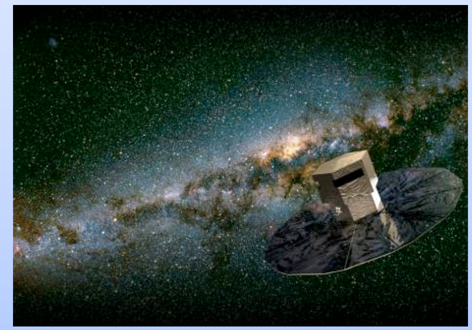
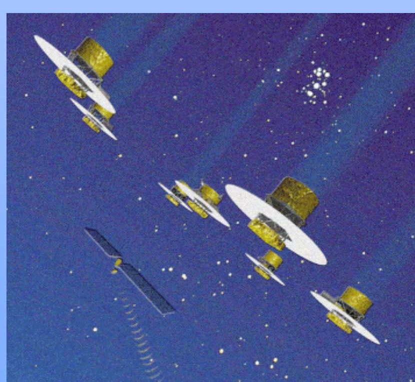
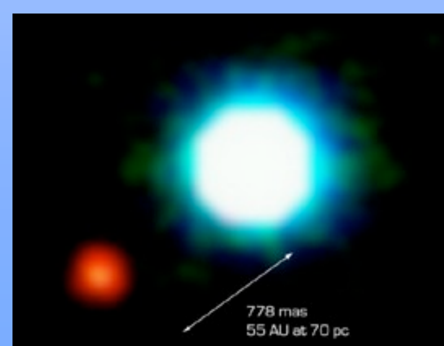
Planet detection methods

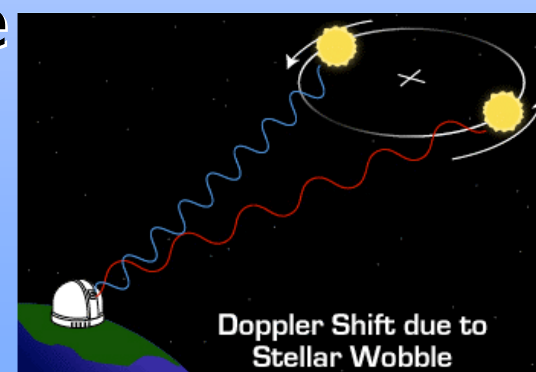


Hugh Jones

University of Hertfordshire







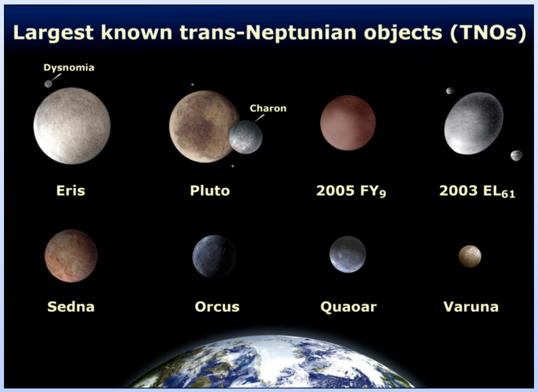
What is a planet ?

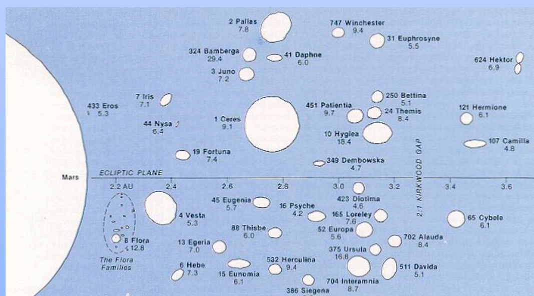
- What are we looking for? Used to be a simple question, made much more complex by discoveries to date
- IAU: “A planet is an object that has a mass between that of Pluto and ~ 13 Jupiter masses (the Nuclear-burning threshold) and that forms in orbit around an object that can generate energy by nuclear reactions.”
- Key characteristics:

  Low mass (Mplanet < 1/100 Msun)

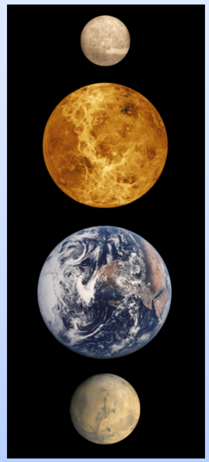
  Orbit a central star

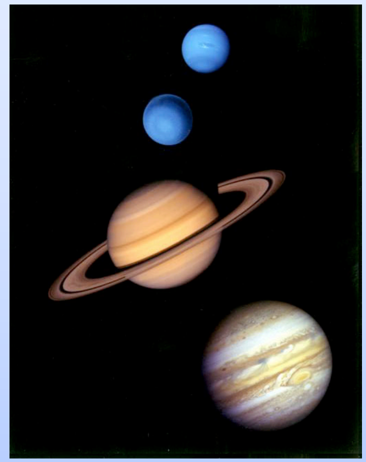
Essentially: Planets orbits stars, and have mass and size between two extremes



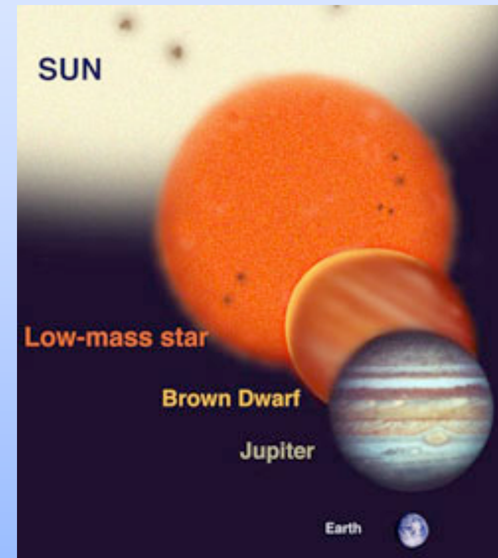


Low-mass end: asteroids and TNOs are known as minor planets)





PLANETS



High mass end: Brown dwarfs (>13 Jupiter masses) are not planets

Planet hunting techniques

- The main challenge in finding planets is their extreme faintness compared to their host stars
- Different search methods deal with this in different ways
- There are at least seven “successful” approaches

  - Direct imaging – taking a picture, while trying to minimise interference from the star

  - Pulsar timing – change in timing of pulses

  - Astrometric wobbles – planet’s effect on the position of the star

  - Detection of debris disks - observation of proto-planetary disk

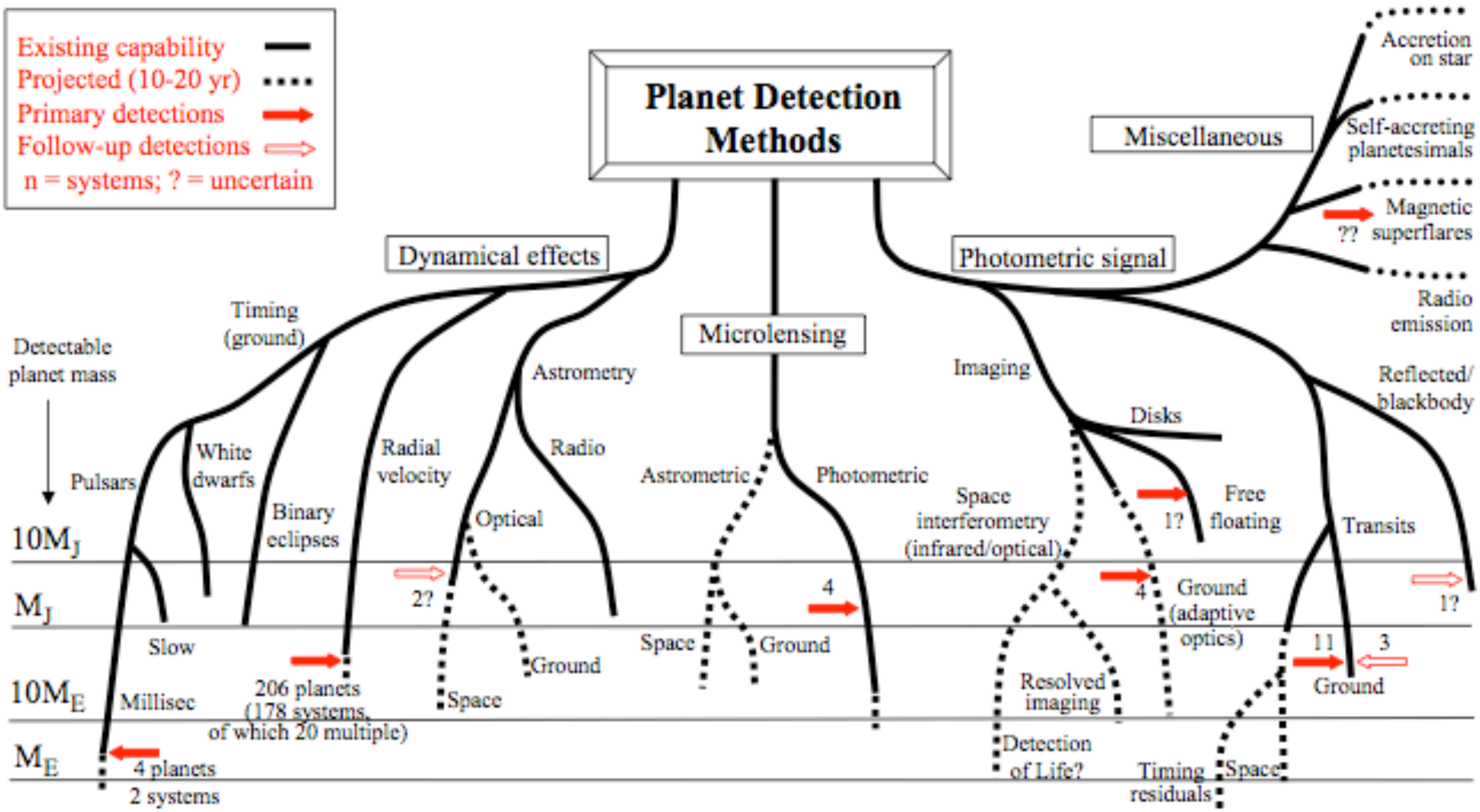
  - Radial velocity Doppler shift – planet’s effect on the velocity of the star

  - The transit method – planet’s effect on the apparent brightness of the star

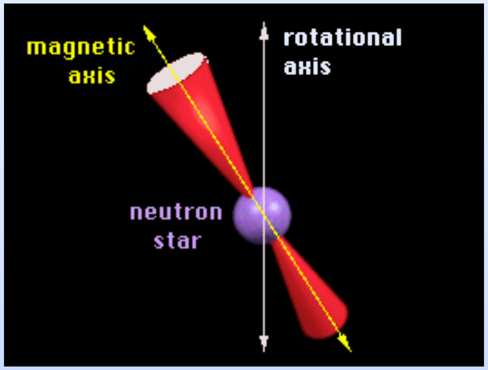
  - Microlensing – planet’s effect on the brightness of background stars

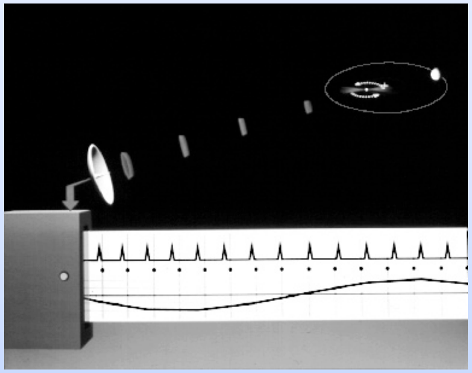
Planet Detection Methods

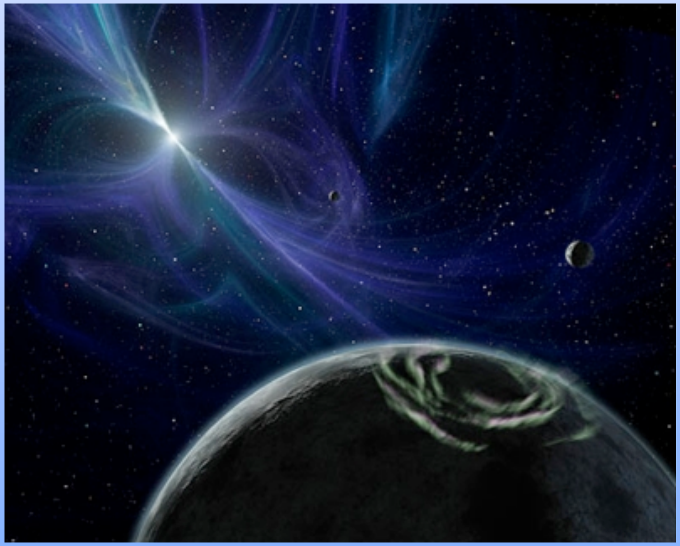
Michael Perryman, Rep. Prog. Phys., 2000, 63, 1209 (updated April 2007)
[corrections or suggestions please to michael.perryman@esa.int]



The 'first' extrasolar planets found





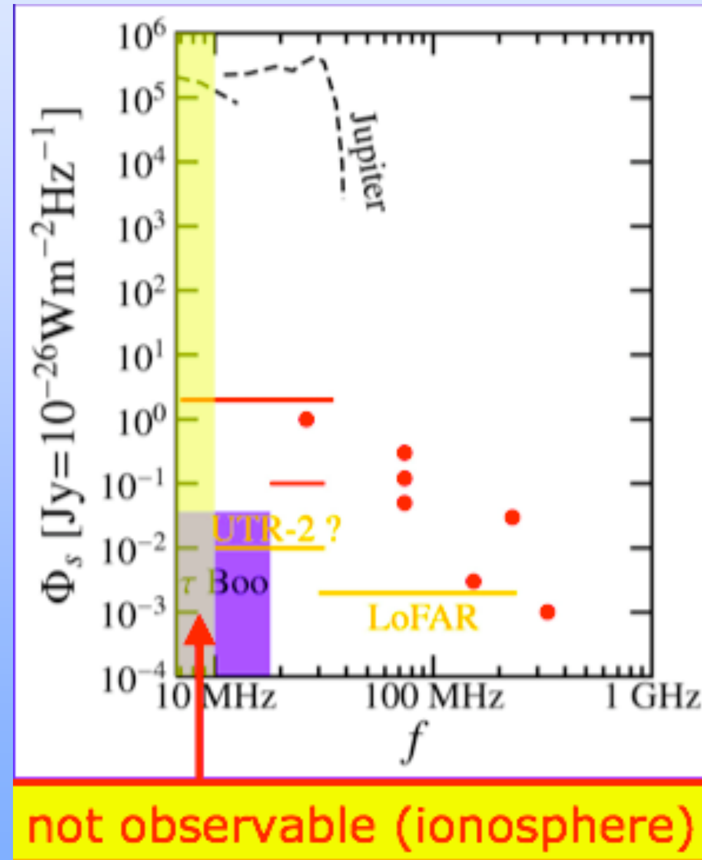


Planet masses 4.3, 3.9, 0.02 earth masses, orbiting with P=66, 98, 25 days (all within a "Mercury" size orbit)

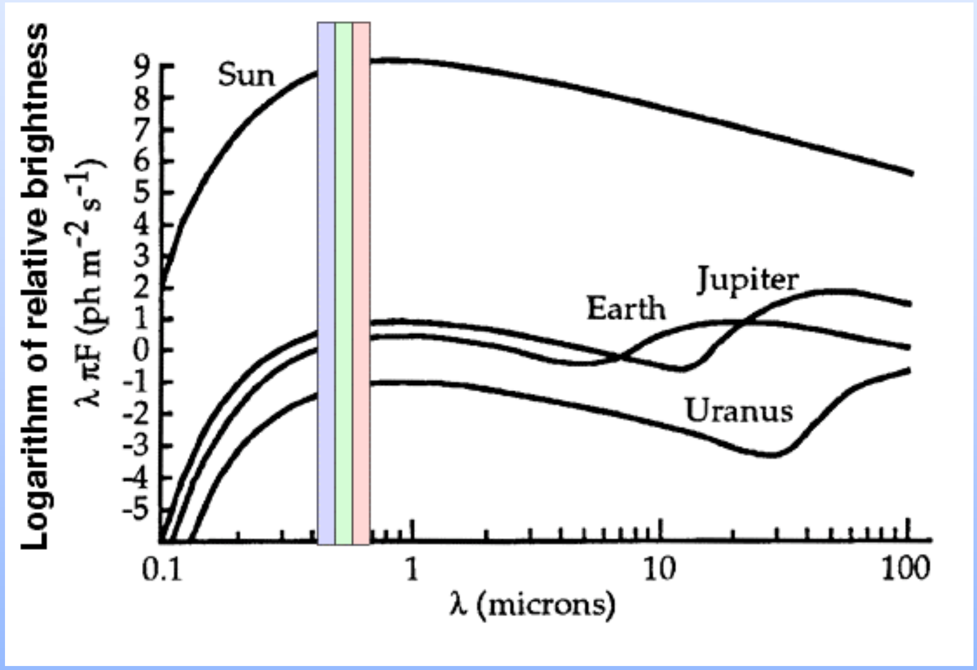
- Wolszczan & Frail 1992discovered several planets orbiting pulsar PSR B1257+12, in the Virgo constellation.
- regular variations in the pulsed radio signal from the pulsar, indicating the gravitational effects of orbiting planets

Radio detections

- Large arrays under construction, e.g.,



Direct imaging

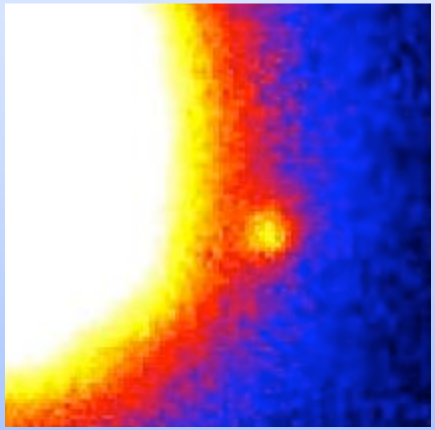


- The simplest way to find planets around other stars is simply to LOOK for them: point a big telescope at a nearby star and see if there are any faint points of light around the star. Unfortunately, the difference in brightness between even a faint star and a planet (even a giant planet) is very large
- In the visible part of the spectrum, Jupiter is ~8 orders of magnitude fainter than the Sun, and the Earth about 8.5

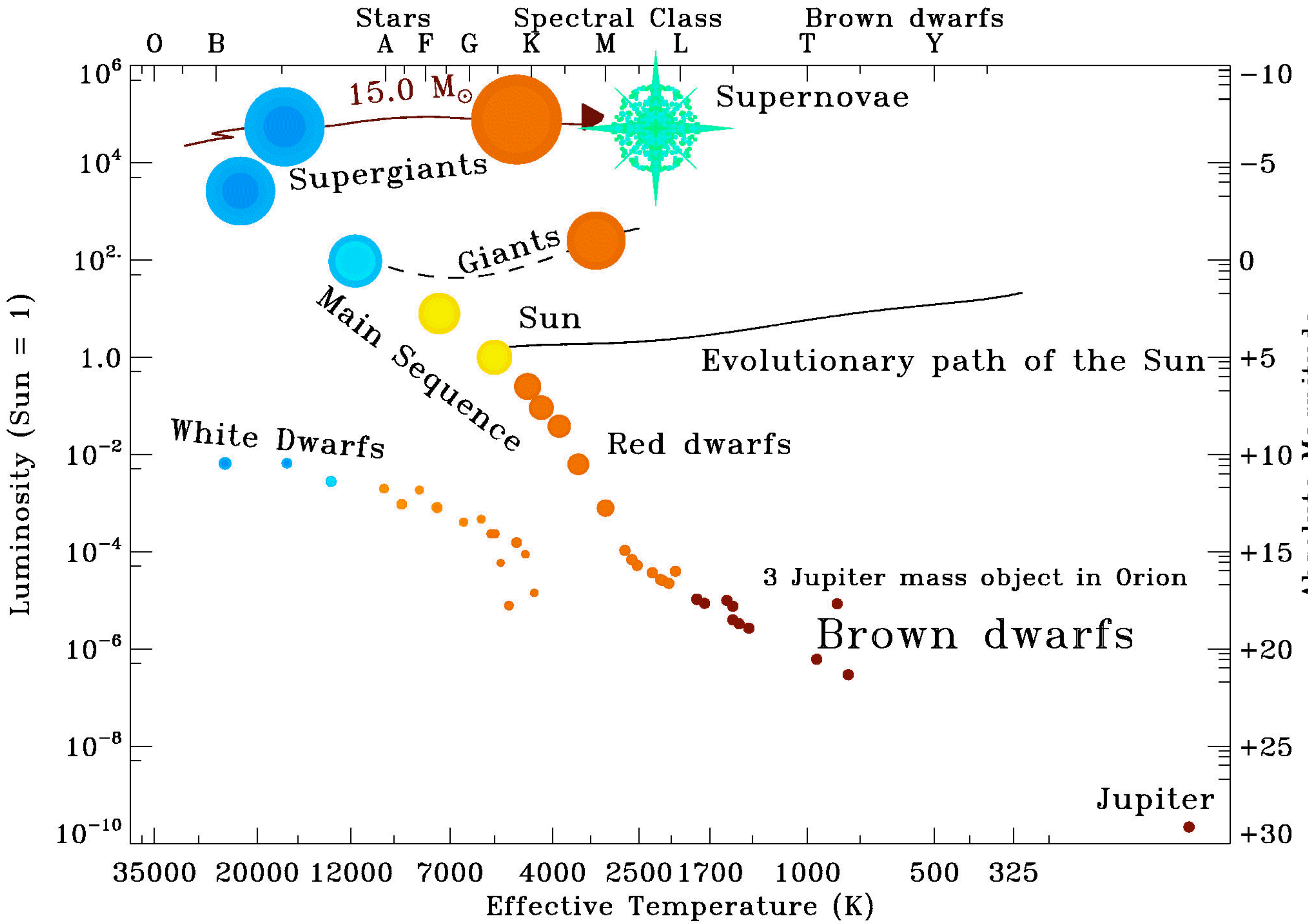
  - Jupiter: 100,000,000 times fainter than the Sun

  - Earth: 300,000,000 times fainter than the Sun

Direct imaging

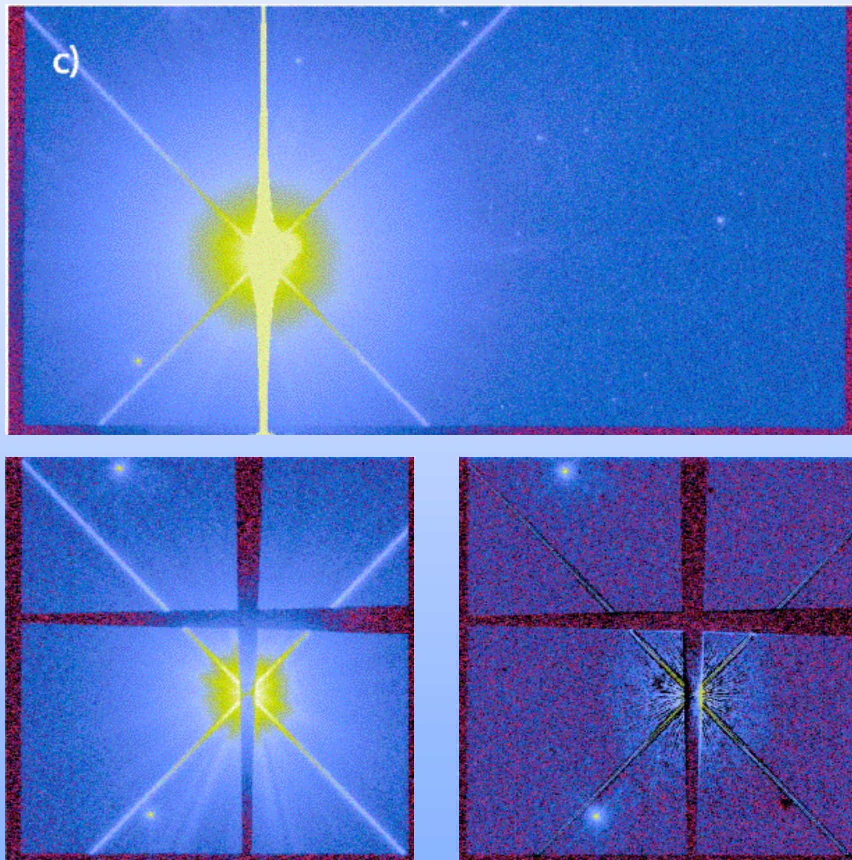


At the same conference when 51 Peg b was presented, a 40 Jupiter mass brown dwarf announced 7 arcsec from a nearby M dwarf.



Stars
Spectral Class
Brown dwarfs
O B A F G K M L T Y
15.0 M⊙
Supernovae
Supergiants
Giants
Main Sequence
Sun
Evolutionary path of the Sun
White Dwarfs
Red dwarfs
3 Jupiter mass object in Orion
Brown dwarfs
Jupiter
Luminosity (Sun = 1)
10^6
10^4
10^2
1.0
10^-2
10^-4
10^-6
10^-8
10^-10
Absolute Magnitude
−10
−5
0
+5
+10
+15
+20
+25
+30
35000 20000 12000 7000 4000 2500 1700 1000 500 325
Effective Temperature (K)

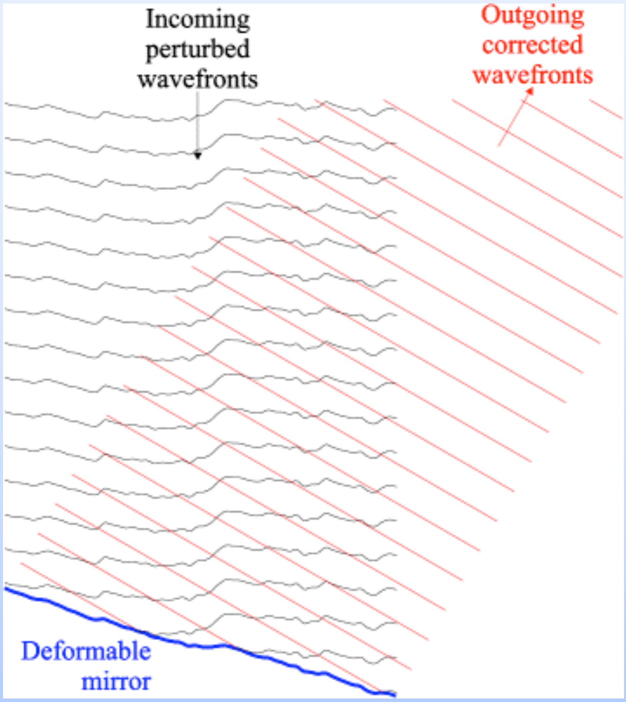
Using a coronagraph



Example of a coronagraph: the STIS camera on the HST

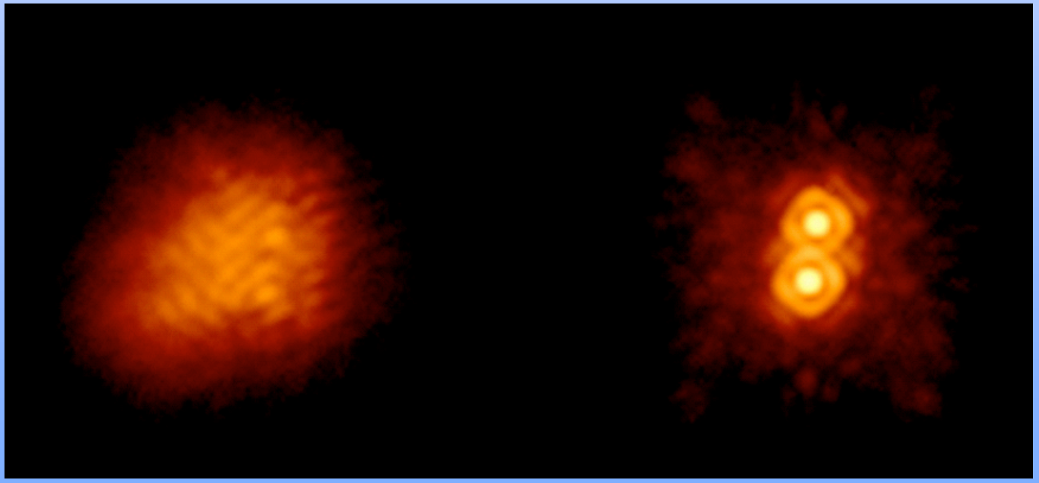
- Even if a tiny fraction of a star's light is scattered out into the wings of the Point Spread Function (PSF), it may overwhelm any planet in orbit around it
- By placing bars, disks, or other opaque objects in the optical path from telescope to camera, one can block alot of a star's light
- One can reduce the scattered light more by subtracting a model of the PSF from the image
- Even so, a significant amount of scattered light remains

Adaptive optics



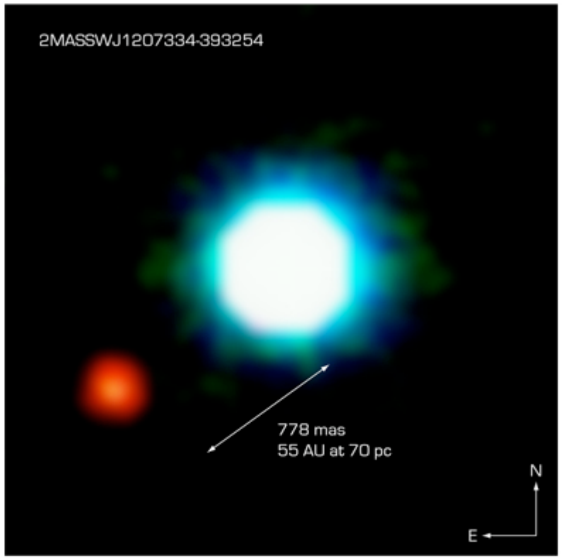
- An alternative way to reduce scattered light in the PSF wings is with AO
- Uses a deformable mirror to correct for the effects of rapidly changing optical distortion from the turbulent atmosphere
- In other words, remove the effects of "seeing"

Use of laser guide star



IW Tau: a young T-tauri binary revealed

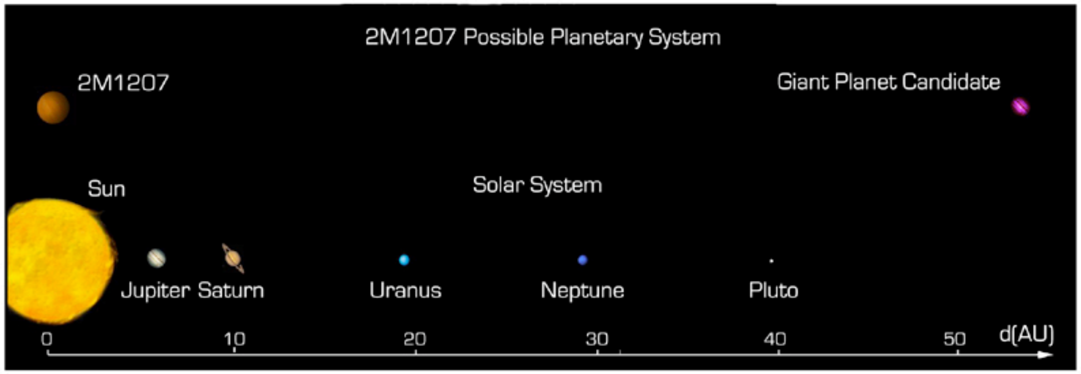
A planet imaged?



NACO Image of the Brown Dwarf Object 2M1207 and GPCC

ESO PR Photo 26a/04 (10 September 2004)

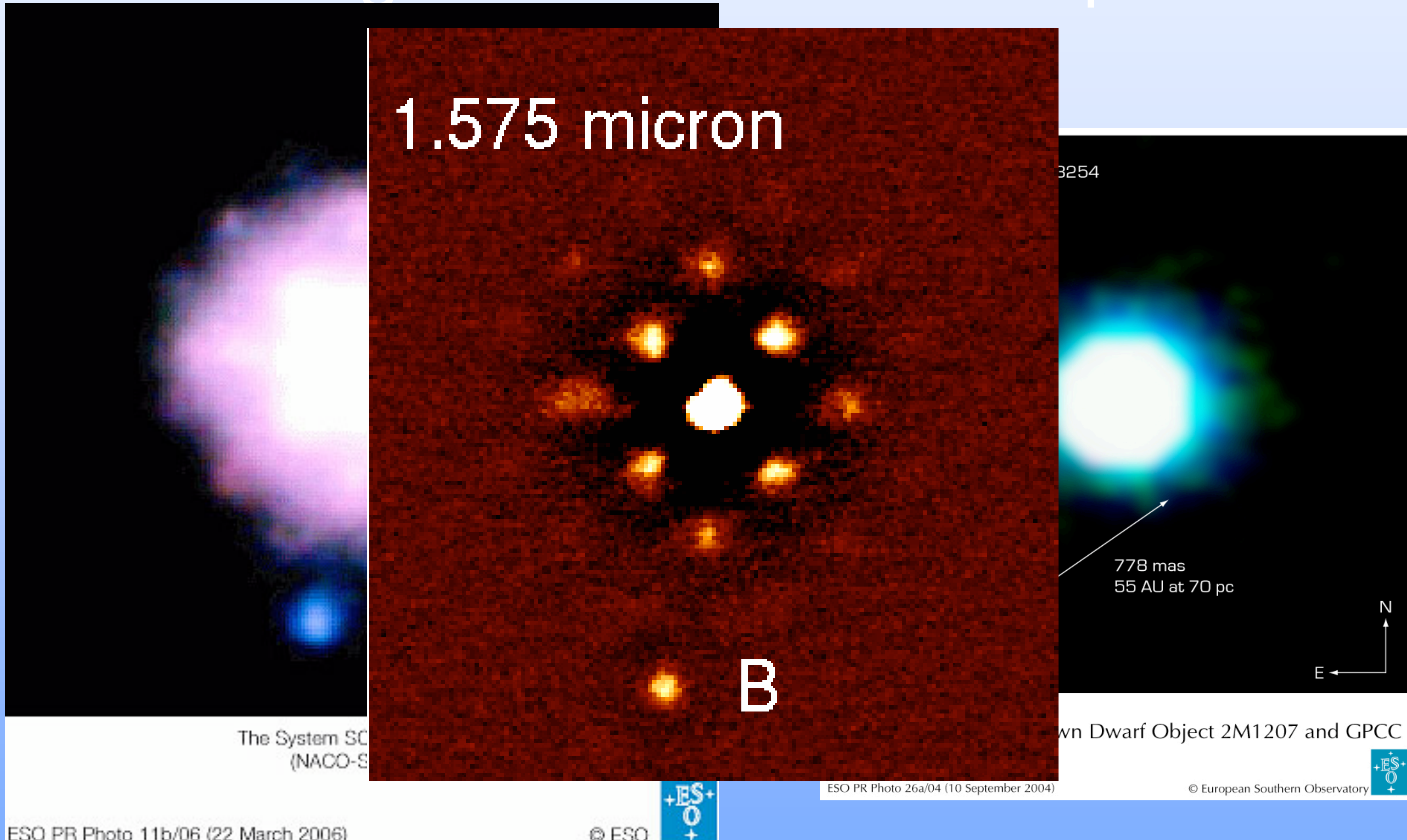
- Three techniques to increase chances of seeing a planet against the glare of its star:
- Intrinsically faint target (ie the brown dwarf) – with a mass ~25 times the mass of Jupiter
- Observed in the near-infrared (wavelengths of 1000-3500 nm), where the star/planet contrast is minimal
- AO to compensate for the atmospheric seeing
- The "planet" has a mass of ~5 times the mass of Jupiter



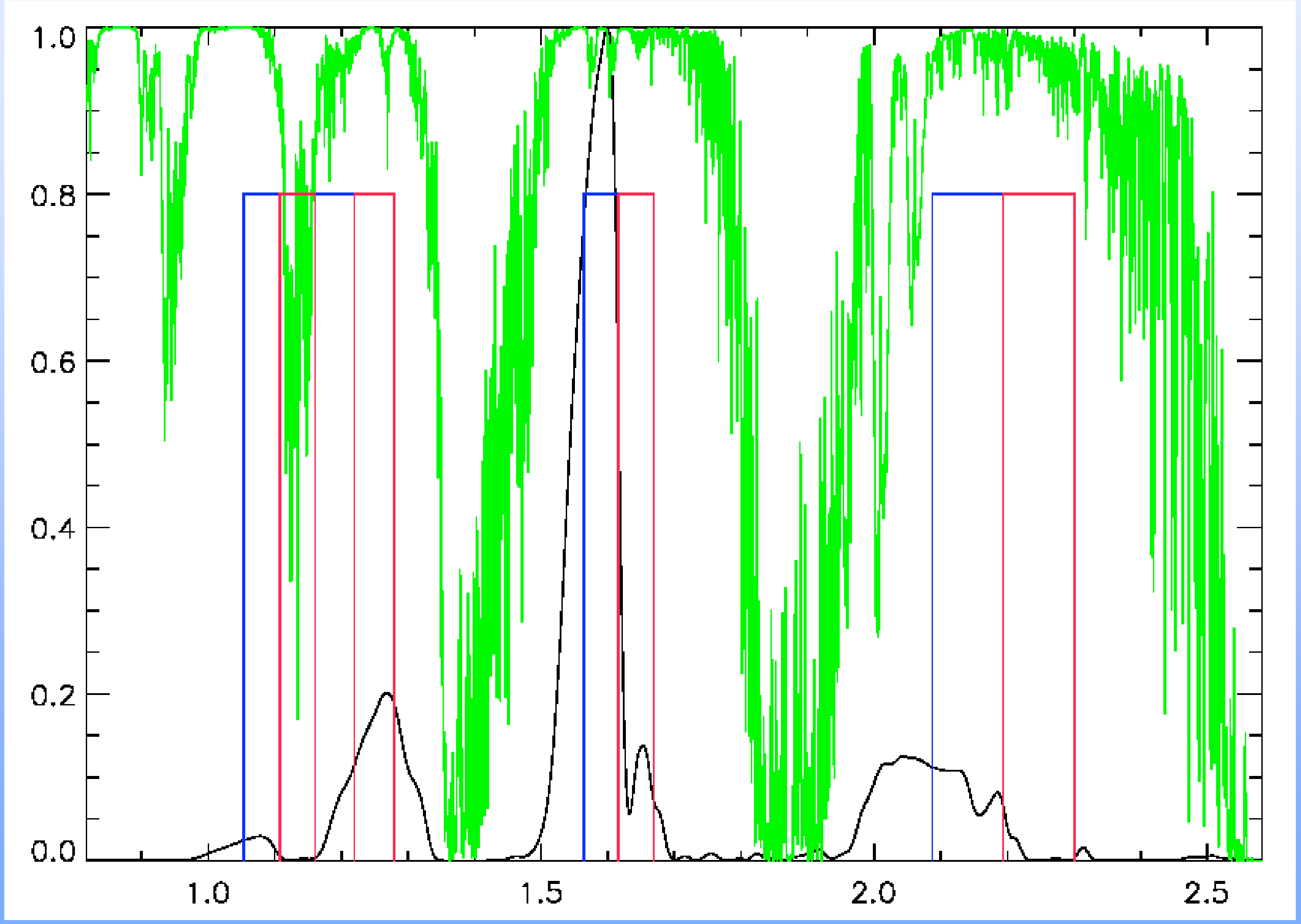
Comparison between the possible 2M1207 System and the Solar System

ESO PR Photo 26c/04 (10 September 2004)

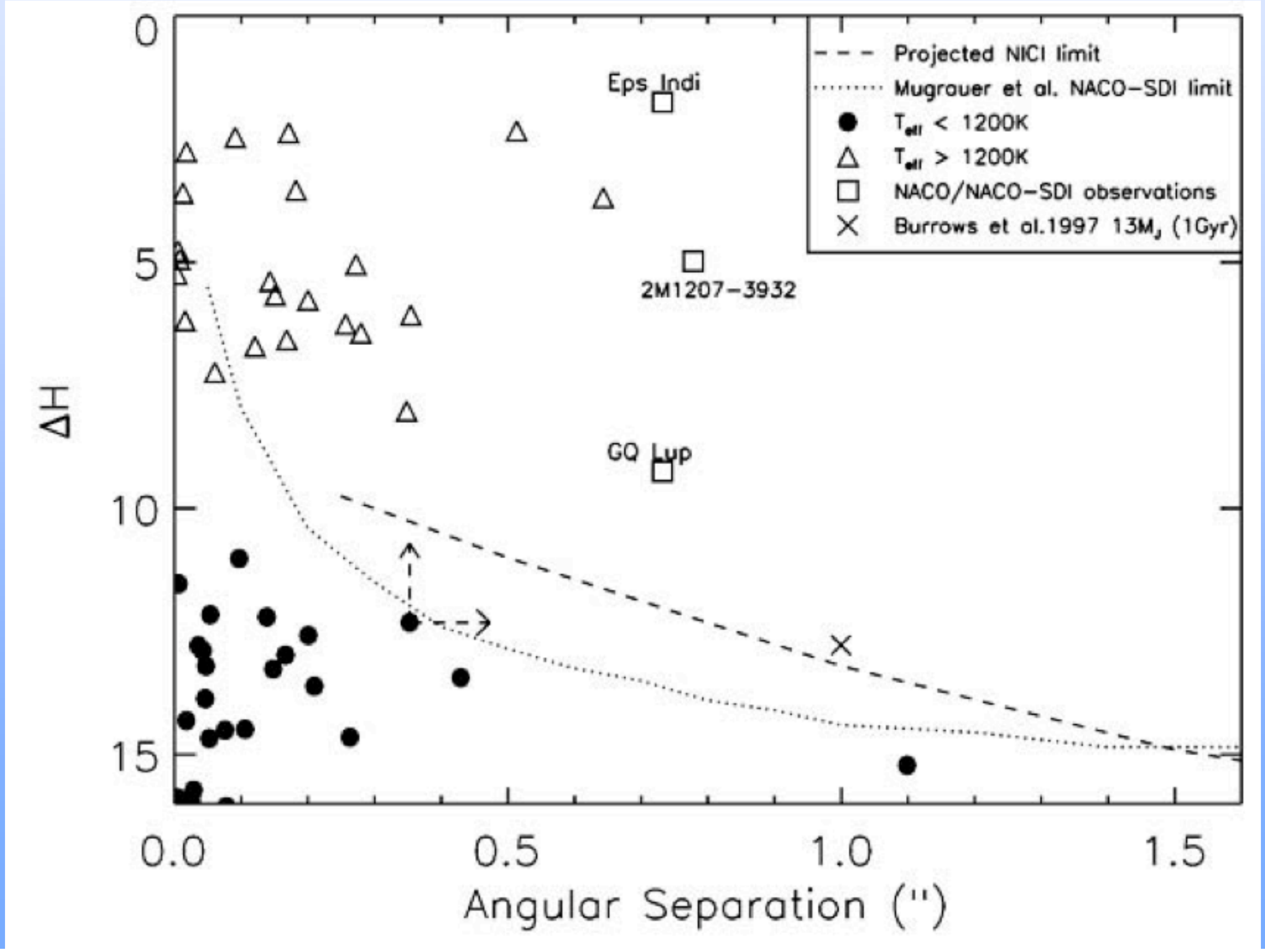
Young brown dwarf / Giant planet



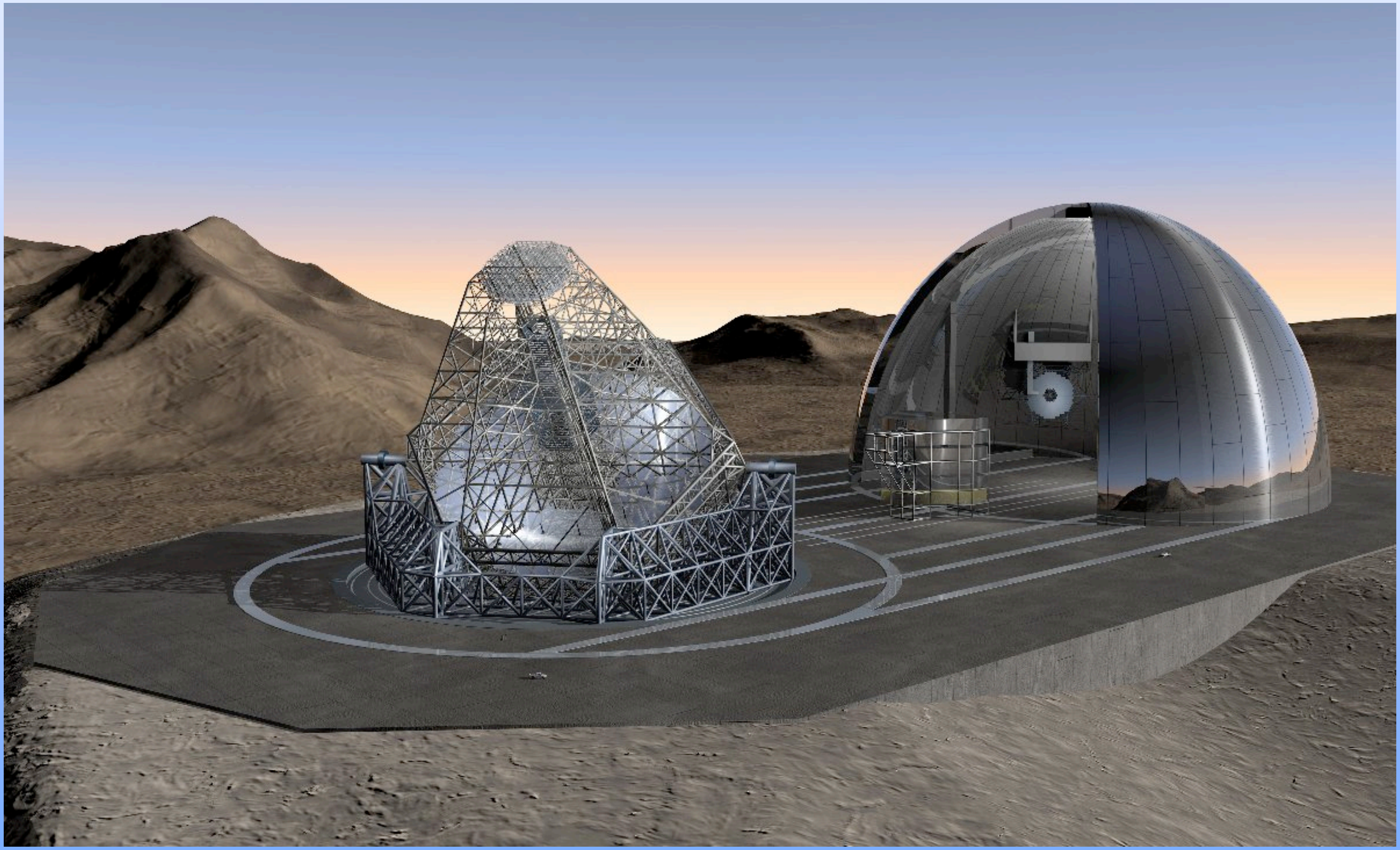
Tunable filters

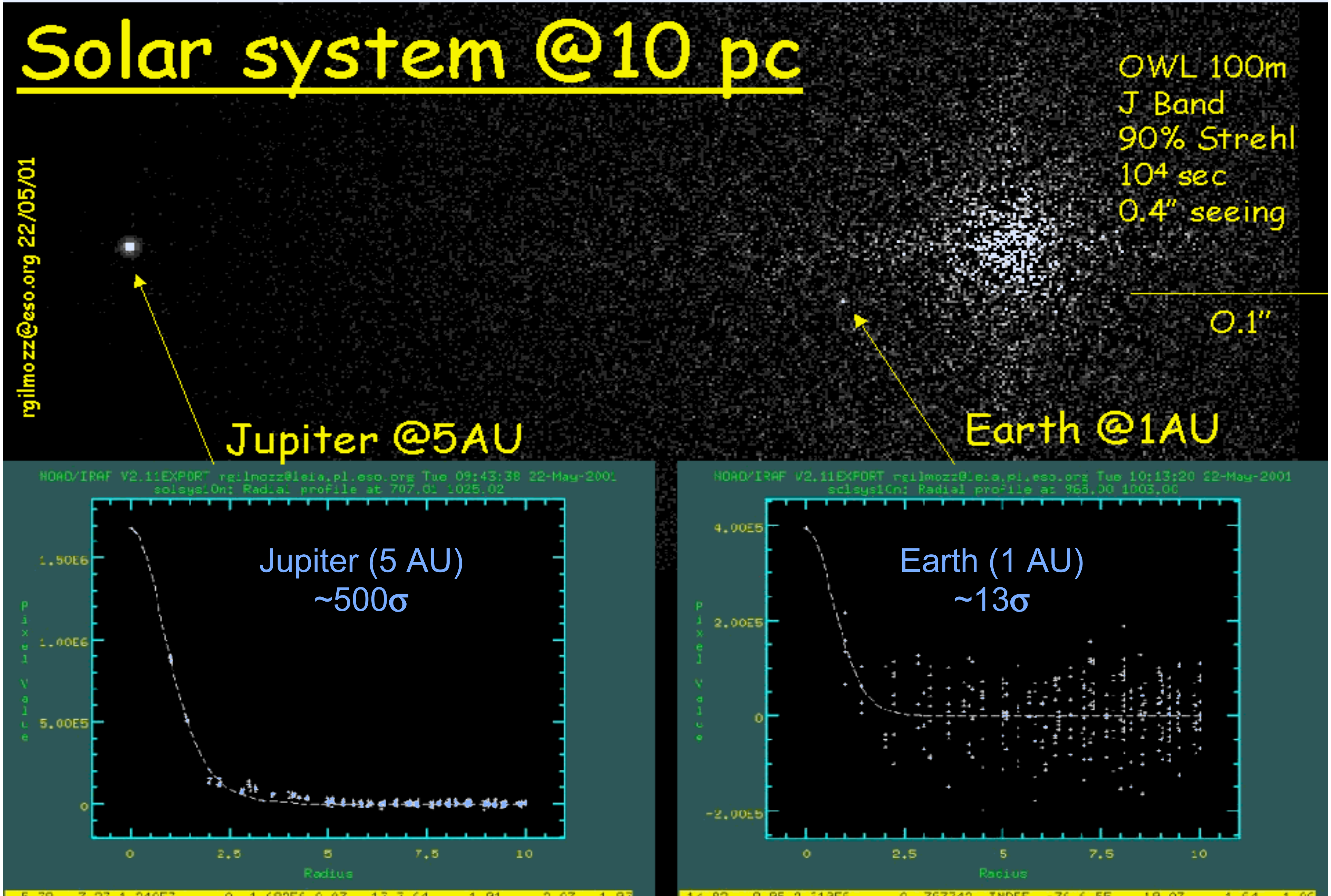


2005 IAU colloq. No. 200 devoted to exoplanetary imaging



Nonetheless to detect exo-Earths, likely to need a really big telescope…

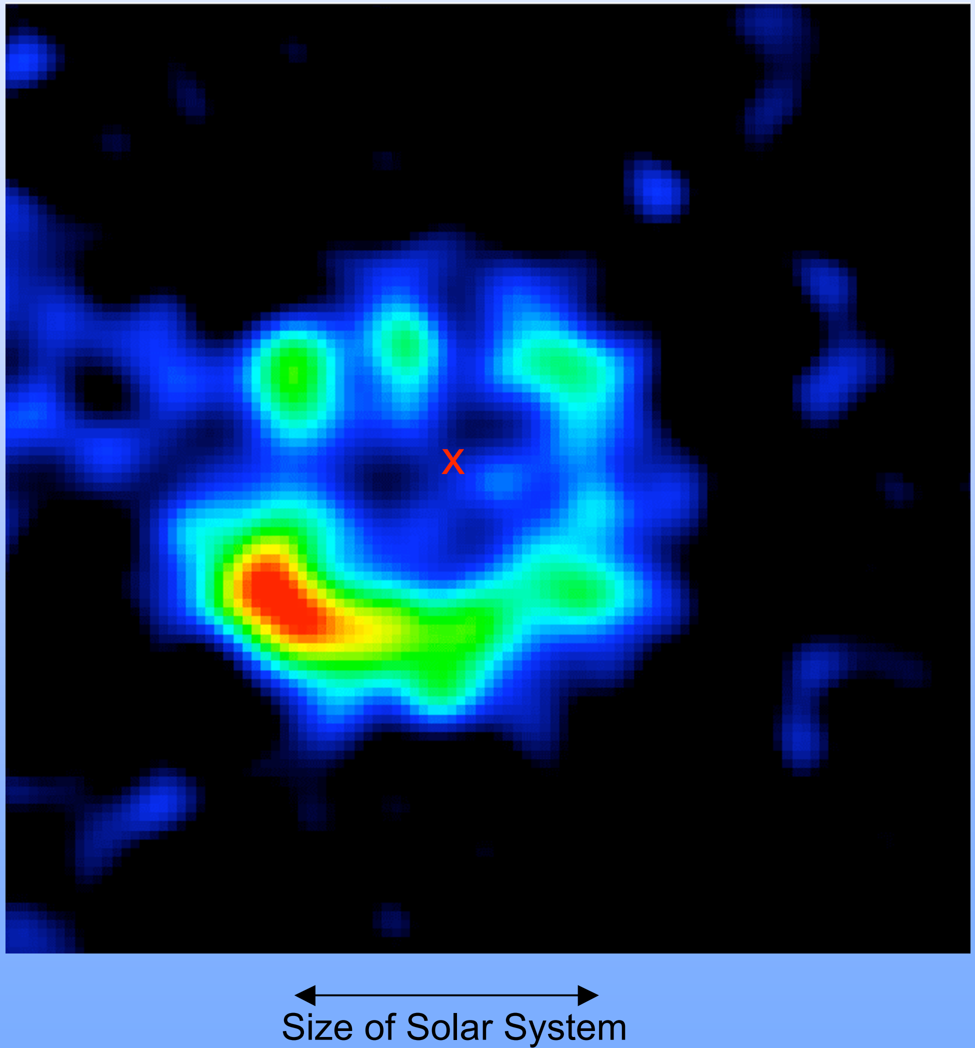


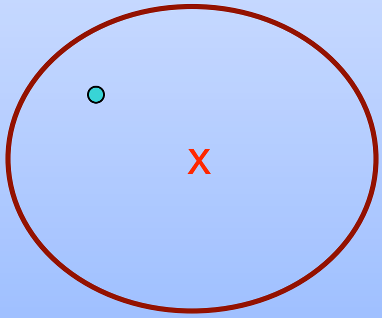


Simulation of Jupiter & Earth detections at 30 light years distance with OWL

Dusty rings and clumps About 10% of stars have clouds of dust.

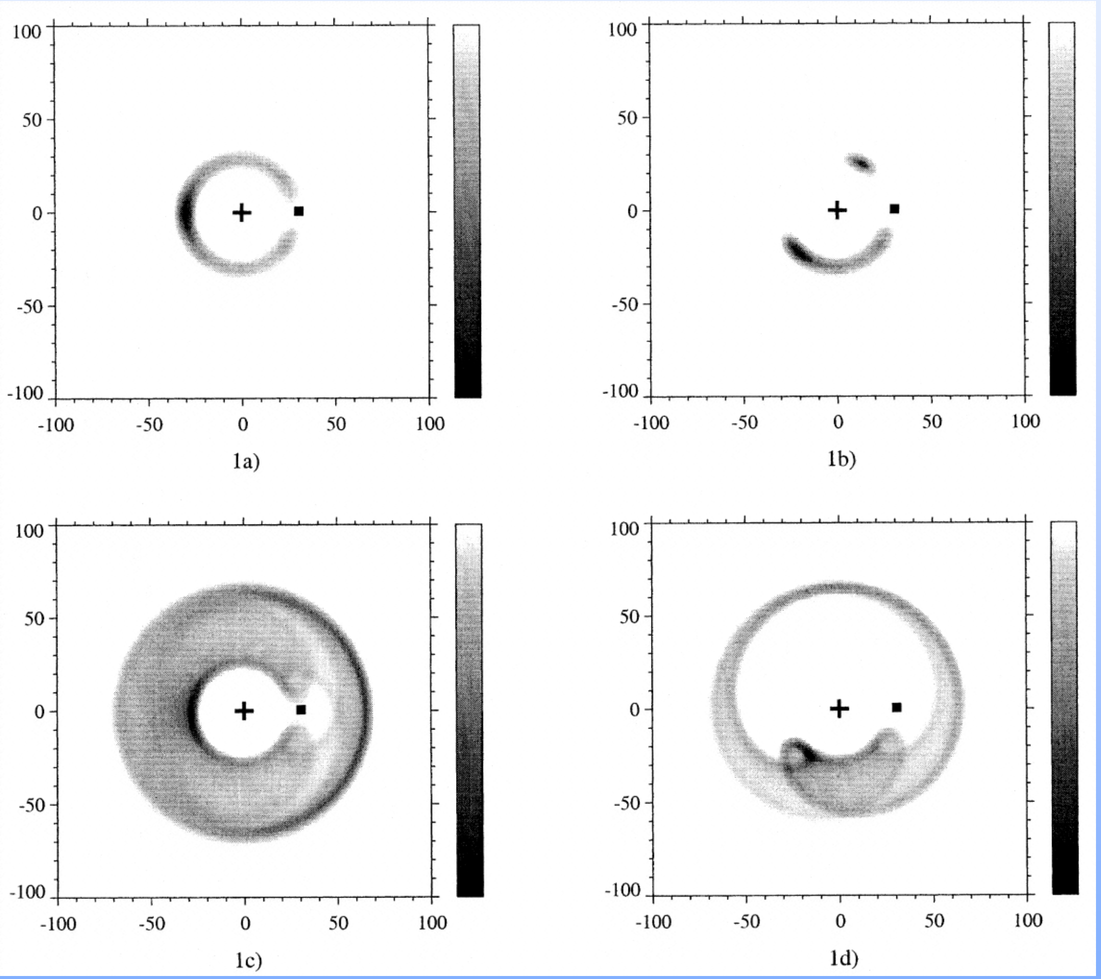
Epsilon Eri. 3rd magnitude star at 9 light years distance



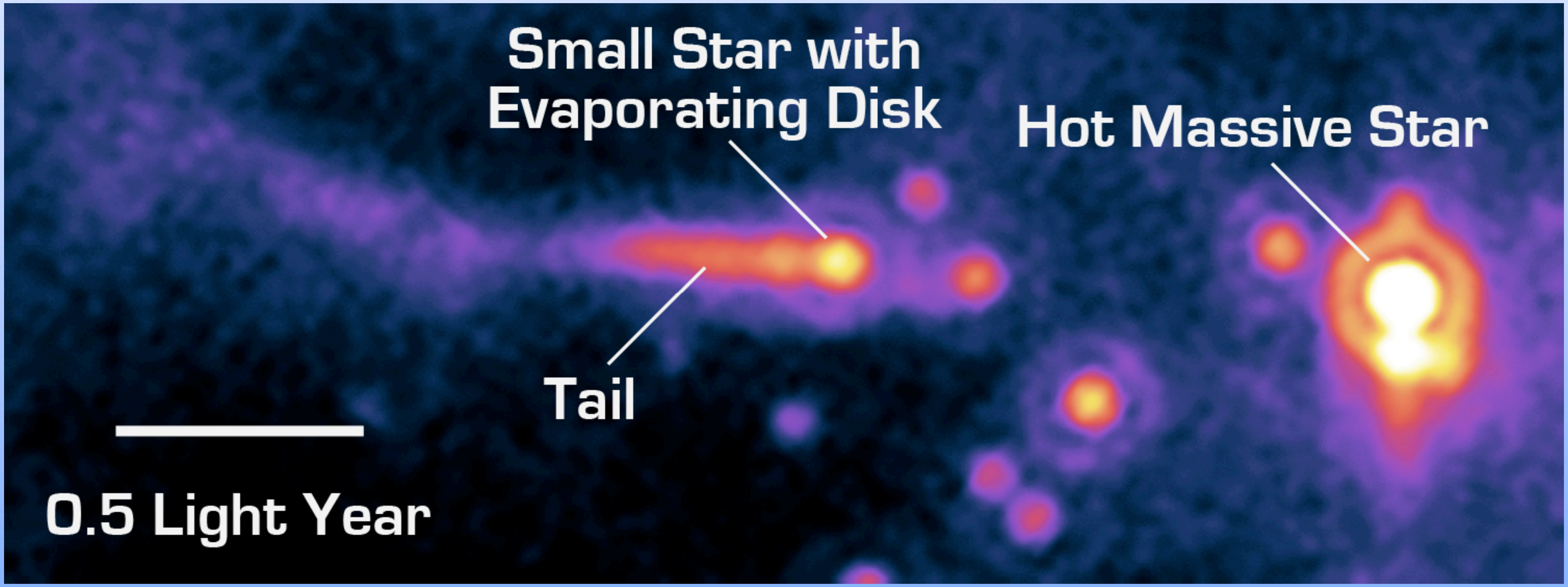


Dusty rings and clumps

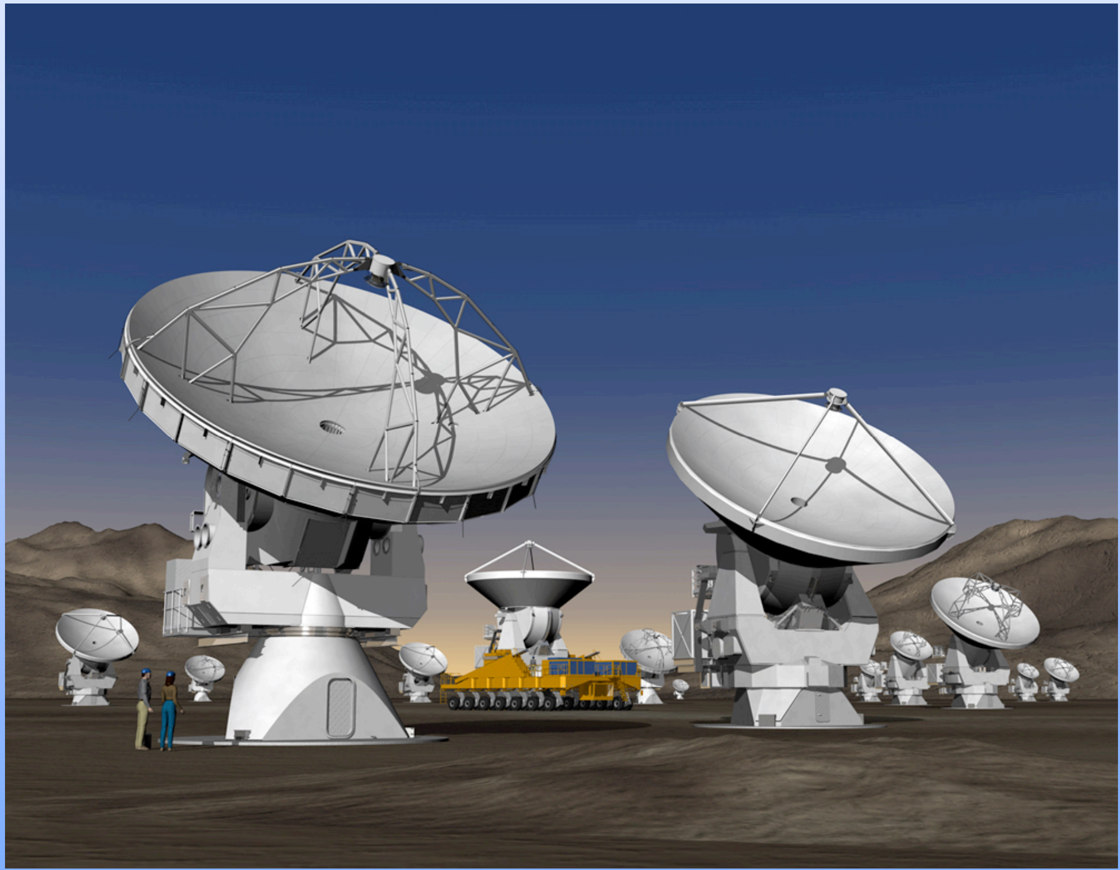
Epsilon Eri. A giant planet at 60AU from the star is the only explanation for the clumps and arcs.



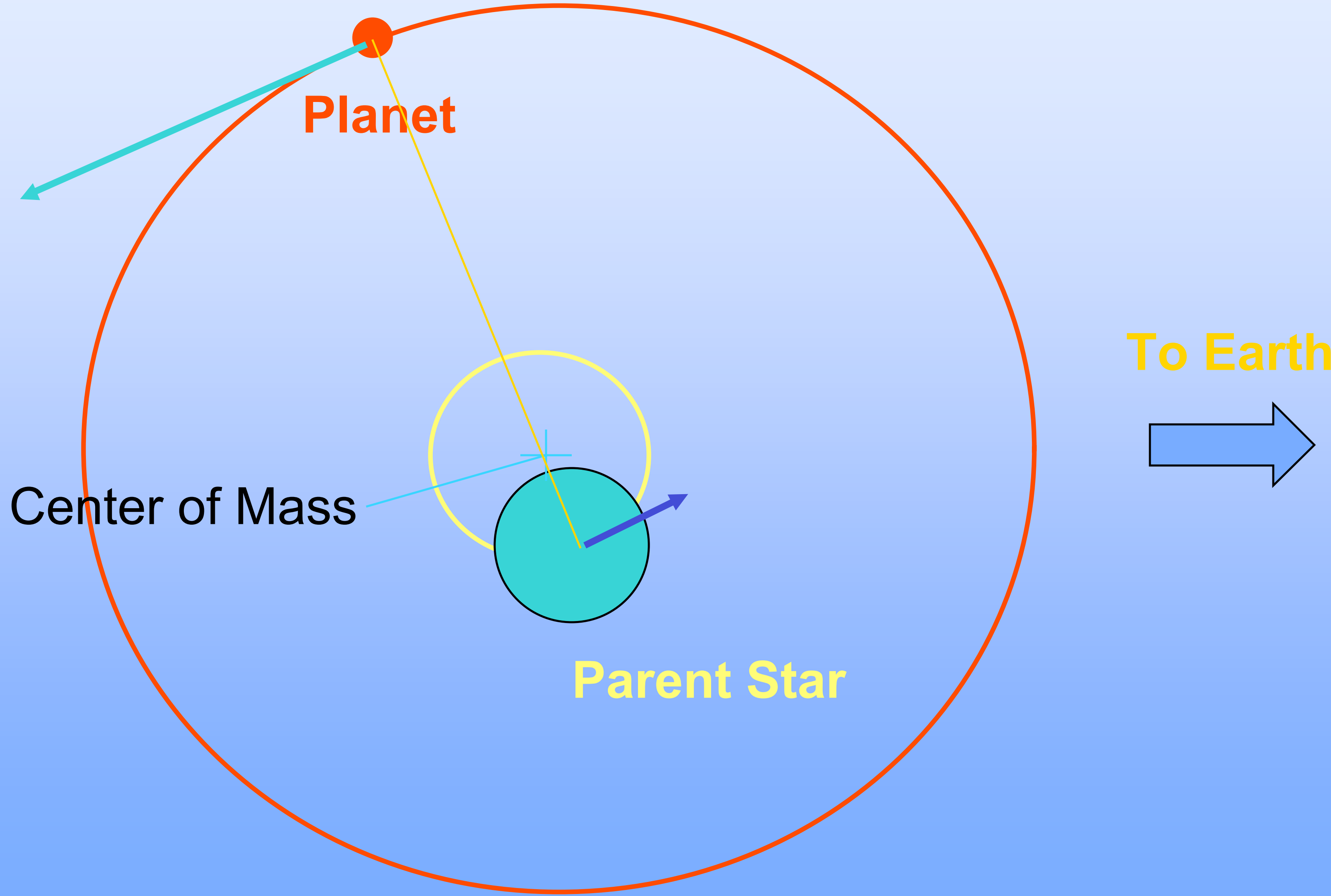
Spitzer discovered disks - many promising environments



New mm facilities, e.g. ALMA

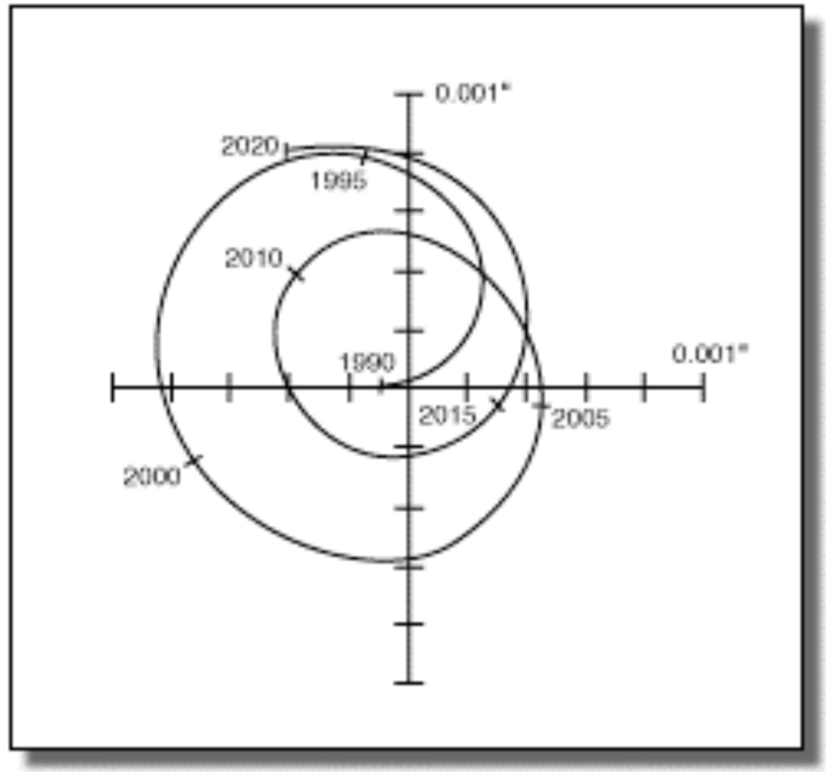


Stellar wobbles



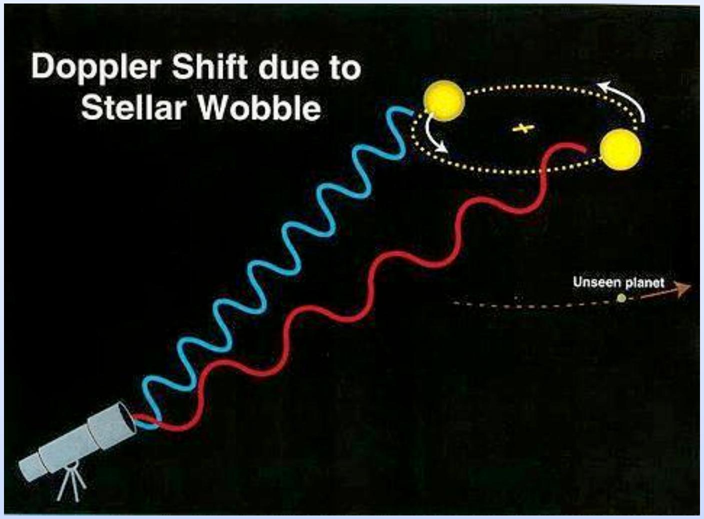
Astrometry

scale arcsec



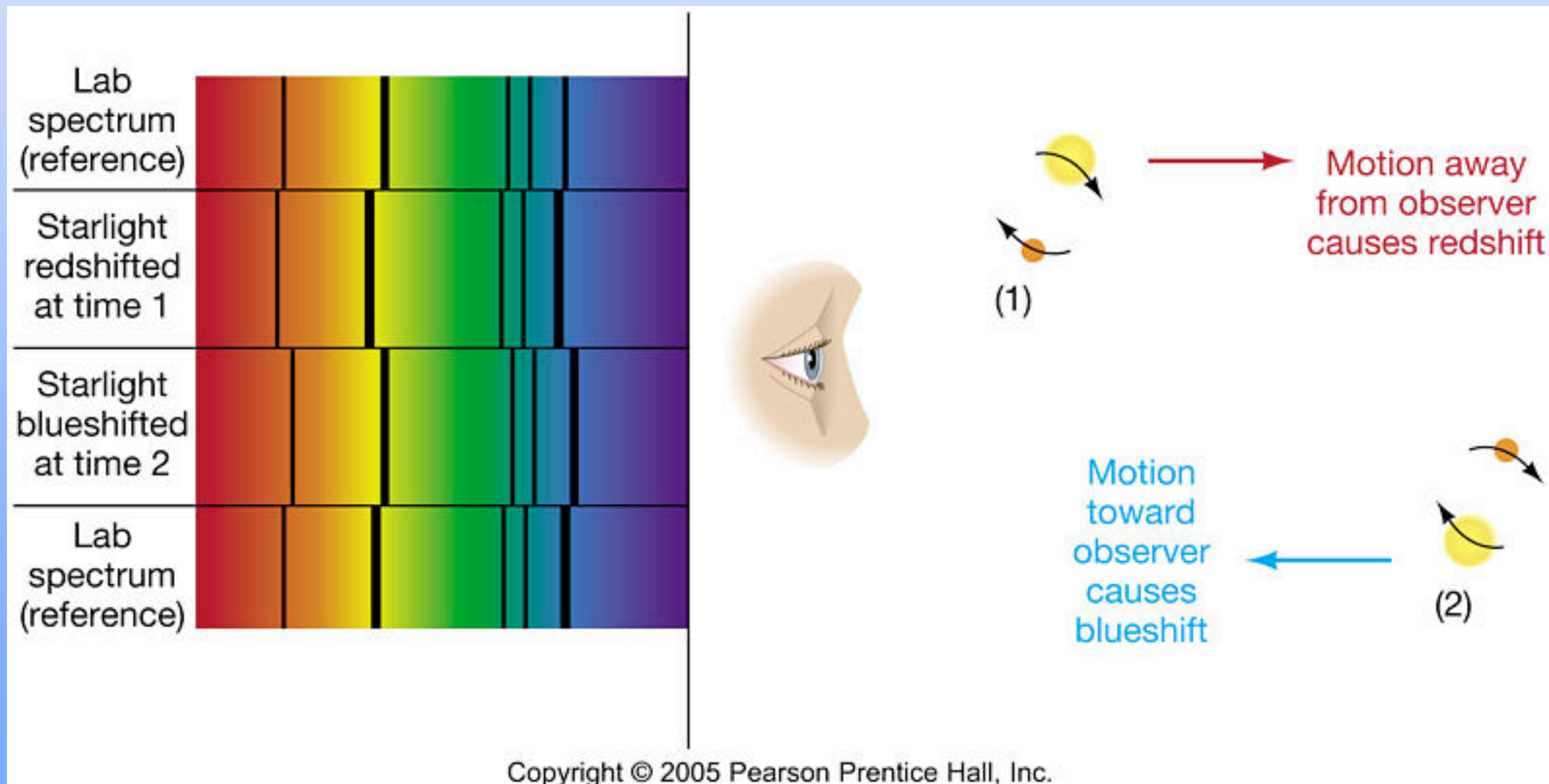
Astrometric displacement of the Sun due to Jupiter as seen from 10 parsecs.

- Hubble space telescope confirms Jupiter mass exoplanet around an M dwarf
- Hipparcos and ground-based studies sensitive to 2 mas
- GAIA (2011) and SIM will continue legacy down to 1μas

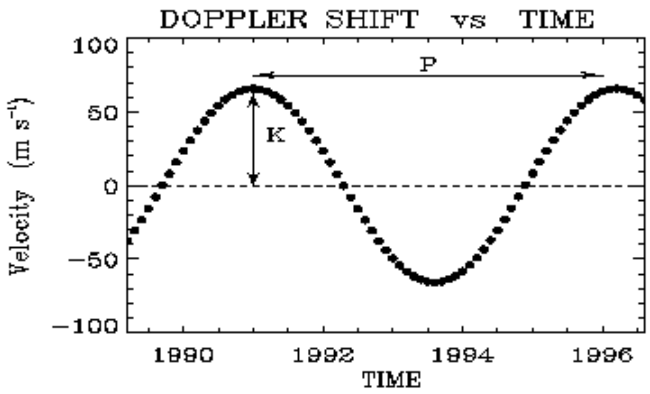


Radial velocity detection

- Doppler wobble of central star induced by the orbiting planet
- Can be measured with sensitive spectrographs



Stellar wobbles



Kepler:

$$r^3 = \frac{GM_*}{4\pi^2} P^2$$

Observe Period.

$$V_{PL} = \sqrt{GM_*/r}$$

−> Vel. of Planet .

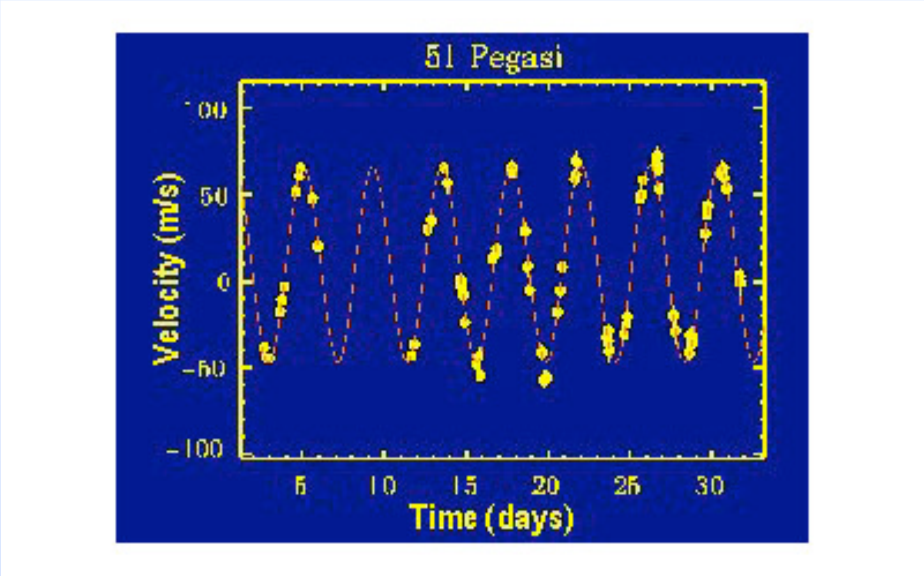
Momentum Conservation:

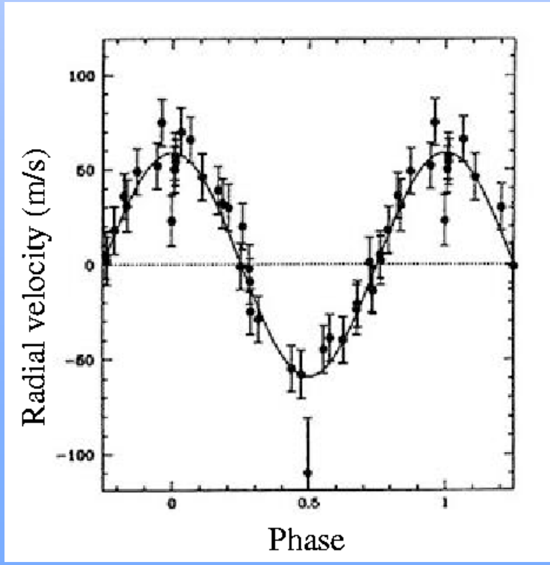
$$M_{PL} = M_* V_* / V_{PL}$$

Observe K $= V_* \sin i$

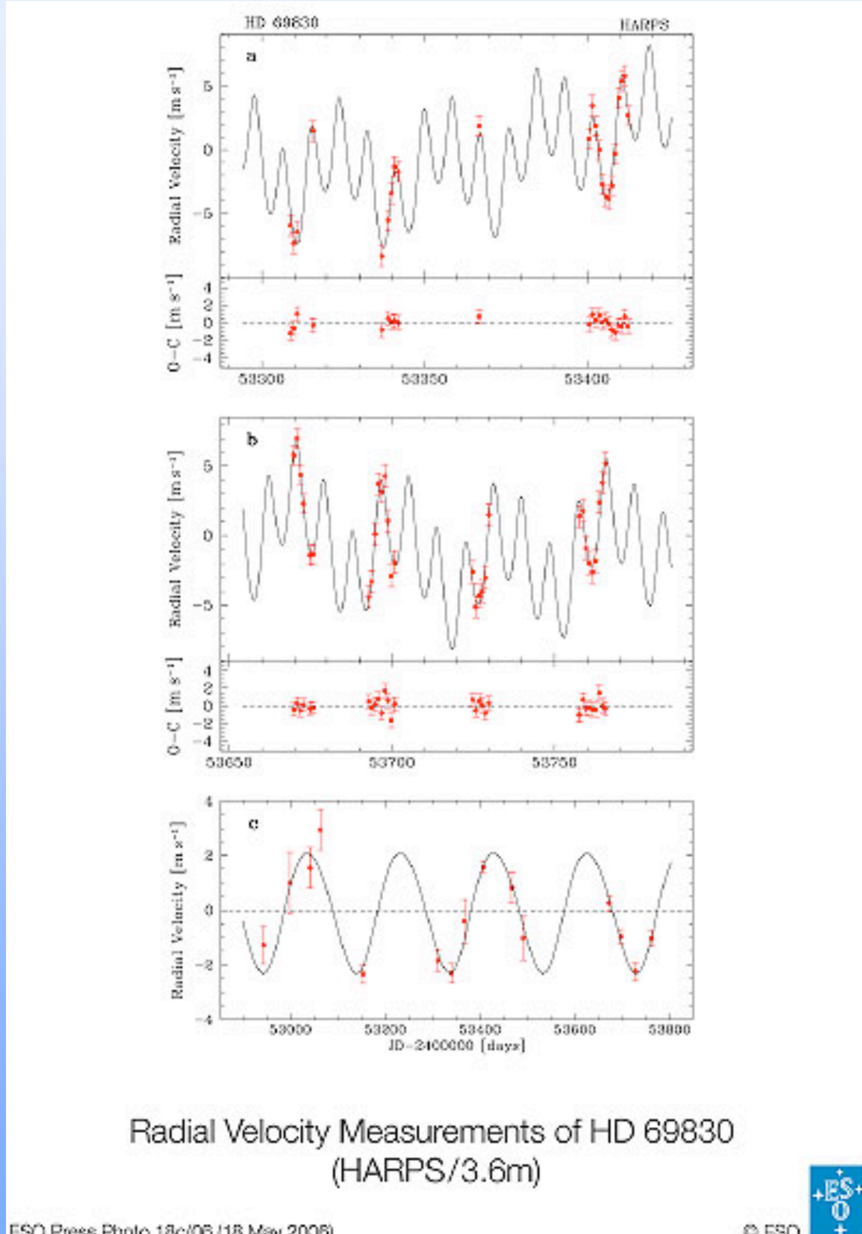
$$==> M_{PL} \sin i$$

The first radial velocity planet



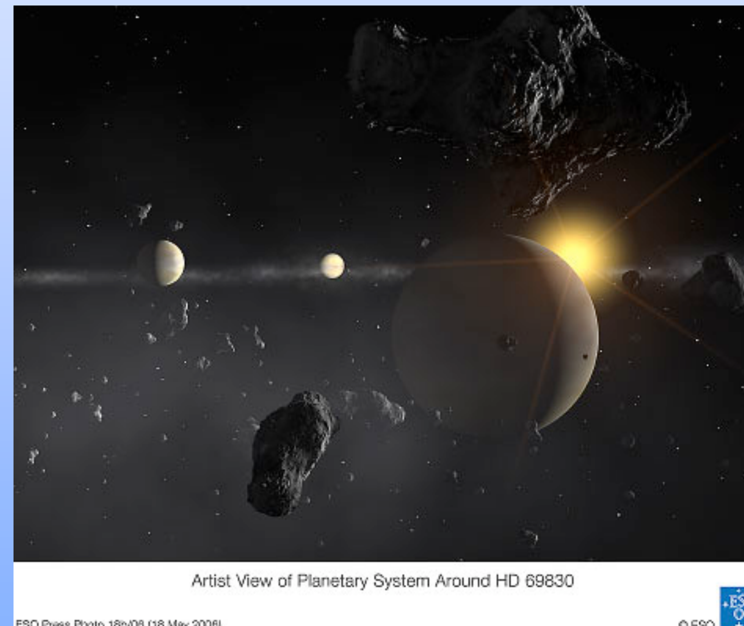


- 51 Pegasi (a solar-like star)
- Radial velocities measured of a few weeks
- A +/-60m/s wobble seen with a period of 4.2 days
- Phase-folded data shows a circular orbit
- The planet has Msini=0.5M_{Jup} and a separation of 0.052AU



Multiple Doppler planets

- Wobbles on top of wobbles can also reveal multiple planet systems



HD 69830: A planetary system containing 3 Neptune-like planets

"Catalog of Nearby Exoplanets", 2006, Astrophysical Journal, Vol. 646, Pg. 505 (PDF) (Abstract)

R. P. Butler[2], J. T. Wright[3], G. W. Marcy[3,4], D. A Fischer[3,4], S. S. Vogt[5], C. G. Tinney[6], H. R. A. Jones[7], B. D. Carter[8], J. A. Johnson[3], C. McCarthy[2,4], A. J. Penny[9,10]

Text-based Table

See Also

Table: Properties of Exoplanet Host Stars. With stellar coordinates and distance, as well as physical parameters.

Figures: Exploration of Exoplanet Parameters.

Catalog of Nearby Exoplanets: Click on column heading to sort.

#	Planet	Per (d)	K (m s^{-1})	e	omega (deg)	T_p (JD-2440000)	T_t (JD-2440000)	M·sin(i) M_{jup}	a (AU)	r.m.s. (m s^{-1})	(chi$^2_\nu$)$^{1/2}$	N_{obs}	Ref.
1	HD 142 b	349.3(3.6)	32.9(4.7)	0.23(18)	308	11967(43)	11737(25)	1.28	1.04	12	2.2	54	Ref.
2	HD 1237 b	133.71(20)	167.0(4.0)	0.511(17)	290.7(3.0)	11545.86(64)	11400	3.37	0.495	19	1.8	61	Ref.
3	HD 2039 b	1120(23)	153(22)	0.715(46)	344.1(3.6)	12041(13)	10992(26)	6.11	2.23	11	0.84	41	Ref.
4	HD 2638 b	3.44420(20)	67.40(40)	0[c]	0[c]	13323.2060(20)	53300	0.477	0.0436	3.3		28	Ref.
5	HD 3651 b	62.235(26)	16.1(1.2)	0.591(51)	235.9(7.4)	12190.40(74)	12175.2(2.3)	0.234	0.296	6.0	1.1	116	Ref.
6	HD 4208 b	828.0(8.1)	19.06(73)	0.052(40)	345	11040(120)	10440(16)	0.804	1.65	3.4	0.72	41	Ref.
7	HD 4308 b	15.560(20)	4.07(20)	0[c]	359(47)	13311.7(2.0)		0.0467	0.118	1.3	1.4	41	Ref.
8	HD 4203 b	431.88(85)	60.3(2.2)	0.519(27)	329.1(3.1)	11918.9(2.7)	11558.7(7.2)	2.07	1.16	4.1	0.80	23	Ref.
9	HD 6434 b	21.9980(90)	34.2(1.1)	0.170(30)	156(11)	11490.80(60)	11500	0.397	0.142	11		130	Ref.
10	HD 8574 b	225.0(1.1)	64.1(5.5)	0.370(82)	2(16)	11475.6(5.5)	11504.8(7.3)	1.96	0.759	23	1.6	26	Ref.
11	upsilon And b	4.617113(82)	69.8(1.5)	0.023(18)	63.4	11802.64(71)	11802.966(33)	0.687	0.0595	13	1.4	268	Ref.
12	upsilon And c	241.23(30)	55.6(1.7)	0.262(21)	245.5(5.3)	10158.1(4.5)	10063.9(3.8)	1.98	0.832	13	1.4	268	Ref.

See Also

[Table: Properties of Nearby Exoplanets.](#)
Includes both orbital and physical characteristics.

[Figures: Exploration of Exoplanet Parameters.](#)

"Catalog of Nearby Exoplanets", 2006, Astrophysical Journal, Vol. 646, Pg. 000 (PDF

R. P. Butler[2], J. T. Wright[3], G. W. Marcy[3,4], D. A Fischer[3,4], S. S. Vogt[5], C. G. Tinney
H. R. A. Jones[7], B. D. Carter[8], J. A. Johnson[3], C. McCarthy[2,4], A. J. Penny[9,10]

Text-based download of this table: here

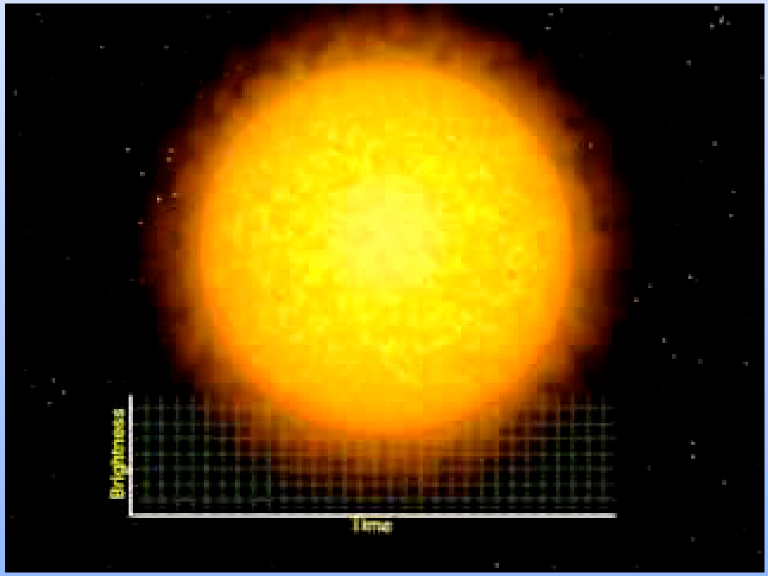
Click on column heading to sort.

HD	Hip #	Alt. Name	RA (J2000)	Dec (J2000)	B-V	V	Distance (pc)	T_{eff} (K)	log g (cm s^{-2})	[Fe/H]	v·sin(i) (m s^{-1})	Mass (M_{sun})	Ref.
142	522		00 06 19.176	-49 04 30.69	0.52	5.70	25.64	6249	4.185	0.0998	10.4	1.24	Ref.
1237	1292		00 16 [illegible]	-79 51 04.25	0.75	6.59	17.62	5536	4.560	0.120		0.900	Ref.

Transits

(like periodic sunspot .. Venus transit)

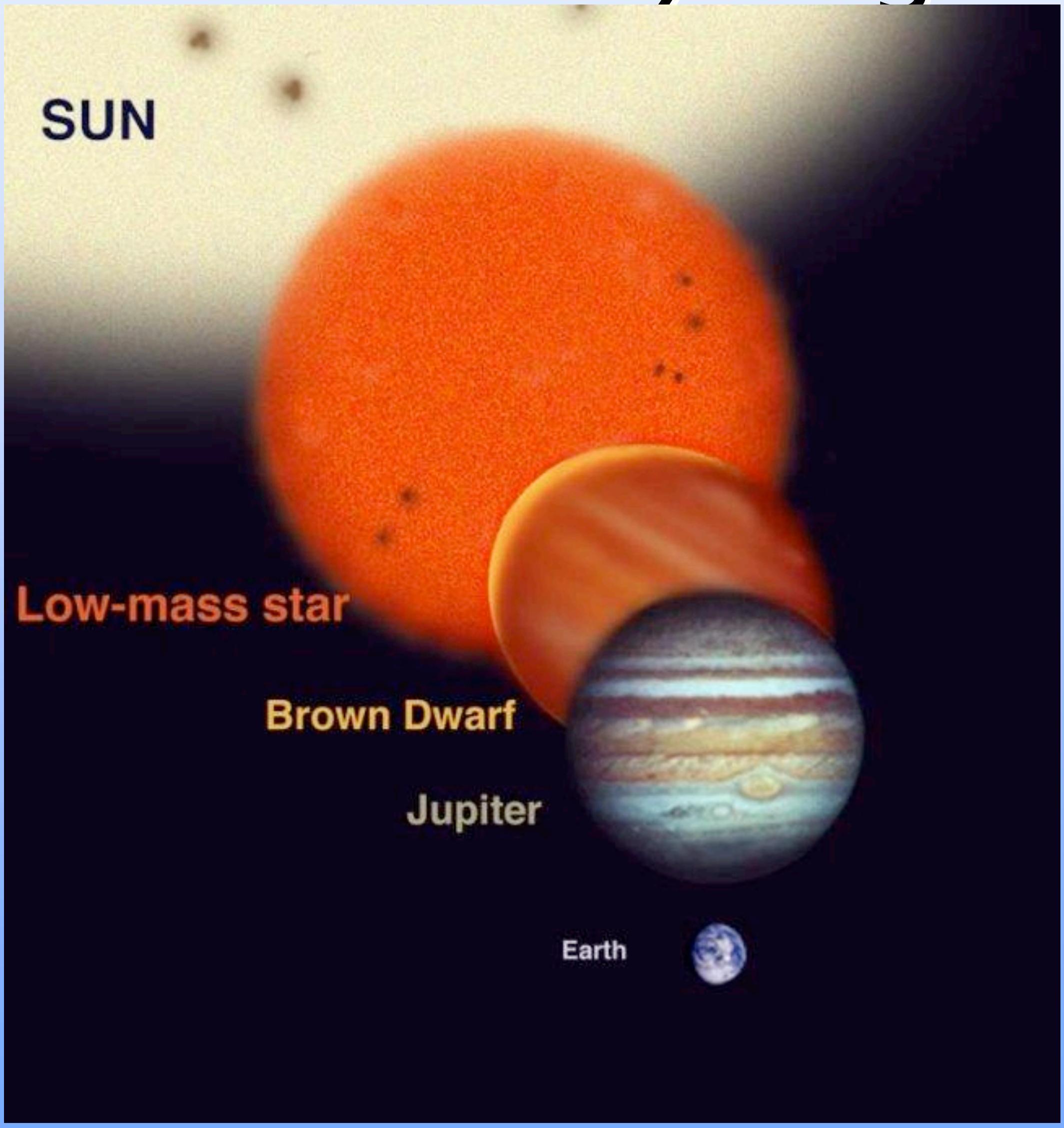
Radial velocity exoplanet around HD209458 confirmed by transit method

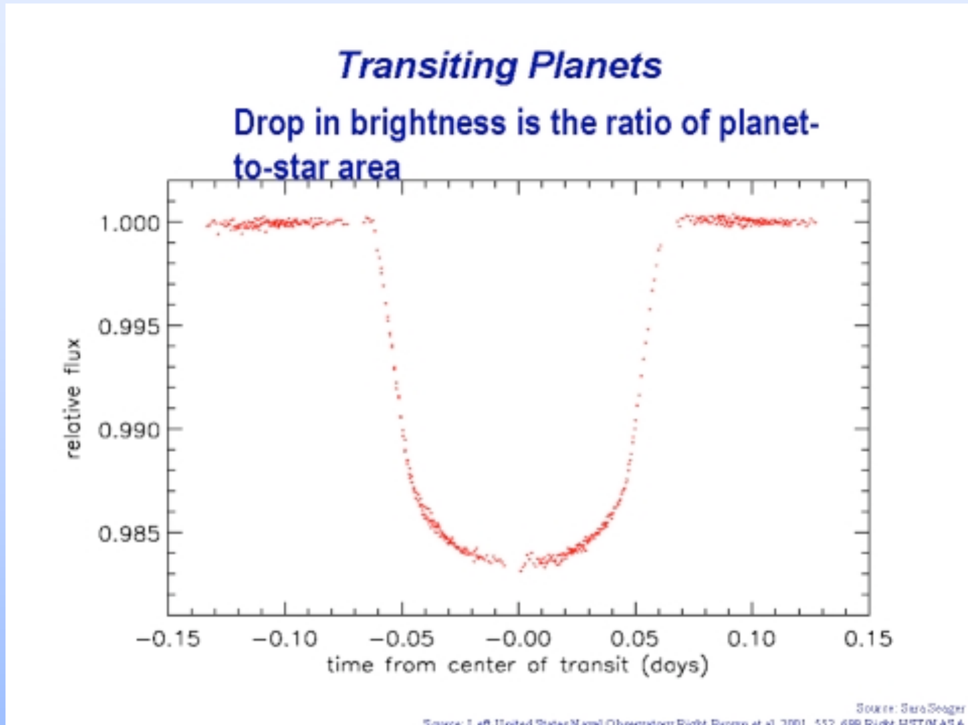


Ground-based telescope are starting to find objects
New era of dedicated searches – e.g., SuperWASP and space-based, e.g., COROT

and even amateur network transitsearch.org

Planets are *relatively* large





HD 209458 transiting planet
This star is a G0 star (ie Sun-like)

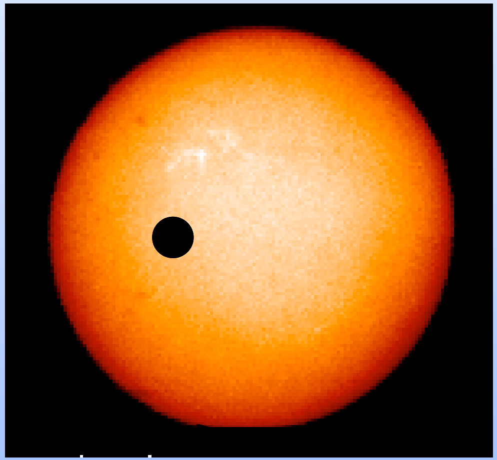
Planet radius = $1.2R_{Jup}$

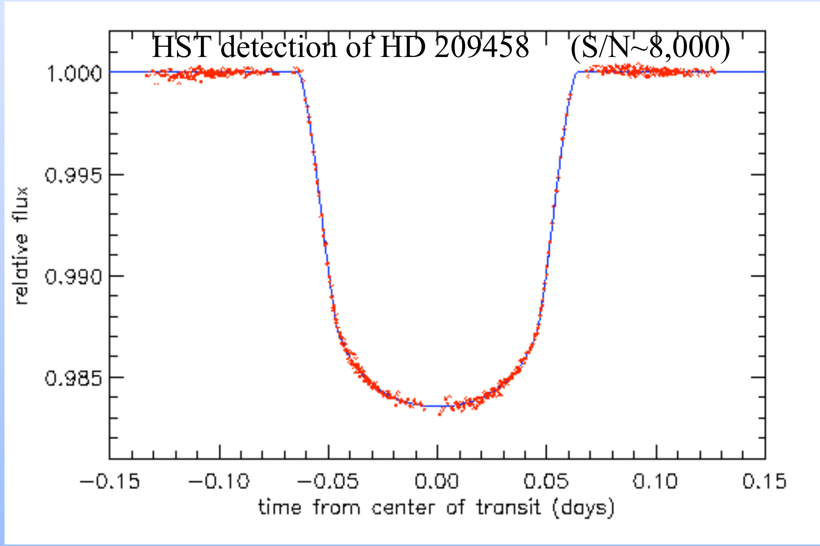
Relative size is the key

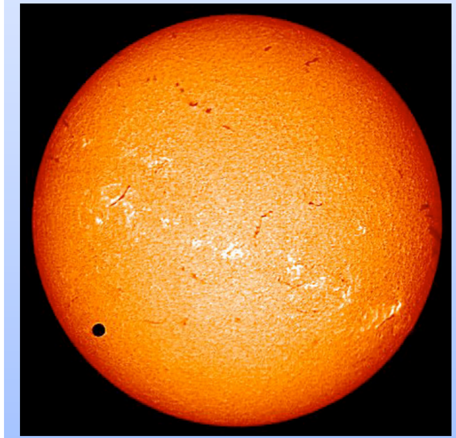
- Consider Jupiter, which is 0.1 solar radii
- It would cause a 1% eclipse dip transiting the Sun.
- A transit depth of 1.7% (e.g. opposite) corresponds to a planet-to-star area ratio of 0.017
- So the relative planet-to-star radii are the square root of 0.017=0.13

EARTH-SIZED PLANETS

- The relative change in brightness is equal to the relative areas (A_{planet}/A_{star})







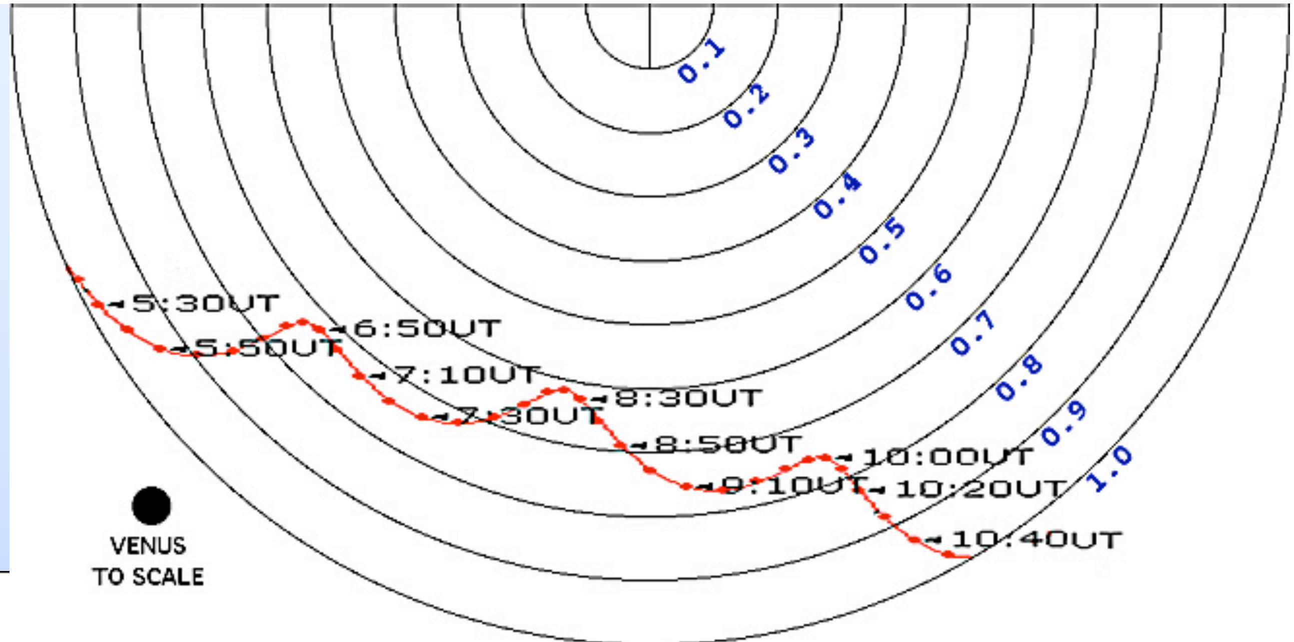
Jupiter:
1% area of the Sun (1/100)

Earth or Venus
0.01% area of the Sun (1/10,000)

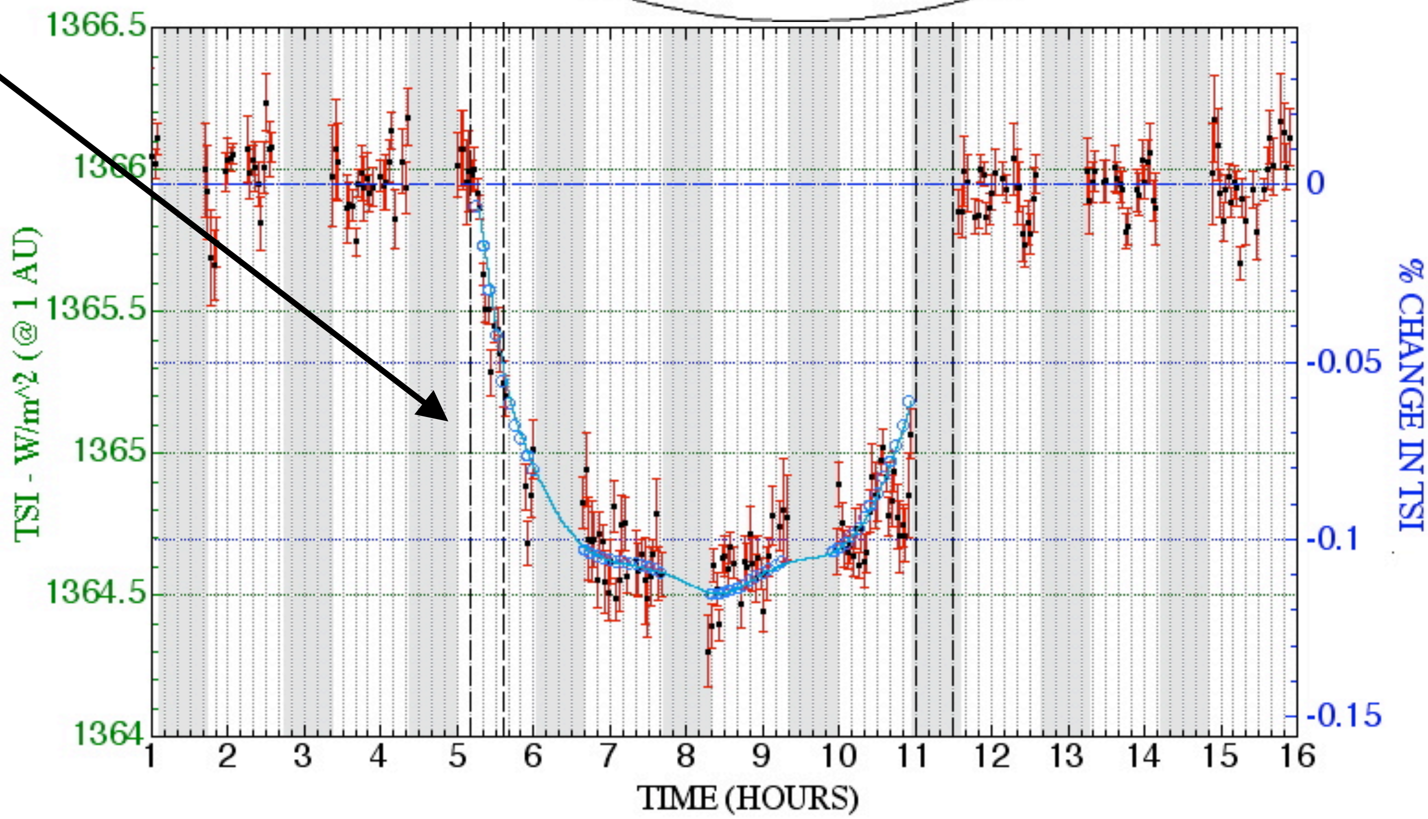
- To measure 0.01% must get above the Earth's atmosphere
- This is also needed for getting a high duty cycle
- Method is robust but you must be patient:
  Require at least 3 transits, preferably 4 with same brightness change, duration and temporal separation
  (the first two establish a possible period, the third confirms it)

The Actual Transit of Venus

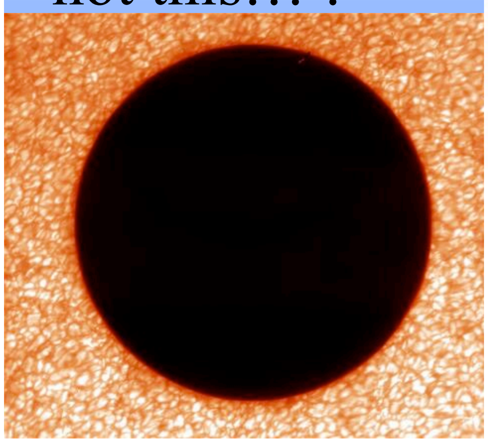
June 8, 2004



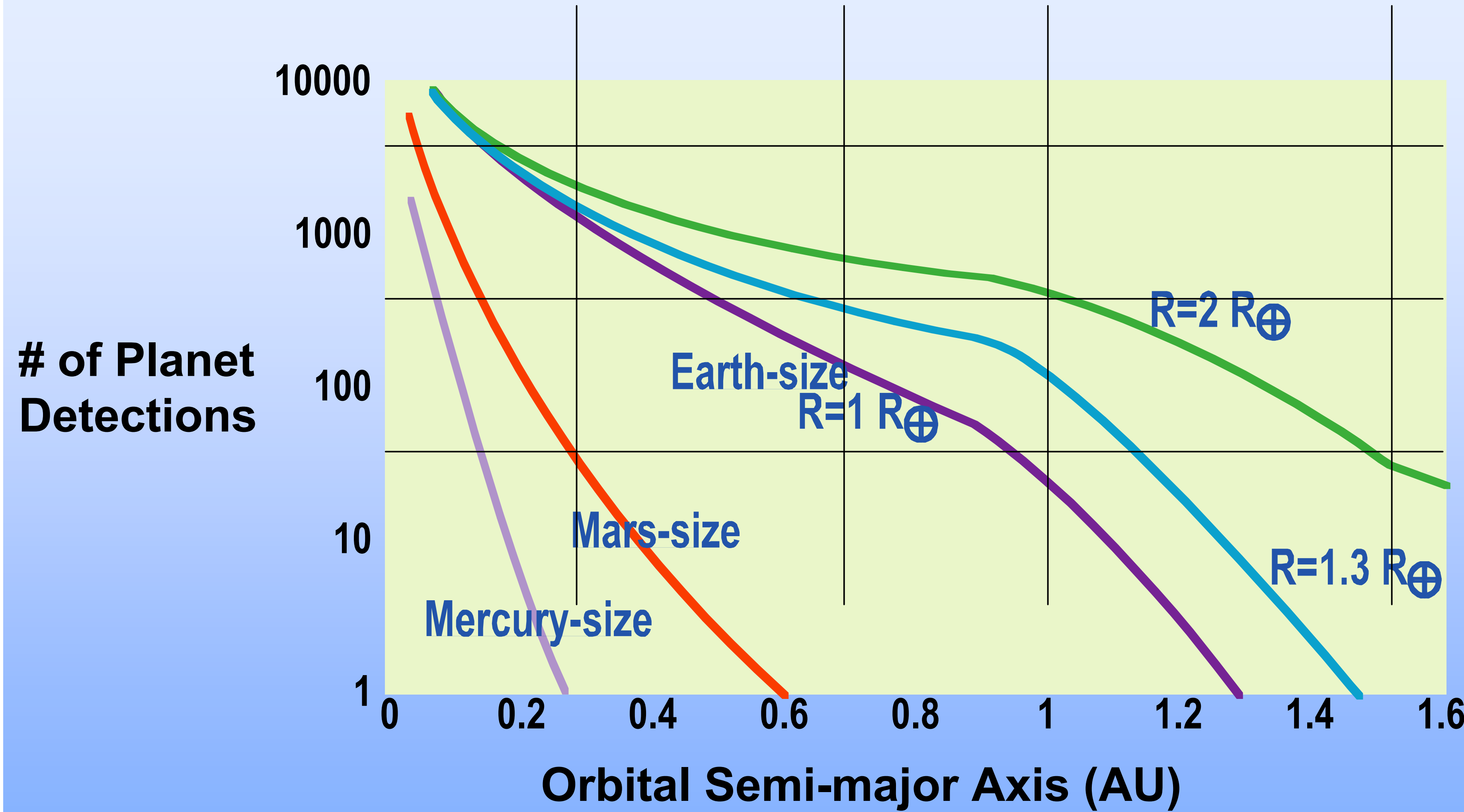
This is very much like what Kepler would have seen from another star.



not this… !

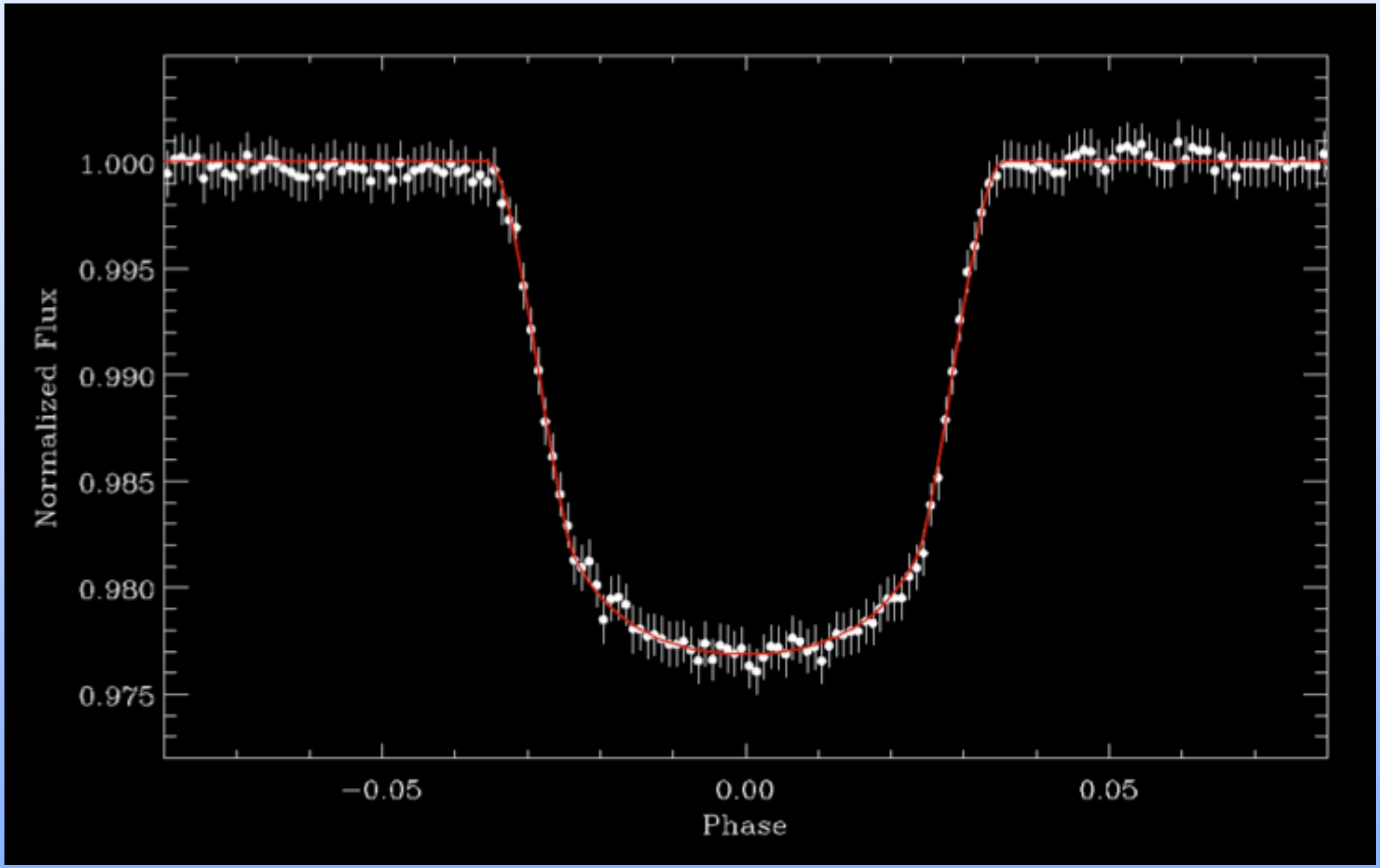


Potential for Planetary Detections

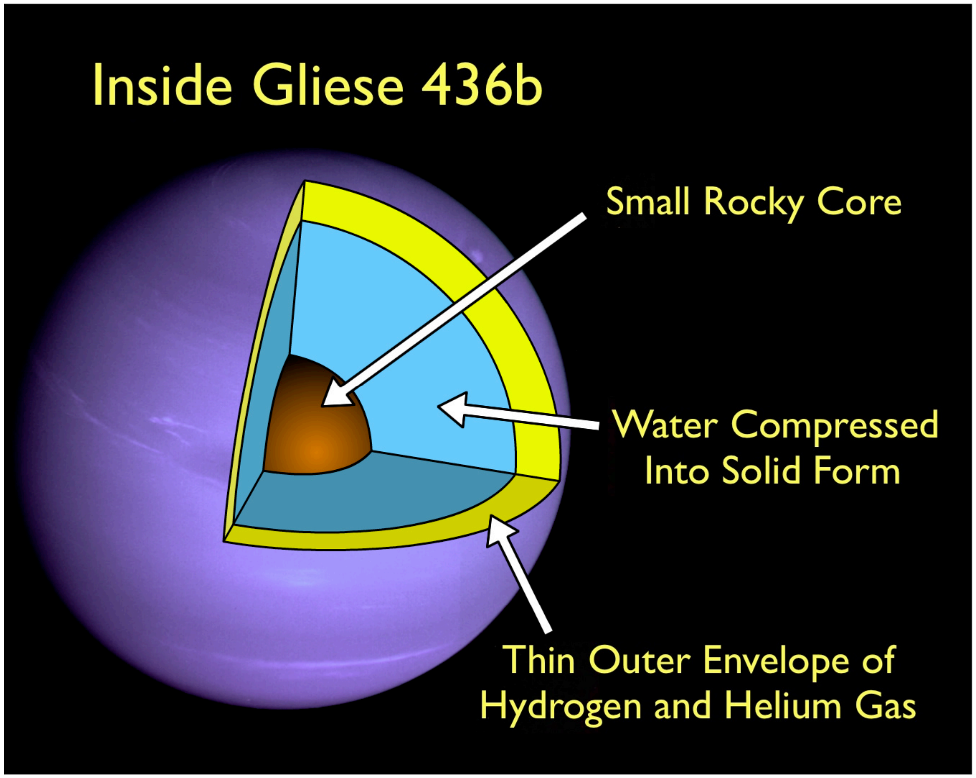


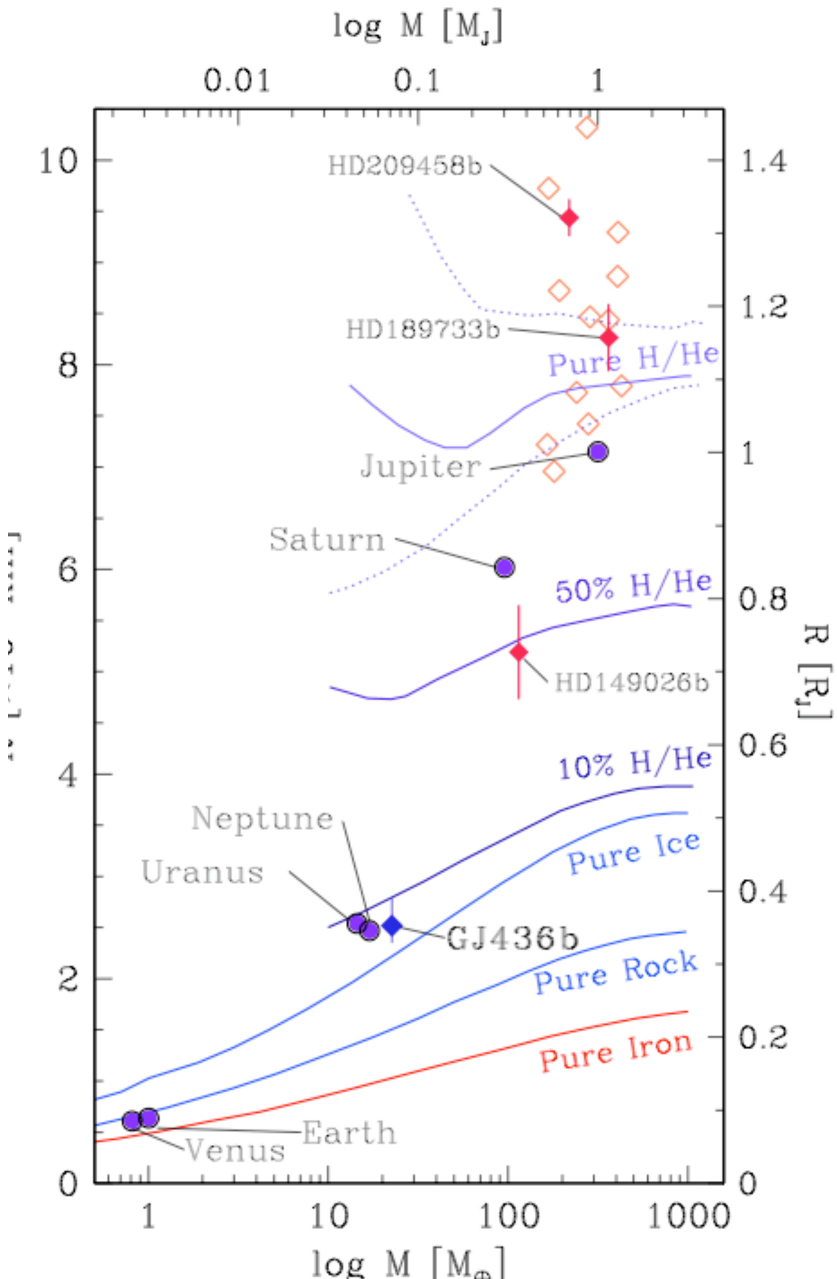
Expected # of planets found, assuming one planet of a given size & semi-major axis per star and random orientation of orbital planes.

First exoplanet from COROT



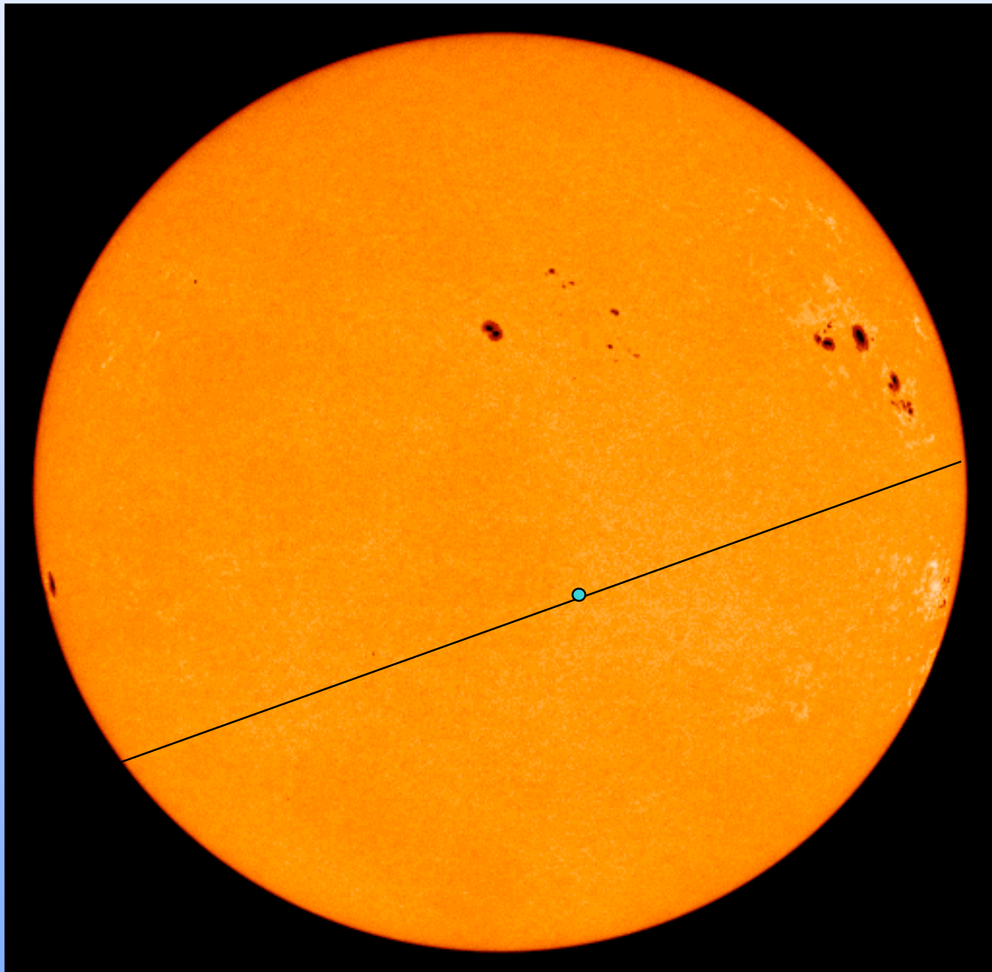
First M dwarf exoplanet transit

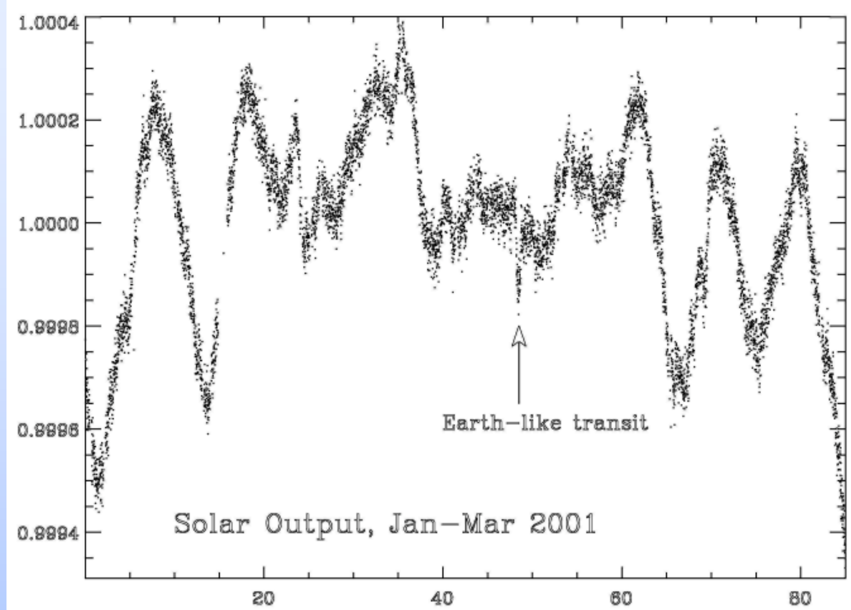


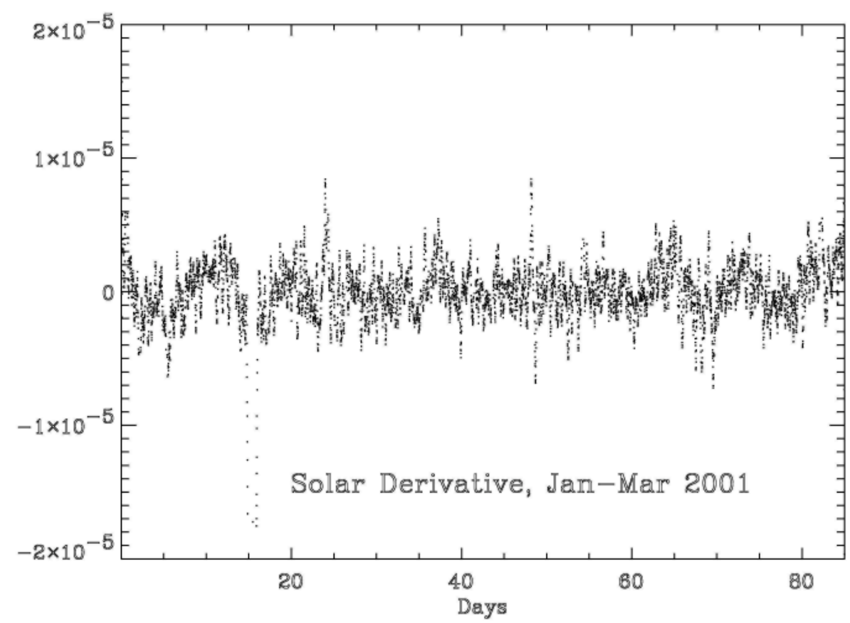


Need to learn lots about stellar activity

Spots and faculae: magnetic activity

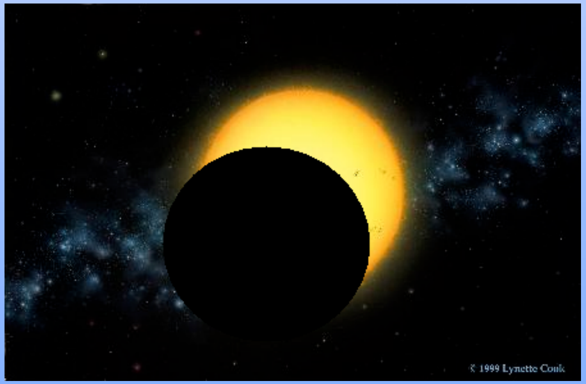


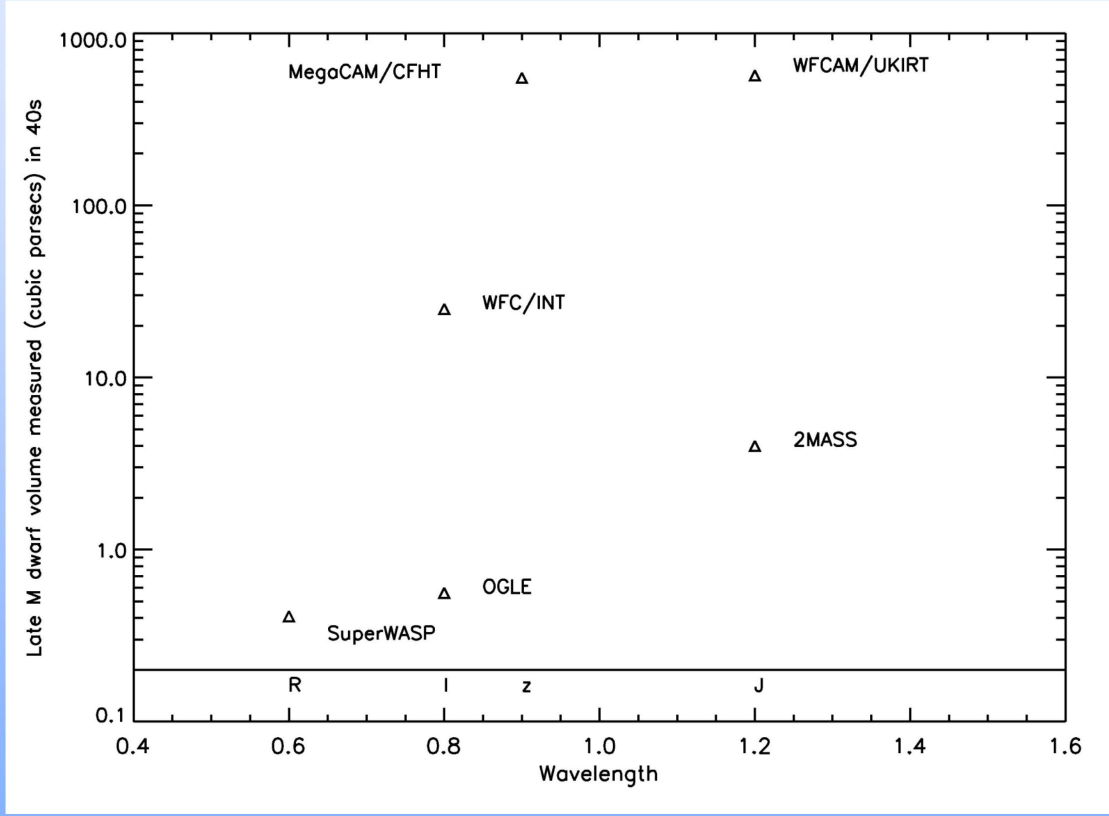




Moving into the near infrared
e.g. WFCAM transit survey

- Late M dwarfs are brightest in the NIR
- They are prohibitively faint in the optical





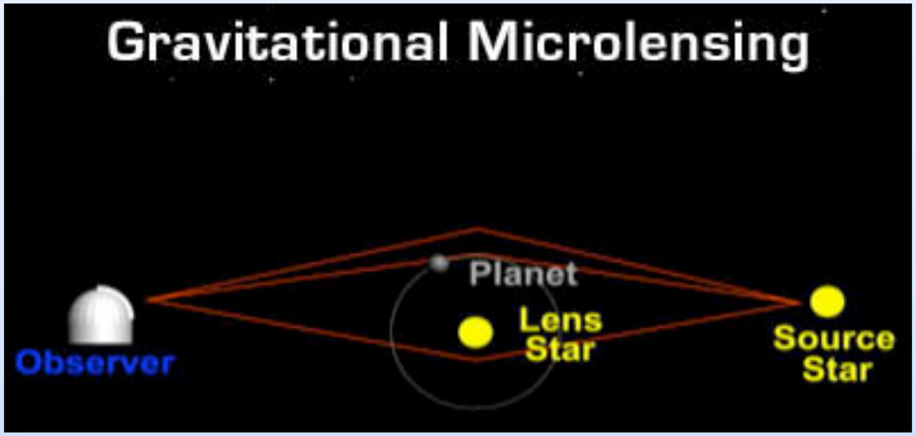
- Rate of volume surveyed for late M dwarfs

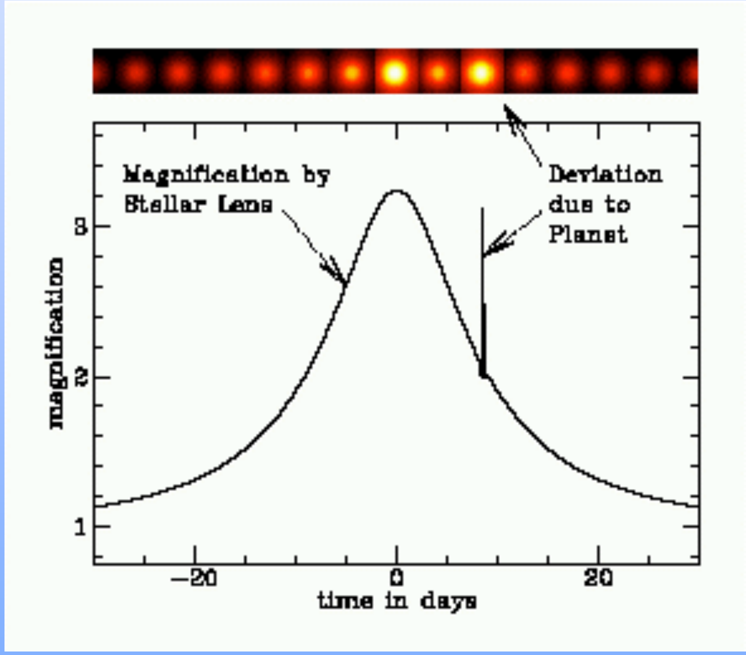
Gravitational Lensing

A cluster of galaxies `lensing' more distant objects …

A star & its planets magnifying a more distant star: "microlensing"

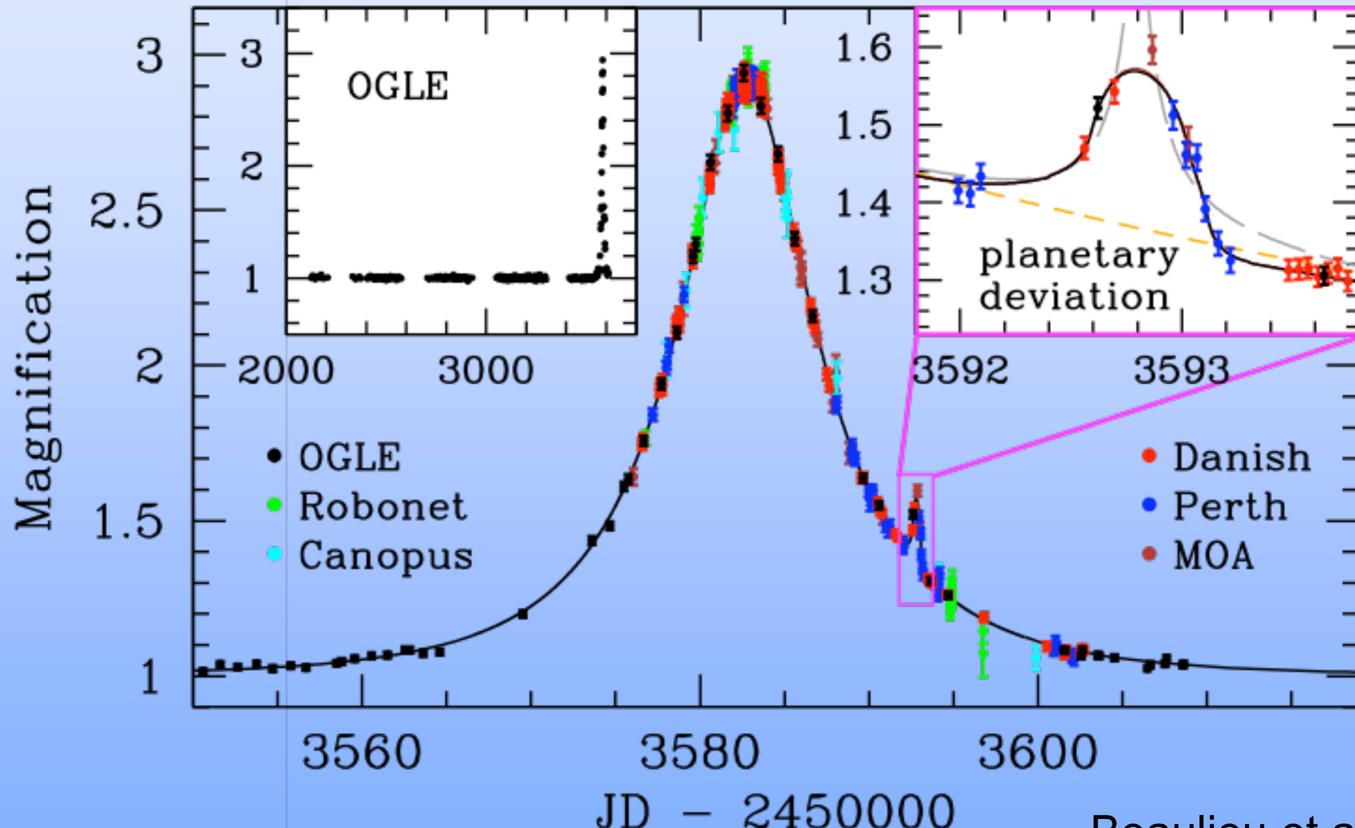
Microlensing planets





- Einstein's General Theory of Relativity says that light rays can be bent by gravity
- Light rays from a distant star can be bent by the gravitational field of a nearby star along the line of sight
- The nearby star behaves like a lens, whose focusing action makes the distant source star appear brighter than it would otherwise be
- This alignment is only temporary, since the two stars are moving relative to one another
- The result is thus a brightening and then dimming of the source star
- When a planet is orbiting the lens star, its own gravitational field can contribute to the bending of light rays, and it behaves like a defect in the lens
- If alignment is just right, this defect will produce a narrow spike in the brightness of the source star, which can be used to infer the presence of the planet

Planetary microlensing



Beaulieu et al. 2006

Summary: Limitations of the different methods

- All planet hunting methods are more sensitive to more massive planets. In addition;

- Direct imaging
  - limited by faintness of planets
  - limited by PSF of star
  - better at finding widely separated giant planets around young stars
- Astrometric
  - limited by the distances of stars
  - limited by the long periods of wide planets
- Radial velocity
  - preferentially finds close-in massive planets
  - limited by the long periods of wide planets
- Transit
  - limited to close-in planets (higher probability of alignment)
- Microlensing
  - Sensitive over a wide range of separation
  - But each event can only be measured once

General information see exoplanets.eu

Planet Detection Methods

Michael Perryman, Rep. Prog. Phys., 2000, 63, 1209 (updated April 2007)
[corrections or suggestions please to michael.perryman@esa.int]