

# Enjeux et limites des futurs imageurs spatiaux d'exoplanètes

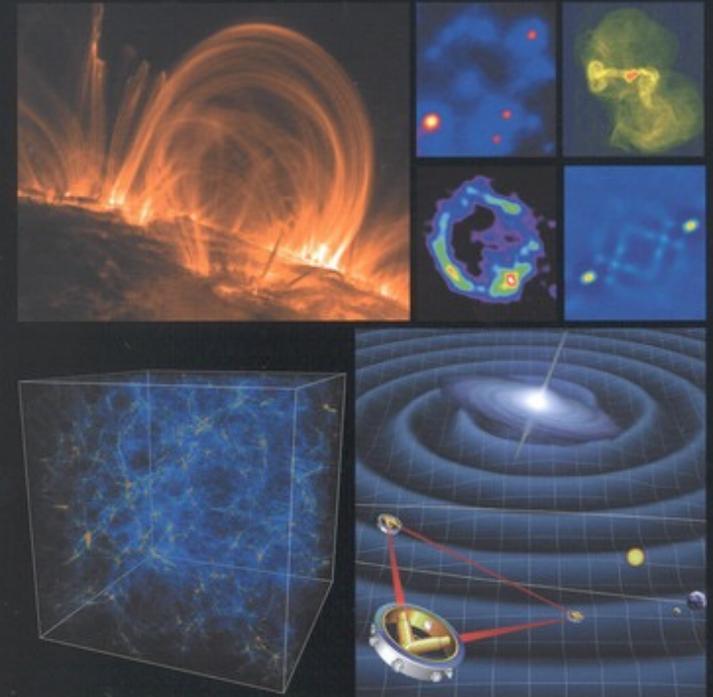
Lucie Leboulleux *et al.*





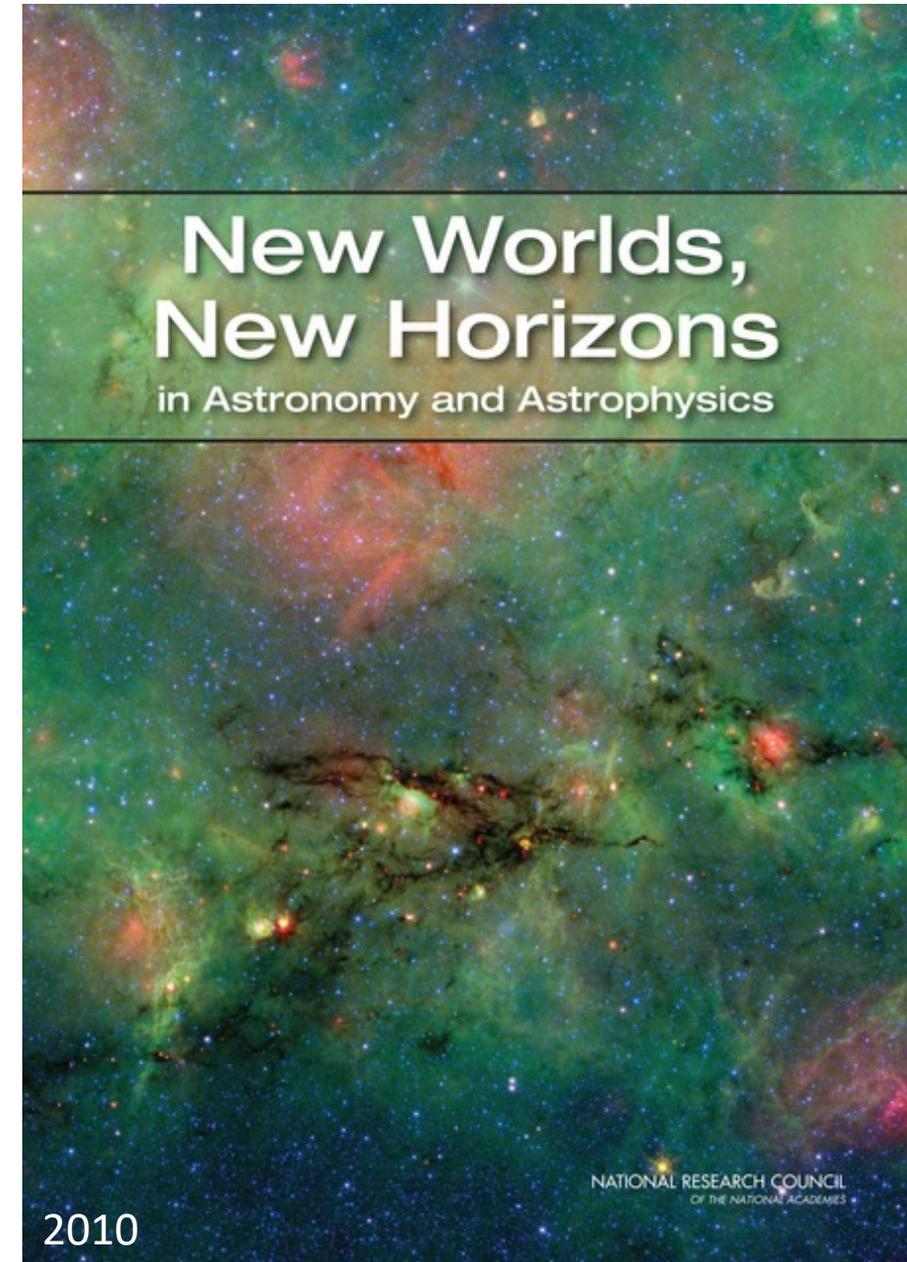
# Astronomy and Astrophysics in the New Millennium

PANEL REPORTS

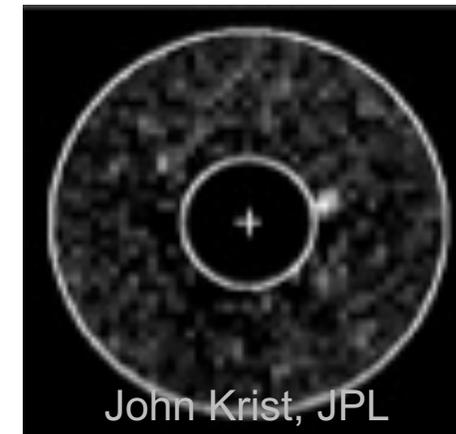
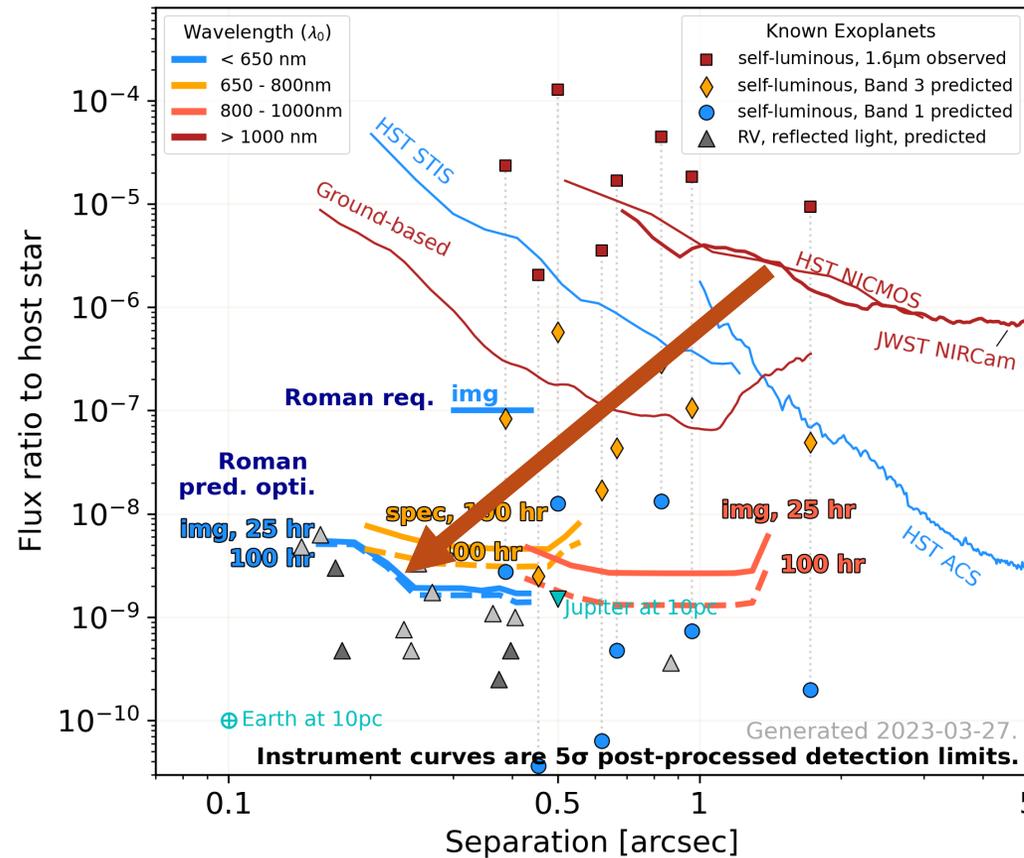


2001

NRC  
National Research Council



V. Bailey



## BESOINS

Haute  
séparation angulaire

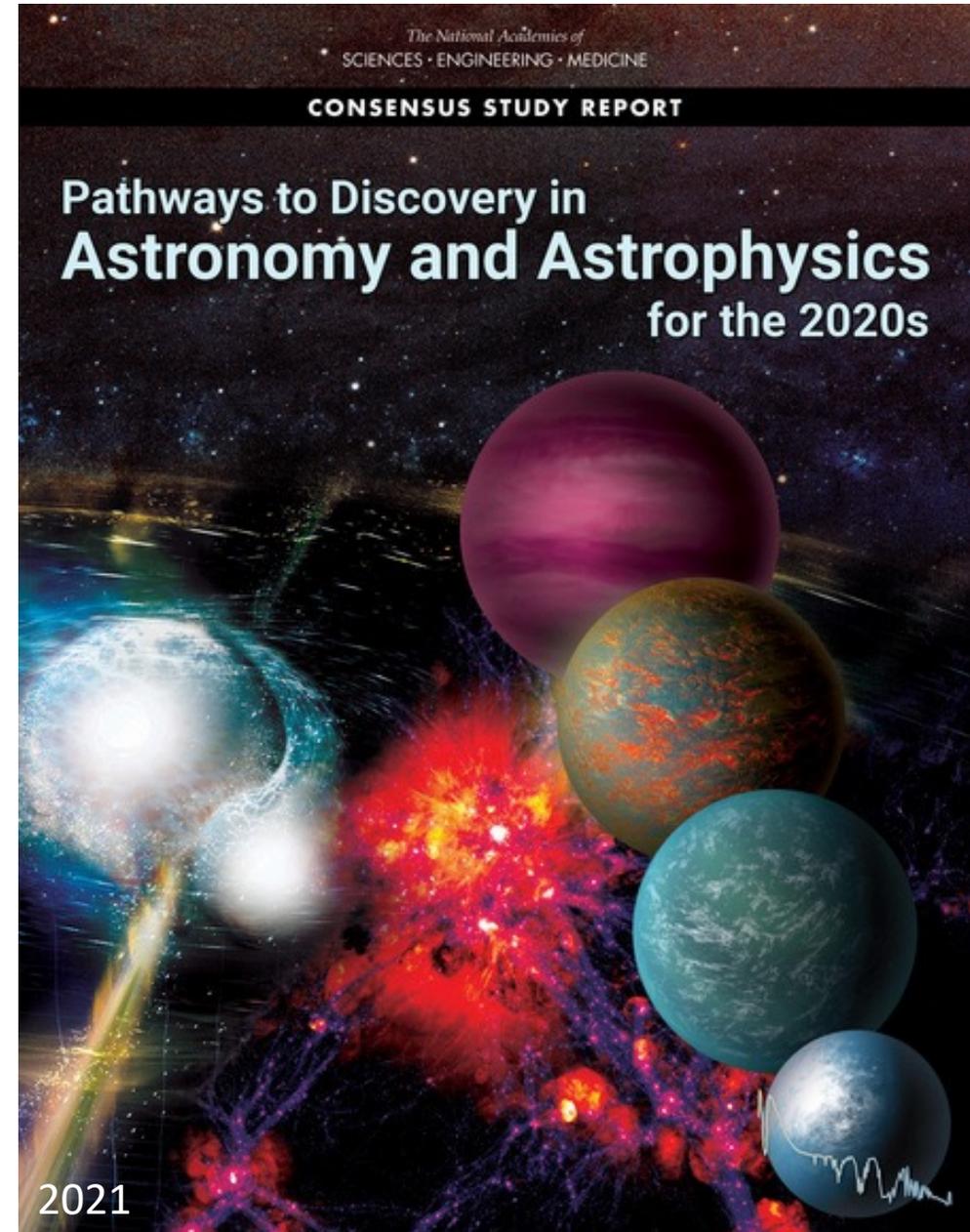
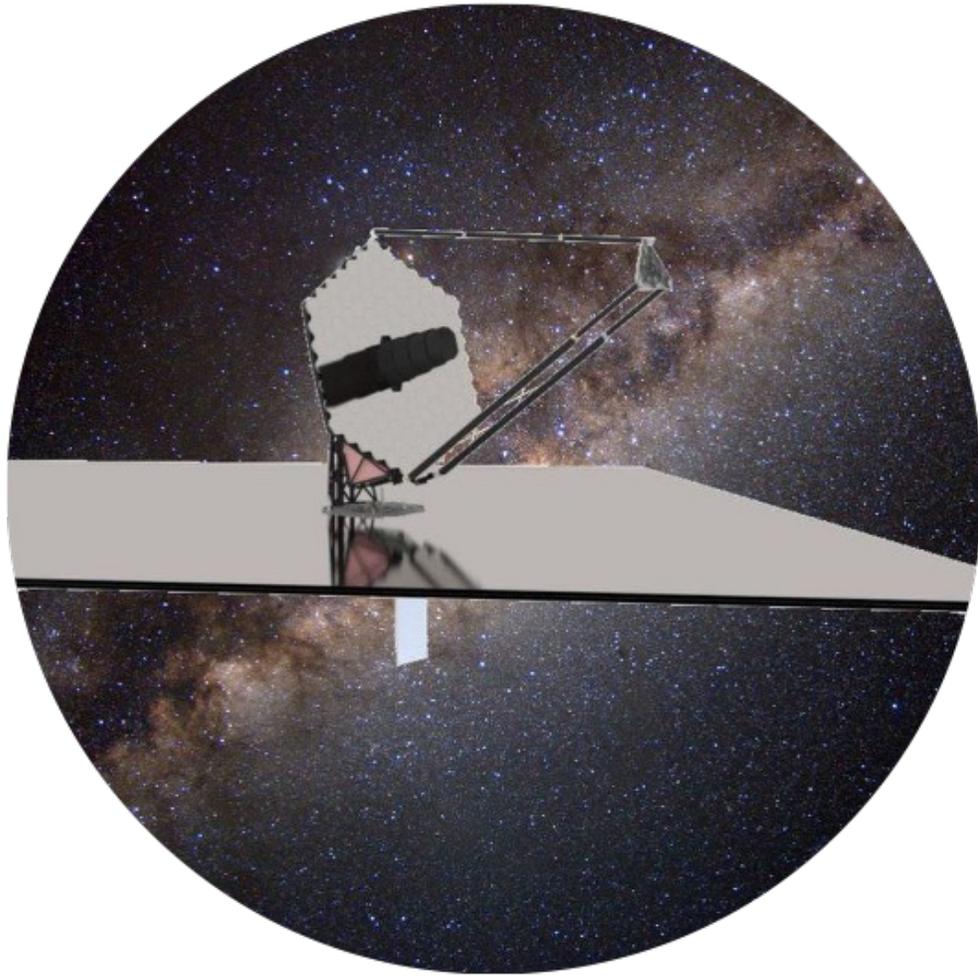
$\sim 200 - 300$  mas

Haut  
contraste

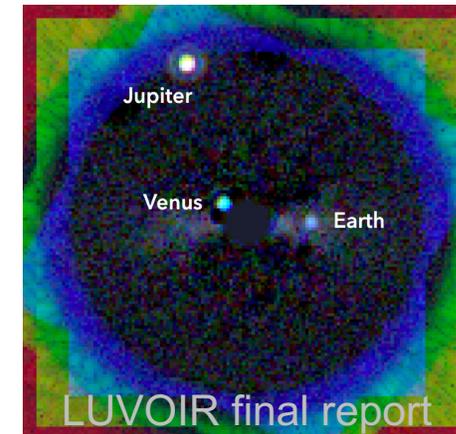
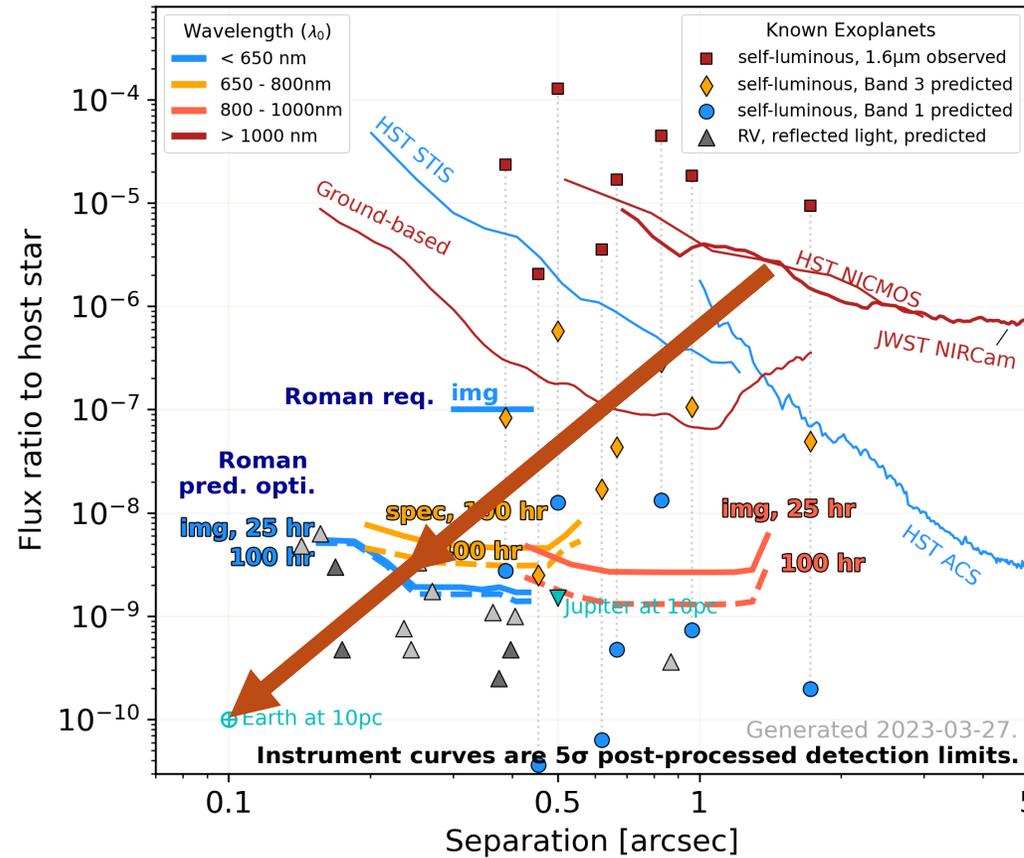
$C \sim 10^{-9} - 10^{-8}$

Information  
spectrale

$R \sim 50 @ \lambda = 0.7 \mu\text{m}$



V. Bailey



## BESOINS

Haute  
séparation angulaire

$\sim 20 - 50$  mas

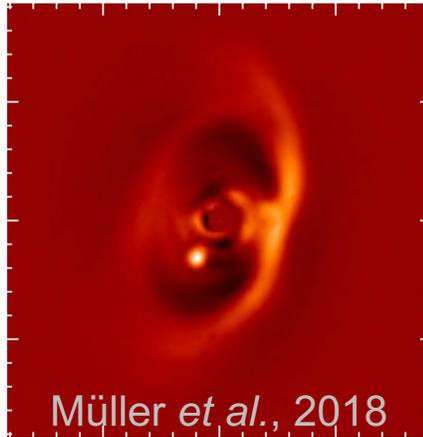
Haut  
contraste

$C \sim 10^{-10}$

Information  
spectrale

$R > 200 - 5000$  @  $\lambda = 0.5 \mu\text{m}$

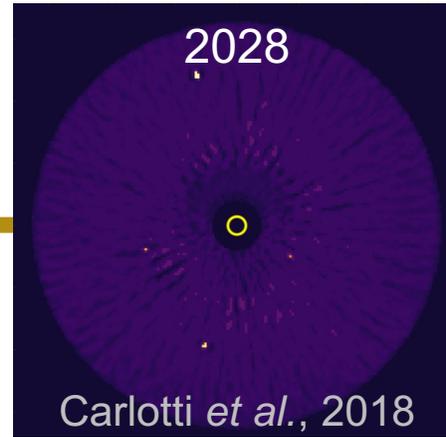
VLT / SPHERE



Müller *et al.*, 2018

>250 mas  
 $C \sim 10^{-6}$

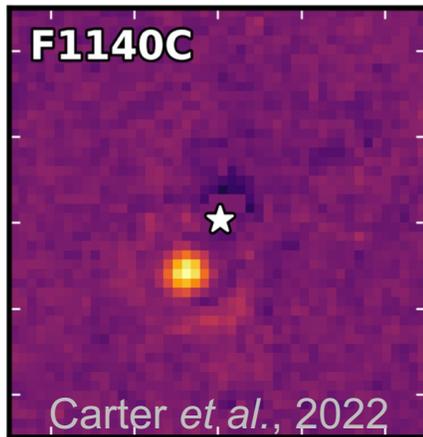
ELT / HARMONI



Carlotti *et al.*, 2018

~50 mas  
 $C \sim 10^{-6}$

JWST / NIRCcam, MIRI

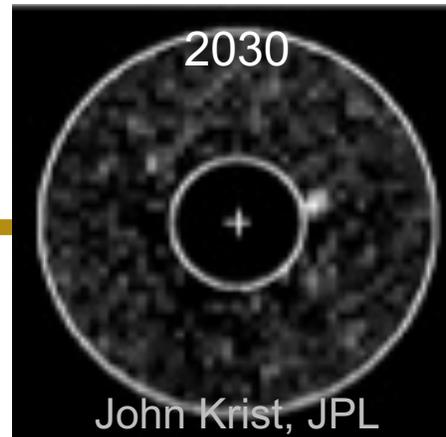


F1140C

Carter *et al.*, 2022

~1''  
 $C \sim 10^{-5} - 10^{-4}$

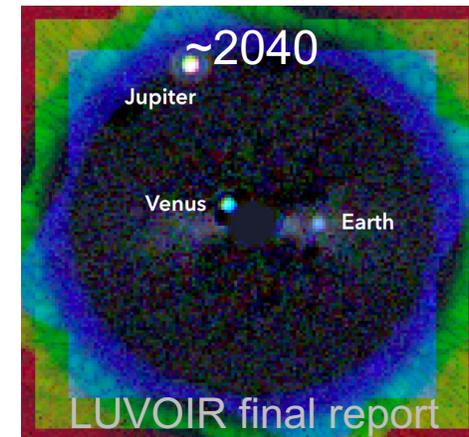
NGRST / CGI



John Krist, JPL

~200 mas  
 $C \sim 10^{-9} - 10^{-8}$

HabWorlds



~2040

Jupiter

Venus

Earth

LUVOIR final report

<50 mas  
 $C \sim 10^{-10}$

**→ Performance**

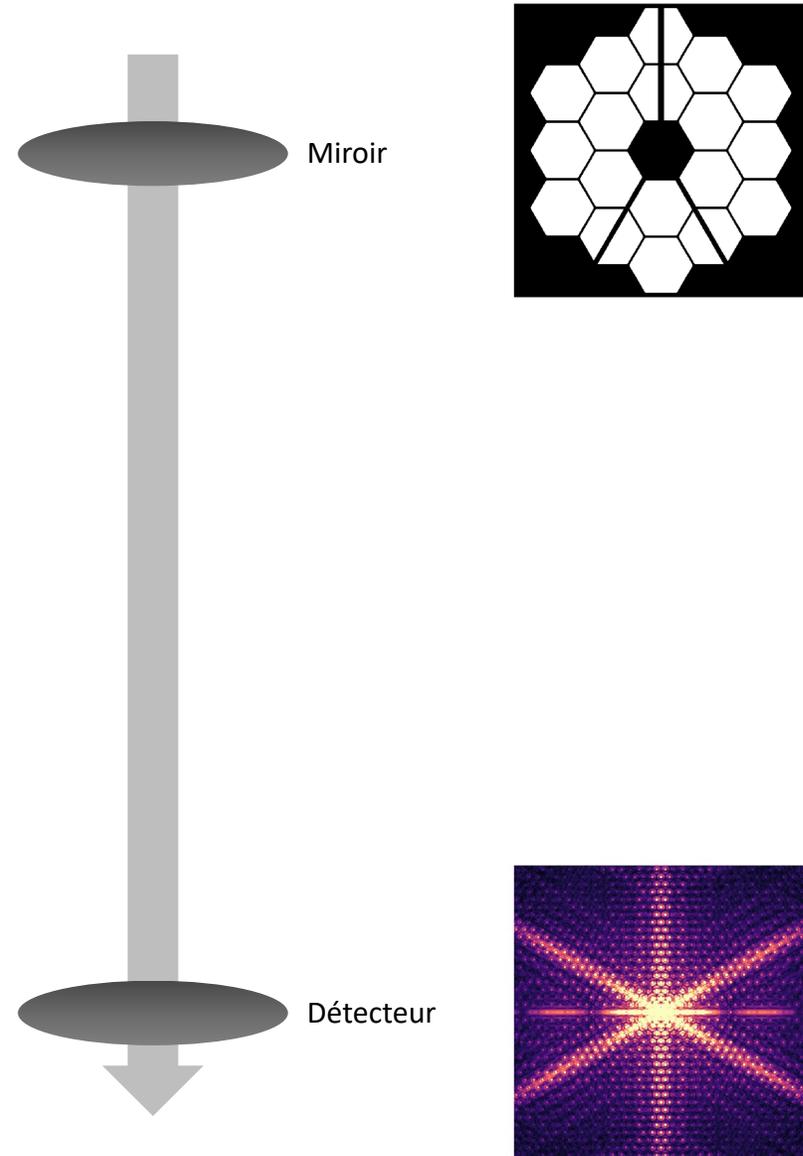
## Recette de l'imageur haut contraste

Temps de préparation : plusieurs années

Coût : \$

### Ingrédients :

- 1 (très grand) miroir primaire
- Une collection de filtres
- 1 détecteur



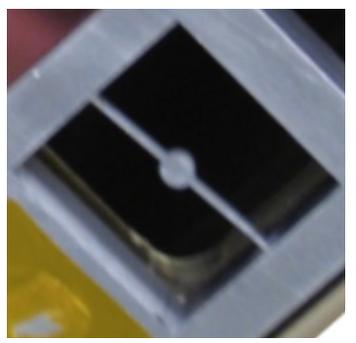
## Recette de l'imageur haut contraste

Temps de préparation : plusieurs années

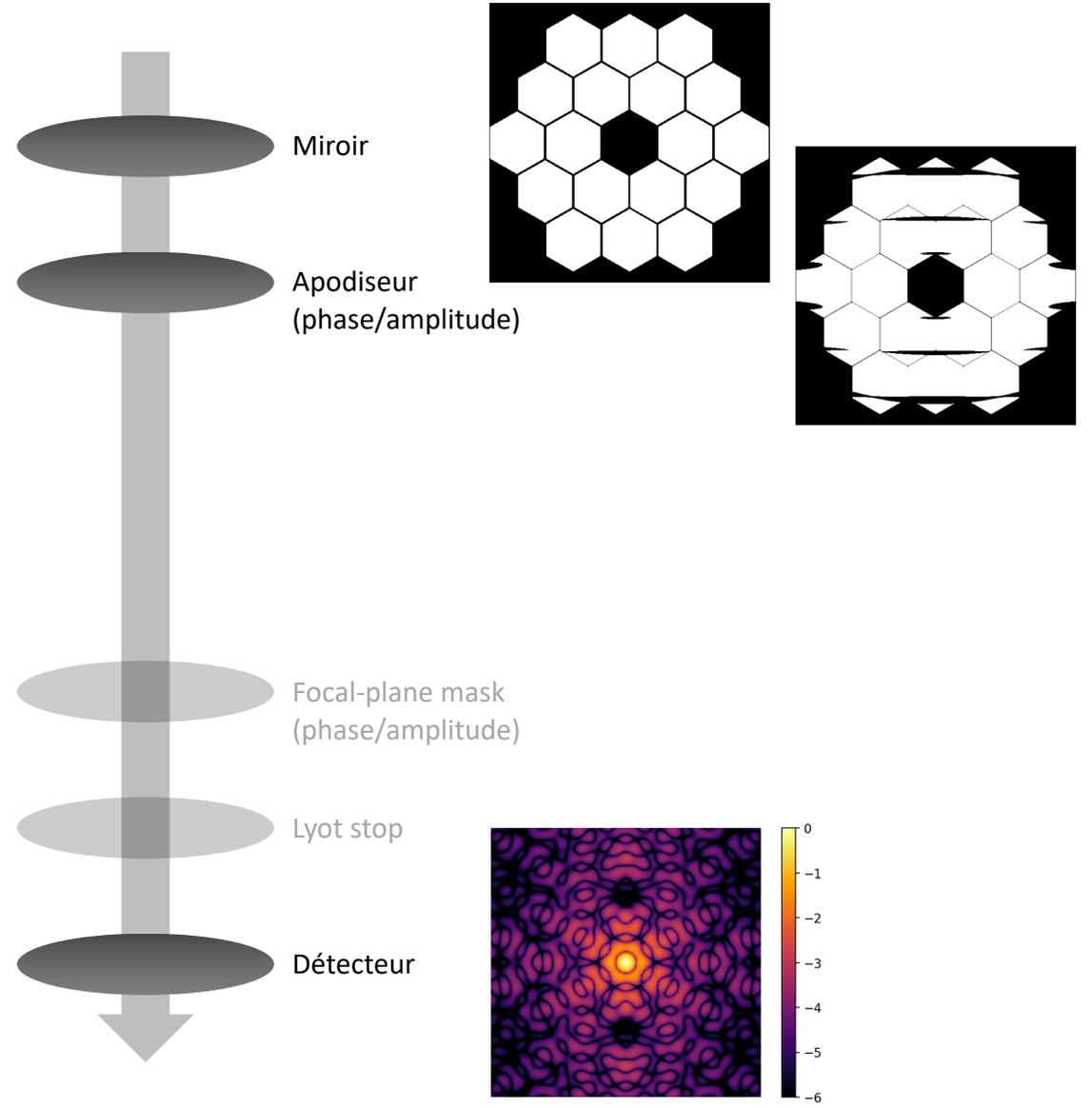
Coût : \$

### Ingrédients :

- 1 (très grand) miroir primaire
- Une collection de filtres
- 1 détecteur
- 1 à 3 masques pour former un coronographe



Boccaletti *et al.*, 2015  
JWST User documentation



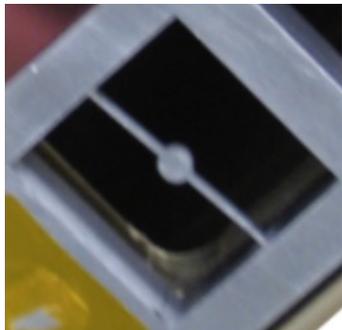
## Recette de l'imageur haut contraste

Temps de préparation : plusieurs années

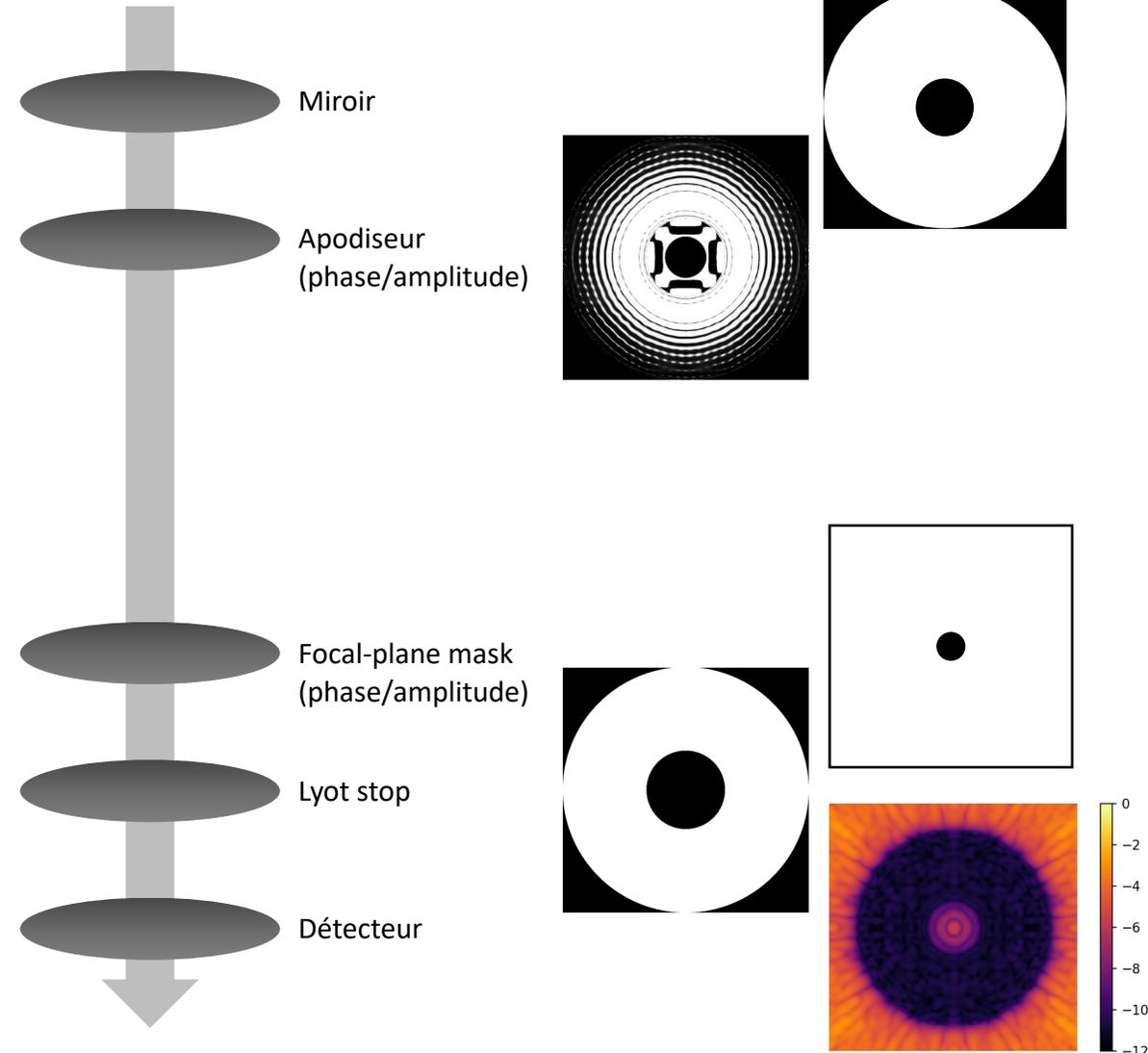
Coût : \$

### Ingrédients :

- 1 (très grand) miroir primaire
- Une collection de filtres
- 1 détecteur
- 1 à 3 masques pour former un coronographe



Boccaletti *et al.*, 2015  
JWST User documentation



Mazoyer *et al.* 2015

APLC : Aime, Soummer, Ferrari, 2002, N'Diaye

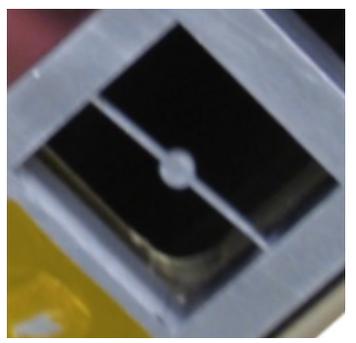
## Recette de l'imageur haut contraste

Temps de préparation : plusieurs années

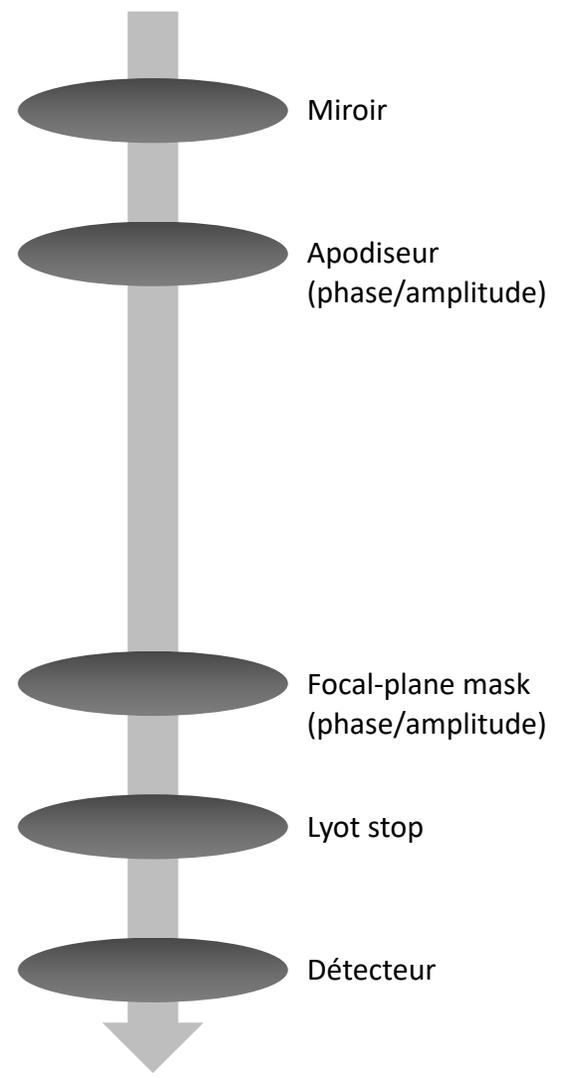
Coût : \$

### Ingrédients :

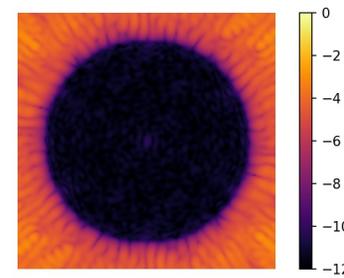
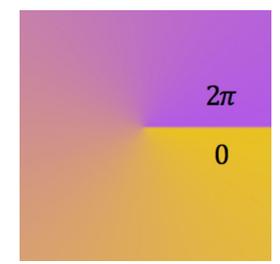
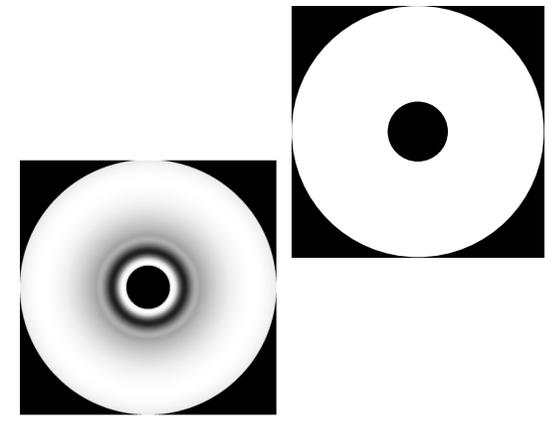
- 1 (très grand) miroir primaire
- Une collection de filtres
- 1 détecteur
- 1 à 3 masques pour former un coronographe



Boccaletti *et al.*, 2015  
JWST User documentation



Mazoyer et al. 2015



Apodized Vortex : Carlotti 2013, Fogarty

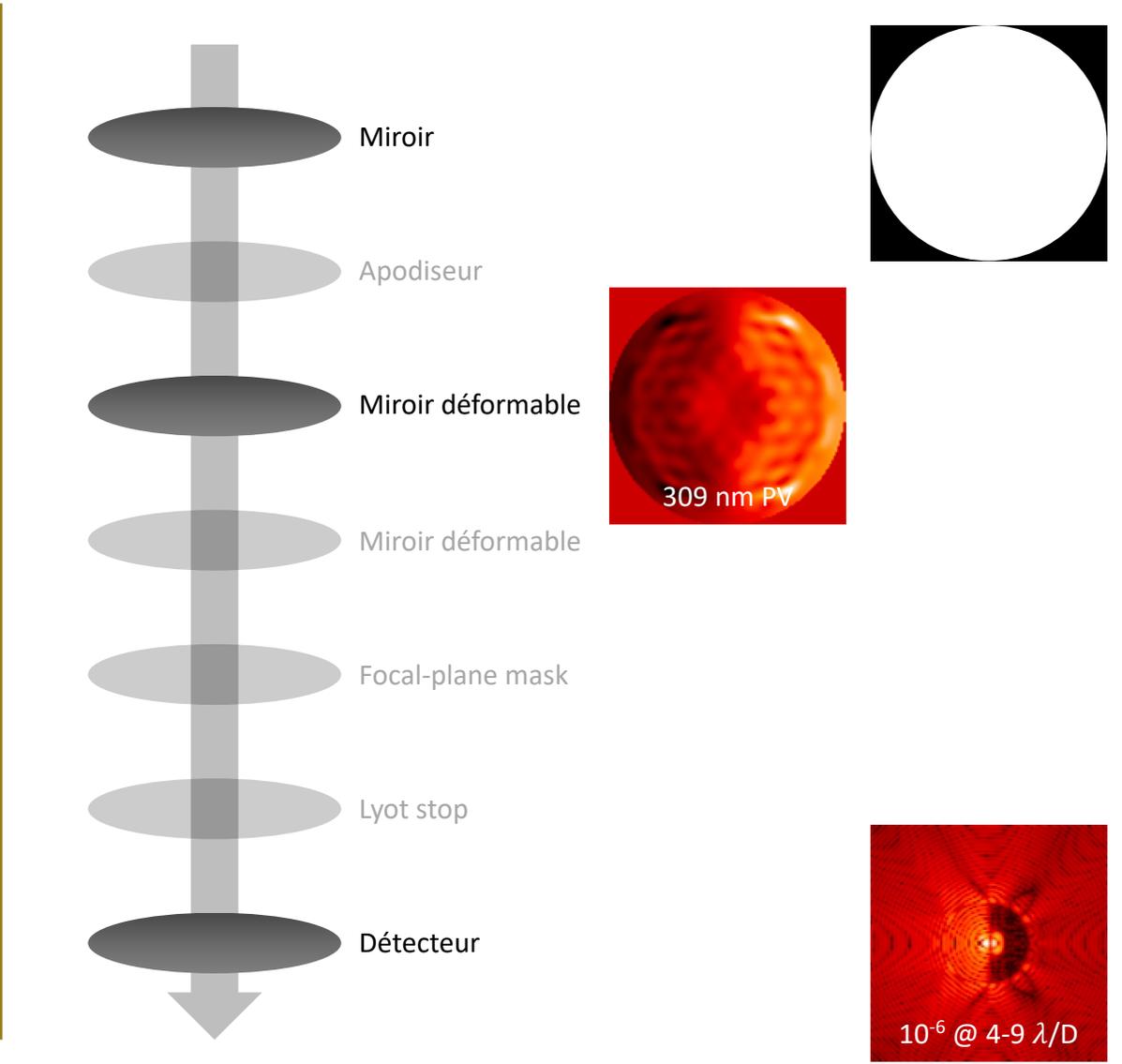
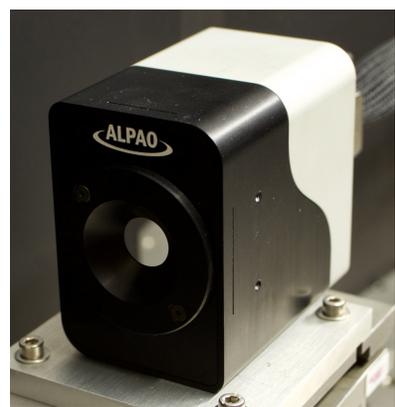
## Recette de l'imageur haut contraste

Temps de préparation : plusieurs années

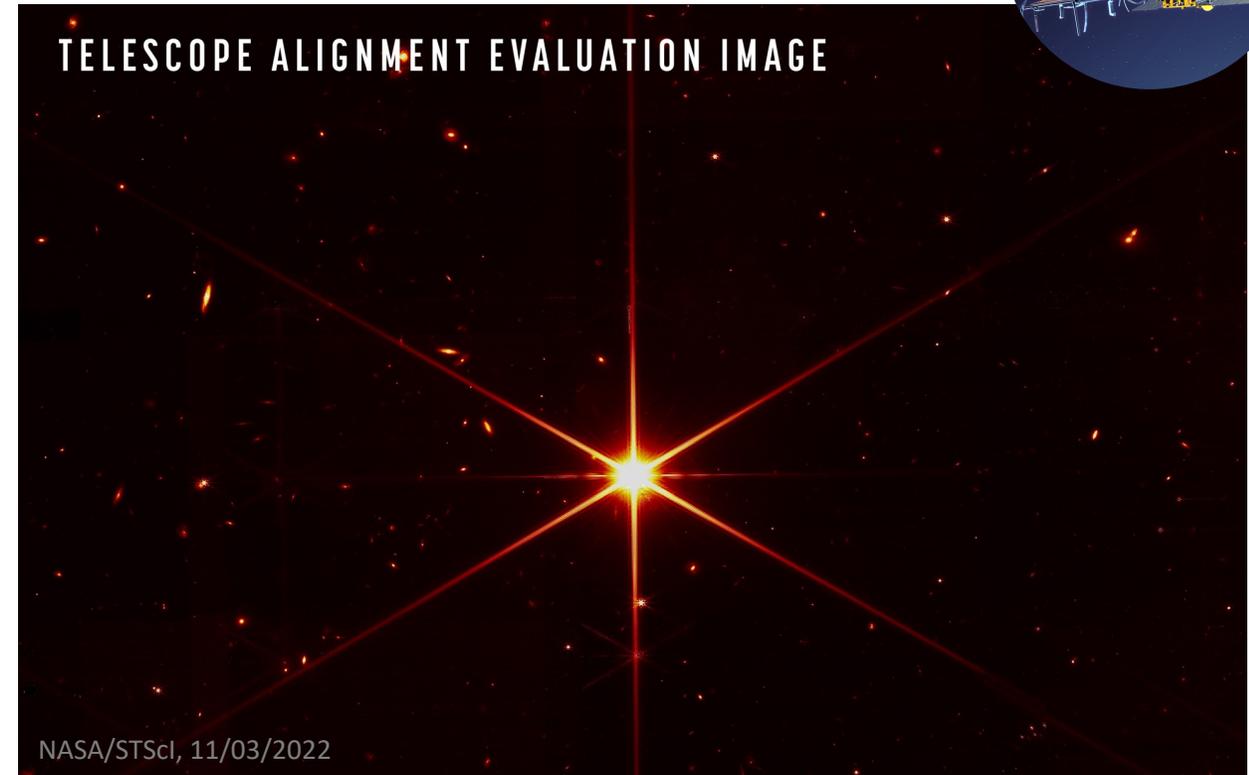
Coût : \$

### Ingédients :

- 1 (très grand) miroir primaire
- Une collection de filtres
- 1 détecteur
- 1 à 3 masques pour former un coronographe
- 1 à 2 miroirs déformables pour contrôler le front d'onde



**Oui, MAIS**

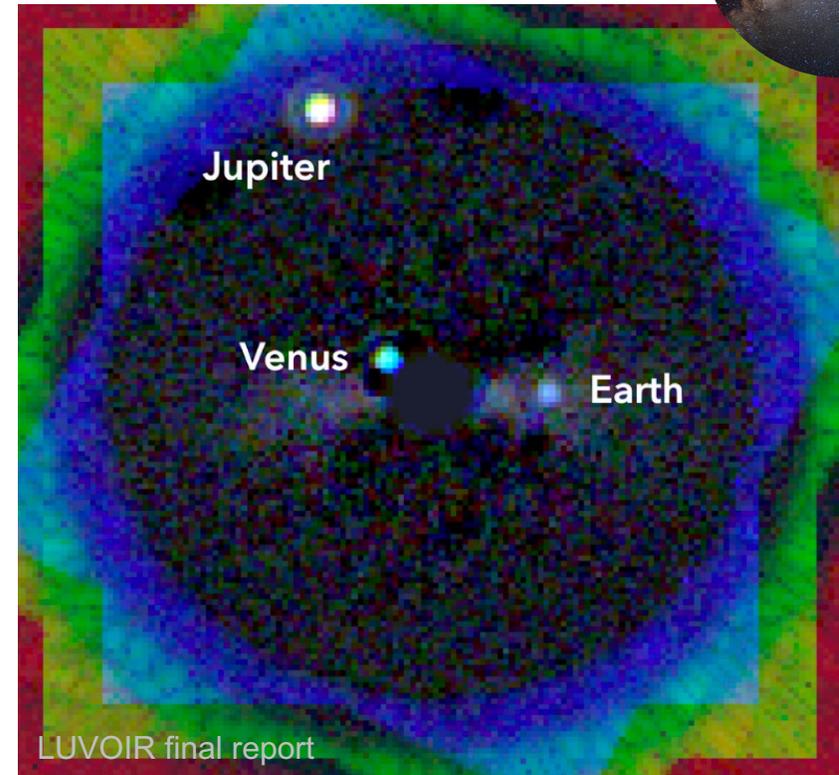
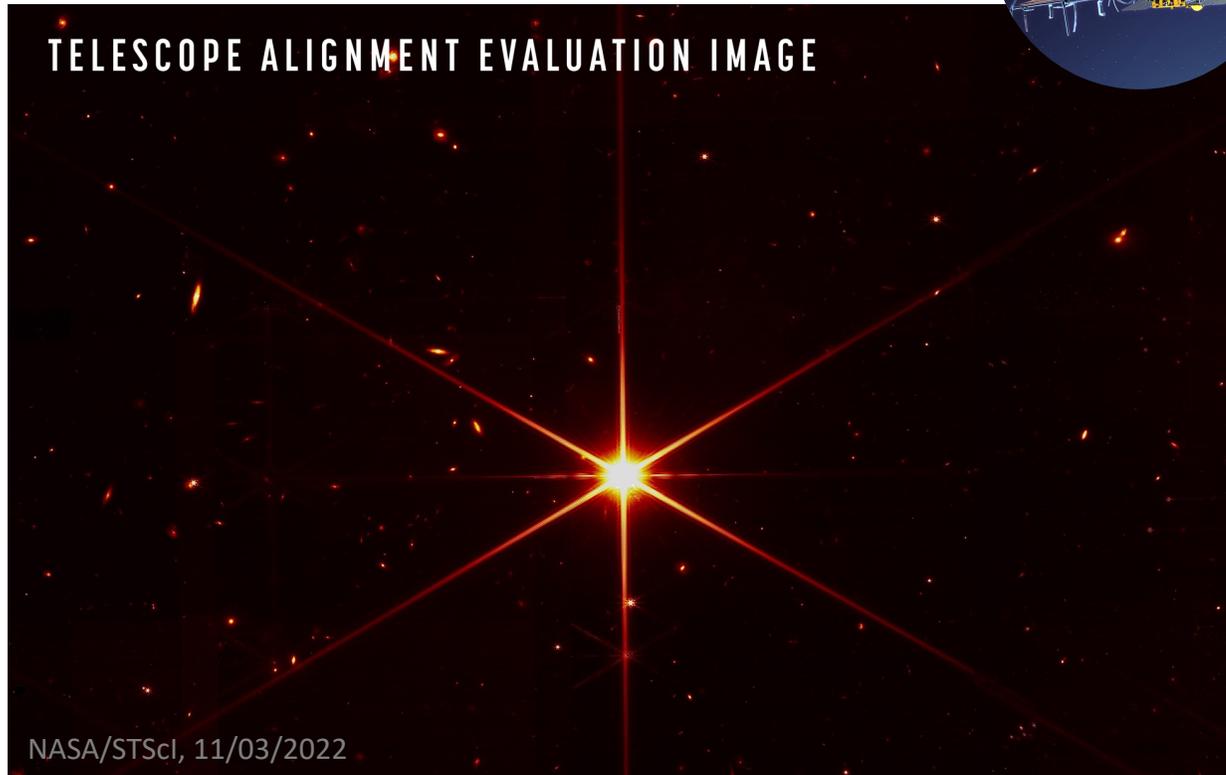
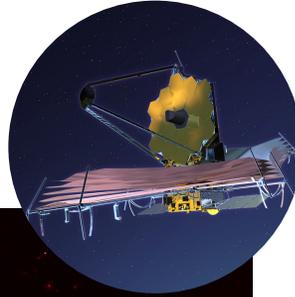


Plusieurs  $\mu\text{m rms}$



**1 MOIS !**

30 nm rms

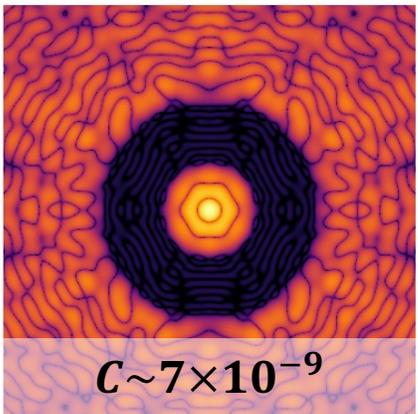
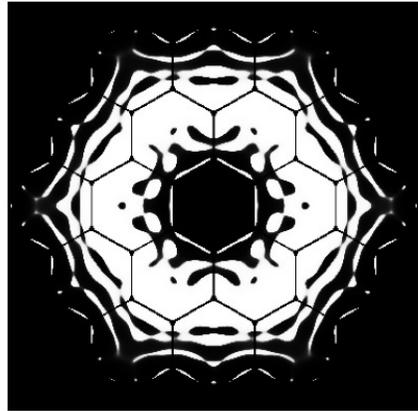


30 nm rms

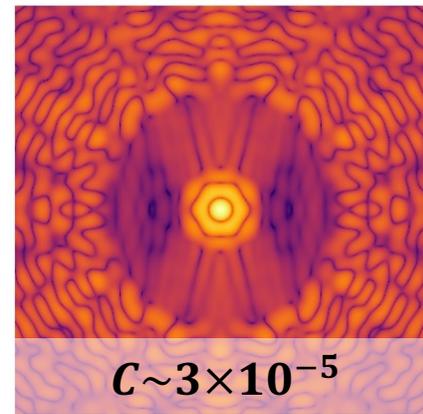
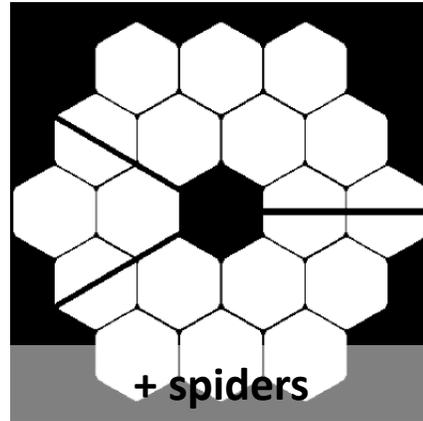


10 pm rms

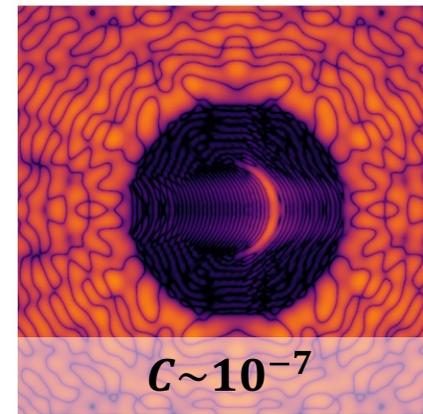
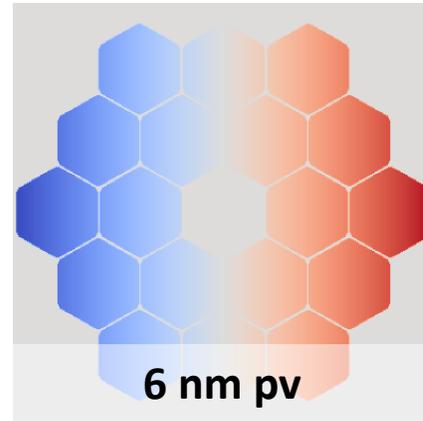
Pas d'erreur



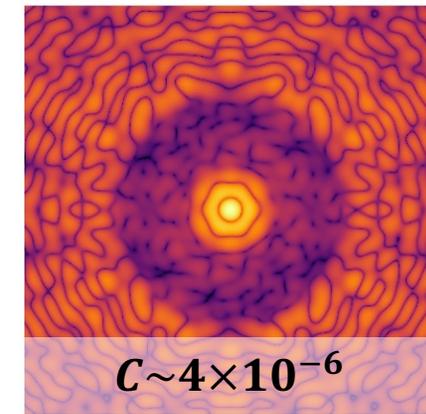
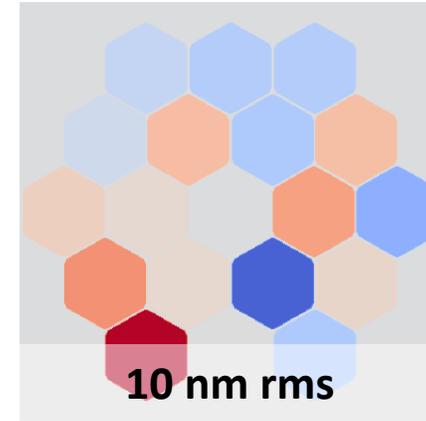
Pupille complexe



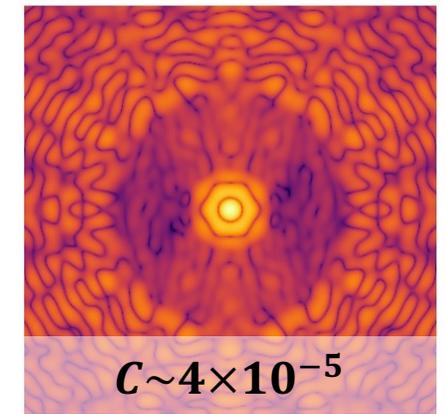
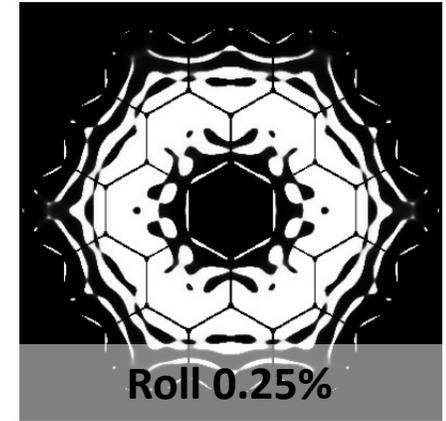
Dépointage



Phasage



Désalignements



**→ Robustesse**

**→ Robustesse**

**PRÉVENIR ou GUÉRIR ?**

**Atteindre et maintenir les performances**

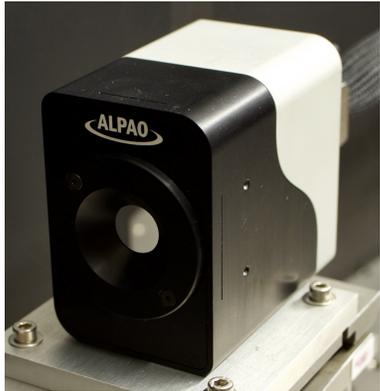


**Diagnostiquer les erreurs**

**Corriger les erreurs**

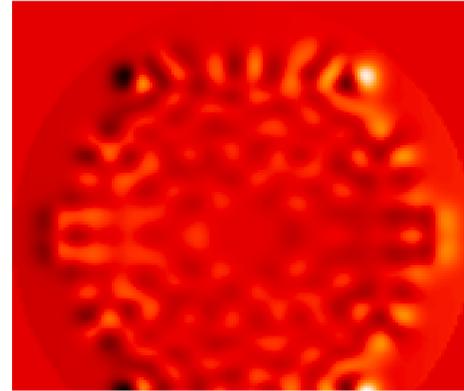
## Contrôle du front d'onde en phase

Erreur de phasage



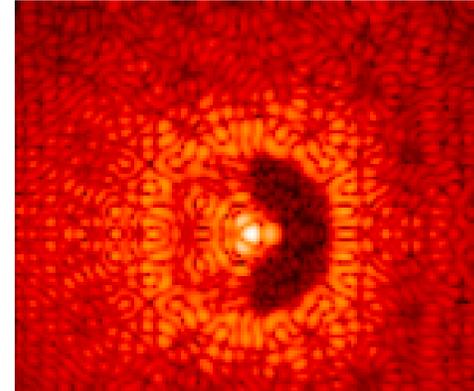
**Pas d'erreur**

Surface du DM

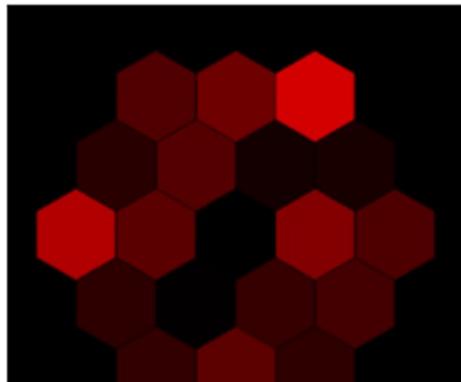


**40 nm rms**

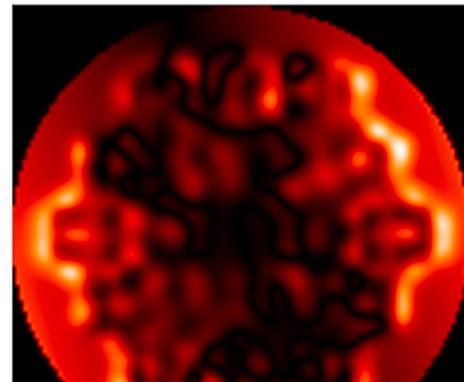
PSF coronographique



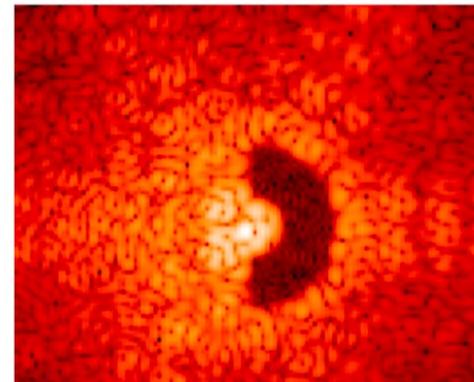
**$C \sim 10^{-6}$  @  $4 - 9\lambda/D$**



**100 nm rms**



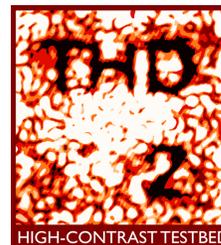
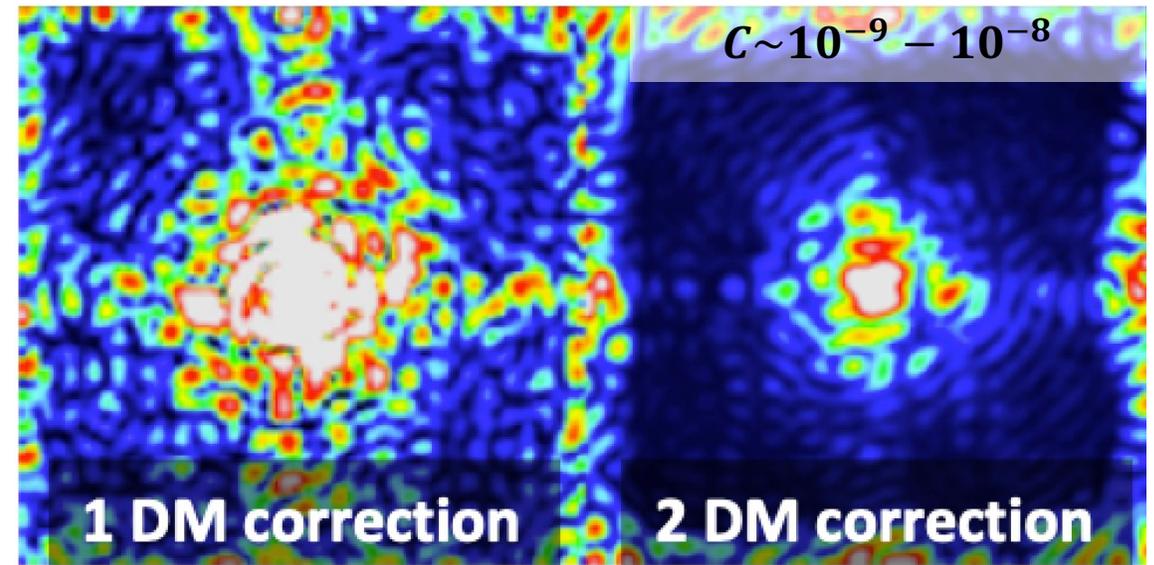
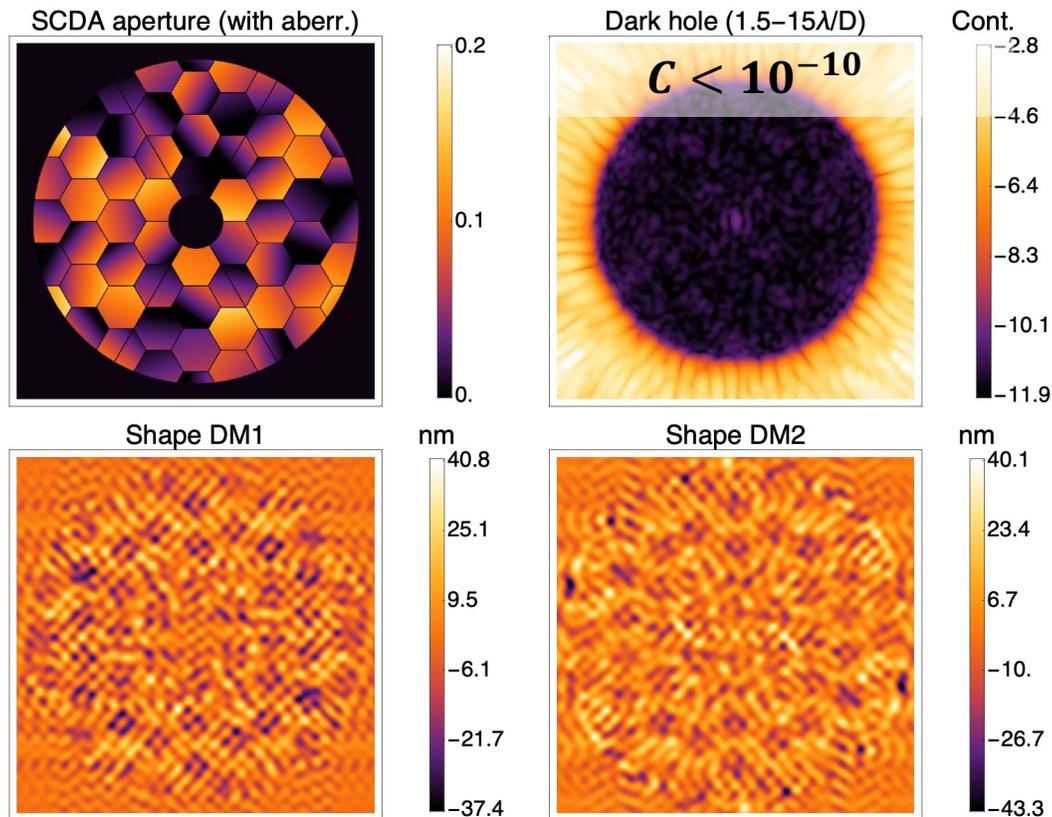
**90 nm rms**



**$C \sim 10^{-6}$  @  $4 - 9\lambda/D$**

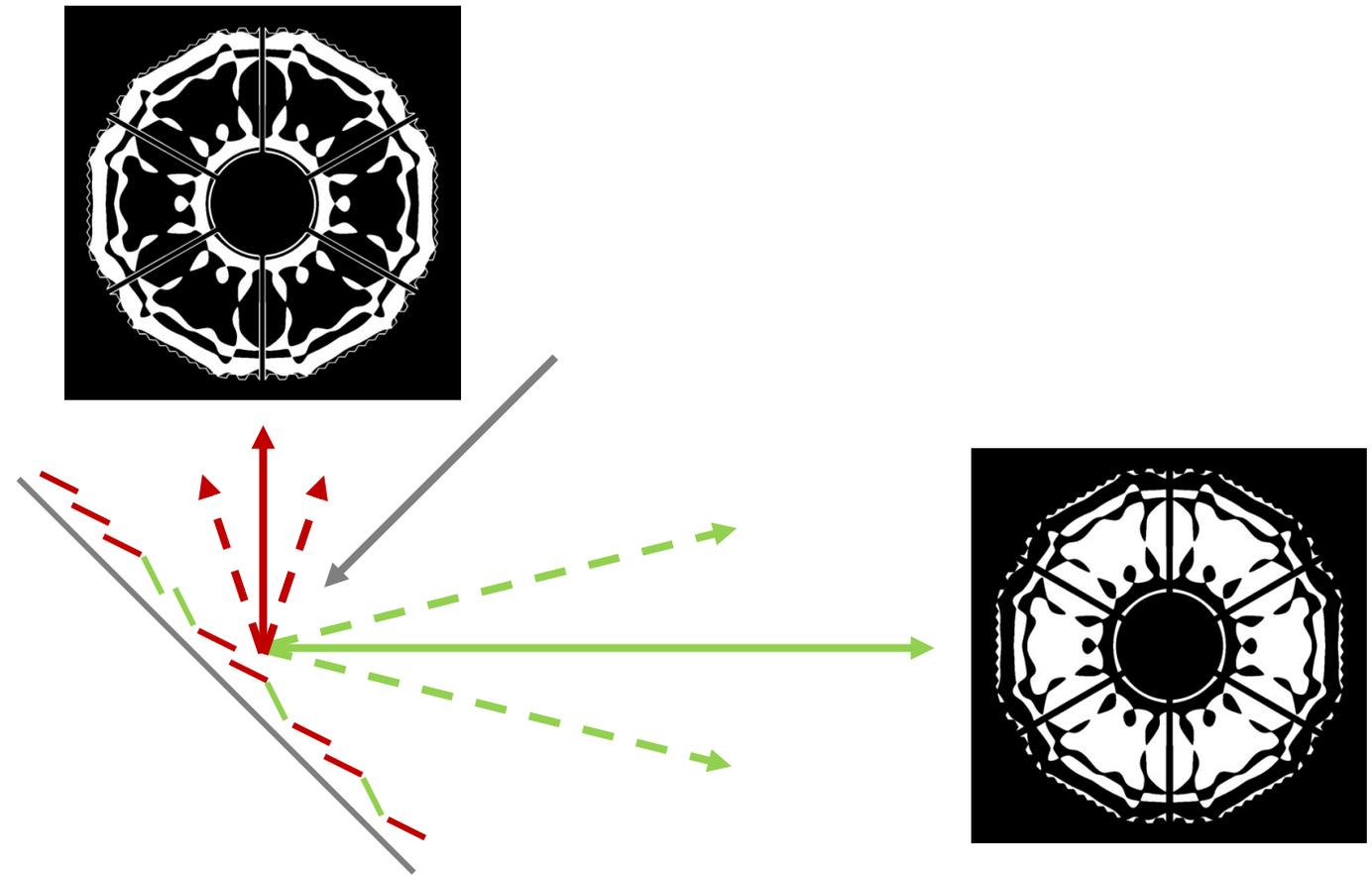
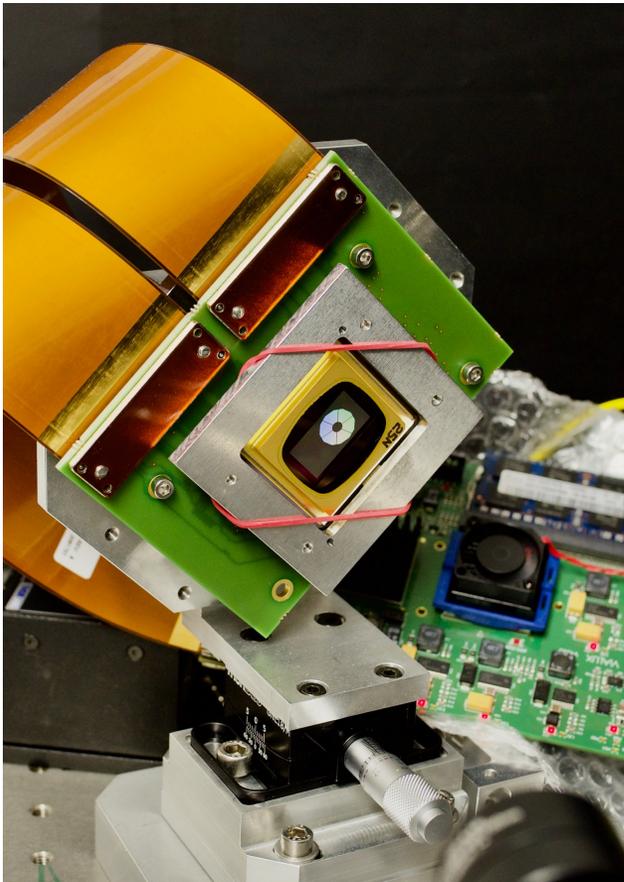
# Contrôle du front d'onde en amplitude

Avec deux miroirs déformables



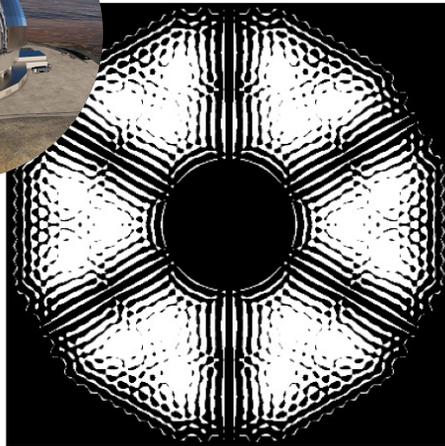
## Contrôle du front d'onde en amplitude

Avec une matrice de micro-miroirs (DMD)

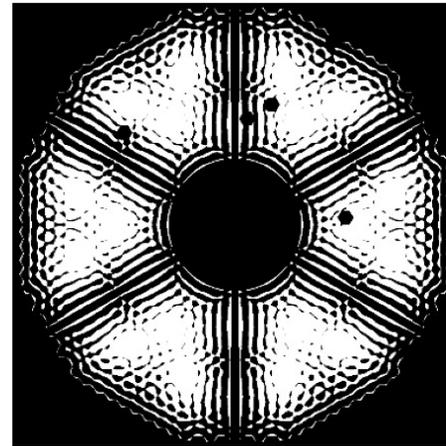


## Contrôle du front d'onde en amplitude

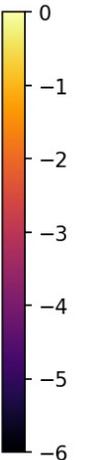
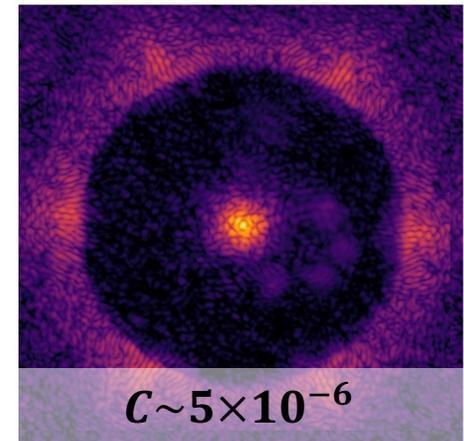
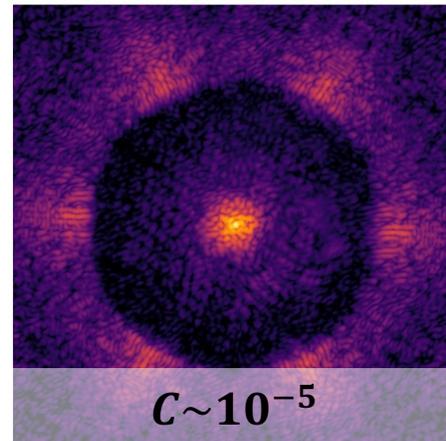
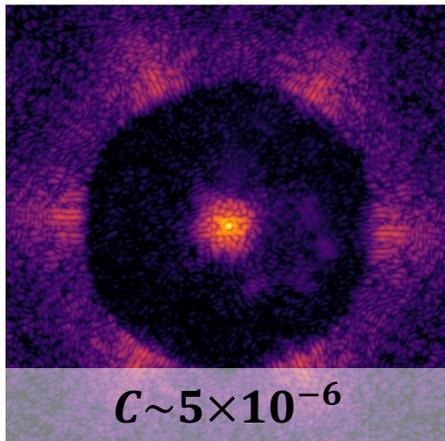
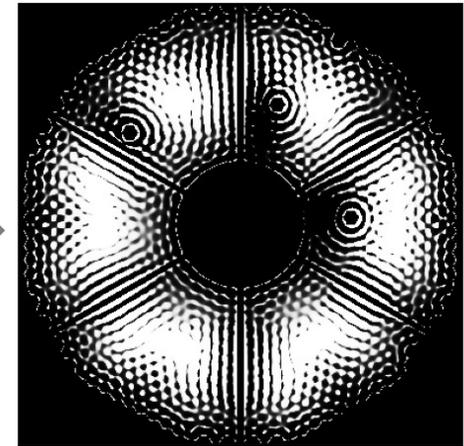
Avec une matrice de micro-miroirs (DMD)



Segments  
manquants 🤖



Coronagraphe  
mis à jour 🤖



**Atteindre et maintenir les performances**

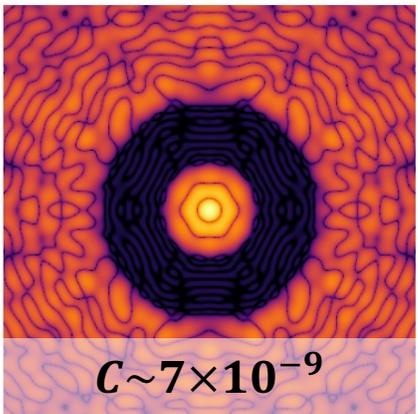
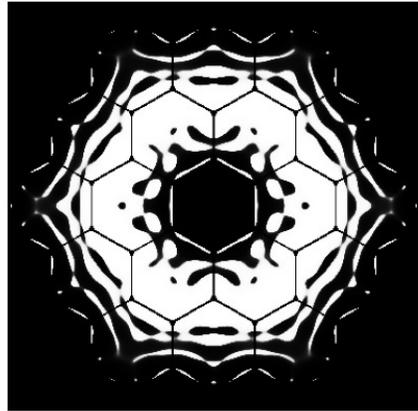


**Diagnostiquer les erreurs**

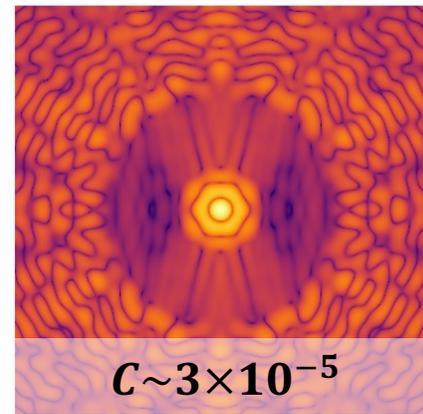
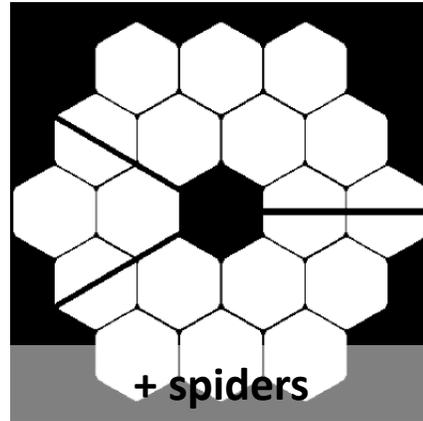
**Corriger les erreurs**

**Rendre l'instrument insensible aux erreurs**

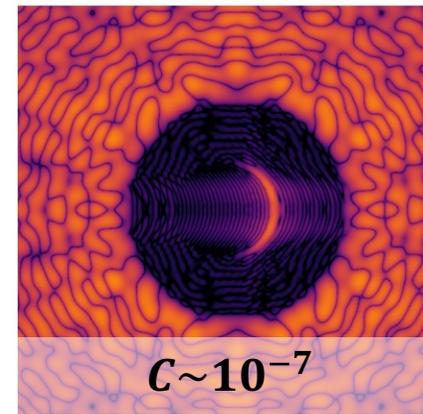
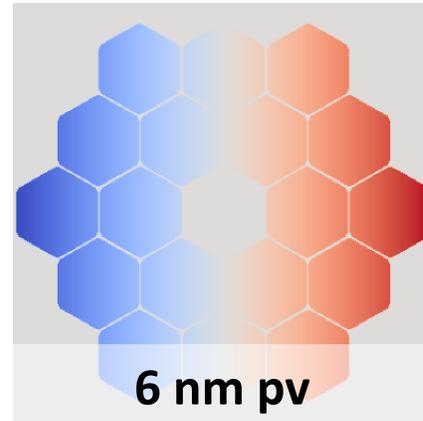
Pas d'erreur



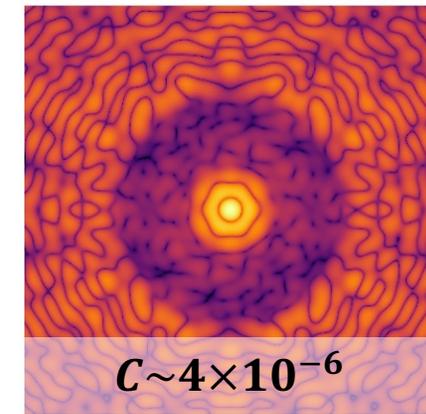
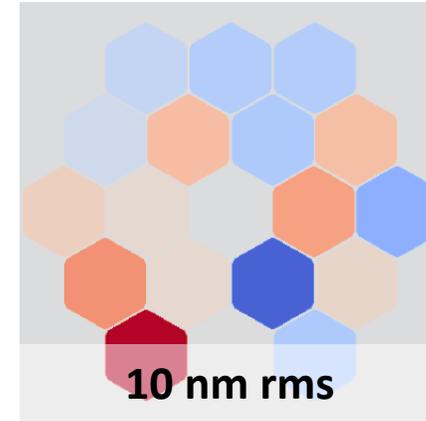
Pupille complexe



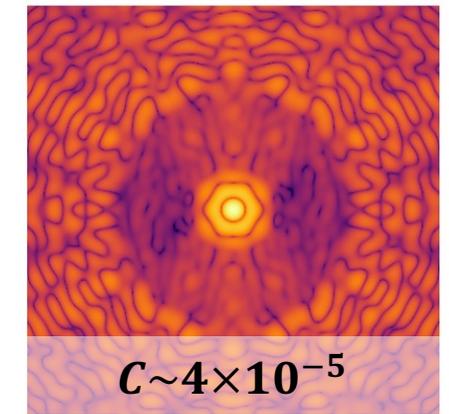
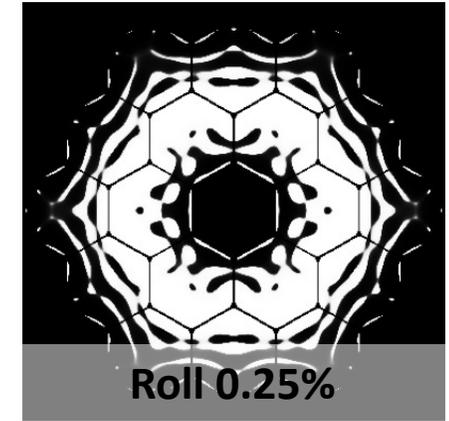
Dépointage



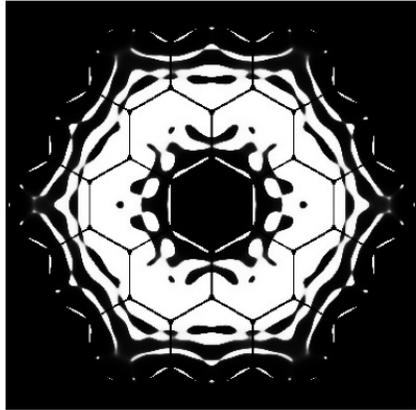
Phasage



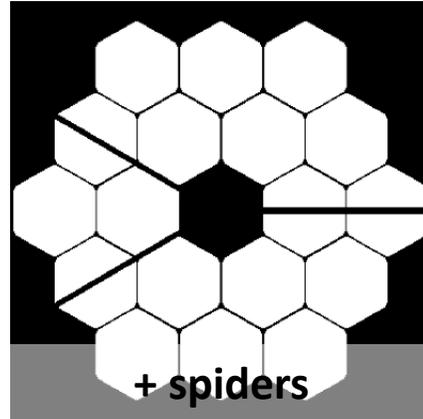
Désalignements



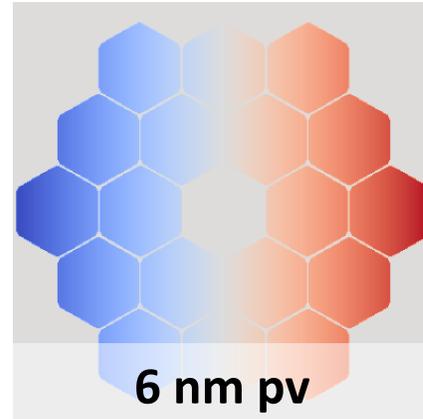
Pas d'erreur



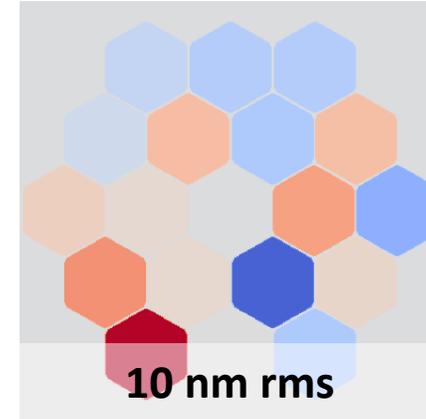
Pupille complexe



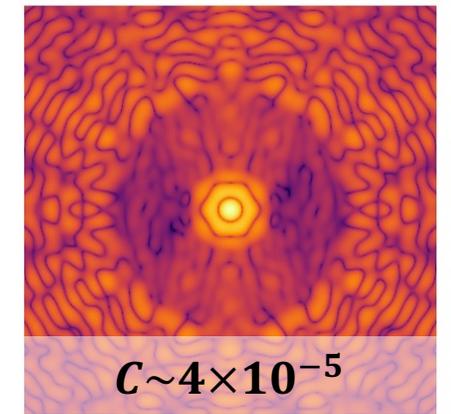
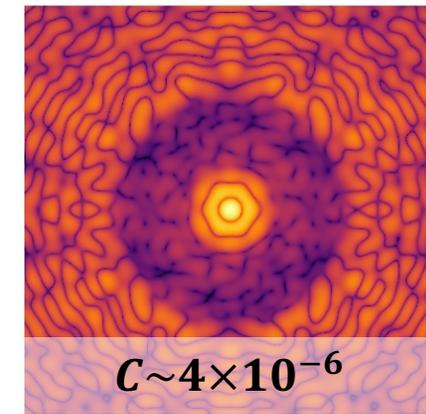
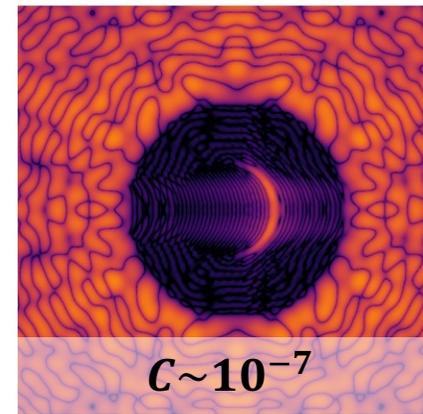
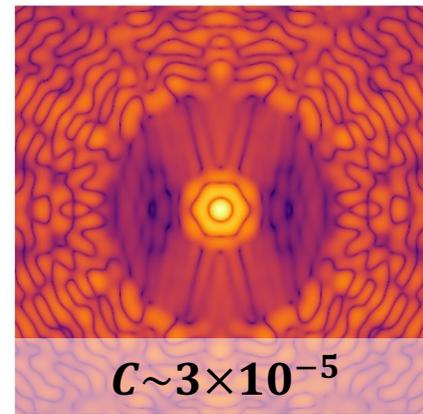
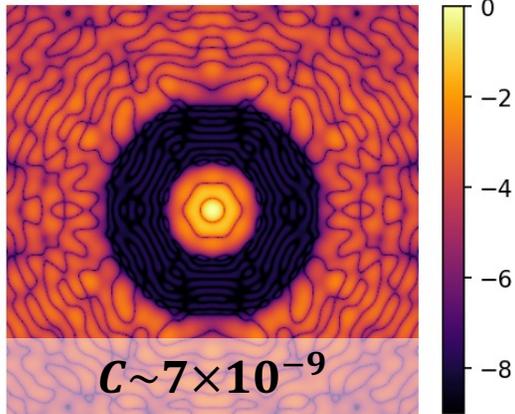
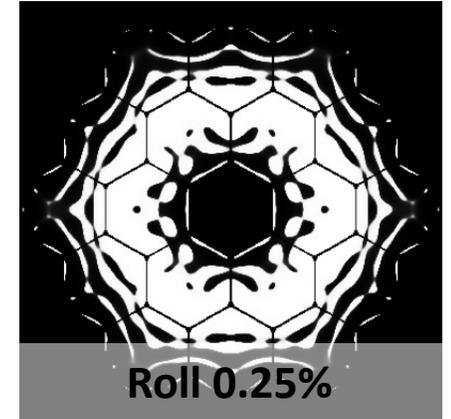
Dépointage



Phasage

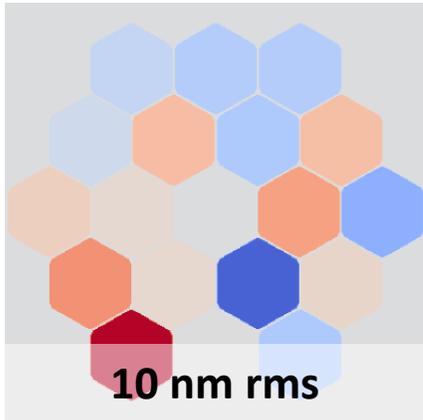


Désalignements



## Conditions

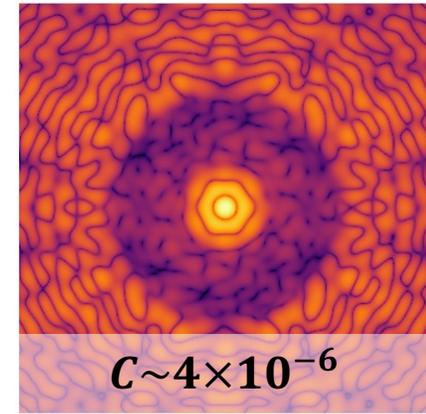
Erreurs de phasage



PASTIS

## Performance

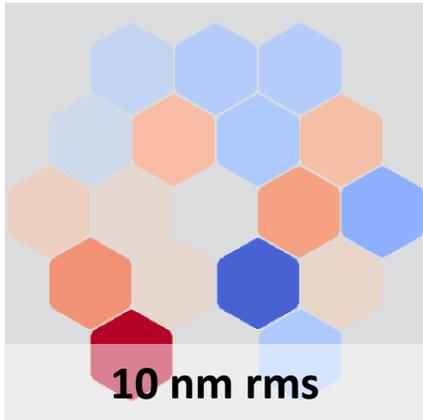
Contraste



$$I(\vec{u}) = \text{[Contour Plot]} \times \sum \sum A_{i,j} \text{[Vertical Stripes]}$$

## Conditions

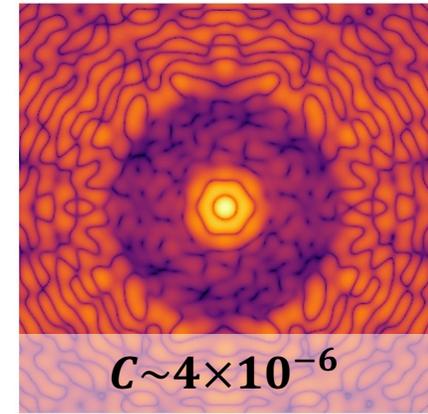
Erreurs de phasage



PASTIS

## Performance

Contraste



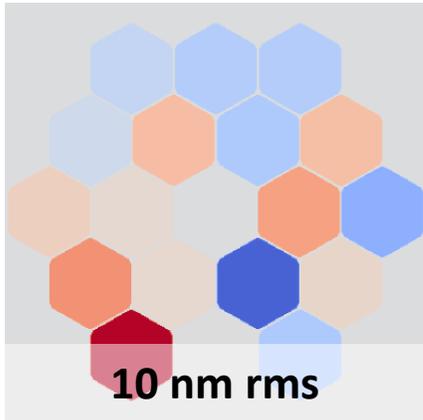
$$I(\vec{u}) = \text{[Envelope]} \times \sum \sum A_{i,j} \text{[Fringes]}$$

↑  
Enveloppe  
(PSF de la forme du segment)

↑  
Fringes d'interférences  
entre tous les segments

## Conditions

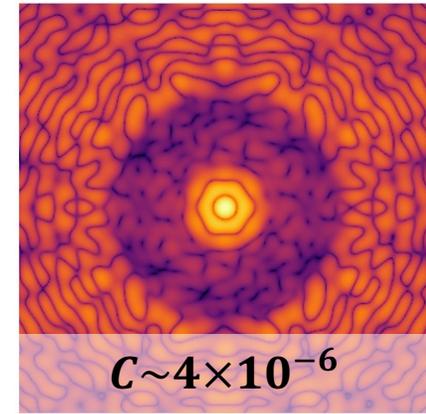
Erreurs de phasage



PASTIS

## Performance

Contraste



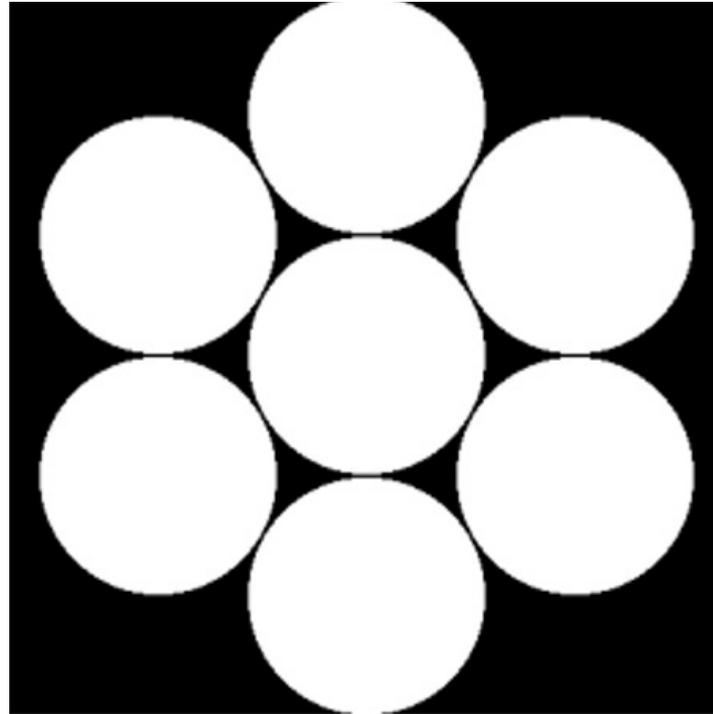
$$I(\vec{u}) = \text{[Envelope]} \times \sum \sum A_{i,j} \text{[Fringes]}$$

Enveloppe  
(PSF de la forme du segment)

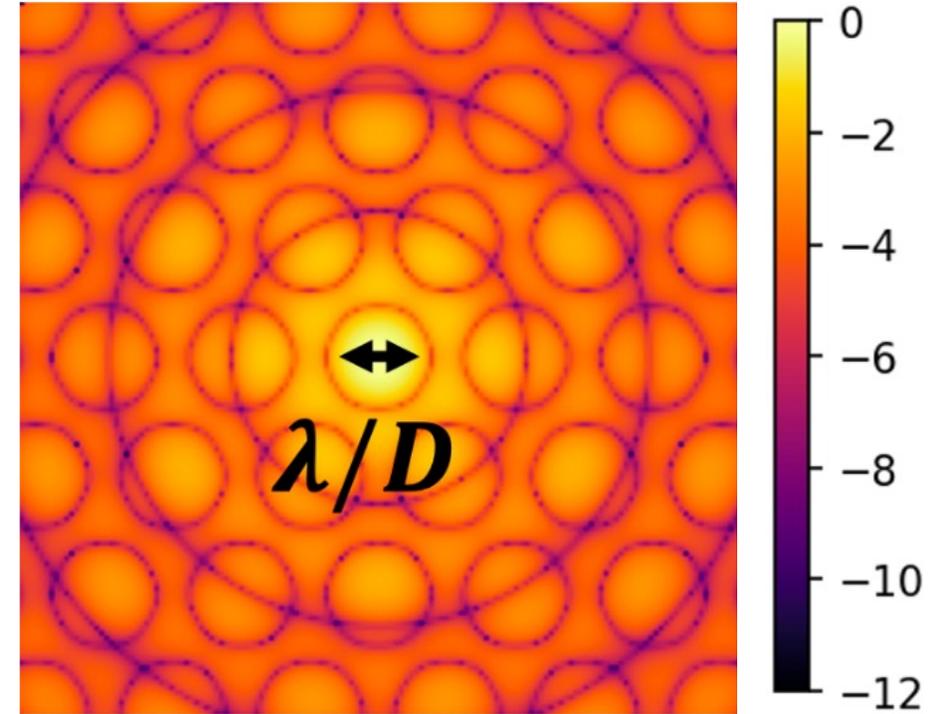
Fringes d'interférences  
entre tous les segments



Pupille

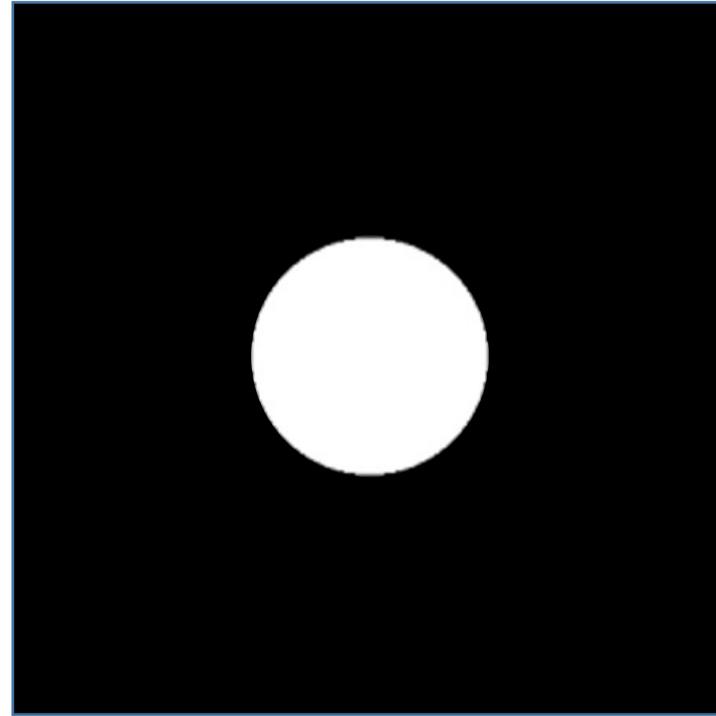


Image

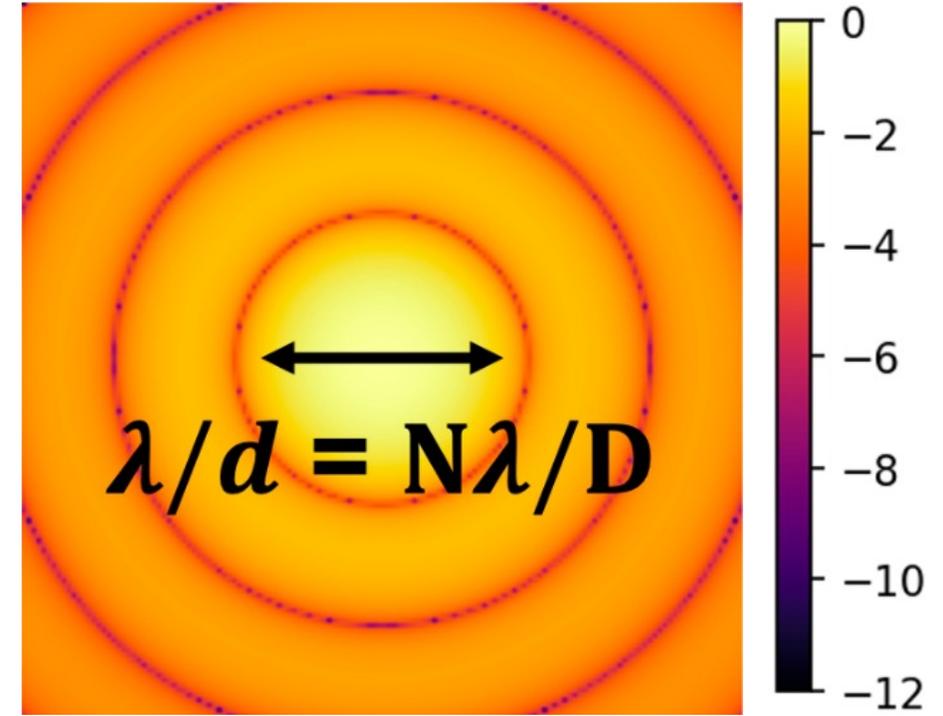




Segment

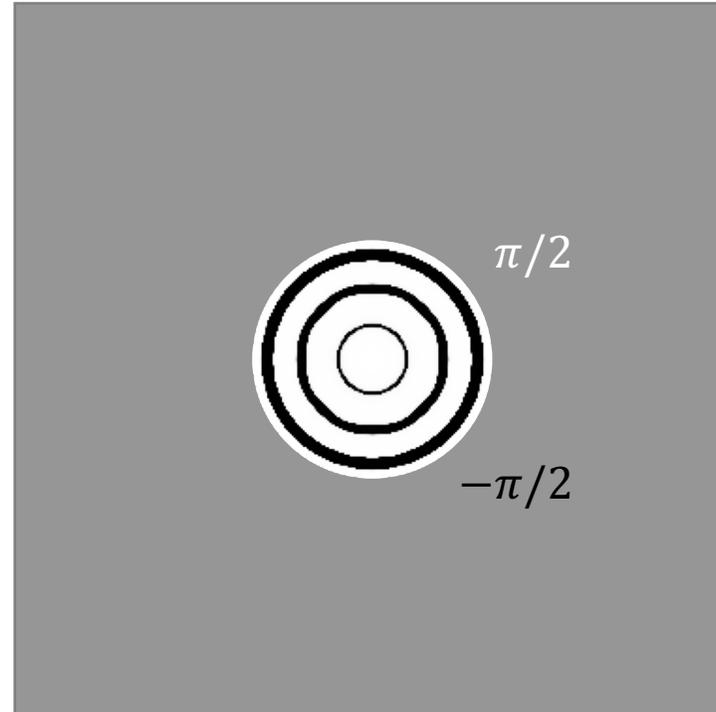


Enveloppe bas ordre



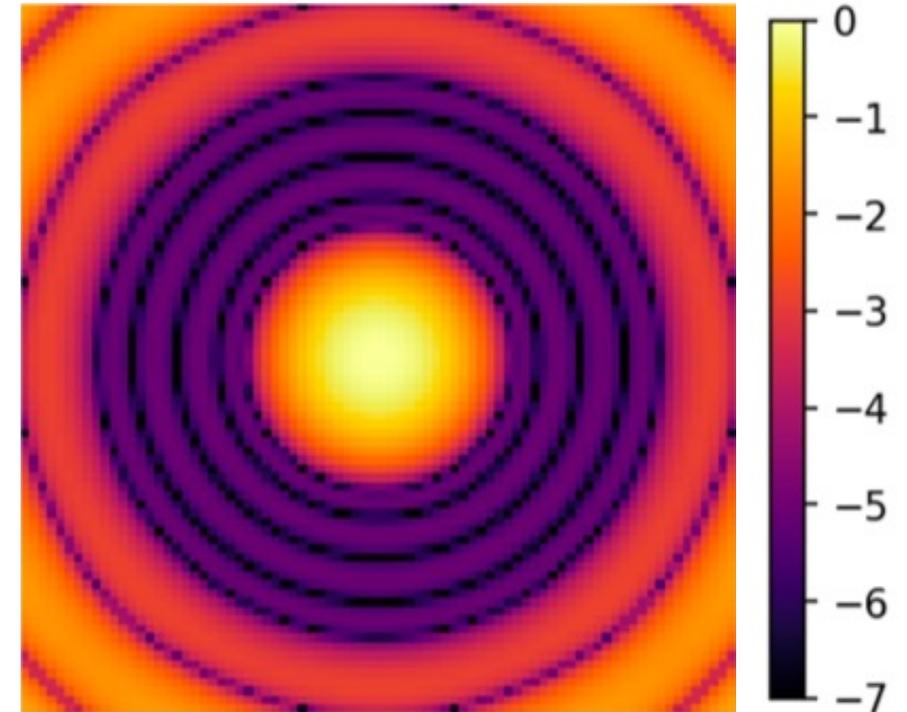


Segment apodisé en phase



$10^{-6}$  @  $2 - 4.1\lambda/d$

Enveloppe bas ordre





Redundant Apodized Pupil

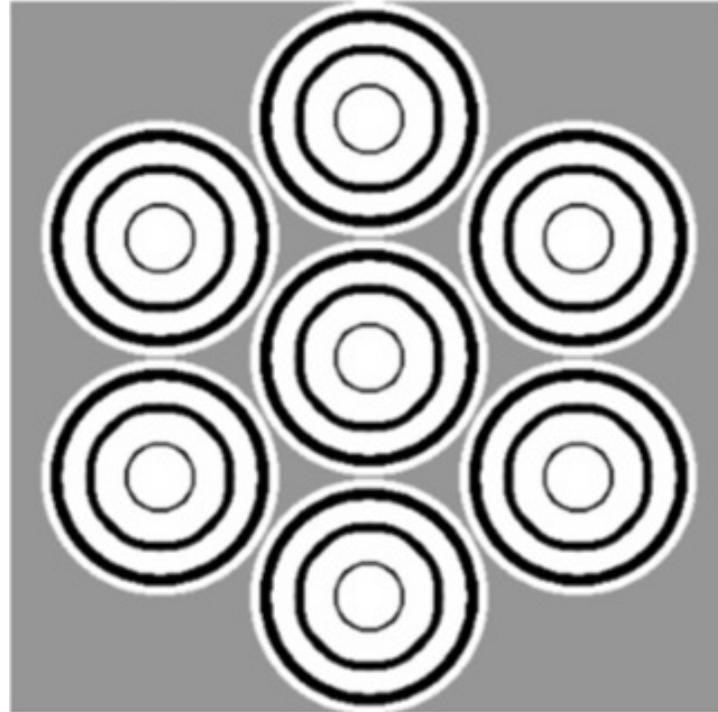
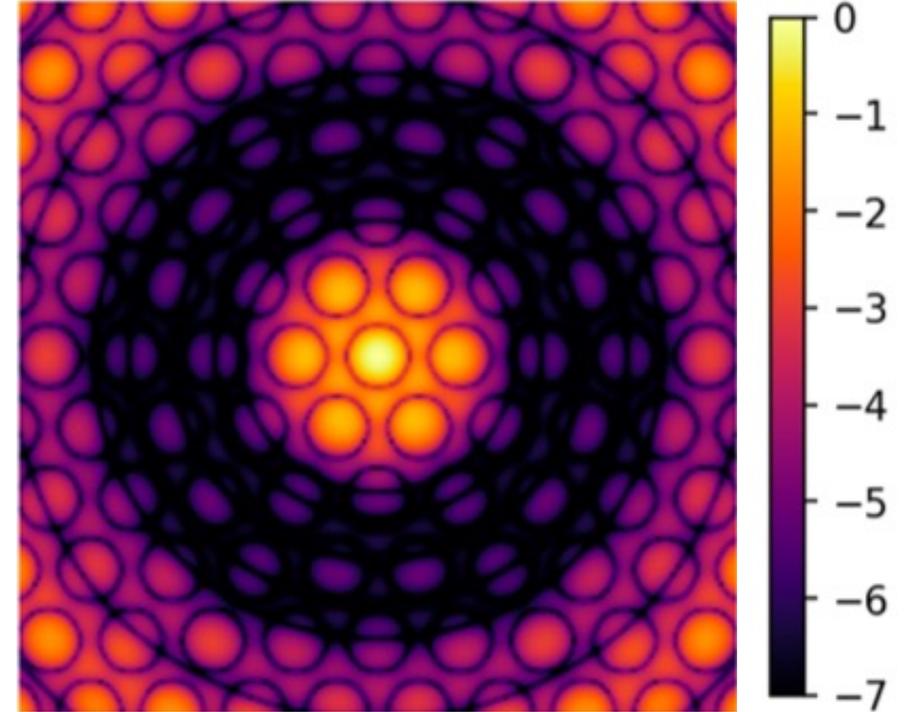
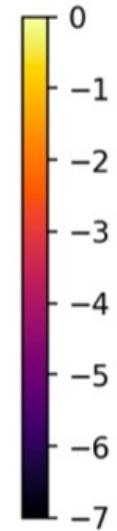
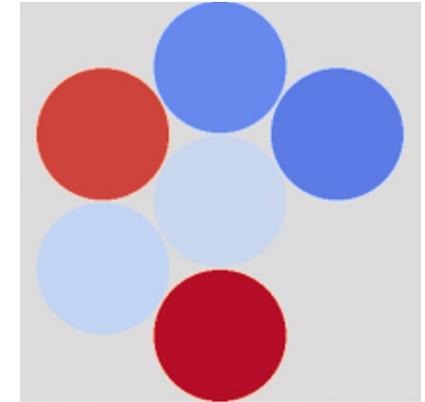
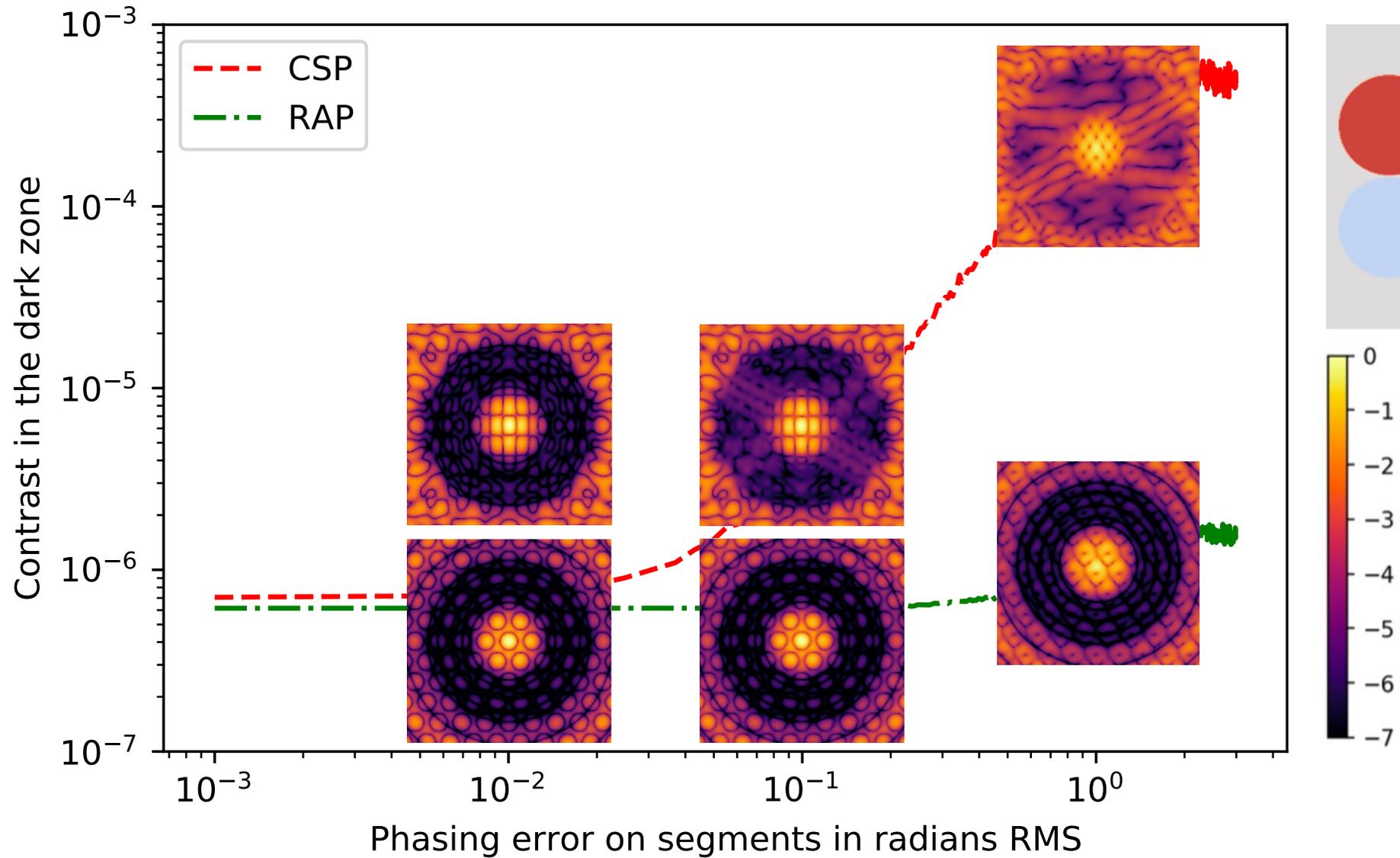


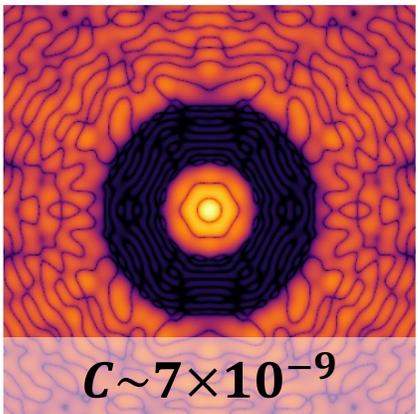
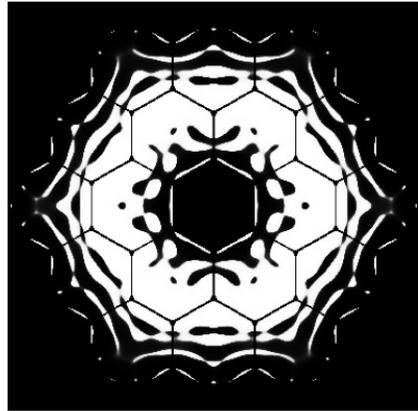
Image coronographique



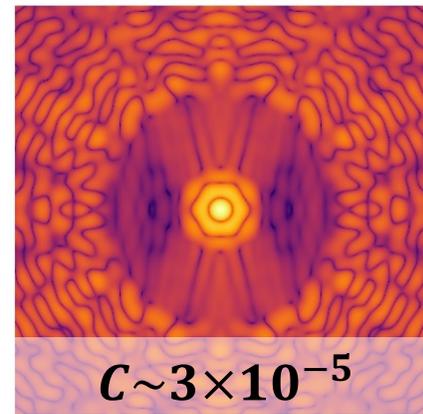
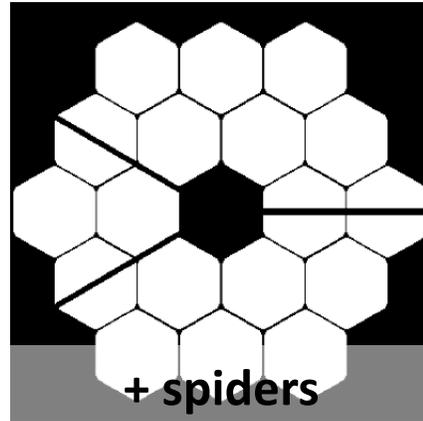
$10^{-6}$  @  $5.5 - 12\lambda/D$   
Throughput: 17.3%



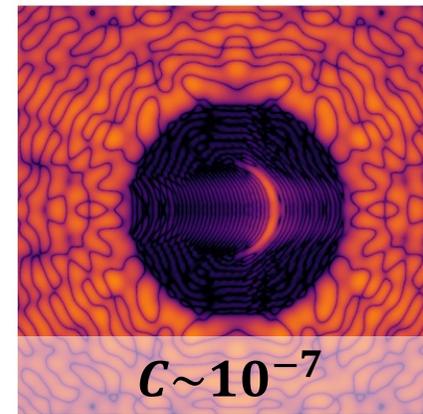
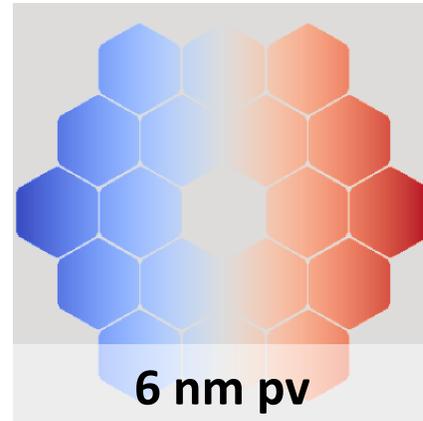
Pas d'erreur



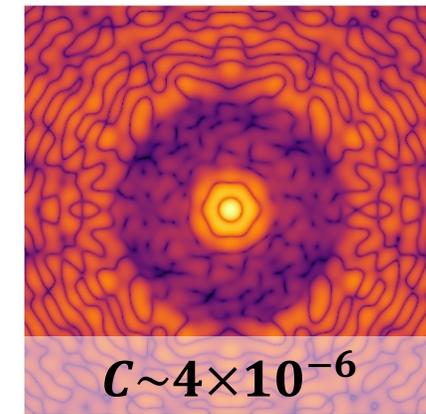
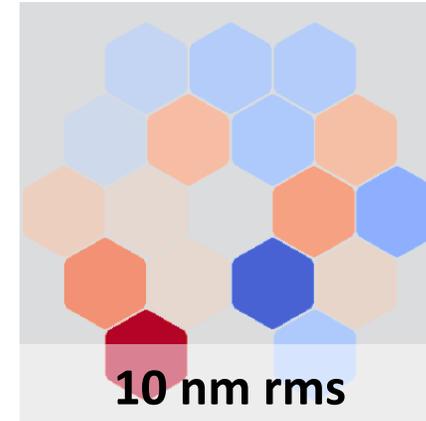
Pupille complexe



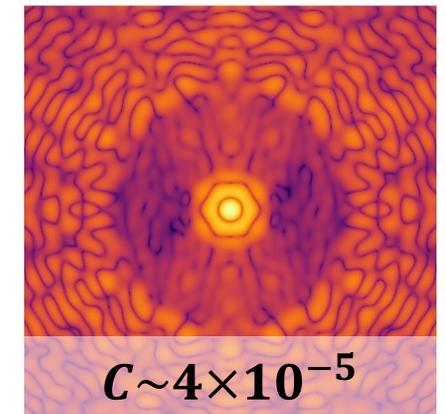
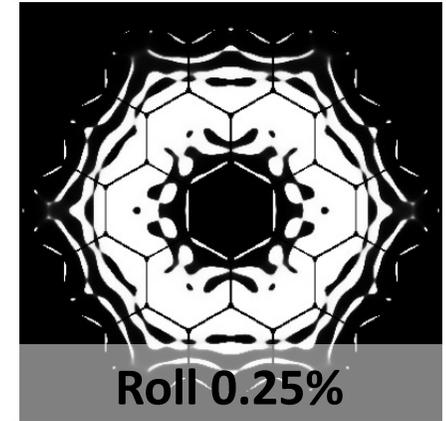
Dépointage



Phasage



Désalignements



Off axis, Aime & Soummer,  
Kenworthy, Codona, Codona  
& Angel, Carlotti, N'Diaye

N'Diaye



Pas d'erreur

Pupille complexe

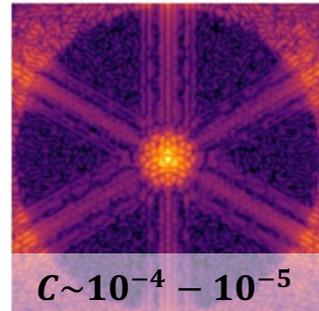
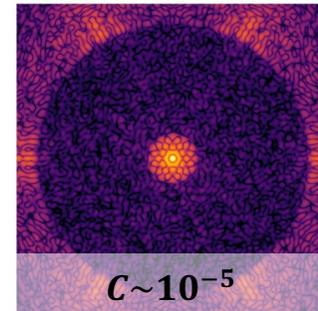
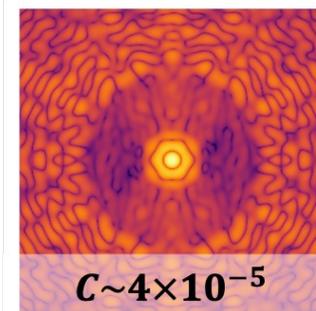
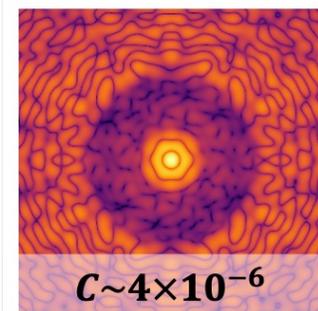
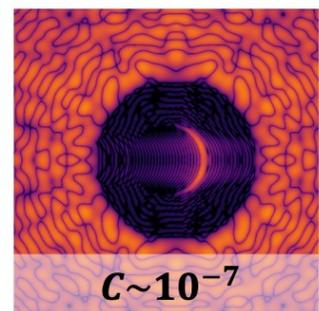
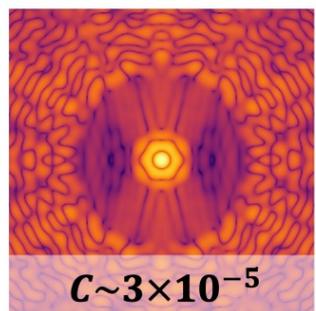
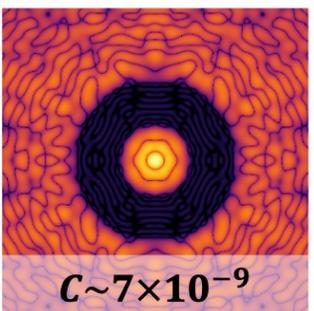
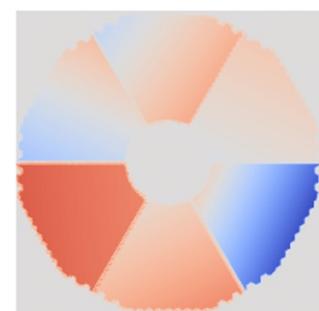
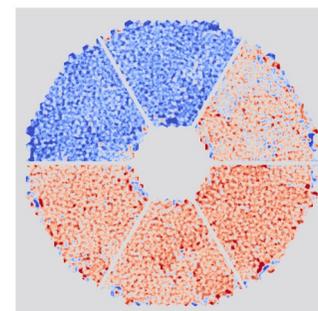
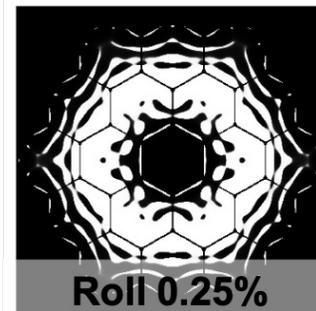
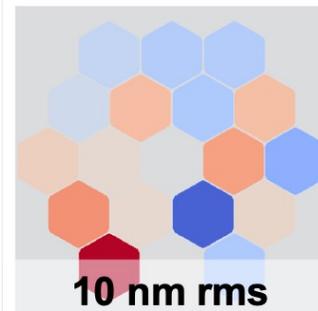
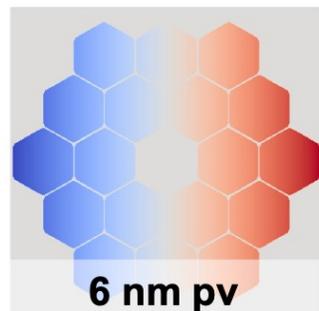
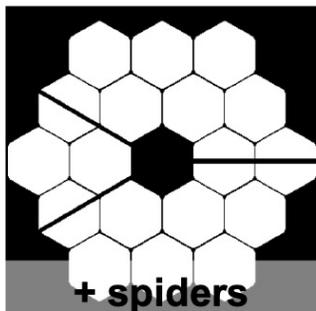
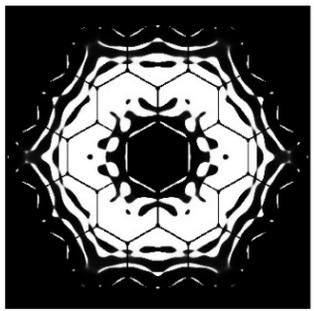
Dépointage

Phasage

Désalignements

Résidus d'OA

Island effects





Pas d'erreur

Pupille complexe

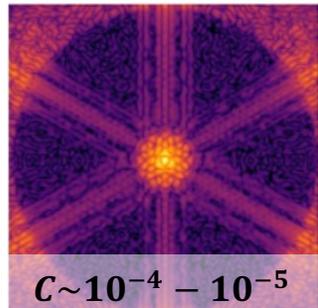
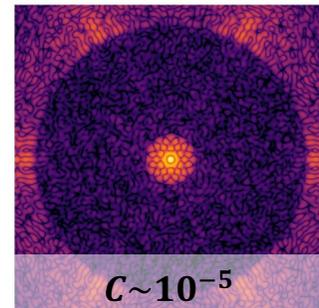
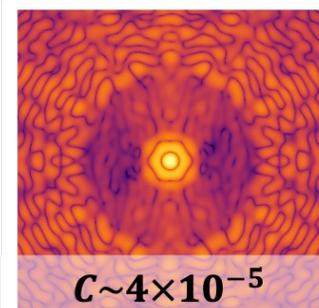
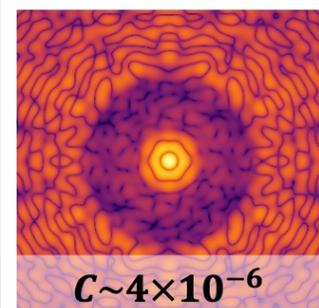
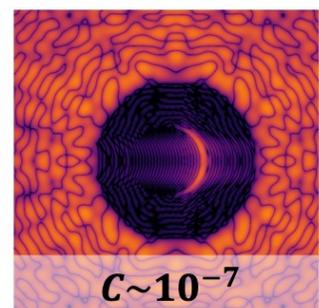
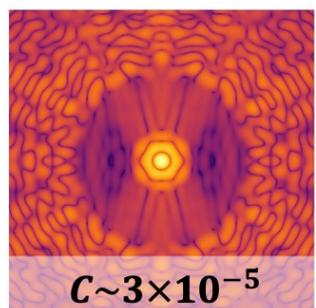
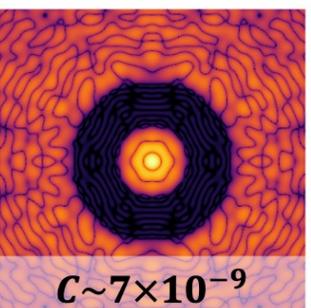
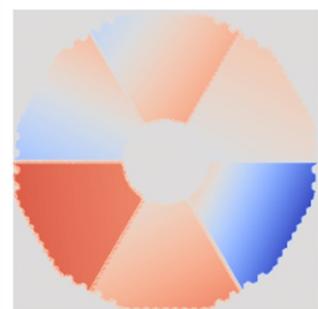
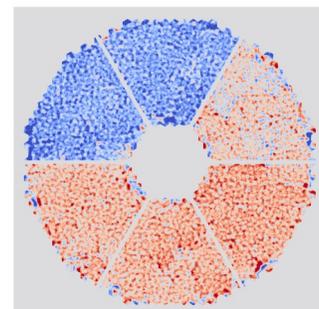
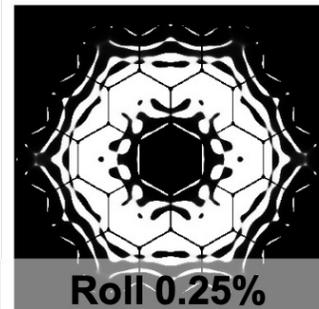
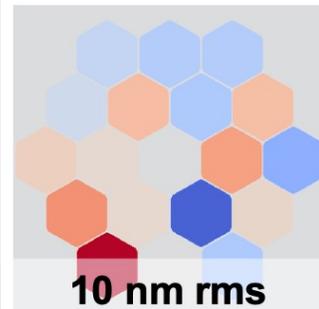
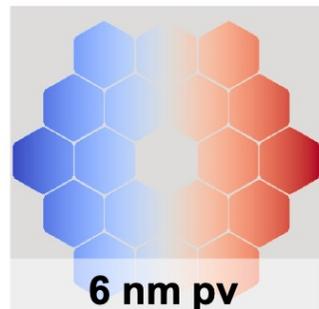
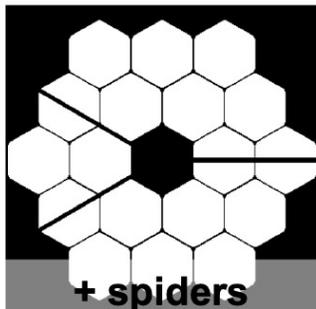
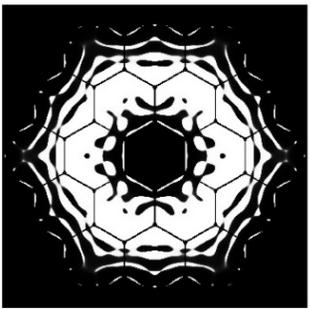
Dépointage

Phasage

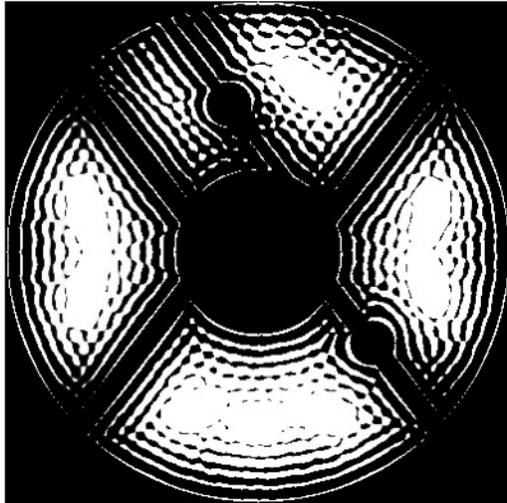
Désalignements

Résidus d'OA

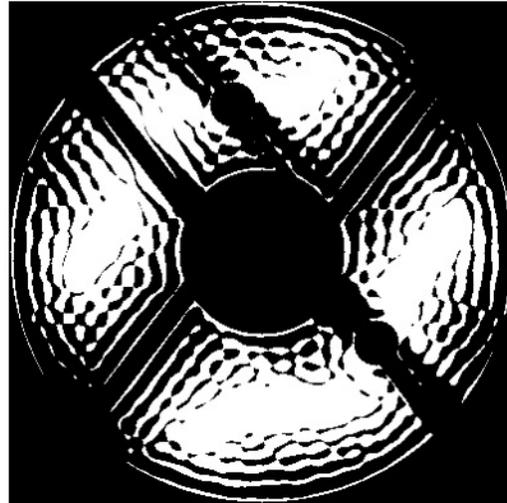
Island effects



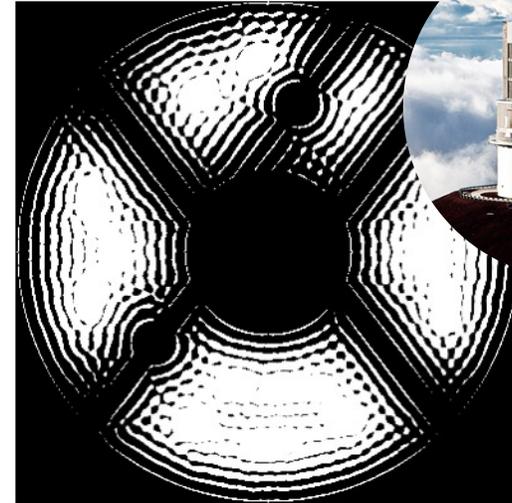
CHAR1



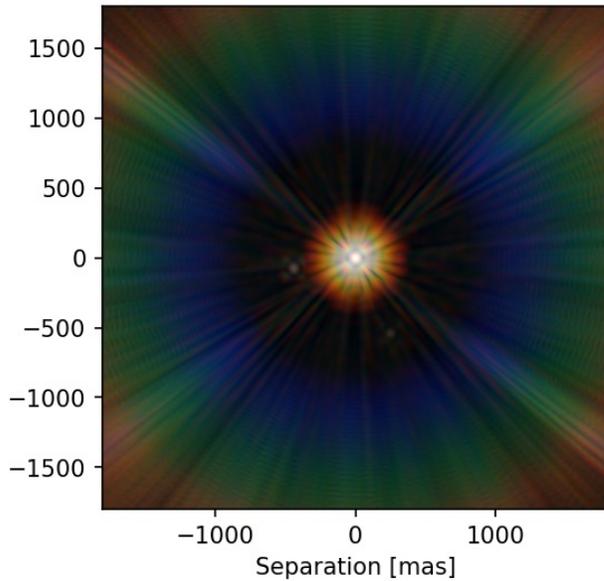
CHAR2



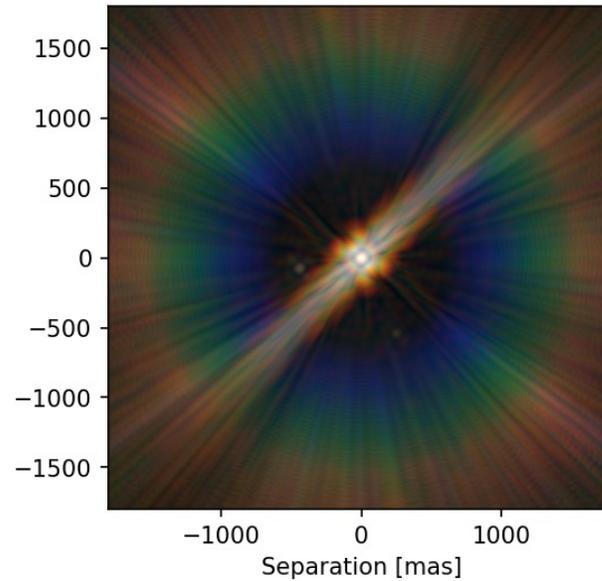
VAMP



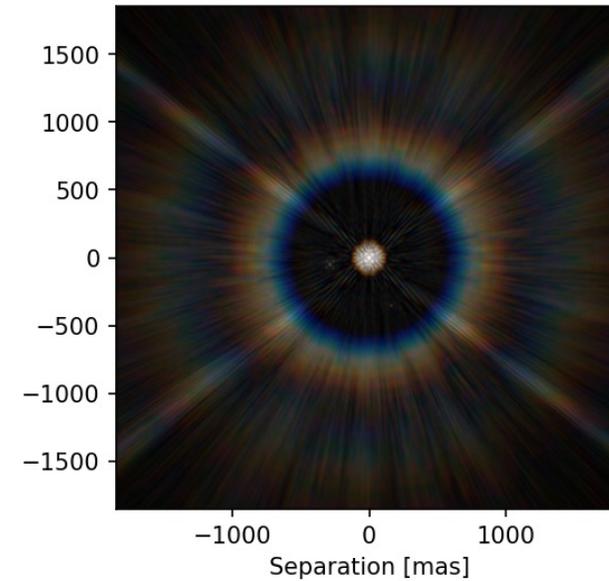
Broadband



Broadband

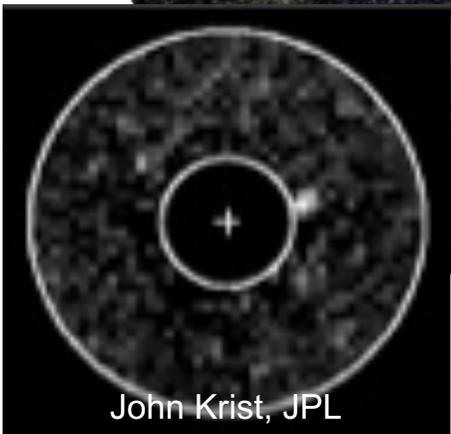
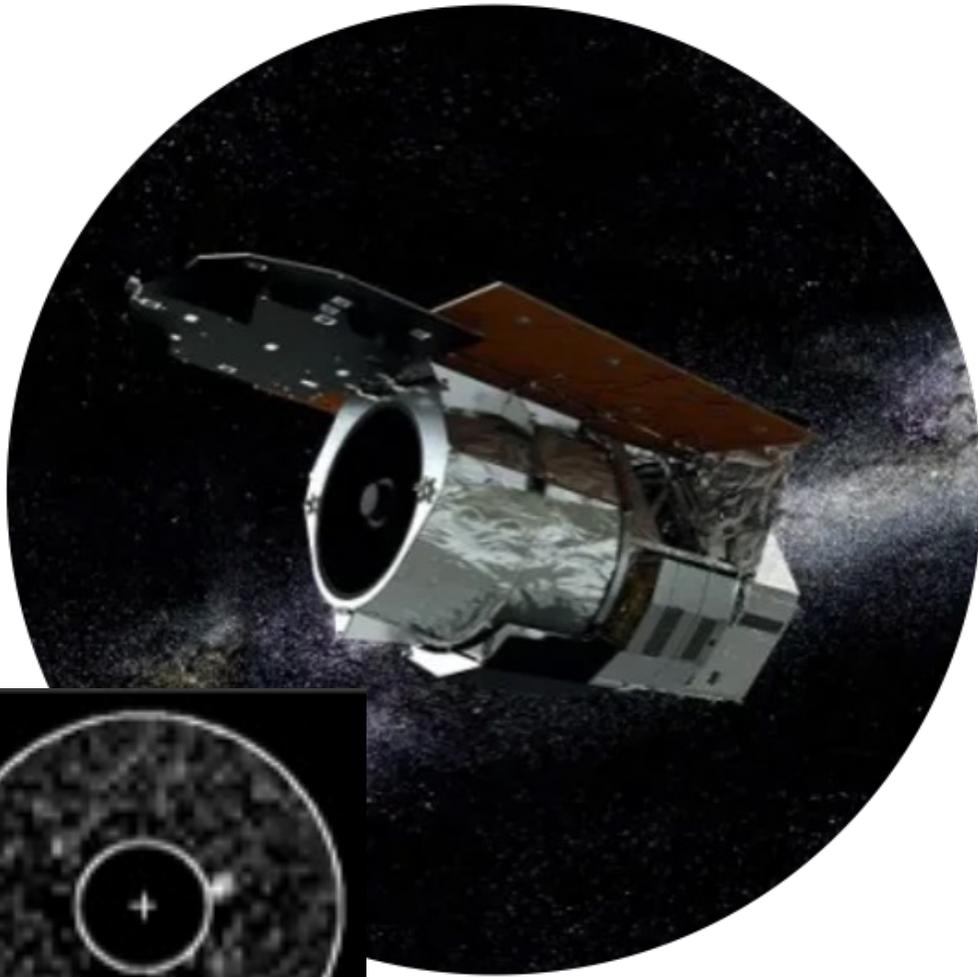


Broadband



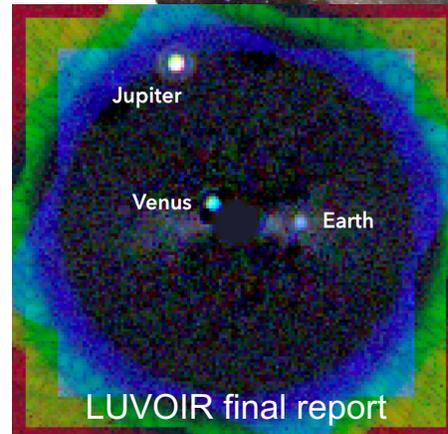
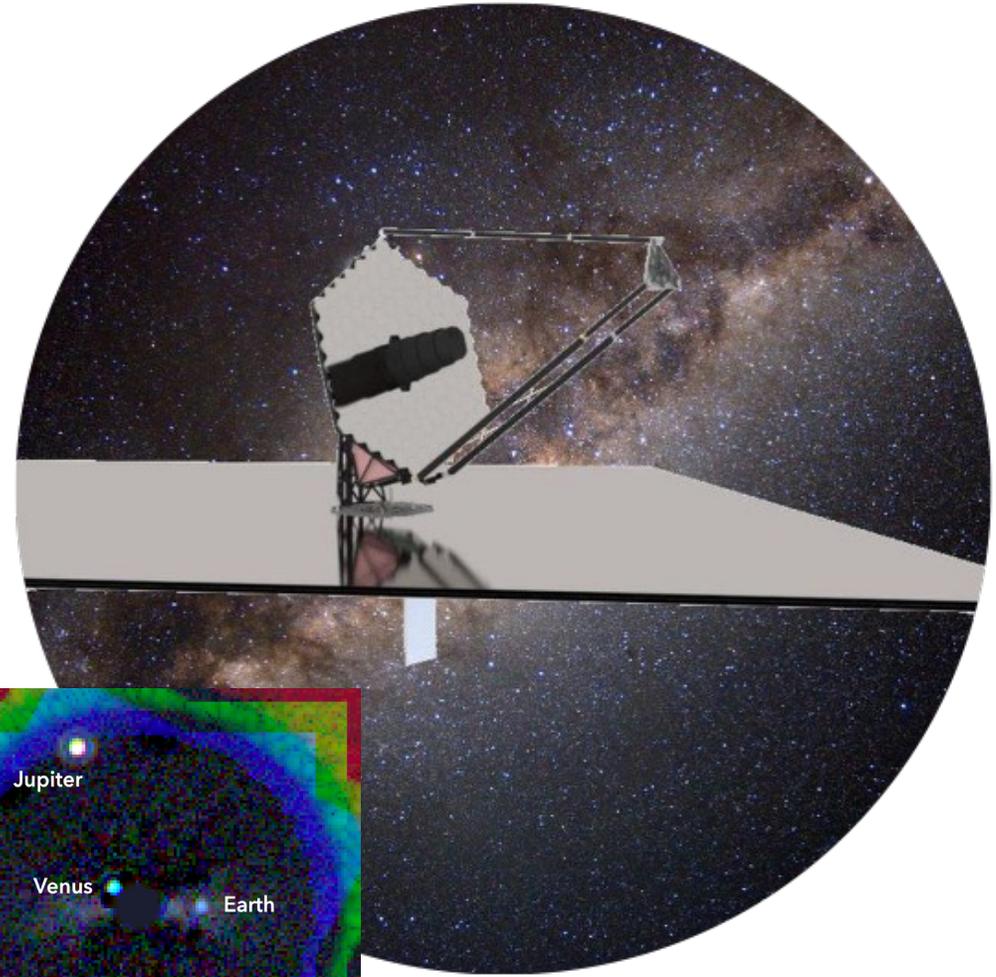
→ Tests en source interne & ciel en Septembre 2023 !

# Conclusions



John Krist, JPL

$C \sim 10^{-9} - 10^{-8}$  @ 200-300 mas



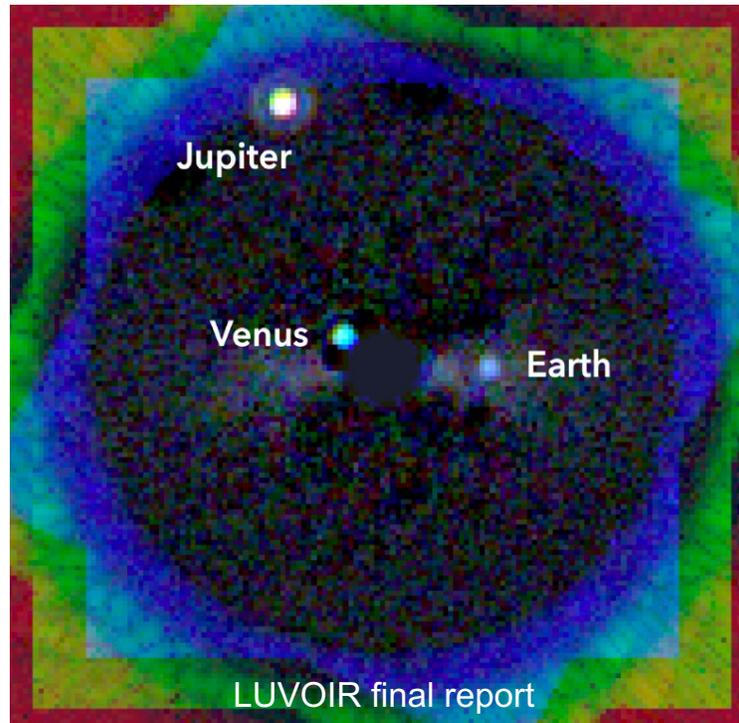
LUVOIR final report

$C \sim 10^{-10}$  @ 50-100 mas

Throughput

Séparation angulaire

Robustesse



Contraste

Bande spectrale

« Il y a une sorte de conservation des choses chiantes » (Carlotti 2023)

Performance



Robustesse