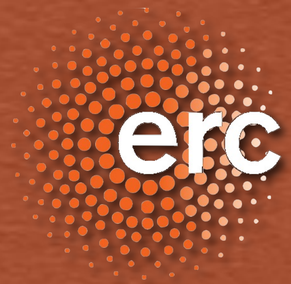
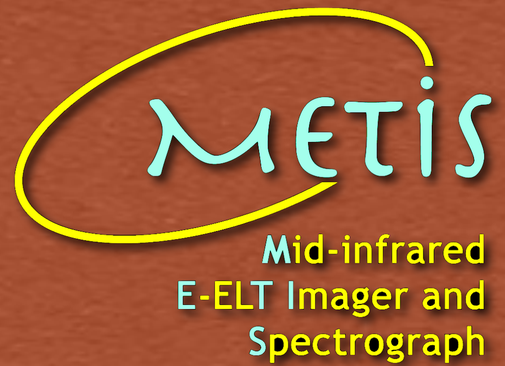
Non-Common Path Aberrations Strategy for the METIS High Contrast Imaging Modes

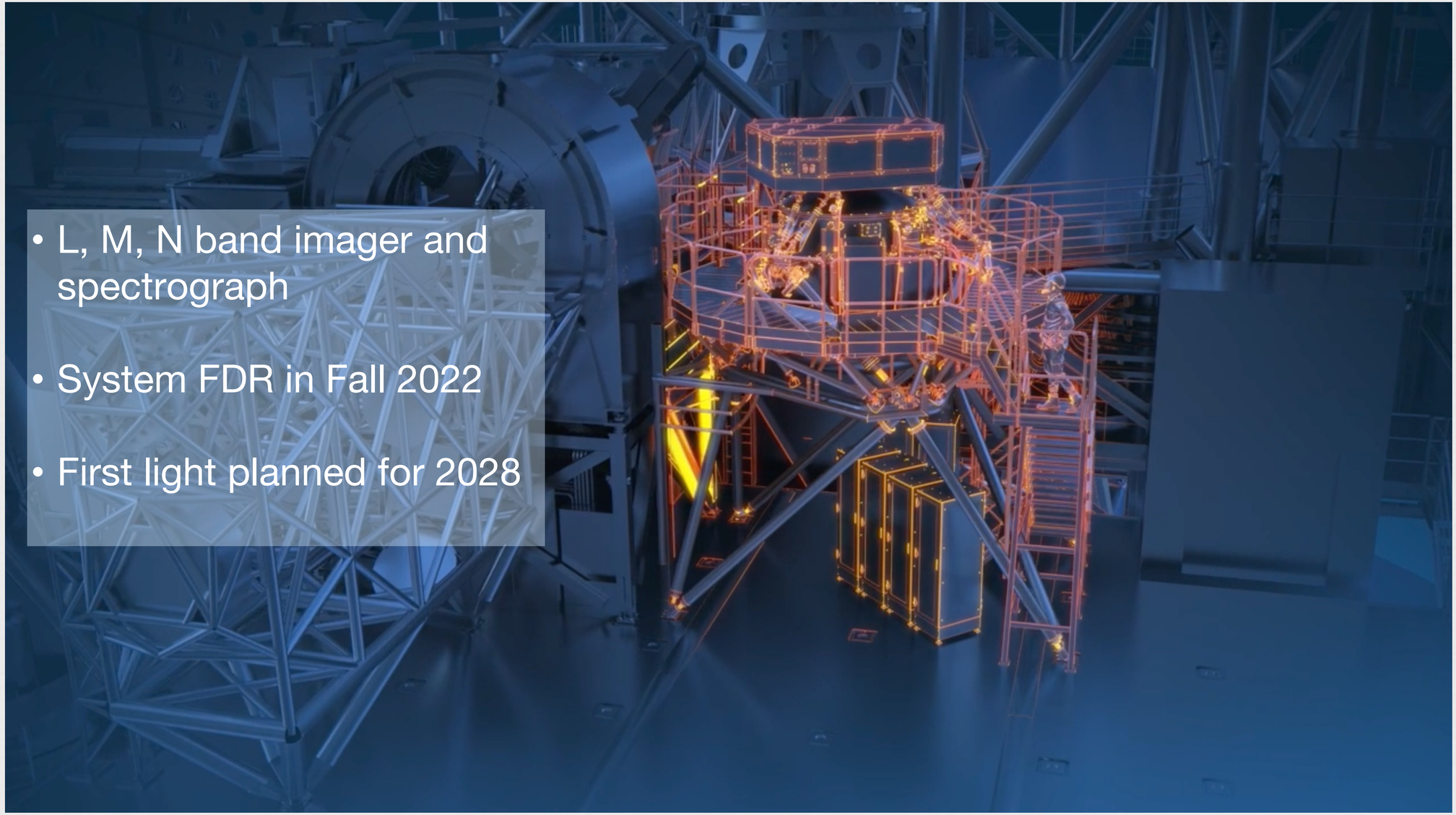
Gilles Orban de Xivry
University of Liège -- Belgium

AO4ELT #7 – June 28th 2023





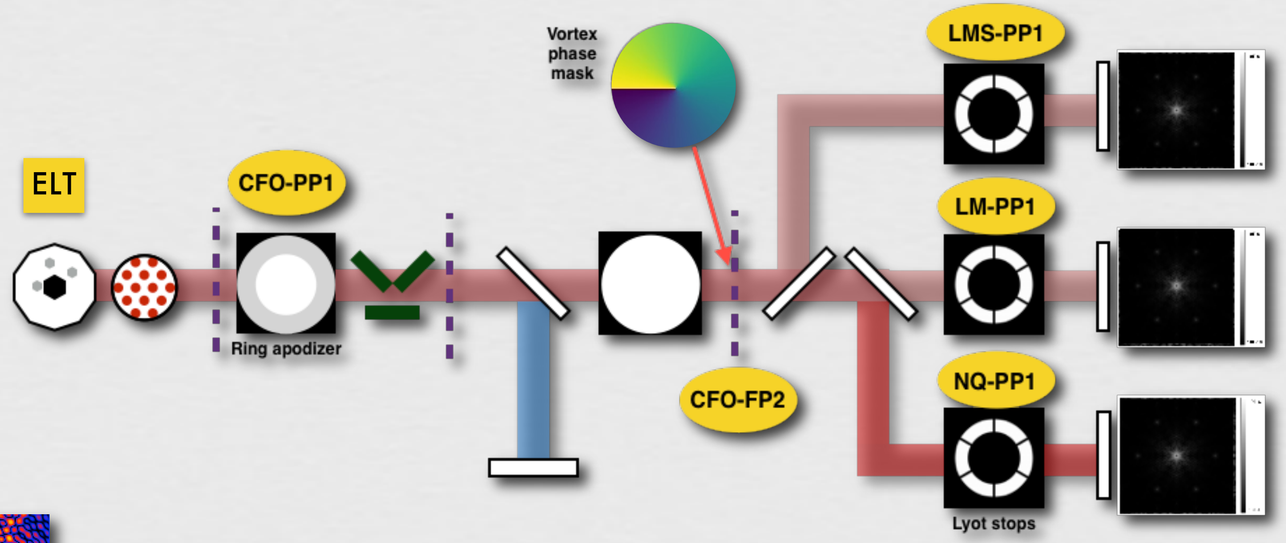
First Generation Instruments @ ESO/ELT



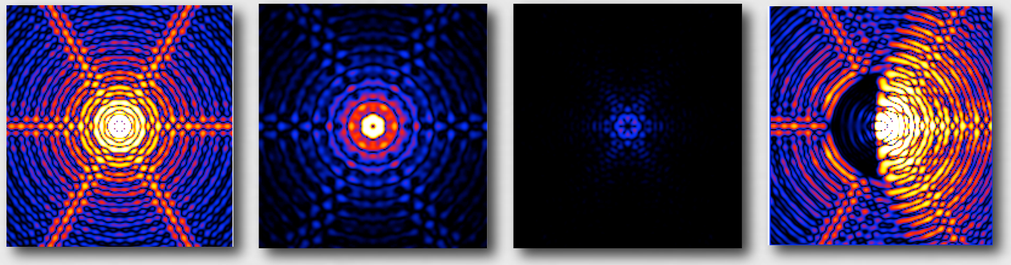
- L, M, N band imager and spectrograph
- System FDR in Fall 2022
- First light planned for 2028

METIS High-Contrast Imaging Modes

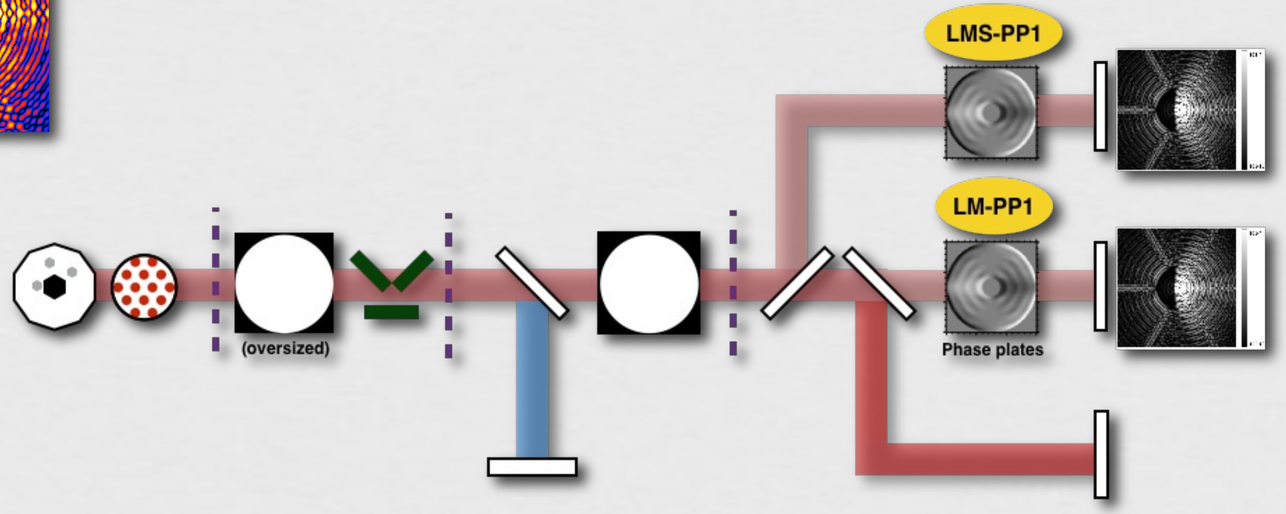
(Ring-Apodized)
Vortex Coronagraph



IMG (ELT) CVC RAVC APP



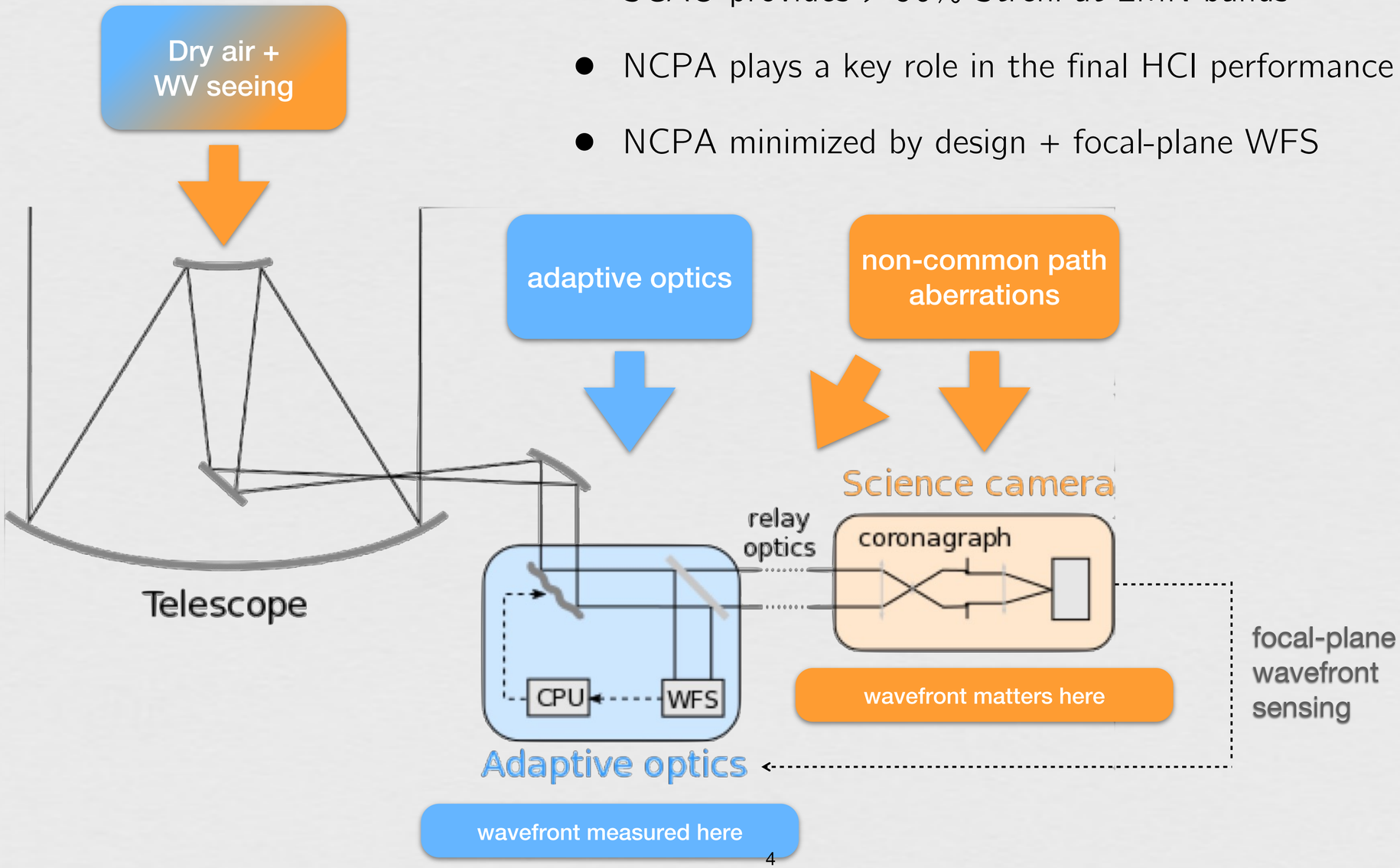
Apodizing
Phase Plate



See also:
- Olivier Absil talk tomorrow

Wavefront Control Strategy

- SCAO provides > 90% Strehl at LMN bands
- NCPA plays a key role in the final HCI performance
- NCPA minimized by design + focal-plane WFS



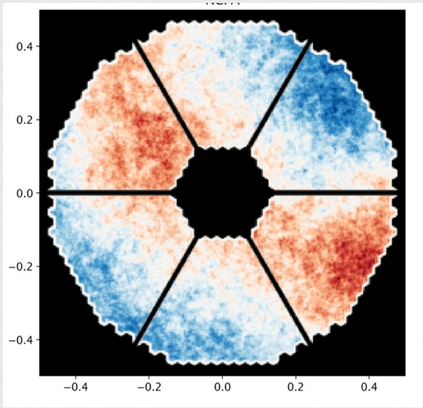
Sources of non common aberrations

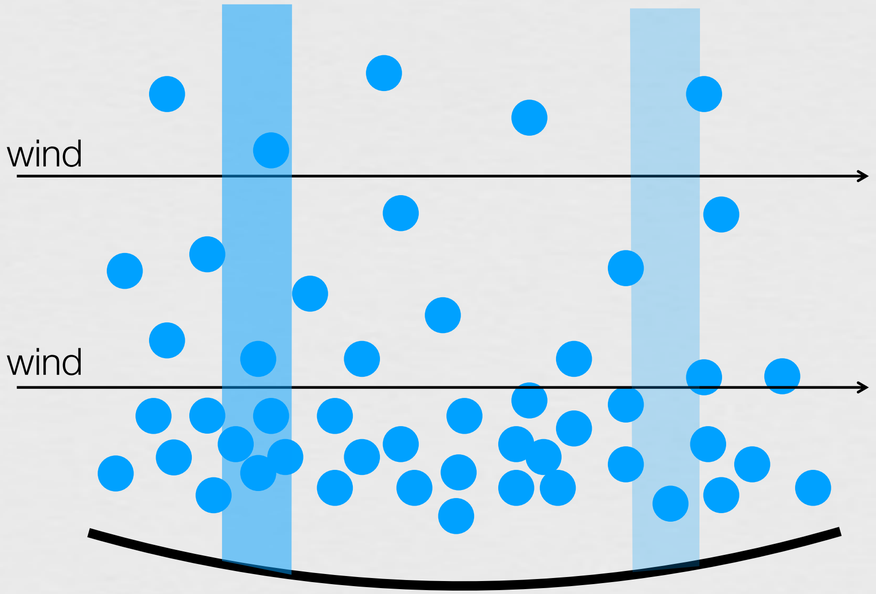
Quasi-static NCPA & Water vapor seeing

- Quasi-static NCPA estimated to **~150nm rms**
- WV column density is variable
- Expected to follow Kolmogorov - von Karman spectrum
- Highly chromatic, especially in mid-IR
  - AO correction at K band not valid at L/N bands

- Estimated water vapor seeing:
  - **~30nm rms in L-band**
  - **~300nm in N-band**

Quasi-static NCPA – Boné et al. in prep





See
- Prashant Pathak poster (WV on mid-IR)
- Olivier Absil talk tomorrow (METIS HCI modes)

Mitigation plan for METIS

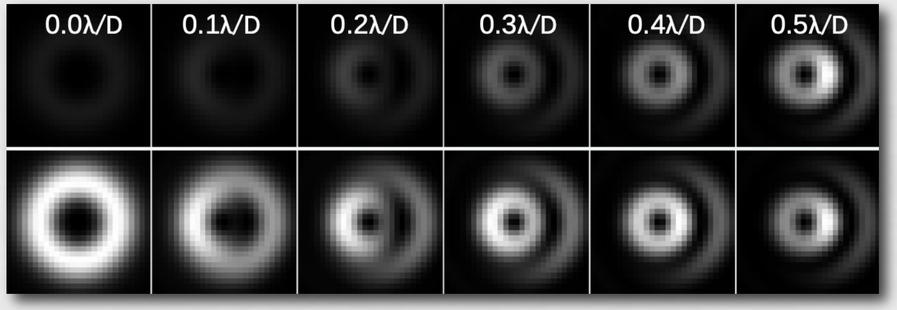
Initial baseline

- Science images fed back to AO system for focal-plane wavefront sensing @ 1 Hz
- Pointing errors: **QACITS**
  - uses asymmetry in coronagraphic PSF
- 4th – 20th/100th Zernike modes: **Phase Sorting Interferometry**
  - 100% duty cycle
  - uses phase diversity introduced by AO residuals

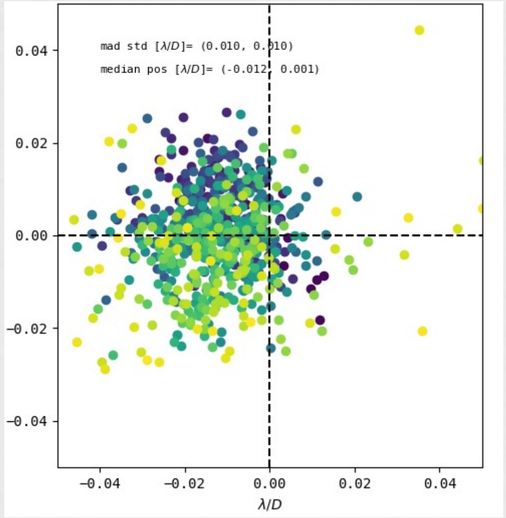
Pointing Control with QACITS

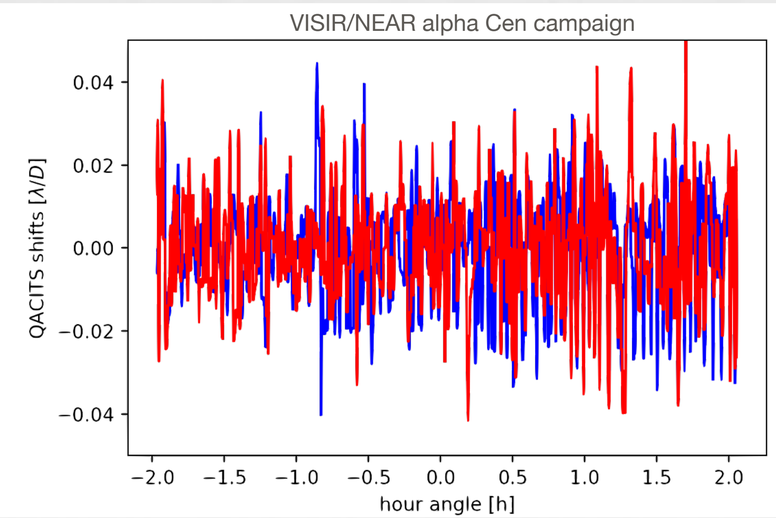
Huby et al. 2015,
Maire et al. 2020

- Tailored to vortex coronagraph
- Reconstruct pointing error with nonlinear model
- Demonstrated accuracy ~0.01 λ/D
- On-sky: Keck/NIRC2, VLT/NEAR, and now VLT/ERIS



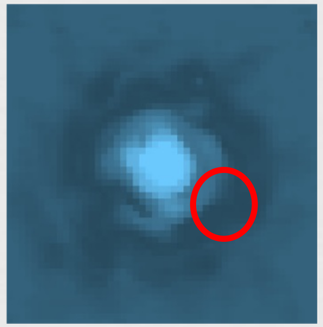
ERIS commissioning



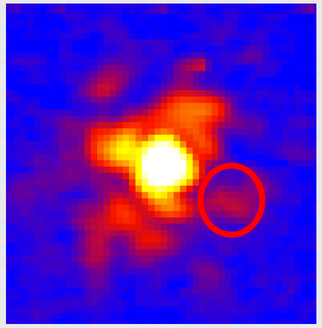


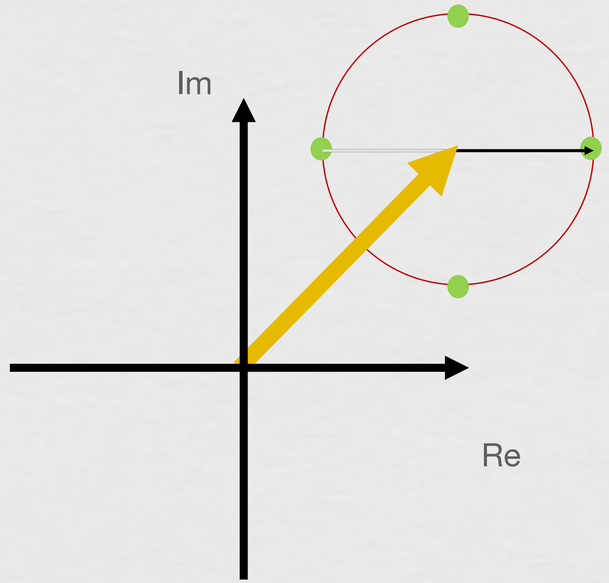
PSI principle

Focal plane Efield
computed from telemetry



Science image





Probe computed
from residual

NCPA to estimate

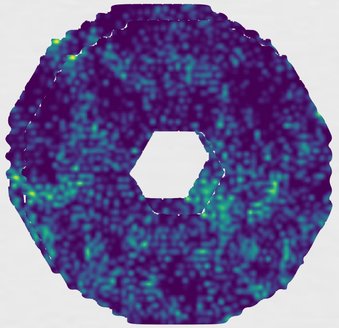
Measured images

- Reference beam or ‘probes' are the known AO residual speckles
- Use SCAO residuals as source of diversity to infer pixel-wise amplitude and phase of NCPA

Codona, Kenworthy, Lloyt-Hart, 2008
Otten+2012
Kenworthy & Codona 2011, AO4ELT
Codona & Kenworthy 2013

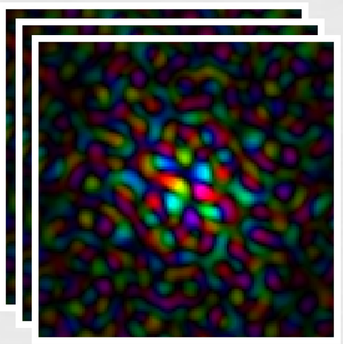
PSI algorithm in a nutshell

AO telemetry

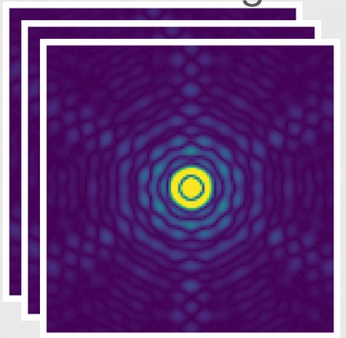


$\mathcal{M}(.)$

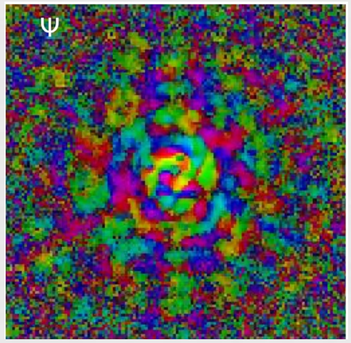
Speckle field ψ in FP



Science images



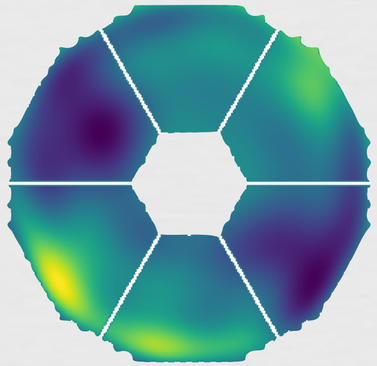
Calculated
Subject field in FP



$$\frac{\langle \psi I \rangle}{\langle |\psi| \rangle^2}$$

Filtering +
$\mathcal{M}^{-1}(.)$

NCPA estimate



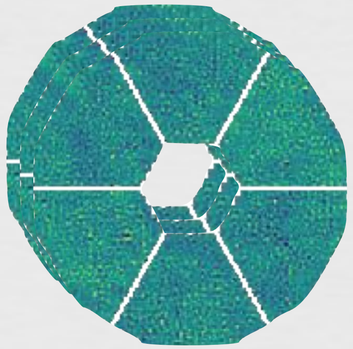
Typical numbers for METIS

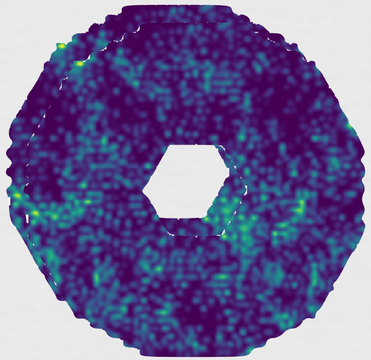
PSI rate	1 Hz
AO rate & telemetry	1kHz, 100Hz
Science DIT	100ms

Codona, Kenworthy, Lloyt-Hart, 2008
Otten+2012
Kenworthy & Codona 2011, AO4ELT
Codona & Kenworthy 2013

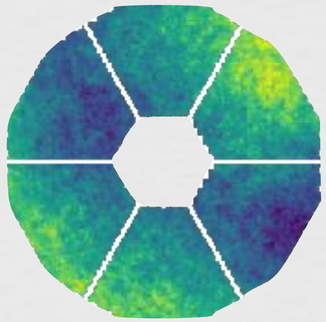
METIS PSI simulation setup

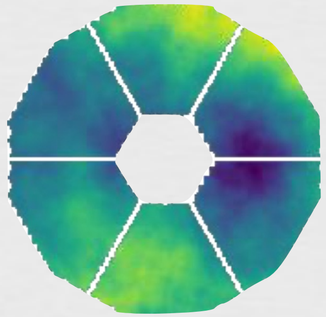
Run SCAO METIS COMPASS
- Save residual wavefront
- Save WF telemetry





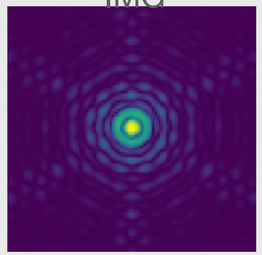
Add variable "NCPA"
- Phase map provided by Optics Team
- Water vapour seeing (Kolmogorv phase screens)



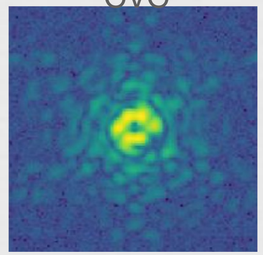


Simulate instrument mode and run PSI simulation

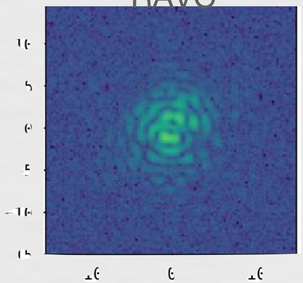
IMG



CVC



RAVC



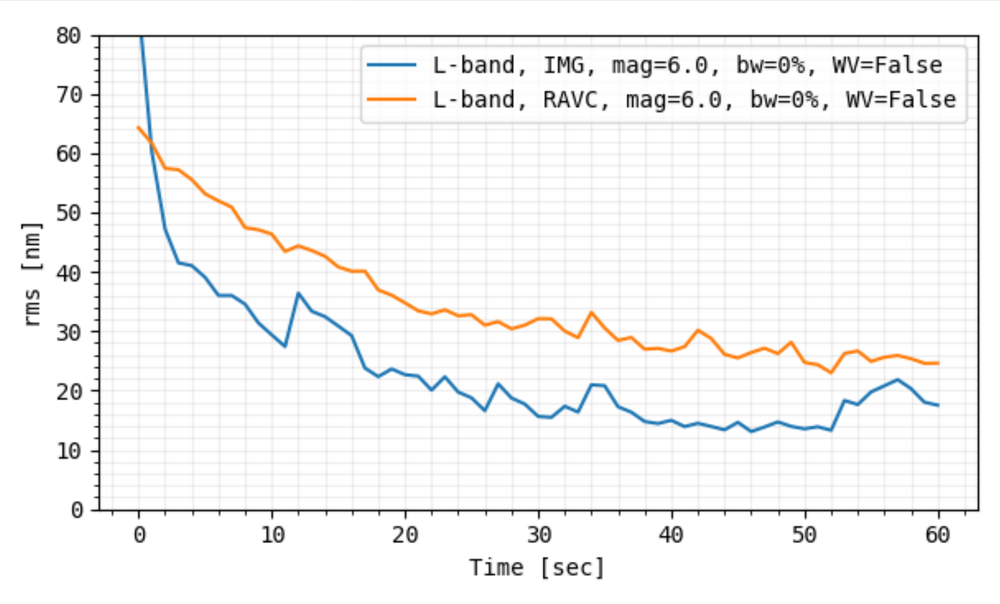
	L-band	N-band
Pupil plane diameter [px]	256	256
Resolution [px / (λ/D)]	4	9
Detector size [(λ/D]	15	15 / 20
Wavelength	3.81e-6	11.33e-6
Flux zeropoint [e-/s]	8.999e+10	3.695+10
Background flux [e-/s/px]	8.878e+4	1.122e+8
Science DIT [sec]	0.1	0.04
Magnitude	6	0
Instrument mode	IMG or RAVC	IMG or CVC
Spatial filtering radius [λ/D]	10	10-17
PSI framerate [Hz]	1	0.1 - 1
Number of corrected Zernike modes	100	100

Results

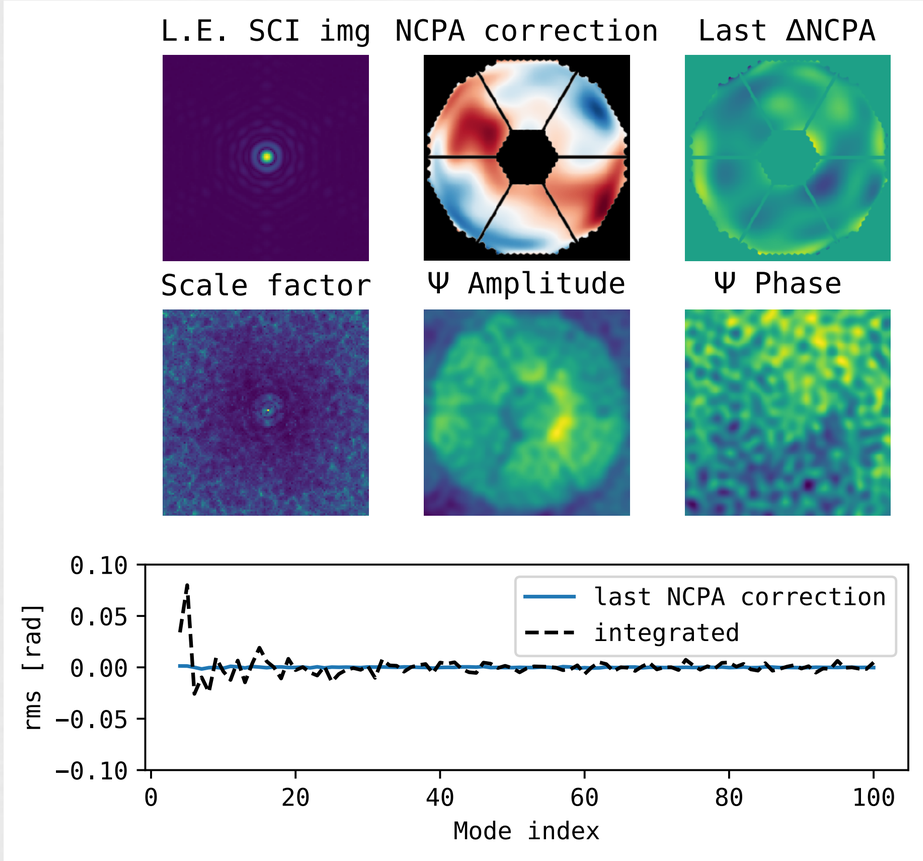
RMS Plots

Static NCPA in L-band
normal and coronagraph imaging

Reaching ~20nm rms
for both IMG and RAVC at mag-6



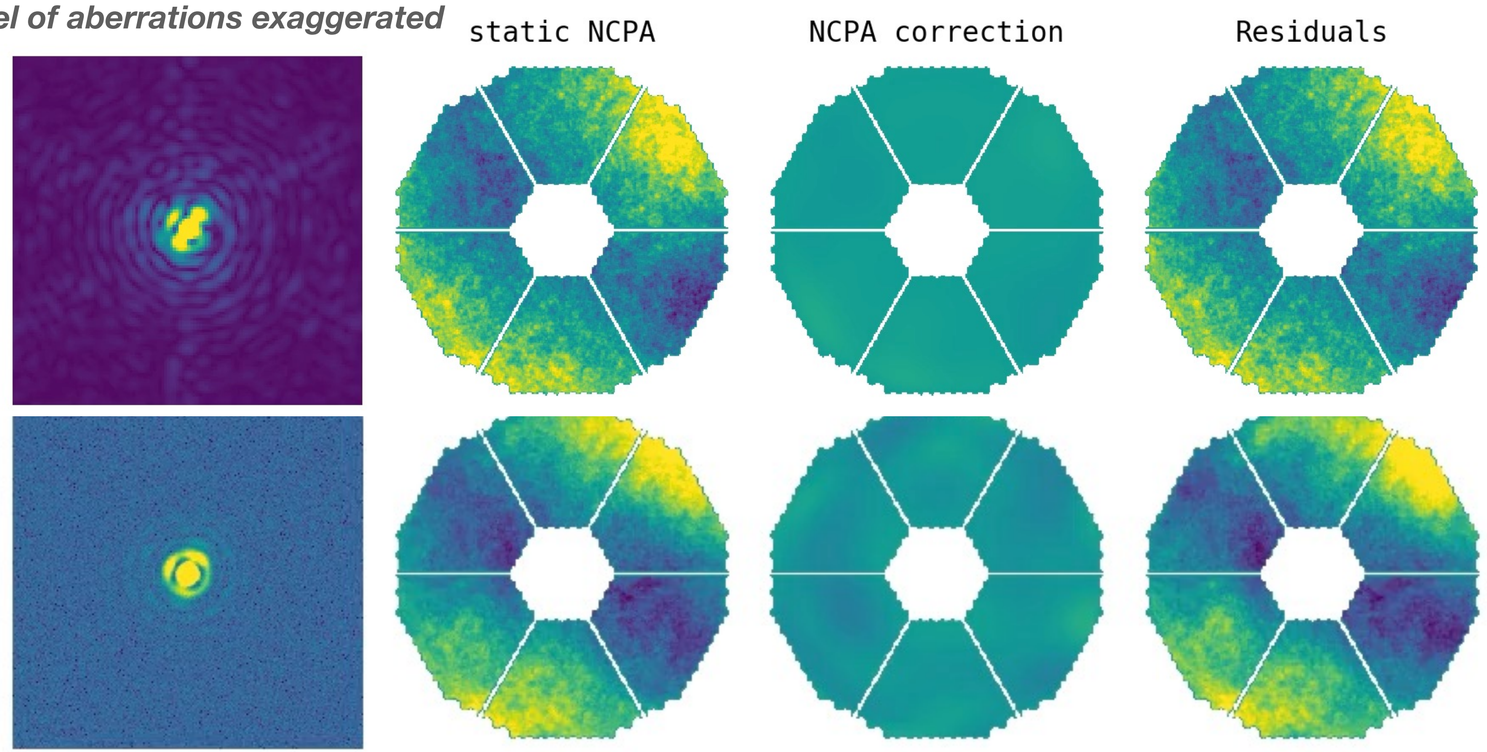
Outputs and diagnostics of PSI



Results

And main limitation

Level of aberrations exaggerated



Static NCPA

Static NCPA
+ Water vapour seeing

→ PSI is ruled out for WV seeing: probe field and subject beam cannot have the same temporal behaviour.

→ Real-time measurement and temporal bandwidth will drive the HCI performance in N-band

An Alternative to PSI in N-band ?

Asymmetric mask to lift phase ambiguity

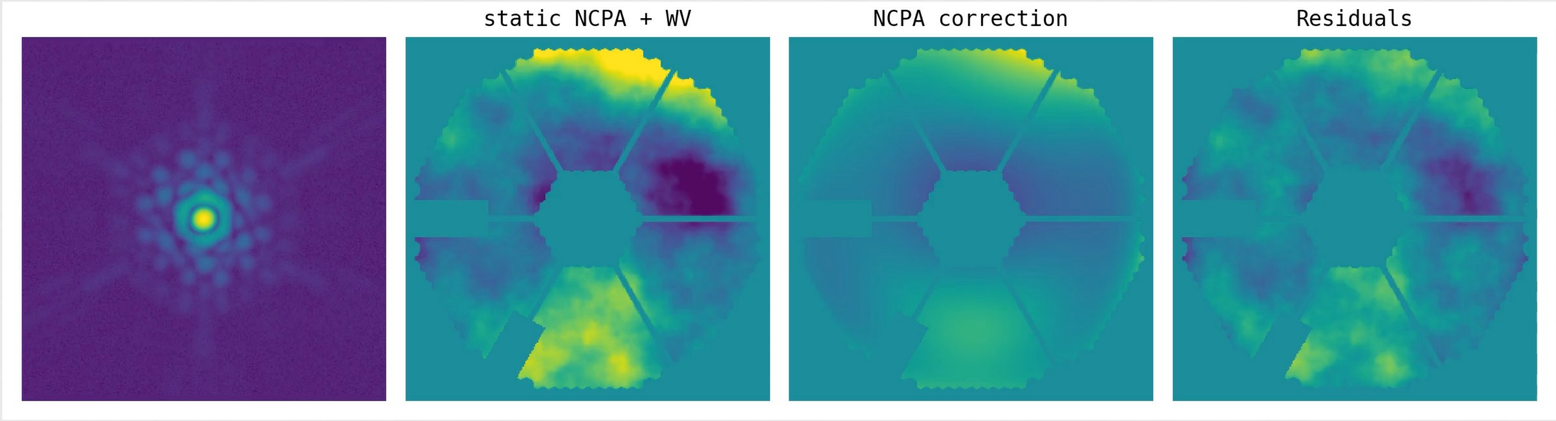
- Selected the asymetric pupil mask: “AP-WFS”
- Demonstrated on-sky on SCExAO for **LO-WFS** (Martinache+2016), and to correct the **island effect** (N’Diaye et al. 2018) ; and also with the **APP** for static aberration (Bos et al. 2019)

Linear solution
using the OTF plane

$$\Phi = A\phi$$

Applicable to normal IMG only

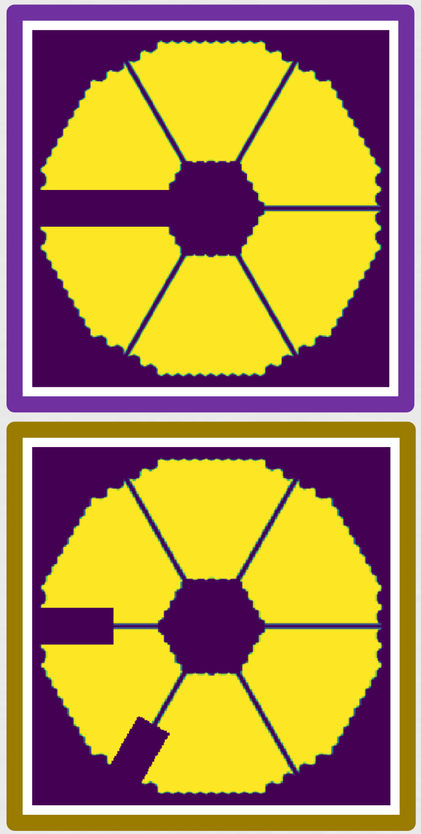
Using XARA (Martinache et al.) together with HCIPy (Por et al.) and our METIS simulation framework



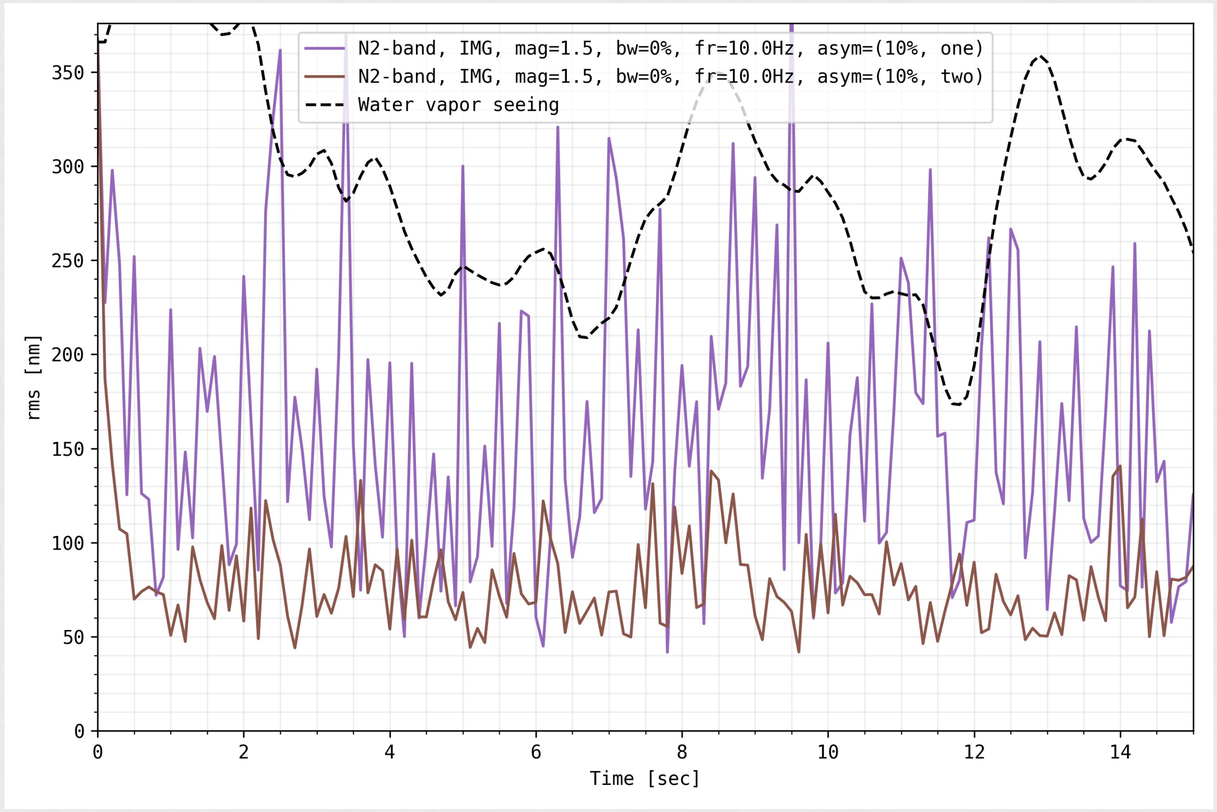
METIS N-band, mag=0, bandwidth=20%, 100ms sampling

AP-WFS in normal imaging

Asymmetric pupil mask type



For a N-mag = 1.5, at 10Hz



- Noise propagation can also be studied by sensitivity matrix
- Modal basis can also have an influence on the noise propagation

AP-WFS in normal imaging

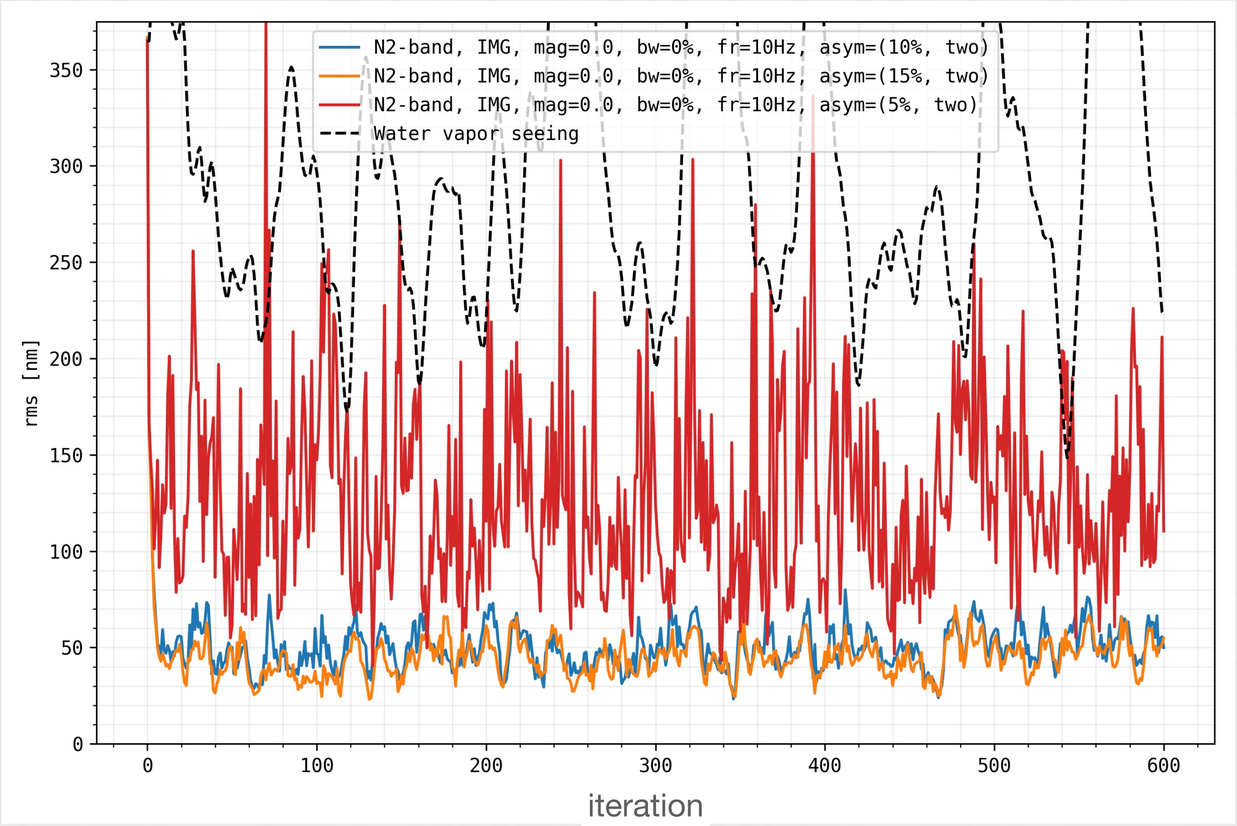
Normal imaging – mask thickness

For a N-mag = 0, at 10Hz

5%

10%

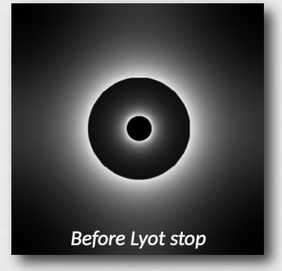
15%



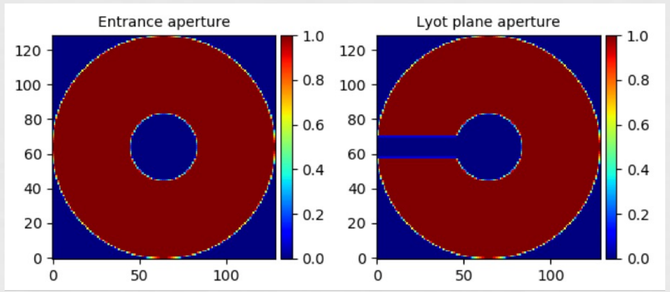
- Trade—off between impact of asymmetry on science vs sensing capability

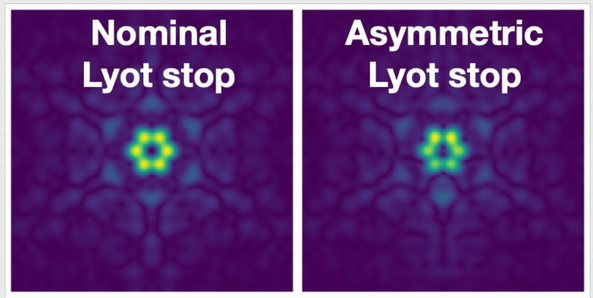
Asymmetric Lyot Stop with the vortex

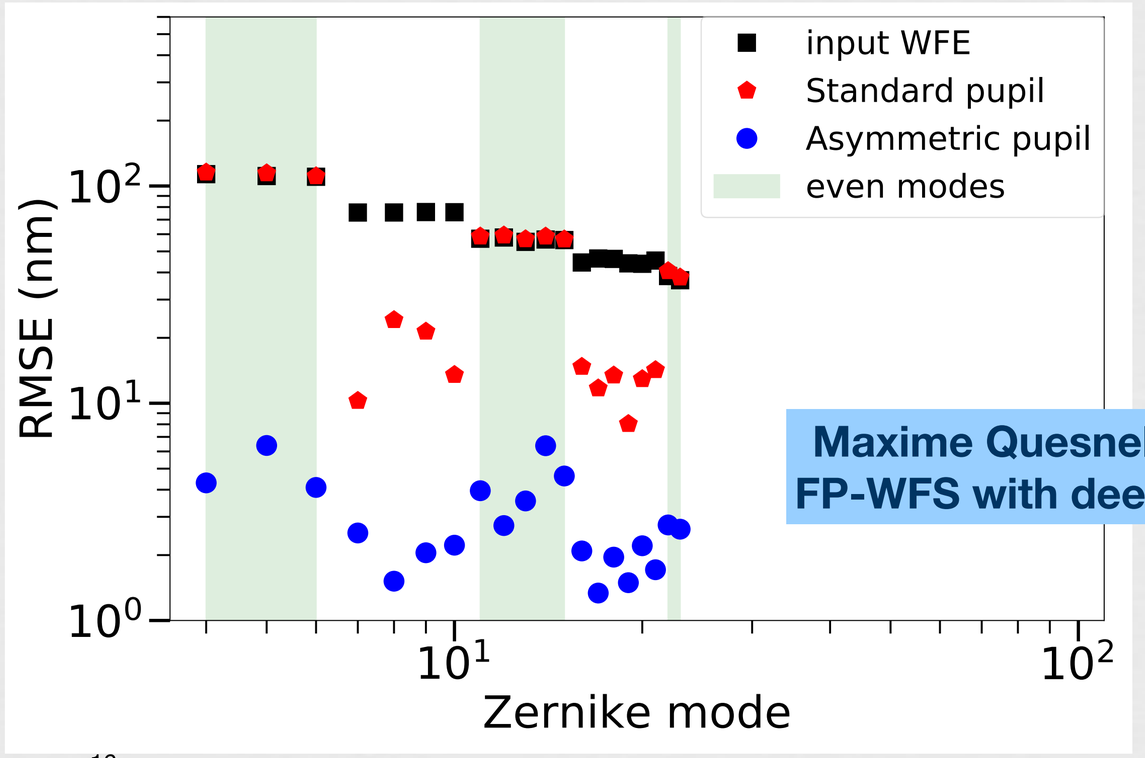
Conceptual validation



- Why in the **Lyot plane**? does not impact coronagraphic performance
- No analytical solution, but non-linear solution learned with a **neural network**





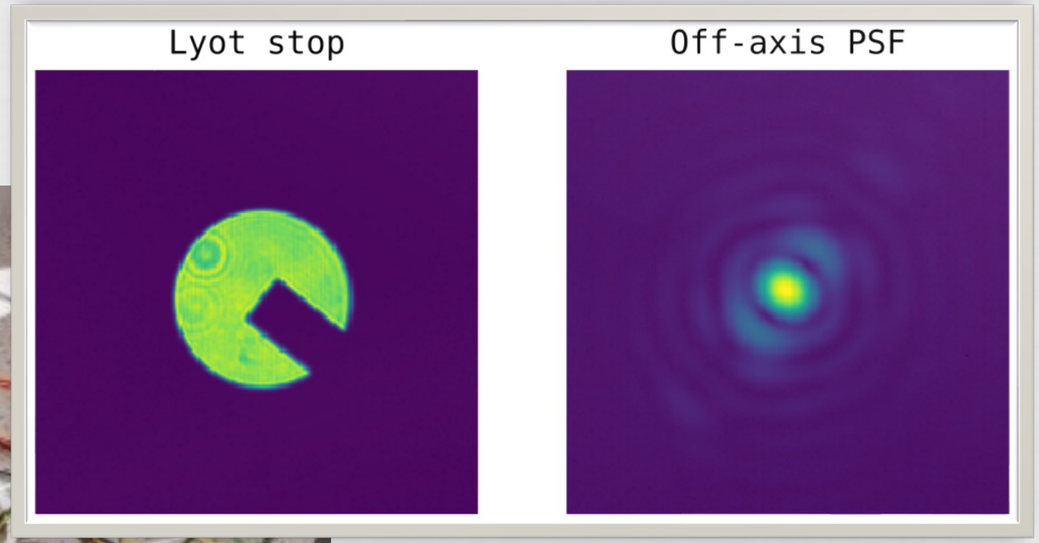


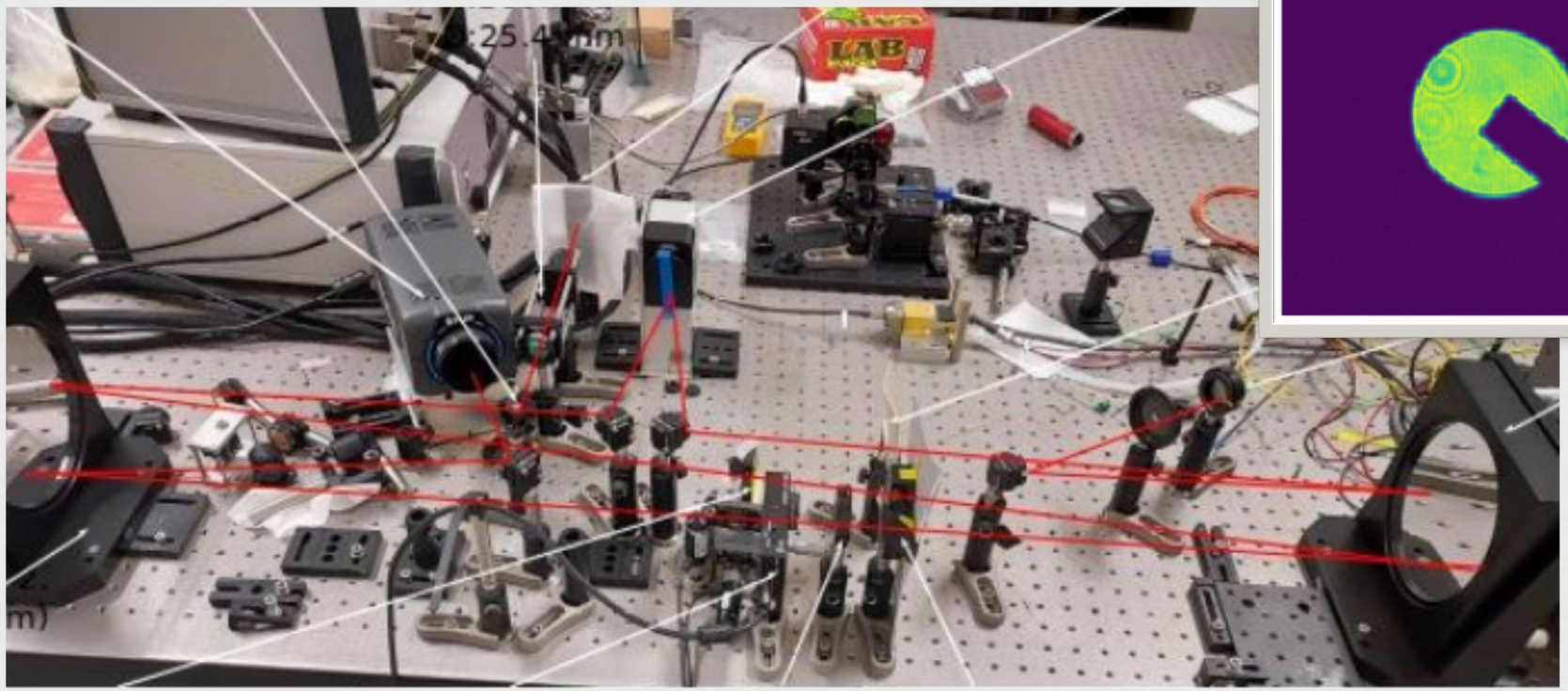
Maxime Quesnel's poster
FP-WFS with deep learning

Asymmetric Lyot Stop with the vortex

Experimental validation

- VODCA : Vortex Optical Demonstrator for Coronagraphic Applications
- L and M band sources; Low order DM
- Lyot plane asymmetric mask





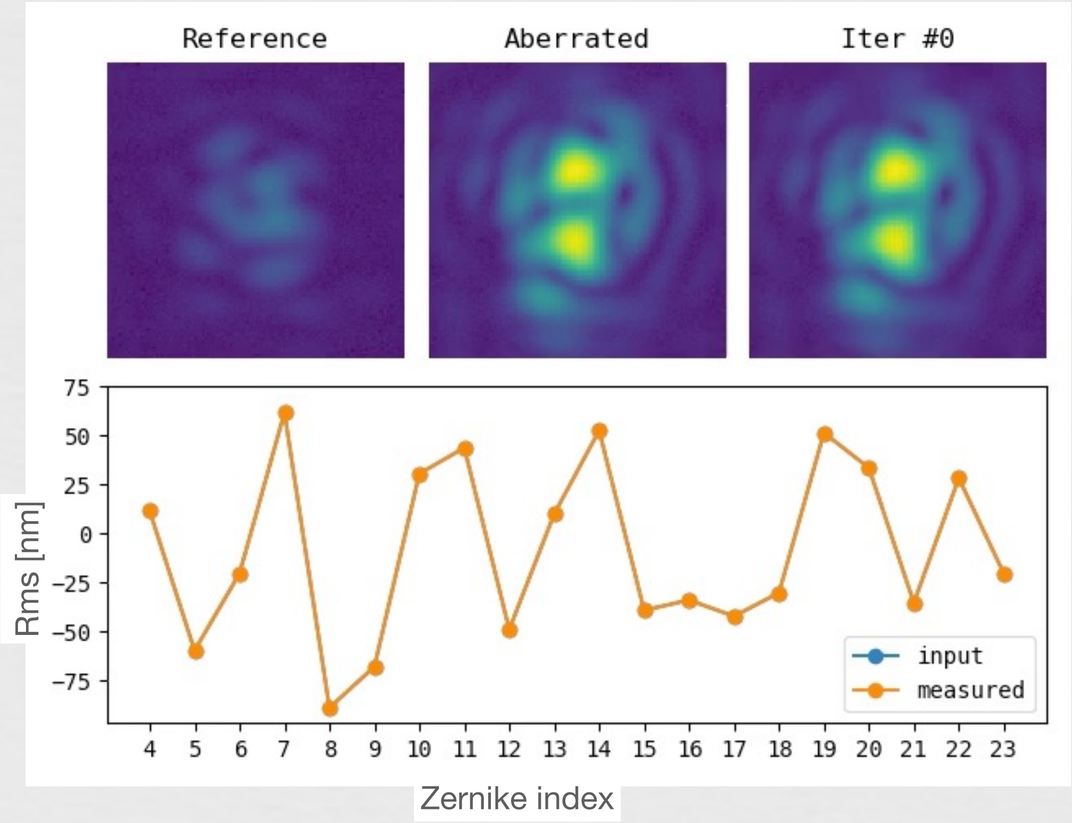
Shared credits with:
- Jyotirmay Paul (Postdoc)
- Yash Saraswat (Undergrad)

Asymmetric Lyot mask with the vortex

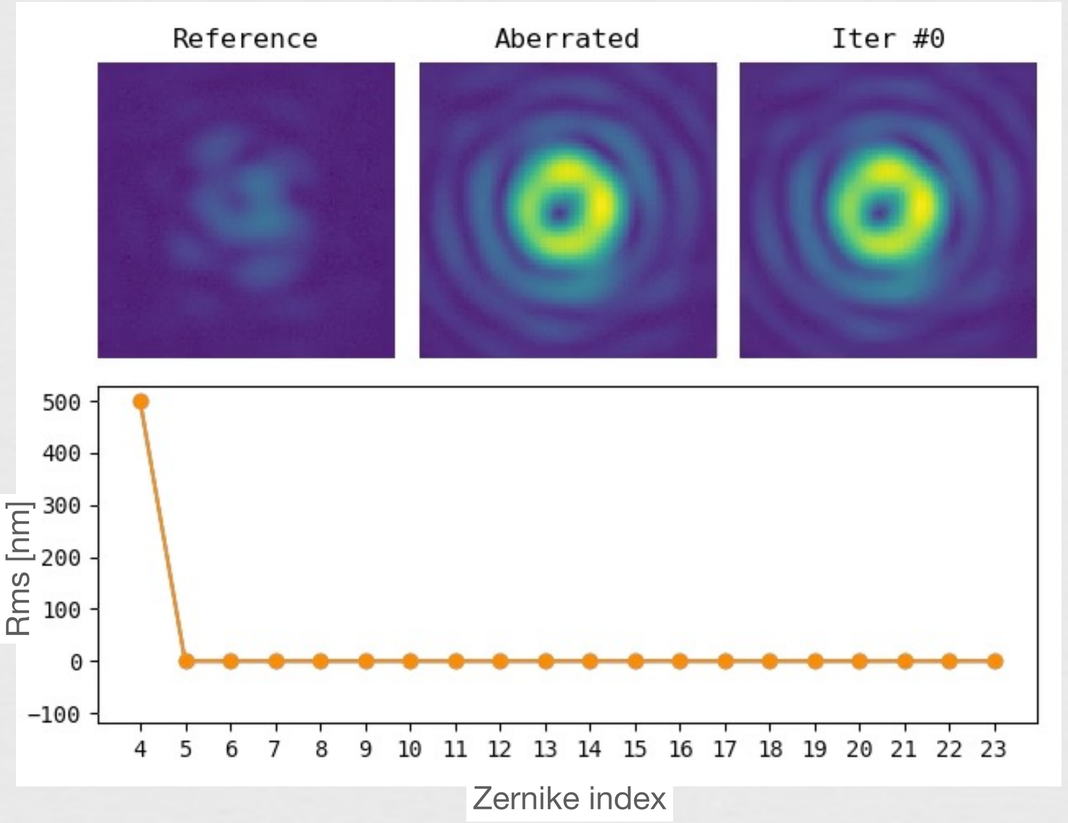
First tests on VODCA bench

Resnet architecture
Dataset: 10,000 entries
Training WFE: 200nm on 20 Zernike

Input WFE: 200nm on 20 modes



Input WFE: 500nm defocus



Future work

- Complete **analysis** and **optimization** of the asymmetric Lyot mask for the vortex coronagraph (incl. **trade-off** with HCI performance)
- Test different **inference** strategies (incl. supervised vs unsupervised)
- Experimental work on VODCA
- Ultimately, **on-sky** tests

Getting real !

June 2022 – ERIS commissioning

Evolution in 1 year

June 2023 – ESO/Facebook

AP-WFS in normal imaging

N-band mag-3

- 1Hz vs 10Hz