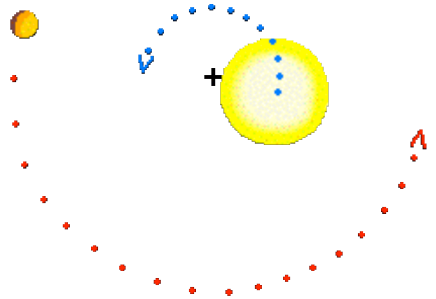
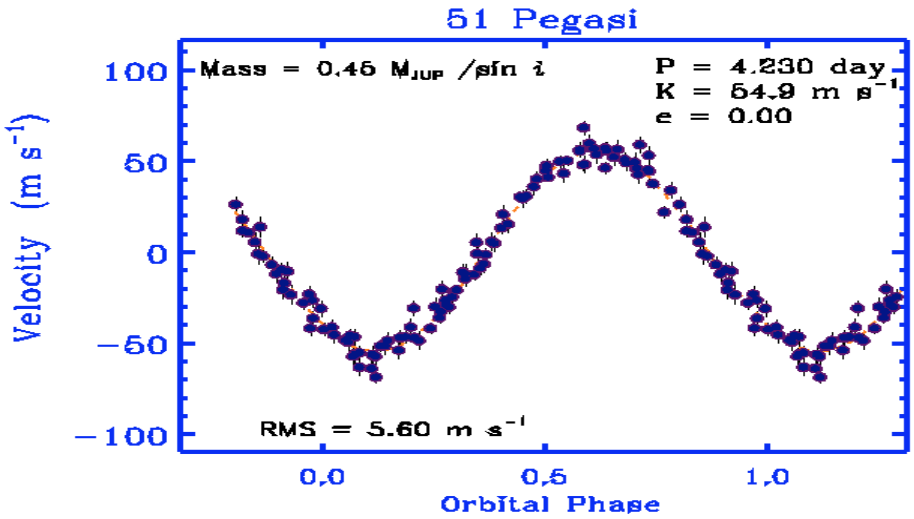
Extra-Solar Planets
The Discovery Era

- < 1995 Solar System planets
- 1995 first extrasolar planet
- (51 Peg) a Hot Jupiter!
- 2005 ~150 exo-Jupiters
- 2010-15 Habitable Earths -- common or rare?
- 2015-25 Are we alone? Extra-solar Life?

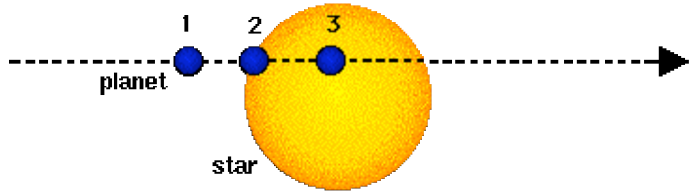
Exo-Planet Discovery Methods

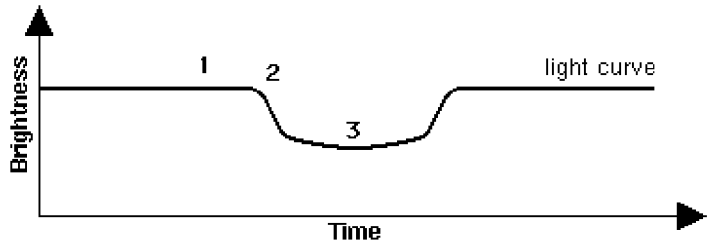
- Doppler Star Wobbles:



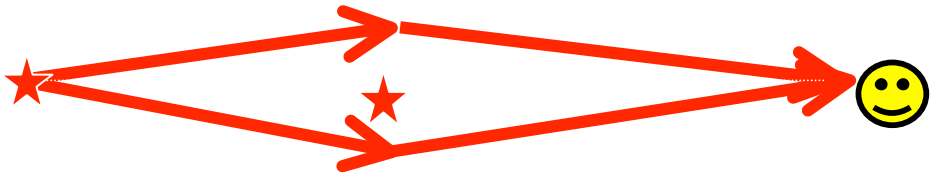


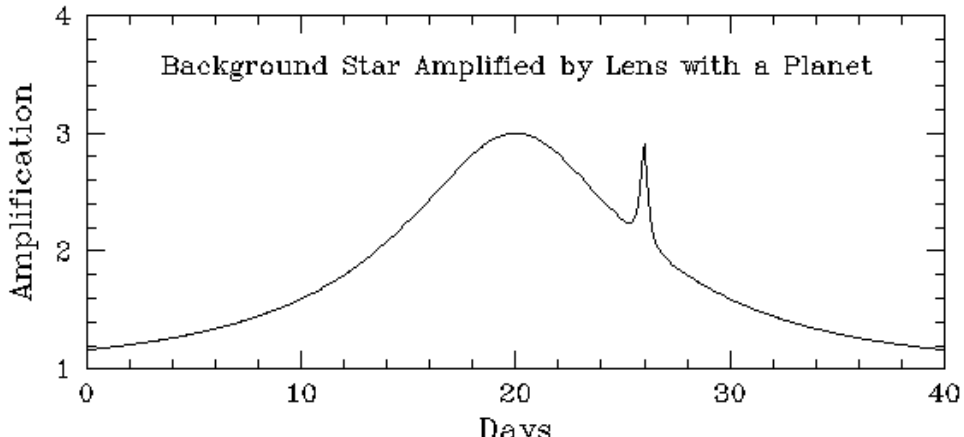
- Transits:





- Microlensing:

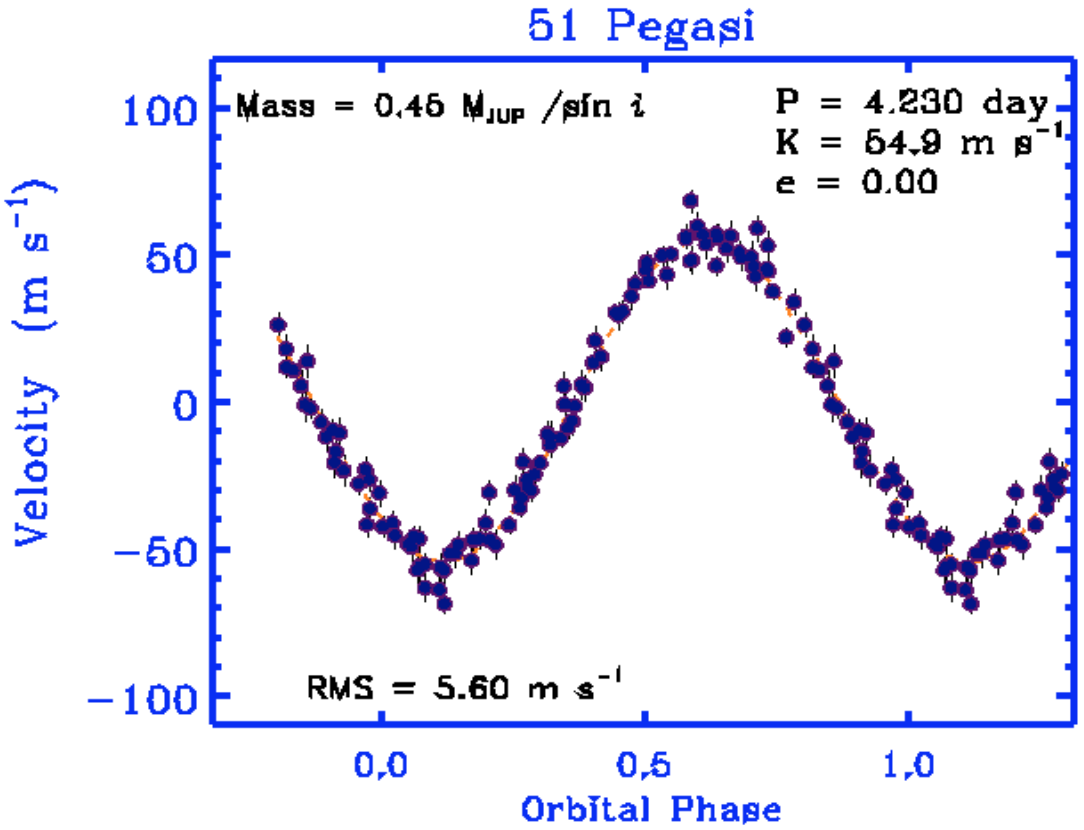




1995: First Doppler Wobble Planet: 51 Peg

Discovered by accident:
Mayor & Queloz (1995)

Quickly confirmed:
Marcy & Butler (1995)



Period = 4.2 days (!)
orbit size a = 0.05 AU
Temperature ~1500K
planet mass x sin(i) = 0.5 m_J

New type of Planet: "Hot Jupiter"

Doppler Wobble Planets 2004 May

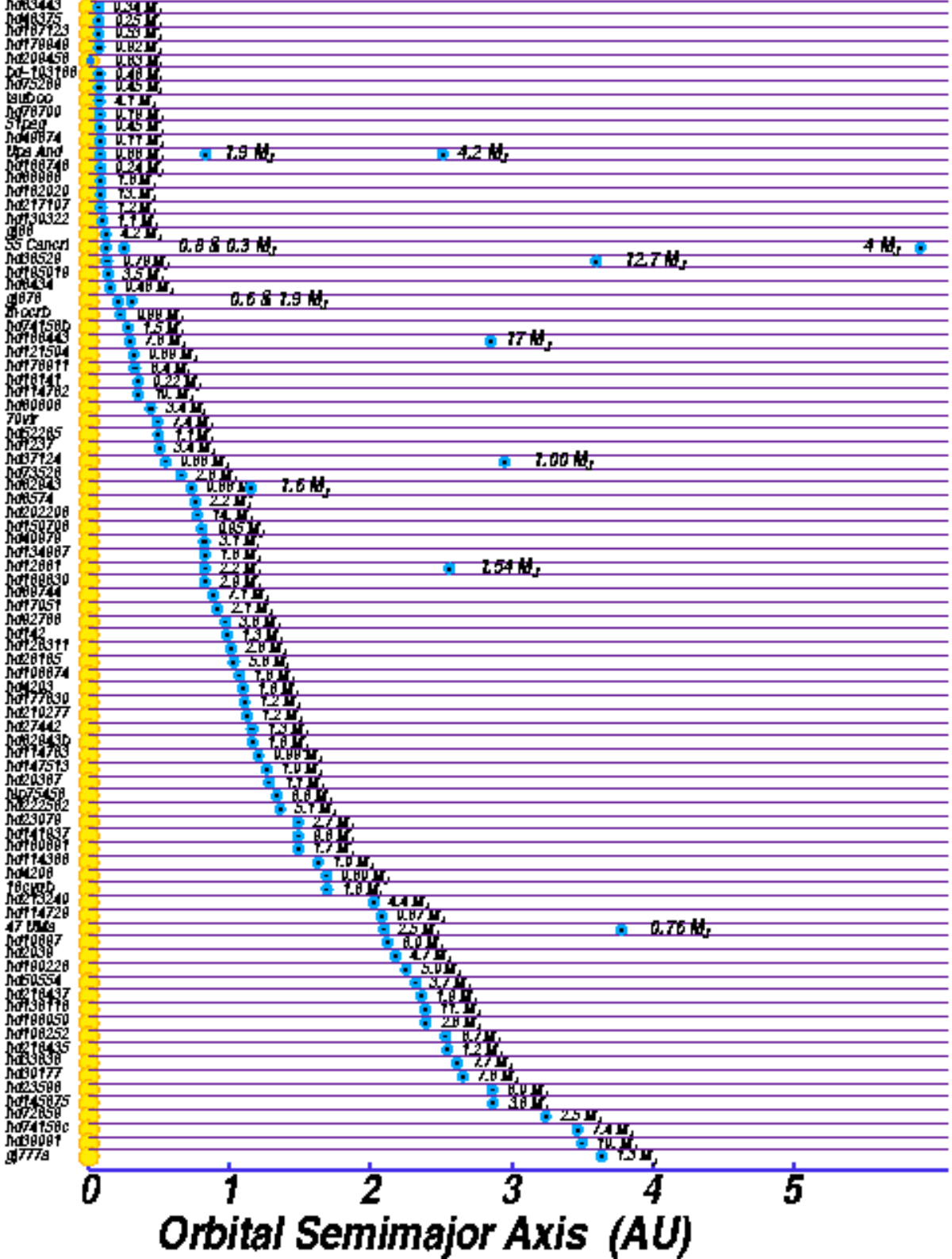
102 stars

122 planets

13 multi-planet systems

~5% of stars “wobble”

1-2 planets / month

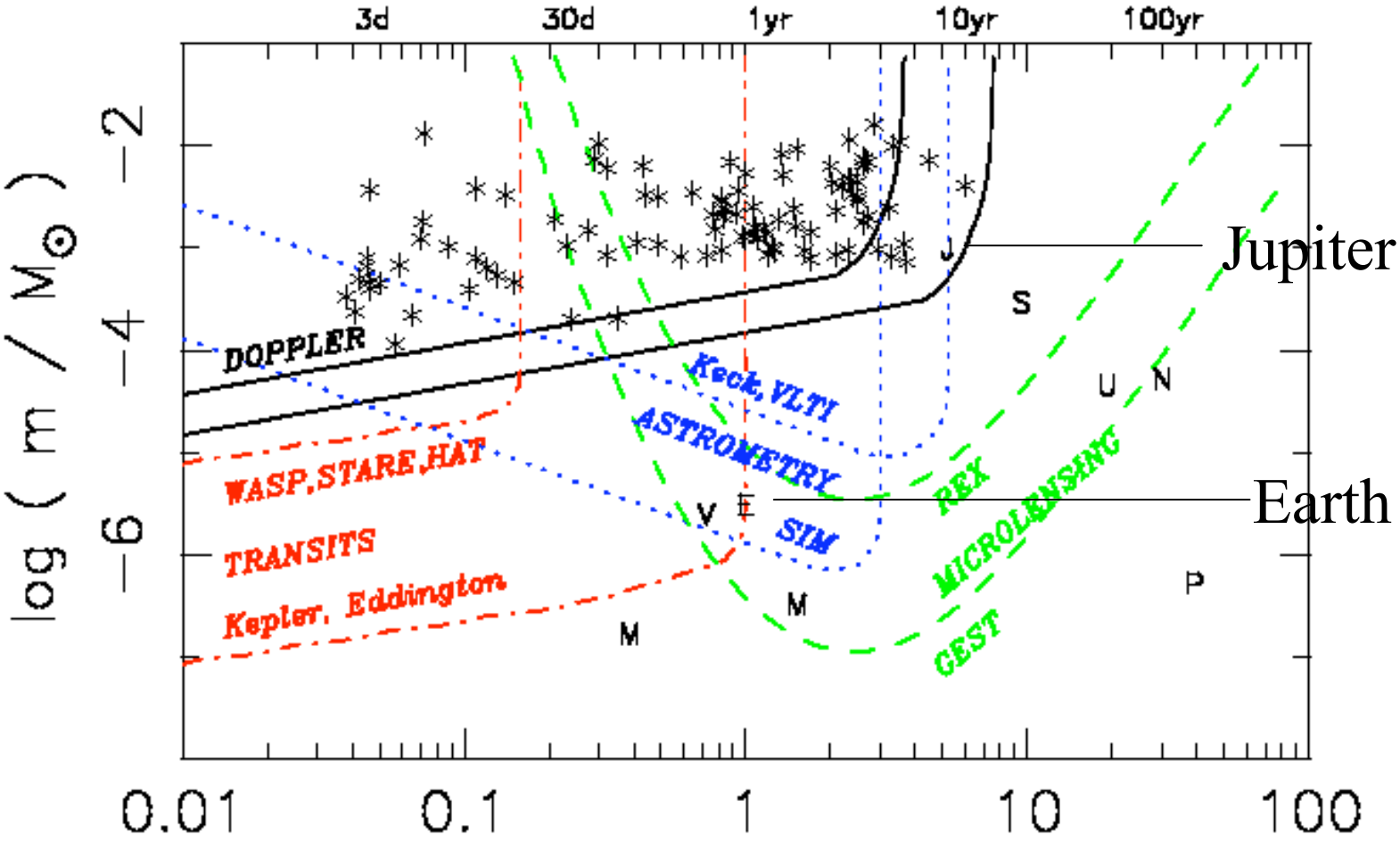


Wide range of planet masses and orbit sizes

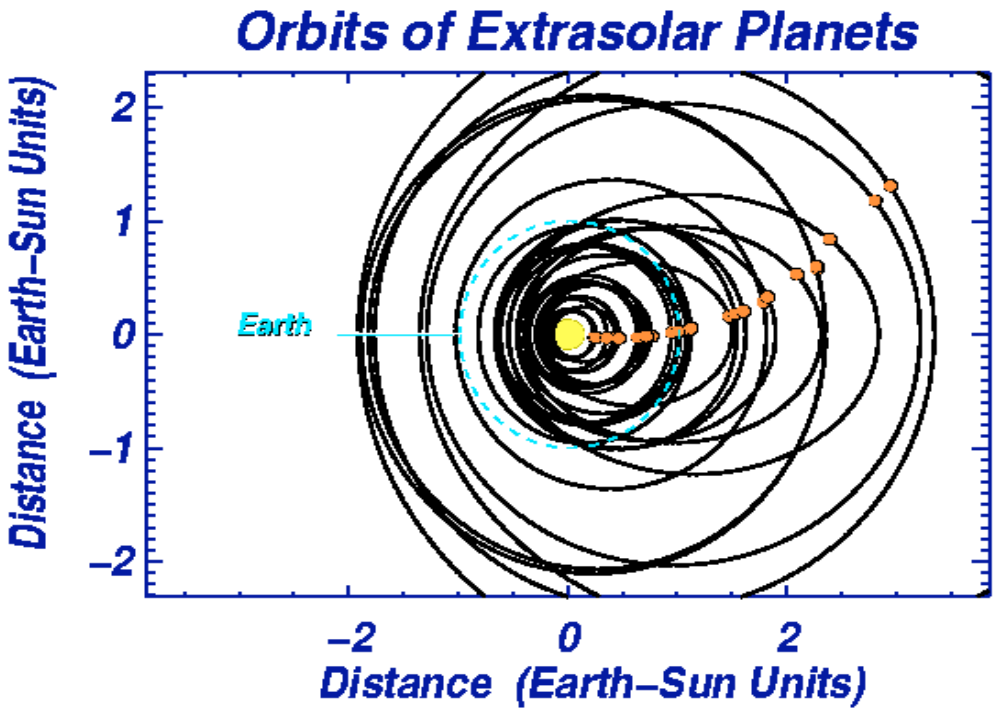
$m < 10\ m_{\mathrm{Jup}}$

$P > 3\mathrm{d}$

~100 Doppler wobble planets



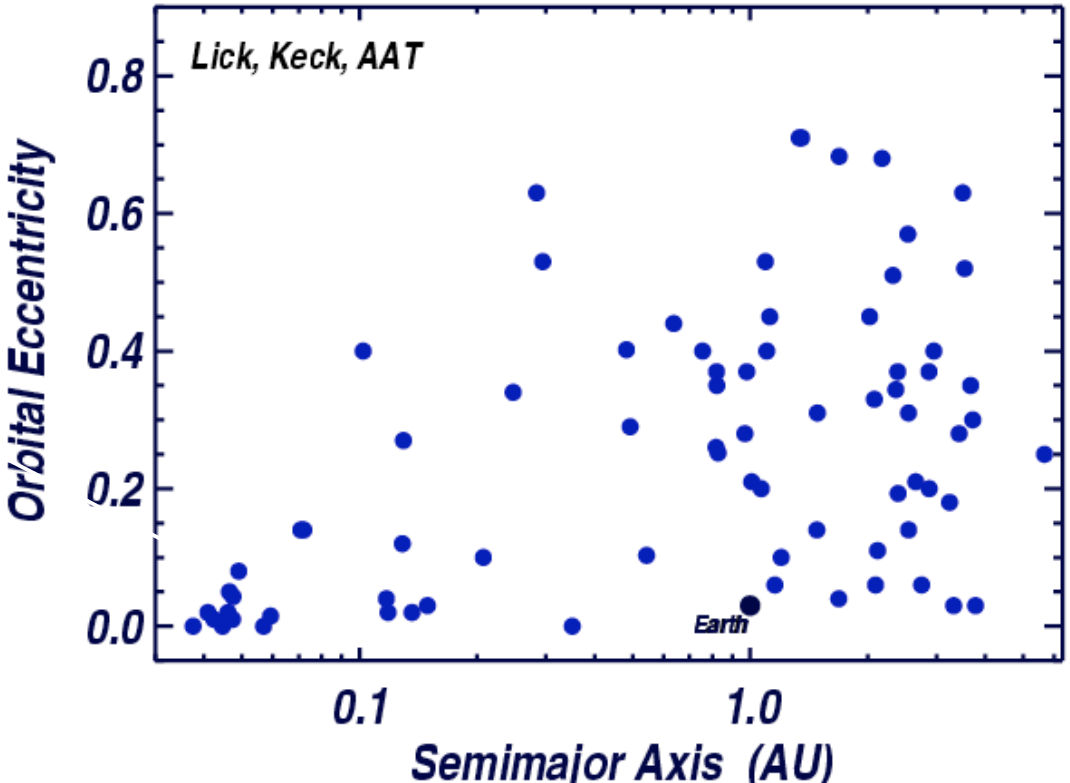
Eccentric Orbits



Planet-planet interactions

Small planets ejected

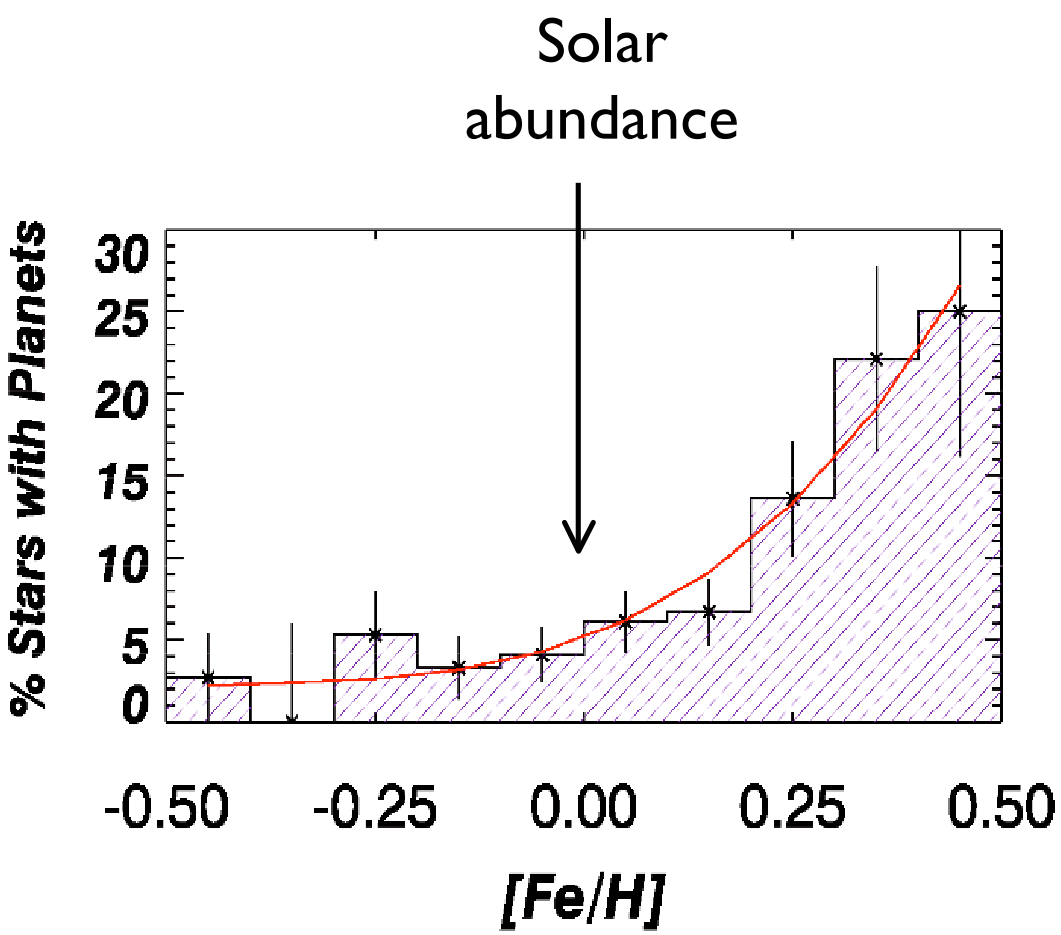
Tidal circularisation



More heavy elements

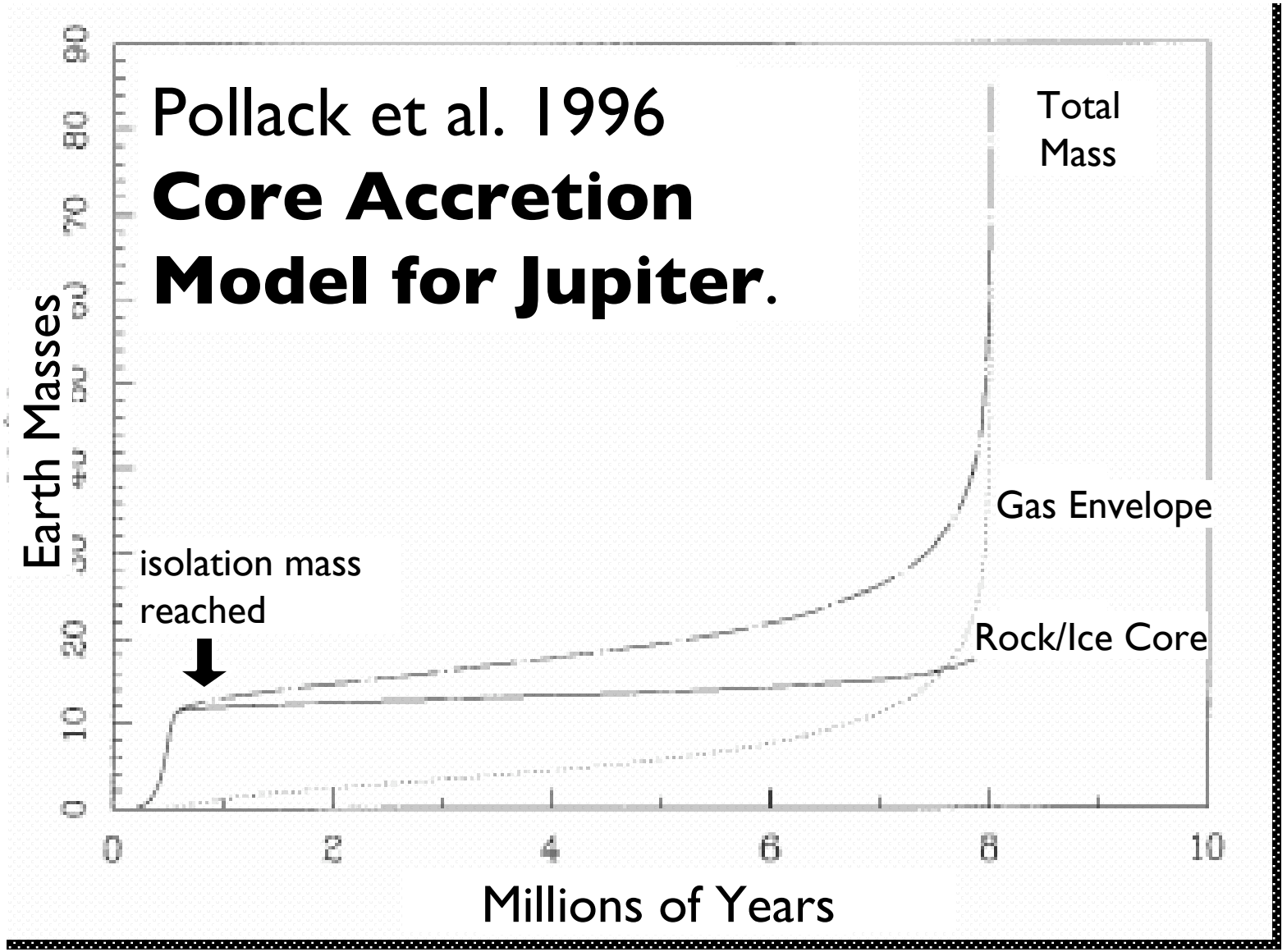
…

More planets



Santos 2003

Fischer & Valenti 2004



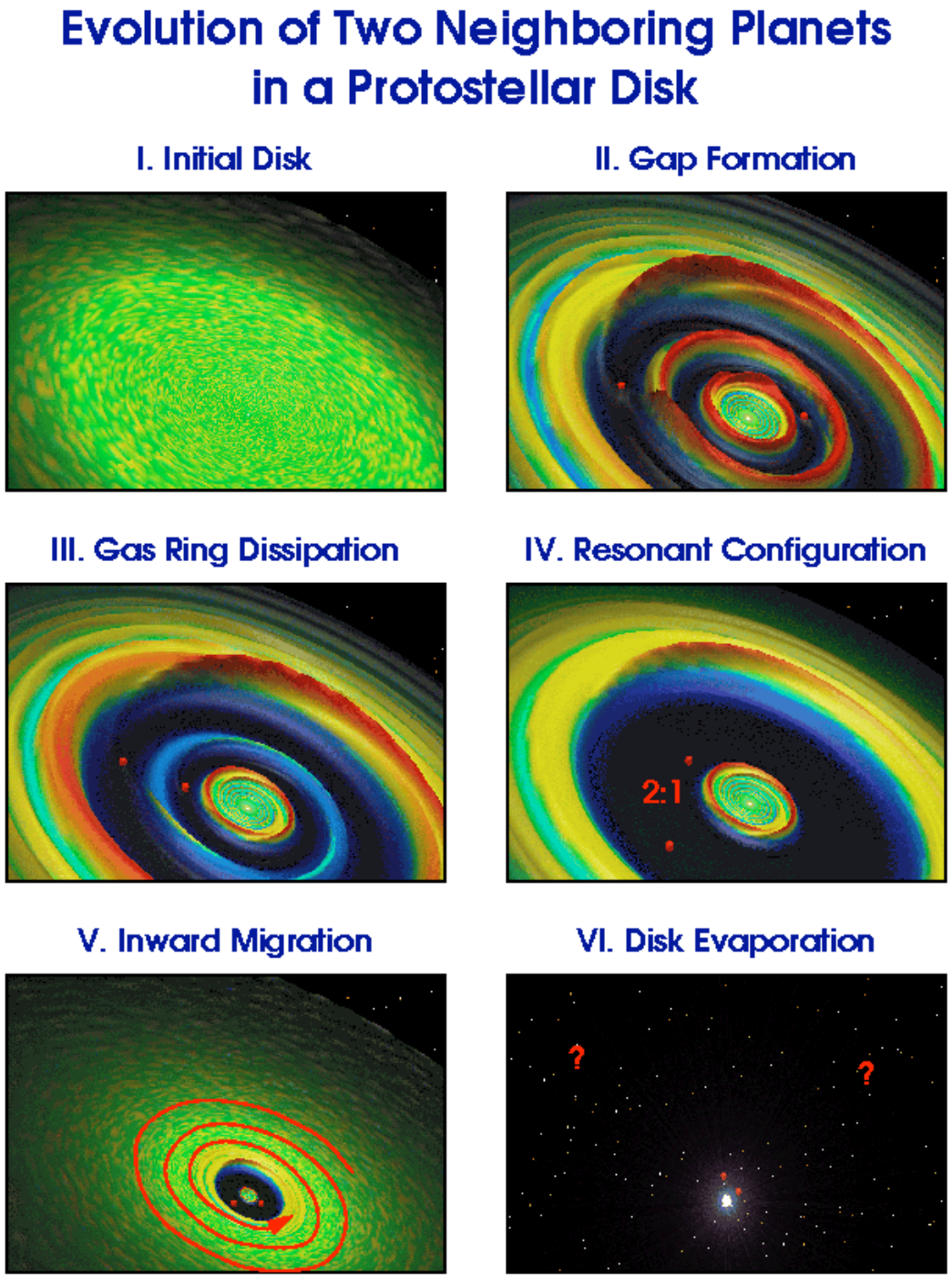
$$d = 5.2\,\mathrm{AU} \qquad \sigma_{solids} = 10\,\mathrm{g\,cm^{-2}}$$

$$T = 150\,\mathrm{K} \qquad \rho = 5 \times 10^{-11}\,\mathrm{g\,cm^{-3}}$$

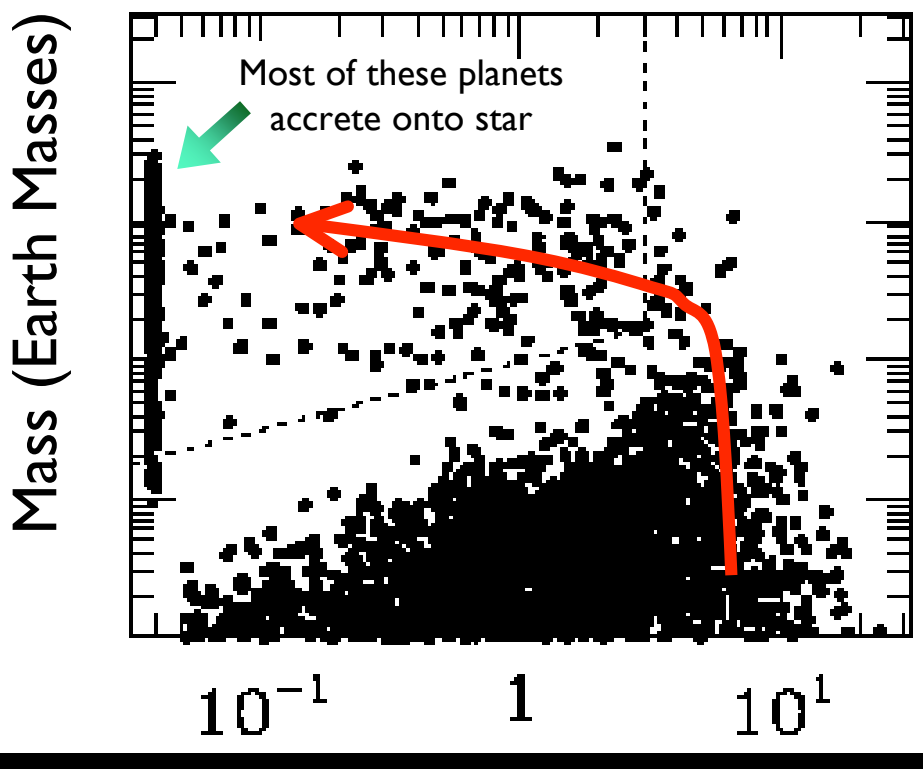
Hot Jupiters were a surprise

...

New Theories of Formation and Evolution

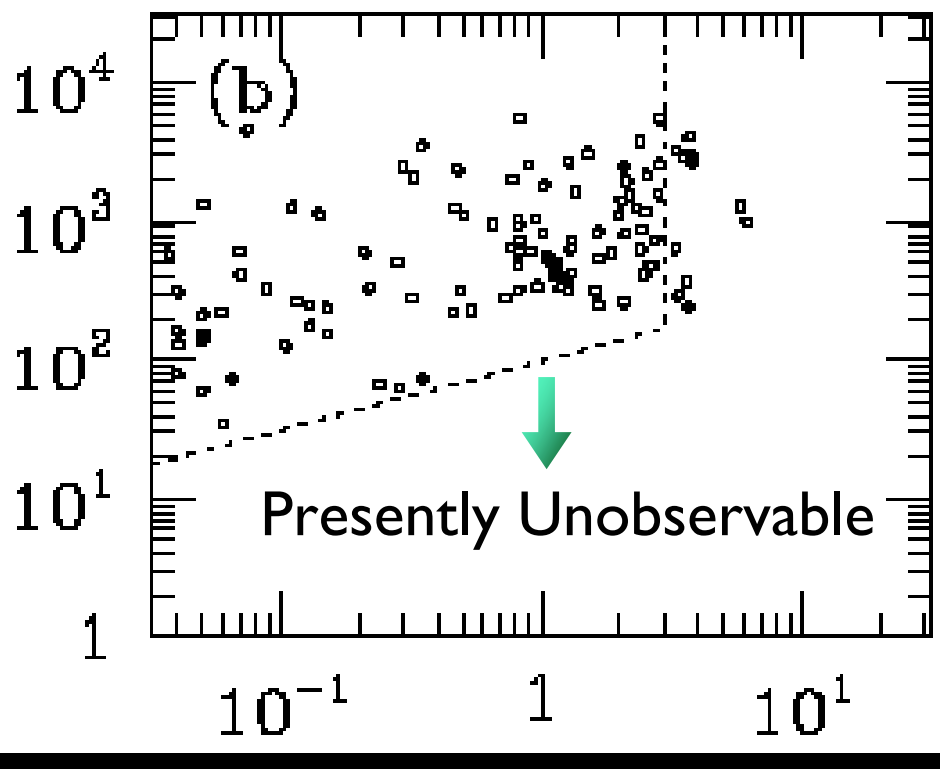


Ida & Lin Model Distribution



Semi-Major Axis (AU)

Observed Distribution

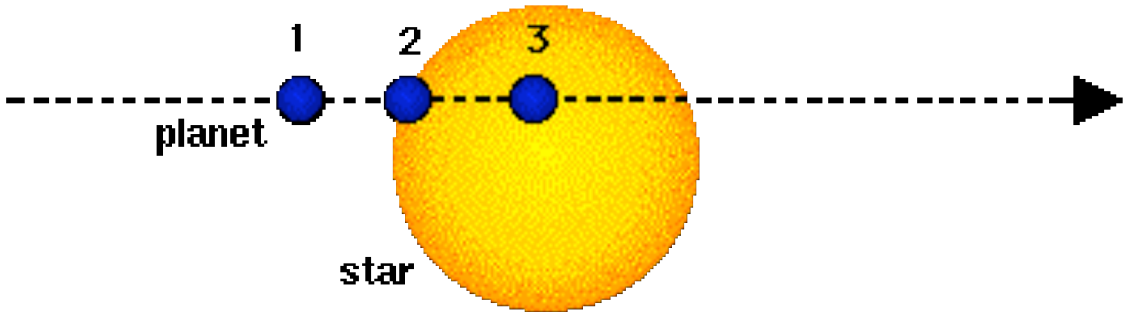


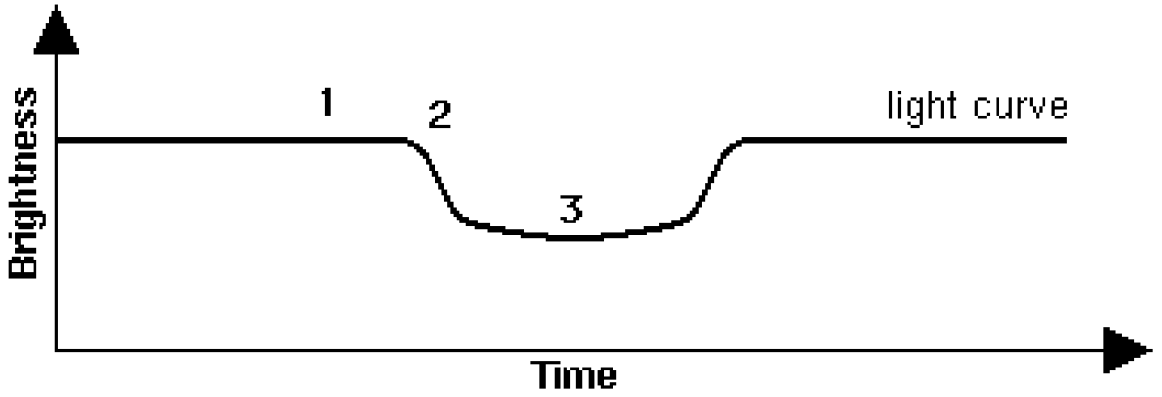
Semi-Major Axis (AU)

Ida and Lin (2004, 2005) carried out a large number of Monte-Carlo simulations which draw from distributions of disk masses and seed-planetesimals to model the process of core accretion in the presence of migration. These simulations reproduce the planet "desert", and predict a huge population of terrestrial and ice giant planets somewhat below the current detection threshold for radial velocity surveys.

$$\tau_{mig} = \frac{a}{\dot{a}} = 10^6 \frac{1}{f_(g,0)} \exp^{t/\tau_{dep}} (\frac{M_p}{M_J})(\frac{a}{1\mathrm{AU}})^{1/2} \mathrm{yr}$$

Transit Lightcurves





$$r_{Jup} \approx 0.1\, R_{Sun}$$

Depth :

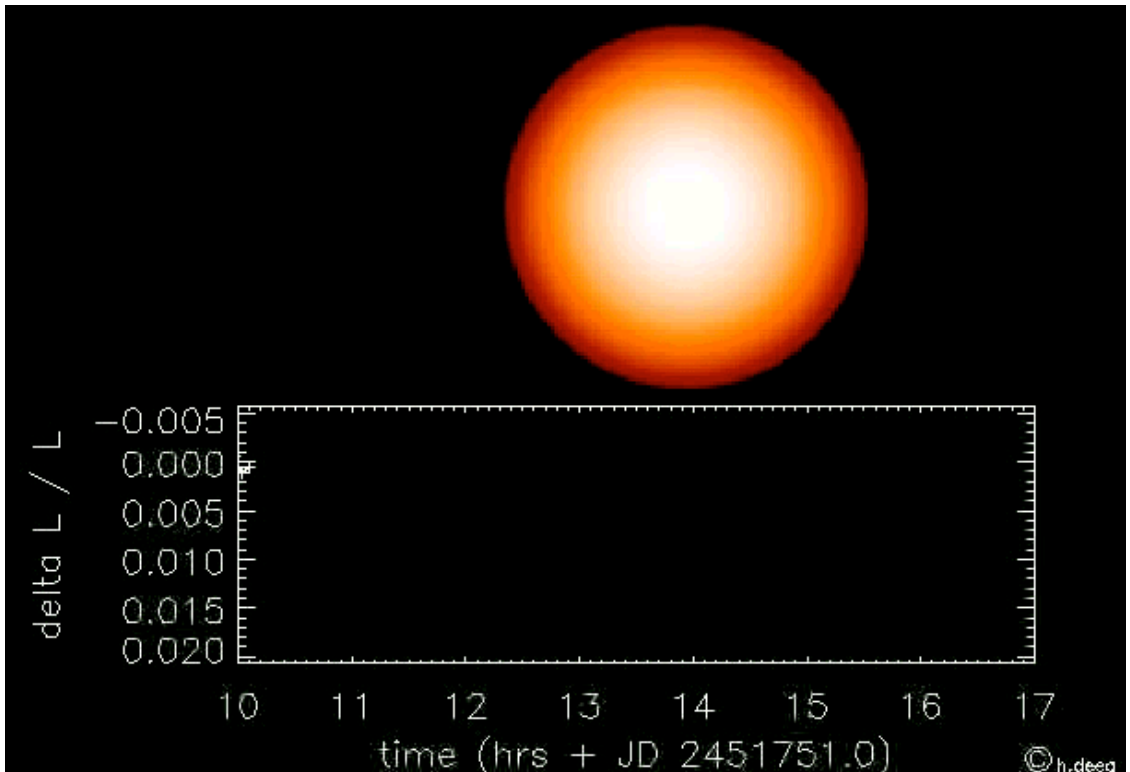
$$\frac{\Delta f}{f} \approx 1\% \left(\frac{r_p}{r_{Jup}}\right)^2 \left(\frac{R_*}{R_{Sun}}\right)^{-2}$$

Duration :

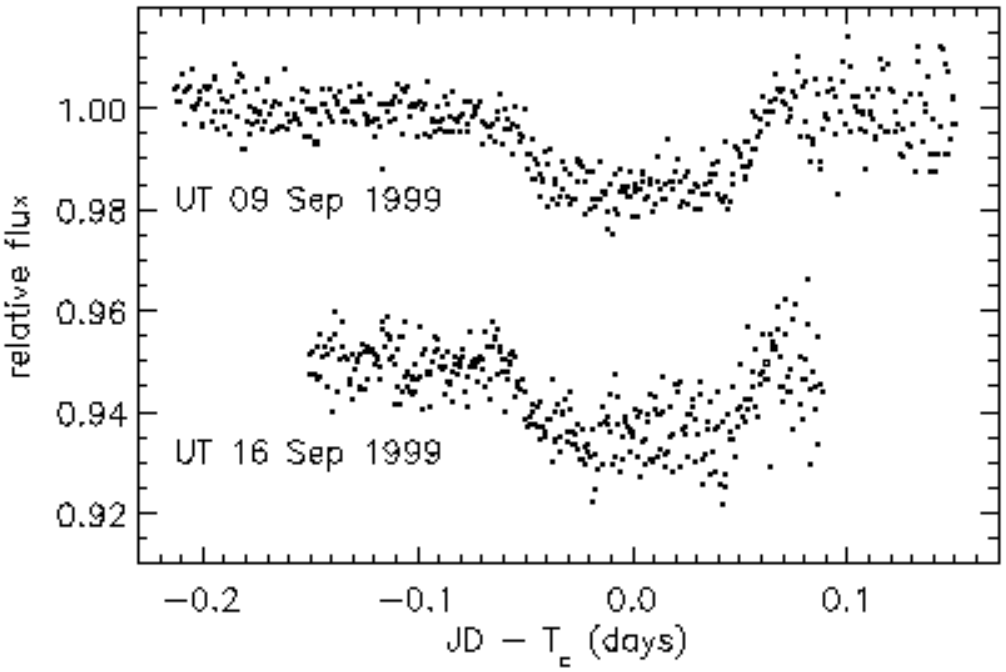
$$\Delta t \approx 3h \left(\frac{M_*}{M_{Sun}}\right)^{2/3} \left(\frac{P}{4d}\right)^{1/3}$$

Probability :

$$P_t \approx 10\% \left(\frac{R_*}{R_{Sun}}\right) \left(\frac{M_*}{M_{Sun}}\right)^{-1/3} \left(\frac{P}{4d}\right)^{-2/3}$$



1999 -- First Transiting Planet

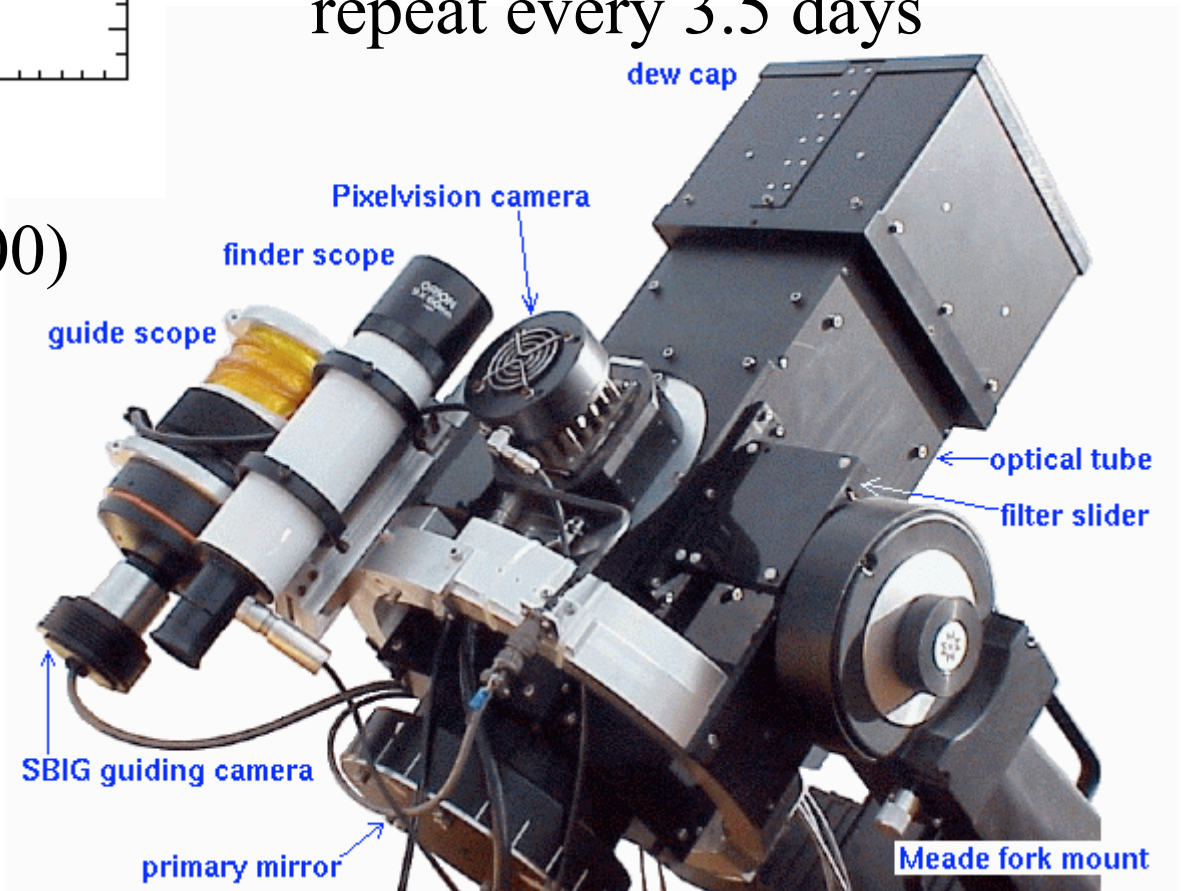


Charbonneau & Brown (2000)

HD 209458
V=7.6 mag

1.6% "winks"
last 3 hours
repeat every 3.5 days

STARE 10 cm telescope

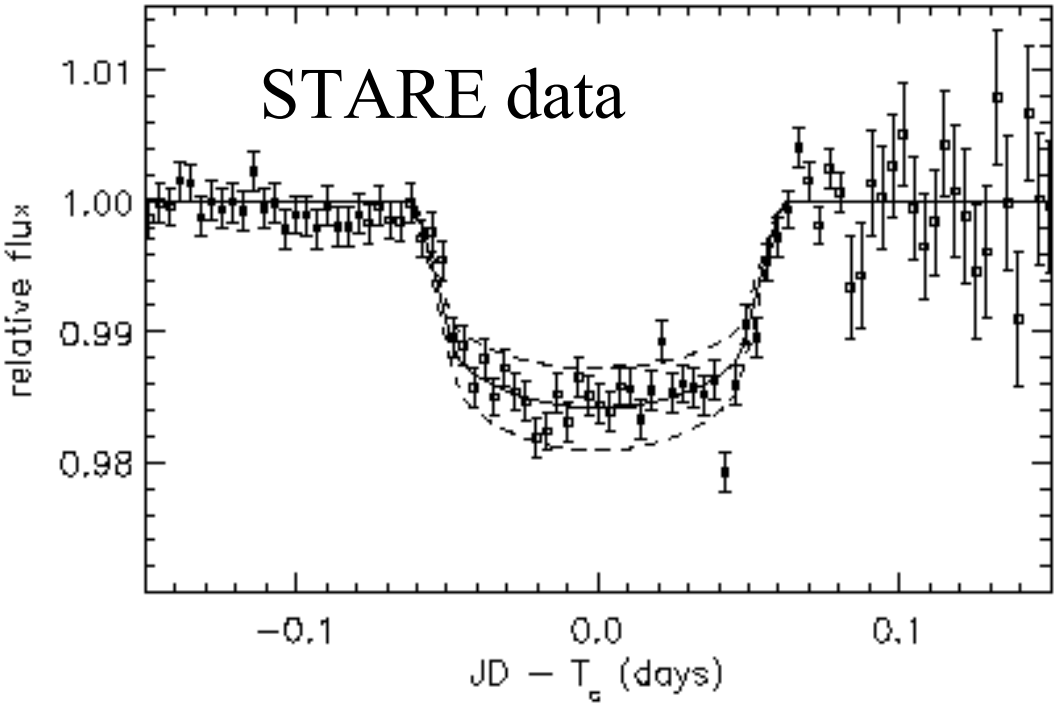


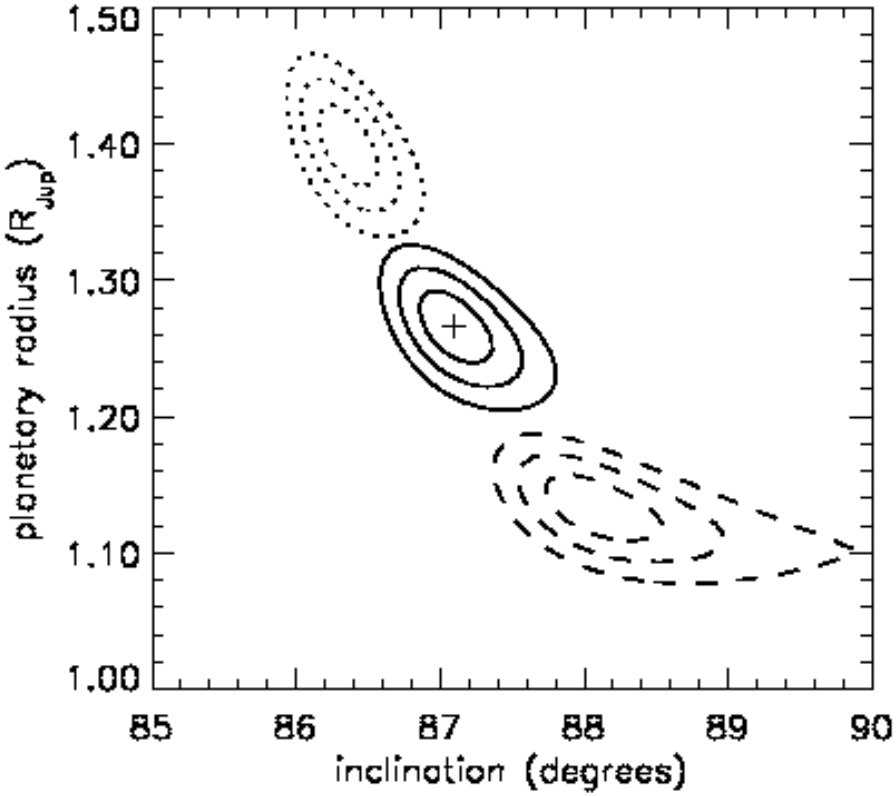
HD 209458b is a "Bloated" Gas Giant a "Fat" Hot Jupiter

$m \sim 0.63\ m_{Jup}$

$r \sim 1.3\ r_{Jup}$

$i \sim 87^{o}$



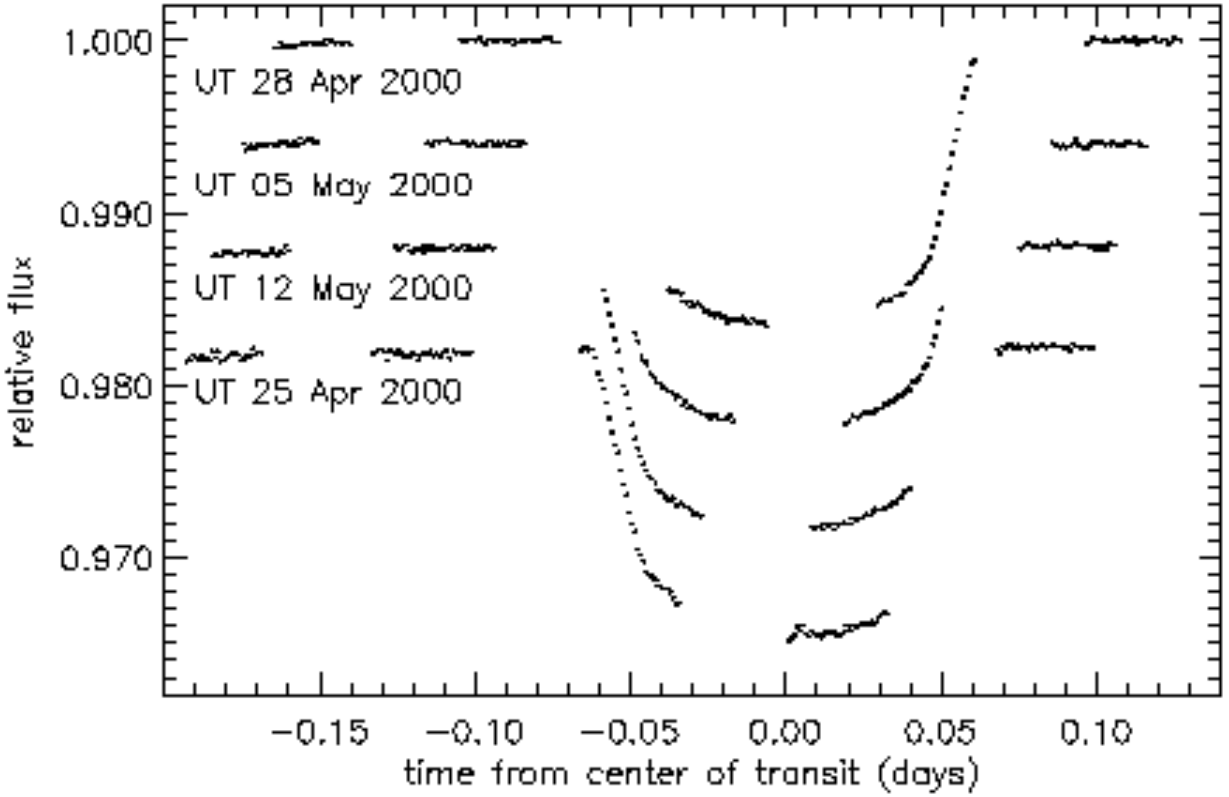


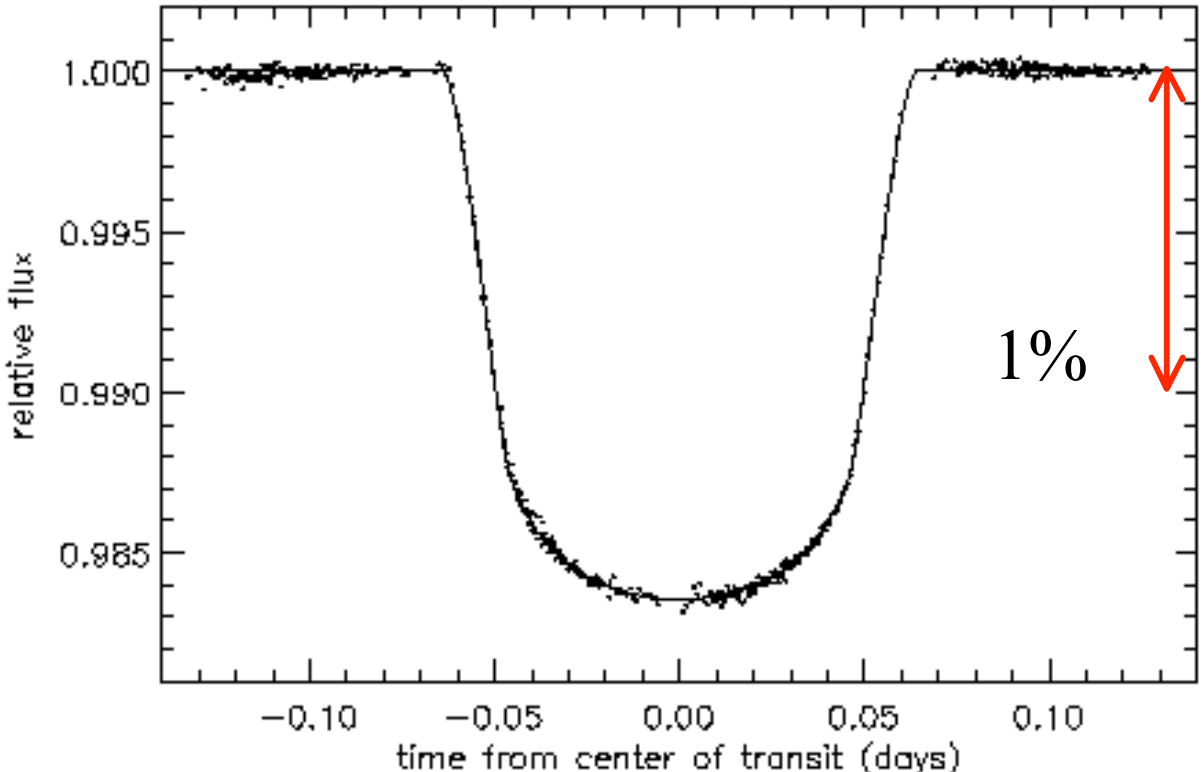
HST/STIS HD 209458 Transits

Brown et al. (2001)

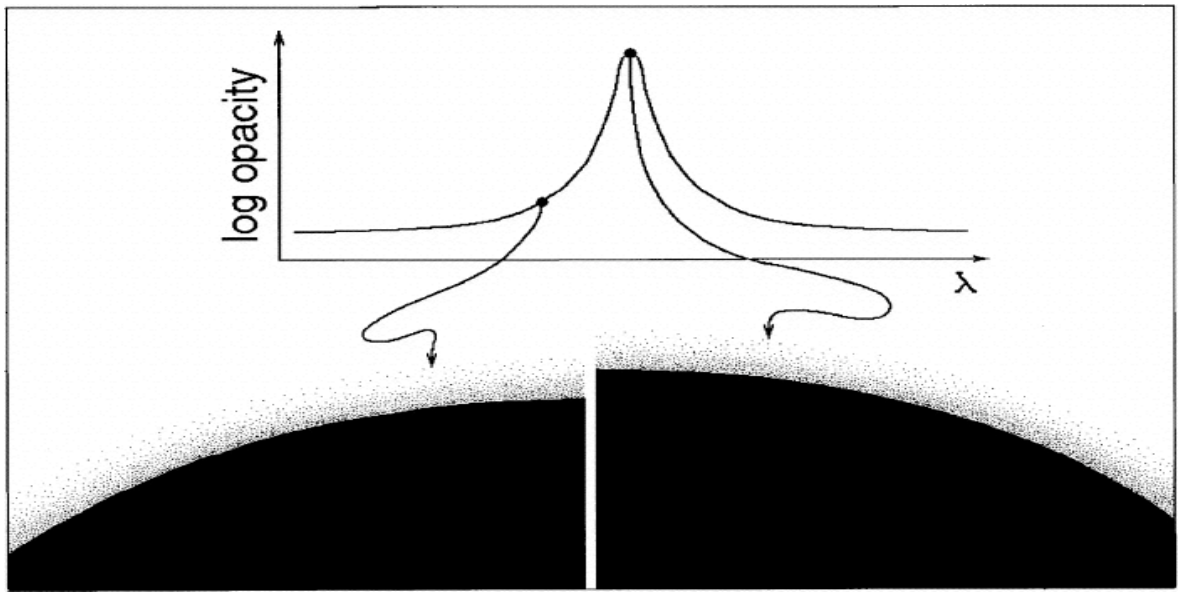
$r = 1.35 \pm 0.06\ r_J$

$i = 86^o.6 \pm 0^o.2$





Transit Spectroscopy



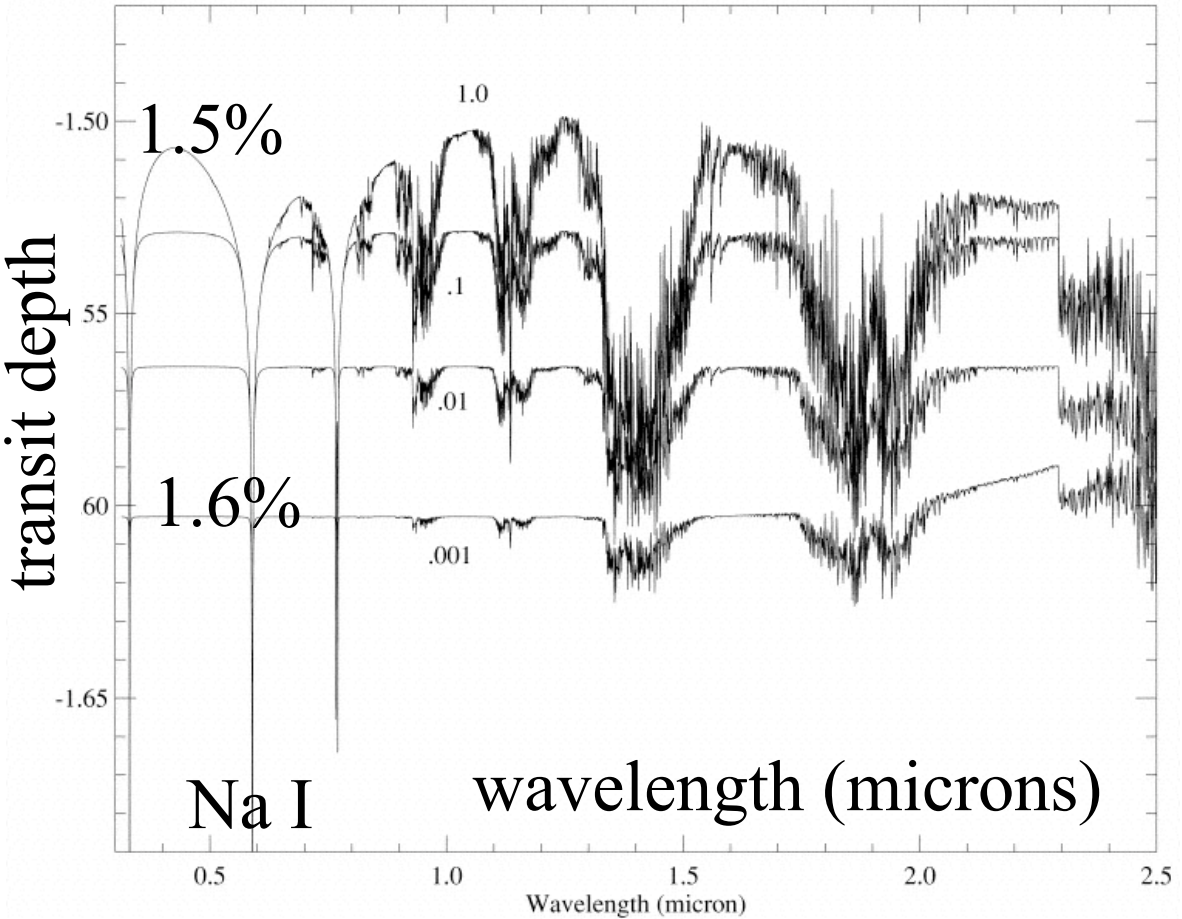
Brown (2001)

planetary atmosphere

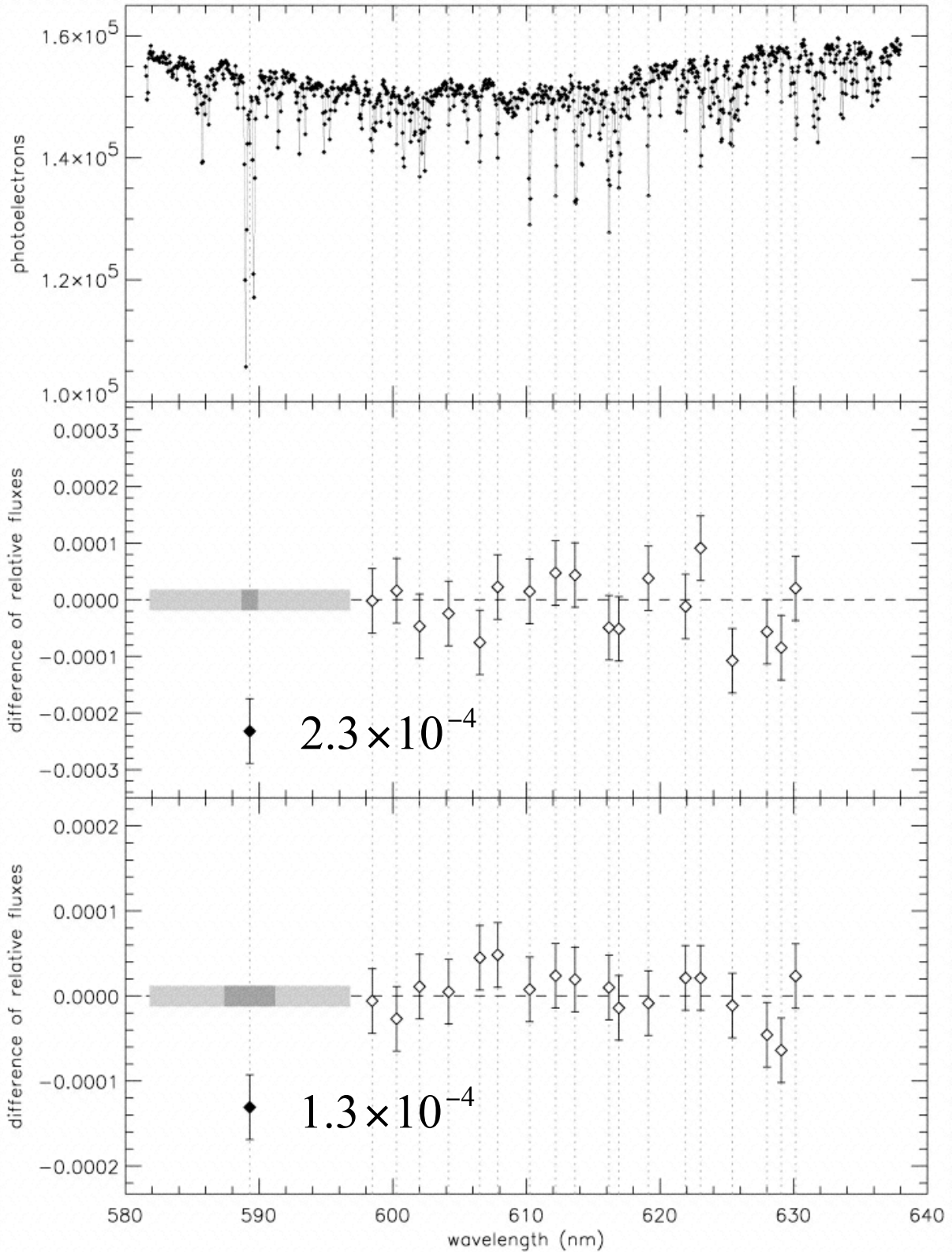
composition

cloud decks

winds



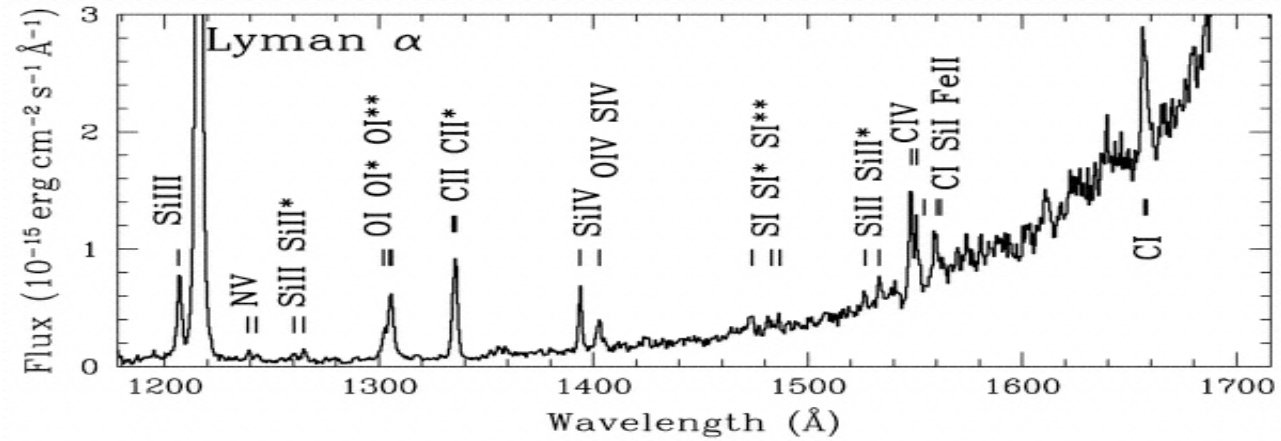
HST Transit Spectroscopy detects Na I in the atmosphere of HD 209458b

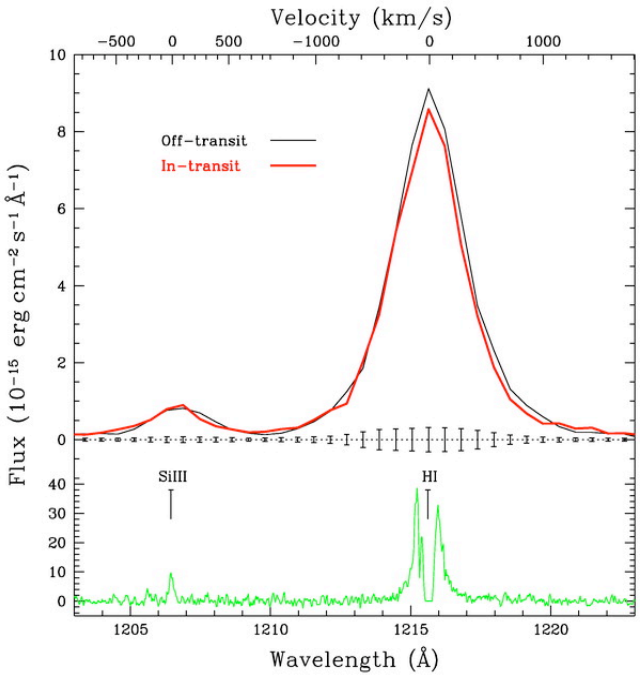


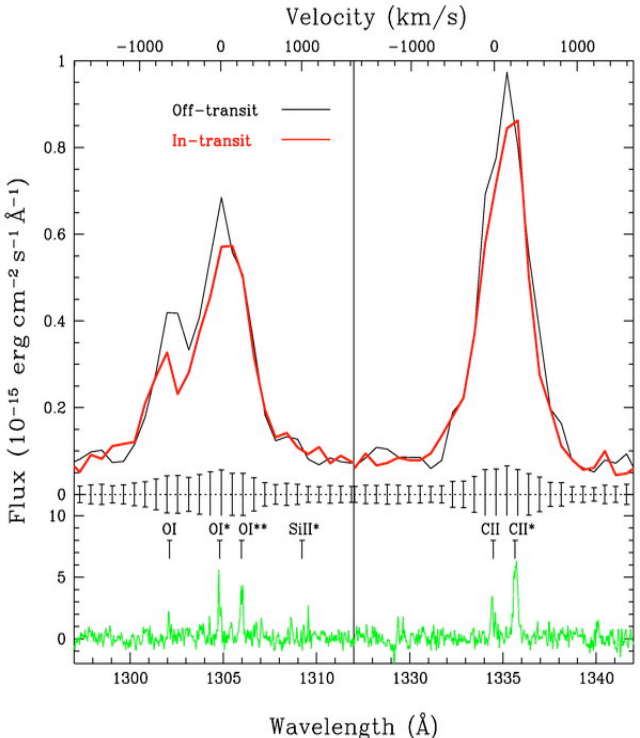
Charbonneau et al. (2002)

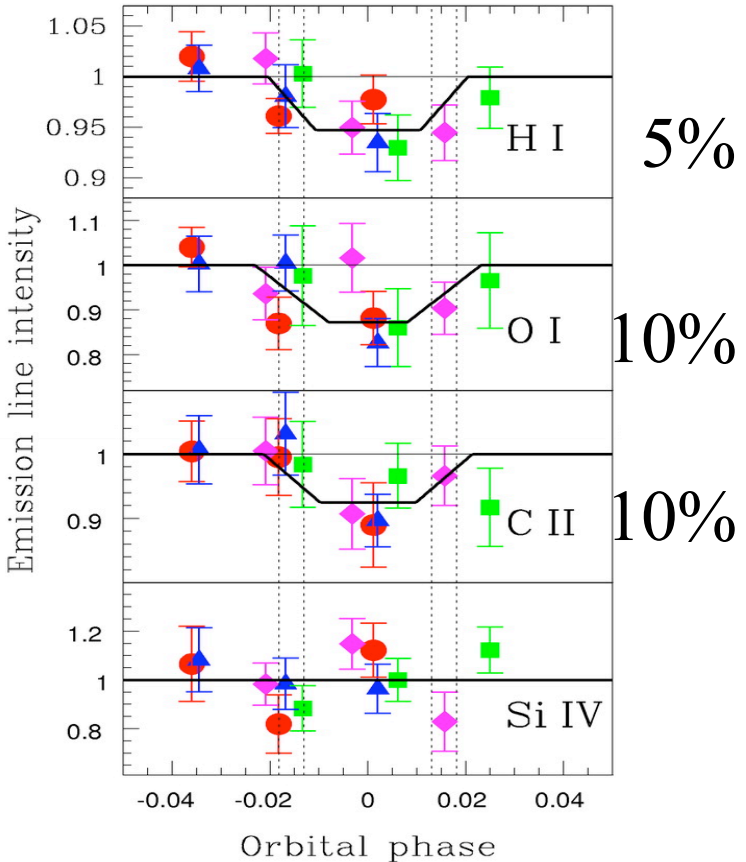
Evaporating Atmosphere

Vidal-Madjar et al. (2003)

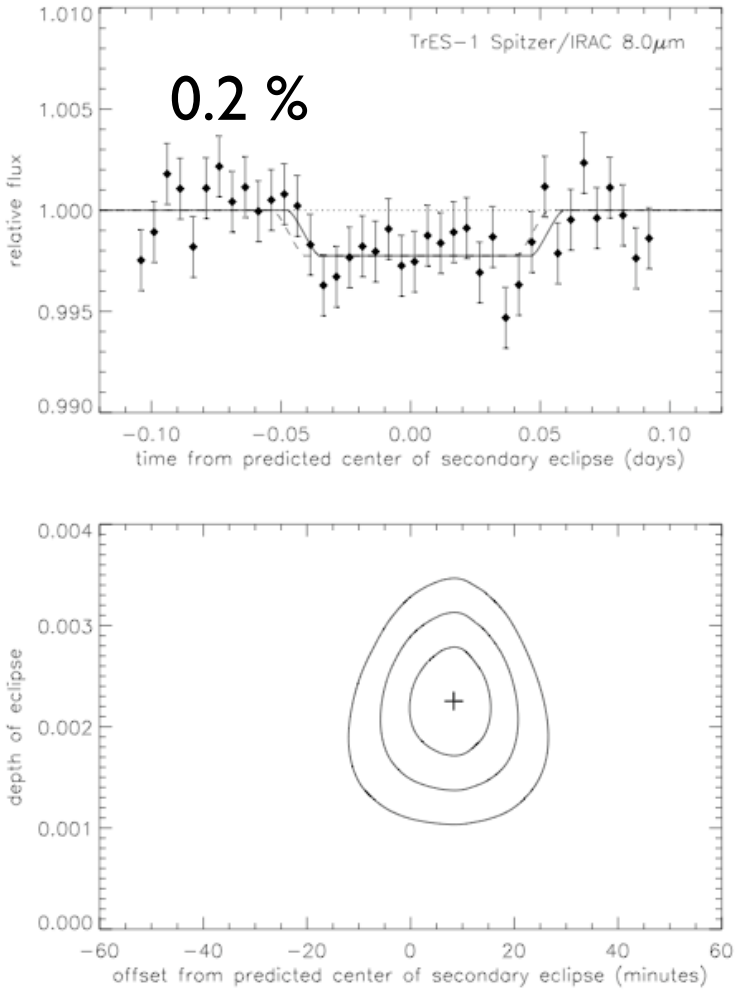




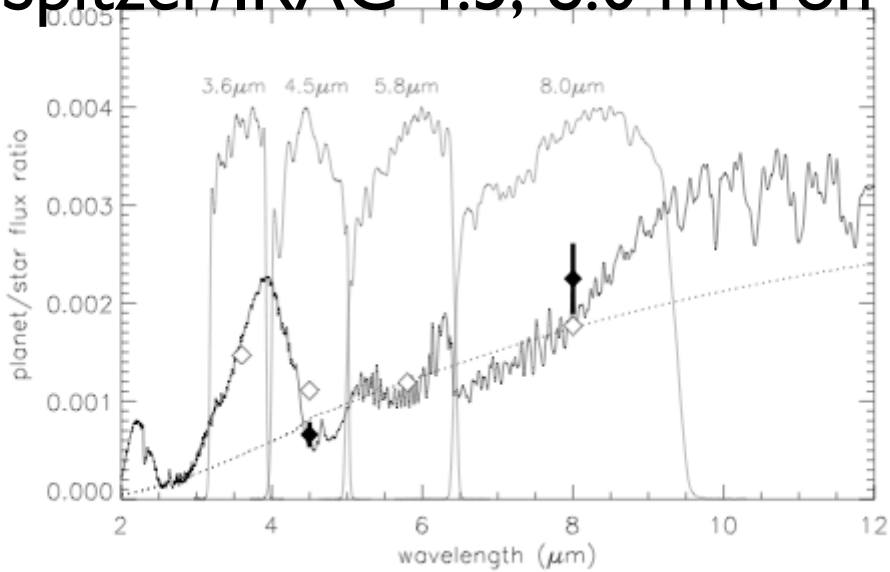




Star occults planet



Infrared Space Telescope:
Spitzer/IRAC 4.5, 8.0 micron



TrES-1: Charbonneau et al. 2005

HD 209458: Deming et al. 2005

Direct detection of infrared light from planet

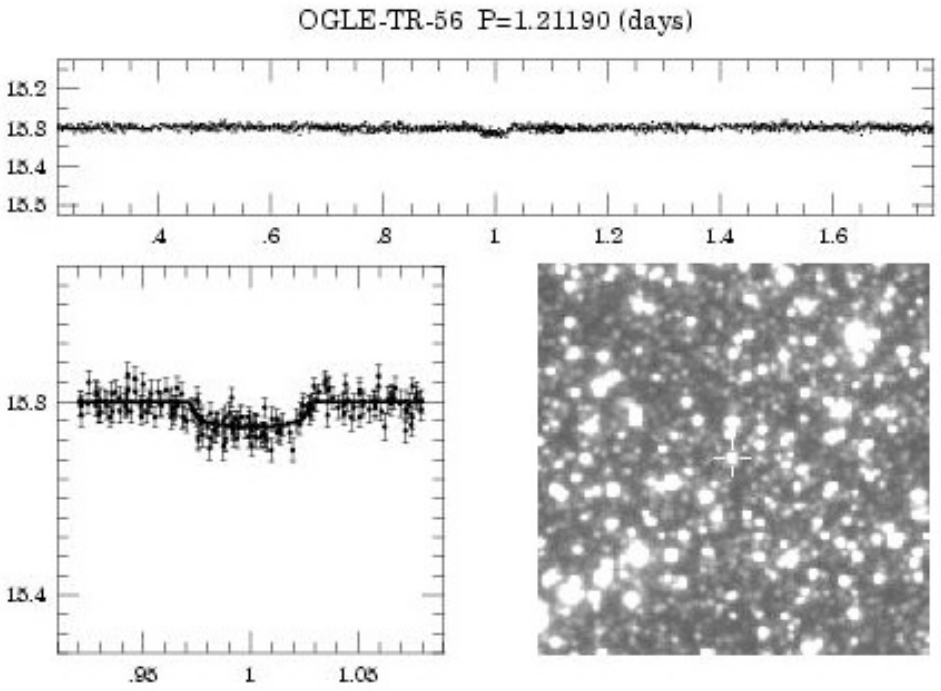
UK WASP Experiment
Wide-Angle Search for Planets

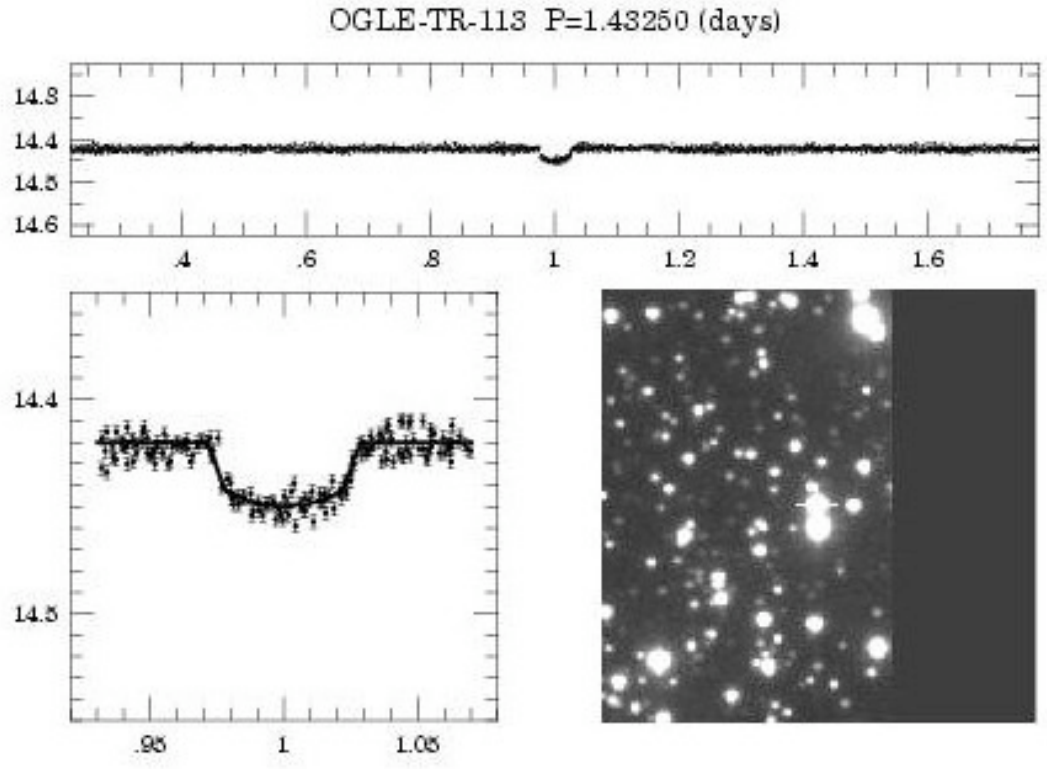
2004 SuperWASP La Palma
2005 SuperWASP SAAO

Robotic Mount
8 cameras / mount
11cm F/1.8 lens
2K x 2K E2V CCD
8^o x 8^o field
15 arcsec pixels

UK WASP Consortium: Belfast, St.Andrews, Keele, Open, Leicester, Cambridge, IAC, ING, SAAO. D.Pollacco = PI

OGLE III Transit Candidates





3m Las Campanas (microlens survey telescope)

Mosaic 8-chip CCD camera

2001 Galactic Bulge -- 64 candidates
2002 Carina -- 73 candidates

2004 Nov

Deep surveys of Galactic Plane fields yield **many false alarms**:

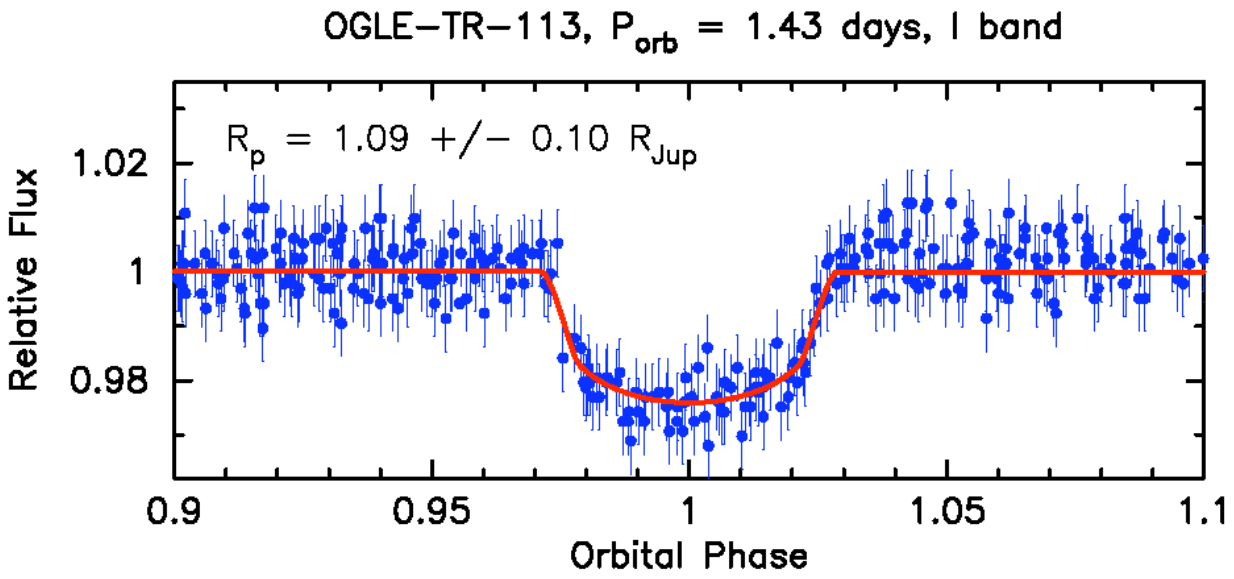
grazing or blended eclipsing binaries,

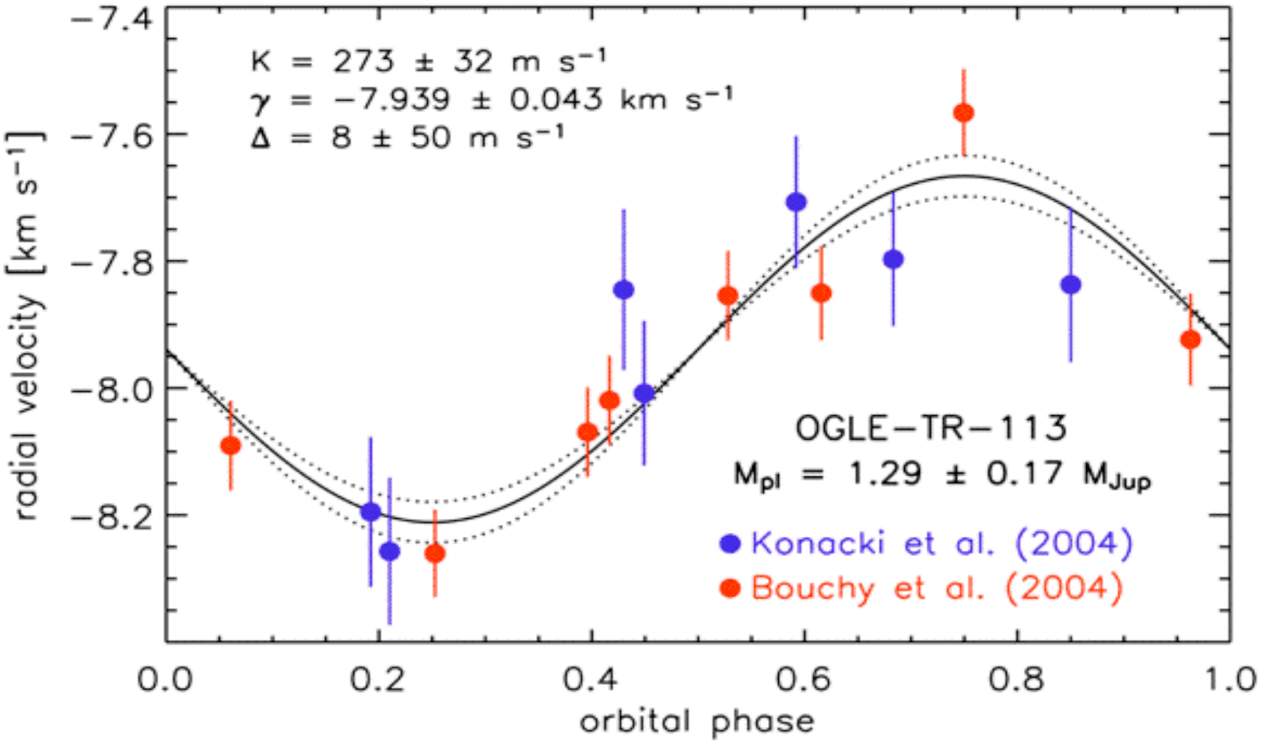
brown dwarf eclipses

6 planets discovered by transits

and confirmed by radial velocities

3 with P < 3d (?)

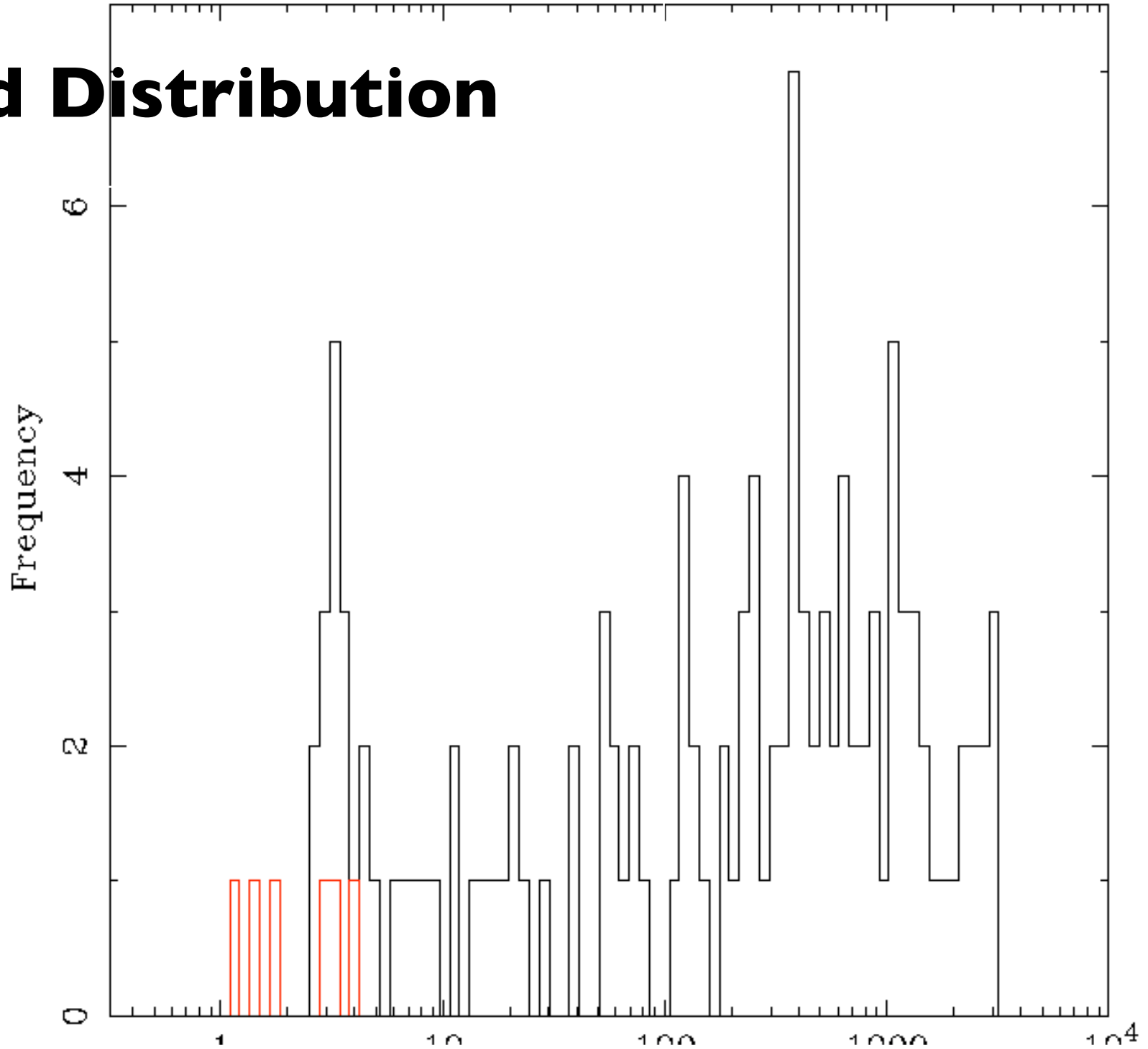




Period Distribution

New class of very-hot Jupiters?

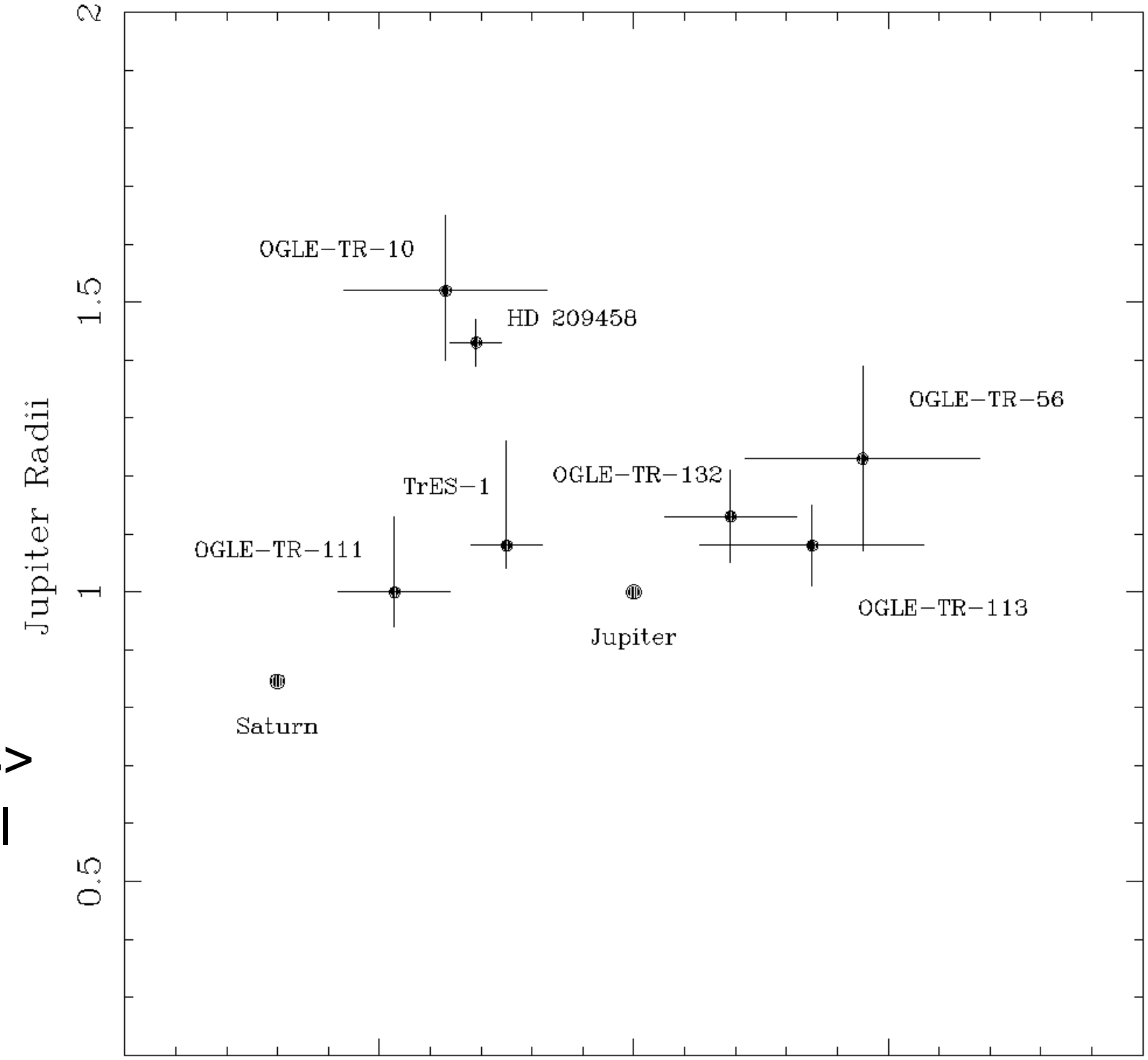
Different selection effects ?



Radius vs Mass

At least 2 parameters

Rapid inspiral --> no time to cool

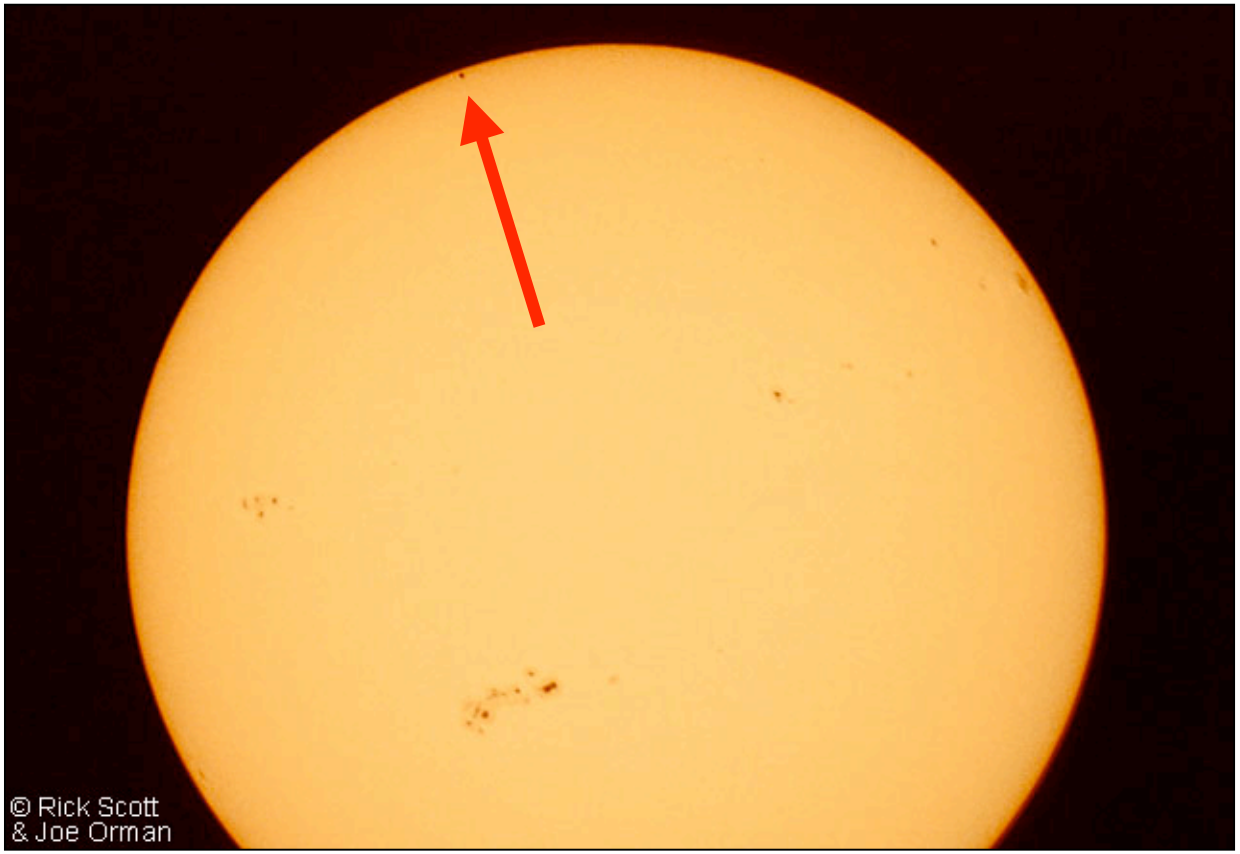


How to find Earths

- ***Hot Earths***: transits from space
  - 2006 … Corot
  - 2008 … Kepler

- ***Cool Earths***: microlensing
  - OGLE, MOA
  - PLANET, microFUN
  - RoboNet (--> REX)

Mercury transiting the Sun 1999 Nov 15



Earth transits:

$$\frac{\Delta f}{f} \sim 10^{-4}$$

HST results suggest this is feasible.

Mercury transits:

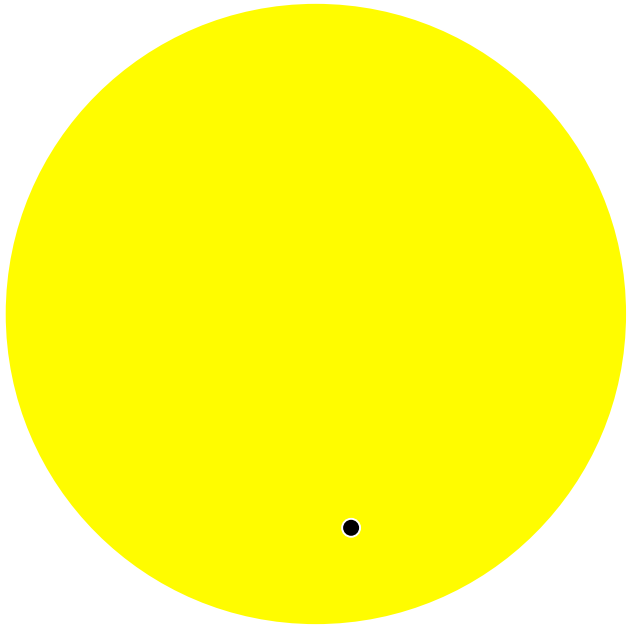
2003 May 07
2006 Nov 08

Venus transits:

2004 Jun 08
2012 Jun 06

Space Transit Missions

Designed to detect Earth analogs



$$r \sim r_{\oplus} \sim 0.01\ R_{sun}$$

$$T \approx 300\text{K}$$

$$P \sim 1\ \text{yr}$$

$$a \sim 1\ \text{au}$$

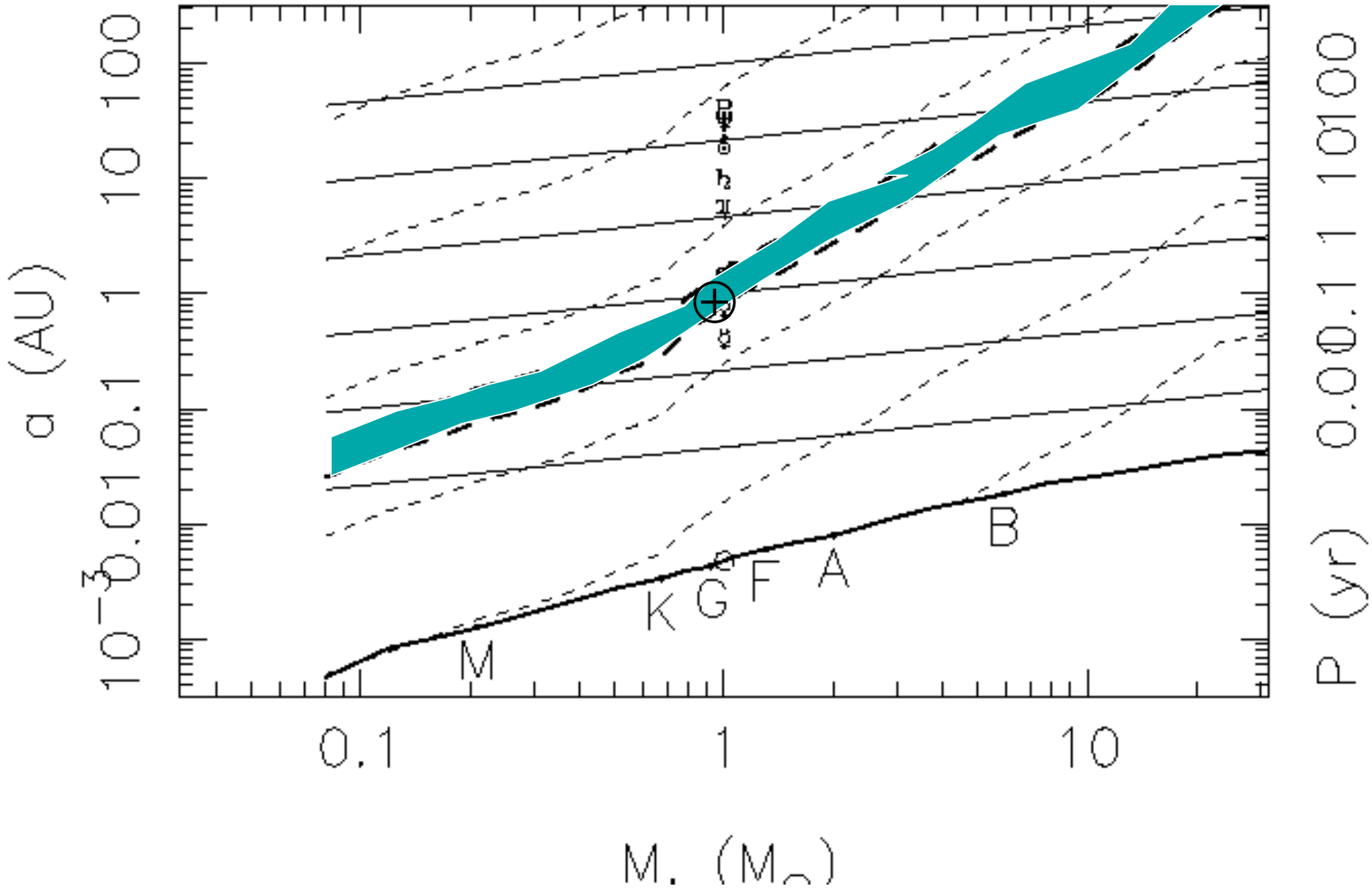
$$\Delta t \sim 13\ \text{h}$$

$$\Delta f / f \sim 10^{-4}$$

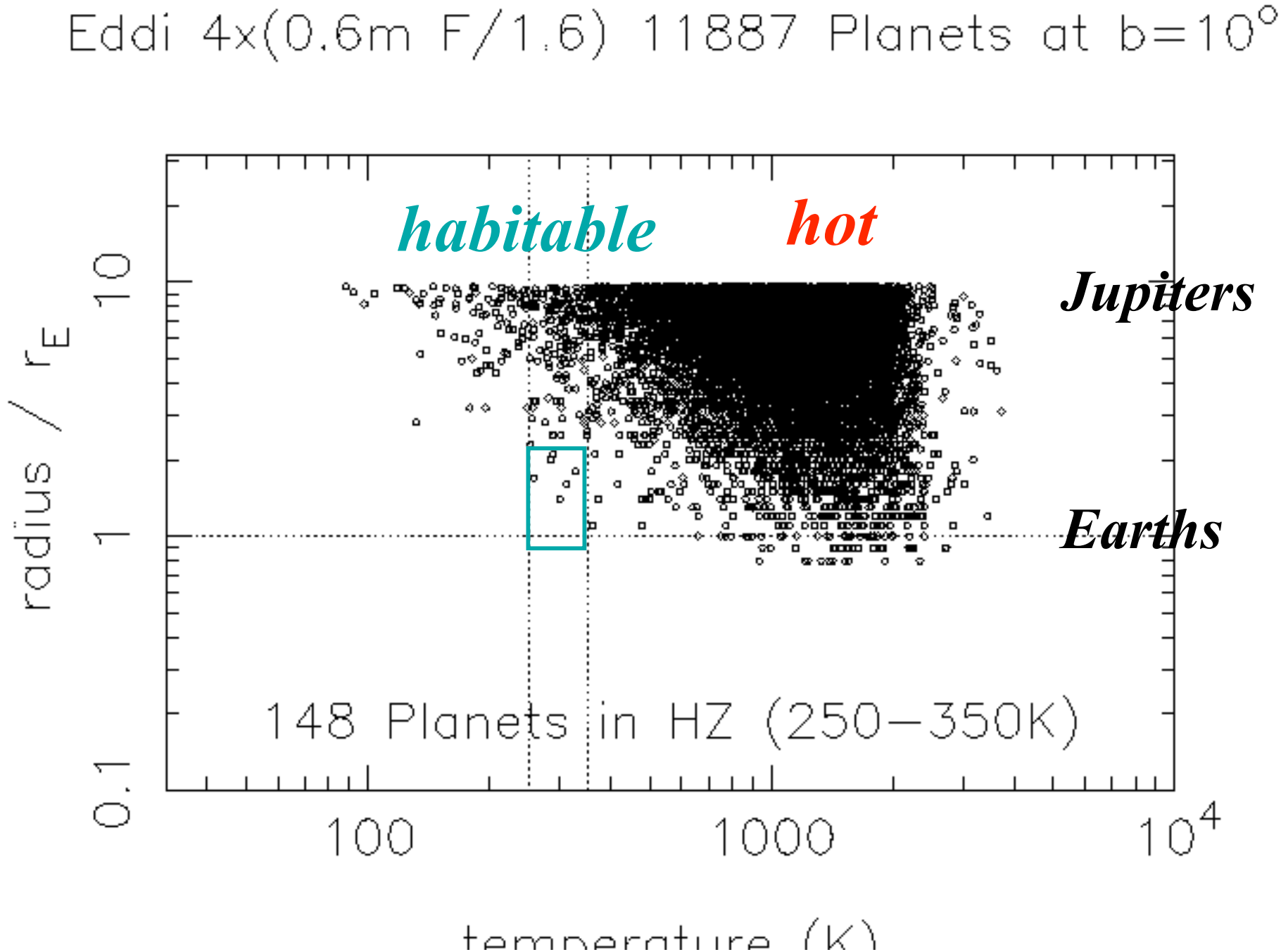
Transit probability: $P_t \sim 0.5\%$

"The Habitable Zone"

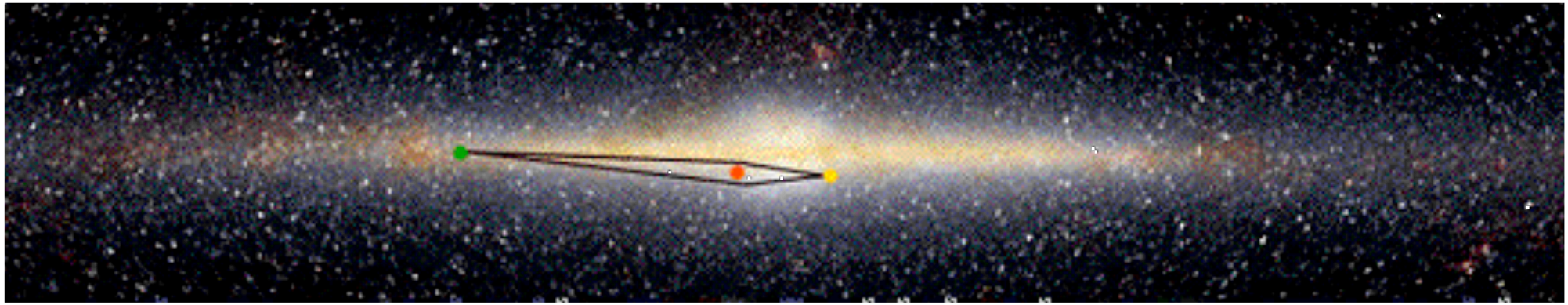
T~300K

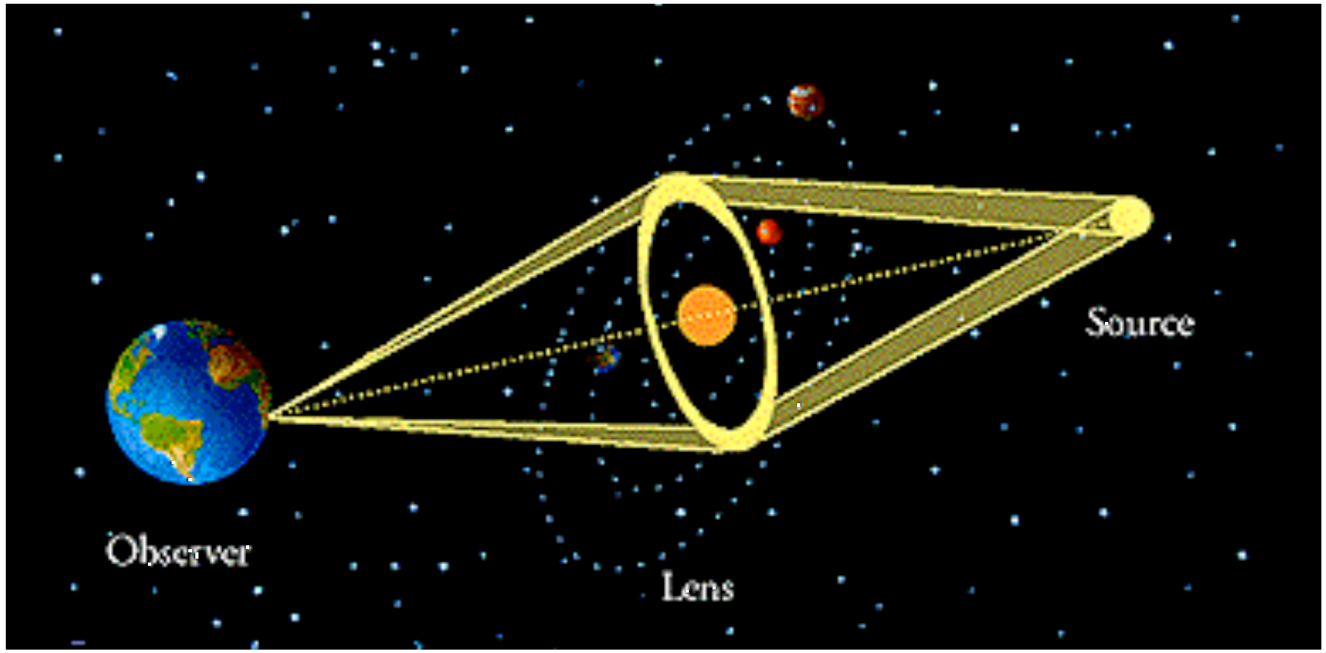


Eddington Planet Catch Simulation



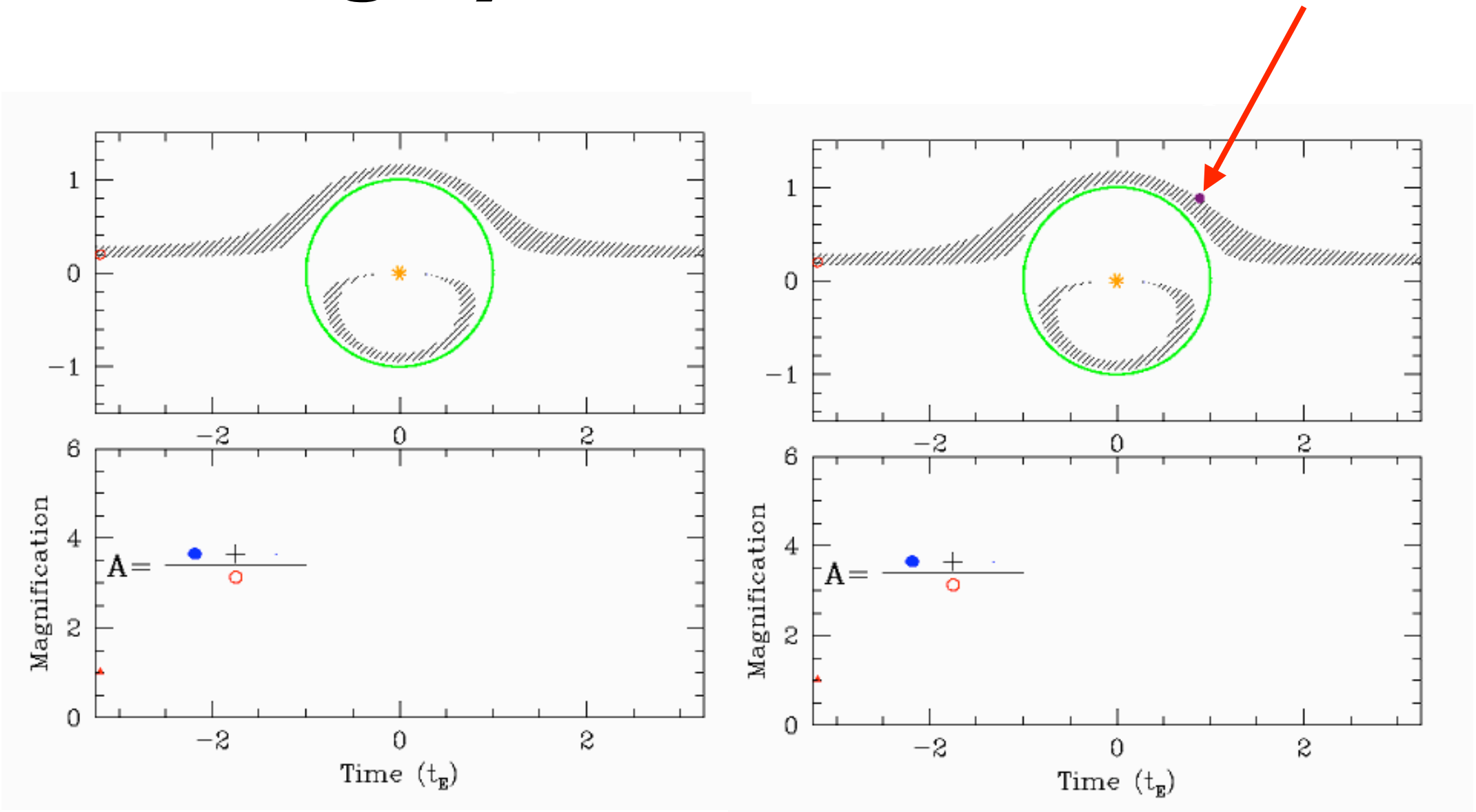
Gravitational Microlensing





Hunting for
Cool Planets
near the
Lens Star

Lensing by a Star with a Planet



~600 Galactic Bulge lensing events found each year

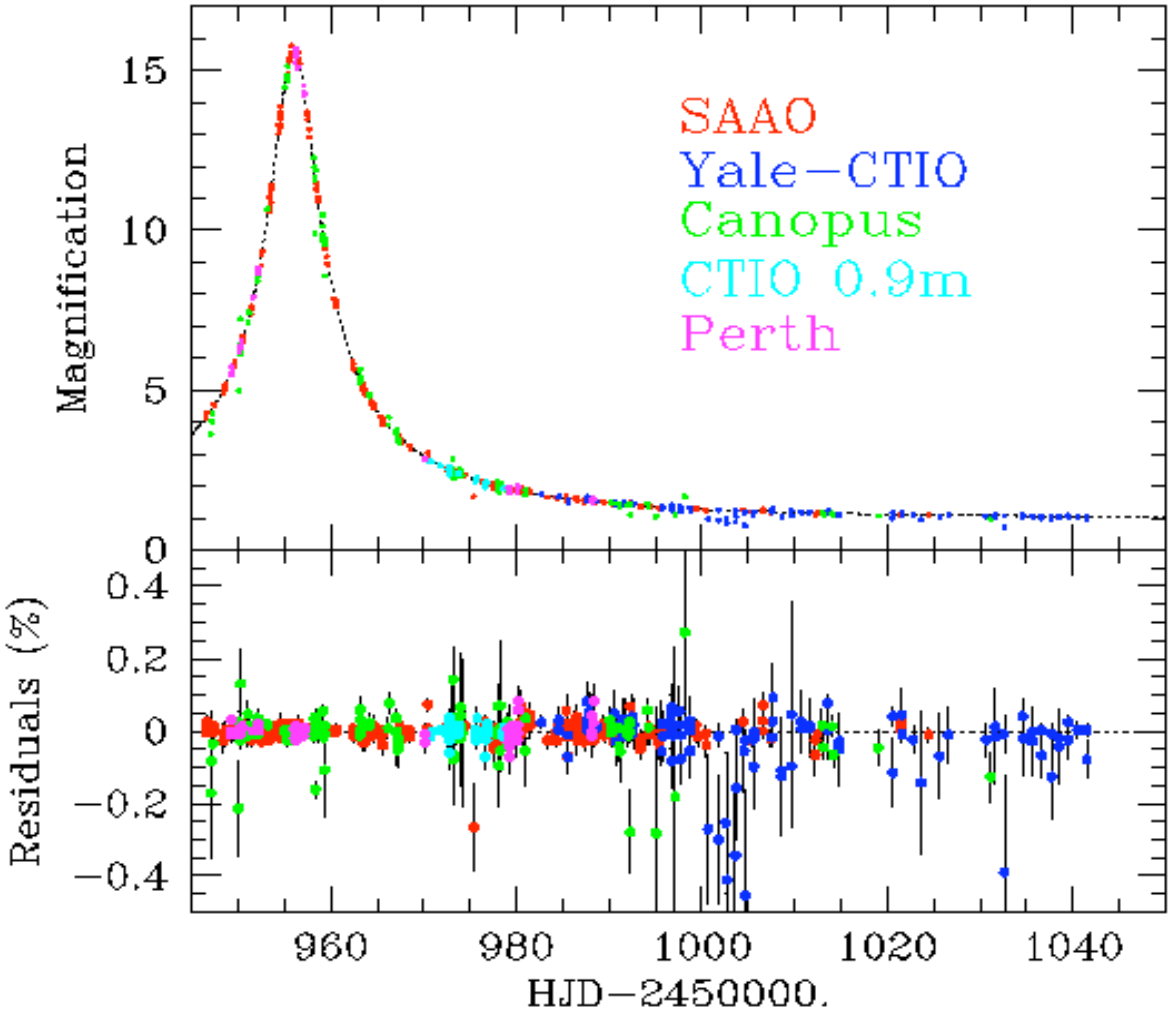
$M_{\rm lens} \sim 0.3\, M_{\rm sun}$ $R_{\rm E} \sim 4$ AU $\sim 10^{-3}$ arcsec

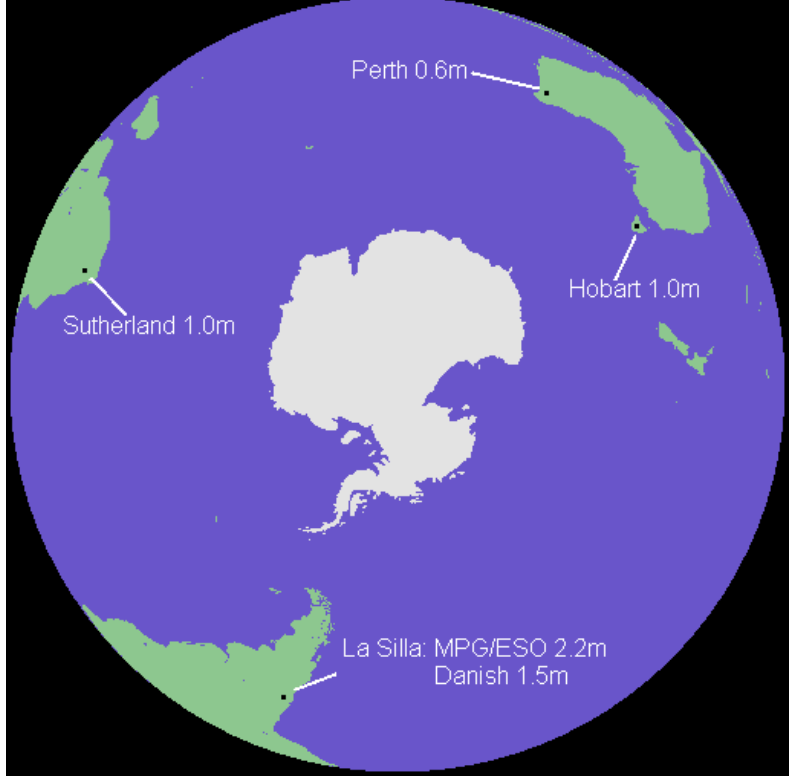
(Animations by Scott Gaudi)

Microlens Network

OGLE MOA microFUN

PLANET / RoboNet





~600 events/year

0.6m - 2m telescopes

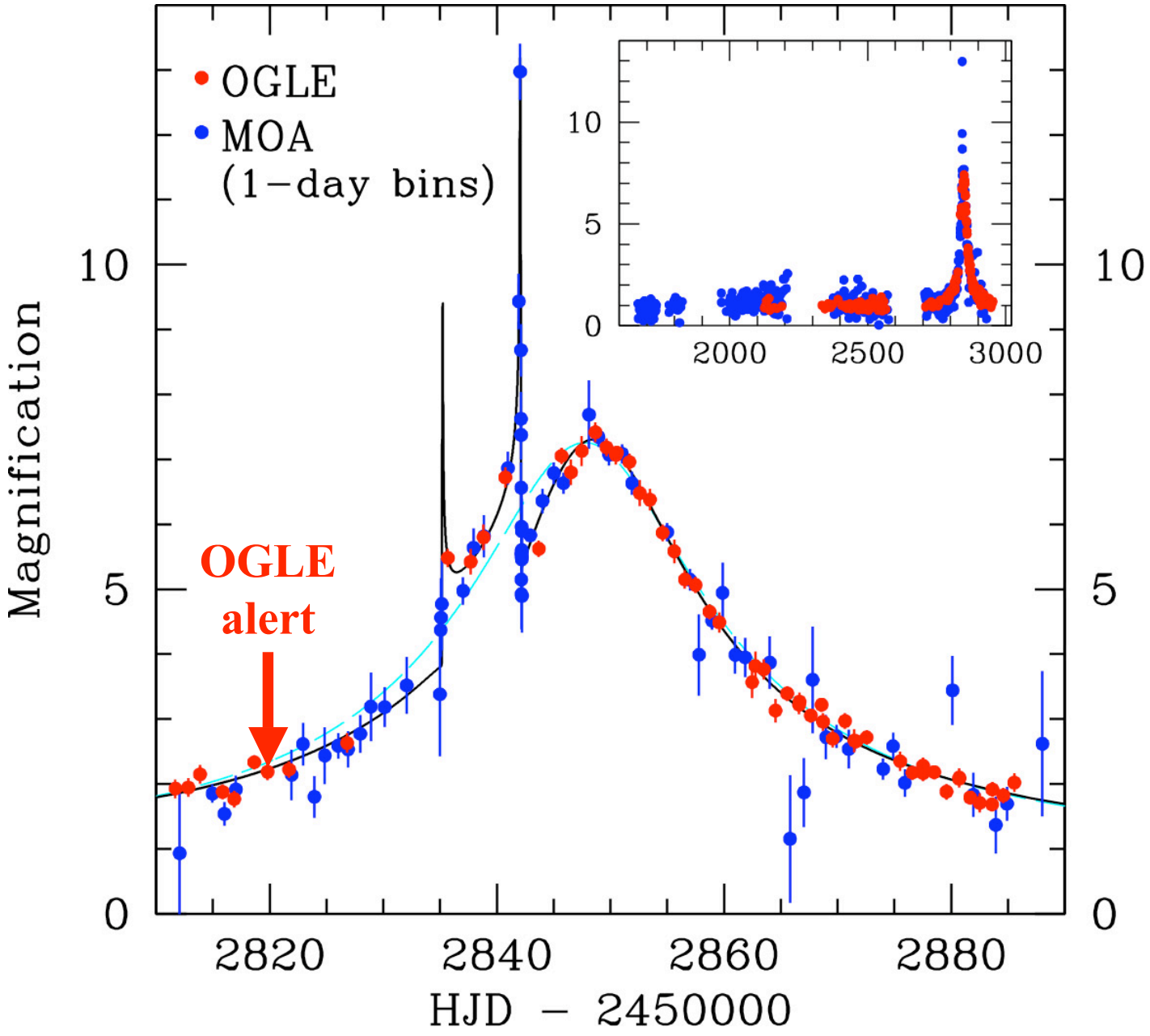
southern sites

selected events

~24-hour coverage

2004 - first microlens planet

$m \sim 1.5\ m_{Jup}$



Bond et al. 2004
(MOA+OGLE)

2005 - 2nd microlens planet

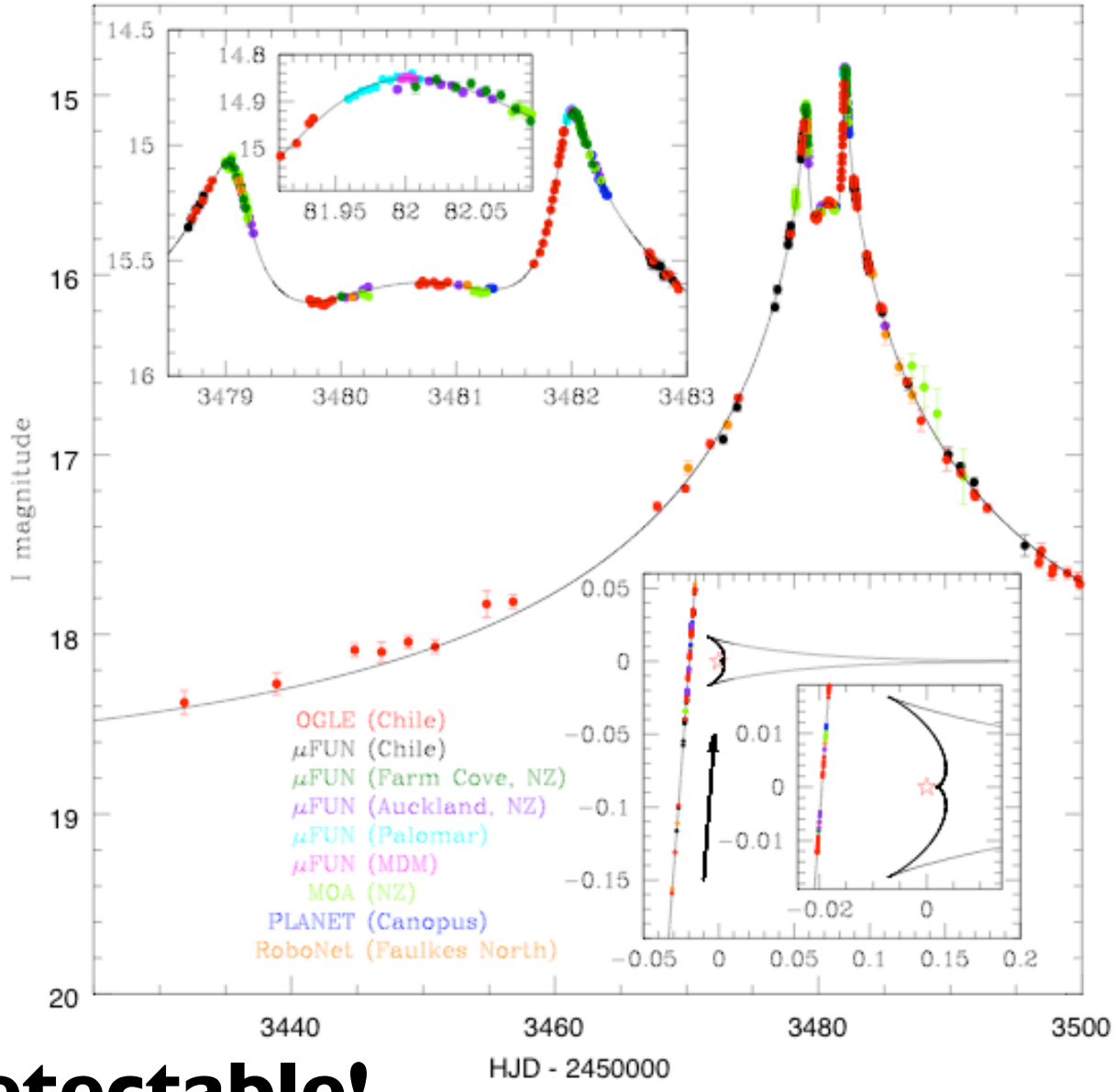
$$m \sim 3\, m_{Jup}$$

Udalski et al. 2005
(OGLE + microFUN + MOA + PLANET + RoboNet)

$$\Delta t \propto m^{1/2}$$

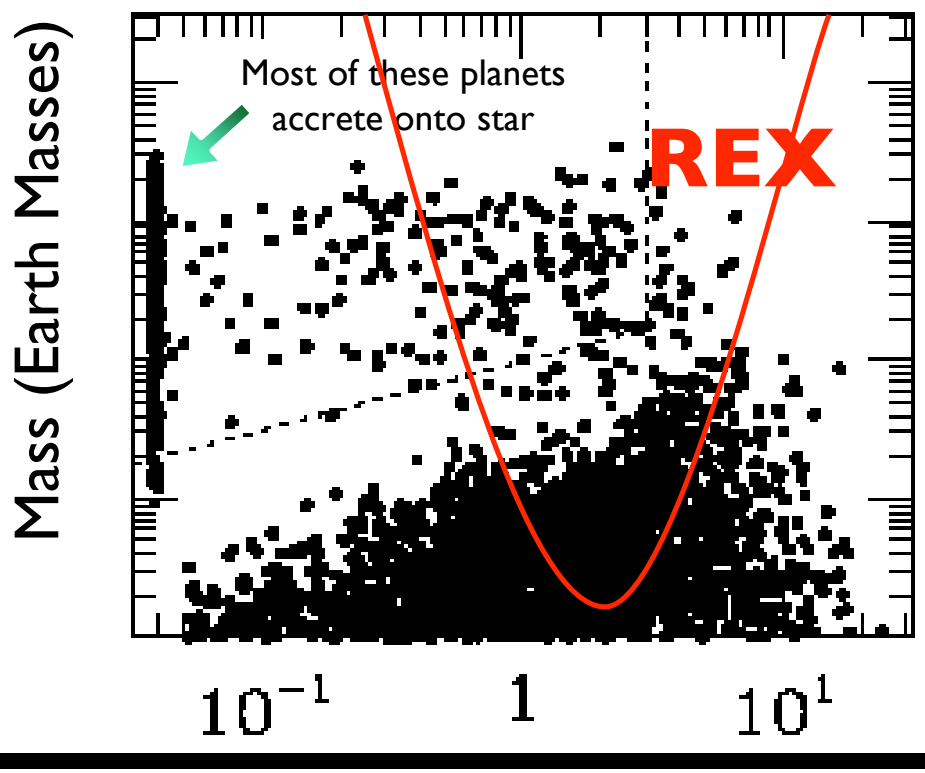
$$\mathrm{Pr} \propto m^{1/2}$$

$$\frac{S}{N} \propto m^{1/4}$$



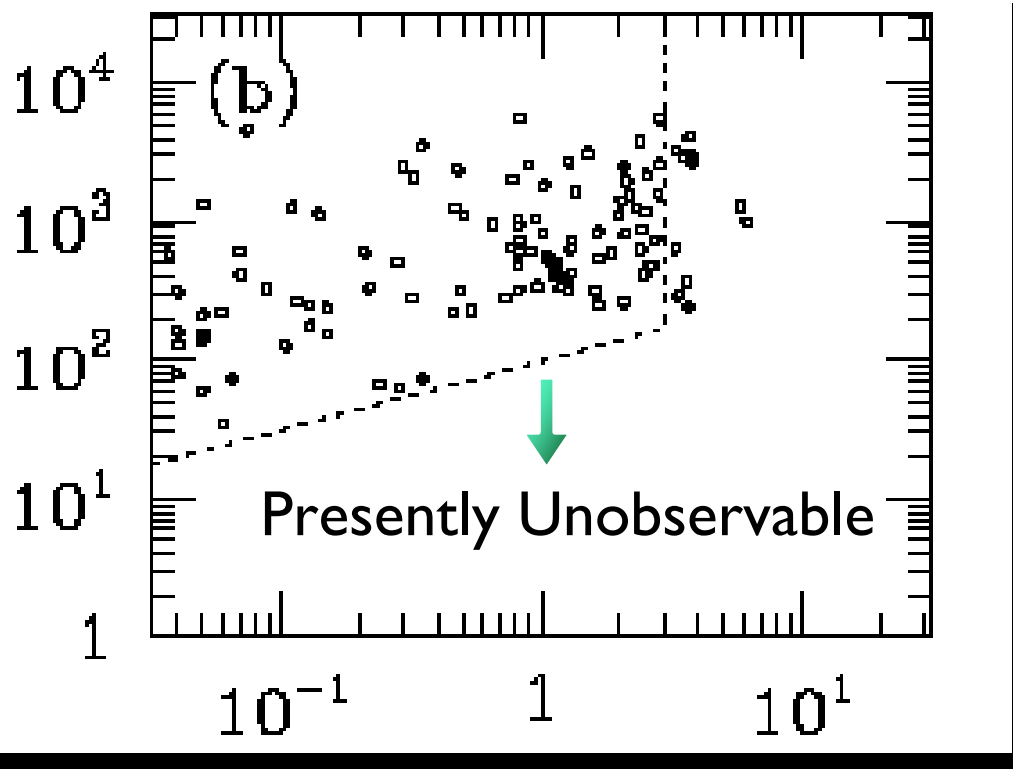
Cool Earths are detectable!

Ida & Lin Model Distribution



Cool Earths detectable via microlensing.

Observed Distribution



Fast (1-5yr)

and Cheap (ground-based)

Cool Planet Hunting with the UK's 2m Robotic Telescopes

Liverpool Telescope: La Palma

Faulkes Telescopes: FT-N, Maui

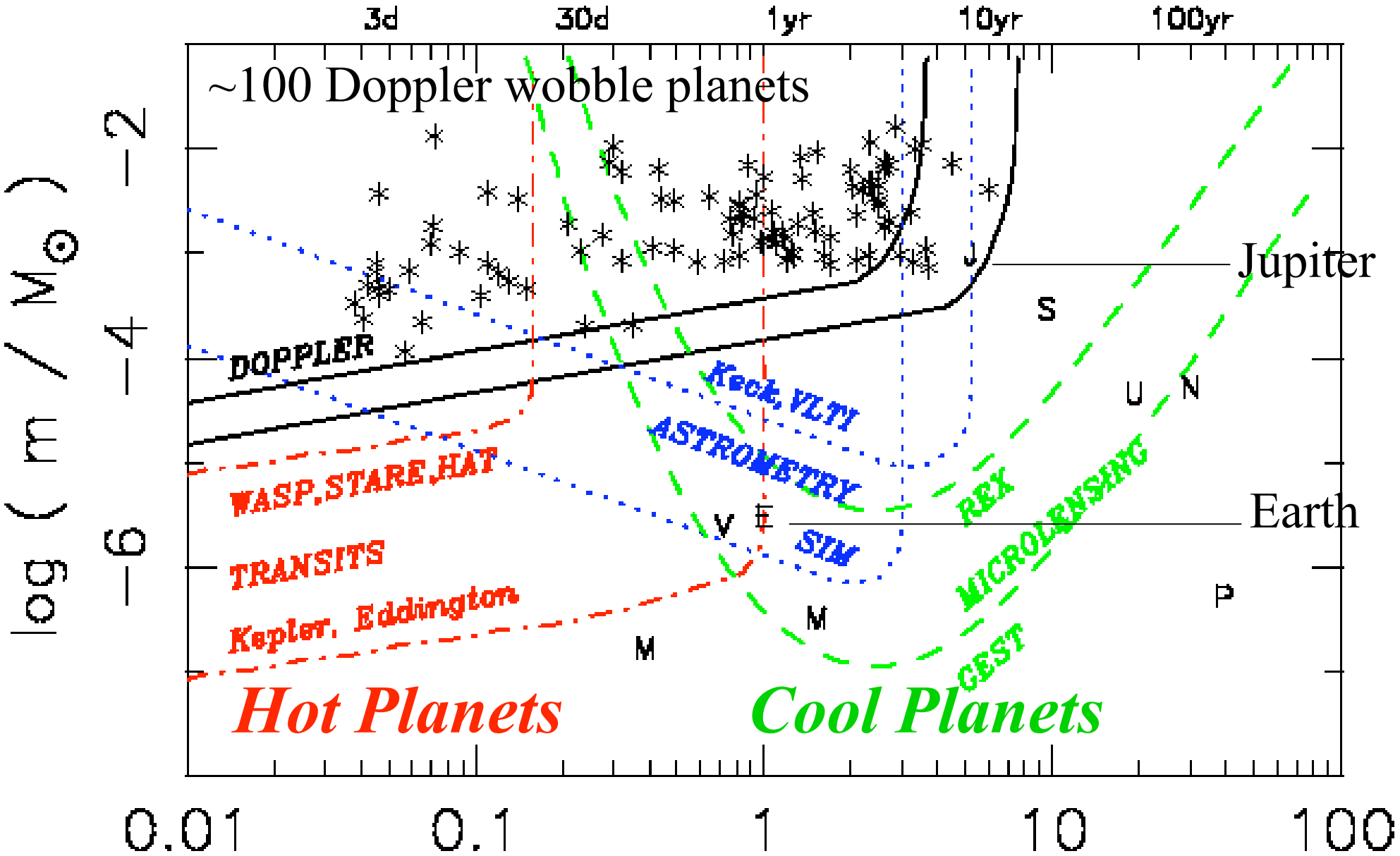
FT-S, Siding Springs

RoboNet I --> REX

REX = Robotic EXoplanet discovery Network

REX proposal for 2 more southern telescopes.
Dedicated to exoplanet hunting
Doppler wobbles, transits, microlensing.

How abundant are Habitable Planets?



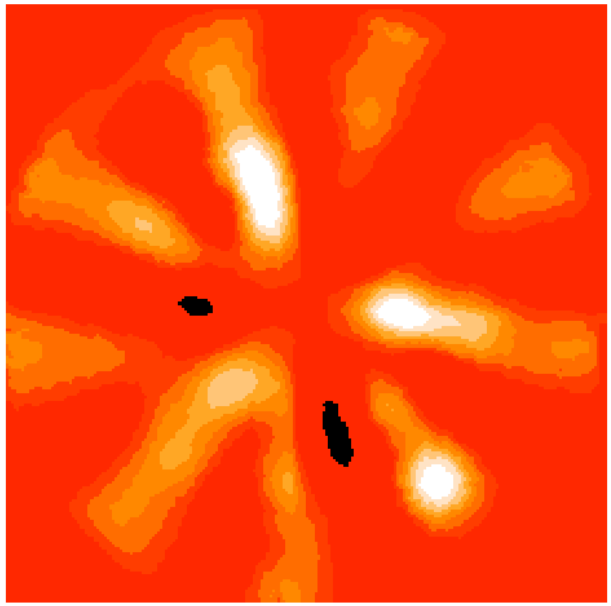
ESA: Darwin

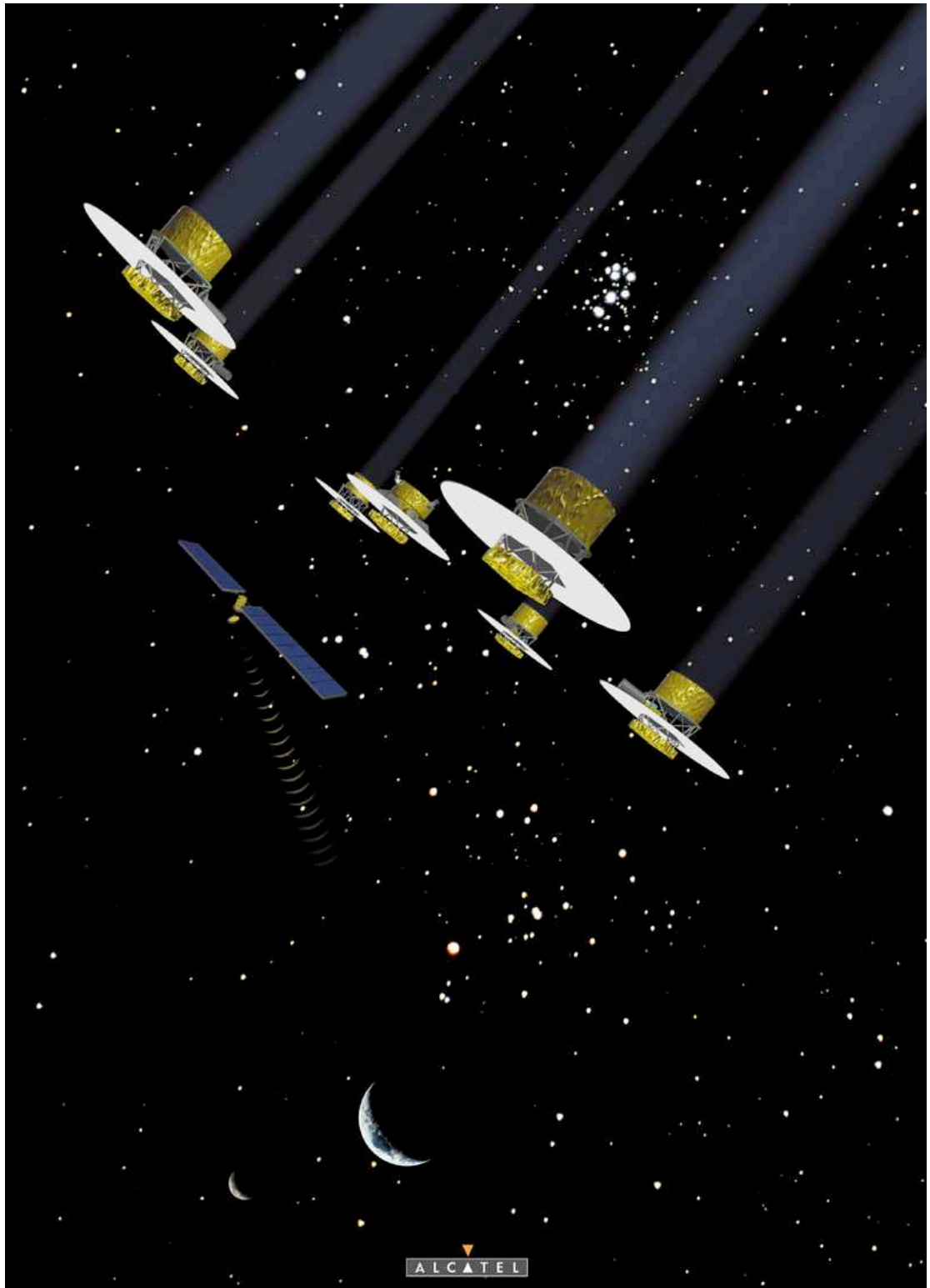
~ 2015-20?

infrared space interferometer

destructive interference to cancel out the starlight

snapshot ~500 nearby systems
study ~ 50 in detail

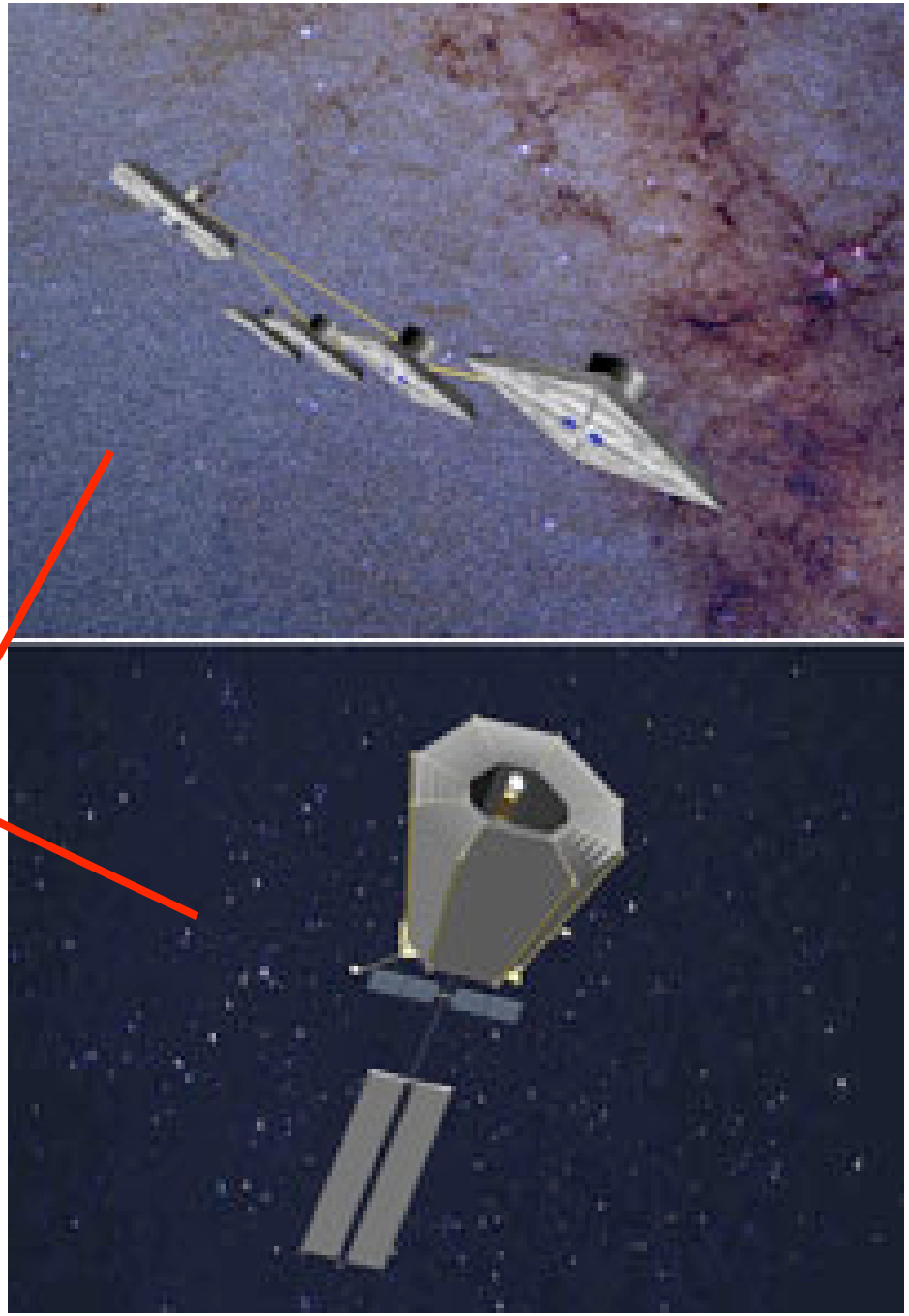




NASA: TPF (Terrestrial Planet Finder)

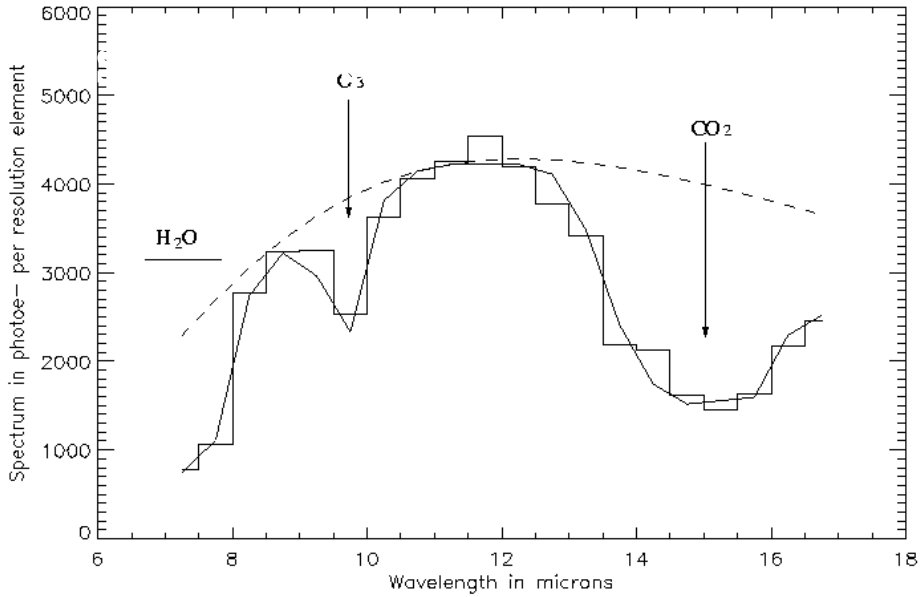
2014: TPF-C
4-6 m visible light coronagraph

2020: TPF-I
3-4 m infrared interferometer

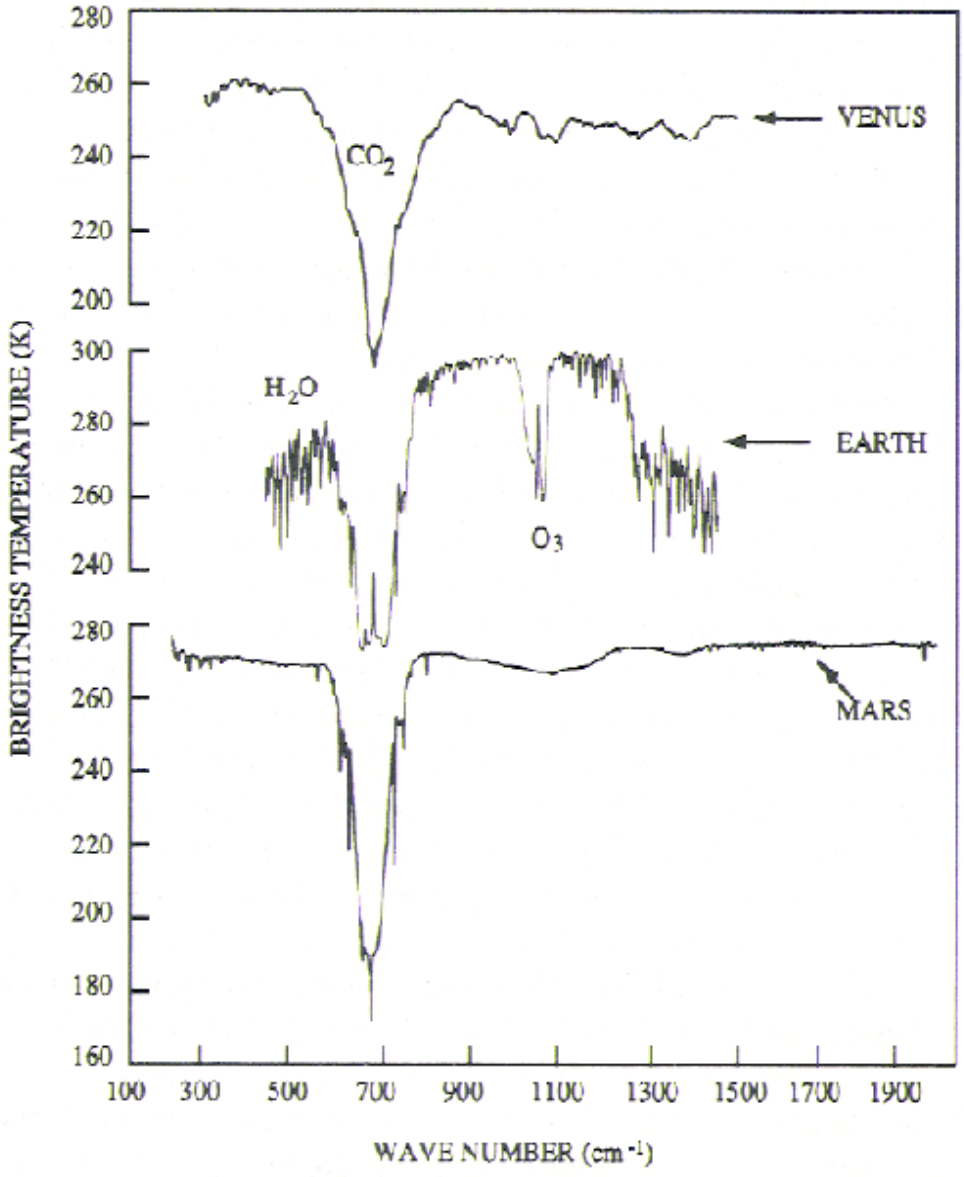


Life's Signature: disequilibrium atmosphere (e.g. oxygen-rich)

Spectroscopy of an Earth at 10pc



Terrestrial Planetary IR Spectra



The Road Ahead

- Doppler Wobbles
  - 2005 ... 150 --> 200 Jupiters
  - longer periods, multi-planet systems
- Transits
  - 2005-10 … WASP ~10^3 Hot Jupiters
  - 2006-08 … Corot Hot Earths
  - 2008-12 … Kepler Hot --> Habitable Earths
- Microlensing
  - 2005-15 … cool Jupiters --> Earths
- Darwin / TPF
  - 2015-2025 … direct images, spectra, signatures of Life?

Thanks for Listening!