SPHERE non-common path aberrations measurement and pre-compensation with optimized phase diversity processes

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Outline

Specificities of SPHERE NCPA calibration

Baseline solution

- Presentation
- First experimental results on SAXO bench

safe

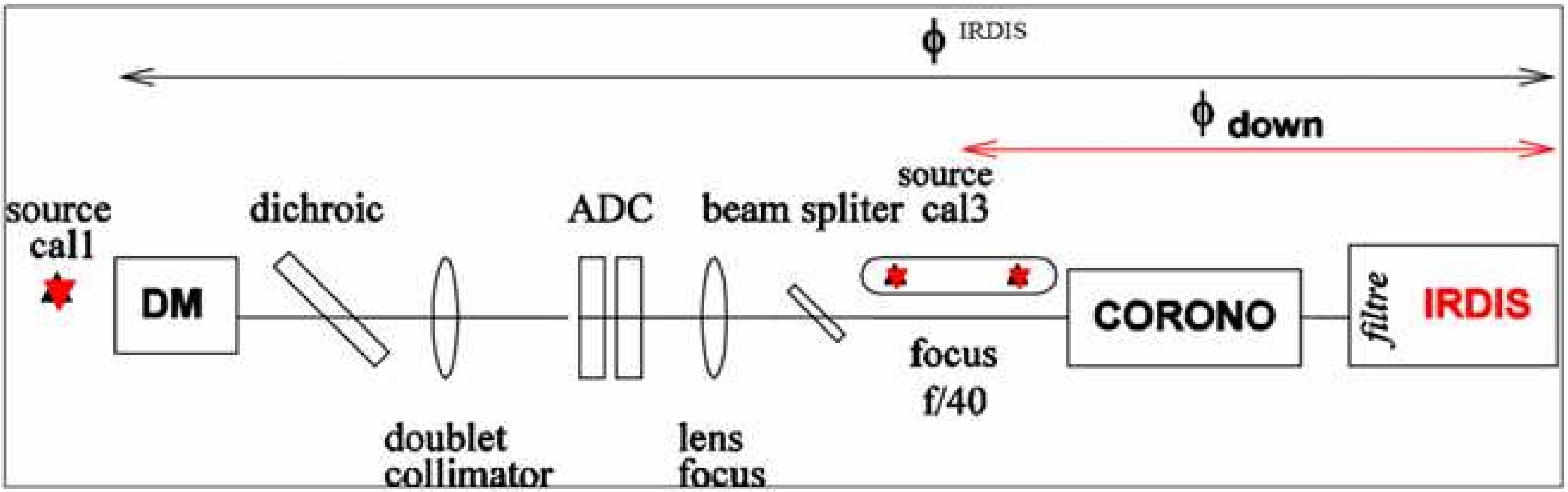
A new alternative approach : coronagraphic phase diversity (COFFEE)

- Concept
- Simulation results
- Toward an experimental validation

smart

Specificities of SPHERE NCPA calibration

- ⇨ Minimisation of the NCPA @ coronagraphic level
- ⇨ Very high accuracy : < 15 nm rms



SPHERE baseline solution

Use of classical phase diversity

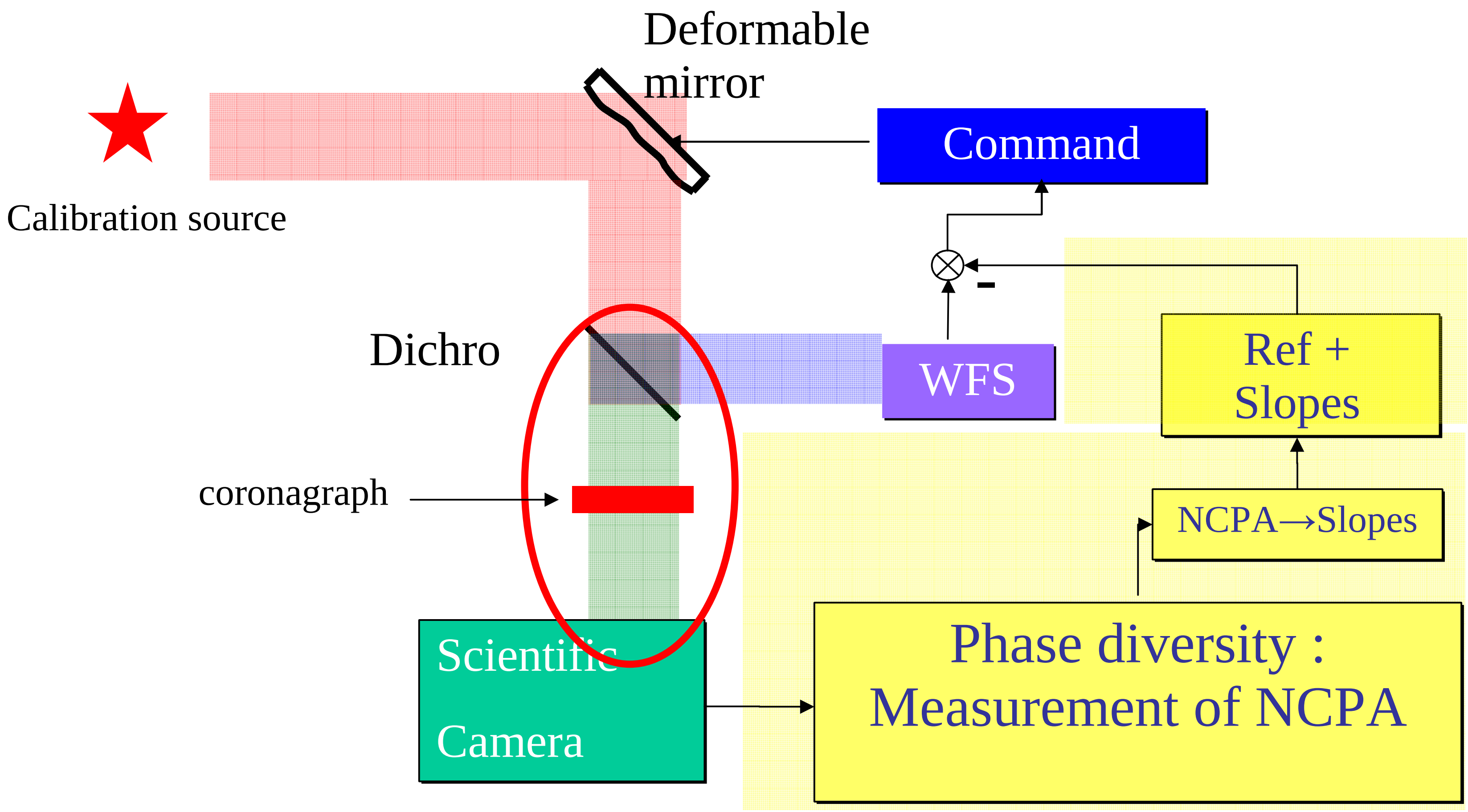
Need to remove the coronagraphic mask from the optical path

Two step measurement process:

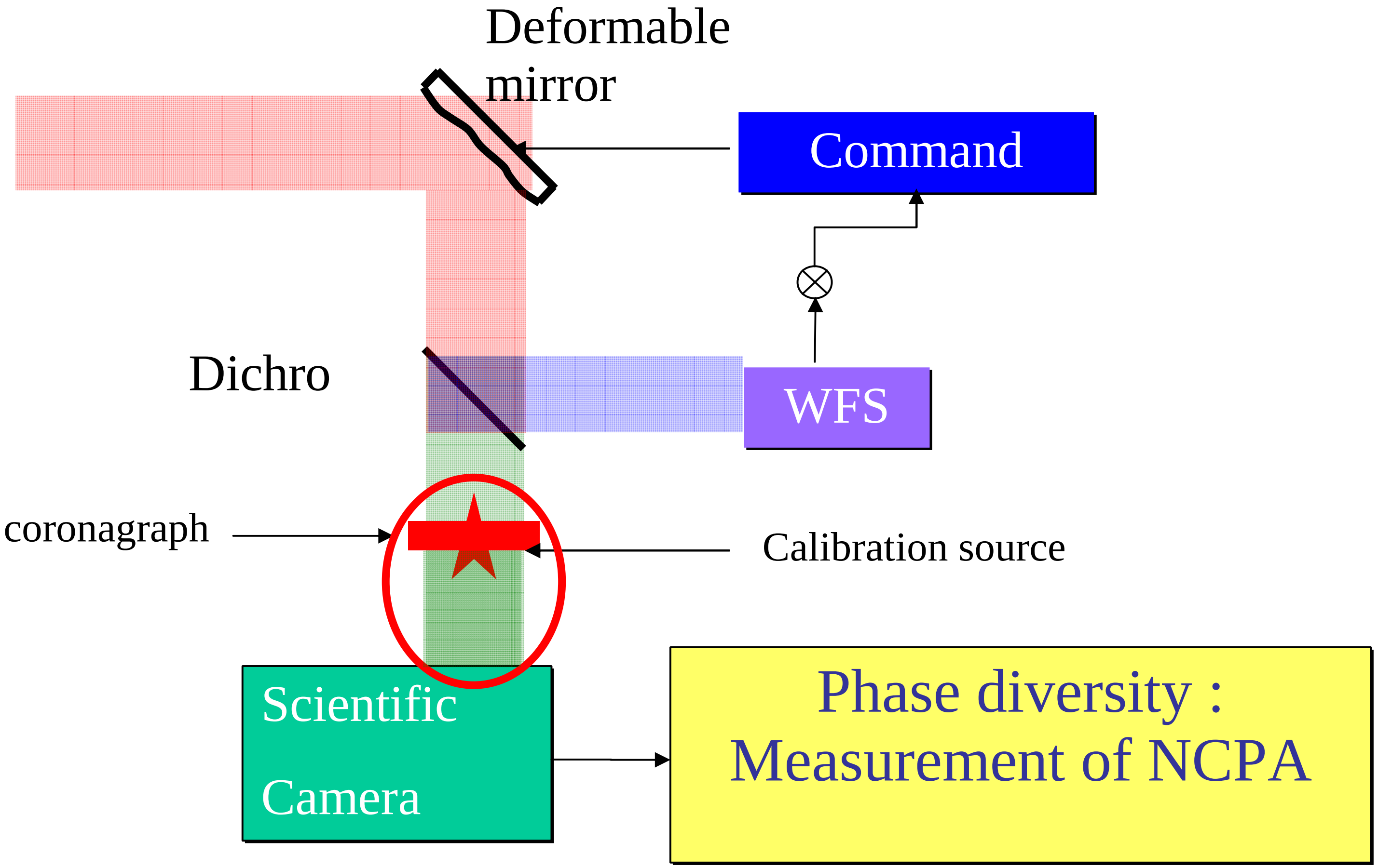
- *Measurement of* φ_{IRDIS}
  (all the aberration down to IRDIS)
  - Pseudo closed loop approach
  - Diversity produced by DM

- *Measurement of* φ_{down}
  (from coronagraphic focal plane down to IRDIS)
  - One shot measurement
  - Diversity provided by source motion along optical axis

Measurement of φ_{IRDIS}



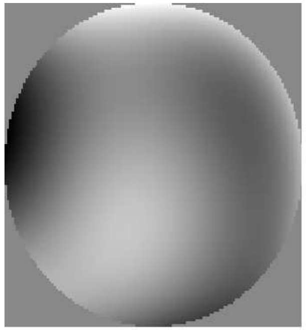
Measurement of φ_{down}



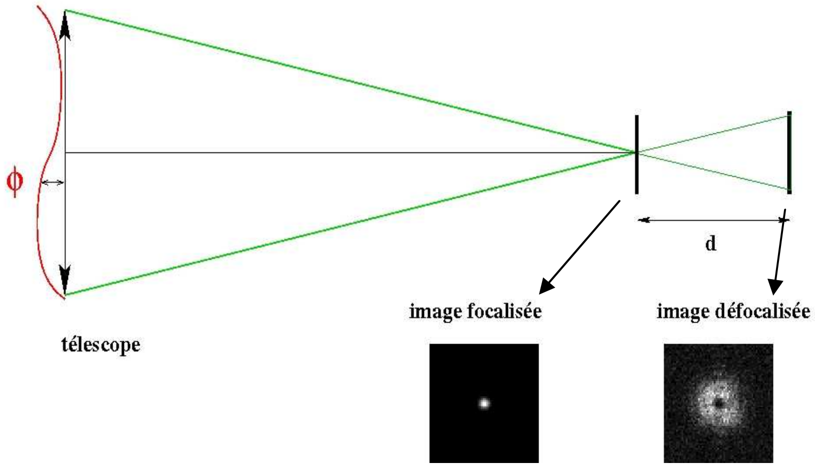
Phase diversity principle

Gonsalves, 1982

And many other since then



Phase dans la pupille

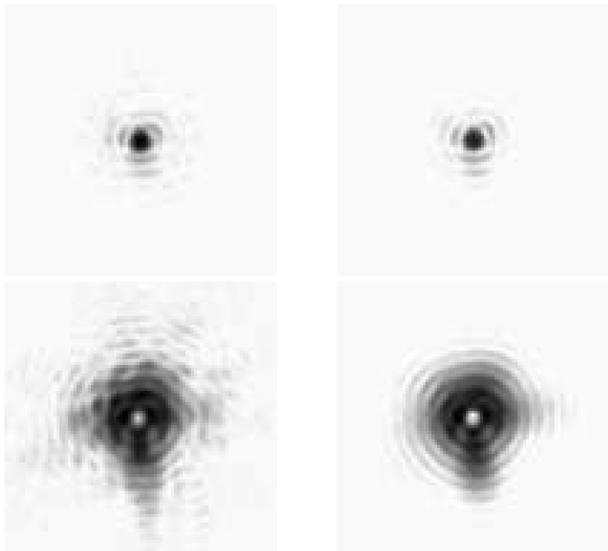


Phase diversity reconstruction

True image | Estimated

Focused

Defocused



$$h = \left| TF^{-1}\left(P.e^{j\phi}\right)\right|^2$$

$$h_d = \left| TF^{-1}\left(P.e^{j(\phi+\phi_d)}\right)\right|^2$$

$$\begin{aligned} i_f &= h_f * o + b_f \\ i_d &= h_d * o + b_d \end{aligned}$$

Algorithm optimisation: MAP approach

Criterion to be minimized

$$J(o,\phi) = \left\| \frac{i_f(\vec{r}) - h_f(\vec{r}) * o(\vec{r})}{\sigma_f(r)} \right\|^2 + \left\| \frac{i_d(\vec{r}) - h_d(\vec{r}) * o(\vec{r})}{\sigma_d(r)} \right\|^2 + \left(\frac{1}{2}\phi^t R_\phi^{-1}\phi\right)$$

Maximum likelihood

- **Noise statistics :**
  - **Non-uniform Gaussian law**

  ⇨Good approximation of photon + detector noise

  ⇨Allows to deal with different exposure time between focused and defocused images

  (↗ SNR on defocused image) + **pixel basis !!!!**

  (the less “informative one”)

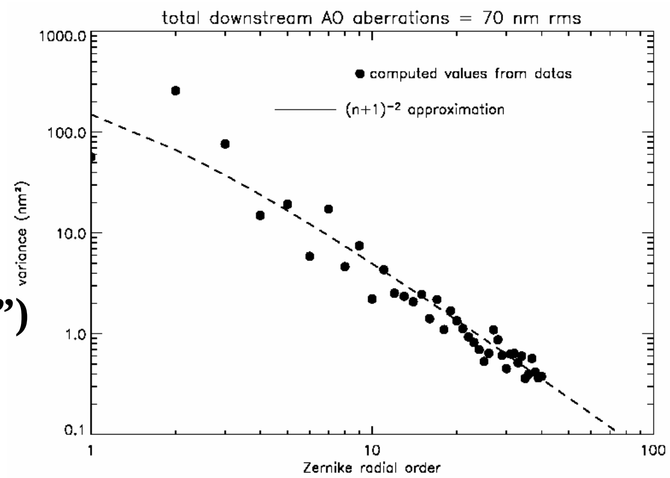
- **Estimation of object map**

  => Deal with Ghosts, Slightly extended object / vibrations and residual turbulence

A priori knowledge

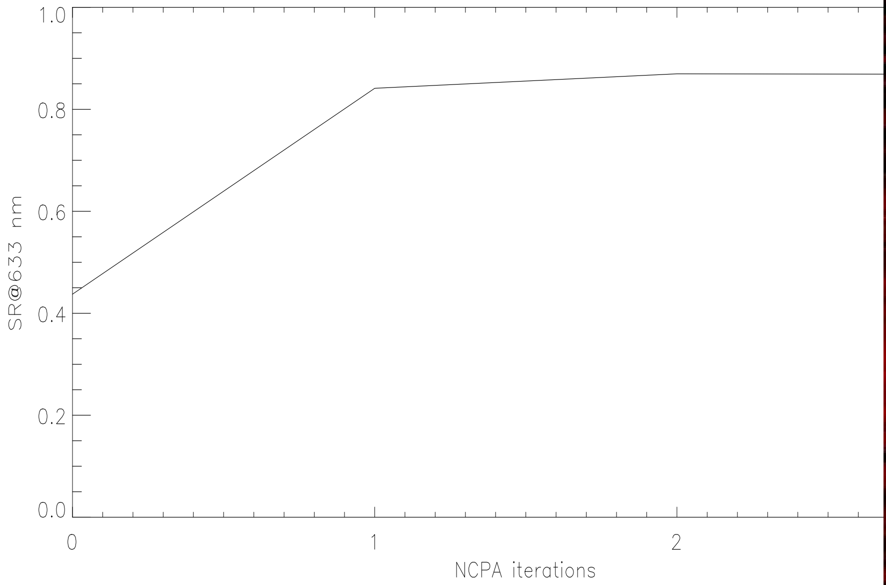
⇨Regularisation term

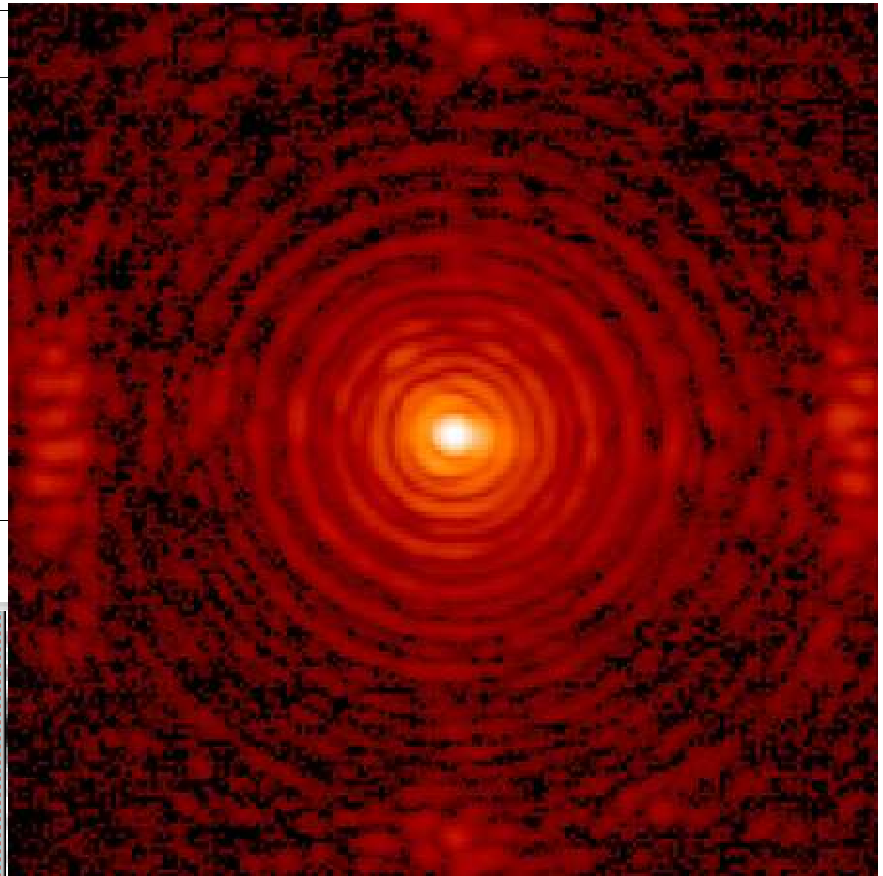
⇨Optical aberrations : known spectrum

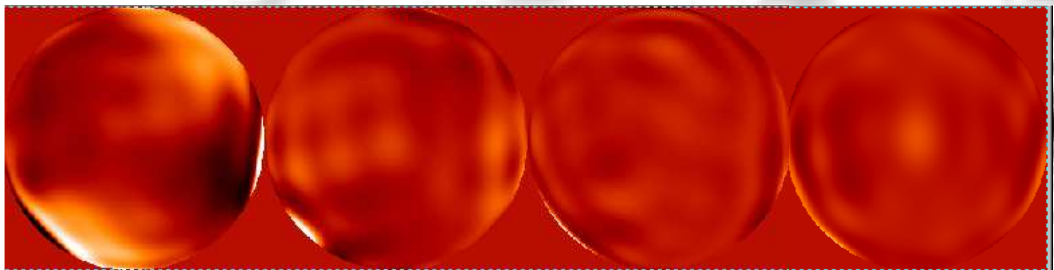


Experimental validation of NCPA compensation on SAXO

Application of phase diversity and pseudo-closed loop scheme for NCPA correction on SAXO







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An alternative approach
the coronagraphic phase diversity

Modification of the "classical phase diversity" direct model

$o*h \rightarrow Fh_c$ where F = flux and h_c = coronagraphic PSF

$$h = \left| TF^{-1}(P\, e^{i(\phi_{total})}) \right|^2$$

$$h_c = \left| TF^{-1}(P\, e^{i(\phi_{upstream}+\phi_{downstream})}) - \eta_0 TF^{-1}(Pe^{i\phi_{downsteam}}) \right|^2$$

Modification of the known phase to produce diversity

Defocus (a few rad) → sum of defocus and astig (0.8 rad each)

$$J = \left| \frac{i_c^{foc} - Fh_c^{foc}}{\sigma^{foc}} \right|^2 + \left| \frac{i_c^{div} - Fh_c^{div}}{\sigma^{div}} \right|^2 = J_{foc} + J_{diversity}$$

→ To be minimized

To be minimized w.r.t. $\phi_{upstream}$ and $\phi_{downstream}$

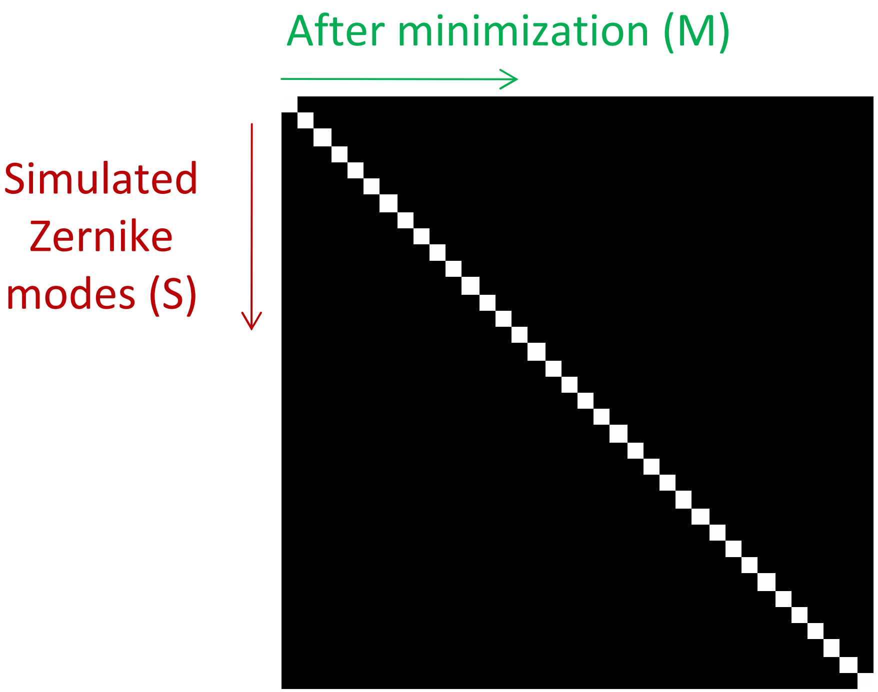
And it has a name : **<u>COFFEE</u>** **COronagraphic Focal-plane wave-Front Estimation for Exoplanet detection**

Case of the perfect coronagraph (I)

Interaction matrix

❖ Simulation :

- $WFE_{upstream}$ = 30 nm (0,34 rad), $WFE_{downstream}$ = 0 nm (λ = 550 nm)
- 36 Zernike modes upstream and downstream
- Simulation : perfect coronagraph ; minimization : perfect coronagraph

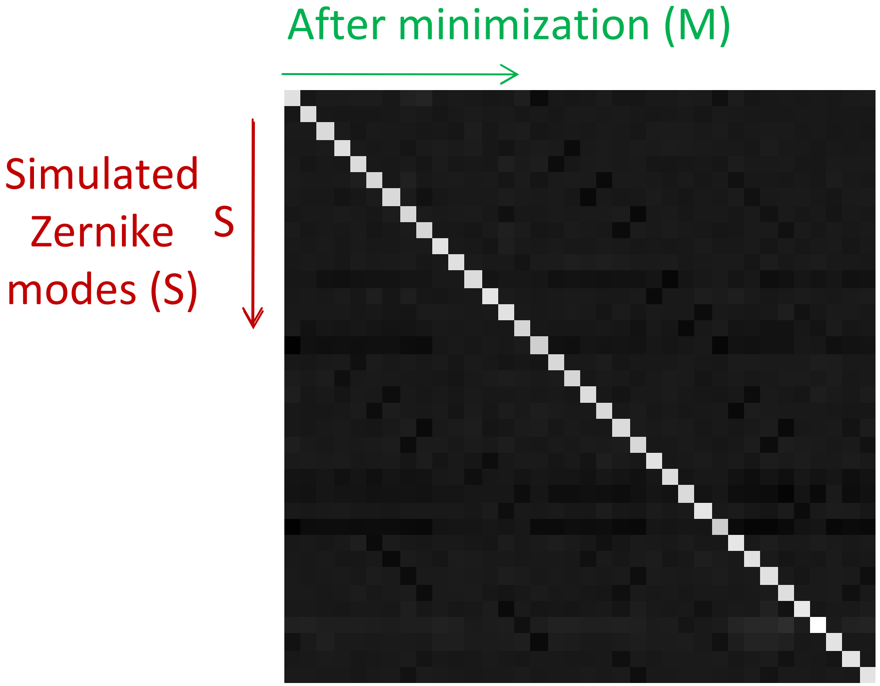


Case of the perfect coronagraph (II)

Interaction matrix with noise

❖ Simulation :

- $WFE_{upstream}$ = 30 nm, $WFE_{downstream}$ = 0 nm (λ = 550 nm)
- 36 Zernike modes upstream and downstream
- Simulation : perfect coronagraph ; minimization : perfect coronagraph
- Noise : shot noise, electronic noise c



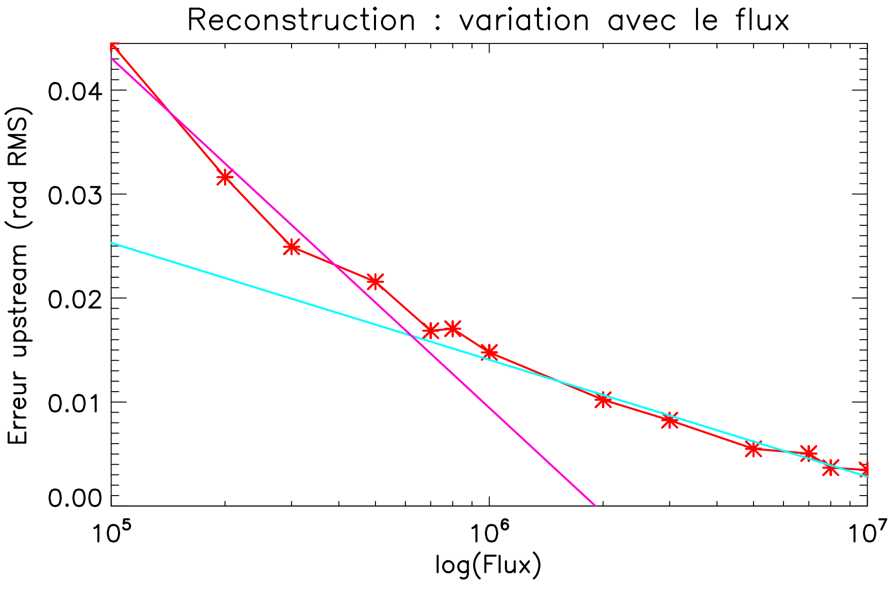
$$\varepsilon = \sqrt{\sum_i \left| a_i^{rec} - a_i^{sim} \right|}$$

Case of the perfect coronagraph (IV)

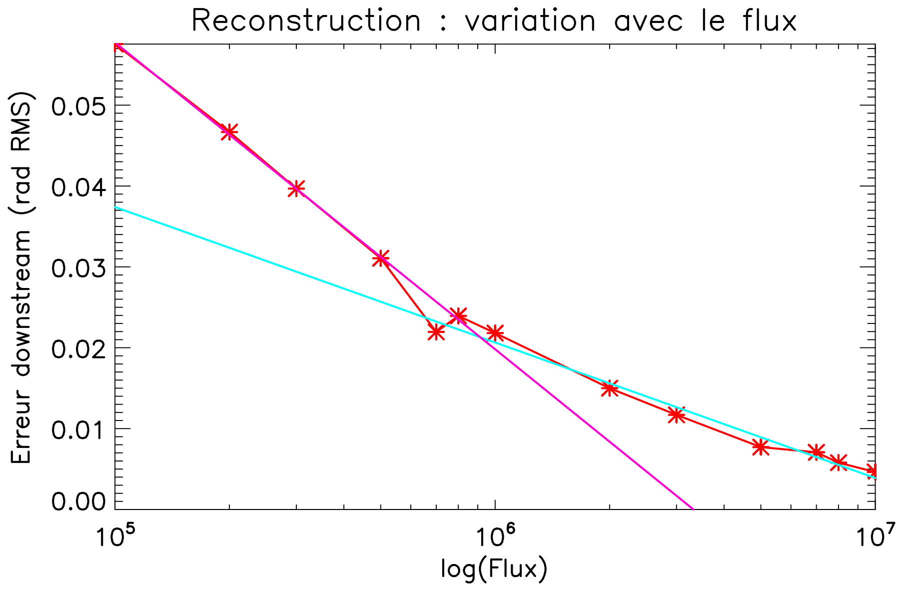
Error sensitivity : flux variations

❖ Simulation :

- $WFE_{upstream}$ = 30 nm, $WFE_{downstream}$ = 30 nm (λ = 550 nm)
- 36 Zernike modes upstream and downstream
- Simulation : perfect coronagraph ; minimization : perfect coronagraph
- Noise : shot noise, electronic noise



Upstream



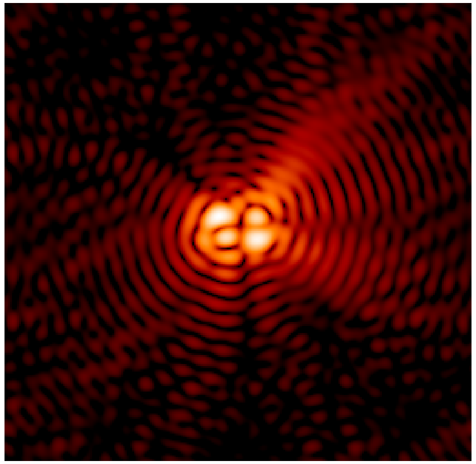
Downstream

From perfect to real coronagraphs (I)

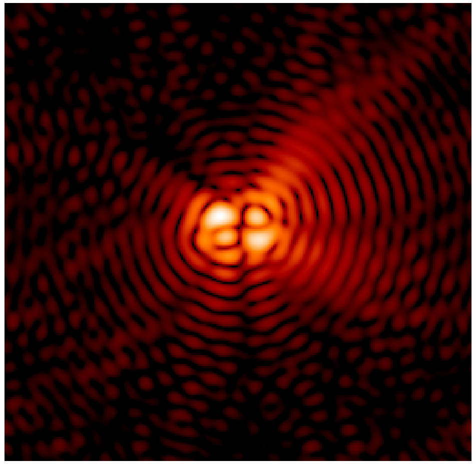
⇒ Goal : find the closest real coronagraph to the perfect model (Application of the previous model to realistic case)

⇒ Simulation :

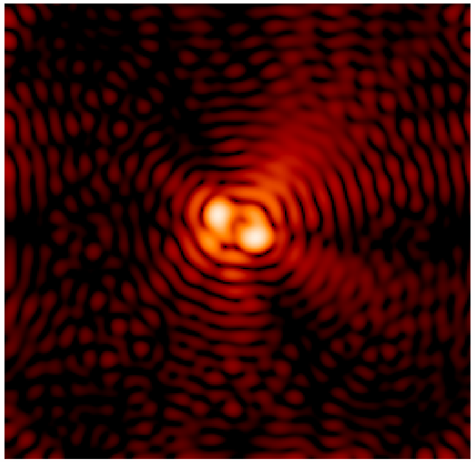
- $WFE_{upstream}$ = 30 nm, $WFE_{downstream}$ = 30 nm (λ = 550 nm)
- 15 Zernike modes upstream and downstream
- Phases upstream and downstream randomly generated



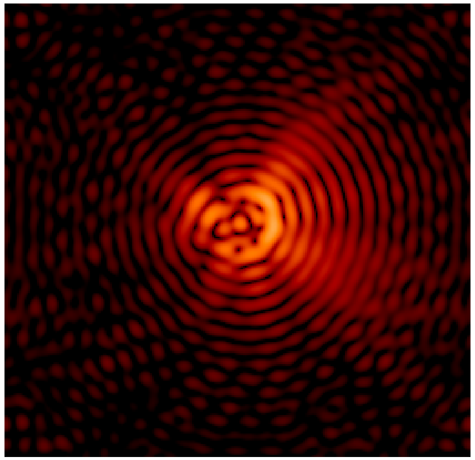
Perfect coronagraph (PC) = MODEL



RRPM



4QPM



Lyot coronagraph (Lyot stop = 0.8)

From perfect to real coronagraphs – case of the Lyot coronagraph

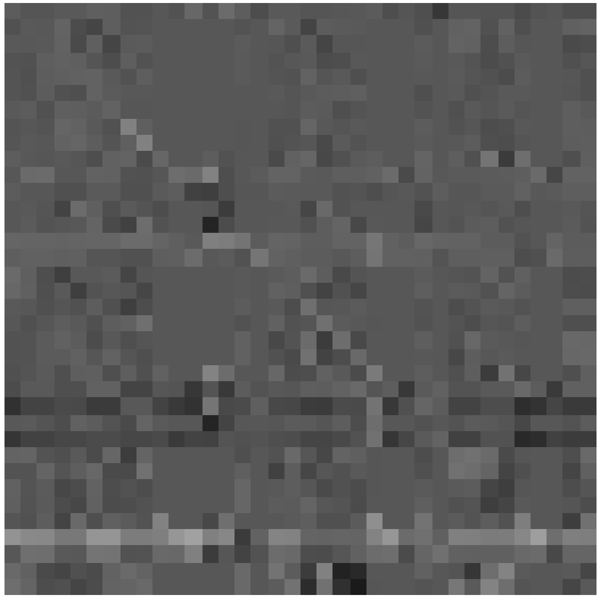
Impact on interaction matrix (no noise)

❖Simulation :

- $WFE_{upstream}$ = 30 nm (0,34 rad), $WFE_{downstream}$ = 0 nm (λ = 550 nm)
- 36 Zernike modes upstream and downstream
- Simulation : Lyot coronagraph ; minimization : perfect coronagraph
- 4 lambda/D -- Lyot Stop = 0.8

After minimization (M)

Simulated Zernike modes (S)

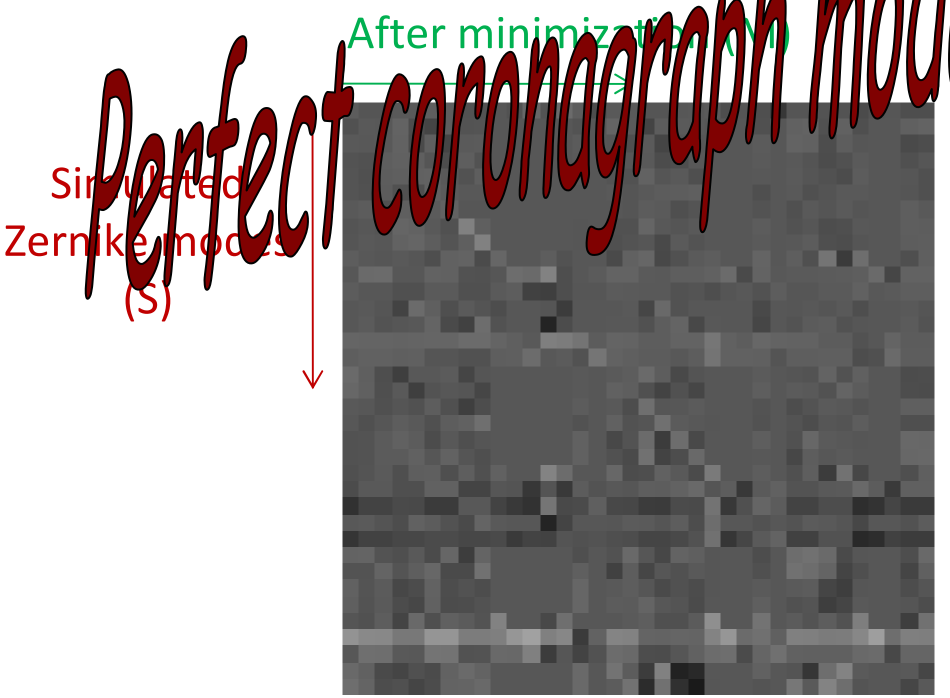


From perfect to real coronagraphs – case of the Lyot coronagraph

Impact on interaction matrix (no noise)

❖Simulation :

- $WFE_{upstream}$ = 30 nm (0,34 rad), $WFE_{downstream}$ = 0 nm (λ = 550 nm)
- 36 Zernike modes upstream and downstream
- Simulation : Lyot coronagraph ; minimization : perfect coronagraph
- 4 lambda/D -- Lyot Stop = 0.8



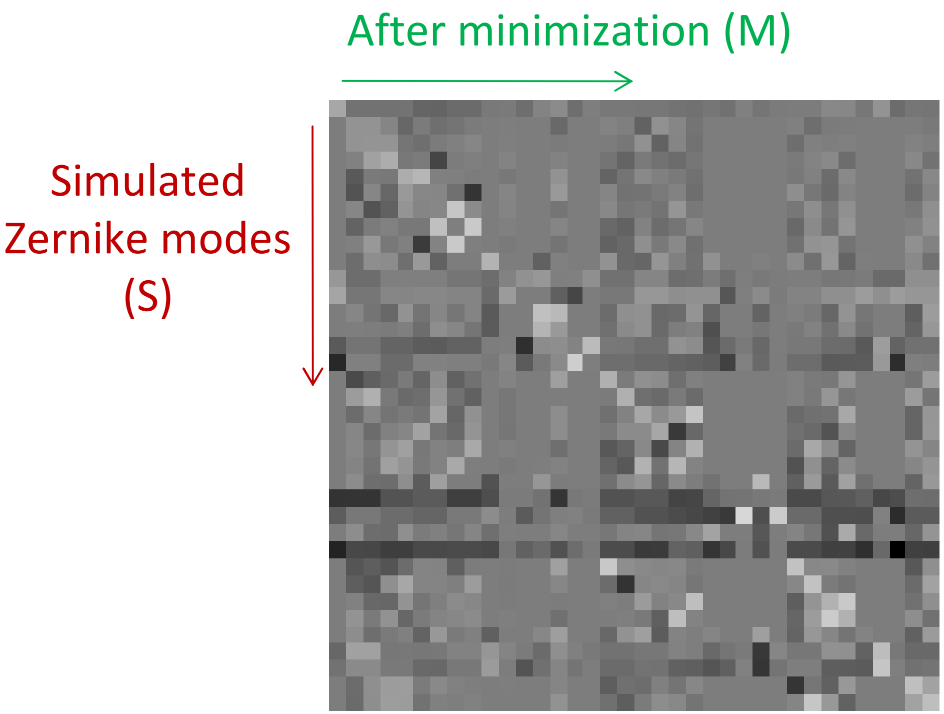
Perfect coronagraph model not accurate enough

From perfect to real coronagraphs – case of the 4QPM

Impact on interaction matrix (no noise)

❖Simulation :

- $WFE_{upstream}$ = 30 nm (0,34 rad), $WFE_{downstream}$ = 0 nm (λ = 550 nm)
- 36 Zernike modes upstream and downstream
- Simulation : 4QPM coronagraph ; minimization : perfect coronagraph



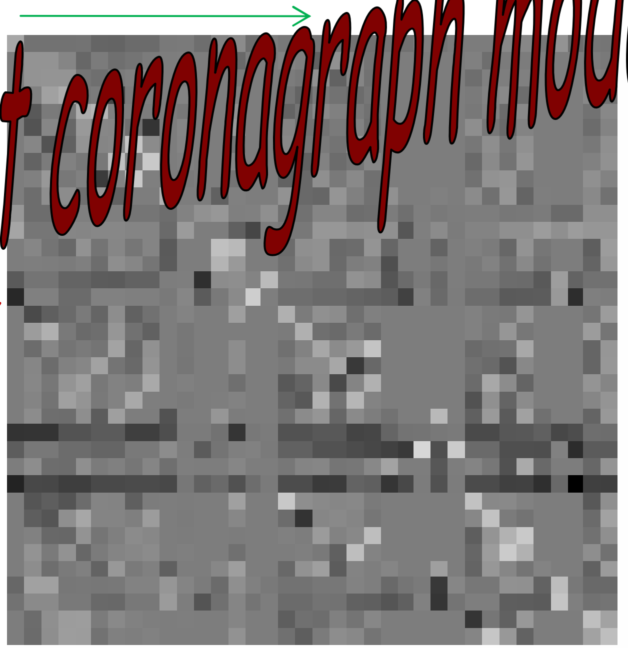
From perfect to real coronagraphs – case of the 4QPM

Impact on interaction matrix (no noise)

❖Simulation :

- WFE$_{upstream}$ = 30 nm (0,34 rad), WFE$_{downstream}$ = 0 nm (λ = 550 nm)
- 36 Zernike modes upstream and downstream
- Simulation : 4QPM coronagraph ; minimization : perfect coronagraph

Perfect coronagraph model not accurate enough



From perfect to real coronagraphs – RRPM

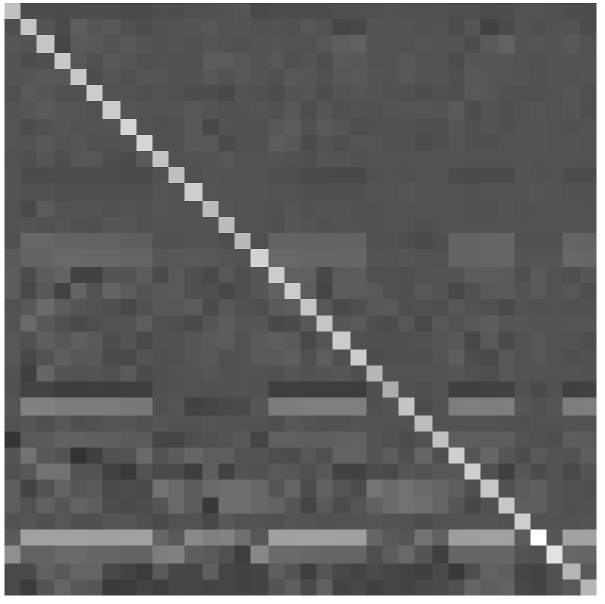
Impact on interaction matrix (no noise)

❖Simulation :

- $WFE_{upstream}$ = 30 nm (0,34 rad), $WFE_{downstream}$ = 0 nm (λ = 550 nm)
- 36 Zernike modes upstream and downstream
- Simulation : RRPM coronagraph ; minimization : perfect coronagraph
- 1.06 l/D – Lyot stop = 1

After minimization (M)

Simulated Zernike modes (S)



From perfect to real coronagraphs – RRPM

Impact on interaction matrix (no noise)

❖Simulation :

- $WFE_{upstream}$ = 30 nm (0,34 rad), $WFE_{downstream}$ = 0 nm (λ = 550 nm)
- 36 Zernike modes upstream and downstream
- Simulation : RRPM coronagraph ; minimization : perfect coronagraph
- 1.06 l/D – Lyot stop = 1

After minimization (M

Simulated Zernike modes (S)

YES ! It works !!!!!

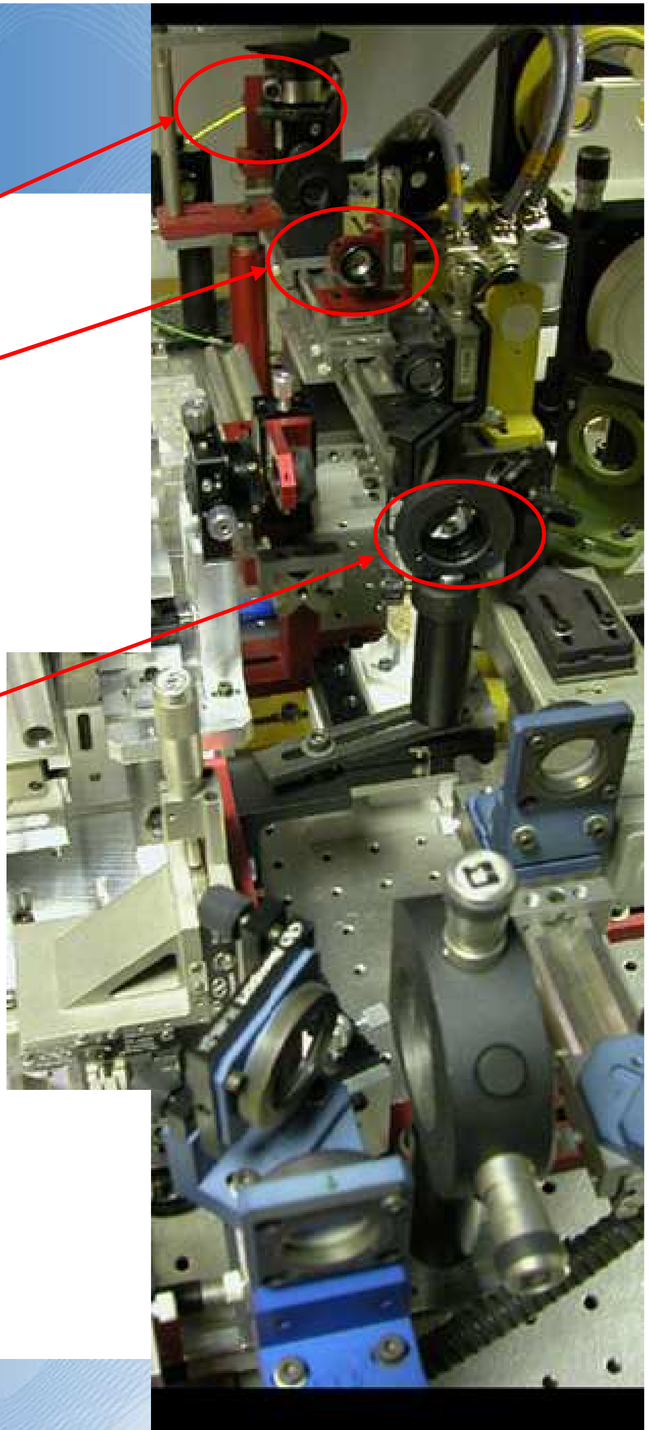
Experimental validation in progress …

- « Non-adapted » RRPM, originaly designed:
  - for λ = 677nm
  - for a FRatio of 100
  - with pupil apodization

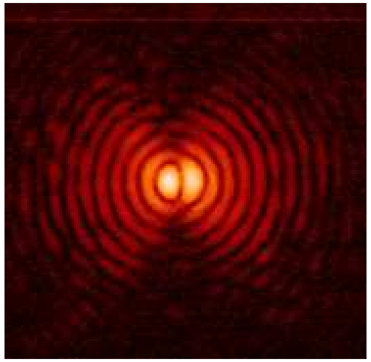
- We used:
  - λ = 675nm
  - FRatio of 90
  - without apodization

- Tilt introduction : coronagraphic mask shift

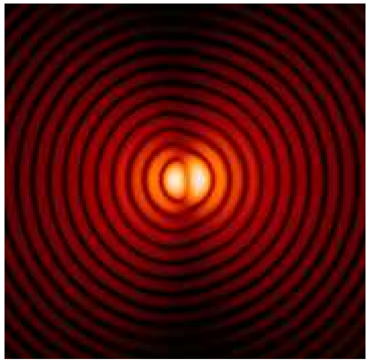
→ corresponds to a beam shift on the coronagraphic mask



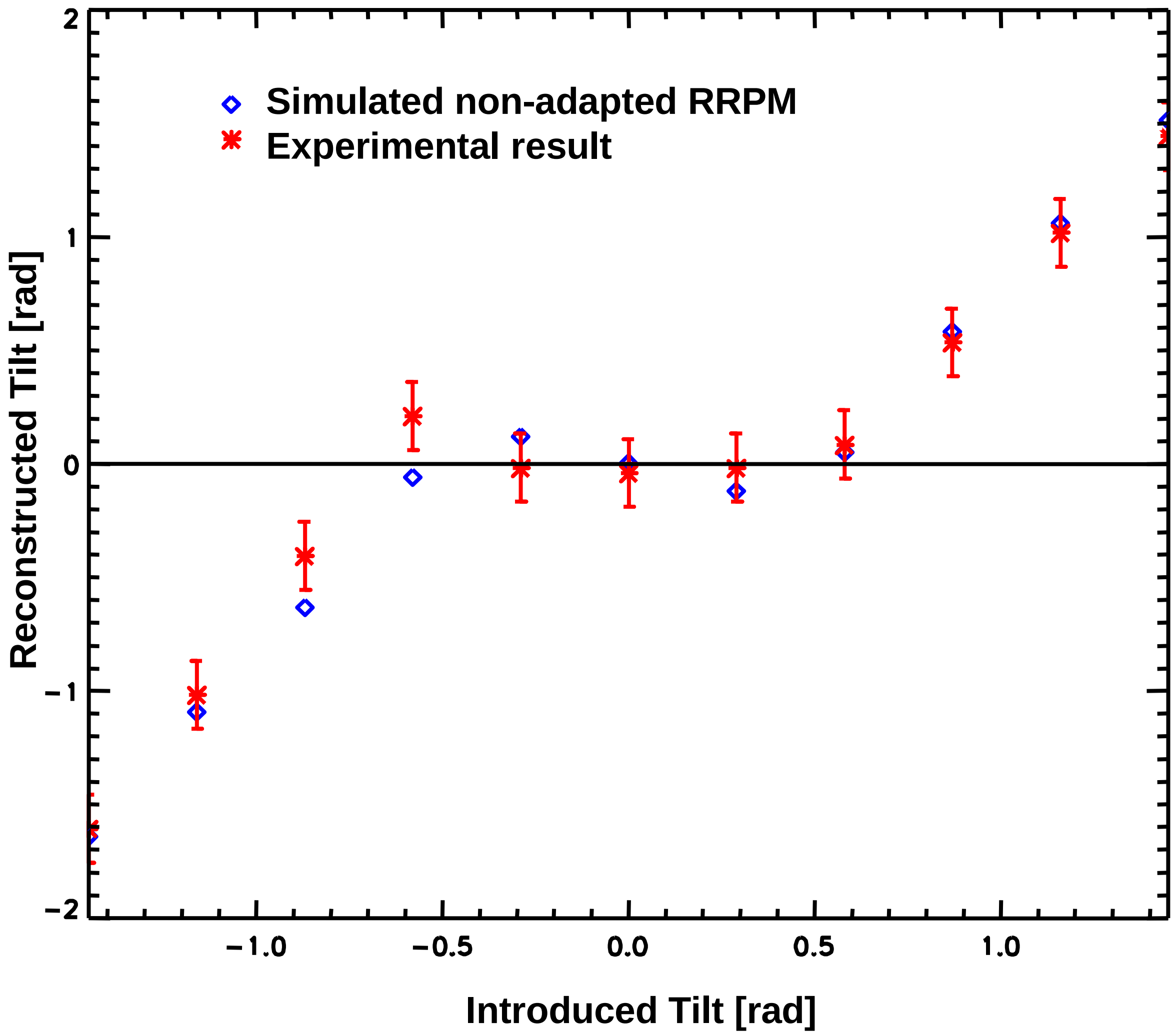
Very first result : reconstruction of a tilt ramp



Exp image



Reconstructed



Conclusions

NCPA pre-compensation for SPHERE : very challenging process

- Very tight performance
- Minimization on coronagraphic mask and not scientific detector

⇒ Complex procedure

⇒ Fully studied and optimized in simulation

⇒ First experimental results => residual = 16 nm rms (without any optimisation)

Full validation of COFFEE by simulation

- Based on « perfect coronagraph » model
- Estimation of both $\phi_{upstream}$ and $\phi_{downstream}$ aberrations on 2 images
- Proposition of a mixed phase diversity defoc + astig
- Classical behaviour wrt noise
- Tested robustness to realistic coronagraph: RRPM

Very first experiments with COFFEE on « non-adapted » RR mask

- seem to be coherents with simulation

Perspectives

Full experimental validation at ONERA with LAM support

- Tip-Tilt and Low orders estimation
- High orders estimation

Extension of coronagraphic imaging model to other coronagraph (4Q, Lyot)

Extension to AO-corrected long exposure images

Extrapolation of performance on SPHERE system