

Des franges à 4 télescopes au VLTI: premiers résultats de PIONIER



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Séminaire AGO – 5 décembre 2011

Comment tout a commencé...

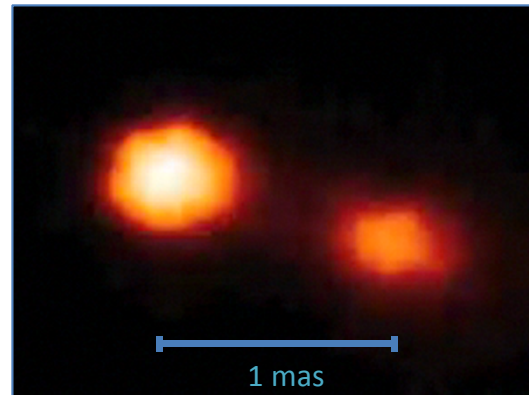
- Juin 2008, conférence SPIE à Marseille
 - CHARA/MIRC: première image de la surface d'une étoile de la séquence principale!
 - Le VLTI a une guerre de retard
- Un groupe d'irréductibles Grenoblois fomentent la révolution à la terrasse d'un troquet...



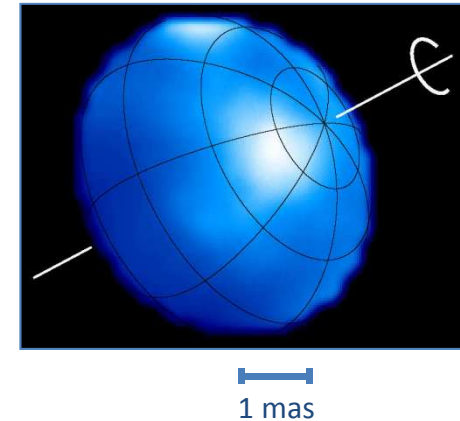
Contexte scientifique en 2008

- CHARA combine 4-6T
 - Imagerie à très haute résolution possible en 1 seule nuit
- Sensibilité limitée
 - Physique stellaire principalement

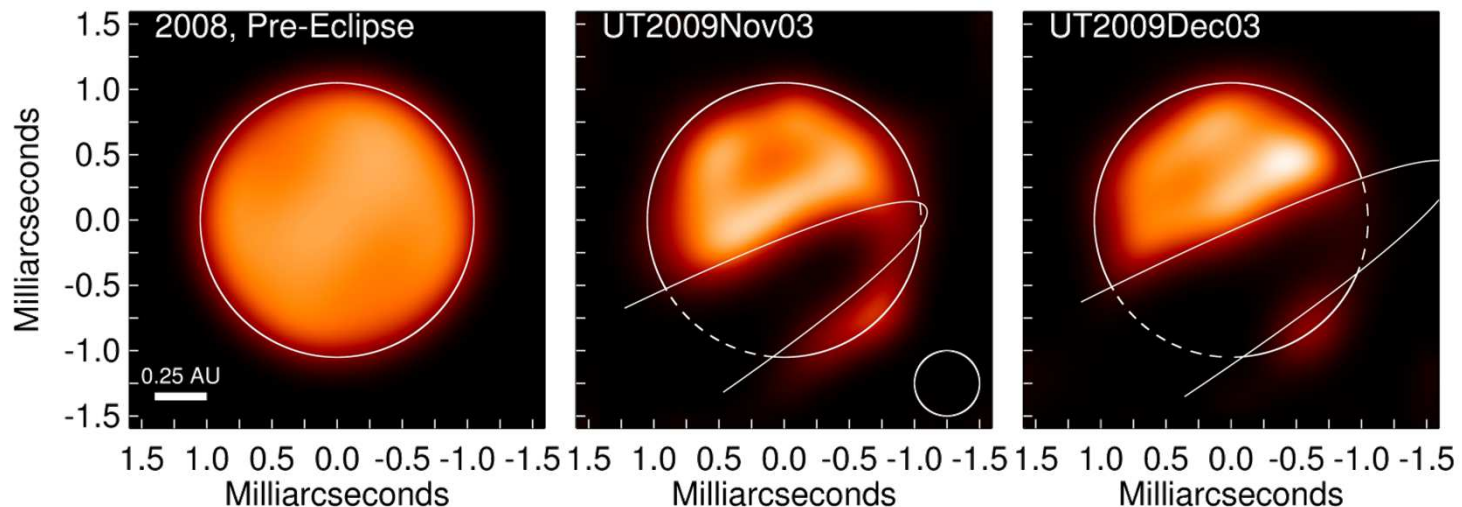
Bet Lyr (Zhao et al. 2008)



Altair (Monnier et al. 2007)



Eps Aur (Kloppenberget al. 2010)

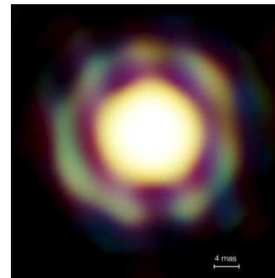


Contexte ESO/Paranal en 2008

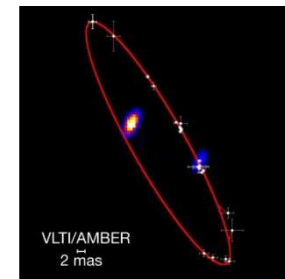
- Very Large Telescope **Interferometer**
 - 8 télescopes (UTs, ATs)
 - 6 lignes à retard
- Instruments disponibles
 - AMBER: 3T bandes JHK
 - MIDI: 2T bande N
 - Imagerie difficile (lent)
- 2^{ème} génération: 4T
 - MATISSE & GRAVITY
 - Prévus pour 2014/2015



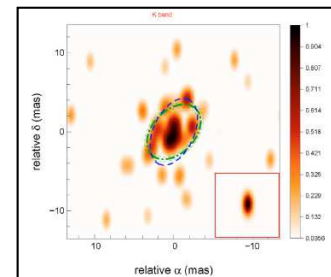
Le Bouquin et al. 2009



Kraus et al. 2009

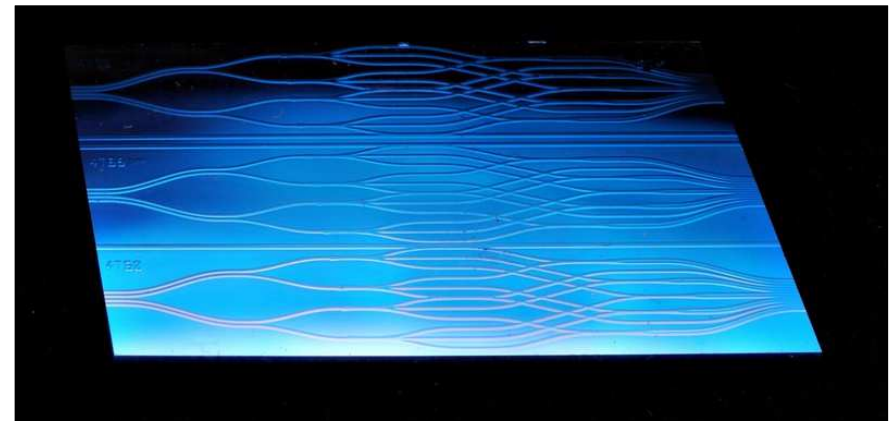


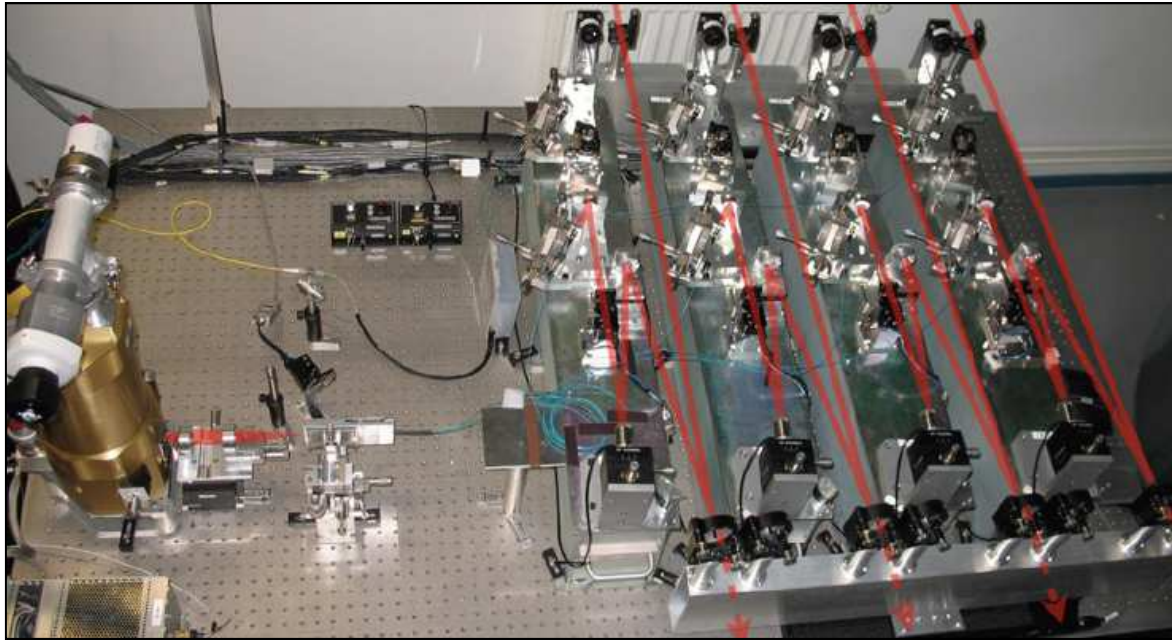
Renard et al. 2010



Contexte LAOG en 2008

- Composants d'optique intégrée pour l'interférométrie
 - 10 ans de développement
 - Composant 3T validé sur le ciel (IOTA)
 - Composant 4T validé au labo
- Expertise complète
 - Conception instrumentale
 - Environnement ESO
 - Imagerie





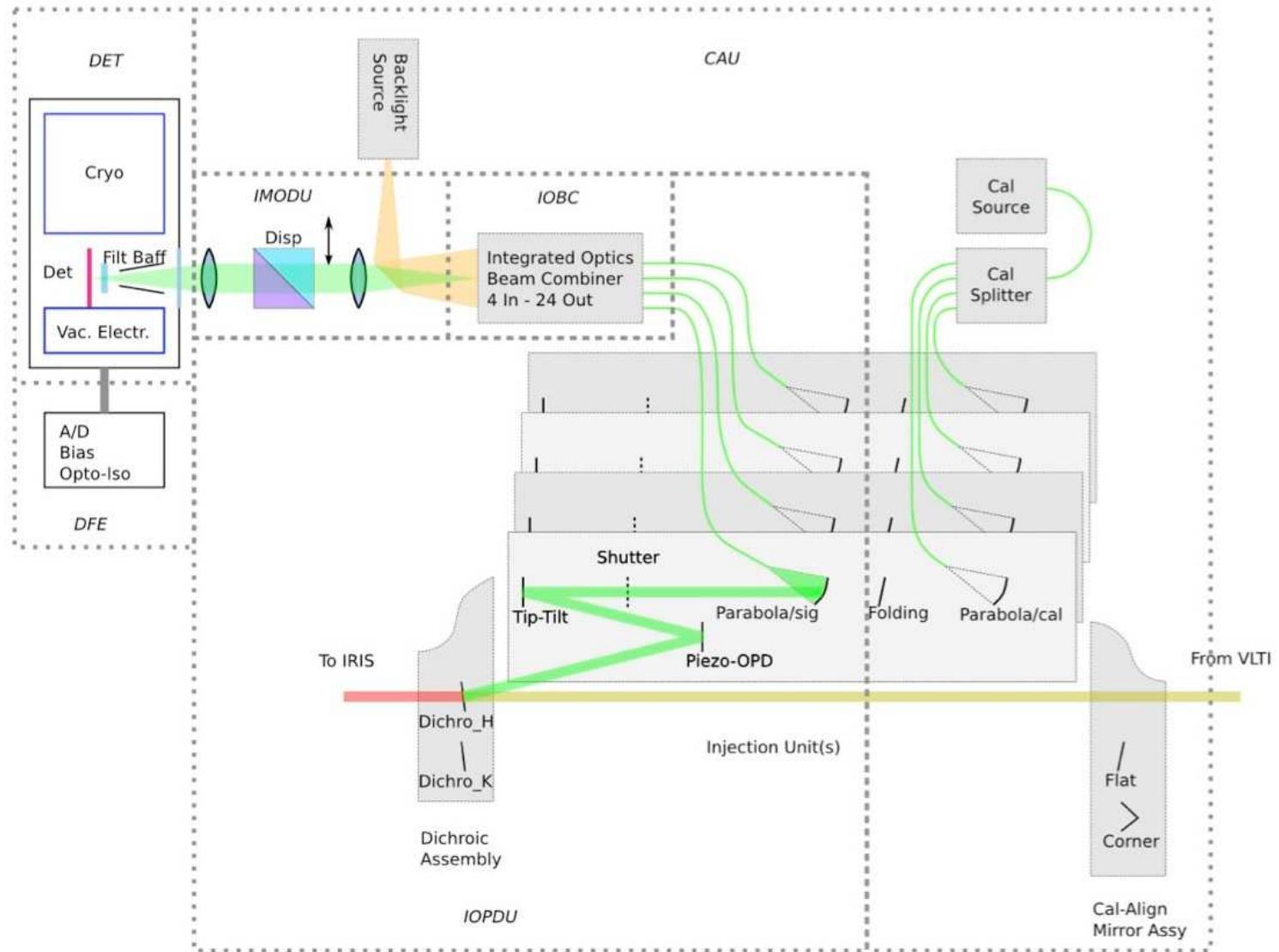
Le projet PIONIER

DÉVELOPPEMENT INSTRUMENTAL

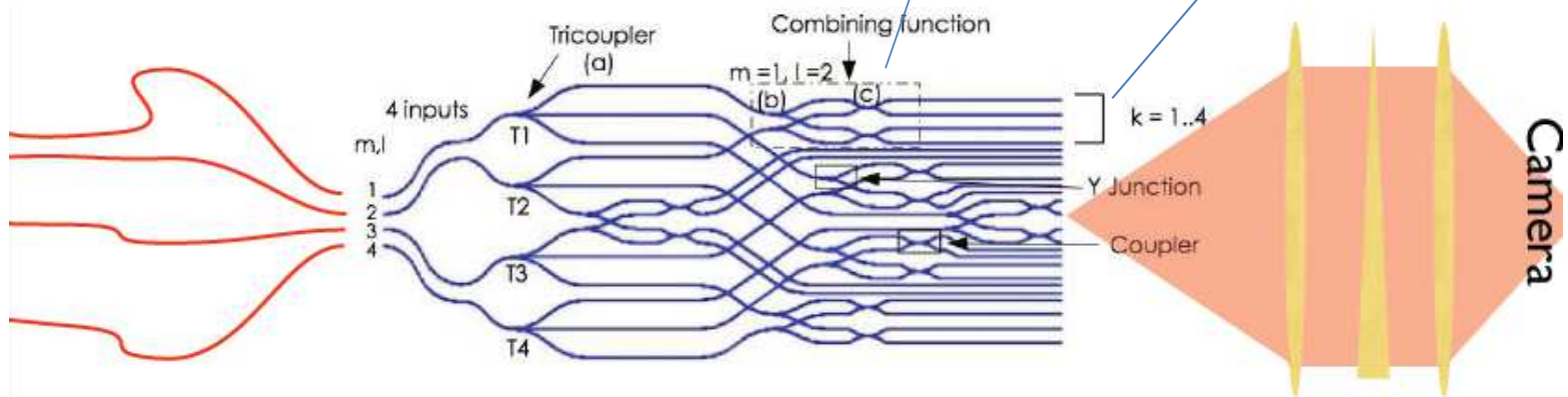
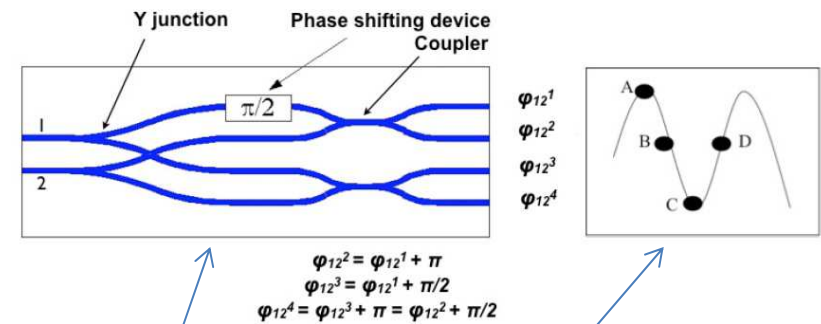
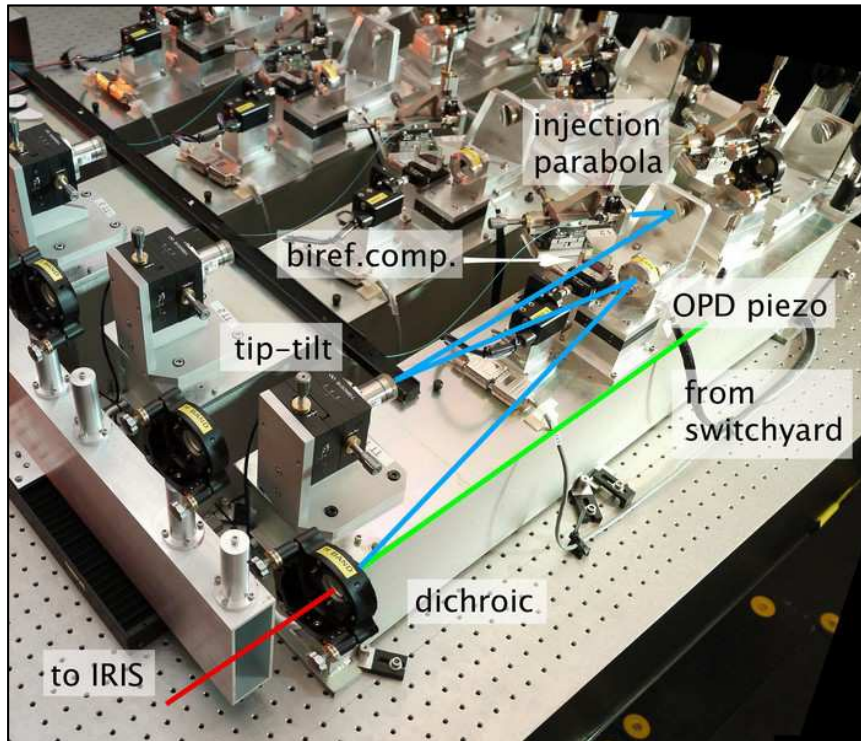
L'historique de PIONIER

- **Precision Integrated Optics Near-infrared Imaging Experiment**
- Démarrage du projet fin 2008
 - Premiers contacts avec l'ESO
 - Recherche de partenaires / soutien financier
- Début de l'intégration de l'instrument mi-2009
 - Caméra PICNIC en provenance de JPL/Caltech
- Feu vert du STC de l'ESO en novembre 2009
 - Statut d'instrument visiteur (le 1^{er} au VLT)
 - Première lumière programmée pour octobre 2010

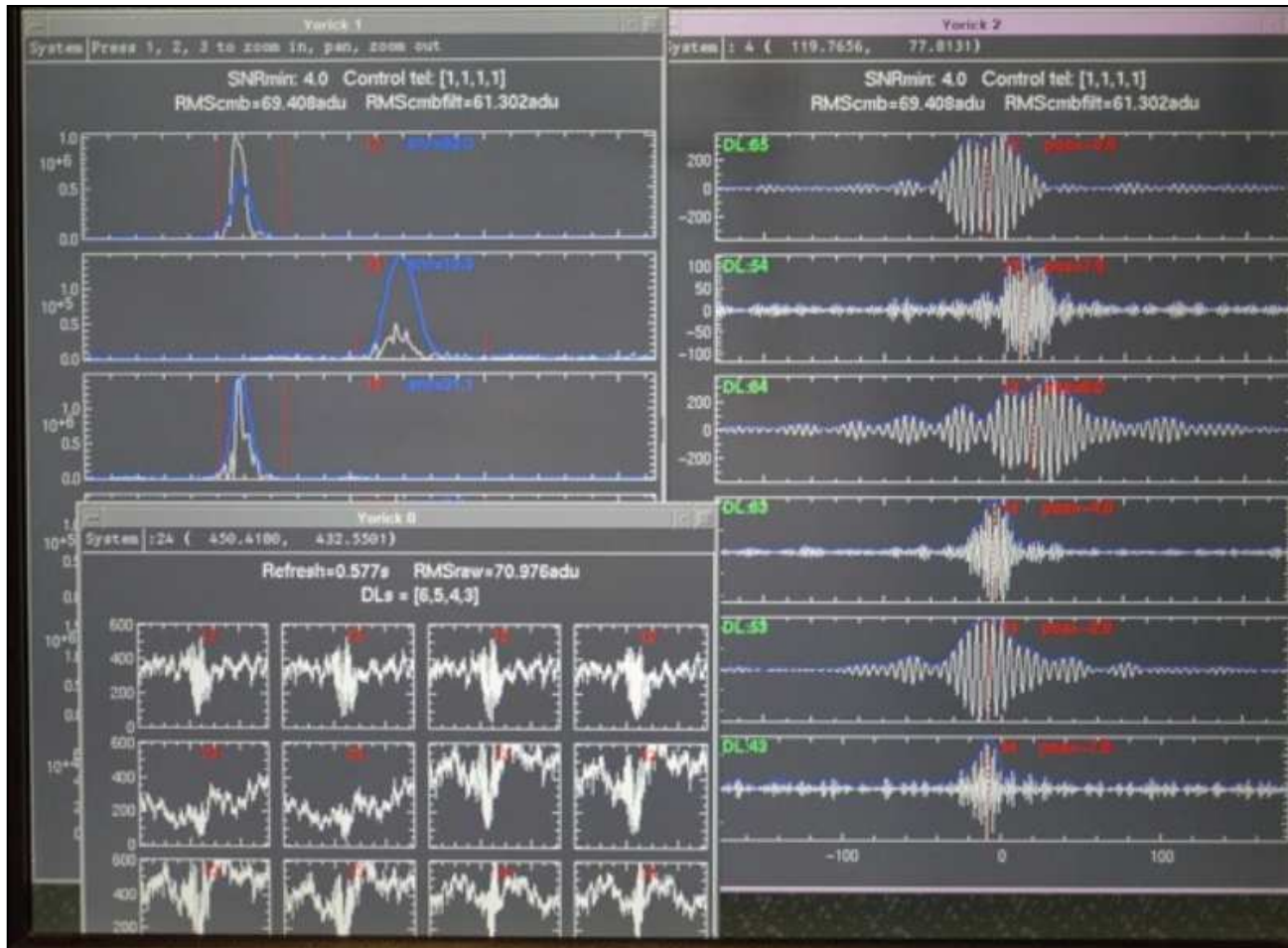
Schéma de principe de PIONIER



Implémentation de PIONIER

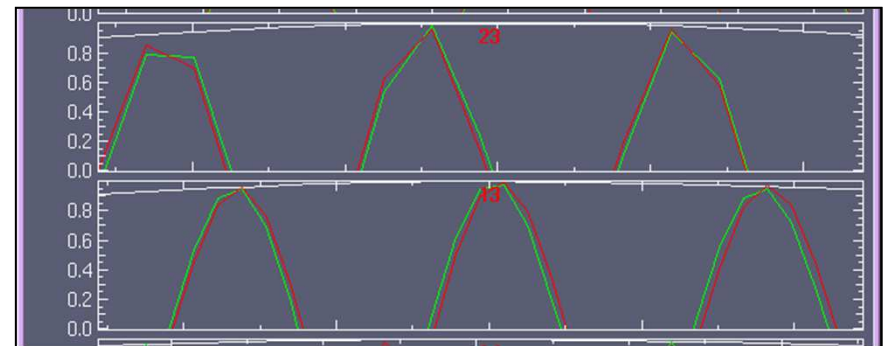
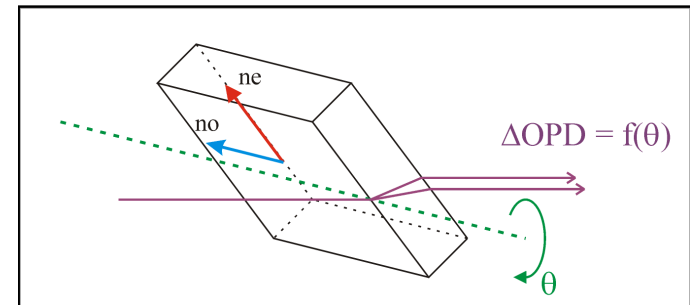
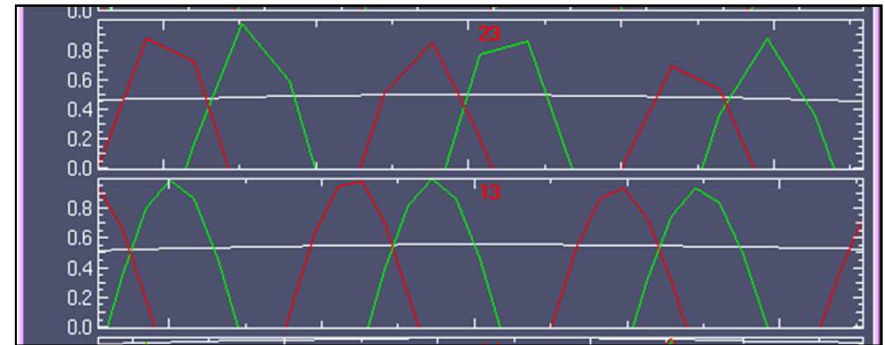


Codage temporel des franges



Utilisation en lumière naturelle

- Fibres à maintien de polarisation sont biréfringentes
- Décalage de l'OPD pour les deux polarisations
- Compensation avec des lames biréfringentes (LiNbO_3) d'inclinaison variable



Intégration à l'IPAG (ex-LAOG)



Cryogeny



Two interventions on the camera dewar ... stress !!



Mecha +
Optics



Project Management
+ Administration



Electronic



Software / Control



Septembre 2010: emballage



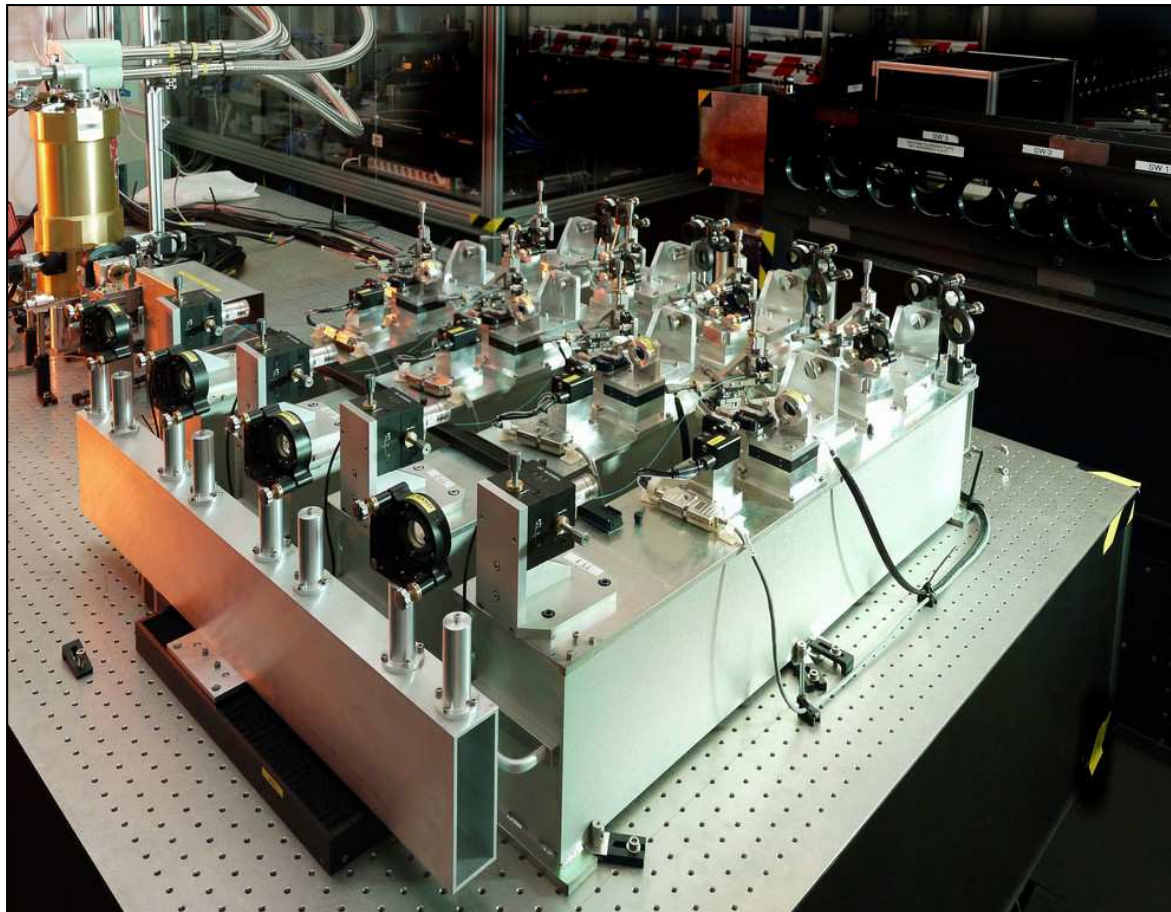
Déballage et installation à Paranal

- Début de l'installation le 20 octobre 2010



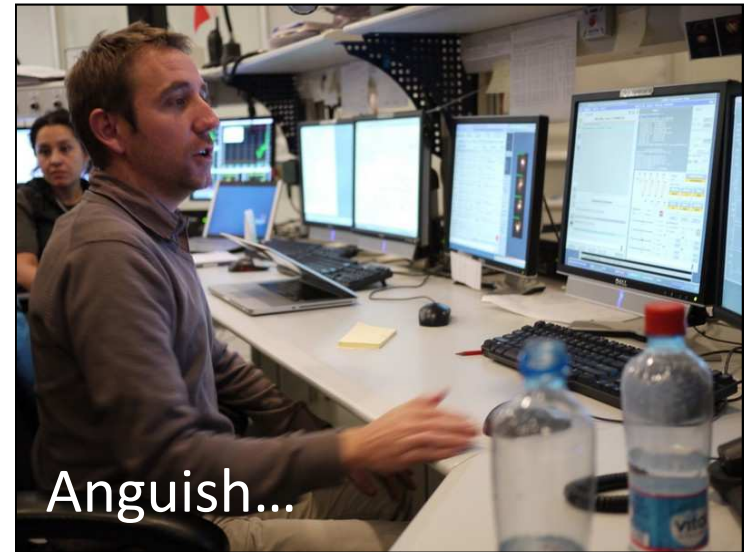
PIONIER au labo du VLTI

- Installation terminée le 24 octobre 2010

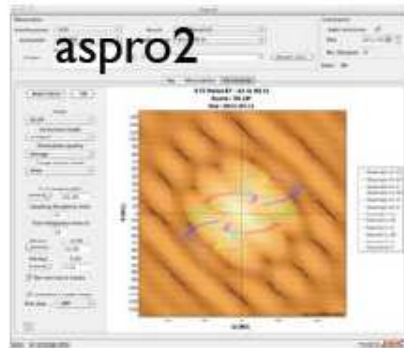


Premières franges le 25 octobre

- t_0 : VLT aligné, lumière injectée dans PIONIER
- $t_0 + 10$ min: franges sur 3 bases
- $t_0 + 30$ min: franges sur 6 bases!!!
- $t_0 + 1$ jour: nuit de démonstration scientifique



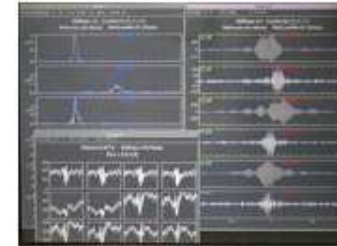
Data flow



PIONIER is included/compatible with the tools from JMMC.

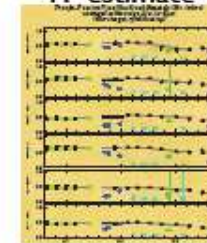
Observations
(visitor-mode only)

RAW data



Data Reduction
(automatic)

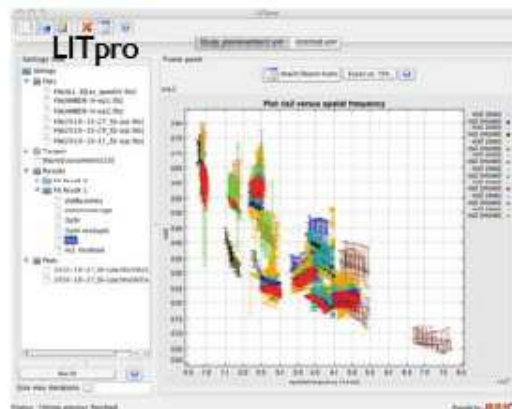
TF estimate



OIFITS file

| Index | Label | Type | Description | Header | Footer | Unit | Scale |
|-------|--------------|--------|-------------------|--------|--------|-------|-------|
| 0 | primary | Image | | | | | |
| 1 | 01_TARGET | Binary | 17 cols X 1 rows | Header | Foot | Pixel | 1/0 |
| 2 | 01_RAWLINGER | Binary | 2 cols X 1 rows | Header | Foot | Pixel | 1/0 |
| 3 | 01_RAWL | Binary | 4 cols X 1 rows | Header | Foot | Pixel | 1/0 |
| 4 | 01_VIS2 | Binary | 10 cols X 3 rows | Header | Foot | Pixel | 1/0 |
| 5 | 01_T1 | Binary | 14 cols X 12 rows | Header | Foot | Pixel | 1/0 |

Model fitting or
Image reconstruction



MIRA ?

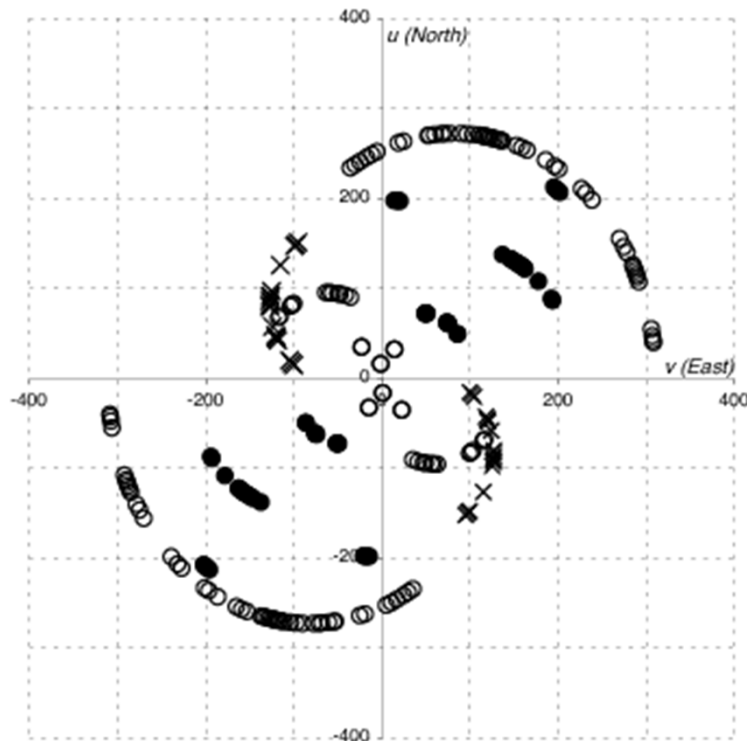
Image reconstruction
algorithm with user-
interface... ??

Performances

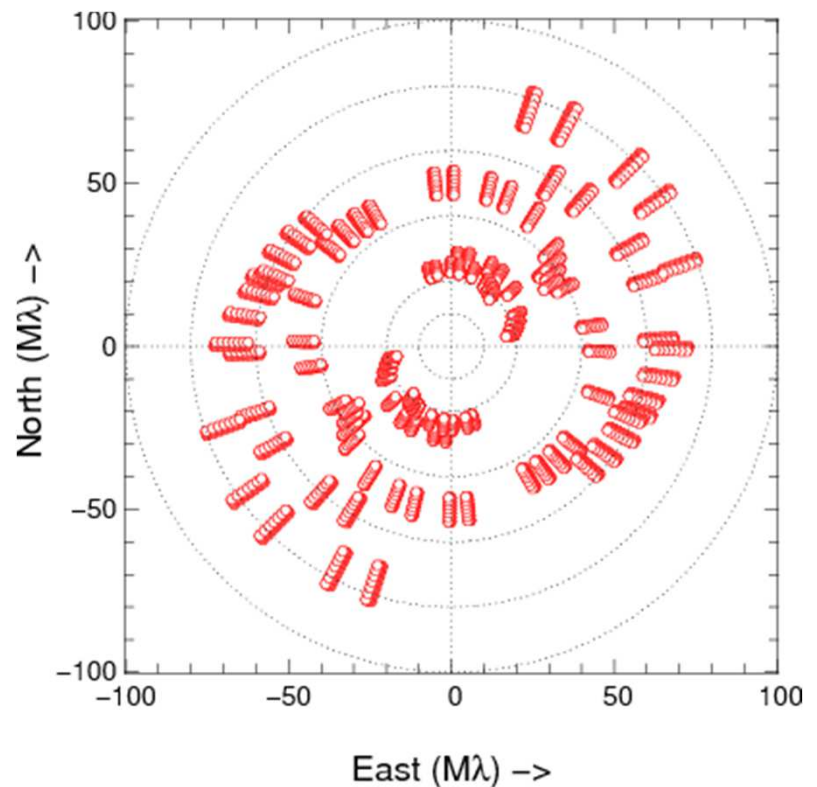
- Magnitude limite pour un seeing de 1.2'' (0.8'') avec les ATs
 - Dispersion sur 7 canaux: $H=5$ (6)
 - Dispersion sur 3 canaux : $H=6$ (7)
 - Bande large: $H=7.5$ (8.5)
- Précision des observables après calibration
 - V2: erreur de 1% à 10% selon le mode
 - T3: erreur de 0.2° à 2° selon le mode

Les avantages de PIONIER

- Achernar par VINCI: plusieurs années de données

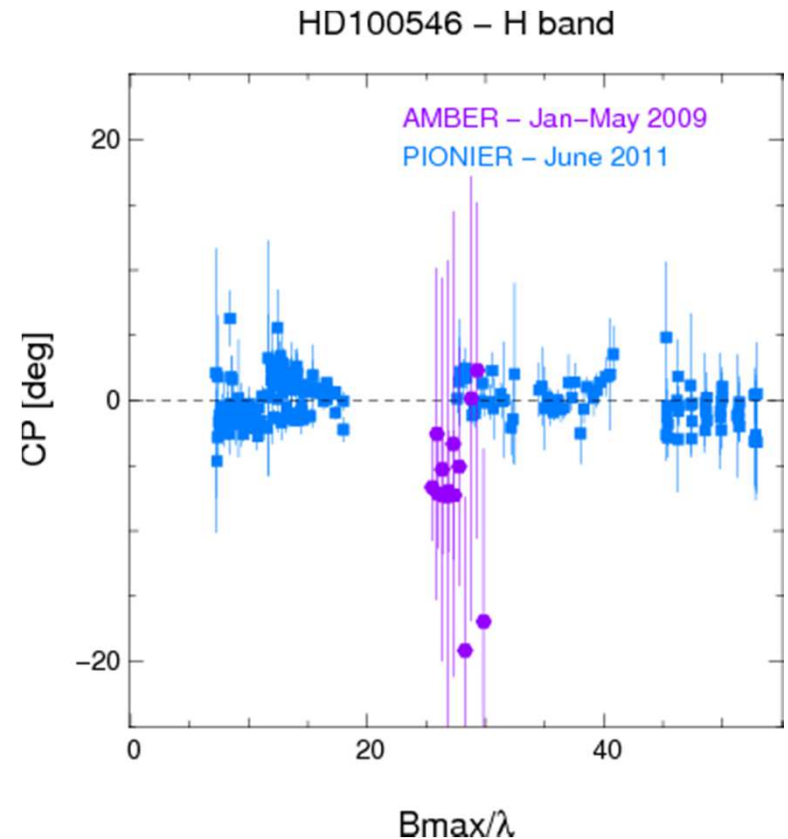


- Achernar par PIONIER: une nuit de données!



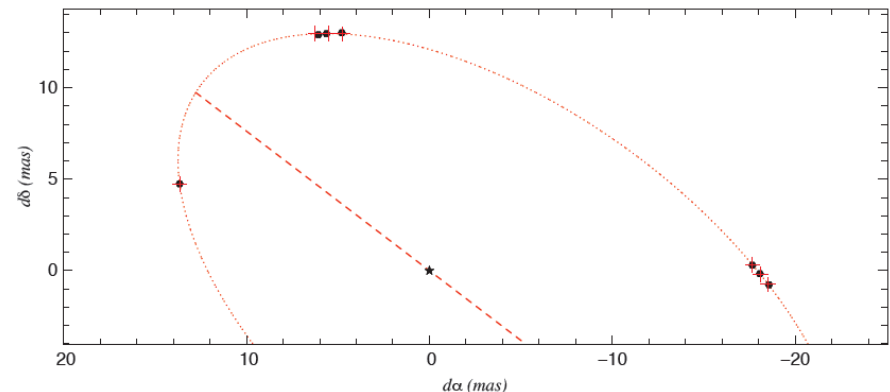
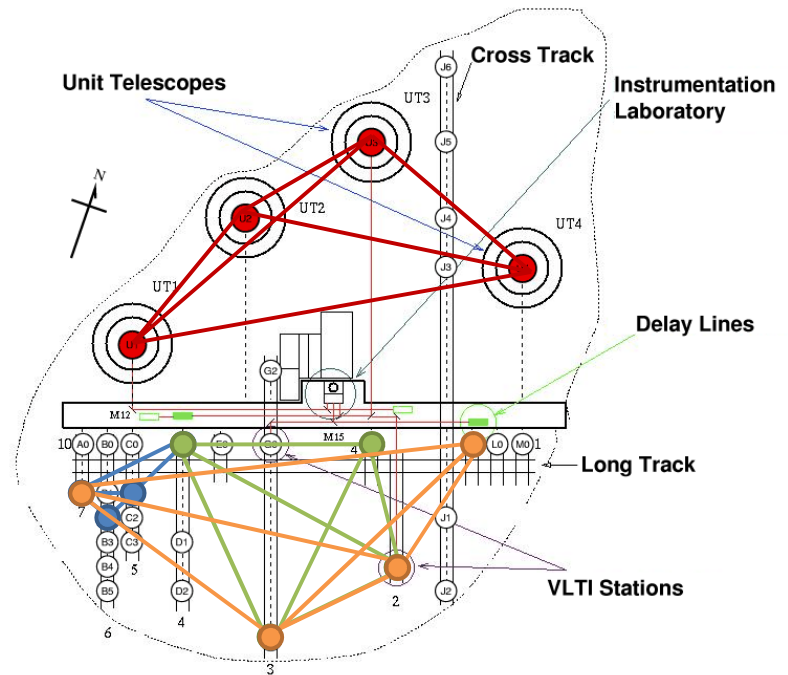
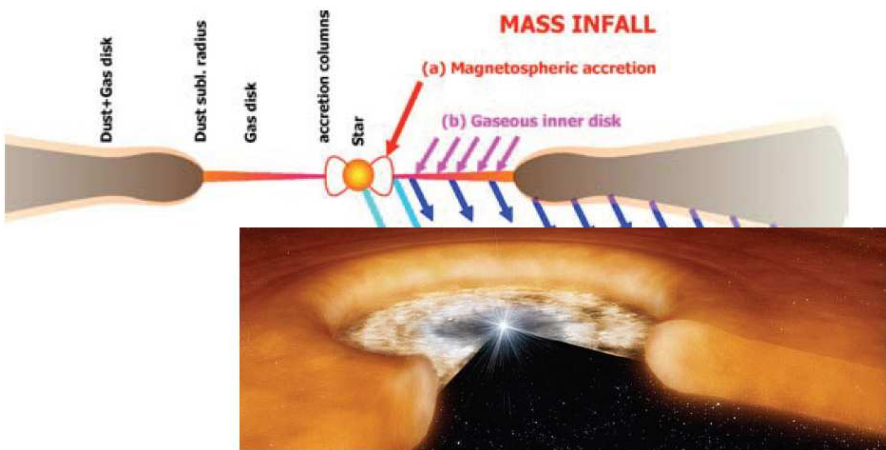
Les avantages de PIONIER

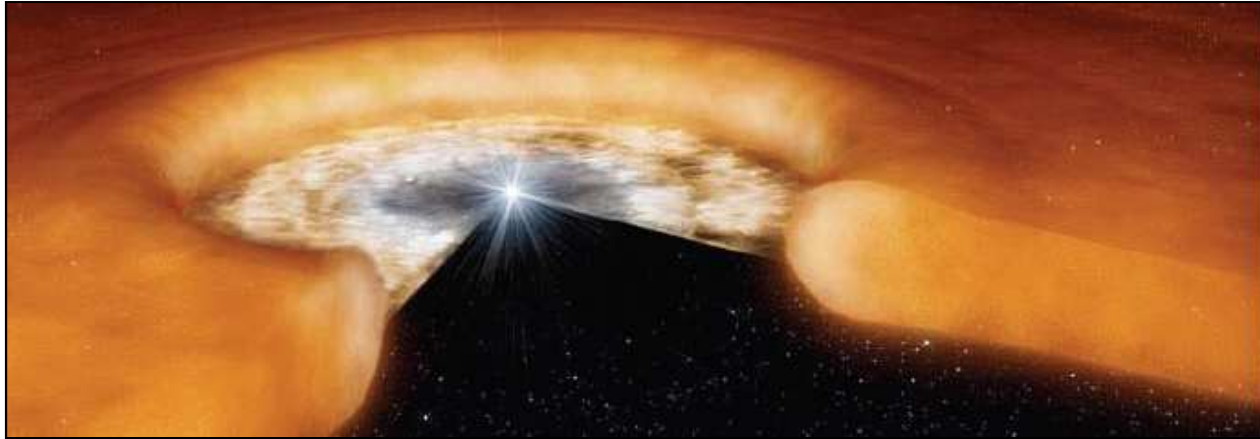
- Efficacité (e.g., mode survey)
 - AMBER: 3-4 cibles par nuit
 - PIONIER: 8 cibles par nuit
- Sensibilité
 - PIONIER sur ATs idem à AMBER sur UTs
- Précision
 - Stabilité de l'instrument
- Robustesse
 - Opération ok même par mauvais seeing



Premier résultats scientifiques

- Observations sur les ATs, en mode visiteur
 - Disques circumstellaires
 - Étoiles binaires et compagnons faibles
- 1 nuit de test sur les 4 UTs (17 mars 2011)



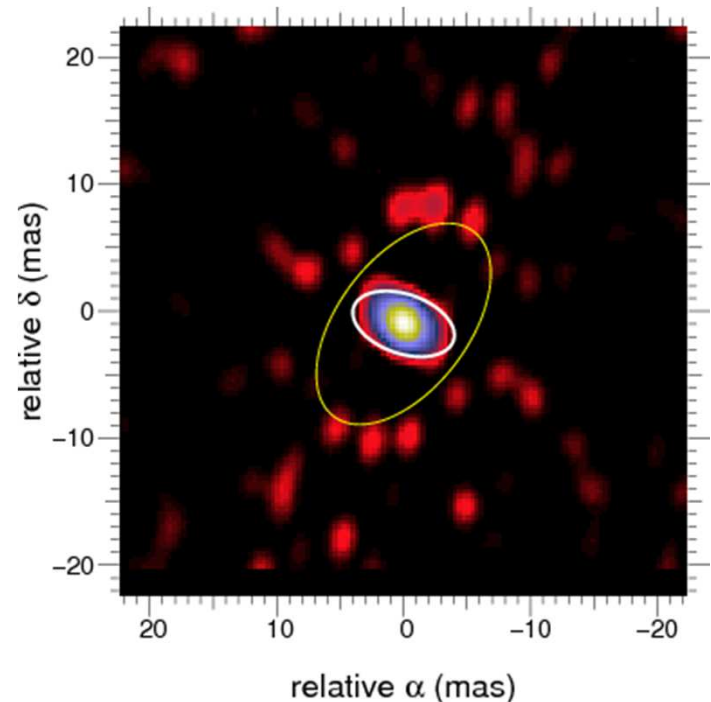
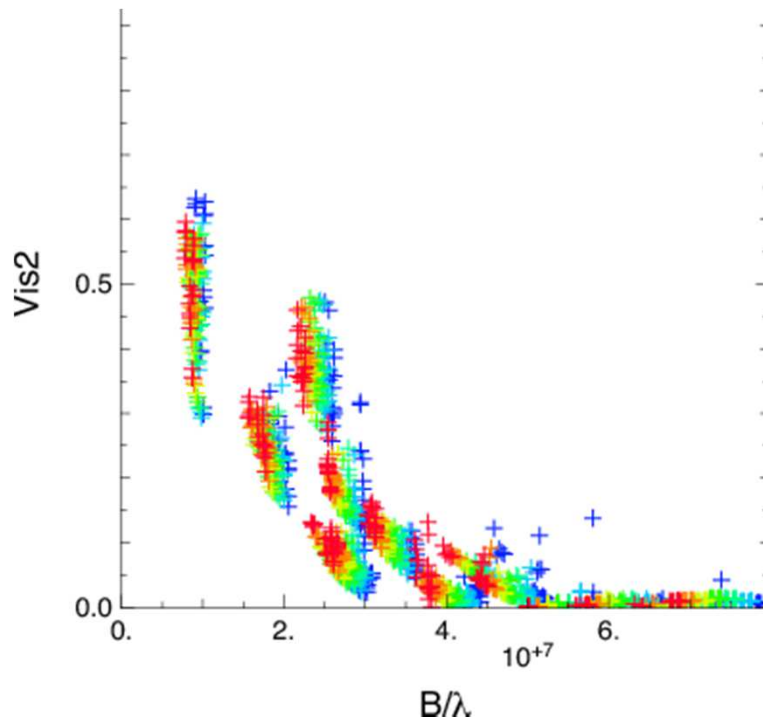


Premiers résultats scientifiques

OBSERVATIONS DE DISQUES CIRCUMSTELLAIRES

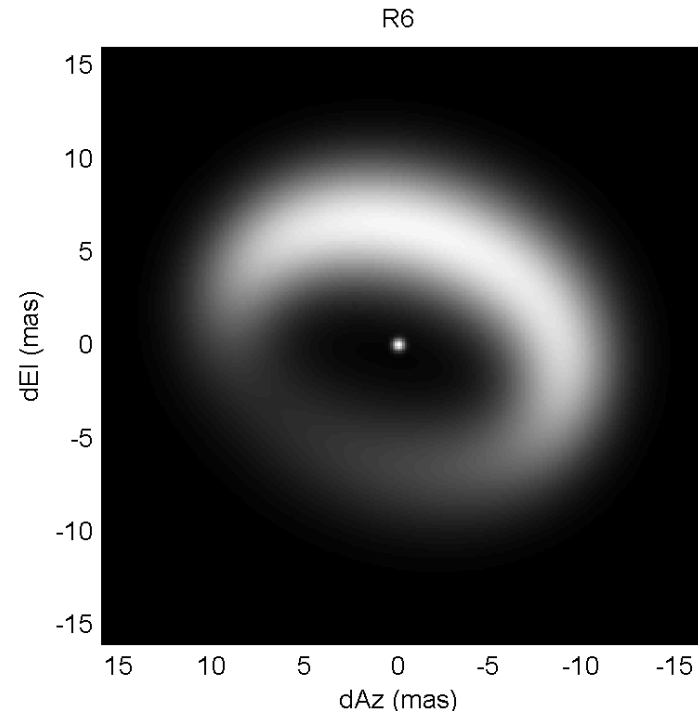
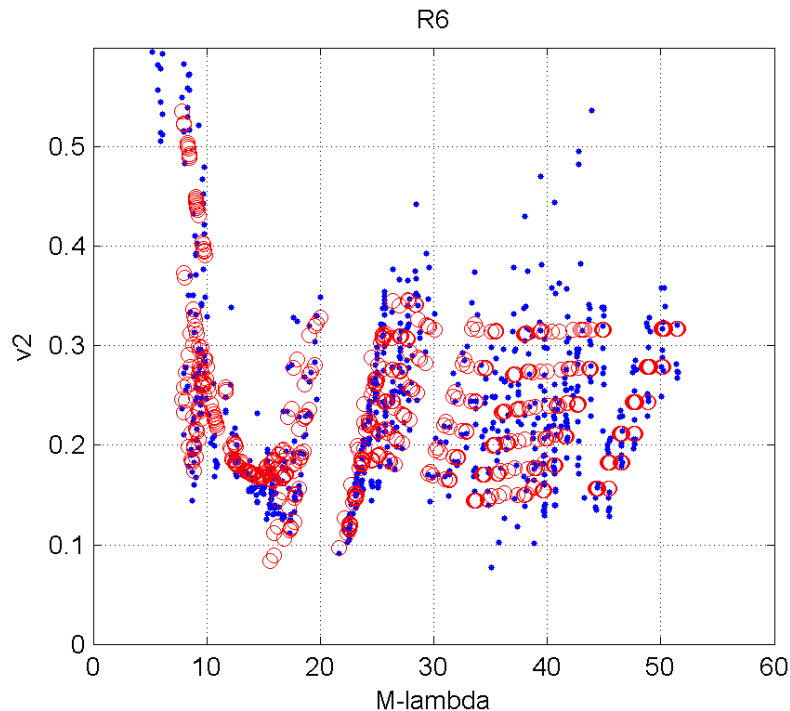
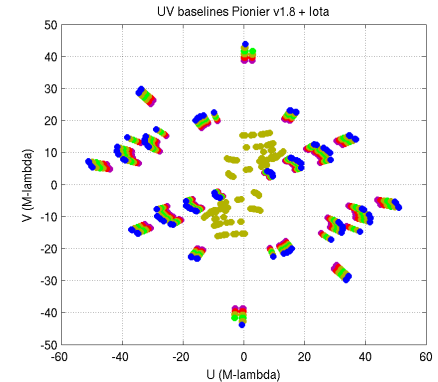
Herbig Ae/Be: imagerie

- Objectif principal: imagerie des premiers AUs
 - Valider modèles théoriques (puffed-up inner rim)
 - Recherche d'asymétries ou de « gaps »
- Exemple: MWC 158 (B6-7 @ 500 pc)



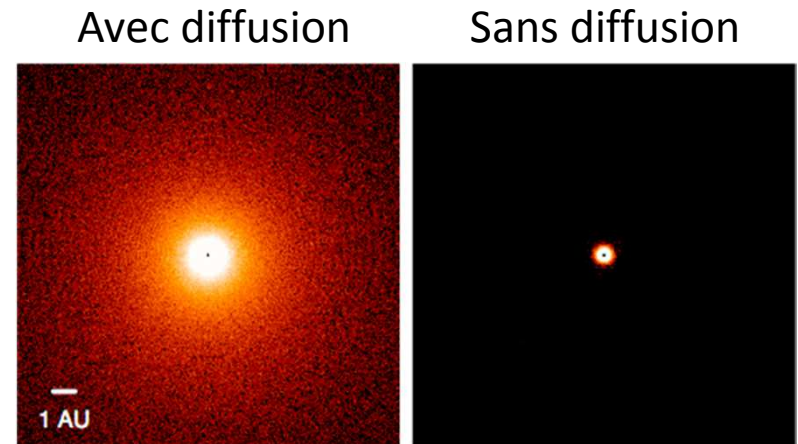
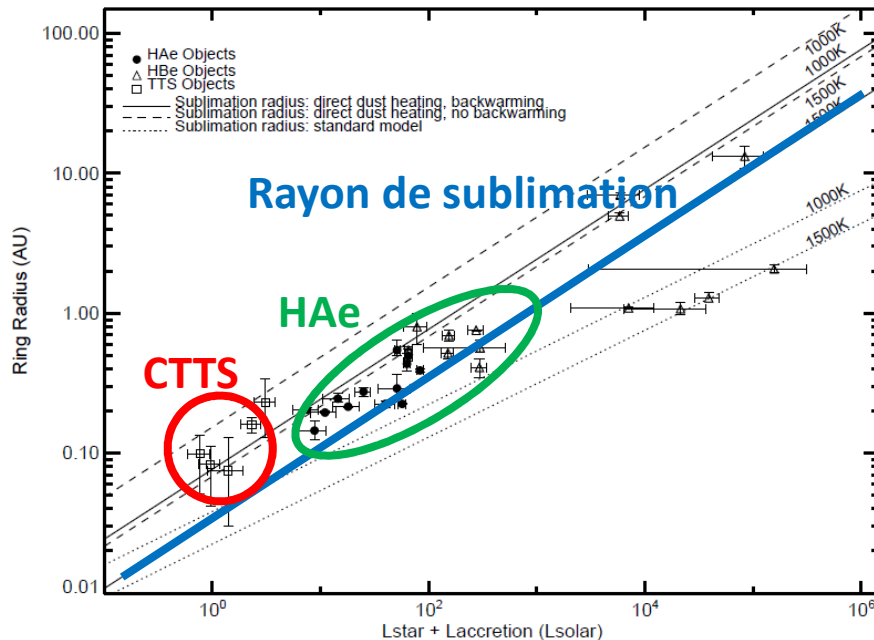
Herbig Ae/Be: modélisation

- Imagerie paramétrique aussi possible
- Exemple: HD 45677 (B2 @ 1kpc)
 - Anneau fin convolué avec gaussienne
 - Modulation azimuthale



T Tauri: contexte

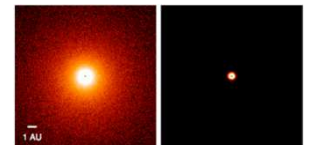
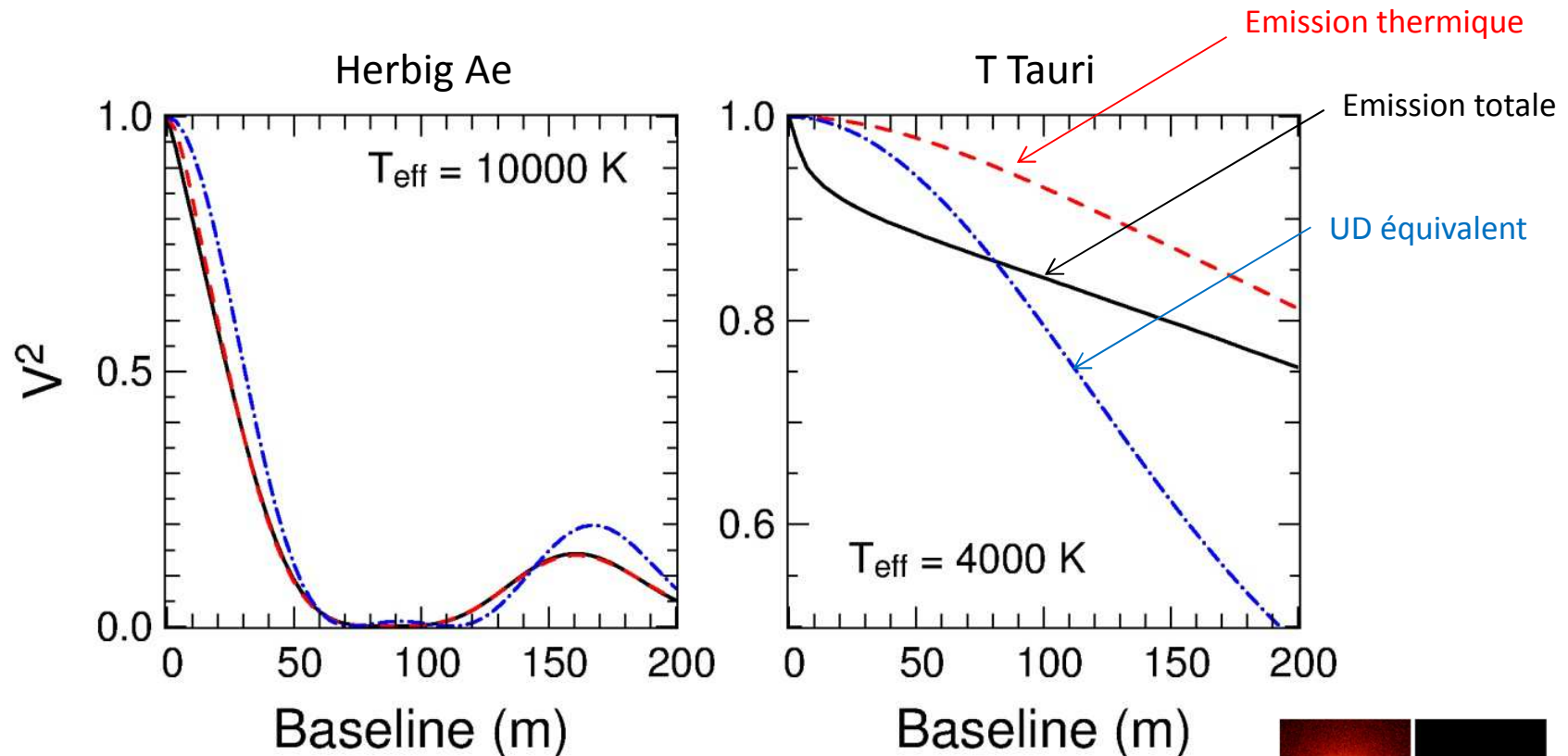
- Une douzaine de T Tauri résolues (Keck+PTI)
- Objectifs:
 - Haute sensibilité \rightarrow observer ~ 40 T Tauri
 - Passer de 1-2 base(s) à 6 bases + CP \rightarrow morphologie
 - Expliquer l'excès de taille des disques T Tauri



Pinte et al. 2008

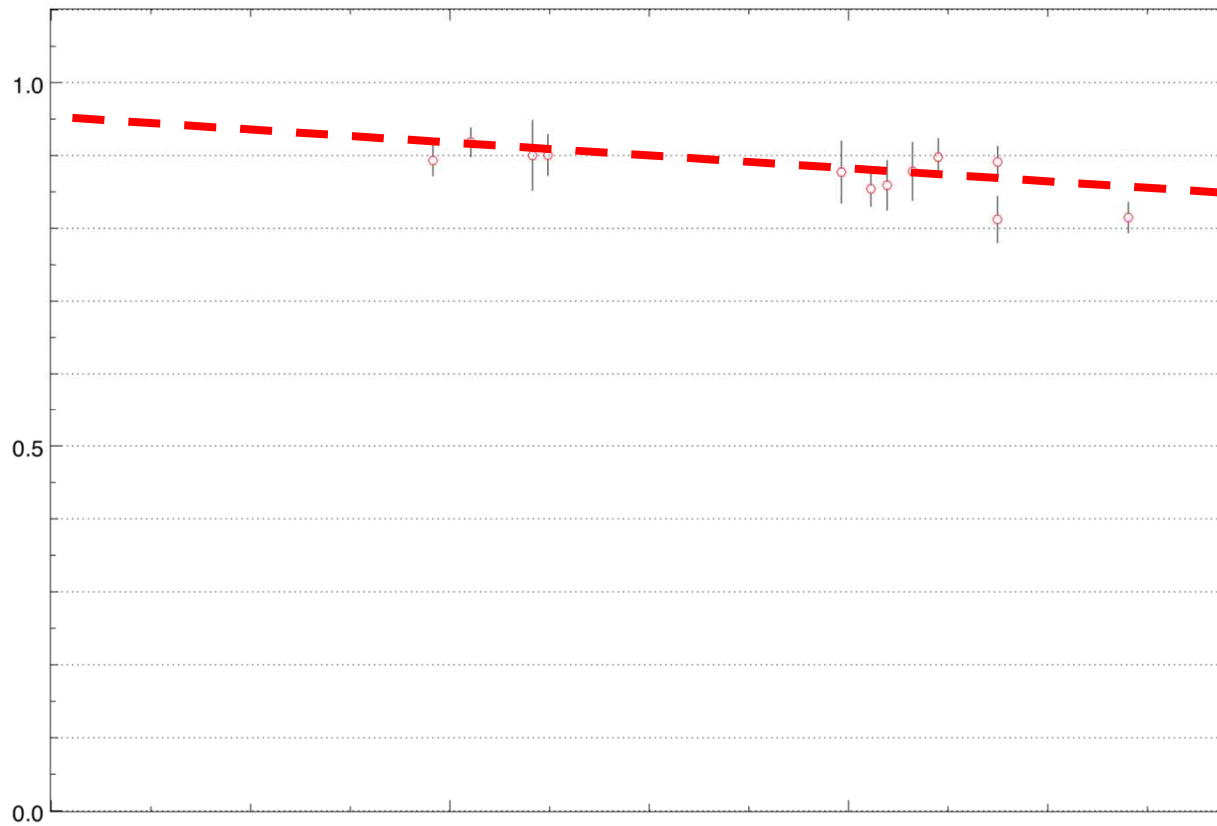
T Tauri: effet de la diffusion

- Effet de la diffusion révélé par les visibilités



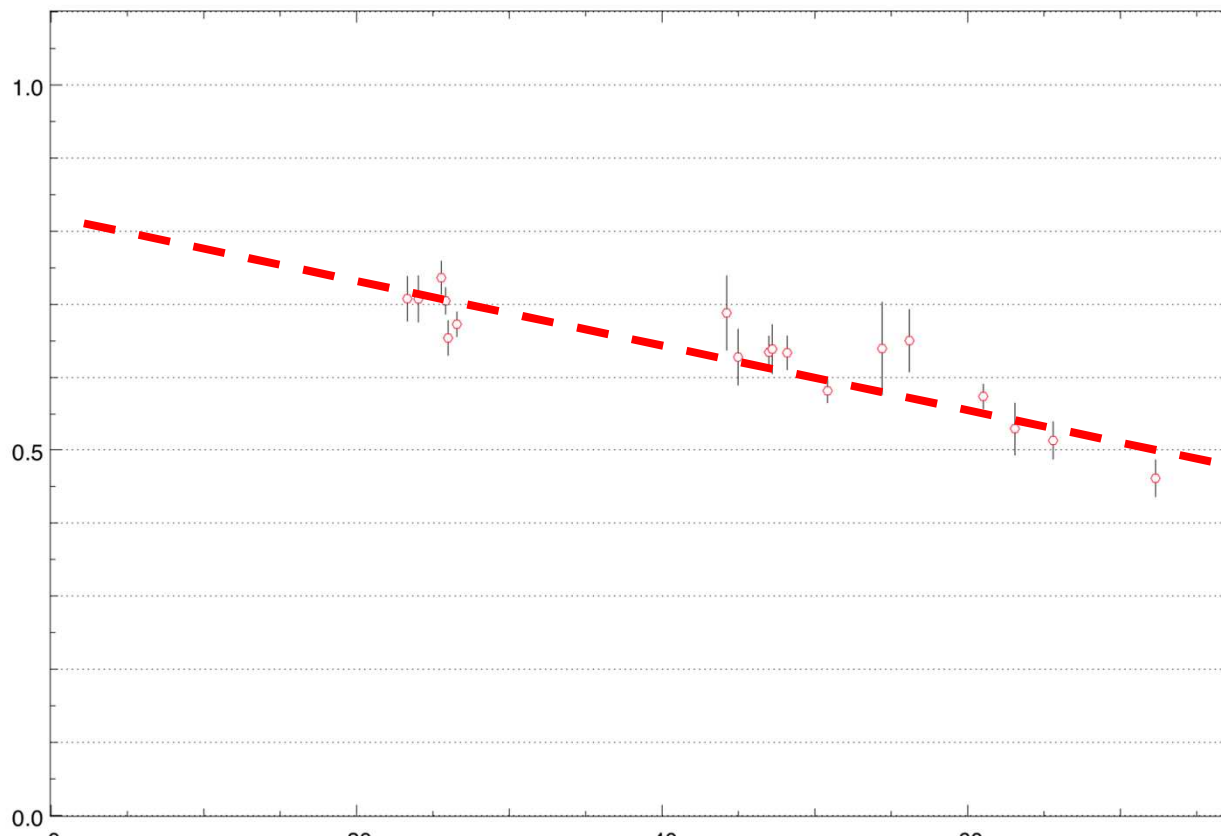
Disques T Tauri vus par PIONIER

- GQ Lupi, K7, ~ 1 Myr
 - 3-5% d'émission incohérente



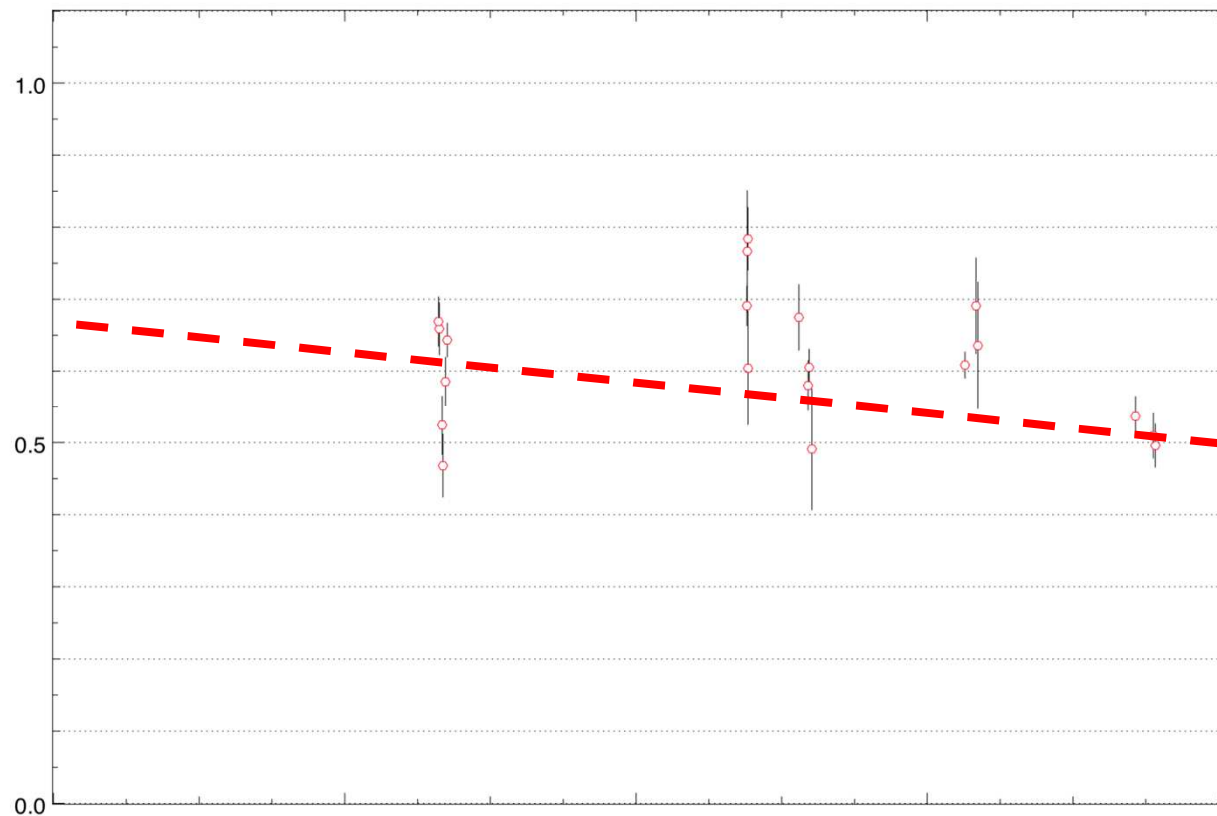
Disques T Tauri vus par PIONIER

- RU Lup, K7-M0, < 1 Myr
 - 10-20% d'émission incohérente



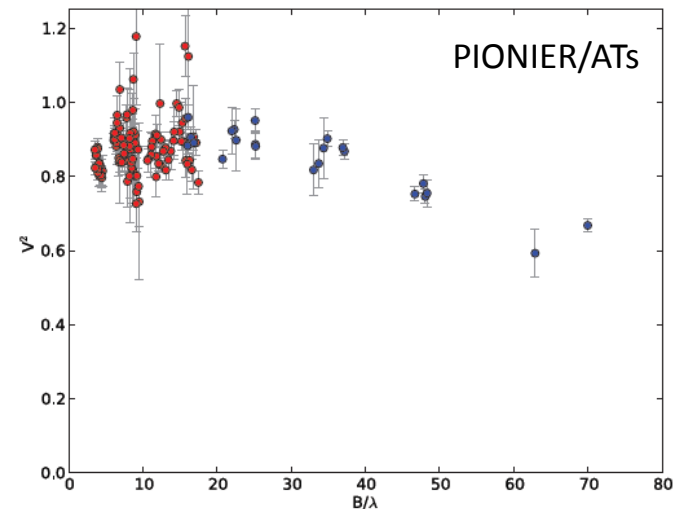
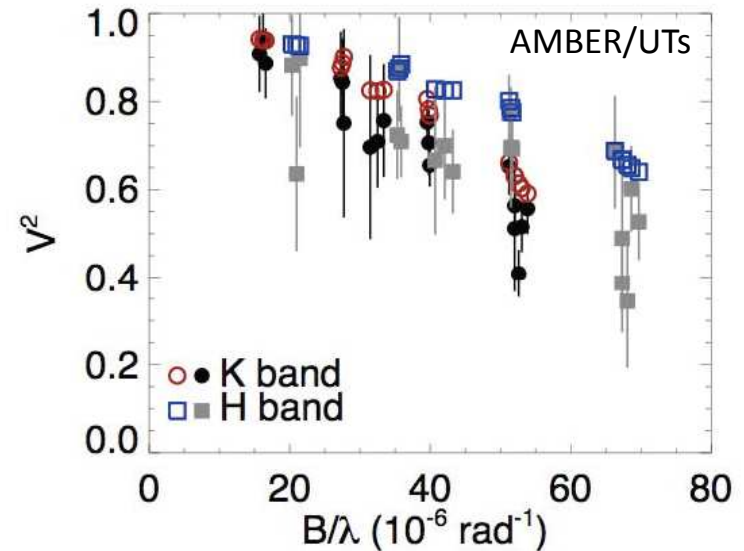
Disques T Tauri vus par PIONIER

- RY Lup, K0-K4, ~ 2 Myr
 - 20-25% d'émission incohérente



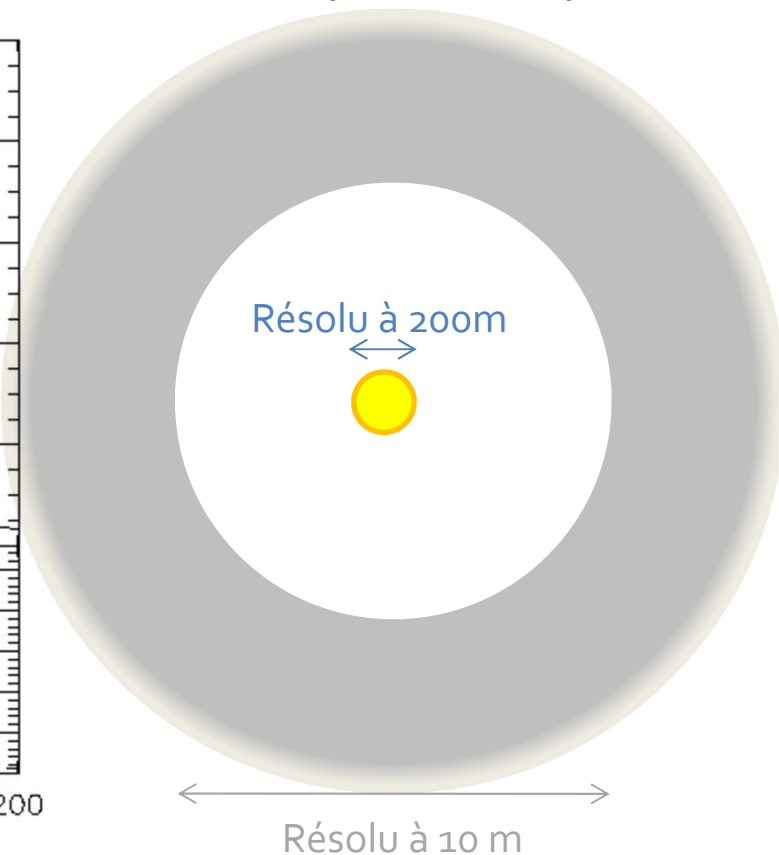
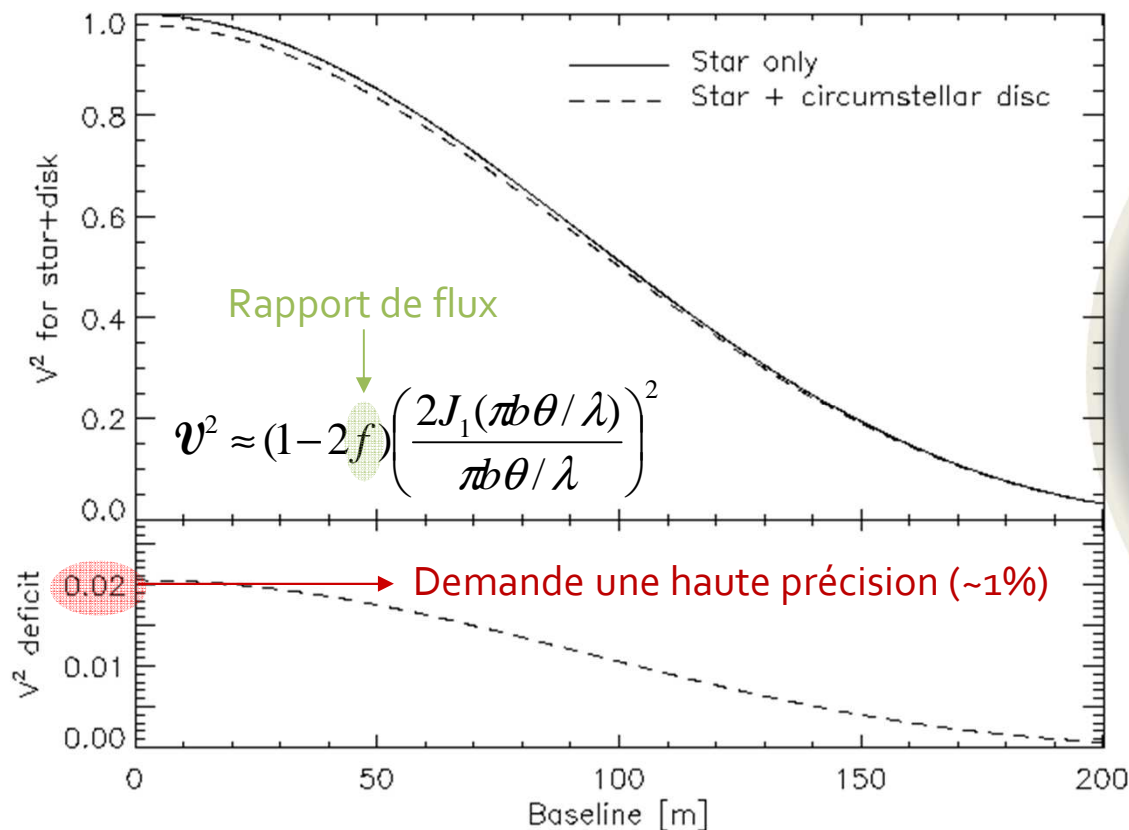
Disques de transition

- Disques jeunes « évolués »
- Gap entre disque interne et externe
 - Formation de planètes?
- Exemple: T Cha
 - PIONIER montre effet similaire aux T Tauri
 - Pas de compagnon détecté



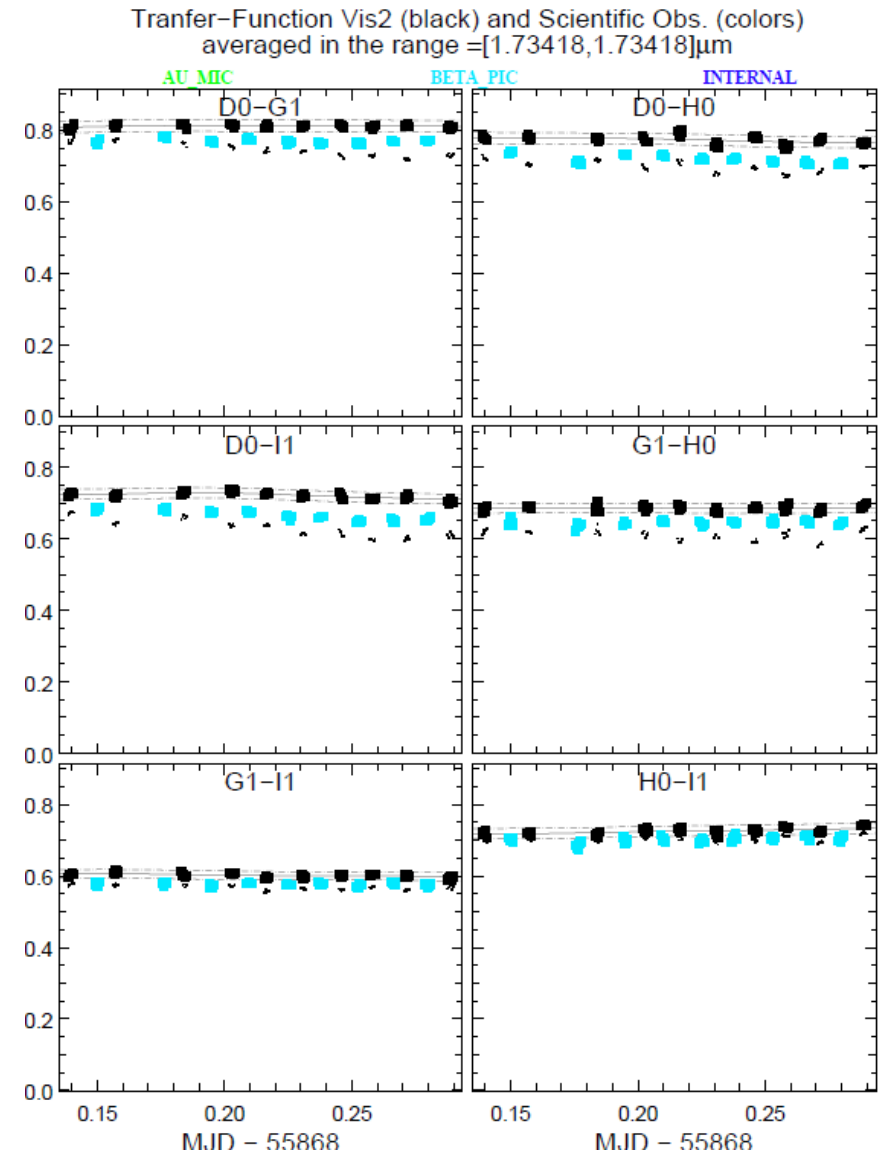
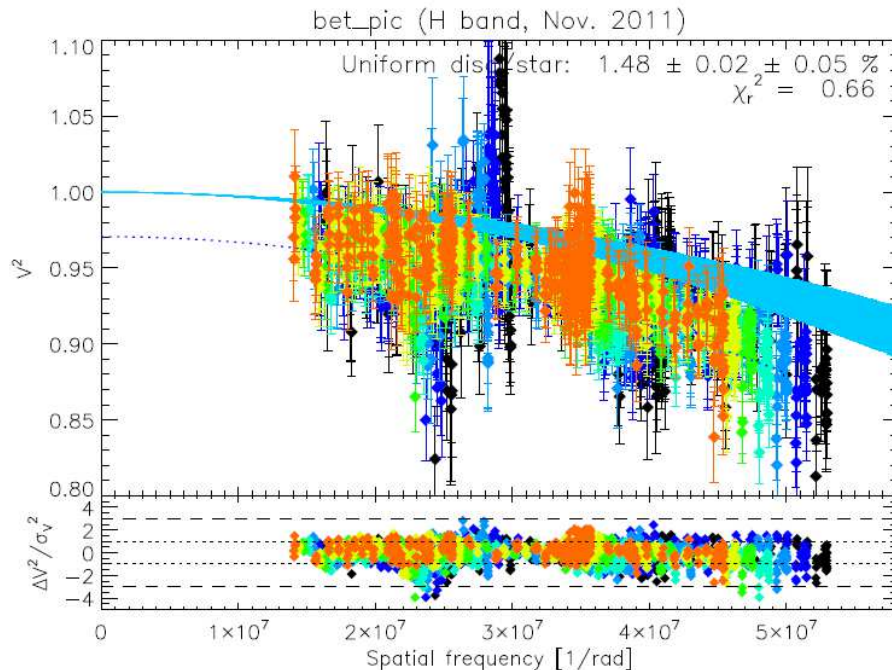
Disques de débris

- Disque plus grand que $\lambda/B \rightarrow$ perte de visibilité
- Détection plus facile aux bases courtes (< 30 m)



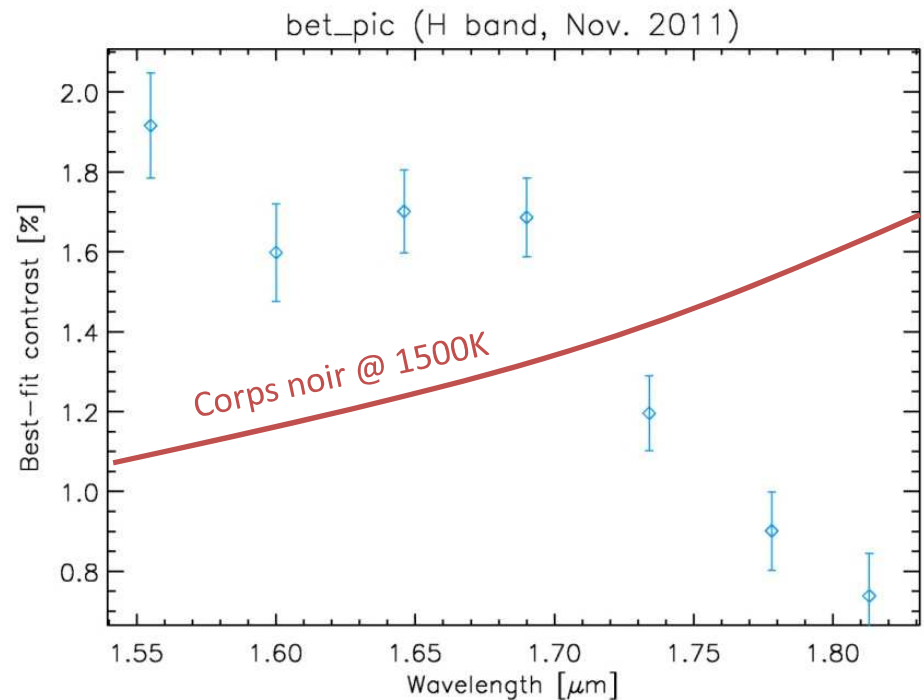
Premier résultat: beta Pictoris

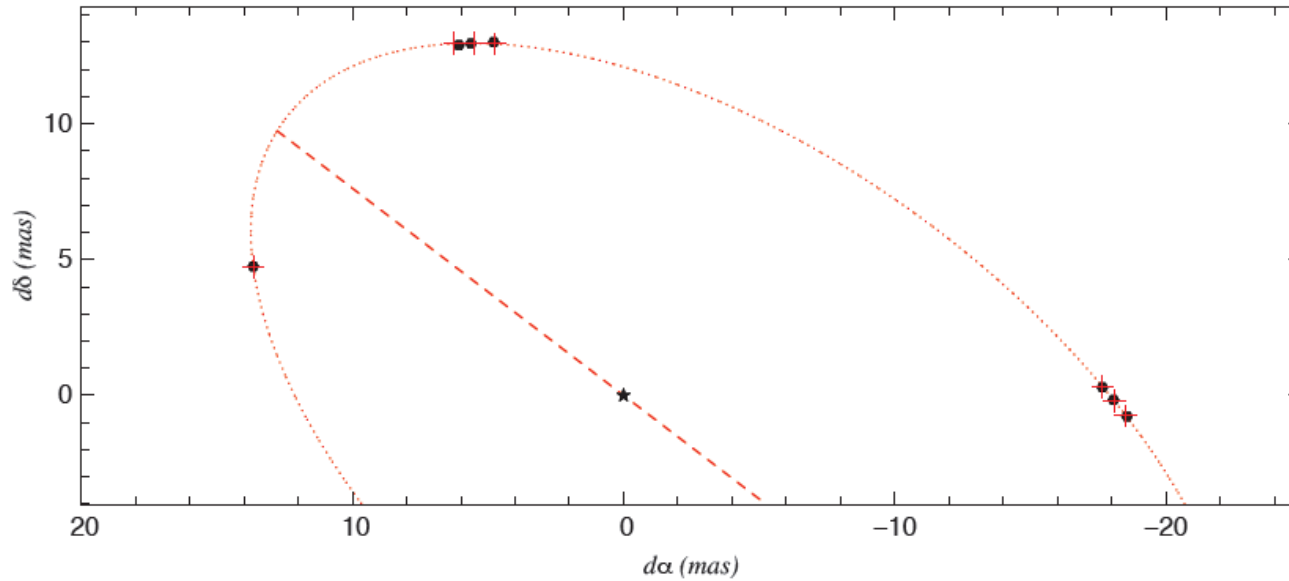
- Stabilité et précision adéquates
- Excès de 1.5% détecté



Beta Pictoris: la surprise du chef

- Dépendance spectrale inattendue
- Émission thermique?
 - Incompatible avec corps noir
 - Possible avec grains de glace d'eau
- Émission réfléchie?
 - Grains très « bleus »
- Autres sources?
 - Signature du gaz



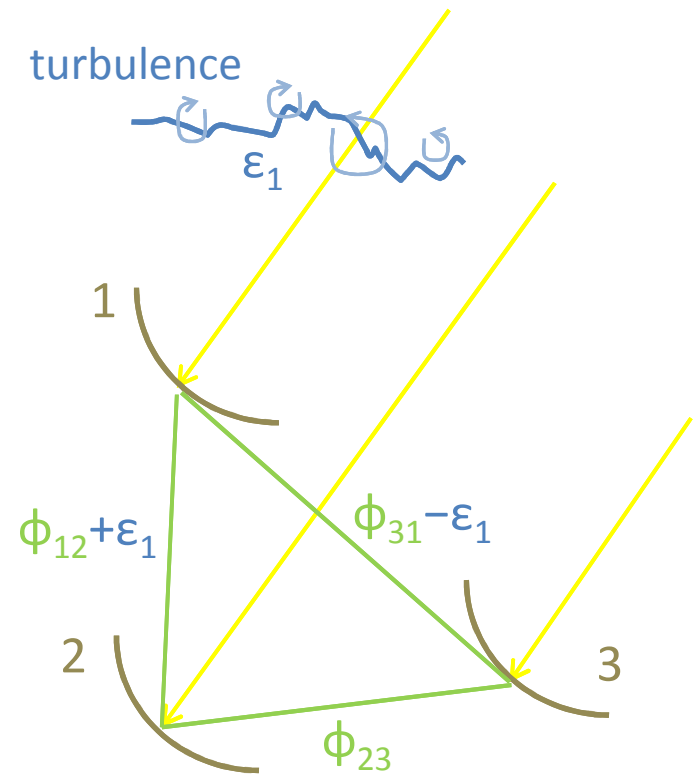


Premiers résultats scientifiques

OBSERVATIONS D'ÉTOILES BINAIRES

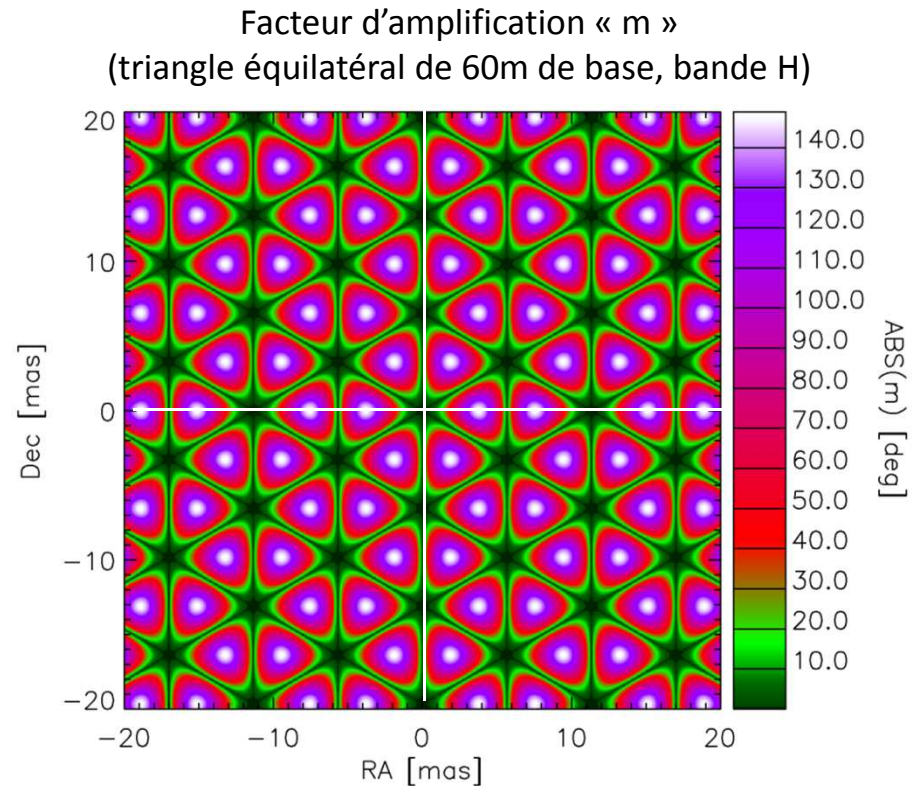
Avantages de la clôture de phase

- Pas influencée par les erreurs de phase individuelles
 - $\psi_{123} = \phi_{12} + \epsilon_1 + \phi_{23} + \phi_{31} - \epsilon_1$
 - Pas biaisée par la turbulence
- $\psi_{123} = 0$ pour les objets à symétrie centrale
 - Sensible aux compagnons hors axe
 - Insensible au modèle stellaire au 1^{er} ordre

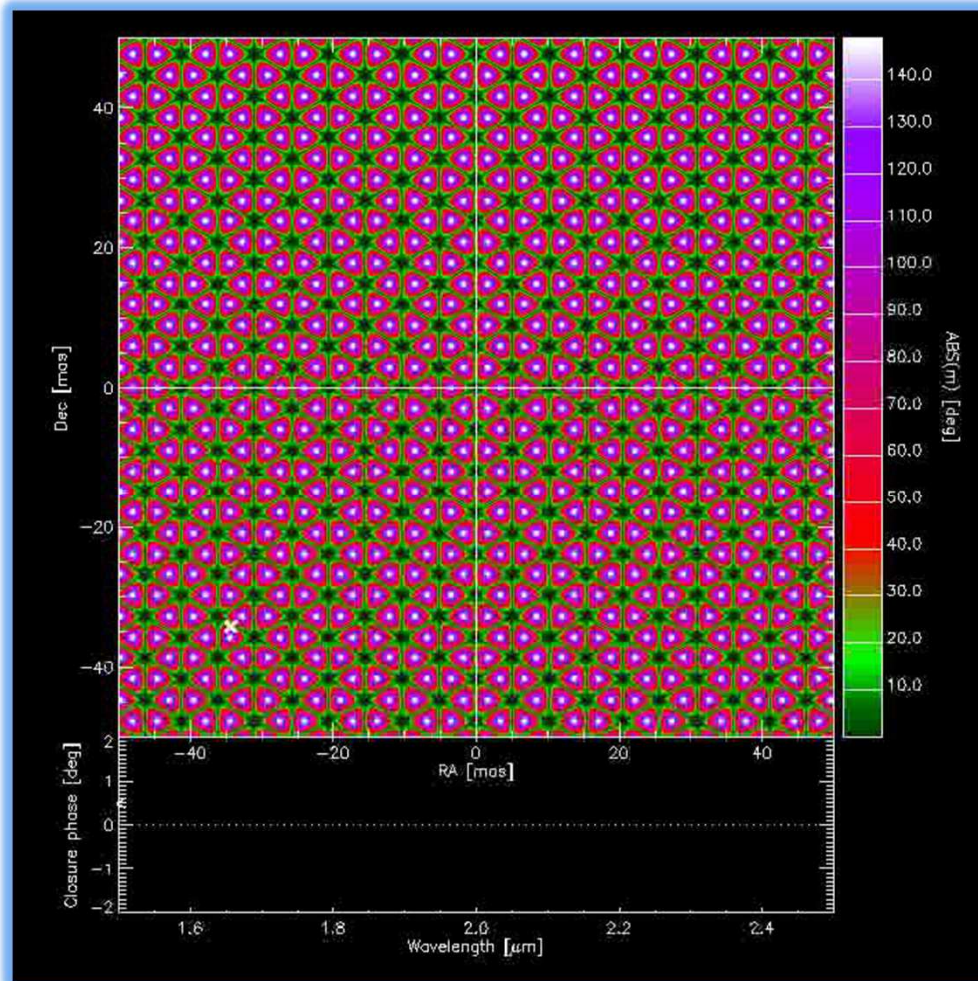


Le régime « compagnon faible »

- Objets individuels non résolus, contraste ρ
 - $\psi = \rho m$
 - $m = \sin \alpha_{12} + \sin \alpha_{23} + \sin \alpha_{31}$
 - $\alpha_{ij} = 2\pi \mathbf{B}_{ij} \cdot \boldsymbol{\theta} / \lambda$
 - Facteur d'amplification « m » va de 0° to 149°
 - Ex: $\rho = 1\% \rightarrow \psi \sim 1^\circ$
- Primaire résolue
 - Signal ψ accru
 - « Closure phase nulling »



ψ en fonction de λ



Binaires « faciles »

Le Bouquin et al. 2011

- Snapshot facile en 2h sur 4 ATs
 - Reconstruction d'image fonctionne bien

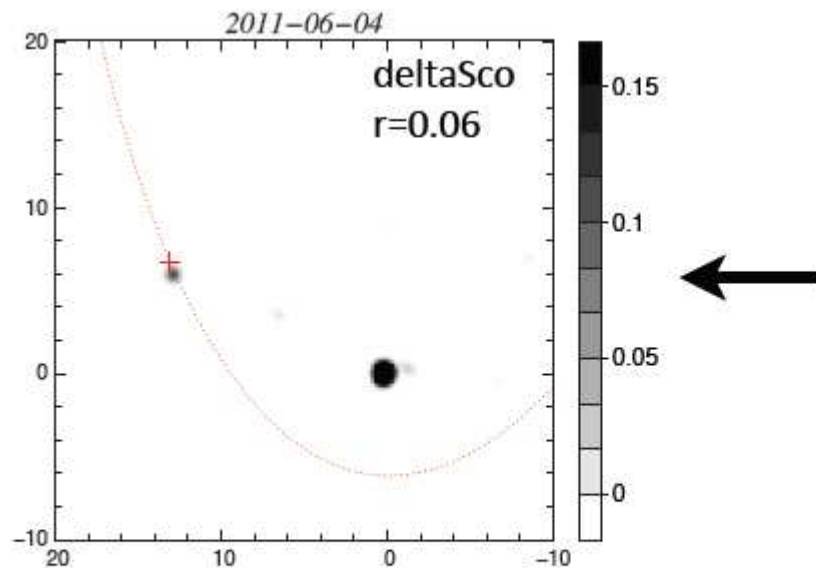
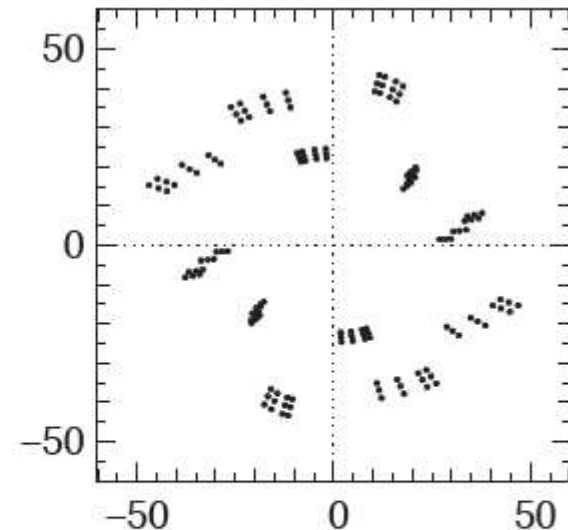


Fig. 7. Image reconstruction of δ Sco. The reference frame is centered on the primary star. The red cross is the position of the companion at the time of the PIONIER observations predicted from Tycner et al. (2011). Scale is in mas, North is up and East is to the left. The image maximum is normalized to unity and the color scale is linear from 0 to 0.15.



uv-plane in ~ 2 h with the D0-H0-G1-I1 configurations and spectral dispersion over 3 channels in H-band.

Exemple: mesure d'orbite

Le Bouquin et al. 2011

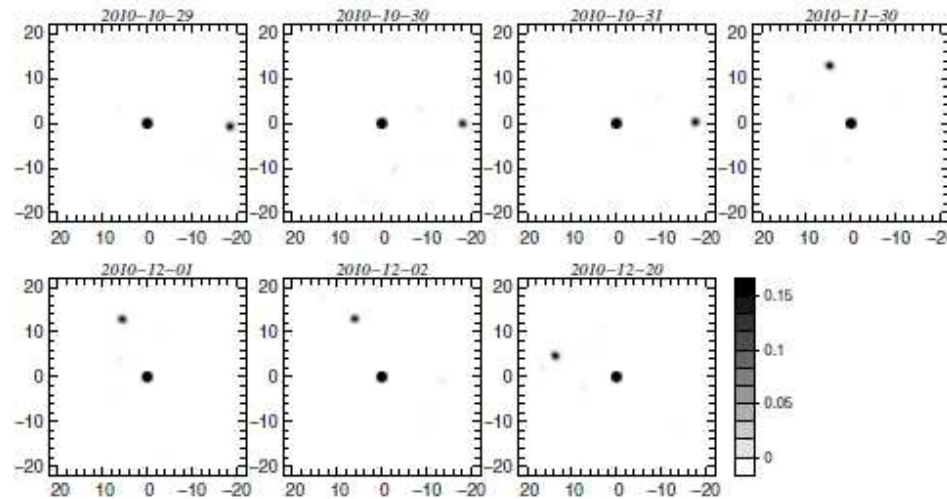


Fig. 8. Model-independent image reconstruction of HIP11231 with the MIRA software. Each night has been reconstructed independently. The reference frame is centered on the primary star, which saturates the color table. Scale is in mas. North is up and east to the left. The image maximum is normalized to unity and the color scale is linear from 0 to 0.15.

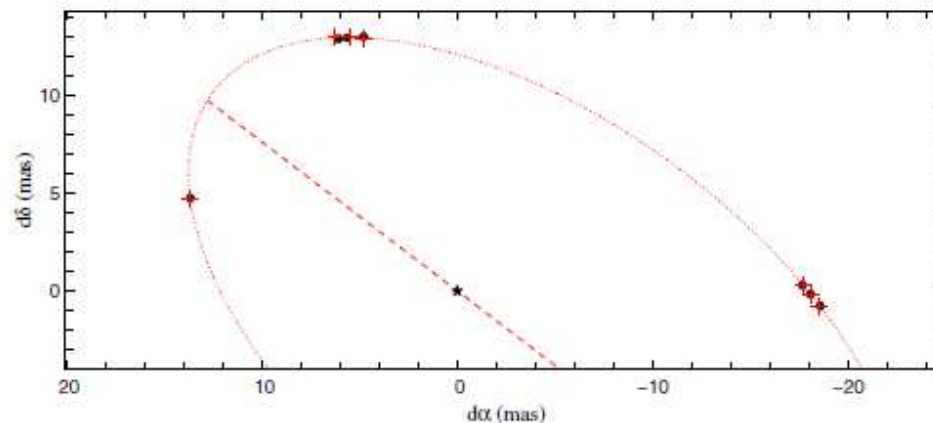
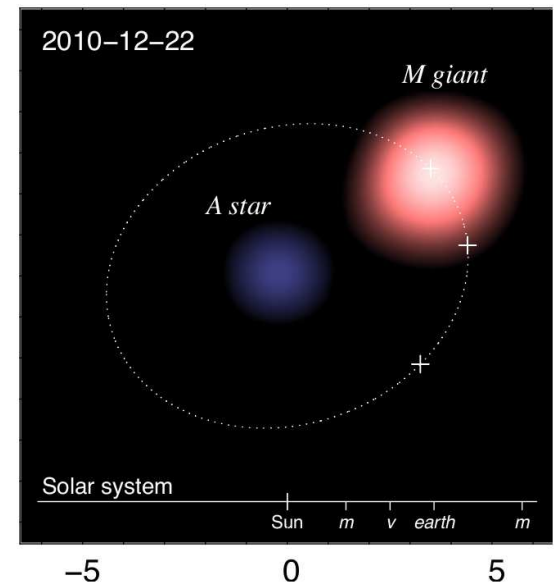
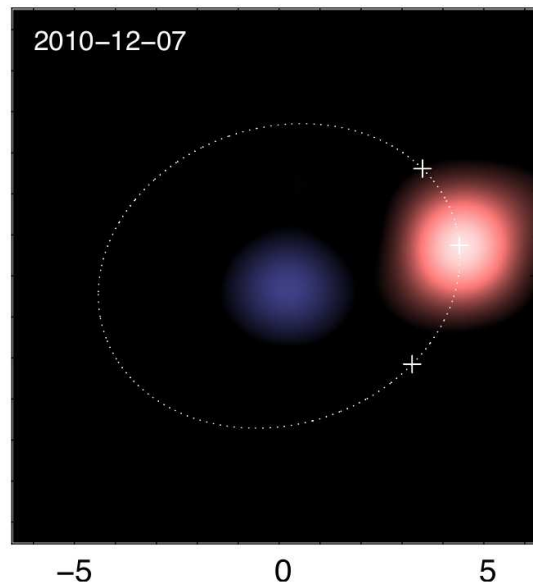
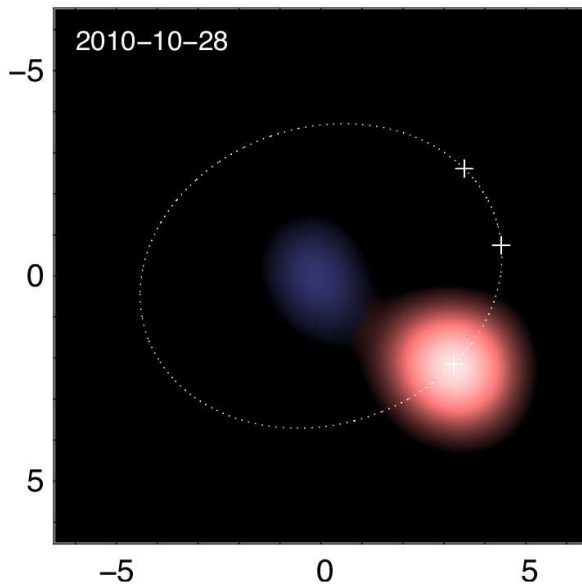
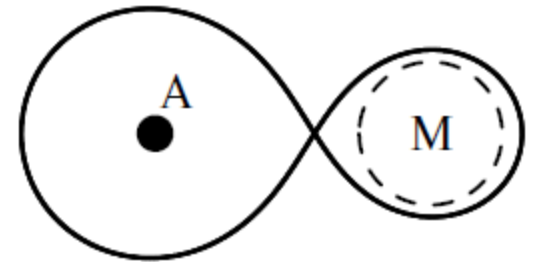


Fig. 9. Best-fit of the apparent orbit of HIP11231, considering all the Campbell elements free except the period (142.33 days, from [Barker et al. 1967](#)). The black circles are the PIONIER astrometric measurements. The red dotted line is the best orbit with its line of nodes in dashes. The red crosses are the positions of the companion at the time of the PIONIER observations predicted by the best-fit orbit. The average residual distance is $60 \mu\text{s}$. The reference frame is centered on the primary star. North is up and east to the left.

SS Lep: binaire symbiotique

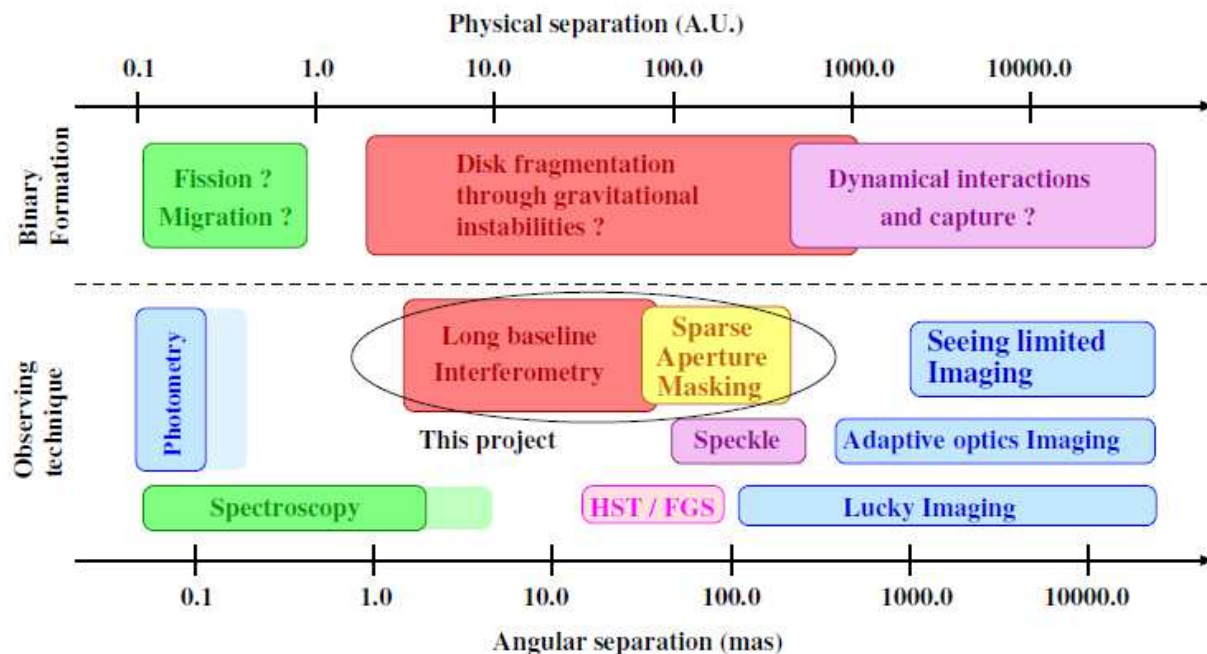
Blind et al. 2012

- Binaire A0V–M1III, $P=260$ jours
- Résultat PIONIER
 - Orbite 3D \rightarrow séparation et masses
 - Rapport de masse plus petit que prévu
 - Le lobe de Roche n'est pas rempli!
 - Mécanisme de transfert de masse inattendu (vent?)



Binaires massives

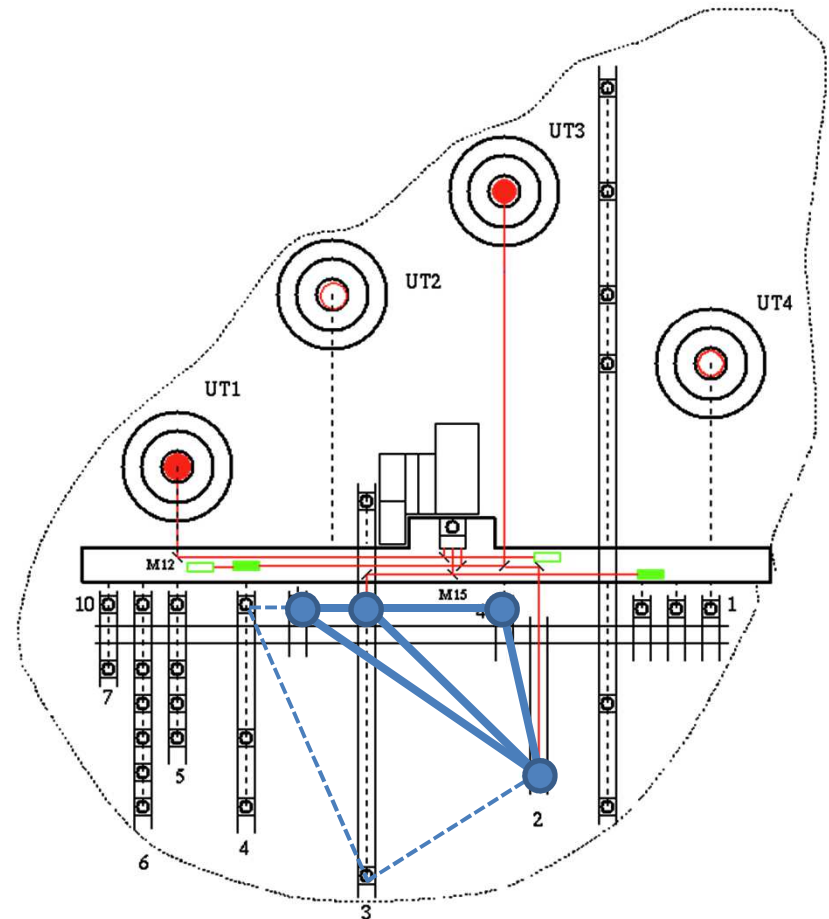
- Étoiles O → haut degré de multiplicité (~100%?)
- Mécanisme de formation a de l'influence sur
 - Fraction de binaire
 - Distribution des séparations
- PIONIER: survey et follow-up d'un grand échantillon



Searching for faint companions

Absil et al. 2011

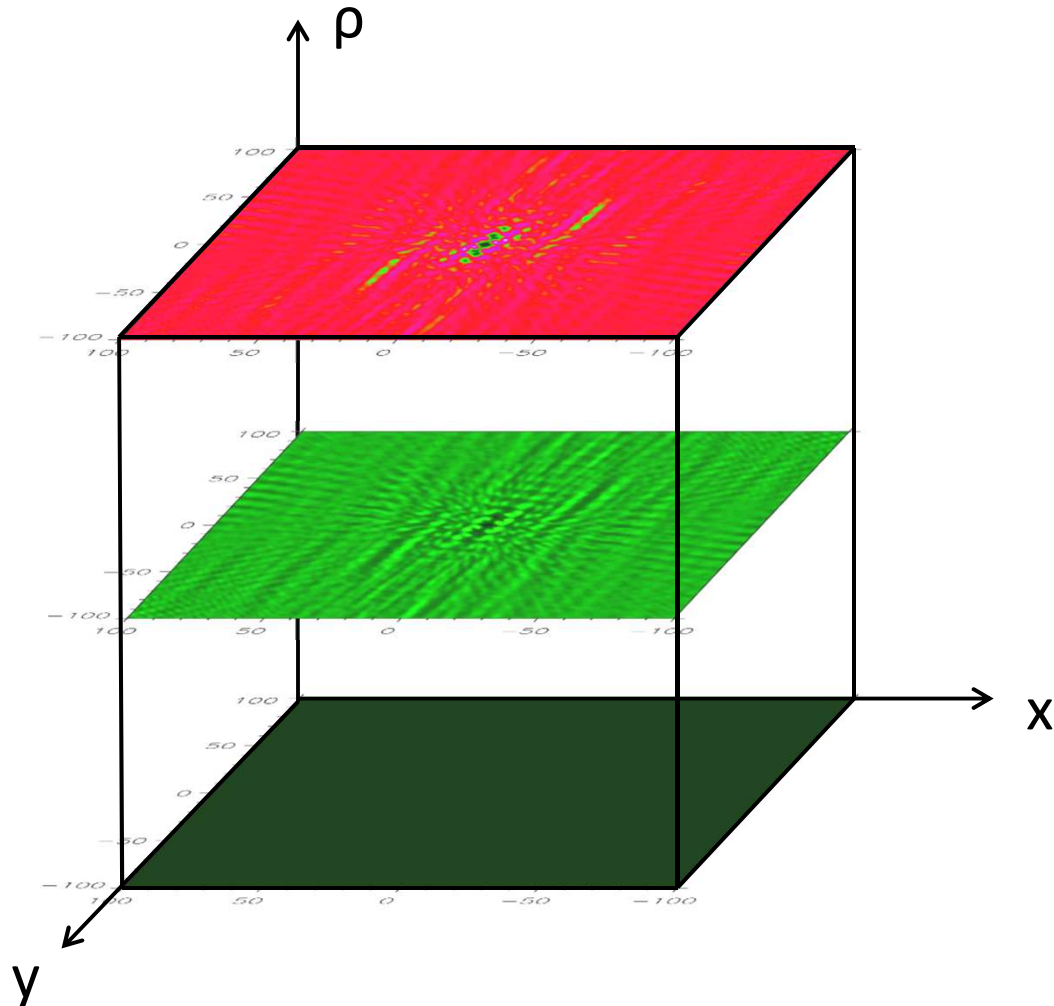
- Oct-Dec 2010
 - Commissioning run
 - First scientific runs
- Deep integrations
 - Fomalhaut (7 OBs)
 - τ Cet (6 OBs)
- Snapshots
 - δ Aqr (1 OB)
 - Regulus (3 OBs)
- 7 spectral channels
- ~50m baselines



Companion search method

Absil et al. 2011

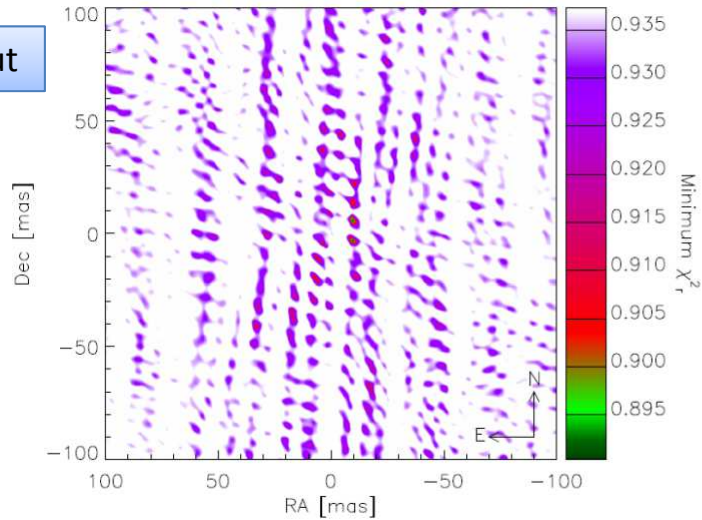
- χ^2 cube
 - Series of binary models compared to $\psi(\lambda)$ data
- Search minimum
- Evaluate significance
 - Renormalise so that $\chi^2_{\min}=1$
 - Probability of null hypothesis?



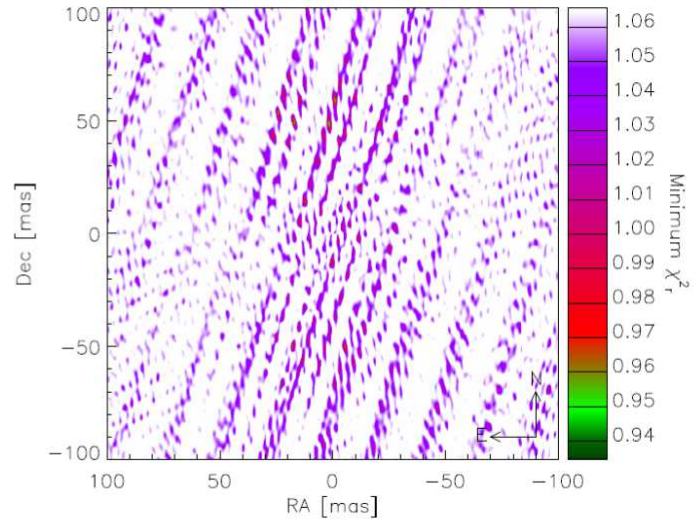
Minimum χ^2 maps

Absil et al. 2011

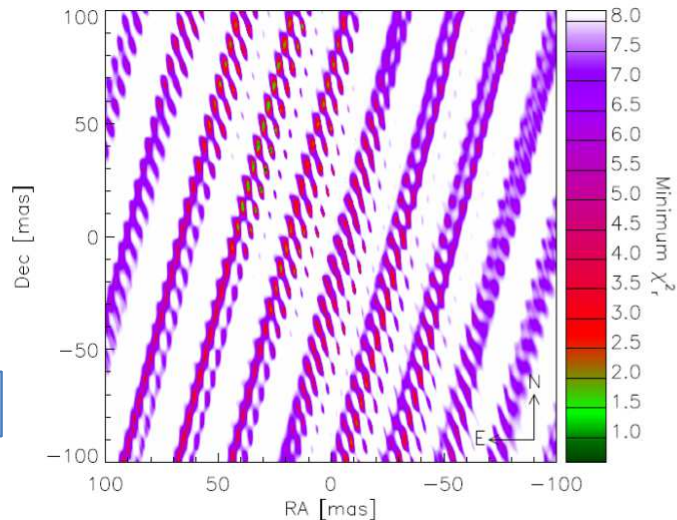
Fomalhaut



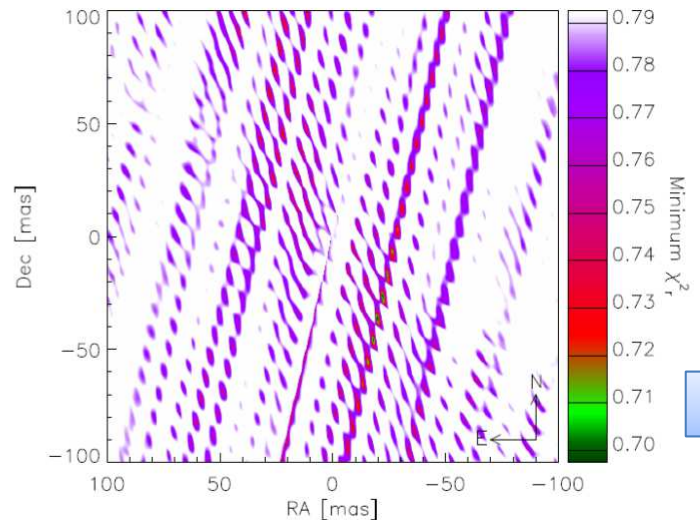
τ Cet



δ Aqr



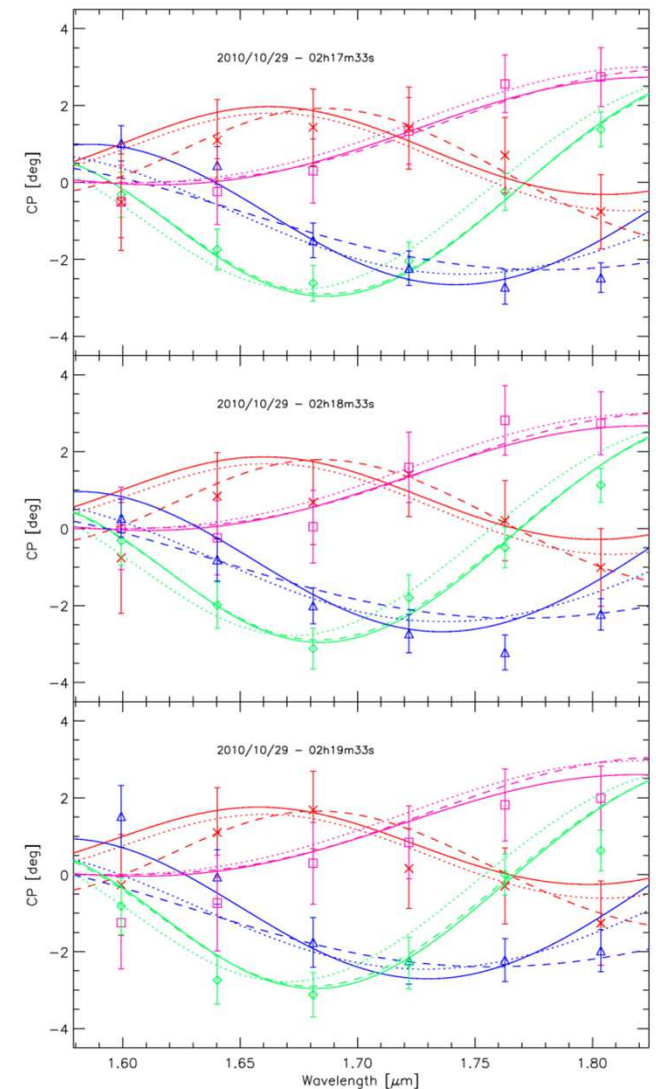
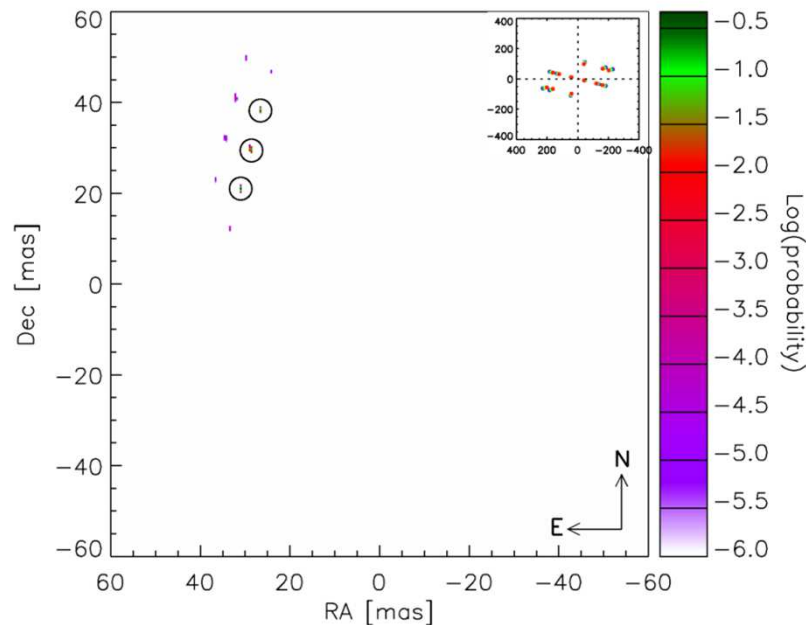
Regulus



A companion around δ Aqr

Absil et al. 2011

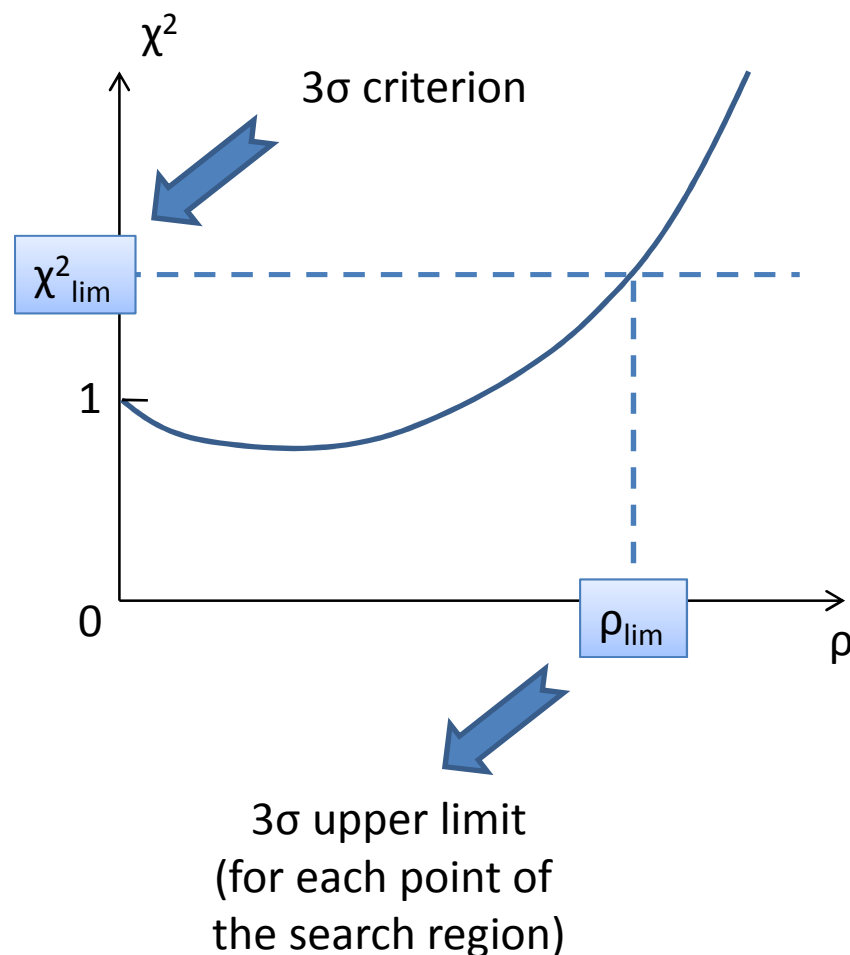
- Long period RV + astrometry
- Contrast $2.05\% \pm 0.16\%$
 - A3V + G5V system
- Position ambiguous



Deriving upper limits

Absil et al. 2011

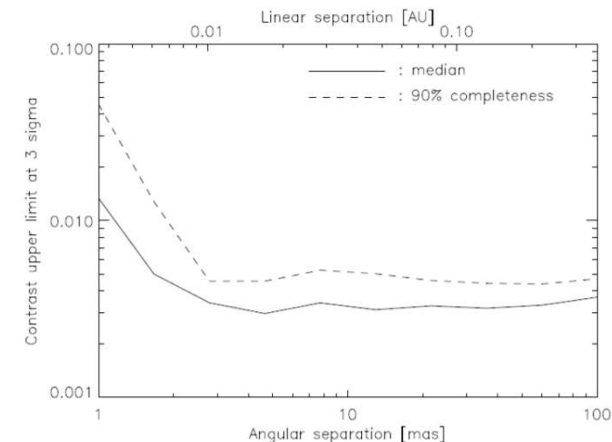
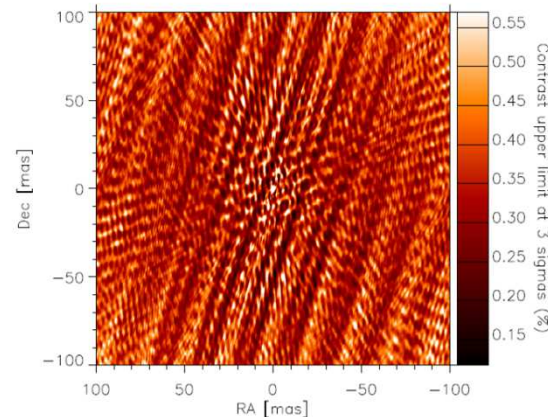
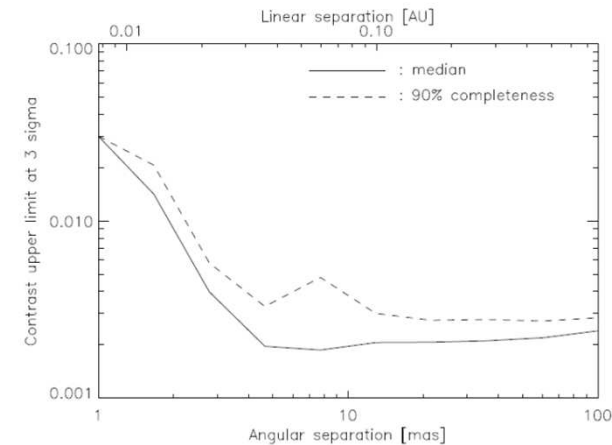
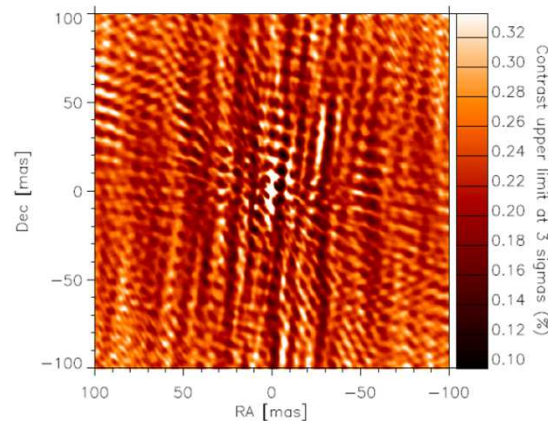
- Based on χ^2 cube
 - Renormalise $\chi^2|_{\rho=0} = 1$
 - Find ρ such that model at more than 3σ from data
- Double blind test
 - Fake companions inserted into calibrated ψ data
 - Count the fraction of good detections vs ρ



Deep search: χ^2 cube results

Absil et al. 2011

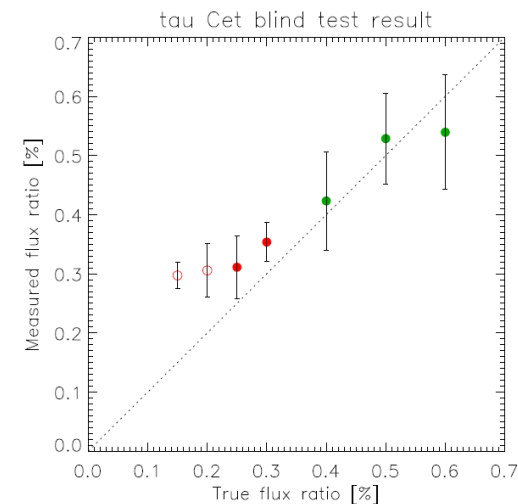
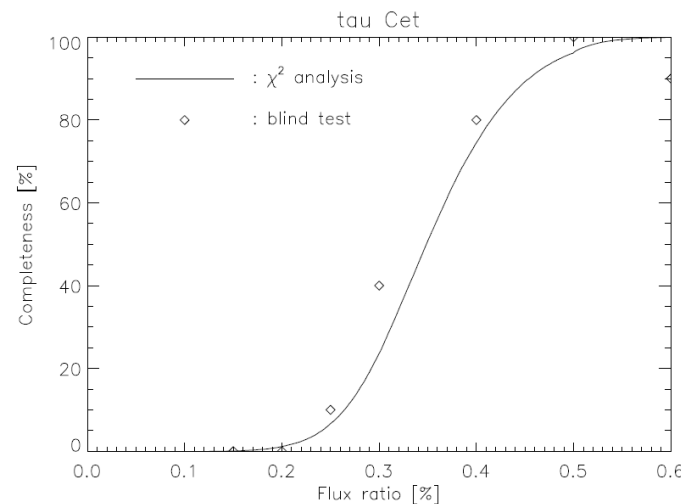
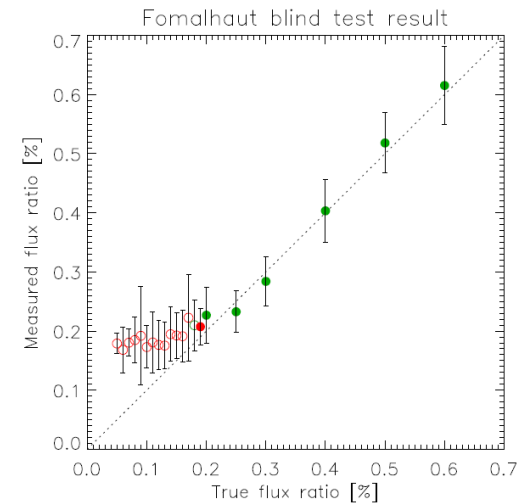
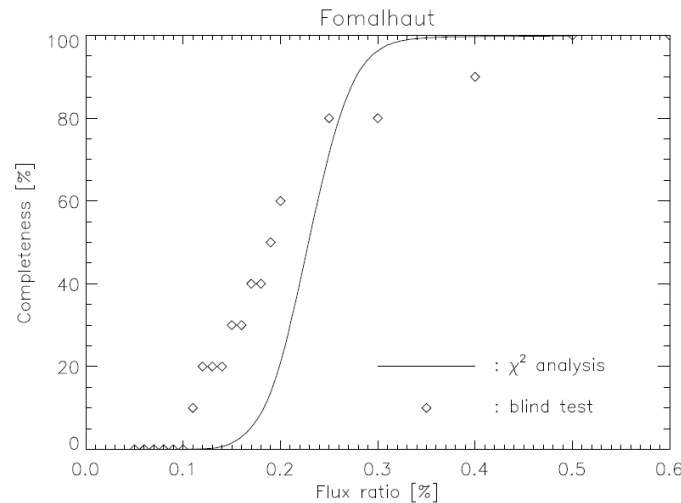
- 3σ sensitivity on 100 mas region
 - Fom: 2.3×10^{-3}
 - τ Cet: 3.5×10^{-3}
- 90% upper limit
 - $0.17 M_{\text{sun}}$ (\sim M6V)
 - $0.09 M_{\text{sun}}$ (\sim BD)
- Exclude companion as source of near-infrared excess



Deep search: blind test results

Absil et al. 2011

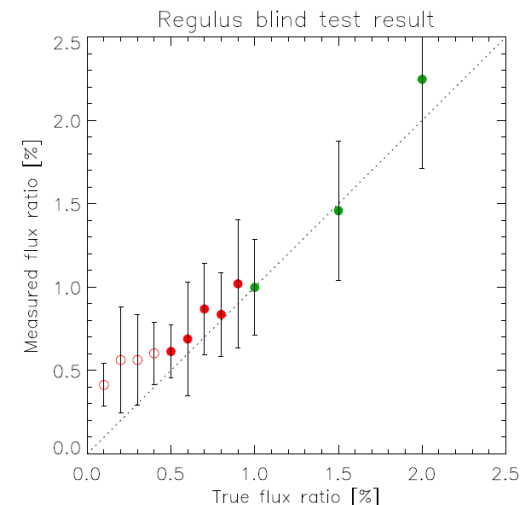
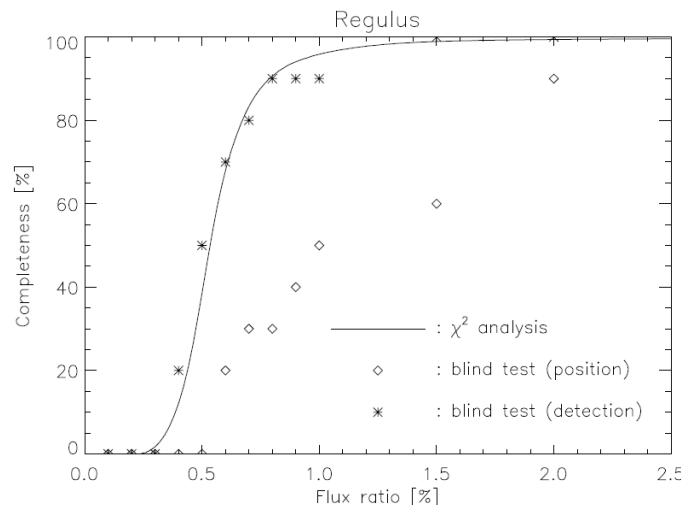
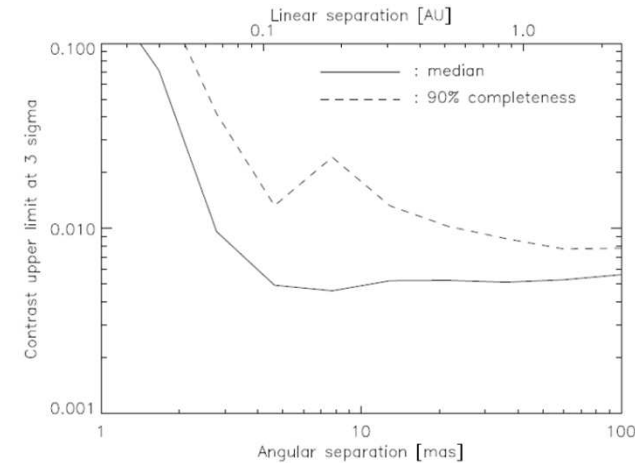
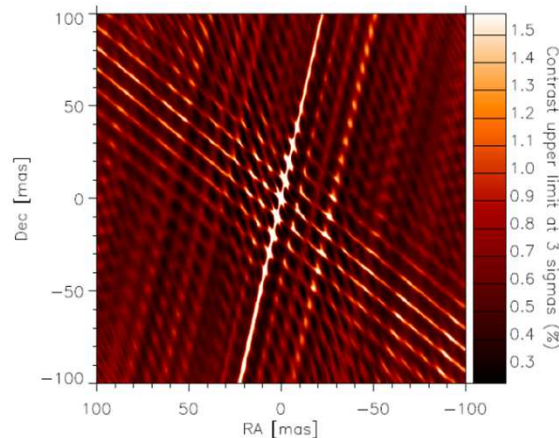
- Confirms the χ^2 results
- Median sensitivity
 - Fom: 1.9×10^{-3}
 - τ Cet: 3.2×10^{-3}
- False detections
 - $\leq 2.3 \times 10^{-3}$
 - $\leq 3.5 \times 10^{-3}$



Snapshot results (Regulus)

Absil et al. 2011

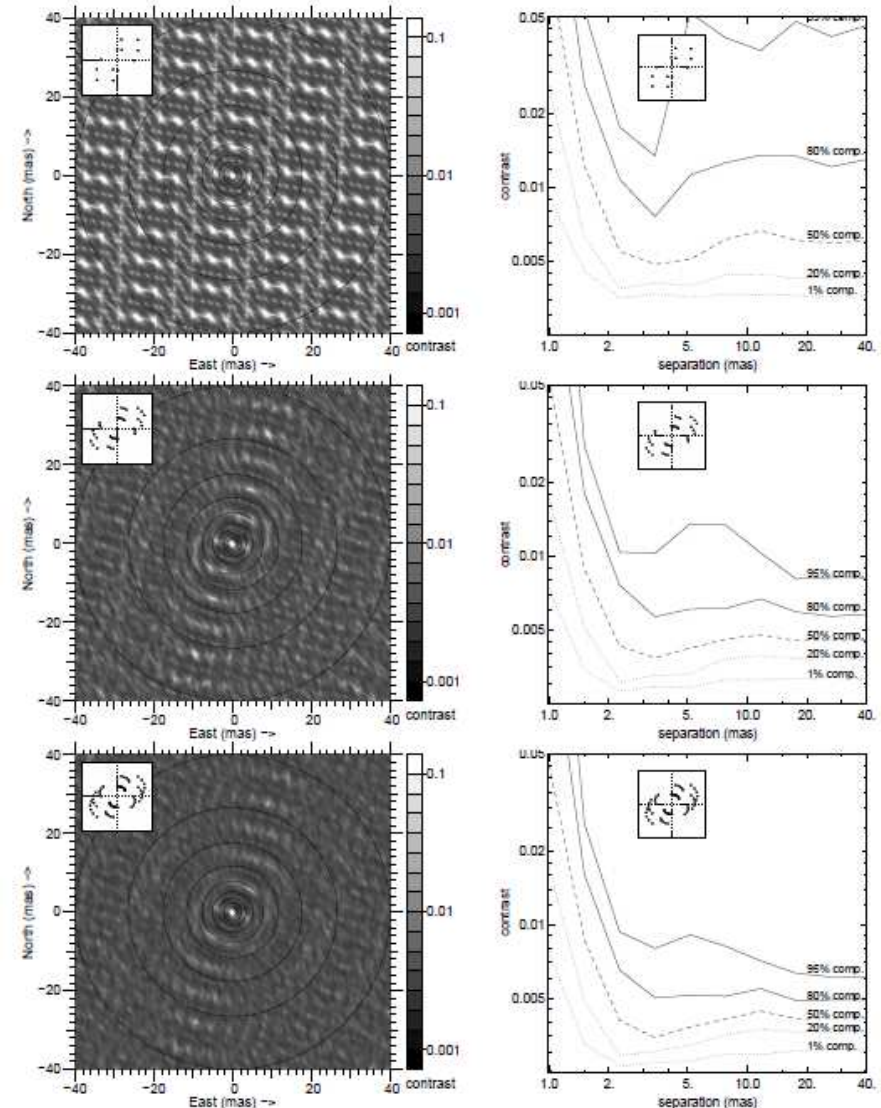
- Median sensitivity: 5.4×10^{-3}
- Poor uv plane coverage \rightarrow zones with low sensitivity
- Blind test ok for contrast but not for position
 - “Side lobes” of instrument PSF



Sensitivity vs number of OBs

Le Bouquin et al. 2012

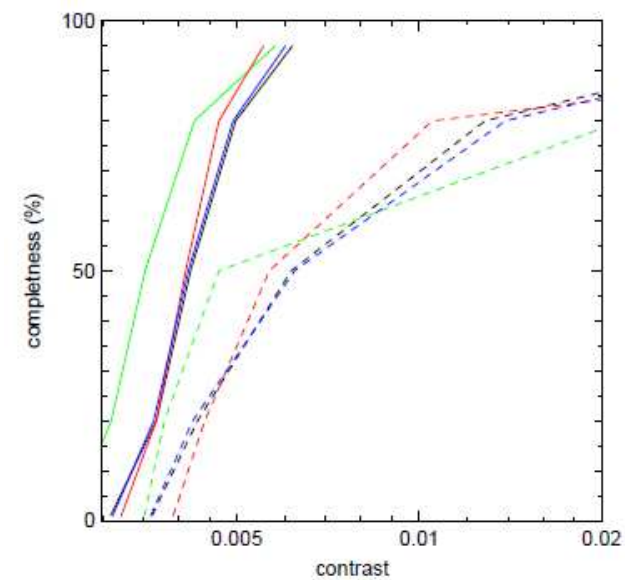
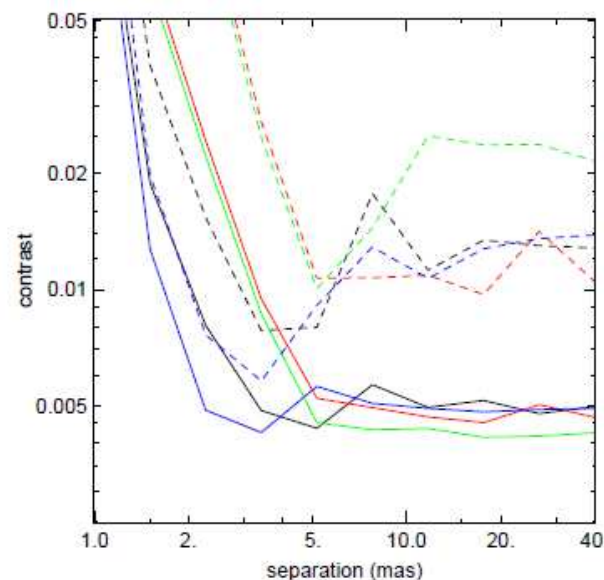
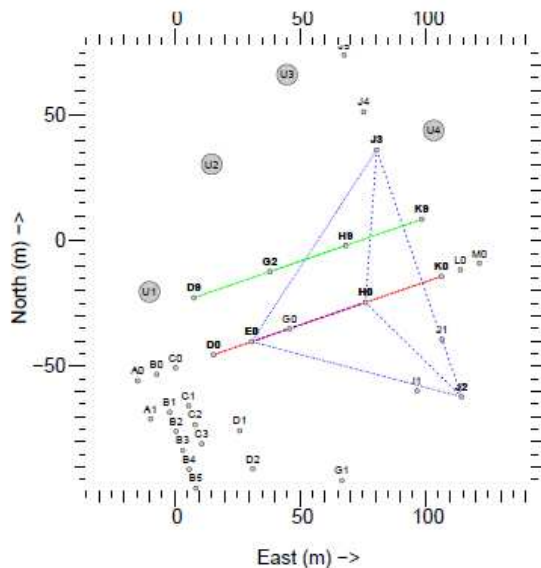
- Assume accuracy of 0.25° on A1-G1-I1-K0
- Pointings at hour angles
 - 0h
 - -1h, 0h, 1h
 - -2h, -1h, 0h, 1h, 2h
- Median sensitivities
 - 6×10^{-3} , 4.5×10^{-3} , 4.0×10^{-3}
 - Huge improvement in completeness
- 3 pointings ok for survey



Sensitivity vs configuration

Le Bouquin et al. 2012

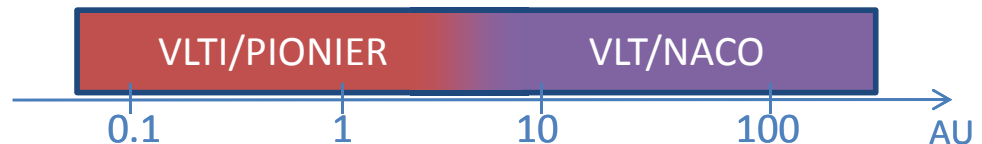
- Sensitivity does not depend on configuration
- Configuration size still matters
 - Sets inner working angle and FOV size
- Companion search = ideal filler program!



Astrophysical applications

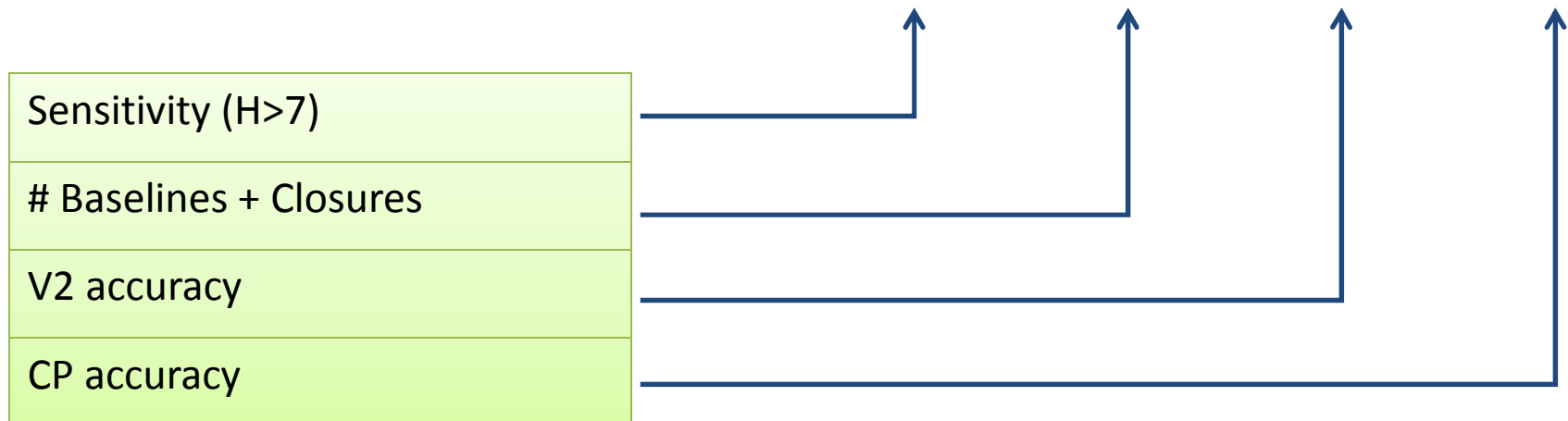
- Performance summary
 - Noise floor $\sim 0.2^\circ$
 - Dynamic range $\Delta H \sim 6$
 - Valid up to $H \sim 6$ (?)
- Warm BD/planets
 - Transition objects
 - Moving groups
 - Hot Jupiters ... not yet
- Binary fraction of massive stars
 - Mass ratio up to ~ 15

| Age | A0V | G0V | M0V |
|---------|-----------------------|------------------------|------------------------|
| 10 Myr | $0.09 M_{\text{sun}}$ | $0.017 M_{\text{sun}}$ | $0.012 M_{\text{sun}}$ |
| 50 Myr | $0.22 M_{\text{sun}}$ | $0.043 M_{\text{sun}}$ | $0.013 M_{\text{sun}}$ |
| 200 Myr | $0.35 M_{\text{sun}}$ | $0.08 M_{\text{sun}}$ | $0.030 M_{\text{sun}}$ |



The PIONIER benefits

| | | | | |
|---------------------------------------|---|---|---|---|
| T Tauri (Ménard) | ■ | ■ | ■ | |
| HAeBe imaging (Berger) | ■ | ■ | | |
| Transitional disks (Benisty) | ■ | ■ | | |
| Debris disks (Absil / Augereau) | | ■ | ■ | |
| Massive binaries (Sana / Le Bouquin) | ■ | | | ■ |
| Faint companions (Absil / Le Bouquin) | | ■ | | ■ |
| Hot Jupiters (Perrier / Absil) | | ■ | | ■ |



Conclusions & perspectives

- PIONIER = succès technique et scientifique
 - Performances compatibles avec les spécifications
 - Le mode 4T du VLTI a été « débuggé »
 - Imagerie « snapshot » enfin possible au VLTI
- Nouveau recombineur bande K
 - En cours de test, installation prévue courant 2012
- Détecteur de nouvelle génération
 - APD infrarouge: SELEX ou RAPID
 - Gain de 1-2 mag dès 2013?
- Proposé à la communauté via l'ESO dans le futur?
 - Entretemps, consortium ouvert aux collaborations