



L'imagerie haute dynamique appliquée aux exoplanètes

développements actuels et futurs

Plan

- Panorama des exoplanètes
- Besoin en Imagerie Haute Dynamique
 - Instruments actuels
 - Futurs instruments

Panorama des exoplanètes

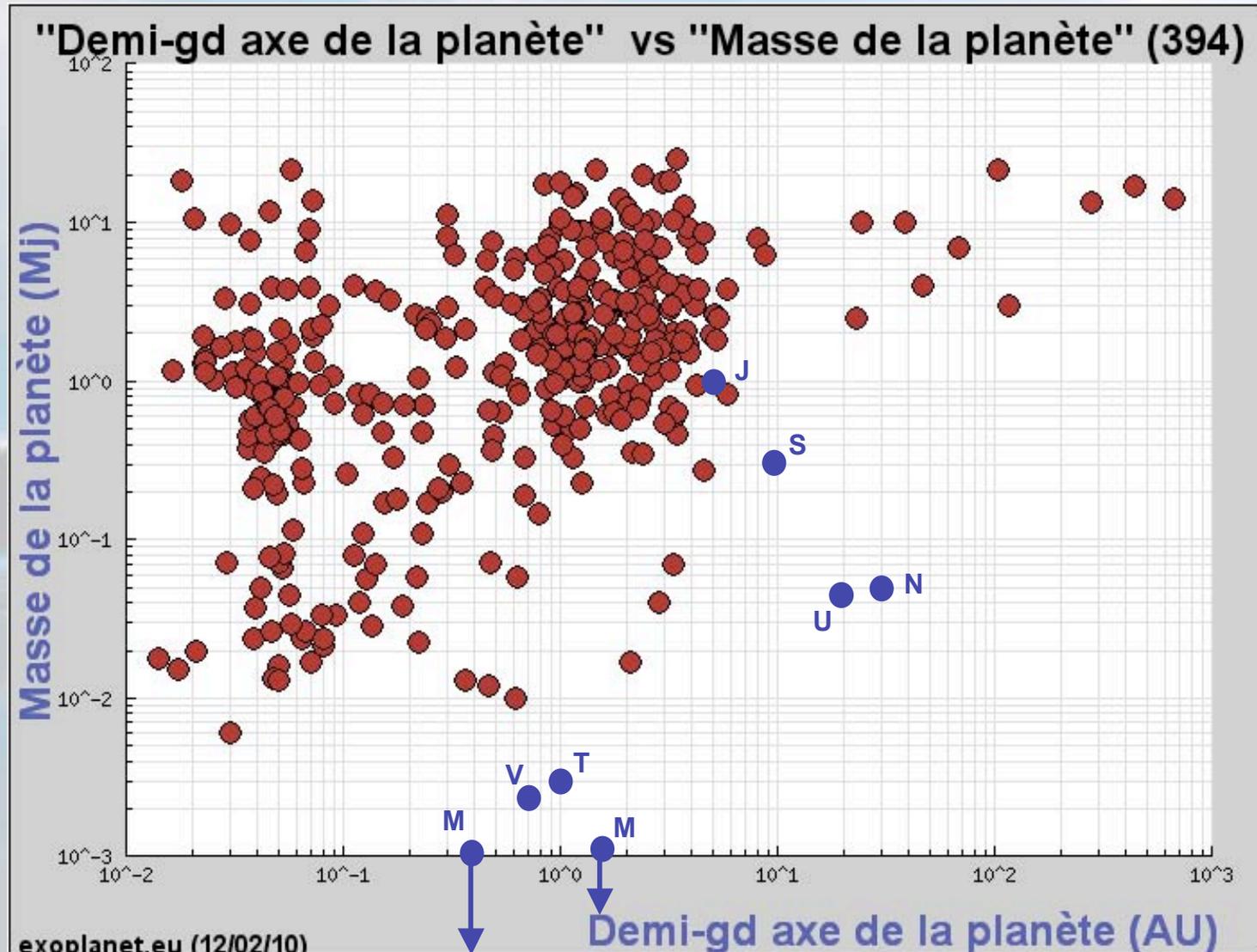
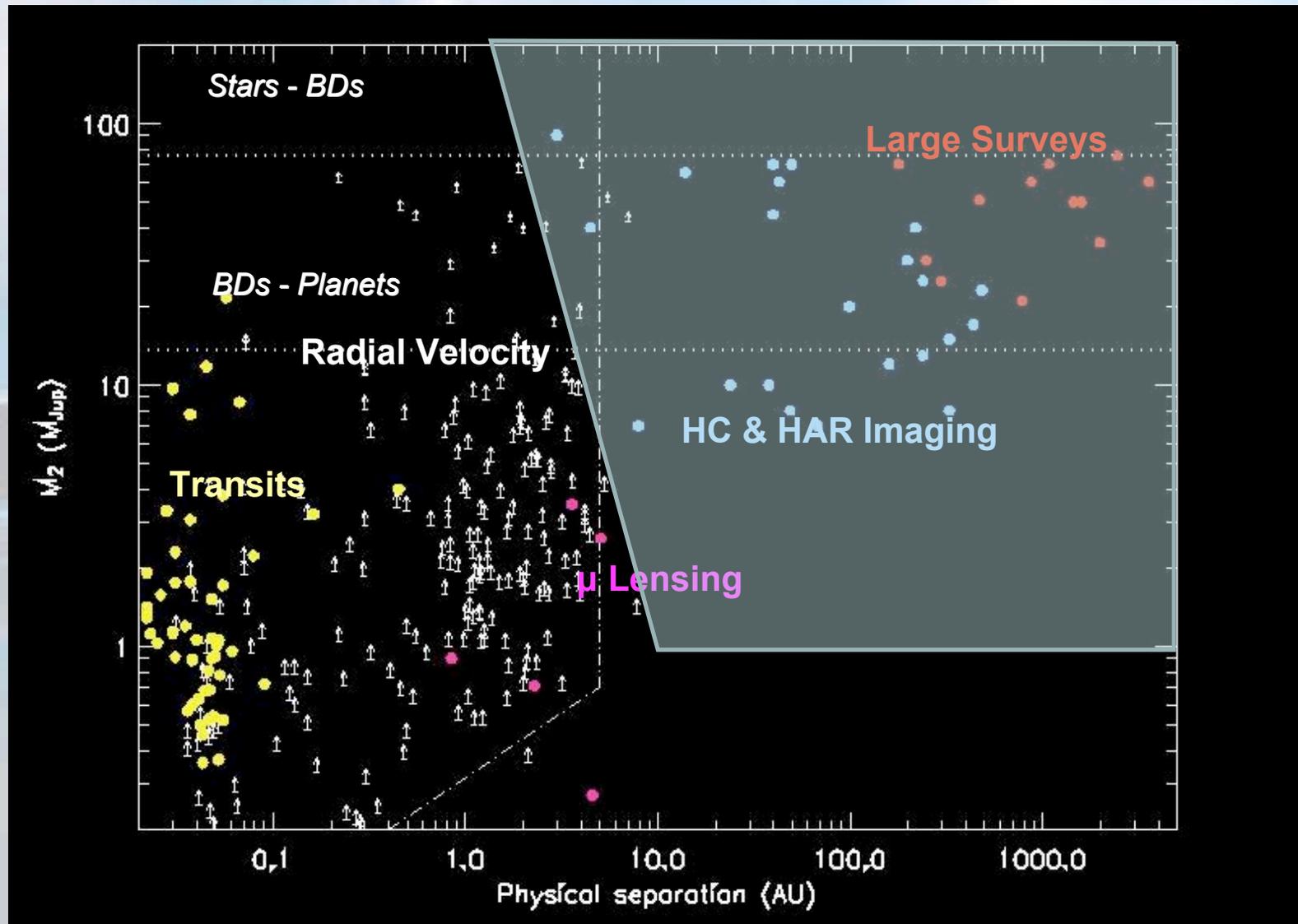
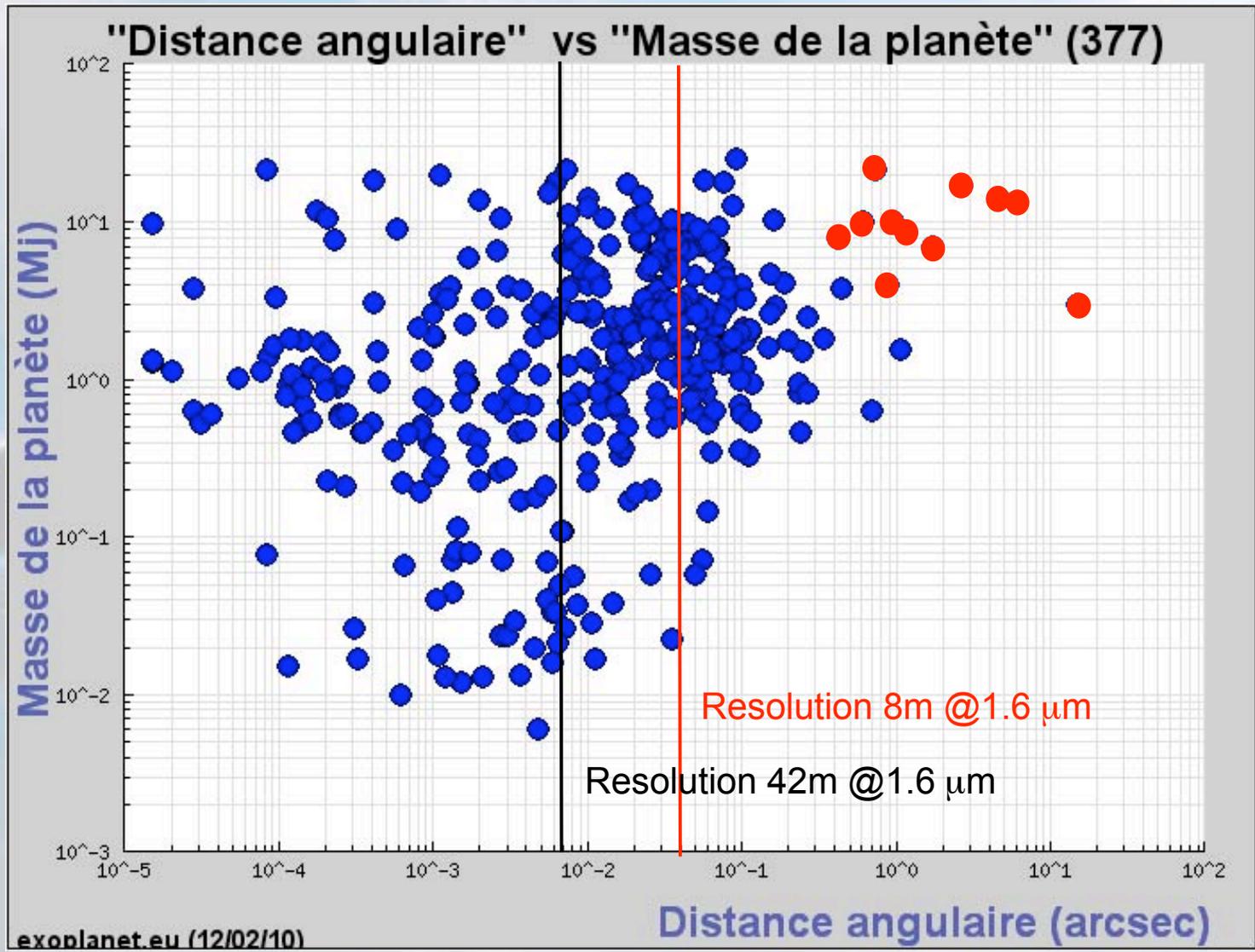
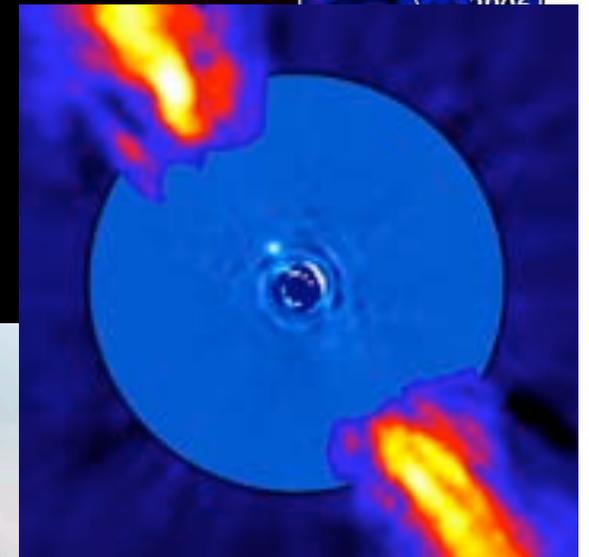
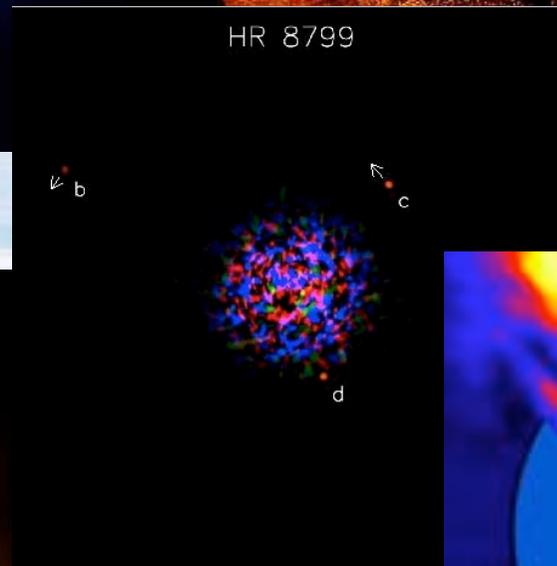
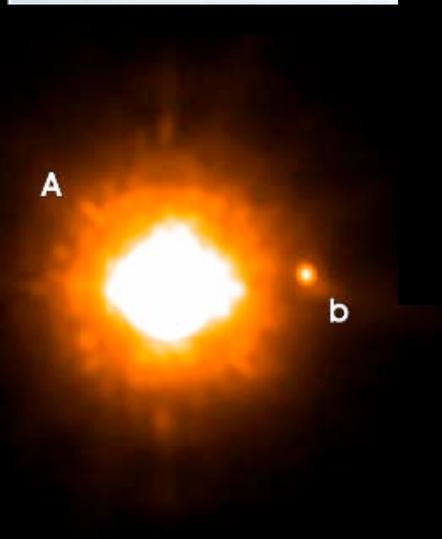
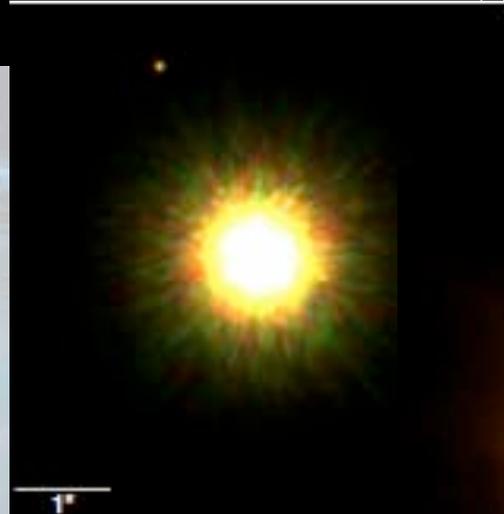
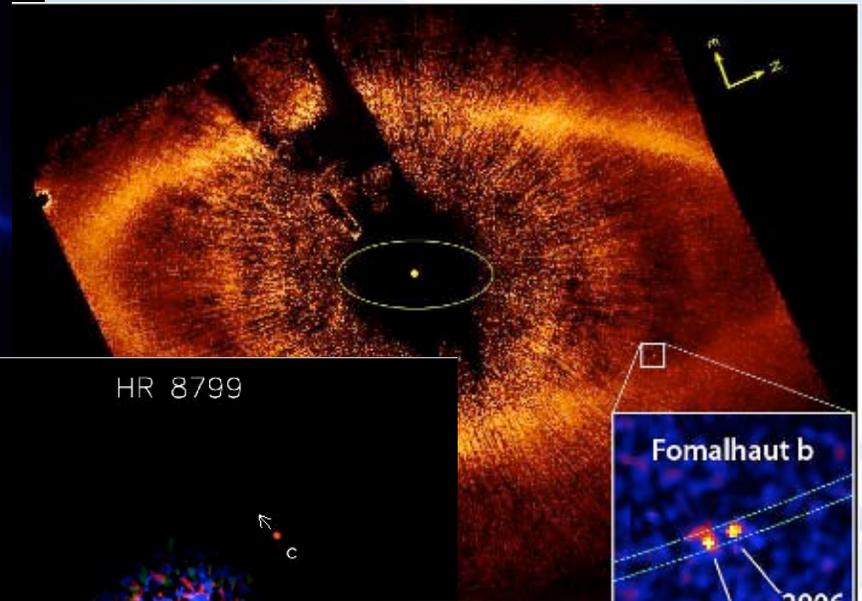
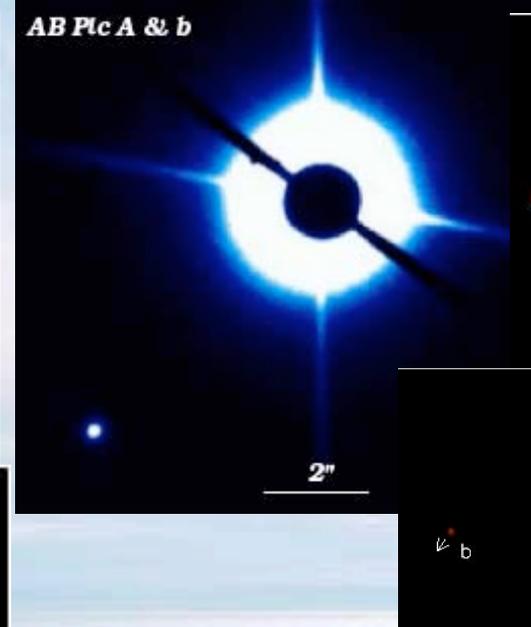
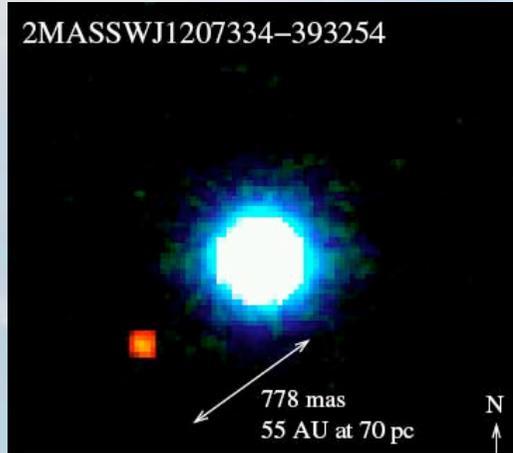


Diagramme Masse-Période





Compagnons de masses planétaires



Une exoplanète, c'est :

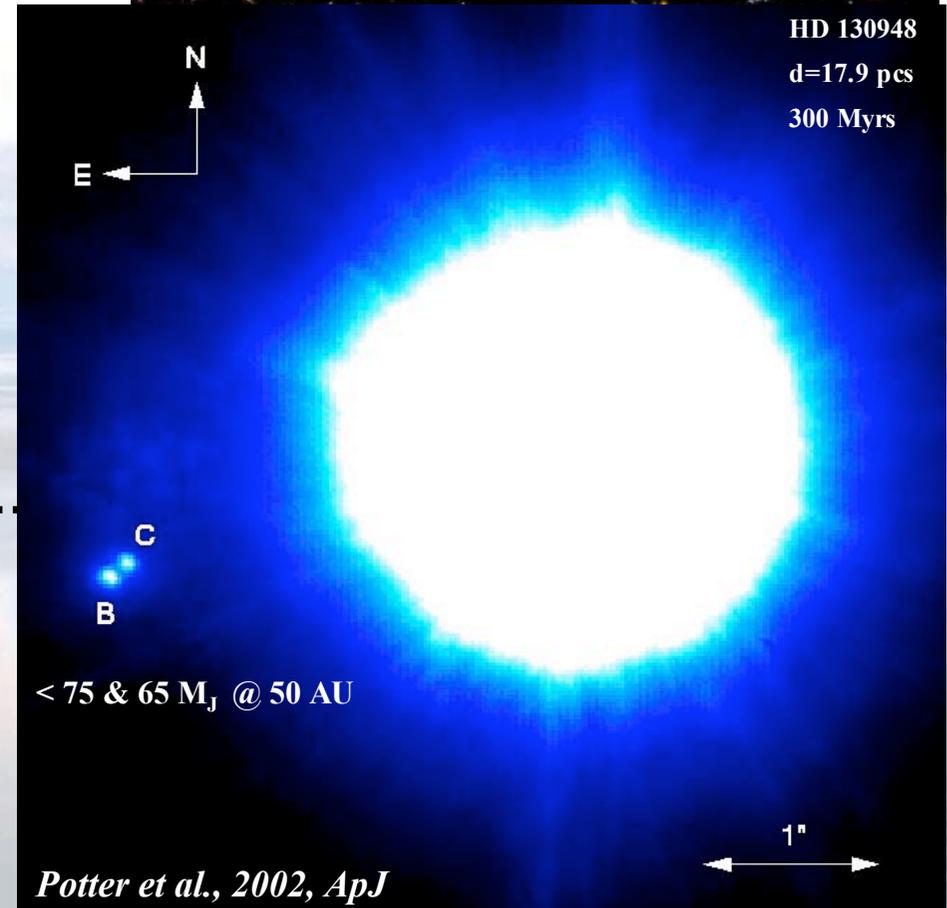
1- Un objet faiblement lumineux

On sait observer de tels objets
(Limite actuelle au sol et dans
l'espace $M=30$)

2- Proche de son étoile hôte

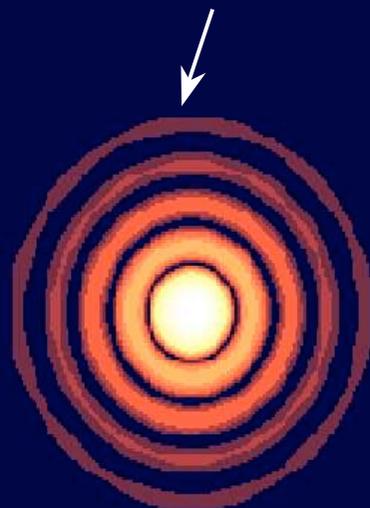
Distances typiques: 50 mas to 1''
(1 to 10 UA @ 10 to 20pc). Résolution du
VLT en IR: 40 mas @ 1.6 μm avec
Optique adaptative

3- Mais... L'étoile est très brillante...

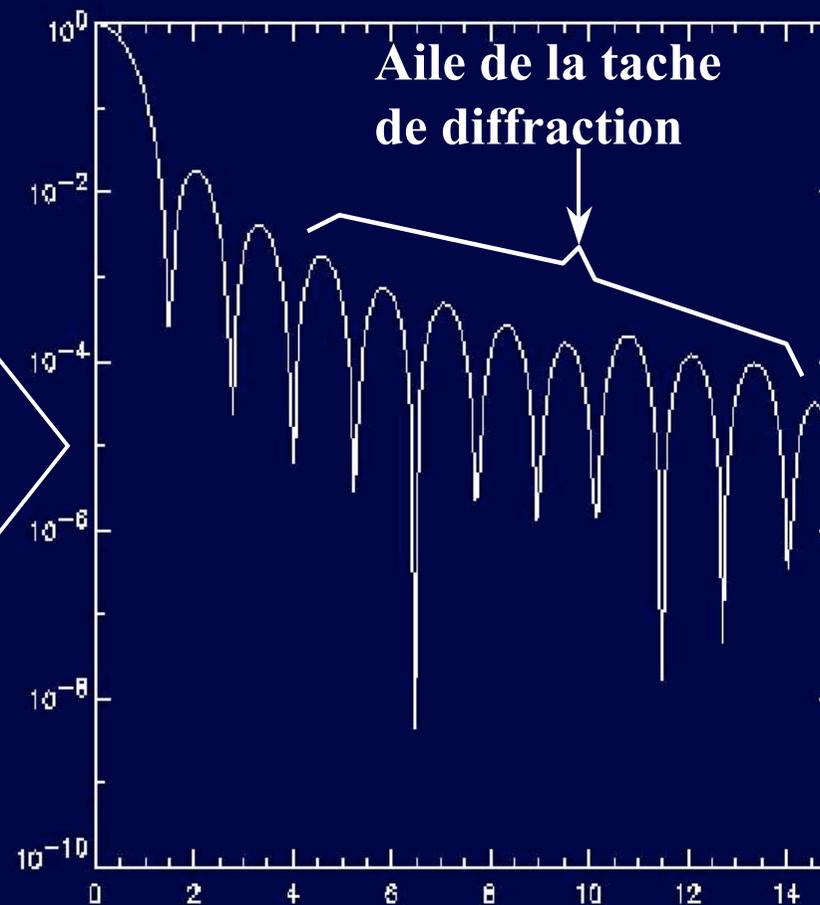


Un problème de contraste

Tache de diffraction

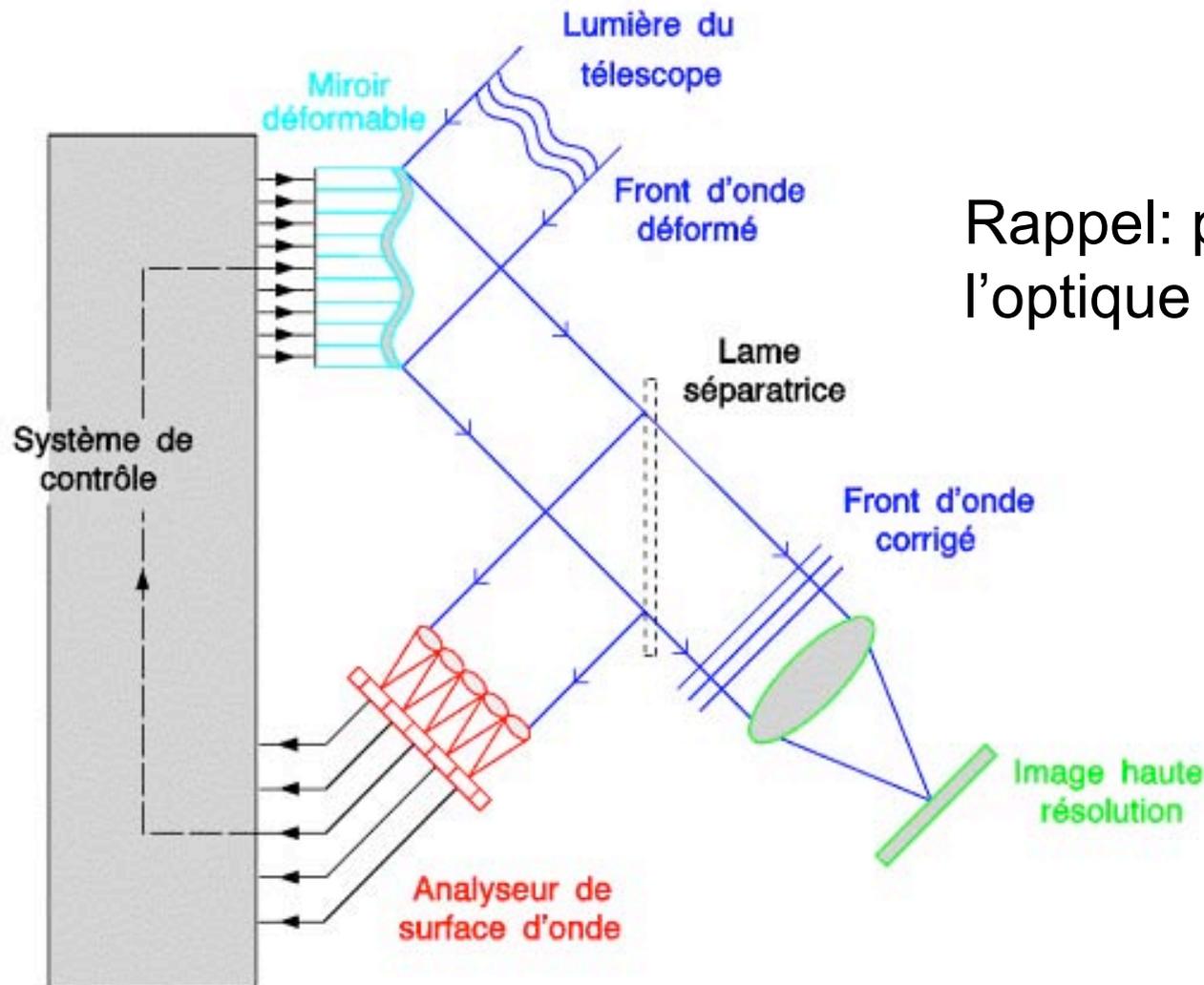


Profil radial



Imagerie à Haute Dynamique

1- Optique Adaptative extreme même sur un télescope spatial !!!



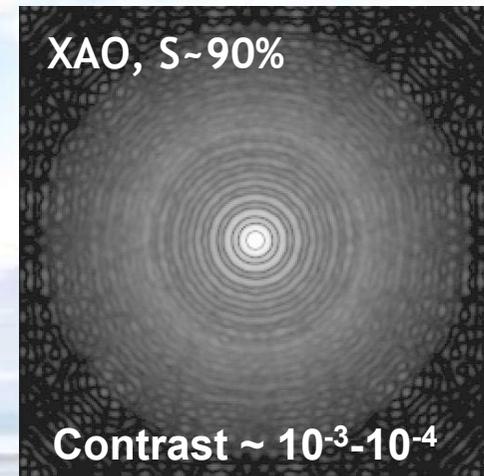
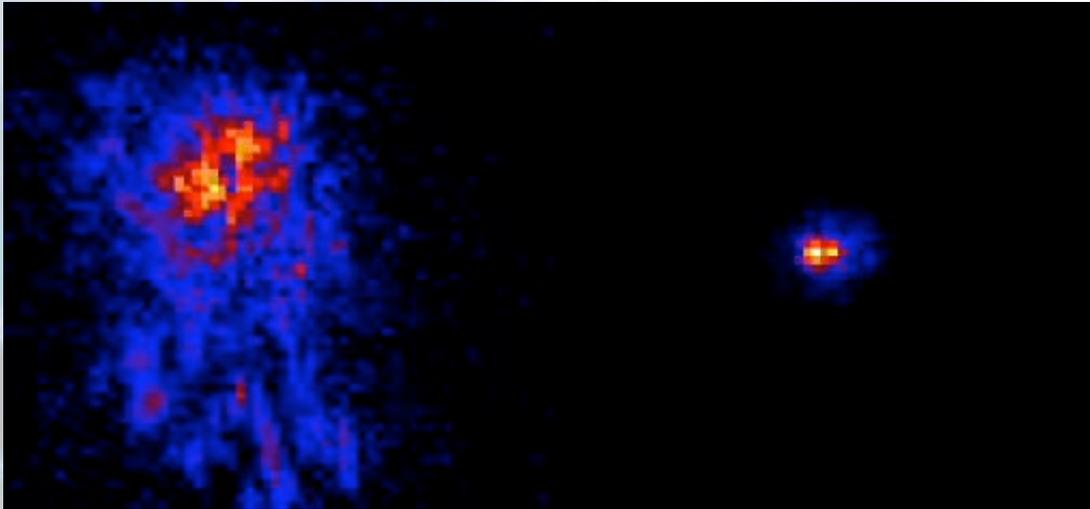
Rappel: principe de l'optique adaptative (OA)



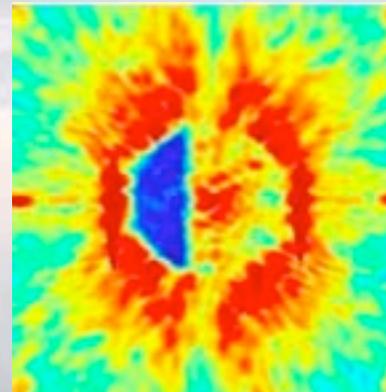
Imagerie à Haute Dynamique

1- **Optique Adaptative extreme même sur un télescope spatial !!!**

Télescope au sol: indispensable....



Optique adaptative
utile aussi sur les
télescopes spatiaux

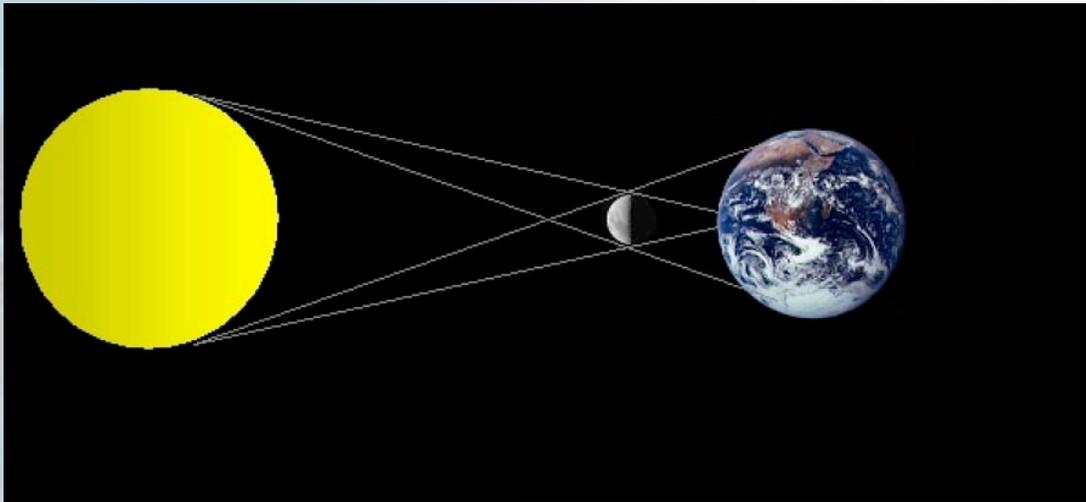


*Speckle nulling
in a limited FOV
with a DM (JPL)*

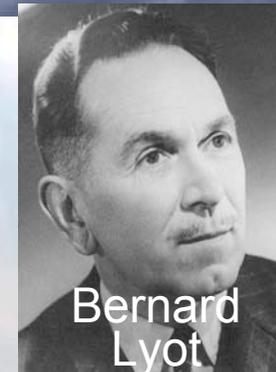
Imagerie à Haute Dynamique

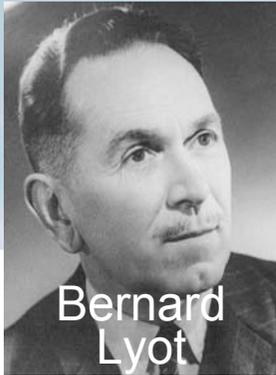
1- Optique Adaptative extreme même sur un télescope spatial !!!

2- Coronographe
éteindre l'étoile sans éteindre la planète



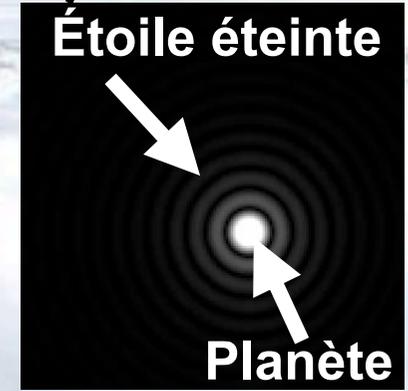
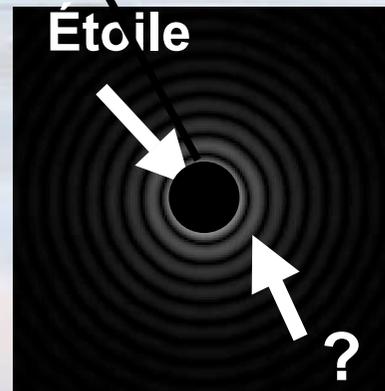
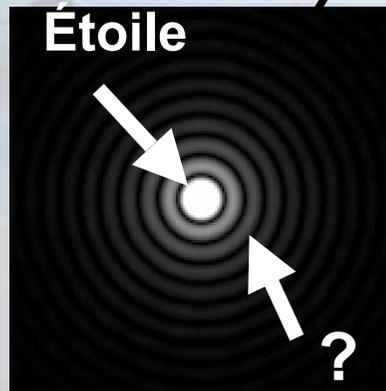
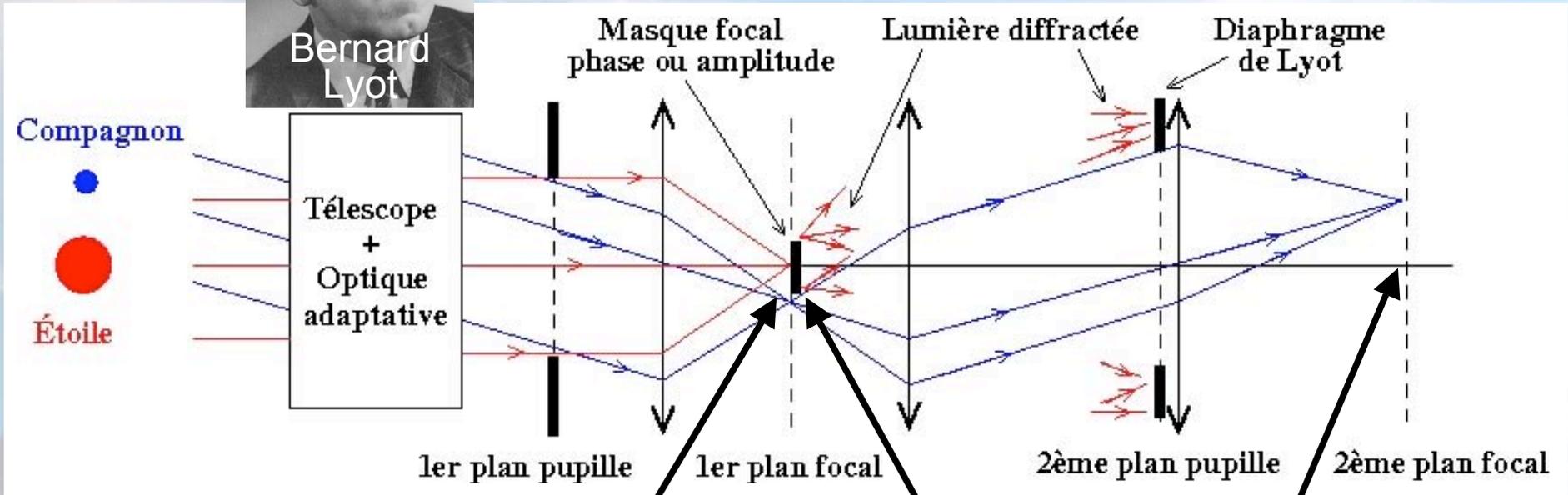
Bernard Lyot 1930: proposition du coronographe solaire

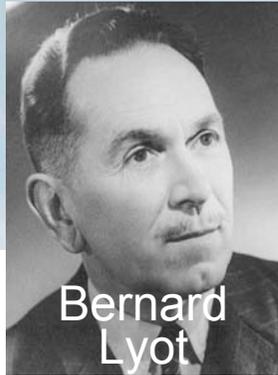




Bernard Lyot

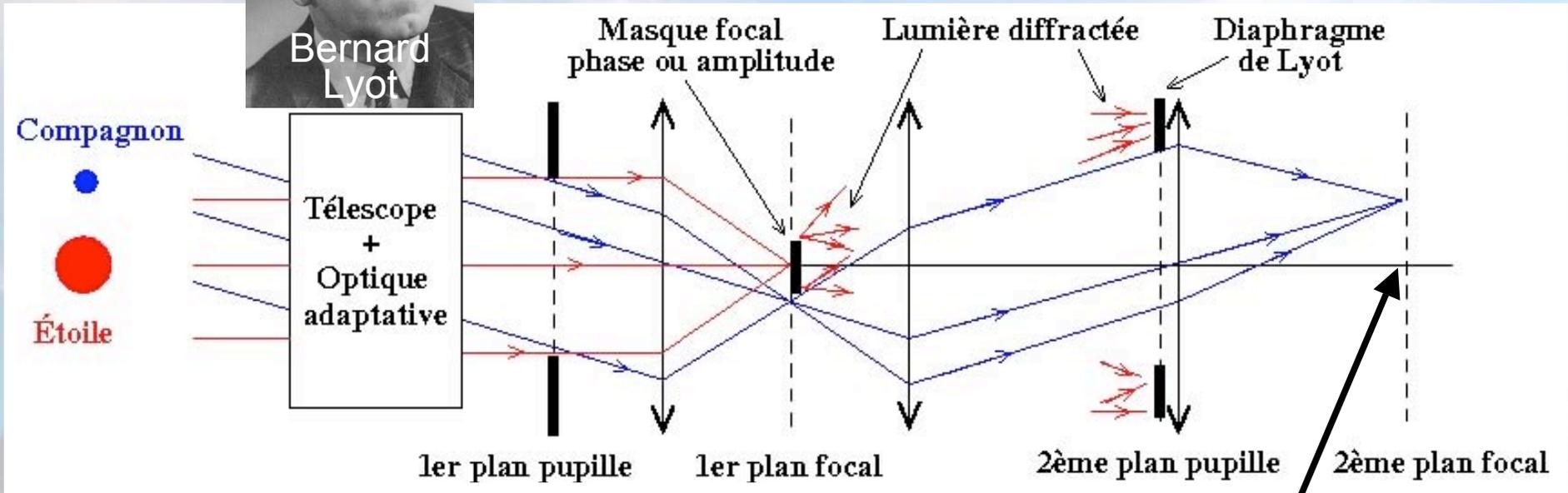
Coronographie





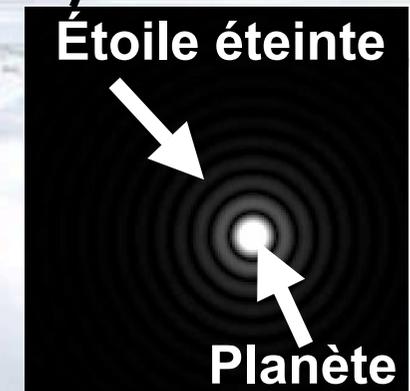
Bernard Lyot

Coronographie

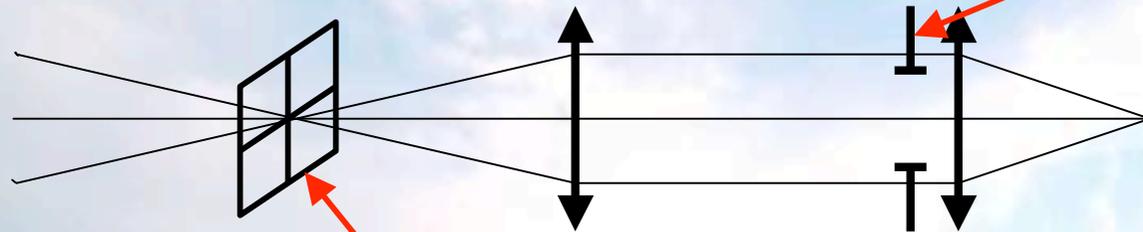


- Coronographe de Lyot
- Coronographe Interférentiel Achromatique
- Coronographe à quatre quadrants
- Band-limited mask coronagraph
- Coronographe de Lyot apodisé
- Phase Induced Amplitude Apodization coronographe
- Optical vortex coronagraph
- Coronographe à quatre quadrants à étages multiples et beaucoup d'autres

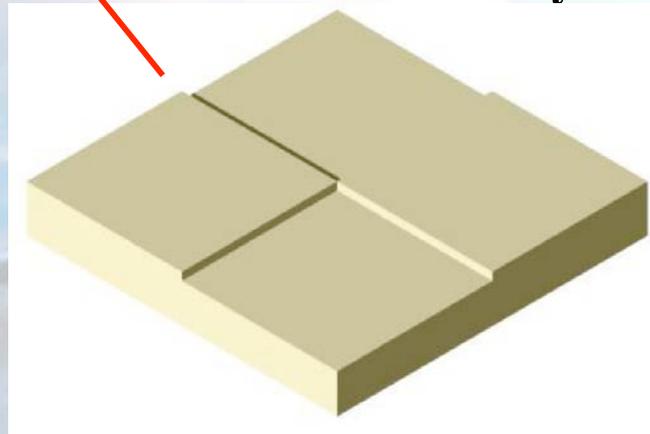
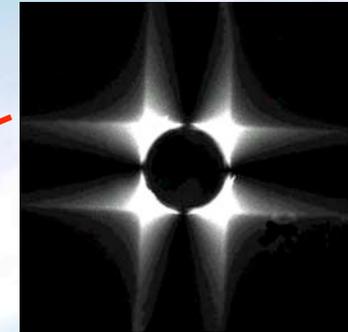
- Lyot 1932*
- Gay & Rabbia 1996*
- Rouan et al. 2000*
- Kuchner & Traub 2002*
- Aime 2005*
- Guyon et al. 2005*
- Mawet et al. 2005*
- Baudoz et al. 2008*



Coronographe à Quatre Quadrants



Lyot stop

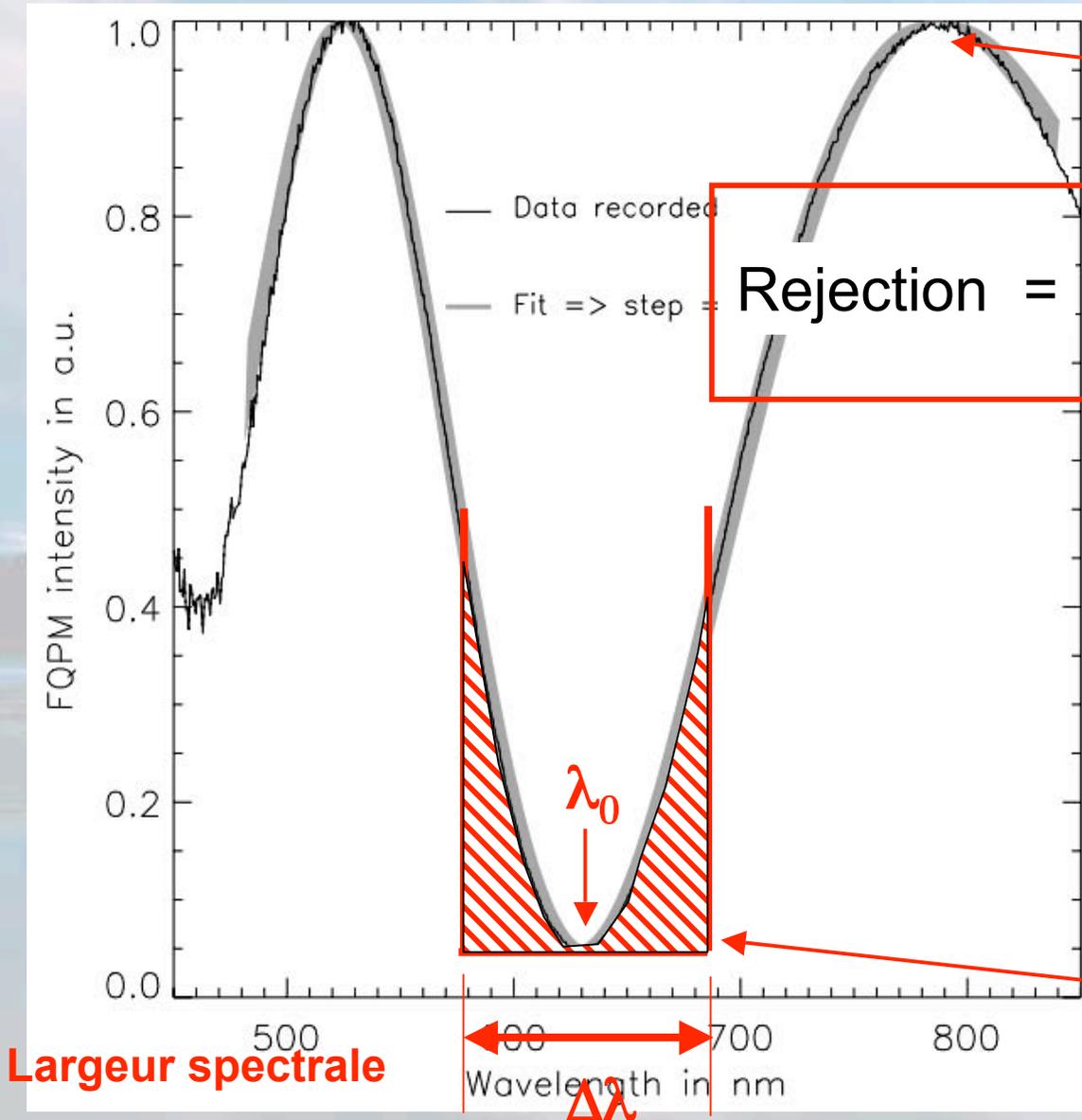


Monochromatique

$$\text{Phase} = 2\pi(n-1).e/\lambda$$

- Simple
- Étudié et/ou utilisé pour différents instruments (VLT-NACO, JWST, SPHERE/VLT)

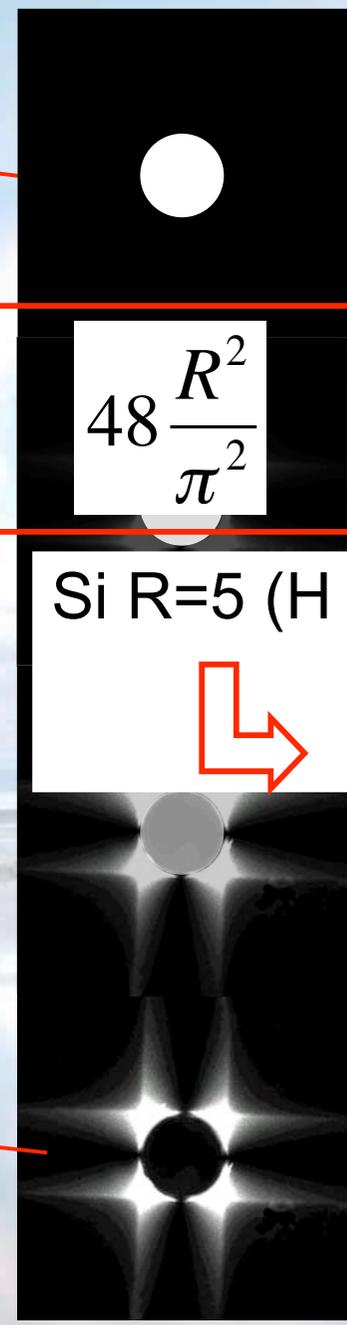
FQPM chromatisme



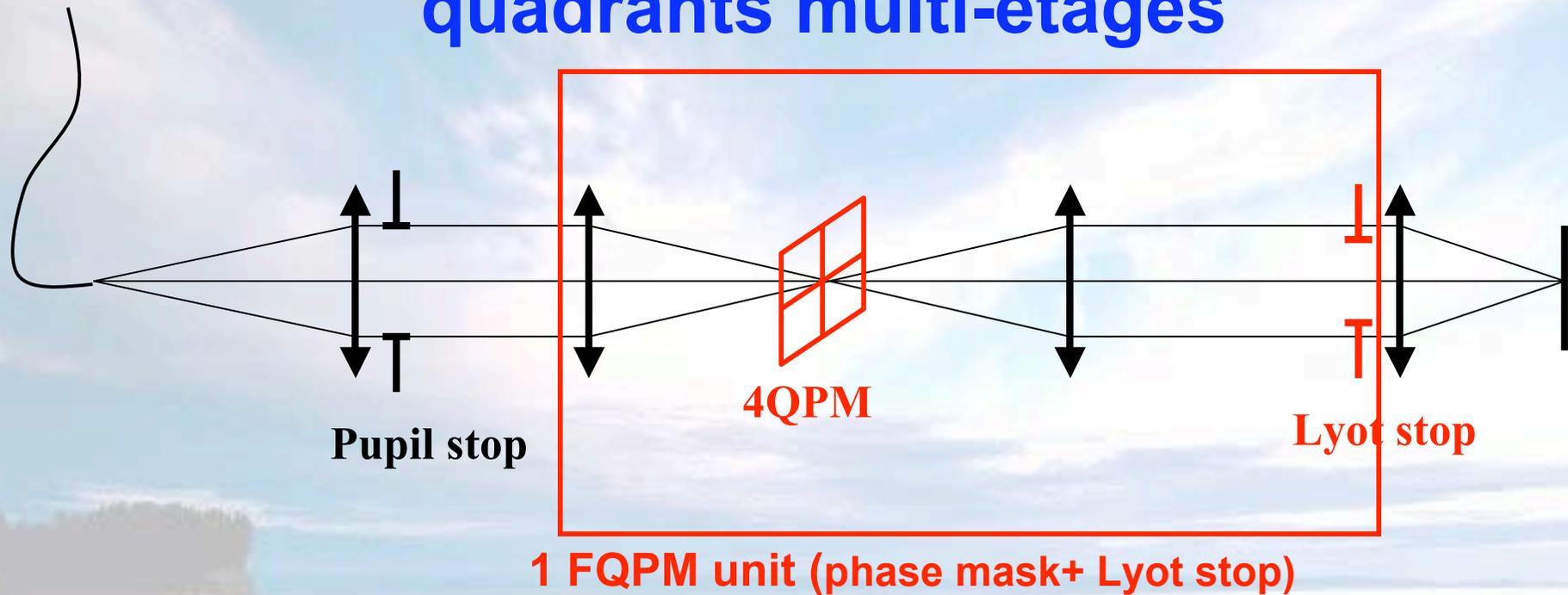
Rejection = $48 \frac{R^2}{\pi^2}$ $R = \frac{\lambda}{\Delta\lambda}$

Si R=5 (H band)

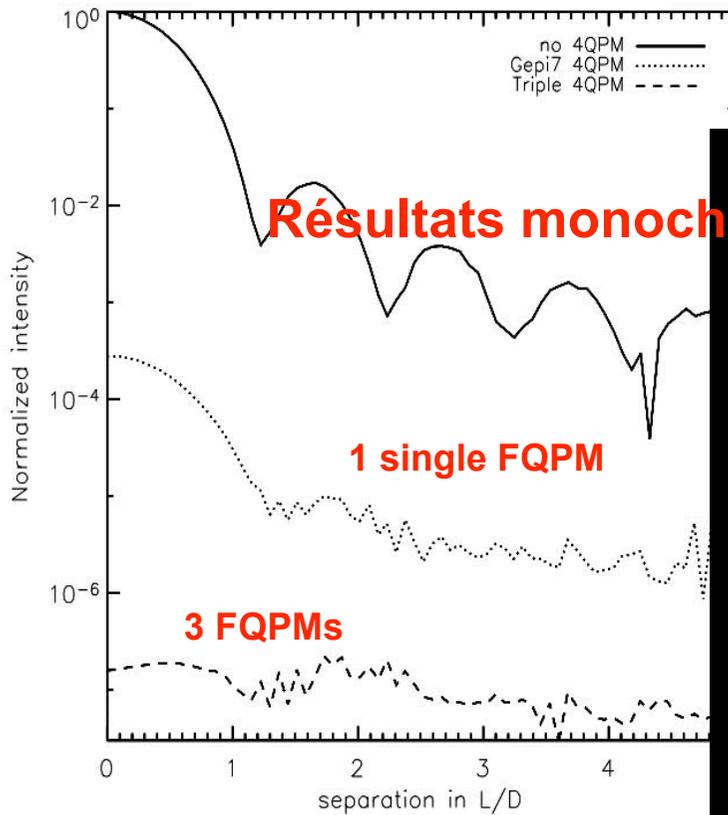
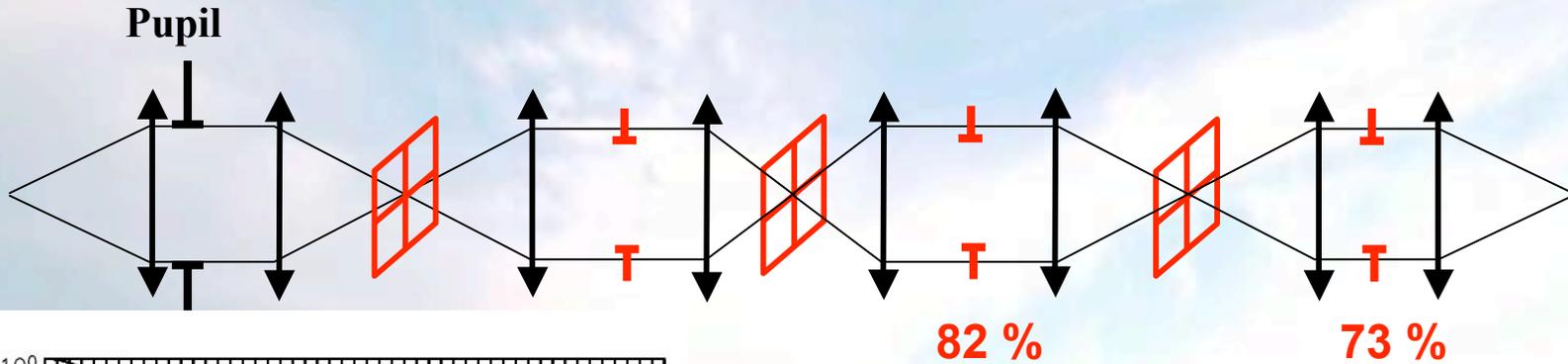
120



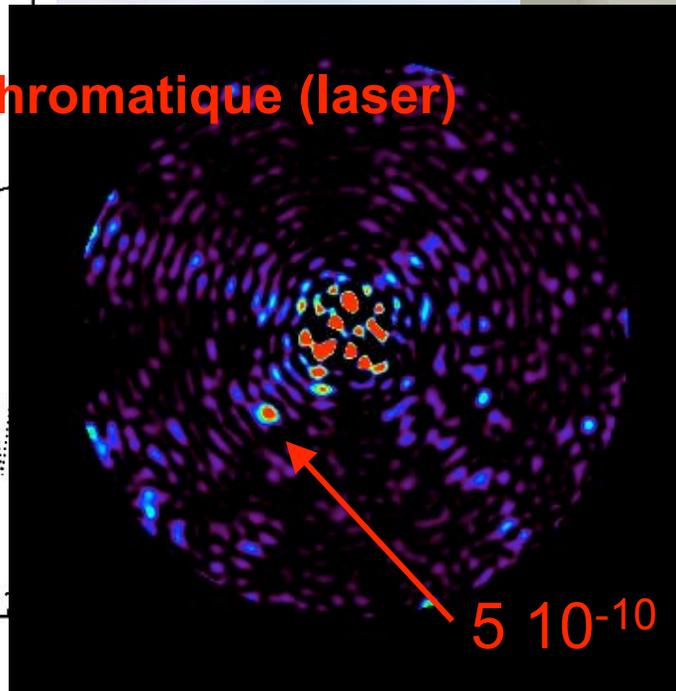
Principe du coronographe à quatre quadrants multi-étages



Tests préliminaires



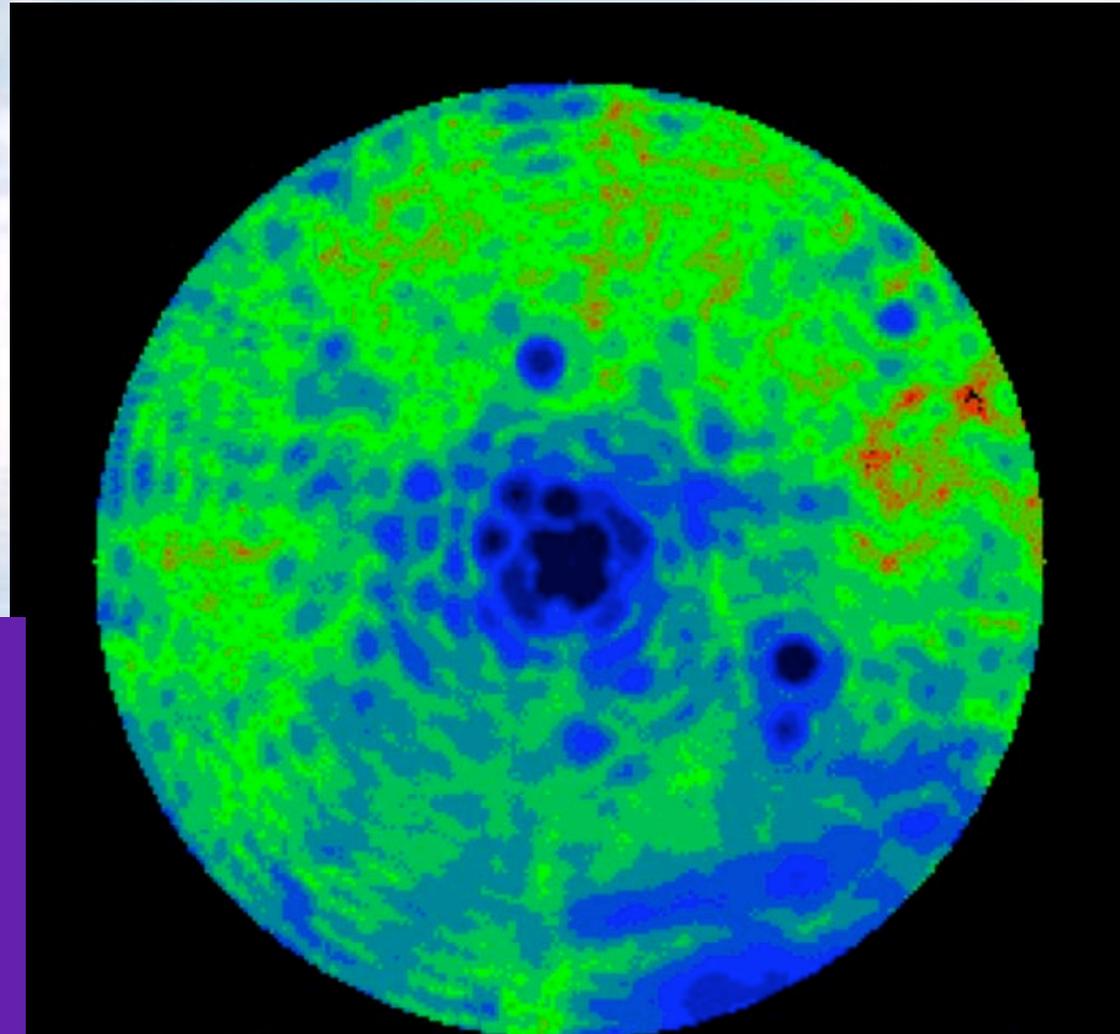
Résultats monochromatique (laser)



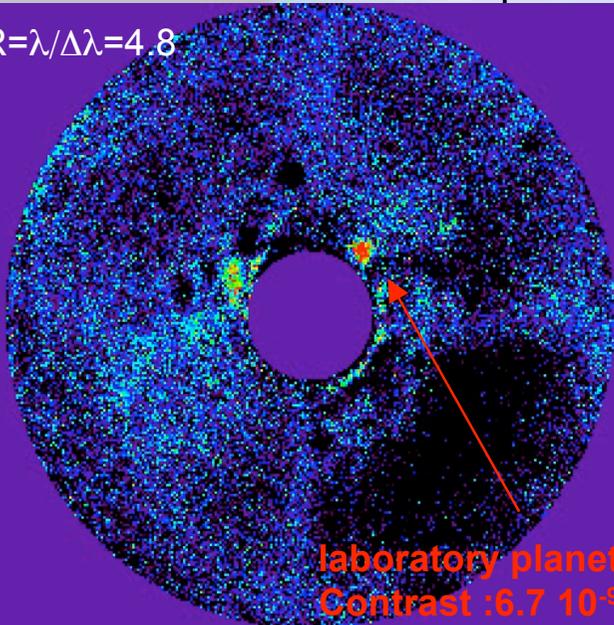
Laboratory results $R=\lambda/\Delta\lambda=11$

3 FQPM

$35 \lambda/D$



$R=\lambda/\Delta\lambda=4.8$



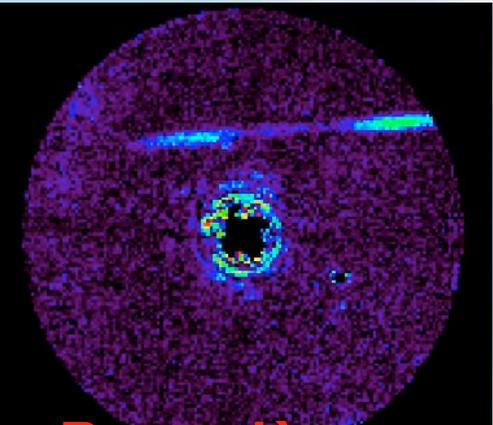
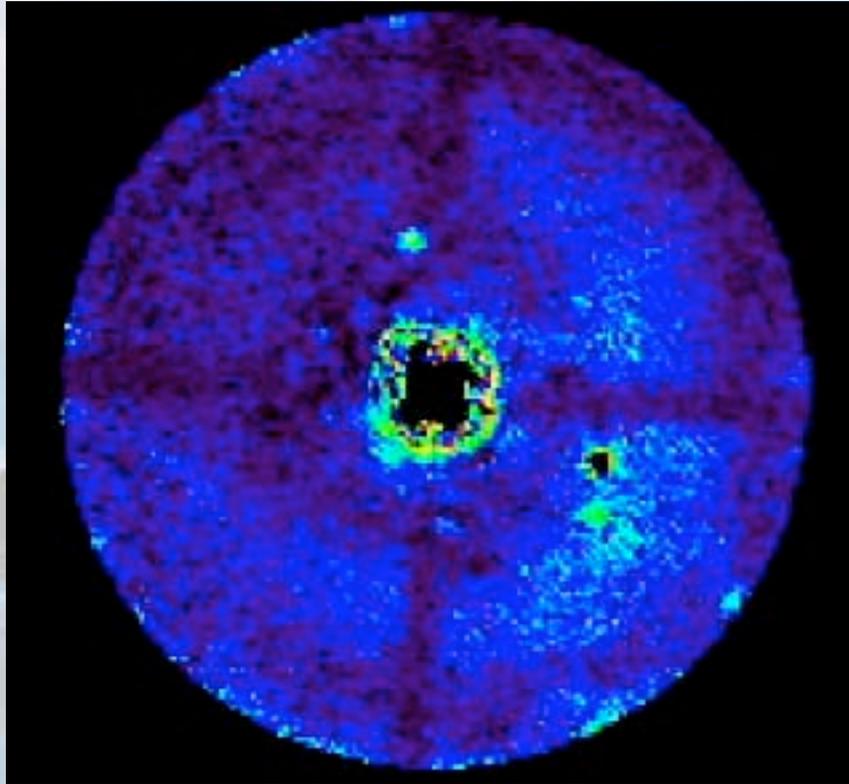
laboratory planet
Contrast :6.7 10^{-9}

10^{-8}

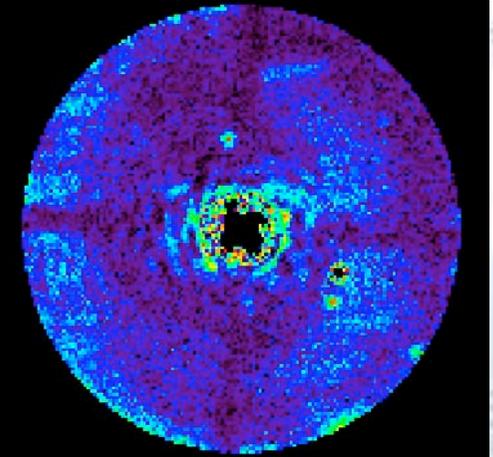
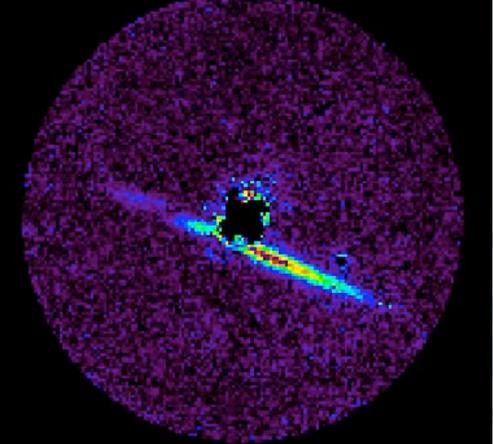
10^{-7}

10^{-6}

Variation temporelle

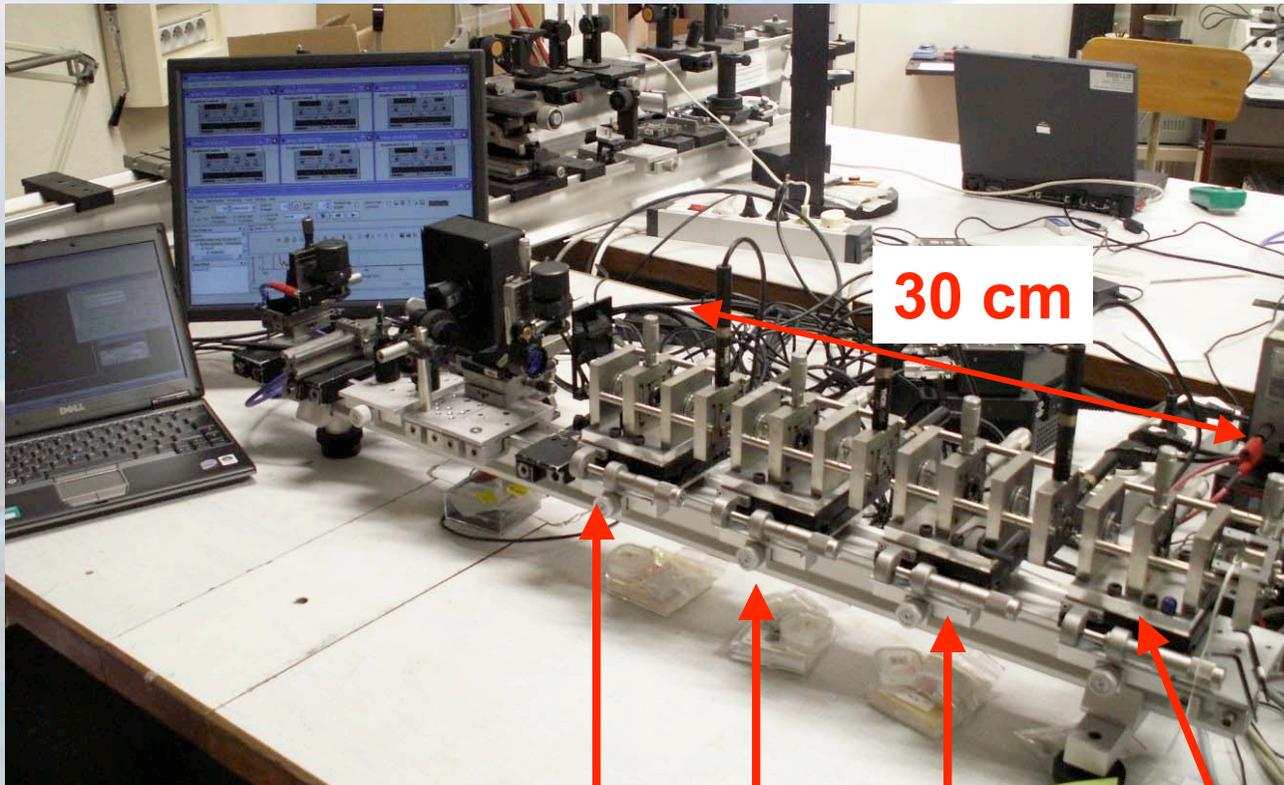


Poussières



3 FQPM, $R=\lambda/\Delta\lambda=4.8$, soustraction de l'image

Banc optimisé compact



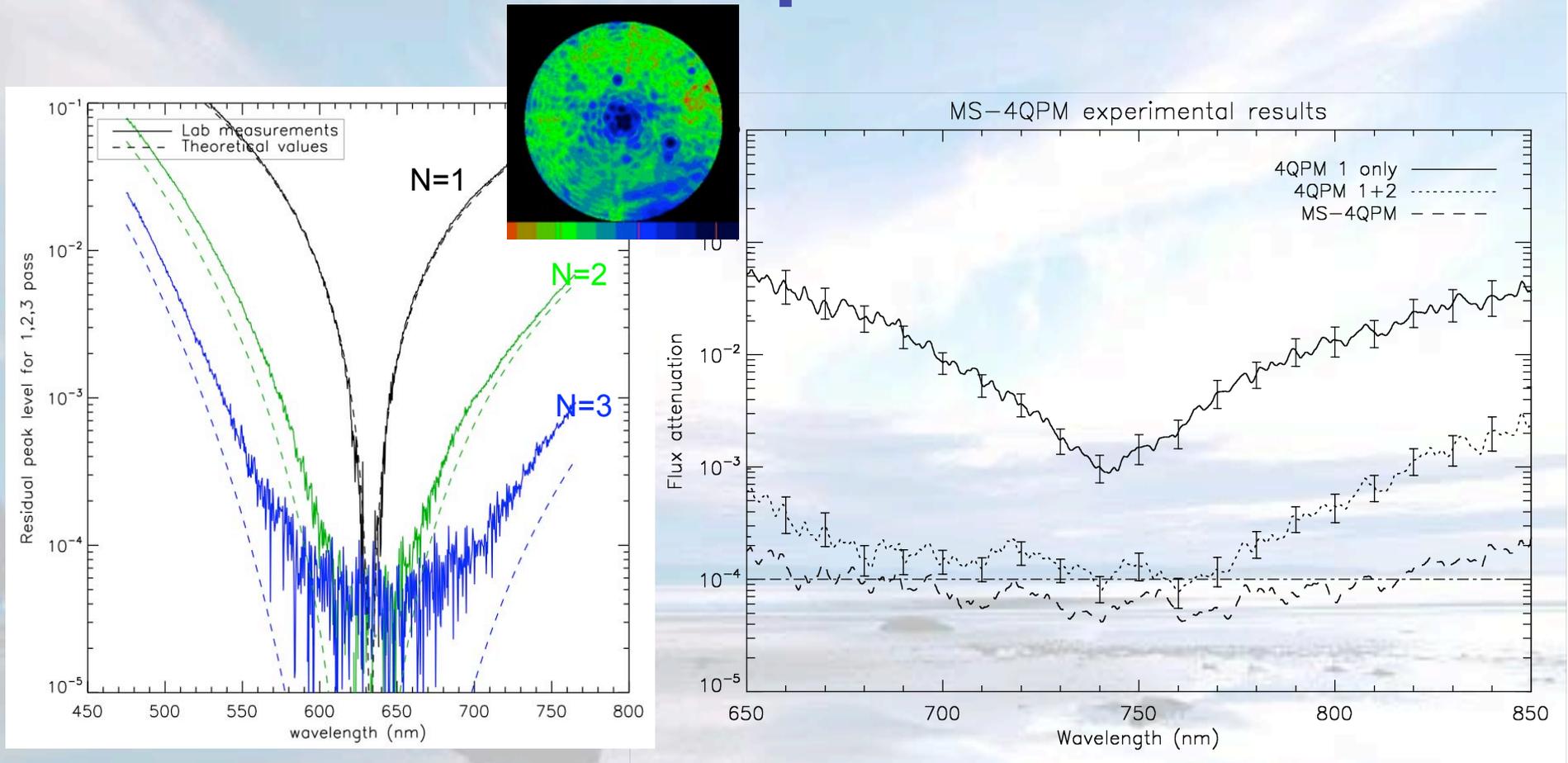
4Q 3

4Q 2

4Q 1

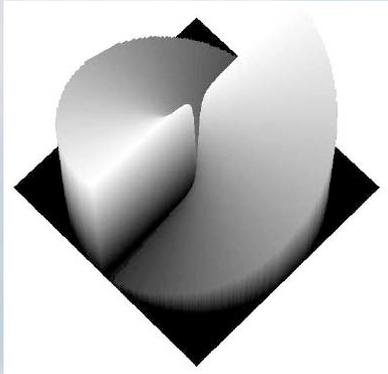
Telescope stage

Résultats expérimentaux



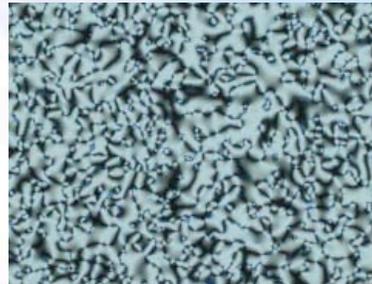
- Avec 3 FQPMs : extinction meilleure que 10^{-4} sur une largeur spectrale de 200 nm ($R \sim 4$)

Coronographe à vortex optique

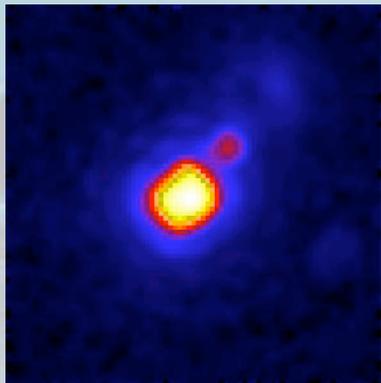
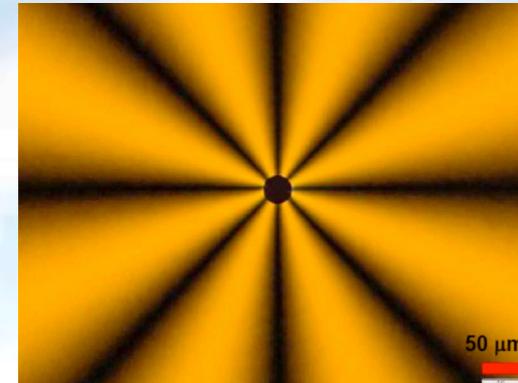


Phase modulée (AGPM, Mawet 2005)
Birefringence de forme

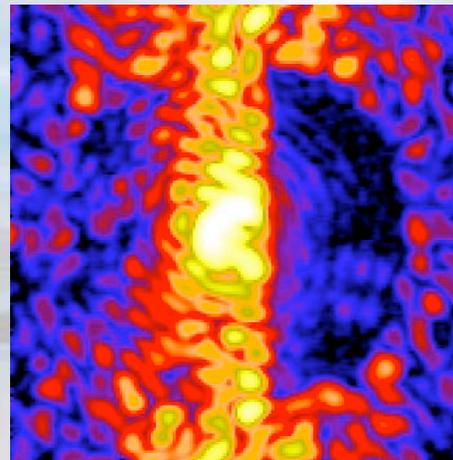
Liquid Crystal Polymer



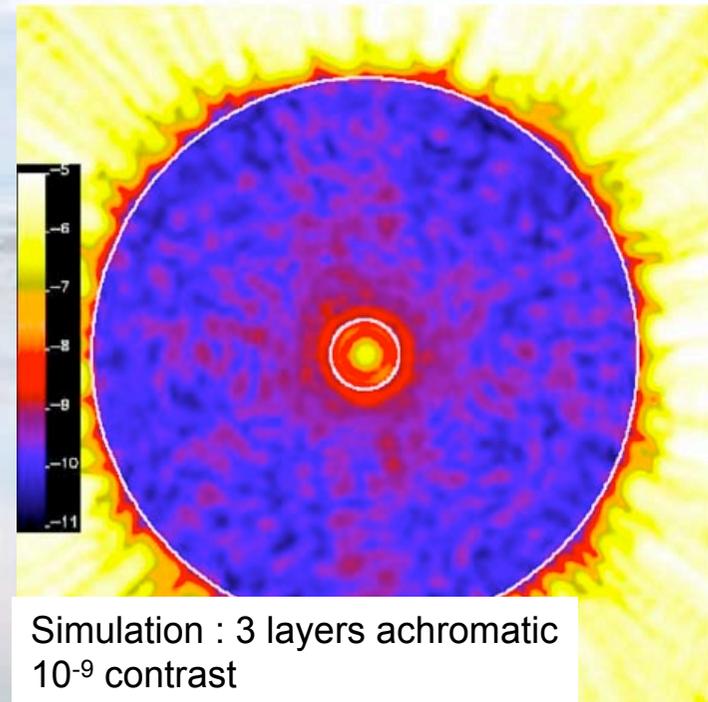
Optical Vortex 4th order



Tested at Palomar
 $5e^{-5}$ @ $2\lambda/D$
⇒ suitable for SPHERE
and EPICS



Mesure HCIT (JPL)
 10^{-7} contrast



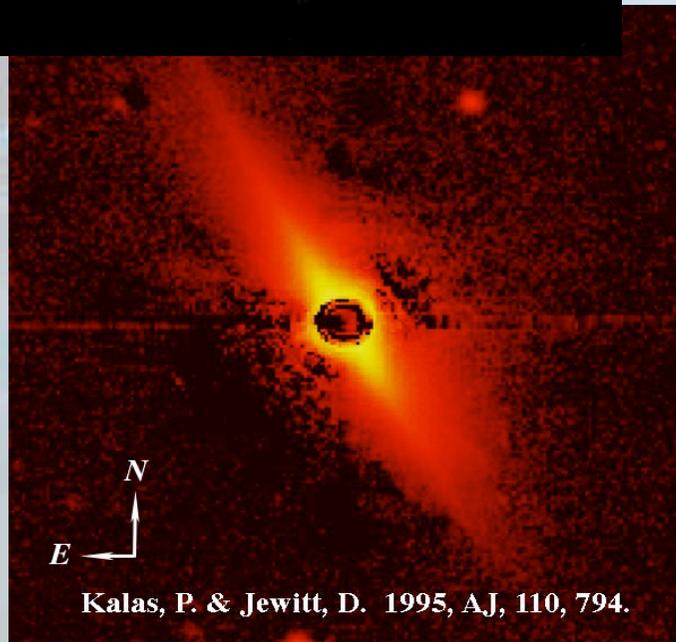
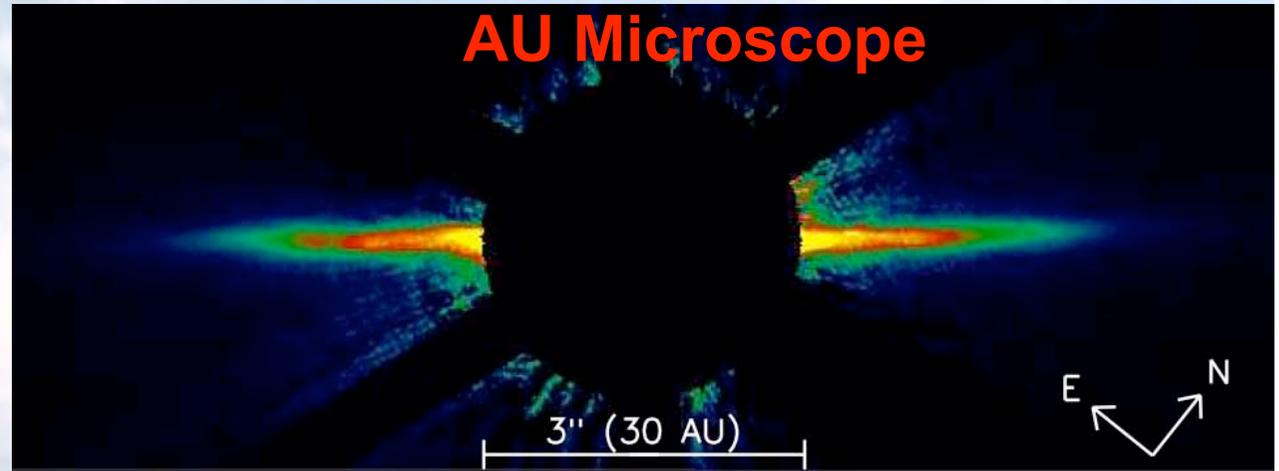
Simulation : 3 layers achromatic
 10^{-9} contrast

Observations avec coronographes

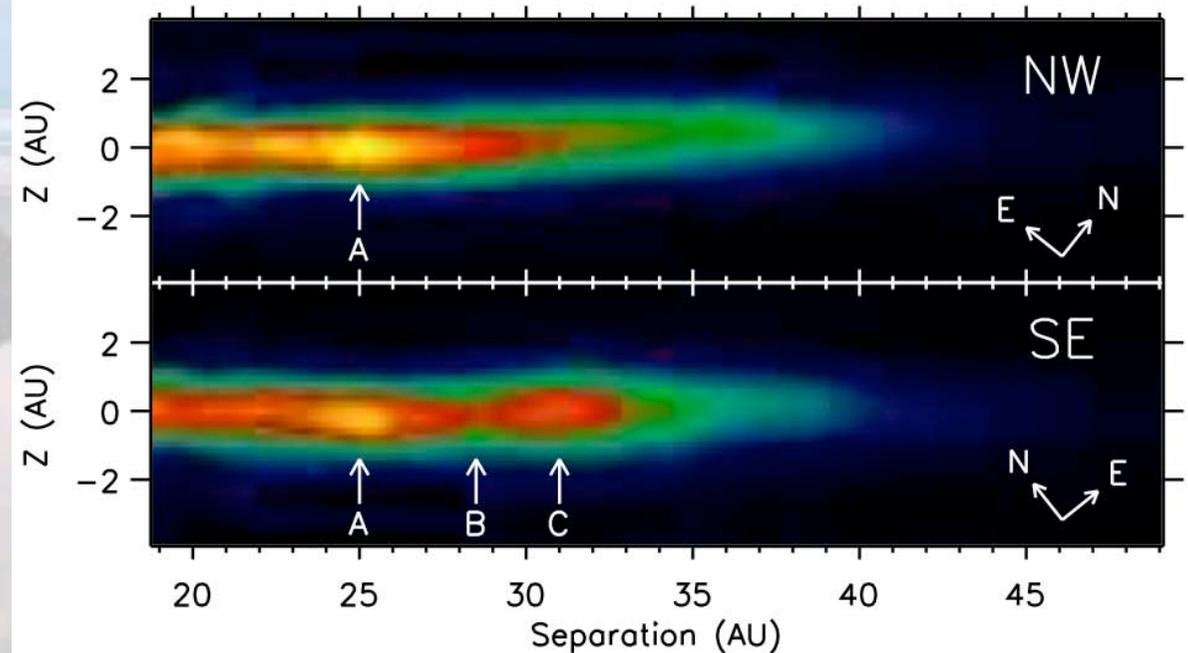
Beta Pictoris



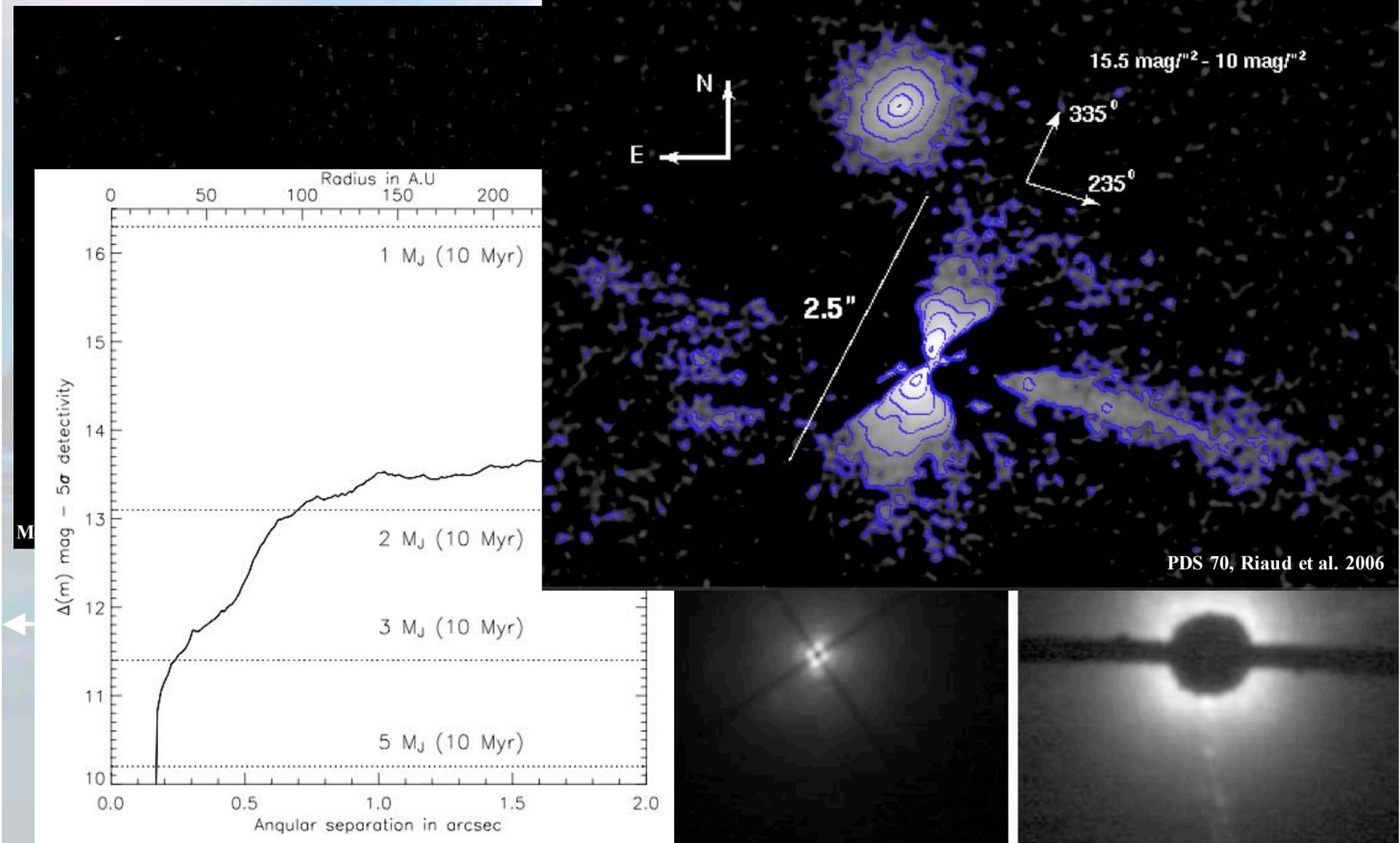
AU Microscope



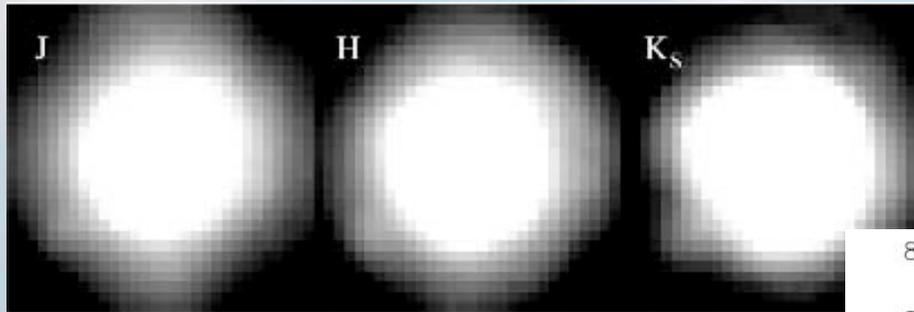
Kalas, P. & Jewitt, D. 1995, AJ, 110, 794.



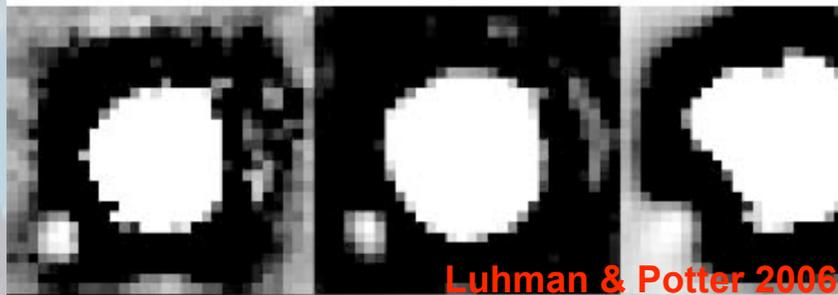
Autre exemples de résultats



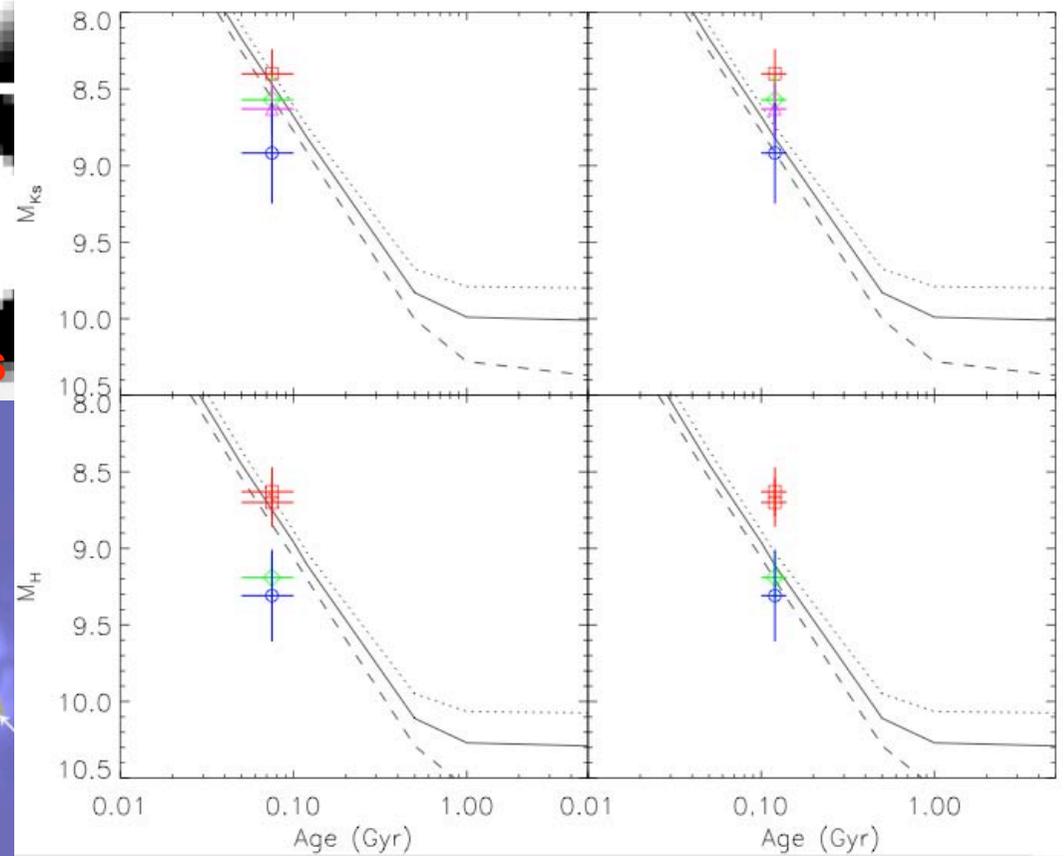
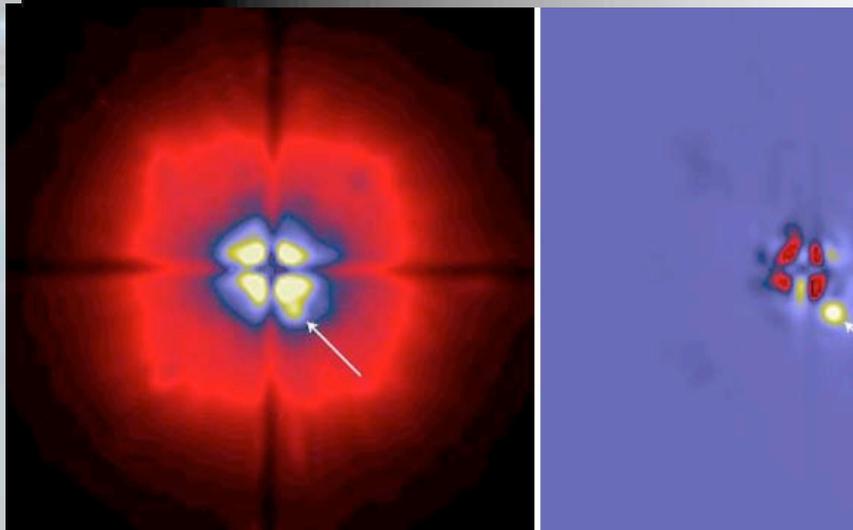
Exemple d'un résultat avec et sans coronographe



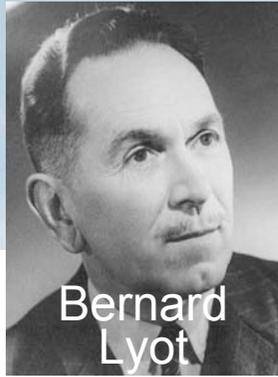
Etoile AB Dor C



Luhman & Potter 2006

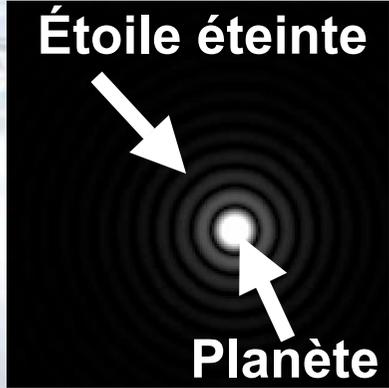
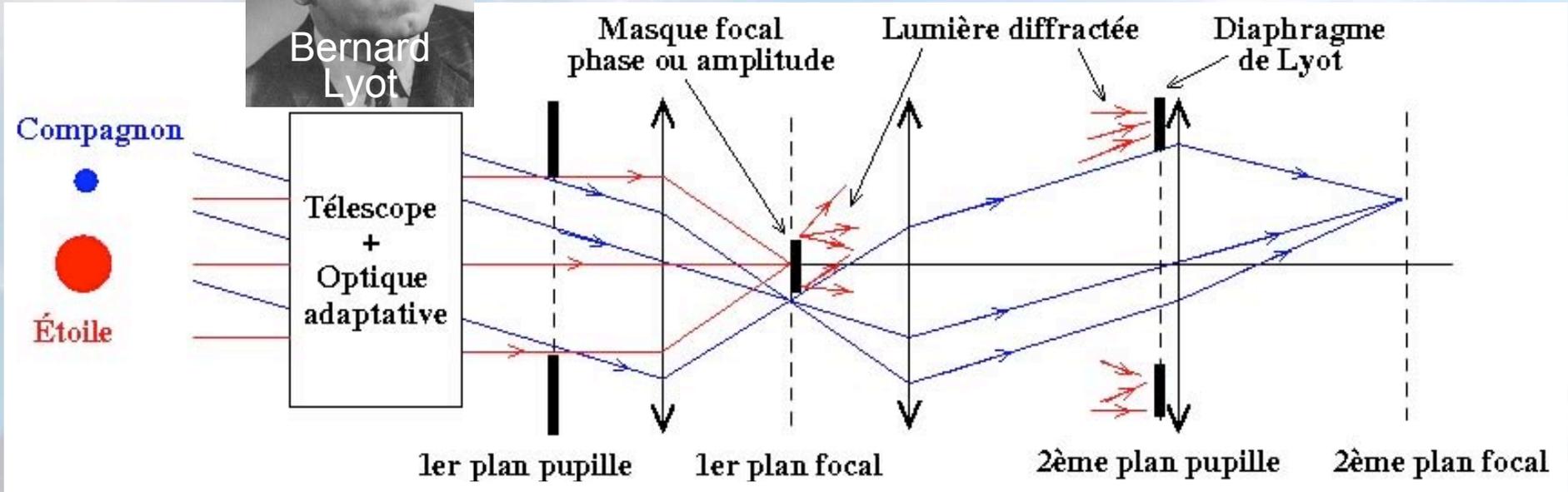


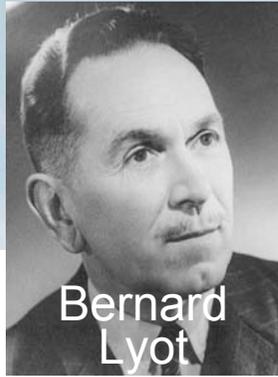
Boccaletti et al. 2008



Bernard Lyot

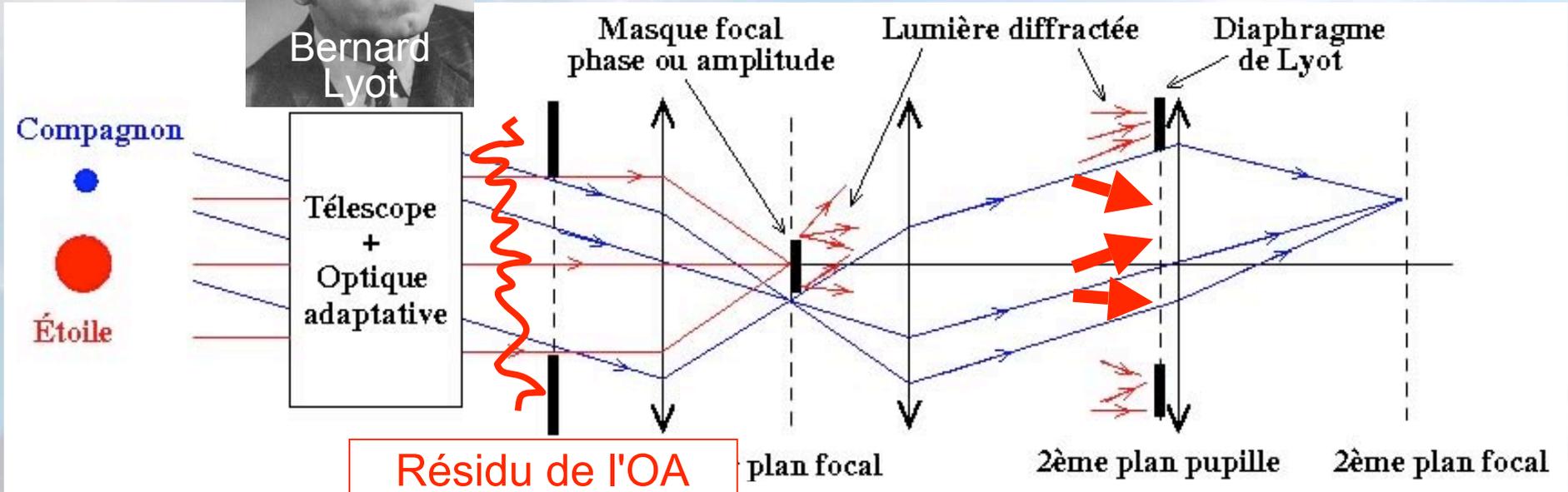
Coronographie





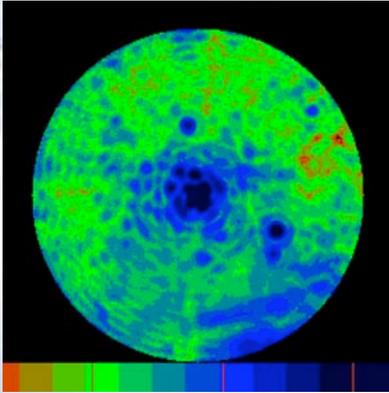
Bernard Lyot

Coronographie



Résidu de l'OA
Défauts optiques
(qq 10nm)

Champ de
speckles
de l'étoile

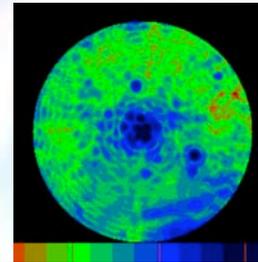
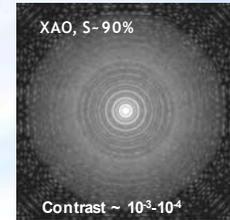


Imagerie à Haute Dynamique

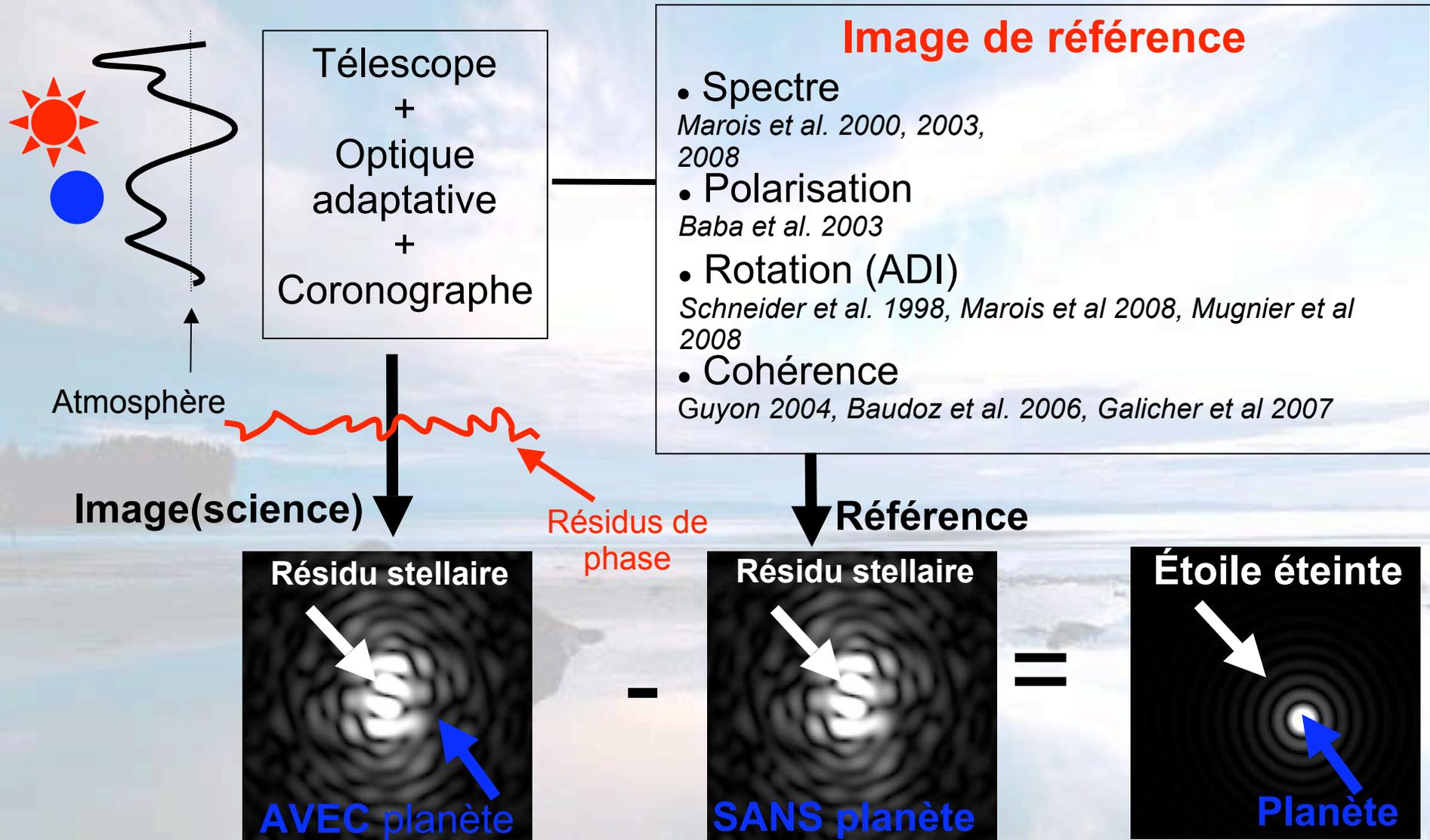
1- Optique Adaptative extreme même sur un télescope spatial !!!

2- Coronographe
éteindre l'étoile sans éteindre la planète
Il y a des résidus...

2- Imagerie différentielle
Discriminer la planète des speckles résiduels



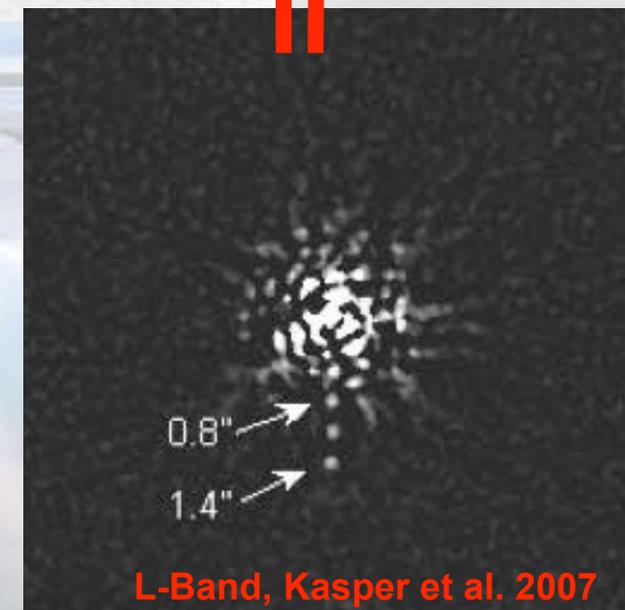
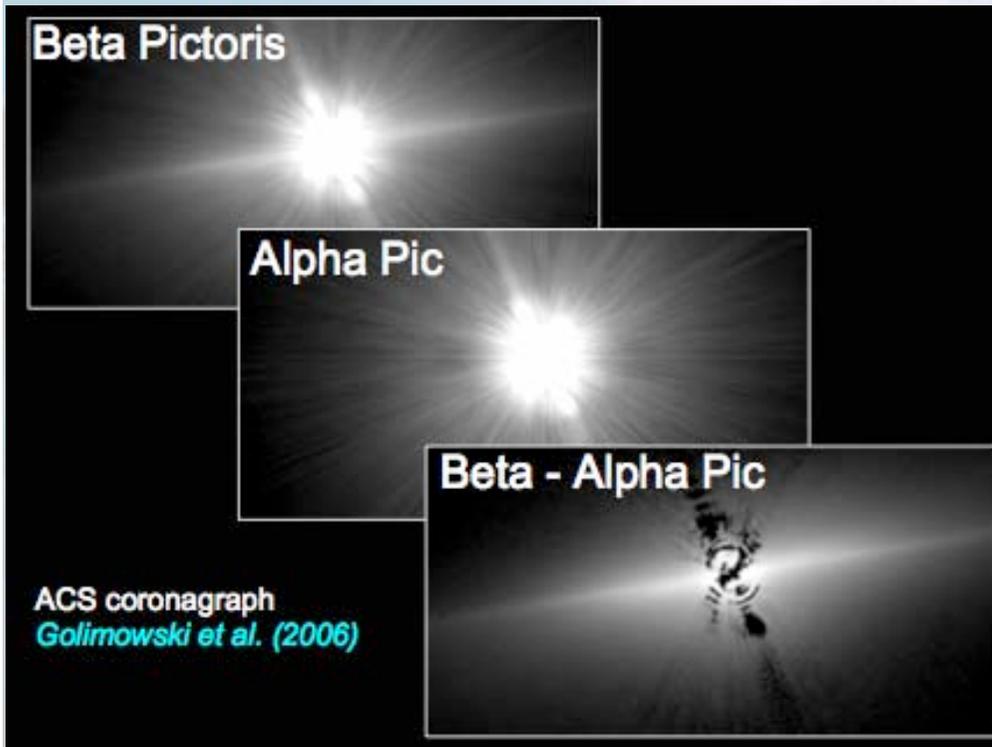
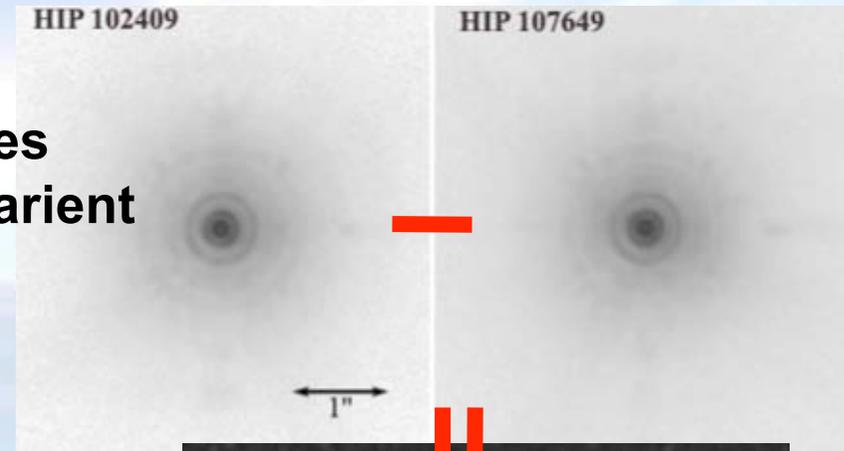
Imagerie différentielle : étalonnage des speckles



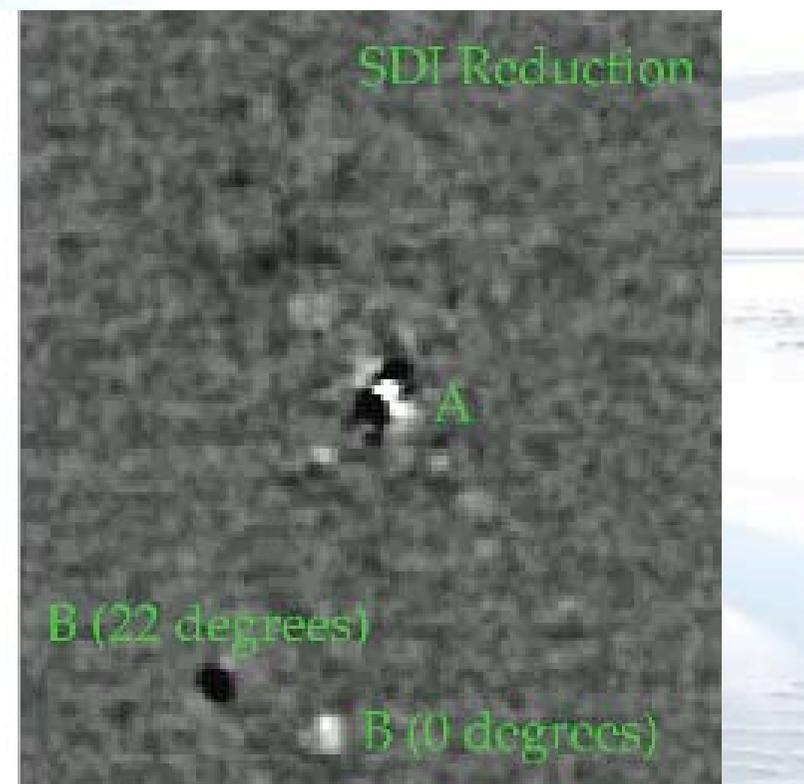
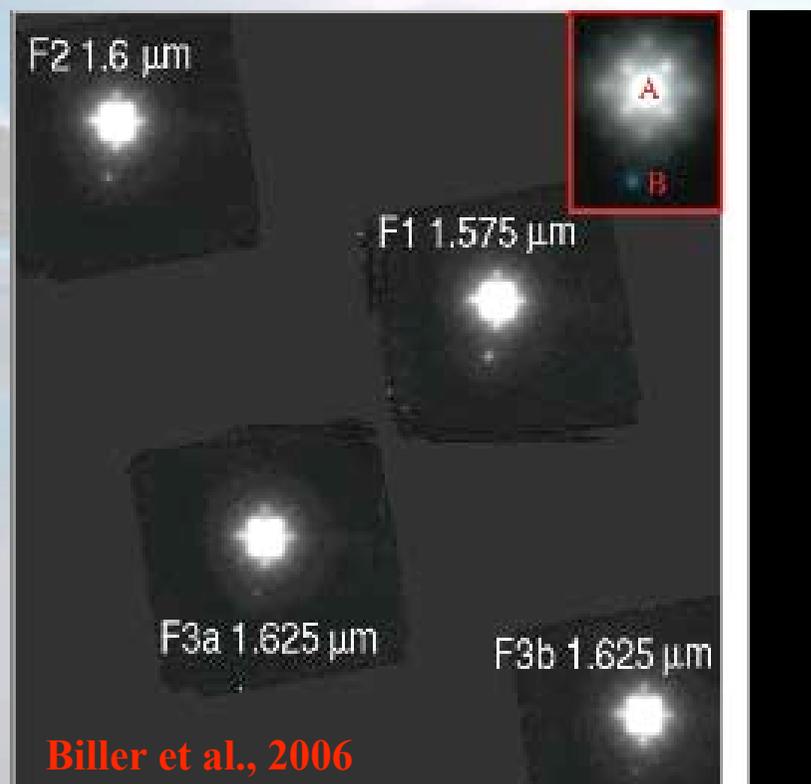
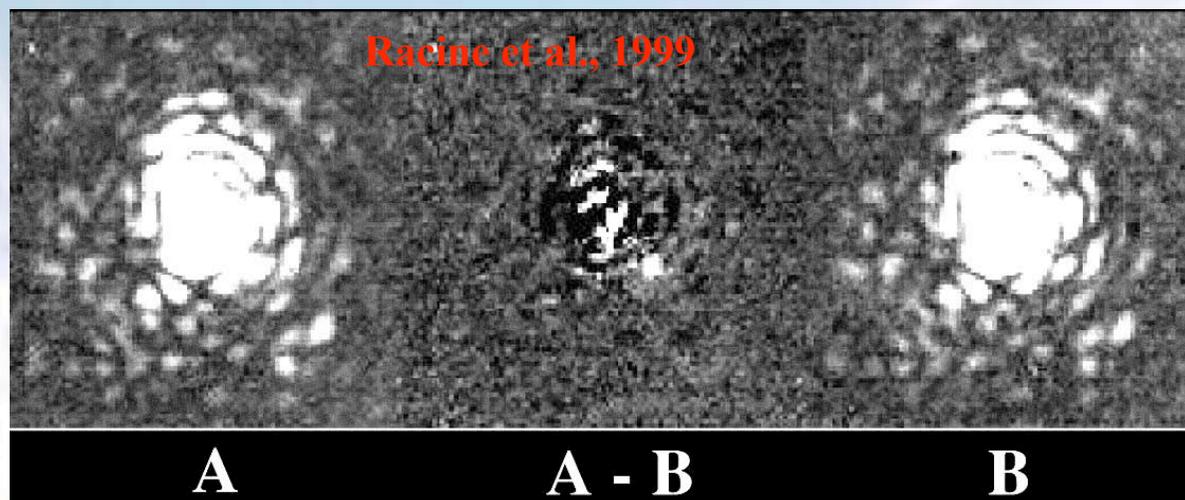
Imagerie différentielle simple

Soustraction d'une étoile de référence

observations non simultanées
conditions d'observations varient



Imagerie différentielle spectrale (SDI)





JWST - Mid IR Imager

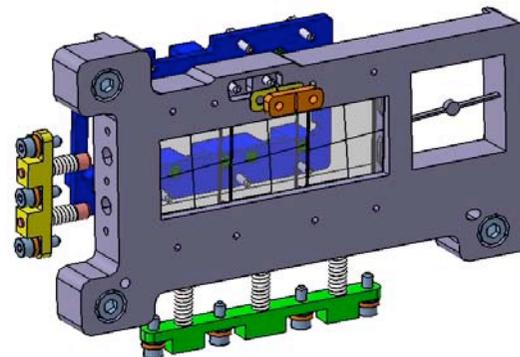
PI: P.O. Lagage (CEA)

monochromatic coronagraphs



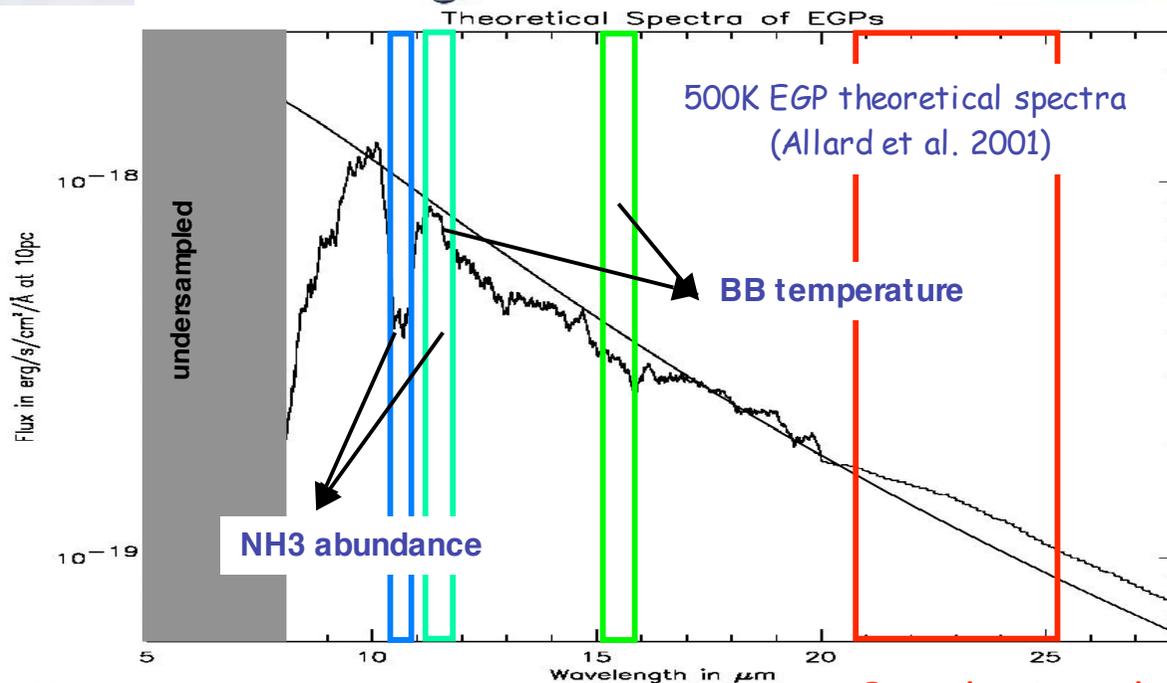
1/4 du champ est dédié à la coronagraphie (prévu 2014)

- 3 coronagraphes FQPM
- 1 coronographe de Lyot



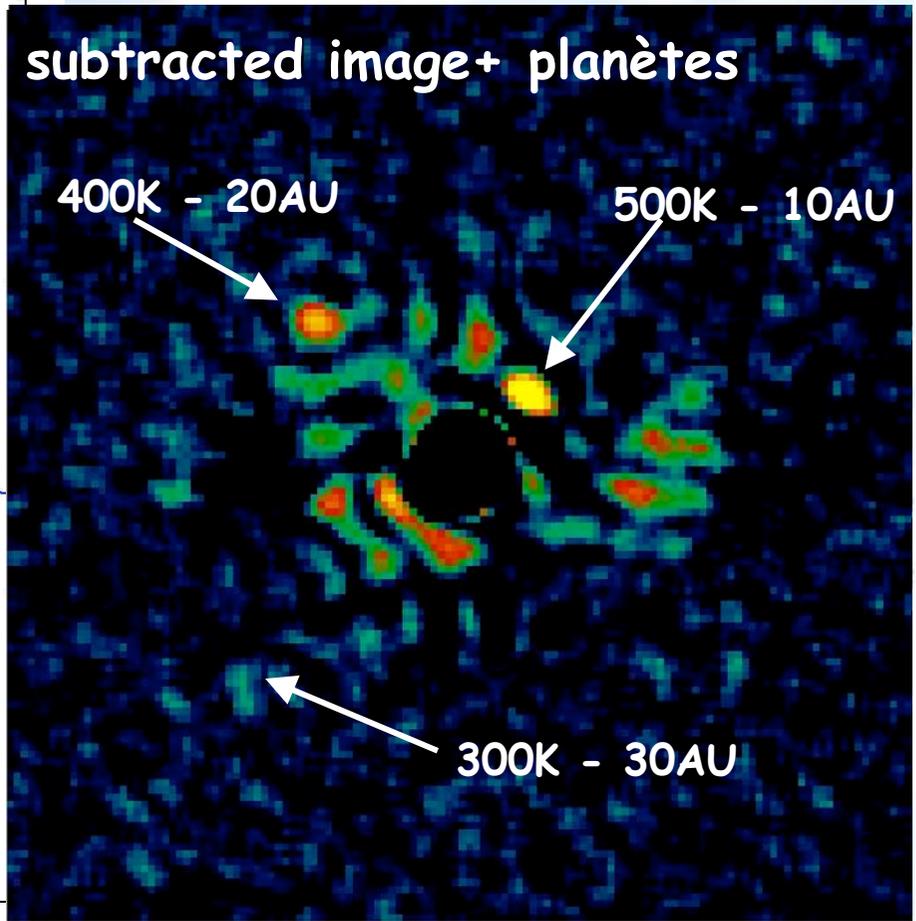
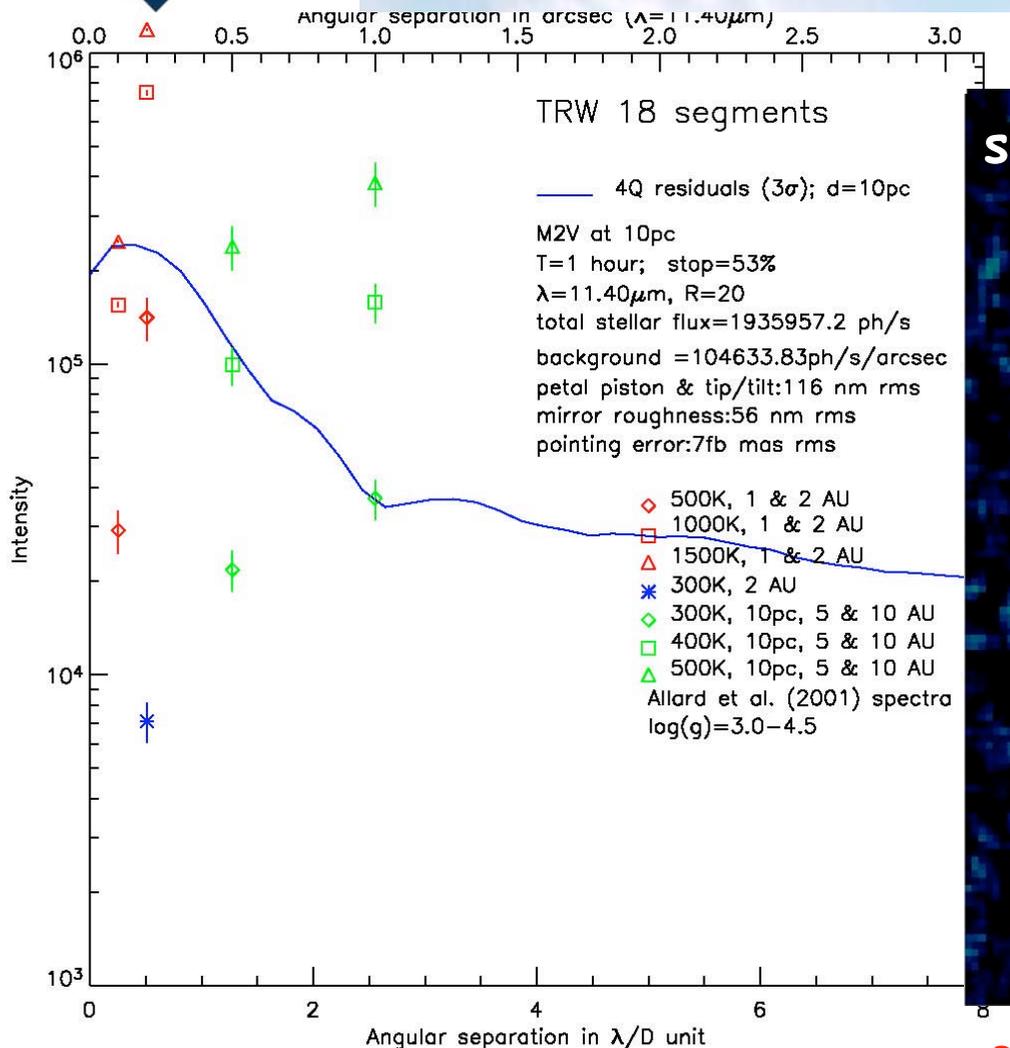
Imagerie différentielle spectrale

bande d'absorption du NH₃ dans le spectre des planètes géantes gazeuses (non simultanées)





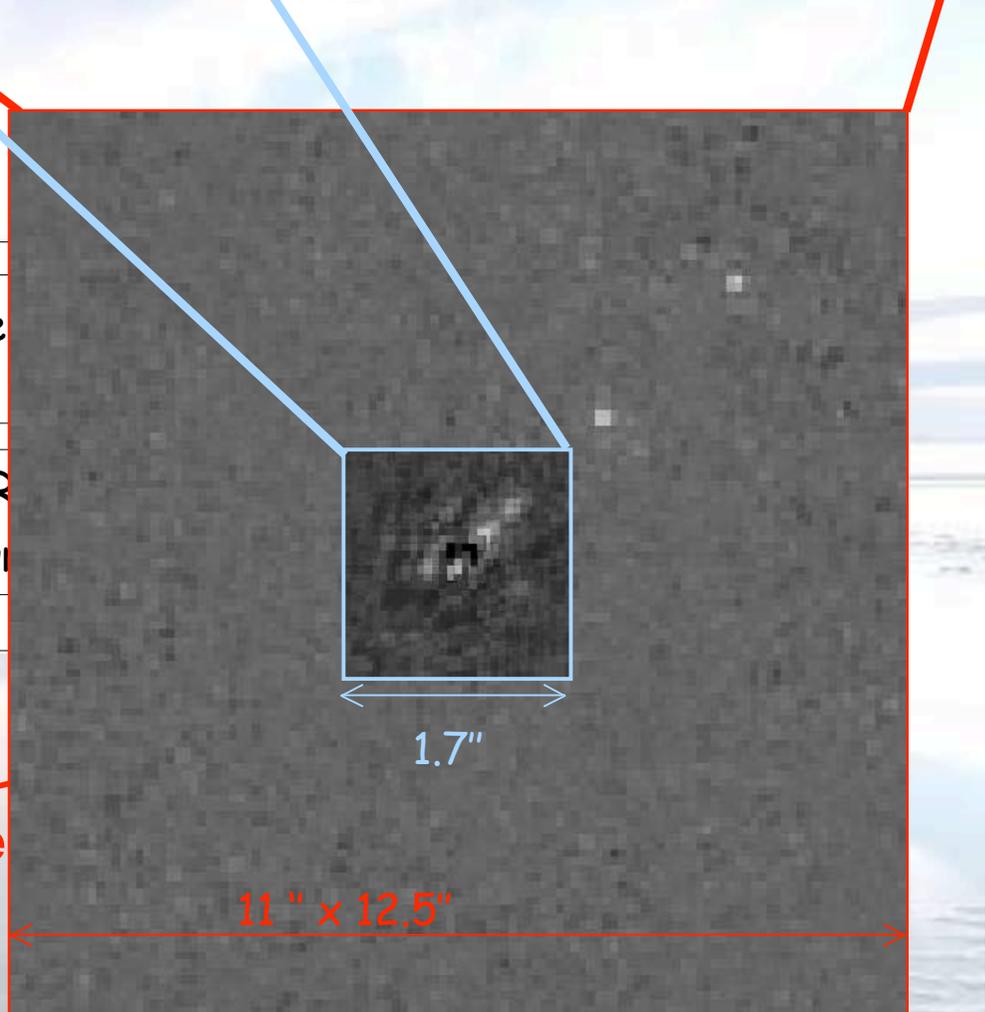
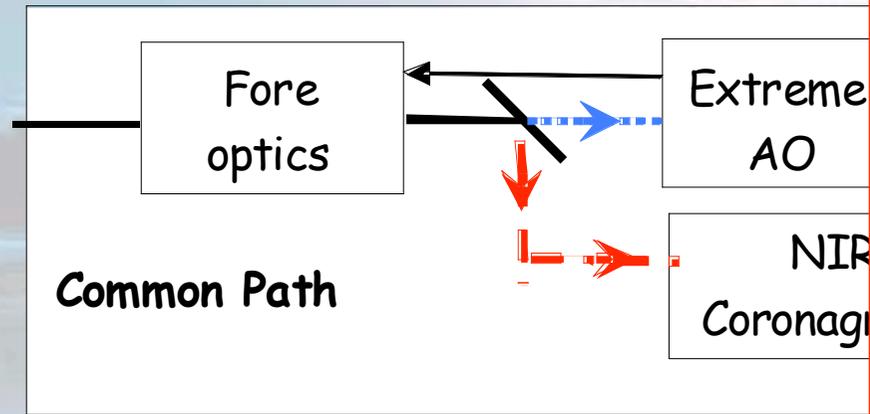
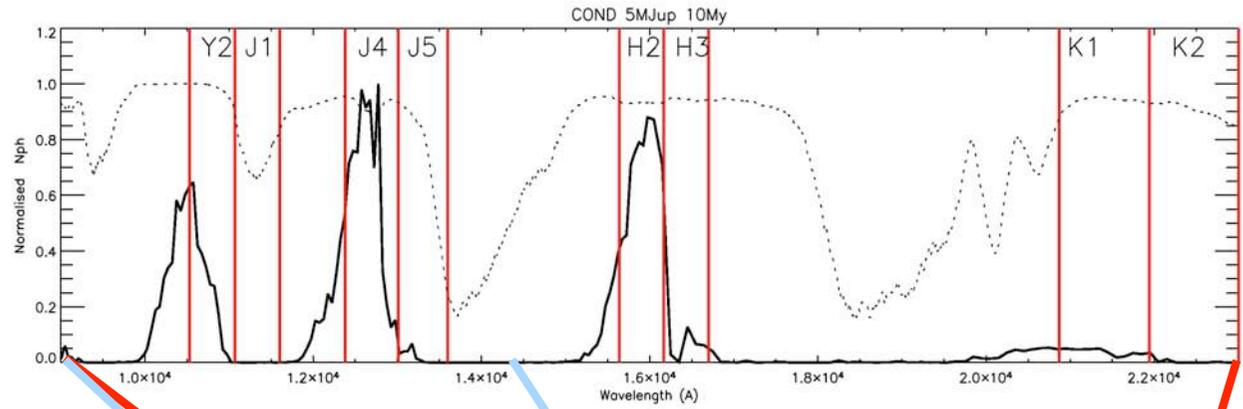
Performances de MIRI/JWST





PI: J.L. Beuzit (LAOG)

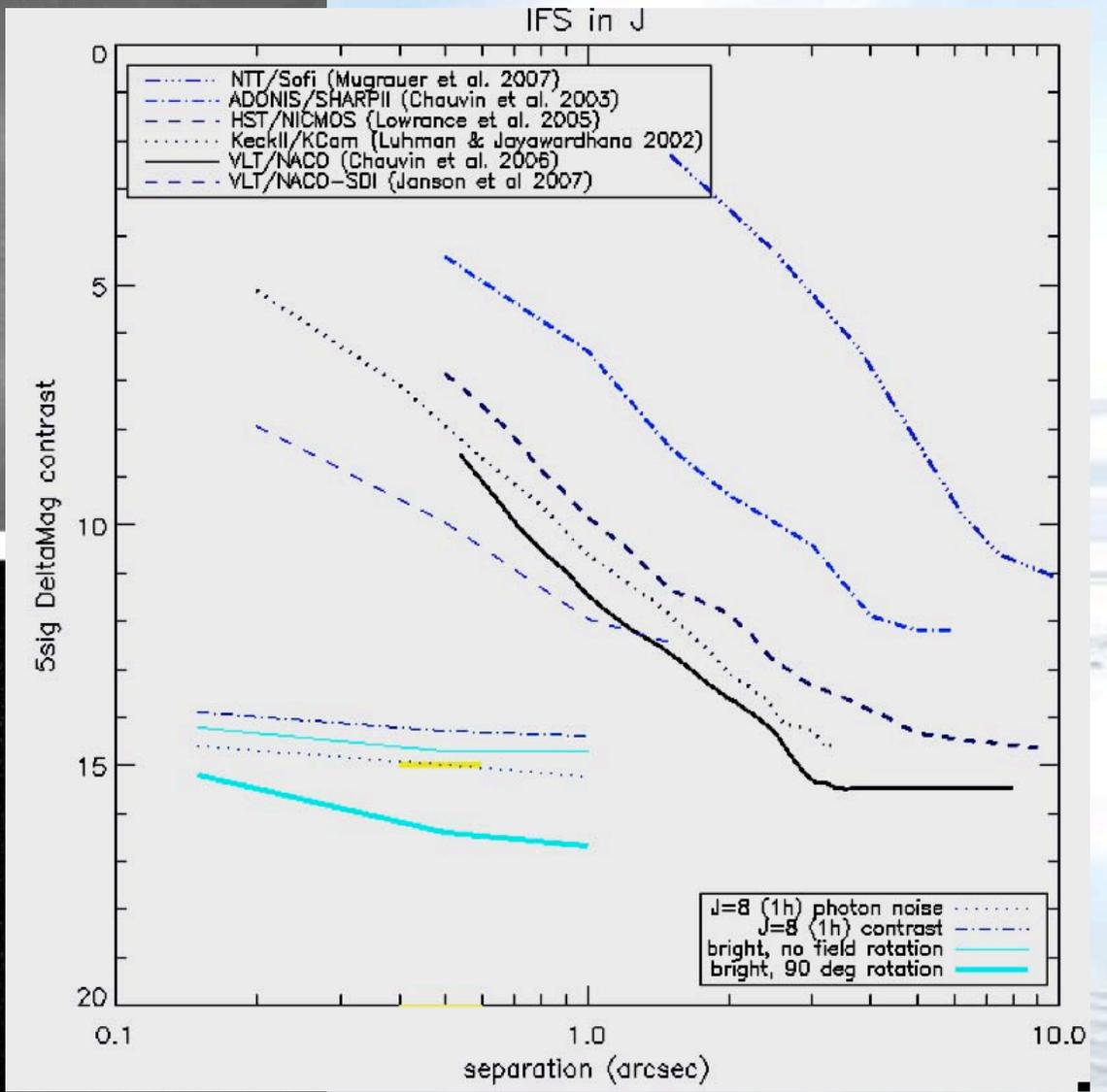
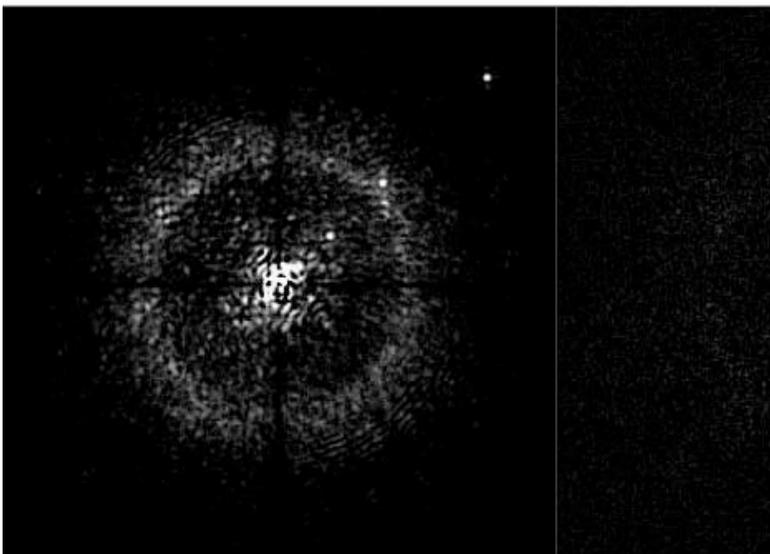
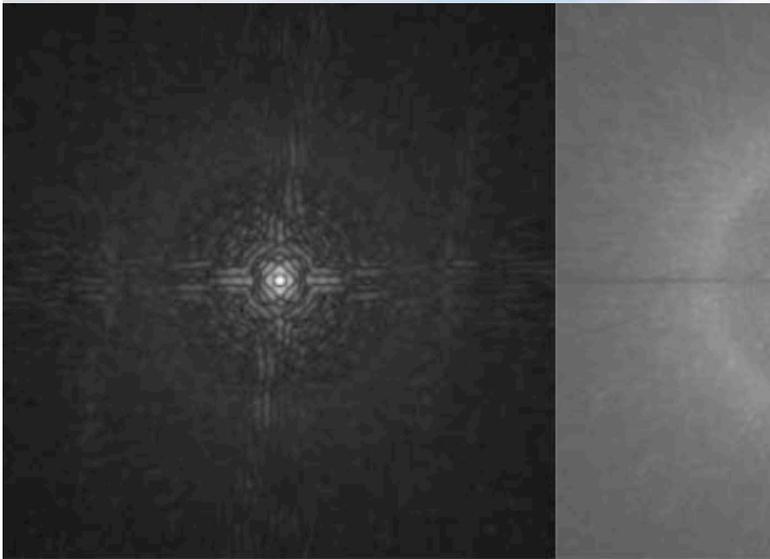
Prévu pour 2011 au VLT



Coronographe + imagerie diff. spe



SPHERE



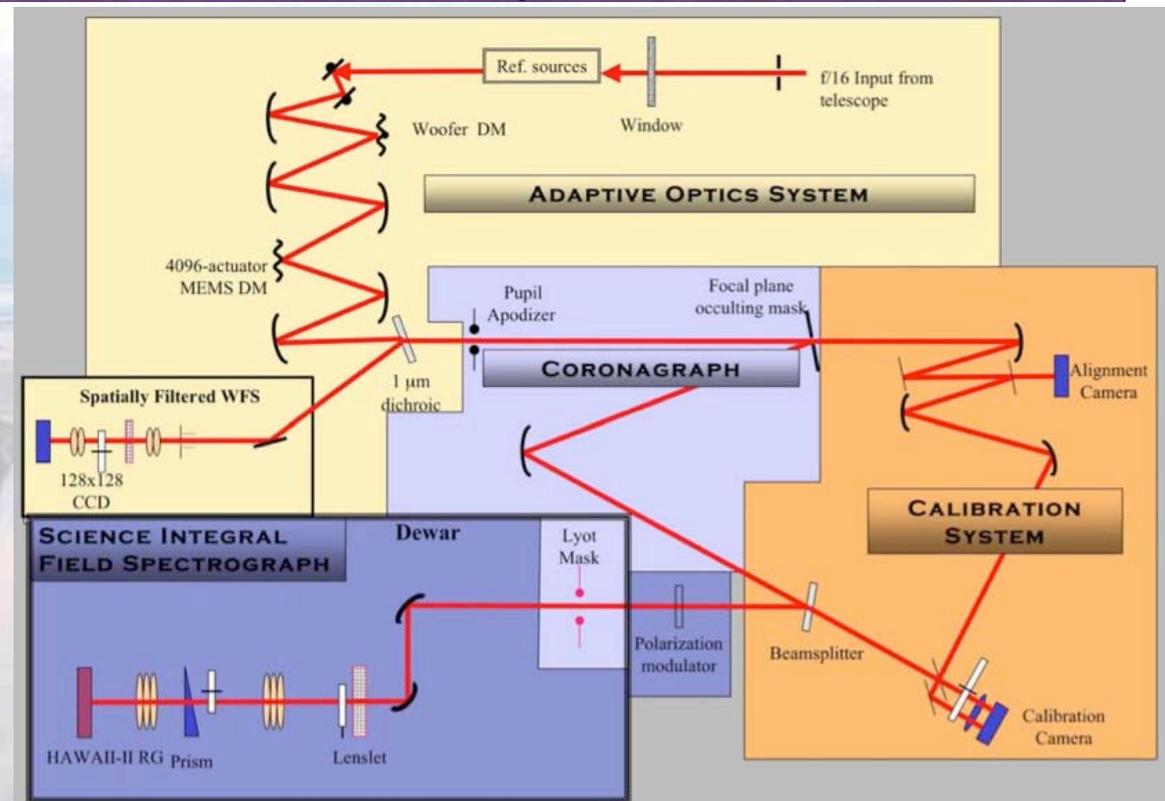
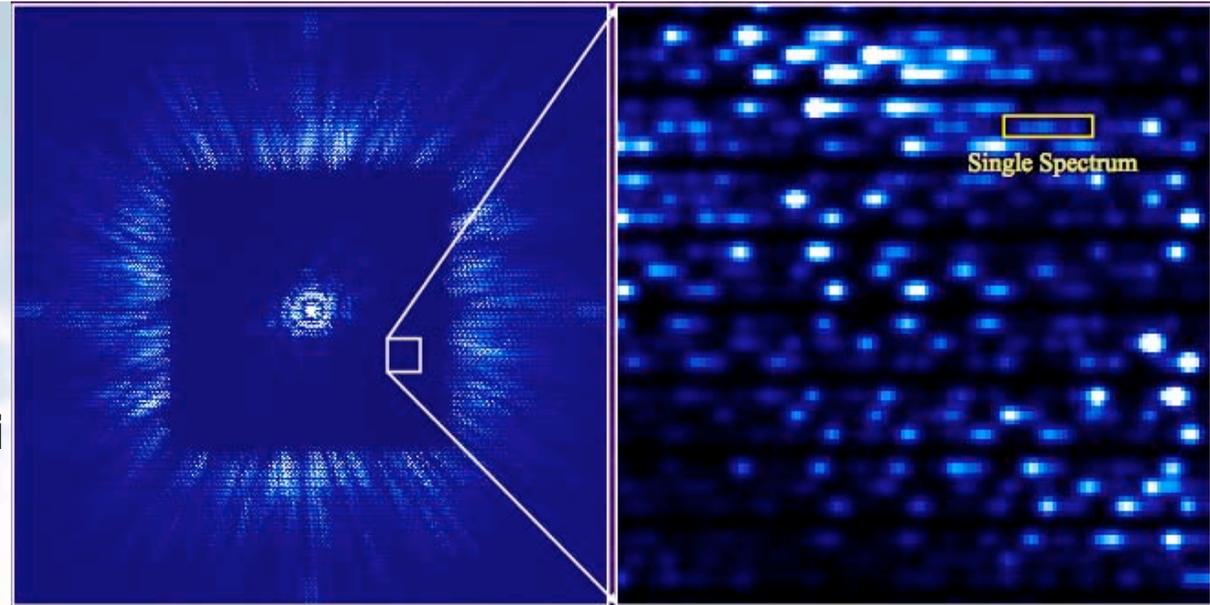


Gemini
Planet
Imager

PI: B. Macintosh (LLNL)

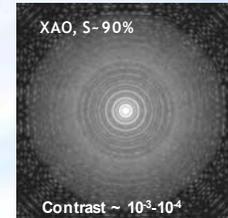
Prévu pour 2011 sur Gemini

Imagerie
différentielle
spectrale à partir
d'un spectromètre à
intégral de champ
(IFS)

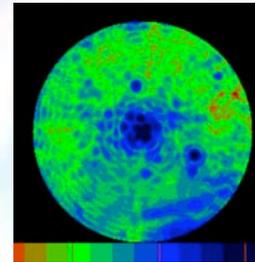


Imagerie à Haute Dynamique

1- Optique Adaptative extreme même sur un télescope spatial !!!

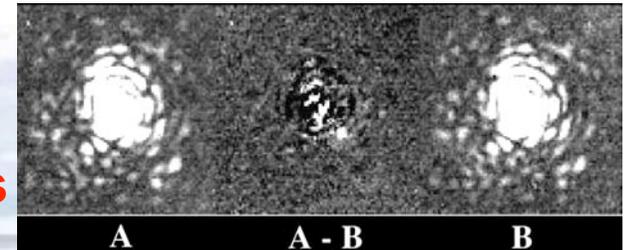


2- Coronographe
éteindre l'étoile sans éteindre la planète
Il y a des résidus...



2- Imagerie différentielle
Discriminer la planète des speckles résiduels

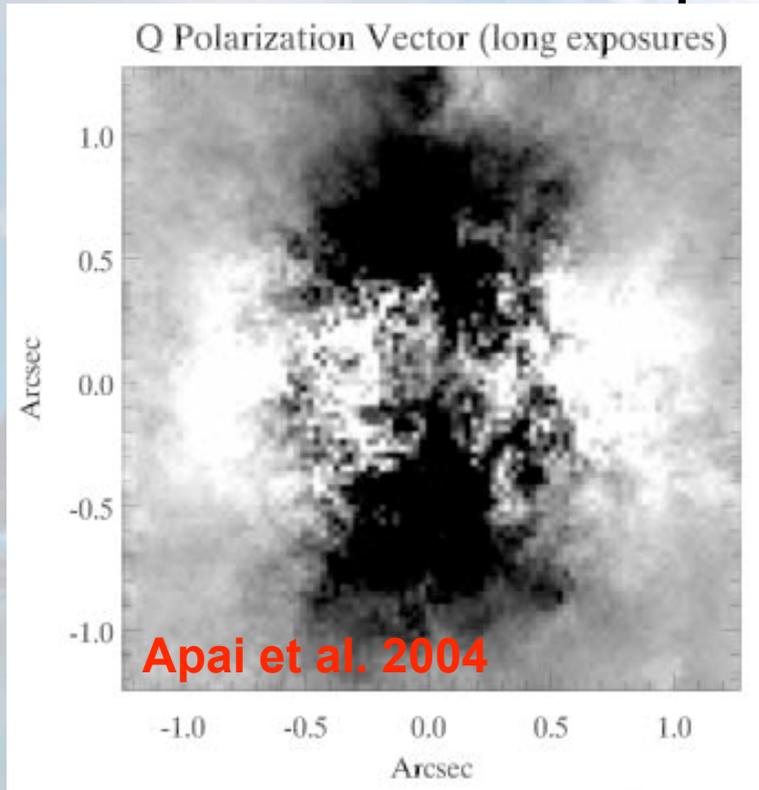
a) Avec le spectre



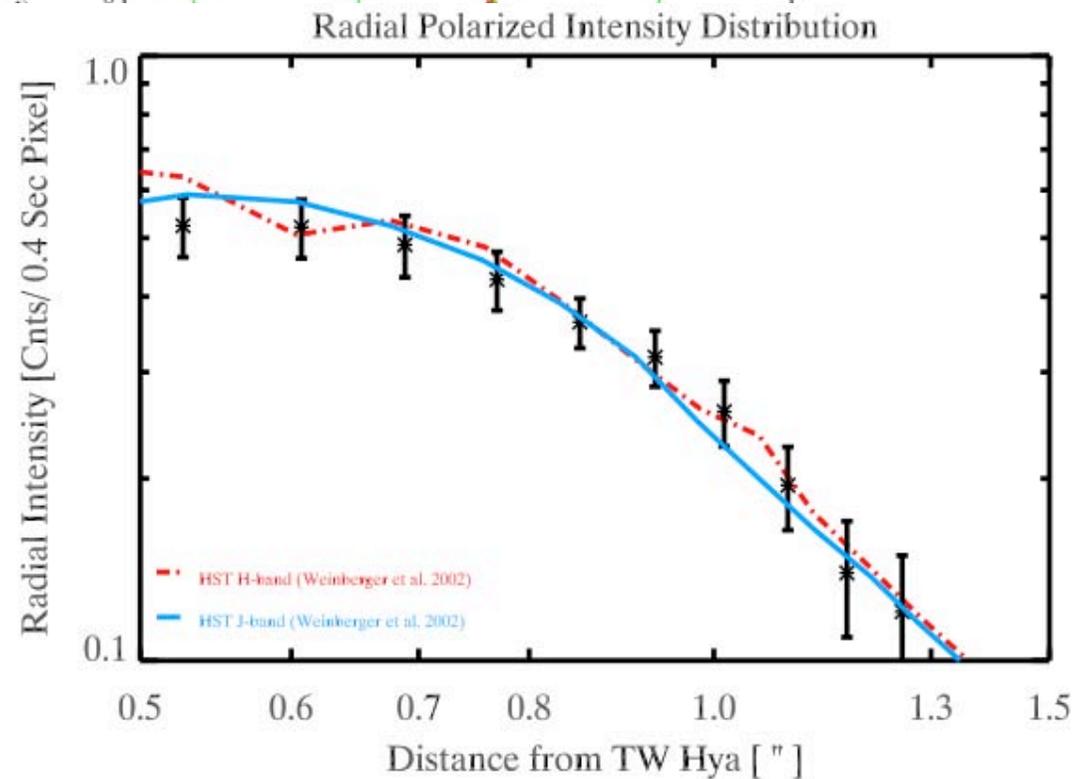
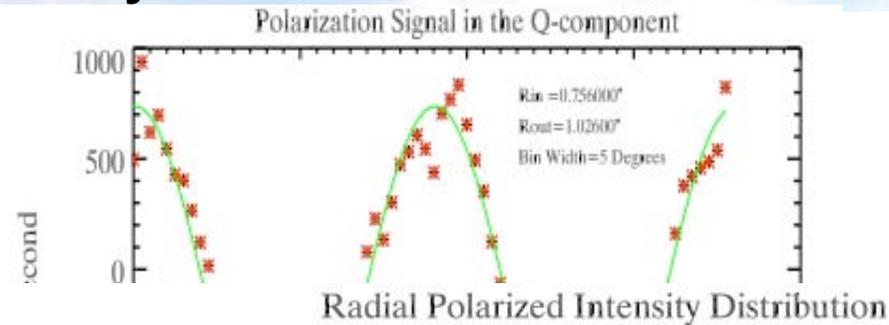
b) Avec la polarisation

Imagerie Différentielle Polarimétrique

Disque TW Hya

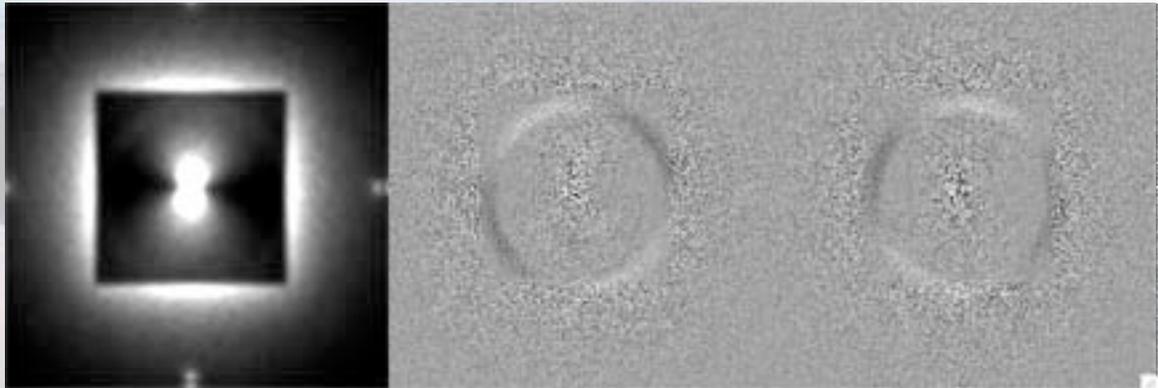
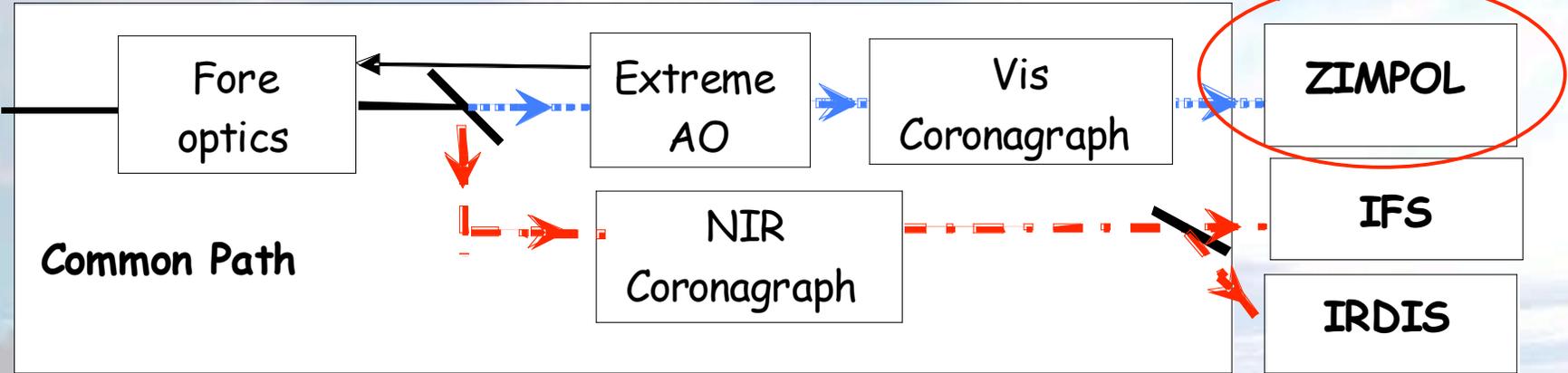


Atteint la sensibilité du
HST depuis le sol





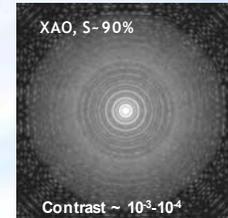
Coronagraph + imagerie différentielle polarimétrique



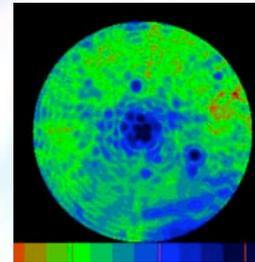
Fomalhaut analog
 $L_{dust}/L_{star}=3.10^{-4}$
 Detectability down to 10^{-5}

Imagerie à Haute Dynamique

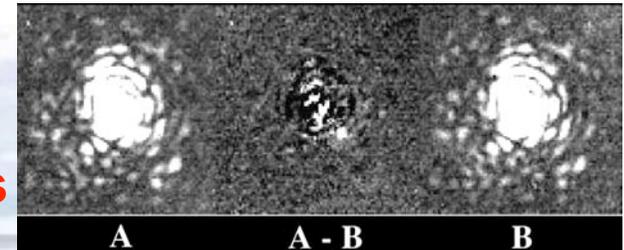
1- Optique Adaptative extreme même sur un télescope spatial !!!



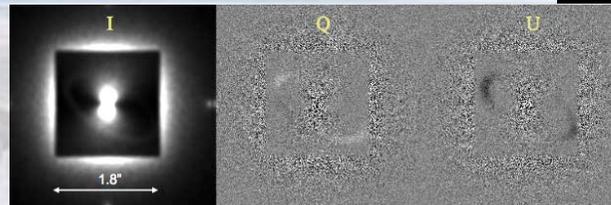
2- Coronographe
éteindre l'étoile sans éteindre la planète
Il y a des résidus...



2- Imagerie différentielle
Discriminer la planète des speckles résiduels



a) Avec le spectre

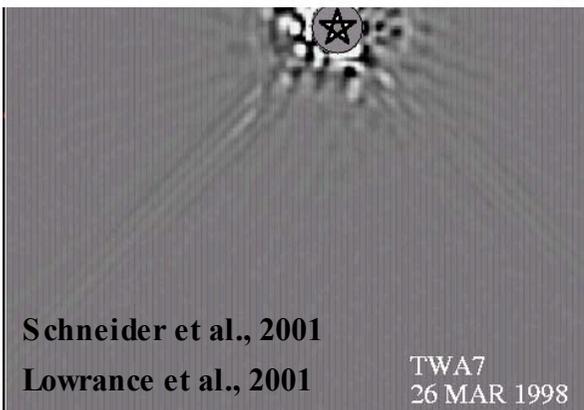
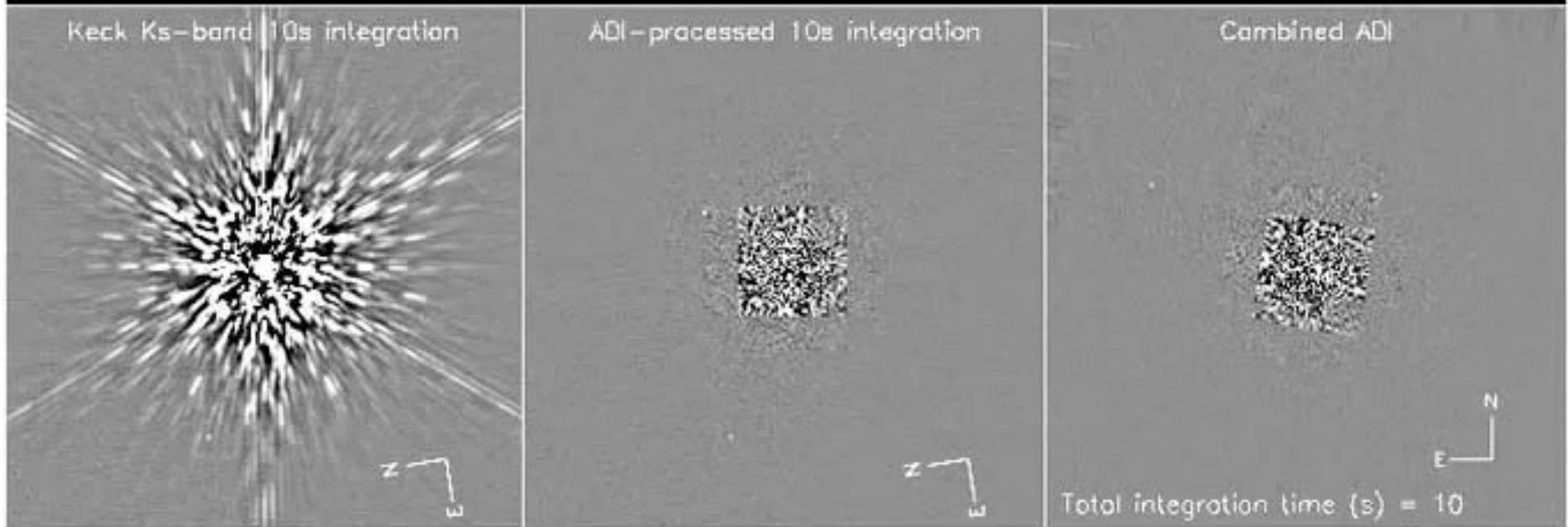


b) Avec la polarisation

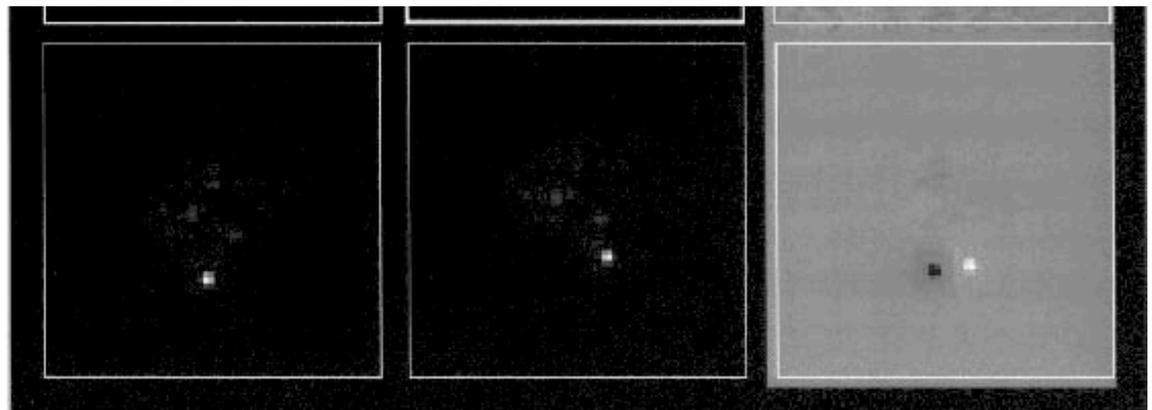
c) Avec la géométrie (rotation ou dispersion spectrale)

Imagerie différentielle Angulaire

Angular Differential Imaging (ADI)

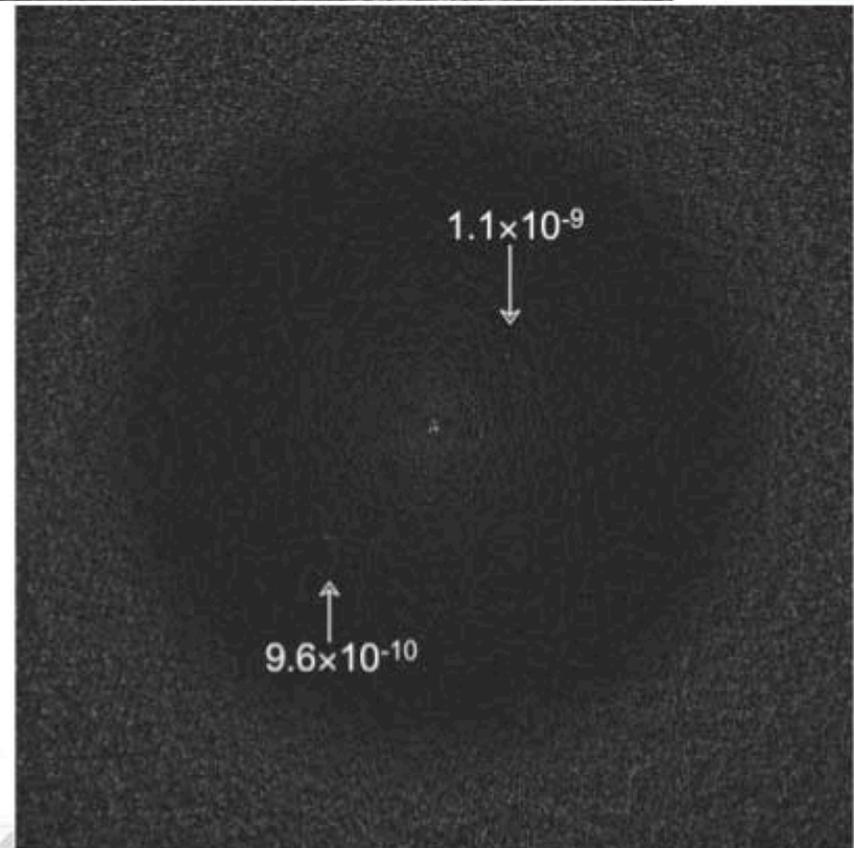
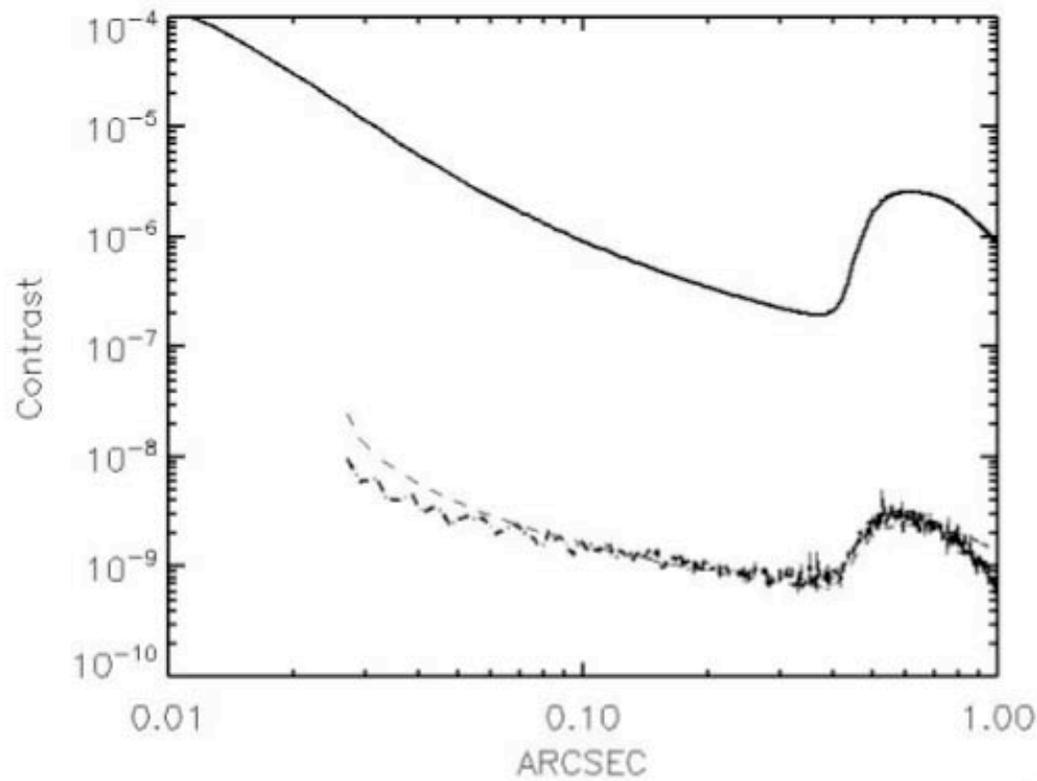


CORONAGRAPH



Trouver des planètes avec les Extremely Large Telescope: EPICS

« Déconvolution
spectrale »

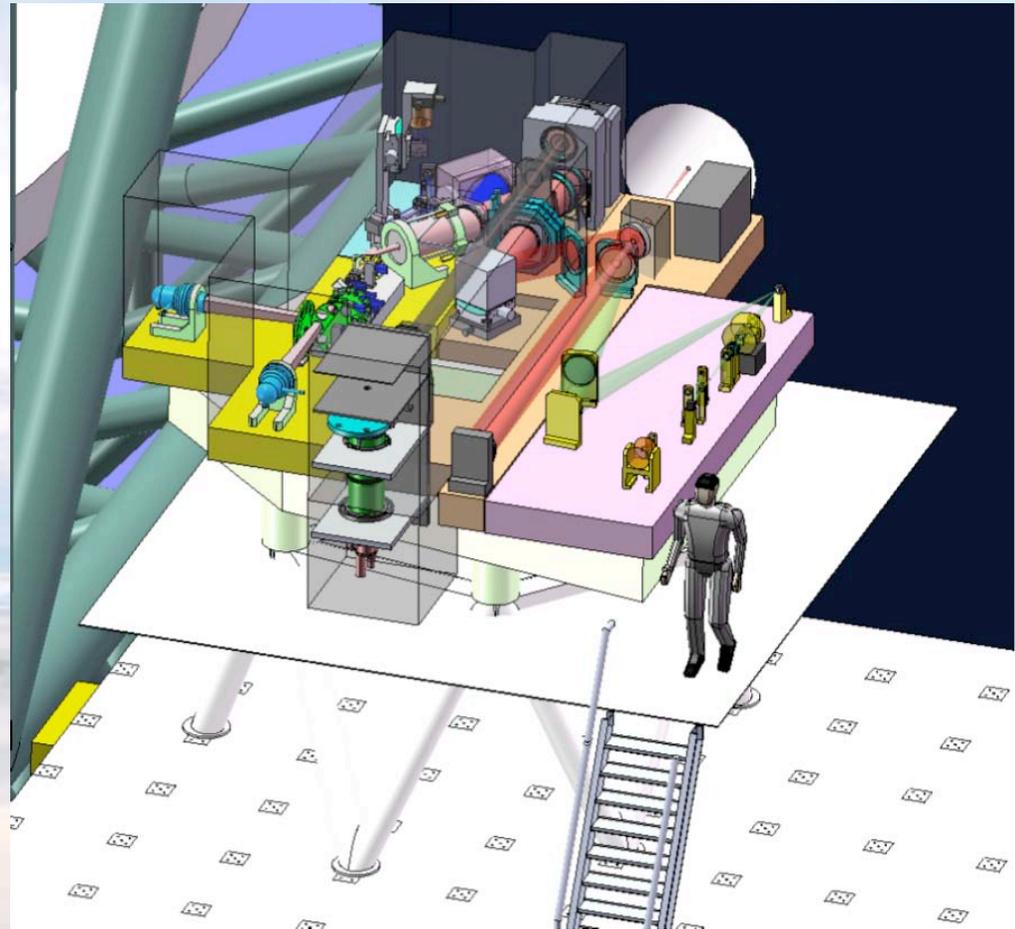


Trouver des planètes avec les Extremely Large Telescope: EPICS

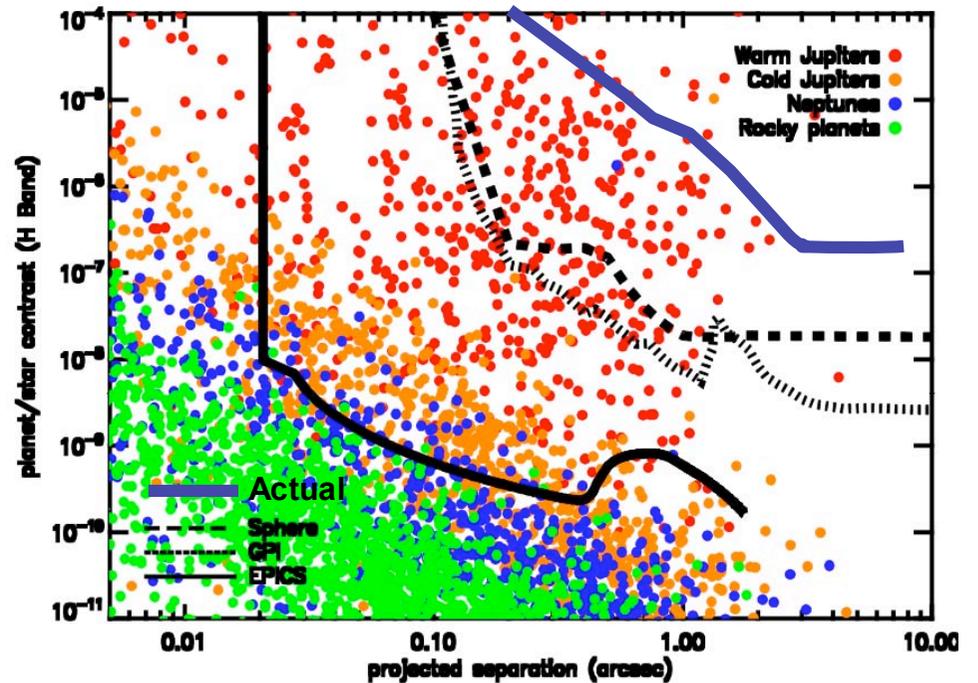
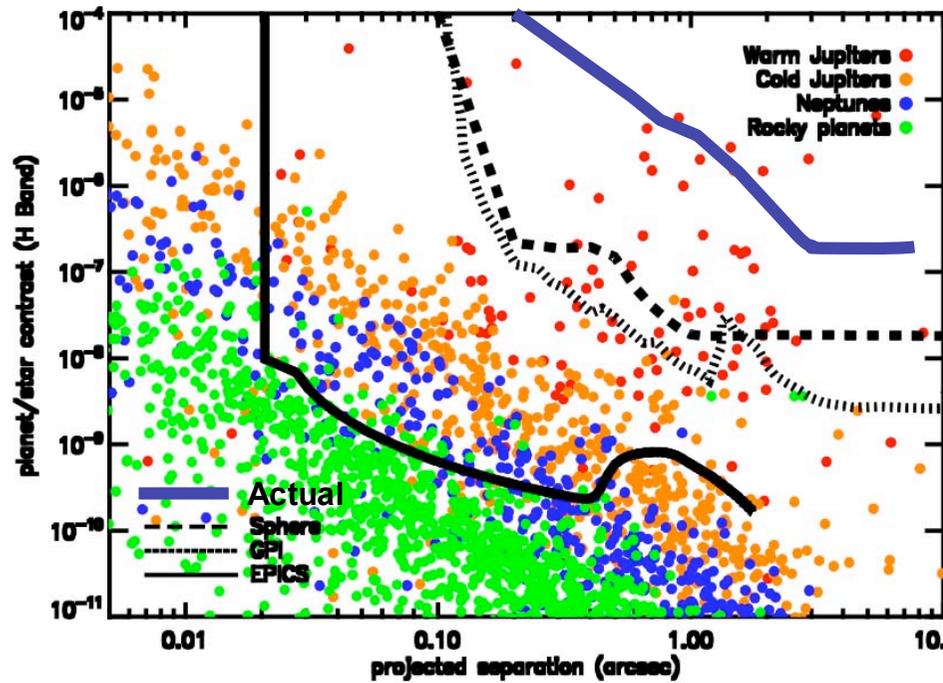
Détection des exoplanètes
est un objectif prioritaire
pour l'ELT Européen
(EPICS: détection directe)

Critères de détection:

- Spectral
- Polarisation
- Cohérence



Quelles Planètes ?

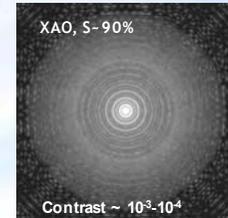


Etoiles proches (<20 parsecs)

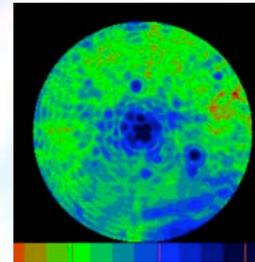
Etoiles jeunes ($<5 \cdot 10^8$ ans)

Imagerie à Haute Dynamique

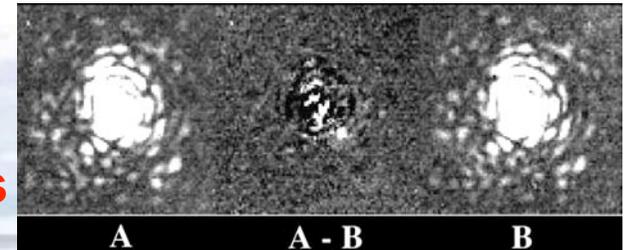
1- Optique Adaptative extreme même sur un télescope spatial !!!



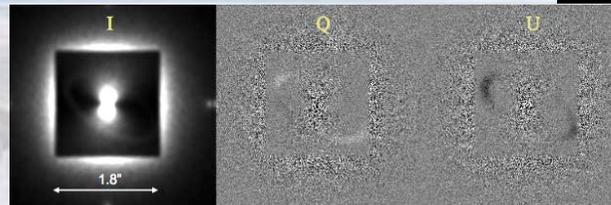
2- Coronographe
éteindre l'étoile sans éteindre la planète
Il y a des résidus...



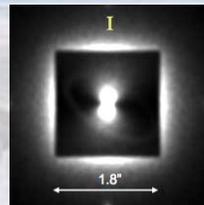
2- Imagerie différentielle
Discriminer la planète des speckles résiduels



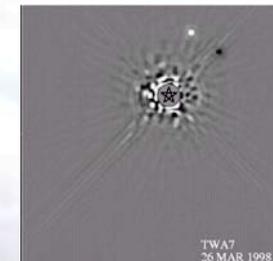
a) Avec le spectre



b) Avec la polarisation



c) Avec la géométrie (rotation ou dispersion spectrale)

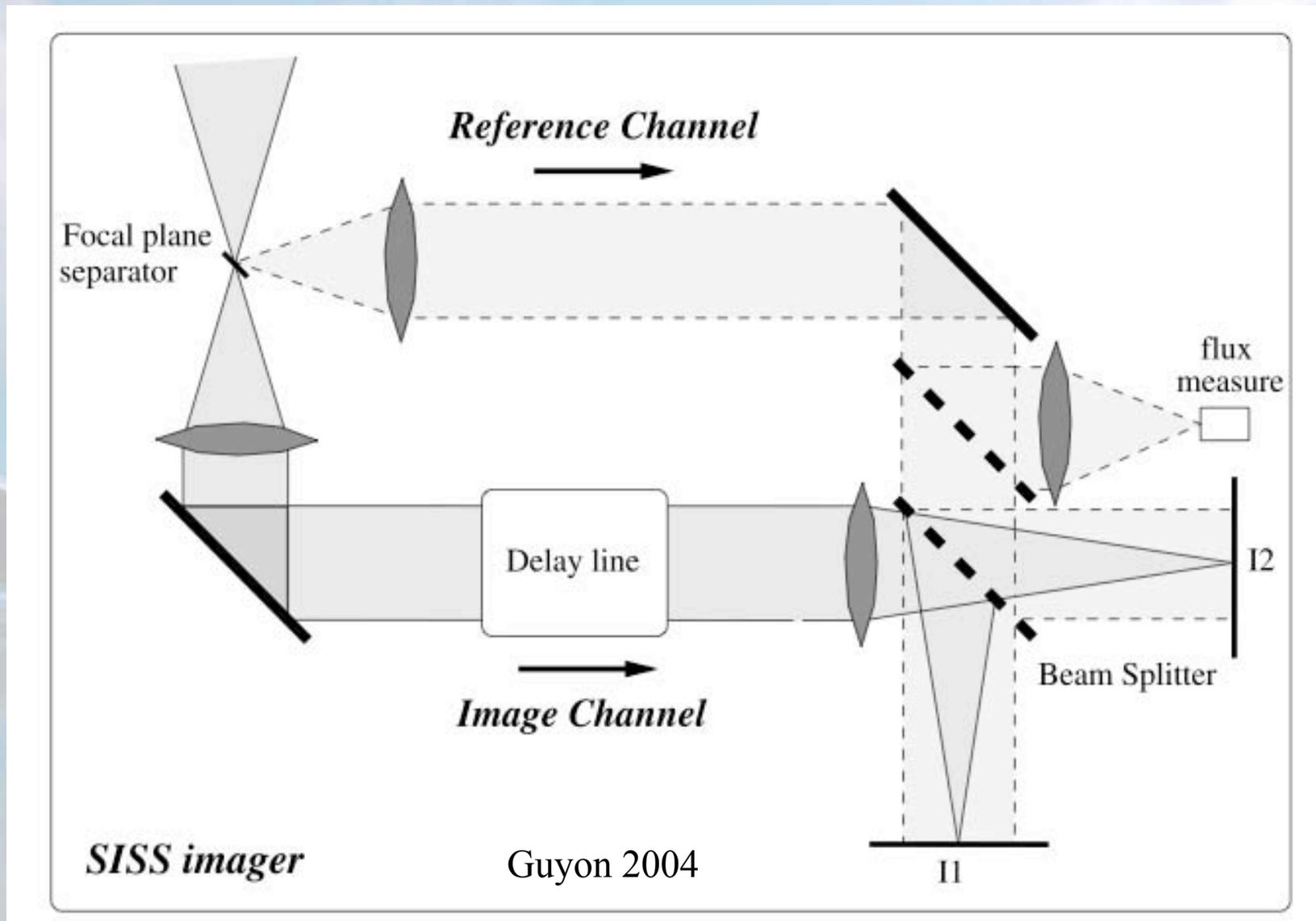


d) Avec la Cohérence

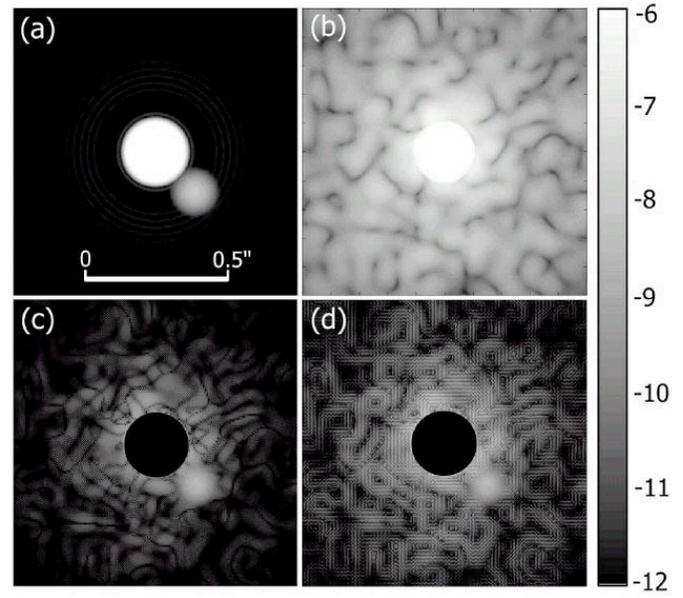
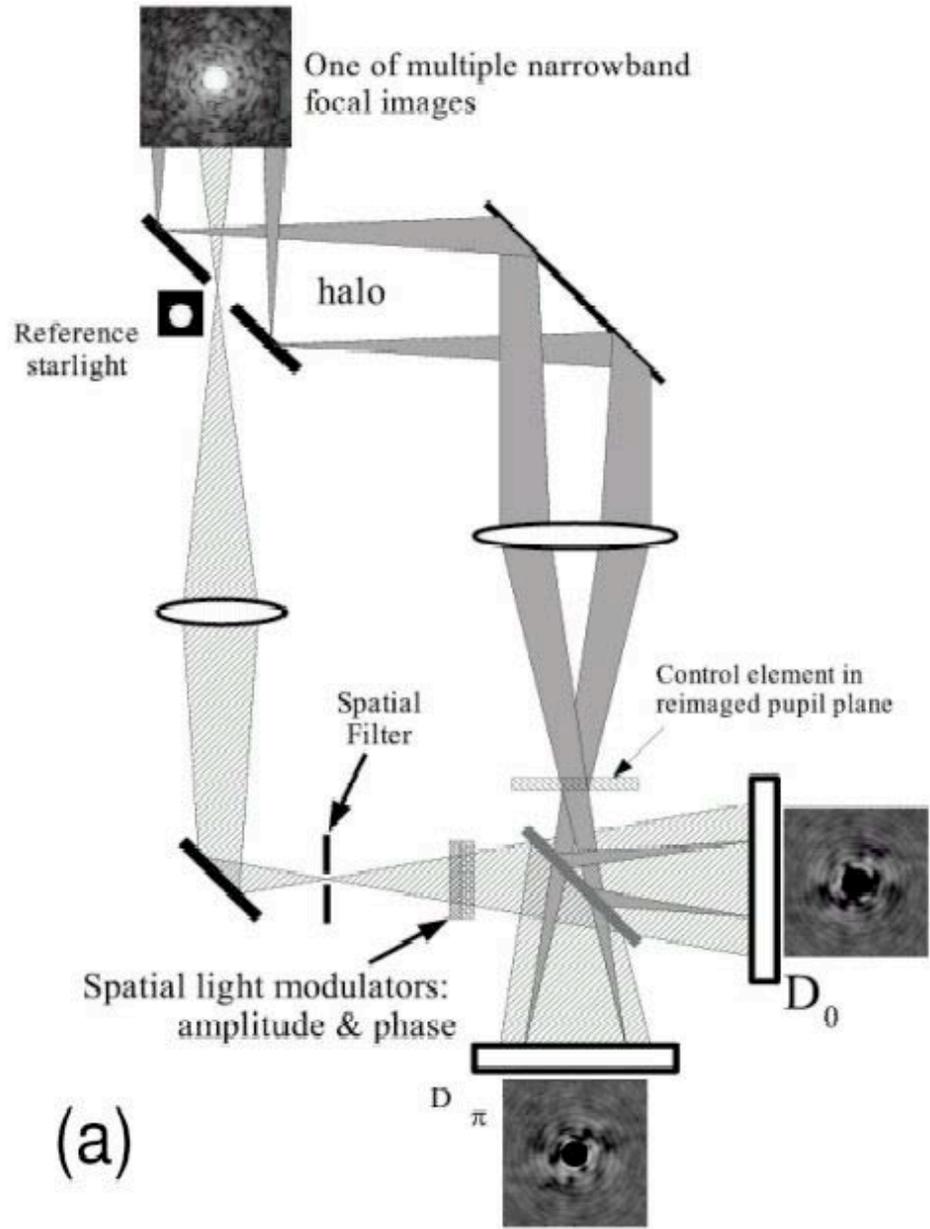
Imagerie différentielle basée sur la cohérence

- Principe: Incohérence entre étoile et planète
Détection planète dans le champ de speckle
- Indépendant du spectre/polarisation de la planète
- Sensibilité optimale : Très proche de l'étoile
- Complémentaire des techniques précédentes
- Plusieurs techniques proposées:
Codona & Angel 04, Guyon 04, Labeyrie 04, Baudoz 06

SISS Imager : Modulation temporelle des franges

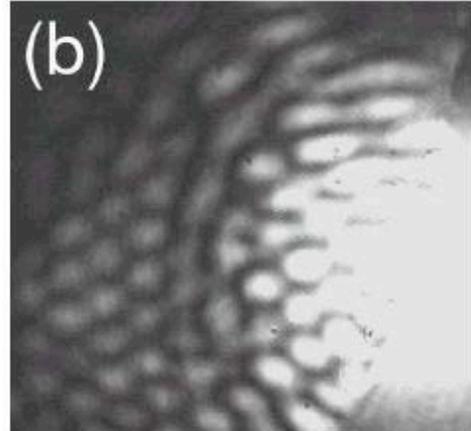


Recombinaison interférentiel de type Mach Zender



Codona & Angel 2004

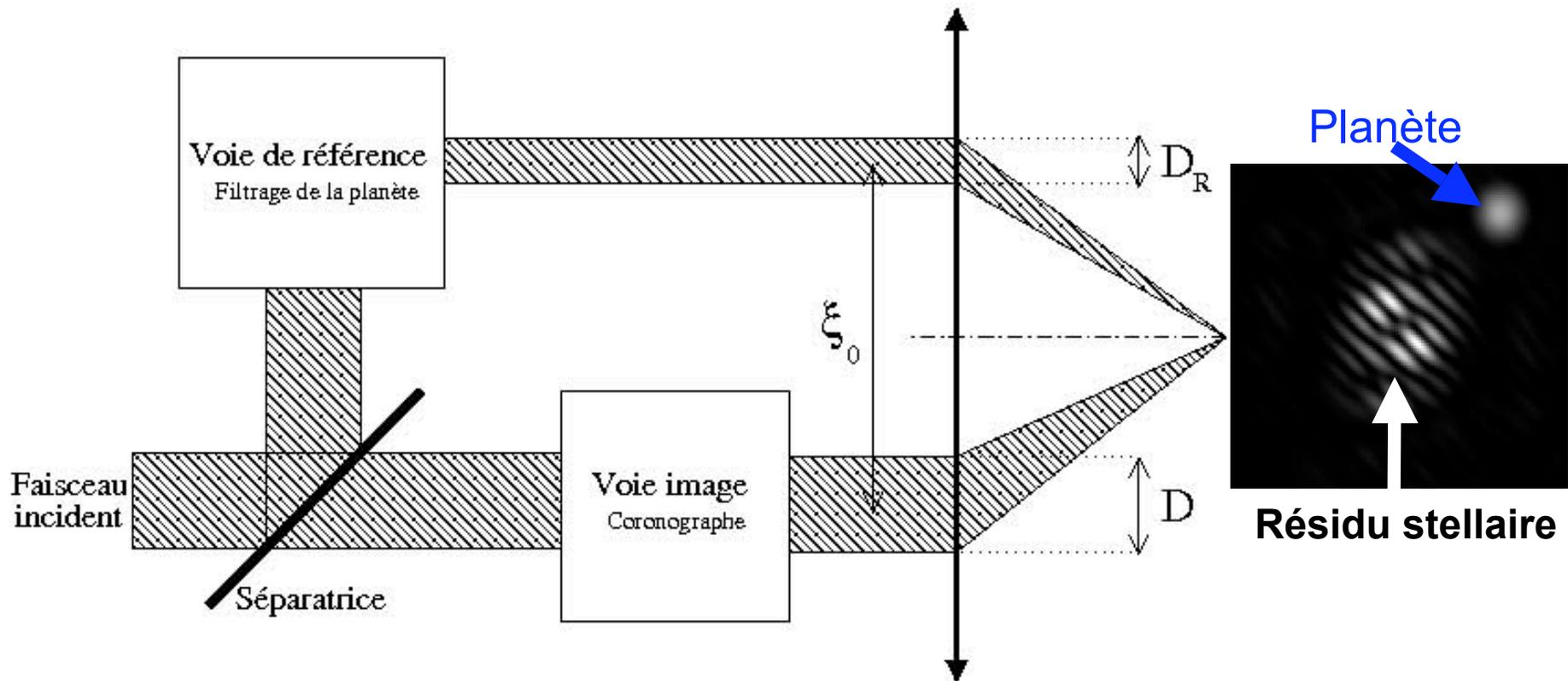
Planète: 10^{-8} @ 2 arcsec
 $D=4m, (D_{eff}=2m)$



Principe de la Self-coherent camera

Incohérence entre l'étoile et le compagnon

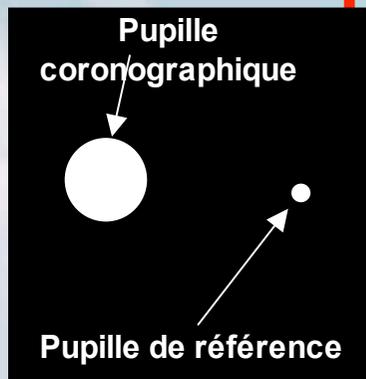
Interférences de Fizeau (trous d'Young)



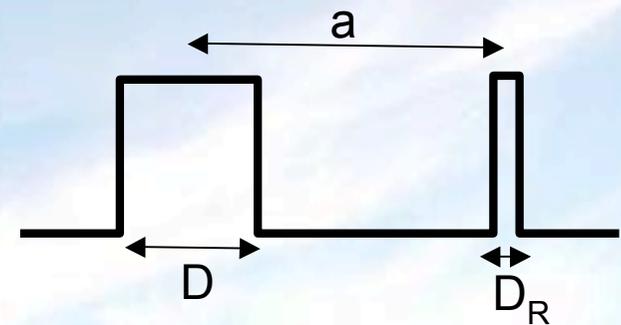
Baudoz et al. 2006

Image codée = Image scientifique

La Self Coherent Camera en 3 Plans



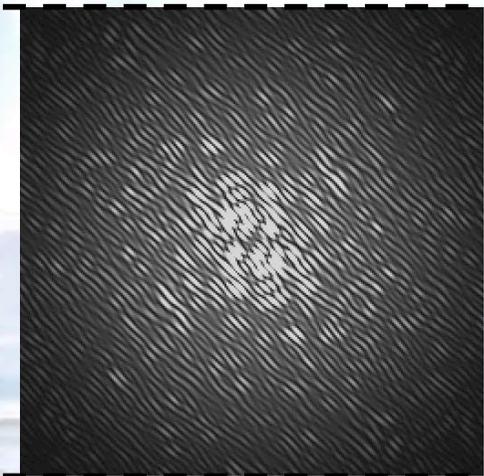
Plan Pupille



Propagation optique



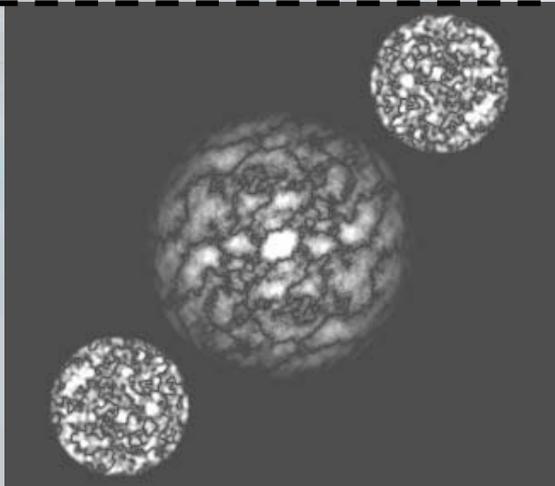
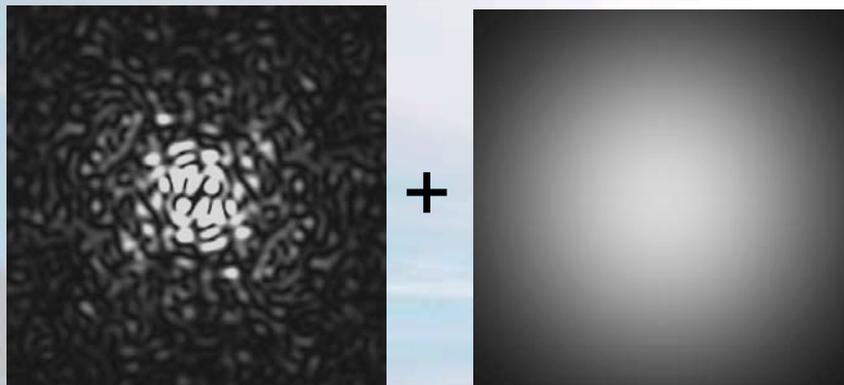
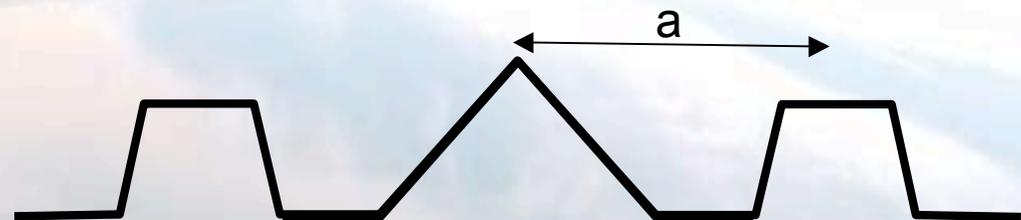
Intensité dans le plan focal



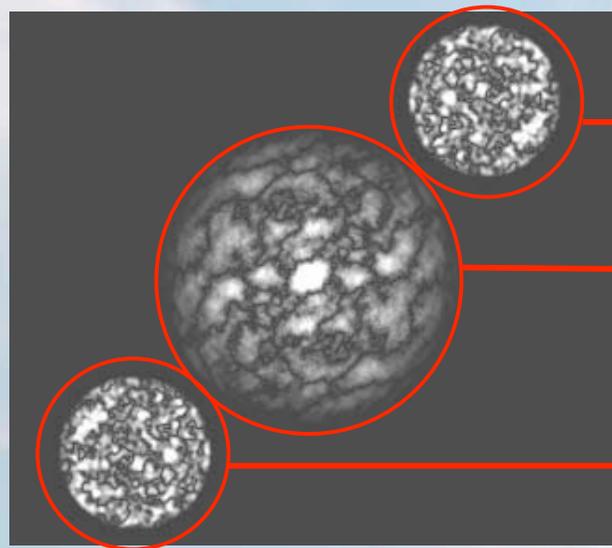
FFT



Plan de corrélation de la pupille



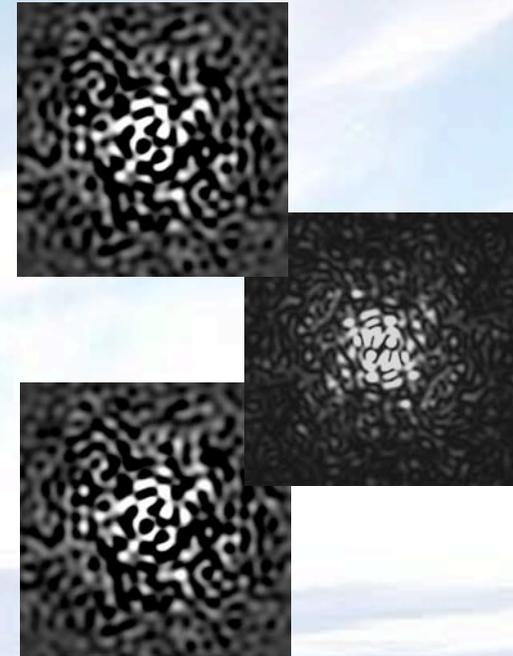
Le traitement de données SCC



$$\text{FFT}^{-1} \rightarrow I_- = \text{TF}^{-1}[P^* * P_R]$$

$$\text{FFT}^{-1} \rightarrow I_c = I + I_R + I_{\text{planet}}$$

$$\text{FFT}^{-1} \rightarrow I_+ = \text{TF}^{-1}[P * P_R^*]$$



I_+ pour mesurer la phase Φ (caché dans P)

(I_+ est quasiment linéaire avec Φ pour des petits défauts)



Analyseur de surface d'onde plan focal (Galicher et al. 2008, 2010)

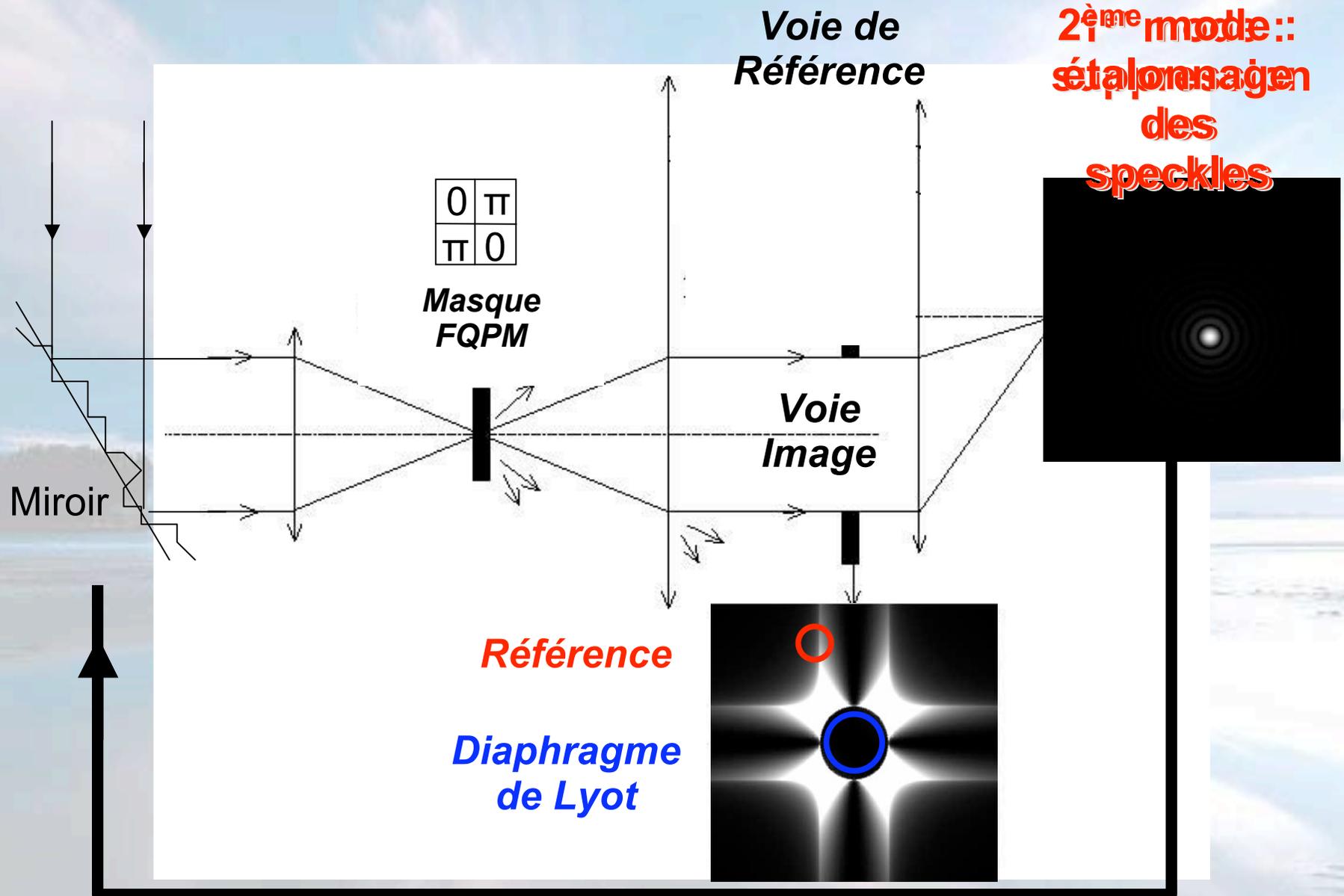
I_+ et I_c pour détecter I_{planet} (I_+ contient I et I_R mais pas I_{planet})



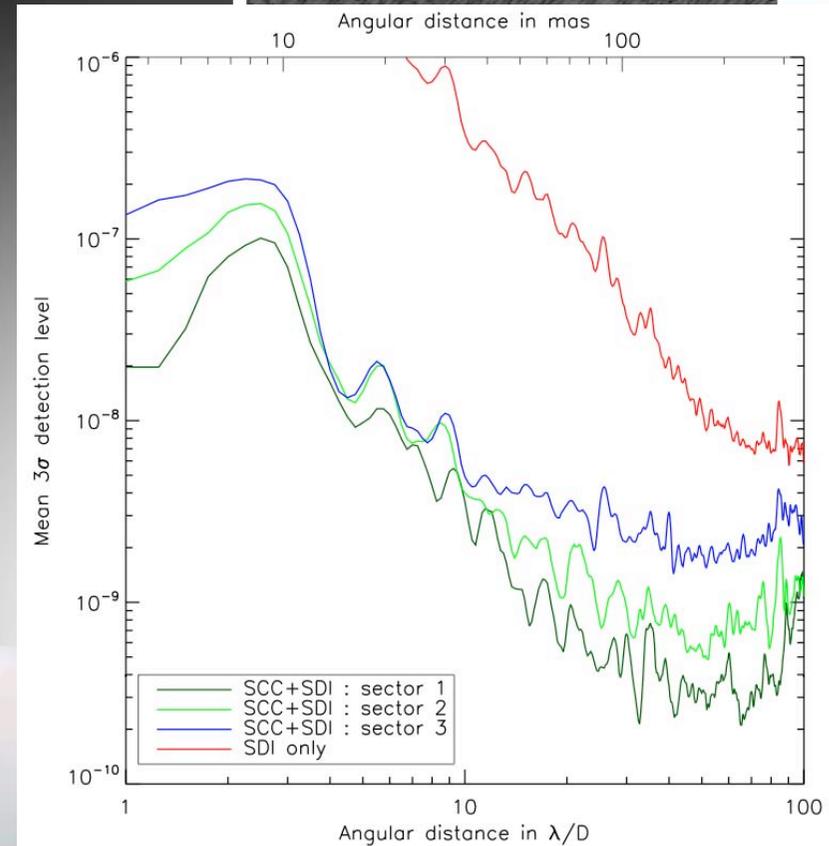
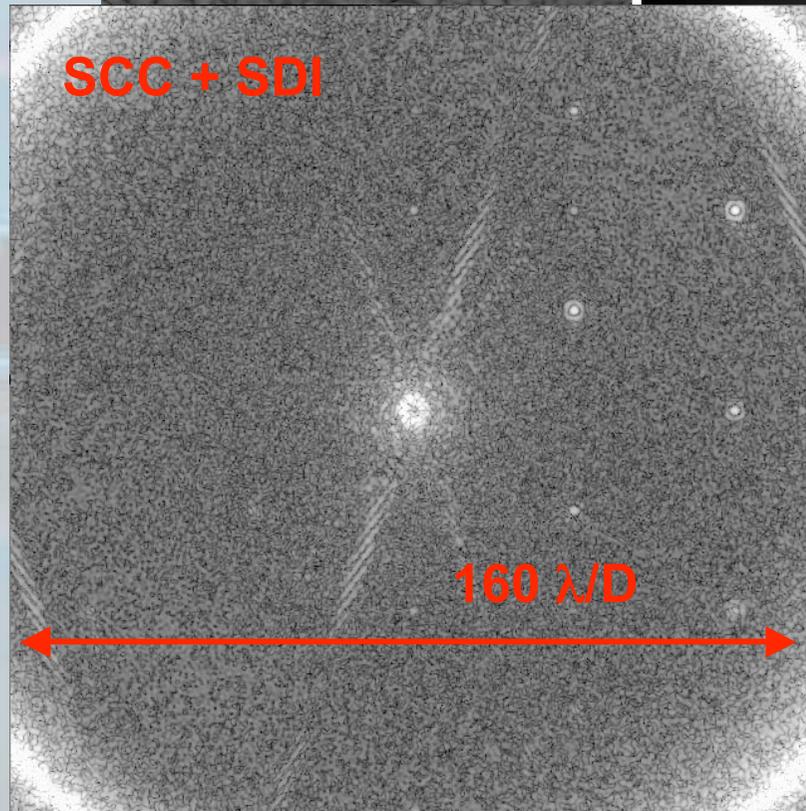
Instrument de détection de planètes

(Baudoz et al. 2006, Galicher & Baudoz 2007)

Coronographe à quatre quadrants et SCC



Instrument proposé pour EPICS basé sur la cohérence



SCC appliqué à un télescope spatial

$$R = \lambda/\Delta\lambda = 5$$

$$R_{\text{Wynne}} = 130$$

64x64

rms phase = 20nm en f^3

rms amplitude = 1% en f^3

$$\gamma = 20$$

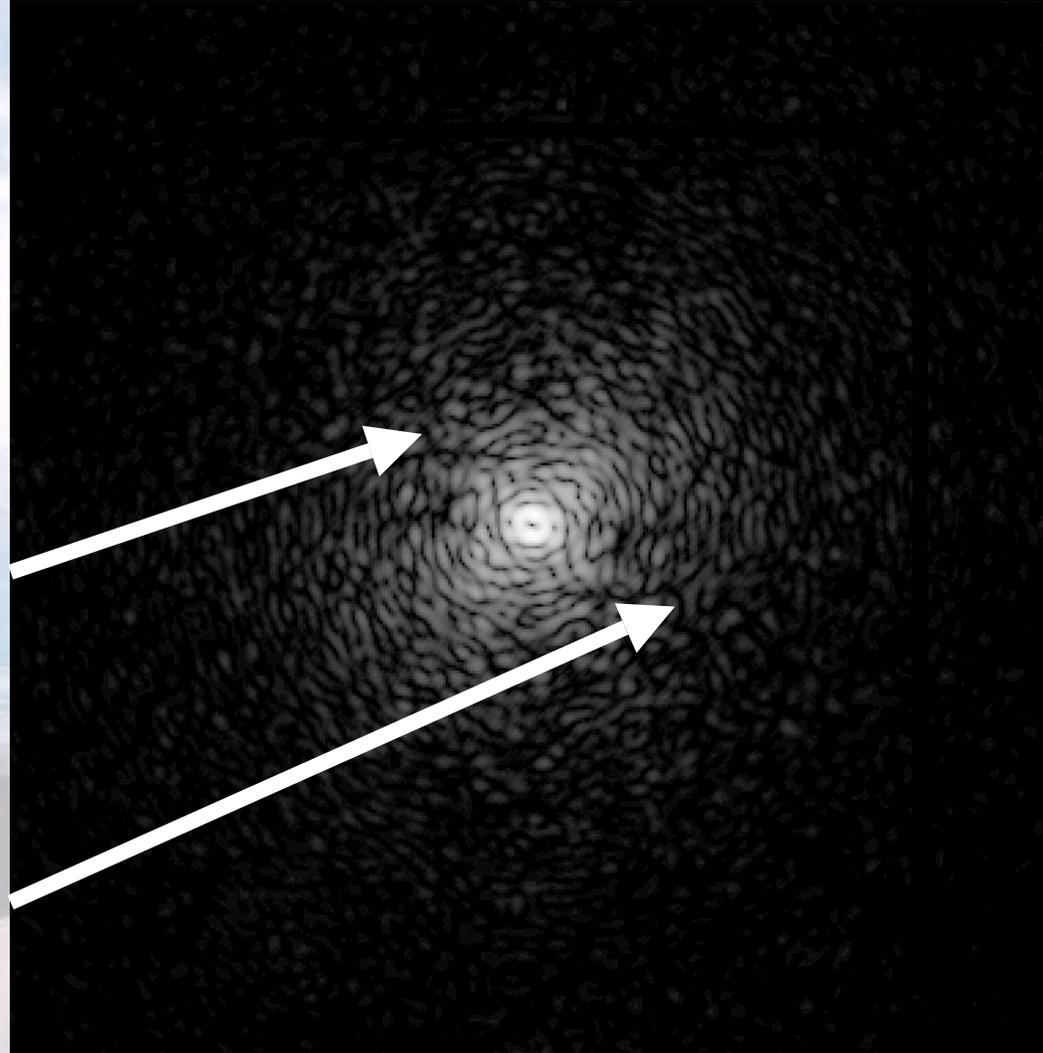
bruit de photons

4m G2 10 parsec

temps de pose total ~ 8h

Défauts
d'amplitude

Dark hole



Détection par étalonnage des speckles

$$R = \lambda/\Delta\lambda = 5$$

$$R_{\text{Wynne}} = 130$$

64x64

rms phase = 20nm en f^3

rms amplitude = 1% en f^3

$$\gamma = 20$$

bruit de photons

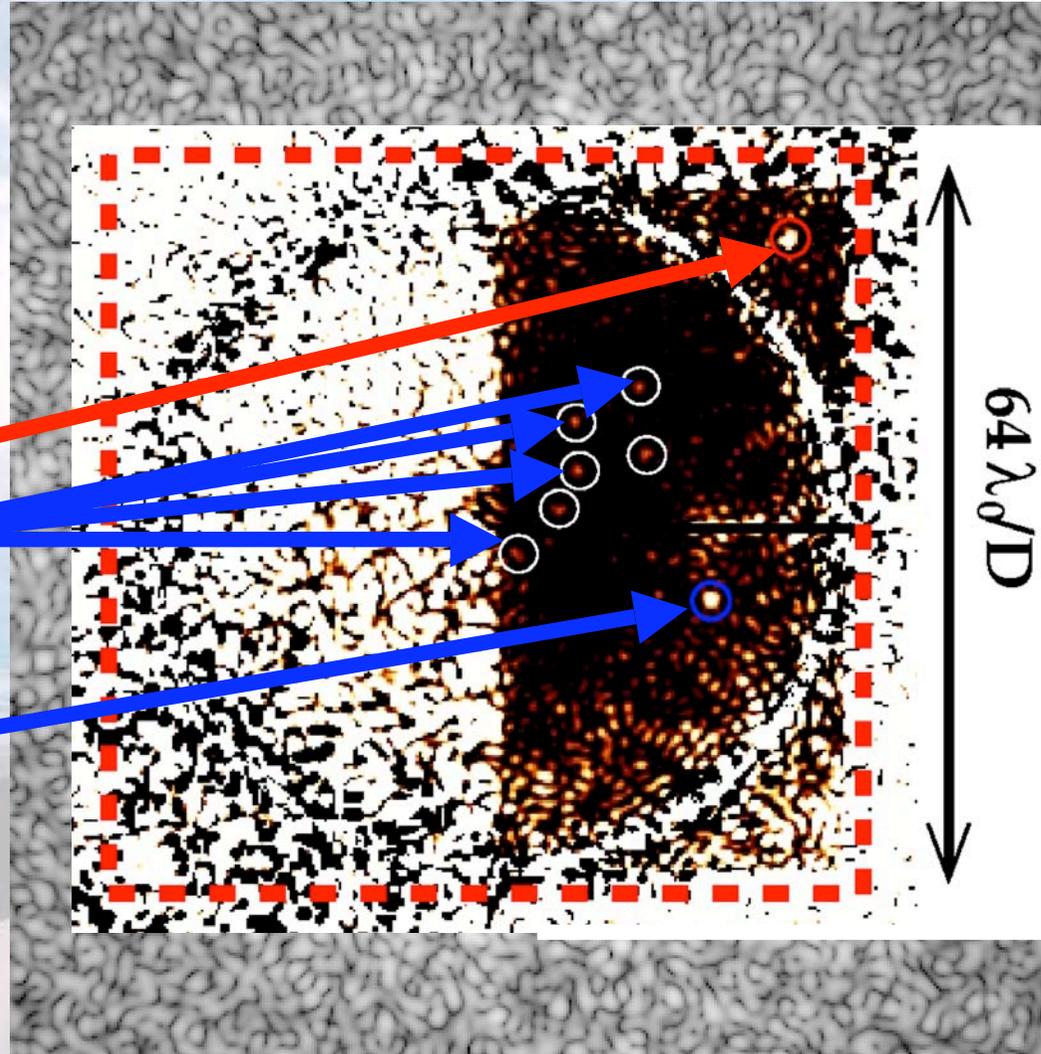
4m G2 10 parsec

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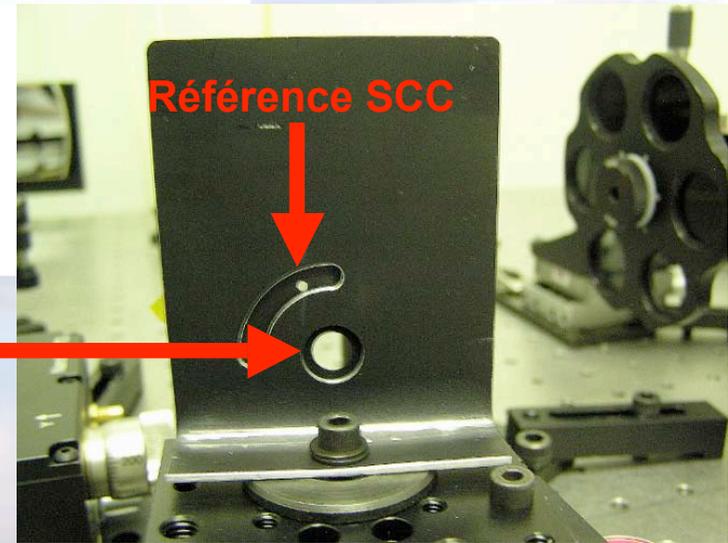
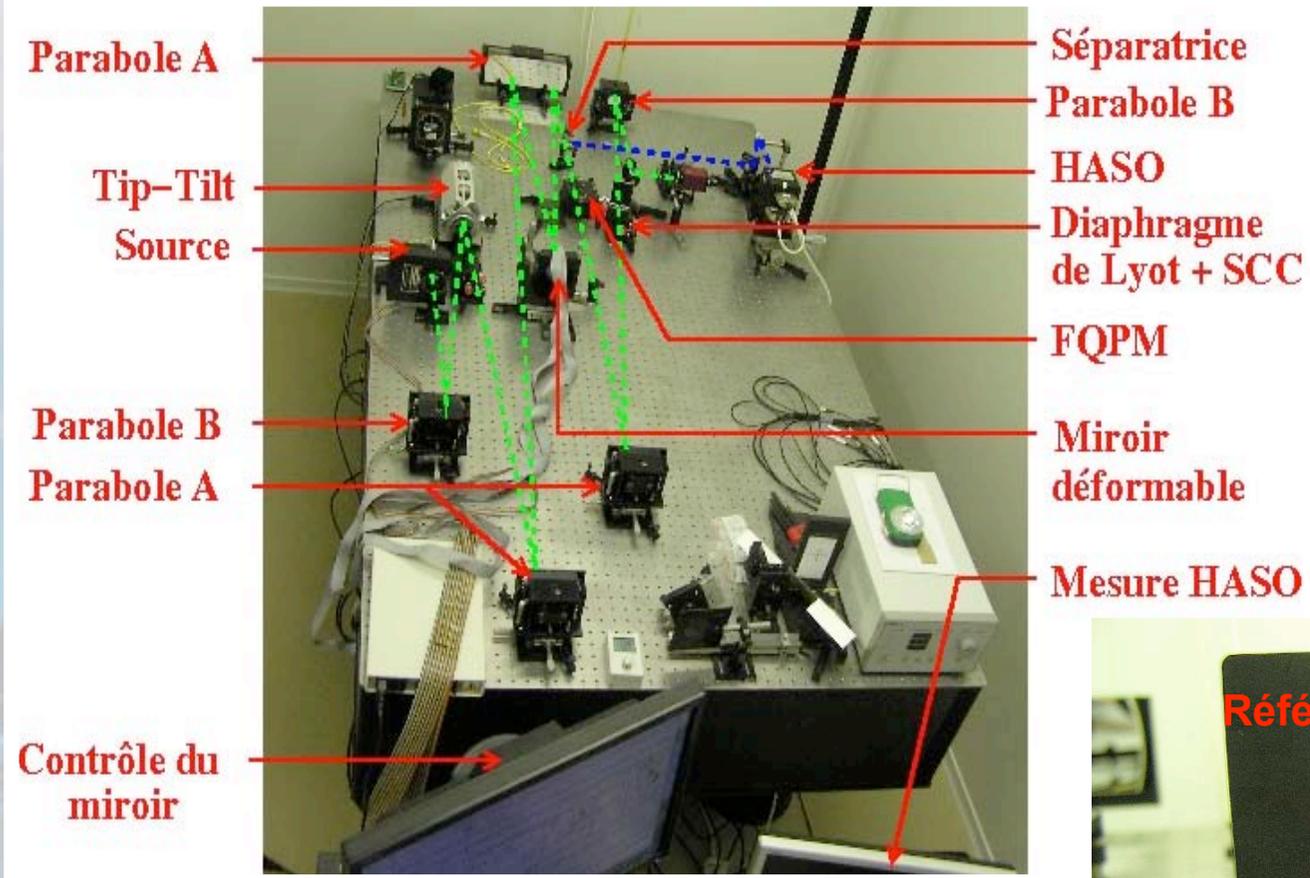
Jupiter

Terre

Super-Terre

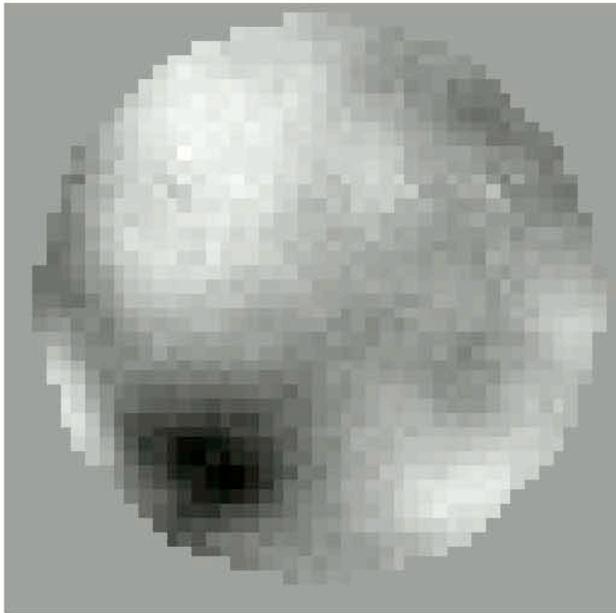


Banc optique ITHD

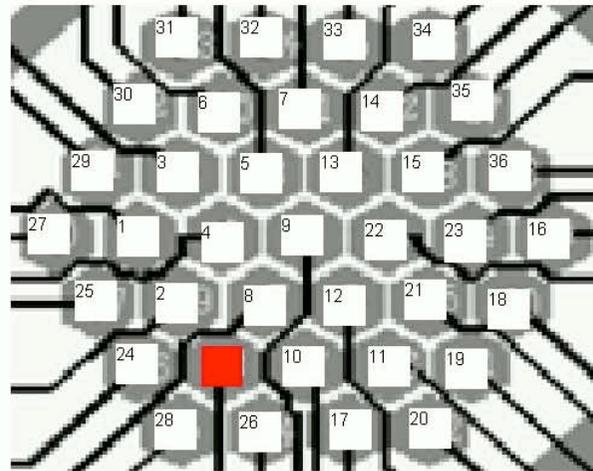


Fonctions d'influence du DM Oko

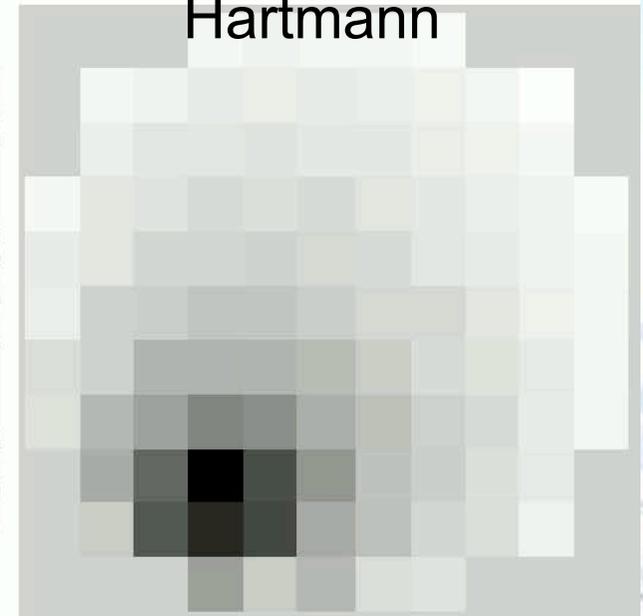
Mesure SCC



Positionnement de l'actionneur



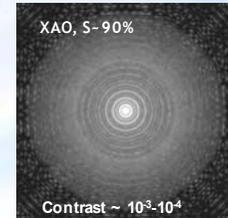
Mesure Shack-Hartmann



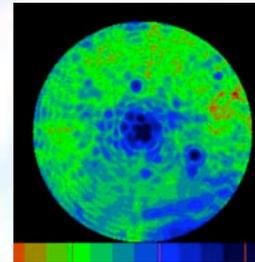
Défauts de quelques dizaines de nm rms

Imagerie à Haute Dynamique

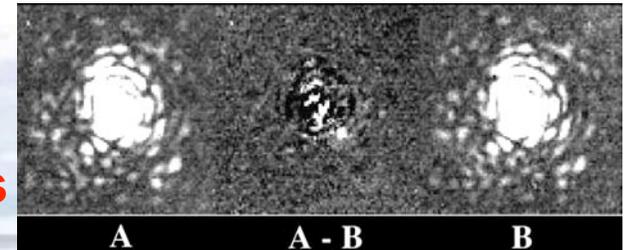
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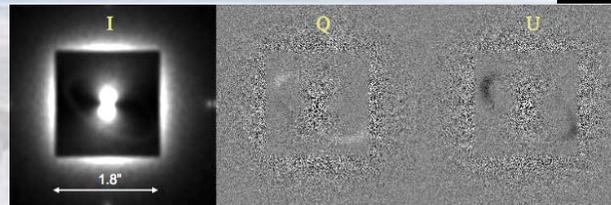
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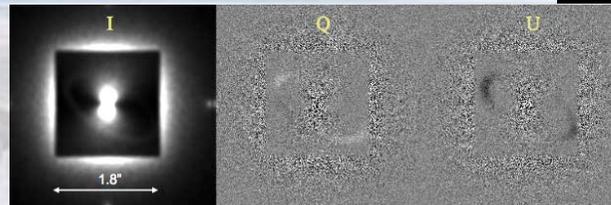
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Discriminer la planète des speckles résiduels



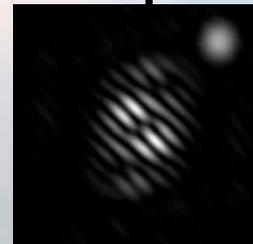
a) Avec le spectre



b) Avec la polarisation



c) Avec la géométrie (rotation ou dispersion spectrale)



d) Avec la Cohérence

