FIRST

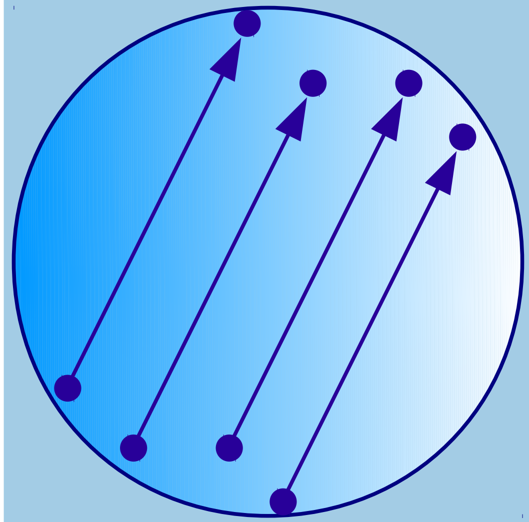
Fibered **I**mager fo**R** **S**ingle **T**elescope

Elsa Huby
LESIA, Observatoire de Paris

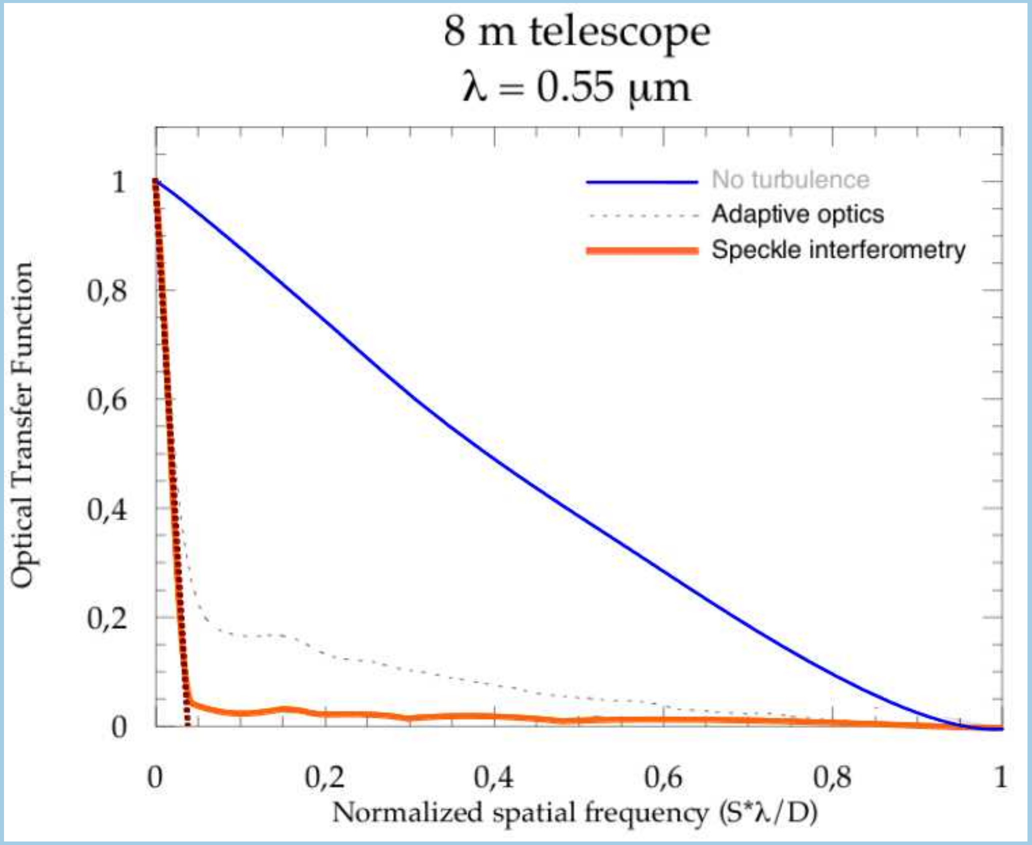
and **G. Perrin**, F. Marchis, **S. Lacour**, T. Kotani, G. Duchêne,
E. Choquet, E. Gates, J. Woillez, O. Lai, P Fédou

Redundant pupil

Telescope pupil

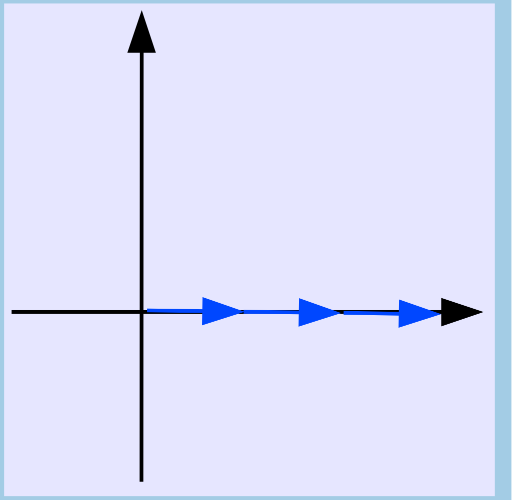


Optical Transfer Function
= pupil autocorrelation



Perrin et al., 2006

Coherent summing



Redundant pupil

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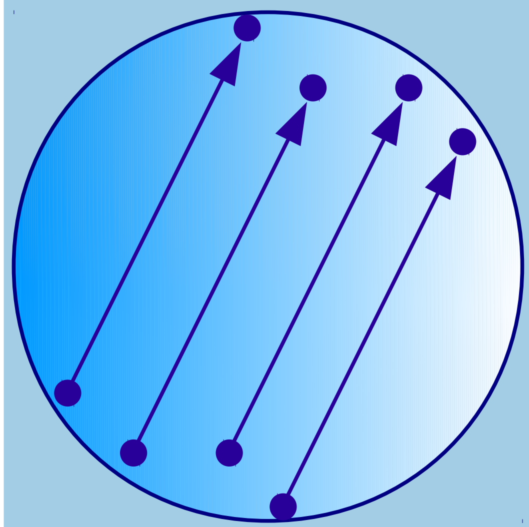
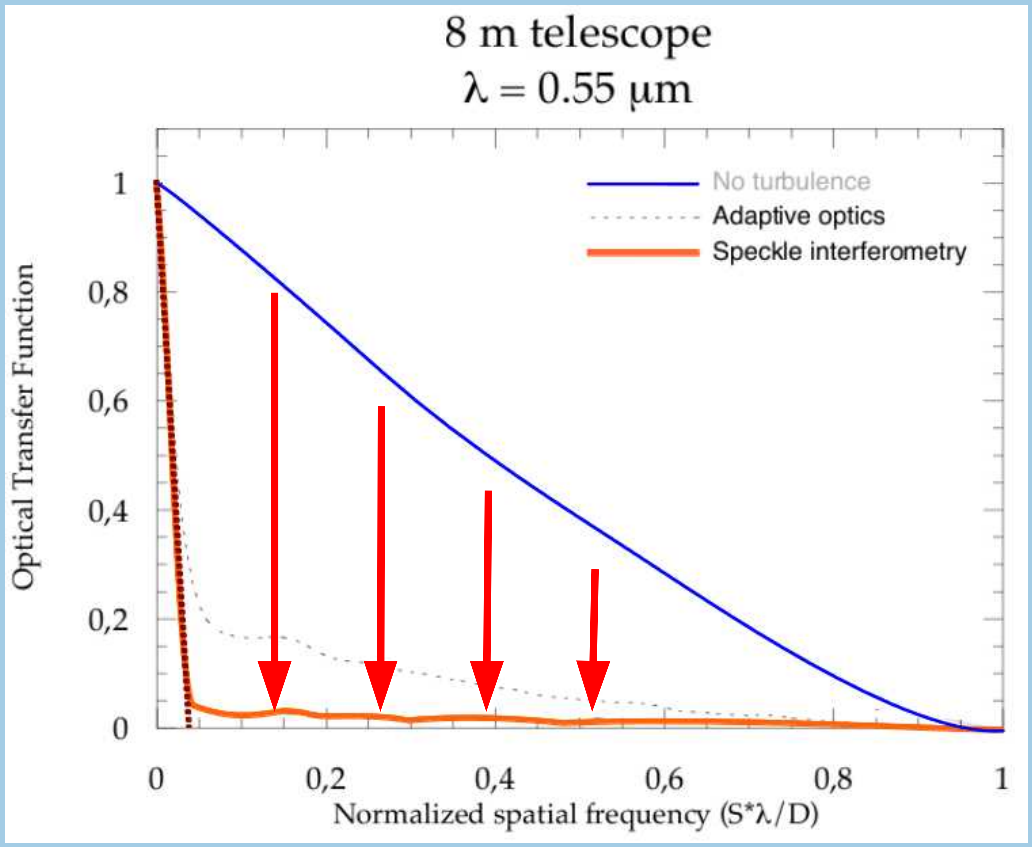
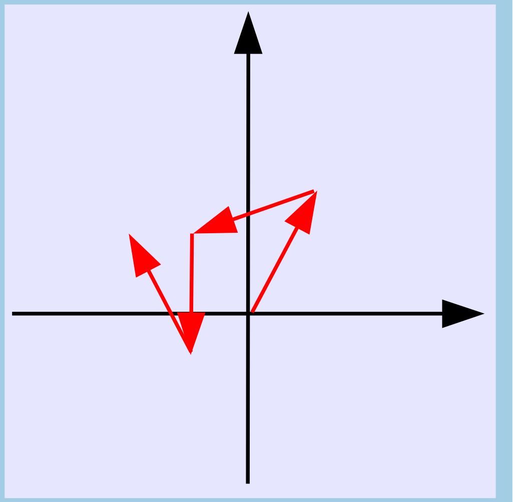




Perrin et al., 2006

Coherent summing

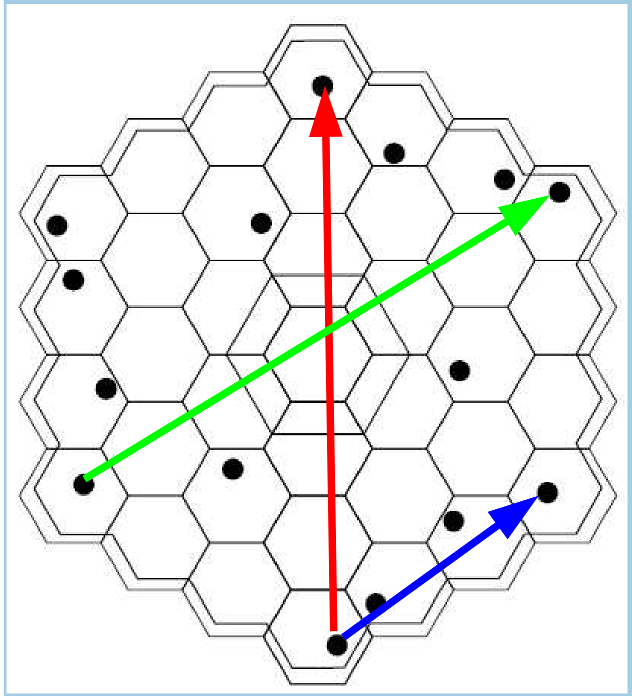


Turbulence → **random phases**

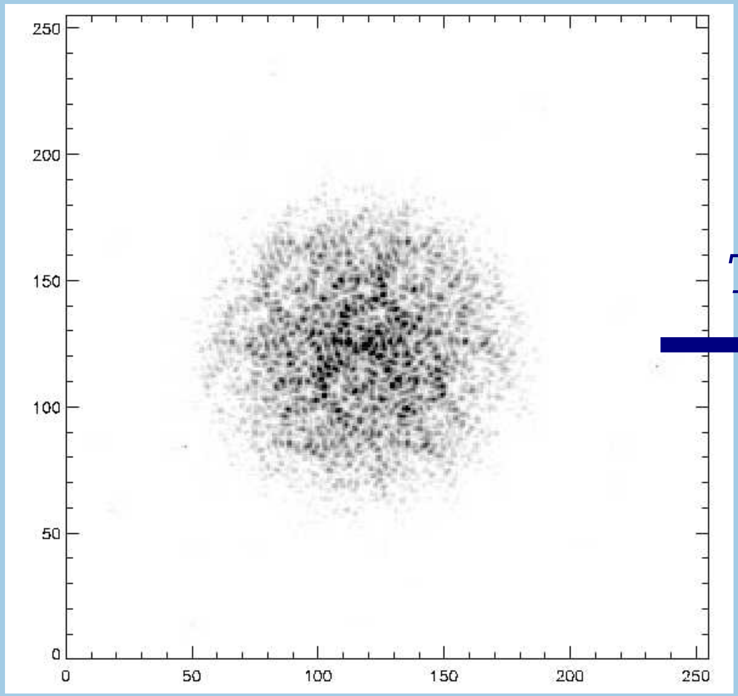
Non redundant pupil

Aperture mask on the Keck telescope : Tuthill et al. 2000

Non-redundant pupil mask

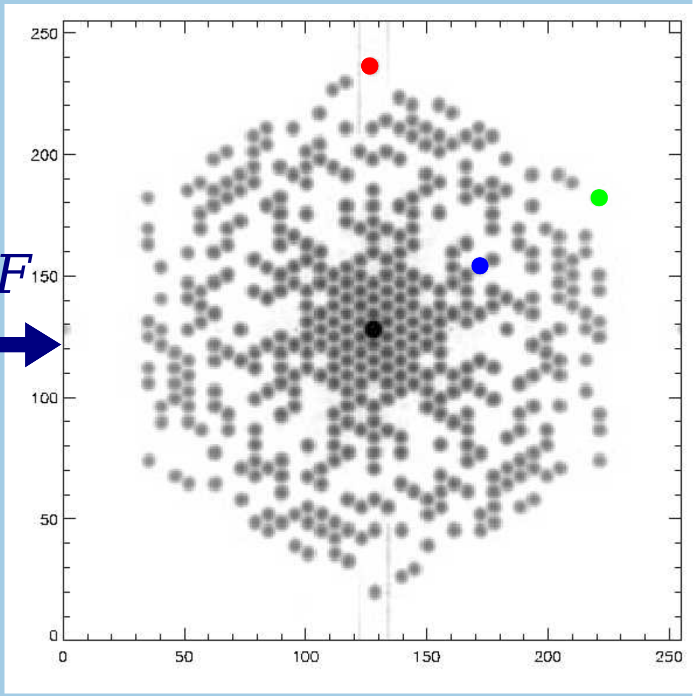


Point Spread Function



TF

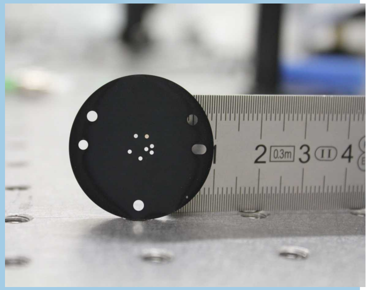
Optical Transfer Function



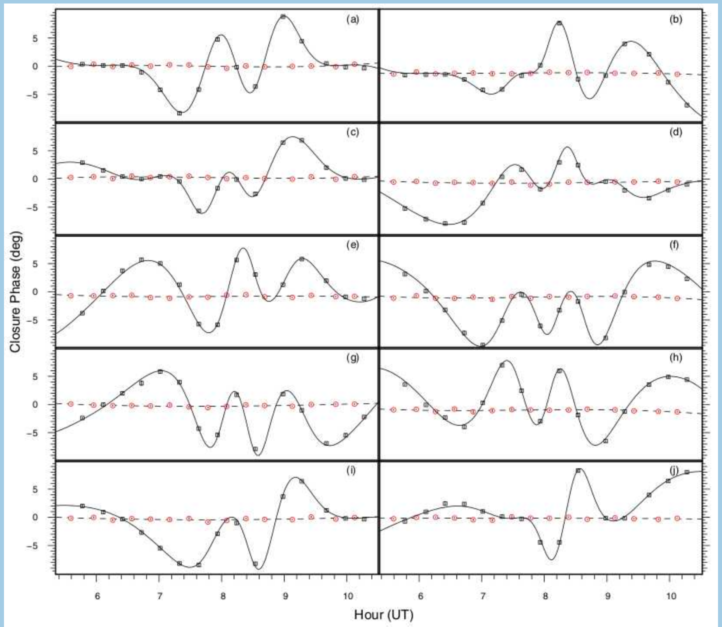
Tuthill et al., 2000

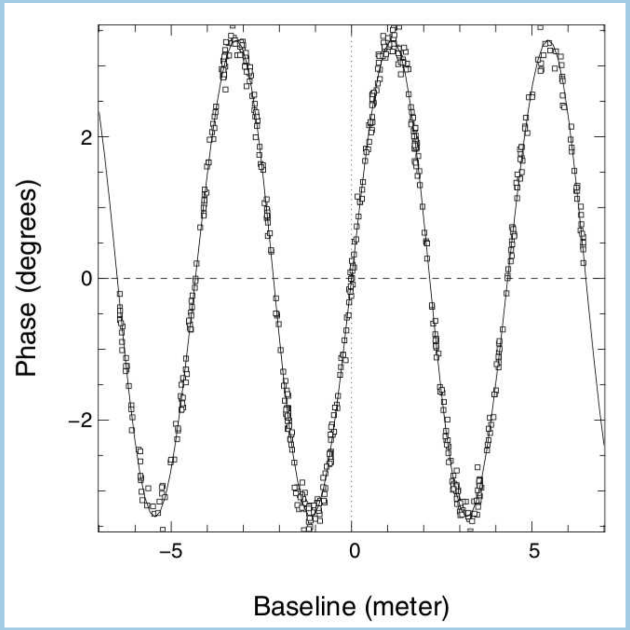
Recent results

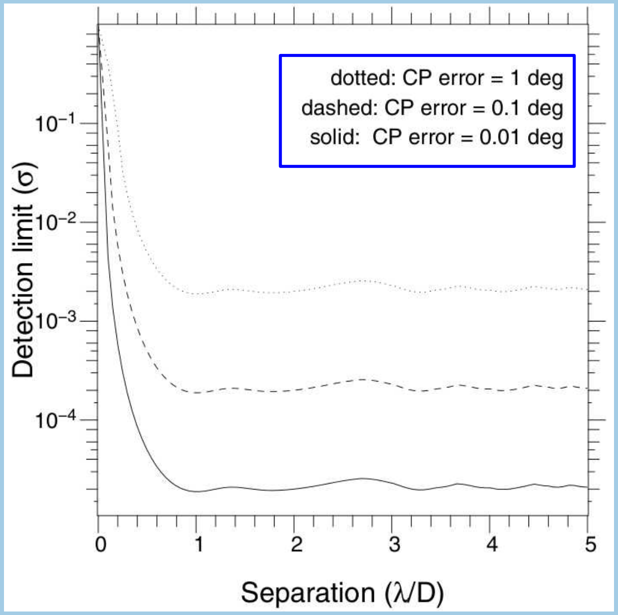
Sparse Aperture Masking at VLT (Lacour et al., 2011)



5σ high-contrast detection limits
at λ/D of 2.5 × 10^{-3} (ΔL = 6.5) for HD 92945
and 4.6 × 10^{-3} (ΔL = 5.8) for HD 141569

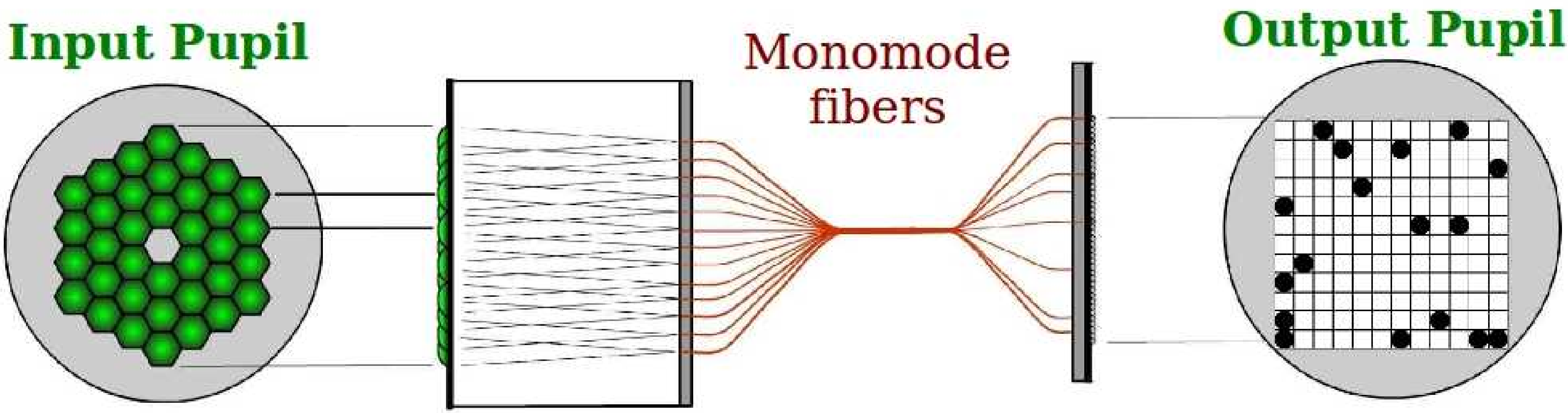






Drawbacks :
- limited collecting area
- spatial corrugations may remain

Pupil remapping



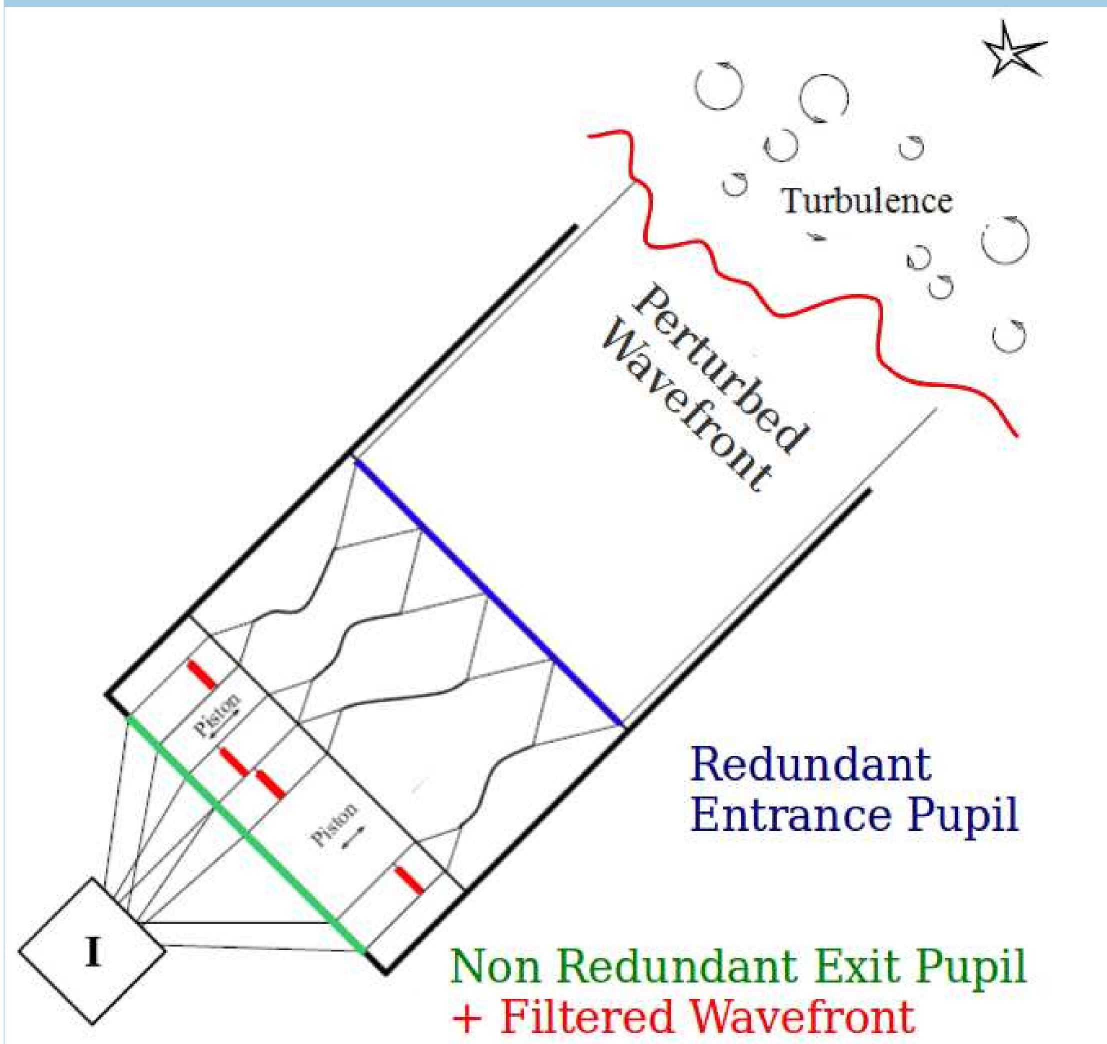
Redundant configuration + Corrugated wavefront

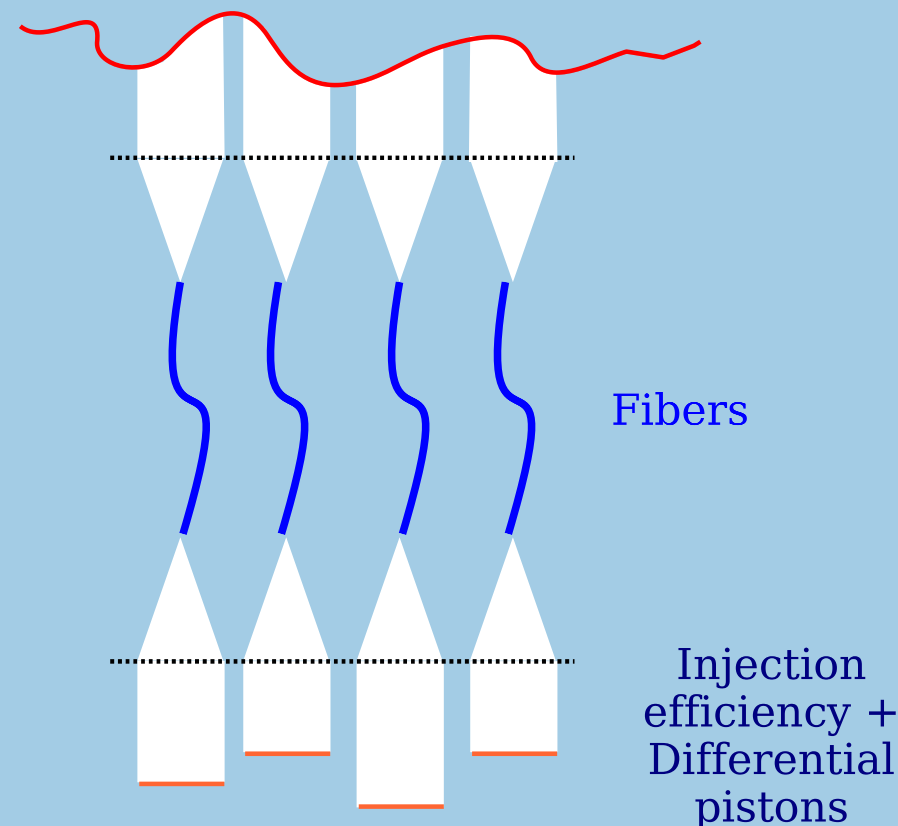
Non redundant configuration + **Plane** wavefronts

Perrin et al., 2006

The entire pupil can be used

Spatial filtering



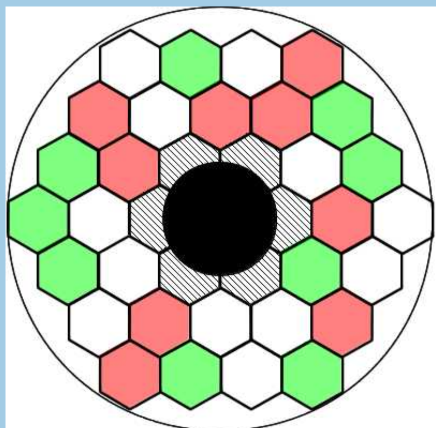


+ Self calibration algorithm

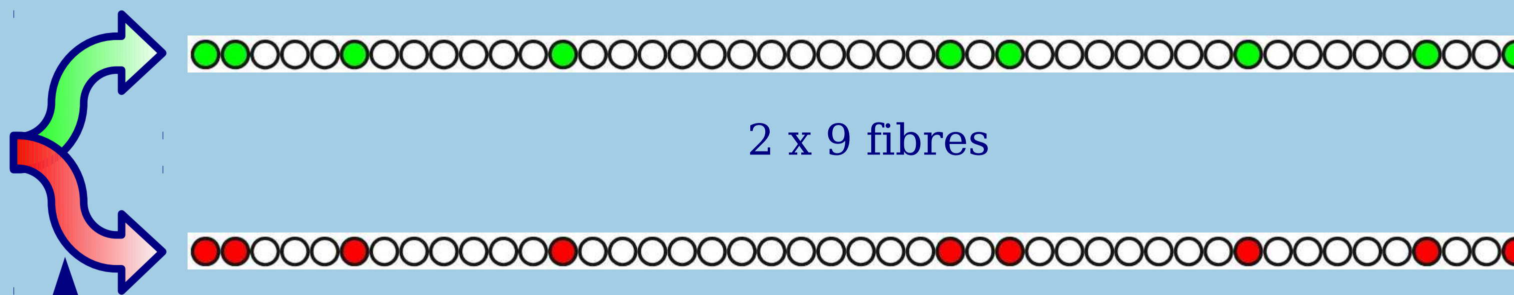
No Speckle noise

FIRST - 18

VIS : 600 – 900nm
RS = 300

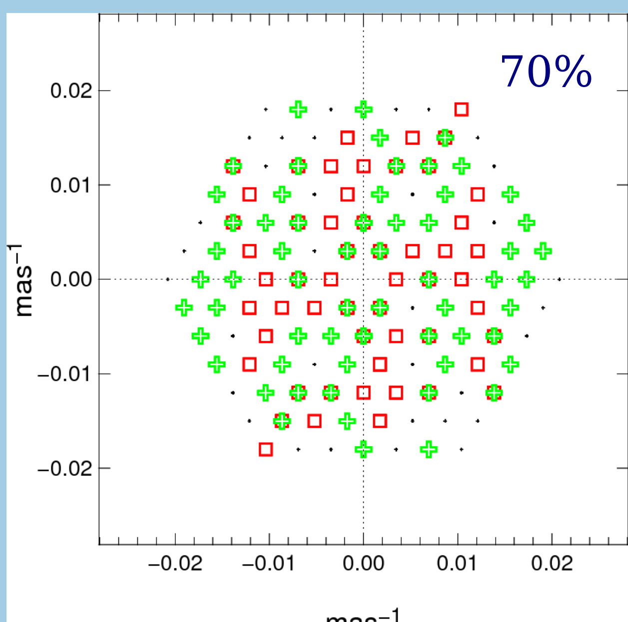


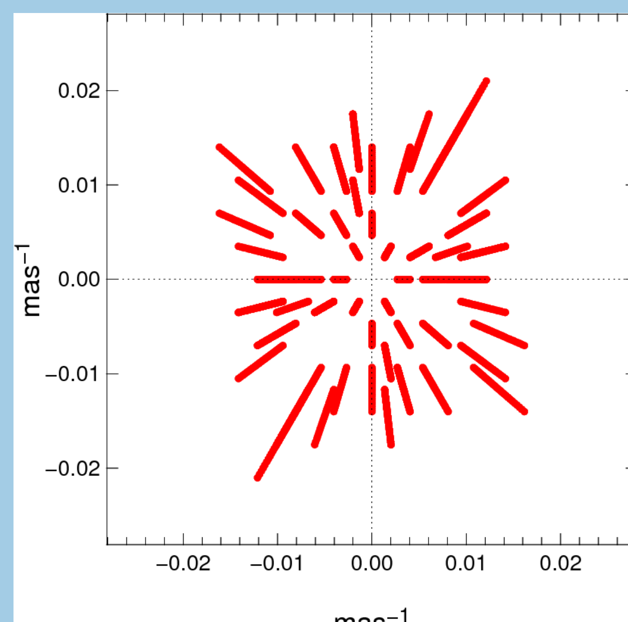
Redundant telescope entrance pupil



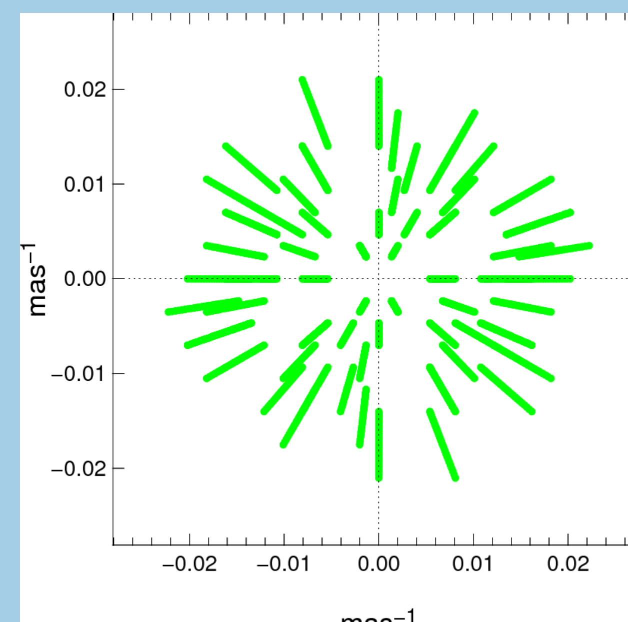
Single-mode fibers

Non-redundant recombination



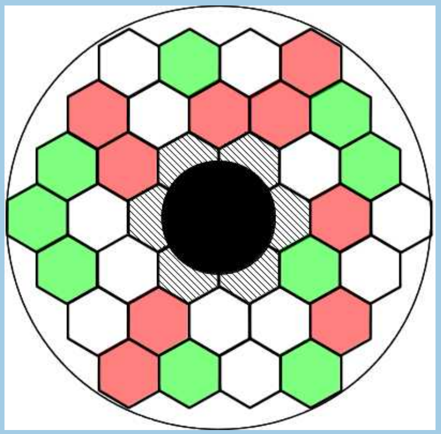


600-900nm

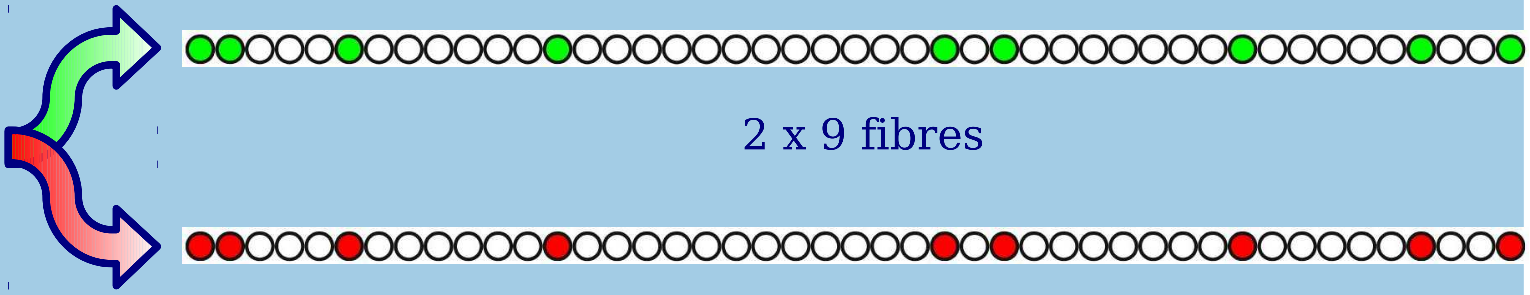


600-900nm

Self calibration algorithm



Redundant telescope entrance pupil



Non-redundant recombination

36 complex equations

$$\mu_{ij} = V_{ij} e^{i\Phi_{ij}} \times G_i G_j e^{i(P_j - P_i)}$$

versus

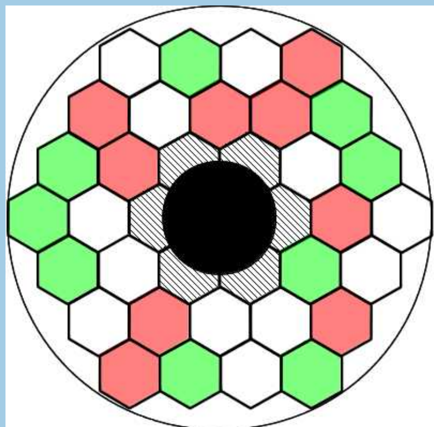
Non redundant case :

36 complex visibilities

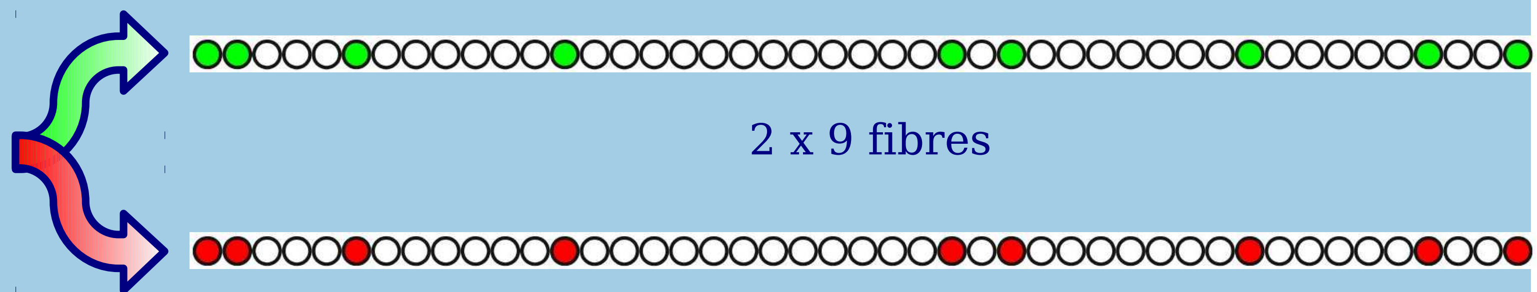
+ 9 complex gains

= 45 unknowns

Self calibration algorithm



Redundant telescope entrance pupil



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versus

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36 complex visibilities

+ 9 complex gains

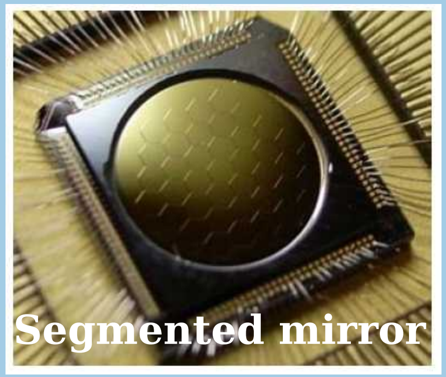
= 45 unknowns

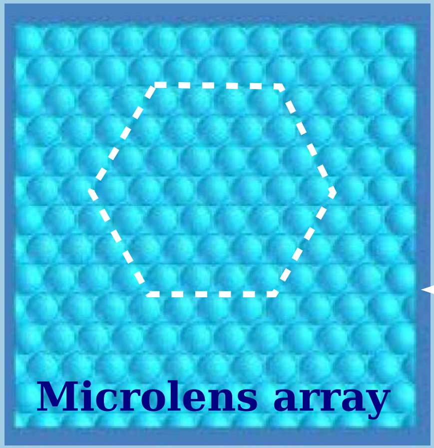
Solution

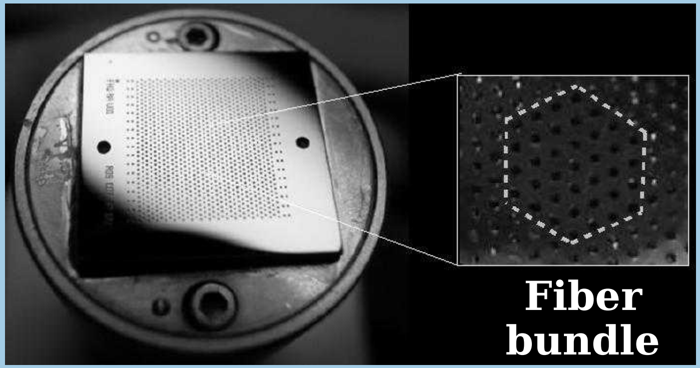
Lacour et al., 2007

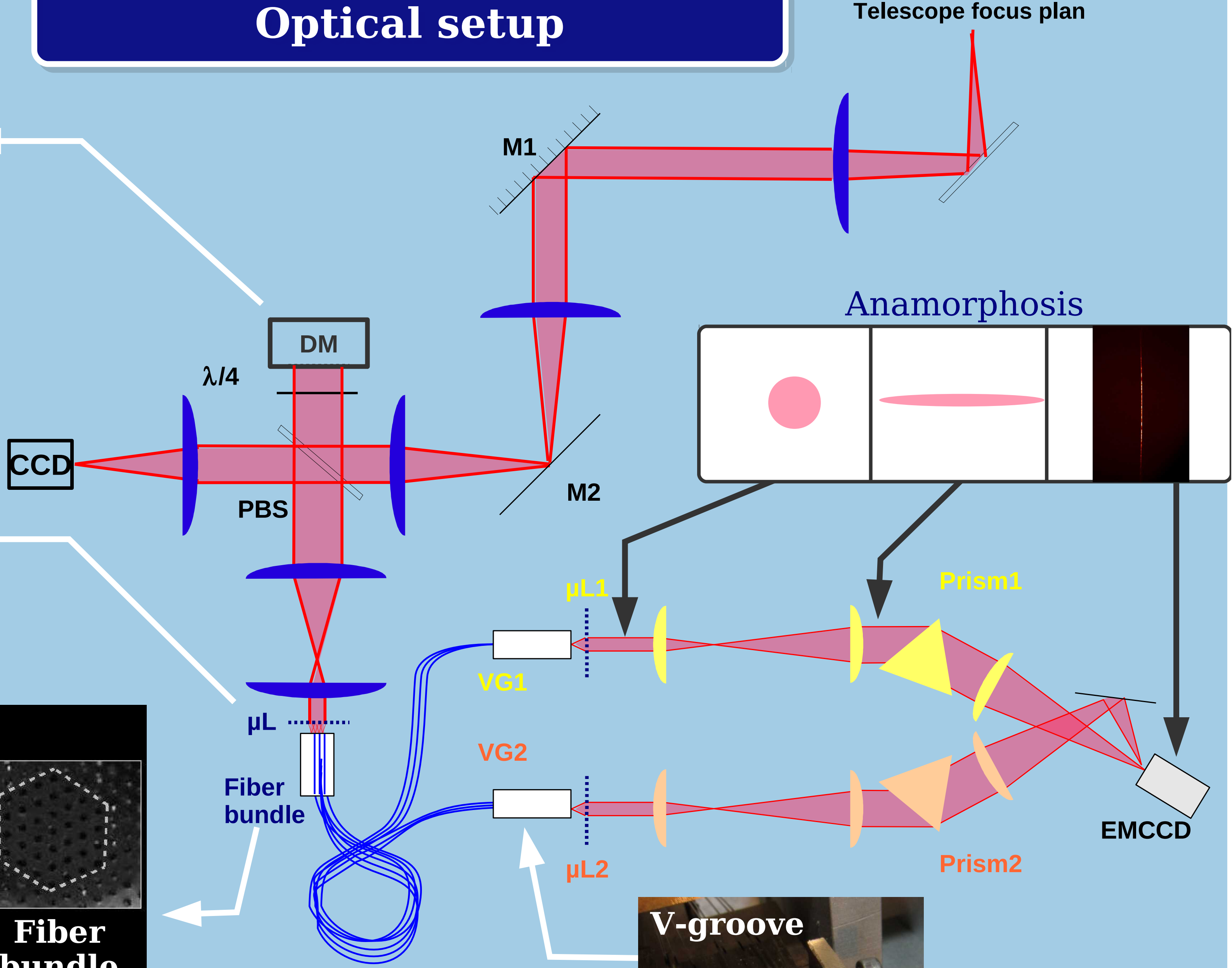
$$\begin{pmatrix}\arg(\mu_1)\\ \arg(\mu_2)\\ \arg(\mu_3)\\ \arg(\mu_4)\\ \arg(\mu_5)\\ \arg(\mu_6)\\ \arg(\mu_7)\\ \arg(\mu_8)\\ \arg(\mu_9)\\ \arg(\mu_{10})\\ \arg(\mu_{11})\\ \arg(\mu_{12})\\ \arg(\mu_{13})\\ \arg(\mu_{14})\\ \arg(\mu_{15})\end{pmatrix} = \underbrace{\begin{pmatrix}1&-1&0&0&0&0&1&0&0&0&0&0&0&0&0\\ 0&1&-1&0&0&0&1&0&0&0&0&0&0&0&0\\ 1&0&-1&0&0&0&0&1&0&0&0&0&0&0&0\\ 0&0&0&1&-1&0&1&0&0&0&0&0&0&0&0\\ 0&0&1&-1&0&0&0&0&1&0&0&0&0&0&0\\ 0&0&0&0&1&-1&0&0&0&1&0&0&0&0&0\\ 0&1&0&-1&0&0&0&0&0&1&0&0&0&0&0\\ 1&0&0&-1&0&0&0&0&0&0&1&0&0&0&0\\ 0&0&1&0&-1&0&0&0&0&1&0&0&0&0&0\\ 0&0&0&1&0&-1&0&0&0&0&1&0&0&0&0\\ 0&1&0&0&-1&0&0&0&0&0&1&0&0&0&0\\ 1&0&0&0&-1&0&0&0&0&0&0&1&0&0&0\\ 0&0&1&0&0&-1&0&0&0&0&0&0&1&0&0\\ 0&1&0&0&0&-1&0&0&0&0&0&0&0&1&0\\ 1&0&0&0&0&-1&0&0&0&0&0&0&0&0&1\end{pmatrix}}_{\text{Invertible matrix}} \cdot \begin{pmatrix}\phi_0\\ \phi_1\\ \phi_2\\ \phi_3\\ \phi_4\\ \phi_5\\ \arg(V_1)\\ \arg(V_2)\\ \arg(V_3)\\ \arg(V_4)\\ \arg(V_5)\\ \arg(V_6)\\ \arg(V_7)\\ \arg(V_8)\\ \arg(V_9)\end{pmatrix}$$

Optical setup

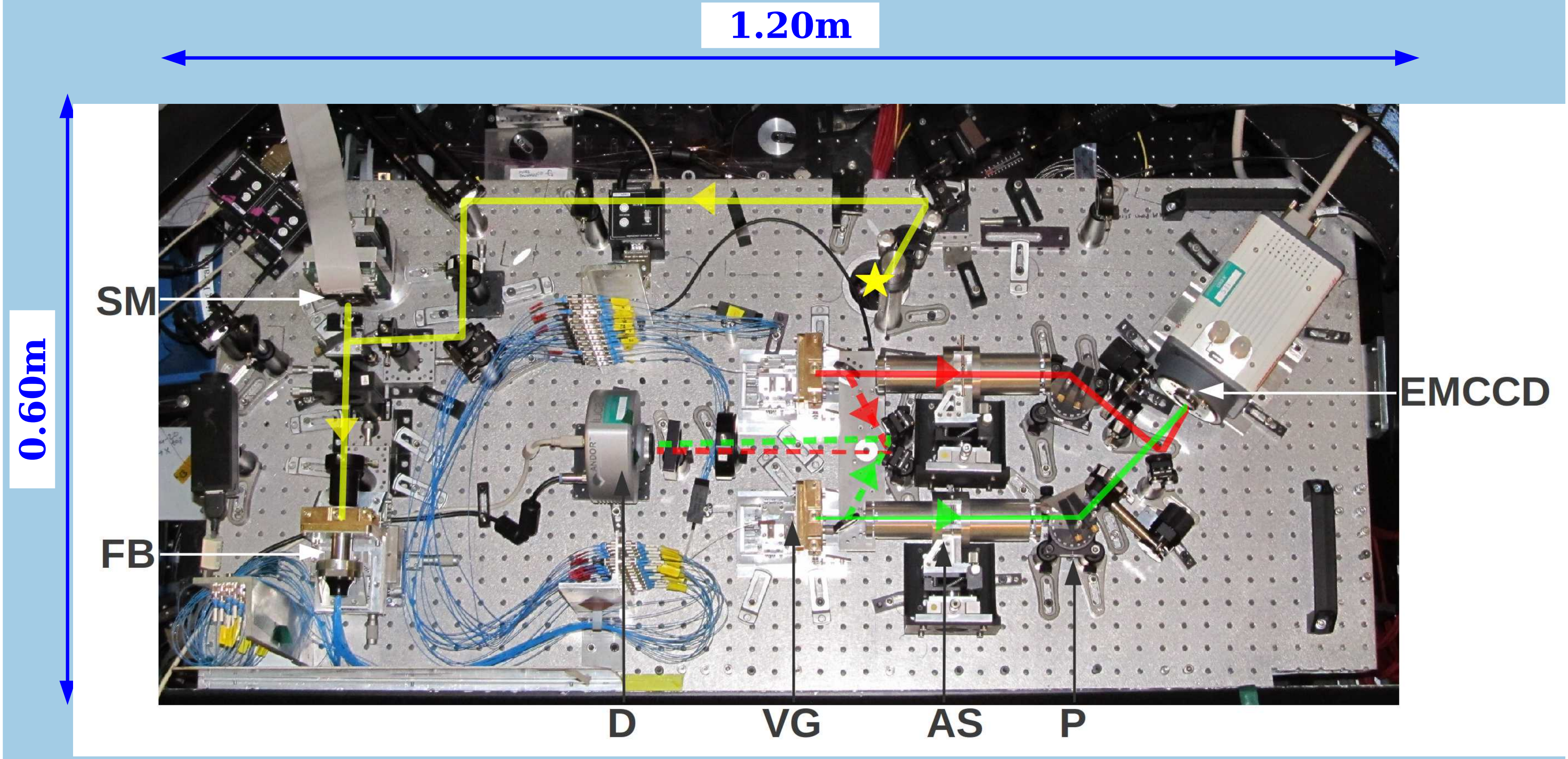




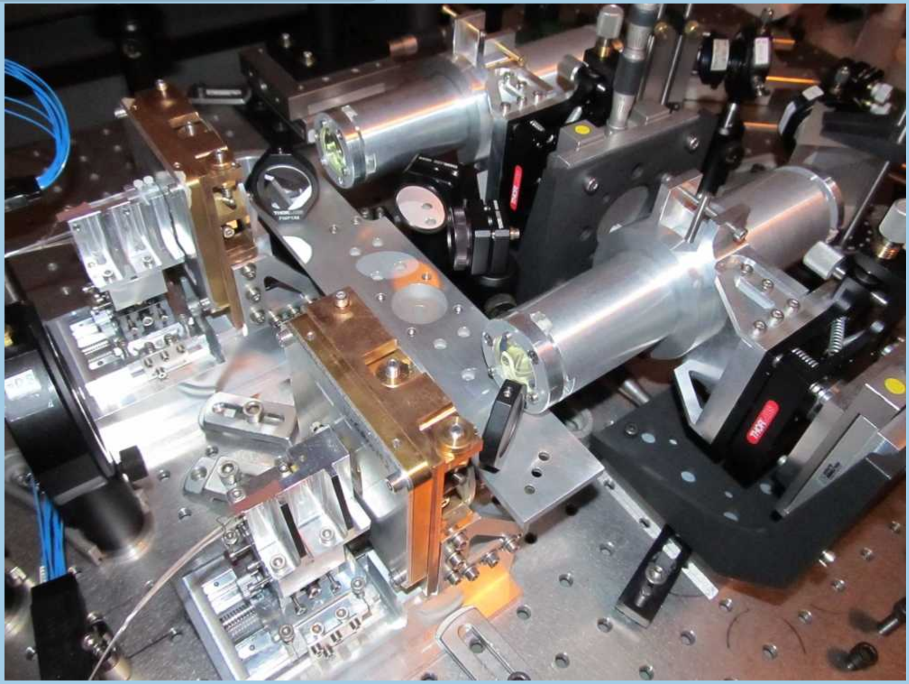


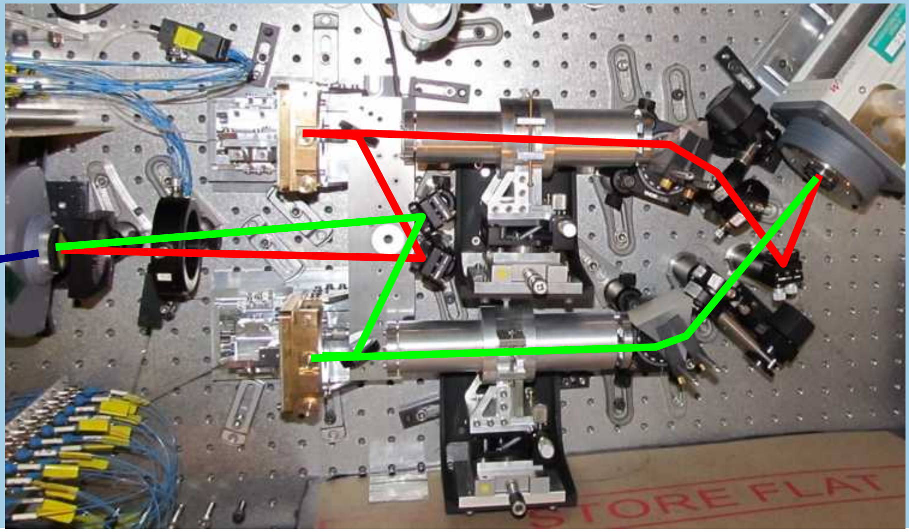


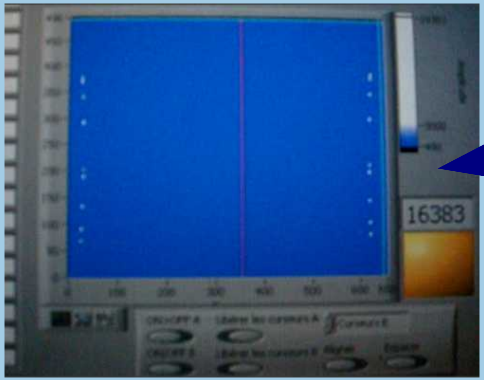
Optical setup



Injection Optimization



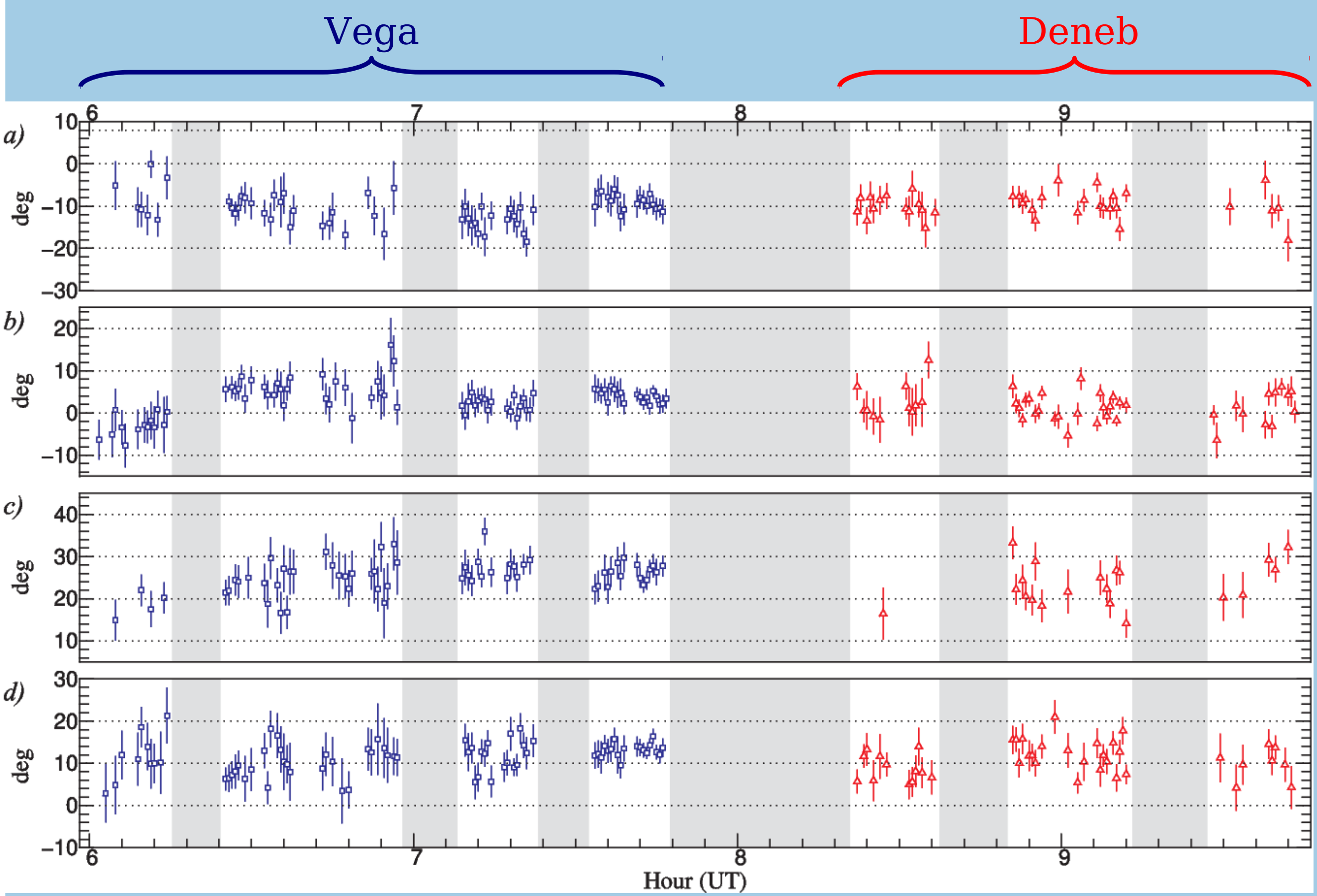


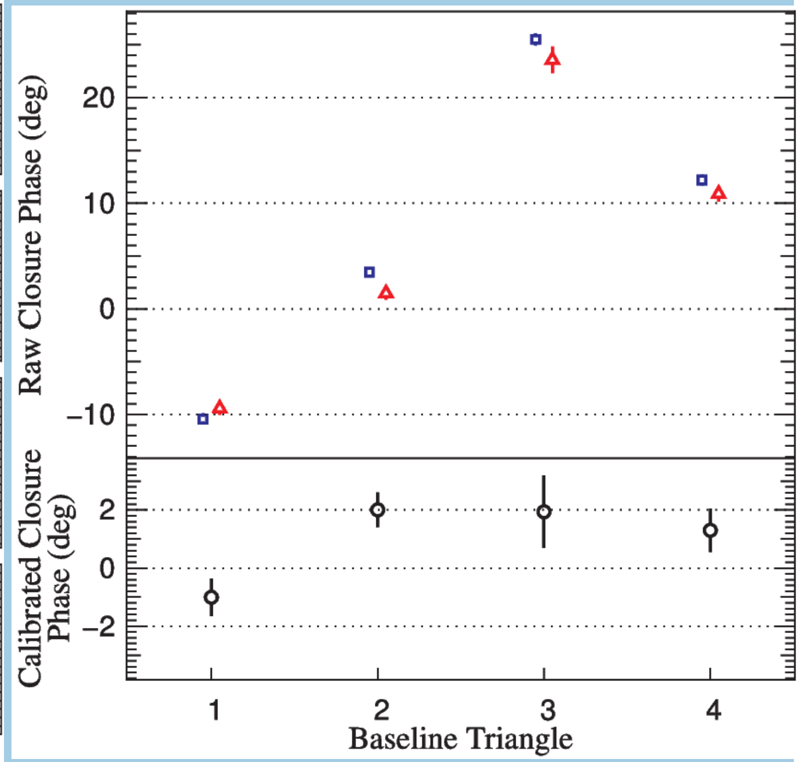


FIRST light !

Lick Observatory, Mount Hamilton
On the **3-m Shane** telescope
Behind **Adaptive Optics system**

Results – First light 2010

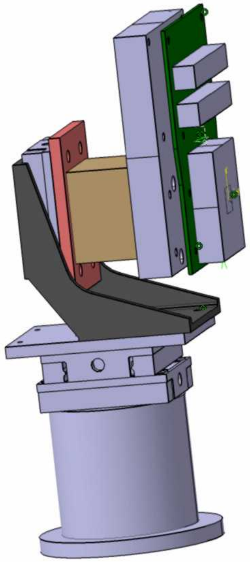




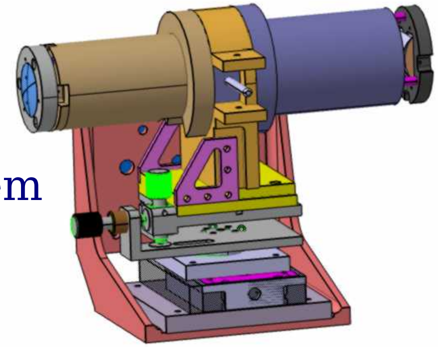
Baseline Triangle	CP Vega (°)	CP Deneb (°)	Calibrated CP (°)
1: 1-2-6	−10.4 ± 0.4	−9.4 ± 0.4	−1.0 ± 0.6
2: 1-2-13	3.5 ± 0.3	1.5 ± 0.4	2.0 ± 0.5
3: 1-6-13	25.5 ± 0.4	23.6 ± 1.1	1.9 ± 1.2
4: 2-6-13	12.2 ± 0.4	10.9 ± 0.6	1.3 ± 0.7

Huby et al. 2012

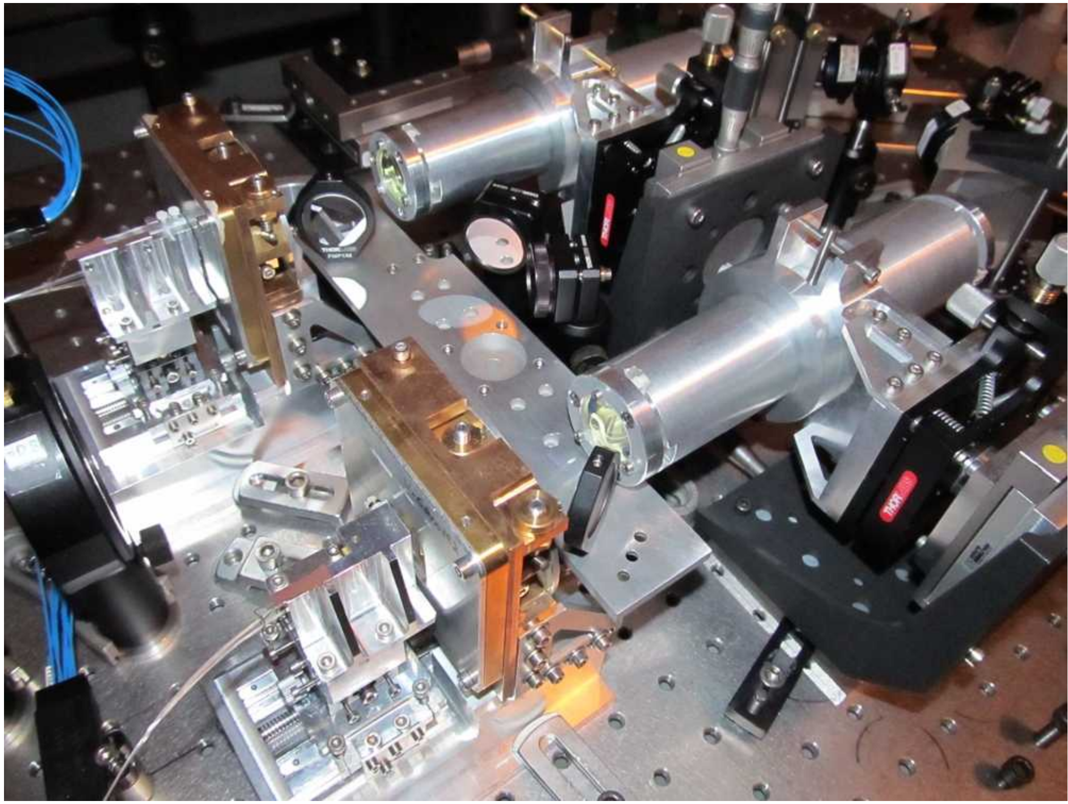
Optical setup



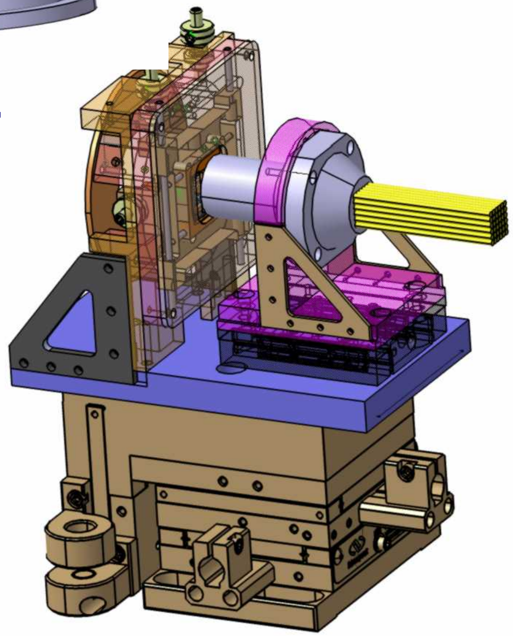
Anamorphic system



V-grooves

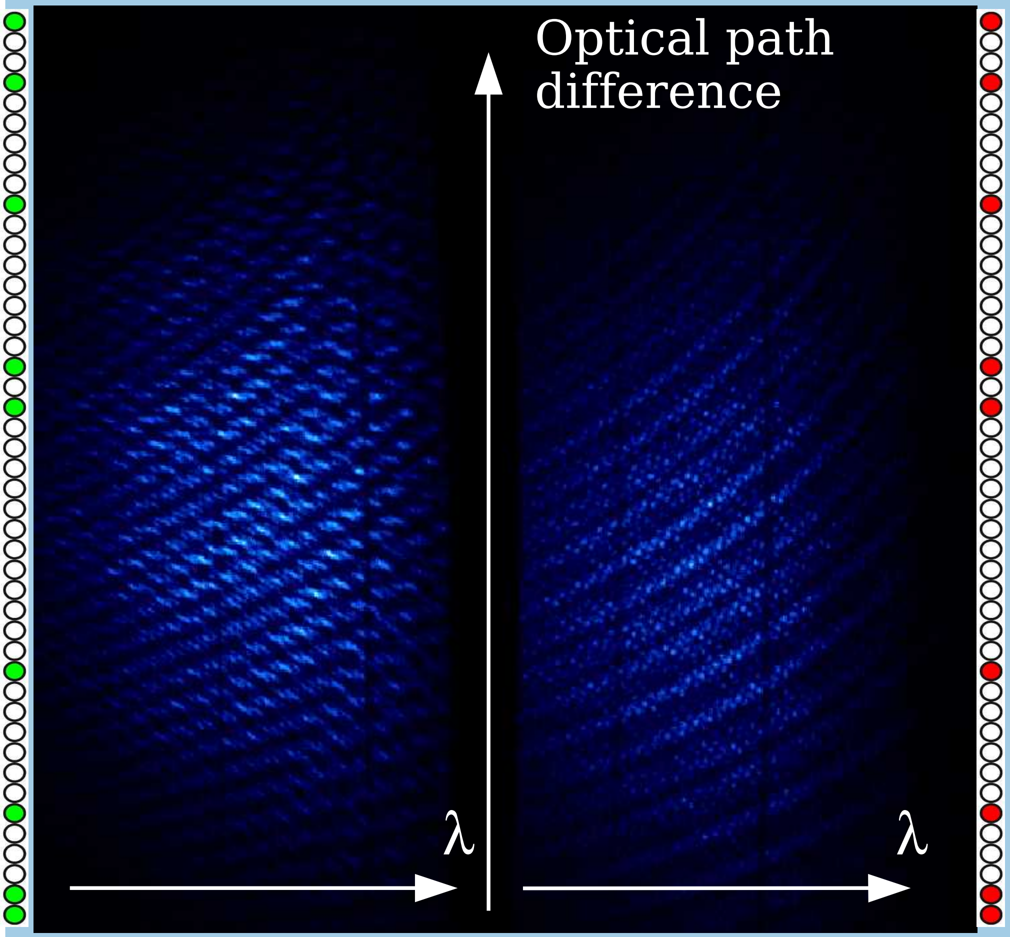


Segmented mirror



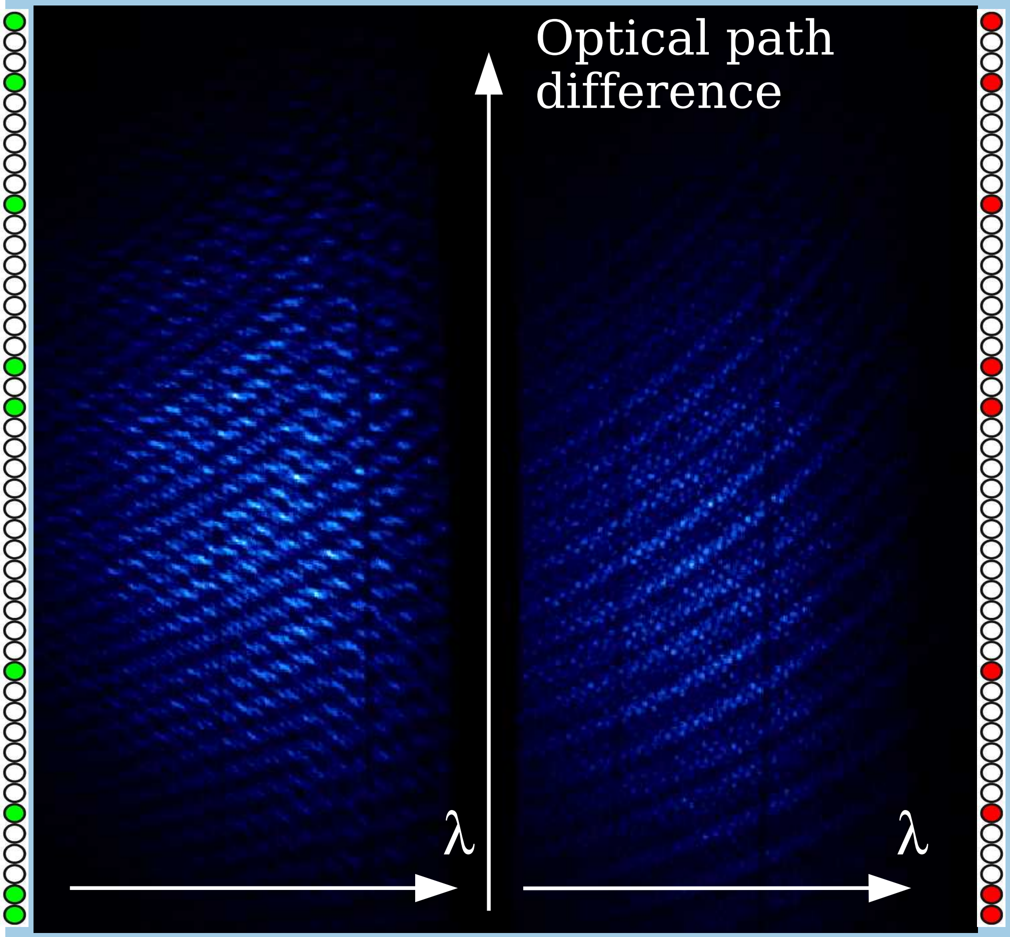
Fiber bundle

Data reduction

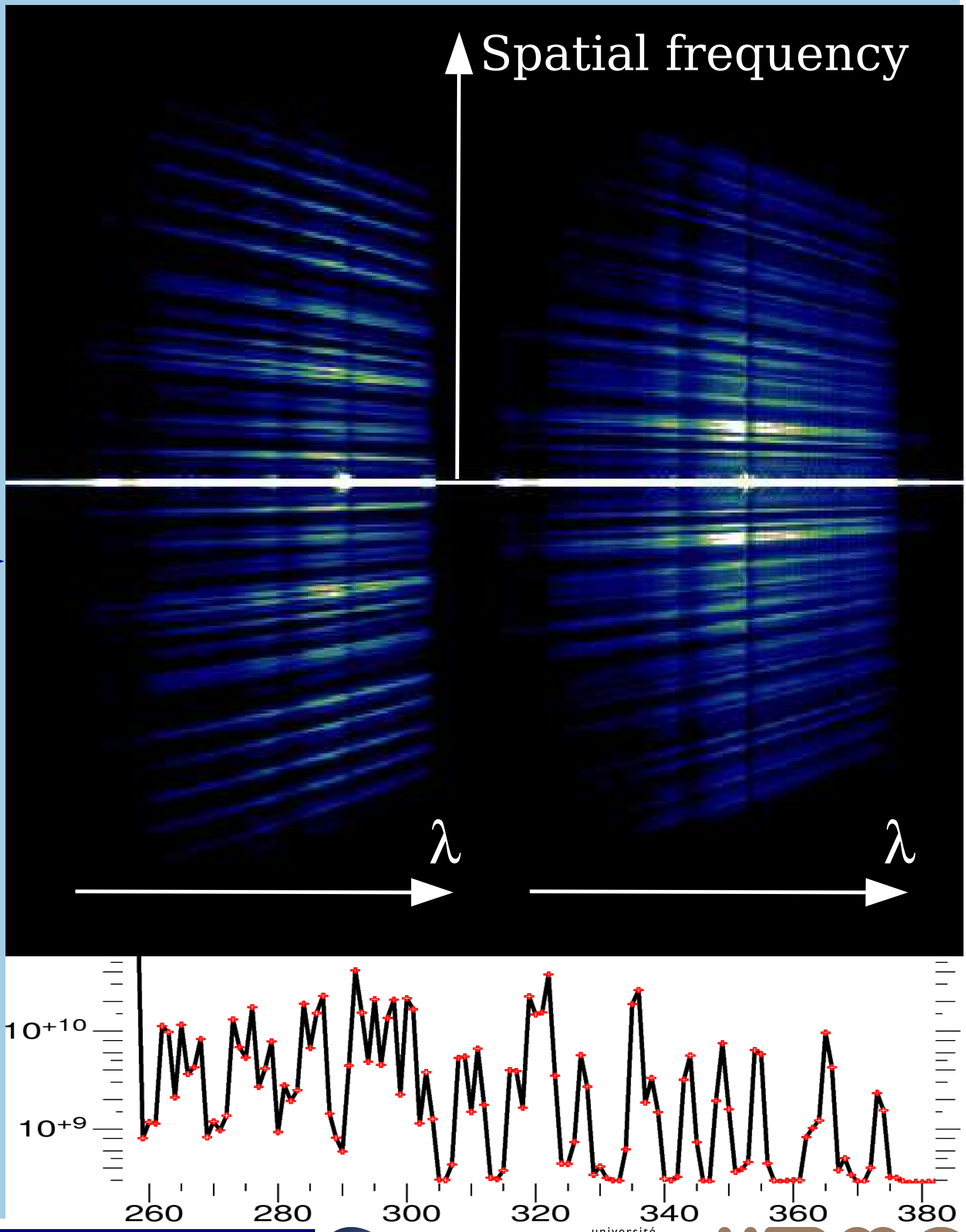


Vega with FIRST-18 (10.2011)

Data reduction

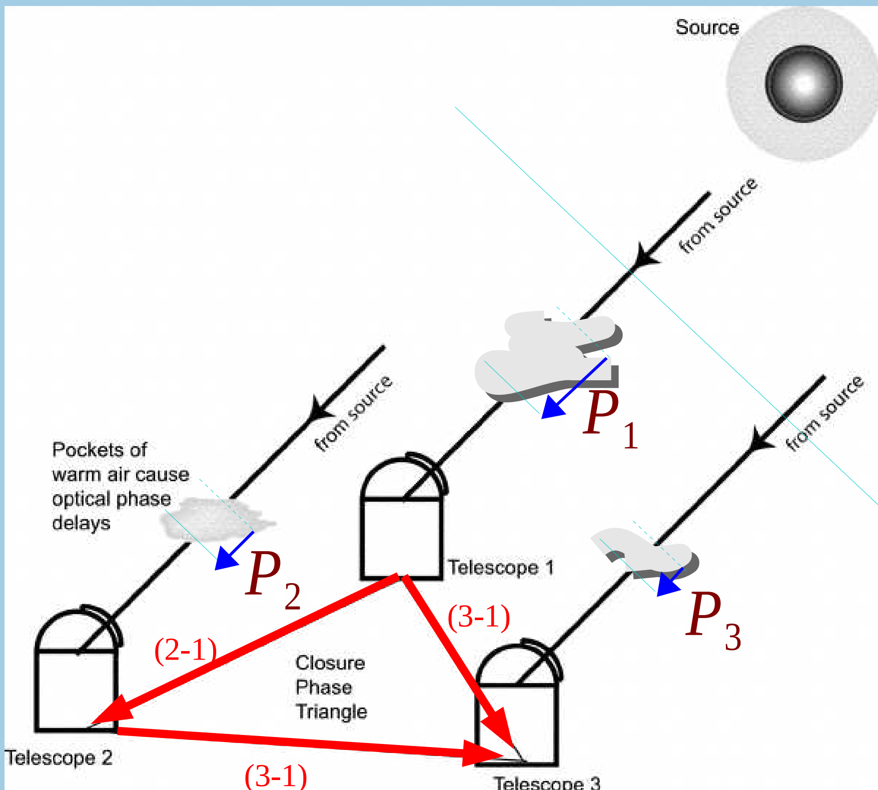


$|TF|^2$



Vega with FIRST-18 (10.2011)

An interesting quantity



Monnier, 2006

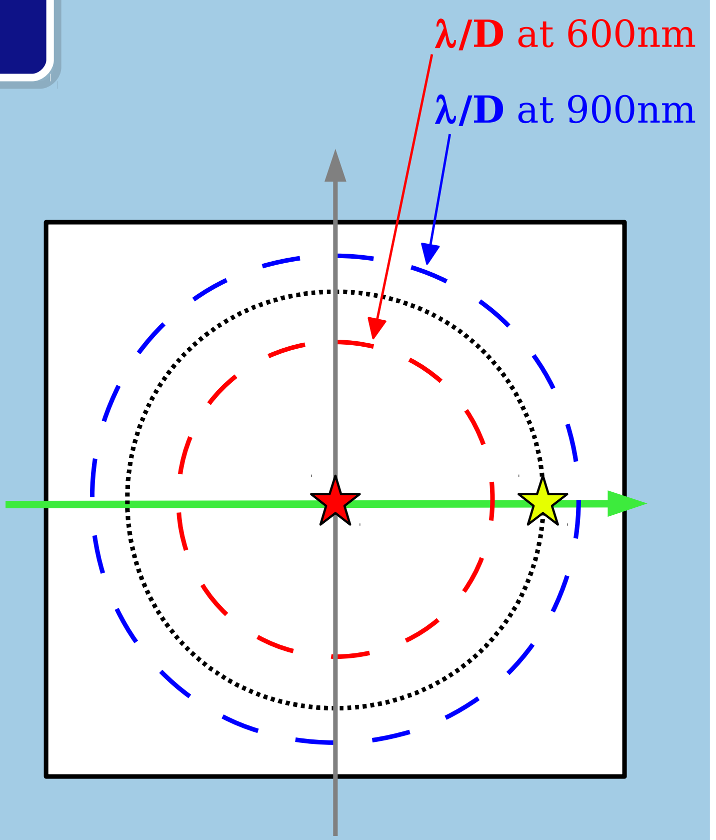
Measurement — Intrinsic object phase — Atmospheric + Instrumental

$$+\quad \varphi_{2-1} = \Phi_{2-1} + (P_2 - P_1)$$
$$+\quad \varphi_{3-2} = \Phi_{3-2} + (P_3 - P_2)$$
$$-\quad \varphi_{3-1} = \Phi_{3-1} + (P_3 - P_1)$$

Closure Phase $= \varphi_{2-1} + \varphi_{3-2} - \varphi_{3-1} = \Phi_{2-1} + \Phi_{3-2} - \Phi_{3-1}$

The closure phase does not depend on atmospheric turbulence

Binary simulation



Separation :

λ/D at 750nm

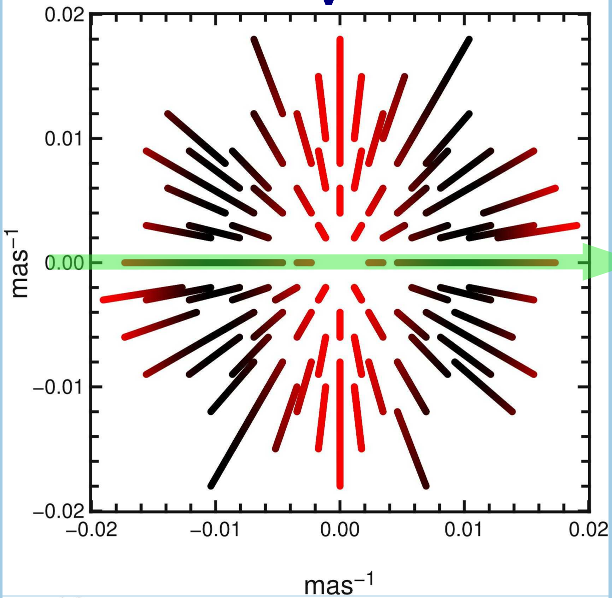
X~52 mas, Y=0

Flux ratio :

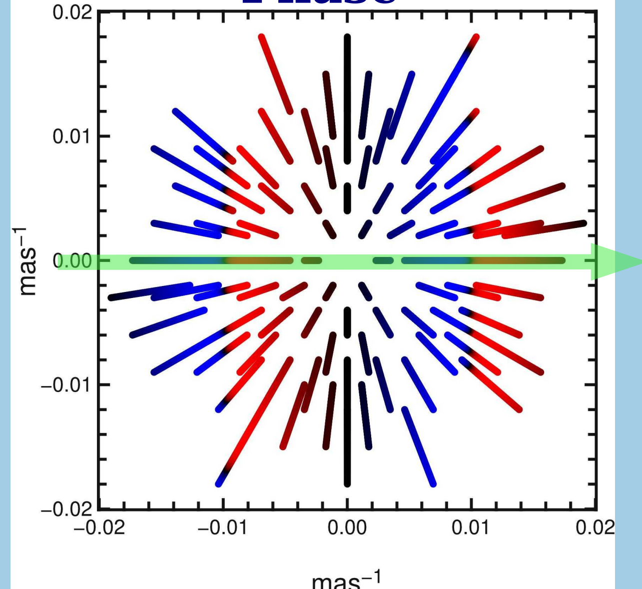
ρ**=0.9** → Δr_{mag}~0.3 mag

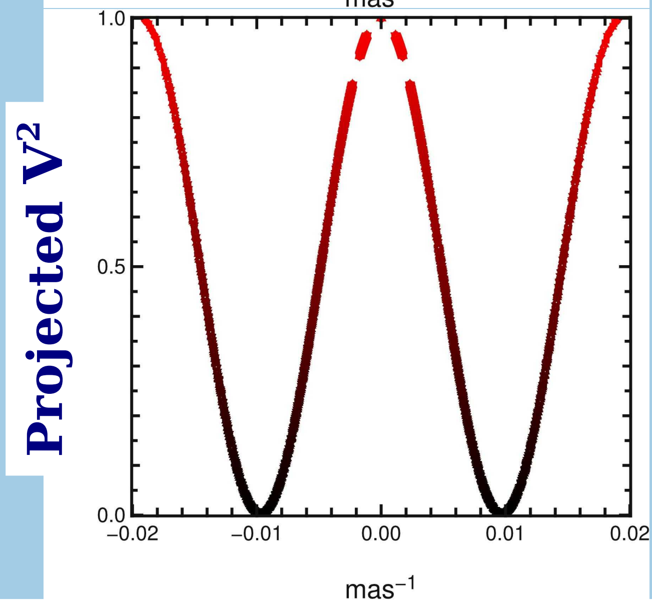
Binary simulation

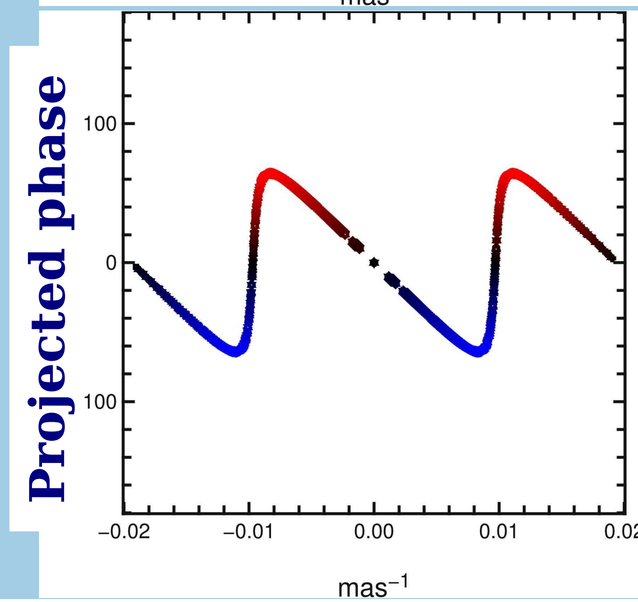
V^2

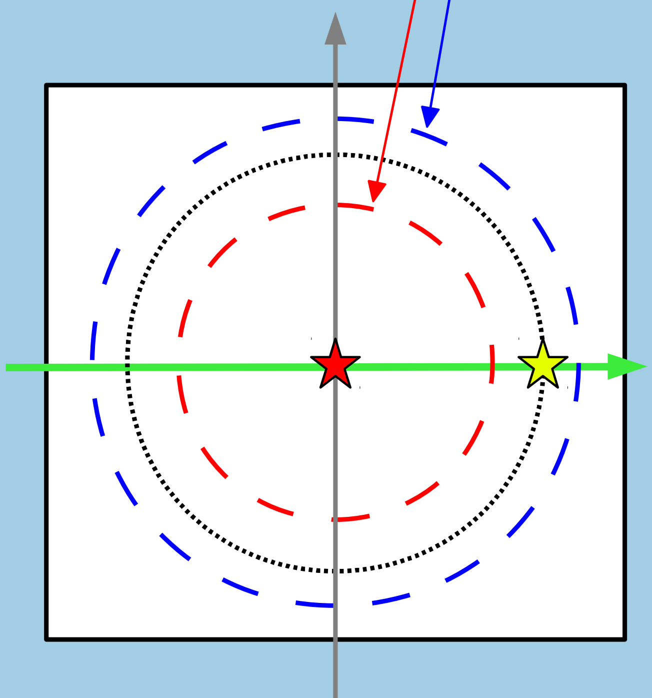


Phase









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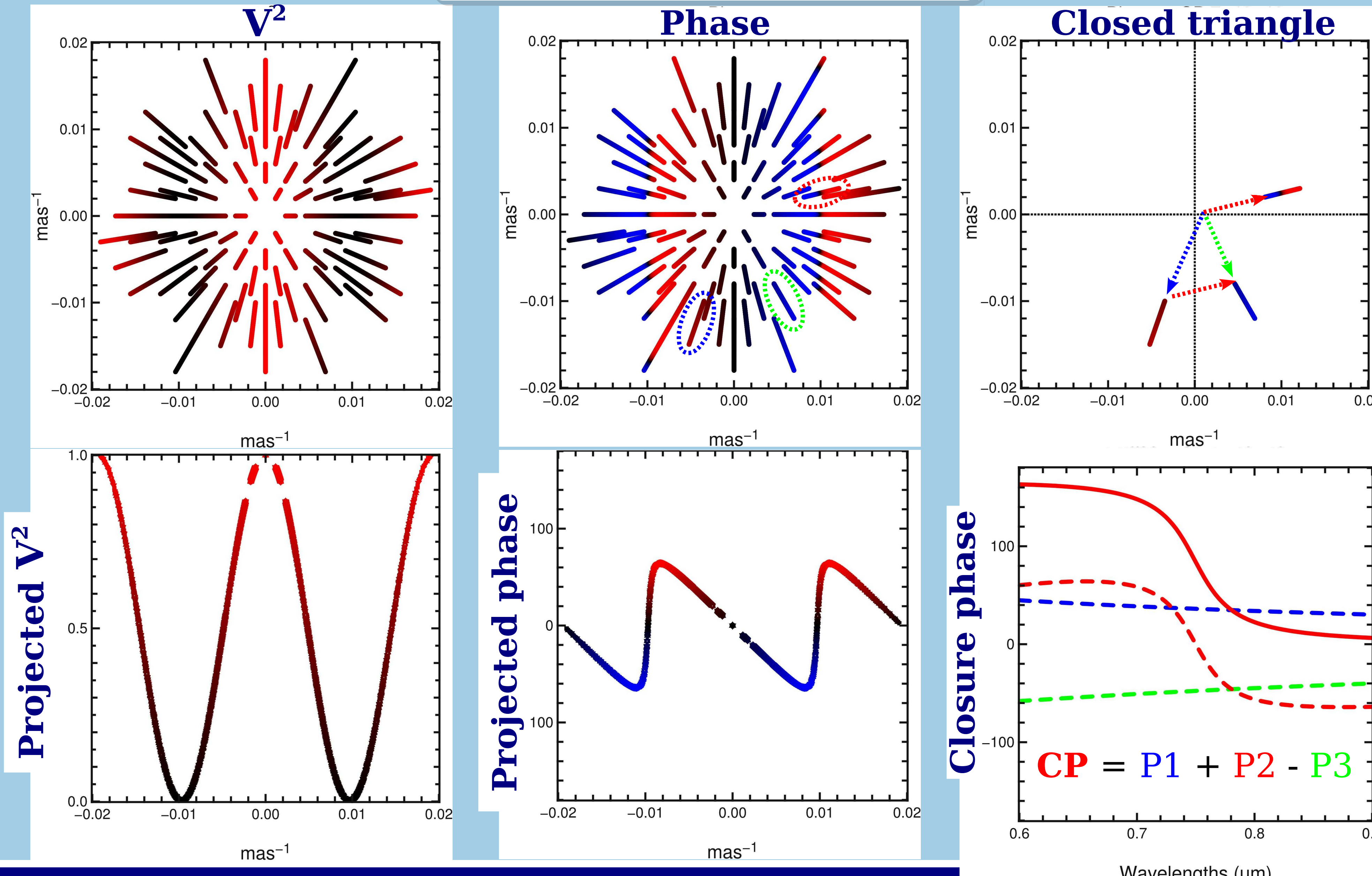


Dynamic range

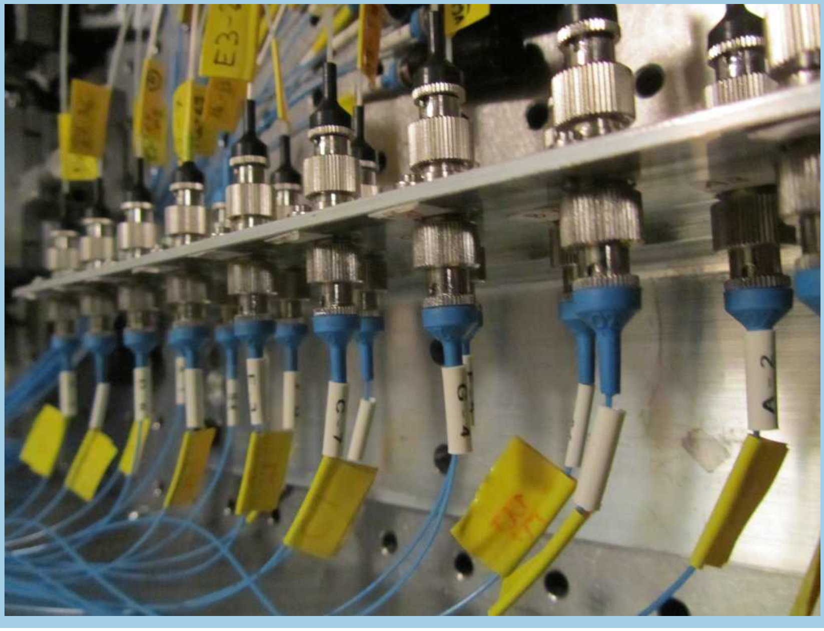
$$\textit{dynamic range} \propto \frac{\sqrt{N_{baselines}}}{\sigma(CP)}$$

Baldwin and Haniff, 2002
Lacour, 2011
Le Bouquin and Absil, 2012

Large number of baselines

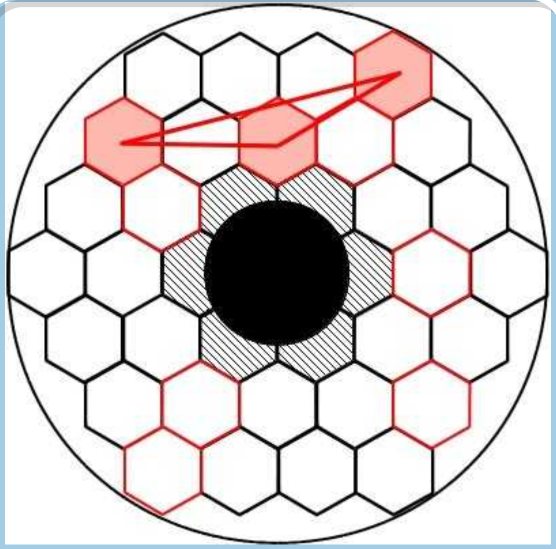
Good accuracy on the CP measurements

Pupil remapping

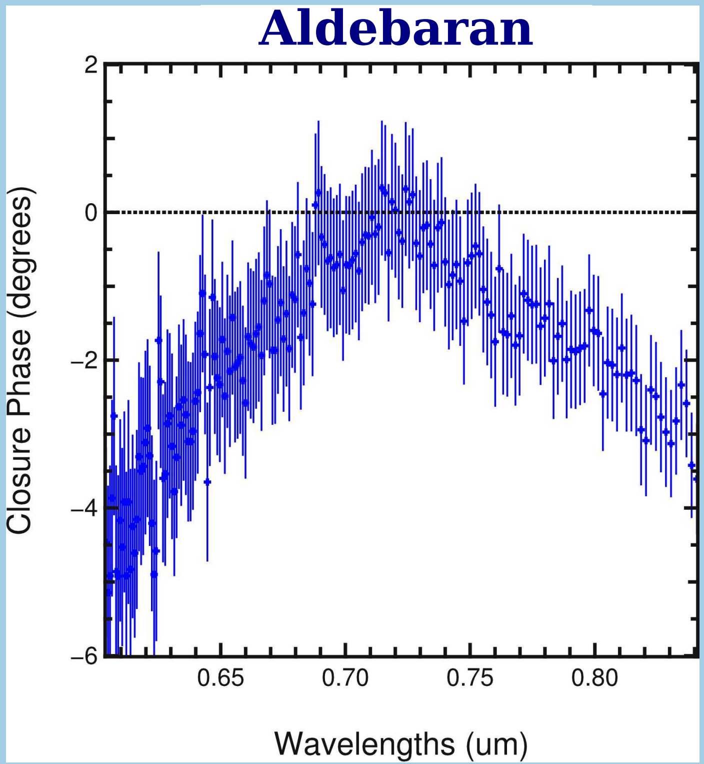


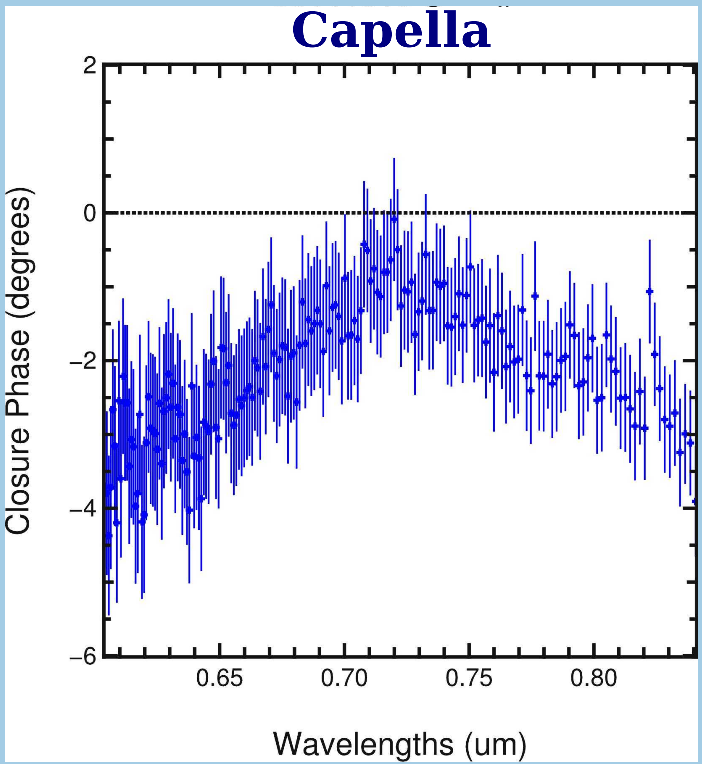
Spatial filtering

Results – Capella



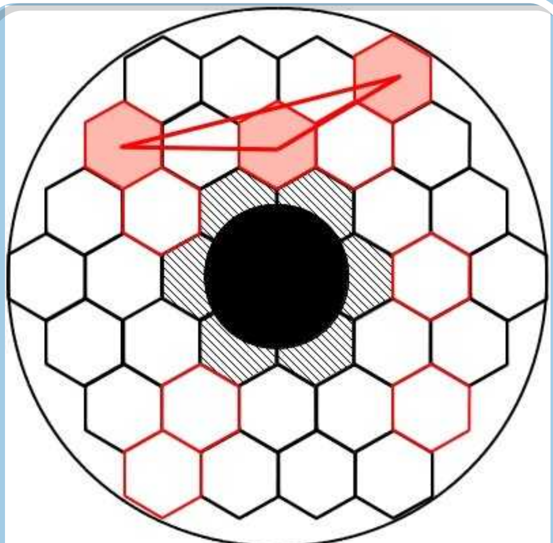
Diffraction limit of a 3-m telescope at 700nm :
48 mas





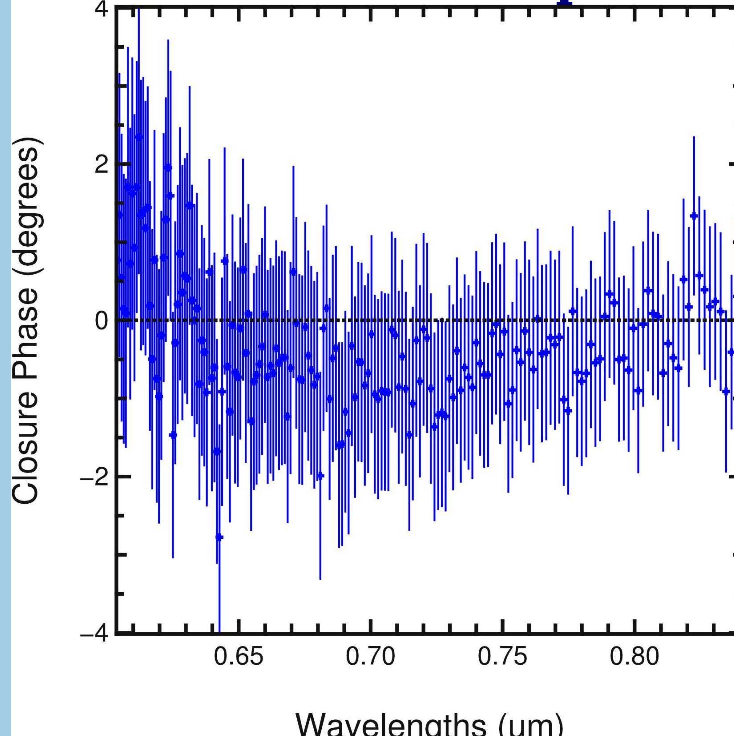
Target	Rmag	Type	Int. time	Total int. time
Aldebaran	0.1	Calibrator	50ms	4min10s
Capella	0.4	Binary (sep~56mas flux ratio~1)	50ms	4min10s

Results – Capella



Diffraction limit of a 3-m telescope
at 600nm : **41 mas**
at 850nm : **mas**

Calibrated closure phase



Mean error bars

	Capella	Aldebaran
Raw	**0.9°**	**1.0°**
Cali-brated	**1.3°**	

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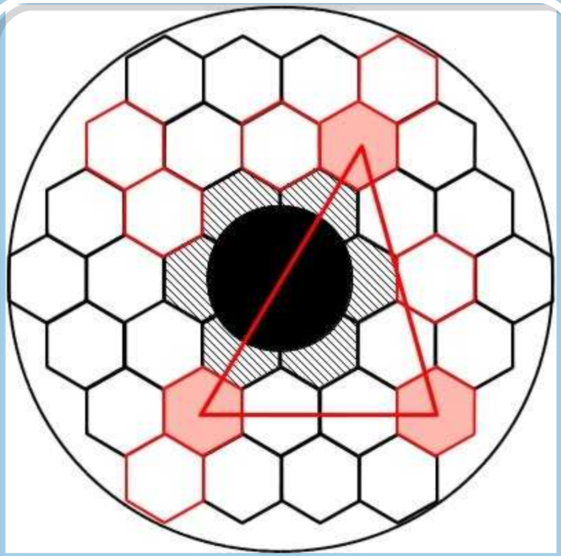
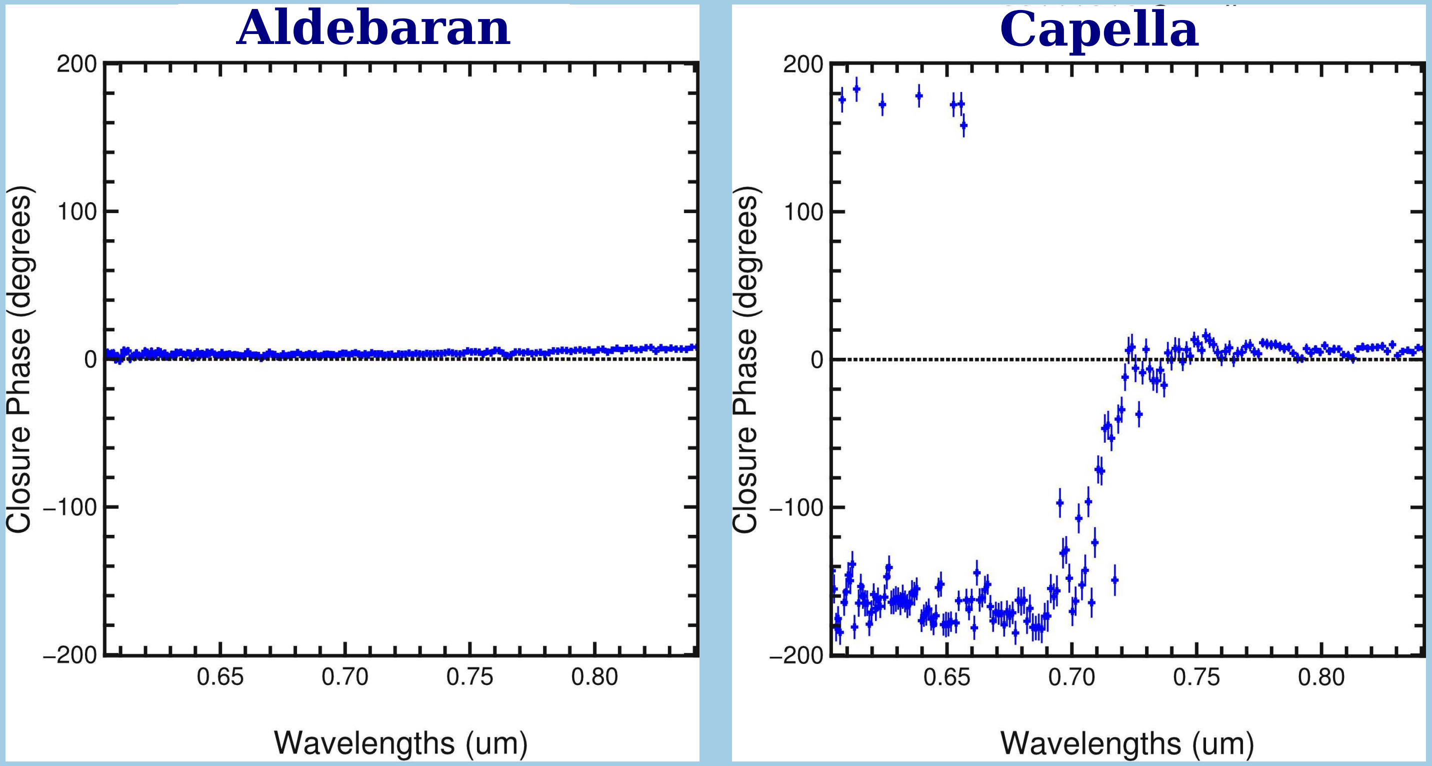
Capella	0.4	Binary (sep~56mas flux ratio~1)	50ms	4min10s

Results – Capella

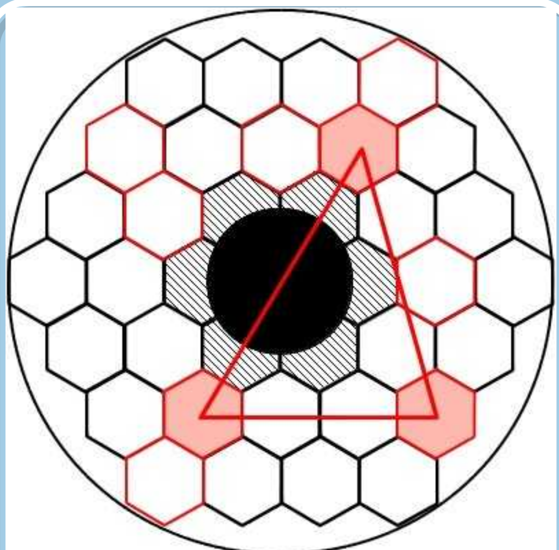


Diffraction limit of a 3-m telescope at 700nm :
48 mas



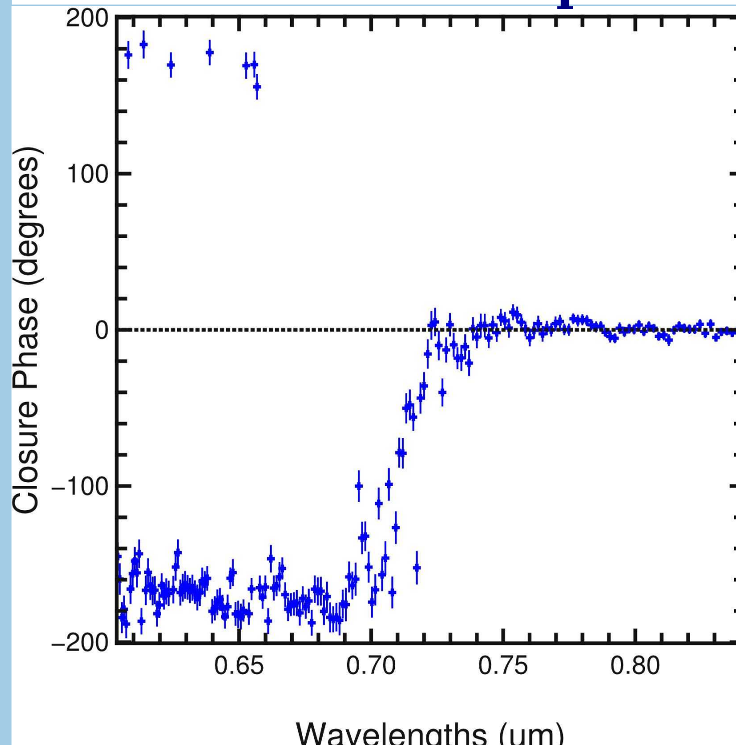
Target	Rmag	Type	Int. time	Total int. time
Aldebaran	0.1	Calibrator	50ms	4min10s
Capella	0.4	Binary (sep∼56mas flux ratio∼1)	50ms	4min10s

Results – Capella



Diffraction limit of a 3-m telescope at 700nm :
48 mas

Calibrated closure phase

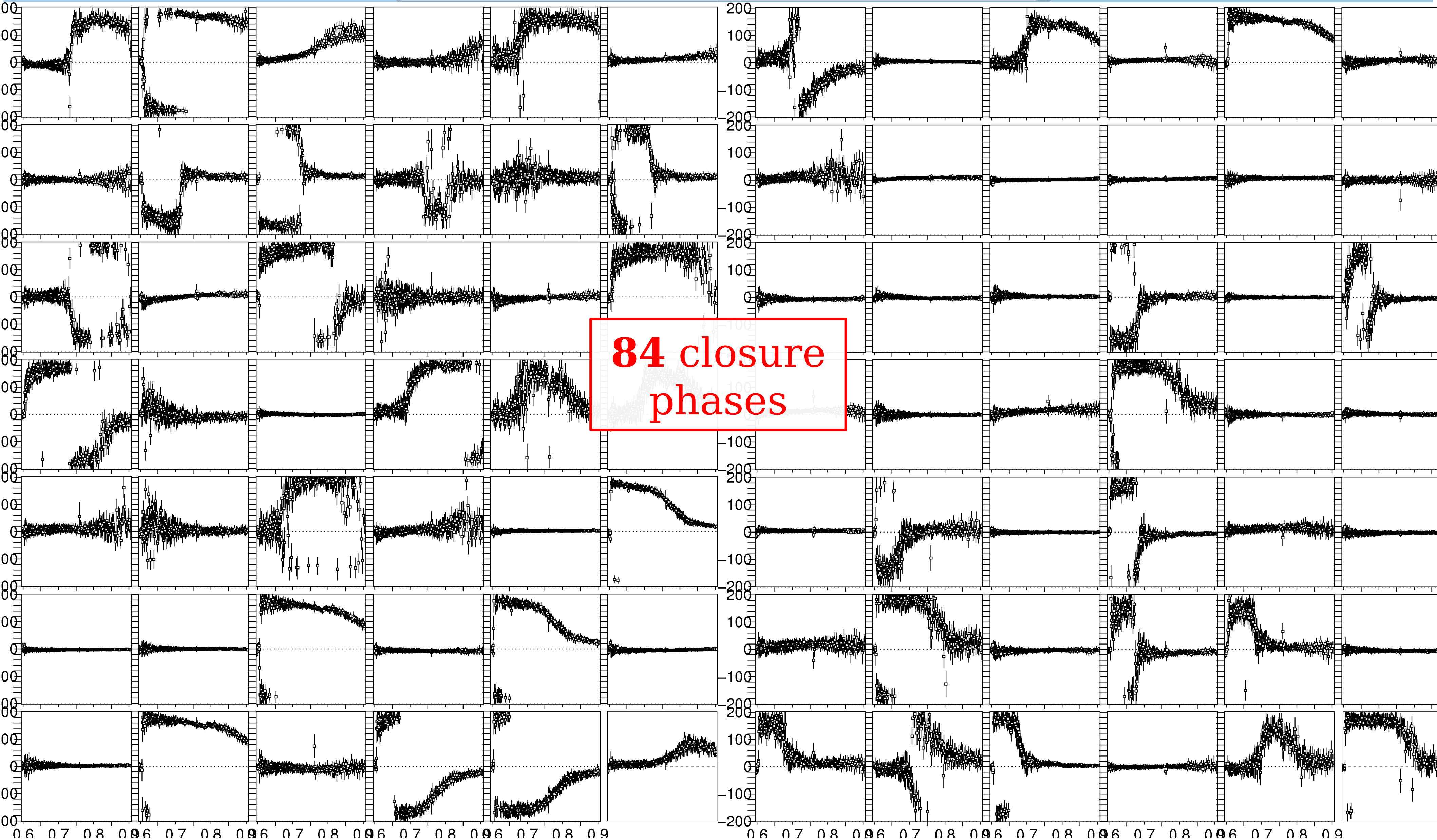


Mean error bars

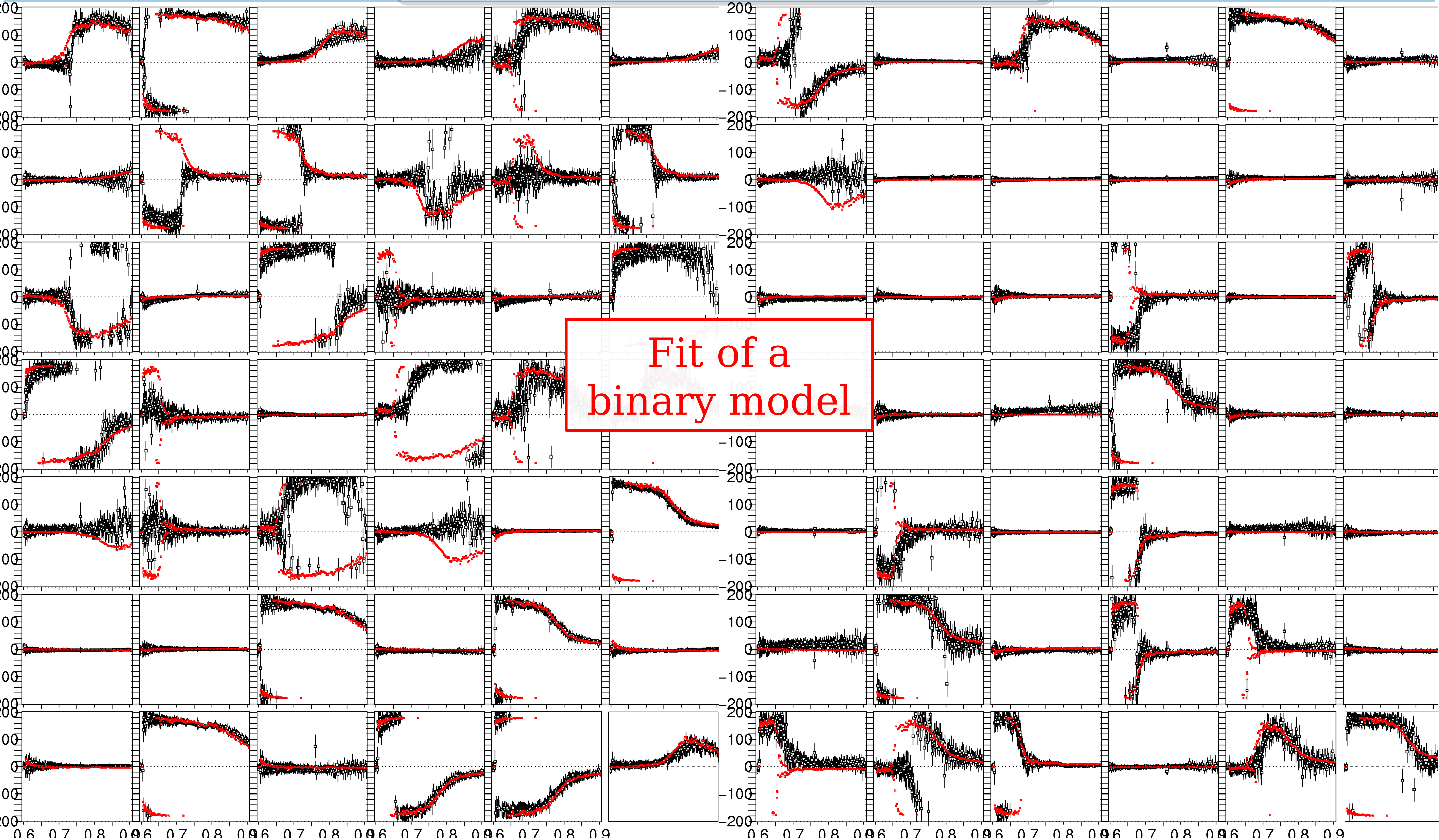
	Capella	Aldebaran
Raw	**6.9°**	**1.4°**
Cali-brated	**7.3°**	

Target	Rmag	Type	Int. time	Total int. time
Aldebaran	0.1	Calibrator	50ms	4min10s
Capella	0.4	Binary (sep~56mas flux ratio~1)	50ms	4min10s

Capella closure phases



Capella closure phases



Results – Capella

Fitted Parameters :

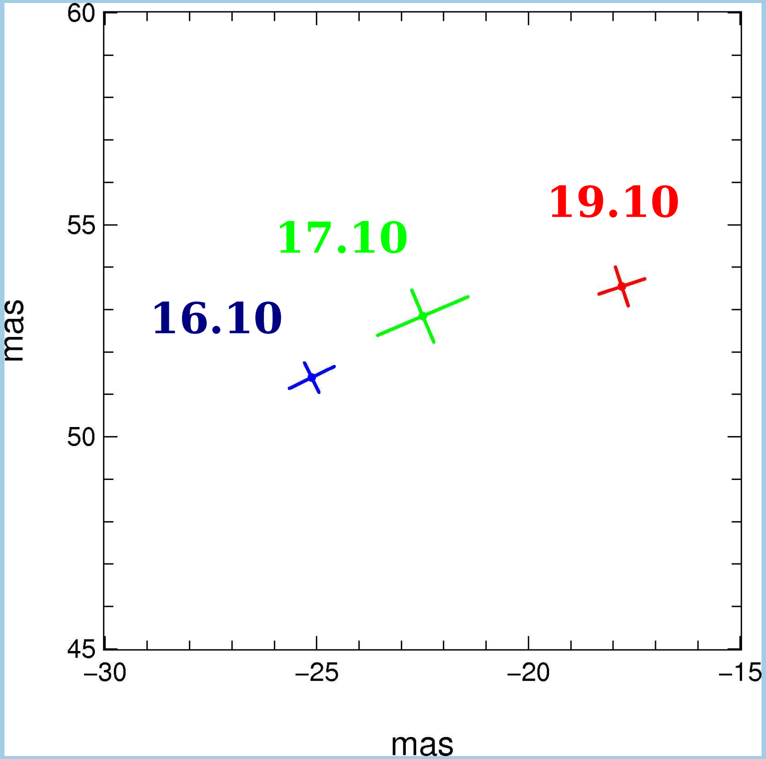
- Spectral flux ratio ρ for every spectral channel
- Angular separation r
- Position angle θ

Results :

- Separation ~ **57 mas** +- 0.5 mas
- Position angle ~ **110°** +- 1°

Need of an astrometric calibrator

→ Algol



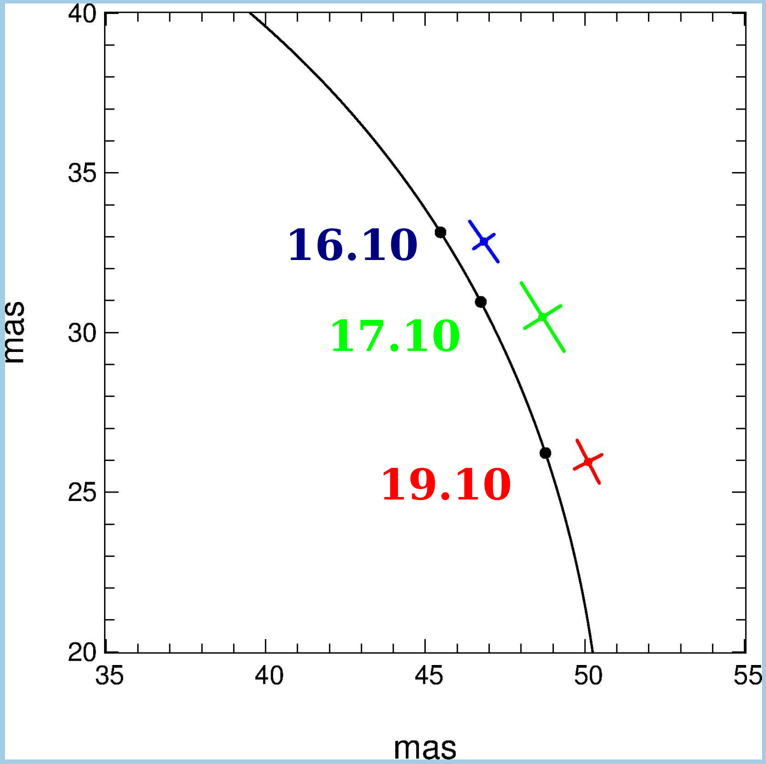
Results – Capella

Fitted Parameters :

- Spectral flux ratio ρ for every spectral channel
- Angular separation r
- Position angle θ

Results :

- Separation ~ **57 mas** +- 0.5 mas
- Position angle ~ **30°** +- 1°

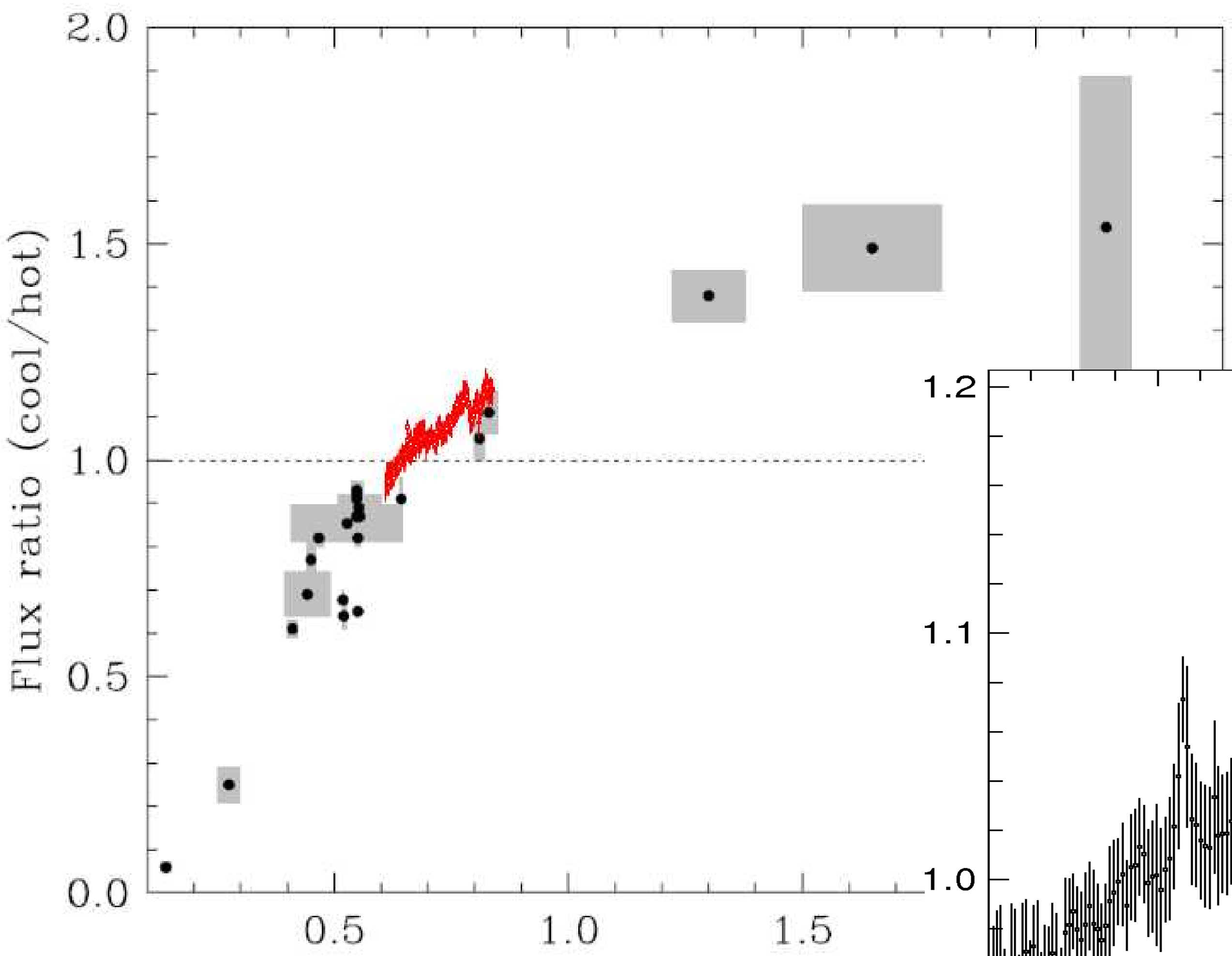


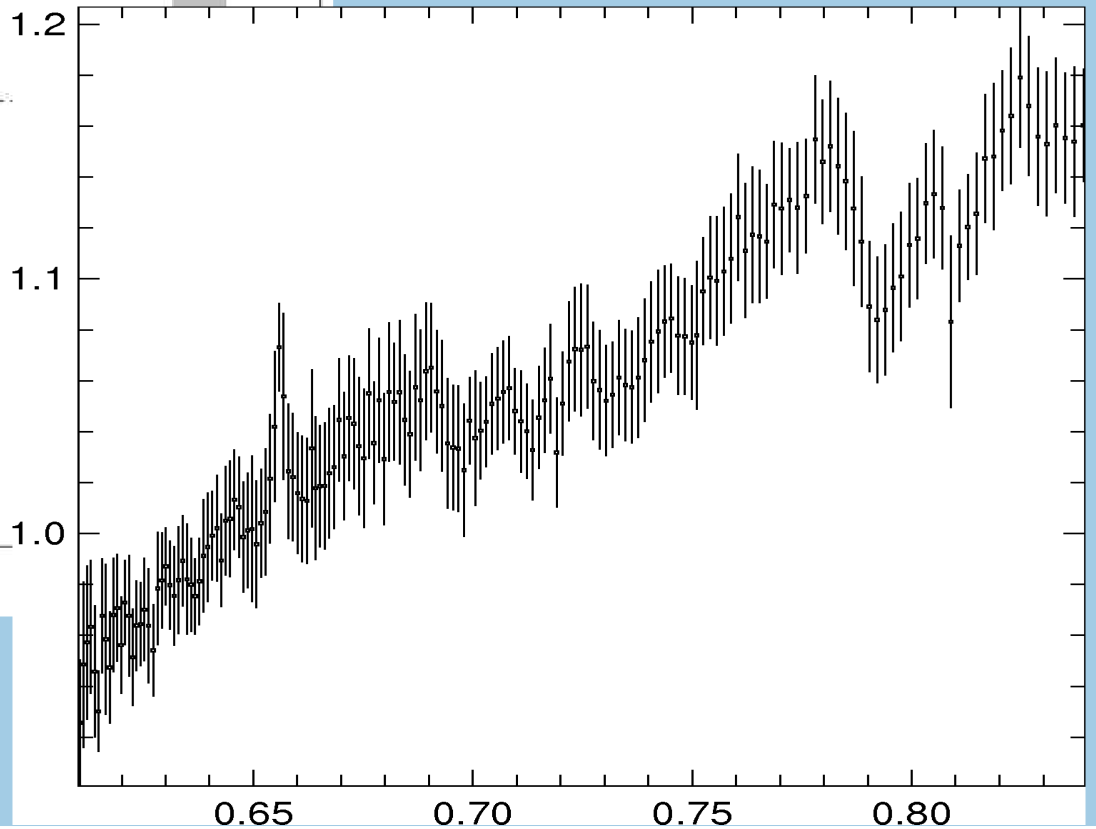
Need of an astrometric calibrator

→ Algol

Rotation : -81° +-0.5°

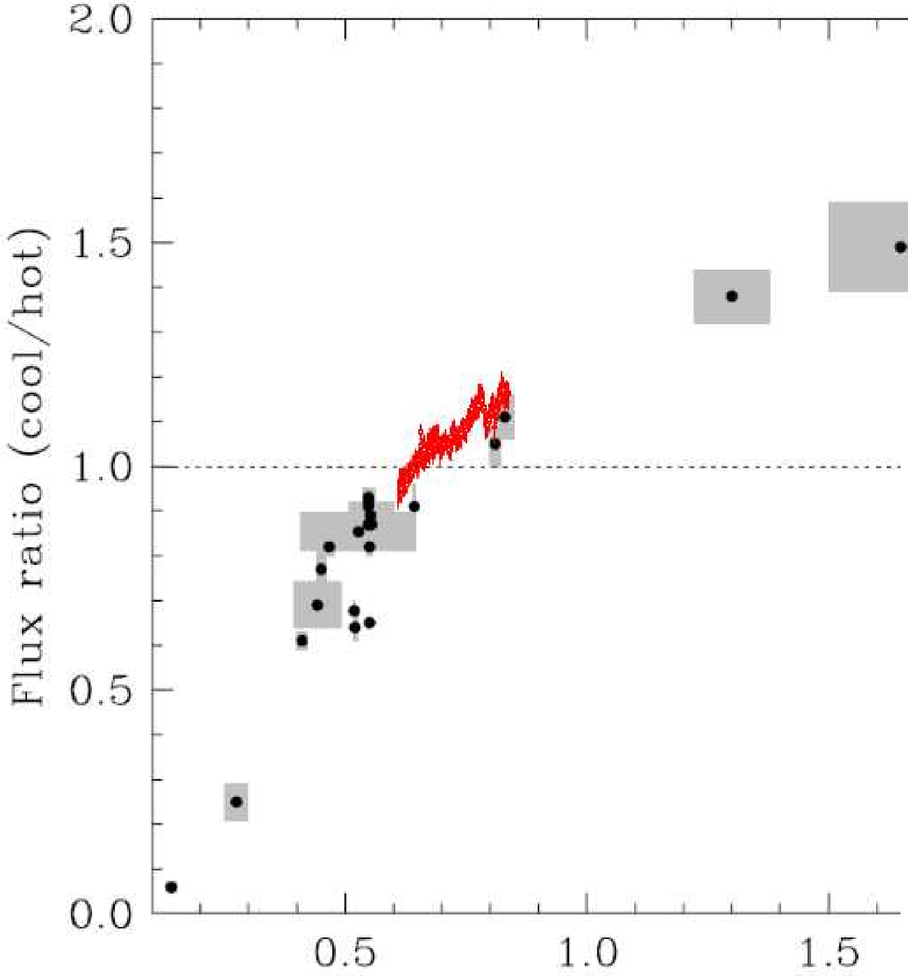
Results – Capella



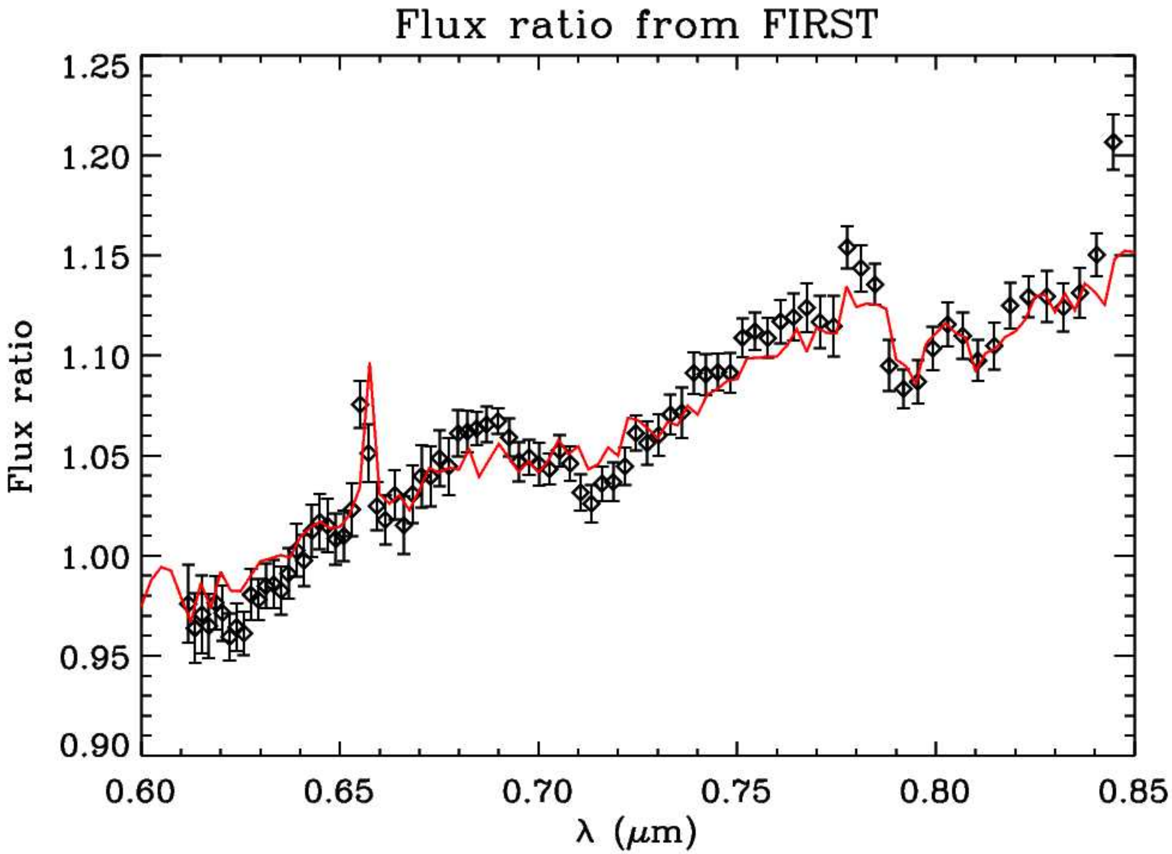


Torres et al., 2009

Results – Capella



Torres et al., 2009



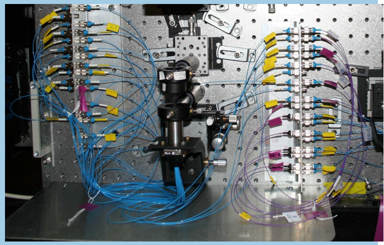
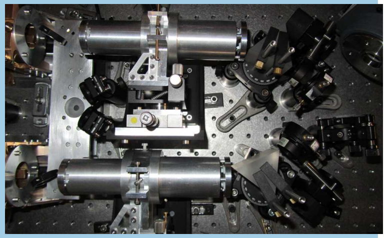
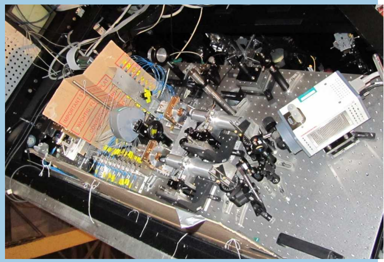
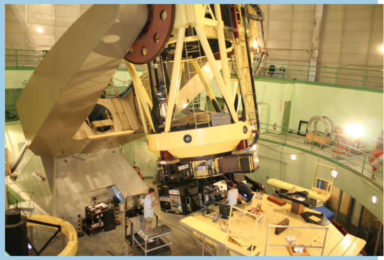
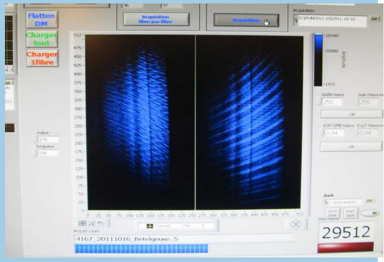
VI. Summary

Promising results

- New chapter in a long story
  - I. An original idea → Perrin et al., 2006
  - II. Performance simulations → Lacour et al. 2007
  - III. Prototype and lab results → Kotani et al. 2009
  - IV. First on-sky results → Huby et al., 2012
  - **V. Binary detection at the diffraction limit**

Next steps

- Implement the self-calibration algorithm
- Image reconstruction
- To increase the stability : accuracy +
- To develop FIRST-30 : number of baselines +
- FIRST on an 8-10m telescope → SUBARU (July 2013)

FIbered Imager FoR Single Telescope

FI(R)ST

Thank you !