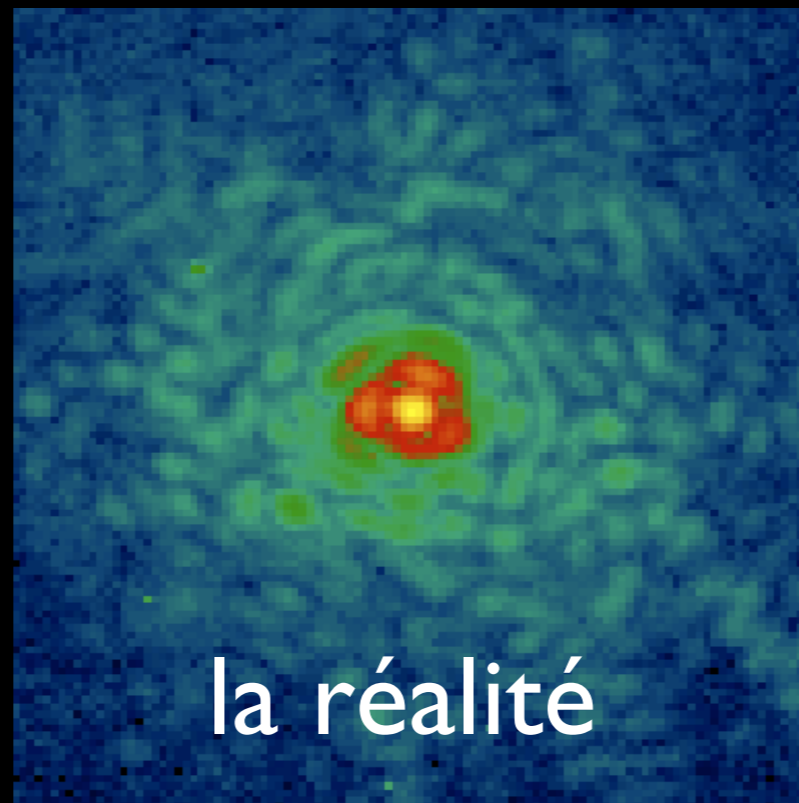
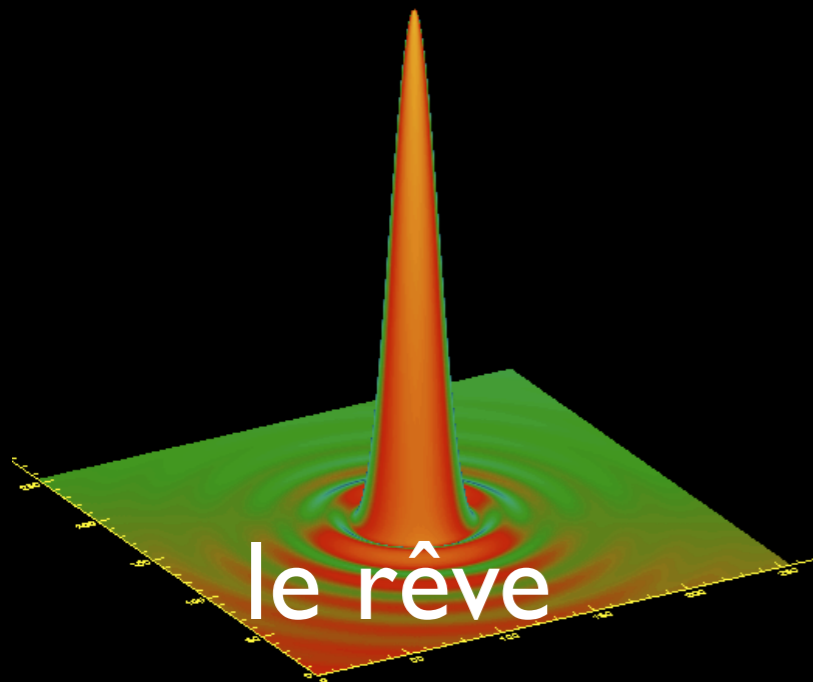
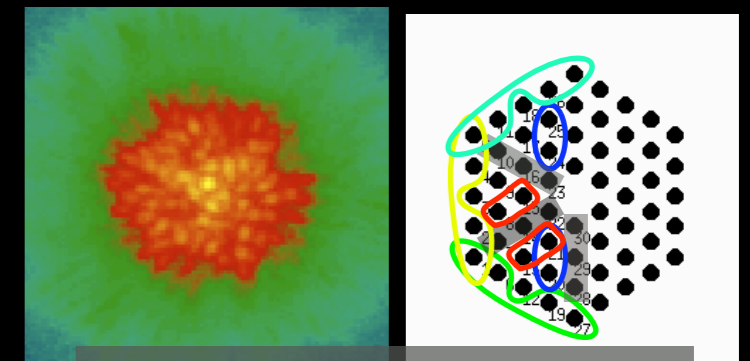


Un flirt avec la diffraction: imagerie haut contraste sur un petit champ



SCEXAO



des solutions

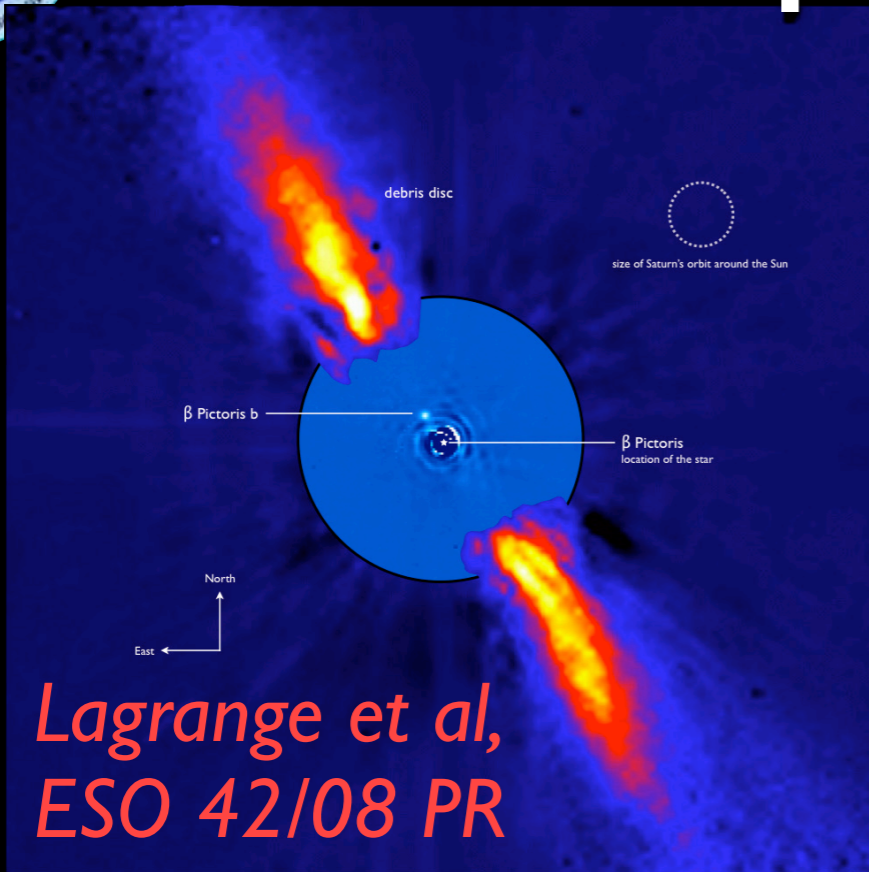


Frantz Martinache
CEAO Research Fellow

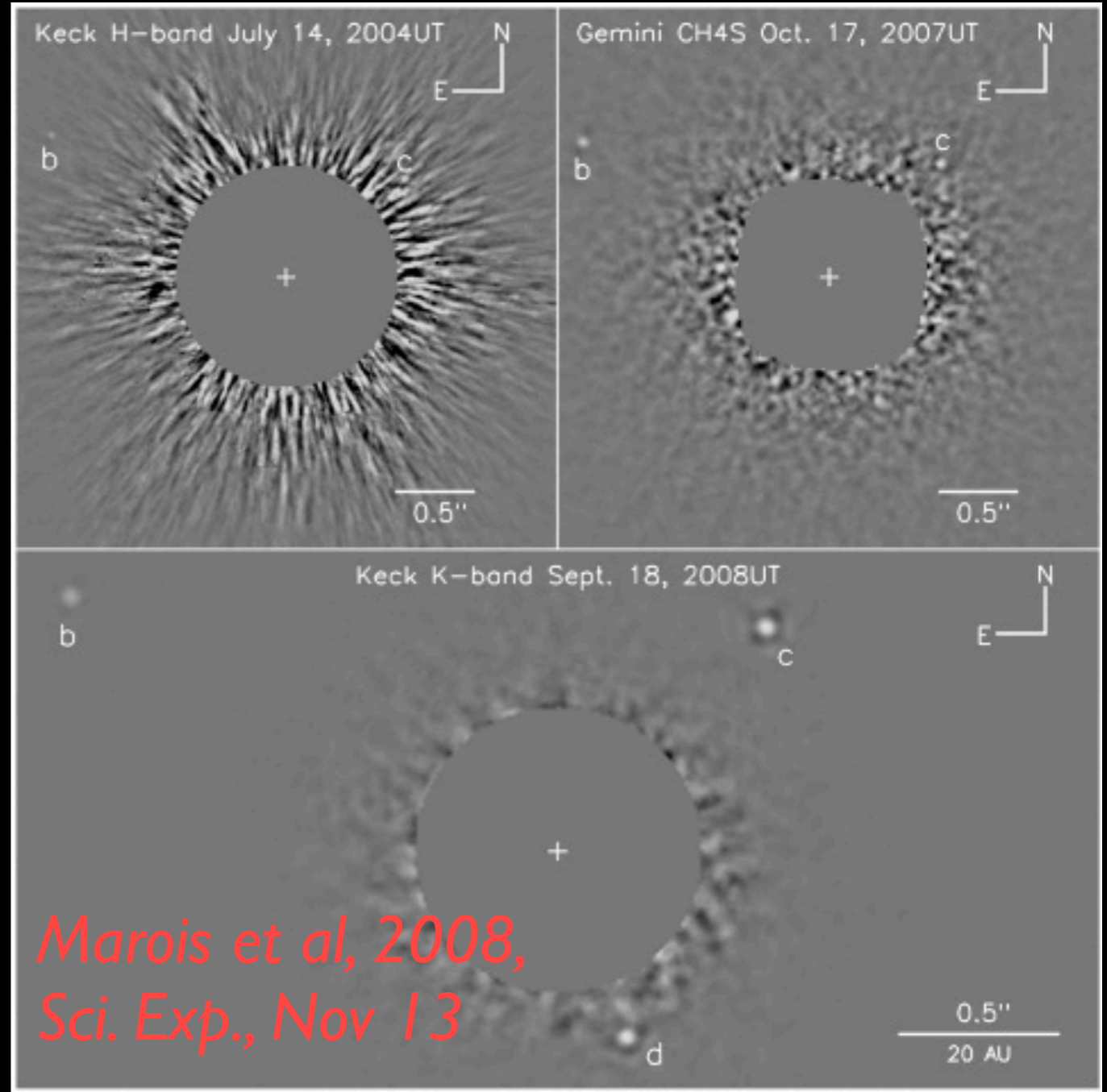
LESIA, Meudon
25/09/2009



Des temps extraordinaires

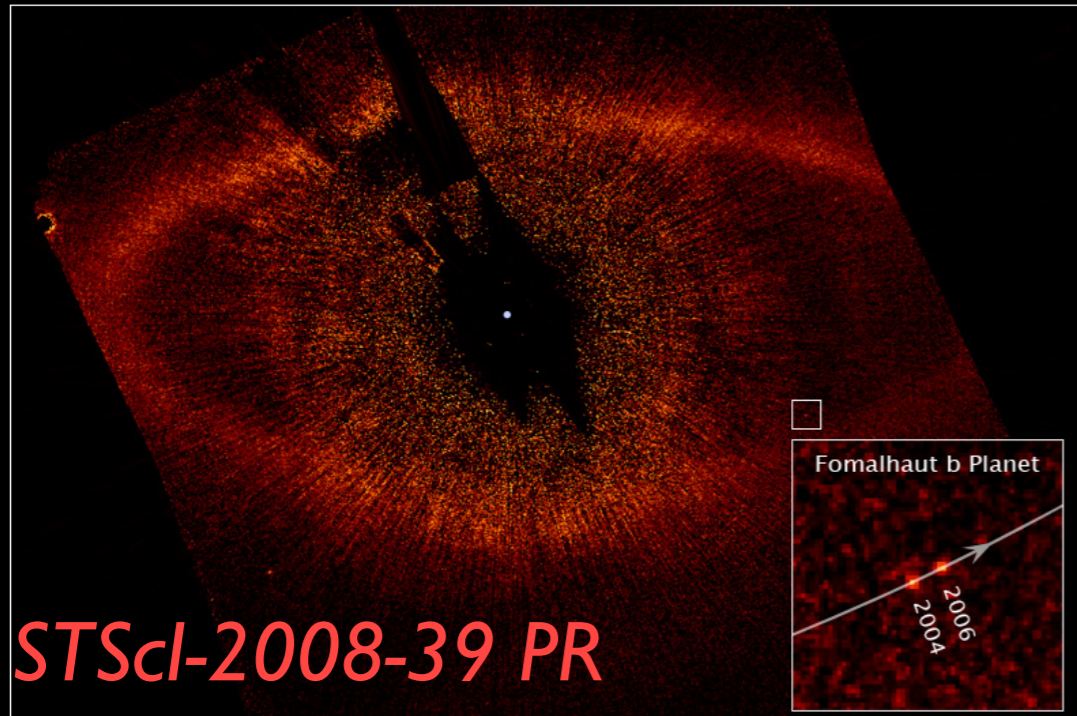


*Lagrange et al,
ESO 42/08 PR*



*Marois et al, 2008,
Sci. Exp., Nov 13*

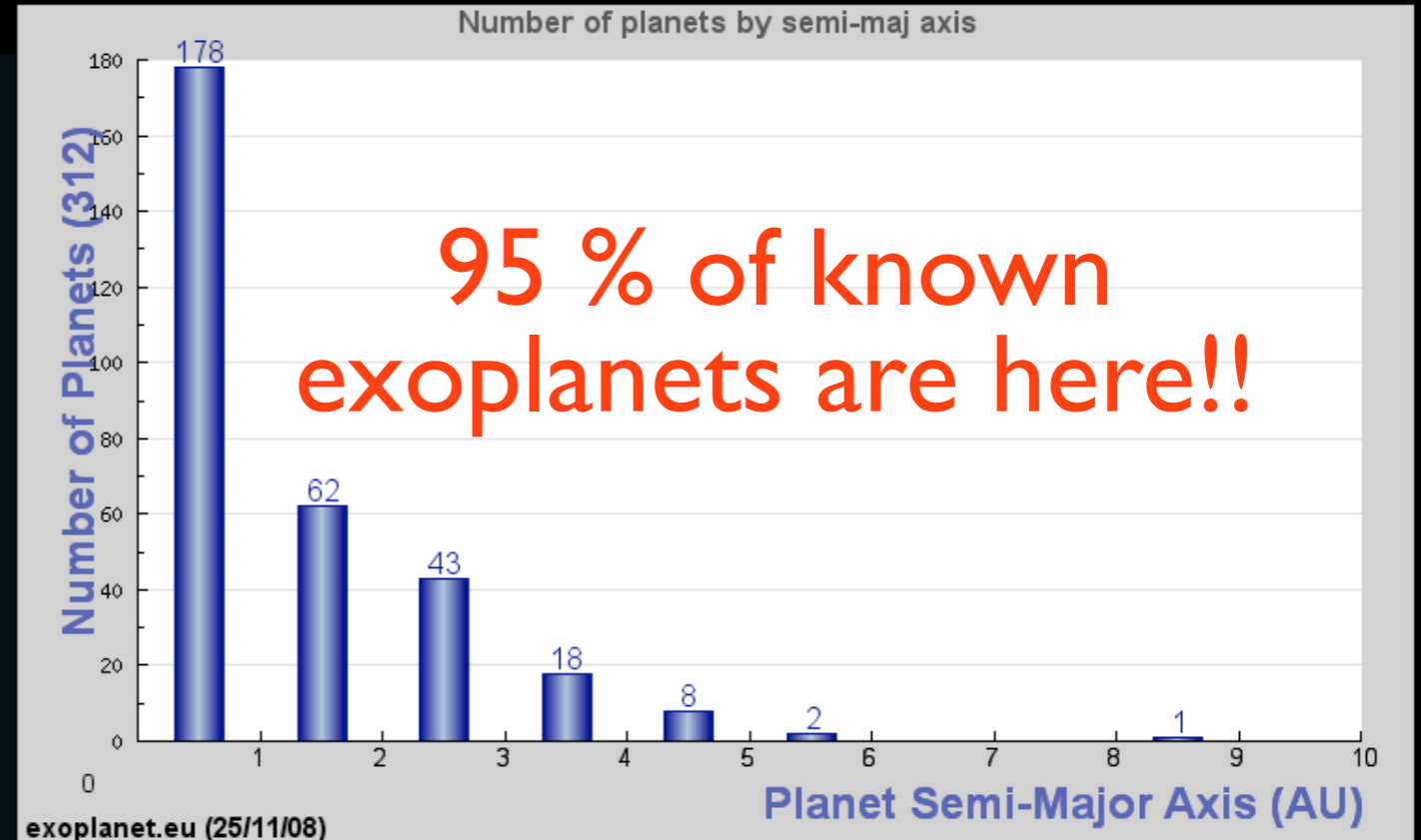
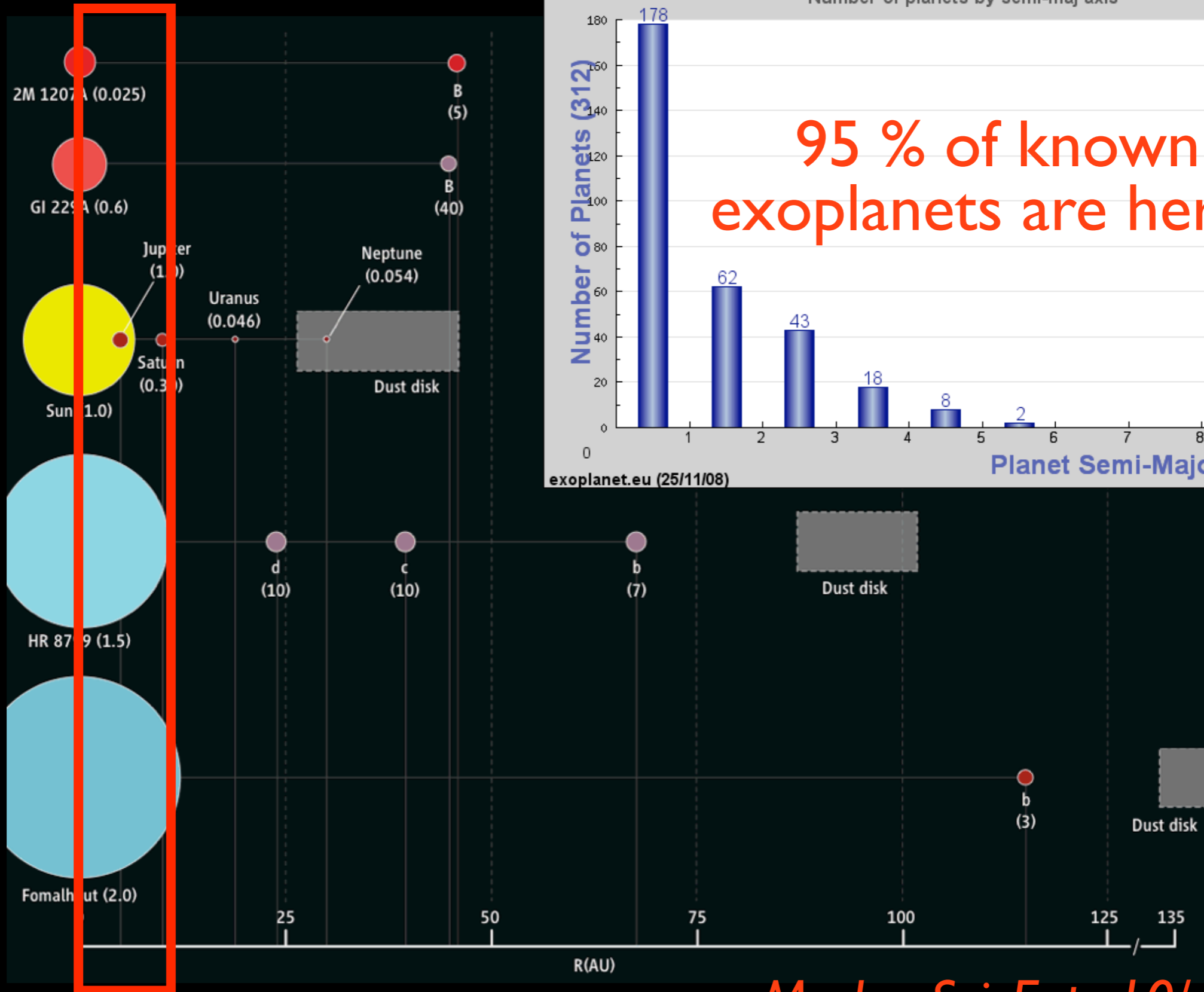
Fomalhaut System *Hubble Space Telescope • ACS/HRC*



STScI-2008-39 PR

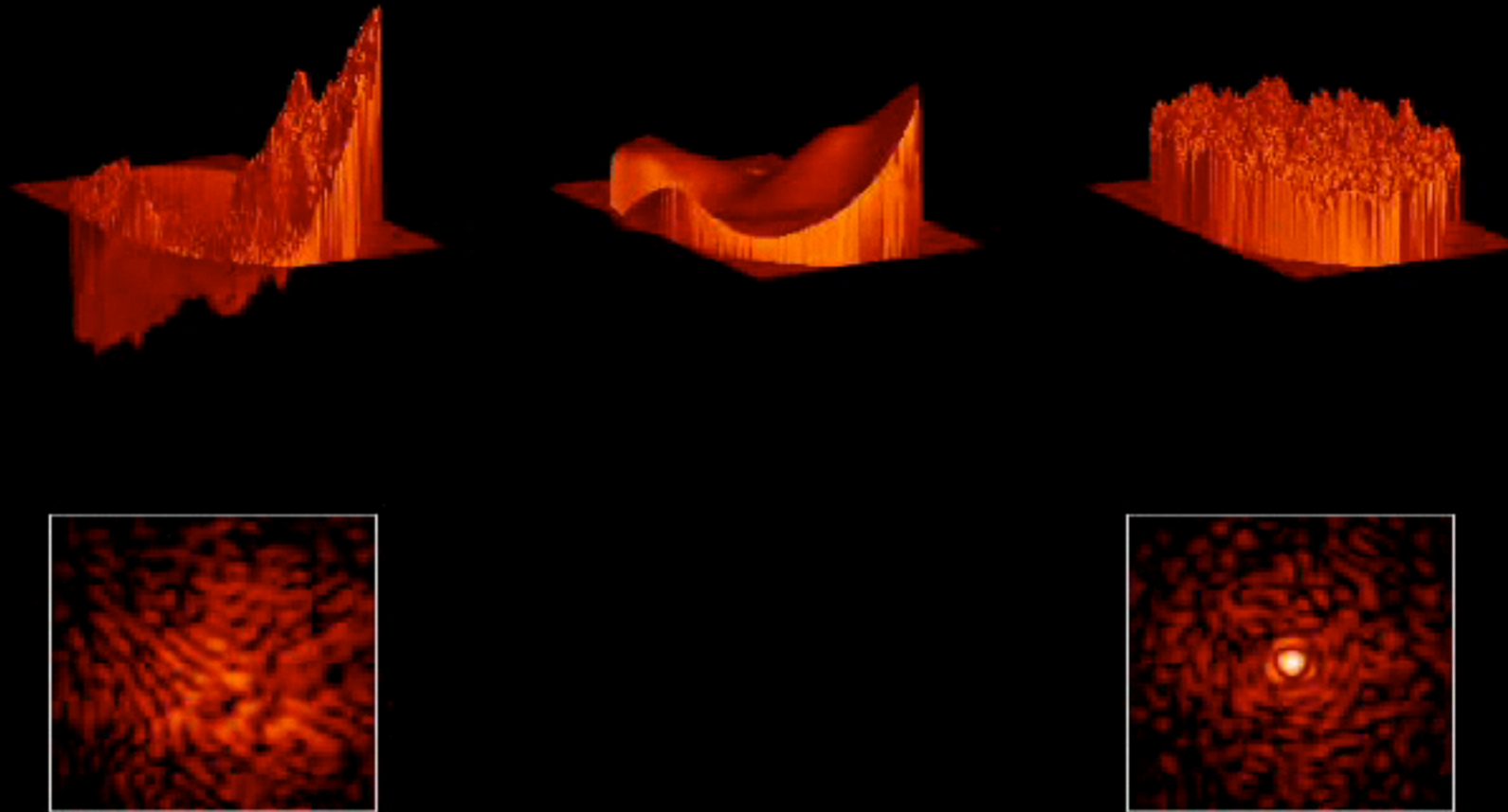


Points de référence





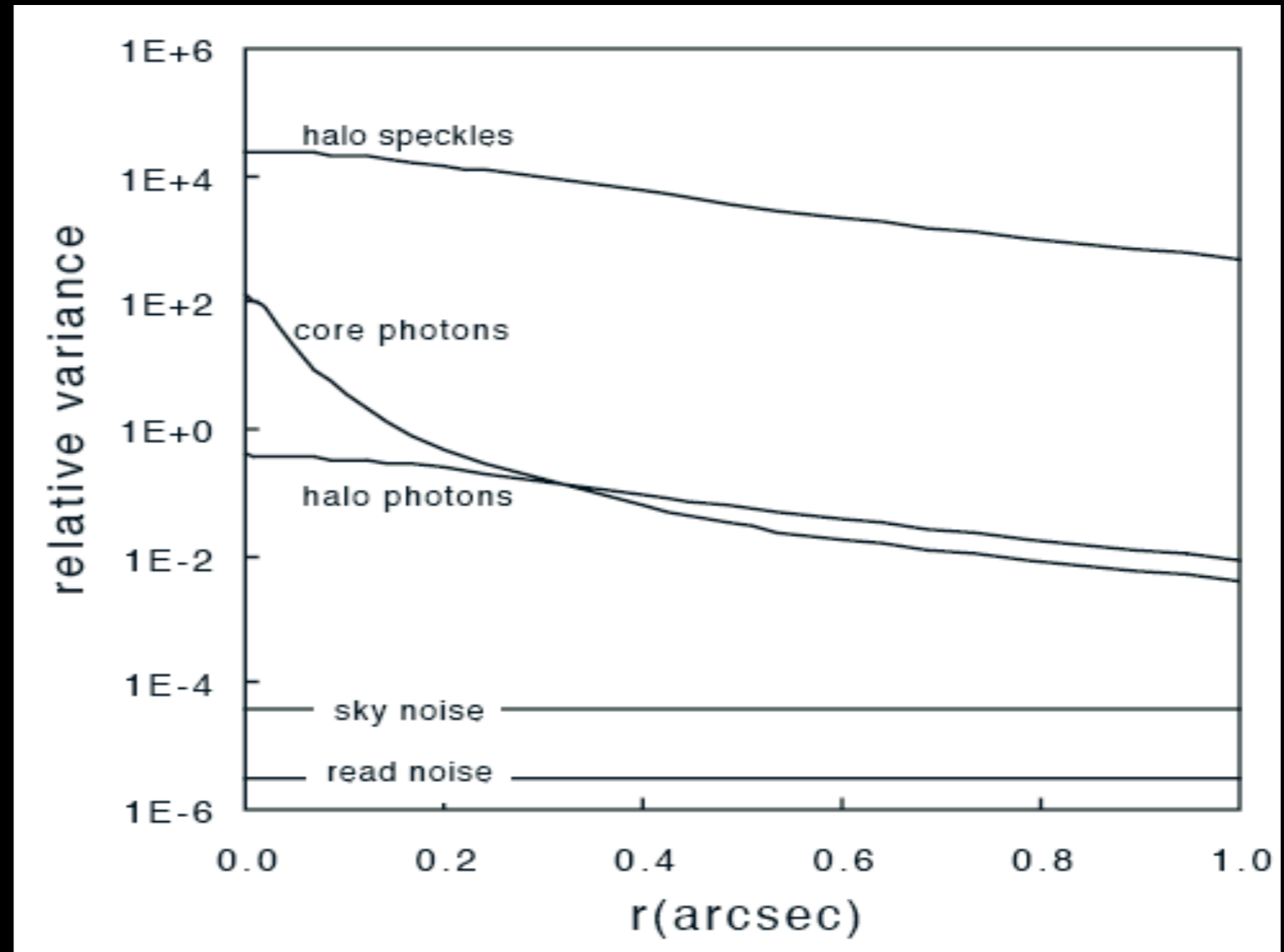
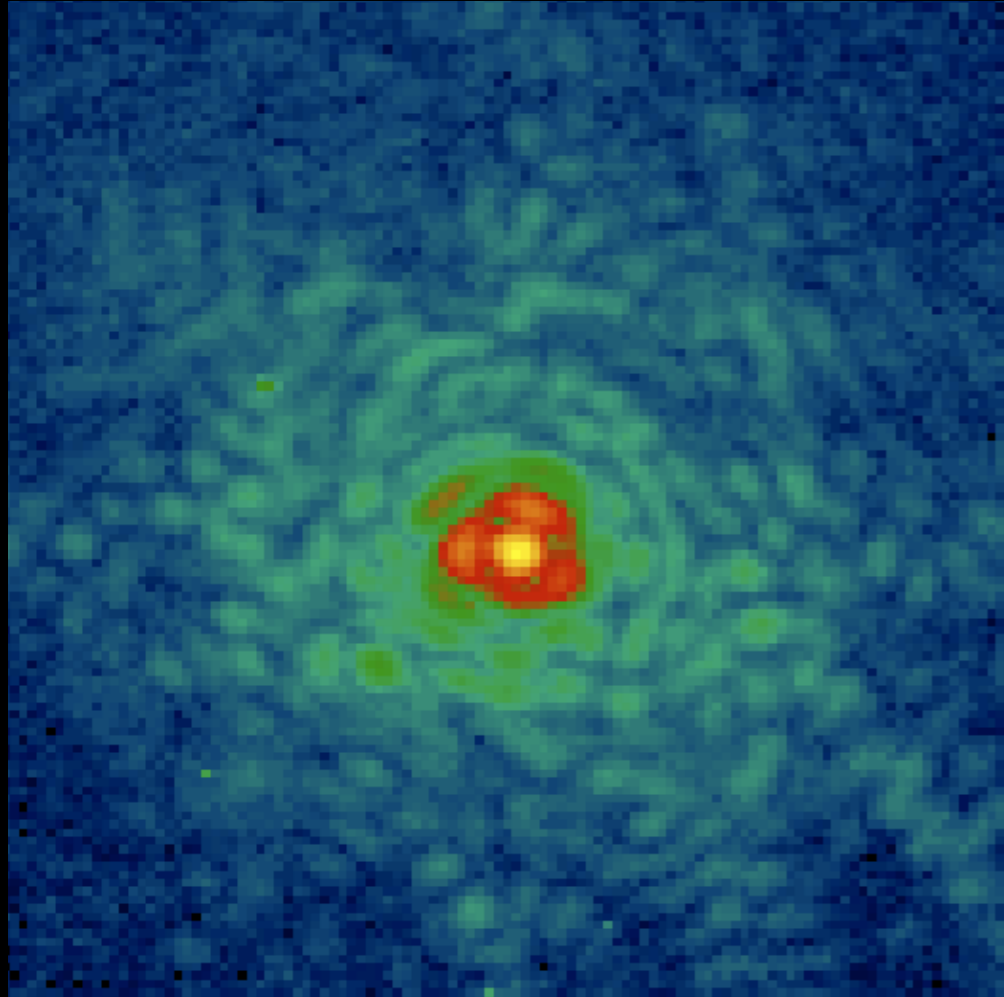
Les limitations de l'OA



simulation by James Lloyd



Le bruit de speckle

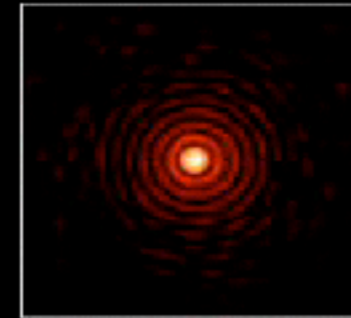
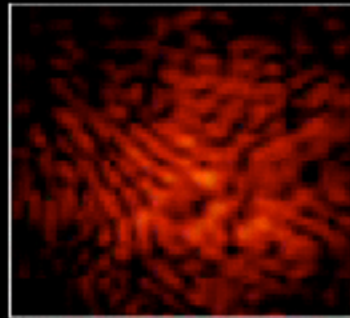
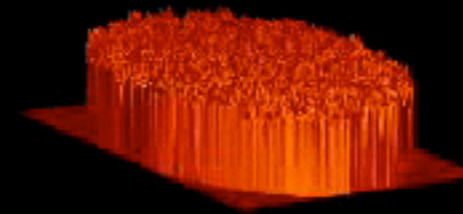
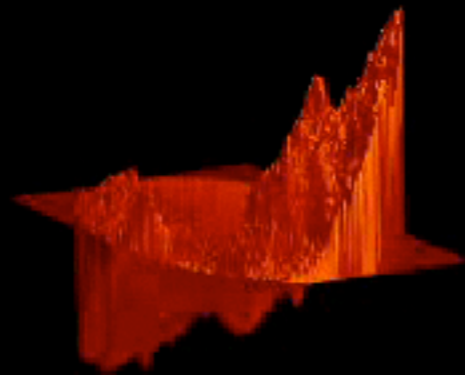


Speckles are the dominant source of noise

Racine et al, 1999, PASP, 111, 587



Approche aggressive: OA extrême



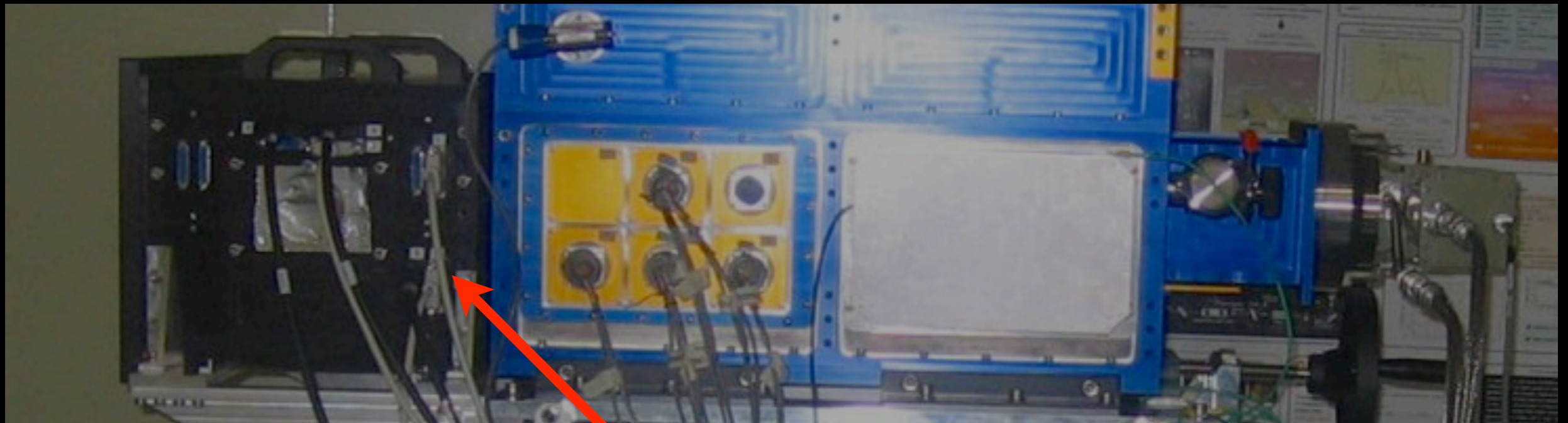


Le système SCExAO

HiCIAO: caméra coronographique à Subaru (AO188)

SEEDS: 120 nuits d'observations dédiées aux planètes
extrasolaires et aux disques

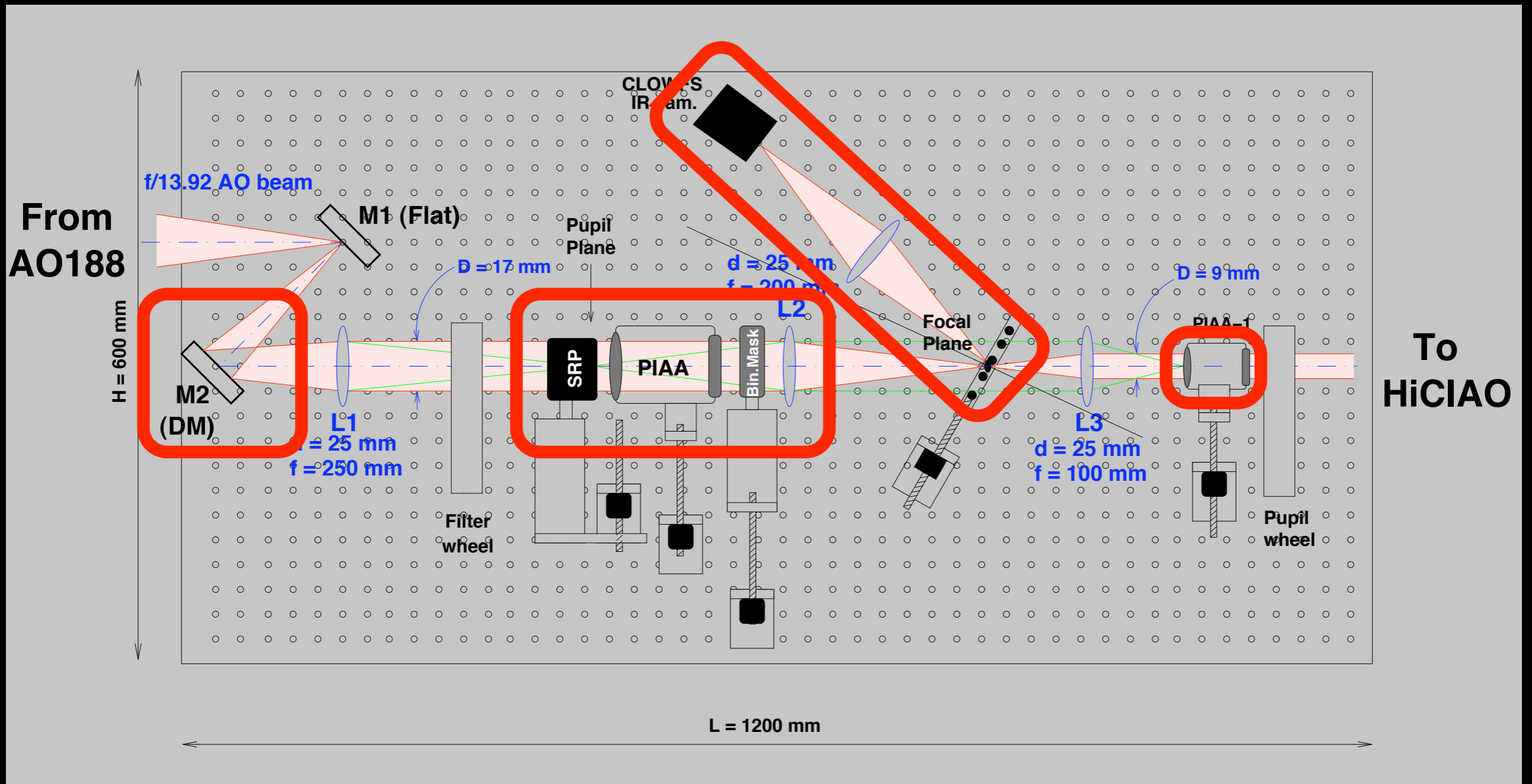
Inner working angle limité à 0.5" ($\Delta H=9.5$) or
1" ($\Delta H=12$)



motivation: remplacer le boîtier coronographique
devant HiCIAO par "quelque chose"...

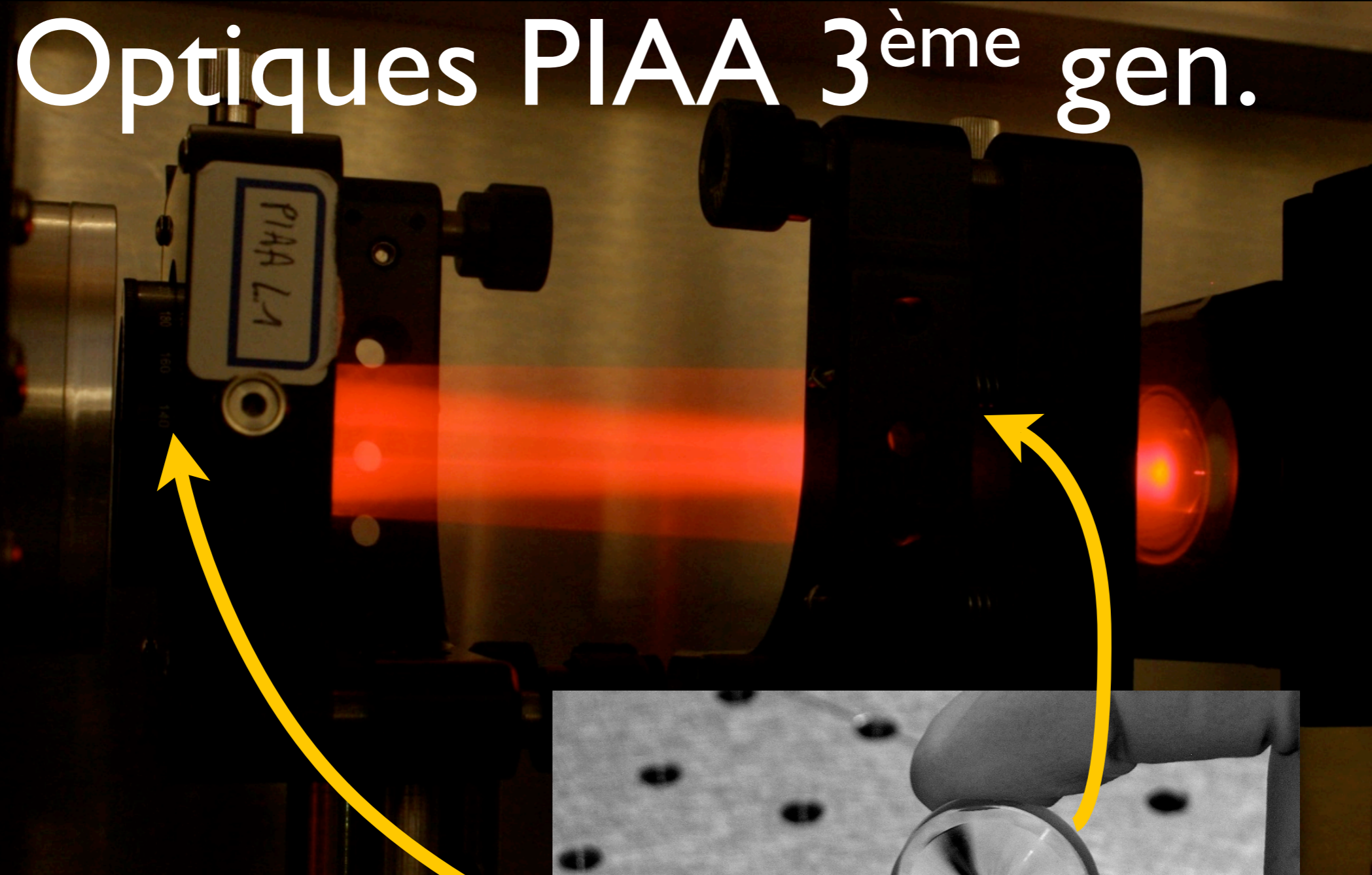


Design optique (phase I)

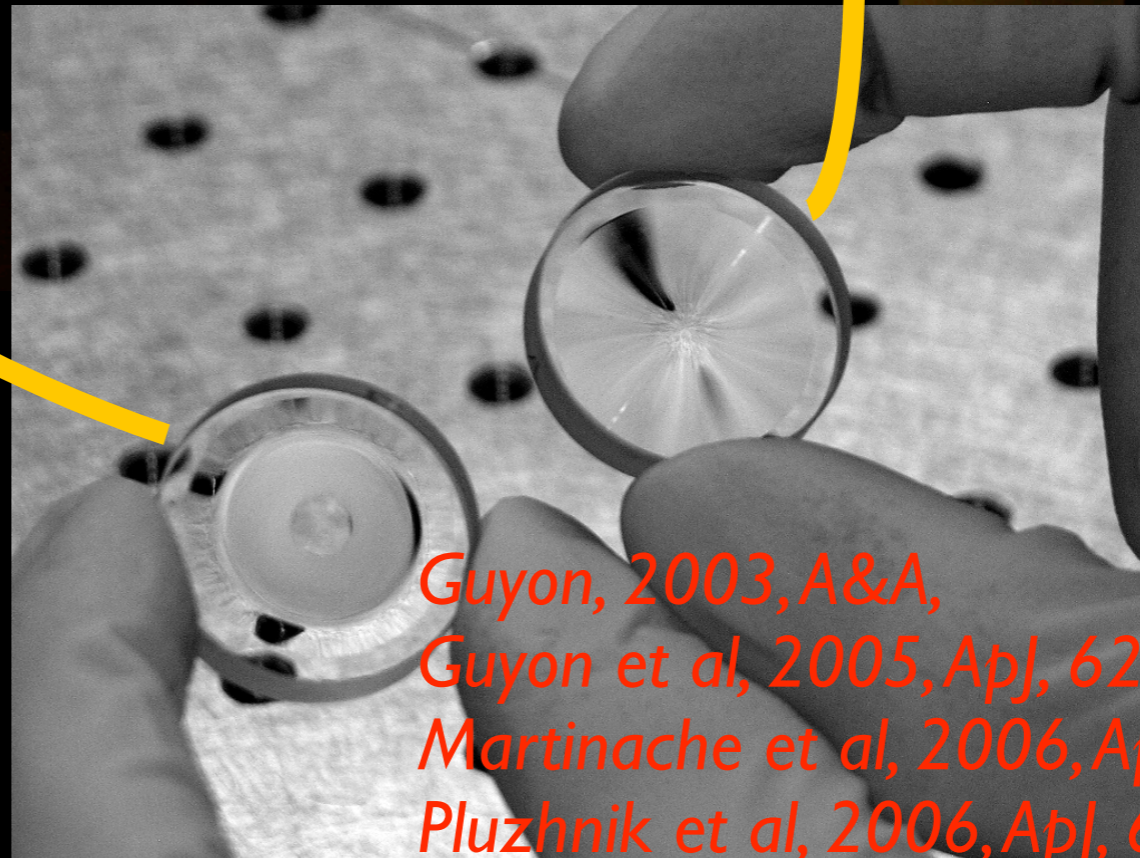




Optiques PIAA 3^{ème} gen.



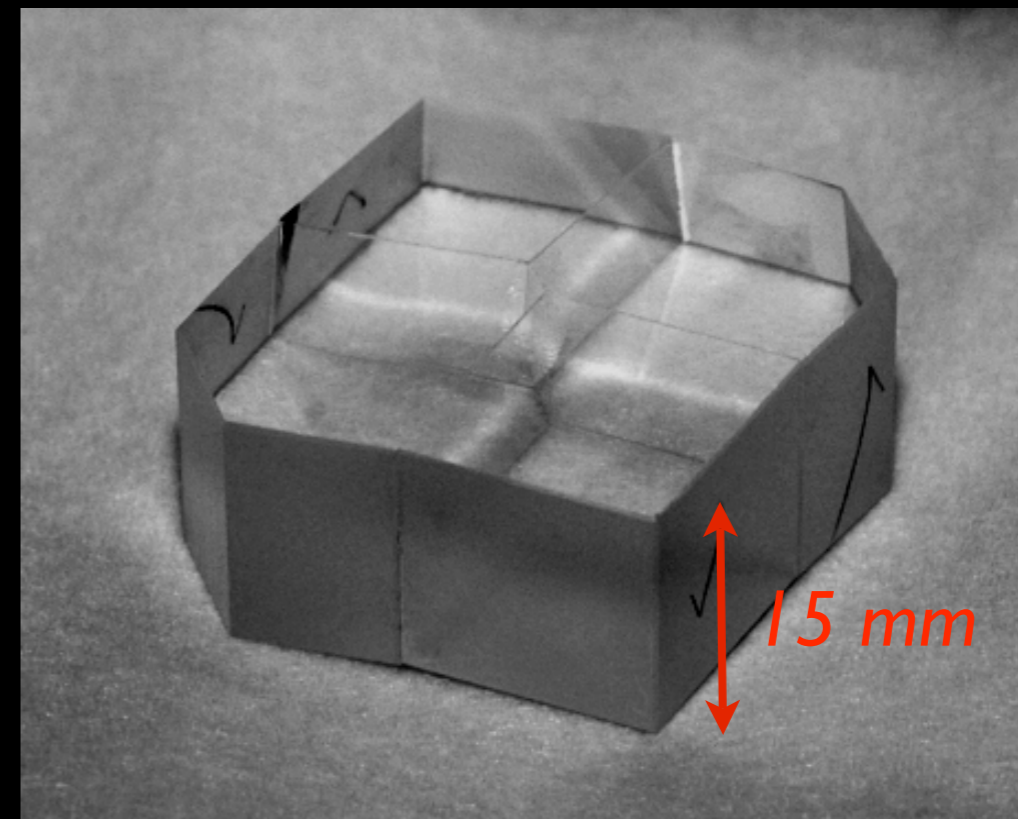
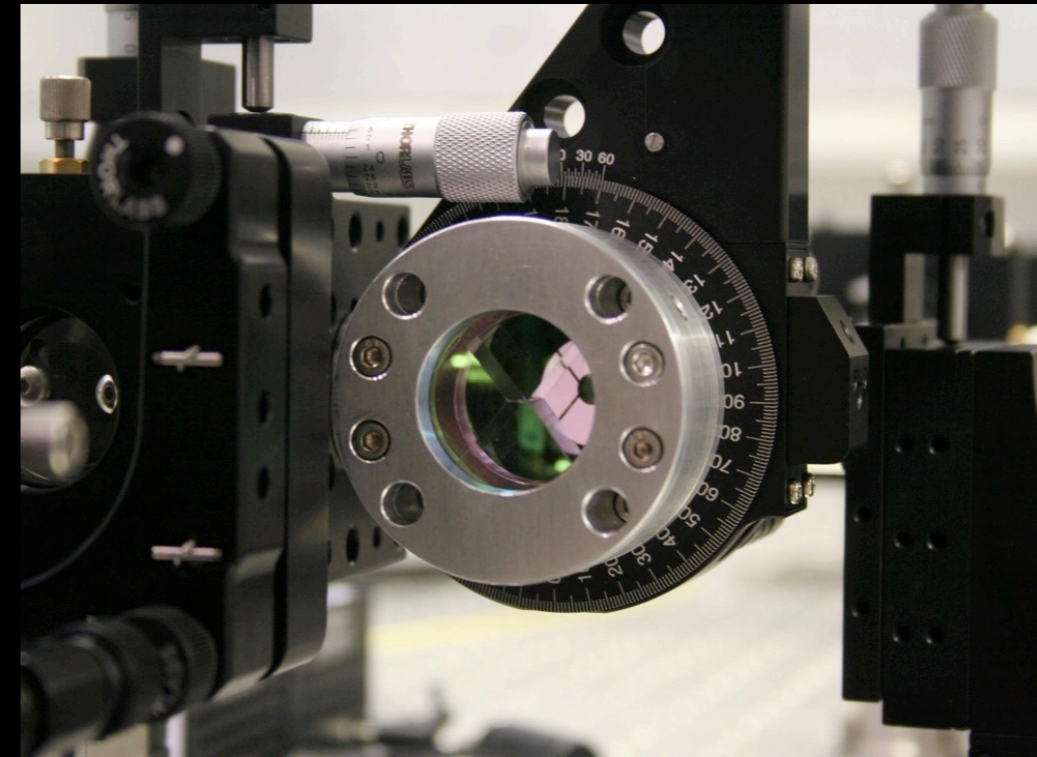
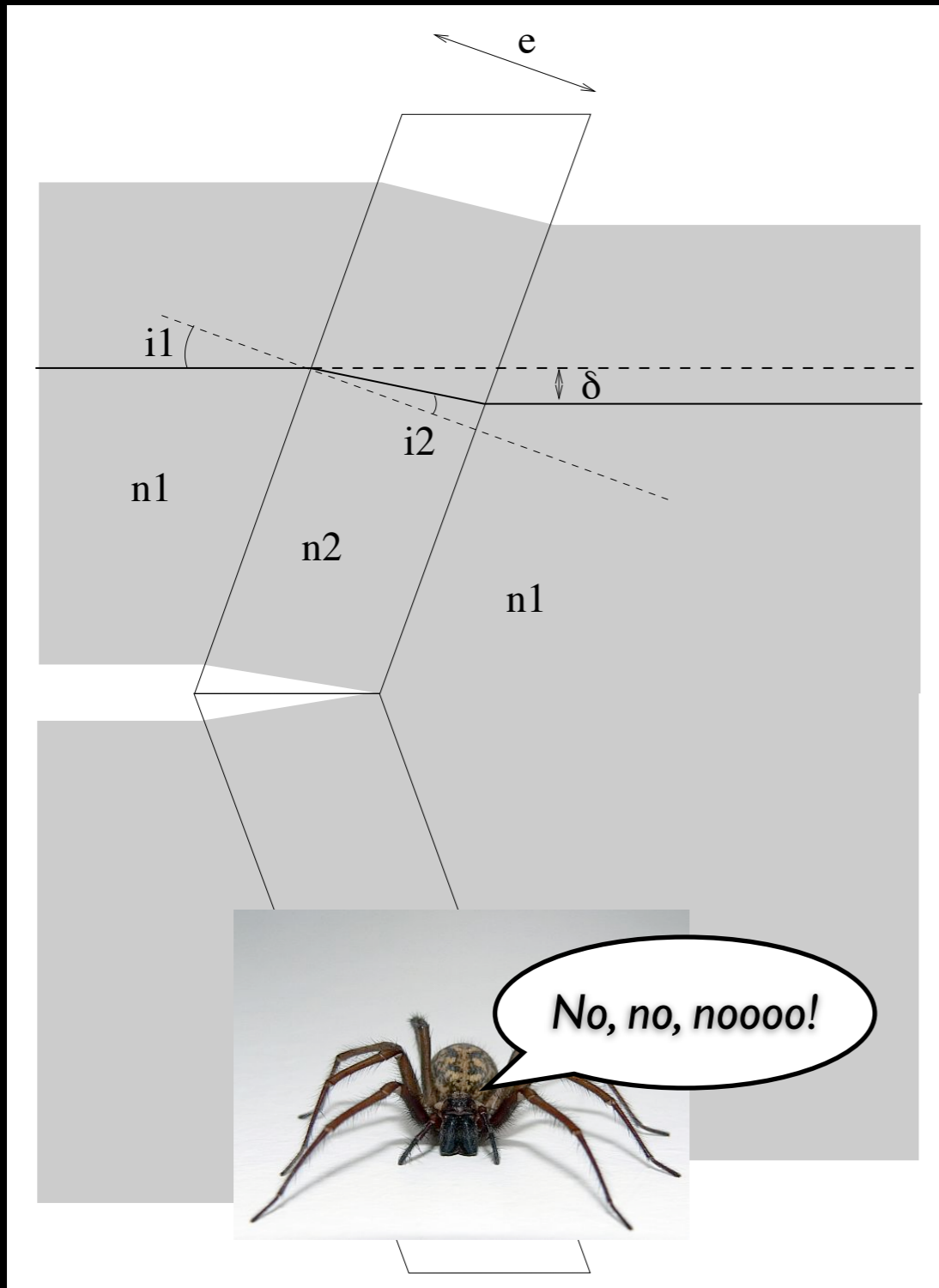
- Lentilles centro-symetriques
- Distance entre lentilles: 96 mm
- Apodise le faisceau
- Retire l'obstruction centrale



*Guyon, 2003, A&A,
Guyon et al, 2005, ApJ, 622, 744
Martinache et al, 2006, ApJ, 639, 1129
Pluzhnik et al, 2006, ApJ, 644, 1246*

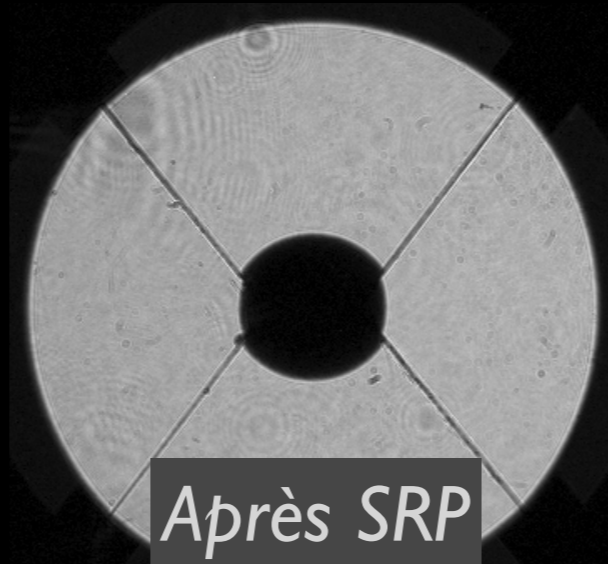
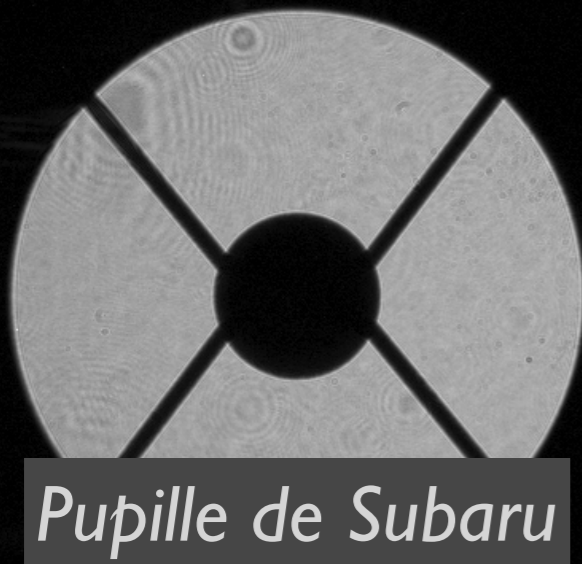
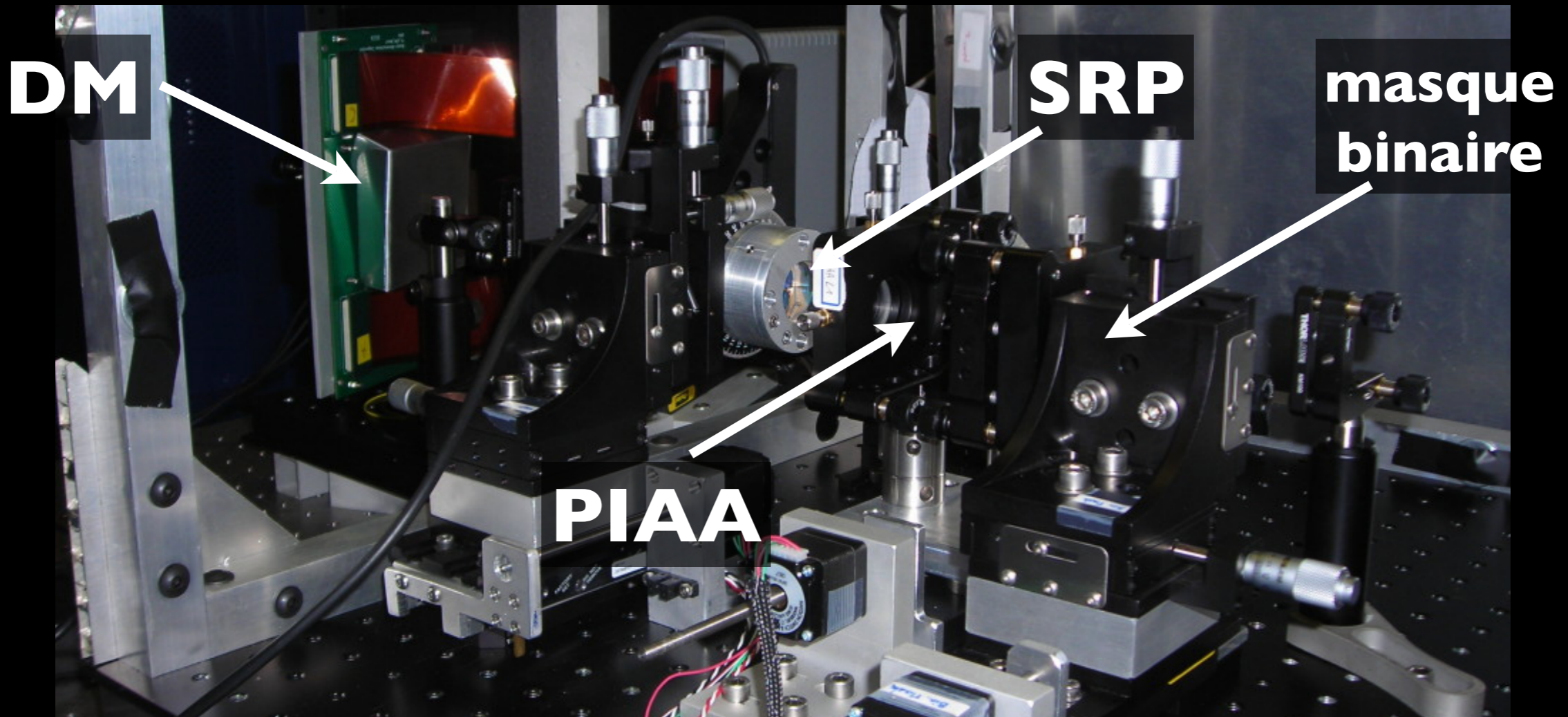


Supprimer les araignées



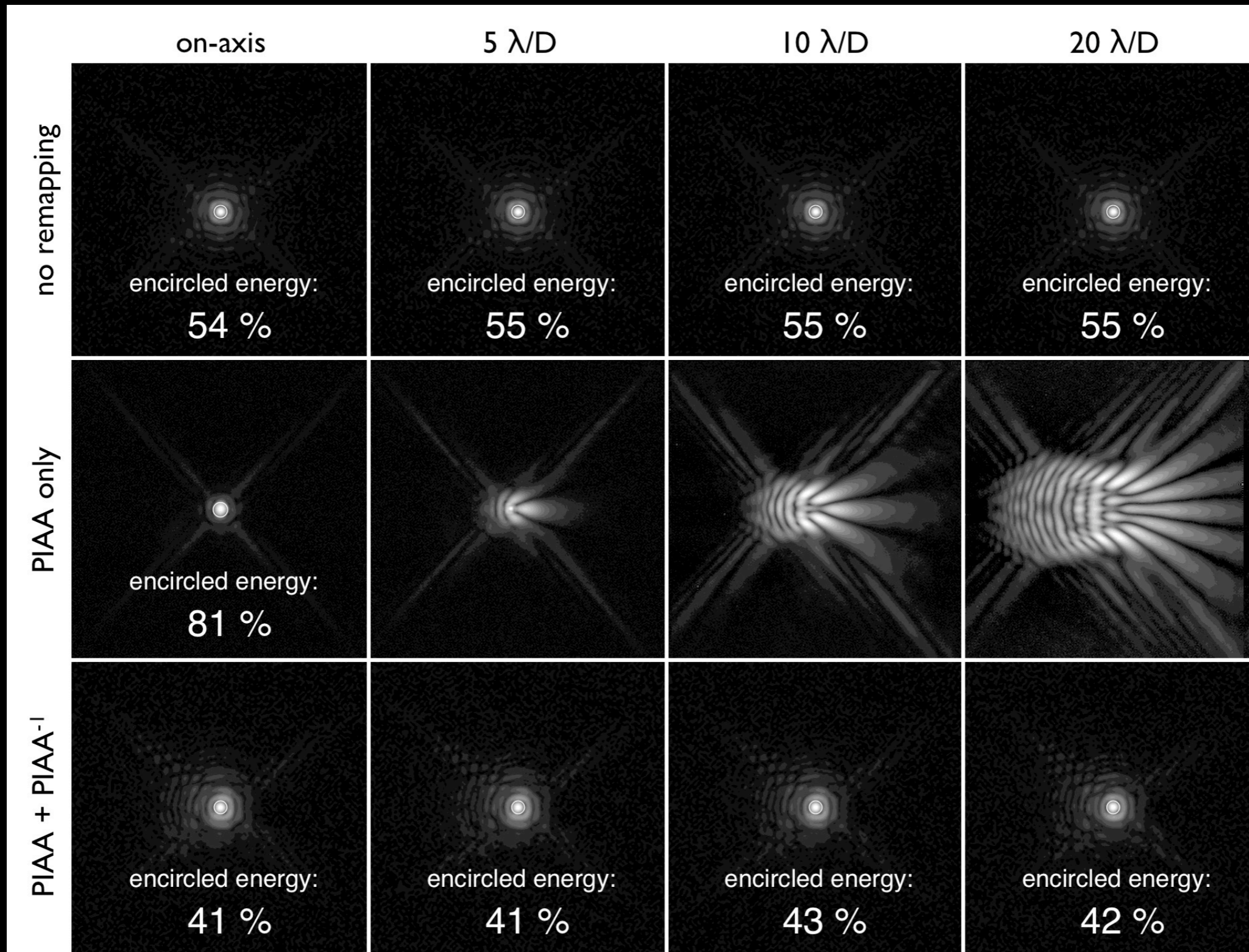


En combo...





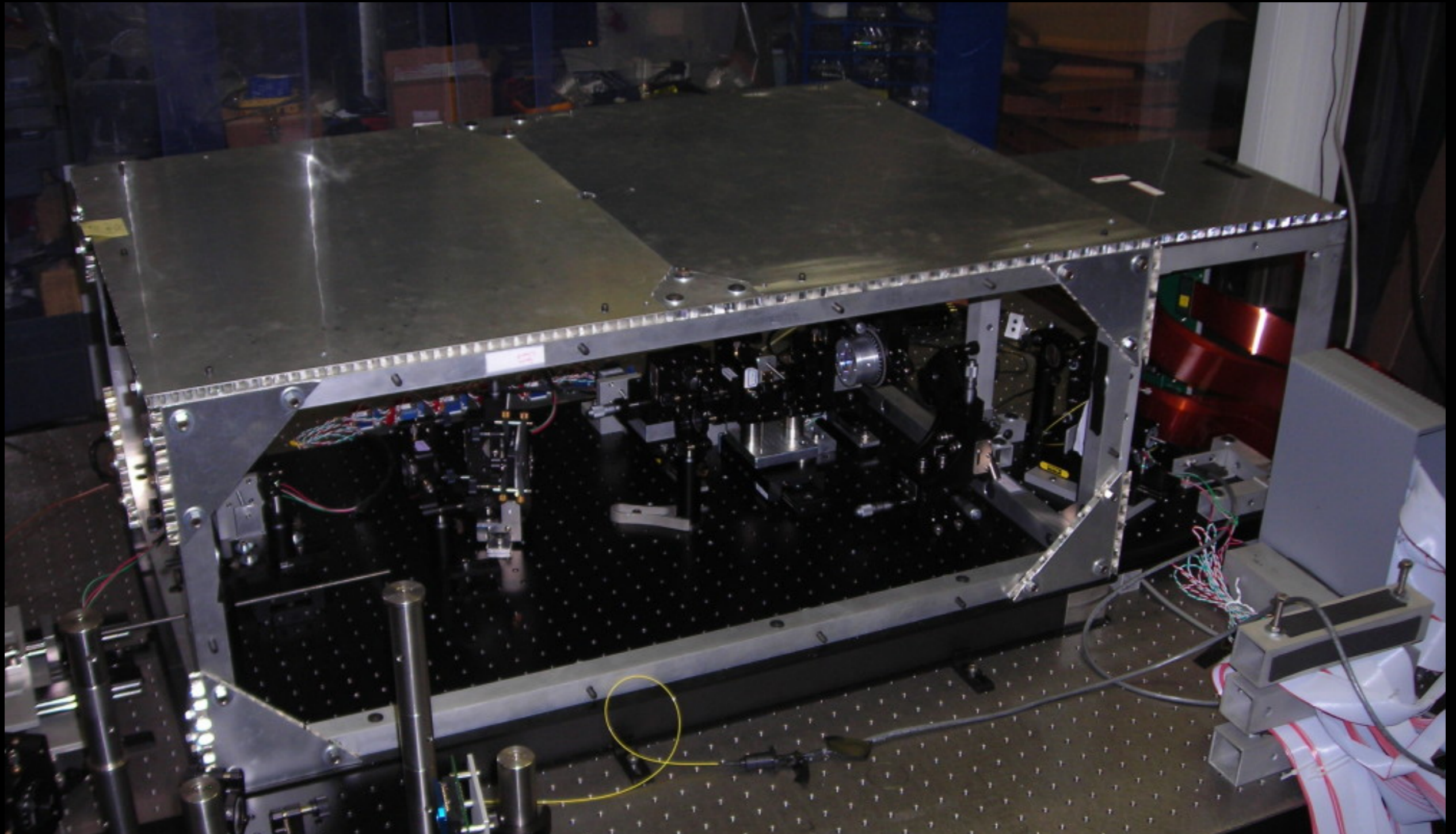
La preuve en images



Lozi et al, 2009, accepté chez PASP

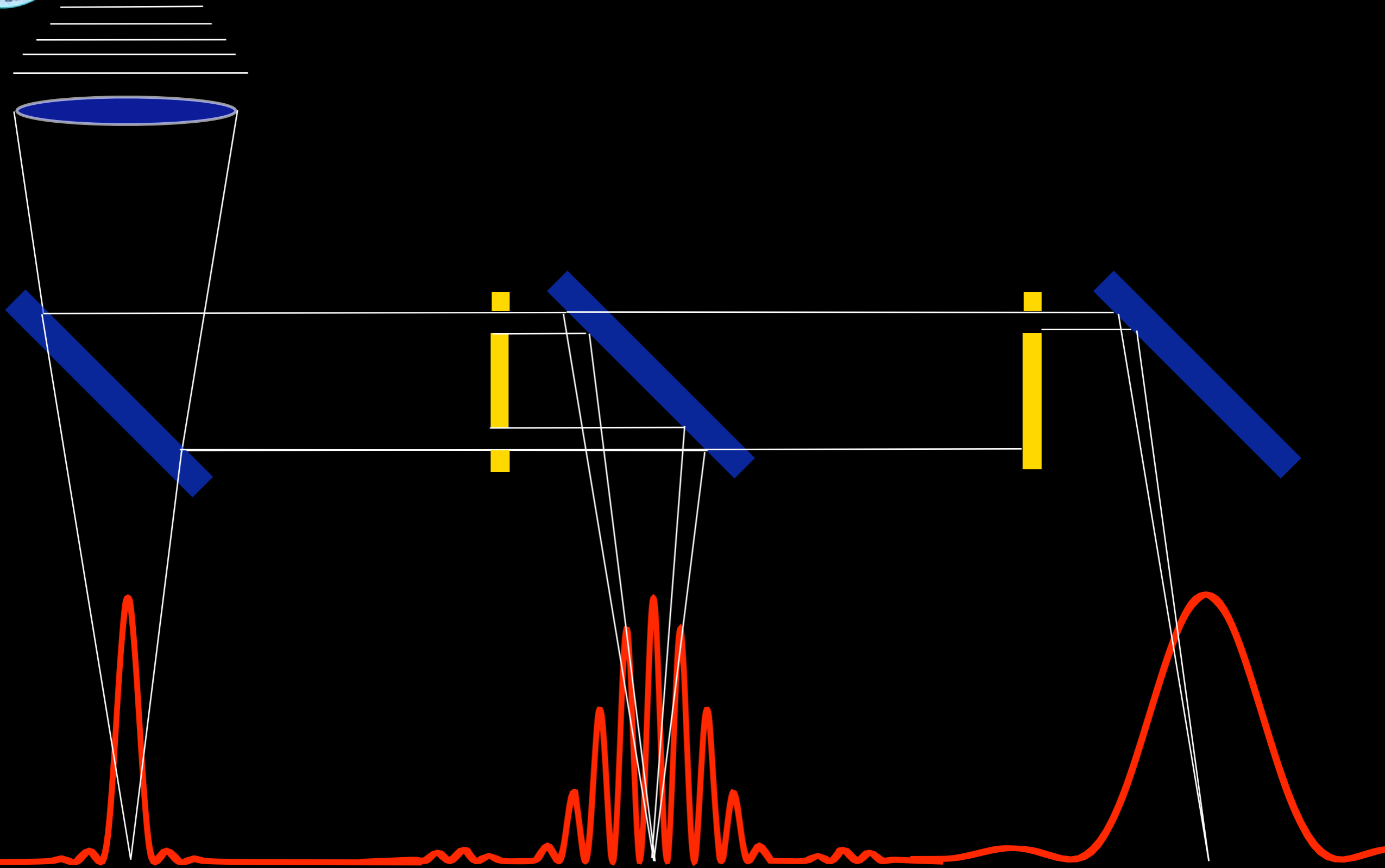


Le labo





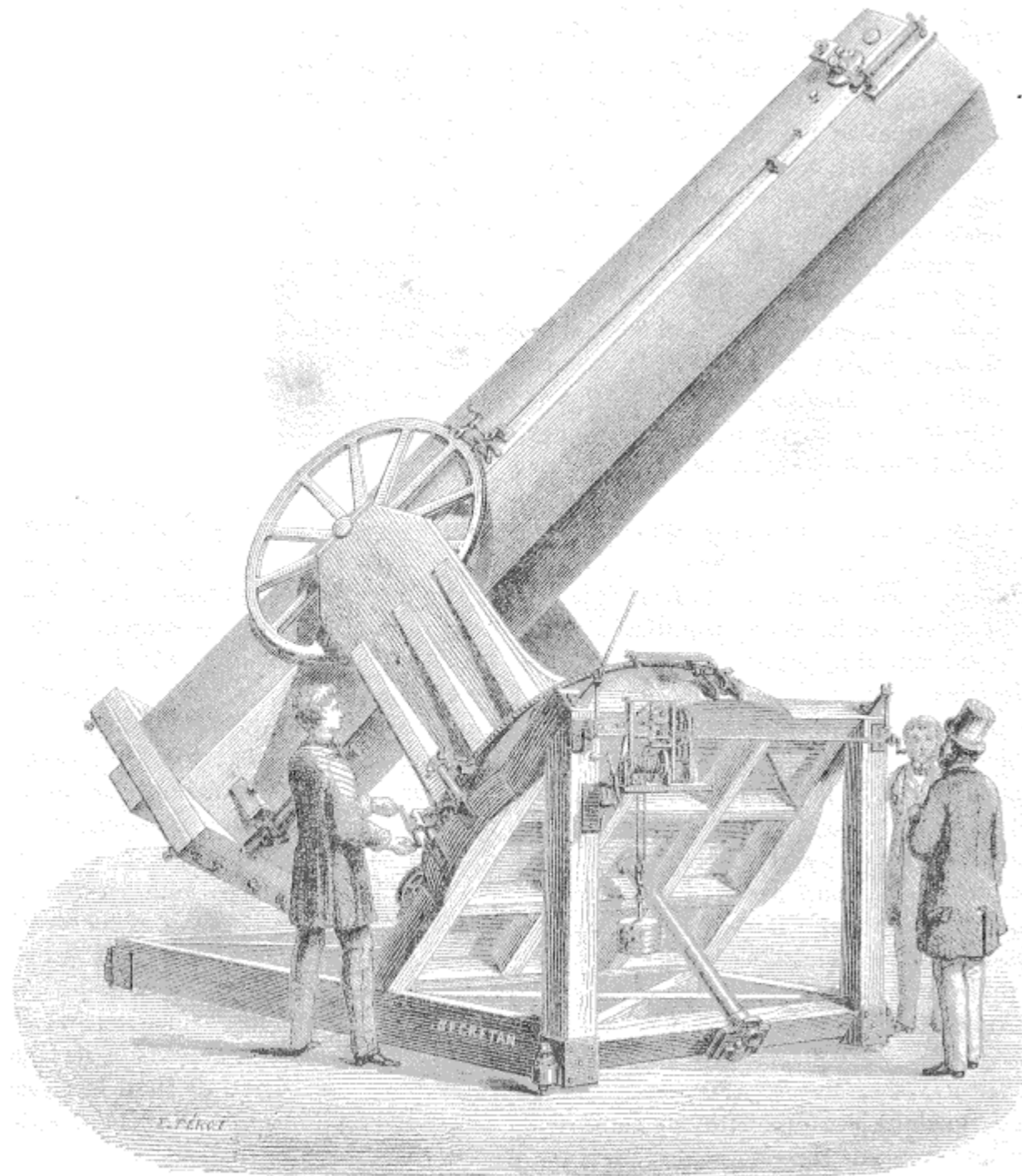
★ Interférométrie à masque



Tuthill et al, 2000, PASP, 112, 555



Rien de nouveau sous les étoiles?



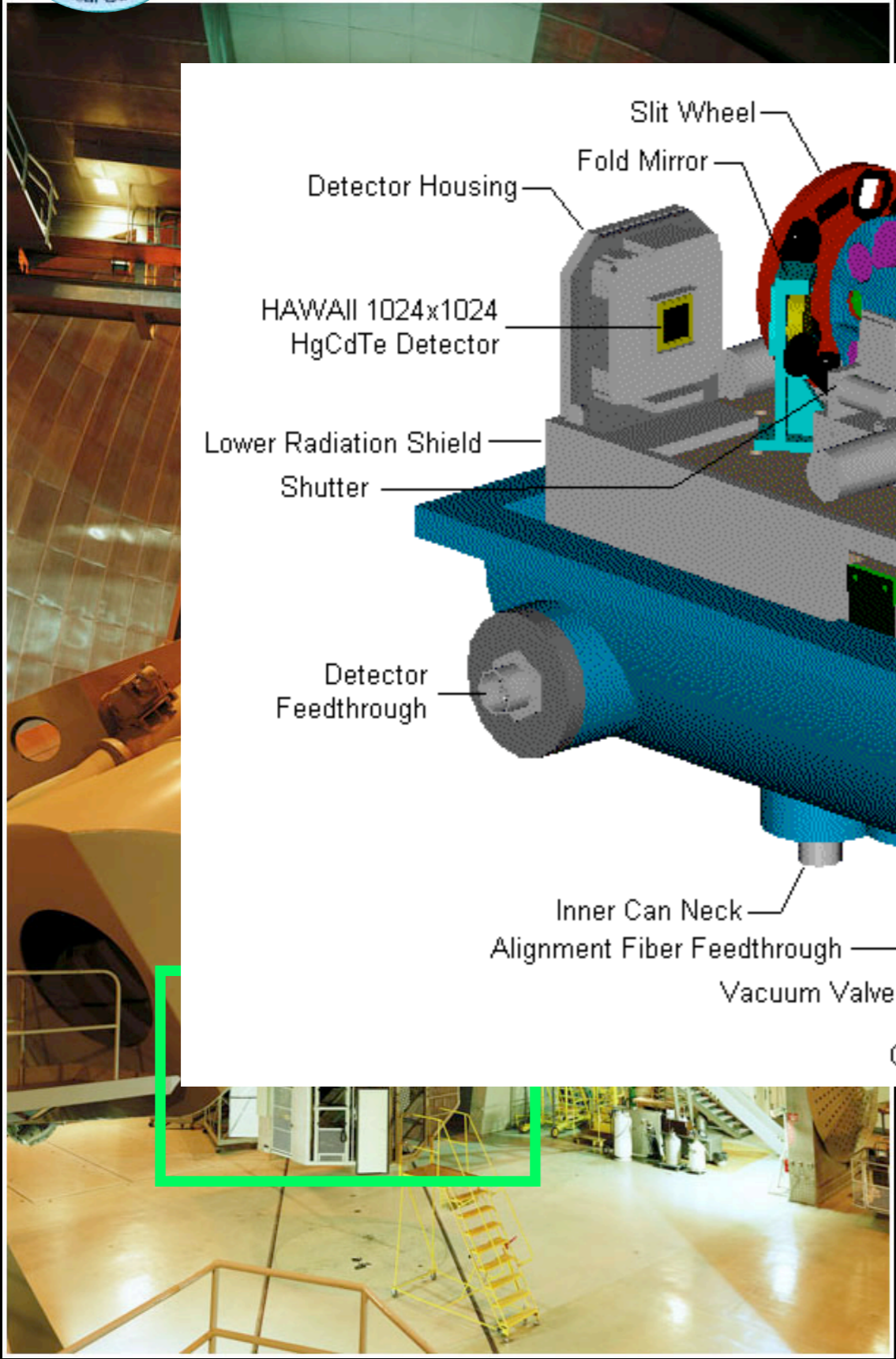
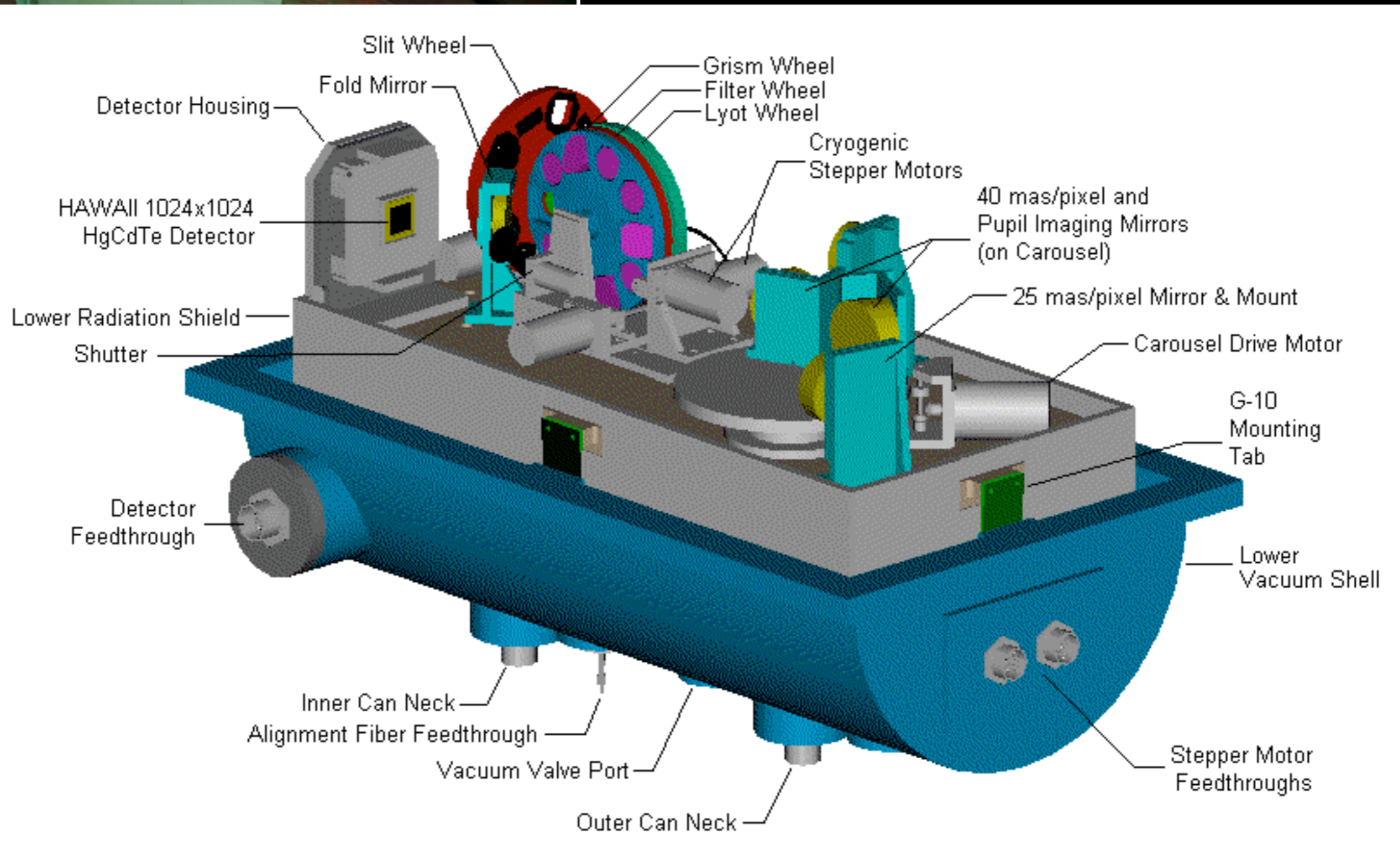
Le grand télescope Foucault, de l'Observatoire de Marseille.

Marseille 1873,
Edouard Stephan
cherche à mesurer le
diamètre angulaire des
étoiles brillantes.

Base max de 80 cm,
 $\varnothing_{\star} < 0.16''$



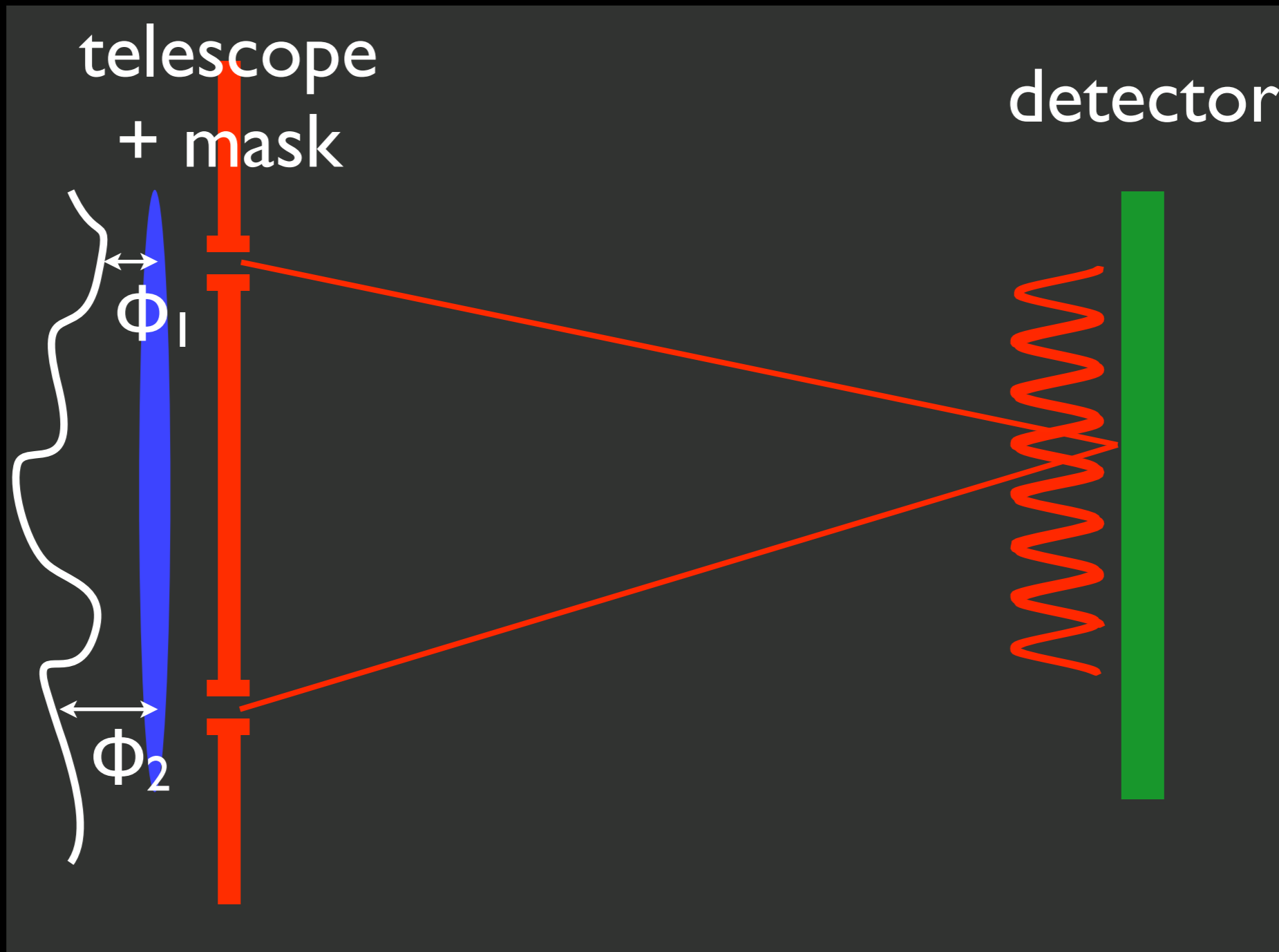
Idée simple sur instrument moderne



Hayward et al, 2005, PASP, 113, 105



Fizeau Interferometry 101

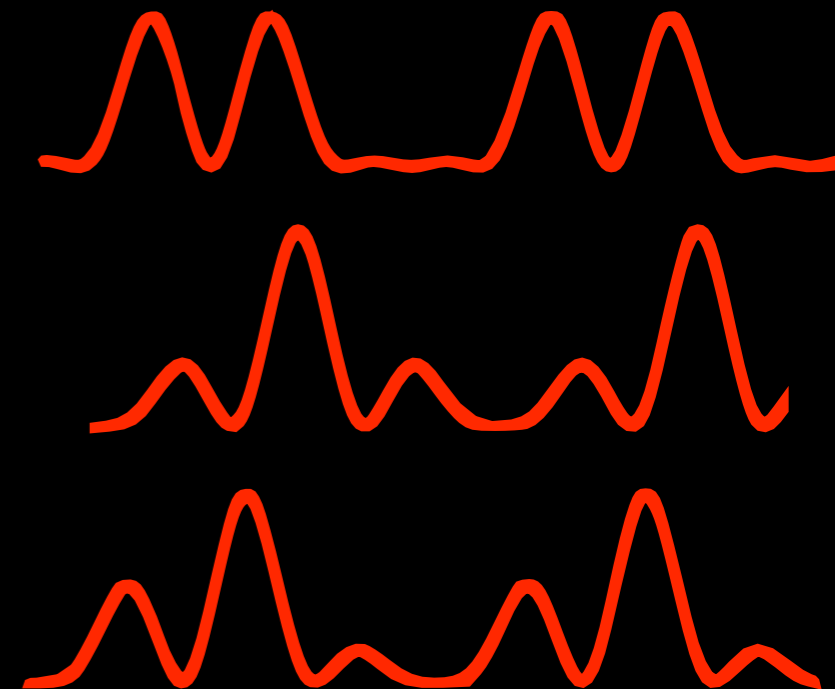
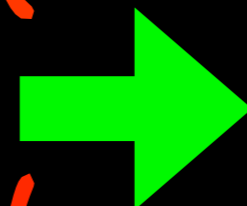
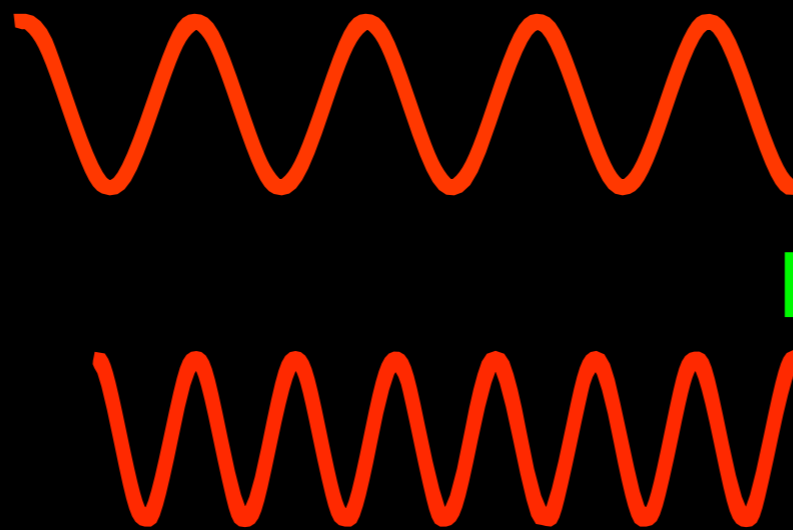
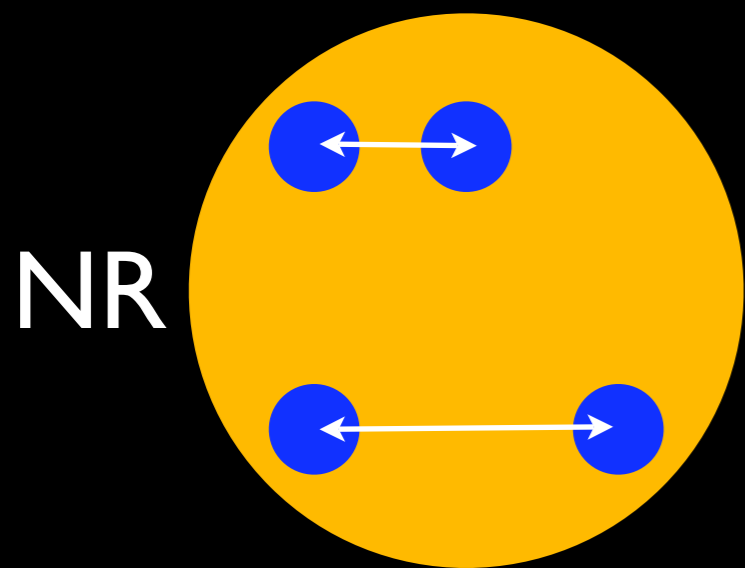
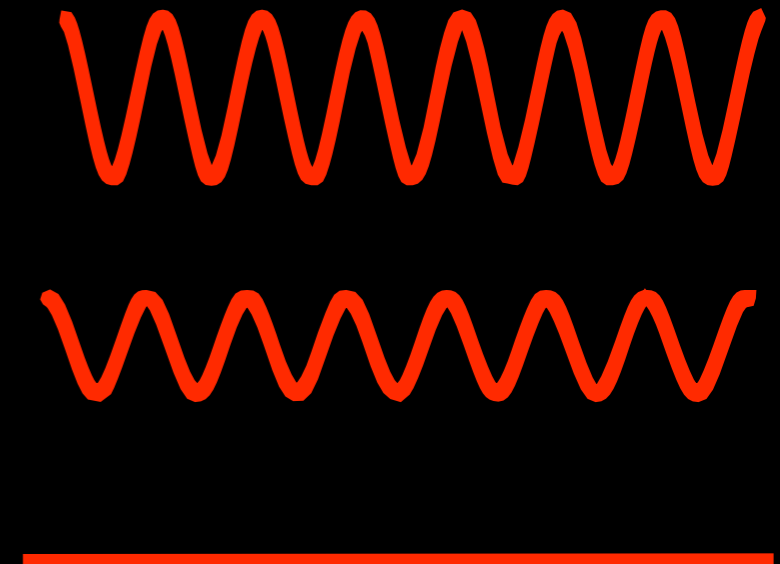
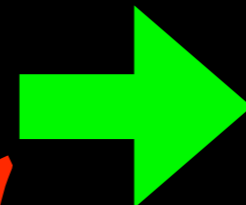
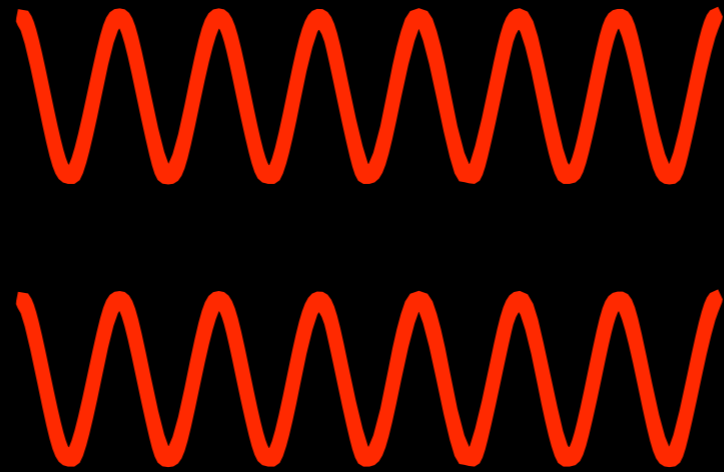
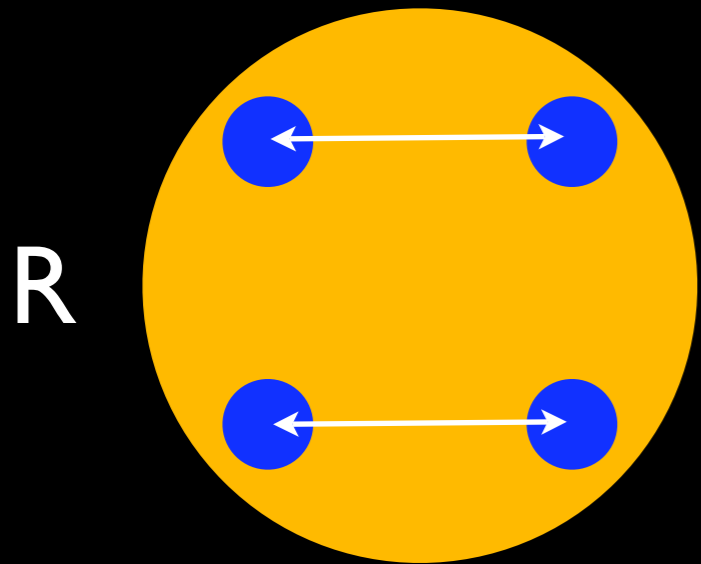


visibility:
 $0 < V^2 < 1$

phase:
 $\Phi = \Phi_0 + (\Phi_1 - \Phi_2)$



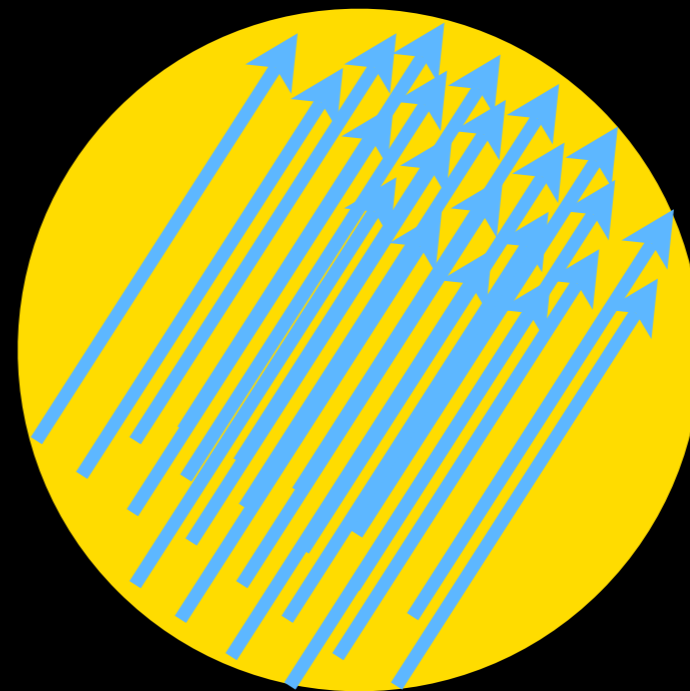
Redundancy





And a full aperture...

is very, very,
very, very,
very redundant

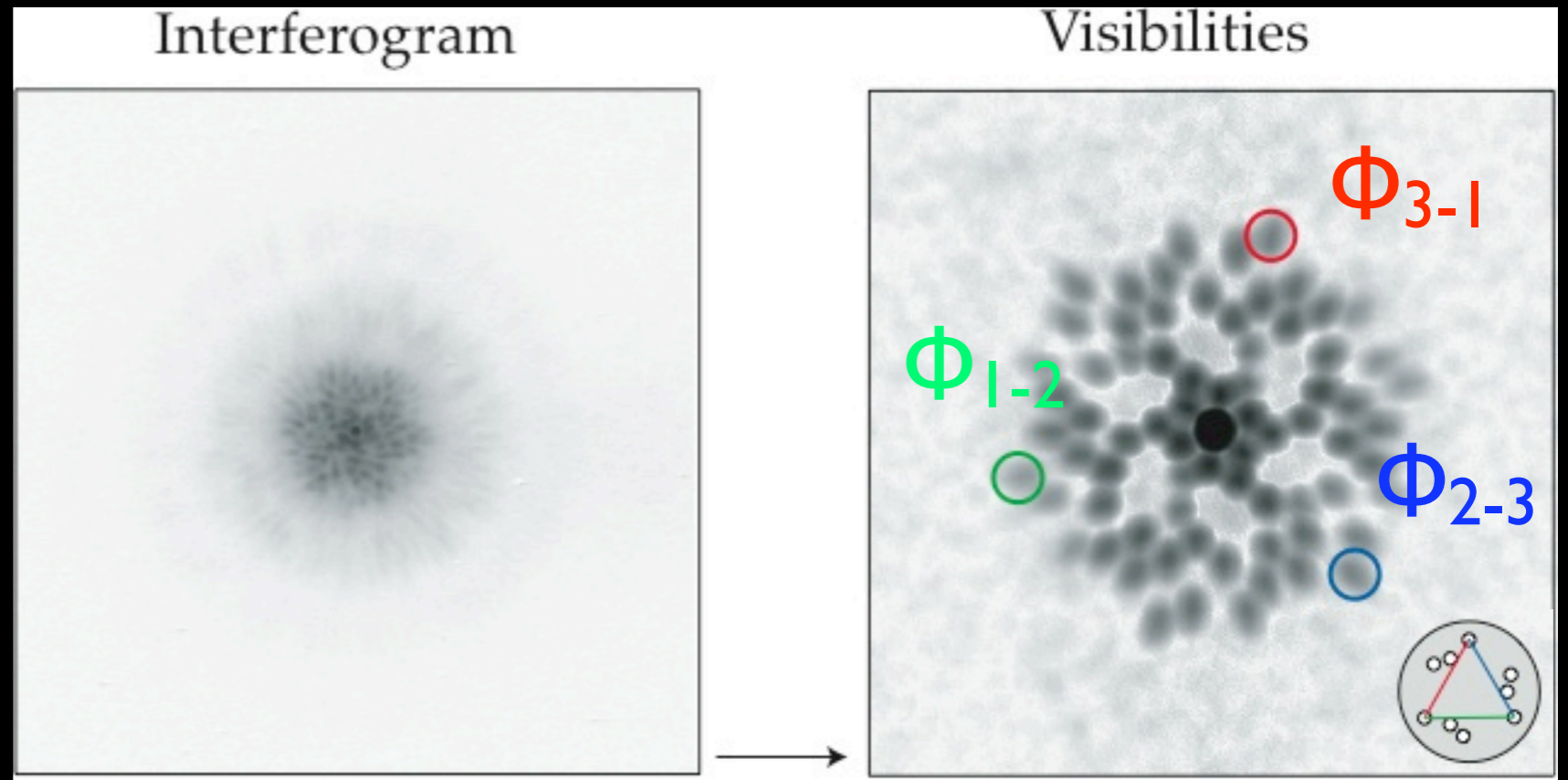


Atmosphere affects the phases
Redundancy destroys the amplitudes



A neat trick: the closure phase

9-hole mask
36 visibilities
84 triangles
(28 independent)



$$\Phi(1-2) = \Phi(1-2)_0 + (\Phi_1 - \Phi_2)$$

$$\Phi(2-3) = \Phi(2-3)_0 + (\Phi_2 - \Phi_3)$$

$$\Phi(3-1) = \Phi(3-1)_0 + (\Phi_3 - \Phi_1)$$

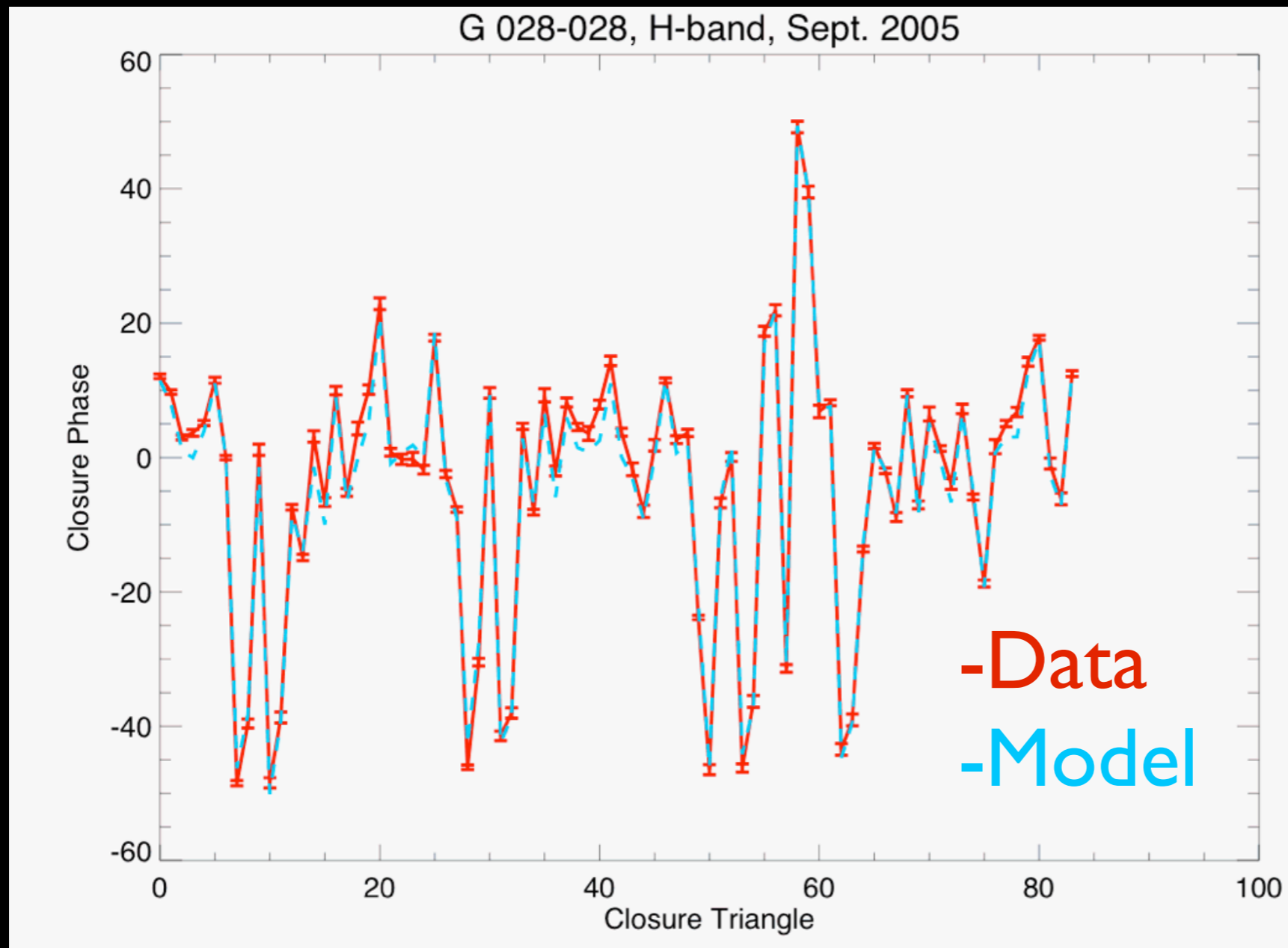
measured = intrinsic + atmospheric

A perfect observable:
the closure phase!!



Binary systems

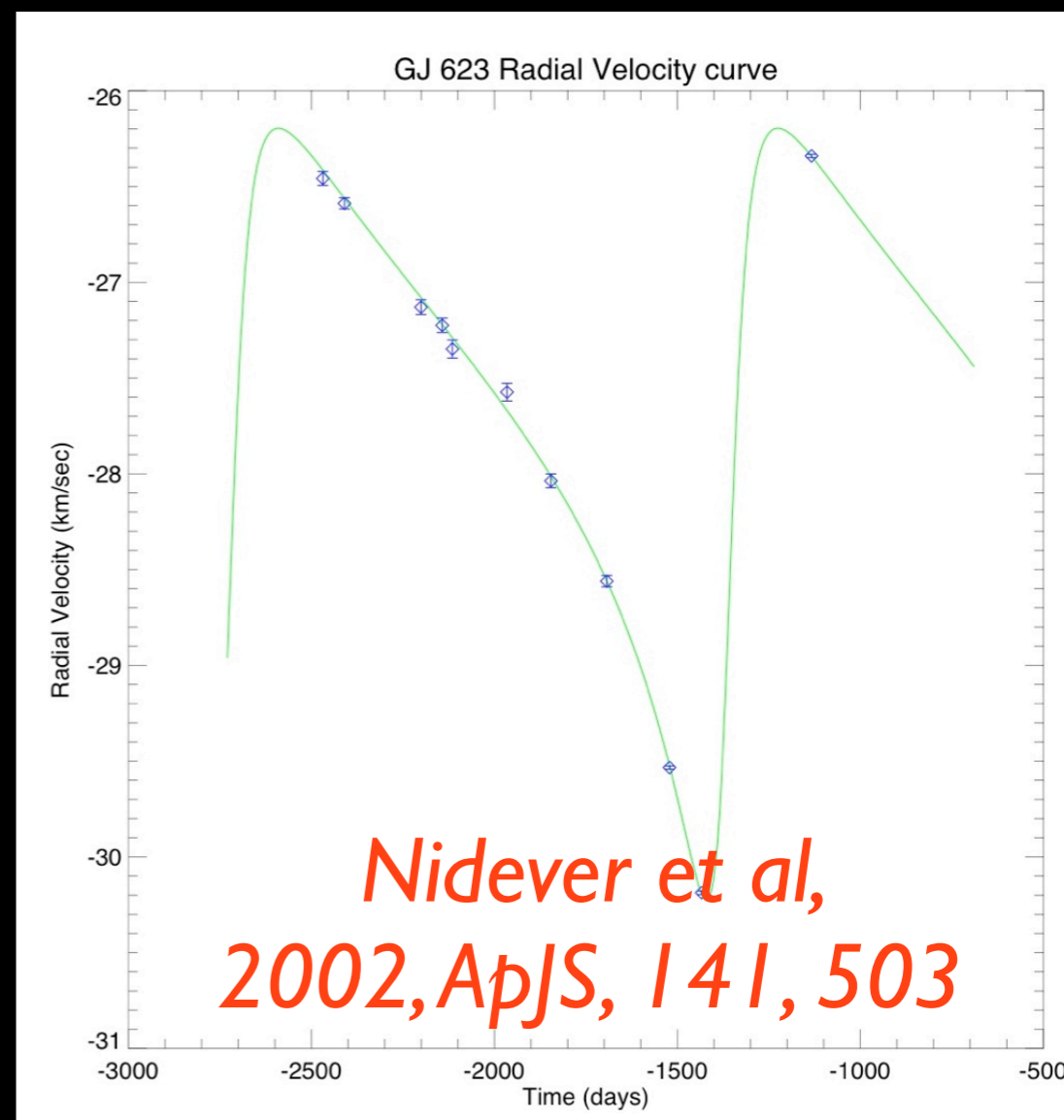
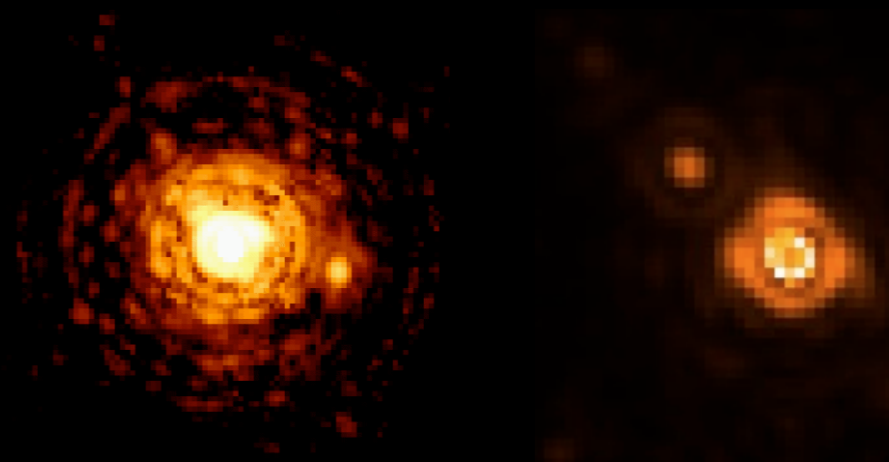
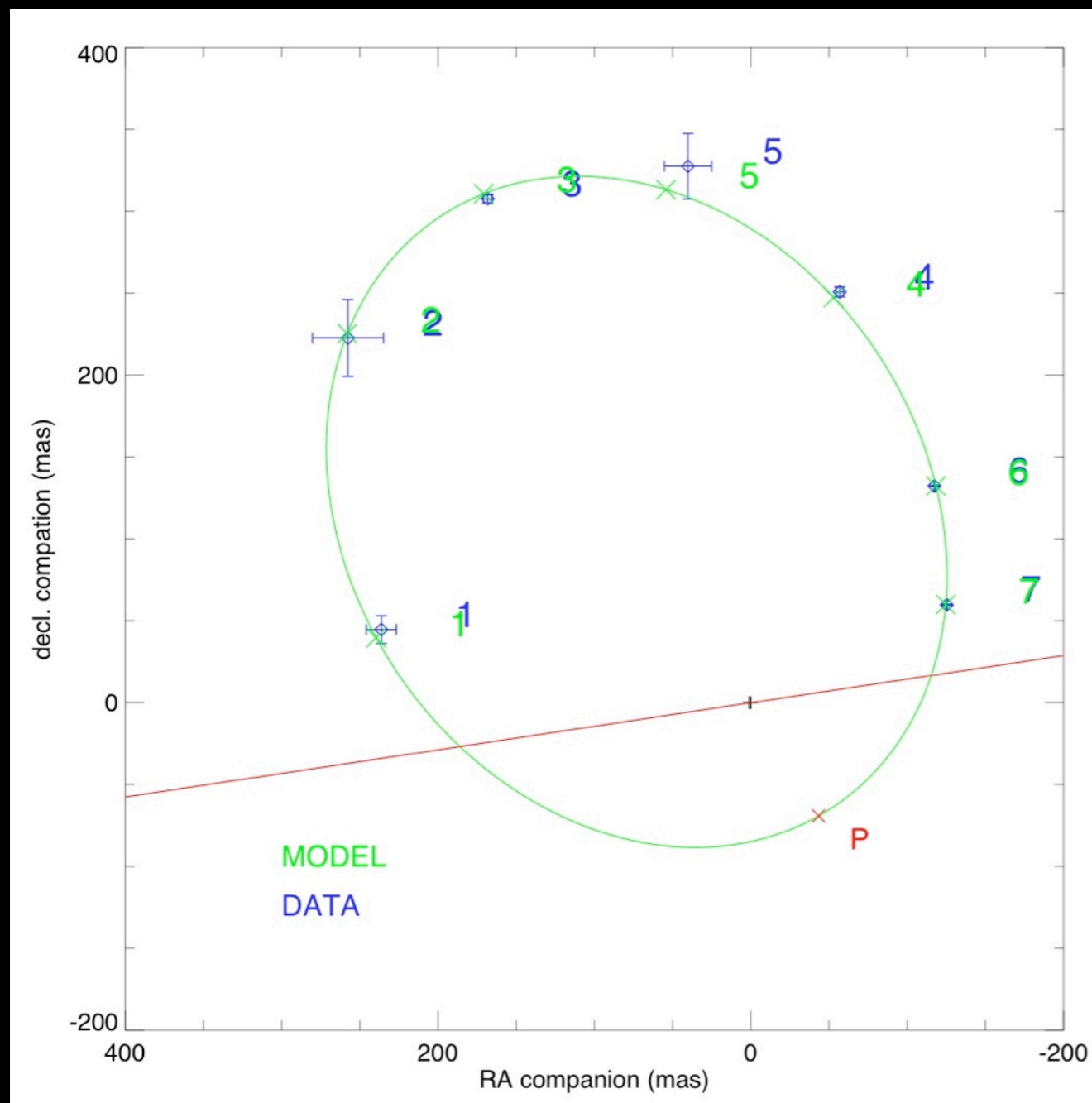
3 parameters: angular separation, position angle, contrast
Error estimate: closure phase scattering
Small systematic error



40 % strehl
0.3 deg scatter
stability $\sim \lambda/1000$
all passive !



Masses de GJ 623 AB



*Nidever et al,
2002, ApJS, 141, 503*

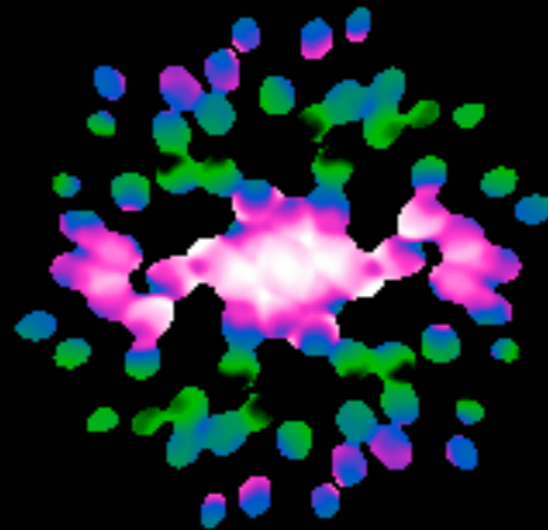
Radial Velocity + Masking:
 $M_1 = 0.371 \pm 0.015 M_S$
 $M_2 = 0.115 \pm 0.0023 M_S$

Martinache et al, 2007, ApJ, 661, 496

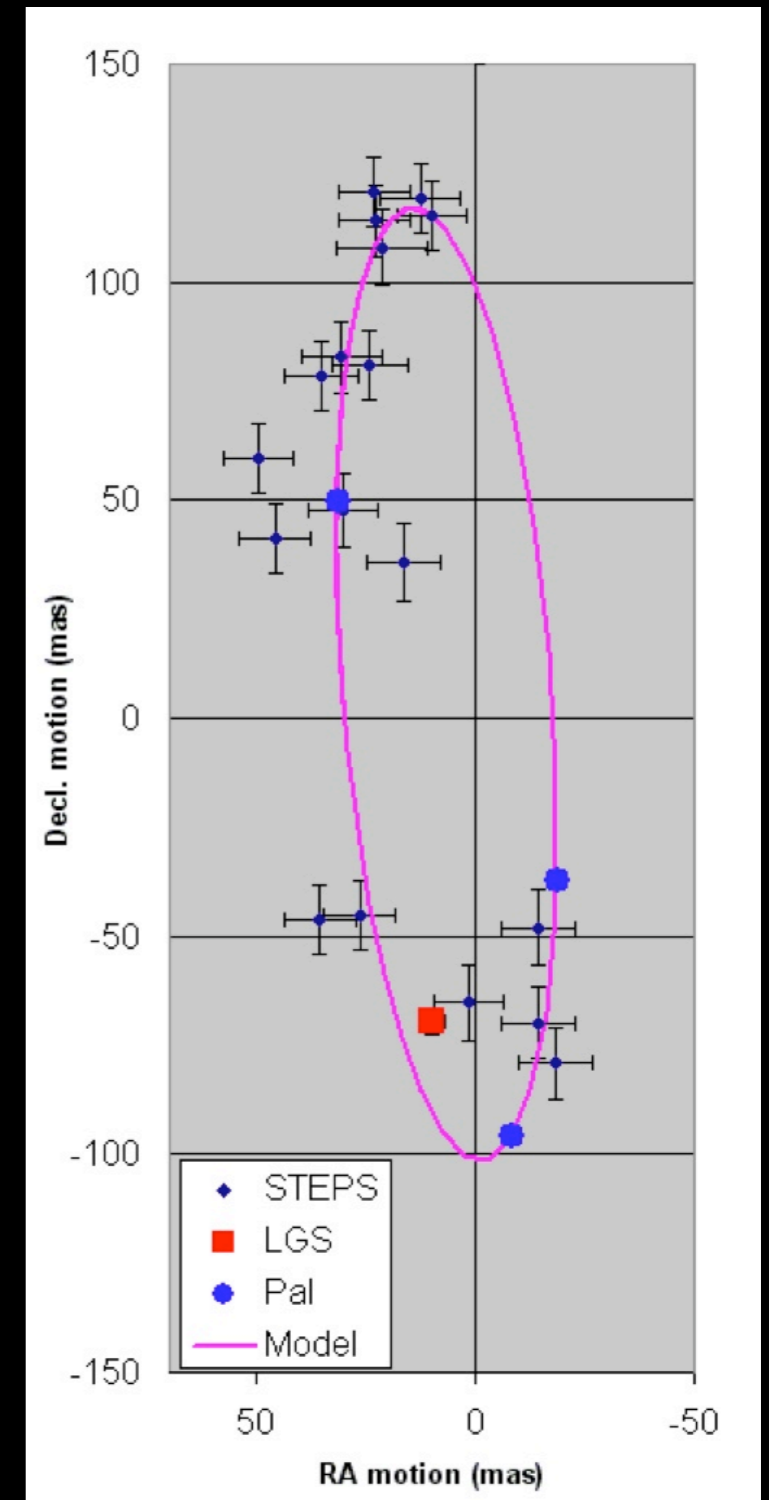


Binary G 078-028

M Dwarf binary
4.2 years orbit
 $\Delta H = 1.29 \pm 0.02$



Jul. date	sep (mas)	PA (deg)
3004.8	58.9 +/- 1.3	32.3 +/- 1.1
3632.9	96.1 +/- 1.1	184.9 +/- 0.7
3779.7	41.8 +/- 0.6	206.6 +/- 0.9

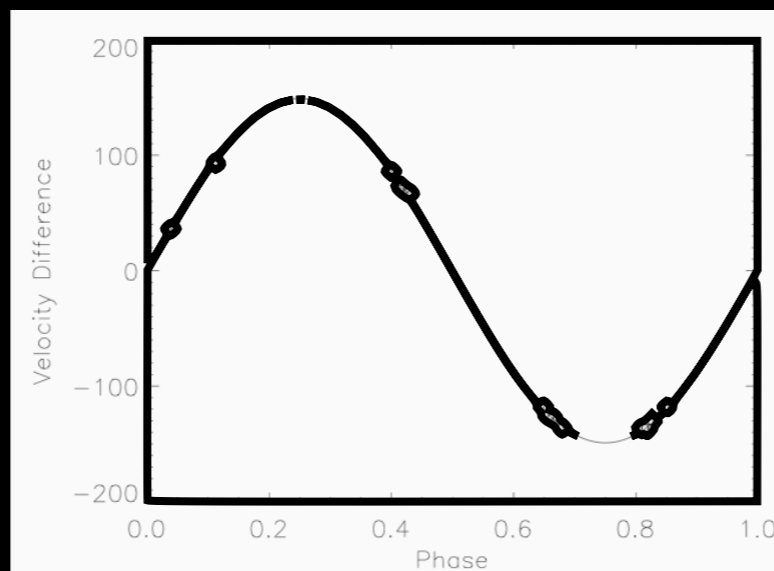
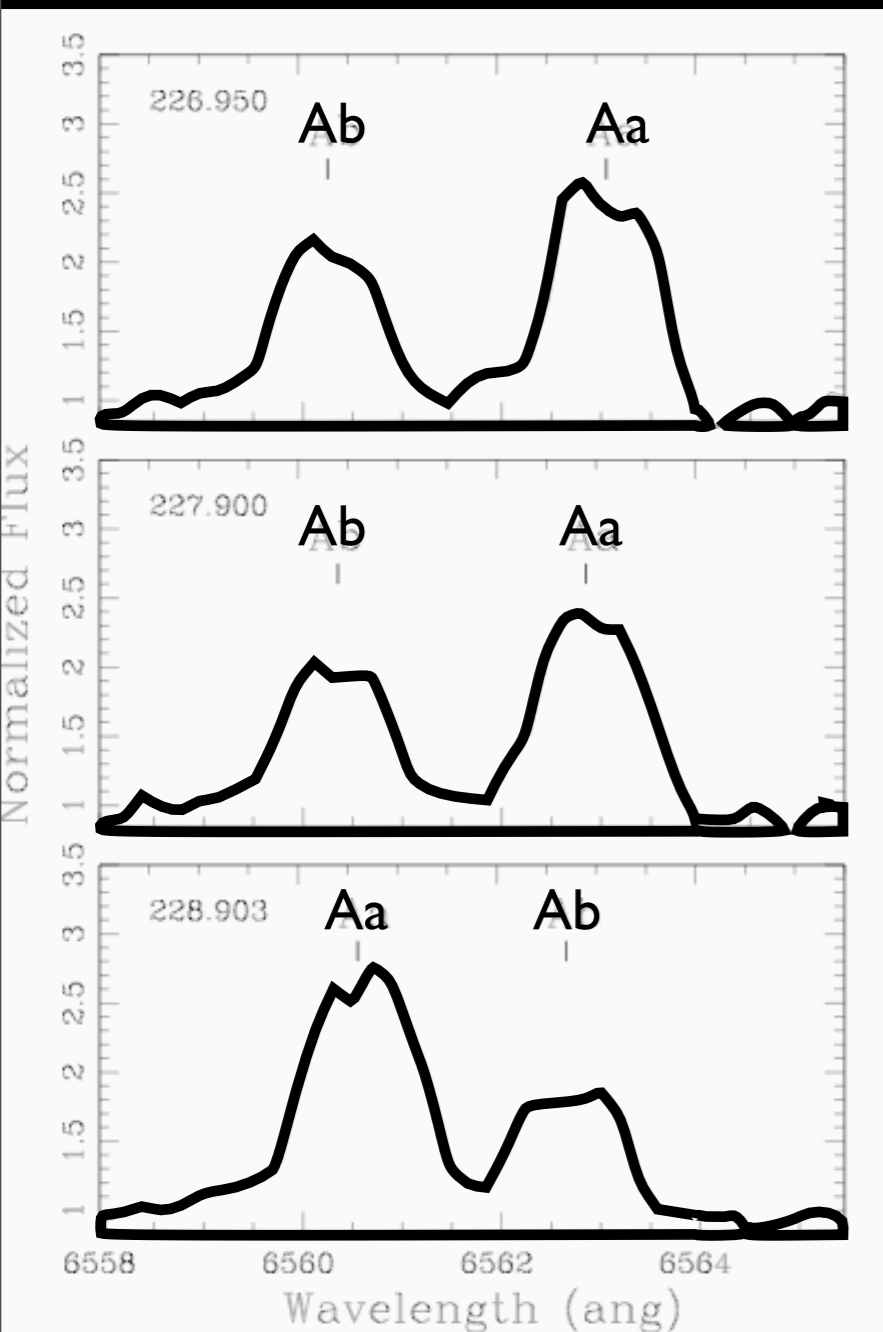


$\lambda/D = 66$ mas

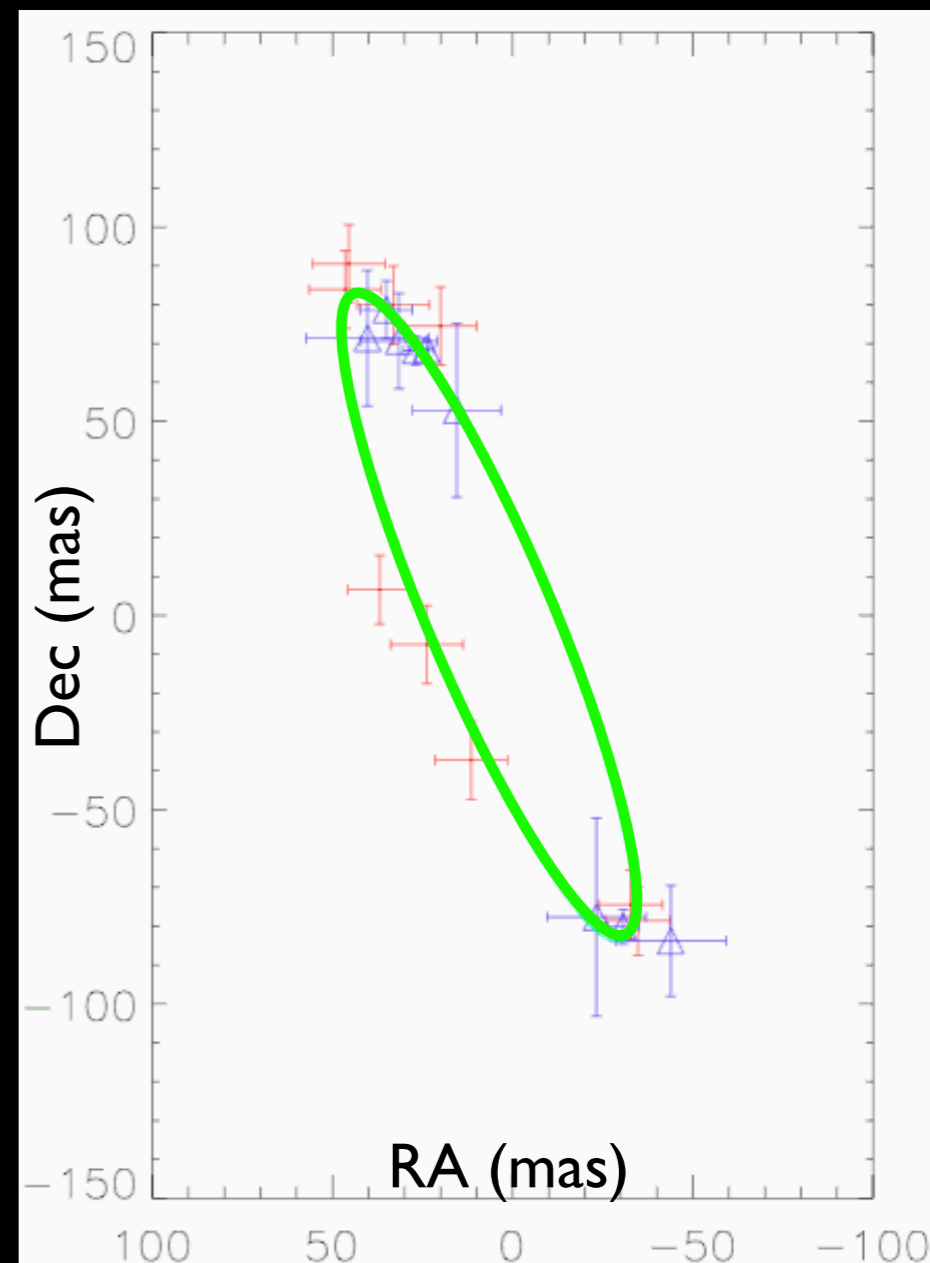
Pravdo et al, 2006, ApJ, 649, 389



Dynamical masses of GJ 802



$M = 63 \pm 5 M_J$
Most accurate L
Dwarf mass
reported



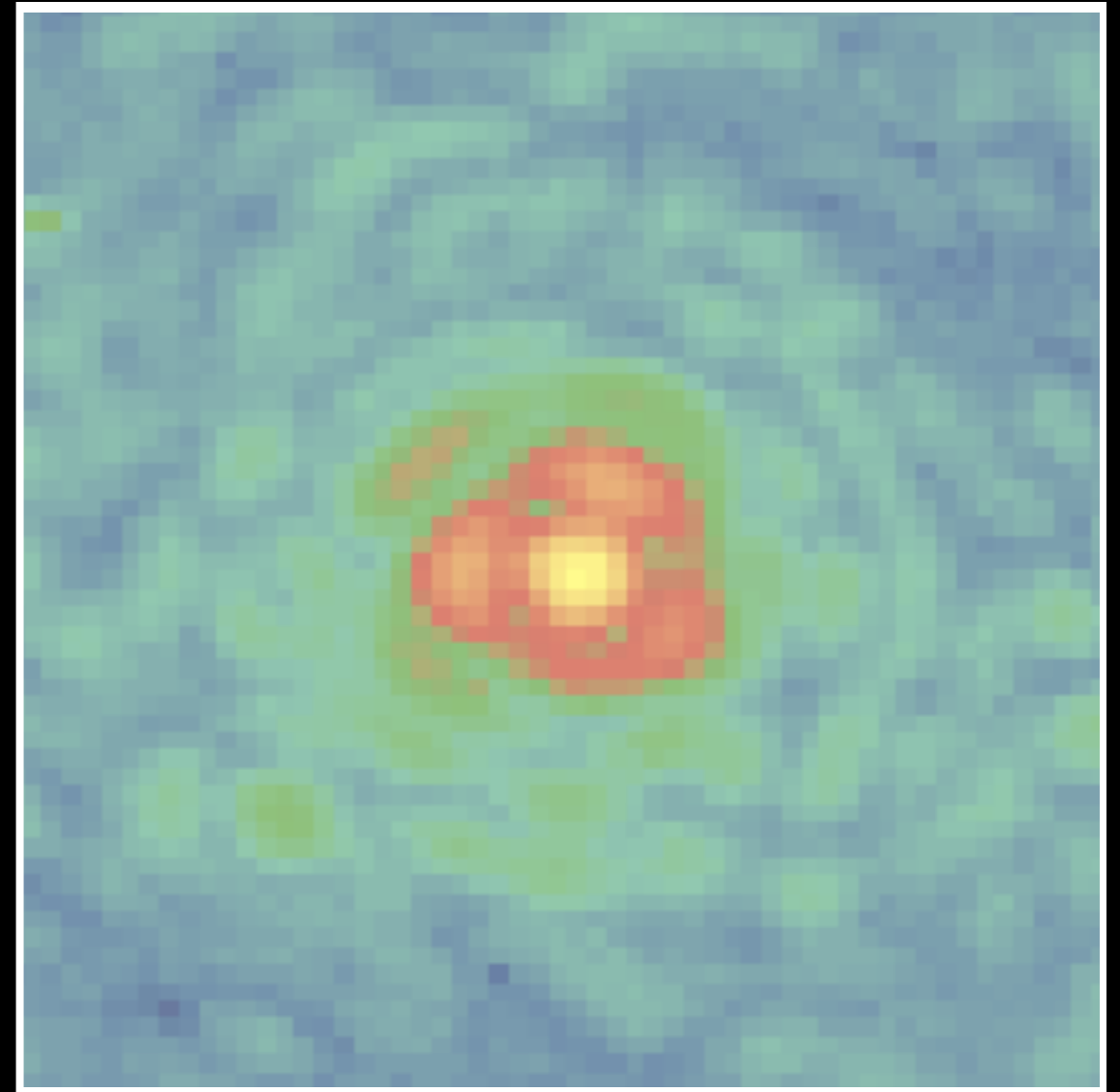
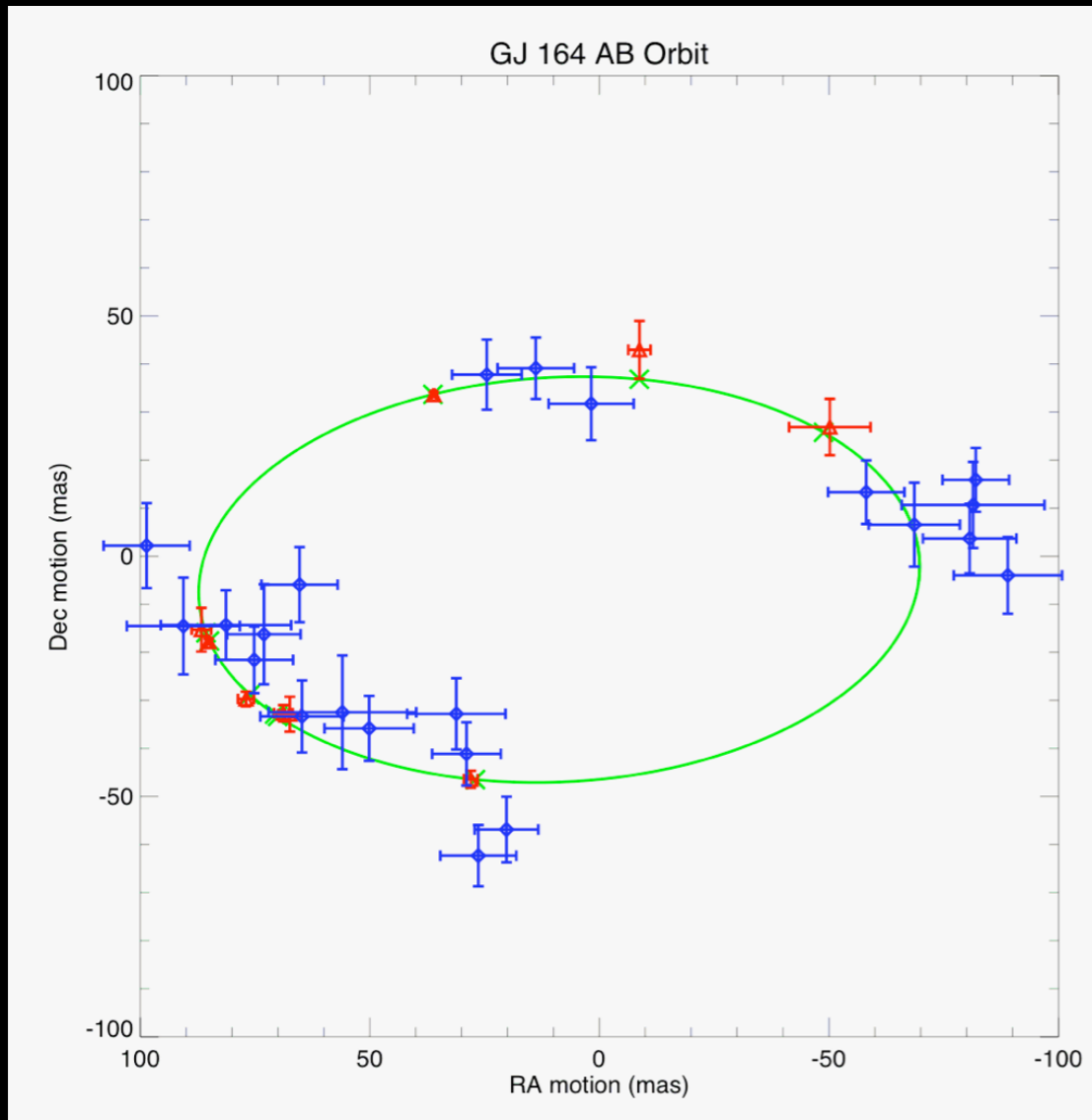
Pravdo et al, 2005, ApJ, 630, 528

Lloyd et al, 2006, ApJL, 650, 131

Ireland et al, 2008, ApJ, accepted



An example of super-resolution



Astrometry + Direct Detection:

$$M_1 = 0.247 \pm 0.019 M_\odot$$

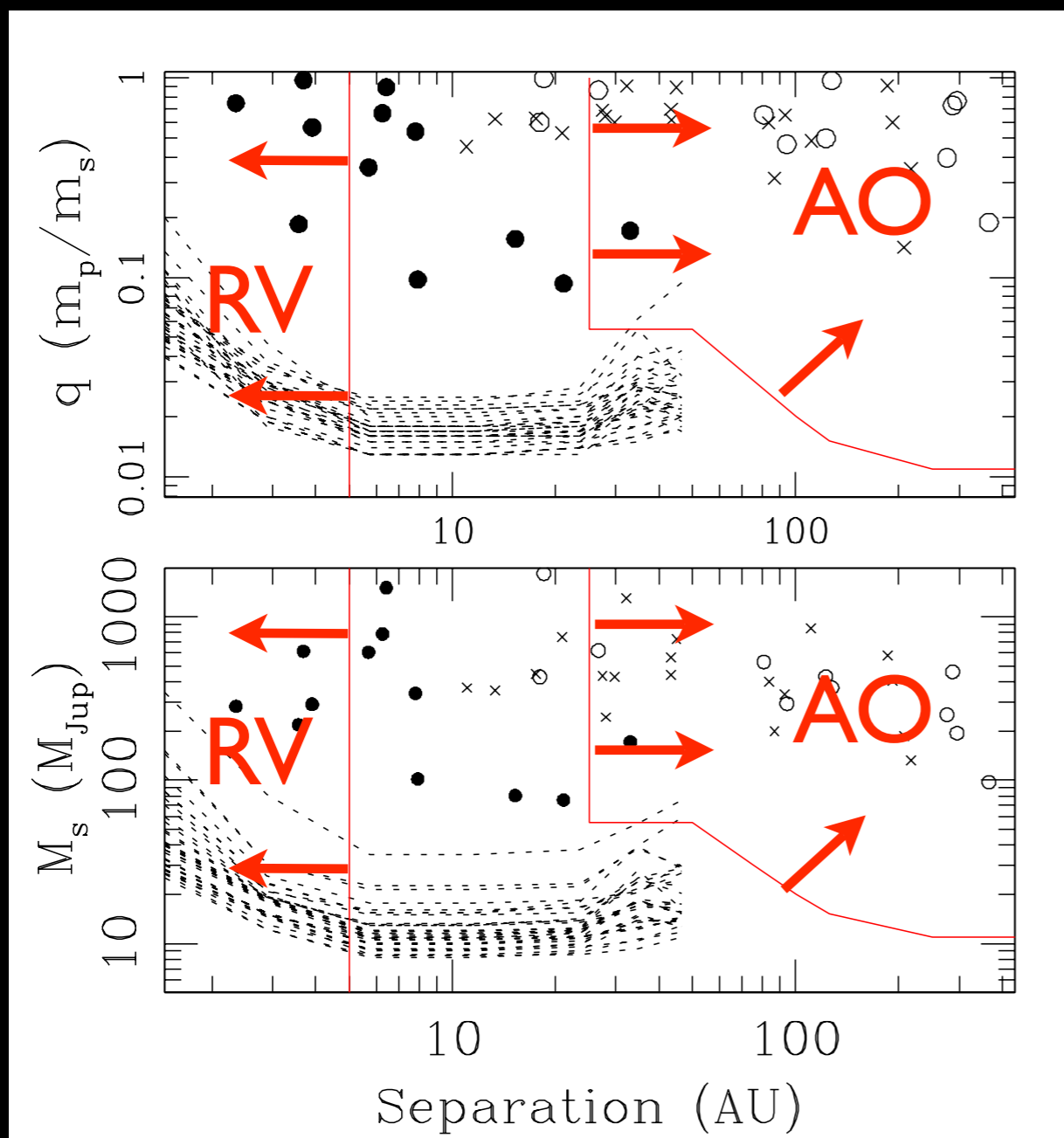
$$M_2 = 0.096 \pm 0.008 M_\odot$$

Martinache et al, 2009, ApJ, 695, 1183



U Sco binarity survey

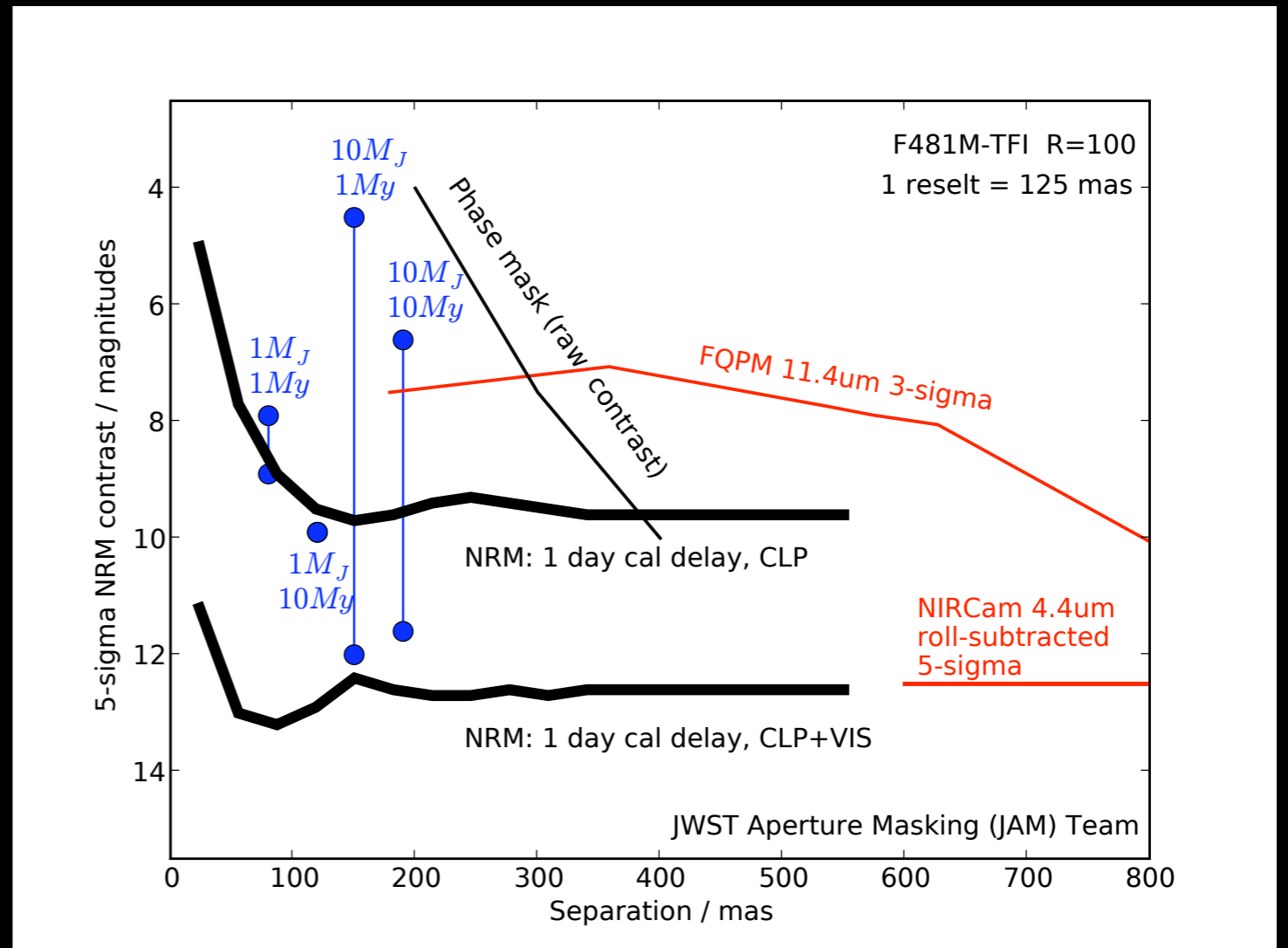
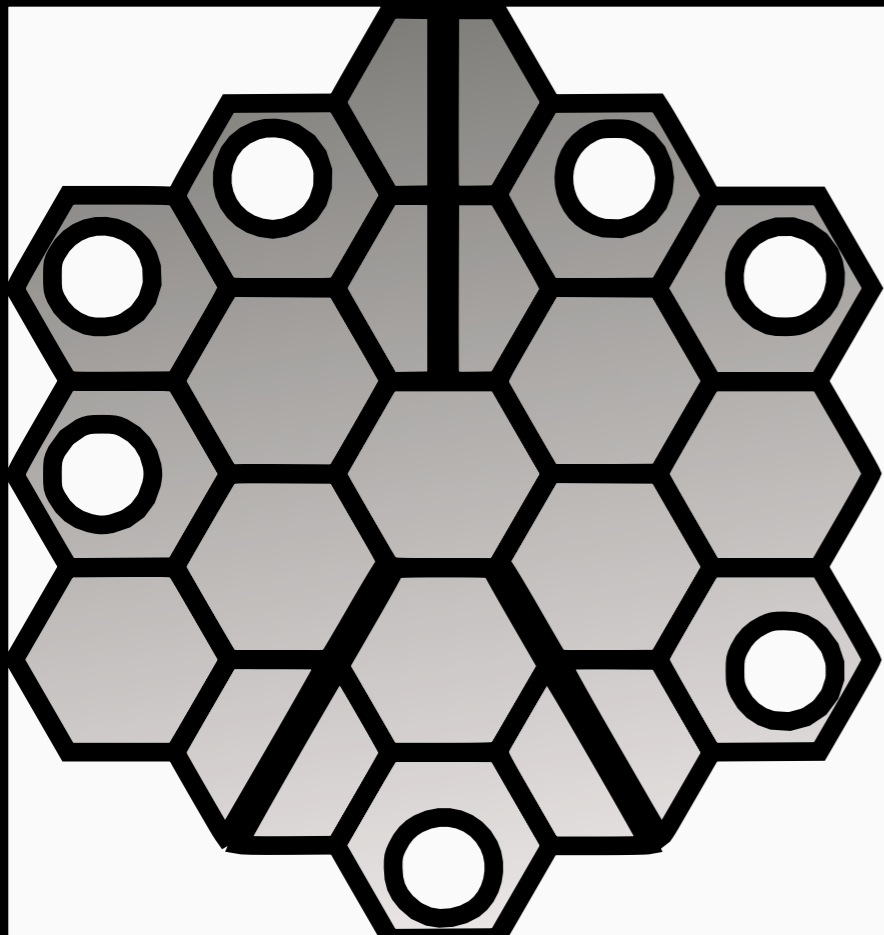
- Contrast limit: $\Delta K \sim 5-6$ @ diffraction limit
- 82 targets, 12 new binaries discovered with masking, below the limits of traditional imaging.



as well as 4 lower confidence (97.5-99.5 %) detections of planetary mass candidates (8-12 M_J)



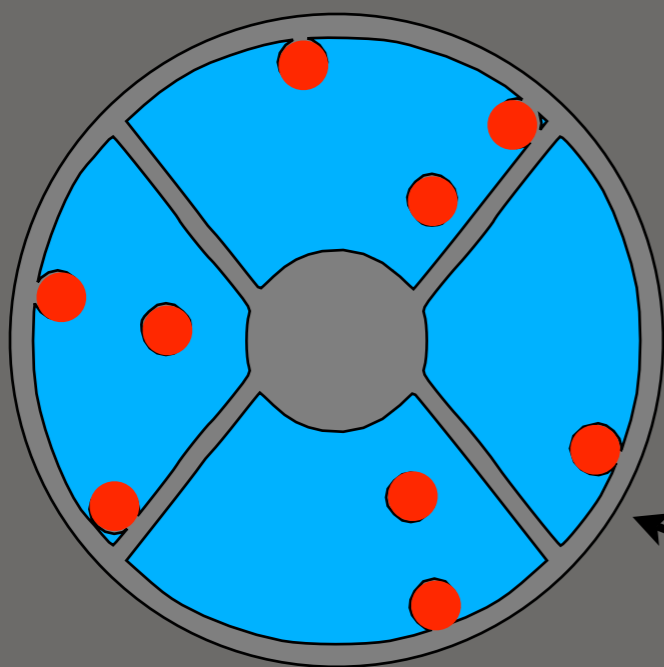
2014: NRM sur JWST



Accueilli dans l'instrument FGS-TFI en septembre 2008



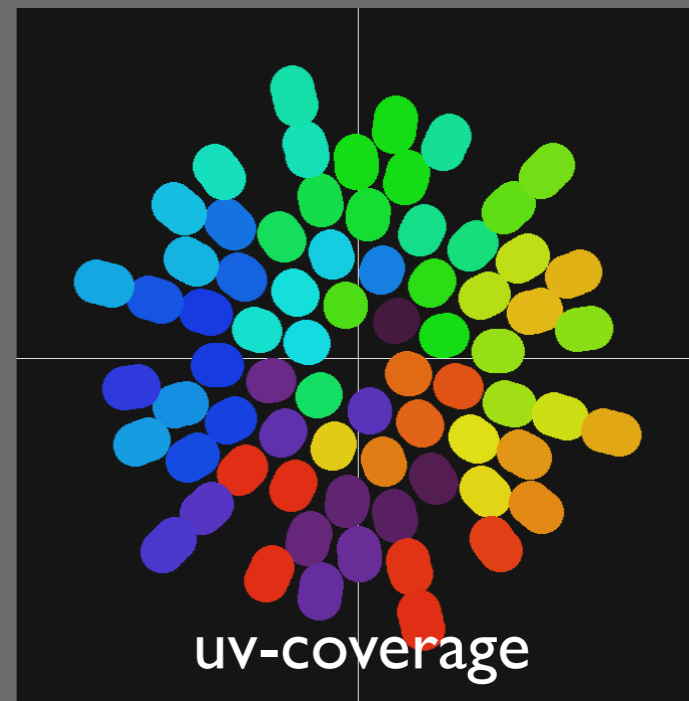
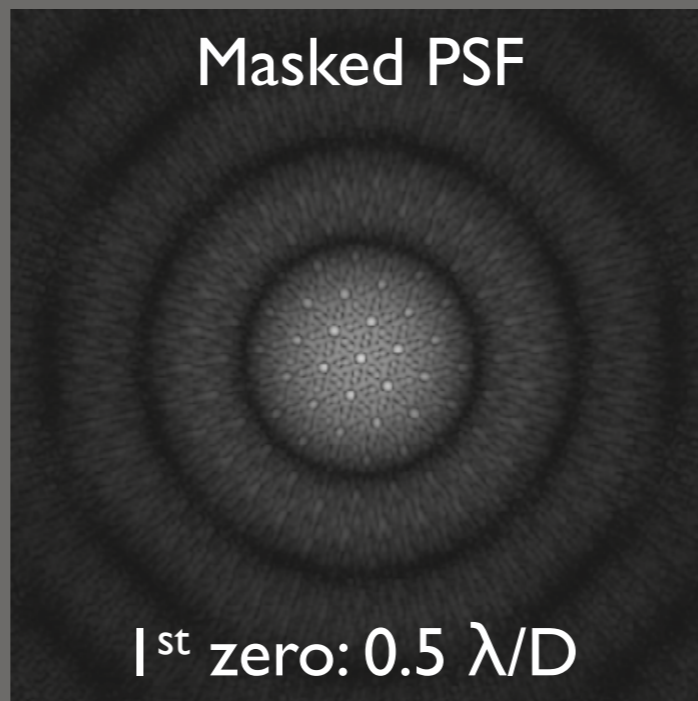
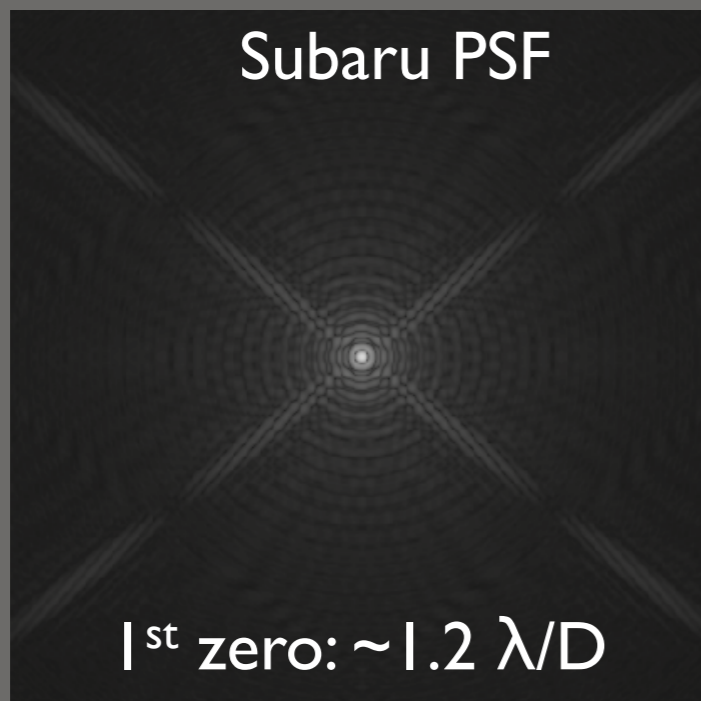
NRM et SCExAO... symbiose?



Mask up to 80 % of the mirror and ...

- Boost the resolution by a factor ~ 3
- Benefit from the self calibration properties of closure phase
- Become insensitive to non-common path errors

Example of **non redundant** 9-hole mask optimized for **Subaru + CH4s** filter

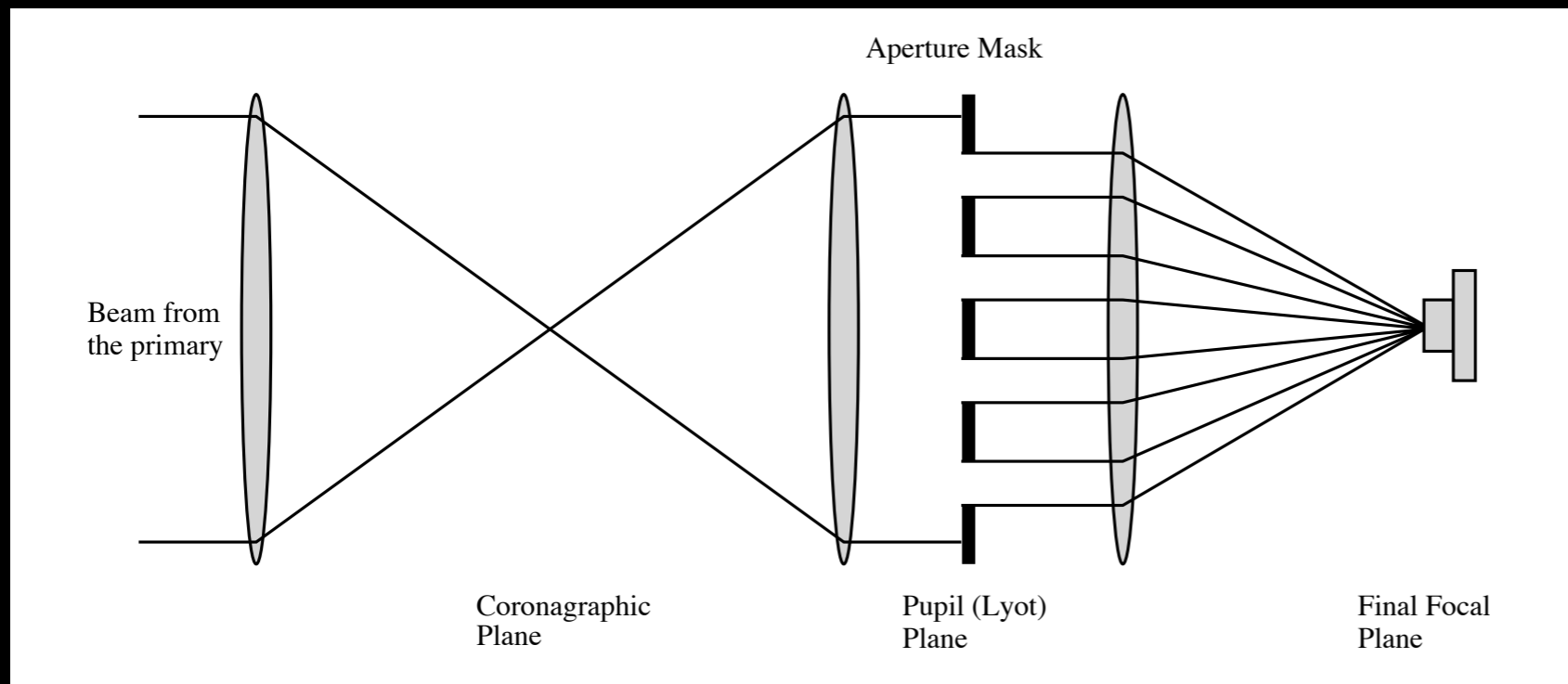




Enseignements d'une expérience ratée

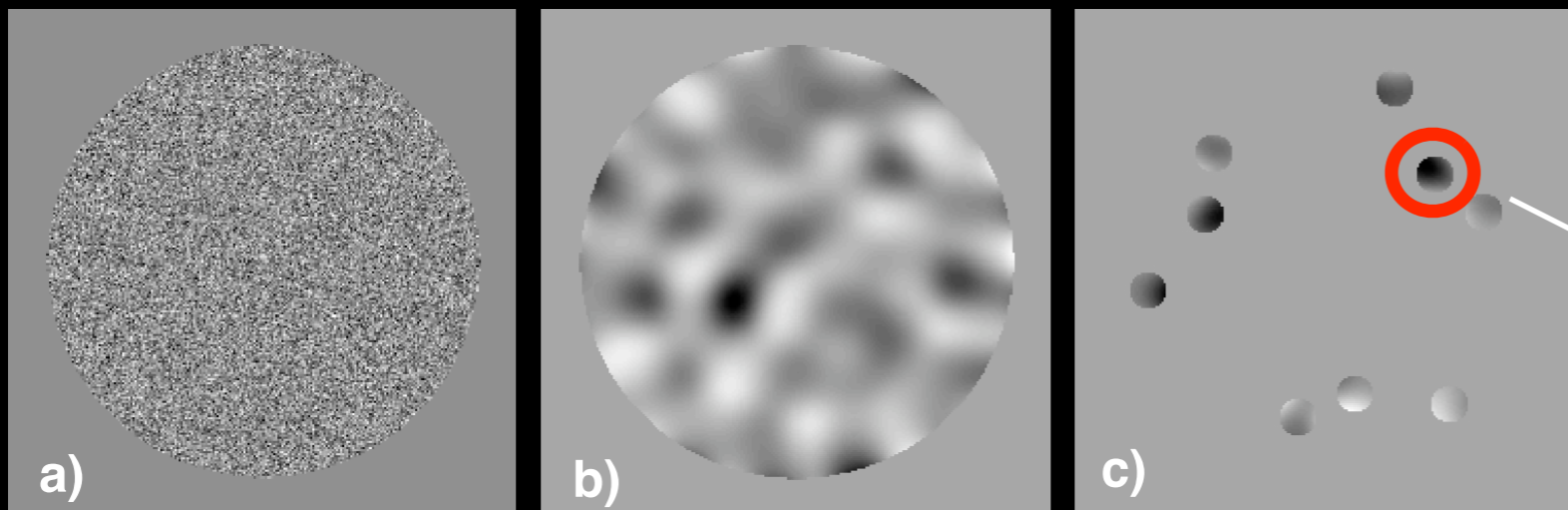
$\Delta H, K, L \sim 6$ entre 0.5 et $4 \lambda/D$
pas mieux?

Filtrage spatial
testé à Palomar



amélioration
marginale
seulement...

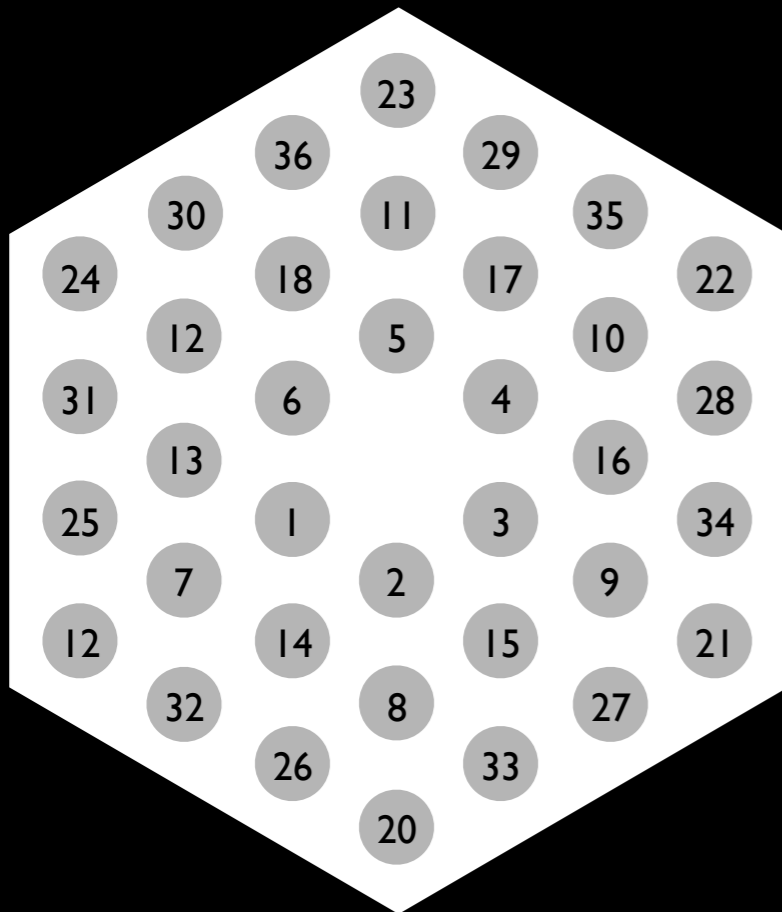
performance
dominée par bas
ordres ^s/ trou



exAO va aider



Généralisation de la clôture de phase?



Discretisation d'une pupille pleine.
Numérotation des trous pour identifier les bases interférométriques

La phase dans le plan UV est la somme de deux termes:

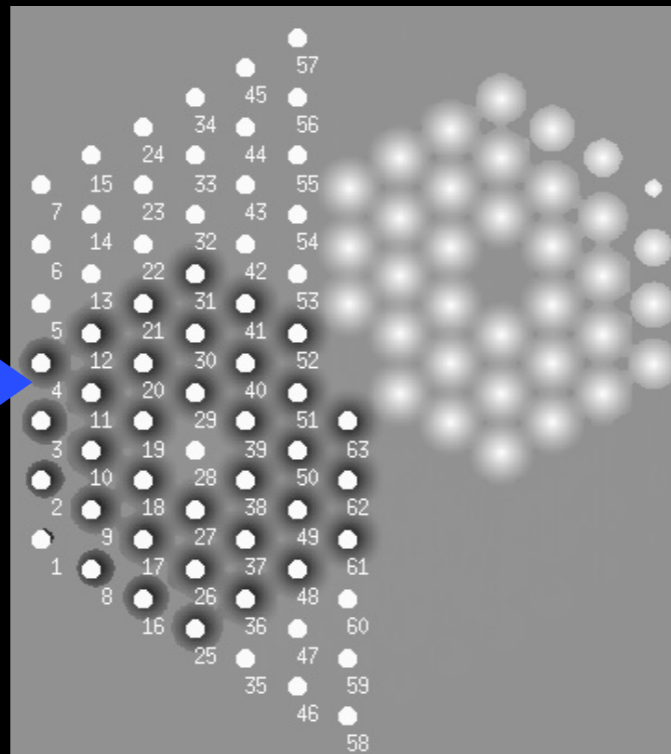
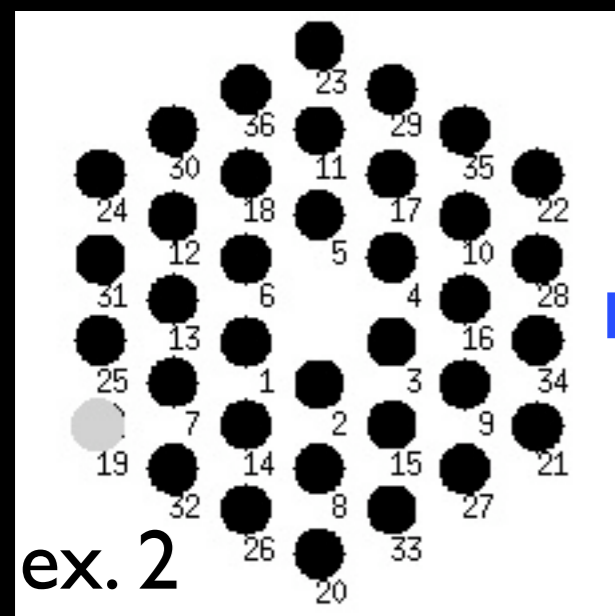
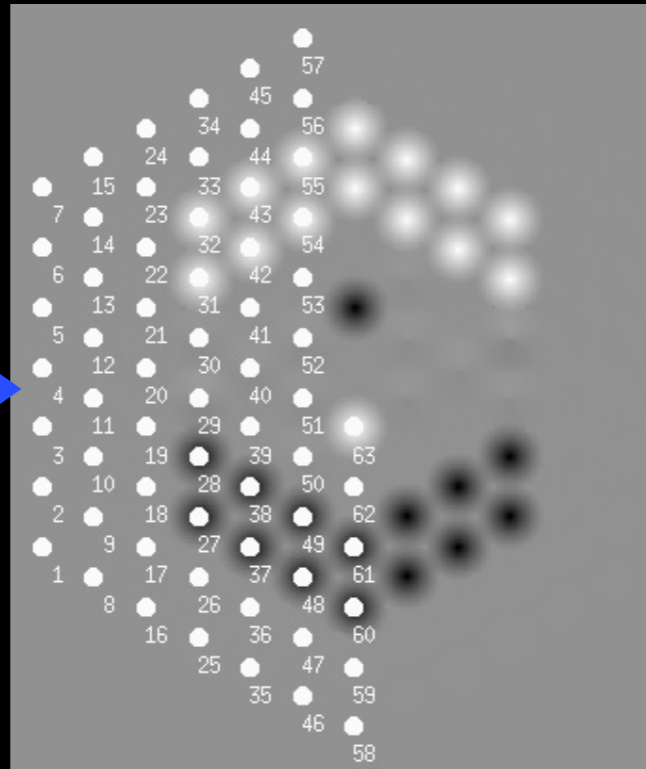
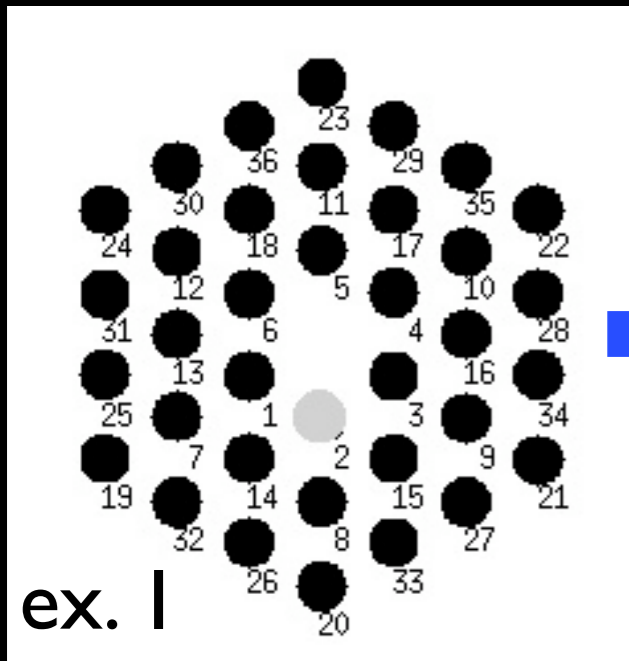
$$\phi = \phi^o + \phi^i$$

Etudions la phase instrumentale en posant

$$\phi^o = 0$$



Matrice d'interaction: pupille => UV



$$[M] =$$

0	0	0	0	0	0	-1	0	0	1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	-1	0	0	1	0	0	-1	0	0	1	0	0	0	0
0	0	0	0	0	0	-1	0	1	1	0	-1	-1	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	-1	-1	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	-1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	-1	0	0	1	0	0	0	-1	0	0	1	0	0	1
-1	0	0	1	0	0	-1	0	0	1	0	0	-1	-1	0	1	1	0	1	0
-1	0	1	1	0	-1	-1	0	1	1	0	-1	-1	-1	0	1	1	0	1	0
-1	0	1	1	0	-1	-1	0	1	1	0	-1	-1	0	1	1	0	-1	1	0
0	0	1	0	0	-1	0	0	1	0	0	-1	-1	0	1	1	0	-1	1	0
0	0	0	0	0	0	0	0	1	0	0	-1	0	0	1	0	0	0	-1	0
0	0	0	0	0	0	-1	-1	0	1	1	0	0	-1	0	0	1	0	0	1
-1	-1	0	1	1	0	-1	-1	0	1	1	0	-1	-1	0	1	1	0	1	0
-1	-1	1	1	1	-1	-1	-1	1	1	1	-1	-1	-1	0	1	1	-1	1	0
-1	0	1	1	0	-1	-1	0	1	1	0	-1	-1	-1	1	1	1	-1	1	-1
-1	1	1	1	-1	-1	-1	1	1	1	-1	-1	-1	0	1	1	0	-1	1	-1
0	1	1	0	-1	-1	0	1	1	0	-1	-1	-1	0	1	1	0	-1	1	-1
0	0	0	0	0	0	0	1	0	-1	-1	0	0	1	0	0	-1	0	0	-1
0	0	0	0	0	0	-1	0	0	1	0	0	-1	0	0	1	0	0	1	0
-1	-1	0	1	1	0	-1	-1	0	1	1	0	0	-1	-1	0	1	1	1	1
-1	-1	0	1	1	0	-1	-1	0	1	1	0	-1	-1	-1	1	1	1	1	1
0	0	0	0	0	0	-1	-1	1	1	1	-1	-1	-1	0	1	1	0	-1	-1
0	1	1	0	-1	-1	0	1	1	0	-1	-1	-1	1	1	1	-1	-1	-1	-1
0	1	1	0	-1	-1	0	1	1	0	-1	-1	0	1	1	0	-1	-1	-1	-1
0	0	0	0	0	0	0	1	0	0	-1	0	0	0	1	0	0	-1	0	0
0	0	0	0	0	0	-1	0	0	1	0	0	-1	0	0	0	0	0	0	0
0	-1	0	0	1	0	0	-1	0	0	1	0	0	-1	-1	0	1	1	1	1
-1	-1	-1	1	1	1	-1	-1	-1	1	1	1	0	-1	-1	0	1	1	1	1
0	0	0	0	0	0	-1	-1	-1	1	1	1	0	-1	-1	0	1	1	1	1

$$\Phi^i = M \varphi$$



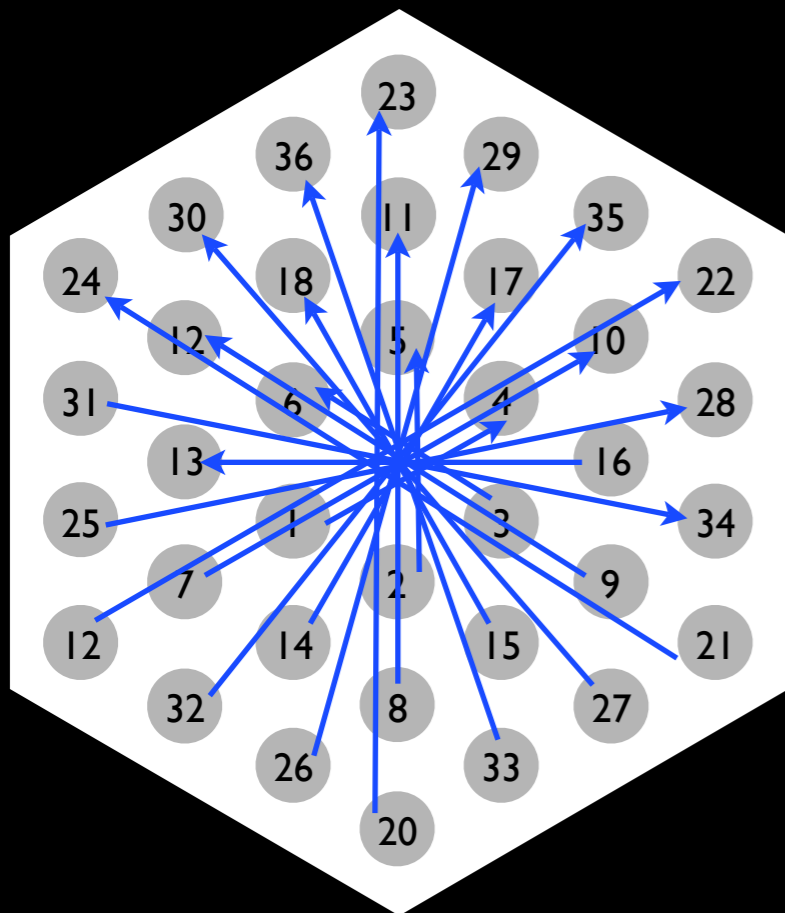
SVD pour tout comprendre?

$$[M] = [U] \times [S] \times [V]^T$$

Valeurs
singulières

$$[S] = \begin{bmatrix} 19.9 & 19.9 & 6.5 & 5.3 & 5.3 \\ 5.2 & 3.9 & 3.9 & 3.6 & 3.3 \\ 3.3 & 3.1 & 2.6 & 2.6 & 2.6 \\ 1.5 & 1.5 & 1.1 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix}$$

$$[M]^{-1} = [V] \times [1/S] \times [U]^T$$

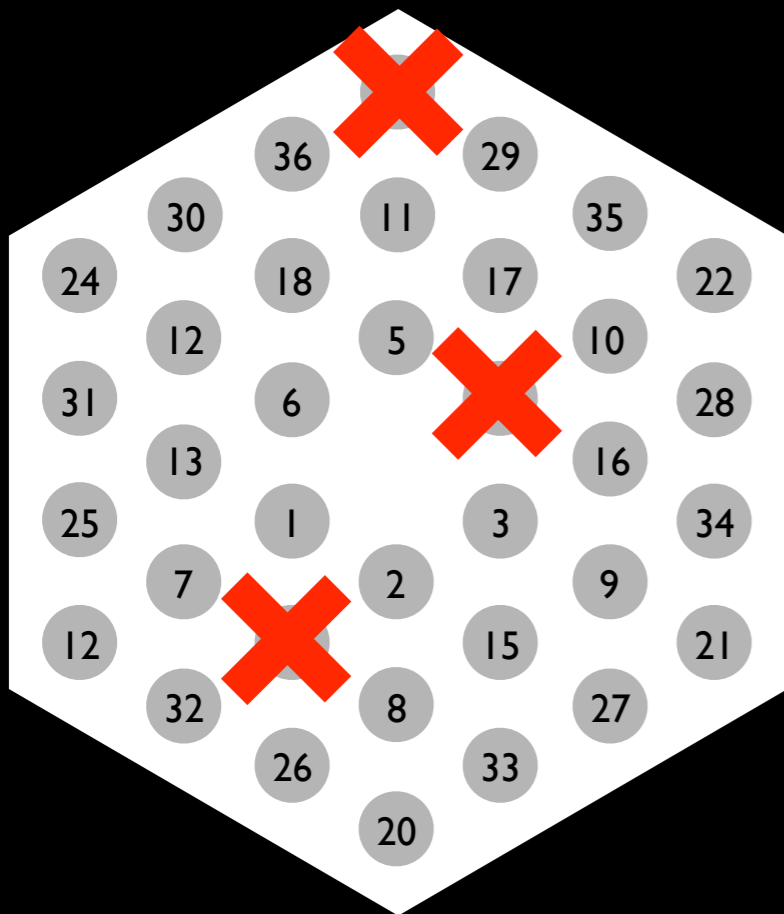


Sur les 36 valeurs singulières, 18 non-nulles, correspondant aux “bases symétriques”



Redondance critique?

Supprime une seule $s/$ ouverture*
 et toutes les valeurs singulieres
 deviennent non nulles!



[S] =

19.3	19.3	6.2	5.5	5.1
4.9	3.5	3.4	3.3	3.1
2.8	2.8	2.7	2.6	2.4
2.0	1.8	1.2	1.0	1.0
1.0	0.9	0.9	0.9	0.9
0.9	0.8	0.8	0.7	0.7
0.7	0.6	0.5	0.5	0.1

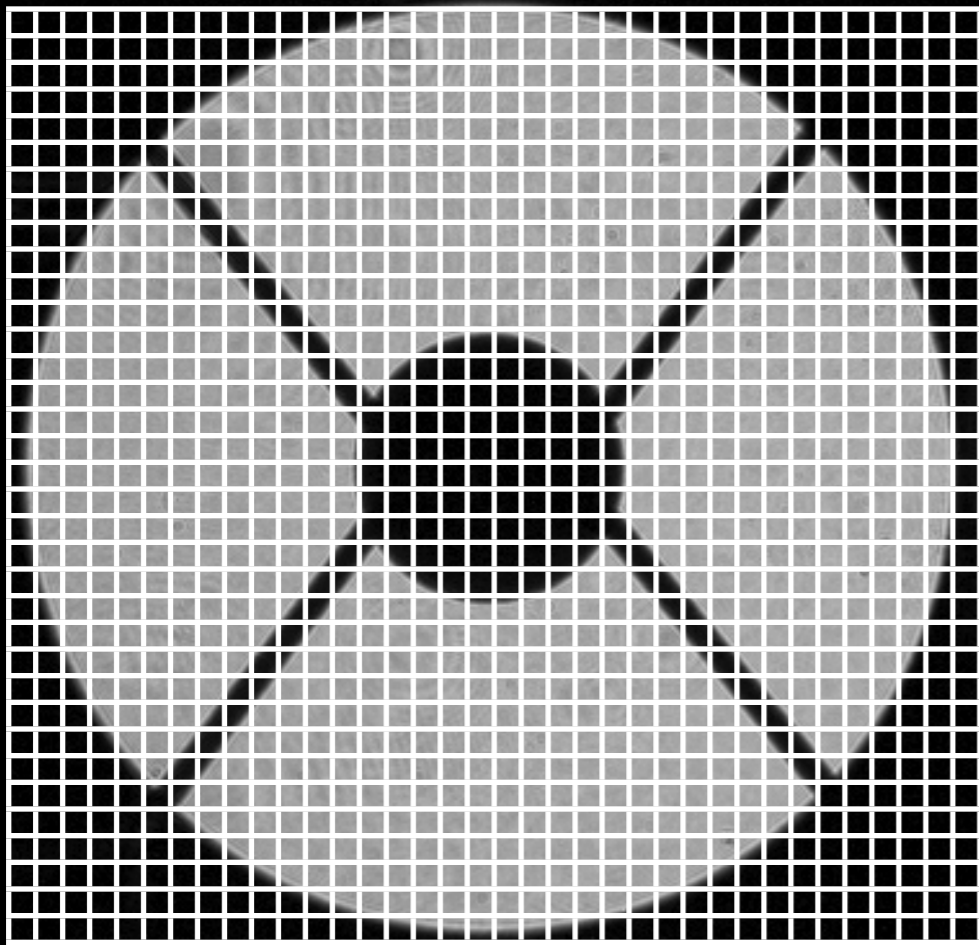
[M] peut donc être
 inversée et les phases dans
 la pupille identifiées

Martinache, 2009, in prep



Quel intérêt?

Raisonnement a priori
généralisable aux
pupilles continues



Possibilité: extraire
d'images OA
classiques (i.e. non
masqué) une
collection finie de
quantités
observables qui sont
indépendentes des
résidus d'OA!

!! Pas de la !!
!! déconvolution !!

Martinache, 2009, in prep



Questions en l'air

Résoudre mathématiquement le problème suivant:

trouver $[T]$, tel que $[T] \times [M] =$

2	2	2	2	2	2	2	2	2	2	2
2	2	2	0	2	2	2	2	2	2	2
0	2	2	2	2	2	2	2	2	2	0
2	2	2	2	0	2	2	2	2	2	2
2	2	2	1	2	2	2	2	2	2	2
0	2	1	2	2	2	2	2	2	2	1
1	2	2	2	2	0	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2	2
2	2	5	2	2	2	1	2	2	2	1
2	2	2	2	3	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2	1
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0

Redondance totale ou redondance critique?

Quel signal sur bruit? Simulations...



Espace des paramètres exploré

