GRD

R&D Optics & Instrumentation

Wavefront control for direct detection and characterization of exoplanets

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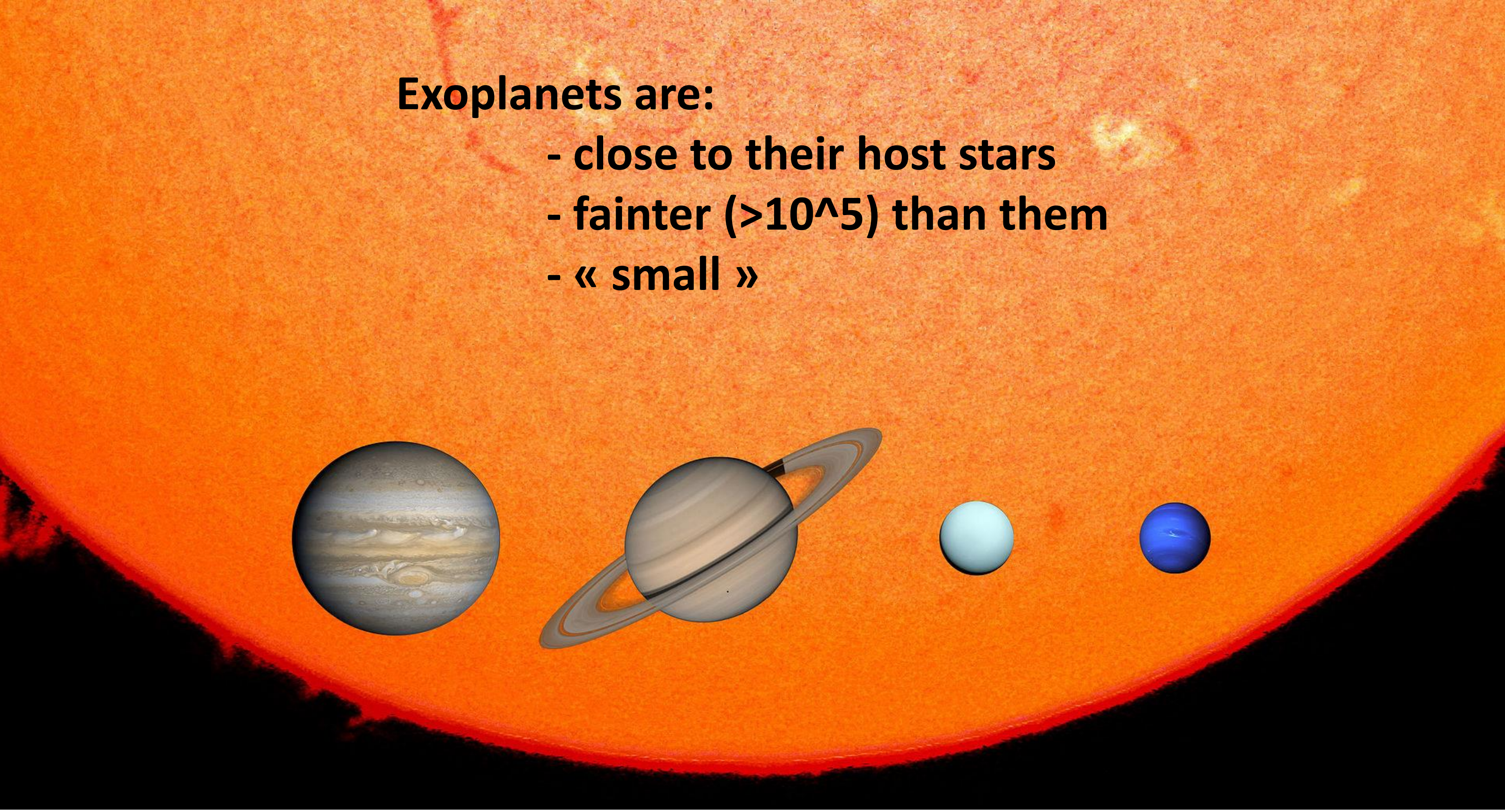
École Centrale Marseille

Marseille, LAM, Thursday, September 13th, 2018

Summary

- Introduction: Exoplanets, High contrast, limitations



The sun and the four bigger planets of the solar system (Wikipedia)

So how to directly see them ?

Context in Optics

Direct Imaging of Exoplanets:

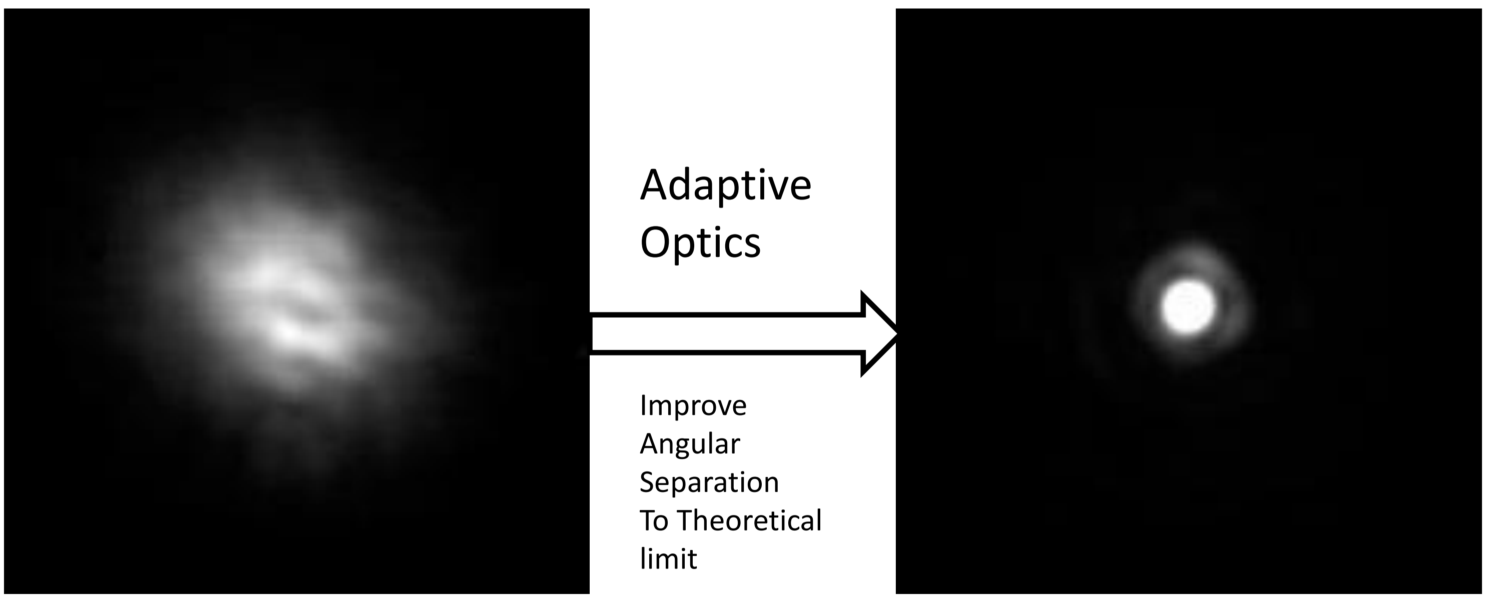
Requirements:

- High angular resolution
- High contrast

Solutions (today):

- Adaptive optics
- Coronagraphy

@VLT
Seeing = 1000 mas
Theoretical Res. K-Band
θ = 60mas



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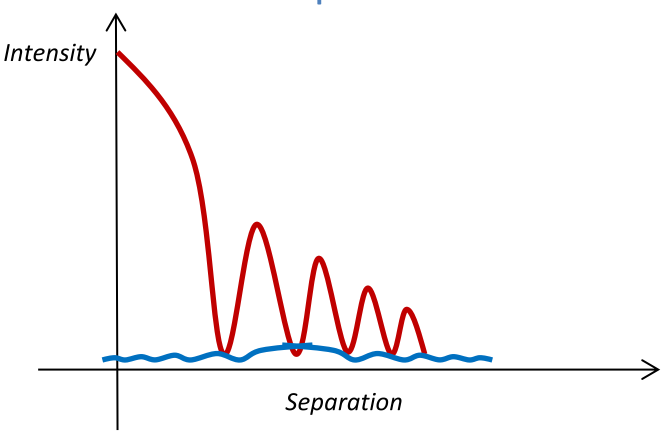
- Coronagraphy: diffraction suppression

Contrast enhancement:
10^4 to 10^5
Long-term Objective:
Up to 10^9

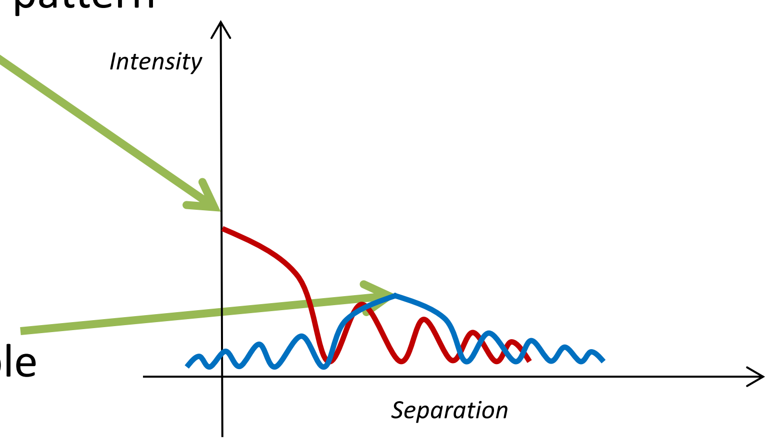
Saturated PSF
+ Exoplanet



Suppressed
diffraction pattern

Coronagraphic Image

Detectable



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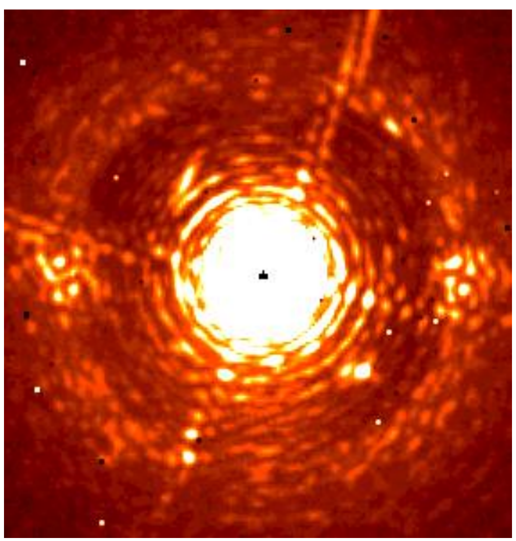
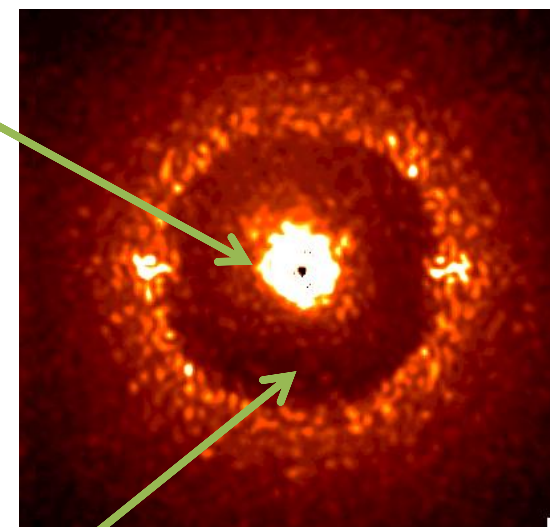


Coronagraphic Image

No diffraction pattern



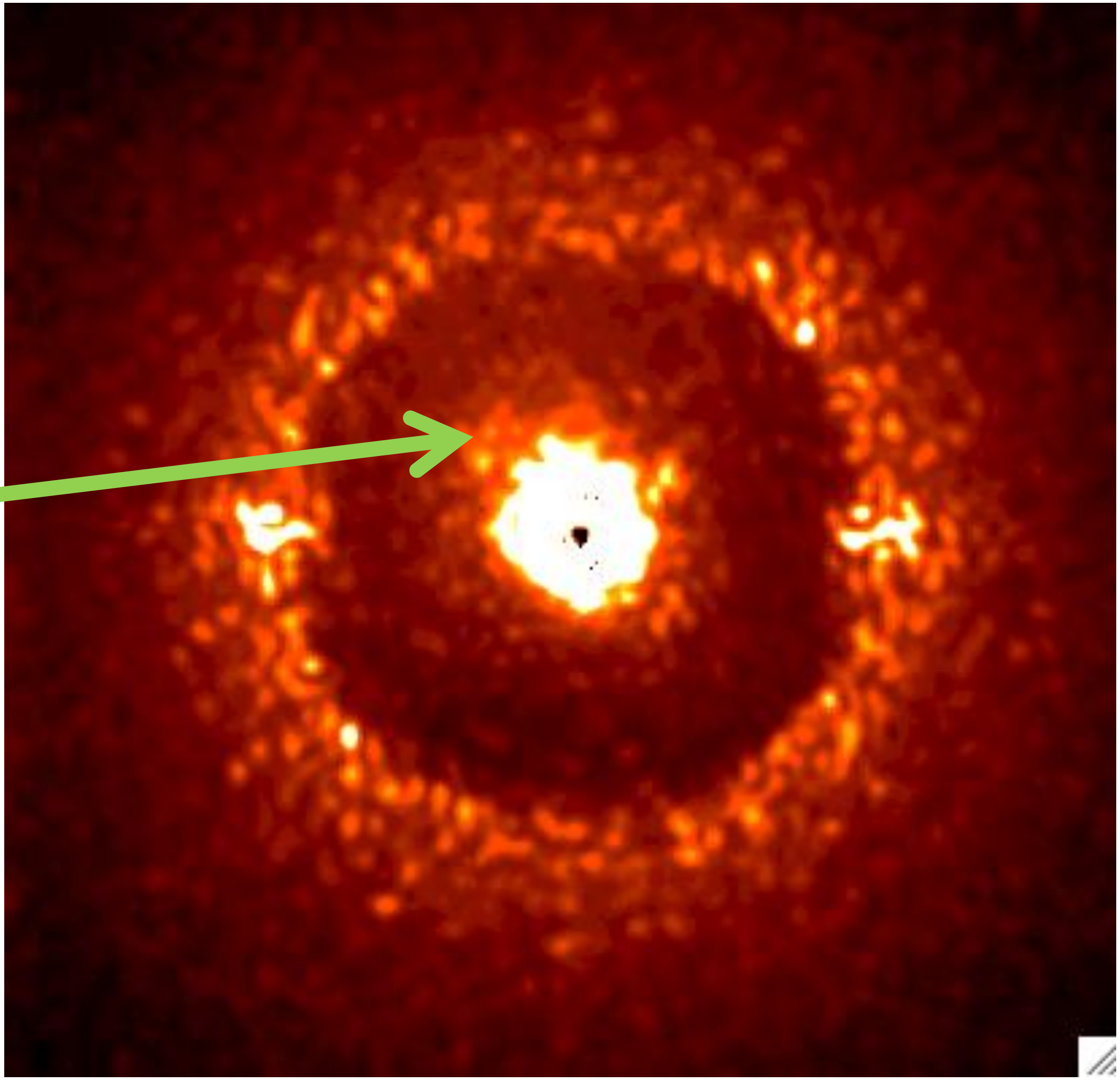
10^5 in contrast

Coronagraphy limitations: speckles

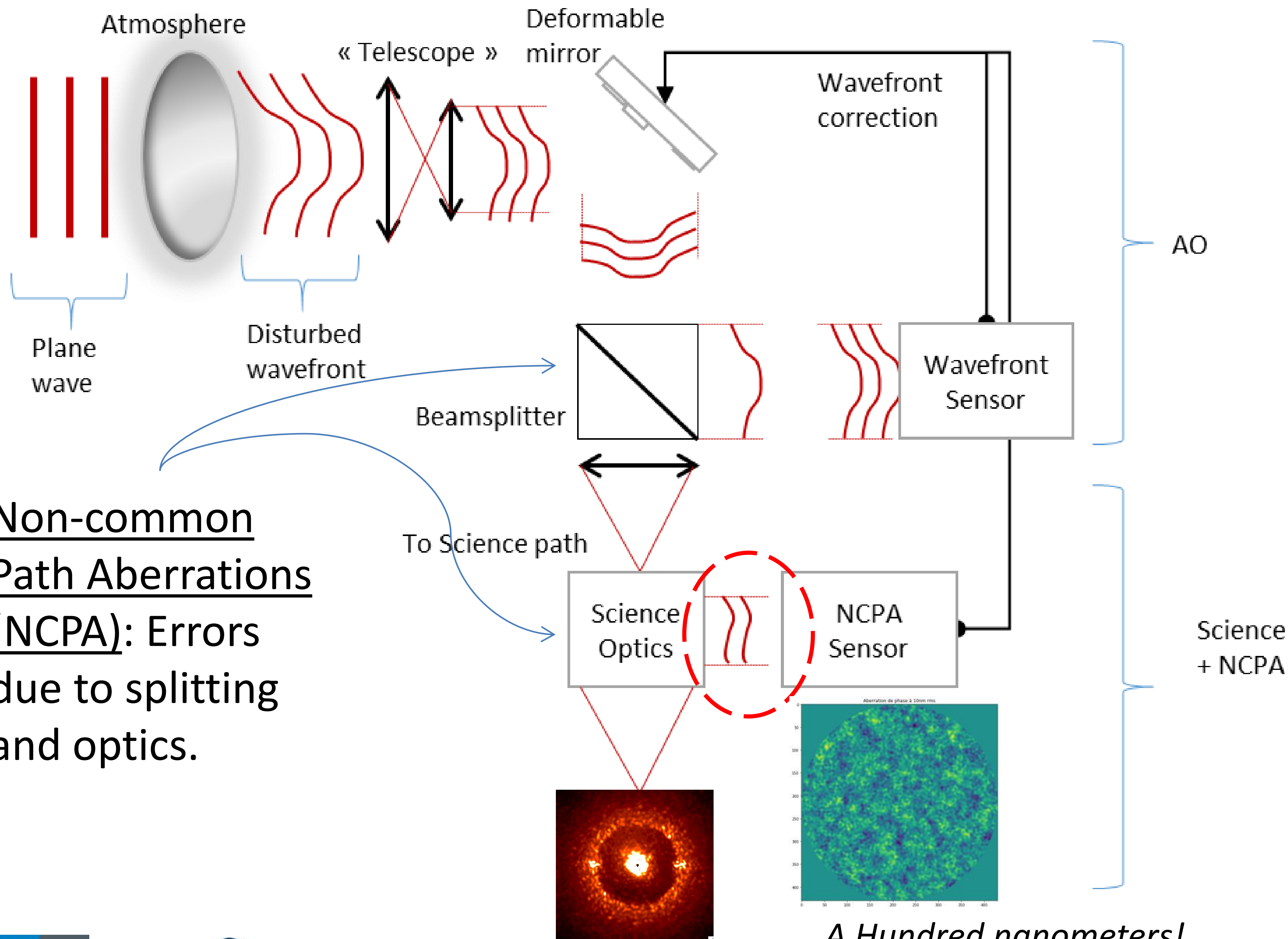
Quasi-static speckles having characteristic size are causing false detection

And

Disturb the maximum contrast



Coronagraphy limitations: speckles caused by NCPA



Non-common Path Aberrations (NCPA): Errors due to splitting and optics.

A Hundred nanometers!

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- ZELDA: Fine aberrations Wavefront sensor
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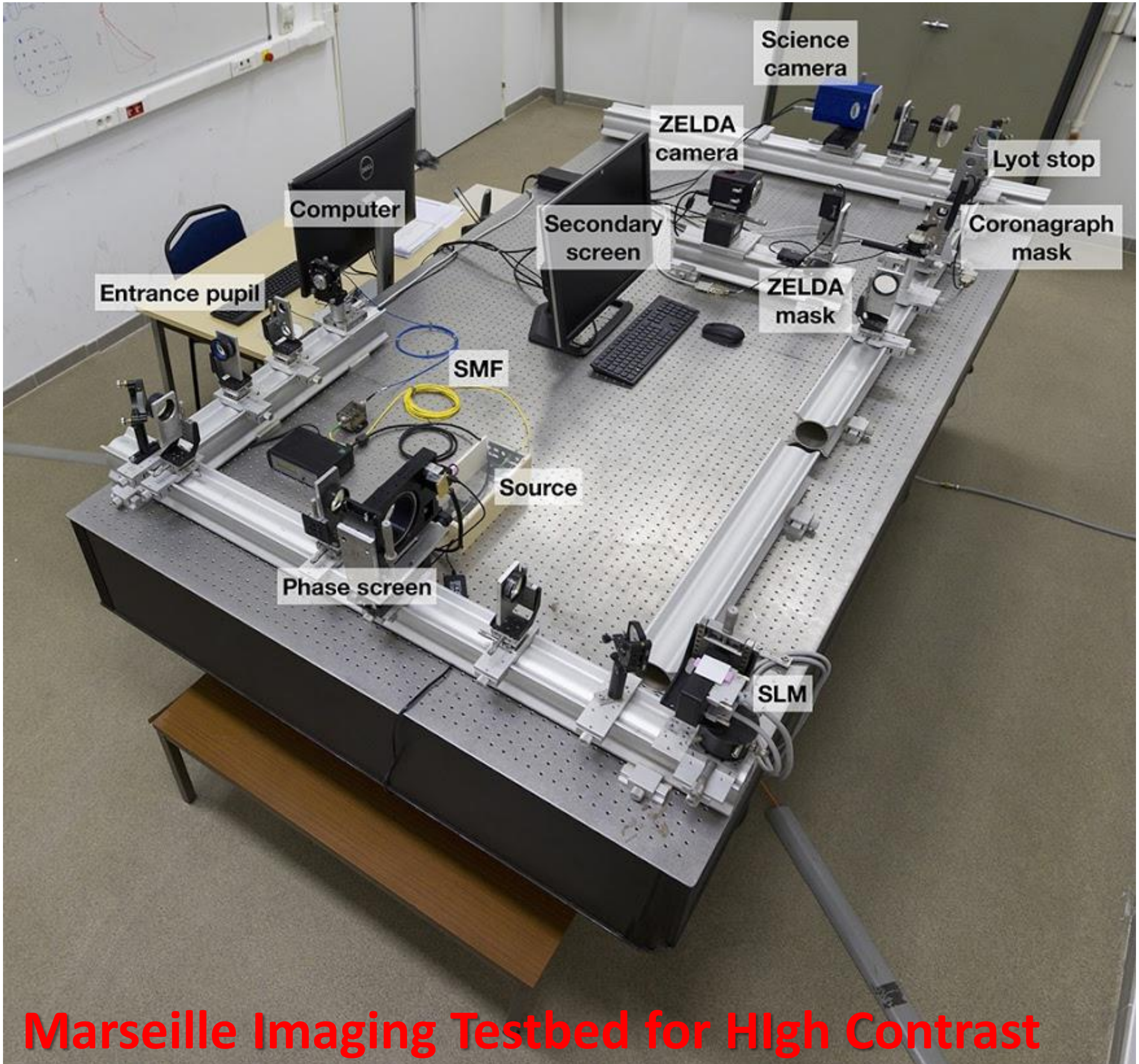
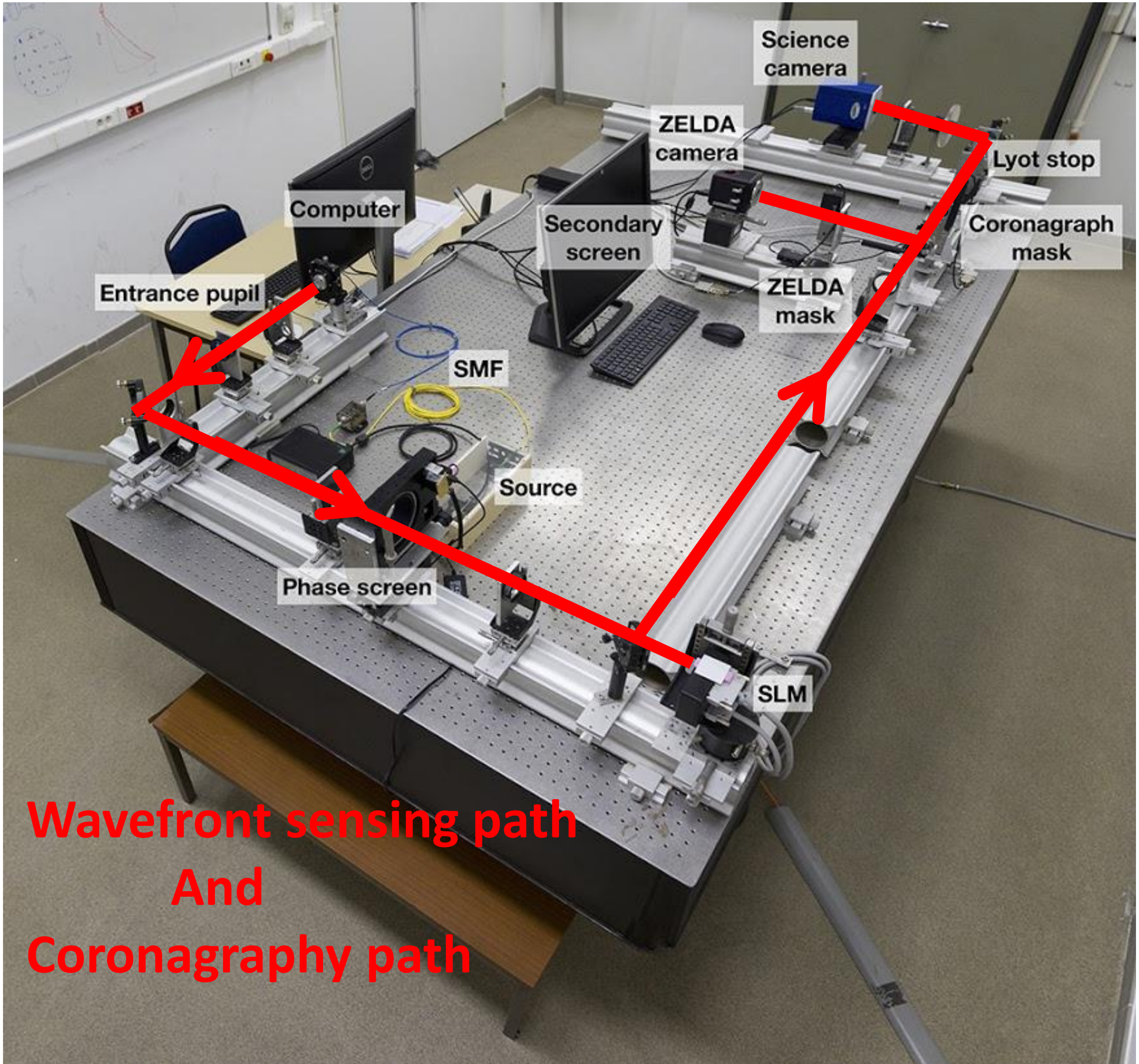
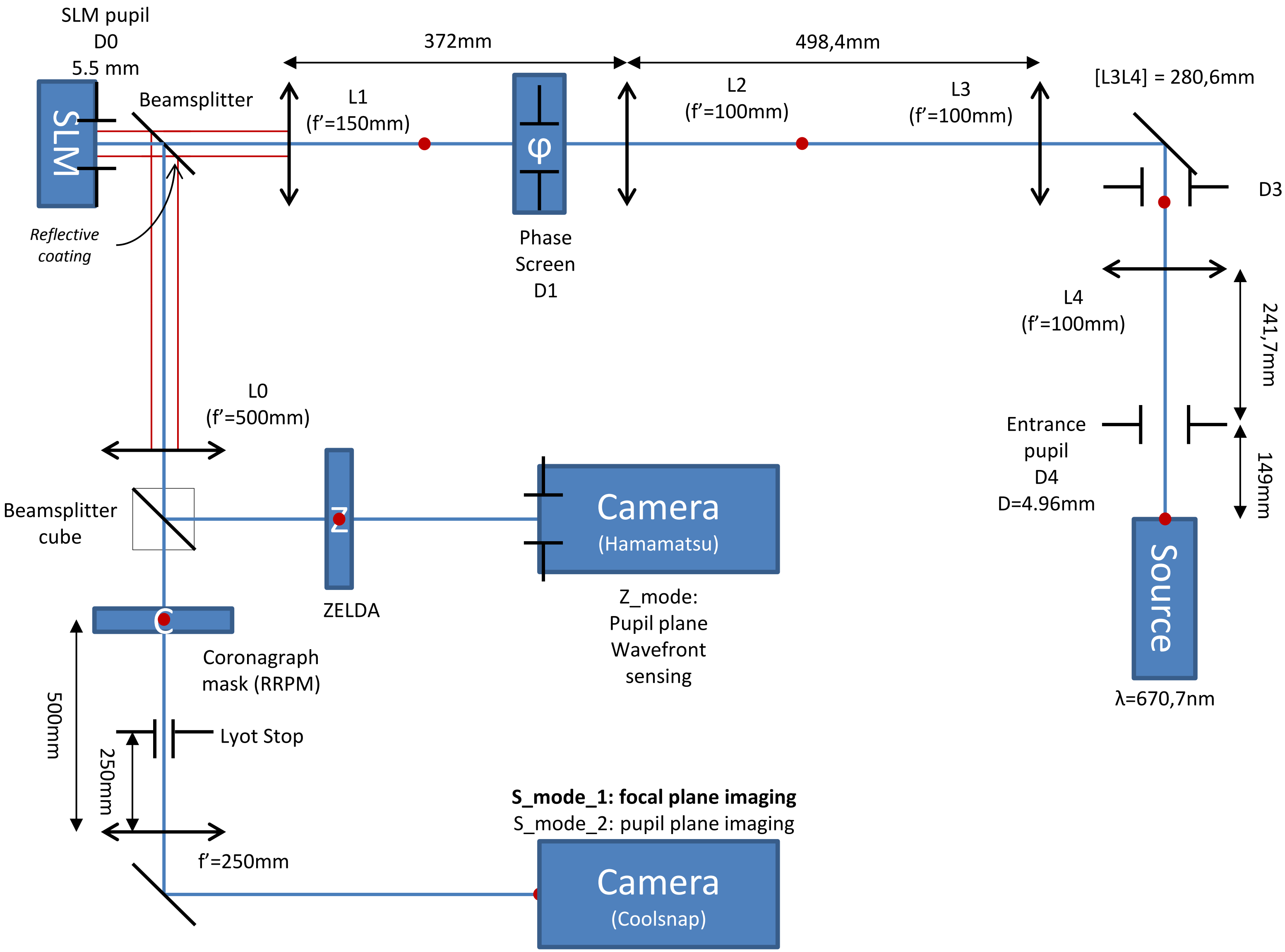


Marseille Imaging Testbed for HIgh Contrast


Science camera
ZELDA camera
Lyot stop
Computer
Secondary screen
Coronagraph mask
Entrance pupil
ZELDA mask
SMF
Source
Phase screen
SLM
Wavefront sensing path
And
Coronagraphy path

MITHIC: Marseille Imaging Testbed for HIgh Constrast

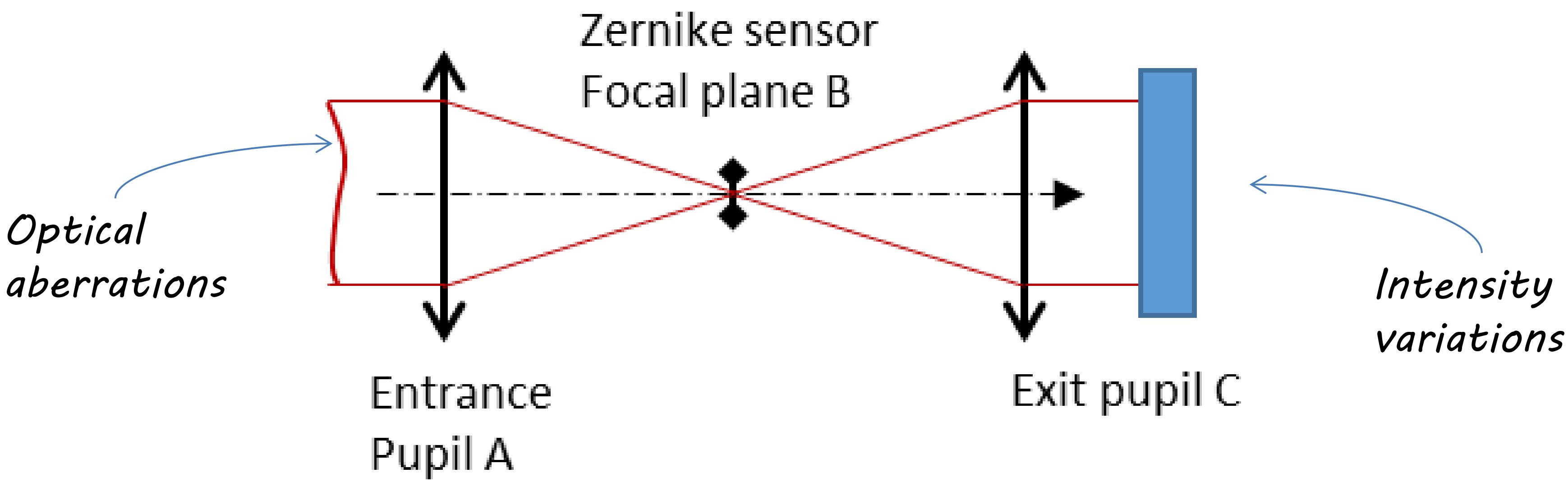


ZELDA: Zernike sensor for Extremely Low-level Differential Aberrations

Developed at LAM (N'Diaye, 2013), tested on SPHERE (N'Diaye, 2016; Vigan, 2018)

NCPA sensor

Transform ***phase variations*** into ***intensity variations***

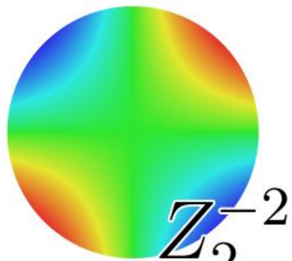


Type	Geometry	Physical parameters	Chromaticity ?	Phase reconstruction
Phase sensor	Polar (r,θ)	Piston $\delta = \frac{\lambda}{4}$ Radius $r_Z \approx 0{,}5\,\frac{\lambda f}{D}$	Yes (double)	Linear, Quadratic (chosen)

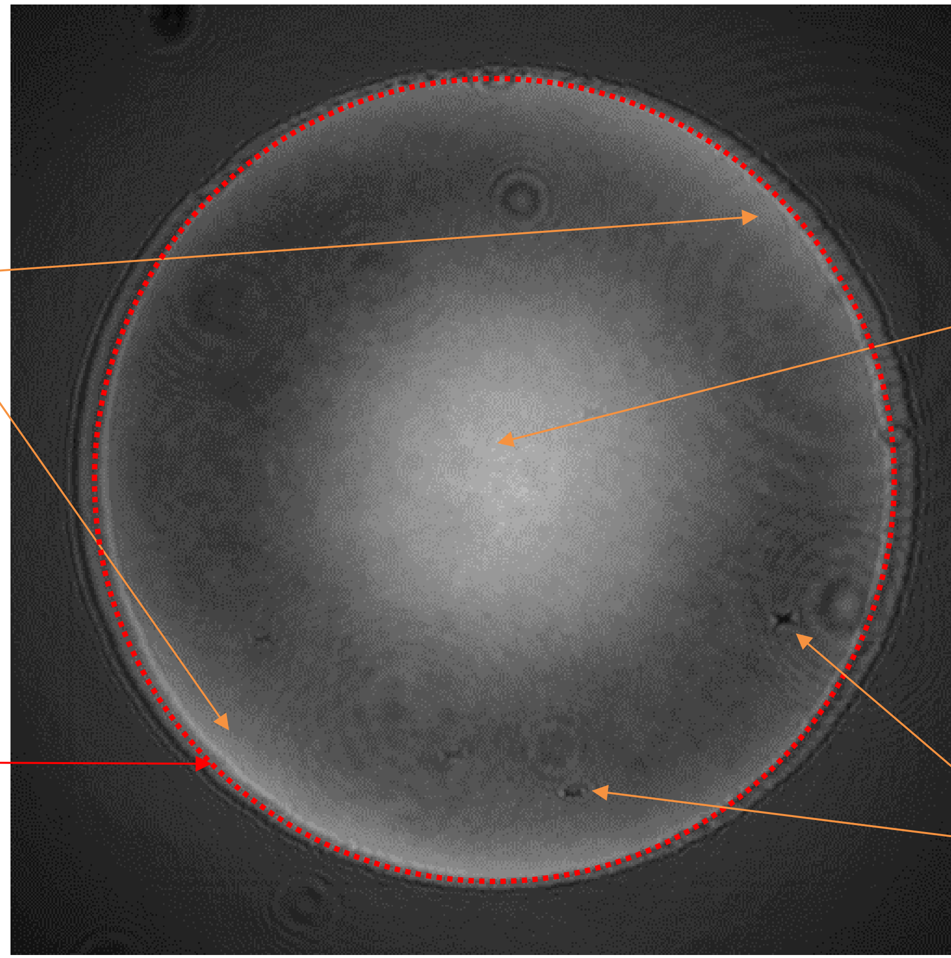
We will refer to optical path difference *d* instead of the phase: $\varphi = \frac{2\pi d}{\lambda}$

ZELDA: Zernike sensor for Extremely Low-level Differential Aberrations

Example of NCPA: typical optical bench aberrations

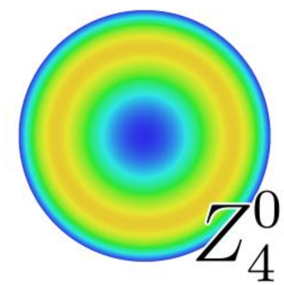


Astigmatism



Spherical aberration

(-1) x



Quantity of aberrations:
σ = 35,1nm

Measurement of σ :
Encircled pupil

Dust

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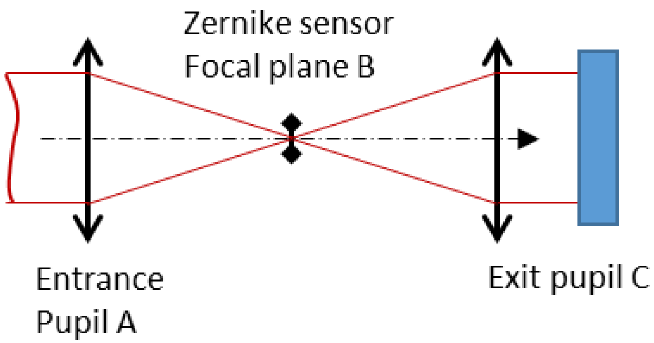
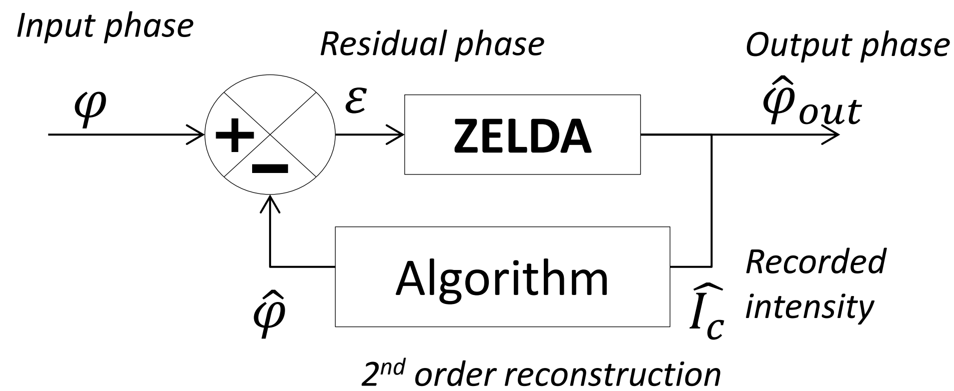
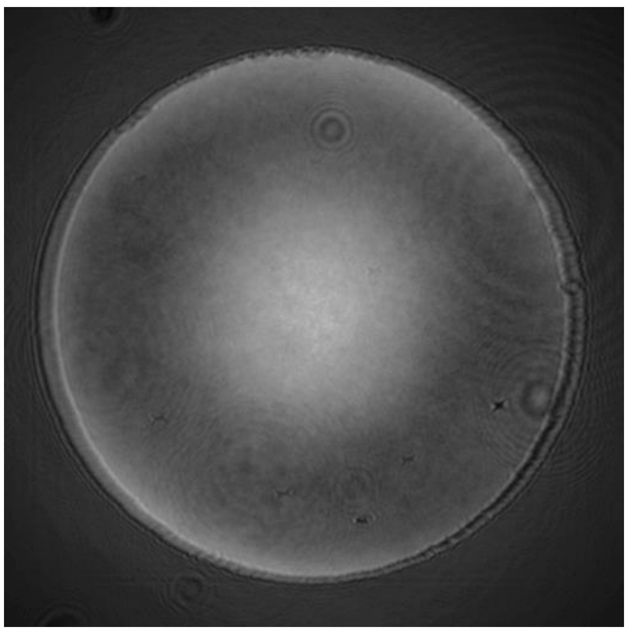
Results (1): global functionning of the WF correction



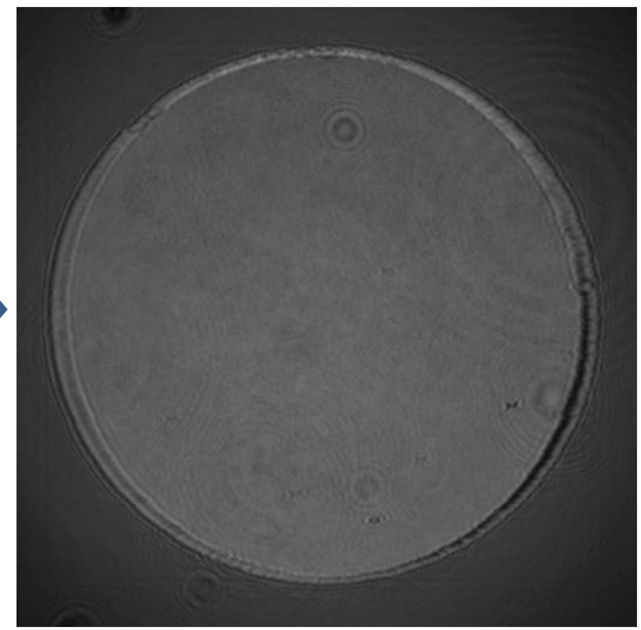


Input WF

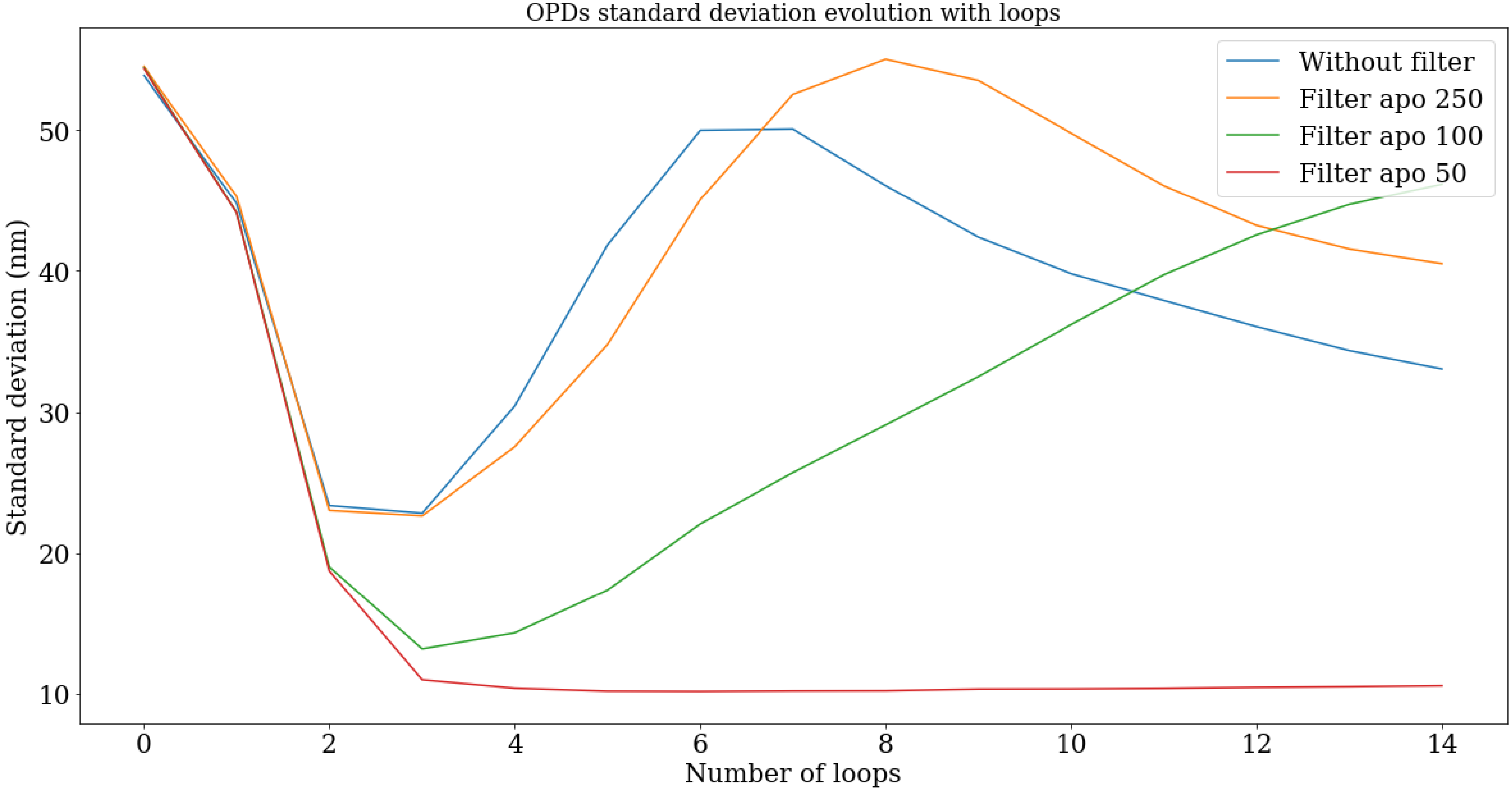


3 iterations

Flat WF

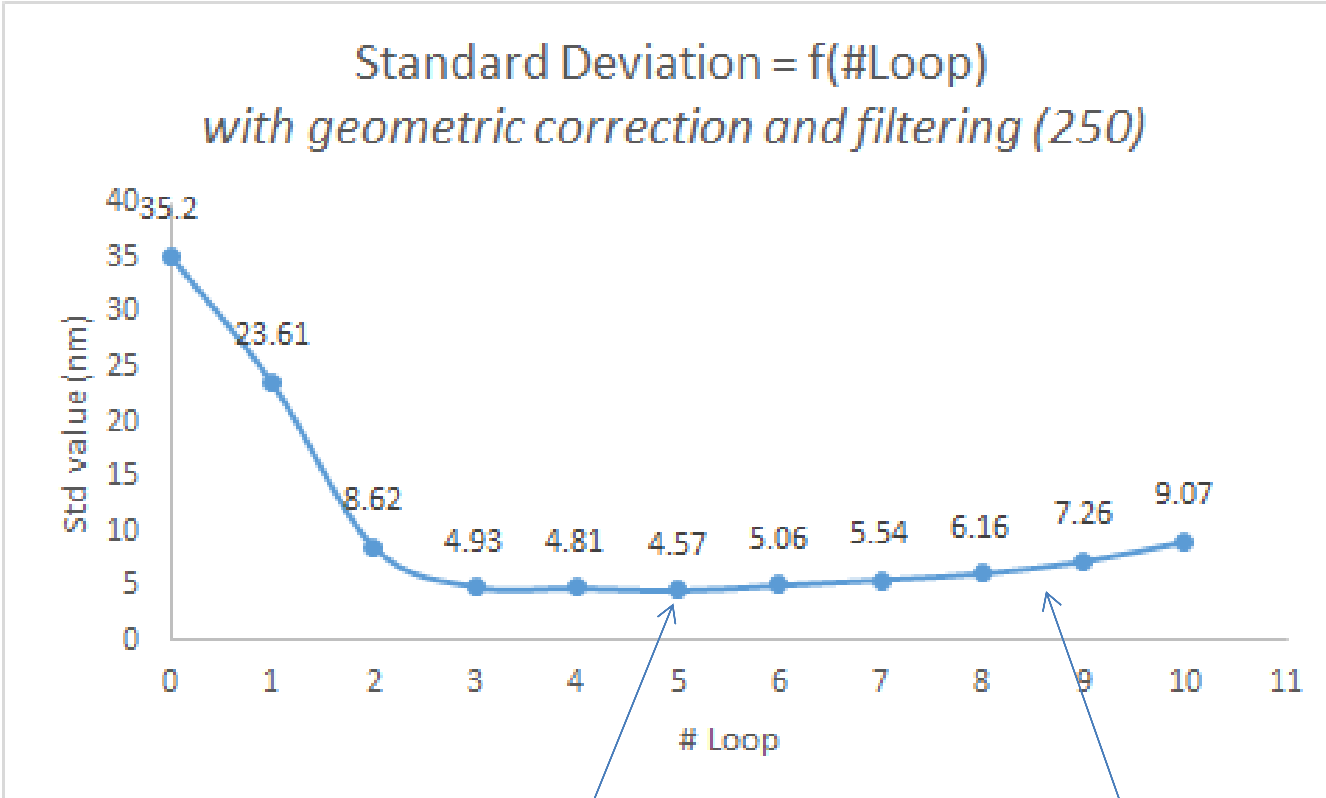


Results (2): 2017 (R. Pourcelot, LAM)



+ Introduction of **apodized filter** for a better correction(up to275 cycles/pupil -> anti-aliasing)
Observation of a divergence in non-highly filtered cases (green, orange, blue curves)
σ(2017) --> 10 nm (low cutoff frequency → did not correct all spatial frequencies)

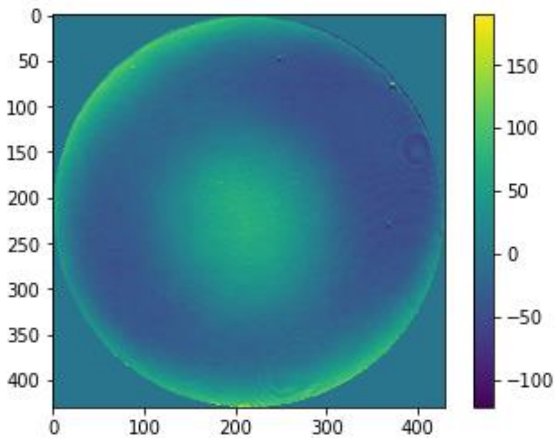
Results (3): mid-2018



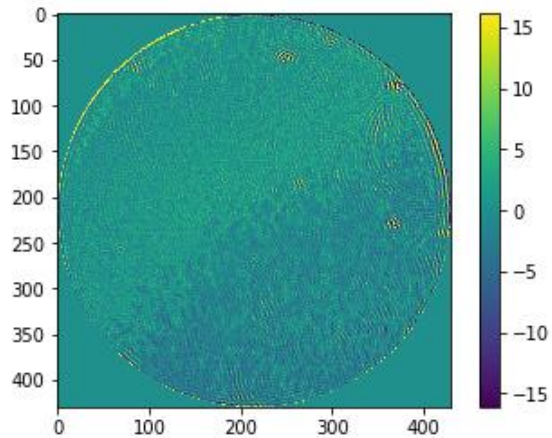
Good drop down to σ(m-2018) = 5nm with low filtering (250/275) , but divergence
+ Correction of geometrical distortion of the pupil (due to lens, SLM…)
by a least-square optimisation method

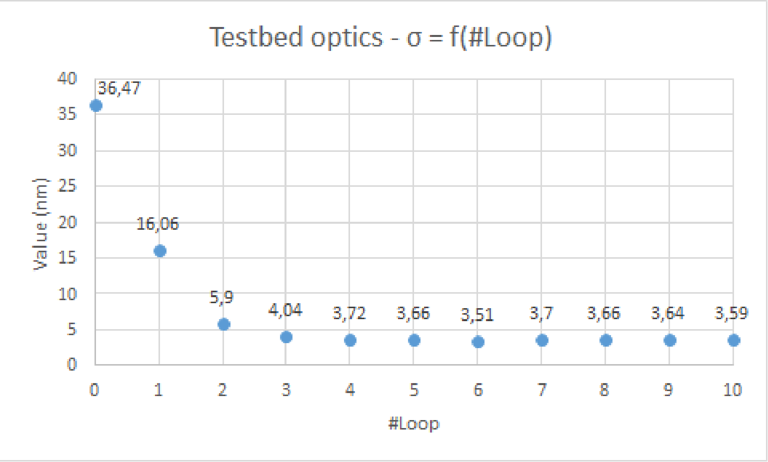
Results (4): August/September 2018

Input WF « natural » bench



Flat WF





Nanometers scales

Results (4): August/September 2018

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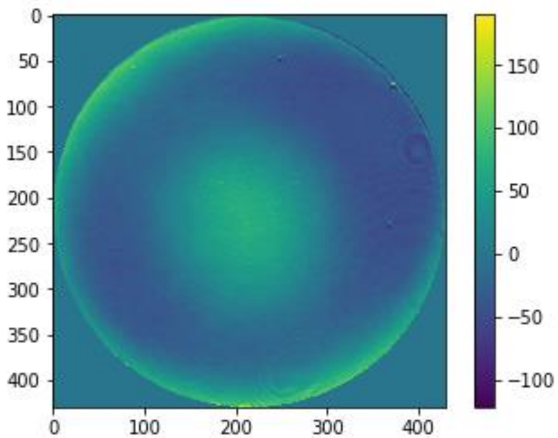
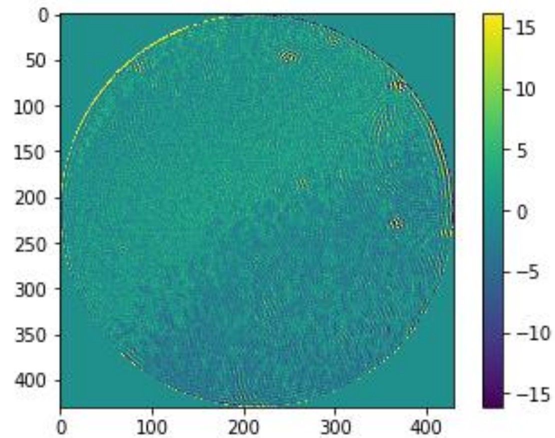
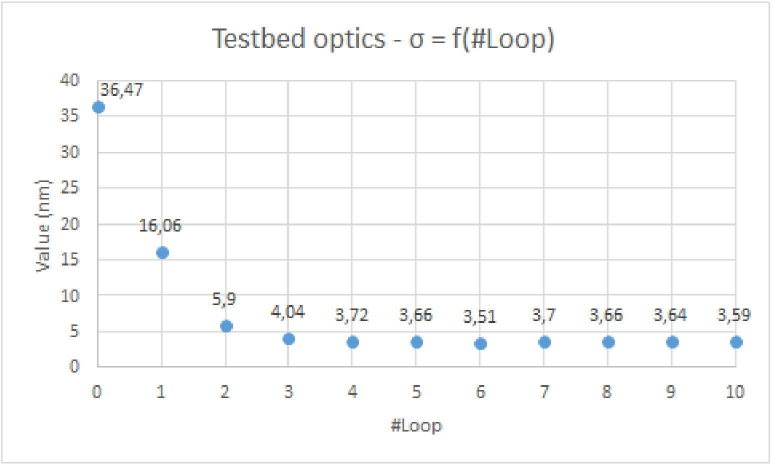
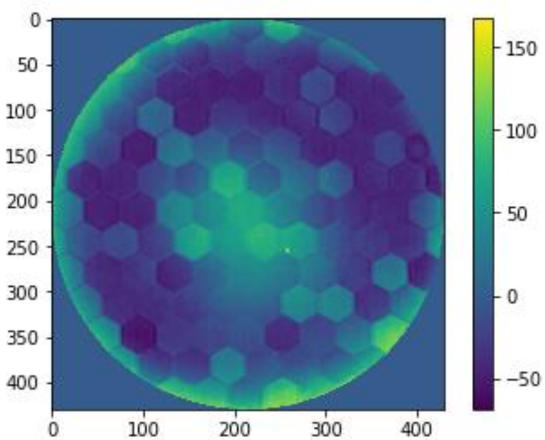


Flat WF

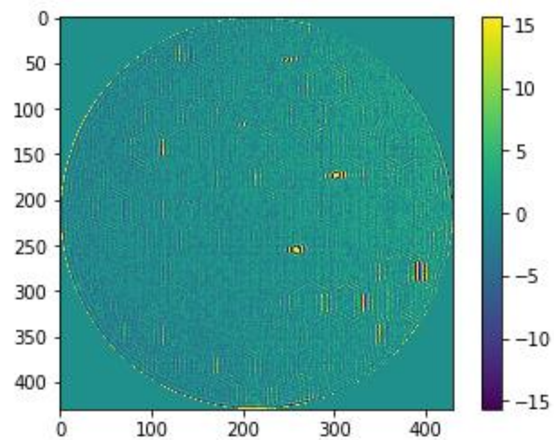


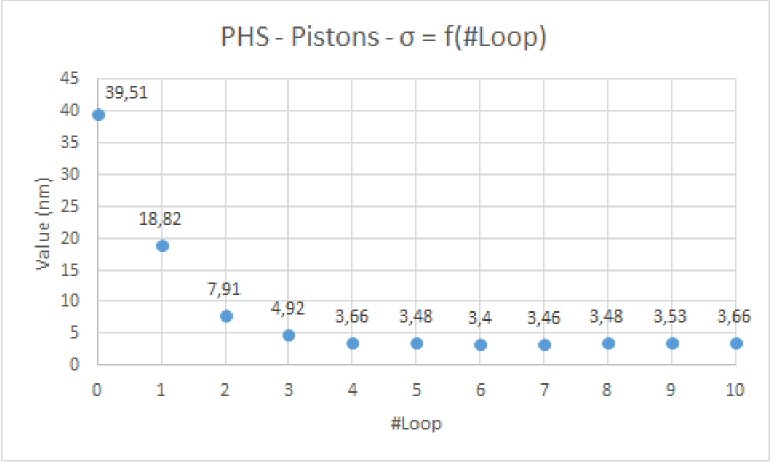


Input WF « hex pistons + bench »



Flat WF (dusts)





Nanometers scales

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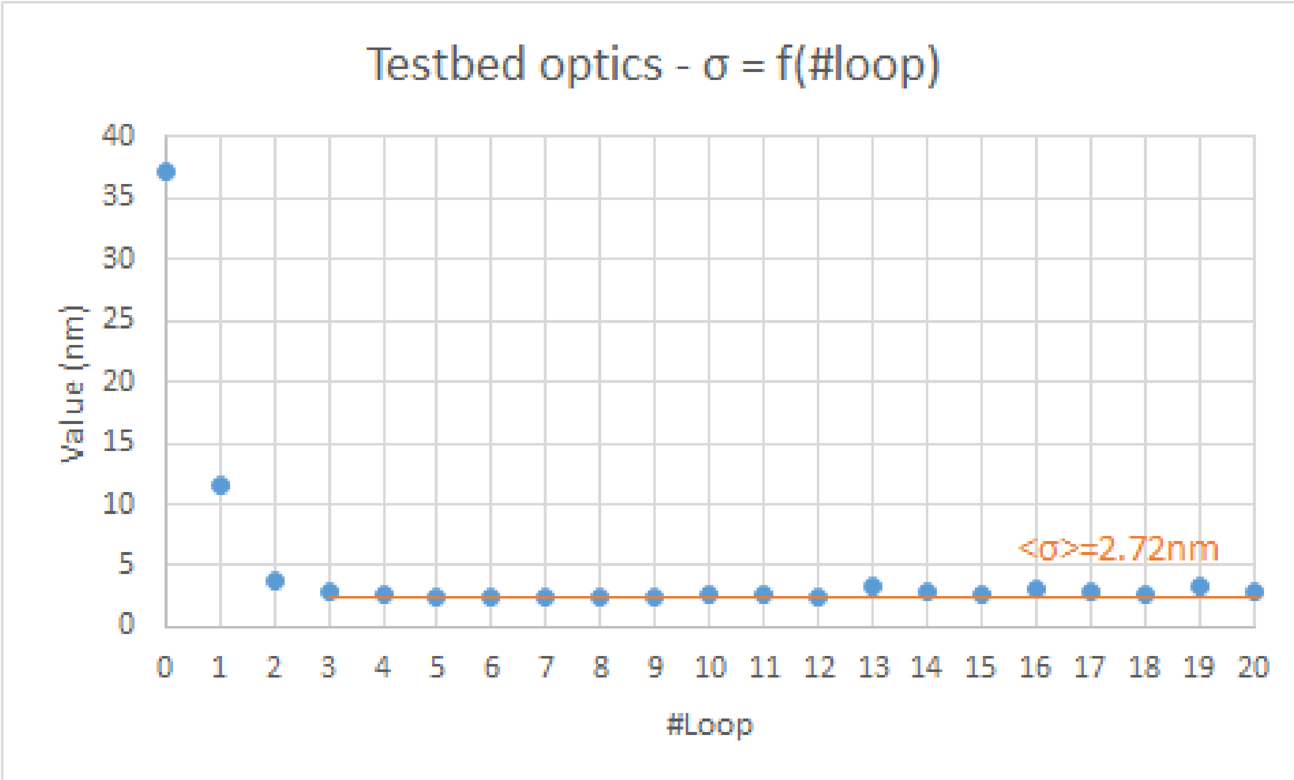

+ Low filtering (high cutoff frequency), here 250/275
+ Geometrical distortion correction
+ *6σ-clipping* (cutting dust)

--> <u>Top performance:</u> reaching plateau below σ(2018) = 3nm (λ/200)

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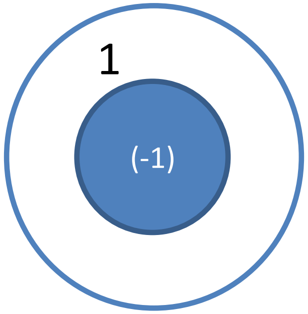
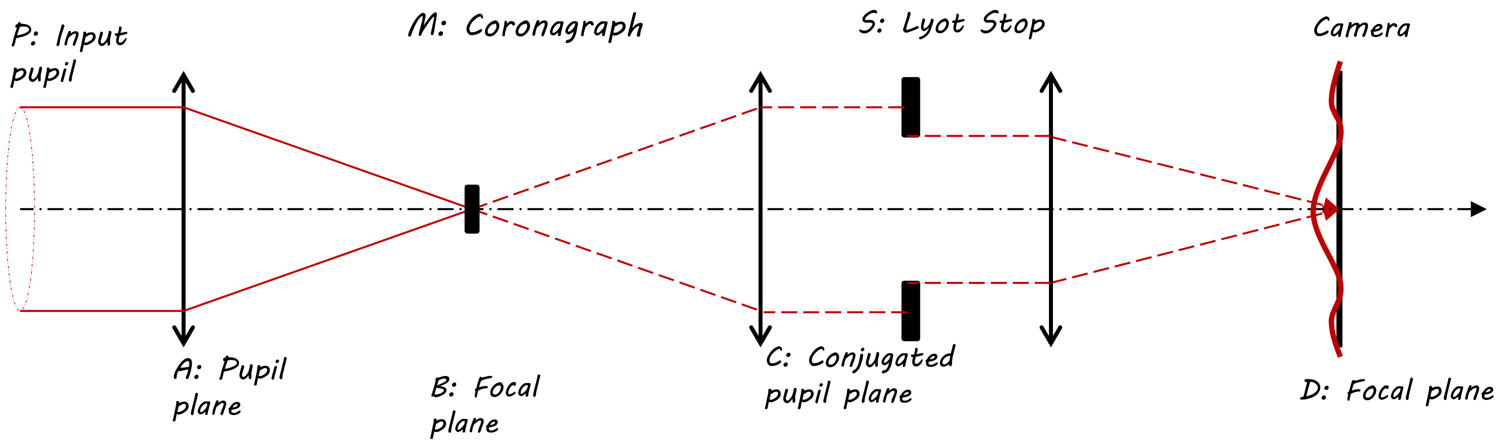
Coronagraphy



<u>Mask used</u>: Roddier-Roddier Phase Mask (RRPM)
(Roddier & Roddier, 1997), (N'Diaye, 2010)

<u>Lyot Stop size</u>: 90% of the input pupil

Type	Geometry	Physical parameters	Chromaticity ?
Phase mask	Polar (r,θ)	Piston $\delta = \frac{\lambda}{2}$ Radius $r_{RRPM} = 0{,}53\,\frac{\lambda f}{D}$	Yes (double)



<u>Simulation expectation:</u> 10^3 extinction @670,7nm @90%Pupil @3nm WF

Coronagraphy: 2018 results

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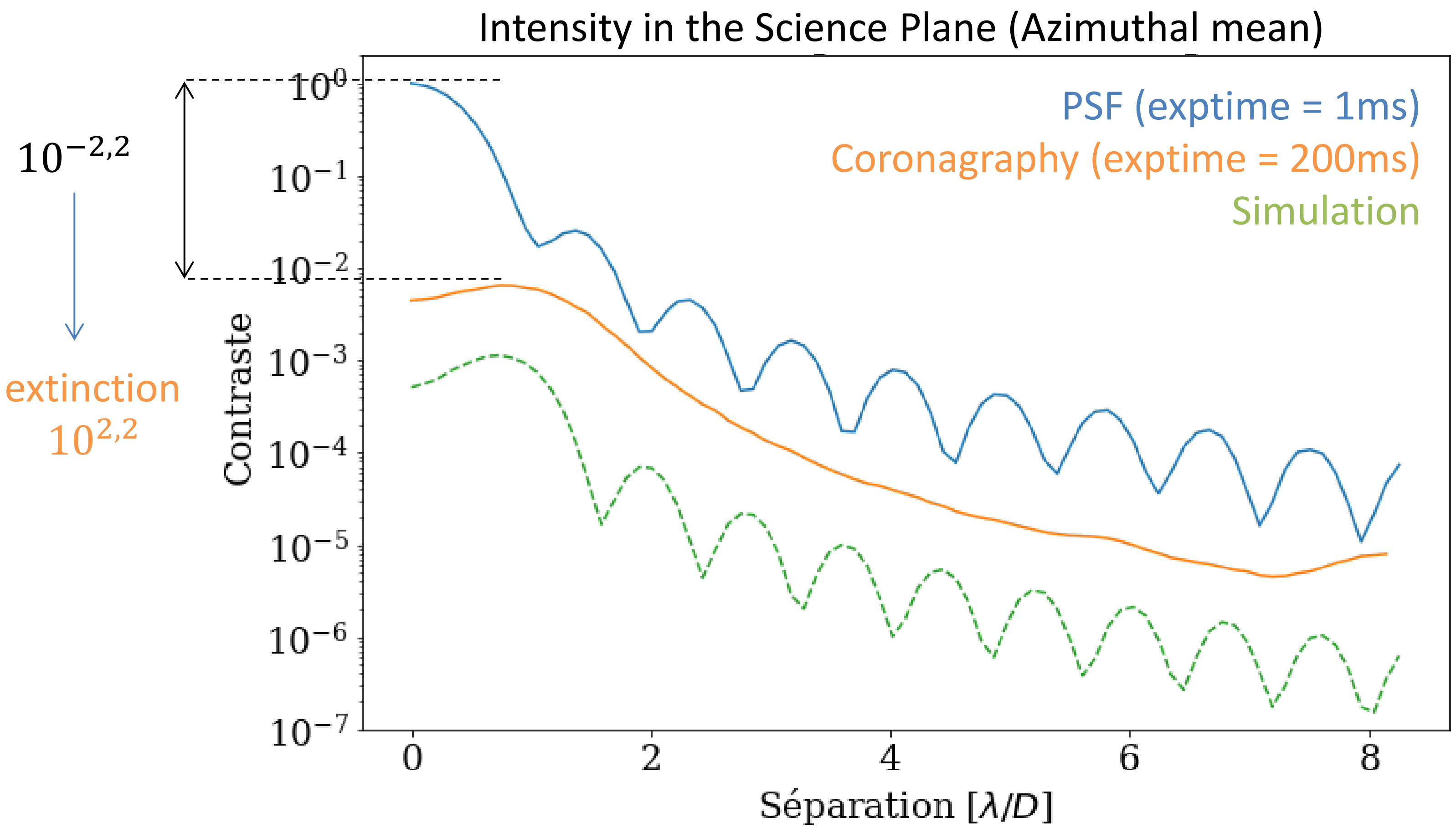

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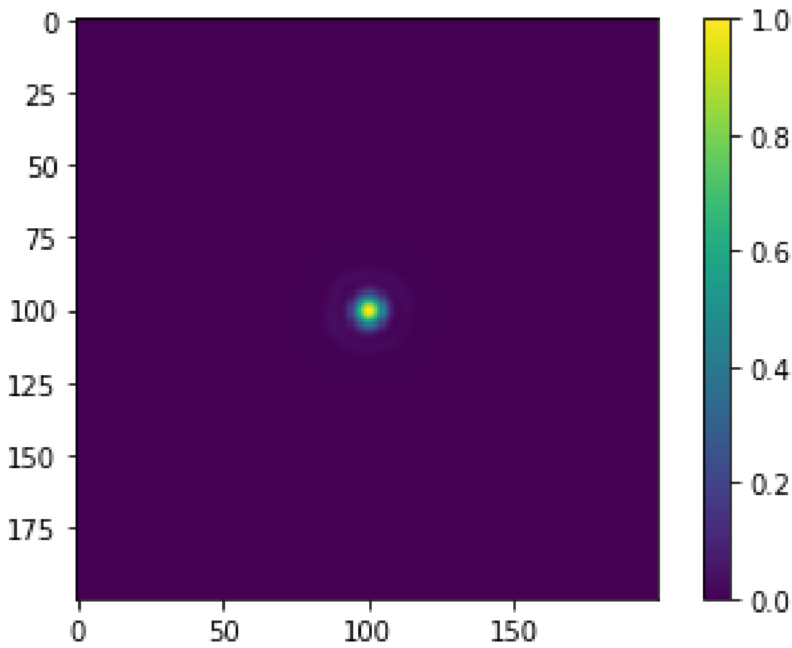
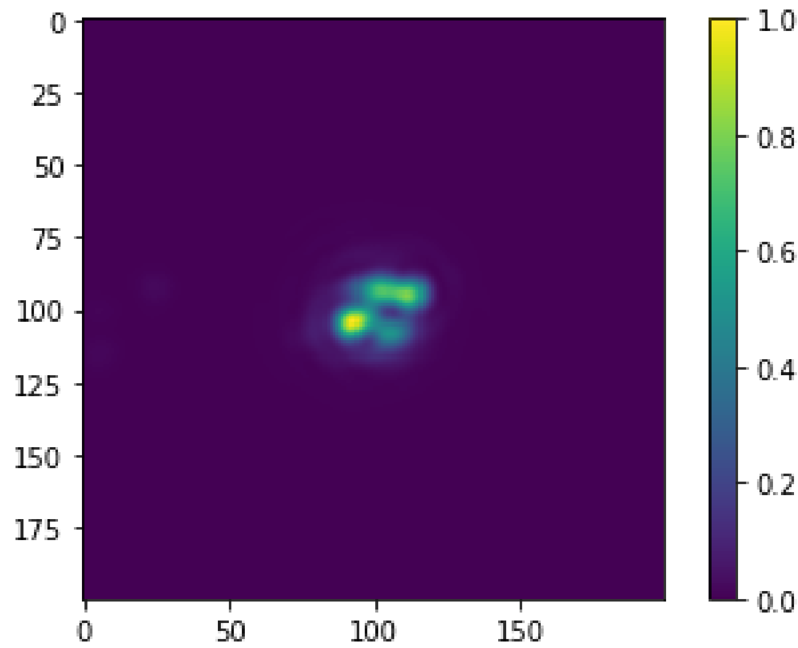
PSF (1ms) (WF corrected)



Coronagraphy (200ms) (WF corrected)



Normalized scales to observe the patterns

Coronagraphy: 2018 results

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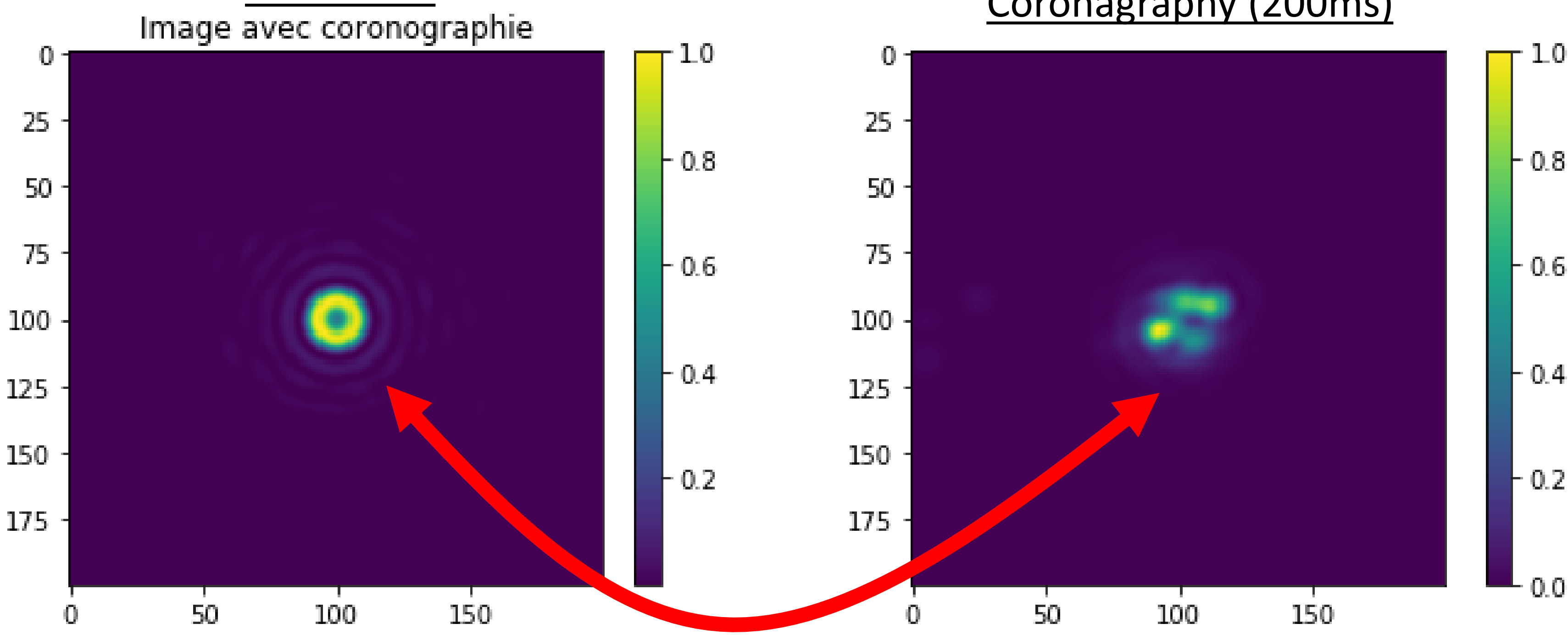
Simulation | Coronagraphy (200ms)



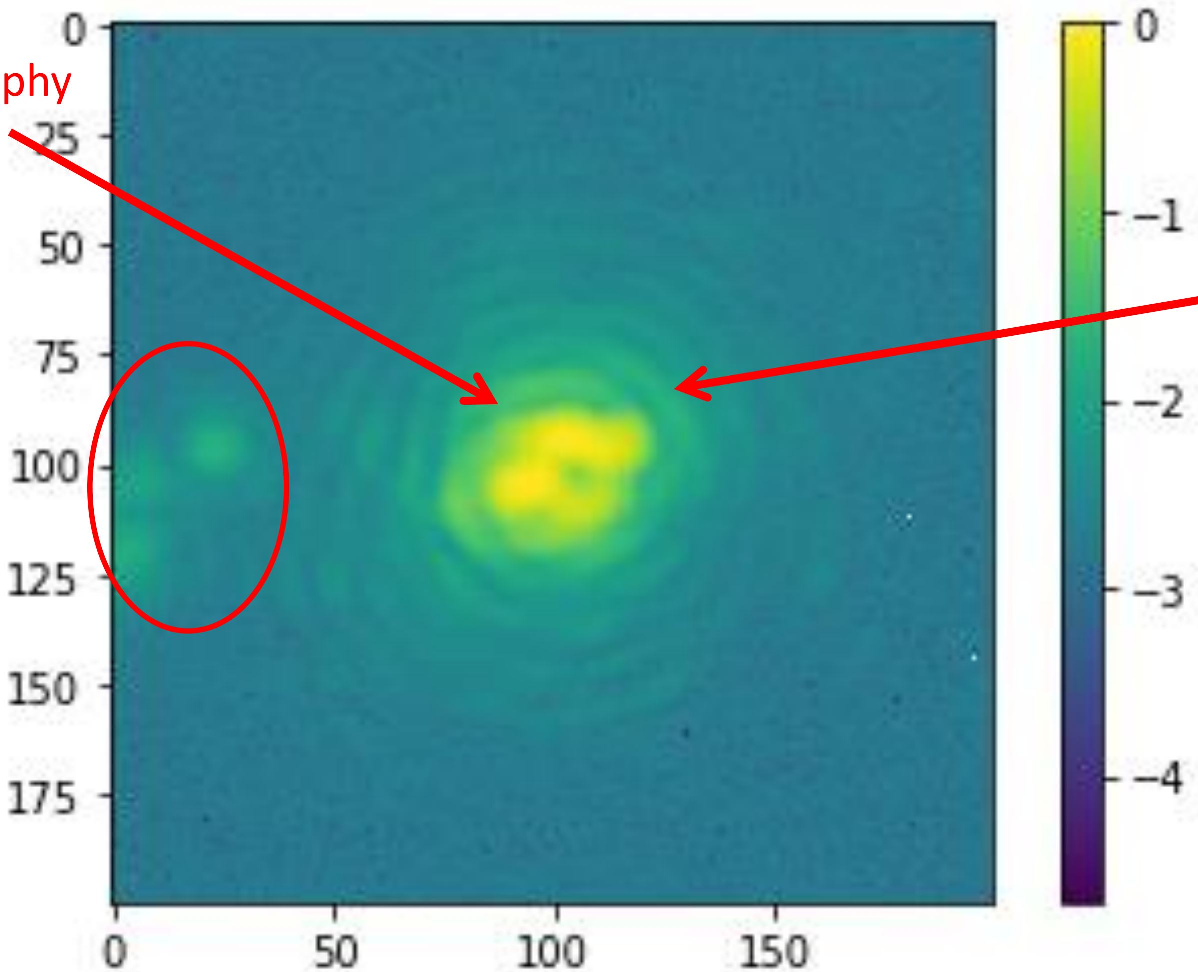
Ring pattern barely visible !!!

Normalized scales to observe the patterns

Coronagraphy: 2018 results… and questioning

« poor » coronagraphy
Ghost effect?
In Focal plane?
Centered?

Ghosts due to the cubic beamsplitter



Globally merged/mixed Airy rings

Normalized Log10 view

Coronagraphy: 2018 results… and questioning

The centered ghosts problem:

- Bad WF correction applied on the SLM → Verified → KO
- COFFEE (PSF based WF algorithm) estimation of WF → KO
  We have a 3nm rms WF
- Ghosts created by the cubic beamsplitter → Verified → KO
- Ghosts created into the beamsplitter plate (in front of the SLM) → KO
- Ghosts created because of our phase screen → KO
- Ghosts created because of a bad polarization state → Maybe ?
  The SLM accepts only one polarisation state
- Weak% reflection on the SLM glass substrate causing
  non-phased signal → Maybe ?

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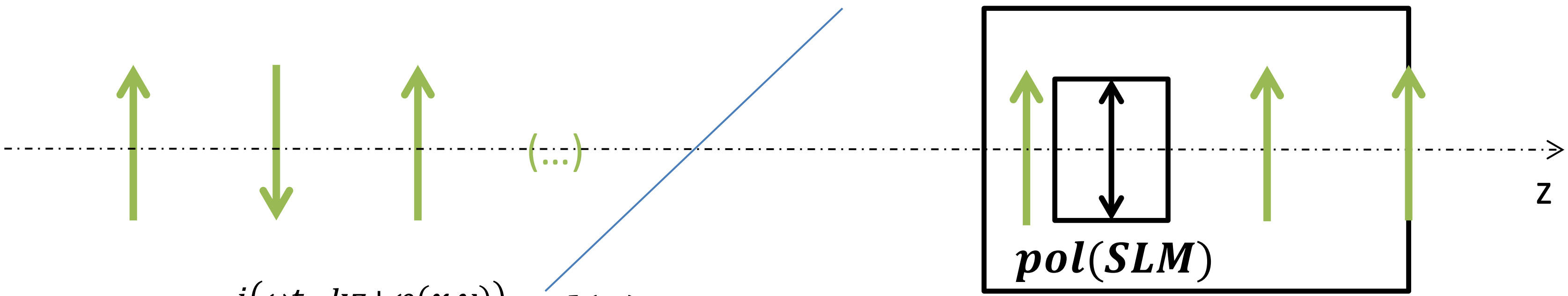
Coronagraphy: 2018 results… and questioning

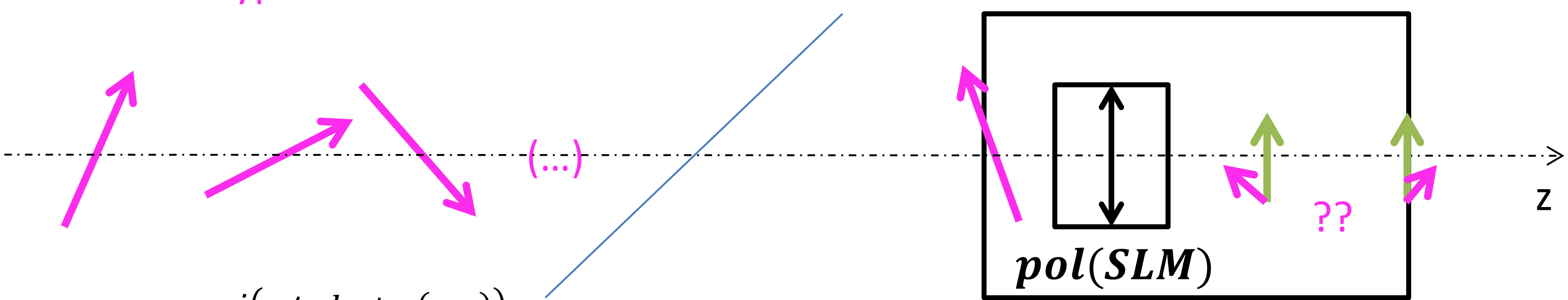
Ideal case:

Good phase correction



$$E = E_0 e^{i(\omega t - kz + \varphi(x,y))} pol(E)$$

Hypothetical real case:



$$E = E_0 e^{i(\omega t - kz + \varphi(x,y))} badpol(E)$$

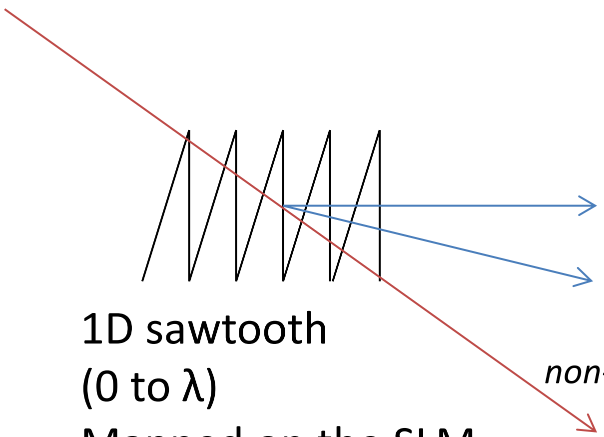
A part of the beam is not corrected by the SLM phase modification

Coronagraphy: 2018 results… and questioning

Splitting polarizations states with a SLM

…with a phase Echellette grating!

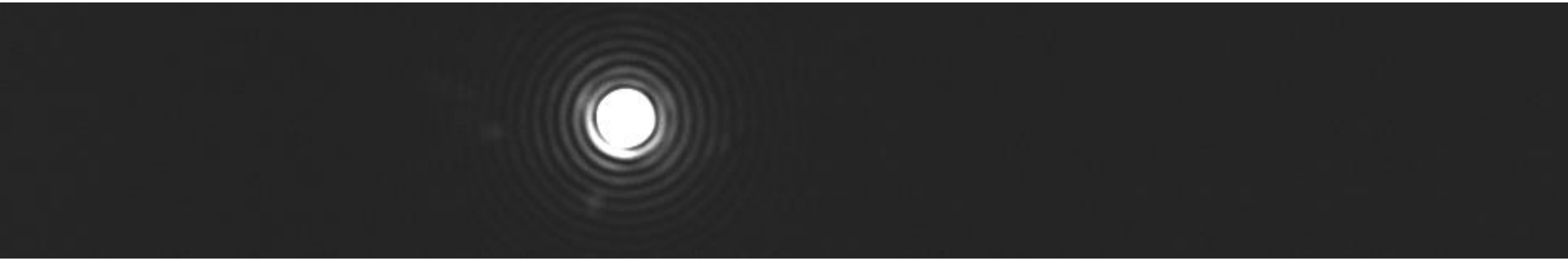
Work in progress !



1D sawtooth
(0 to λ)
Mapped on the SLM

non-eigenmode polarization state is passing through

Nothing displayed on the SLM



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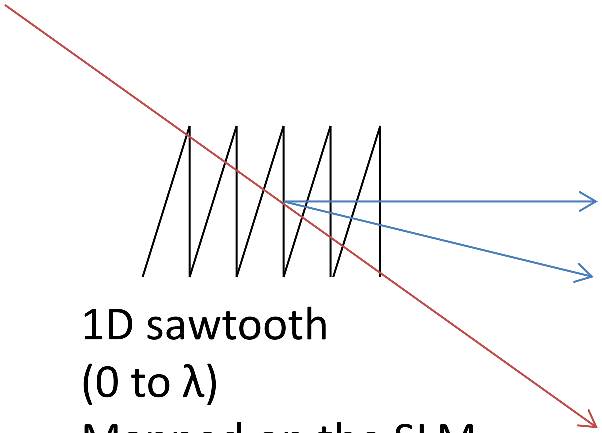
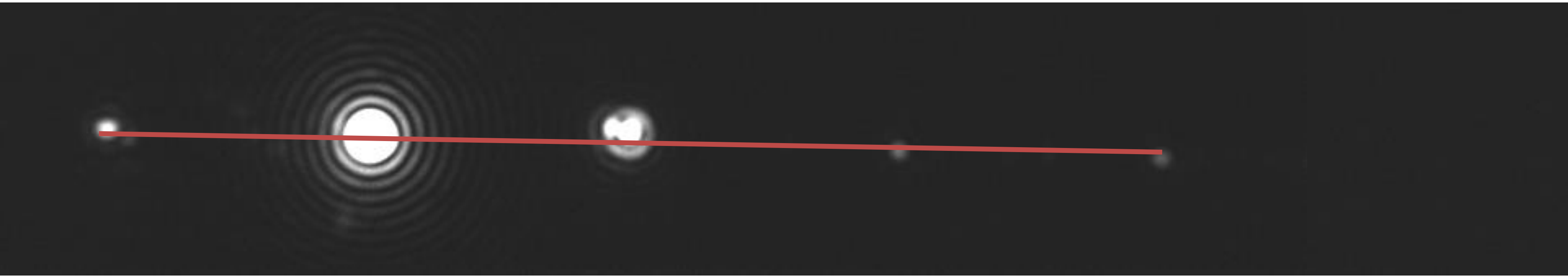


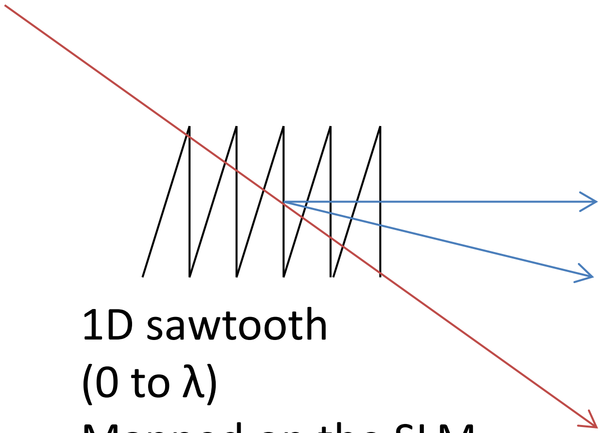
1D sawtooth
(0 to λ)
Mapped on the SLM

Tip Grating + 100nm tilt



Coronagraphy: 2018 results… and questioning

Splitting polarizations states with a SLM

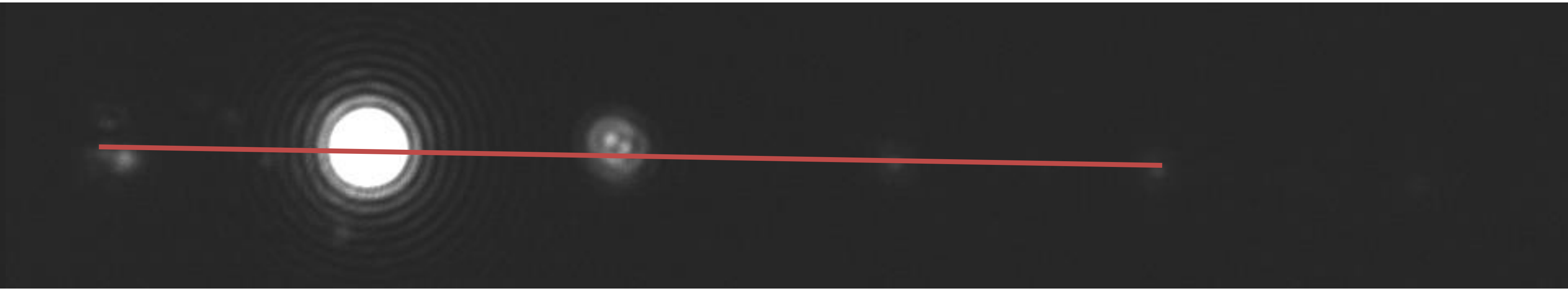


1D sawtooth
(0 to λ)
Mapped on the SLM

…with a phase Echellette grating!

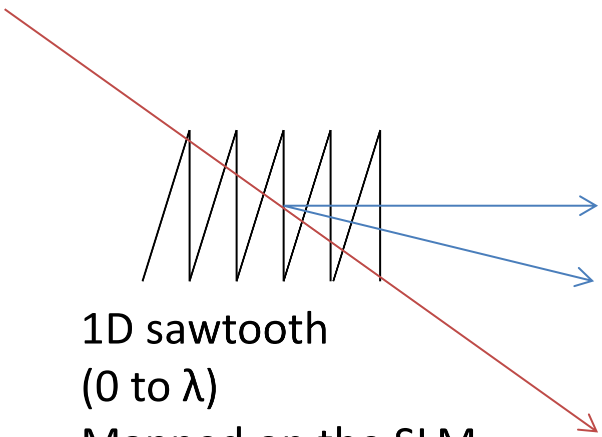
Work in progress !

Tip Grating + 100nm tilt + Maximizing order 1



Coronagraphy: 2018 results… and questioning

Splitting polarizations states with a SLM

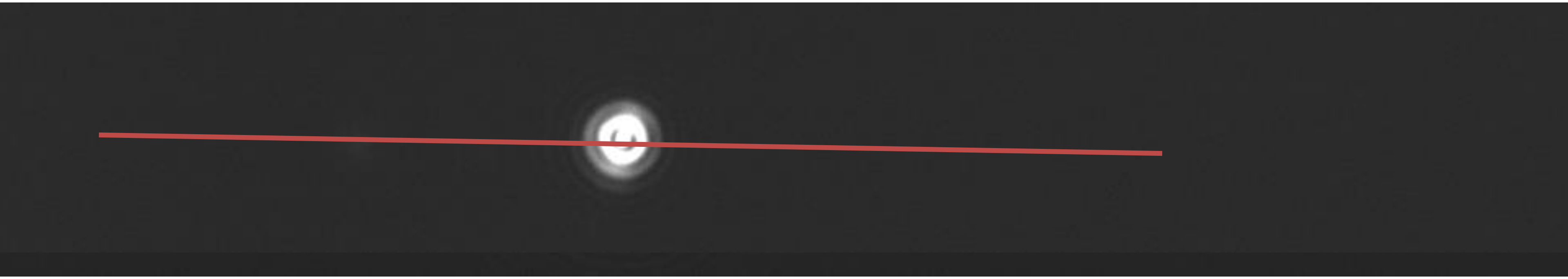


…with a phase Echellette grating!

Work in progress !

1D sawtooth
(0 to λ)
Mapped on the SLM

Tip Grating + 100nm tilt + Minimizing order 1



Conclusion

Improvement of MITHIC optical setup and Python codes

Measurements of NCPA and Residual Phase Variations

Toward Coronagraphic imaging

Characterization of the bench in this last period

Future: fine characterization of the SLM and study of polarization. Ghosts suppression or coronagraphy assuming a grating. By 2019, these issues might be fixed and we could expect a significant gain in contrast, GRD

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Merci beaucoup !

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