



**LABEX
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UNIVERSITÉ DE LYON

Integrated Mach-Zehnder (iMZ) wavefront sensor

Wavefront sensing at nanometric scale for XAO and high precision metrology

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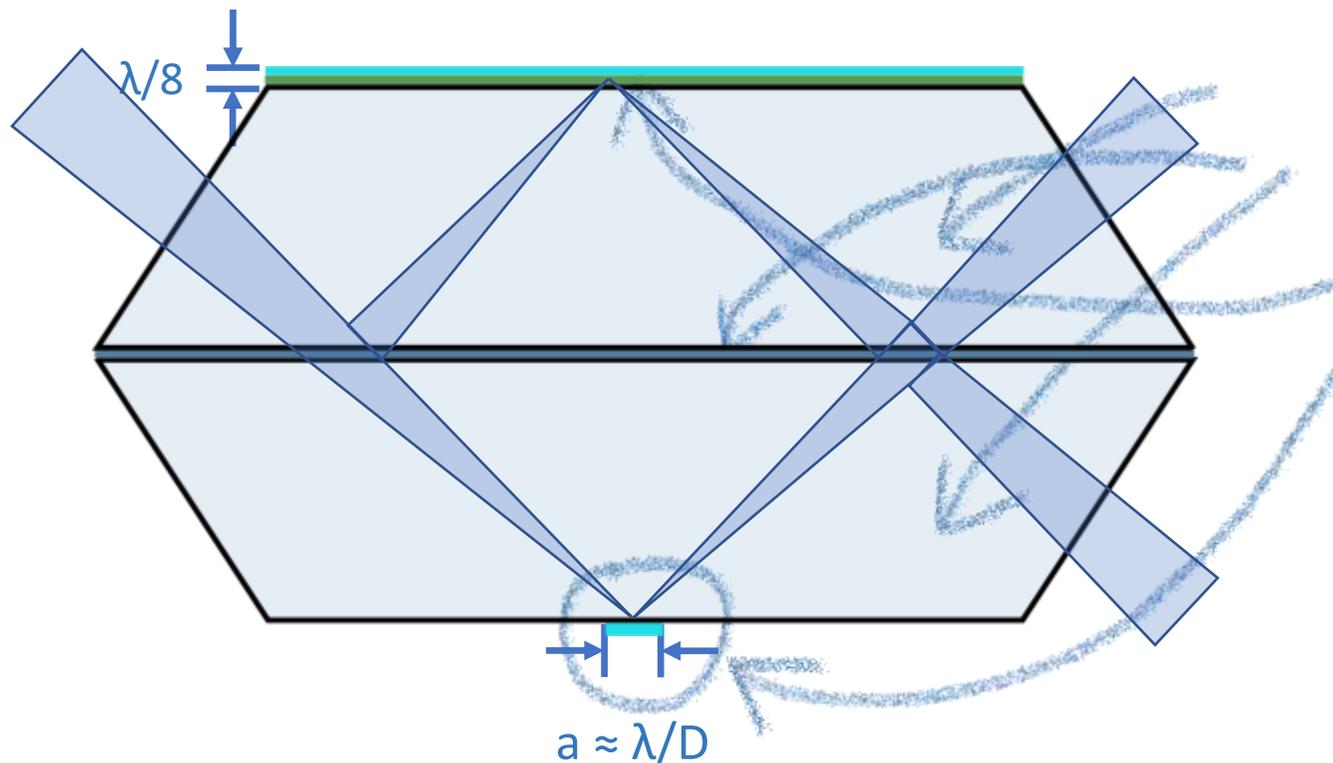
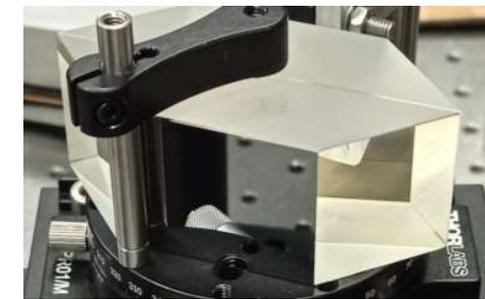
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WFS Workshop in the VLT/ELT era
Porto, 19-21 October 2022

The iMZ : integrated Mach-Zehnder

Mach-Zehnder interferometer with glass propagation

Fourier-filtering family of wavefront-sensor



iMZ schematic representation

- 2 glass plates of exact same width
- $\lambda/4$ beam splitter layer (r_s, t_s)
- $\lambda/8$ layer + reflective layer (r_m)
- reflective dot : pinhole ($\varnothing \approx \lambda/D$)

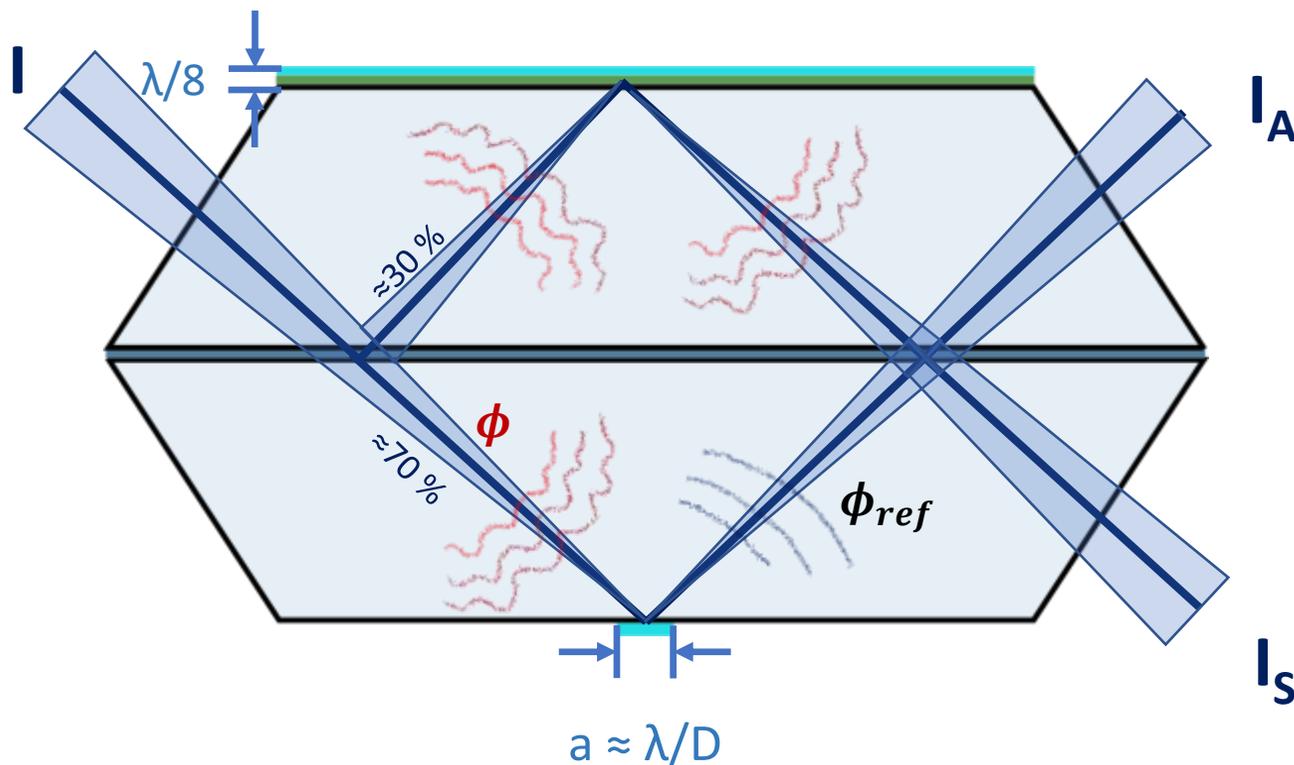
spatial filtering

Creation of the reference signal

iMZ = self-referenced interferometer

The iMZ : integrated Mach-Zehnder

⇒ Two complementary outputs I_S & I_A



iMZ schematic representation

Anti-symmetric output

I_A  $NF(\alpha_A + \beta \sin(\phi - \phi_{ref}))$

N : incoming photon number

F : intensity distribution on the pupil

ϕ : incoming phase

ϕ_{ref} : reference phase

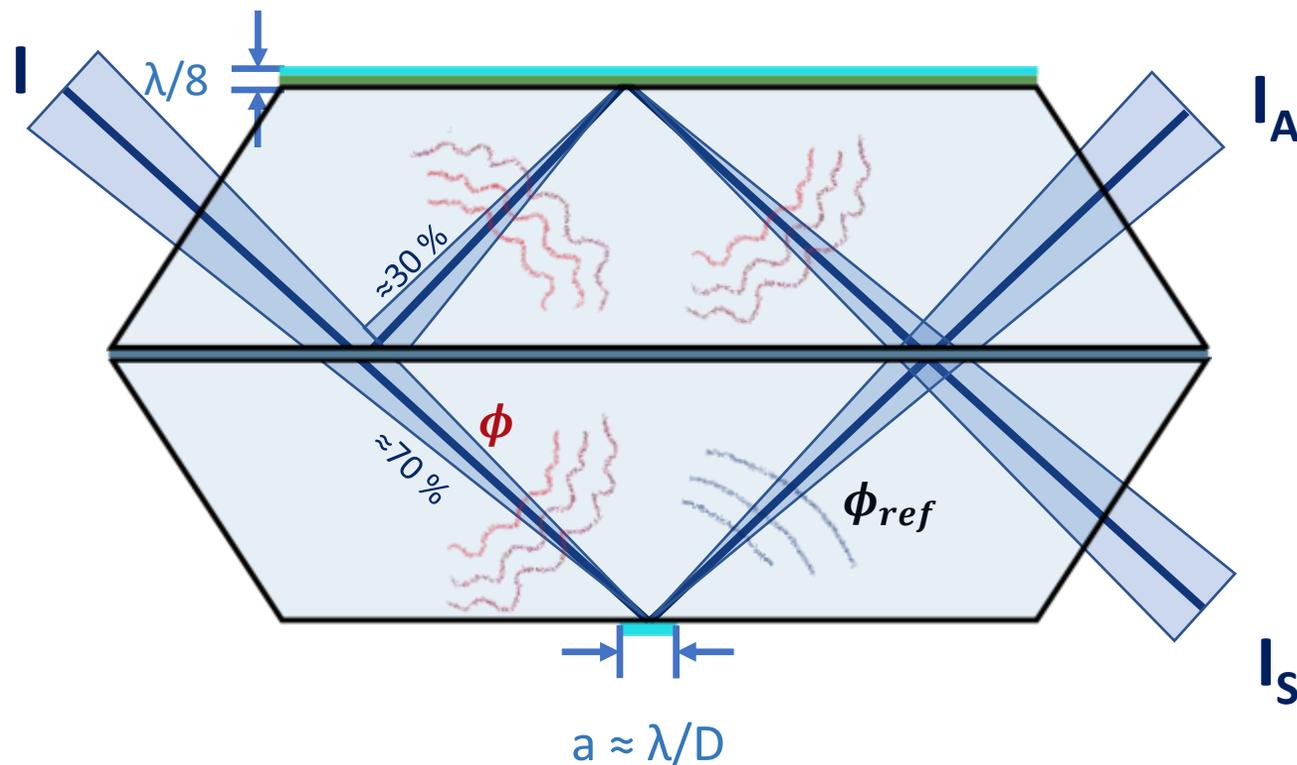
$\alpha_A, \alpha_S, \beta$: calibration coefficients, depending on the coatings and of the filtering ($I_{ref} \approx \gamma_f I$)

I_S  $NF(\alpha_S - \beta \sin(\phi - \phi_{ref}))$

Symmetric output

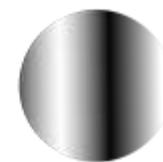
The iMZ : integrated Mach-Zehnder

⇒ Two complementary outputs I_S & I_A



iMZ schematic representation

Anti-symmetric output



$$NF(\alpha_A + \beta \sin(\phi - \phi_{ref}))$$

- Complementary information
- Sum of the 2 outputs : separate retrieval of phase and intensity
- Signal linear with small phases

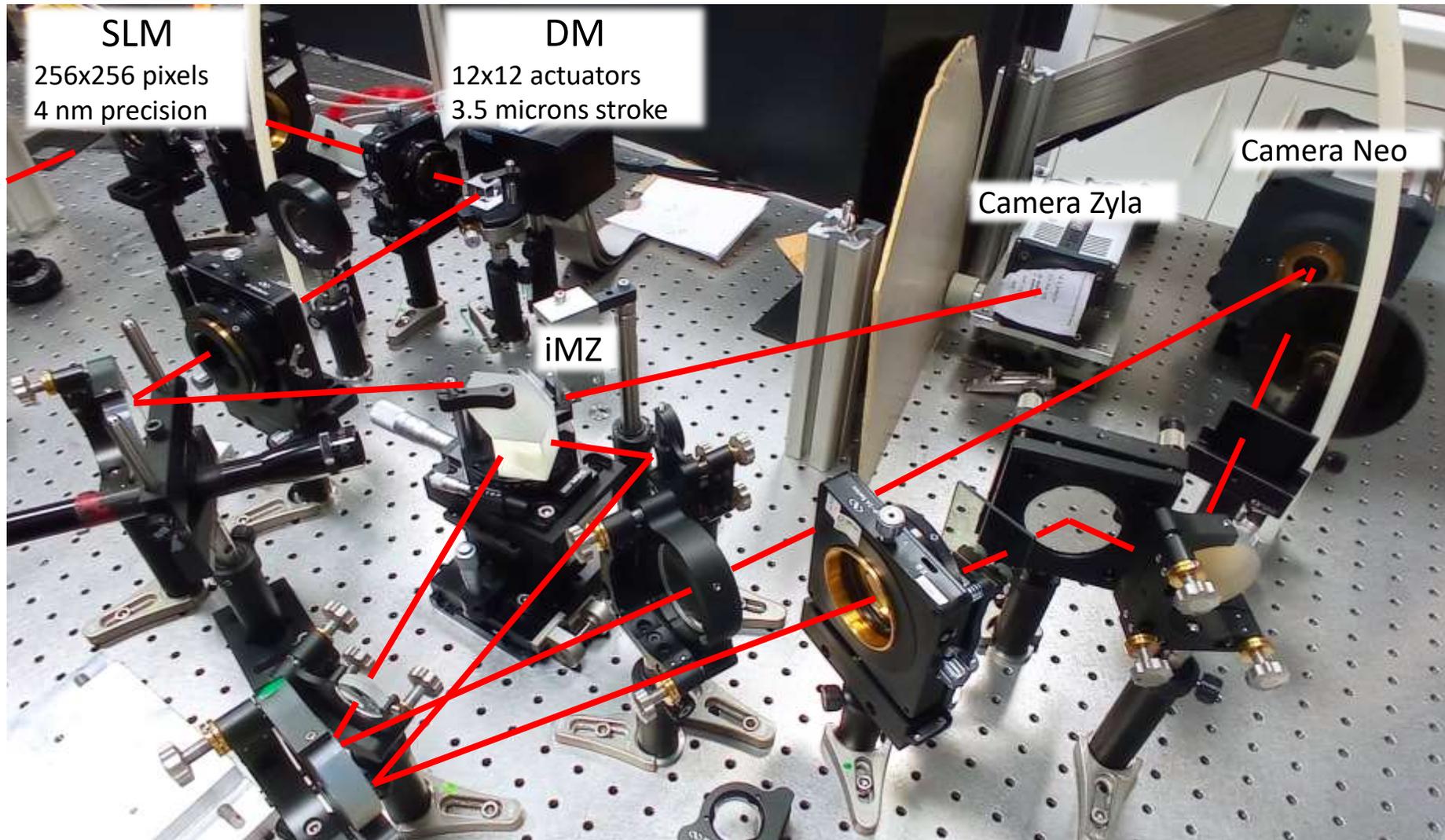
I_S



$$NF(\alpha_S - \beta \sin(\phi - \phi_{ref}))$$

Symmetric output

The XAO test bench at CRAL :



Calibration method :

Objective : extract the calibration phase ϕ_0 and the coefficient $\alpha_A, \alpha_S, \beta$ from iMZ signal for each pixel of the pupil

Method : linear inverse problem resolution

Hypothesis : - perfect filtering : $\phi - \phi_{ref} \approx \phi$
- $\alpha_A, \alpha_S, \beta$ are phase independent

Calibration model (anti-symmetric output, $\alpha_C = \alpha_A$) :

$$m = \alpha_C + \beta_C \sin(\phi_0) + z$$

Linearization of the model : introduction of a set of known modulations c_i with a deformable mirror (DM) :

$$\begin{aligned} m_i &= \alpha_C + \beta_C \sin(\phi_0 + c_i) + z \\ &= \alpha_C + \delta \sin(c_i) + \gamma \cos(c_i) + z \end{aligned}$$

where $\delta = \beta_C \cos(\phi_0)$ and $\gamma = \beta_C \sin(\phi_0)$.

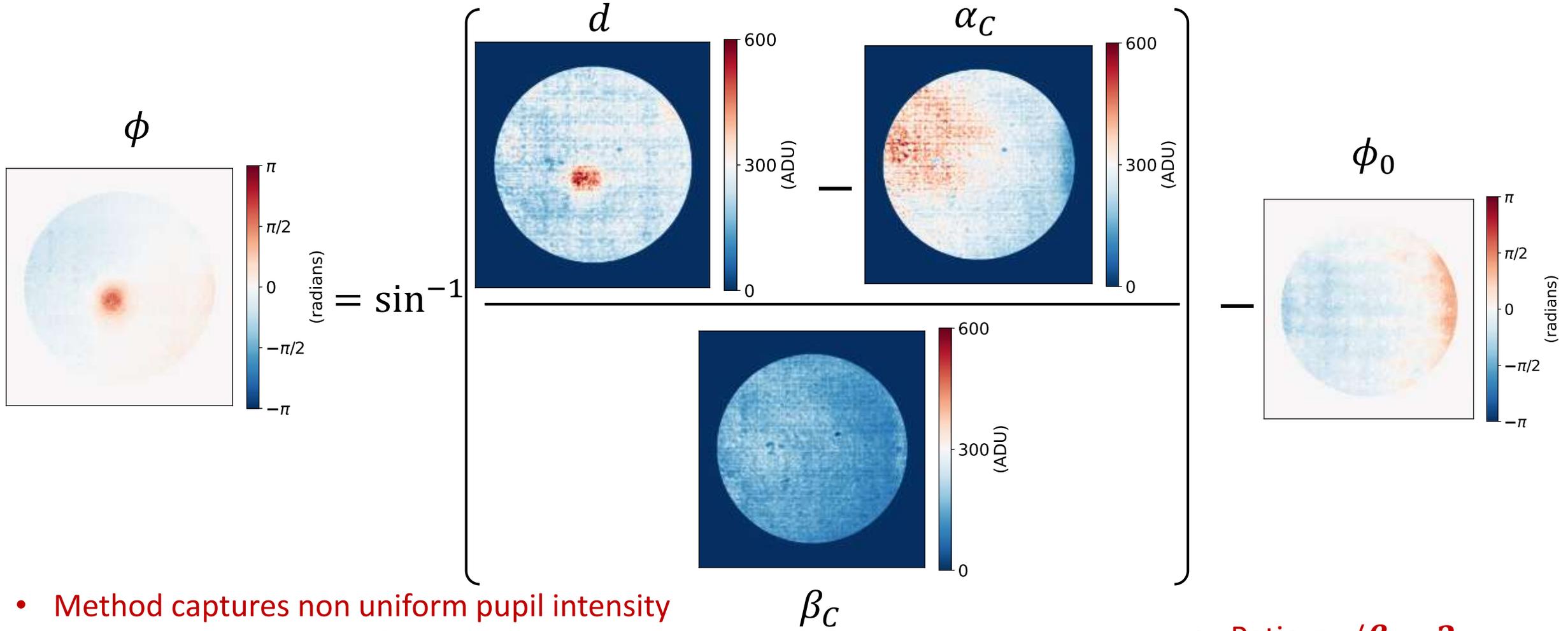
Estimator (Least Mean Square Estimator) : $\hat{x} = \arg \min_x \|d - Hx\|_W^2$

with d the data, H the direct model matrix, $x = (\alpha_C \ \delta \ \gamma)$ the parameters vector and W the noise matrix such as $W = \text{cov}(d)^{-1}$

- **Independent calibration of the iMZ coefficients per subaperture using inverse approach**
- **Optimized to accurately disentangle phase and intensity**

Phase extraction :

Extraction of the phase using the calibration coefficients and reversing the model :

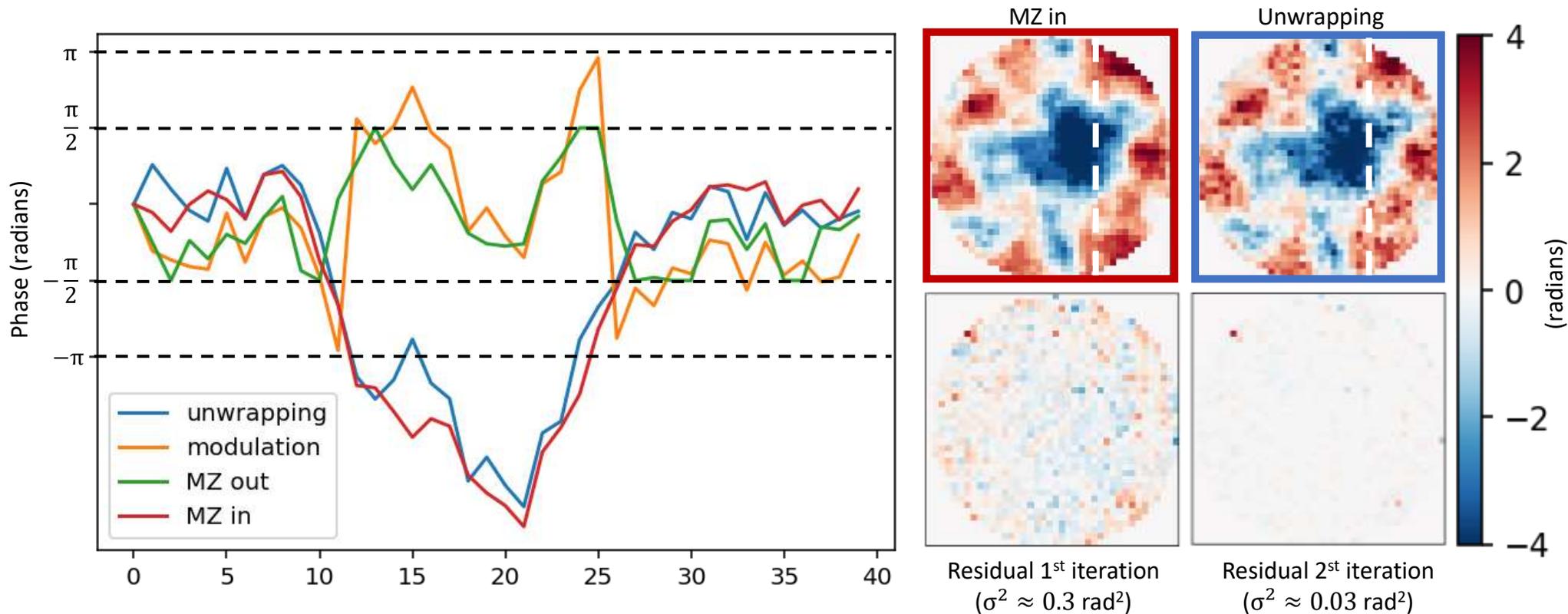


- Method captures non uniform pupil intensity
- Non uniformity coming from the DM

- Ratio $\alpha_c/\beta_c \approx 2$

Simulation results : Increasing dynamic

- iMZ signal $\Rightarrow \phi \in [-\frac{\pi}{2}; \frac{\pi}{2}]$ without unwrapping strategy
- Modulation : introduction of a known phase step and its inverse $\Rightarrow \phi \in [-\pi; \pi]$
- Unwrapping¹ on the modulated signal $\rightarrow \phi$ up to several microns

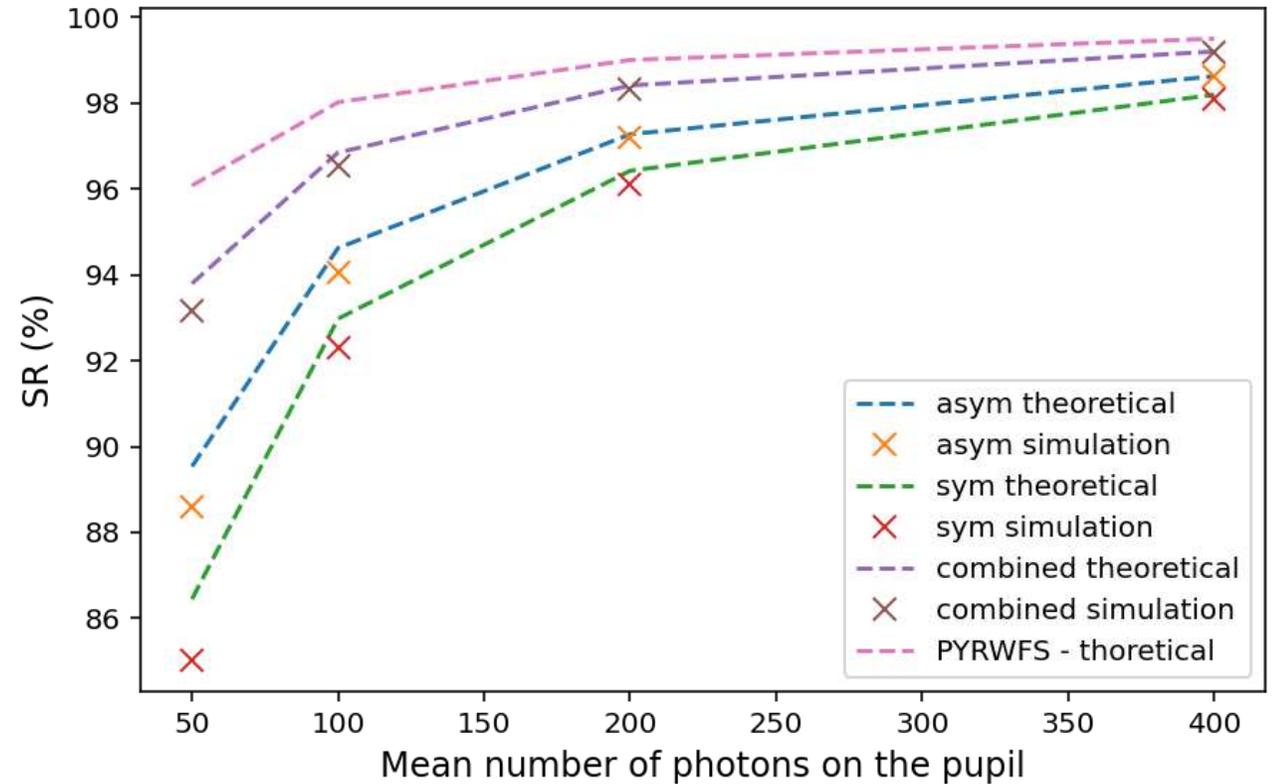
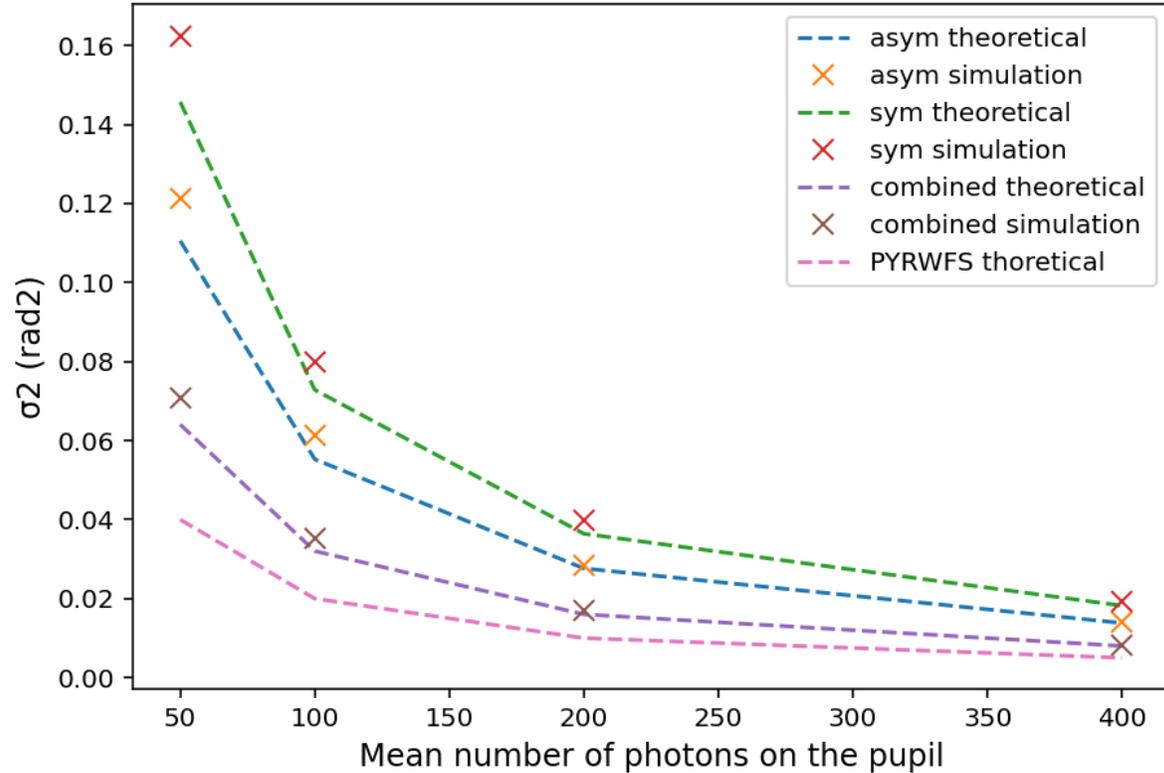


¹D. C. Ghiglia and L. A. Romero, "Robust two-dimensional weighted and unweighted phase unwrapping that uses fast transforms and iterative methods," J. Opt. Soc. Am. A 11, pp. 107–117, Jan 1994.

M. J. Townson, O. J. D. Farley, G. O. de Xivry, J. Osborn, and A. P. Reeves, "AOTools: a python package for adaptive optics modelling and analysis," Optics Express 27, p. 31316, oct 2019.

Noise propagation :

Theoretical limit : $\sigma^2 \propto \frac{1}{N} \frac{\alpha}{\beta^2}$ (photon noise only)



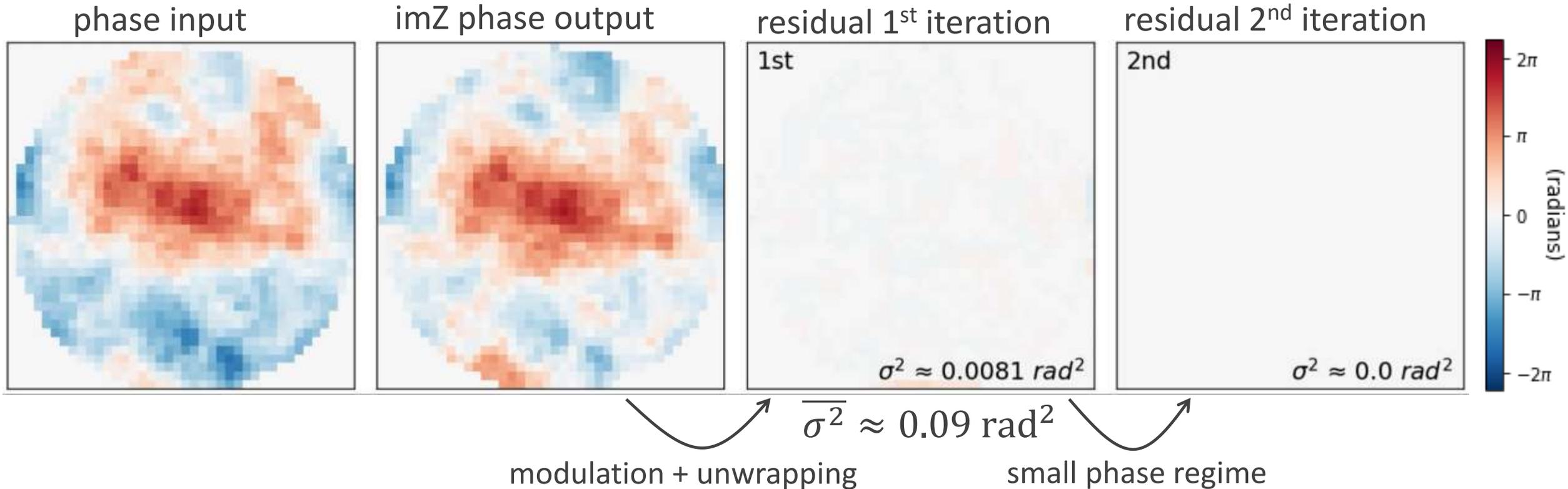
Low noise propagation close to the theoretical limit of non modulated Pyramid WFS

O. Guyon, "Limits of adaptive optics for high-contrast imaging," The Astrophysical Journal 629, pp. 592–614, aug 2005

Simulation results : Wavefront reconstruction

Noise free simulation :

D = 8m, 40x40 subapertures, medium seeing



Accurate wavefront reconstruction in one iteration (SR > 90%)

Perfect wavefront reconstruction in the second iteration (SR > 99%)

Simulation results : Wavefront reconstruction

Realistic flux simulation : $m_v = 9$, framerate = 500 Hz

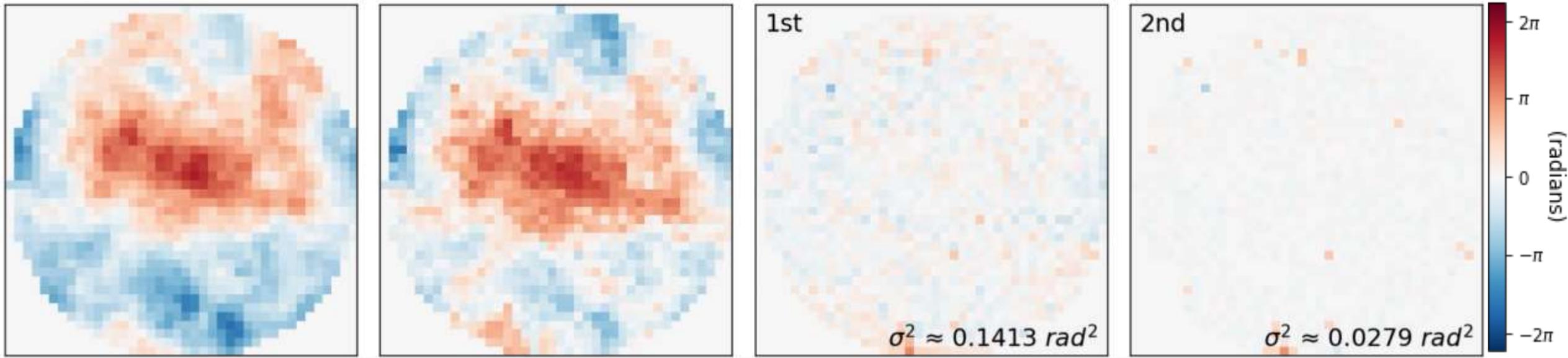
$D = 8\text{m}$, 40x40 subapertures, medium seeing

phase input

imZ phase output

residual 1st iteration

residual 2nd iteration



$\overline{\sigma^2} \approx 0.29 \text{ rad}^2$

modulation + unwrapping

$\overline{\sigma^2} \approx 0.04 \text{ rad}^2$

small phase regime

SR $\approx 75\%$ for bootstrapping (modulation + unwrapping)

SR $\approx 96\%$ for small phases reconstruction

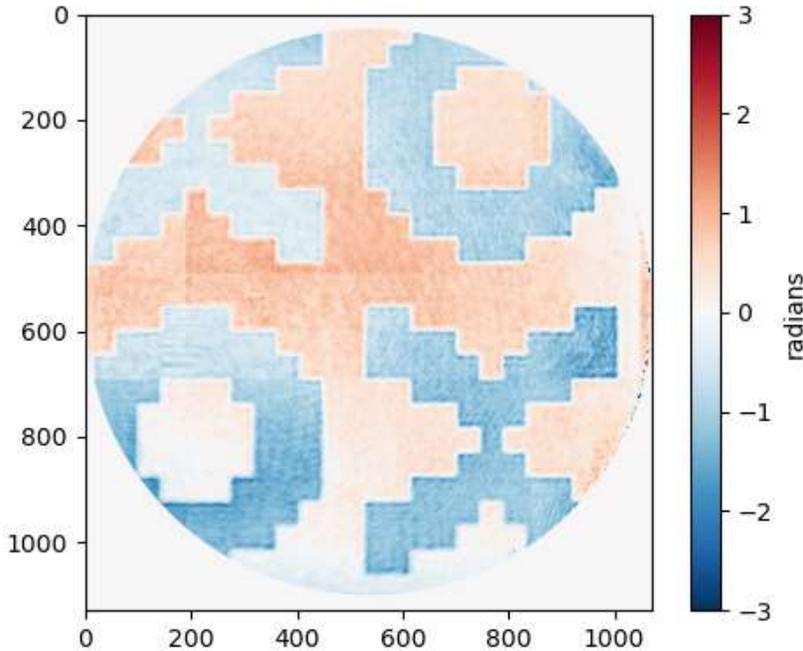
Experimental results :

Comparison of the phase from the two outputs :

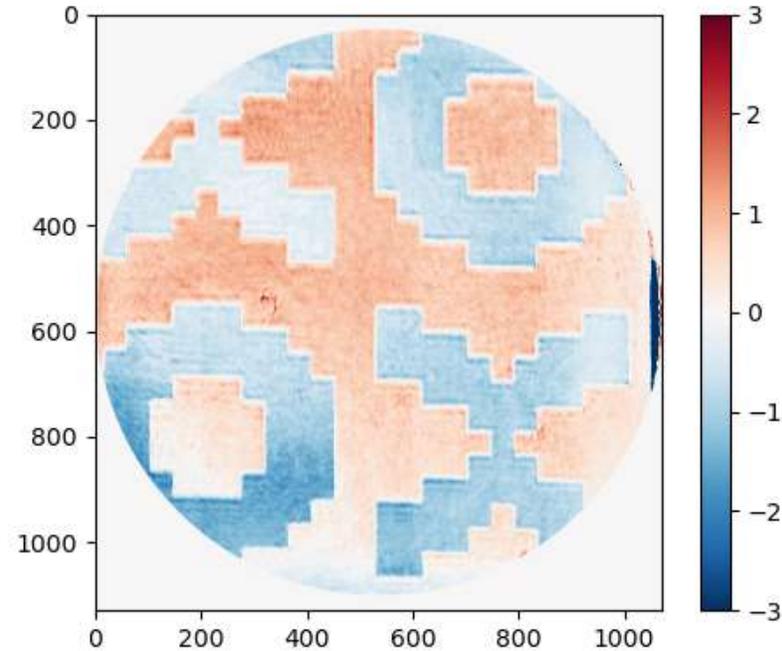
Phase step introduced by a SLM (≈ 150 nm)

residual variance: $\sigma^2 \approx 0.12 \text{ rad}^2$

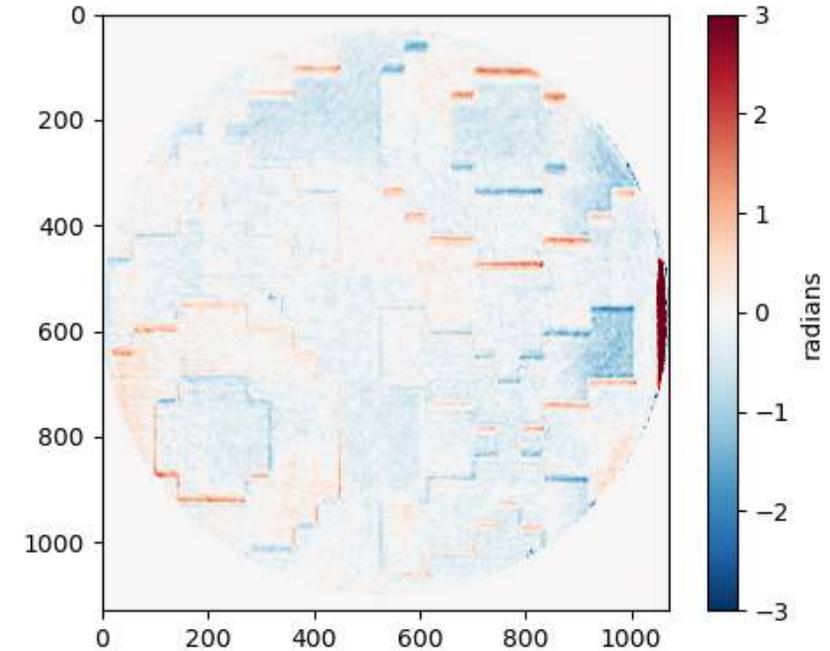
Anti-symmetric output



Symmetric output



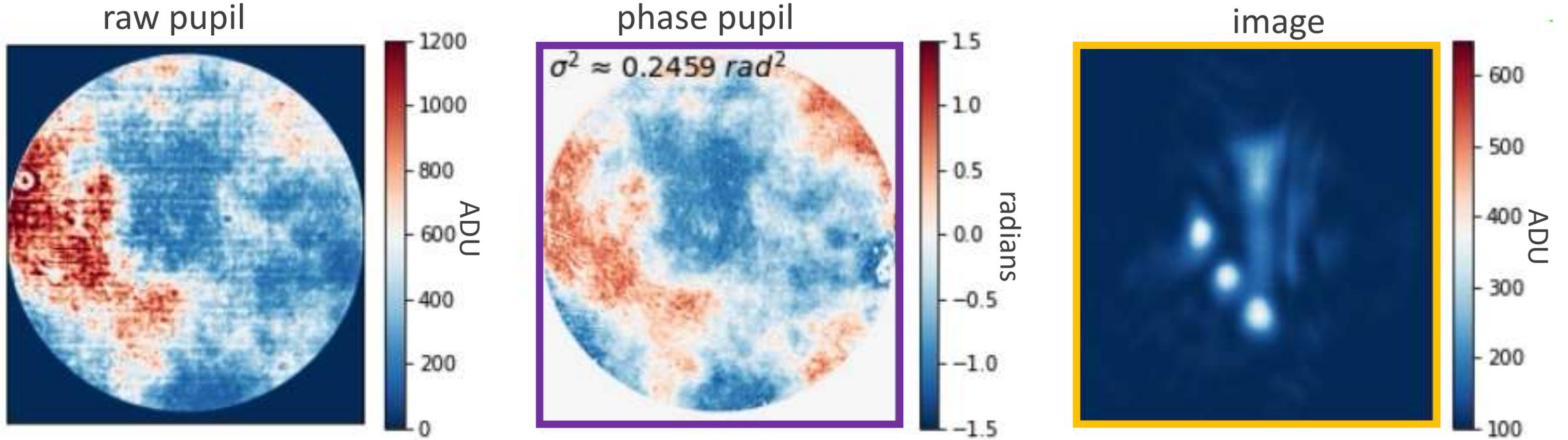
Difference



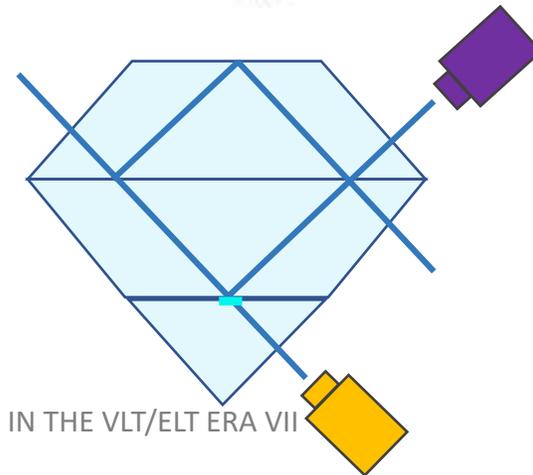
iMZ high sensitivity to phase steps + measure of amplitude

Experimental results :

Correction loop : phase screen on a 256x256 SLM correction with a 12x12 DM



Accurate measurement at 1st iteration
Strehl ratio > 90% after 2 iterations



PSF on the coronagraphic path
(behind the pinhole)

Take-away :

- **Accurate measurement** of both **phase** (at nanometer scale) and **amplitude** of the signal (scintillation)
- **Efficient calibration** method to extract the phase from the iMZ signal which **captures the non uniformity** of the intensity in the pupil
- **Good sensitivity** : low noise propagation
- Simulation tool to realistically simulate the iMZ response to different phase : **accurate phase reconstruction** outside the iMZ linearity range thanks to **modulation + unwrapping strategies**
- iMZ very efficient for XAO without first stage correction (except tip-tilt)

