

ZELDA: a Link to exoplanet imaging

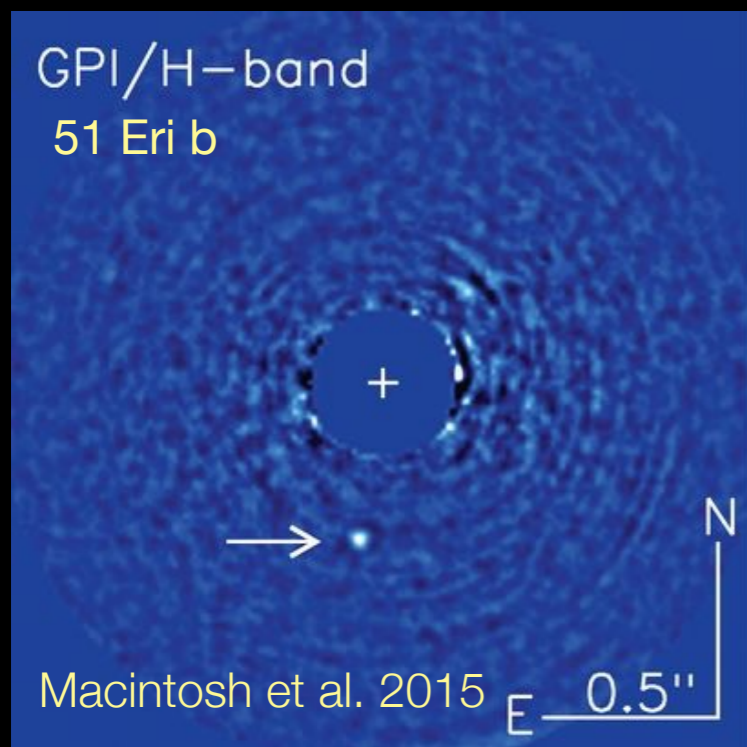
Mamadou N'Diaye (Observatoire de la Côte d'Azur) & Arthur Vigan (LAM)

**K. Dohlen, J.-F. Sauvage, J. Milli, G. Zins, C. Petit, Z. Wahhaj, F. Cantalloube,
A. Caillat, J. Le Merrer, A. Carlotti, J.-L. Beuzit, D. Mouillet, and many others**

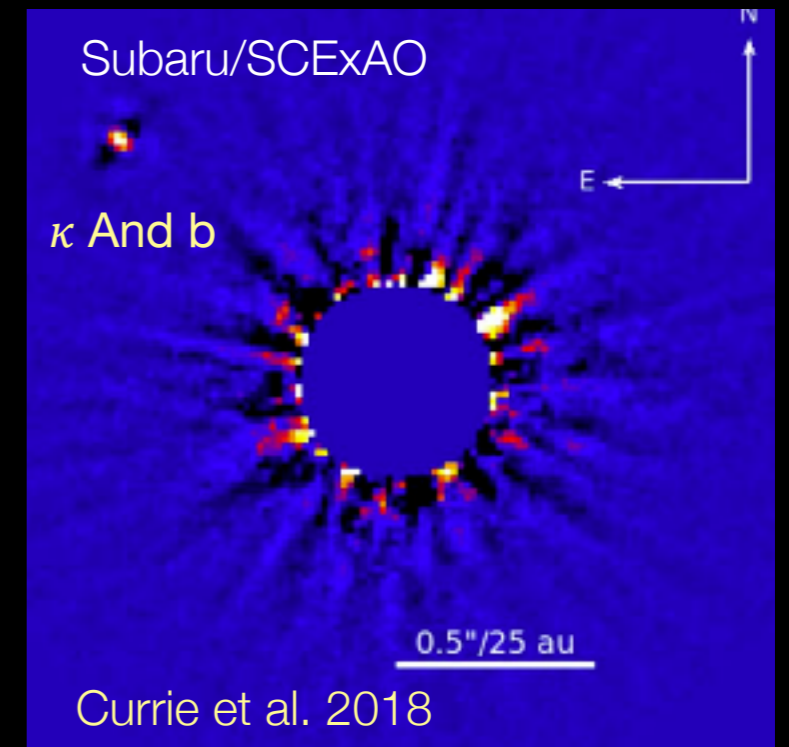
Virtual Workshop on Advanced Wavefront Sensing - May 1st, 2020

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



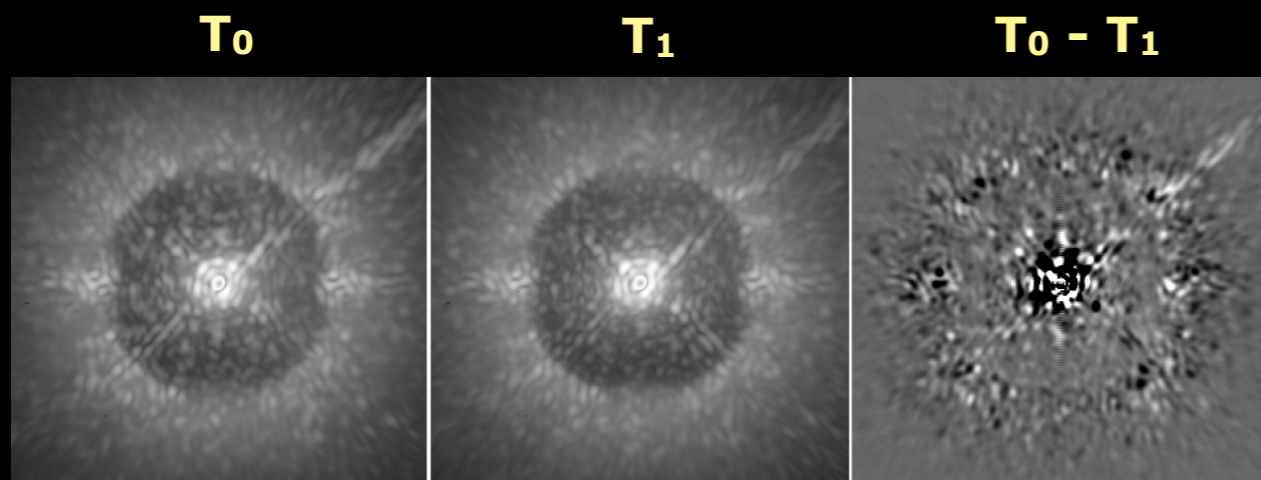
VLT/SPHERE
PDS 70 b



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

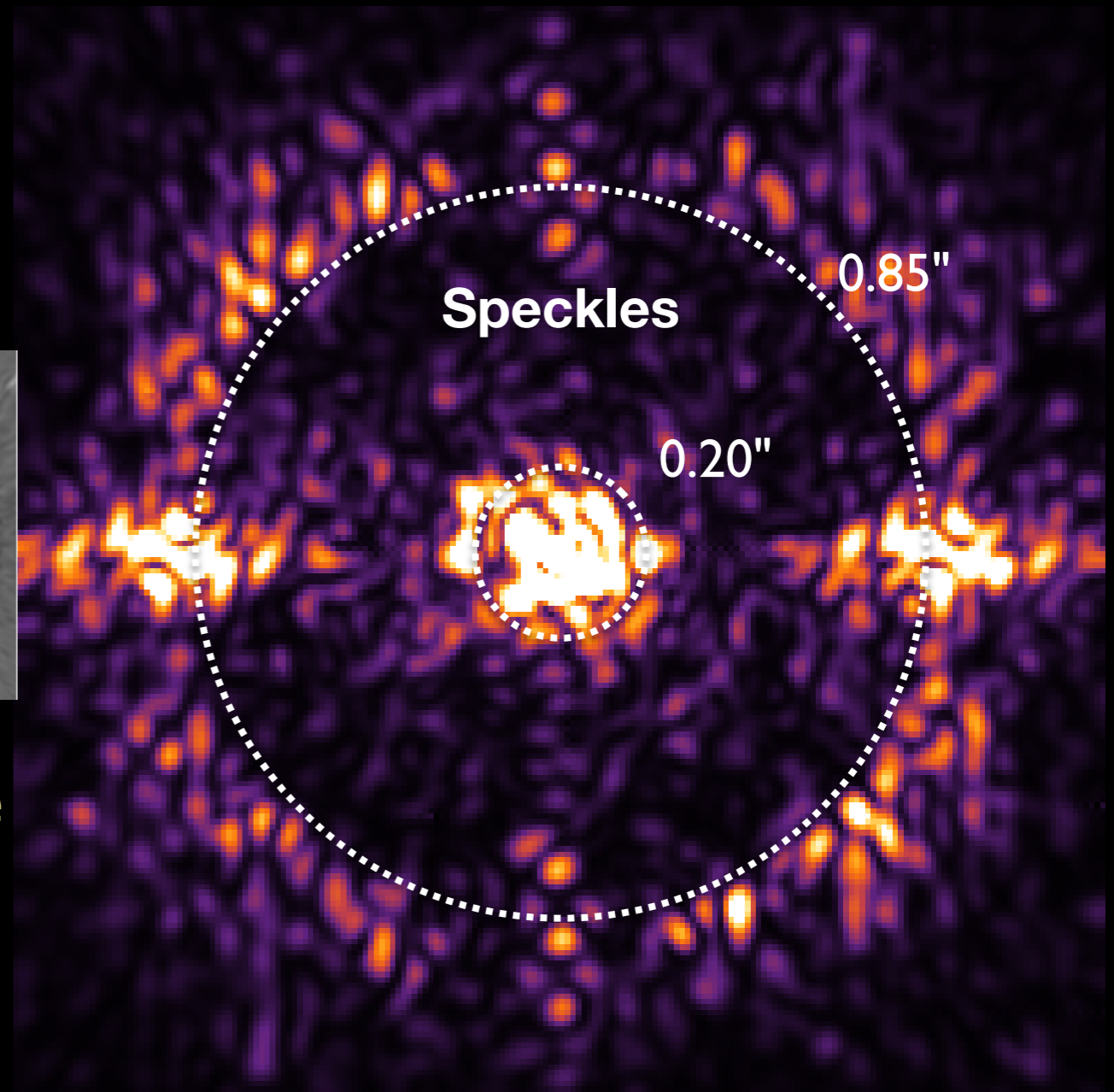
Imaging colder/lighter exoplanets

- 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

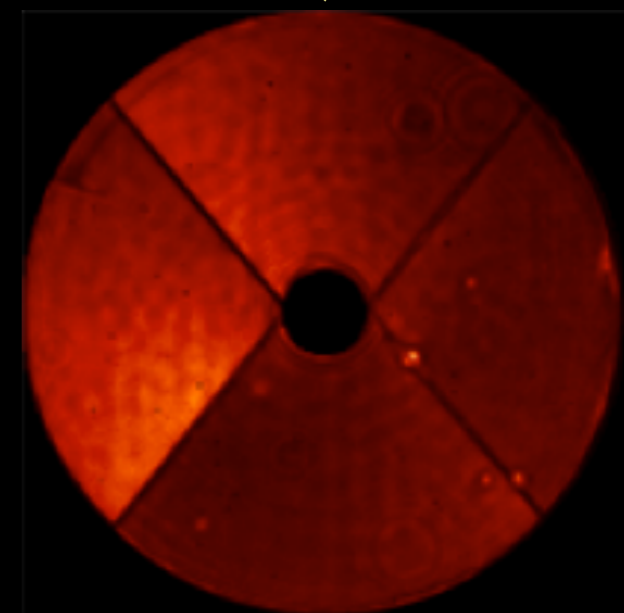
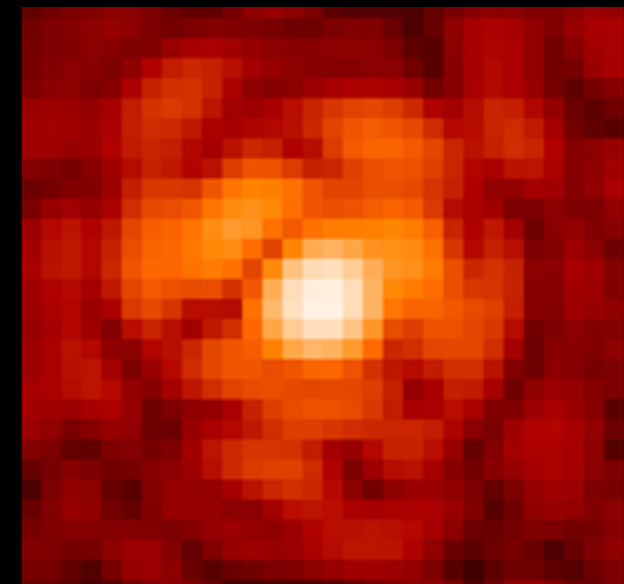
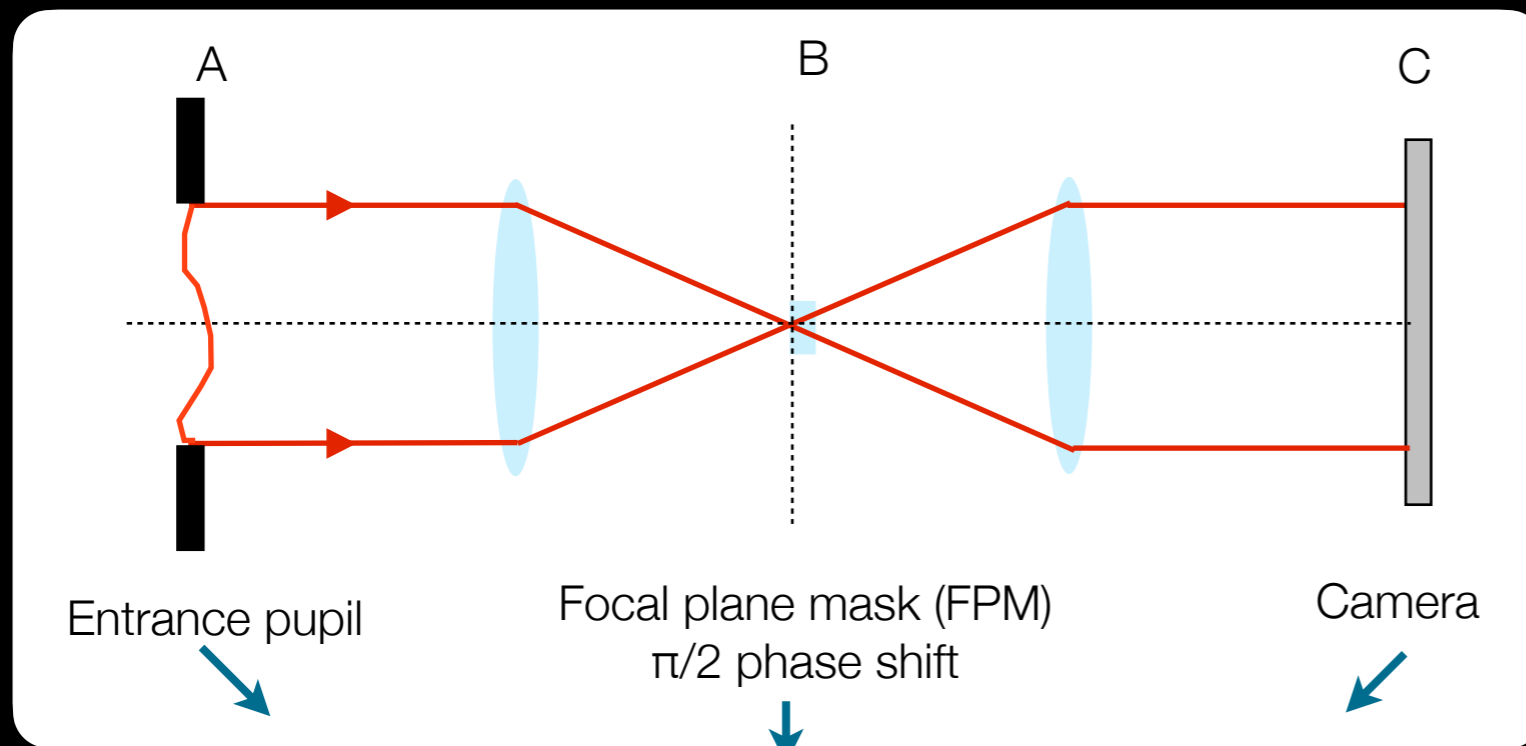
The Legend of ZELDA



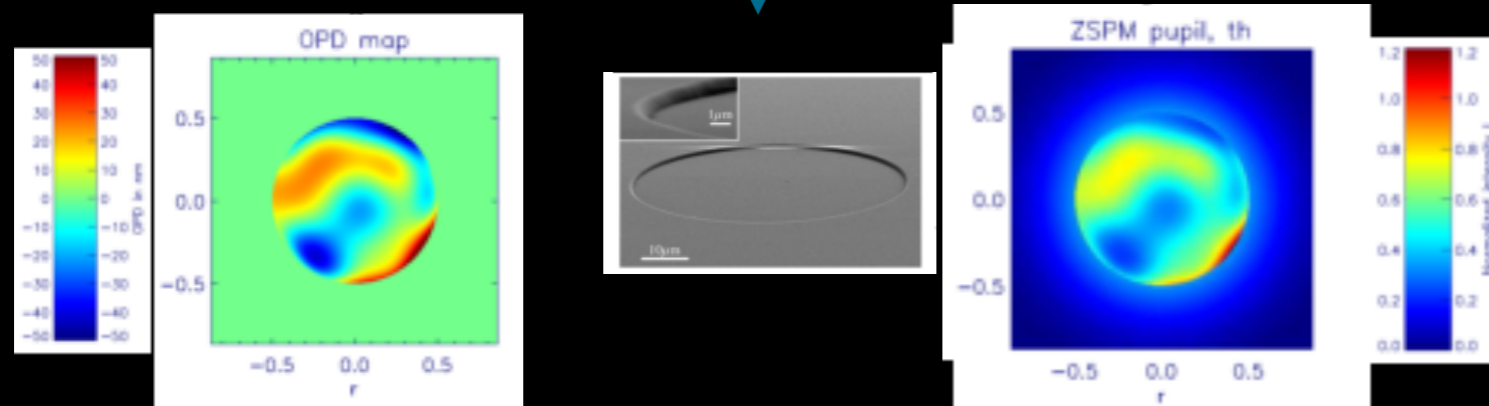
Zernike wavefront sensor

- Conversion of phase errors φ into intensity I_c

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



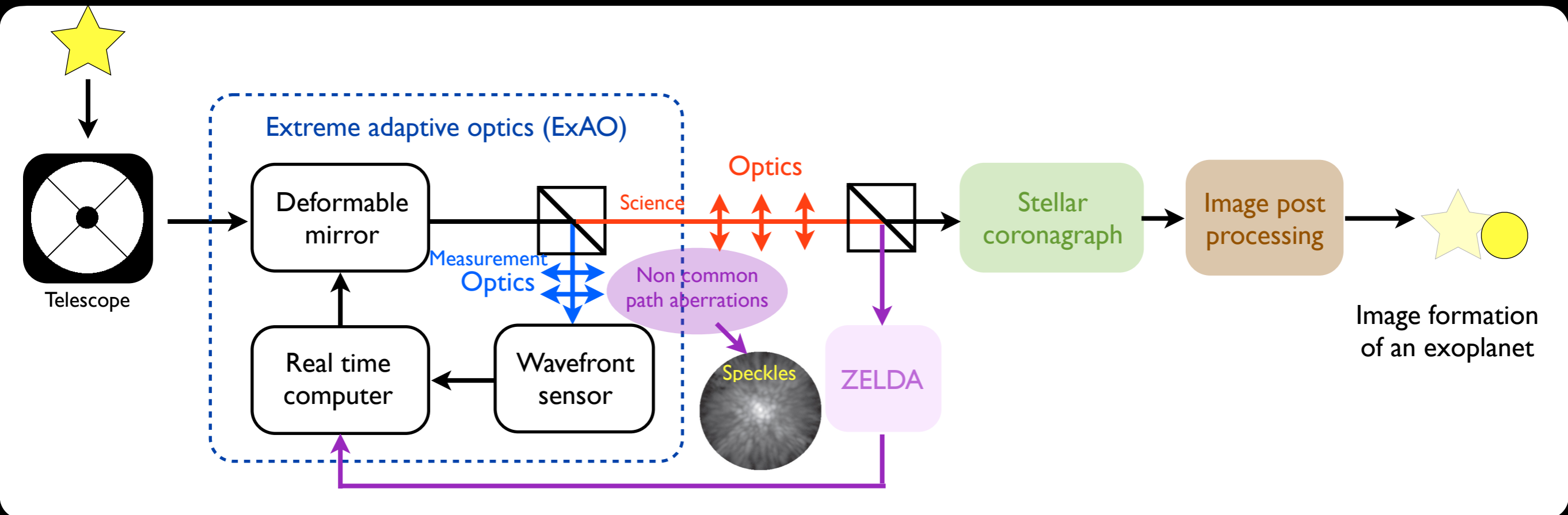
Low-wind effects



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

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

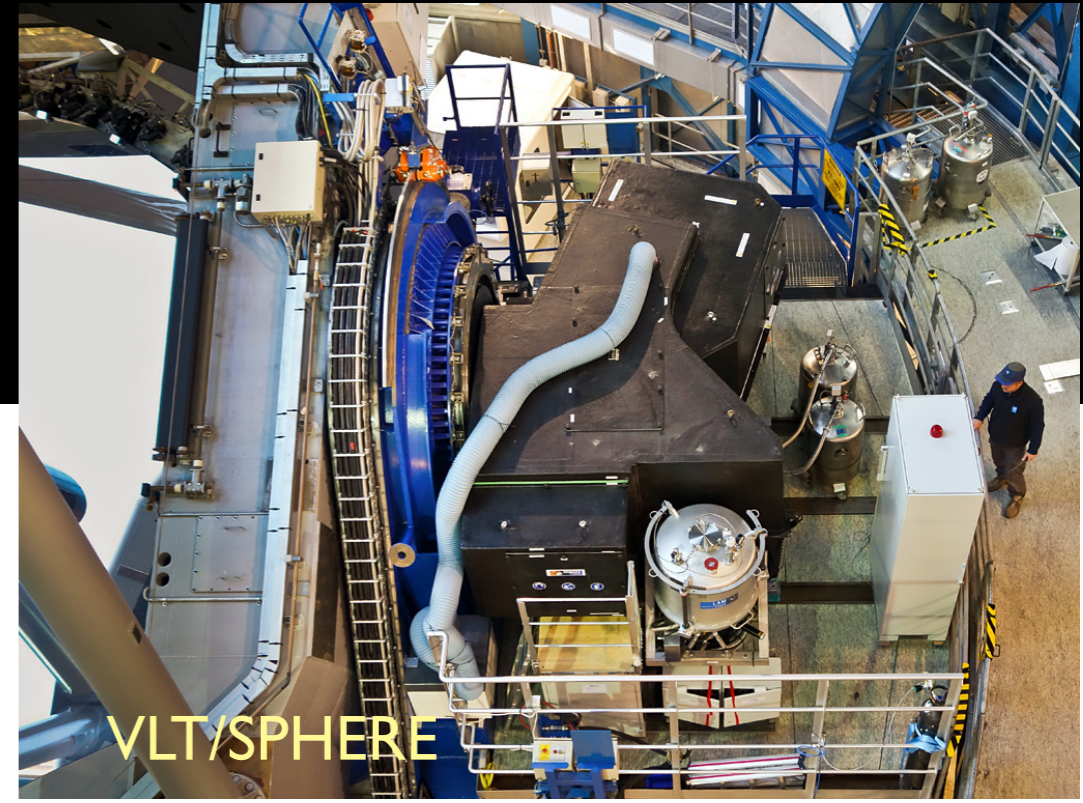
- Our proposal

- ▶ ZELDA, a concept based on phase-contrast technique

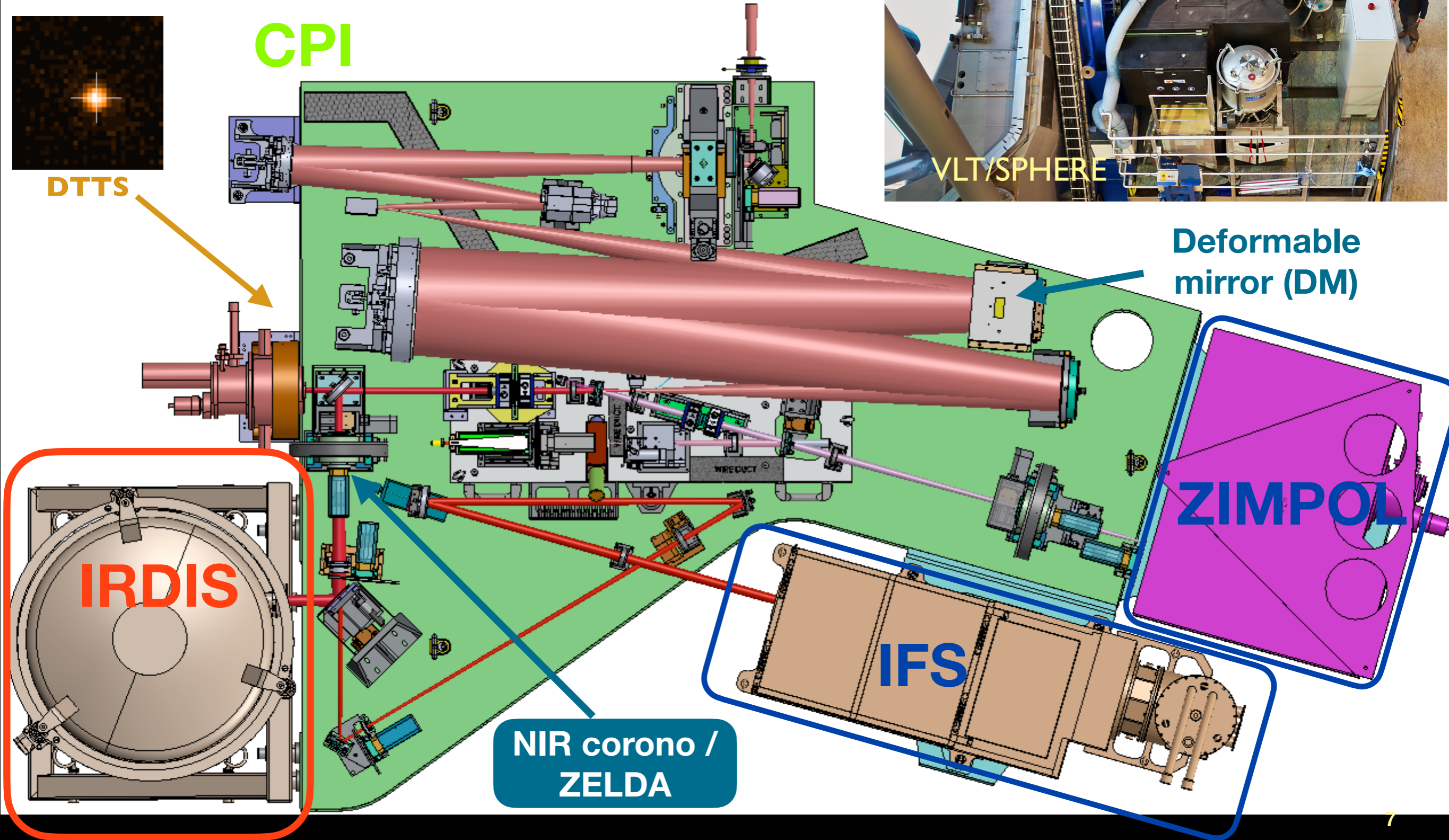


Current implementation in VLT/SPHERE

Beuzit et al. 2019



VLT/SPHERE



Deformable mirror (DM)

ZIMPOL

IFS

NIR coronano / ZELDA

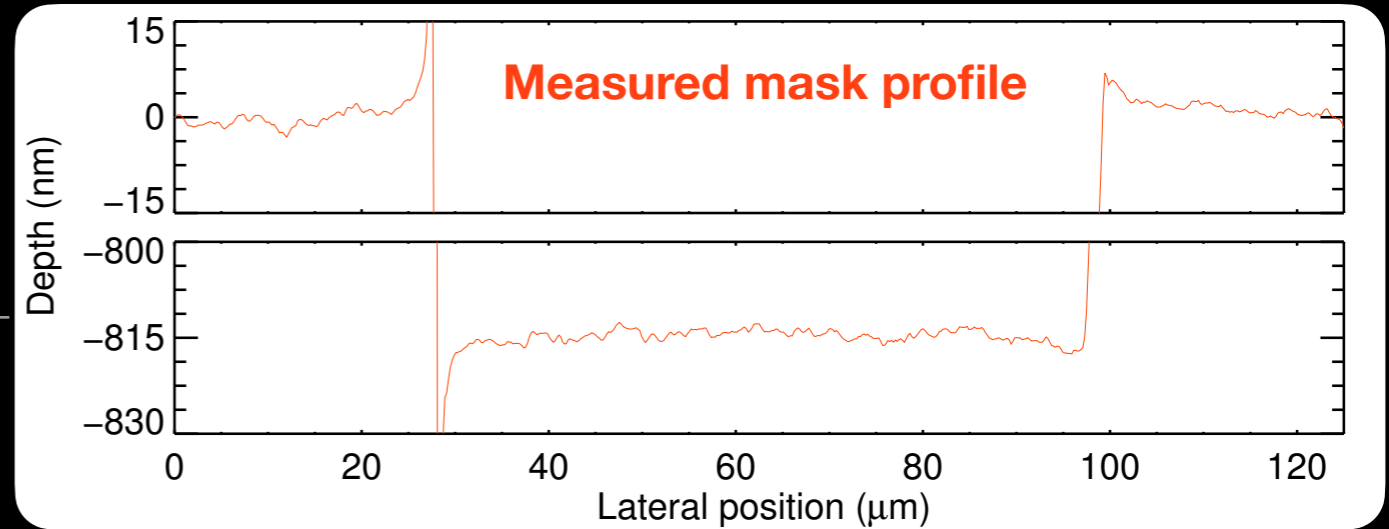
IRDIS

DTTS

CPI

ZELDA prototype in SPHERE

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



Installation during SPHERE integration in Paranal in April 2014

The image shows the title screen of the video game 'Zelda II: The Adventure on Sphere'. The background is a dark, textured brown. In the upper left, there is a shield with a cross design, containing a heart, a key, a sword, and another heart. In the center, the title 'ZELDA II : The adventure on SPHERE' is written in a bold, yellow, sans-serif font. Below the title, a horizontal line separates it from a dark rectangular box containing the text 'ZELDA II' in a serif font. At the bottom, the words 'The Adventure of' are written in a cursive script. On the right side, a large, ornate sword with a red gem on its hilt and a cross-shaped guard is visible, partially overlapping the title and the bottom text.

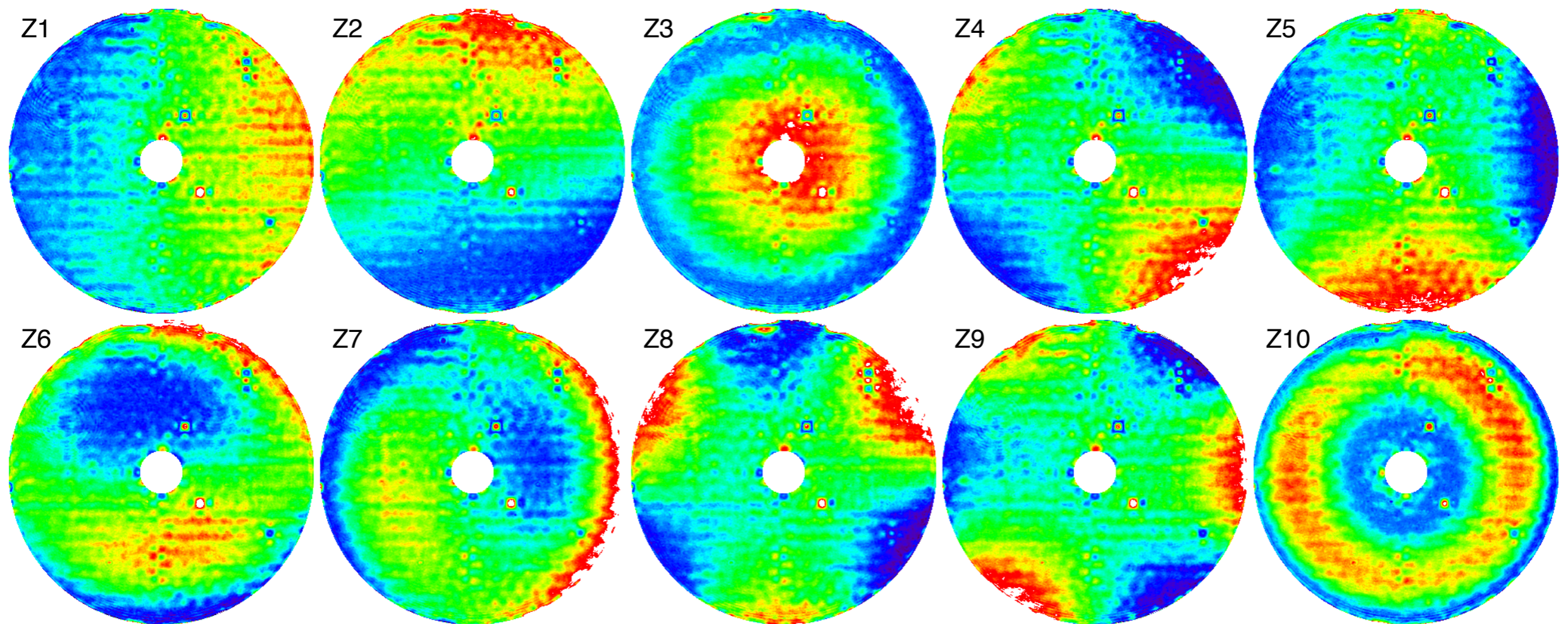
ZELDA II : The adventure on SPHERE

ZELDA II

The Adventure of

Measurement of introduced low-order aberration

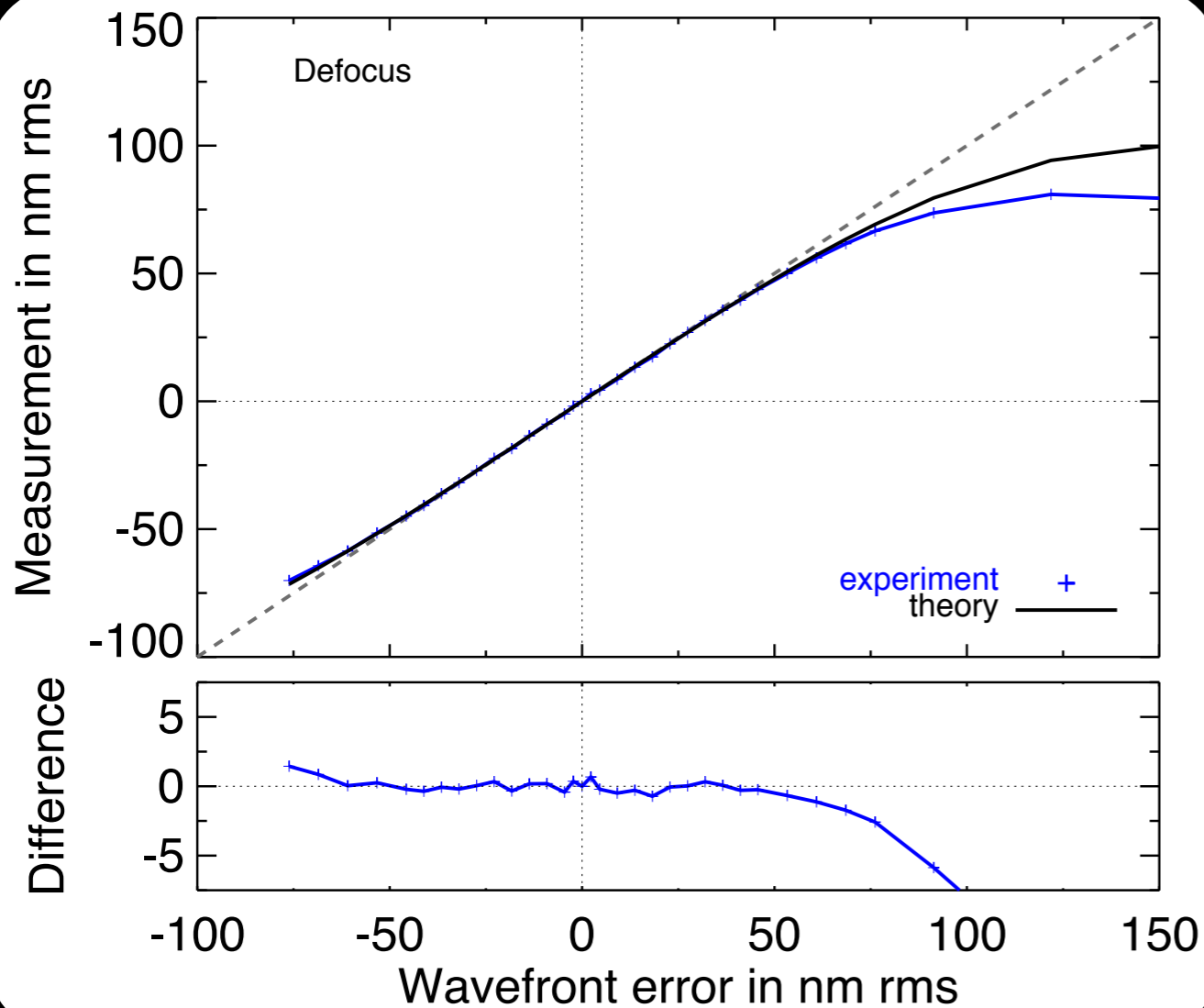
- Internal point source
- IRDIS pupil-imaging mode, $\lambda = 1642$ nm (Fe II filter)
- PSF centered manually + closed loop on near-IR DTTS
- Zernike and Fourier modes, amplitude ramps: $-250 \rightarrow 600$ nm PtV



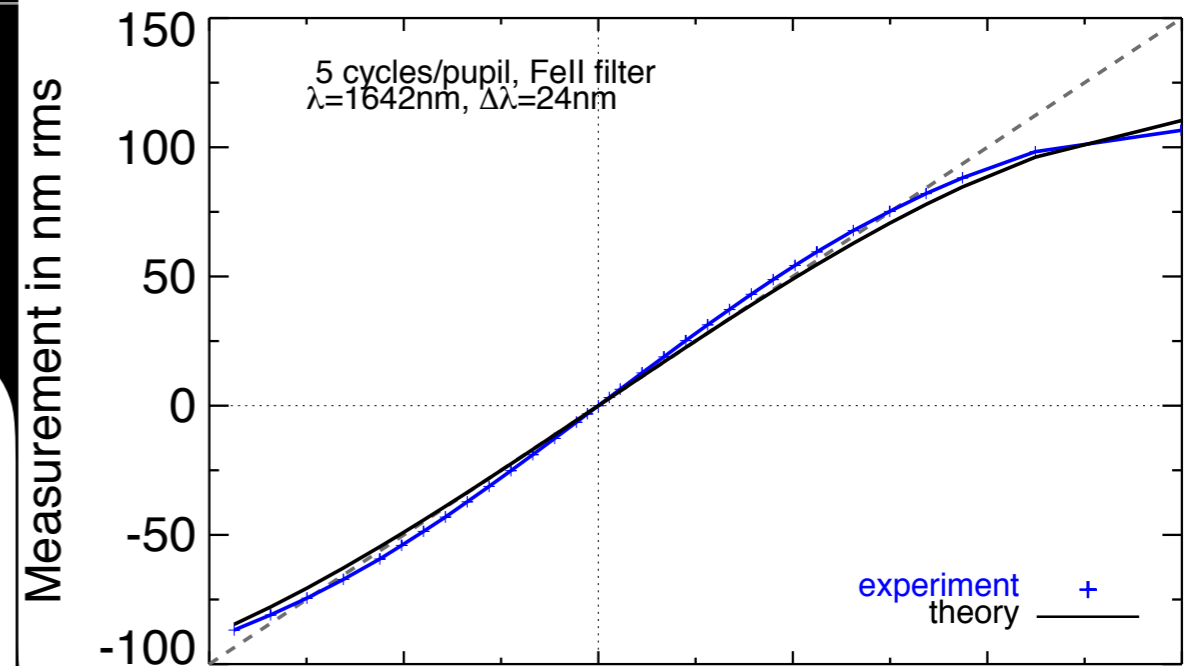
Zernike modes introduced with 400nm on the deformable mirror

Performance assessment

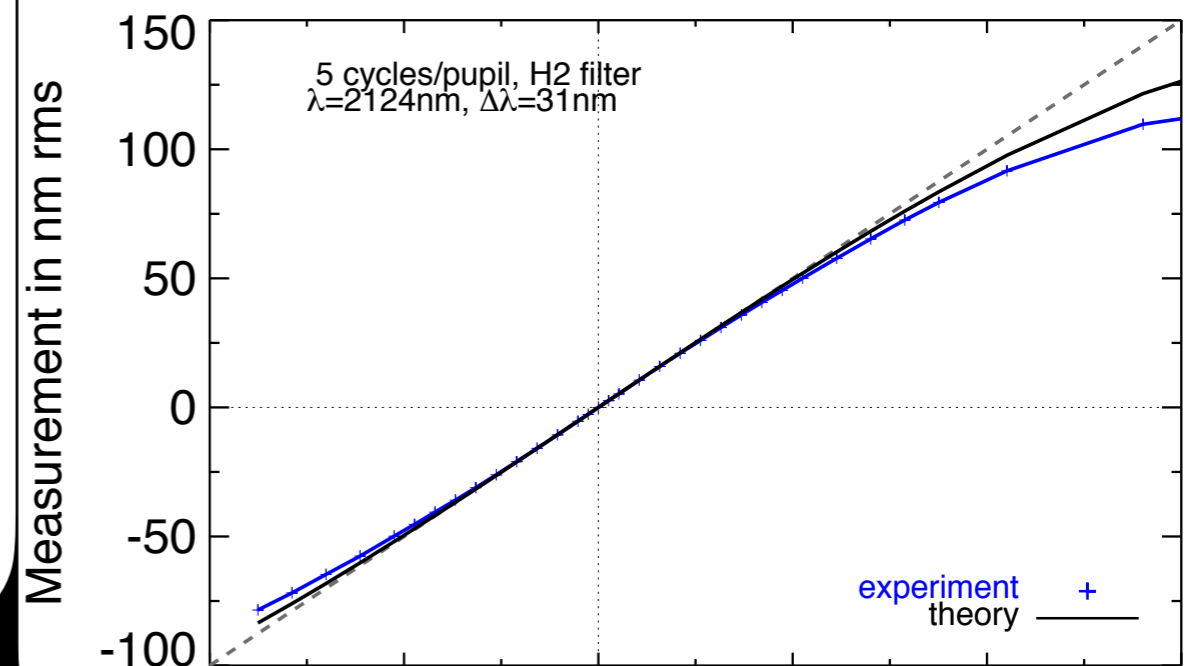
- theory vs. measurements:
 - excellent agreement!
- low sensitivity to wavelength of measure



Reference wavelength (H-band)



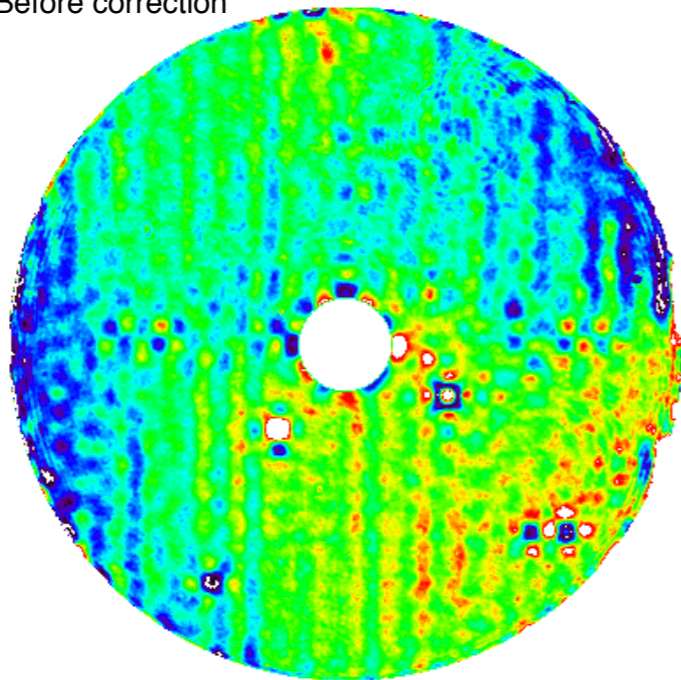
Measurement in K-band



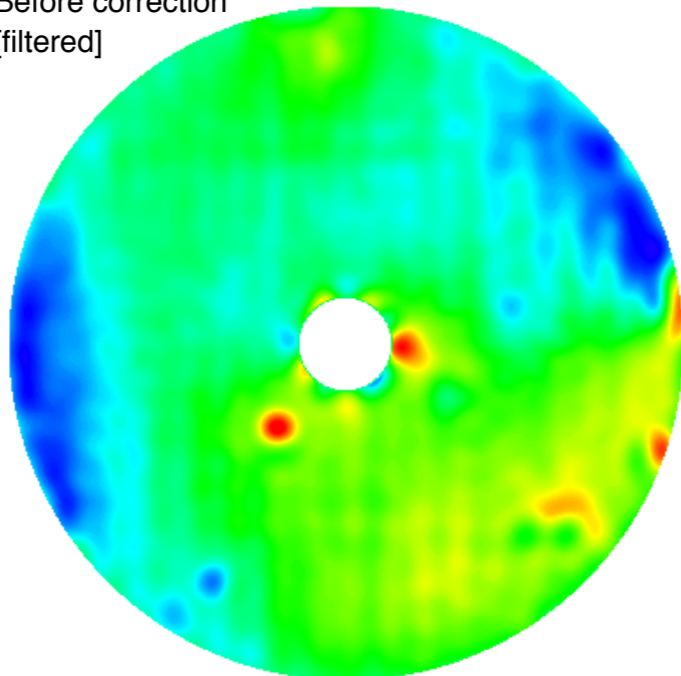
NCPA measurement and compensation

45 nm RMS

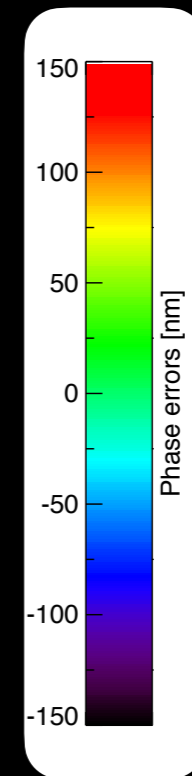
Before correction



Before correction
[filtered]



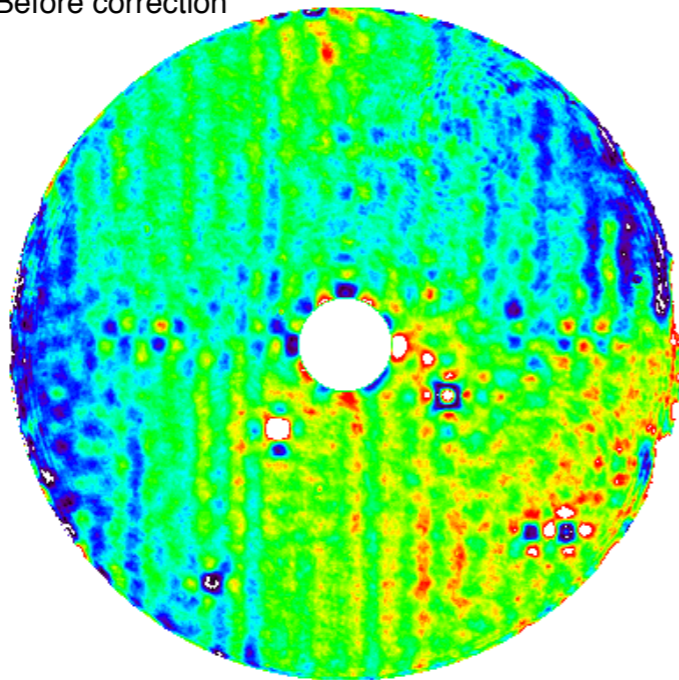
30 nm RMS



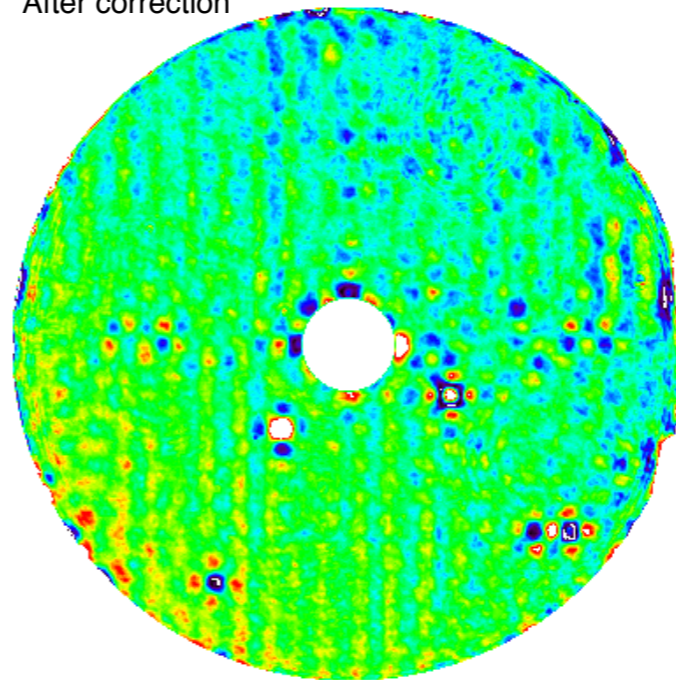
NCPA measurement and compensation

45 nm RMS

Before correction

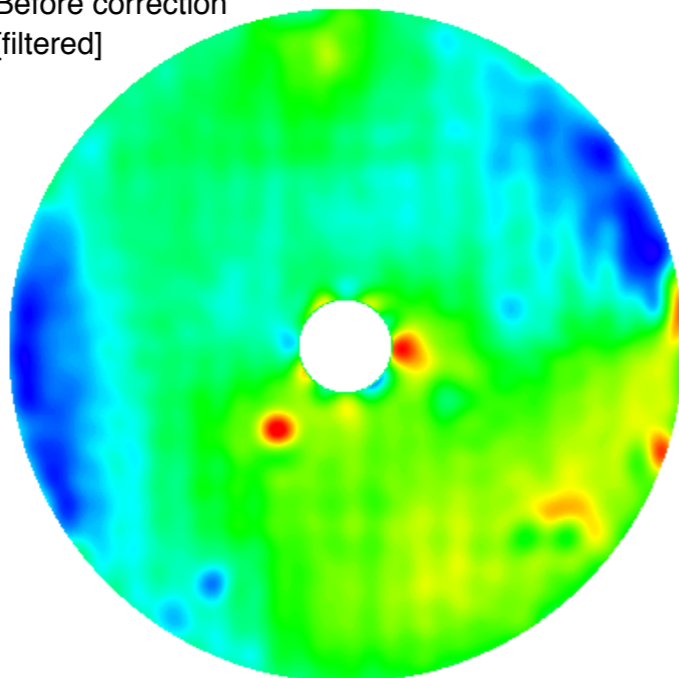


After correction

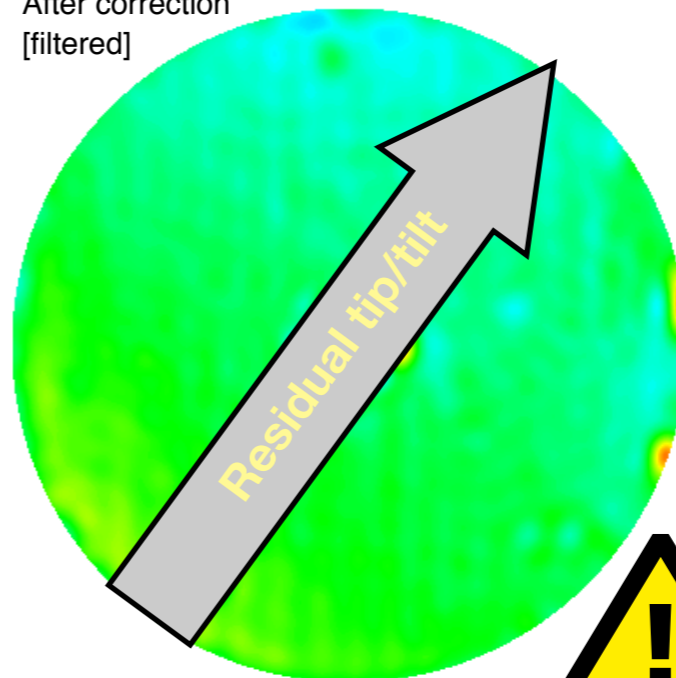


35 nm RMS

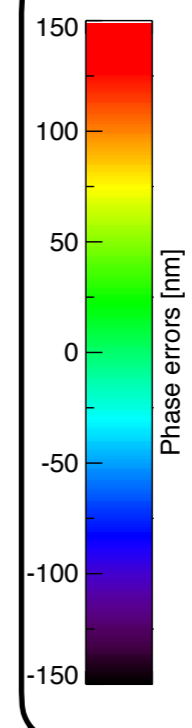
Before correction
[filtered]



After correction
[filtered]



30 nm RMS



16 nm RMS

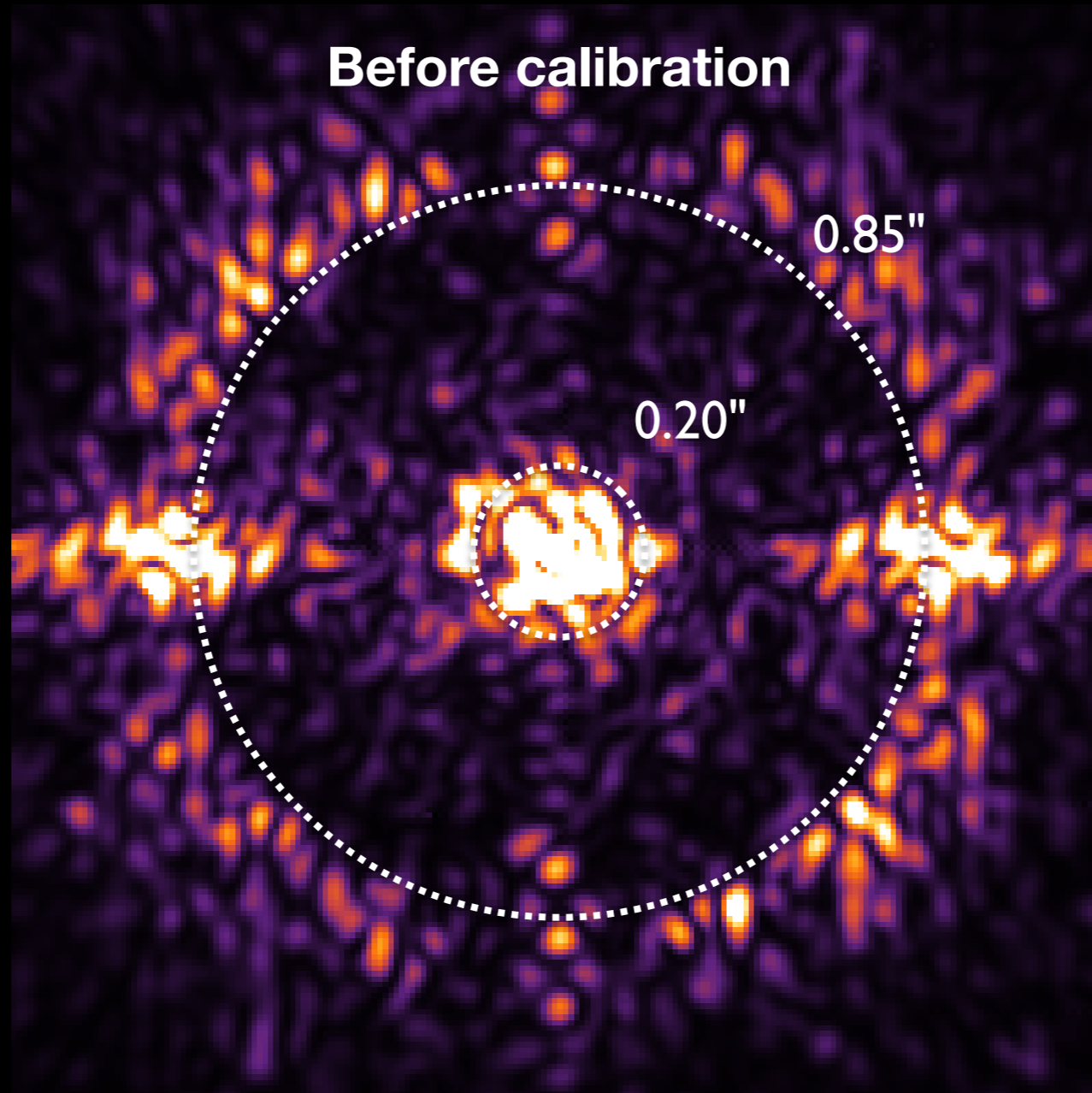
Manual centering +
tip-tilt closed loop

Impact on coronagraphic images on internal source

Tests in
Dec. 2015

APLC image in H-band

Before calibration

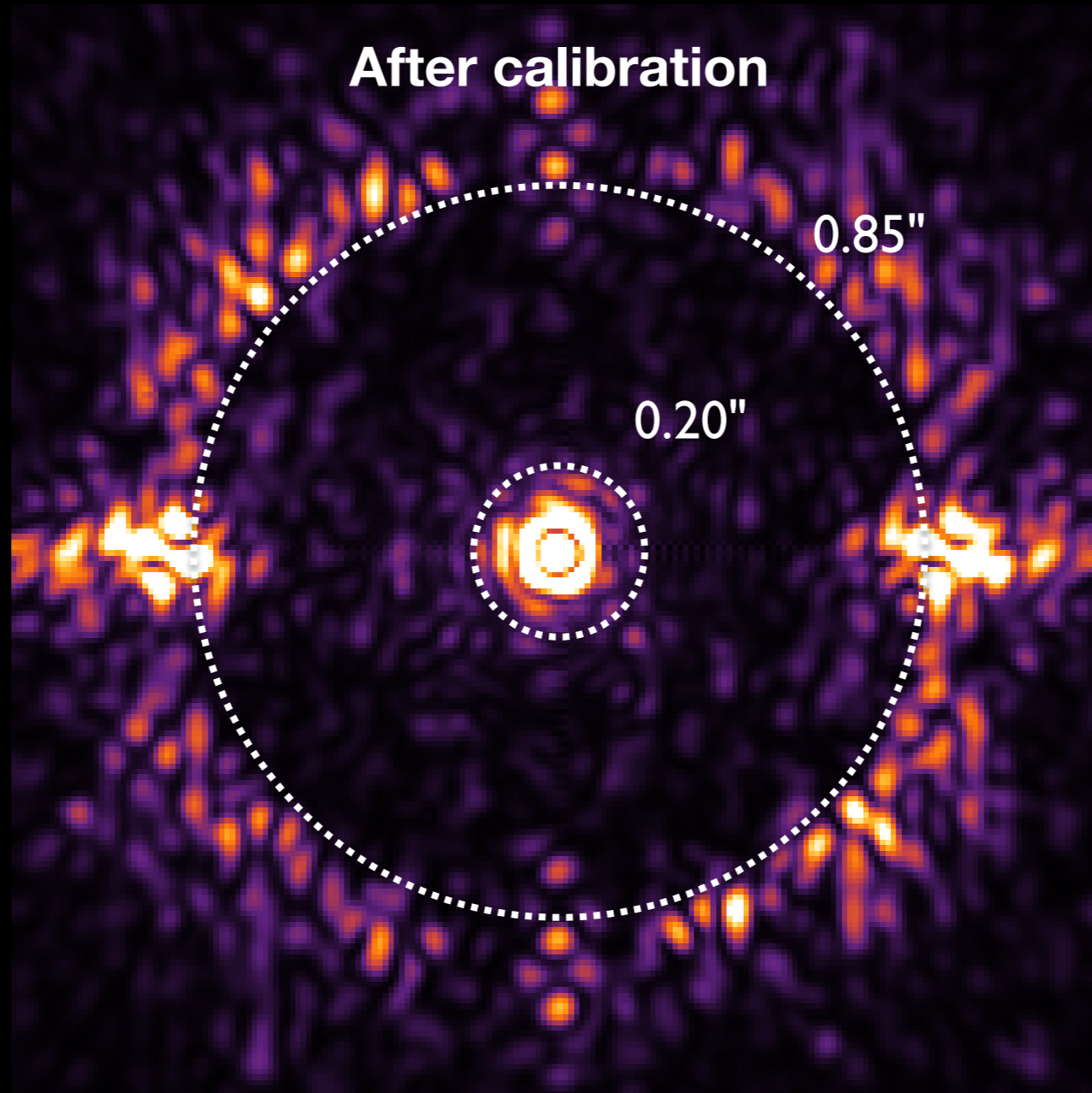


Impact on coronagraphic images on internal source

Tests in
Dec. 2015

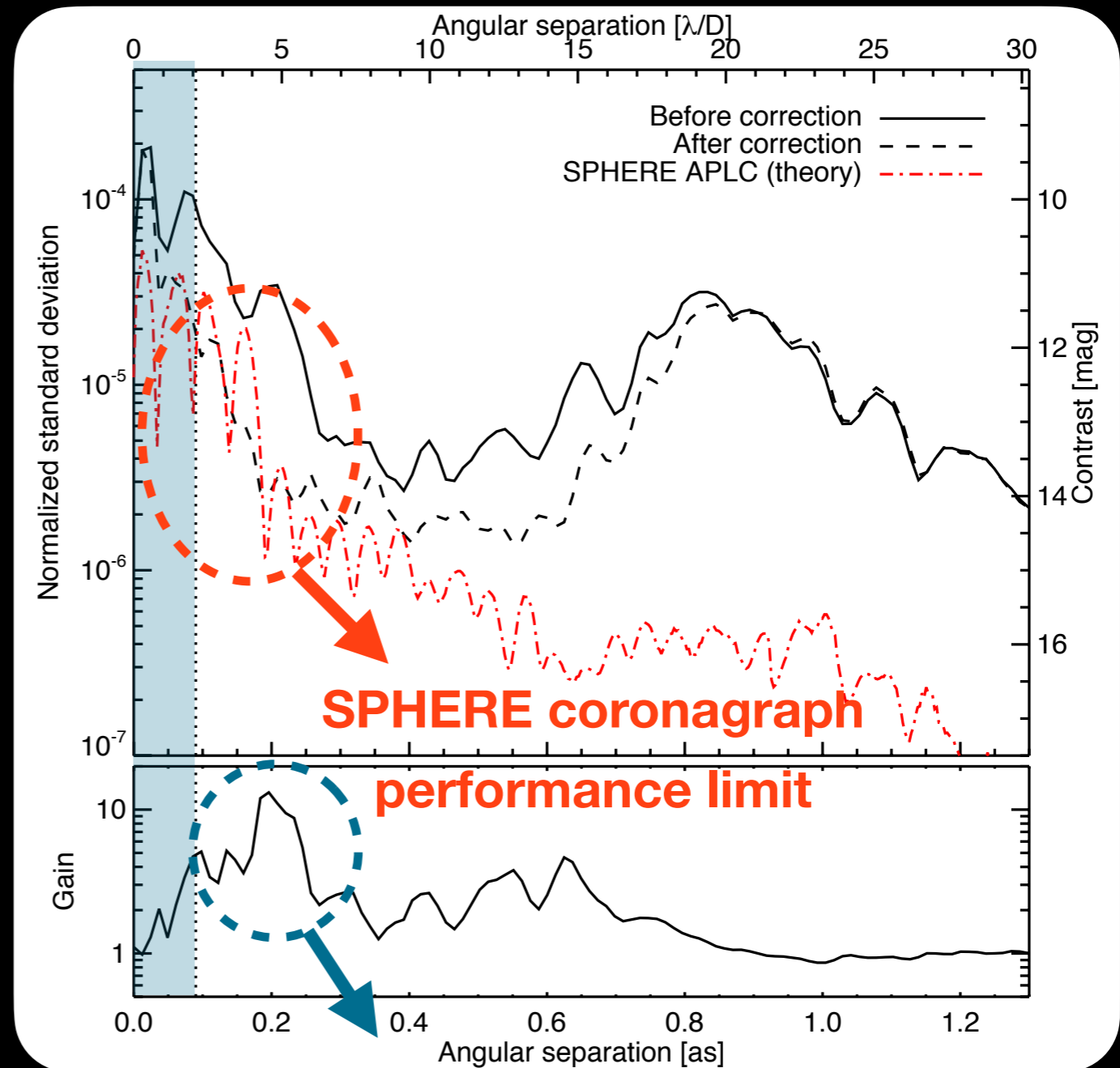
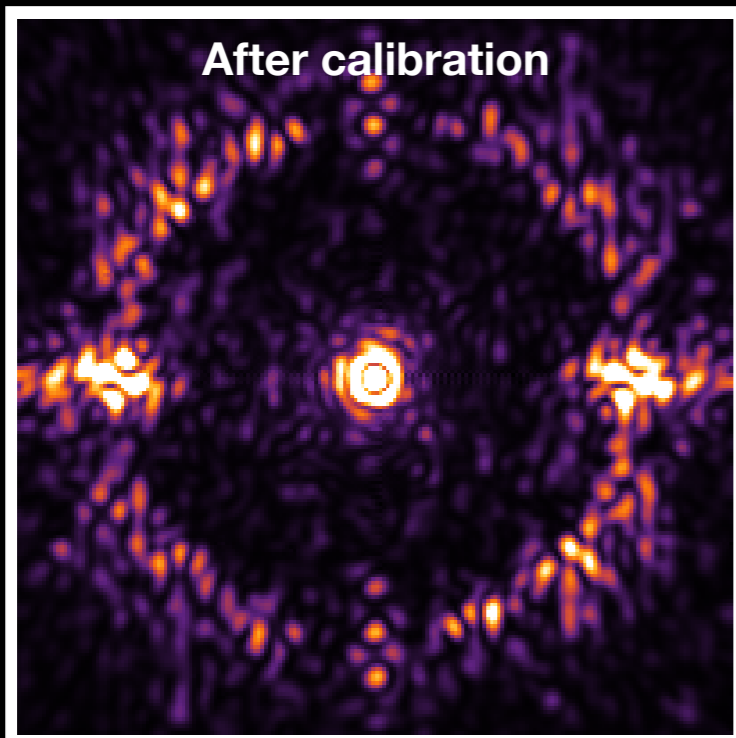
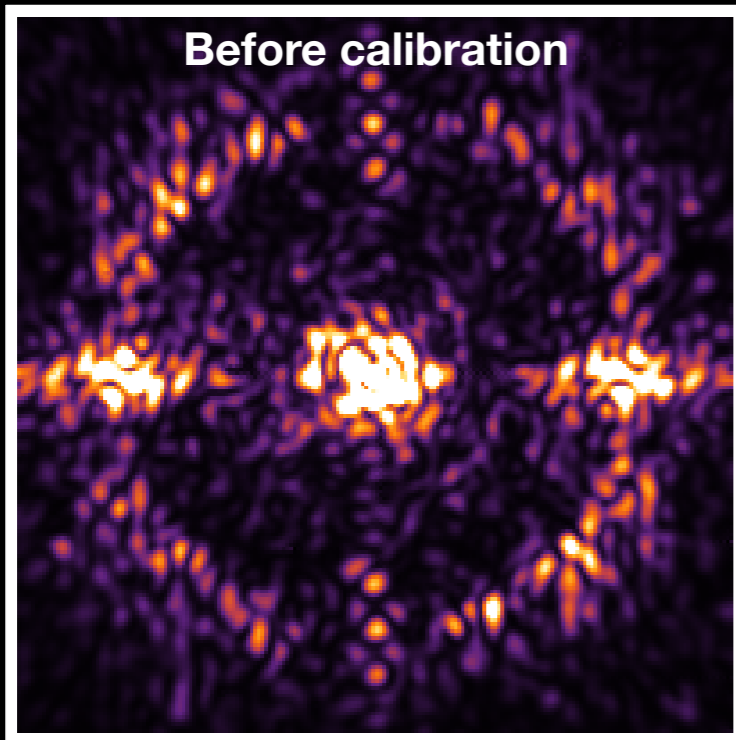
APLC image in H-band

After calibration



Gain x10 in contrast @ 0.2"

Impact on coronagraphic images on internal source



Gain x10 in contrast @ 0.2''

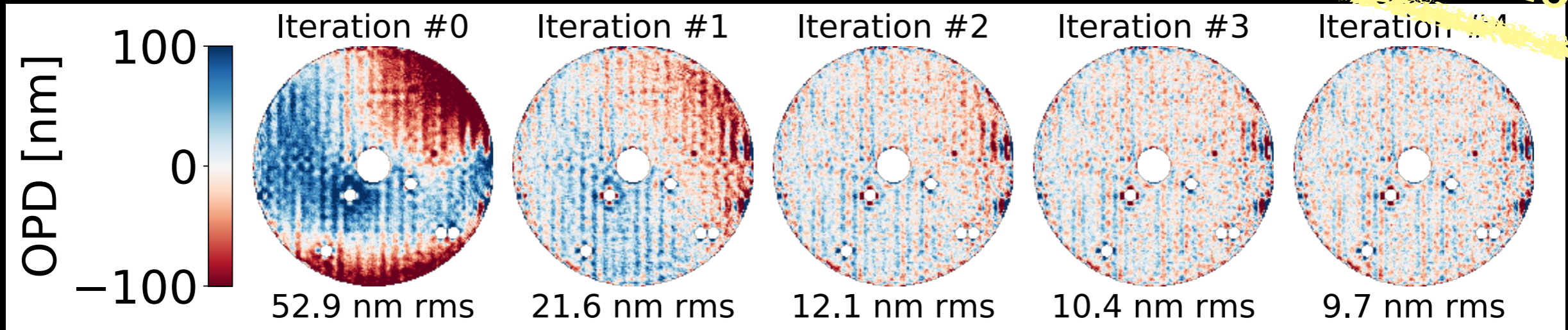
The background of the slide is a faded, dark version of the title screen for the video game 'The Legend of Zelda III: A Link to the Past'. It features the Hylian shield on the left, the sword in the center, and the title text on the right. The text 'THE LEGEND OF ZELDA' is at the top, 'A LINK TO THE PAST' is at the bottom, and 'ZELDA III' is in the middle in large, stylized letters. The shield and sword are rendered in a detailed, metallic style with various colors like red, blue, and gold.

ZELDA III : A link to the sky

On-sky closed-loop correction

Tests in
April 2018

On internal source

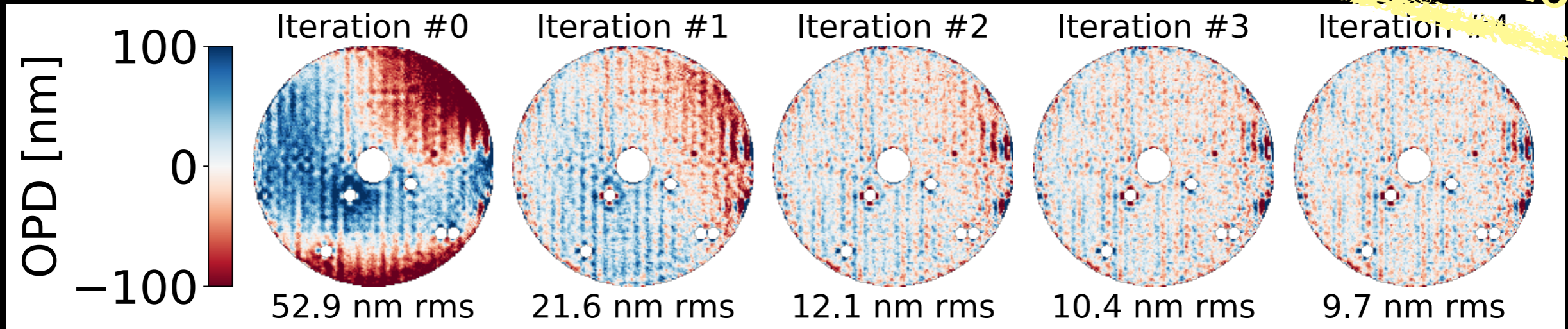


nm RMS WFE for $0 < \text{freq.} < 15 \text{ cyc/p}$

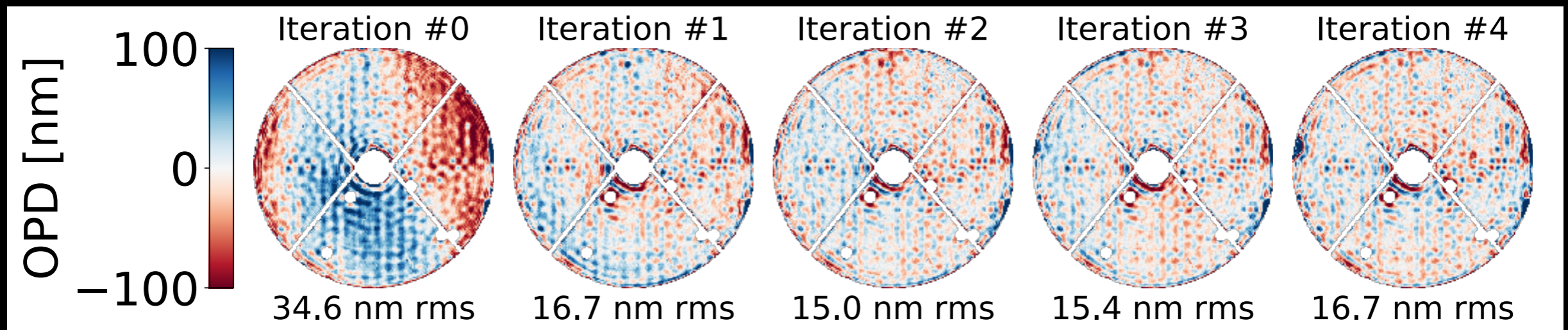
On-sky closed-loop correction

Tests in
April 2018

On internal source



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

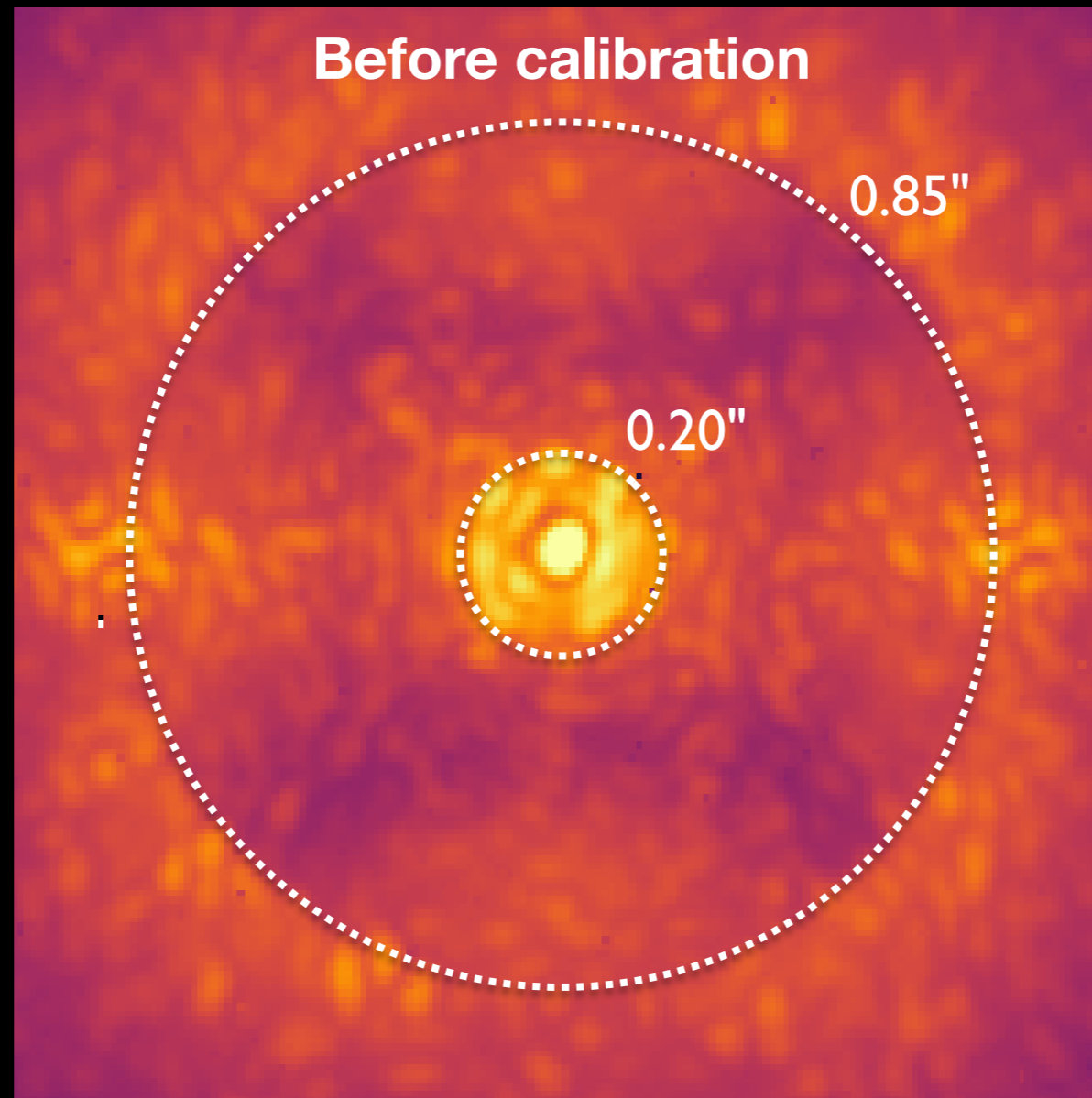
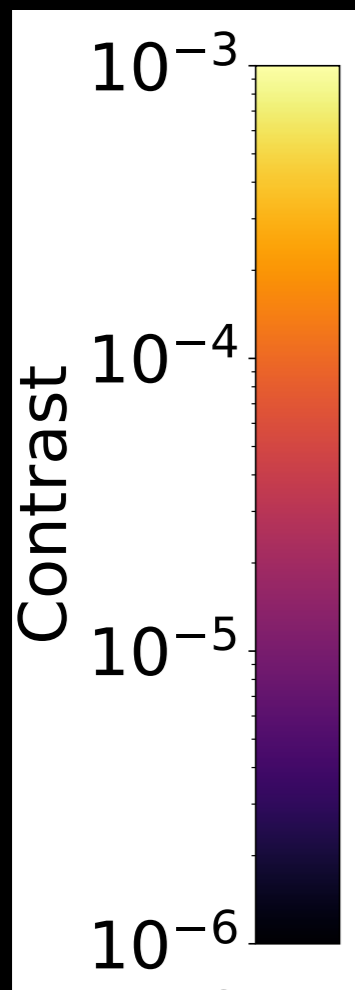


Reduction of the aberrations by a factor 2 on sky

nm RMS WFE for $0 < \text{freq.} < 15 \text{ cyc/p}$

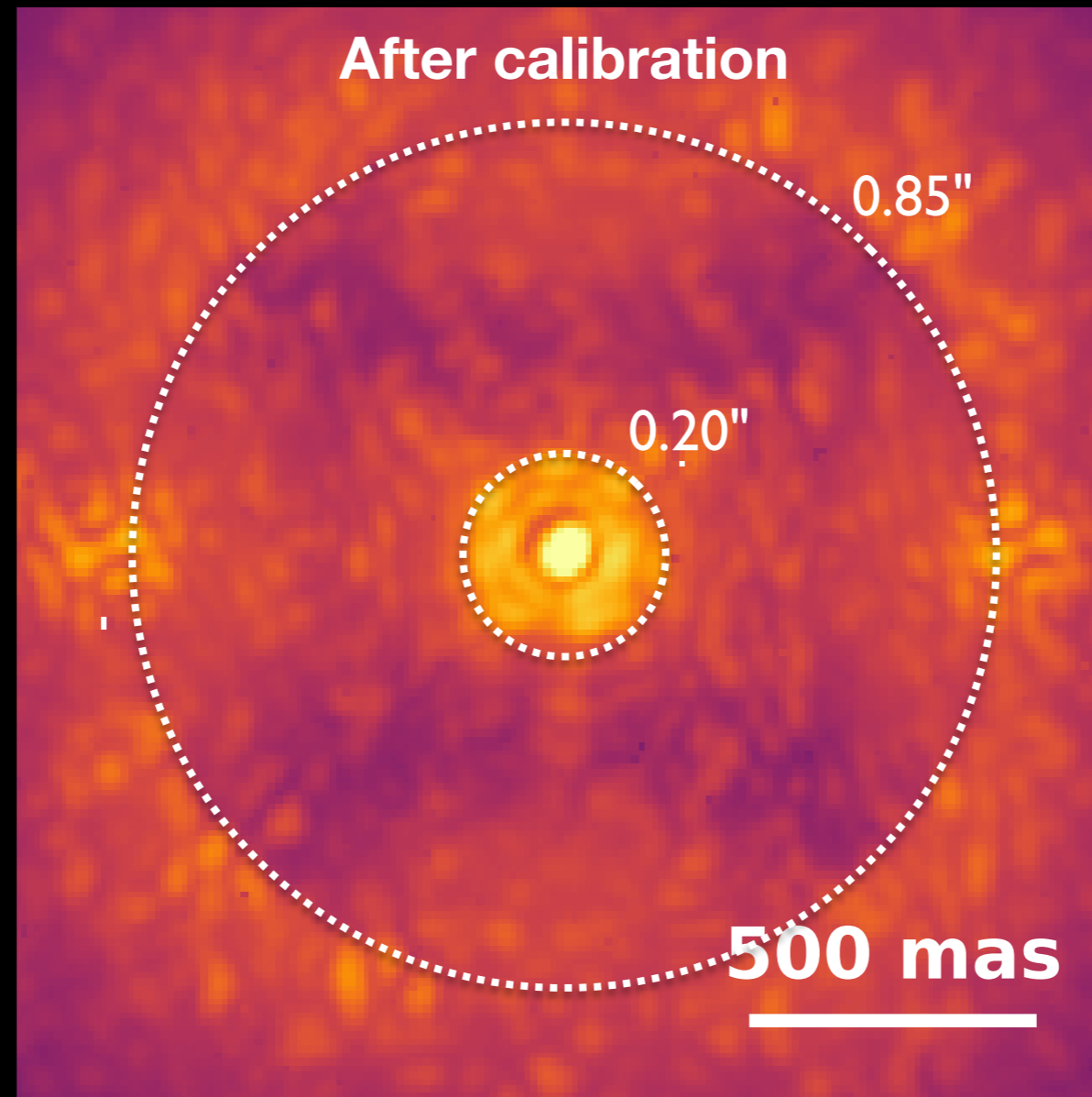
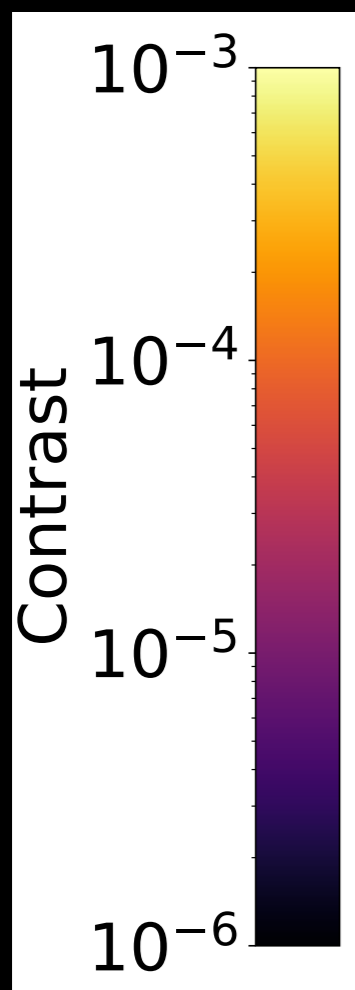
On-sky contrast performance

APLC image in H-band

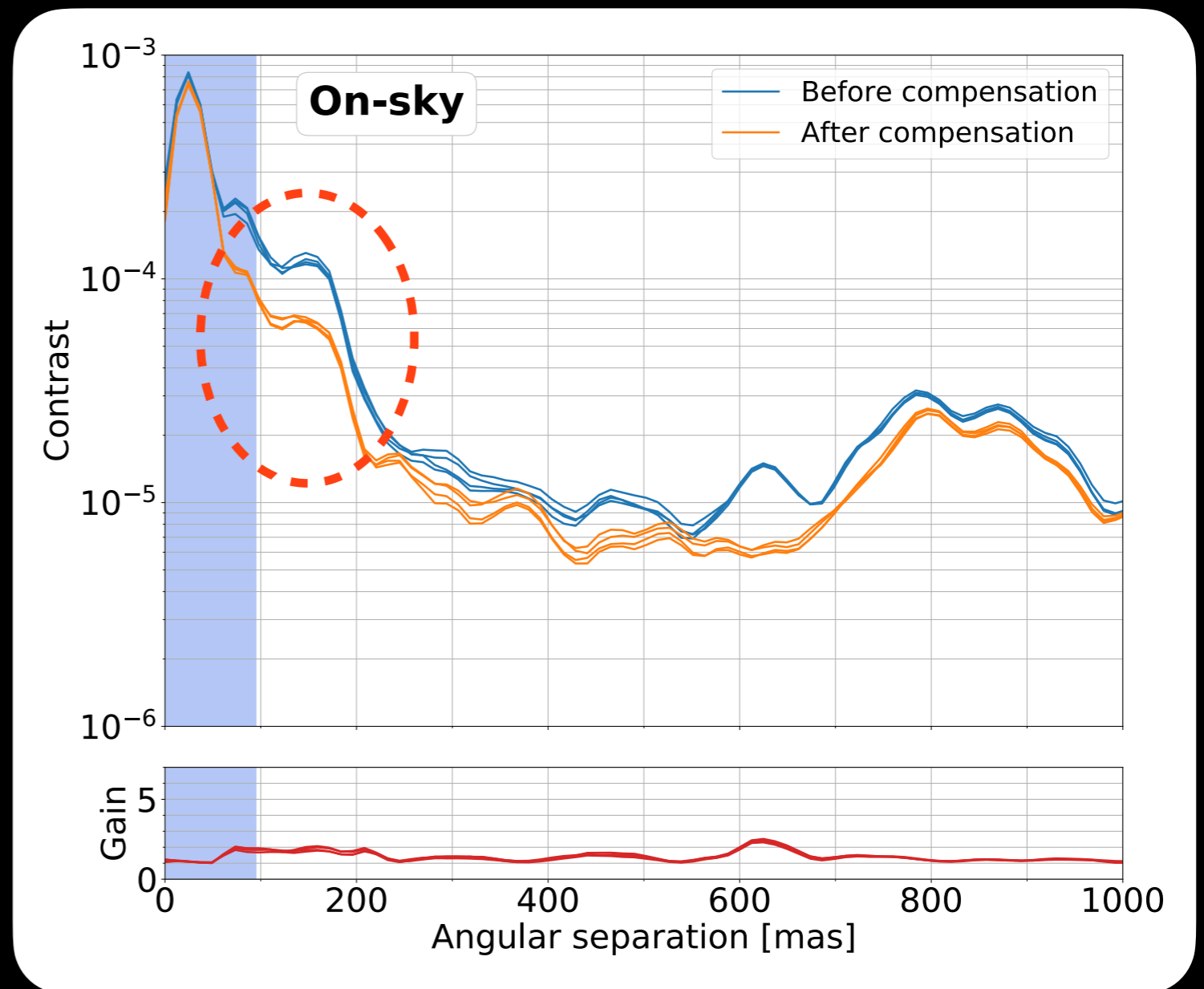
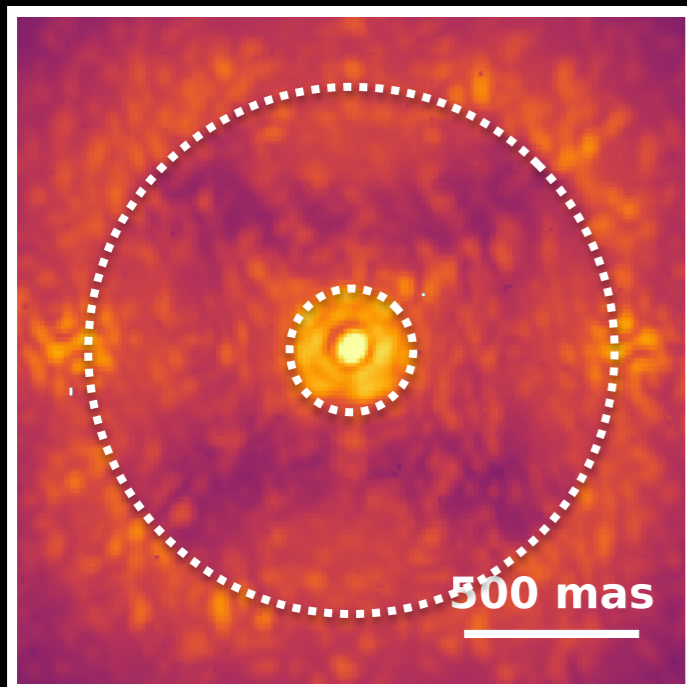
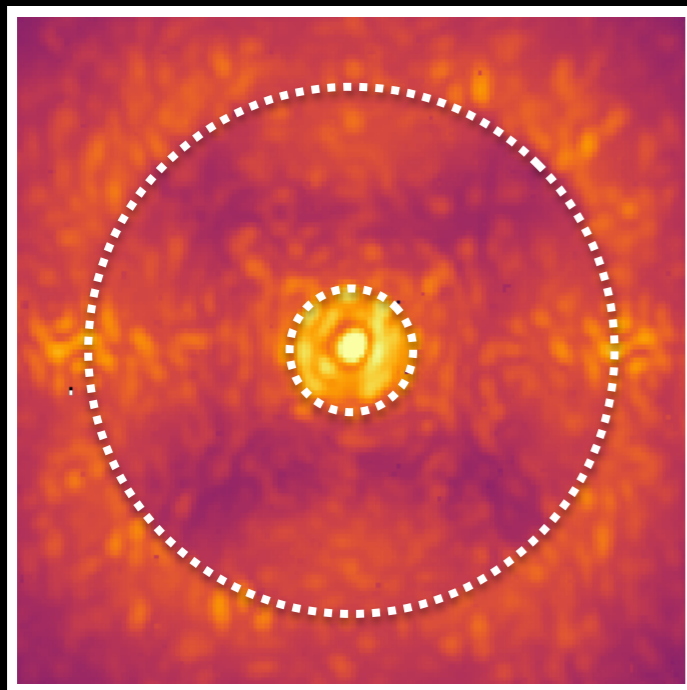


On-sky contrast performance

APLC image in H-band



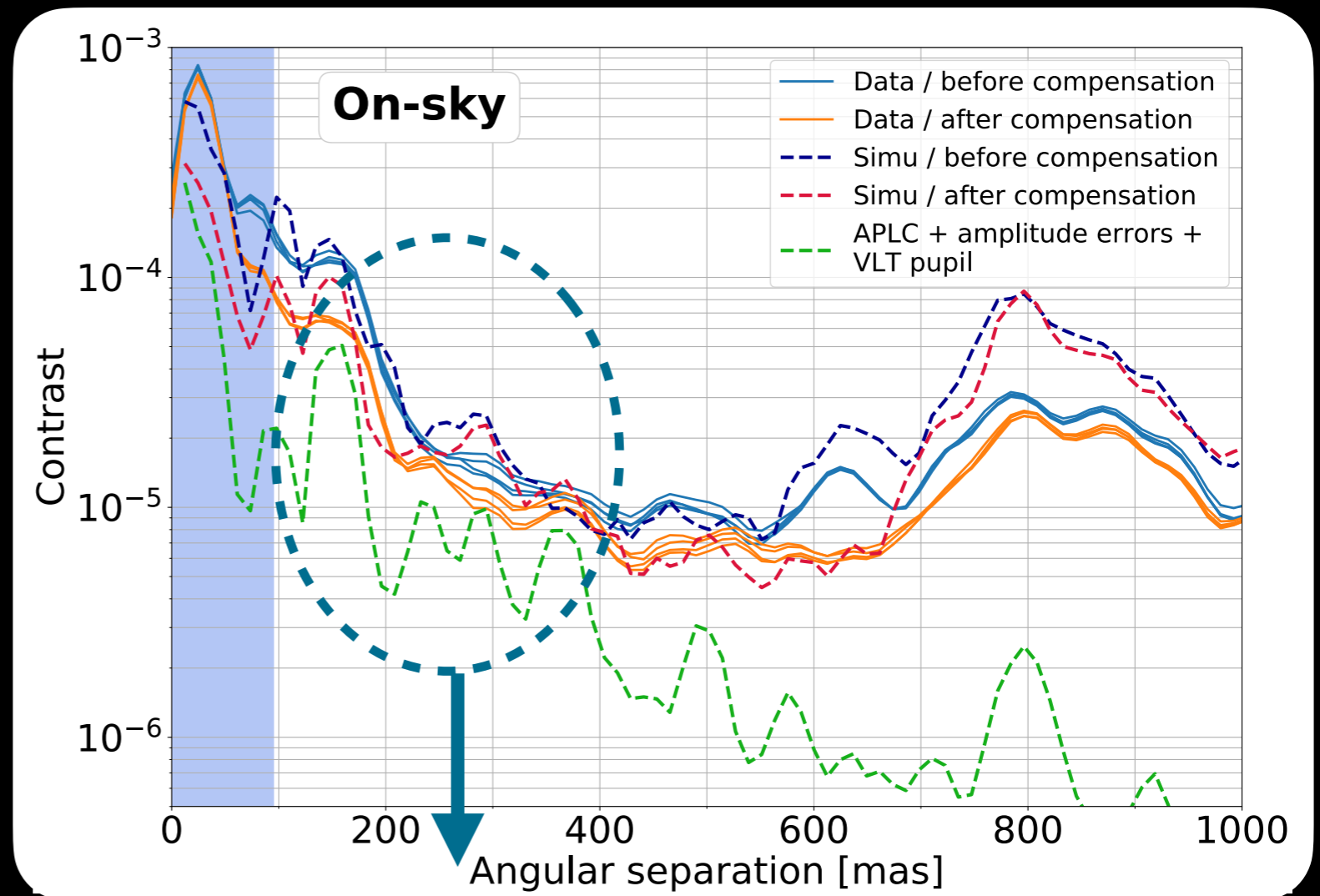
On-sky contrast performance



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

Analysis of the limitations

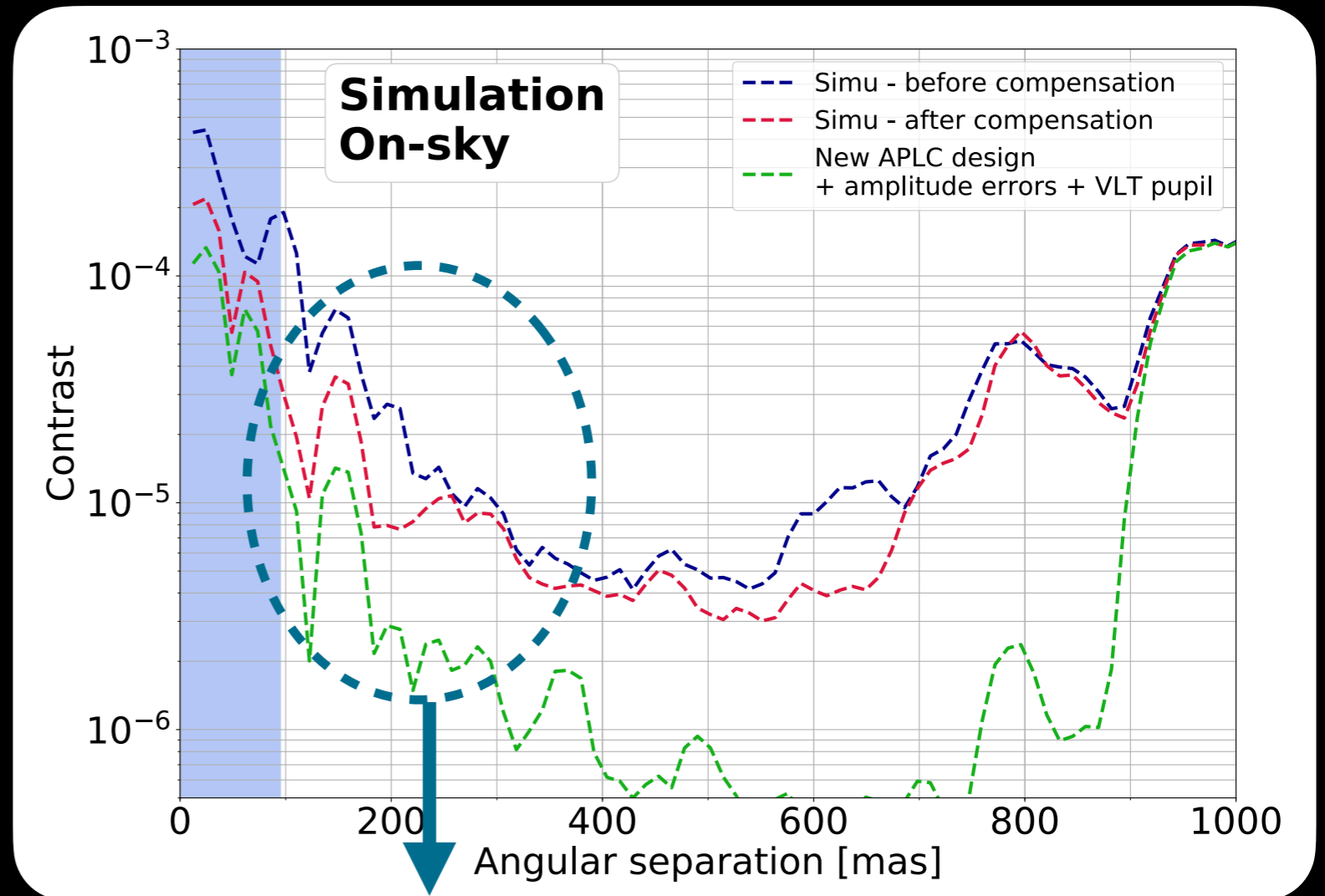
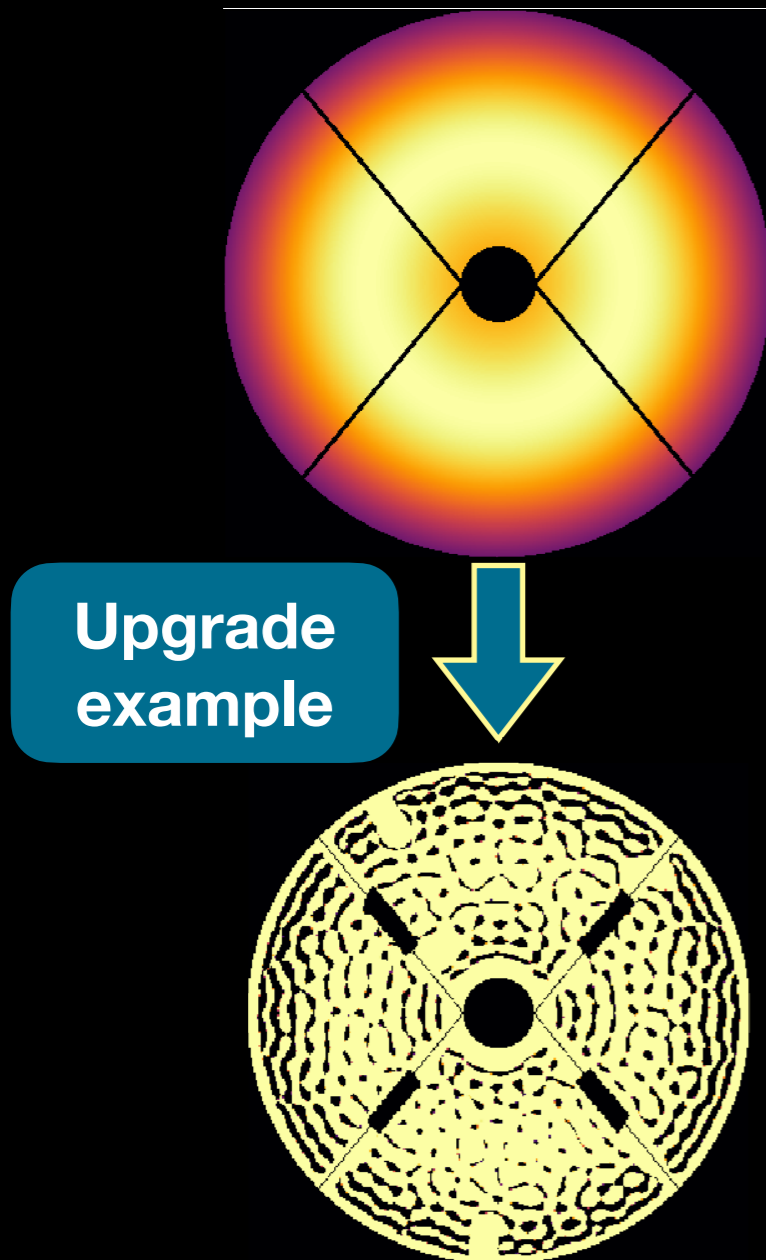
- Coronagraphic image reconstruction with analytical model using
 - XAO residuals from telemetry data
 - NCPA from ZELDA
 - Pupil amplitude errors
 - APLC components



Good agreement between model and data
Limitations due to the coronagraph

Analysis of the limitations

- Analysis of the expected performance by just replacing the apodizer



Improved contrast with ZELDA NCPA correction + new coronagraph

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