Revealing Planets: Post-processing Methods for the Direct Detection of Planets

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Outline

- The Problem
- The Solutions
  - Simultaneous Differential Imaging
  - **Angular Differential Imaging**
  - Spectral Deconvolution (v. briefly)

Atmospheric Speckles

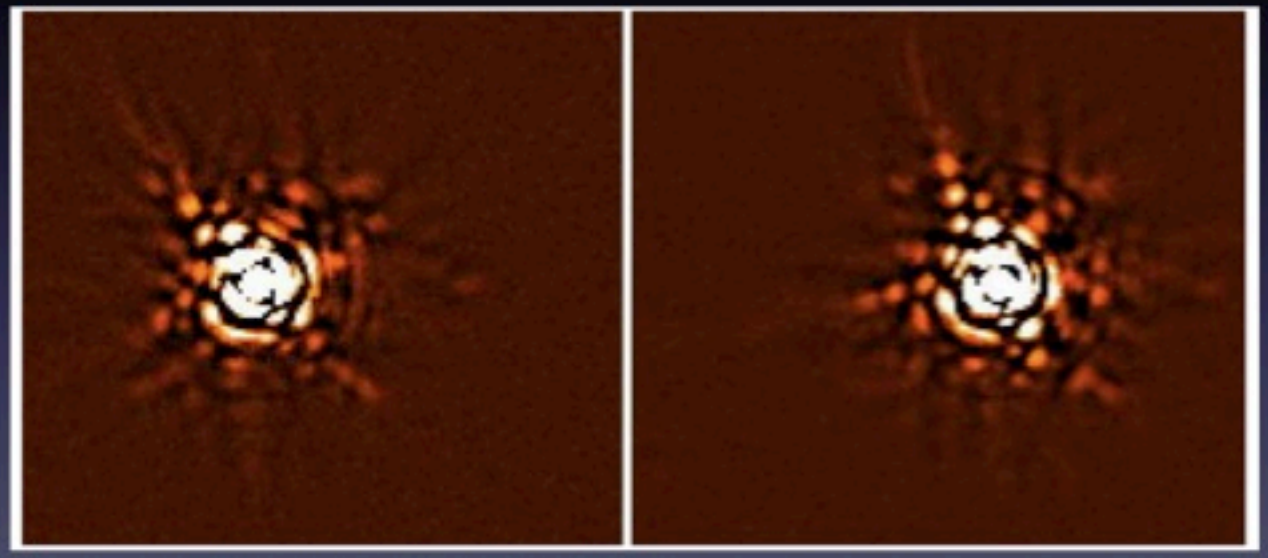
+ Phase due to atmosphere

+ Adaptive Optics

Quasi-Static Speckles

Imperfect Optics produce Quasi-Static Speckles

- Long Lived
- ~λ/d in size

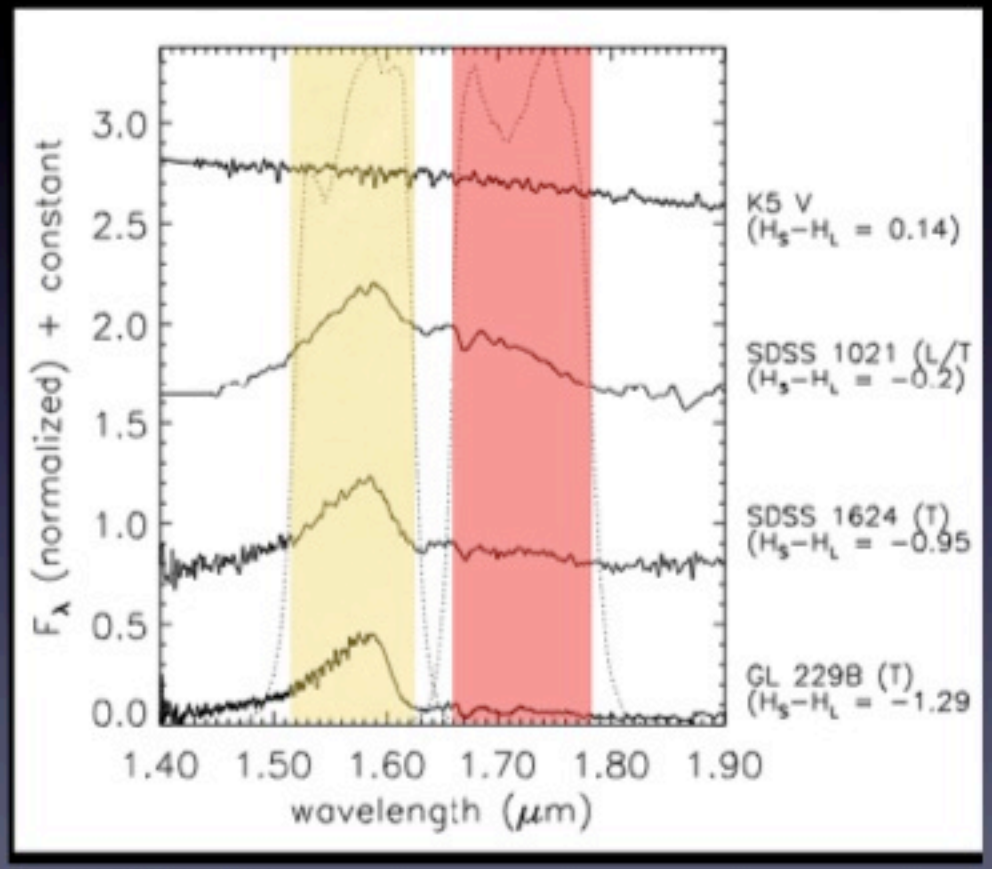


VLT-NACO images separated by 1 hour
Verinaud et al 2006

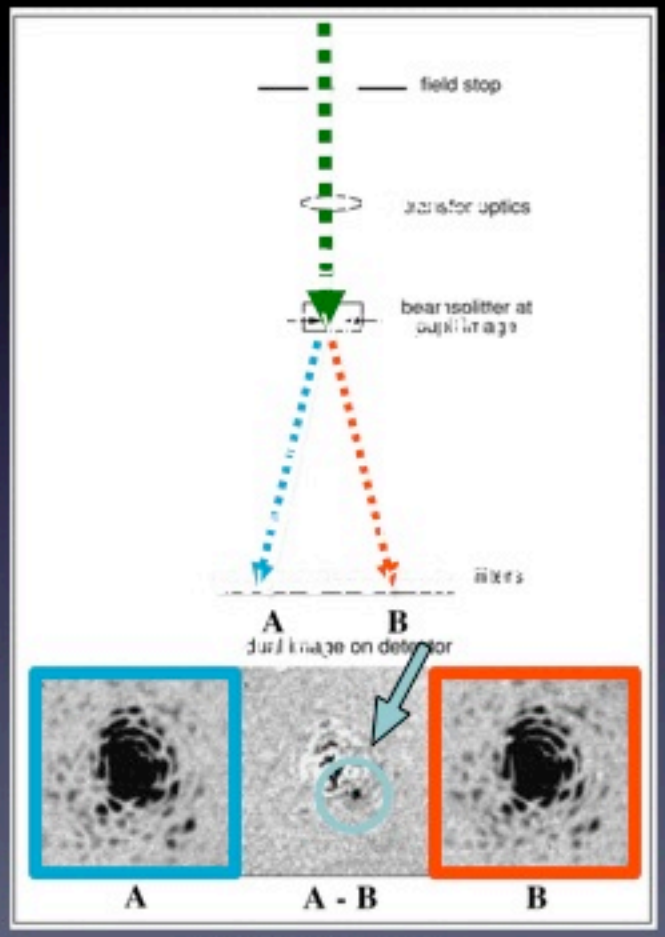
What Do We Want?

- Distinguish the planets from the speckles
- A characteristic of the speckles that is different to the planet
- Post processing methods to fit and remove the speckles

Simultaneous Differential Imaging



Rosenthal et al 1996



Racine et al 1999

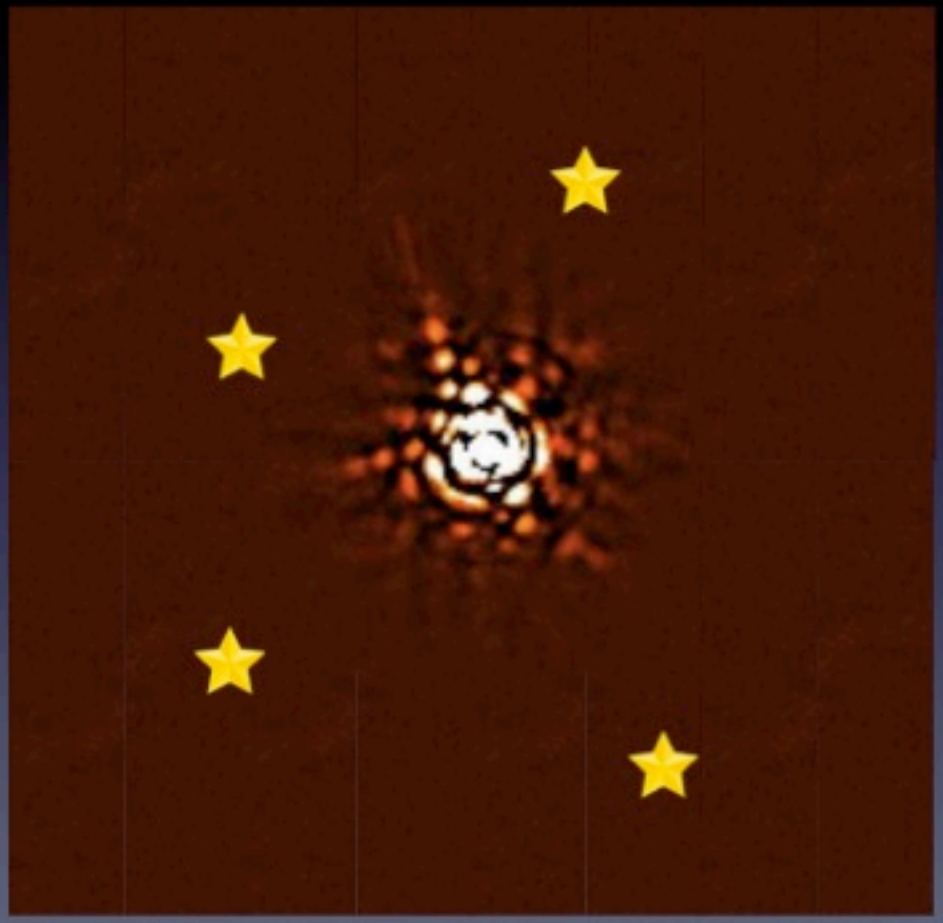
SDI Limitations

- Relies on prior knowledge of a spectral feature of the companion
- Non-Common path errors between the channels have to be extremely low .
  - Downfall of the first instruments of this type (ie. TRIDENT)

Angular Differential Imaging

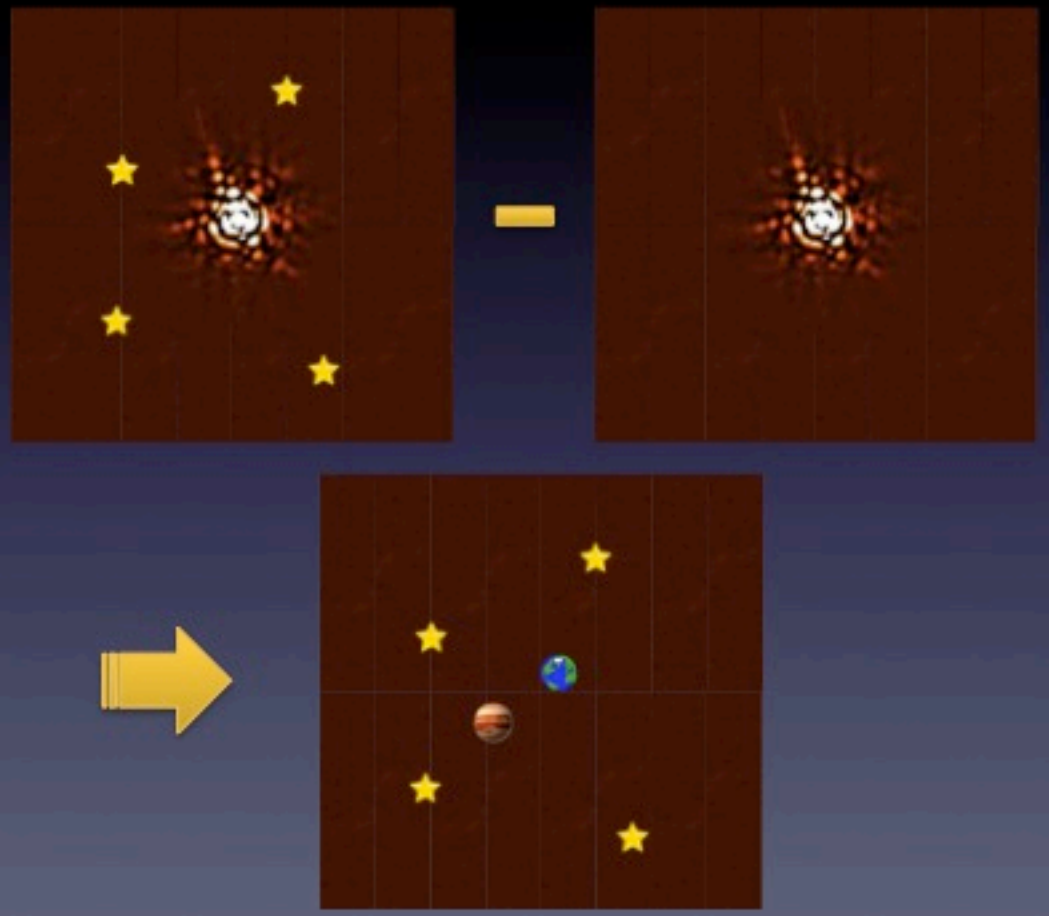
Concept:

- Optics in the telescope rotate to track the sky (Alt-Az telescope)
- Speckle pattern rotates with the optics causing them
- By turning off the sky de-rotator the speckles stay fixed



Angular Differential Imaging

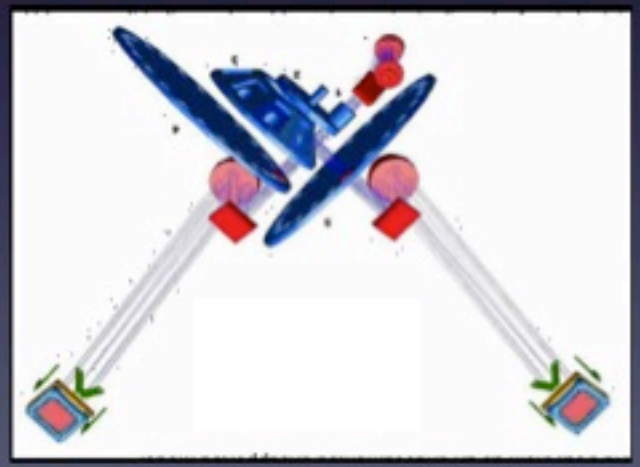
- Determine a PSF from what doesn't move
- Subtract from original images
- Combine all frames

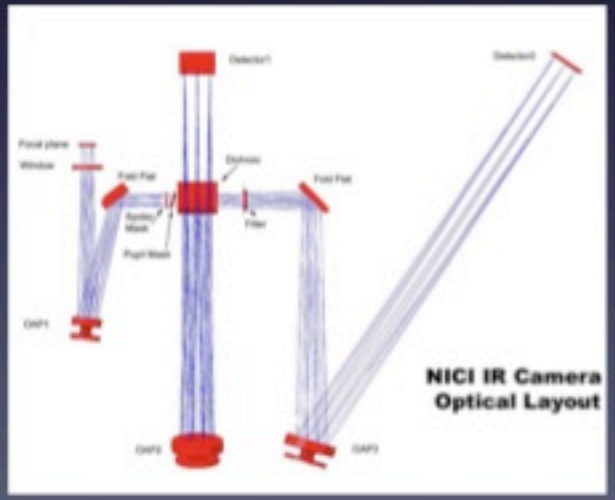


Our Application

- Long Period companions seen in Radial Velocity from AAPS
- Follow up with Gemini South – Near Infared Coronographic Imager

A.O. + Focal/Pupil plane masks + Beam Splitter

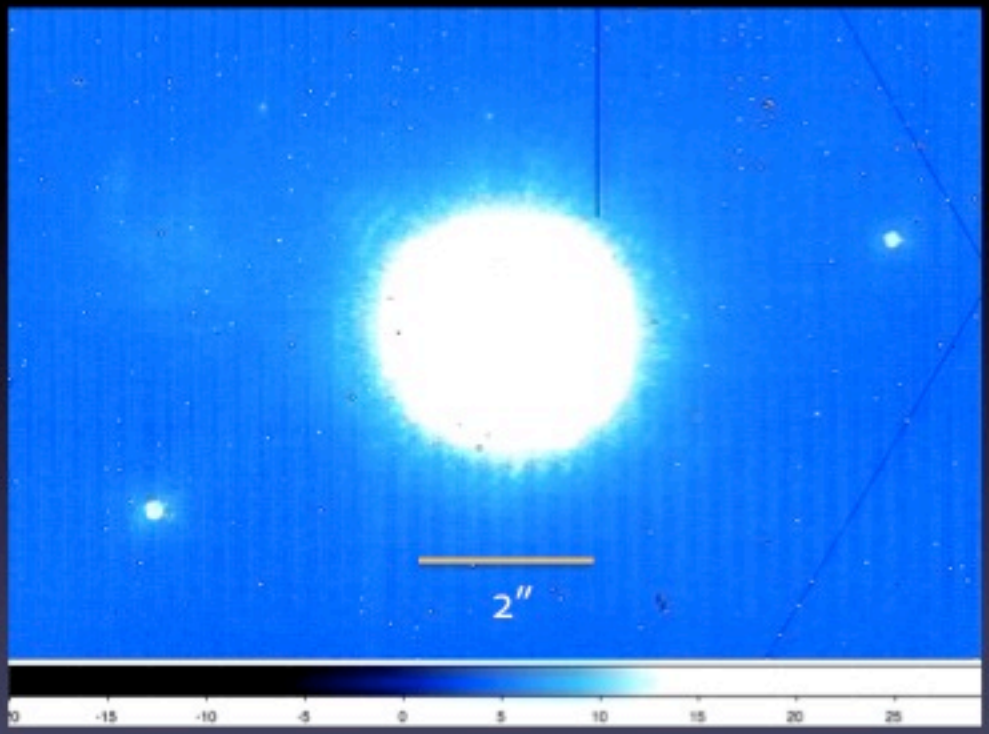




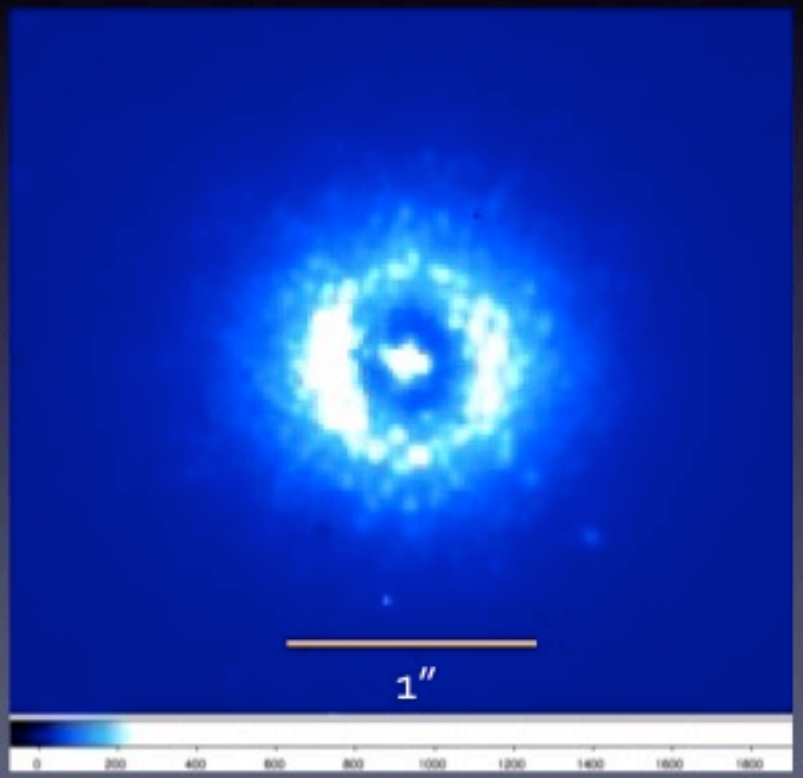
NICI-Example

- GO star, Hmag ~5.5 (2Mass)
- ~1.4hrs of data in good seeing conditions
- ~35degrees of field rotation
- 9 frames (5 x 12.9sec each)
- Located close to galactic plane (lots of background stars)

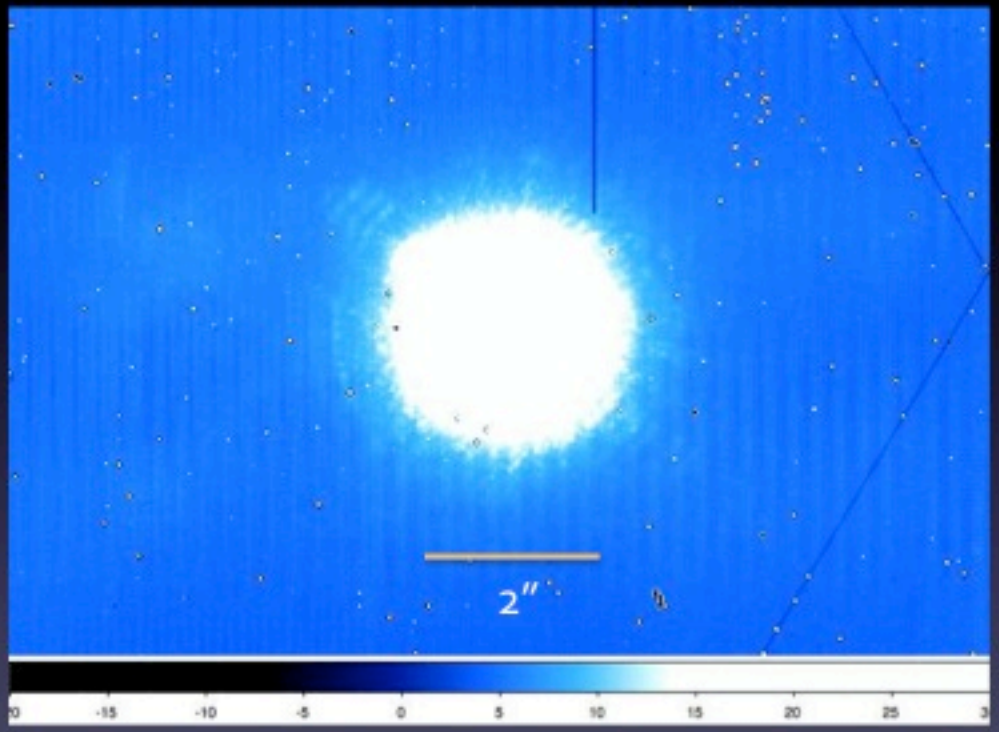
Angular Differential Imaging



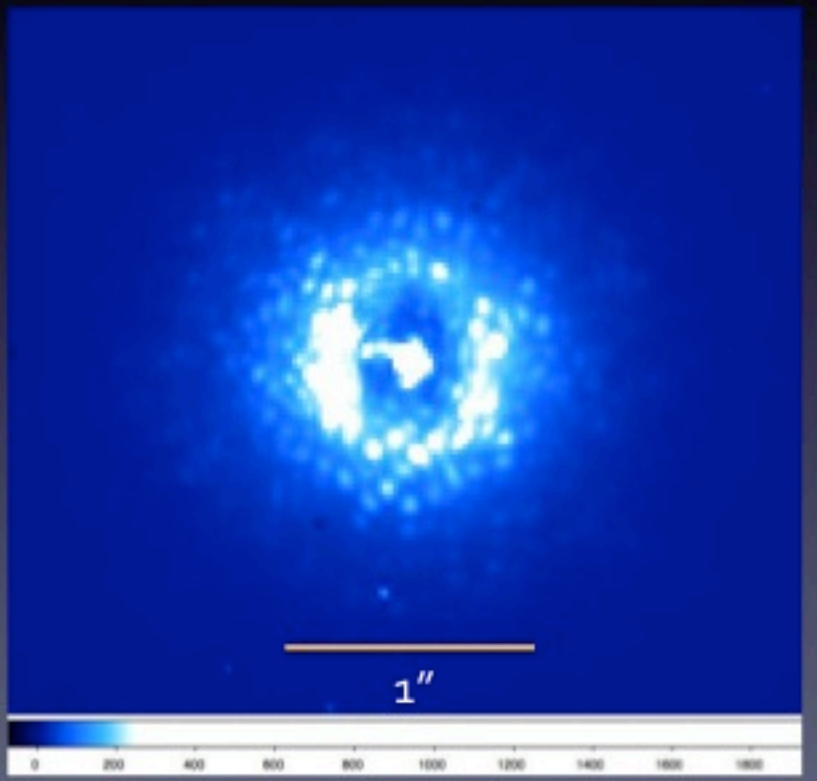
Original Data



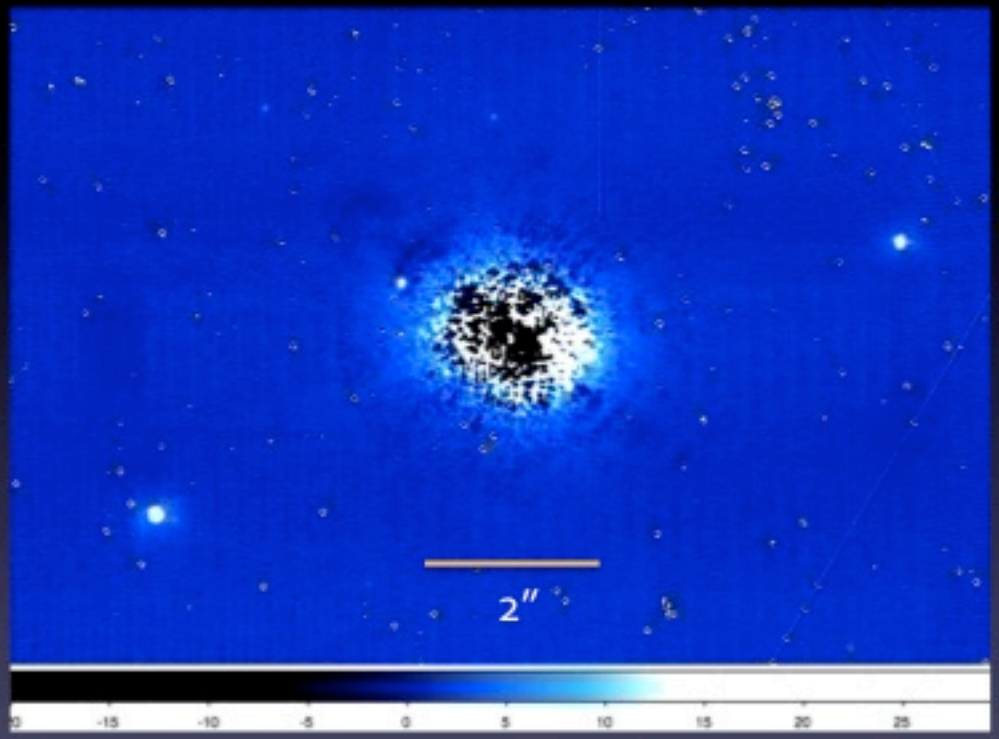
Angular Differential Imaging



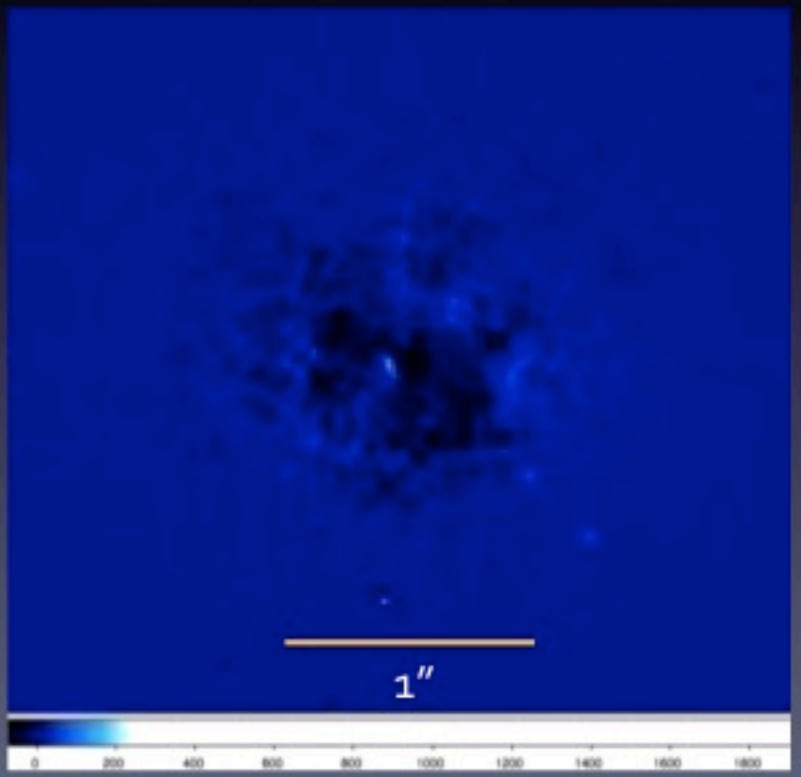
Reconstructed PSF



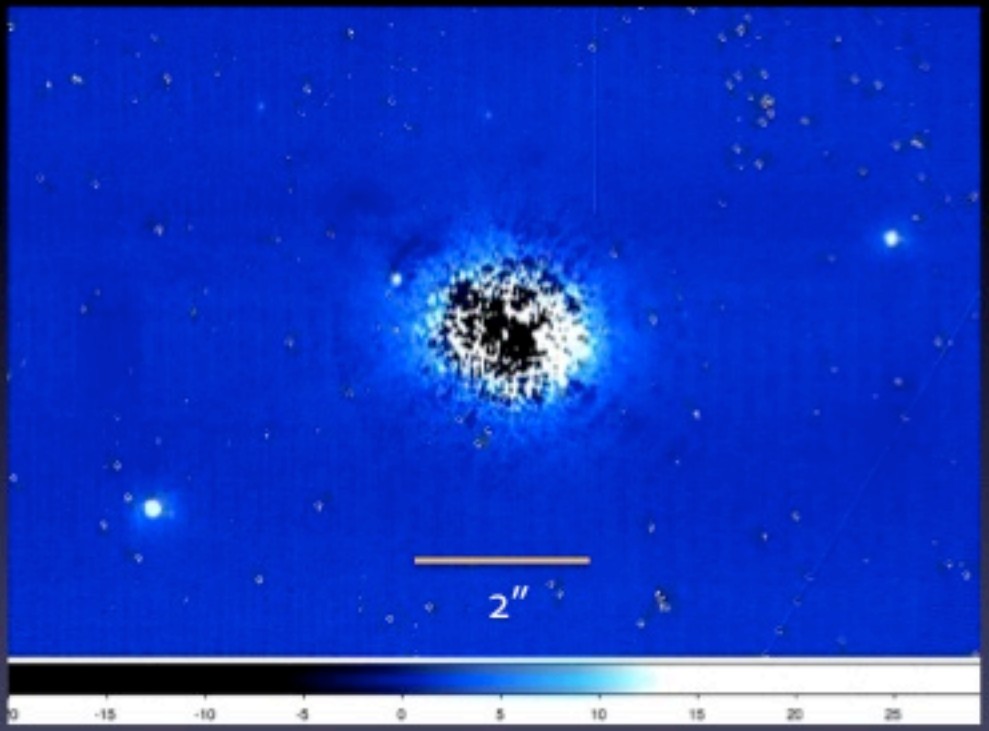
Angular Differential Imaging



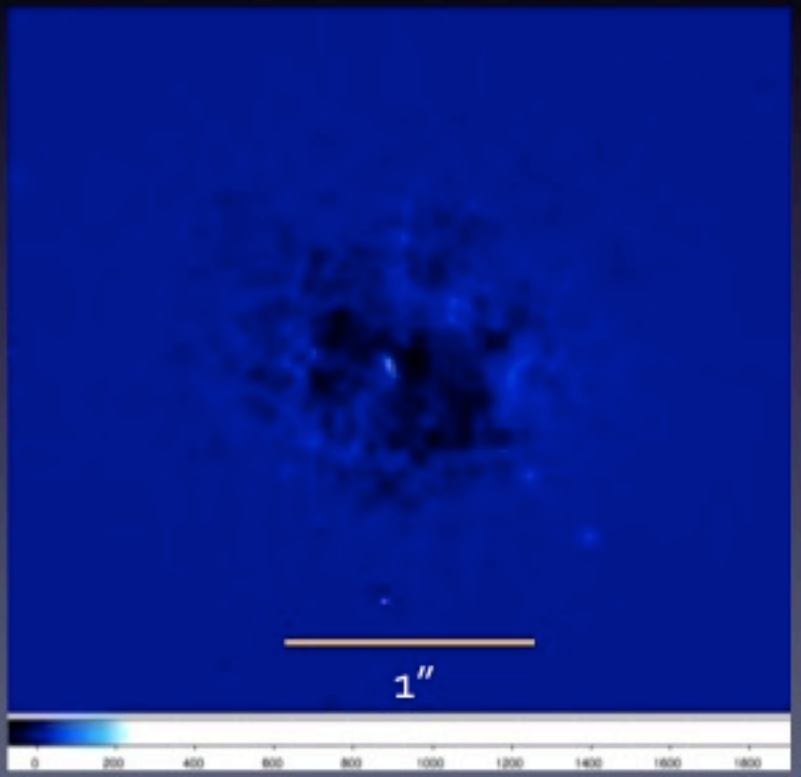
PSF Subtracted



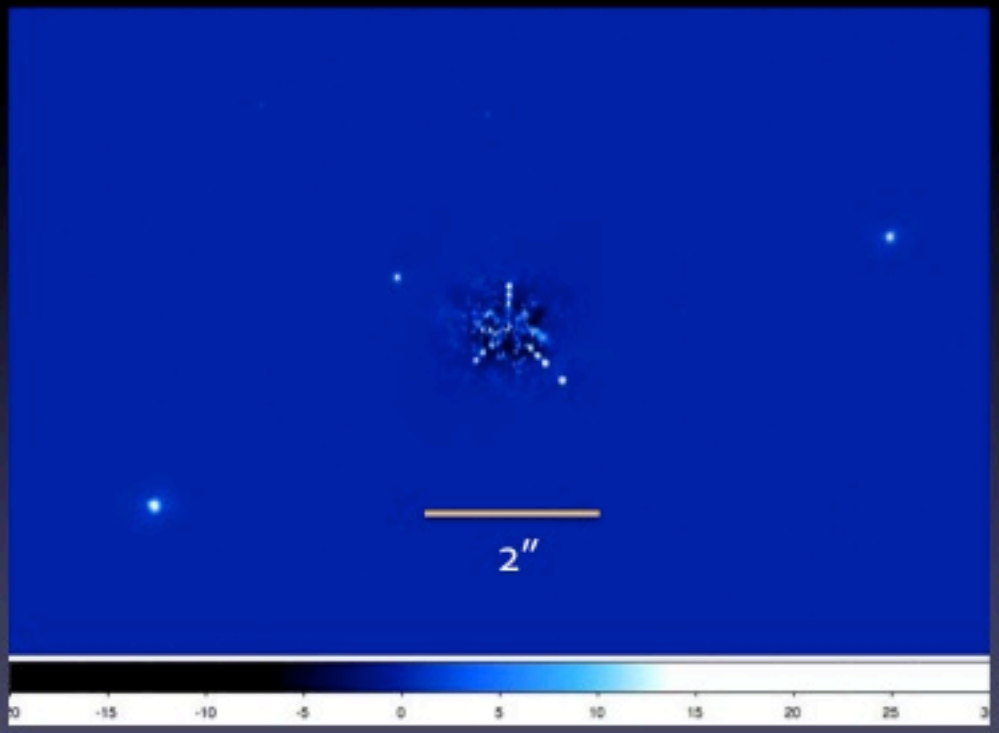
Angular Differential Imaging



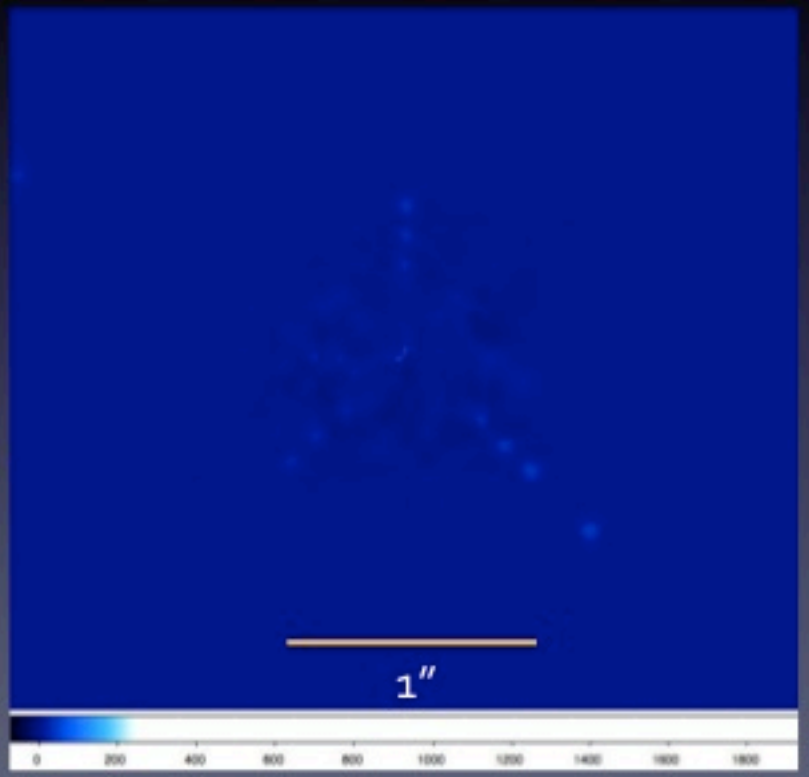
De-rotated Images



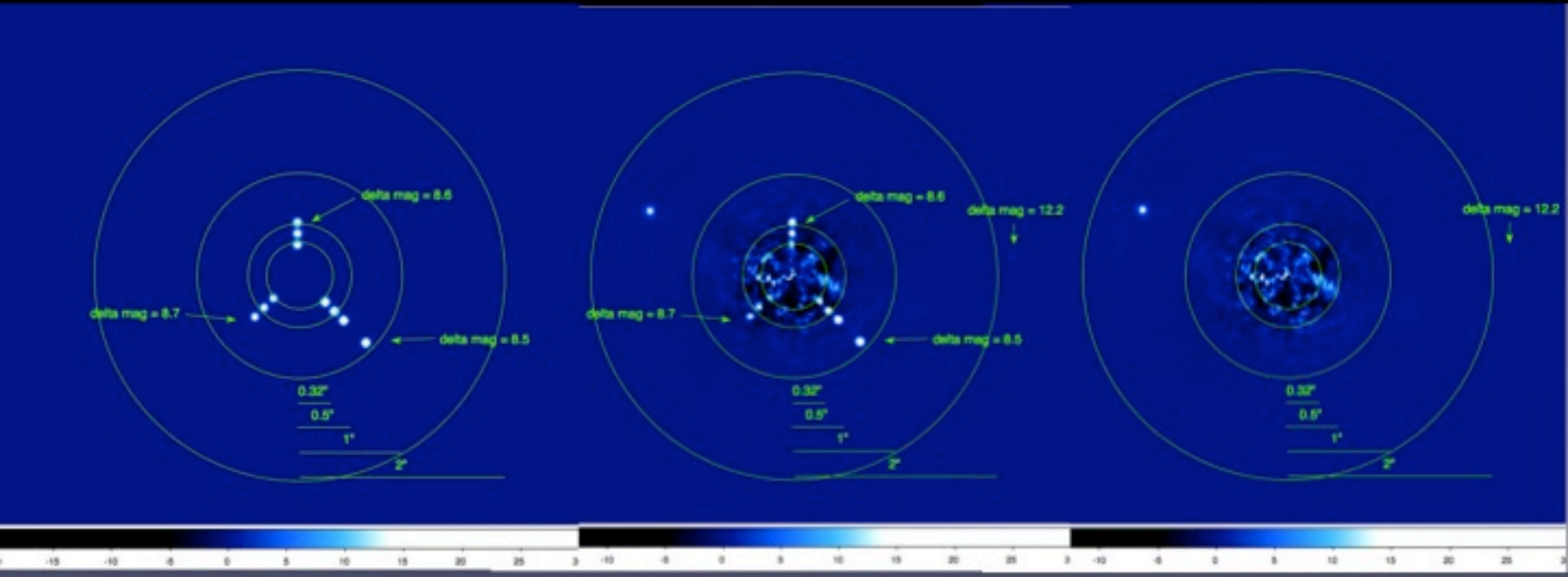
Angular Differential Imaging



Final Result After Combining All Images



Angular Differential Imaging



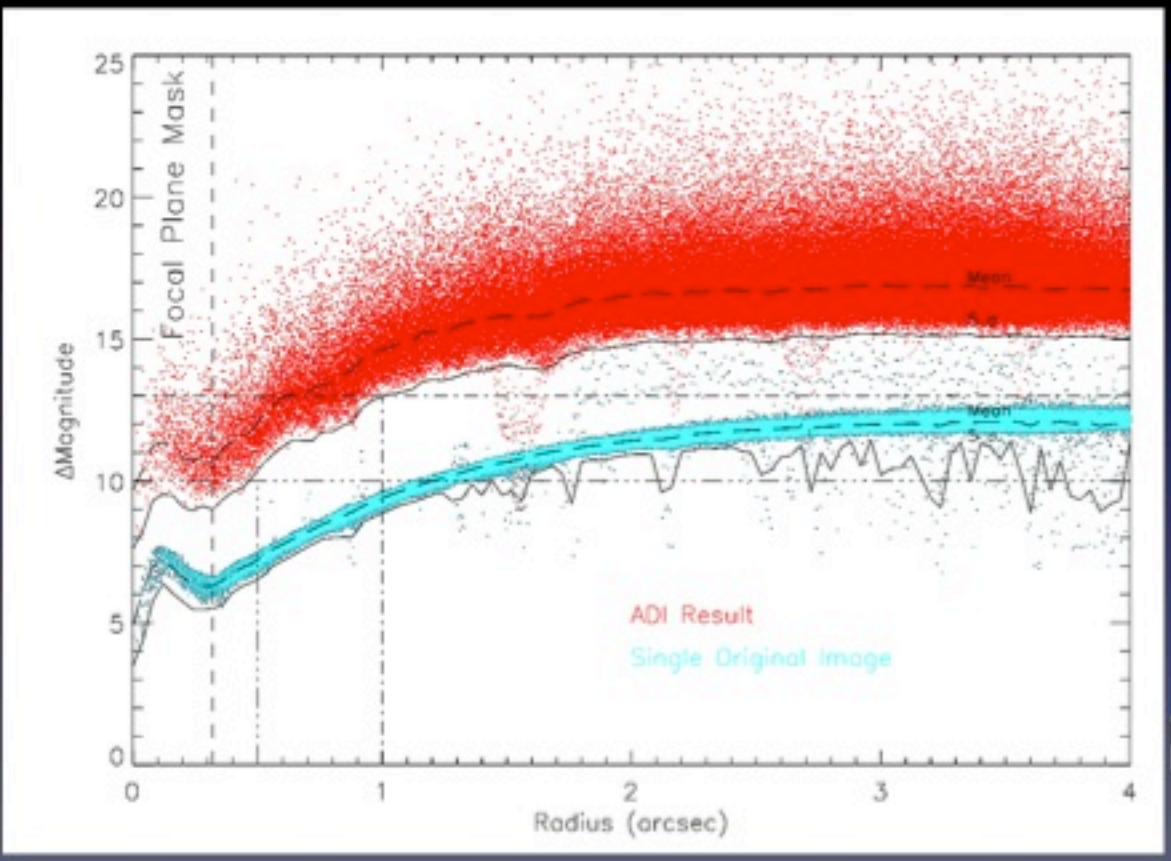
Fake Companions

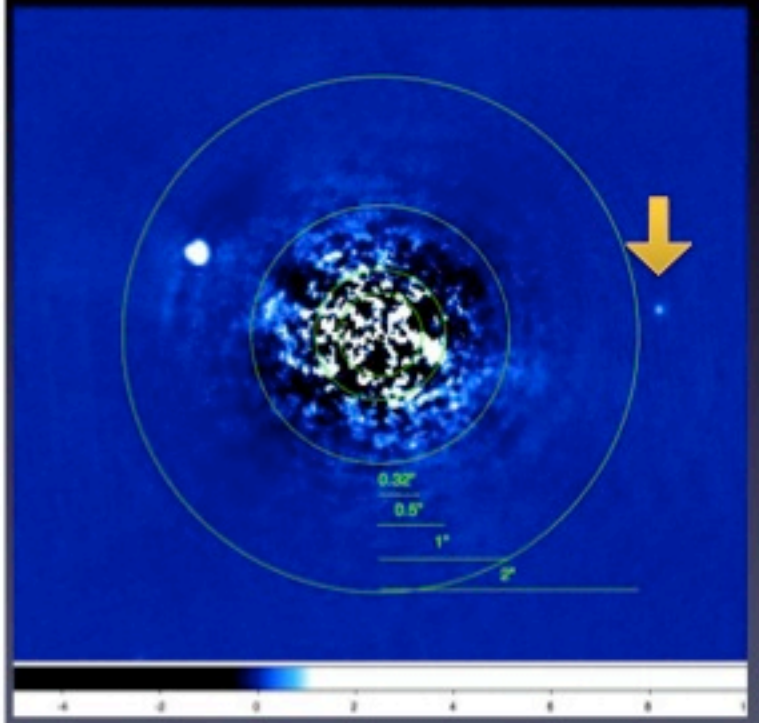
ADI Result

Result without fake objects

Angular Differential Imaging

Radial Profile

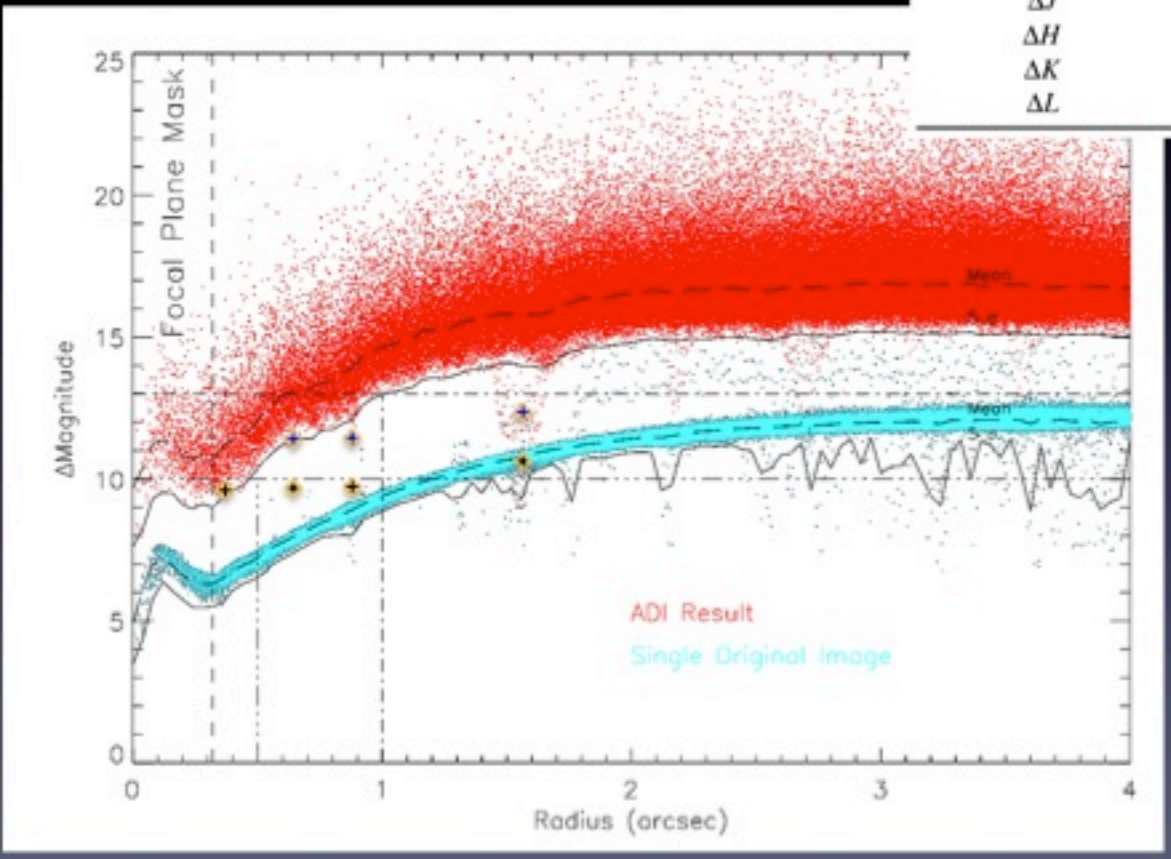


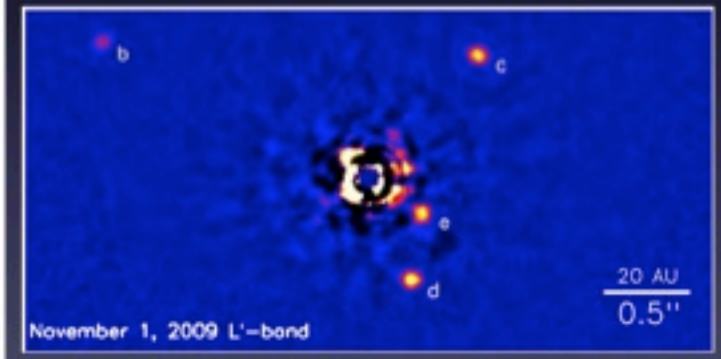


HR 8799 Comparison

Radial Profile

	HR8799 b	HR8799 c	HR8799 d	HR8799 e
Separation	68*AU*	38*AU*	24*AU*	14.5 ± 0.5*AU*
	1.73"	0.95"	0.63"	
ΔJ	13.8	12.2	12.9	
ΔH	12.6	11.6	11.6	
ΔK	11.8	10.9	10.9	10.7 ± 0.22
ΔL	10.5	9.5	9.4	9.37 ± 0.12





Many more observations with multiple telescopes!

ADI limitations

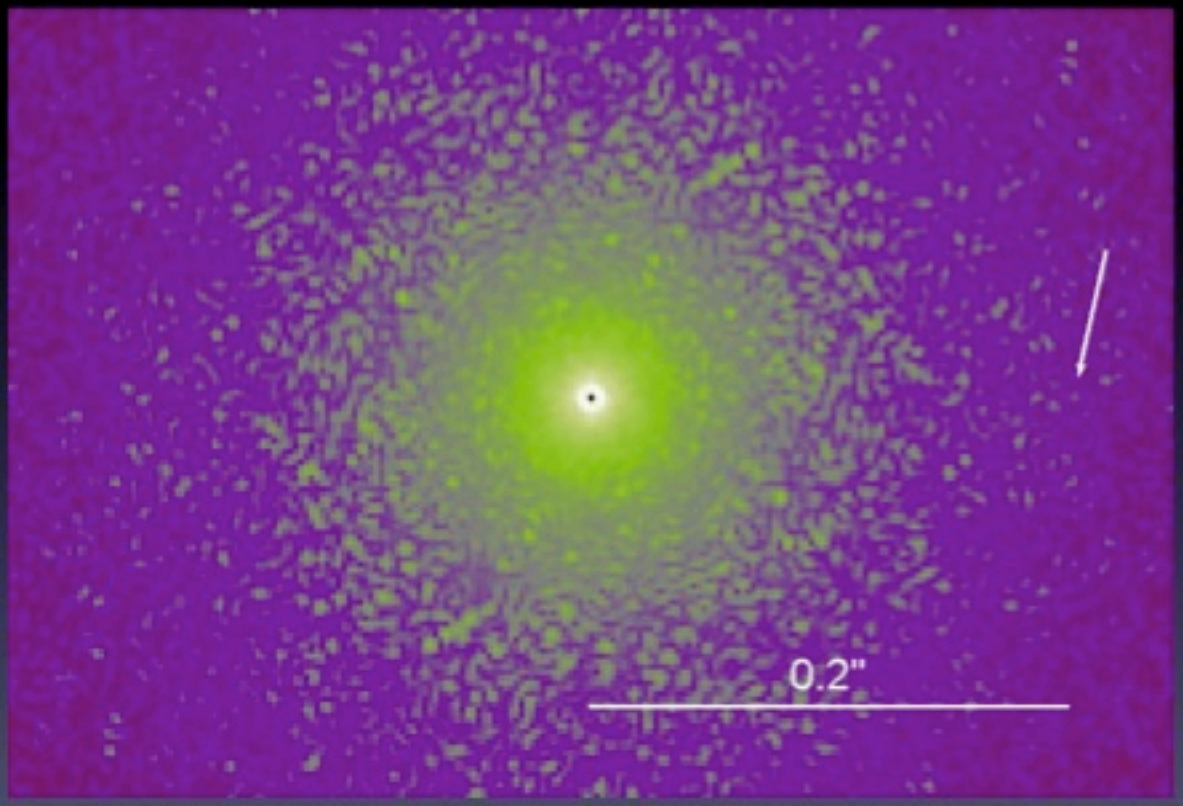
- Assumes a temporal stability of the speckle pattern.
  - Requires no movement of any optics
  - Highly stable atmosphere and AO correction
- Need adequate field rotation to avoid fitting a real source.

Spectral Deconvolution

Concept:

- Speckle location scales with wavelength
  - Move radially from the central star
- Planets are at a fixed position

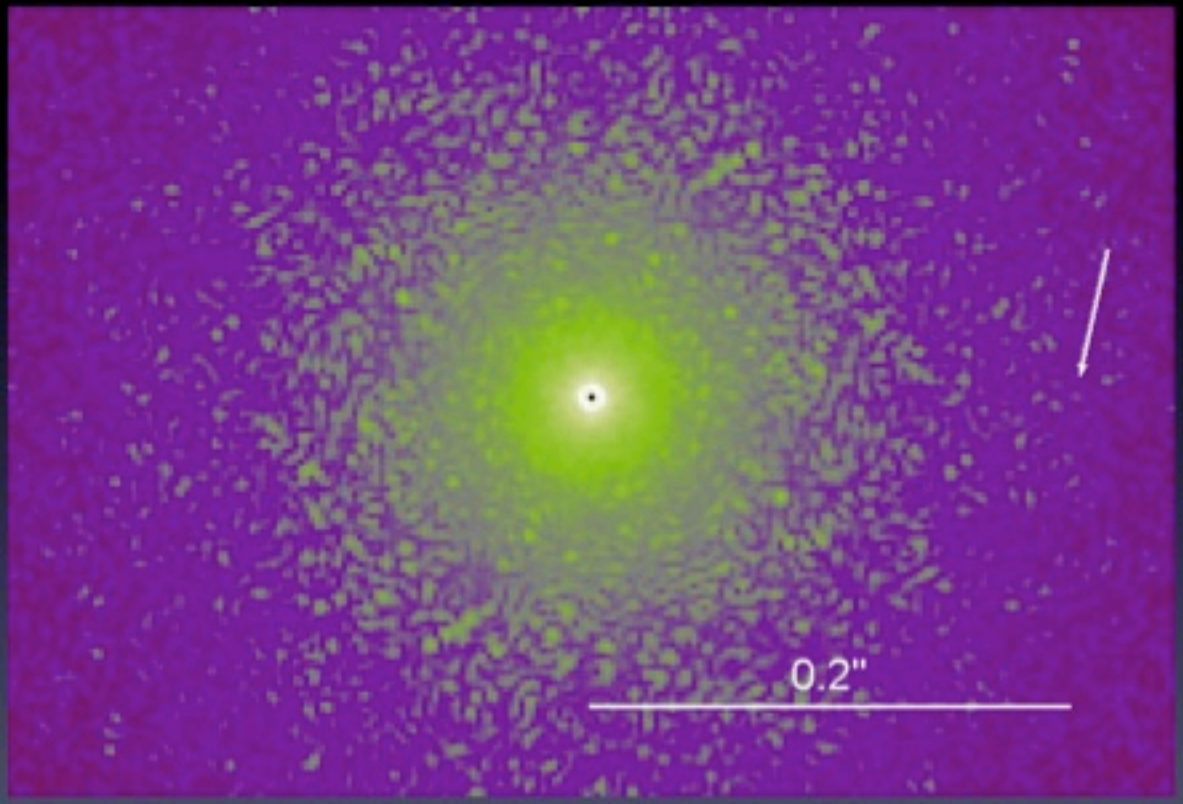
Spectral Deconvolution



Speckles Scale
with Wavelength

Further Details: Sparks & Ford 2002, Thatte et al 2007, Salter et al 2008

Spectral Deconvolution



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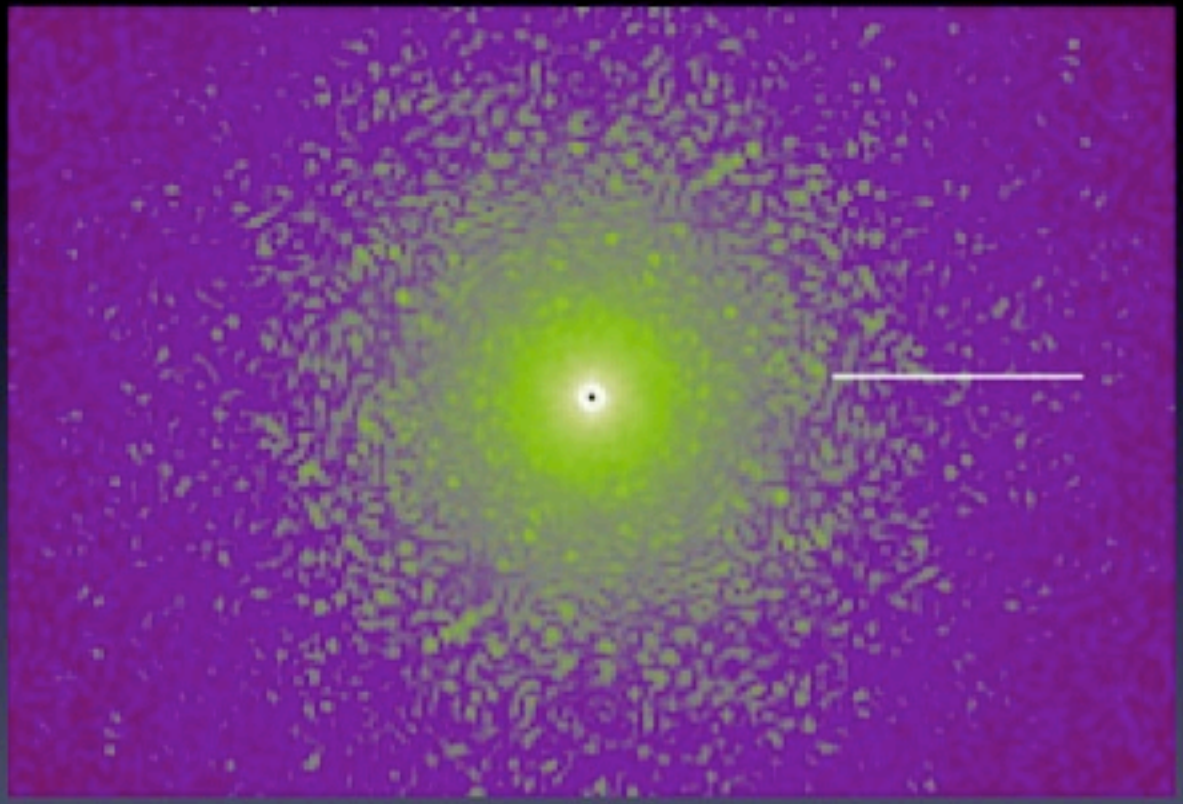
Spectral Deconvolution

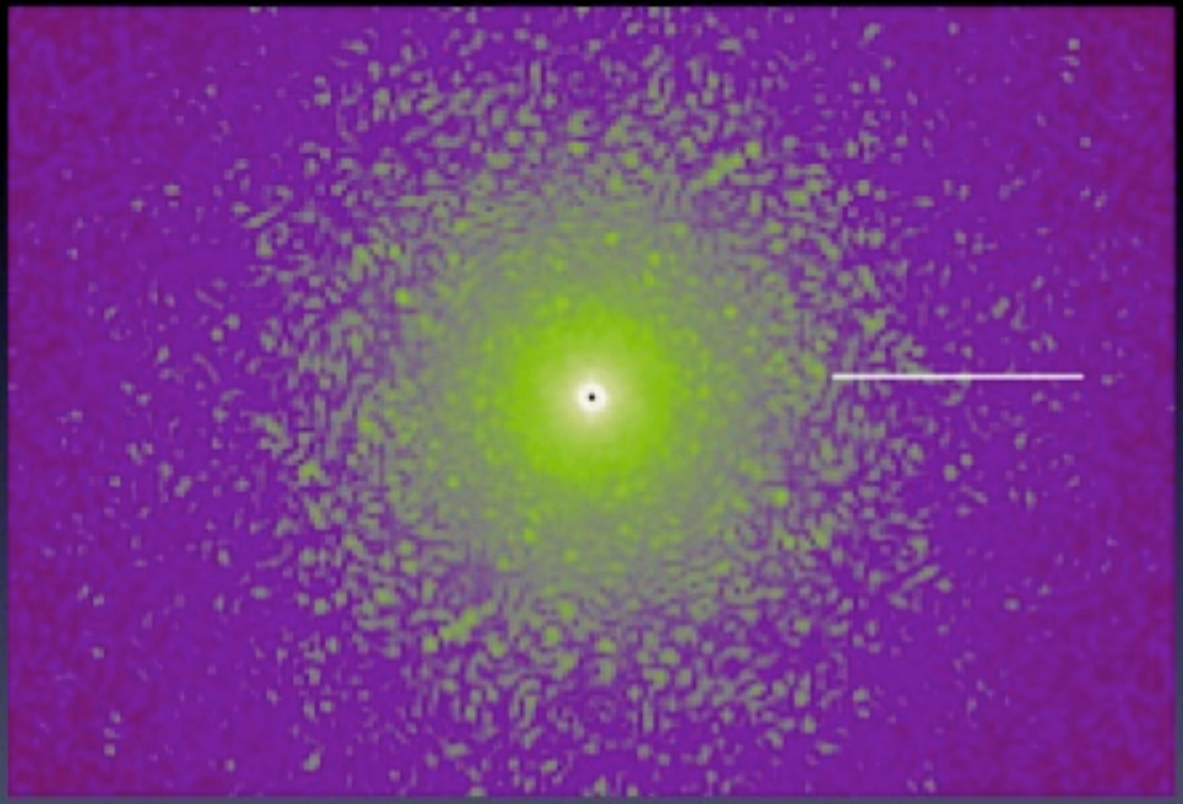


Scale each wavelength channel wrt wavelength

Speckles and airy pattern are now stationary and planet moves with wavelength

Further Details: Sparks & Ford 2002, Thatte et al 2007, Salter et al 2008

Spectral Deconvolution



Scale each wavelength channel wrt wavelength

Speckles and airy pattern are now stationary and planet moves with wavelength

Further Details: Sparks & Ford 2002, Thatte et al 2007, Salter et al 2008

Spectral Deconvolution

Concept:

- Speckle location scales with wavelength
  - Move radially from the central star
- Planets are at a fixed position
- Use wavelength scaling to fit and remove the speckle noise

- Spectral Deconvolution Benefits:
  - No prior knowledge of the companion spectra is needed
  - Temporal stability of the speckle pattern is not needed
  - No need for large numbers of observation

- Can be combined with ADI

SD Limitations

- Inner working angle dependent on wavelength coverage
- Outer working angle dependent on spectral resolution
- Instrumental performance
  - Speckle pattern need to be highly achromatic
  - Requires very high fidelity calibrations

Application Of Methods

- ----------CURRENT----------
- VLT – SINFONI: Spectral Deconvolution
- Gemini NIFS: Spectral Deconvolution (not as good)
- VLT – NACO: SDI
- GEMINI – NICI: ADI & SDI
- Palomar 200" – P1640: ADI & Modified SDI not Spectral Deconvolution
- ----------2012-2013----------
- VLT-SPHERE: ADI. SDI & SD – low spectral resolution
- GEMINI – GPI: ADI. SDI & SD– low spectral resolution
- ----------FUTURE----------
- TMT – PFI
- E-ELT - EPICS
- E-ELT- EPICS: Optimised for SD (most likely in combination with ADI)

Summary – My Involvement

- AAPS long period candidates follow up with NICI
  - ADI pipeline - improvements (psf fitting and subtraction)
  - Combine SDI & ADI

- Doctorate work based on improvement and application of Spectral Deconvolution and IFS instrumentation for EPICS
  - Proof that using a slicer based IFS will not limit your achievable contrast

- Spectral Deconvolution routines are ready for data from current and future instruments – SINFONI, NIFS, GPI, SPHERE & …EPICS
  - Improvements : combine ADI & SDI