Breaking the symmetry

Asymmetric Lyot stops for focal plane wavefront sensing

METIS focal plane wavefront control

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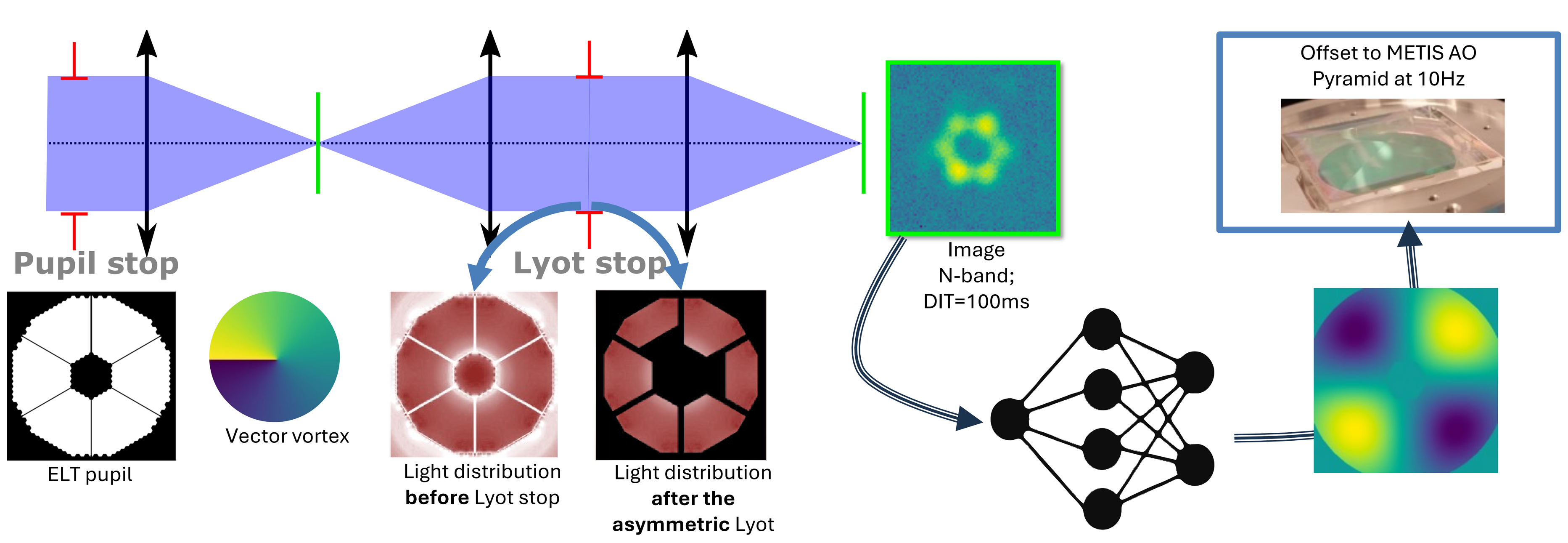
Context: ELT/METIS & HCI challenges

- **Mid-infrared** ELT imager and spectrograph, covering wavelength from **3 to 12μm**
- High-contrast imaging: **vortex coronagraph**, apodising phase plate, shaped pupil plate
- Chromaticity of **water vapor seeing** will play a key role in the final HCI performance: dynamical aberration with up to 300nm rms WFE at 11.5μm

➜ **Requirement:**
Instantaneous wavefront measurement with a single focal plane coronagraphic image
➜ **Operation goal:**
- **correction rate:** 10Hz or DIT of 100ms
- **loop delay :** 200-300ms,
- **low-order correction:** min. 20 modes (Zernike or ELT-M4 basis)

Asymmetric Lyot waveFront Sensing

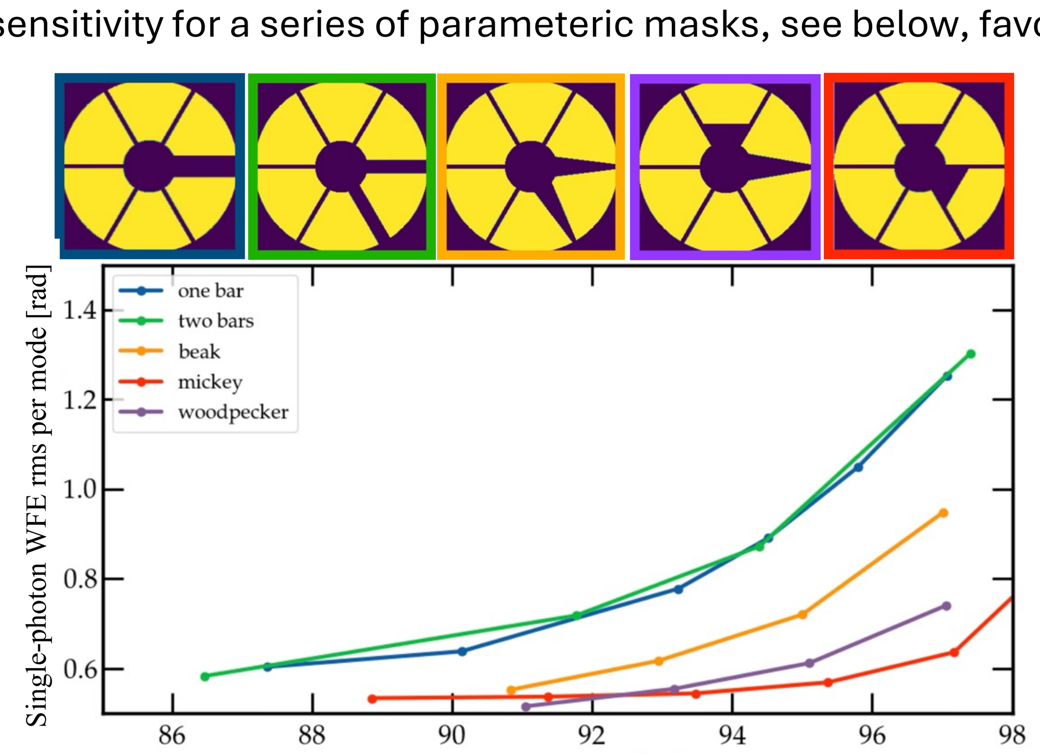
- Asymmetric Lyot stop: **1/** break the sign ambiguity , **2/** in the Lyot plane to preserve coronagraphic efficiency
- Inversion problem solved with **deep learning** to recover modal coefficients
- ALF is a **slow real-time loop**, offsetting the Pyramid, to follow up the water vapor dynamics



Which asymmetry to choose?

Maximizing sensitivity thanks to Fisher information & automatic differentiation

- Fundamental wavefront sensing precision quantified by **Fisher Information Matrix** (FIM)
- FIM calculation (see more on the right) enabled by **differential optical model of the vortex coronagraph**
- Evaluation of the sensitivity for a series of parameteric masks, see below, favors the '**mickey**' pattern



🎉 Our winner 🎉
(for classical vortex coronagraph)

- This hybrid theoretical-numerical analysis is then confirmed by end-to-end simulations using supervised learning (CNN) to validate our Lyot stop patterns. Then full end-to-end simulations predict the water vapour correction performance . See more on the right.

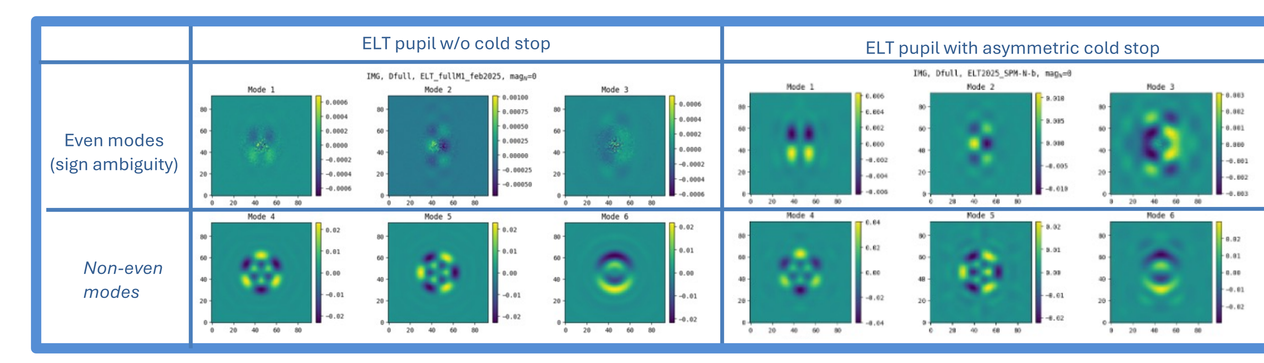
More in-depth

Breaking the degeneracy

Illustration of the impact of asymmetries on the sign ambiguity in PSF

- For individual modes m, we compute

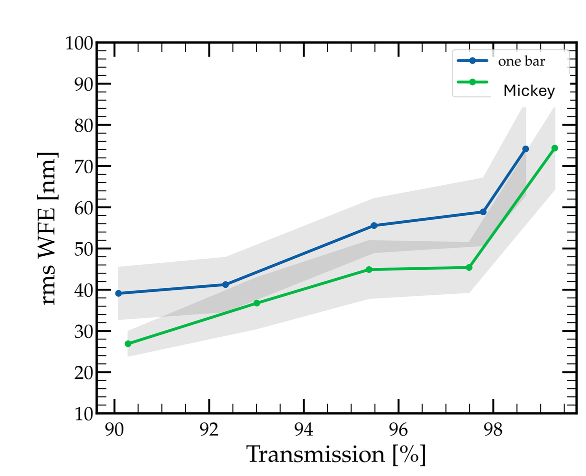
$$[psf(+m) - psf(-m)] \,/\, max(psf)$$



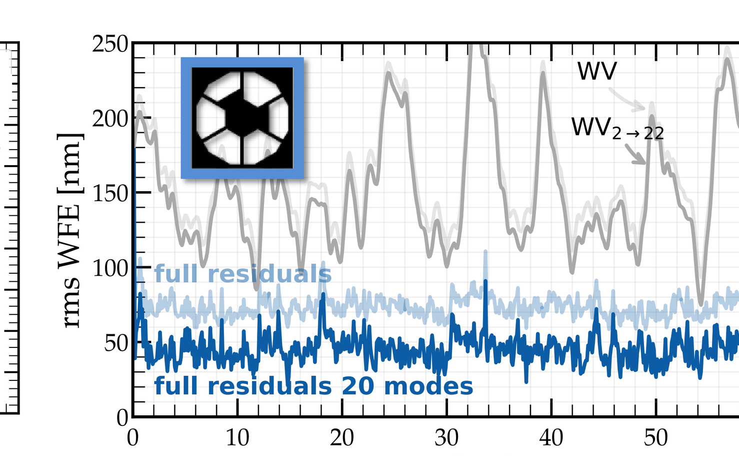
➜ The **ELT aperture asymmetric spider** is **not large enough** : effect is buried in photon and background noise. **Need to inject larger asymmetry, which is done with the METIS cold stops**

End-to-end simulations

- Supervised learning, using ResNet-18, takes one scientific image in input to output a vector of modal coefficients
- **Validation** of Lyot asymmetric mask in simulations, see bottom left figure.
- **Realistic simulations** of the METIS imager include the instrumental setup, SCAO residual phase screens, water vapor and NCPA phase screens, and METIS photometry, see bottom right figure.



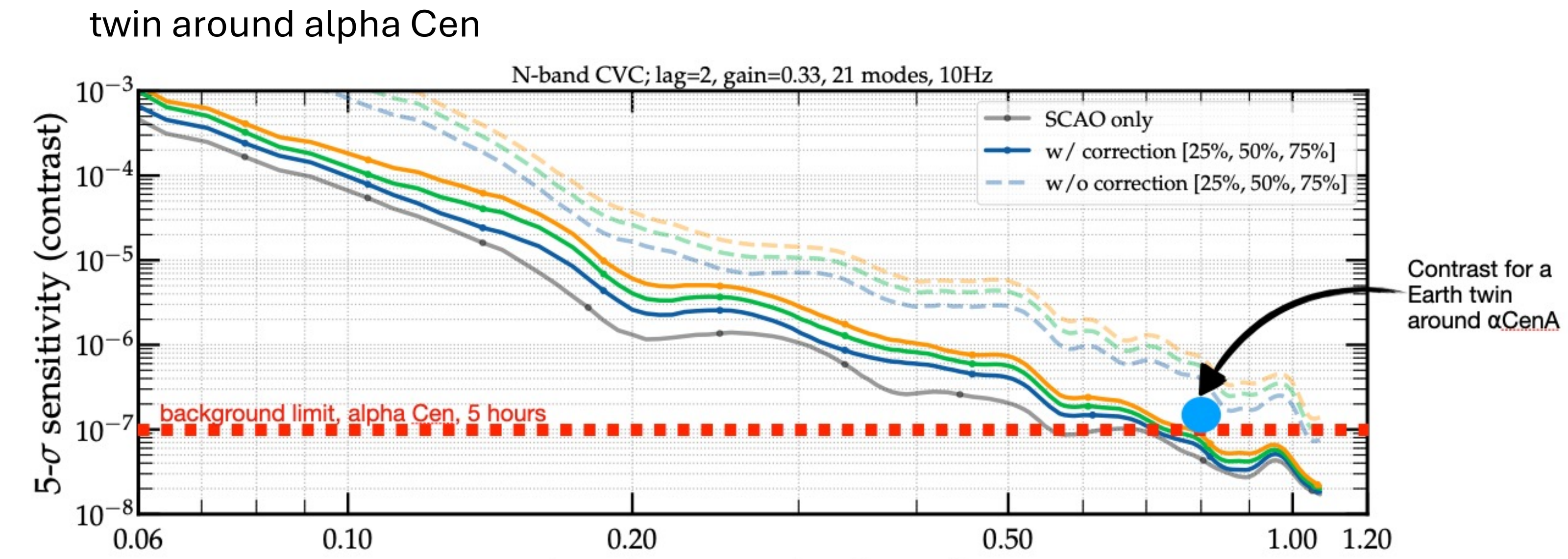
End-to-end evaluation of WFS sensitivity for different asymmetric masks. Residual WFE 20 modes for an input of 200nm rms.
N-magnitude = 0; include photon & background noise



Closed-loop simulation with SCAO residuals & water vapor. Correction framerate at 10Hz.
Using the "mickey" Lyot stop with 8% loss of transmission

Enabling the detection of temperate planets

- Water vapor seeing is the key driver of HCI performance in N-band with METIS
- FPWFS with ALF will improve the contrast, enabling the detection of, e.g., Earth-twin around alpha Cen



Perspectives

- **Supervised learning** using the METIS SCAO telescope simulator, i.e. an optical unit developped for METIS AIT
- Currently investigating **reinforcement learning** methods (see Taskin et al., and Nousianen et al., in this conference) for **self-calibration on-sky**

References

1. Pathak et al., water vapour in the mid-infrared, submitted
2. Nousianen et al, PO4NCPA, submitted
3. Taskin et al, *this conference, RL for METIS*
4. Paterson 2008, JPhCS, 139, 012021
5. Desdoigts et al. 2024, arXiv, 2406.08704
6. Orban de Xivry et al. 2024, SPIE, 13097, 130973Z

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