Repousser les limites de la diffraction pour l'astronomie à haute résolution angulaire

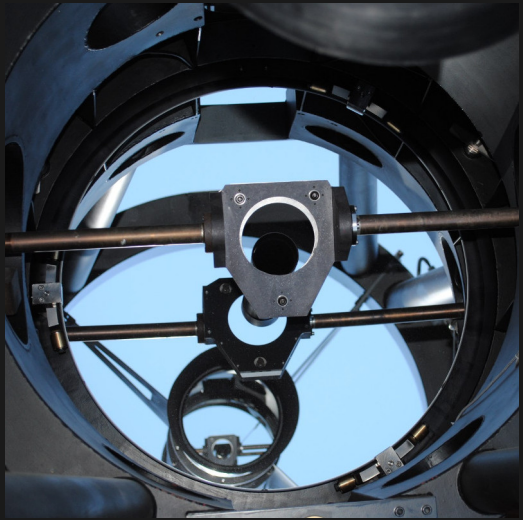
Frantz Martinache

4 octobre 2018

Master plan

1. **Astronomie à la limite de la diffraction**
2. **Interférométrie à masque non-redondant**
3. **Contrôle actif pour l'imagerie haut-contraste**
4. **L'interférométrie des kernels**
5. **Vers un haut-contraste robuste... enfin?**

L’image et l’astronome



La formation des images

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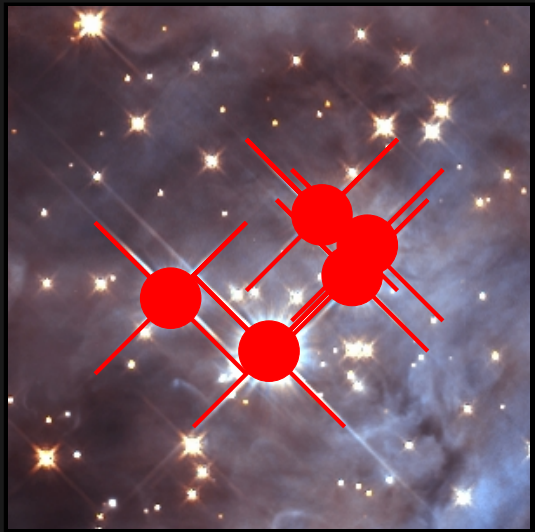

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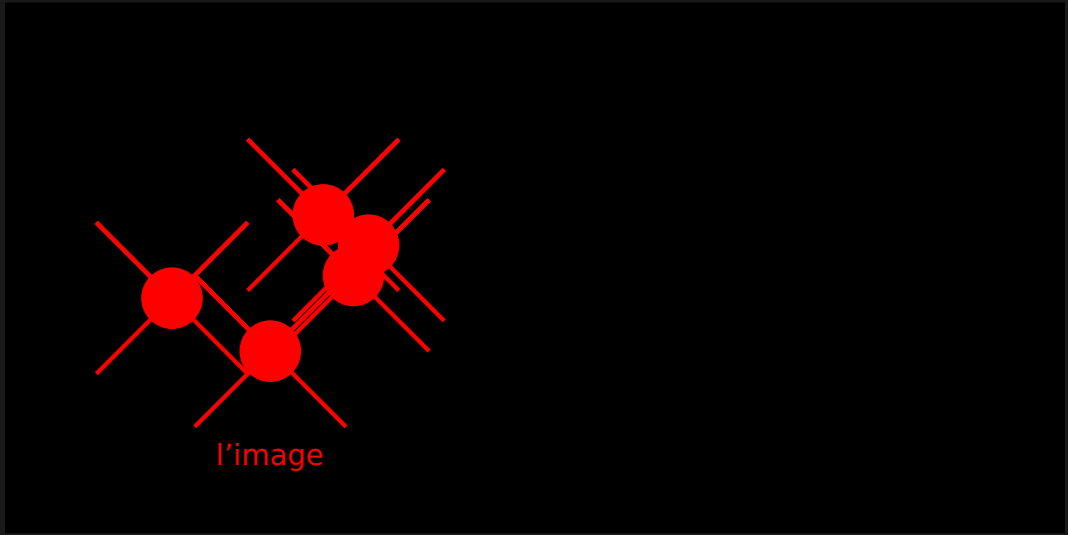

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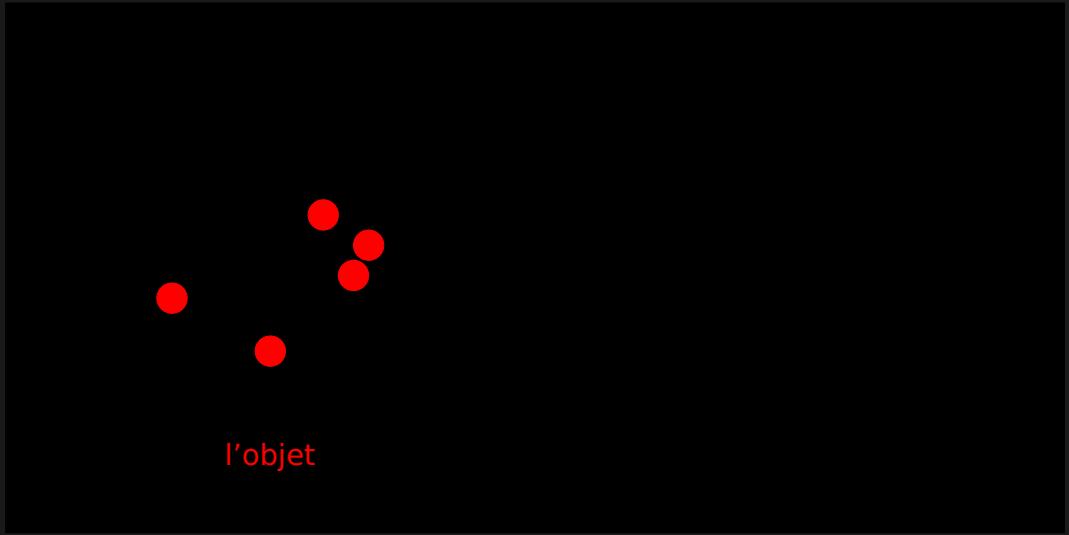

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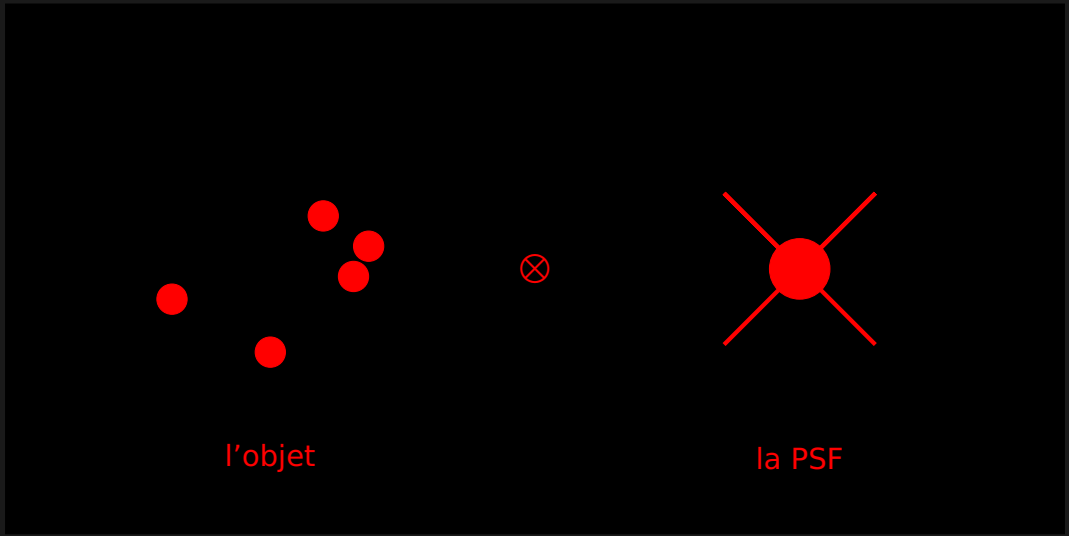
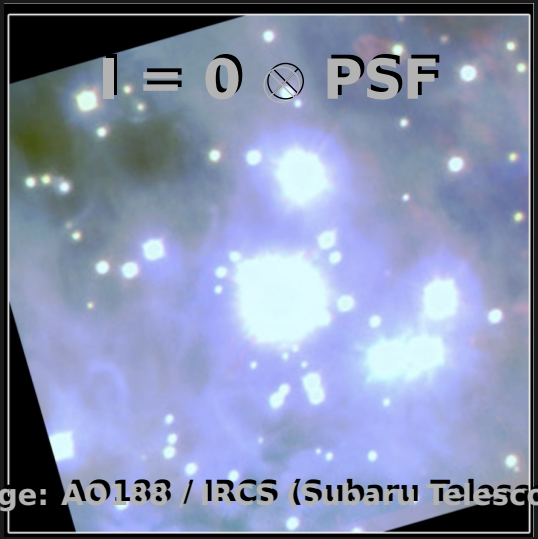


Les images dominées par la diffraction



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Astronomie dominée par la diffraction

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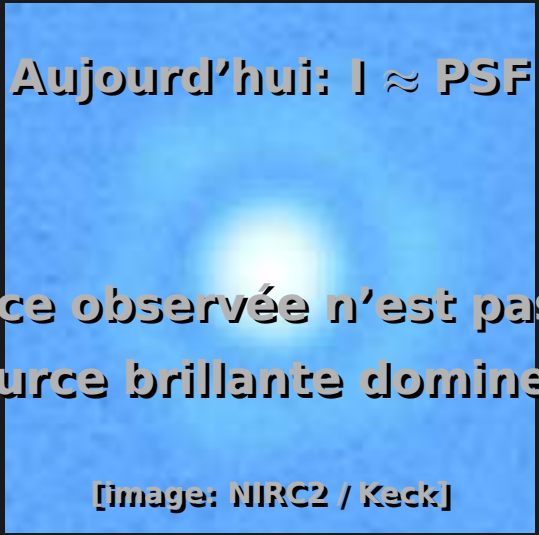
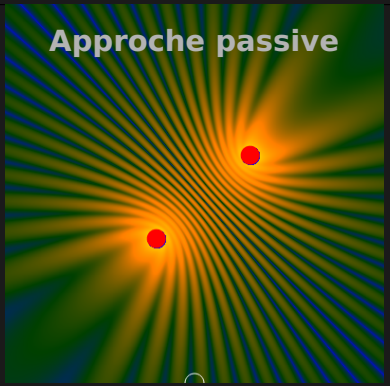


Deux méthodologies possibles



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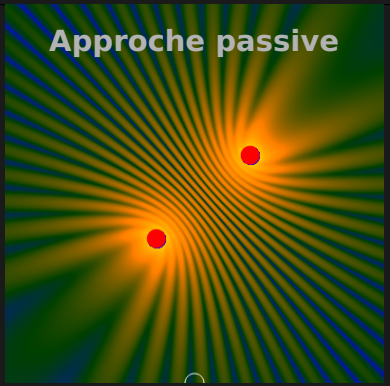

Mesure de qualité:
clôtures et kernels
interférométrie

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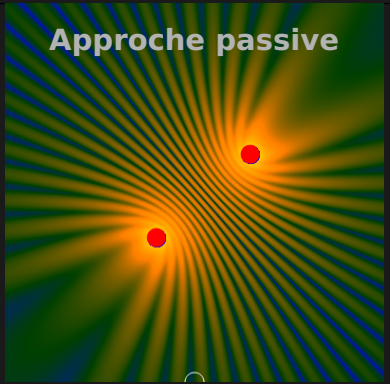

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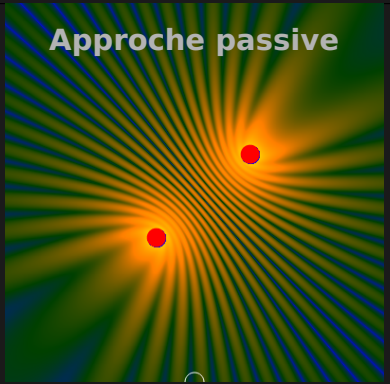

Mesure de qualité:
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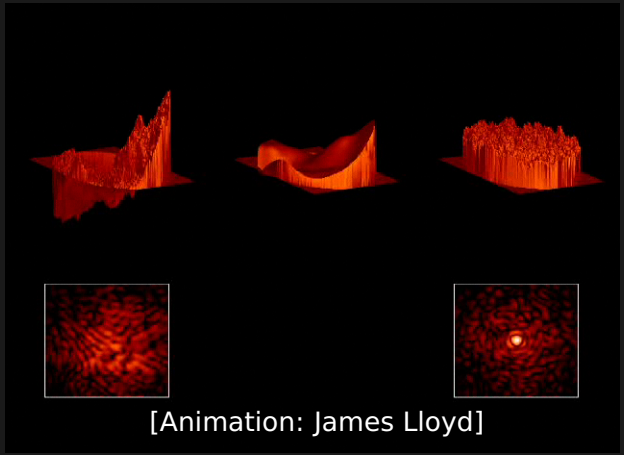
Atténuation des bruits:
de phase et de photon
coronographie + XAO

Ce qui a tout changé. . .



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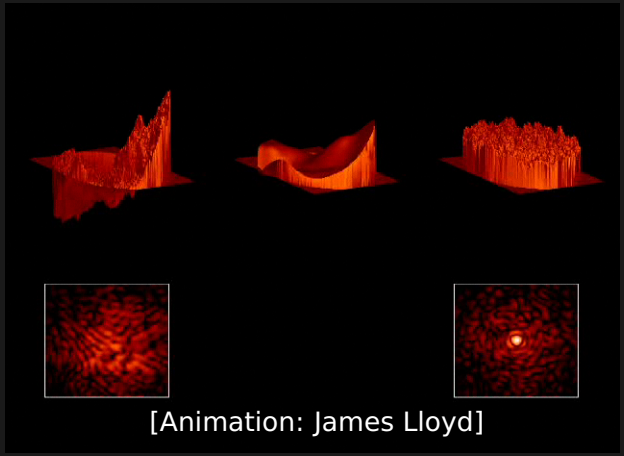
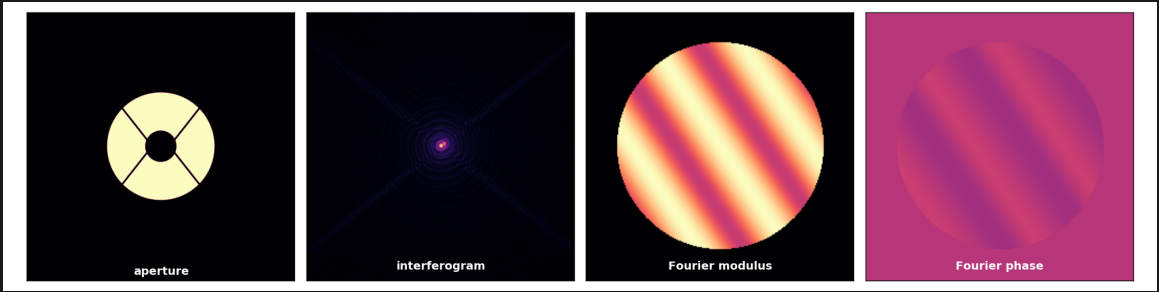


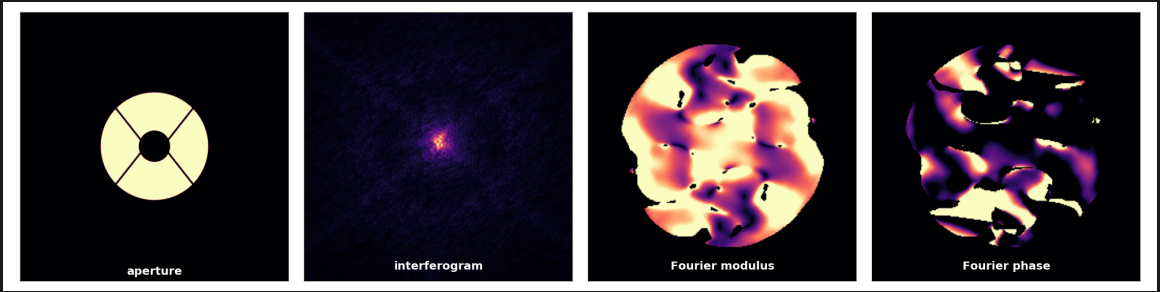
C’est l’optique adaptative!

L’image et sa Transformée de Fourier



La pupille L’image La Transformée de Fourier de l’image

L’image et ses fréquences spatiales perturbées



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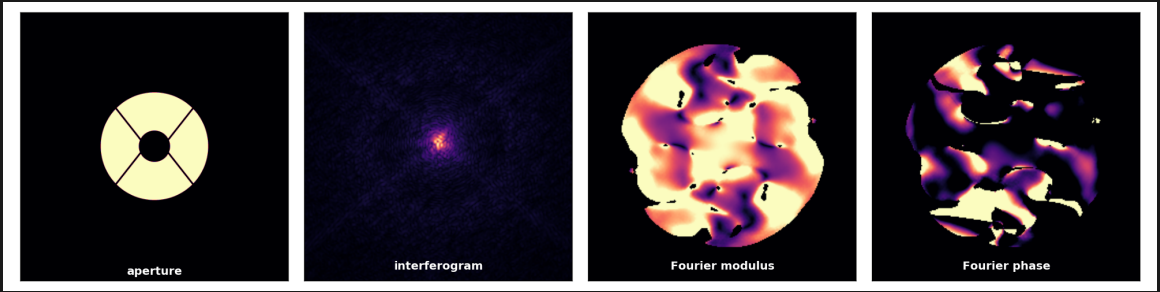

L’image et sa transformée sont affectées par les erreurs de front d’onde

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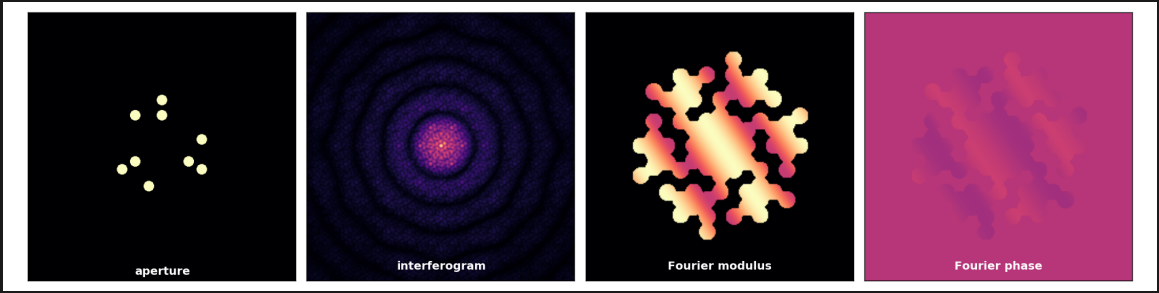
Simplifier l’interprétation des images



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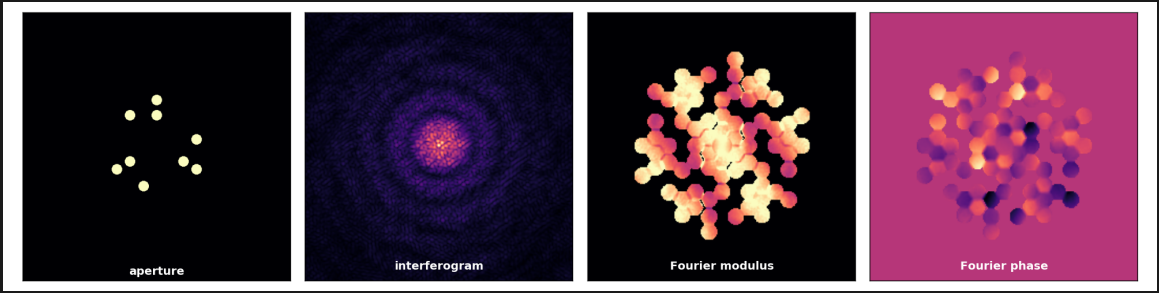
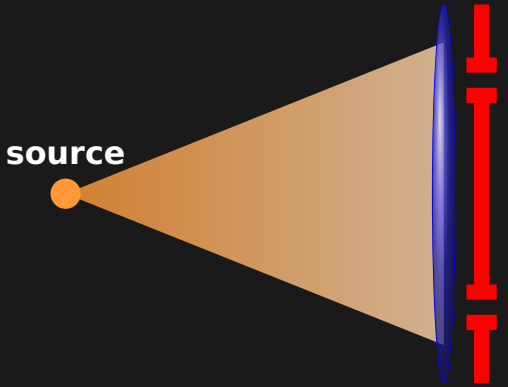


Même en présence de turbulence résiduelle:
Pupille non-redondante $\rightarrow$ accès au module de visibilité!
L’information de phase reste perdue...

Le masque à deux trous

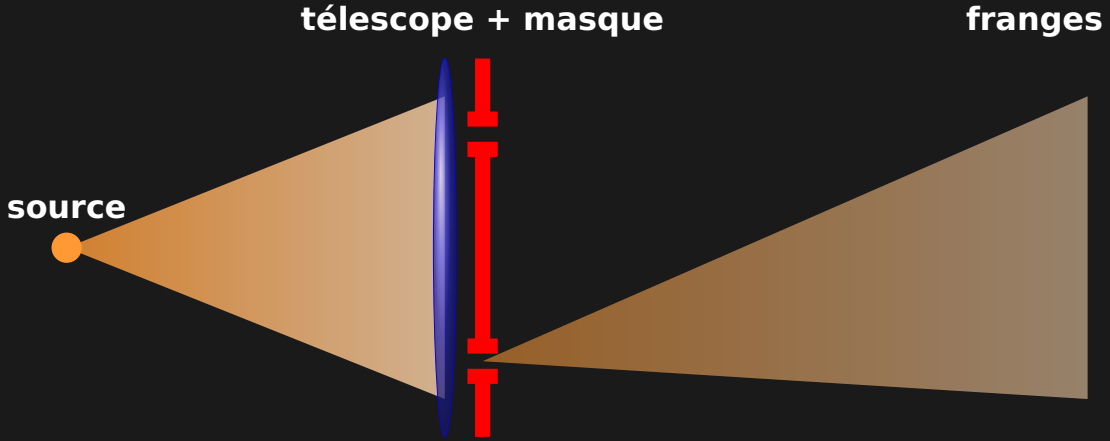
télescope + masque

franges



Avec une ouverture diffractive aussi simple:

Le masque à deux trous



Avec une ouverture diffractive aussi simple:

$$I(x) = I_0 \times \left(1 + \mu \cos\left(kx - \phi\right)\right)$$

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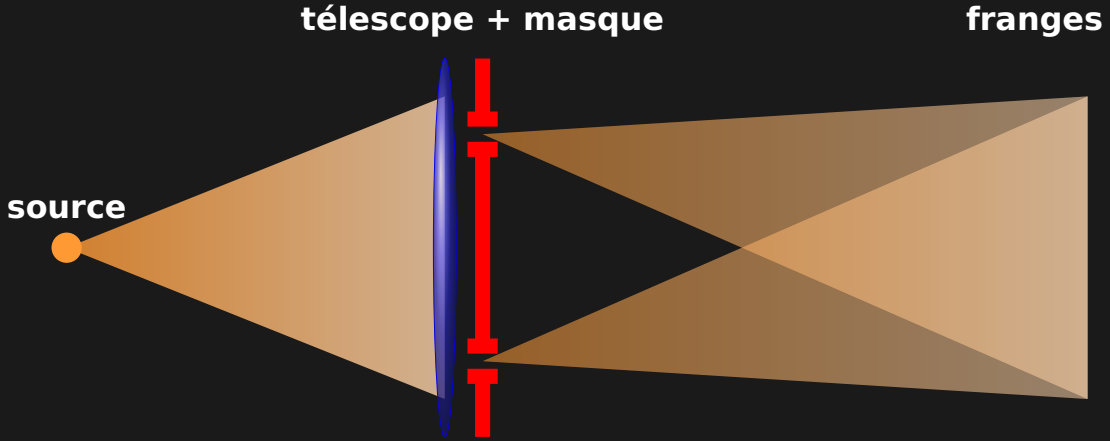

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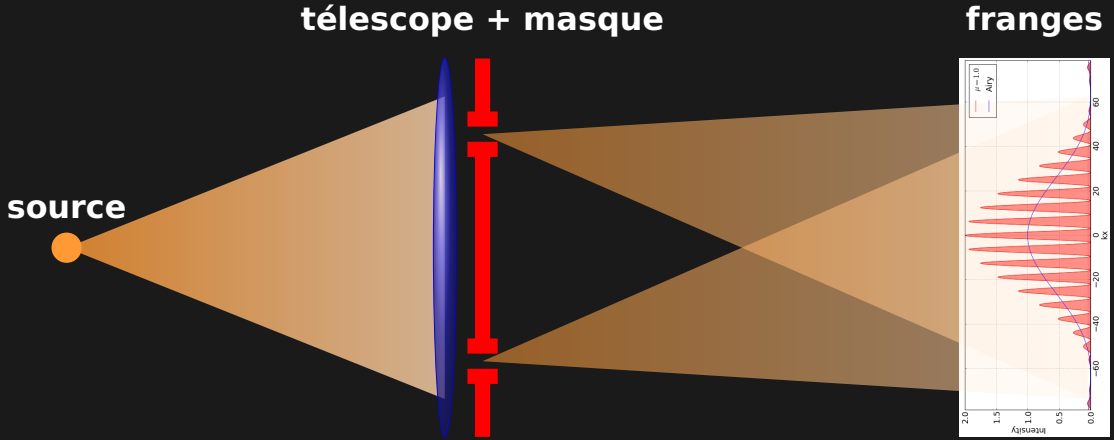

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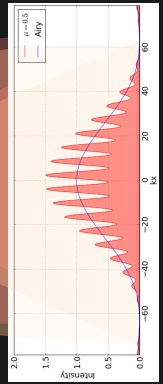
La mesure interférométrique

télescope + masque

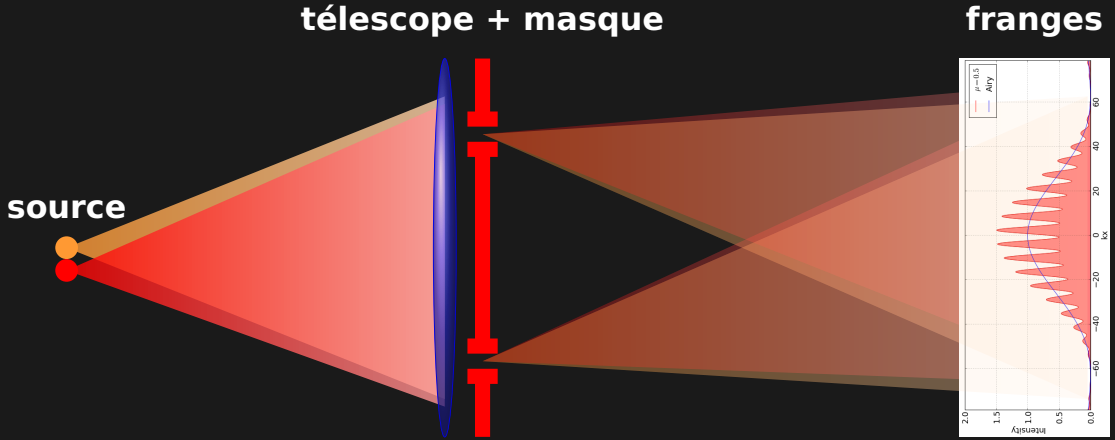
franges

source



$$I(x,t) = I_0 \times \left(1 + \mu \cos(kx - \phi)\right)$$

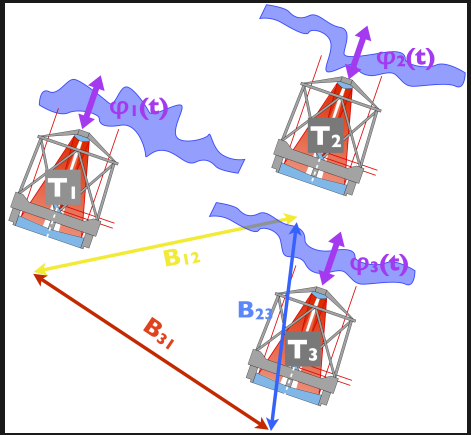
La mesure interférométrique



En présence de perturbations

$$I(x,t) = I_0 \times \left(1 + \mu \cos\left(kx - \phi + \Delta\varphi(t)\right)\right)$$

Couplage des perturbations de phase



$$\Phi(1-2) = \Phi_O(1-2) + (\varphi_1 - \varphi_2)$$

$$\Phi(2-3) = \Phi_O(2-3) + (\varphi_2 - \varphi_3)$$

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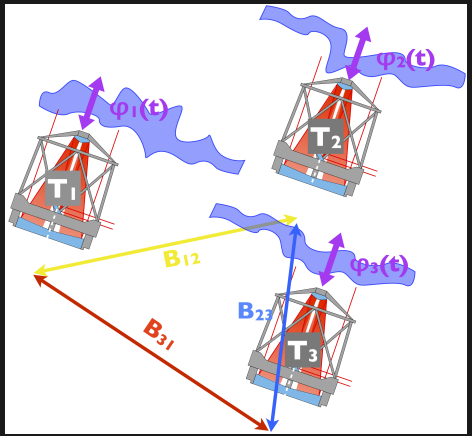

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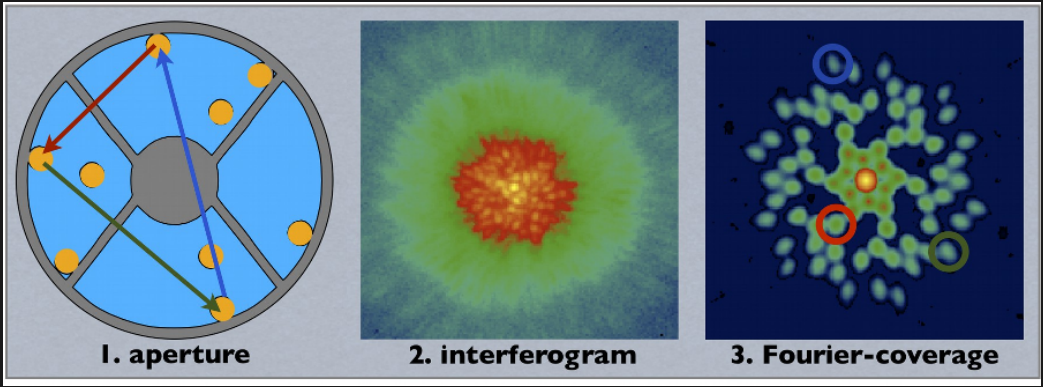
La somme de ces trois termes est indépendante de la source de perturbation: la clôture de phase!

Jennison, 1958
Baldwin et al, 1986

Un masque non-redondant à 9 trous



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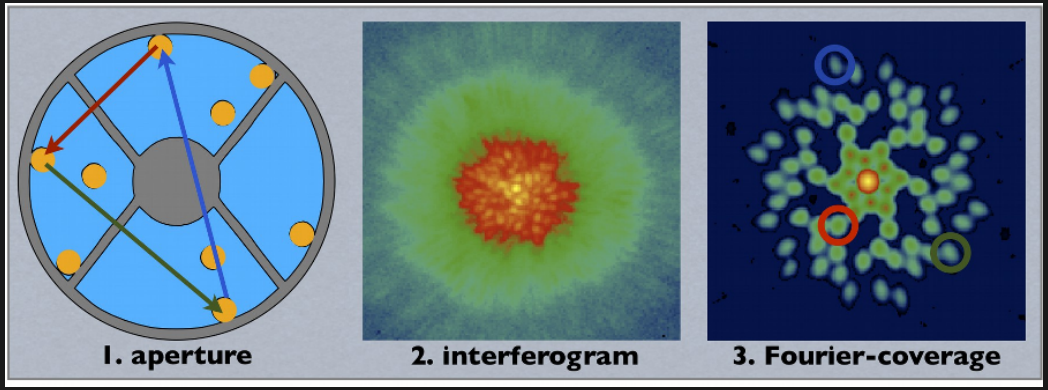
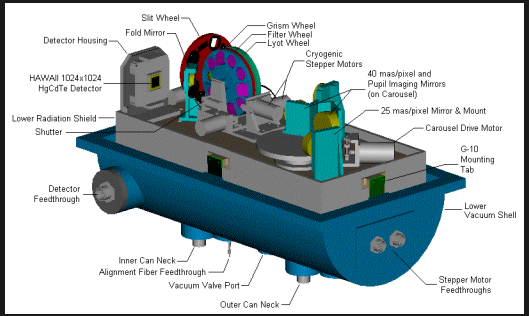
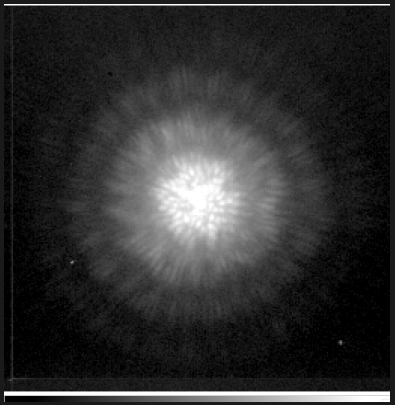


- $n_A = 9$
- $n_B = n_A \times (n_A - 1) / 2 = 36$ visibilités
- $n_C = (n_A - 1) \times (n_A - 2) / 2 = 28$ clôtures

Masque dans PHARO @ Palomar: NRM + AO!





Cornell $\rightarrow$ Palomar?

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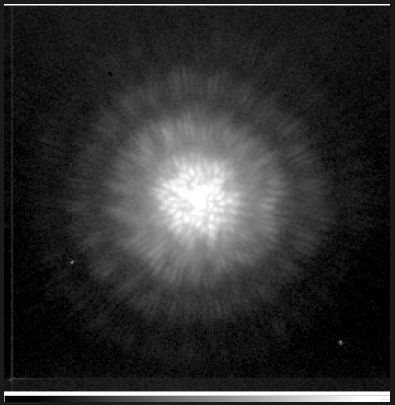

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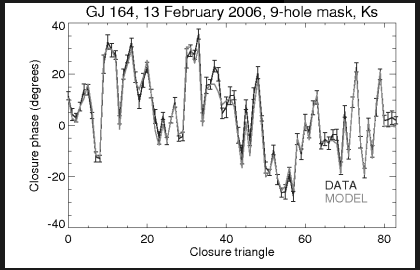
Exploitation astrophysique?

suivi dynamique
naines M, L



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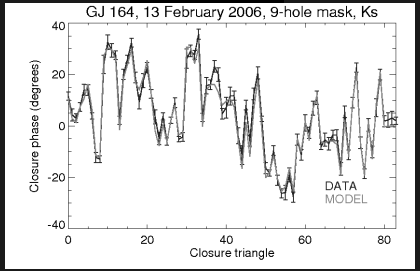

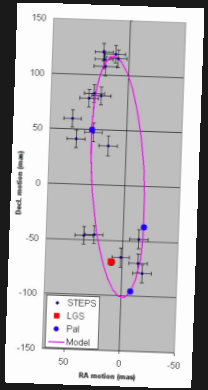

G78-28

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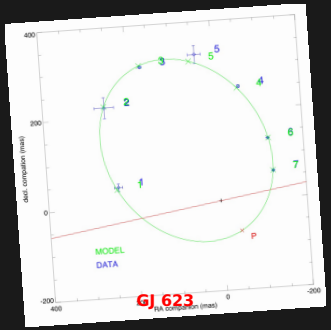

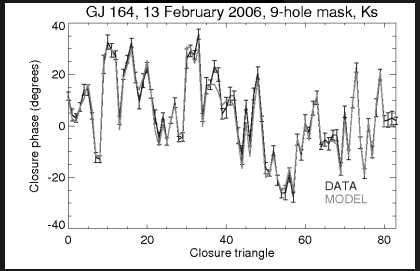

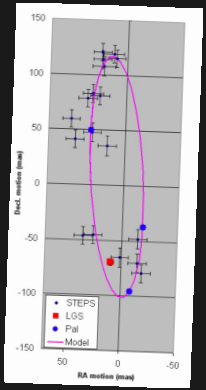

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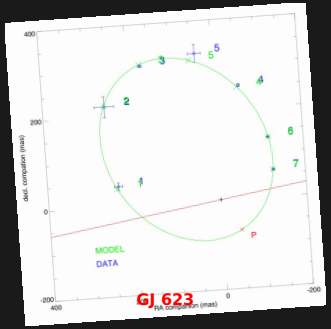

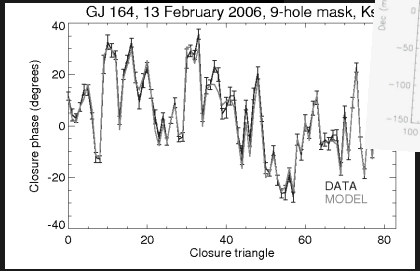

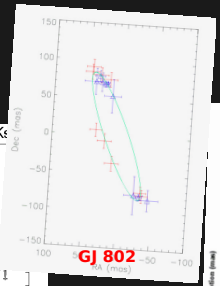

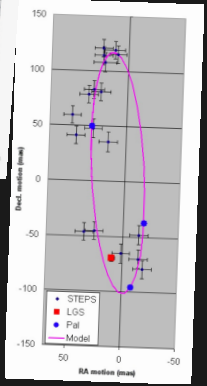

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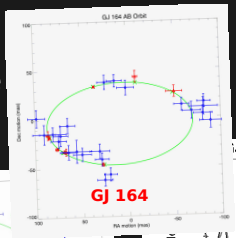

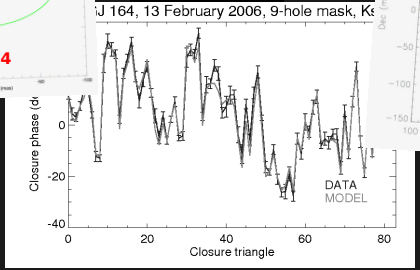

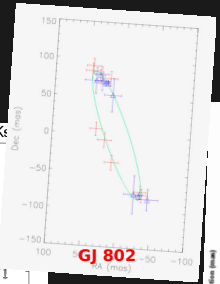

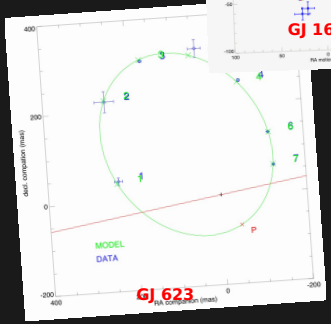

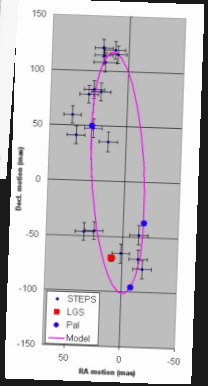

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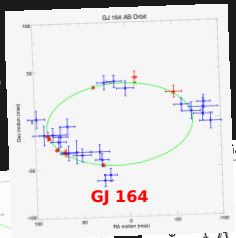

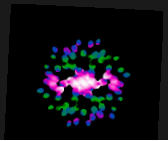

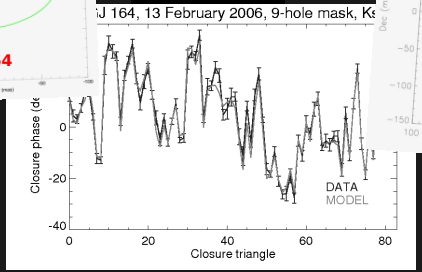

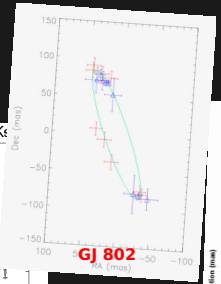

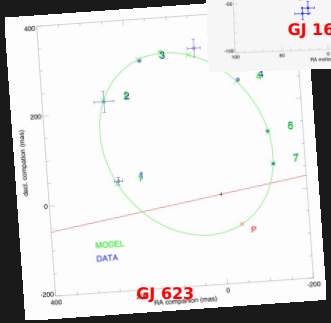

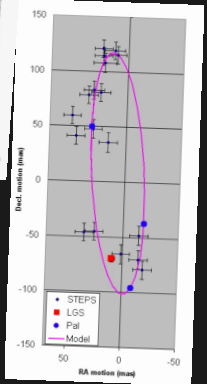

G78-28

grands surveys de:
U.Sco, Taurus,
associations proches

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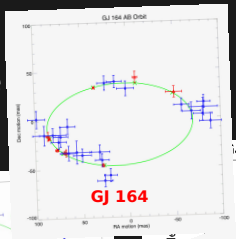
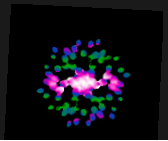
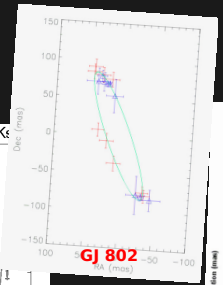
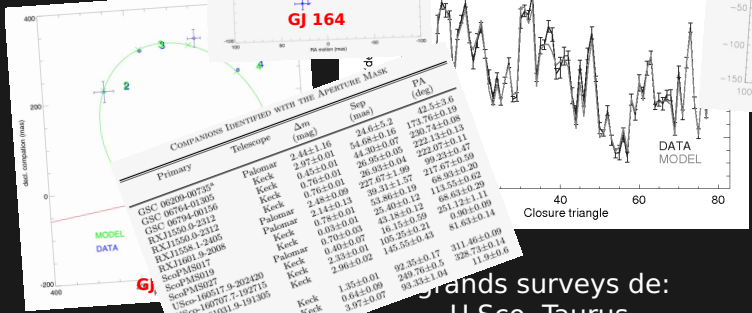
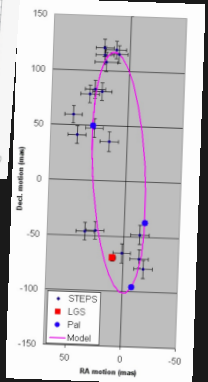
naines M, L











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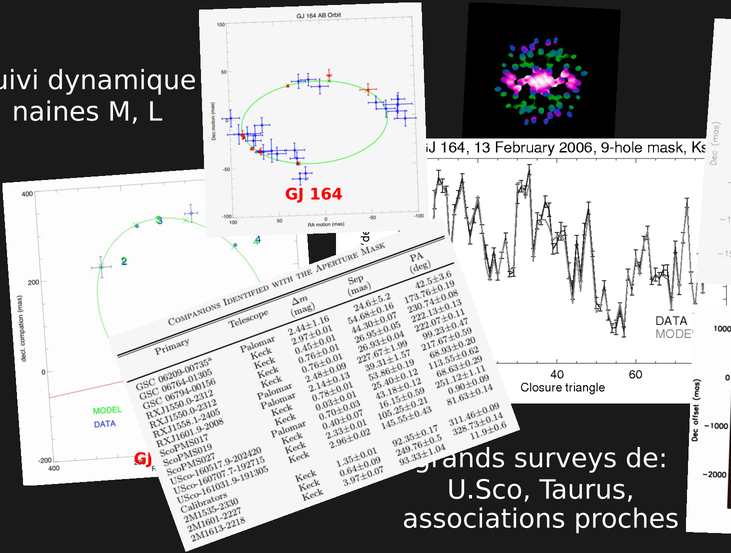
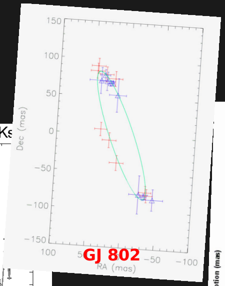
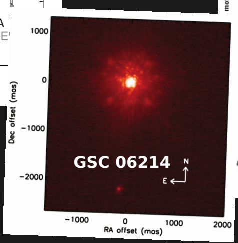
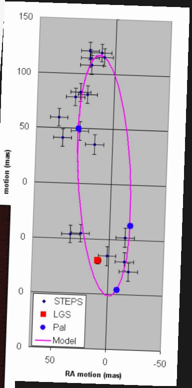


Companions Identified with the Aperture Mask				
Primary	Telescope	Δm (mag)	Sep (mas)	PA (deg)
GSC 06209-00735[a]	Palomar	2.44±1.16	24.6±5.2	42.5±3.6
GSC 06764-01305	Keck	2.97±0.01	54.68±0.16	173.76±0.19
GSC 06794-00156	Keck	0.45±0.01	44.30±0.07	230.74±0.08
RXJ1550.0-2312	Keck	0.76±0.01	26.95±0.05	222.13±0.13
RXJ1550.0-2312	Keck	0.76±0.01	26.93±0.04	222.07±0.11
RXJ1558.1-2405	Palomar	2.48±0.09	227.67±1.99	99.23±0.47
RXJ1601.9-2008	Palomar	2.14±0.13	39.31±1.57	217.67±0.59
ScoPMS017	Keck	0.78±0.01	53.86±0.19	68.93±0.20
ScoPMS019	Keck	0.03±0.01	25.40±0.12	113.55±0.62
ScoPMS027	Palomar	0.70±0.03	43.18±0.12	68.63±0.29
USco-160517.9-202420	Keck	0.40±0.07	16.15±0.59	251.12±1.11
USco-160707.7-192715	Keck	2.33±0.01	105.25±0.21	0.90±0.09
USco-161031.9-191305	Keck	2.96±0.02	145.55±0.43	81.63±0.14
Calibrators				
2M1535-2330	Keck	1.35±0.01	92.35±0.17	311.46±0.09
2M1601-2227	Keck	0.64±0.09	249.76±0.5	328.73±0.14
2M1613-2218	Keck	3.97±0.07	93.33±1.04	11.9±0.6







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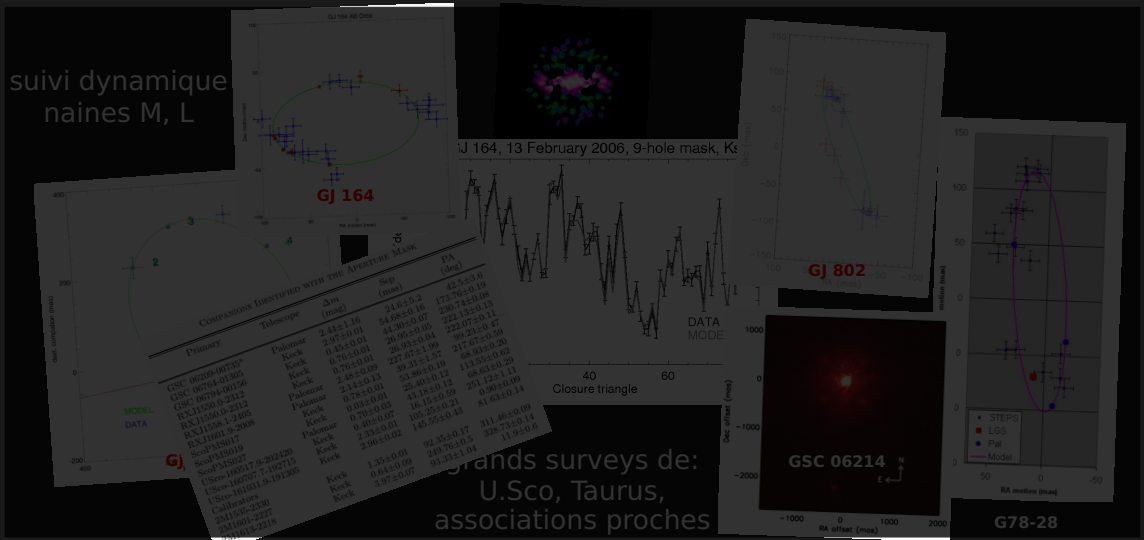

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UT

'Mom' to stargazers

Manager of Monastery quarters keeps visitors fed, happy

By Paula Story

July 6, 2007

PALOMAR MOUNTAIN – World-class astronomers and engineers visit Palomar Observatory almost every night of the year to peer at far corners of the universe through five telescopes, including the famous 200-inch Hale Telescope.

SEAN DuFRENE / Union-Tribune

Visiting astronomers dining at the Monastery recently included Adam Kraus (left), Michael Ireland (center) and Frantz Martinache.

These stargazers rotate in and out every three or five days. They hope for clear skies and work long hours in the dark, and their quest includes identifying new classes of cosmic explosions and finding unknown asteroids, meteors and planets.

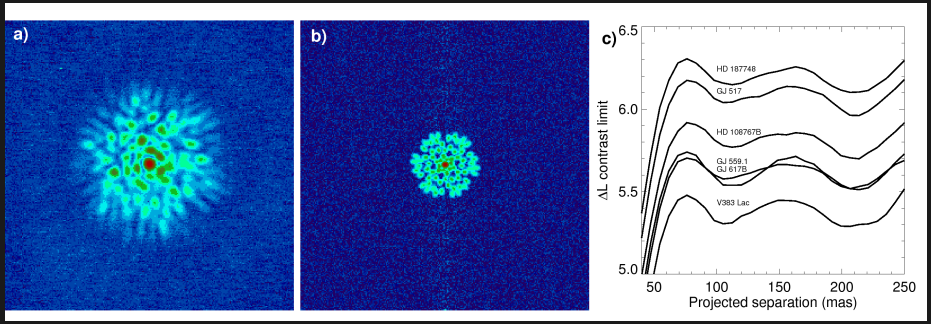
While such heavenly discoveries are unpredictable, there is one constant: the tradition of a proper sit-down meal, which at Palomar remains as certain as the Earth's revolution around the sun.

GJ 802

GSC 06214

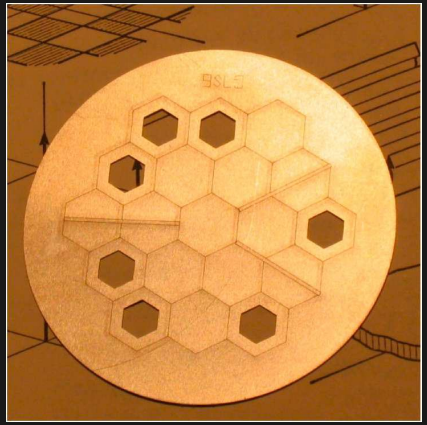
G78-28

Observable pas biaisé... mais biaisé quand même?



Limites de détection imposées par de subtils effets systématiques? Stricte non-redondance? Variance temporelle? Filtre non étroit? Optiques hors pupille?

Epilogue



- ambition grandissante (contraste)
- question des systématiques non-résolue
- des masques NR sur tous les grands télescopes optiques
- un masque NR volera sur JWST!

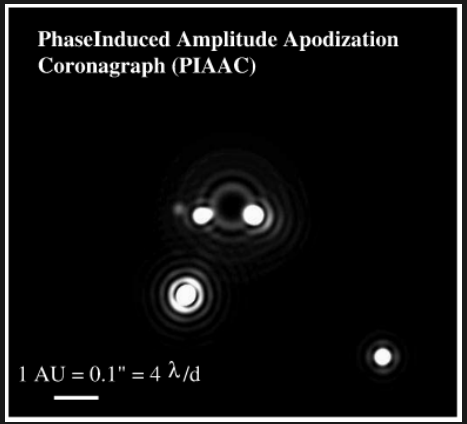
Sivaramakrishnan et al, 2010

Master plan

1. Astronomie à la limite de la diffraction
2. Interférométrie à masque non-redondant
3. **Contrôle actif pour l'imagerie haut-contraste**
4. L'interférométrie des kernels
5. Vers un haut-contraste robuste... enfin?

2008: Le démon de la coronographie me reprend

- NRM victime de son succès?
- technique dédiée: la coronographie!
- retour à Subaru?



Guyon et al (2005)

Quand la technologie est là, y’a plus qu’à!

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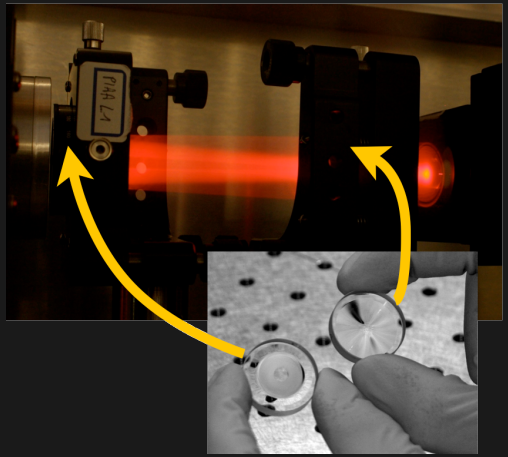
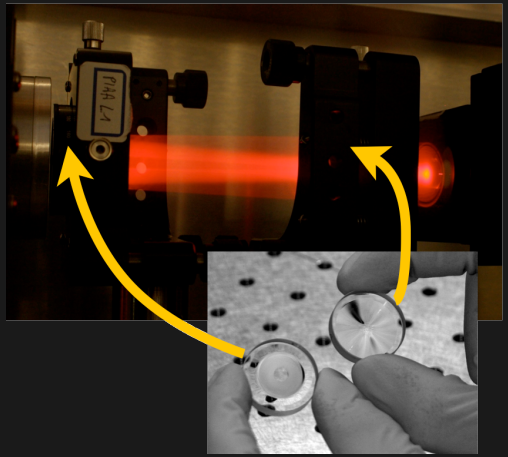


Un PIAA pour le Subaru Telescope!

Quand la technologie est là, y’a plus qu’à!



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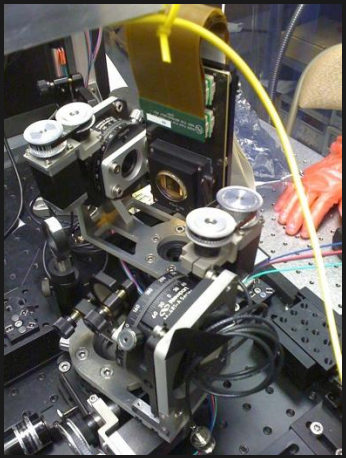

DM à 1000 ou 2000 actuateurs?

Le projet SCExAO

SCExAO: le coucou de l'instrumentation?

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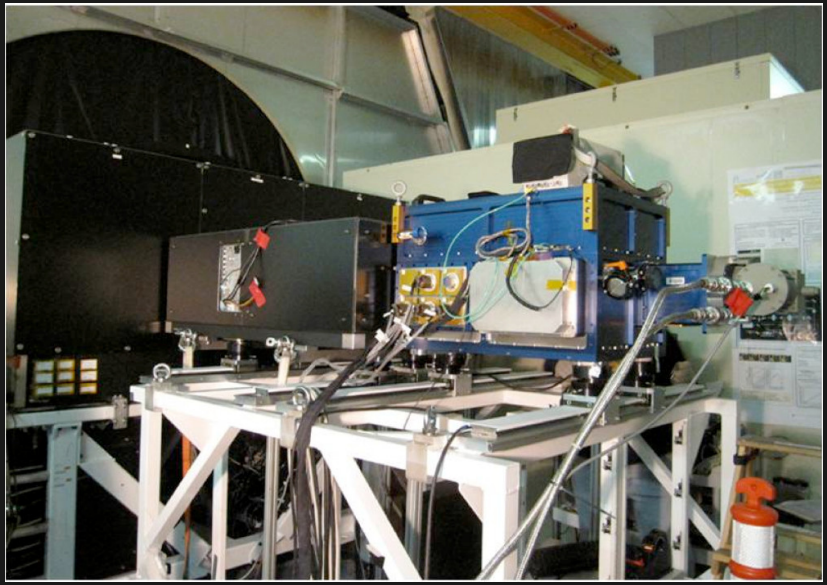
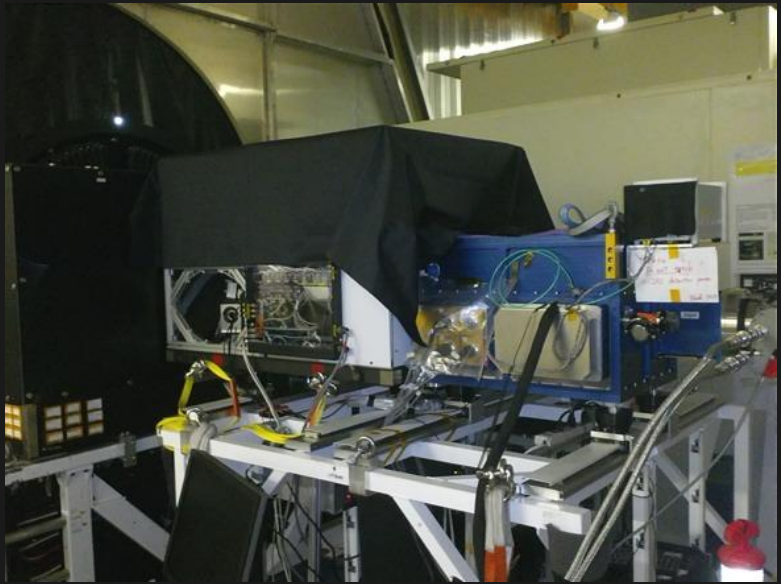


SCExAO: le coucou de l'instrumentation?



SCExAO: le coucou de l'instrumentation?

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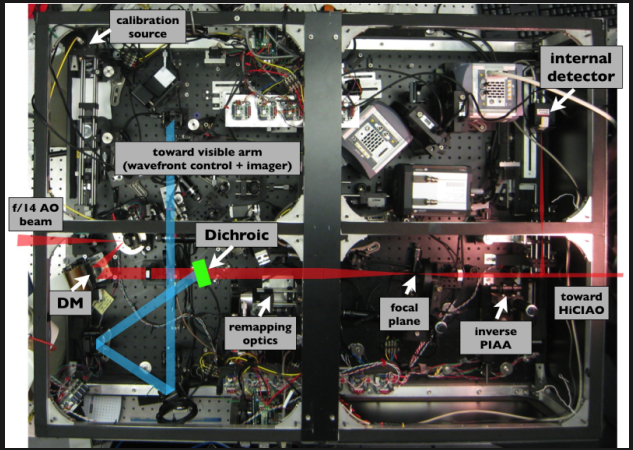
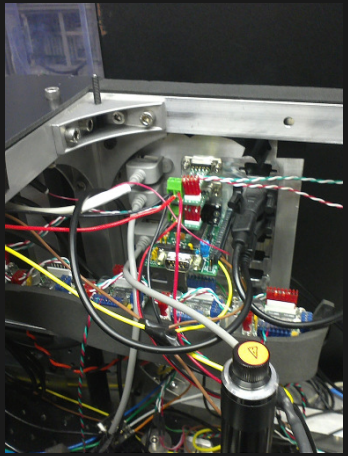
Le paradis de l'expérimentateur



- ∼40 parties mobiles
- un DM à 2000 actionneurs
- cinq caméras
- plans pour deux ASOs?
- PIAA, 8OPM, vortex, Lyot
- en autonomie ou au télescope!
- pilotable à distance

L’enfer de l’ingénieur système



- de multiples alimentations
- une vingtaine de devices à contrôler
- des dizaines de connecteurs
- des "upgrades" en permanence
- des étudiants créatifs
- un effort constant de fiabilisation
- un fer à souder toujours prêt!

Au jour d’aujourd’hui, un instrument plutôt fiable!

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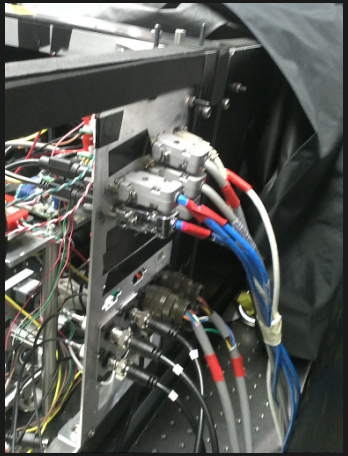

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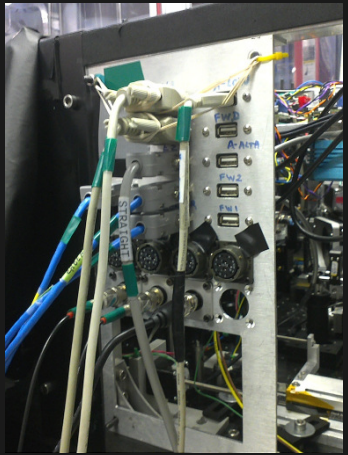

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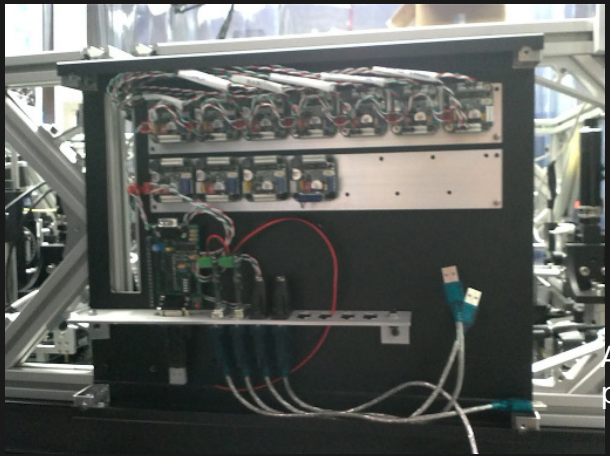

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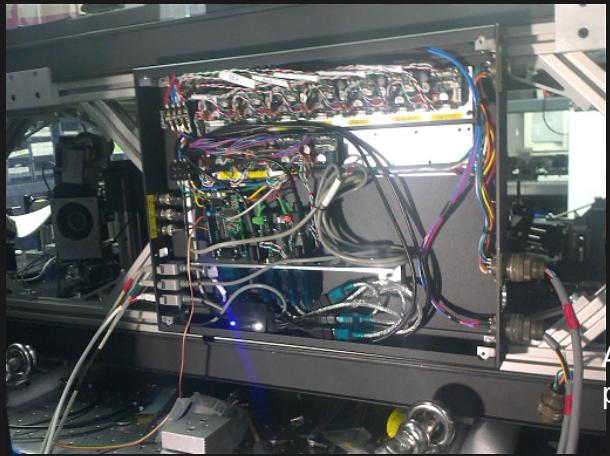

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La famille SCExAO (2008 - 2013)

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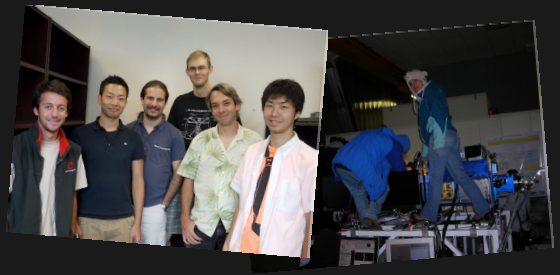

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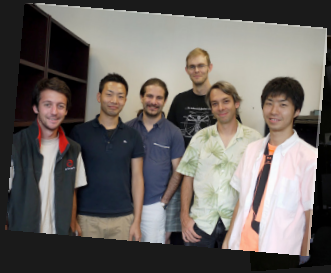

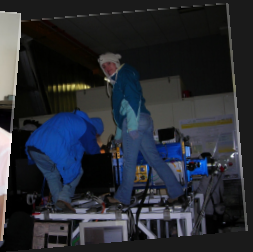

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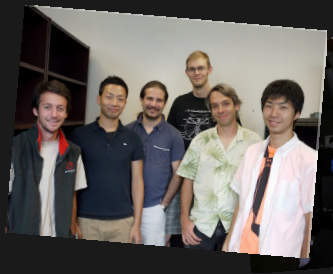

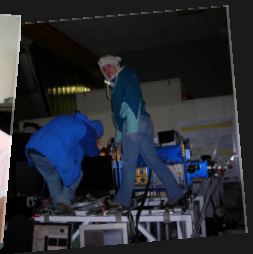

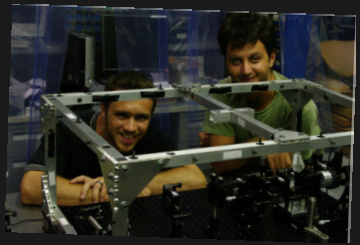

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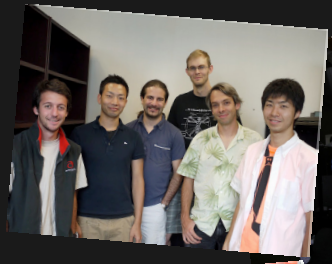

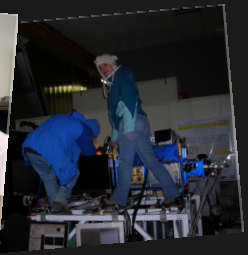

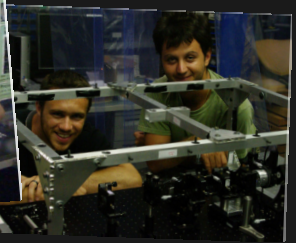

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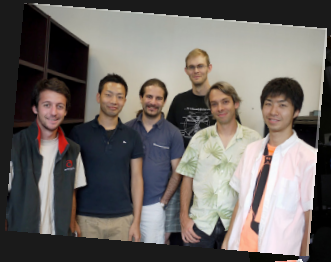
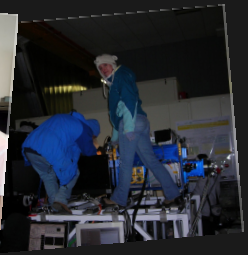
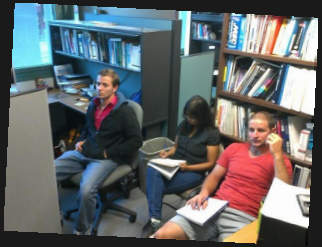
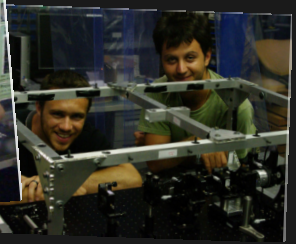
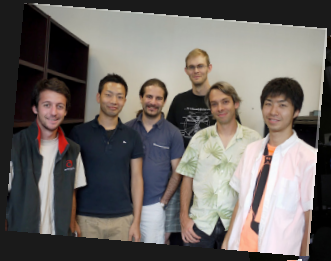


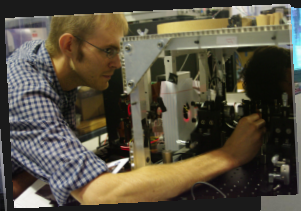
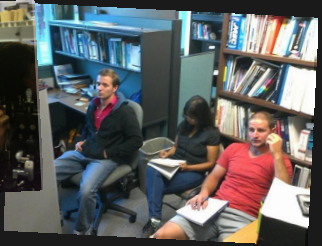


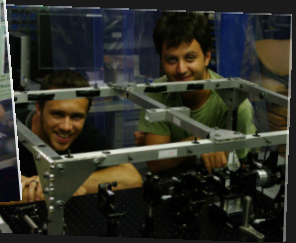




La famille SCExAO (2008 - 2013)





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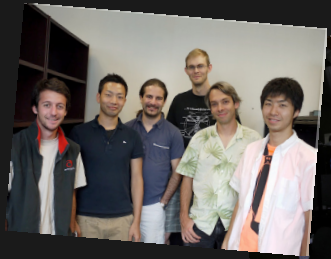

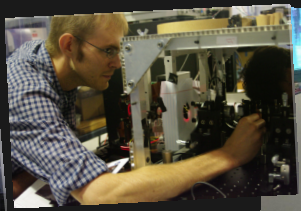
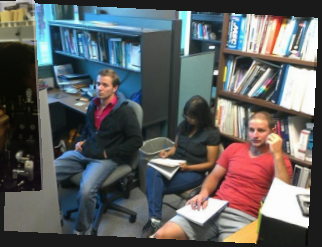

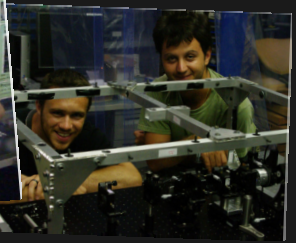

La famille SCExAO (2008 - 2013)

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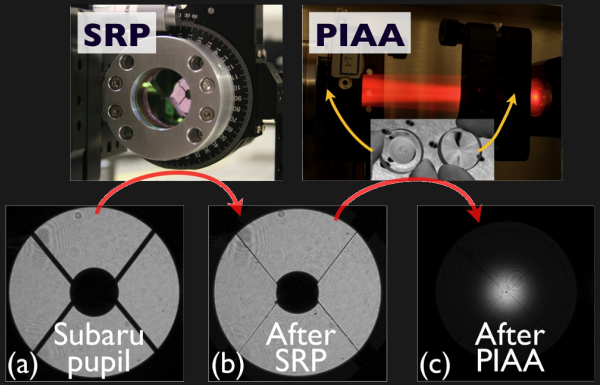
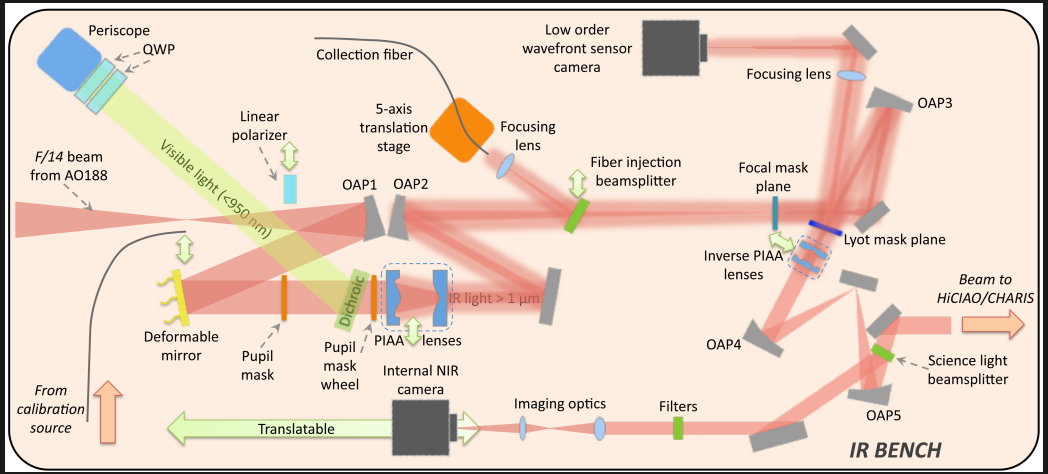
Haut-contraste @ 1 λ/D avec le PIAA



Première démo sur le ciel (Septembre 2011)

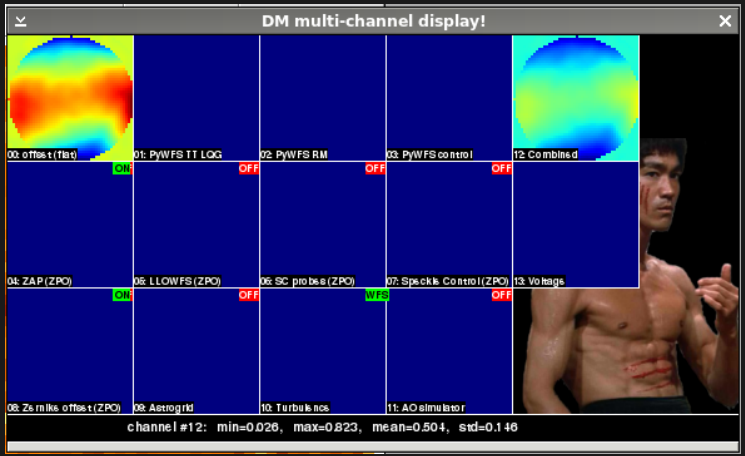
- les optiques PIAA (précédemment testées en labo)
- le PIAA inverse (la nouveauté)

SCExAO infrarouge



Intelligence distribuée pour le contrôle du front d'onde!

Mise au point d'une interface logicielle commune



http://github.com/fmartinache/xaosim/blob/master/xaosim/shmlib.py

Parlez vous SCExAO?

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"Chuck"
Caméra science

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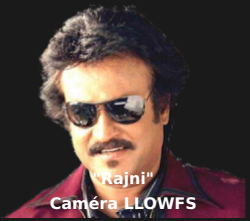

"Rajni"
Caméra LLOWFS

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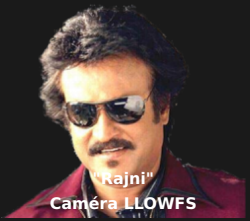
"Chuck"
Caméra science



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Caméra SAPHIRA (UH)

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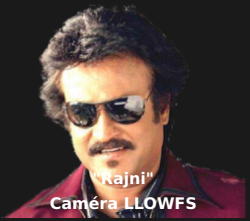

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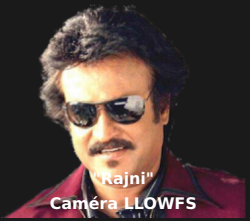

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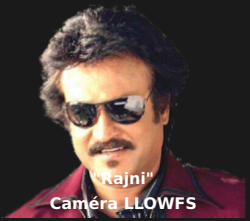
Speckle nulling



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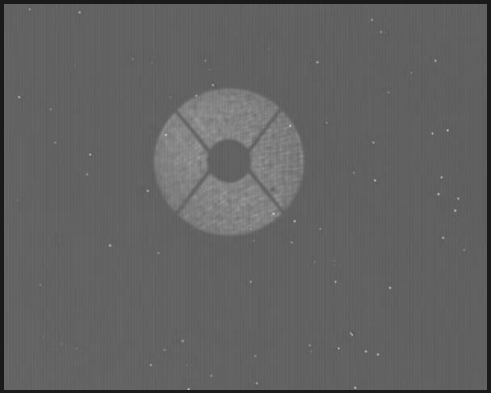
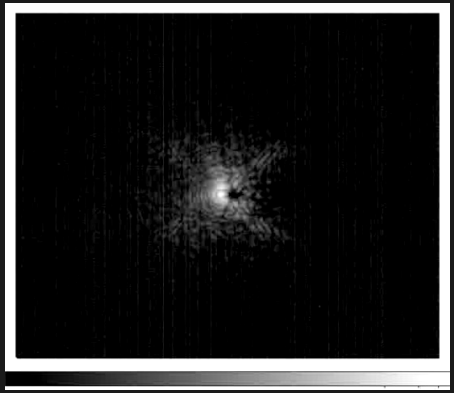
"DM disp Lee"
Miroir déformable

APF-WFS

"Sparkle"
Caméra SAPHIRA (UH)

Contrôle de front d'onde plan focal (2011)

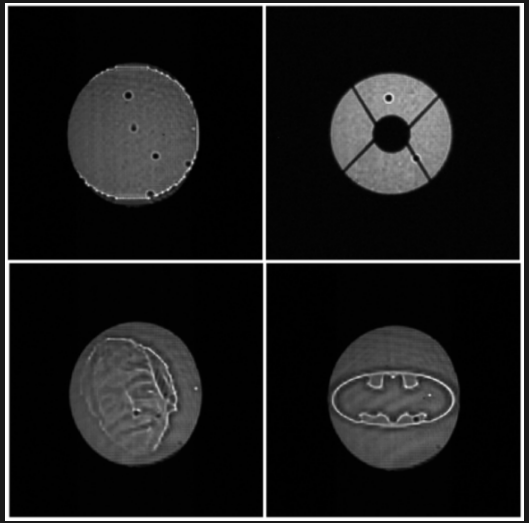




- PIAA + PIAA^{-1}
- contrôle de speckles

dark-hole possible en labo!

Le miroir déformable seul contre les speckles?



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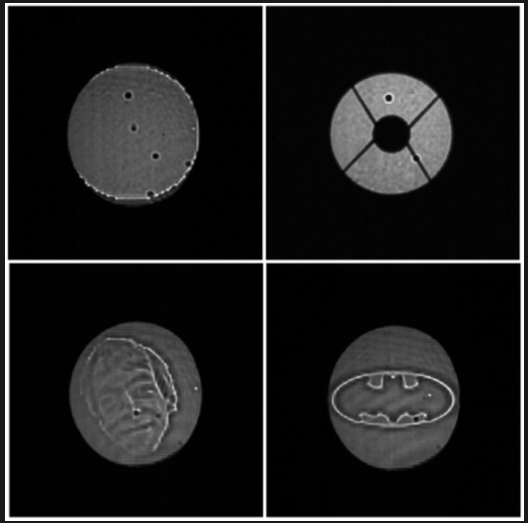
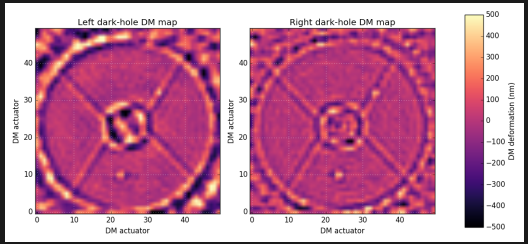
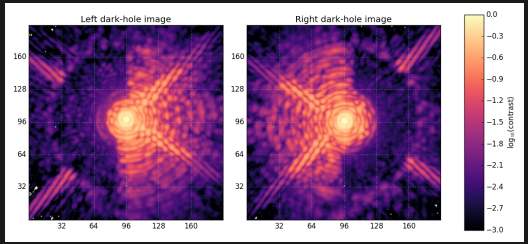
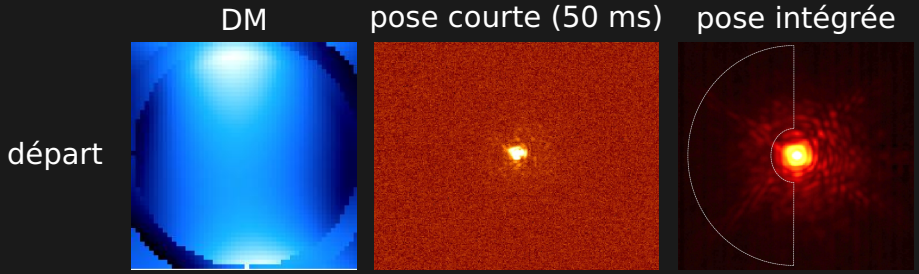




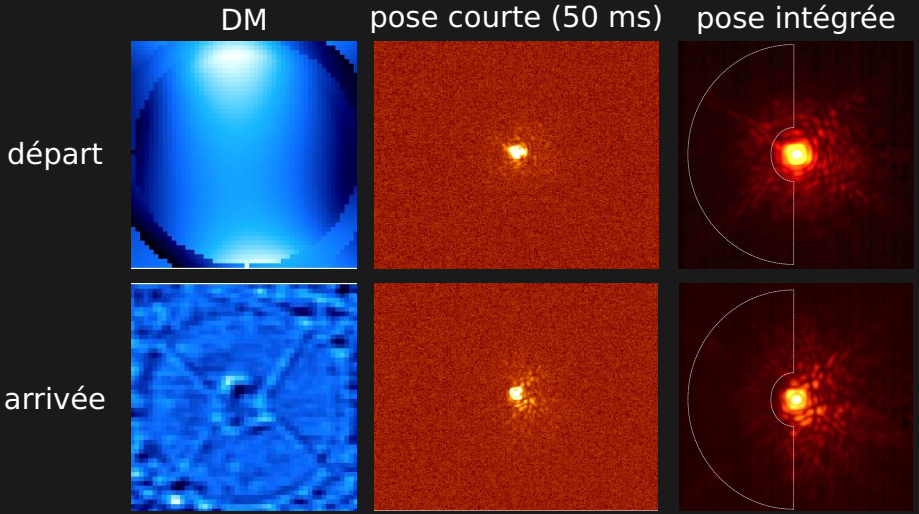


Speckle-nulling avant la XAO?



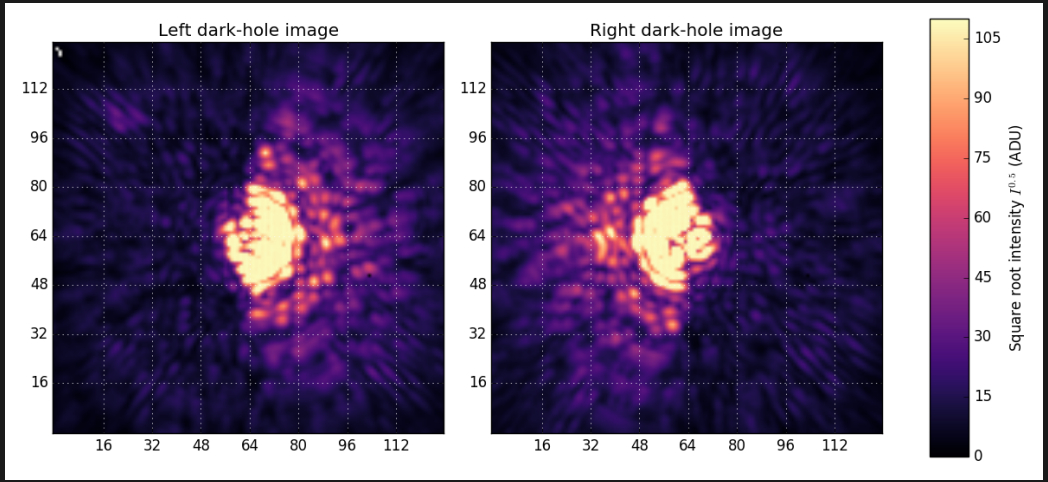
Observation de RX Boo, juin 2014

Speckle-nulling avant la XAO?



Observation de RX Boo, juin 2014

Expériences récentes (juin 2018) de speckle nulling



Avec un coro, quelques dizaines de nanomètres font toute la différence!

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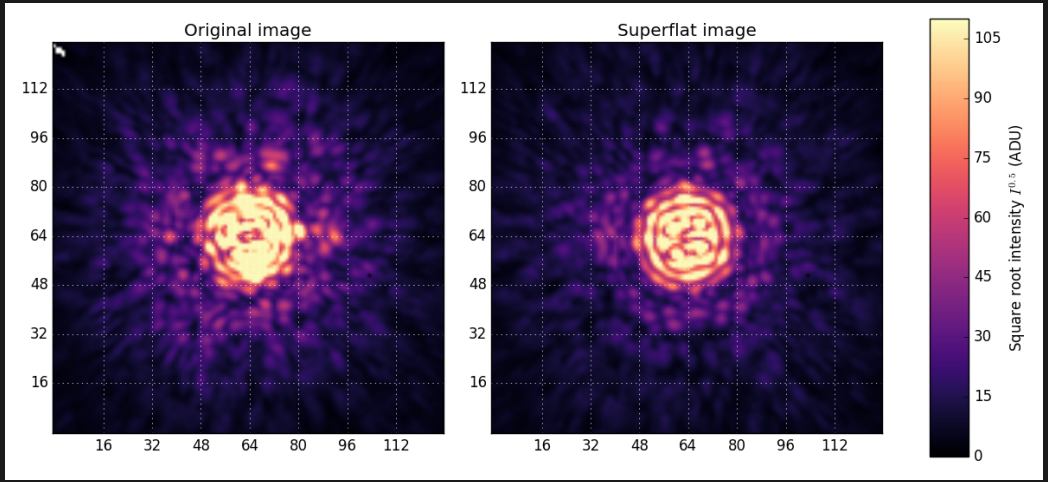

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Les coronographes sont-ils des chochottes?

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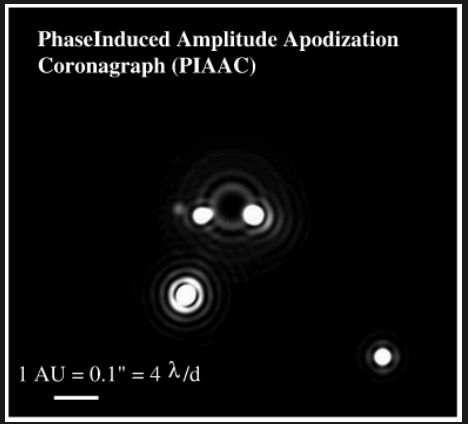
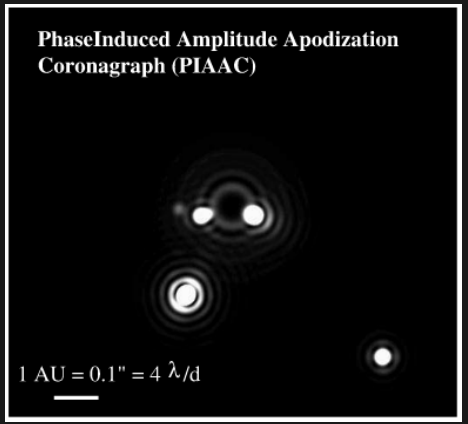
La promesse de la corono. . .



Guyon et al (2005)

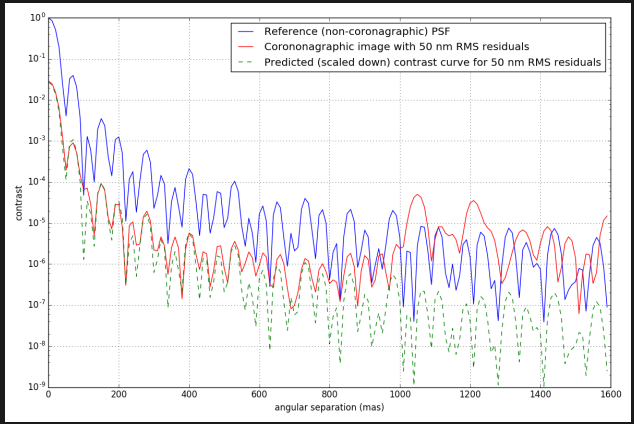
Les coronographes sont-ils des chochottes?

La promesse de la corono...



Guyon et al (2005)

Face à la réalité de l'environnement

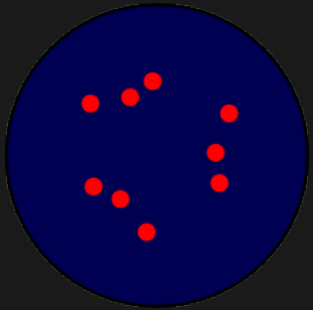


(σ = 50 nm RMS)

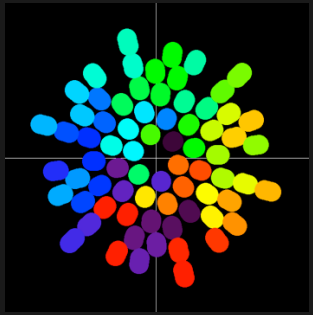
Master plan

1. Astronomie à la limite de la diffraction
2. Interférométrie à masque non-redondant
3. Contrôle actif pour l'imagerie haut-contraste
4. **L'interférométrie des kernels**
5. Vers un haut-contraste robuste... enfin?

Interférométrie sans masque non-redondant?



Non-redondant



couverture uv

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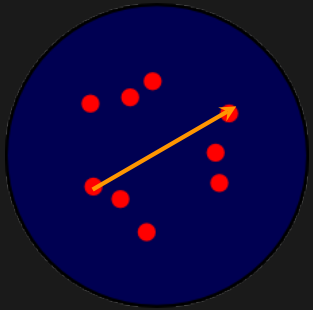

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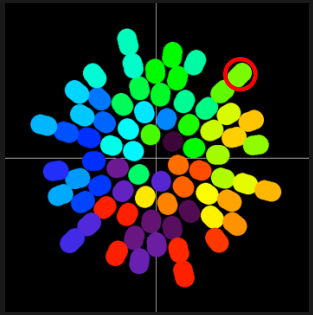

couverture uv

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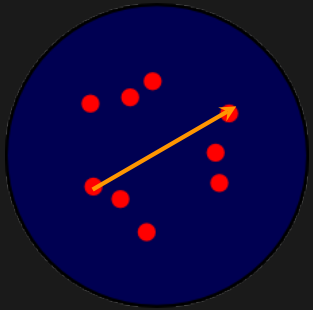
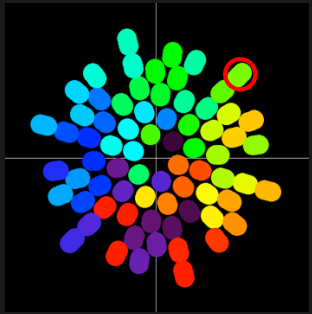


Non-redondant

Pleine ouverture



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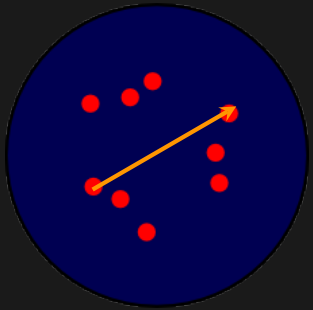

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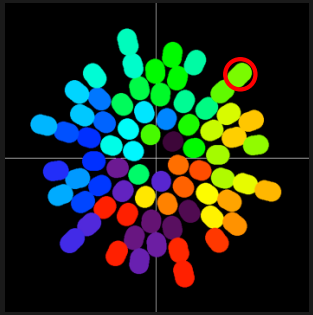

couverture uv

Mais que fait l’optique adaptative?

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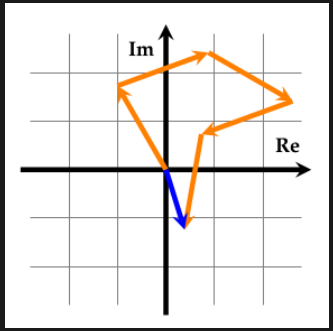

Somme de phaseurs aléatoires = n'importe quoi!

$\rightarrow$ phase et amplitude résultantes inutiles

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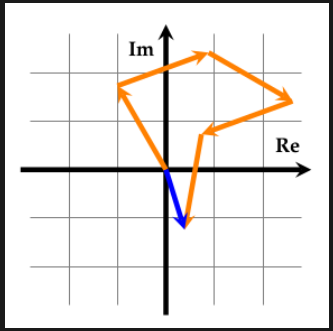

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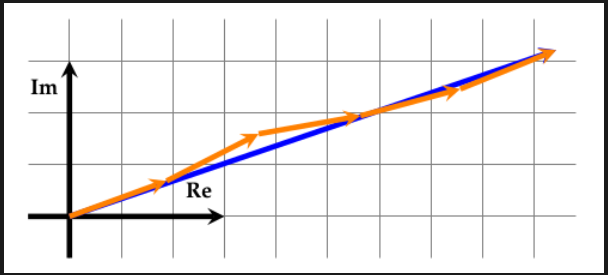

AO $\rightarrow$ correction partielle:

- les phaseurs tendent à s'aligner.
- vraie phase $\approx$ la phase de la somme
- plus c'est redondant, mieux c'est!?

Reformuler la relation de convolution?

L'équation générale d'une composante de la phase dans l'espace de Fourier:

$$\Phi^k = \Phi_O^k + Arg\left(\sum_{i=0}^{r} \exp\left(j\Delta\varphi_i^k\right)\right),$$

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peut être linéarisée lorsque de l'OA est utilisée:

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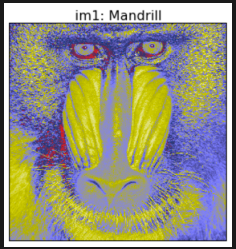
La relation de convolution objet-image peut être reformulée:

$$I = O \otimes PSF \rightarrow \Phi = \Phi_0 + \mathbf{R}^{-1} \cdot \mathbf{A} \cdot \varphi$$

Mais ça n’est que la moitié du problème?



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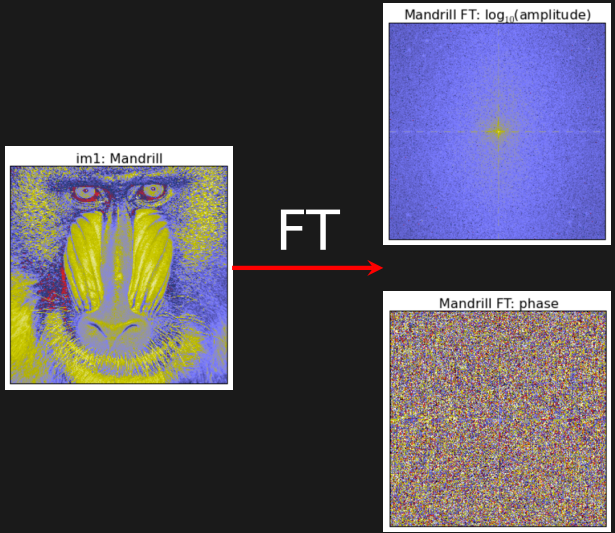
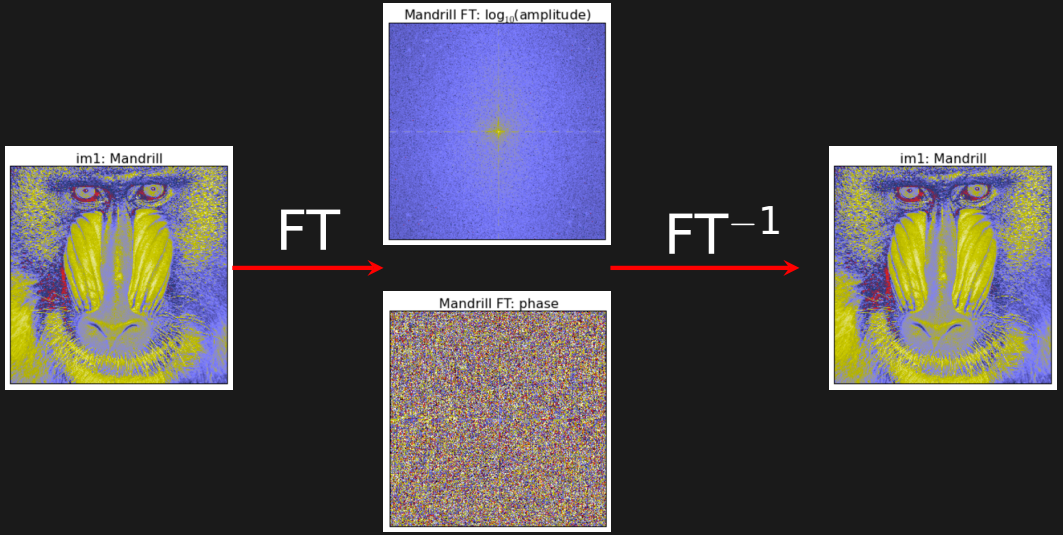


Mais ça n’est que la moitié du problème?



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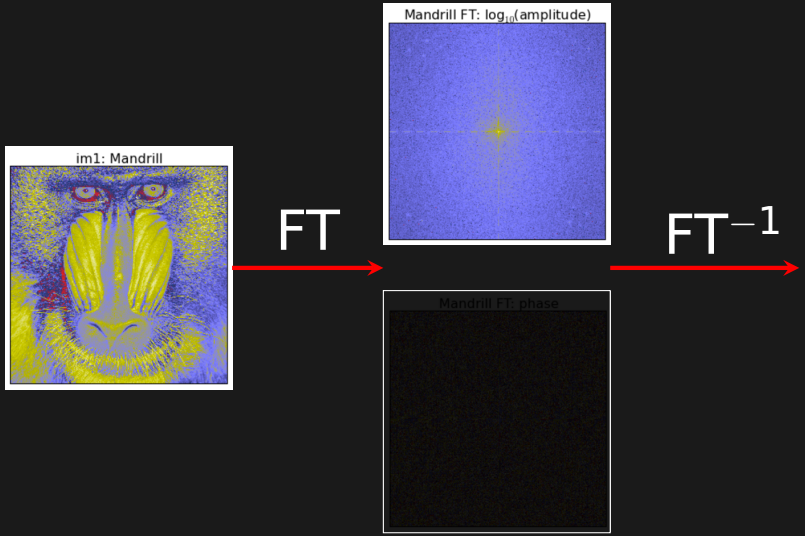

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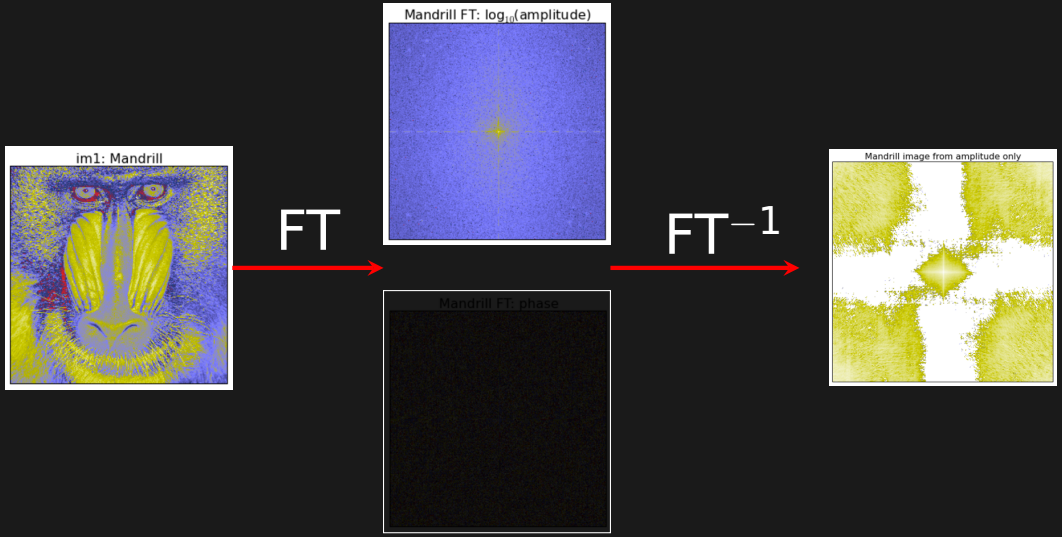
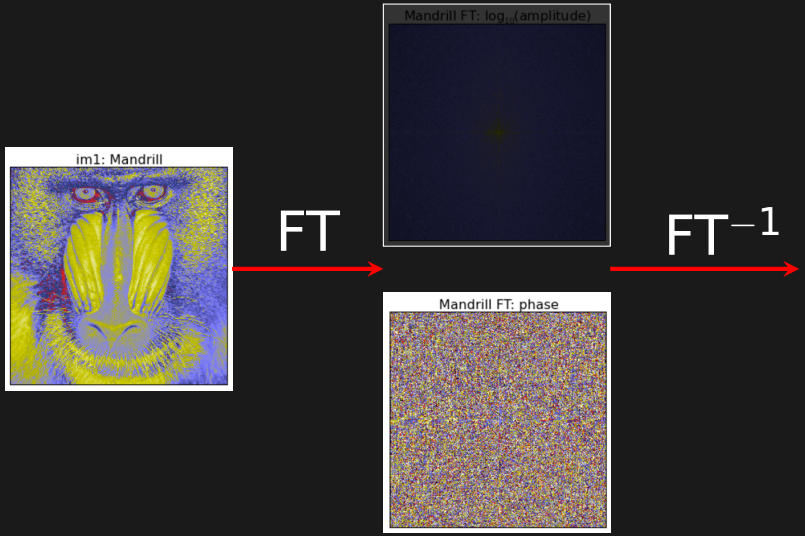


Mais ça n’est que la moitié du problème?



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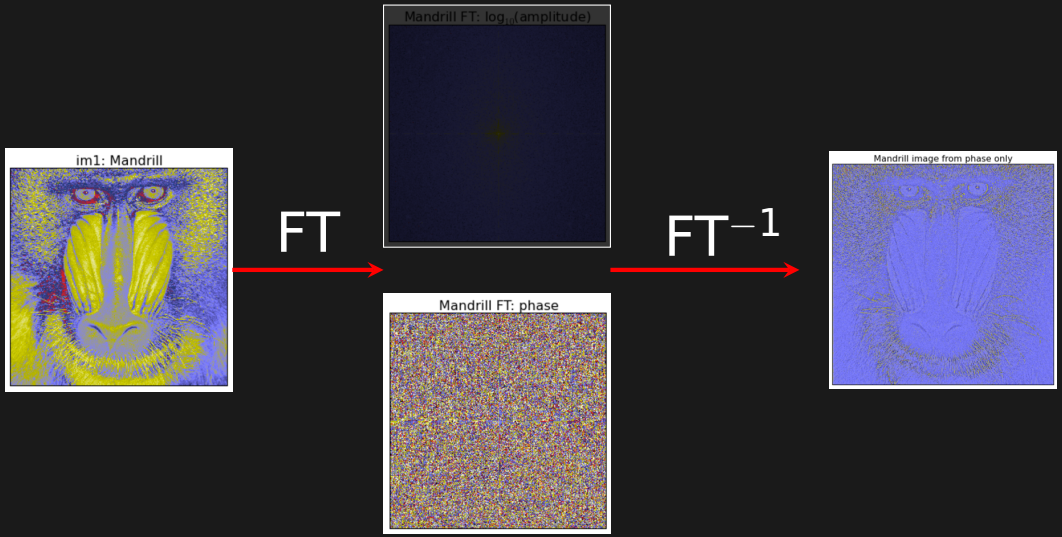
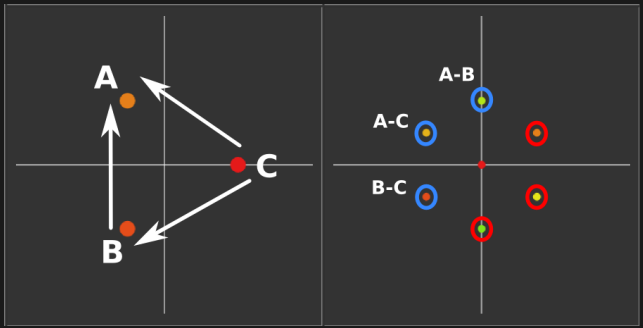


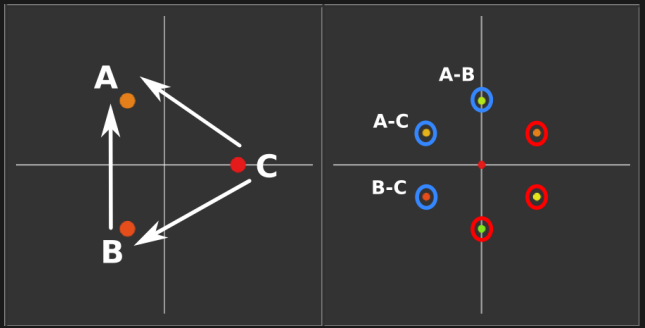
(flashback) La clôture de phase



relations de phase

- $\Phi(A\text{-}B) = \Phi(A\text{-}B)_0 + (\varphi_A - \varphi_B)$
- $\Phi(A\text{-}C) = \Phi(A\text{-}C)_0 + (\varphi_A - \varphi_C)$
- $\Phi(B\text{-}C) = \Phi(B\text{-}C)_0 + (\varphi_B - \varphi_C)$

La clôture de phase reformulée

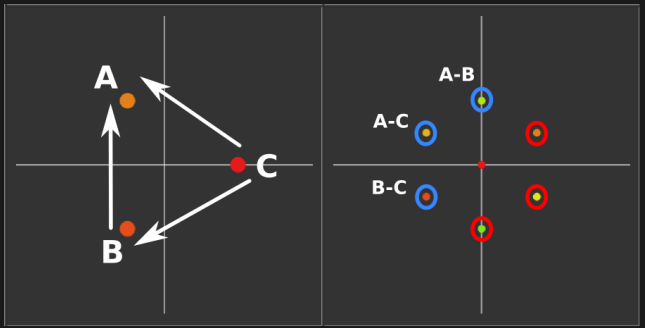


modèle linéaire

$$\Phi = \Phi_0 + \mathrm{A} \cdot \varphi$$

$$\mathbf{A} = \begin{bmatrix} 1 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & 1 & -1 \end{bmatrix}$$

La clôture de phase reformulée



modèle linéaire

$$\Phi = \Phi_0 + \mathbf{A} \cdot \varphi$$

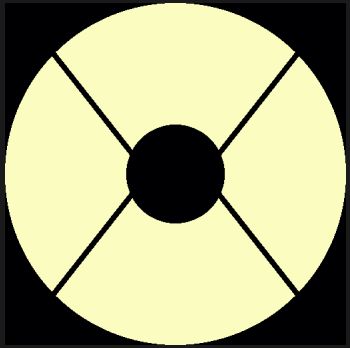
$$\mathbf{A} = \begin{bmatrix} 1 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & 1 & -1 \end{bmatrix}$$

kernel = clôture de phase

$$\mathbf{K} = \begin{bmatrix} 1 & -1 & 1 \end{bmatrix}$$

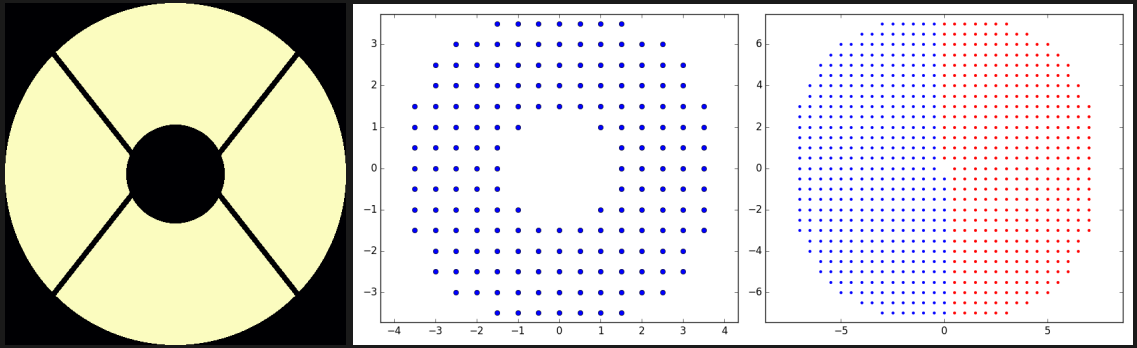
Verifies $\mathbf{K} \cdot \mathbf{A} = 0$

Le clôture de phase généralisée



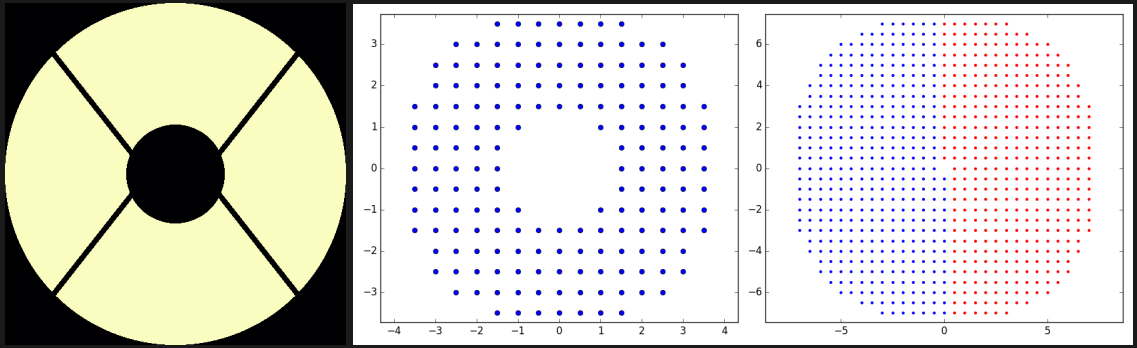
Pupille continue d’un télescope de 8-m

Le clôture de phase généralisée



Pupille continue d'un télescope de 8-m
identifiée à un interféromètre redondant de 172 éléments

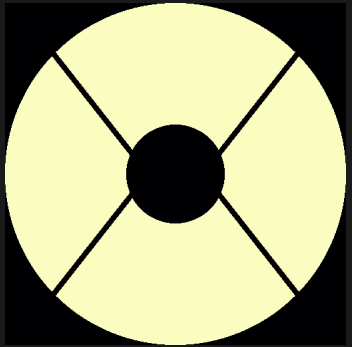
Le clôture de phase généralisée

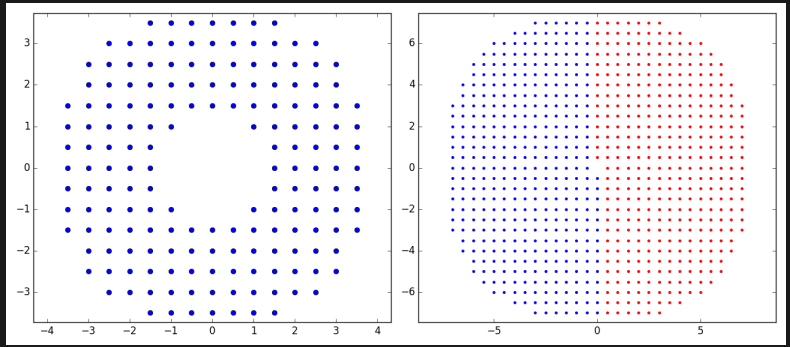


Pupille continue d'un télescope de 8-m

identifiée à un interféromètre redondant de 172 éléments formant 366 bases interférométriques

Le clôture de phase généralisée



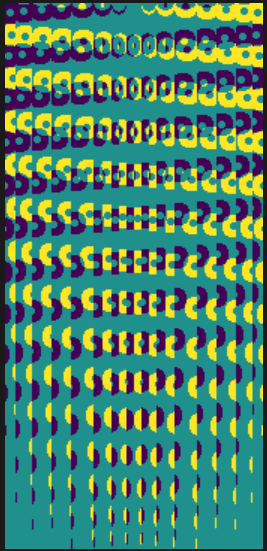


Pupille continue d'un télescope de 8-m

identifiée à un interféromètre redondant de 172 éléments formant 366 bases interférométriques

A est une matrice 366x172: $\Phi = \Phi_0 + R^{-1} \cdot A \cdot \varphi$

Les propriétés de la matrice A

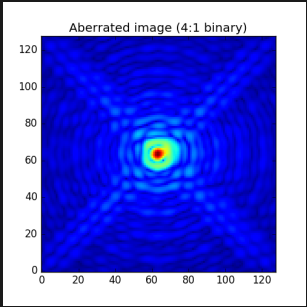


La matrice de transfert est:

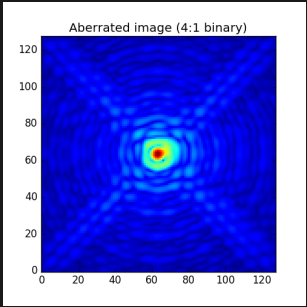
- rectangulaire, éparse
- contient des 0, des +1 et des -1
- SVD $\rightarrow$ rang et taille du kernel

Comme $n_{UV} > n_A$: il y a toujours un kernel!

En pratique

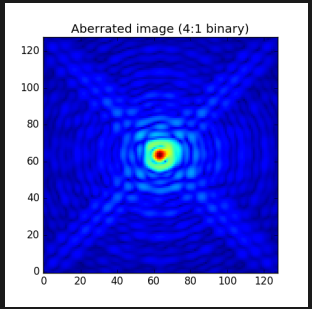

Aberrated image (4:1 binary)
120
100
80
60
40
20
0
0
20
40
60
80
100
120

En pratique

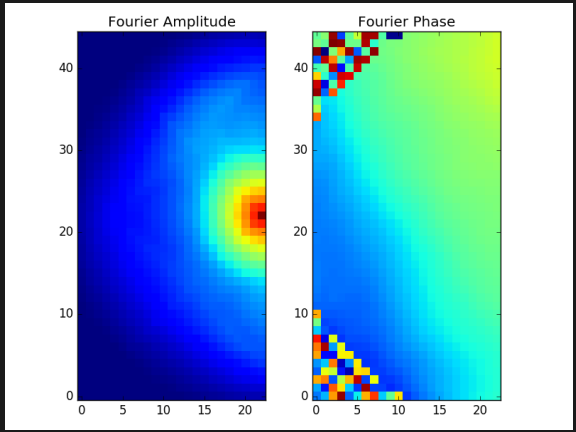


TF

En pratique

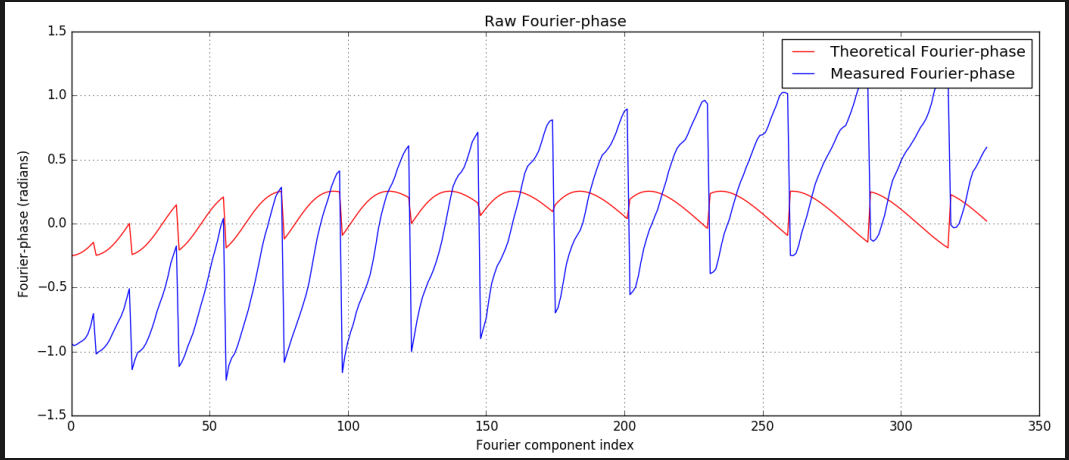


TF



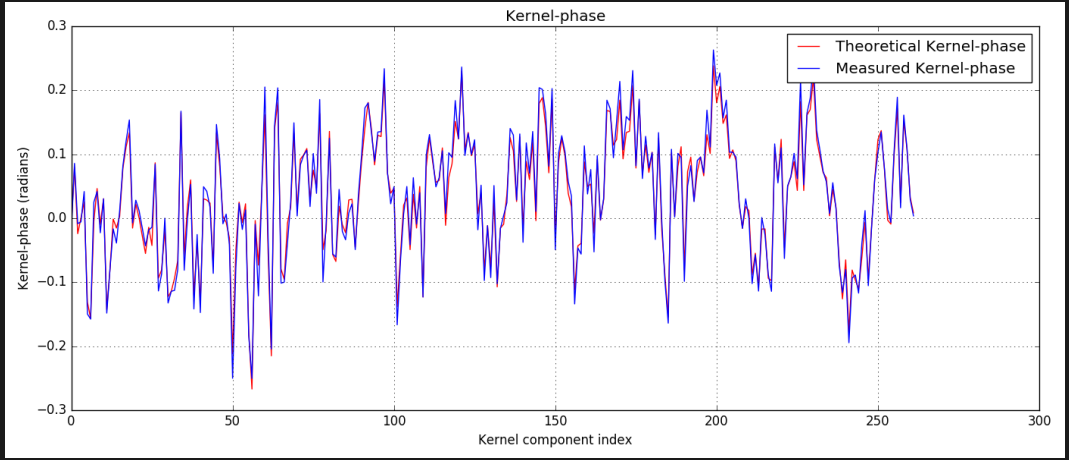
phase: dominée par les aberrations

En pratique



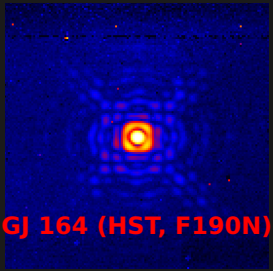
la phase brute Φ: information inutilisable

En pratique



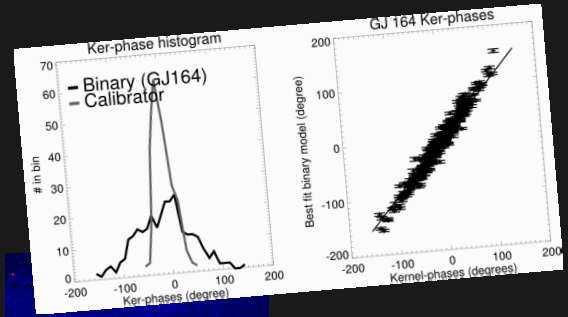
kernels $K \cdot \Phi$: 100 % utilisable!

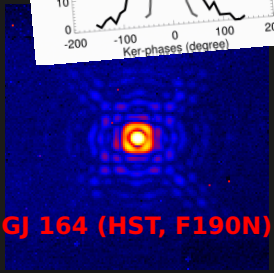
Et ça sert!



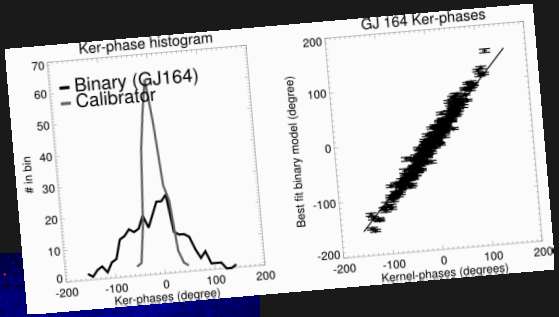
GJ 164 (HST, F190N)

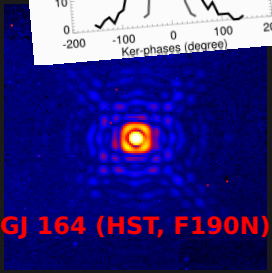
Et ça sert!


Ker-phase histogram
Binary (GJ164)
Calibrator
in bin
Ker-phases (degree)
GJ 164 Ker-phases
Best fit binary model (degree)
Kernel-phases (degrees)


GJ 164 (HST, F190N)

Et ça sert!





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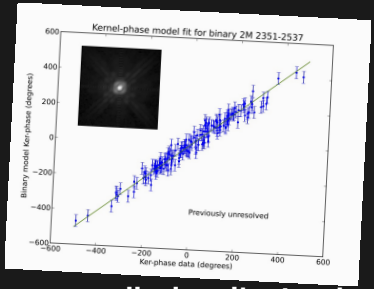
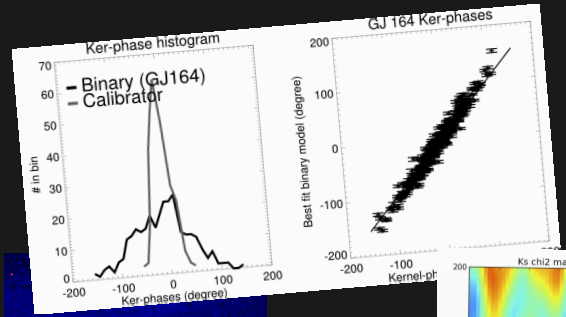
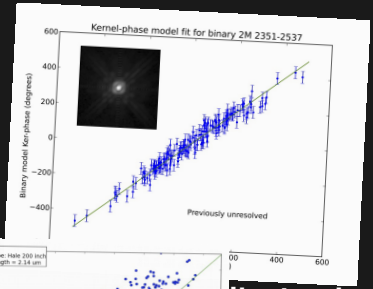


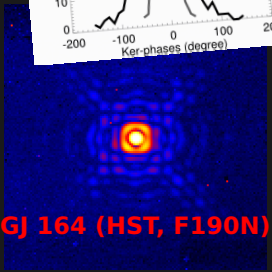
+ une dizaine d'autres!

Et ça sert!

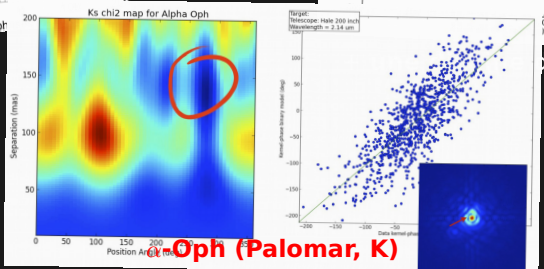




d'autres!

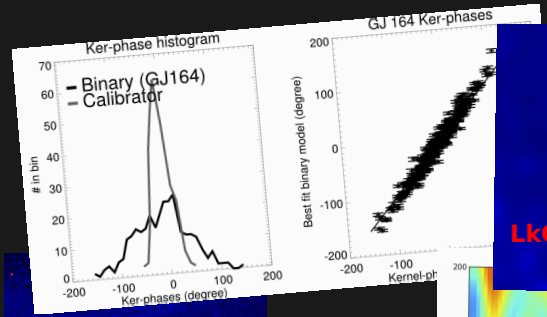


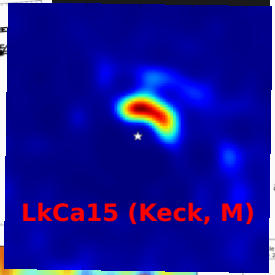
GJ 164 (HST, F190N)

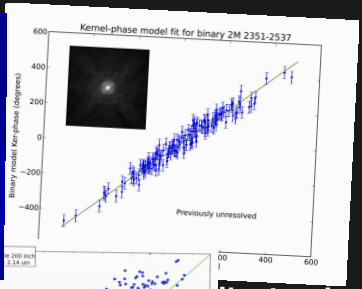


α Oph (Palomar, K)

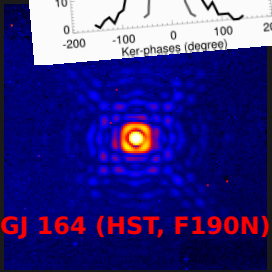
Et ça sert!

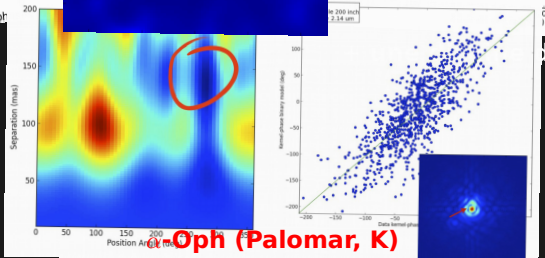






d'autres!





Utilisation métrologique du modèle linéaire?

inverser le modèle linéaire: $\Phi = \Phi_0 + R^{-1} \cdot A \cdot \varphi$

Utilisation métrologique du modèle linéaire?

inverser le modèle linéaire: $\Phi = \Phi_0 + R^{-1} \cdot A \cdot \varphi$

$\rightarrow \varphi = R \cdot A^T \cdot (\Phi - \Phi_0)$ **est il possible?**

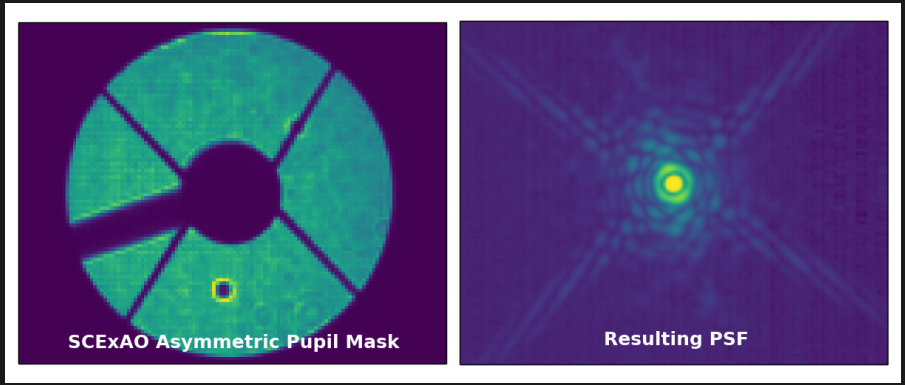
Utilisation métrologique du modèle linéaire?

inverser le modèle linéaire: $\Phi = \Phi_0 + R^{-1} \cdot A \cdot \varphi$

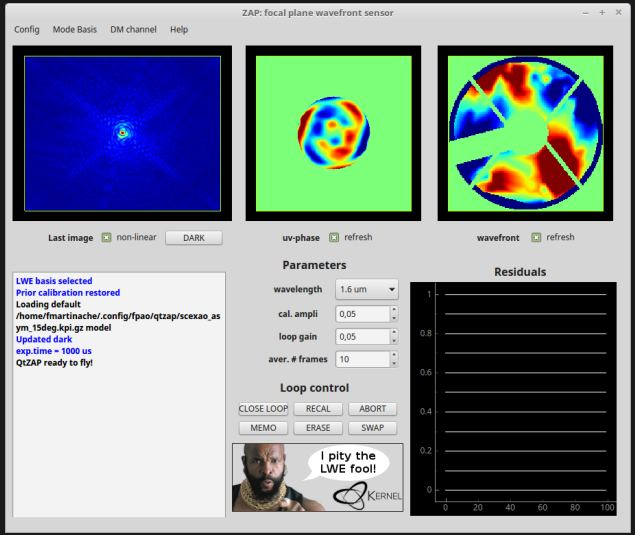
$\rightarrow \varphi = R \cdot A^T \cdot (\Phi - \Phi_0)$ **est il possible?**

tout dépend des propriétés de A... et donc de la pupille!

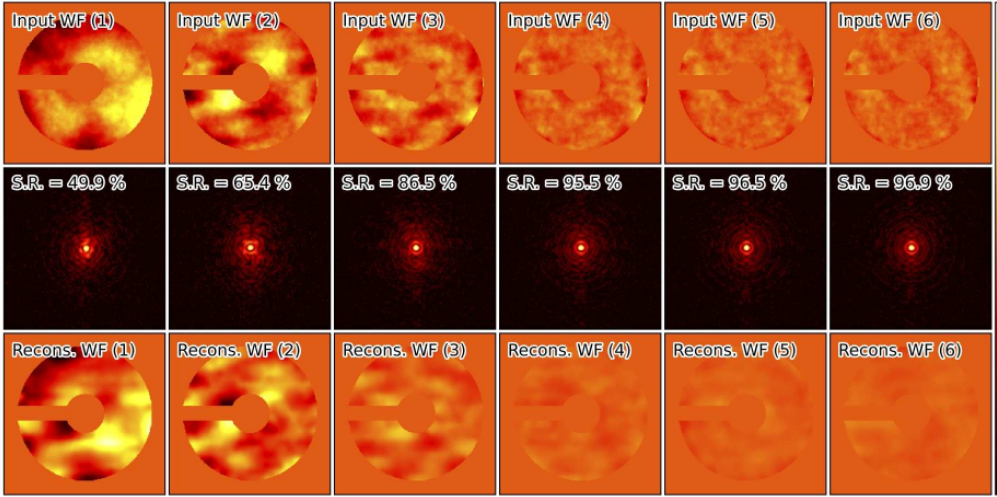
Utilisation métrologique du modèle linéaire?



Utilisation métrologique du modèle linéaire?



Utilisation métrologique du modèle linéaire?



Le projet KERNEL (2016 - 2021)

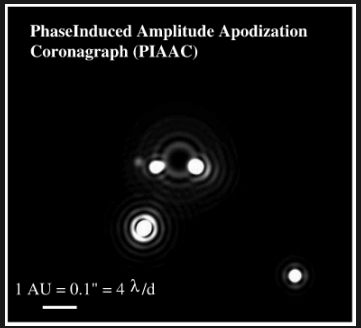
- déterminer des limites fondamentales du framework
- utiliser les outils du traitement du signal (papier en préparation)
- systématiser de l'analyse de données
- exploiter le potentiel astro (papier soumis demain?)
- développement de nouvelles utilisations
- notre outil XARA **https://github.com/fmartinache/xara**

Master plan

1. Astronomie à la limite de la diffraction
2. Interférométrie à masque non-redondant
3. Contrôle actif pour l'imagerie haut-contraste
4. L'interférométrie des kernels
5. **Vers un haut-contraste robuste... enfin?**

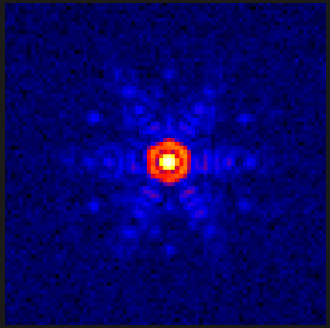
Bruit de photon vs bruit de phase

CORONOGRAPHIE



Bruit de photon ✓
Bruit de phase ✗

KERNEL

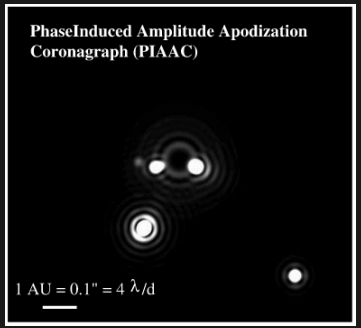


Bruit de photon ✗
Bruit de phase ✓

Peut on marrier les deux?. . .

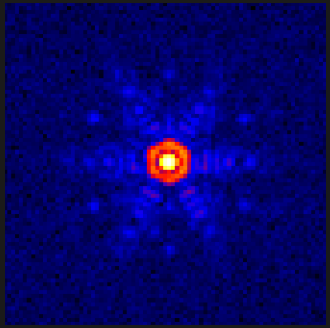
Bruit de photon vs bruit de phase

CORONOGRAPHIE



Bruit de photon ✓
Bruit de phase ✗

KERNEL

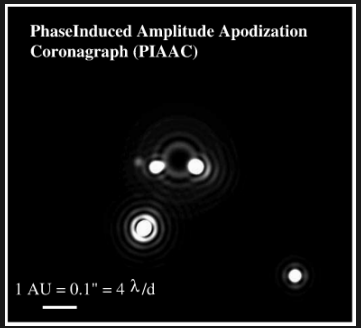


Bruit de photon ✗
Bruit de phase ✓

Peut on marrier les deux?... non...

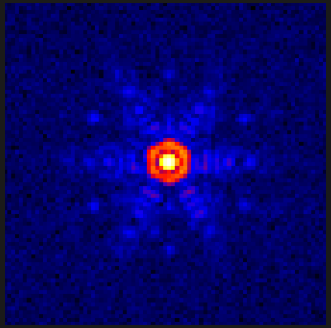
Bruit de photon vs bruit de phase

CORONOGRAPHIE



Bruit de photon ✓
Bruit de phase ✗

KERNEL



Bruit de photon ✗
Bruit de phase ✓

Peut on marrier les deux?... non... mais...

Piste #1: la Kernel-apodisation?

Masque apodisant pour Subaru, compatible avec KERNEL.

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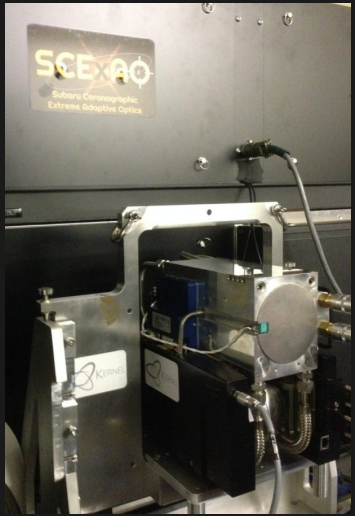

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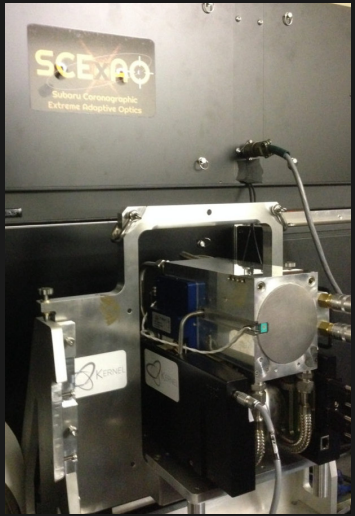


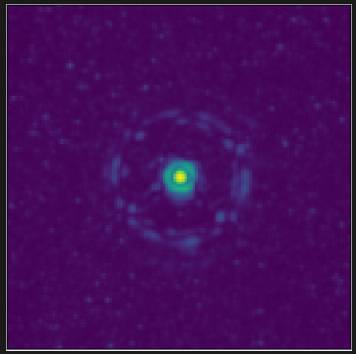
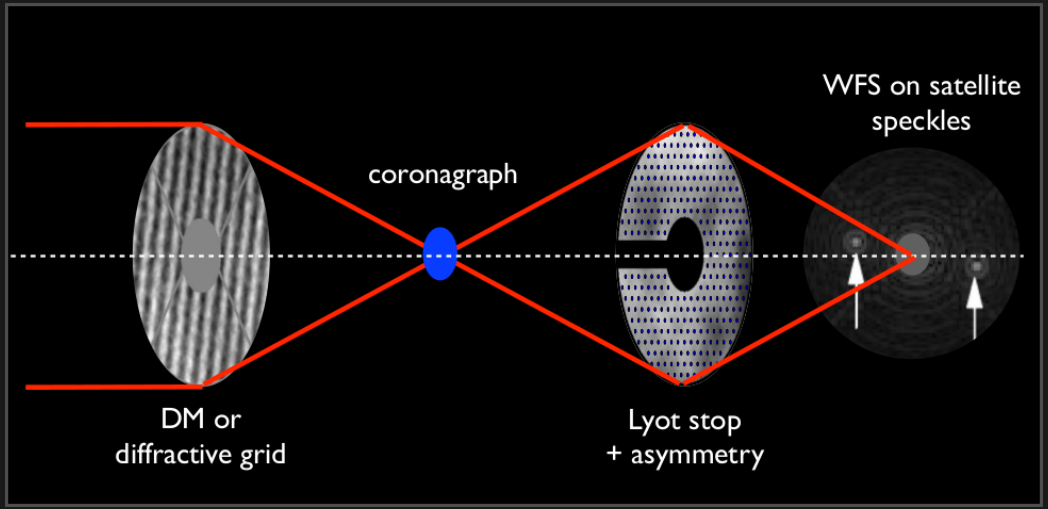


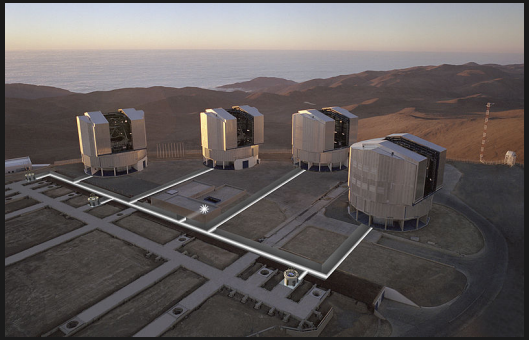
Image apodisée Véga (juin 2018)

Piste #2: coronographie sans OA



Piste #3: le Kernel-nulling?

Un télescope? Trop compliqué! Mettez m'en quatre SVP!



[VLTI [Credit: ESO]]

Besoin de résolution angulaire $\rightarrow$ VLTI

Pour le haut contraste $\rightarrow$ Nulling

- Quatre telescopes: efficacité 75 %
- Un nombre fini de degrés de liberté
- Un nombre fini de covariances
- $\rightarrow$ Un problème bien posé

Le nulling... en théorie

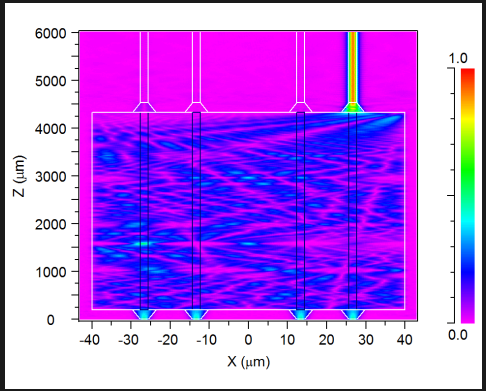
$$\mathbf{N} = 0.5 \times \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

- Quatre faisceaux en entrée
- Une sortie brillante
- Trois sorties sombres

Les photons d'une planète sont couplés dans les sorties sombres

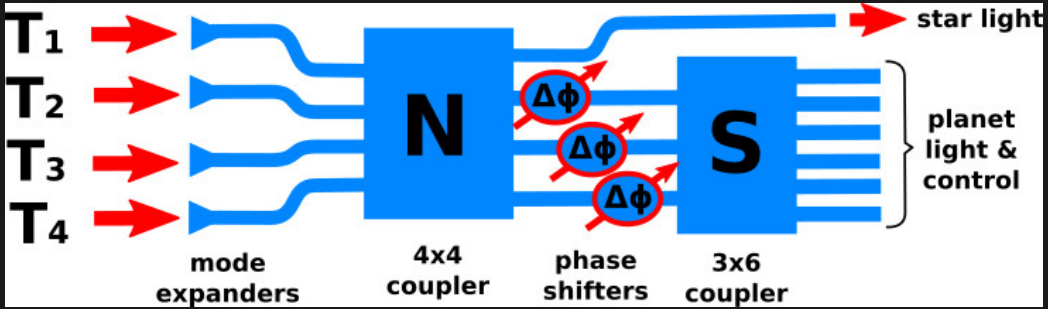
Mais, reste sensible aux perturbations!

4x4 nuller



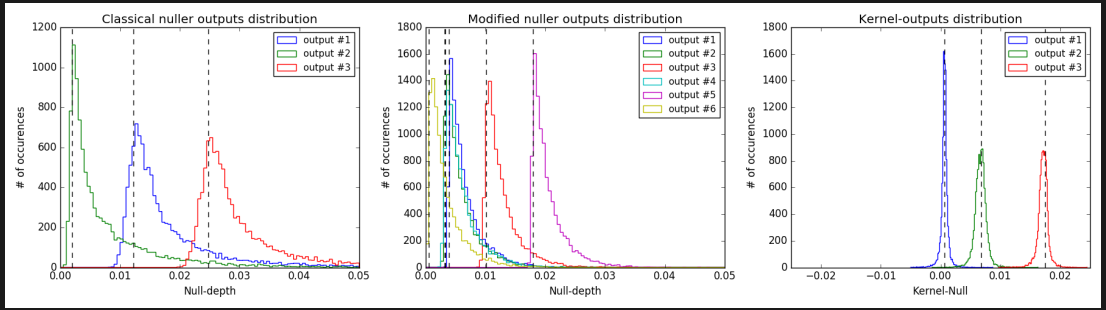
(MMI design by Harry-Dean Kenchington Goldsmith, ANU PhD candidate)

Nuller $\rightarrow$ Kernel-nuller



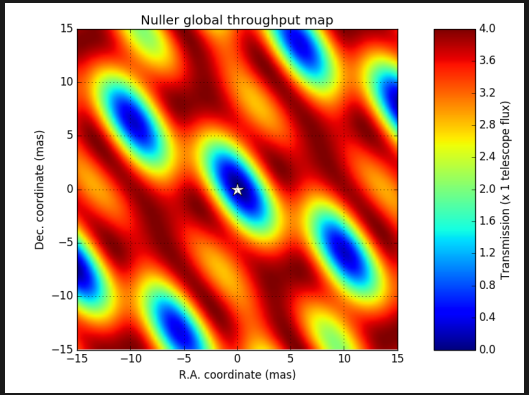
- Rajouter un 2^{eme} étage pour mélanger les signaux sombres
- Rendre la réponse aux perturbations asymétrique!
- Identifier des kernels, combinaisons linéaires de mesures indépendantes de la perturbation

Kernel-nulled outputs: mesures robustes possibles

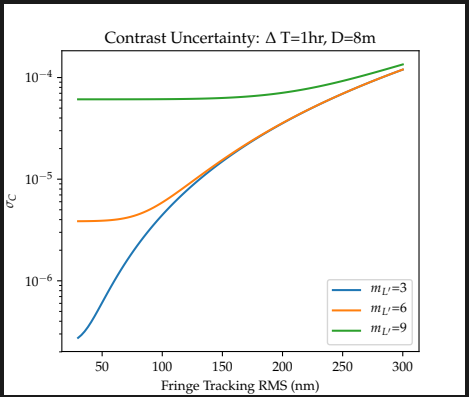


Les kernels permettent de filtrer les perturbations du deuxième ordre

L-band VLTI 4UT



Transmission globale du nuller



Incertitude médiane sur le contraste

Le potentiel de détecter des planètes détectées par vitesse radiale!

VIKiNG: the VLTI Infrared Kernel NullinG

Kernel-nulling

La puissance du marteau de Thor (le nuller) frappant avec une justesse chirurgicale (le kernel): l'arme parfaite pour le VIKiNG se destinant à découvrir de nouveaux mondes!

Pour plus de détails:
https://arxiv.org/abs/1802.06252

[Image Credit: http://www.kungfury.com/]

Merci