Direct Imaging of Exoplanets: Prospects for Comparative Exoplanetology

Beth Biller, Institute for Astronomy, University of Hawaii

The Tally So Far…

- 277 total planets discovered
- 261 detected via the radial velocity technique
- 36 detected via transit
- 6 detected via microlensing
- “5” detected via direct imaging
- 5 pulsar planets

From exoplanet.eu

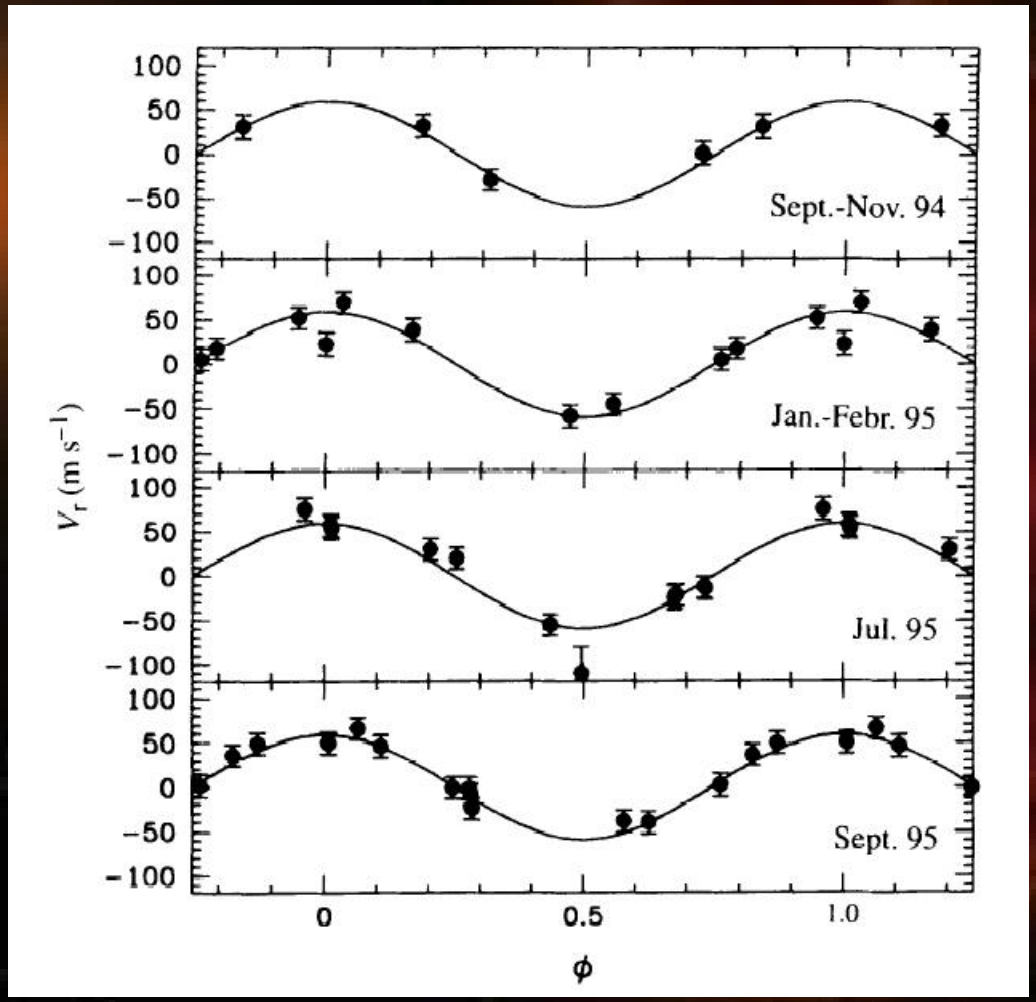
Comparative Exoplanetology

Two big questions to be answered:

1) What is the "typical" setup of a solar system?
2) What are the physical properties of planets? Can we set up "spectral types" for planets?

Different planet detection techniques possess different strengths and weaknesses with regard to answering these questions.

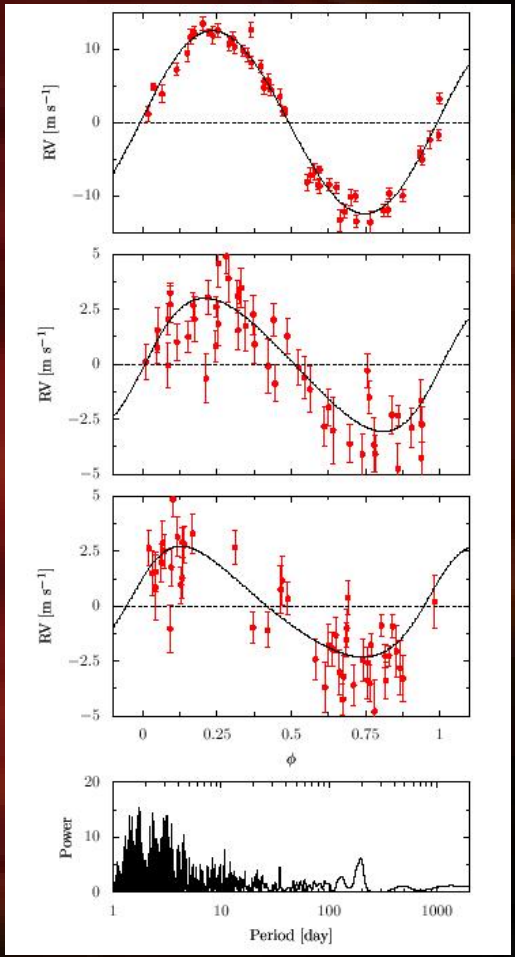
Radial Velocity



Mayor and Queloz 1995

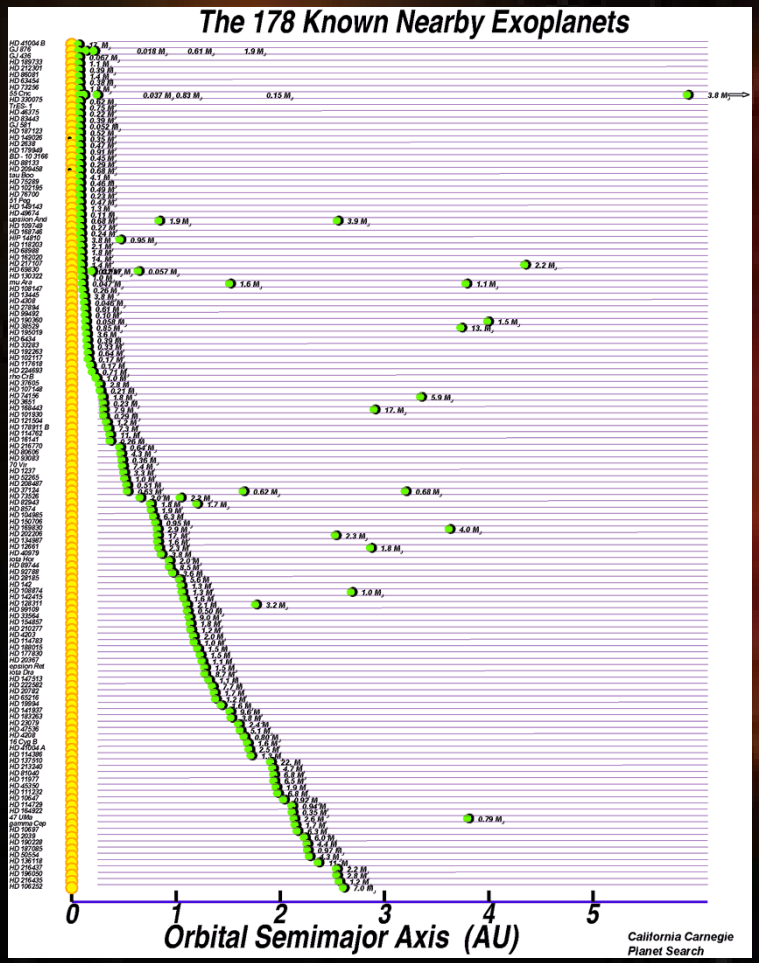
Radial Velocity

- PROS: by far the most successful technique so far, can retrieve period, orbit, and mass information
- CONS: selection effect due to sensitivity to massive close-in planets, retrieve Msini not M.



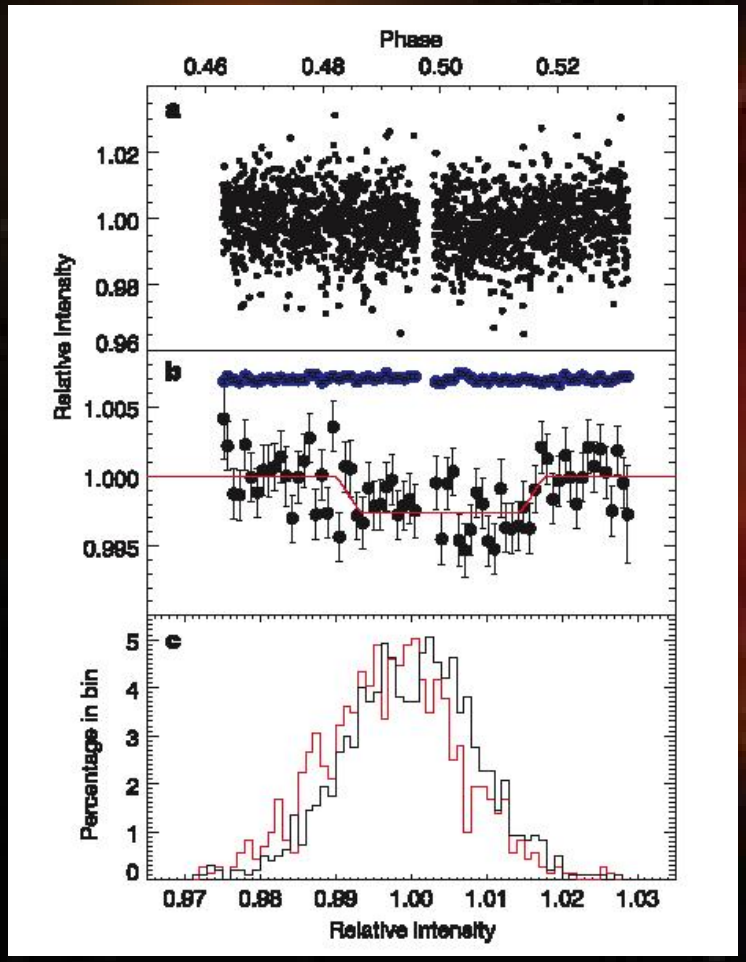
Udry et al. 2007

RV Selection Effects



- Current selection bias for close-in planets
- Slowly moving outwards – now we are beginning to be able to detect Jupiter analogues.

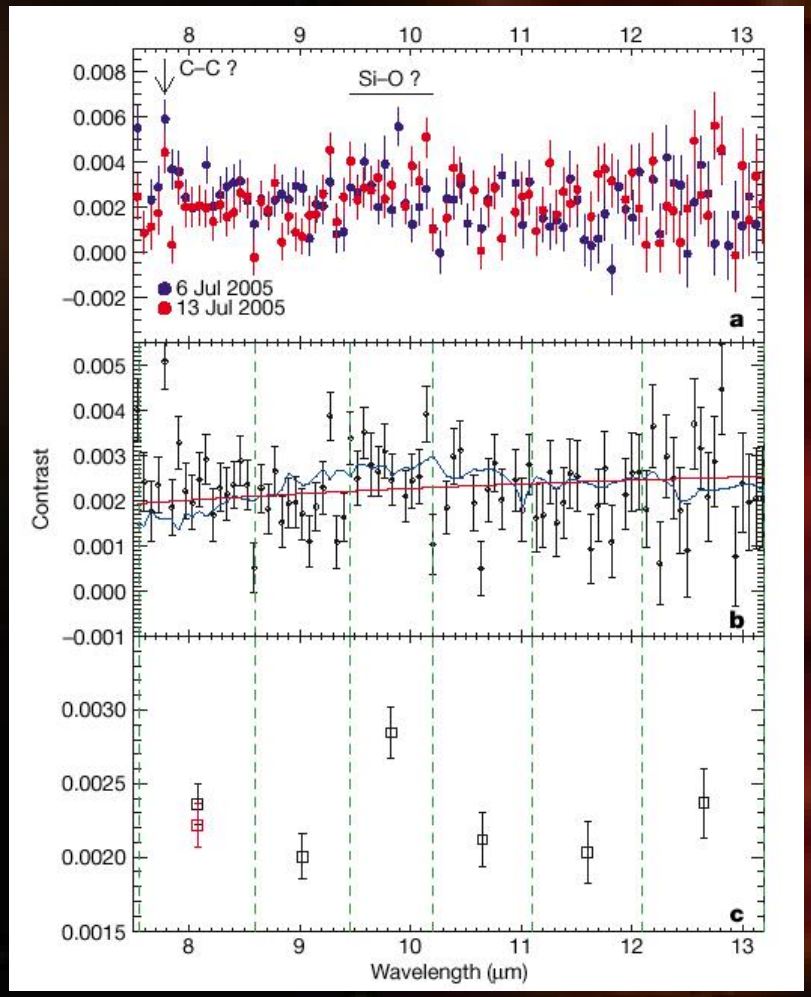
Transits



- PROS: provides mass, radius, and (in some cases) spectral information.
- CONS: currently samples only a very specific close in, hot type of planets, can only detect planets at the right inclination relative to the star and Earth.

Deming et al. 2005

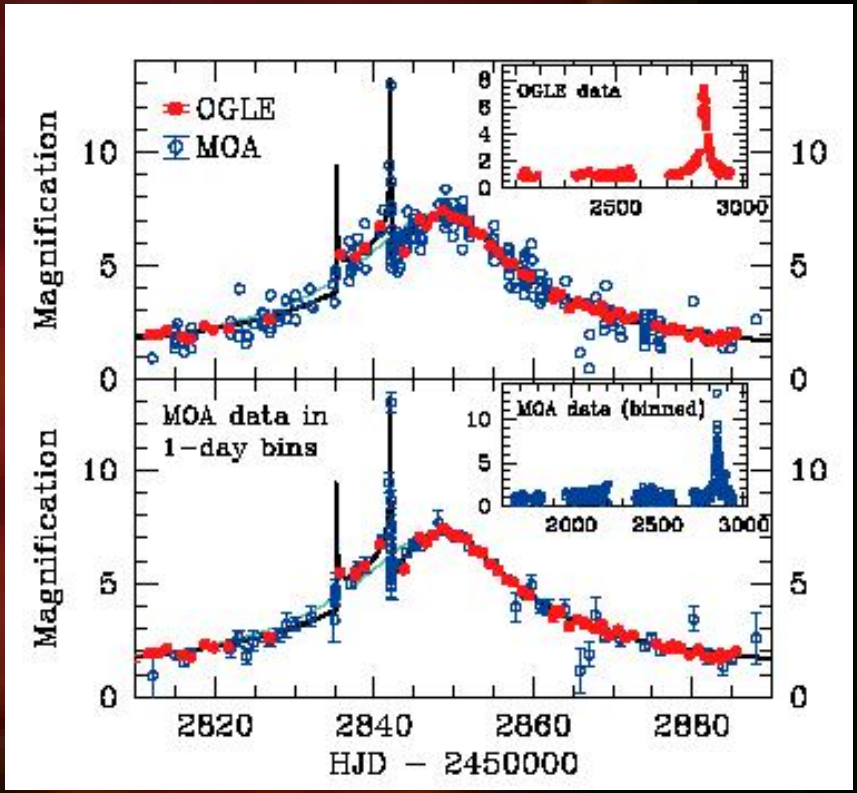
Spectroscopy from Transit



Richardson et al. 2007

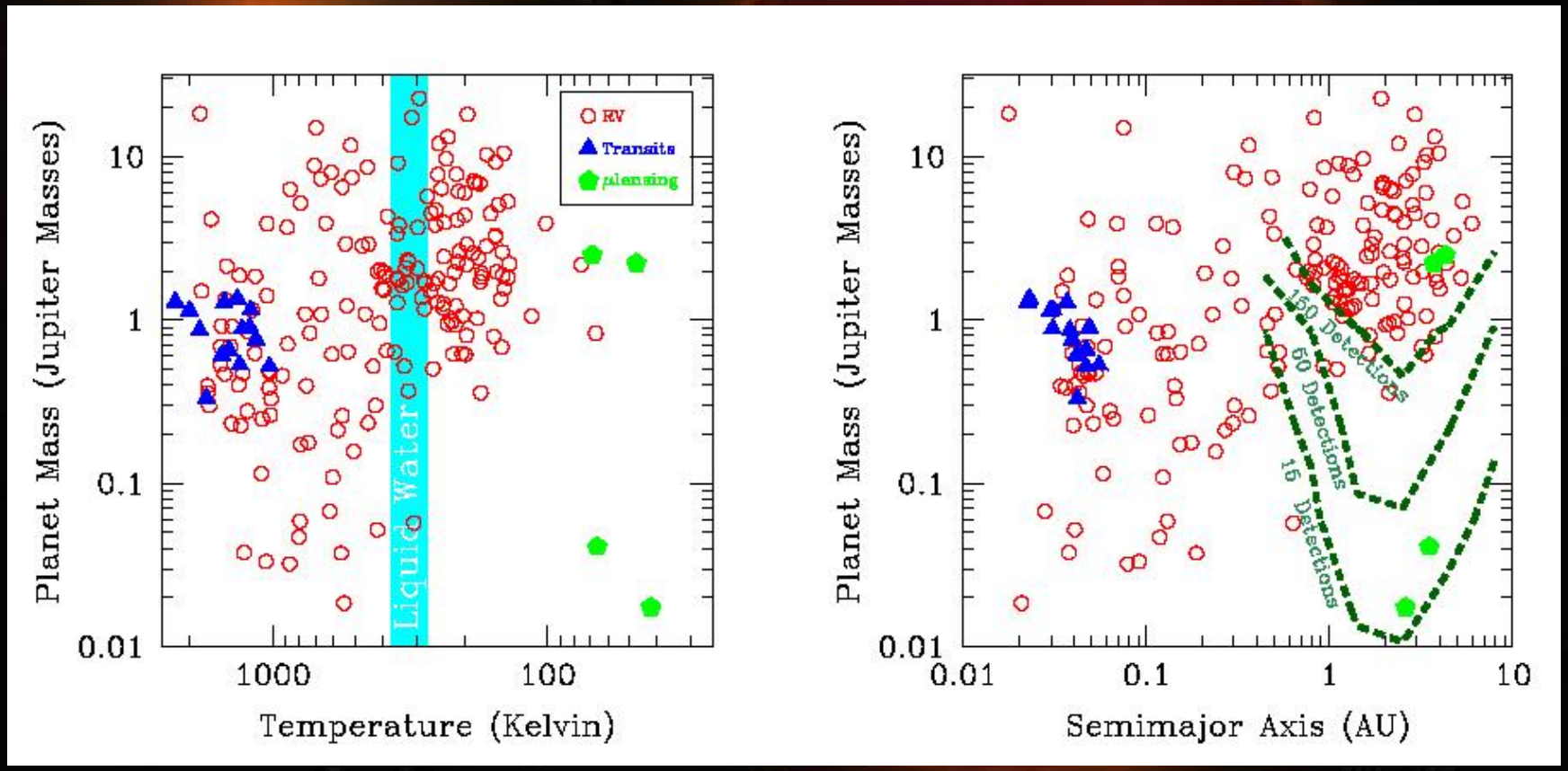
Microlensing

- PROS: sensitive to planets beyond the snowline, at a variety of masses, and even planets in other galaxies.
- CONS: no possibility of followup ever!



Bond et al. 2004

Distribution of Currently Known Planets



Direct Detection

Chauvin et al. 2004

- PROS: lots of instant physical information: photometry, astrometry, eventually spectroscopy.
- CONS: must overcome huge contrast difference, speckle noise.
- So far no planets have been directly imaged around main sequence stars.

Difficulties with Direct Detection (1)

- Two major difficulties:

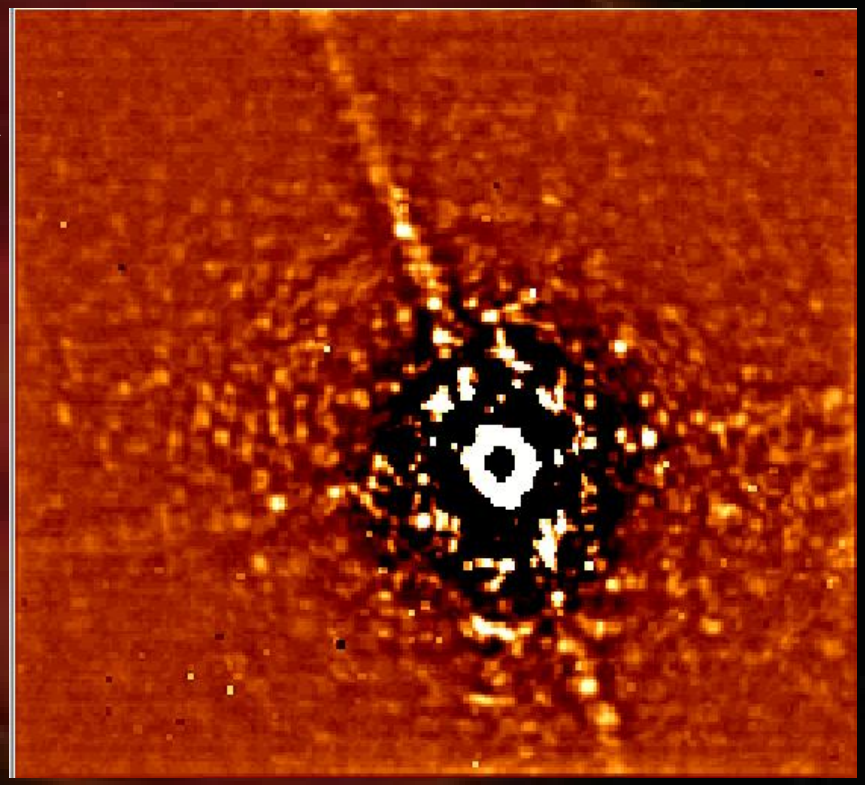
1) Huge contrast difference between planet and star:

- Old (>2 Gyr) giant gas planets >10^8 fainter than primary and lie within ~1" of primary.
- However, young planets are still self-luminous and ~10^{4-7} times fainter than primary.
- Adaptive optics systems that are photon noise limited can detect (1 hr exposure) an object up to 10^{5-6} times fainter than and >1" from its primary.

Difficulties with Direct Detection (2)

2) Speckle Noise –

Within 1" of star, the field is filled with super speckles left over after adaptive optics correction.



For photon-noise limited data:

$S/N \sim t_{exp}^{0.5}$

For speckle-noise limited data:
S/N does not increase with time past a speckle noise floor.

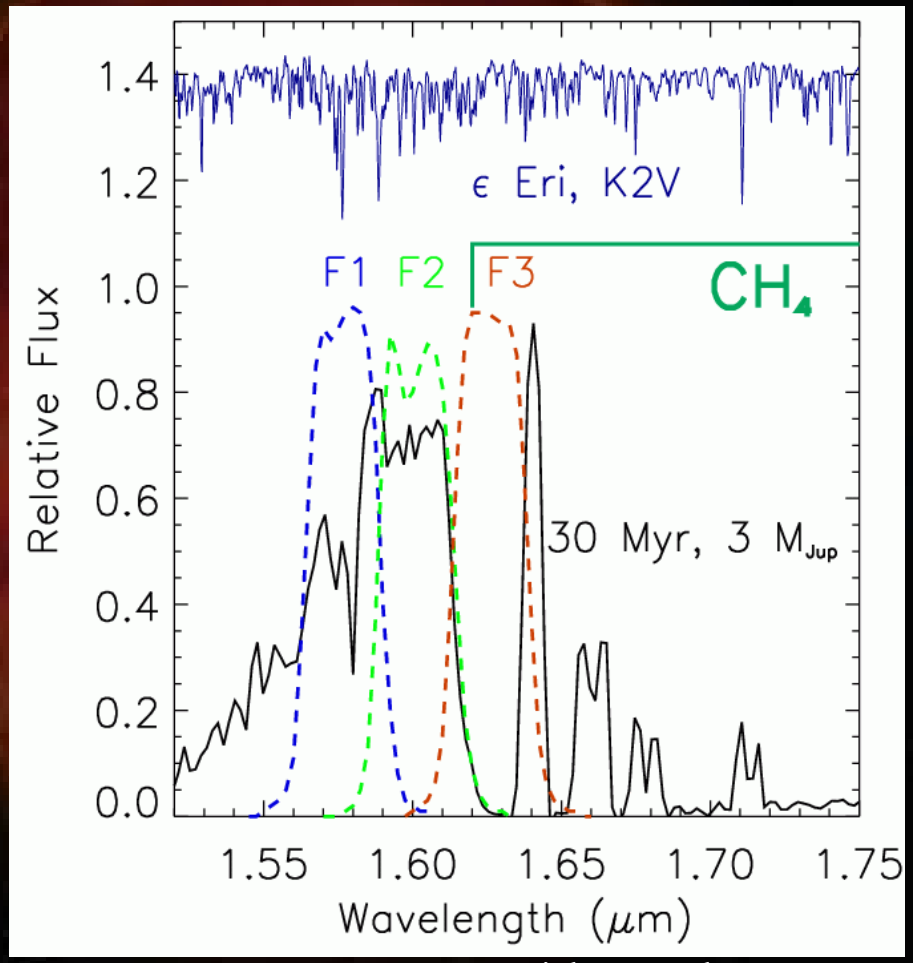
Direct Detection Surveys

3 major surveys recently finished or soon to be completed:

- Simultaneous Differential Imager (SDI) survey at the VLT and MMT (Biller et al. 2007, Nielsen et al. 2008)
- Gemini Deep Planet Survey (GDPS) at Gemini North (Lafreniere et al. 2007)
- NICMOS Planet Survey with HST (Farihi et al. in prep.

The Simultaneous Differential Imaging (SDI) Technique

- Pioneered by Marois et al. 2000.
- Sample inside and outside of the strong CH_4 (methane absorption) bandhead at 1.62 μm in extrasolar giant planets (T < 1200 K)
- Subtract out star and speckles between filters – any CH_4 rich companion should remain.

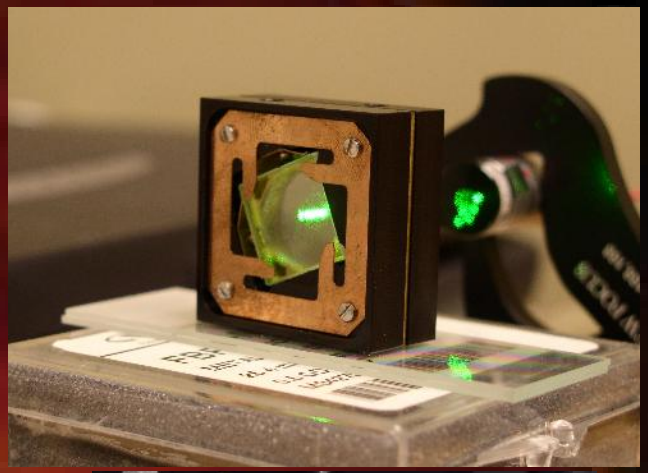


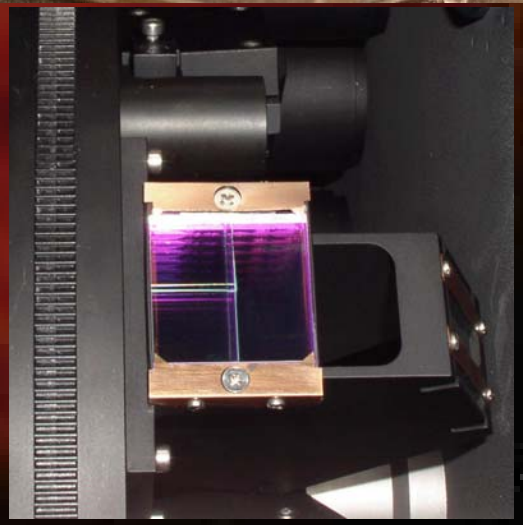
Nielsen et al. 2006

SDI Hardware

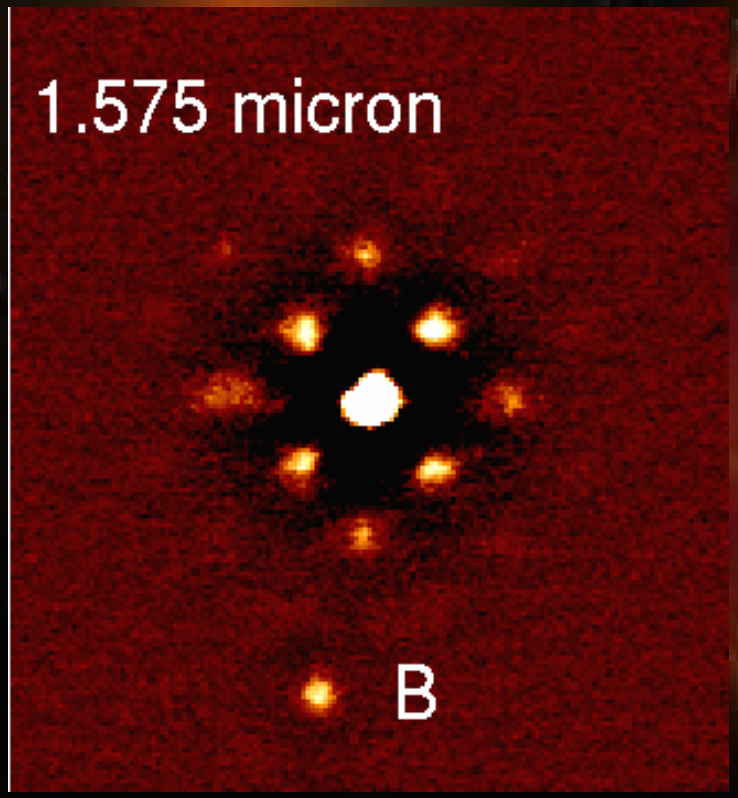
Double Wollaston and Quad Filter– Calcite Prisms split beam into 4 identical beams while minimizing non common path error (Close et al. 2004).

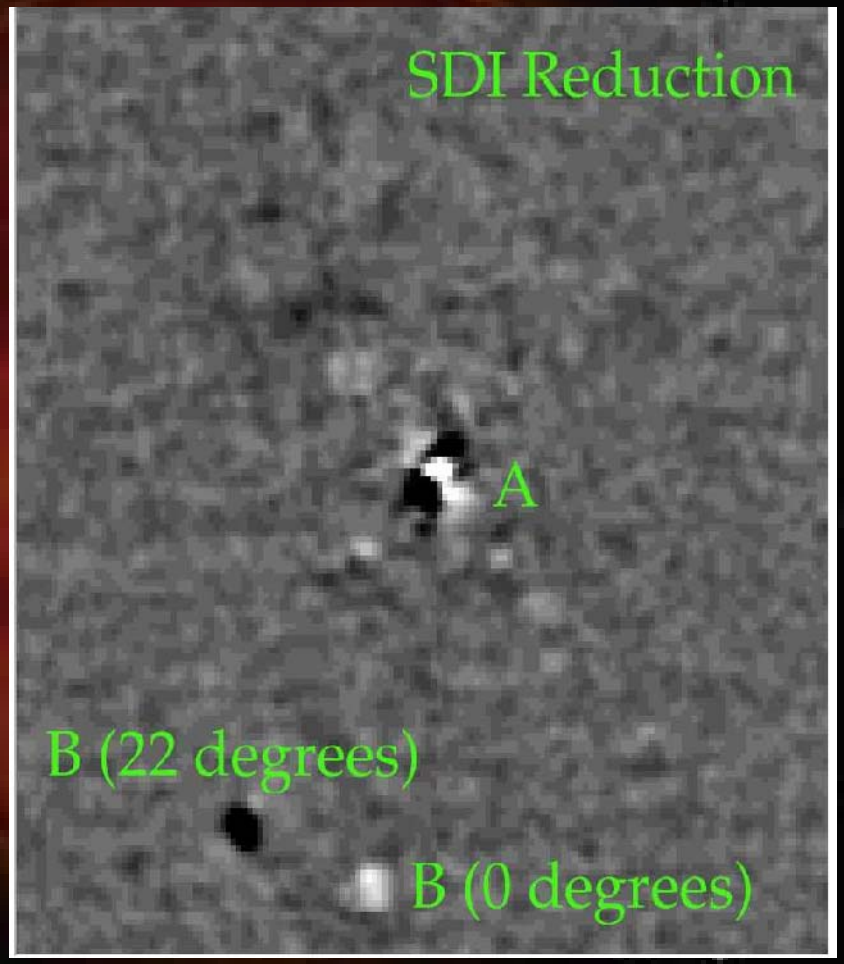
- Installed in the ARIES camera at the MMT AO system by Don McCarthy and Laird Close and in the CONICA camera inside the VLT NACO AO system by Laird Close and Rainer Lenzen.





Proof of Concept – The Discovery of the Methane Rich Brown Dwarf SCR 1845B



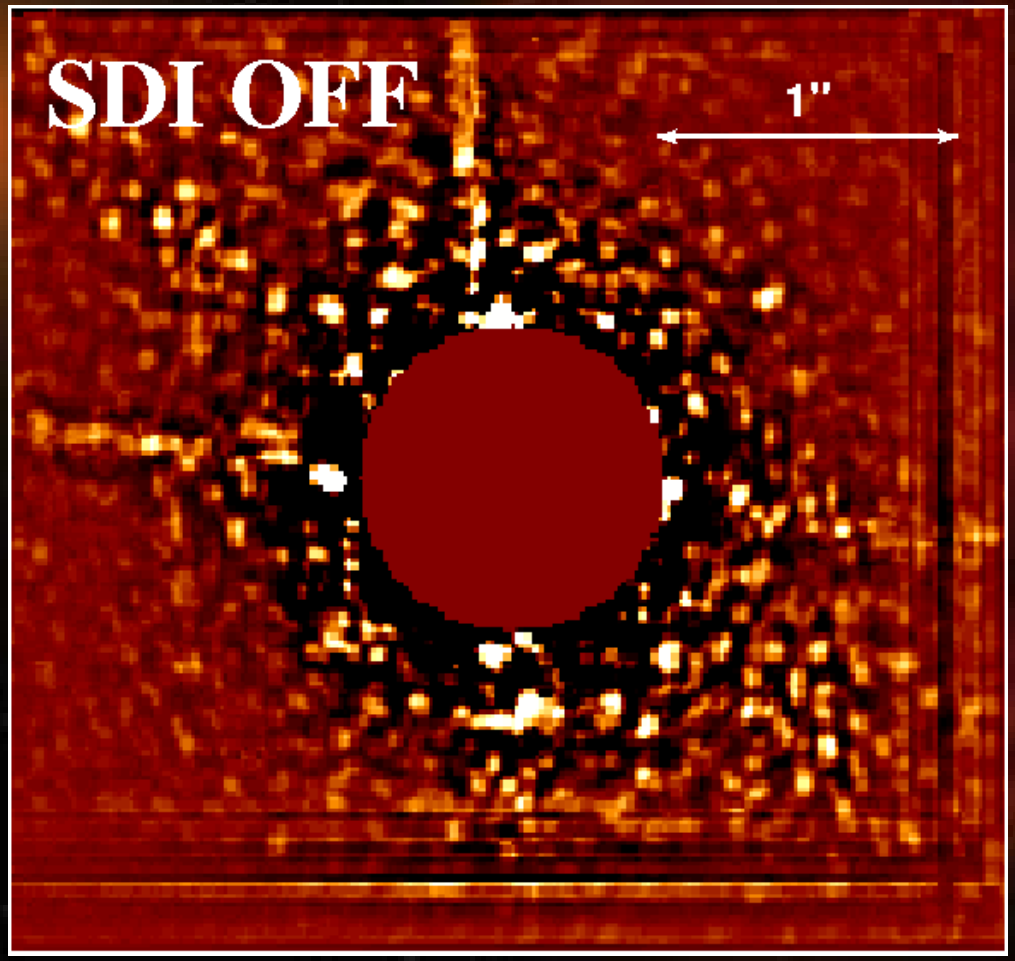


M8.5 + T5.5

Separation: 4.5 AU

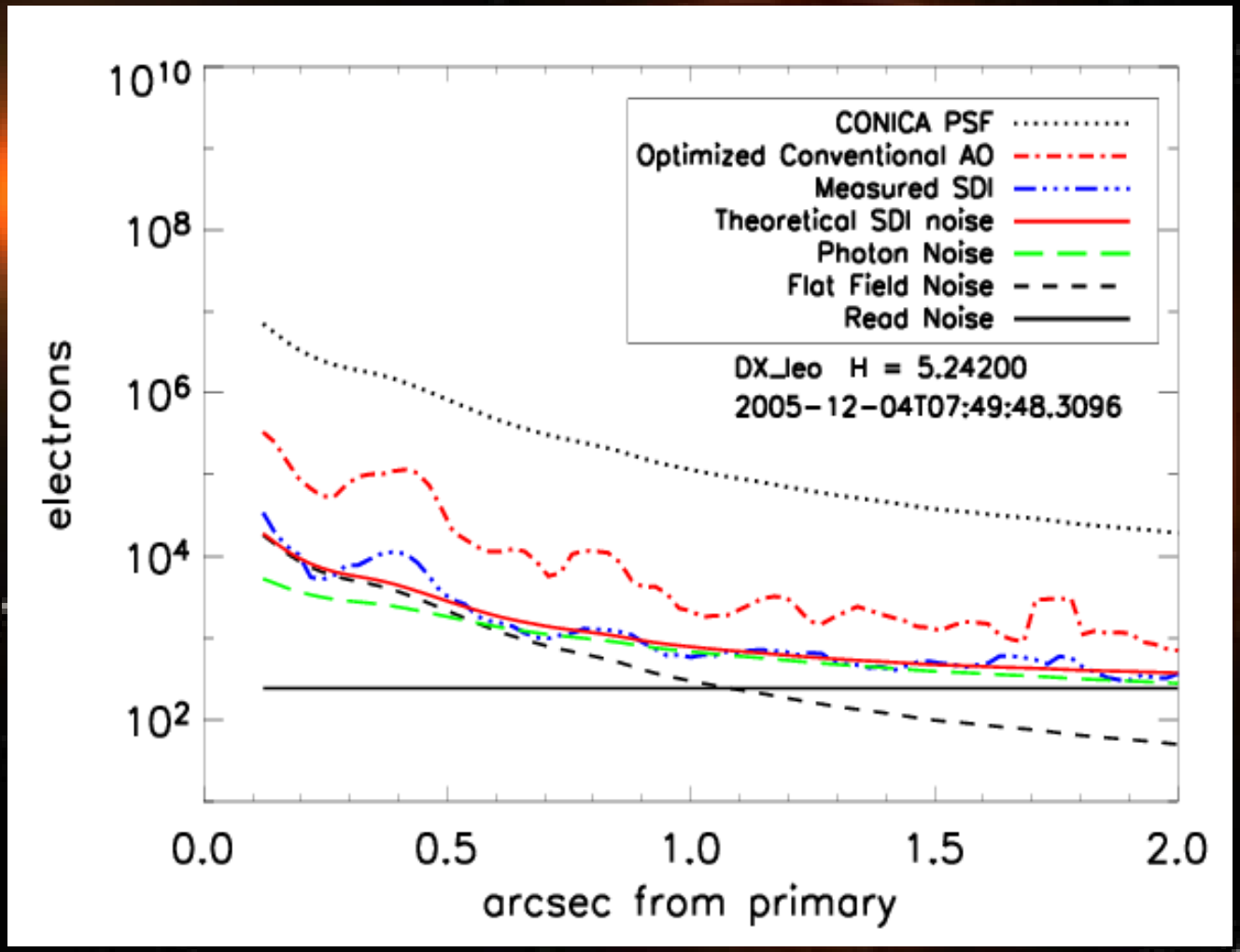
Biller, Kasper, Close, Brandner, and Kellner 2006

Reduced Data – Standard AO vs. SDI

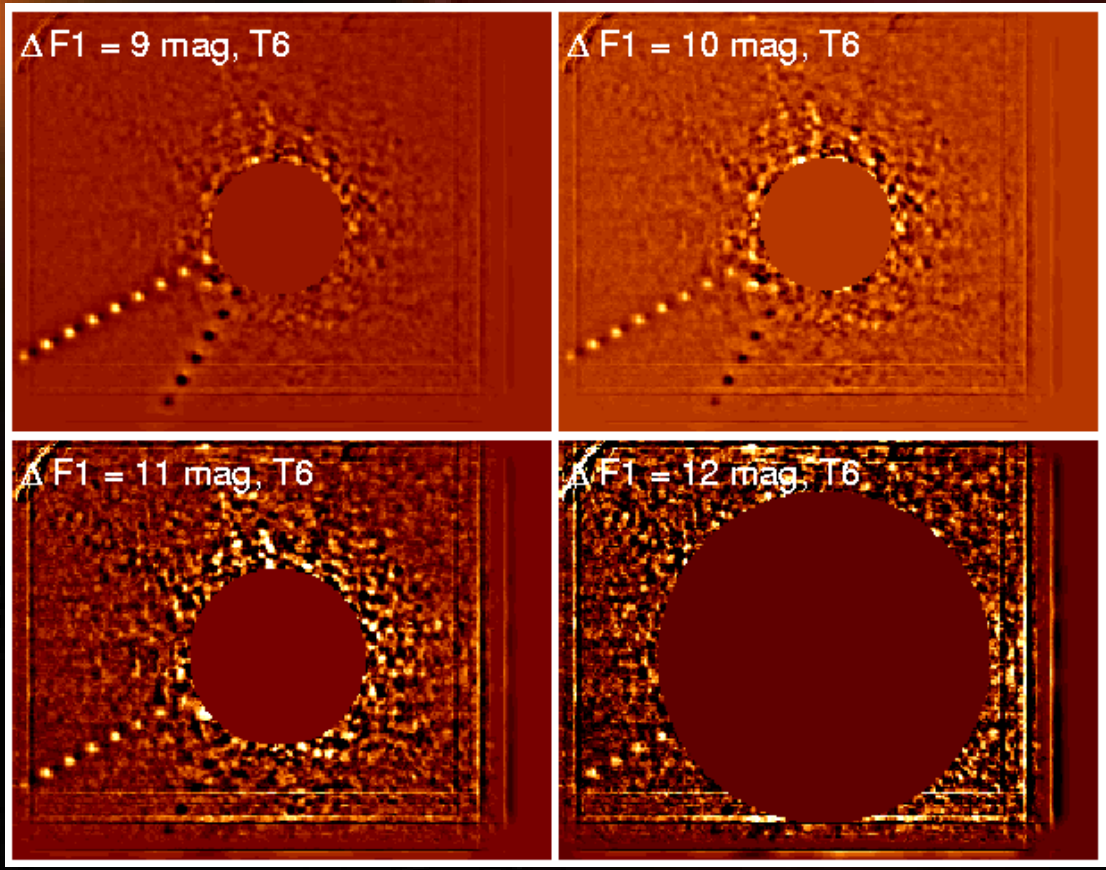


Biller et al. 2006

Noise Sources



Case Study: Achievable Contrasts for AB Dor (**K1V, 15 pc, ~70 Myr, V=6.88**)



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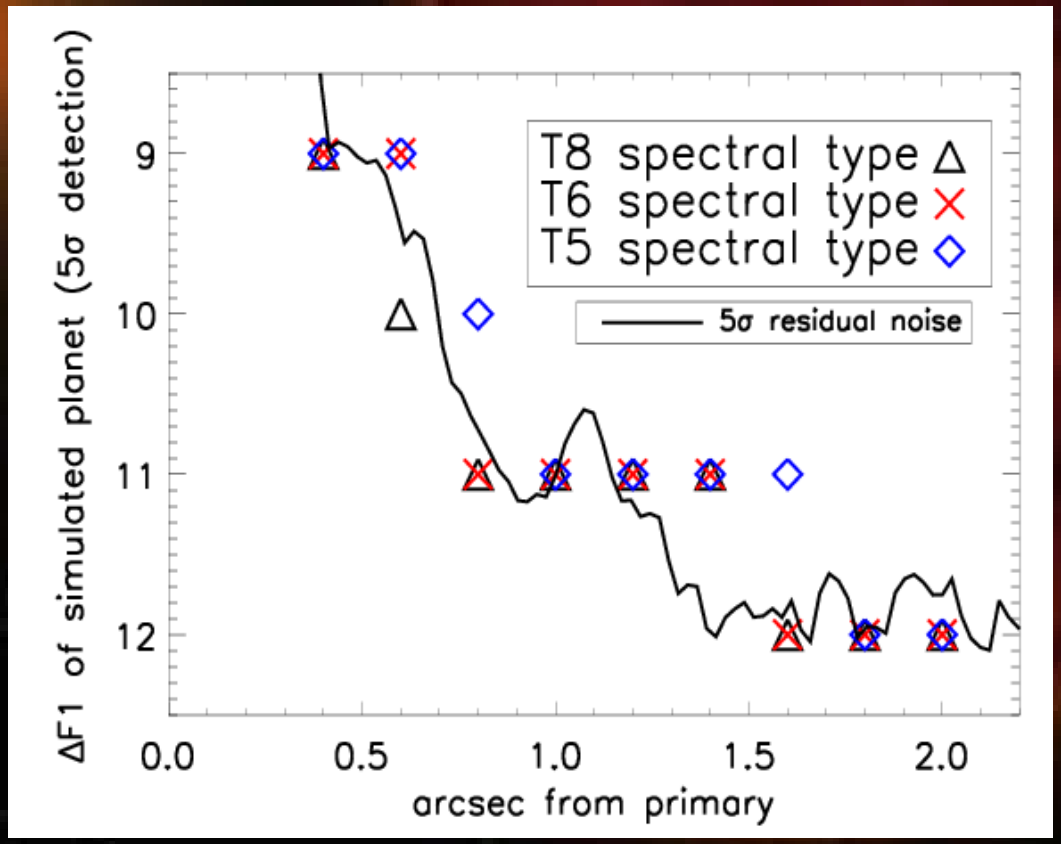
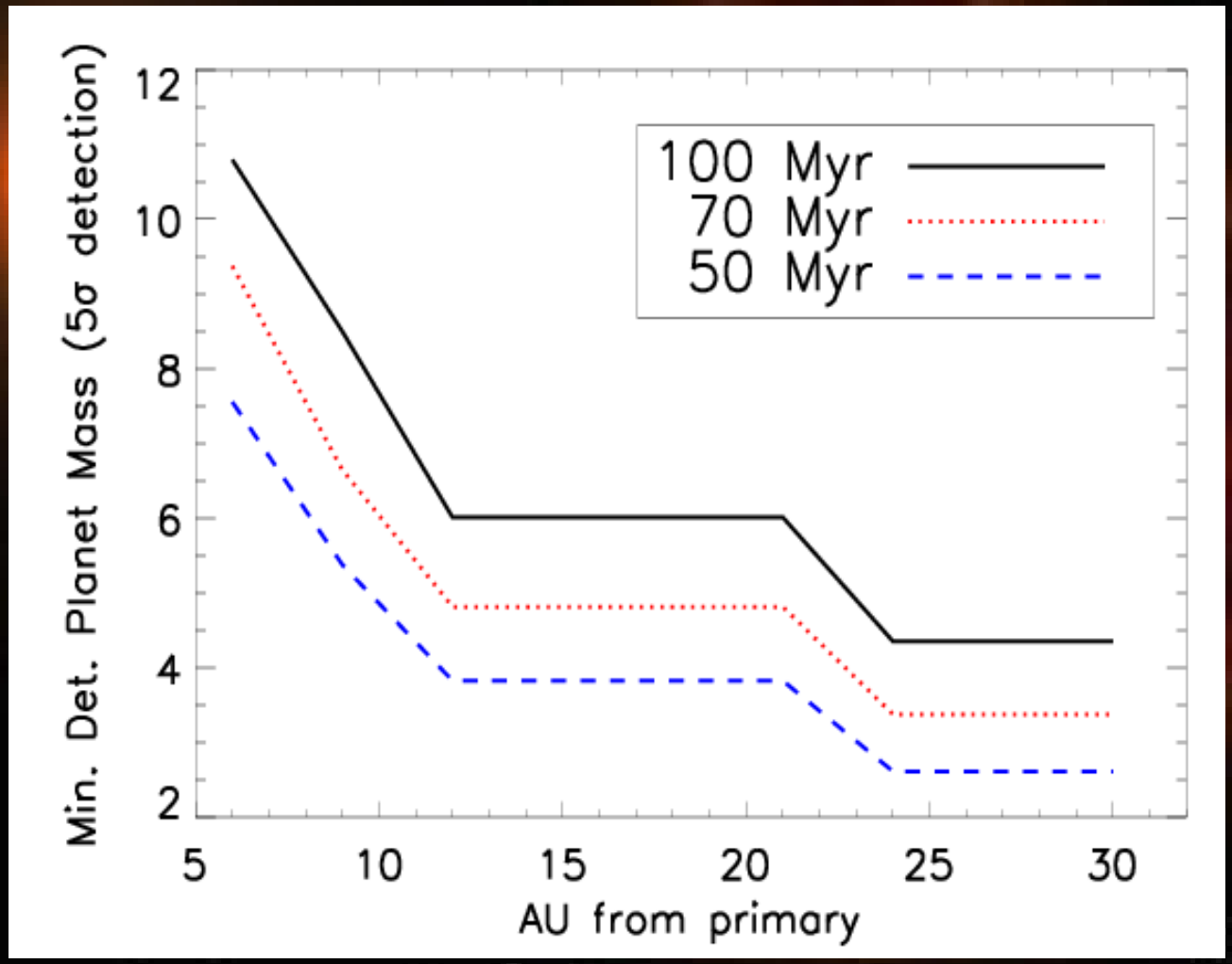
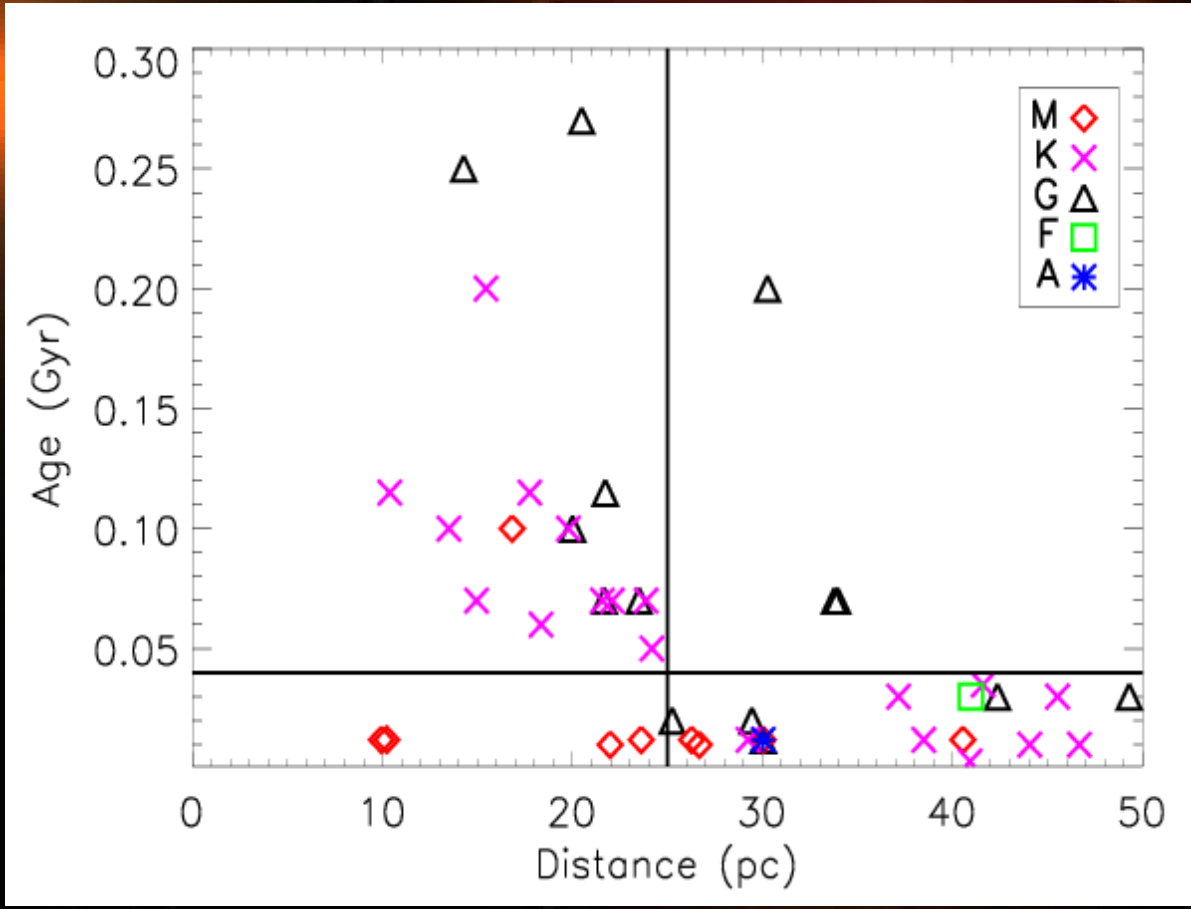


Minimum Detectable Mass for AB Dor



SDI Survey Target Objects

The "median" survey object: K2V star, 30 Myr old, at a distance of 25 pc



Milestones

- We achieve ΔF1(1.575 μm) > 10 mag (5σ) at a separation of 0.5" from the star with both the VLT and MMT SDI devices.
- A number of exciting discoveries from the SDI devices:

  SCR 1845B -- a very nearby (3.85 pc) T5.5 brown dwarf companion to a low mass star (Biller et al. 2006)

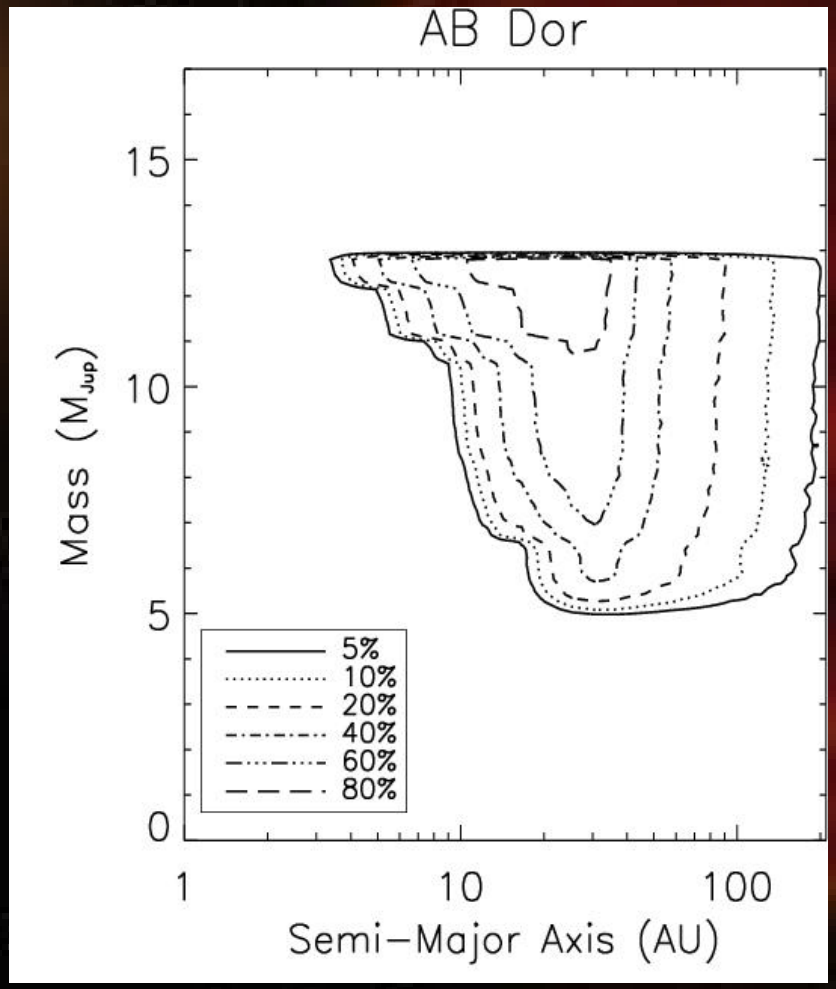
  AB Dor C – the tightest (ΔF1 ~ 7.5 mag, 0.16" separation) low mass companion yet discovered (Close et al. 2005)

  The first surface maps of Titan (Hartung et al. 2004)

  Eps Indi Ba-Bb – the nearest binary brown dwarf (McCaughrean et al. 2005)

  4 new close binaries
- We have observed 54 stars and completed followup observations for 8 tentative candidates (<2 σ, none of these candidates were confirmed.) See Biller et al. 2007.
- Candidates had to appear in 4 independent images – none of 10000 speckles did so at the 5σ level (except for SCR 1845B and Eps Indi Ba-Bb).

Constraining the Distribution of Exoplanets



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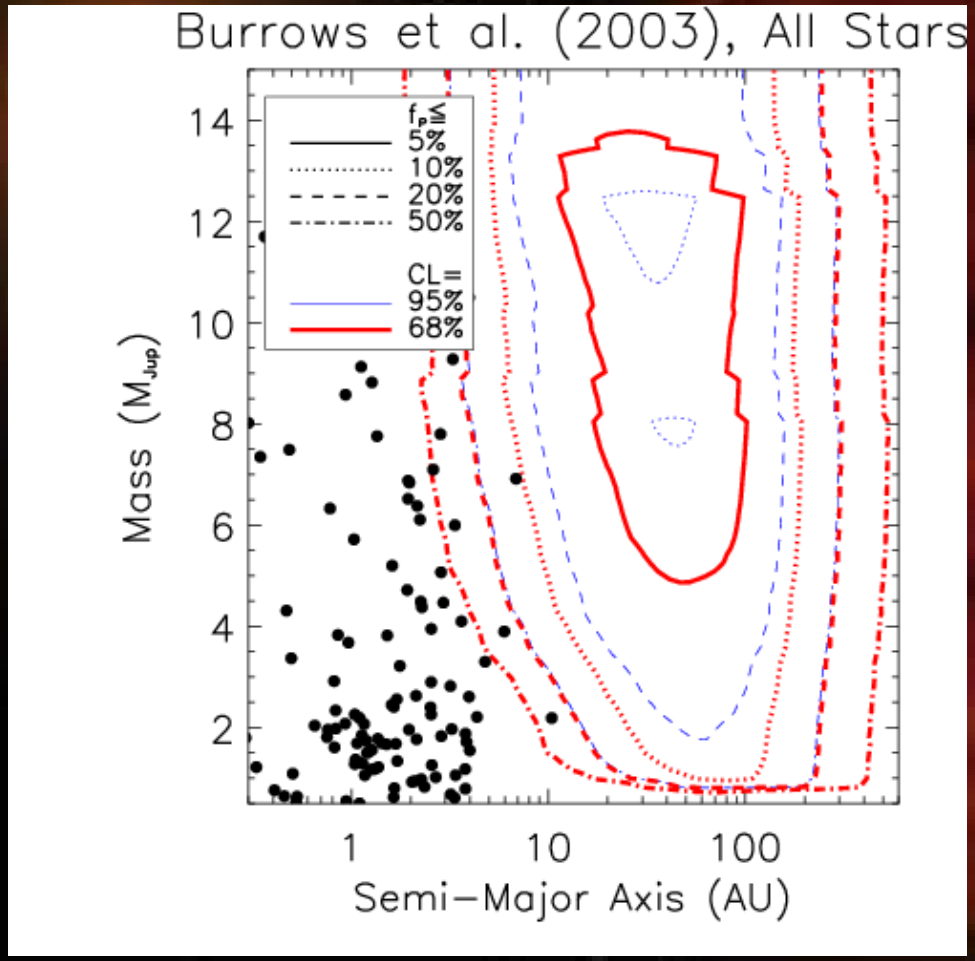
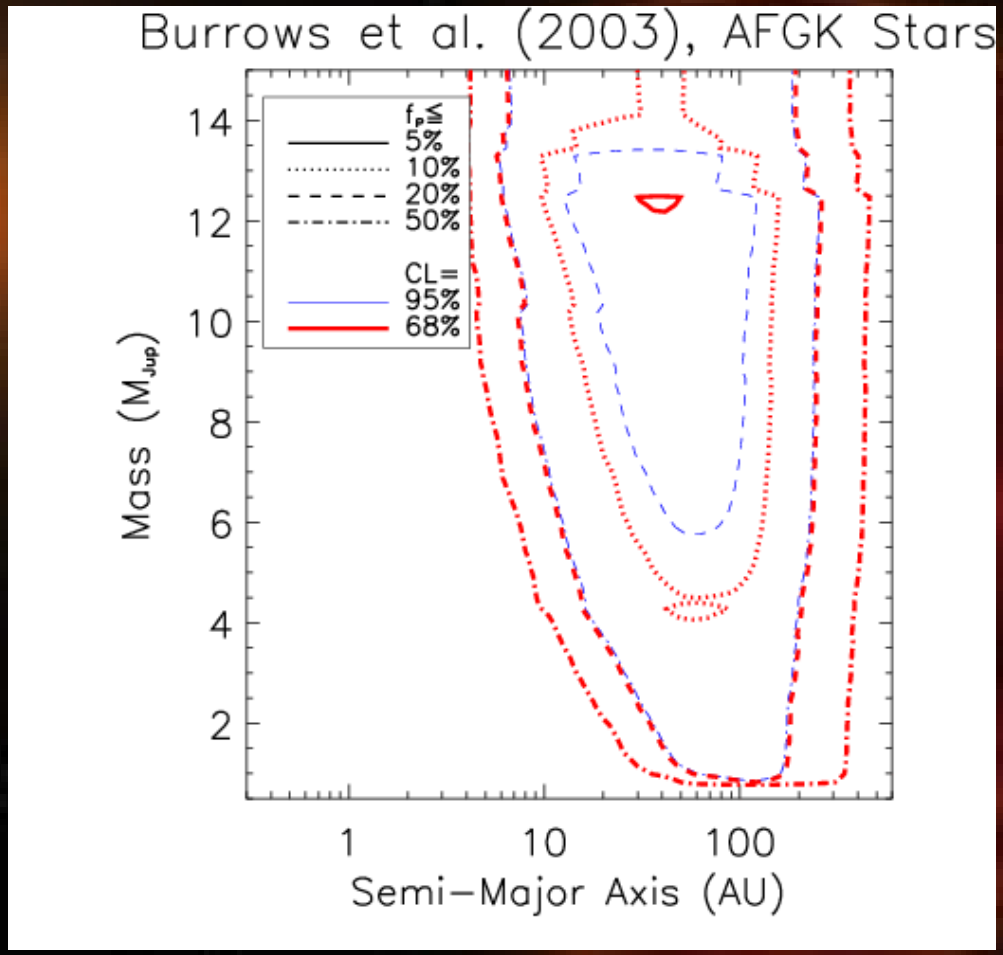
>5 M_{jup} Planets > 20 AU are Uncommon (<20% of Survey Stars)



Nielsen et al. 2008

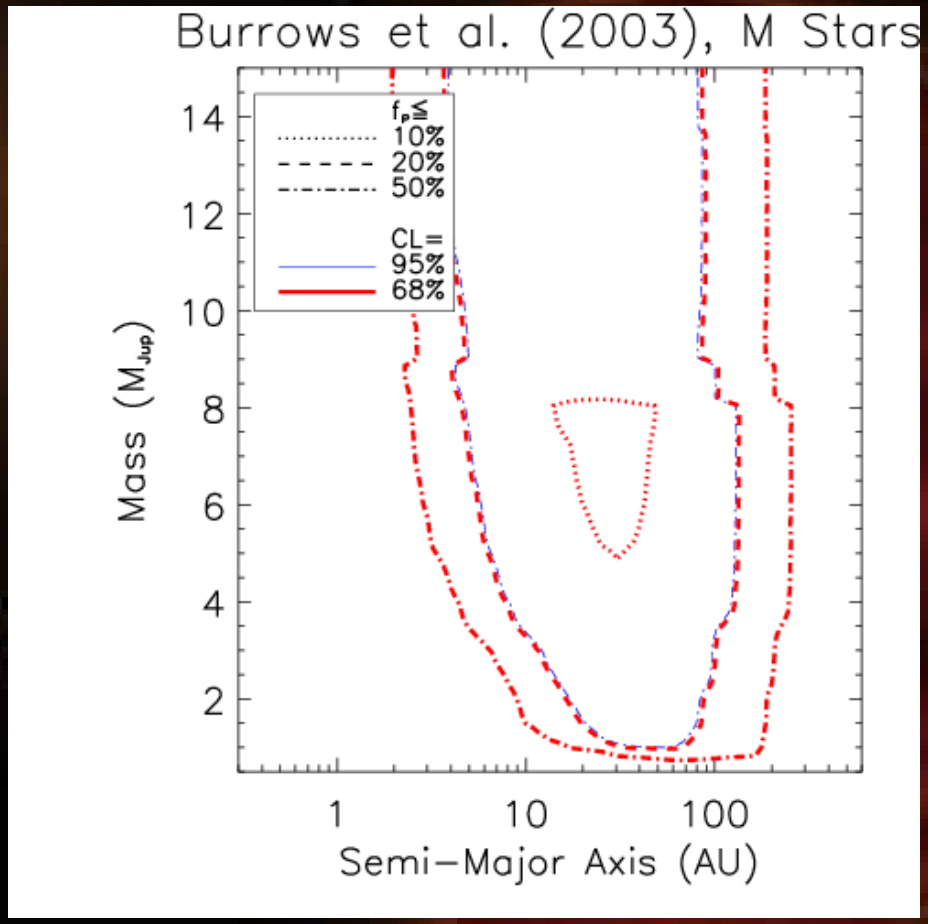
FGK Stars



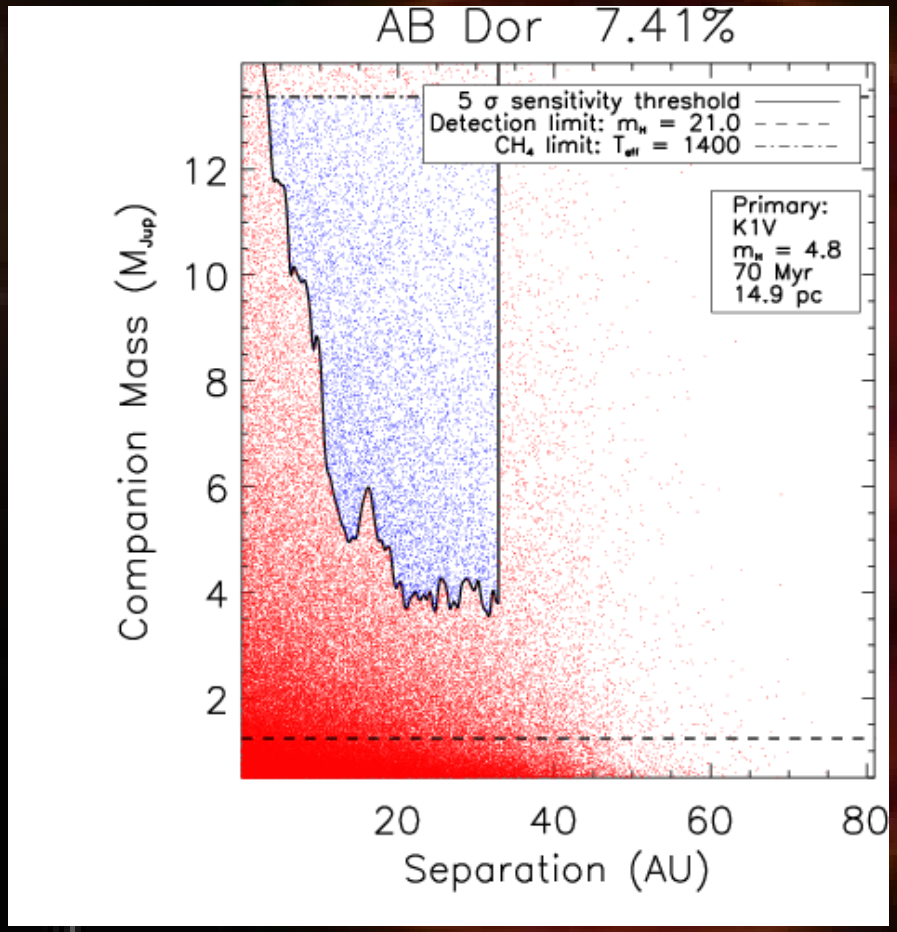
St. Patrick's Day!

Beth Biller, Institute for Astronomy

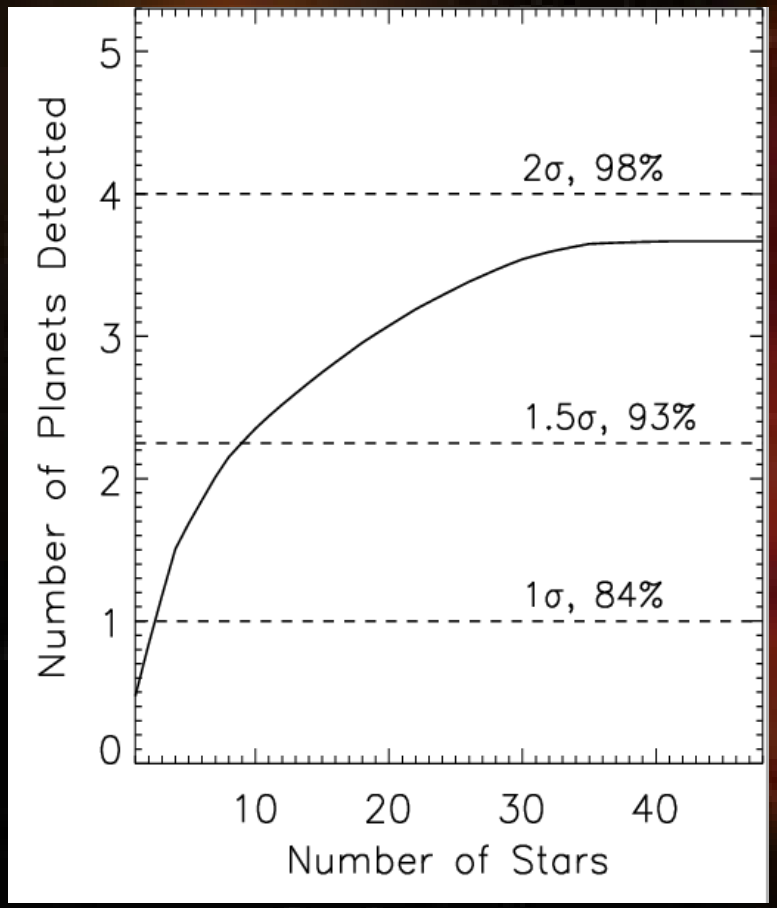
M stars


Burrows et al. (2003), M Stars
$f_p \leq$
10%
20%
50%
CL=
95%
68%
Mass (M_{Jup})
14
12
10
8
6
4
2
1
10
100
Semi−Major Axis (AU)

Testing Models



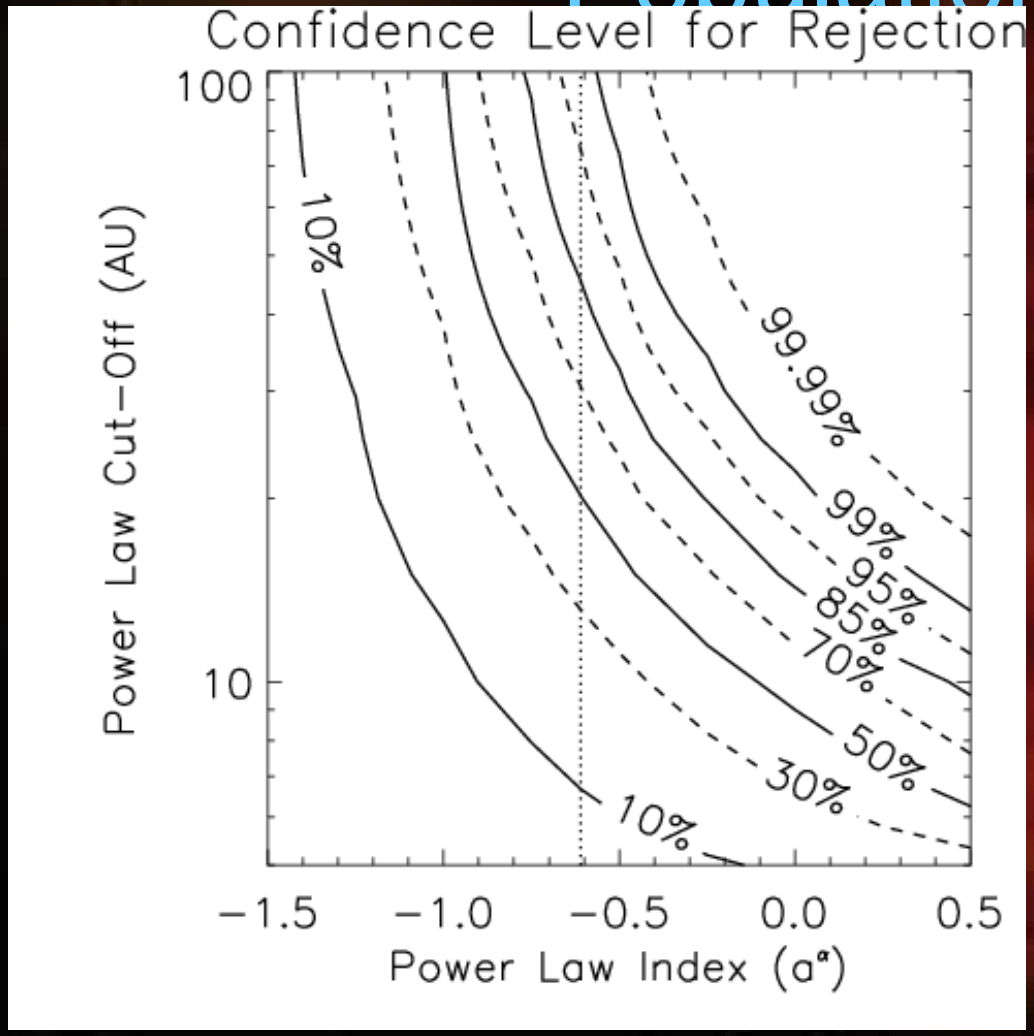
So what does this all mean?



Nielsen et al. 2007

- Determine detection probabilities from Monte Carlo simulations of 10^6 objects per star with N(a) $\propto$ constant (assuming each star has 1 planet)
- For a ~50 object survey, we expect to detect ~3-4 planets (from Monte Carlo simulations using realistic scaling laws (Marcy et al. 2003) and models (Burrows et al. 2003))
- **Even with a null result (no planets), we will be able to place strong constraints ($\geq 2\sigma$) on the frequency and semimajor axis distribution of young massive extrasolar planets >5 AU from their primaries.**

Constraining Exoplanet Populations



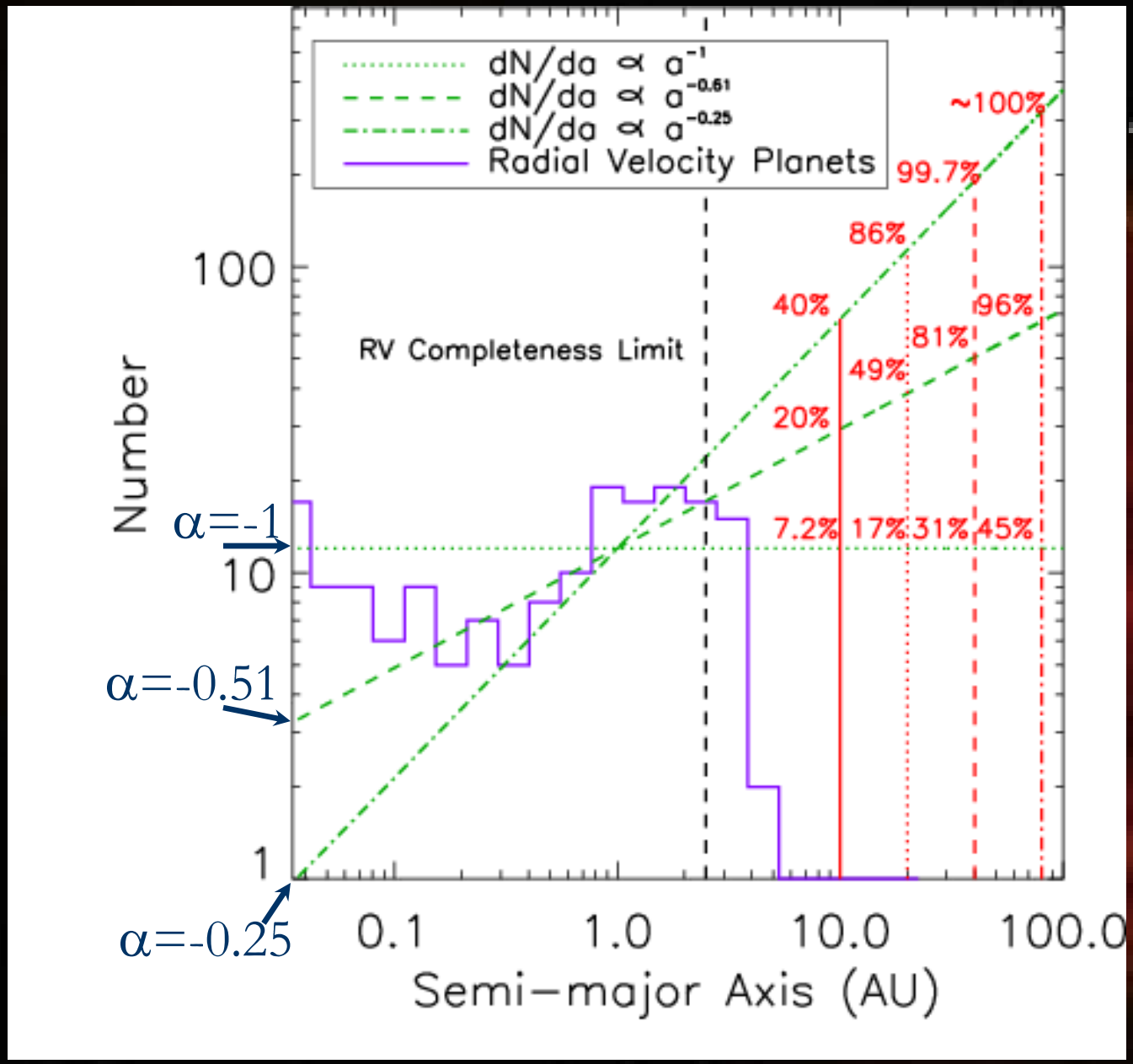
(This survey + 12 stars from Masciadri et al. 2005)

$dN/dM \propto M^{-1.16}$

$dN/da \propto a^{\alpha}$ until cutoff radius where $0>\alpha>-0.75$

Cumming et al. in prep found $\alpha \sim -0.63$ for RV planets out to ~8 AU

Nielsen et al., 2008



For a model with α= 0, we can rule out a power law cutoff past 17 AU with >95% confidence.

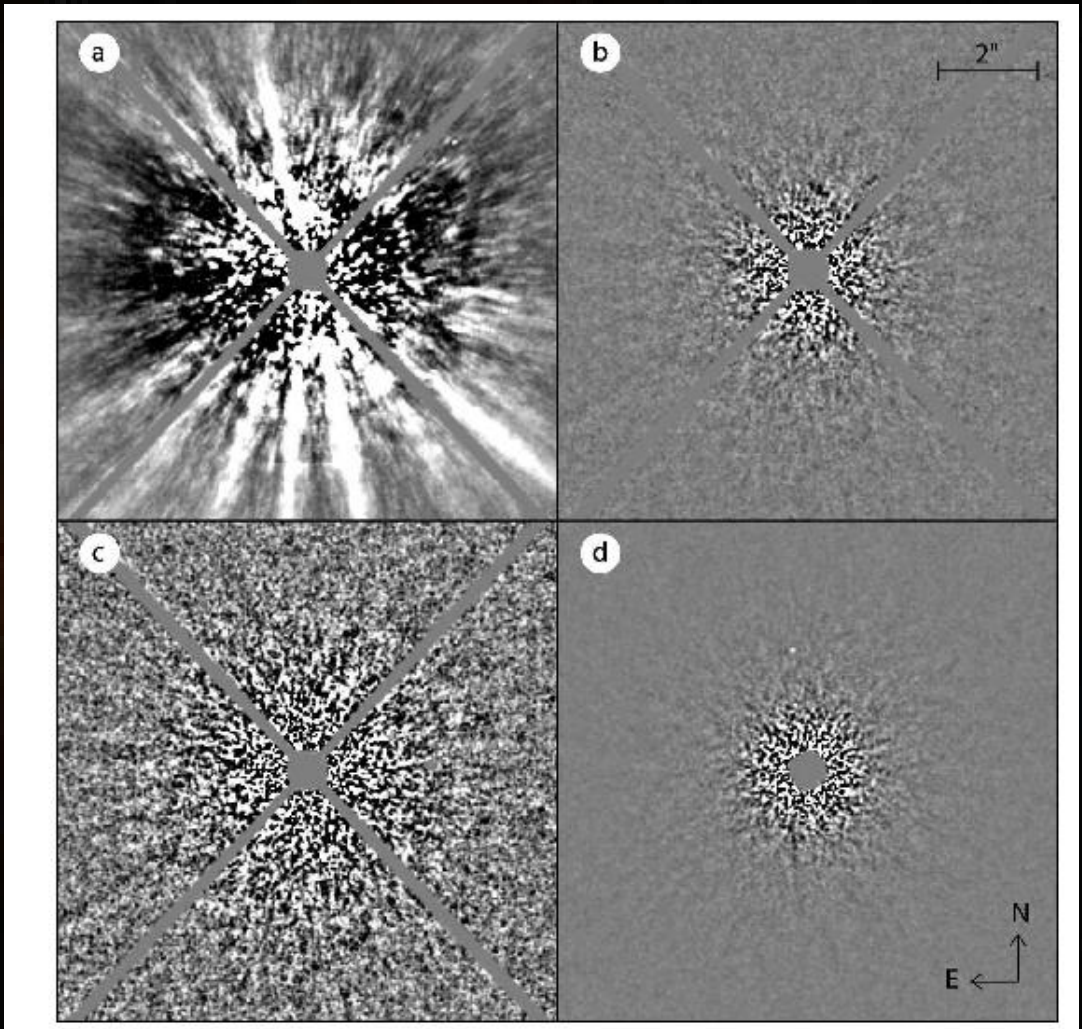
Nielsen et al. 2008

Summary and Conclusions

- First major differential imaging survey for exoplanets complete and published (Biller et al. 2007, ApJ Supp. In press, astro-ph:0705.0066).
- >5 M_{jup} Planets > 20 AU are Rare (<15% of Survey Stars, 95% confidence, Burrows models), Nielsen et al. 2007
- Can constrain outer population of extrasolar planets: for example rule out $\alpha = 0$, cutoff > 20 AU models at >95% confidence (Biller et al. 2007)

ADI and GDPS

- 85 star survey with Gemini Altair AO system, using the Angular Differential Imaging Technique
- Followed up ~50 candidate objects, no planets detected.



Lafreniere et al. 2007

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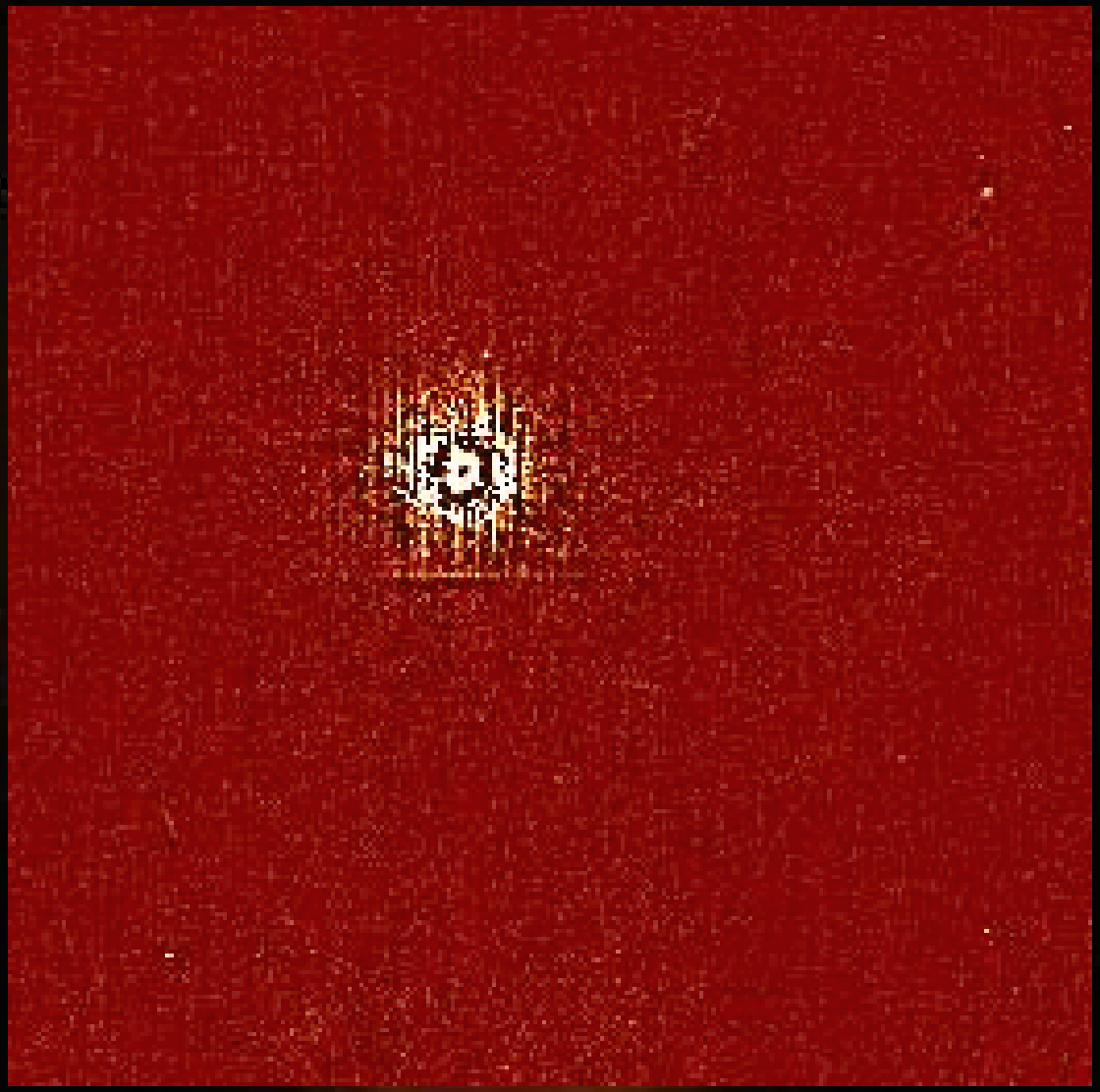
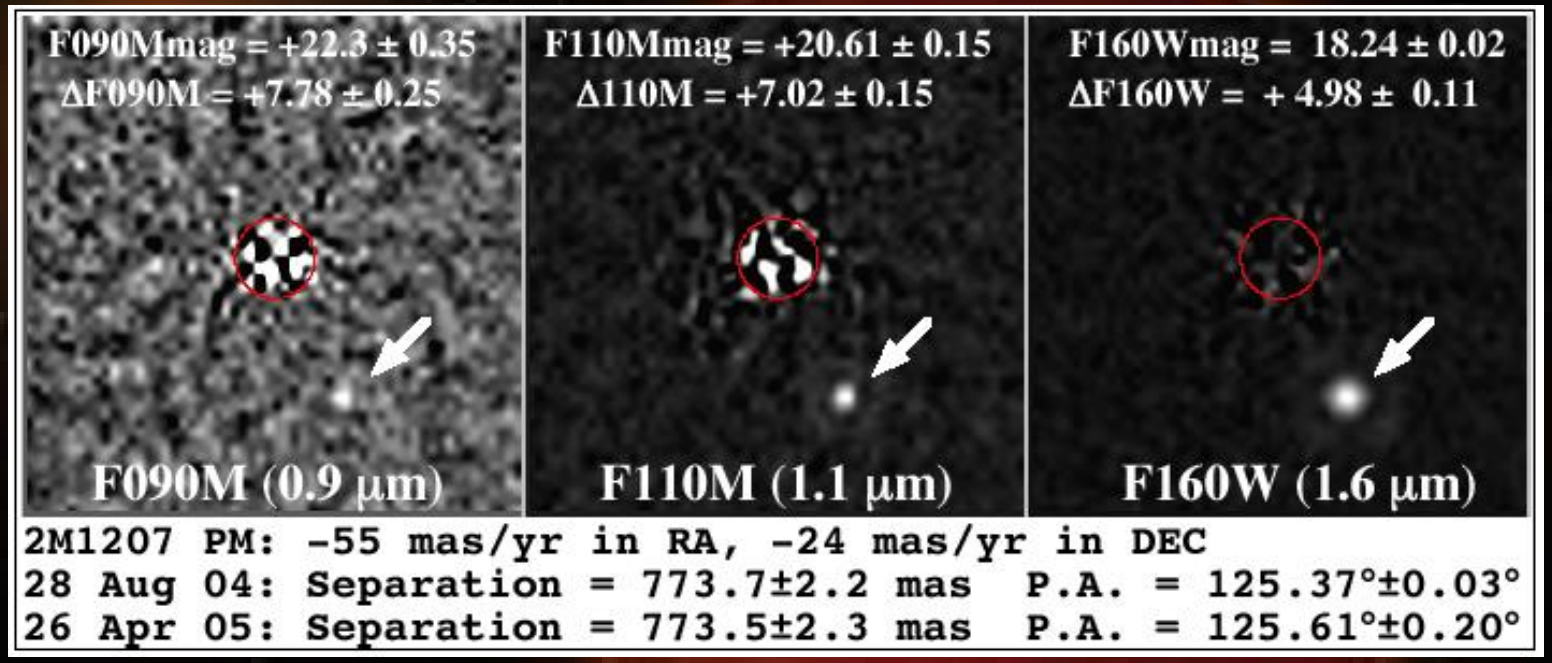
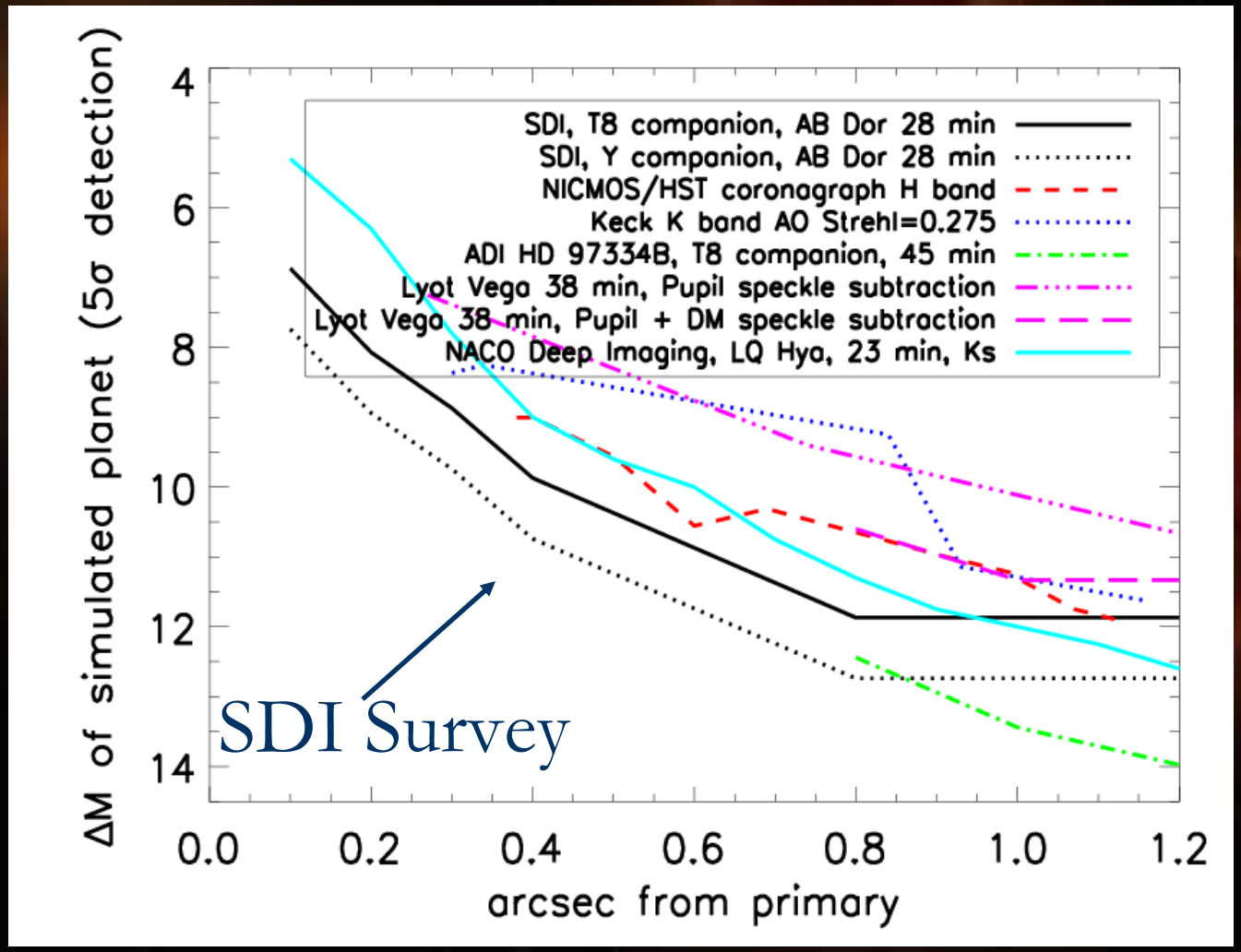


HST NICMOS survey



- ~100 star survey using HST NICMOS.
- Also a null result (Farihi et al., in prep)

Comparison to Other Surveys



Conclusions

SDI Survey: First major differential imaging survey for exoplanets complete and published (Biller et al. 2007). >5 M_{jup} Planets > 20 AU are Rare (<15% of Survey Stars), Nielsen et al. 2008

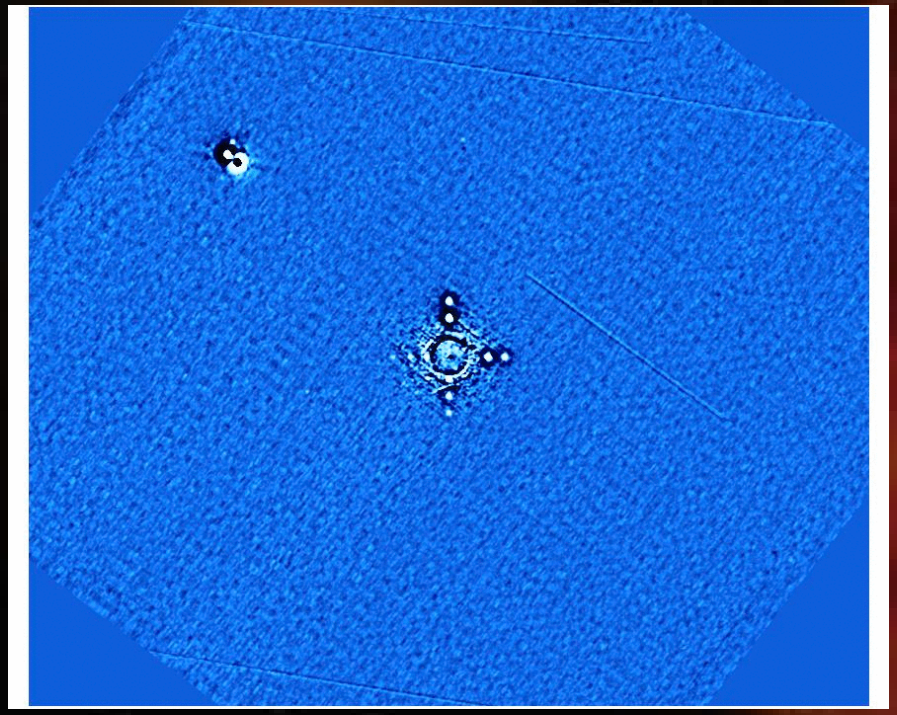
Can constrain outer population of extrasolar planets: for example rule out α = 0, cutoff > 20 AU models at >95% confidence (Biller et al. 2007)

Both GDPS (Lafreniere et al. 2007) and the NICMOS Survey (Farihi et al. in prep) also produced null results (but useful constraints on planet distributions.)

The Need for Dedicated Planet Finding Instruments

- All three of the current generation of direct detection surveys for self-luminous giant extrasolar planets have yielded useful limits but no confirmed giant planet candidates (Biller et al. 2007, Nielsen et al. 2008, Lafreniere et al. 2007, Farihi et al. in prep)
- To go deeper, VLT and Gemini are developing dedicated planet-finding cameras ($30M)
- NICI (Near Infrared Coronagraphic Imager) is the first of the new generation of planet finding cameras to come online.

NICI: Current Status

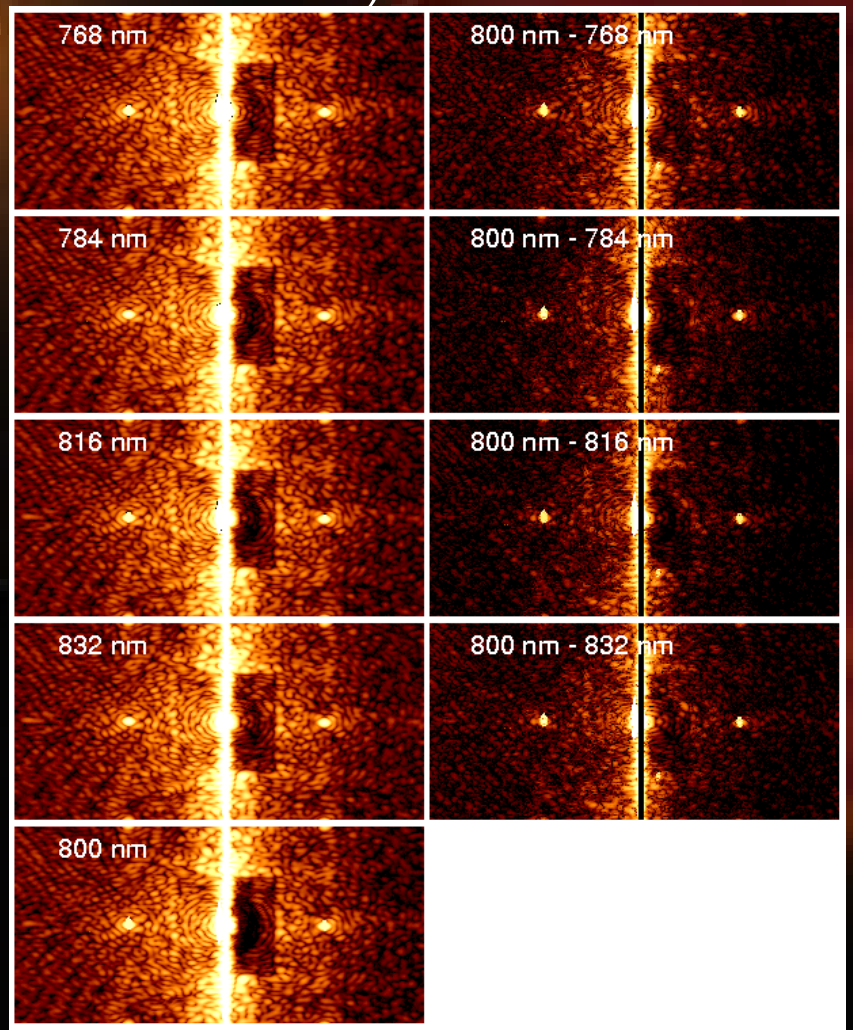


- Commissioning run this week
- First campaign run this summer

“SDI” Experiment for the HCIT

Goal: Develop a 2nd Generation Differential Imaging technique for extremely high Strehls and contrasts (10^{-6} – 10^{-9} – the contrasts necessary to detect exo-Earths.)

Original



Differential

St. Patrick's Day!

Conclusions

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(Biller et al. 2007, ApJ Supp. In press, astro-ph:0705.0066).

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Can constrain outer population of extrasolar planets: for example rule out α = 0, cutoff > 20 AU models at >95% confidence (Biller et al. 2007)

Discovered 0.16" disk (60 AU at 390 pc) with PA of 120° and inclined 30-45° from edge on around RV Boo (Biller et al. 2005) – first possibly Keplerian disk imaged around an AGB star.

SDI technique can be generalized at HCIT to develop a 2nd Generation Differential Imaging technique for extremely high Strehls and contrasts up to 10^{-8}.

Summary and Conclusions

- First major differential imaging survey for exoplanets complete and published (Biller et al. 2007, ApJ Supp. In press, astro-ph/xxxxxx,).
- >5 M_{jup} Planets > 20 AU are Rare (<5% of Survey Stars), Nielsen et al. 2007
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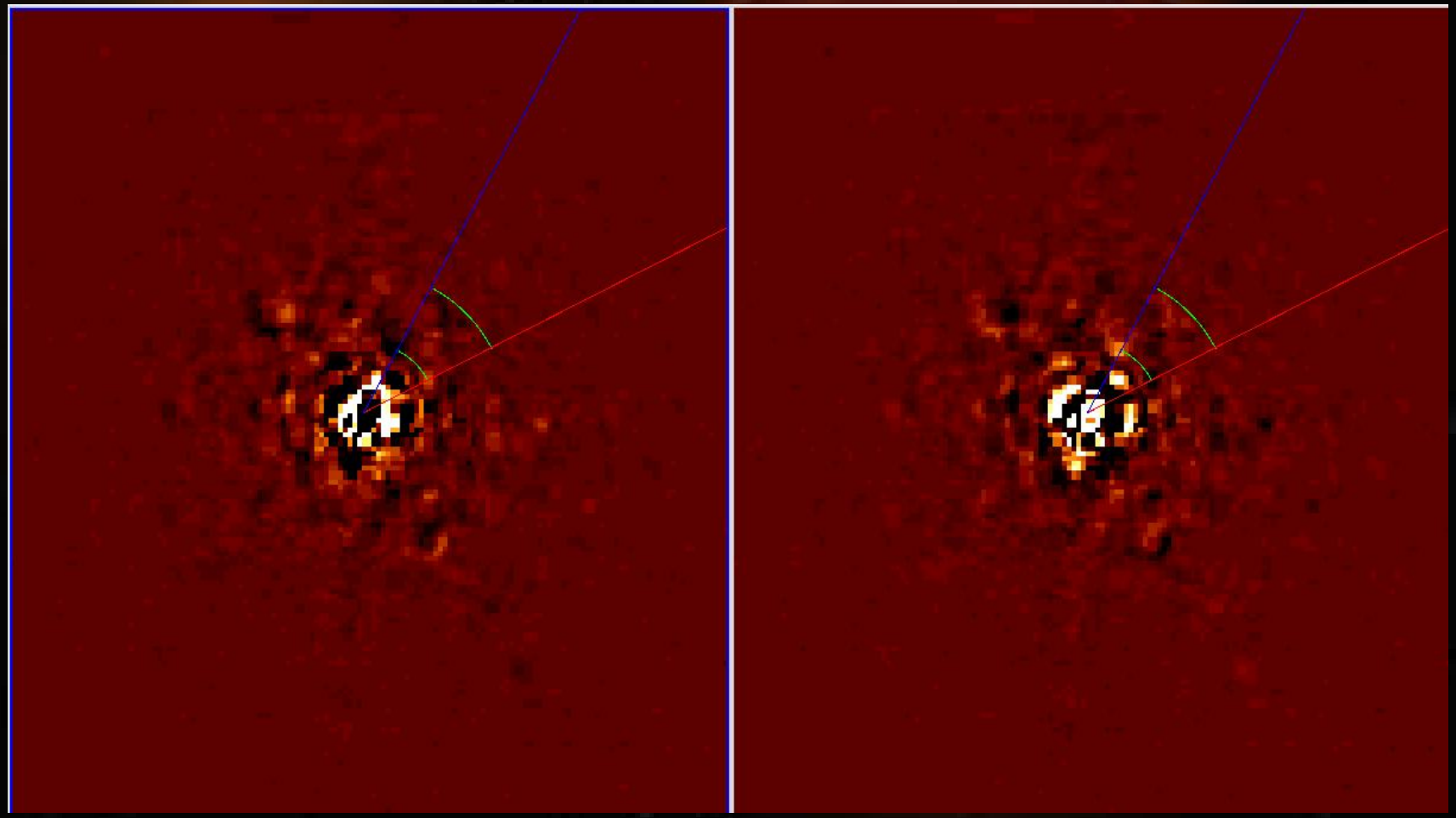
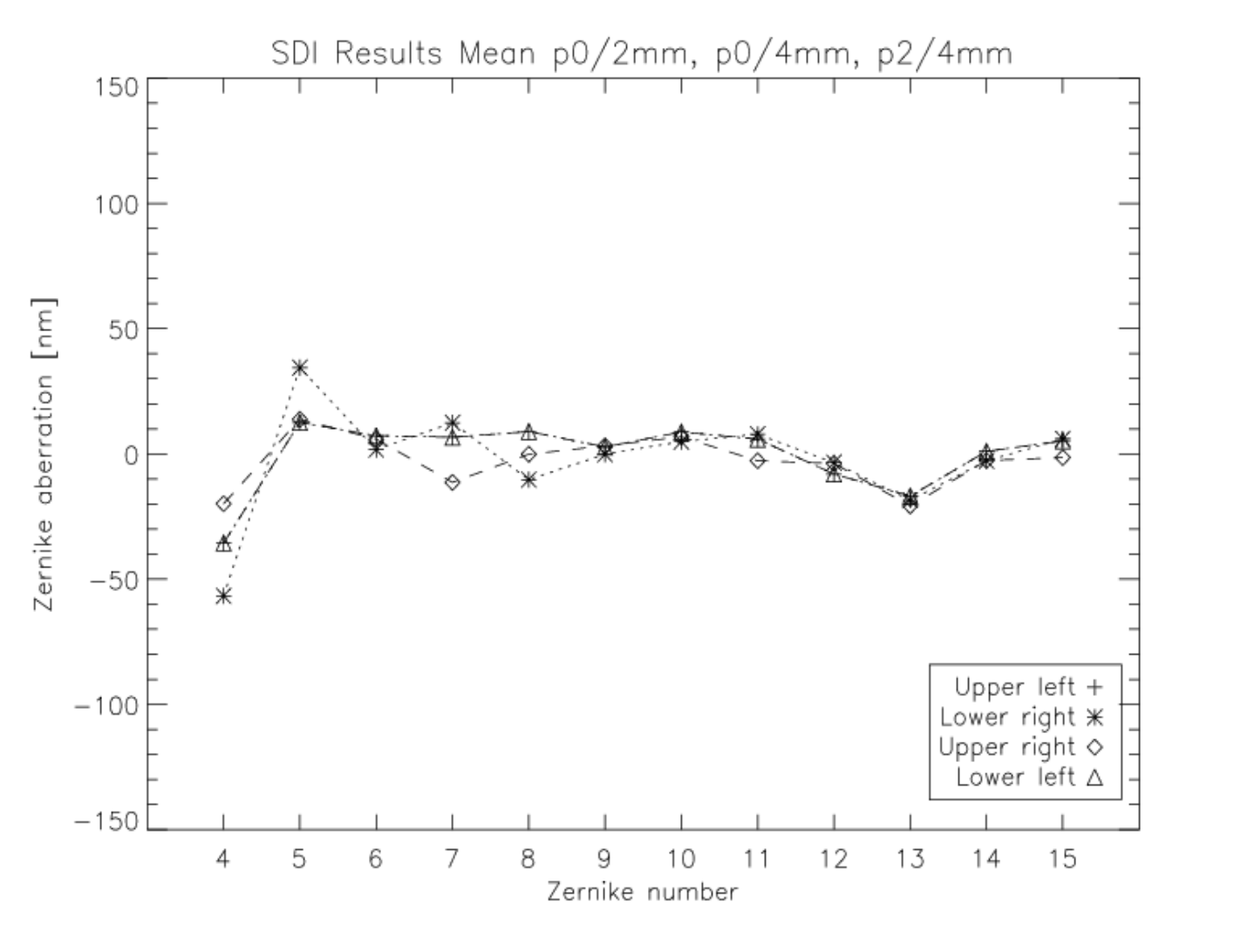
A Tentative Candidate Faint Companion



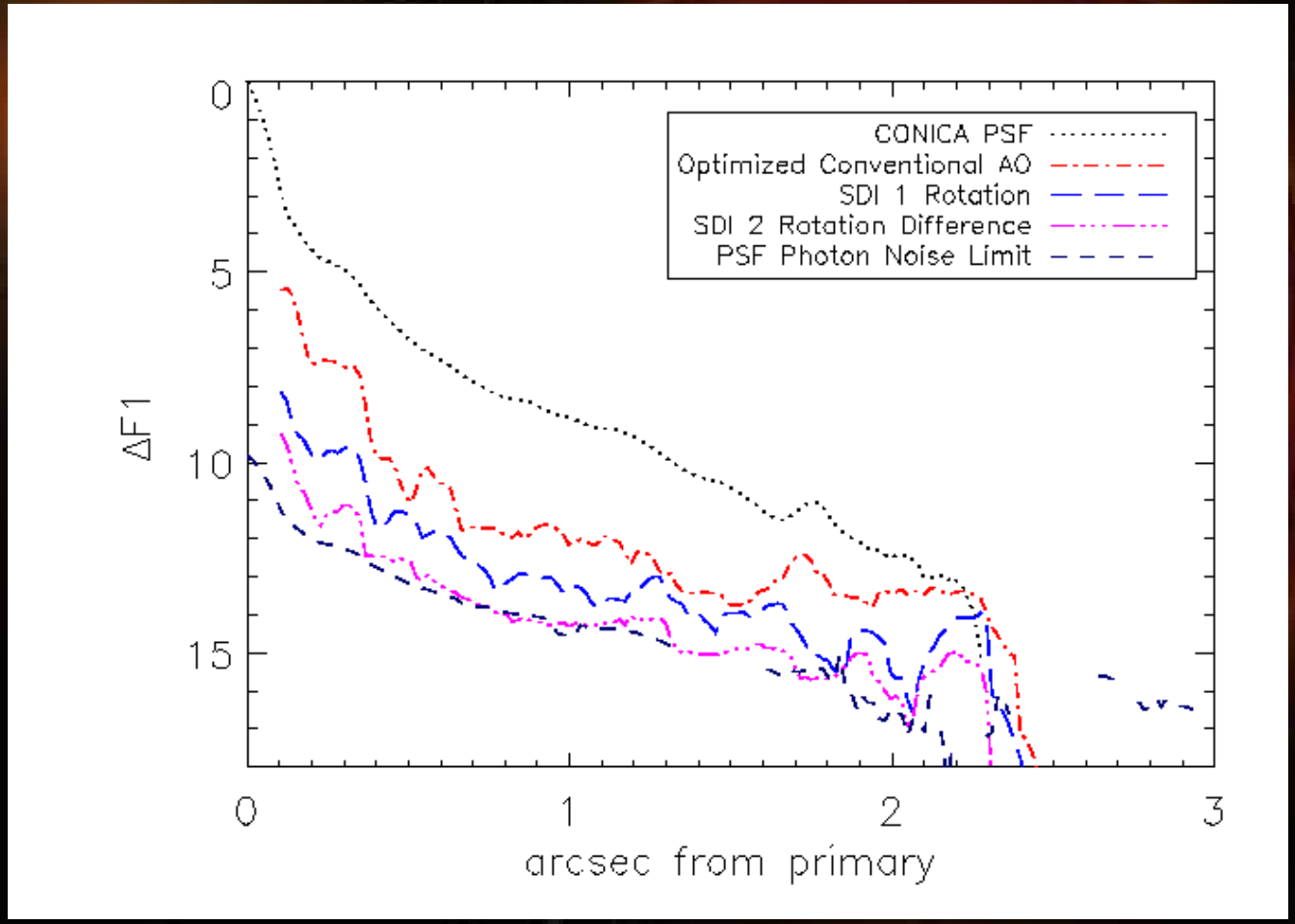
Non-common Path Errors



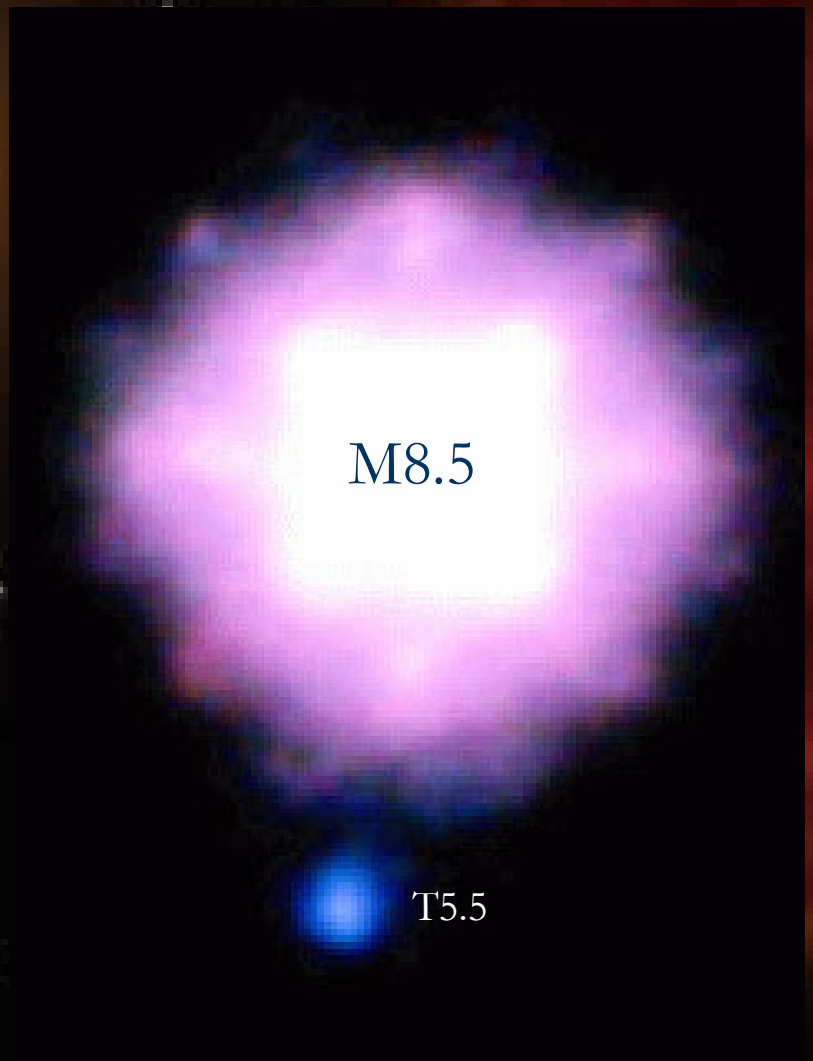
St. Patr

Lenzen et al. 2004

1 vs. 2 Roll Angles



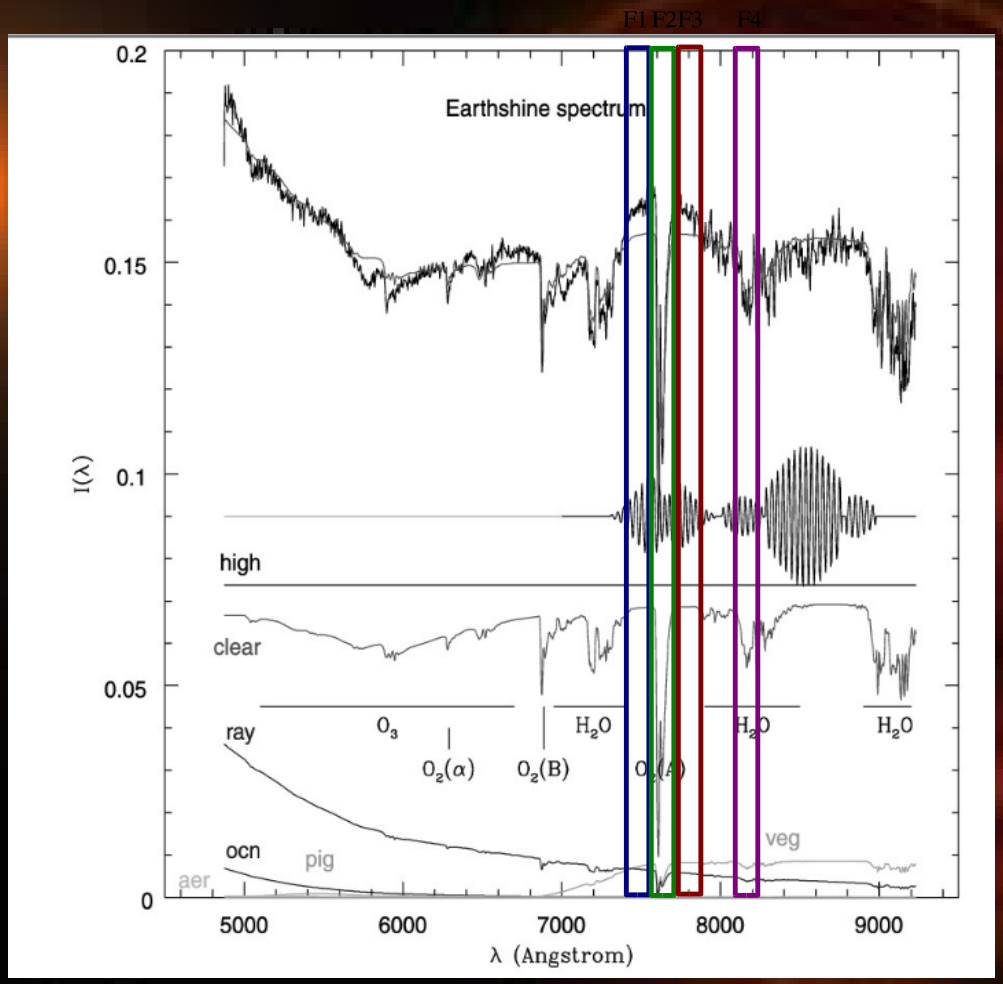
Proof of Concept – The Methane Rich Brown Dwarf SCR 1845B



Biller et al. 2006

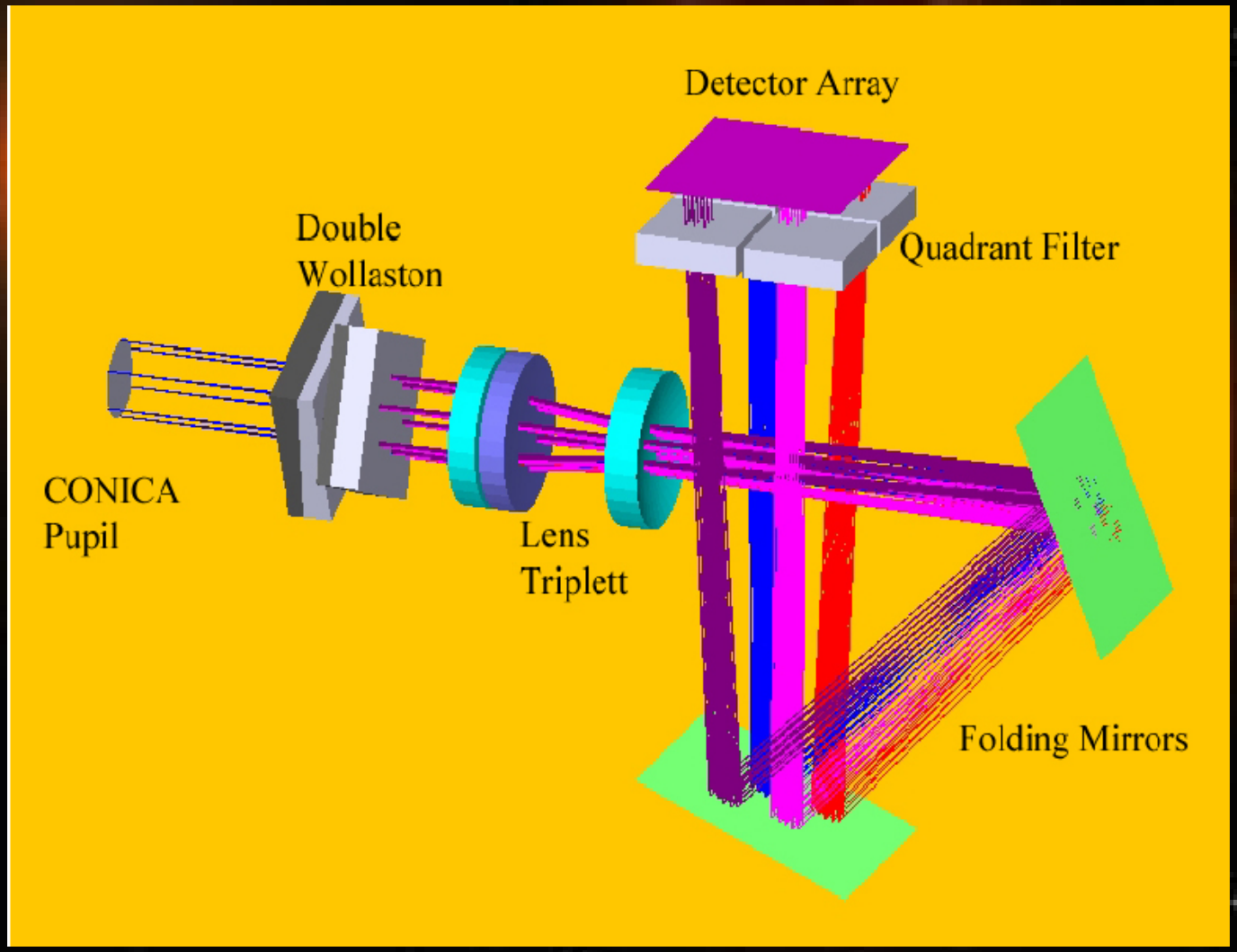
St. Patrick's Day!

“SDI” Experiment for the HCIT



Earthshine Spectrum from Woolf et al. 2002

Optical Design for NACO SDI



Lenzen et al. 2004

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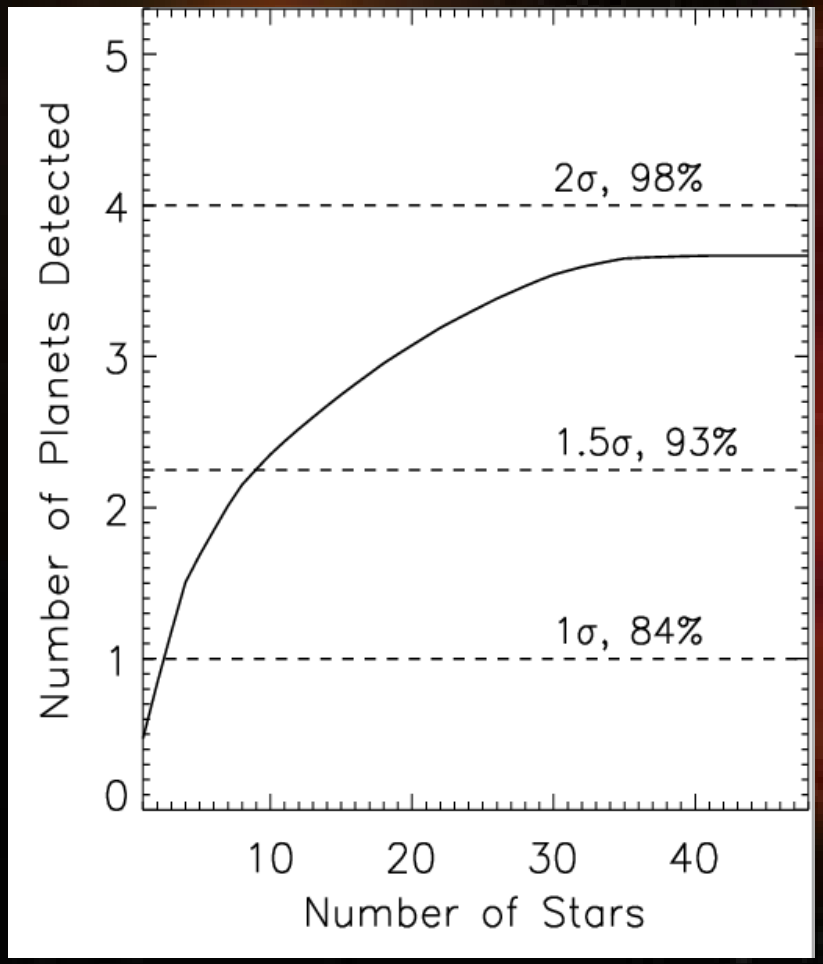

Nielsen et al. 2007

- Determine detection probabilities from Monte Carlo simulations of 10^6 objects per star with N(a) $\propto$ constant (assuming each star has 1 planet)
- For a ~50 object survey, we expect to detect ~3-4 planets (from Monte Carlo simulations using realistic scaling laws (Marcy et al. 2003) and models (Burrows et al. 2003))
- **Even with a null result (no planets), we will be able to place strong constraints ($\geq 2\sigma$) on the frequency and semimajor axis distribution of young massive extrasolar planets >5 AU from their primaries.**