RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

ONERA
THE FRENCH AEROSPACE LAB

LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

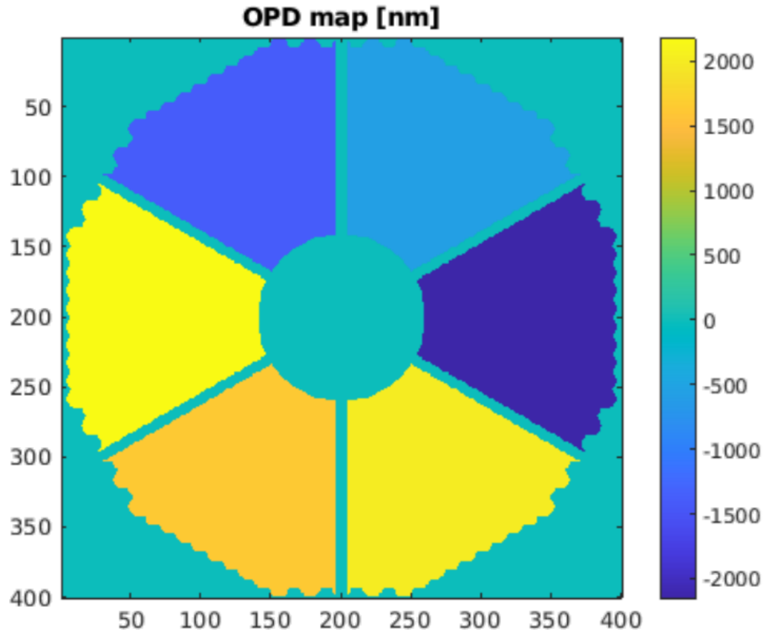
Dynamic, optical gain compensation and phase unwrapping for the Zernike Wave-Front Sensor

Mahawa CISSE, Vincent CHAMBOULEYRON, Olivier FAUVARQUE, Charlotte BOND, Nicolas LEVRAUD, Jean-François SAUVAGE, Benoît NEICHEL, Thierry FUSCO

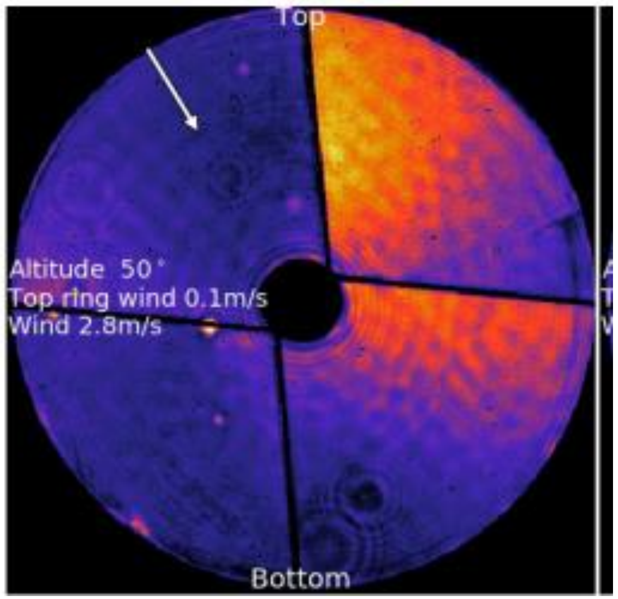
FOCUS
Focal Plane Array for Universe Sensing

WOLF

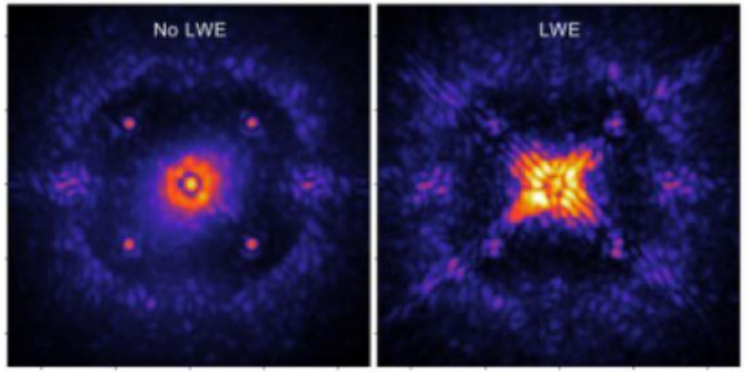
Context : High angular resolution with the ELTs



Differential piston



Low-Wind Effect (LWE)

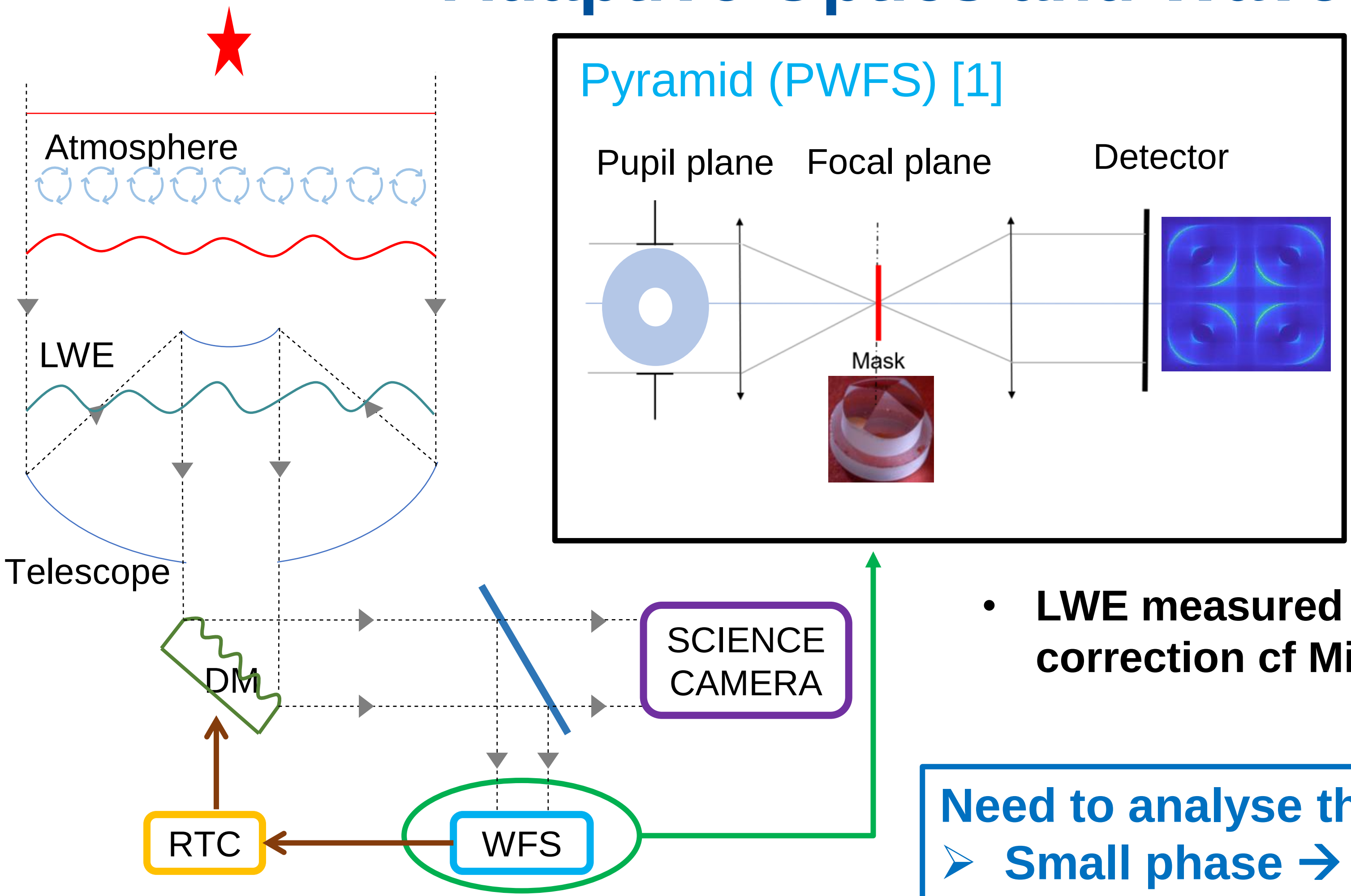


High contrast imaging

New challenges for Wave-Front Sensing (WFS) for Adaptive Optics (AO) systems to achieve high angular resolution

Reference :
Milli, J., et al 2018

Adaptive Optics and Wave-Front Sensing



- More sensitive than the Shack-Hartmann (SH)
- But highly non-linear sensor

  → modulation

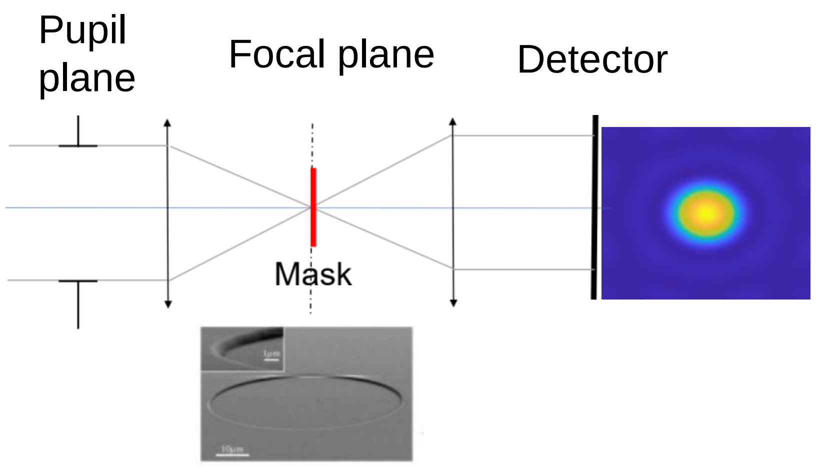
- « Gradient sensor »
- **Modulated PWFS and SH are not sensitive to the petal mode or LWE**

- **LWE measured by the ZELDA for the VLT as a 2nd stage correction cf Milli et al 2018**

Need to analyse the Zernike WFS to measure aberrations
- **Small phase → 2nd stage WFS, petalometer etc**
- **Large phase → AO WFS**

References :
[1] : Ragazzoni, R. (1996). Pupil plane wavefront sensing with an oscillating prism. *Journal of modern optics*, *43*(2), 289-293.

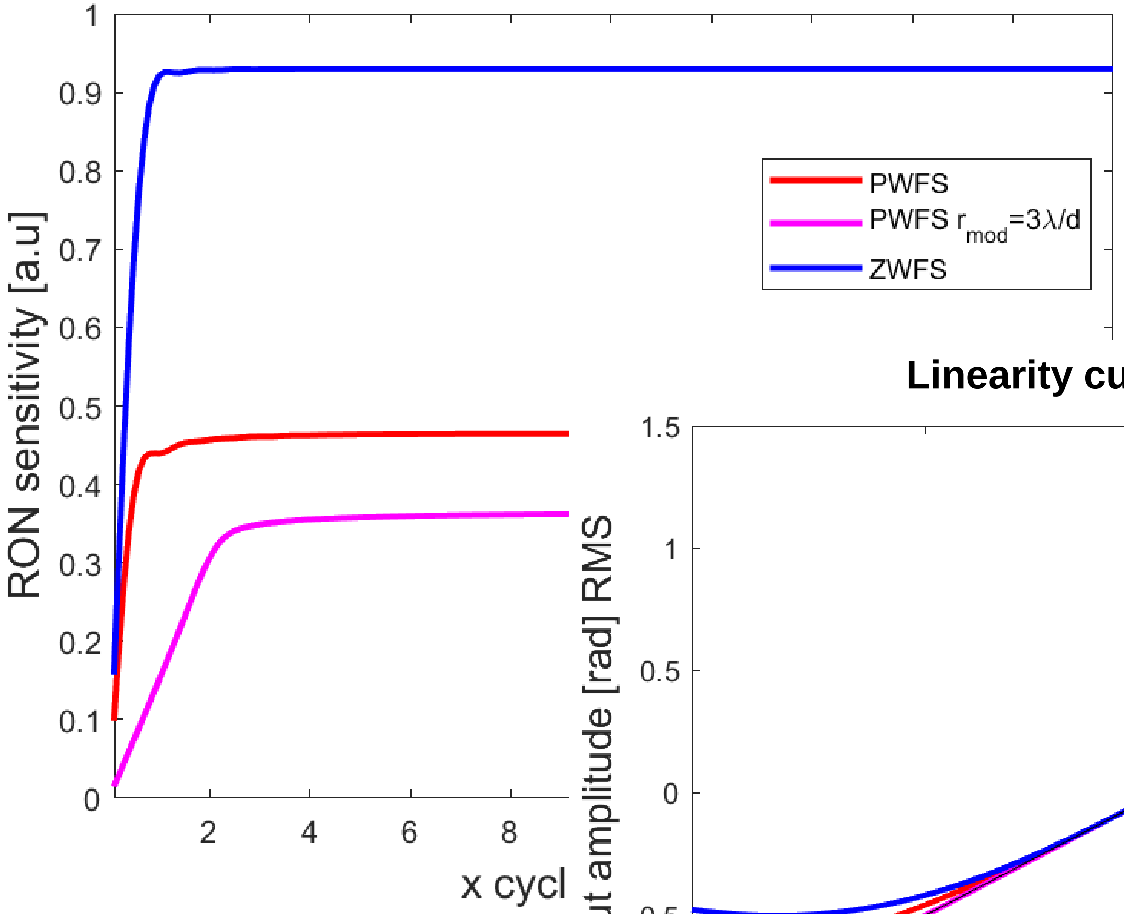
Zernike Wave-Front Sensor (ZWFS)

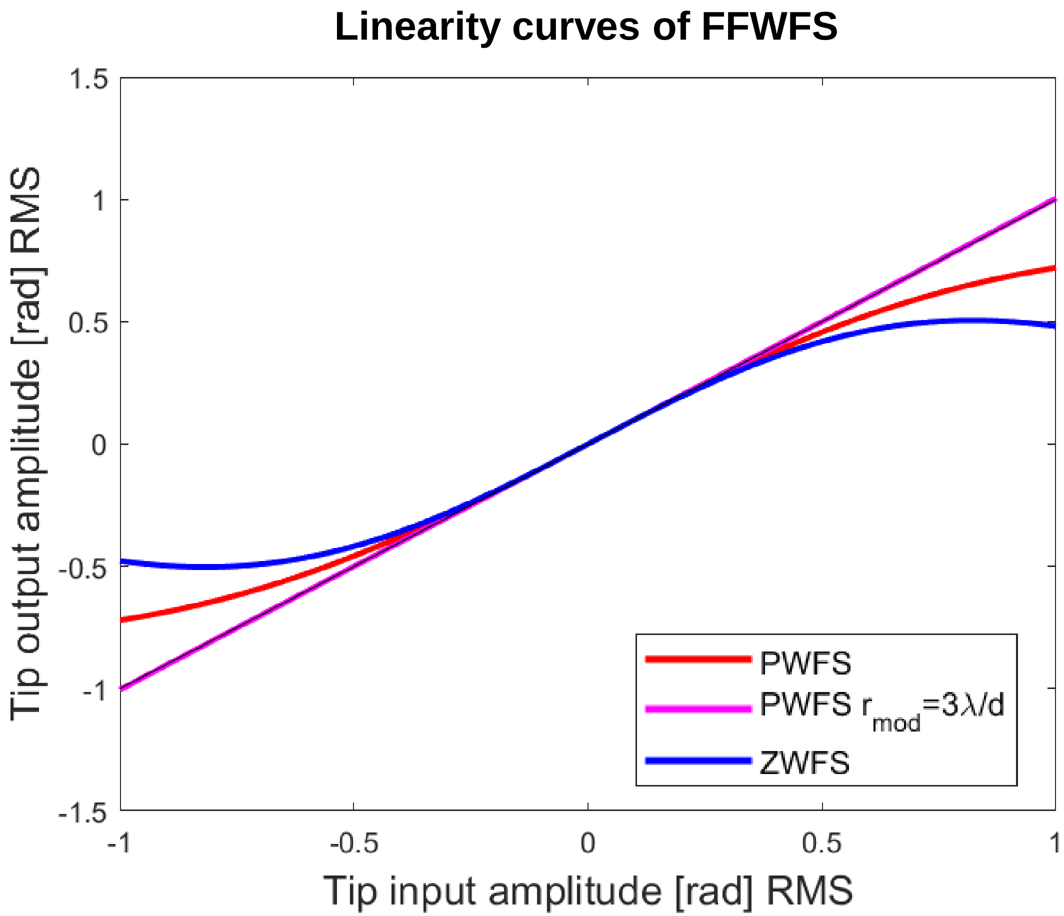


Source [1]

- **More sensitive than the PWFS**
- **Phase sensor**

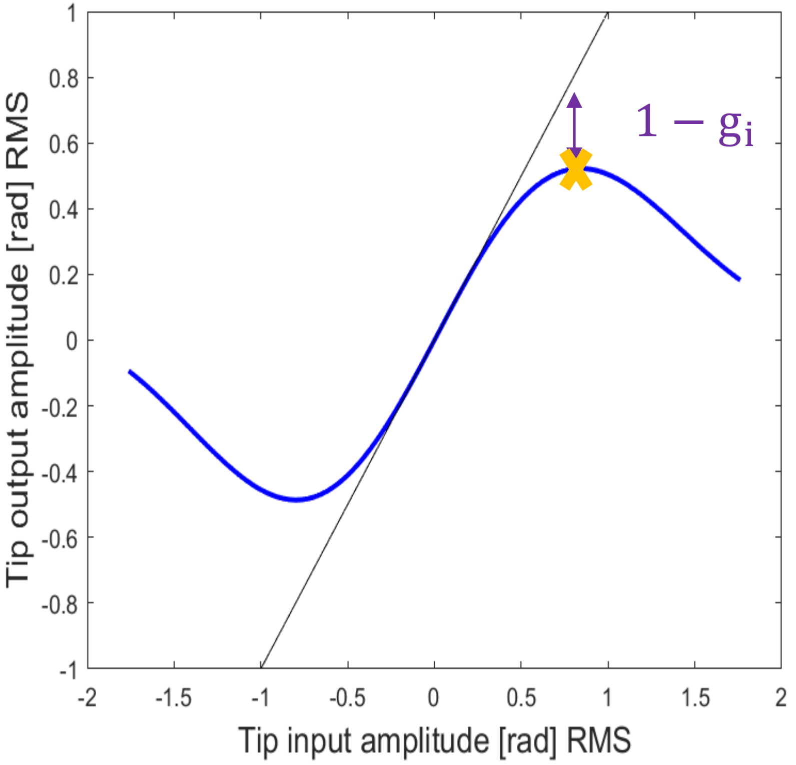
- **Less linear than the PWFS**

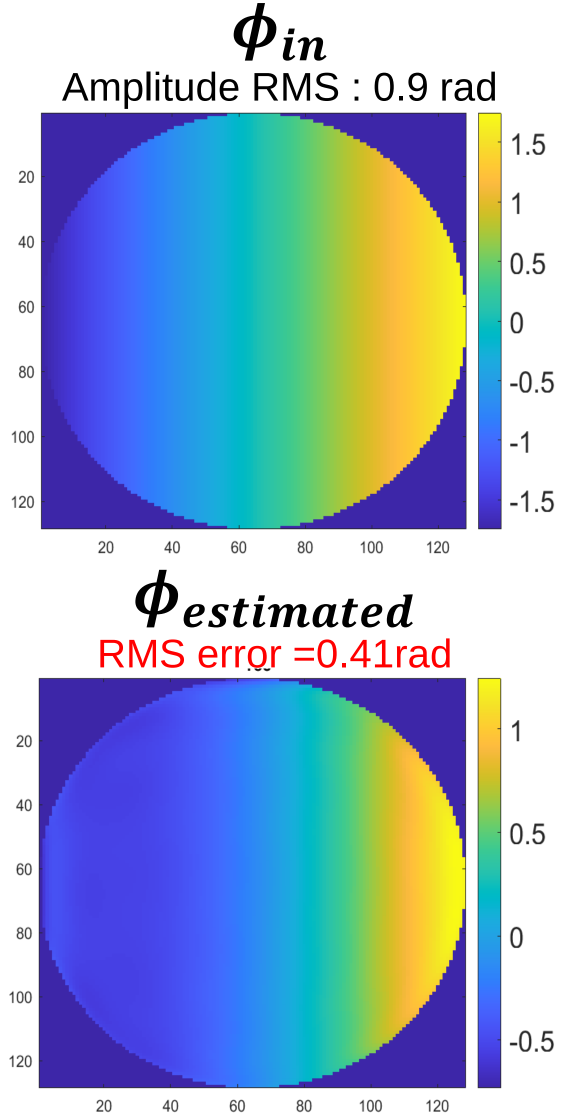


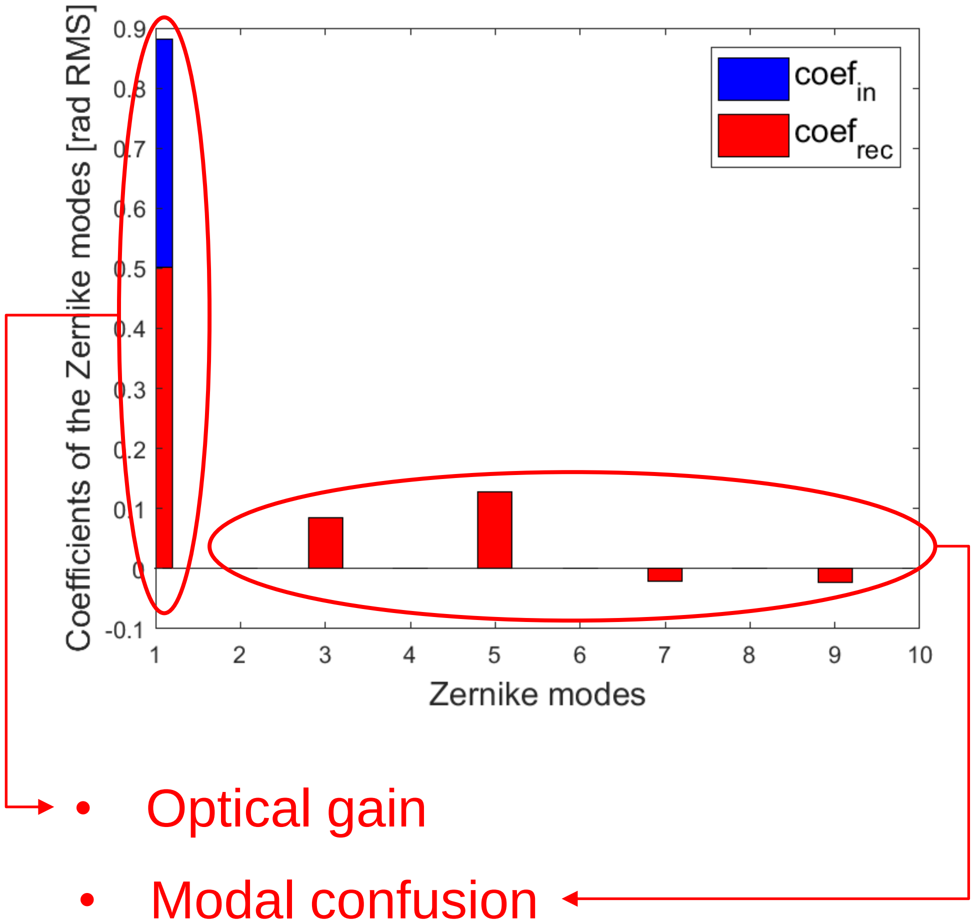


References :
[1]: N'Diaye et al 2016

Non-linearities of the ZFWFS : Example with a Tip



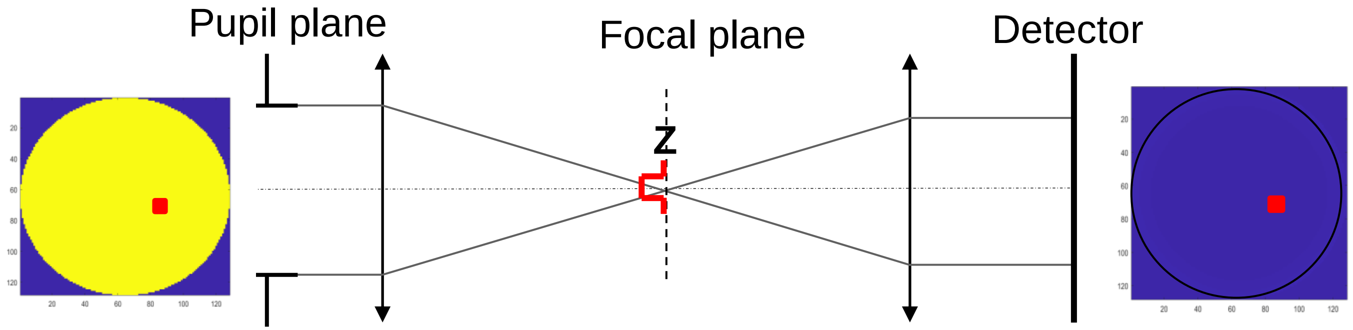


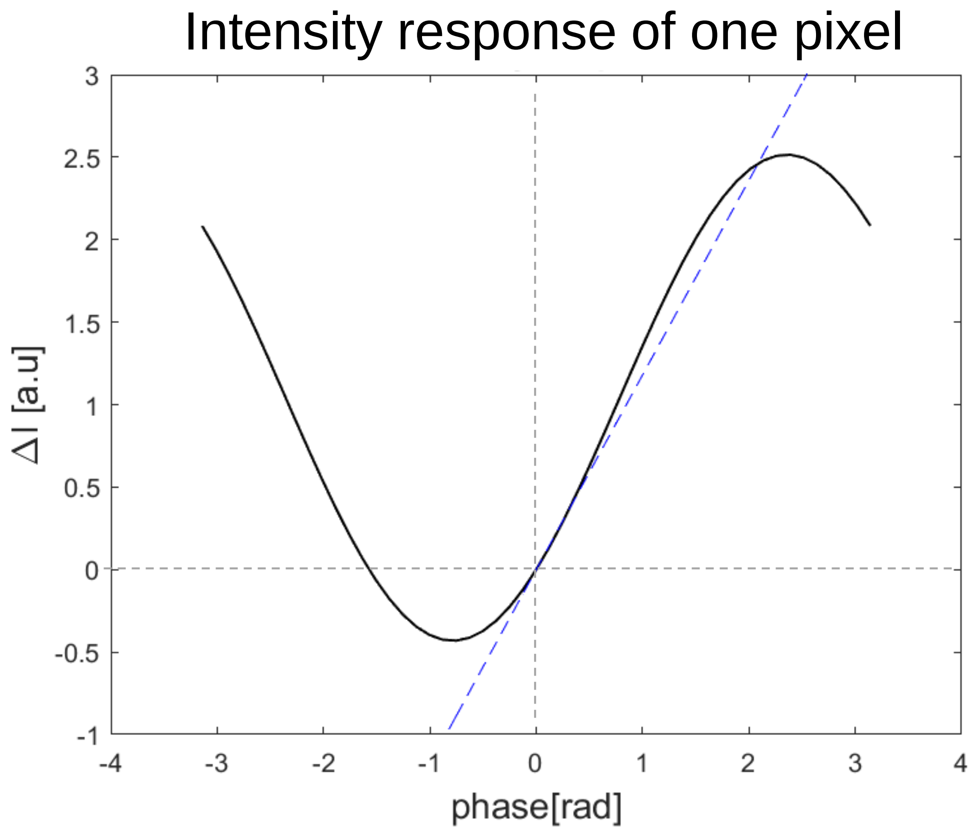


- Optical gain
- Modal confusion

Necessary to deal with the non-linear effects of the sensor

Phase reconstructors





Linear reconstructor :

- $\varphi = \Delta I$

Matrix formalism :

- Calibration matrix $\varphi = D_c \Delta I$
- In presence of phase residuals $\varphi = D_{res} \Delta I$

$D_{res} = (\delta I_{res}(Z_1), \quad \ldots \quad \delta I_{res}(Z_N))$ with $\delta I_{res}(Z_i) = \frac{\Delta I(\Phi_{res}+\epsilon Z_i) - \Delta I(\Phi_{res}-\epsilon Z_i)}{2\epsilon}$

Optical gains computation

Matrix formalism :

- Calibration matrix D_c
- In presence of phase residuals D_{res}

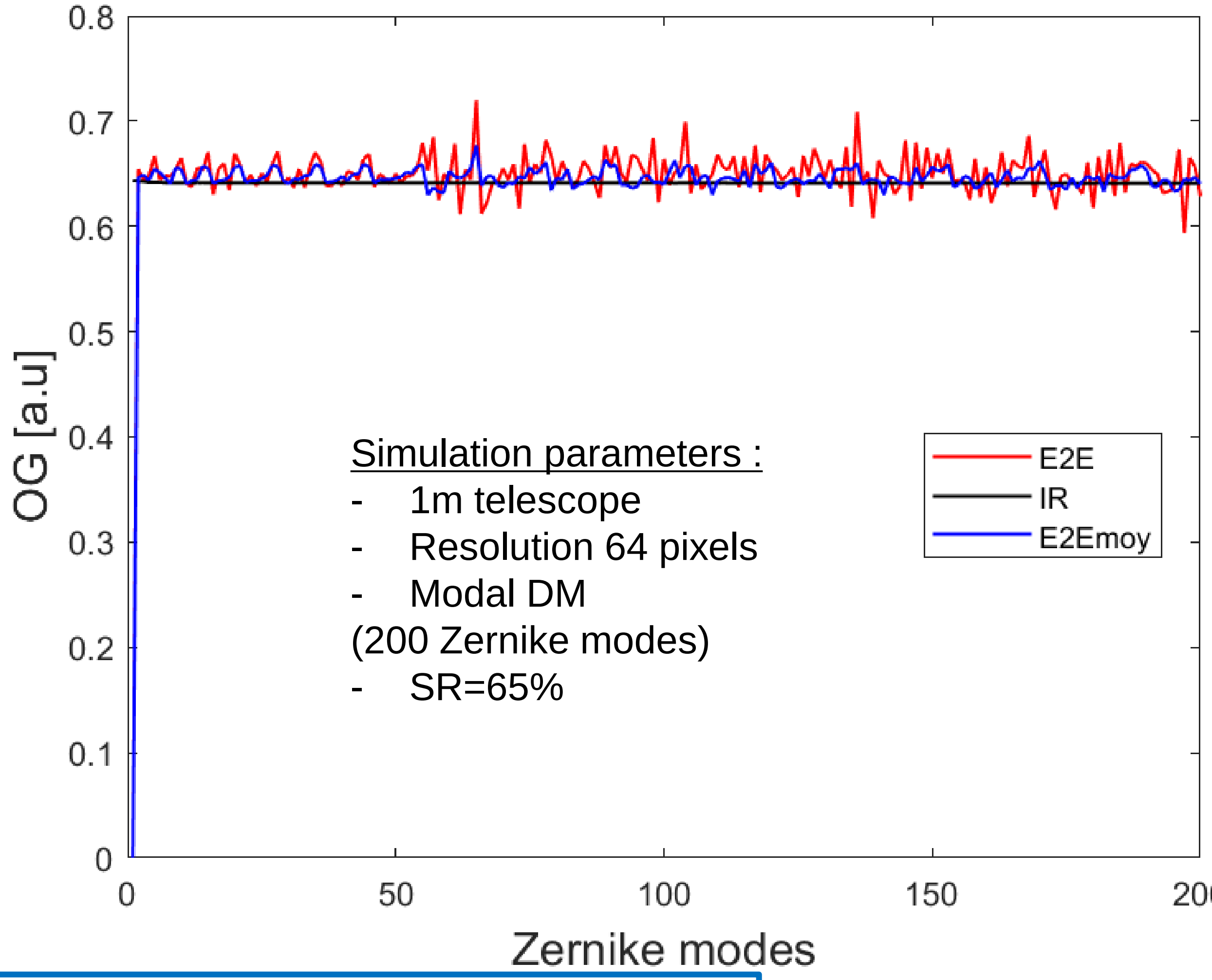
Hypothesis : $D_{res} = D_c T_\varphi$

Impulse response approach :

- At calibration : $IR_c = 2Im\left(\overline{\widehat{m}}\left(\widehat{m} * \widehat{PSF}\right)\right)$
- In presence of phase residuals : IR_{res}

Optical gain : $g_i = \dfrac{\left\langle IR_{res} * \widehat{\widehat{IR_c}} \middle| \varphi_i * \widehat{\widehat{\varphi_i}} \right\rangle}{\left\langle IR_c * \widehat{\widehat{IR_c}} \middle| \varphi_i * \widehat{\widehat{\varphi_i}} \right\rangle}$,

$(\varphi_i)_{1 \le i \le n}$ modal basis



References :

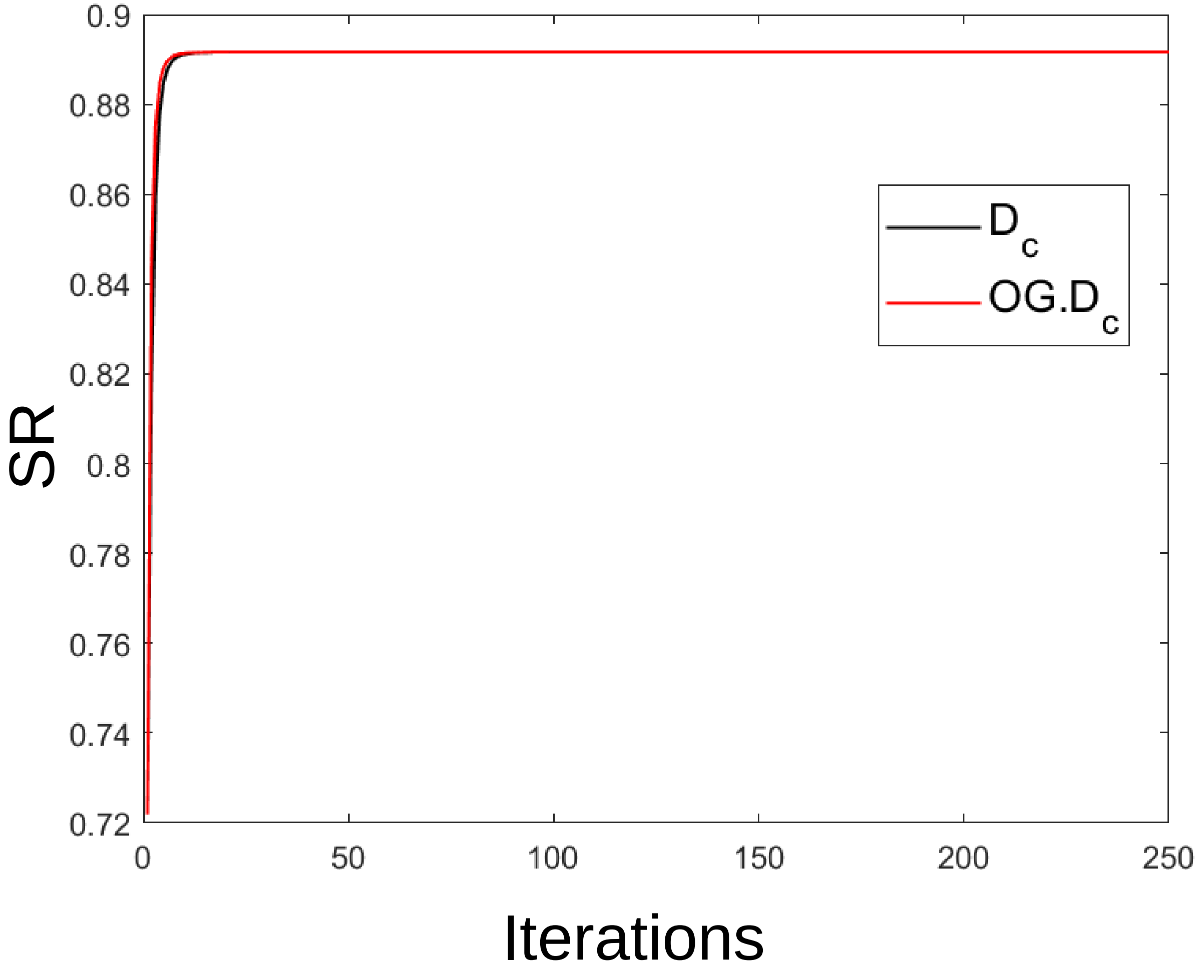
[1] : Chambouleyron, V. (2021). *PhD Thesis*

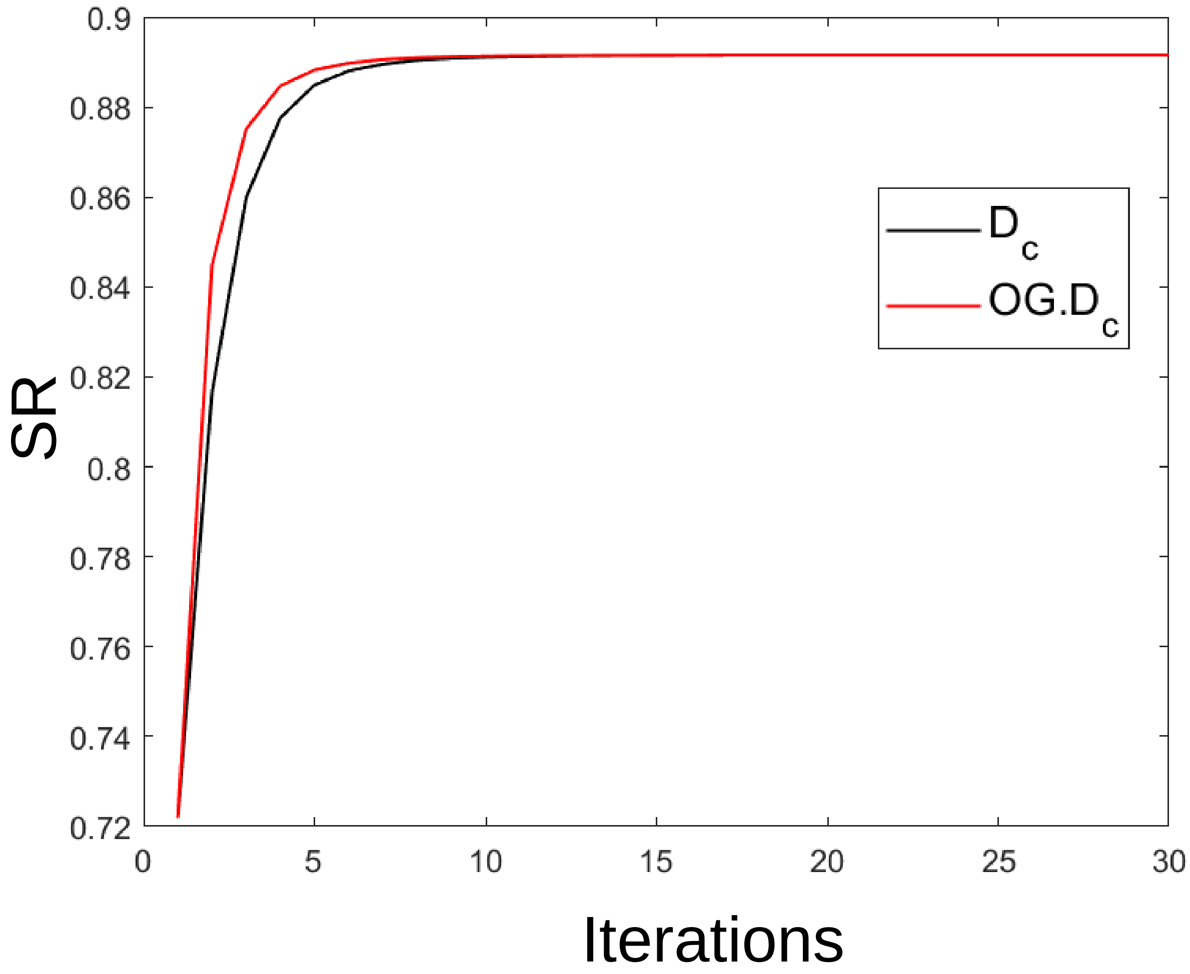
[2] : Chambouleyron, V et al 2021

- **E2E & IR approach give the same OG**
- **OG independant of the modes → $D_{res} = OG.D_c$**

<u>Simulation parameters :</u>
- 1m telescope
- Resolution 64 pixels
- Modal DM
(200 Zernike modes)
- **SR=72%**

Close Loop test on phase residuals





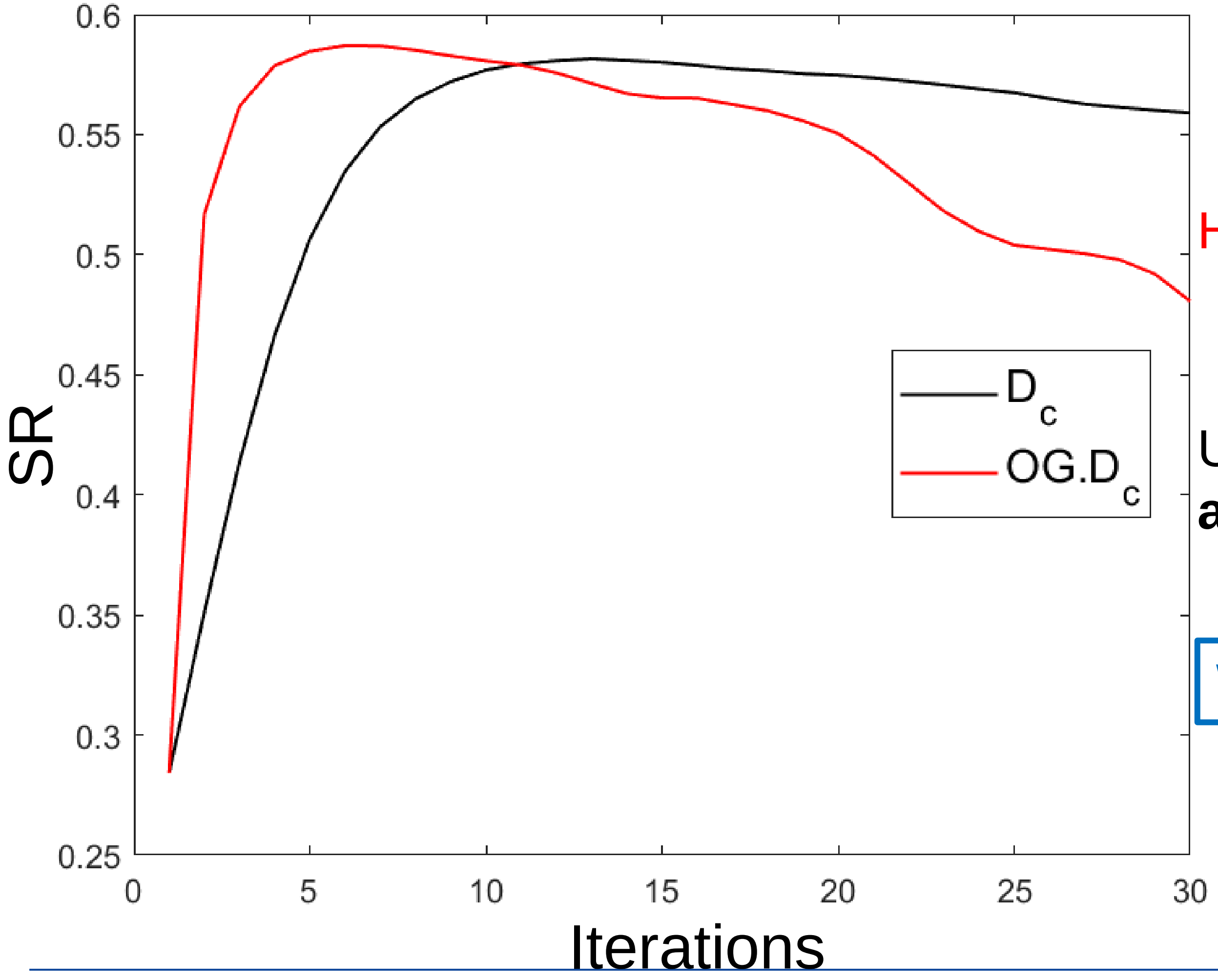
Simulation parameters :

- 1m telescope
- Resolution 64 pixels
- Modal DM

(200 Zernike modes)

- **SR=29%**

Close Loop test : stronger turbulence



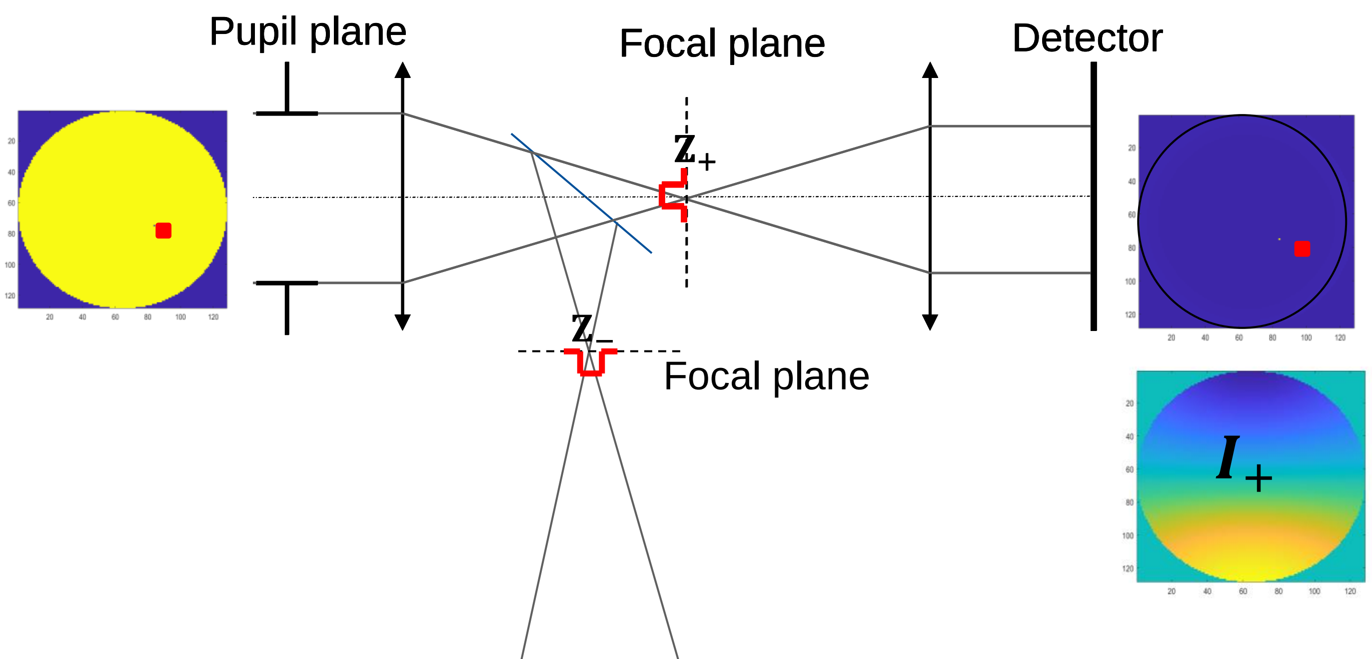
Hypothesis $D_{res} = OG.D_c$ no longer true

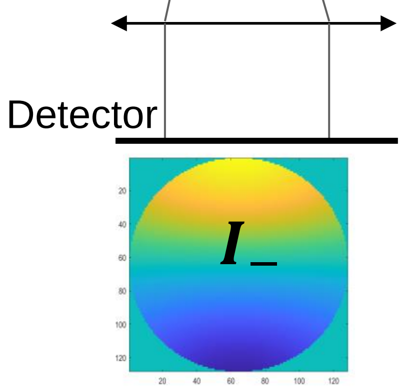
- Modal confusion has to be taking into account → non diagonal terms of T_{φ}

Use OG to modelize ZWFS response for **faint aberrations**

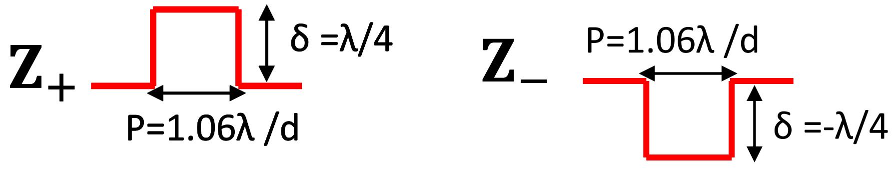
What about increasing the dynamic of the ZWFS

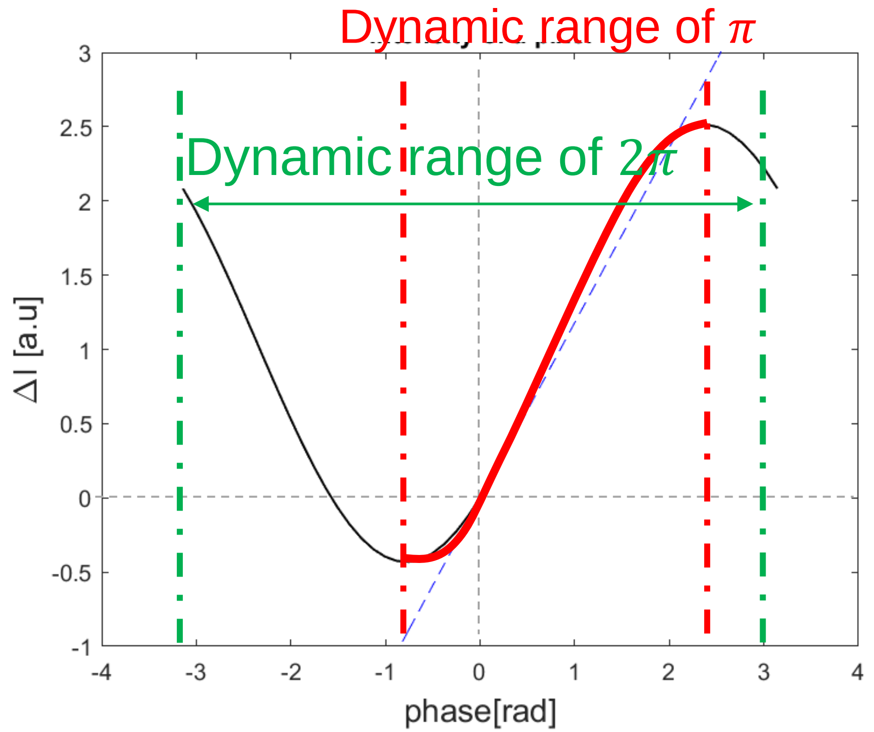
The Phase-Shifted ZWFS





$$I_+ - I_- \rightarrow \sin(\varphi)$$
$$I_+ + I_- \rightarrow \cos(\varphi)$$





Increased dynamic

Reference:
David S. Doelman et al (2019)

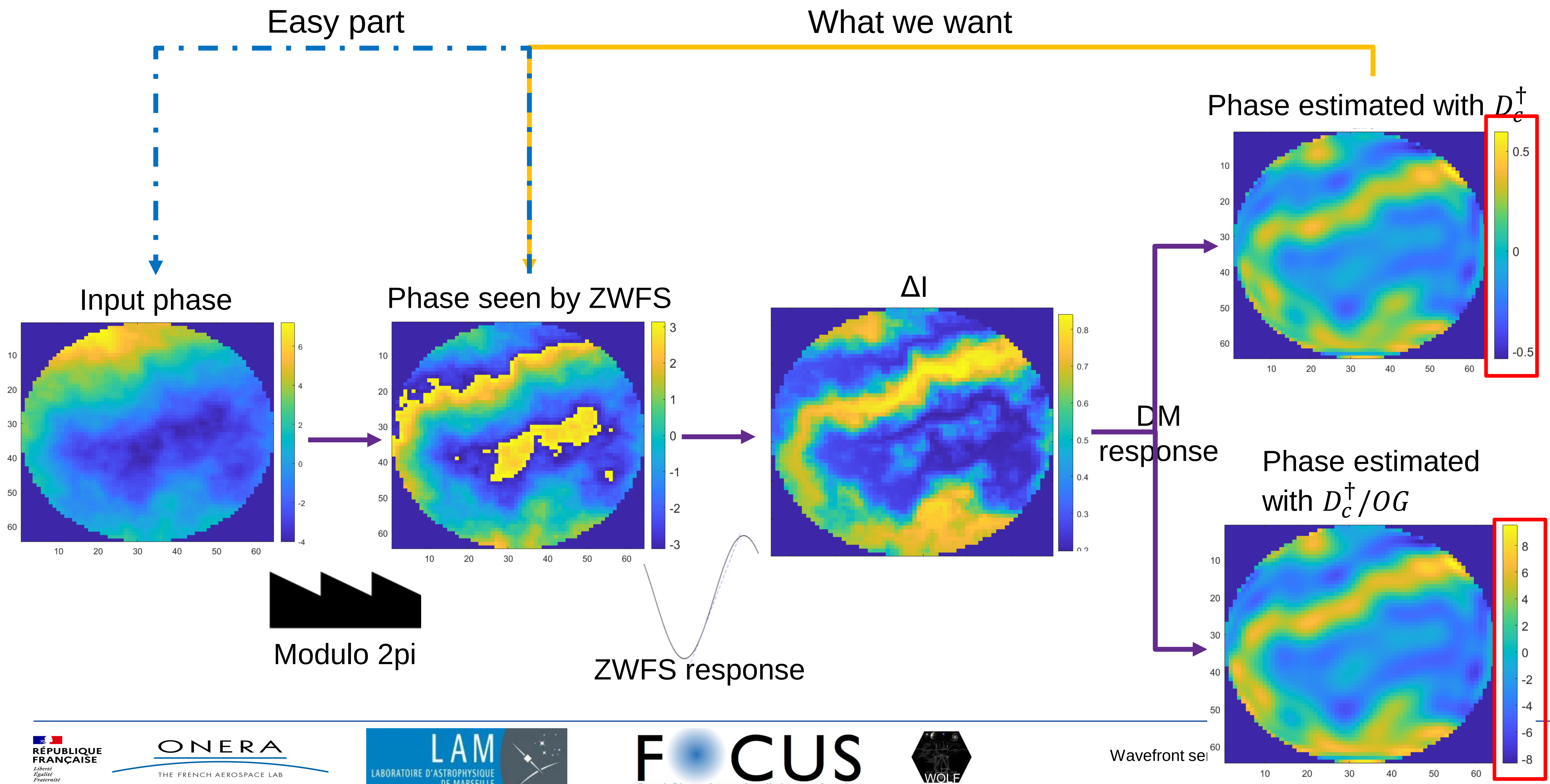
Review : ZWFS non-linearities & dynamic

- Use of OG limited by the phase residuals regime
- Modal confusion has to be taken into account
- Phase-Shifted ZWFS :
  - ➢Increase the dynamic range
  - ➢Less constraints on the phase residuals regime

On going work

Can we bootstrap with the ZWFS?

ZWFS 1st stage AO: phase wrapping issues



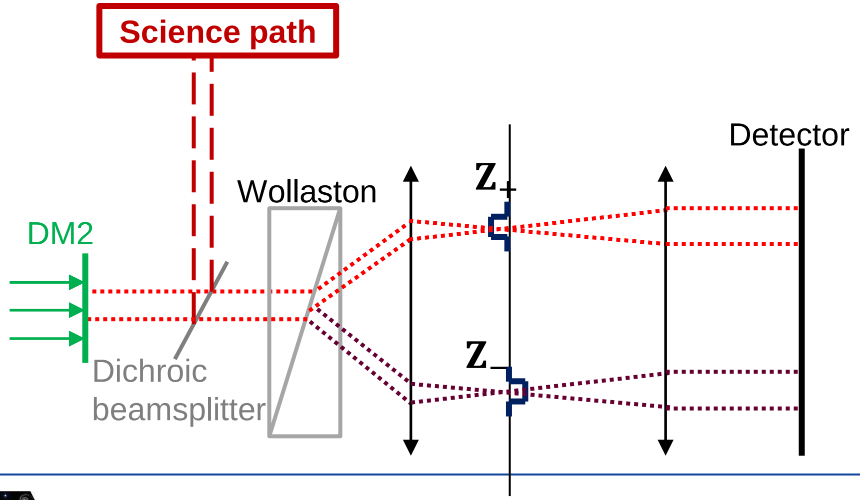
Conclusion

To have a better understanding of the non-linear behavior of the ZWFS to improve the phase estimation

- Using $D_{res}^{\dagger}$ is the best approach to close the loop **BUT** not possible on sky
- ZWFS **strongly non-linear** → bias the phase estimation with the **classical phase reconstructors**
- **OG compensation is limited** because it does not take into account all the non-linear effect
- ZWFS give a **wrap phase estimation** when φ>π
- **Smoothing of the estimated phase → phase unwrapping not possible** with the classical unwrapping algorithm

Perspectives :

- Improve the dynamic range of the ZWFS → Phase-Shifted ZWFS
- Non-linear phase reconstructors



Thank you for listening

AO 4 ELT - 7th Edition

ONERA
THE FRENCH AEROSPACE LAB

LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

cnrs

Aix*Marseille université
Initiative d'excellence

INAF ISTITUTO NAZIONALE DI ASTROFISICA

LABORATORIO NAZIONALE ADONI OTTICA ADATTIVA

ESO

PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR
ANR

WOLF

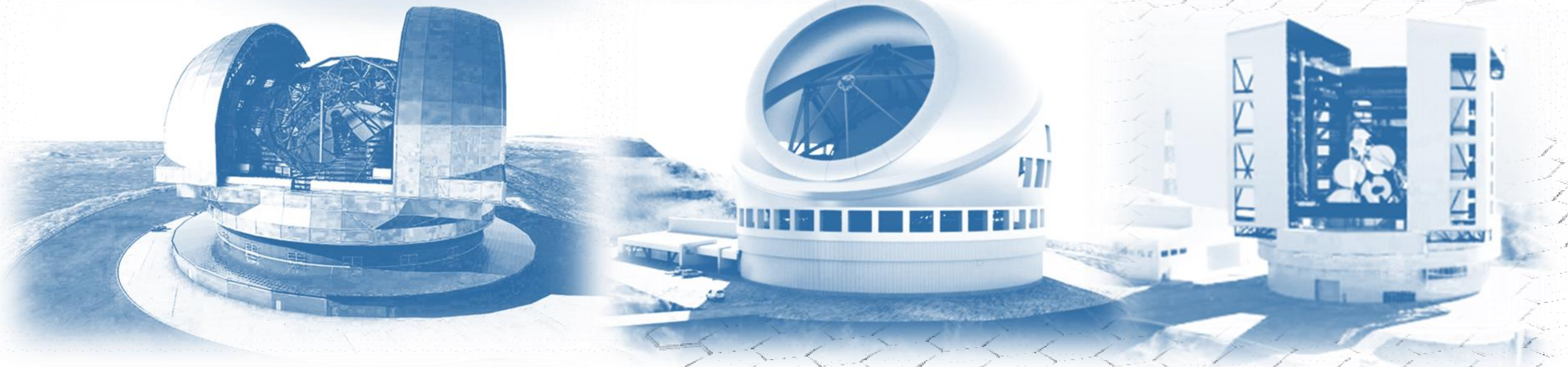
horizon europe
Le programme européen pour la recherche et l'innovation

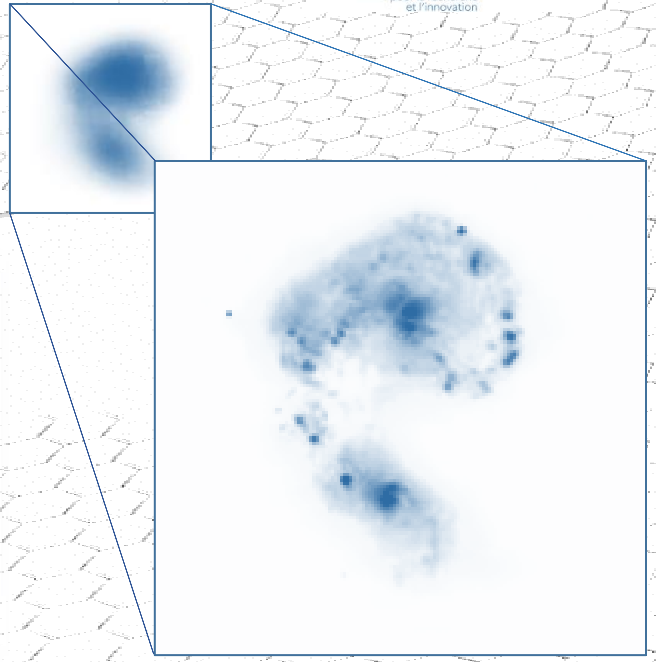
25 to 30 th June 2023

Palais des Papes, Avignon, France

Web site : ao4elt7.sciencesconf.org

More information: Thierry.Fusco@onera.fr, Benoit.Neichel@lam.fr





Annexe 1 : Optical gains (OG)

- Matrix formalism : $\Delta I(\Phi) = D_c\Phi$ if $\Phi \ll 1$
- For large phase amplitude : $\Delta I(\Phi) = D_\Phi \Phi$ with $D_\Phi = D_c T_\Phi$
- T_Φ the matrix which describes the non linear regime : $T_\Phi = D_c^\dagger D_\Phi$

Reconstruction of the phase :

$$\Delta I(\Phi) = D_\Phi \Phi$$
$$\Delta I(\Phi) = D_c T_\Phi \Phi$$

By using M_{com} computed during the calibration we have :

$$\hat{\Phi} = D_c^\dagger D_c T_\Phi \Phi = T_\Phi \Phi$$

- The optical gain g_i are on the diagonal of T_Φ
- Diagonal approximation : $g_i = \frac{\langle \delta I_{res}(\Phi_i) | \delta I_c(\Phi_i) \rangle}{\langle \delta I_c(\Phi_i) | \delta I_c(\Phi_i) \rangle}$, with $\delta I_{res}(\Phi_i) = \frac{\Delta I(\Phi_{res} + \epsilon\Phi_i) - \Delta I(\Phi_{res} - \epsilon\Phi_i)}{2\epsilon}$

Annexe 2 : impulse response of a FFWFS

- Impulse response of a FFWFS $IR = 2Im\left(\tilde{\tilde{m}}\left(\widetilde{m|\tilde{\mathbb{I}}_p|^2}\right)\right)$ with m the phase mask and $FT(m) = \tilde{m}$
- Linear intensity expression : $\Delta I_{lin} = \mathbb{I}_p \Phi * IR$

ZWFS impulse response :