Calibration of residual aberrations in coronagraphic instruments with ZELDA: validation in VLT/SPHERE

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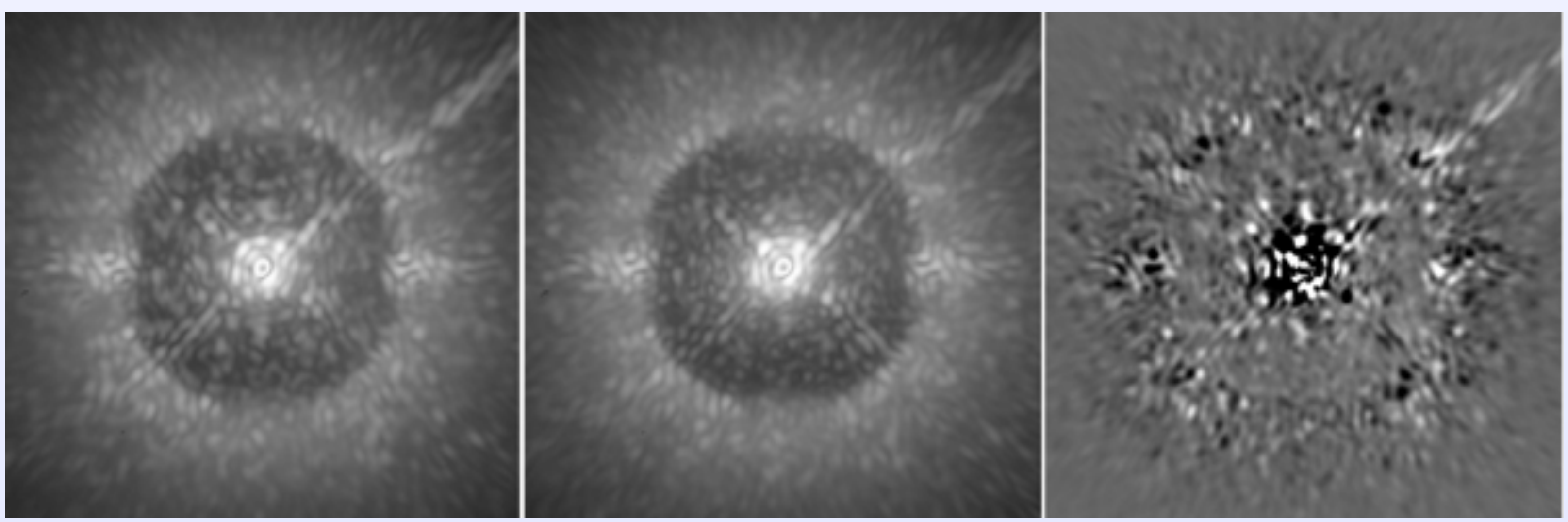
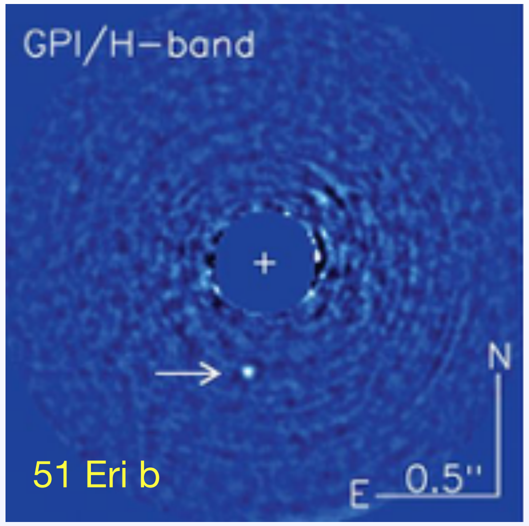
Context

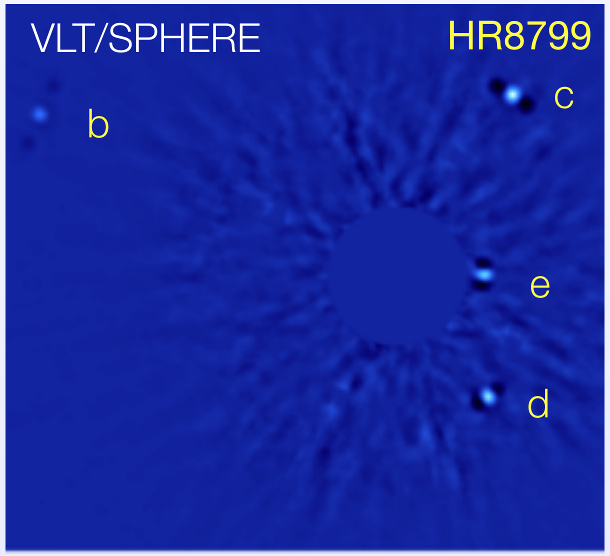
- Direct imaging and spectroscopy of exoplanets
  - VLT/SPHERE, Gemini/GPI, Subaru/SCExAO, etc
  - disks, warm or massive gas giant planets
  - high contrast (Δmag>10) at small separations (0.1″-0.5")
- Instrument limitations
  - **quasi-static aberrations**
  - **temporal stability**

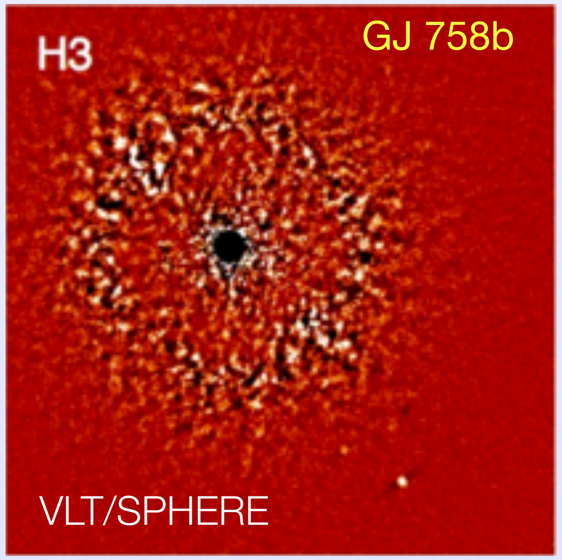
T_0 **T_1** **$T_0 - T_1$**



- Need of a clean PSF for optimal starlight rejection
  - **Calibration of pre-coronagraph aberrations**





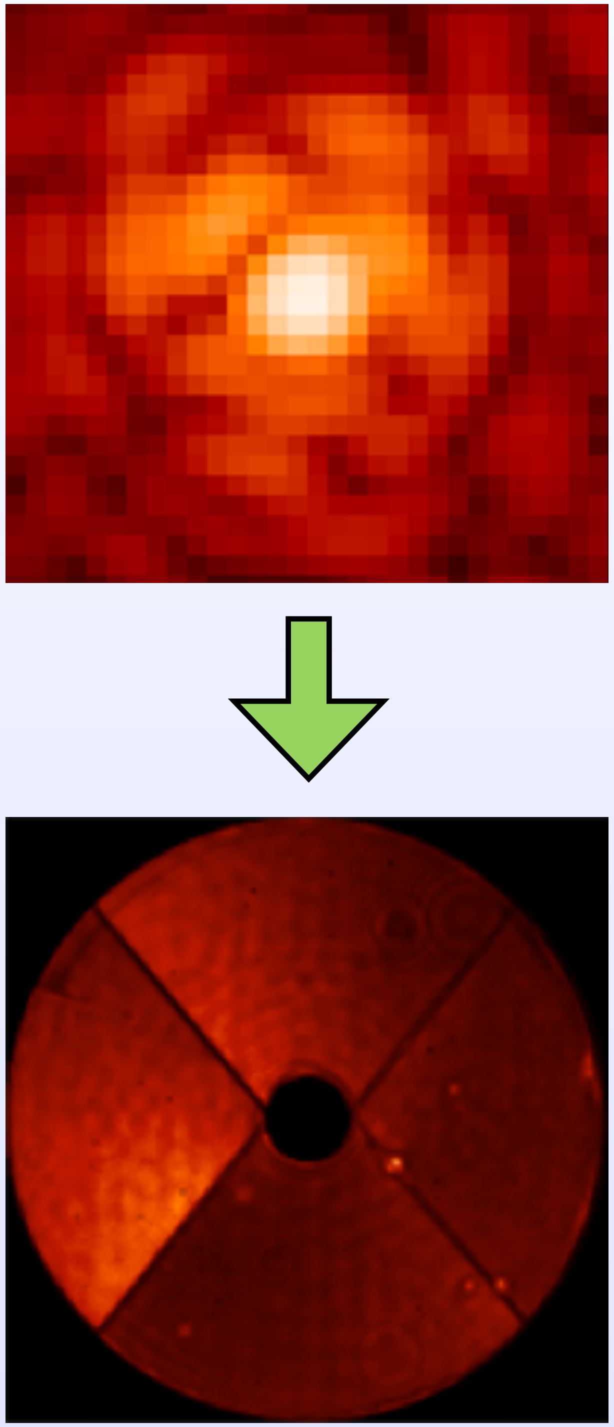


Macintosh et al. 2015, Zurlo et al. 2016, Vigan et al. 2016

Direct imaging of colder or lighter exoplanets

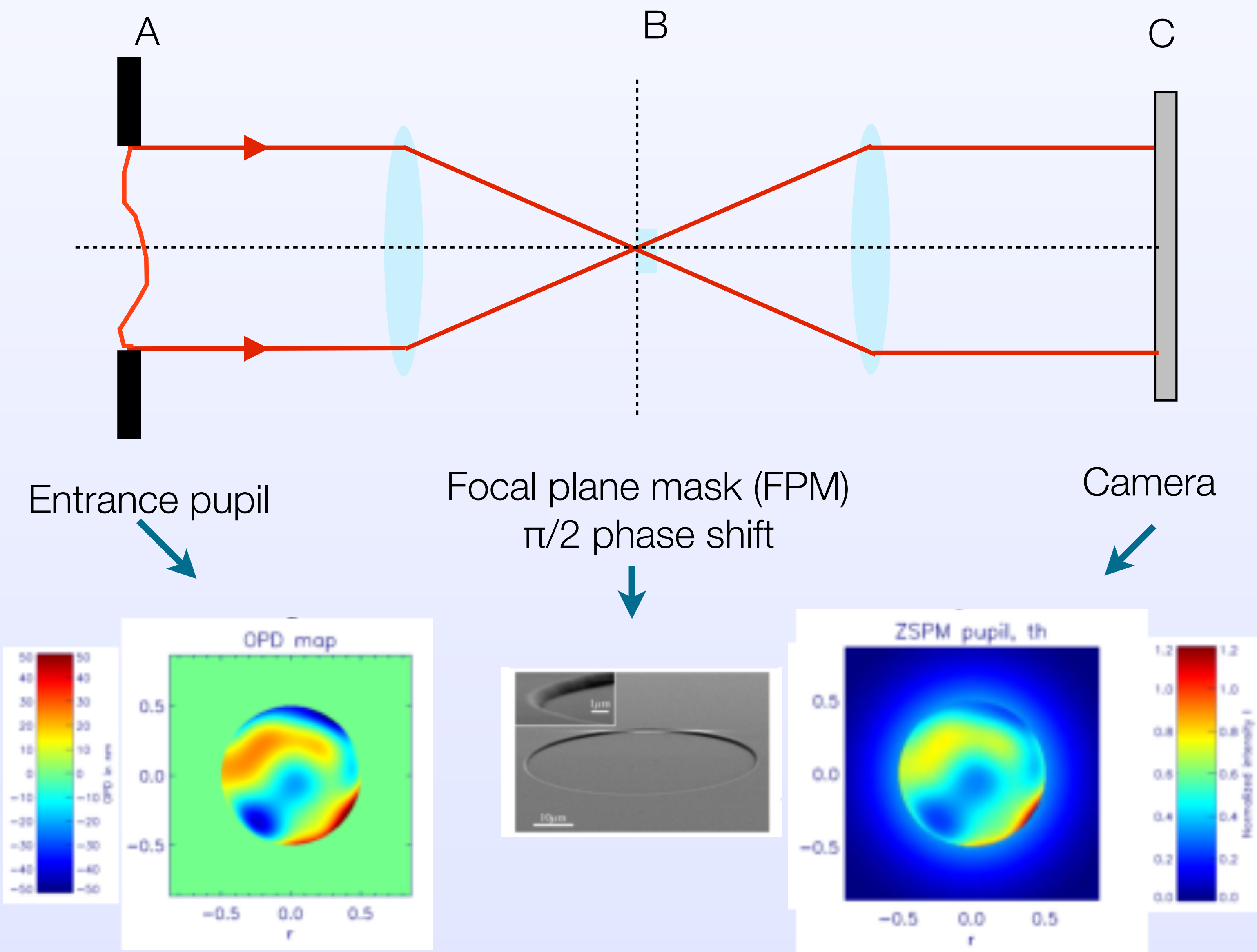
- Residual aberrations:
  - How to calibrate them?
  - Their origin?
  - Their temporal evolution?

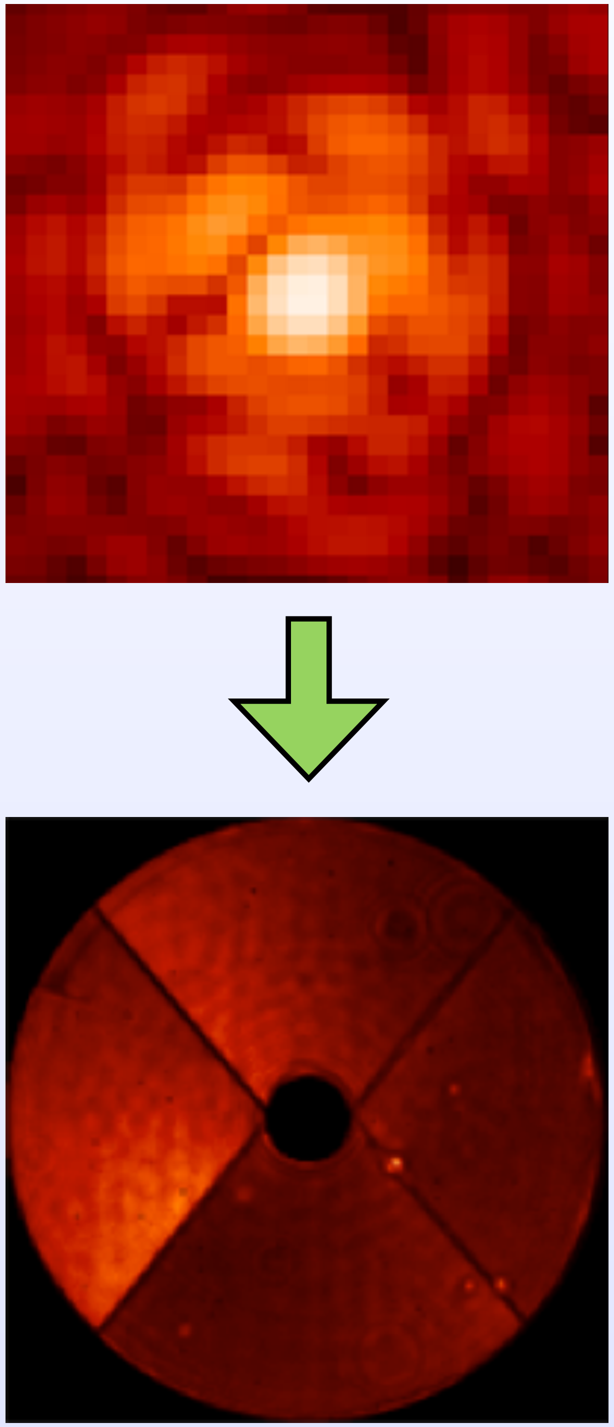
- Our solution:
  - Zernike wavefront sensor
    - *N'Diaye et al. A&A 2013, 2016*



Zernike wavefront sensor

- Conversion of the phase aberrations into intensity variations
  - $I_c = \alpha \sin \varphi + \beta$
  - Small aberrations: $I_c = \alpha\varphi + \beta$

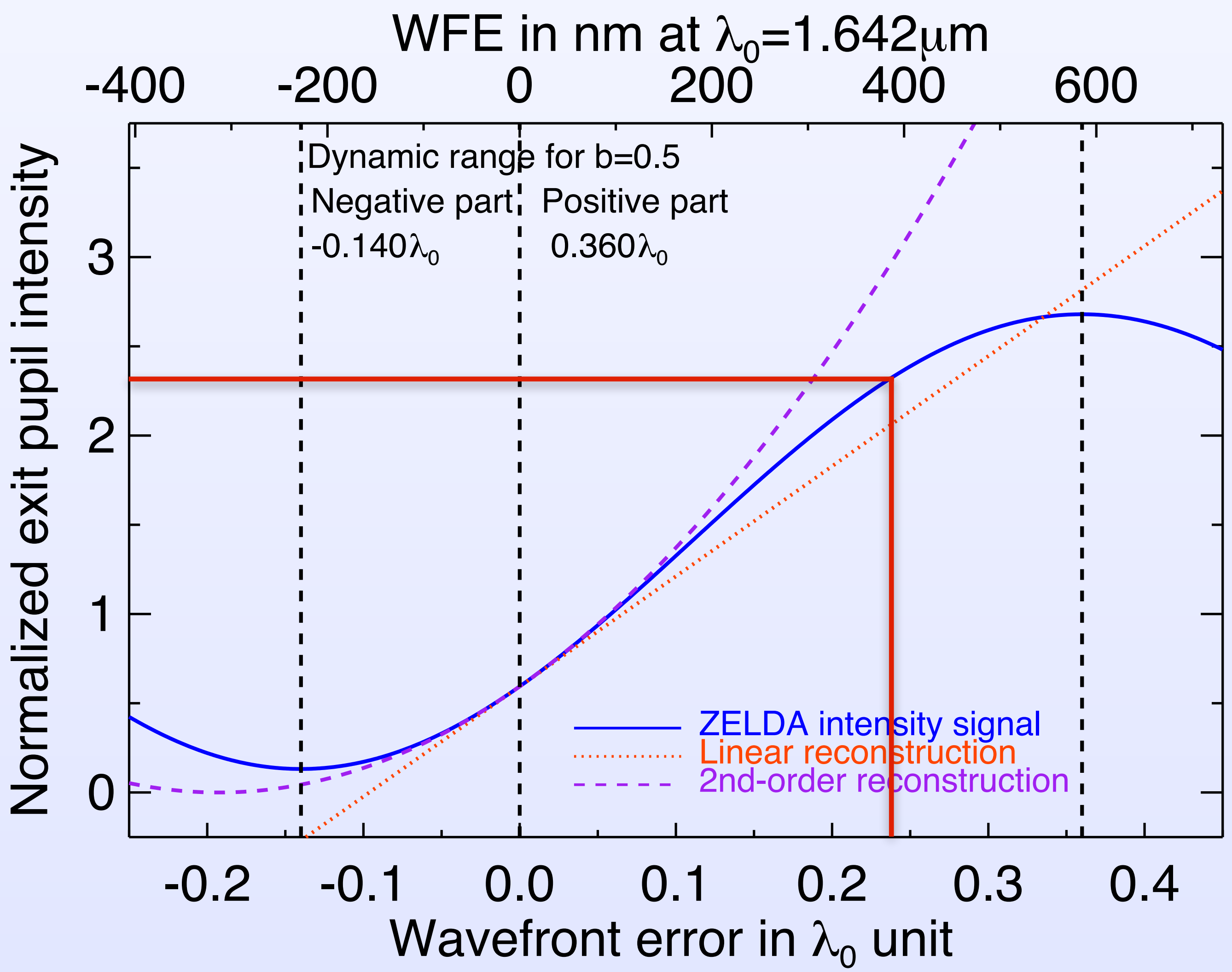


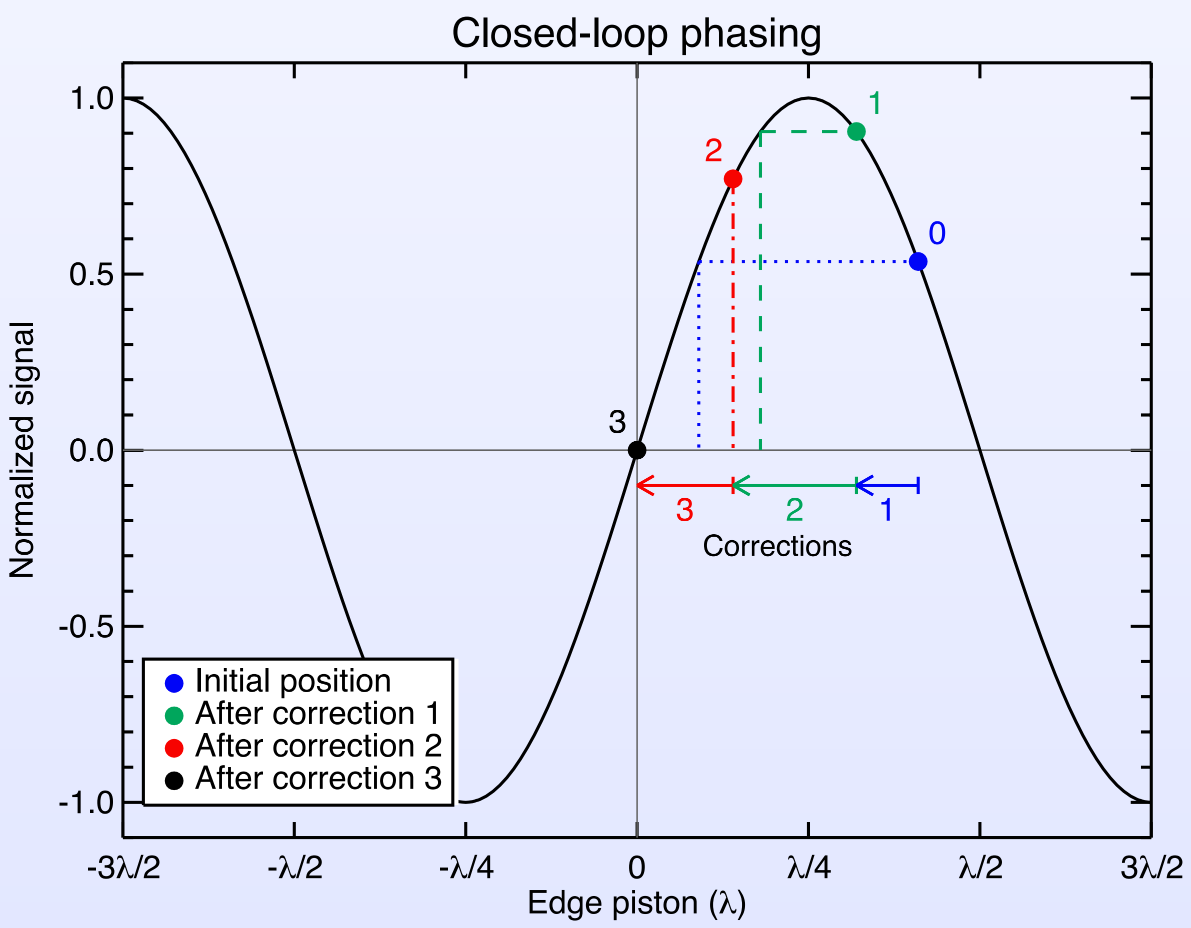


N'Diaye et al. 2013

Linearity range of the sensor

- Linearisation of the amplitude ➙ expression valid only near zero phase error
- Limited capture range: -0.14 λ_0 ➙ 0.36 λ_0
- Possible extension of the capture range in closed loop



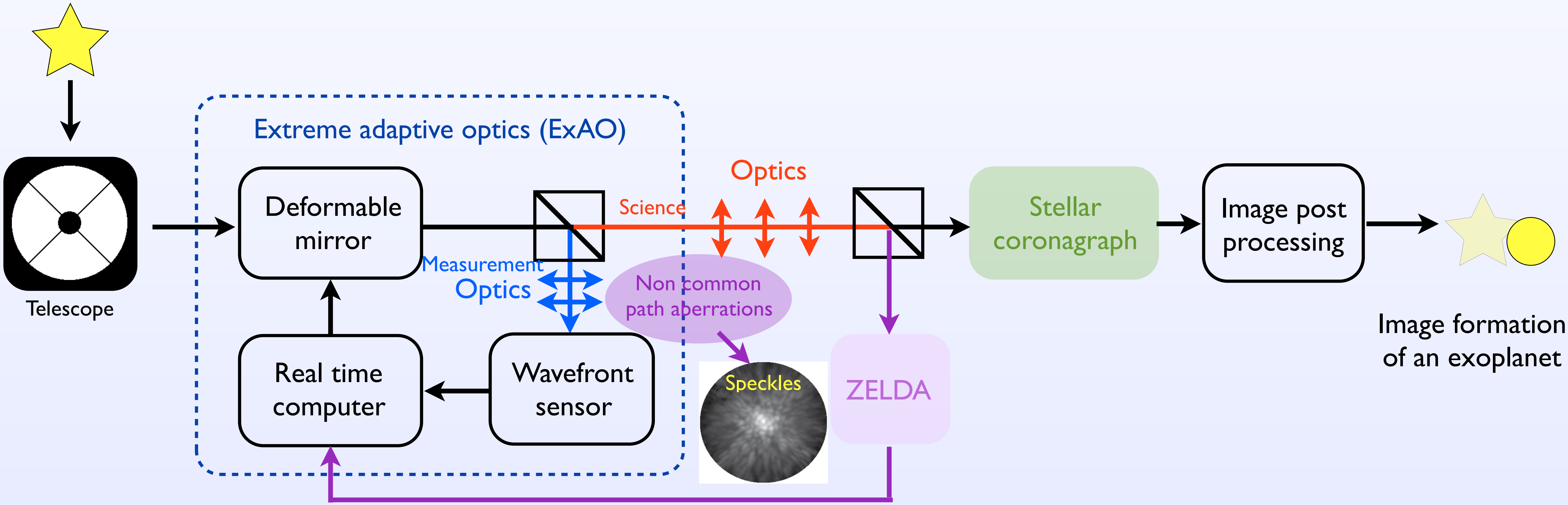


Vigan et al. 2011, N'Diaye et al. 2013

Implementation in VLT/SPHERE

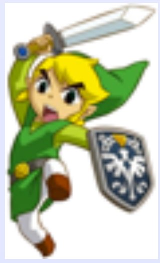
ZELDA

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

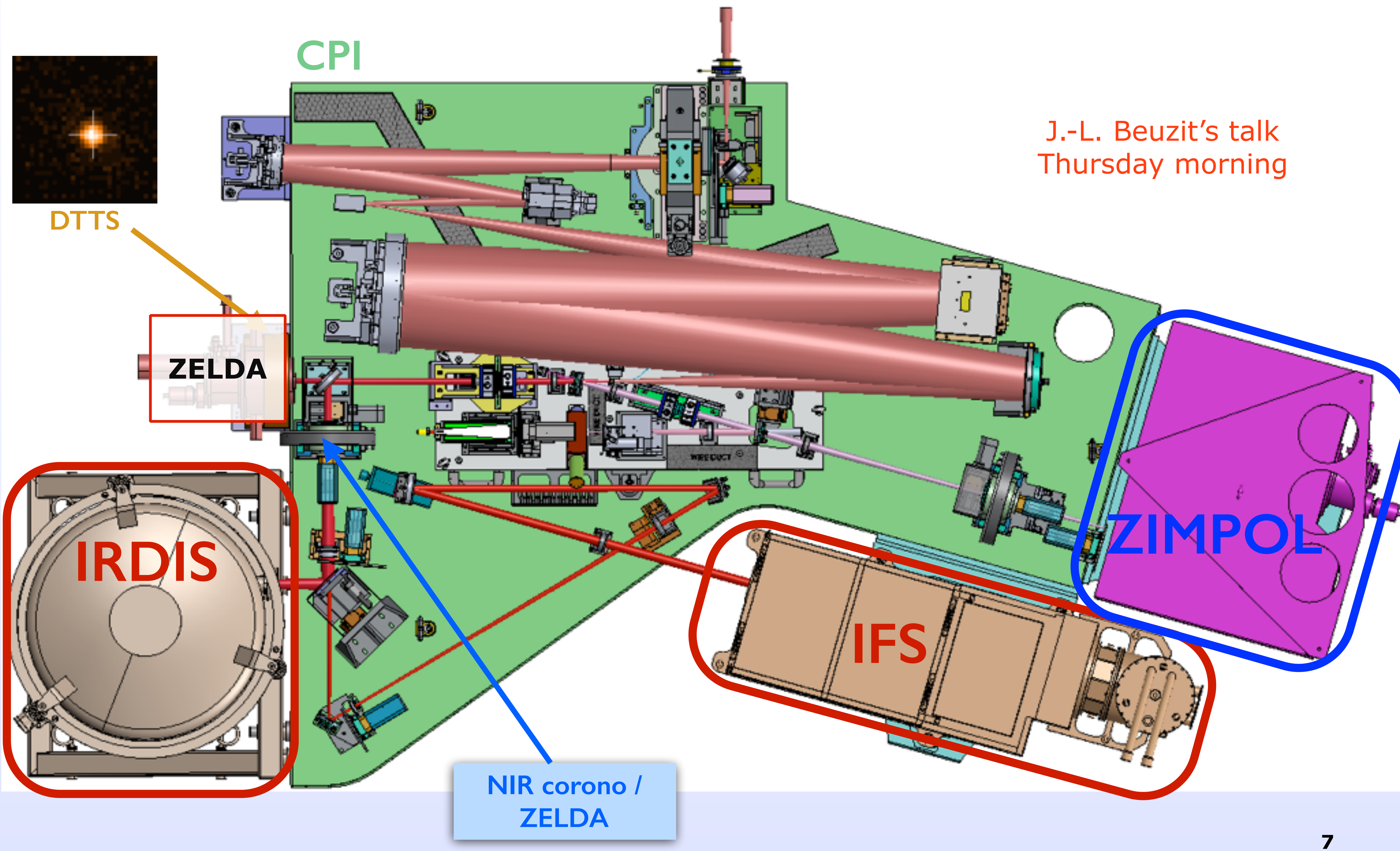


- Original measurement strategies:
  - VLT/SPHERE: off-line phase diversity
  - GPI: Mach-Zehnder interferometer behind coronagraph

- Our proposal:
  - ZELDA a concept based on phase-contrast technique

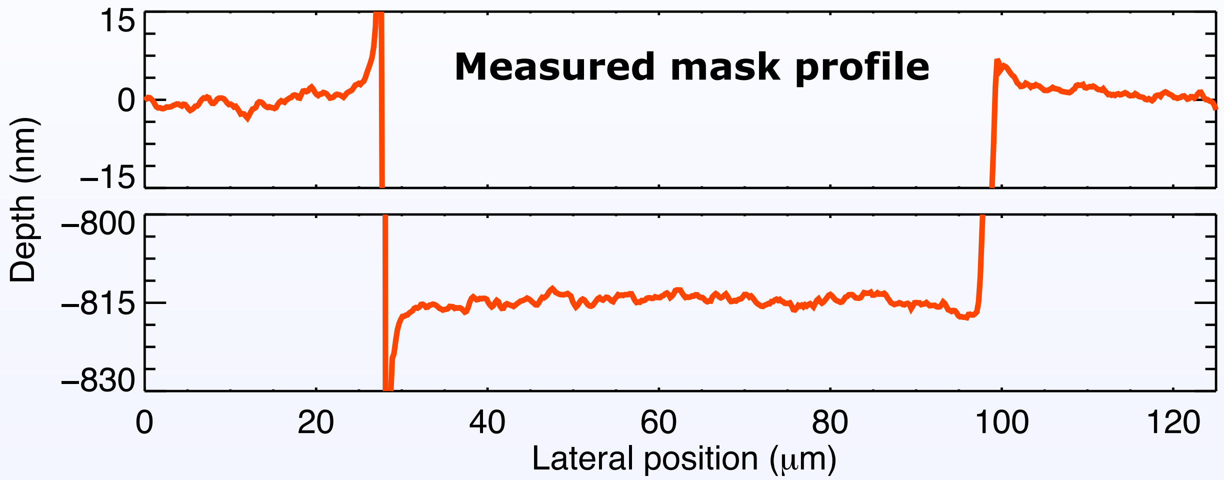


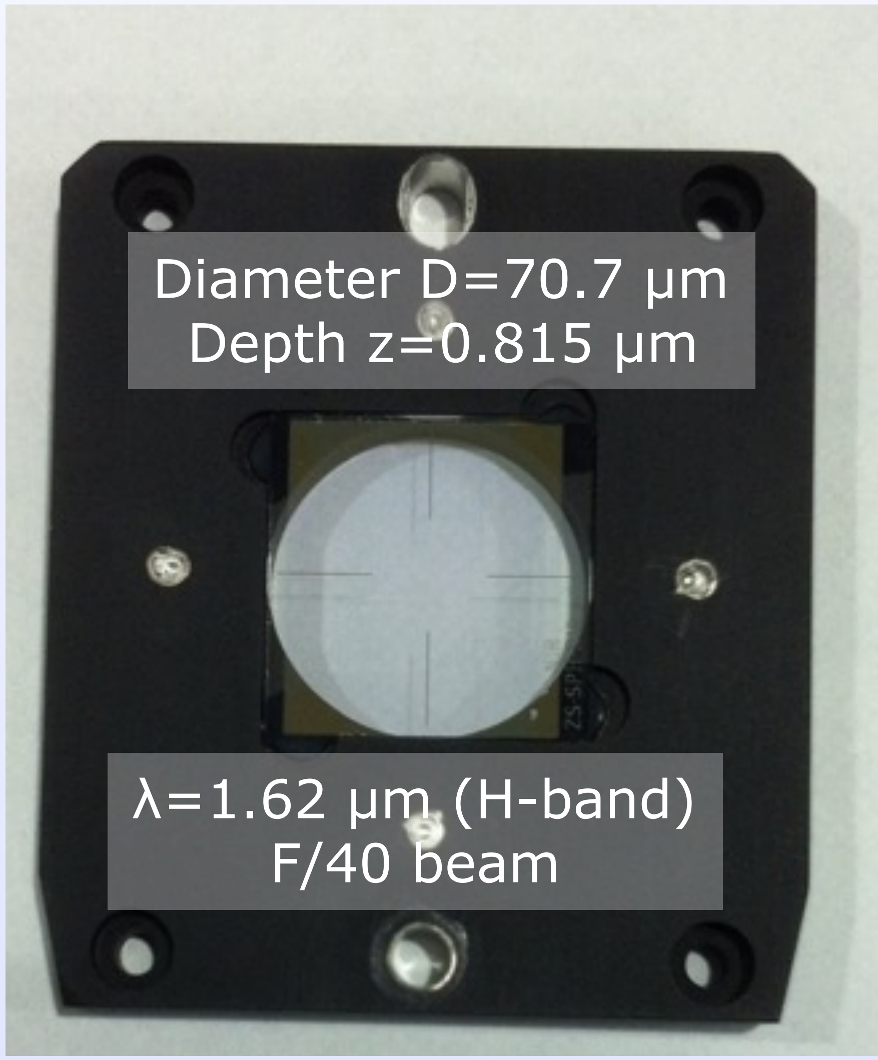
Current implementation in SPHERE

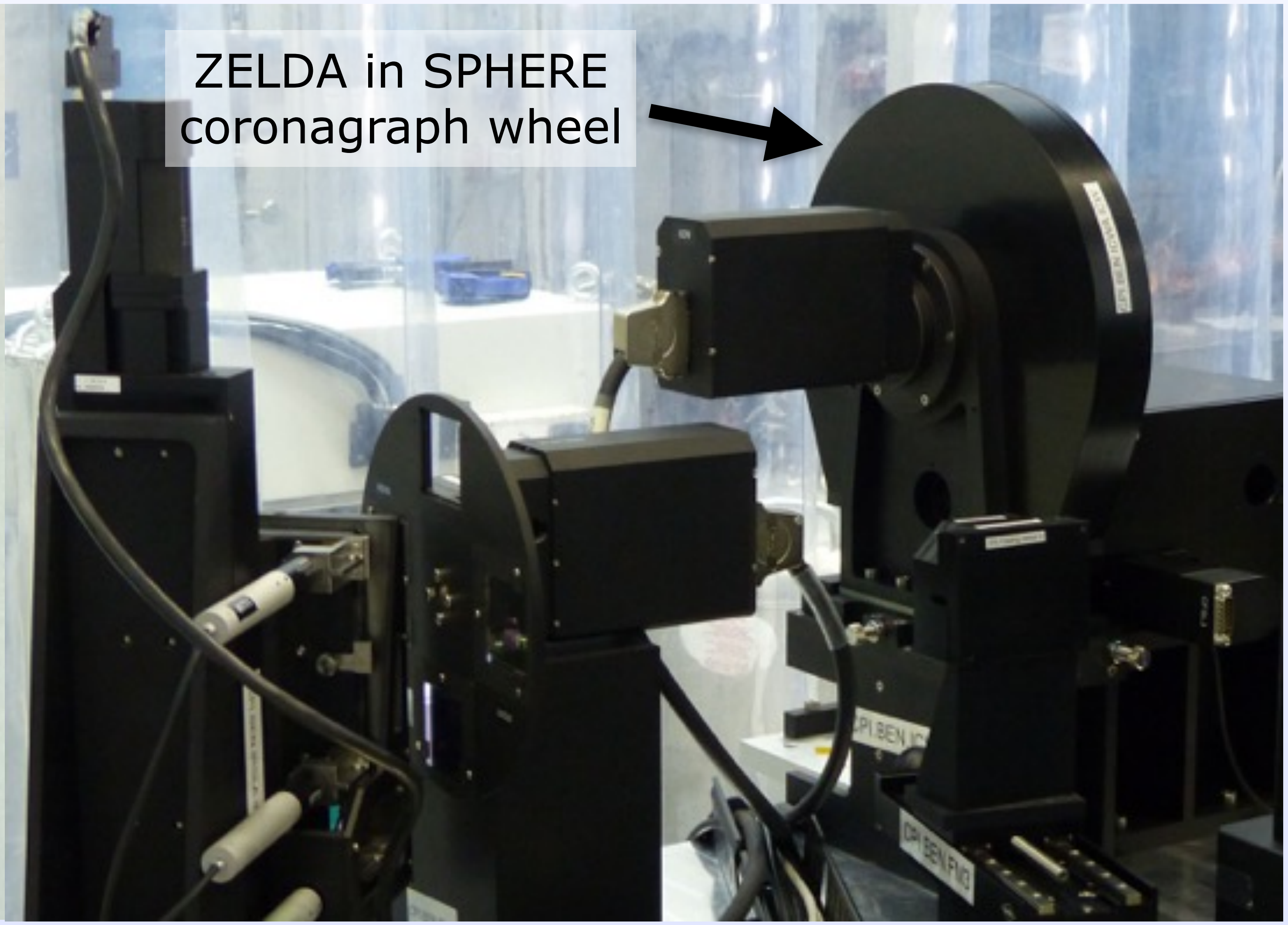


ZELDA prototype in SPHERE

- Fused silica substrate
- Mask by photolithographic reactive ion etching (SILIOS, France)
- Within 1% of the specifications



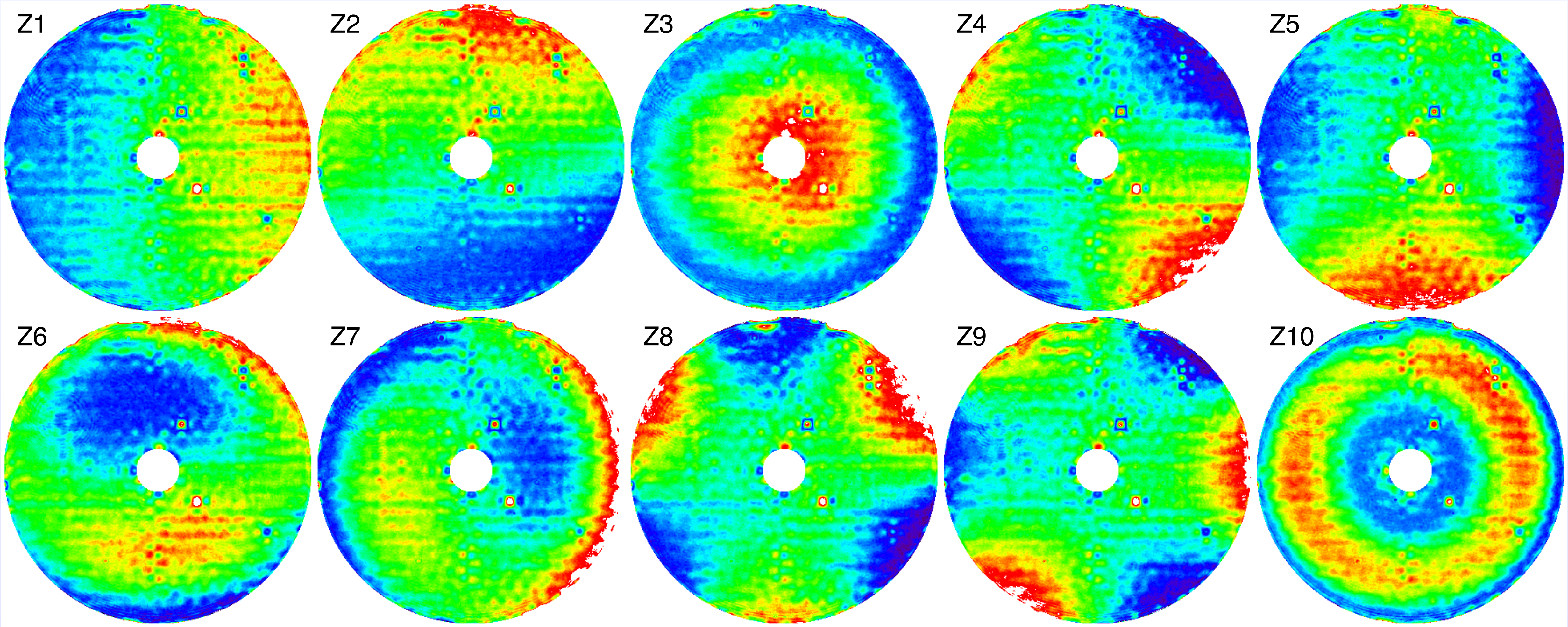




Installation during SPHERE reintegration at Paranal in April 2014

Validating ZELDA in SPHERE

- 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

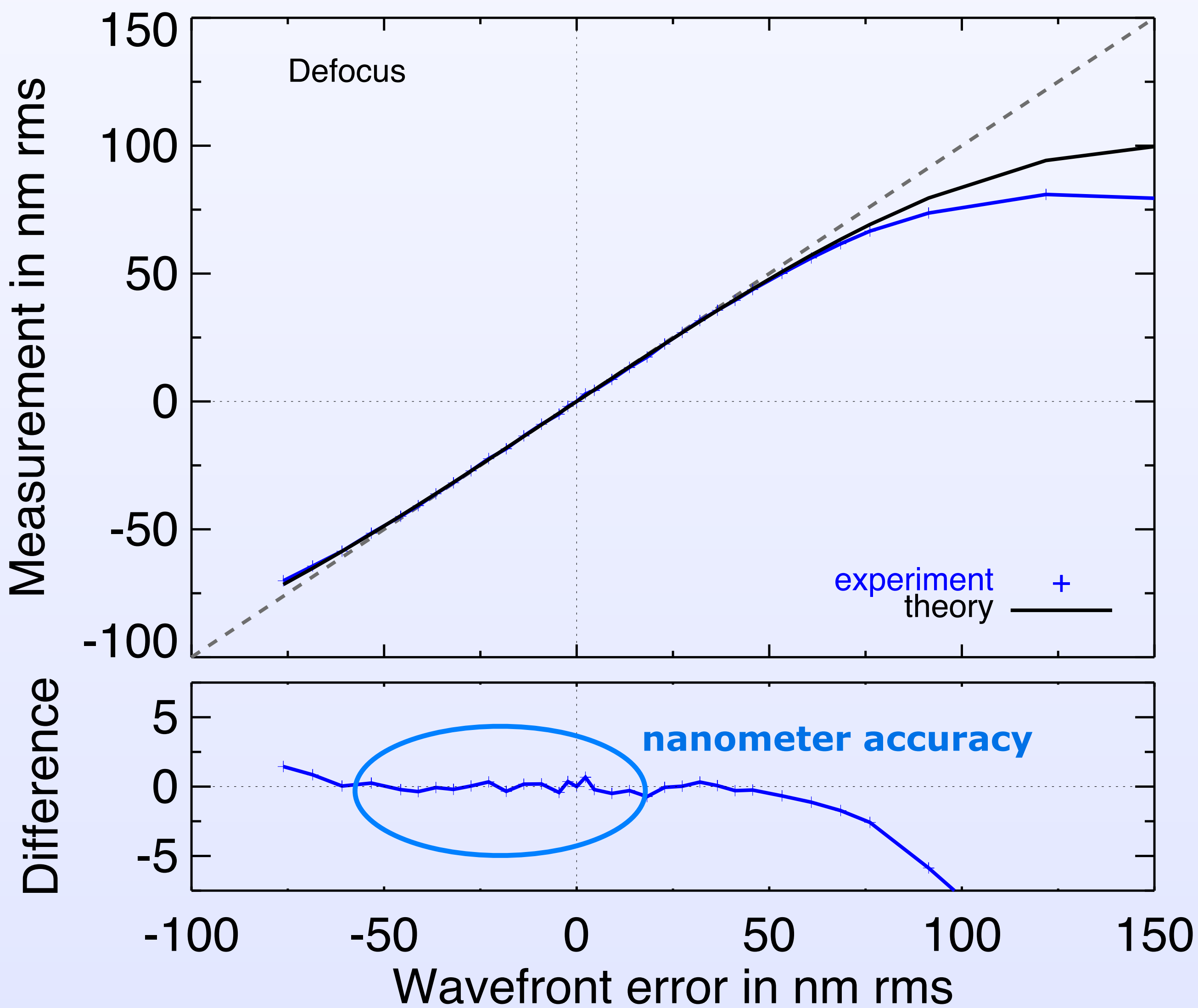


Zernike modes introduced with 400 nm PV on the DM

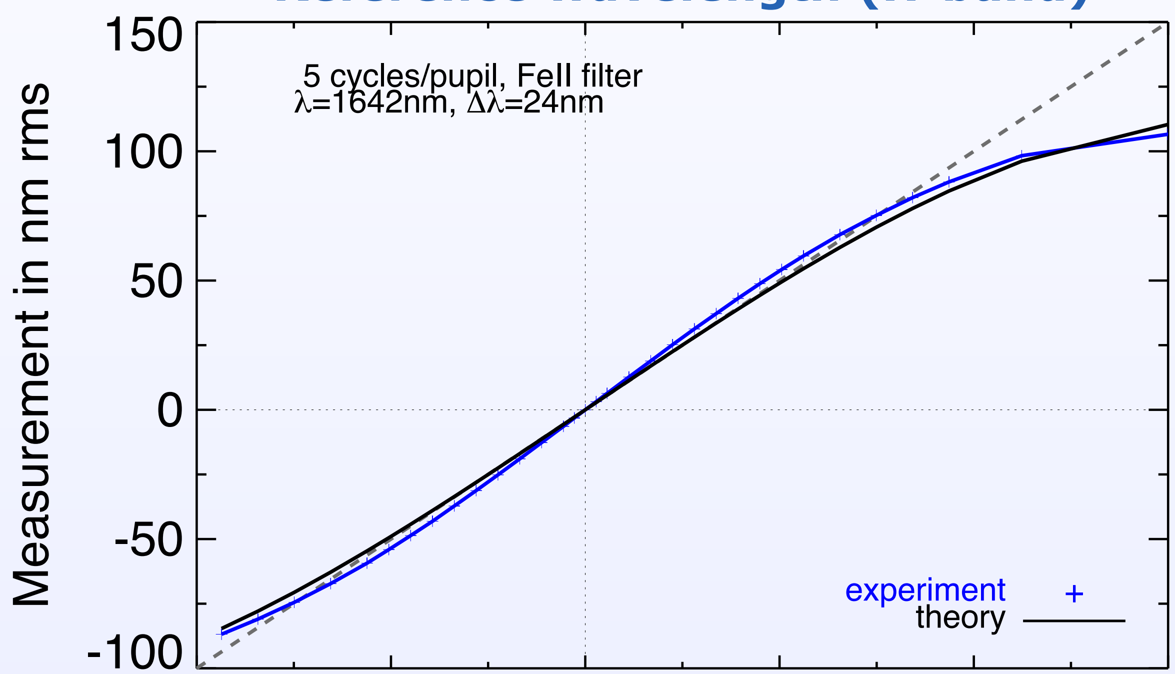
N’Diaye et al. 2016

Quantitative performance assessment

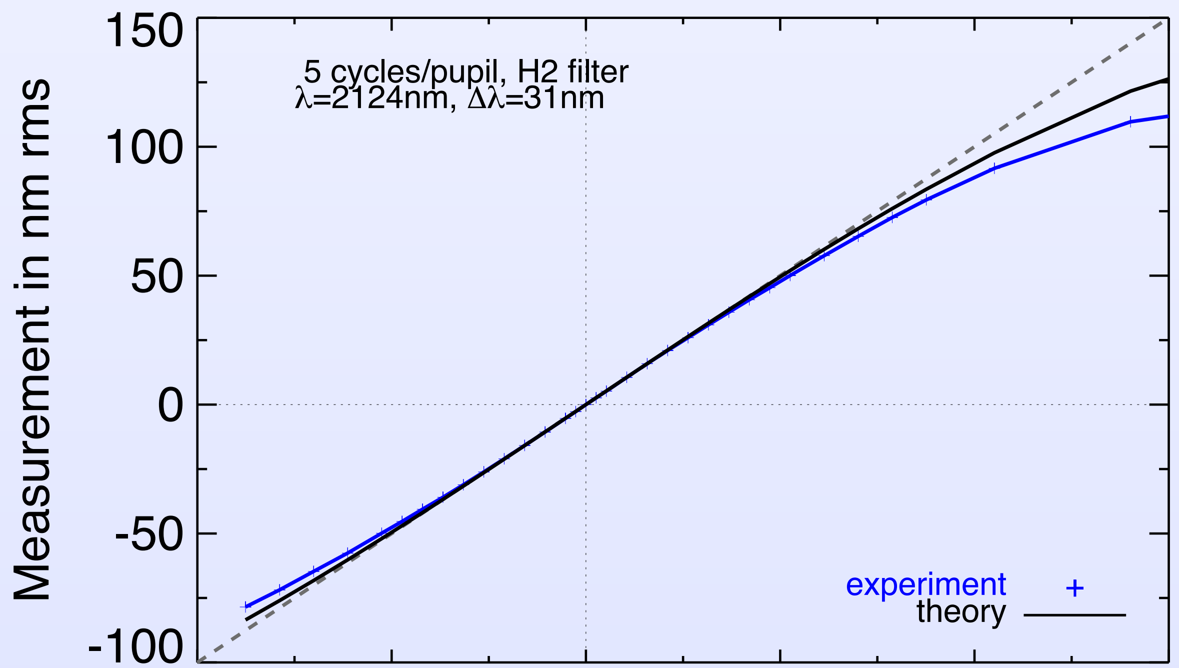
- theory vs. measurements:
  - excellent agreement!
- low sensitivity to wavelength of measure



Reference wavelength (H-band)



Measurement in K-band

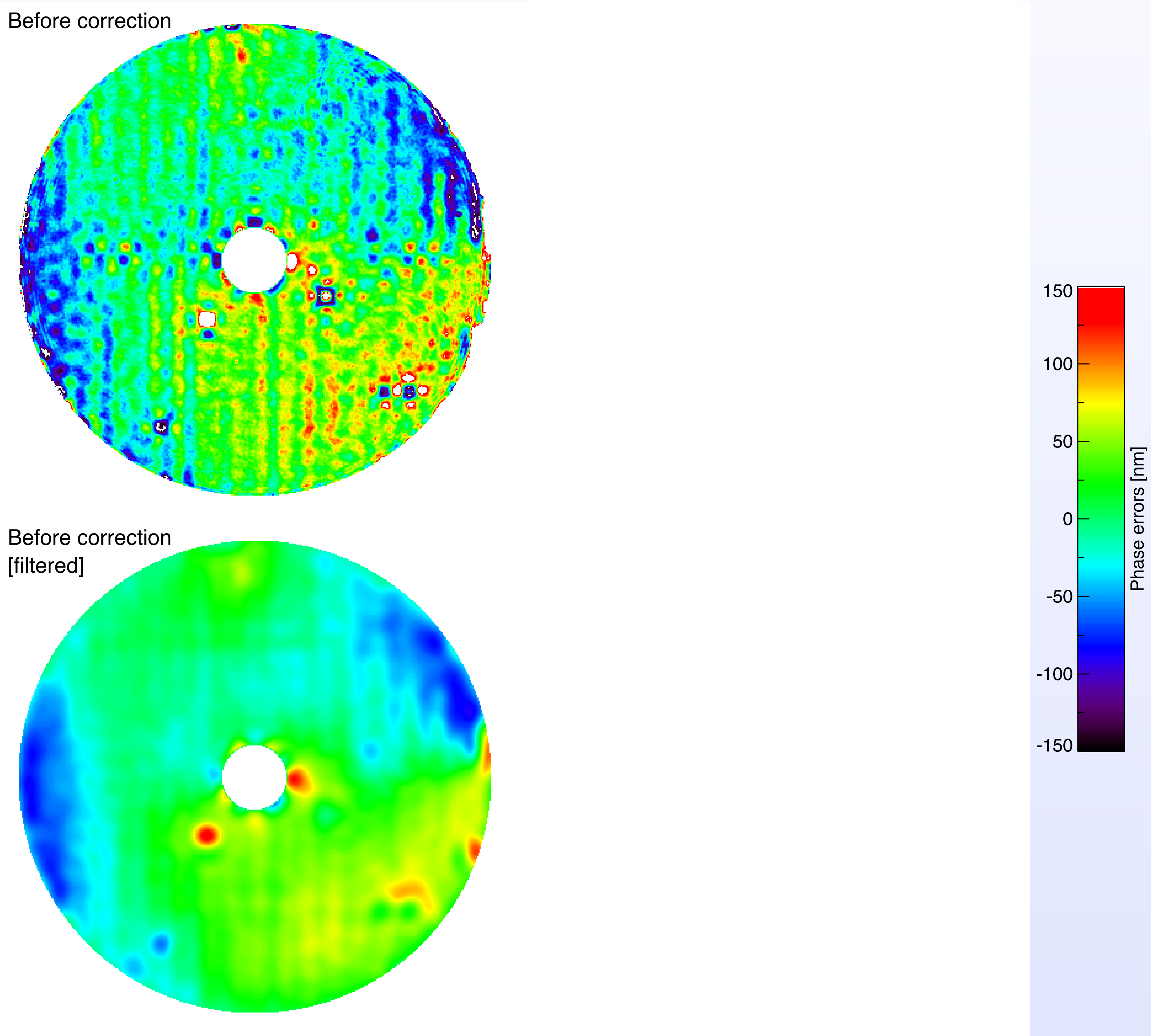


N'Diaye et al. 2016

NCPA measurement and compensation

45 nm RMS

30 nm RMS



N'Diaye et al. 2016

NCPA measurement and compensation

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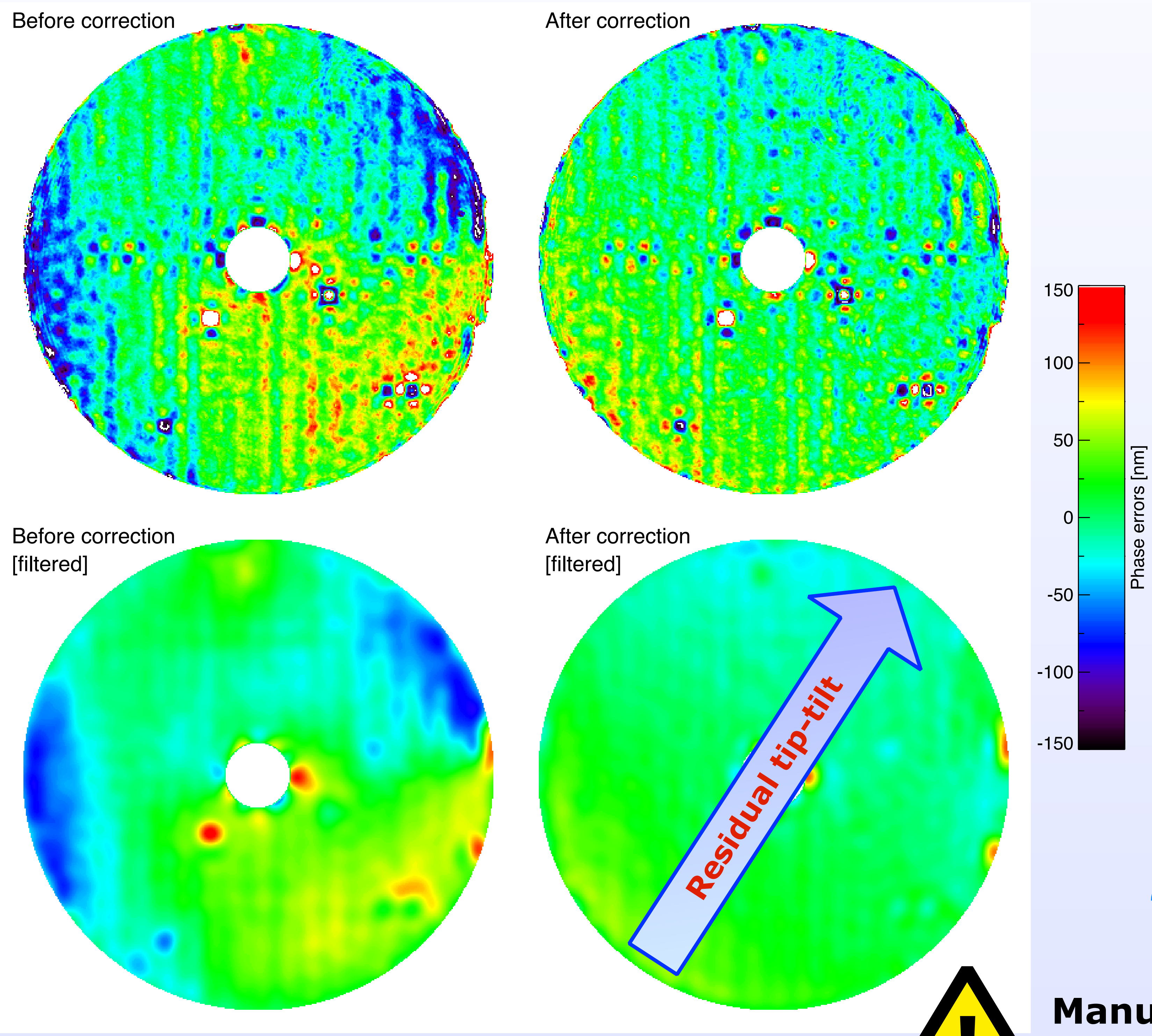


35 nm RMS

16 nm RMS

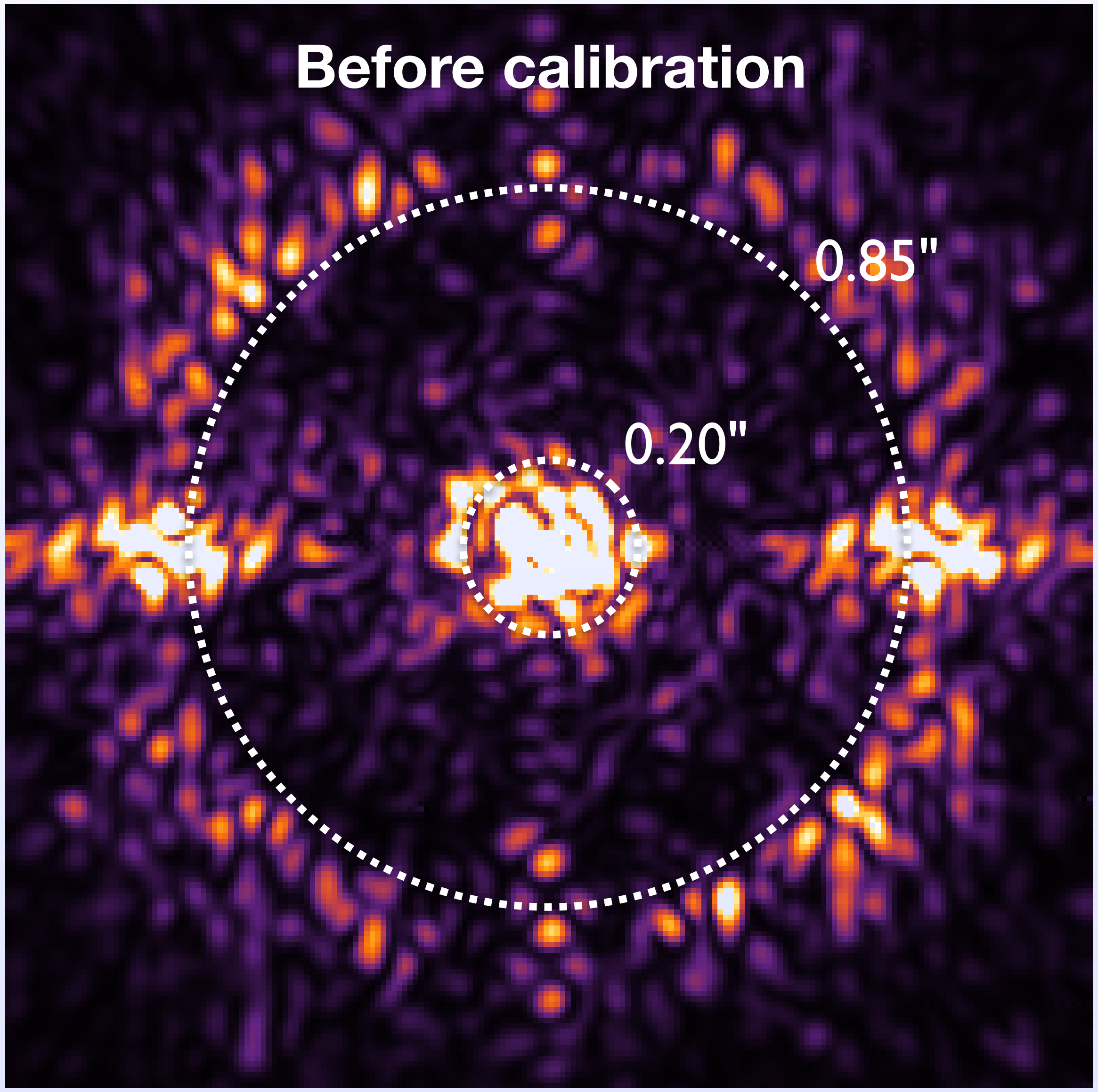
Tip-tilt:
~12 nm RMS

Manual centering + tip-tilt closed loop

N'Diaye et al. 2016

Impact on coronagraphic images

Apodised pupil Lyot coronagraph, H-band



N’Diaye et al. 2016

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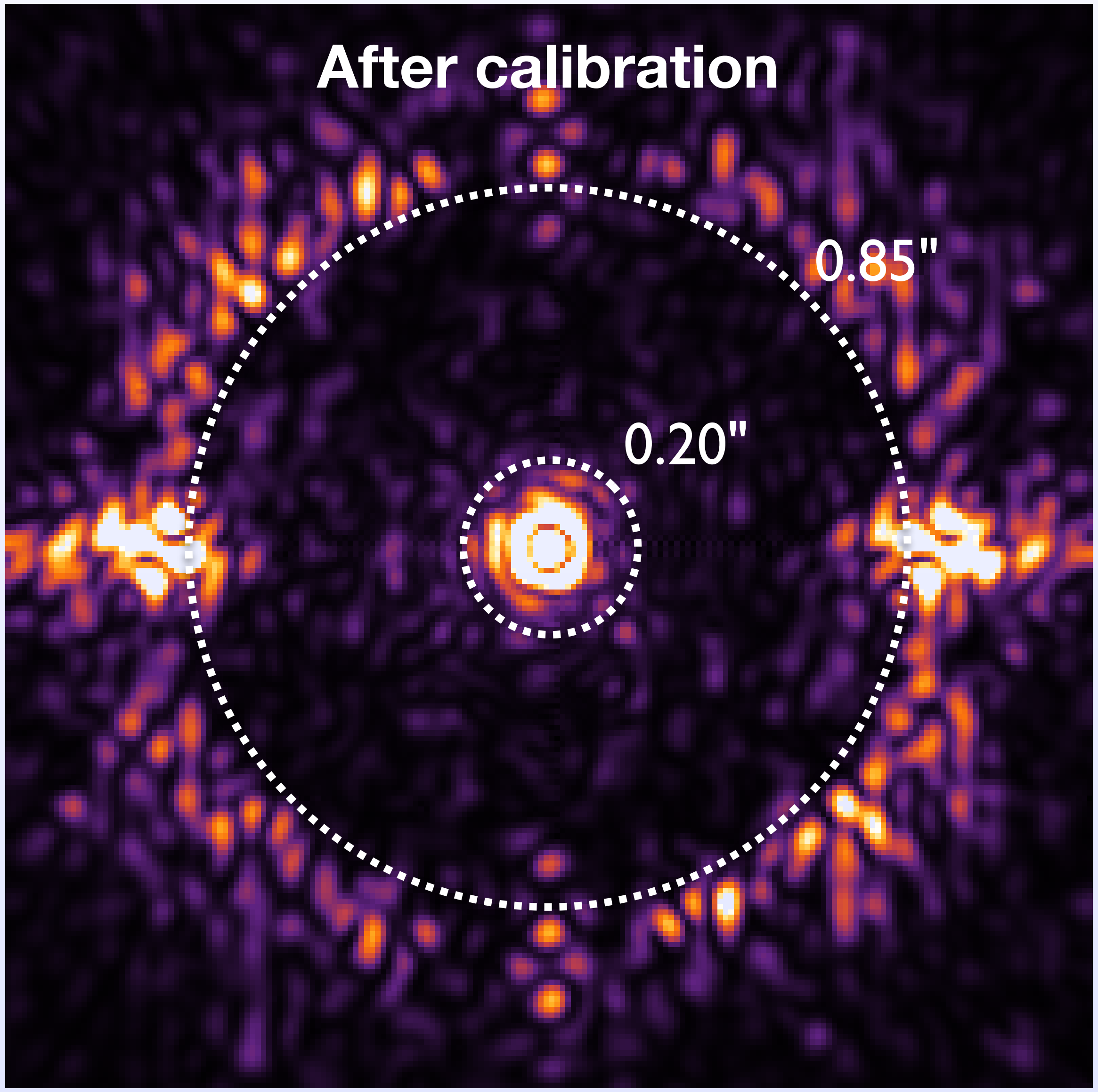
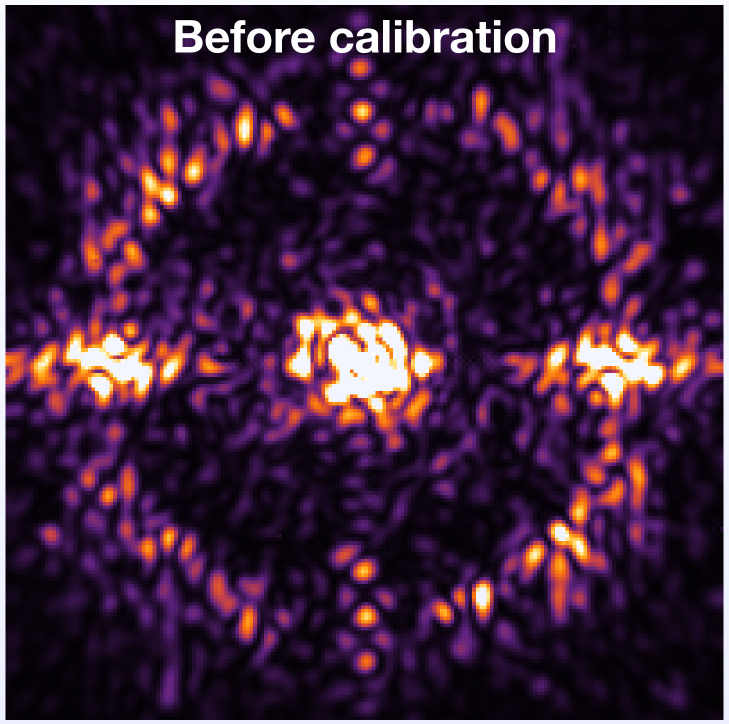
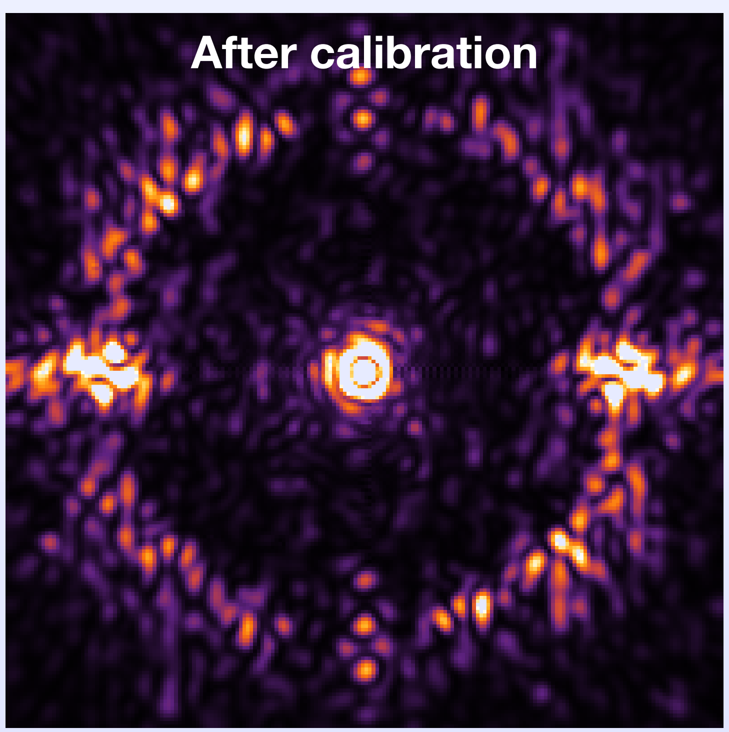


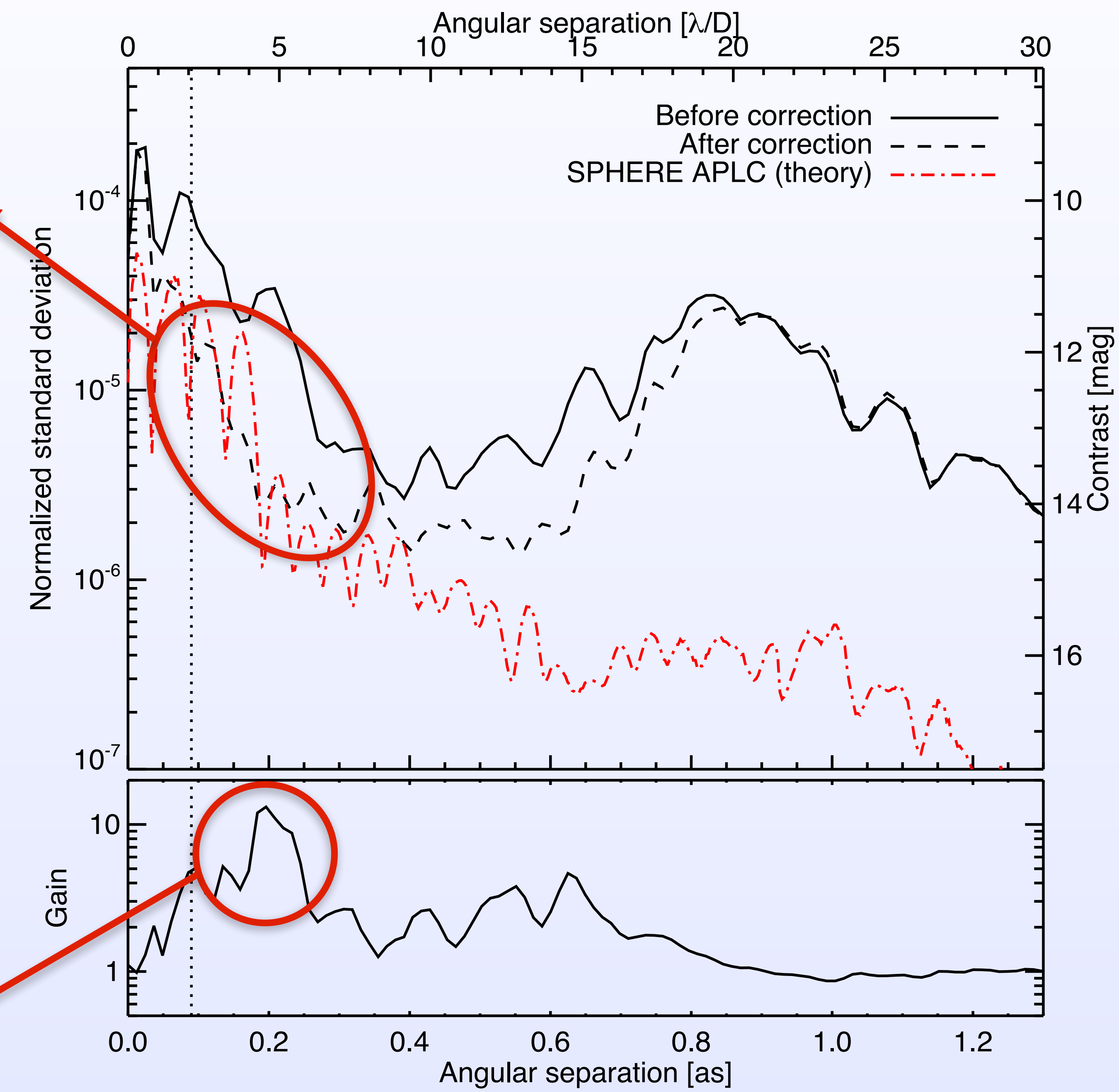
N’Diaye et al. 2016

Contrast gain after ZELDA calibration





perf. limit of SPHERE coronagraph

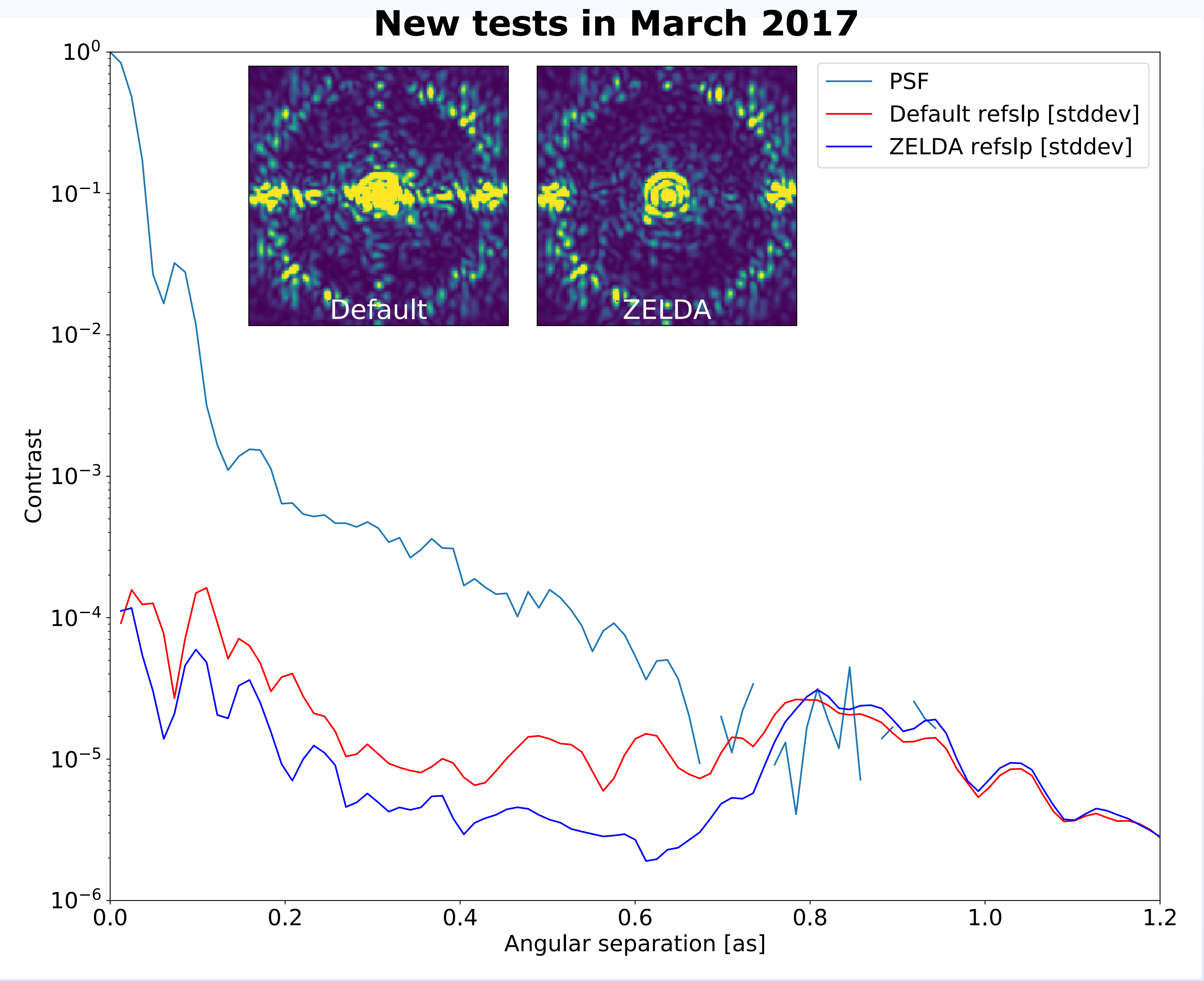


x10 gain @ 0.2"

→ZELDA will be used for NCPA calibration in SPHERE this year

N'Diaye et al. 2016

Towards ZELDA on sky



Procedure

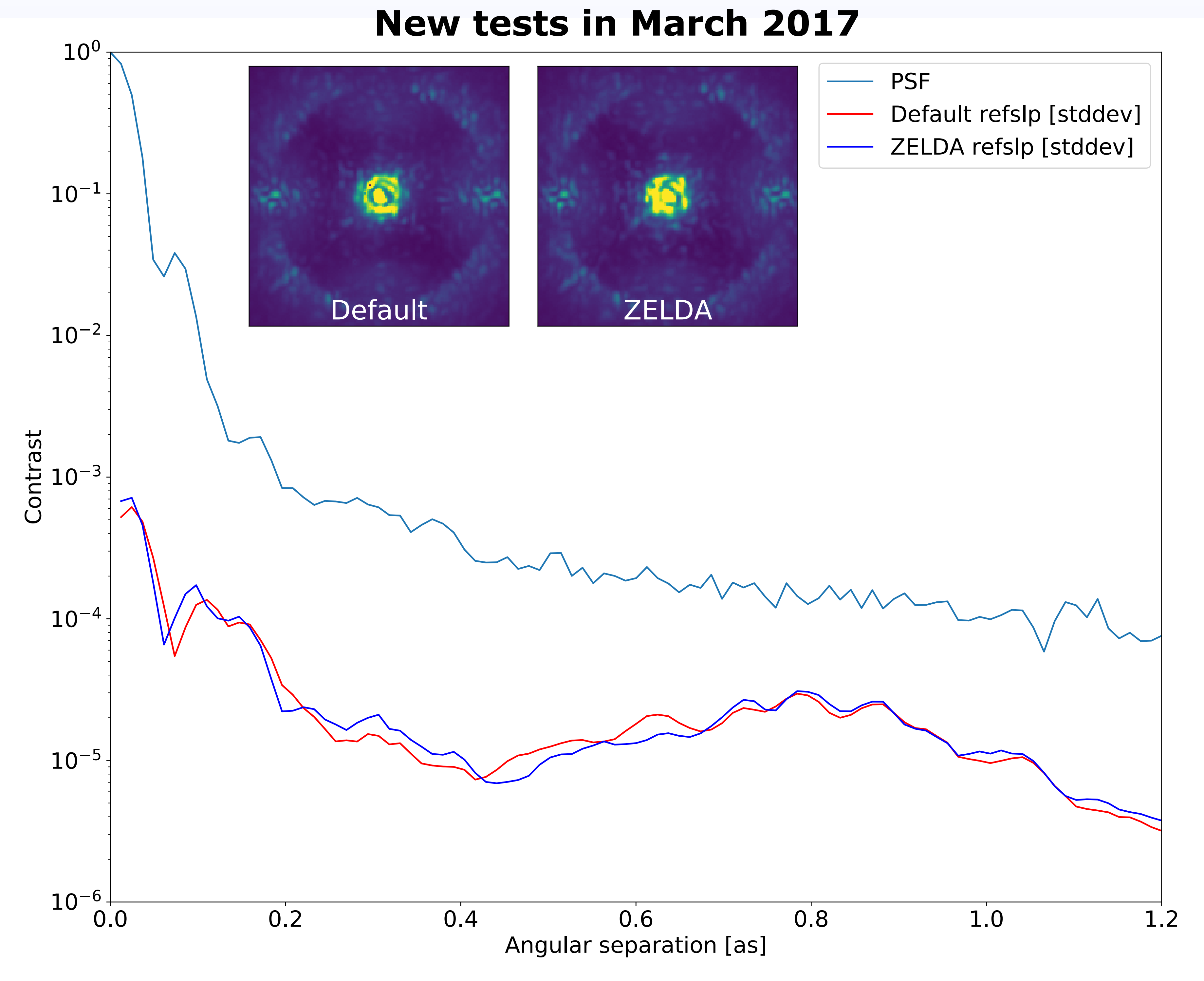
- internal NCPA calibration
- calibrated reference slopes applied on-sky

Internal performance

- **on-par with 2015**
- 5-10 contrast gain

Vigan et al. in prep

Towards ZELDA on sky



Procedure

- internal NCPA calibration
- calibrated reference slopes applied on-sky

Internal performance

- **on-par with 2015**
- 5-10 contrast gain

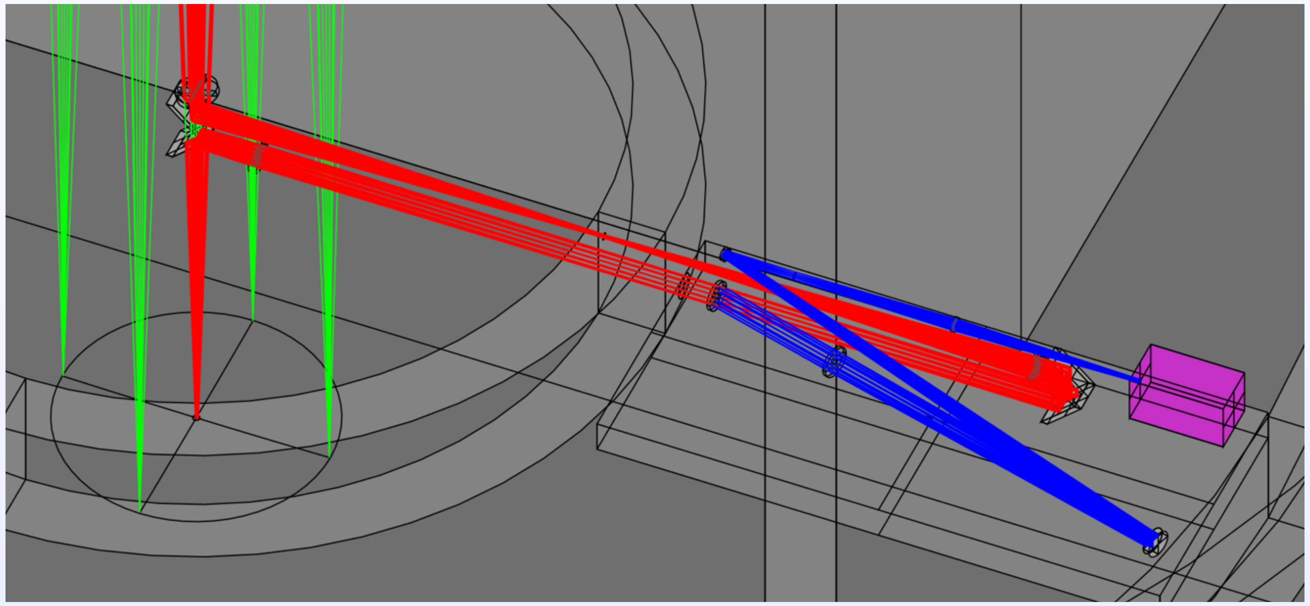
On-sky performance

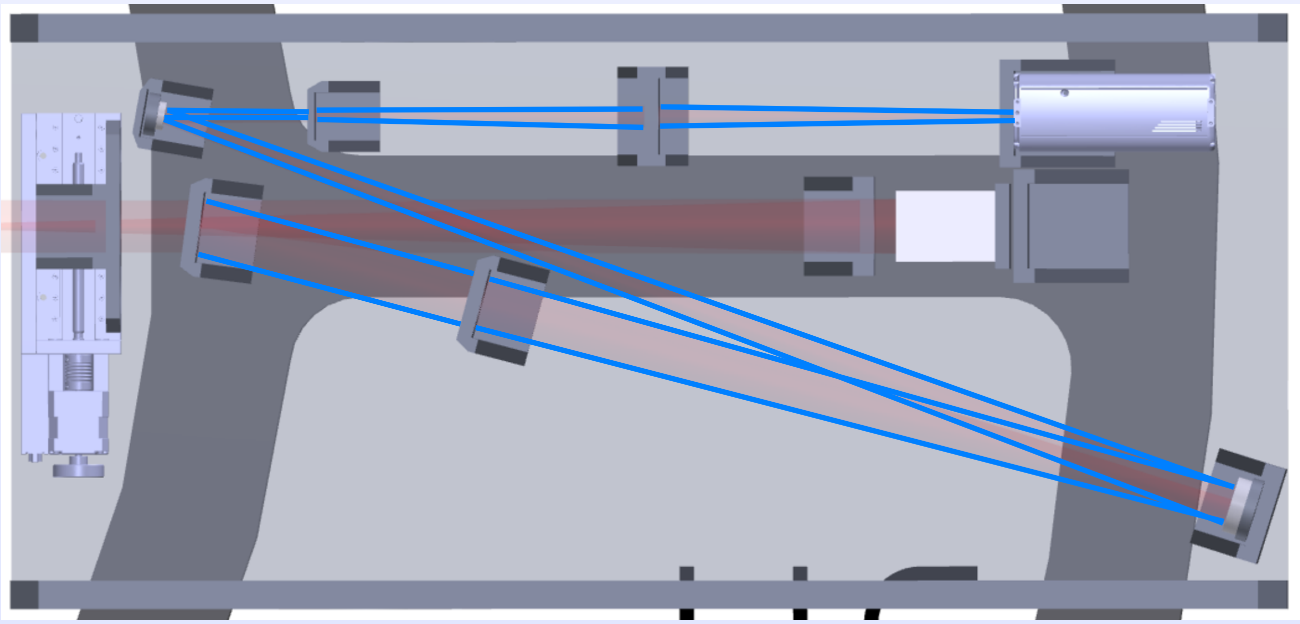
- **no contrast gain yet!**
- reason unknown:
  - chromatic beam-shift?
  - near-IR ADCs?
  - amplitude aberrations?

Vigan et al. in prep

ZELDA in E-ELT/HARMONI high-contrast mode

Opto-mechanical design of
high-contrast module



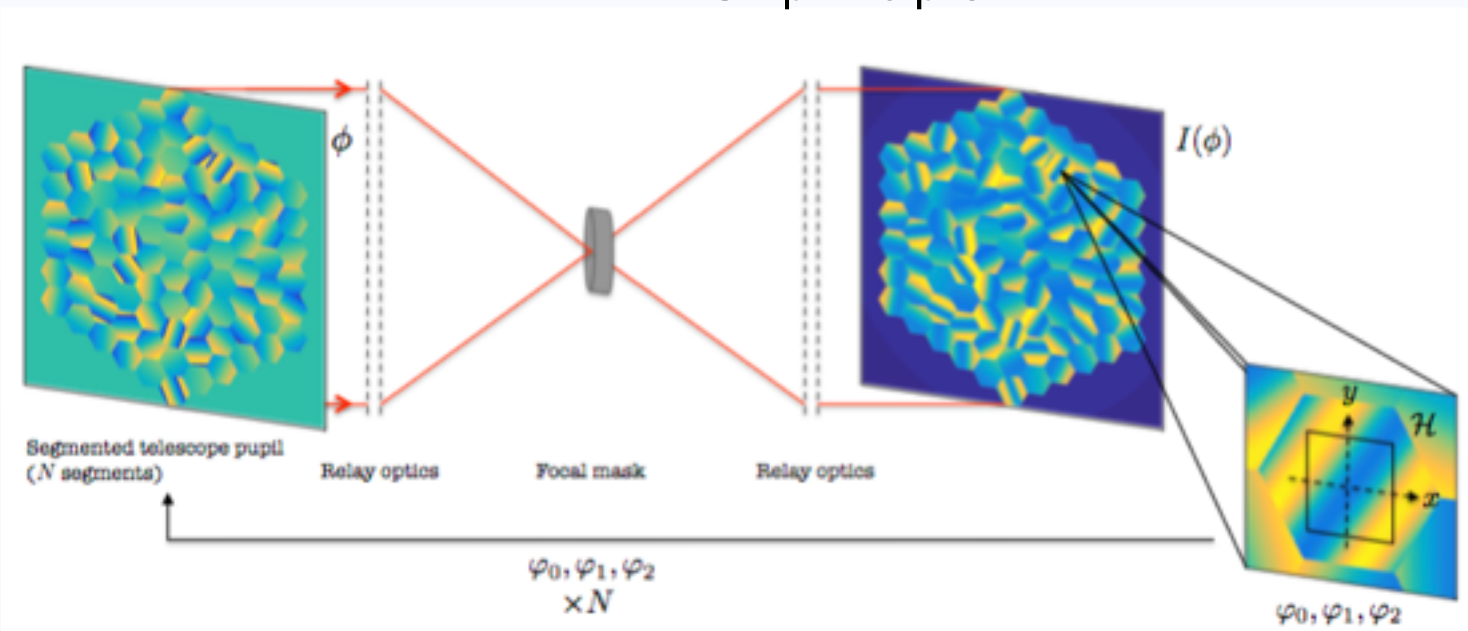


- Goal:
  - spectro-imaging of young giants
  - R=3000-20000 ; 10^{-6} contrast at 0.2'' and closer, in H & K bands
- No ADC in the instrument:
  - Dispersed beam & PSF
  - SCAO sensing at 0.8 um & science at 1.45-2.45 um:
    - *significant NCPA*
- ZELDA @ 1.25 um, prospects:
  - NCPA calibration: less constraints on surface quality of upstream optics
  - Pupil centering follow-up (0.5% accuracy): good for pupil masking
  - Fine E-ELT cophasing

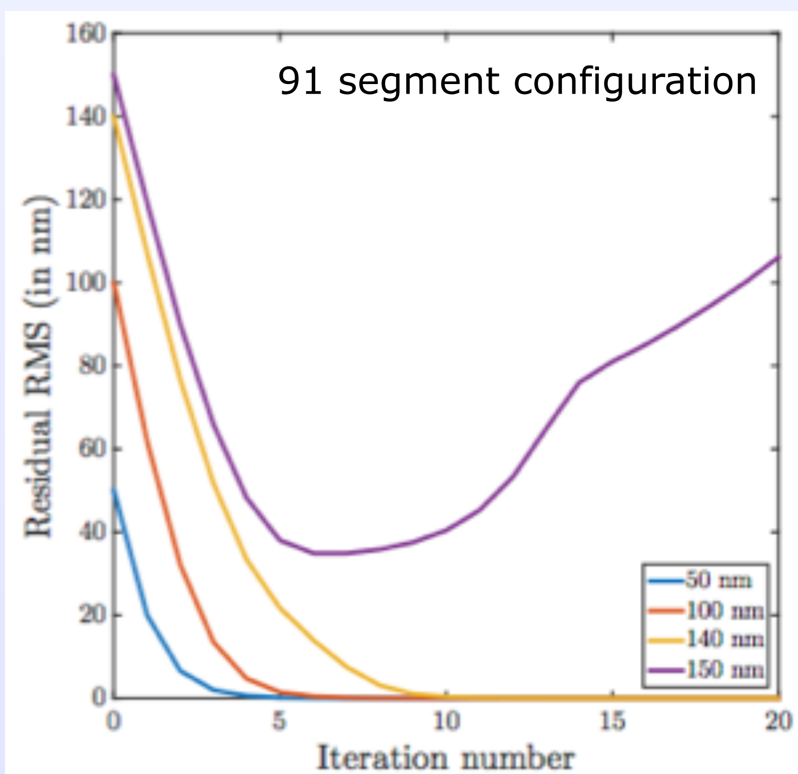
Courtesy from A. Carlotti (IPAG)

ZELDA-Phasing Sensor

ZELDA-PS: principle



Closed-loop control of combined piston, tip-tilt



- Fine phasing sensor in diffraction-limited regime
  - For each segment, measurements of piston, tip, tilt
- ZELDA-Phasing sensor
  - Mode estimation with nanometric accuracy
  - Closed-loop wavefront control for fine segment alignment
  - promising option for fine cophasing of ELTs

Janin-Potiron et al. 2017

Conclusions

- **ZELDA for the calibration of residual aberrations**
  - easy to manufacture
  - simple alignment
  - no calibration required
  - fast and straightforward data analysis

- **Validation in VLT/SPHERE**
  - excellent agreement between measurements and theory
  - NCPA compensation: gain x10 in contrast at 0.2"
  - implementation in the calibration plan of SPHERE in 2017

- **Powerful diagnostic tool for current and future AO facilities**
  - internal and on-sky measurements
  - several SPHERE examples: low-wind effects, internal turb., derotator behavior