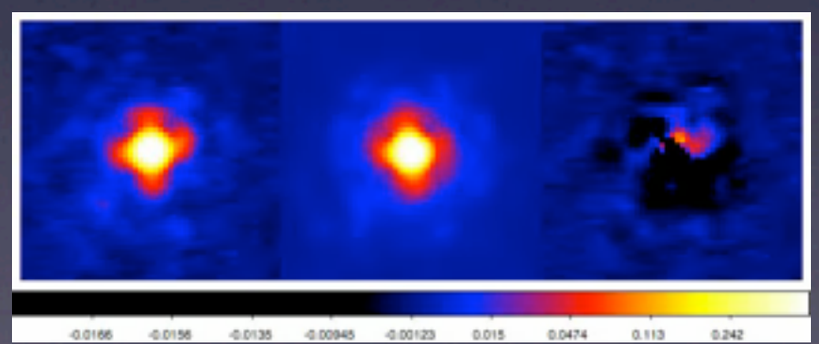
On-sky demonstration of Focal Plane Wavefront Sensing and Quasi-static Speckle Suppression

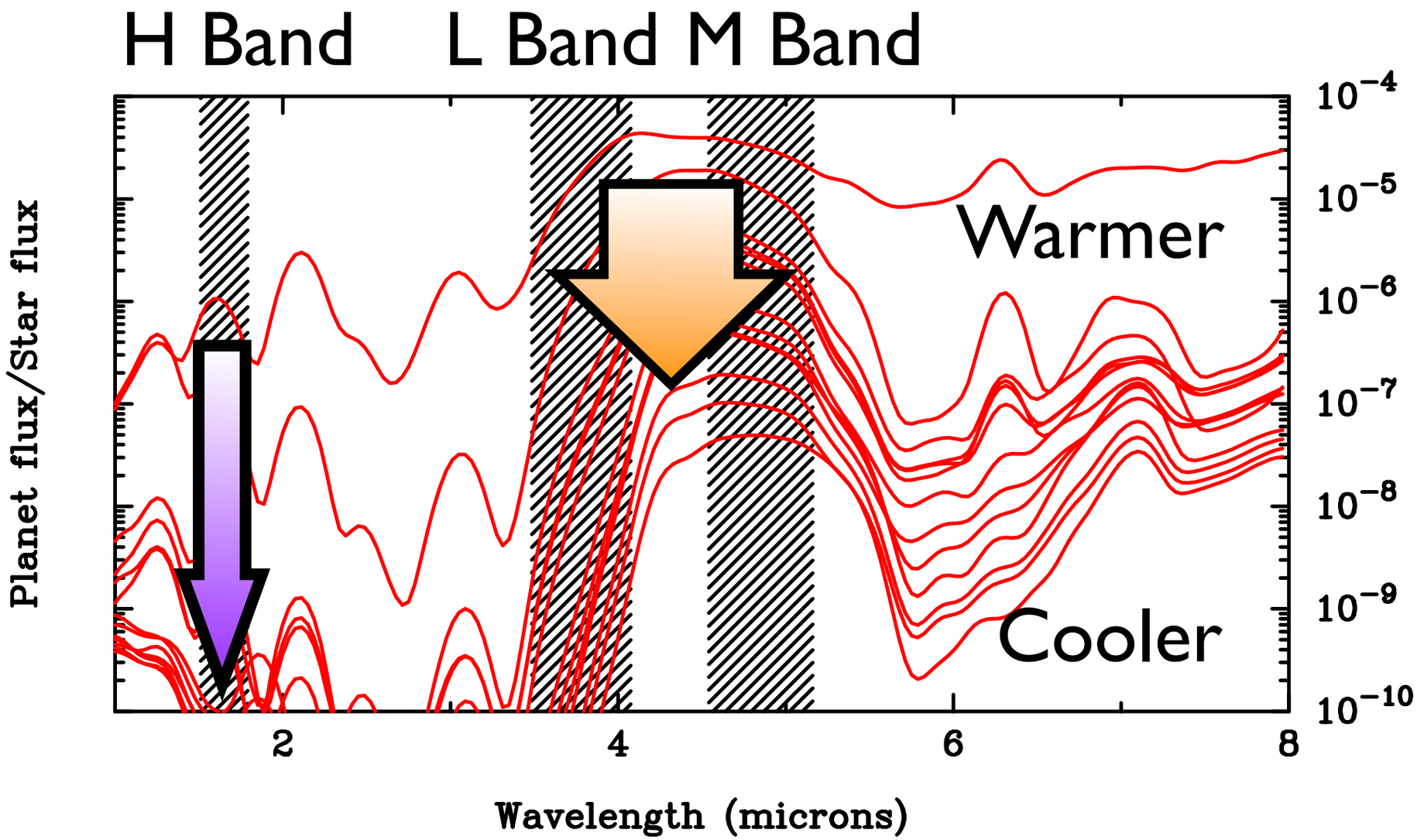
Matthew Kenworthy and Johanan Codona
Leiden Observatory // Steward Observatory



Funded by NSF

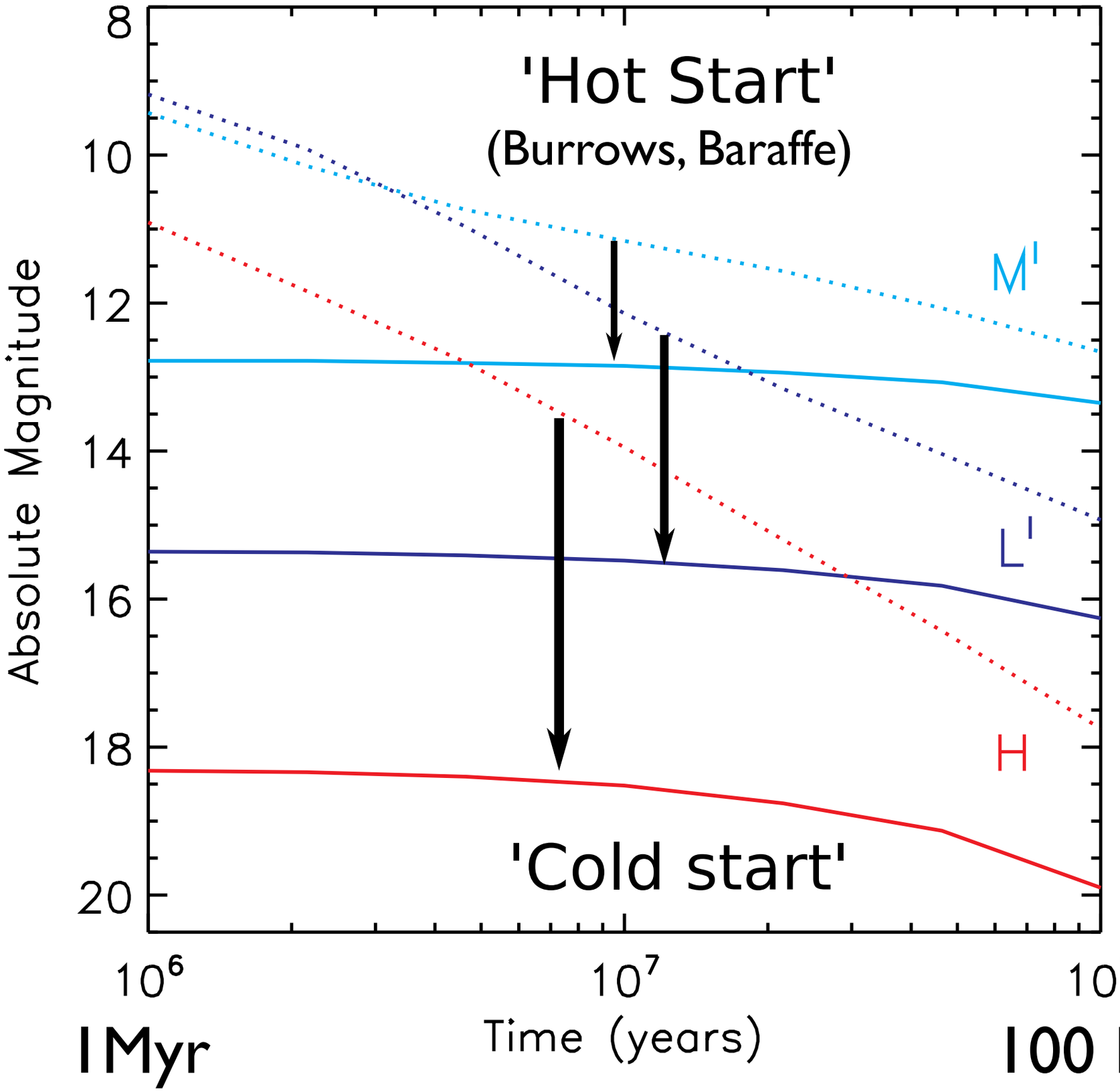
AO4ELT2 // September 2011 // Victoria, Canada

Looking for planets in the thermal IR



Burrows et al. (2004)

Hot and Cold Models



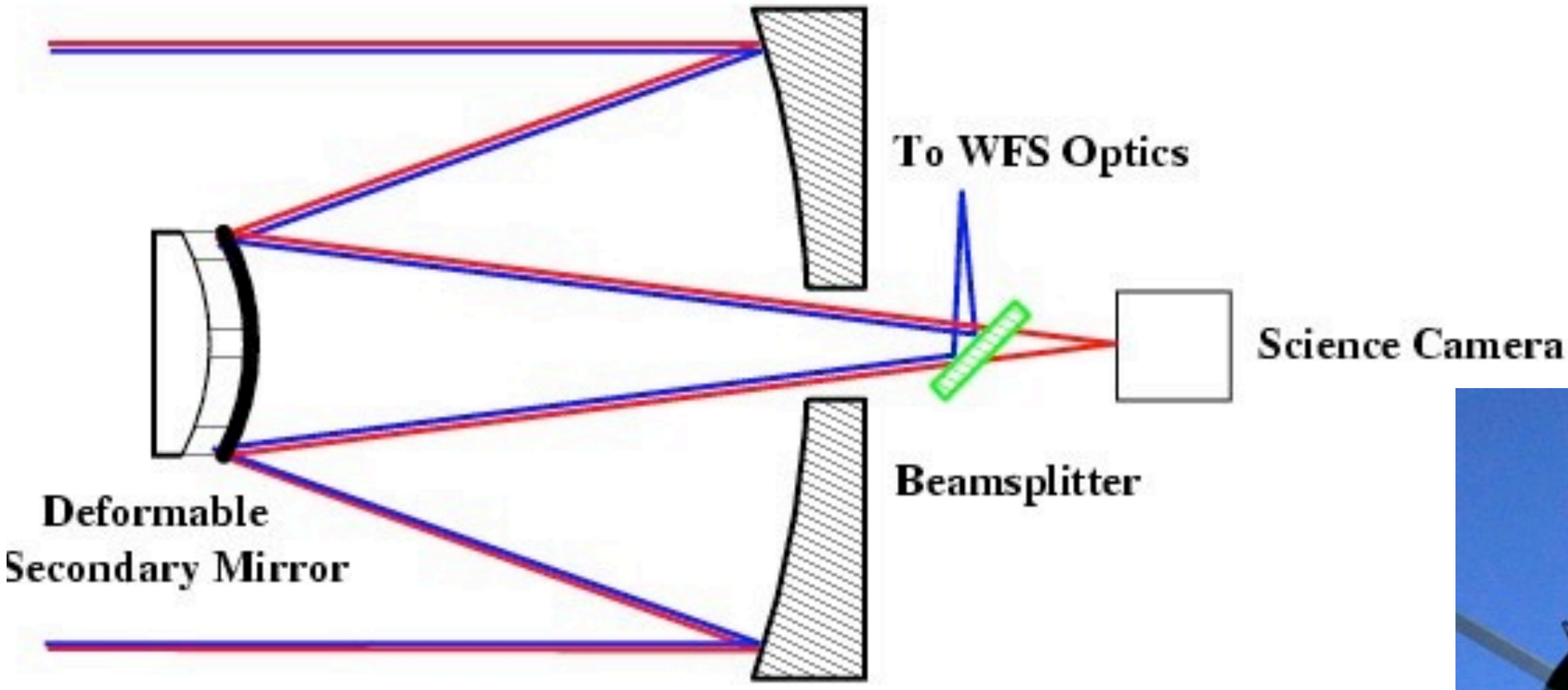
t < 100 Myr

delta H = 5

delta M' = 1.5

Fortney et al. 2008

The MMT Adaptive Optics System



Two warm surfaces
Minimal thermal background

Thermal Imaging with Clio

- 3-5 micron imaging camera/coronagraph
- 12 by 15 arcsec FOV

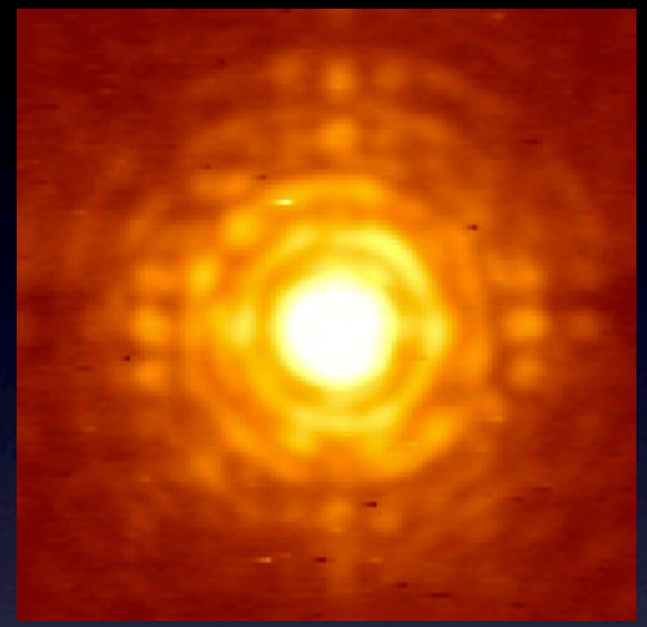
Designed and built for
THERMAL IR DIRECT DETECTION
of exoplanets

L and M band exoplanet surveys:
Heinze et al. 2010a,b - Hinz et al. 2006
Other results:
Mamajek et al. 2010
Kenworthy et al. 2009

Quasi-static speckles

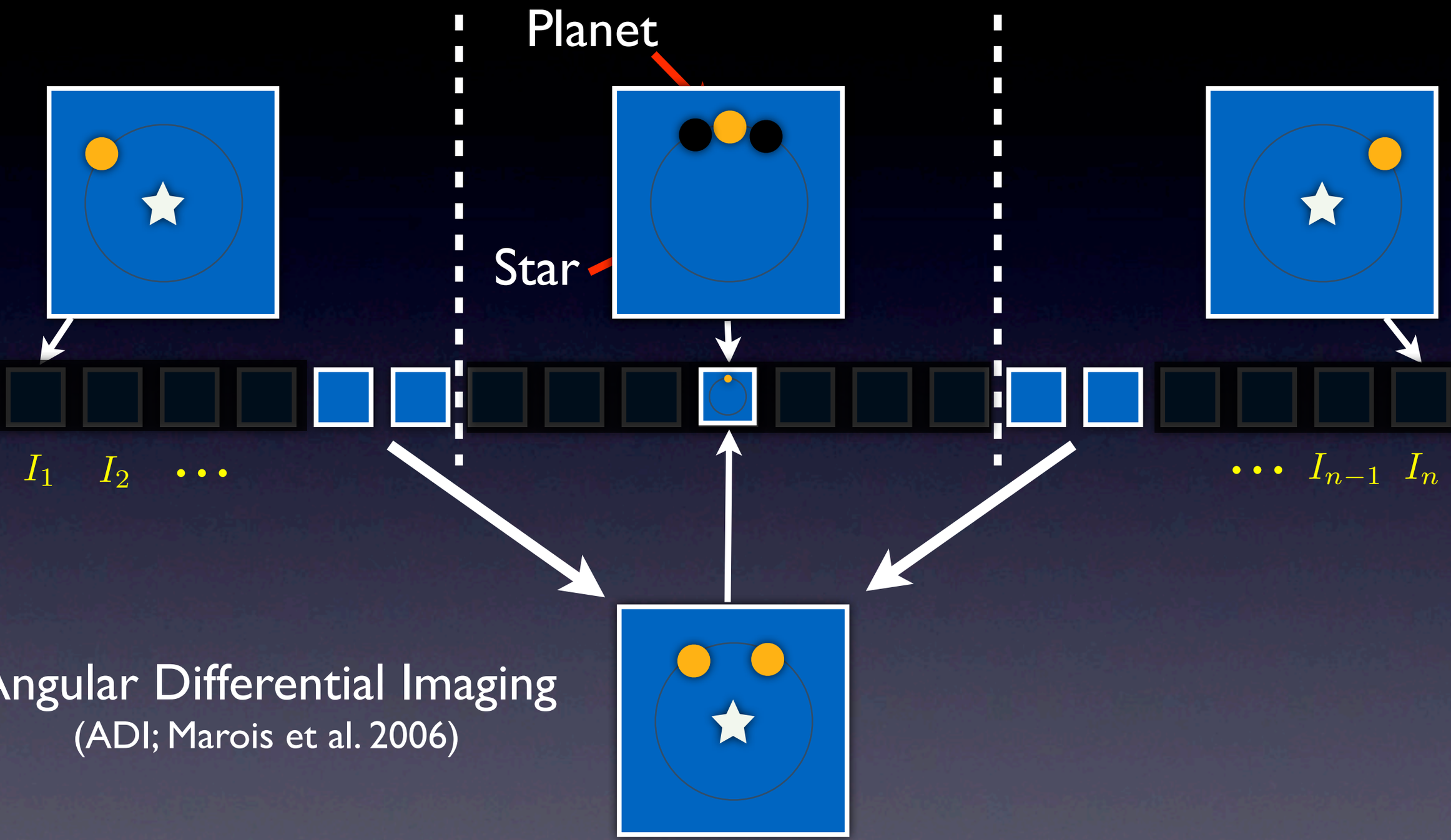
What do we want?

The instrumental PSF
for each Science Camera Image...



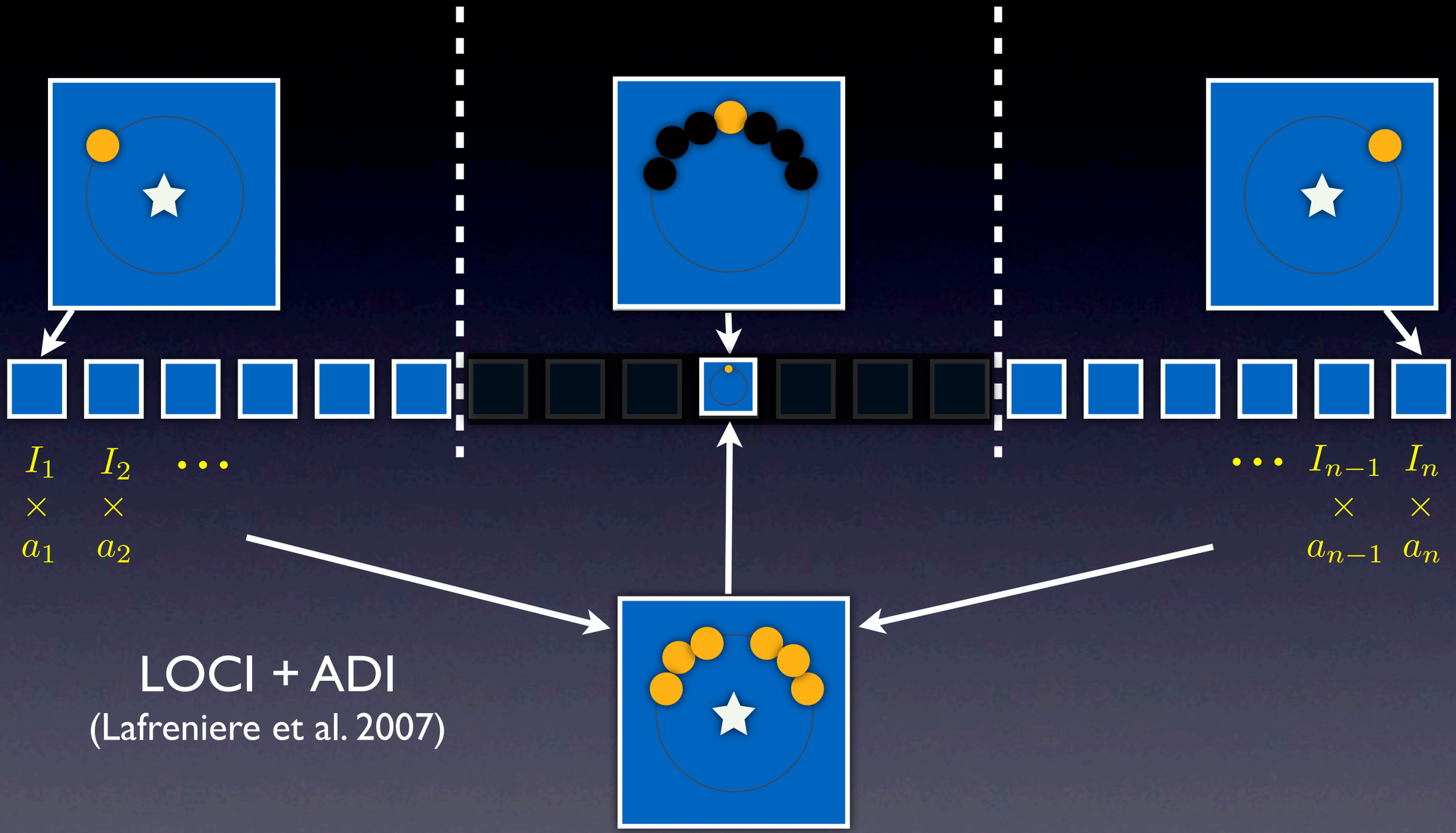
...so that we can subtract off the star
to leave the planet's signal

Approximating the Science PSF



Angular Differential Imaging
(ADI; Marois et al. 2006)

Approximating the Science PSF



LOCI + ADI
(Lafreniere et al. 2007)

Approximating the Science PSF

ADI - Angular Differential Imaging

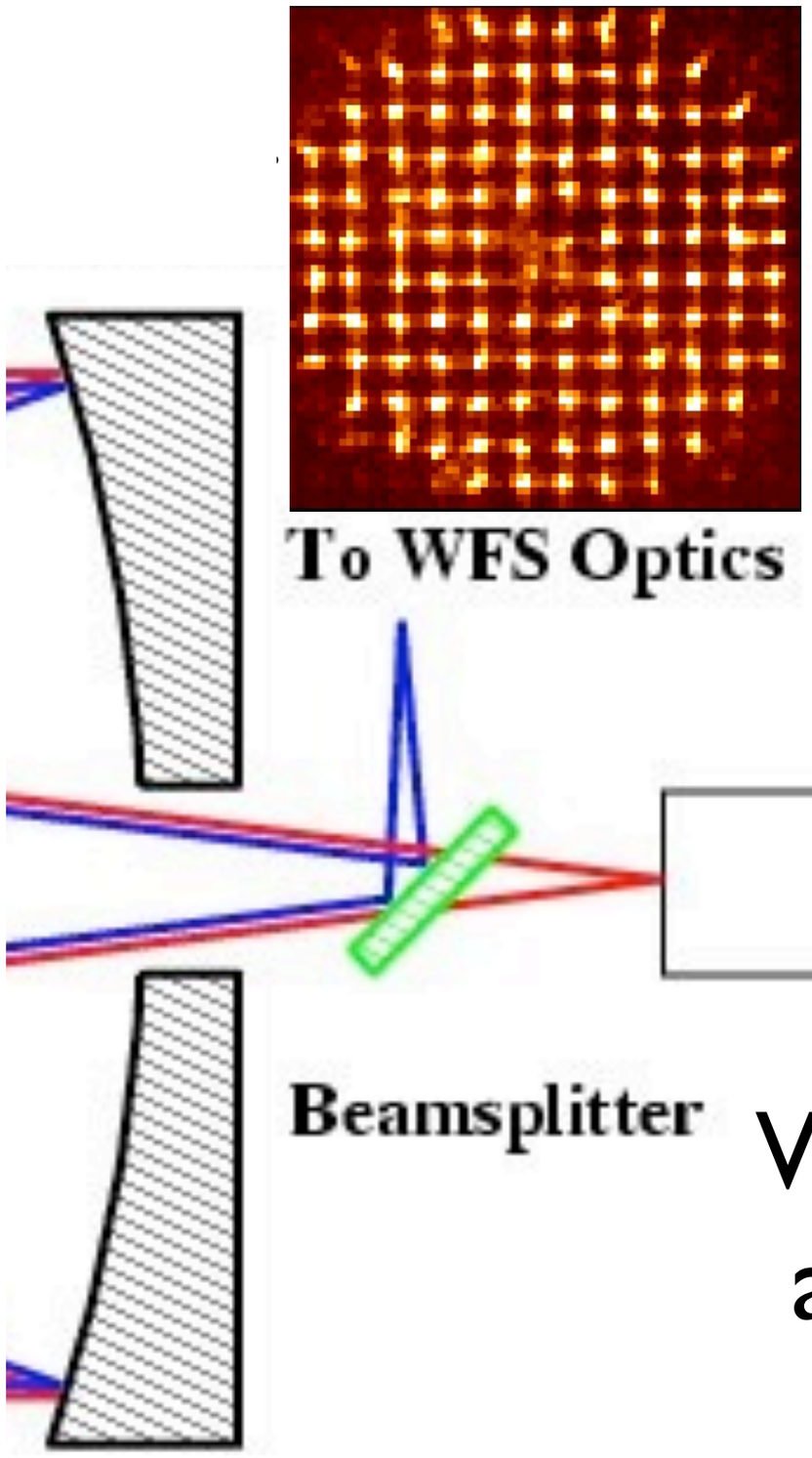
SDI - Simultaneous Differential Imaging

Need rotation to make sure planet does not self subtract

CDI - Computed Differential Imaging

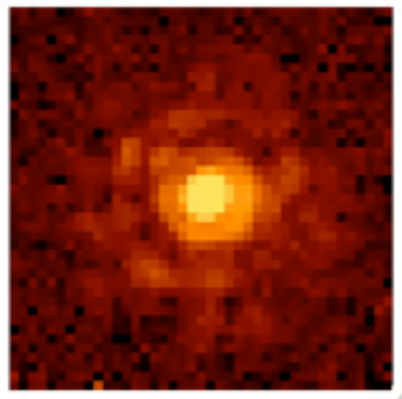
CDI PSFs do not have the planet
Are generated for the exact time of the Science PSF

Non Common Path (NCP) error



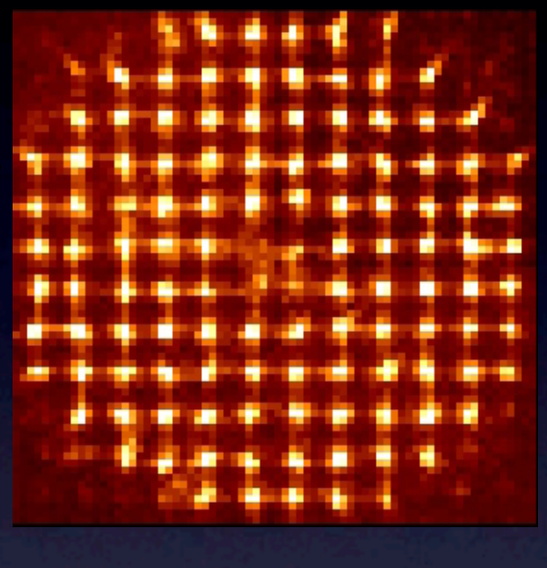
+NCP

=

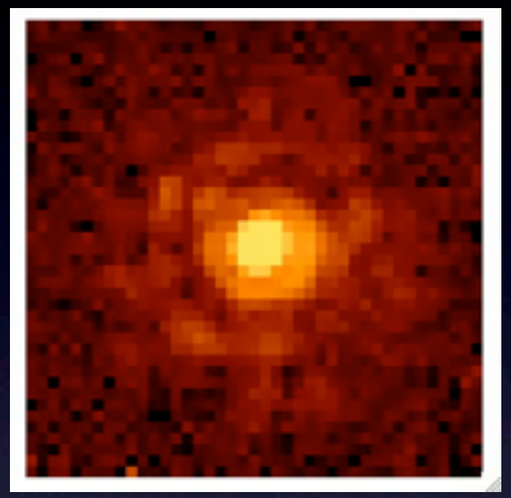


We can solve for NCP as a function of time!

On sky data



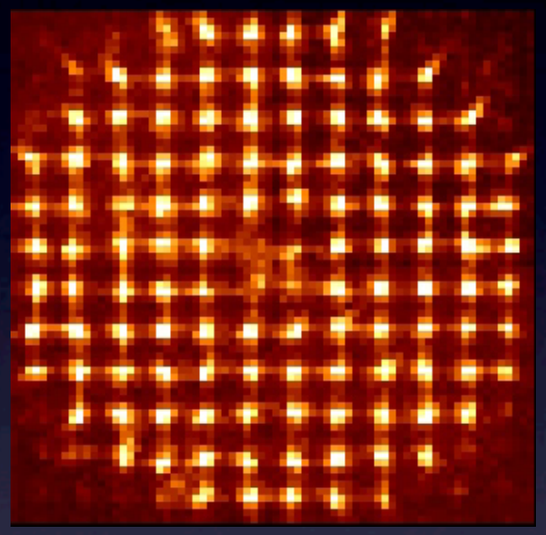
6.480 WFS frames to
each Clio frame



Shack Hartmann WFS
Visible band
12x12 subapertures
on 6.35m pupil
220 Hz rate

Clio 5 micron camera
100 frame readout
30 msec
diffraction limited

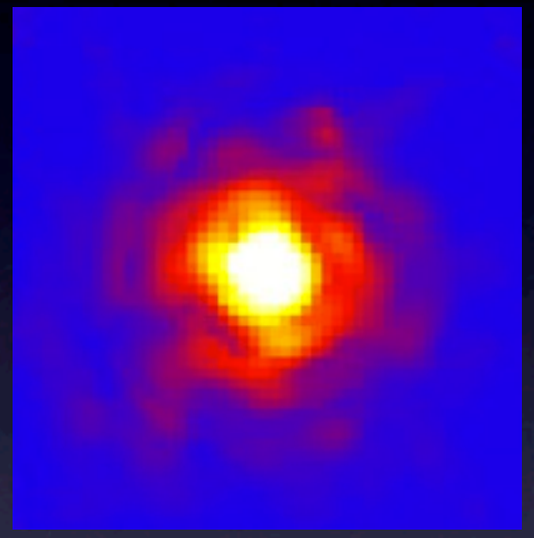
Principle of CDI



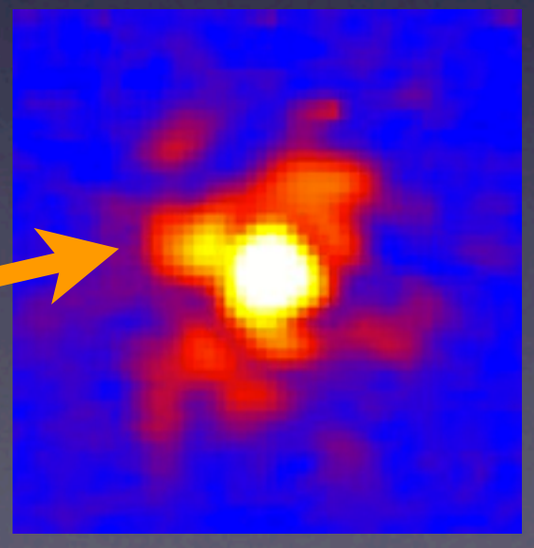
Reconstruct phase screen from WFS

Make complex amplitude PSF at 5 microns

WFS PSF



Clio 5 micron

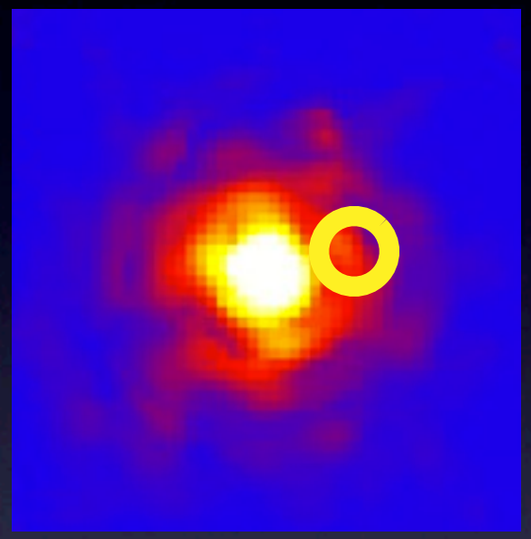


Compare with 5 micron Clio frames

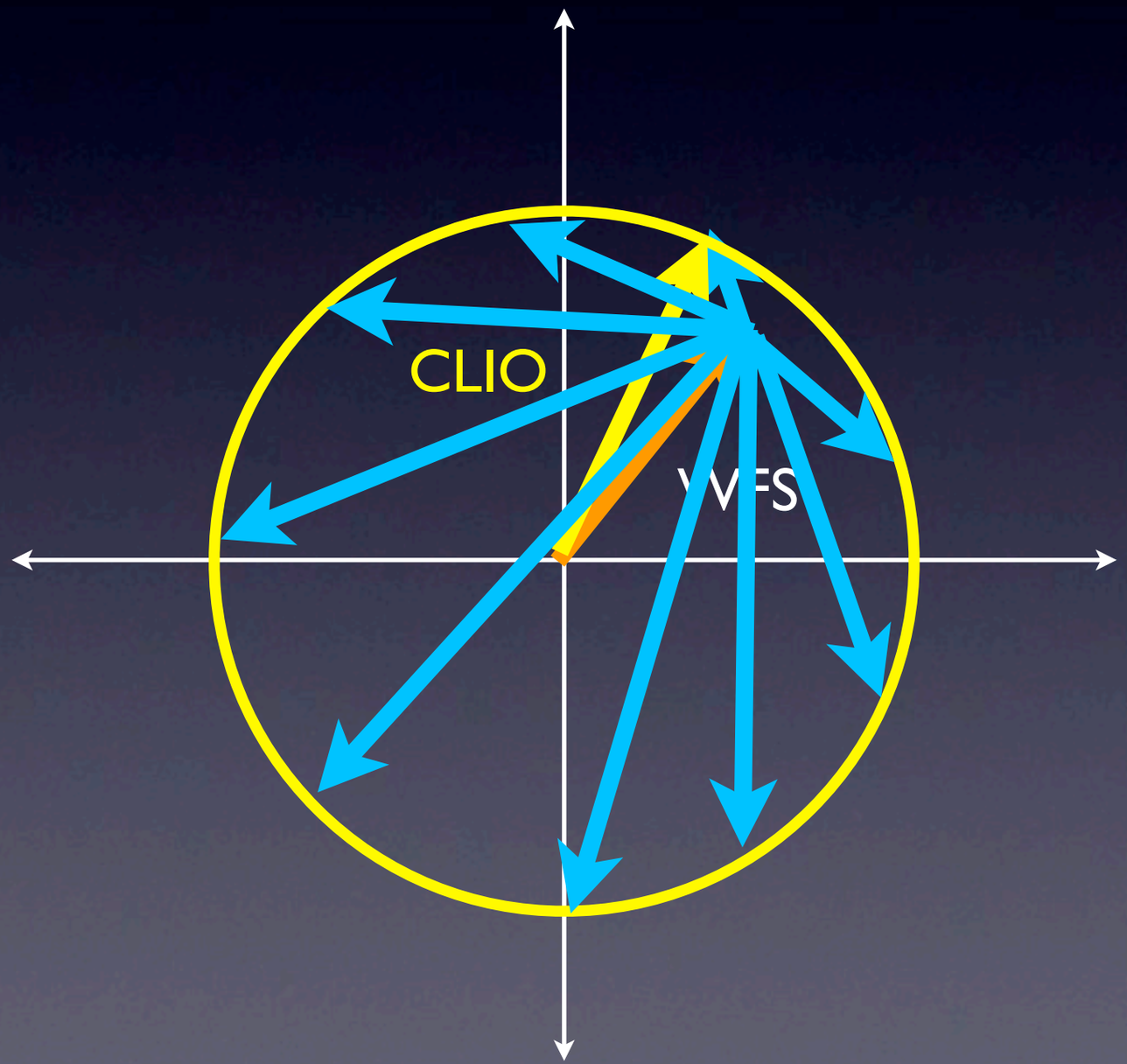
Not identical == NCP

Principle of CDI

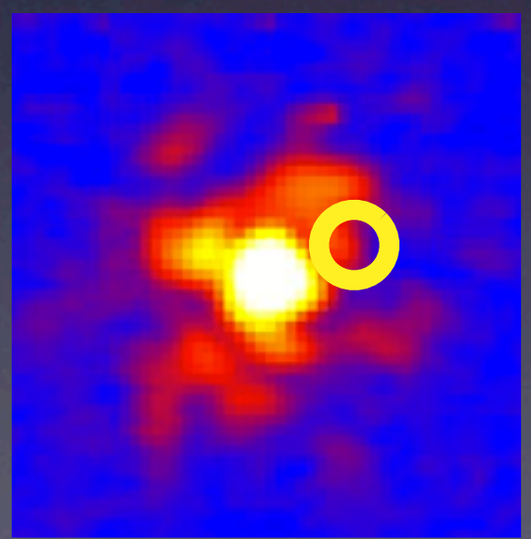
WFS PSF



+ NCP =

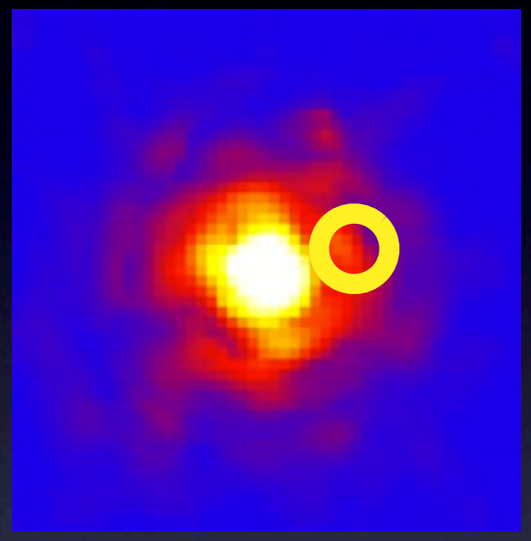


Clio 5 micron

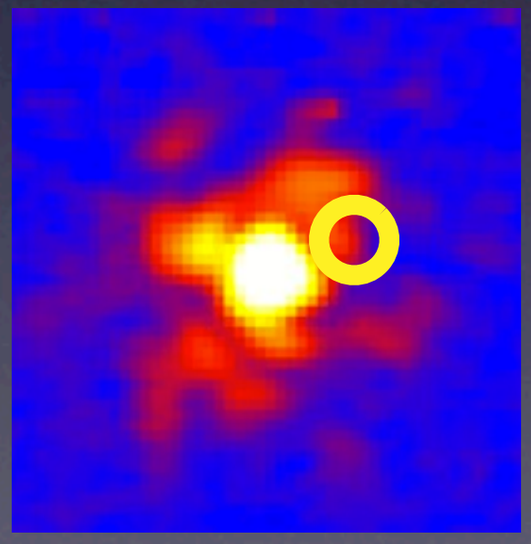


Atmosphere provides phase diversity

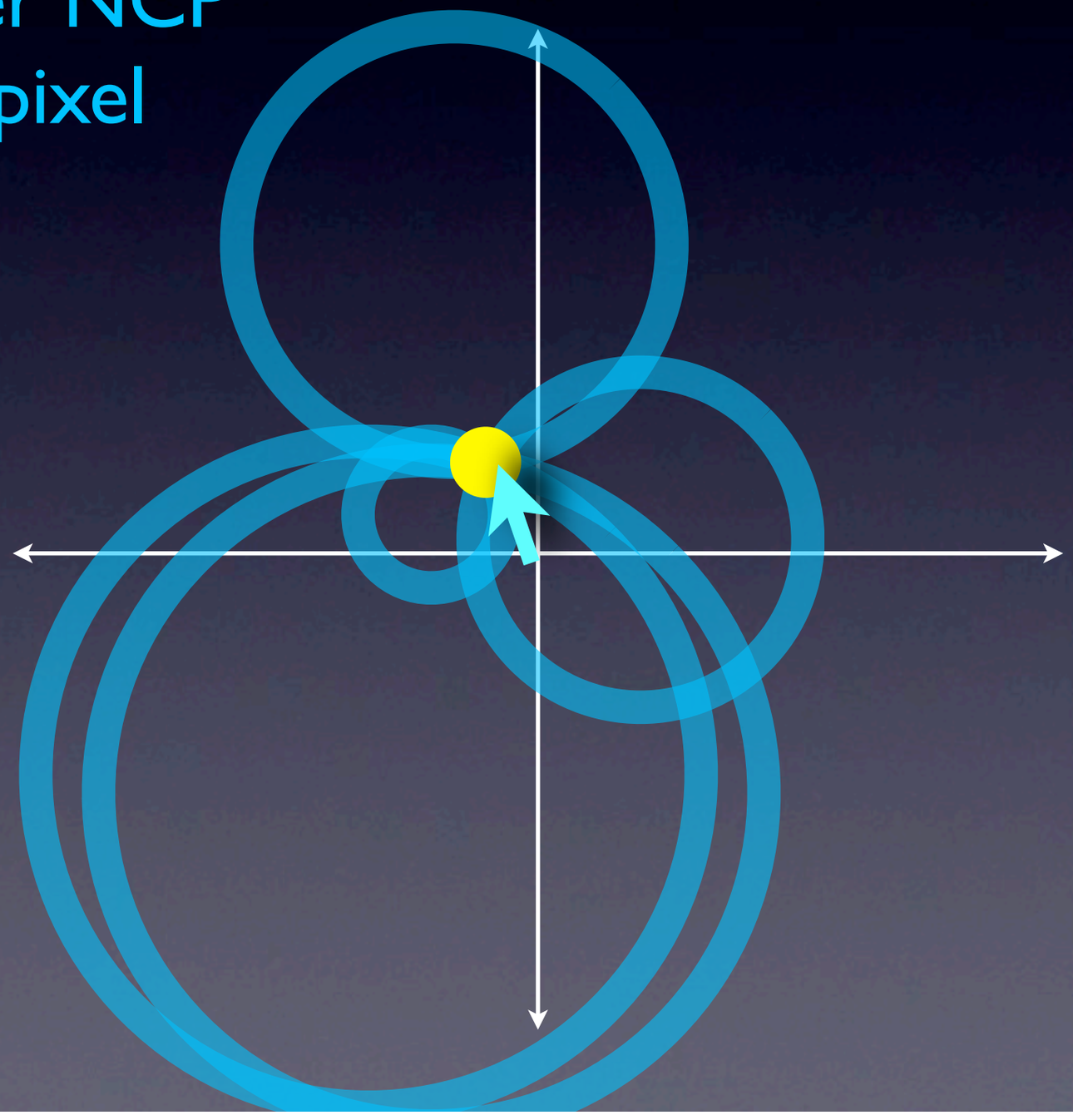
WFS PSF



Clio 5 micron

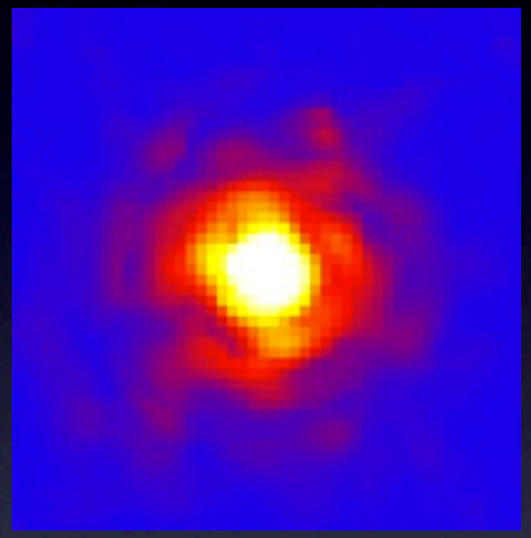


You recover NCP for that pixel

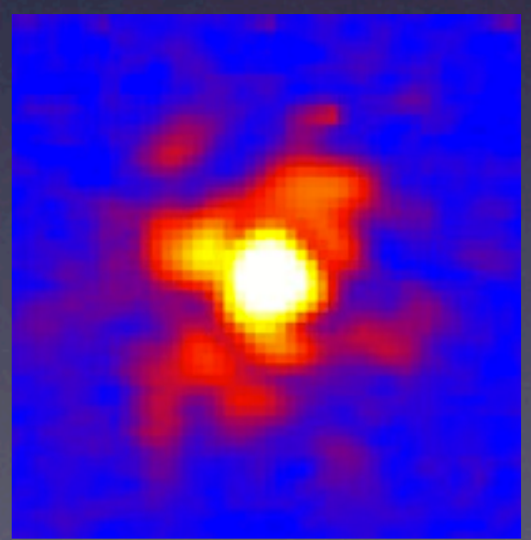


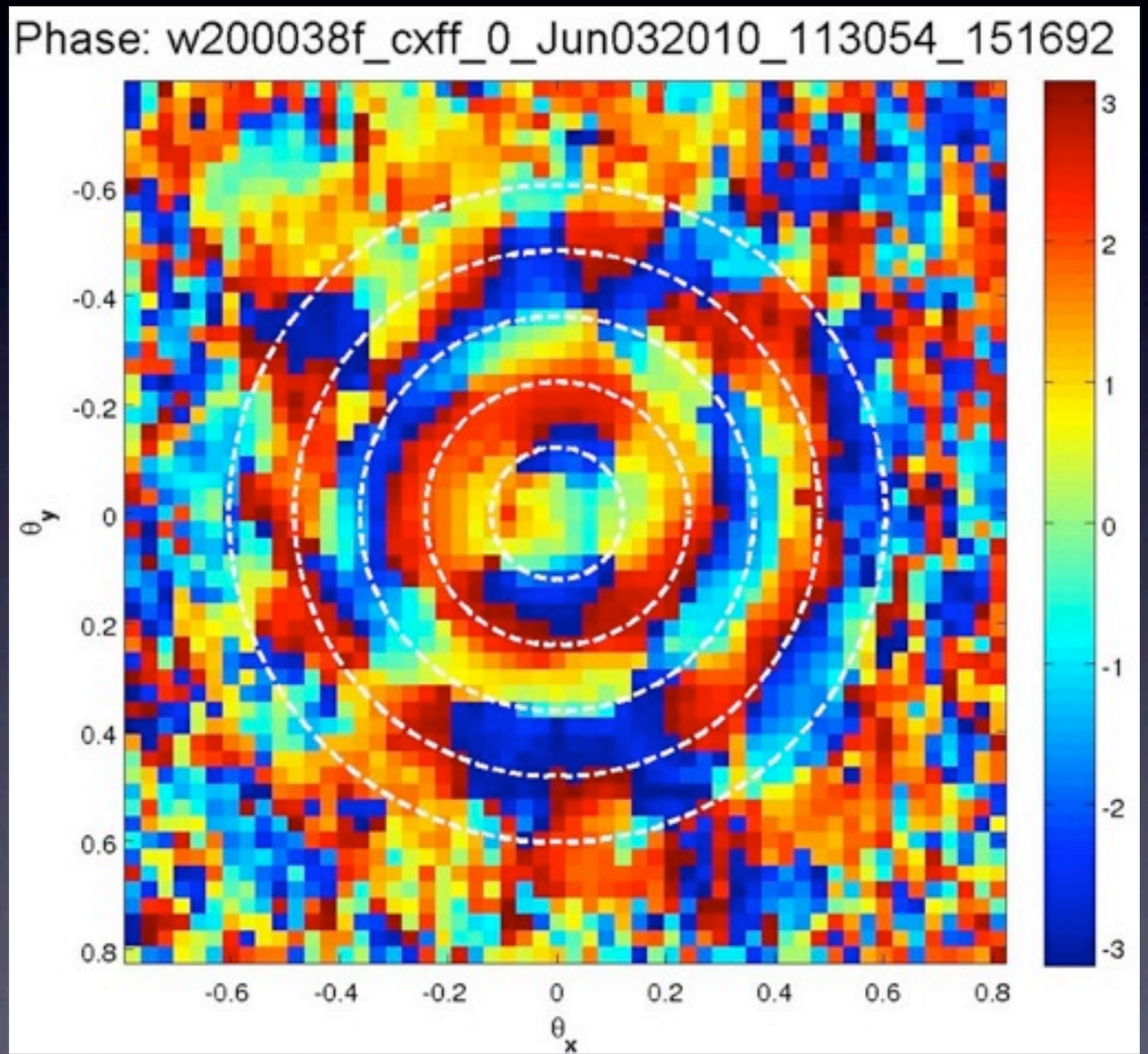
Atmosphere provides phase diversity

WFS PSF



Clio 5 micron





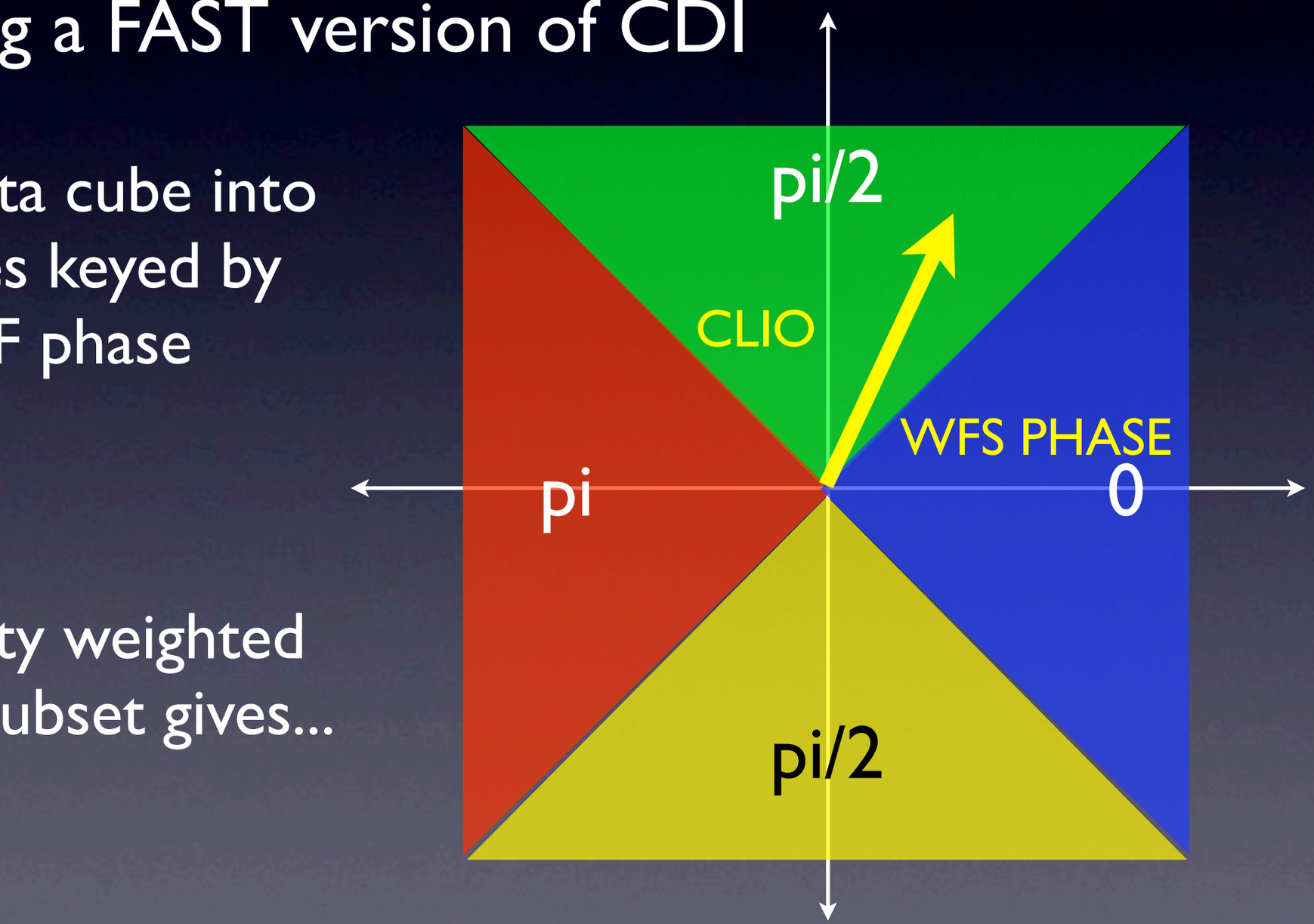
Phase Sorting Interferometry

Codona, Kenworthy and Lloyd-Hart (2008)

- Implementing a FAST version of CDI

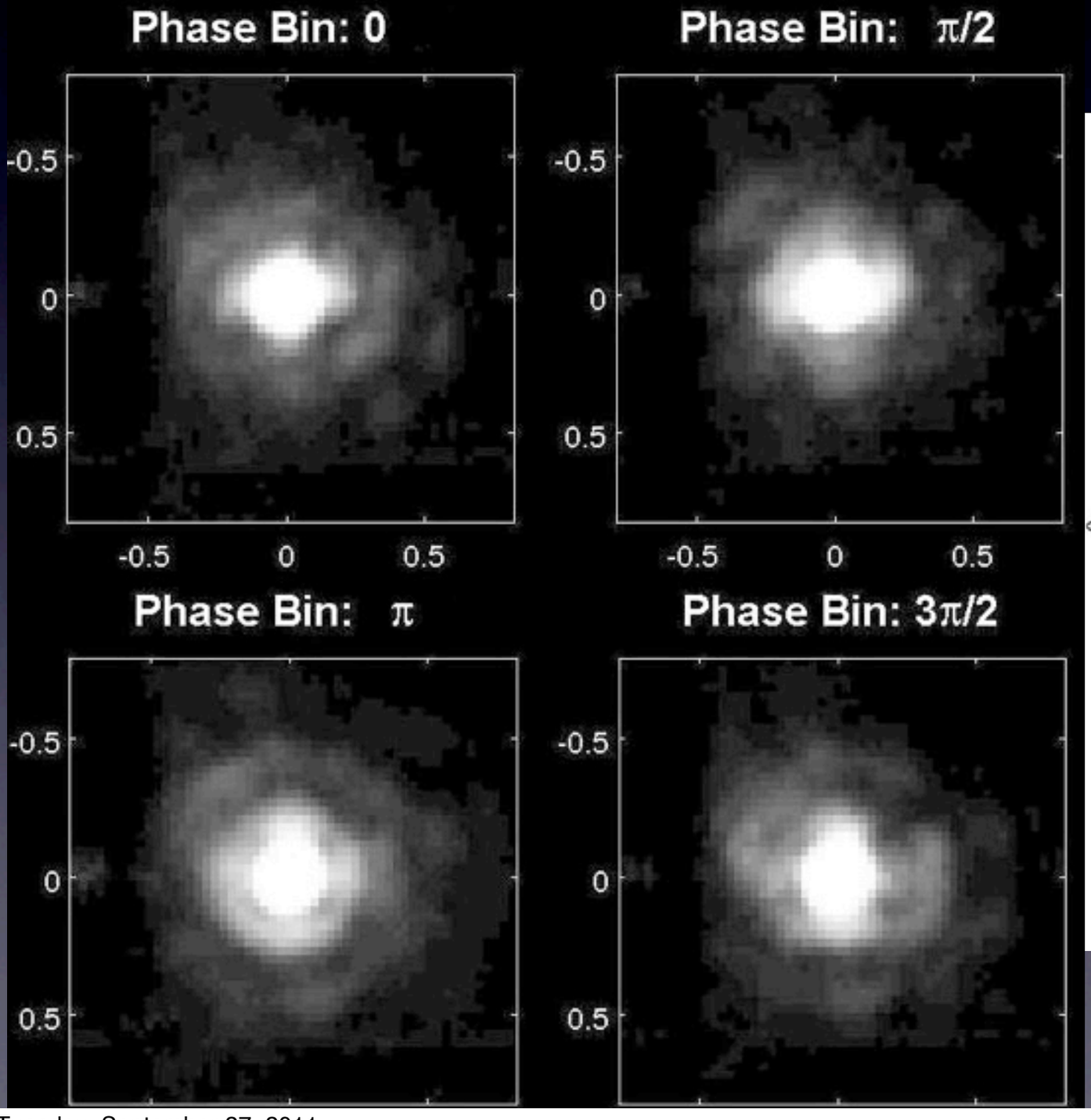
Split CLio data cube into 4 sub images keyed by WFS PSF phase

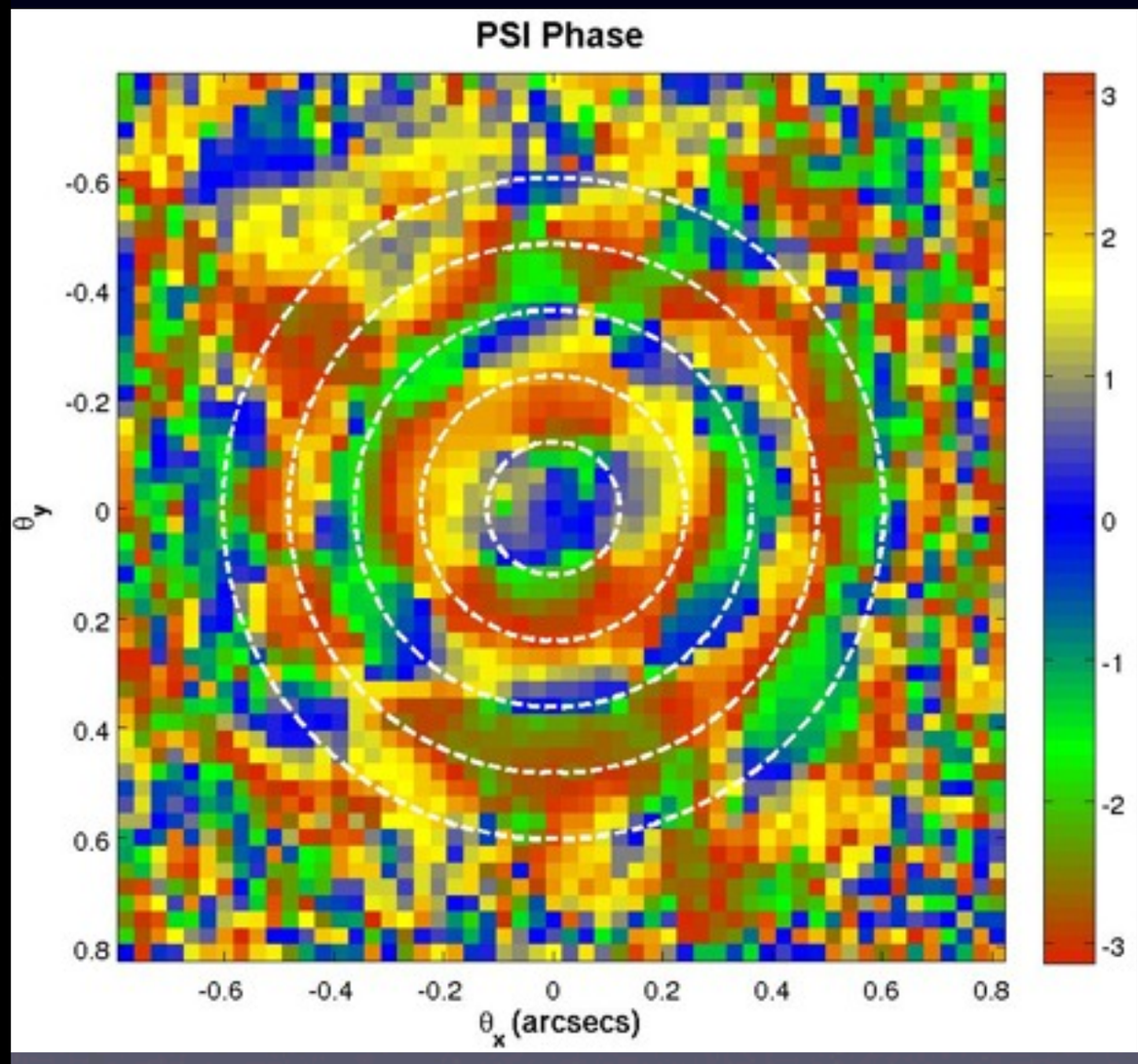
Then intensity weighted sum of each subset gives...



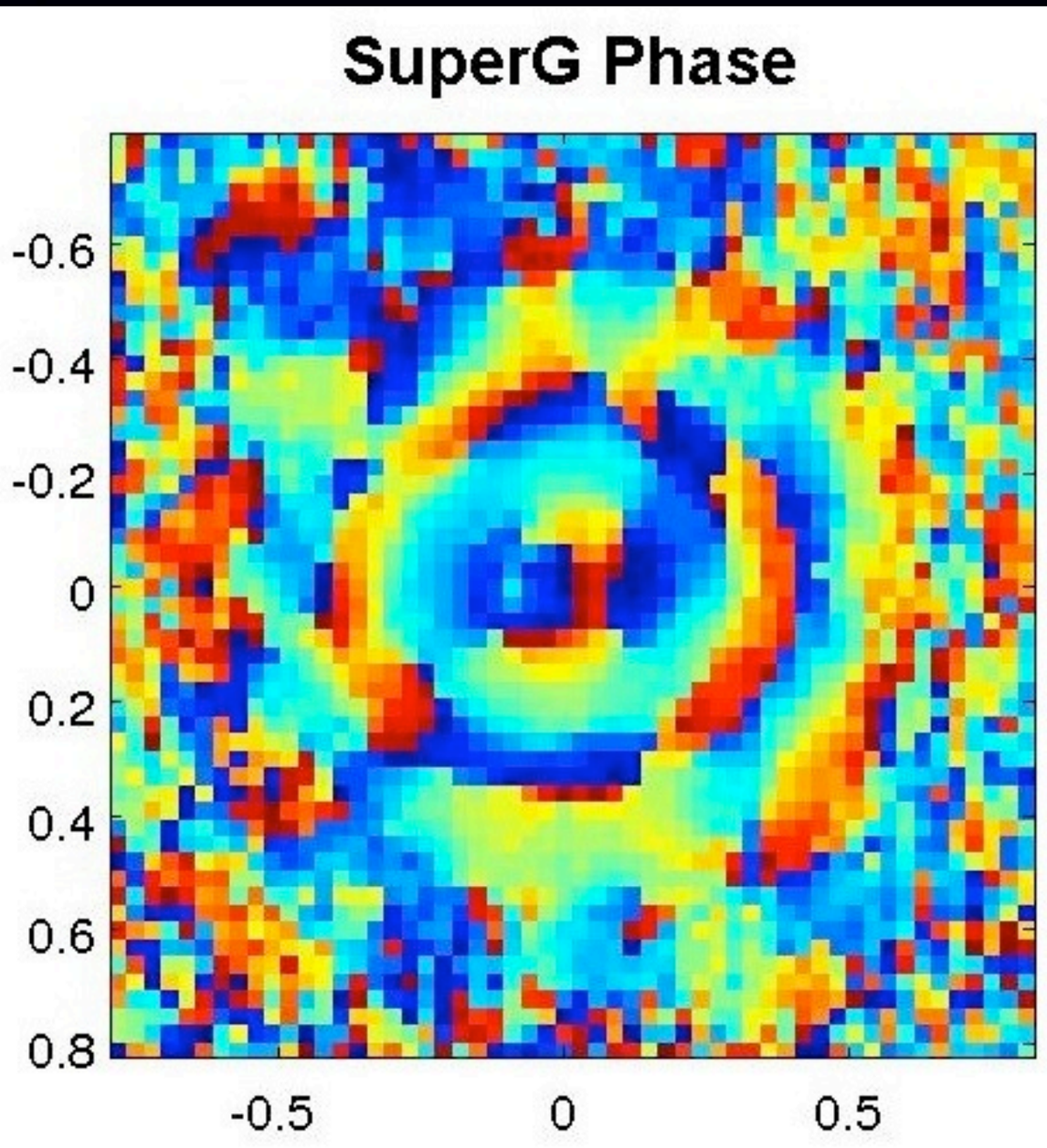
Phase Sorting Interferometry

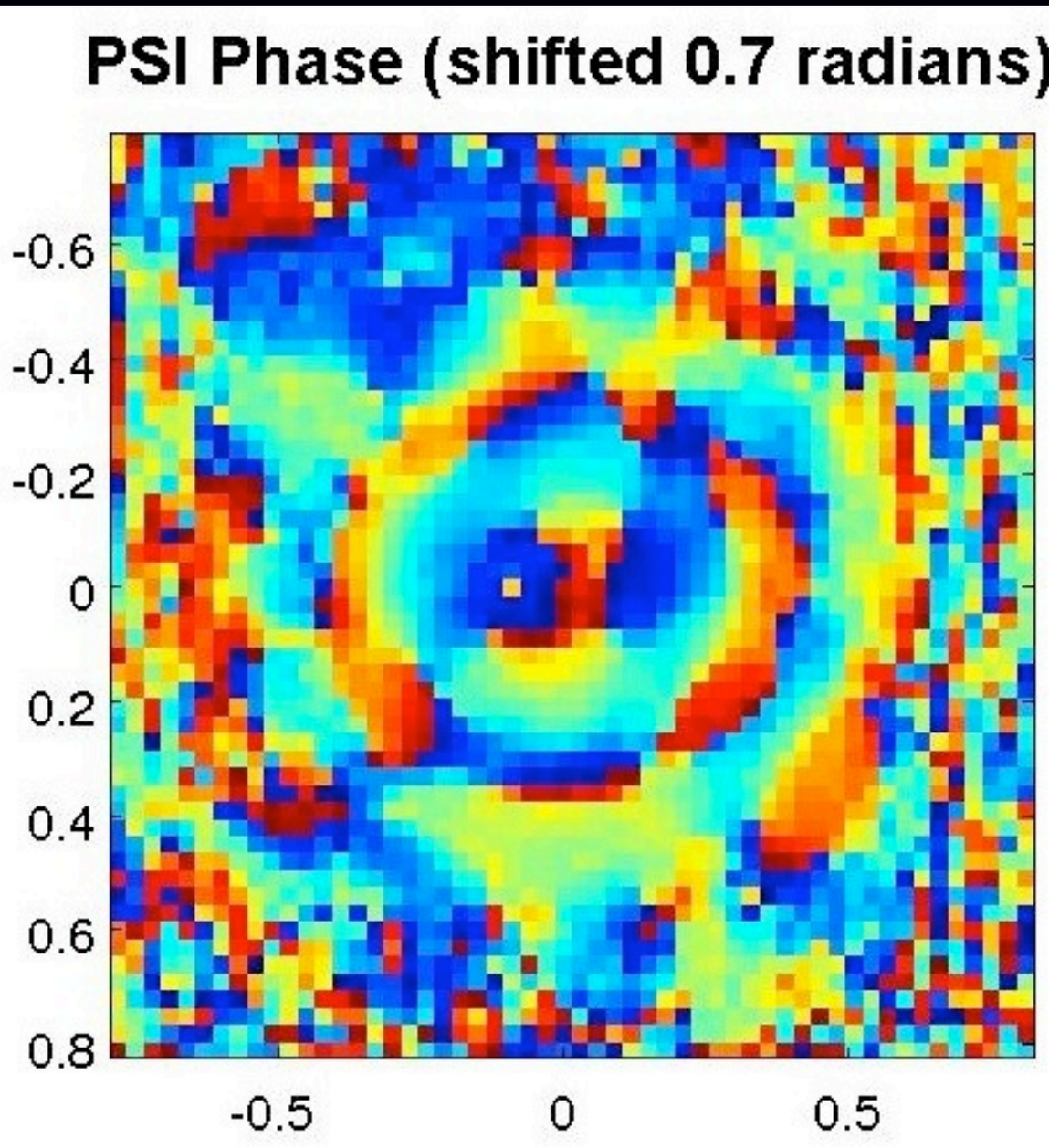
Codona, Kenworthy and Lloyd-Hart (2008)



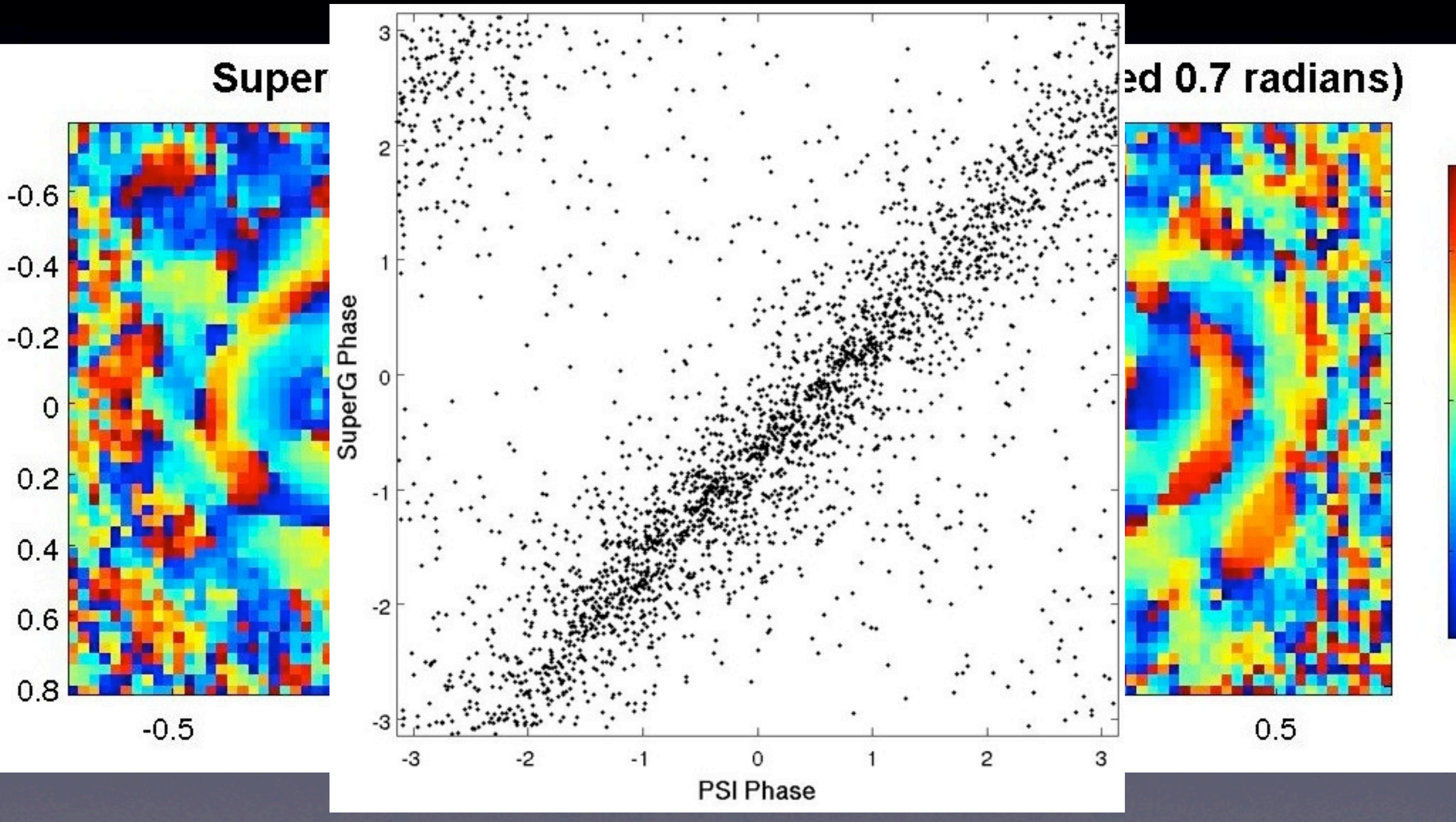


PSI comparison



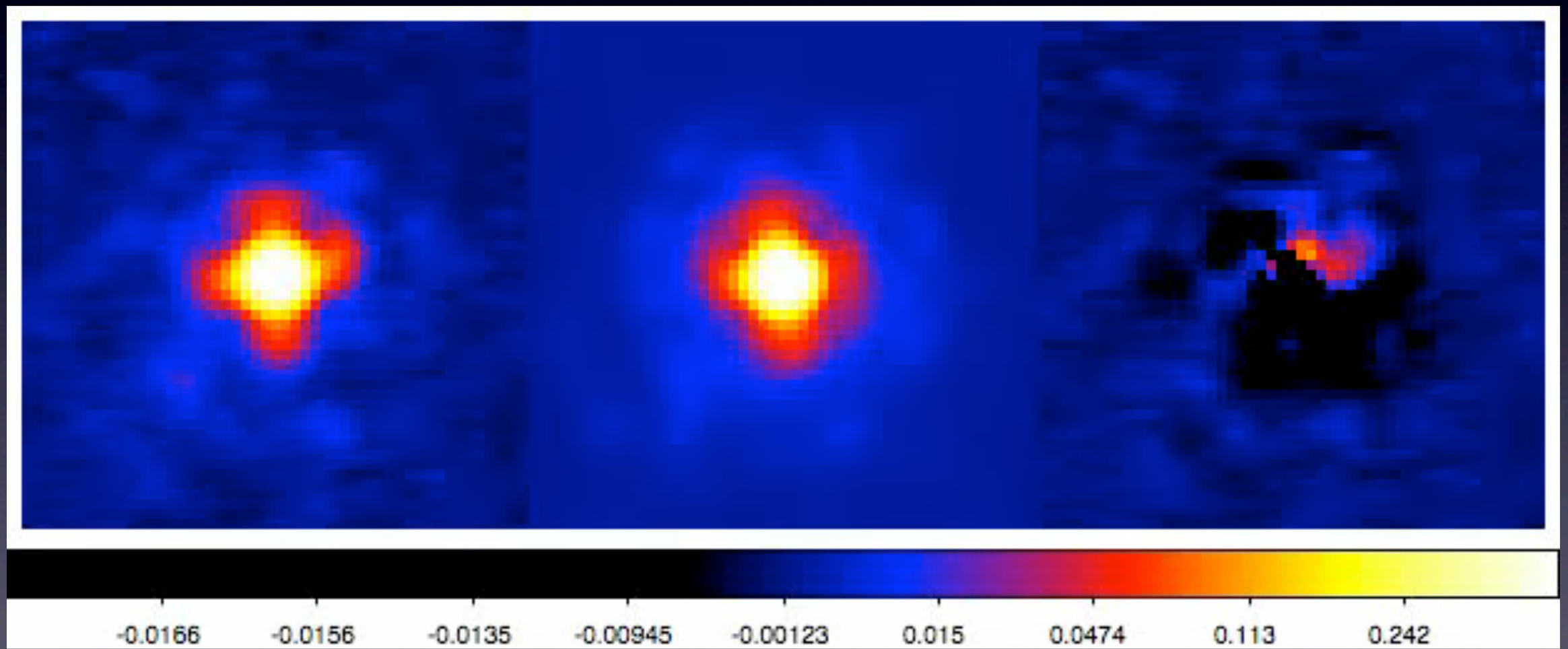


PSI comparison



Testing PSI

Clio 5um PSF WFS PSF Difference



3 seconds of on-sky data

Testing PSI

Qualitatively, speckles are reproduced

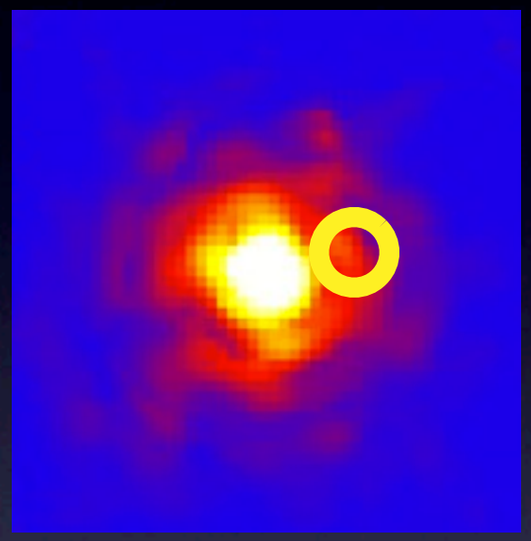
but...

Residuals are not great.

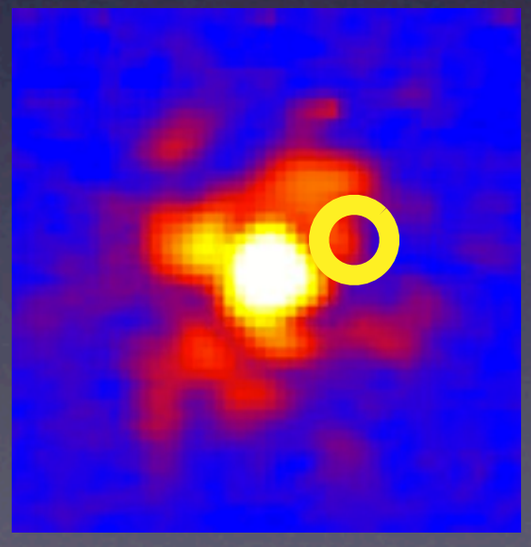
Why?

WFS Gain is a free parameter

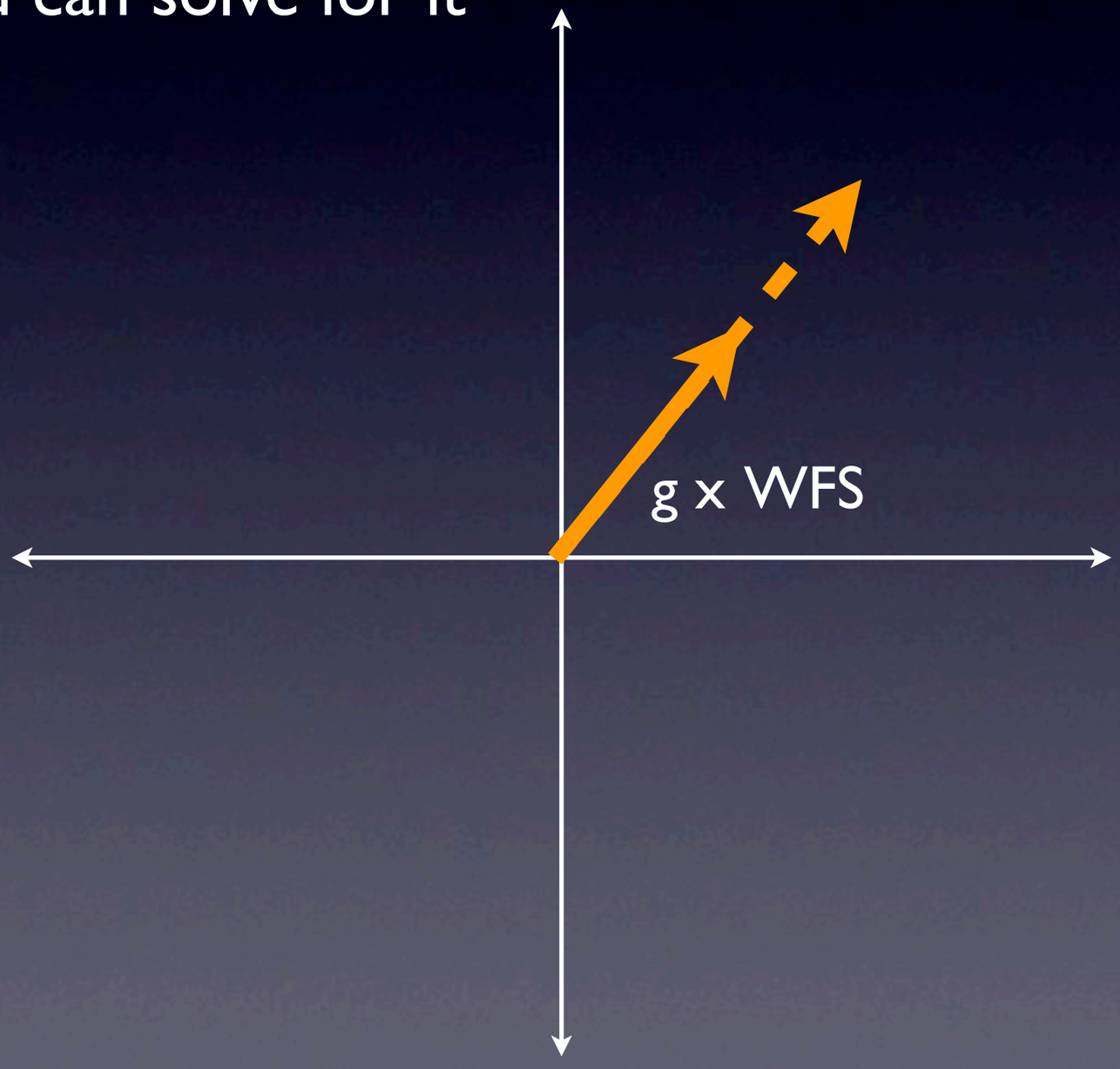
WFS PSF



Clio 5 micron



g varies as a function of SEEING
...but you can solve for it



Conclusions

- PSI has been demonstrated on-sky
- Generating Science PSFs is work in progress
- No hardware required - can be implemented on any current AO system with ‘burst’ mode
- No need for DM telemetry!

Future Directions

- Map out NCP for MMTO and LBT telescopes
- Make a dedicated PSI computer to supply new DM offsets and generate Science PSFs for observers
- Mapping out parameter space - how long an exposure can you take?

See Johanan Codona's Poster on PSI

Phase-Sorting Interferometry for High-Contrast Imaging with the GMT

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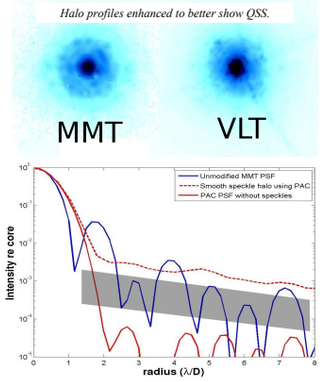
jlcodona@gmail.com

Dust and Aberrations cause Semi-Static Speckles and Imperfect Halo Suppression

Quasi-static speckles are ubiquitous and limit sensitivity



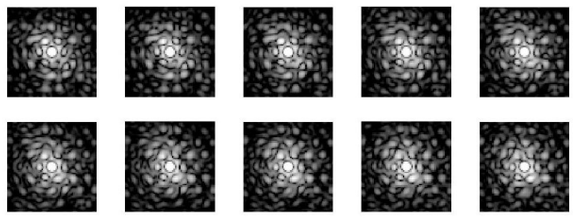
Quasi-static speckles are caused by aberrations and imperfections within the telescope optics. They are typically fainter than the AO speckle halo which averages to a smooth background and can be removed in a long exposure. The slower speckles change, but not fast enough to average, nor are they static enough to be calibrated. They can be adaptively "dialed-out" with the DM, but only by using measurements made during the observation, and at the science camera to avoid non-common-path errors.

PSI has been Successfully Demonstrated at the MMTO

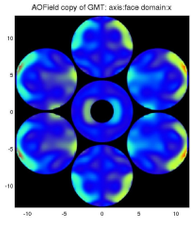
Residual AO Speckles are probes-of-opportunity

Direct Imaging L-Band Speckles

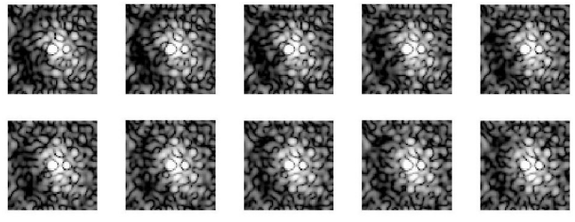
Simulation used AOSim2 with a 1200-mode non-predictive reconstructor. WFS @ 1kHz. Science frames @ 100 FPS. Only monochromatic fields were used for this simulation.



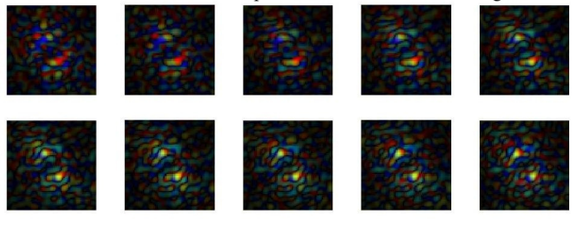
GMT TIGER PAC APP OPD



PAC APP Imaging L-Band Speckles



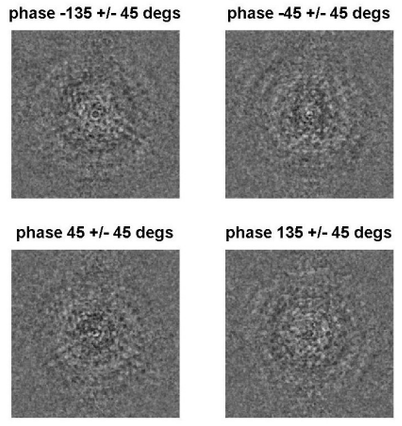
Complex Speckles can be computed from WFS measurements. Phases are then used to bin pixels of Science Camera images.



Construction of a Speckled Halo

Computed speckle phases allow per-pixel sorting into 4 images where speckle halo is in-phase.

Phase-Sorting Counts



The speckles are taken around the mean halo. This ensures a reasonable balance into all phases for real atmospheric speckles. Resonance and vibrations may not be so equally distributed.

PSI-Generated Interferograms at 4 90-degree Phases