ZELDA: a Link to exoplanet imaging

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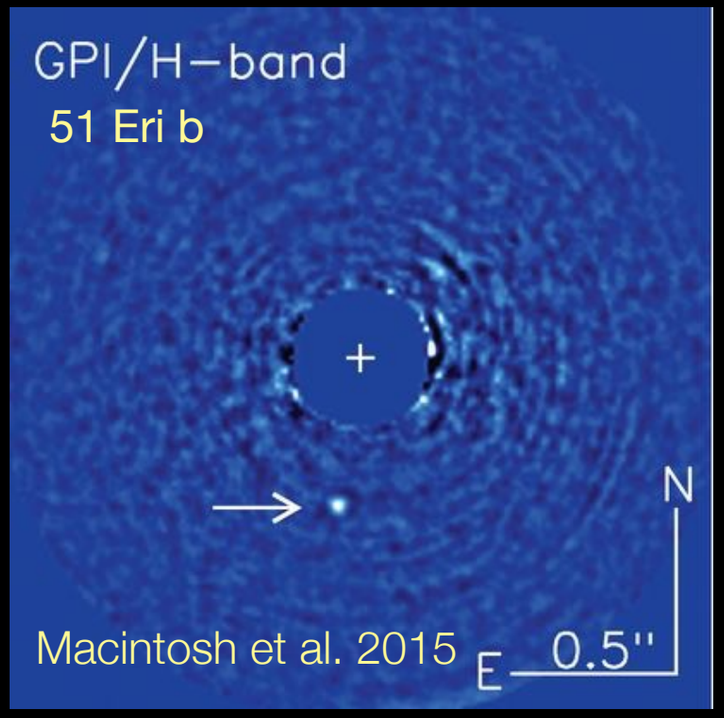
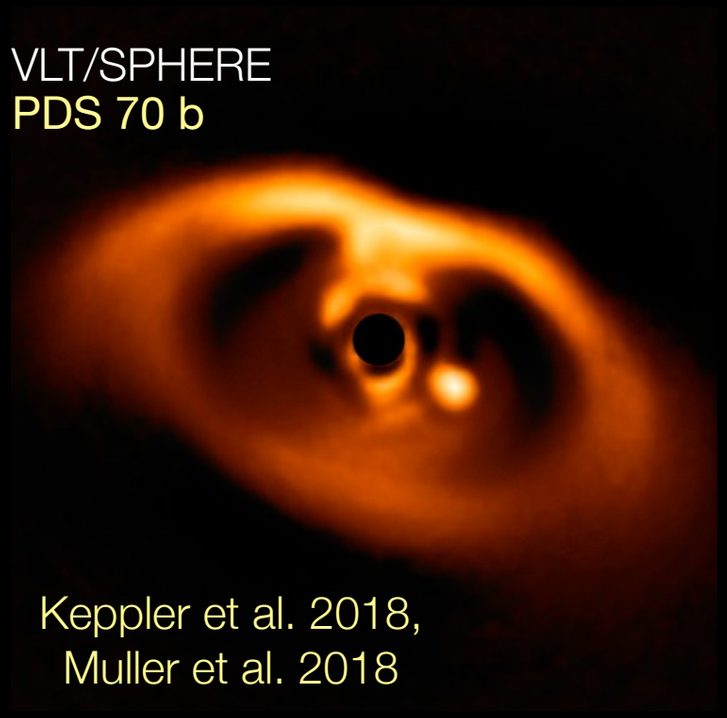
A. Caillat, J. Le Merrer, A. Carlotti, J.-L. Beuzit, D. Mouillet, and many others

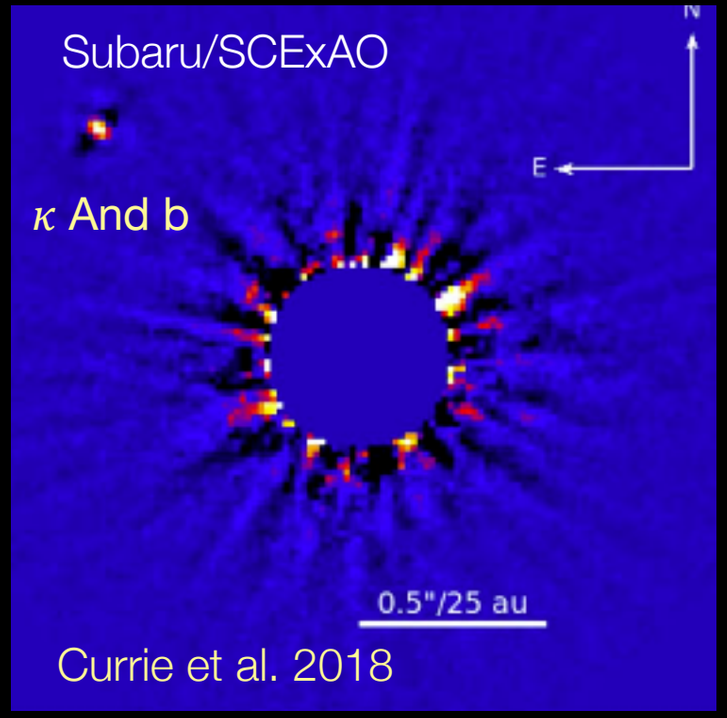
Virtual Workshop on Advanced Wavefront Sensing - May 1st, 2020

Exoplanet imaging and spectroscopy

- Ground-based observations in the near-infrared
  - VLT/SPHERE, Gemini/GPI, Subaru/SCExAO, etc
  - Extreme adaptive optics (XAO), coronagraphy, image processing
  - disks, warm or massive gas giant planets
  - Expected contrast up to 10^7 @0.2” in H-band



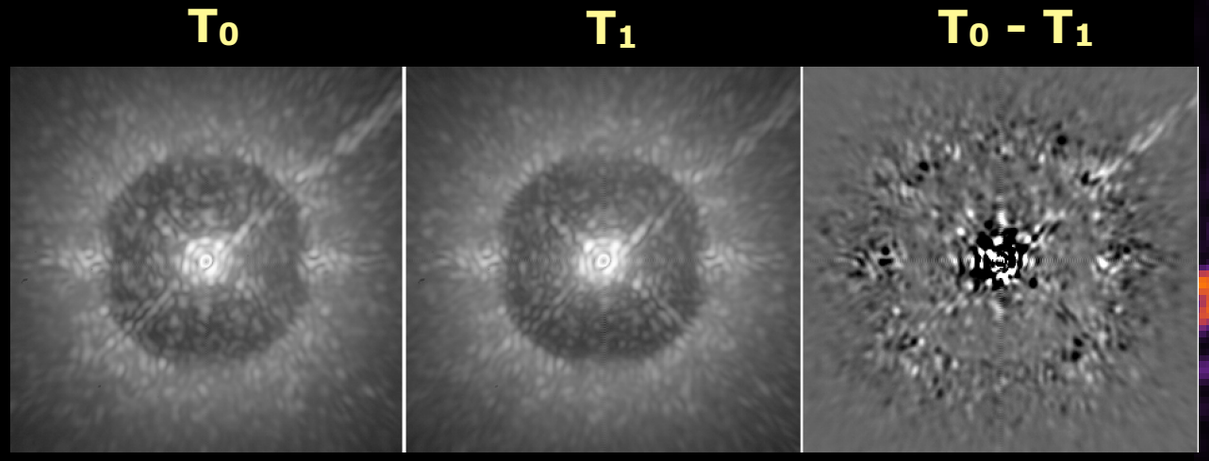




Current performance: 10^4-10^6 contrast @ 0.1-0.5”

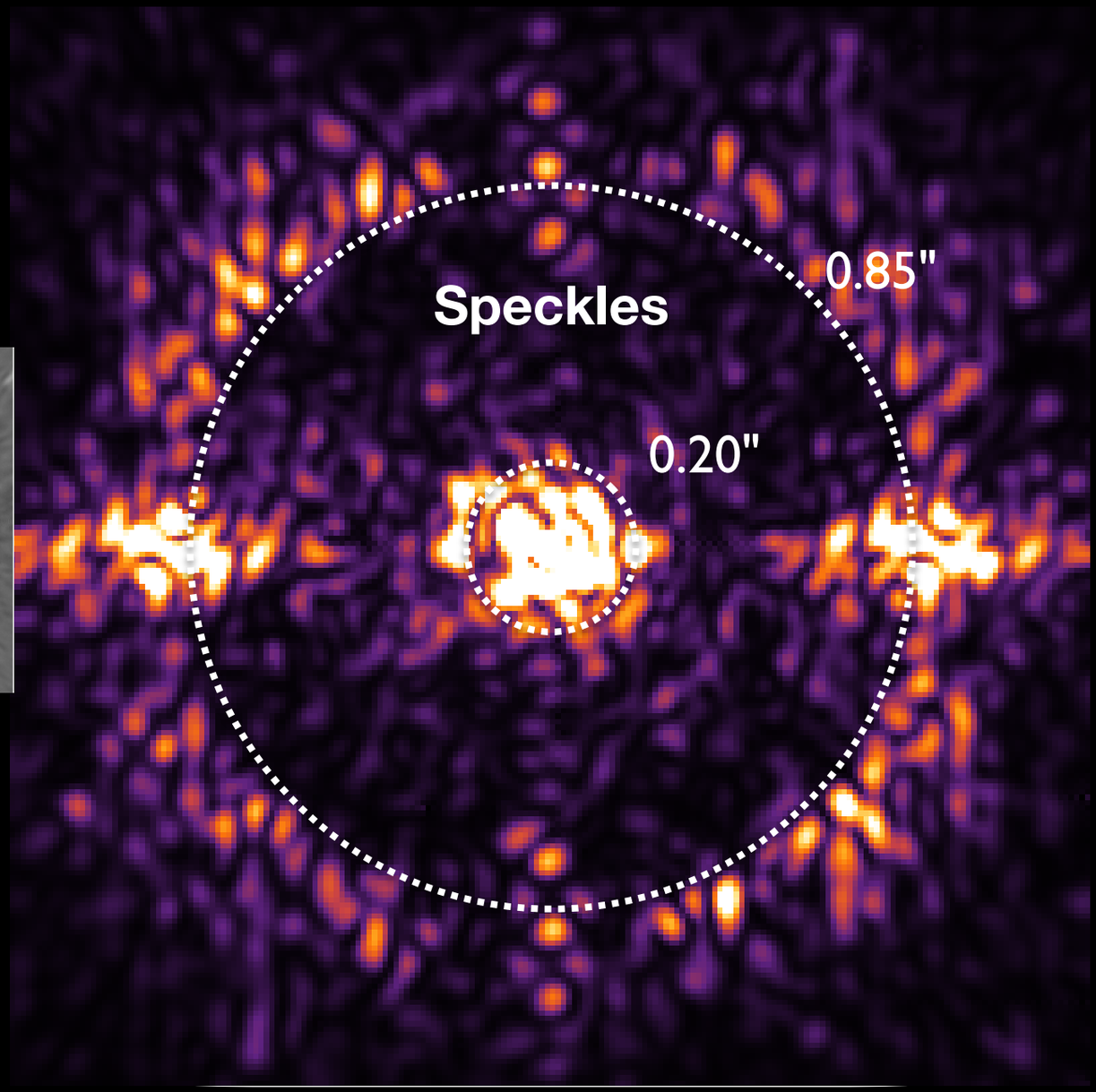
Imaging colder/lighter exoplanets

- Instrument limitations
  - **quasi-static aberrations**
  - **temporal stability**



- Need for a clean and stable star image optimal starlight rejection
- Our solution:
  - calibration with ZELDA
    - N'Diaye+2013, 2016, Vigan+2019

Coronagraphic image on VLT/SPHERE



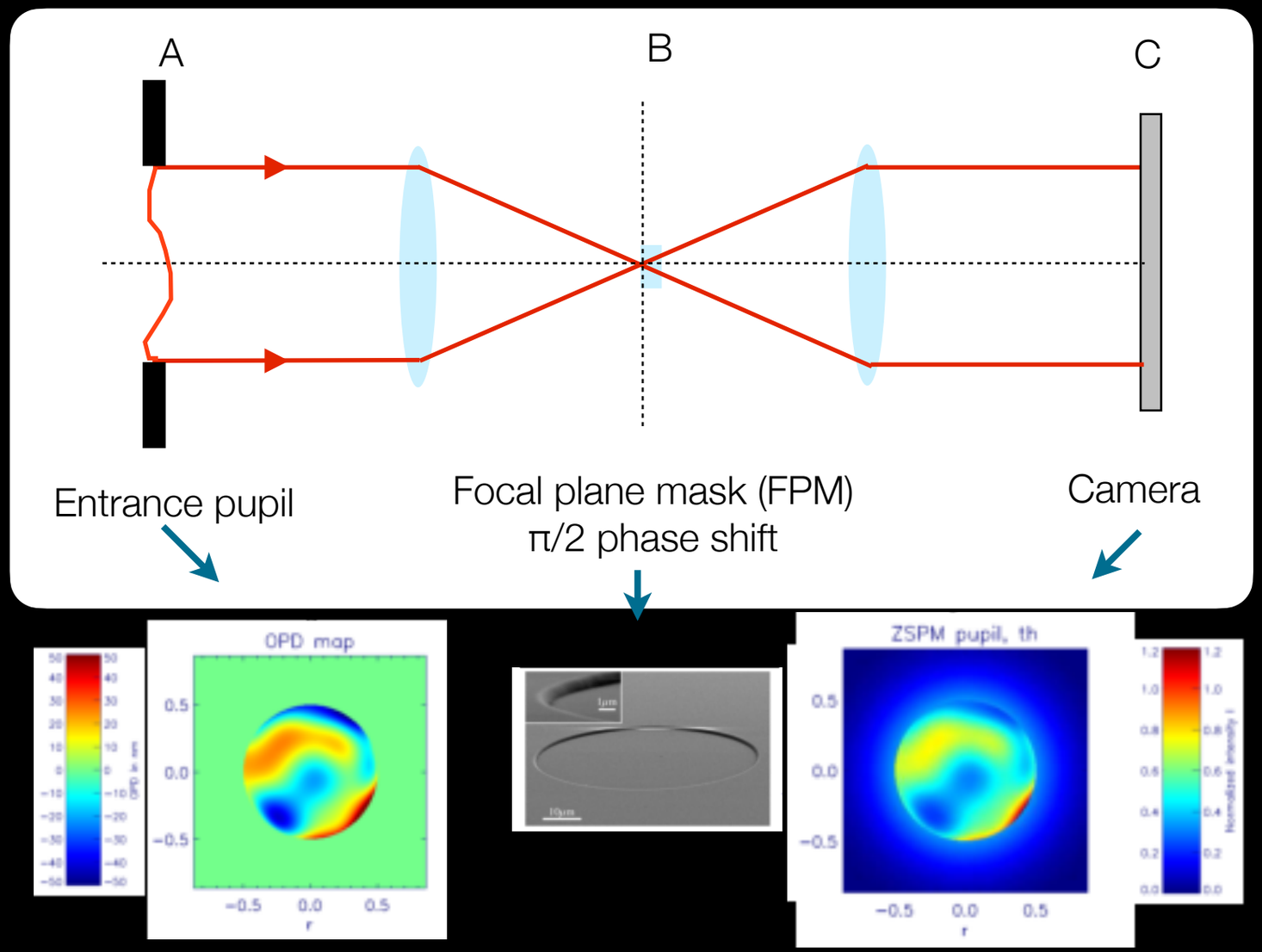
Contrast limit: 10^4-10^6

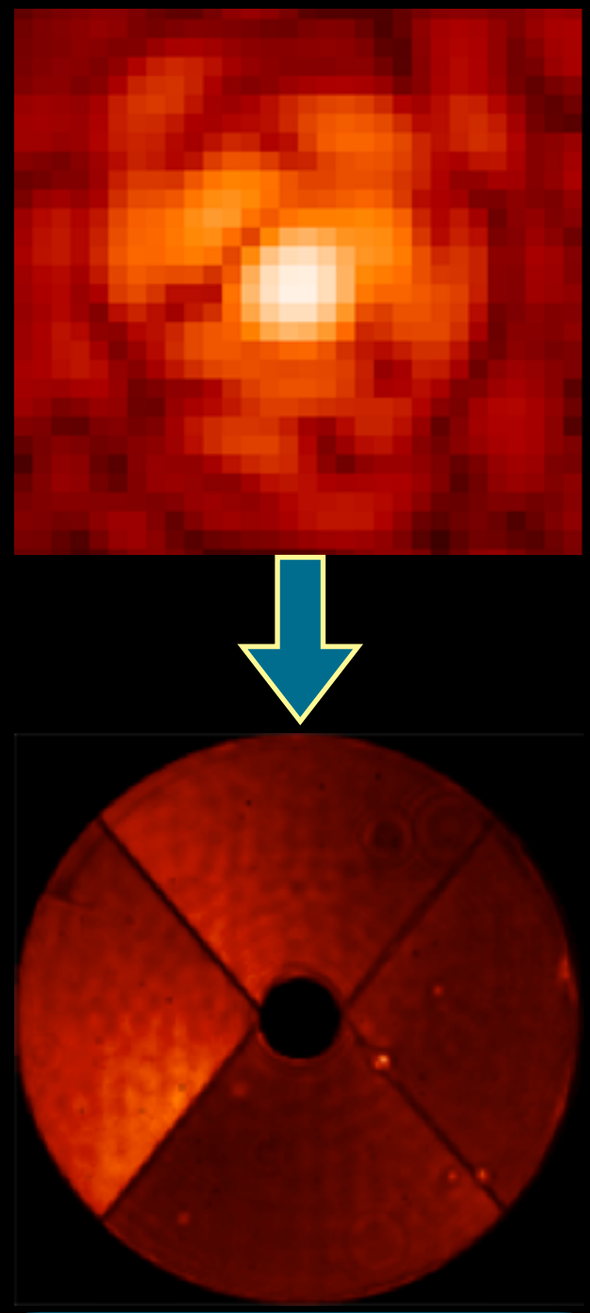
The Legend of ZELDA

Zernike wavefront sensor

- Conversion of phase errors φ into intensity Ic

$$Ic = \alpha \sin(\varphi) + \beta$$





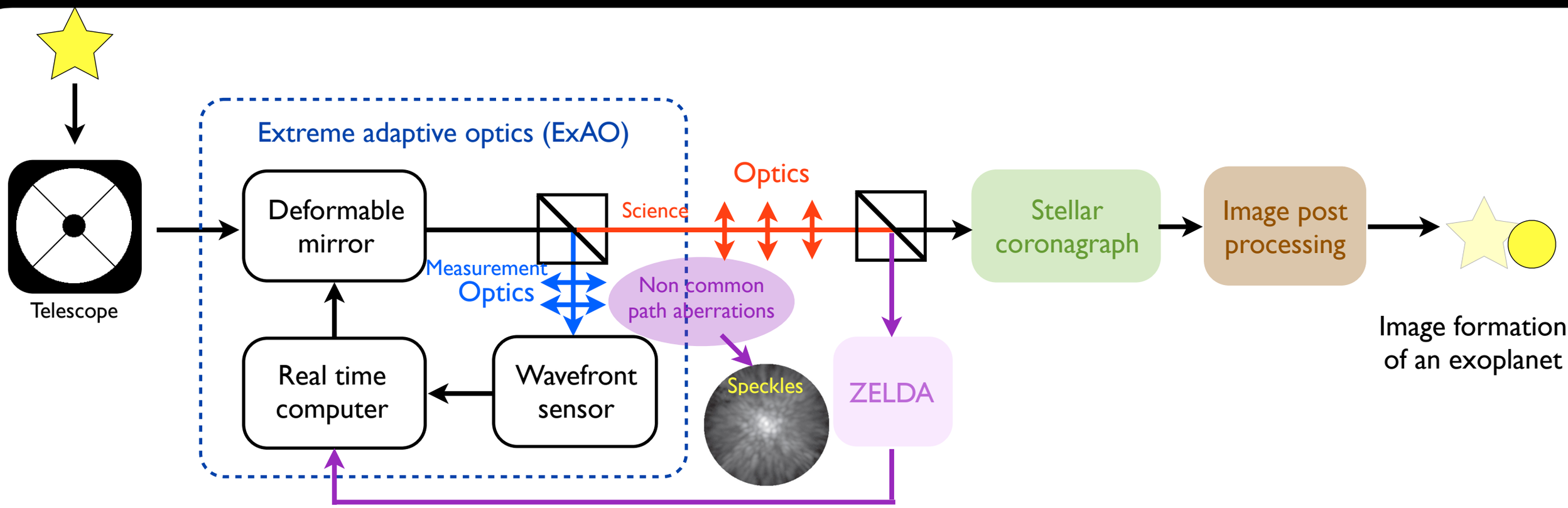
Small errors: Ic = $\alpha\varphi + \beta$

Low-wind effects

N'Diaye et al. 2013

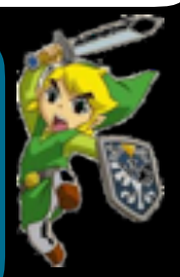
Implementation in VLT/SPHERE

Zernike sensor for Extremely accurate measurements of Low-level Differential Aberrations



- Initial measurement strategies
  - VLT/SPHERE: off-line phase diversity
  - Gemini/GPI: Mach-Zehnder interferometer behind coronagraph

- **Our proposal**
  - **ZELDA, a concept based on phase-contrast technique**

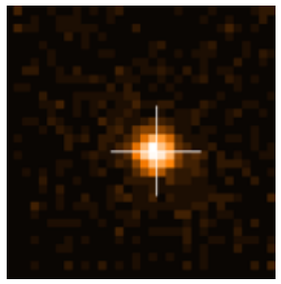


Sauvage et al. 2007, Wallace et al. 2010

N'Diaye et al. 2013, 2016, Vigan et al. 2019

Current implementation in VLT/SPHERE

Beuzit et al. 2019



DTTS

CPI

Deformable mirror (DM)

ZIMPOL

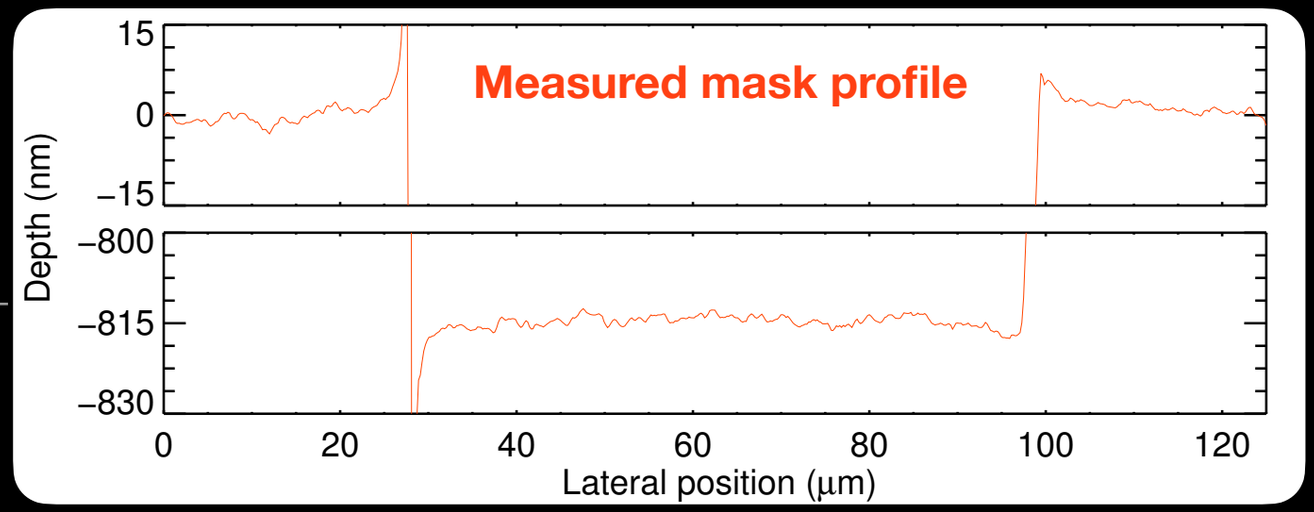
IFS

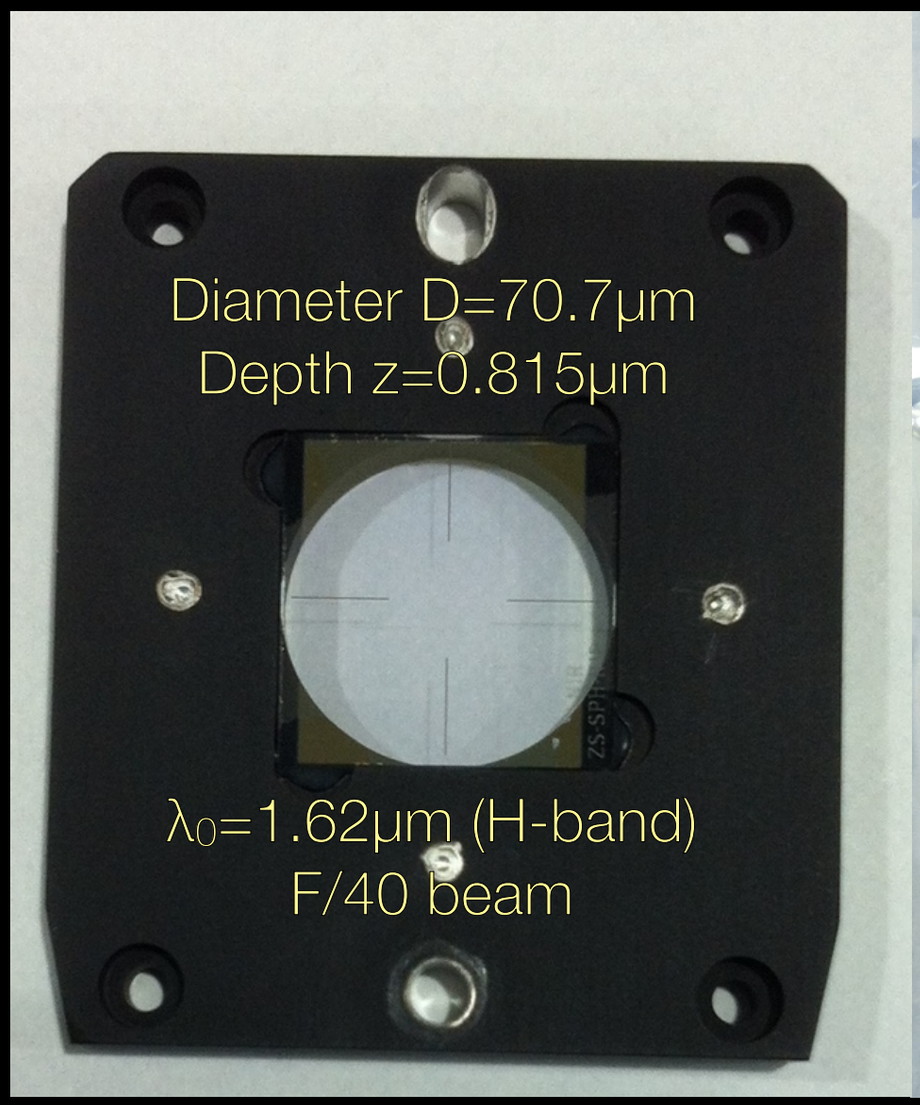
IRDIS

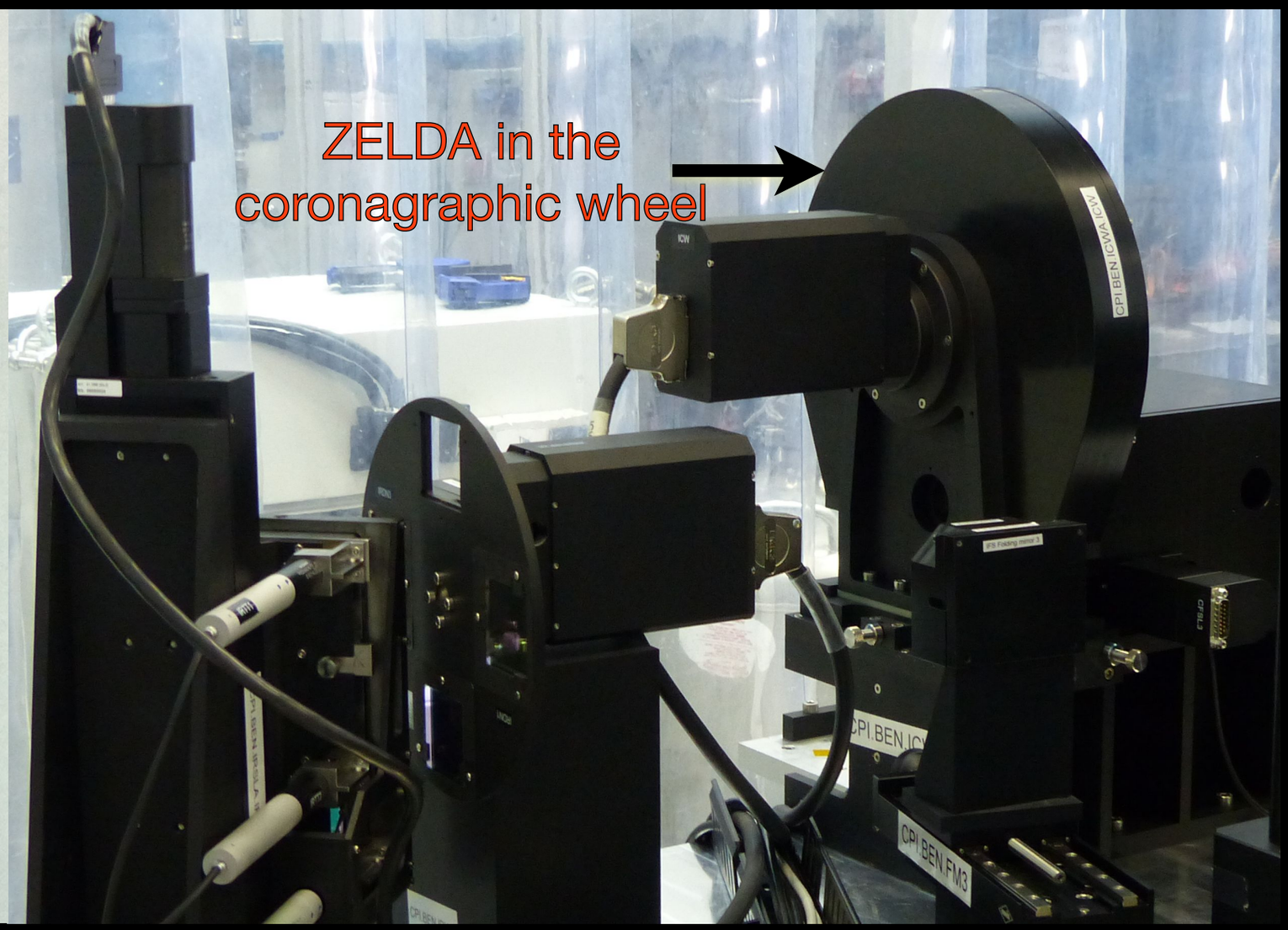
NIR corono / ZELDA

ZELDA prototype in SPHERE

- Fused silica substrate
- Photolithography (SILIOS,France)
- Within 1% specs





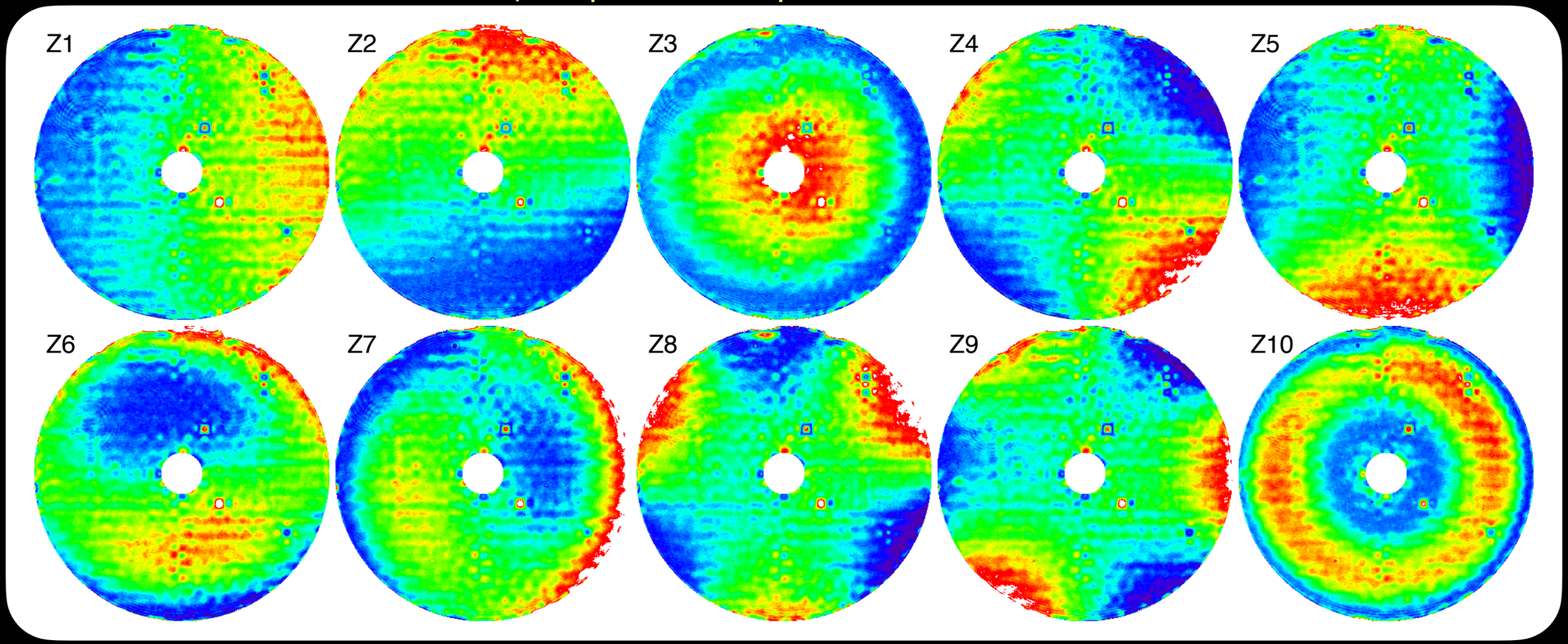


Installation during SPHERE integration in Paranal in April 2014

ZELDA II : The adventure on SPHERE

Measurement of introduced low-order aberration

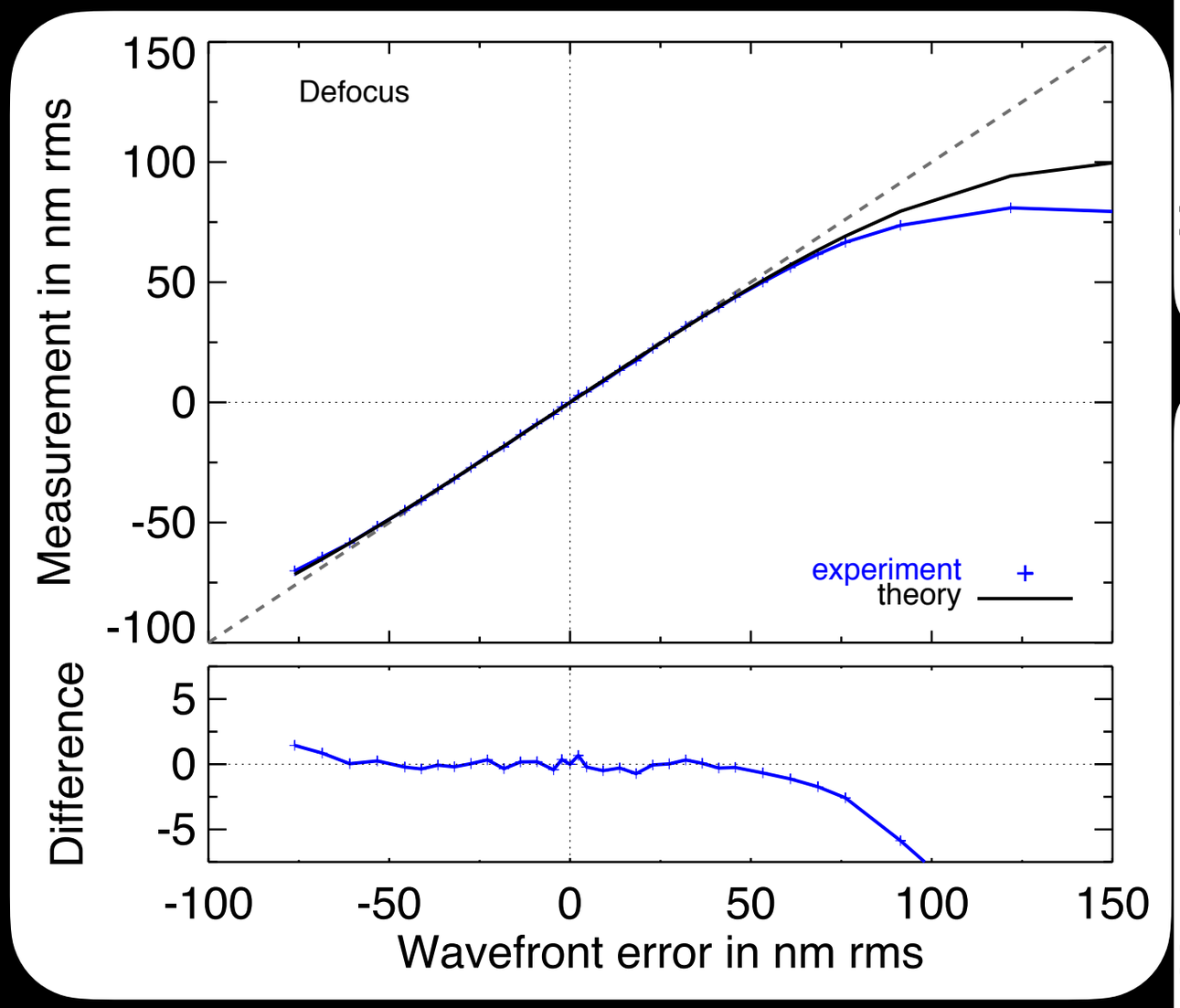
- Internal point source
- IRDIS pupil-imaging mode, λ = 1642 nm (Fe II filter)
- PSF centered manually + closed loop on near-IR DTTS
- Zernike and Fourier modes, amplitude ramps: -250 ➙ 600 nm PtV



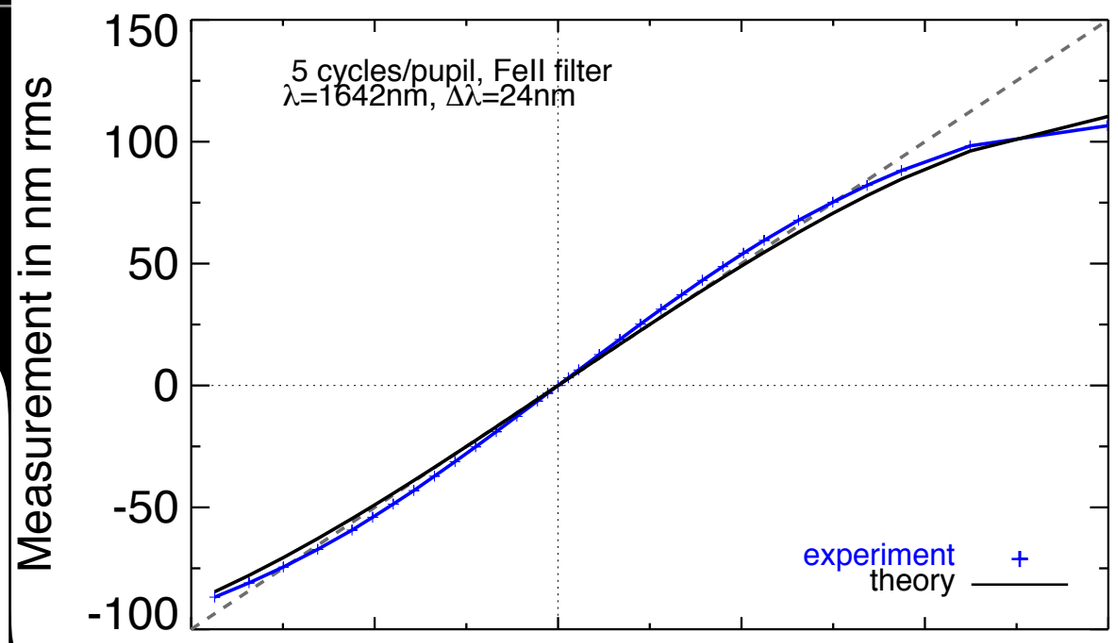
Zernike modes introduced with 400nm on the deformable mirror

Performance assessment

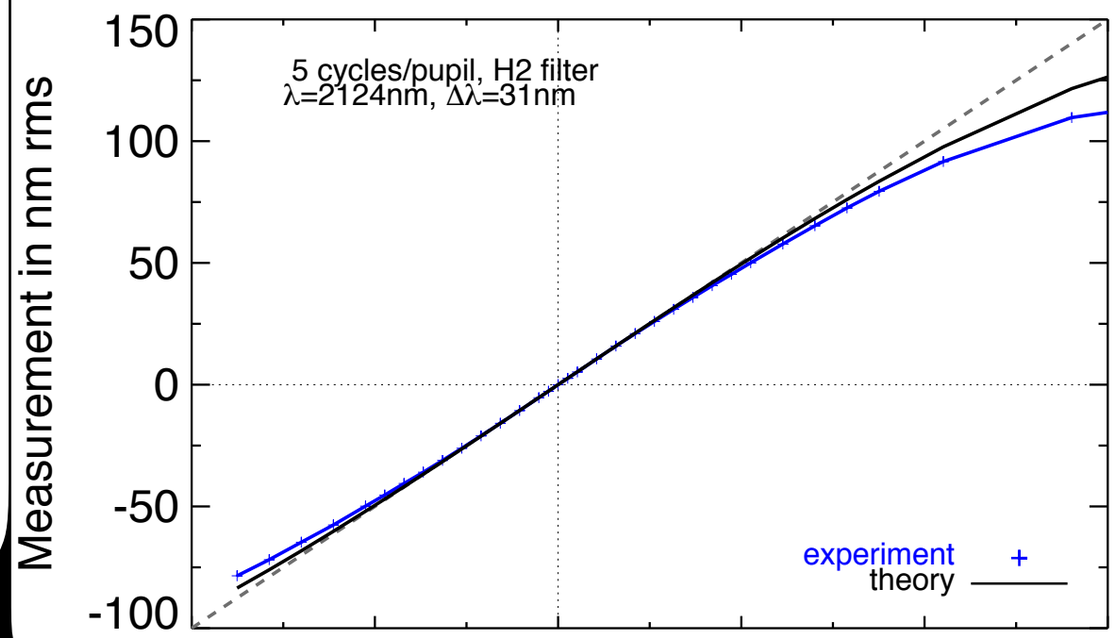
- theory vs. measurements:
  - excellent agreement!
- low sensitivity to wavelength of measure



Reference wavelength (H-band)

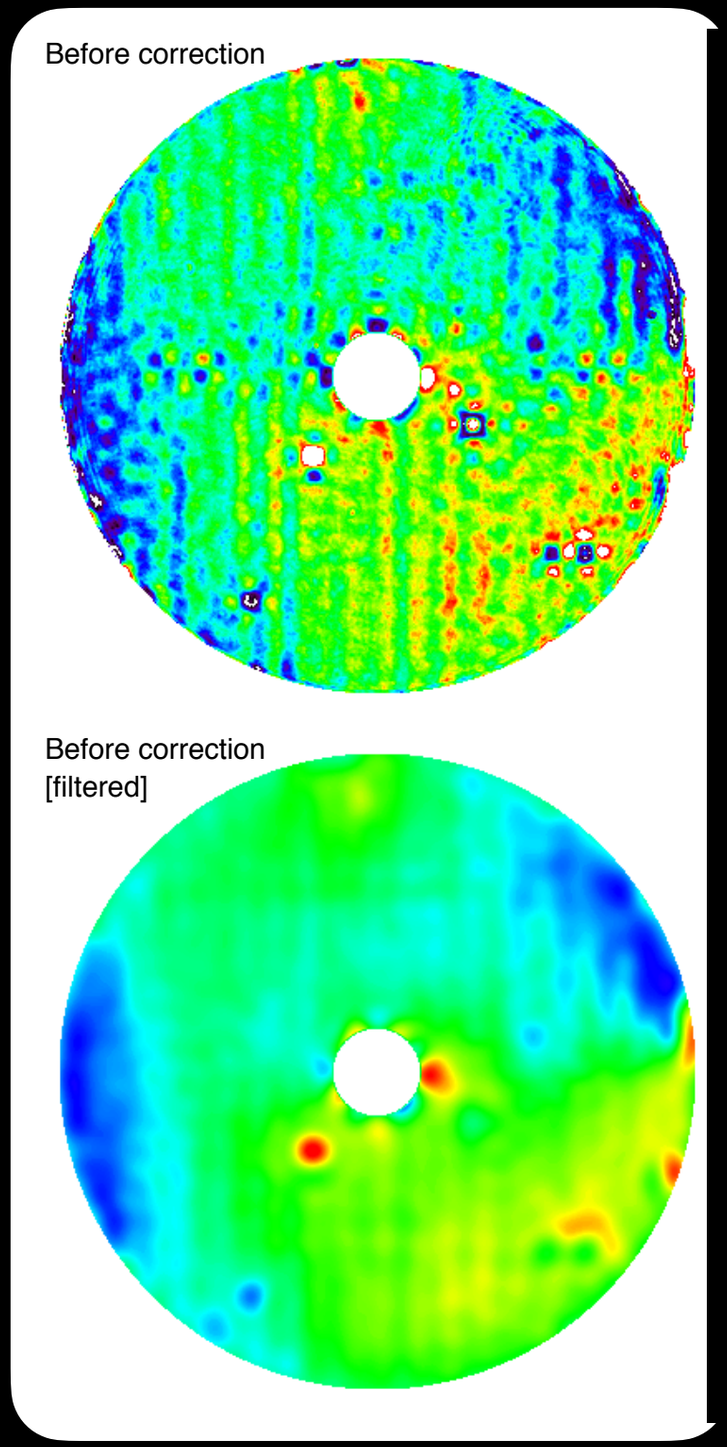


Measurement in K-band

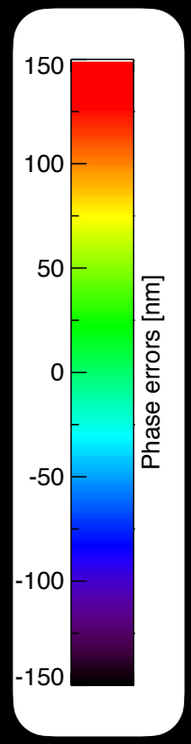


NCPA measurement and compensation

45 nm RMS



30 nm RMS



NCPA measurement and compensation

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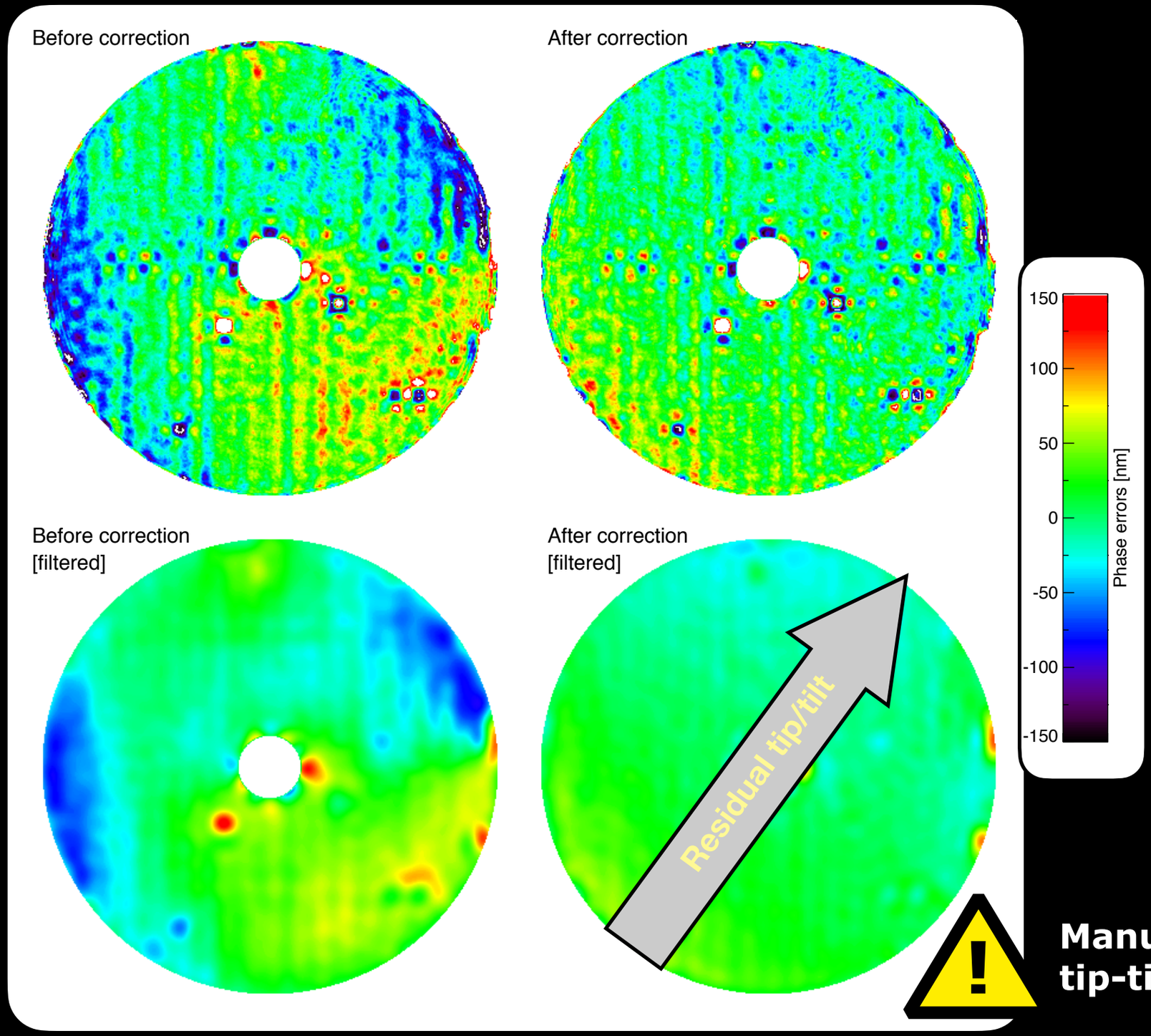


35 nm RMS

30 nm RMS

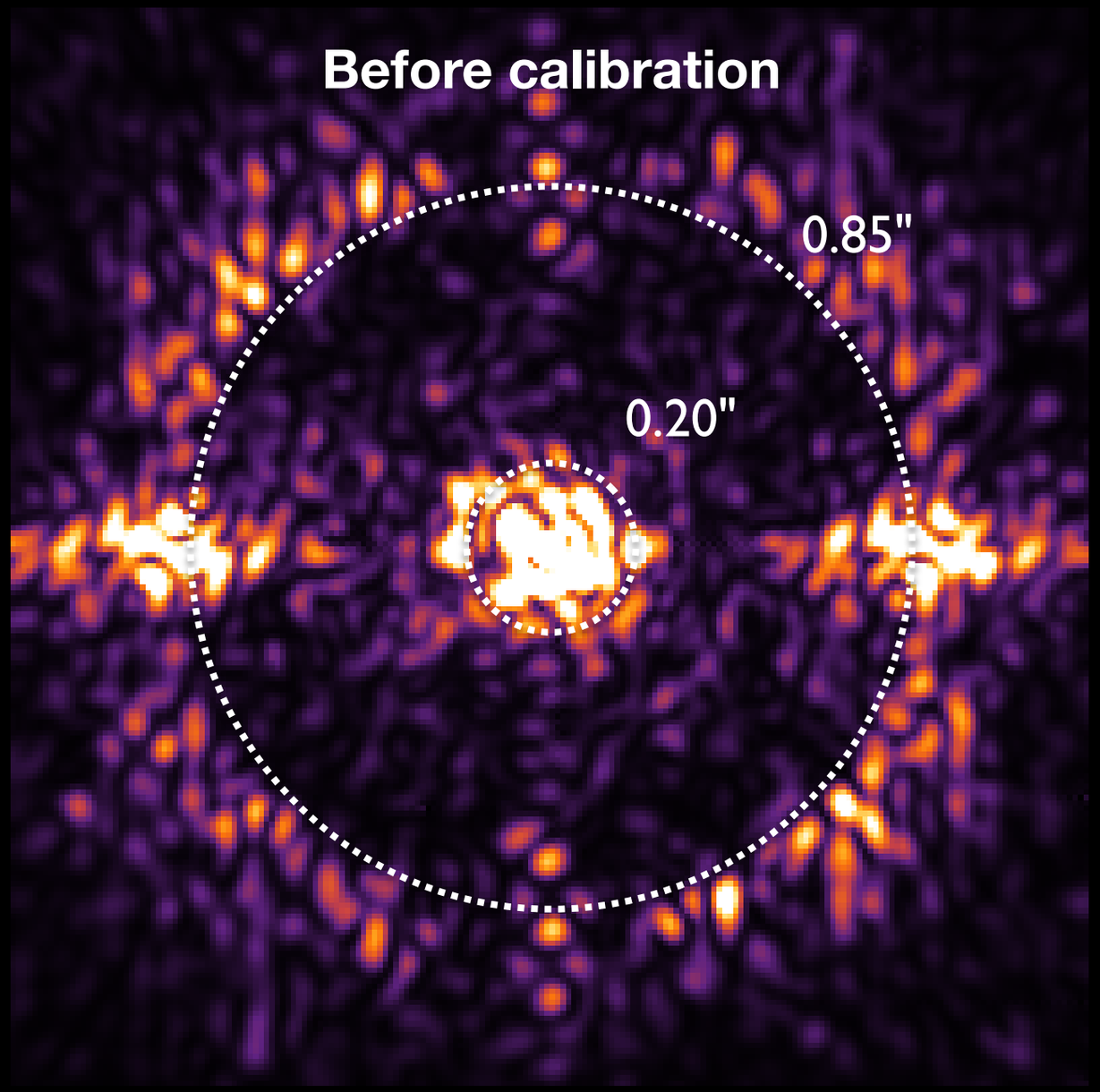
16 nm RMS

Manual centering +
tip-tilt closed loop

Impact on coronagraphic images on internal source

Tests in Dec. 2015

APLC image in H-band

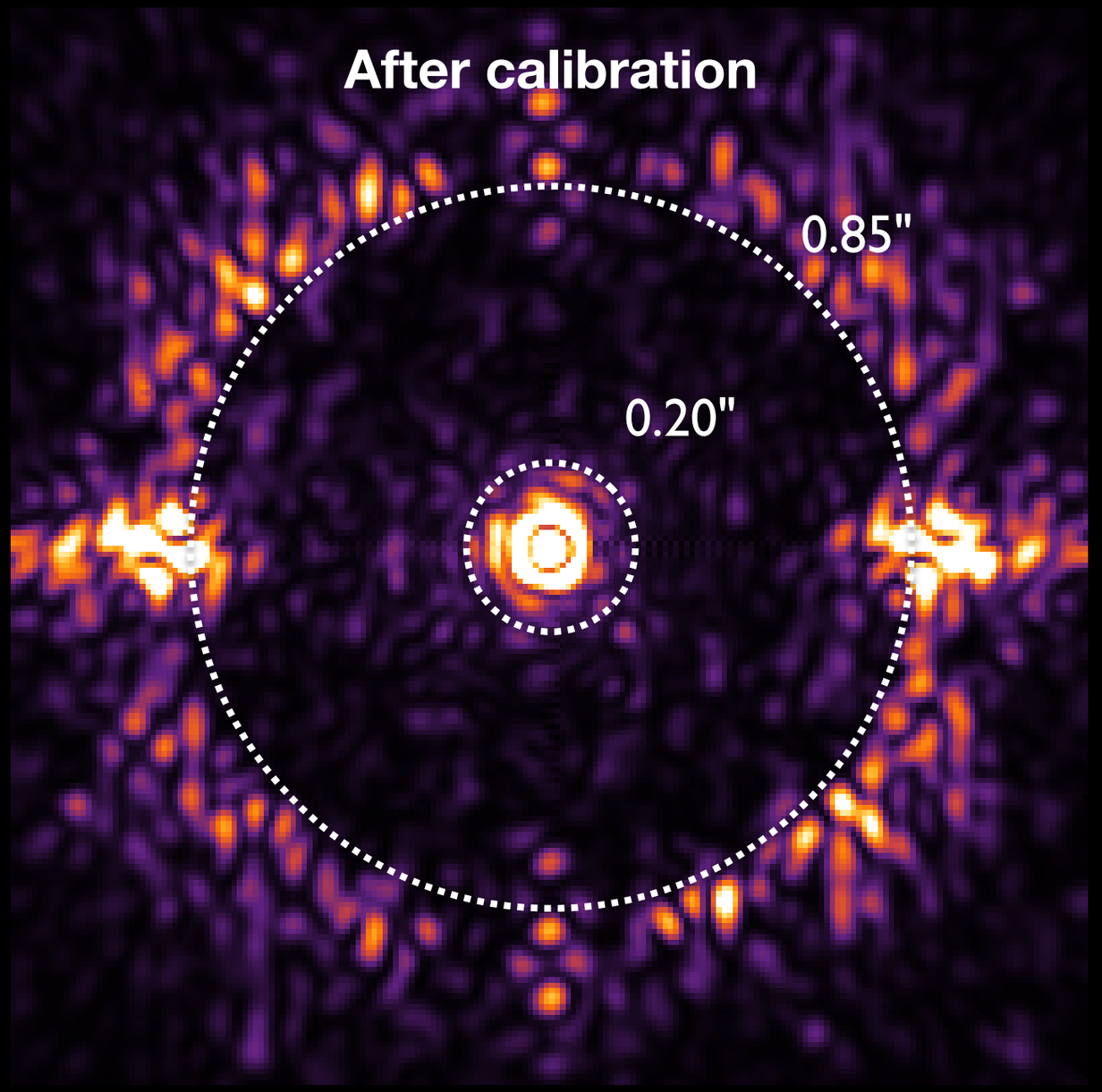


N'Diaye et al. A&A 2016

Impact on coronagraphic images on internal source

Tests in Dec. 2015

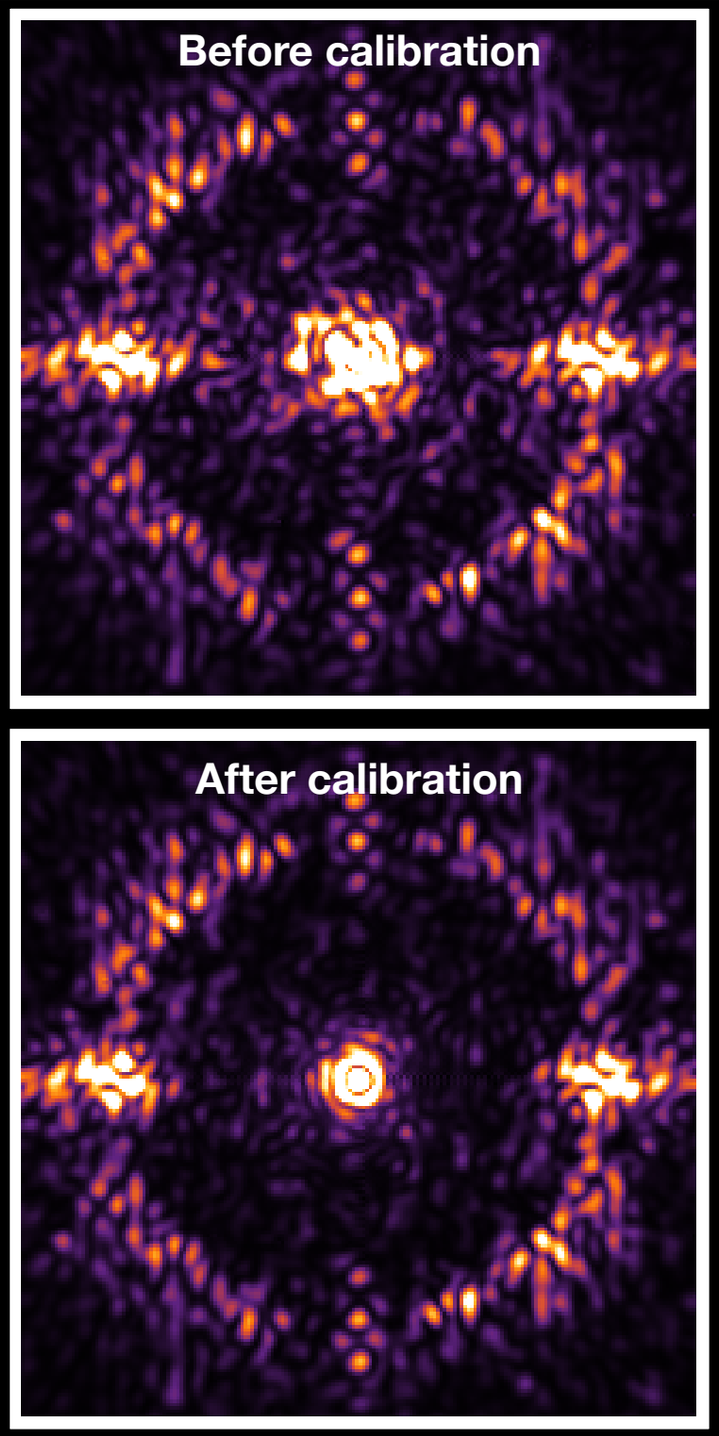
APLC image in H-band

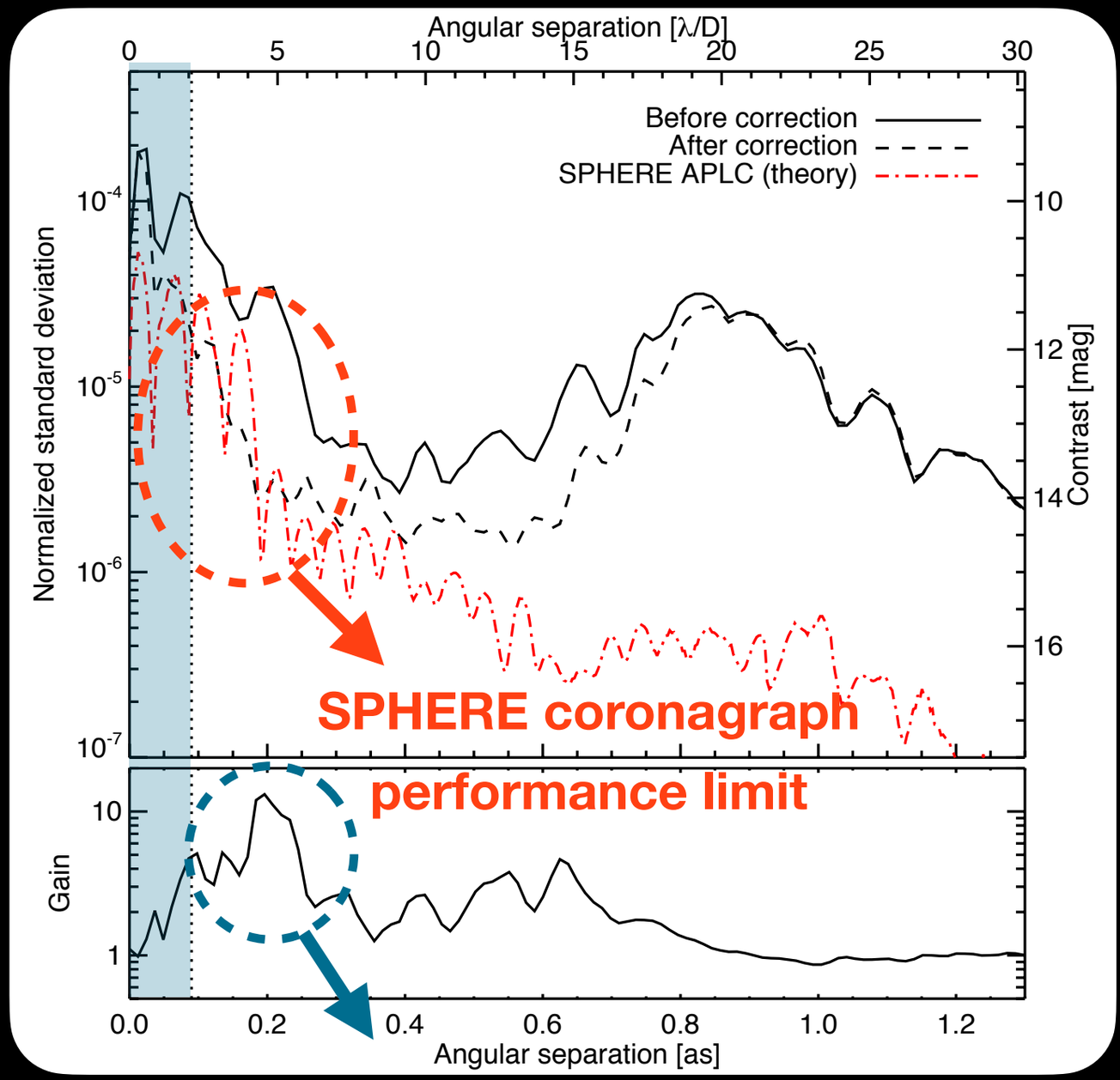


Gain x10 in contrast @ 0.2”

N’Diaye et al. A&A 2016

Impact on coronagraphic images on internal source





Gain x10 in contrast @ 0.2”

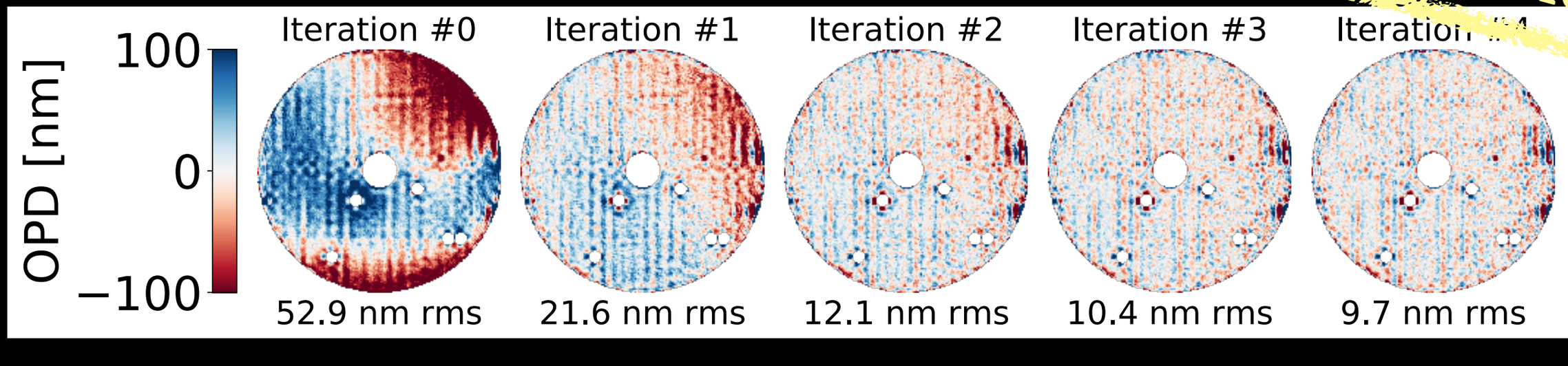
N’Diaye et al. A&A 2016

ZELDA III : A link to the sky

On-sky closed-loop correction

Tests in April 2018

On internal source

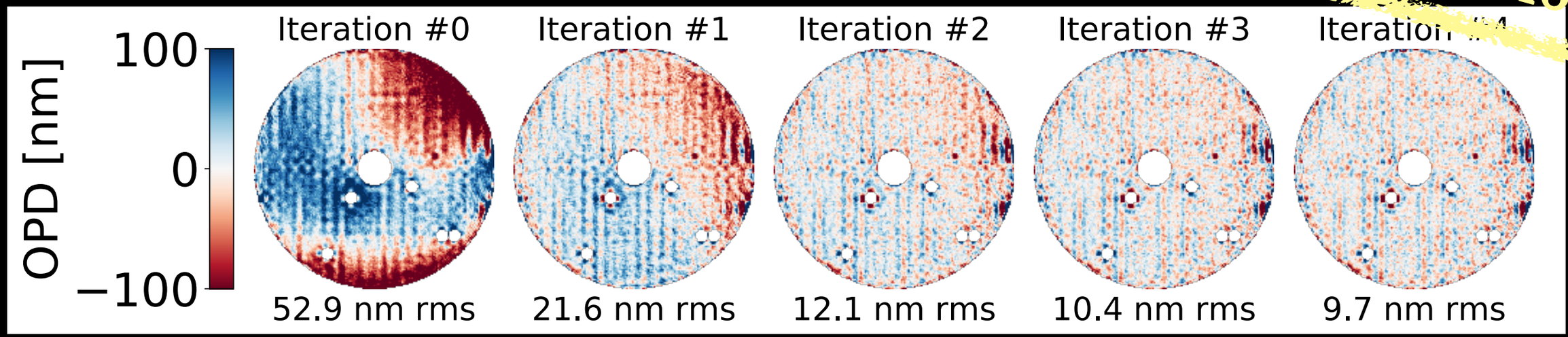


Vigan et al. A&A 2019

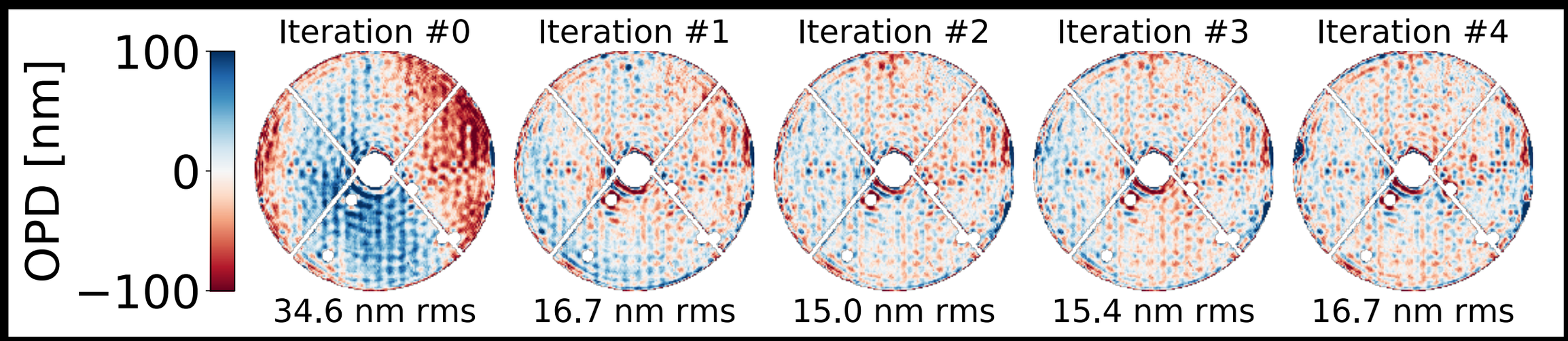
On-sky closed-loop correction

Tests in April 2018

On internal source



On sky (0.7” seeing, $\tau_0 \sim 5$ ms)

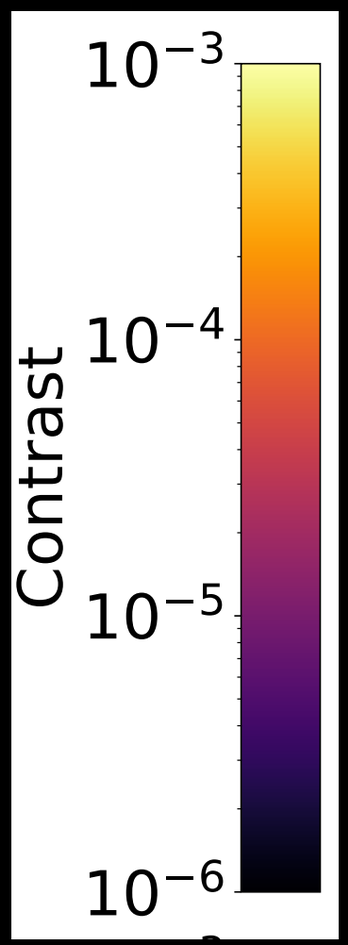


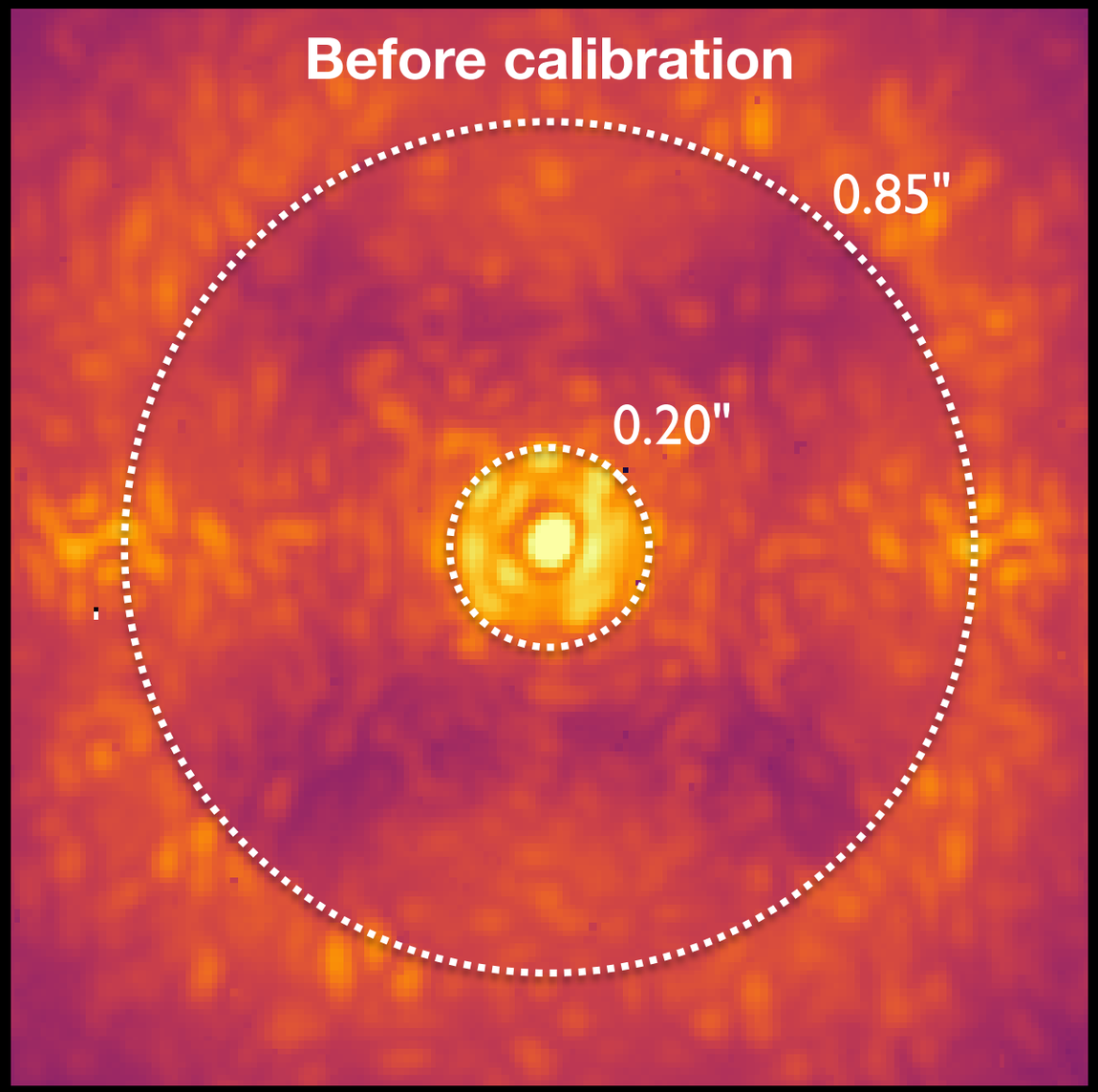
Reduction of the aberrations by a factor 2 on sky

Vigan et al. A&A 2019

On-sky contrast performance

APLC image in H-band

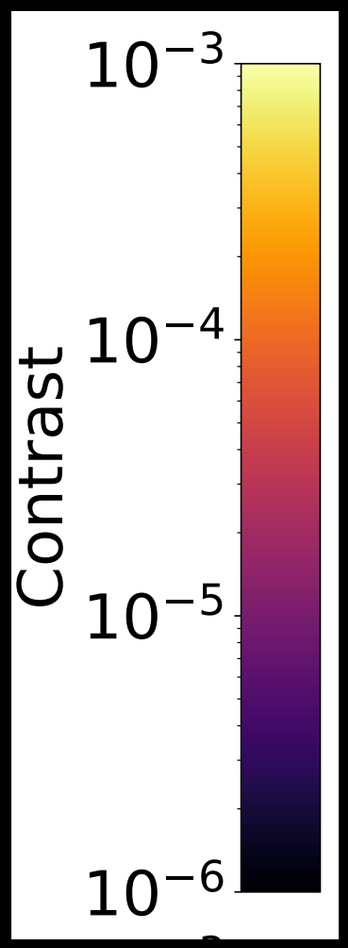


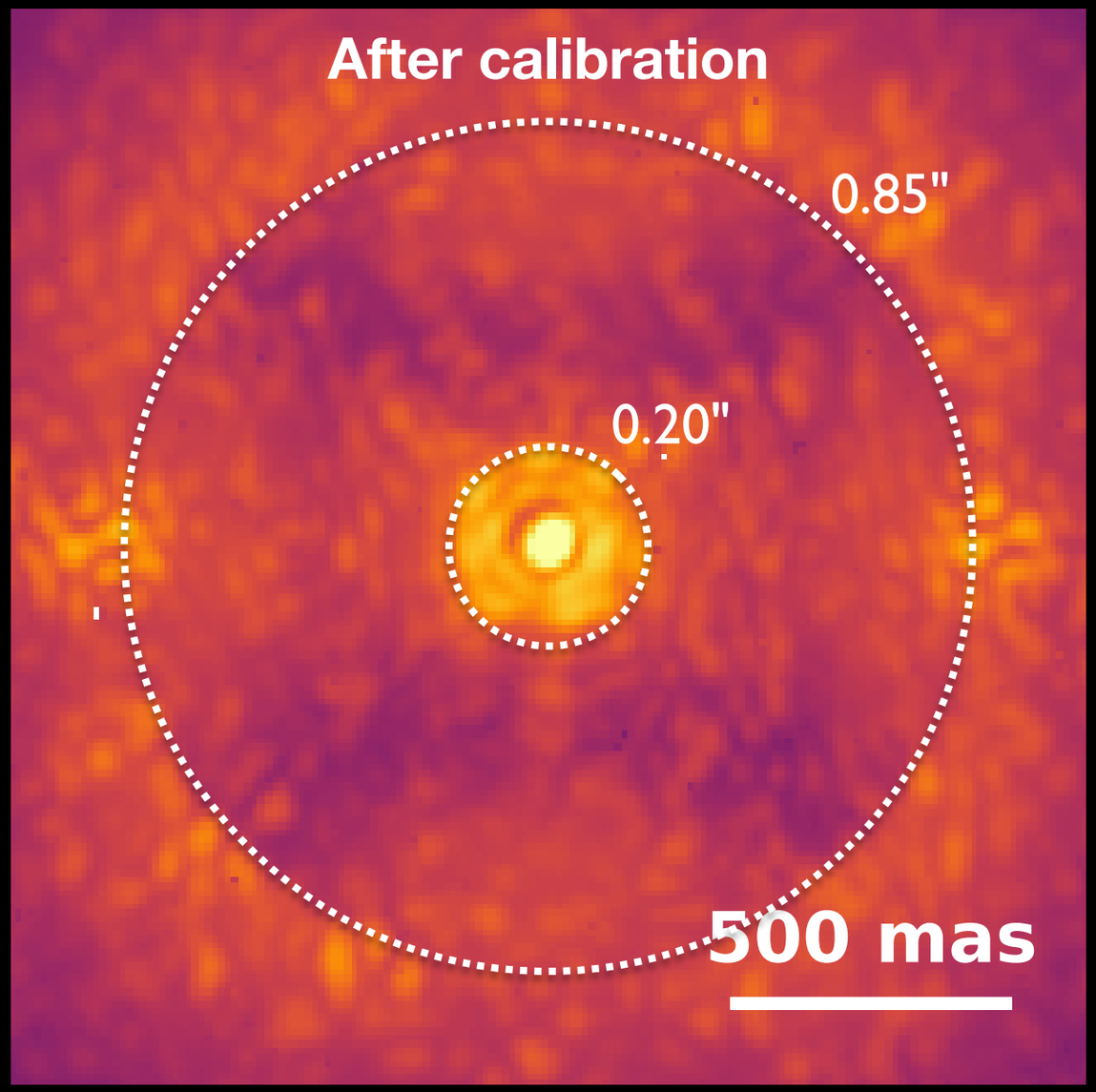


Vigan et al. A&A 2019

On-sky contrast performance

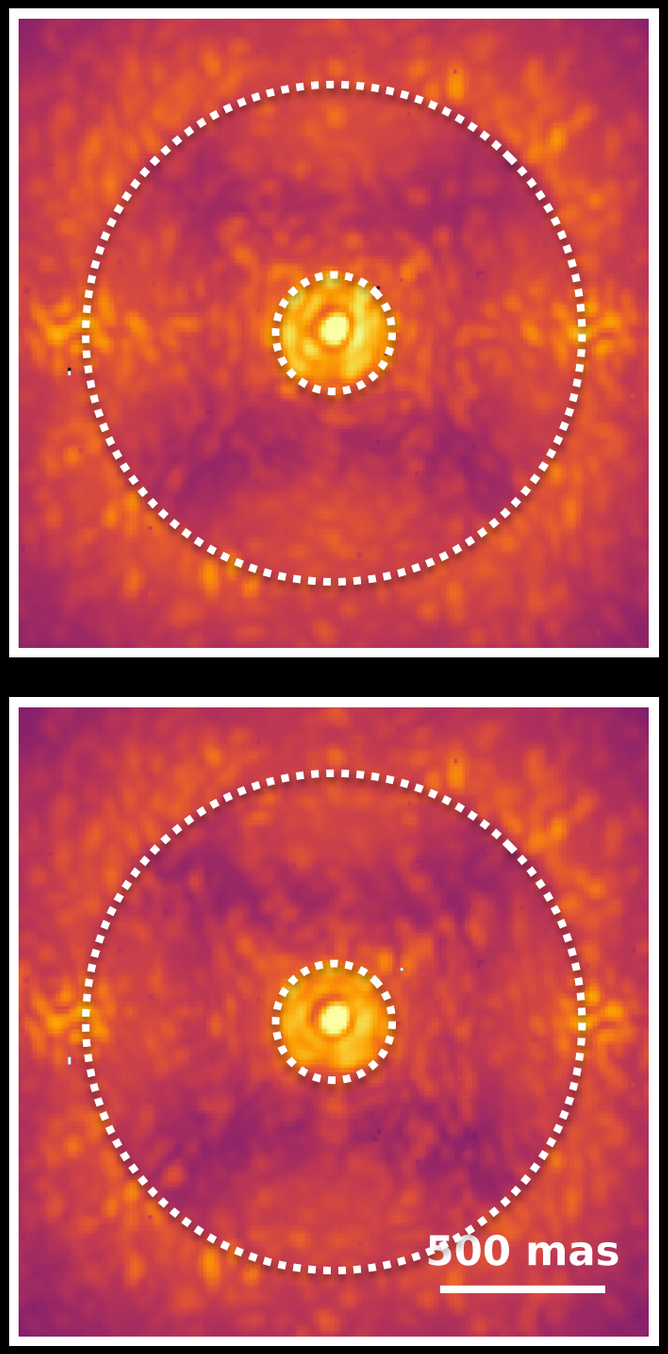
APLC image in H-band

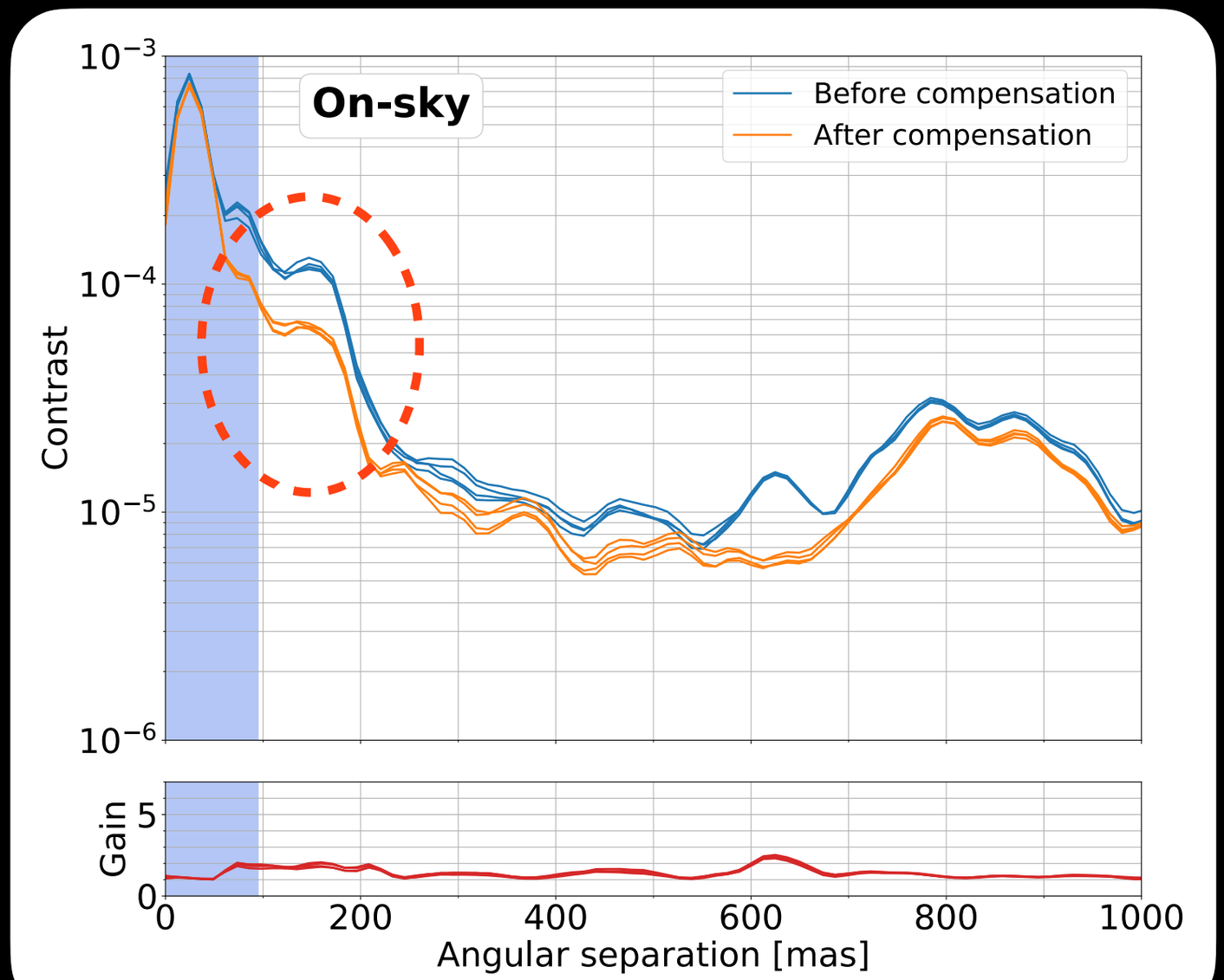




Vigan et al. A&A 2019

On-sky contrast performance



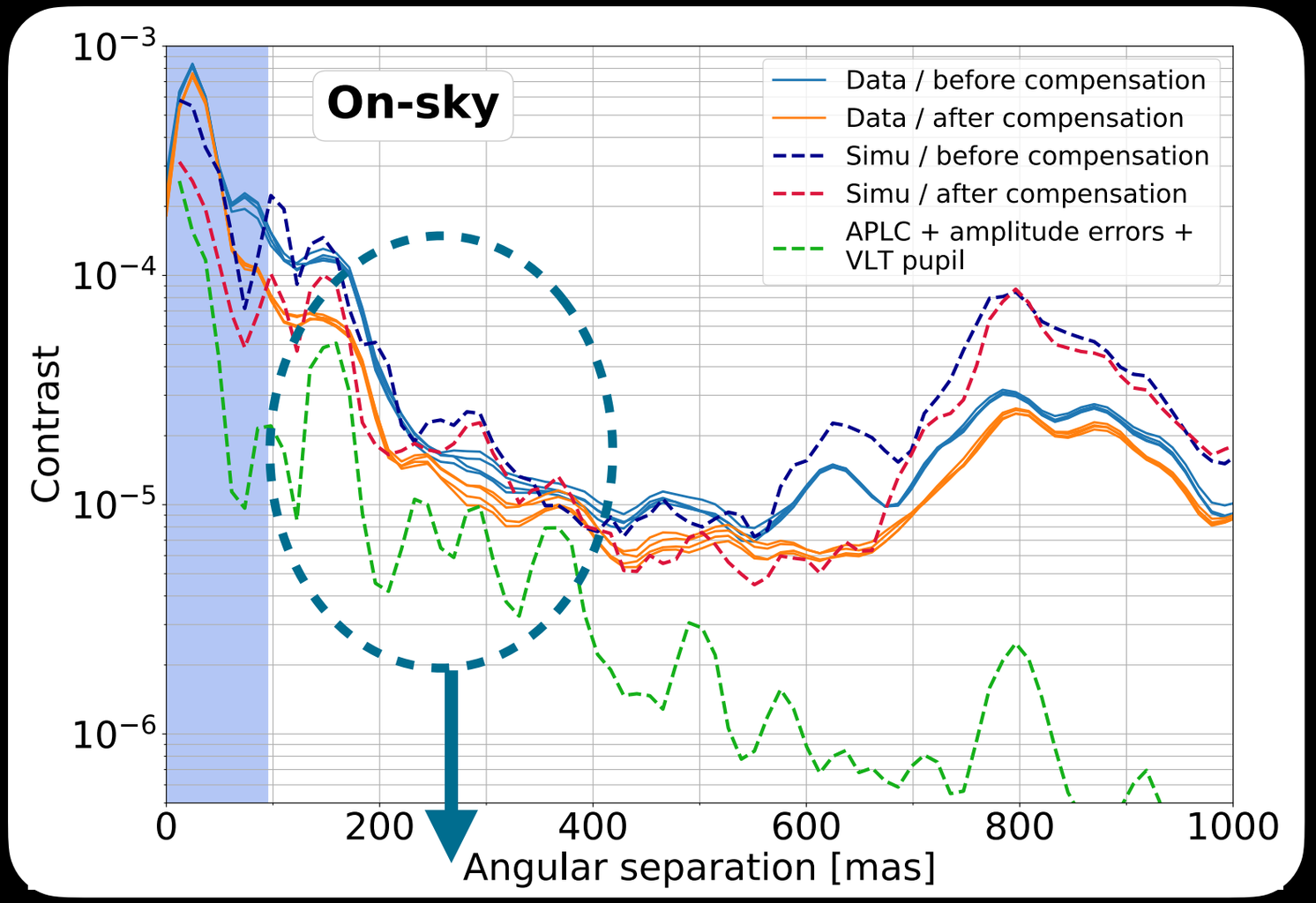


Modest gain x2.5 - Images dominated by XAO residuals and aliasing term

Vigan et al. A&A 2019

Analysis of the limitations

- Coronagraphic image reconstruction with analytical model using
  - XAO residuals from telemetry data
  - NCPA from ZELDA
  - Pupil amplitude errors
  - APLC components

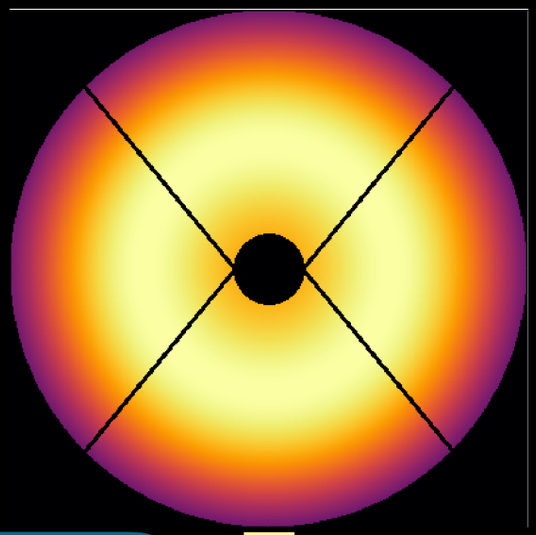


Good agreement between model and data
Limitations due to the coronagraph

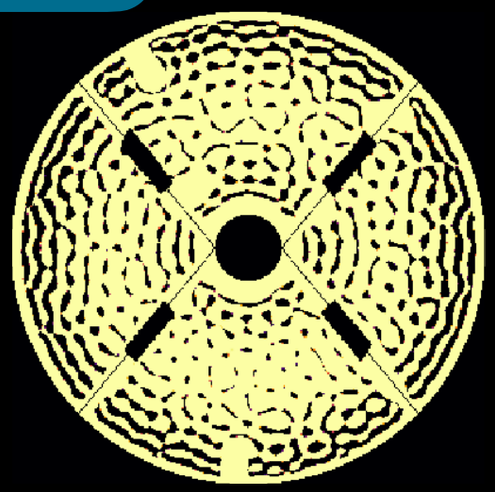
Vigan et al. A&A 2019

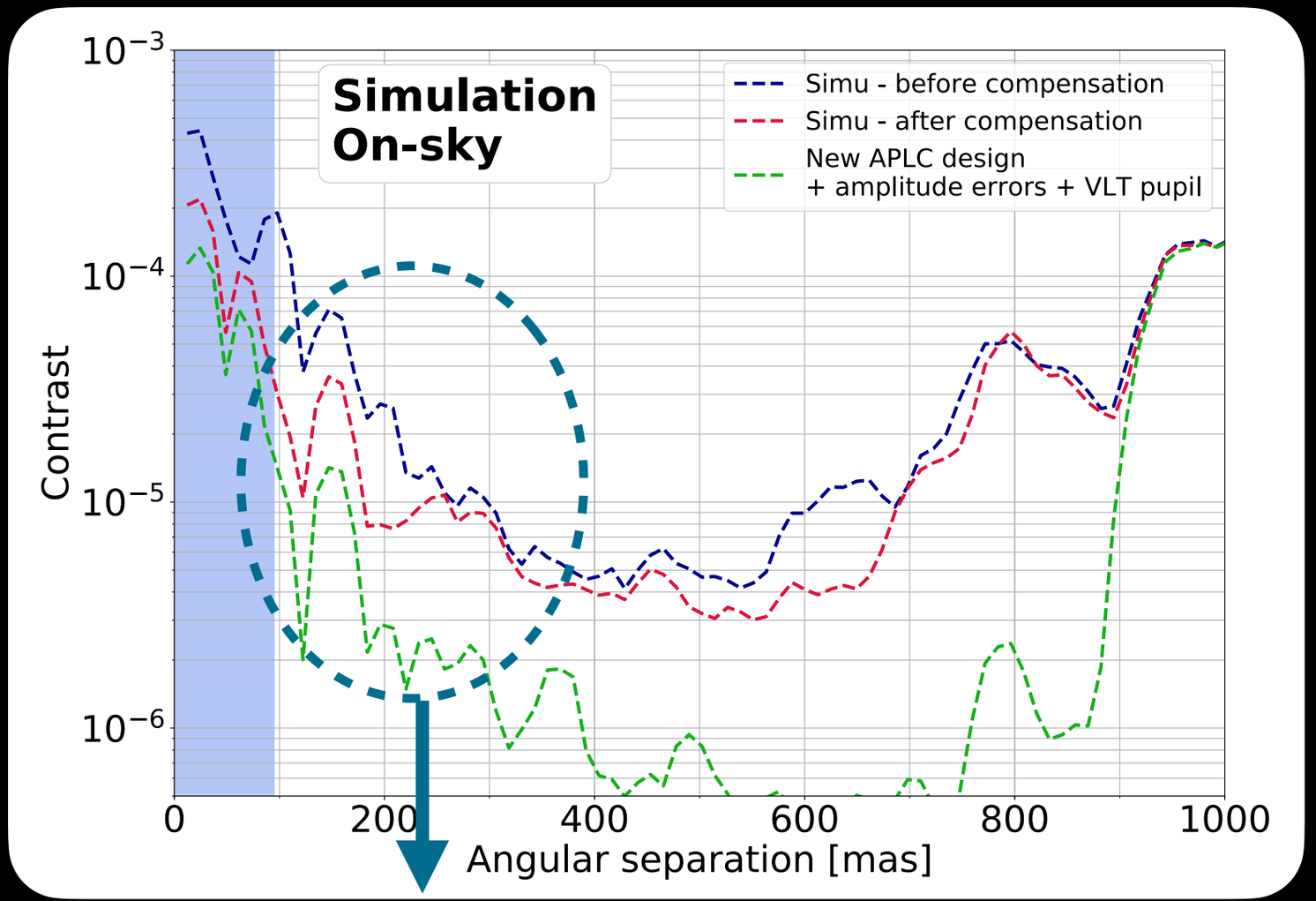
Analysis of the limitations

- Analysis of the expected performance by just replacing the apodizer



Upgrade example





Improved contrast with ZELDA NCPA correction + new coronagraph

Vigan et al. A&A 2019

Conclusion

- **ZELDA for the calibration of residual aberrations**
  - easy to manufacture, align, and simple data analysis

- **Validation on VLT/SPHERE**
  - excellent agreement between measurements and theory
  - NCPA compensation:
    - x10 gain in contrast on internal source
    - factor of 2 reduction of the aberrations on sky
  - promising ZELDA NCPA compensation scheme + new coronagraph
    - imaging colder/lighter planets with current AO facilities

- **Promising diagnostic tool for current and future facilities**
  - low-wind effects, internal turbulence, derotator behavior
  - segment cophasing, low-order aberrations through coronagraph