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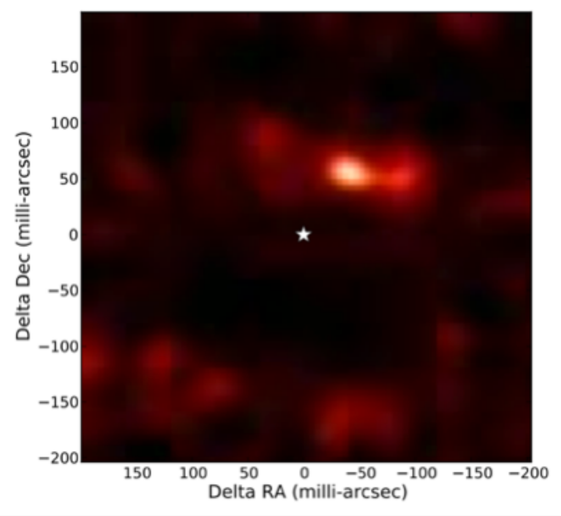
Aperture masking and kernel phases: extracting cophasing errors from science data.



Michael Ireland *On behalf of*/collaborators: Benjamin Pope (Oxford), Adam Kraus, Trent Dupuy (UT Austin), Frantz Martinache (Nice OCA), Peter Tuthill, Barnaby Norris (University of Sydney), Olivier Guyon (Subaru/Arizona), Simon Gross, Alex Arriola (Macquarie)

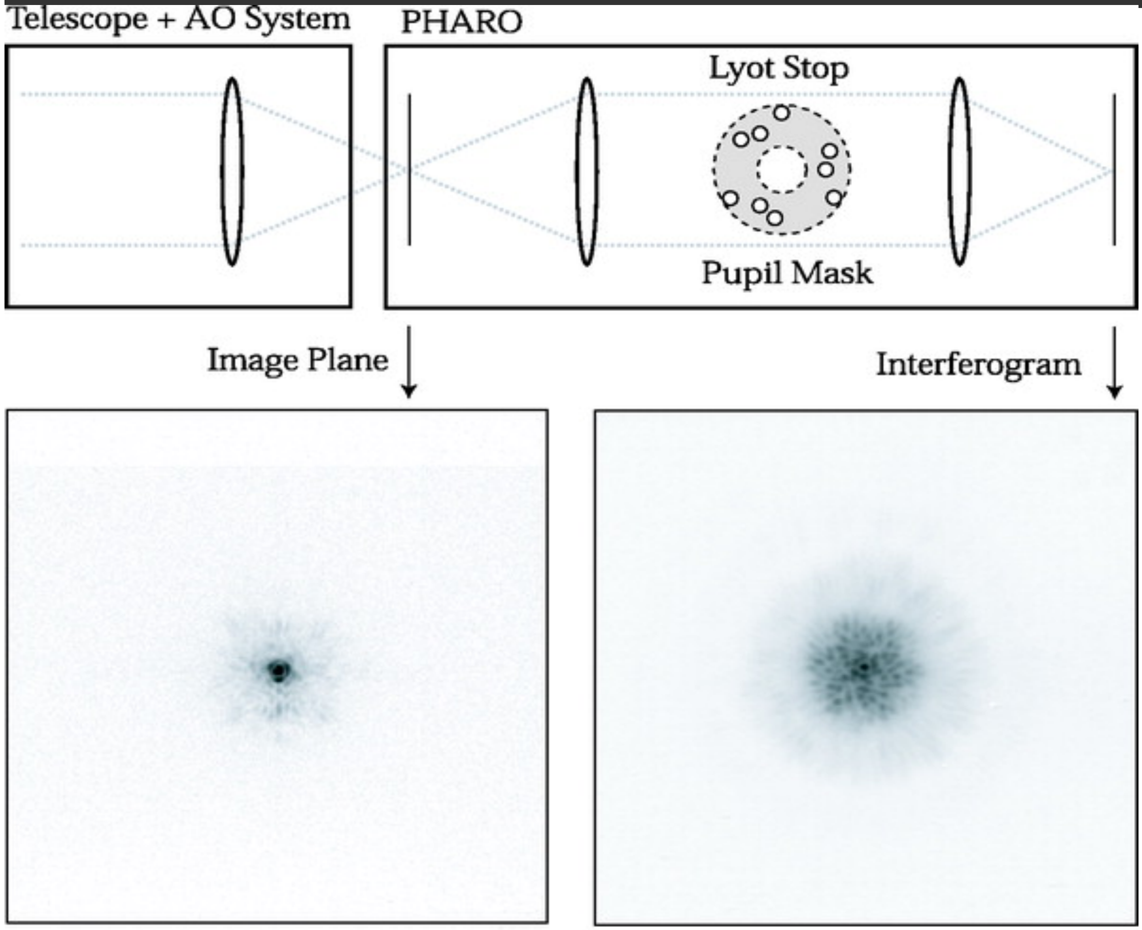
Topics I would like to see covered:

- - using Kphases for precise sensing of cophasing errors from focal plane images
- how does the technique extend to coronagraphic images ?
- - coherent photonics nulling as an alternative to conventional mask-based coronagraphy
- advantages for segmented apertures, precursor systems (photonics nuller on Subaru ?)

Outline

- Aperture Masking and Kernel-Phase/eigenphase Background
- Using an asymmetric pupil for wavefront sensing.
- Wavefront sensing for GMTIFS: intra/extra-focal images or asymmetric pupil.
- Photonic pupil segmentation and nulling: convenient phase and amplitude control with high null depth?

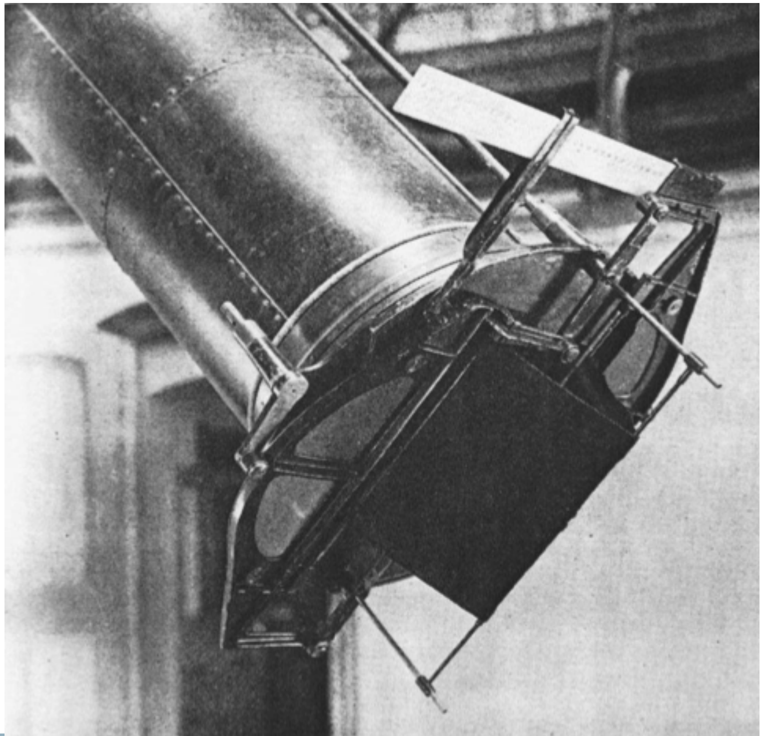
Aperture Mask Interferometry



Placing an aperture mask in the pupil plane *cleans up* aberrations like defocus, coma etc.

This enables better calibration of images, and has been used as a high-resolution imaging technique for more than 100 years (although only 2 holes before 1980).

Right: Michelson in ~1890…



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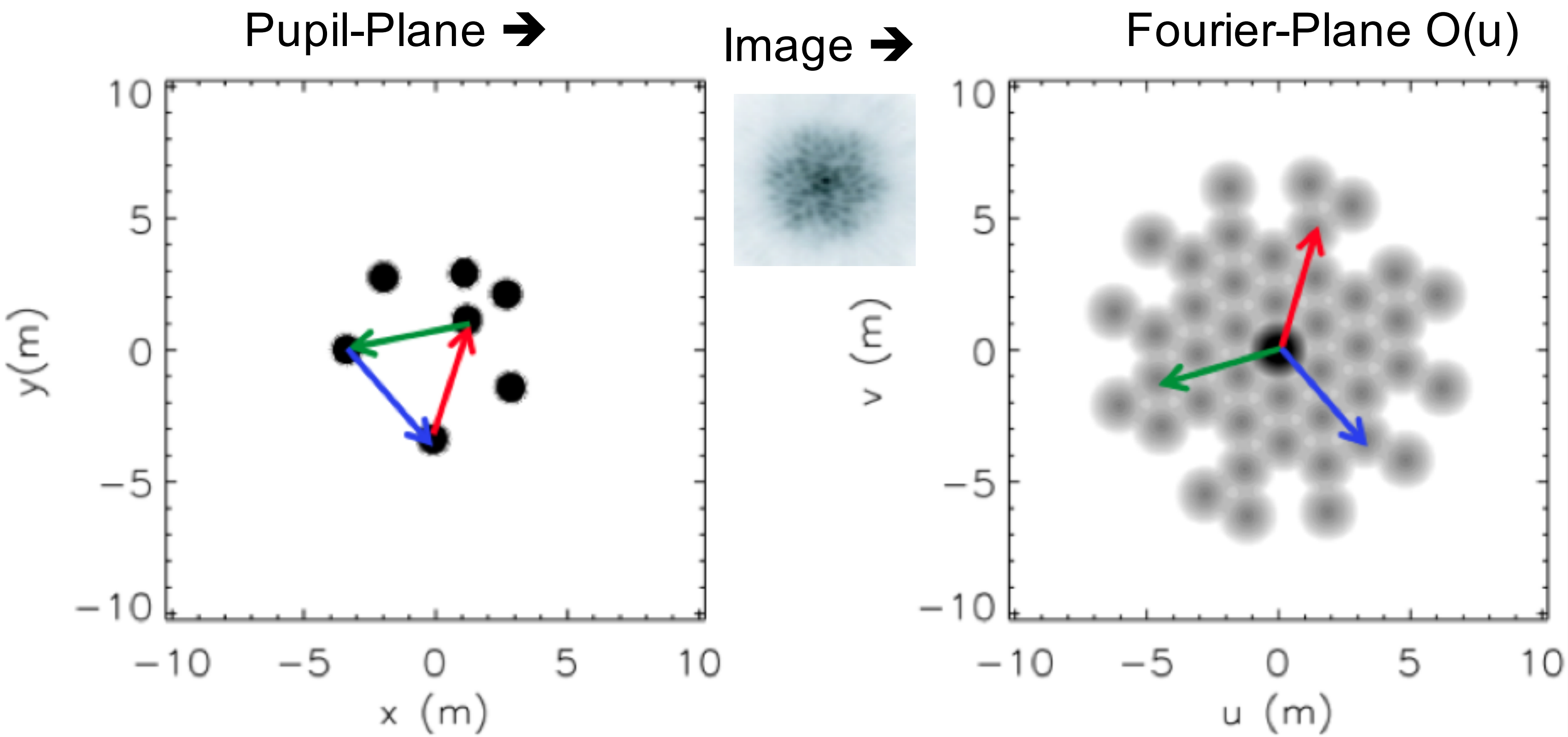
Aperture Mask Interferometry



- The primary observables are typically derived from the image Fourier-transform, which is *the auto-correlation* of the pupil function for a point-source.

$$i(\alpha) = m(\alpha) * o(\alpha) \qquad\qquad I(\mathbf{u}) = M(\mathbf{u}) \cdot O(\mathbf{u})$$

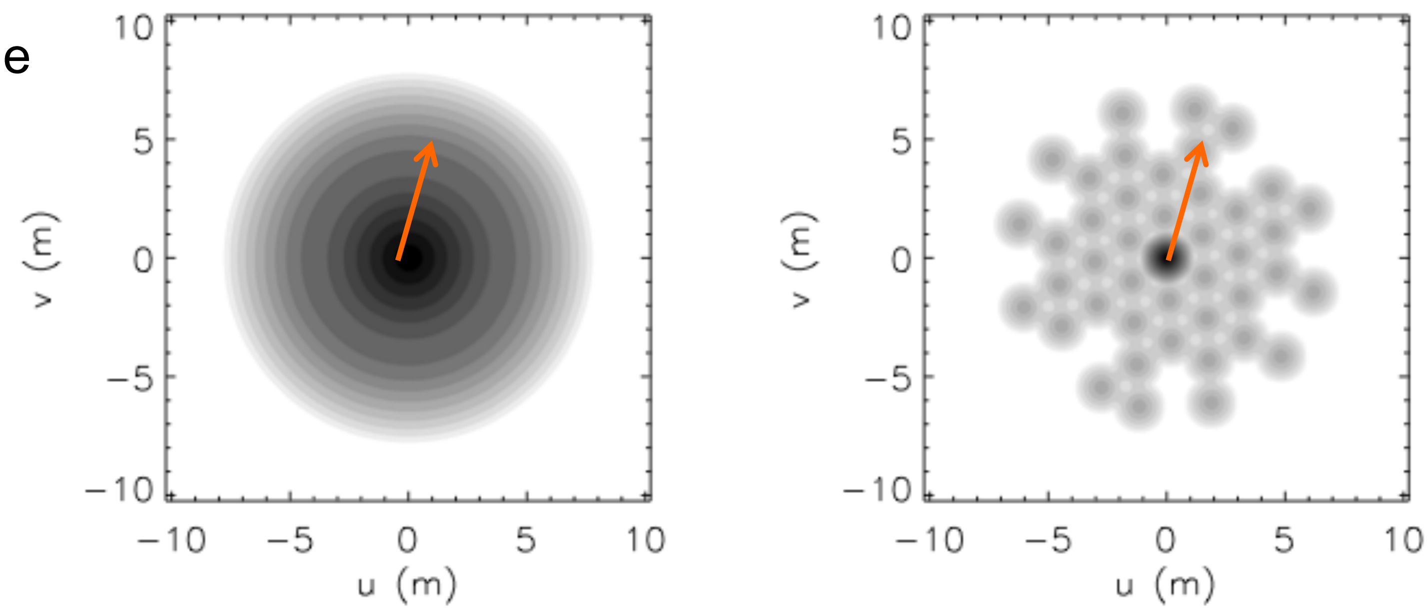
- An image *i* is formed by the convolution of a PSF *m* and the true object *o*. This is simply multiplication in the Fourier domain – as long as most of the Fourier plane is covered, the object information is available.

Full Pupil Versus SAM/NRM

In the (*u*,*v*) or Fourier-plane (image Fourier transform), Sparse Aperture Masking (SAM, Europe) or Non-Redundant Masking (NRM, US) has a much smaller pupil-plane footprint for each baseline compared to a full pupil.

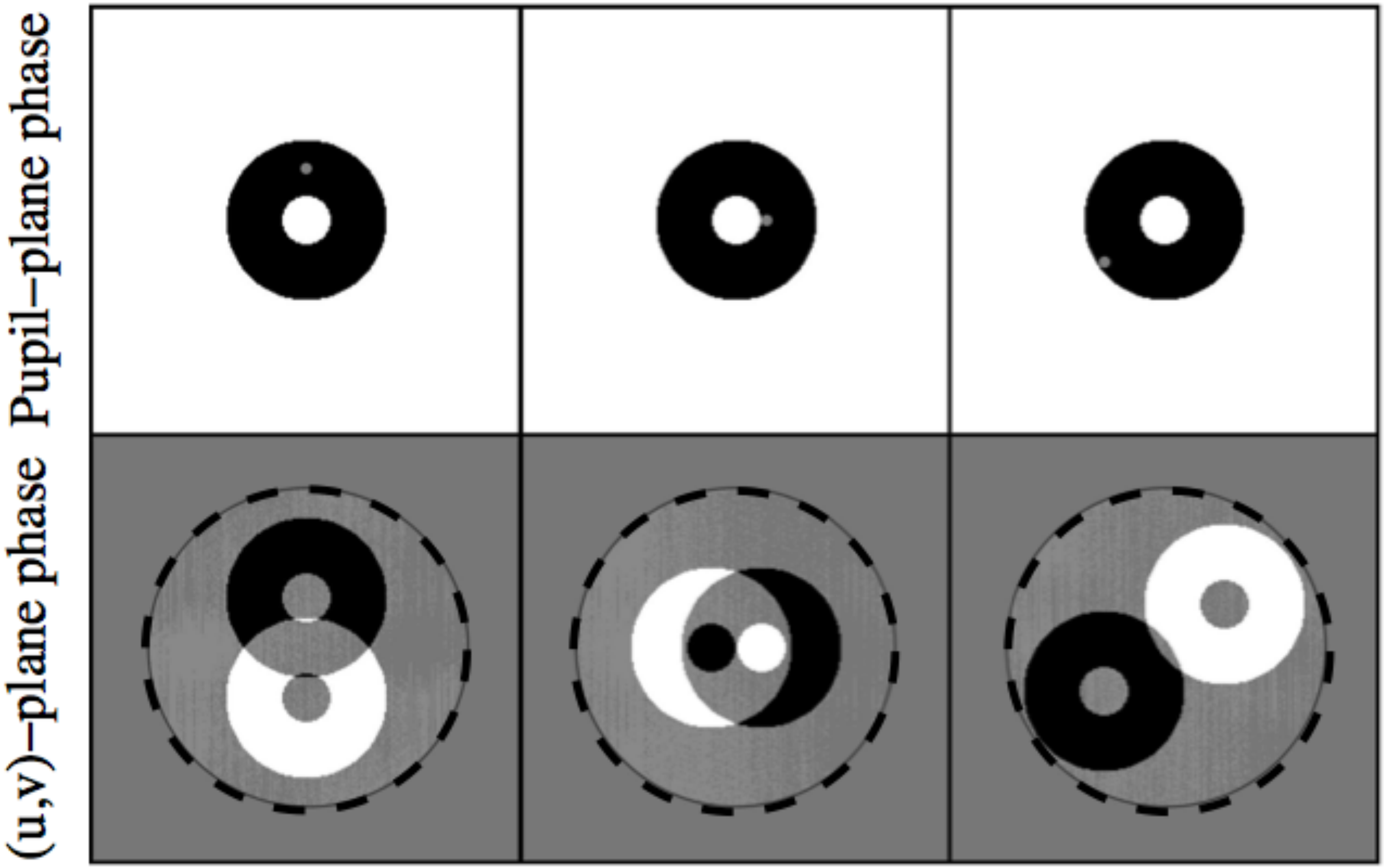
However, the (*u*,*v*)-plane remains mostly filled.

Despite losing light, high-angular resolution information is retained and calibrates better.

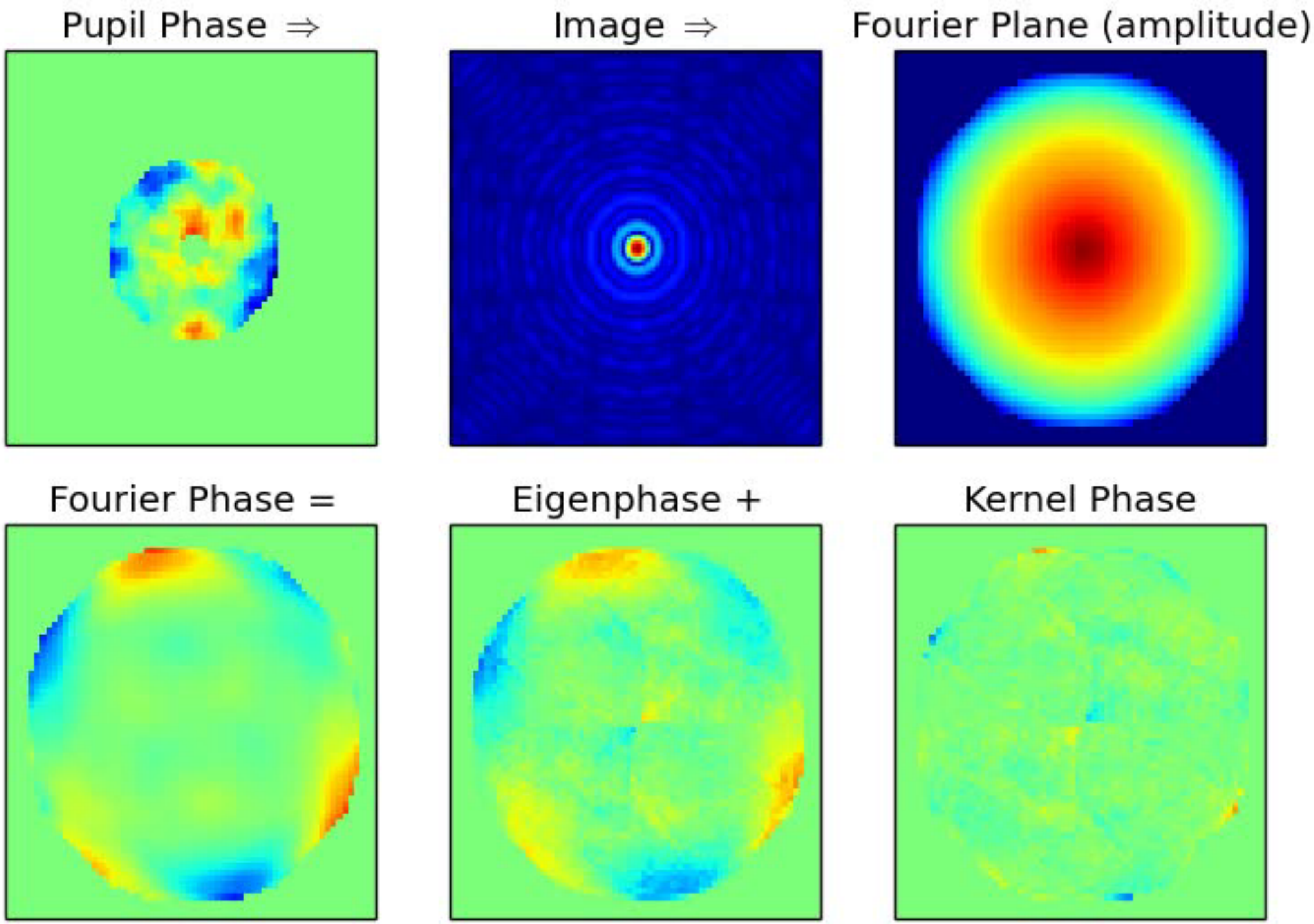


Kernel Phase

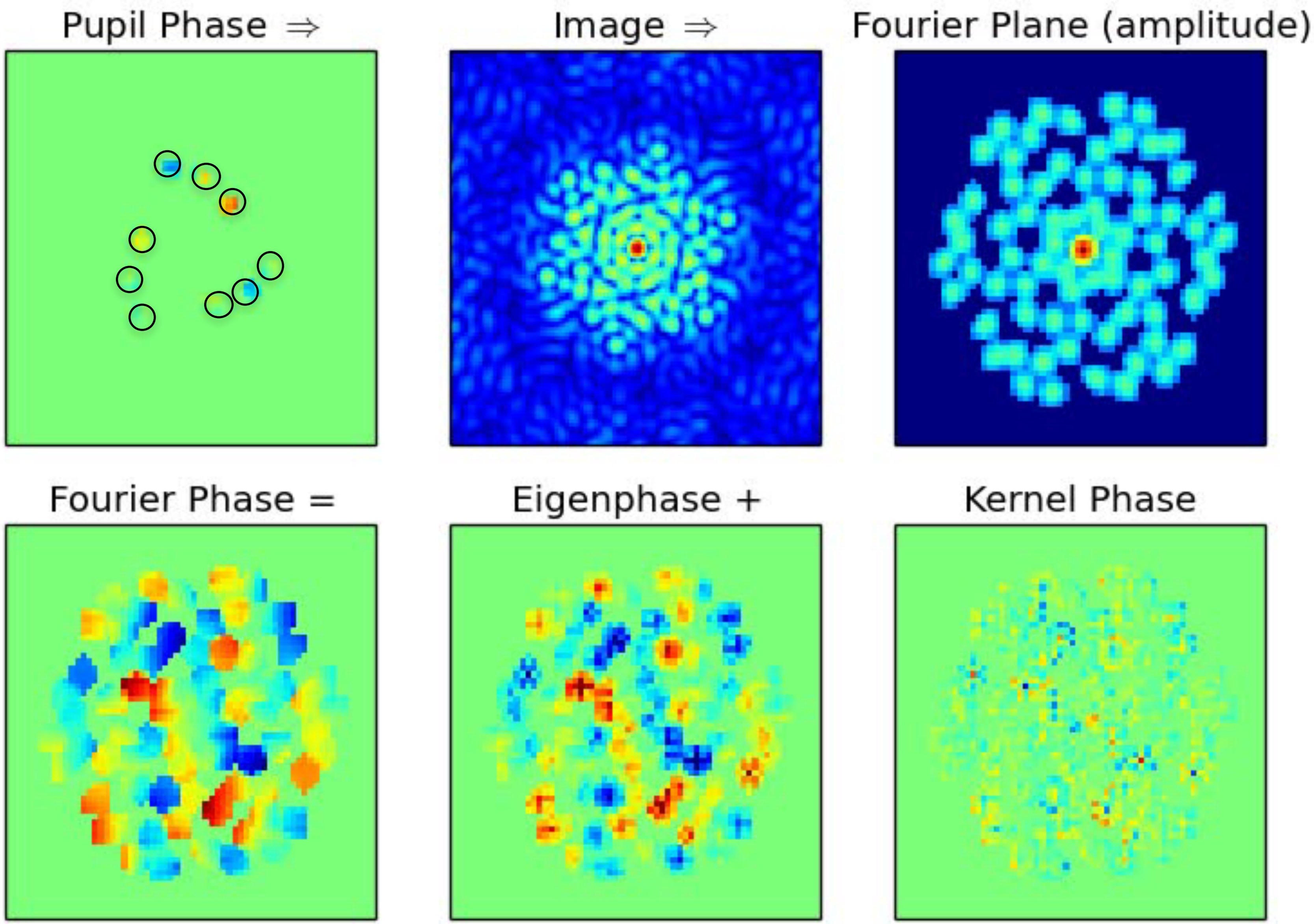
There is *always* more phase information in the (u,v)-plane than the pupil-plane. This extra information is the *Kernel-Phase* (Martinache 2010) and represents the smallest principle components of Fourier phase on point source images.



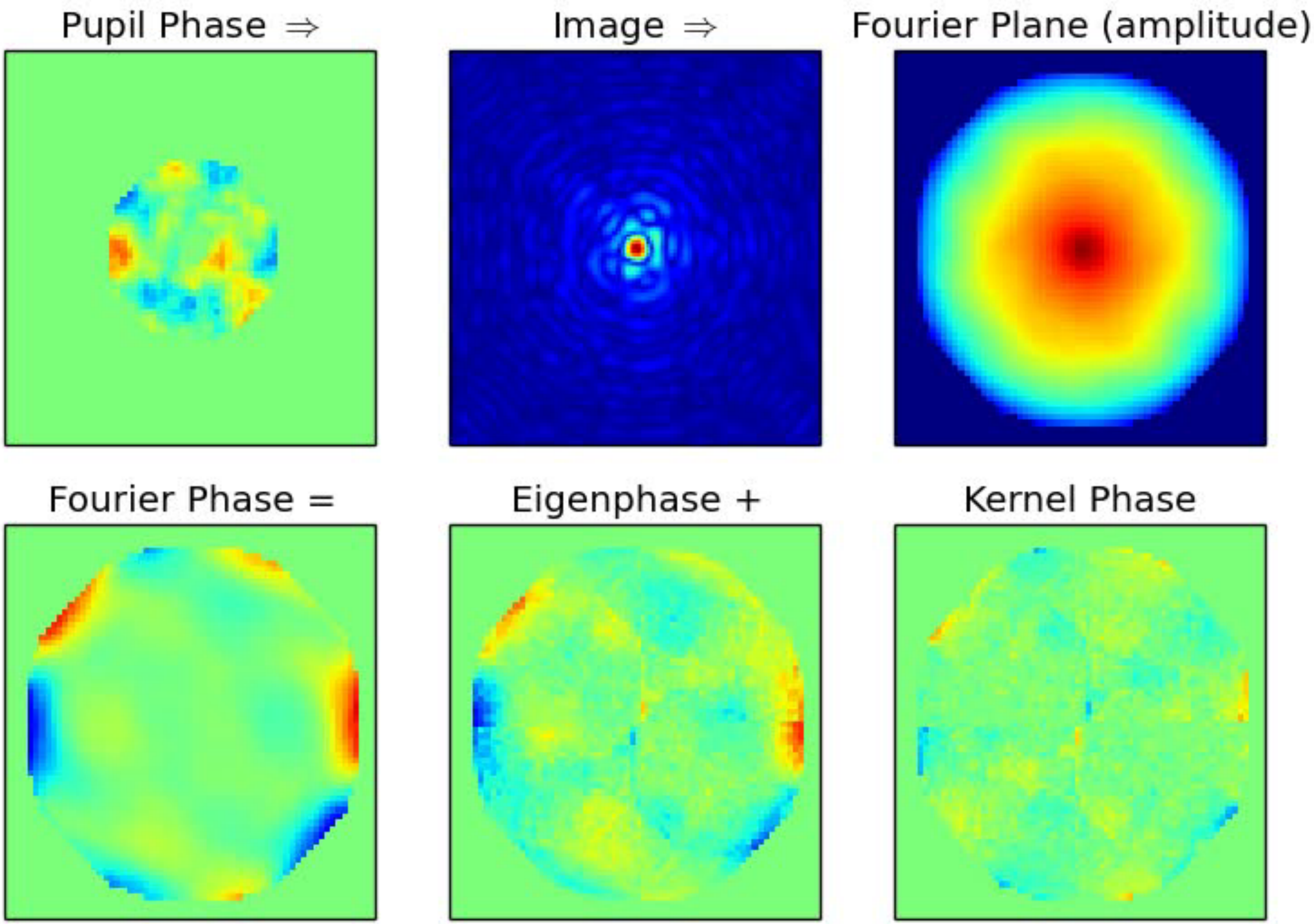
Example: High Strehl (full pupil)



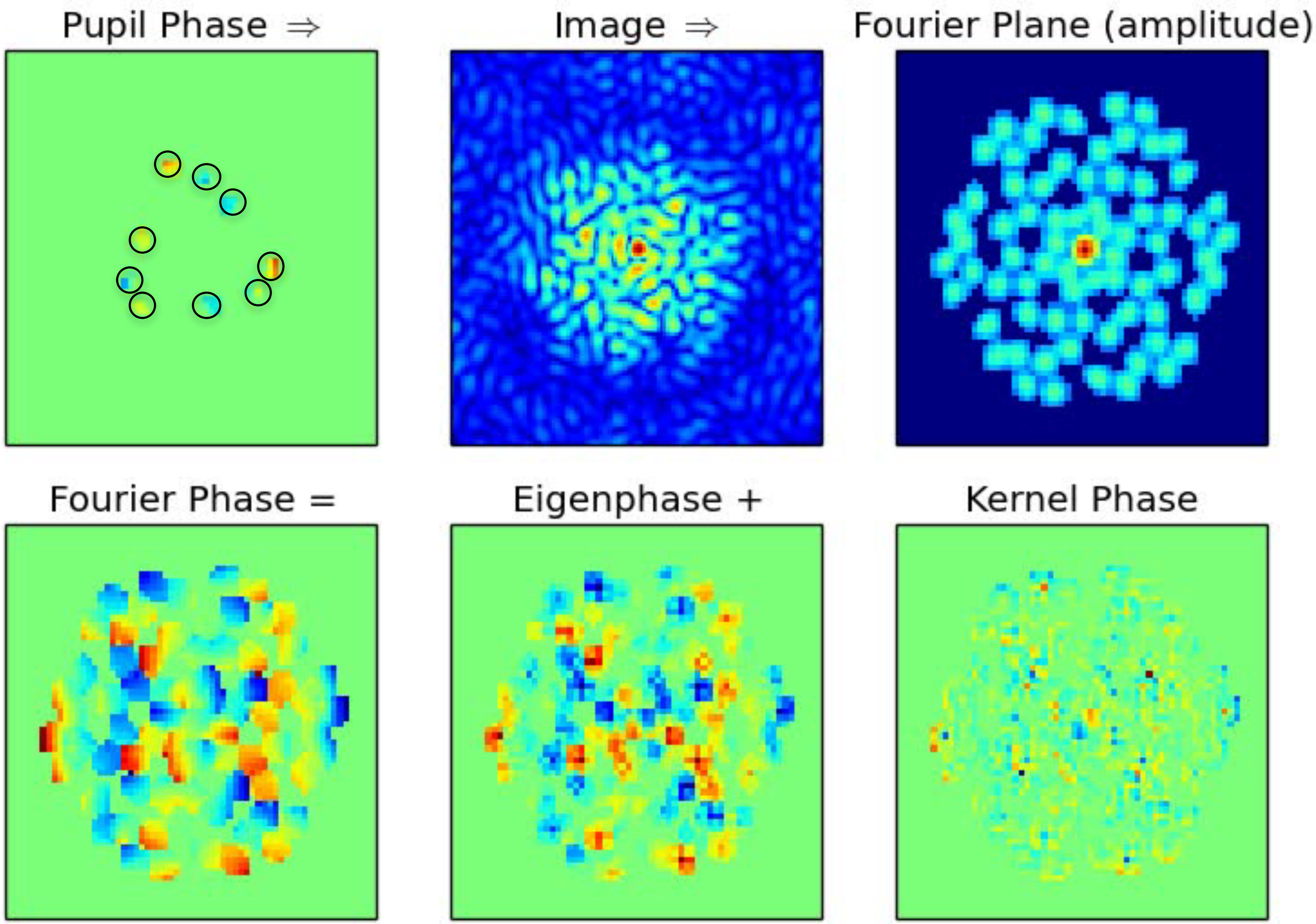
Example: High Strehl (9h mask)



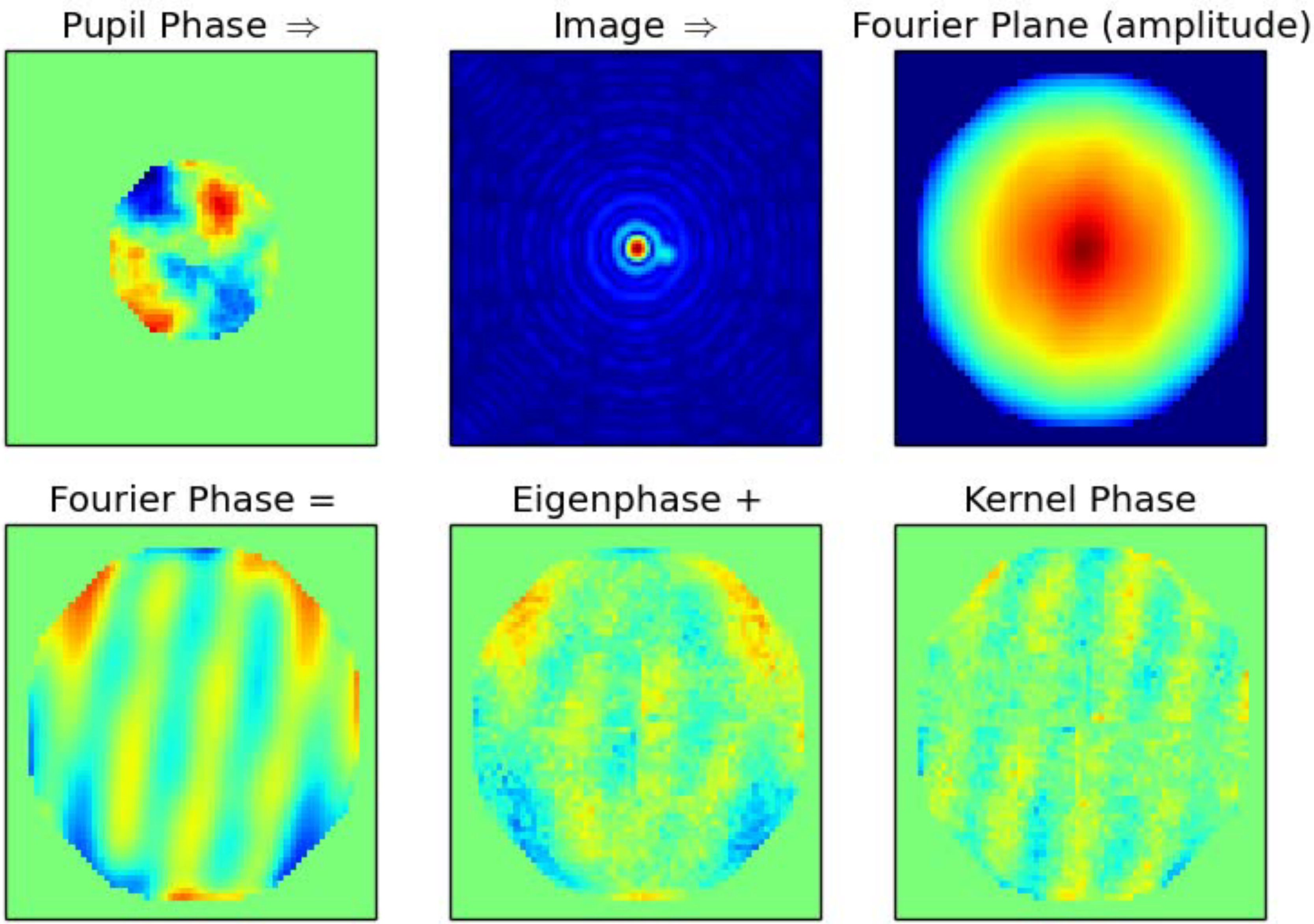
Example: Low Strehl (full pupil)



Example: Low Strehl (9h mask)



Example: With Binary (full pupil)

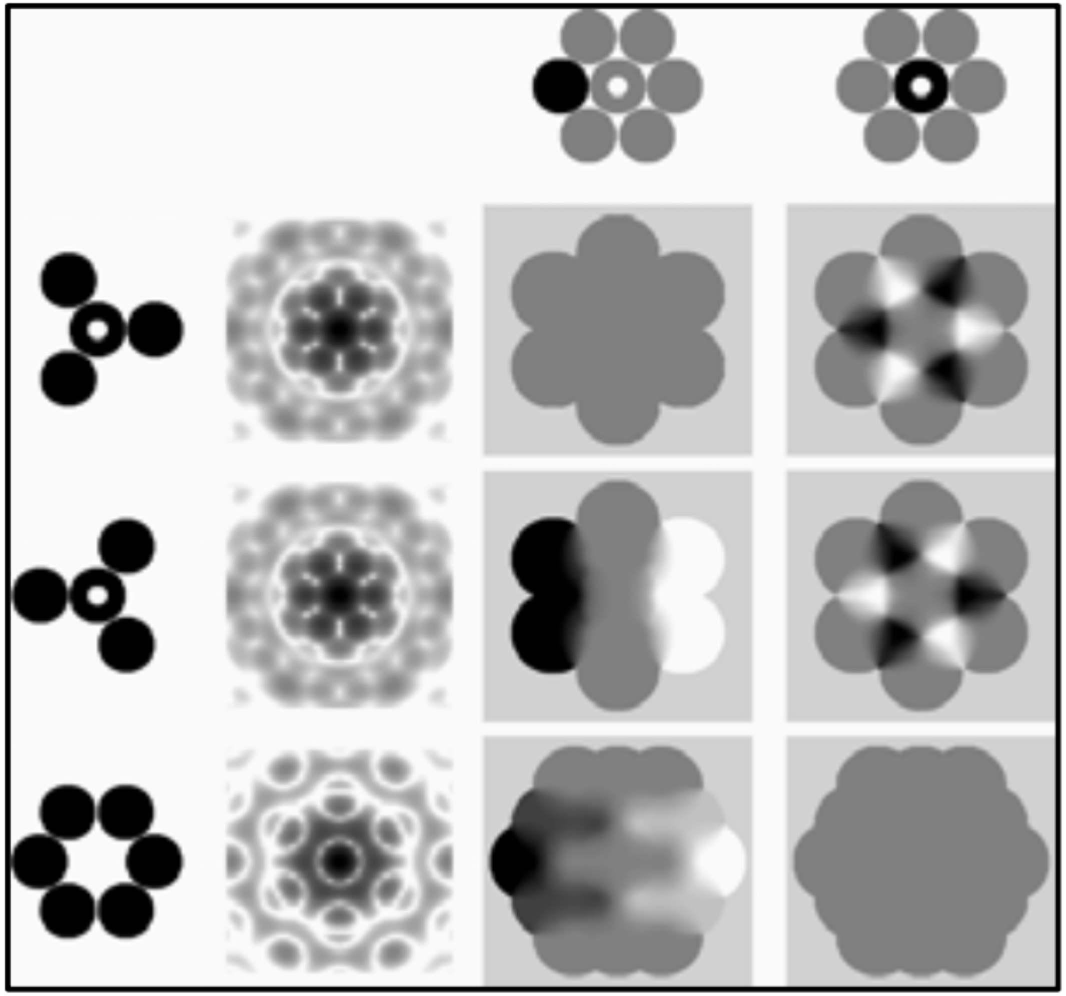


Five recent published/submitted) masking phase or Kerphase implementations:

- Angel and Lloyd-Hart (AMOS figure caption, 2005)
- Cheetham et al. (Optics Express, 2014): Masking only.
- Martinache et al. (PASP, 2013; ApJ, 2016): asymmetric full-pupil mask + SCExAO
- Pope et al. (SPIE and MNRAS, 2014): asymmetric full-pupil mask + SWIFT/
- Greenbaum et al. (submitted): full-pupil +masking.

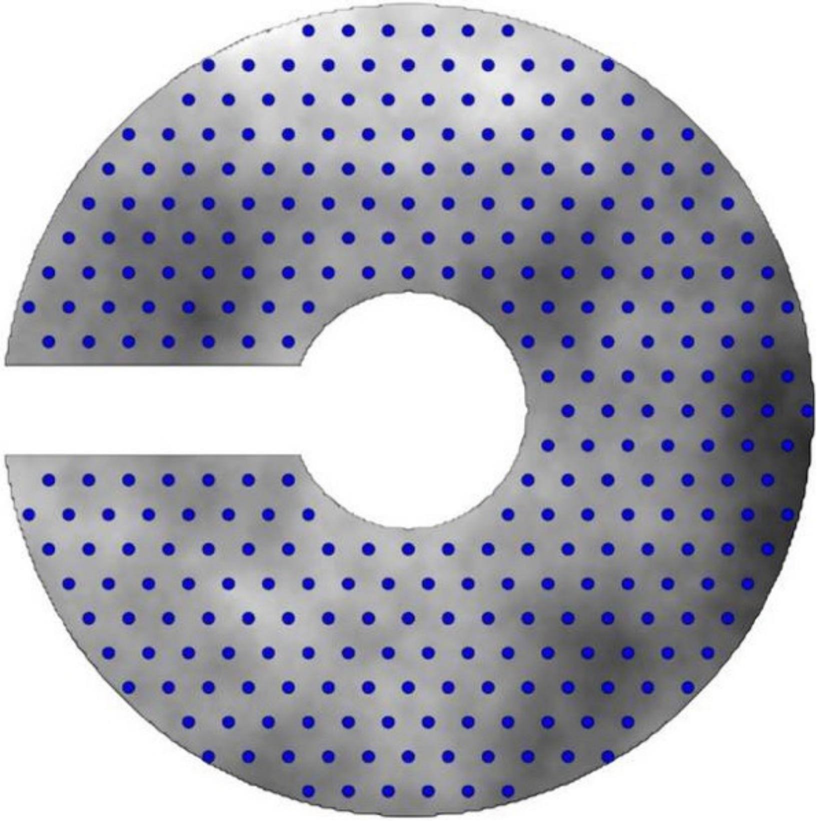
[my 2002 honours thesis and Monnier et al. 2004,2008,2009: masking only]

Angel/Lloyd Hart et al (2005) concept

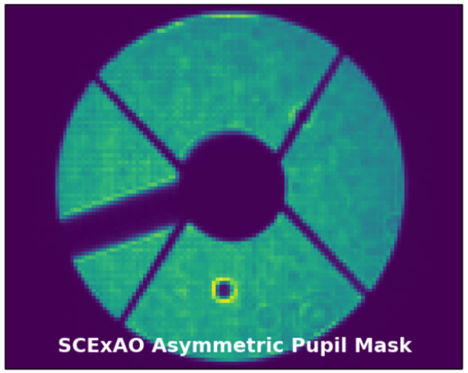


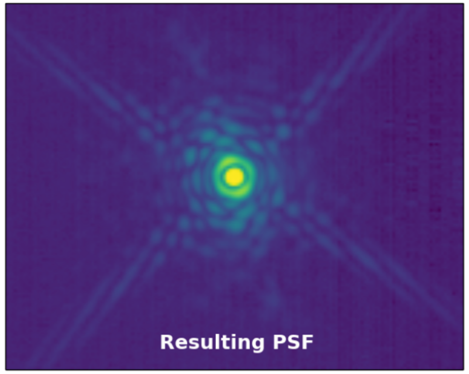
- Original GMT NGS piston phasing concept.
- Pupil split 3 ways, with strong signals in MTF phase.
- Given up on (I think) because in practice it needed >3 movable infrared WFS.

The Asymmetric Pupil



- The Fourier plane (FT of the image) is the autocorrelation of the pupil
  - Not sensitive to all symmetries! A symmetric pupil can sense only even modes
- A Fourier wavefront sensor needs to have pupil asymmetry to sense asymmetric modes
  - This could be achieved with thick spider(s), e.g. right.
  - Alternatively, could mask out subapertures

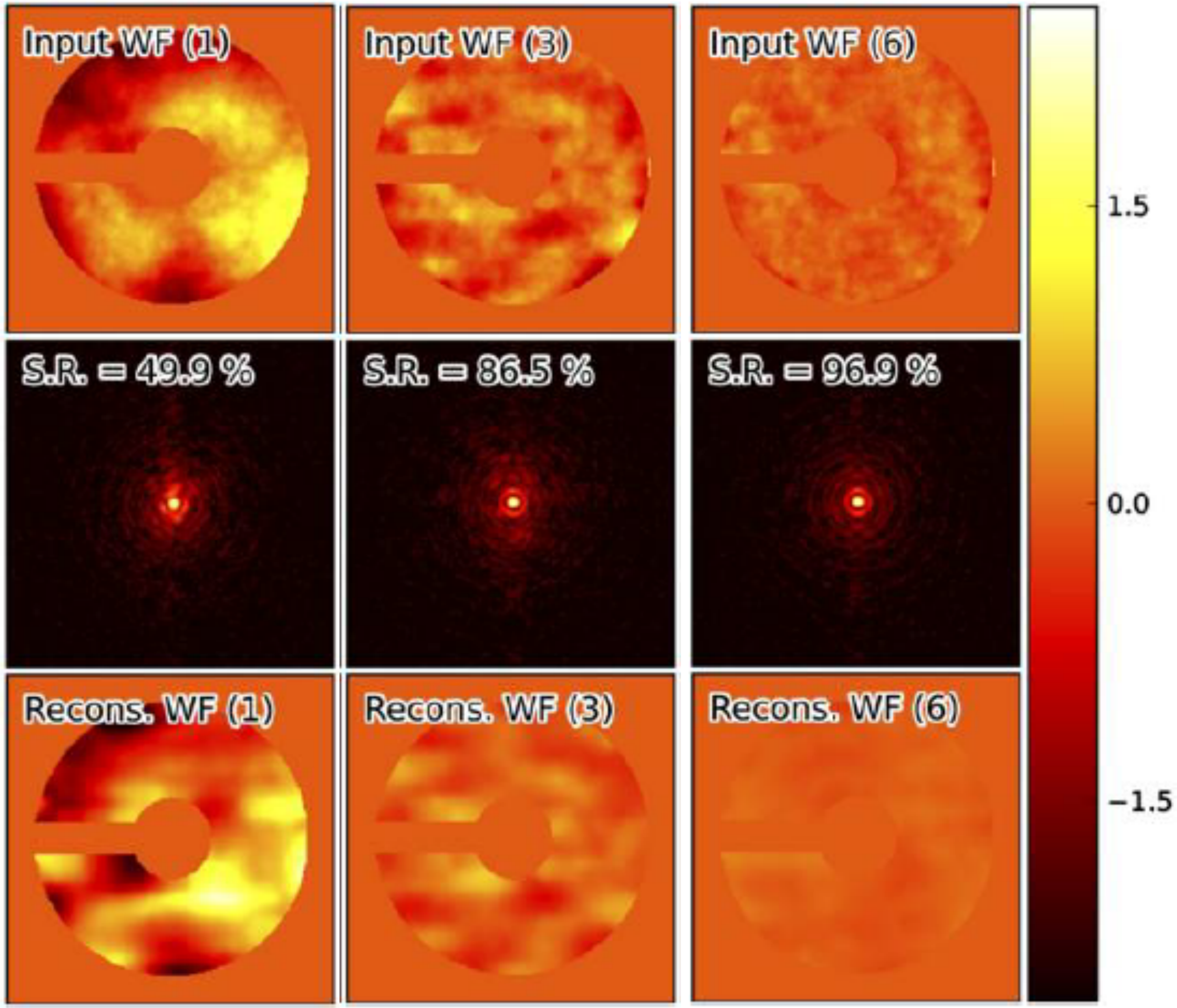




Martinache (2013, 2016) and Pope (2014)

Martinache Wavefront Sensor Simulations

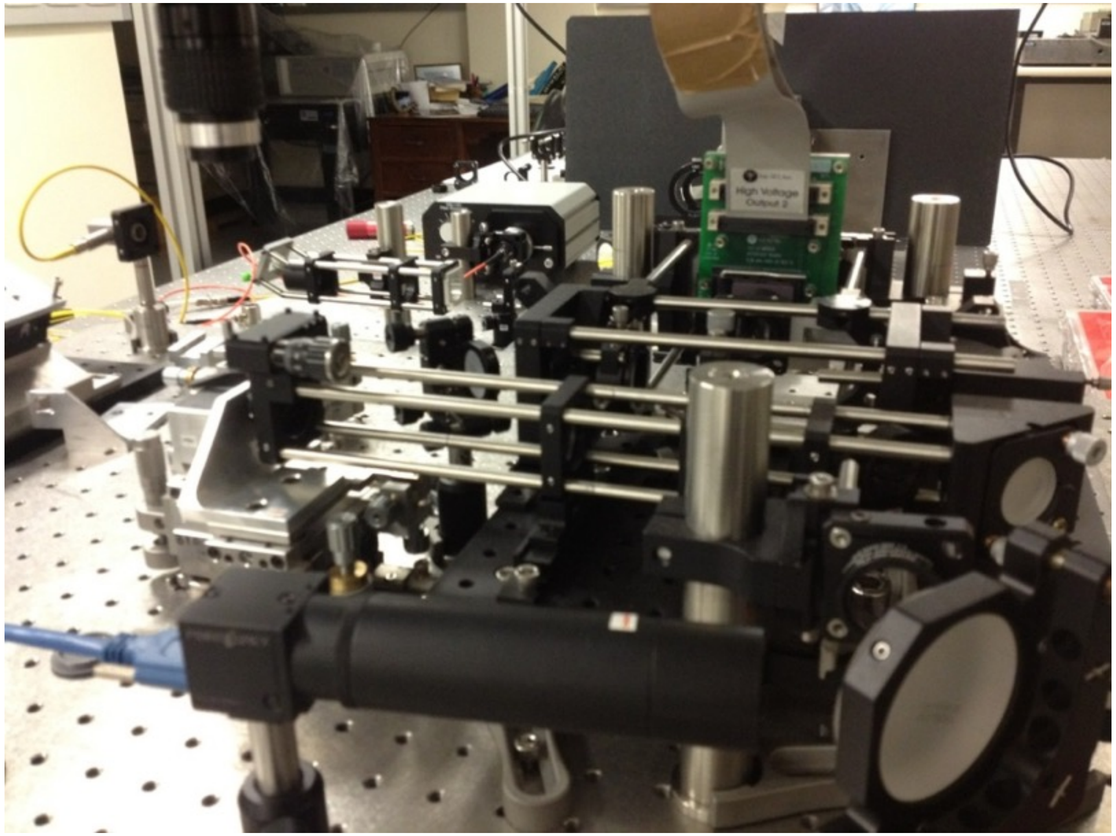
- Uses row phases (complement of kernel space, sometimes called eigenphases)
- Wavefront sensor is your science camera!
- Initial Strehl > 35% required – can iterate to as high as 97% in simulations
- Sensitivity near-optimal for a given flux and wavefront error



Martinache (2013) and Pope (2014)

Usyd Experimental Setup

- The microelectromechanical (MEMS) segmented mirror from Dragonfly was used as a JWST analogue
- This has piston, tip and tilt on each segment with ~ few nm precision
- Phasing JWST is hard – no apparatus in space!
- Ideal test case for the new wavefront sensor



Pope (2014)

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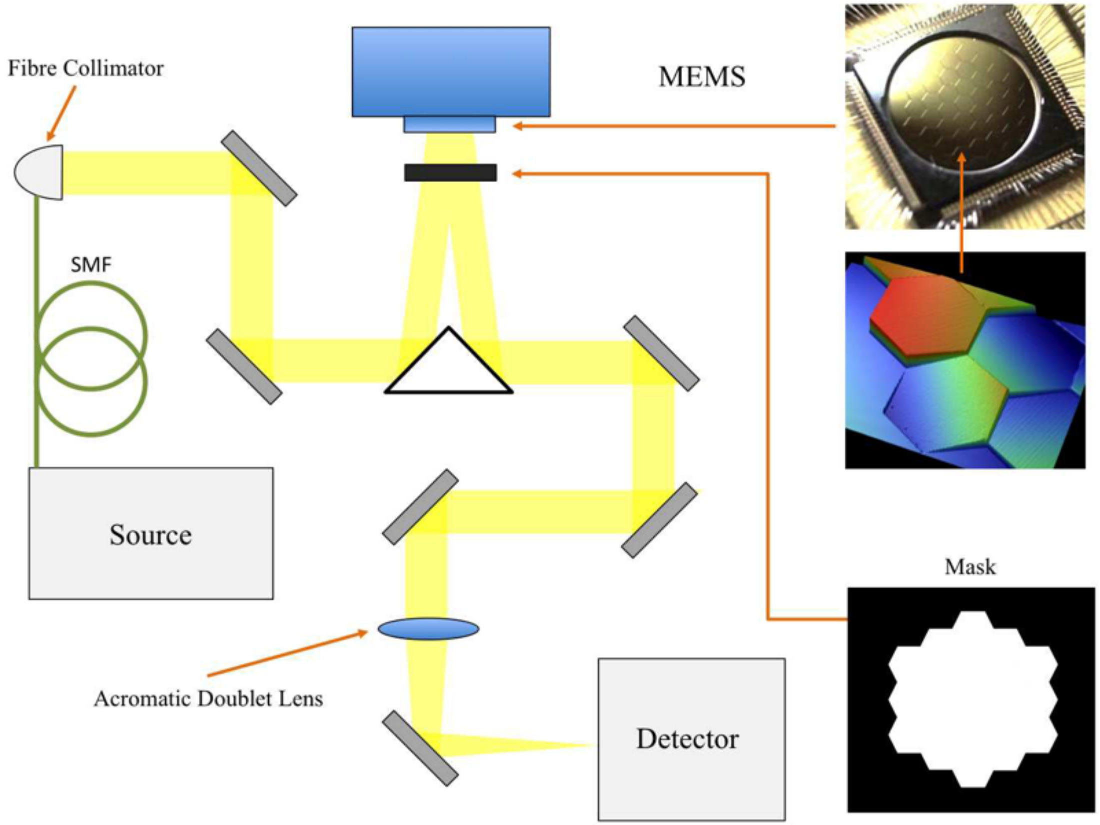
Experimental Setup II

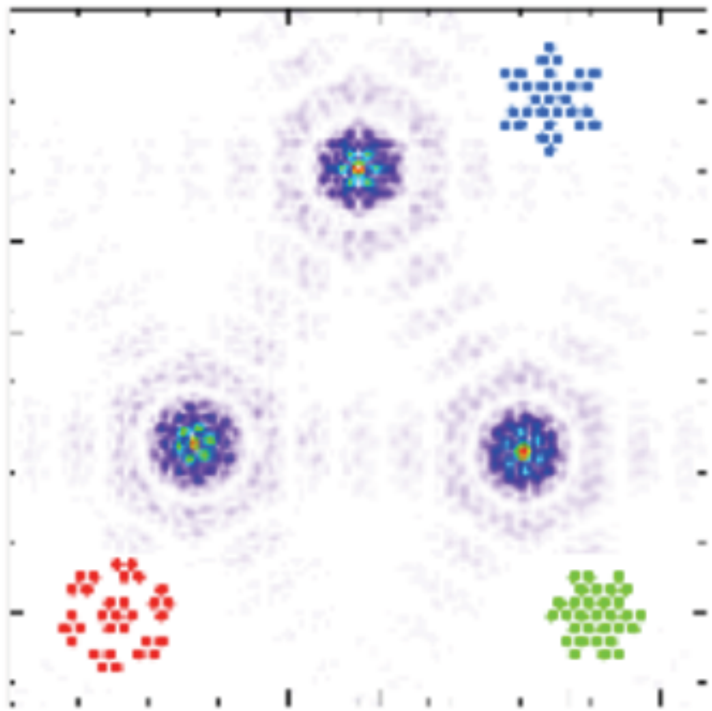
- Laser introduced from single mode fibre
- Passed to MEMS array and through mask
- Imaged onto Xenics IR camera



Pope (2014)

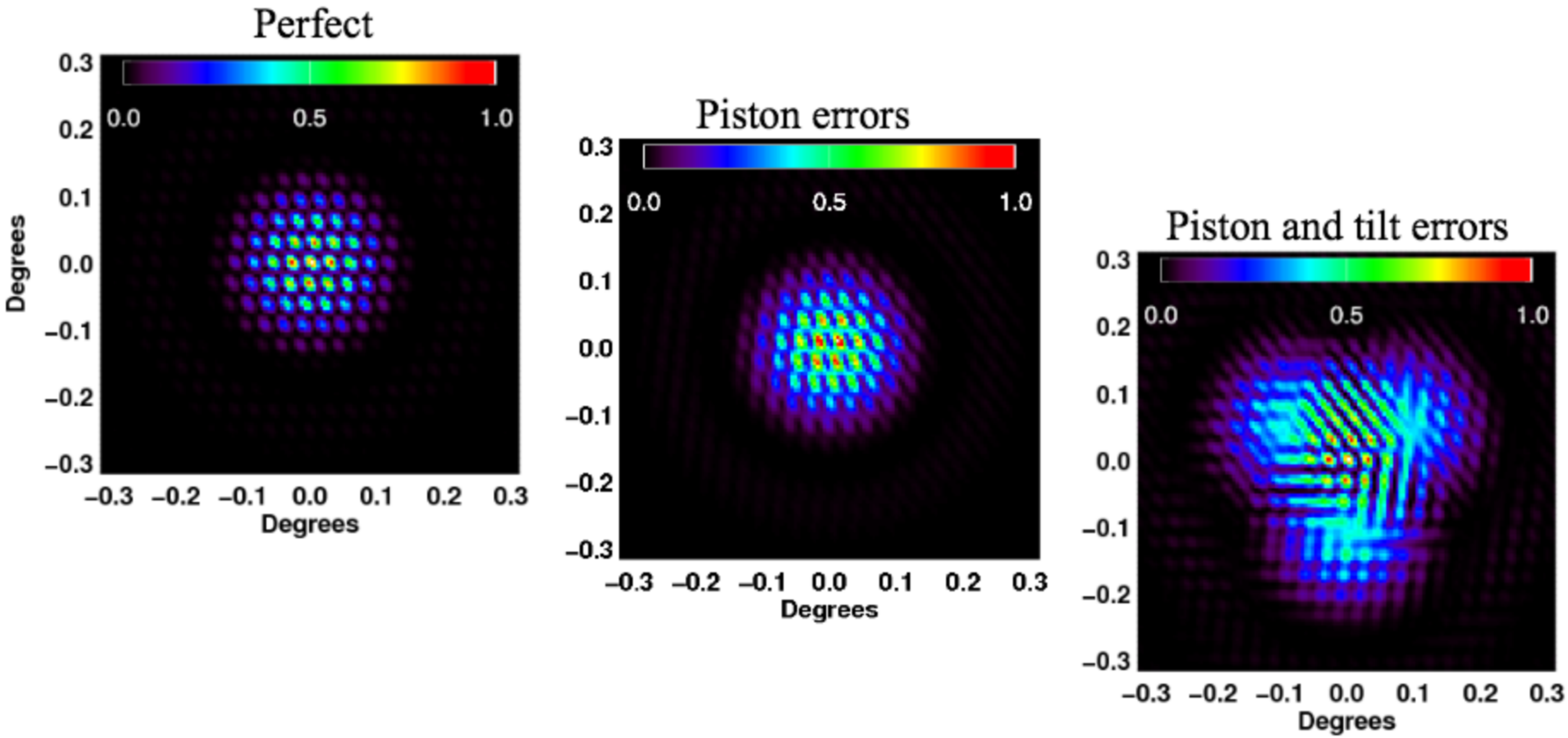
First Step - FICSM

- The first step in phasing a segmented mirror like this is the FICSM approach – ‘Fizeau interferometric cophasing of segmented mirrors’ (Cheetham et al.)



Pope (2014),
Cheetham (2014)

FICSM – Monochromatic data



Pope (2014),
Cheetham (2014)

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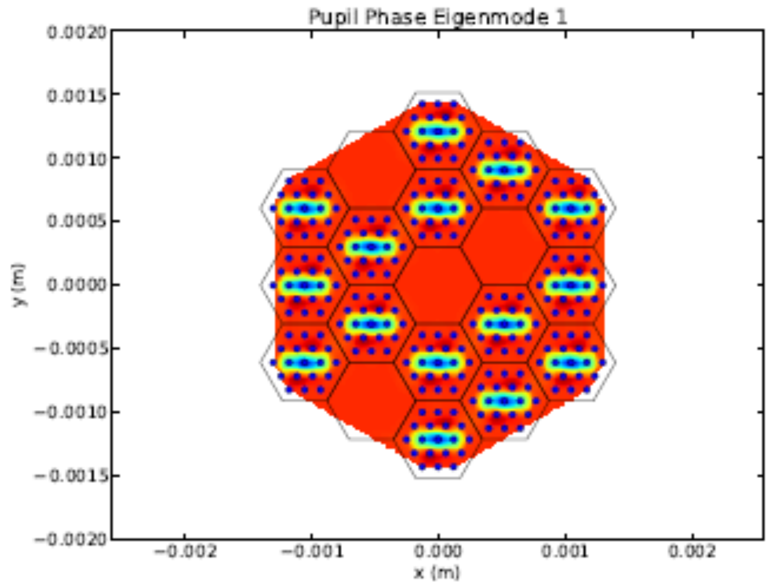
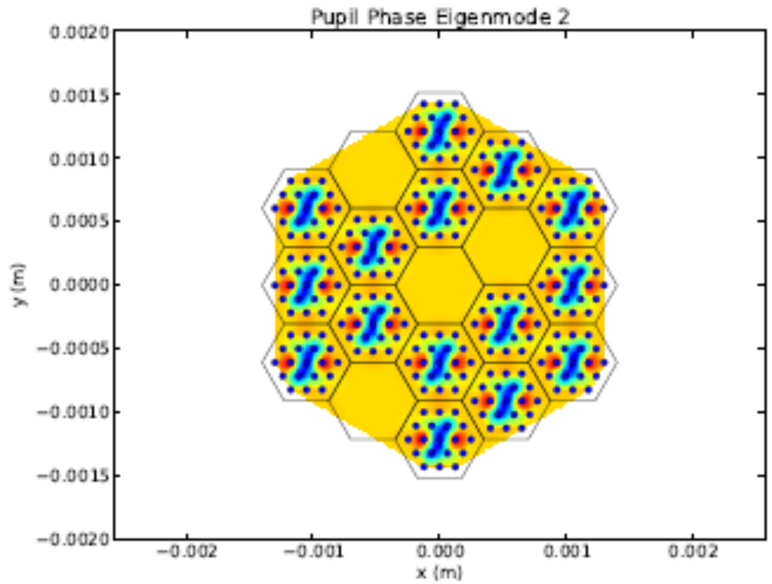
Pupil Modes

- Below: examples of normal modes of the discrete pupil model used in our experiment
- These play the role of the Zernike basis for expanding optical aberrations on a circular pupil





Pope (2014), Cheetham (2014)

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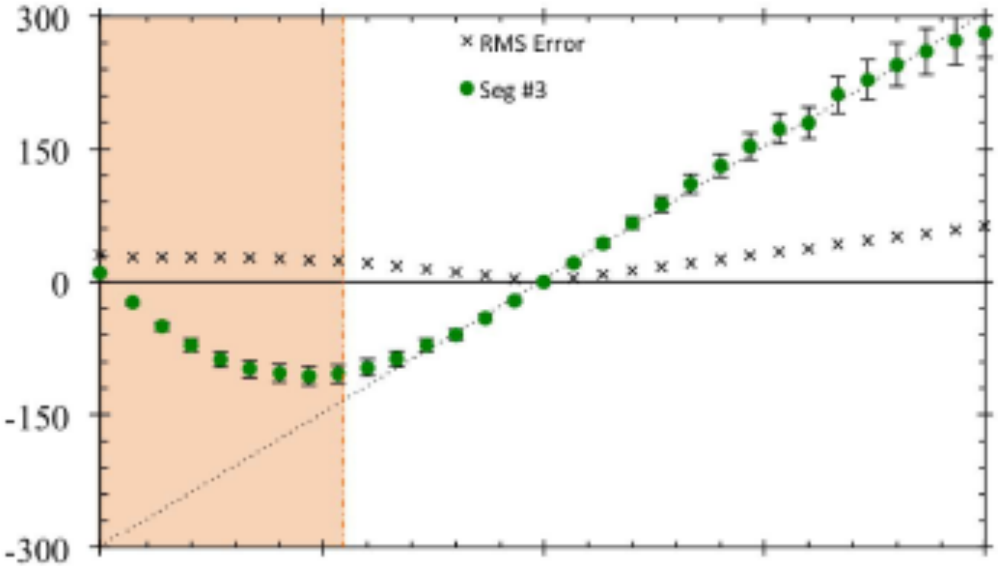
How well can we Measure a Single Segment?

- Pistoned a single segment (3) in 20 nm steps from -300 to +300
- Reconstruction is very accurate… within limits
- You lose it when linearity fails
- Phases are also correlated – sensing modes globally is a bad way to reconstruct phases on a single segment
- When phasing the whole mirror in closed loop, this correlated error beats down to zero as you make the whole thing flat



Pope (2014), Cheetham (2014)

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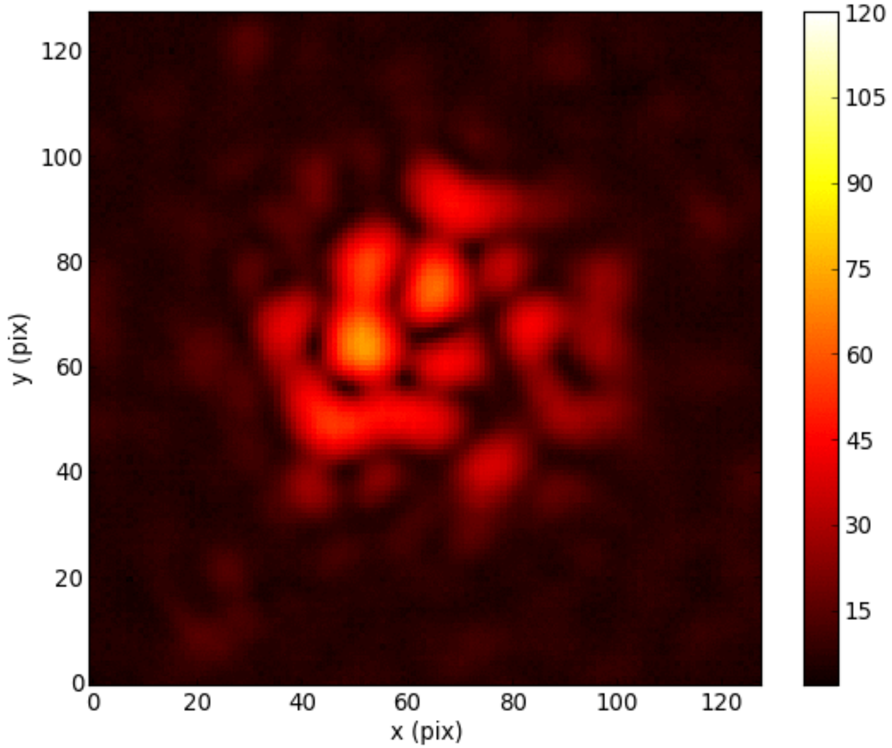
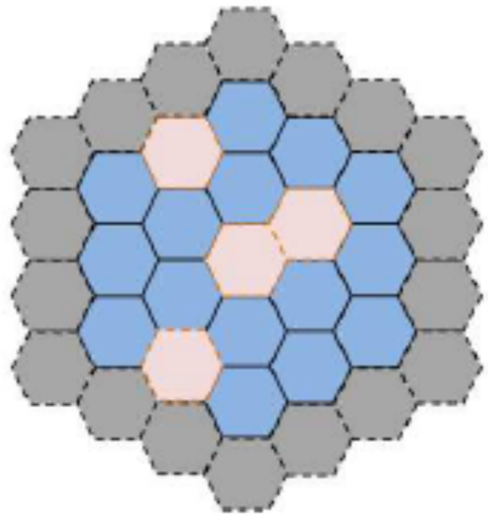
Restoring a PSF

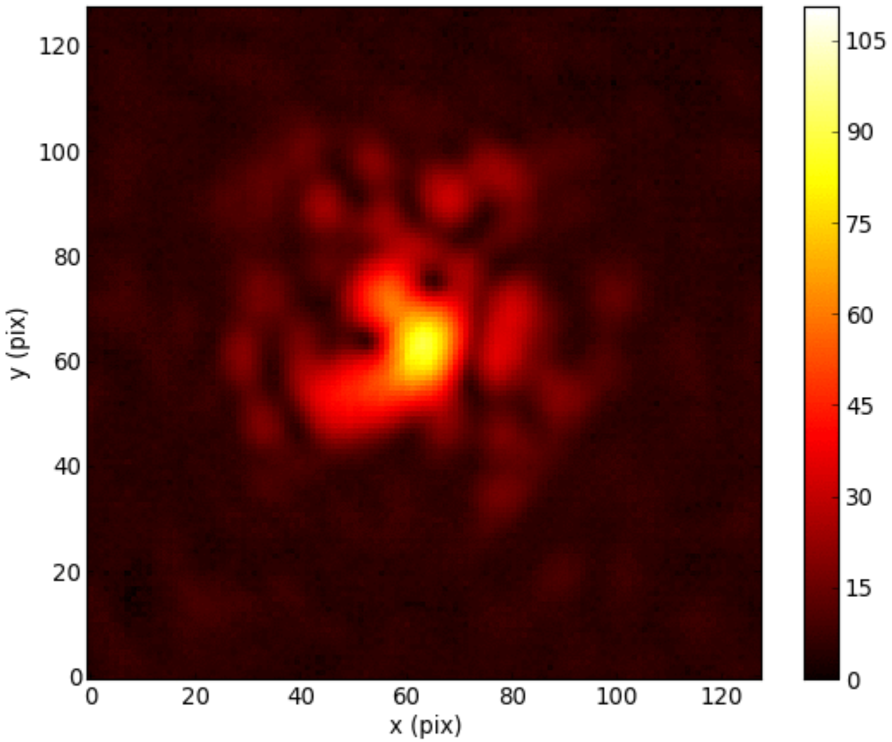


- Left: animation of a stretched PSF as our algorithm converges
- This is with a scalene triangle of segments removed

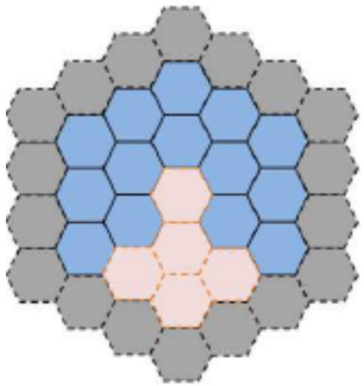


Pope (2014), Cheetham (2014)

Restoring a PSF



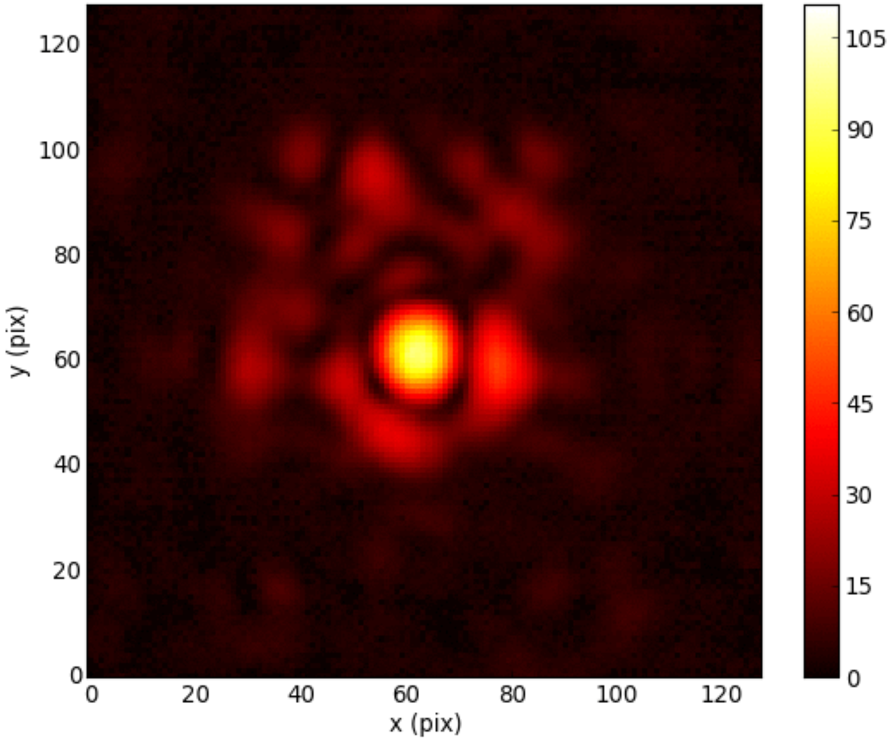
- Also works with a wedge removed

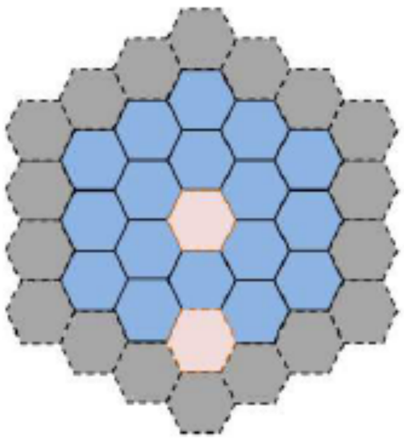


Pope (2014), Cheetham (2014)

Restoring a PSF

- Or in fact a single segment!





Pope (2014), Cheetham (2014)

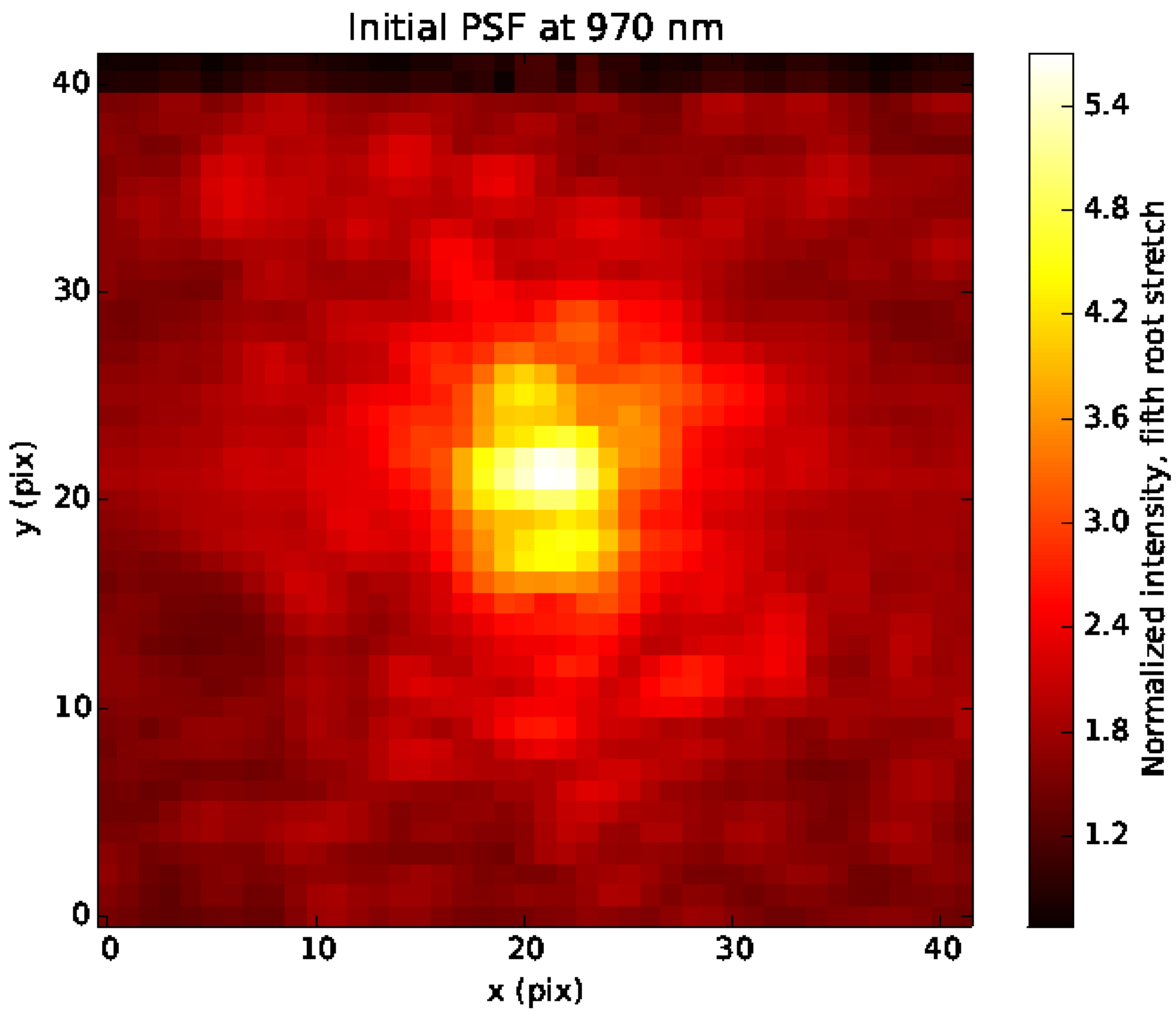
Oxford-SWIFT at Palomar

- Hale 200-inch telescope has the PALM-3000 extreme AO system – the highest order AO currently available for experiments
- Oxford has the Short Wavelength Integral Field specTrograph (SWIFT) on P3K – a high spatial and spectral resolution IFU from 650-1000 nm
- SWIFT has historically had problems with non common path error – never achieves even internal diffraction limit
  - Hard to correct with conventional methods, because of the optical layout
- Ideal test case for our wavefront sensing method

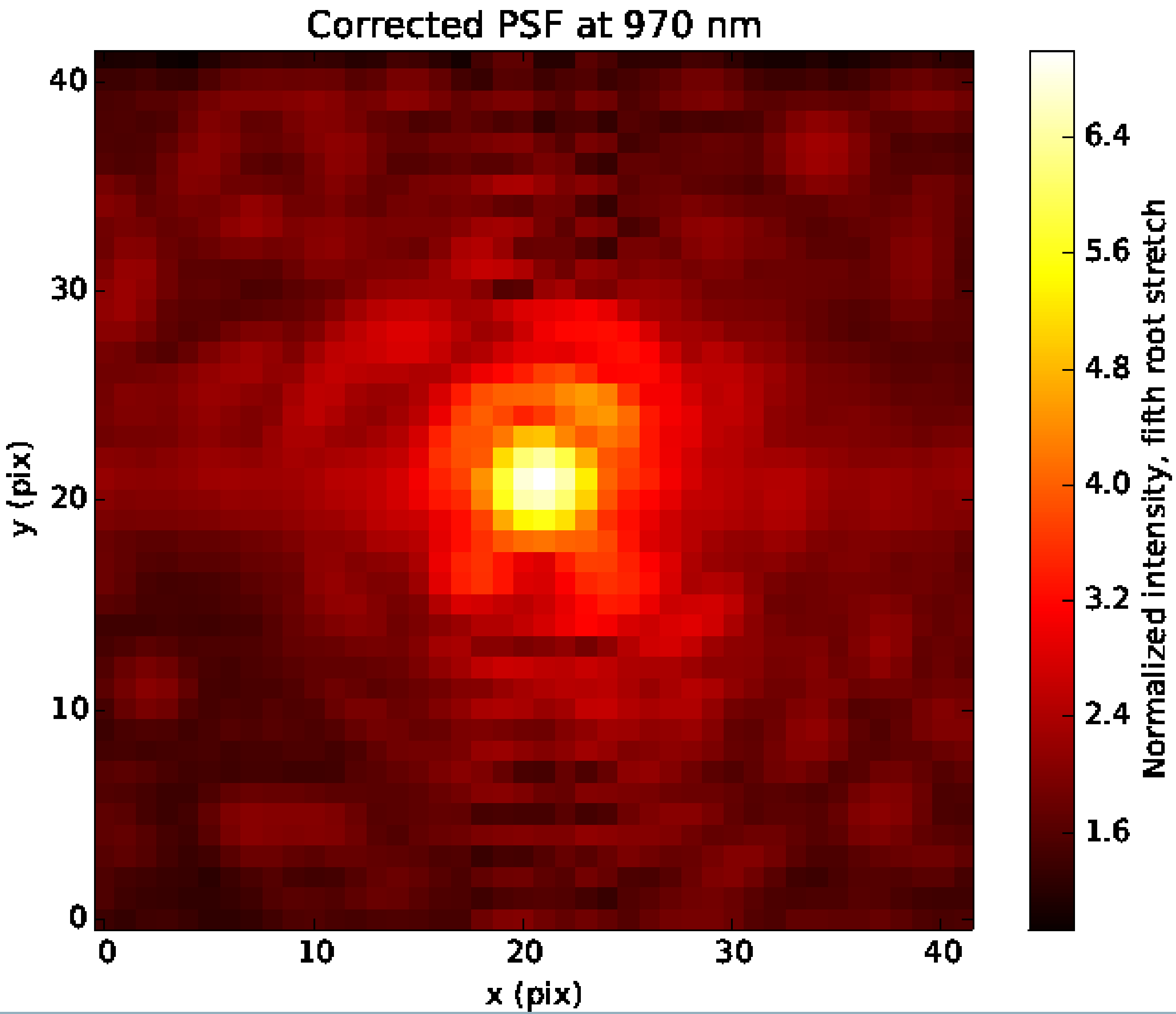
HODM Mask

- Right: the mask we placed over the high order DM to get the pupil asymmetry
- This was probably overkill, but we wanted to make sure it worked the first time!

Before Phasing

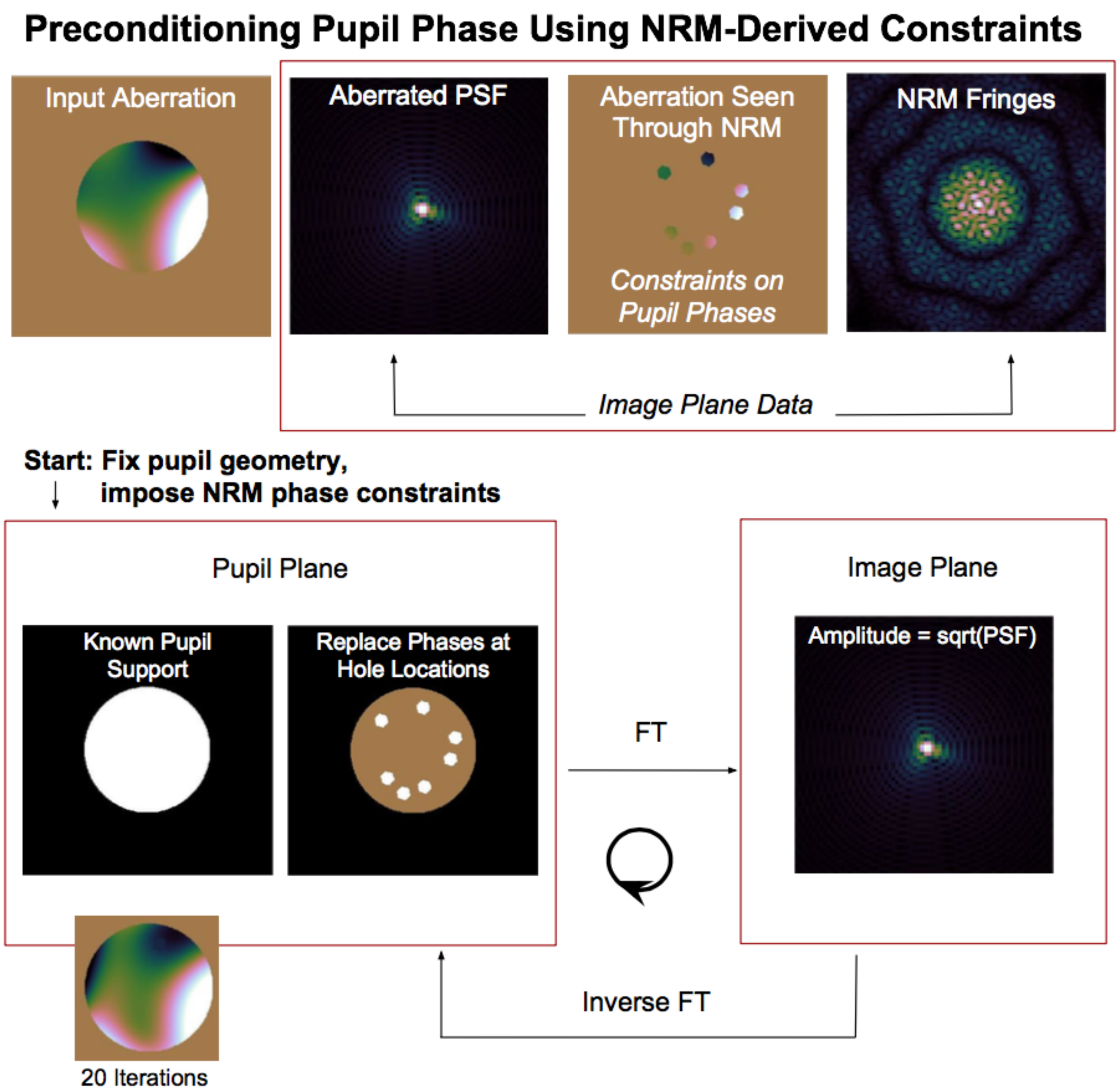


After Phasing

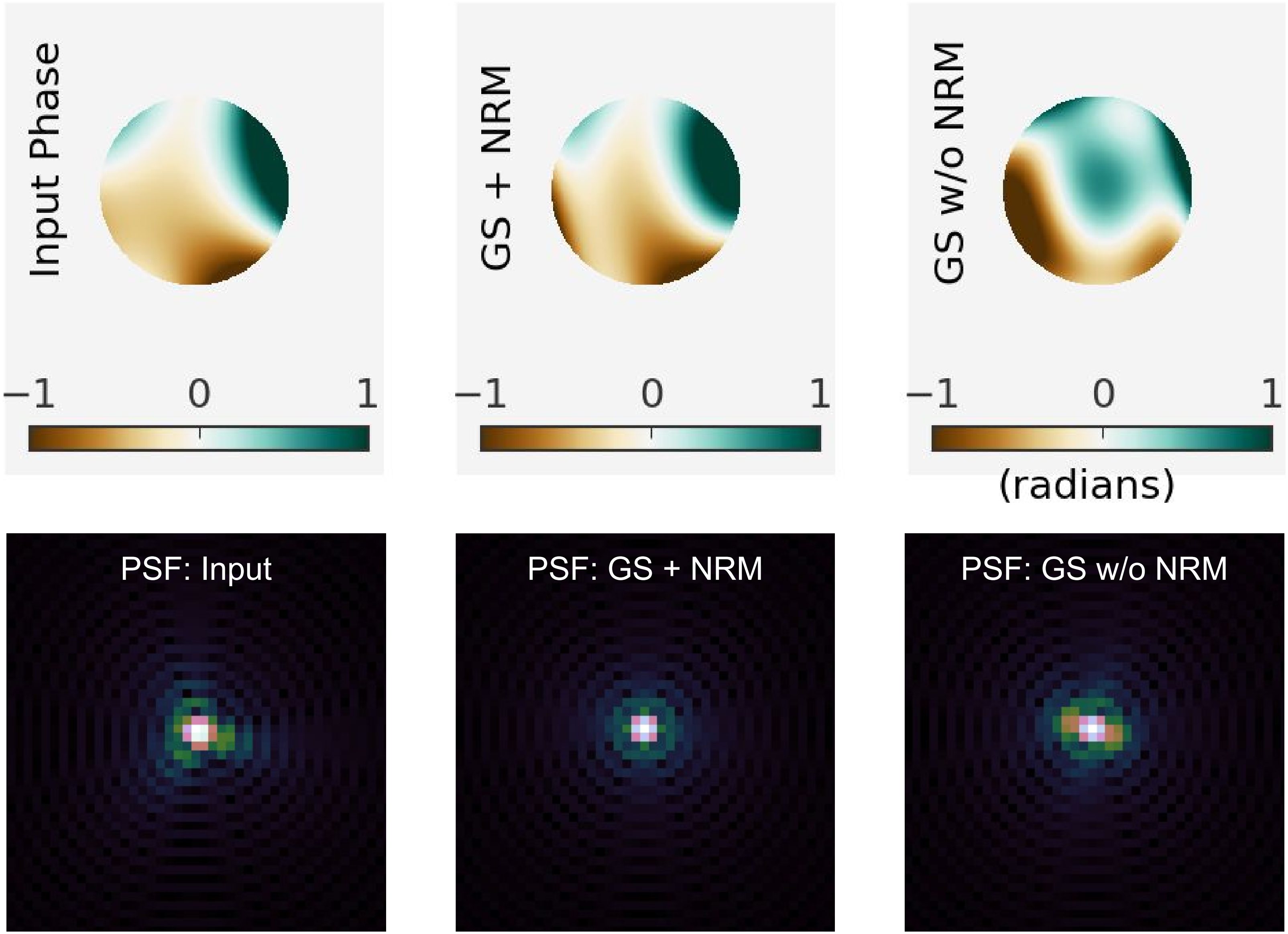


Masking Plus Full-Pupil

- Assume static aberration, or dual wavebands?
- Masking and the Gerchberg–Saxton algorithm can be combined (Greenbaum et al, submitted)

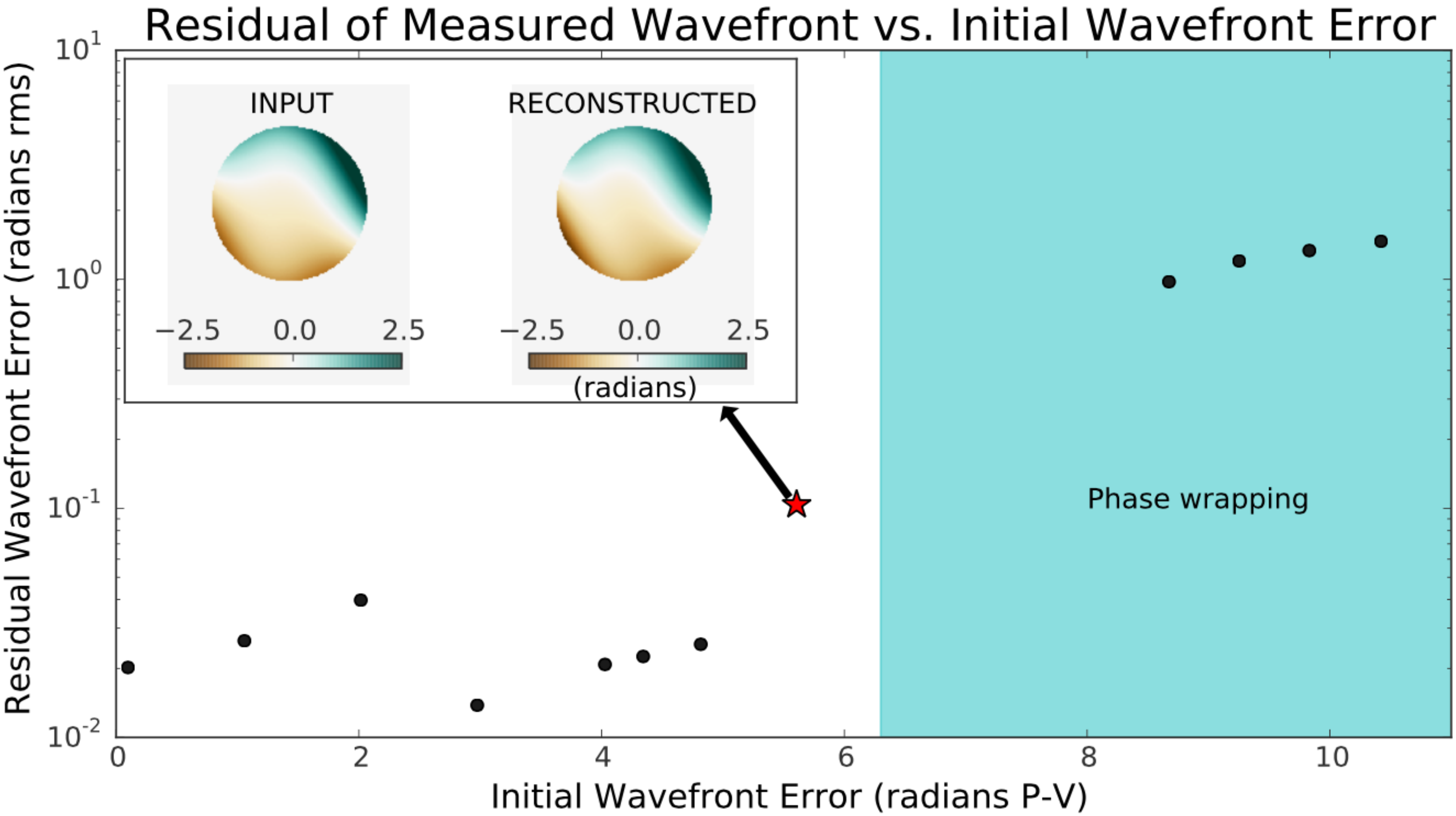


Great Results for Small Aberrations



Greenbaum et al (2016)

Great results for moderate aberrations



Greenbaum et al (2016)

GMTIFS (LGS) Minimum Requirements

- For K-band moderate-contrast imaging: Strehl above 50% for median seeing LGS with an on-axis reference with H=9. Piston, tilt, focus < 0.3 radians RMS < 100nm. 0.5 x 1" field of view (i.e. IFS) OK.
- For H-band high-contrast imaging: same but piston, tilt, focus < 70nm RMS, and a K=8 reference star.
- For Paschen-Beta observations, piston, tilt, focus < 0.5 radians RMS at 1282nm wavelength, i.e. RMS < 100nm.

Better performance than this significantly increases contrast – it is the quasi-static terms that are most important in practice.

GMTIFS Imager WFS Options

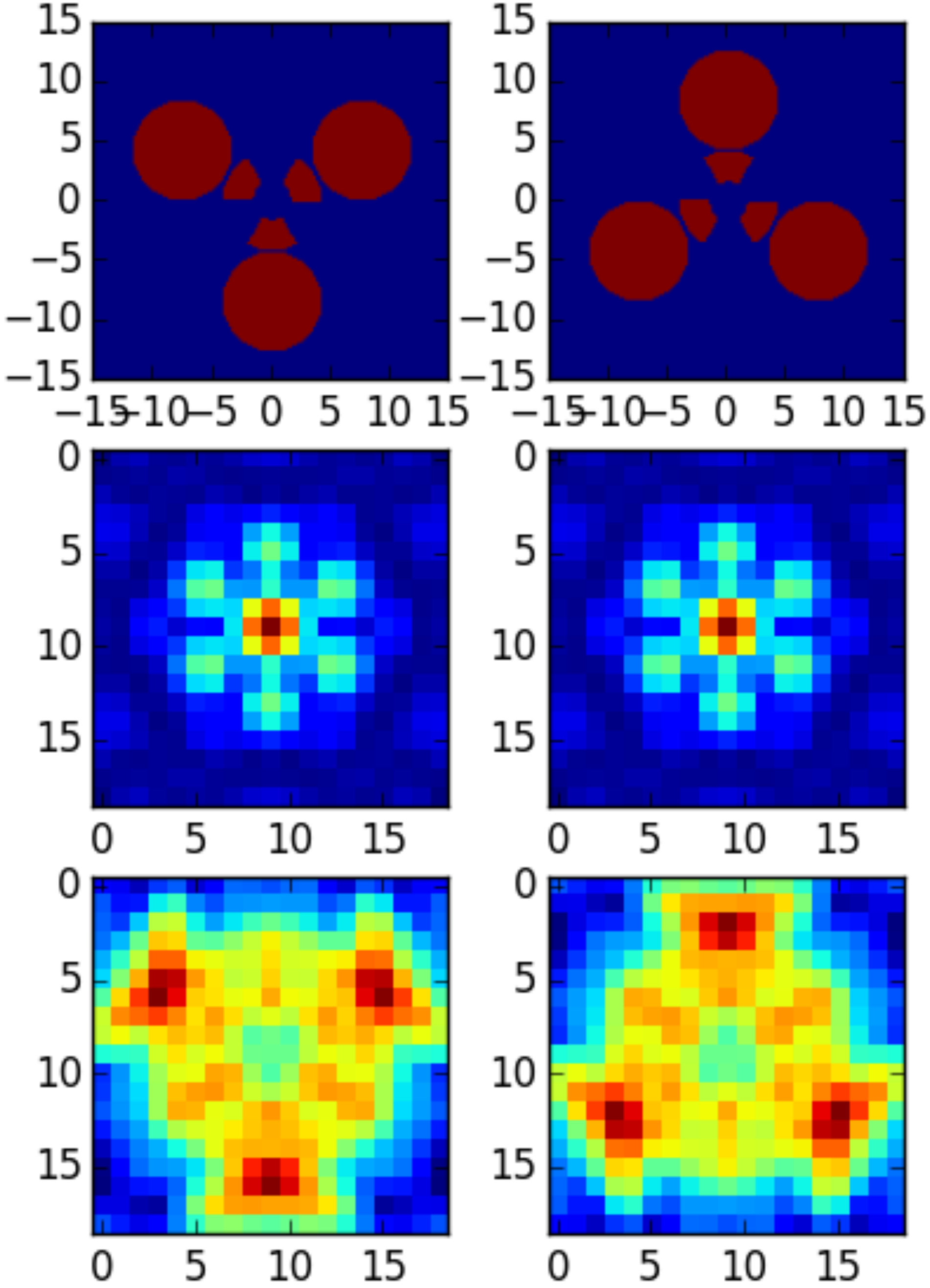
- GMTIFS is primarily an LGS instrument, with poor low order mode correction from LTAO.
- Image-plane wavefront sensing enables simultaneous science, and requires relatively simple optics only. As a baseline, the pupil could be split in two, +/- 2 radians of phase defocus could be applied to the pupil.
- This wavefront sensor is highly non-linear when outside 1 radian of aberration, so would at least need an acquisition mode that can handle large piston offsets.
- The fixed 5 milli-arcsec pixel scale of the imager means that in order to sample the full core of an 8m PSF, 16 x 16 pixels are needed in H-band. Simply achieving 50% encircled energy at high piston values only requires 8x8 pixels.
- Assuming a 30% efficiency (atmosphere->detection) and a 50% 8m Strehl, back of the envelope calculations gives operation at mean photon counts = 2 x readout noise for the Hawaii detector at:

Band	Speed	Magnitude Limit
H	250Hz	13.2
H	125Hz	14.0
K	250Hz	12.3
K	125Hz	13.1

Ireland in prep.

Principle

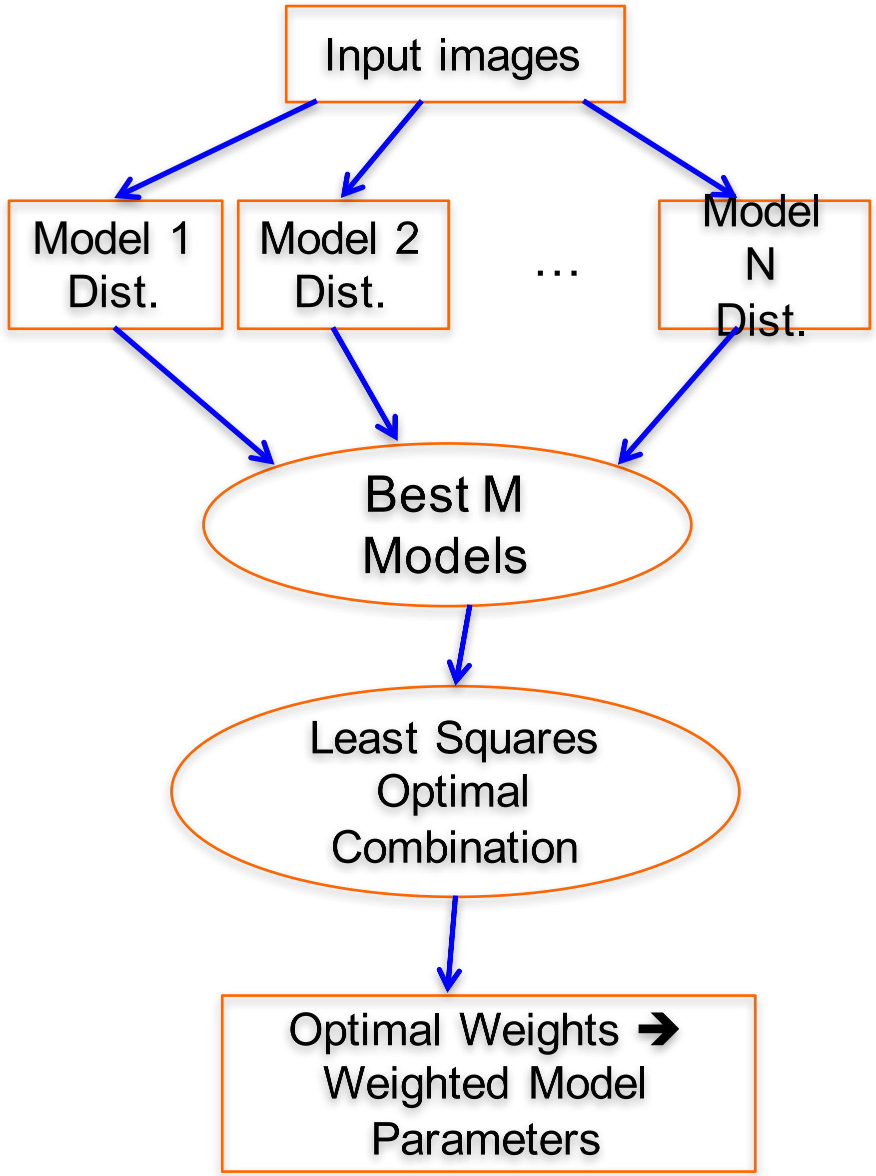
- Focal-plane wavefront sensors are in general *ambiguous*. E.g. a positive and negative focus image looks identical for a point-symmetric pupil
- An alternative is to split the pupil in 2 or more parts.
- One way to do this is an asymmetric pupil wavefront sensor (e.g. right, Martinache). Super-easy to manufacture, but not ideal in terms of sensitivity or requiring a particular pupil rotation.
- Another (slightly better) way is to just take images on either side of focus, or a pupil that uses 180 degree phase for the asymmetry...



Ireland in prep.

Non-Linear WFS Algorithm

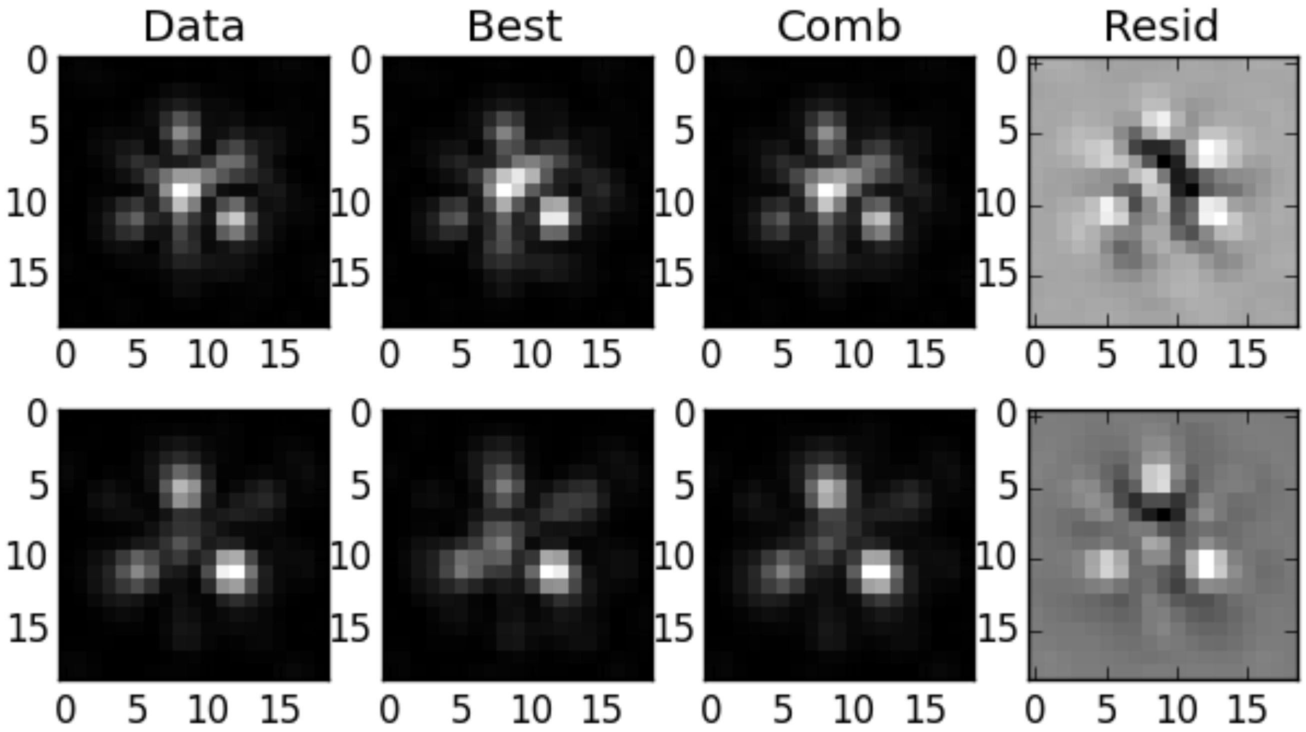
- In the past, focal-plane wavefront sensing has been seen as too difficult because linear algorithms only work at high Strehl.
- This remains true for sensing many modes… but for GMTIFS, if we have an LGS correction, arguably only 9 modes need to be sensed (tip/tilt, focus and 6 piston modes).
- Instead of a linear WFS algorithm, a *locally-linear* algorithm works, and is highly parallelisable….



Ireland in prep.

Simulations

- With a library of 250,000 PSFs on 19x19pixels, a simple python program on a laptop can compute the best-fit wavefront in <1s. Running at 250Hz is a simple CPU+GPU problem.
- RMS with over 1 wave of piston, focus, tilt is 0.16 radians. Smaller (photon-limited – as good as unmodulated pyramid) in the linear regime (after loop is closed).



Example analysis frame…

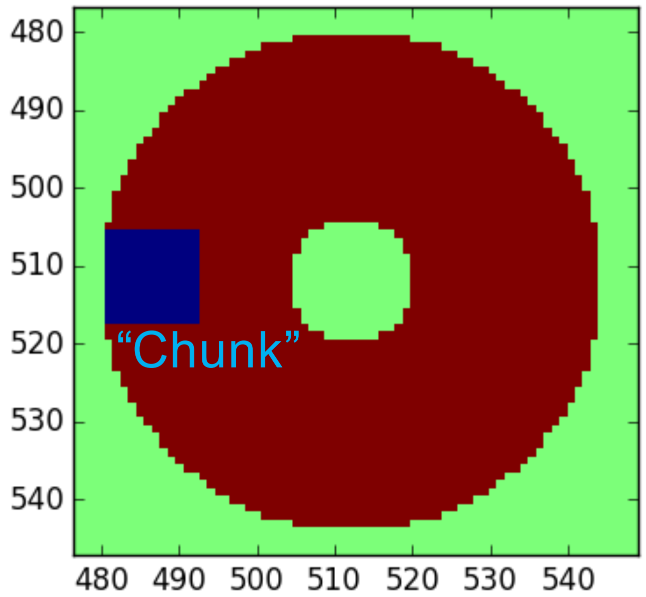
Input pistons:
-0.57 -2.58 0.12 -1.12 0.85 -1.84

Fitted pistons:
-0.60 -2.71 0.05 -1.07 0.91 -1.75

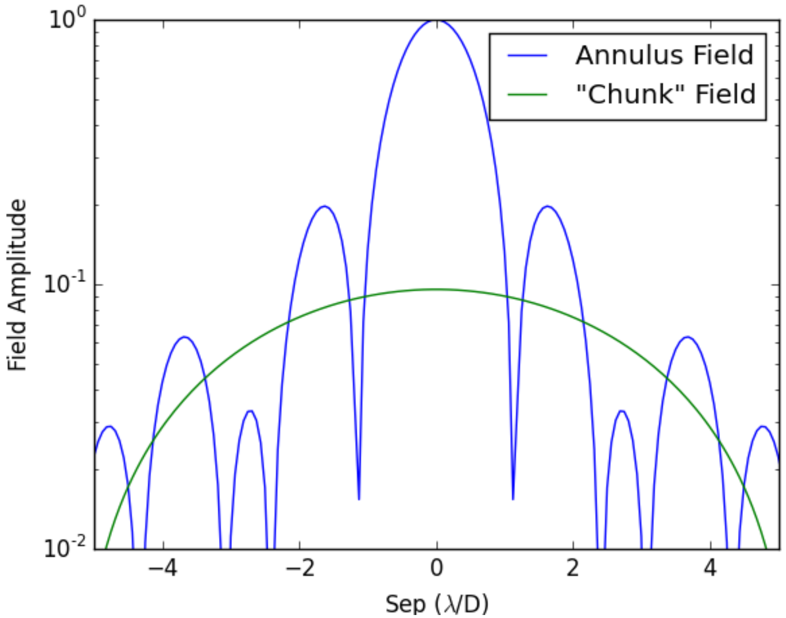
Additional focus, tilt terms, plus 1 radian RMS over each aperture

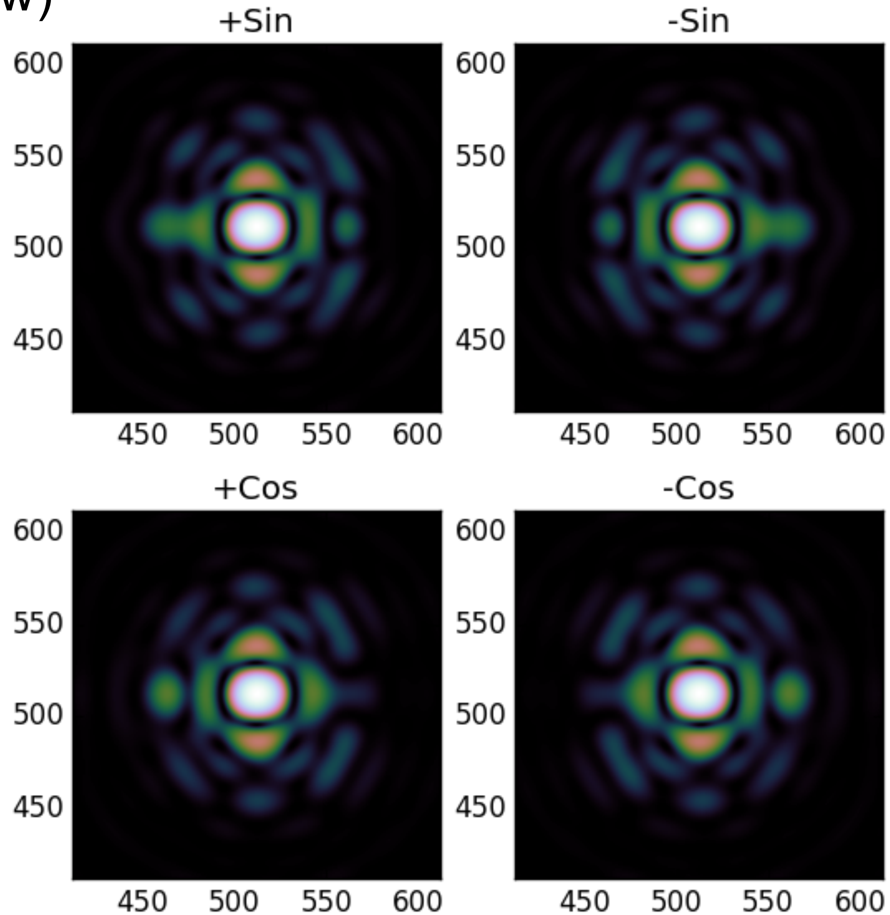
Ireland in prep.

Asymmetric Pupil WFS in the Image Plane



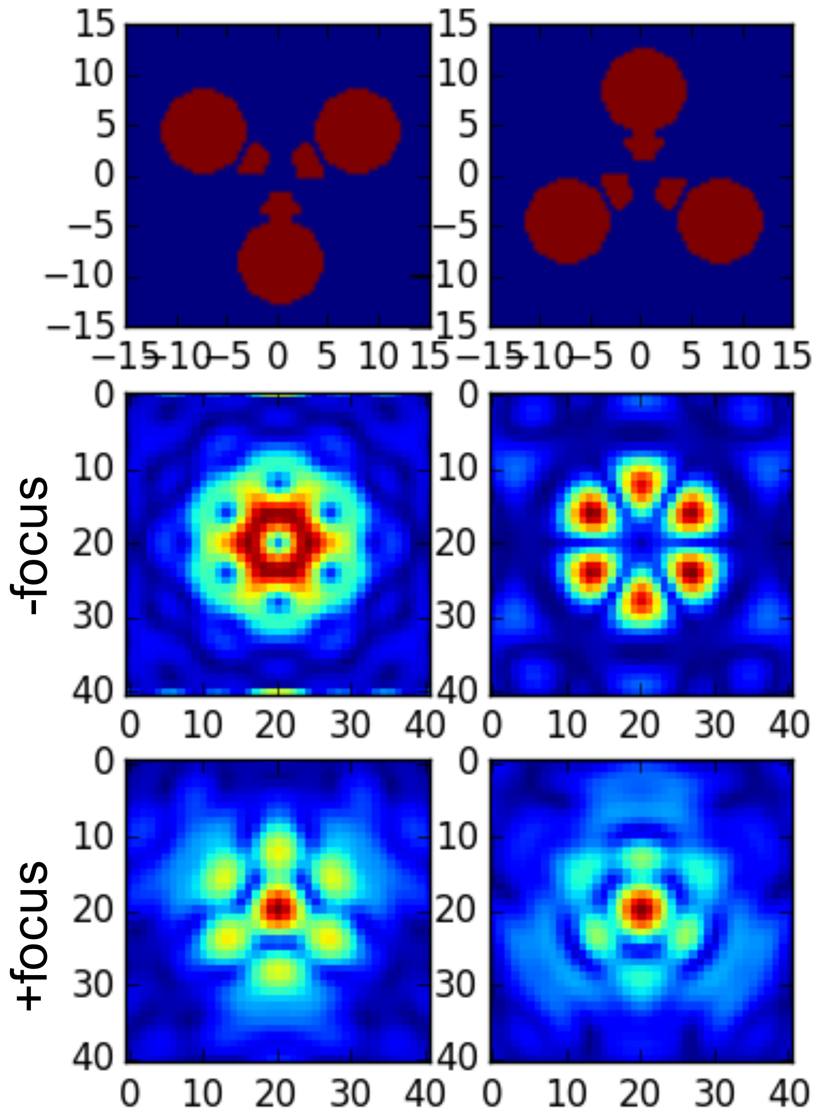
- An asymmetric pupil is the sum of the pupil field and the asymmetric component.
- In the image plane, the asymmetric component breaks the degeneracy between the even aberrations of positive and negative sign (2 λ/D below)





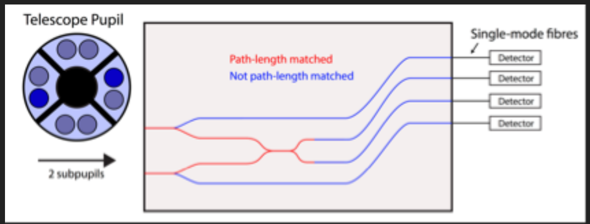
Extension to Coronagraphic Images

- For a leaky coronagraph, the photon-limited sensitivity of any image-plane WFS is the same, so long as aberration speckle amplitudes are smaller than diffraction speckle amplitudes.
- Once this condition isn't met, the WFS is nonlinear.
- Uncertain when this nonlinearity produces ambiguity or sensitivity loss, especially with an IFU.
- With e.g. stellar leakage or tip/tilt errors, asymmetric pupil wavefront sensing fails – but dual-image plane sensing works…



“GLINT”: Guided Light Interferometric Nulling Telescope (Barnaby Norris et al, USyd)

- Uses a 3D photonic chip (ULI) to destructively interfere starlight, revealing the faint planet nearby
  - Telescope pupil imaged onto chip
  - Remapping + interference via evanescent couplers in chip
  - 10s of outputs, encoding time domain signal as pupil rotates



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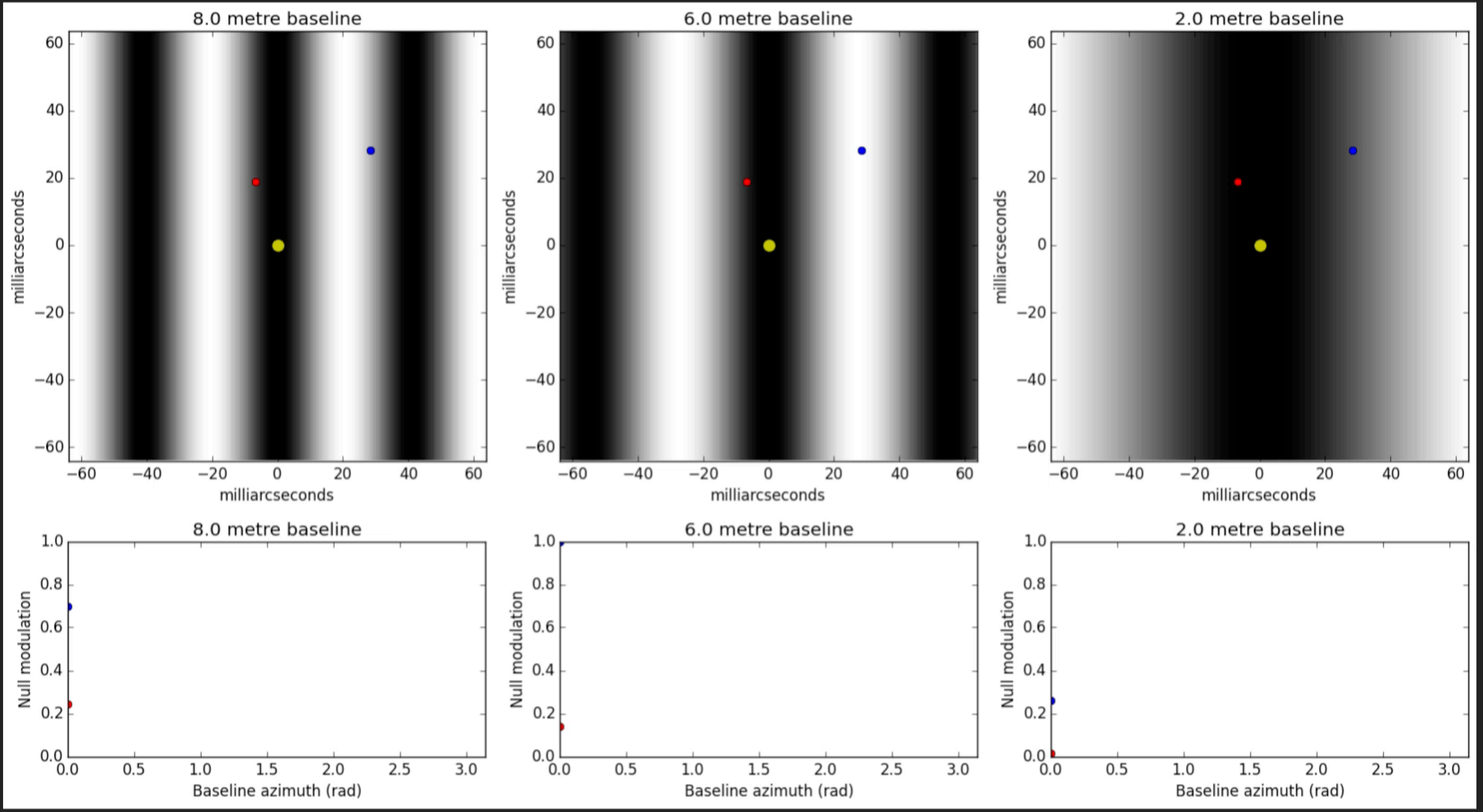
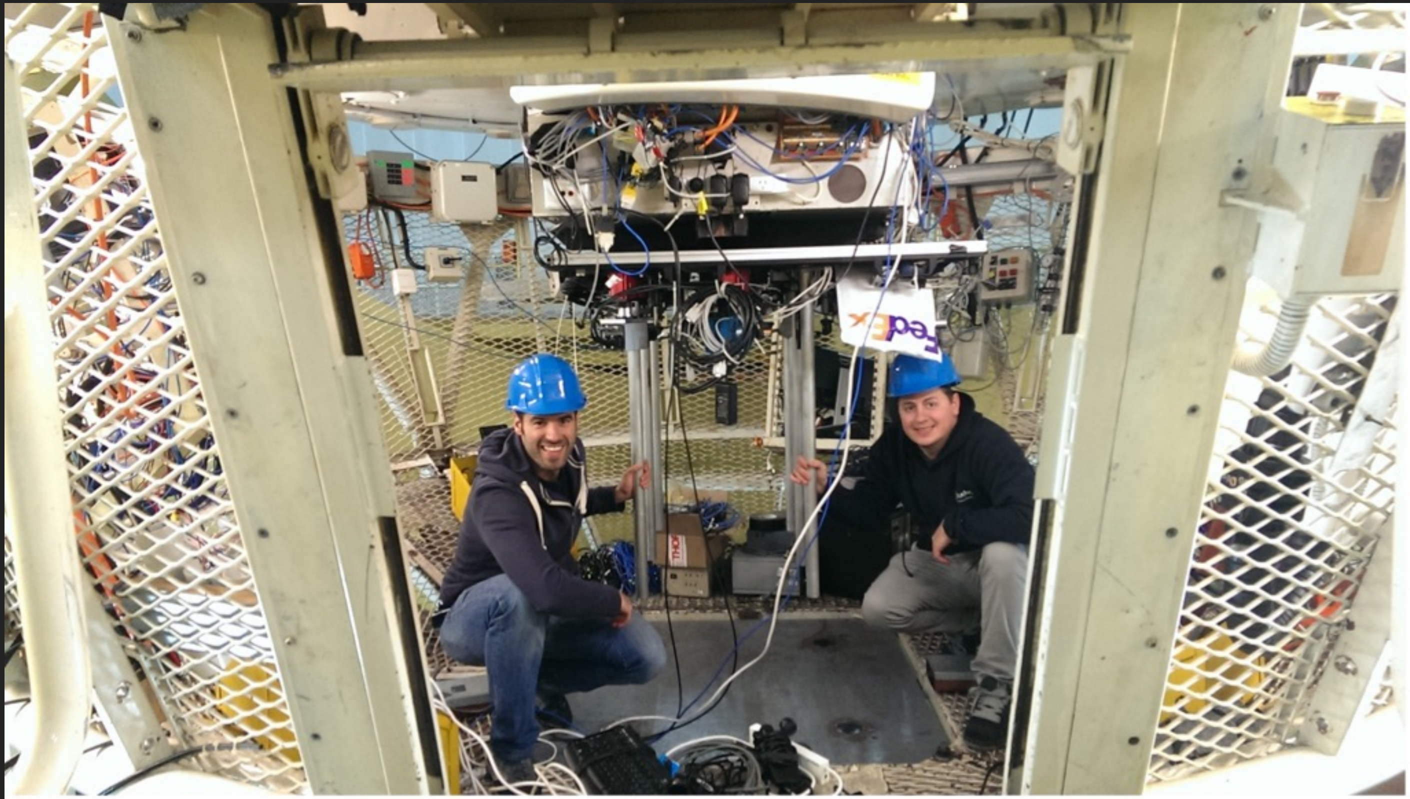
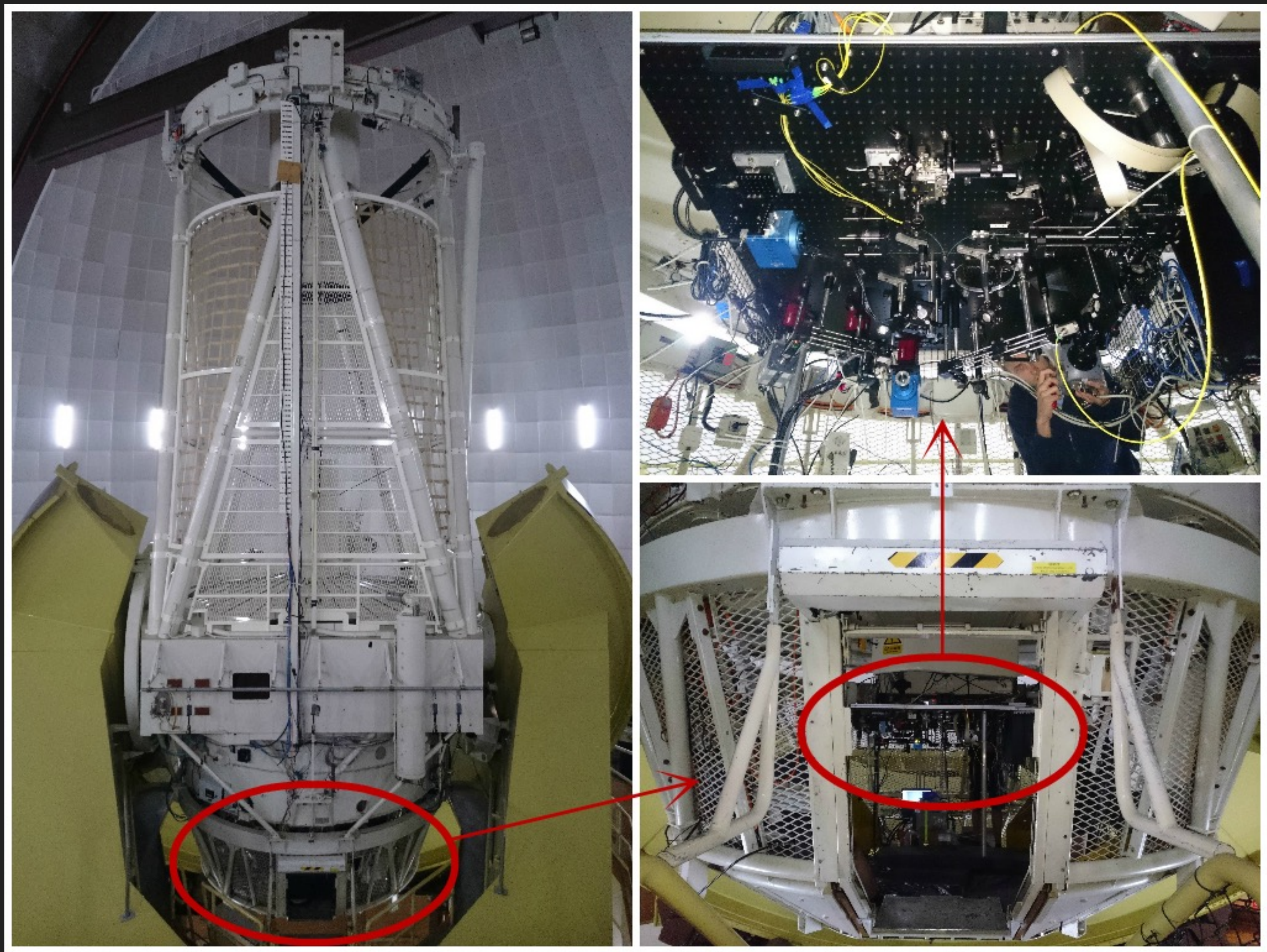
Single baseline nuller Concept



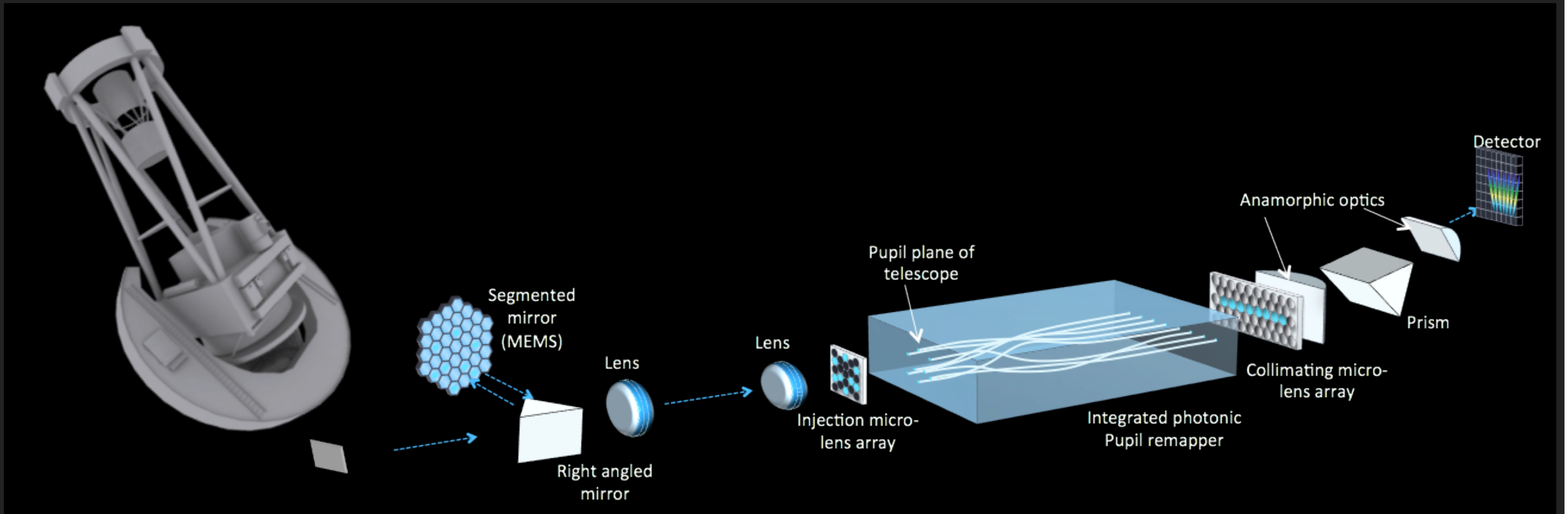
Previous test at AAT



Previous test at AAT



Glint @ subaru



Photonic pupil remapper (NIR) - Remaps arbitrary 2D pattern into 1D

- Redundant (full pupil coverage) → non-redundant
- 1D → can be spectrally dispersed
- <u>Single-mode waveguides</u> → flat phase across sub-aperture

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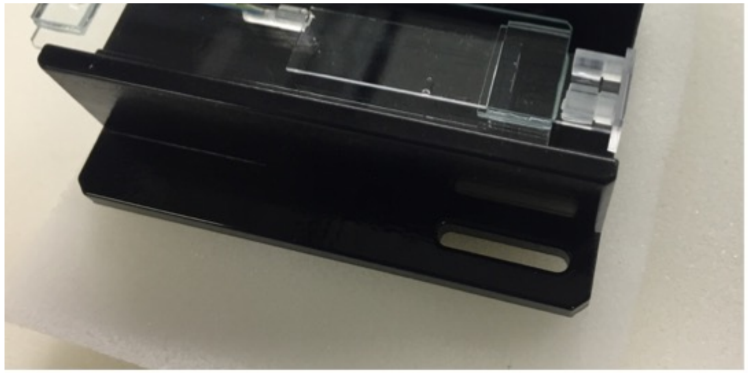
Glint @ subaru



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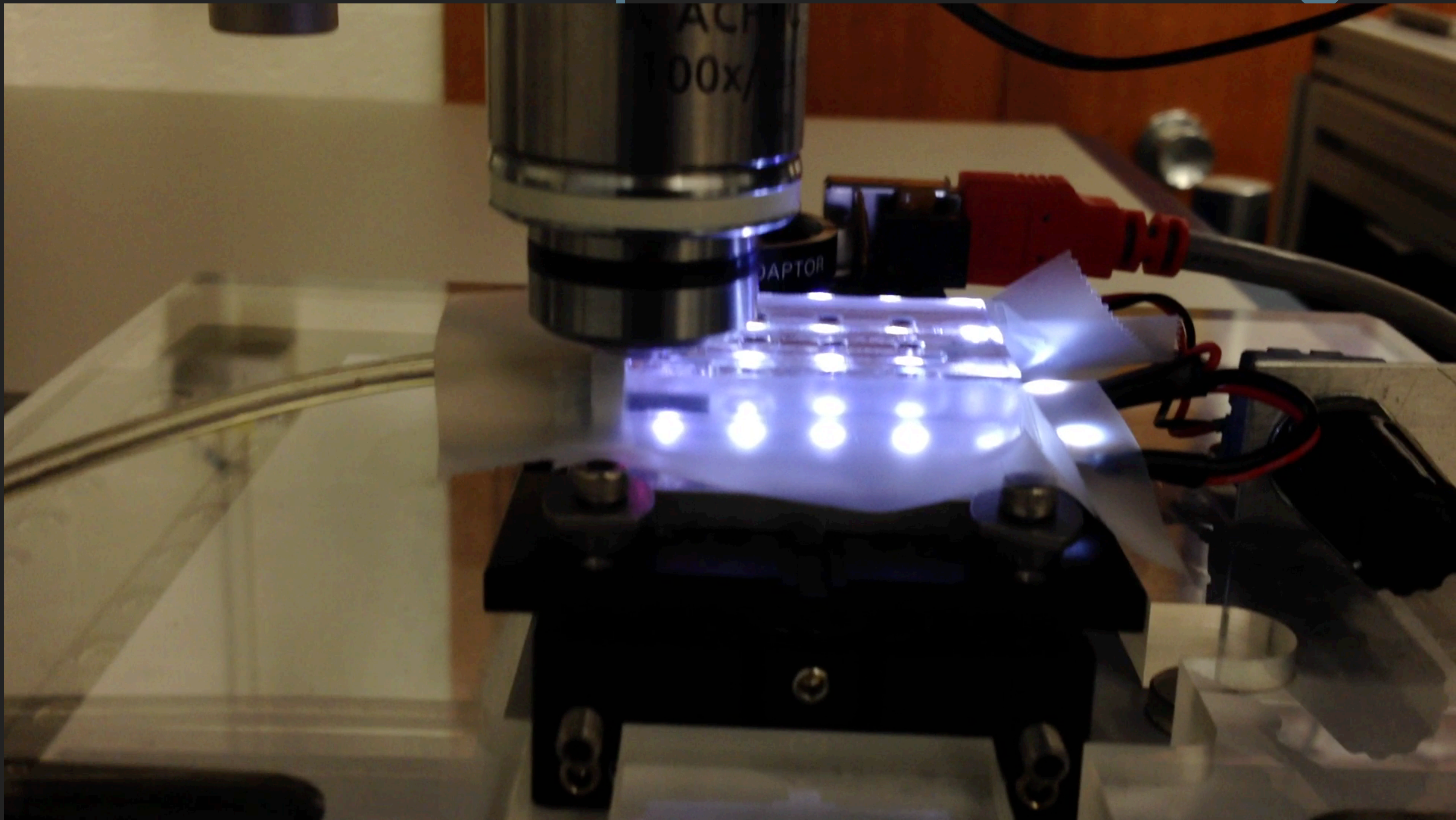
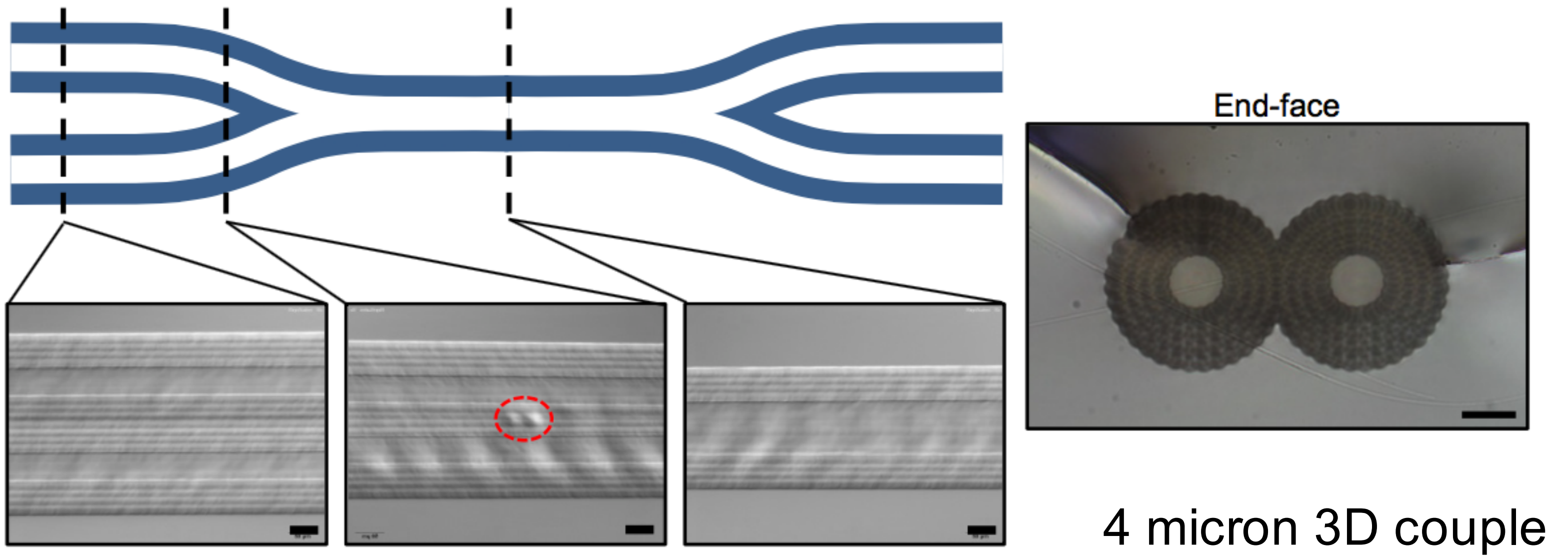
Photonic chip manufacturing



Next Steps…

- Efficient operation at 3-5 microns (Harry Kenchington Goldsmith @ ANU: 2D, A. Arriola @ Macquarie Uni: 3D). *See Harry's work at SPIE.*
- On-chip modulation.
- Second generation ELT instrument concept? Developments even more relevant for long-baseline interferometry (e.g. Planet Formation Imager).



4 micron 3D coupler in ZBLAN (Gross et al. 2016)