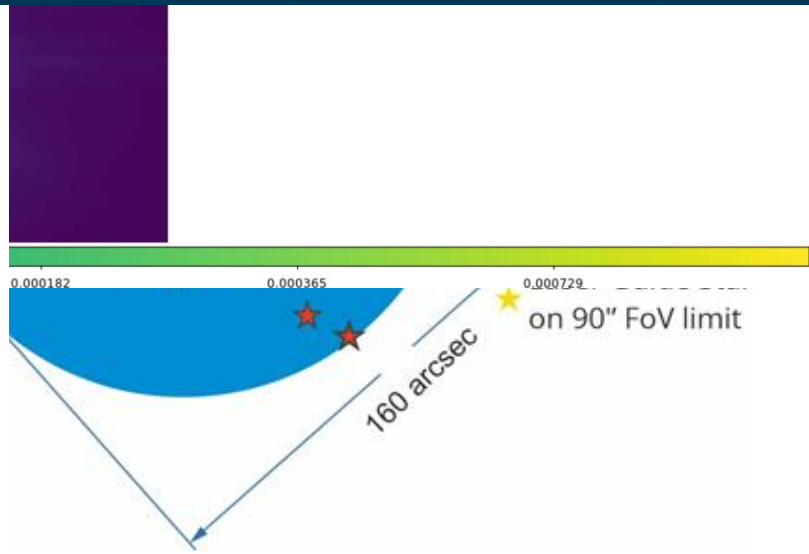





30 mas
30 mas
30 mas


z=30deg, b=−90deg, ϵ=0.65asec
Sky coverage
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
SR (2200 nm)
ϕ=60asec
ϕ=20asec


Strehl Ratio [%]
0
20
40
60
80
100
Encircled Energy [30mas]
100
80
60
40
20
0


0.000182
0.000365
0.000729
160 arcsec
on 90" FoV limit

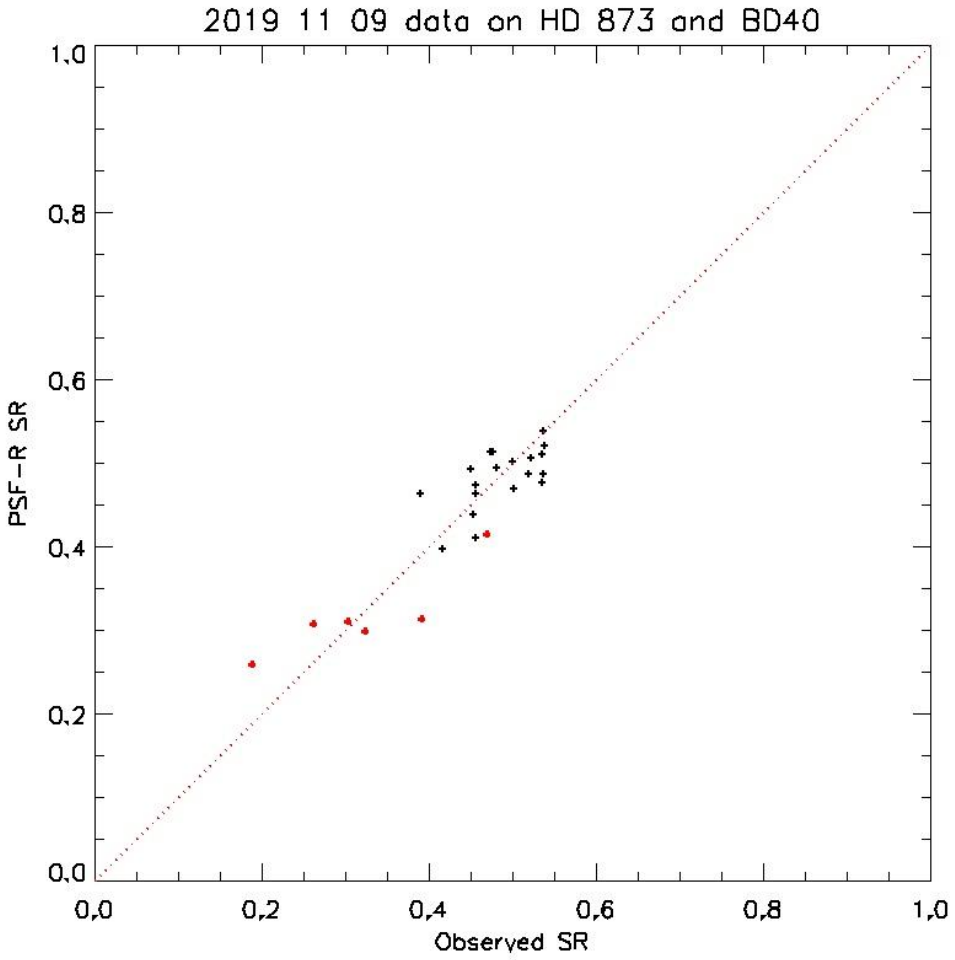
Toward the end of the talk – some note on

Observational challenges – PSF Reconstruction

- the time-varying nature of the PSF (atmospheric turbulence, wind induced telescope behaviors)
- The PSF, which varies across the field of view and with time, presents challenges in data analysis, particularly for fields lacking bright stars (e.g., at high galactic latitudes). Without reliable point sources, reconstructing the PSF becomes critical for accurate photometric and morphological analysis.
- MICADO, in combination with MORFEO, uses a blind PSF reconstruction (PSF-R) algorithm. This method leverages adaptive optics (AO) telemetry data (such as wavefront sensor measurements) to reconstruct the PSF without relying on focal plane science data. This approach is crucial for observations in regions with few or no suitable PSF reference stars
- PSF-R is essential for extracting fine details in diffraction-limited imaging. It allows astronomers to:Perform deconvolution to remove optical distortions. Enable morphological studies of compact objects, such as distant galaxies or stellar populations, by compensating for spatial PSF variability
- The PSF-R tool works in both Single-Conjugate AO (SCAO) and Multi-Conjugate AO (MCAO) modes, significantly improving the fidelity of the reconstructed image across the field of view. This helps tackle PSF degradation, a known issue with large fields of view observed with MCAO systems.
- With the ability to reconstruct the PSF in real-time, MICADO and MORFEO ensure that even in crowded fields or sparse-star regions, astronomers can achieve reliable photometric and astrometric precision

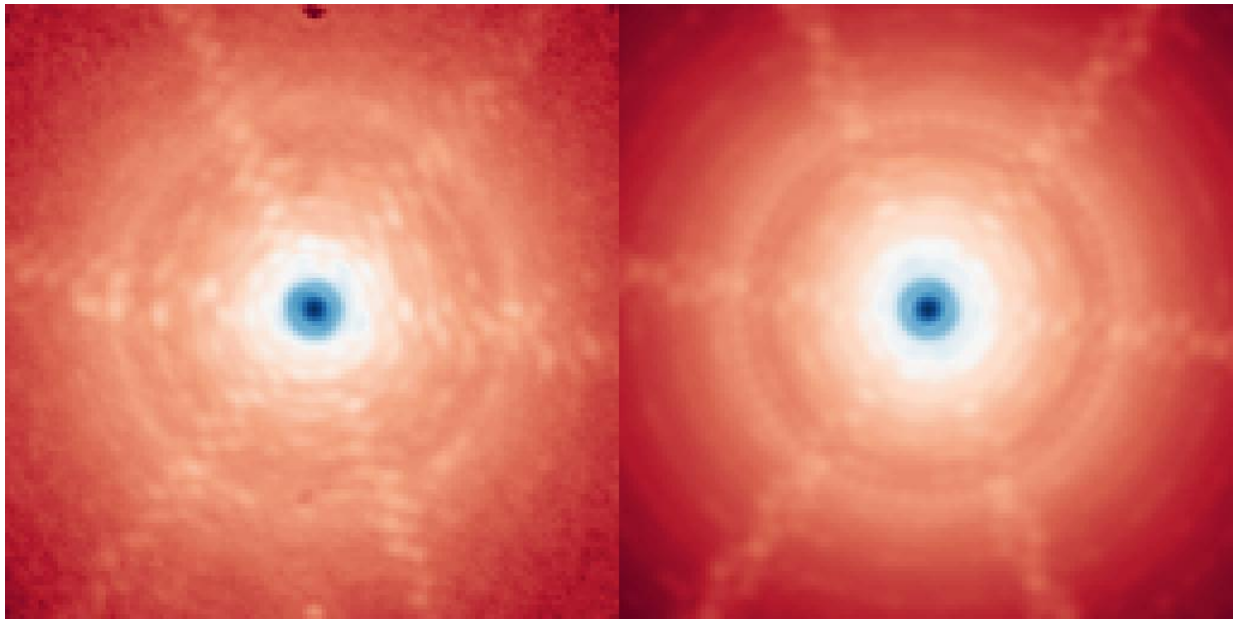
It's worth mentioning that MORFEO will store on disk the information (telemetry) produced by the WFSs (WF slopes ≈ first derivative) and DMs control commands. The combination of the two will allow a posteriori WF estimation for any direction within the FoV

PSF-R Results – LBT – SCAO High SR > 40%



PSF Observed

PSF Reconstructed



Std dev spread on the 25 points is 0.045 SR points (~10%)

Exposure Time Calculator(s)

MICADO-MORFEO
AETC - Advanced Exposure Time Calculator (Web)

- Web site: http://aetc.oapd.inaf.it/
- Two **options for MCAO: top (**0%skycov) med (50%)

SCOPESIM (python)

- an updated version of the software was released (0.8.3) on June 2nd
- the latest version is available on GitHub

SHARP-MORFEO (Web)

- **Exposure Time Calculator (ETC)**: this calculator provides a guess on the spectroscopic performance of SHARP

Conclusions

- MORFEO further advances the AO capabilities of ELT by providing diffraction-limited performance over a wide field of view.
- The high sky coverage of MORFEO at high galactic latitudes opens to systematic studies of cosmological objects
- **The 2,5 arcmin corrected FoV offered on the 2nd port is extremely valuable being the PSF/optical performance homogeneously spread at the diffraction limited resolution**

That’s all

Thanks for listening

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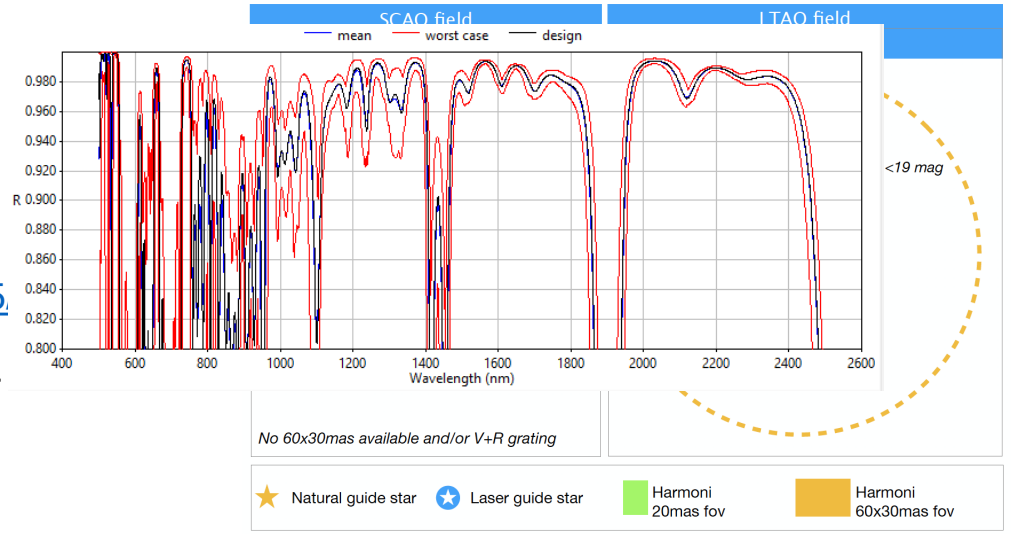
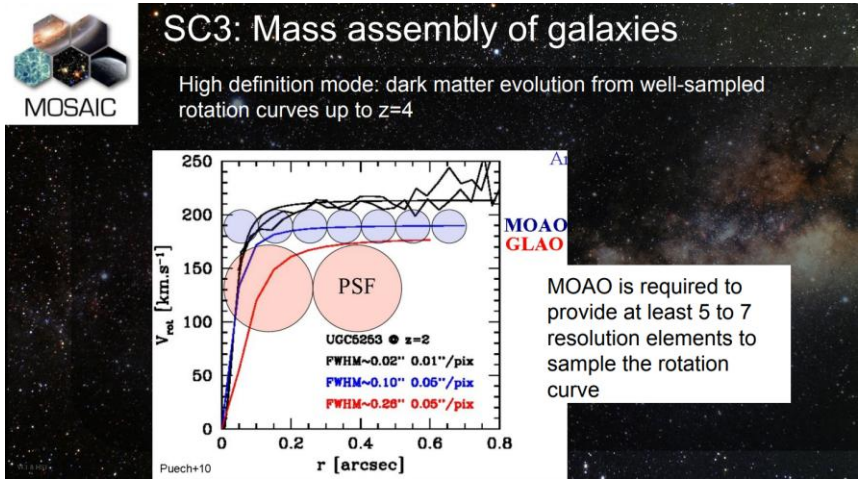


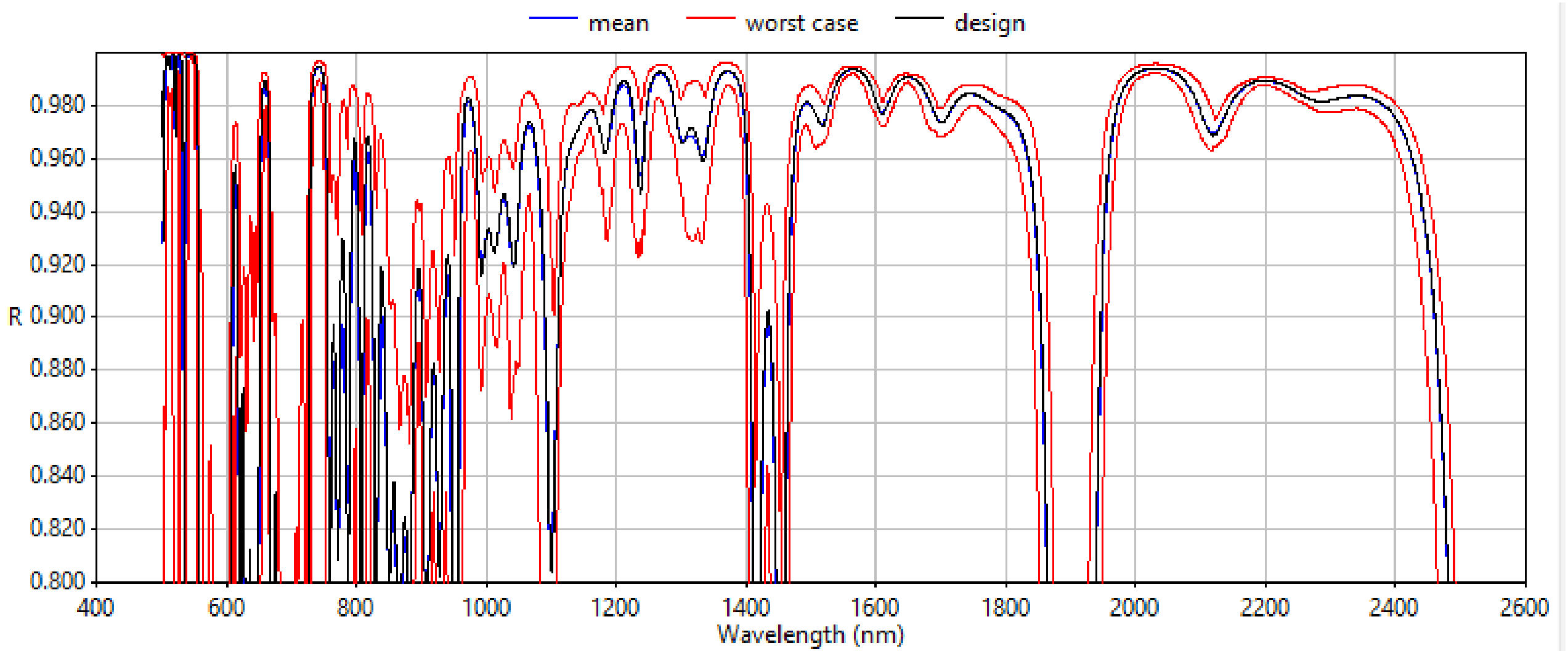


Instrumentation roadmap

Phasing

1st Generation 2nd Generation

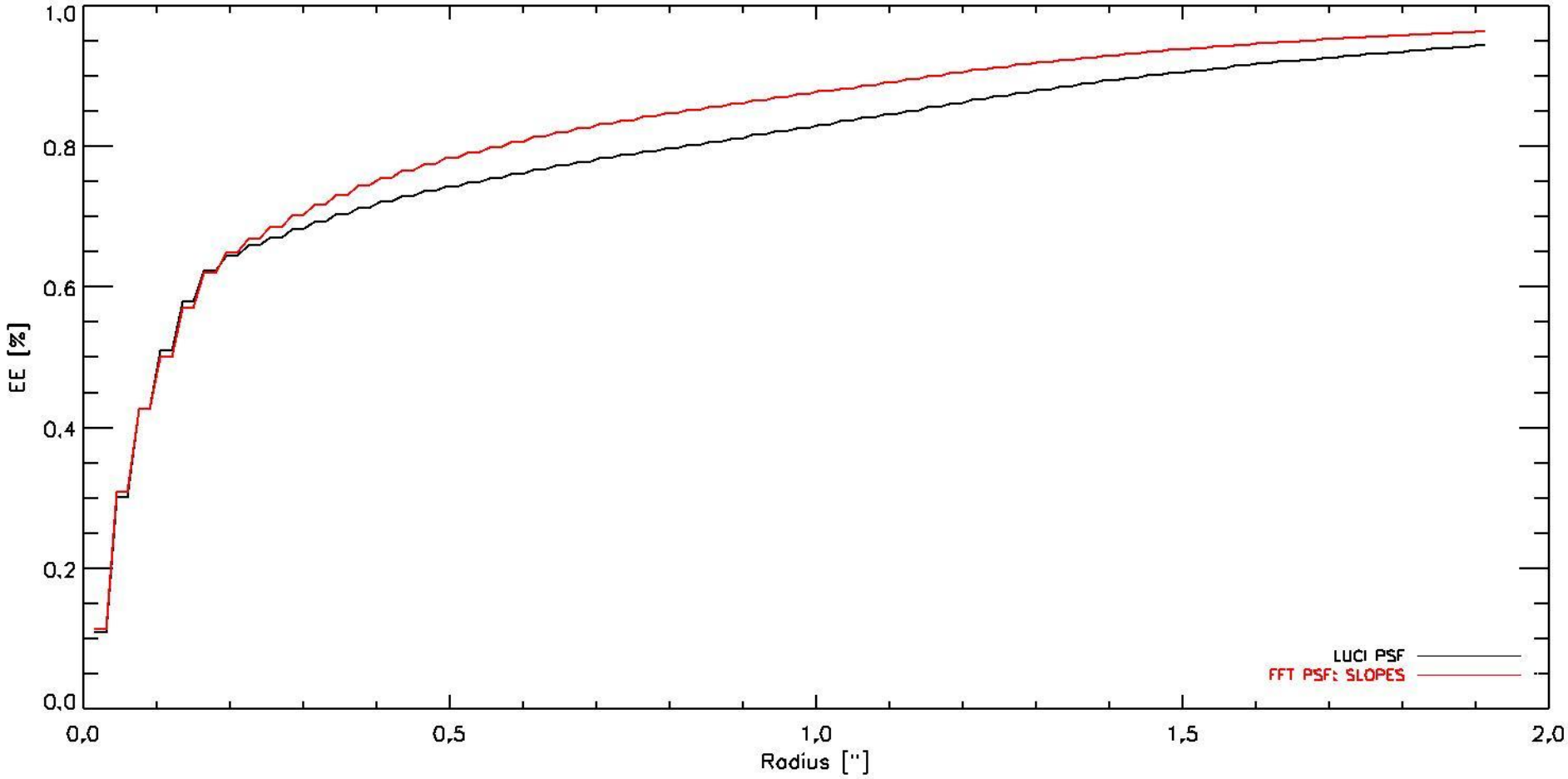
Instruments - First Light	Description	AO	λ (µm)	Resolution	FoV	Add. Mode
MORFEO/MICADO (PdR/FdR) (2027-2028)	Spectro-imager	SCAO, MCAO	0.8 – 2.4	3000 - 20 000	53.0" 19.0" 6.0"	Astrometry 40µas Coronography Long-Slit Spectro
HARMONI (PdR completed) (2027-2028)	IFU Spectrograph	SCAO, LTAO	0.5 – 2.4	3500 7000 18 000	1.0" 10.0"	Coronography
METIS (PdR completed) (2028-2030)	IFU & Spectro-Imager	SCAO LTAO	3 – 20 3 - 5	5000 100 000	18" 0.4"×1.5"	Coronography Long-Slit Spectro
ANDES (HIRES) (Phase A completed) (2032+)	Optical and NIR High-Resolution Spectrograph	SCAO	0.37 – 0.71 0.84 – 2.50	200 000 120 000	0.82" 0.5"	Polarimetry IFU mode
MOSAIC (Phase A completed) (2032+)	Optical and NIR Wide/Narrow field Multi Object Spectrograph	- - MOAO	0.37 – 1.4 0.37 – 1.4 0.8 – 2.45	300- 2500 5000 – 30 000 4000 – 10 000	6.8" 420' 2"	Multiplex ~ 400 Multiplex ~100 Multiplex ~10 Imaging?
PCS (2033+)	Optical and NIR High Contrast IFU Spectrograph & imager	XAO	0.6 – 0.9 0.95 – 1.65	125 – 20 000 100 000?	2.0" 0.8"	Coronography Polarimetry

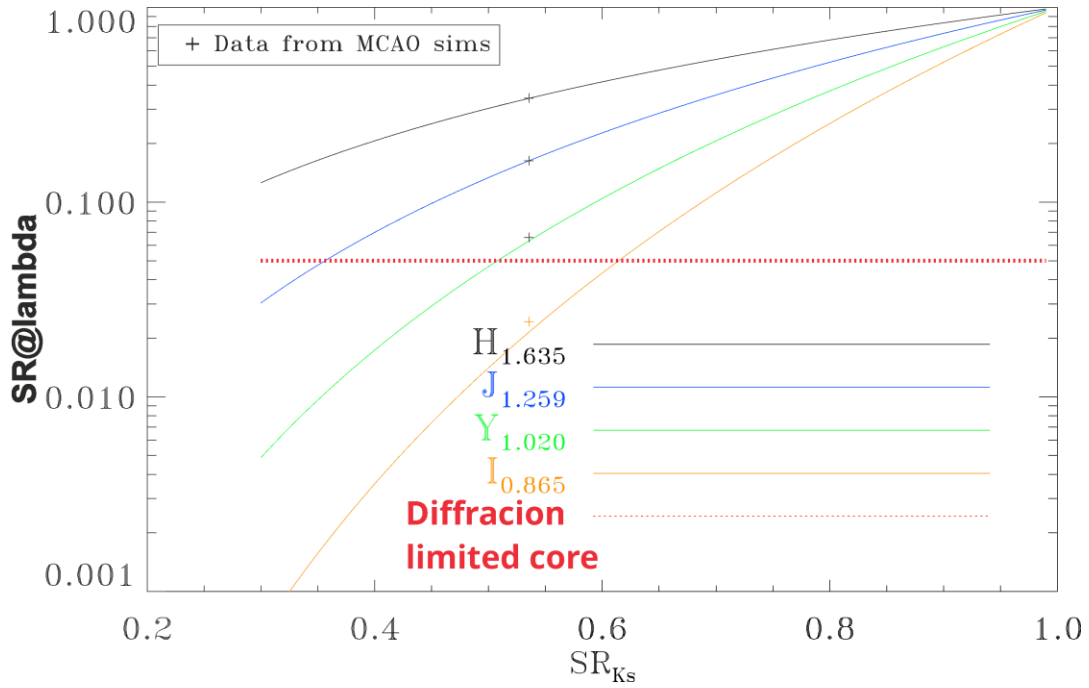

mean
worst case
design
R
0.980
0.960
0.940
0.920
0.900
0.880
0.860
0.840
0.820
0.800
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
Wavelength (nm)

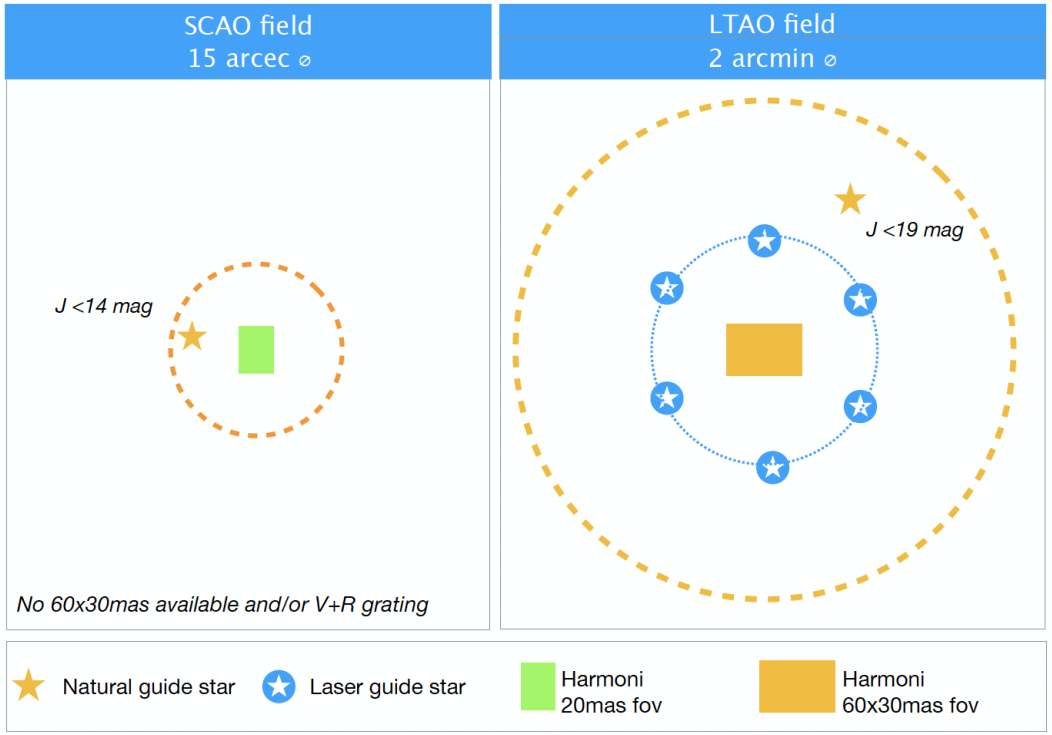
Encircled Energy profile

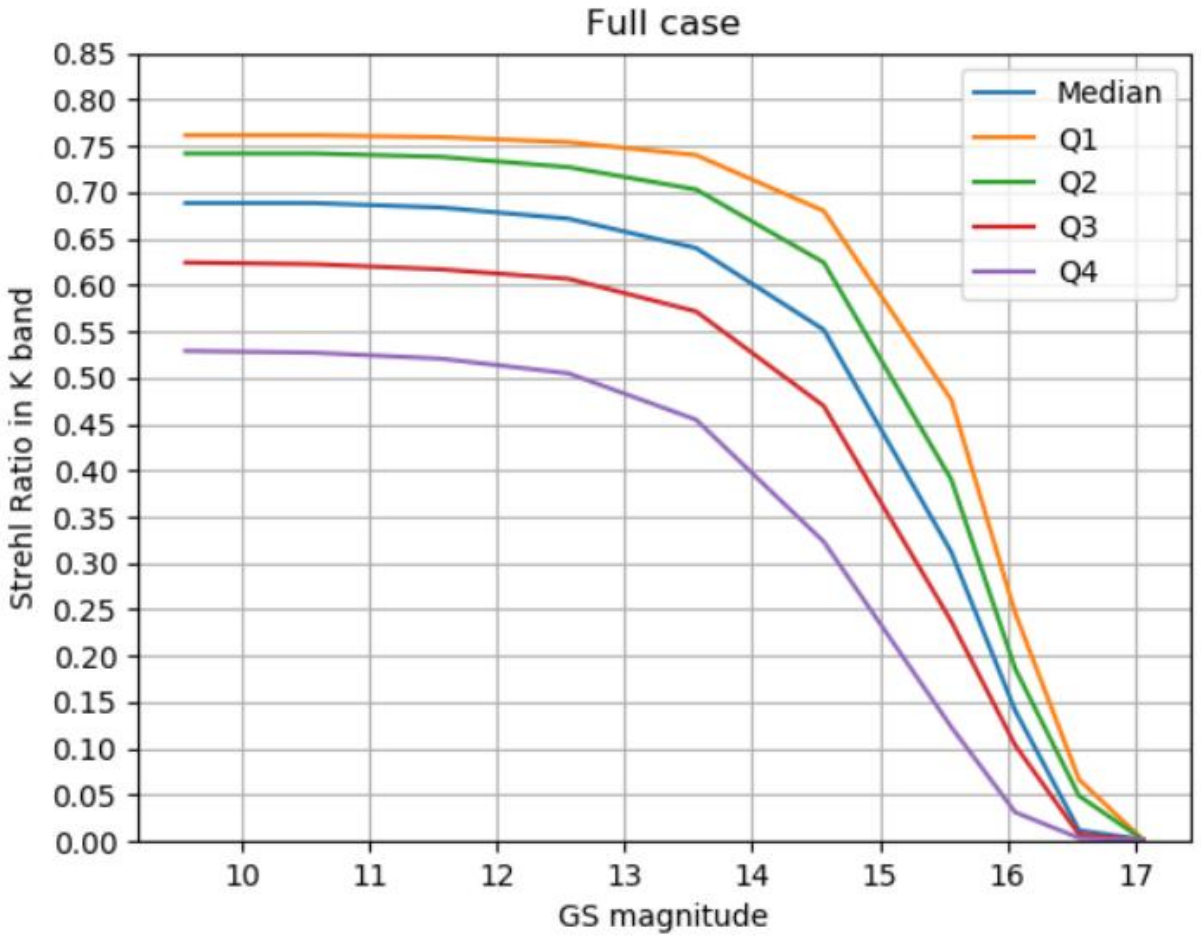
The Encircled Energy profile is very precise within control radius (< 0.6 arcsec).

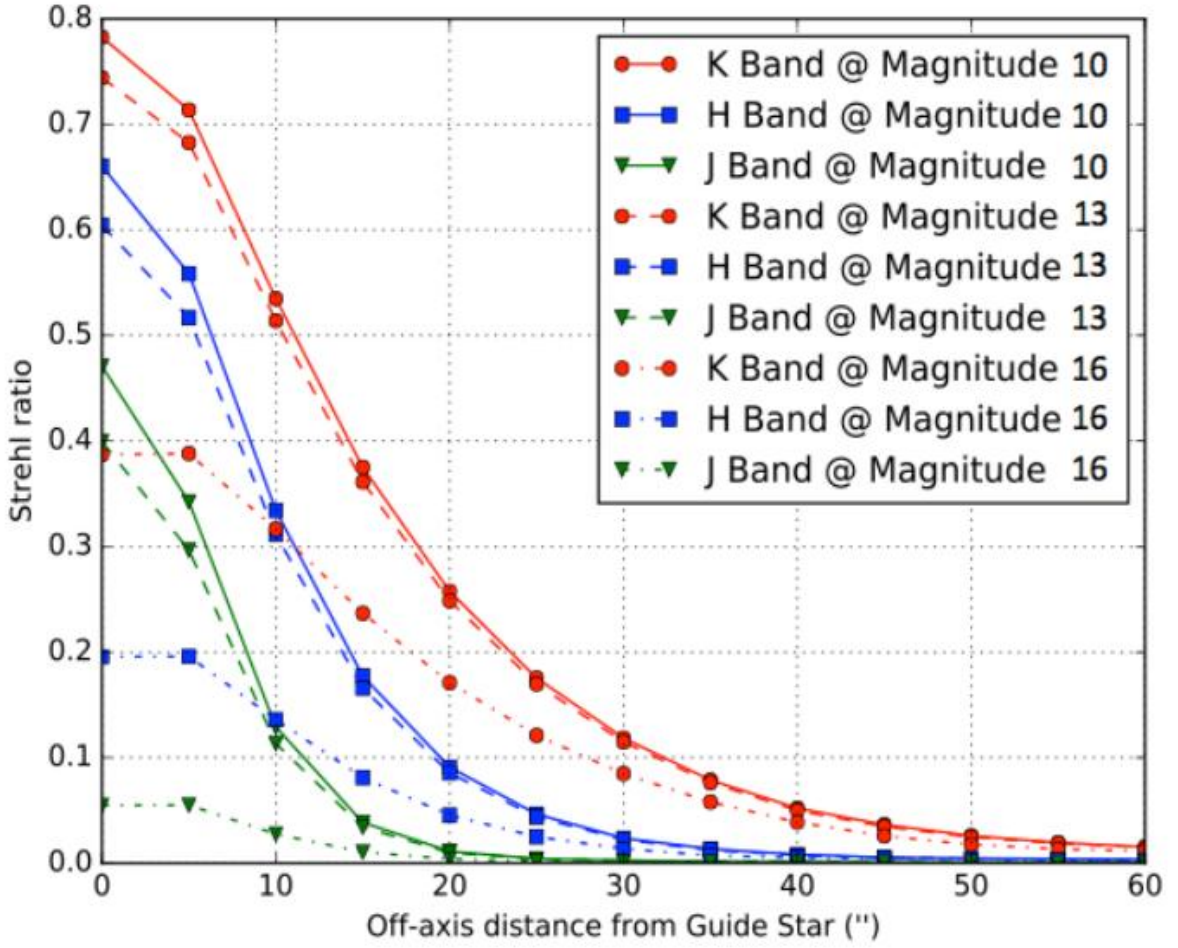
On the external region (wings) the background subtraction may play a major role.




+ Data from MCAO sims
SR@lambda
1.000
0.100
0.010
0.001
0.2
0.4
0.6
0.8
1.0
SR_Ks
H 1.635
J 1.259
Y 1.020
I 0.865
Diffracion
limited core


SCAO field
15 arcec ⌀
LTAO field
2 arcmin ⌀
J <14 mag
J <19 mag
No 60x30mas available and/or V+R grating
Natural guide star
Laser guide star
Harmoni
20mas fov
Harmoni
60x30mas fov


Full case
Median
Q1
Q2
Q3
Q4
Strehl Ratio in K band
GS magnitude
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
10
11
12
13
14
15
16
17


K Band @ Magnitude 10
H Band @ Magnitude 10
J Band @ Magnitude 10
K Band @ Magnitude 13
H Band @ Magnitude 13
J Band @ Magnitude 13
K Band @ Magnitude 16
H Band @ Magnitude 16
J Band @ Magnitude 16
Strehl ratio
Off-axis distance from Guide Star (")
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
40
50
60