The quest for exoplanets

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Are we alone in the Universe?

The plurality of worlds

In some worlds there is no Sun and Moon, in others they are larger than in our world, and in others more numerous. In some parts there are more worlds, in others fewer (...); in some parts they are arising, in others failing. There are some worlds devoid of living creatures or plants or any moisture.

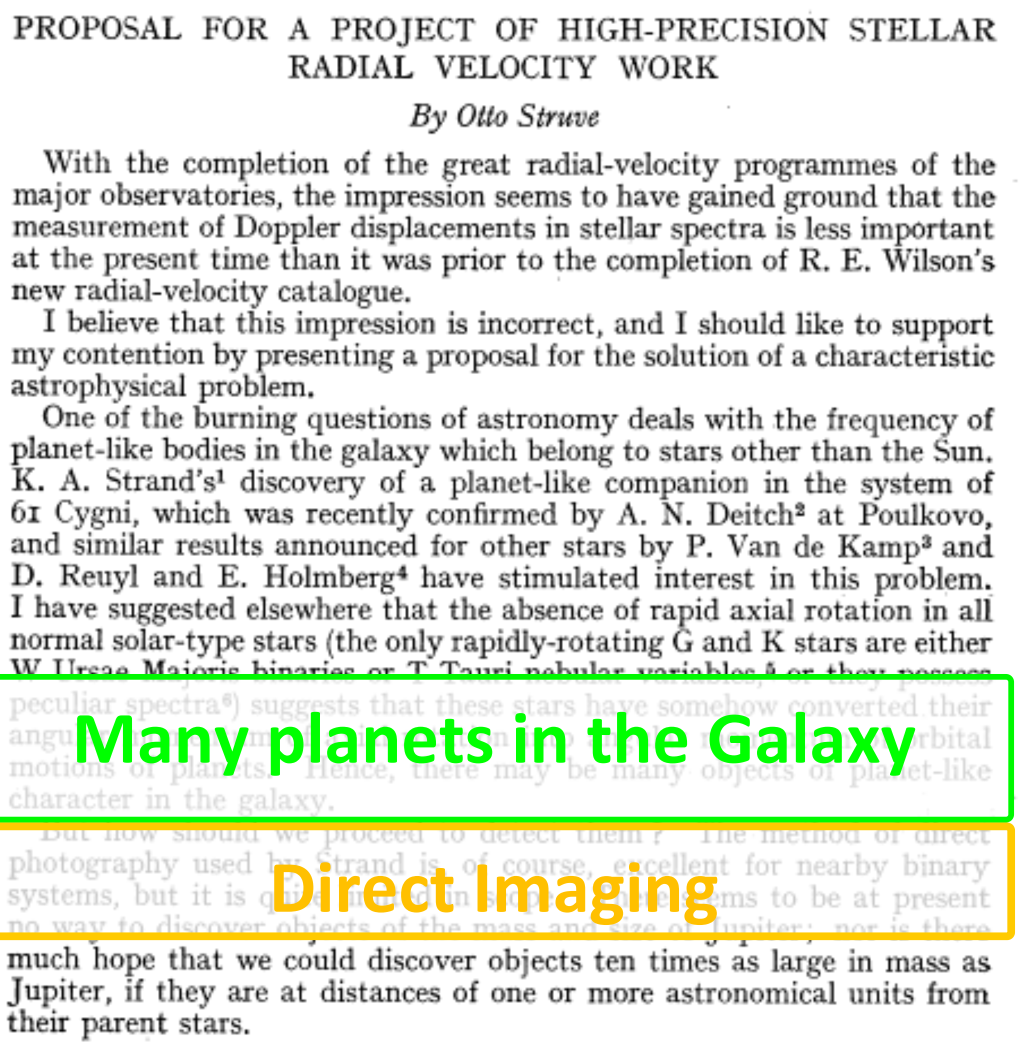
–*Democritus (ca. 460-370 B.C.), after Hippolytus (3rd cent. A.D.)*

There cannot be more worlds than one.

Aristotle [De Caelo]

Otto Struve

The Observatory, Vol. 72,
p. 199-200 (1952)



PROPOSAL FOR A PROJECT OF HIGH-PRECISION STELLAR RADIAL VELOCITY WORK

By Otto Struve

With the completion of the great radial-velocity programmes of the major observatories, the impression seems to have gained ground that the measurement of Doppler displacements in stellar spectra is less important at the present time than it was prior to the completion of R. E. Wilson's new radial-velocity catalogue.

I believe that this impression is incorrect, and I should like to support my contention by presenting a proposal for the solution of a characteristic astrophysical problem.

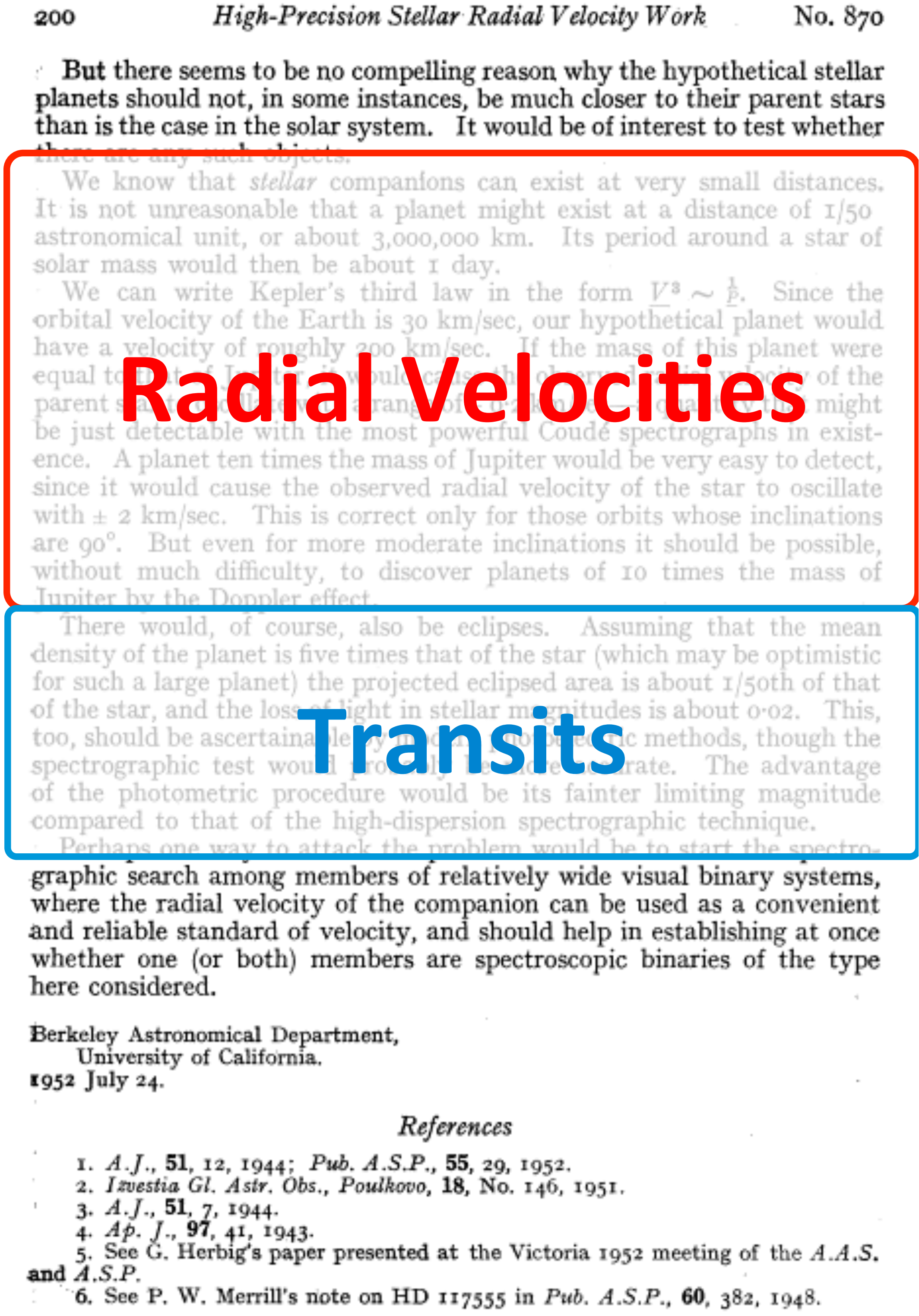
One of the burning questions of astronomy deals with the frequency of planet-like bodies in the galaxy which belong to stars other than the Sun. K. A. Strand's[1] discovery of a planet-like companion in the system of 61 Cygni, which was recently confirmed by A. N. Deitch[2] at Poulkovo, and similar results announced for other stars by P. Van de Kamp[3] and D. Reuyl and E. Holmberg[4] have stimulated interest in this problem. I have suggested elsewhere that the absence of rapid axial rotation in all normal solar-type stars (the only rapidly-rotating G and K stars are either W Ursae Majoris binaries or T Tauri nebular variables,[5] or they possess

Many planets in the Galaxy

peculiar spectra[6]) suggests that these stars have somehow converted their angular momentum of axial rotation into the angular momentum of orbital motions of planets. Hence, there may be many objects of planet-like character in the galaxy.

Direct Imaging

But how should we proceed to detect them? The method of direct photography used by Strand is, of course, excellent for nearby binary systems, but it is quite inadequate in scope. There seems to be at present no way to discover objects of the mass and size of Jupiter; nor is there much hope that we could discover objects ten times as large in mass as Jupiter, if they are at distances of one or more astronomical units from their parent stars.



But there seems to be no compelling reason why the hypothetical stellar planets should not, in some instances, be much closer to their parent stars than is the case in the solar system. It would be of interest to test whether there are any such objects.

Radial Velocities

We know that *stellar* companions can exist at very small distances. It is not unreasonable that a planet might exist at a distance of 1/50 astronomical unit, or about 3,000,000 km. Its period around a star of solar mass would then be about 1 day.

We can write Kepler's third law in the form $V^3 \sim \frac{1}{P}$. Since the orbital velocity of the Earth is 30 km/sec, our hypothetical planet would have a velocity of roughly 200 km/sec. If the mass of this planet were equal to that of Jupiter, it would cause the observed radial velocity of the parent star to oscillate with a range of ± 0·2 km/sec—a quantity that might be just detectable with the most powerful Coudé spectrographs in existence. A planet ten times the mass of Jupiter would be very easy to detect, since it would cause the observed radial velocity of the star to oscillate with ± 2 km/sec. This is correct only for those orbits whose inclinations are 90°. But even for more moderate inclinations it should be possible, without much difficulty, to discover planets of 10 times the mass of Jupiter by the Doppler effect.

Transits

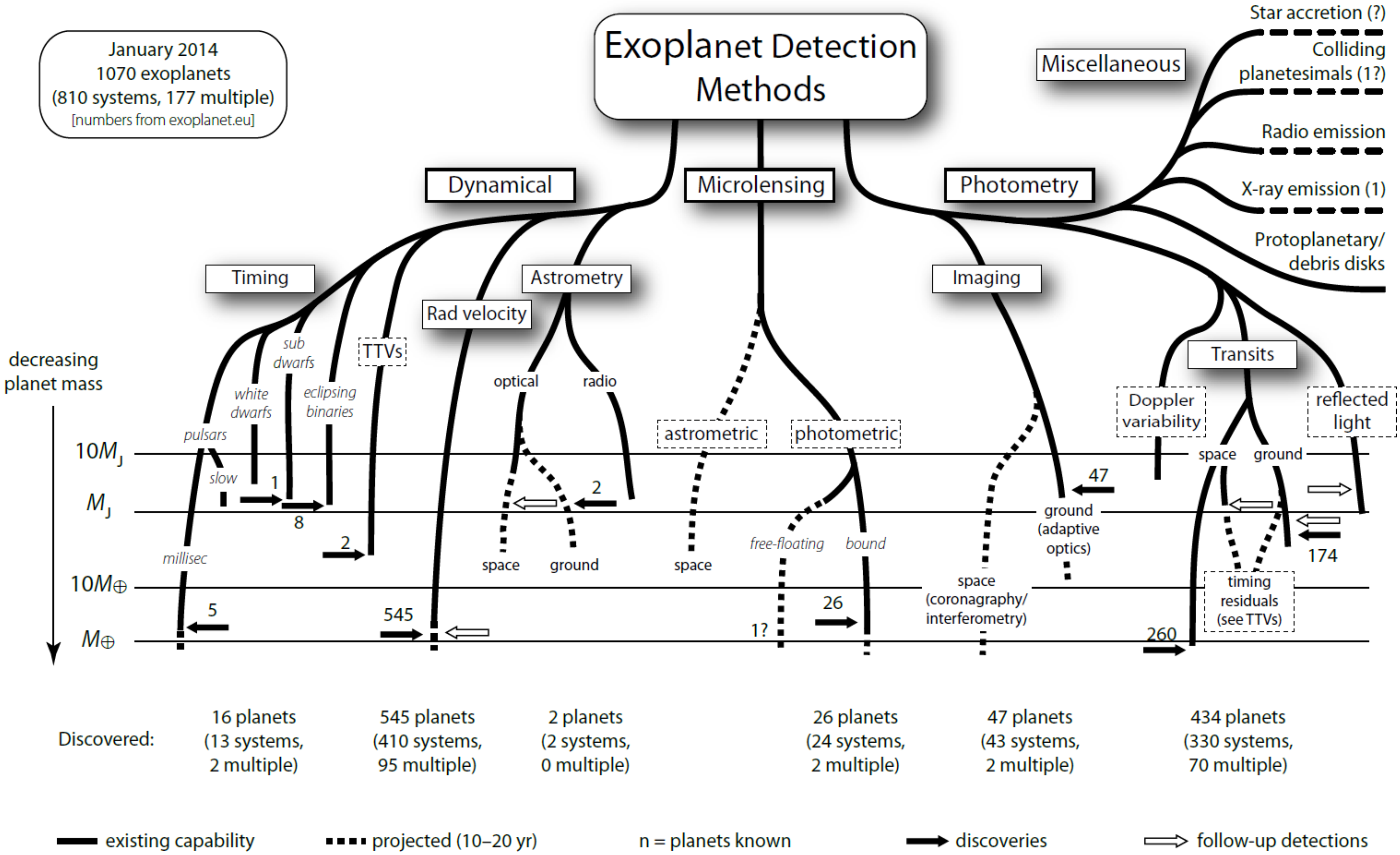
There would, of course, also be eclipses. Assuming that the mean density of the planet is five times that of the star (which may be optimistic for such a large planet) the projected eclipsed area is about 1/50th of that of the star, and the loss of light in stellar magnitudes is about 0·02. This, too, should be ascertainable by modern photoelectric methods, though the spectrographic test would probably be more accurate. The advantage of the photometric procedure would be its fainter limiting magnitude compared to that of the high-dispersion spectrographic technique.

Perhaps one way to attack the problem would be to start the spectrographic search among members of relatively wide visual binary systems, where the radial velocity of the companion can be used as a convenient and reliable standard of velocity, and should help in establishing at once whether one (or both) members are spectroscopic binaries of the type here considered.

Berkeley Astronomical Department,
University of California.
1952 July 24.

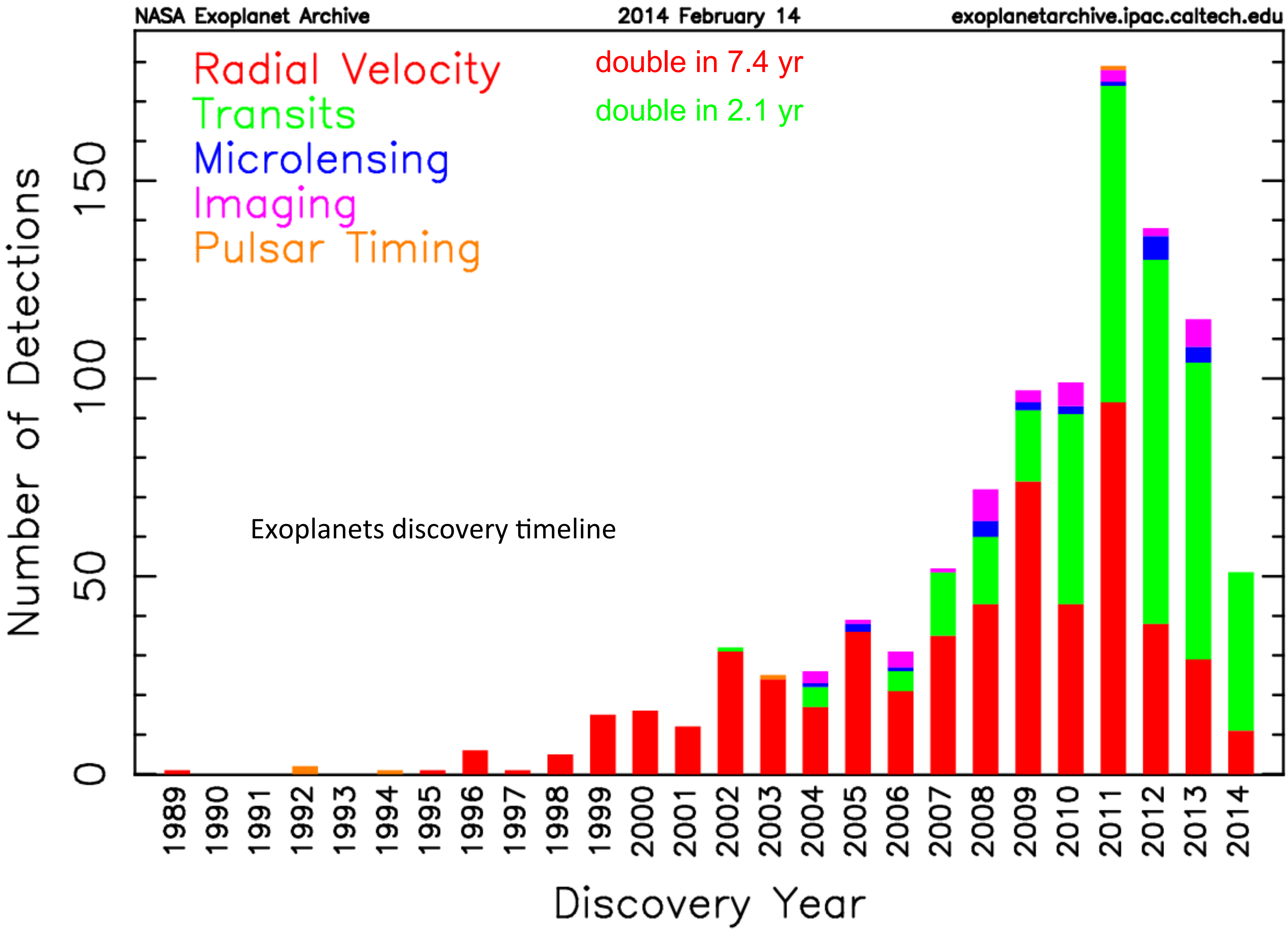
References

1. *A.J.*, **51**, 12, 1944; *Pub. A.S.P.*, **55**, 29, 1952.
2. *Izvestia Gl. Astr. Obs., Poulkovo*, **18**, No. 146, 1951.
3. *A.J.*, **51**, 7, 1944.
4. *Ap. J.*, **97**, 41, 1943.
5. See G. Herbig's paper presented at the Victoria 1952 meeting of the *A.A.S.* and *A.S.P.*
6. See P. W. Merrill's note on HD 117555 in *Pub. A.S.P.*, **60**, 382, 1948.


January 2014
1070 exoplanets
(810 systems, 177 multiple)
[numbers from exoplanet.eu]
Exoplanet Detection Methods
Miscellaneous
Star accretion (?)
Colliding planetesimals (1?)
Radio emission
X-ray emission (1)
Protoplanetary/ debris disks
Dynamical
Microlensing
Photometry
Timing
Astrometry
Rad velocity
Imaging
Transits
decreasing planet mass
10M_J
M_J
10M⊕
M⊕
pulsars
white dwarfs
sub dwarfs
eclipsing binaries
TTVs
slow
millisec
1
8
2
5
545
optical
radio
space
ground
2
astrometric
photometric
space
free-floating
bound
1?
26
space (coronagraphy/ interferometry)
ground (adaptive optics)
47
Doppler variability
reflected light
space
ground
timing residuals (see TTVs)
174
260
Discovered:
16 planets (13 systems, 2 multiple)
545 planets (410 systems, 95 multiple)
2 planets (2 systems, 0 multiple)
26 planets (24 systems, 2 multiple)
47 planets (43 systems, 2 multiple)
434 planets (330 systems, 70 multiple)
existing capability
projected (10–20 yr)
n = planets known
discoveries
follow-up detections

Discovery Method	Number of Planets
Radial Velocity	553
Transit	397
Imaging	38
Microlensing	23
Eclipse timing variations	9
Eclipse timing variations	4
Pulsar timing variations	5
Pulsation timing variations	1
Astrometry	2
Orbital brightness modulations	3

KEPLER PLANETS AND CANDIDATES	
Confirmed planets	249
Total candidates	3841
Candidates in habitable zone (180 K < T < 310 K)	659
Eclipsing binaries	2177

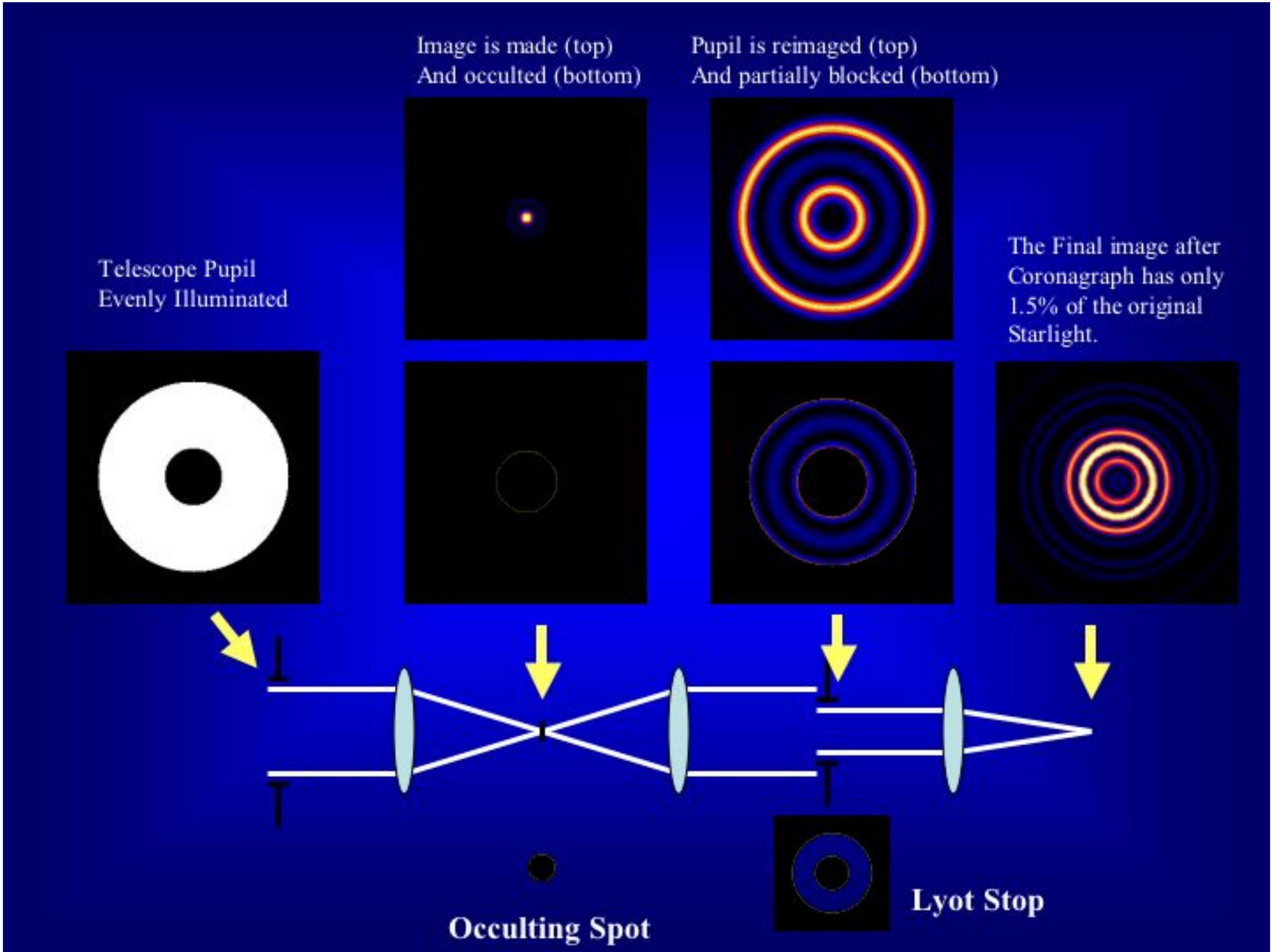


double in 7.4 yr

double in 2.1 yr

Exoplanets discovery timeline

Direct Imaging



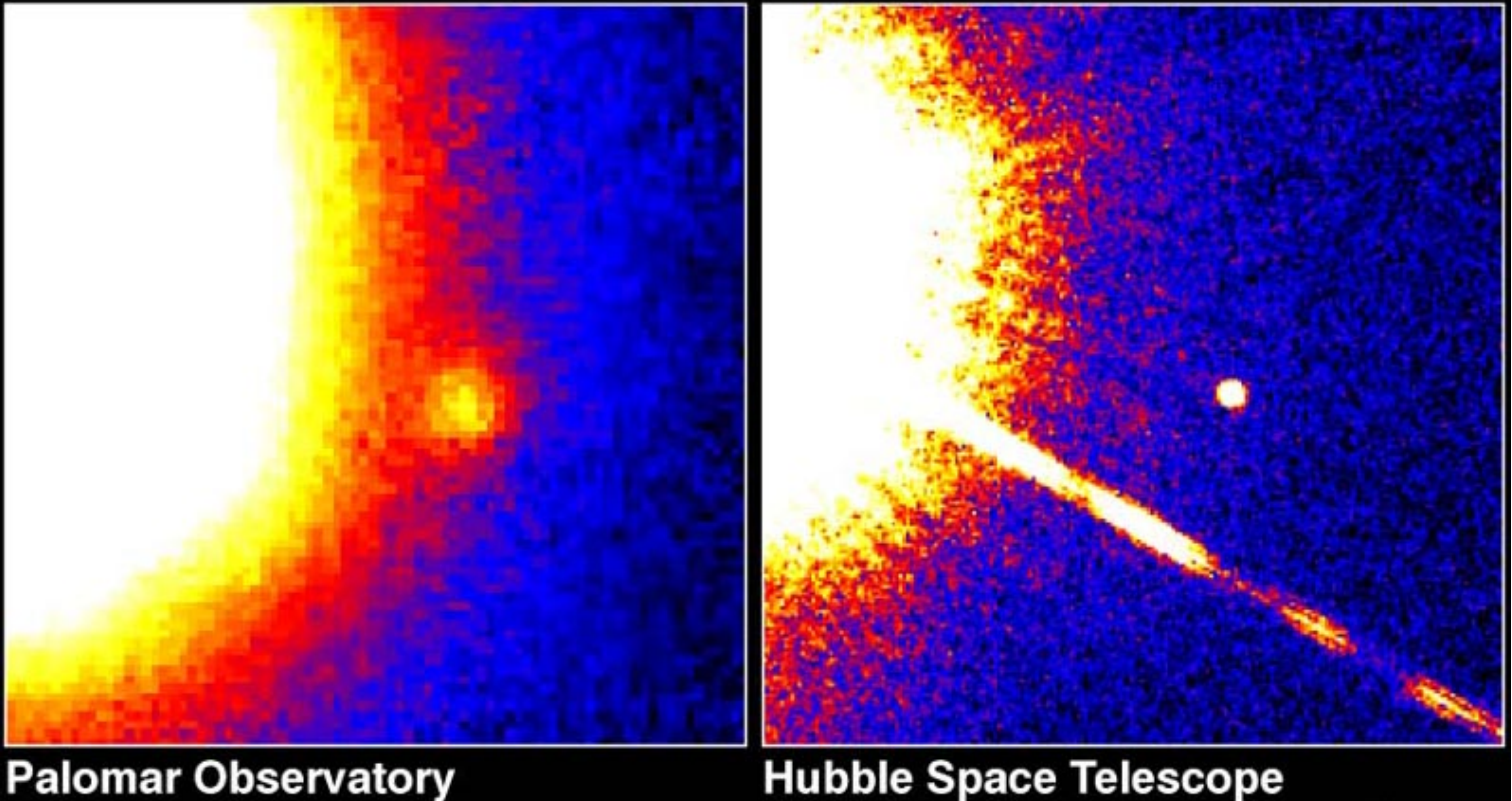
Telescope Pupil
Evenly Illuminated

Image is made (top)
And occulted (bottom)

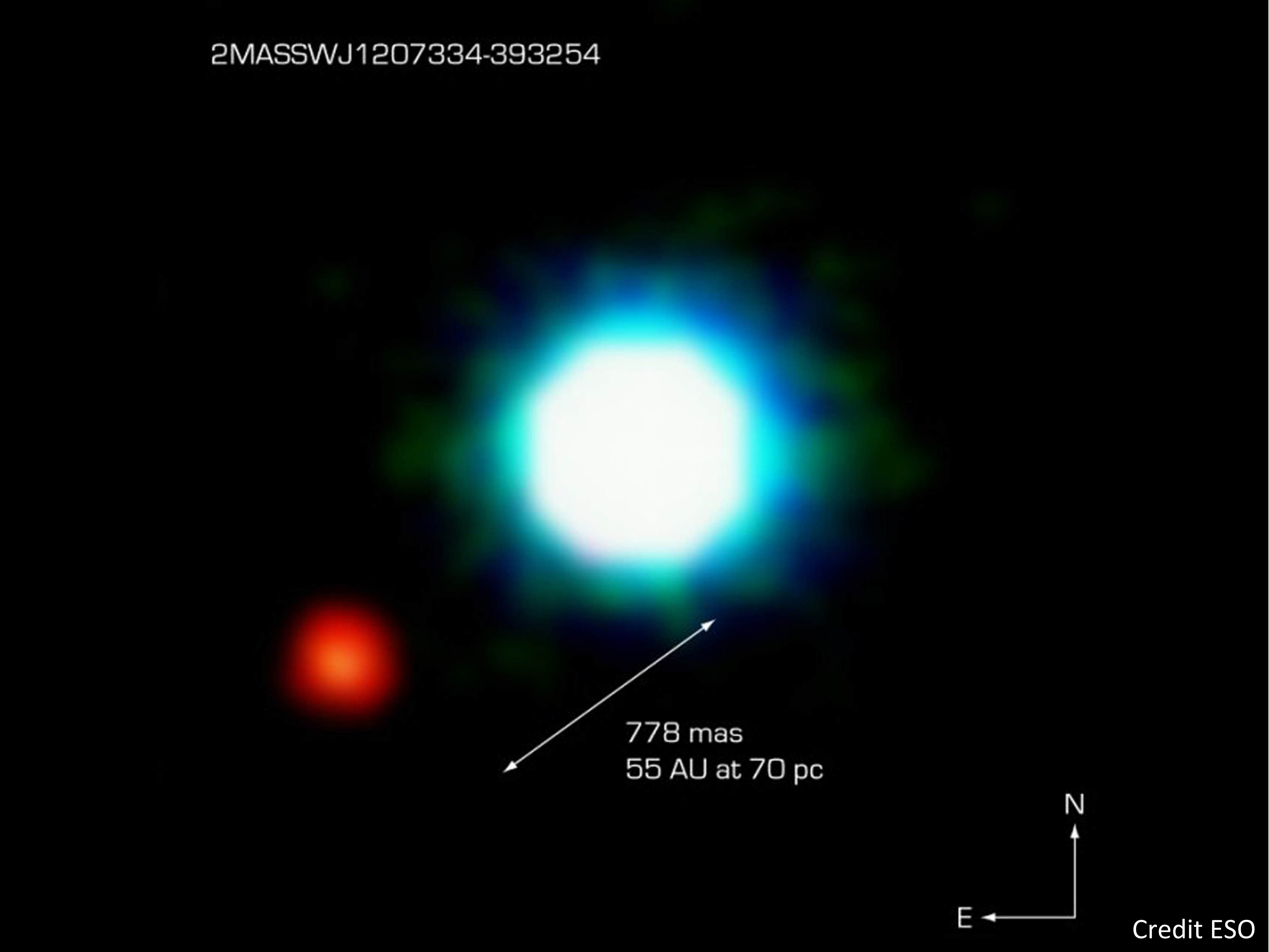
Pupil is reimaged (top)
And partially blocked (bottom)

The Final image after
Coronagraph has only
1.5% of the original
Starlight.

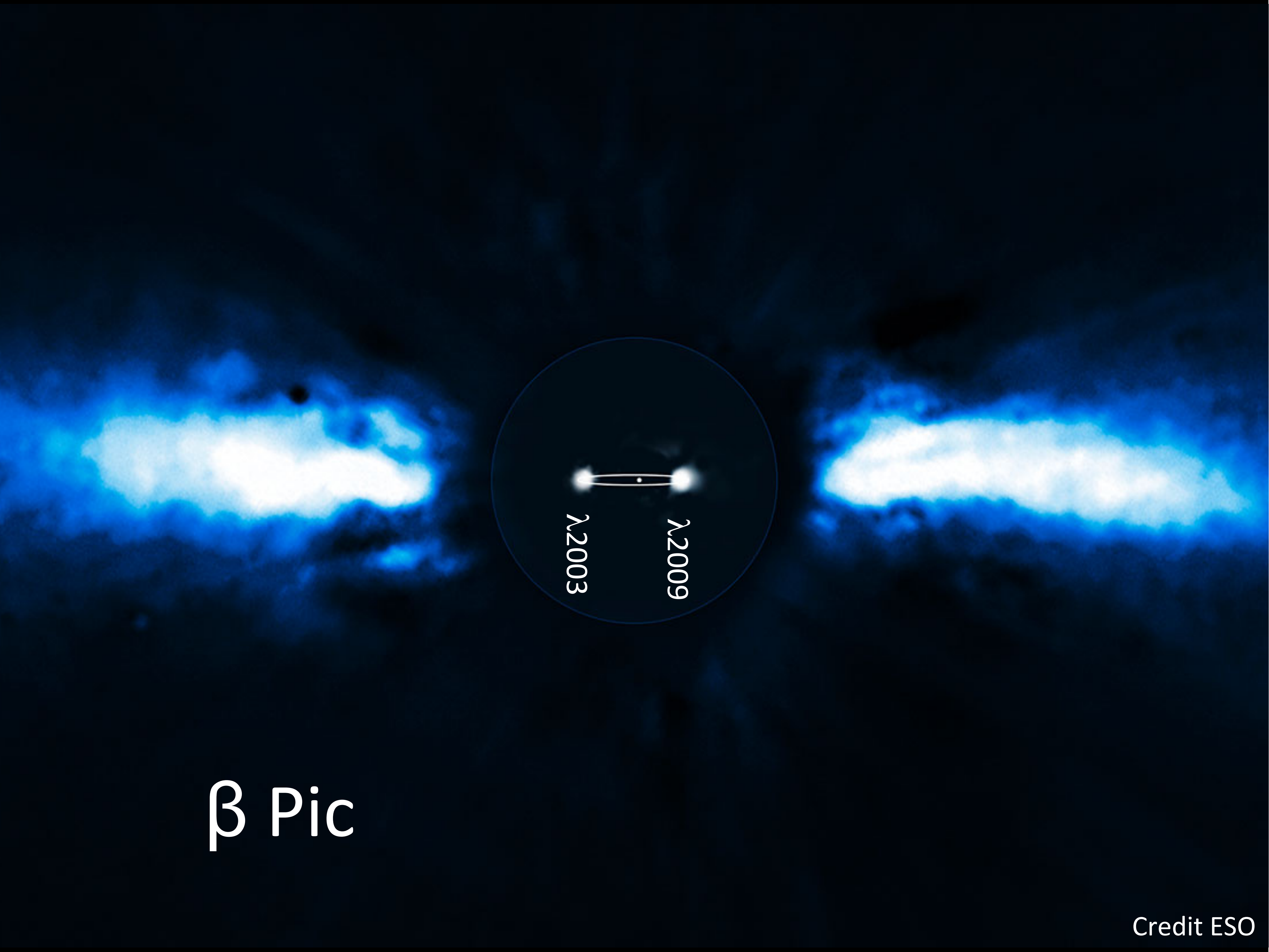
Brown Dwarf Gliese 229B



Credit HST



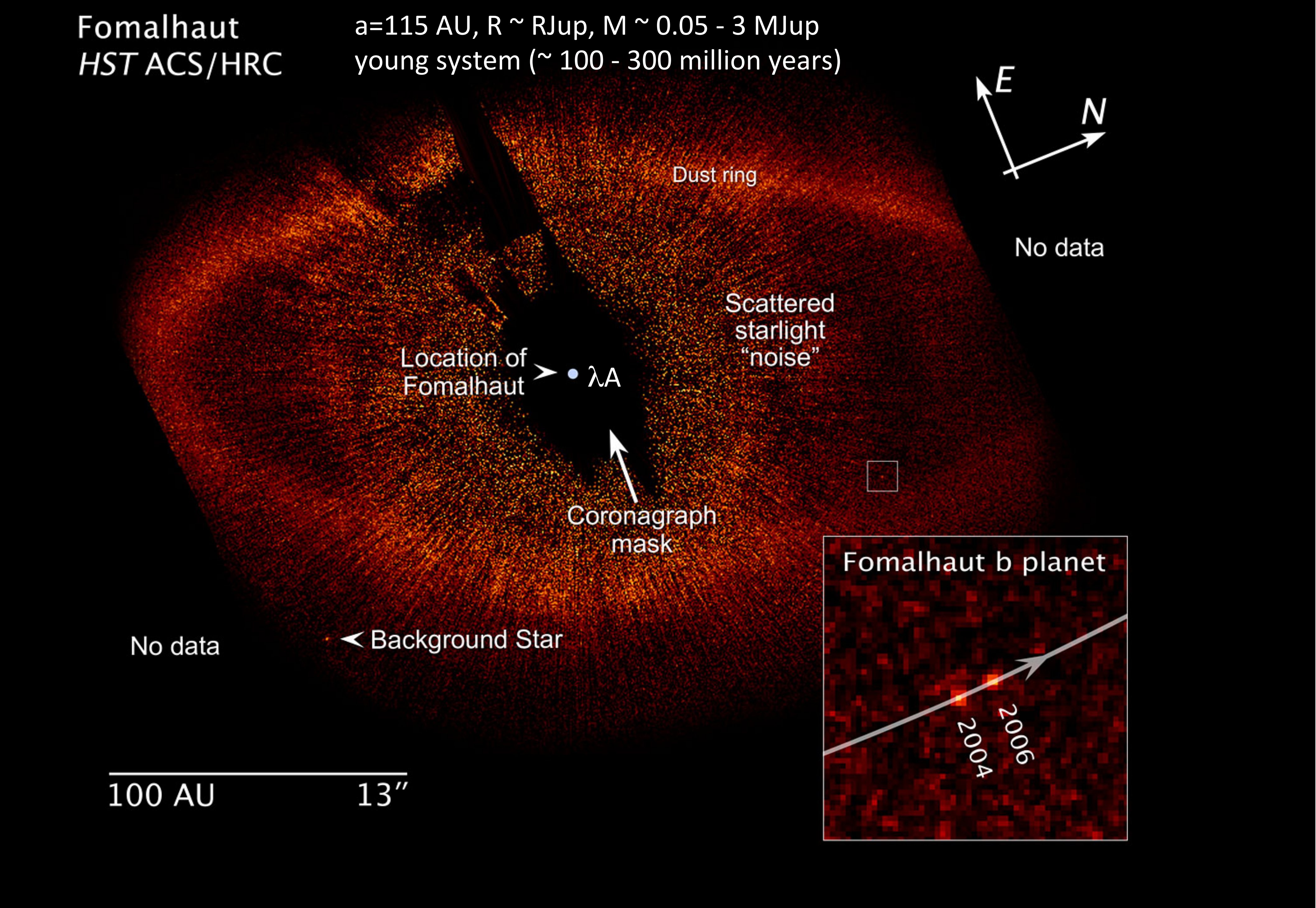
Credit ESO



β Pic

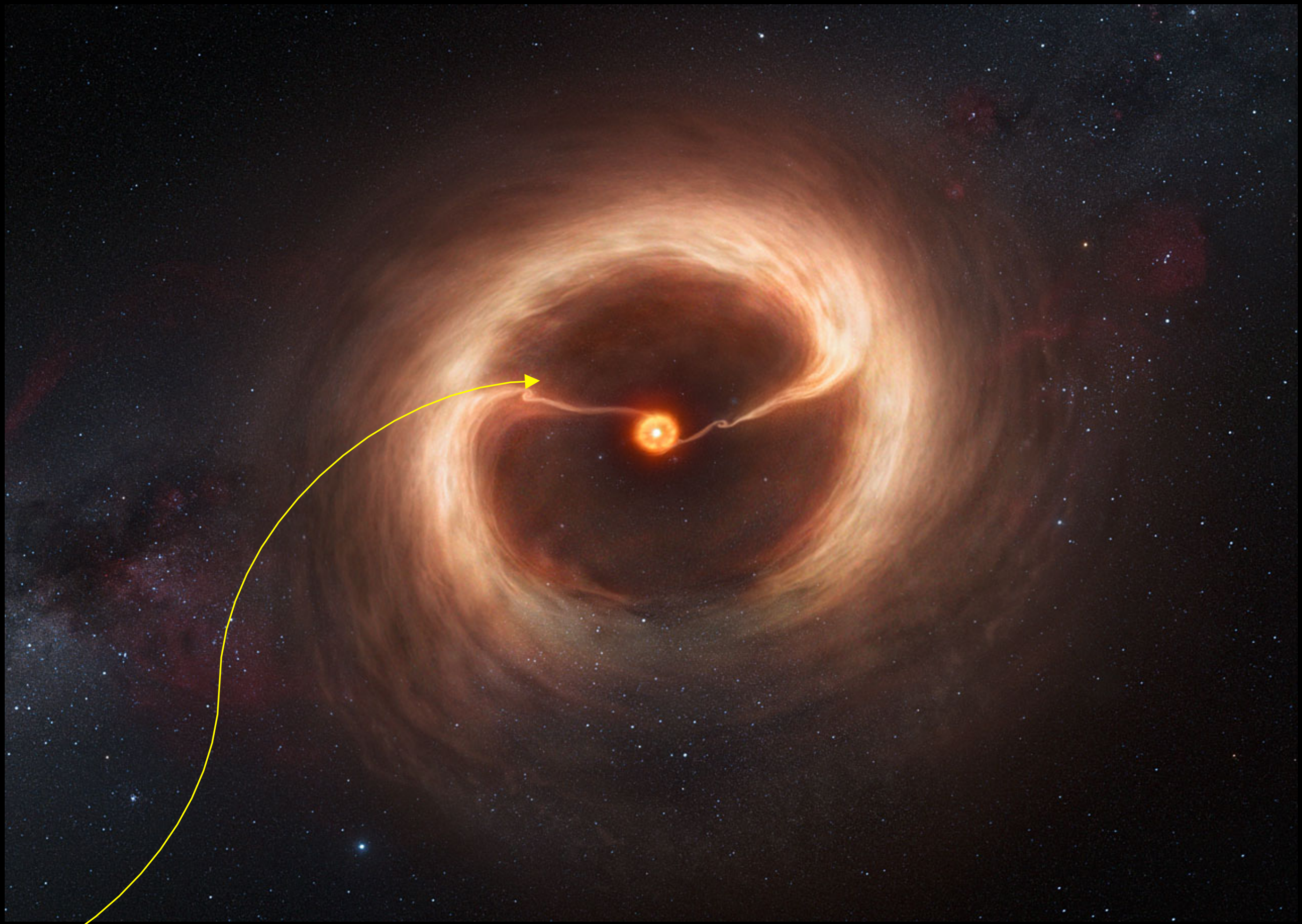
Credit ESO

a=115 AU, R ~ RJup, M ~ 0.05 - 3 MJup
young system (~ 100 - 300 million years)



Credit HST

Dust and gas around HD 142527 with ALMA

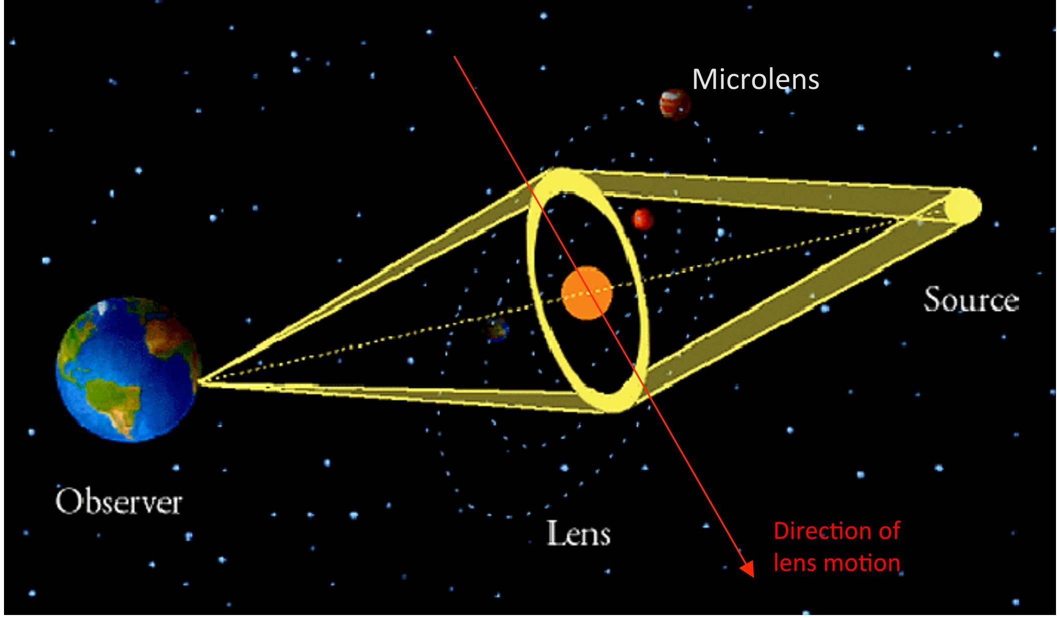


Streams of gas flowing across the gap in the disc.

Dust
Dense gas (HCO+)
Diffuse gas (CO)

Credit ALMA

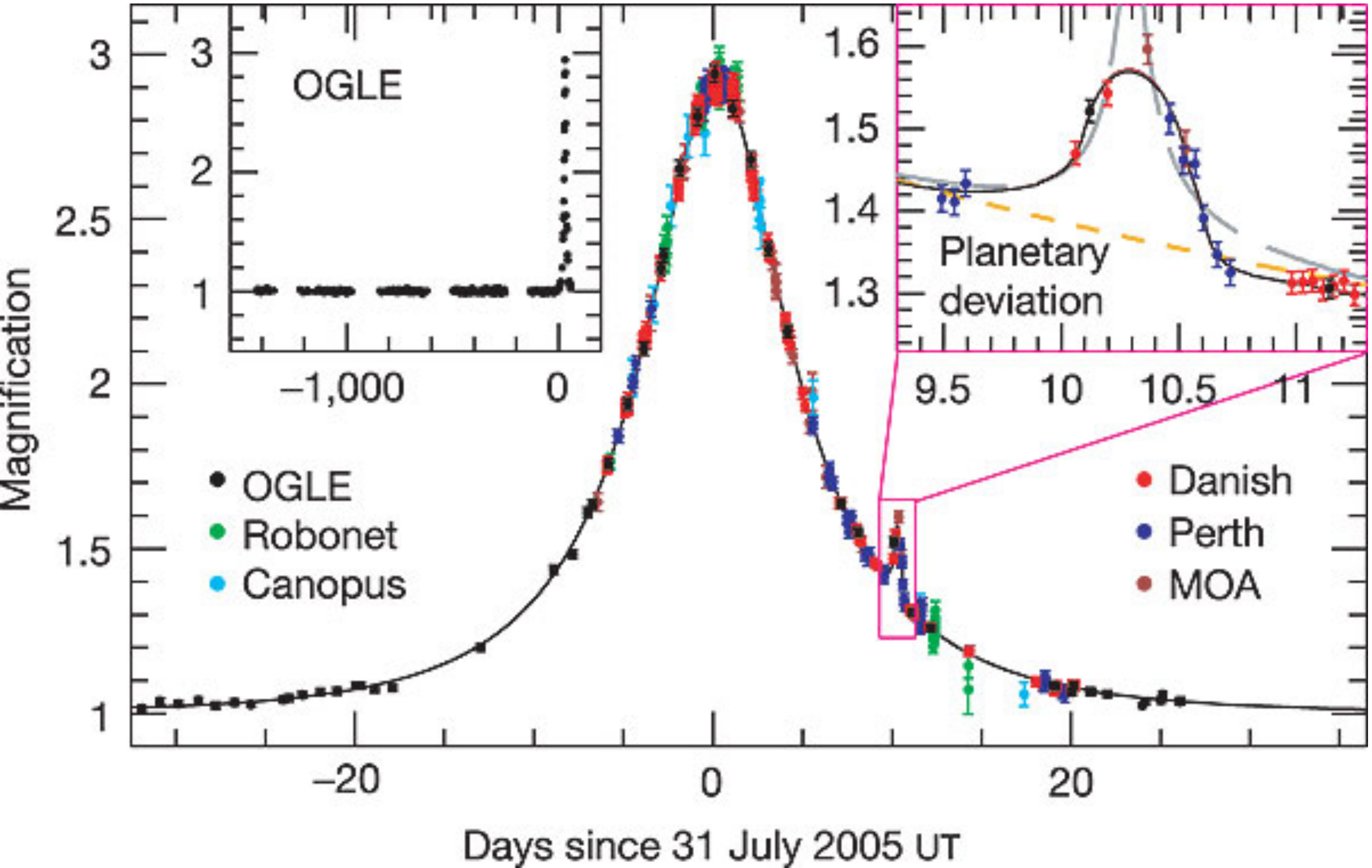
Microlensing



$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_S - d_L}{d_S d_L}}$$ Einsten radius

$$A(u) = \frac{u^2+2}{u\sqrt{u^2+4}}$$ Amplification factor

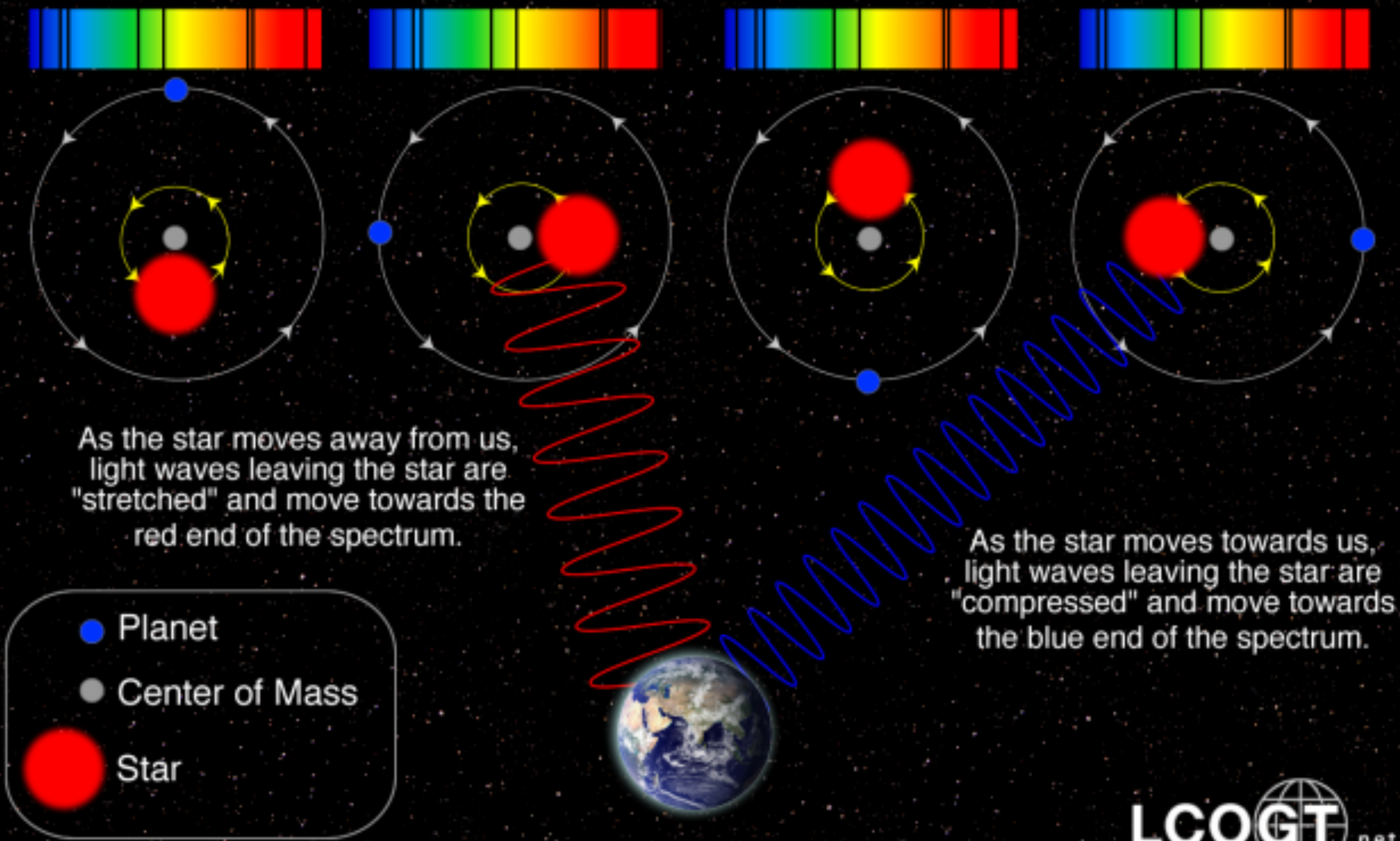
OGLE-2005-BLG-390 microlensing event



- Timescales: days to months
- Long time before source become separated and follow-up can be performed
- Works only in crowded environments (i.e. the galactic bulge)

Radial Velocity Method

The star and planet orbit their common center of mass.



Spectral lines move towards the red as the star travels away from us.

Spectral lines move towards the blue as the star travels towards us.

As the star moves away from us, light waves leaving the star are "stretched" and move towards the red end of the spectrum.

As the star moves towards us, light waves leaving the star are "compressed" and move towards the blue end of the spectrum.

● Planet

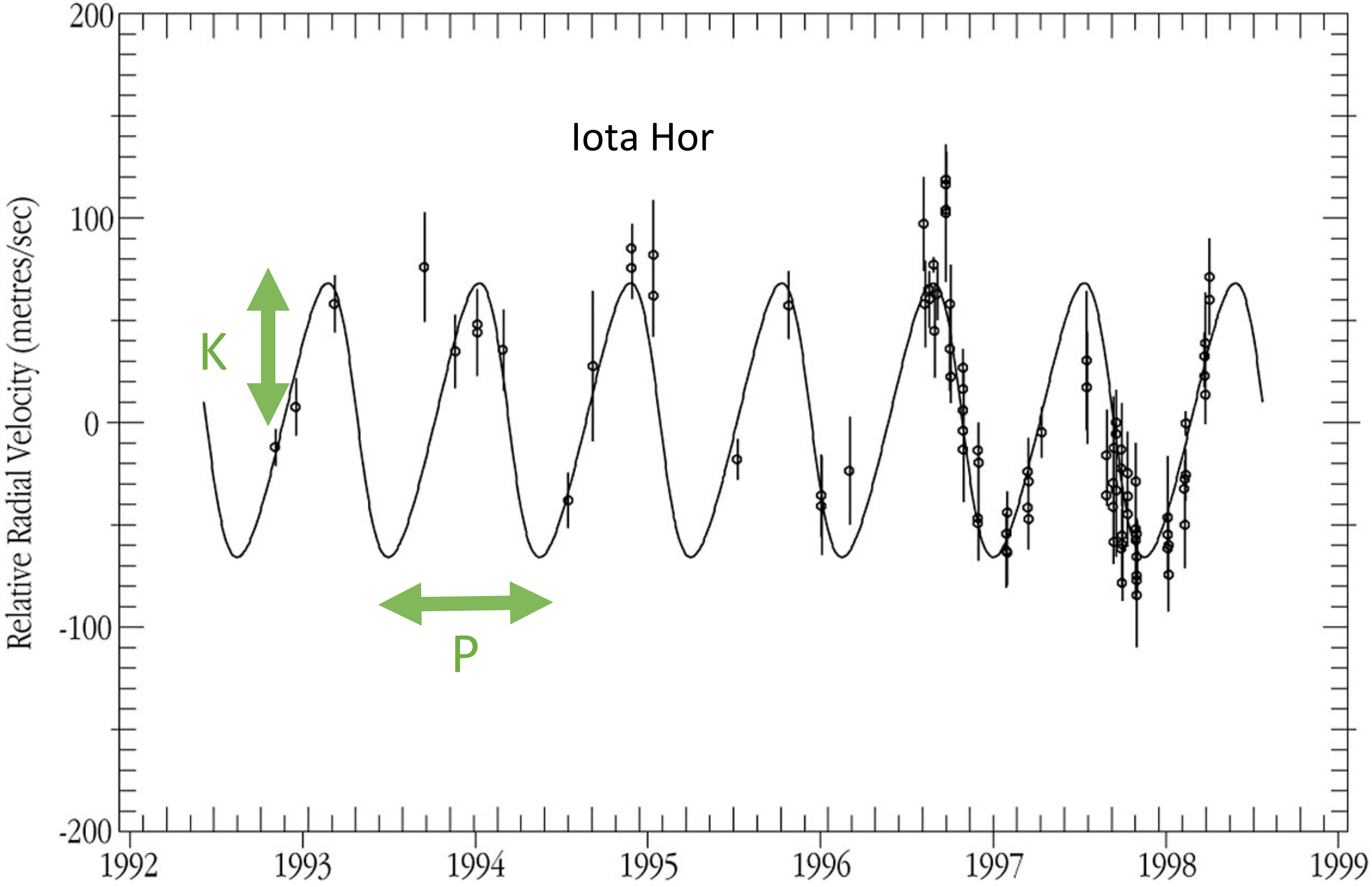
● Center of Mass

● Star

Not to scale

LCOGT.net

Radial Velocities

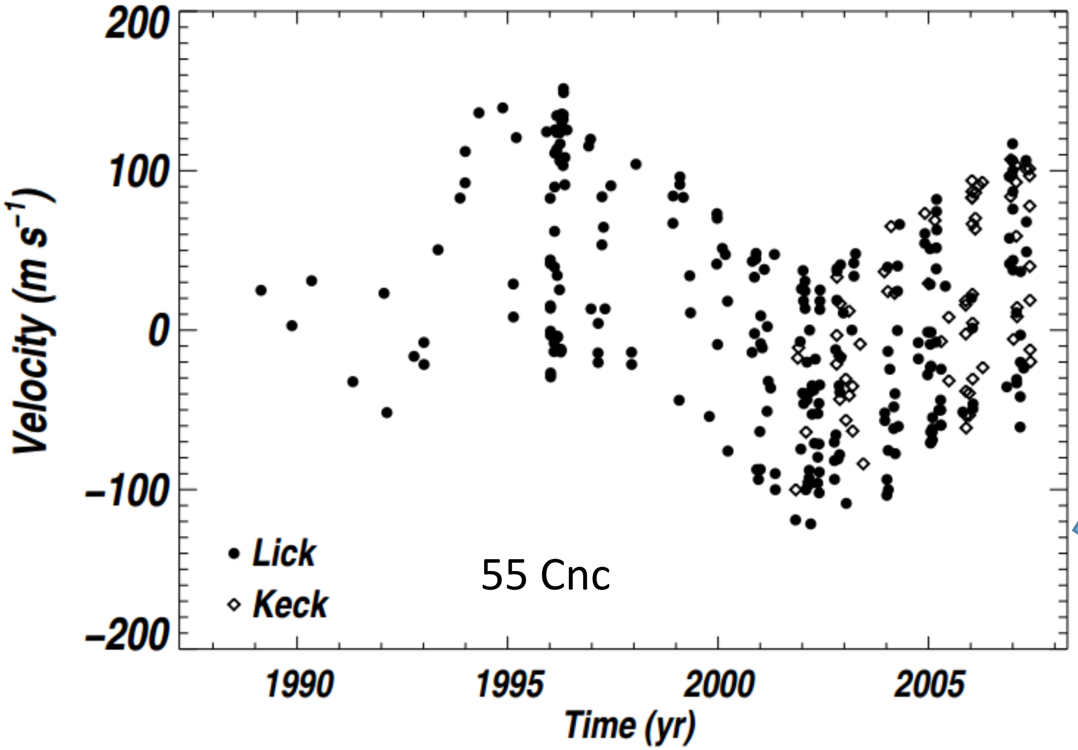


$$K = m_p \sin i / M^{2/3} \sqrt{1-e^2} \ (2\pi G/P)^{1/3}$$

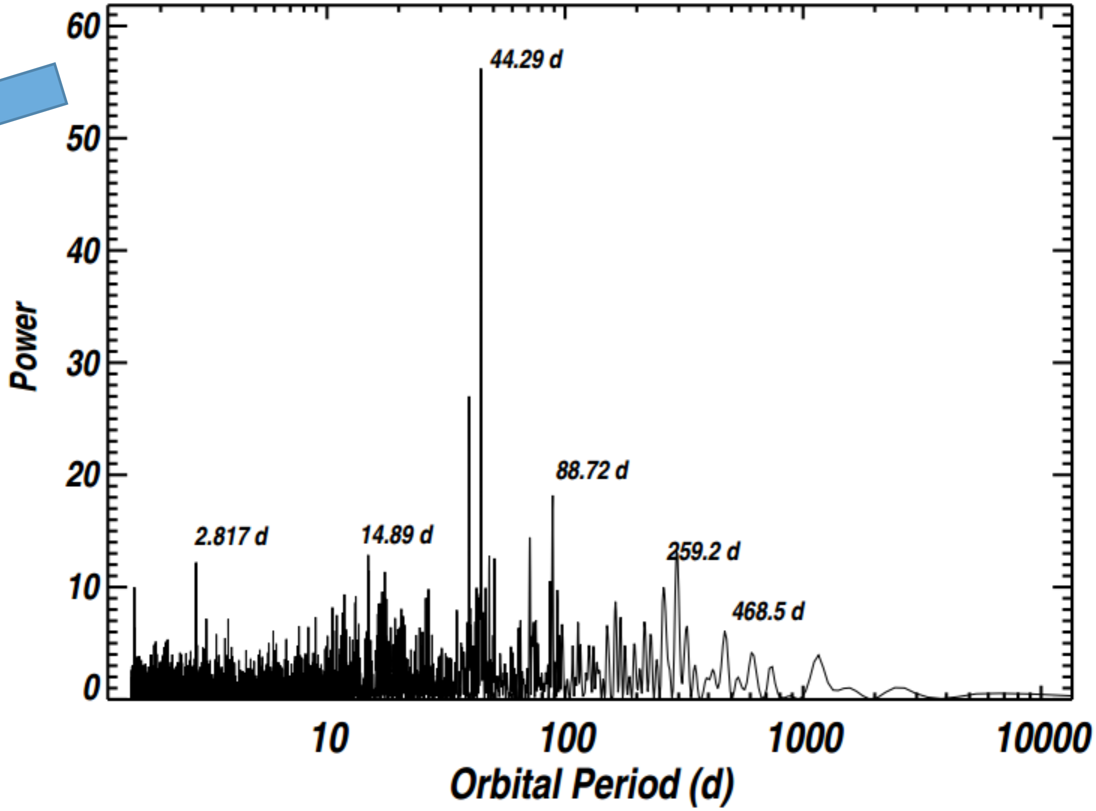
K = 1 m/s to few km/s
P = few hours to years

- The orbital period is determined via periodogram analysis
- Provides only minimum mass (msini)
- Is necessary a priori knowledge of the stellar mass (via spectroscopic analysis or isochrones fitting)

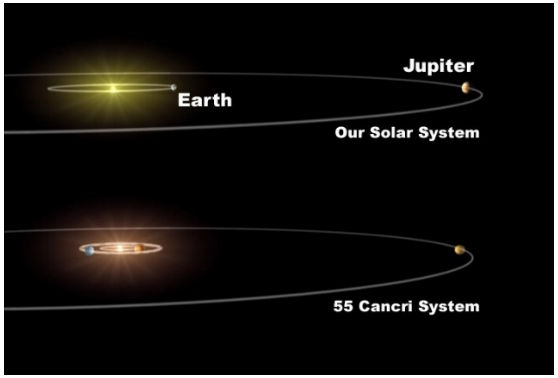
Radial Velocities



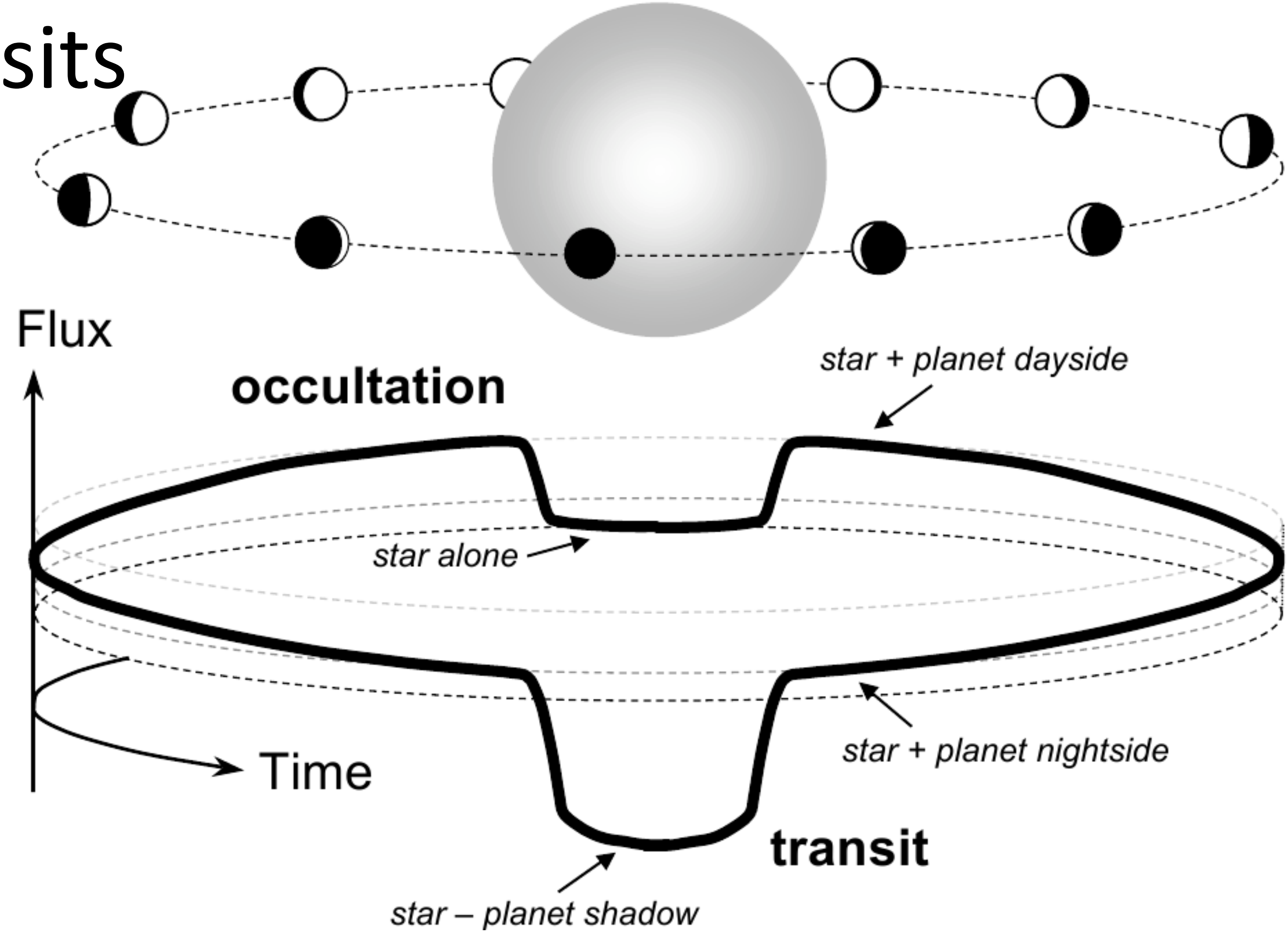
$K = m_p \sin i / M^{2/3} \sqrt{1-e^2} (2\pi G/P)^{1/3}$

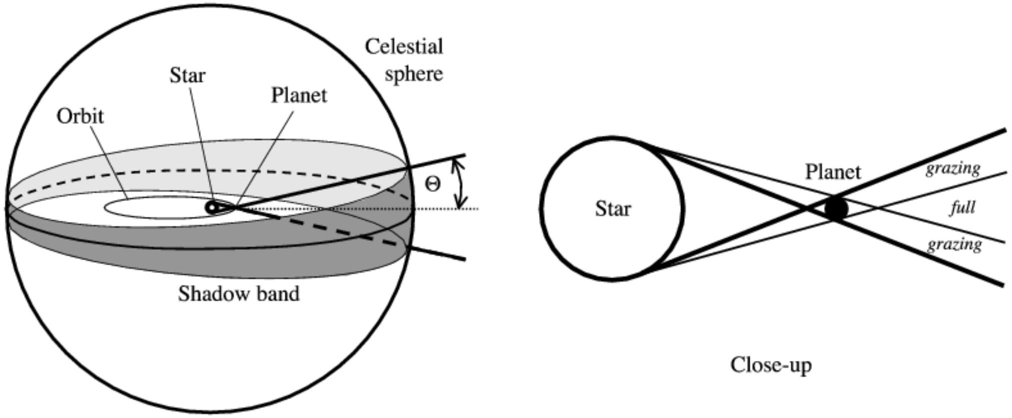


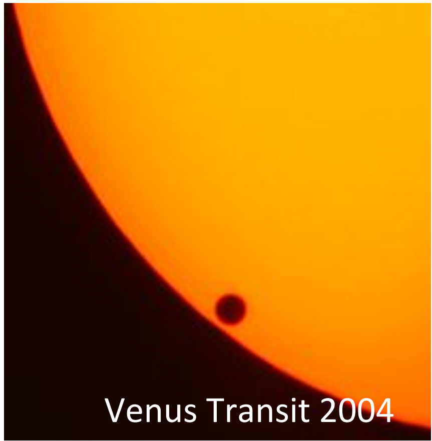
- 55 Cnc solar like star (binary)
- 20 years of data revealed 5 planets via keplerian fit



Transits






Venus Transit 2004

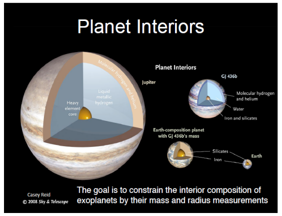
What we can learn from transits ?

Stellar density

$$\frac{\rho_*}{\rho_\odot} = \frac{M_*/M_\odot}{(R_*/R_\odot)^3} = \left[\frac{4\pi^2}{P^2 G}\right] \left[\frac{(1+\sqrt{\Delta F})^2 - b^2(1-\sin^2\frac{t_T \pi}{P})}{\sin^2\frac{t_T \pi}{P}}\right]^{3/2}$$

Planet gravity and mean density

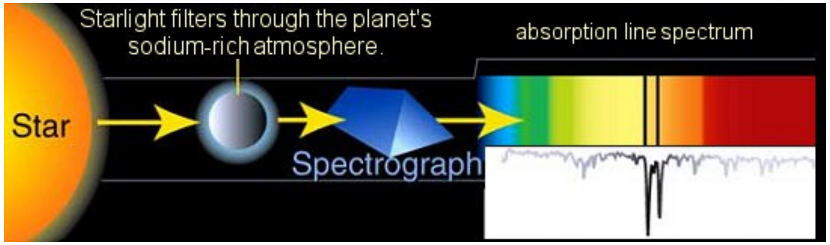
$$g_p = \frac{2\pi}{P}\frac{\sqrt{1-e^2}\,K_\star}{(R_p/a)^2 \sin i}.$$



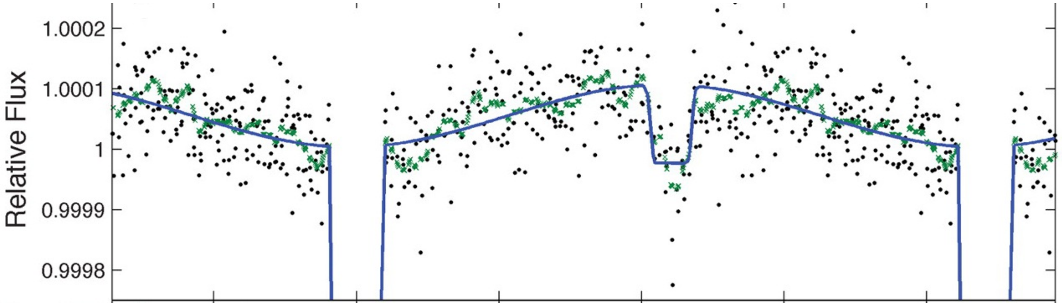
Casey Reid
© 2008 Sky & Telescope

The goal is to constrain the interior composition of exoplanets by their mass and radius measurements

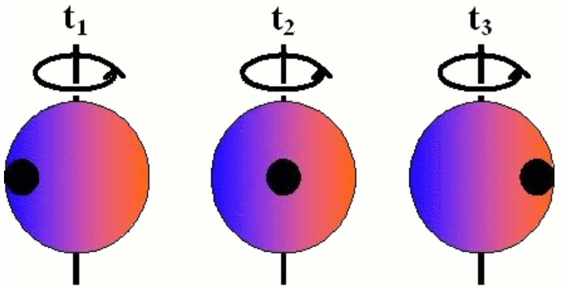
The atmospheric chemical composition

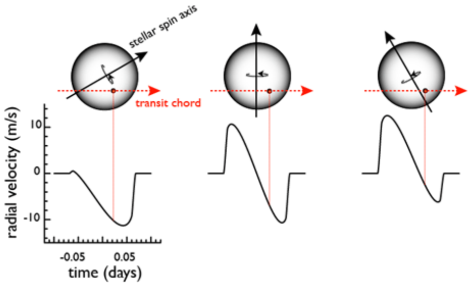


The equivalent temperature



The spin-orbit misalignment

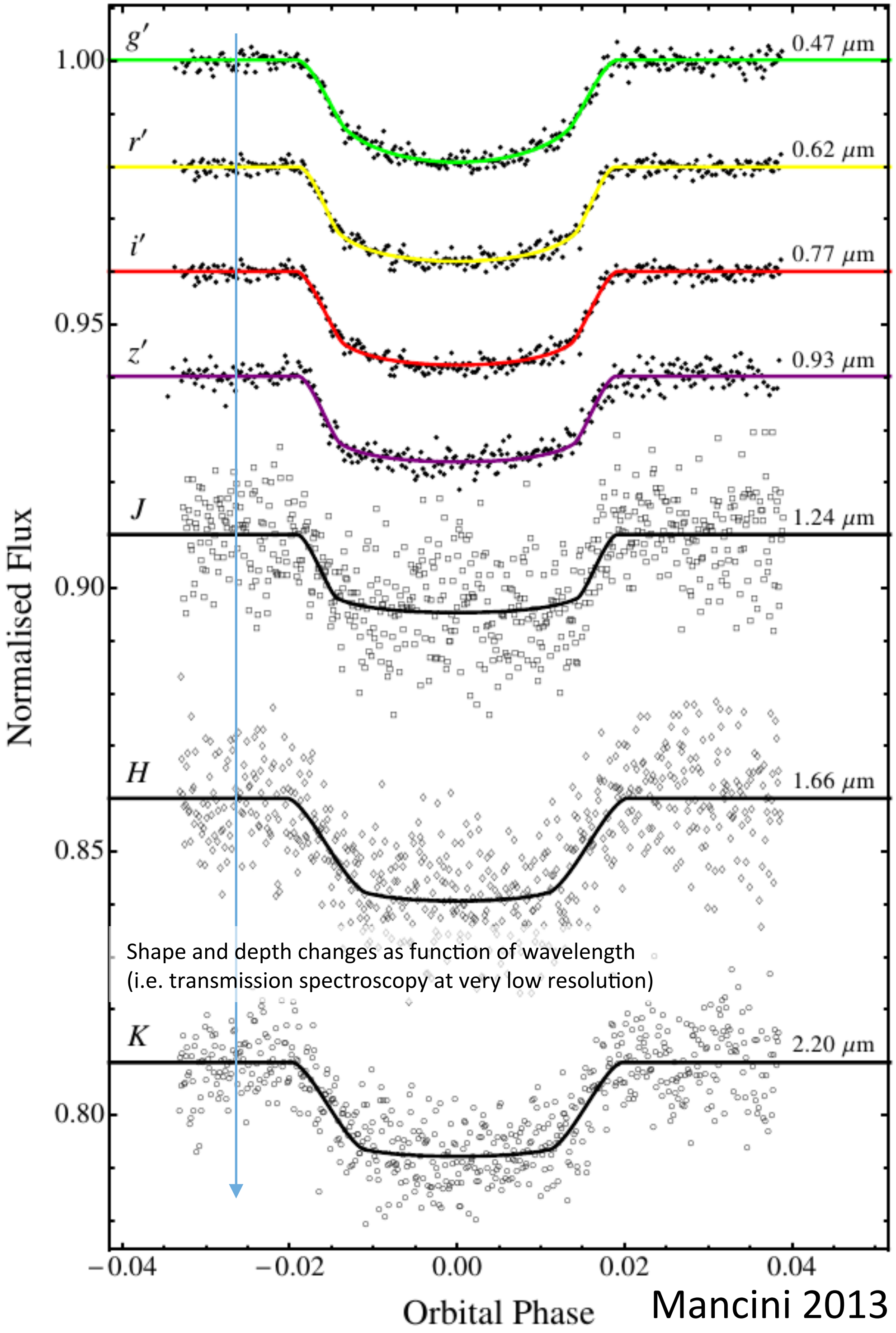




Transit parameters

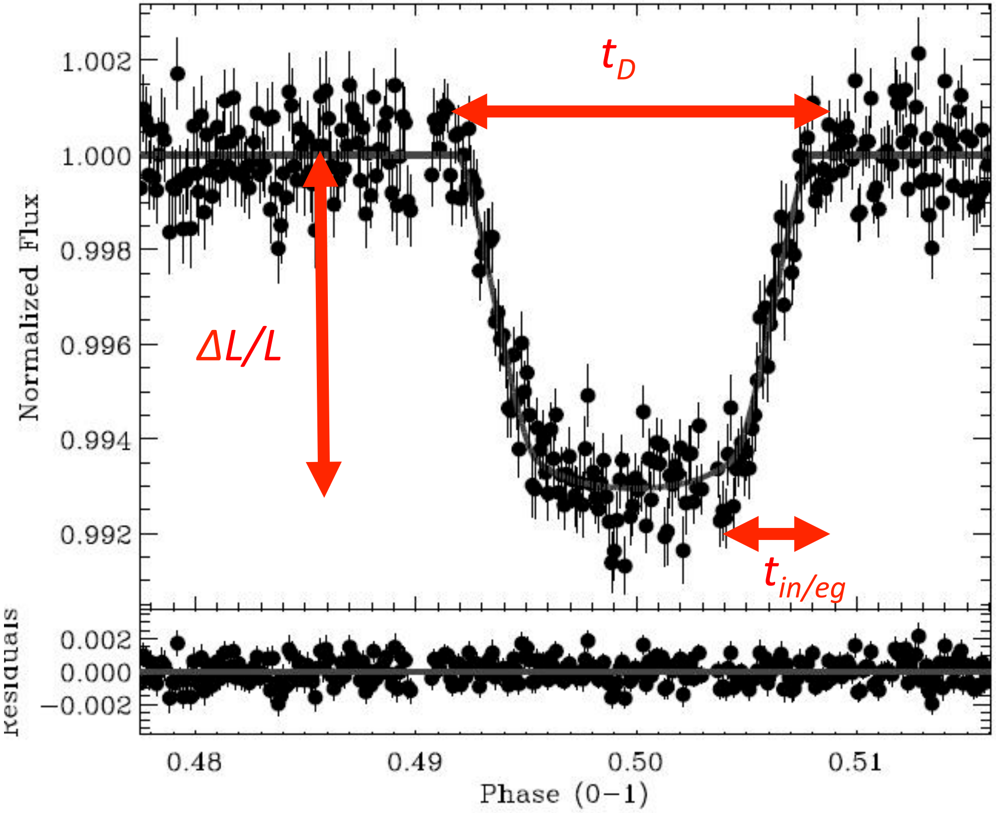
$$\frac{\Delta L}{L} = \left(\frac{R_P}{R_\star}\right)^2$$

$$t_D \leq \frac{P \times R_\star}{\pi \times a}$$

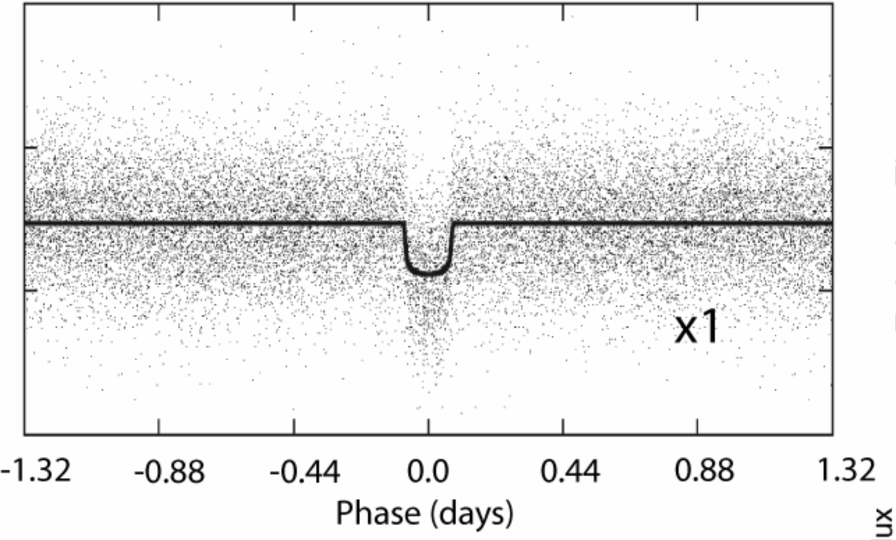


Shape and depth changes as function of wavelength
(i.e. transmission spectroscopy at very low resolution)

Mancini 2013

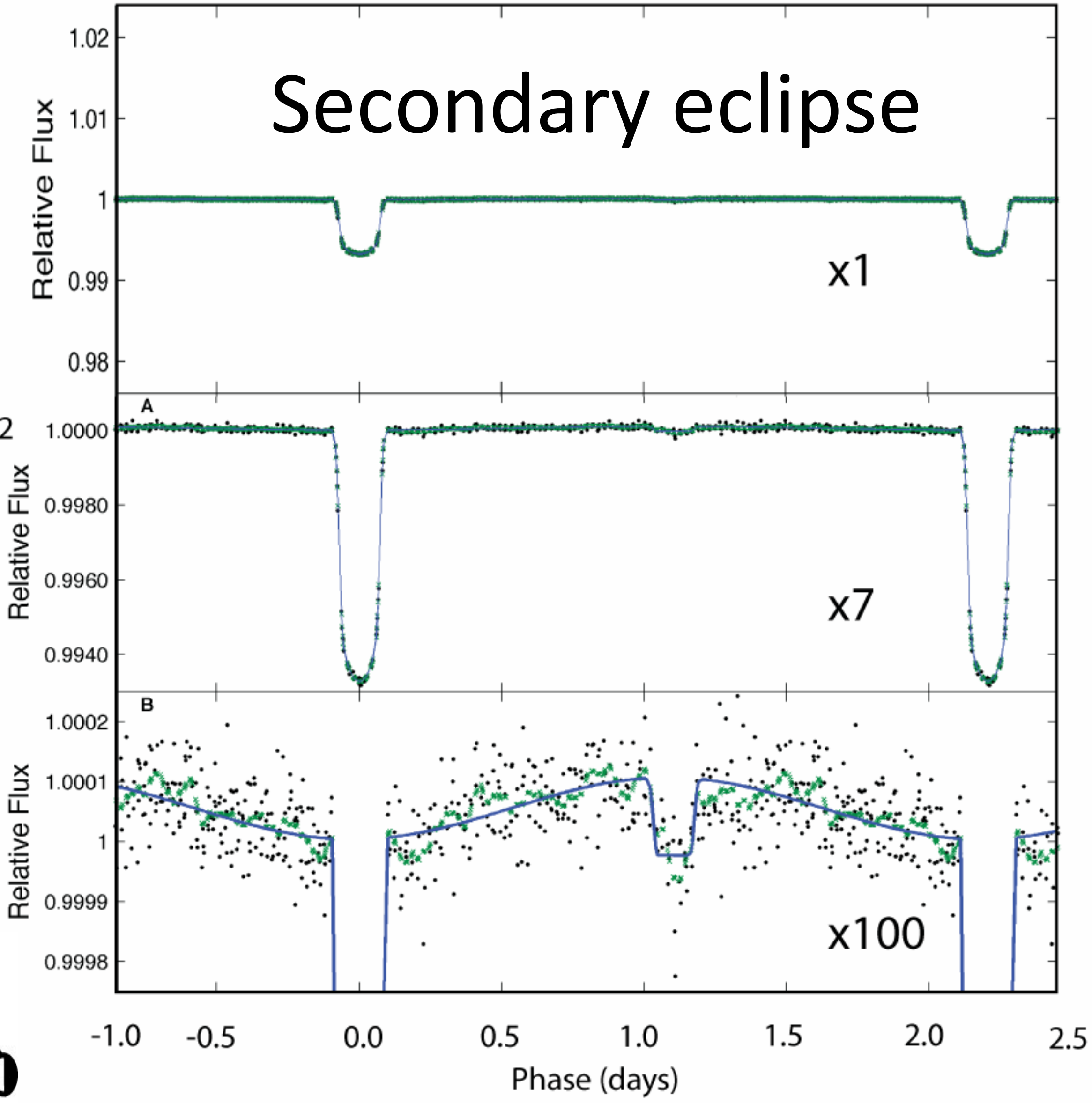


Secondary eclipse

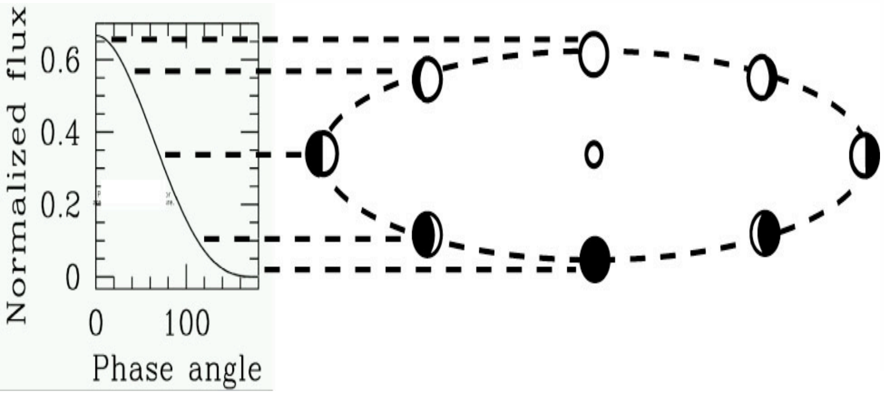


16,620 HATNet data points (57.7 days of data)

HAT-P-7b data from the ground
A. Pal et al., 2008

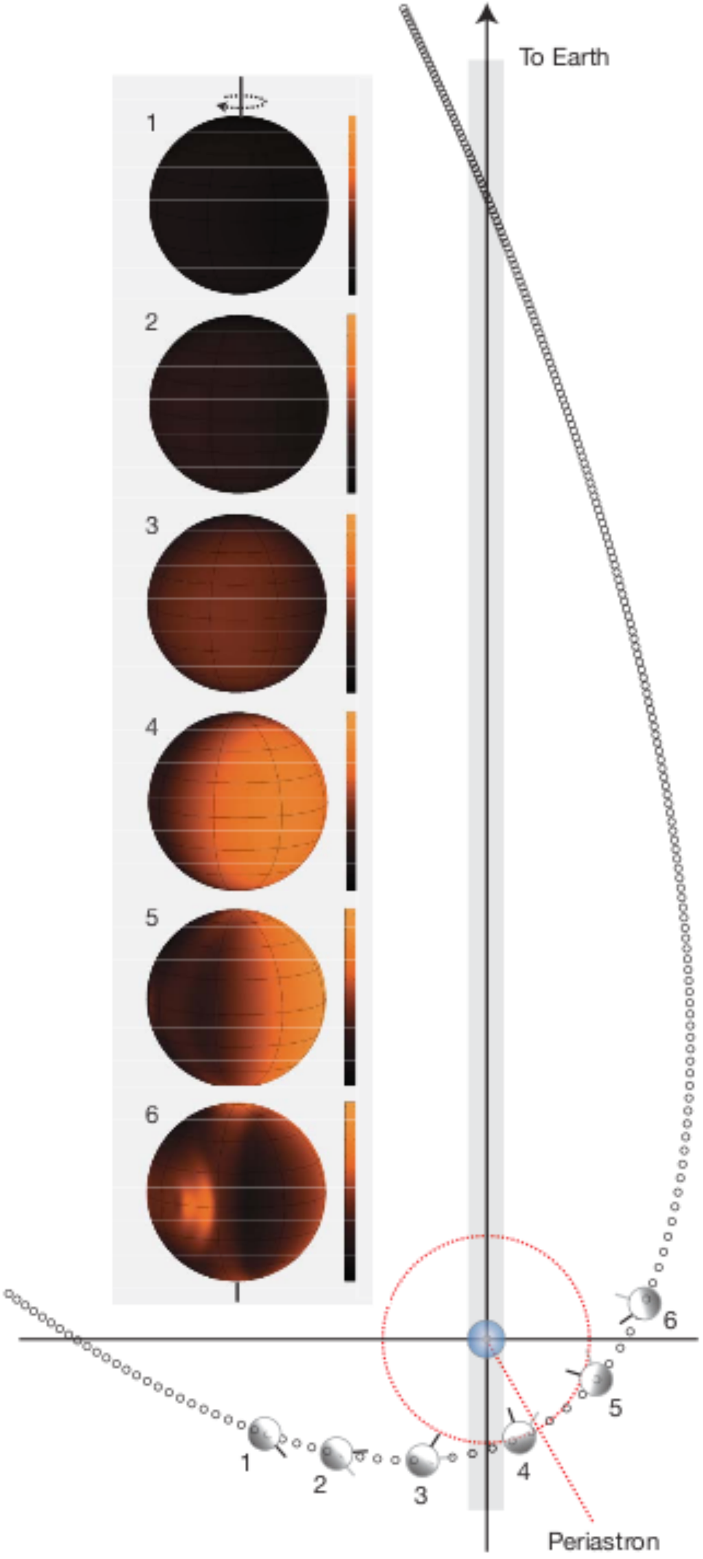


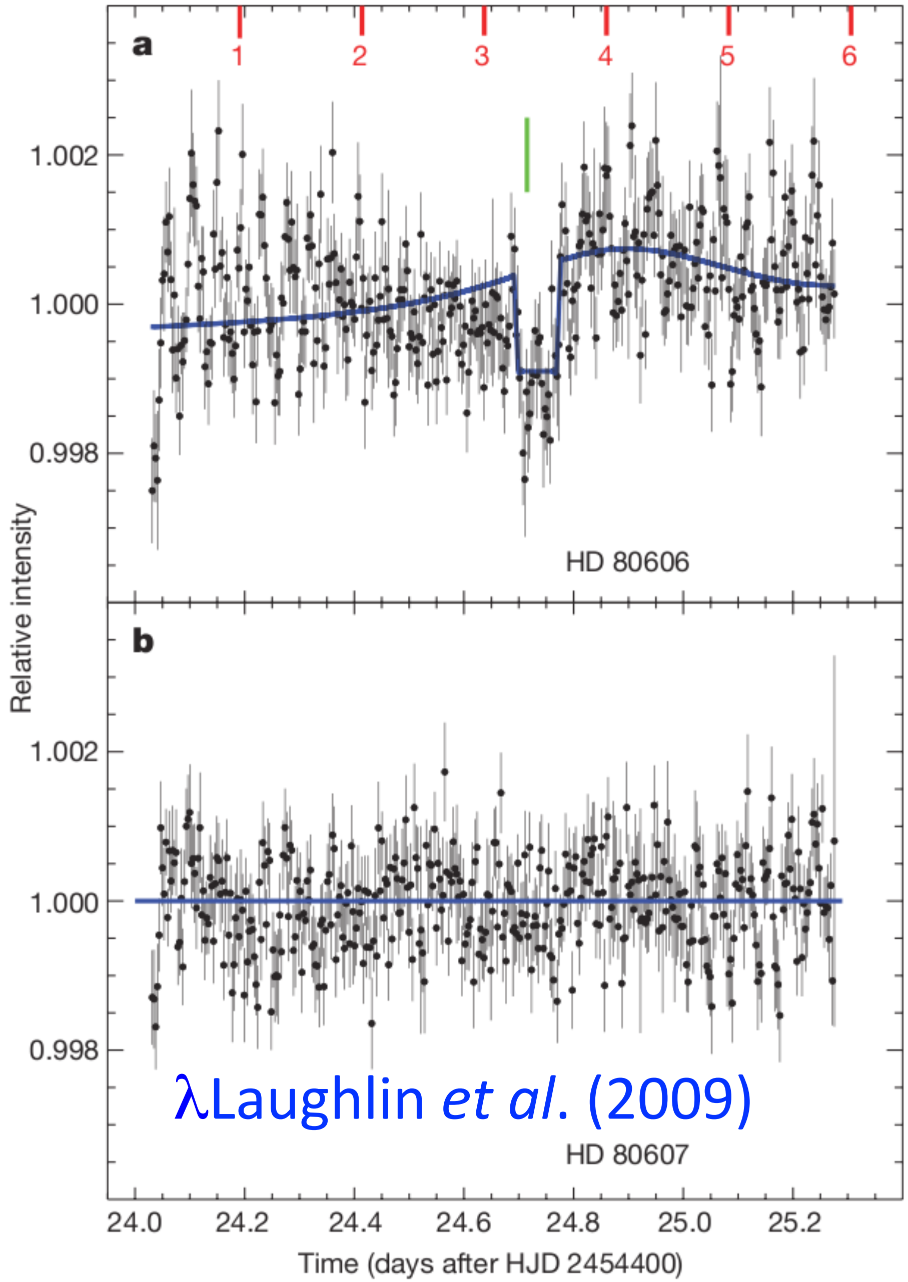
Kepler Commissioning data (10 days)
W. Borucki et al., 2009



transit depth = 6726+/- 11 part per million
occultation depth = 130 +/- 11 part per million
Teq = 2650 +/- 100 K

Phase Curves





λLaughlin *et al*. (2009)

HD 80606b

Secondary transit

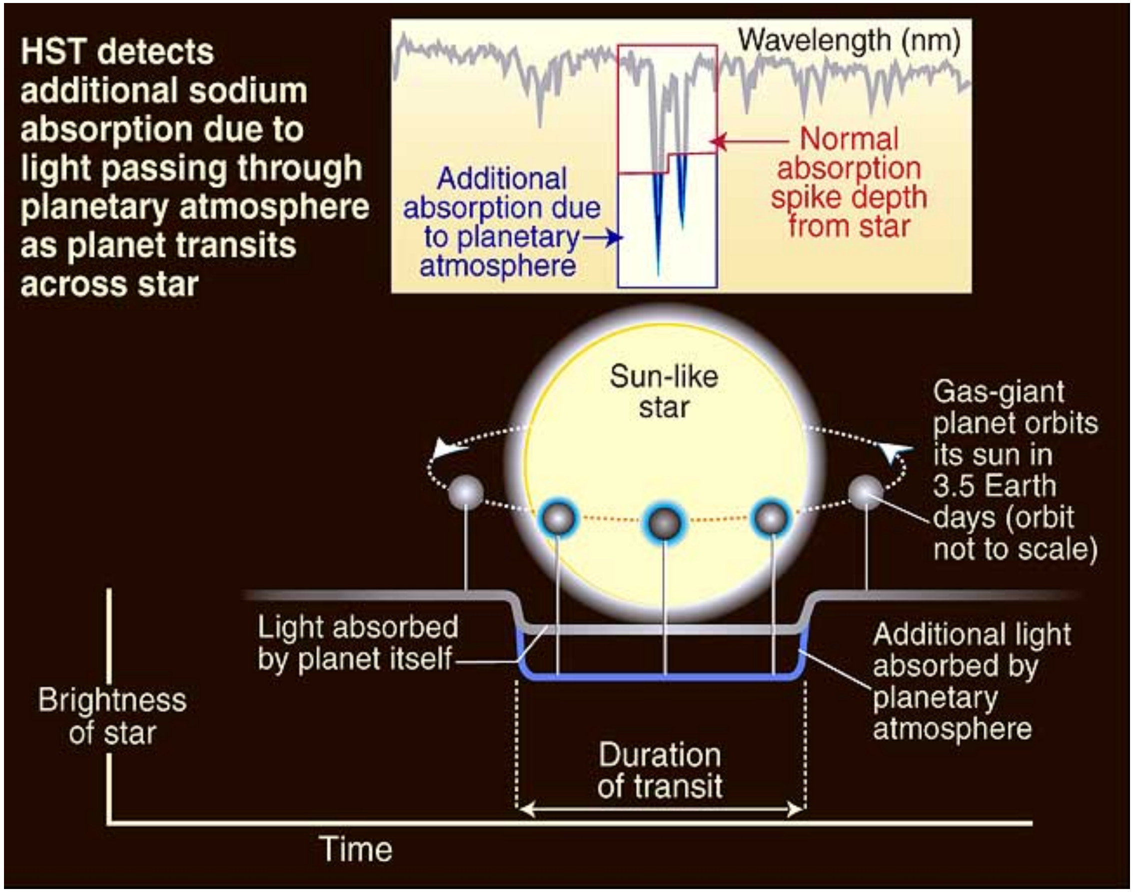
IRAC 8μm

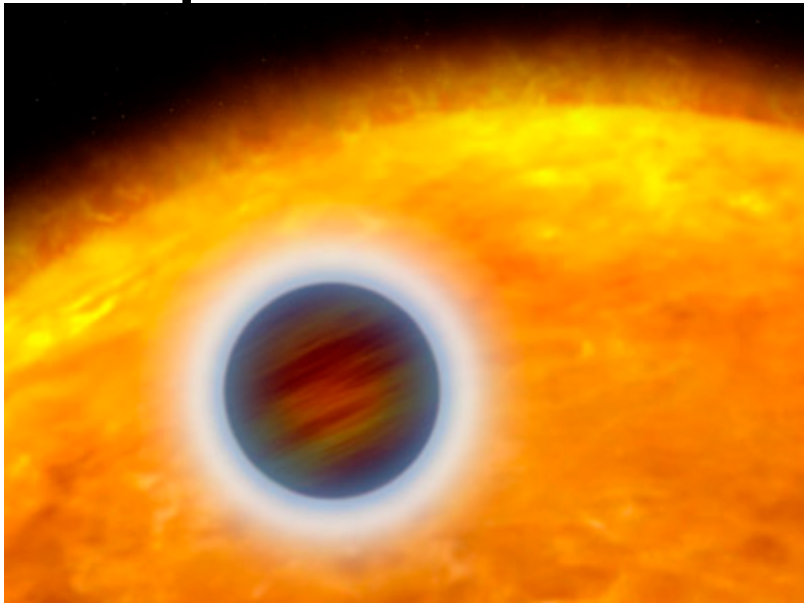
e=0.93

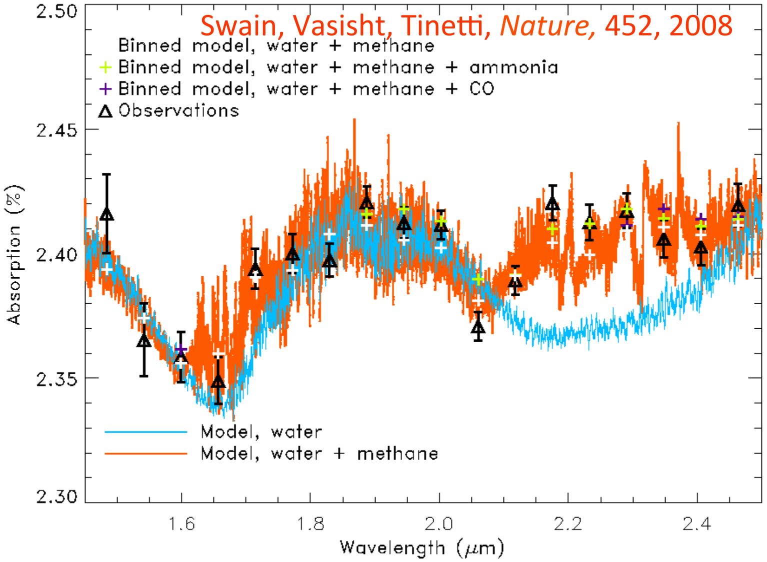
Flux variation 828 t

Pseudosyncronized

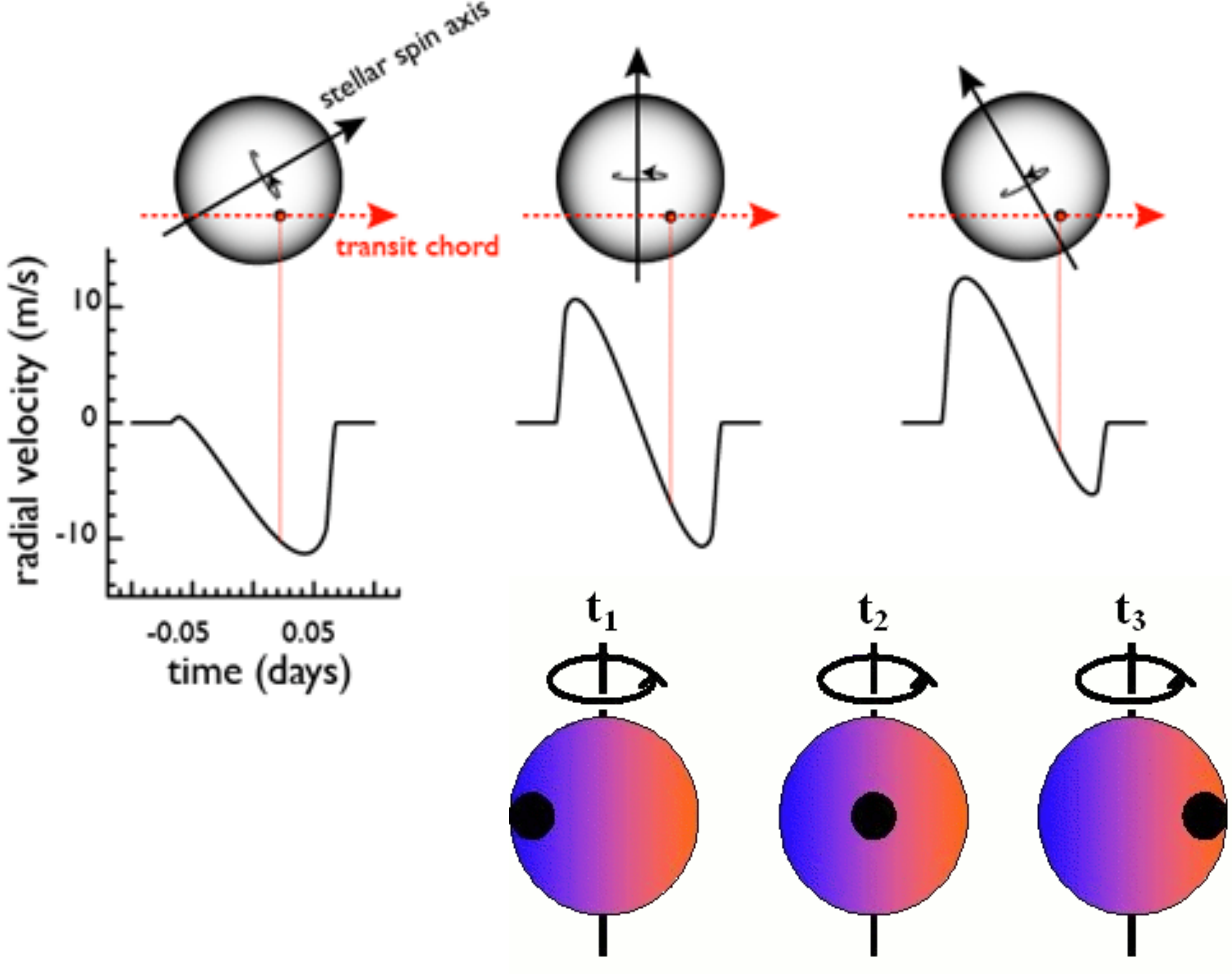
Detection of an Extrasolar Planet Atmosphere



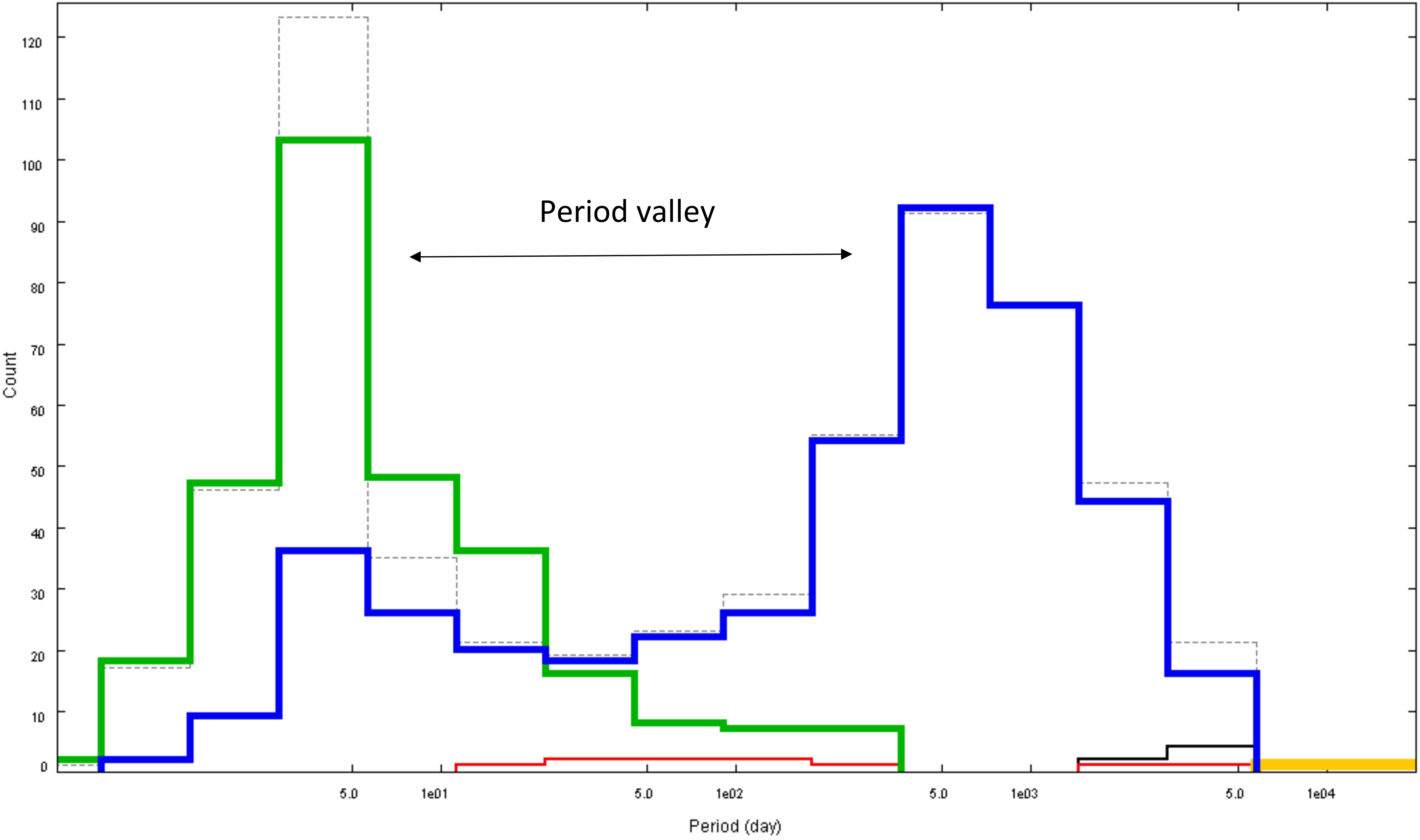



Swain, Vasisht, Tinetti, *Nature*, 452, 2008

ROSSITER-McLAUGHLIN EFFECT



Orbital periods



Imaged planets

Timing planets

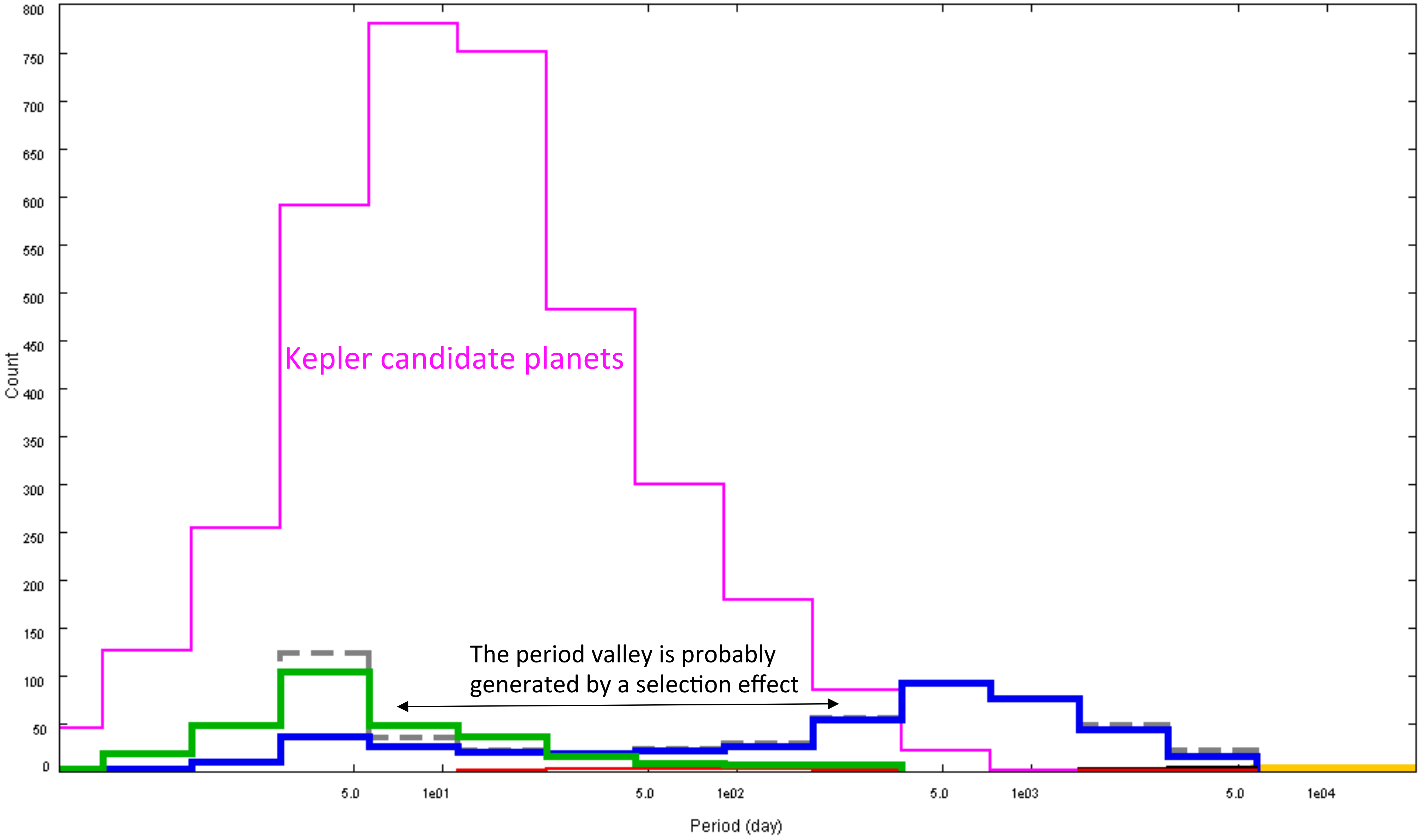
Microlensing planets

Transiting planets

Radial vel. planets

all planets

Orbital periods



The period valley is probably generated by a selection effect

Imaged planets

Timing planets

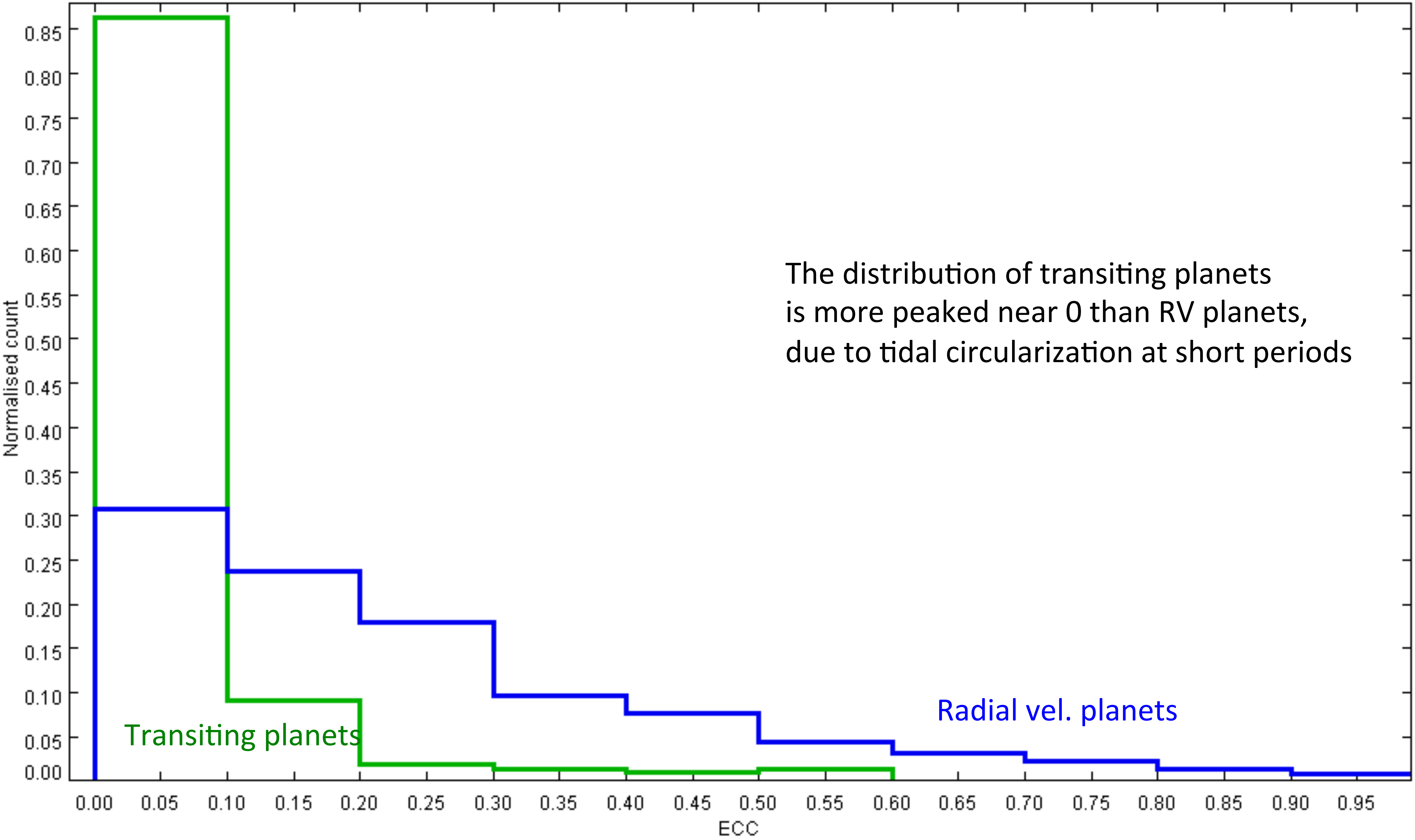
Microlensing planets

Transiting planets

Radial vel. planets

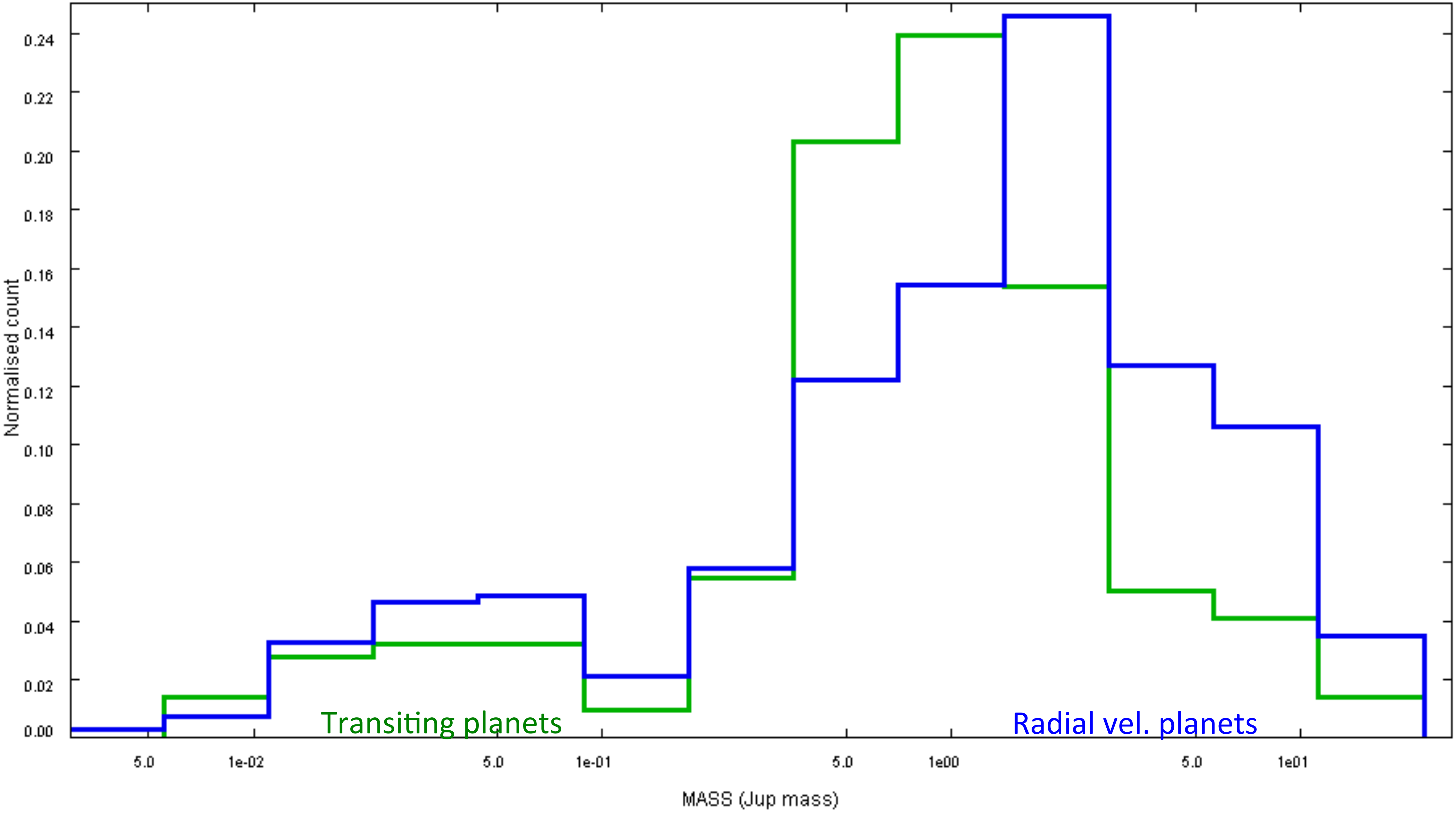
all planets

Orbital eccentricity

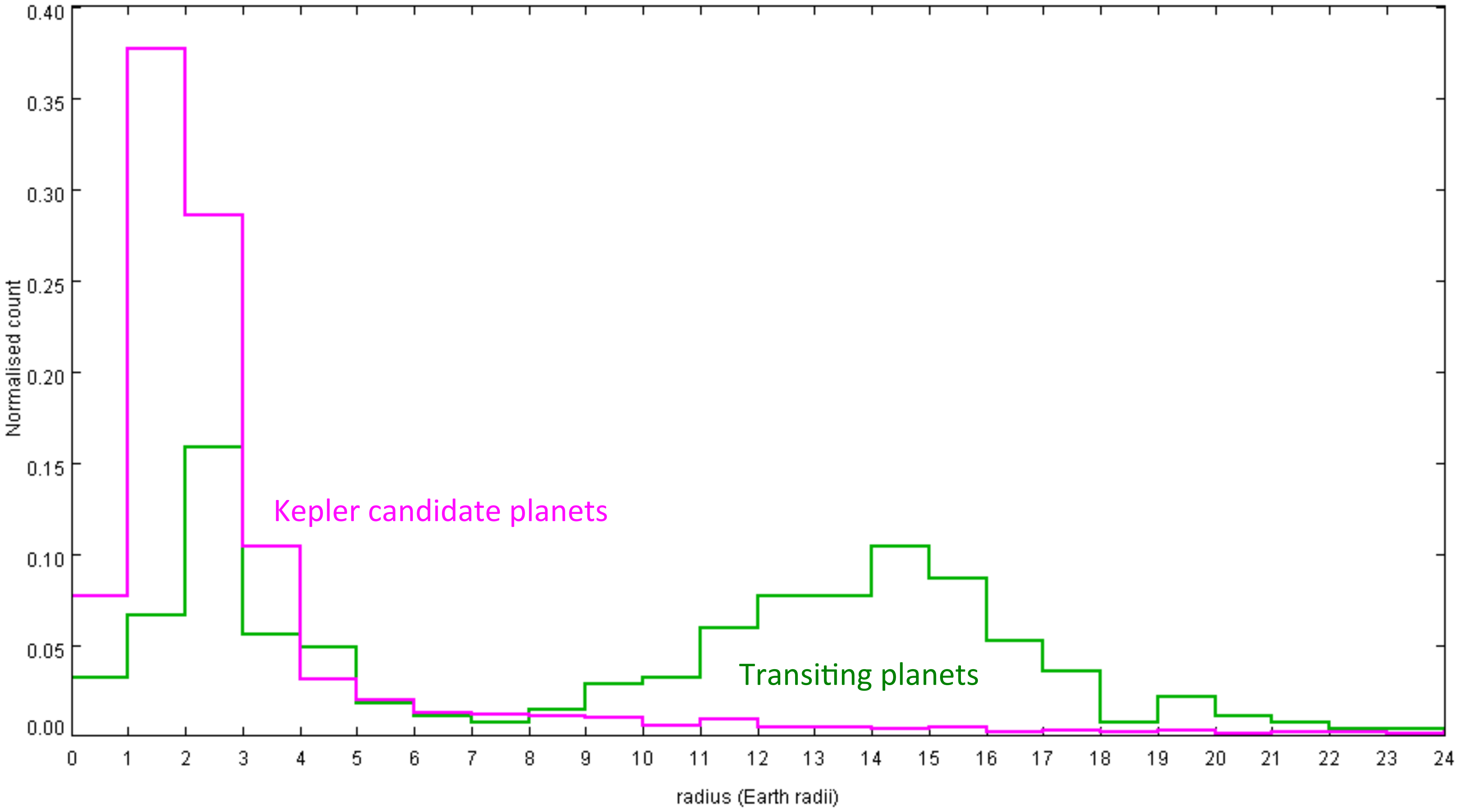


The distribution of transiting planets
is more peaked near 0 than RV planets,
due to tidal circularization at short periods

Mass


Normalised count
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
5.0
1e-02
5.0
1e-01
5.0
1e00
5.0
1e01
MASS (Jup mass)
Transiting planets
Radial vel. planets

Radius


0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Normalised count
0
1
2
3
4
5
6
7
8
9
10
11
12
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14
15
16
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18
19
20
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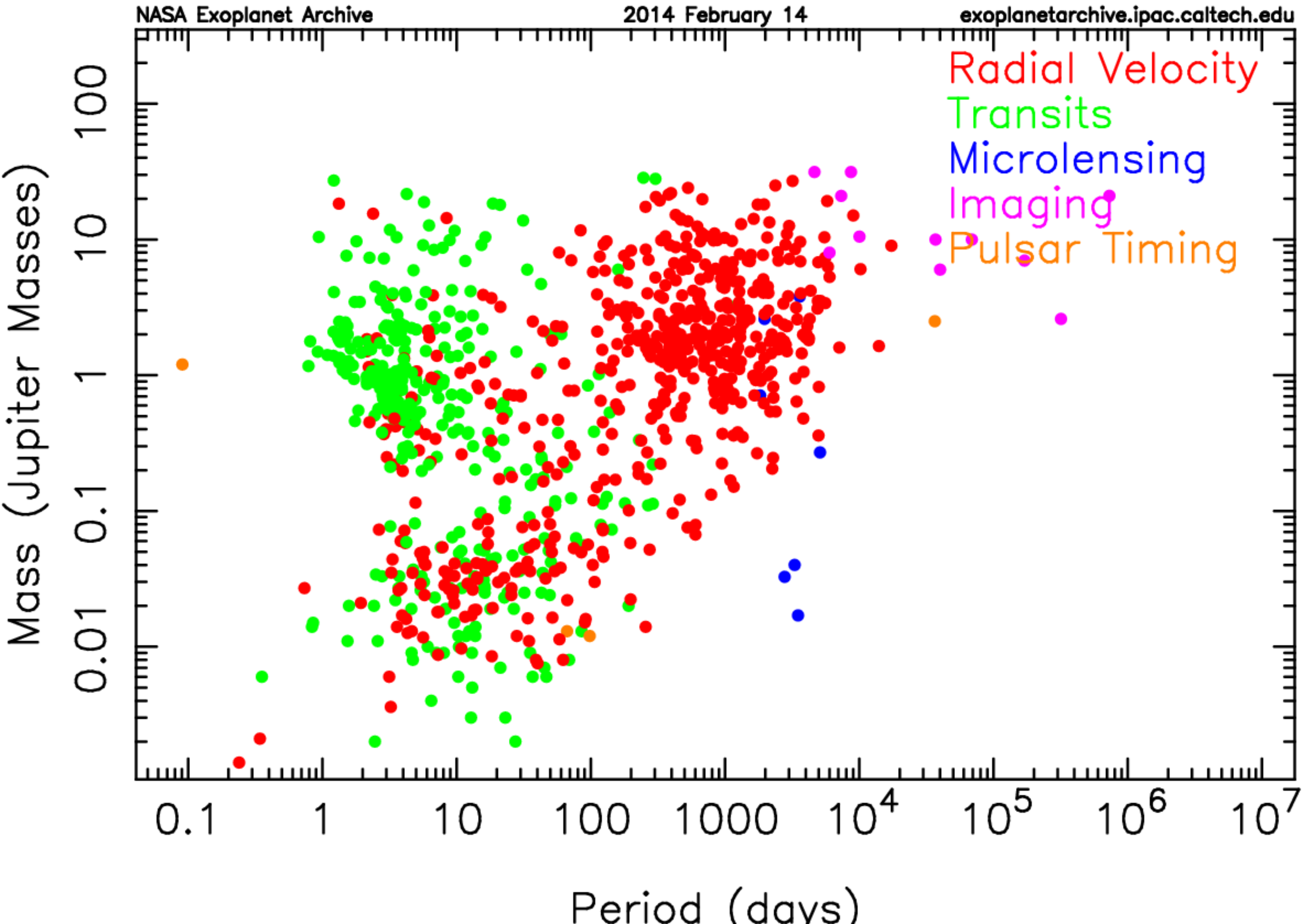
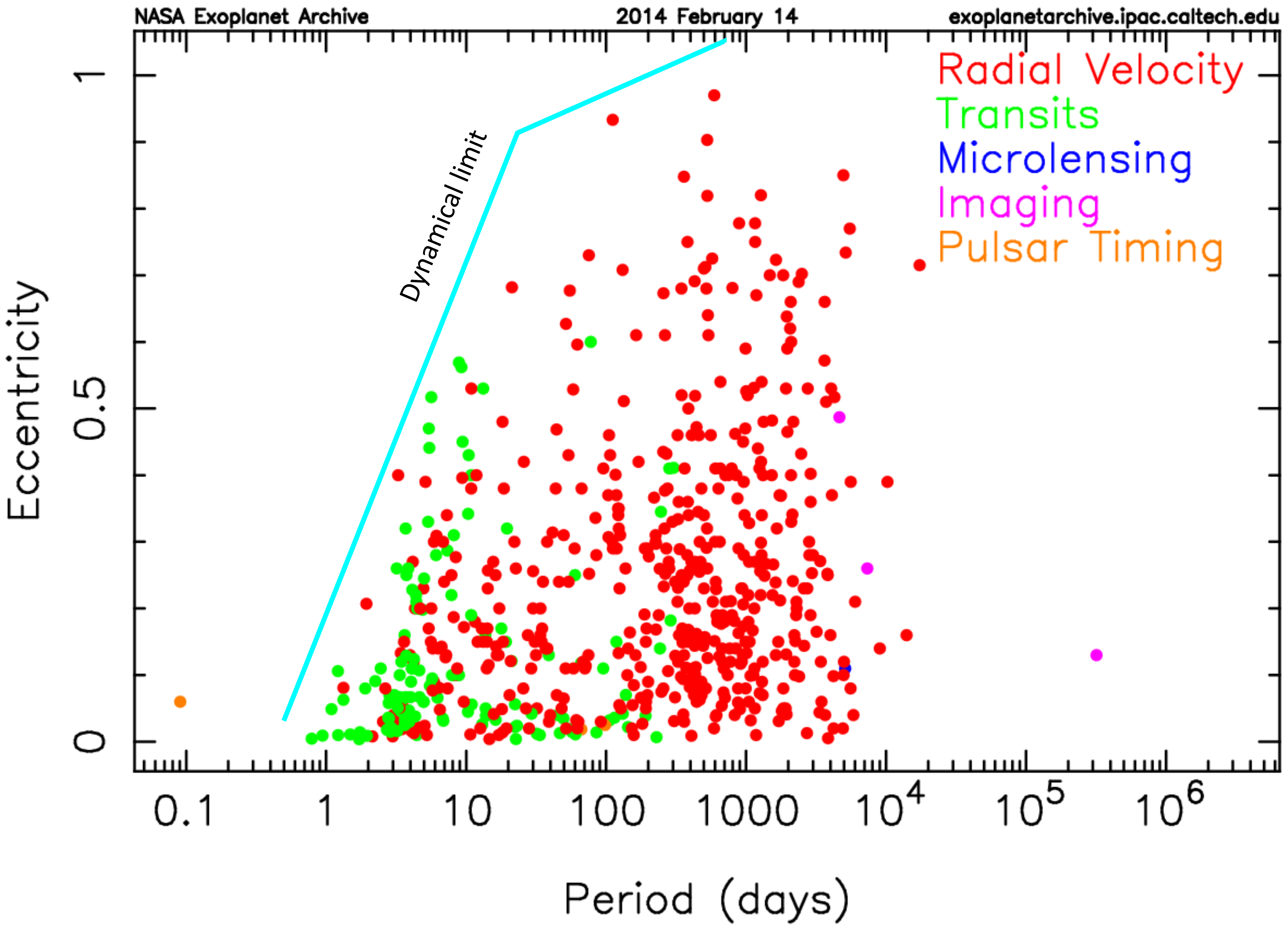
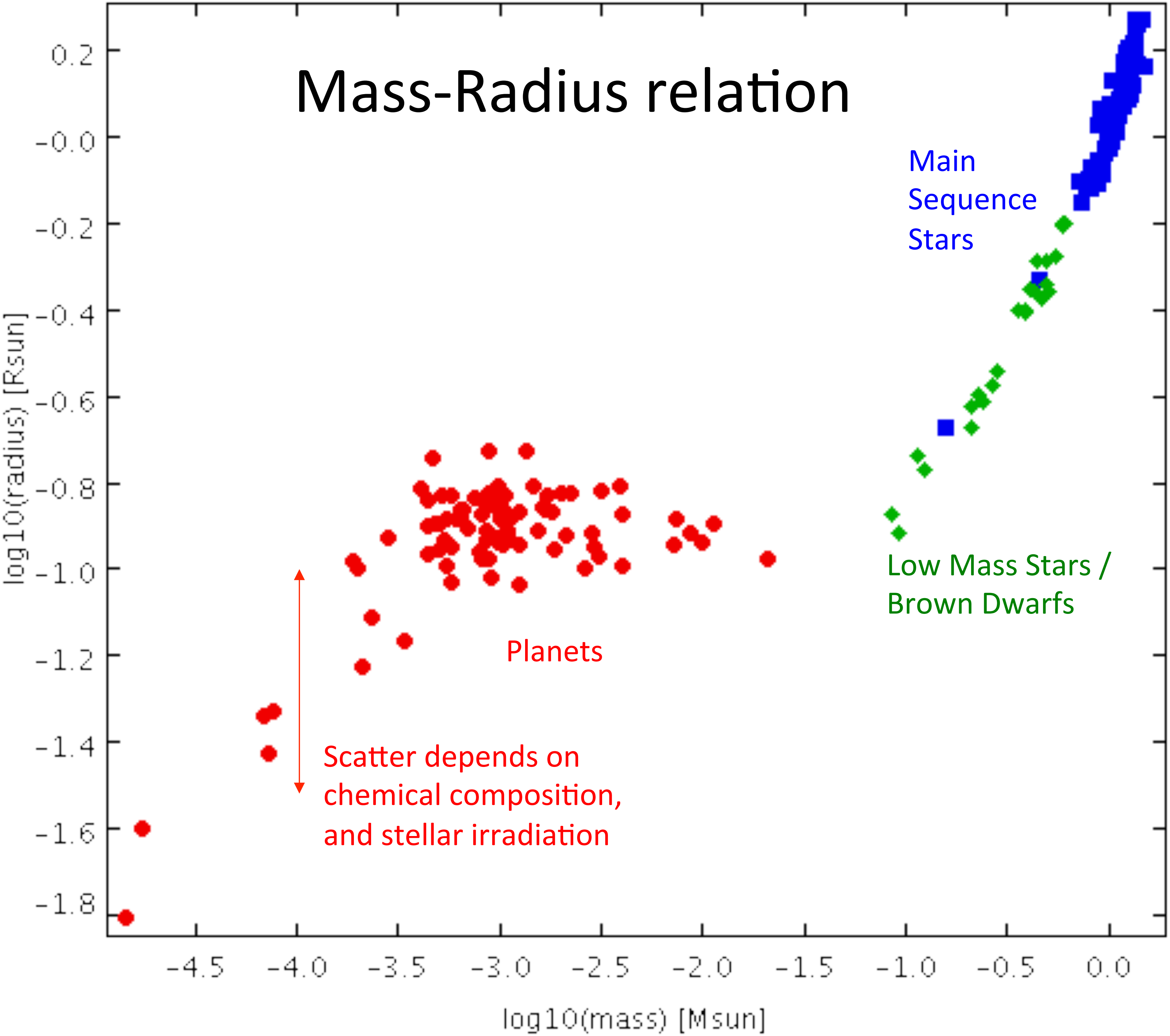
22
23
24
radius (Earth radii)
Kepler candidate planets
Transiting planets


NASA Exoplanet Archive
2014 February 14
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Pulsar Timing
Mass (Jupiter Masses)
100
10
1
0.1
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
Period (days)

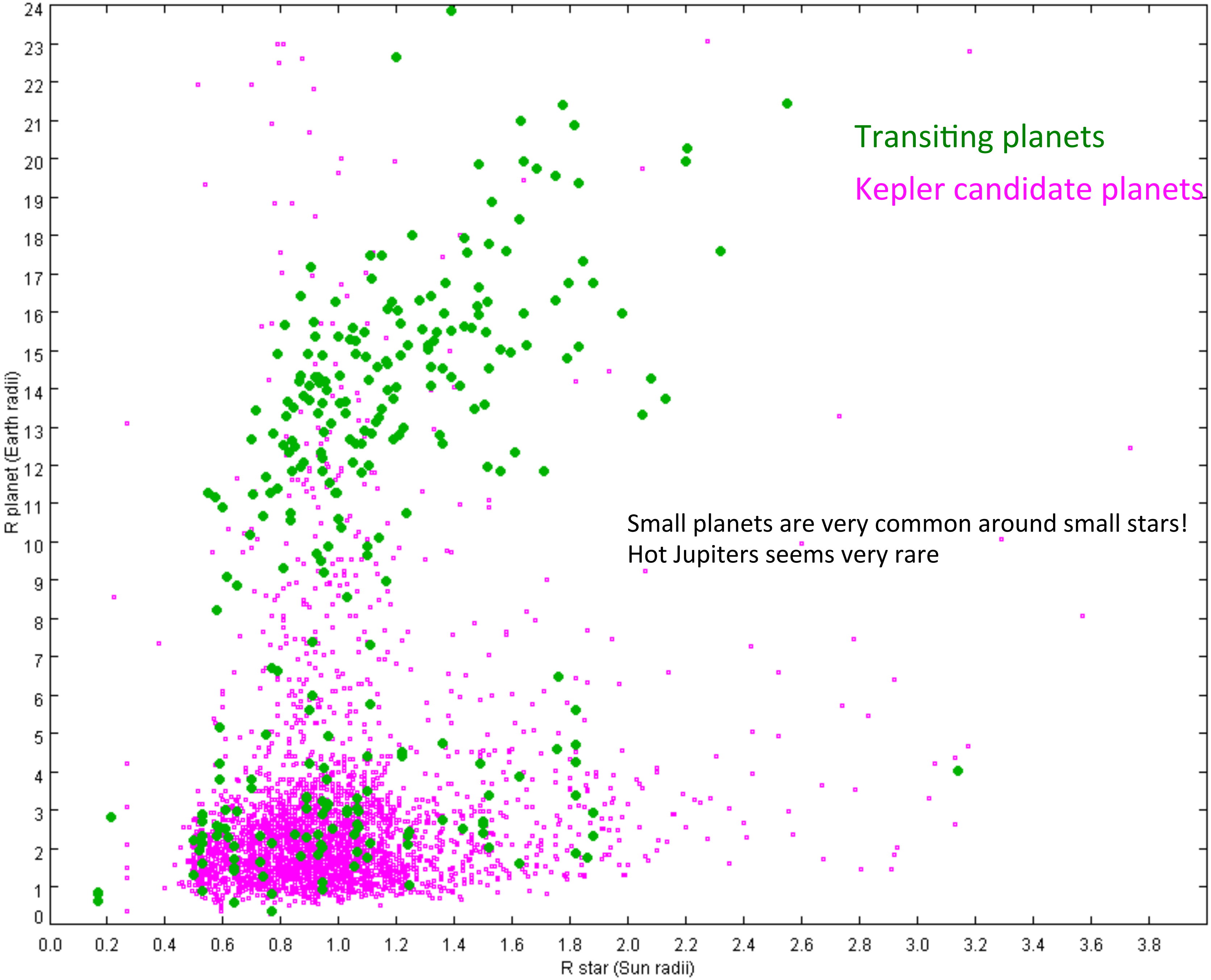

NASA Exoplanet Archive
2014 February 14
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Pulsar Timing
Dynamical limit
Eccentricity
0
0.5
1
Period (days)
0.1
1
10
100
1000
10^4
10^5
10^6

Mass-Radius relation



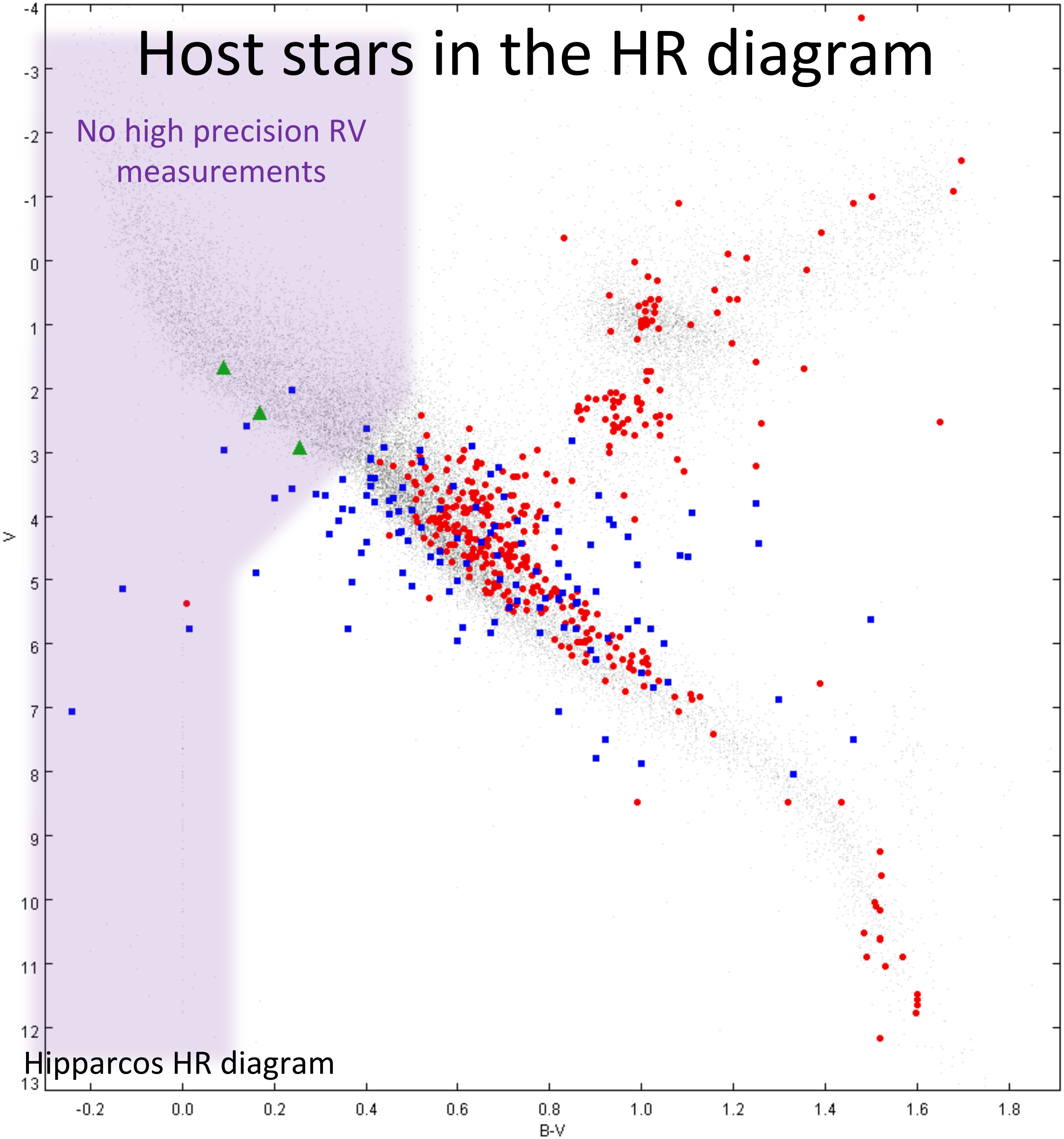
Scatter depends on chemical composition, and stellar irradiation

Planet radius against Stellar radius



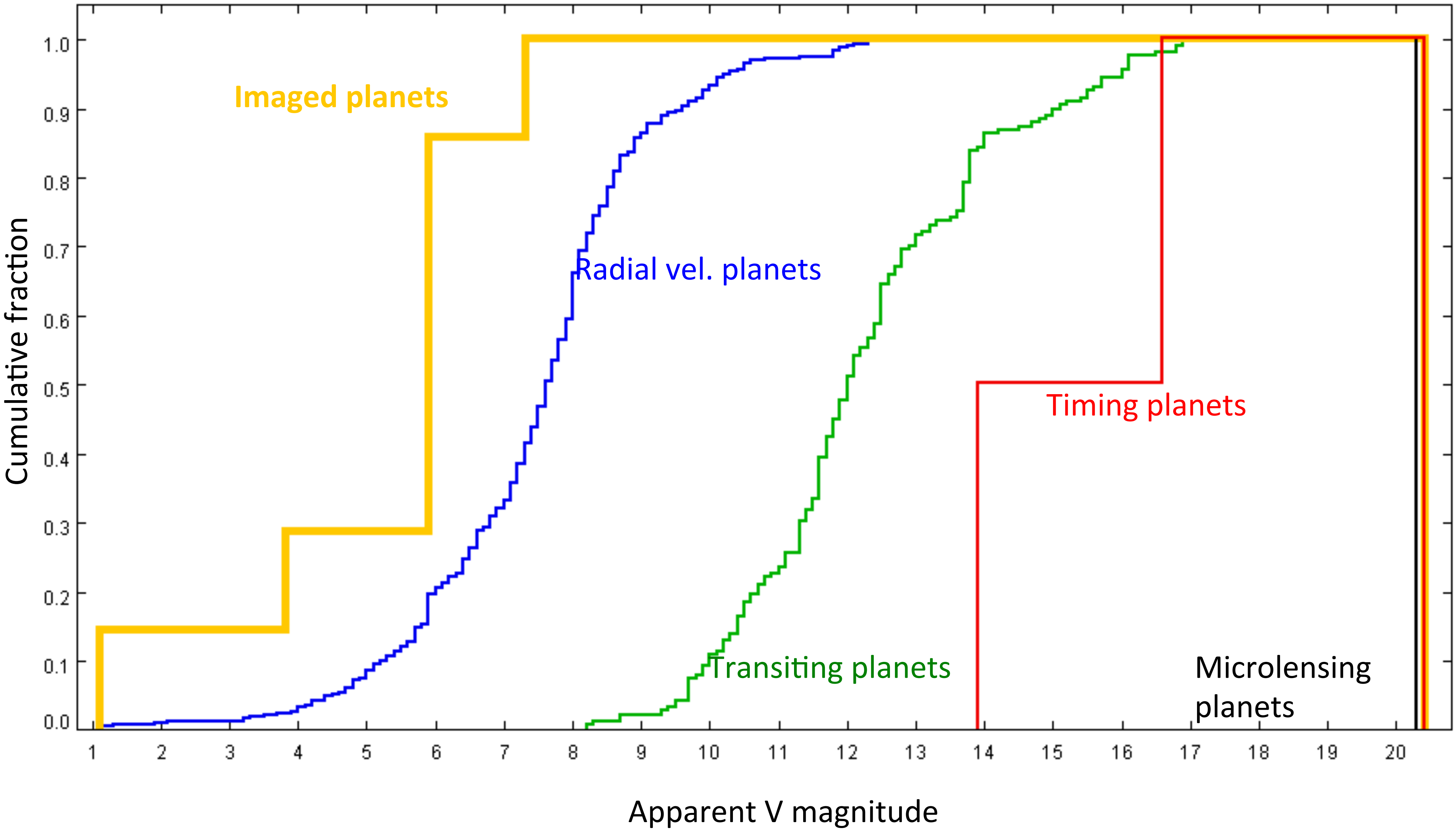
Small planets are very common around small stars!
Hot Jupiters seems very rare

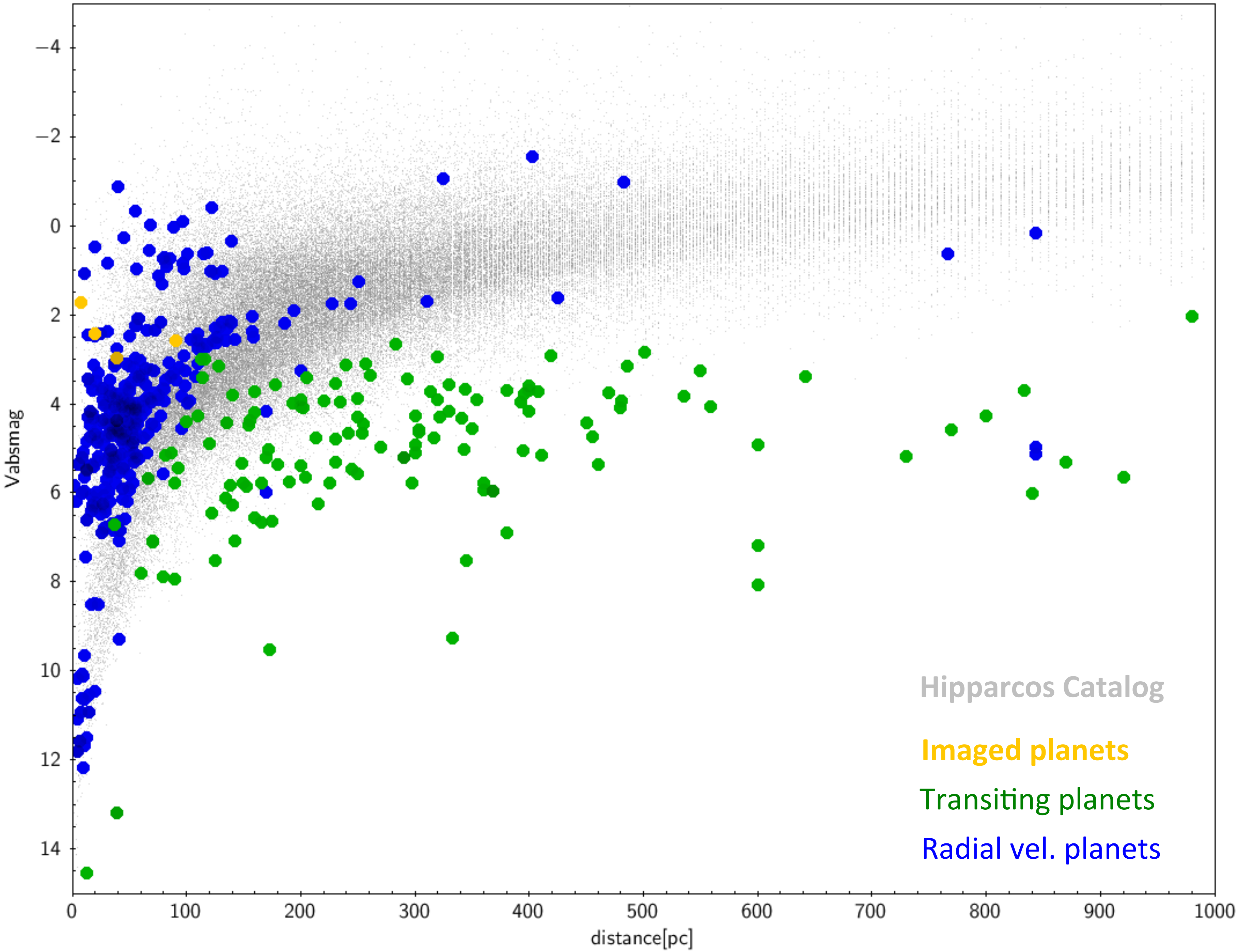
Host stars in the HR diagram


No high precision RV measurements

Hipparcos HR diagram

Apparent magnitude





−4
−2
0
2
4
6
8
10
12
14
Vabsmag
0
100
200
300
400
500
600
700
800
900
1000
distance[pc]
Hipparcos Catalog
Imaged planets
Transiting planets
Radial vel. planets

Oxygen concentration in Earth atmosphere