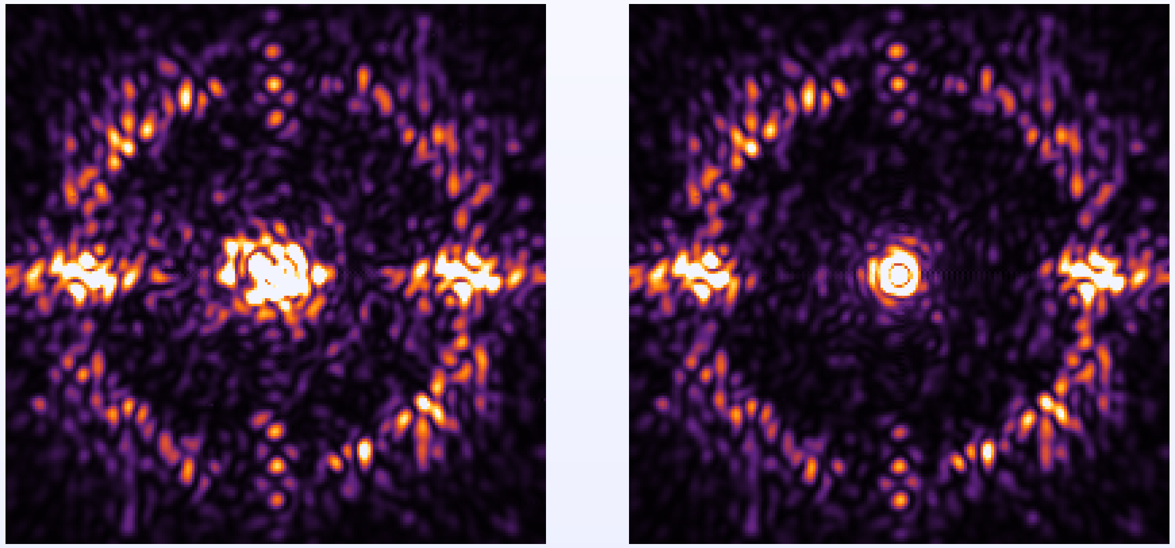
Calibration of quasi-static aberrations in exoplanet imaging instruments with a Zernike wavefront sensor

Application to VLT/SPHERE

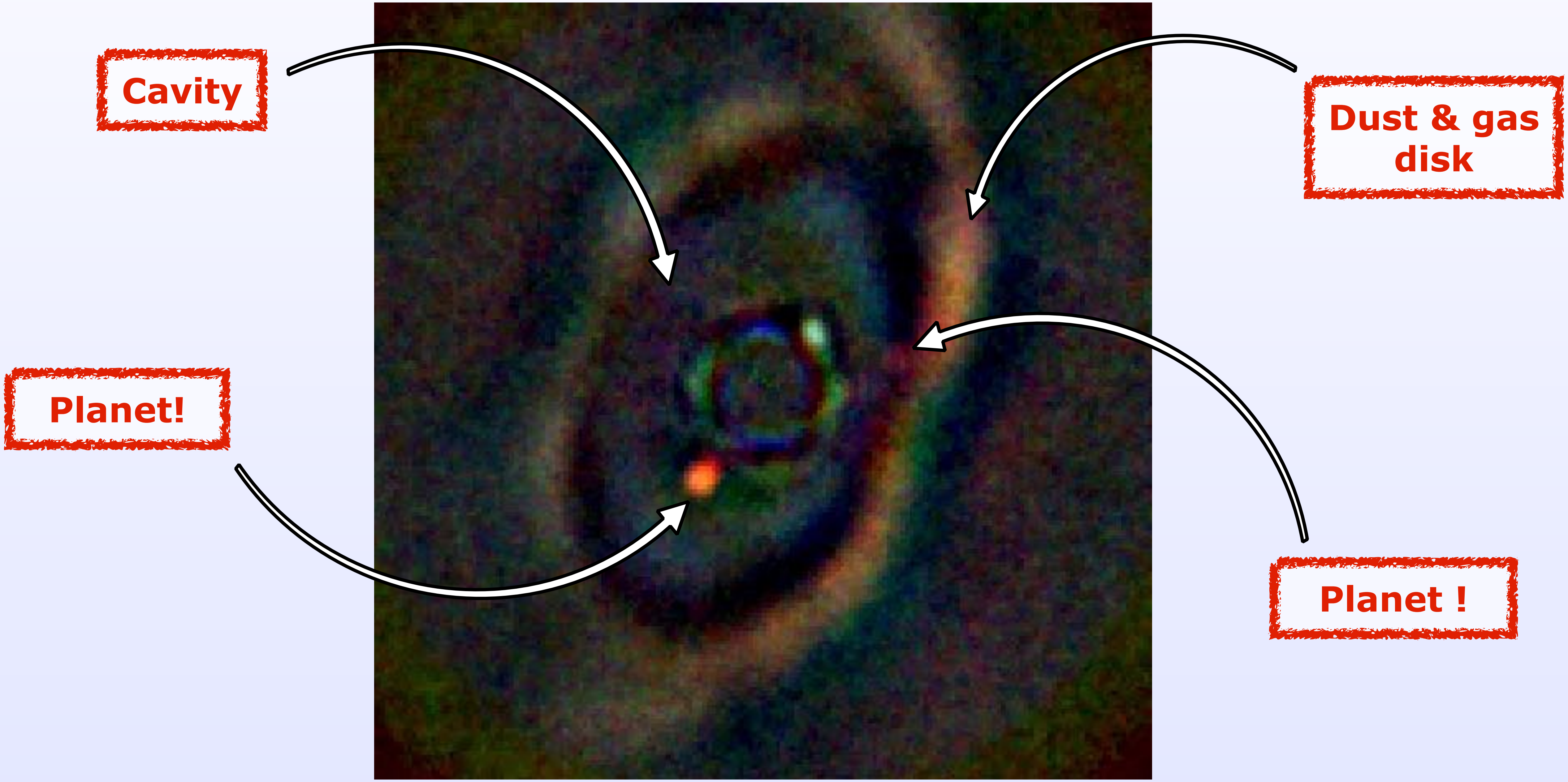


Arthur Vigan, Mamadou N'Diaye & Kjetil Dohlen
Centre National de la Recherche Scientifique (CNRS)

LAM: P. Blanchard, A. Caillat, F. Cantalloube, A. Costille, K. Dohlen, J. Le Merrer, D. Le Mignant, F. Madec, G. Moreaux, A. Vigan
Lagrange: M. N'Diaye, R. Pourcelot
ESO: J. Girard, J. Milli, Z. Wahhaj, G. Zins
ONERA: T. Fusco, J.-F. Sauvage
IPAG: J.-L. Beuzit, A. Carlotti, D. Mouillet, P. Puget

Imaging of exoplanetary systems

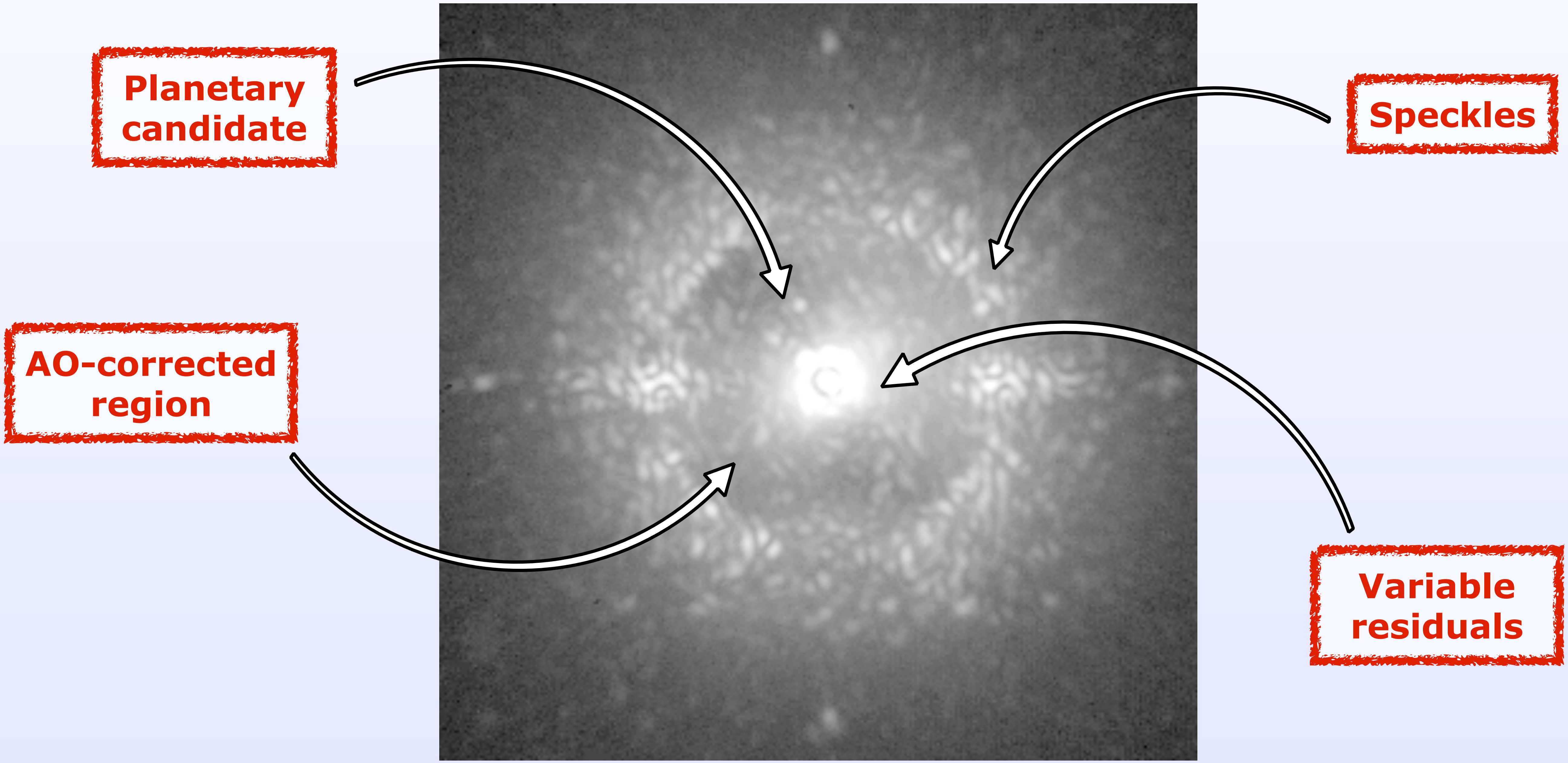
What we all want to see…



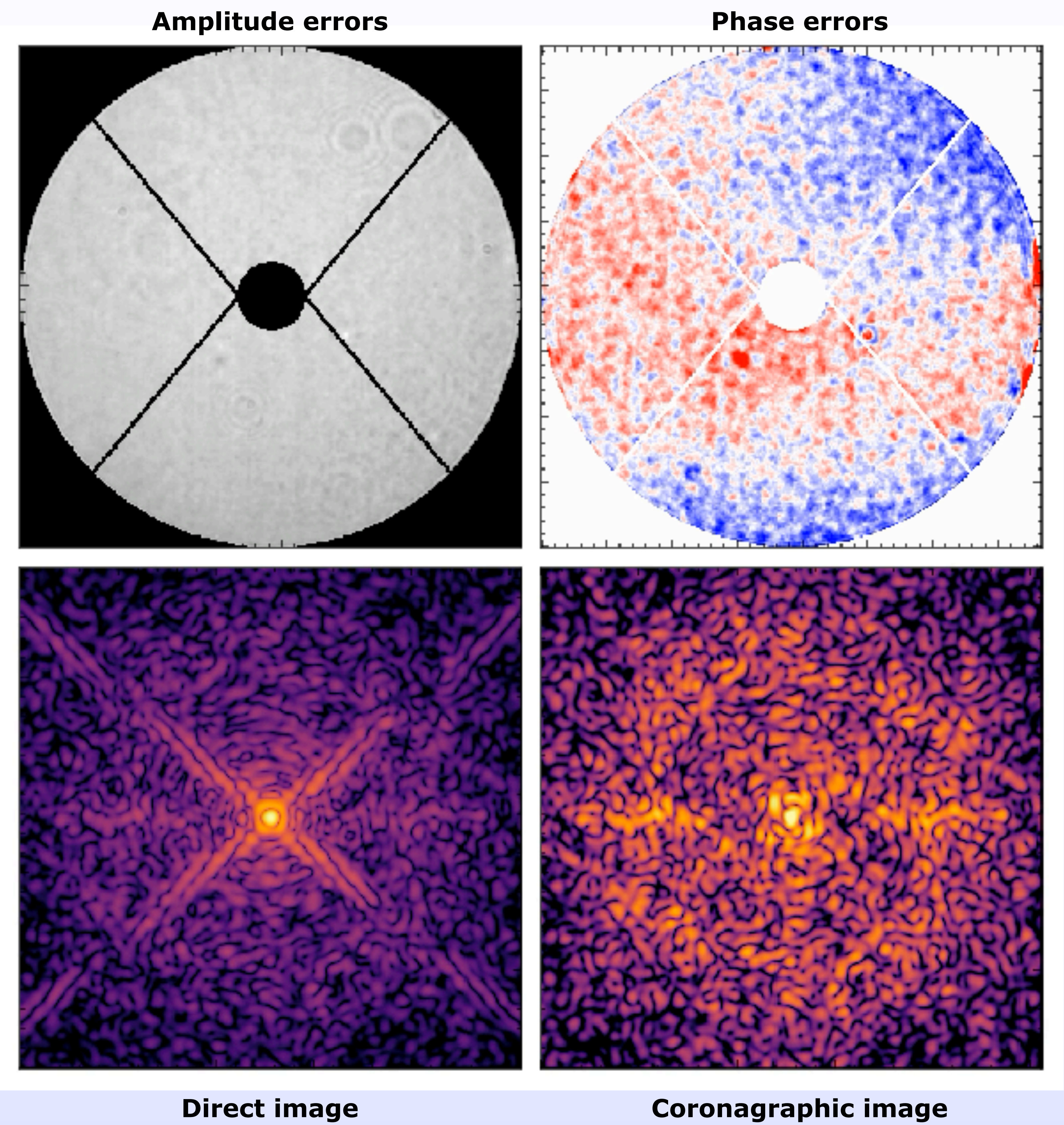
PDS 70 - Keppler et al. (2018)

Imaging of exoplanetary systems

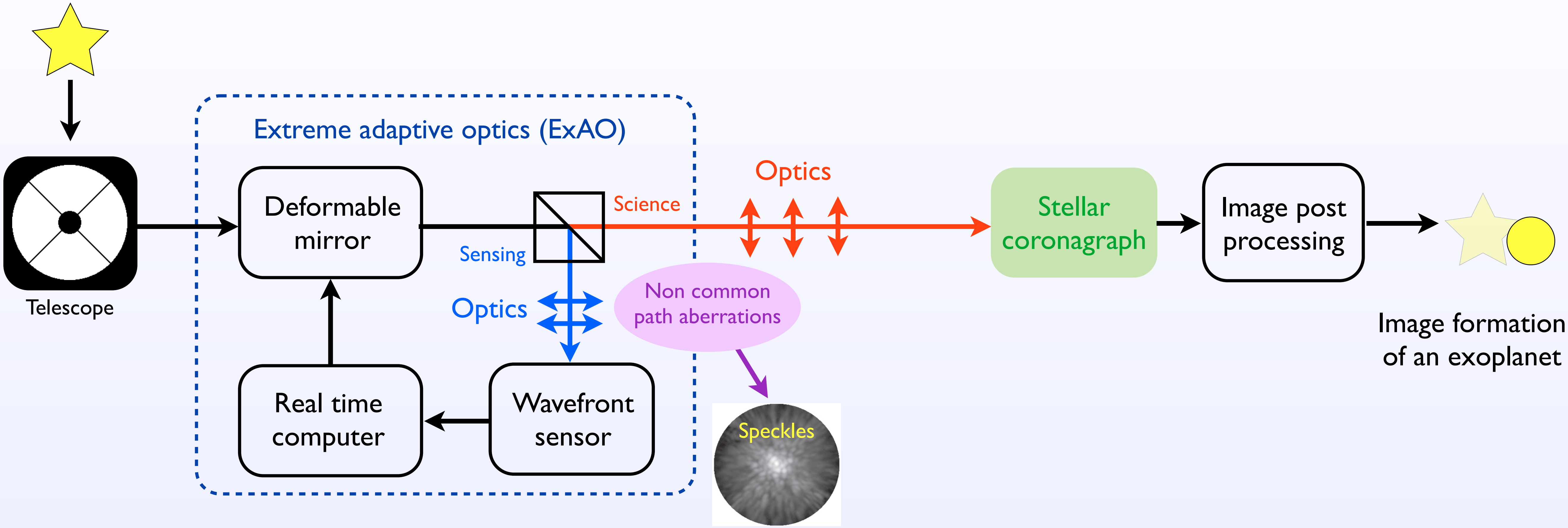
What we really see!



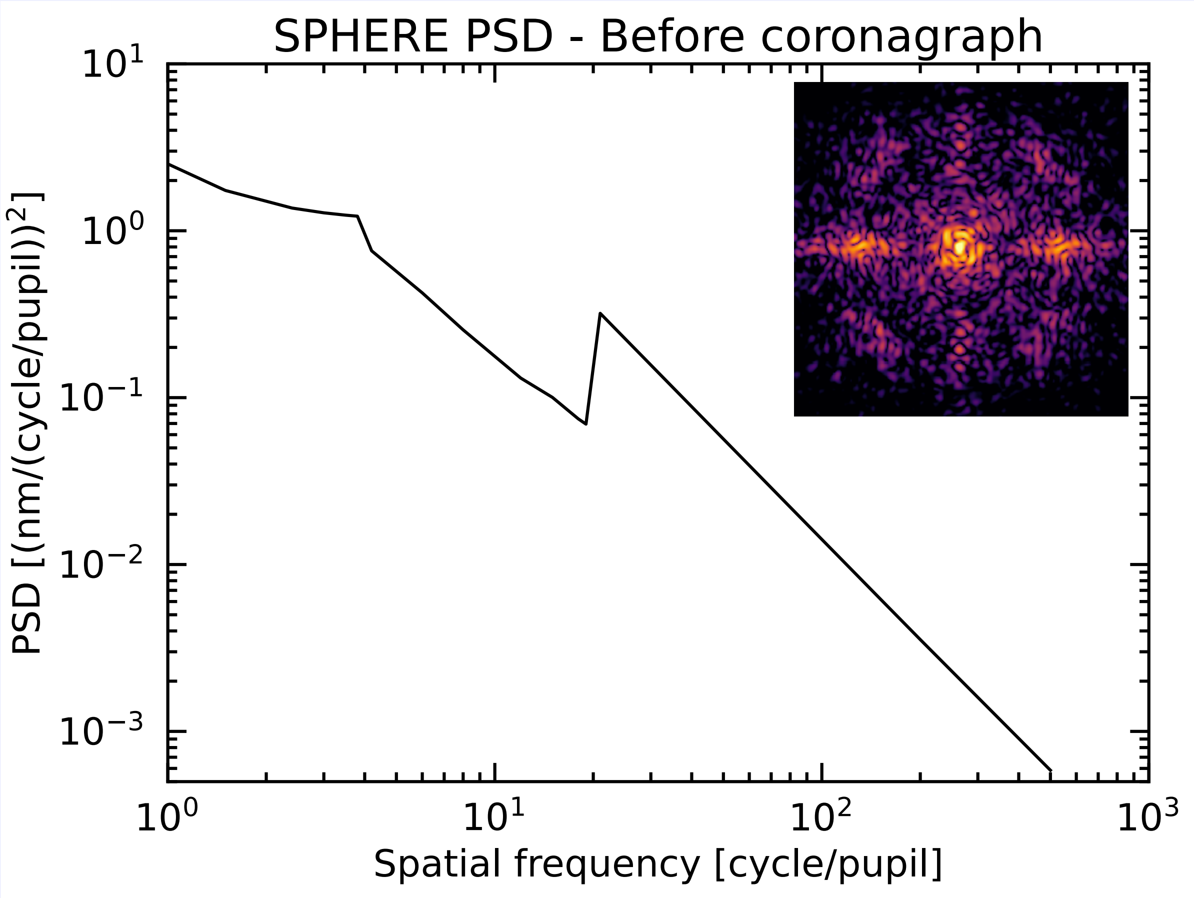
Coronagraphic image formation



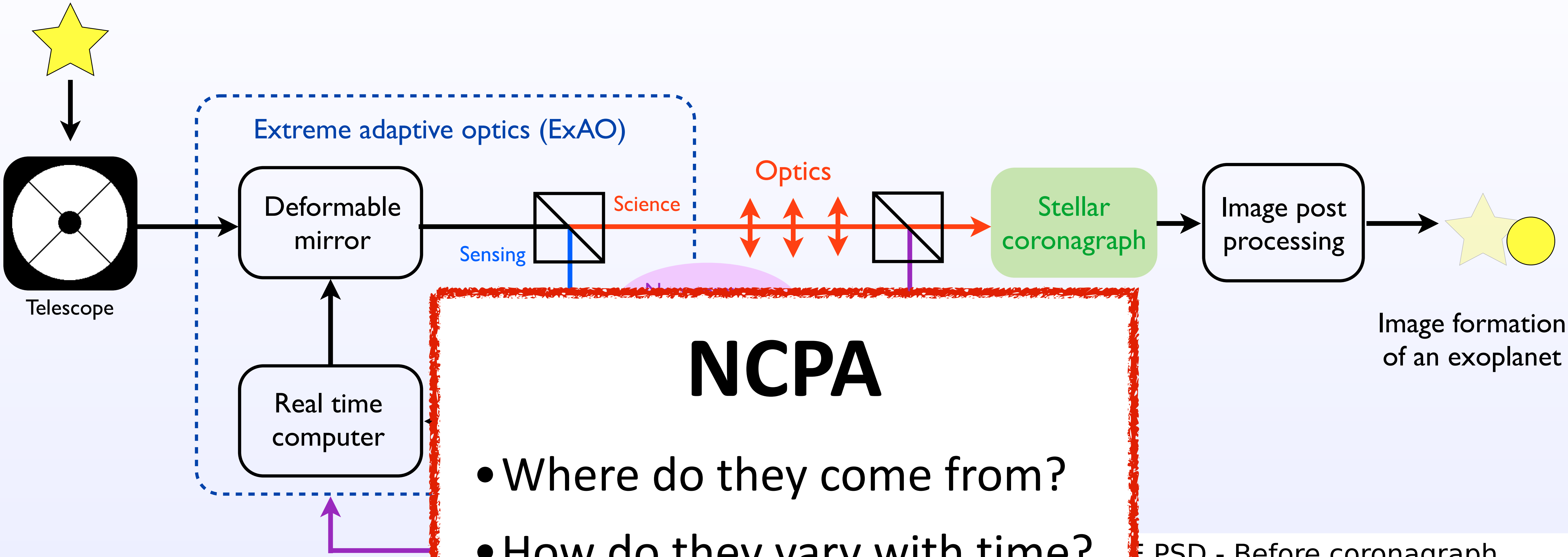
PSD, speckles and NCPA



- Speckles caused by <u>uncorrected optical aberrations</u> (atmosphere, instrument)
- Aberrations upstream of the coronagraph are the most critical (e.g. Cavarroc et al. 2006)
- Non-common path aberrations = <u>differential aberrations</u> between the WFS and the science channels



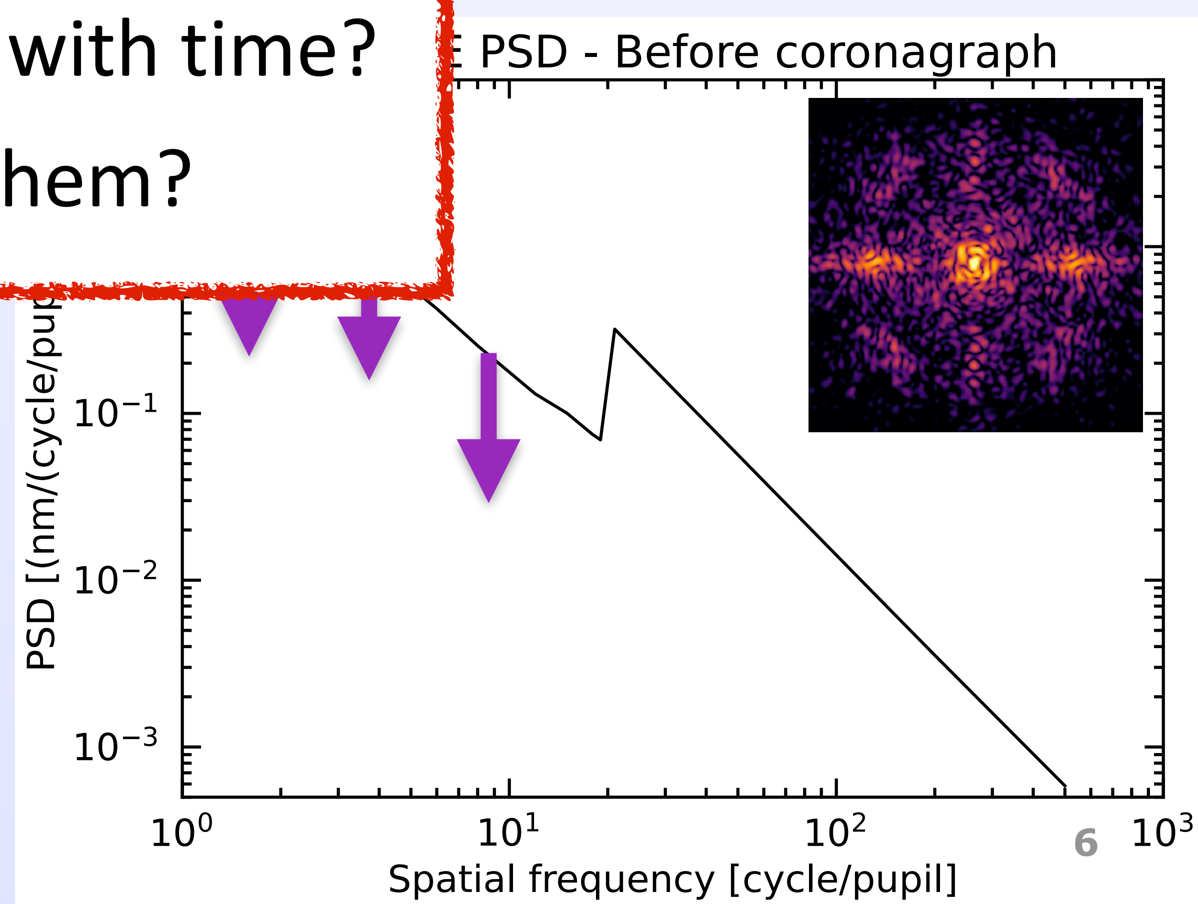
PSD, speckles and NCPA



NCPA

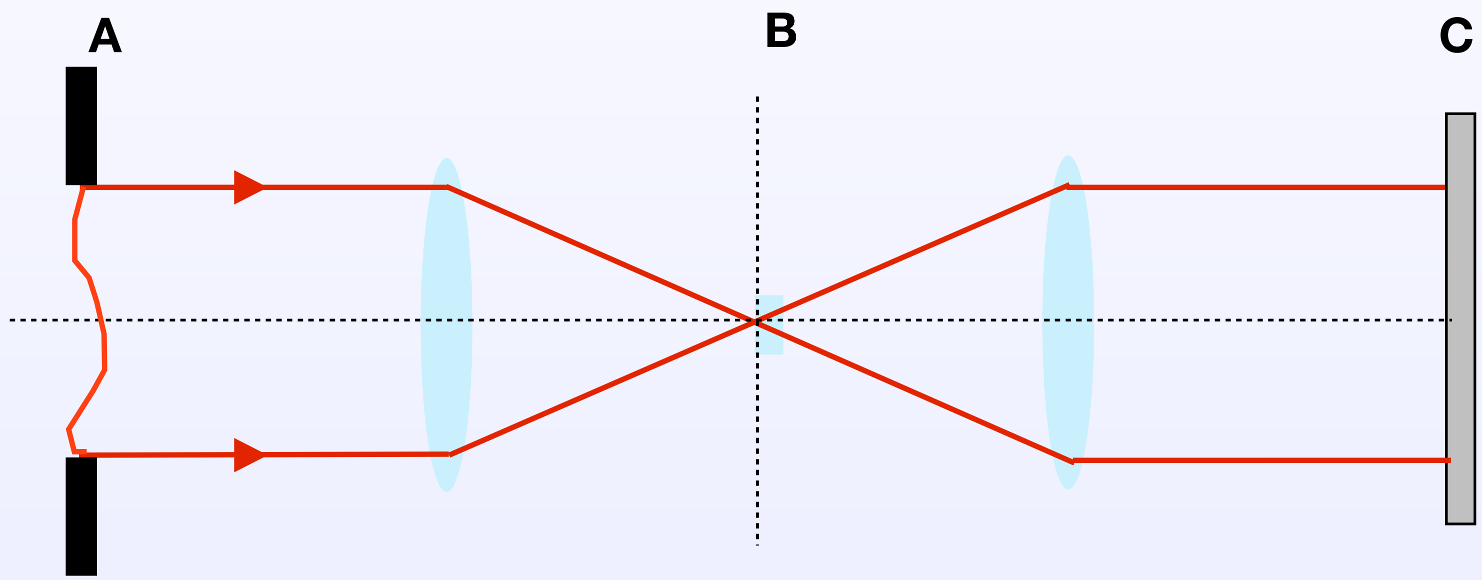
- Where do they come from?
- How do they vary with time?
- How to measure them?

- Speckles caused by unc... aberrations (atmosphere...
- Aberrations upstream of the coronagraph are the most critical (e.g. Cavarroc et al. 2006)
- Non-common path aberrations = differential aberrations between the WFS and the science channels → dedicated sensing?



Zernike wavefront sensor

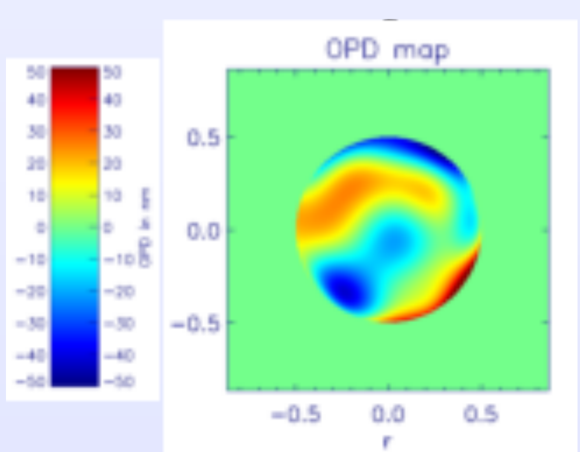
- Conversion of the (small) phase aberrations into intensity variations:
  - Ic = α sin(φ) + β
  - Small aberrations: Ic = αφ + β

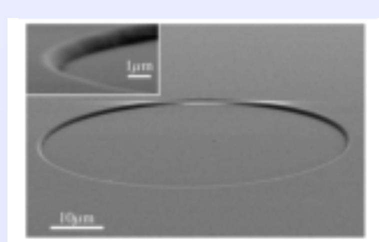


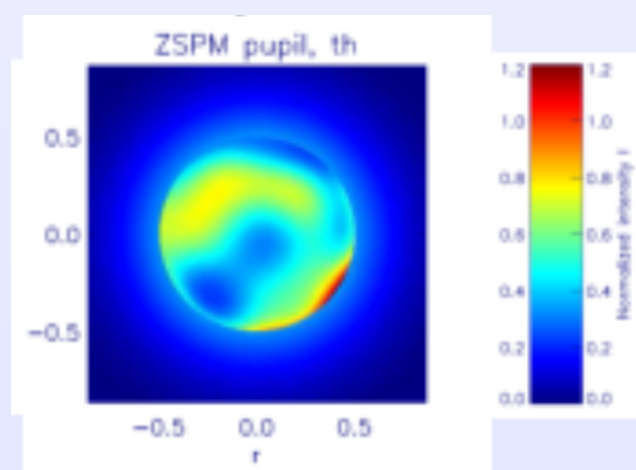
Entrance pupil

Focal plane mask (FPM)
π/2 phase shift

Camera







N'Diaye et al. (2013):

$$\varphi = -1 + \sqrt{3 - 2b - (1 - I_C)/b}$$

Phase errors

Normalised intensity

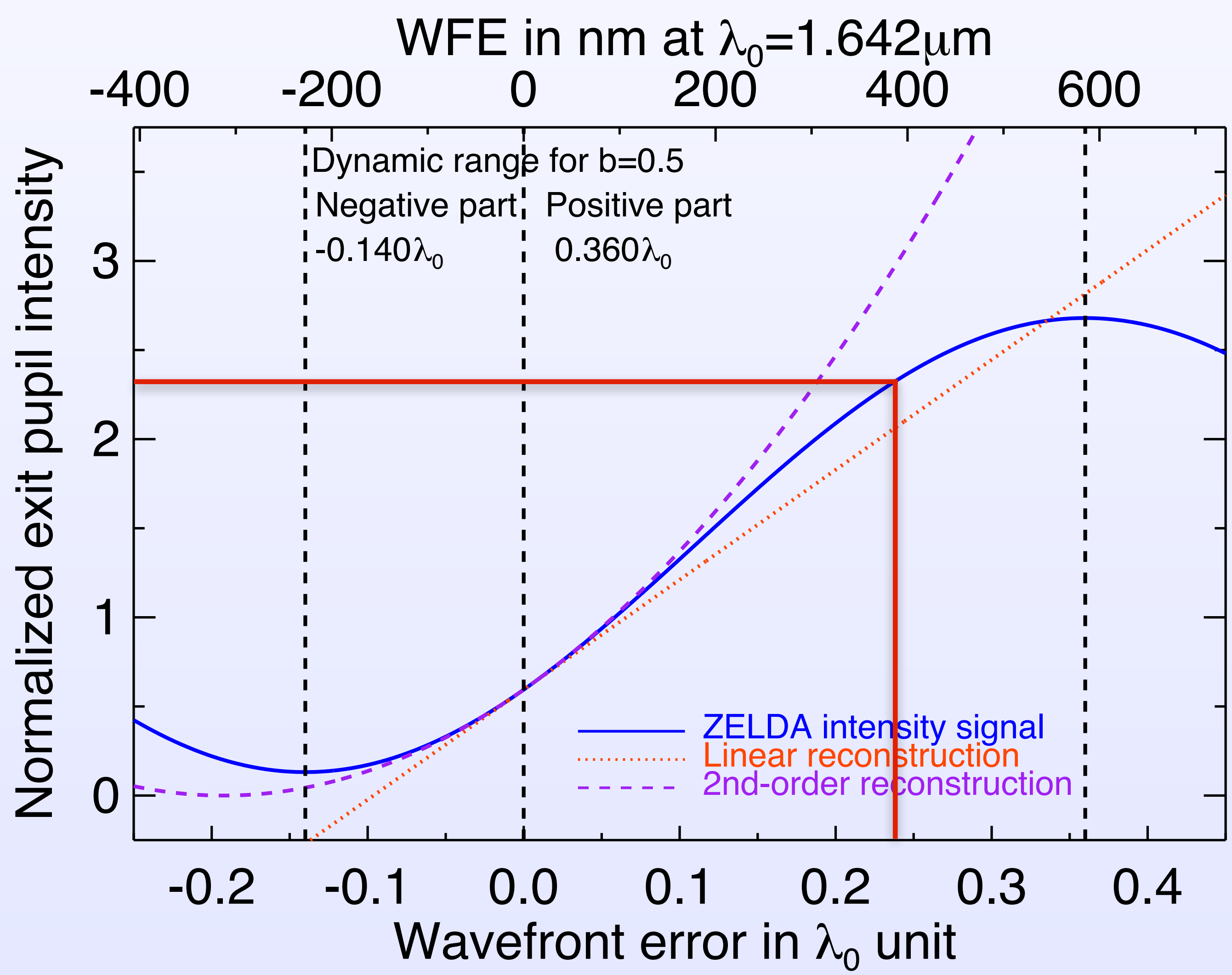
Amplitude of a perfect wave diffracted by the mask

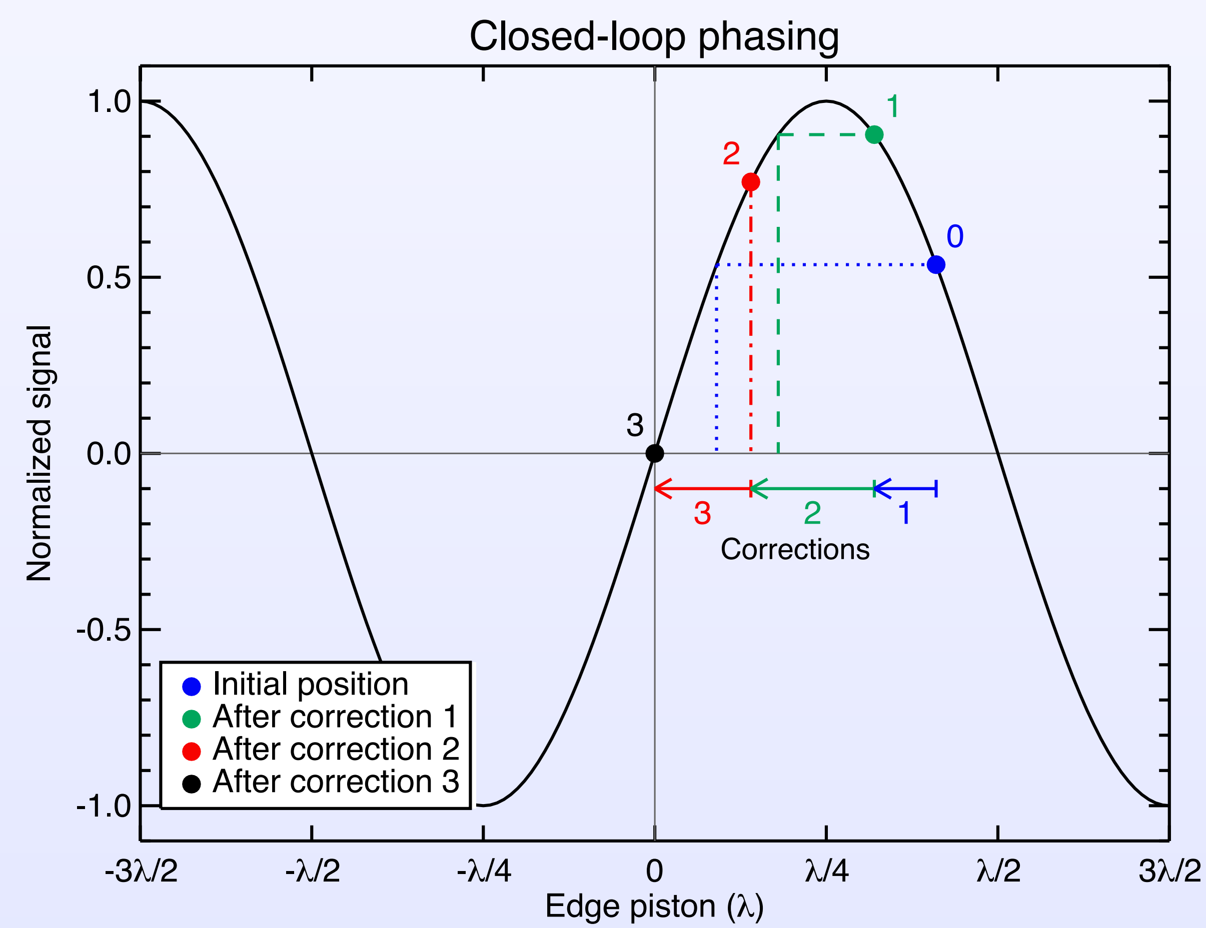
- Very simple expression
- *b* can be precomputed
  - ➡ fast computation!

pyZELDA

Linearity range of the sensor

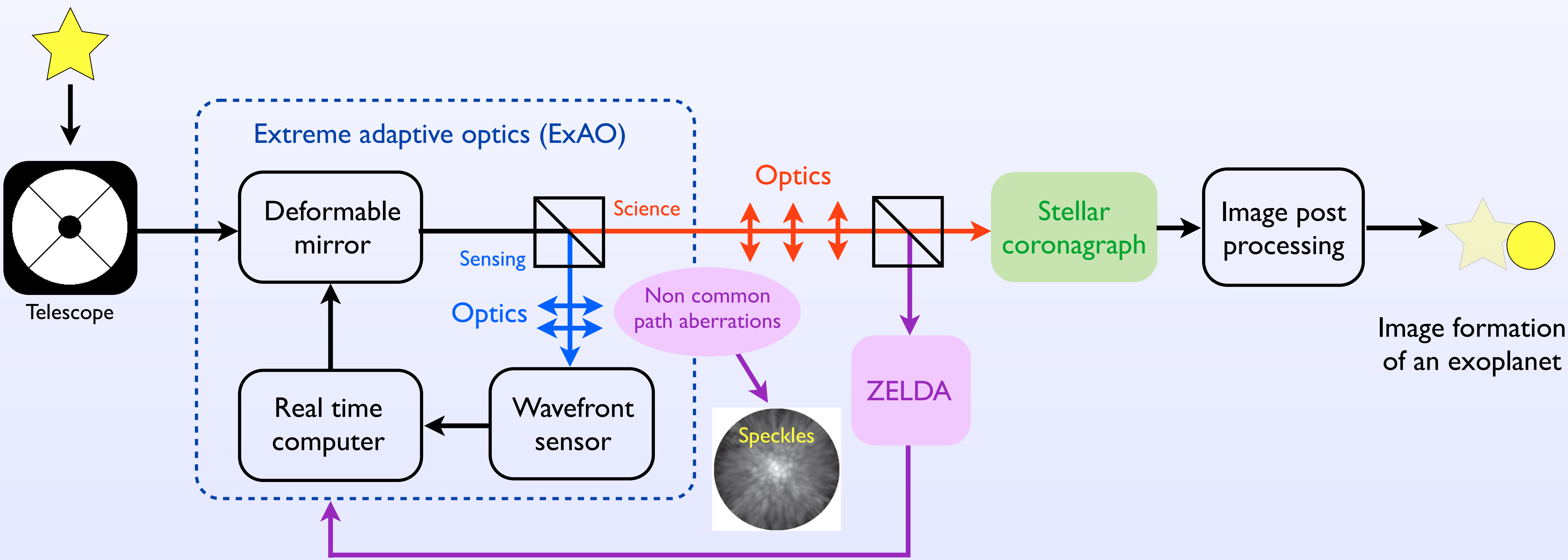
- Linearisation of the amplitude ➙ expression valid only near zero phase error
- Limited capture range: -0.14 λ_0 ➙ 0.36 λ_0
- Possible extension of the capture range in closed loop





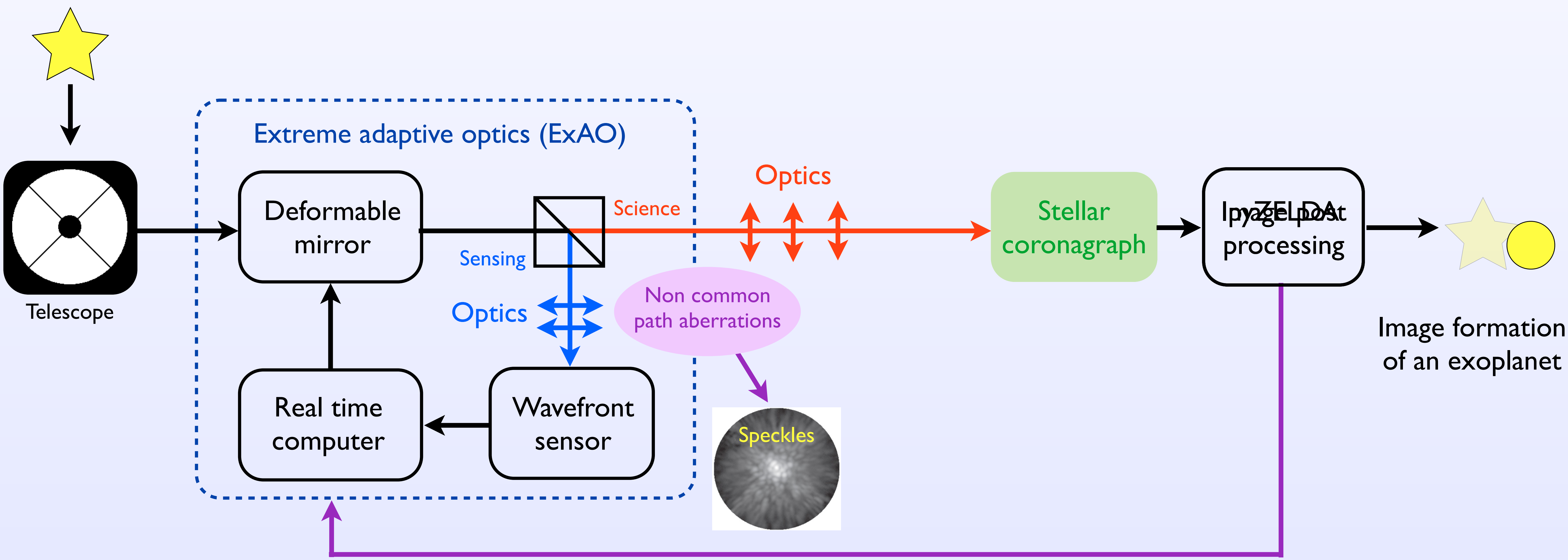
ZELDA sensor in the ideal case

- ZELDA fed with a fraction of the science light
- Correction applied continuously on the HODM



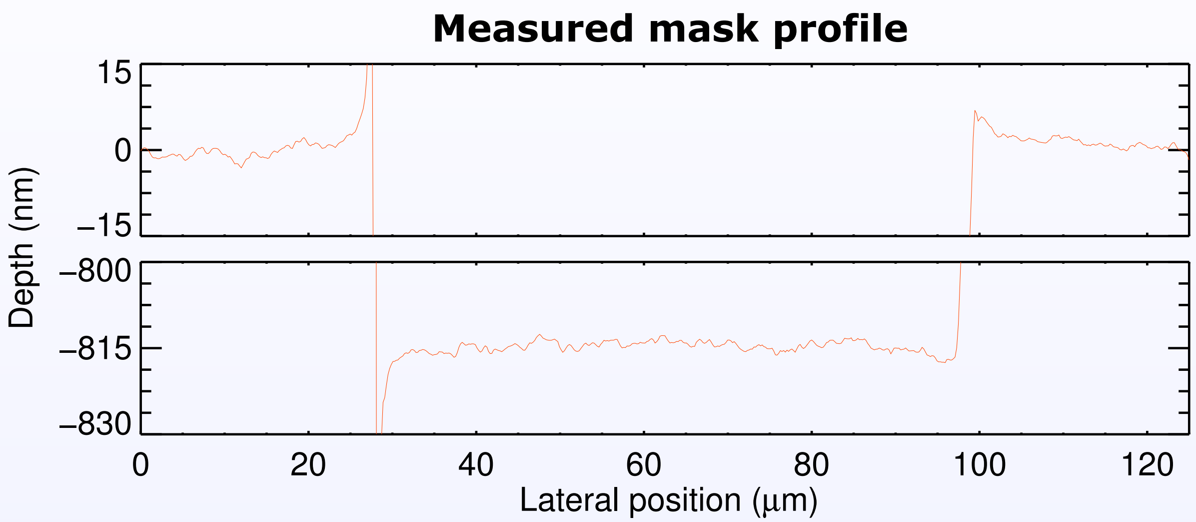
ZELDA sensor in VLT/SPHERE

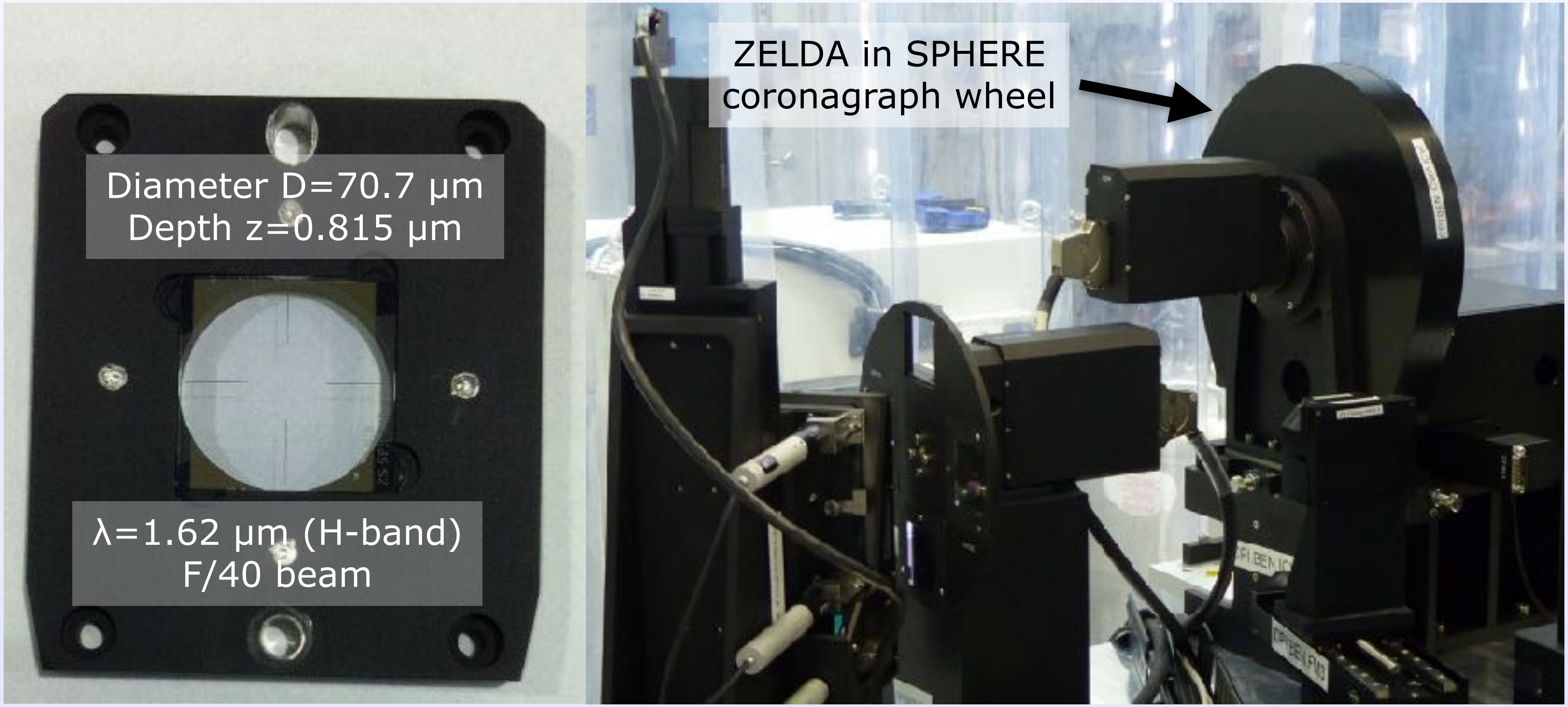
- ZELDA located in coronagraphic wheel
- 2-step process for the wavefront correction:
  - ZELDA mask inserted in beam for wavefront measurement
  - Coronagraph inserted in beam for astrophysical observations



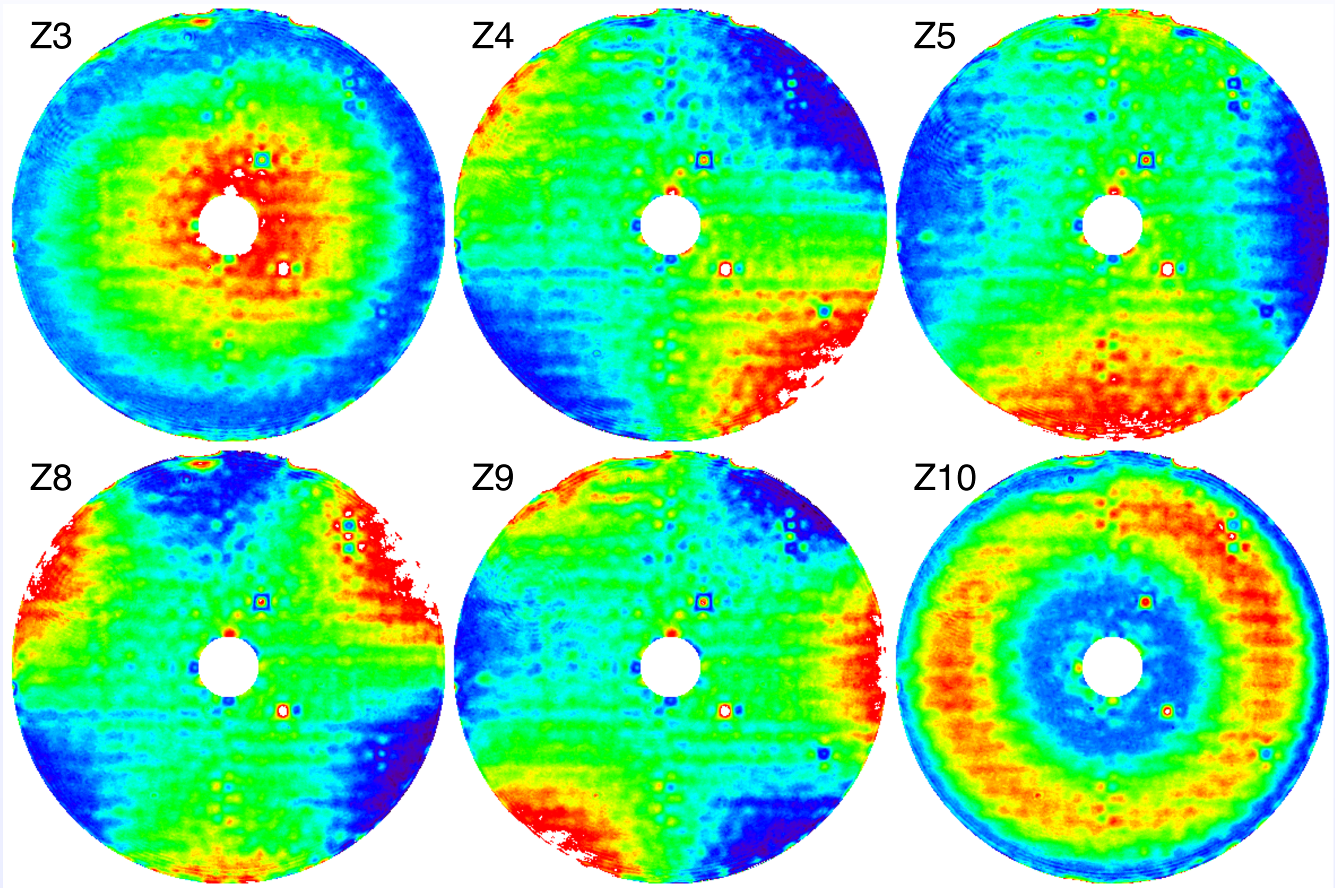
ZELDA was a prototype

- Fused silica mask manufactured by photolithographic reactive ion etching (SILIOS, France)
- Installed during commissioning of the instrument in 2014

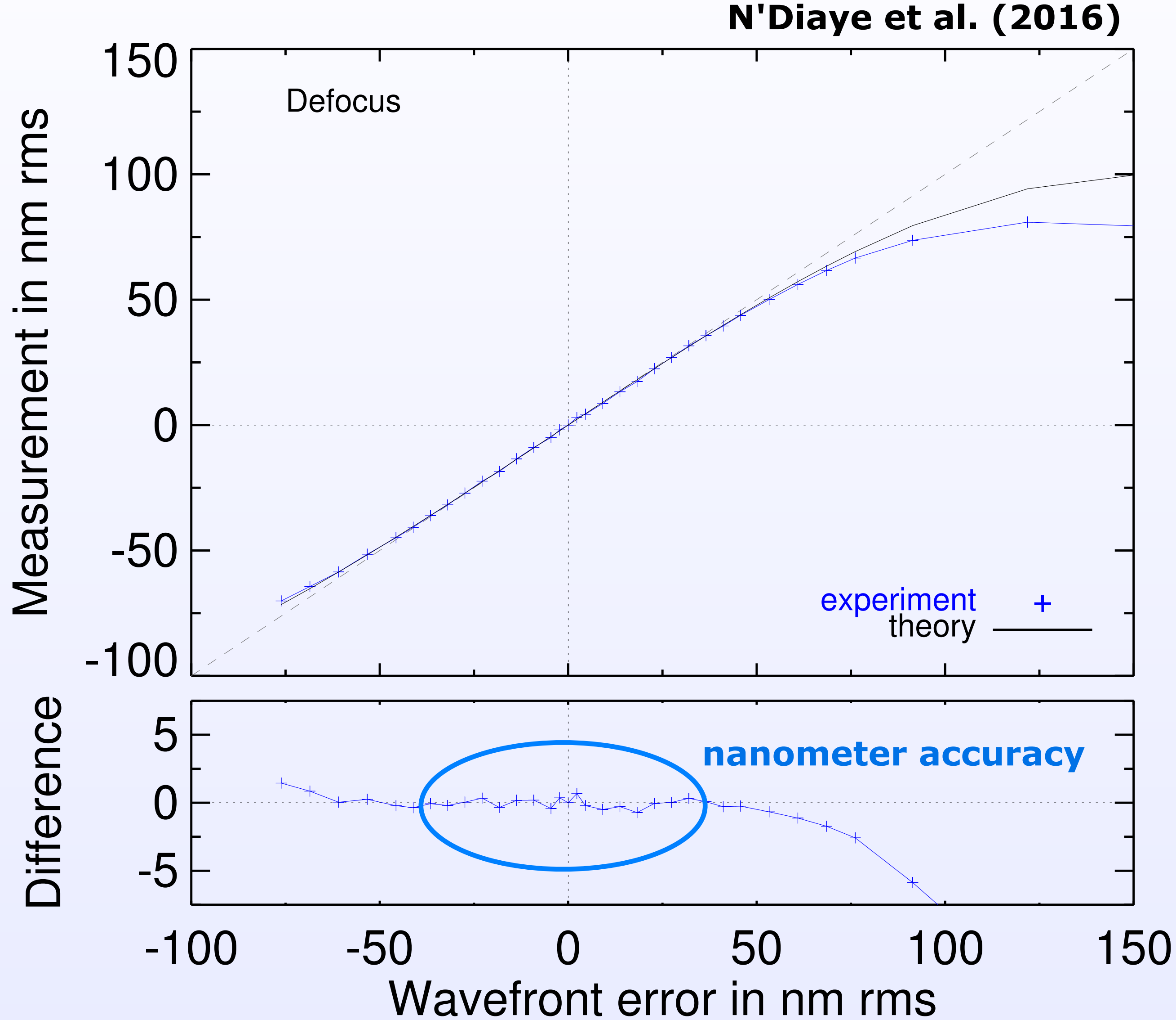




Validating ZELDA in SPHERE



Zernike modes introduced with 400 nm PV on the SPHERE HODM



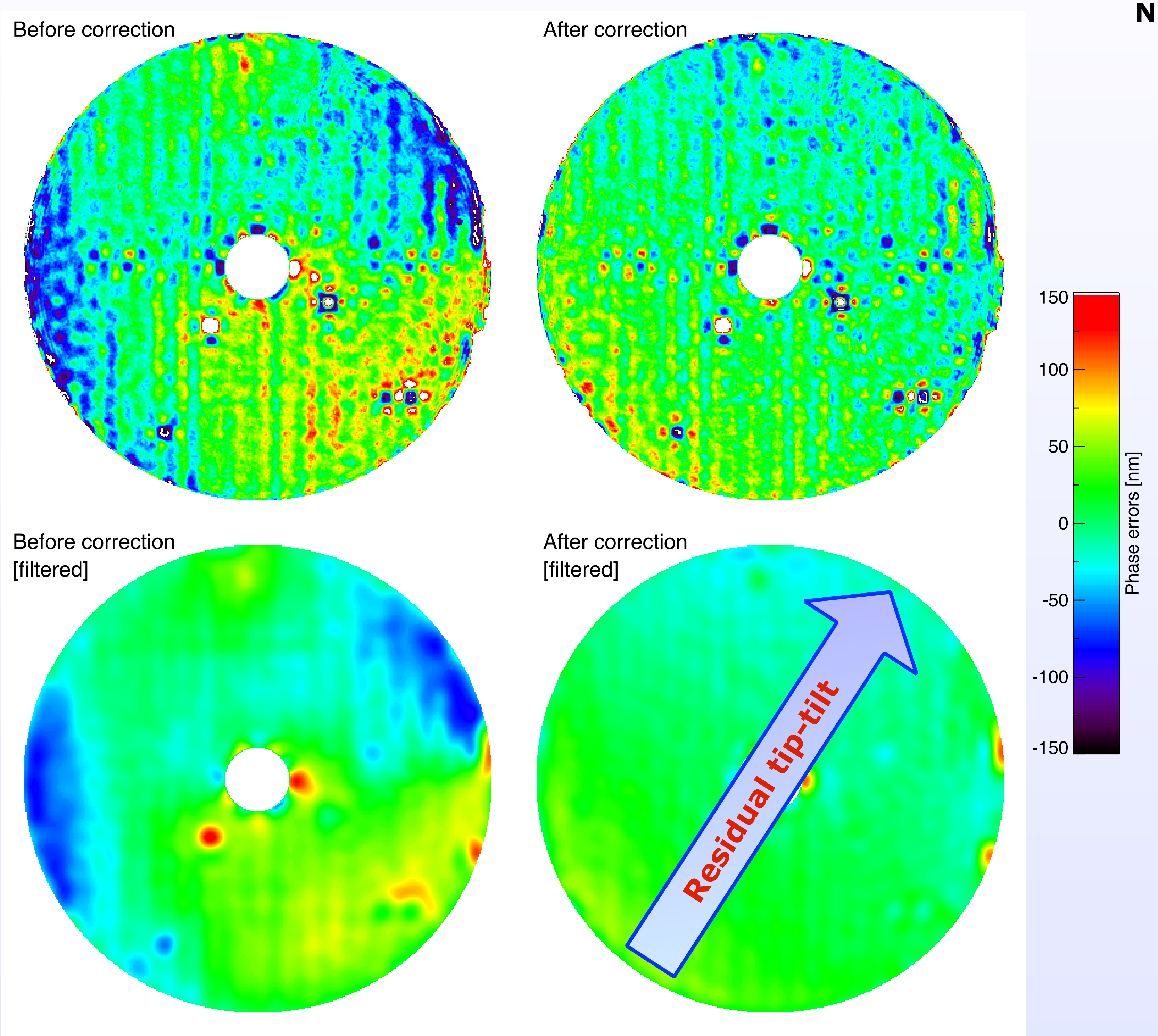
- Internal point source
- IRDIS pupil-imaging, λ = 1642 nm (FeII filter)
- PSF centred manually + closed loop on near-IR DTTS
- Zernike and Fourier modes, amplitude ramps: -250 → 600 nm PtV

NCPA compensation

N'Diaye et al. (2016)

45 nm RMS
f < 192 c/p

30 nm RMS
f < 20 c/p



35 nm RMS

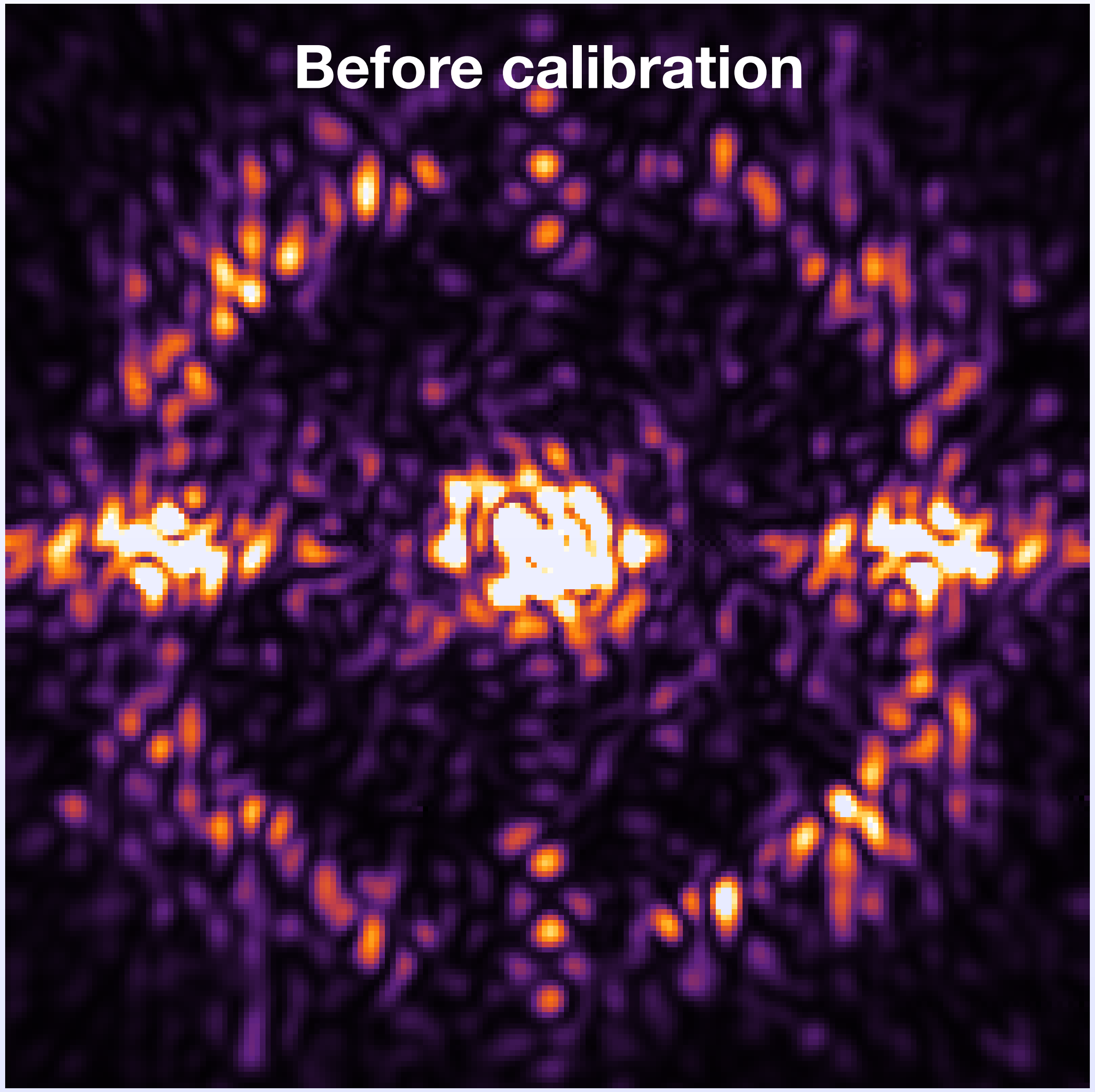
16 nm RMS

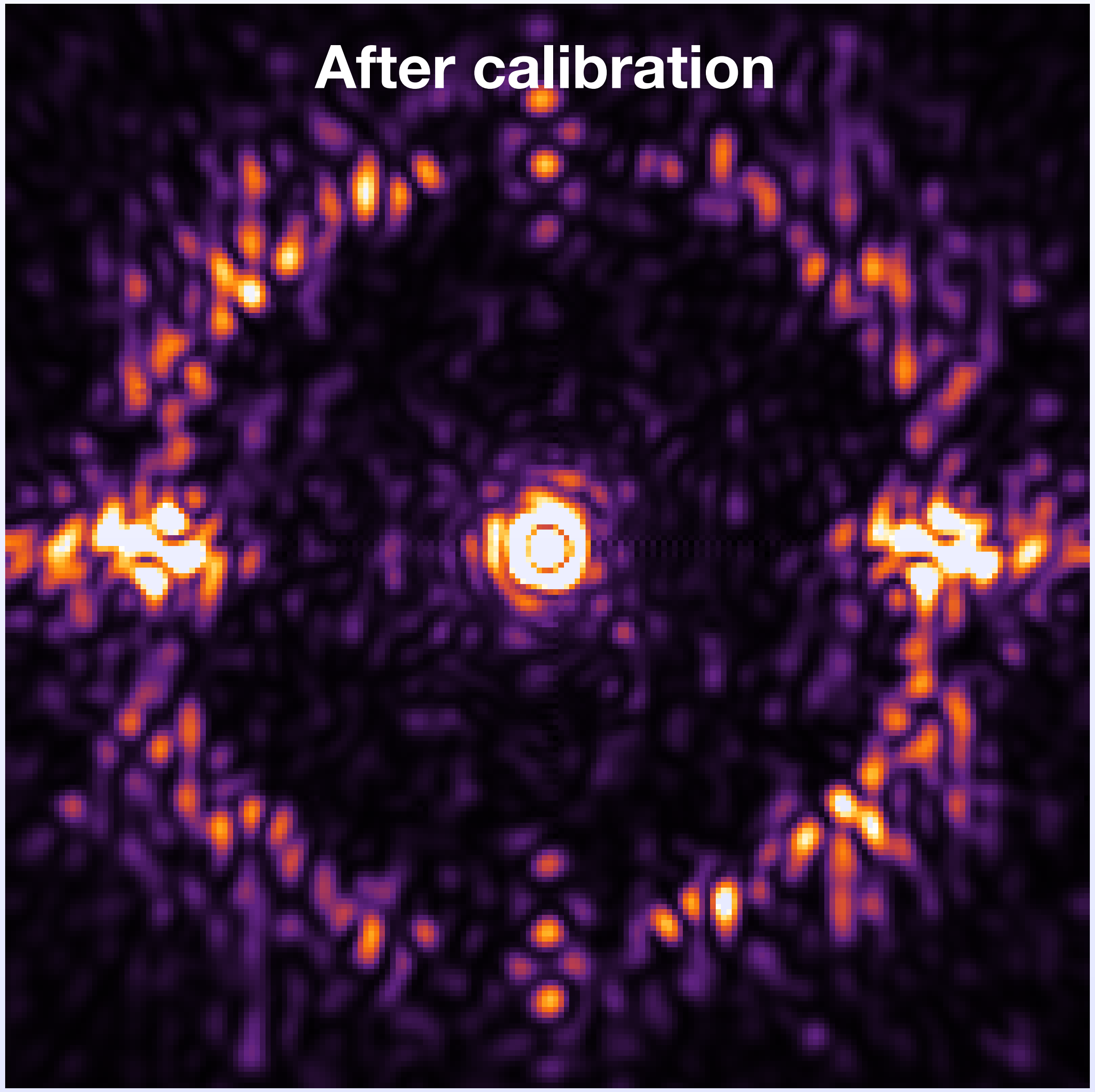
- **Manual centering + tip-tilt in closed loop**
- **Simple filtering in Fourier space at 25 c/p**

Effect on coronagraphic images

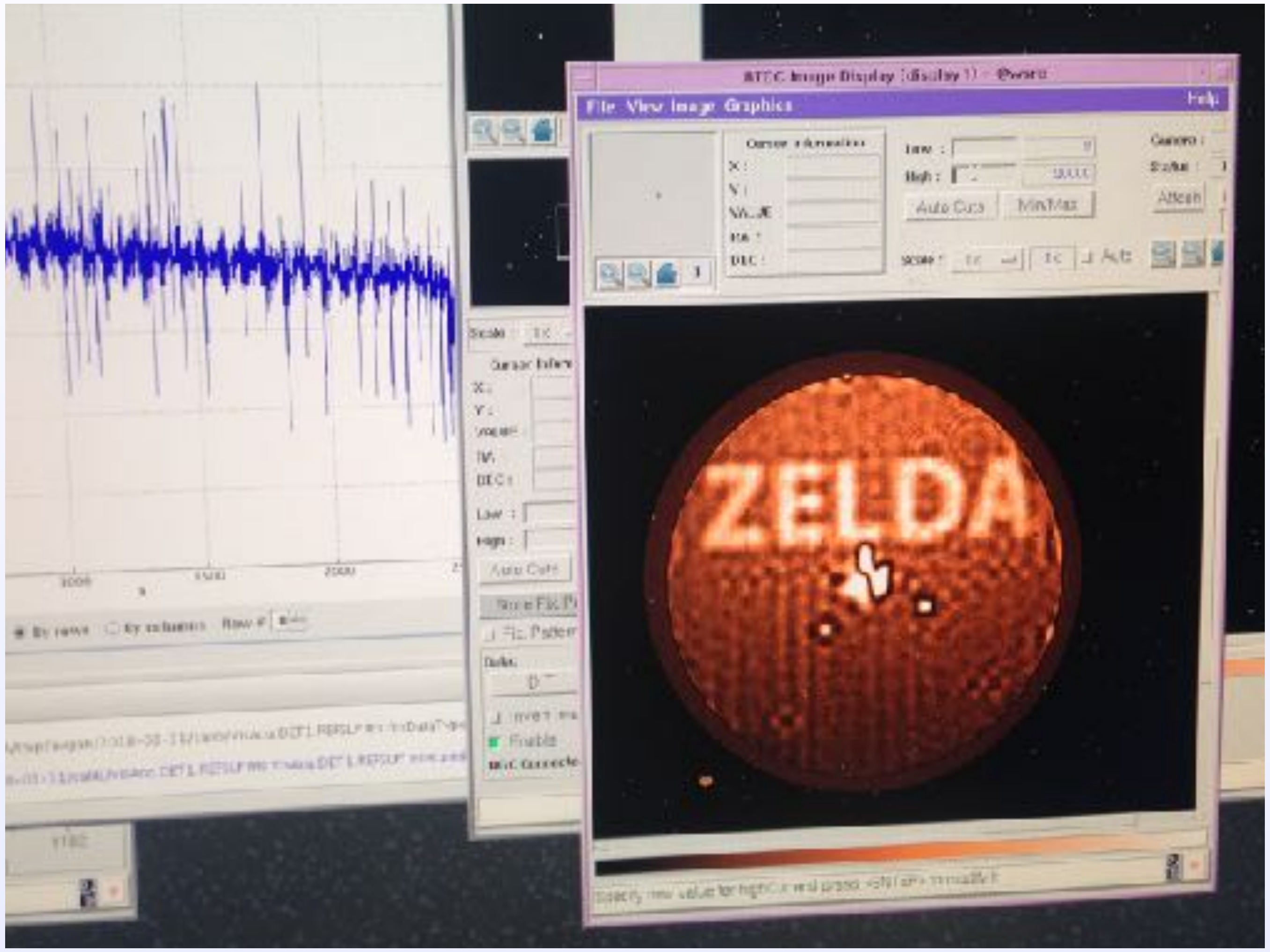
N'Diaye et al. (2016)

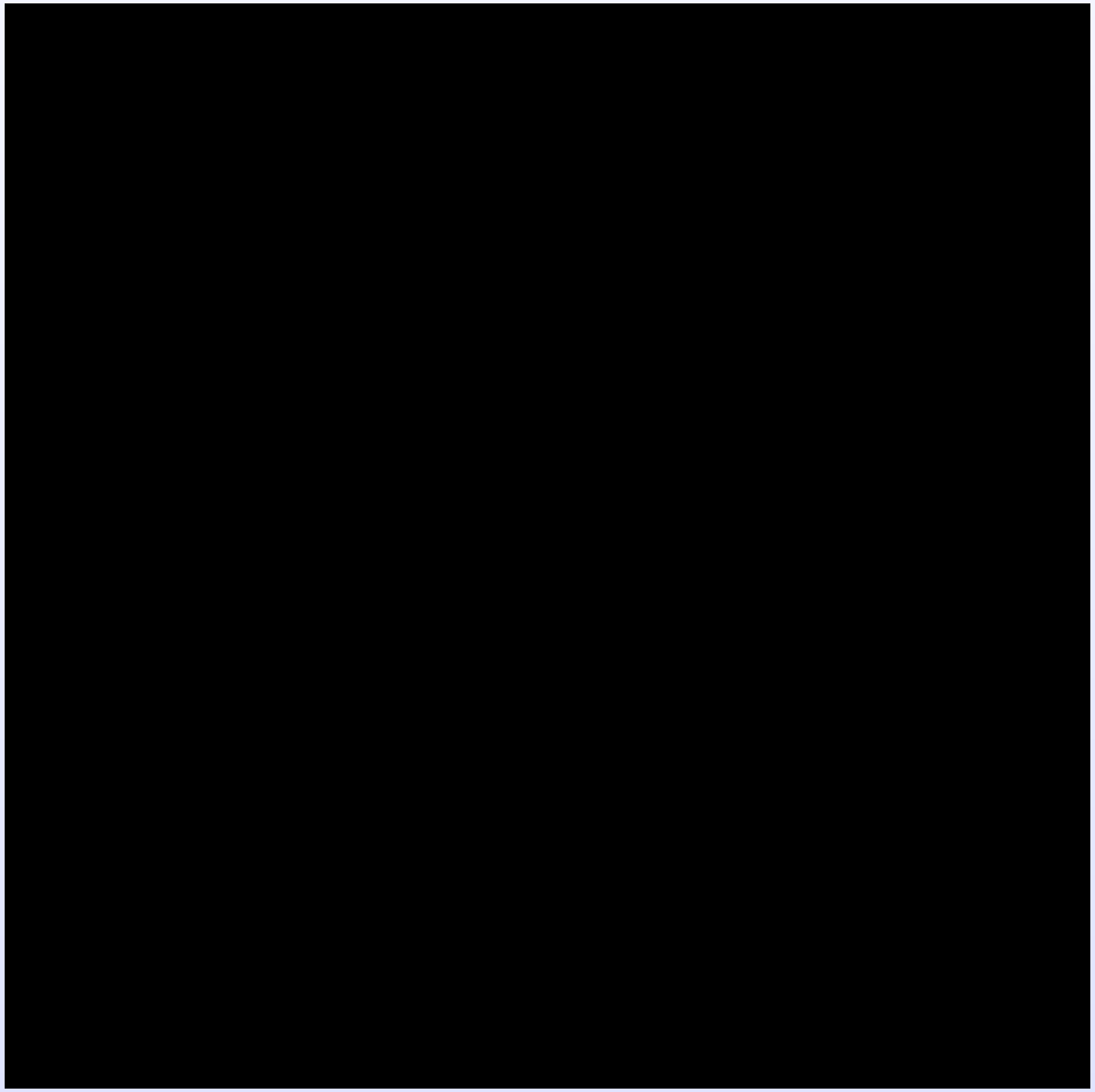
Apodised pupil Lyot coronagraph, H-band





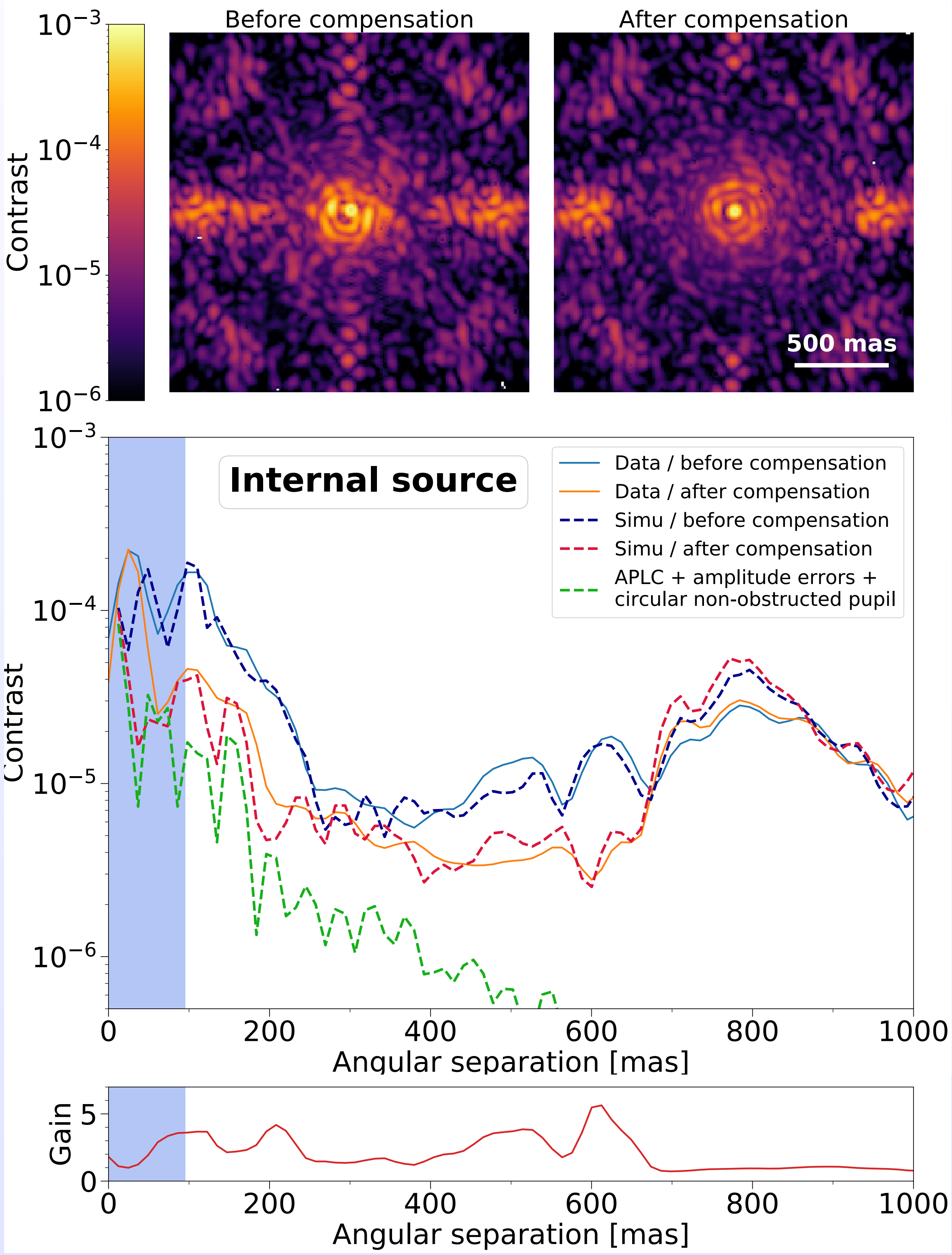
ZELDA on-sky

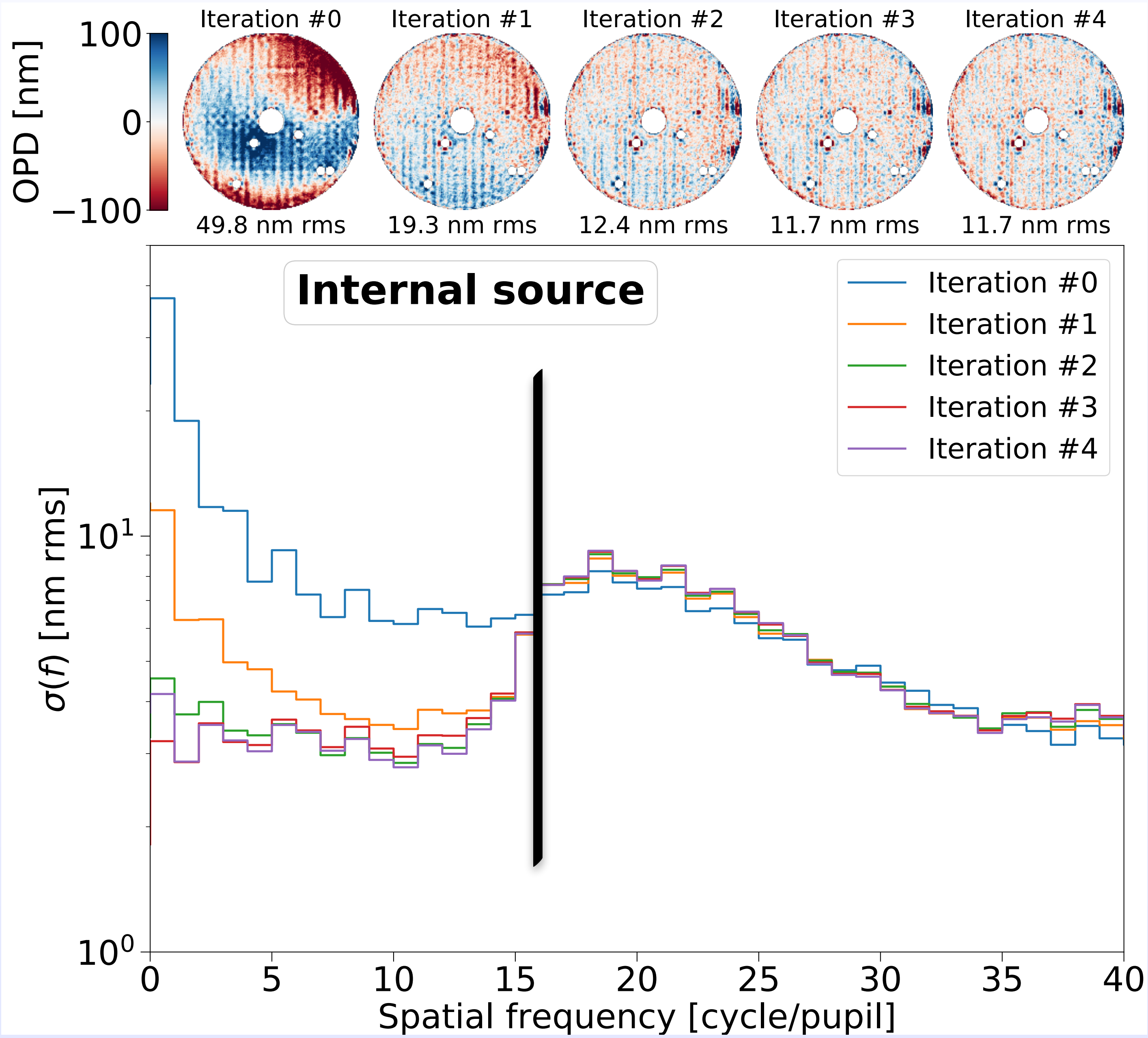




Further testing - internal source

Vigan et al. (2019)

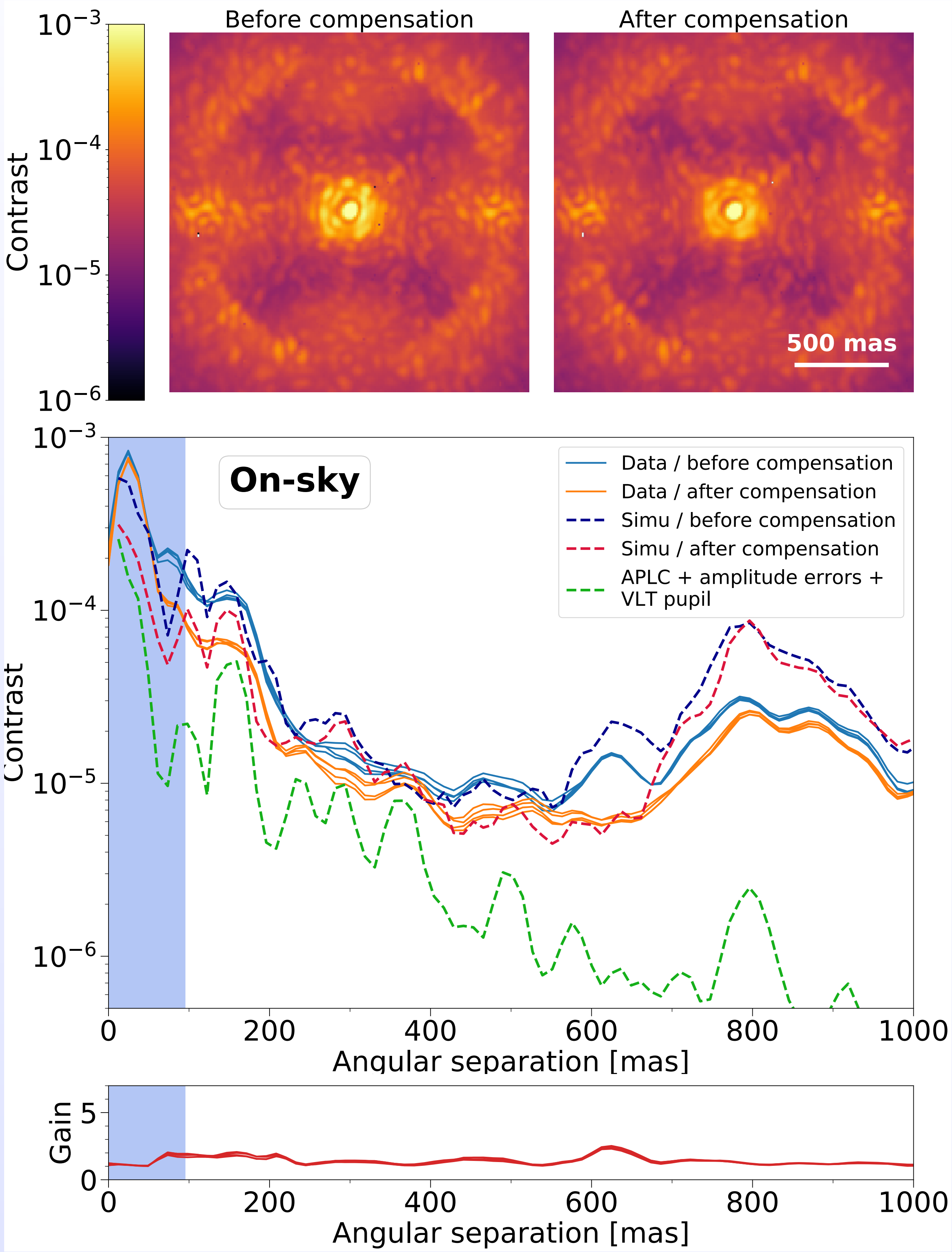


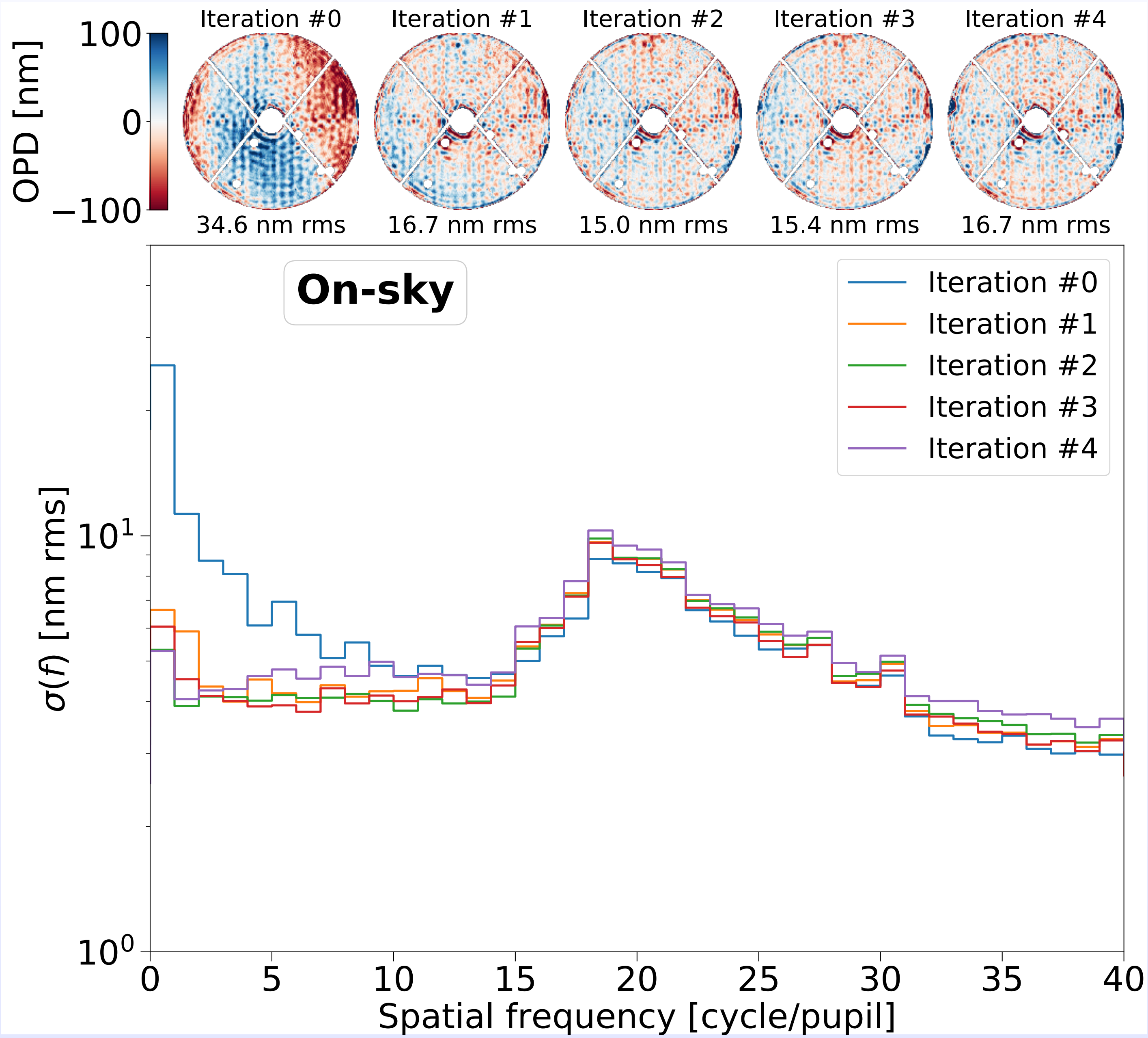


- Filtering with 700 SAXO KL modes
- Tip-tilt offloaded on DTTS

Further testing - on-sky

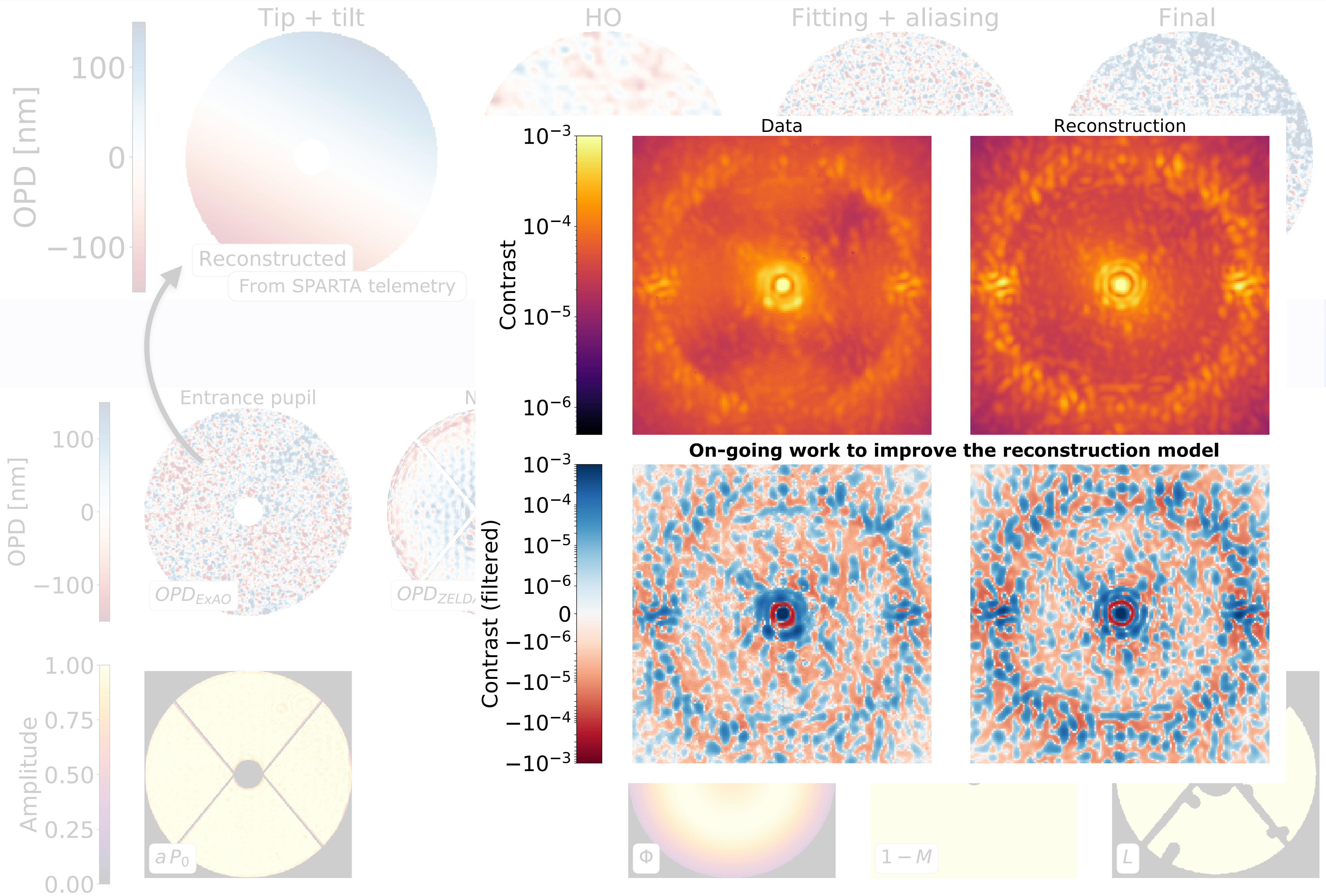
Vigan et al. (2019)





- **Filtering with 700 SAXO KL modes**
- **Tip-tilt offloaded on DTTS**

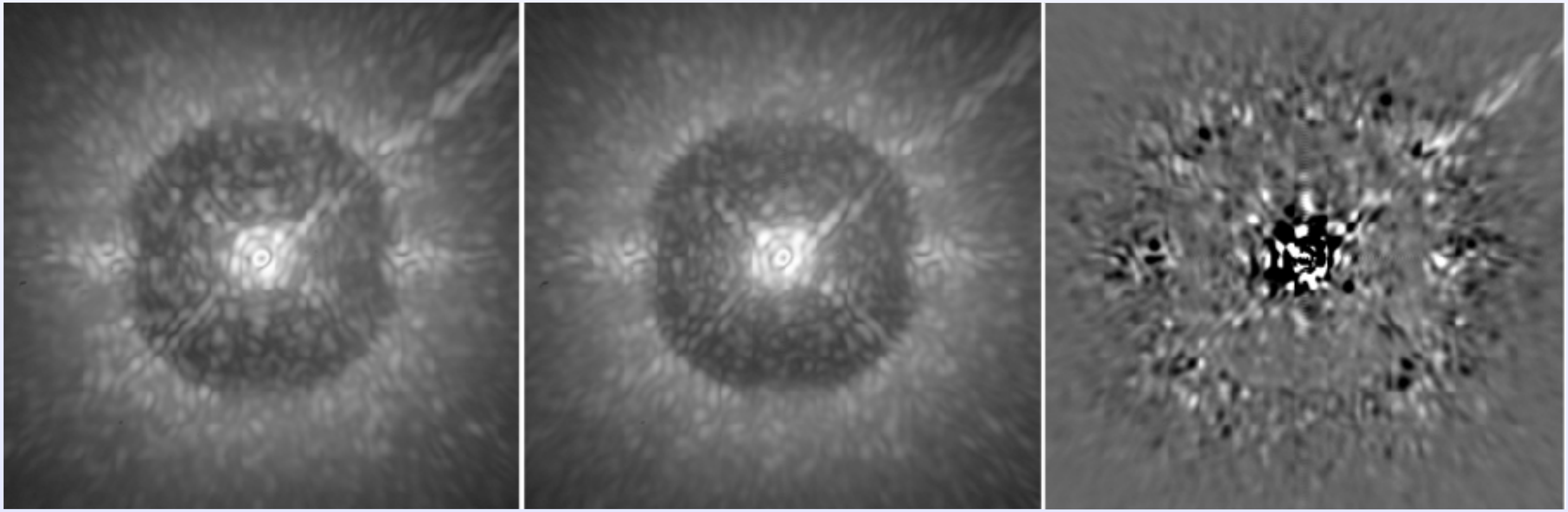
Coronagraphic image reconstruction



Quasi-static speckles

- Atmospheric and instrumental speckles are a major limitation
  - The Good: they can be <u>measured and corrected</u>
  - The Bad: speckles are <u>not static</u>, but definitely <u>not random</u> ➙ "quasi-static" behaviour
  - The Ugly: <u>multiple timescales</u> are involved

T_0 | $T_1 = T_0 + 20$ min | $T_0 - T_1$

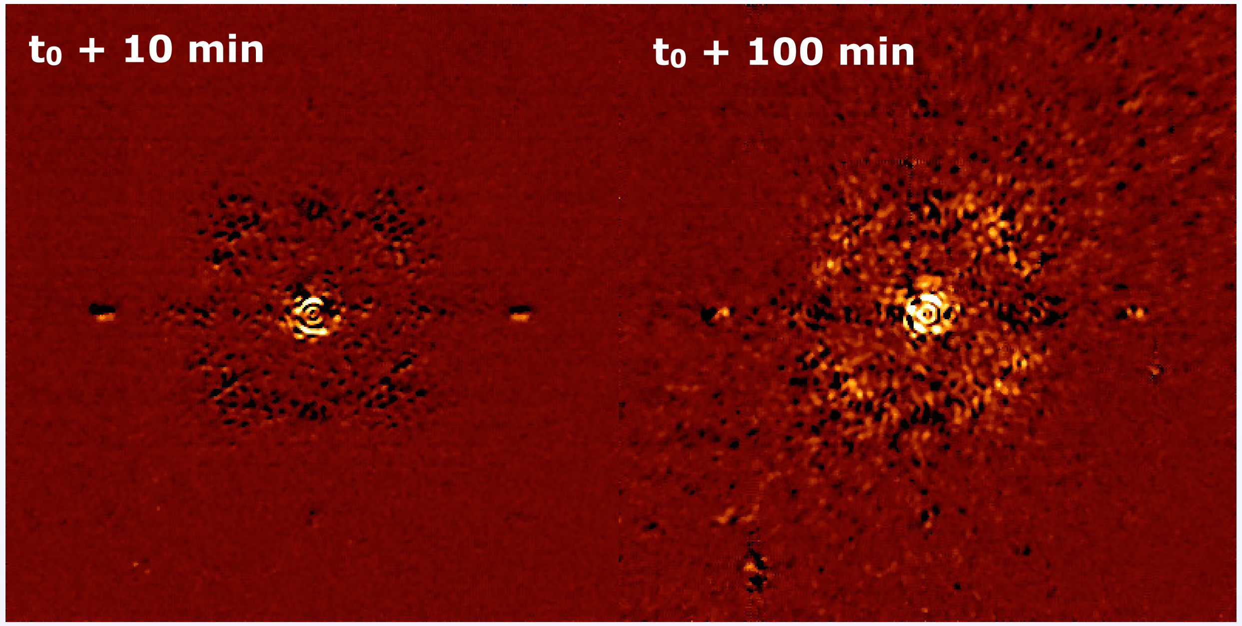


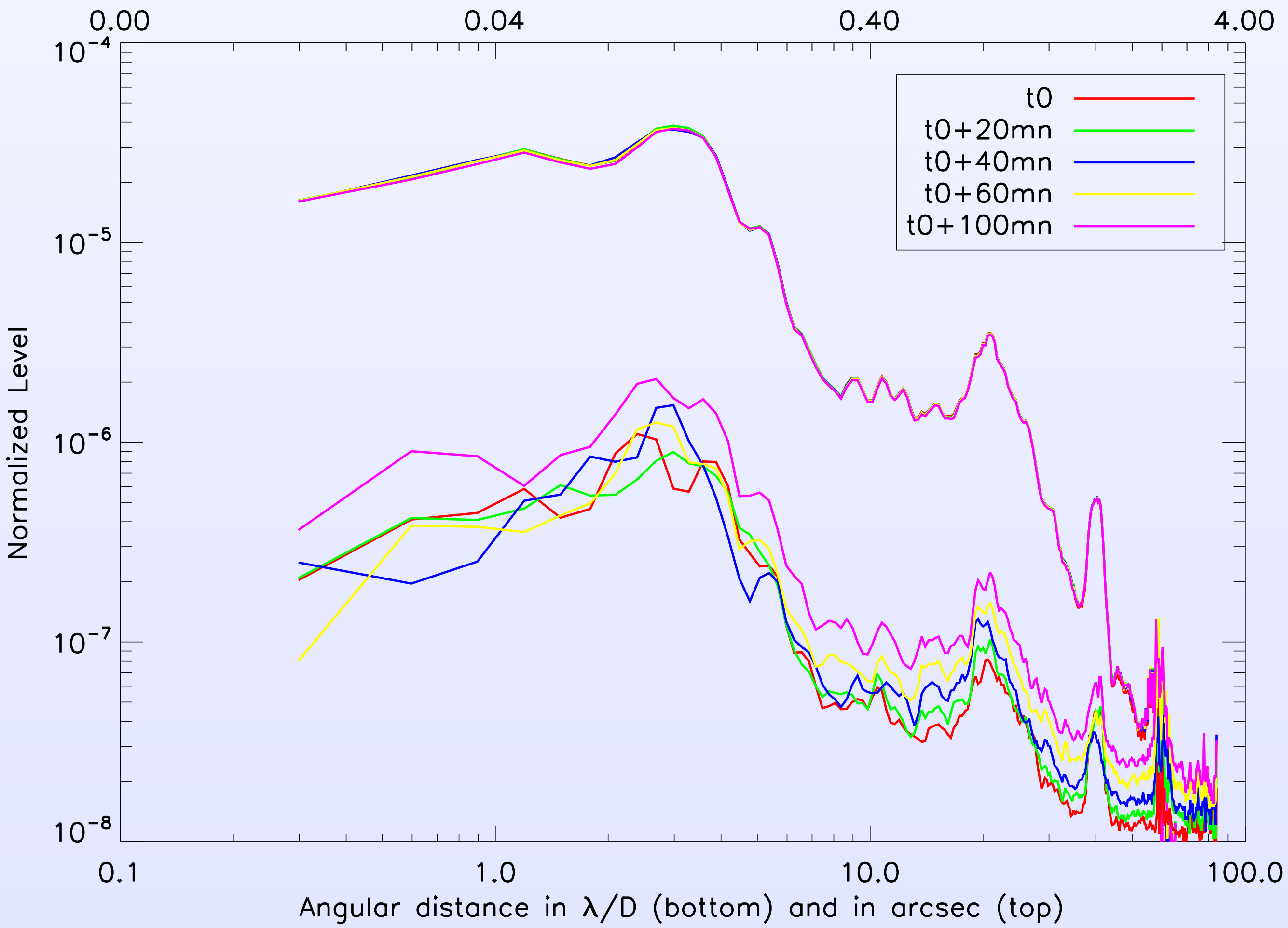
VLT/SPHERE

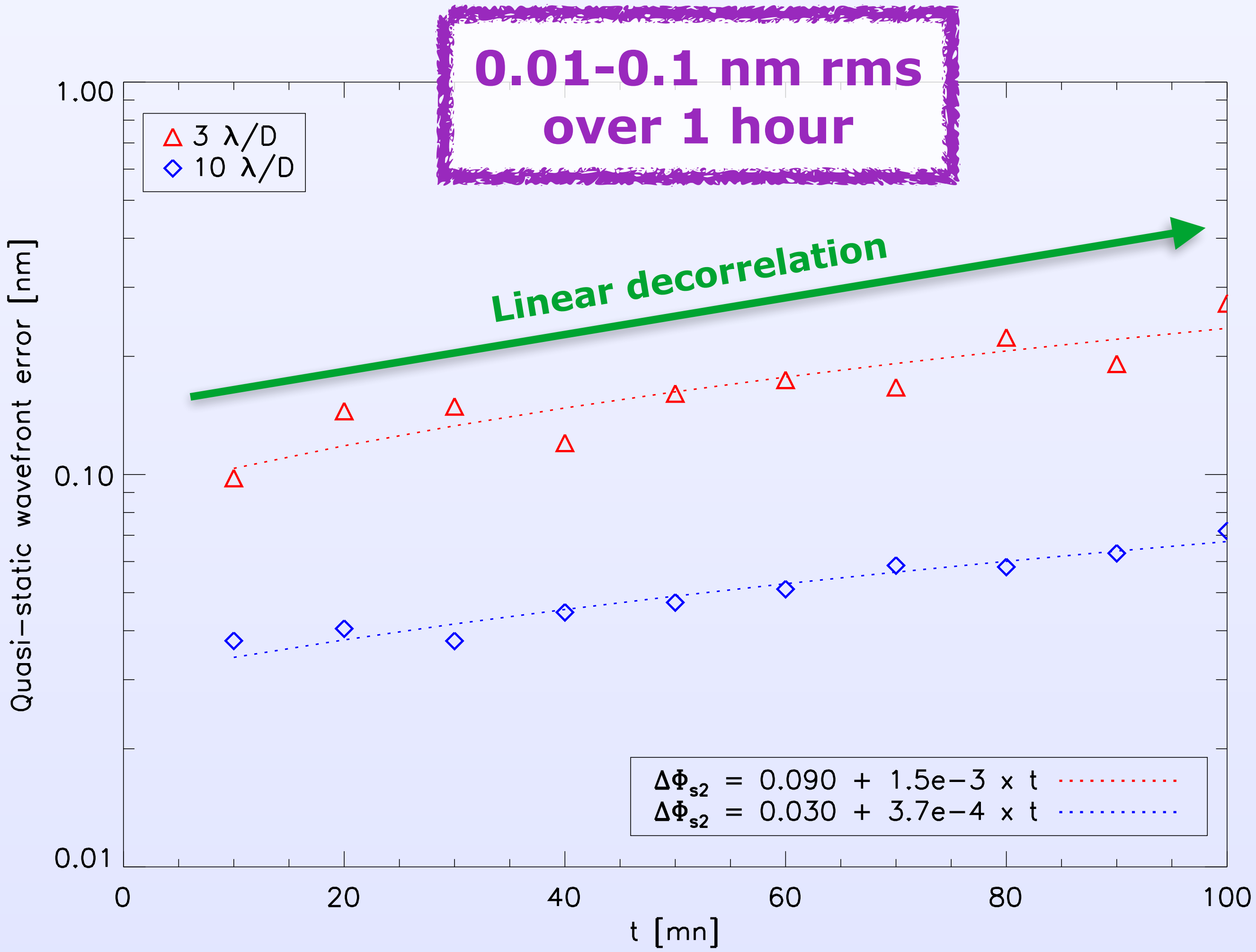
Racine et al. (1999)
Macintosh et al. (2005)
Soummer et al. (2007)
Hinkley et al. (2007)
Martinez et al. (2013, 2013)
Milli et al. (2016)

Speckles decorrelation in SPHERE

- Martinez et al. (2013, A&A)
- SPHERE in Europe, at ~10°C
- Difference of coronagraphic images
- Loss of contrast ➙ WF error variations, based on a theoretical prescription ⚠

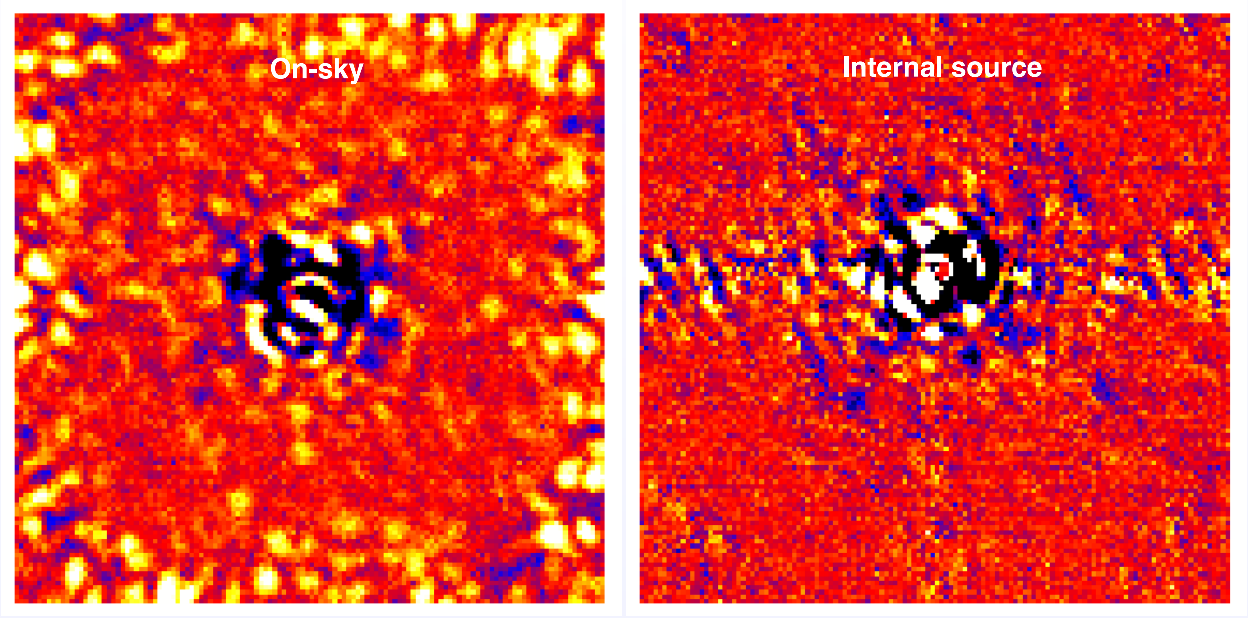


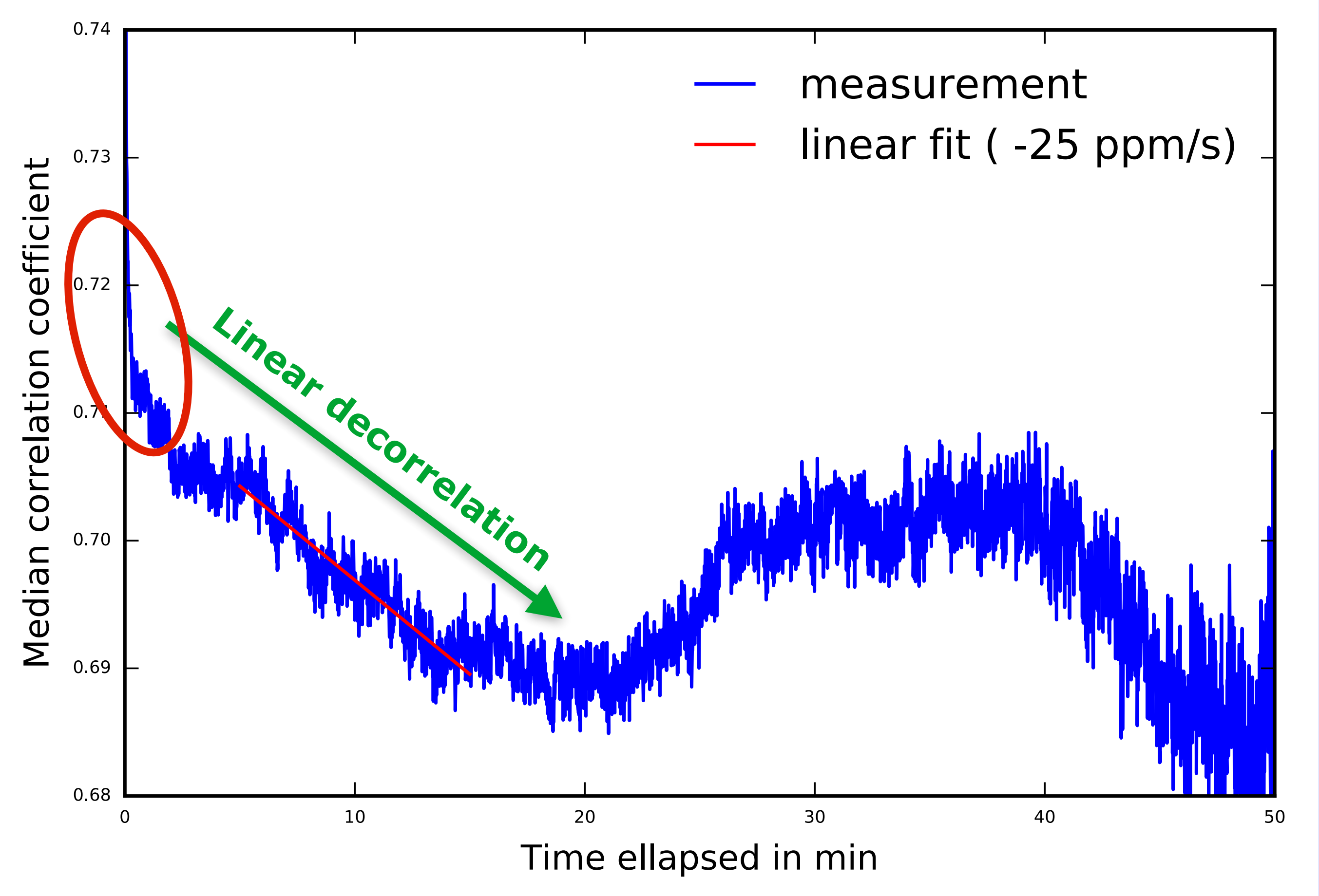


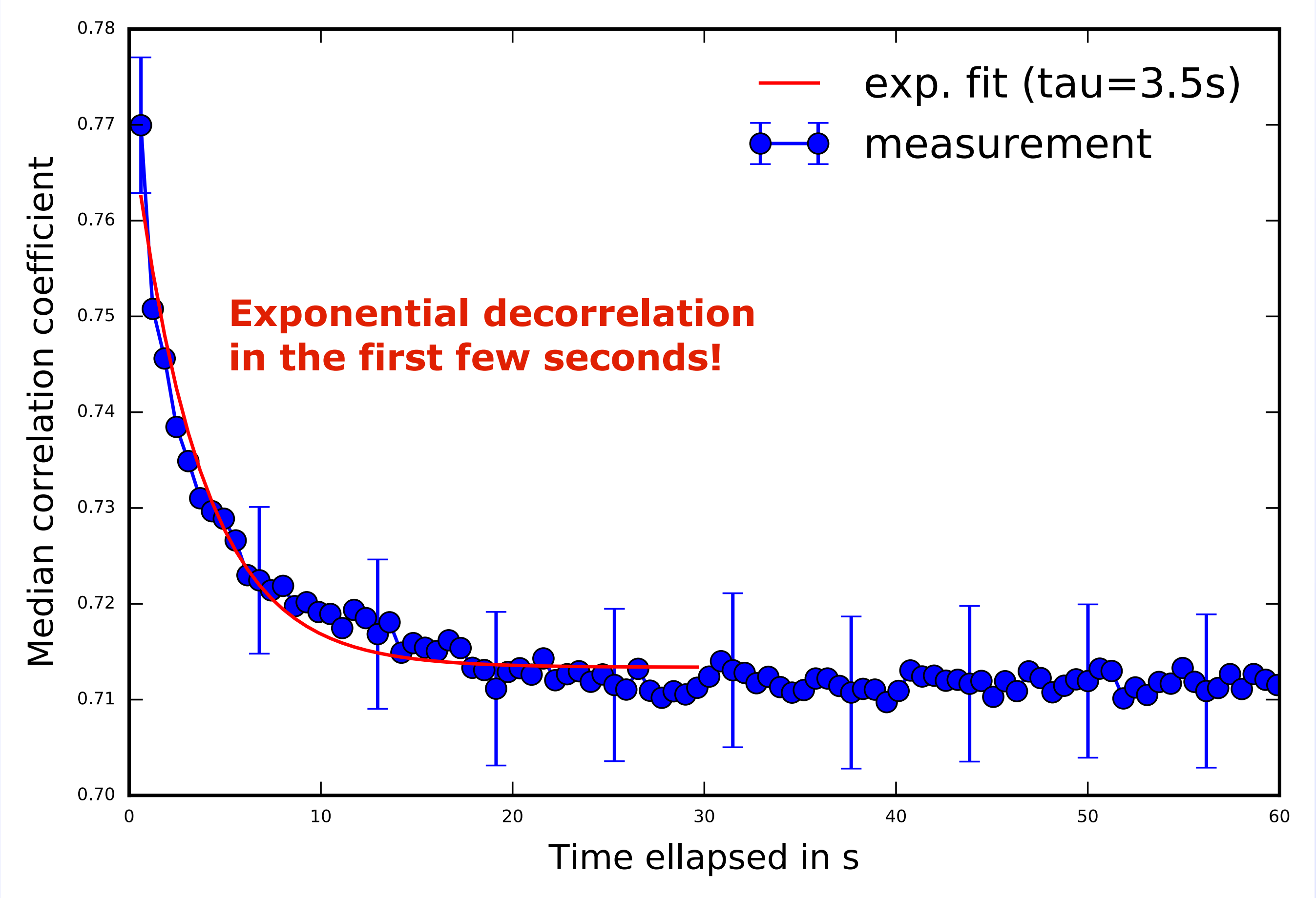


Speckles decorrelation in SPHERE

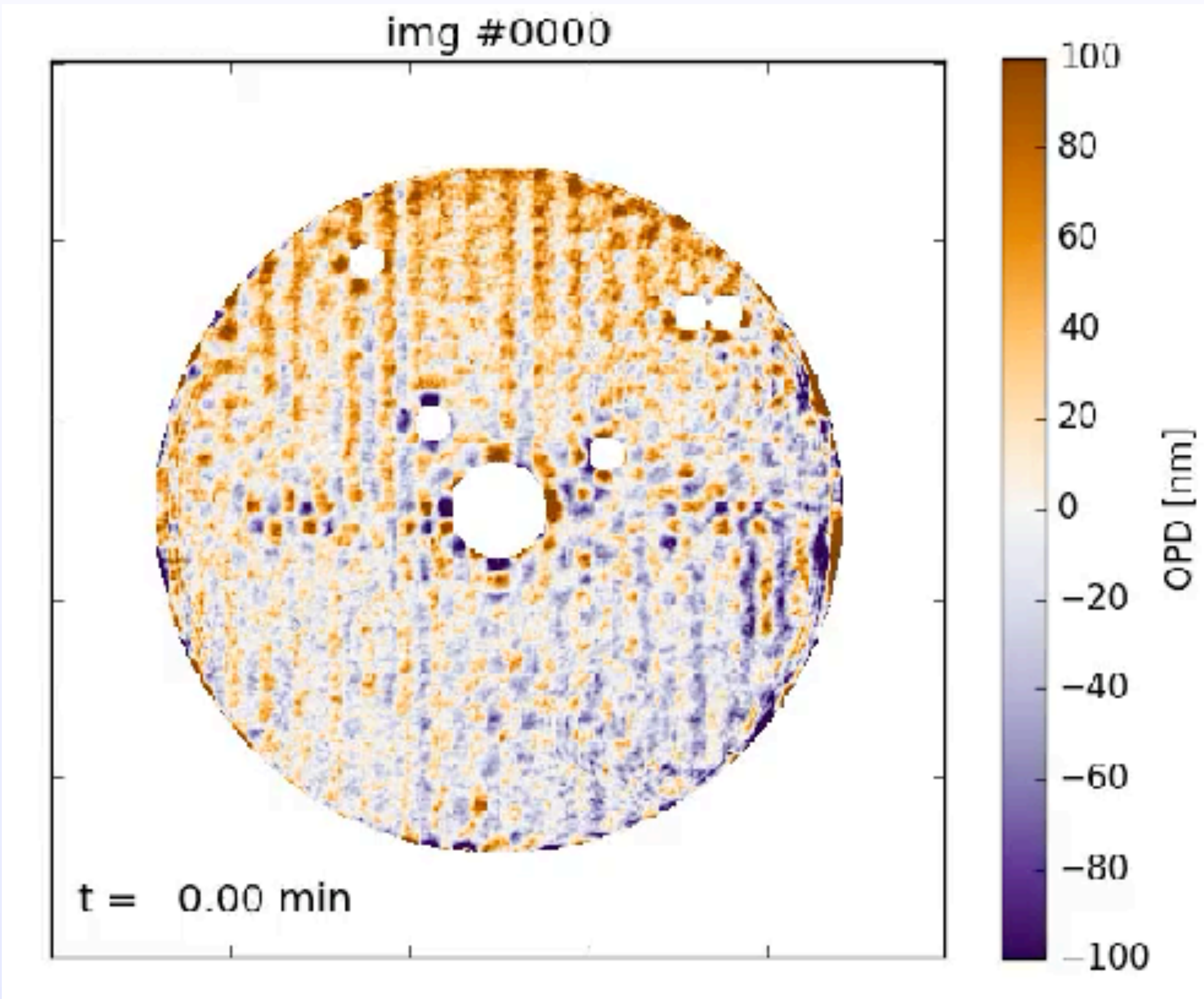
- Milli et al. (2016, SPIE)
- SPHERE in Paranal, internal source + on-sky
- Series of images at high-cadence (~0.7 s)
- Decorrelation of the speckles in the focal plane
- No conversion to wavefront errors







ZELDA sequences at high cadence

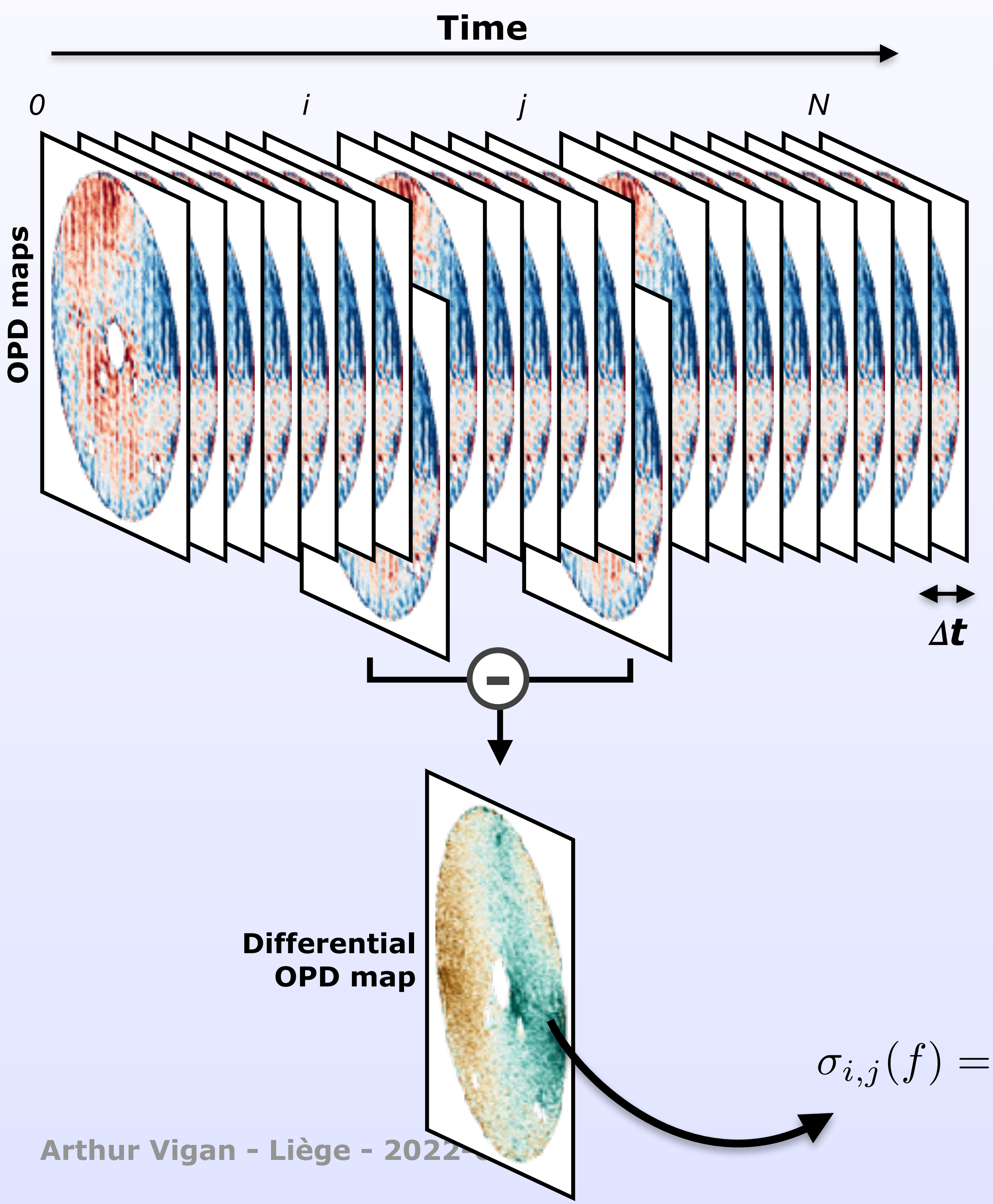


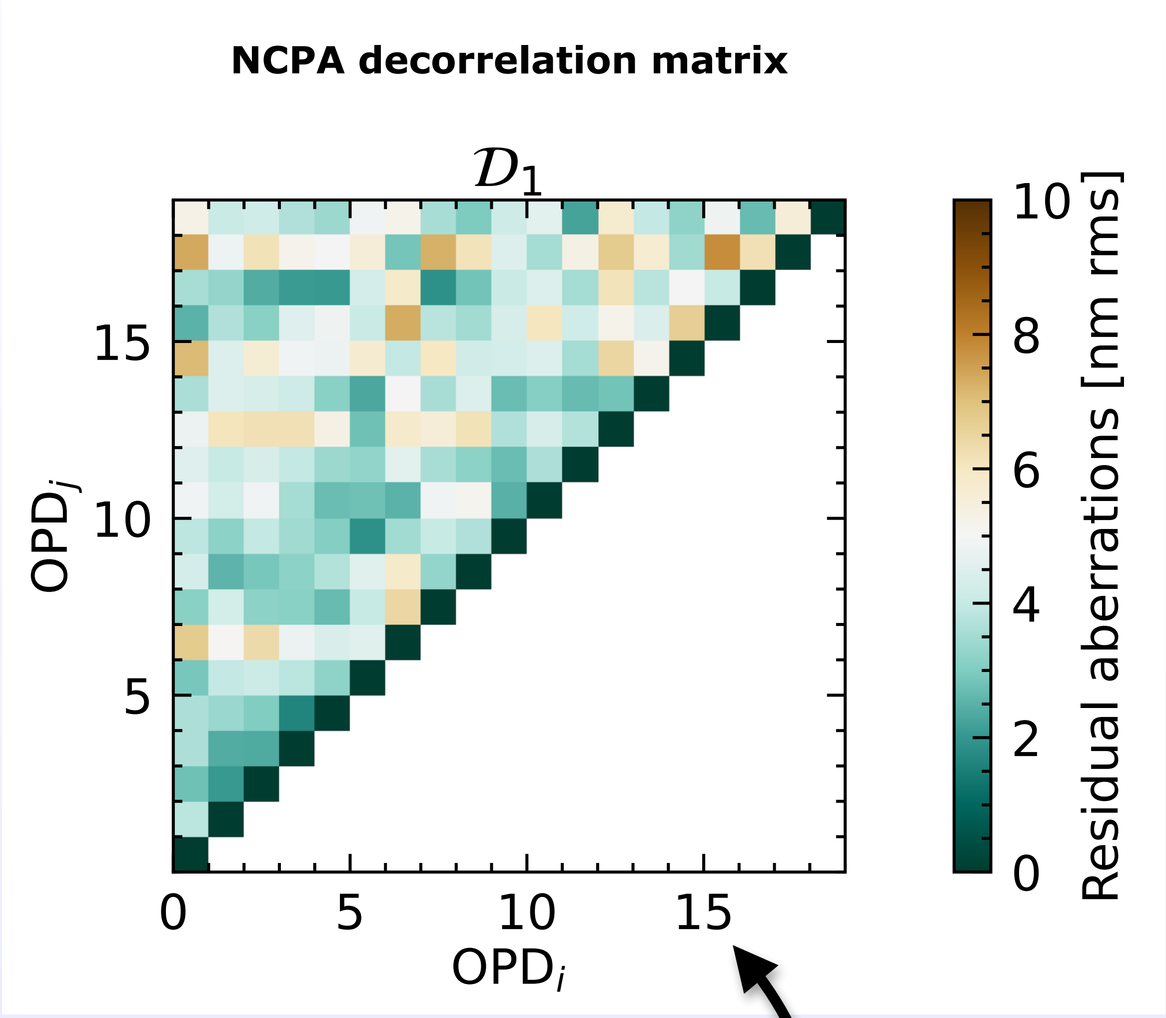
Internal turbulence!

10 nm PtV ~ 3 nm rms over few seconds

NCPA decorrelation analysis

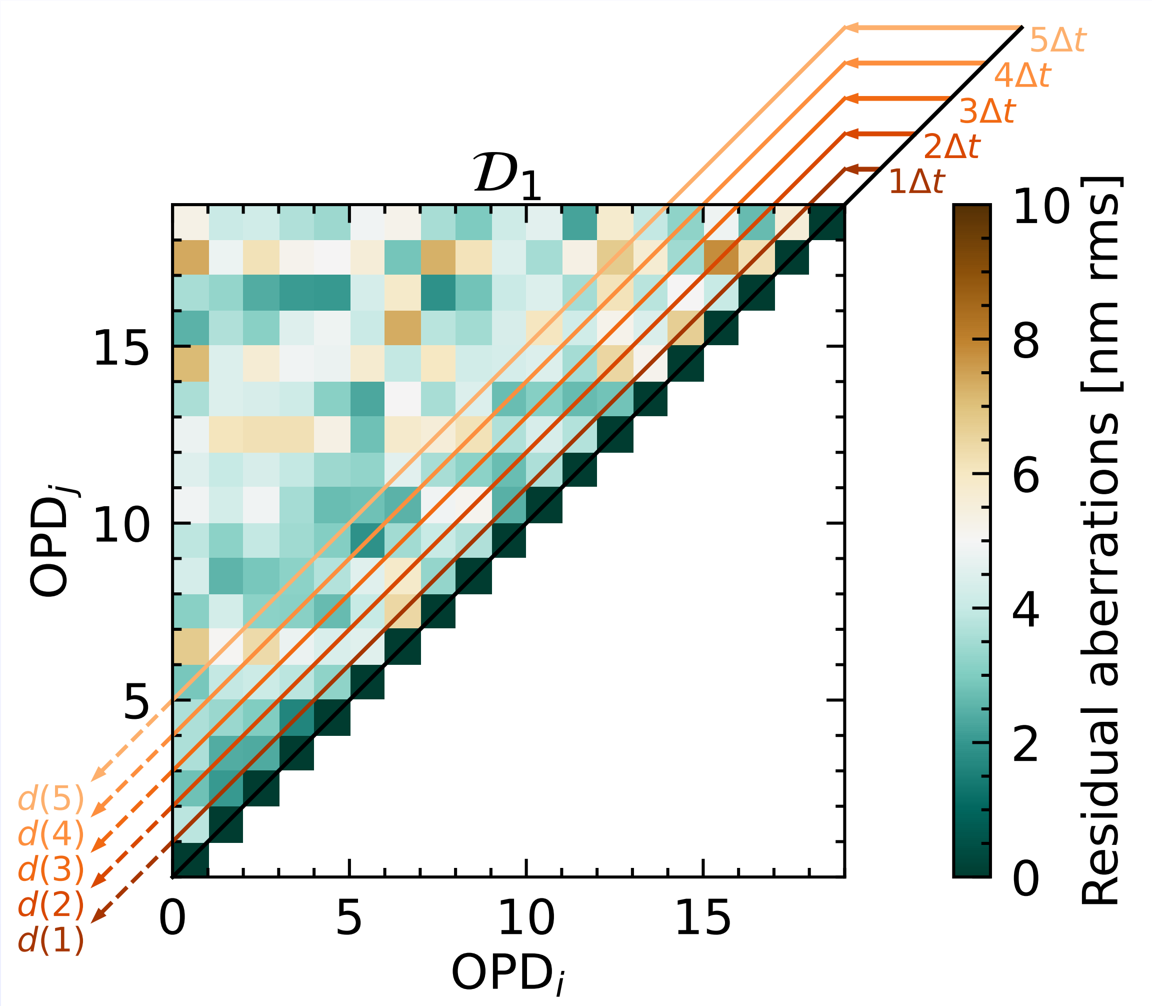
- Analysis based on differences of OPD maps

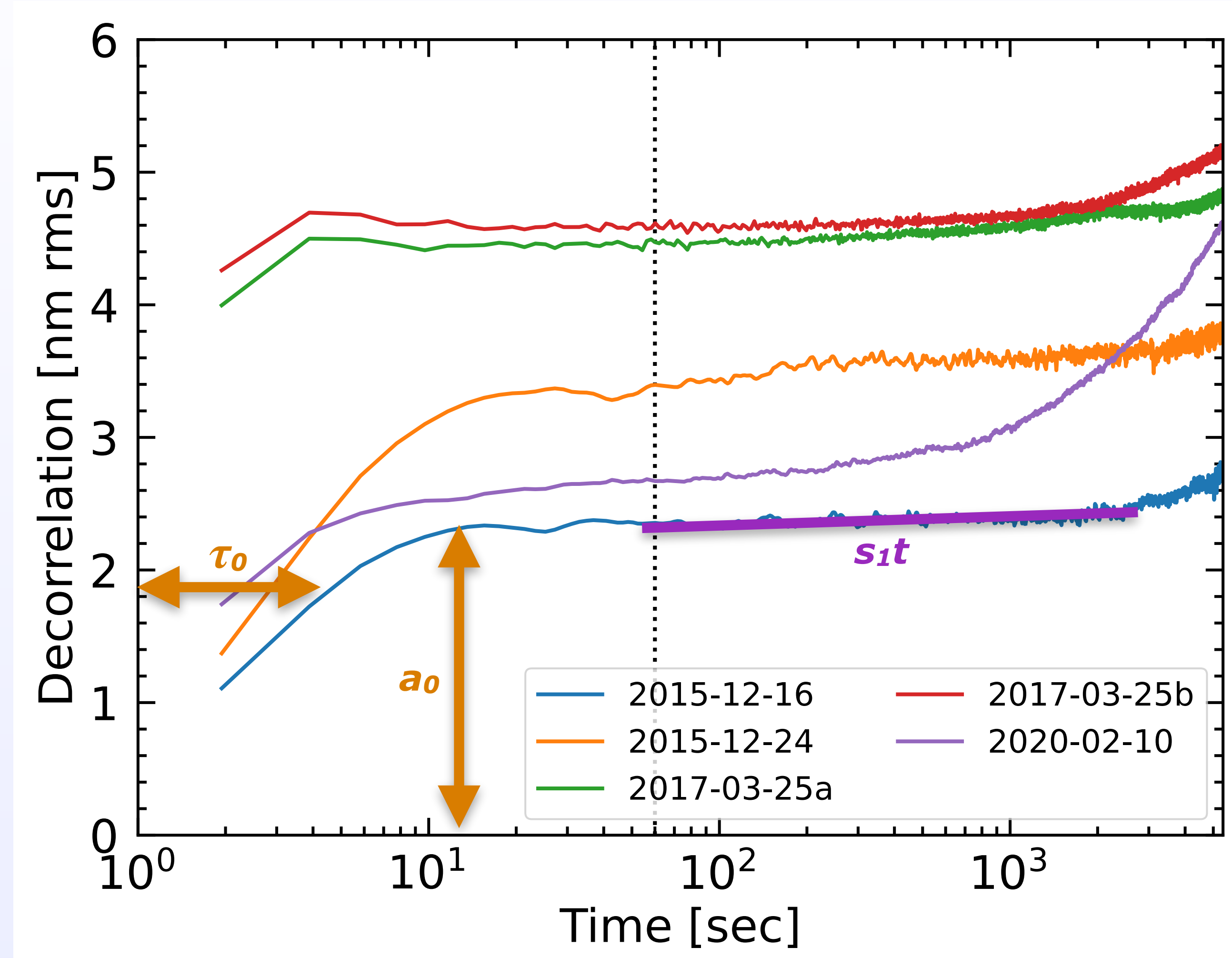




$$\sigma_{i,j}(f) = \sqrt{\int_{f}^{f+1} \int_{0}^{2\pi} \mathrm{PSD}(\nu, \theta) \nu d\nu d\eta}$$

Temporal decorrelation





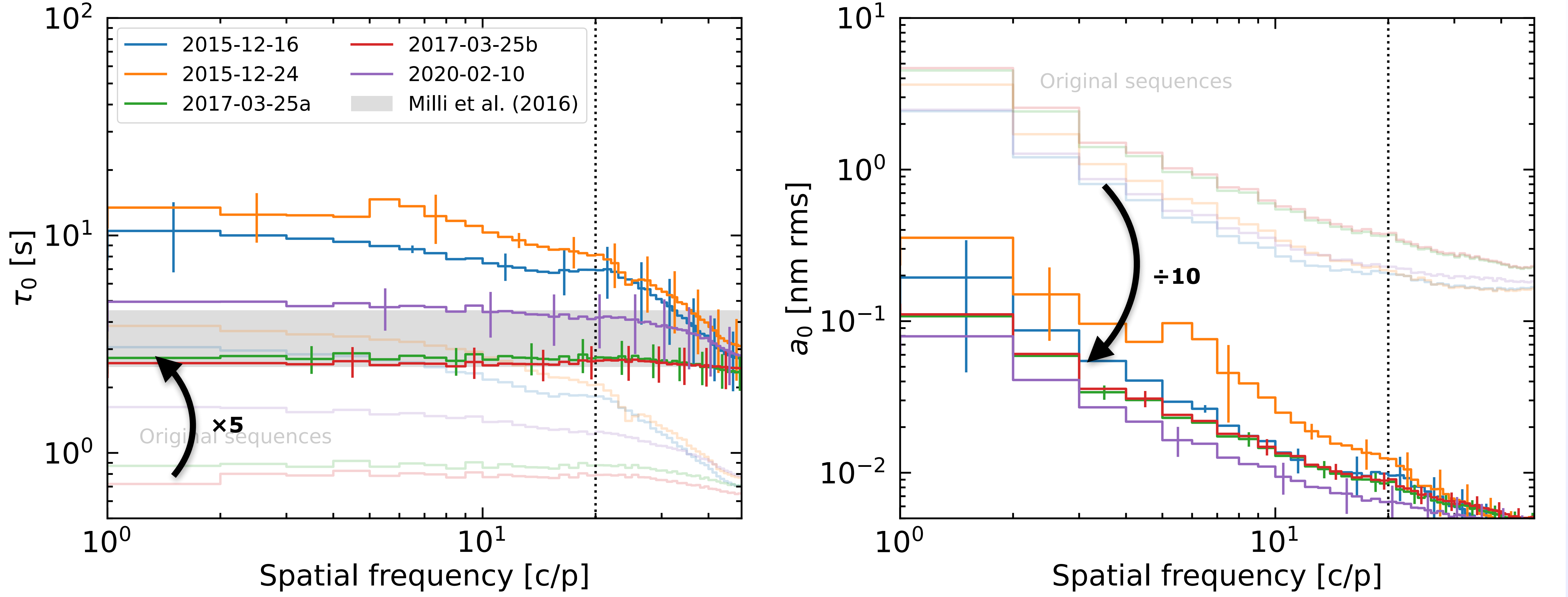
- Two distinct regimes
- Empirical modelling:

Fast decorrelation due to internal turbulence

$$d(t) = \begin{cases} a_0\left(1 - e^{-\frac{t}{\tau_0}}\right) + s_0 t & \text{for } t \leq 60\,s \\ s_1 t + a_1 & \text{for } t > 60\,s \end{cases}$$

Slow NCPA decorrelation

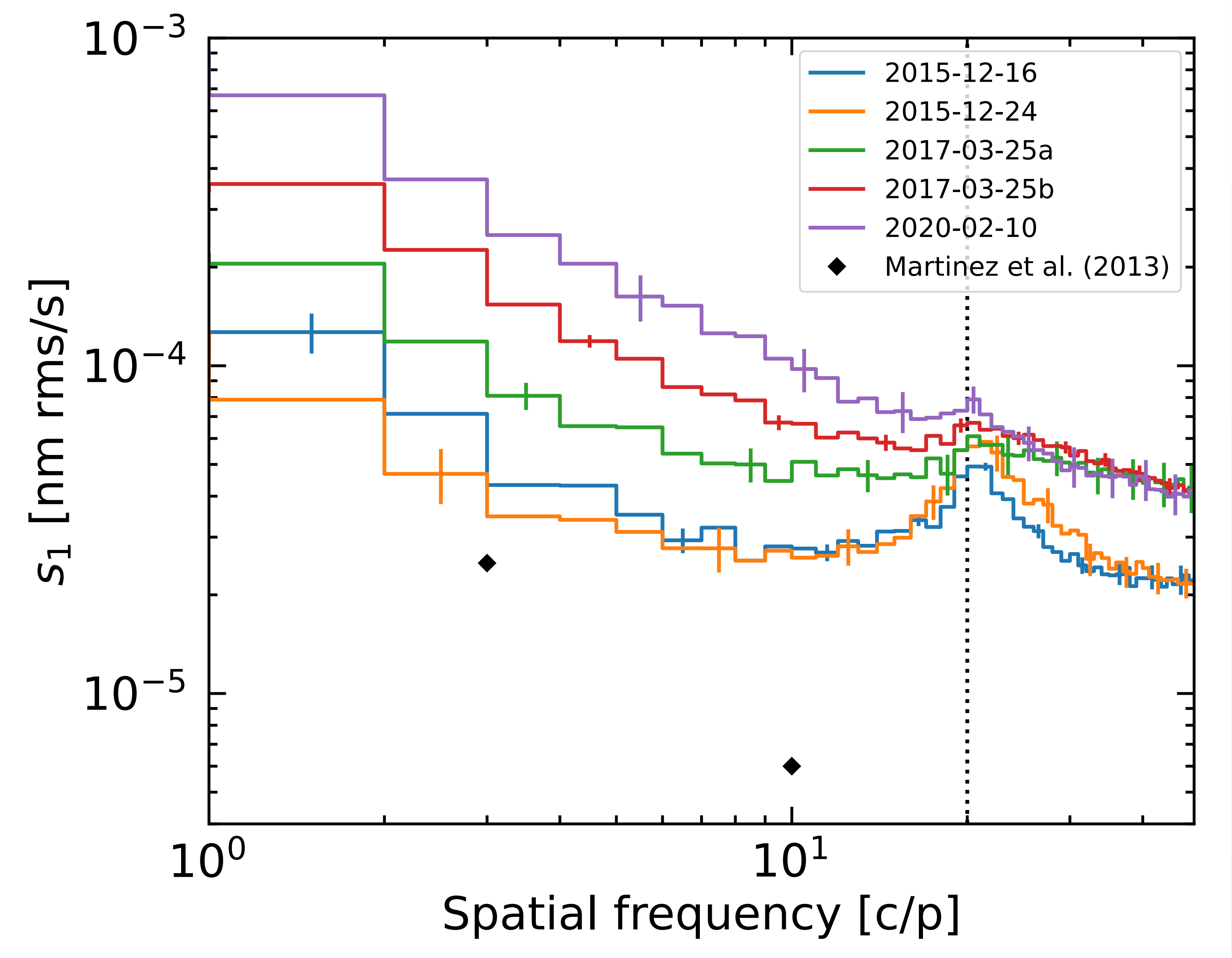
Internal turbulence parameters



- Fit of the parameters: characteristic timescale compatible with Milli et al. (2016)
- Procedure to remove the turbulence
  - Low-pass temporal filter
  - Turbulence attenuated by a factor >10

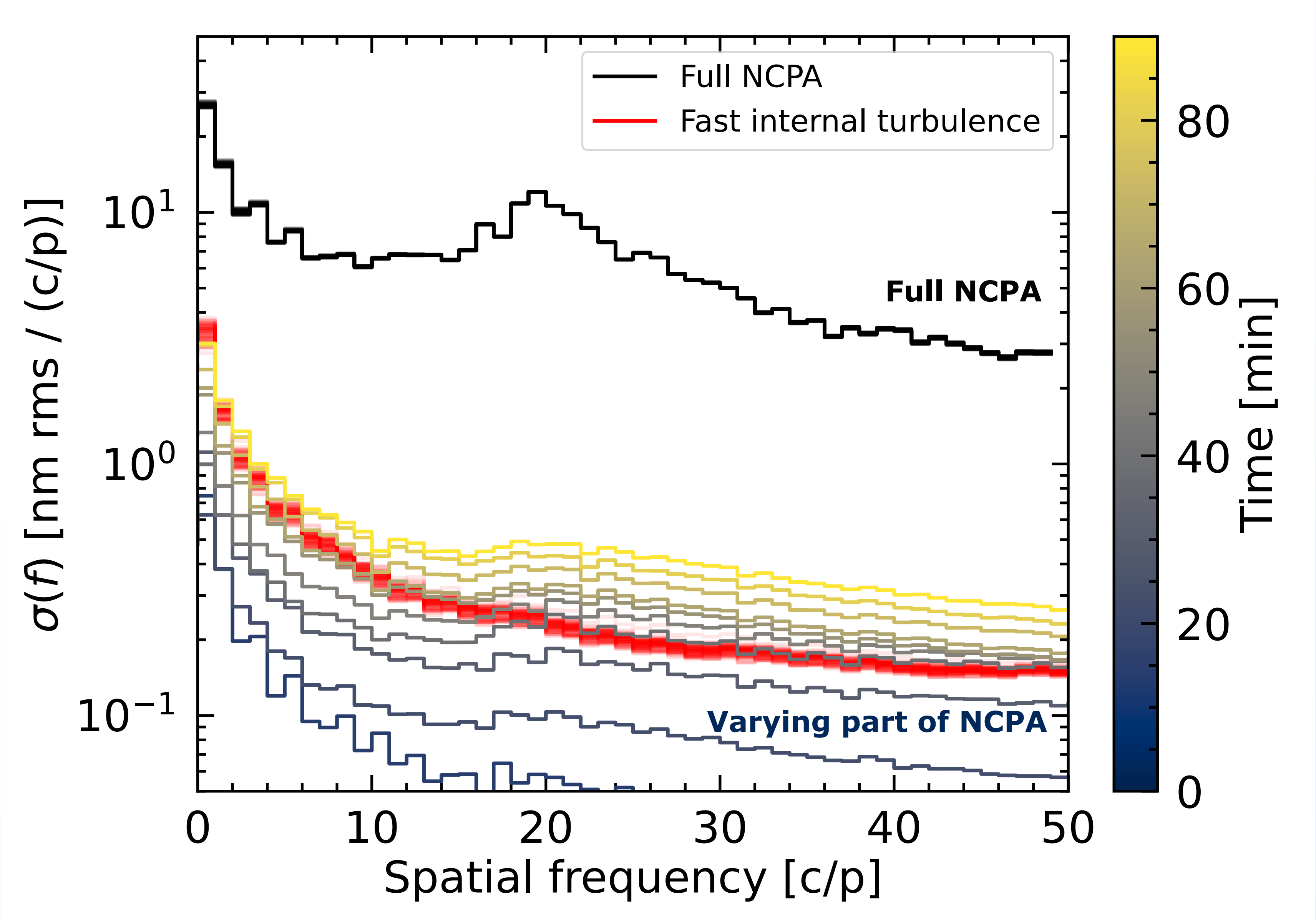
Internal turbulence efficiently removed

Slow NCPA decorrelation amplitude



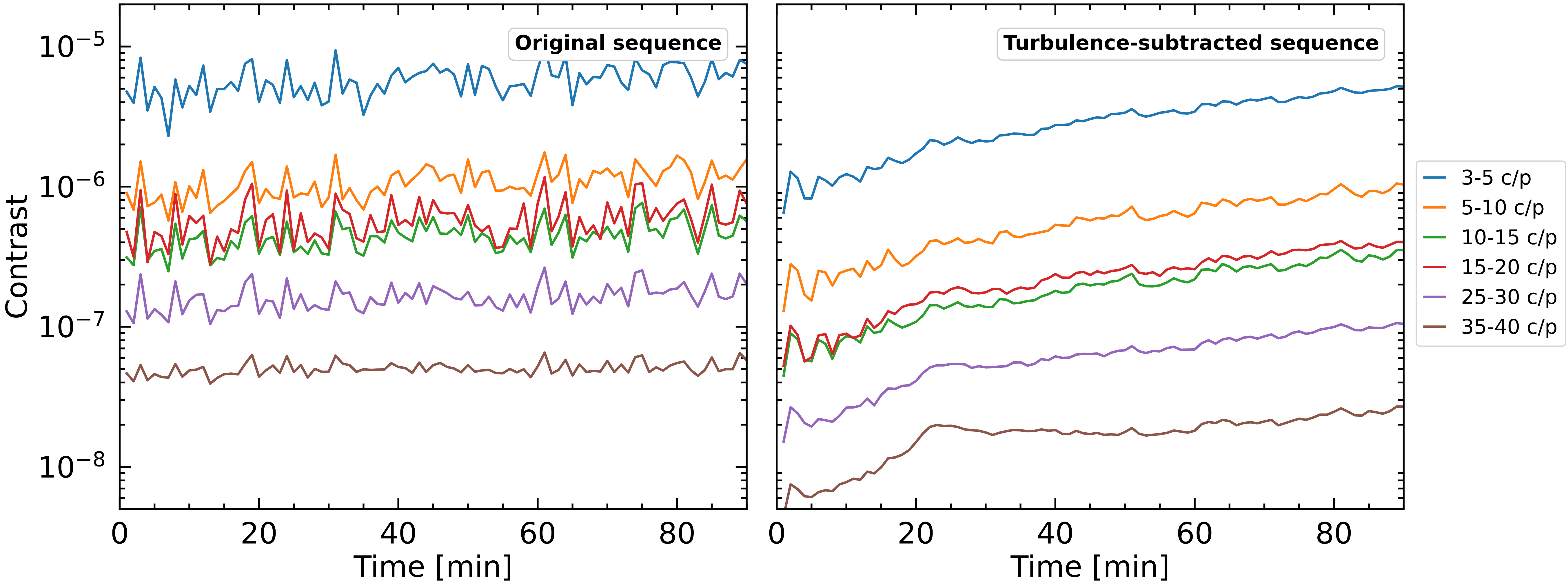
- Slow NCPA decorrelation estimated after removing the internal turbulence
- Clear dependance on spatial frequency
- Not in good agreement with previous measurements
  - Different environment? Possible ageing of the instrument?

Slow NCPA decorrelation amplitude



- Slow rise of NCPA with time
- Dominated by internal turbulence < 30-40 min
- Equal contribution over long timescales ➙ essential to remove the internal turbulence contribution

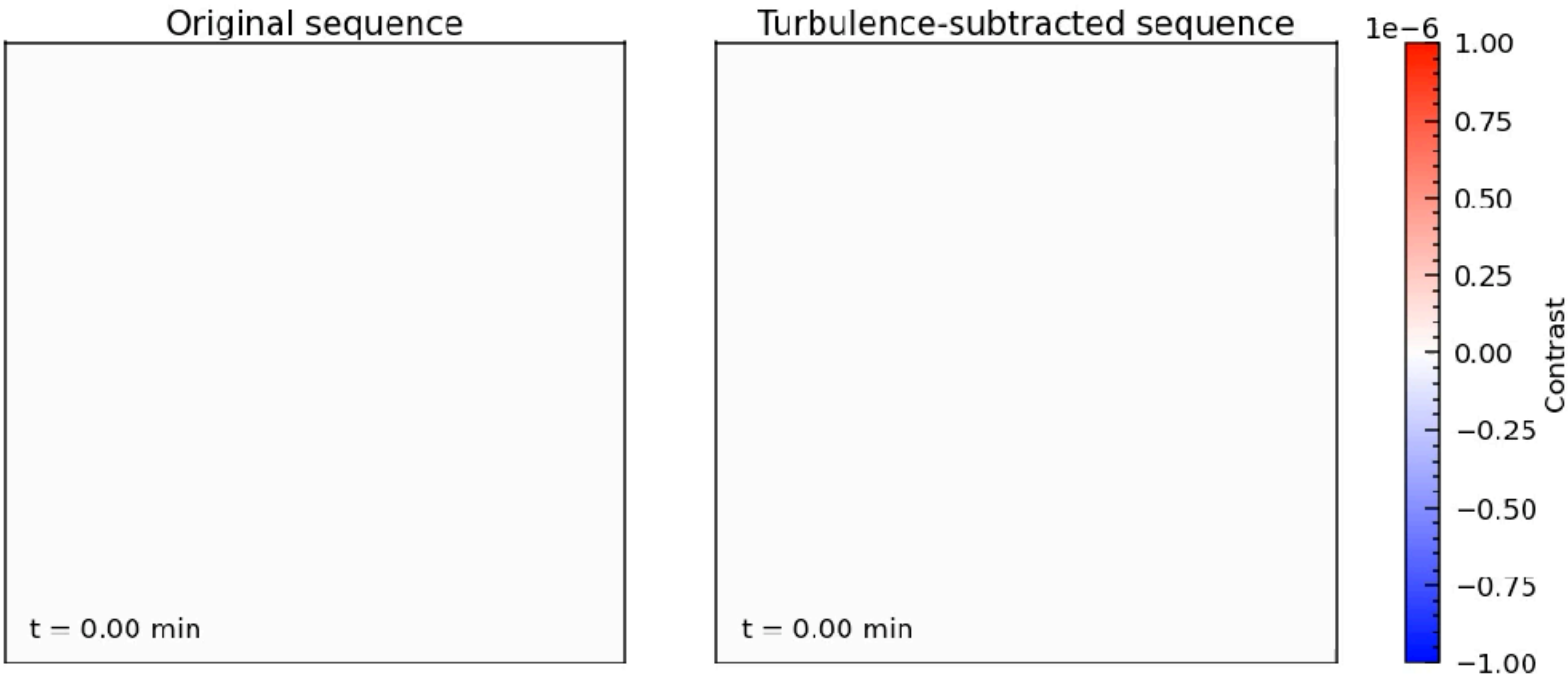
Impact on contrast in coronagraphic images



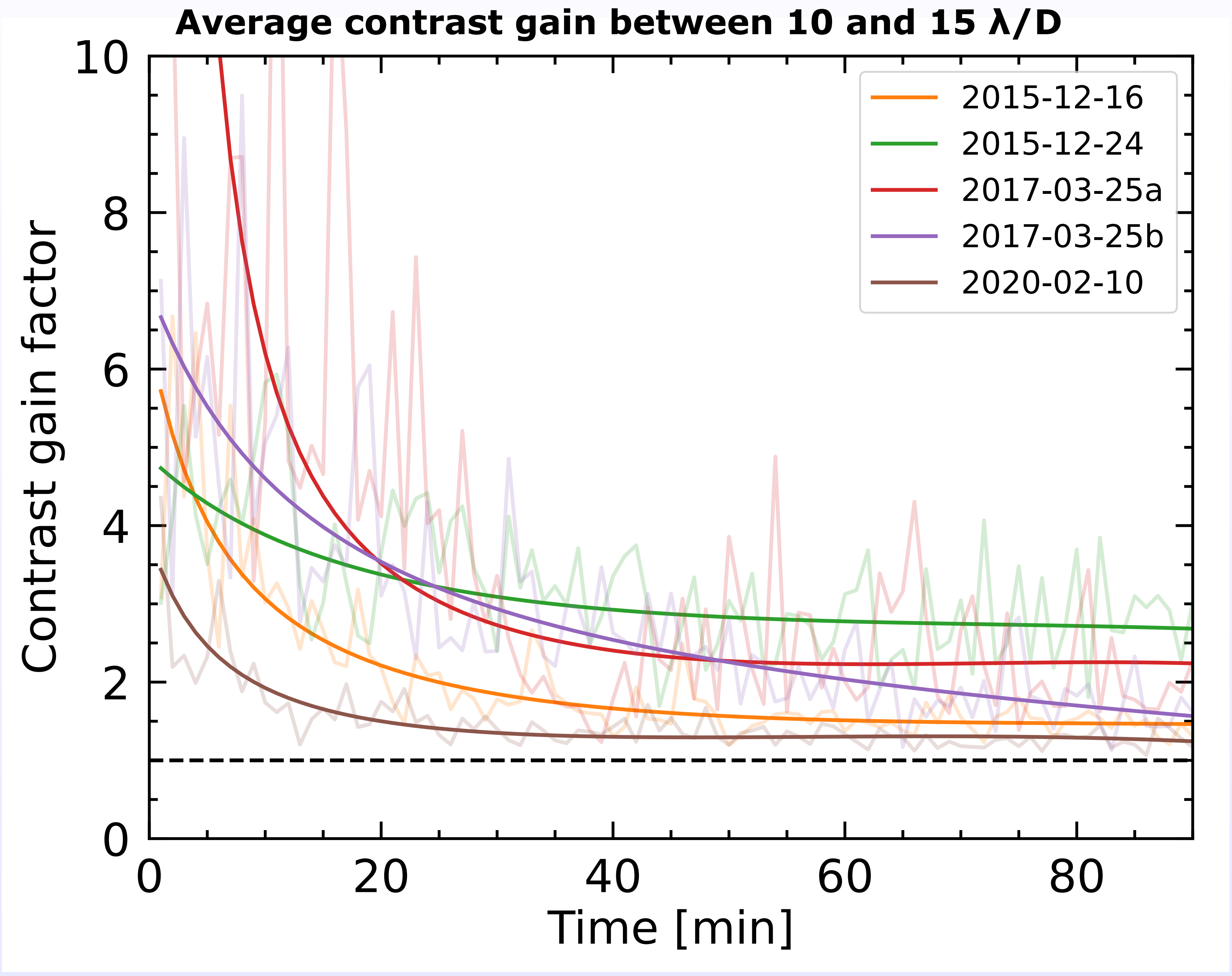
- Simulation of coronagraphic images with our model
- Subtraction of the first image to all sub-sequent images
- Contrast estimated with azimuthal standard deviation:
  - In raw coronagraphic images
  - In the subtracted images

Major impact of internal turbulence!

Impact on contrast in coronagraphic images

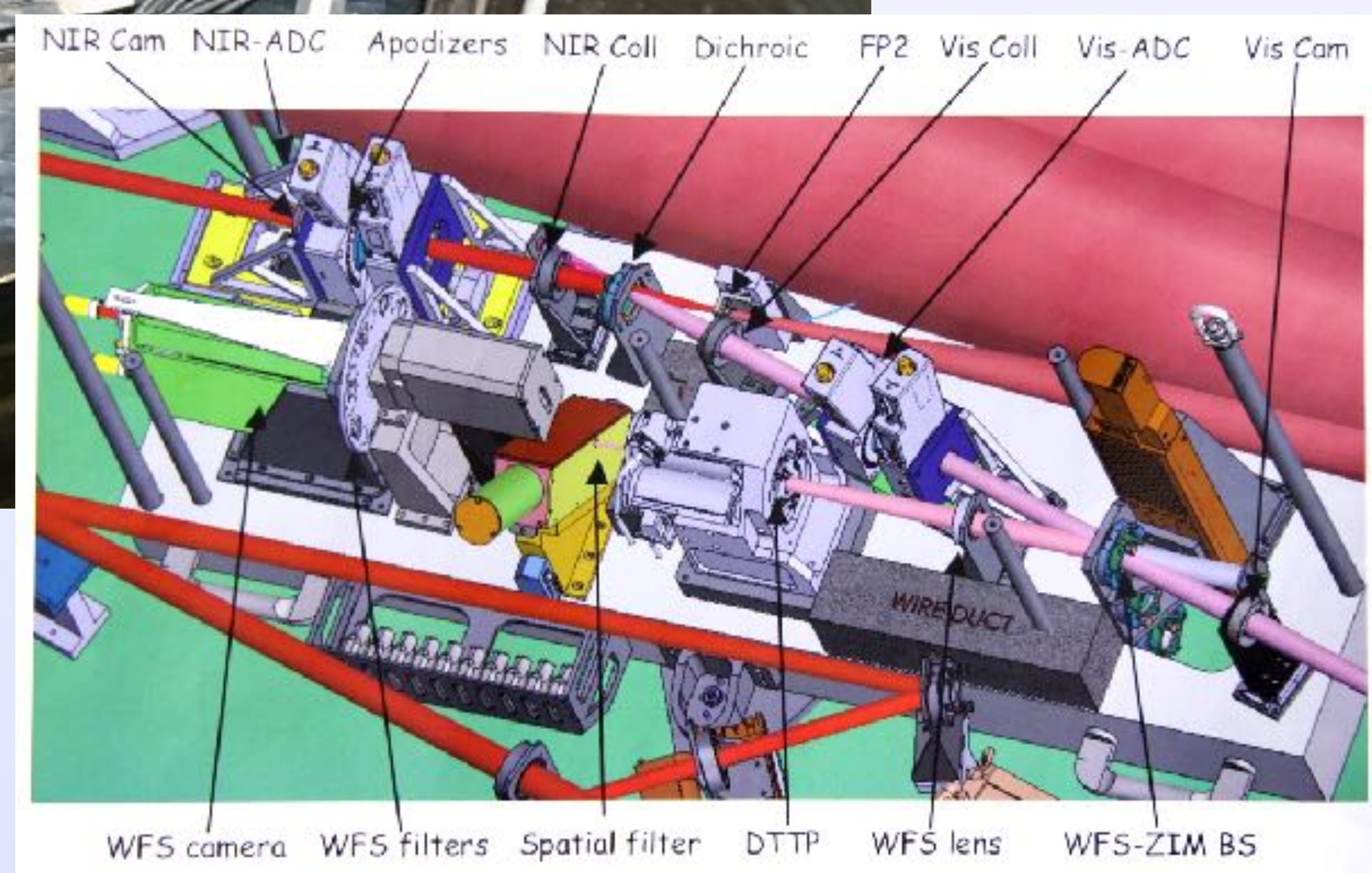


Impact on contrast in coronagraphic images



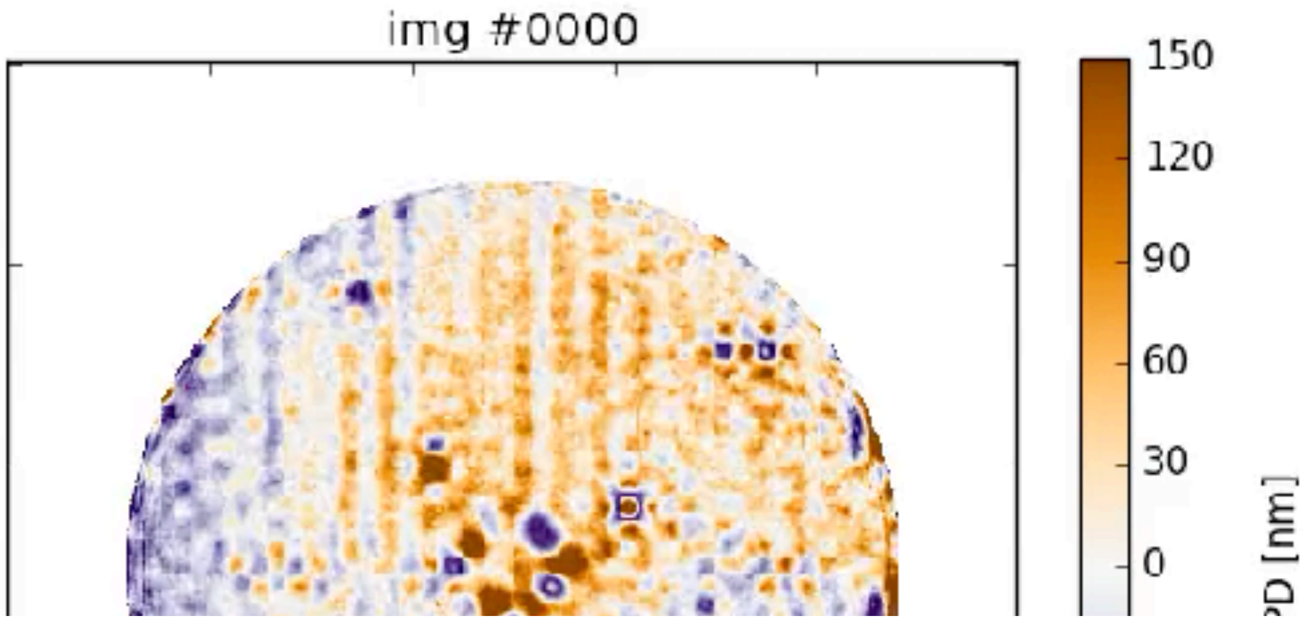
Internal turbulence is variable but affect all data sets

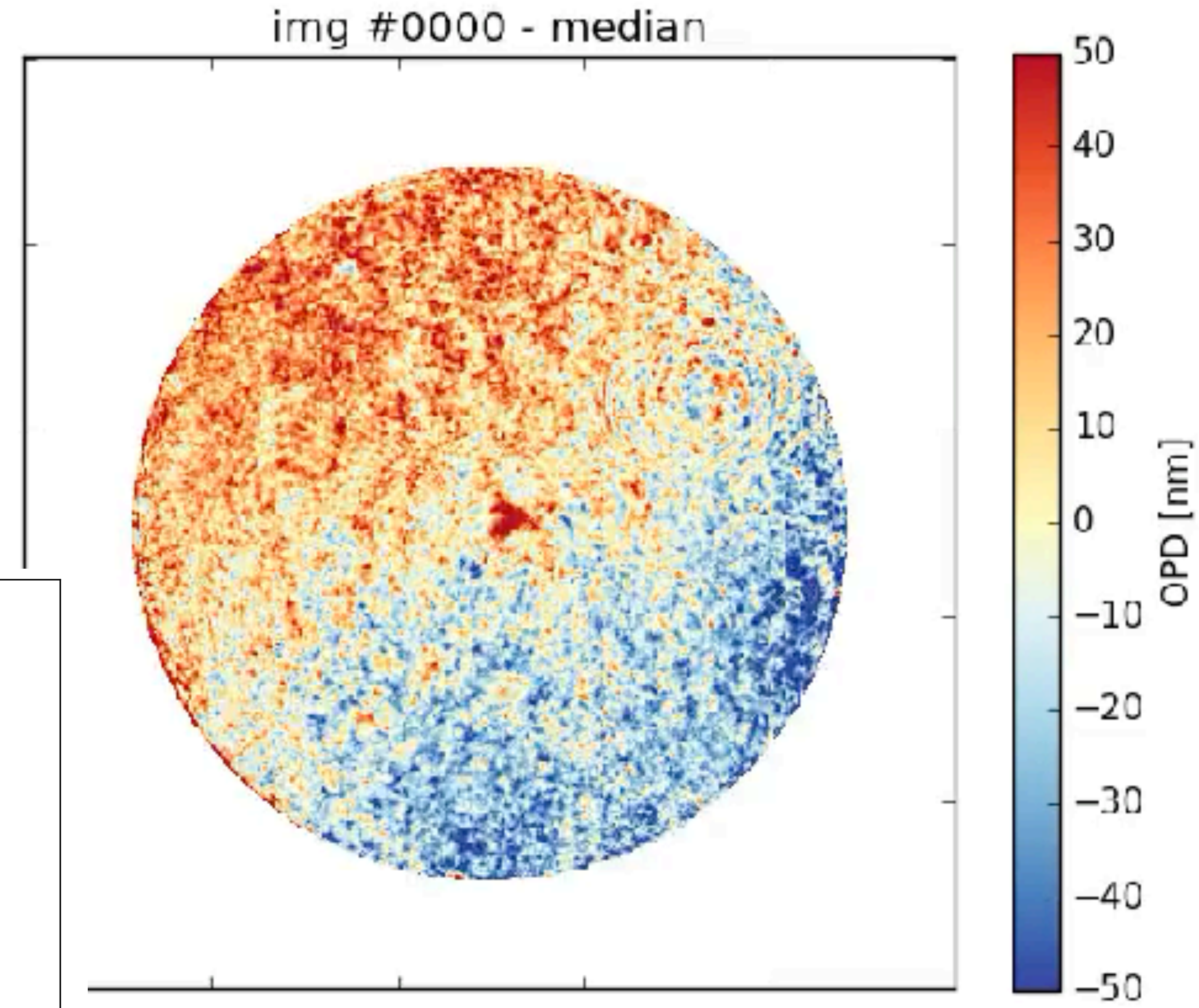
Origin of the turbulence?

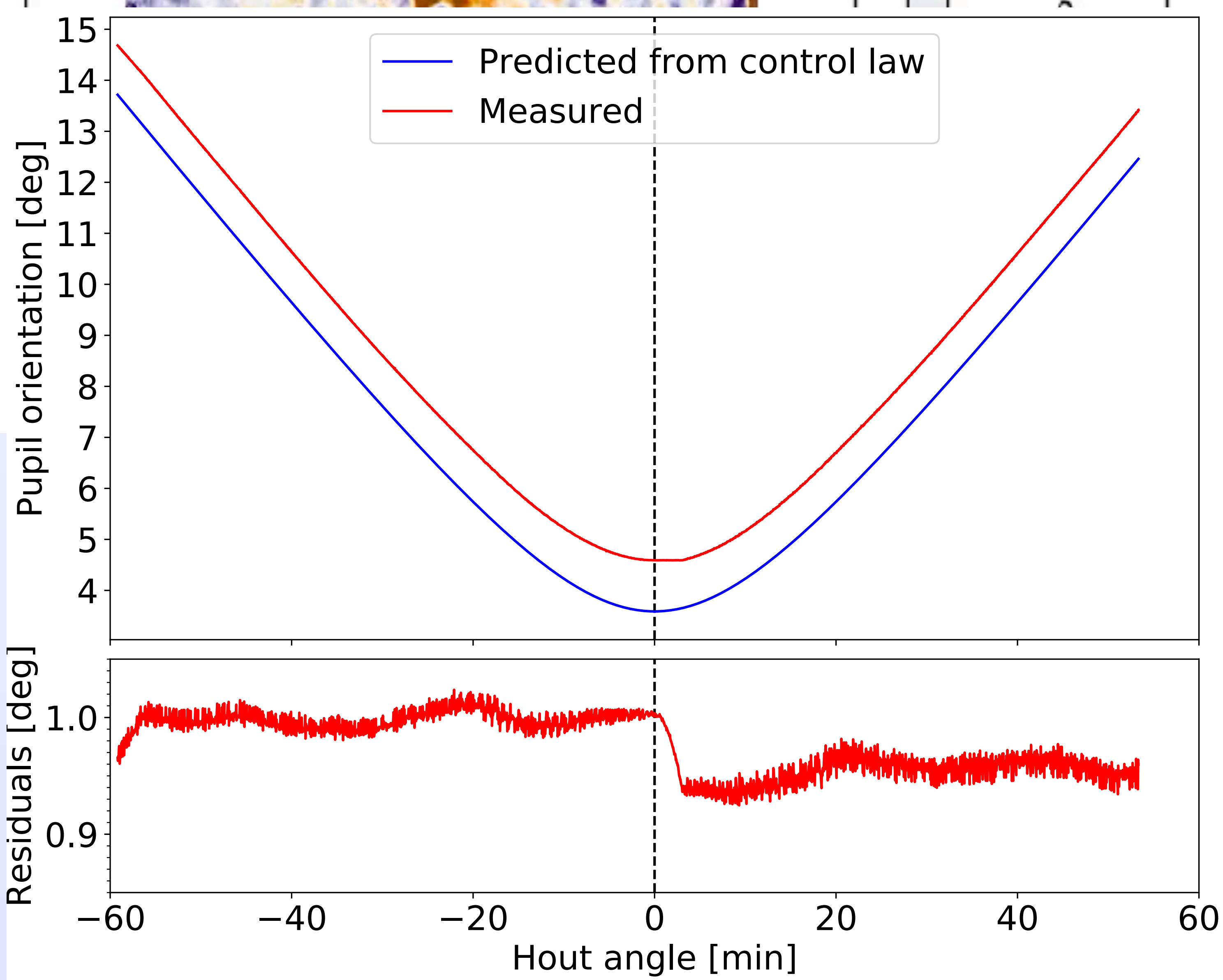


- Clean air supply
- Apodizer wheel motor

Impact of the derotator







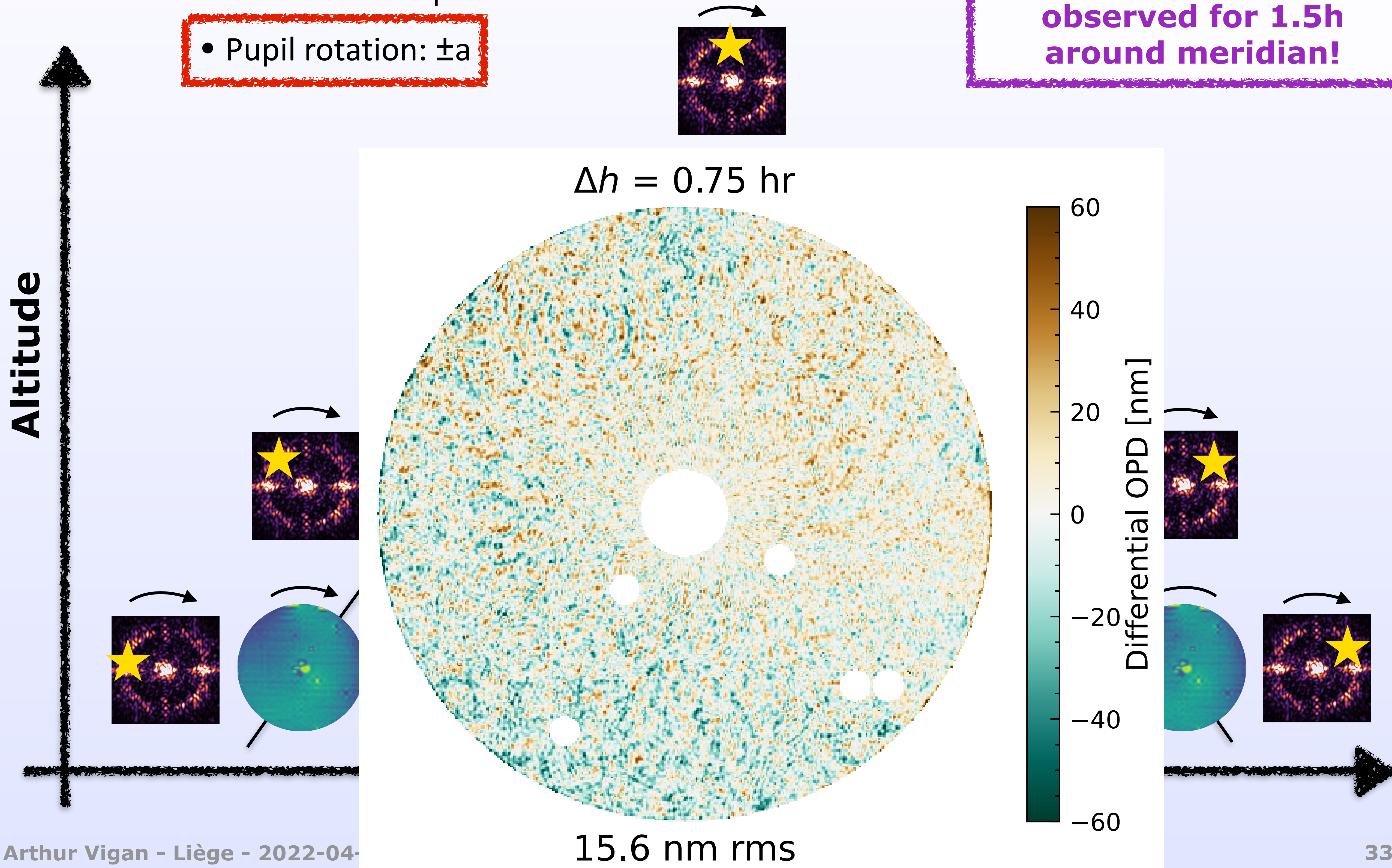
Detector backlash discovered with ZELDA

Rotation in pupil-stabilised sequences

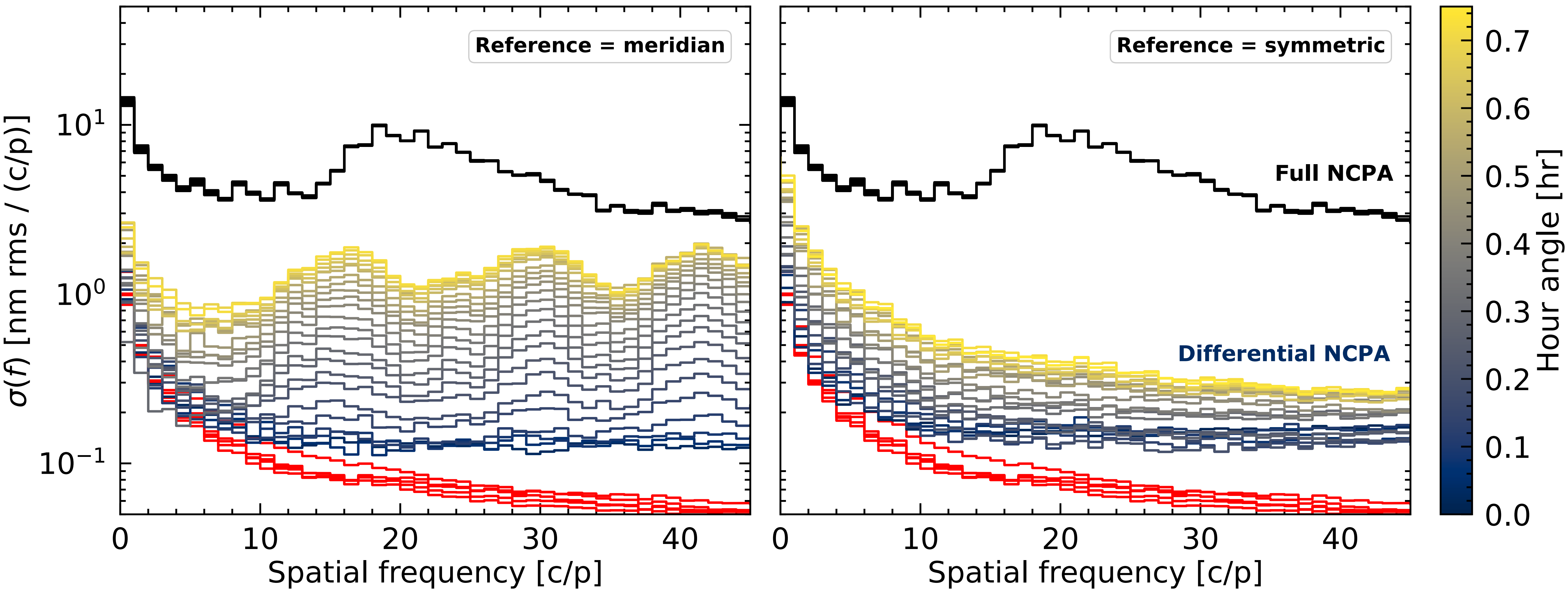
Nasmyth focus:

- Field rotation: p±a
- Pupil rotation: ±a

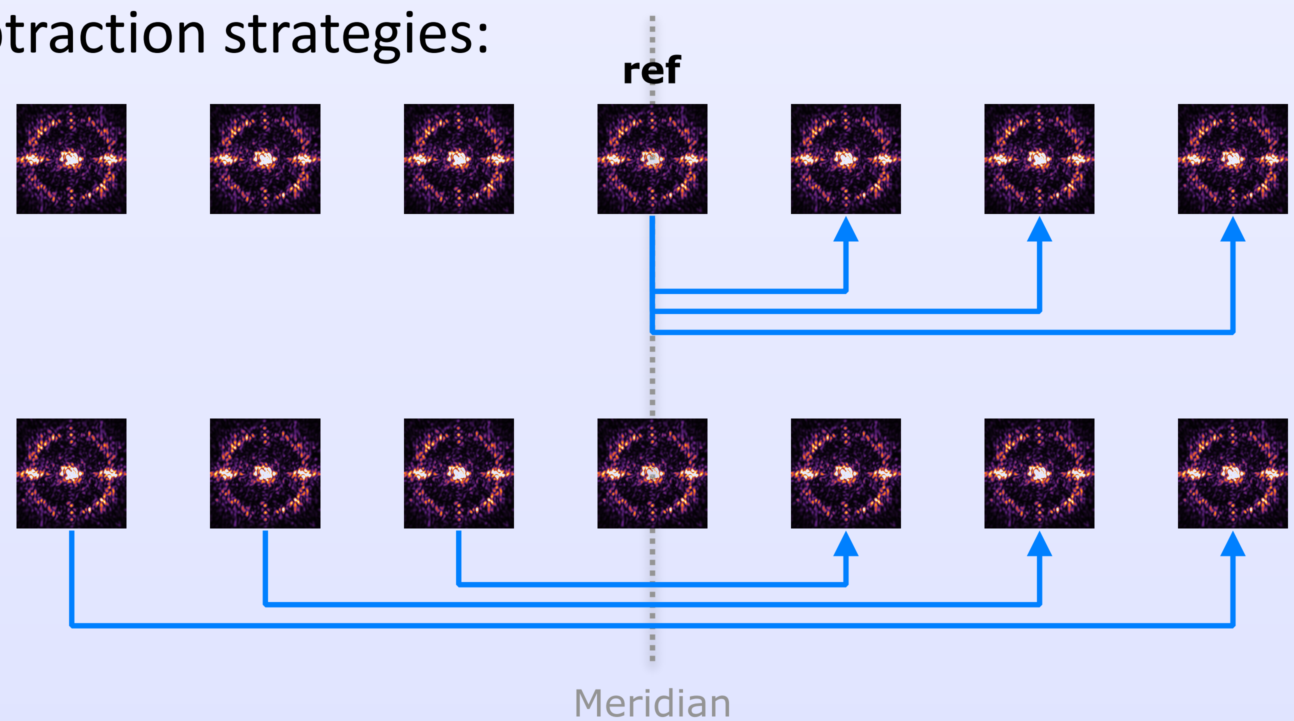
At most 4.5° for targets observed for 1.5h around meridian!



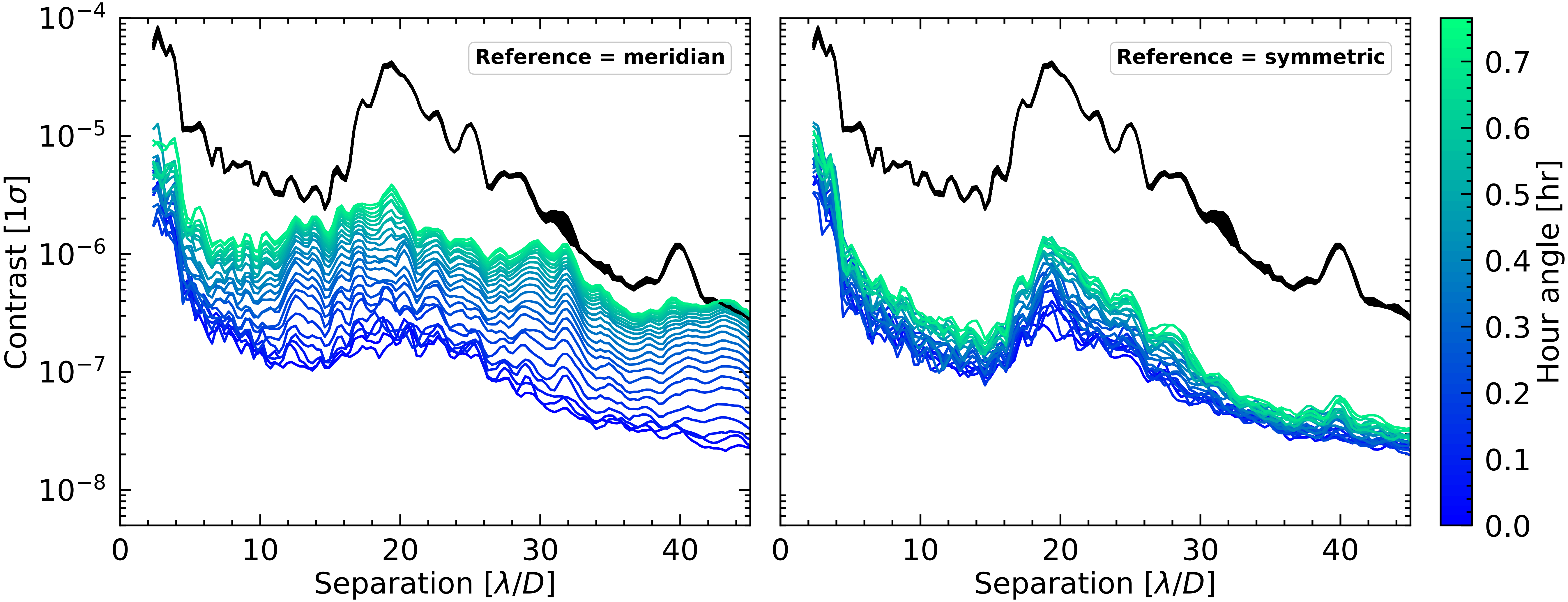
Impact on contrast in coronagraphic images



- Very basic ADI following two image subtraction strategies:
  - Subtraction of a single reference
  - Subtraction by symmetric pairs



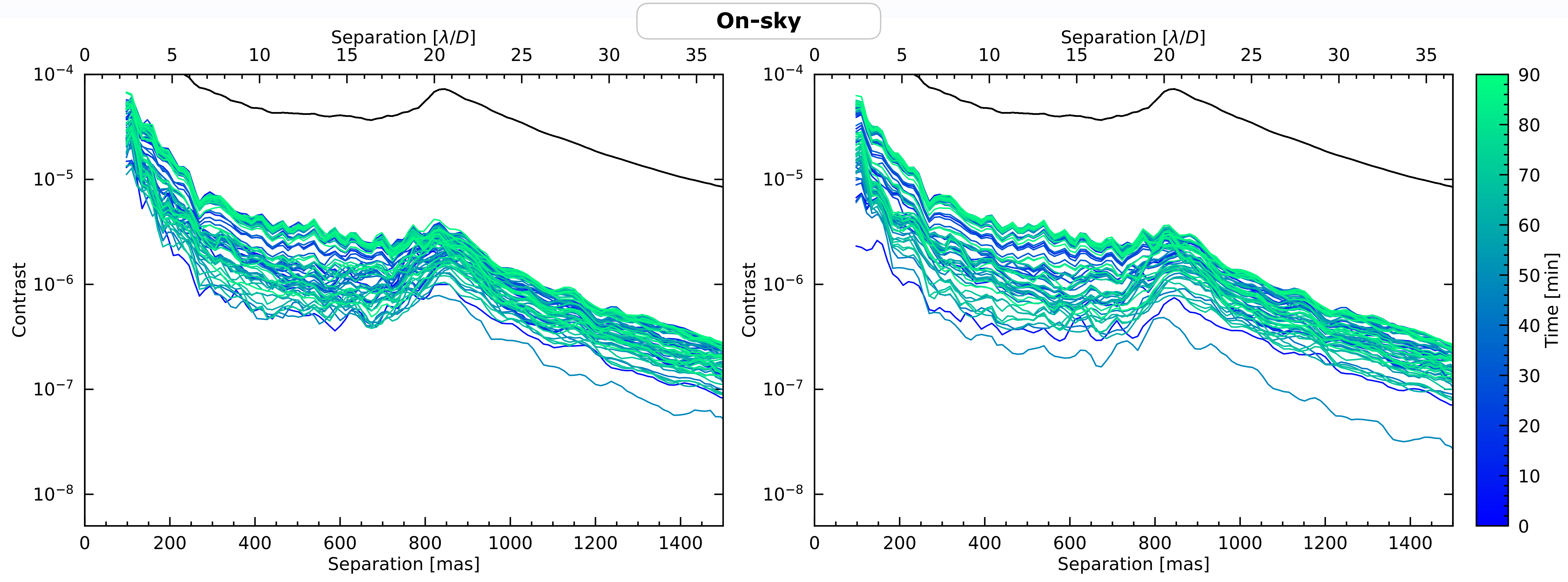
Impact on contrast in coronagraphic images



- Subtraction of symmetric pairs ➙ much smaller level of residuals
- Slow rise compatible with slow NCPA decorrelation timescales

First experimental demonstration of the importance of observations symmetric around meridian!

What happens with residual atmospheric turbulence?



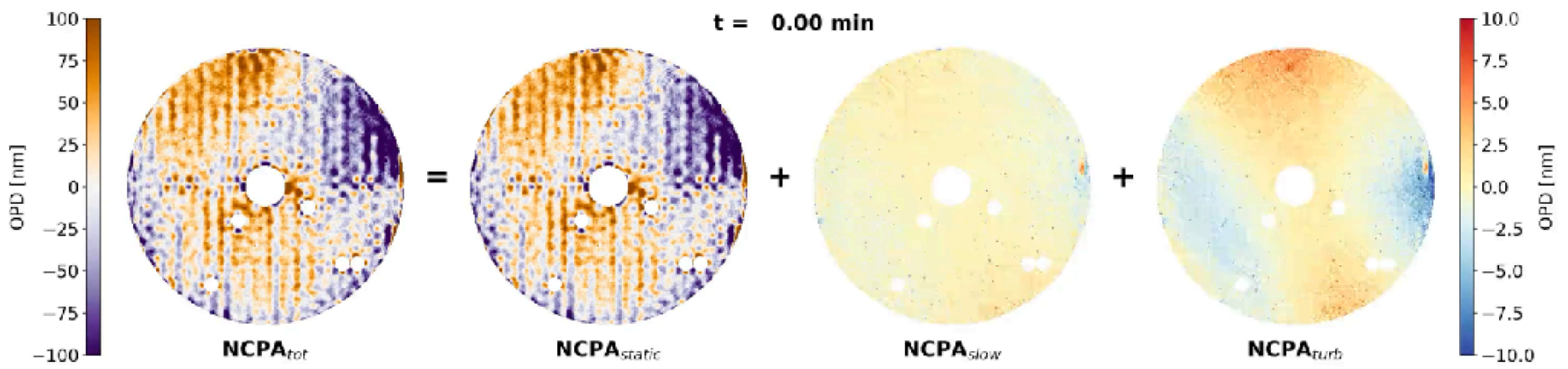
- Impact of residual atmosphere downstream of ExAO?
  - Simulation based on reconstructed SPARTA residuals

Residuals dominated by turbulence

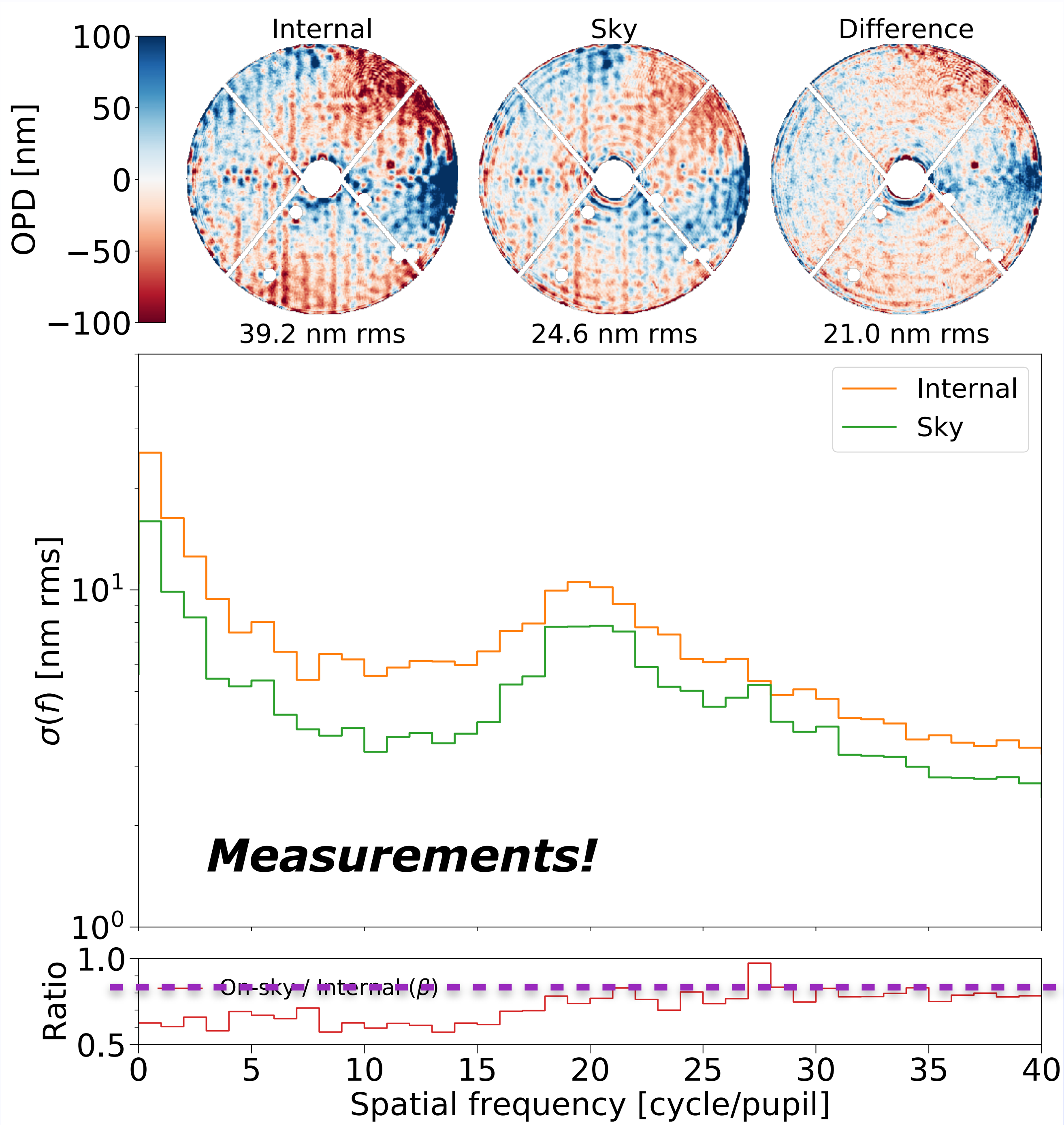
- Disappointing, but...
  - Fast and slow decorrelation detected on sky by Milli et al. (2016)
  - Upgrade of SAXO could change the game in the coming years!

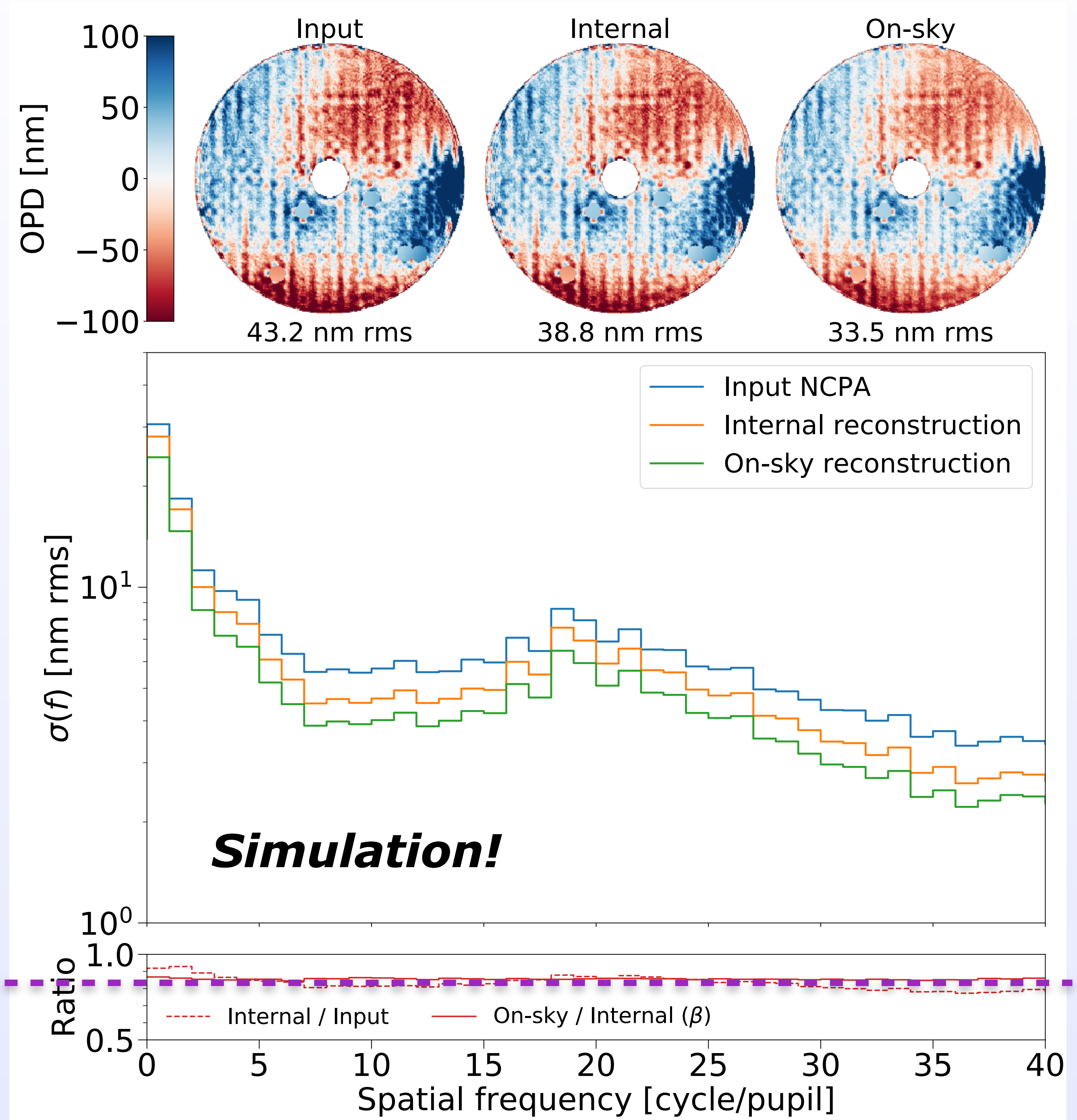
Conclusions & future work

- ZELDA is a powerful sensor for HCI
- Prototype in SPHERE has demonstrated:
  - NCPA calibration with manometric accuracy
  - NCPA compensation, internally and on-sky
  - Diagnosis of various effects in the instrument
- NCPA stability in SPHERE is currently limited by internal turbulence
- Slow NCPA variations are of the order of a few 0.1 pm rms/s
- Internal turbulence not a major limitation on-sky, but could become one with SAXO+
  - Important to develop a hardware mitigation for SPHERE+!



Optical gains and on-sky reconstruction





- Internal and on-sky reconstructions do not match
- Likely related to Strehl variations ➙ optical gains of the sensor (Chambouleyron et al. 2020)