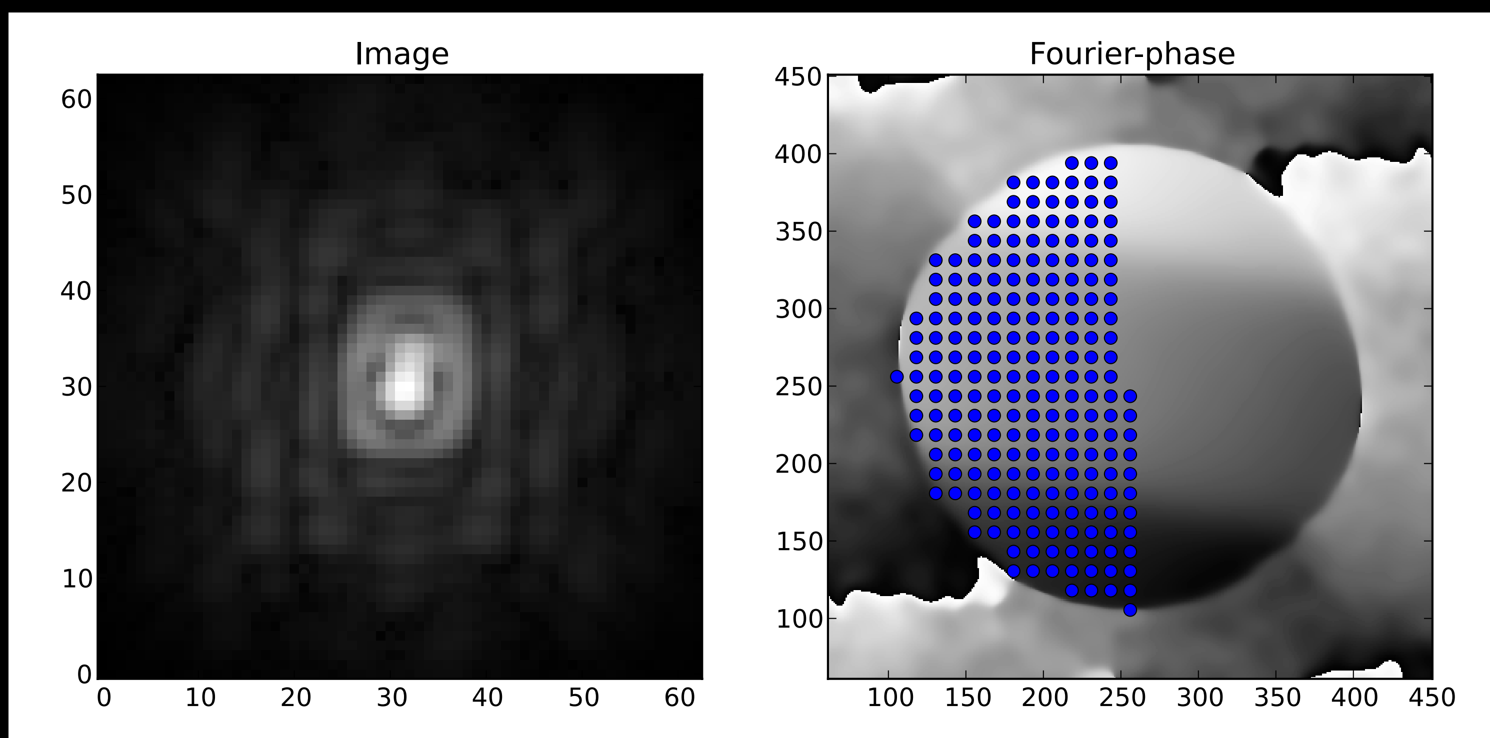
Kernel-phase for interferometry with a rich aperture



$$I = O \otimes PSF$$

At high Strehl

$$\Phi = \Phi_0 + A.\varphi$$

Observatoire de la CÔTE d'AZUR

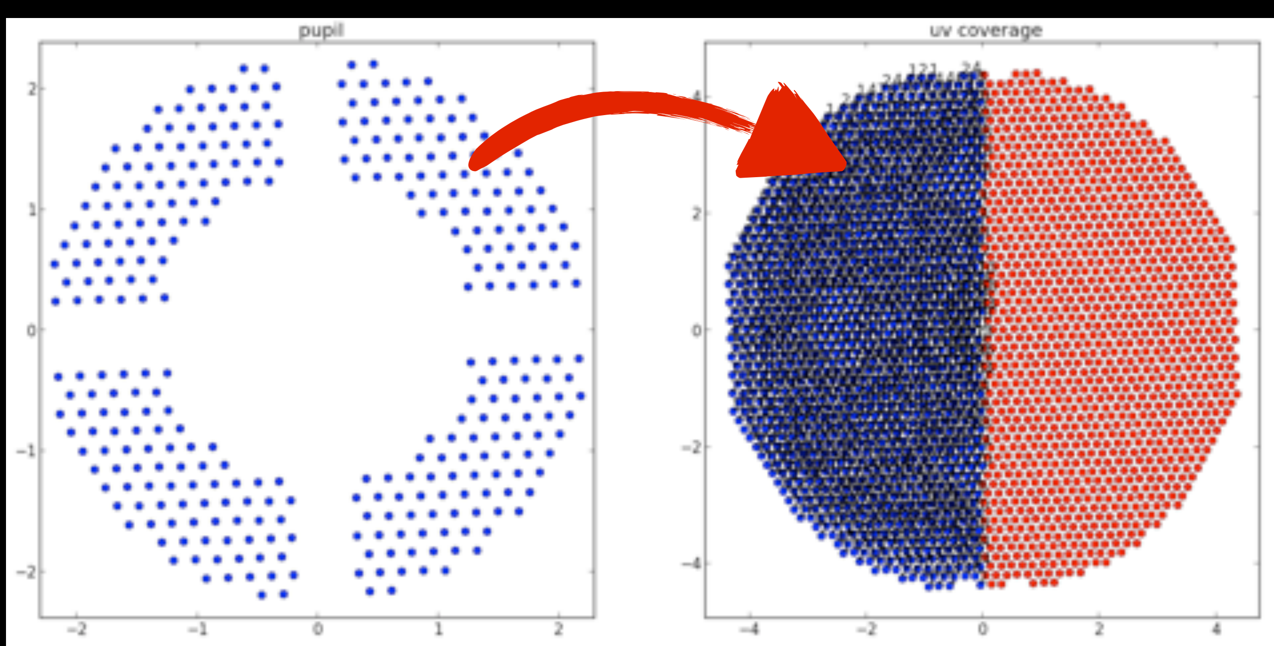
Frantz Martinache

OHP interferometry workshop
September 27, 2013

How not to solve the full problem!

$$[\Phi] = [\Phi_0] + [A] \times [\varphi]$$

measured — unknown — known — unknown



Find an operator K so that:

$$K\,\phi = K\,\phi o + K\,A\,\varphi$$

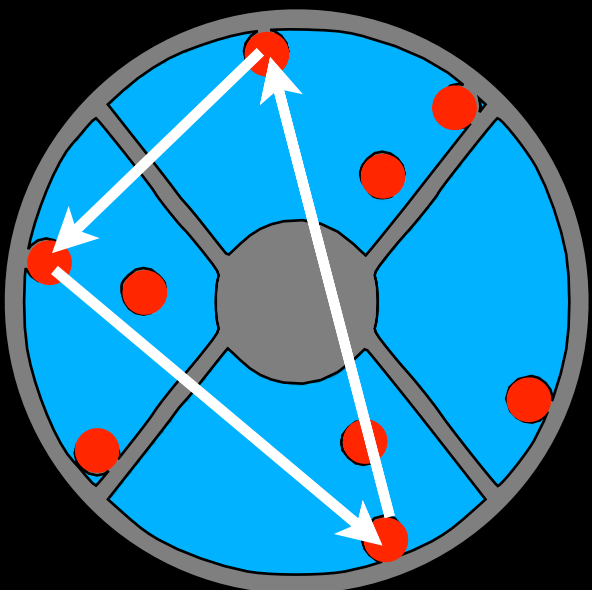
$$K\,\phi = K\,\phi o$$

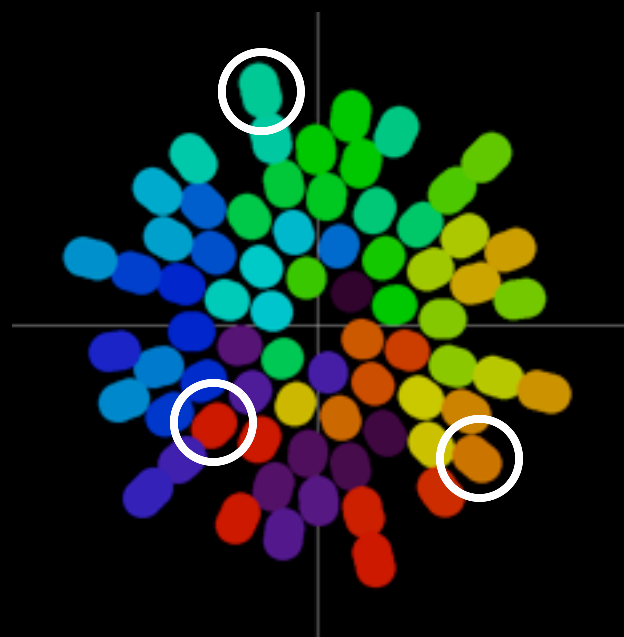
K is the **kernel** of A

K ϕ are called **kernel-phases**

Martinache, 2010, ApJ, 724, 464

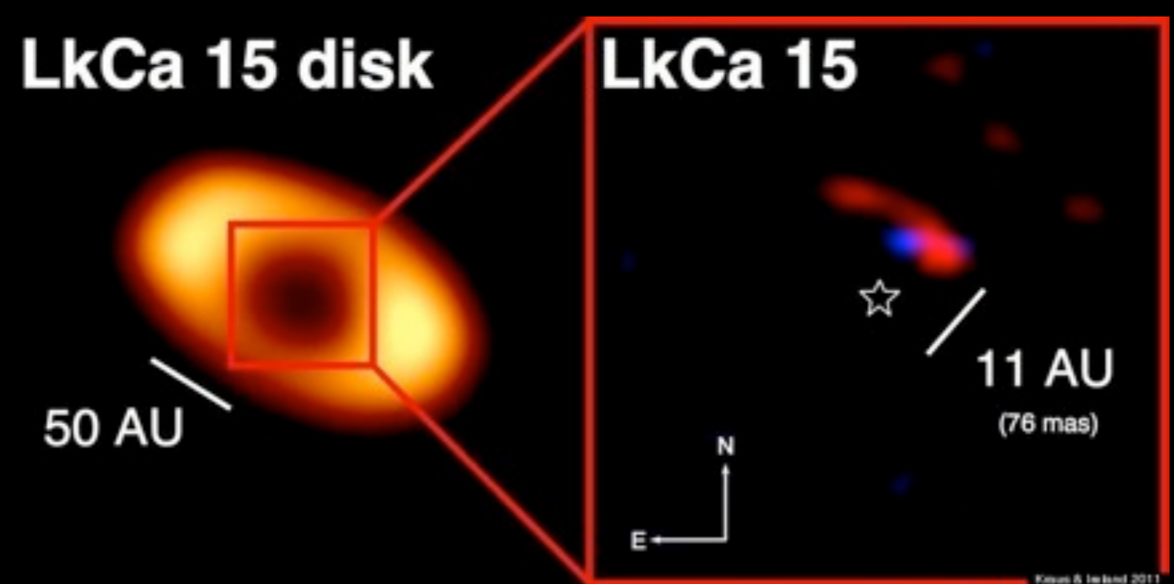
Closure-phase: a special case of Kernel





This is very relevant to the extrasolar planet direct detection game

$$\Phi(1\text{-}2) = \Phi(1\text{-}2)_0 + (\Phi_1 - \Phi_2)$$
$$\Phi(2\text{-}3) = \Phi(2\text{-}3)_0 + (\Phi_2 - \Phi_3)$$
$$\Phi(3\text{-}1) = \Phi(3\text{-}1)_0 + (\Phi_3 - \Phi_1)$$

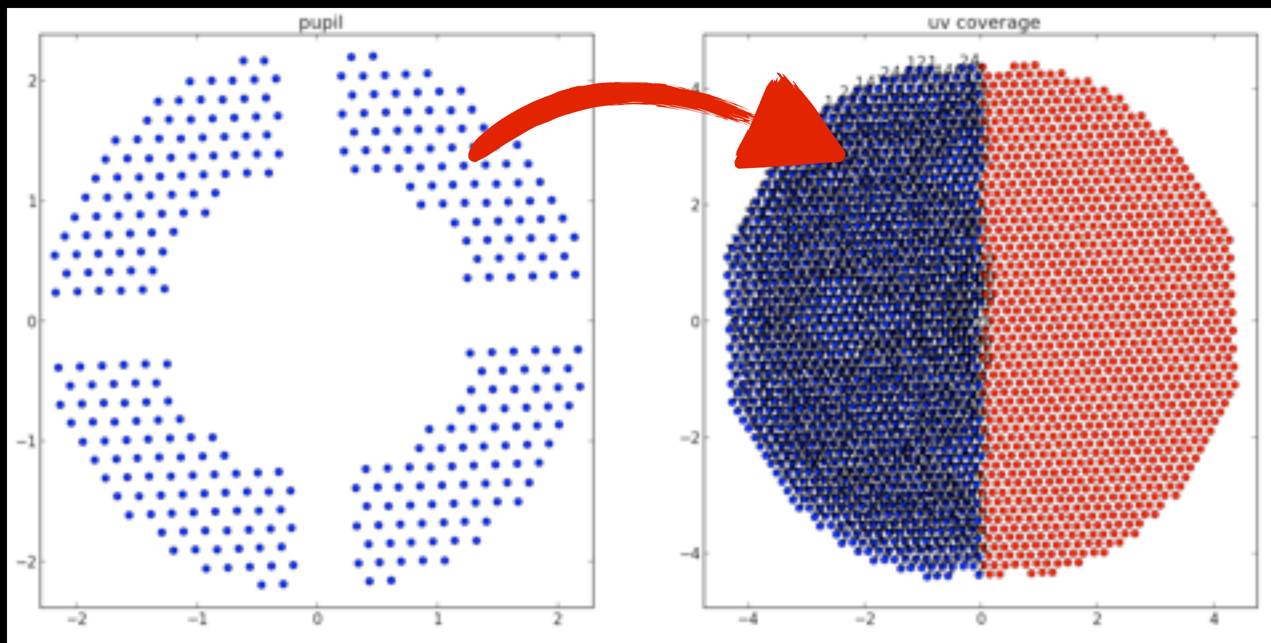


Jennison, 1958, MNRAS, 118, 276

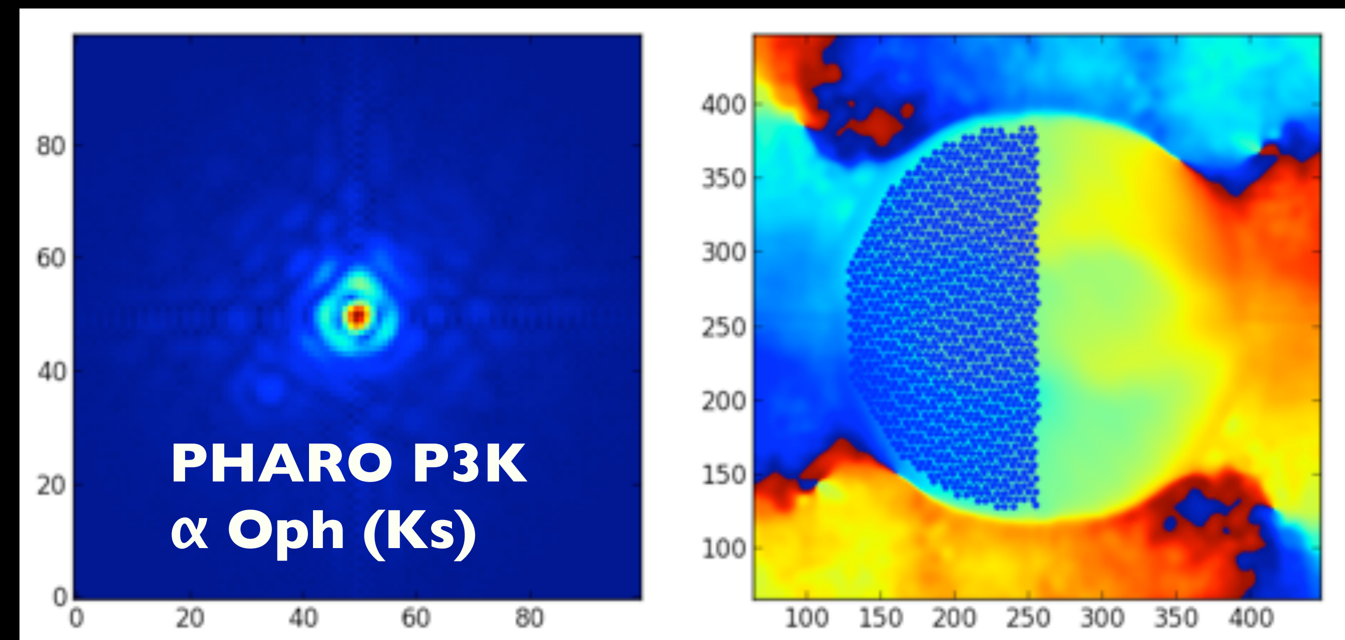
Kraus & Ireland, 2012, ApJ, 745, 5

Data analysis

1. Build a instrument model => A
2. Find the Kernel of A: K

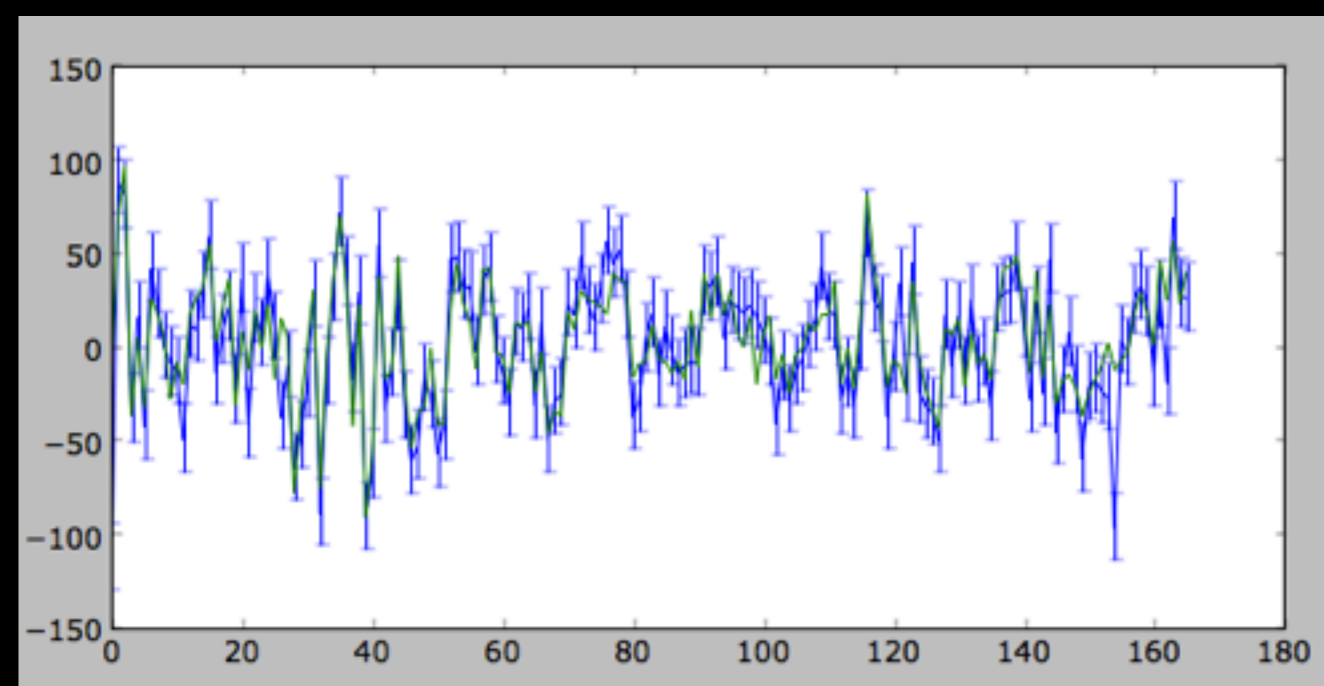


3. Fourier Transform each image
4. Extract phase ϕ



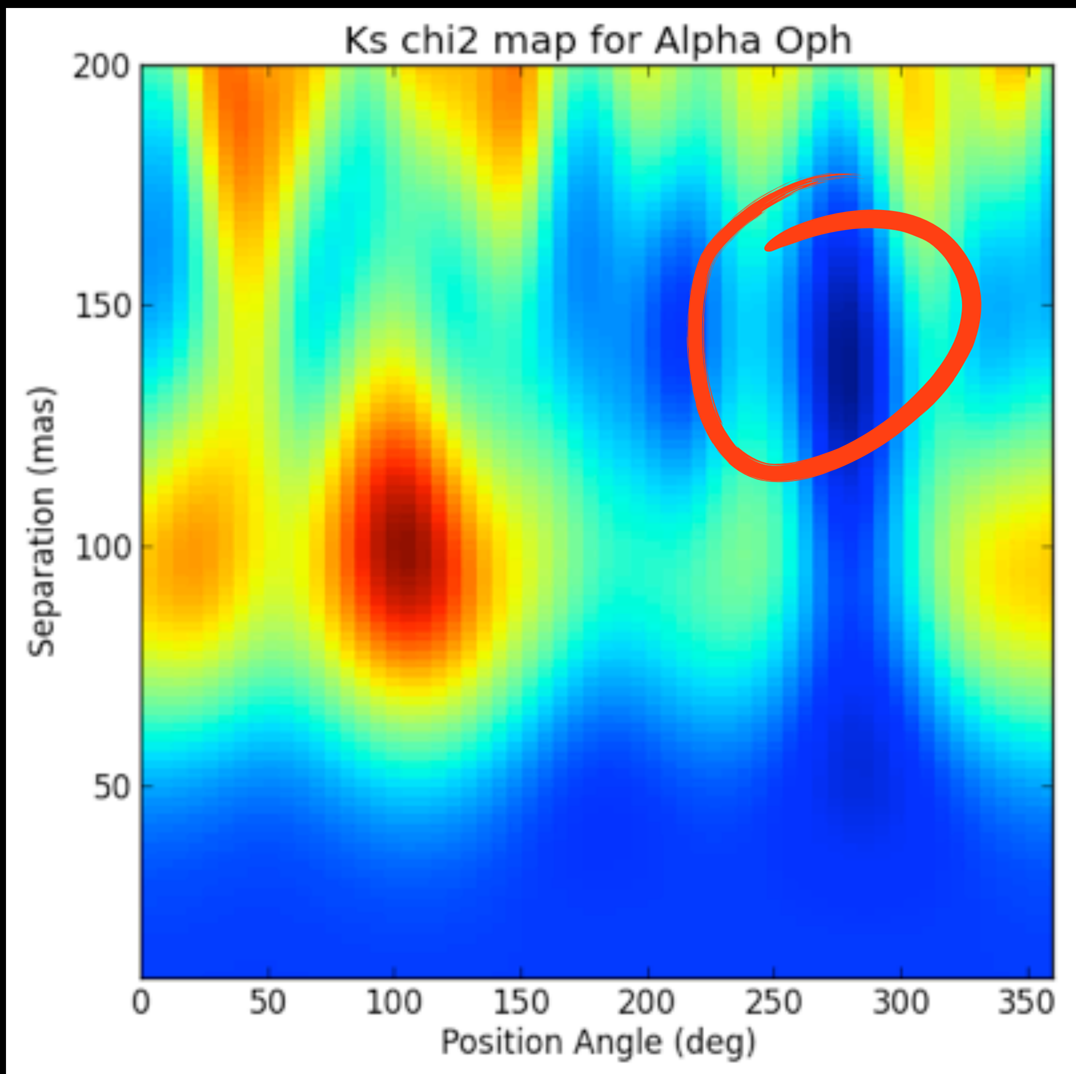
5. Multiply K ϕ: you are done!

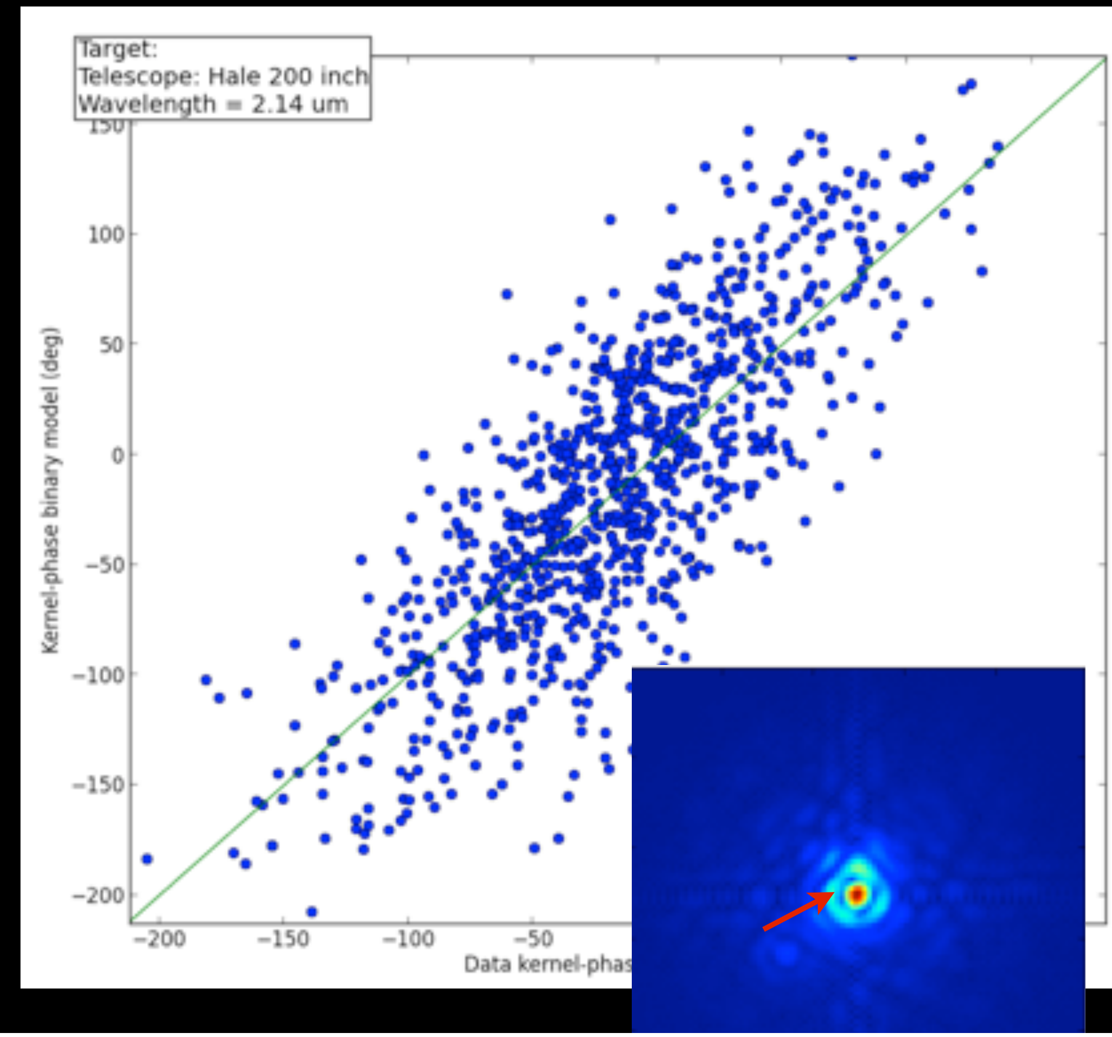
<u>Additionally</u>:
- statistics
- model the data (e.g. binary)
- determine contrast limits

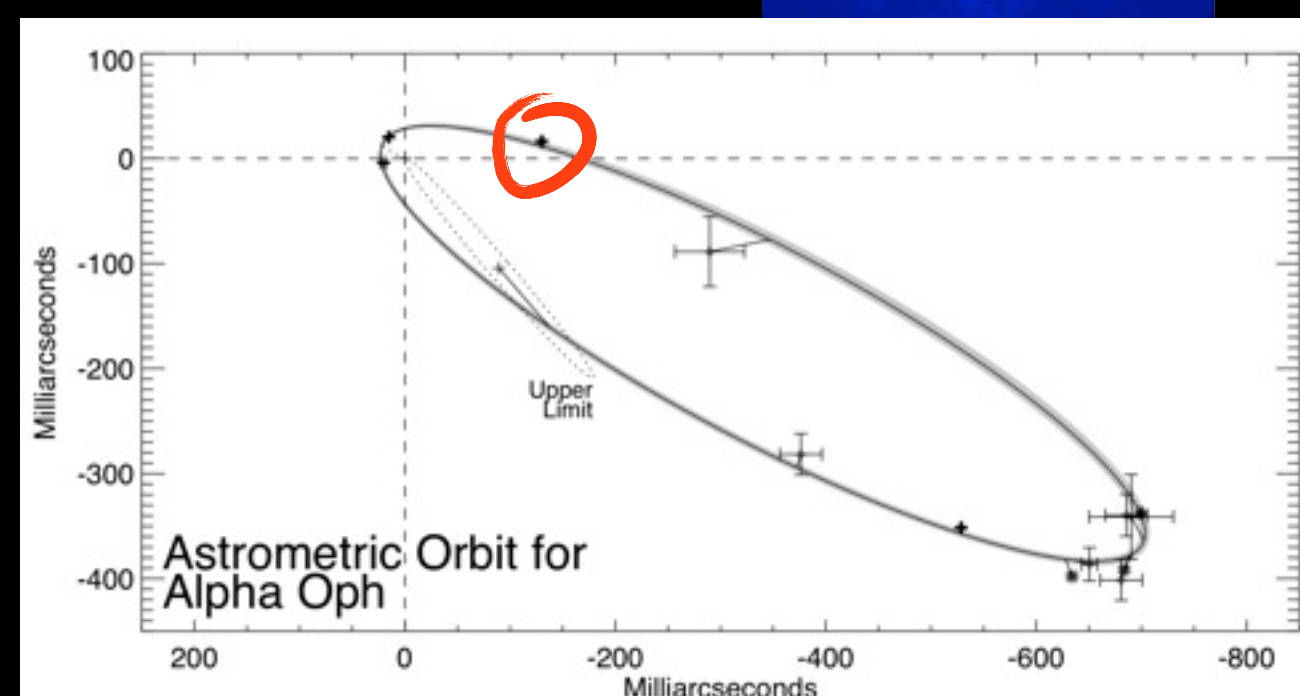


http://code.google.com/p/pysco/

First ground based Ker-phase detection







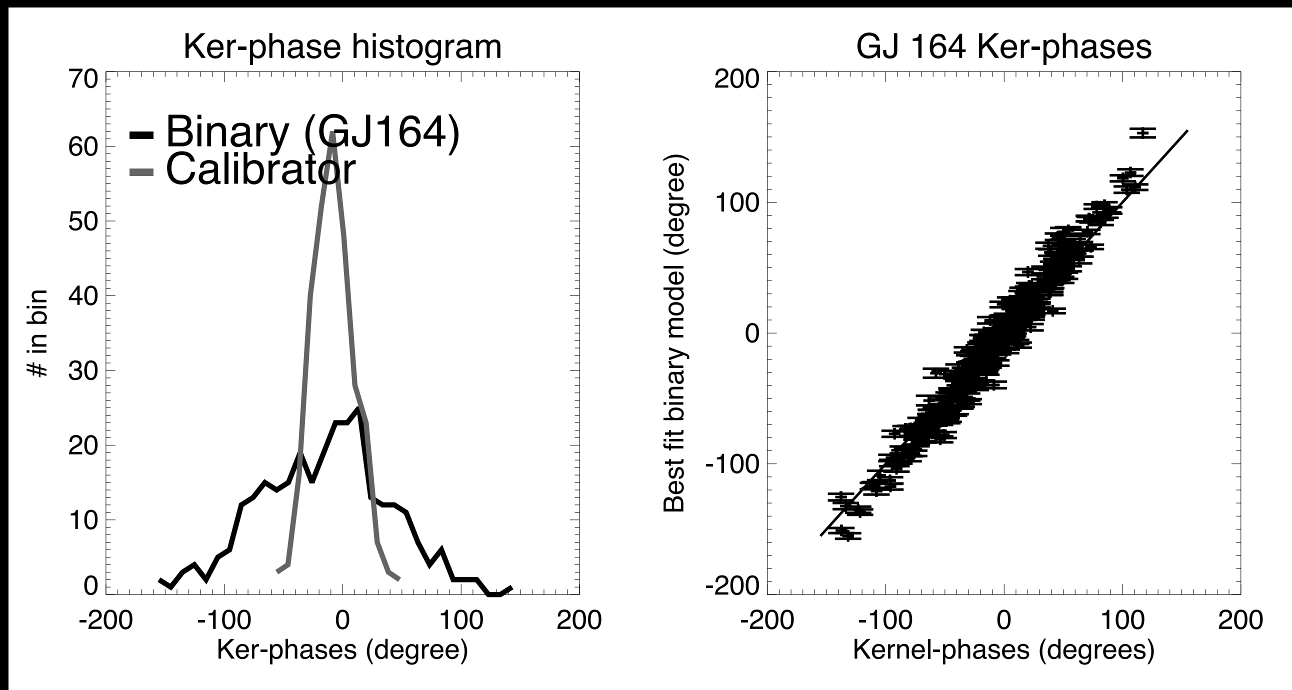
- Separation: 136.1 +/- 3 mas
- Position Angle: 274.6 +/- 2 deg
- Contrast: 23.6 +/- 4

Data, courtesy of S. Hinkley

Martinache, 2013, 221st AAS conference

Hinkley et al, 2011, ApJ, 726, 104

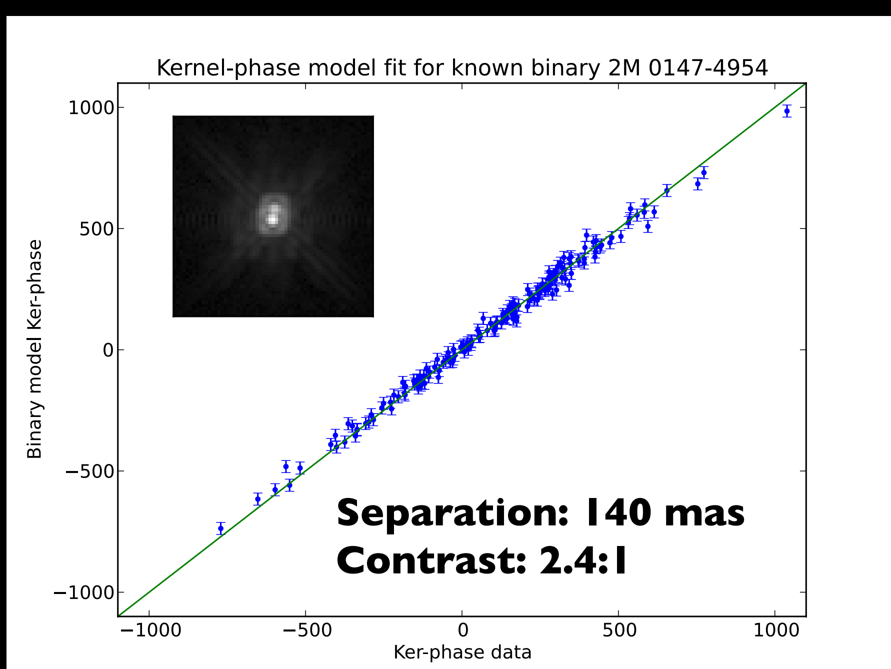
Re-analysis of NICMOS I data

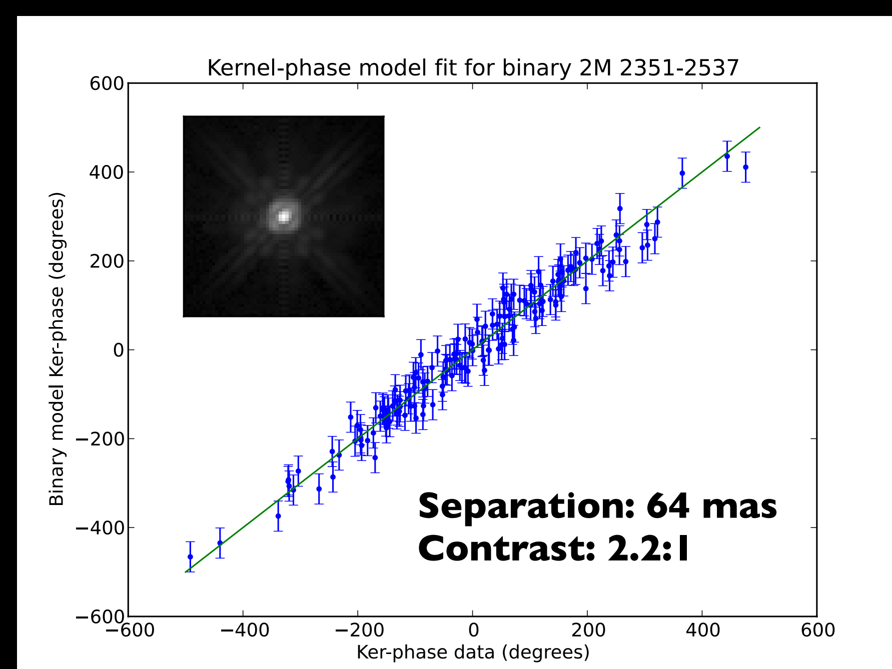


Data @ 1.9 µm (λ/D=150 mas)

A ~10:1 contrast companion to a nearby M-dwarf identified with **milli-arc-second precision** at **0.5 λ/D**

Martinache, 2010, ApJ, 724, 464





Original survey:
Reid et al, 2006, 2008

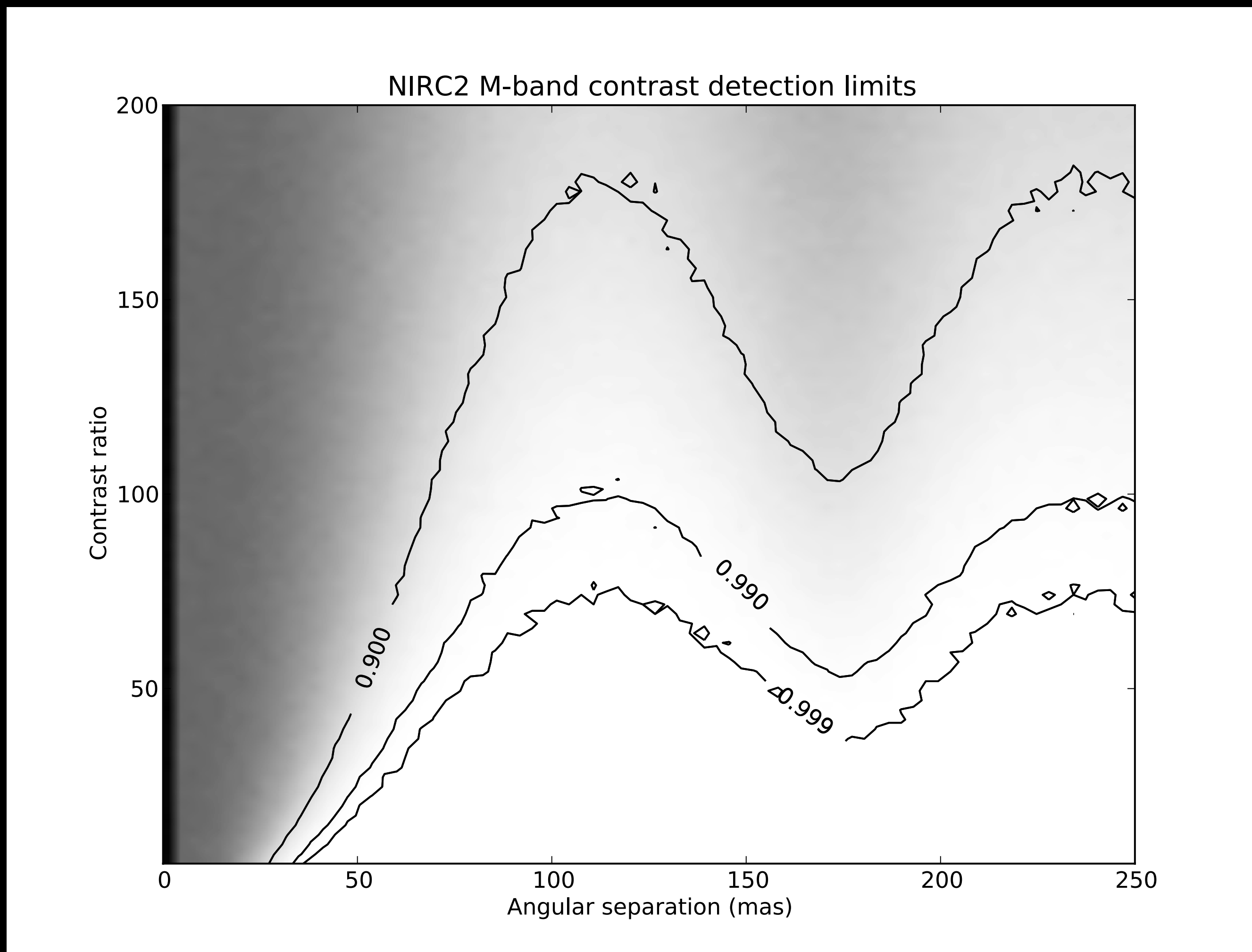
Revisit ~ 80 brown dwarfs observed with HST/NIC1 in the F110W and F170M filters

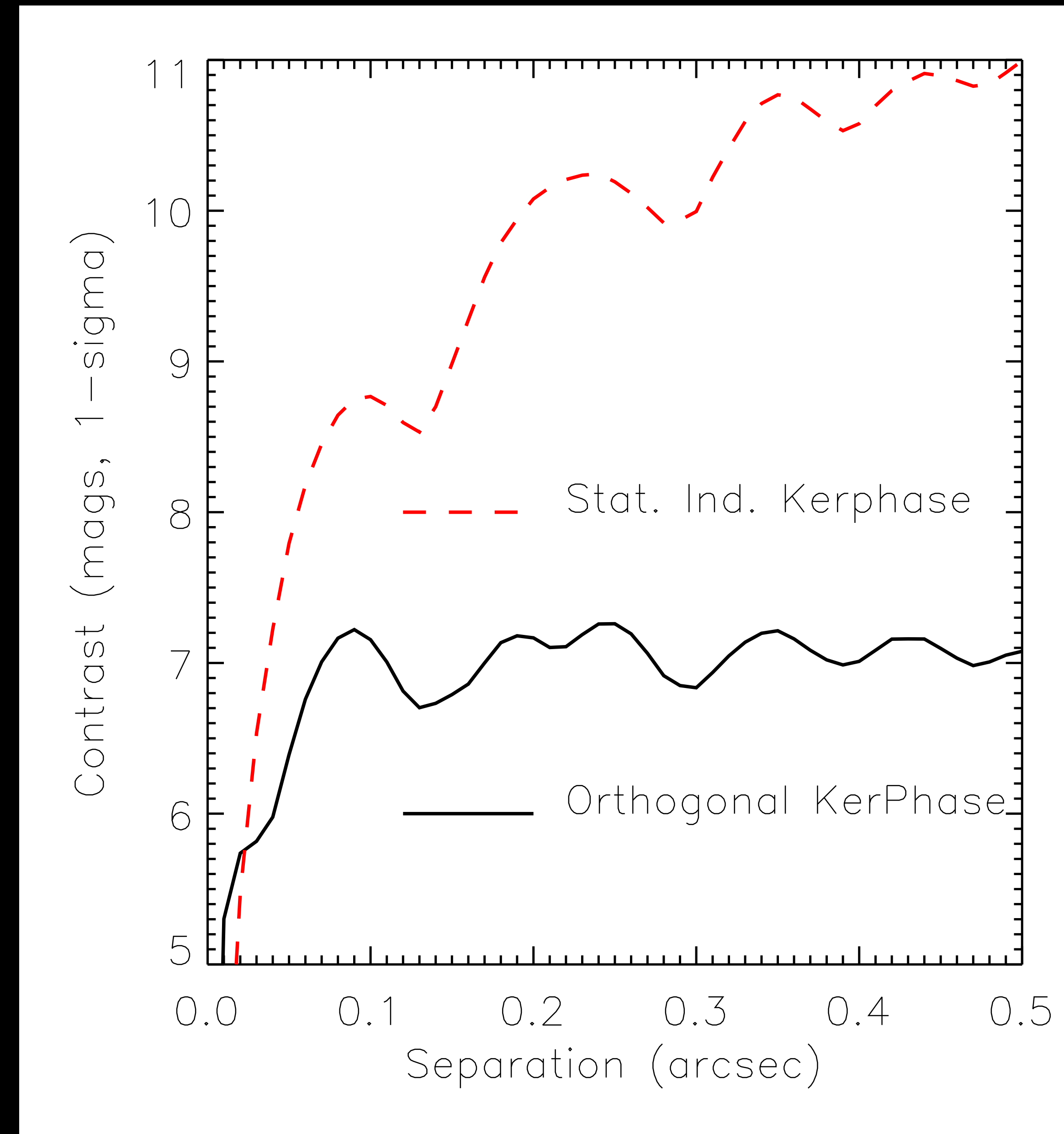
- Doubled the fraction of known L-dwarf binary systems
- Improved astrometry x10

Grant HST-AR-12849.01-A

Pope et al, 2013, ApJ, 767, 110

Contrast detection performance?





Orthogonal kernel-phases
De-correlated signals, but not necessarily de-correlated noises

Martinache, 2010, ApJ, 724, 464

Statistically independent kernel-phases
Taking into account data covariance translates into improved contrast detection limits

Ireland, 2013, MNRAS, 433, 1718

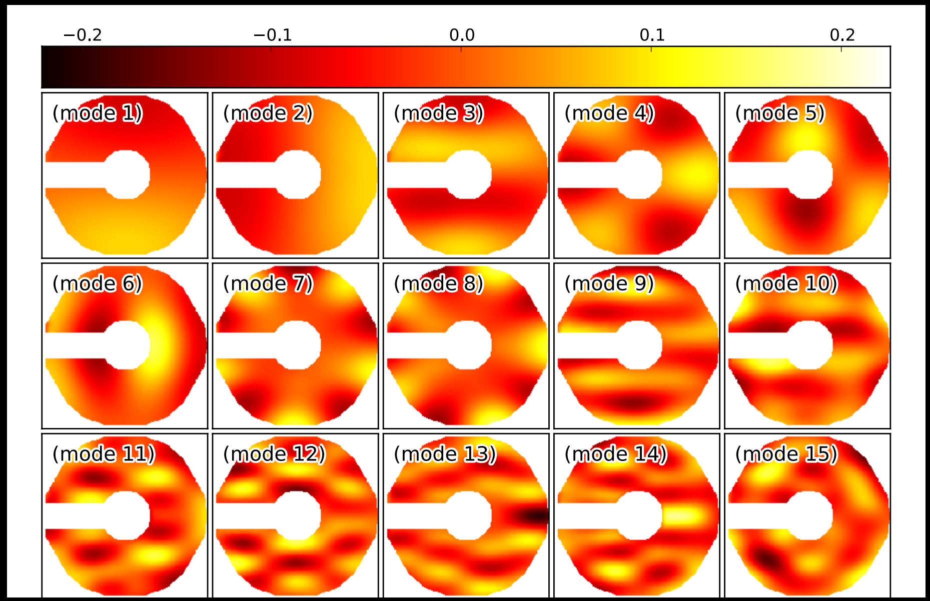
Eigen-phases for wavefront sensing

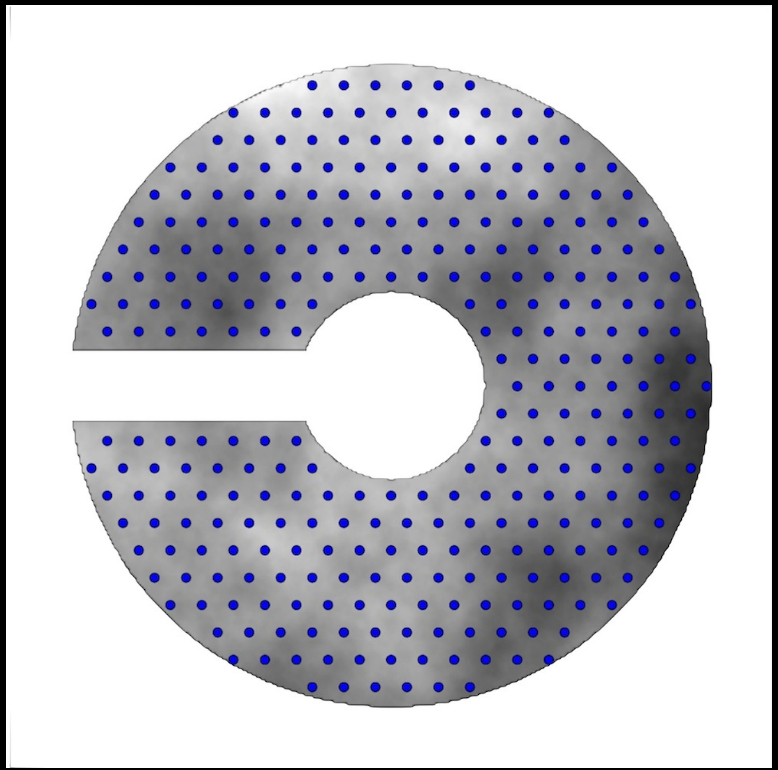
$\Phi = \Phi_0 + A.\varphi$ ⟶ $\varphi = A^{-1}.(\phi-\phi_0)$

For wavefront sensing purposes, need to maximize the number of non-singular values of **A**.

Introduce some **asymmetry** in the pupil suffices in making the matrix invertible.

Eigen modes of the PSF Fourier transform



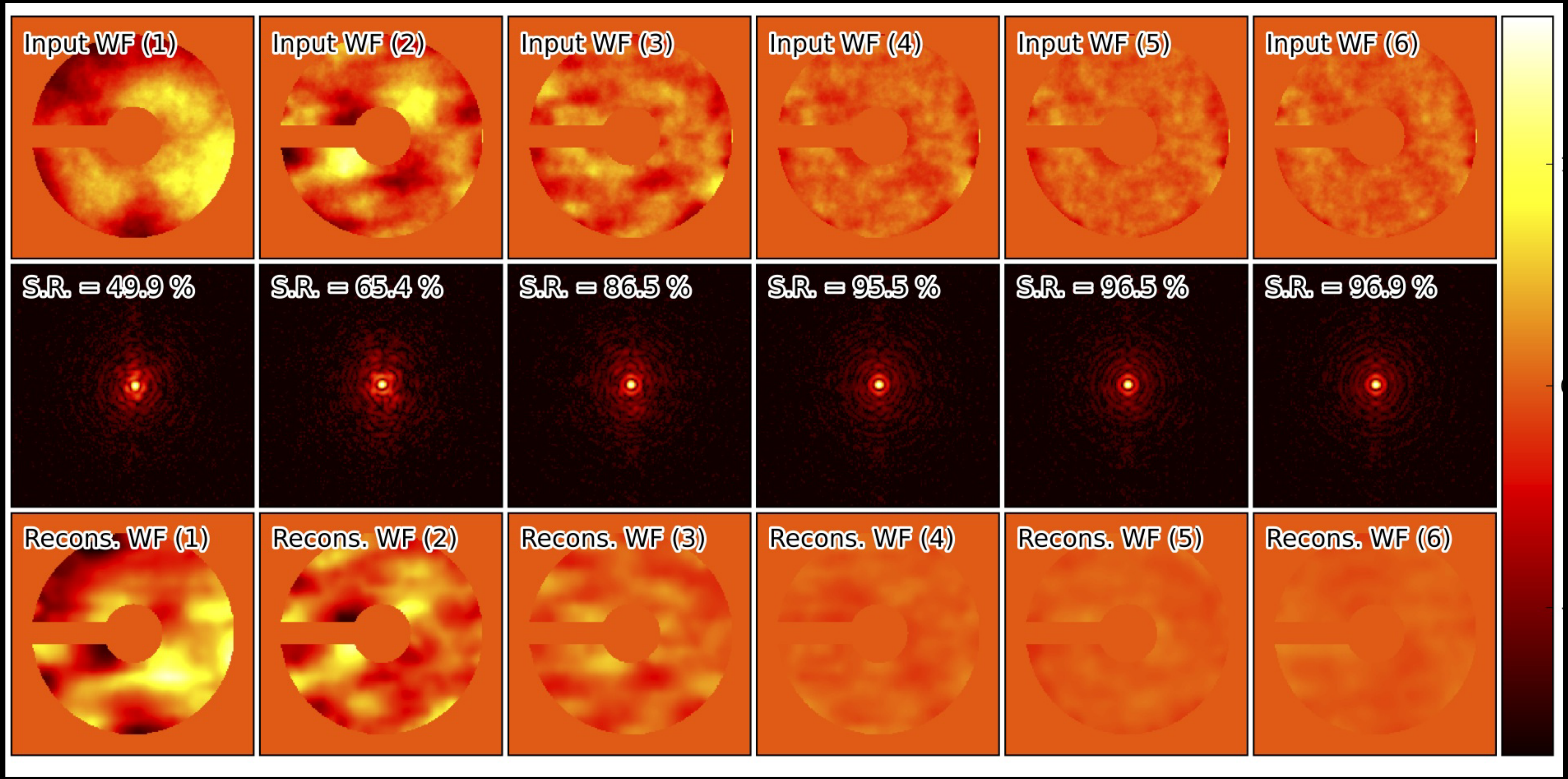


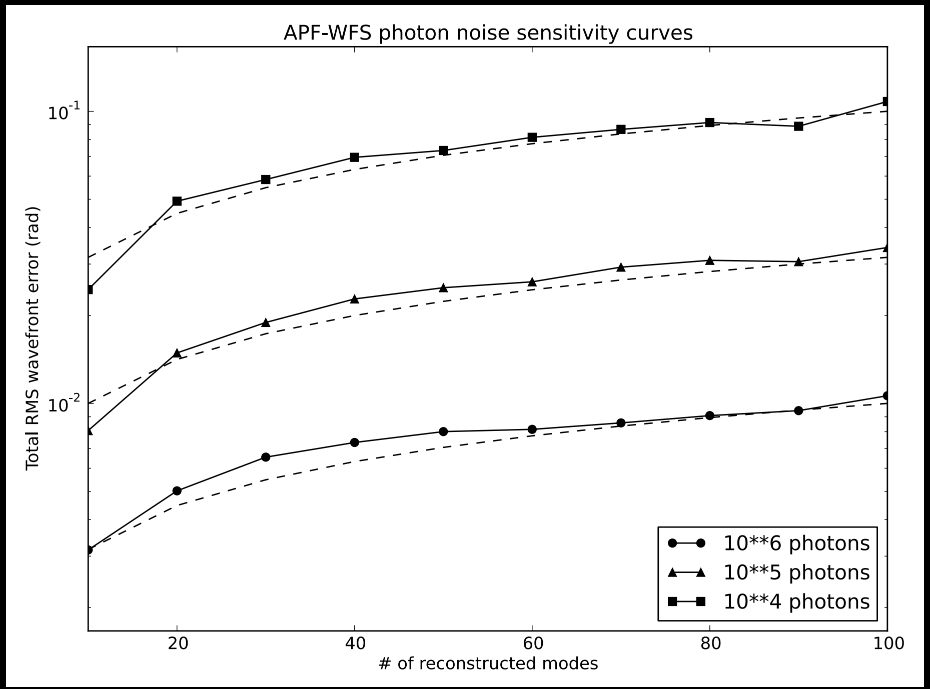
Limitation: restricted to initial Strehl ~ 50 %.

Application for now restricted to the non-common path error calibration in XAO systems, but can be extended.

Martinache, 2013, PASP, 125, 422

Focal plane based wavefront sensing

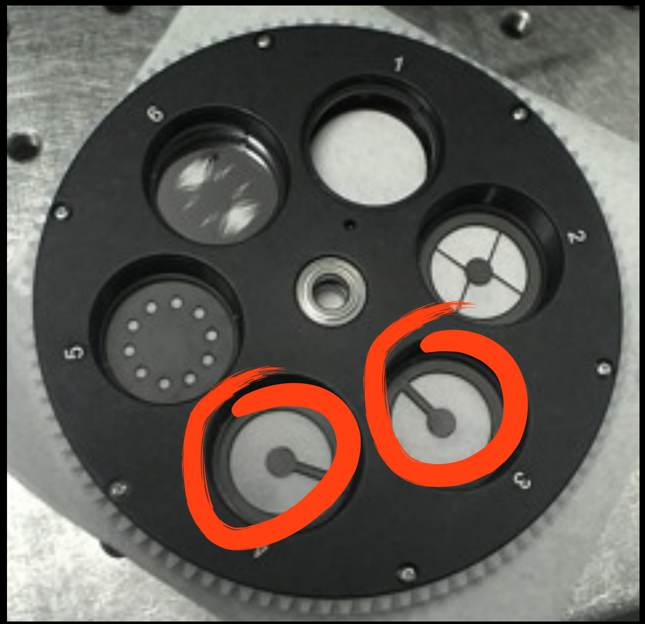




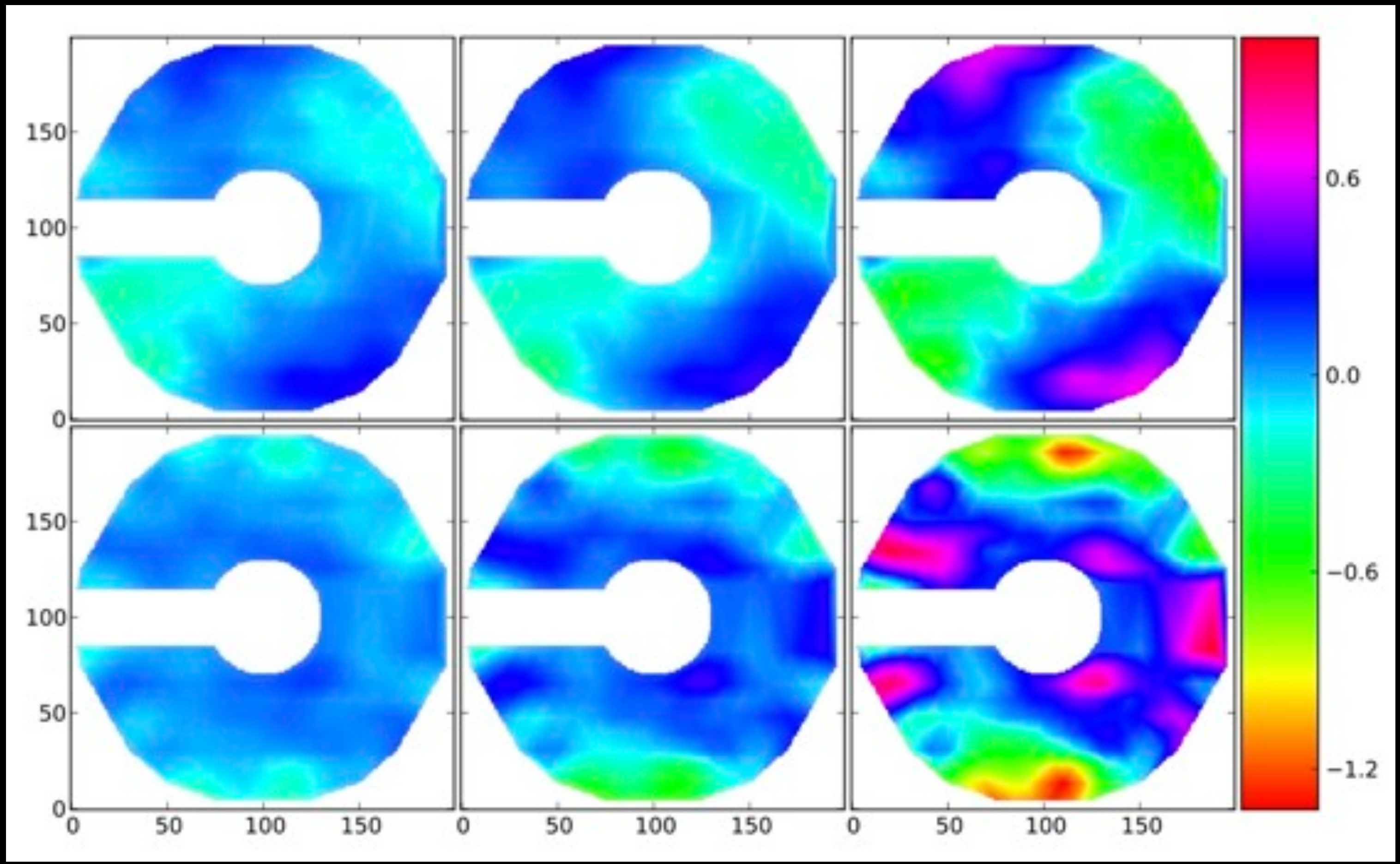
Because it is a focal plane based sensing technique, sensitivity is set by the diffraction limit. Performance is particularly good for the low order modes... good for small IWA coronagraphy.

Martinache, 2013, PASP, 125, 422

Quick lab test (SCExAO)



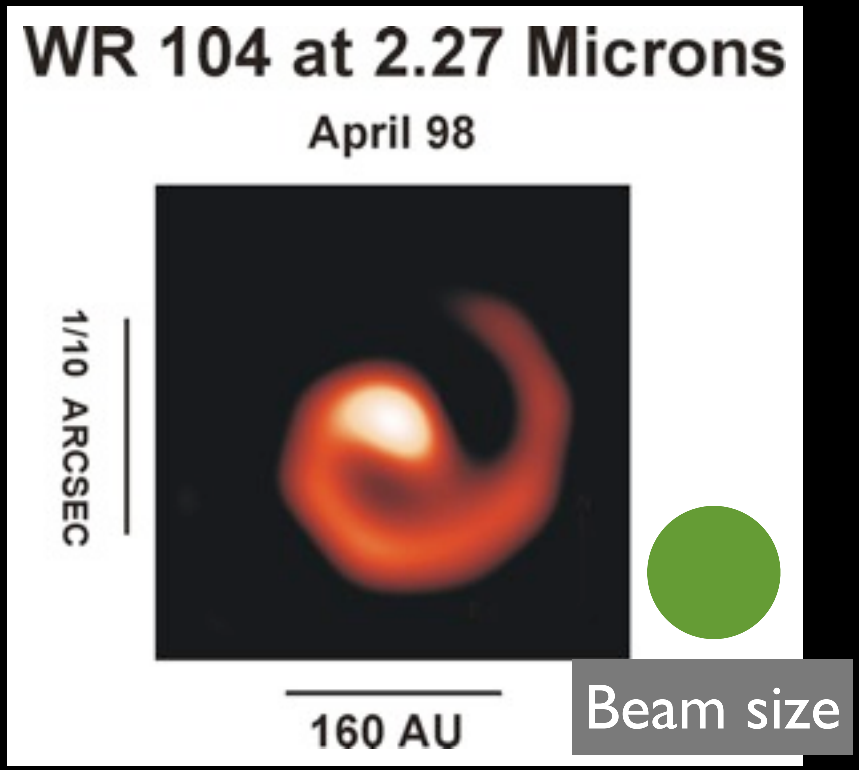
SCExAO pupil wheel



- Very low impact - high payoff
- Asymmetric masks (at two different azimuths) in a pupil wheel after the SCExAO DM inside the instrument.
- Preliminary experimental result shows that the sensor works.
- Ongoing work toward a close-loop system for the non-common path error calibration on SCExAO.
- Close-loop on-sky demonstration?

http://www.frantzmartinache.com/subaru/02projects/03kerphi/02wfs/02wfs.html

Interferometric imaging with rich aperture

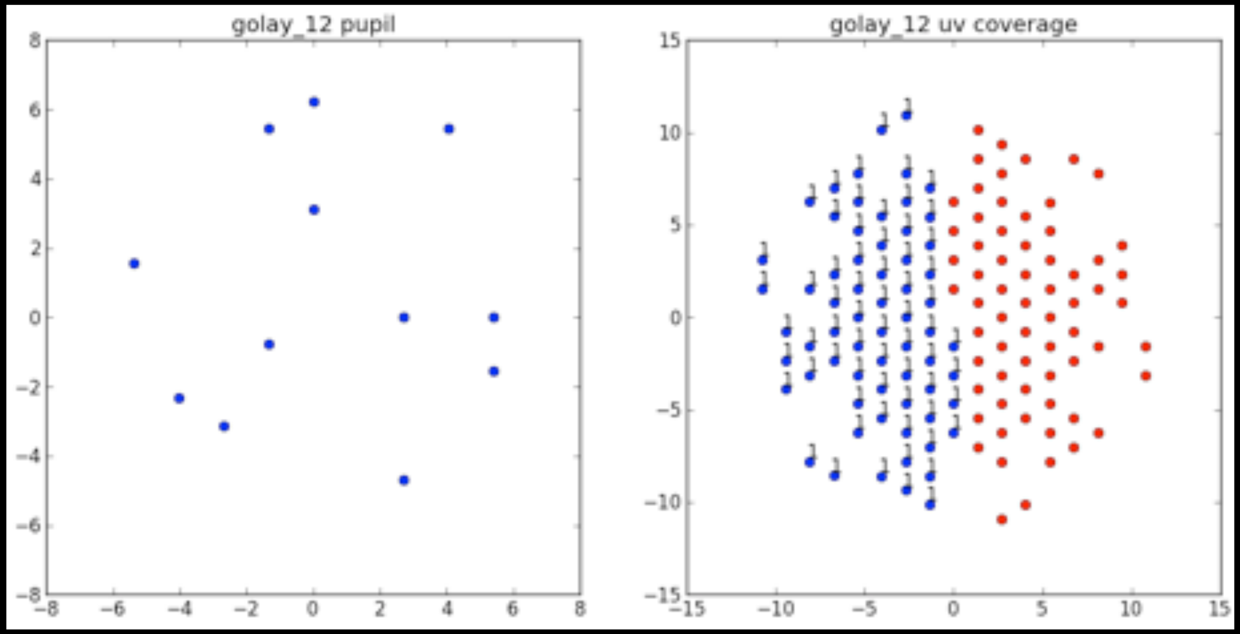


Example of super-resolution image with Keck @ 2.3 μm
Using NRM-interferometry (λ/D = 45 mas).

Tuthill et al, 1999, Nature, 398, 487

With a 30-meter aperture, interferometric imaging on an ELT offers an incredible opportunity to obtain very high resolution NIR images of complex sources.

NRM geometry: Golay 12



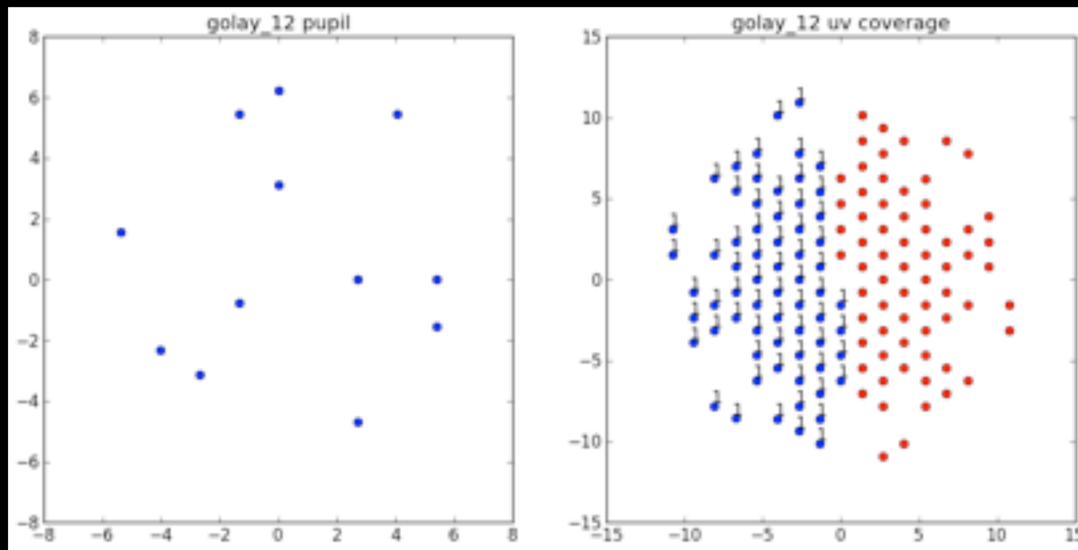
This sort of imaging relies on non-redundant masks and is therefore compatible with even seeing limited observations.

But with good AO, non-redundancy is no longer a strict requirement...

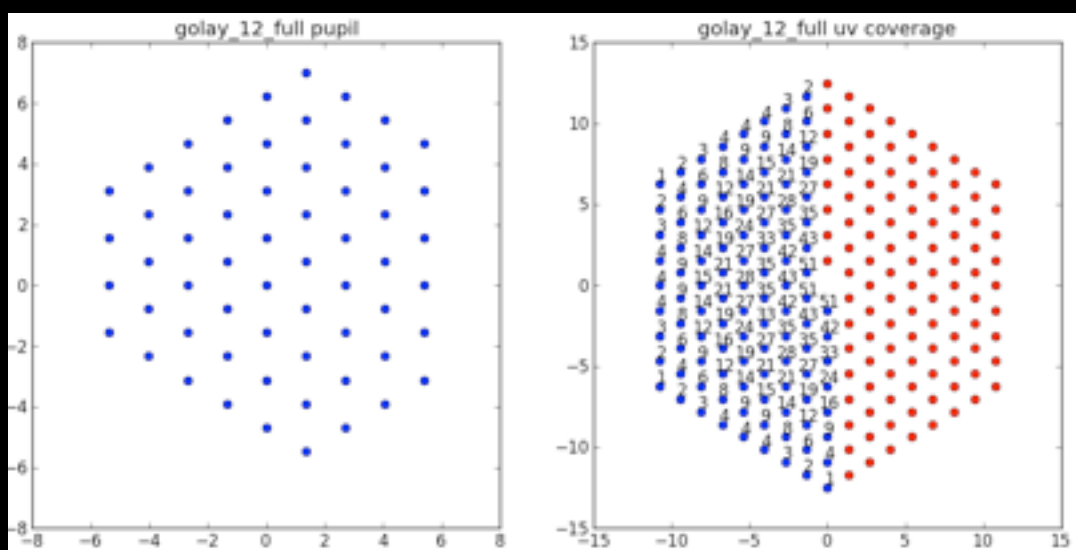
Golay, 1971, JOSA, 61, 272

interferometric pupil for imaging

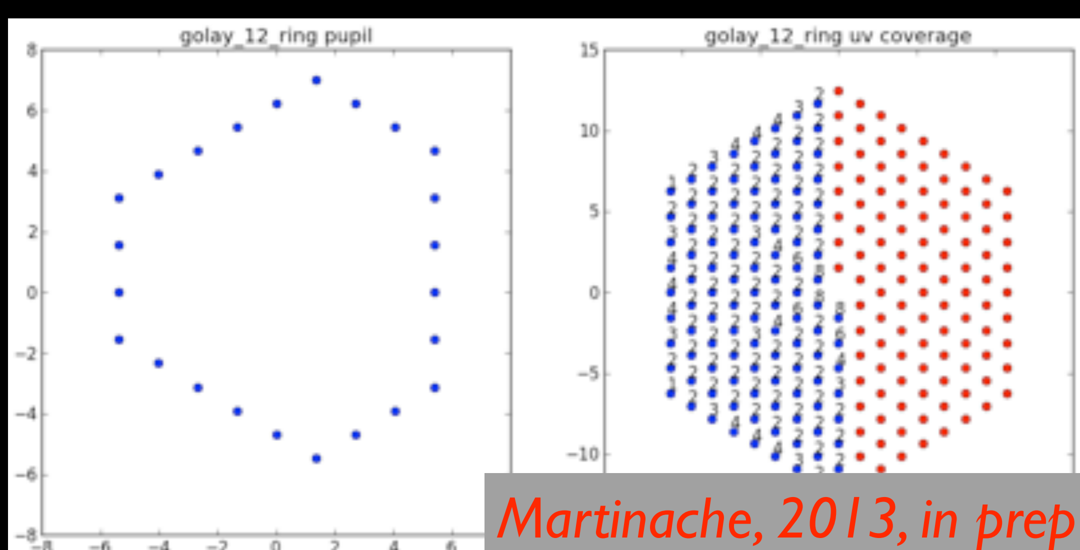
G12



Full



Ring



Kernel-phase allows to go beyond the rules of Golay and offer better solutions for the imaging of complex sources

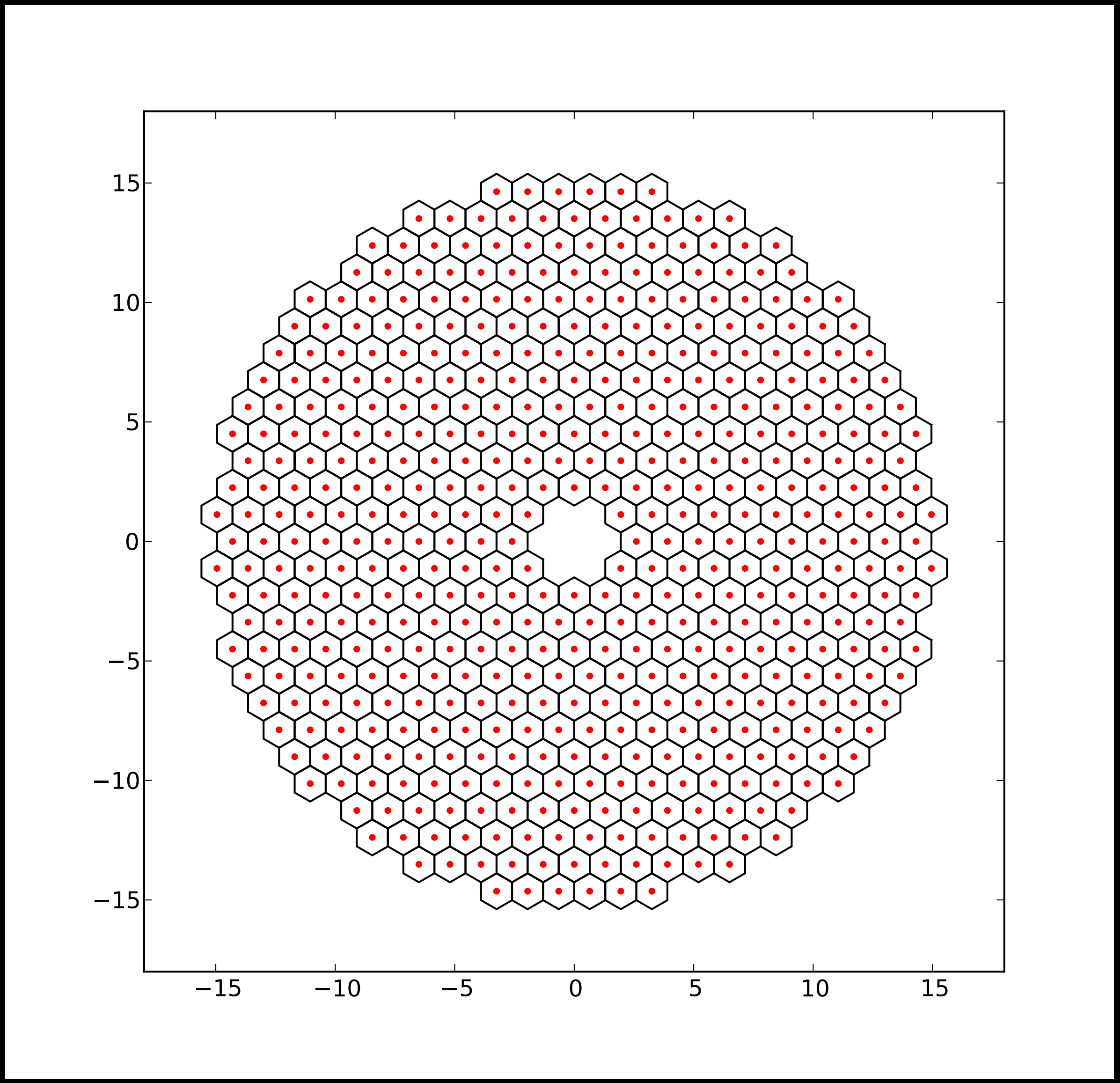
	Golay 12	Full	Ring
n_A	12	27	15
n_{UV}	66	108	108
n_K	55	49	85
% info	51%	45%	79%

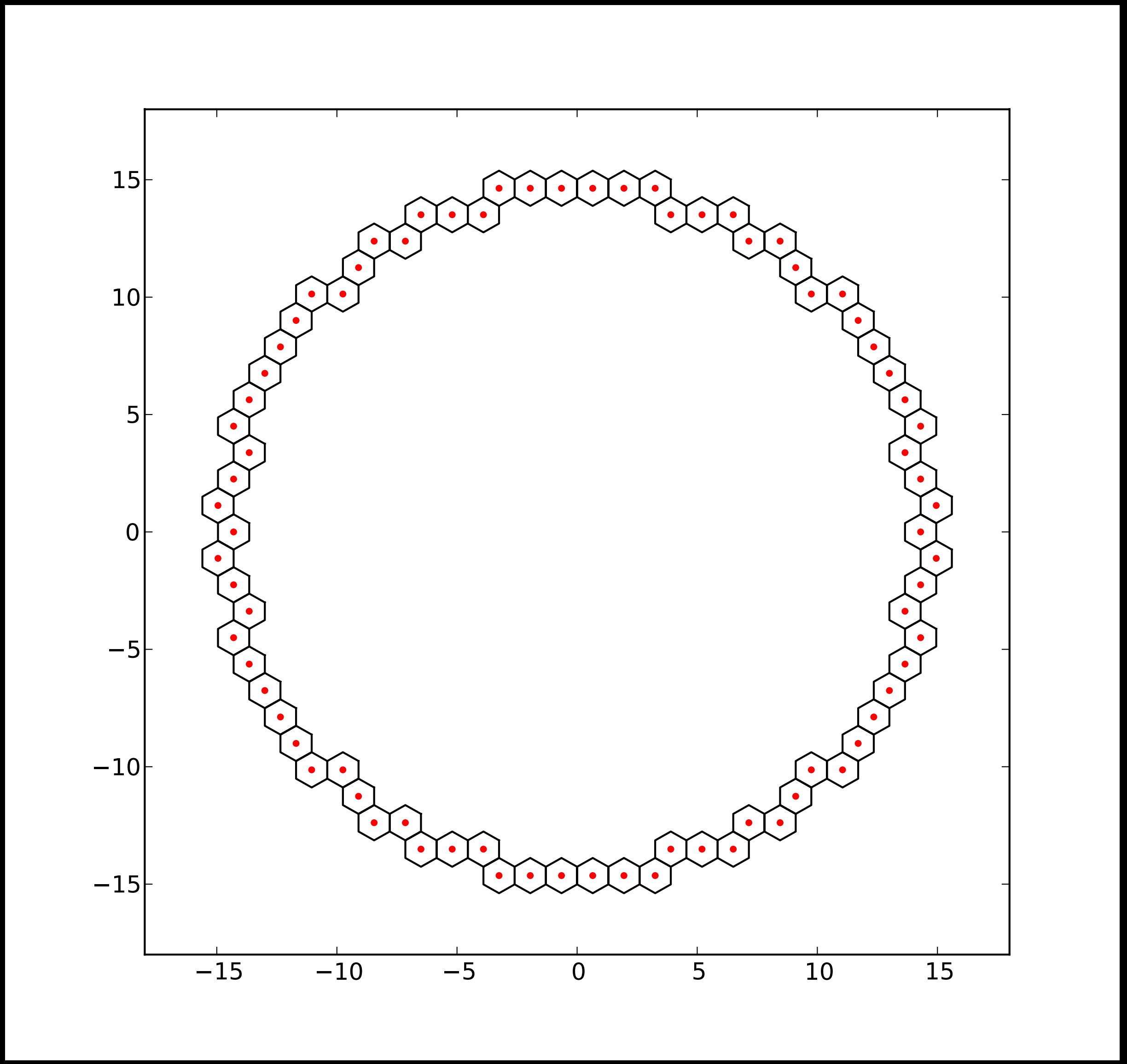
The Ring pupil gives the same uv-coverage, but recovers a higher fraction of the phase information.

Martinache, 2013, in prep

http://www.frantzmartinache.com/subaru/02projects/03kerphi/01imaging/01imaging.html

The ELT ring - interferometer



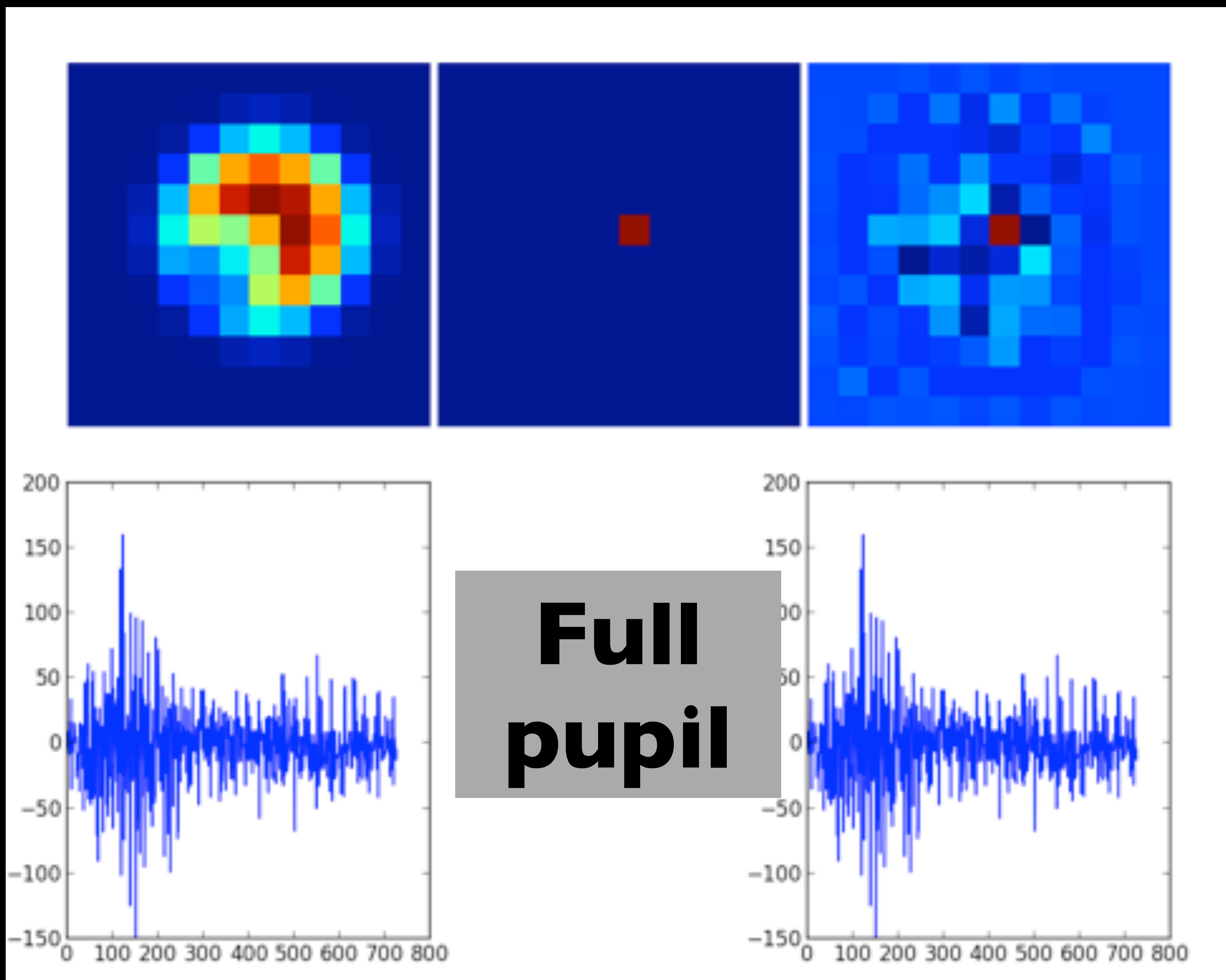


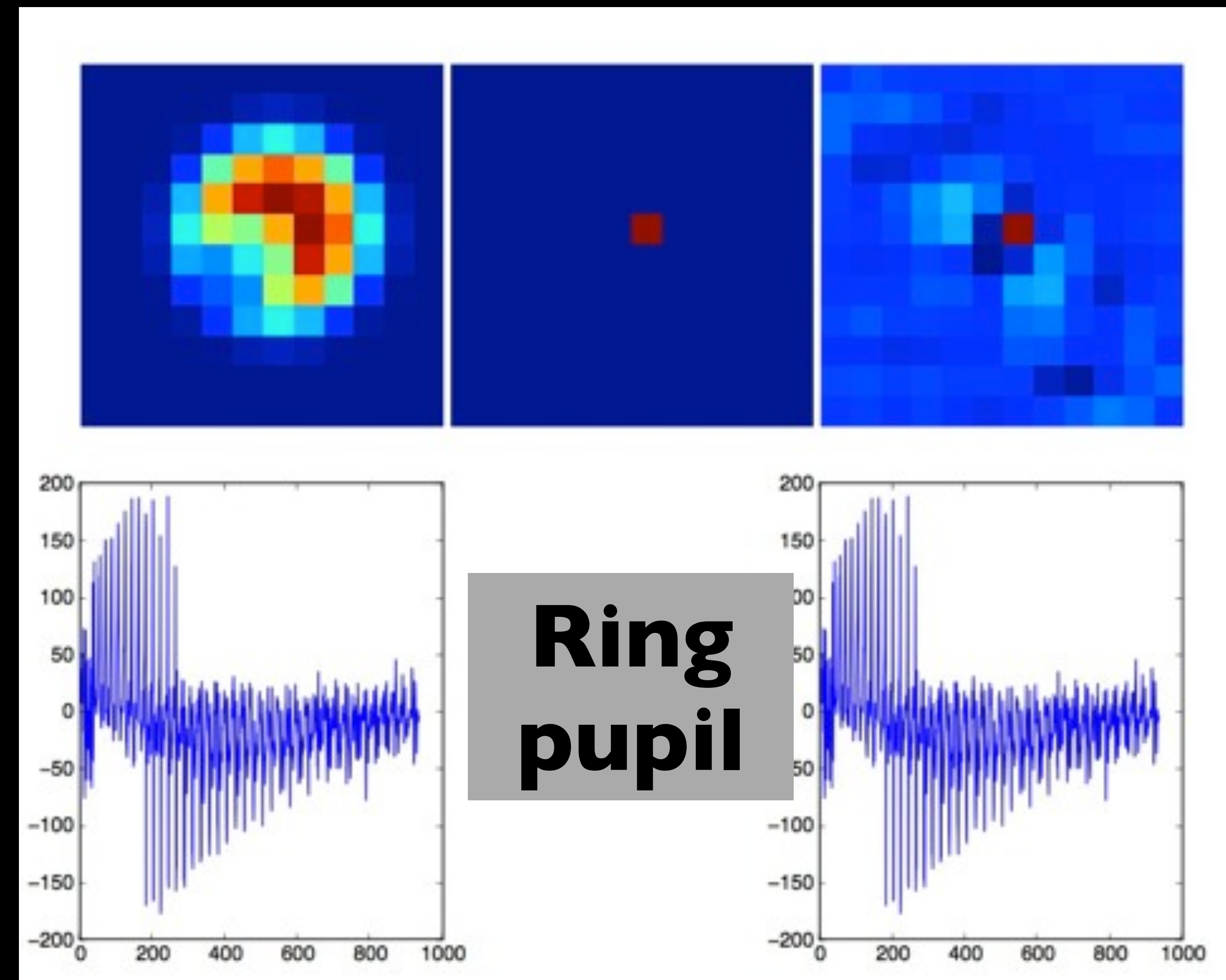
492 segments
972 spatial frequencies
726 kernel-phases (75 %)
Max redundancy: 462
Mean redundancy: 124

78 segments used
972 spatial frequencies
933 kernel-phases (96 %)
Max redundancy: 26
Mean redundancy: 3

Martinache, 2012, SPIE, 8445, 04

Image reconstruction experiments





Imaging reconstruction algorithm based on Ker-phase χ^2 minimization only.

With enough d.o.f in the model, the problem quickly becomes degenerate.
Visibilities and/or regularization (e.g. entropy) are required.

=> Need to learn how to do interferometric imaging

Enough information for direct inversion?

One “difficulty” is that Ker-phases are abstract quantities (even more so than closure-phases).

Option: Properties of data histogram

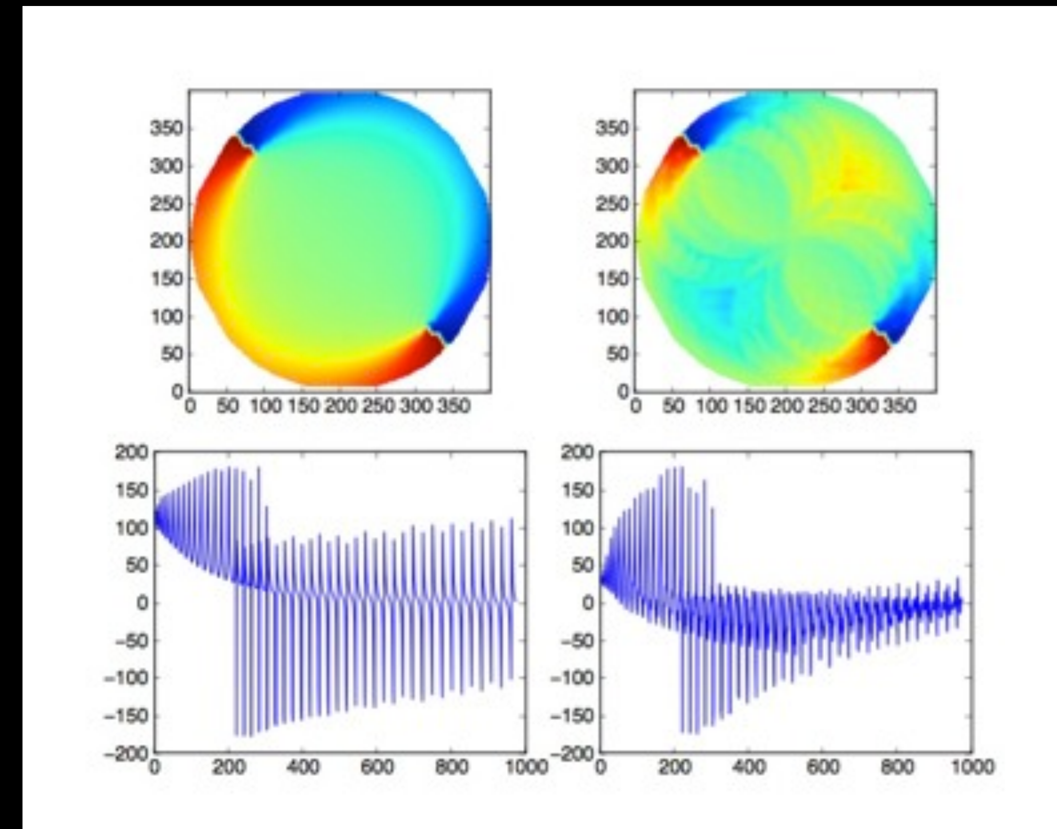
<u>However, in doing</u>:

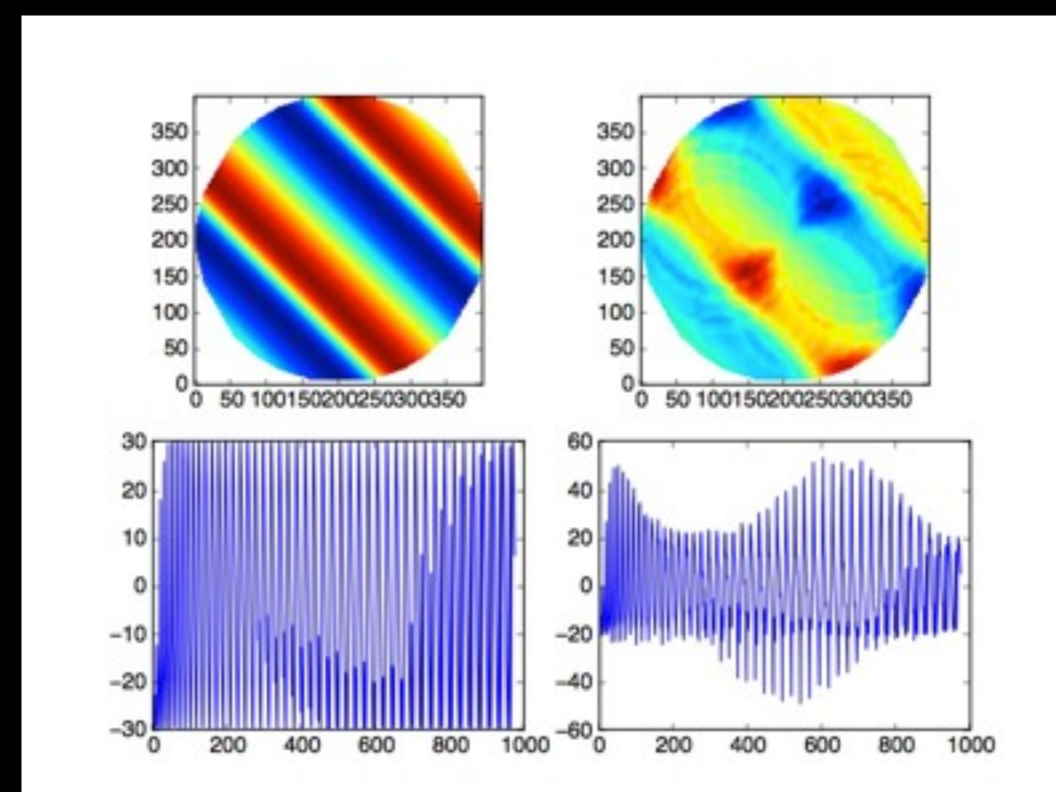
$$K \phi = K \phi_o + K A \varphi$$
$$K \phi = K \phi_o$$

with a well designed array > 95 % of the phase information is preserved: a pseudo inverse K^{-1} does not sound that silly anymore.

$$\phi_o' = K^{-1} K \phi$$

For quick look applications, and/or to give a first input to an imaging package?





Conclusions

- Kernel-phase is a generalization of the idea of closure-phase.
- Works for arbitrary apertures, even highly redundant if Strehl is high.

Bridges the gap between conventional imaging and interferometric imaging. Unlike what most astronomers think, a big telescope (“think ELT!”) is really a rich aperture interferometer, with a not necessarily optimized overall pupil geometry.

- First applications are:
  - HST NICMOS data in the near IR
  - L- and M-band AO data
  - H- and K-band XAO data

With the following constraints:
  - well sampled data
  - non-saturated data
  - data with well-corrected AO

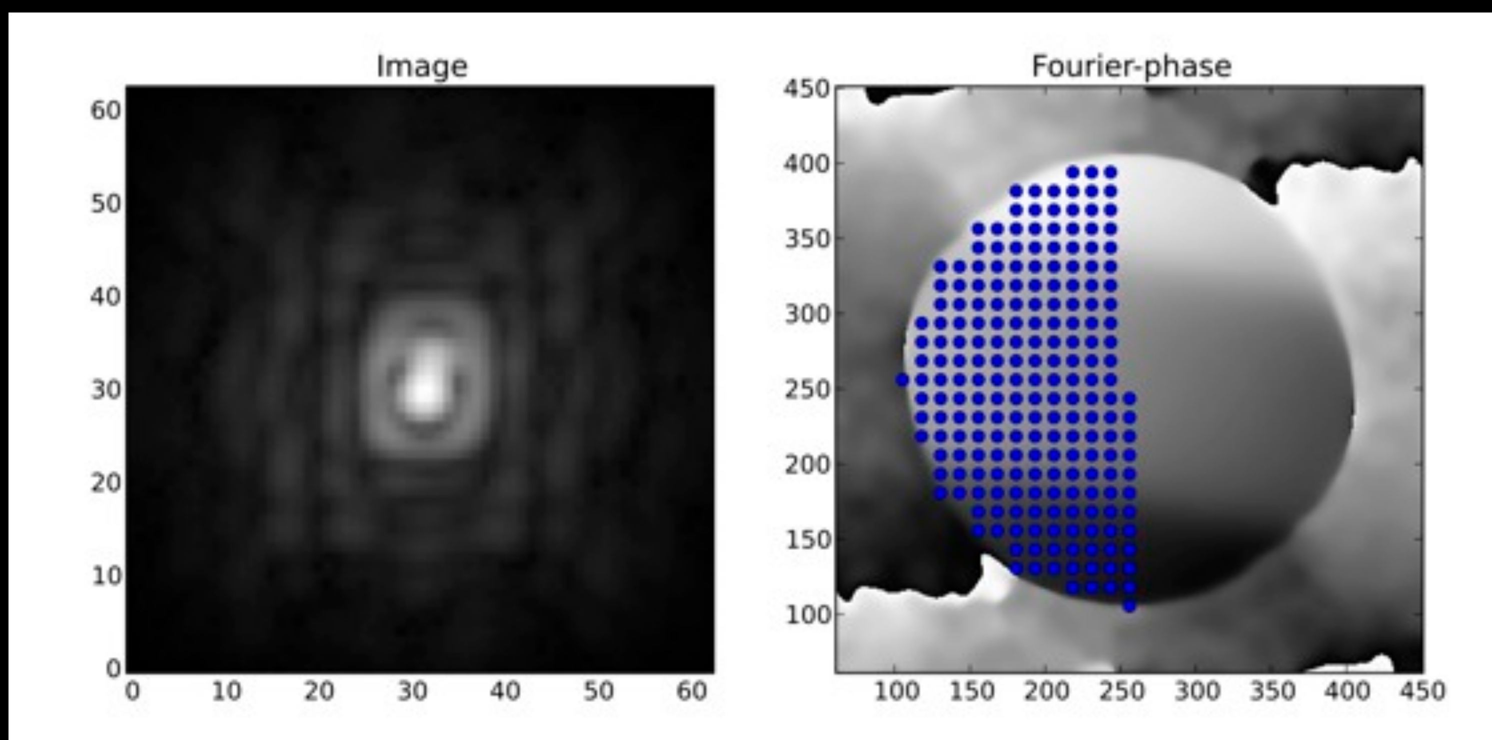
BUT:

Can handle slightly under-sampled data.
May be able to interpolate saturated regions of image?
Multiple λ increases the range of the technique (cf. dispersed fringe trackers)

- How to push toward higher contrast detection limit?
Need to look for kernels in the context of coronagraphy and/or nulling.
My guess: gray coronagraphs and gray nullers

- Learn and use the image reconstruction tricks used by real interferometrists!

Kernel-phase for interferometry with a rich aperture



$$I = O \otimes PSF$$

At high Strehl

$$\Phi = \Phi_0 + A.\varphi$$

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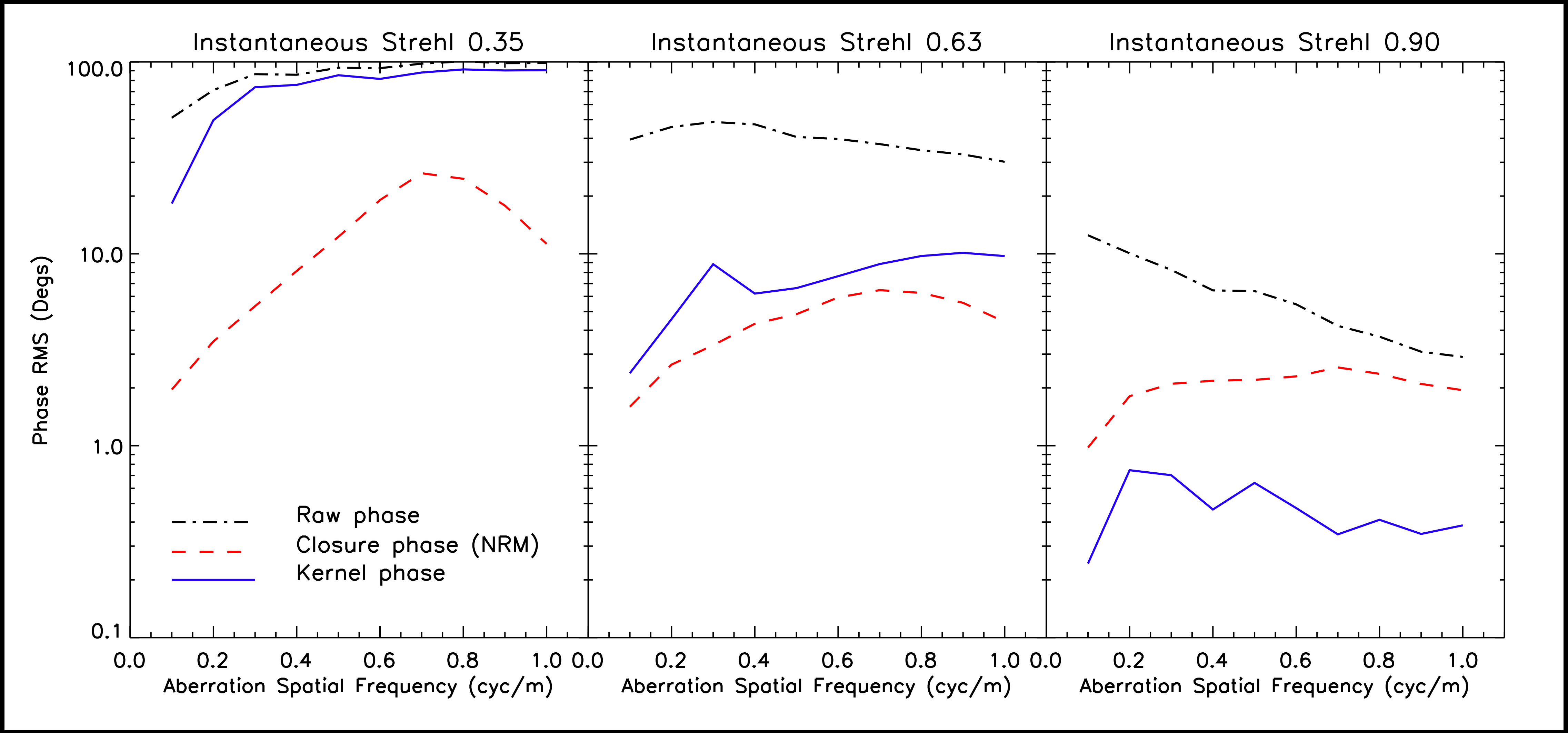
Kernel or closure phase?



Low-Strehl: closure-phase wins...

Medium-Strehl: tie!

High-Strehl: kernel-phase gives another order of magnitude

Ireland, 2013, MNRAS, 433, 1718