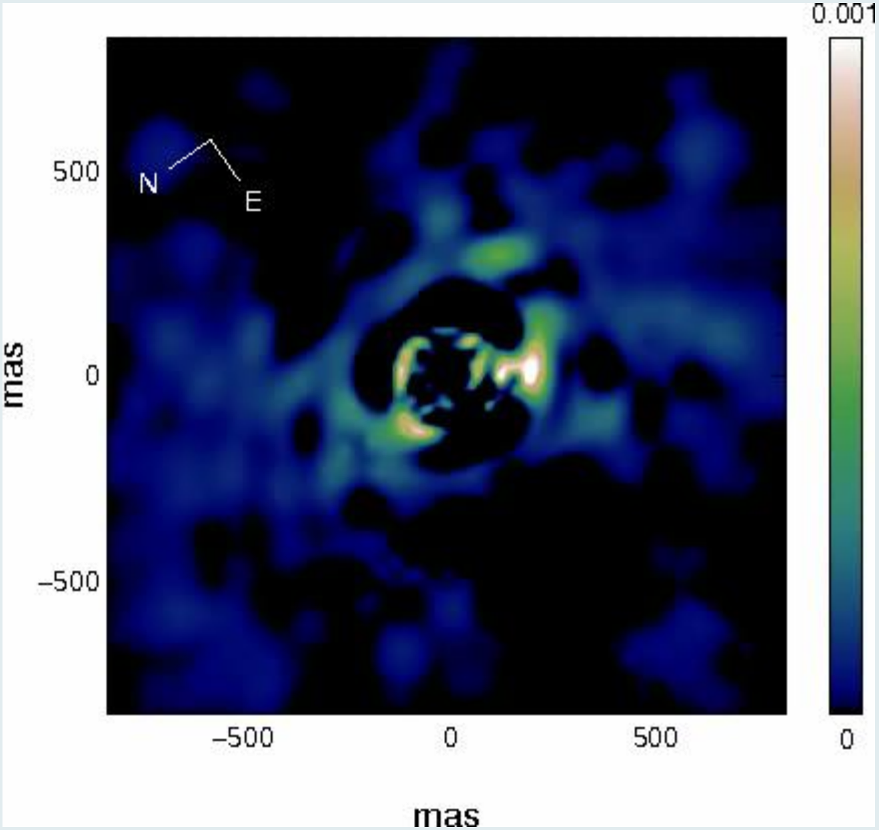
Sparse Aperture Masking

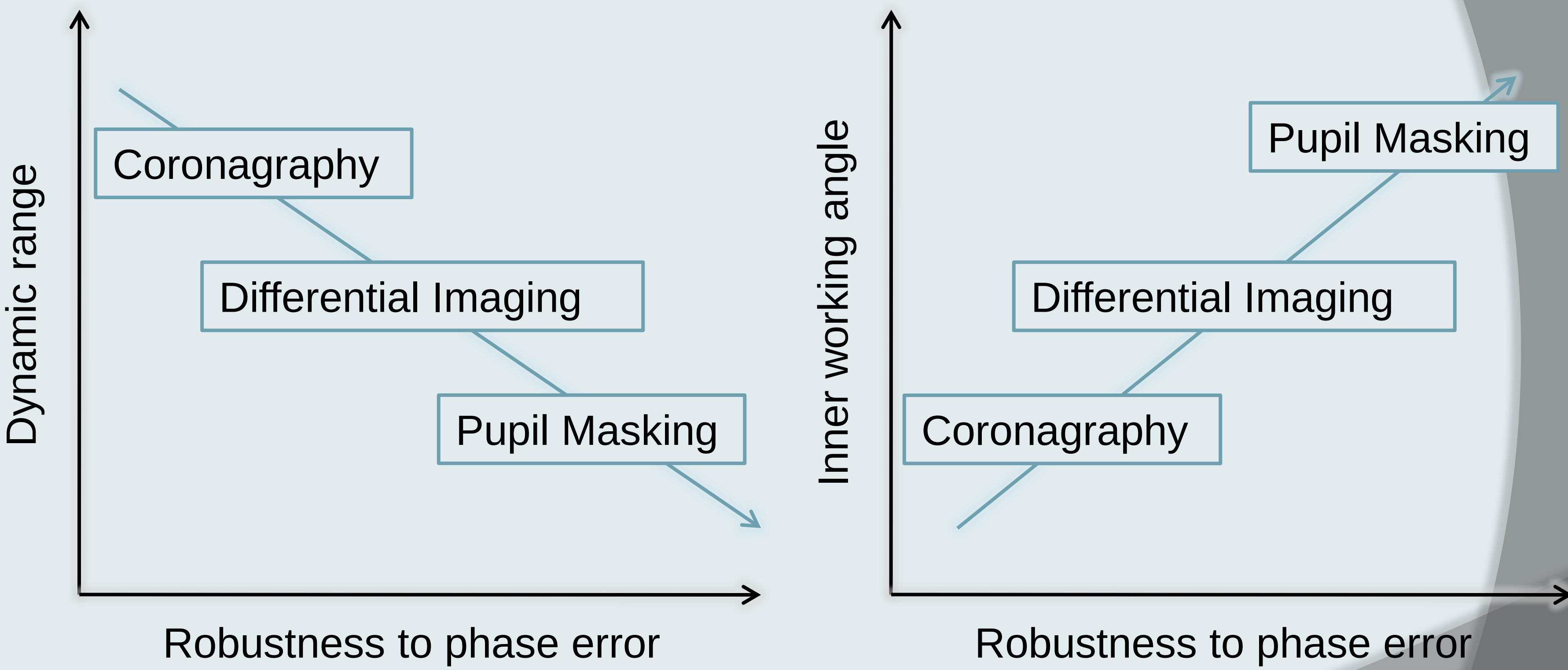
SAM

Beta Pictoris b – THE ADVANTAGE OF PUPIL TRACKING

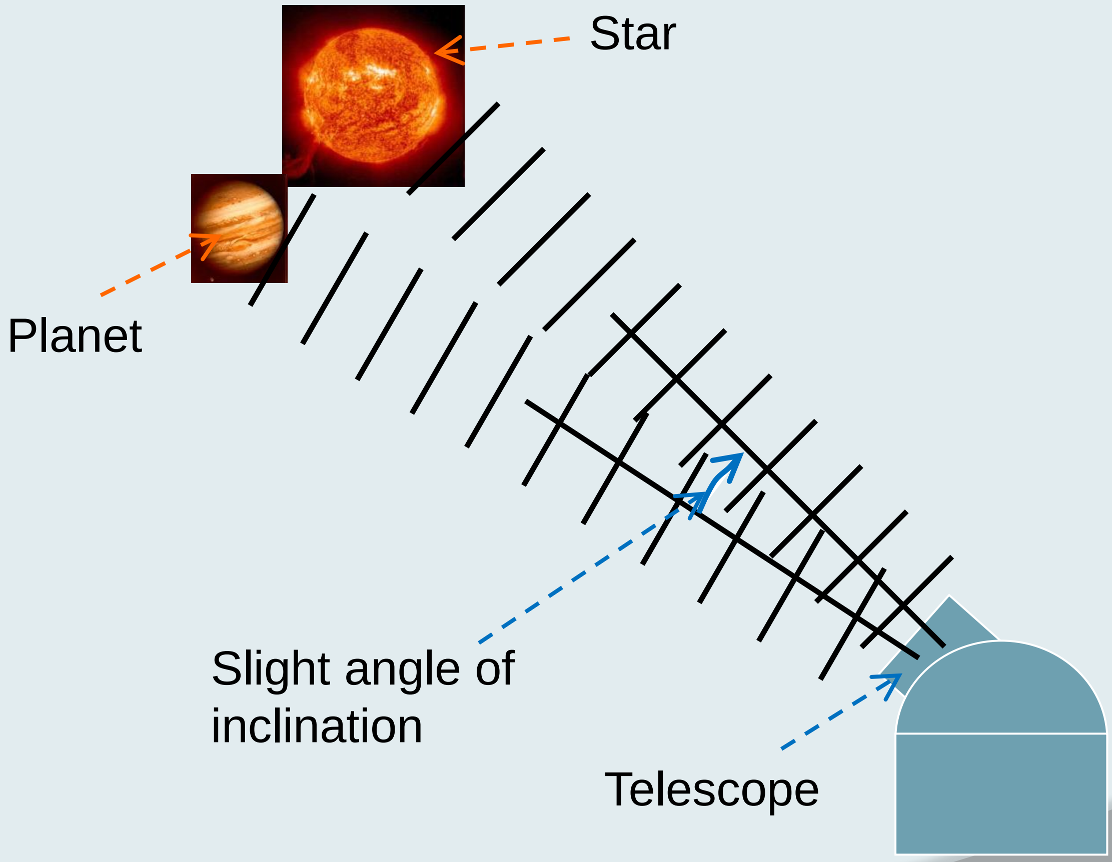


December 2009 – confirmation of Beta Pic b – Lagrange et al., Science 2010

Principle


Dynamic range
Coronagraphy
Differential Imaging
Pupil Masking
Robustness to phase error
Inner working angle
Pupil Masking
Differential Imaging
Coronagraphy
Robustness to phase error

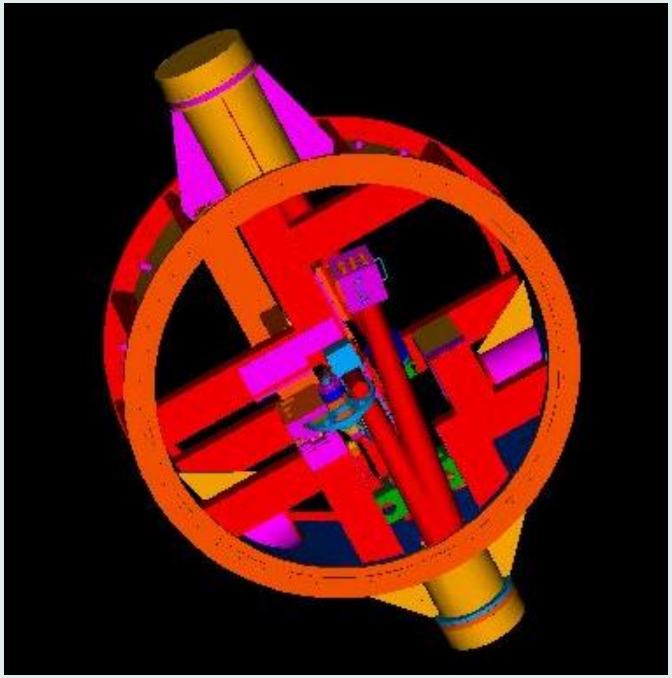
Principle



Past

I) APERTURE MASKING

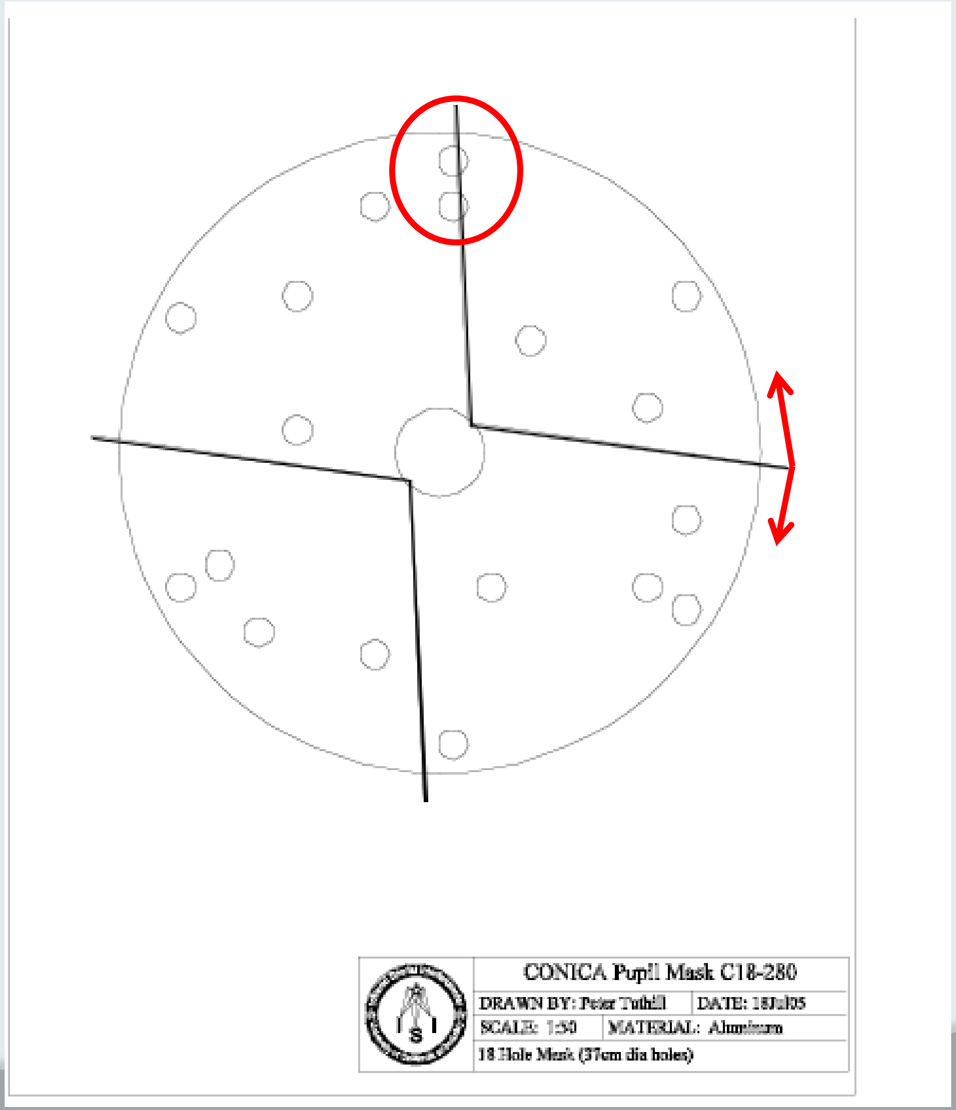
NACO@ the VLT: NAOS

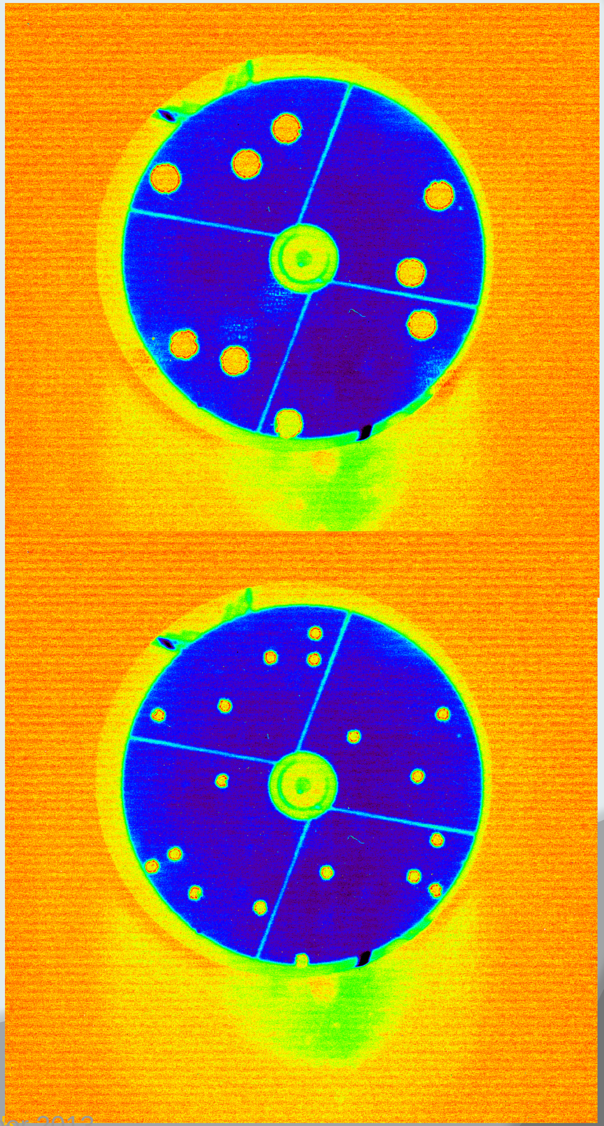


NAOS

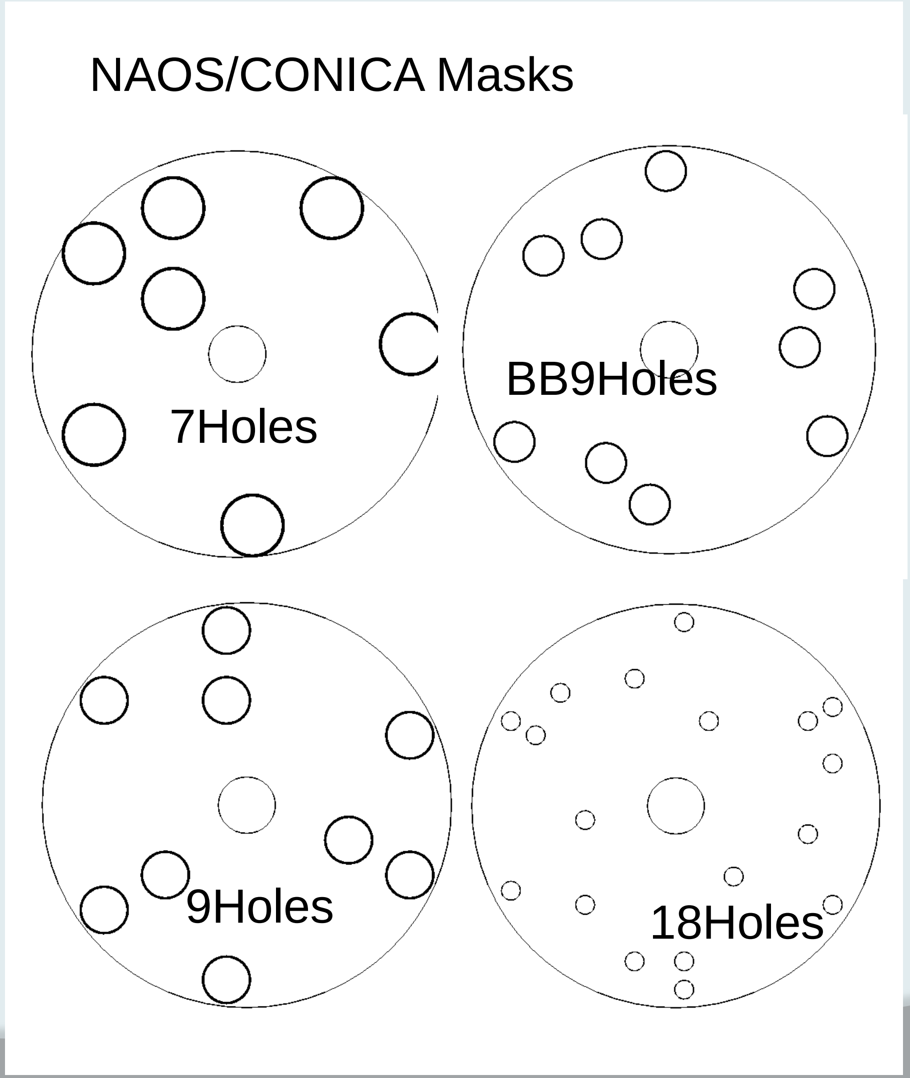
- NAOS is an adaptive optics system equipped with both visible and infrared, Shack-Hartmann type wavefront sensors.
- NGS maximum distance 55”
- Dichroics: VIS, IR-N20C80, IR-N90C10, IR-JHK, IR-K
- Operates also with LGSF + VIS WFS + STRAP unit

Pupil tracking

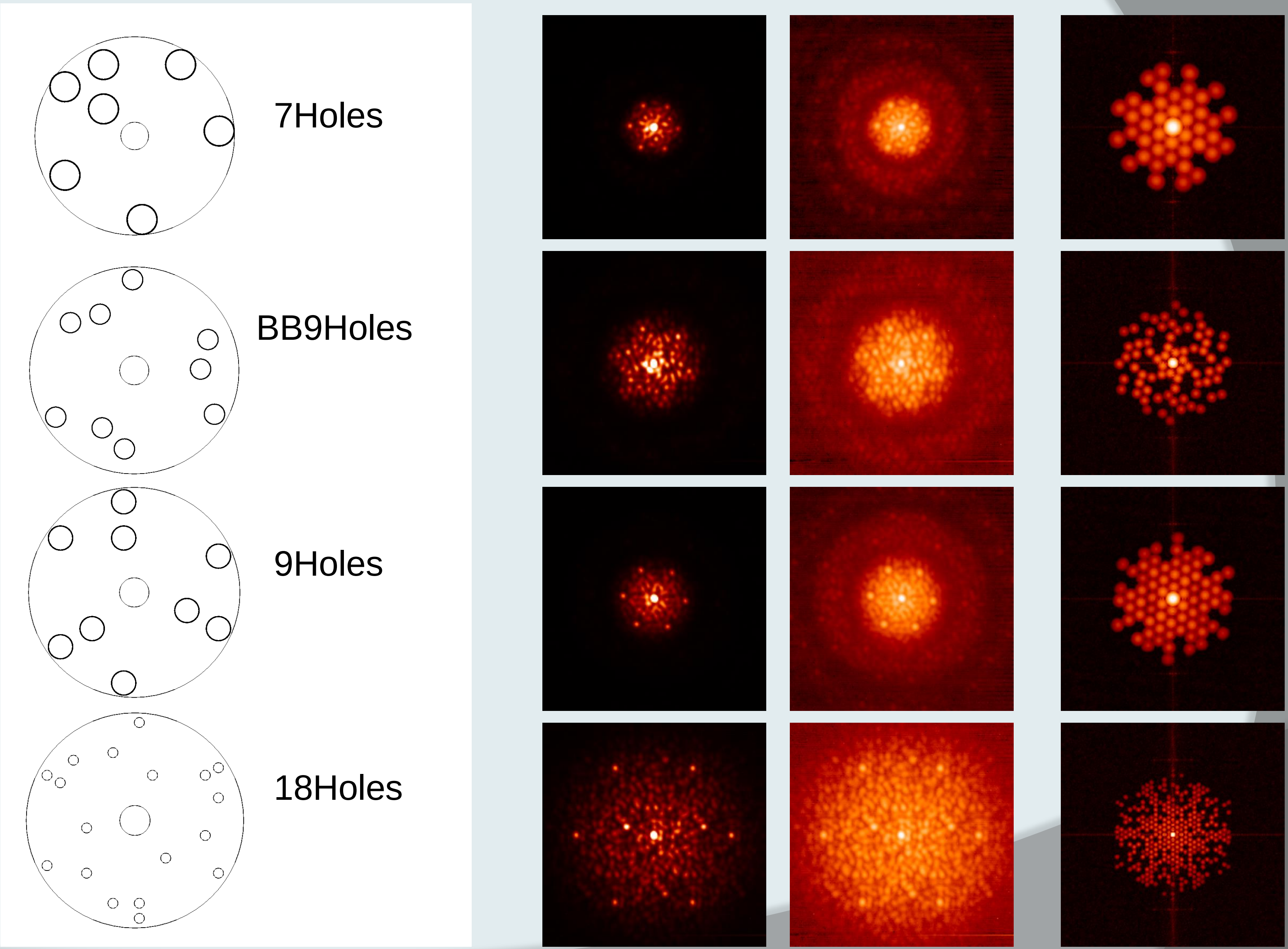


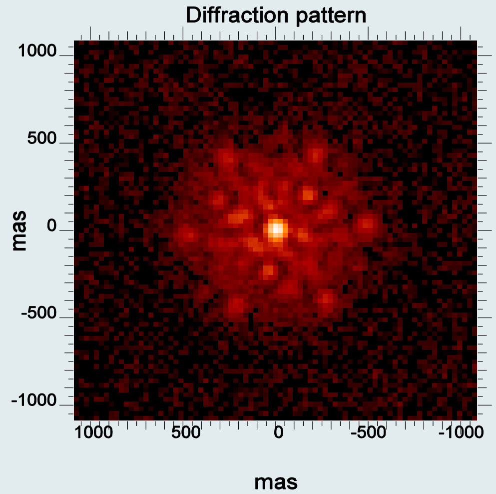


Uses of the SAM masks

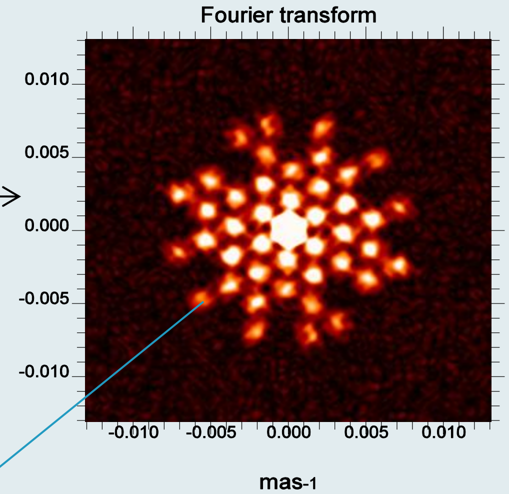


- Narrowband Imaging (bright targets)
- Broadband Imaging (fainter targets)
- Optical Interferometric Polarimetery (differential measurement at high contrast ratio)
- Faint companion detection at high contrast ratio and high resolution


7Holes
BB9Holes
9Holes
18Holes

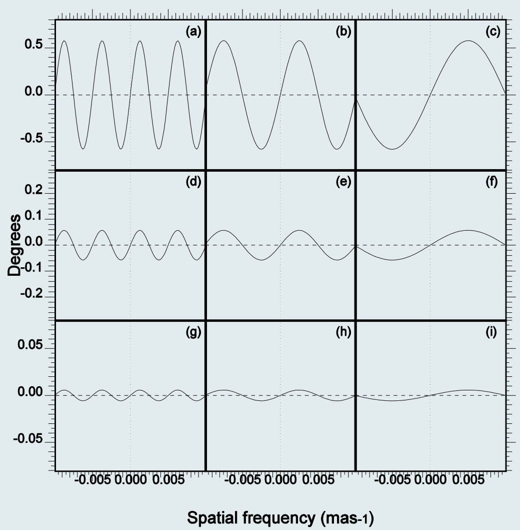


TF

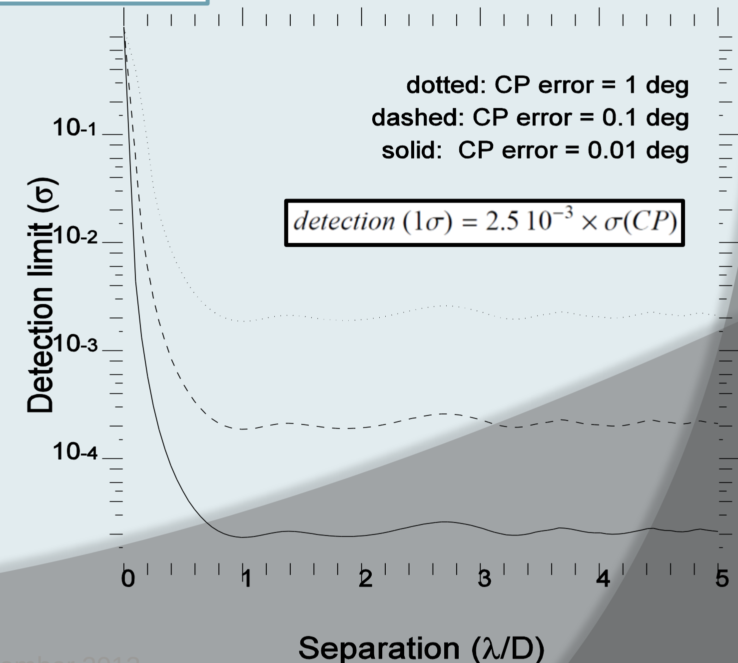


Phase deconvolved from atmospheric/instrumental piston (closure phase)

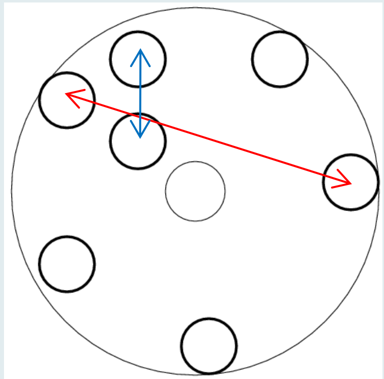
modeles

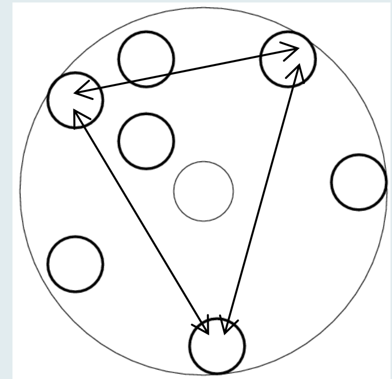


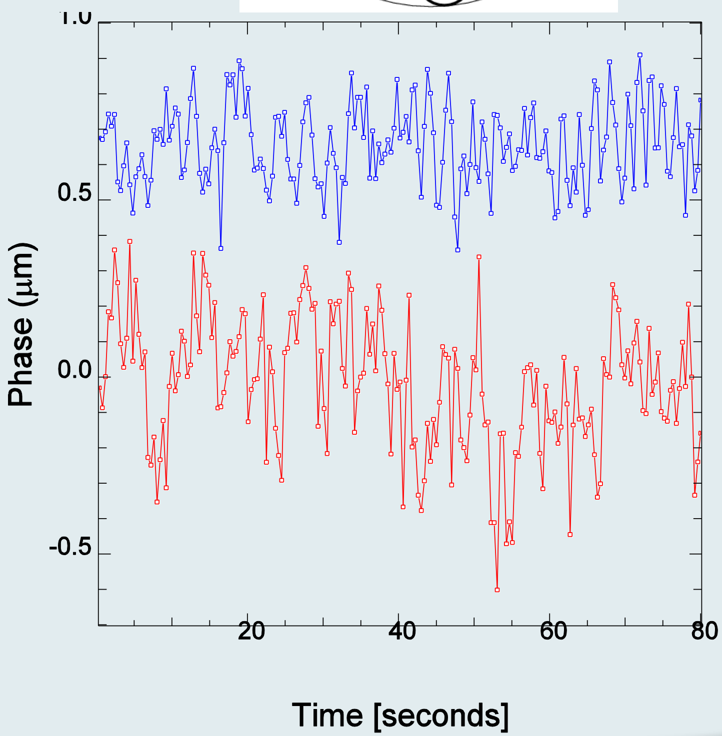
détection

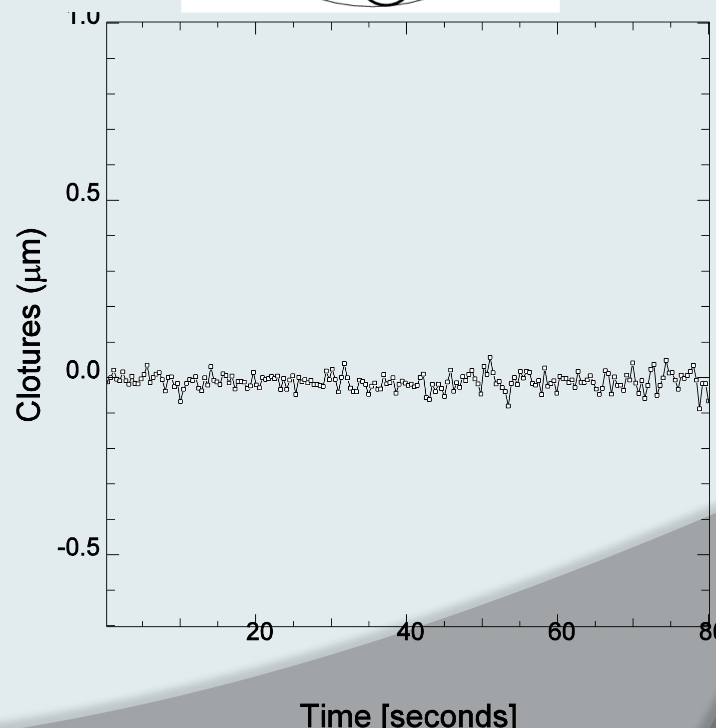


Phase & Closure Phase



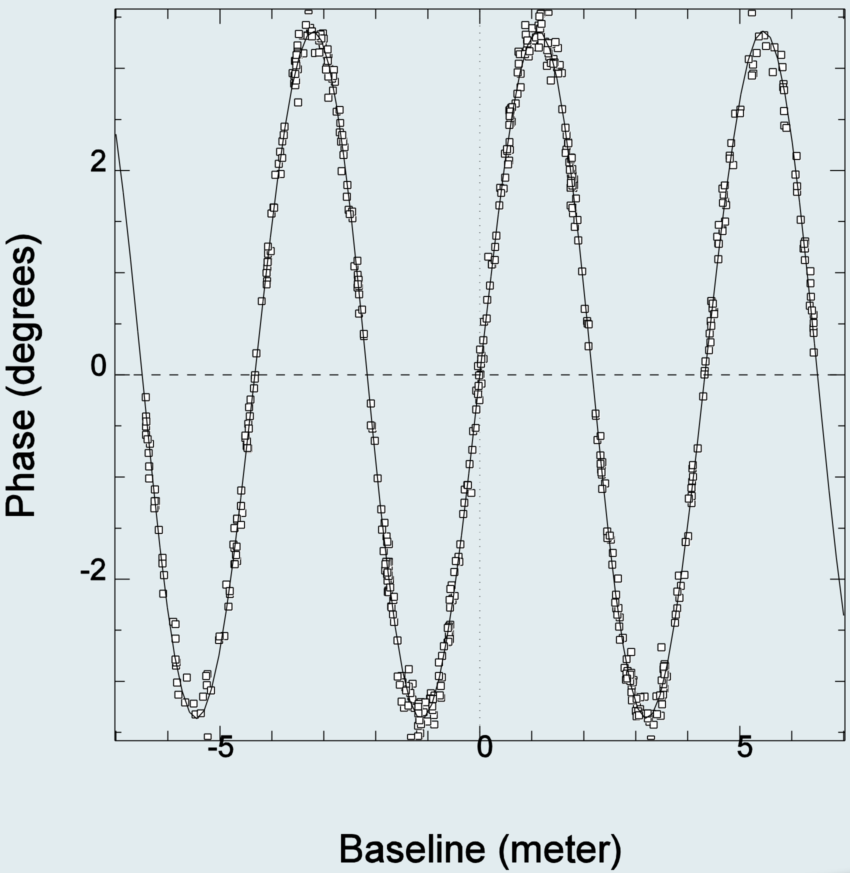






Detection: HD135549B

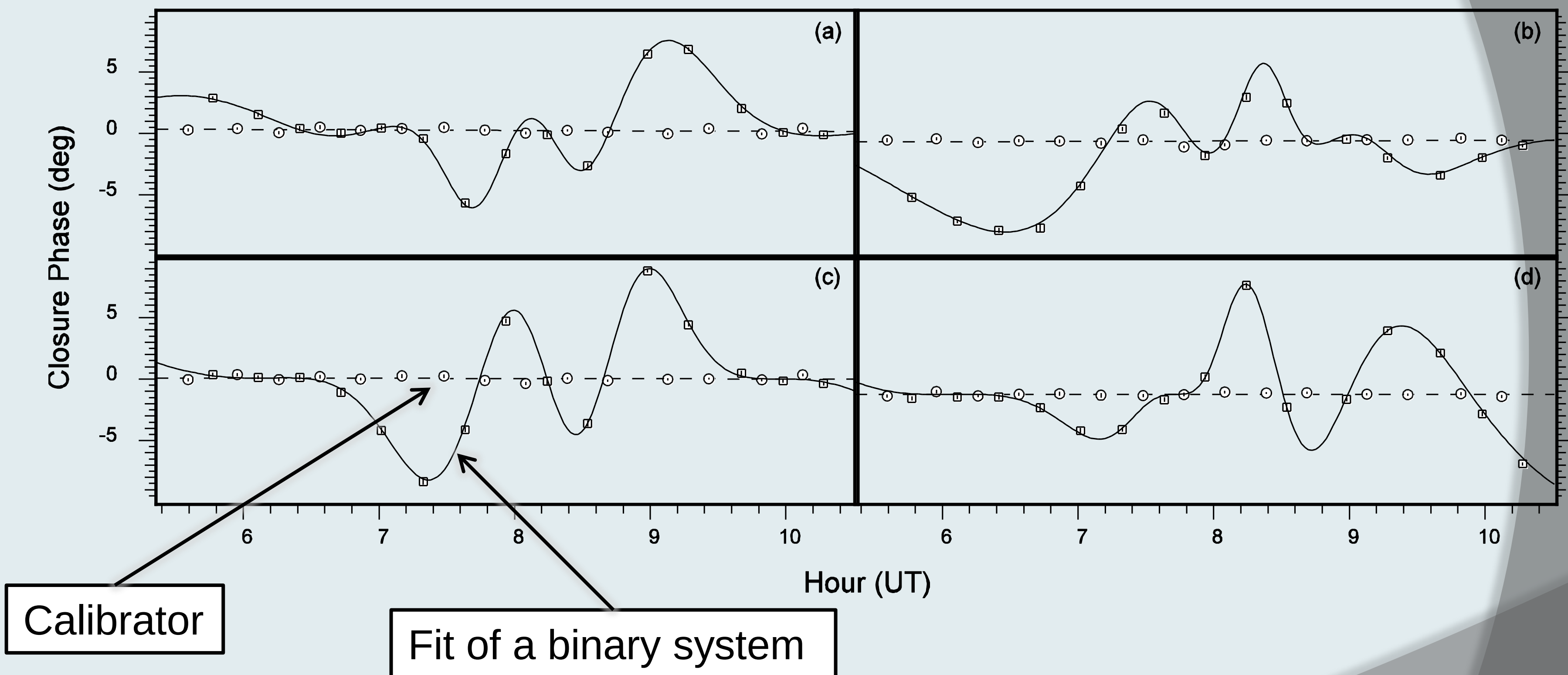
Target	Max χ^2	Min χ^2	Freedom degrees	Separation	Position angle	contrast ratio
HD 135549	248318	1136	522	179.99 ± 0.10	2.59 ± 0.00	0.06 ± 0.00



UT	Detector Position Angle (deg)	Separation (mas)	Position Angle (deg)	Flux (% of central object)
05:43:27	−153.38	179.32 ± 0.38	148.24 ± 0.13	5.62 ± 0.07
06:03:35	−148.63	179.33 ± 0.37	147.96 ± 0.11	5.51 ± 0.07
06:21:57	−143.54	181.52 ± 0.26	148.25 ± 0.09	5.69 ± 0.04
06:40:14	−137.46	179.55 ± 0.58	148.64 ± 0.21	5.60 ± 0.07
06:58:02	−130.17	179.46 ± 0.37	148.28 ± 0.10	5.62 ± 0.06
07:16:34	−120.66	179.24 ± 0.30	149.15 ± 0.12	5.60 ± 0.05
07:35:08	−108.48	179.42 ± 0.29	148.41 ± 0.10	5.57 ± 0.06
07:53:06	−93.93	179.34 ± 0.46	148.59 ± 0.18	5.45 ± 0.08
08:11:23	−77.02	180.50 ± 0.91	148.10 ± 0.21	5.43 ± 0.08
08:29:18	−60.32	180.80 ± 0.50	148.41 ± 0.19	5.47 ± 0.07
08:55:48	−39.29	181.44 ± 0.28	148.72 ± 0.10	5.58 ± 0.04
09:13:54	−28.29	180.80 ± 0.30	148.50 ± 0.12	5.57 ± 0.05
09:37:18	−17.41	181.60 ± 0.39	148.56 ± 0.11	5.27 ± 0.07
09:55:46	−10.75	180.40 ± 0.54	148.07 ± 0.16	5.33 ± 0.07
10:13:37	−5.44	179.73 ± 0.34	147.61 ± 0.13	5.49 ± 0.04
Full Fit		180.02 ± 0.11	148.36 ± 0.04	5.53 ± 0.02

DIT 200ms, NDIT 200, Lp=6.5mag

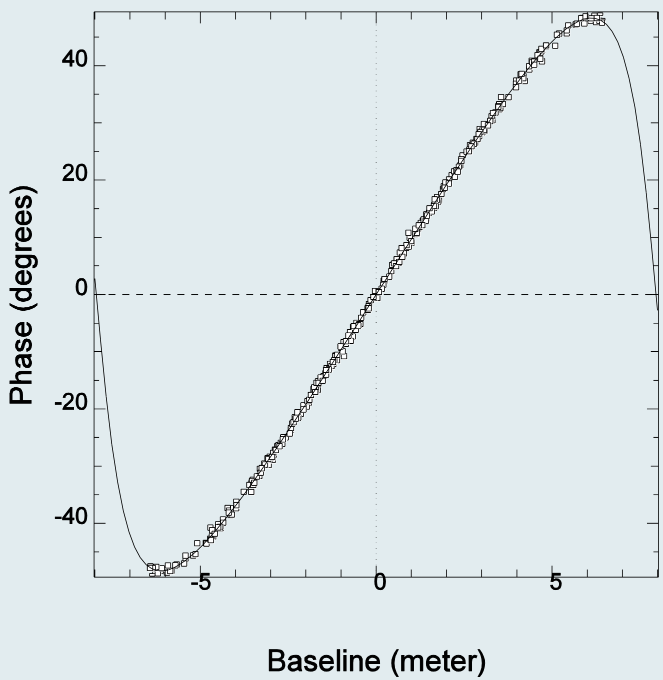
Detection: HD135549B

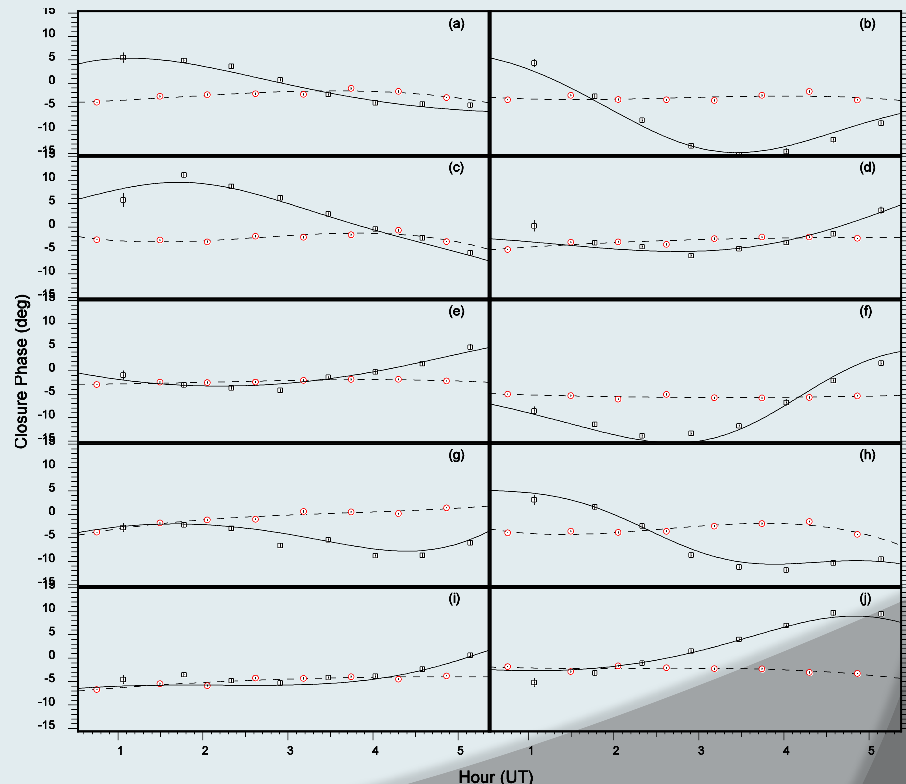


Error bars : 0.3 degrés => Dynamic range of 7e-4

super-resolution: CS Cha

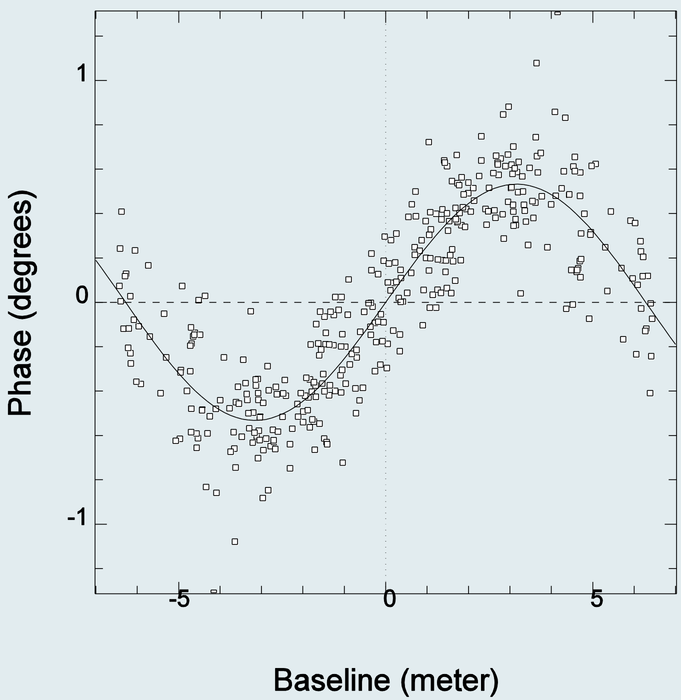
- Detection at 0.4 λ/D on a 8.2mag star in K band

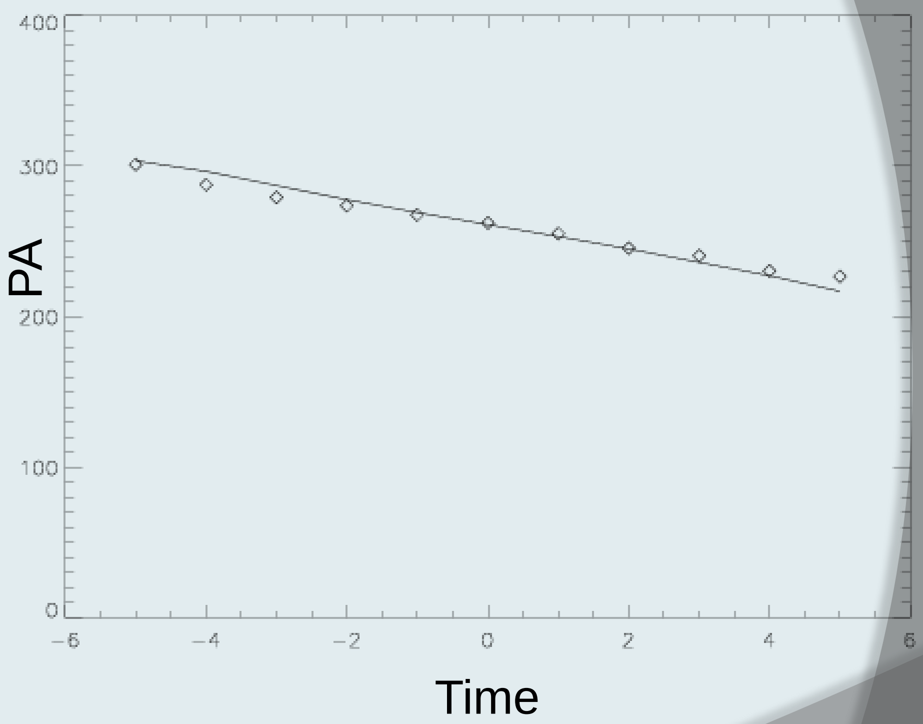




Flux ratio 76.8+/-1.2% -- Separation 27.6+/- 0.4 mas

Transition disk : T Cha

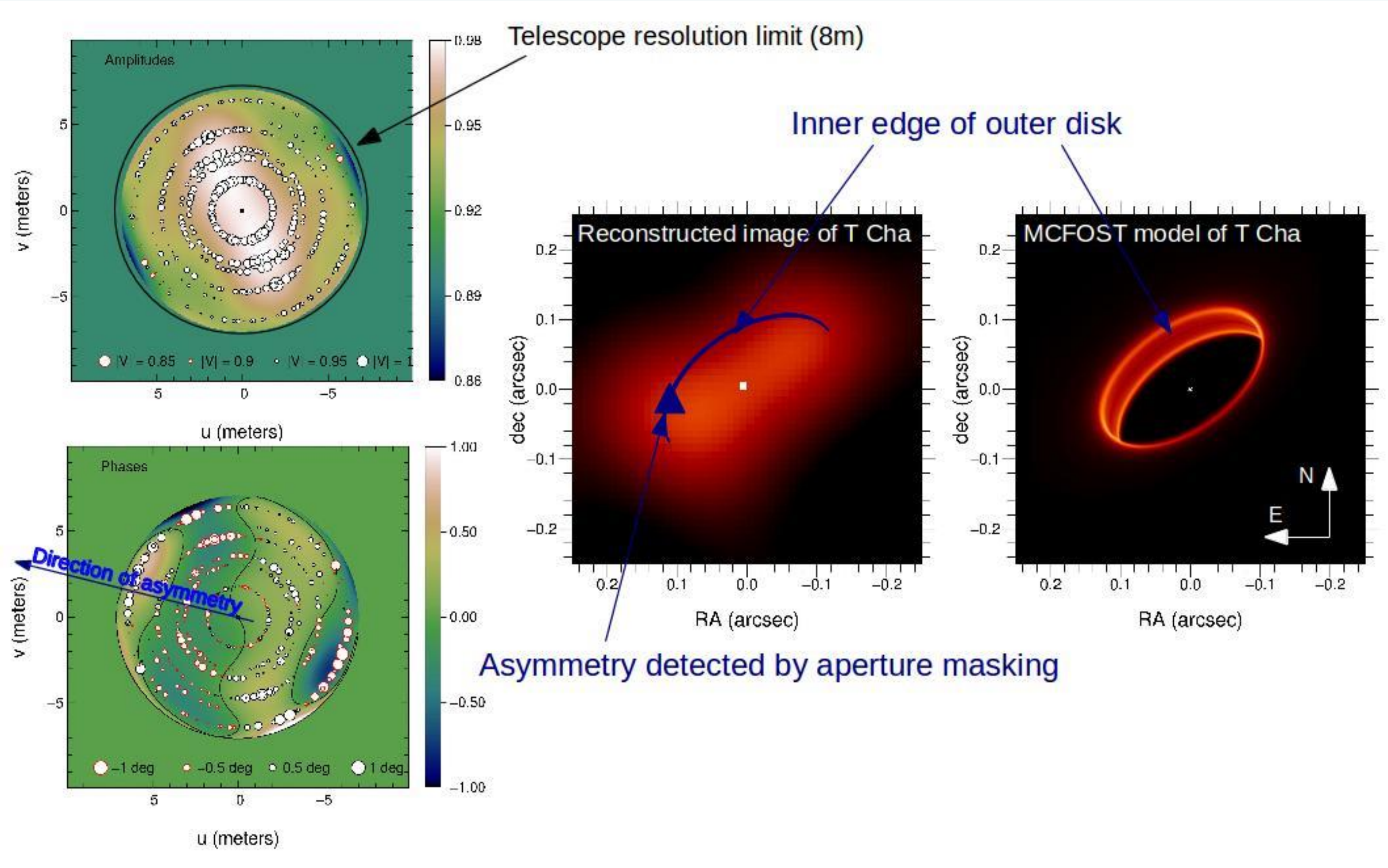




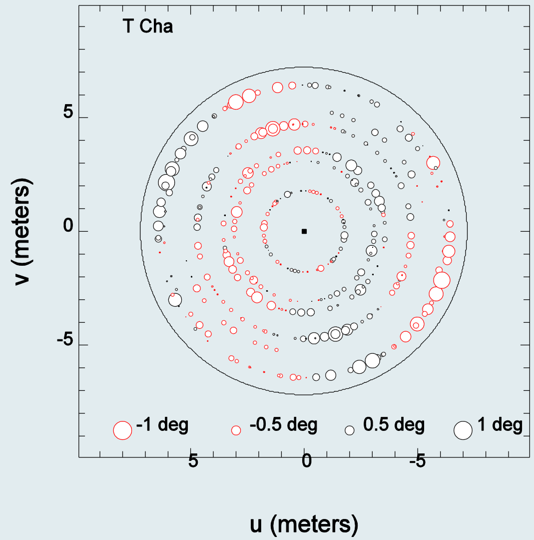
Separation: 62+/-7.3mas   Contrast ratio 0.92+/-0.2%

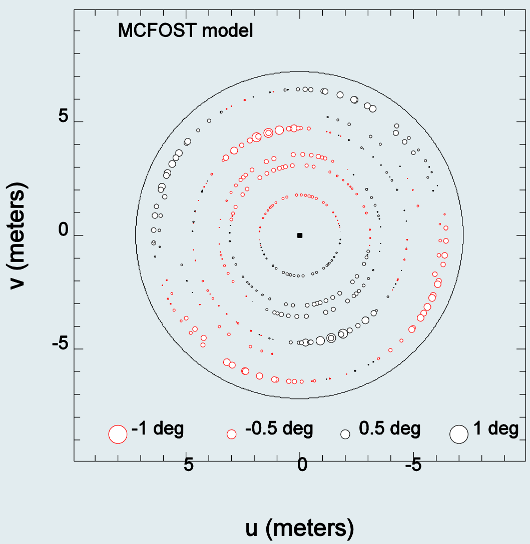
Huelamo et al. 2011

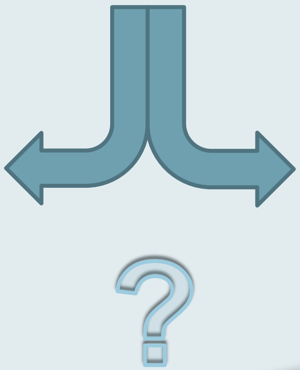
Transition disk : T Cha

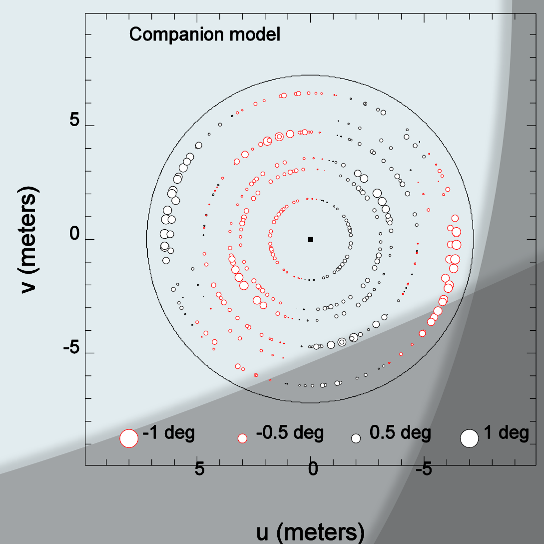


Transition disk : T Cha





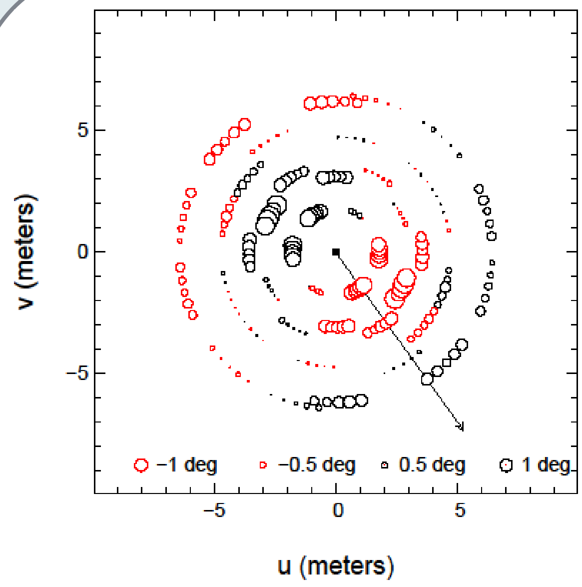




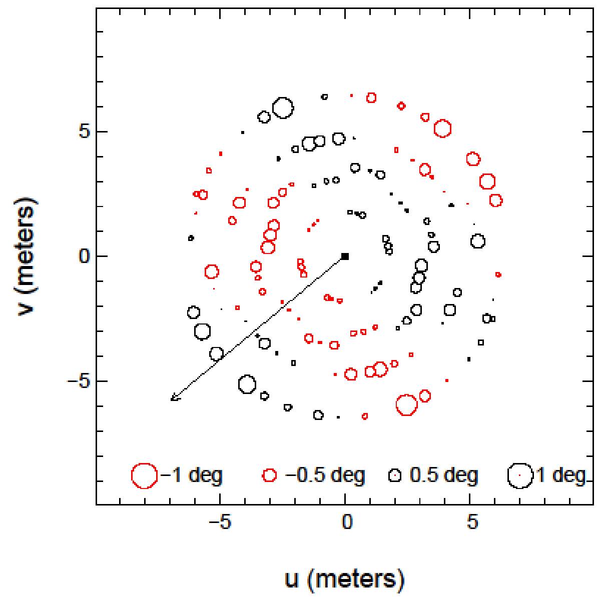
Disk model by Olofsson et al. 2013

Binary model by Huelamo et al. 2011

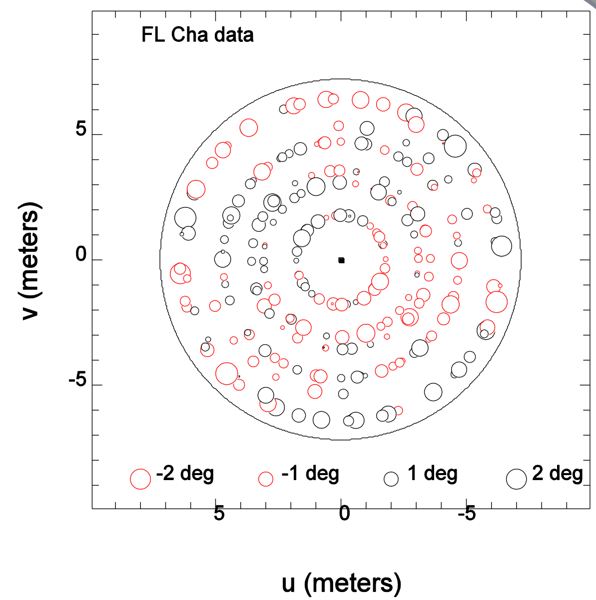
Transition disks: companions or disk?



HD100456

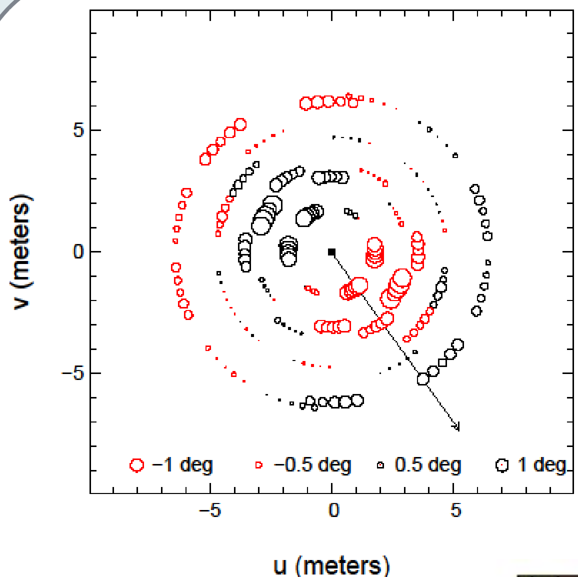


HD142527 (Biller et al. 2012)

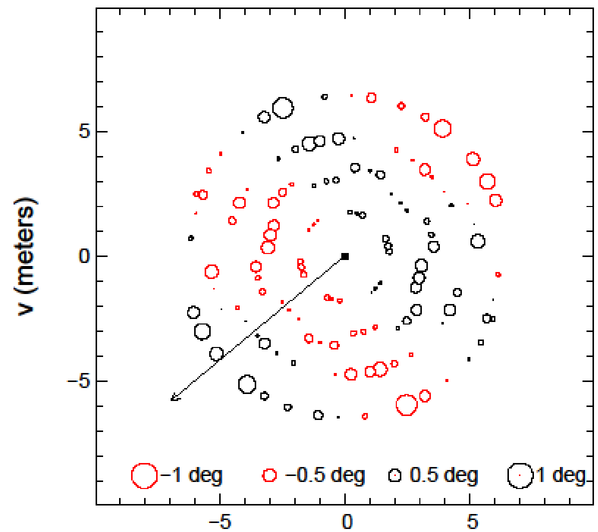


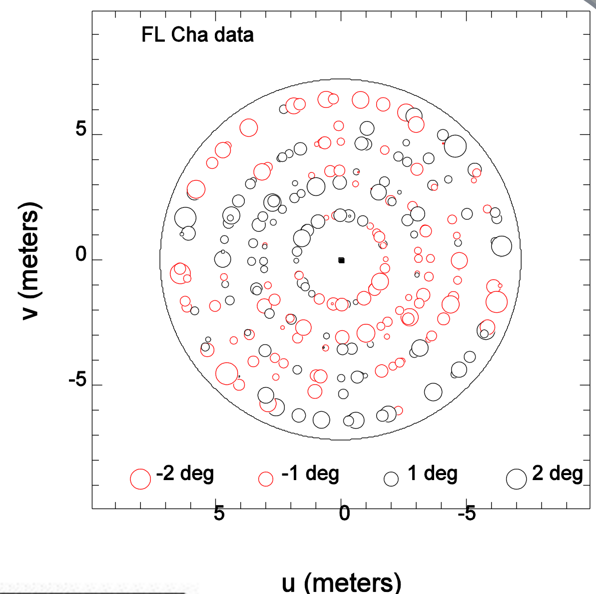
FL Cha (Cieza et al. 2012)

Transition disks: companions or disk?

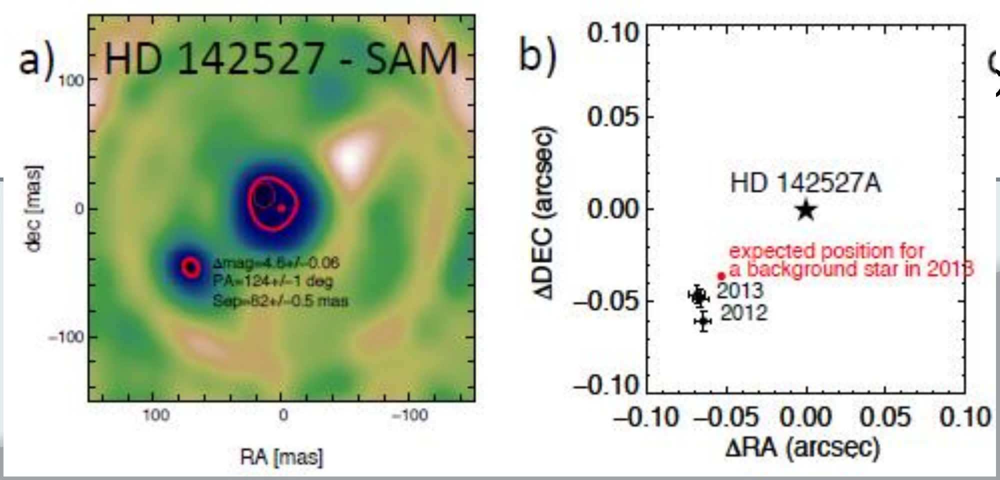


HD100456





ha (Cieza et al. 2012)

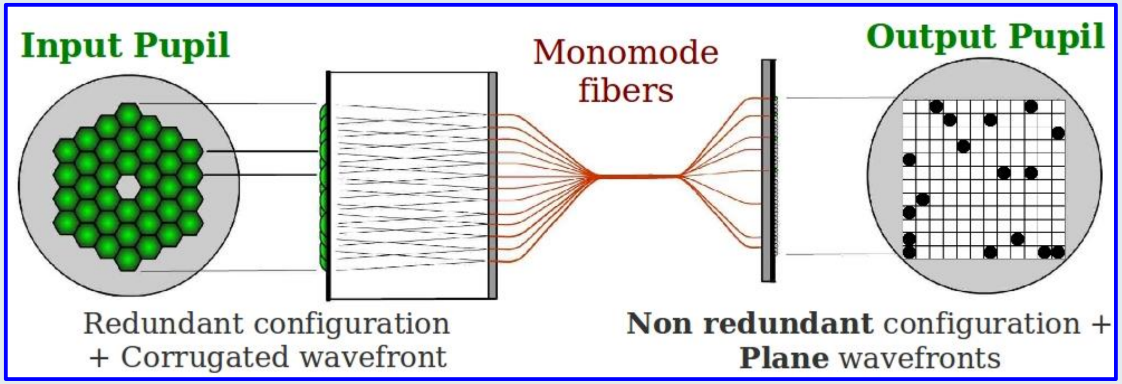


Present

II) PUPIL REMAPPING

FIRST – Fibered Imager foR a Single Telescope

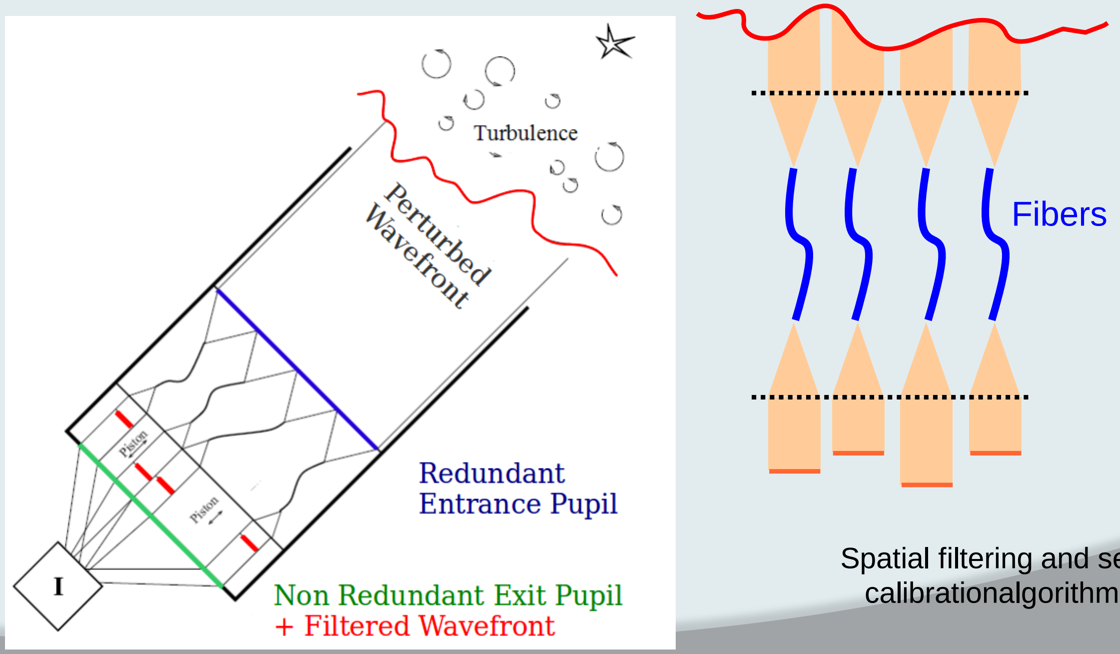
Pupil remapping



Perrin et al., 2006

The totality of the telescope pupil is used

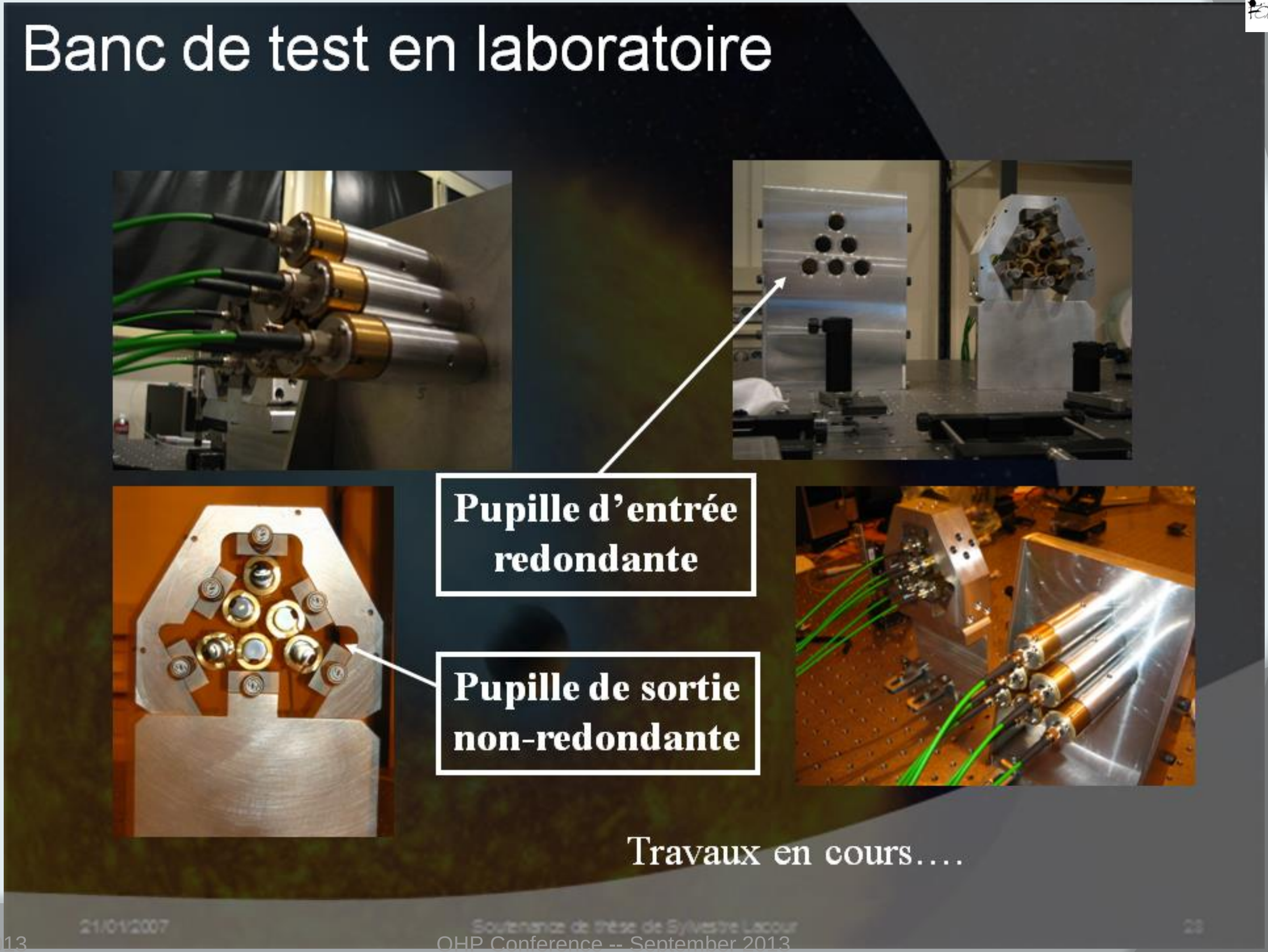
Spatial Filtering



Spatial filtering and self calibrationalgorithm

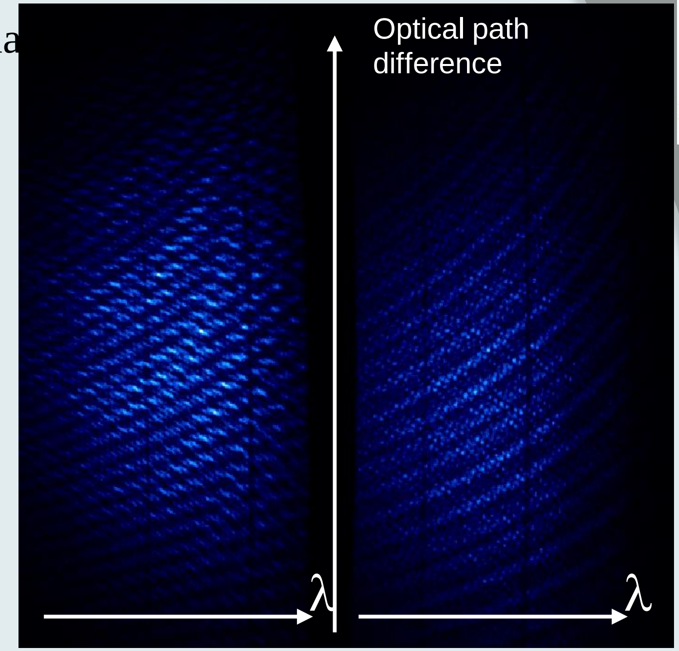
Optical aberration at the level of sub-pupils are filtered

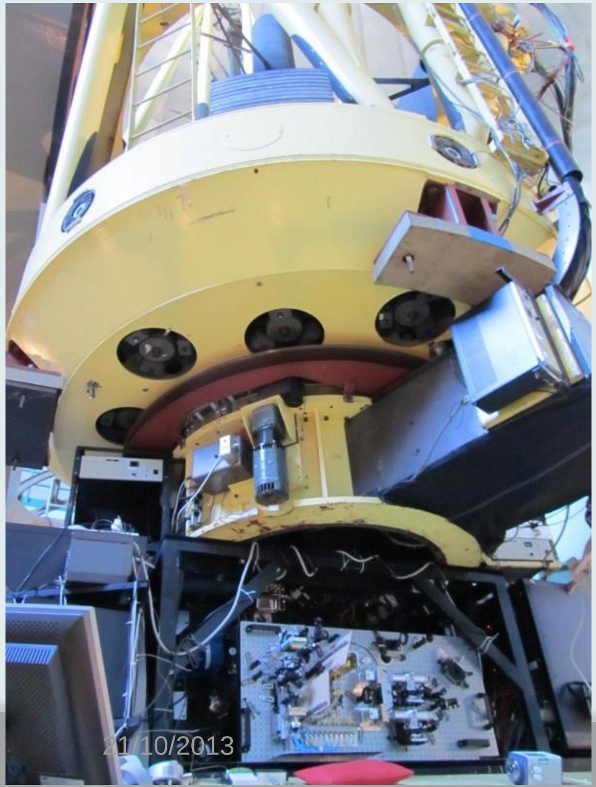
FIRST – Fibered Imager foR a Single Telescope

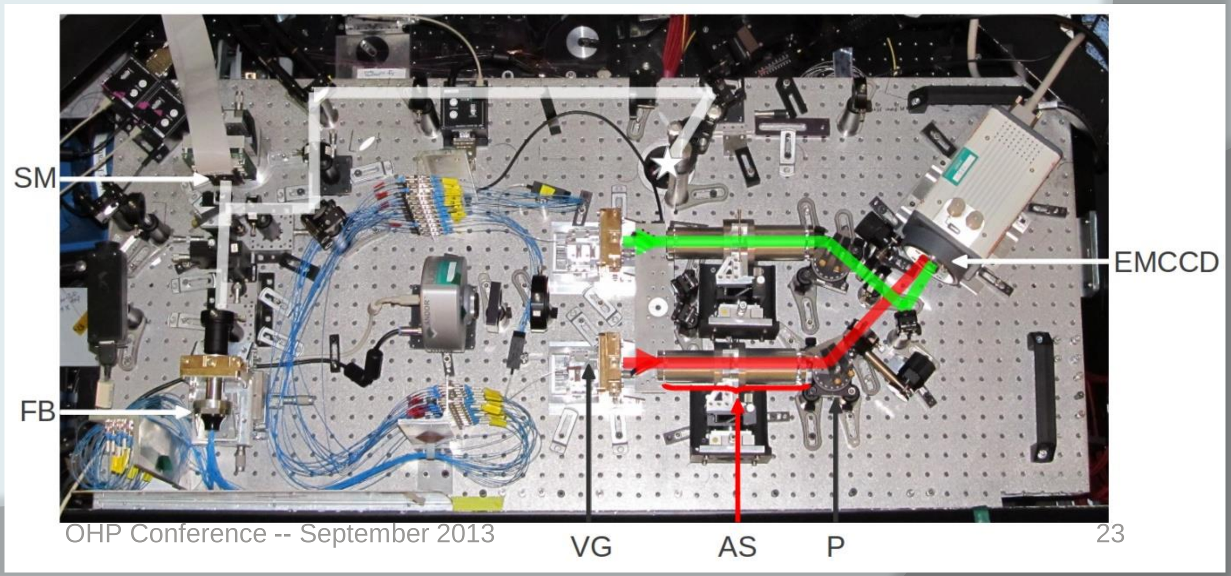


FIRST – Fibered Imager foR a Single Telescope

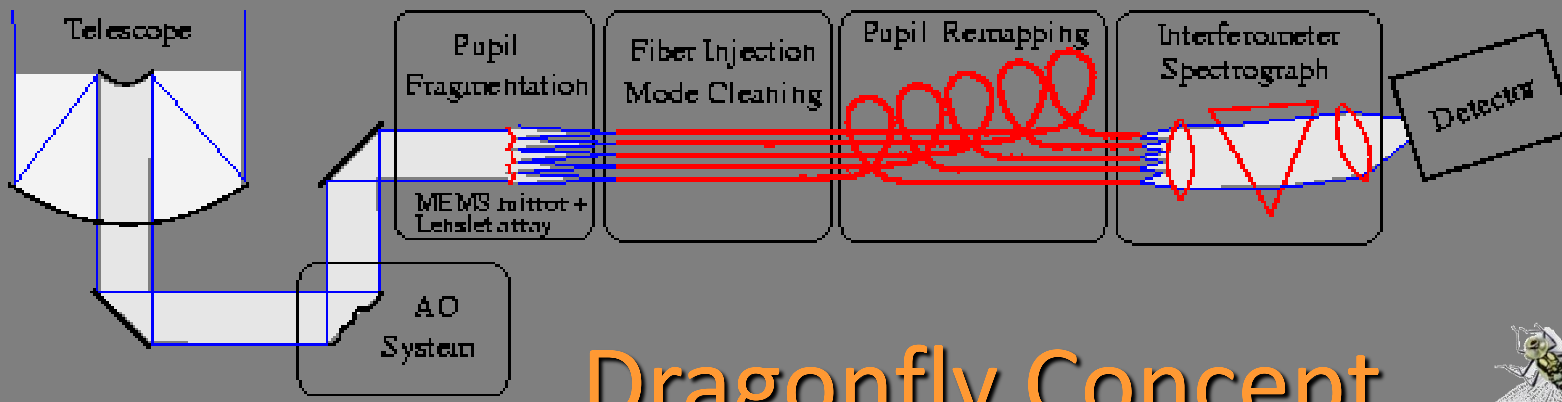
- Objectif : Haute dynamique & haute résolution angula
- Technologie : fibre optique monomodes
- Sur le ciel à l'obsevatoire Lick (CA)
- L'année prochaine sur le telescope SUBARU (HI)
- Collaborateurs
  - UC Berkeley (Gaspard Duchêne)
  - SETI (Franck Marchis)
  - SUBARU telescope (Olivier Guyon)







Dragonfly - Benefits of pupil remapping



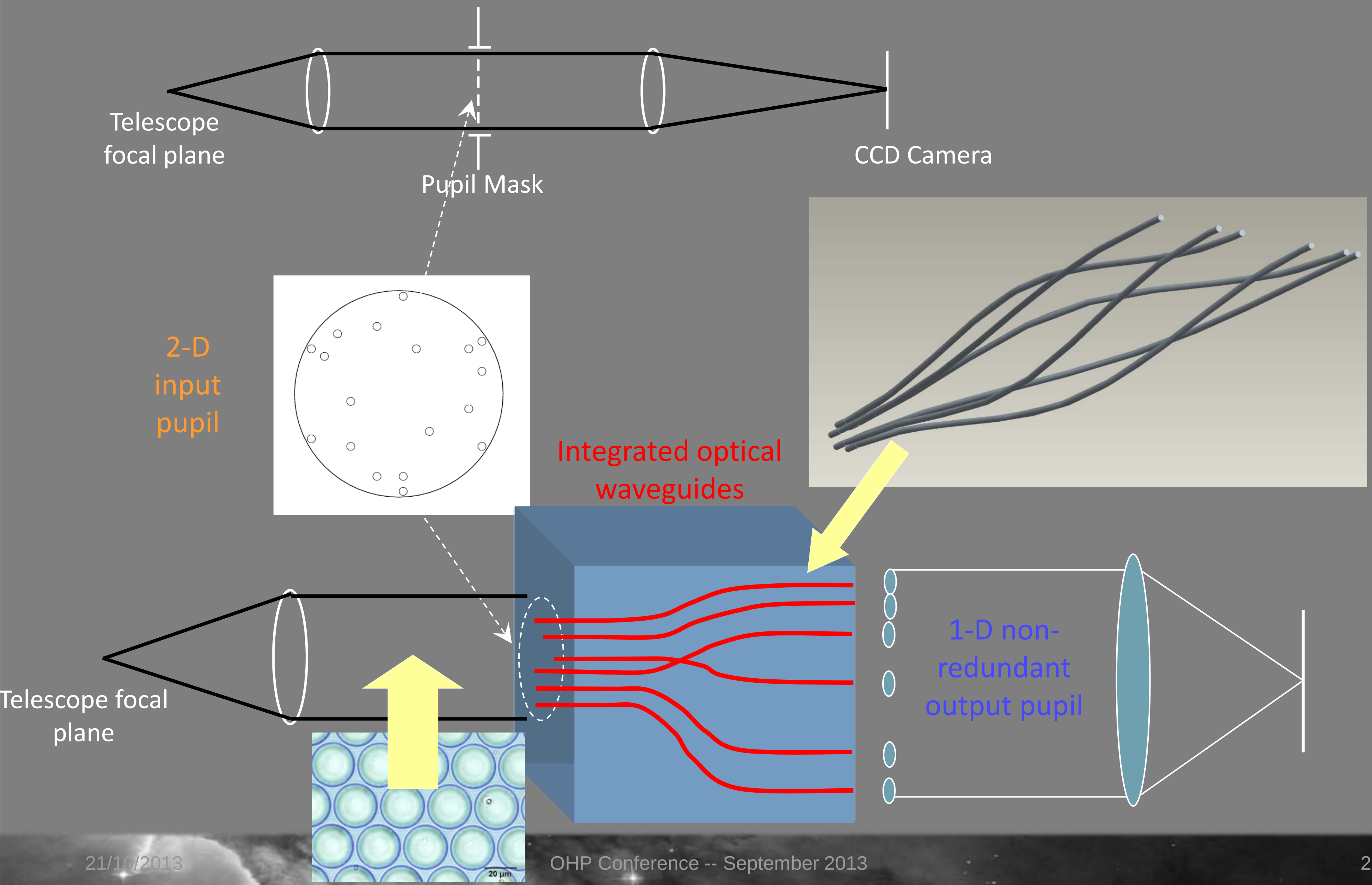
MEMS Mirror Array
(Image Iris AO)

Dragonfly Concept

Benefits of remapping with single mode guides

- Single mode fibres offer spatial filtering – flat phase across each sub aperture/mode – higher signal to noise ratio.
- Can remap from redundant 2D to a non-redundant 1D pattern!
- This allows more of the aperture, or all of it to be used i.e. higher throughputs.
- Easier to work with a 1D diffraction pattern.

Pupil remapping – Without fibres



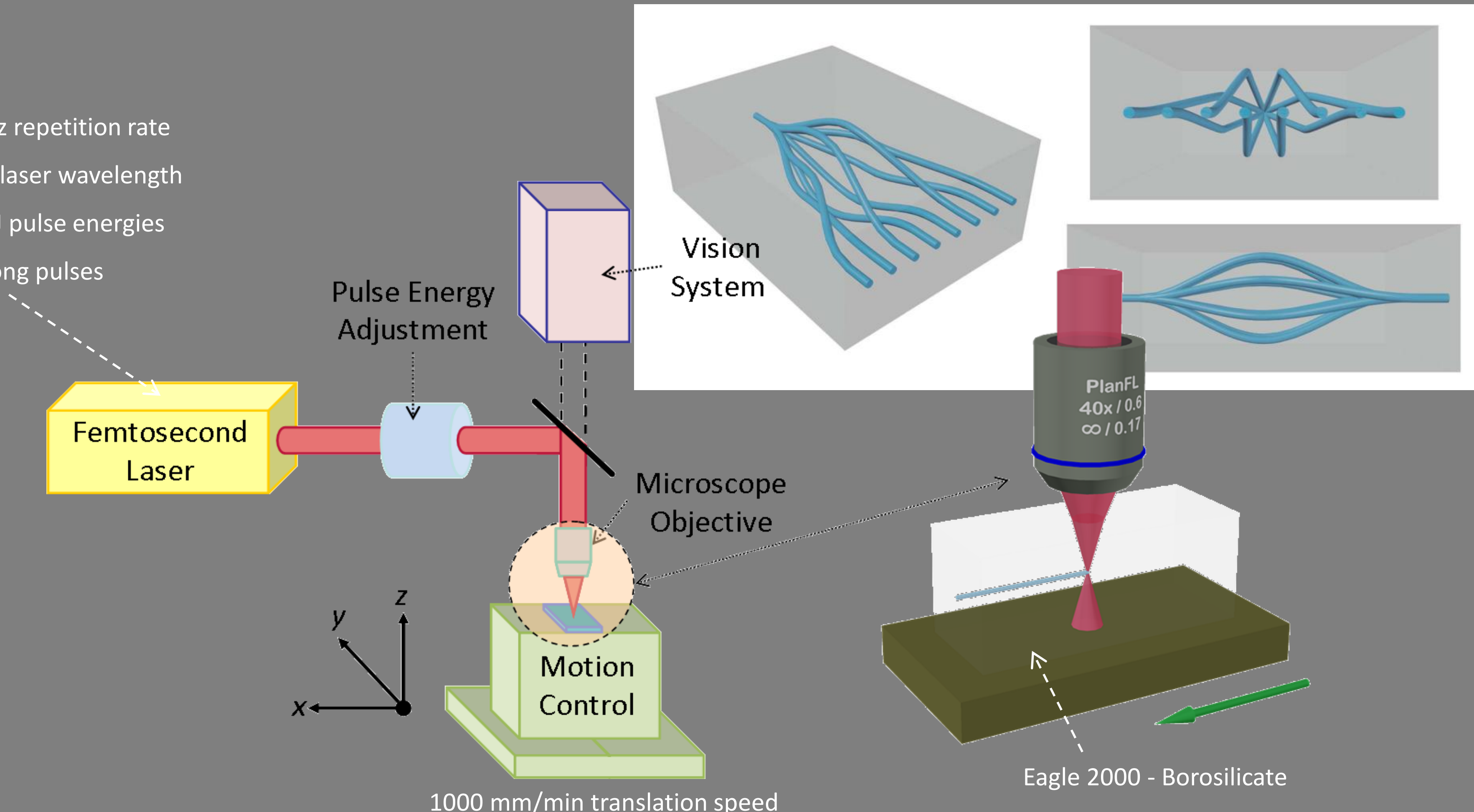
Waveguide fabrication particulars

5.4 MHz repetition rate

800 nm laser wavelength

35-45 nJ pulse energies

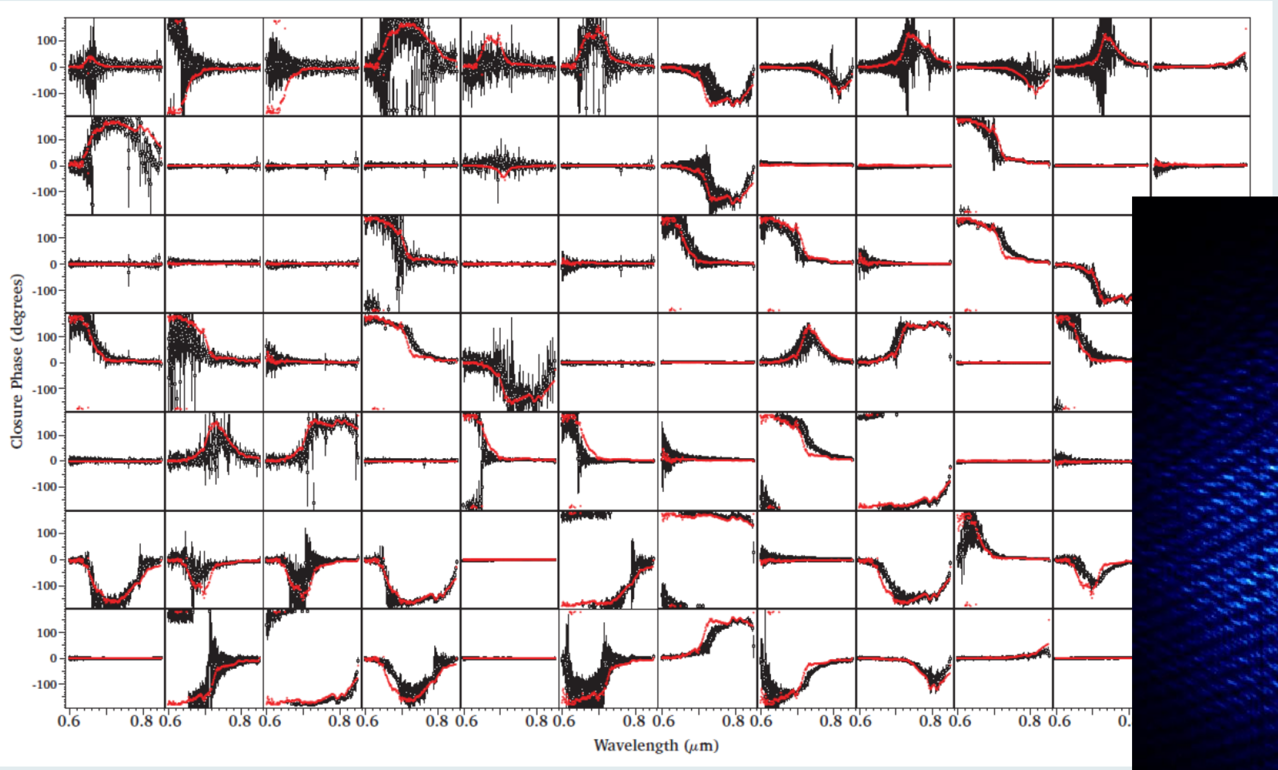
<50 fs long pulses

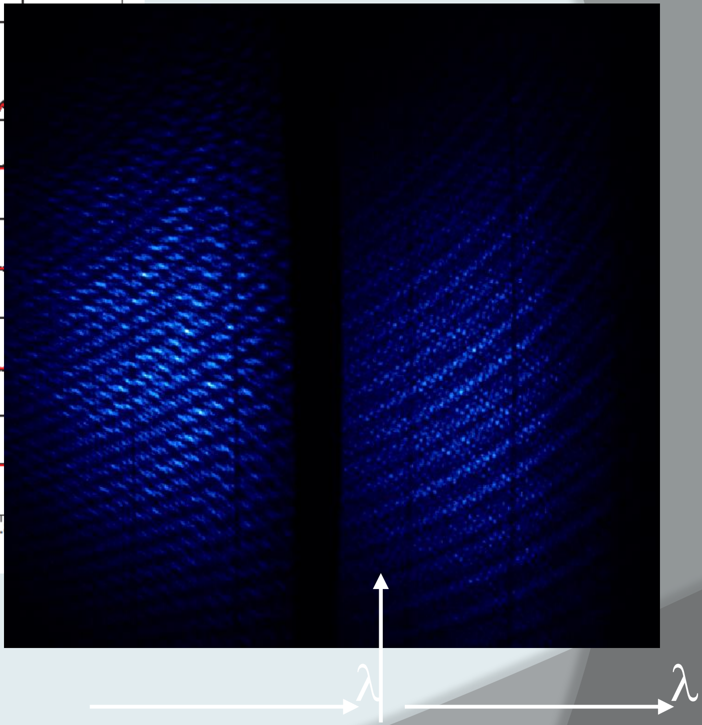


Fabrication time for a 30 mm long 8 waveguide device is 29 seconds!!!!!

FIRST – Fibered Imager foR a Single Telescope

- First astrophysical Result: Capella observations





- Flux ratio of Capella between 600 and 850nm.

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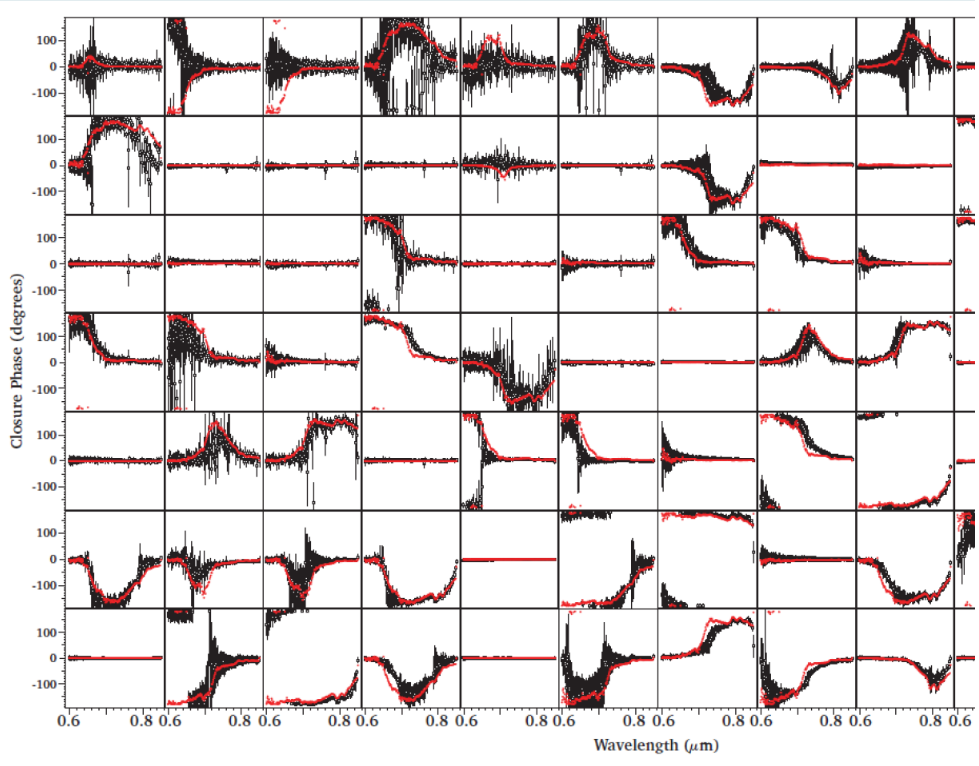

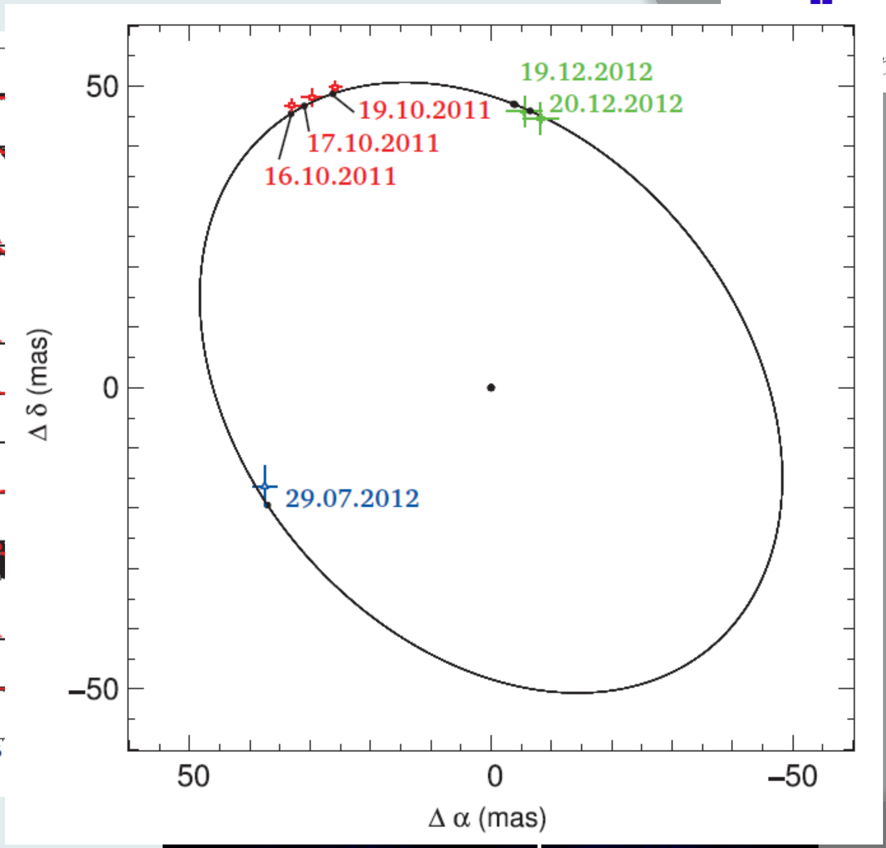

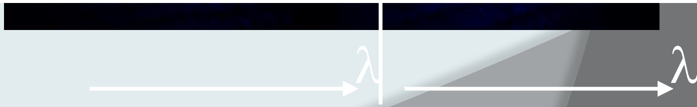

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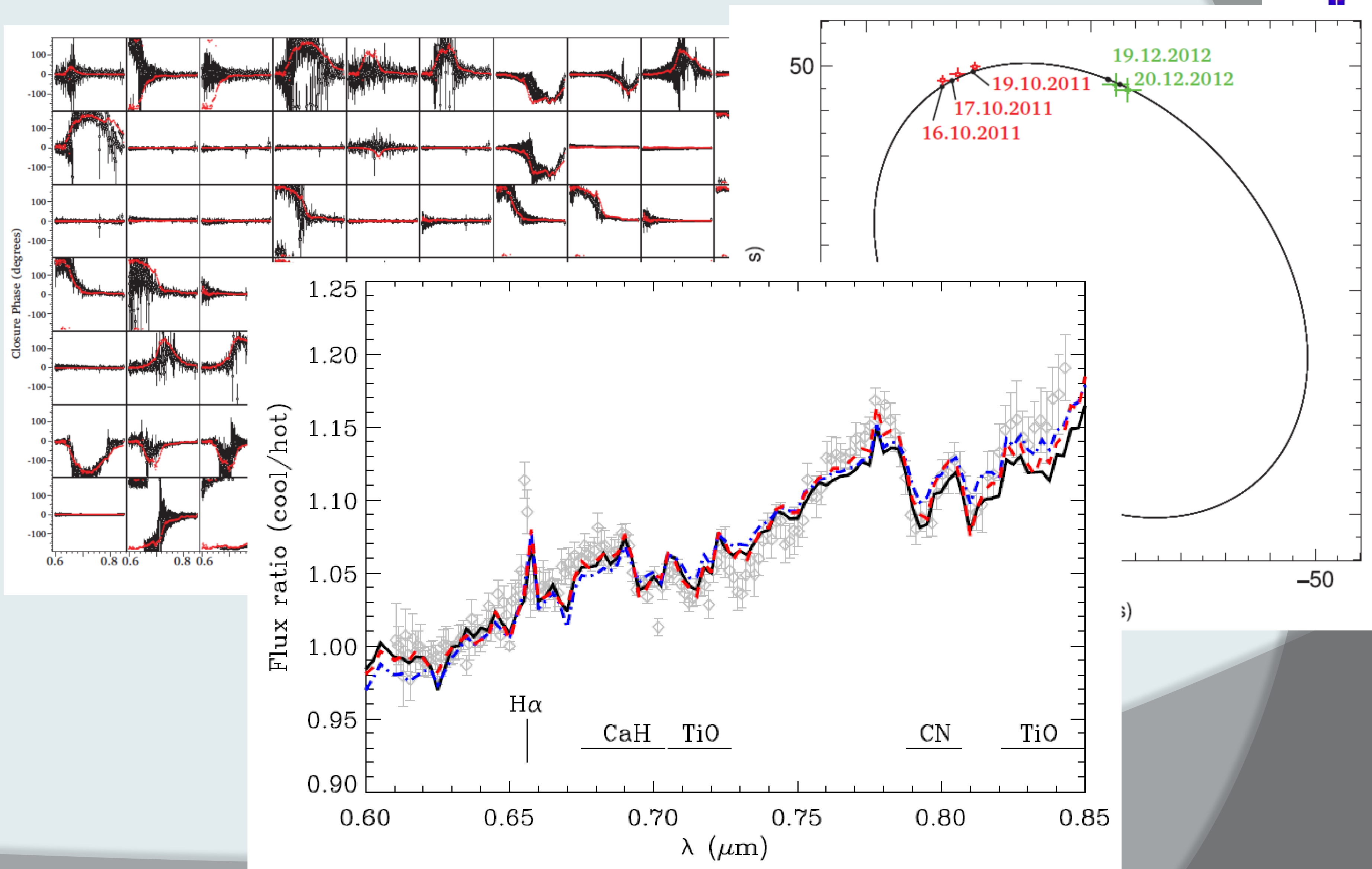
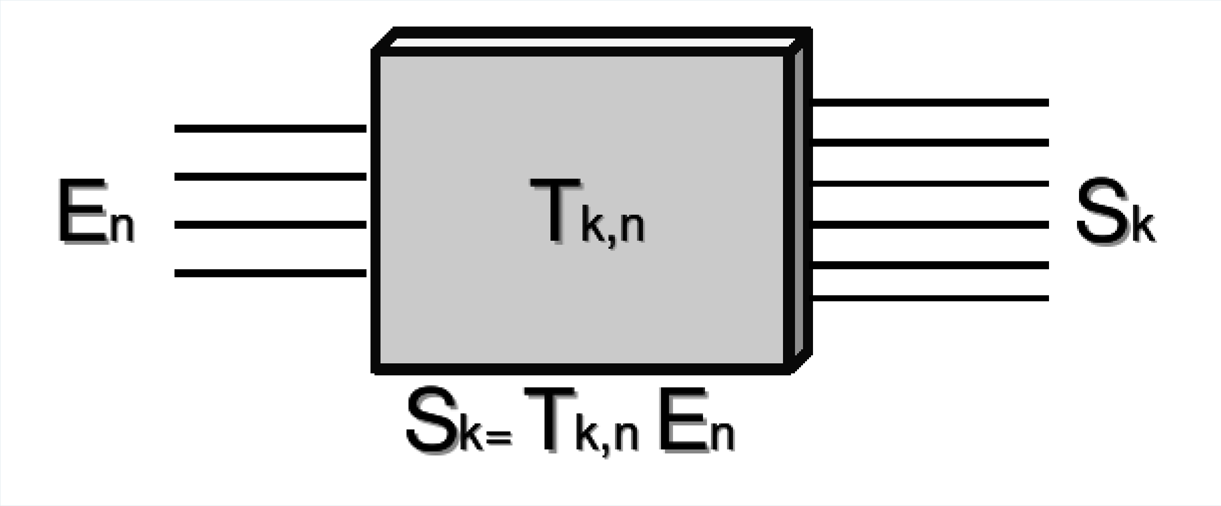


- Flux ratio of Capella between 600 and 850nm.

Future

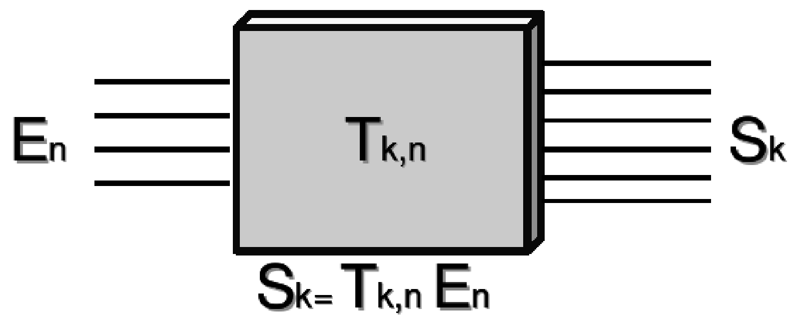
II) ASTROPHOTONIQUE

The optical transfer function



$$
\begin{aligned}
|S^k|^2 &= \left| \sum_n T_n^k E_n \right|^2 \\
&= \Re \left[\sum_n |T_n^k E_n|^2 + 2 \sum_n \sum_{m>n} T_n^k T_m^{k*} \; E_n E_m \right] .
\end{aligned}
$$

The optical transfer function



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\begin{aligned}
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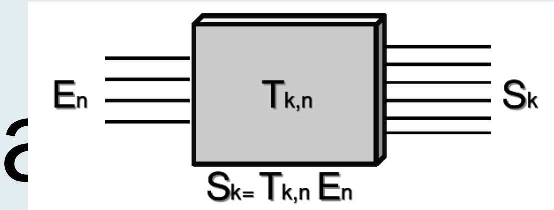
&= \Re\left[\sum_n |T_n^k E_n|^2 + 2\sum_n \sum_{m>n} T_n^k T_m^{k*}\ E_n E_m\right].
\end{aligned}
$$

$$
\begin{pmatrix} |S^1|^2 \\ \vdots \\ |S^K|^2 \end{pmatrix} = \Re\left[V2PM \cdot \begin{pmatrix} |E_1|^2 \\ \vdots \\ |E_N|^2 \\ E_1 E_2^* V_{1,2} \\ \vdots \\ E_{N-1} E_N^* V_{N-1,N} \end{pmatrix} \right]
$$

The optica function



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\begin{aligned}
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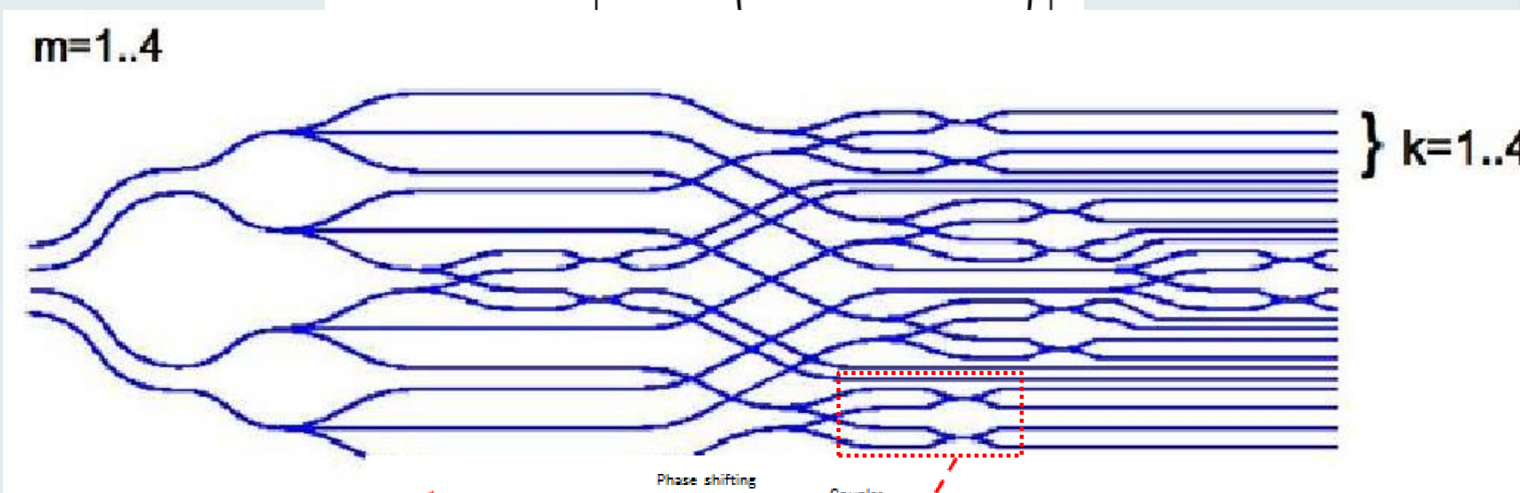
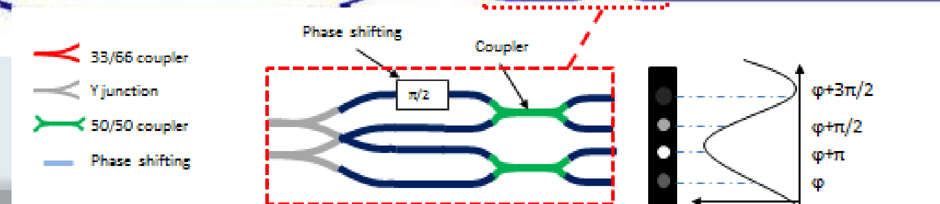
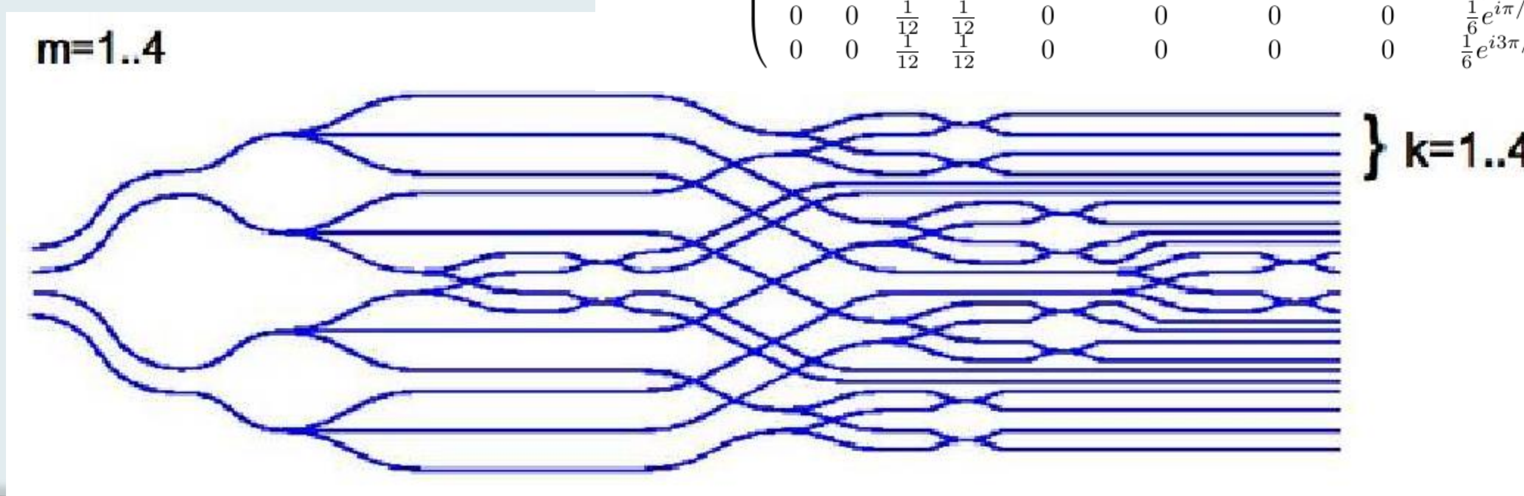
\begin{pmatrix} |S^1|^2 \\ \vdots \\ |S^K|^2 \end{pmatrix} = \Re\left[V2PM \cdot \begin{pmatrix} |E_1|^2 \\ \vdots \\ |E_N|^2 \\ E_1 E_2^* V_{1,2} \\ \vdots \end{pmatrix} \right]
$$



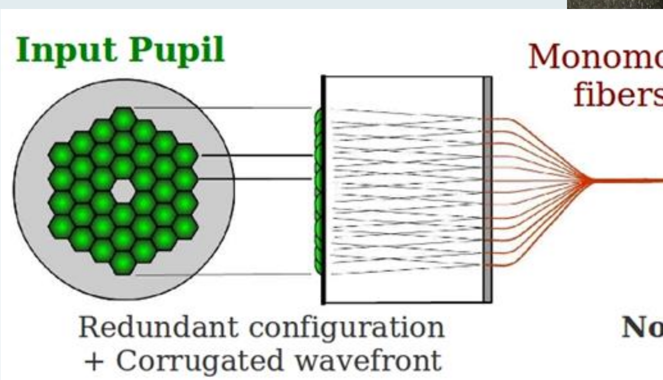


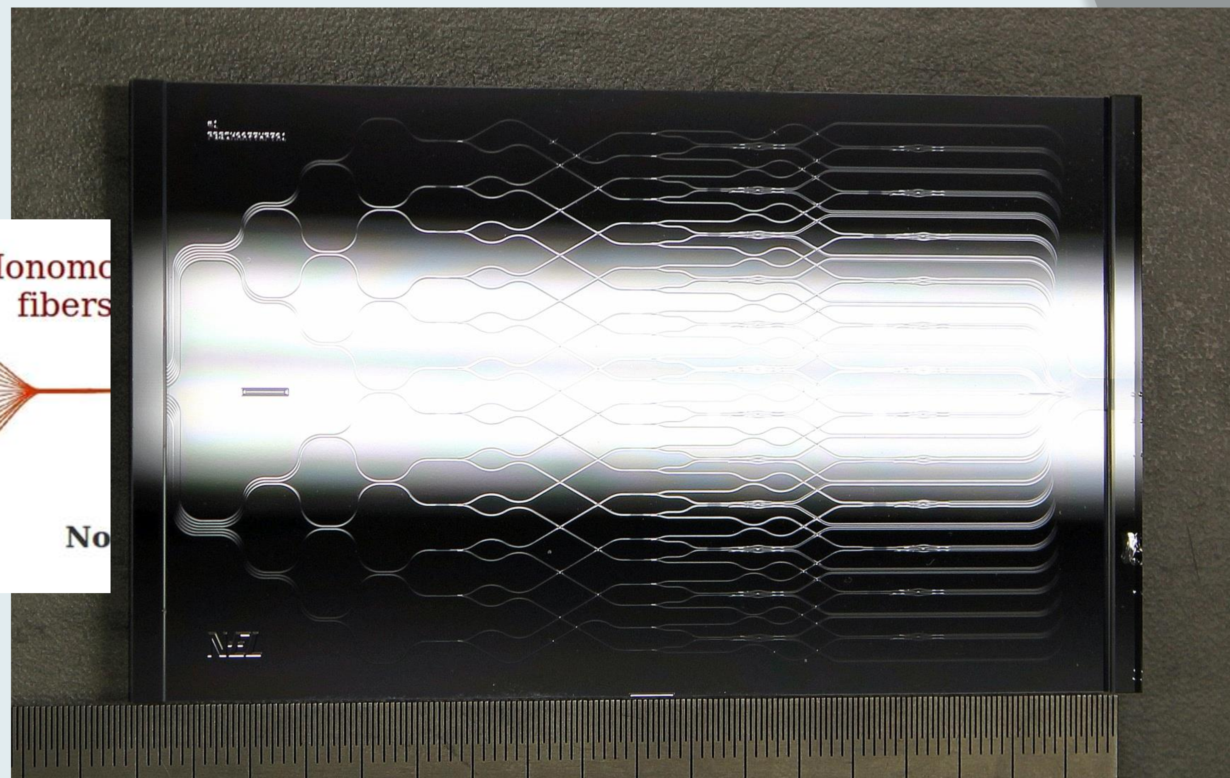
$$\begin{pmatrix} |S^1|^2 \\ \vdots \\ |S^K|^2 \end{pmatrix} = \Re \left[V2PM \cdot \begin{pmatrix} |E_1|^2 \\ \vdots \\ |E_N|^2 \\ E_1 E_2^* V_{1,2} \\ \vdots \\ E_{N-1} E_N^* V_{N-1,N} \end{pmatrix} \right]$$

$$V2PM = \begin{pmatrix}
\frac{1}{12} & \frac{1}{12} & 0 & 0 & \frac{1}{6} & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{12} & \frac{1}{12} & 0 & 0 & \frac{1}{6}e^{i\pi} & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{12} & \frac{1}{12} & 0 & 0 & \frac{1}{6}e^{i\pi/2} & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{12} & \frac{1}{12} & 0 & 0 & \frac{1}{6}e^{i3\pi/2} & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{12} & \frac{1}{12} & 0 & 0 & \frac{1}{6} & 0 & 0 & 0 & 0 \\
0 & \frac{1}{12} & \frac{1}{12} & 0 & 0 & \frac{1}{6}e^{i\pi} & 0 & 0 & 0 & 0 \\
\frac{1}{12} & 0 & \frac{1}{12} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{6} \\
\frac{1}{12} & 0 & \frac{1}{12} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{6}e^{i\pi} \\
\frac{1}{12} & 0 & \frac{1}{12} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{6}e^{i\pi/2} \\
\frac{1}{12} & 0 & \frac{1}{12} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{6}e^{i3\pi/2} \\
\frac{1}{12} & 0 & 0 & \frac{1}{12} & 0 & 0 & 0 & \frac{1}{6} & 0 & 0 \\
\frac{1}{12} & 0 & 0 & \frac{1}{12} & 0 & 0 & 0 & \frac{1}{6}e^{i\pi} & 0 & 0 \\
\frac{1}{12} & 0 & 0 & \frac{1}{12} & 0 & 0 & 0 & \frac{1}{6}e^{i\pi/2} & 0 & 0 \\
\frac{1}{12} & 0 & 0 & \frac{1}{12} & 0 & 0 & 0 & \frac{1}{6}e^{i3\pi/2} & 0 & 0 \\
0 & \frac{1}{12} & 0 & \frac{1}{12} & 0 & 0 & \frac{1}{6} & 0 & 0 & 0 \\
0 & \frac{1}{12} & 0 & \frac{1}{12} & 0 & 0 & \frac{1}{6}e^{i\pi} & 0 & 0 & 0 \\
0 & \frac{1}{12} & 0 & \frac{1}{12} & 0 & 0 & \frac{1}{6}e^{i\pi/2} & 0 & 0 & 0 \\
0 & \frac{1}{12} & 0 & \frac{1}{12} & 0 & 0 & \frac{1}{6}e^{i3\pi/2} & 0 & 0 & 0 \\
0 & \frac{1}{12} & \frac{1}{12} & 0 & 0 & \frac{1}{6}e^{i\pi/2} & 0 & 0 & 0 & 0 \\
0 & \frac{1}{12} & \frac{1}{12} & 0 & 0 & \frac{1}{6}e^{i3\pi/2} & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{12} & \frac{1}{12} & 0 & 0 & 0 & 0 & \frac{1}{6} & 0 \\
0 & 0 & \frac{1}{12} & \frac{1}{12} & 0 & 0 & 0 & 0 & \frac{1}{6}e^{i\pi} & 0 \\
0 & 0 & \frac{1}{12} & \frac{1}{12} & 0 & 0 & 0 & 0 & \frac{1}{6}e^{i\pi/2} & 0 \\
0 & 0 & \frac{1}{12} & \frac{1}{12} & 0 & 0 & 0 & 0 & \frac{1}{6}e^{i3\pi/2} & 0
\end{pmatrix}$$



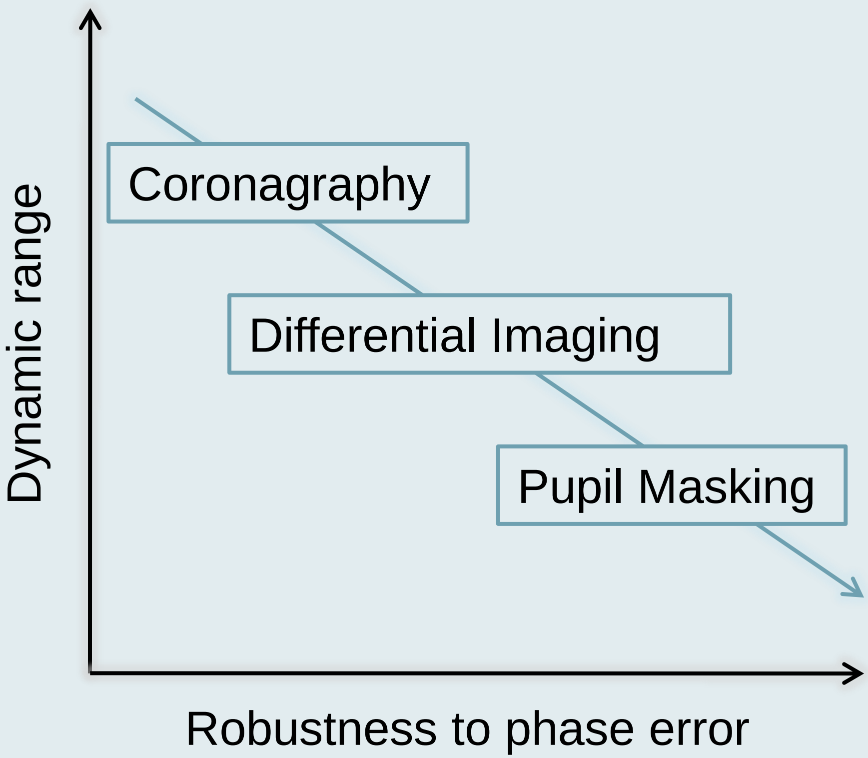
12 telescope beam combiner





NTT Electronics (Japan)

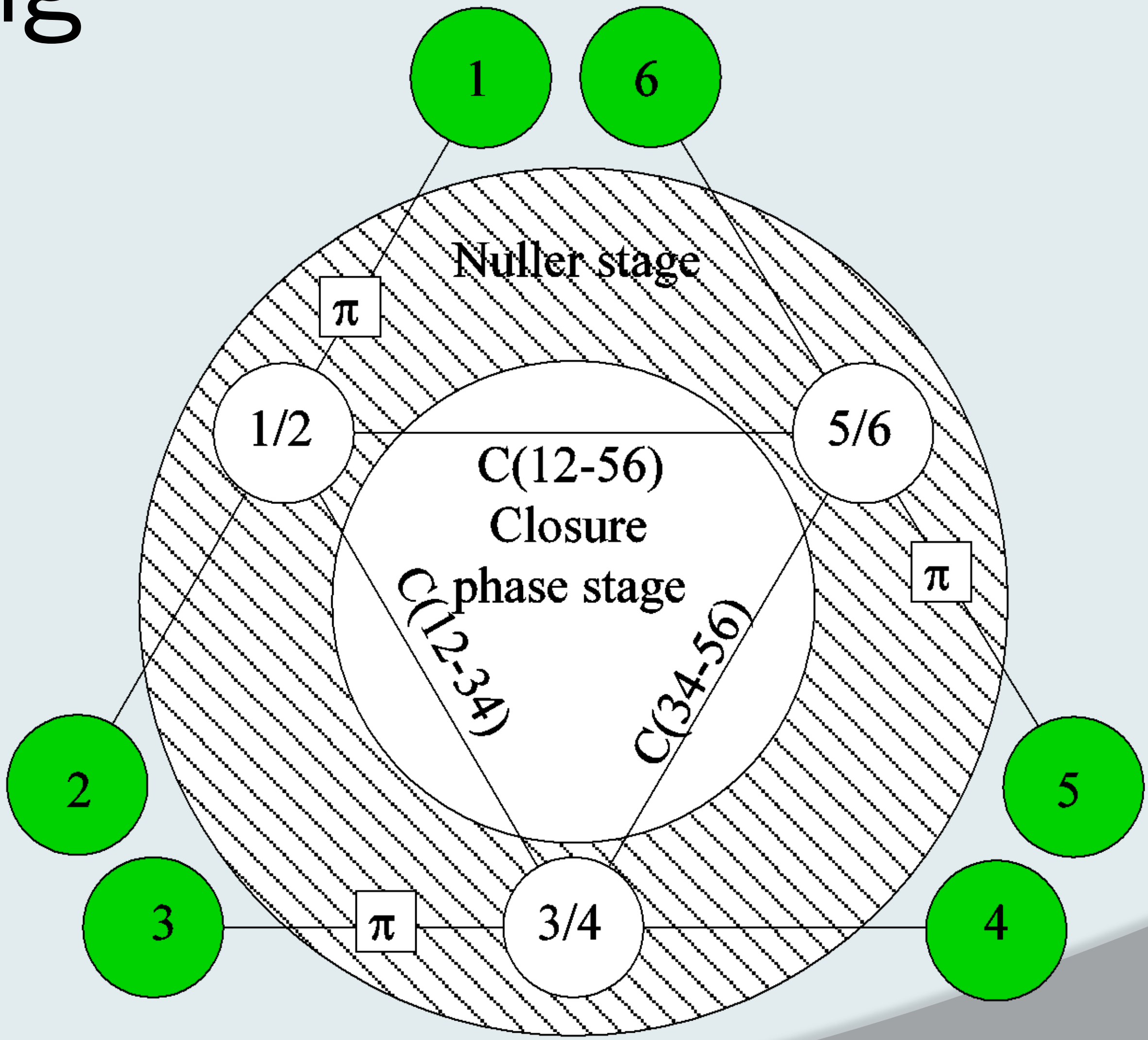
Photon noise



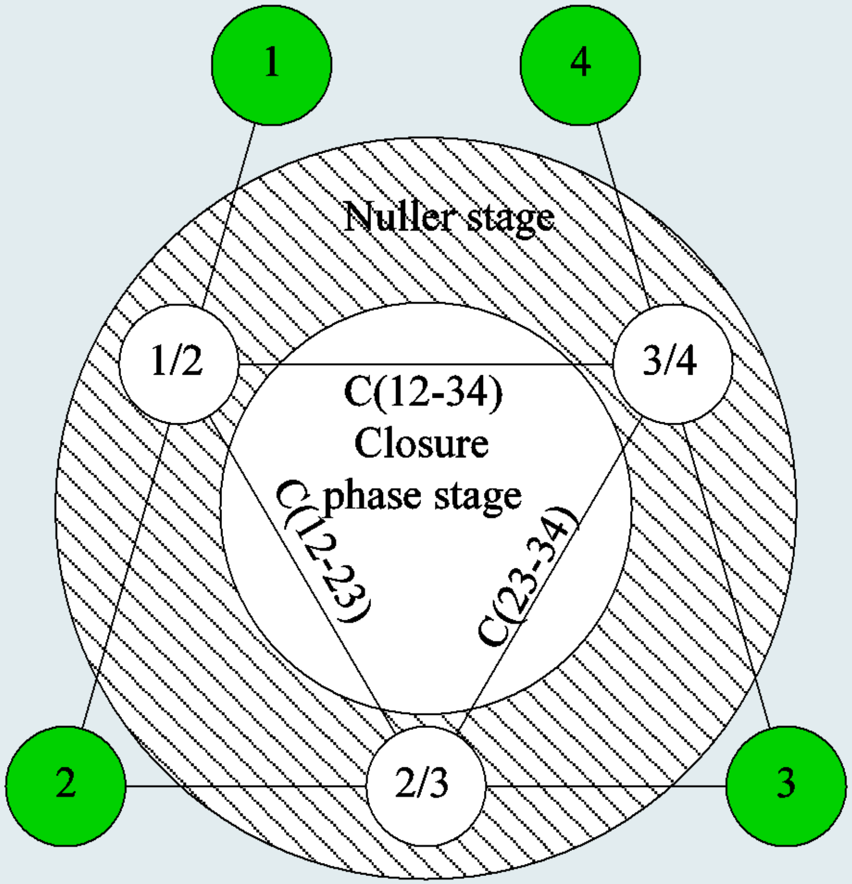
Ex: Planet/star flux ratio : 1e6:

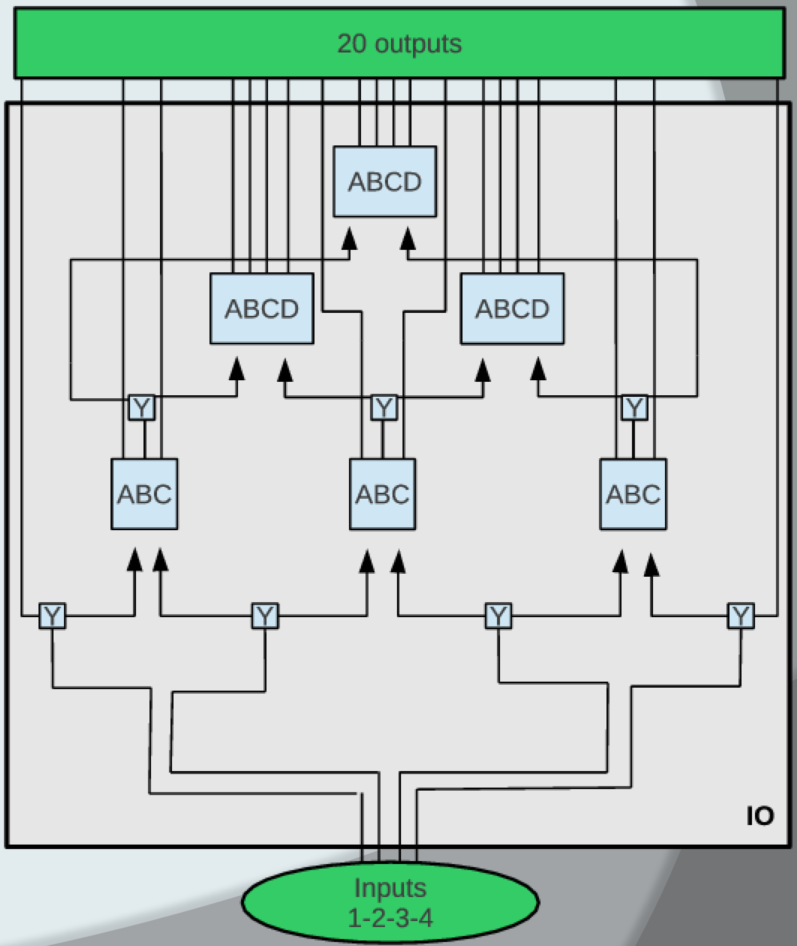
SNR Planet if photon separated: N
SNR Planet if photon not separated: N/1e3

Nulling

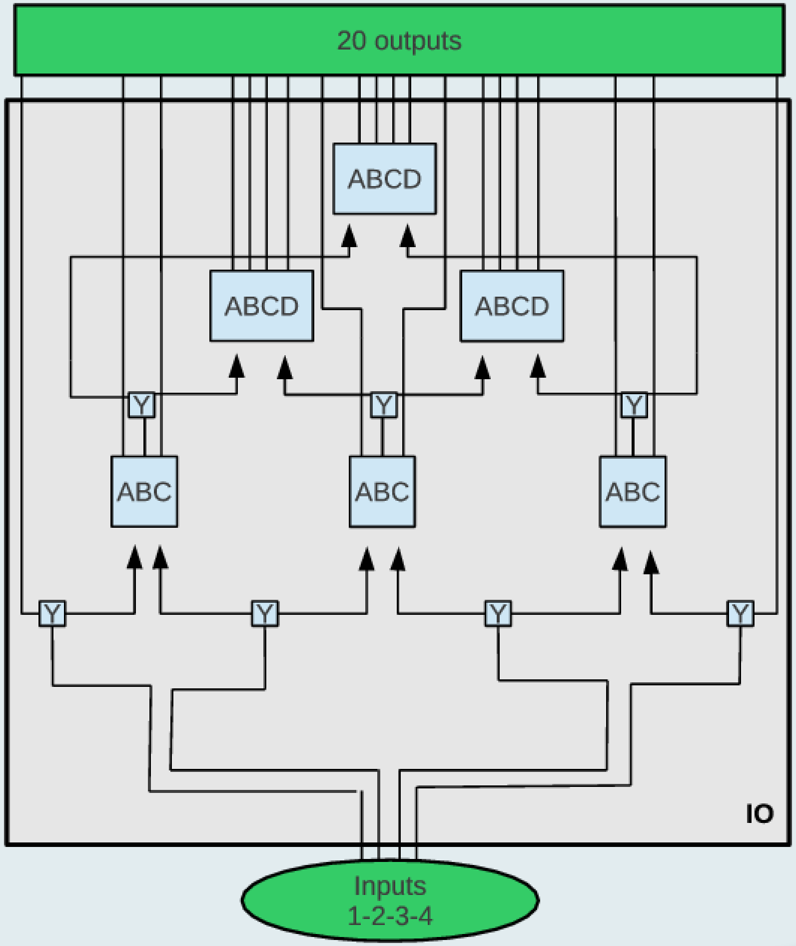

1
6
Nuller stage
π
1/2
5/6
C(12-56)
Closure
phase stage
C(12-34)
C(34-56)
π
2
5
3
π
3/4
4

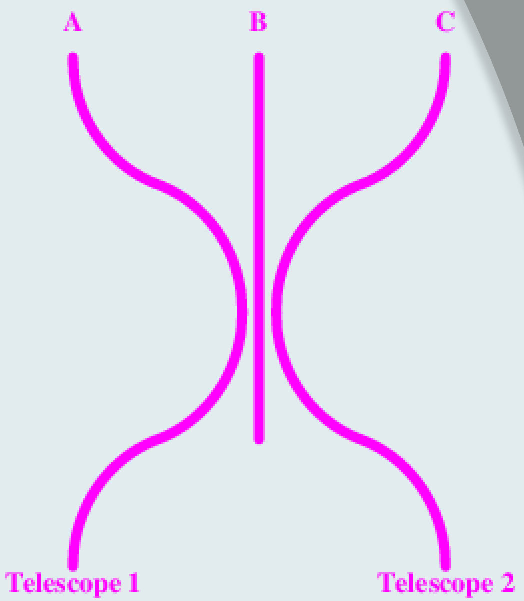
Nulling

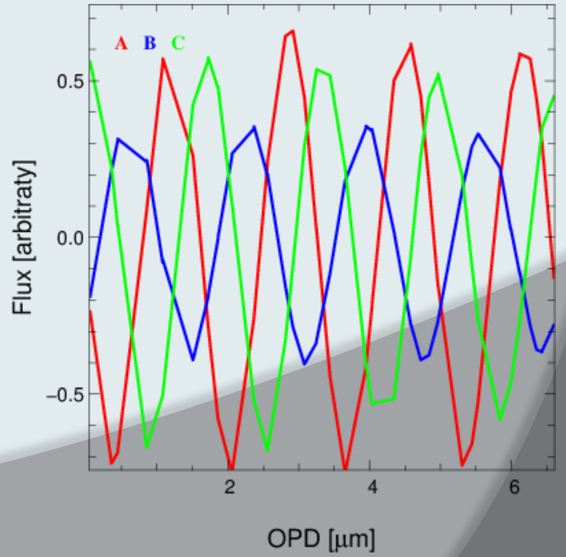

1
4
Nuller stage
1/2
3/4
C(12-34)
Closure
phase stage
C(12-23)
C(23-34)
2
2/3
3


20 outputs
ABCD
ABCD
ABCD
Y
Y
Y
ABC
ABC
ABC
Y
Y
Y
Y
IO
Inputs
1-2-3-4

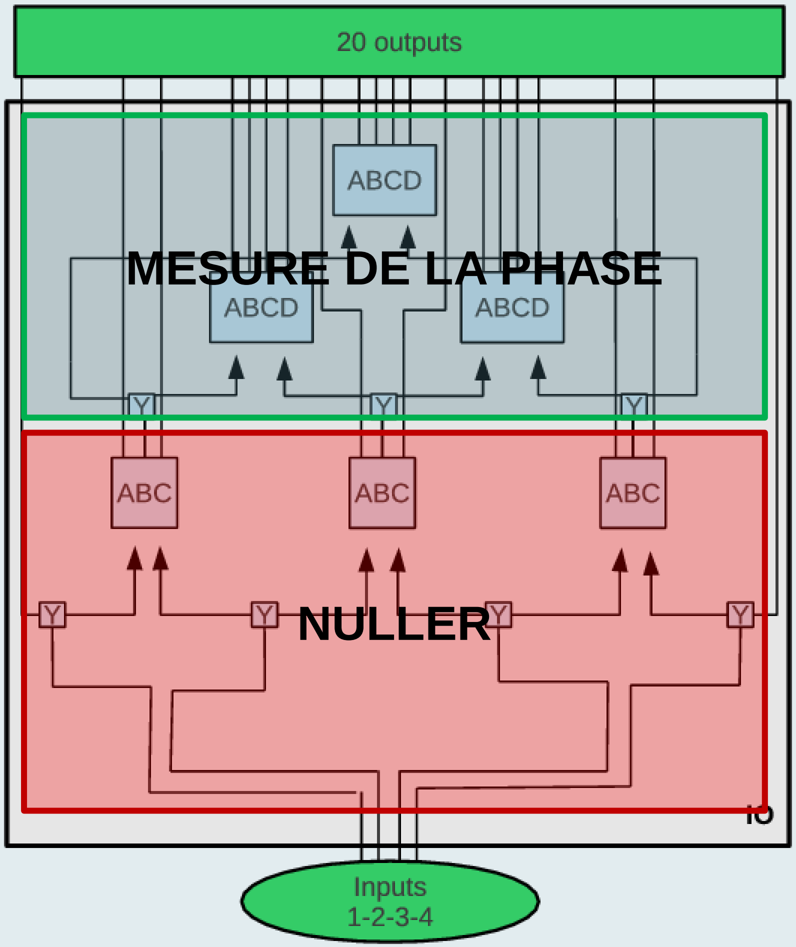
Nulling


20 outputs
ABCD
ABCD
ABCD
Y
Y
Y
ABC
ABC
ABC
Y
Y
Y
Y
IO
Inputs
1-2-3-4

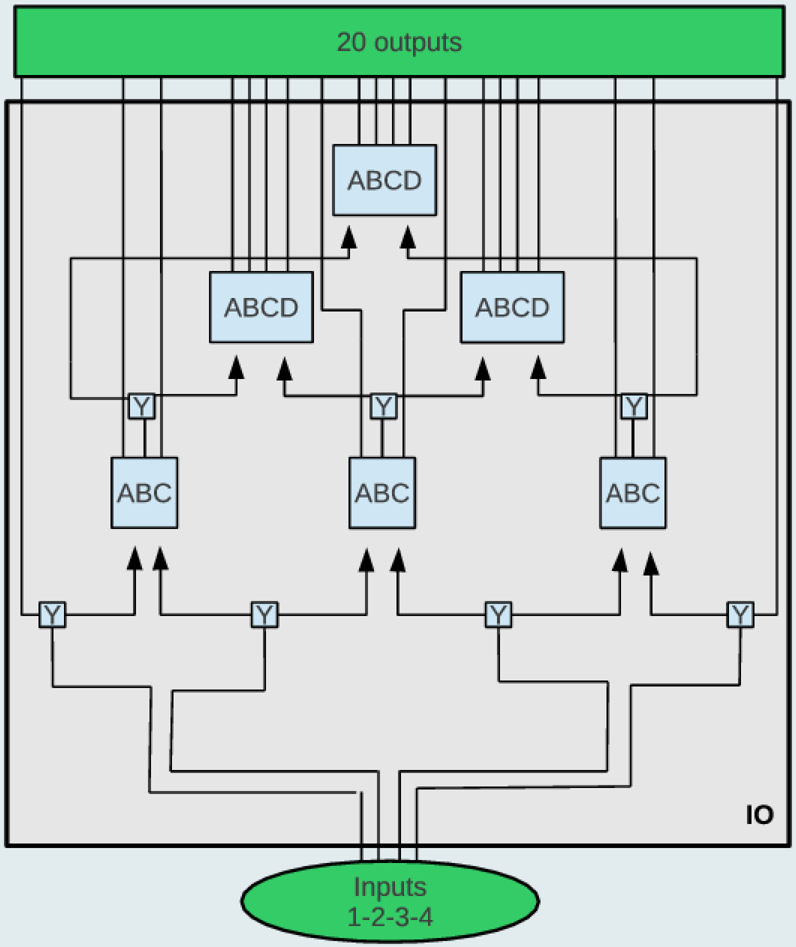

A
B
C
Telescope 1
Telescope 2

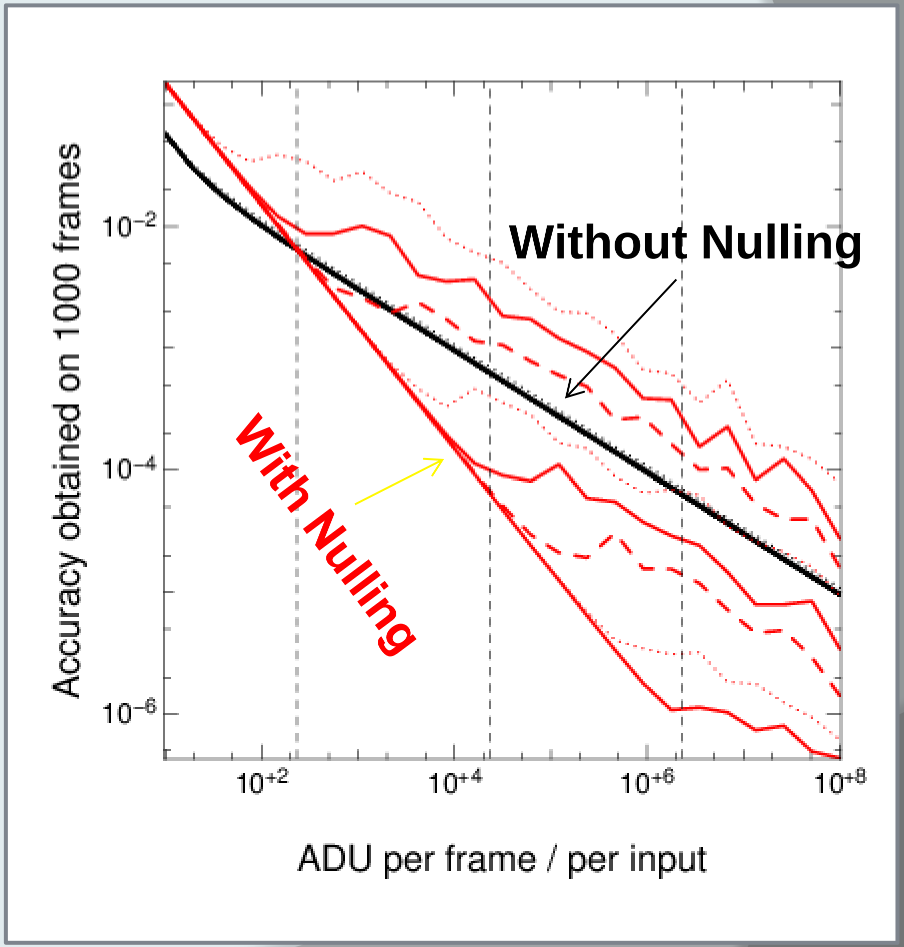

A B C
0.5
0.0
−0.5
Flux [arbitraty]
2
4
6
OPD [µm]

$$\begin{pmatrix} |S^1|^2 \\ \vdots \\ |S^K|^2 \end{pmatrix} = \Re \left[V2PM \cdot \begin{pmatrix} |E_1|^2 \\ \vdots \\ |E_N|^2 \\ E_1 E_2^* V_{1,2} \\ \vdots \\ E_{N-1} E_N^* V_{N-1,N} \end{pmatrix} \right]$$



$$\begin{pmatrix}
\frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{6} & \frac{1}{6} & 0 & 0 & \frac{1}{3}e^{i2\pi/3} & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{6} & \frac{1}{6} & 0 & 0 & \frac{1}{3}e^{-i2\pi/3} & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{48} & \frac{4}{48} & \frac{1}{48} & 0 & \frac{1}{24}+\frac{1}{24} & \frac{1}{24} & 0 & \frac{1}{24}+\frac{1}{24} & 0 & 0 \\
\frac{1}{48} & 0 & \frac{1}{48} & 0 & \frac{1}{24}+\frac{1}{24}e^{i\pi} & \frac{1}{24}e^{i\pi} & 0 & \frac{1}{24}+\frac{1}{24}e^{i\pi} & 0 & 0 \\
\frac{1}{48} & \frac{2}{48} & \frac{1}{48} & 0 & \frac{1}{24}+\frac{1}{24}e^{i\pi/2} & \frac{1}{24}e^{i\pi/2} & 0 & \frac{1}{24}+\frac{1}{24}e^{i\pi/2} & 0 & 0 \\
\frac{1}{48} & \frac{2}{48} & \frac{1}{48} & 0 & \frac{1}{24}+\frac{1}{24}e^{i3\pi/2} & \frac{1}{24}e^{i3\pi/2} & 0 & \frac{1}{24}+\frac{1}{24}e^{i3\pi/2} & 0 & 0 \\
0 & \frac{1}{6} & \frac{1}{6} & 0 & 0 & 0 & 0 & \frac{1}{3}e^{i2\pi/3} & 0 & 0 \\
\frac{1}{48} & \frac{1}{48} & \frac{1}{48} & \frac{1}{48} & \frac{1}{24} & \frac{1}{24} & \frac{1}{24} & \frac{1}{24} & \frac{1}{24} & \frac{1}{24} \\
\frac{1}{48} & \frac{1}{48} & \frac{1}{48} & \frac{1}{48} & \frac{1}{24} & \frac{1}{24}e^{i\pi} & \frac{1}{24}e^{i\pi} & \frac{1}{24}e^{i\pi} & \frac{1}{24}e^{i\pi} & \frac{1}{24} \\
\frac{1}{48} & \frac{1}{48} & \frac{1}{48} & \frac{1}{48} & \frac{1}{24} & \frac{1}{24}e^{i\pi/2} & \frac{1}{24}e^{i\pi/2} & \frac{1}{24}e^{i\pi/2} & \frac{1}{24}e^{i\pi/2} & \frac{1}{24} \\
\frac{1}{48} & \frac{1}{48} & \frac{1}{48} & \frac{1}{48} & \frac{1}{24} & \frac{1}{24}e^{i3\pi/2} & \frac{1}{24}e^{i3\pi/2} & \frac{1}{24}e^{i3\pi/2} & \frac{1}{24}e^{i3\pi/2} & \frac{1}{24} \\
0 & \frac{1}{6} & \frac{1}{6} & 0 & 0 & 0 & 0 & \frac{1}{3}e^{-i2\pi/3} & 0 & 0 \\
0 & \frac{1}{48} & \frac{4}{48} & \frac{1}{48} & 0 & 0 & 0 & \frac{1}{24}+\frac{1}{24} & \frac{1}{24} & \frac{1}{24}+\frac{1}{24} \\
0 & \frac{1}{48} & 0 & \frac{1}{48} & 0 & 0 & 0 & \frac{1}{24}+\frac{1}{24}e^{i\pi} & \frac{1}{24}e^{i\pi} & \frac{1}{24}+\frac{1}{24}e^{i\pi} \\
0 & \frac{1}{48} & \frac{2}{48} & \frac{1}{48} & 0 & 0 & 0 & \frac{1}{24}+\frac{1}{24}e^{i\pi/2} & \frac{1}{24}e^{i\pi/2} & \frac{1}{24}+\frac{1}{24}e^{i\pi/2} \\
0 & \frac{1}{48} & \frac{2}{48} & \frac{1}{48} & 0 & 0 & 0 & \frac{1}{24}+\frac{1}{24}e^{i3\pi/2} & \frac{1}{24}e^{i3\pi/2} & \frac{1}{24}+\frac{1}{24}e^{i3\pi/2} \\
0 & 0 & \frac{1}{6} & \frac{1}{6} & 0 & 0 & 0 & 0 & 0 & \frac{1}{3}e^{i2\pi/3} \\
0 & 0 & \frac{1}{6} & \frac{1}{6} & 0 & 0 & 0 & 0 & 0 & \frac{1}{3}e^{-i2\pi/3} \\
0 & 0 & 0 & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}$$





Lacour et al. (Astro-ph for now)

CONCLUSION

- Pupil masking allows high precision measurement. But be careful of « over-interpretation ».
- Astrophotonics can push the idea one step further, by discretization of the OTF
- But photon noise is still a primordial issue