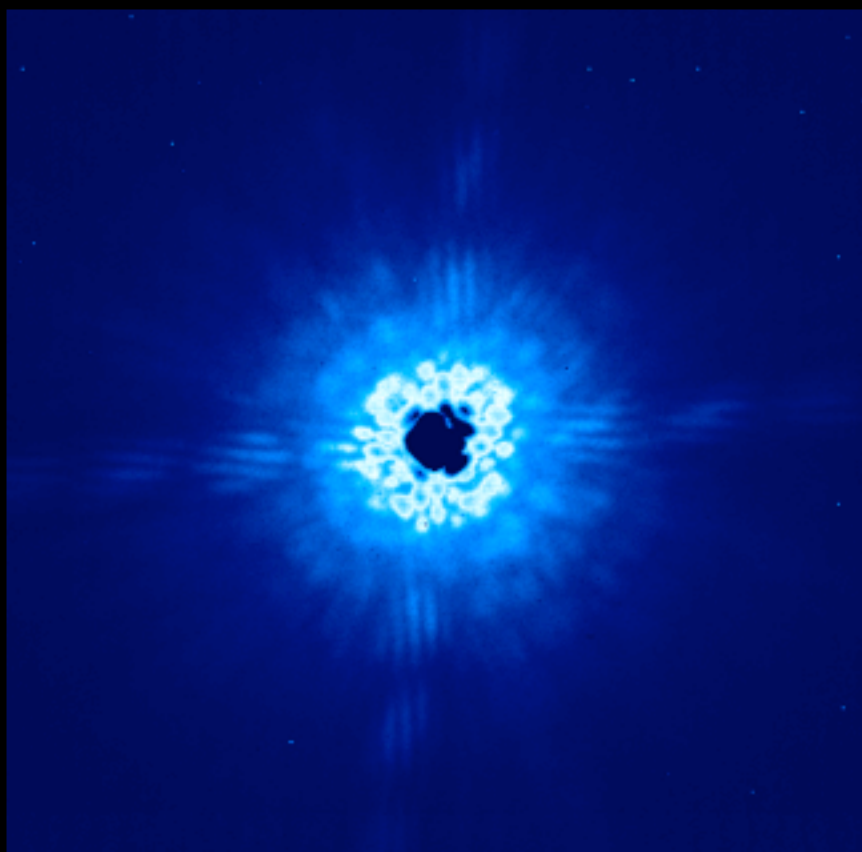
Behind the coronagraphic mask



A new approach to look for companions in the so-called "super resolution" regime

Not about instrumentation, but about data processing

Frantz Martinache
CEAO Research Fellow
Subaru Telescope

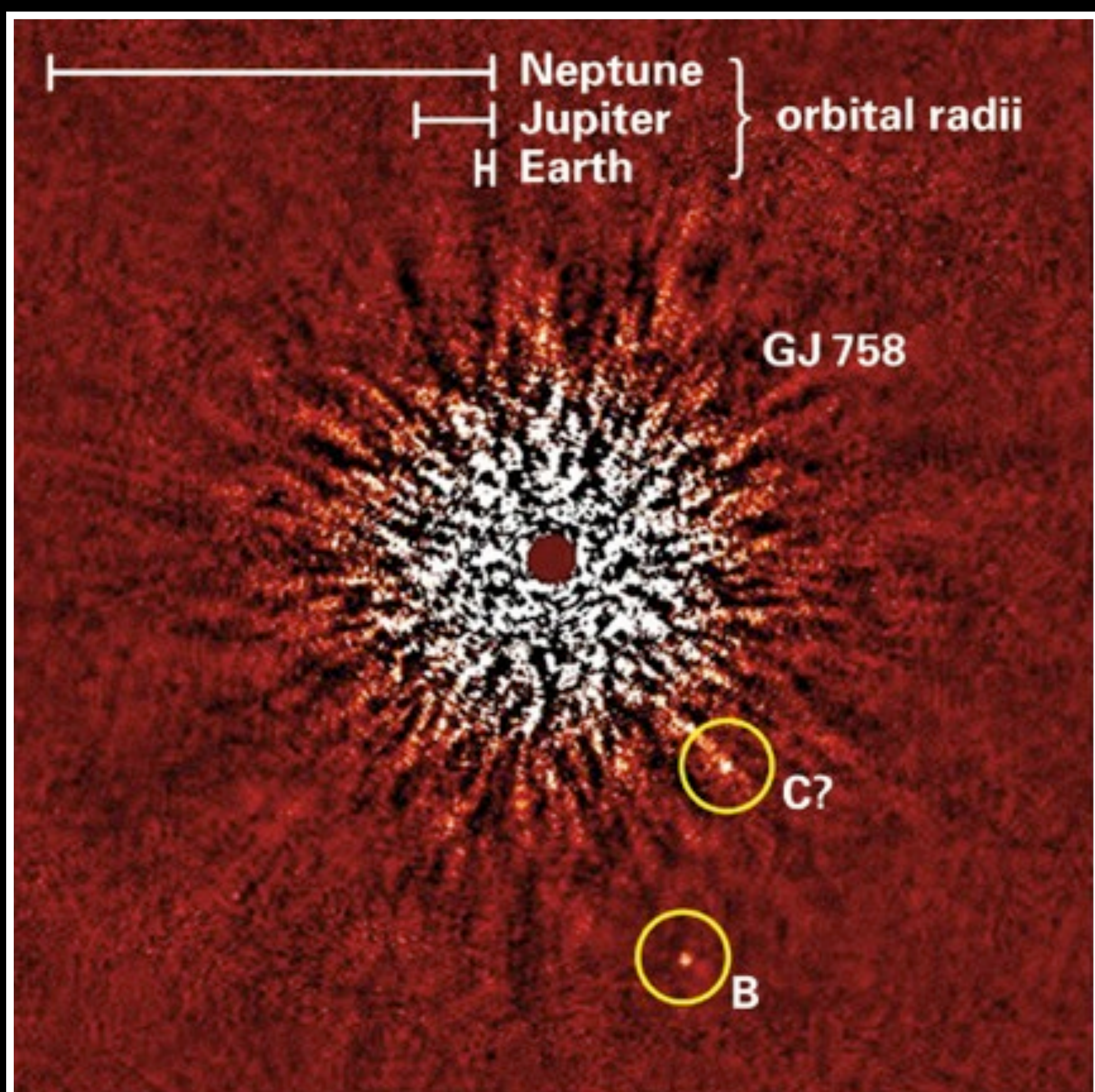
Paris, 10/10/29, Spirit of Lyot 2010

Take care of an ill-posed problem

$I = O \otimes PSF$

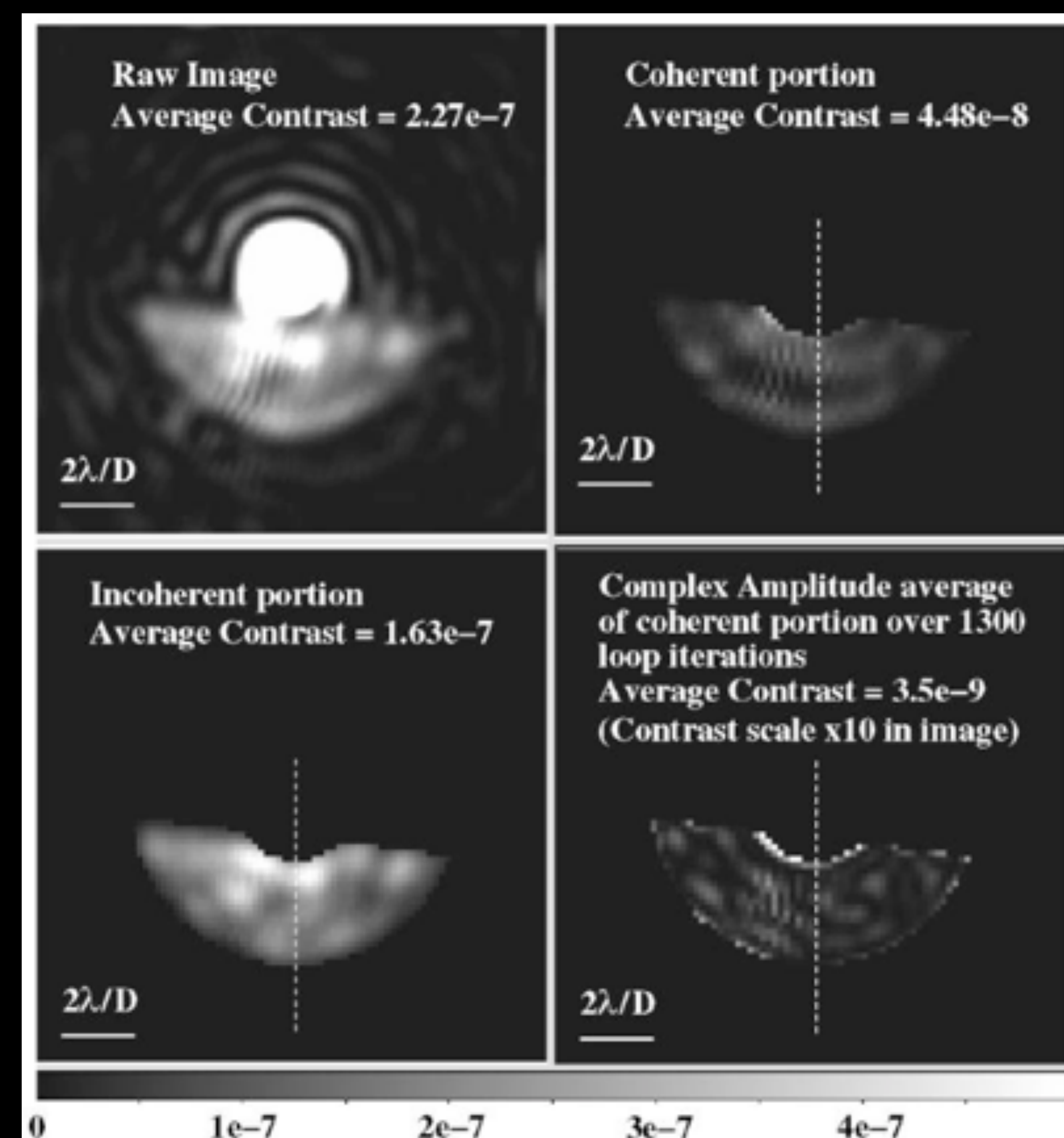
Eliminate the PSF out of the equation

the ADI way...



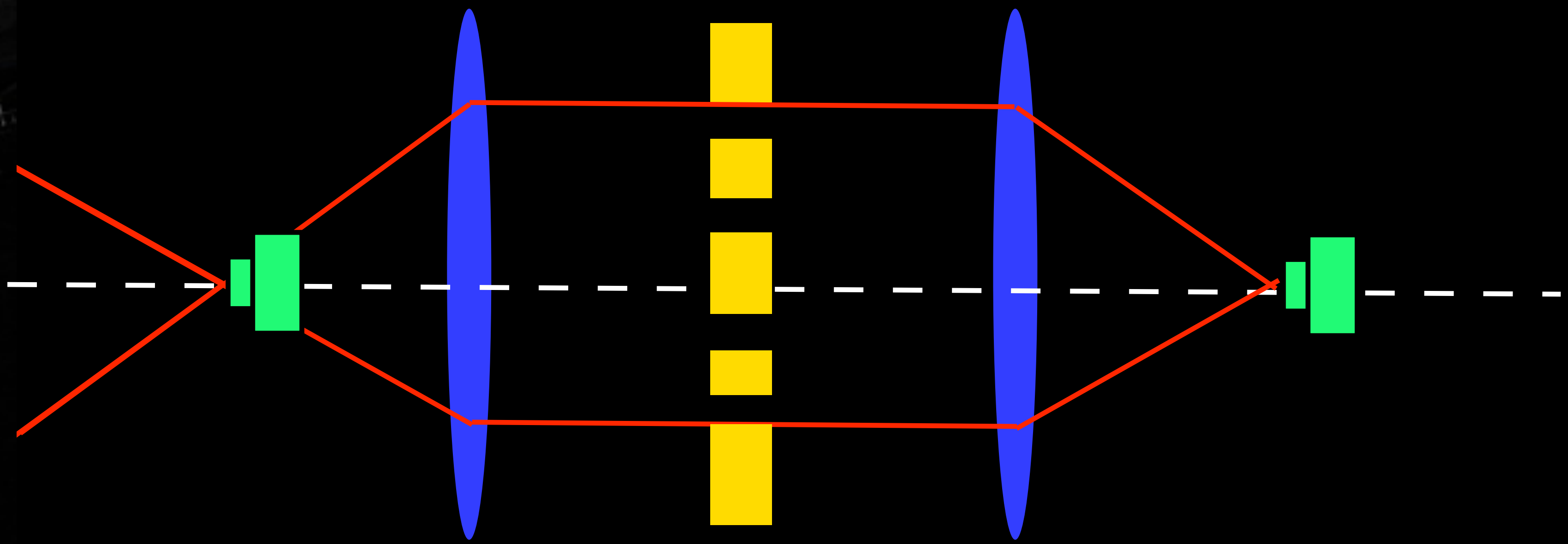
Thalman et al, 2009, ApJ, 707, 123

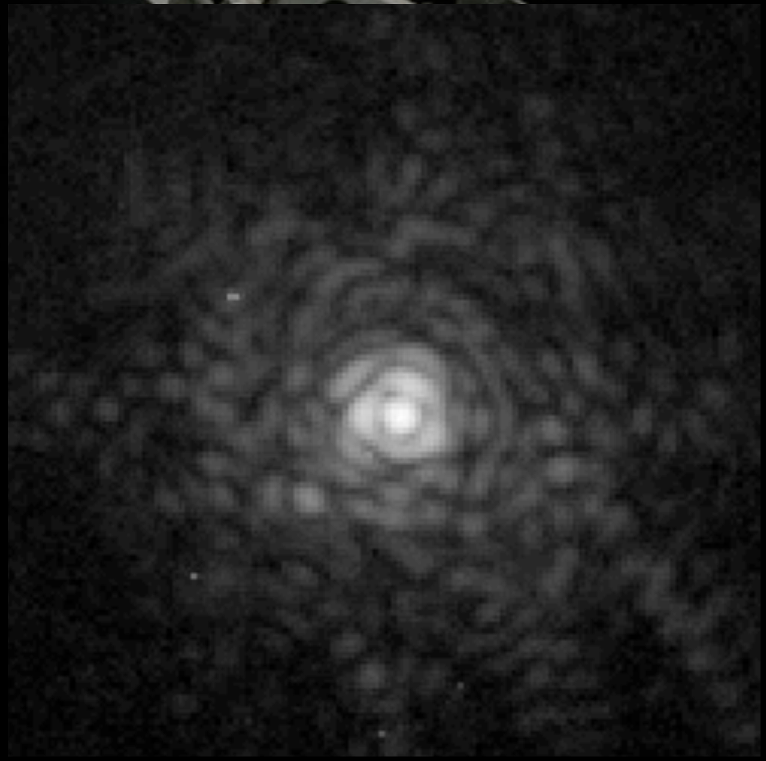
the exAO way...

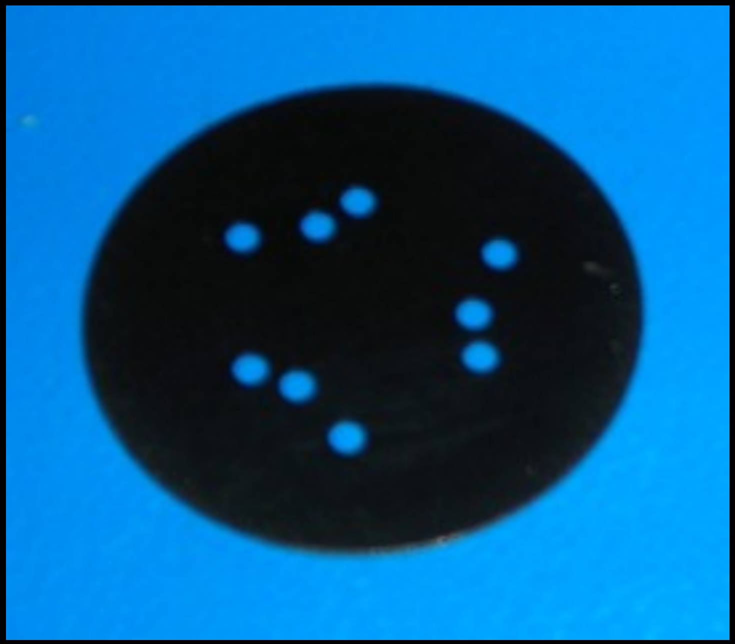


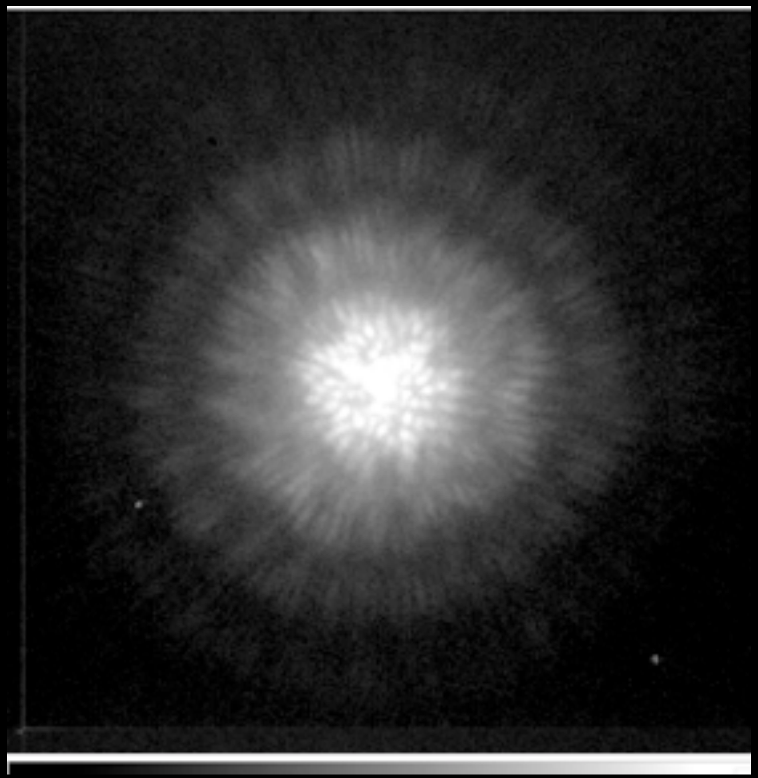
Guyon et al, 2009, PASP, 122, 71

... or use interferometry!

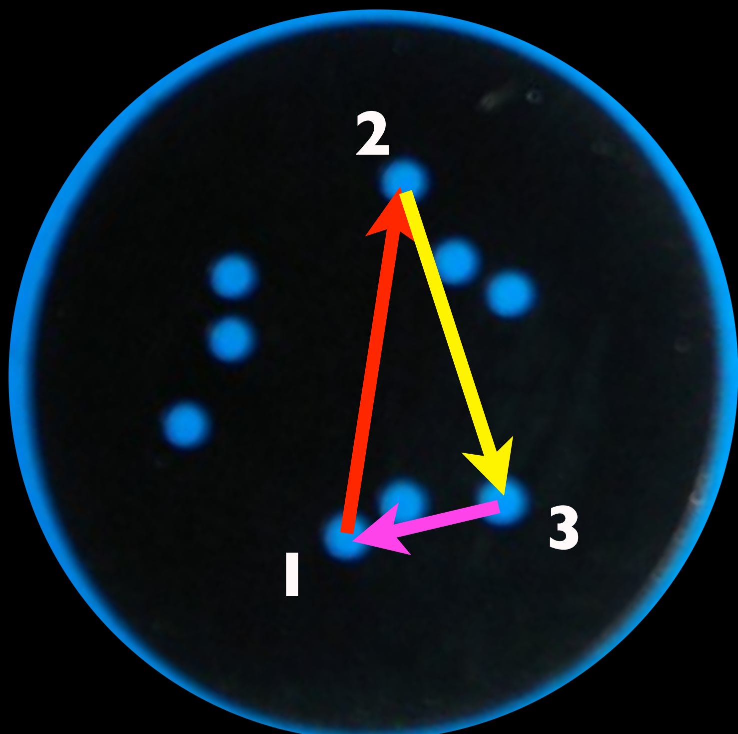


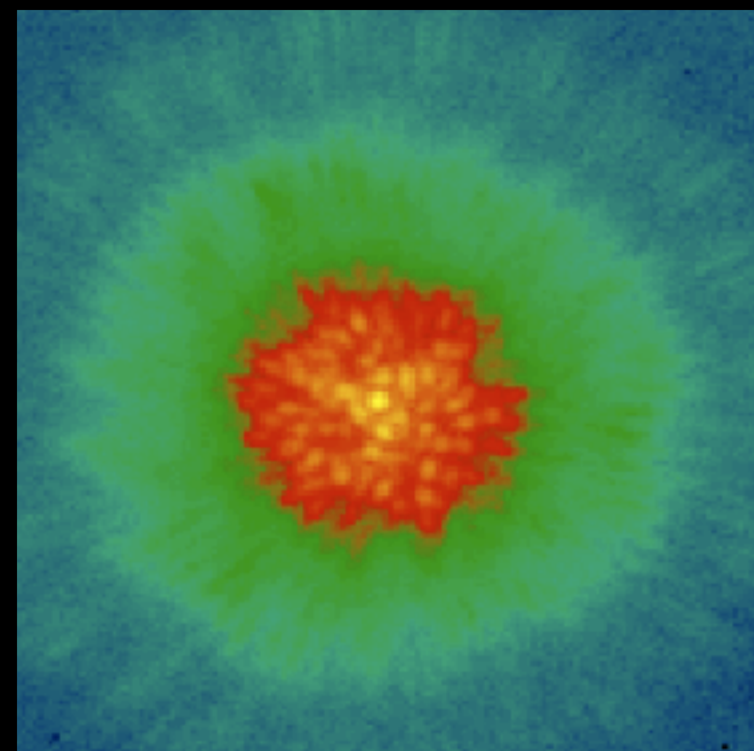


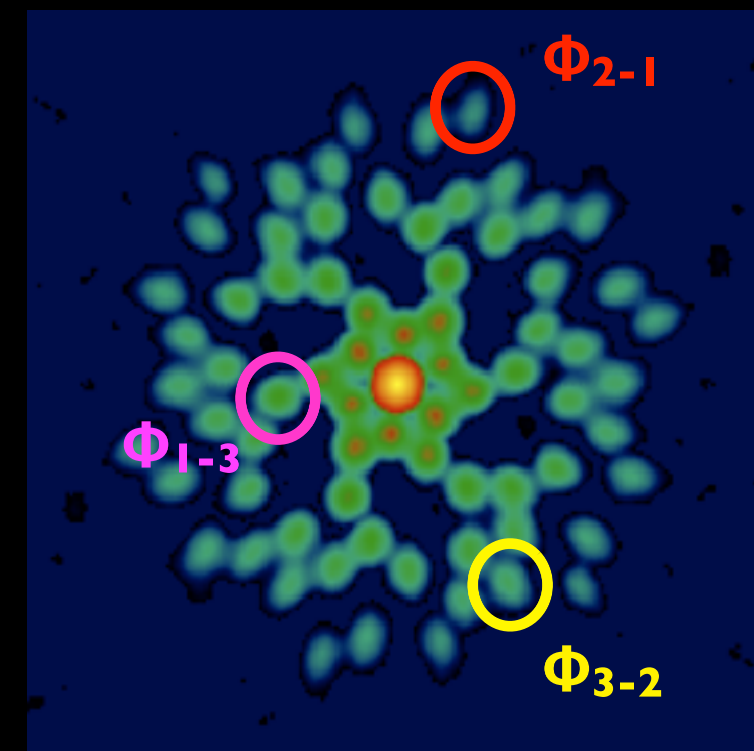




Interferometry produces good observable quantities







$$\Phi(2\text{-}1) = \Phi(2\text{-}1)_0 + (\varphi_2 - \varphi_1)$$

$$\Sigma \quad \Phi(3\text{-}2) = \Phi(3\text{-}2)_0 + (\varphi_3 - \varphi_2)$$

$$\Phi(1\text{-}3) = \Phi(1\text{-}3)_0 + (\varphi_1 - \varphi_3)$$

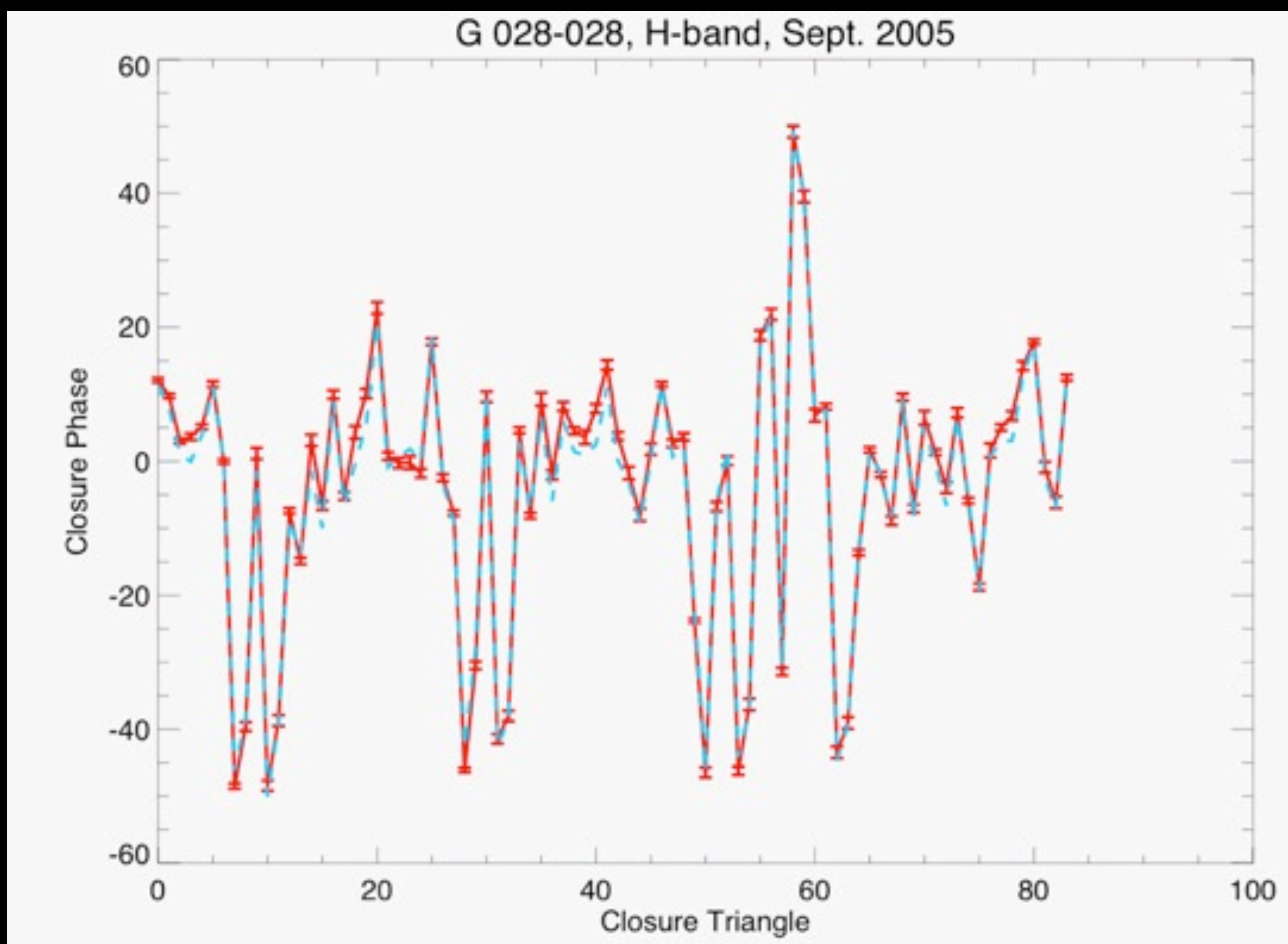
measured = intrinsic + atmospheric

Not about producing the best image possible, but about extracting observable quantities (**closure-phase**) that do not depend on phase residuals

Jennison, R. C. 1958, MNRAS, 118, 276

Ditch these dirty images, keep clean information only!

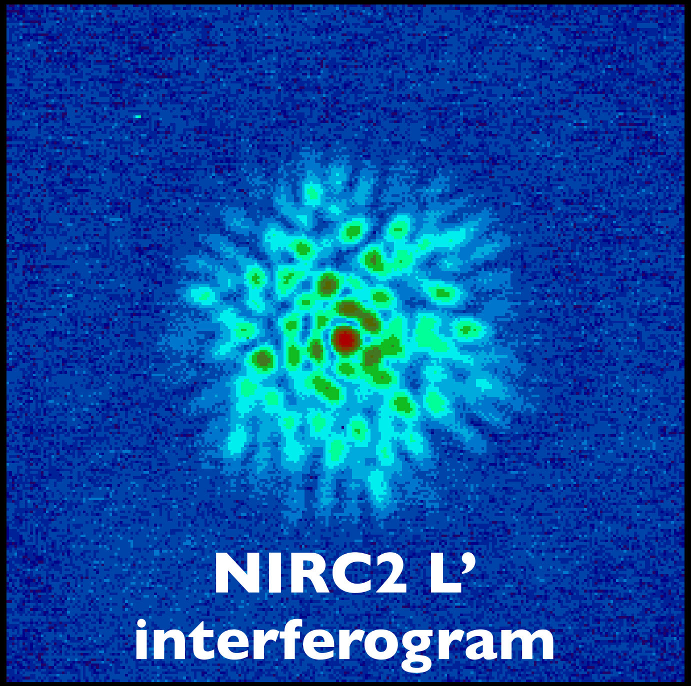
The best "picture" you can give of one or more companions around a star is a series of astrometric data: separation, PA, contrast with associated uncertainties

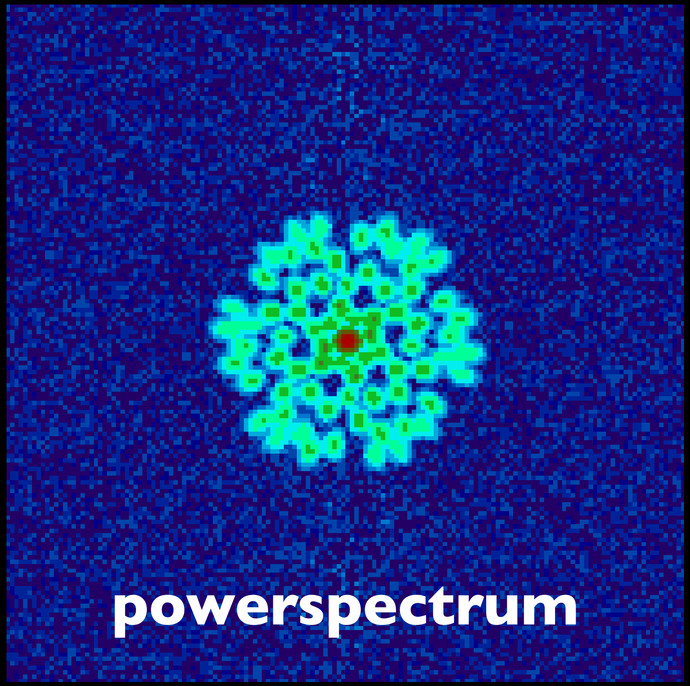


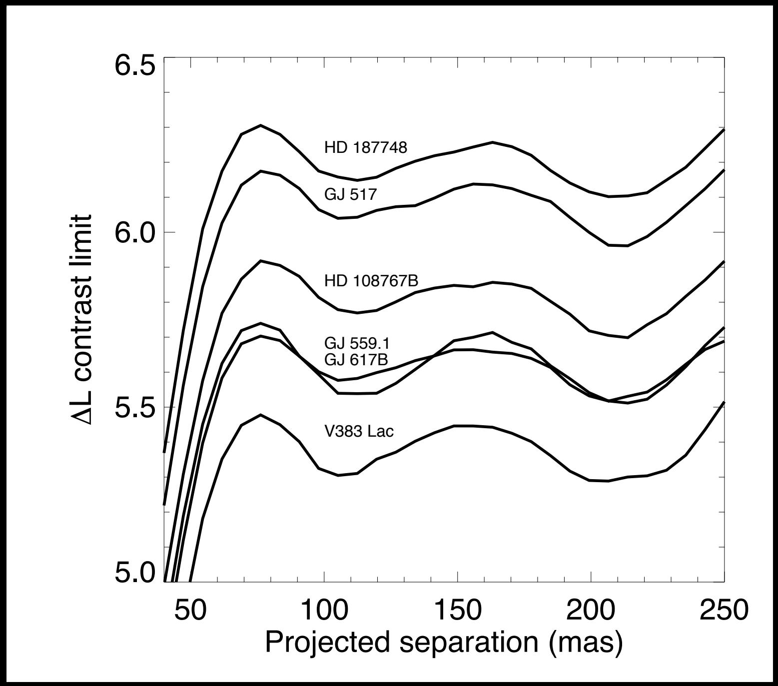
Example of Palomar closure-phase data

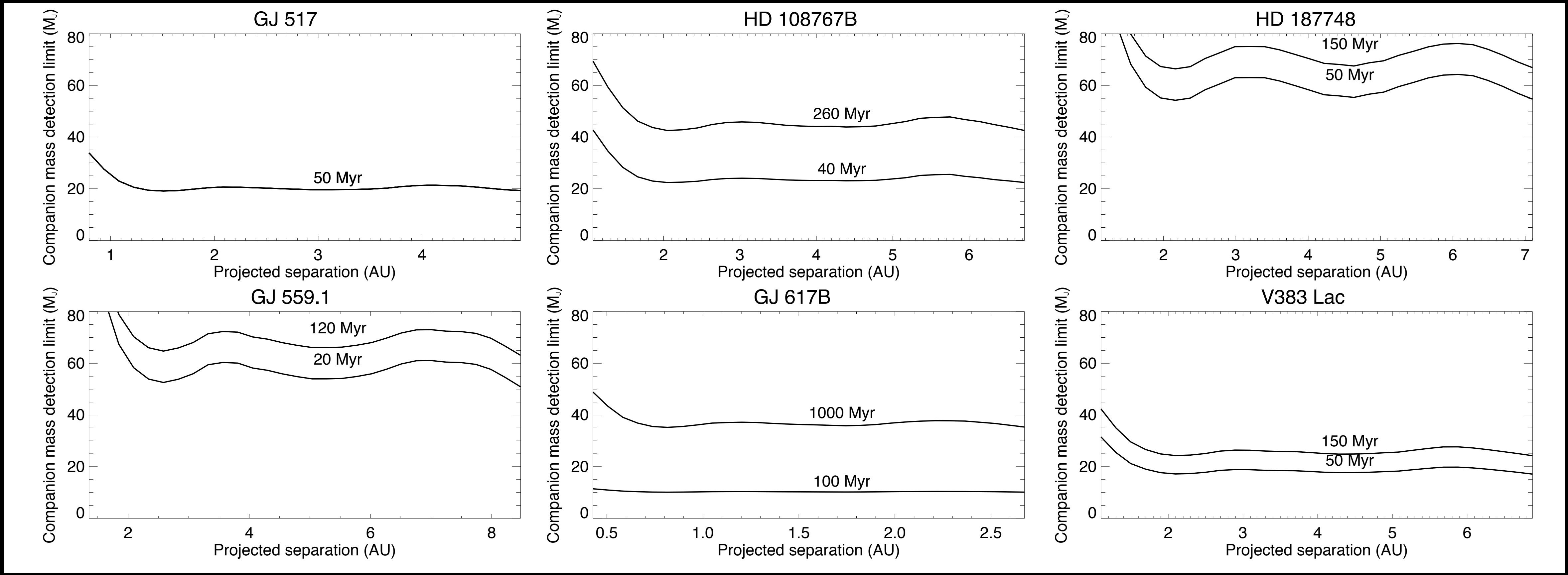
40 % strehl
0.3 deg scatter
stability ~ λ/1000
all passive !

A new regime of angular separations





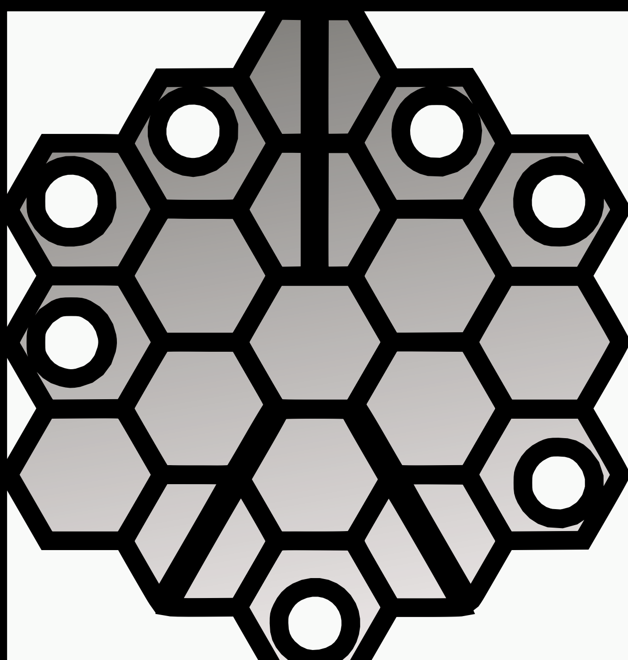


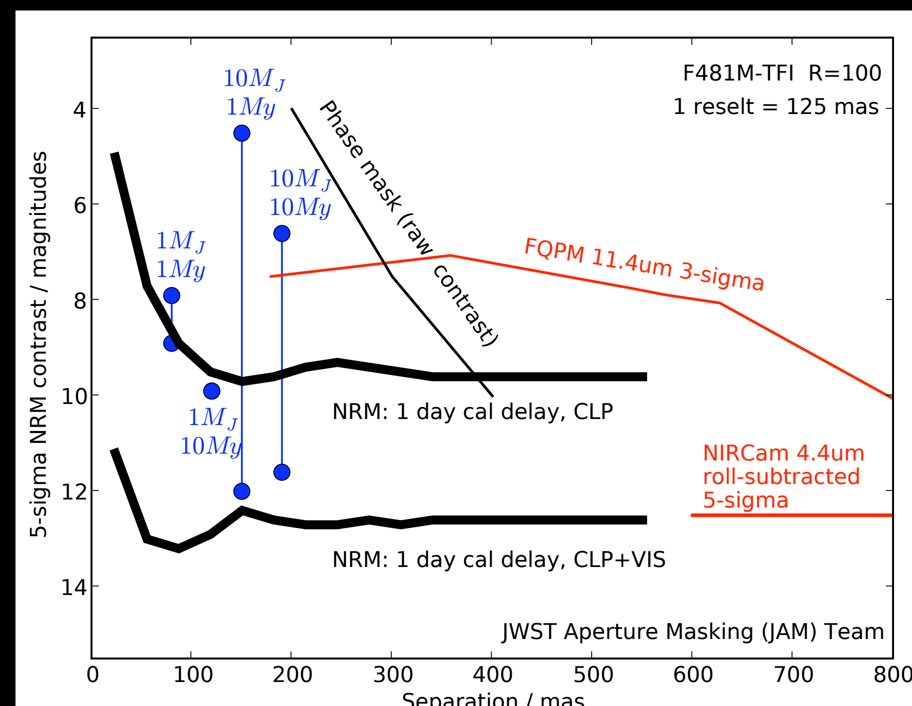


Martinache et al, in prep

Strengths and limitations of NRM

Self-calibration properties of closure phase make NRM "bullet-proof"



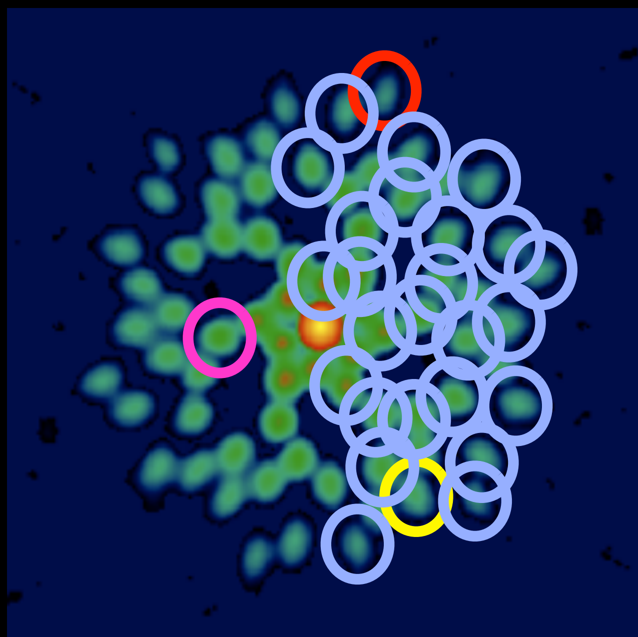


NRM onboard JWST in the TGS-TFI.
If anything goes wrong with the primary, this might be the only instrument that will still work

Sivaramakrishnan et al, Astro2010T, 40

But: it requires a non-redundant pupil.
Is there anything comparable we could do without masking at all?

A more "general" formalism



$$\begin{bmatrix} \Phi \end{bmatrix} = \begin{bmatrix} \Phi_0 \end{bmatrix} + \begin{bmatrix} A \end{bmatrix} \times \begin{bmatrix} \varphi \end{bmatrix}$$

measured Fourier phase | "true" Fourier phase | transfer matrix | pupil phase errors

$\Phi(2\text{-}1) = \Phi(2\text{-}1)_0 + (\varphi_2 - \varphi_1)$

$\Phi(3\text{-}2) = \Phi(3\text{-}2)_0 + (\varphi_3 - \varphi_2)$

$\Phi(1\text{-}3) = \Phi(1\text{-}3)_0 + (\varphi_1 - \varphi_3)$

... ...

$\Phi(k\text{-}l) = \Phi(k\text{-}l)_0 + (\varphi_k - \varphi_l)$

... ...

Matrix form anyone?

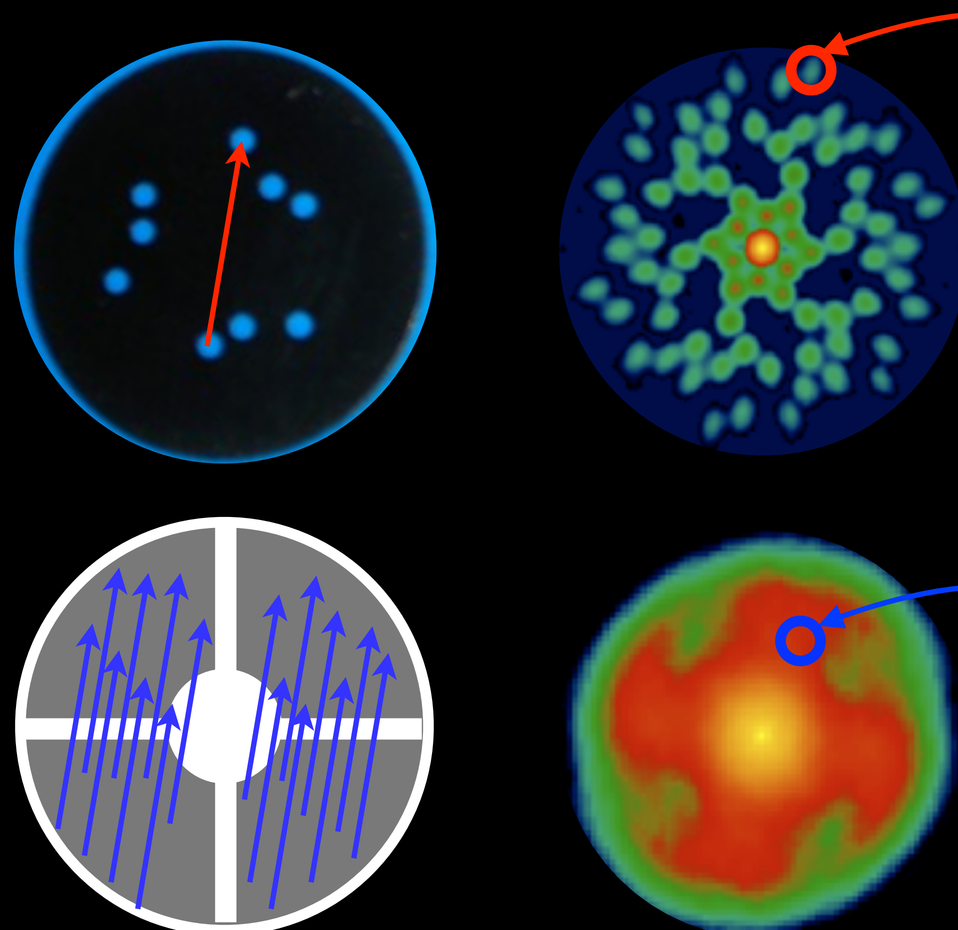
For a non-redundant array:
The transfer matrix is essentially filled with zeroes
Except: per line, one +1, one -1

Closure phase relations are *one example* of a left-hand operator **K**, so that **K**x**A** produces rows of zeros.

Redundant scenarios

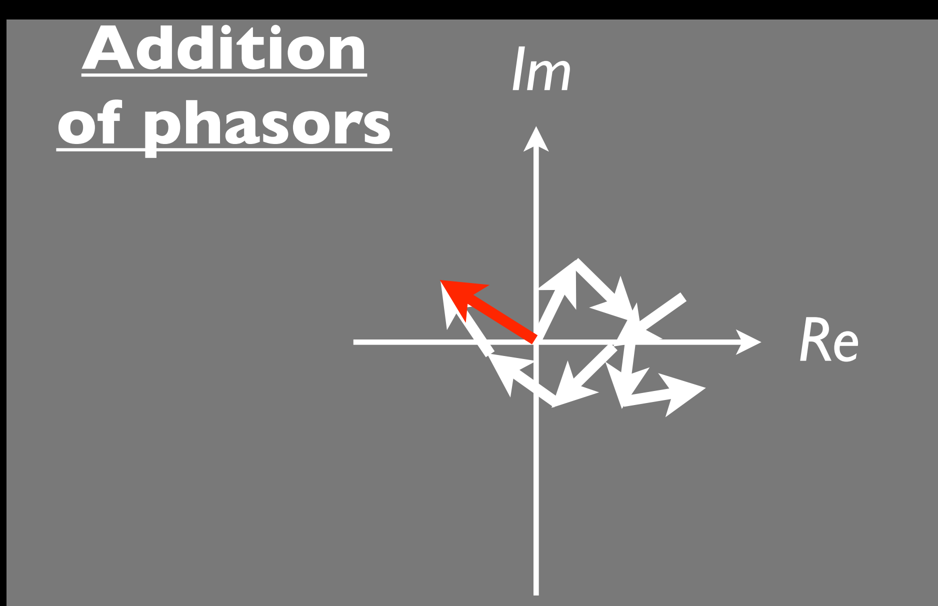
non-redundant

full aperture



$\Phi = \Phi_0 + 1\ \Delta\varphi$

$\Phi = \Phi_0 + \mathrm{Arg}(e^{j\Sigma_i\ \Delta\varphi_i})$

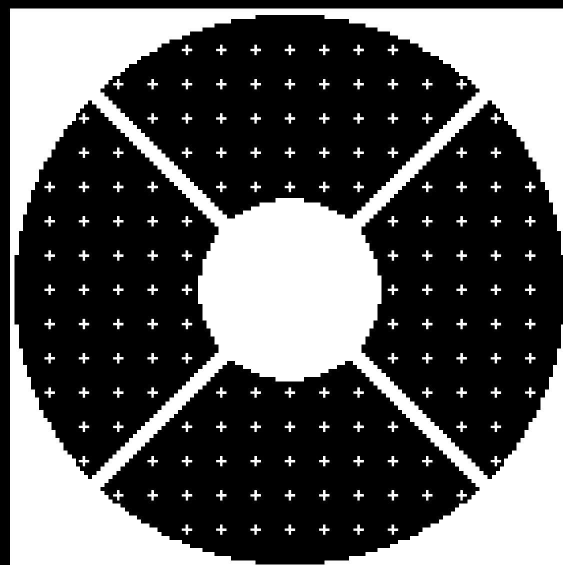


BUT: with a reasonably well corrected aperture, this complicated (non sortable) expression can be linearized, and becomes:

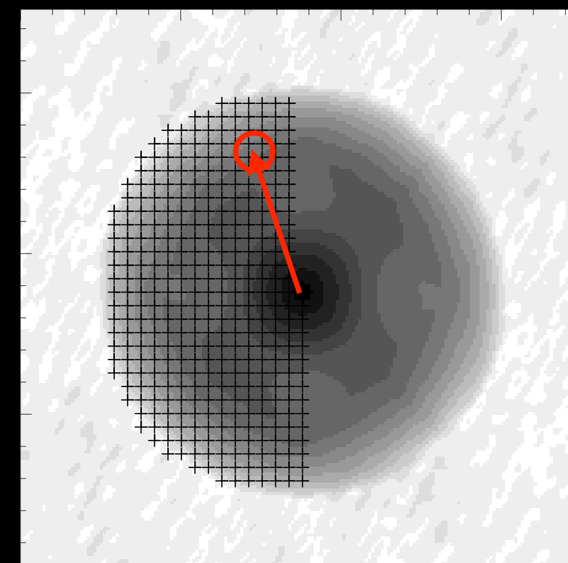
$$\Phi = \Phi_0 + \Sigma_i\ \Delta\varphi_i$$

Our linear model still holds... just need a slightly more filled transfer matrix.

Determine the HST transfer matrix



discretize the HST pupil



corresponding UV coverage

Count the baselines contributing to each UV point and fill up a line of **A** with -1, 0, 1

A =

… … … … … … … … …
… … … … … … … … …
… … … … … … … … …

… 0 +1 -1 … 0 -1 …

… … … … … … … … …
… … … … … … … … …
… … … … … … … … …

In this example, **A** is a rectangular 155 x 366 matrix, manageable on a netbook

Kernel-phase

Idea: construct a new operator **K** so that **K**x**A** = 0, but how?
By hand? Painful, but manageable if not too big...
Or use a tool more versatile: Singular Value Decomposition (SVD)

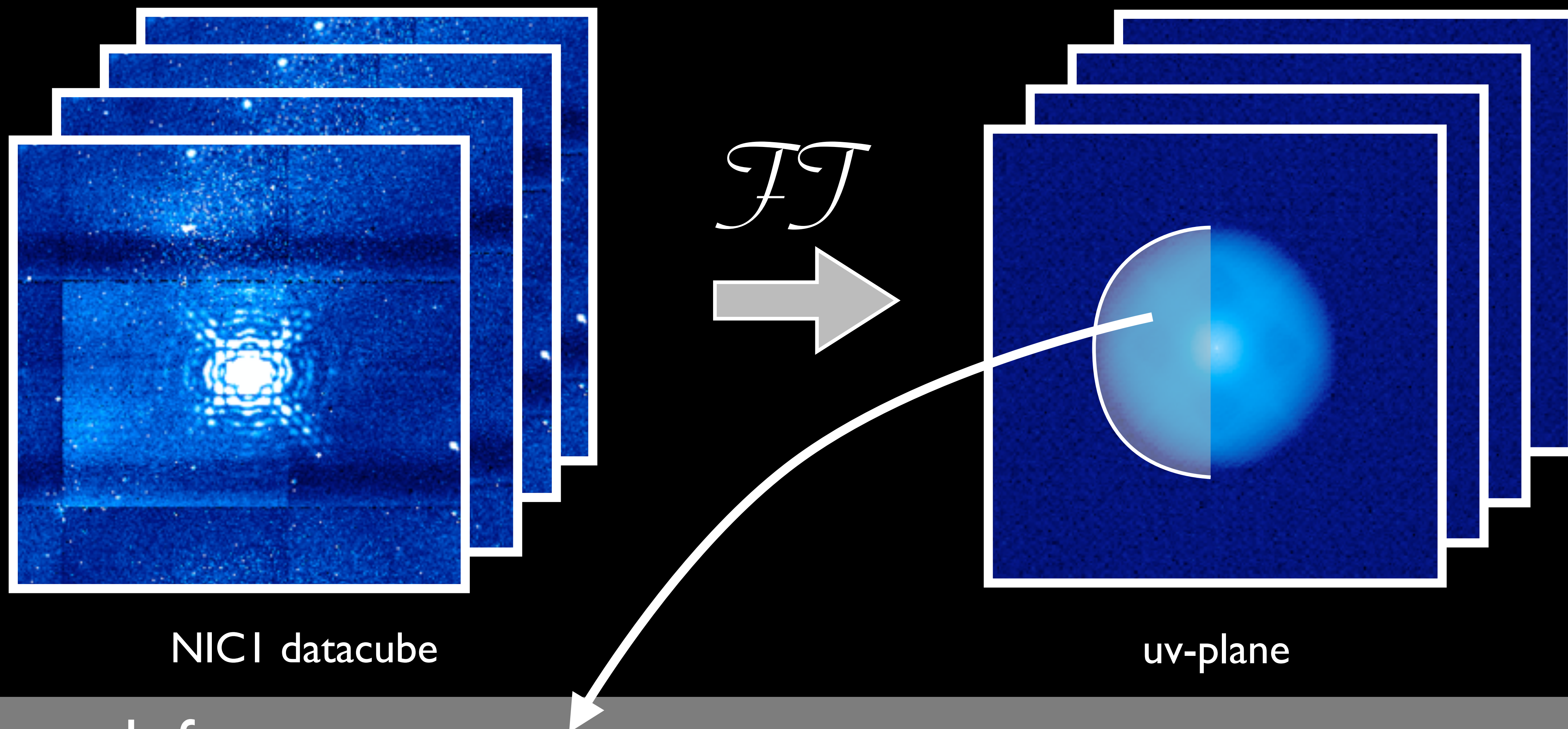
Rows of **K** form a basis for the left null space of **A**

The SVD of $\mathbf{A}^T = \mathbf{U} \times \mathbf{W} \times \mathbf{V}^T$ gives it all: the columns of **V** that correspond to zero singular values (Wi = 0) do the trick

These new closure-phase relations are called Ker-phases

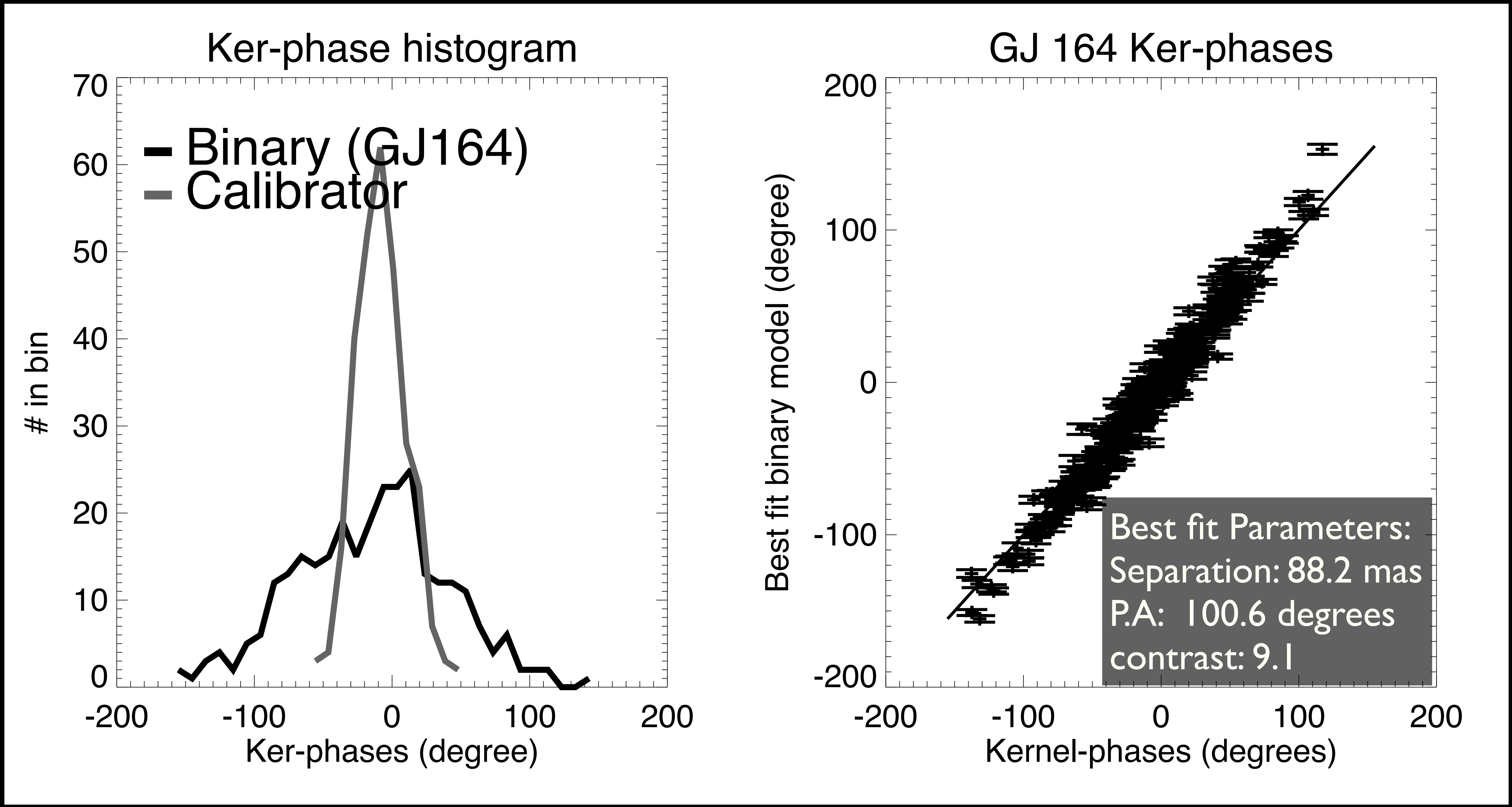
Martinache, 2010, arXiv 1009.3933

Data reduction



For each frame:
Read the Fourier-phase information
Assemble into Ker-phases using the relations identified earlier...
Then:
do some statistics (frame-to-frame variability), propagate errors
... and you're done!

NICMOS 1 data analysis

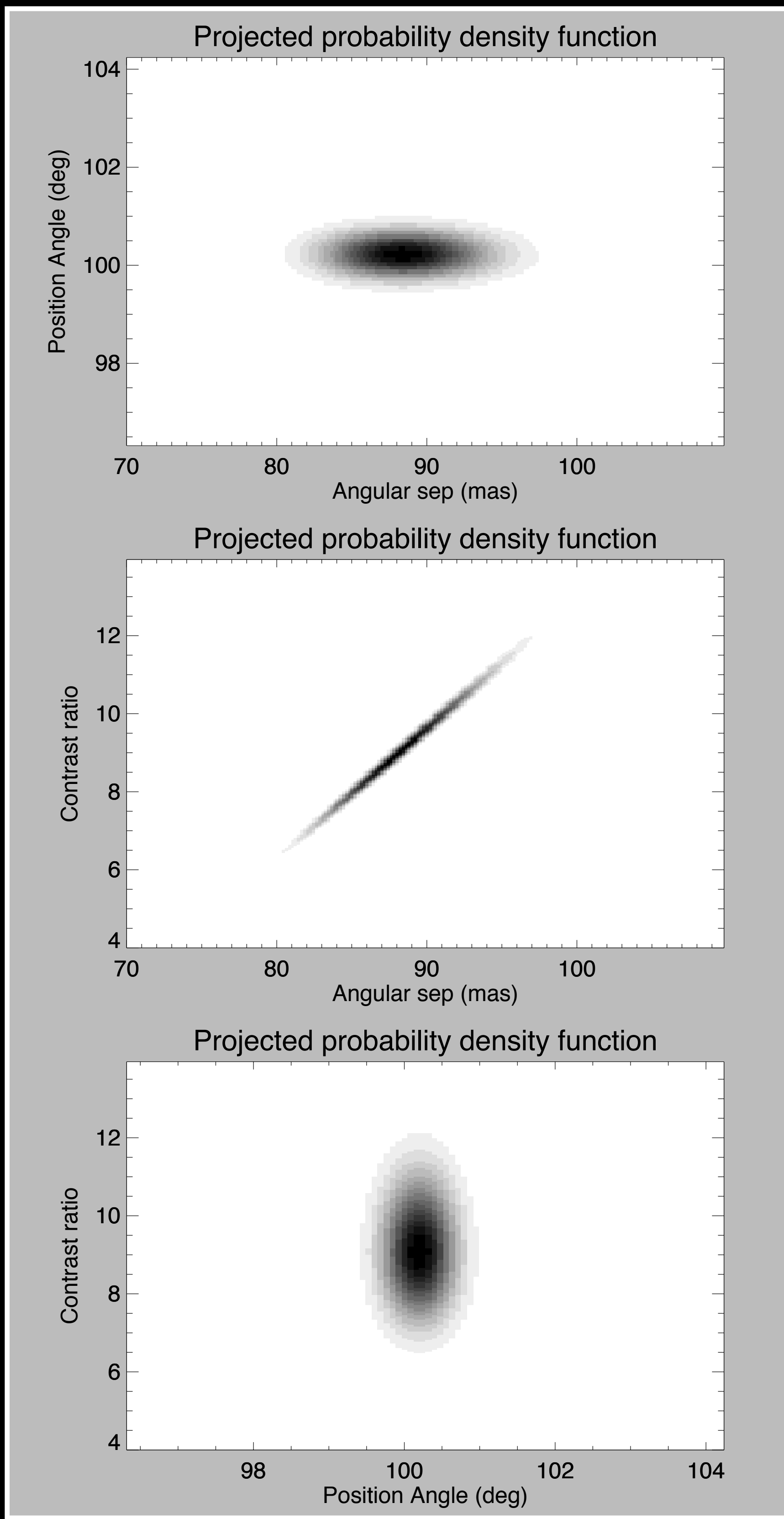


- 4 frame dataset on SAO 179809 (1998)
- 8 frame dataset on GJ 164 (2004)

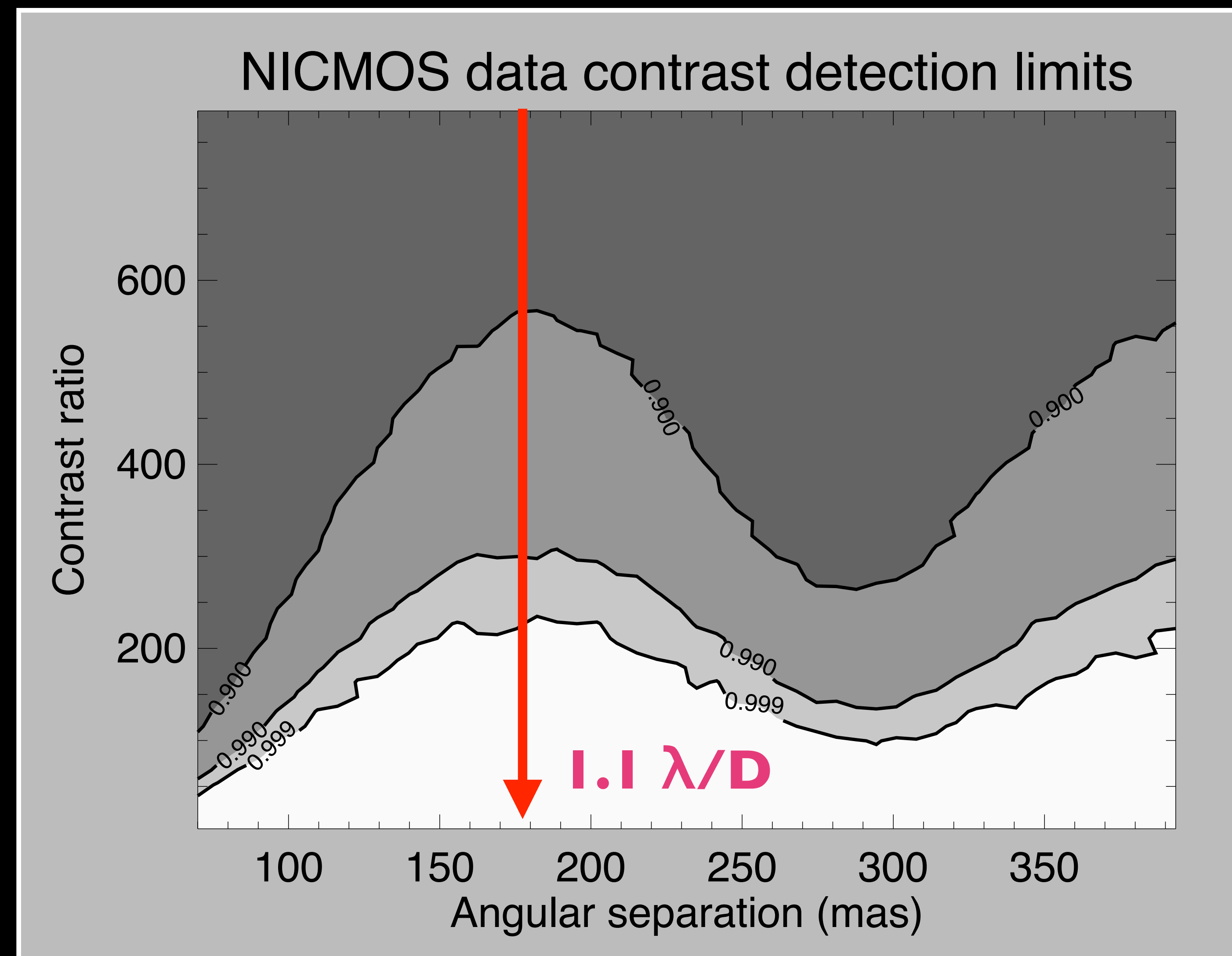
Martinache, 2010, arXiv 1009.3933

Performance of the approach

Detection



Detection limits

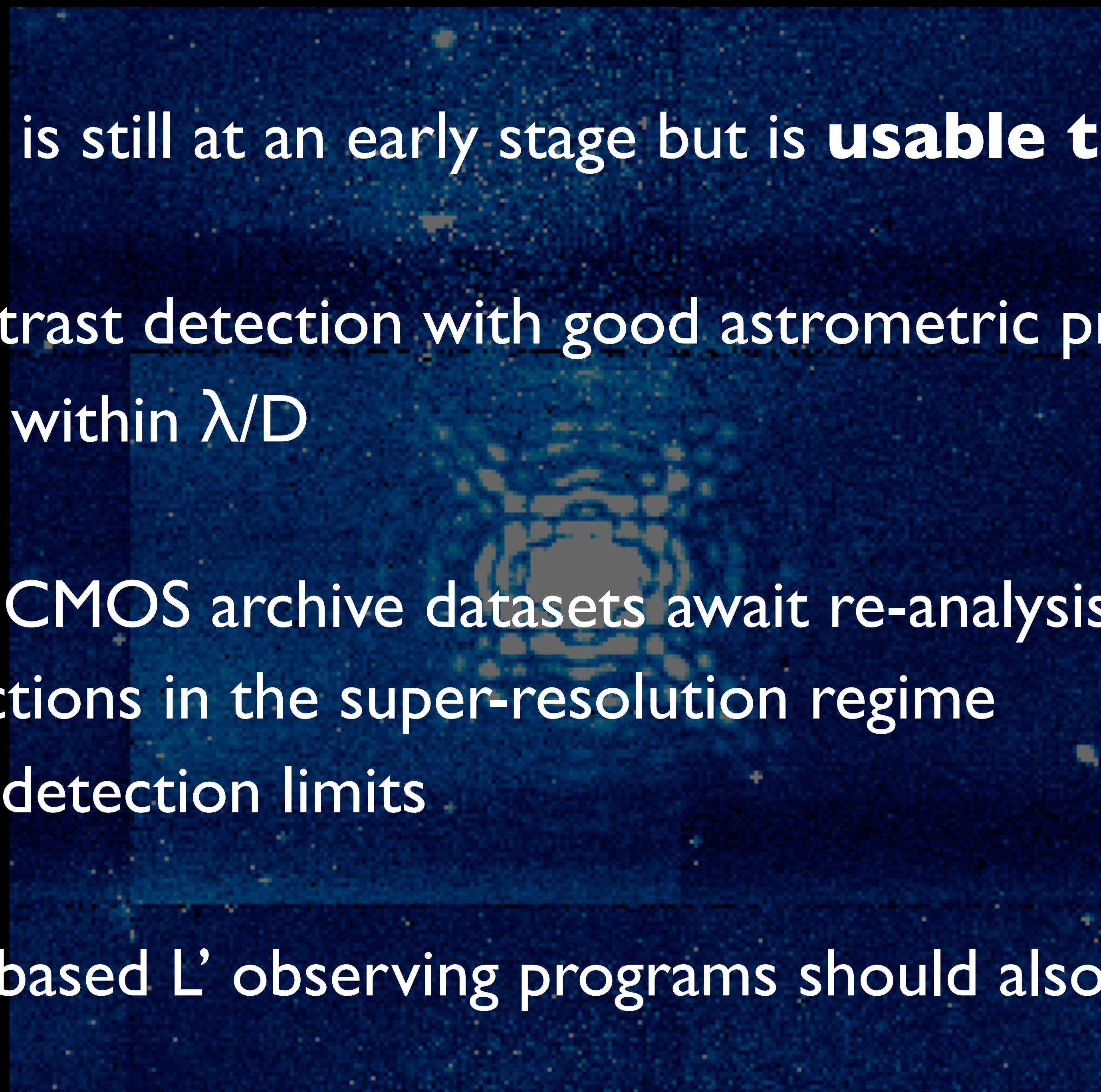


Limits based on MC simulations
from errors measured on a dataset acquired on a single star.

Parameters:
Separation: 88.2 +/- 3 mas
P.A: 100.6 +/- 0.3 degree
contrast: 9.1 +/- 1.2

Martinache, 2010, arXiv 1009.3933

Concluding remarks



The technique is still at an early stage but is **usable today**

Moderate contrast detection with good astrometric precision was demonstrated within λ/D

- dozens of NICMOS archive datasets await re-analysis:
  > new detections in the super-resolution regime
  > improved detection limits

- new ground based L’ observing programs should also benefit this