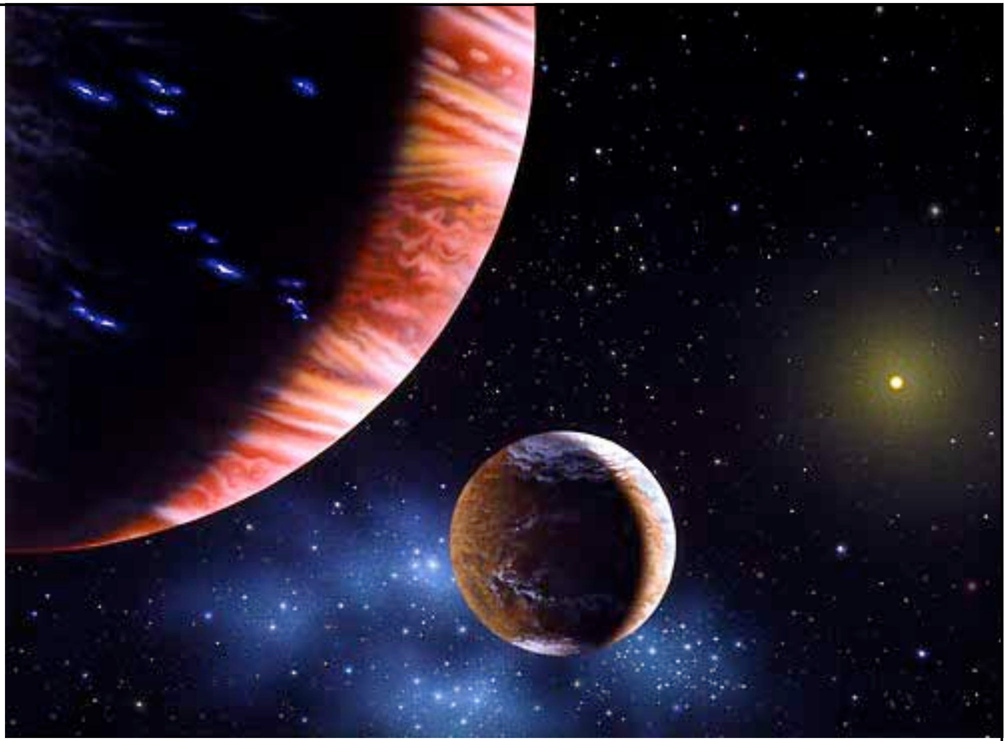
A S 3012

Exoplanetary Science



Keith Horne

(kdh1) Room 315A

Ian Bonnell

(iab1) Room 312

AS 3012: Exoplanetary Science

Young and rapidly developing subject:
1995: first exoplanet around an ordinary star (Mayor & Queloz).
2010: > 350 exoplanets known
.   (~30 found by our WASP and microlensing teams)
Observations: (Keith Horne)   ~ 6 lectures
Theory: (Ian Bonnell)   ~12 lectures

Detection Techniques and Characteristics of the Planet Population

- How do we discover extrasolar planets?
- What can we learn about them?
- Characteristics of the exoplanet population.
- Tests of planet formation/migration theories.

Resources

Observations: good starting points on the web:
Extrasolar Planets Encyclopedia
`http://exoplanet.eu/`
Berkeley Search for Extrasolar Planets
`http://exoplanets.org/`

Theory: Annual Reviews article by Lissauer (1993) is a good summary of the state of theory prior to exoplanets.
Lecture notes on the formation and early evolution of planets by Philip Armitage (astro-ph/0701485)

Lecture slides to be posted at

http://star-www.st-and.ac.uk/~kdh1/esp/esp.html

Paper for next Tue:

Mayor, M. et al. 2009 A&A 493, 639.

HARPS search for Southern Exoplanets XIII:

A planetary system with 3 Super Earths

Motivational Questions

Where did we come from?

How did:

The Universe, Galaxies, Stars, **Planets, Life**, Intelligence

form and evolve ?

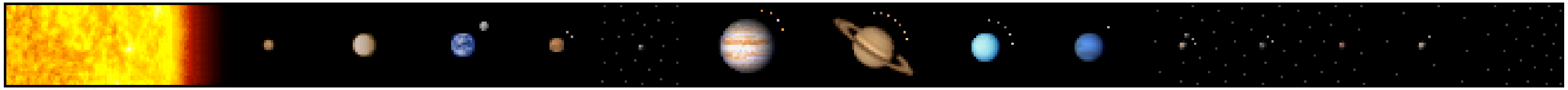
Are there Other Earths?

How far away?

Do they harbour Life?

Are we alone?

Planet Formation Theory (~1995) based on Solar System Planets



Co-planar circular orbits

Inner planets : **small, rocky**

Mercury, Venus, Earth, Mars

Outer planets : **gas giants**

Jupiter, Saturn, Uranus, Neptune

Debris:

Moons, Asteroids, Comets, Pluto (and other Kijper-belt objects)

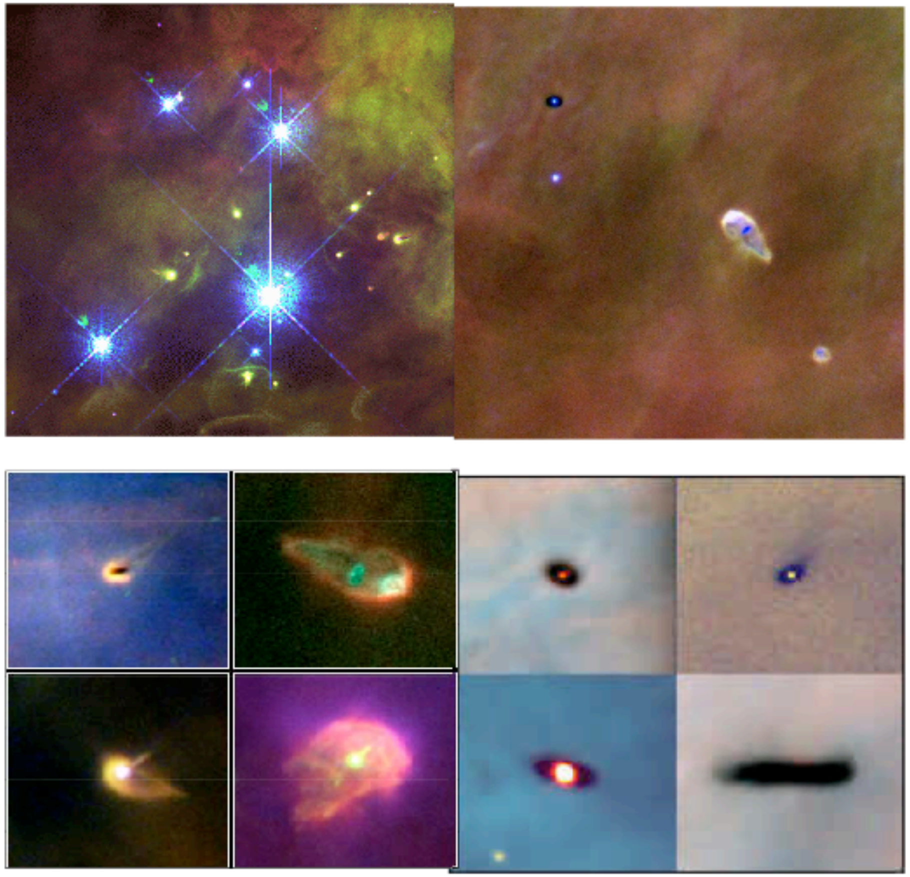
Planets form in a thin **proto-stellar disk**
by concentrating **dust (and later gas)**

Gas giants form outside the "**Snow Line**" ($a > 4$ AU, $T < 170$K)
where dust grains have **ice mantles** (H_2O, NH_3, CH_4)

(Snowballs easy to form, but "sandballs" harder.)

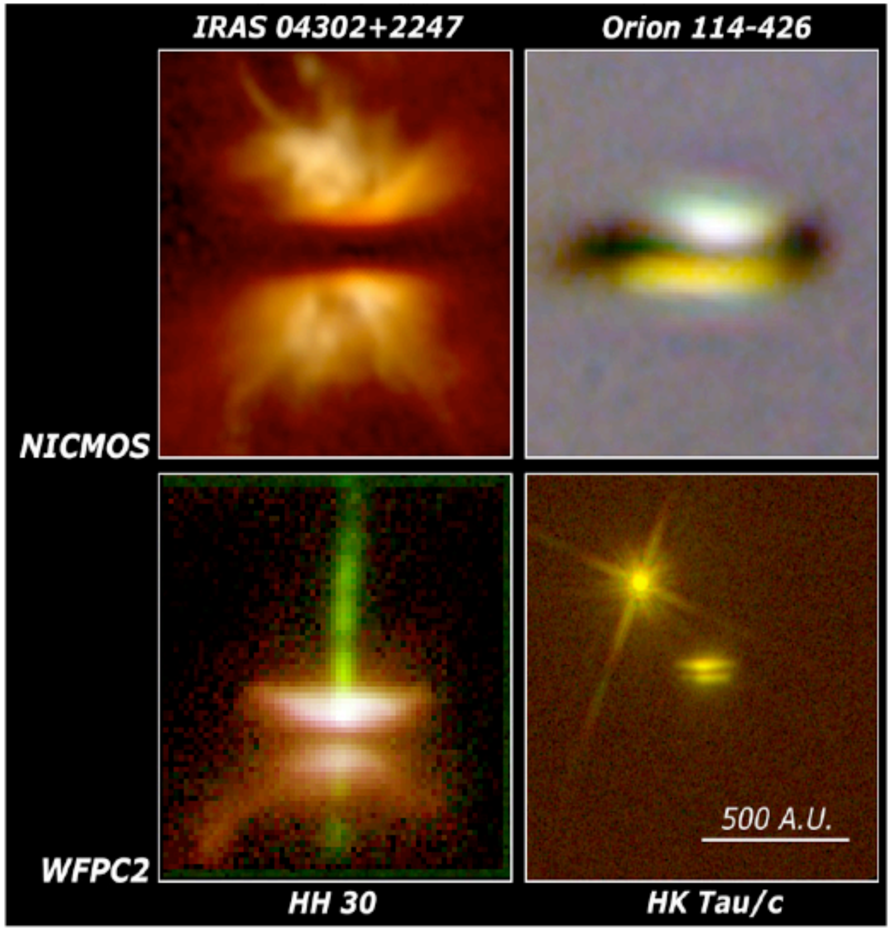
Young Stars have Dusty Disks

Proto–stars growing inside their dusty cocoons

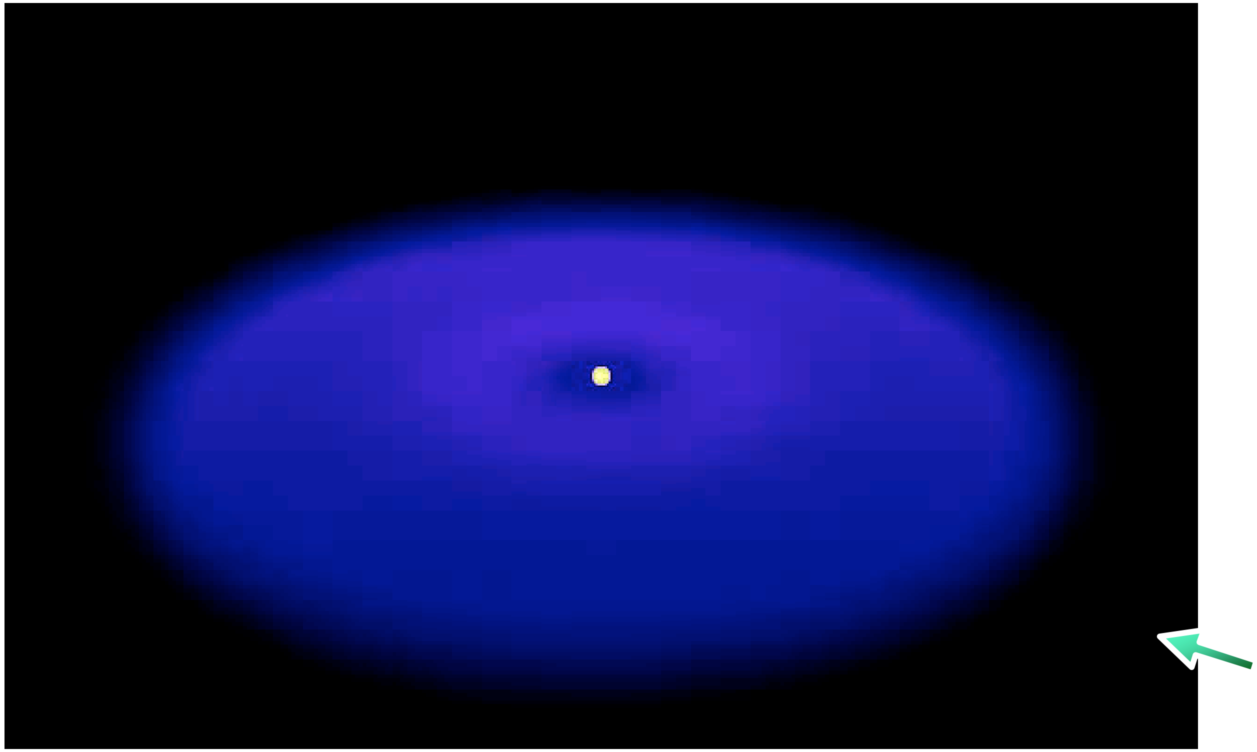


Hubble Space Telescope Images

Proto–stars growing inside rotating accretion disks, some spewing out Jets.



Method 1: Gravitational Instability



Kuiper 1951
Cameron 1978
DeCampli & Cameron 1979
Boss 1998
Boss 2000
Mayer et al. 2002
Pickett et al. 2003
Rice et al 2003a
Rice et al 2003b
Boss 2003
Cai et al 2004
Boss 2004
Mayer et al 2004
Mejia et al 2005

Requirements for **gravitational instability**:

$$\boxed{M_{disk} > \frac{H}{R} M_*}$$

1. *Toomre (1964)* . $Q \equiv \frac{c_S \, \Omega}{\pi \, G \, \Sigma} < Q_{crit} \sim 1$

2. Cooling of fragments faster than orbit time *Gammie (2001).*

Method 2: Core Accretion

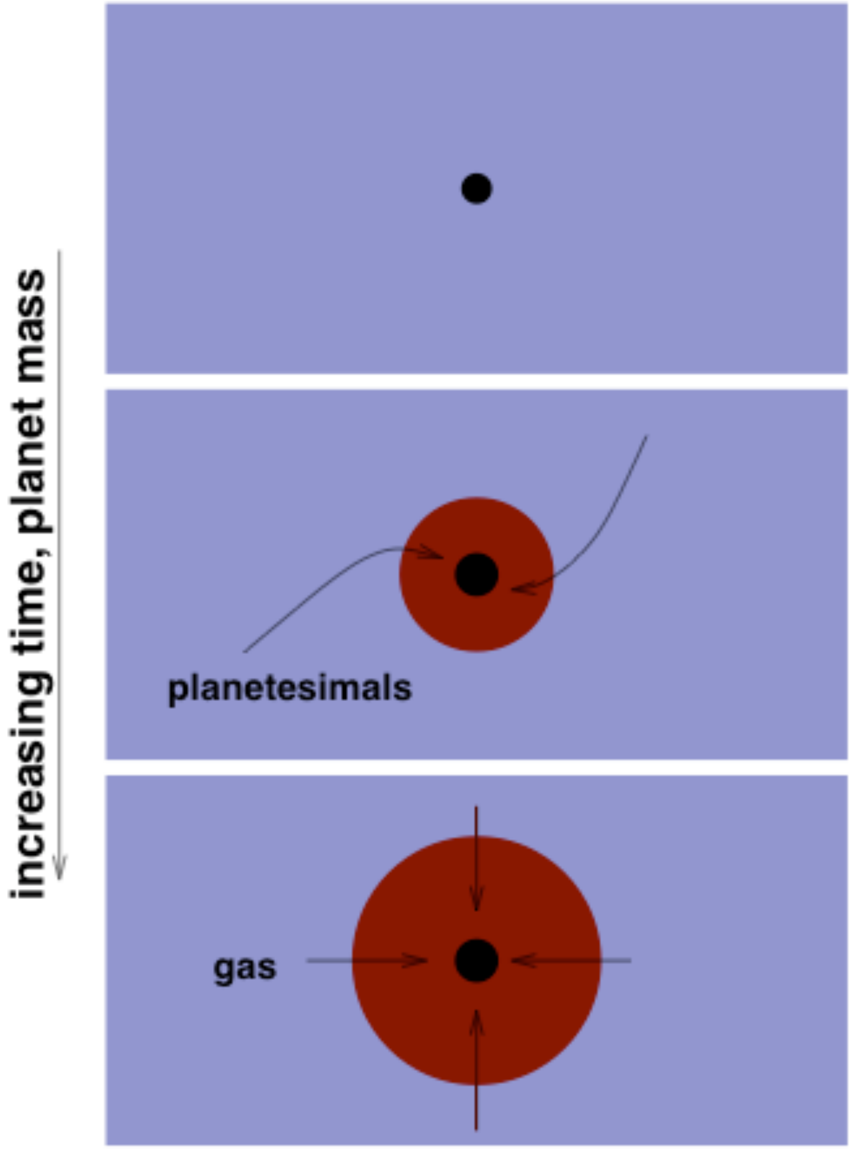


FIG. 23 Illustration of the main stages of the core accretion model for giant planet formation.

Coagulation of planetesimals to form a small core.

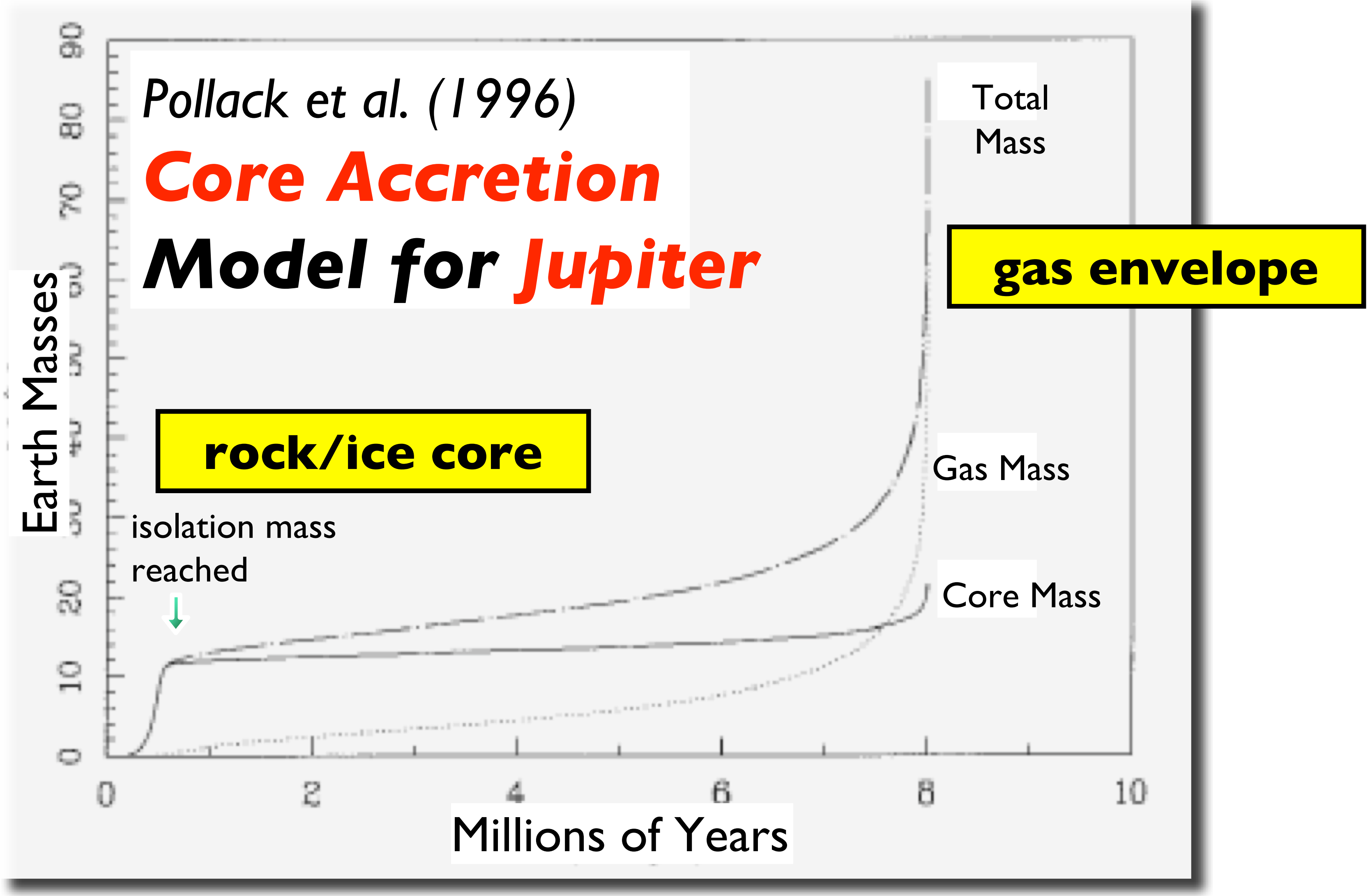
A thin gas envelope.
More planetesimals accreted.

When core reaches critical mass, it rapidly accretes a deep gas envelope.

The critical core mass ~ 10-15 Me

Formation time depends on surface density of planetesimals in the disk and opacity of the gas

Pollack et al. (1996) Core Accretion Model for Jupiter



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

$$T_{neb} = 150\,\mathrm{K} \qquad \rho_{neb} = 5 \times 10^{-11}\,\mathrm{gcm}^{-3}$$

The Exo-Planet Discovery Era

- 1995 first extra-solar planets

  (51 Peg) Hot Jupiters!
- 2009 ~330 exo-planets known
- 2005-10 first Hot and Cool exo-Earths
- 2010-15 Habitable Earths -- common or rare?
- 2020-30 Extra-solar Life? Are we alone?

Two Classes of Planet Discovery Methods

Direct detection:

Detect light from the planet.

1) starlight reflected from the planet
2) thermal radiation emitted by the planet

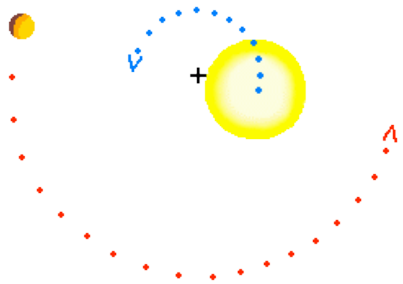
Indirect detection:

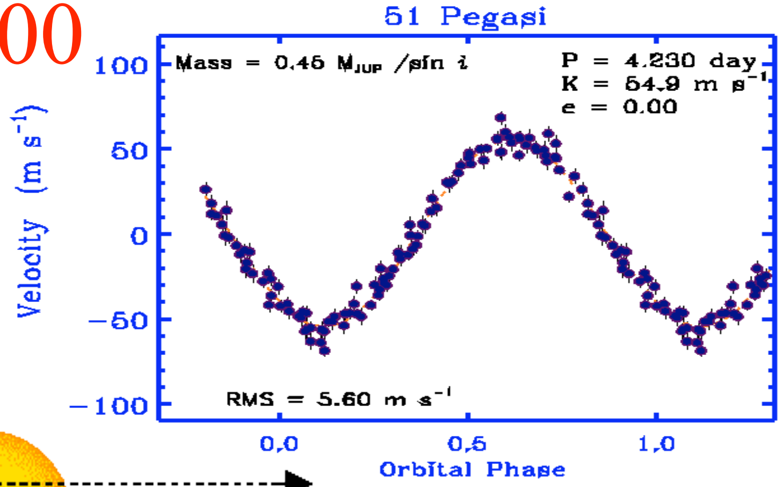
Detect effect of planet on light from a star.

1) Stellar wobble (astrometry, radial velocity)
2) Transits (planet in edge-on orbit occults stellar surface)
3) Microlensing (planet’s gravity deflects background starlight)

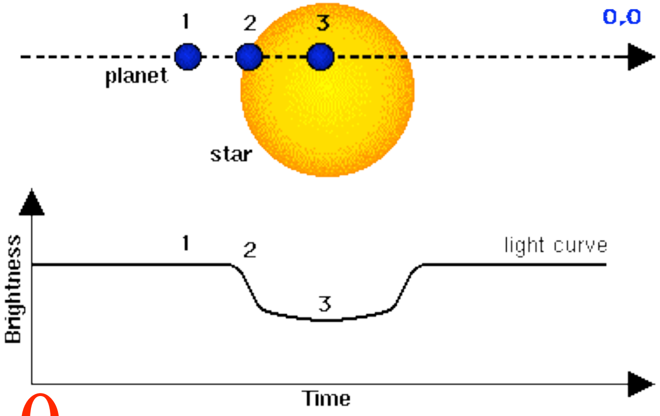
Indirect Discovery Methods

- Doppler Star Wobbles: ~300

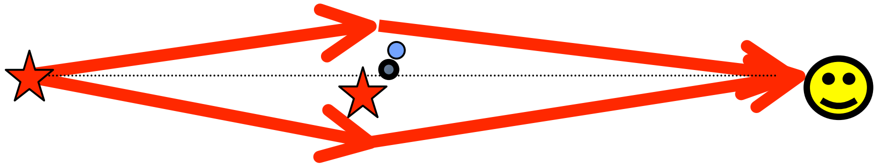


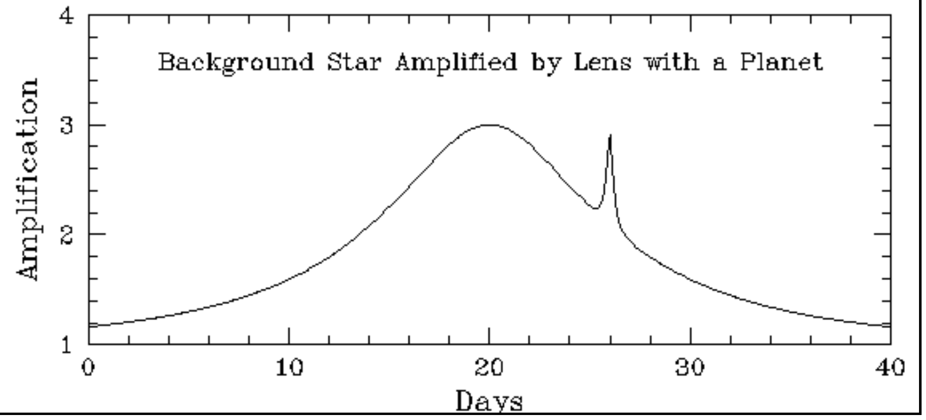


- Transits: ~50



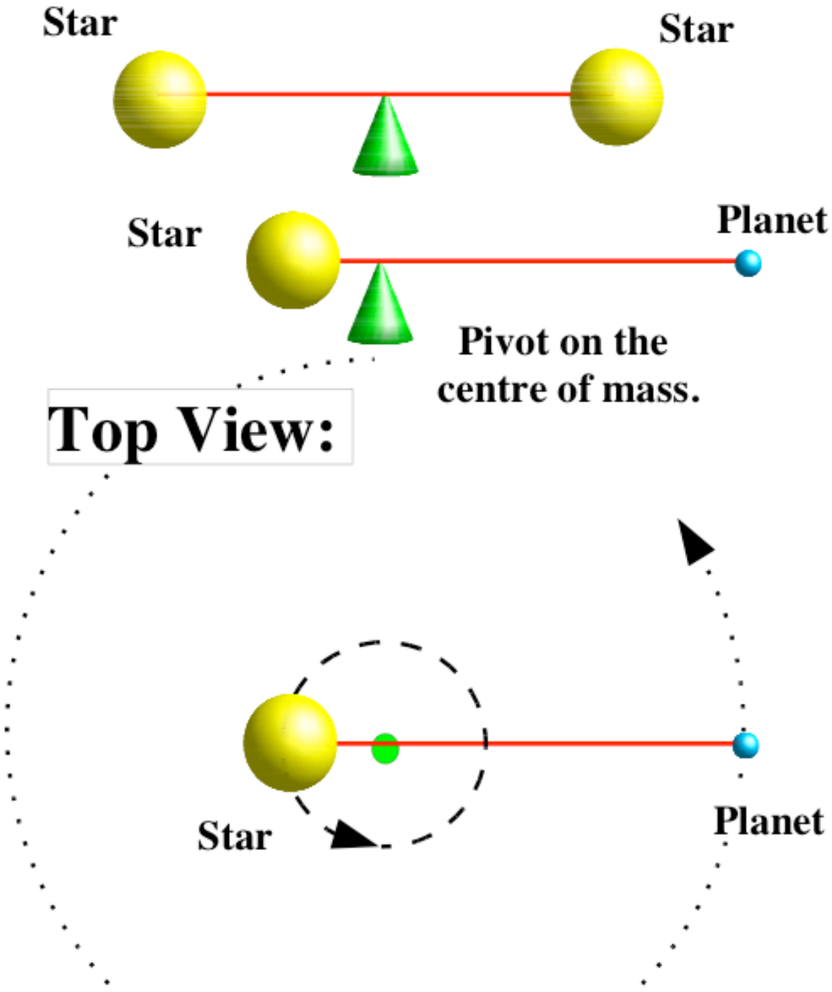
- Microlensing: ~10



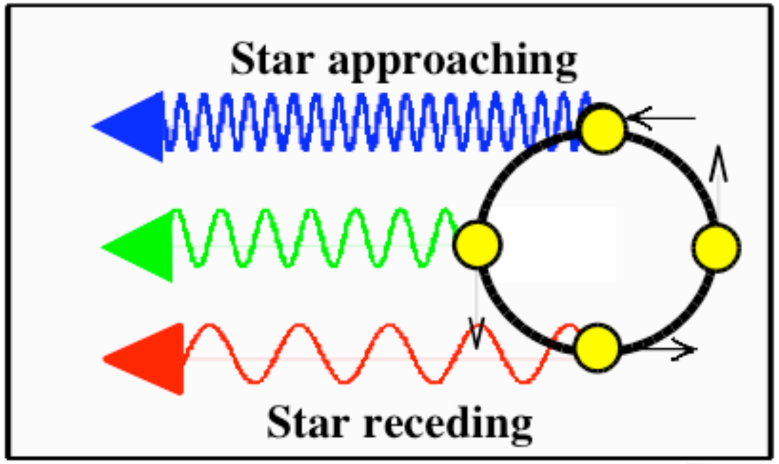


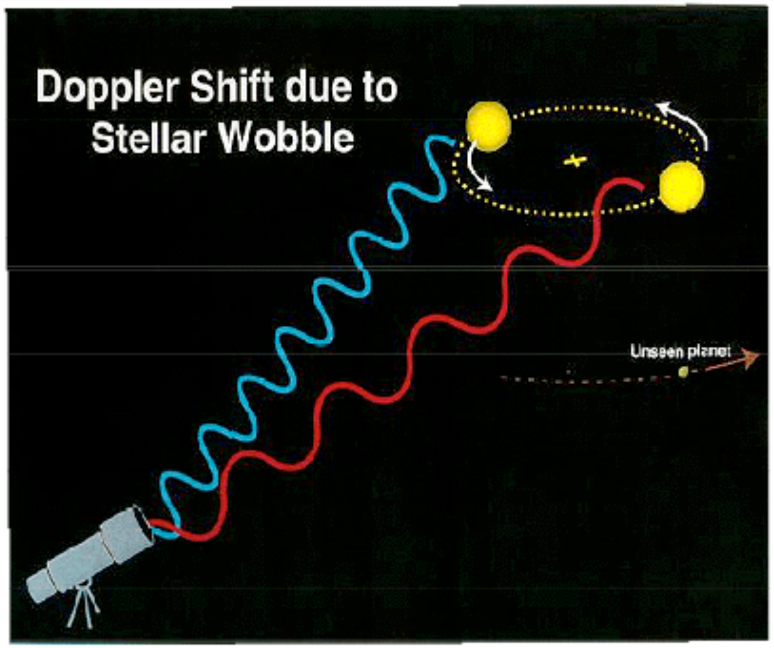
Doppler Wobble Method

Indirect Method: Star Wobble



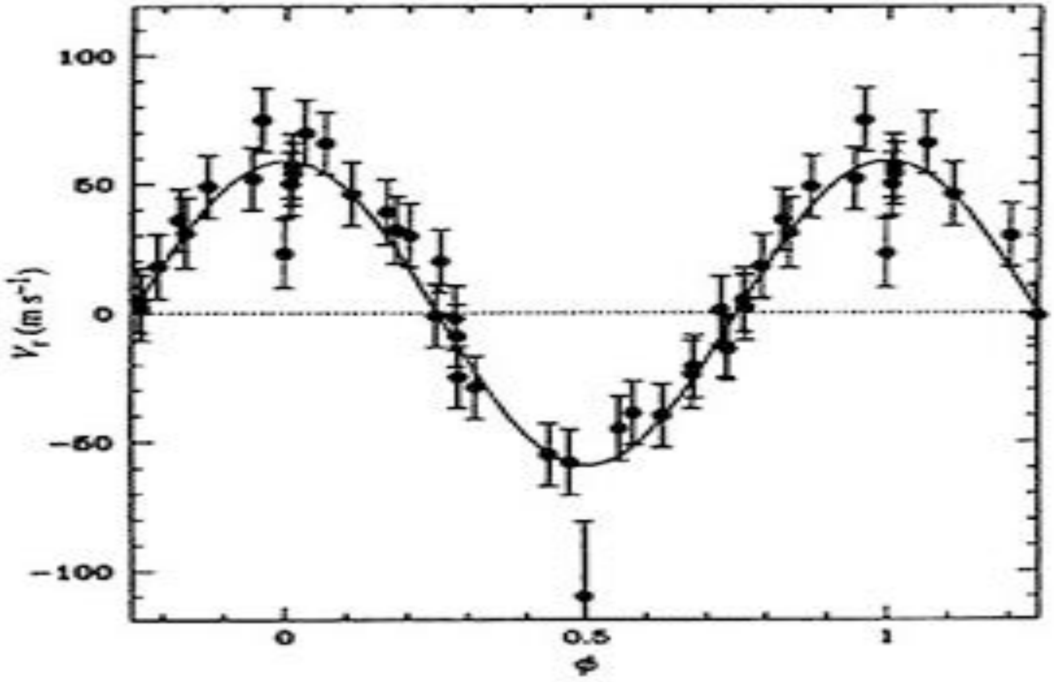
Doppler effect





1995 ***First Doppler Wobble Planet: 51 Peg b***

- Mass: $m_p \sim 0.5\ M_j$
- Orbital Period: $P = 4.2$ days!
- Orbit Radius: $a \sim 7\ R_*$
- Temperature: $T \sim 2000$K



Michel Mayor and Didier Queloz

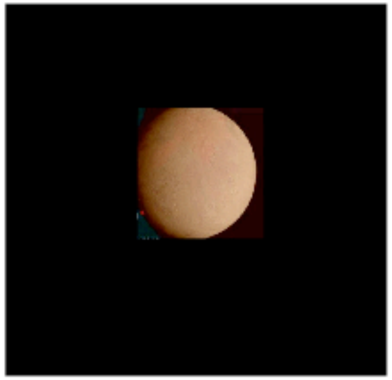
A new type of planet.

Unknown in the solar system.

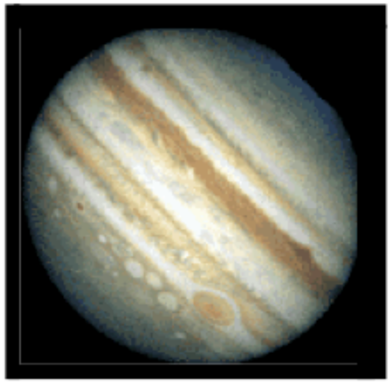
Hot Jupiters !

What are these "Hot Jupiters" ?

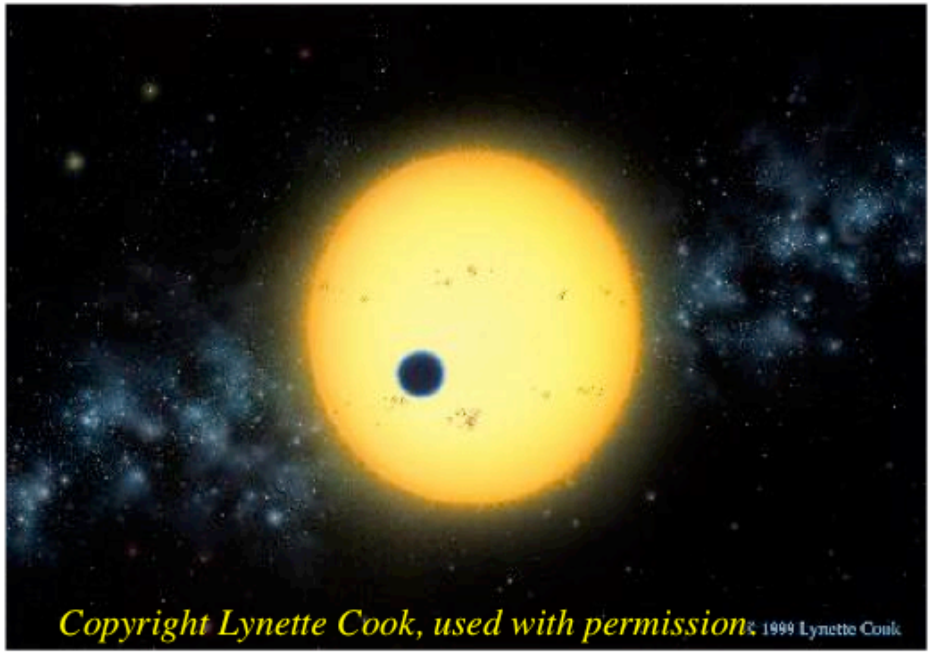
Rock Giants ?



Gas Giants?



To measure a Planet's size ...



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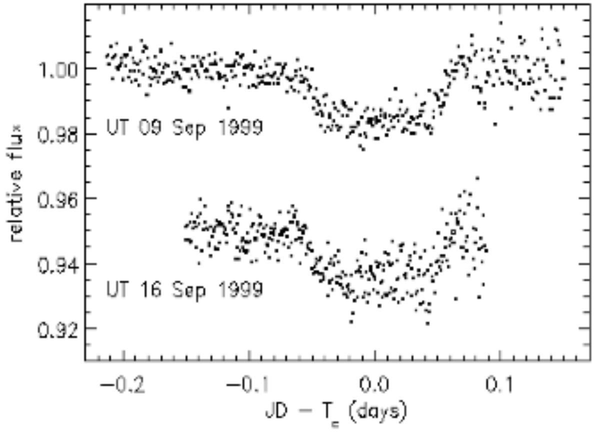
. . . look for its silhouette as it transits across the face of the star.

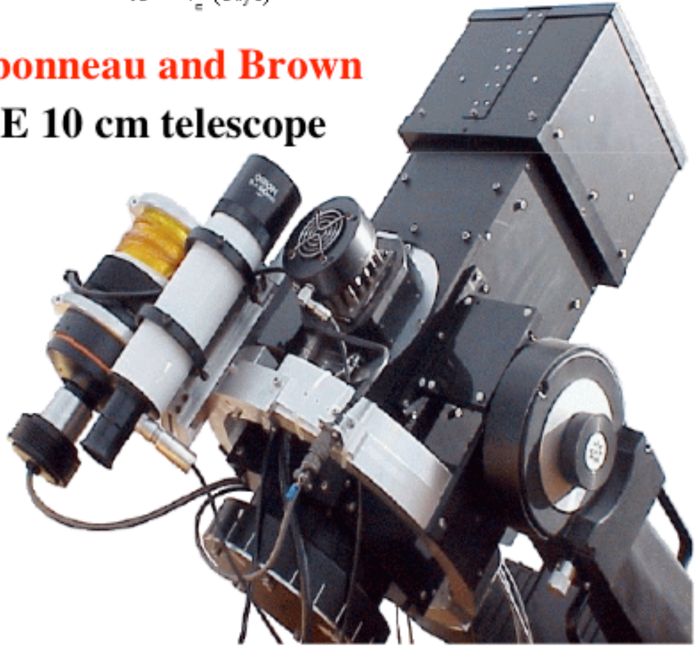
1999 First Planet Transits



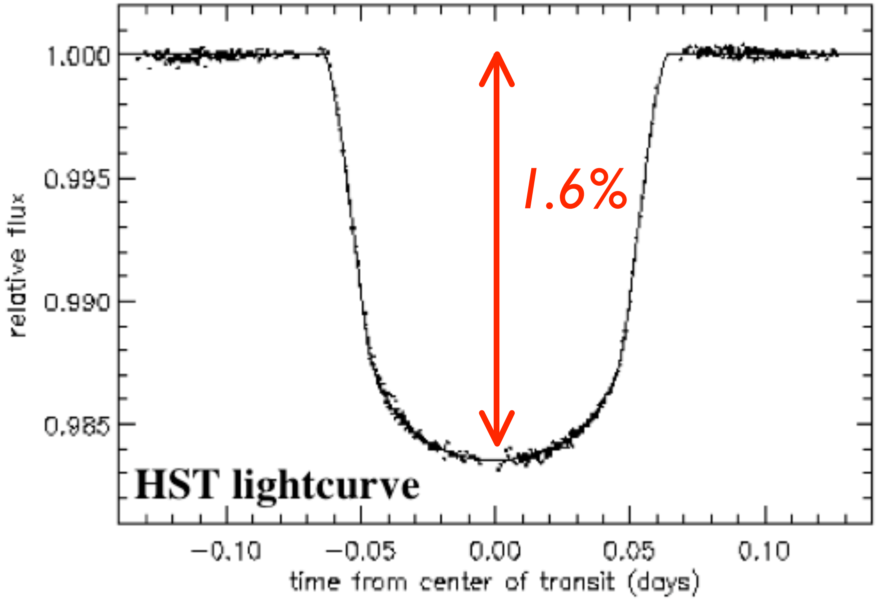
1.6% "winks"
last 3 hours
repeat every
3.5 days.

Charbonneau and Brown

STARE 10 cm telescope

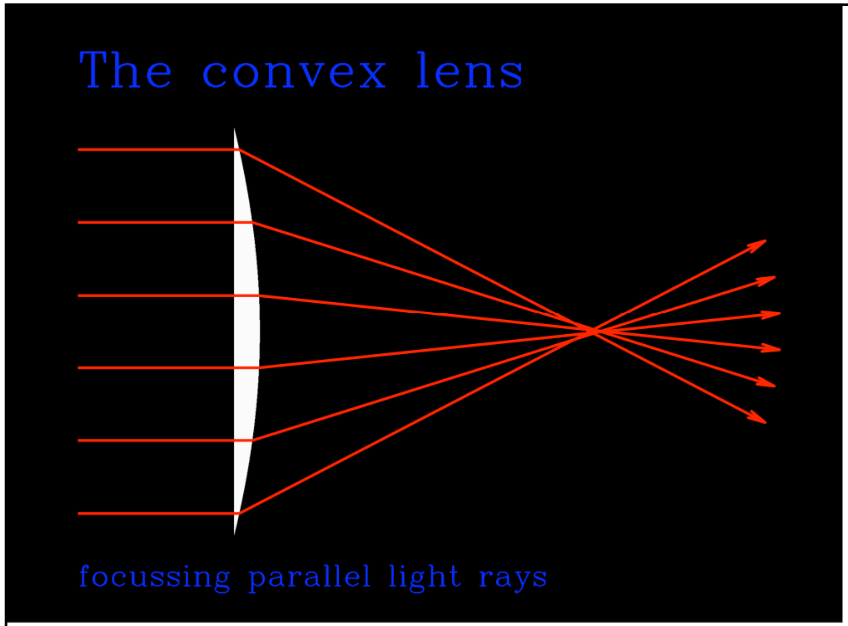


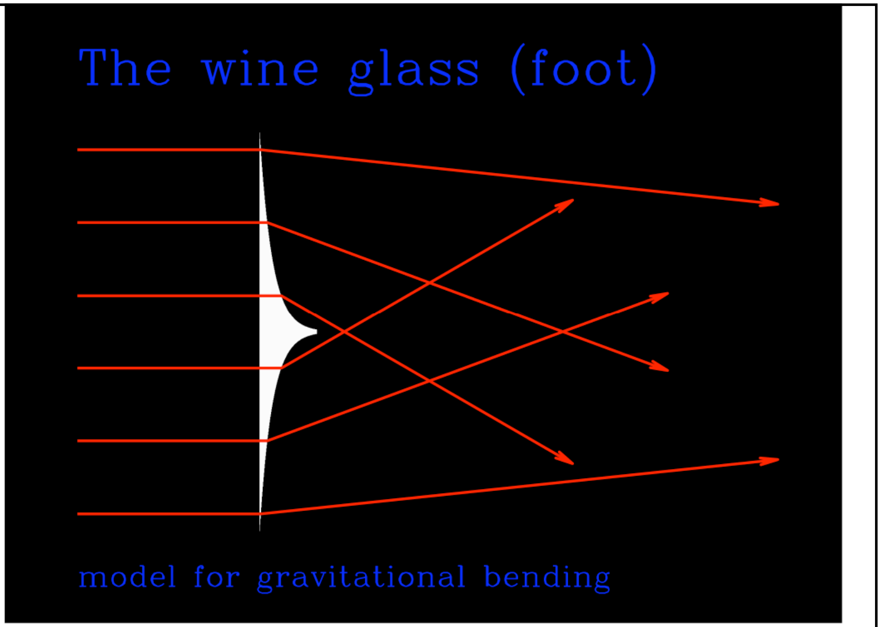
HD 209458
The First Transiting Planet



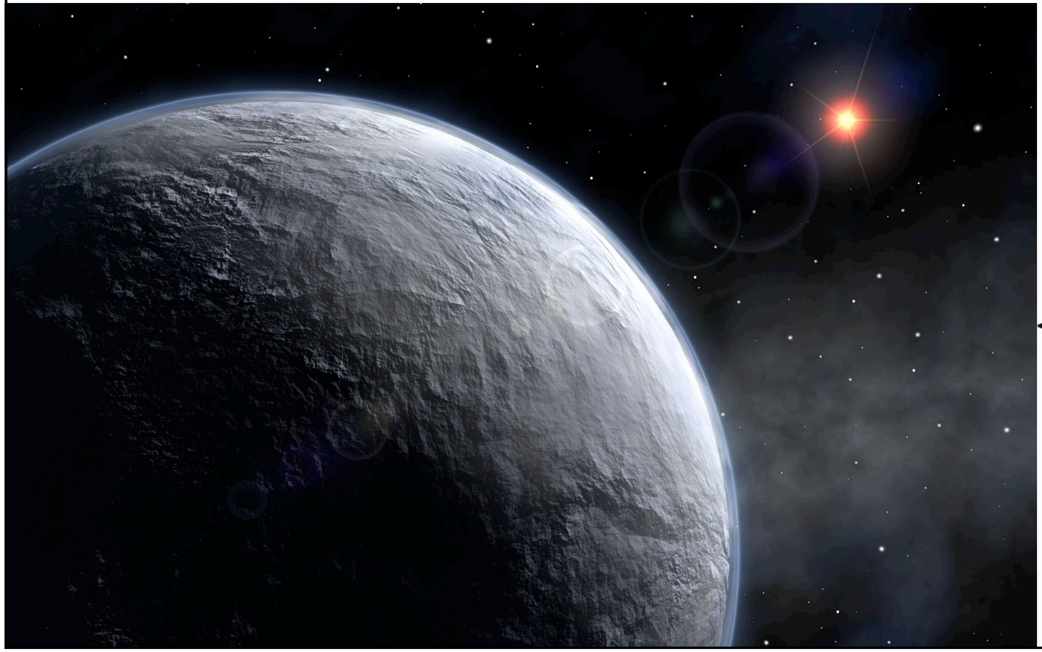
Diameter = 1.3 x Jupiter
Mass = 0.6 x Jupiter
Temp = 2000 Centigrade

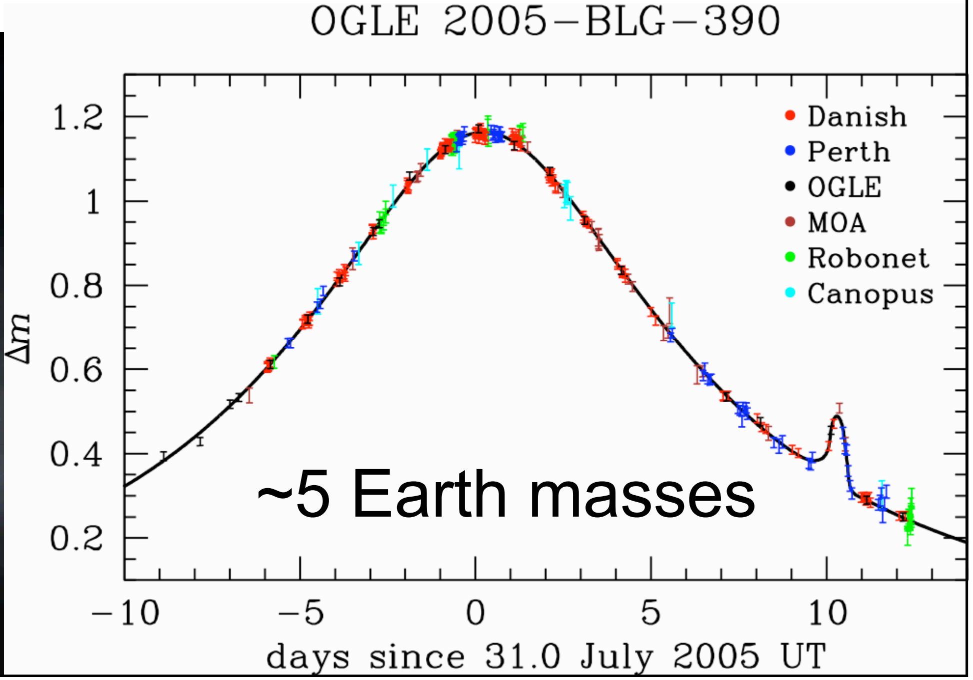
This "Hot Jupiter" is a Gas Giant.





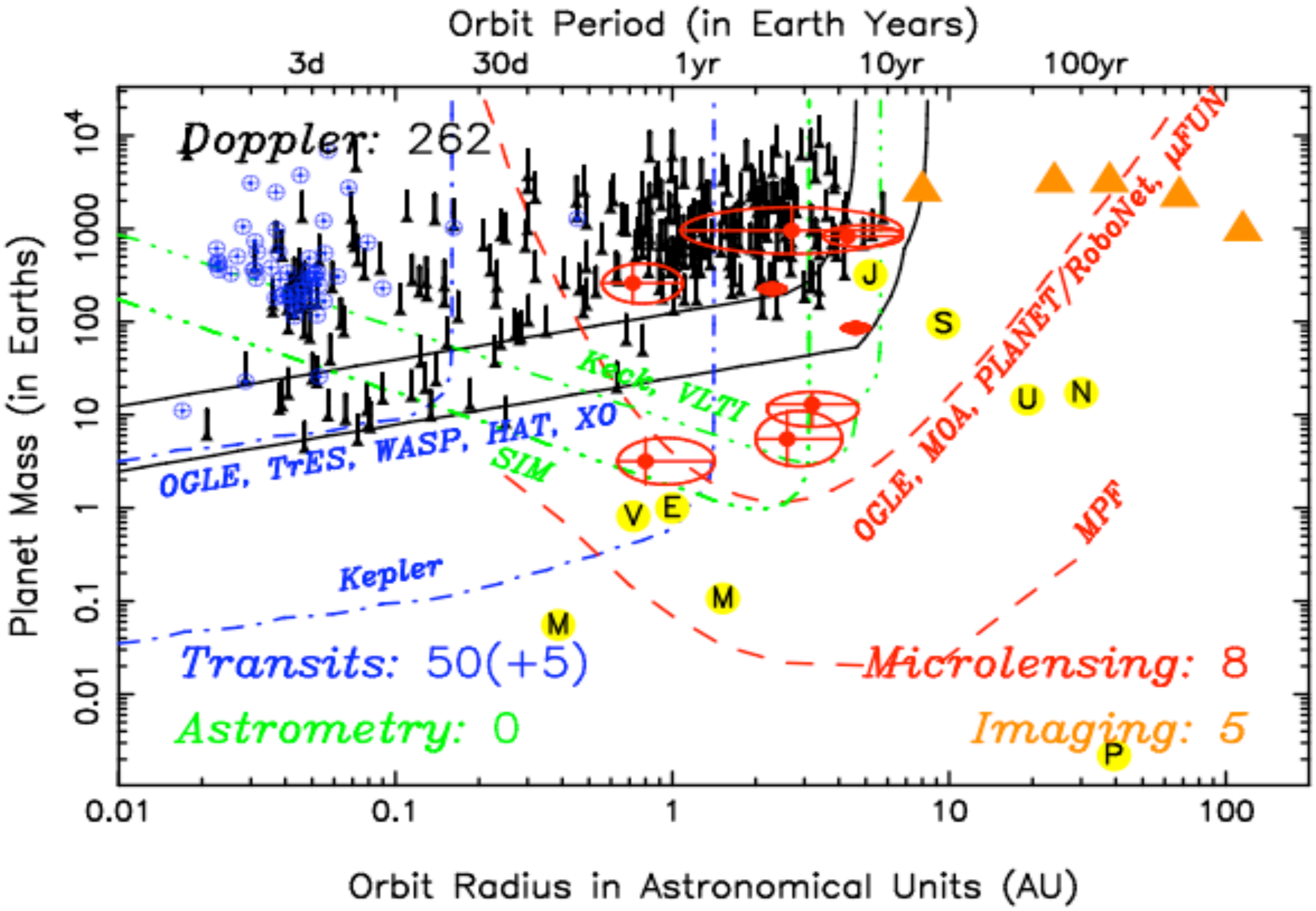
Microlensing searches: cool planets





~5 Earth masses

Exoplanets: 50+262+8+5=325 (Mar 2009)



Definition of a planet

Simplest definition is based solely on mass

- Stars: burn hydrogen
- Brown dwarfs: burn deuterium
- Planets: do not burn deuterium

Deuterium burning limit occurs at around 13 Jupiter masses

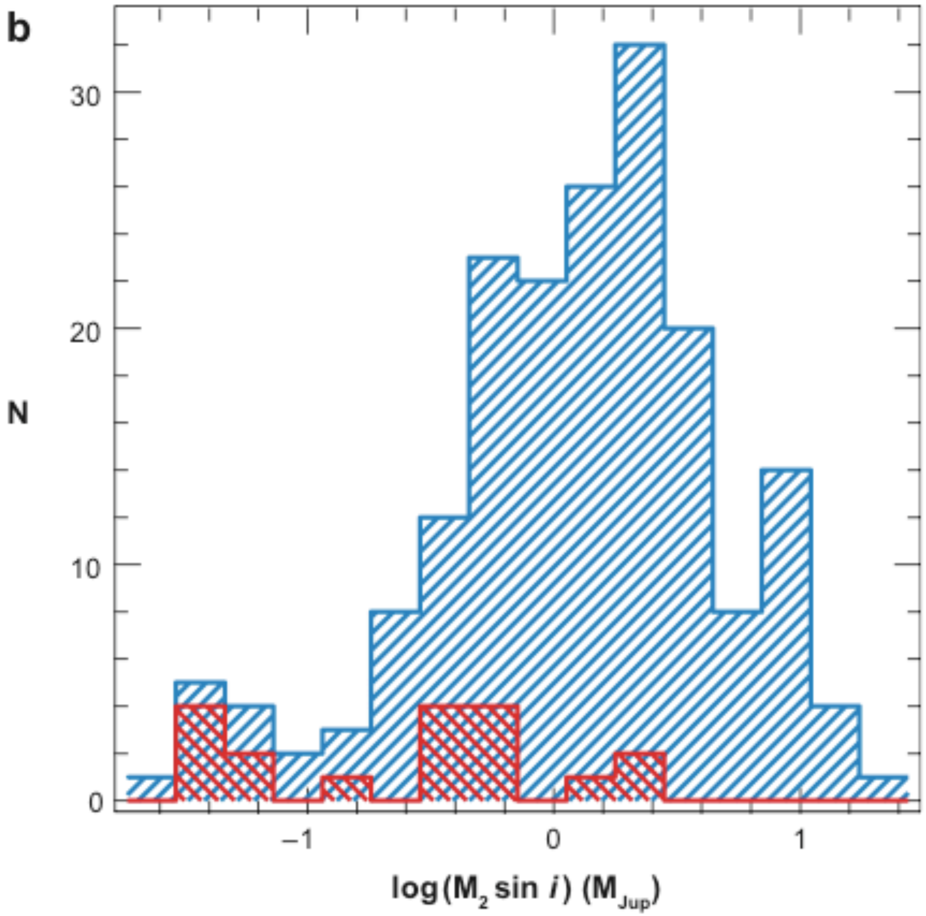
$$1\,M_J = 1.9\times 10^{27}\,\mathrm{kg} \approx 10^{-3}\,M_{sun}$$

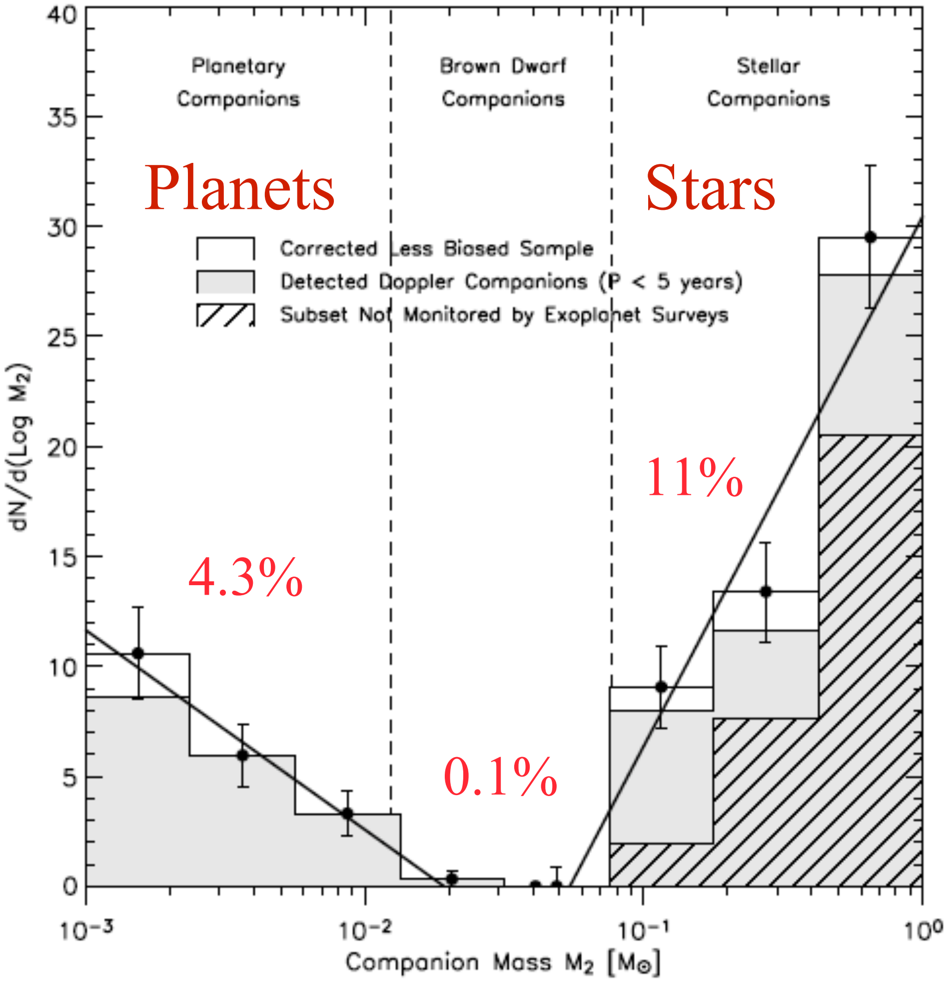
For young objects, there is no large change in properties at the deuterium burning limit. ALL young stars / brown dwarfs / planets liberate gravitational potential energy as they contract

Brown Dwarf Desert

A “brown dwarf desert” separates planets and stars
in the mass distribution of close companions (*P* < 5yr)
Suggests different formation mechanisms.

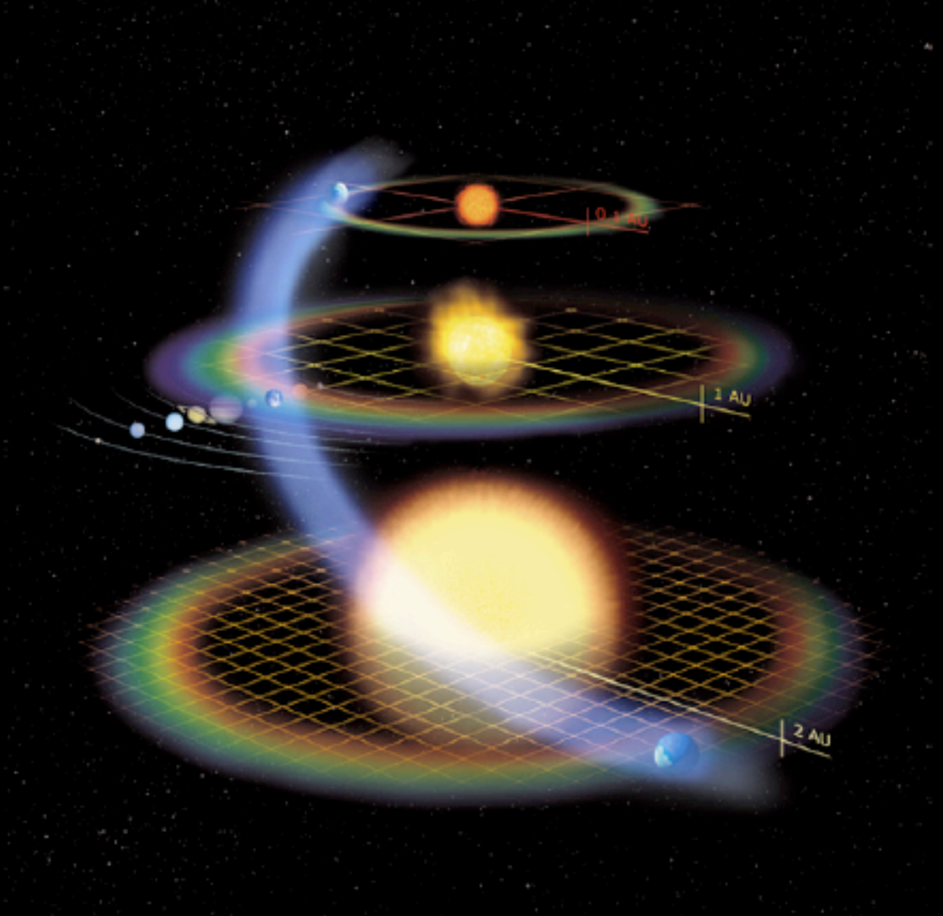
Planet mass distribution





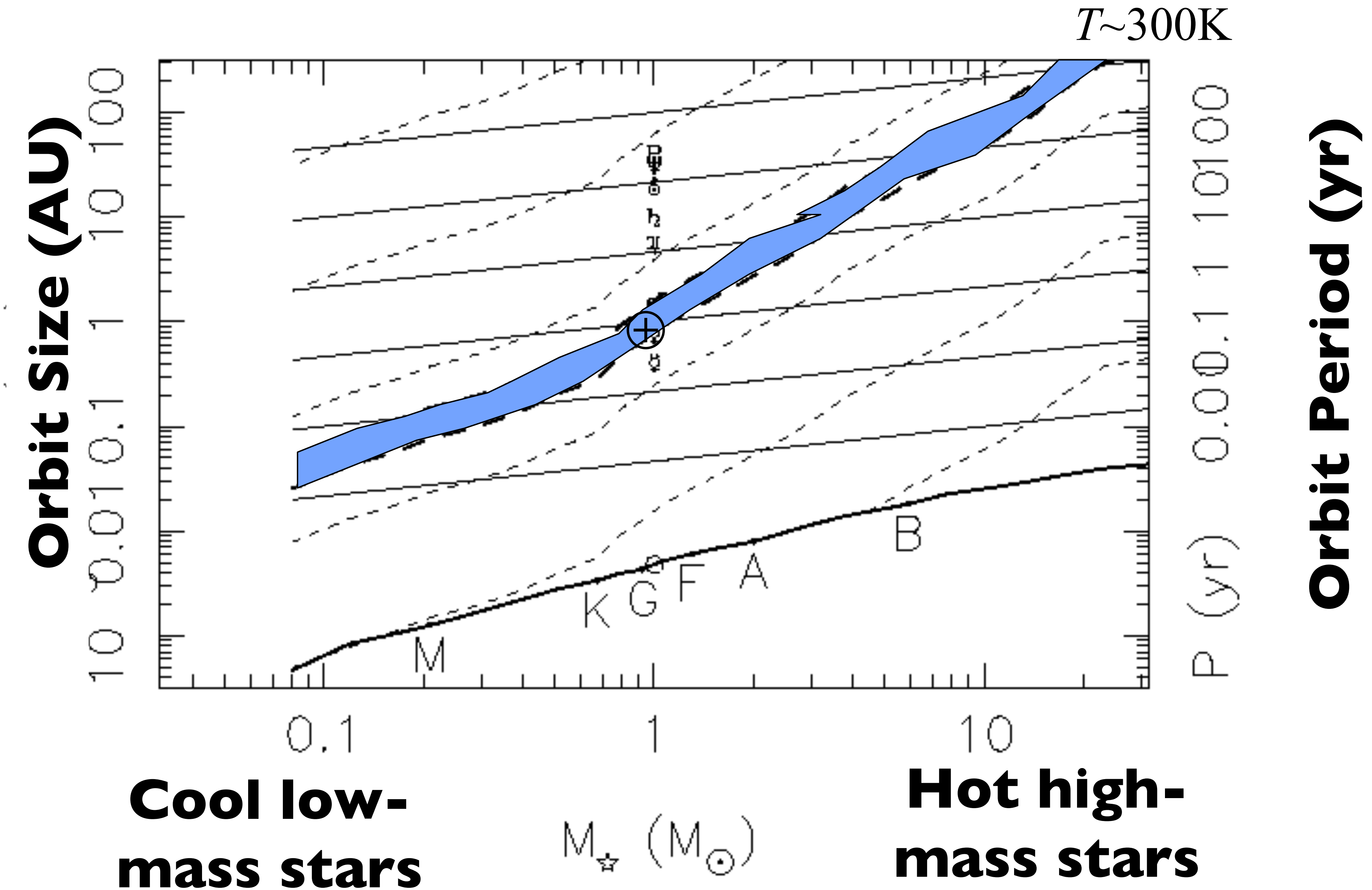
Companion Mass (Msun)

The Habitable Zone



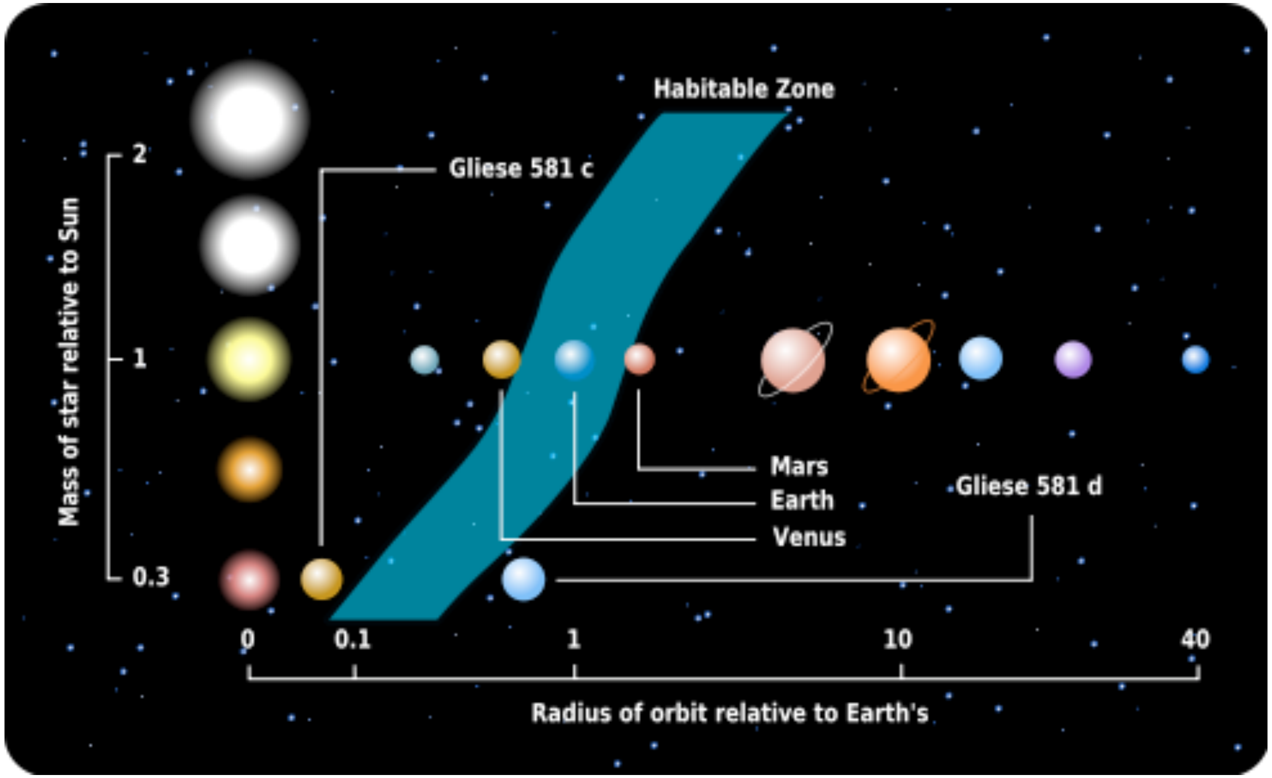
- The habitable zone is that region where liquid water is able to exist on the surface of a planet, but depends on the spectral type and age of the parent star

“The Habitable Zone” (Liquid Water)



Cool low-mass stars

Hot high-mass stars



The mean habitable zone distance for a 1 $L_\odot$ star is ~1 AU

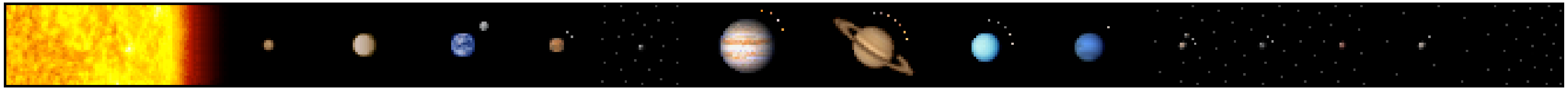
$$\frac{a_{HZ}}{\mathrm{AU}} = \left(\frac{L}{L_{sun}}\right)^{1/2}$$

Planets around Gliese 581:

Gliese 581 is M2.5V (0.3 Msun red dwarf star) 6 pc from Earth.
The star, with T~3500 K (L=0.013 $L_\odot$), is much cooler and less luminous than the Sun. Its habitable zone is much closer to the star.

Gliese 581c: $m_p\sin(i) = 5.5\ m_{earth}$ P = 13 day.
Gliese 581d: $m_p\sin(i) = 7.7\ m_{earth}$ P = 84 day orbit.

Planet Formation Theory (~1995) based on Solar System Planets



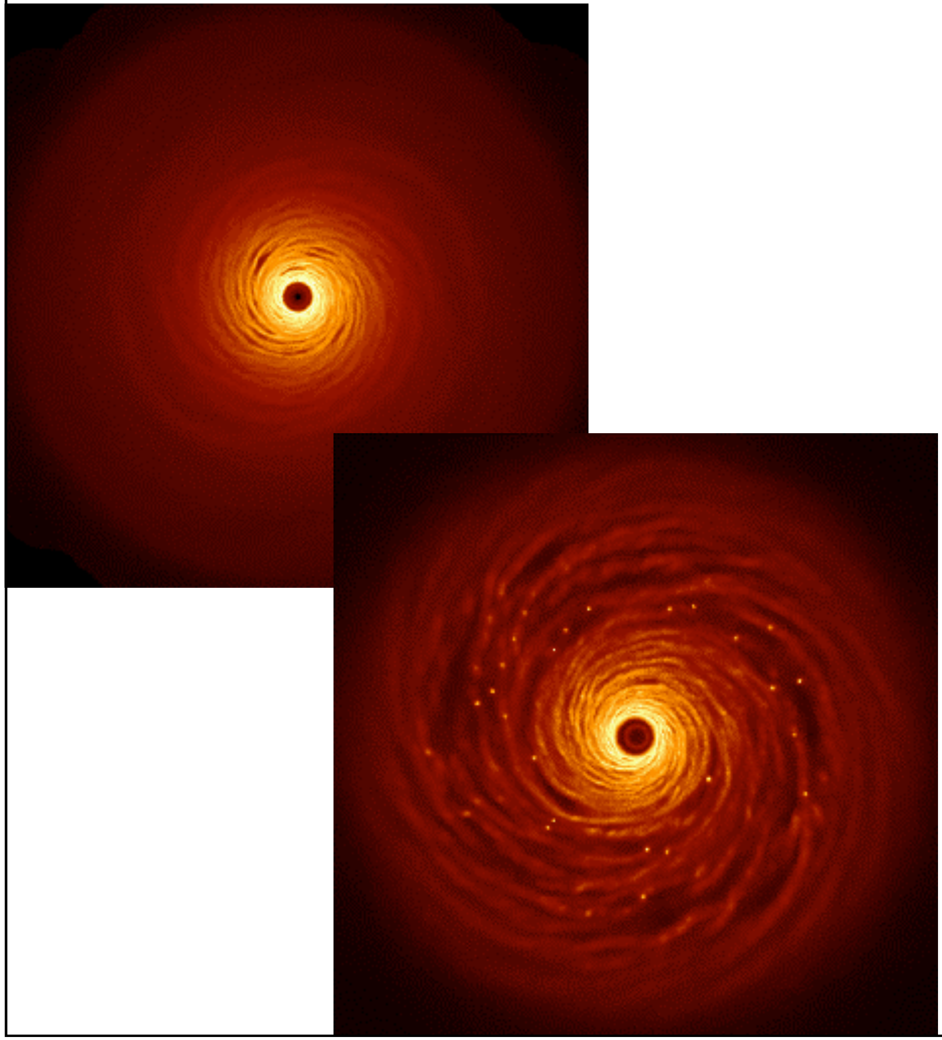
If gas giants form outside the "**Snow Line**" (R > 4 AU, T <170K) where dust grains have **ice mantles** (H_2O,NH_3,CH_4).

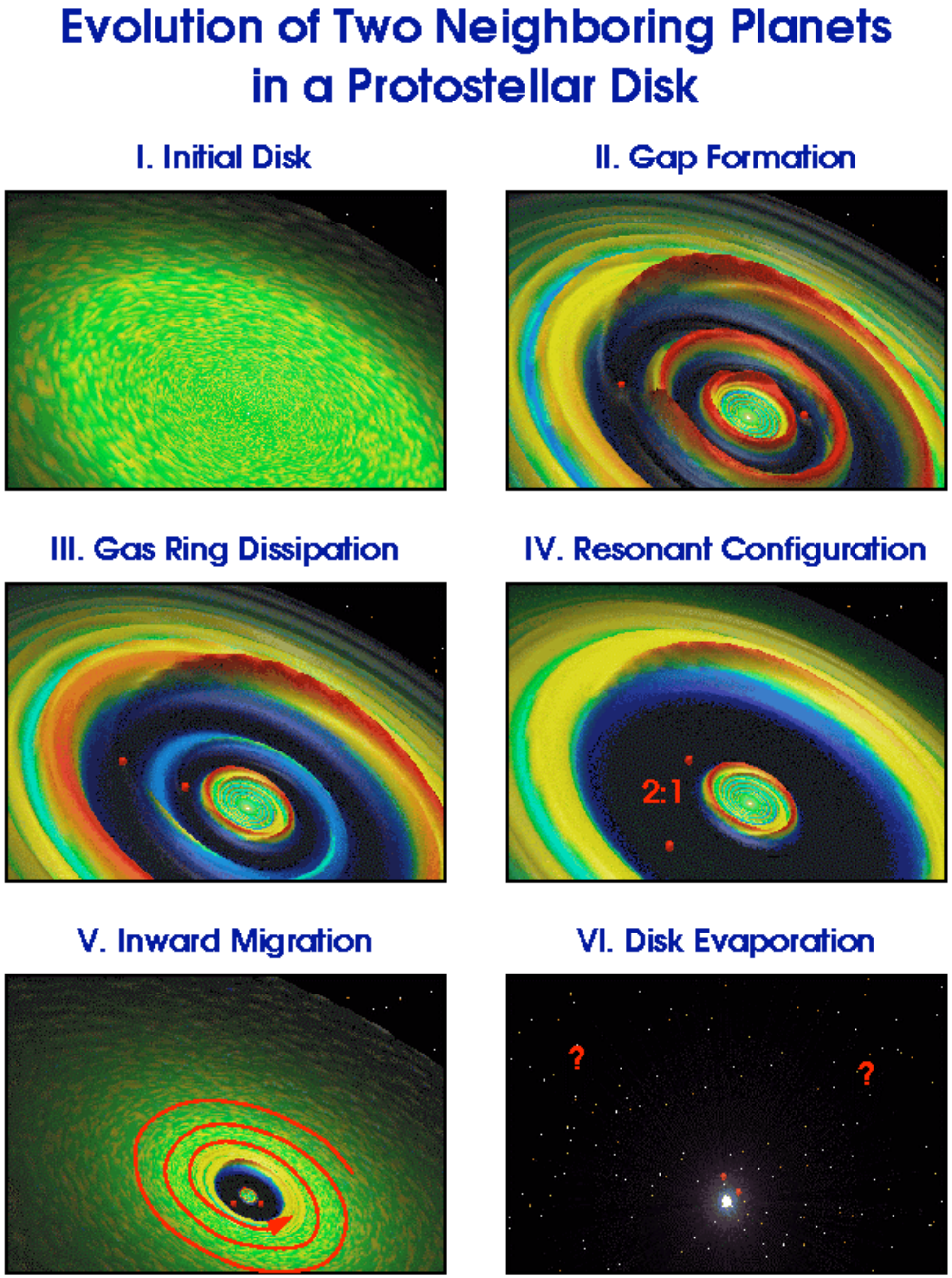
How then can Hot Jupiters arise?

Something important is missing from our understanding of how planetary systems form.

Is our system typical, or rare ?

Simulations of Planet **Formation** and **Migration**

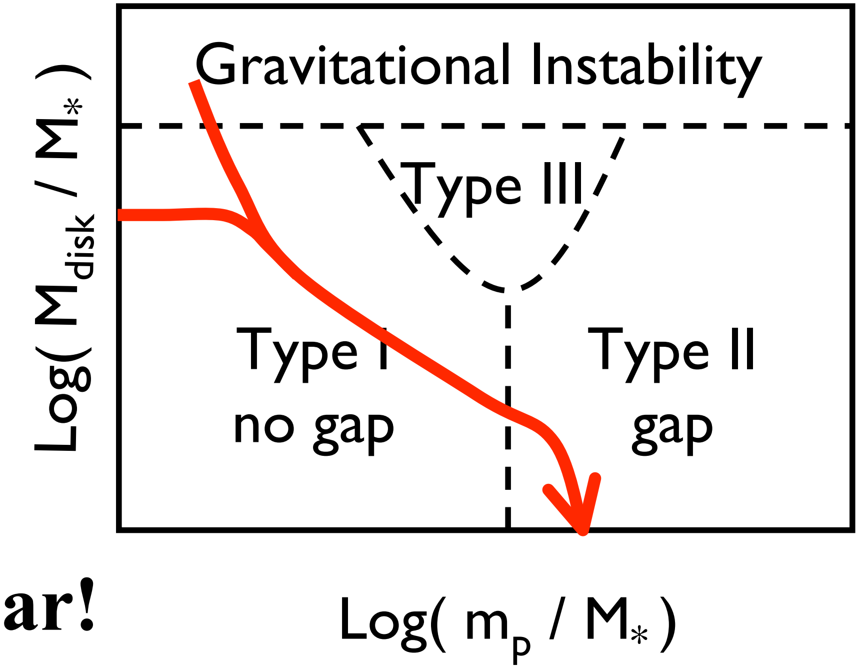




Bryden/Lin 2001
http://www.ucolick.org/~bryden/2planet

Orbit Migration isToo Fast : (

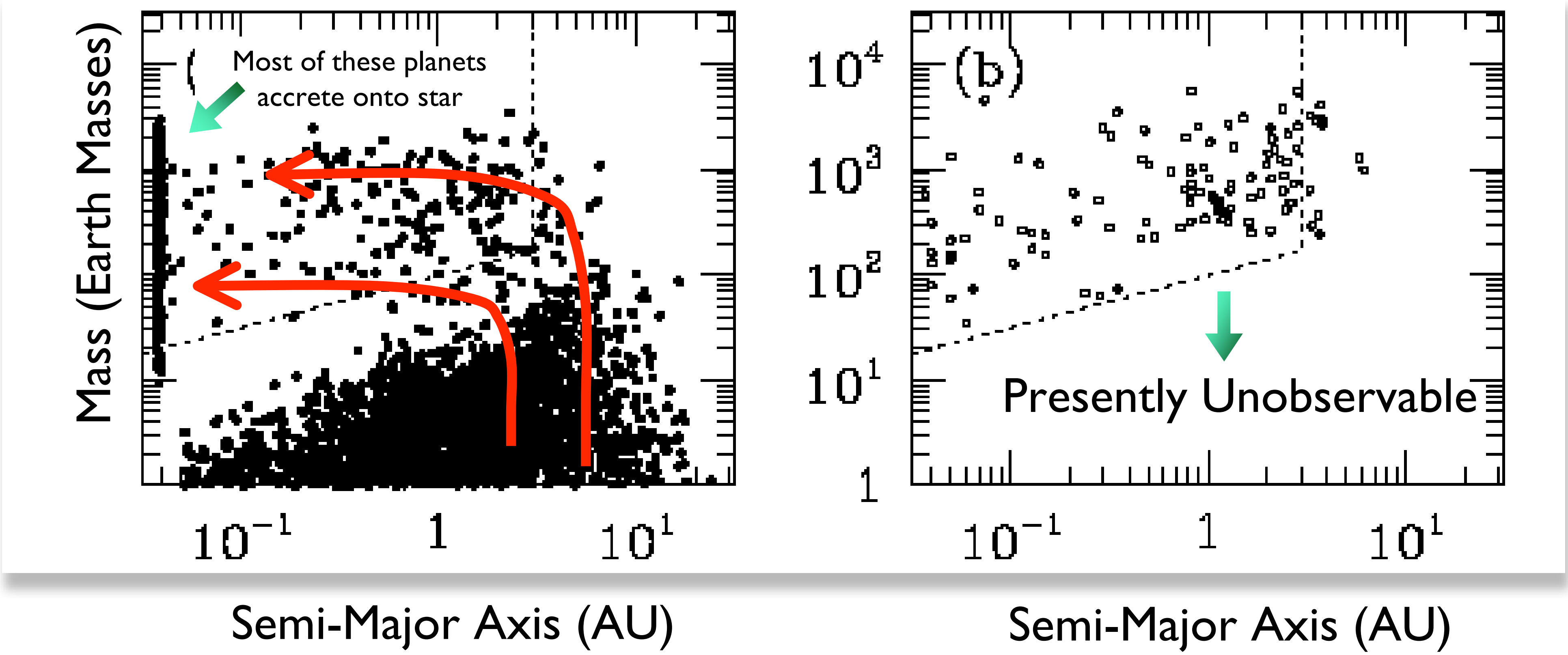
- Spiral waves induced by planet
  - Exchange angular momentum with disk
- Type 1 -- no gap. Fast.
  - m < Saturn $\sim 10^{4-5}$yr
- Type II -- gap. Slow.
  - m > Saturn $\sim 10^{6-7}$yr
- Type III -- Runaway.
  - m ~ Saturn $\sim 10^{2-3}$yr



- **Planets migrate into the star!**
  - **Must suppress Type I migration.**

(To make plansts, a small miracle is needed!)

e.g. *Masset & Papaloizou (2003)*


Ida & Lin Model Distribution

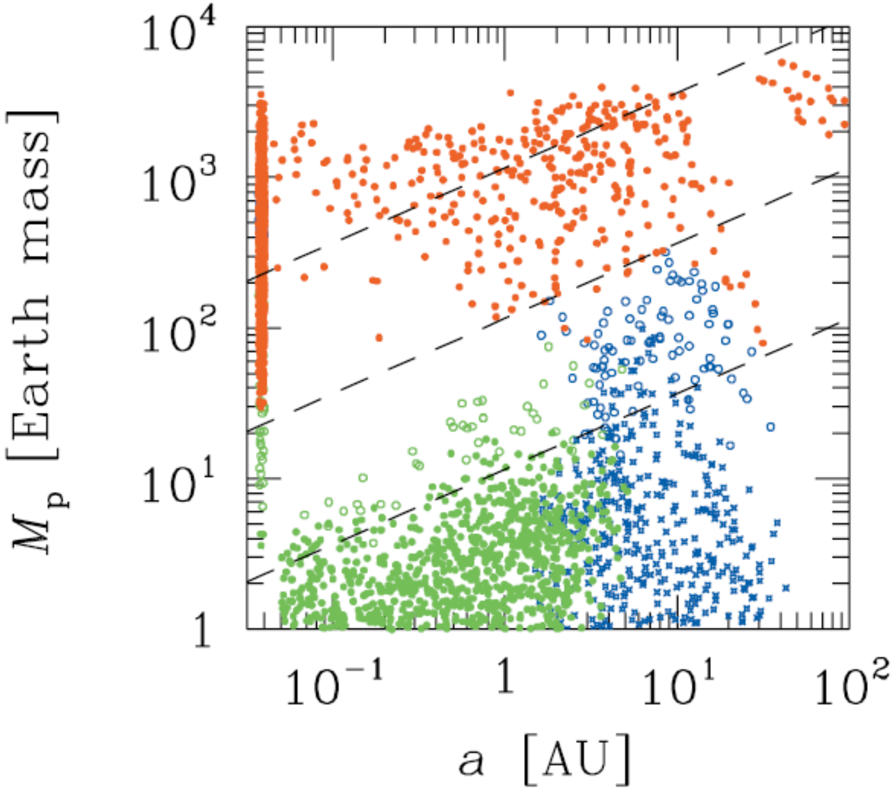
Observed Distribution

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.

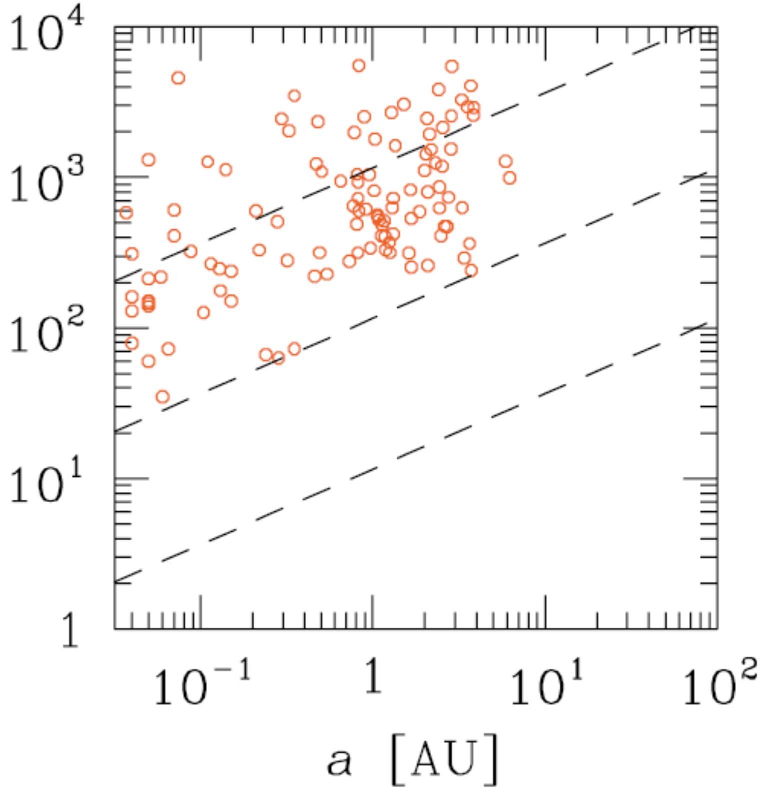
$$\tau_{mig} = \frac{a}{\dot{a}} = 10^6 \frac{1}{f(g,0)} \exp^{t/\tau_{dep}} (\frac{M_p}{M_J})(\frac{a}{1\text{AU}})^{1/2}\,\text{yr}$$

Formation / Migration Simulations

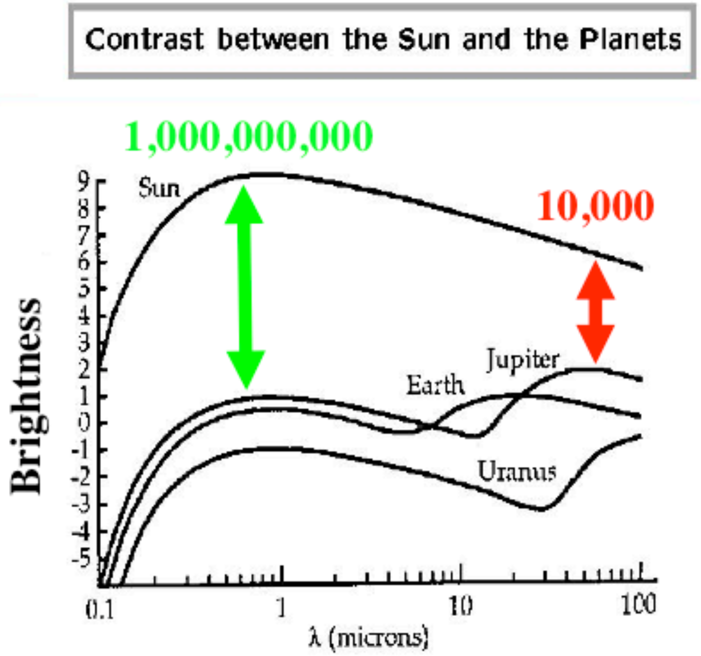
Core accretion + migration simulation by Ida & Lin (2004), showing gas giants, ice giants, rocky planets.



Doppler wobble planets.



Stars are much brighter than their Planets



Visible light **Infra–Red light**

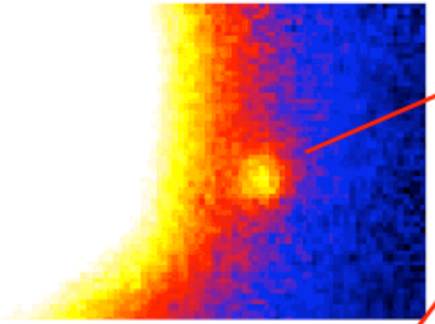
Starlight reflected from clouds

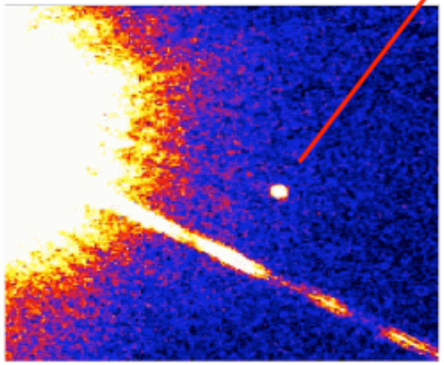
Heat

Direct Imaging is difficult. Brown Dwarfs found ~~but no Planets ... yet.~~

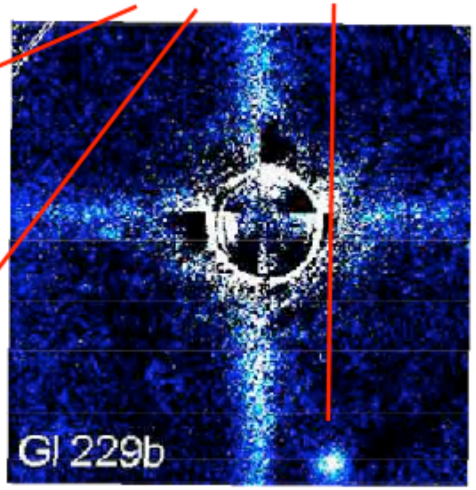
Mt.Palomar 1.5 m Telescope

Brown Dwarf





Hubble Space Telescope



Infrared Coronagraph with Adaptive Optics

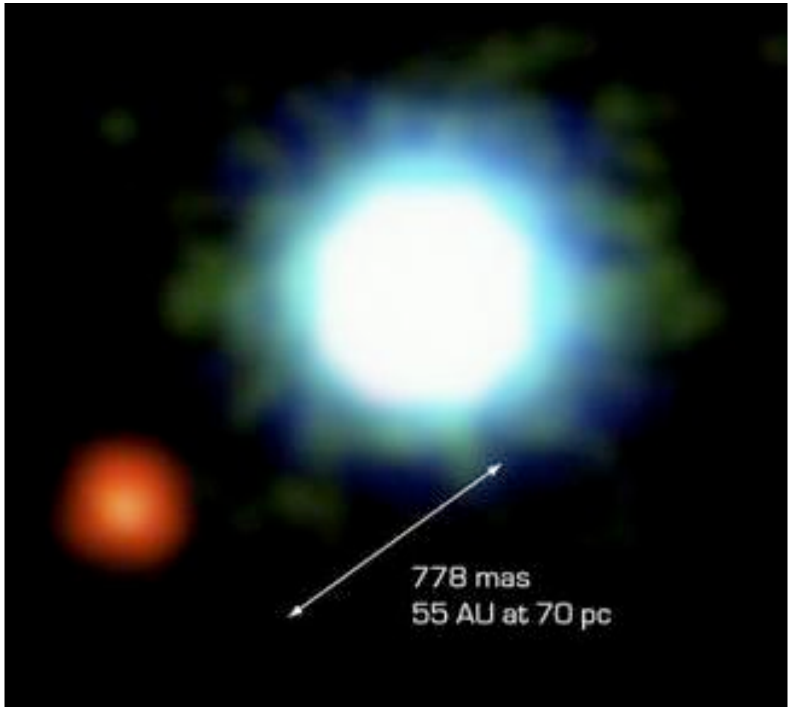
2005: Direct Imaging (with Adaptive Optics)

2MASSW J1207334-393254
young brown dwarf (mass~70 M_J)
companion (mass ~ 5 M_J)

Detectable because:

(1) brown dwarf (T~2950K) much cooler and fainter than the Sun

(2) Companion quite far from the brown dwarf (~55 AU - beyond the orbit of Pluto)



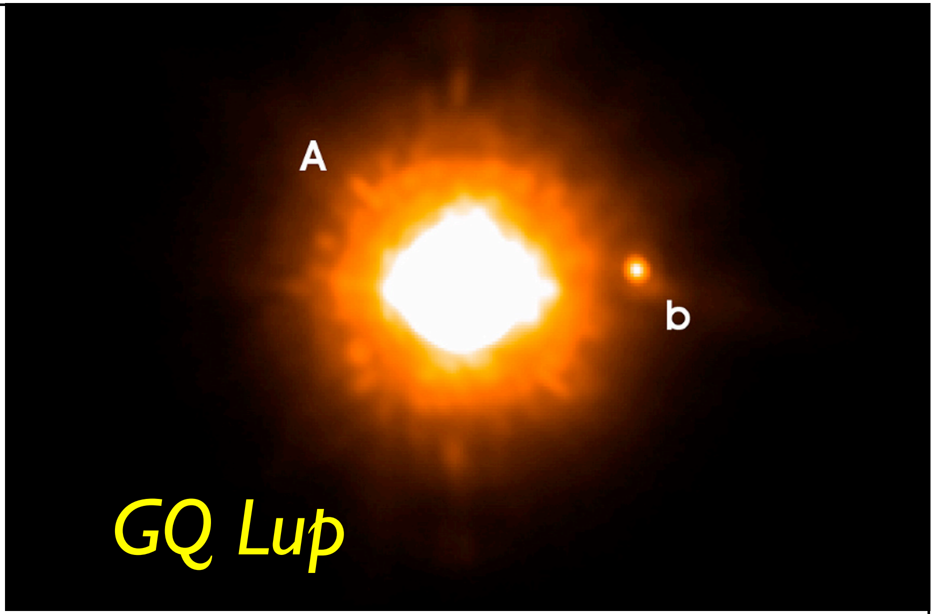
First directly detected exoplanet -- How do we know it is a planet? Do planets form differently than stars and brown dwarfs or are they just less massive -- but form in the same way?

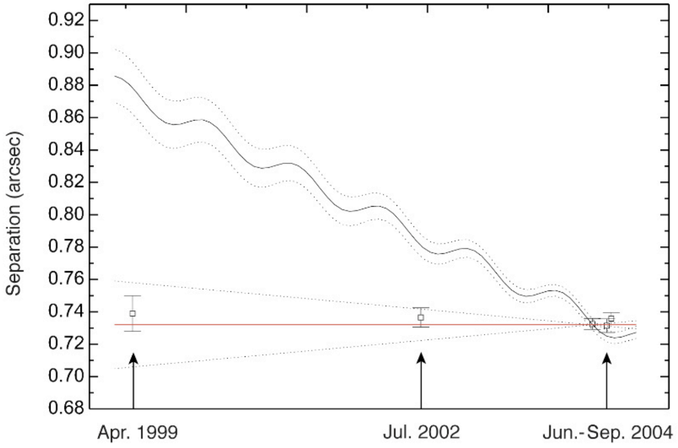
Direct Imaging

HARD!

Extreme Adaptive Optics
Coronography
Nulling Interferometry

Target dim stars:
white dwarfs, brown dwarfs
for faint companions
with *common proper motion*





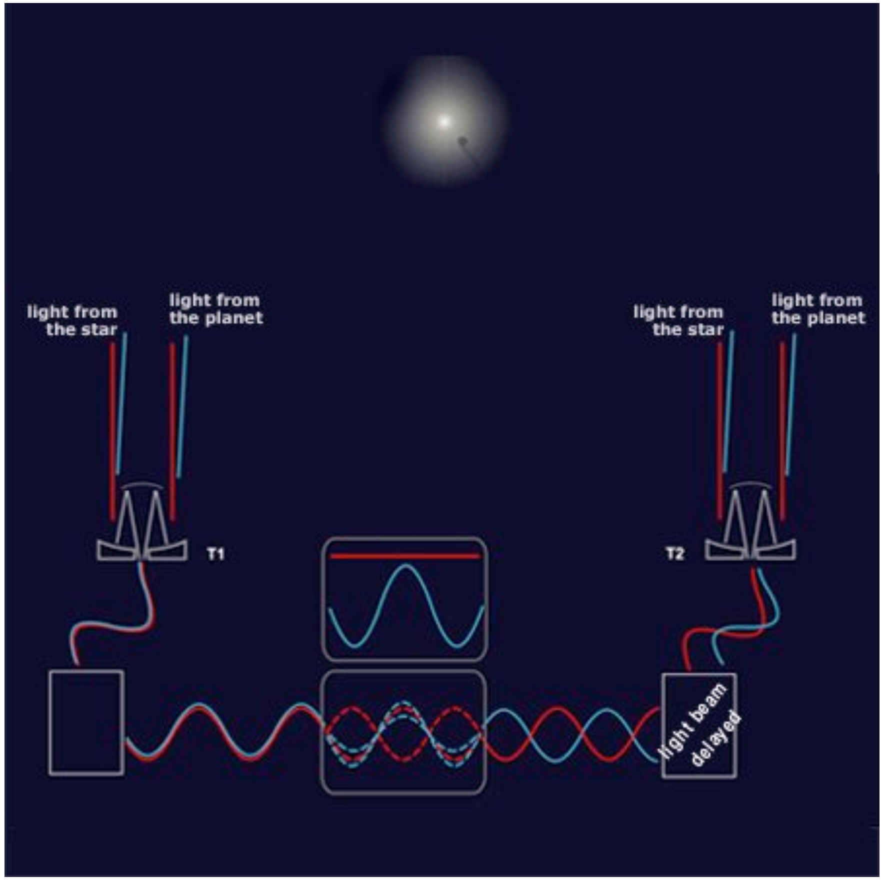
en GQ Lupi and its Companion
ubaru, HST)

© European Southern Observatory

GQ Lup:	22 m_J	100 AU	*Neuhaeuser et al. 2005*
AB Pic :	14 m_J	280 AU	*Chauvin et al. 2005*
2M1207:	5 m_J	55 AU	*Chauvin et al. 2005*

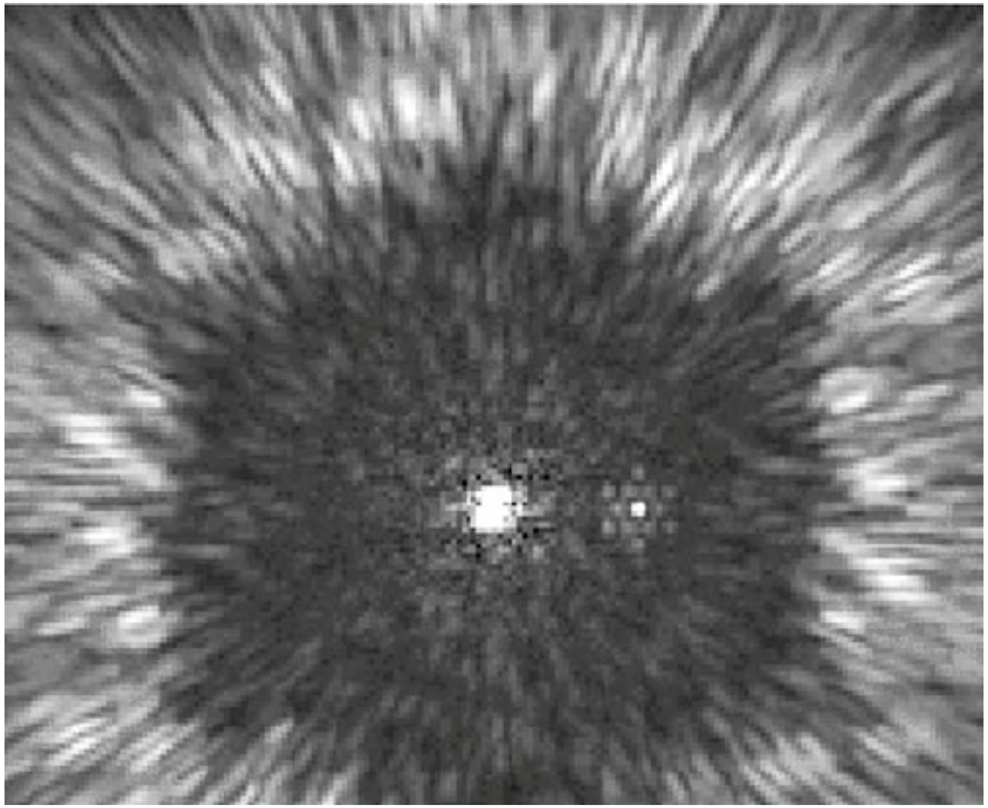
Blocking Stellar Light

Nulling Interferometry



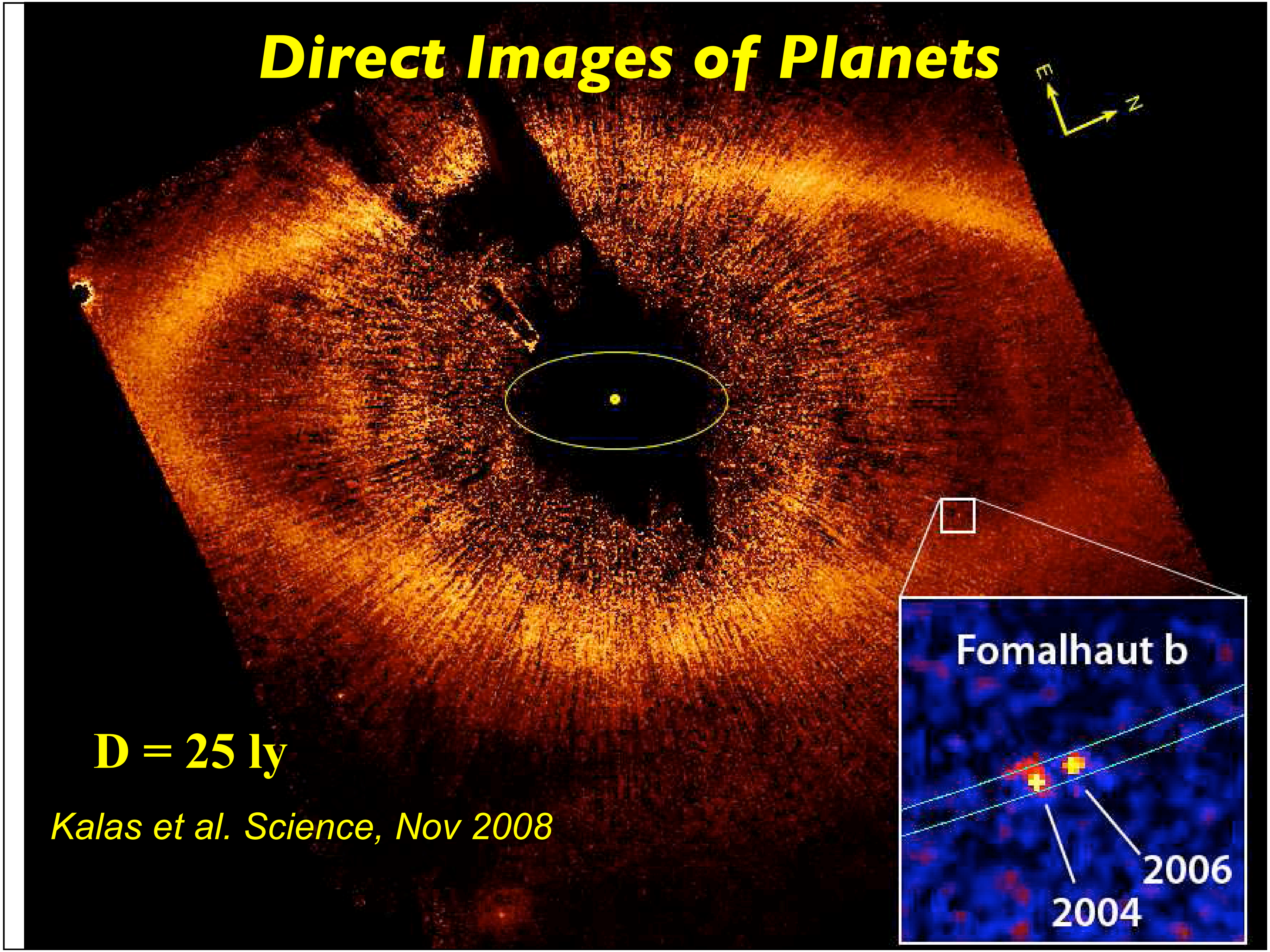
- Use destructive interference to "cancel" the light of the star
- ESA's Darwin, NASA's TPF-I (Terrestrial Planet Finder – Interferometry)

Coronographic telescope



Simulation of a mid-IR image from a space-based coronagraphic telescope of an Earth-like planet orbiting a Sun-like star at a distance of 8 ly.

Direct Images of Planets



D = 25 ly

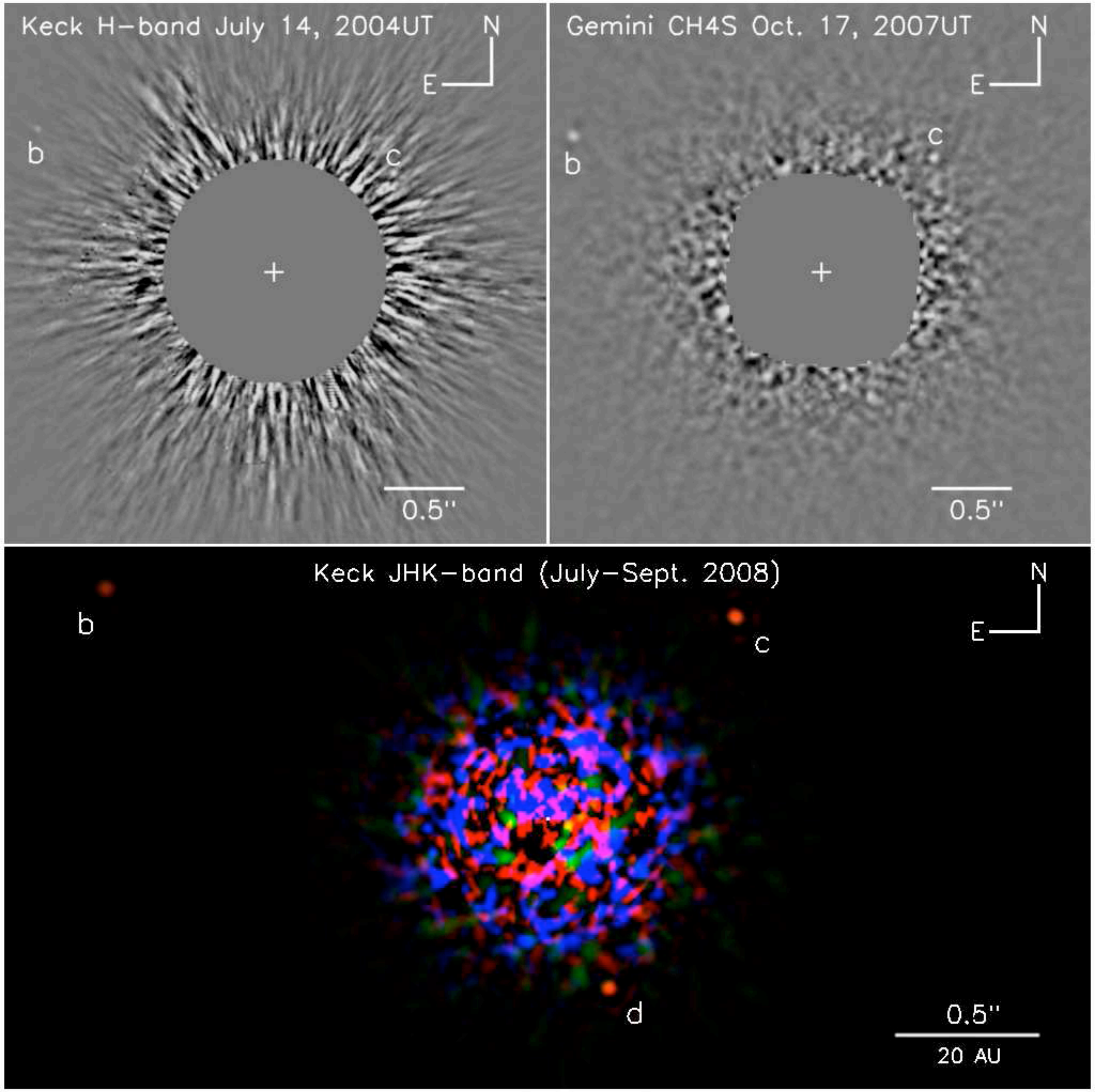
Kalas et al. Science, Nov 2008

Direct Images of Planets

HR 8799
b,c,d

D = 120 ly

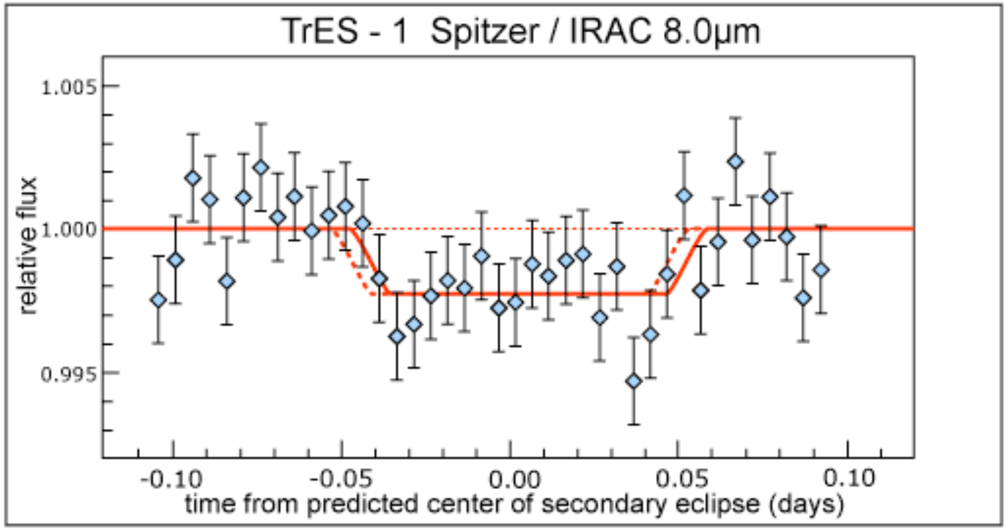
- *Marois et al. Science, Nov 2008*



Secondary Transits in the Mid-IR

Observe a drop in infrared flux when the planet goes behind the star.

Only possible at long wavelengths where the planet/star flux ratio is increased, and for hot Jupiters ($T > 1000$ K)

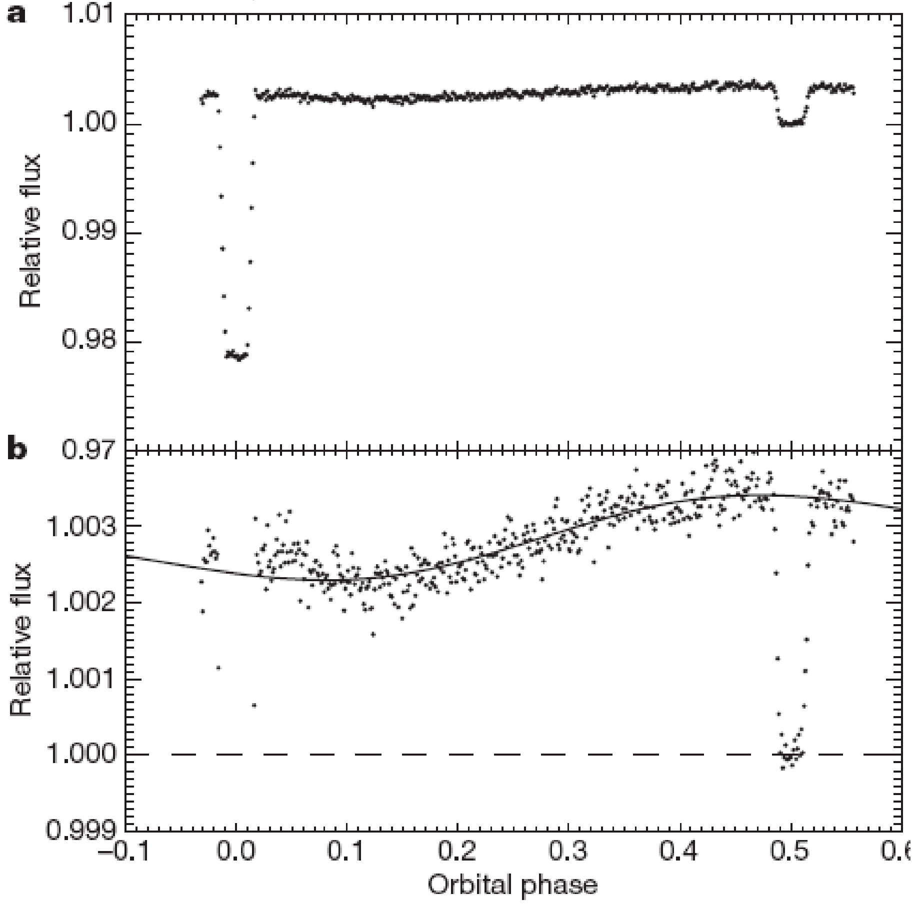


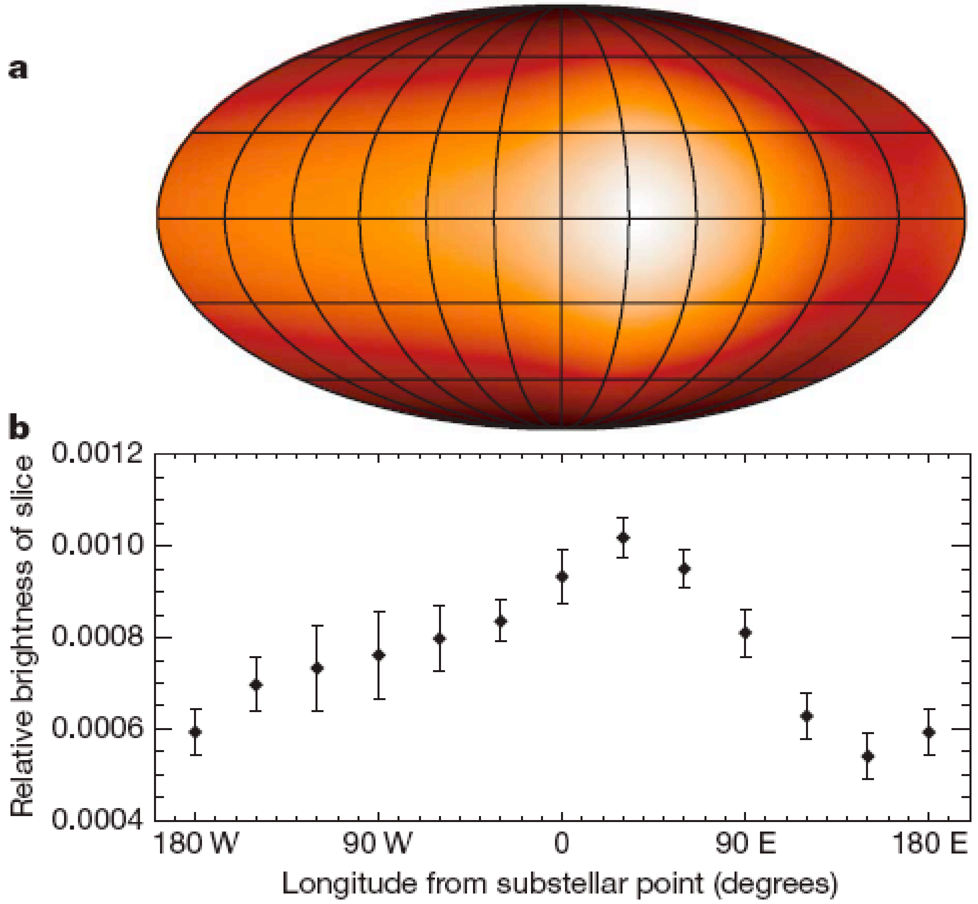
Secondary transit of known transiting planet TRES-1. Depth of 0.00225 => T ~ 1060 K albedo = 31% (if the planet is in thermal equilibrium with the star).

Note: This is not a discovery technique -- it is a follow-up technique to learn more about known planets.

HD189733b 8μm brightness map

- Spitzer/IRAC transit, eclipse, and orbital modulation.
- Planet hotter on star-facing side
- Asymmetric -> partial heat flow





Knutson et al 2007, Nature 447, 183

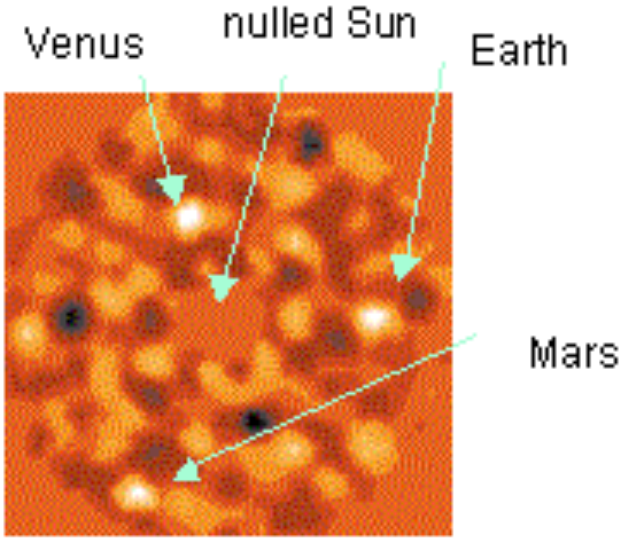
ESA: Darwin

~ **2025-35?**

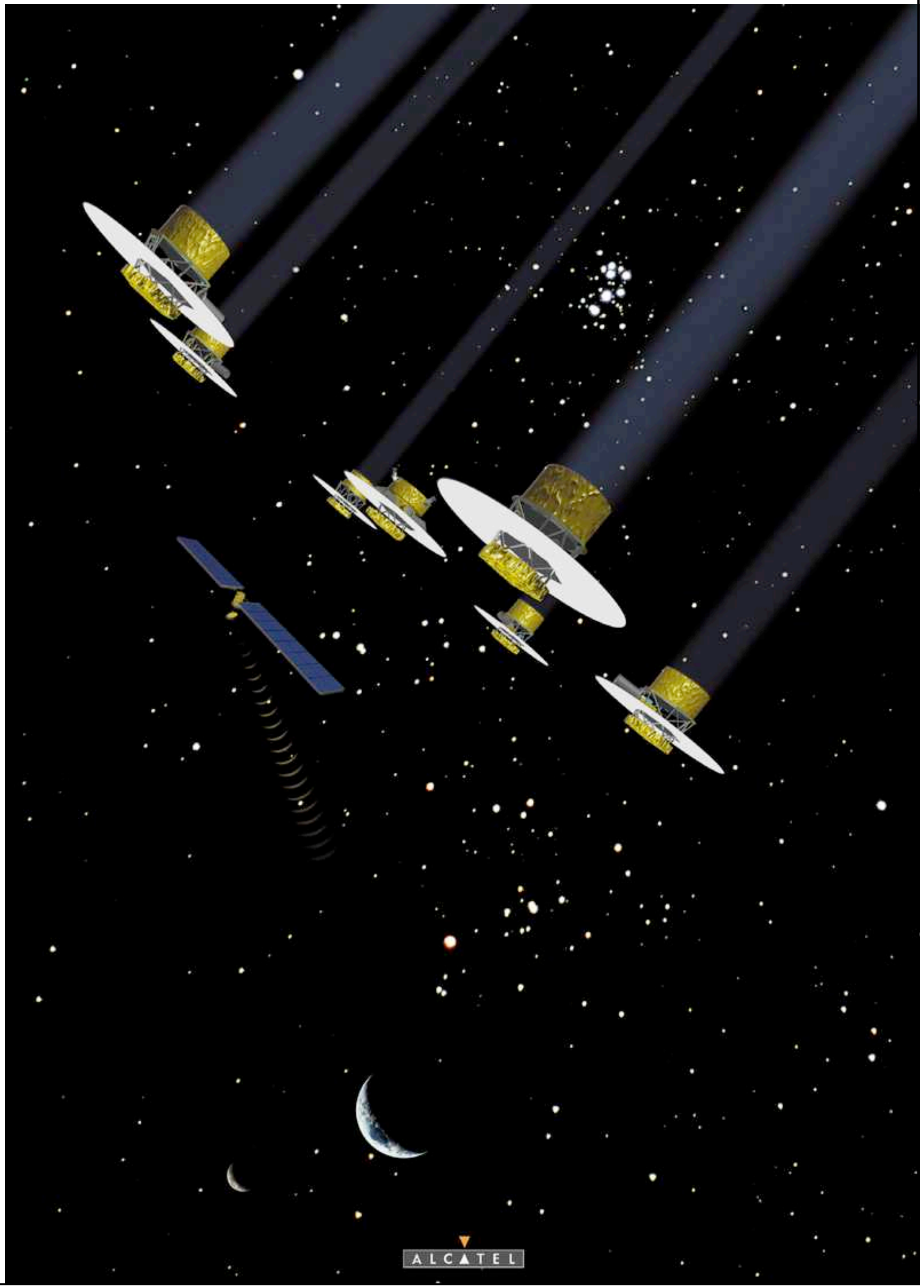
infrared space interferometer

destructive interference cancels out the starlight

snapshot ~500 nearby systems
study ~ 50 in detail



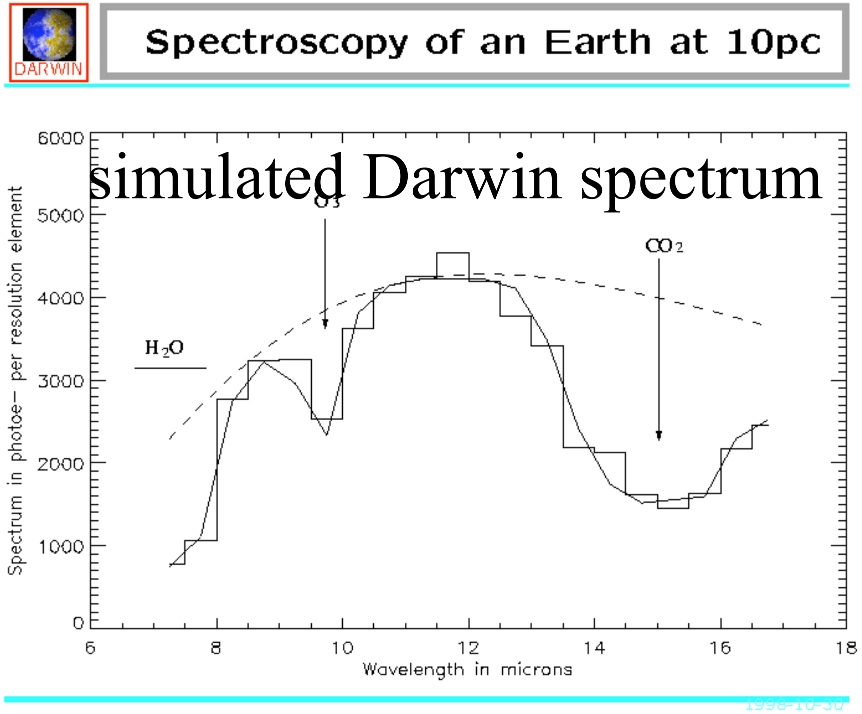
Simulation of an integration on a Solar System analogue at 10 pc.



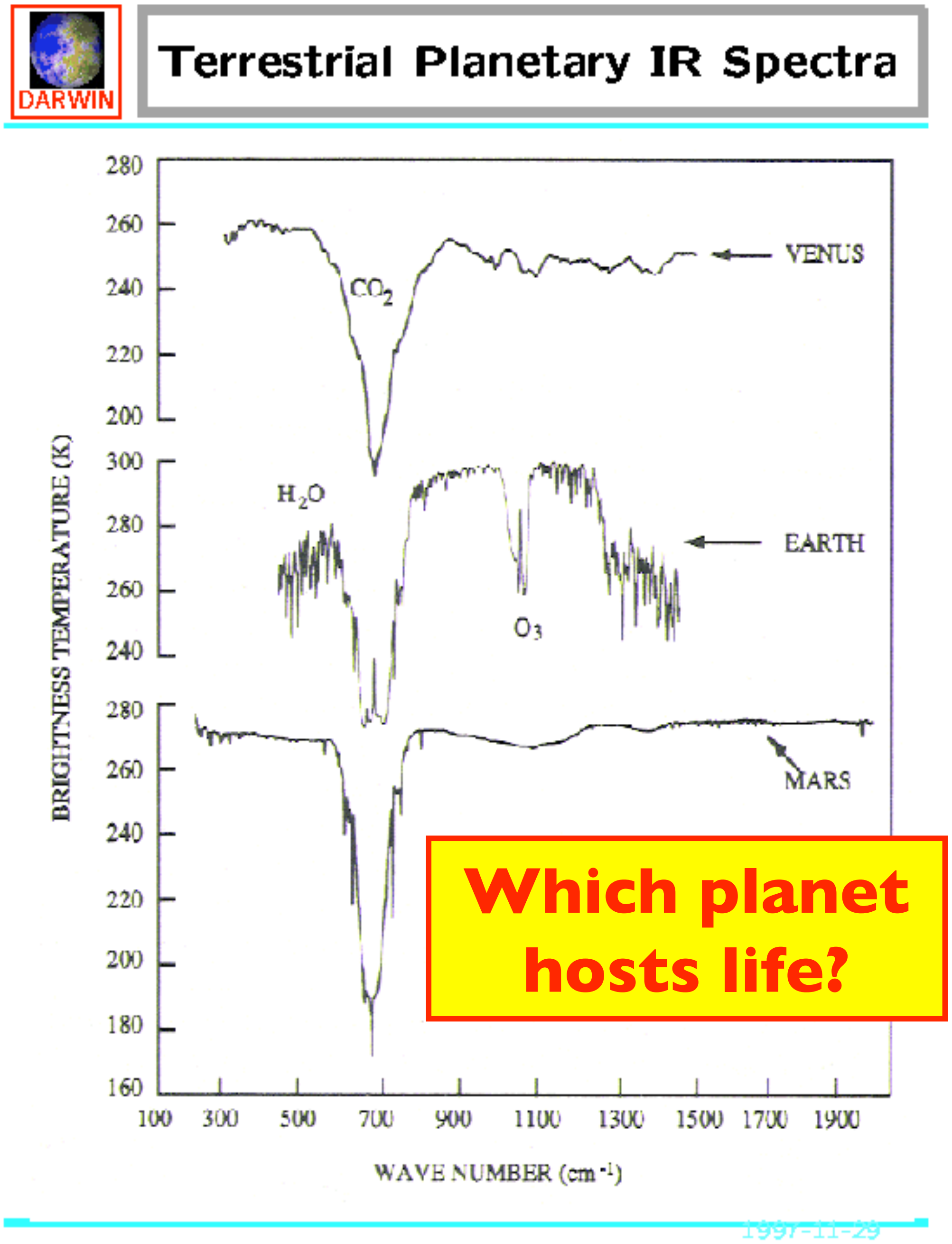
Life's Signature:

disequilibrium atmosphere

(e.g. oxygen-rich)



simulated Darwin spectrum



Which planet hosts life?