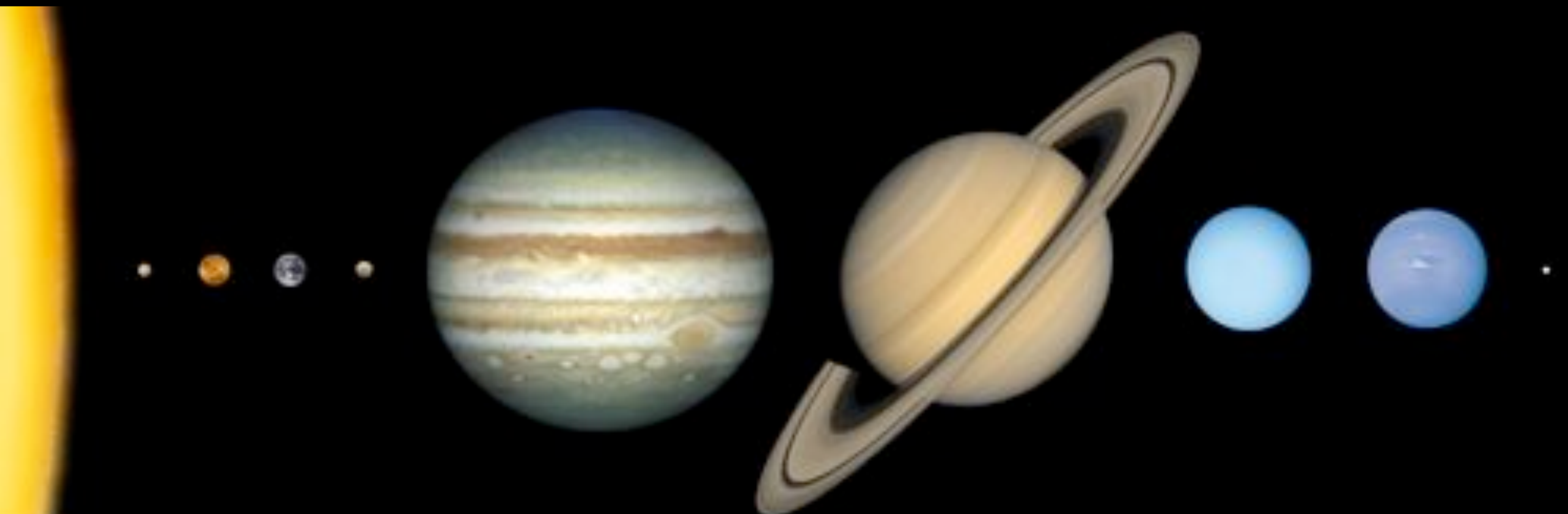
Finding Exoplanets

Ray Jayawardhana
University of Toronto



Commotion over Pluto's demotion…

HOUSE JOINT MEMORIAL 54

48TH LEGISLATURE - STATE OF NEW MEXICO - FIRST SESSION, 2007

INTRODUCED BY

Joni Marie Gutierrez

A JOINT MEMORIAL

DECLARING PLUTO A PLANET AND DECLARING MARCH 13, 2007, "PLUTO PLANET DAY" AT THE LEGISLATURE.

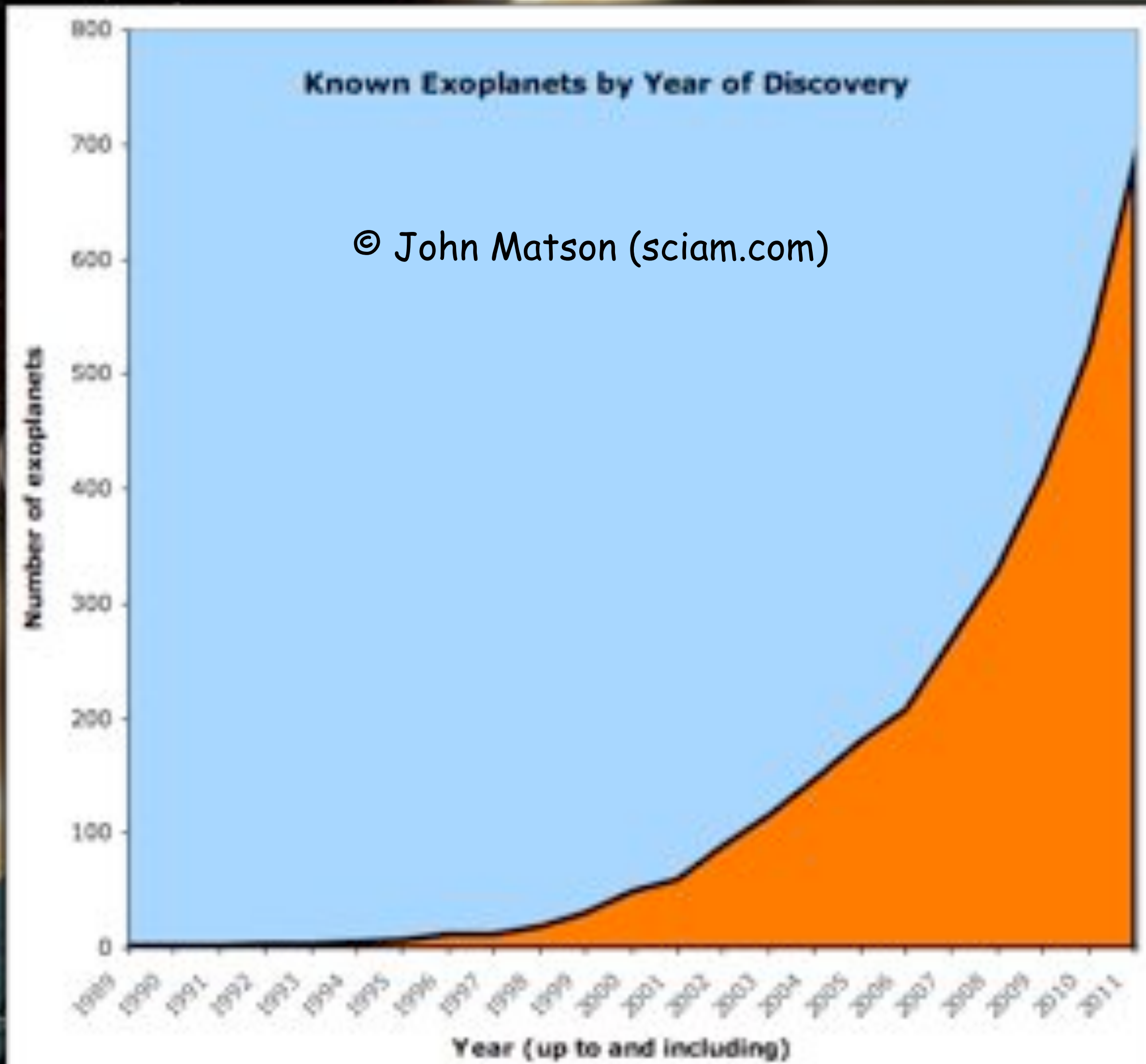
WHEREAS, the state of New Mexico is a global center for astronomy, astrophysics and planetary science; and

WHEREAS, New Mexico is home to world class astronomical observing facilities, such as the Apache Point observatory, the very large array, the Magdalena Ridge observatory and the national solar observatory; and

WHEREAS, Apache Point observatory, operated by New Mexico state university, houses the astrophysical research consortium's three-and-one-half meter telescope, as well as the unique two-and-one-half meter diameter Sloan digital sky survey telescope; and

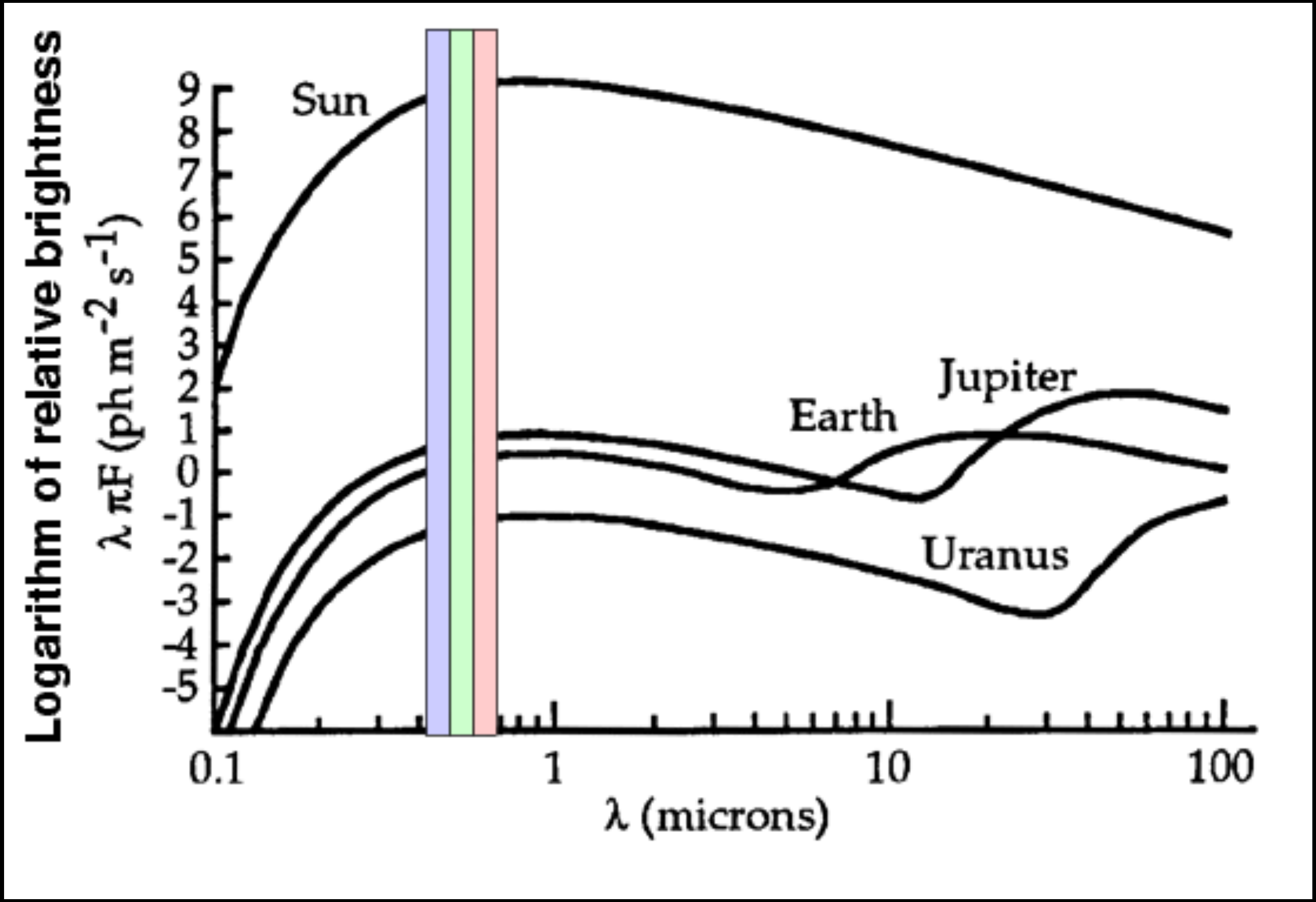
WHEREAS, New Mexico state university has the state's on

1995-2011: 700+ Confirmed Planets Around Others Stars



Art Credit: David A. Hardy, astroart.org
(c) Particle Physics and Astronomy Research Council

A Question of Contrast (and Angular Resolution)



Courtesy Robert Brown

Exoplanet Detection Techniques

Measure star's motion:

1. Astrometry
2. Pulsar timing
3. Doppler Radial Velocity

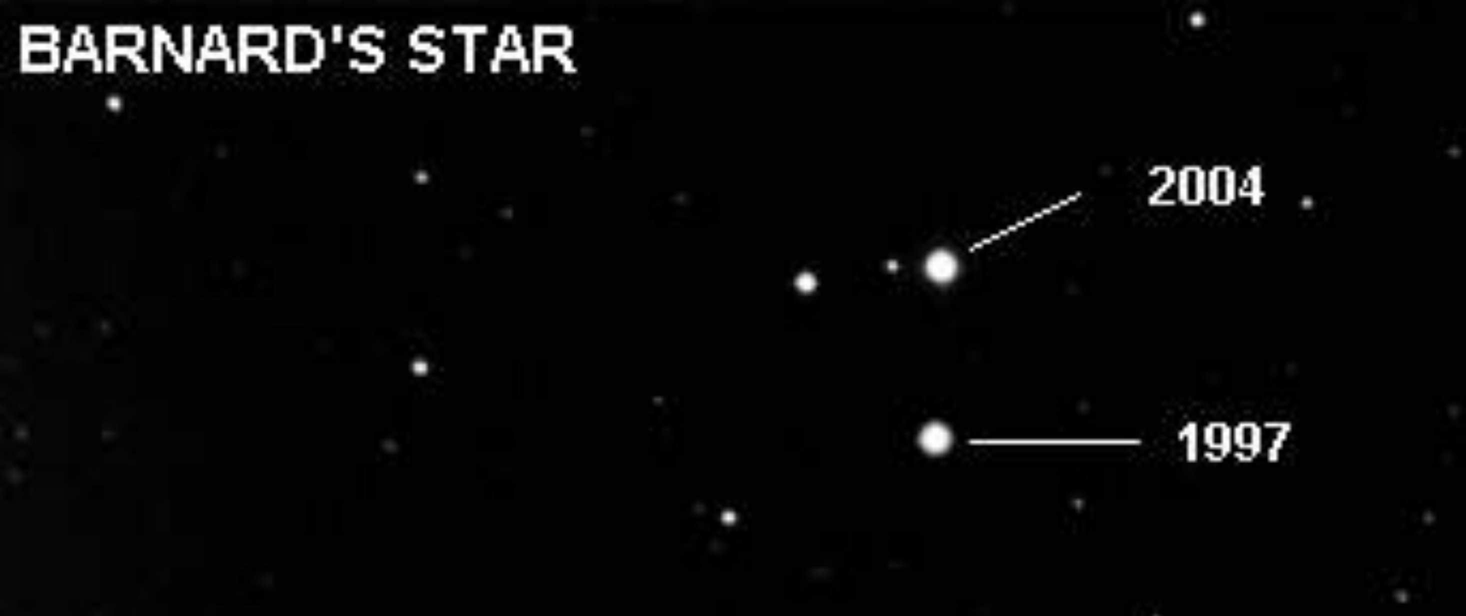
Measure star's brightness variations:

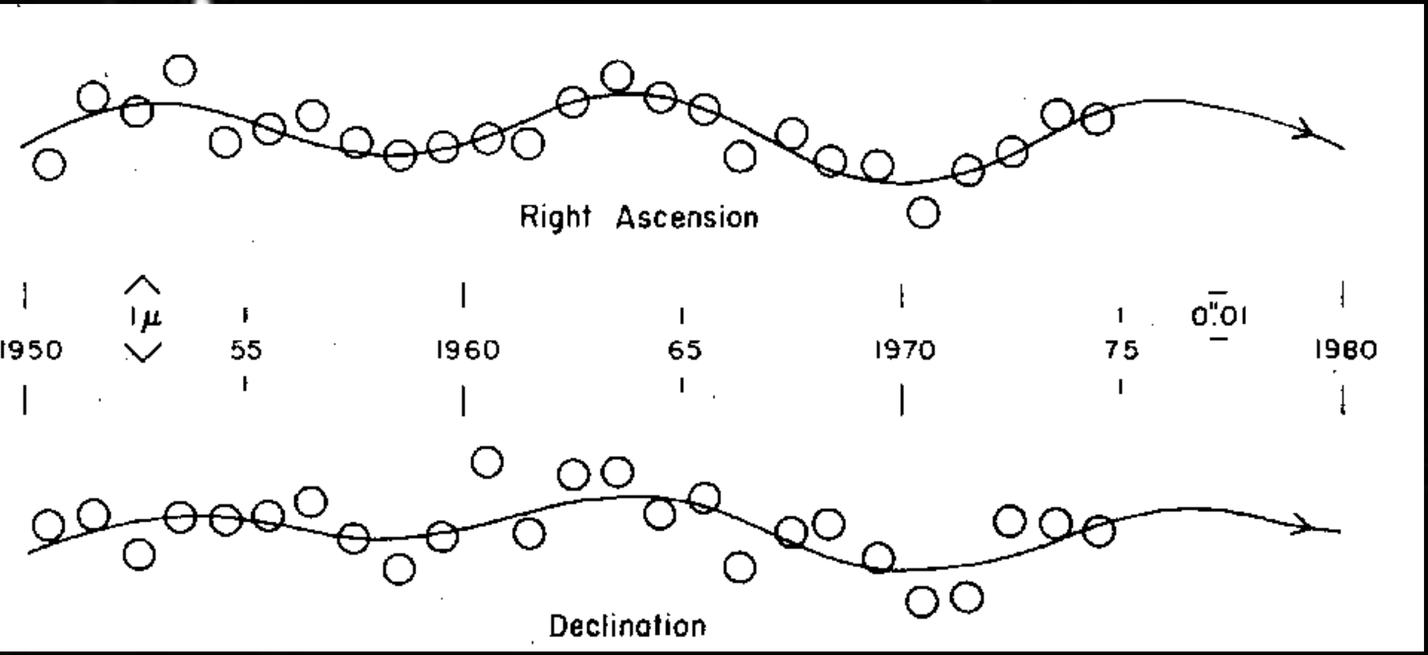
4. Transits
5. Gravitational microlensing (light of background star)

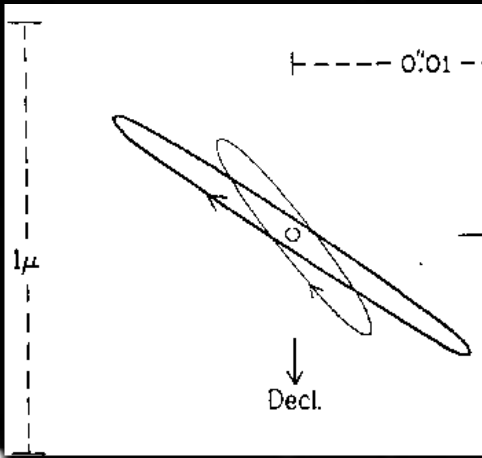
Direct detection:

6. High-contrast imaging

Half a century of false starts...

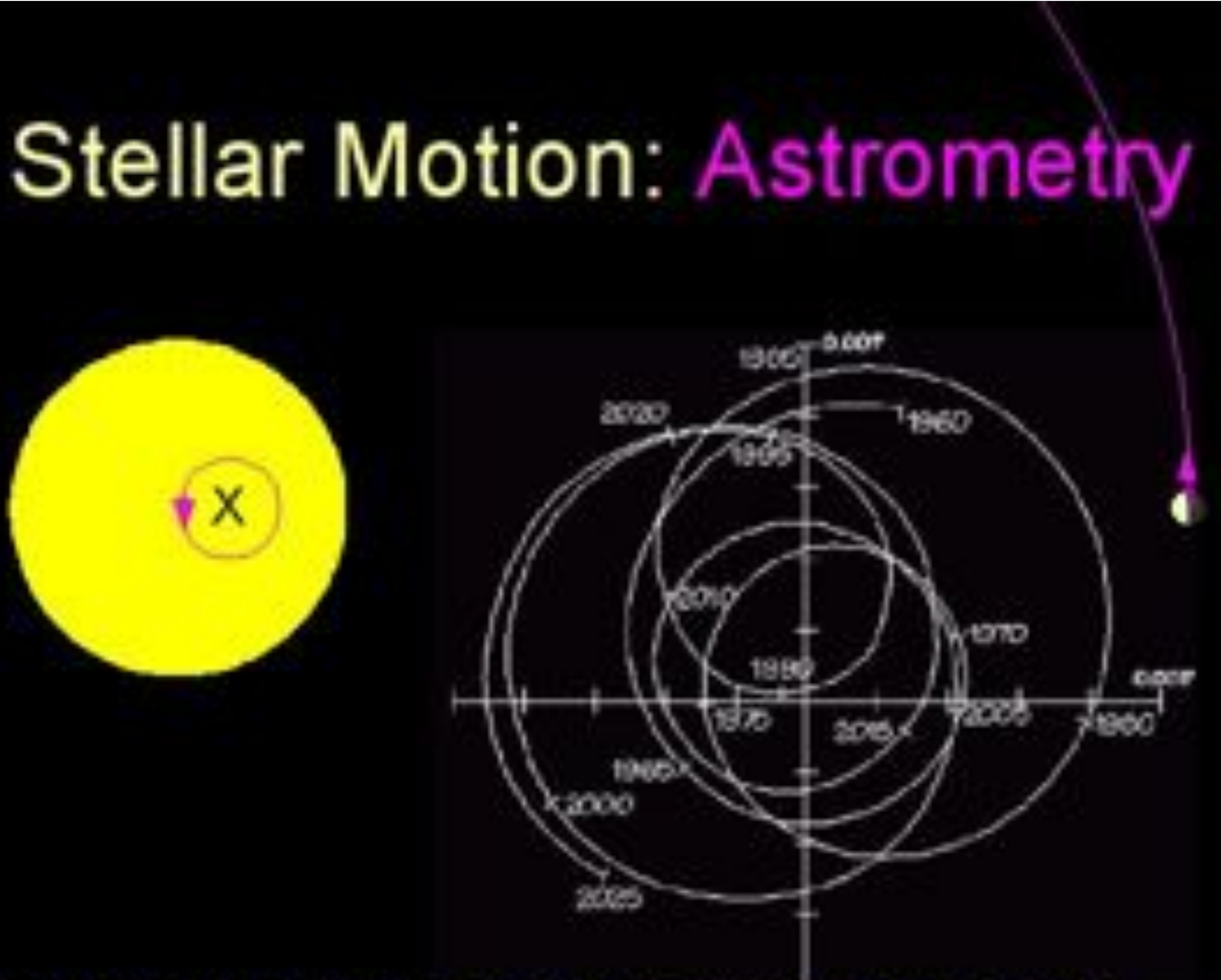


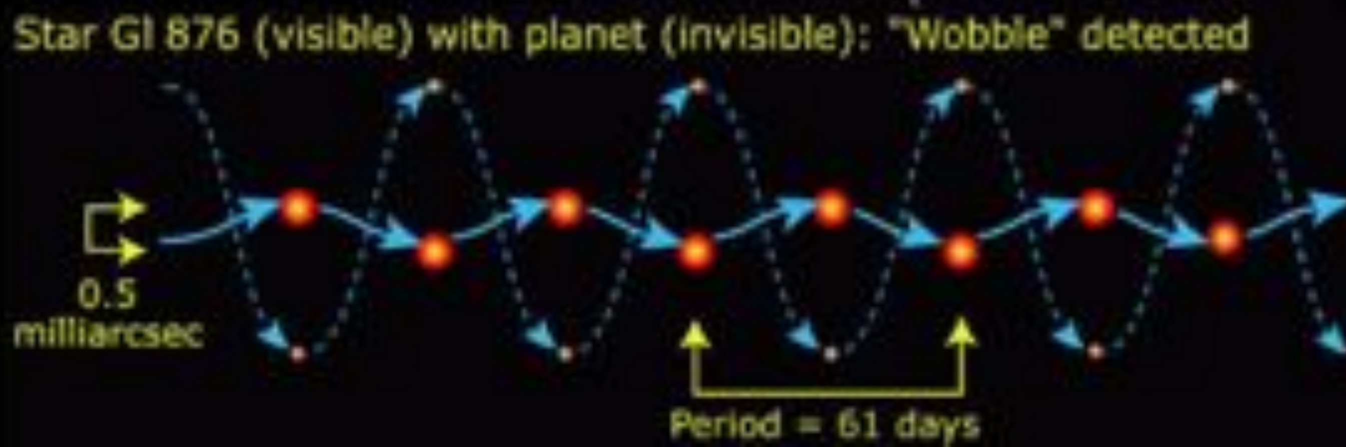




Extrasolar Planets

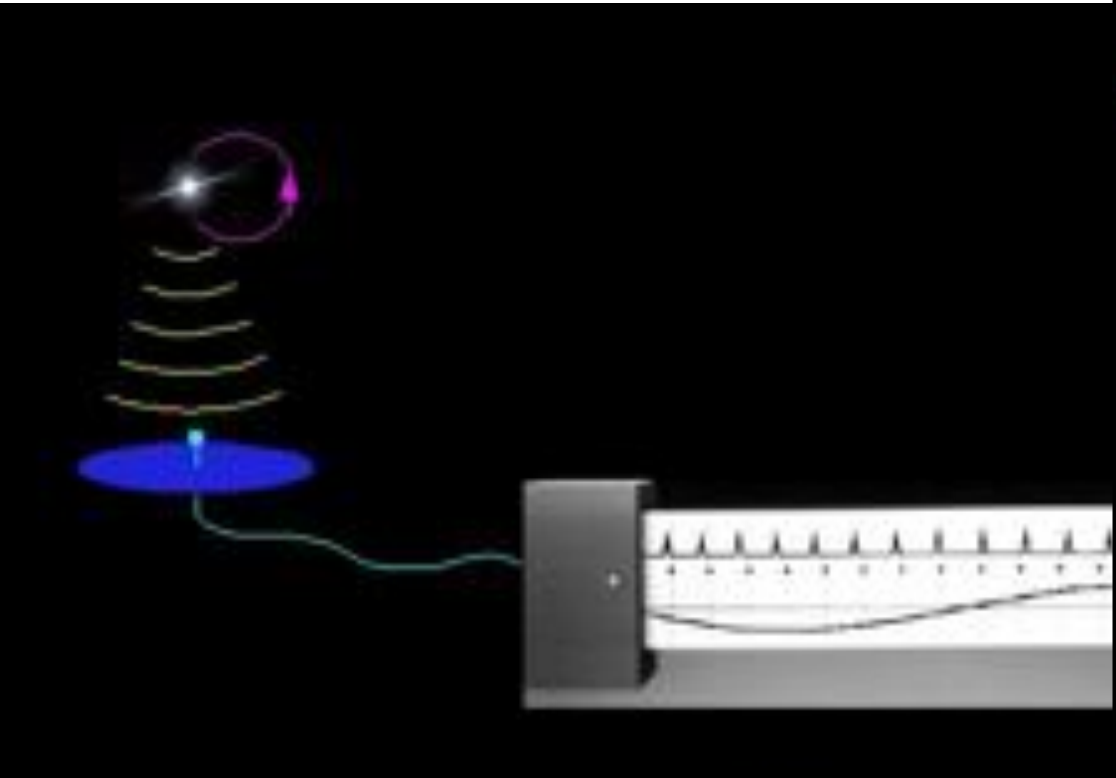
Stellar Motion: Astrometry

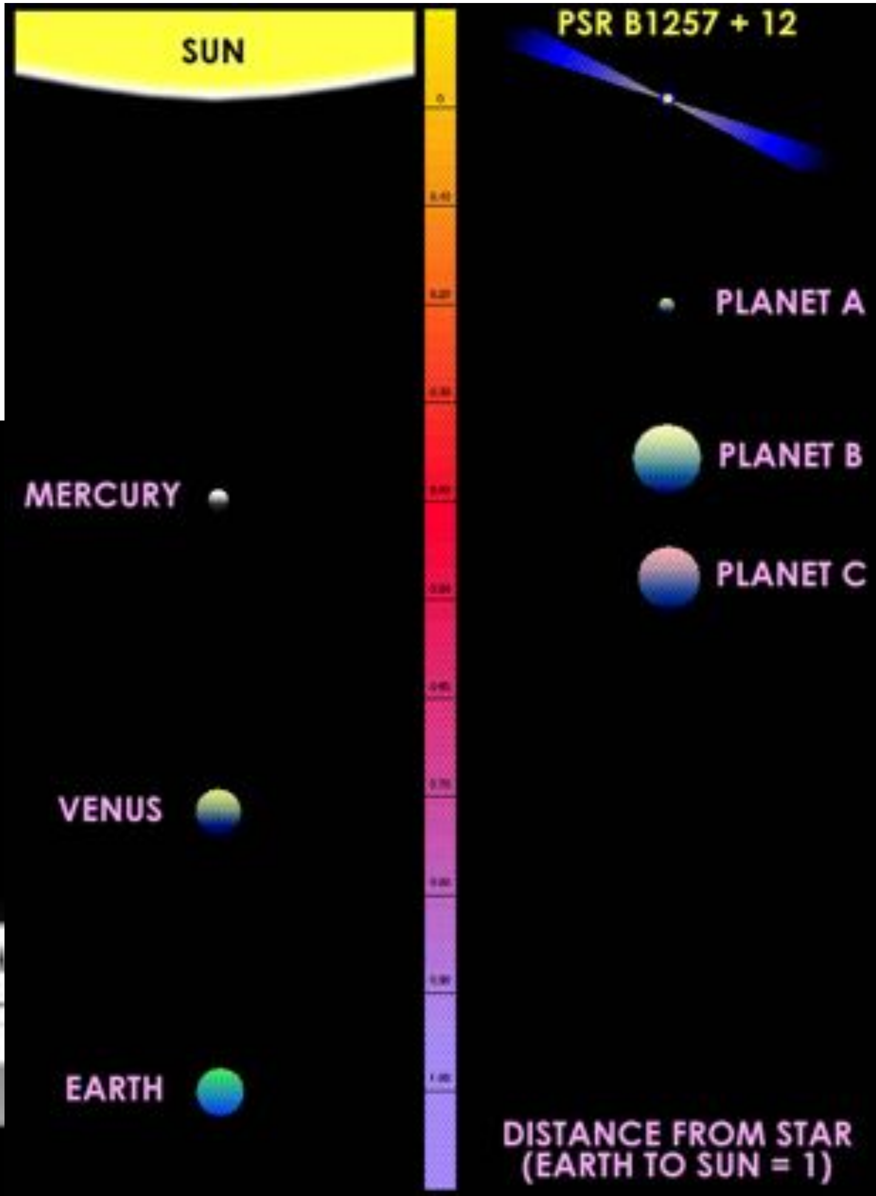




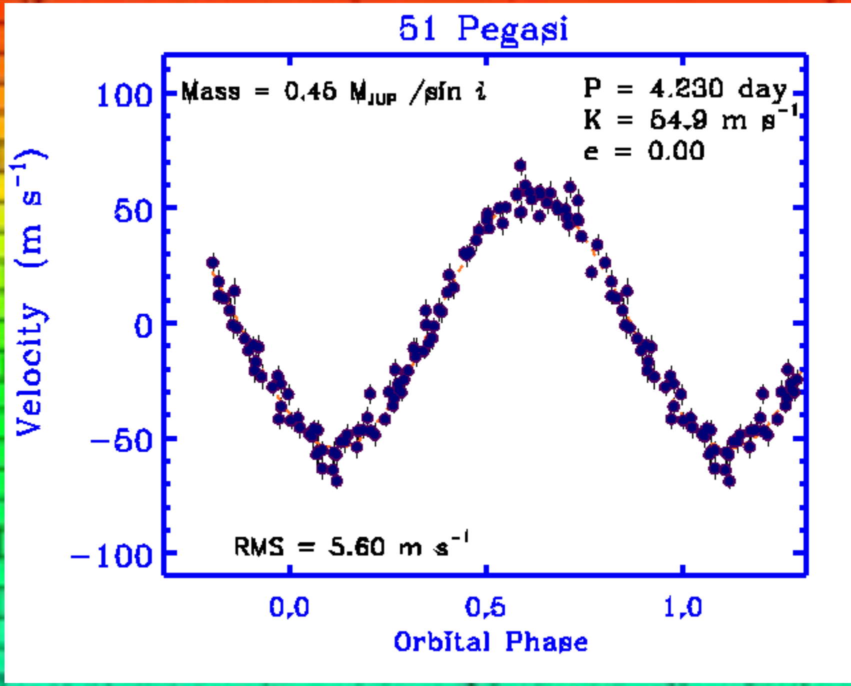
Stellar Motion: Timing of Pulsar Radio Signals

The first extra-solar planets to be found are actually around a dead star

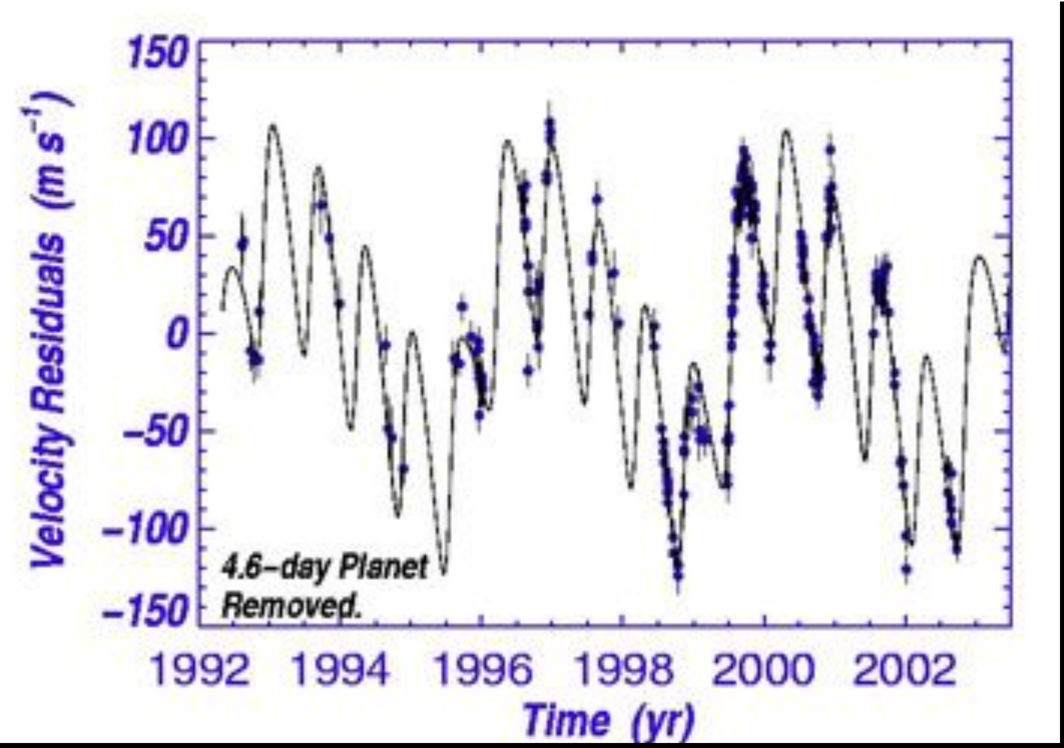




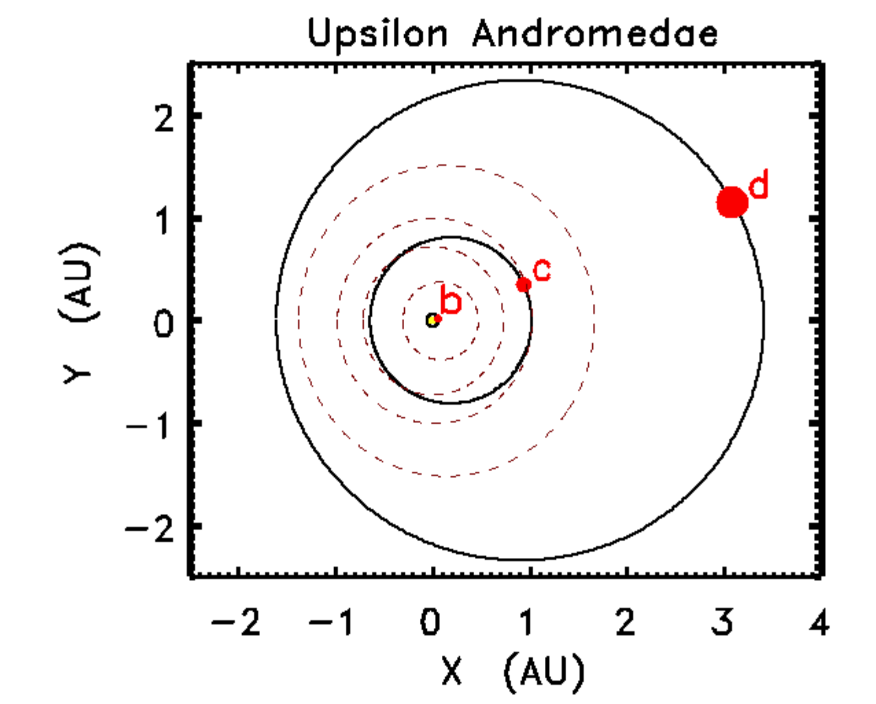
Until Recently, Majority from Radial Velocity



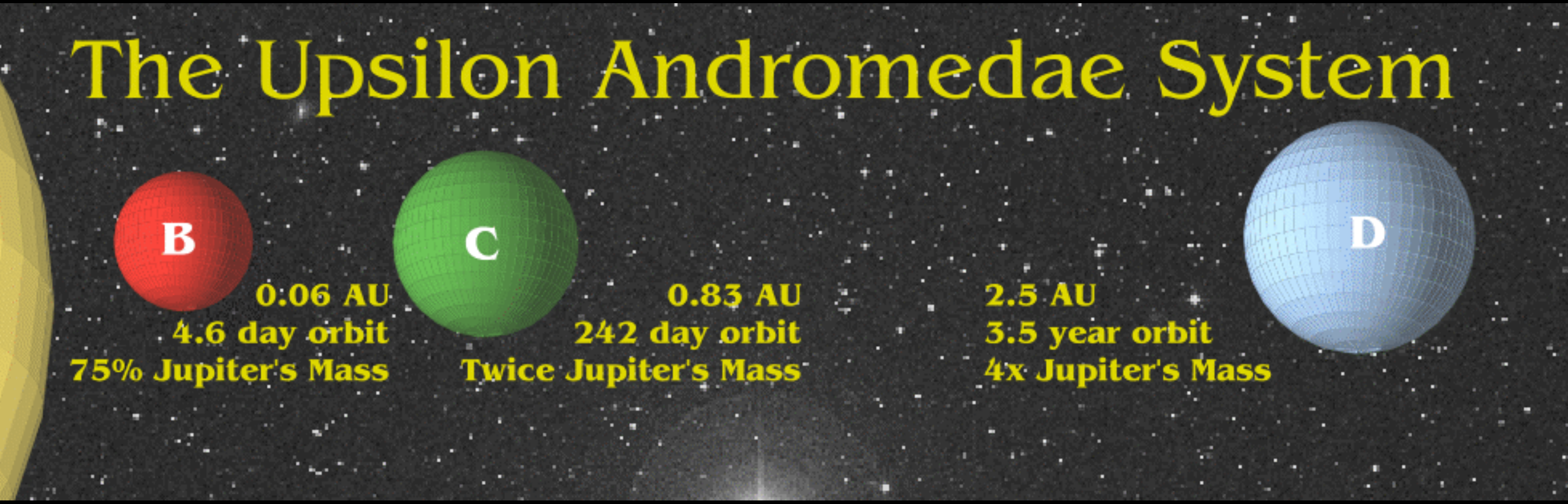
Solar spectrum from R. Kurucz



150
100
50
0
−50
−100
−150
Velocity Residuals (m s⁻¹)
4.6−day Planet Removed.
1992
1994
1996
1998
2000
2002
Time (yr)

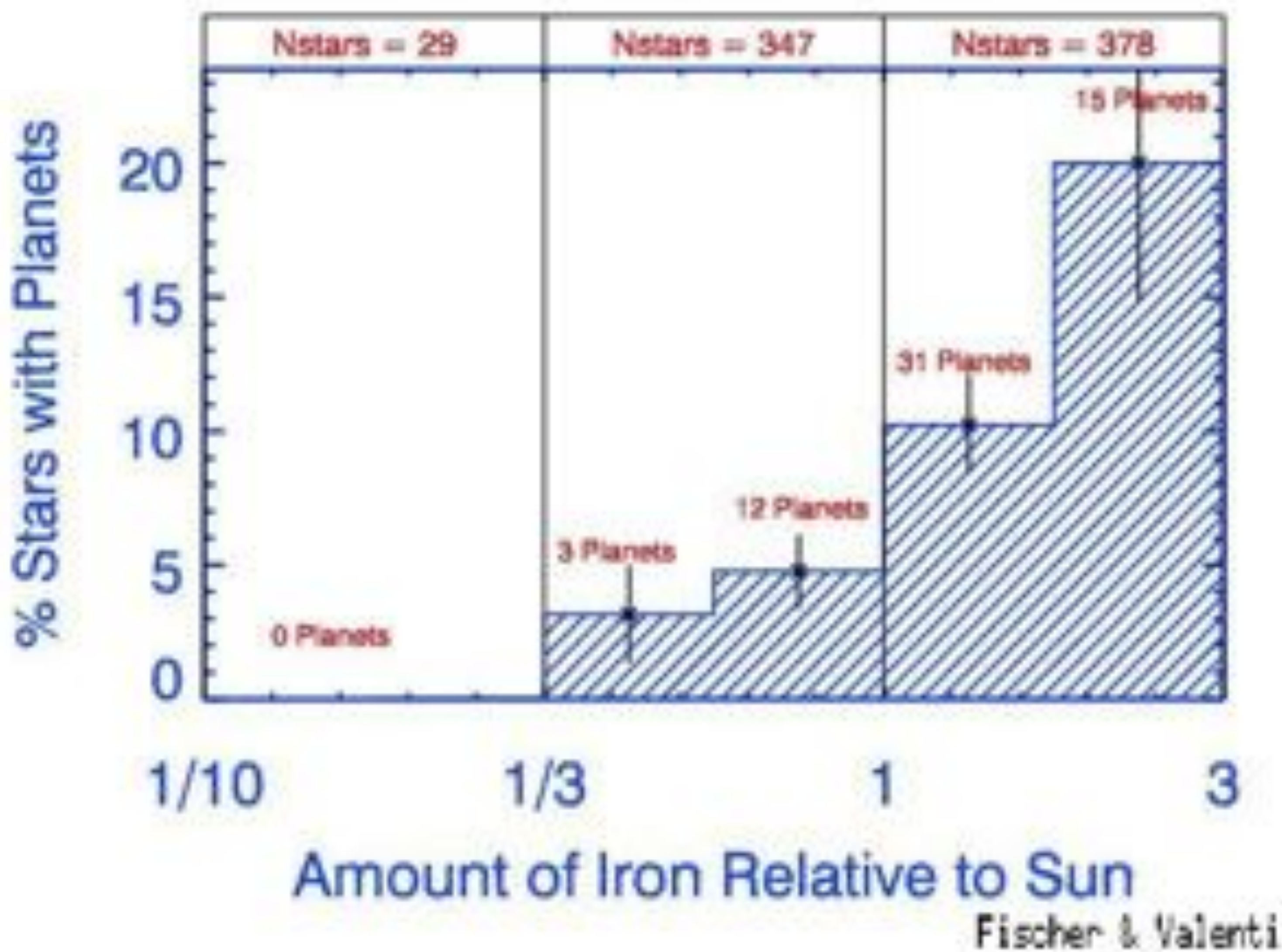


Upsilon Andromedae
d
c
b
Y (AU)
X (AU)



The Upsilon Andromedae System
B
C
D
0.06 AU
4.6 day orbit
75% Jupiter's Mass
0.83 AU
242 day orbit
Twice Jupiter's Mass
2.5 AU
3.5 year orbit
4x Jupiter's Mass

Stars with more heavy elements seem more likely to have giant planets



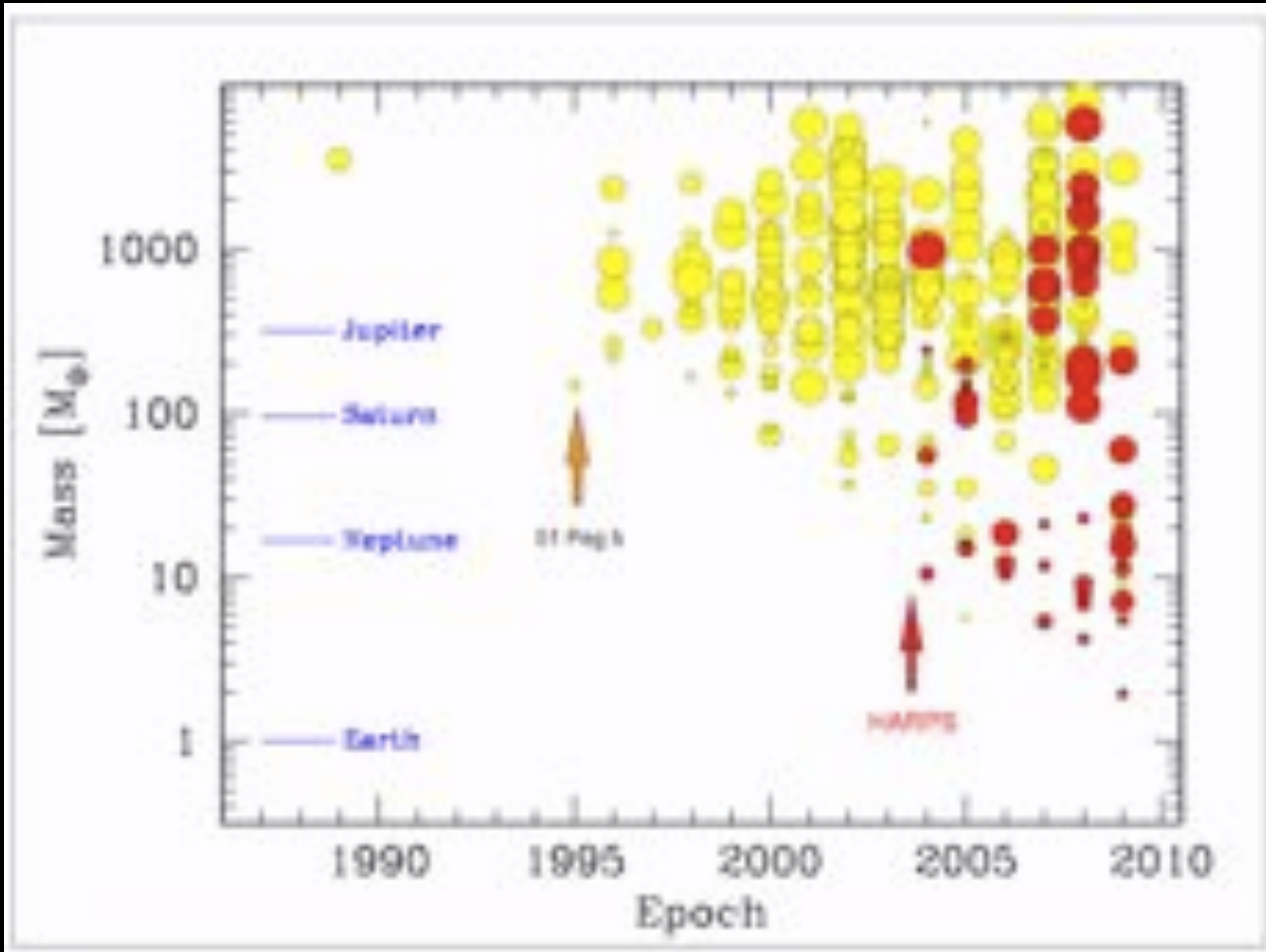
Why might stars with more heavy elements have more giant planets?

Possible explanations

1. Stars may *look* enriched in heavy elements if they accrete planets and if they're not diluted by convection

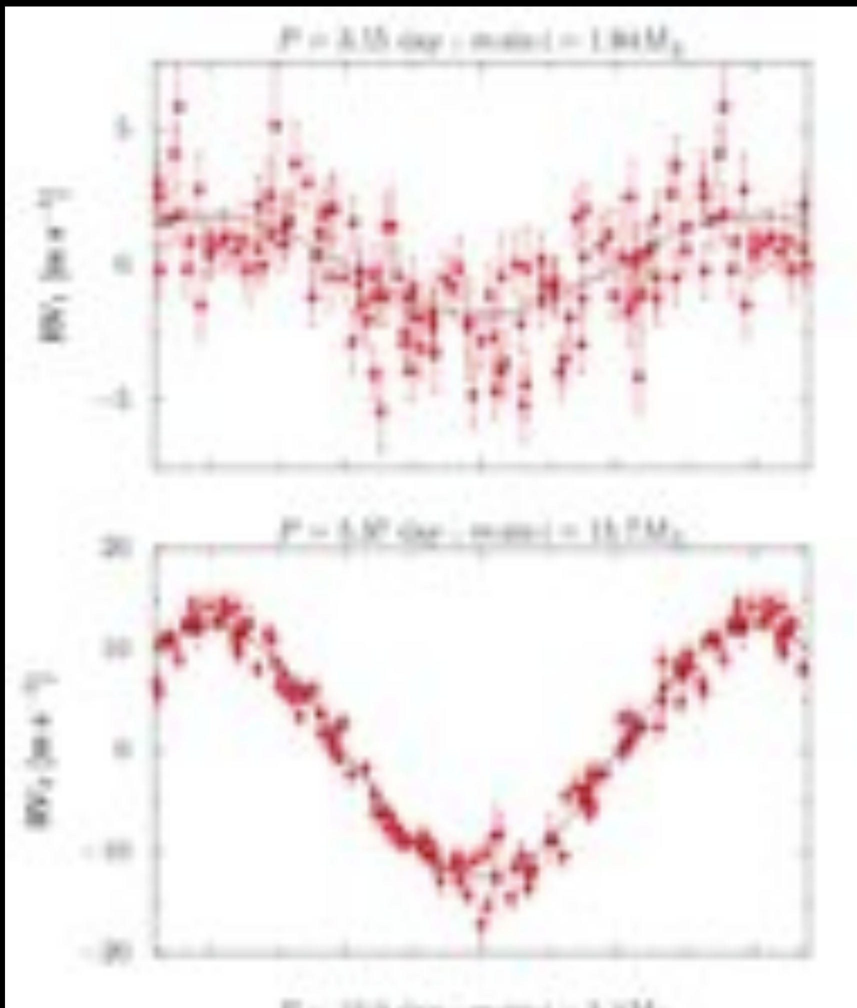
2. More heavy elements means more solid material in the nebula to build planets with – so the chances of forming a 15 Earth-mass core for a gas giant are higher

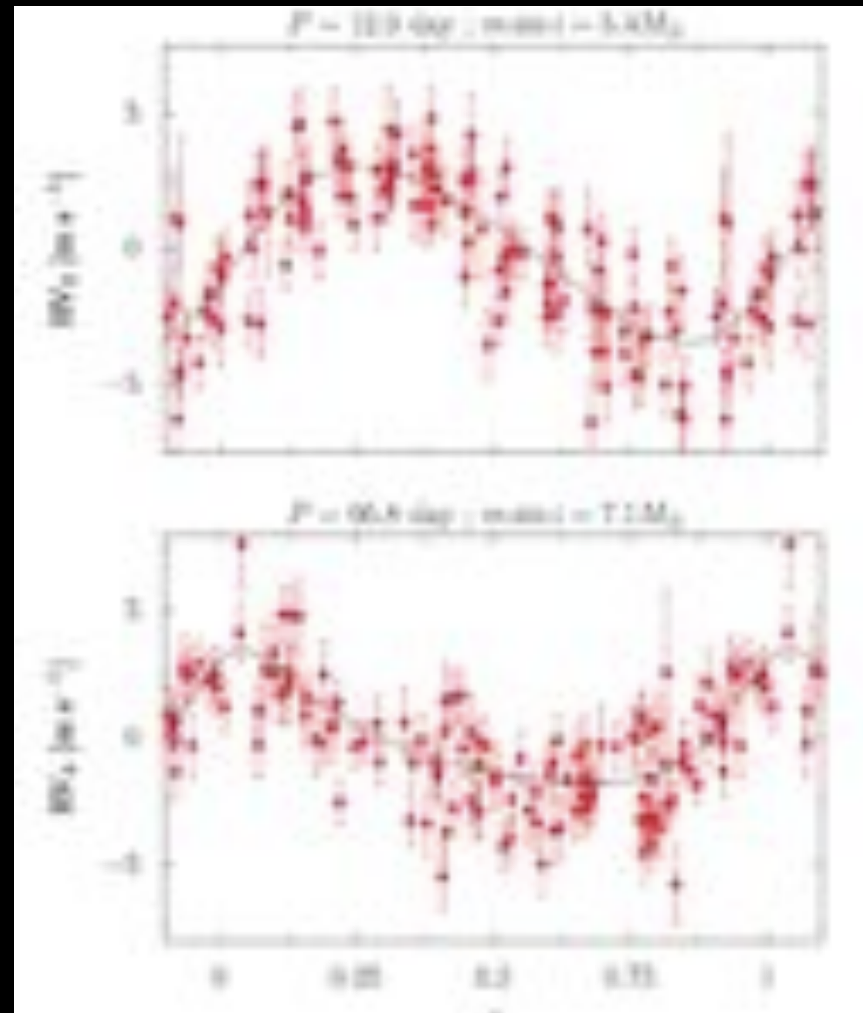
Improving Precision of RV



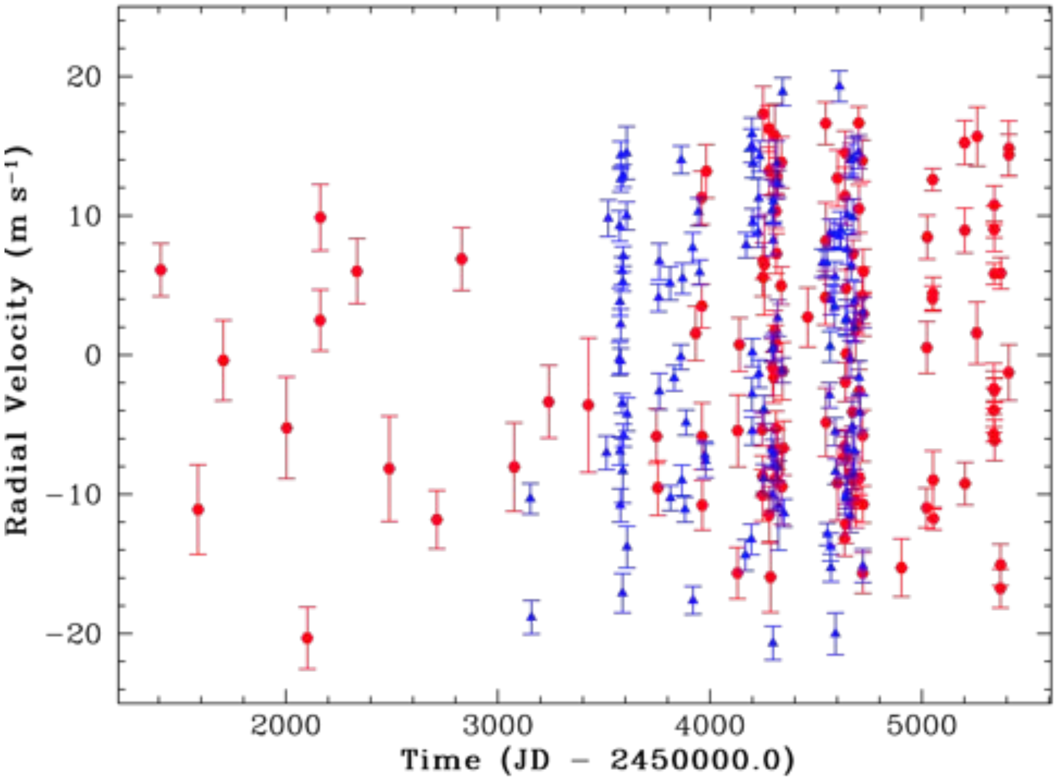
Gliese 581 : M Dwarf with Multiple Planets

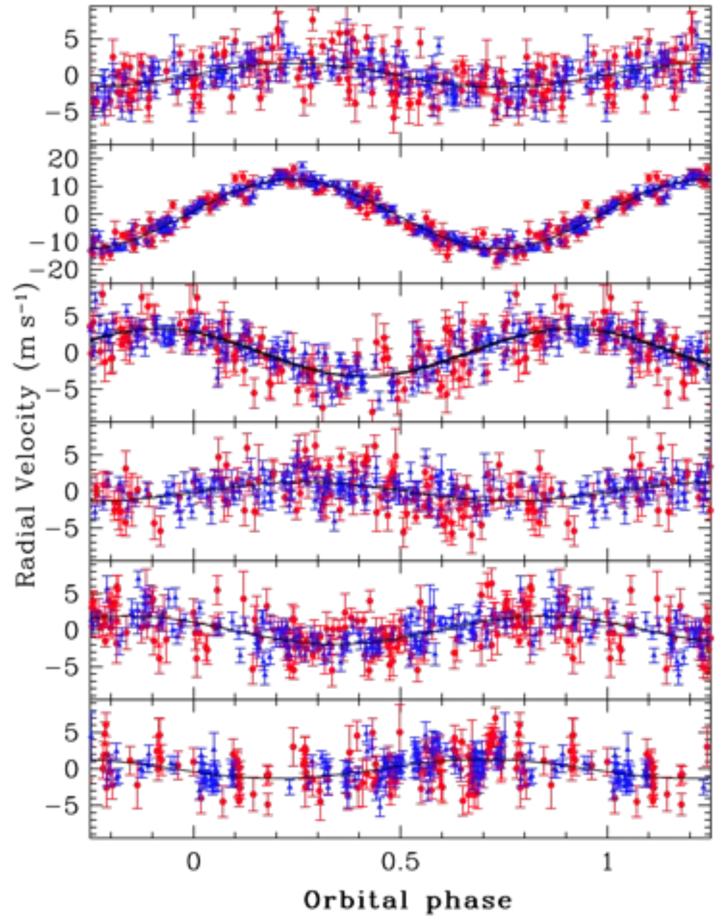
(Mayor et al. 2009)





On-going Controversy over Gliese 581g





Vogt et al. (2010) reported 2 more planets
Forveille et al. (2011) couldn’t confirm
Vogt et al. (2012) claim they can with more data

Alpha Centauri Bb: ~1M_E planet in a ~3-day orbit?

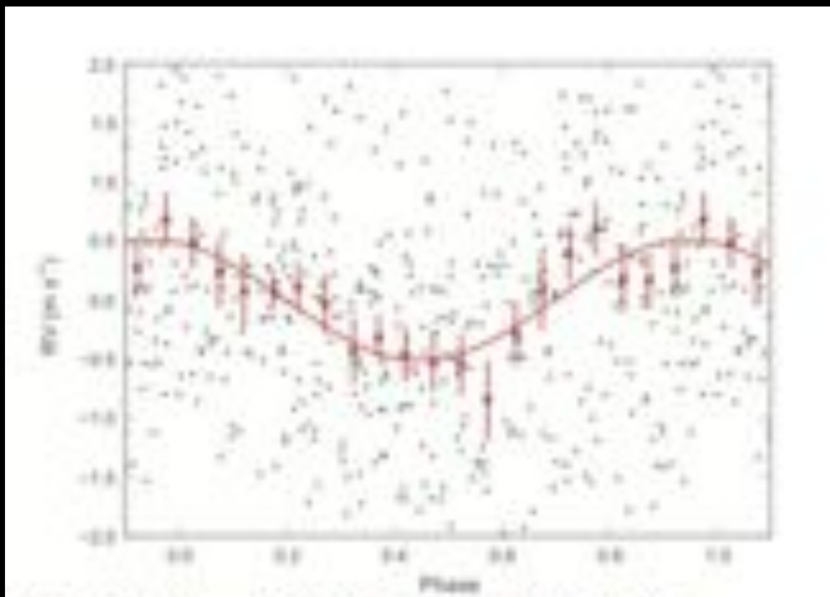


Fig. 5: Phase-folded radial-velocity (RV) curve

Table 1: Orbital parameters of the planet orbiting Alpha Centauri B ($m.s^{-1}$ stands for meters-per-second).

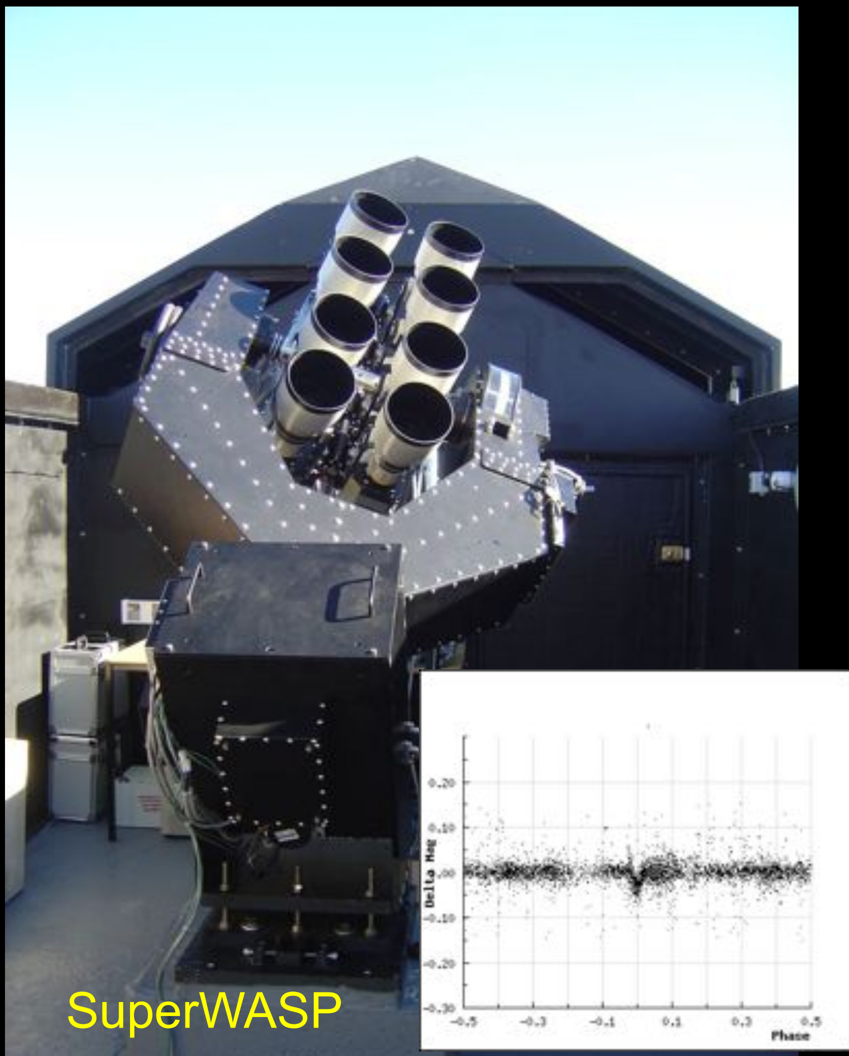
Parameter	Value
Orbital period (days)	3.2357 ± 0.0008
Time of maximum velocity (BJD)	2455280.17 ± 0.17
Eccentricity	0.0 (fixed)
Velocity semi-amplitude ($m.s^{-1}$)	0.51 ± 0.04
Minimum mass (M_{Earth})	1.13 ± 0.09
Number of data points	459
O-C residuals ($m.s^{-1}$)	1.20
Reduced chi2 value	1.51

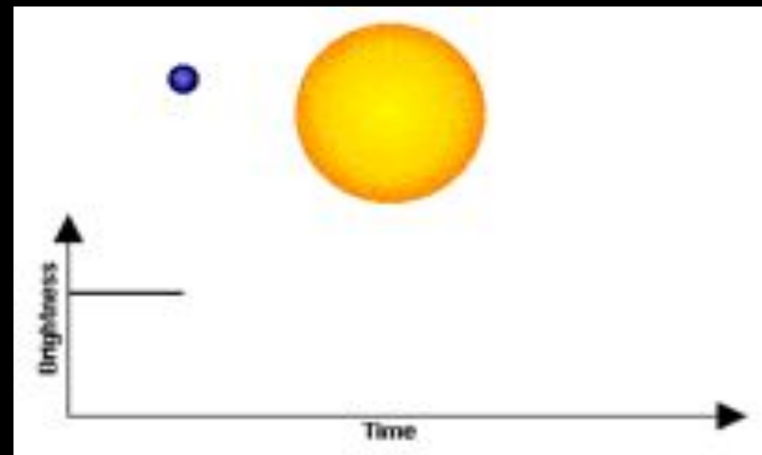
Dumusque et al. (2012) reported planet in HARPS data after removing stellar activity

Hatzes (2013) finds a false alarm probability of a few percent:

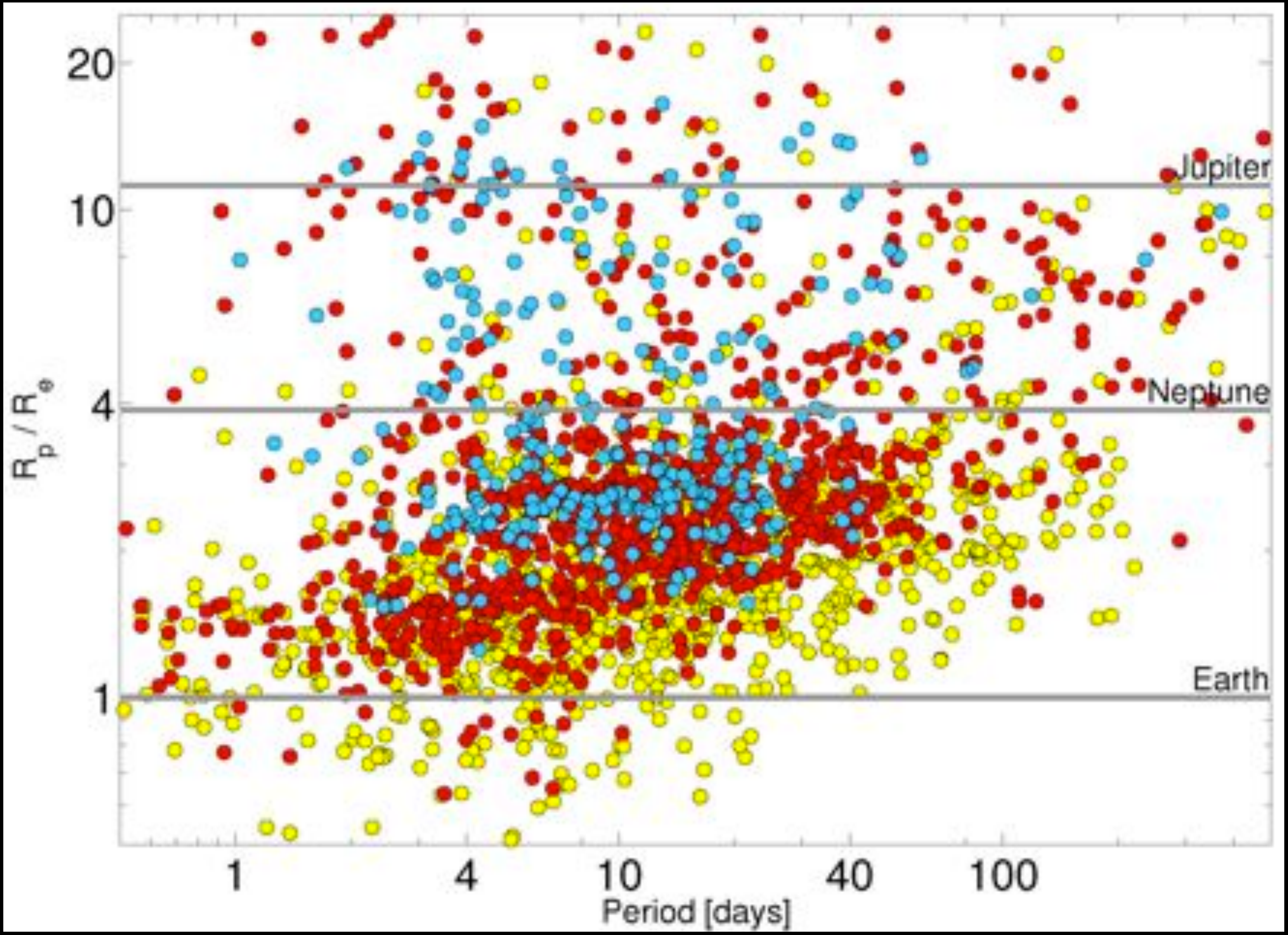
"It may be premature to attribute the 3.24 day RV variations to an Earth-mass planet. A better understanding of the noise characteristics in the RV data as well as more measurements with better sampling will be needed to confirm this exoplanet."

Growing Number from Transits



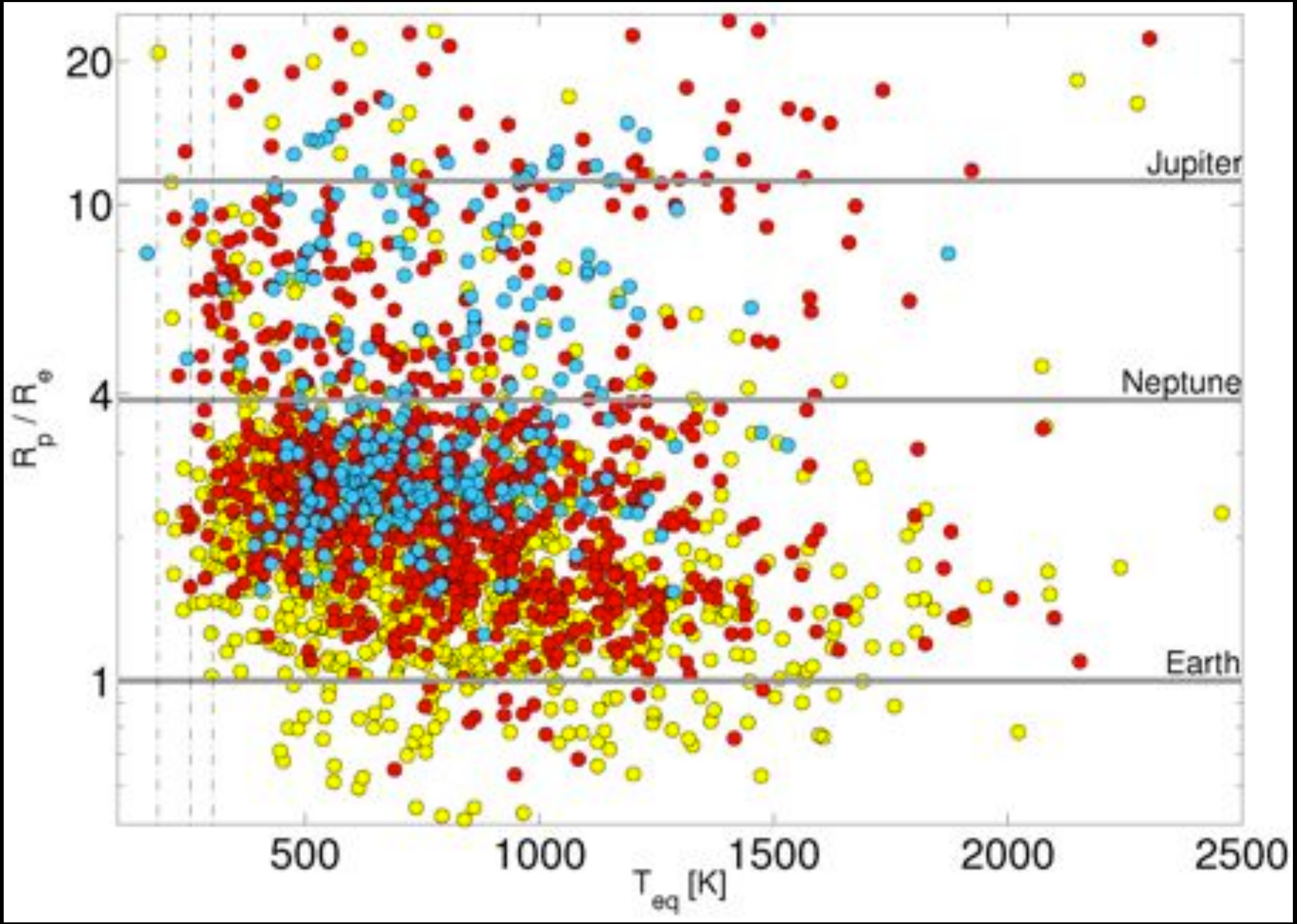


Kepler's ~2300 Planet Candidates



Batalha et al. (2012)

Kepler's ~2300 Planet Candidates

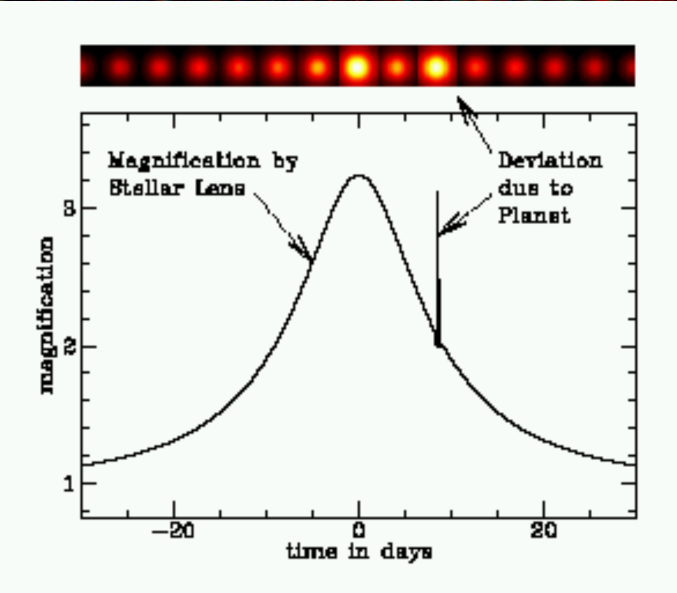


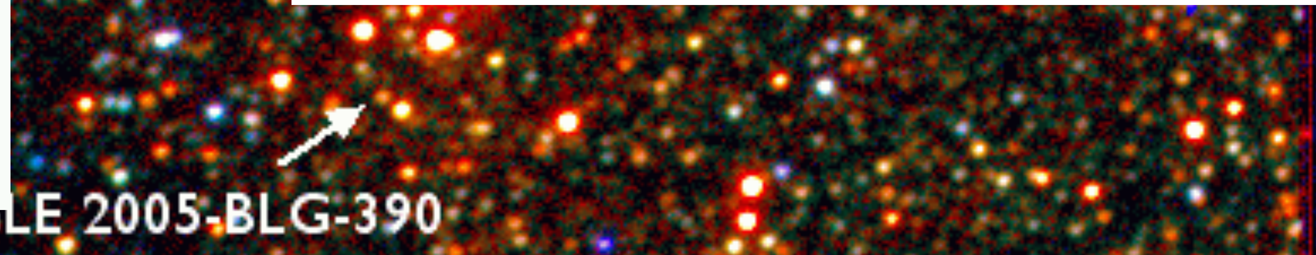
Batalha et al. (2012)

Kepler 11: System of Six Planets Seen in Transit

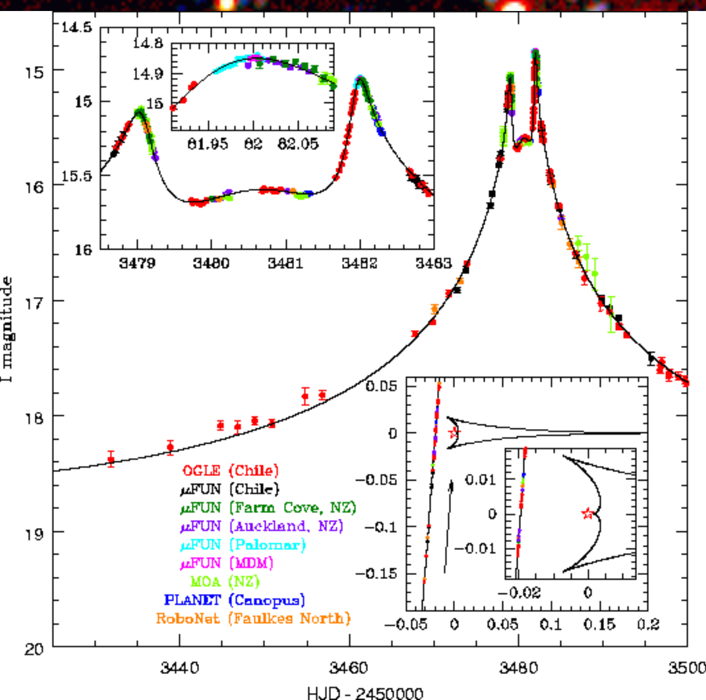
Monitoring Stellar Brightness: Microlensing

Of a background star when a star with a planet passes in front

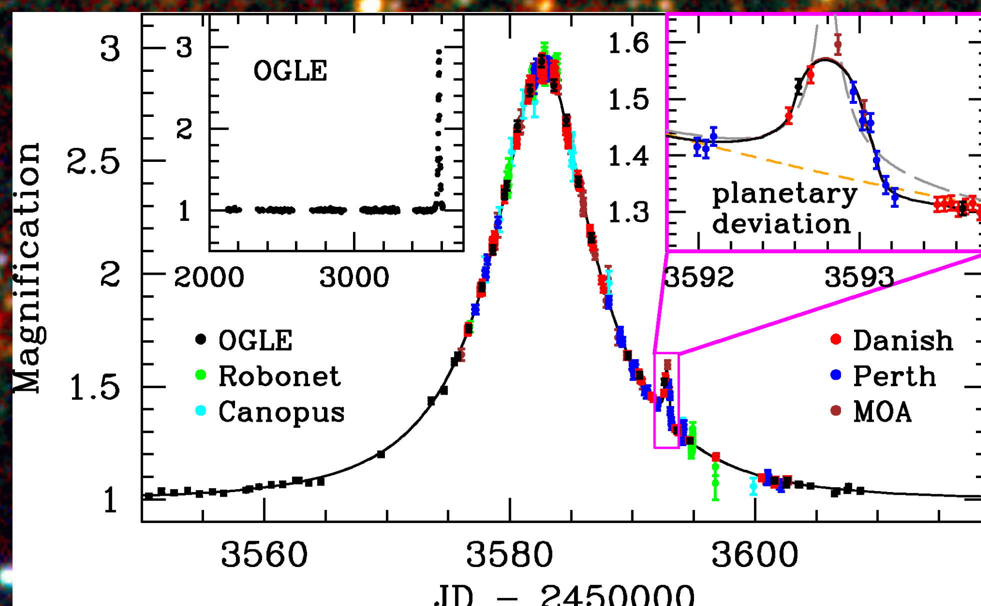




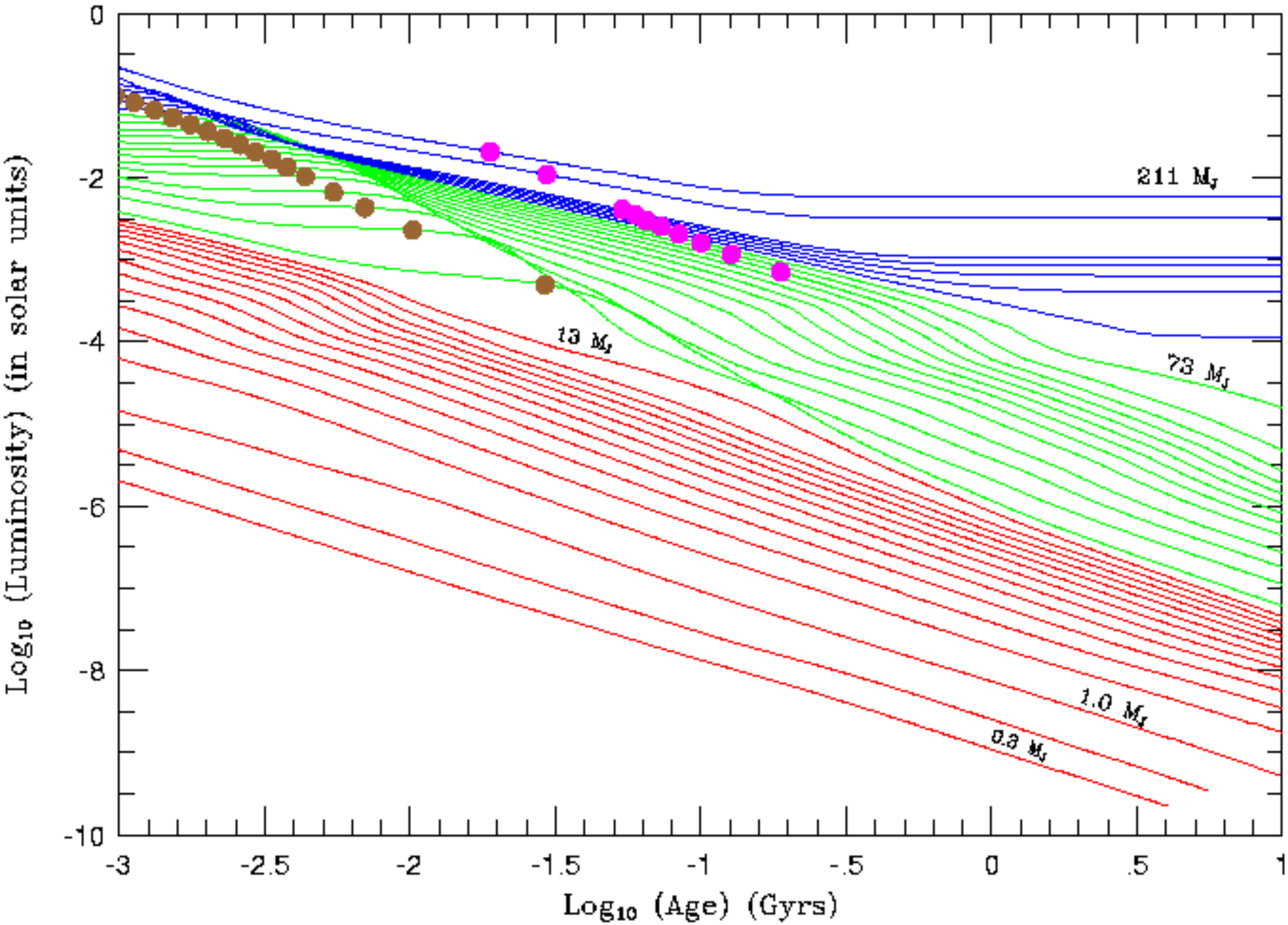
OGLE 2005-BLG-071:
a Jovian planet



OGLE 2005-BLG-390Lb: a 5-Earth-mass planet 3 AU from an M dwarf



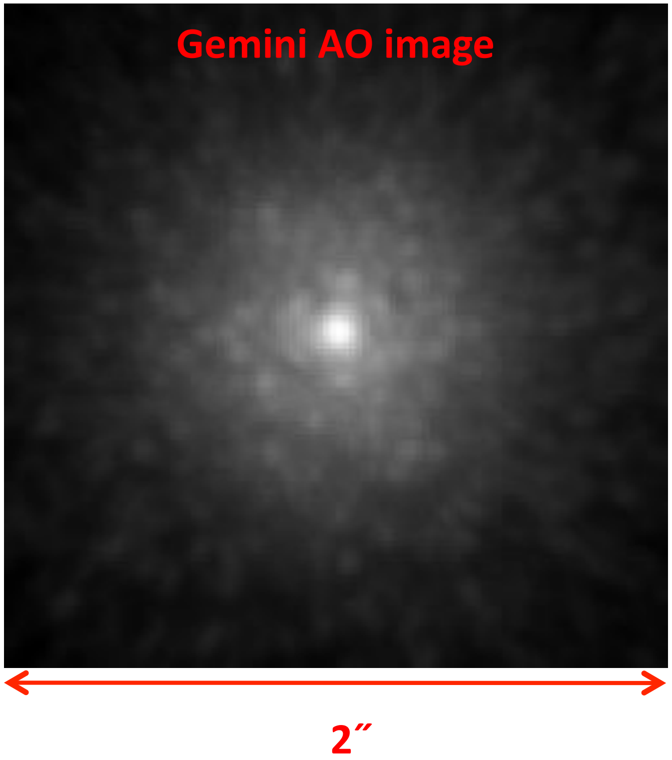
Luminosity Evolution with Age



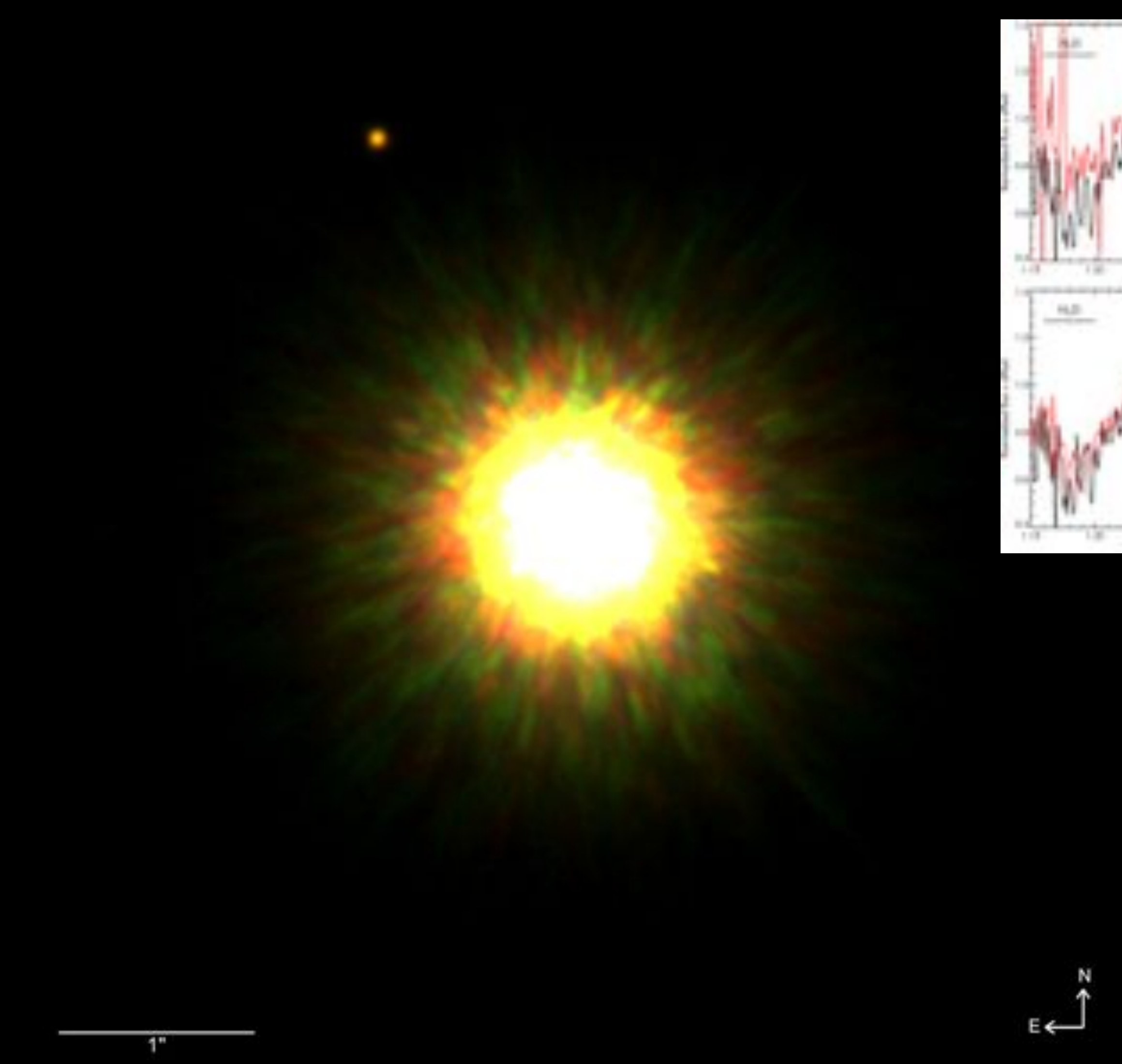
Burrows et al. (1997)

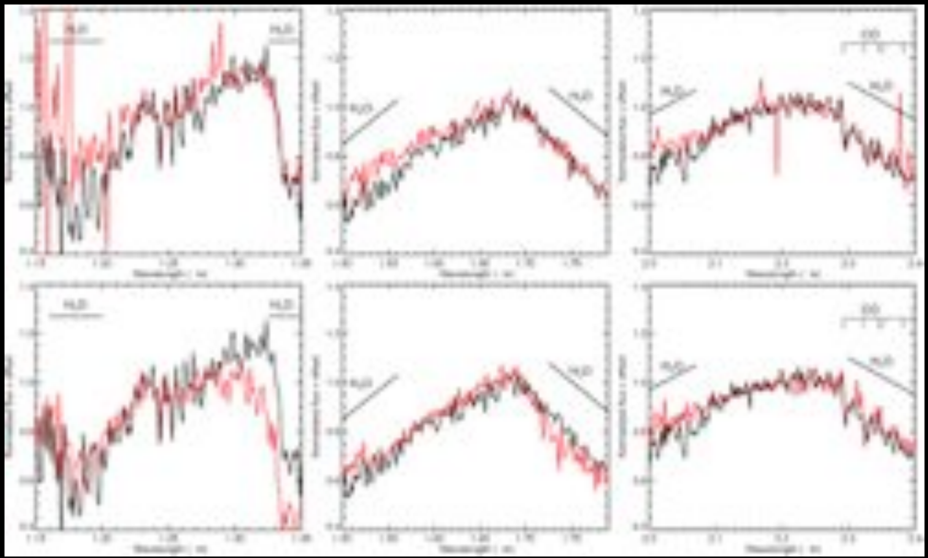
Technical challenge

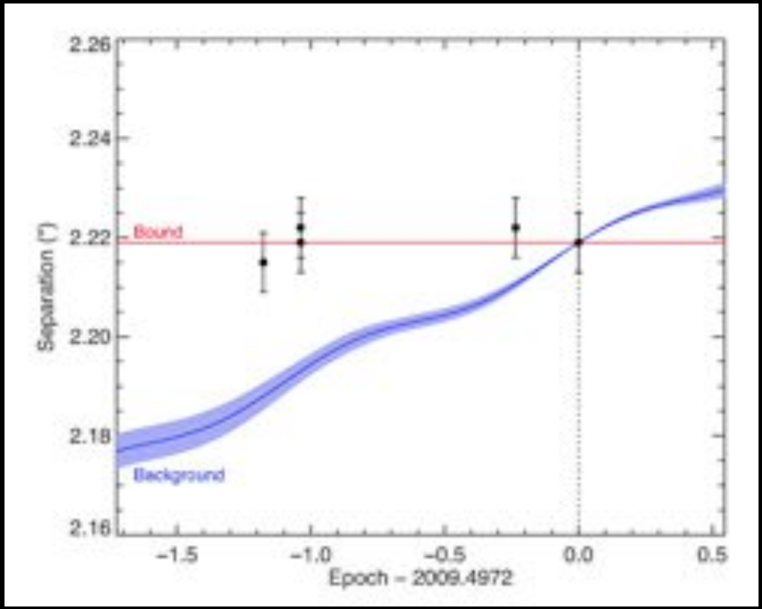
- Scattering from atmosphere and small defects on optical surfaces
  - Creates speckles around the PSF core, these mask the planet
  - Quasi-static speckles (from optics) are by far the most problematic ones



Direct Imaging of Exoplanets







Lafreniere, Jayawardhana & van Kerkwijk (2008, 2010)

So is it a planet?

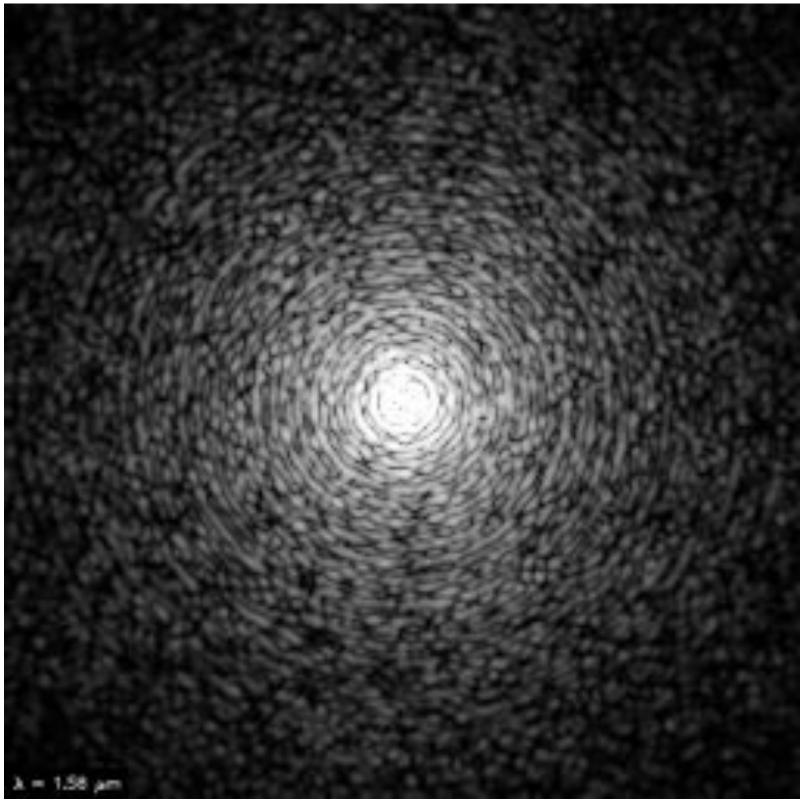
IAU working group definition of an exo-planet:

"Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars or stellar remnants are "planets" (no matter how they formed)."

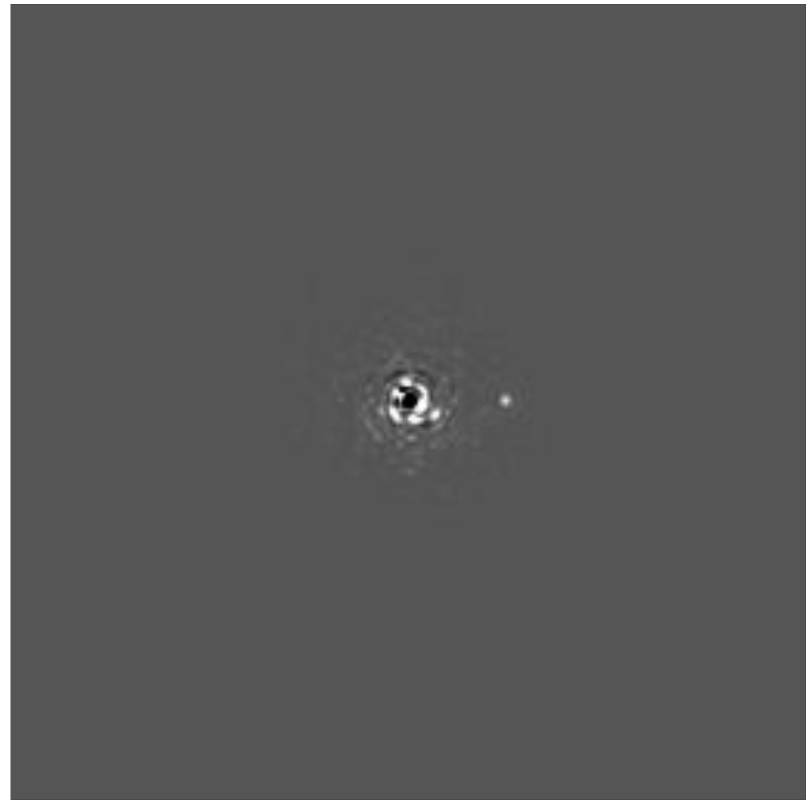
Variations of differential imaging

- Spectral Differential Imaging (SDI)
- Angular Differential Imaging (ADI)
- Roll Deconvolution, Roll Subtraction
- Subtraction of a reference star’s PSF
  - Not very efficient

Spectral Differential Imaging - SDI



Two simultaneous images
at different wavelengths

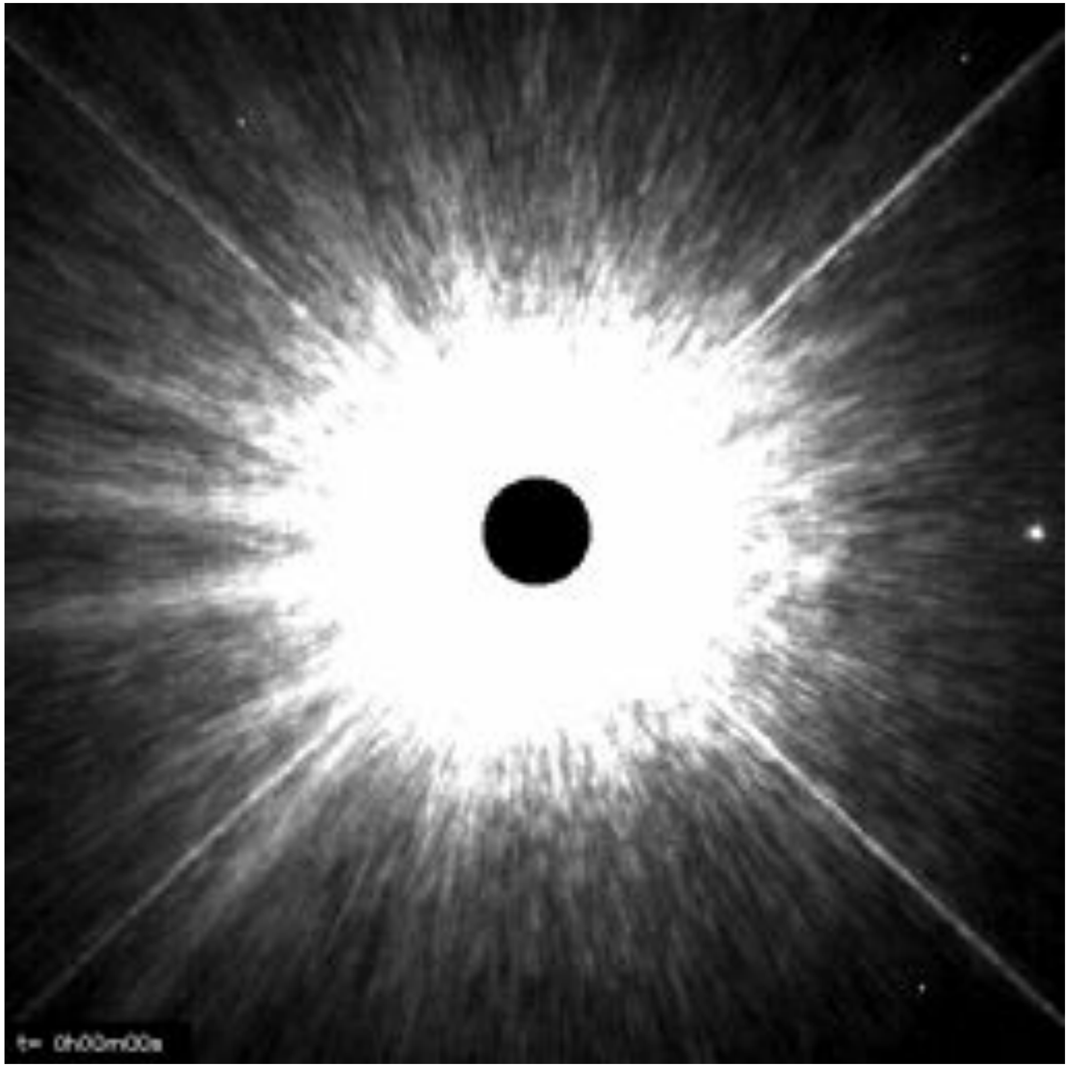


Difference

Angular Differential Imaging (ADI)

- Need an Altitude/Azimuth mount
  - Not aligned with Earth's rotation axis
  - By default, field of view rotates with time
- An instrument de-rotator compensates for this rotation
  - Moving optical component
  - Speckle pattern evolves with time
- For ADI we turn it off
  - Field of view rotates
  - All optical components stay aligned, so the speckle pattern is more stable

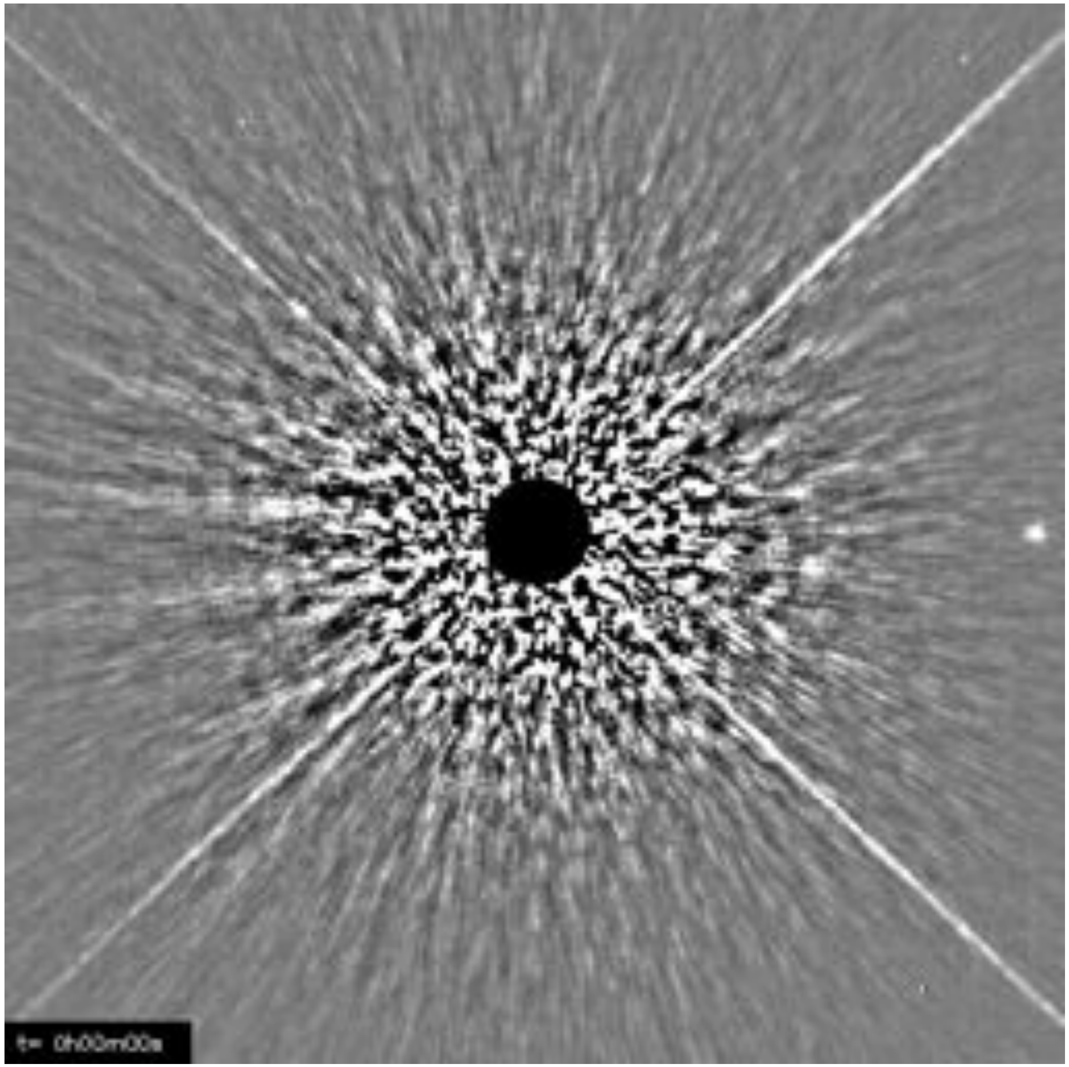
Angular Differential Imaging – ADI



~11” on a side

Sequence of 90 30s images, ALTAIR/NIRI, Gemini

ADI sequence



~11" on a side

Same sequence after high-pass filter

ADI subtraction

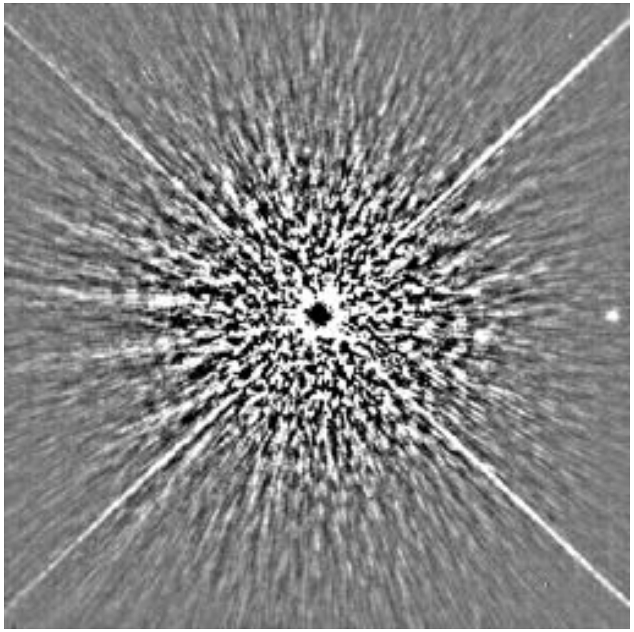


Image 1

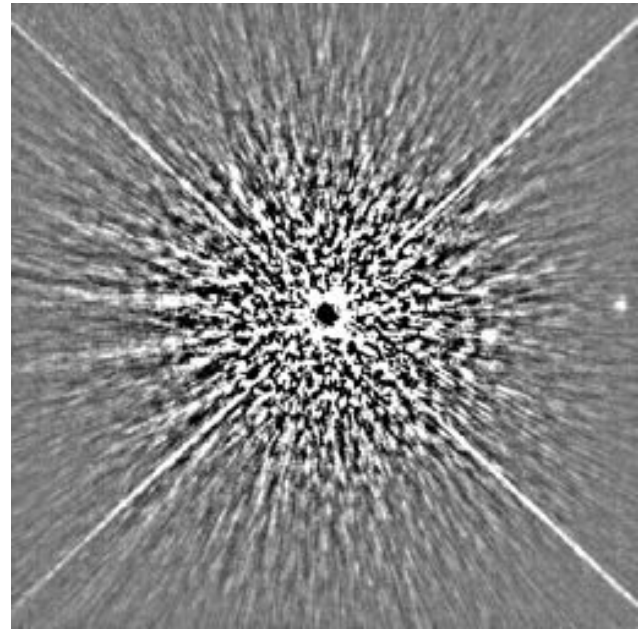
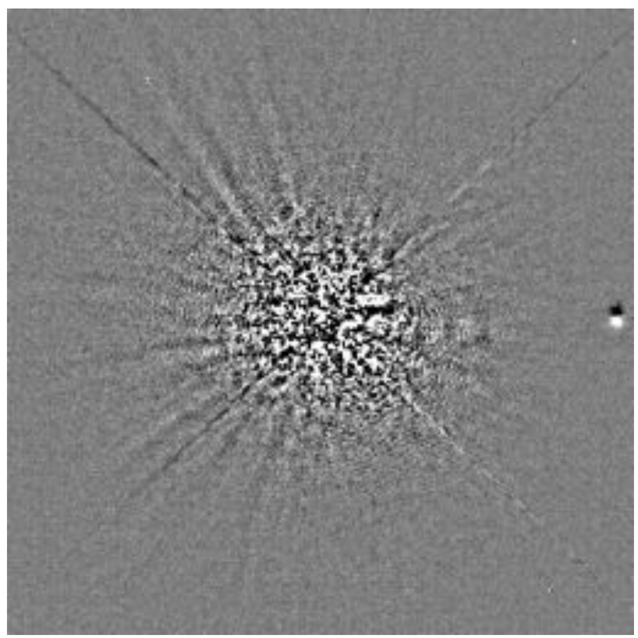
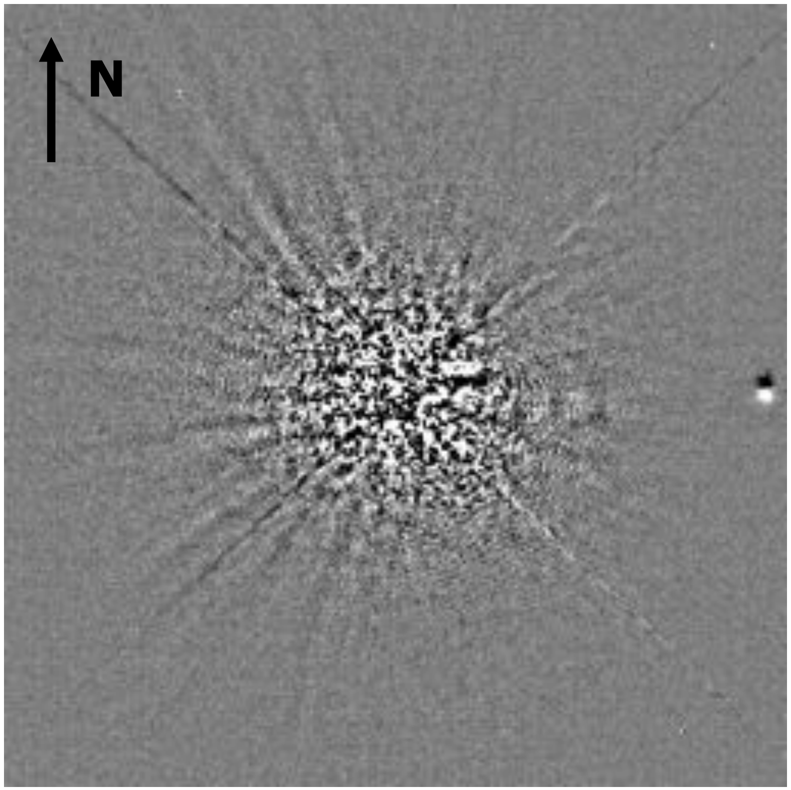


Image 2

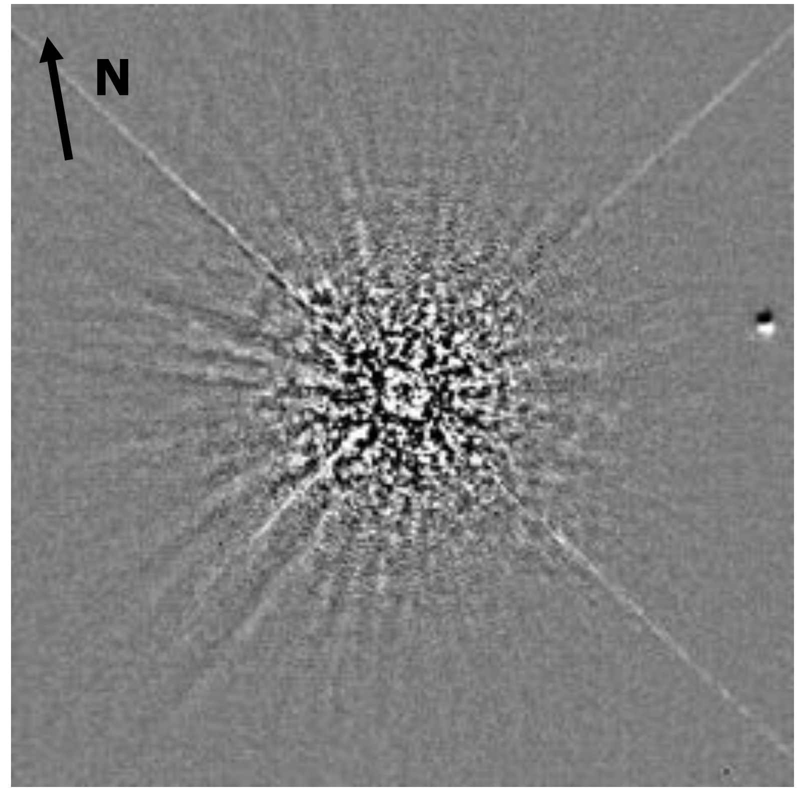


Co-addition of residual images



Difference 1

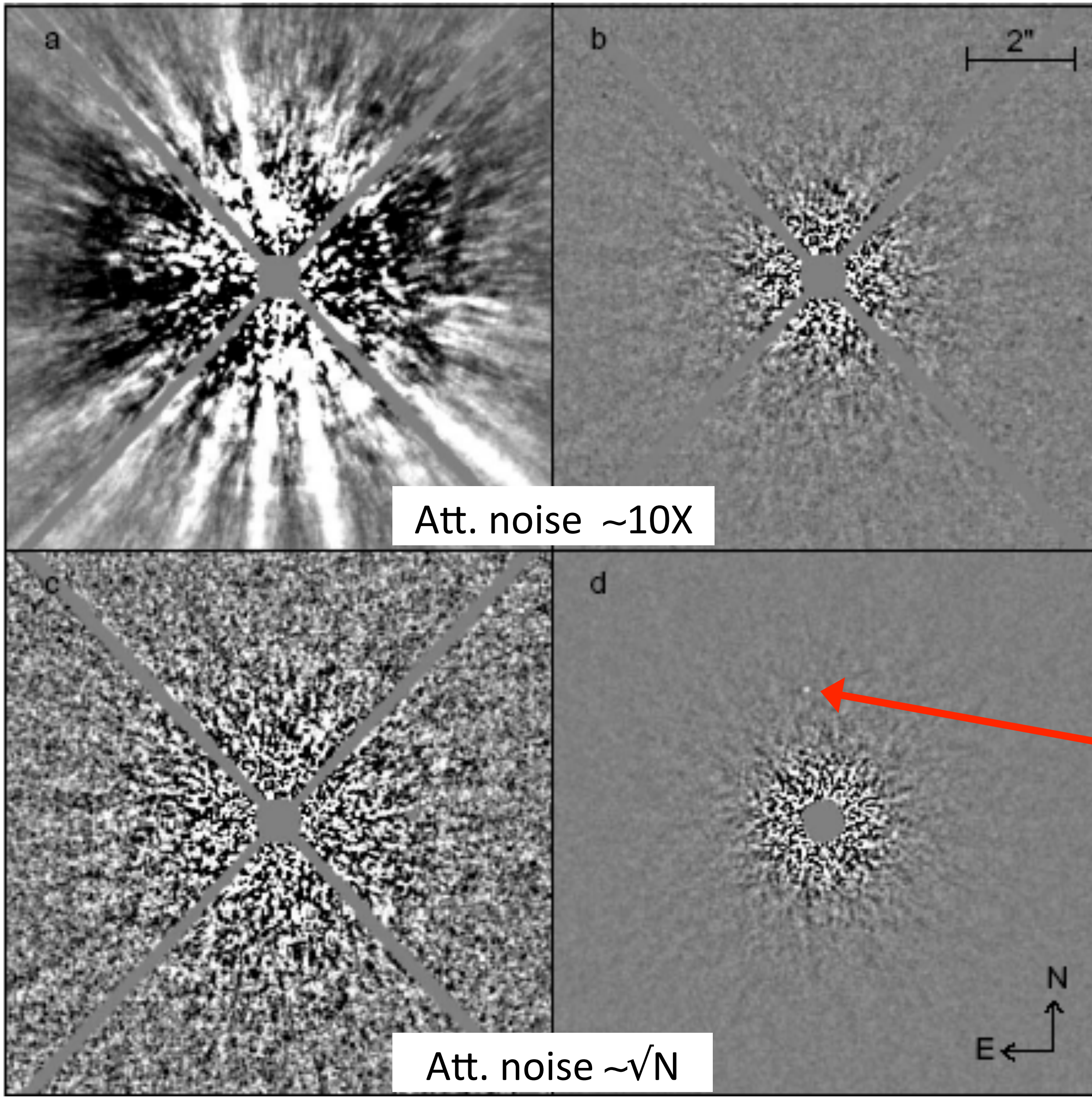
+



Difference 2

- Residuals of additional images are added incoherently
- Average flat-field, remove bad pixels and detector defects… while maintaining stable PSF

Complete ADI processing example



a) 30s exposure

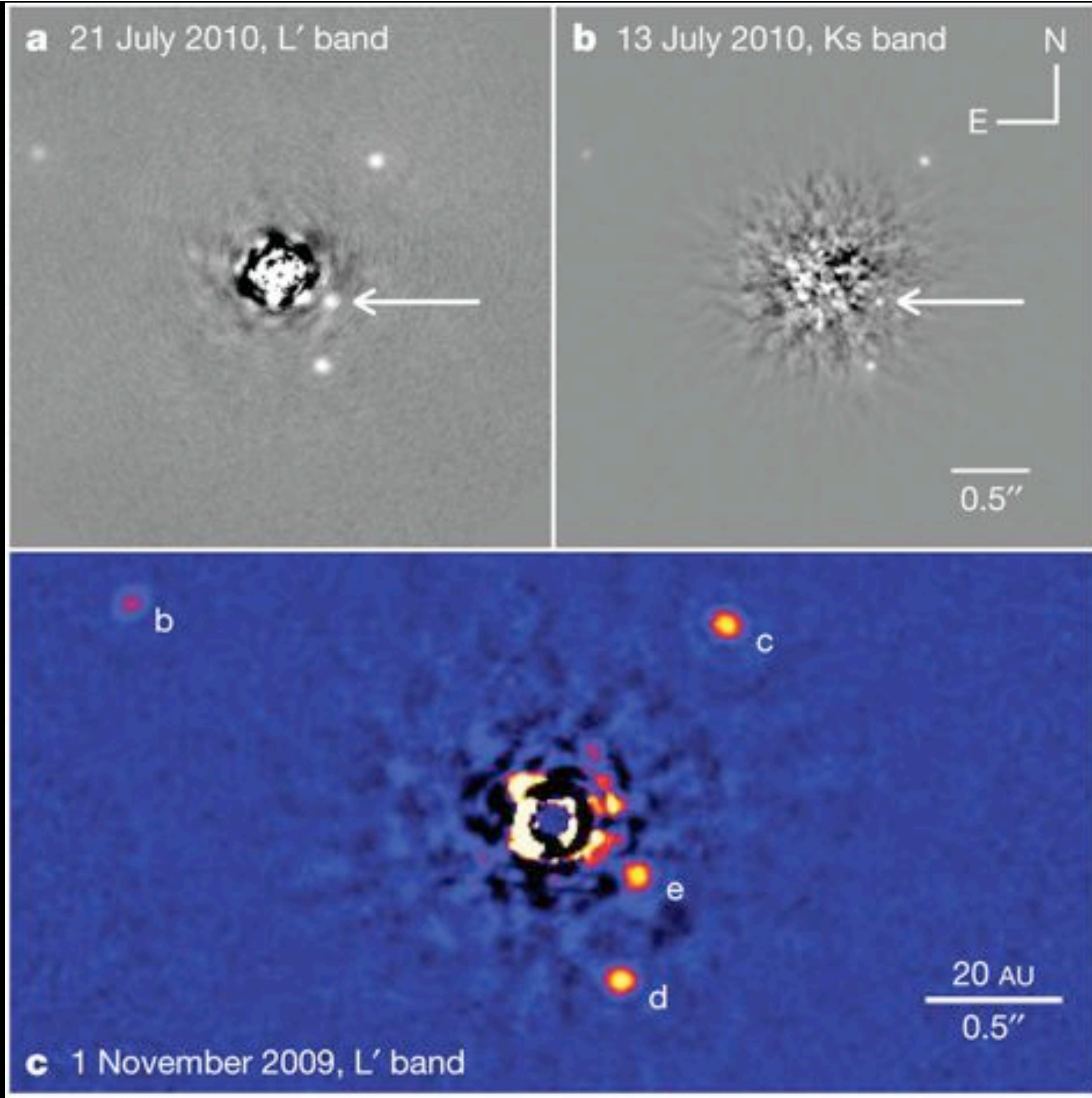
b) Single ADI subtraction

c) Same as (b) with 5x intensity scale

d) Combination of 117 residual images (~1 hr)

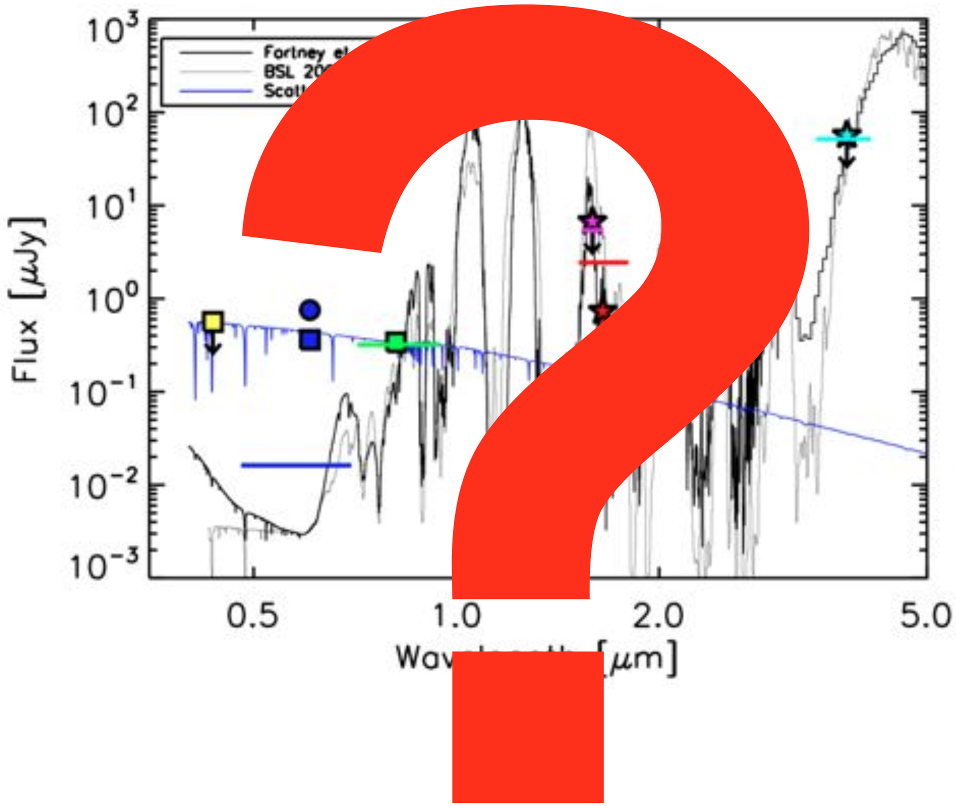
Δm=14.9 (H=21.2) at 2.4"

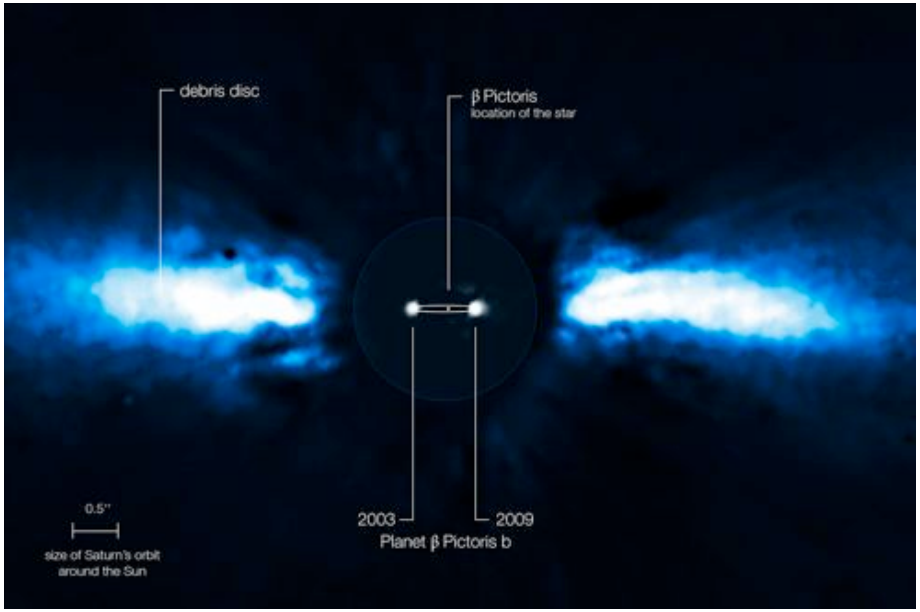
~100x improvement !



Marois et al. (2008, 2010)

More discoveries





Fomalhaut

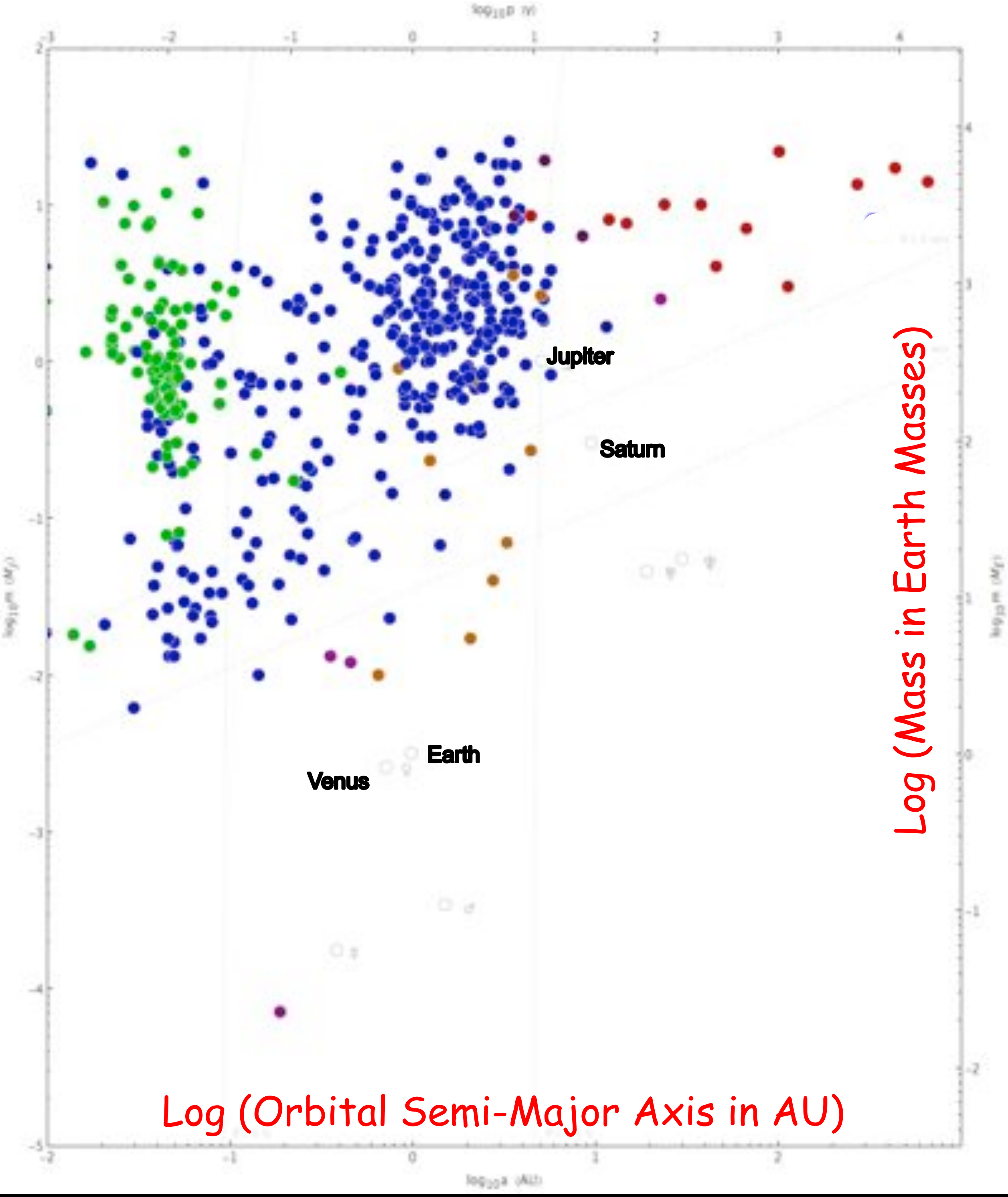
~1-3 Mjup at 100 AU

Kalas et al. (2008 & submitted)
Janson et al. (2012); Currie et al. (2012)

β Pictoris

~9 Mjup at ~8 AU

Lagrange et al. (2008, 2010)



Exoplanet Population

from

RV,

Transits,

Microlensing,

Pulsar Timing

and Direct Imaging