Astrophotonic Quantum Astronomy…

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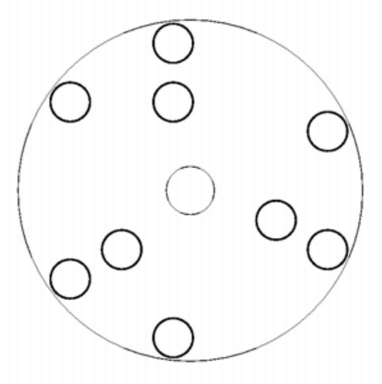
The Remarkable Rebirth of Masking Interferometry

Keck / NIRC2

Anthony Cheetham

VLT / CONICA



9 Hole pupil mask

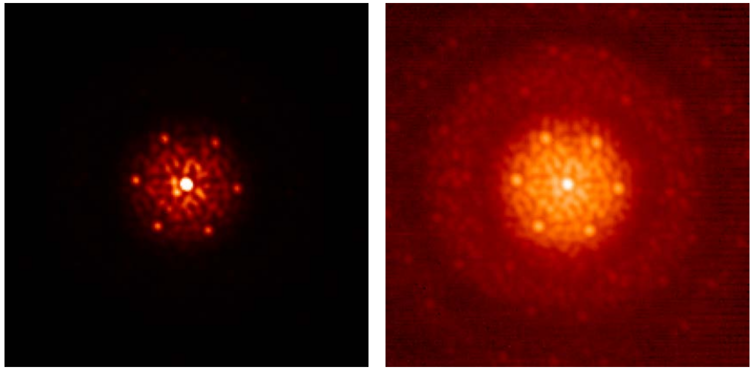
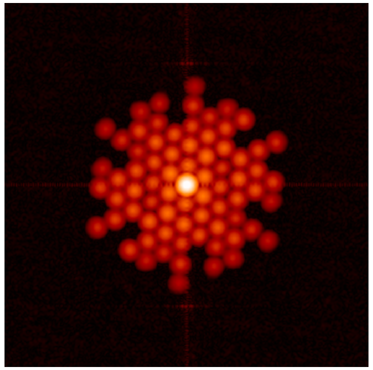
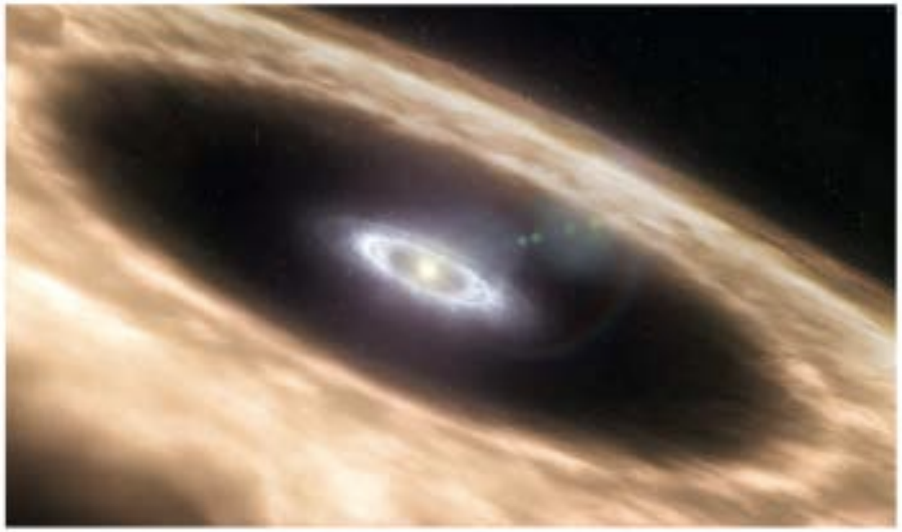


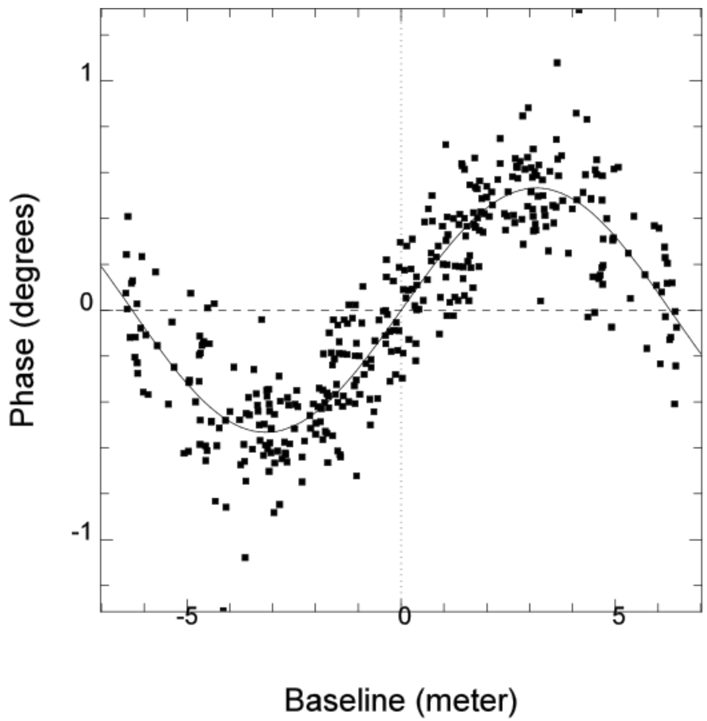
Image Plane (linear/log)

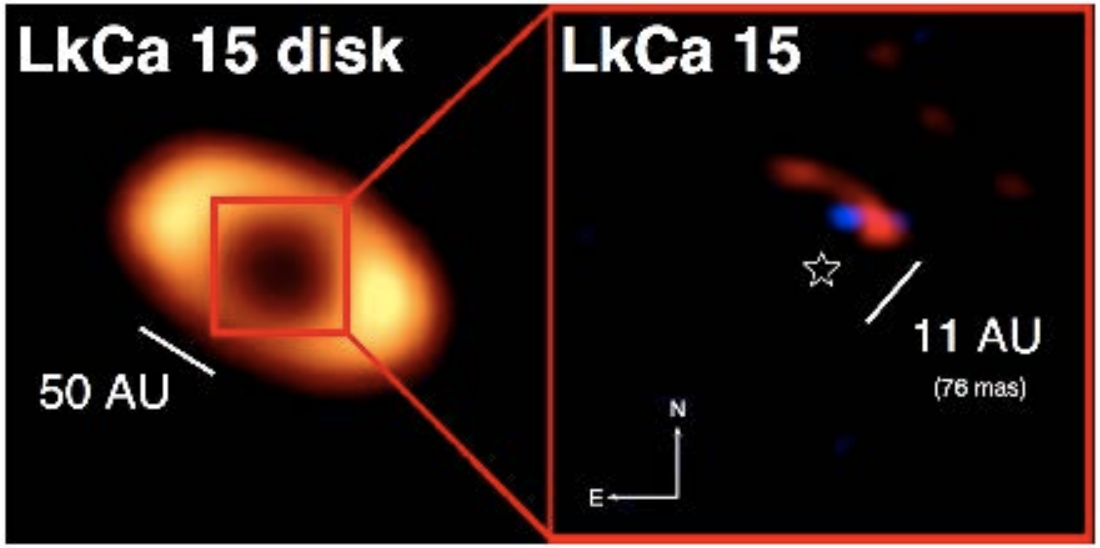


Fourier Plane

Asymmetric structures in Transition Disks







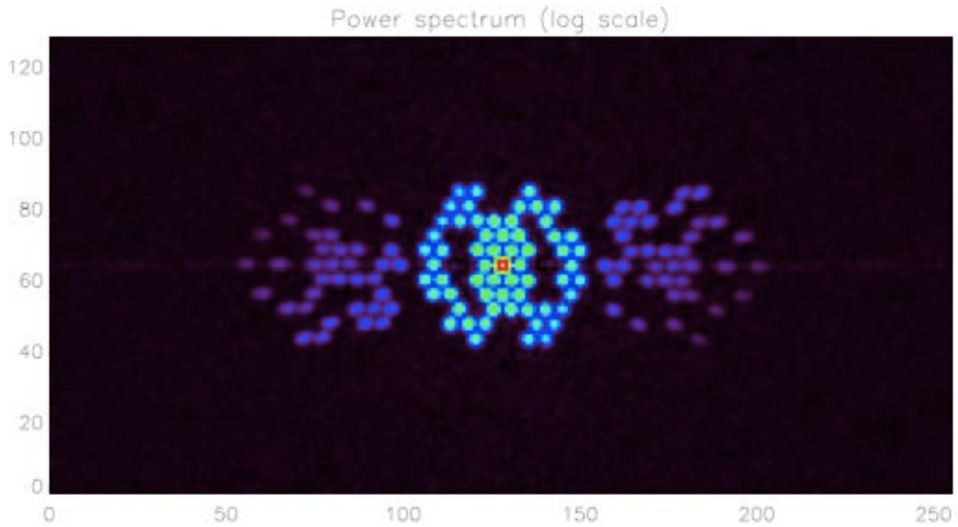
Huelamo et al. A&A 2011 2013 (+Cheetham)…

Kraus & Irelad ApJ 2011

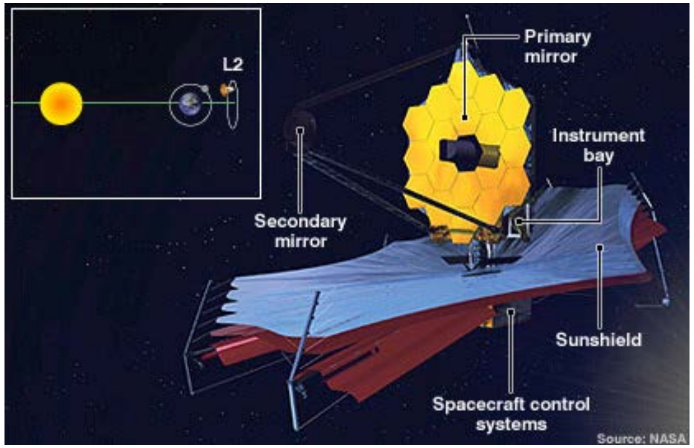
Masking: present status

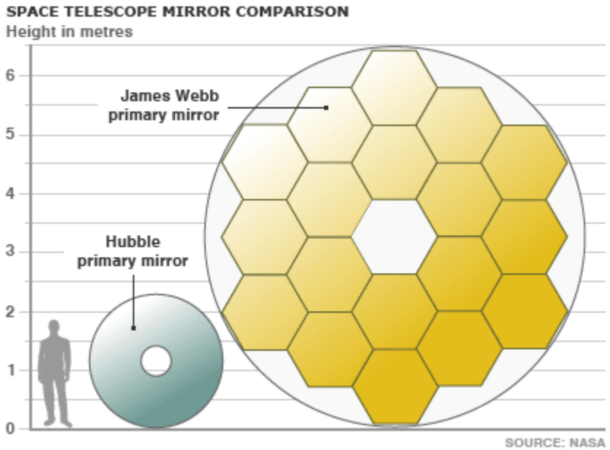
- Mostly L band (some K band detections)
- Now more than half dozen detections of asymmetry
- What are we seeing?
- Search for evidence of orbital motion.
- NACO is going away (probably)
- NIRC2 going strong
- New opportunities at GPI, LBT
- Also big algorithmic gains

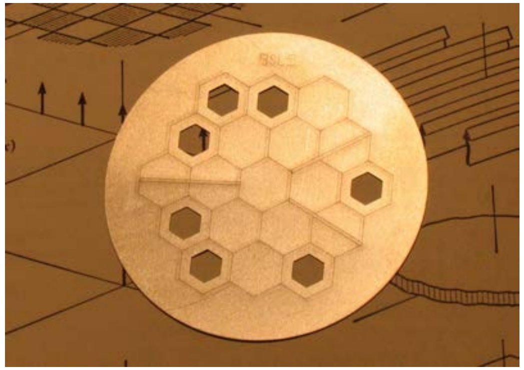
Image Credit: ESO/L. Calçada

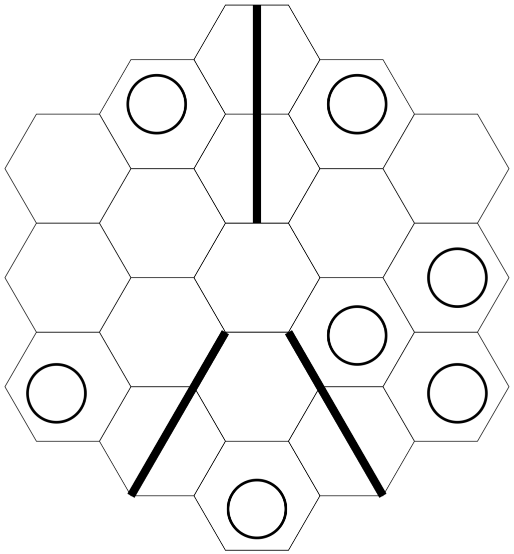


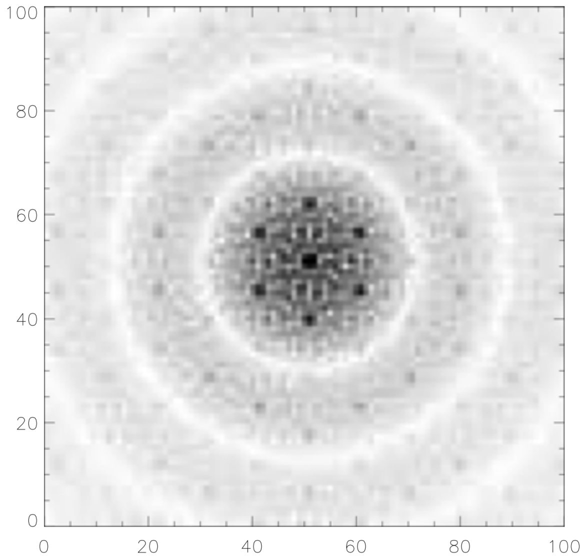
JAM: JWST Aperture Mask

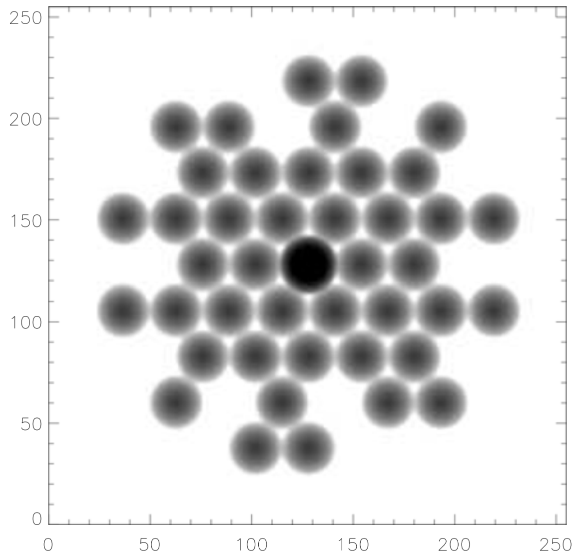




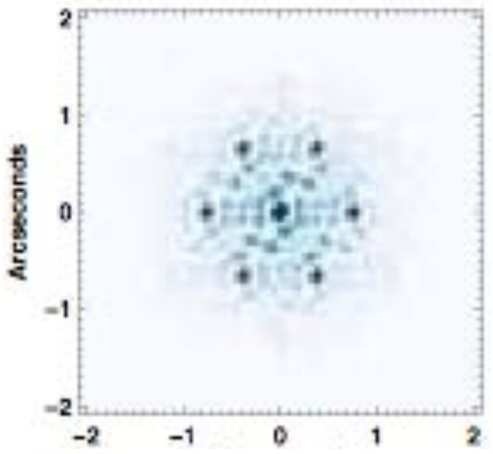


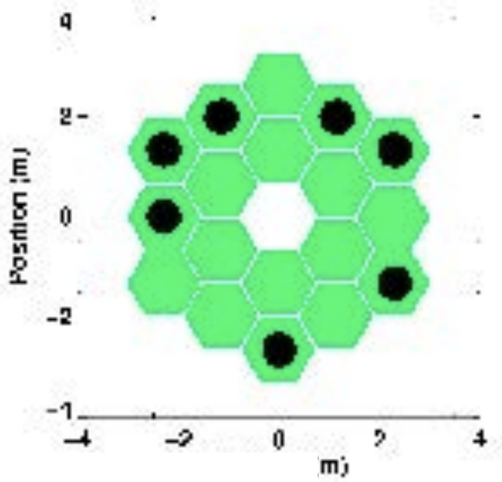


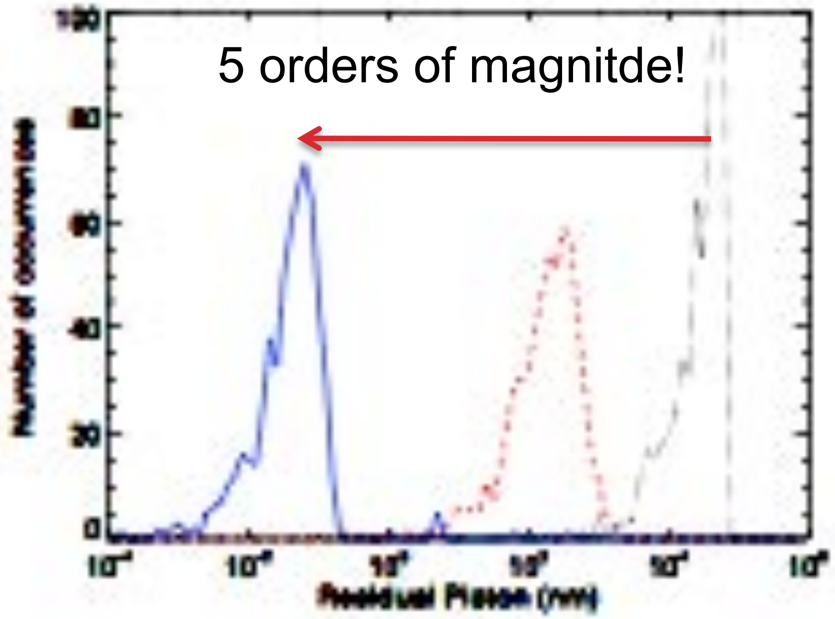




FICSM: Fizeau Interferometric Cophasing of Segmented Mirrors







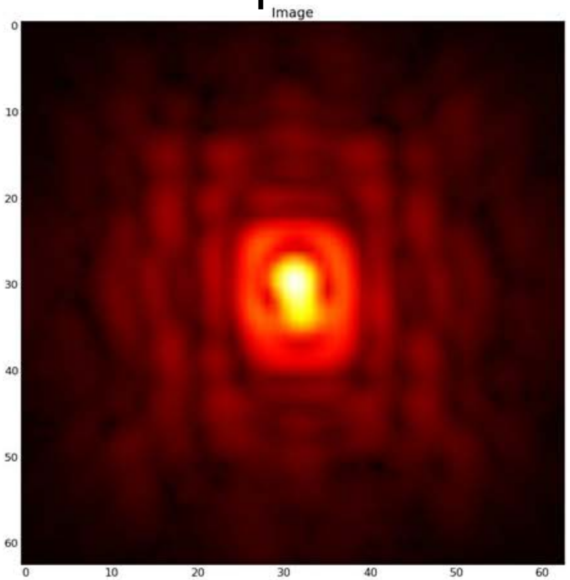
- Initial state mirror has tilt 0.5 arcsec and phase errors of 150 microns
- Algoithm requires one broadband and one narrowband image. Repeat once (two cycles).
- Delivers 3.7mas tilt and 0.75nm in a single application of the algorithm (does not require convergence).
- Now adopted as primary backup strategy for phasing JWST mirrors in the event of a failure of NIRCAM.
- Can be extended to any segmented mirror
- Does not require a mask
- Working on seeing limited case

Cheetham, Tuthill et al. Applied Optics 2013

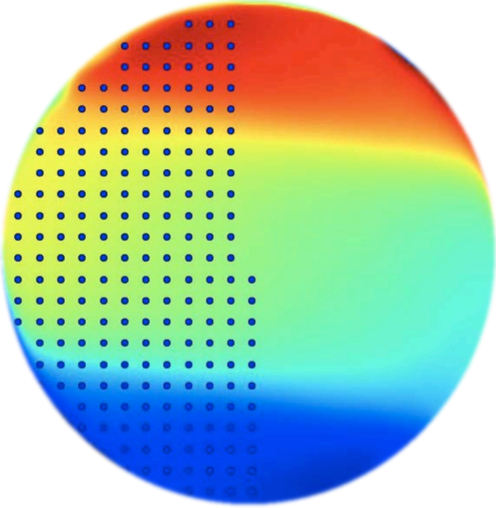
Kernel Phase detection of Brown Dwarf binaries

Ben Pope

- Reanalysis of archival Hubble Space Telescope data from a previous survey looking for brown dwarf binaries (Reid et al., 2006)
- Use Kernel Phase – a generalization of Closure Phase which applies to redundant pupils (Martinache 2010)
- Kernel Phase works at high Strehl when wavefronts can be approximated as a linear sum of phase errors



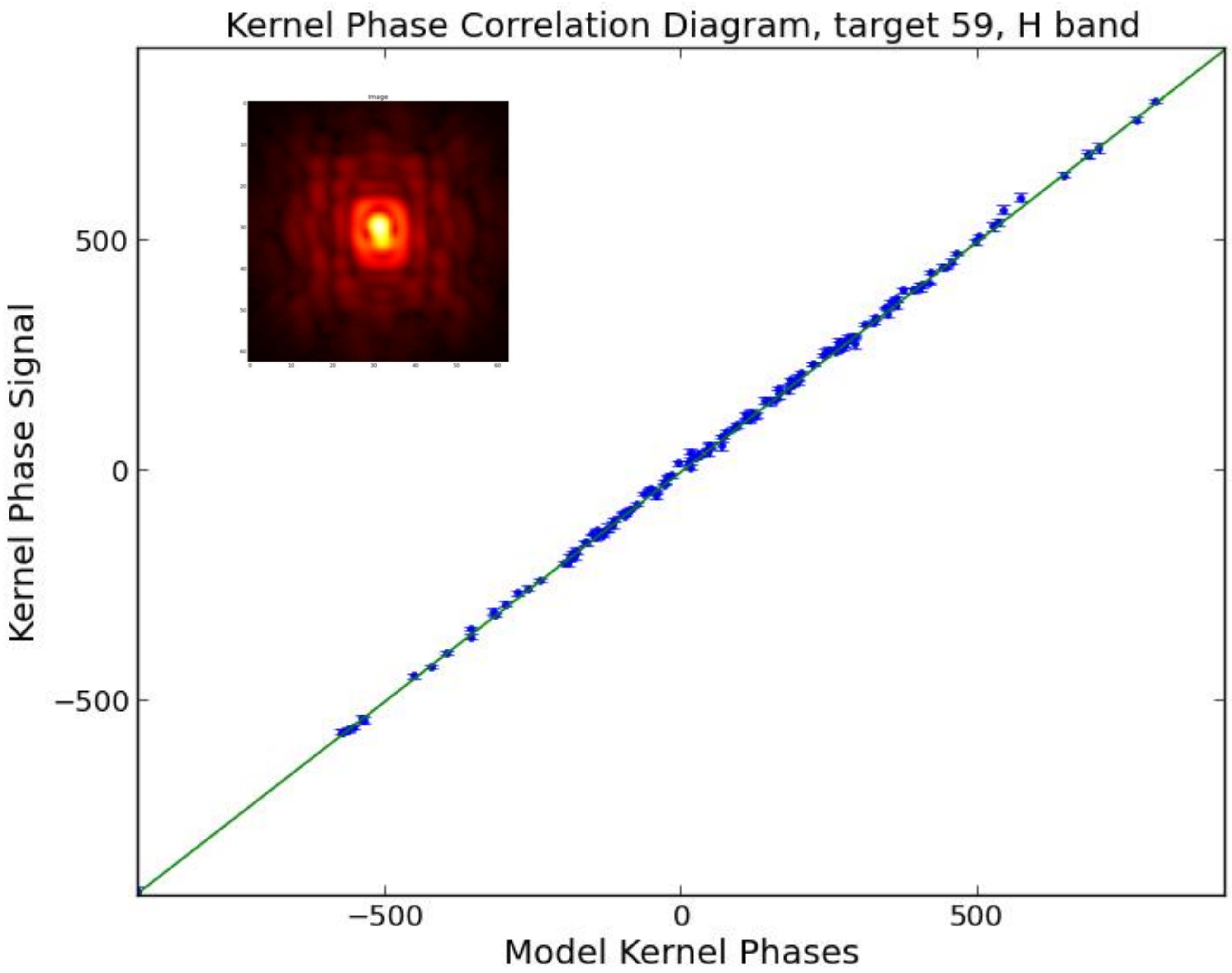
Close binary from Reid et al. (2006), 2M 0149-4954



Fourier phases

The Incredible Precision of Kernel Phase I

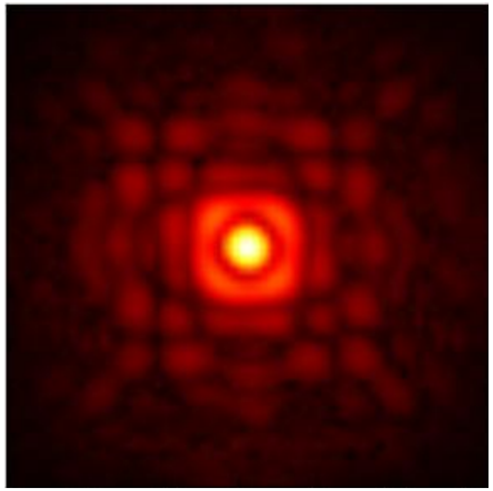
- Data vs. model for best parameter fit for the known binary from earlier
- With error bars!
- A good fit lies on the $y = x$ line – this does over its entire range
- Parameters are an order of magnitude more precise than visual estimates

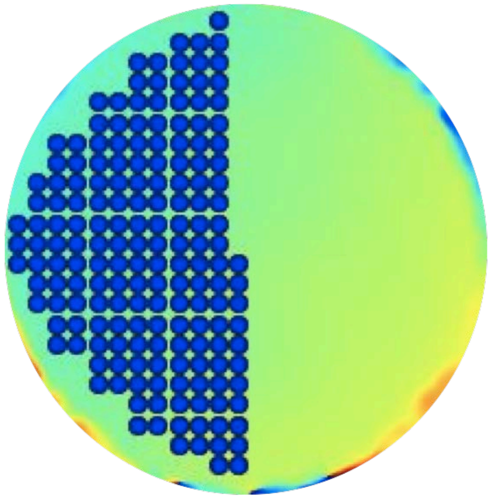


Comparison with Previous Survey

Target – 2MASS	Old		New	
2252-1730	H	J	H	J
Separation	140		127.8 ± 2.3	125.8 ± 1.5
θ	341.5		353.1 ± 0.5	353.7 ± 0.4
Contrast	4.2	2.47	3.5 ± 0.1	2.47 ± 0.05
0147-4954				
Separation	190		139.9 ± 0.3	139.7 ± 0.2
θ	67.6		72.7 ± 0.1	72.5 ± 0.1
Contrast	1.58	3.5	2.07 ± 0.01	2.36 ± 0.01

New Binaries

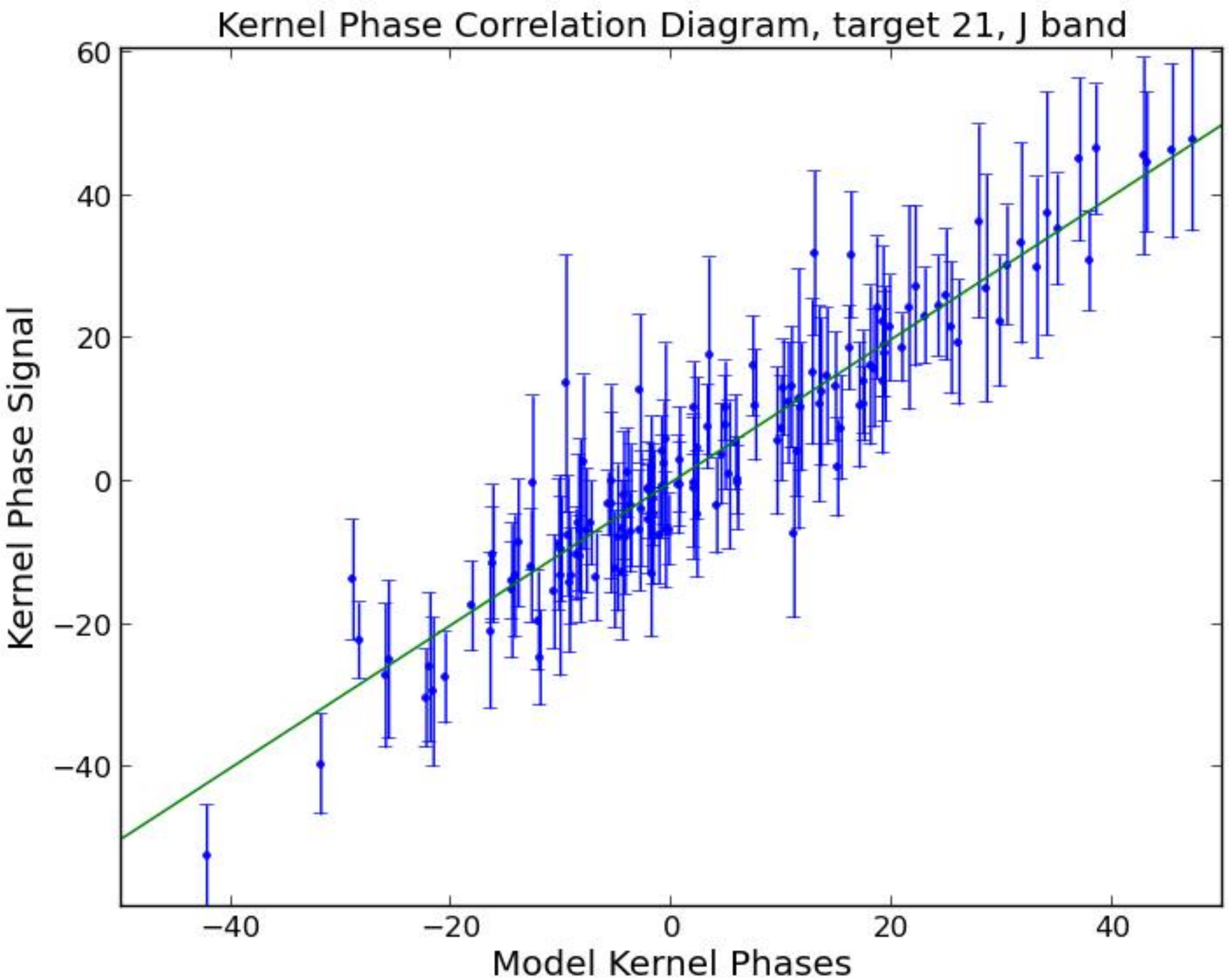




- Here is an L dwarf which is not obviously a binary
- Reid et al. (2006) looked hard and noted 'PSF abnormality' in some targets
- Is there a slight gradient in the Fourier phases?
- Can kernel phases detect anything in such a marginal case?

New Binary Detections

- Data vs. model for a new L dwarf binary, 2M 2028+0052
- We have five strong candidates of this form
  - mostly with no PSF abnormality noted
- All close binaries at low contrast
  - Follow up to confirm and get masses



Kernel Phase Outcomes

- Two orders of magnitude more precise astrometry on eight known binaries for follow-up
- Discovered five new brown dwarf binaries
- Higher Binary Fraction lends further weight against embryo ejection models, favouring gravo-turbulent collapse
- Uncovered a population of a half dozen high contrast (>10) potential planetary-mass candidates
- Illustrated the power of kernel phase for space and ground based high contrast detection
- Required the development of sophisticated data analysis (Nested Sampling Bayesian Methods).

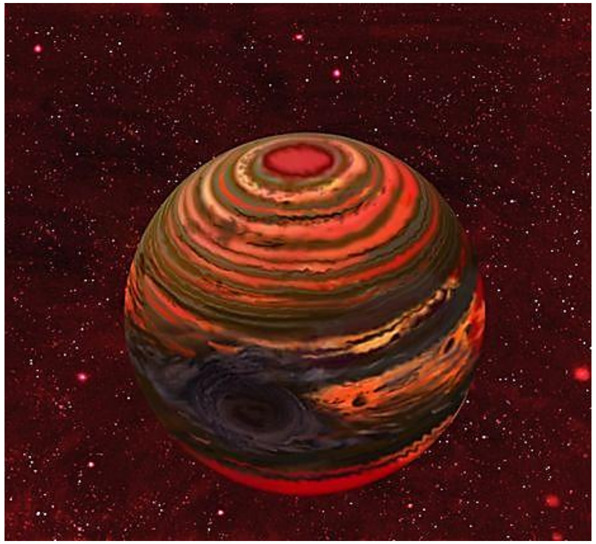
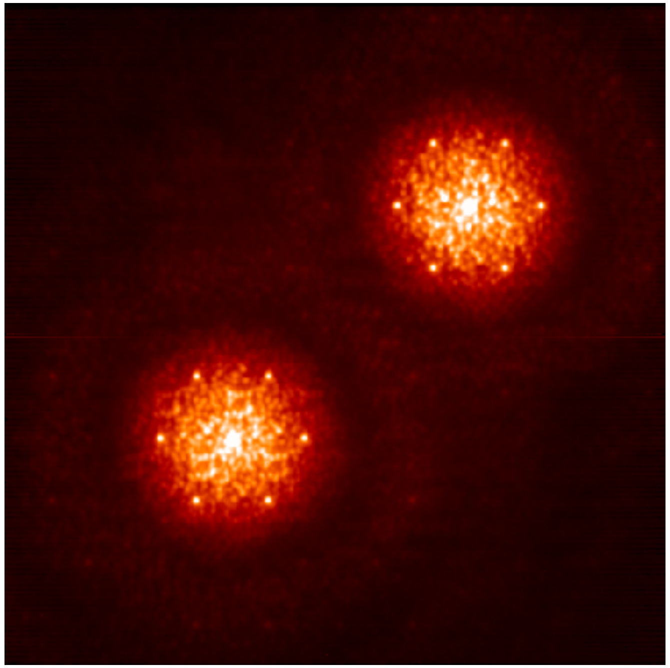


Illustration by Jon Lomberg, University of Toronto. Published in *National Geographic*, September 13, 2011.

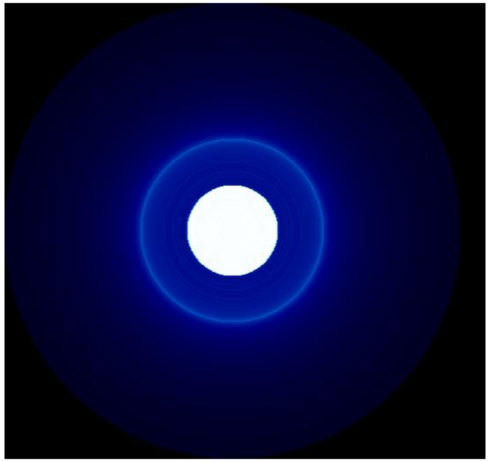
Pope, Martinache and Tuthill 2013 ApJ

A masking go-faster stripe: Polarimetric Interferometry for enhanced precision

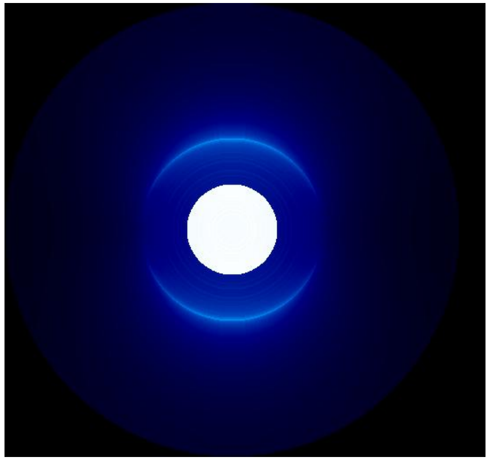
CONICA camera with Wollaston Prism



Normal Imaging

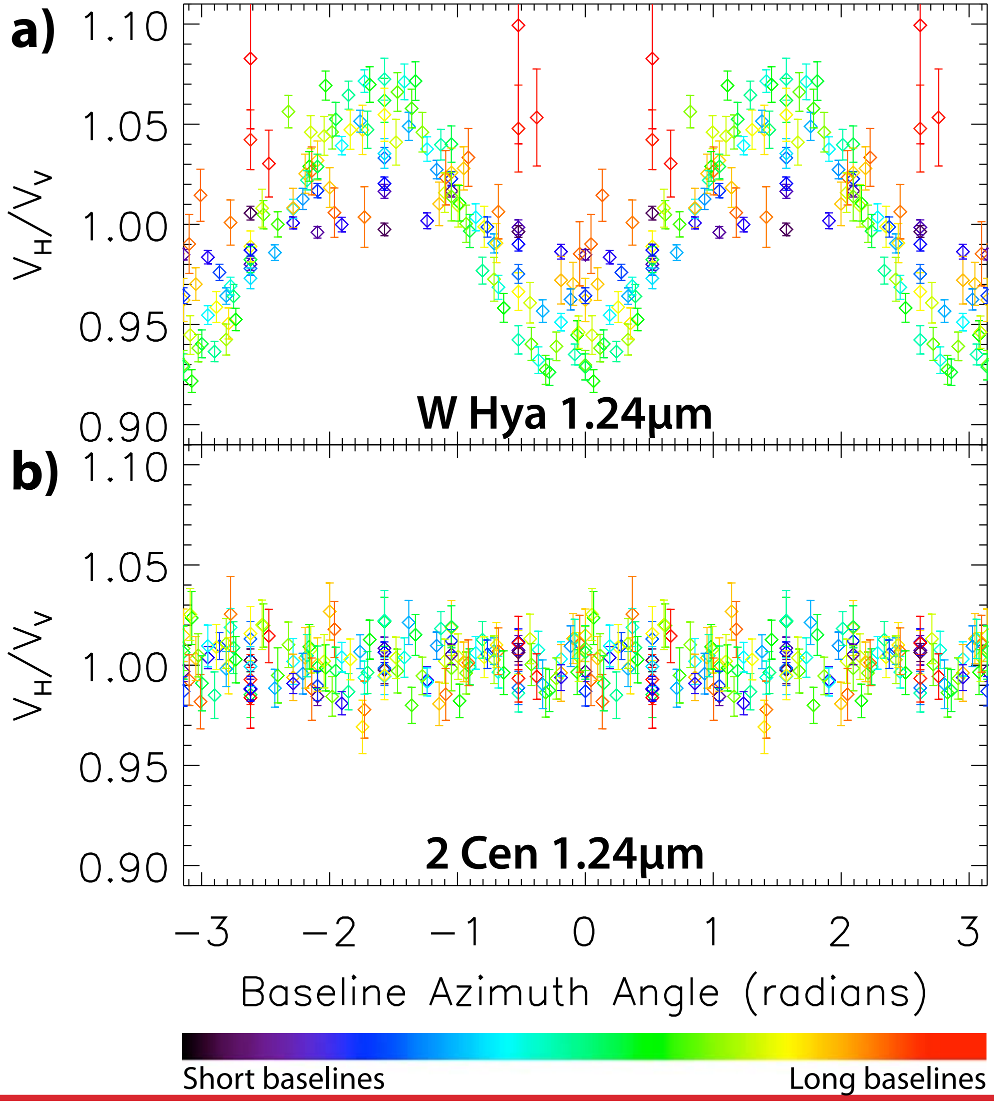


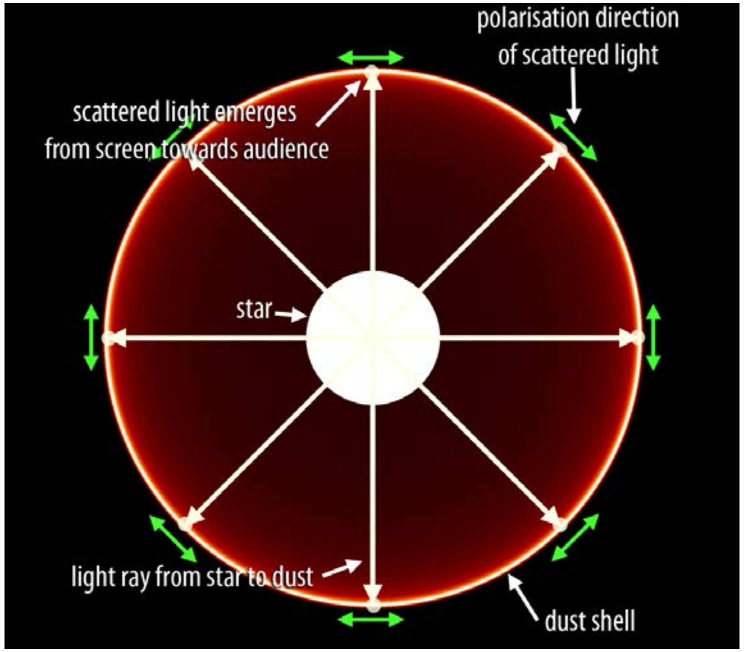
Polarised light



Barnaby Norris

Optical Interferometric Polarimetry: W Hydrae

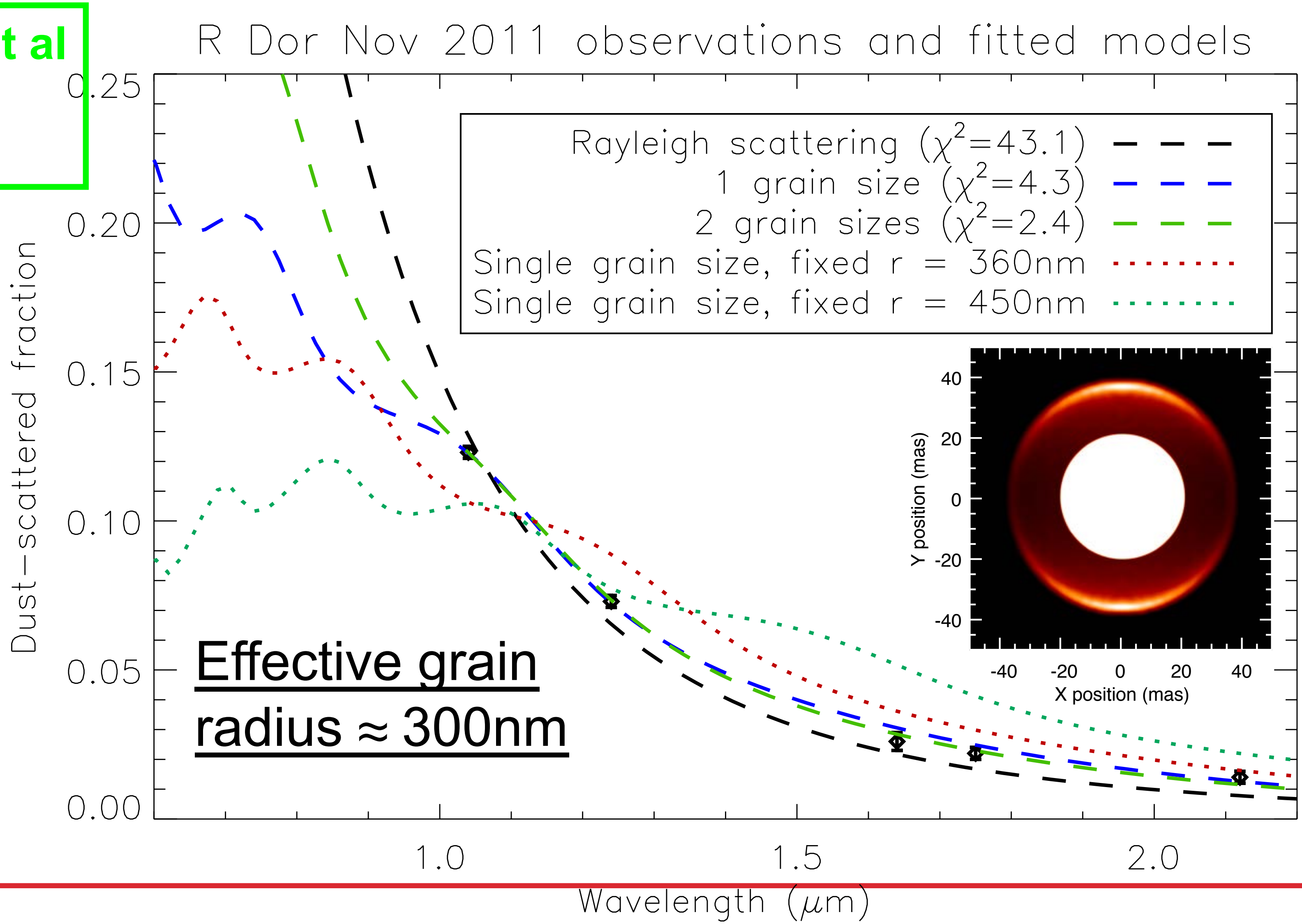




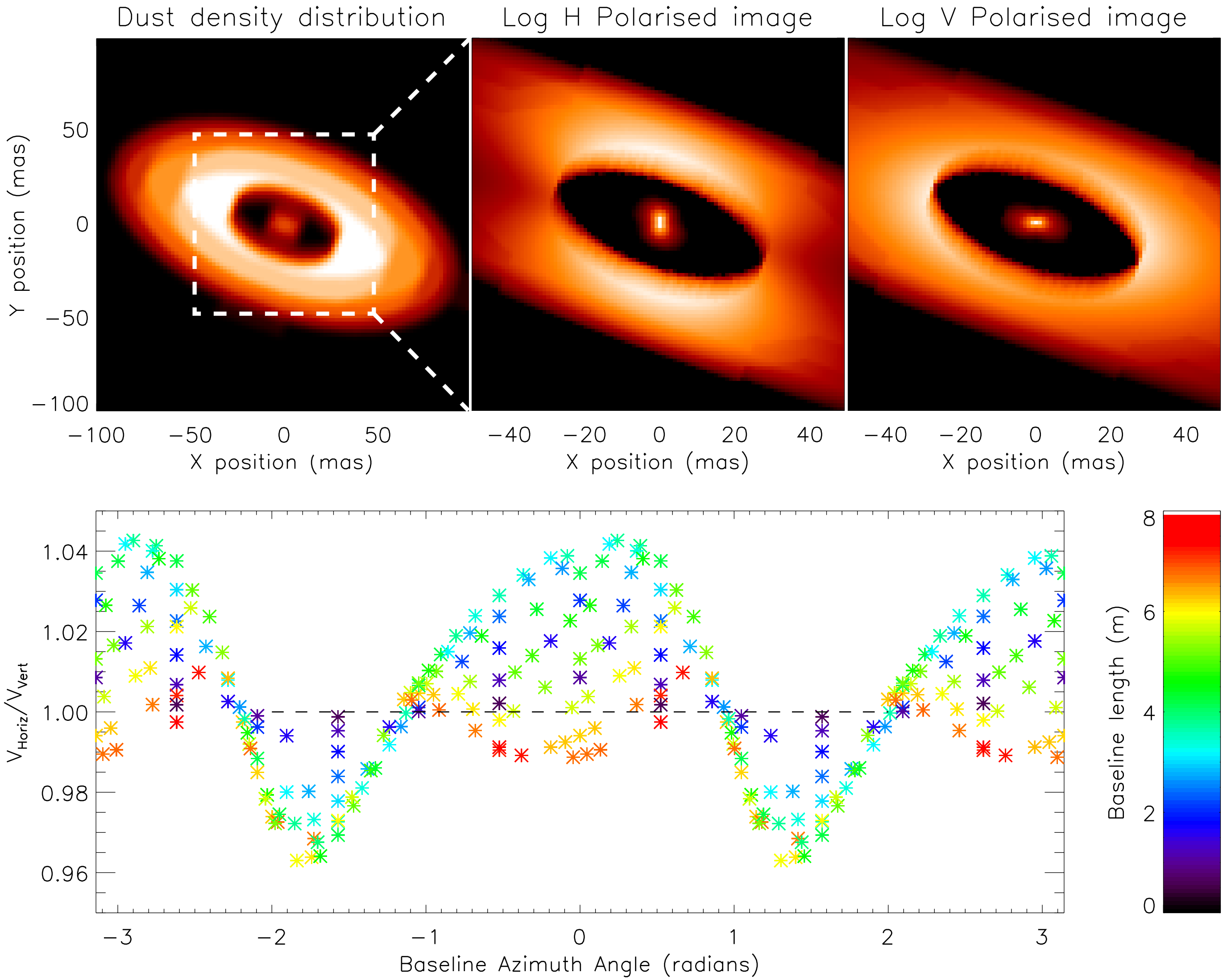
Grain Size: 10 nm metrology precision at 100 PC !

Dust grain size and mass tightly constrained from multi-lambda scattering

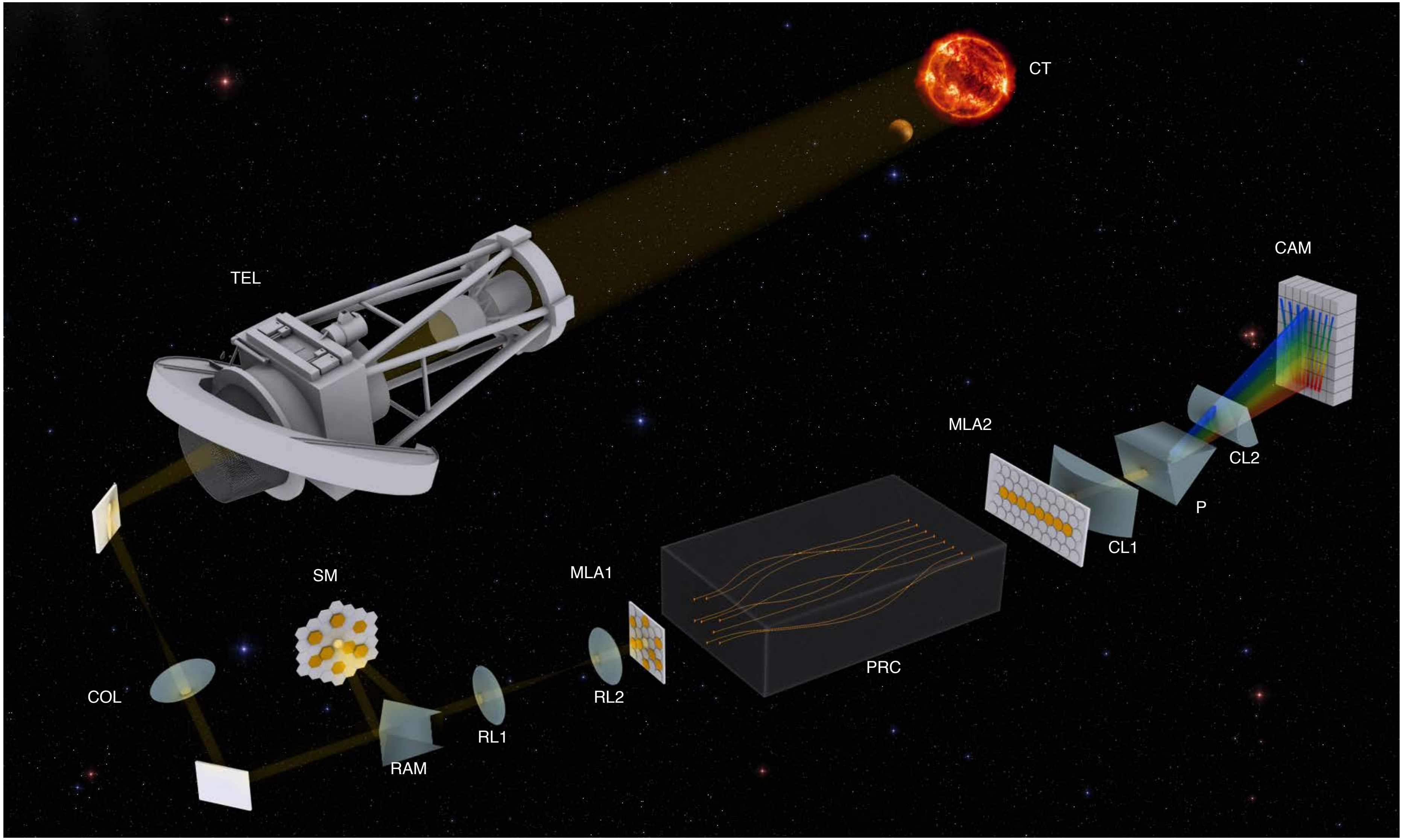
Norris et al 2012 Nature



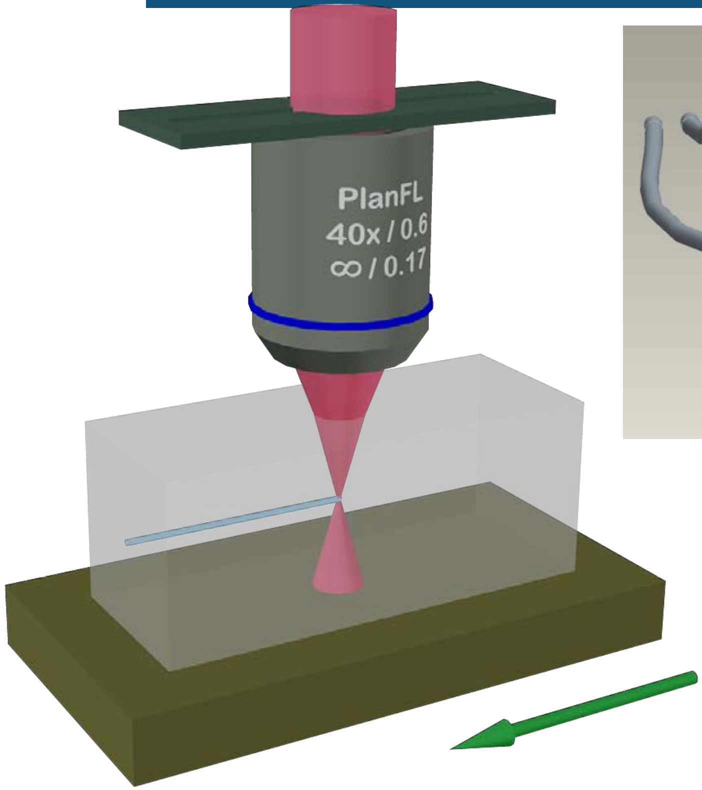
VAMPIRES: Visible Aperture Masking Polarimetric Interferometer for Resolving Exoplanetary Signatures

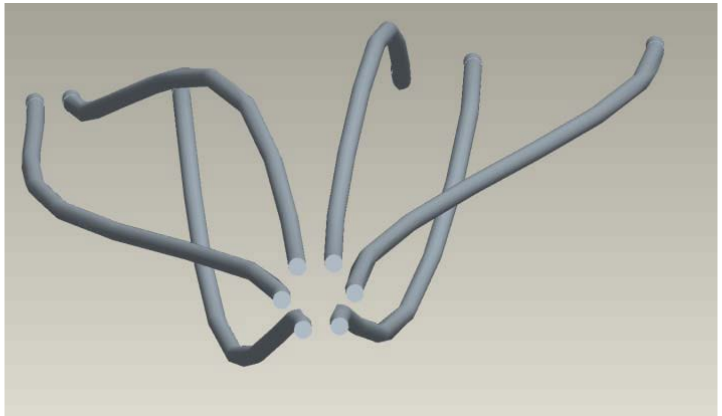


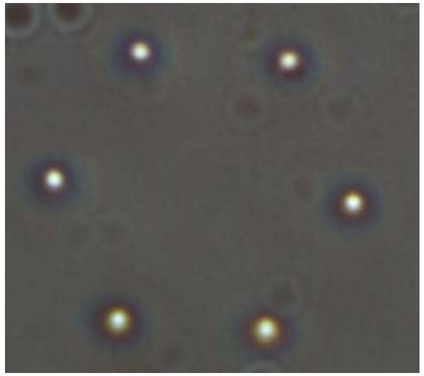
The Dragonfly Instrument

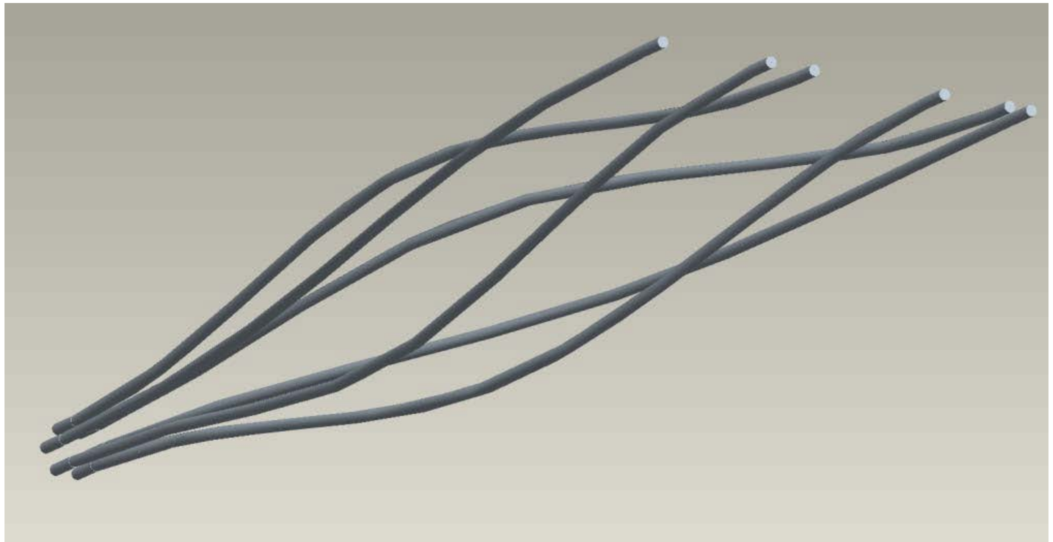


2-D to 1-D Pupil Reformatting

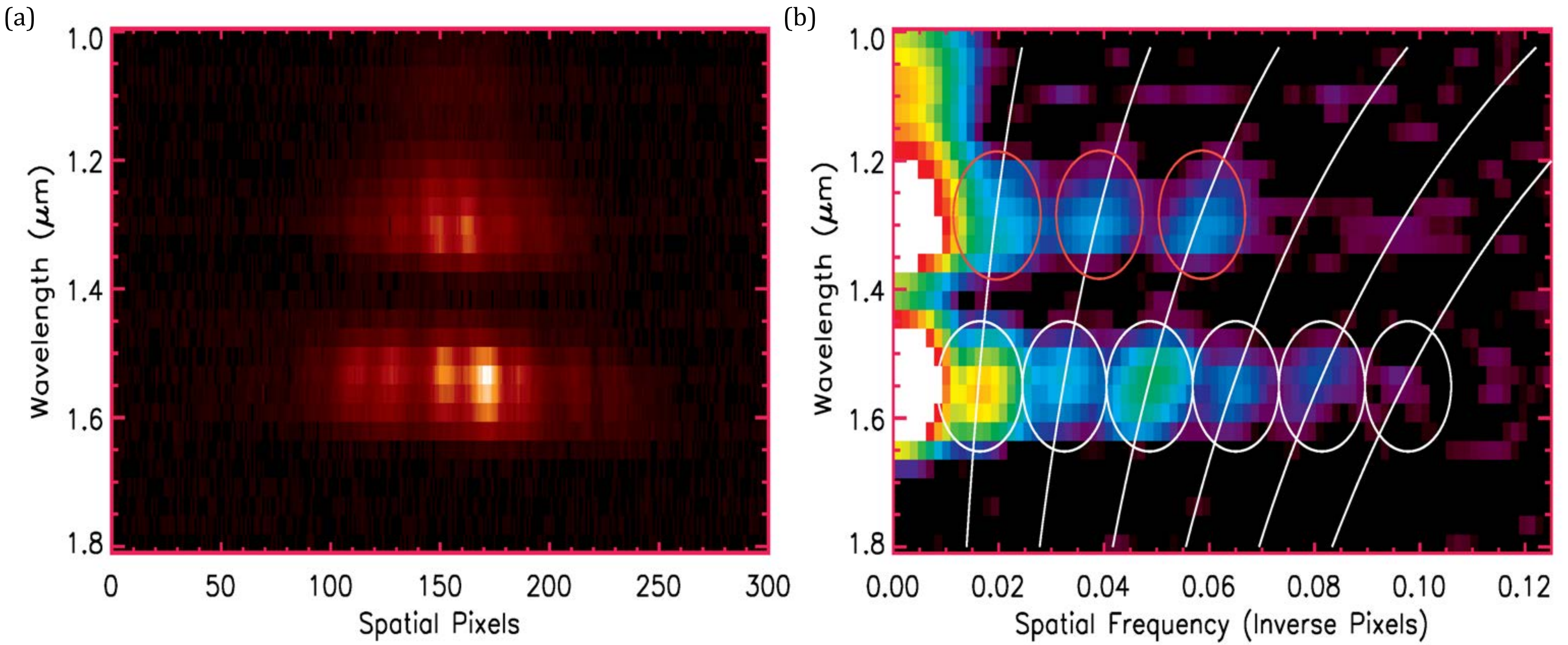








First *DRAGONFLY* on-sky data



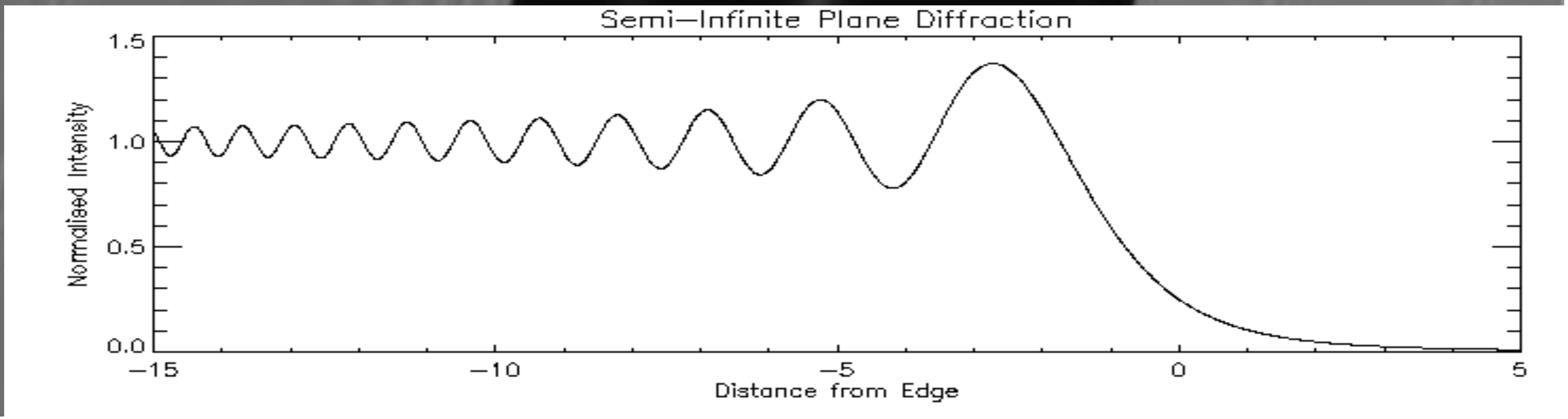
Cassini's Ringside view of Mira

Paul Stewart

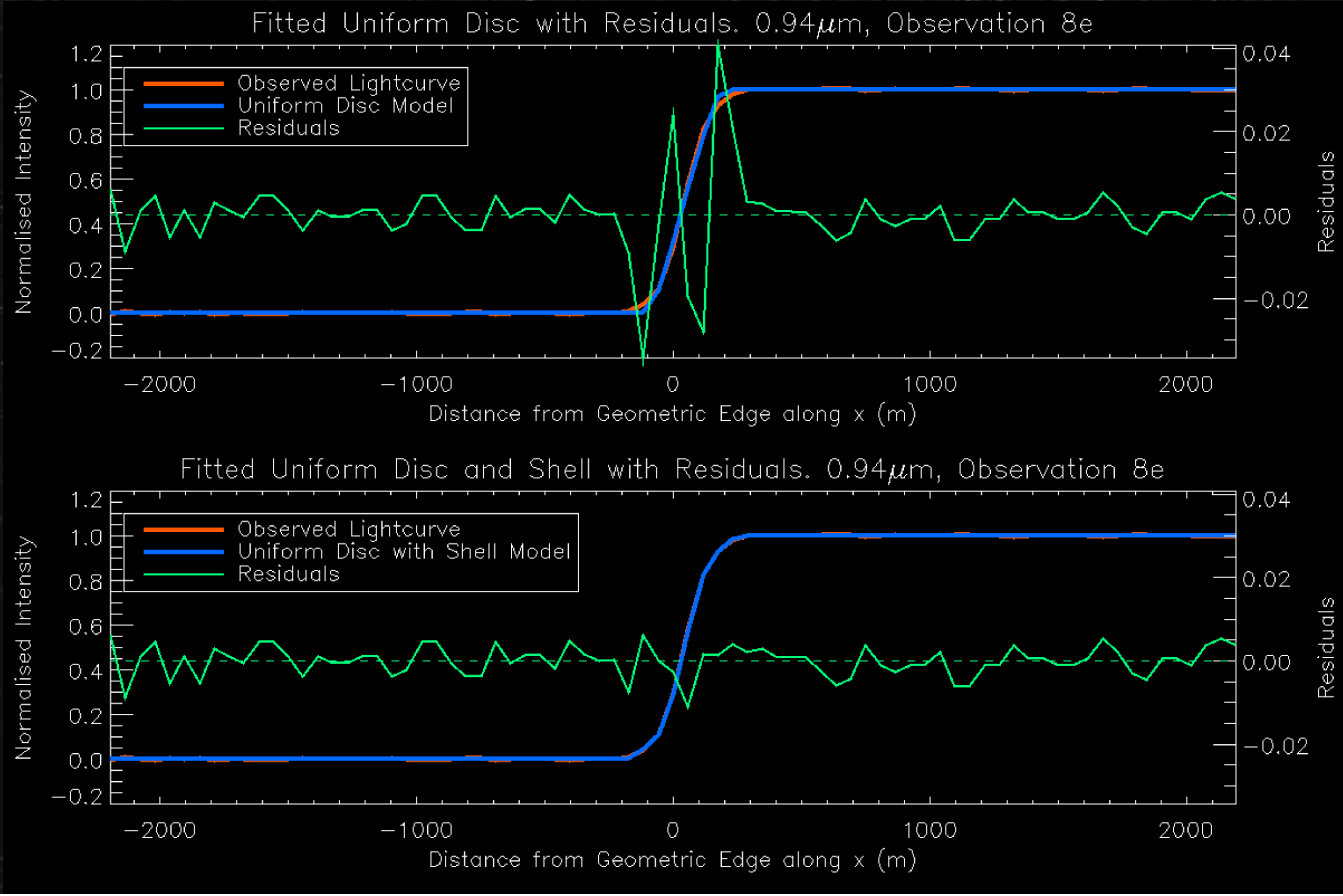
- VIMS instrument
  - Visible & Infrared Mapping Spectrograph
  - Designed for stellar occultations
  - Continuous spectra 1-5 microns
  - Space: no scintillation noise!

Cassini-Saturn System Geometry

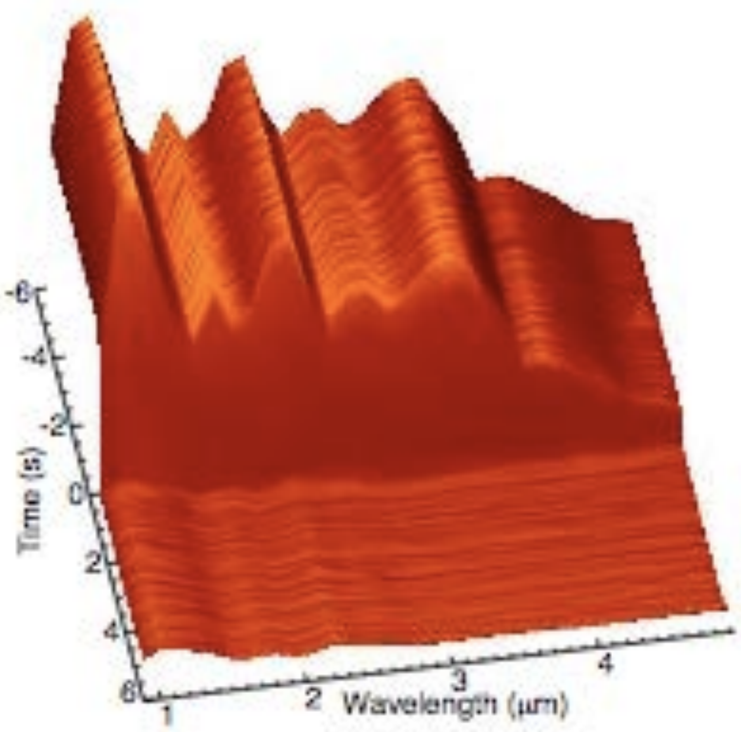
- Inner Encke Gap edge is sharp
- Highly elliptical 18 day orbit
- ~4 times Earth-Moon distance
- Apogee, most distant and slowest point, best for occultations

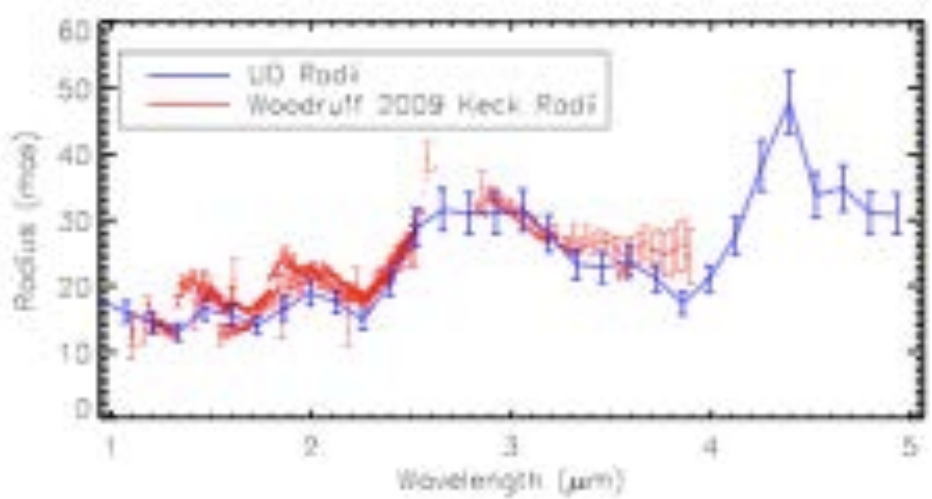


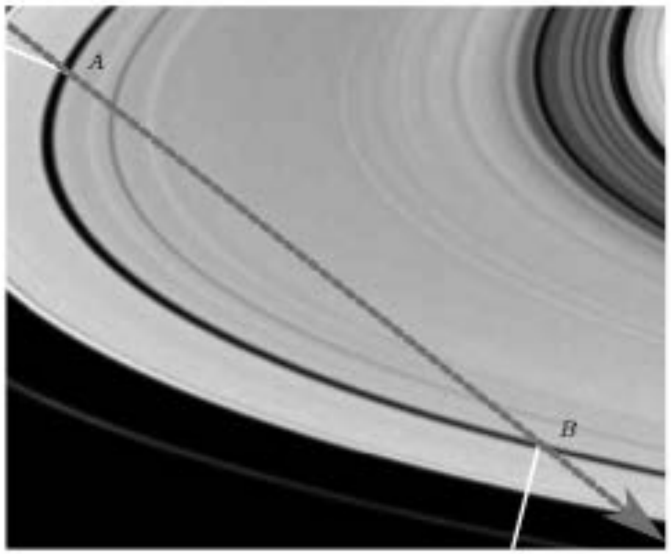
Model Fitting Examples



First results on Mira







Stewart, Tuthill et al 2013 MNRAS (in press)

- Resolved molecular atmosphere of Mira with stellar occultations from Cassini over 1-5 micron region

- Able to constrain state of the art models in this critical wavelength range in the windbase region around the star

CODEX Mira Atmosphere model