Exoplanet direct detection with NICI and EPICS

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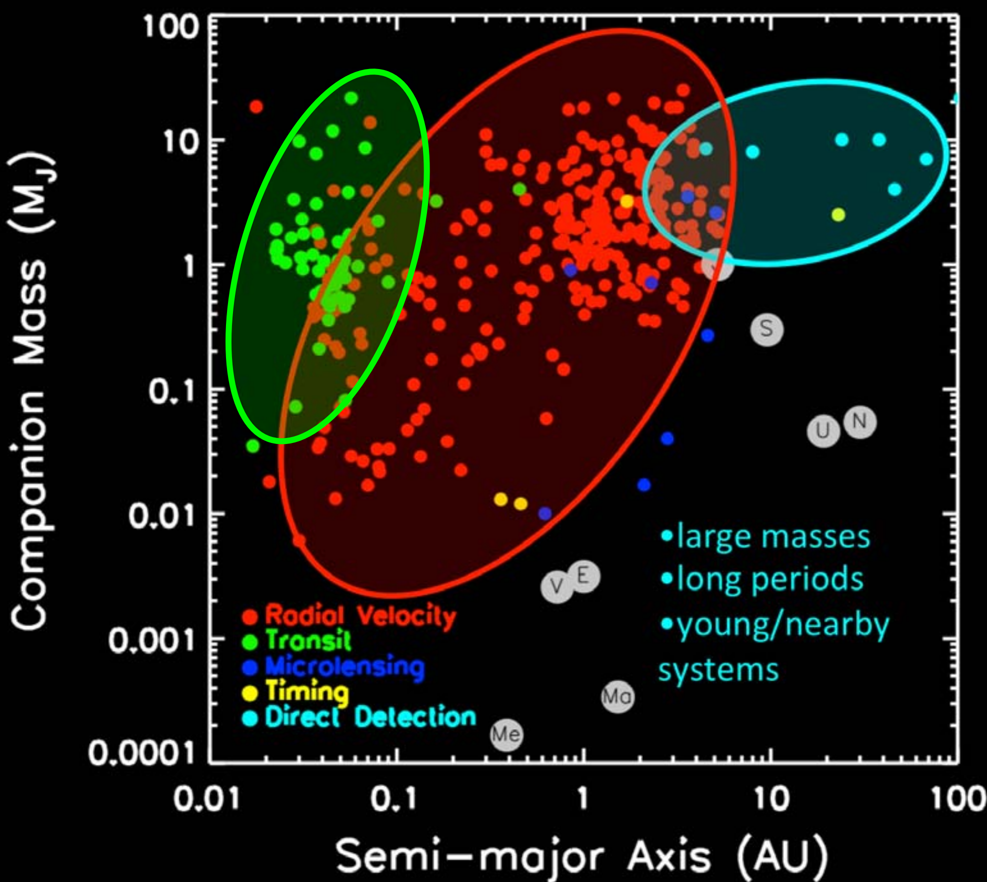
+ NICI team (especially Mike Liu (PI), Beth Biller, Zahed Wahhaj)

+ EPICS team (especially Christophe Verinaud, Markus Kasper (PI))

Why Direct Detection?

Radial Velocity & Transit methods are biased towards giant planets at small separations

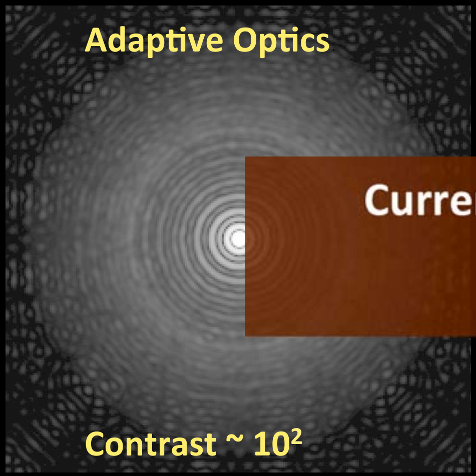


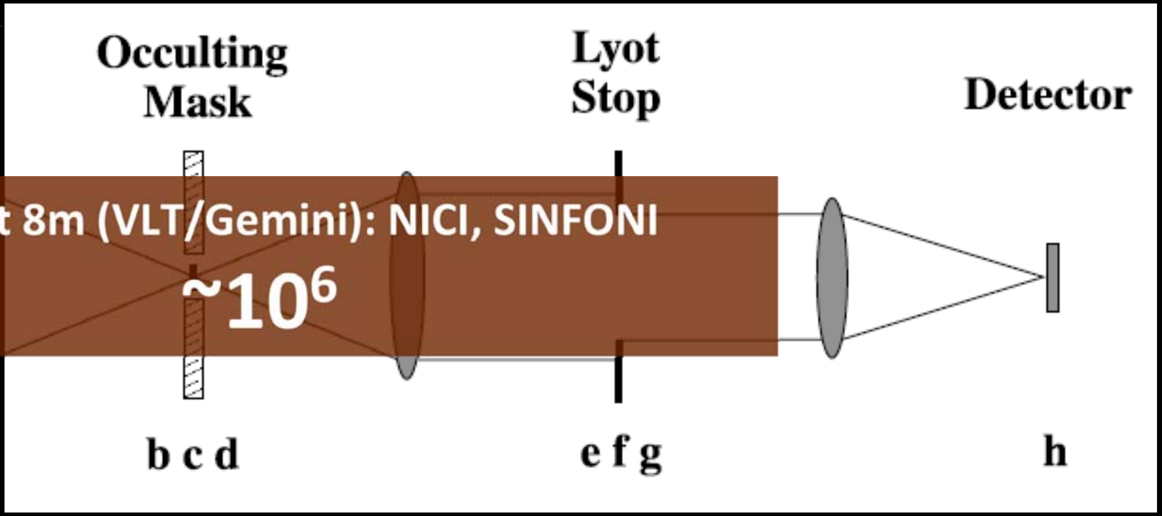
- Large separations (3-40AU) are crucial to understand formation mechanisms of planetary systems
- Indirect methods are not efficient at large separations:
  - Radial velocity signal very small
  - Transits too rare and inefficient
  - Astrometry very slow
  - Microlensing very rare

- Direct detection allows planet characterisation
- Direct detection of faint planets is challenging
  - For young giant planets if contrast is ~10^6-10^7
  - For rocky planets in the habitable zone and old giant planets if contrast is ~10^8-10^9!

High Contrast Imaging

- Highest contrast observations require multiple stages
  - Atmospheric turbulence ("fast speckles")
    - » Adaptive Optics
  - Diffraction pattern
    - » Coronagraph/Apodiser
  - Quasi-static instrumental aberrations (or "Super-speckles")
    - » Differential methods
- Best in NIR due to AO correction





Current 8m (VLT/Gemini): NICI, SINFONI

~10^6

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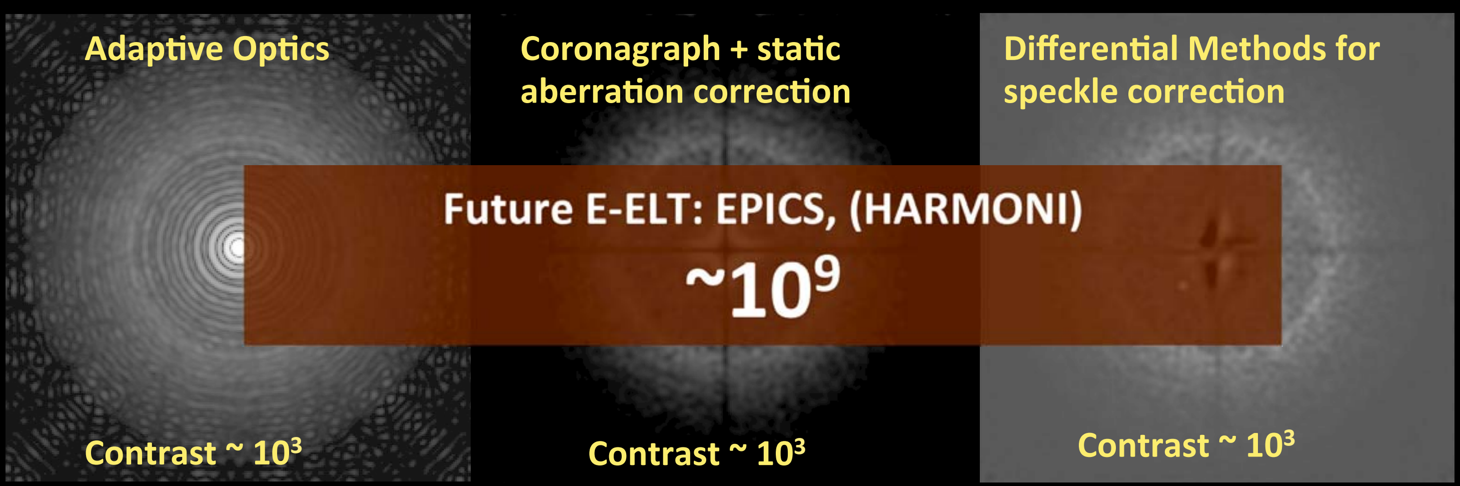
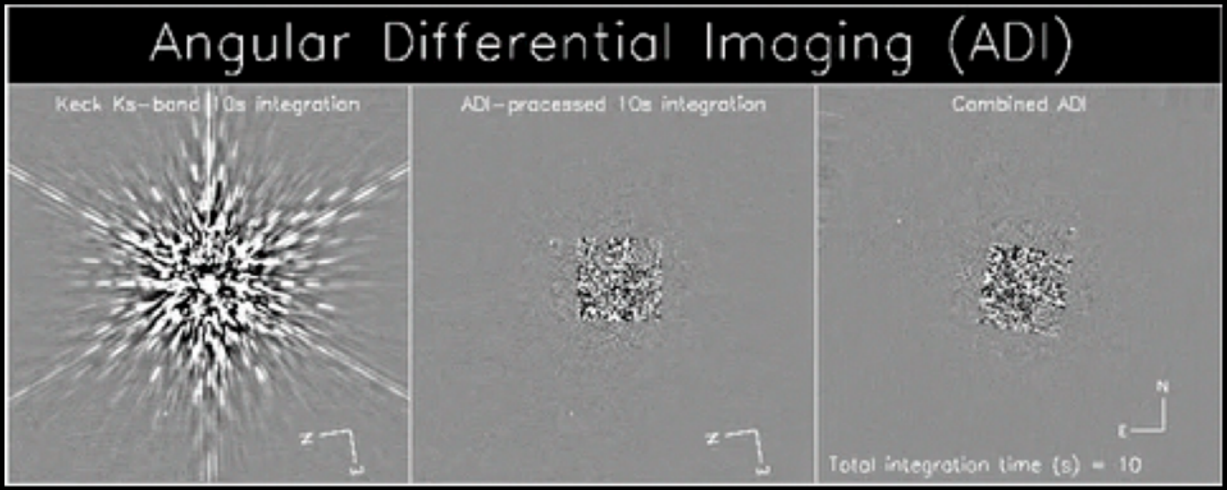


Differential Imaging

Angular Differential Imaging

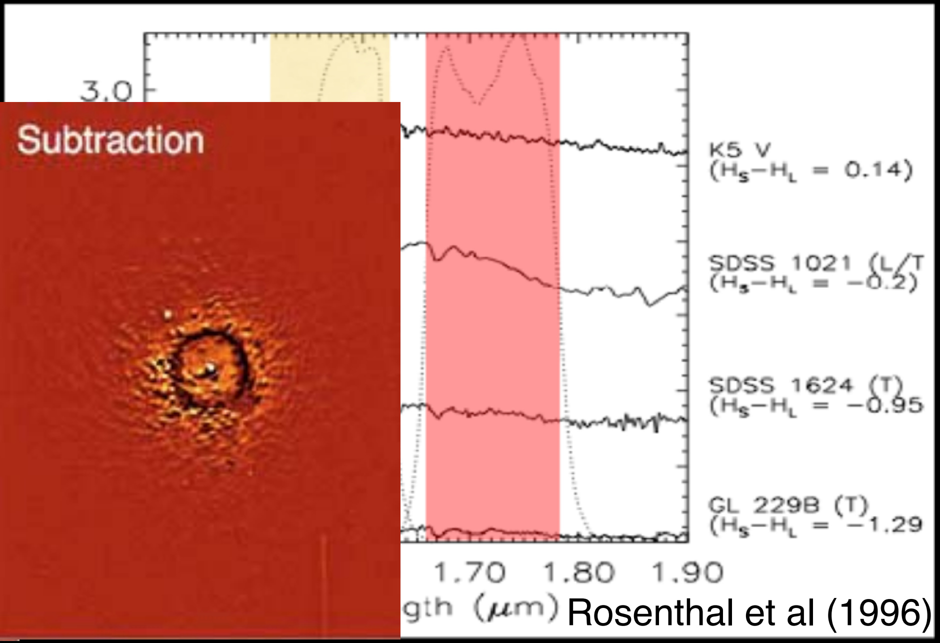
- Uses rotation of the sky to distinguish planets from super-speckles
- Super-speckles are quasi-static wrt instrument optics
- Planets are fixed on sky
- Fast (atmospheric) speckles are smeared out over “long” exposures



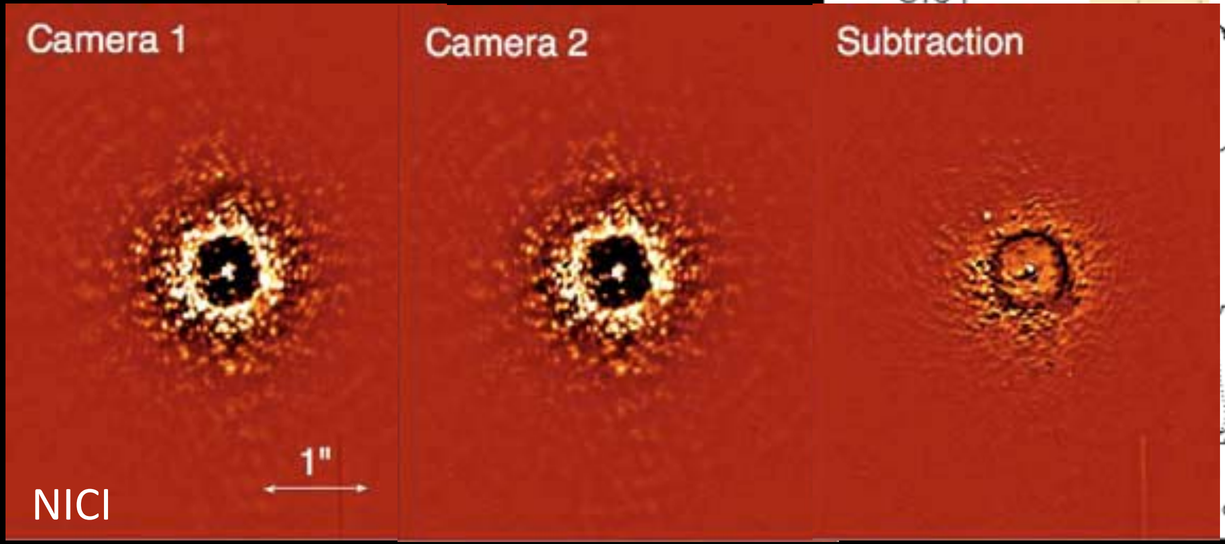
Marois et al 2009

Spectral Differential Imaging

- around the 1.6µm methane absorption feature



Rosenthal et al (1996)



NICI - Near Infrared Coronagraphic Imager

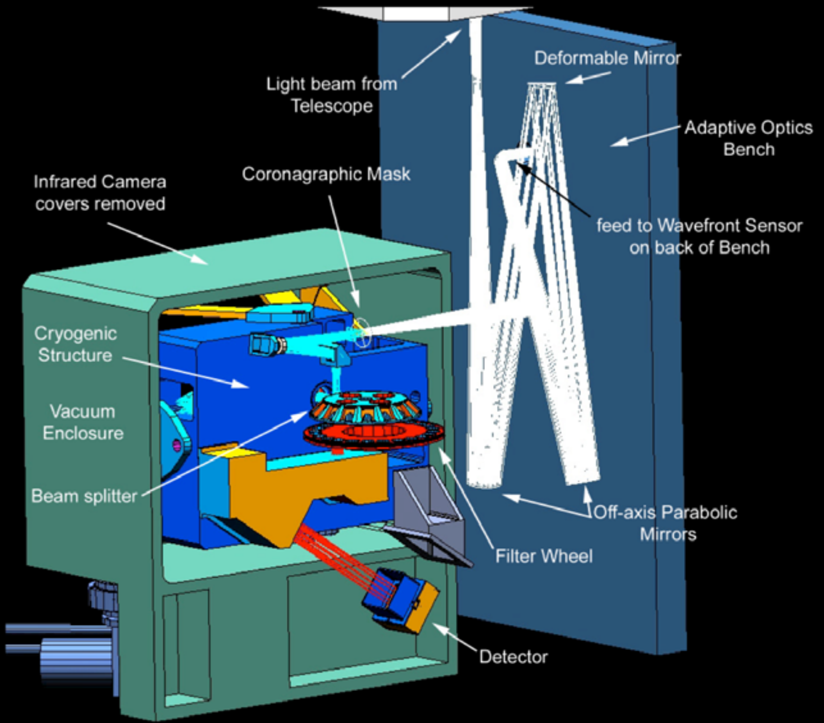
Dedicated extra-solar planet imager
for Gemini-South

PI: Doug Toomey (Mauna Kea Infrared)

- 85-element curvature adaptive optics
- Lyot Coronagraph
- Dual band camera

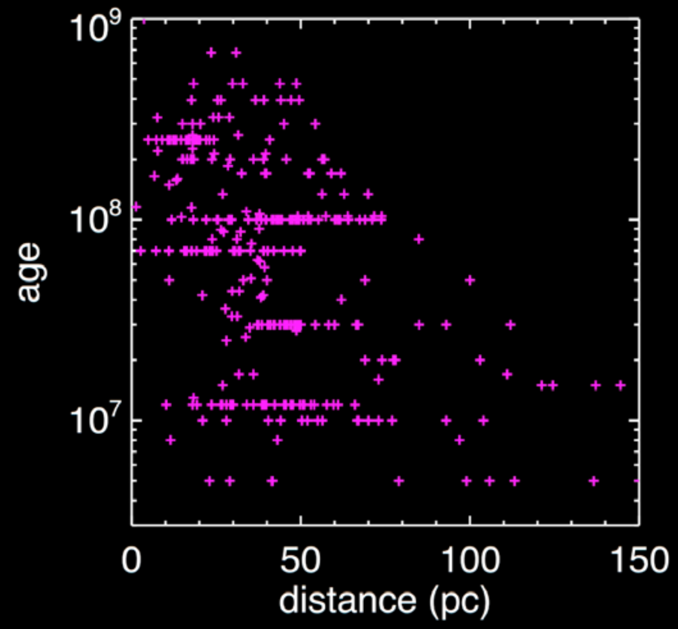
- Spectral Difference Imaging
  - around the 1.6μm CH_4 absorption feature
- Angular Difference Imaging
  - suitable for non-methane

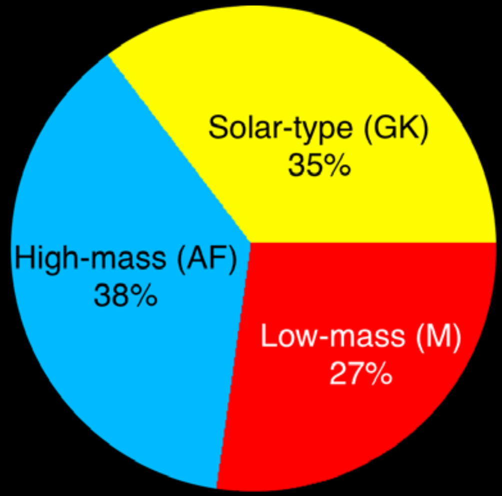
- Mean A/SDI contrast = 10^6 @ 1” sep.



NICI Planet-Finding Campaign

- 2-3 year major campaign for direct imaging of extra-solar planets
  - PI: Michael Liu (University of Hawaii)
  - ≈300 carefully chosen stars, spanning a range of ages, distances & masses
  - 50 nights
  - Started in Dec 2008, now well into 2nd epoch observations
- What do the spectra of these planets look like?
  - spectral type, T_{eff}
  - age and distance from primary
  - mass, surface gravity from models





Team: Mark Chun, Beth Biller, Evgenya Shkolnik, Christ Ftaclas, Zahed Wahhaj, Laird Close, Adam Burrows, Doug Toomey, Neill Reid, Niranjan Thatte, Matthias Tecza, Fraser Clarke, Harvey Richer, Jane Gregorio Hetem, Elisabete De Gouveia Dal Pino, Sylvia Alencar, Pawel Artymowicz, Doug Lin, Shigeru Ida, Alan Boss, Mark Kuchner, Chris Tinney, Tom Hayward, Markus Hartung, Etienne Artigau

CD35-2722 : a dusty young benchmark

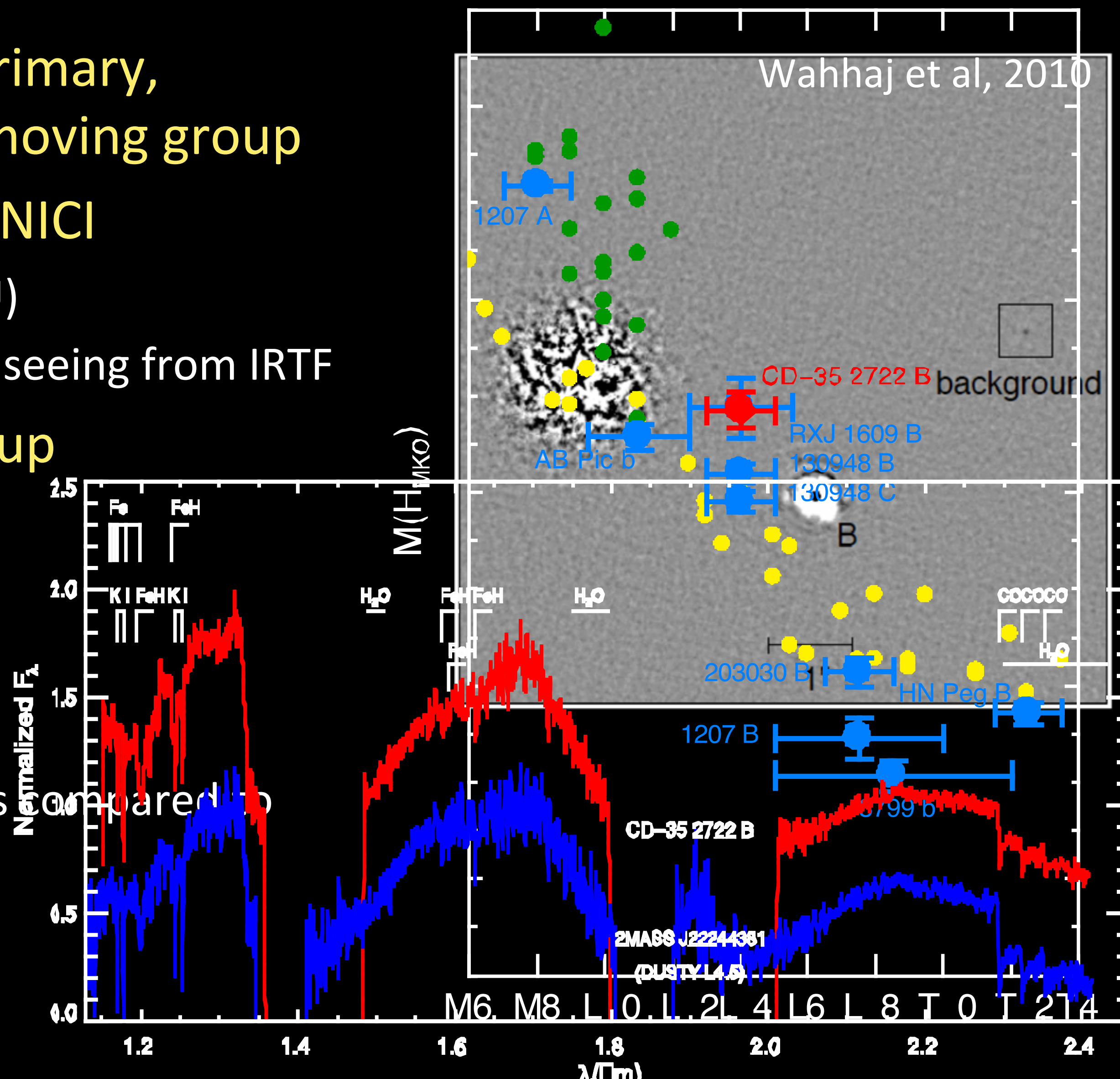
Companion to M1 primary, member of AB Dor moving group

Very easy target for NICI

- ΔH=5.5 at 3.1” (67AU)
- Confirmed in natural seeing from IRTF

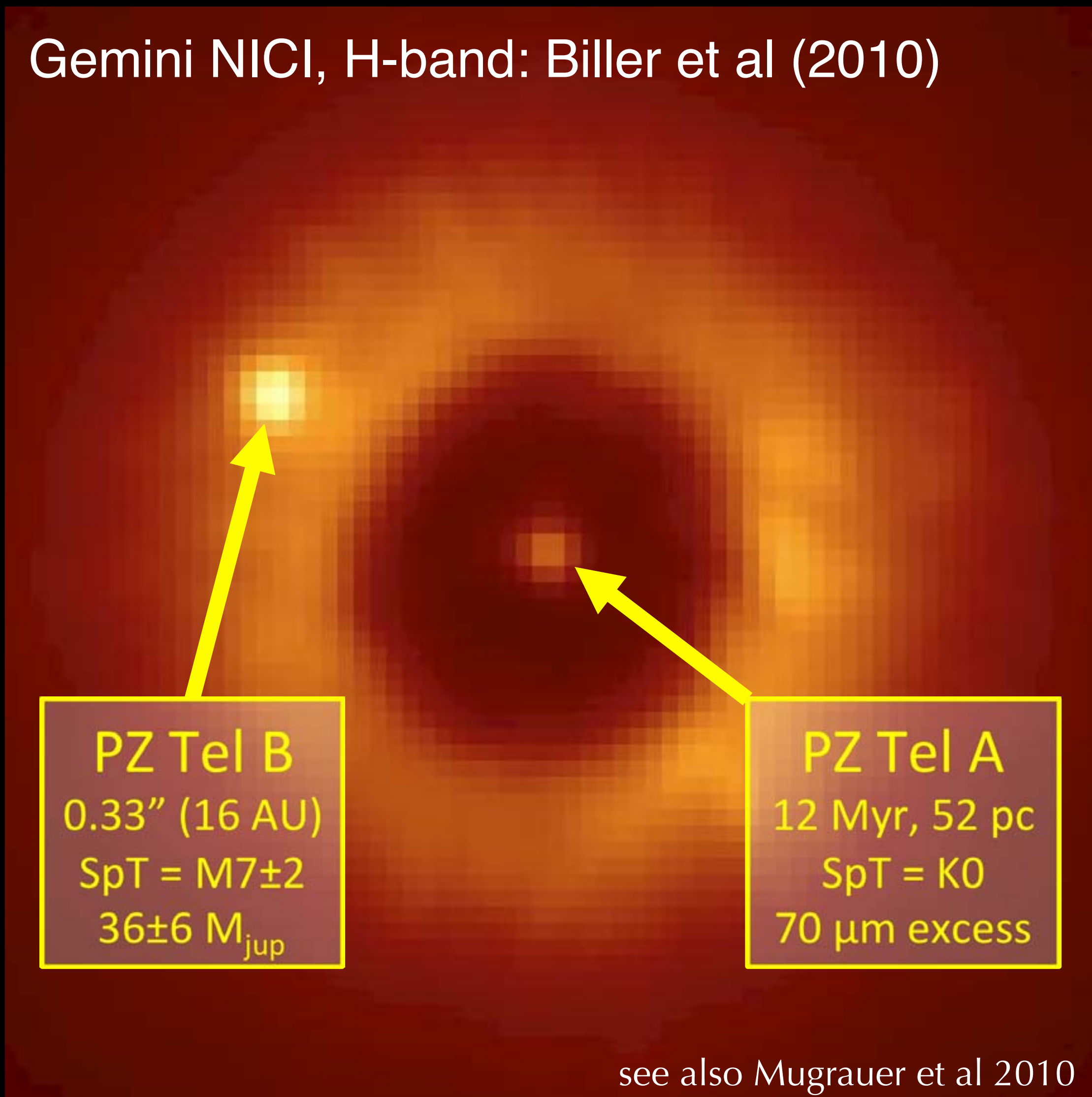
Gemini/NIFS follow-up

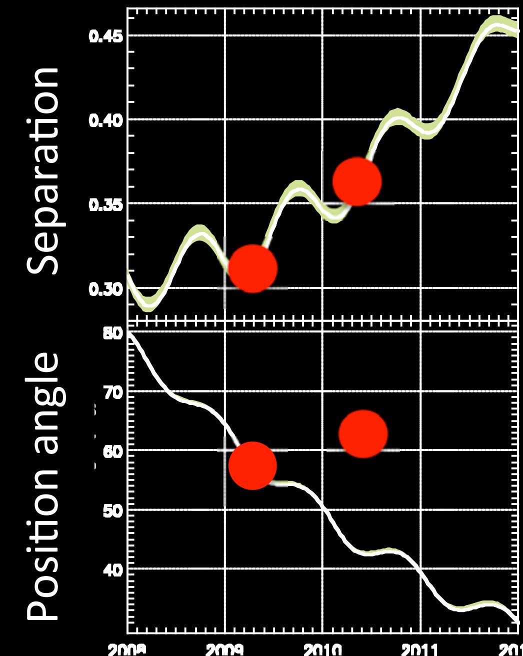
- Spectral type: L4 ± 1
- Mass: 31 ± 8 M_{jup}
- log(g): 4.5 ± 0.5
- Age: 100 ± 50 Myr
- Seems over-luminous compared to field objects

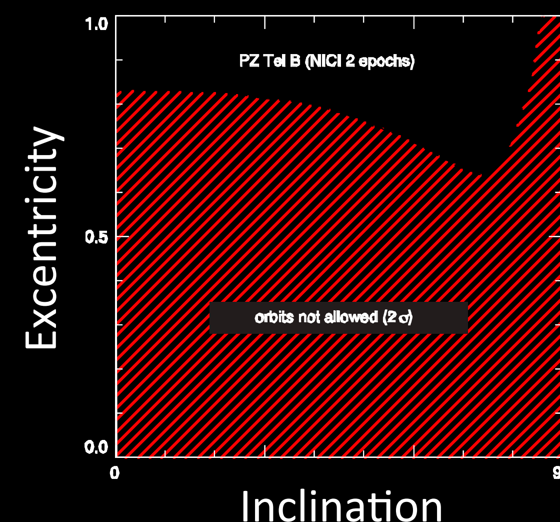


A tight BD around a young debris disk star

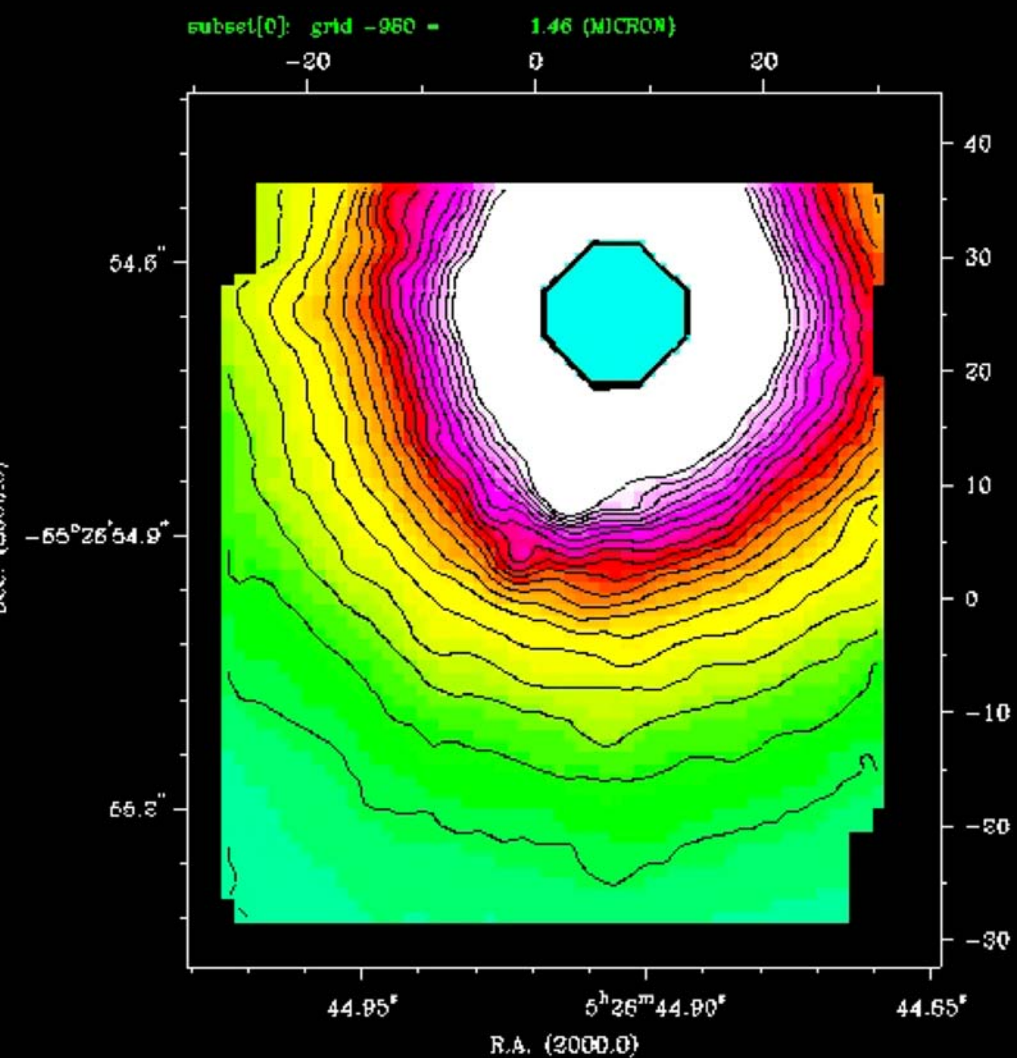
with a high excentricity orbit





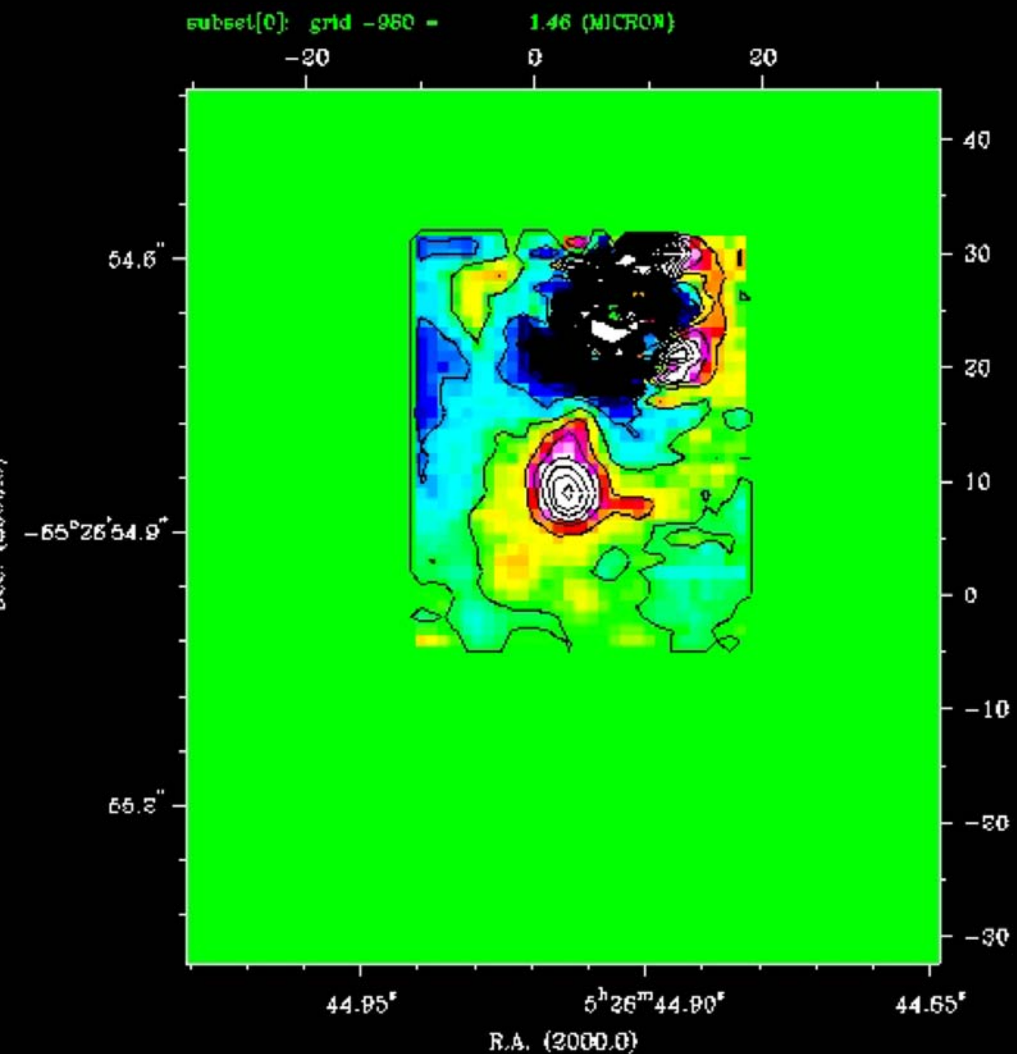


Spectral Deconvolution

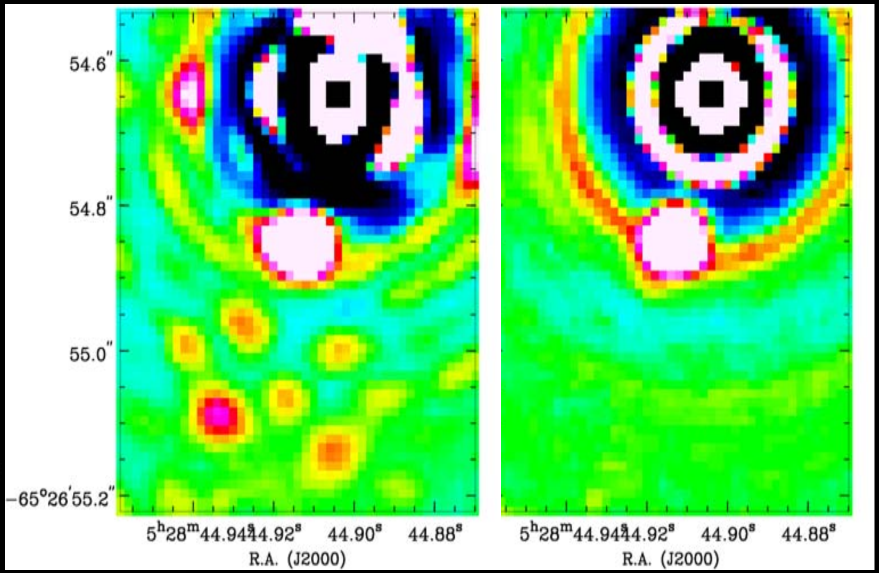


- AB Doradus C
  - SINFONI/VLT (image slicer)
  - 25mas, H+K band
  - 20 min on-source
  - 15pc distance
  - 3 AU separation
- Raw data cube
  - Diffraction & speckle pattern scales as function of wave-length
  - Pattern moves out from star with increasing wavelength
  - Exoplanet position is fixed
  - Hence distinguish speckles from exoplanets/companions (Sparks & Ford 2002)

Spectral Deconvolution

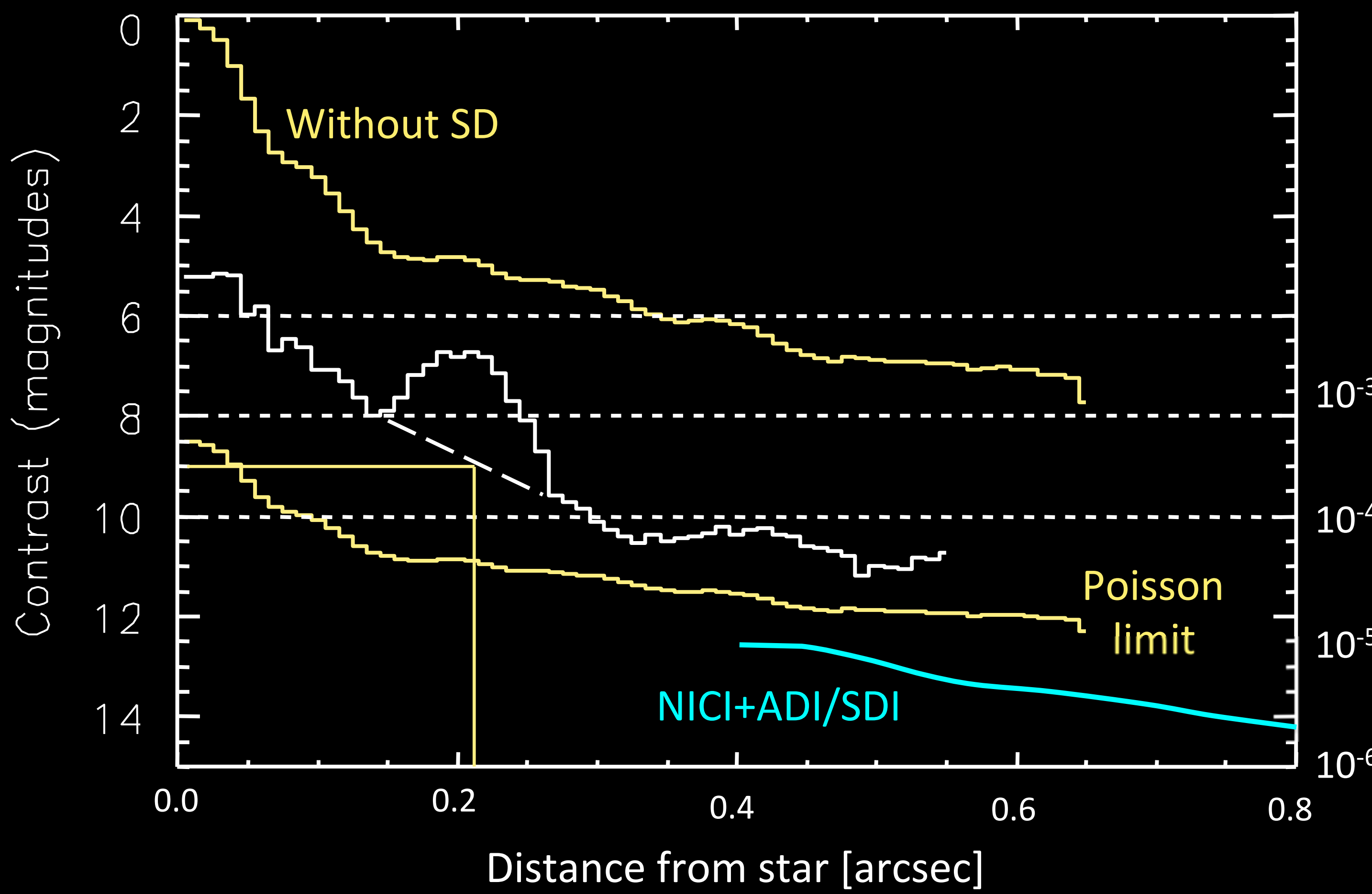


- Cleaned data cube
  - Full spectral deconvolution applied



- Single wavelength channels
  - Radial profile removed
  - Full SD applied

Spectral Deconvolution - Contrast



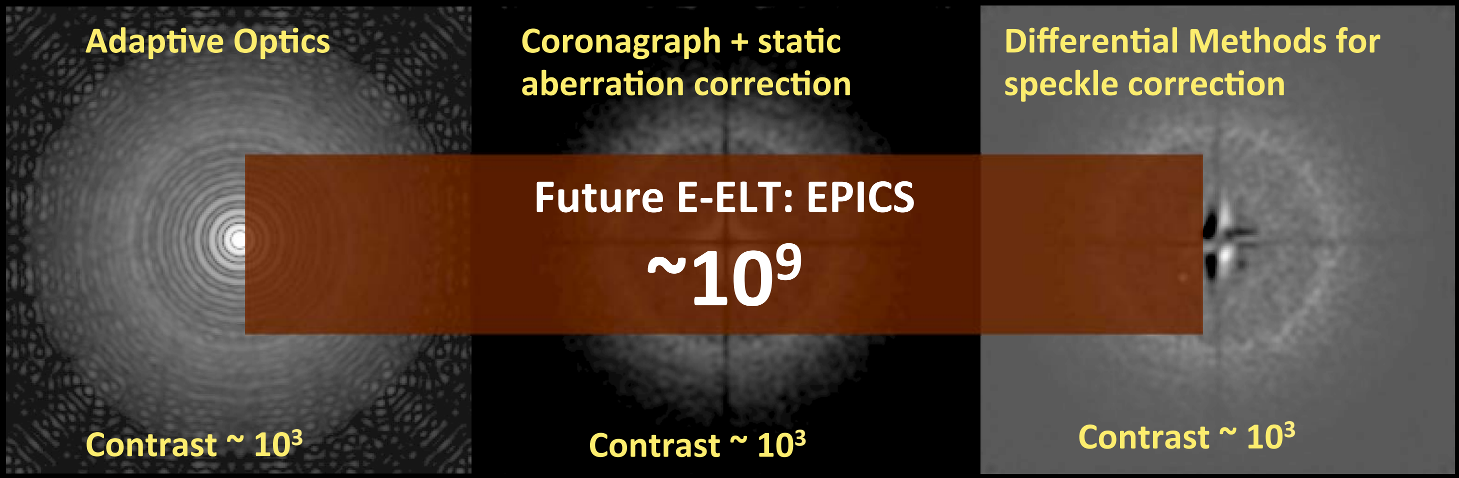
Thatte, Abuter, Tecza et al 2007, MNRAS, 378, 1229

Spectral Deconvolution – Advantages

- Distinguish between exoplanets and speckles without prior assumption on exoplanet spectrum
- Detect and characterise exoplanets at the same time
- Planet finding instruments at 8m and future extremely large telescope have integral field spectrographs as major science instrument
  - GPI @ Gemini (PI Bruce Macintosh)
  - SPHERE @ VLT (PI Jean-Luc Beuzit)
  - EPICS @ E-ELT (PI M. Kasper, ESO)
  - HARMONI @ E-ELT (Talk by Niranjan Thatte, Wednesday)
  - IRIS @ TMT, GMTIFS @ GMT, …
- 2 main Integral Field Unit technologies
  - Slicer (SINFONI, NIFS)
    - Wide wavelength range
    - Efficient use of detector pixels
  - Lenslet based (GPI & SPHERE, OSIRIS)
    - Many but short spectra

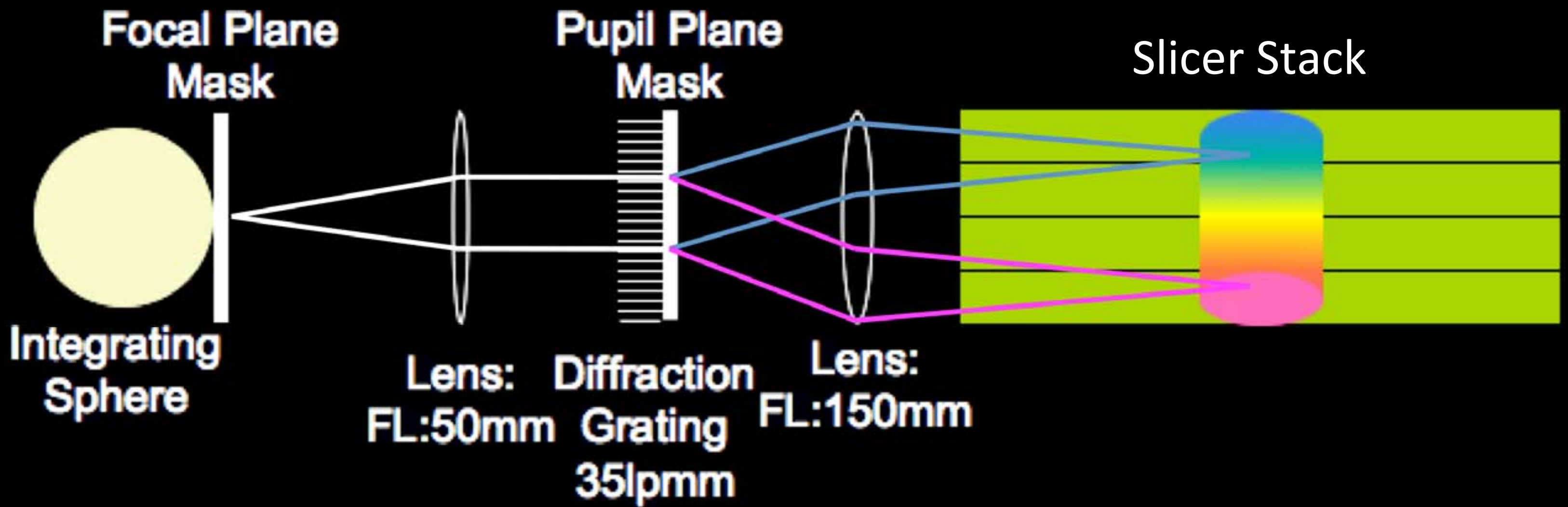
EPICS Phase A Study

see poster by Raffaele Gratton

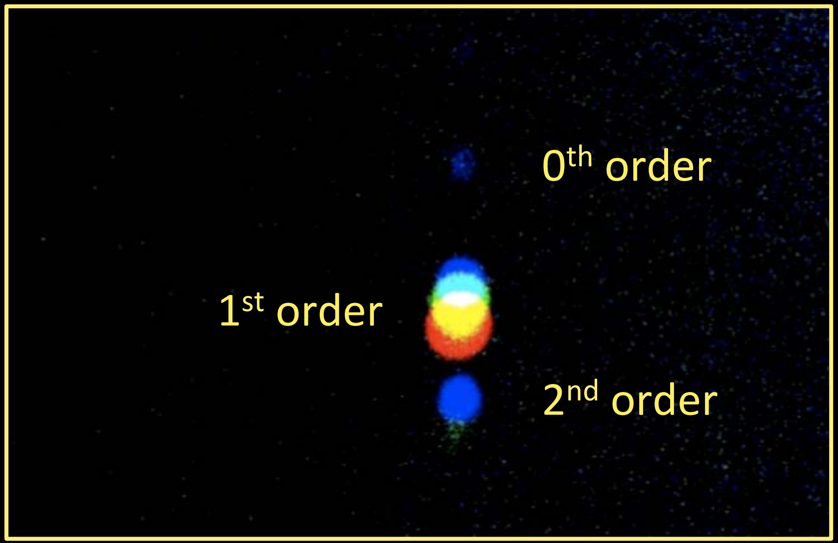


- Can slicer based IFS achieve the required contrast of $\approx 10^3$?
  - Build a test bed to study the effect of the errors not addresses by the simulations, such as
  - Scattered light, diffraction, non-pupil plane and manufacturing errors
  - Use polished glass image slicer IFS
  - Diffraction limited pre-optics to create artificial speckle
  - cf Salter et al. 2010, 2011

Test bed – Speckle Generation



Test image with SLR



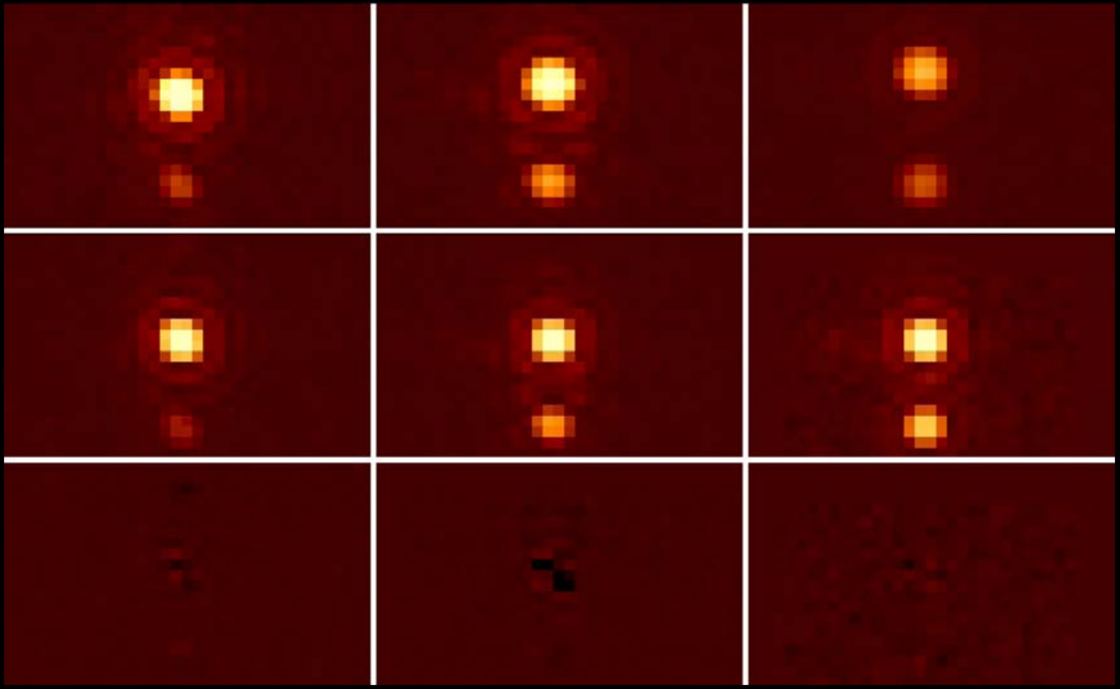
Test bed – Data & Results

750nm 850nm 950nm

Original

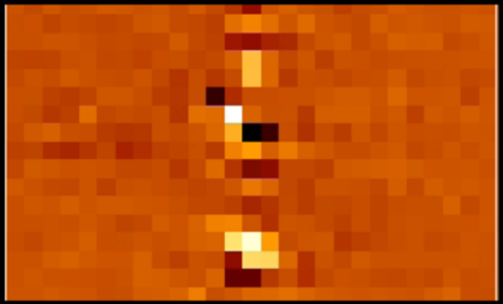
λ-scaled

SD residuals



"monochromatic" speckle rejection ×90

Broadband image



detection speckle rejection factor ×500

Conclusions

- NICI + differential techniques can detect planets
  - Successful planet finding instrument
  - Two low-mass companions already discovered
- Spectral deconvolution is powerful differential technique for high-contrast spectroscopy
  - Distinguish between exoplanets and speckles without prior assumption on exoplanet spectrum
  - Detect and characterise exoplanets at the same time
- Slicer based IFS can achieve contrast ≥500
  - Currently limited by calibration errors
  - With optimised IFS & SD contrast of ≈1000 should be achievable
  - No significant limit in achievable contrast due to the use of a slicer is seen