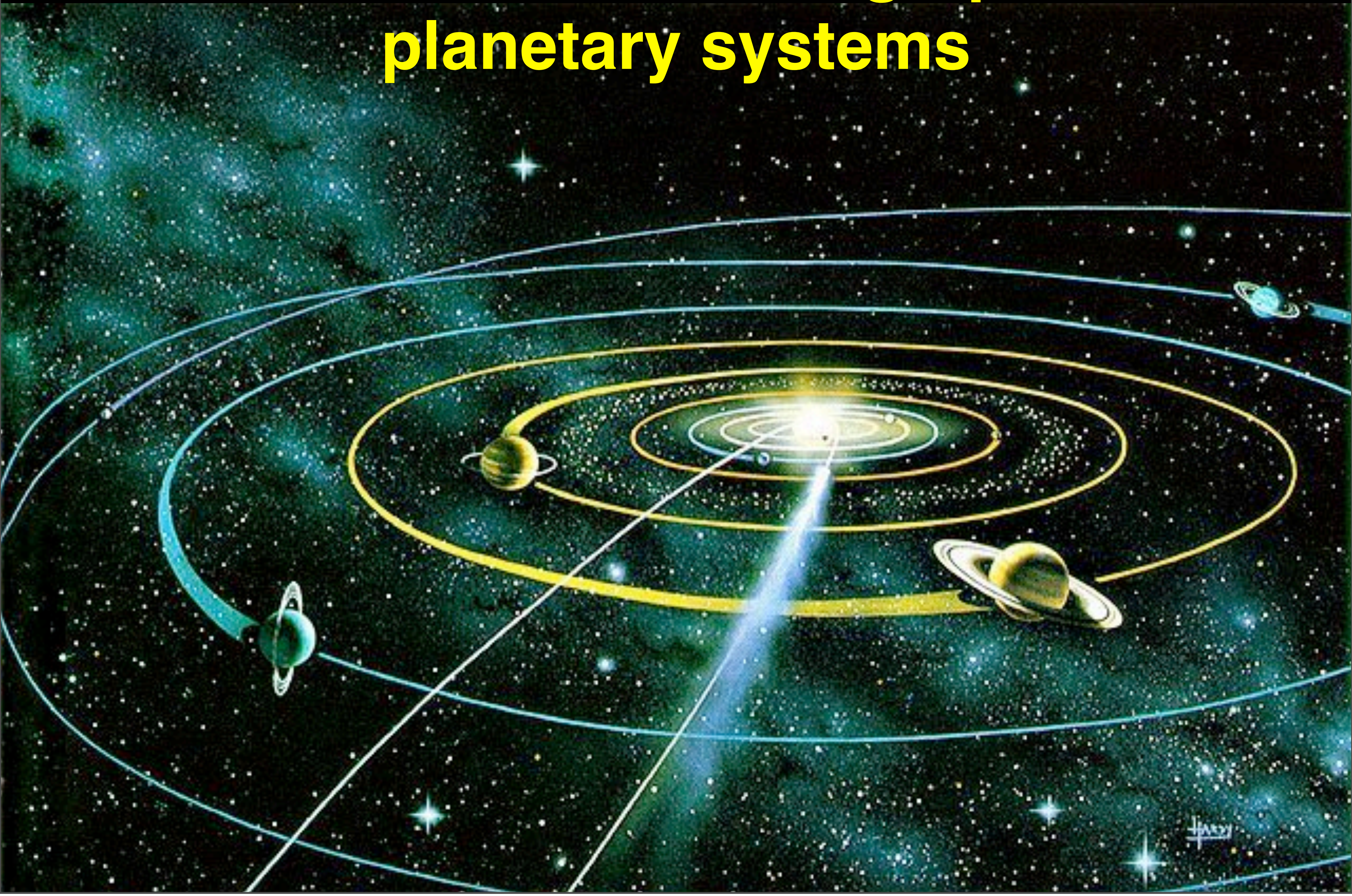
Architecture and demographics of planetary systems



Struve (1952)

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.

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.

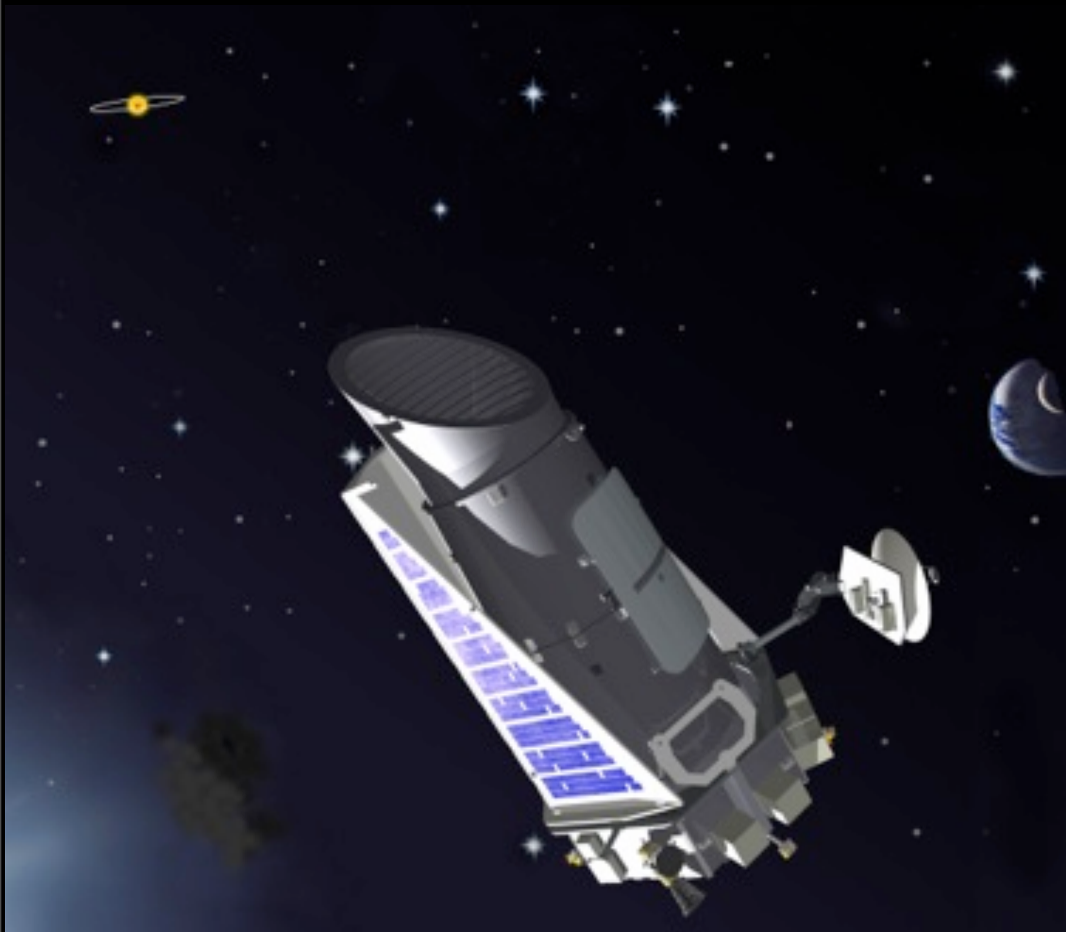
There would, of course, also be eclipses. Assuming that the mean density of the planet is five times that of the star (which may be optimistic for such a large planet) the projected eclipsed area is about 1/50th of that of the star, and the loss of light in stellar magnitudes is about 0·02. This, too, 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.

The demography of the planets that we detect is strongly affected by

- detection methods
- psychology of the observer

Understanding planet demography requires multiple detection methods:

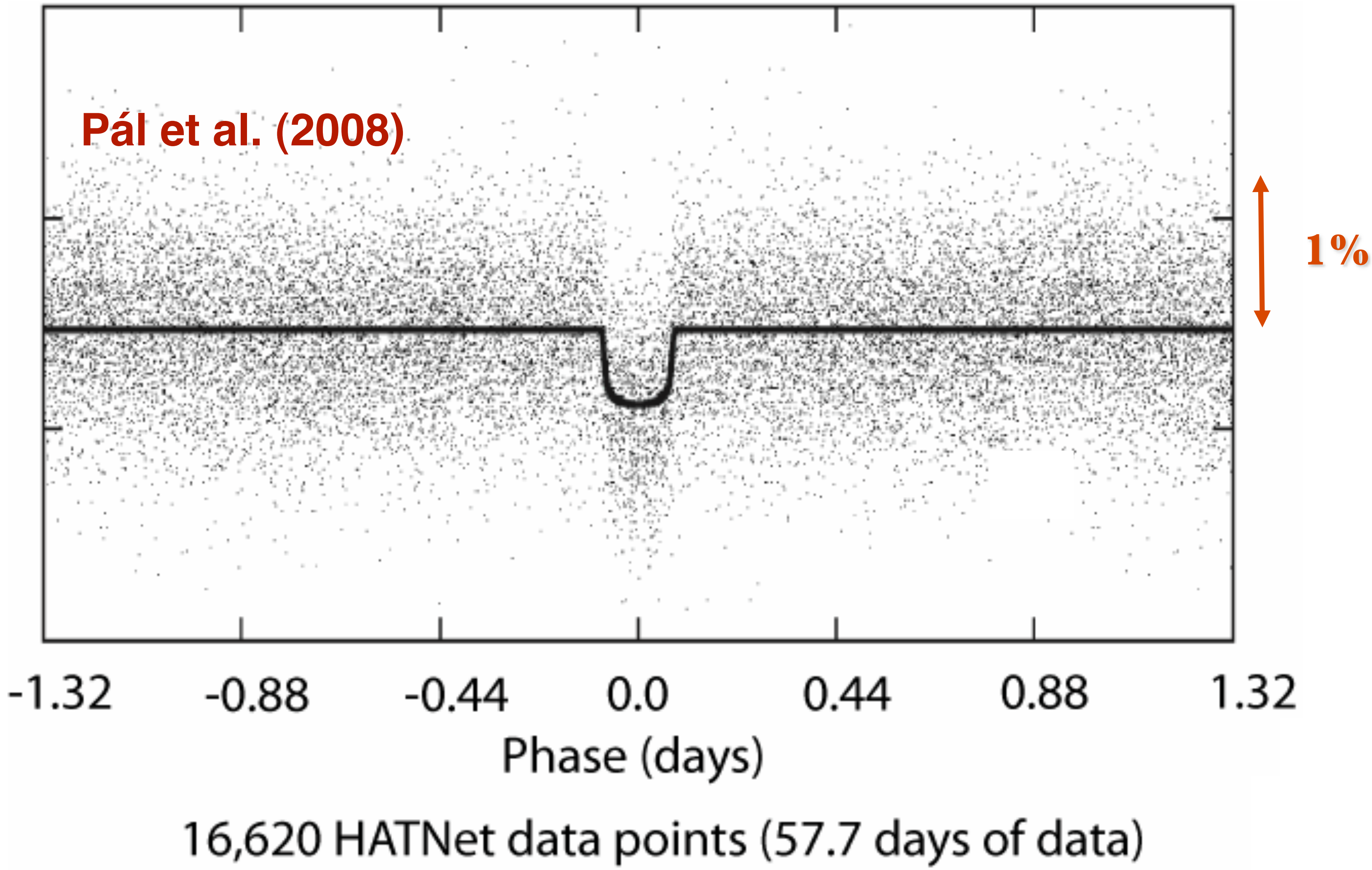
- radial velocities
- transits ←
- gravitational lensing ←
- direct imaging
- astrometry

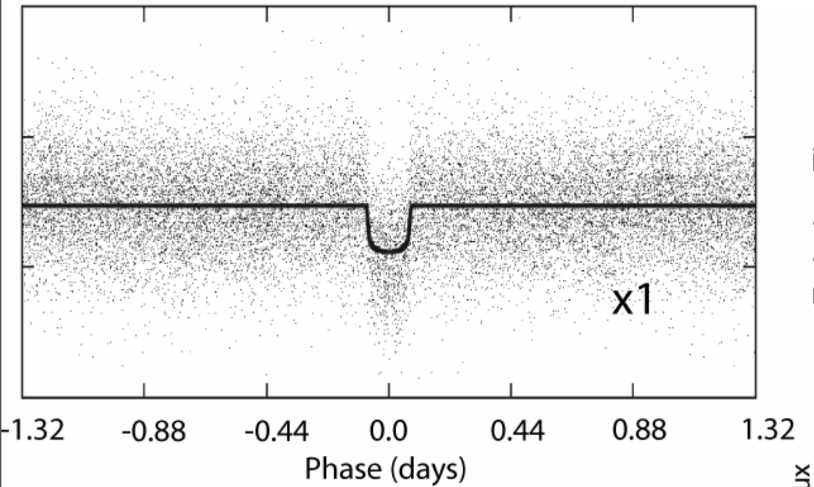


Kepler

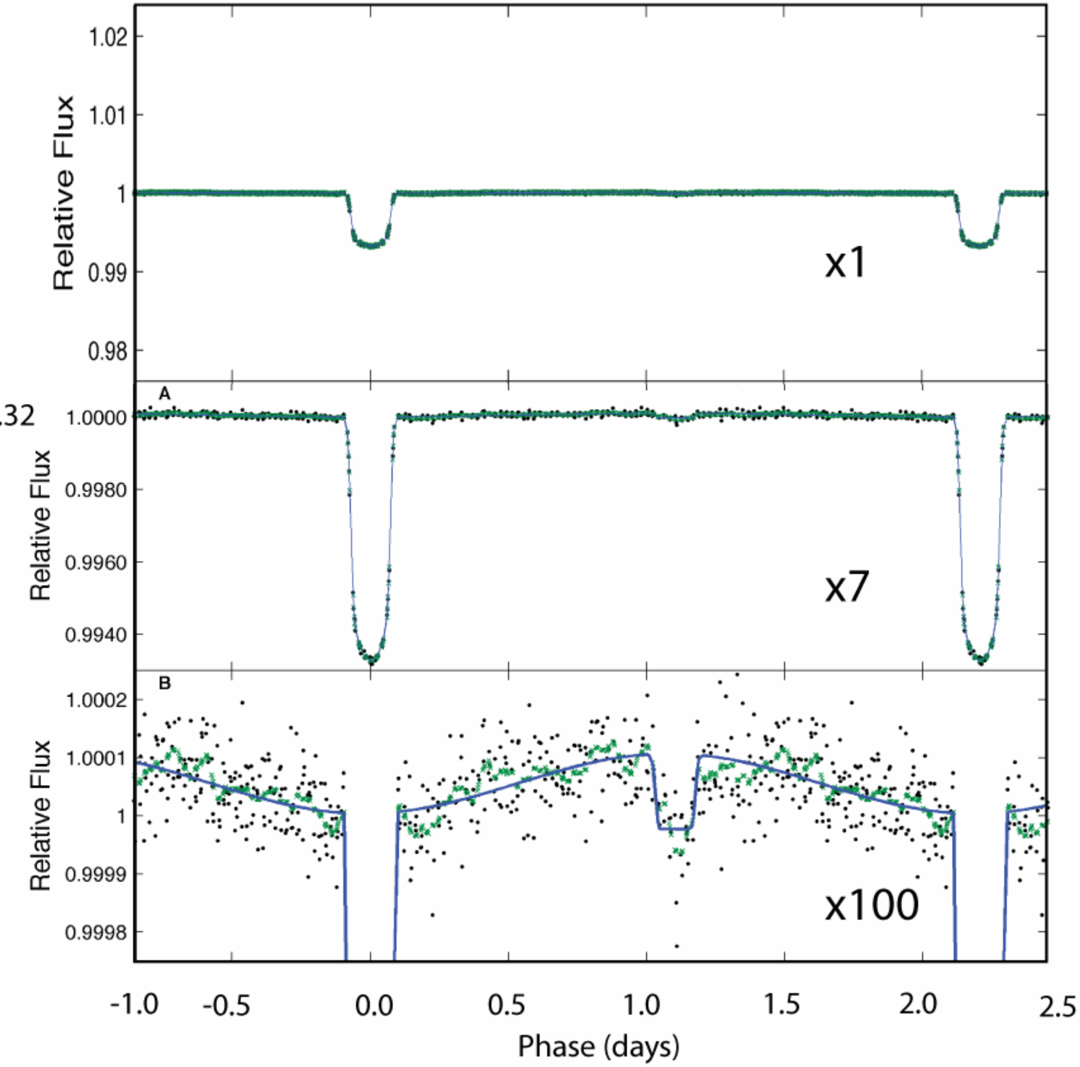
- launch March 6 2009
- 0.95 meter mirror, 100 megapixel camera, 12 degree diameter field of view
- monitor ~10^5 stars continuously over ~6 yr mission
- 30 parts per million photometric precision

fractional brightness dip: Jupiter 0.01 = 1%
Earth 0.0001=0.01%

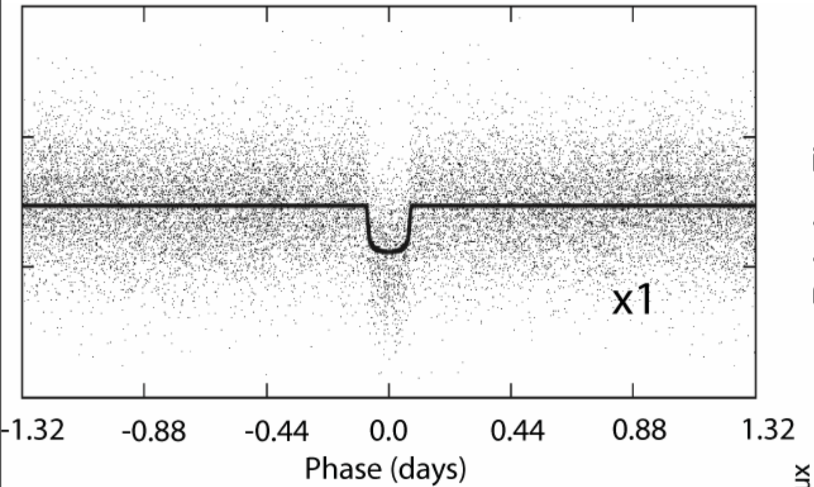




16,620 HATNet data points (57.7 days of data)



Kepler Commissioning data (10 days)



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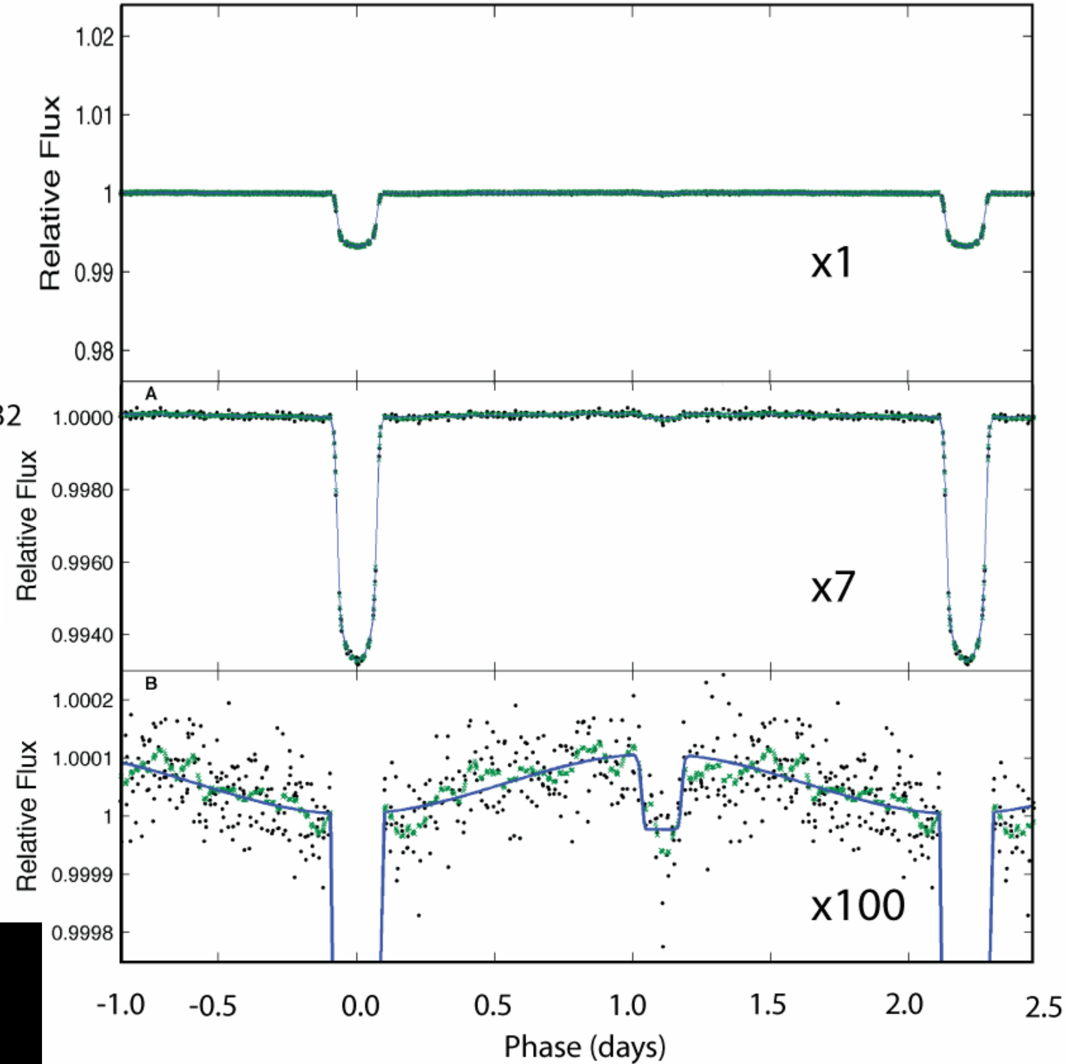

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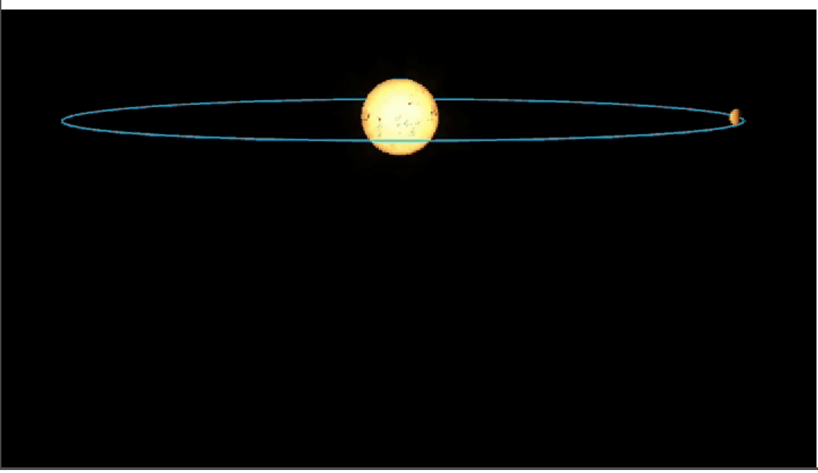


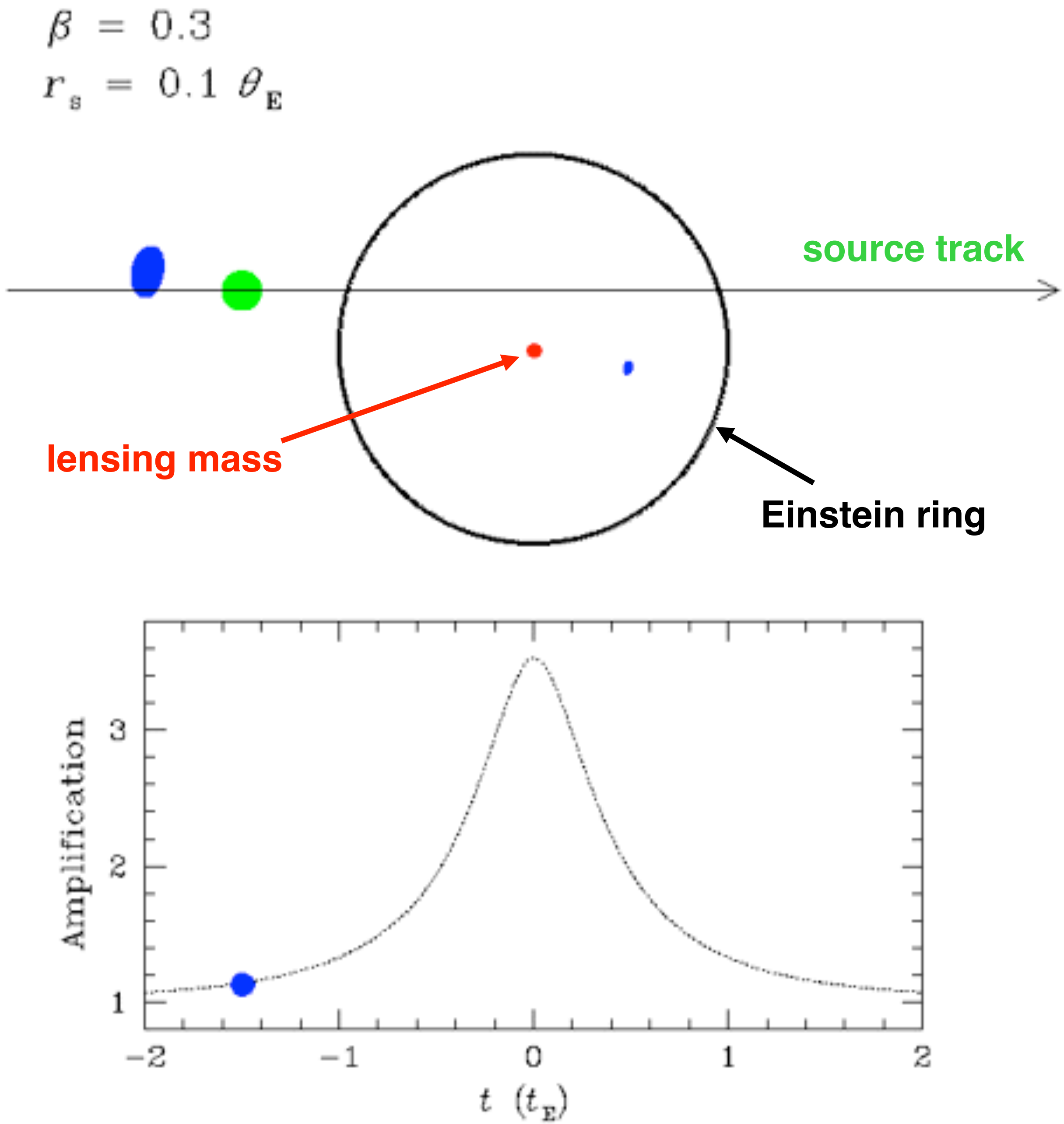
Gravitational lensing

the gravitational field from the lensing star:

- splits image into two
- magnifies one image and demagnifies the other
- if source, lens and observer are exactly in line the image appears as an Einstein ring

currently about 20 planets have been detected by lensing

Gravitational lensing



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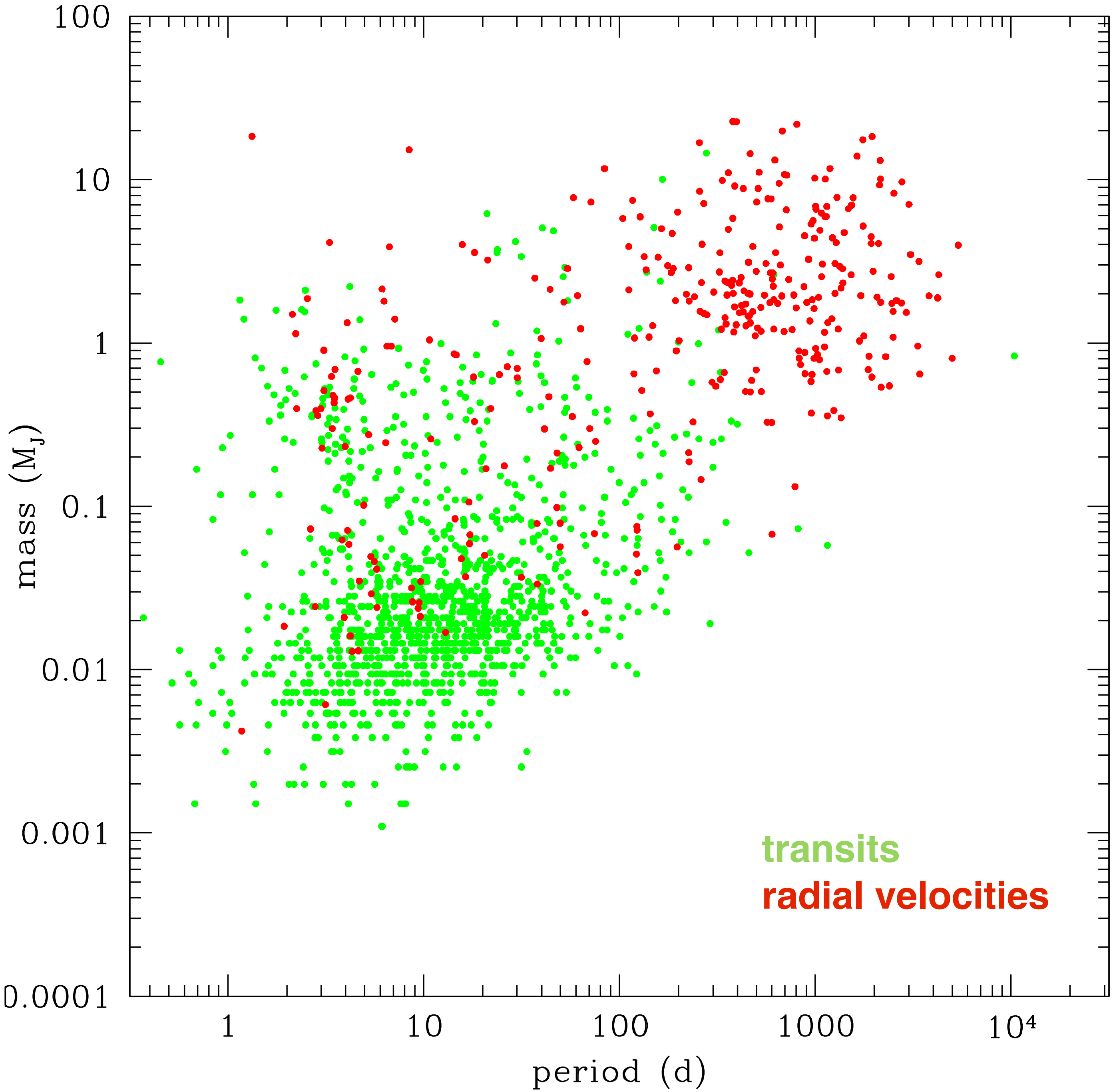

100
10
1
0.1
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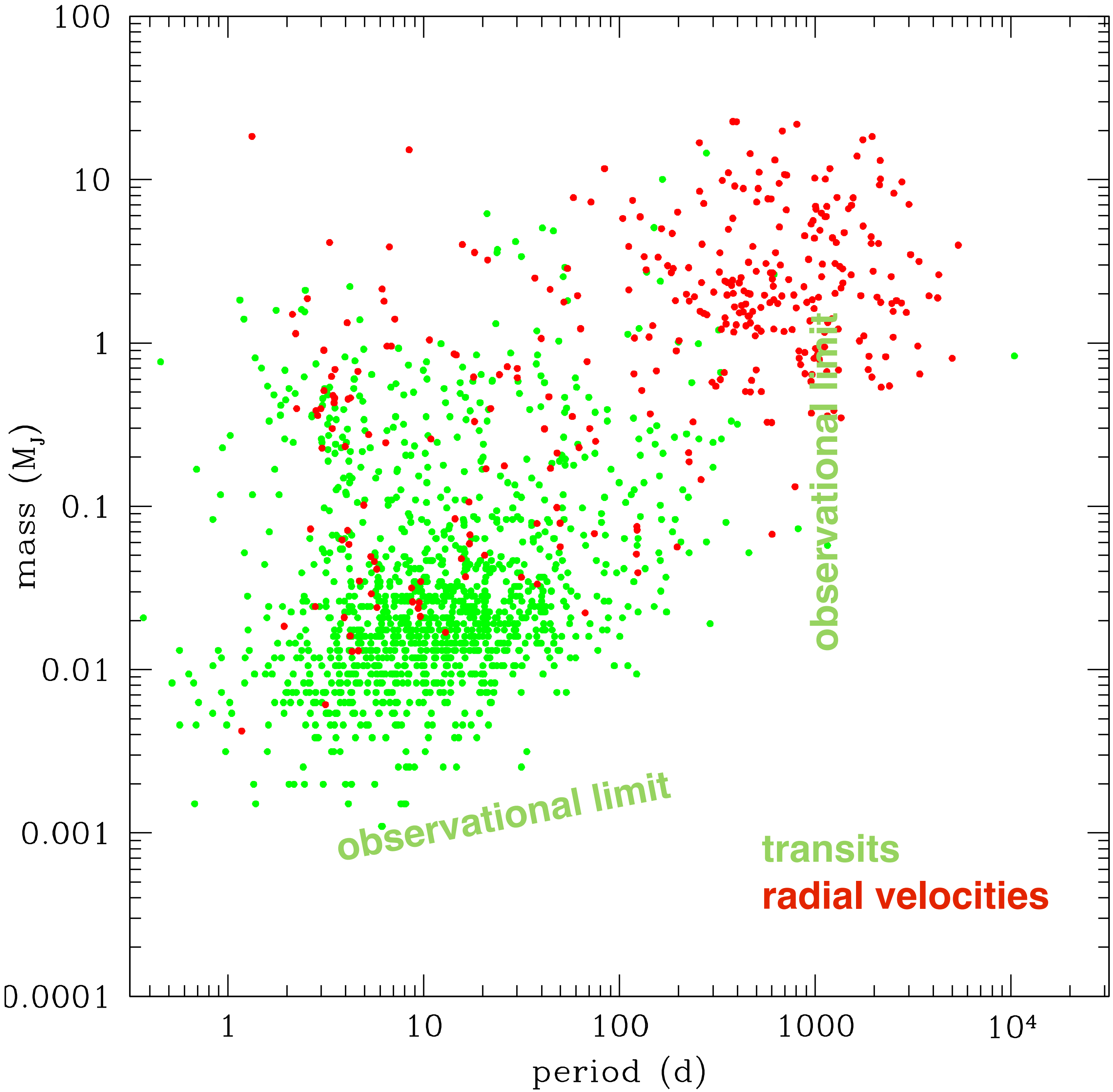
mass (M_J)
1
10
100
1000
10^4
period (d)
transits
radial velocities


100
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mass (M_J)
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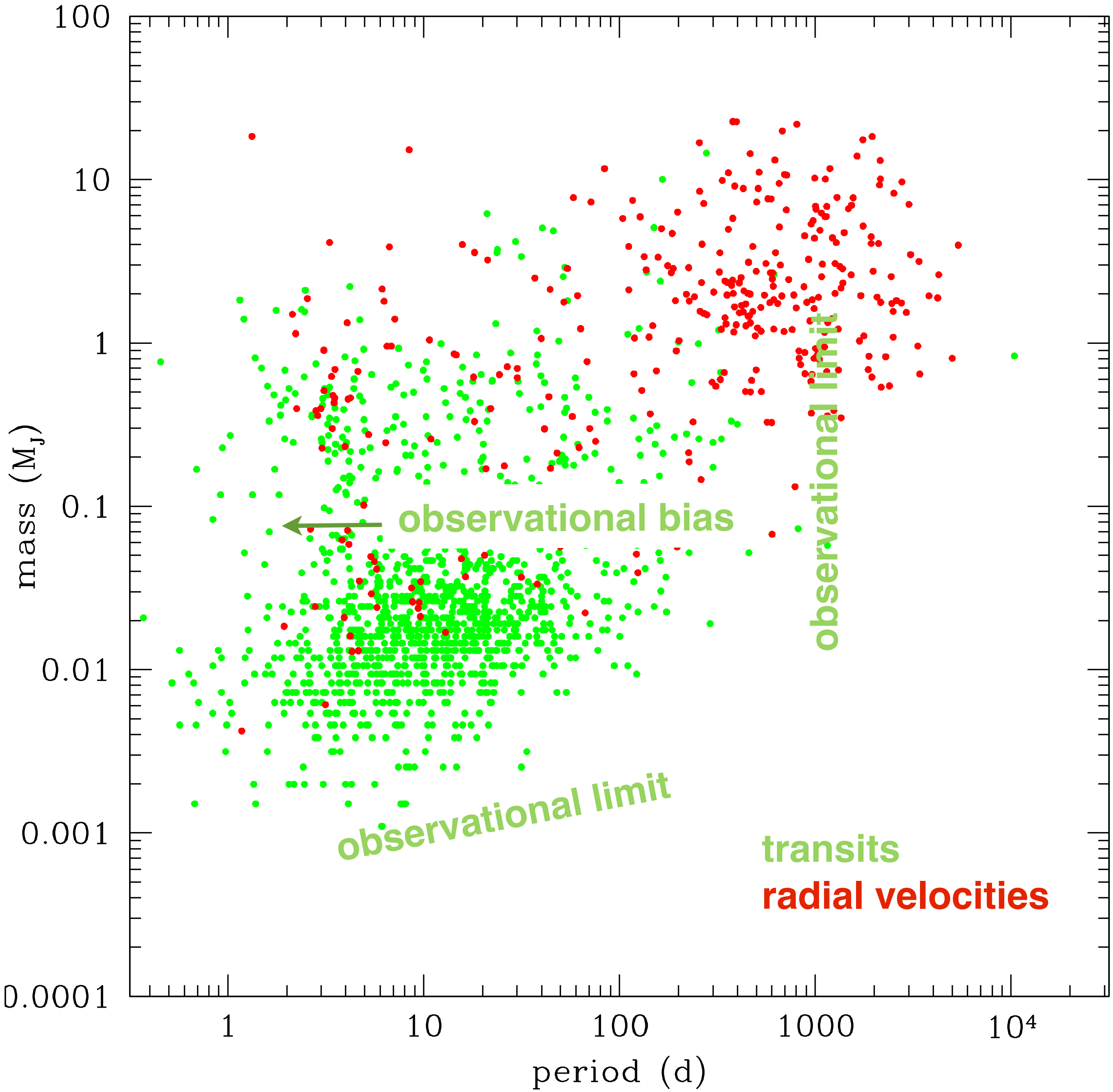
period (d)
observational limit
observational limit
transits
radial velocities


100
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mass (M_J)
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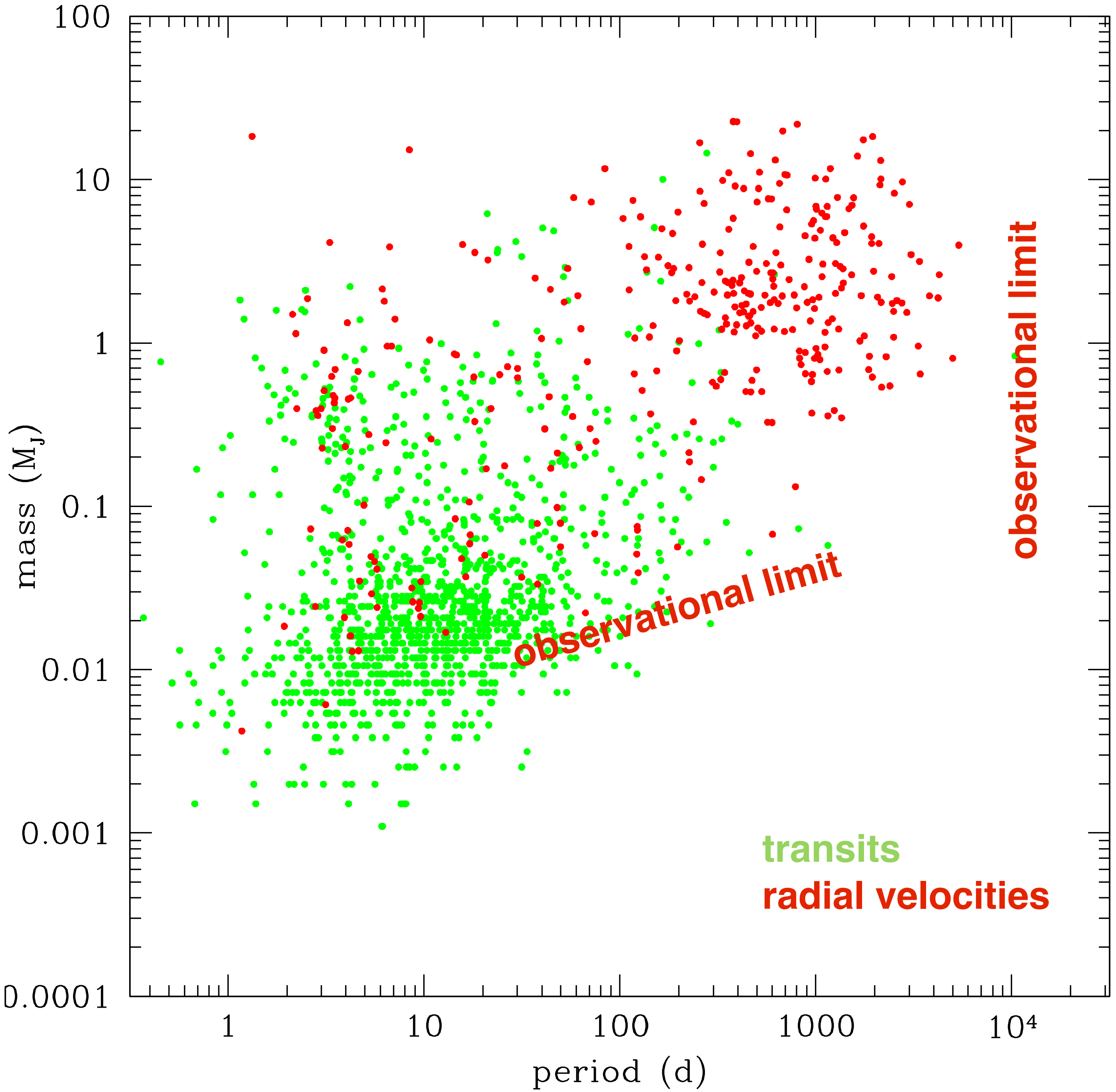
10^4
period (d)
observational bias
observational limit
observational limit
transits
radial velocities


100
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mass (M$_J$)
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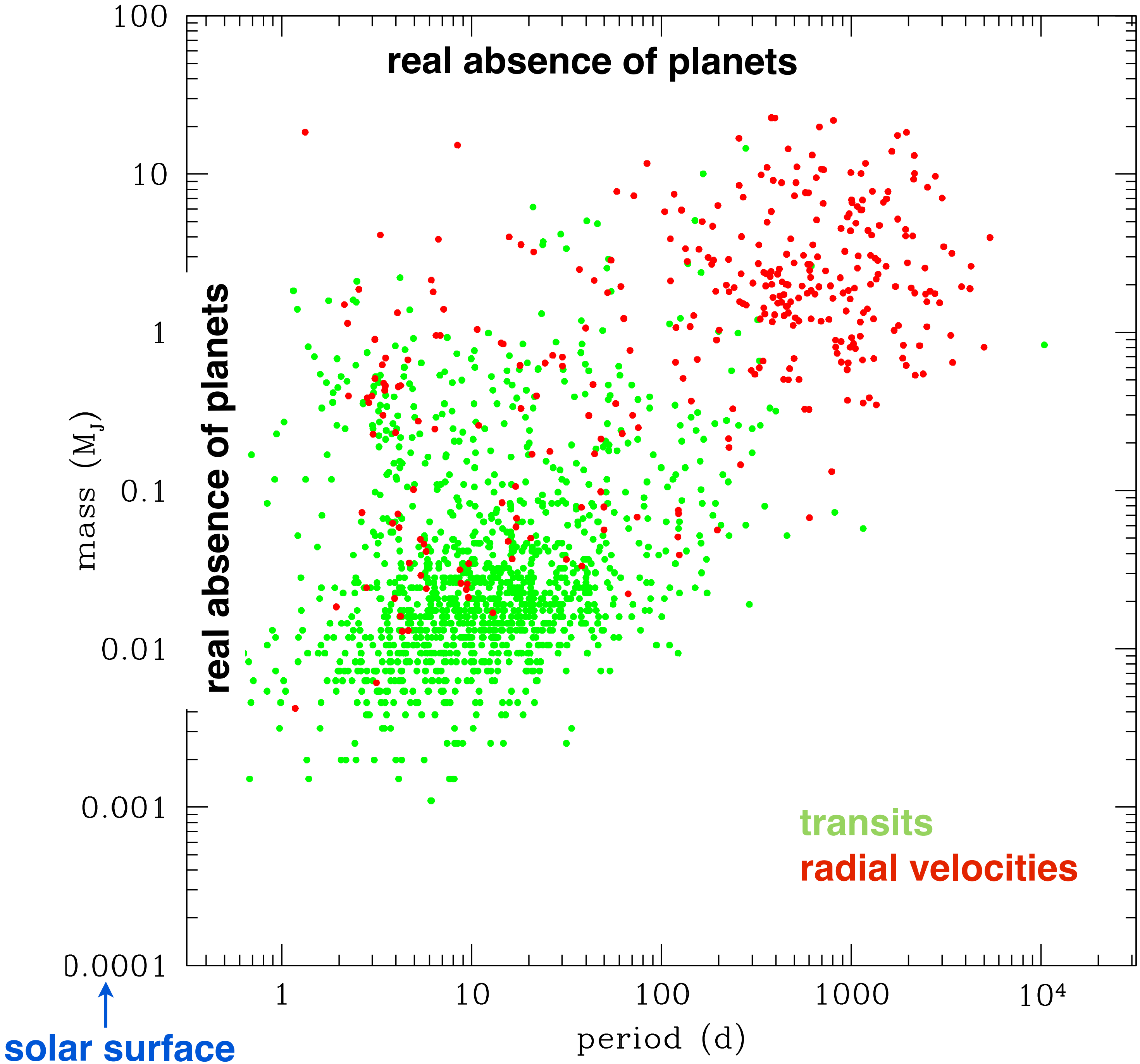
10^4
period (d)
observational limit
observational limit
transits
radial velocities



real absence of planets
real absence of planets
100
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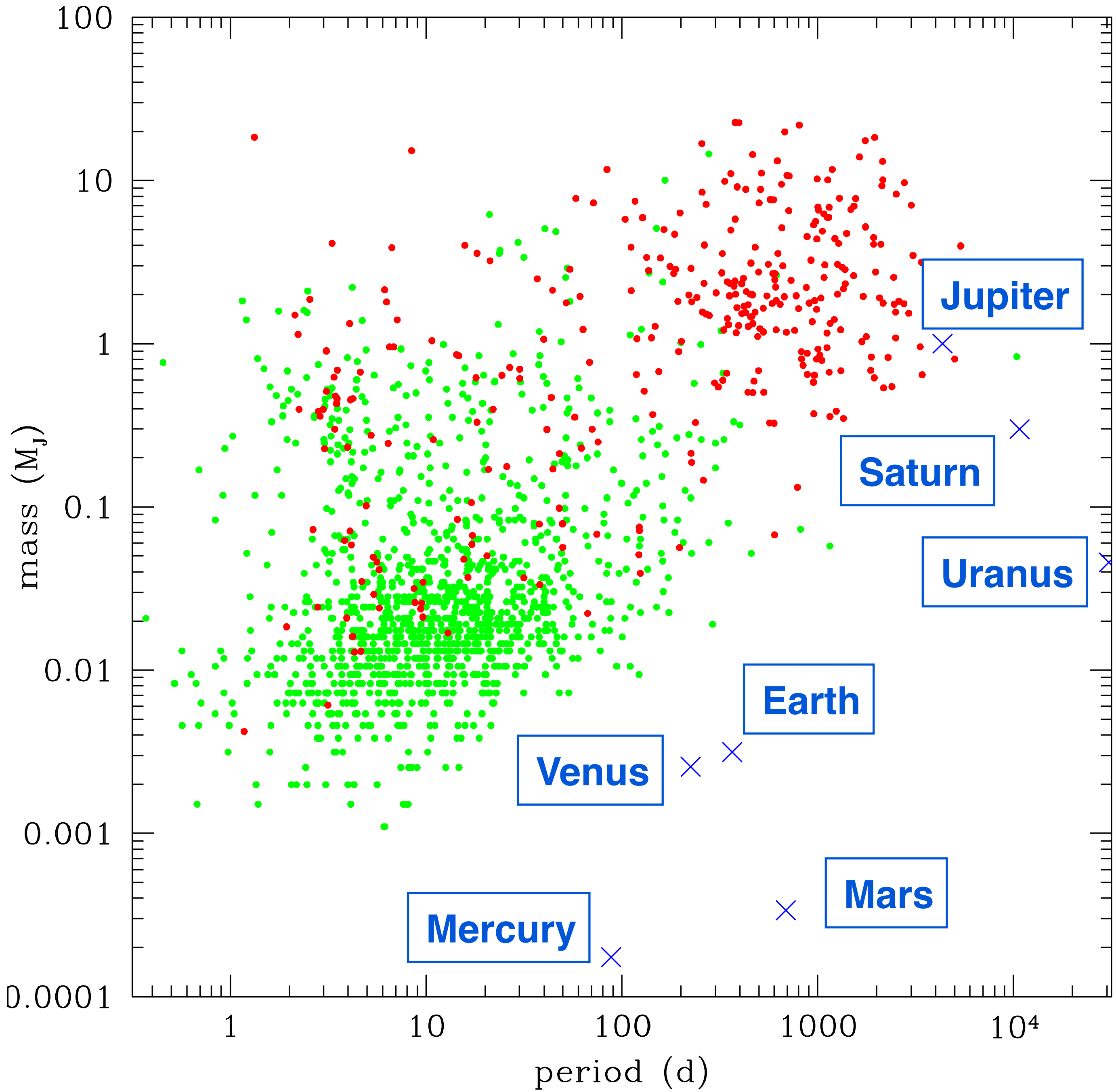
mass (M$_J$)
1
10
100
1000
10^4
period (d)
transits
radial velocities
solar surface



100
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1
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0.001
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mass (M_J)
1
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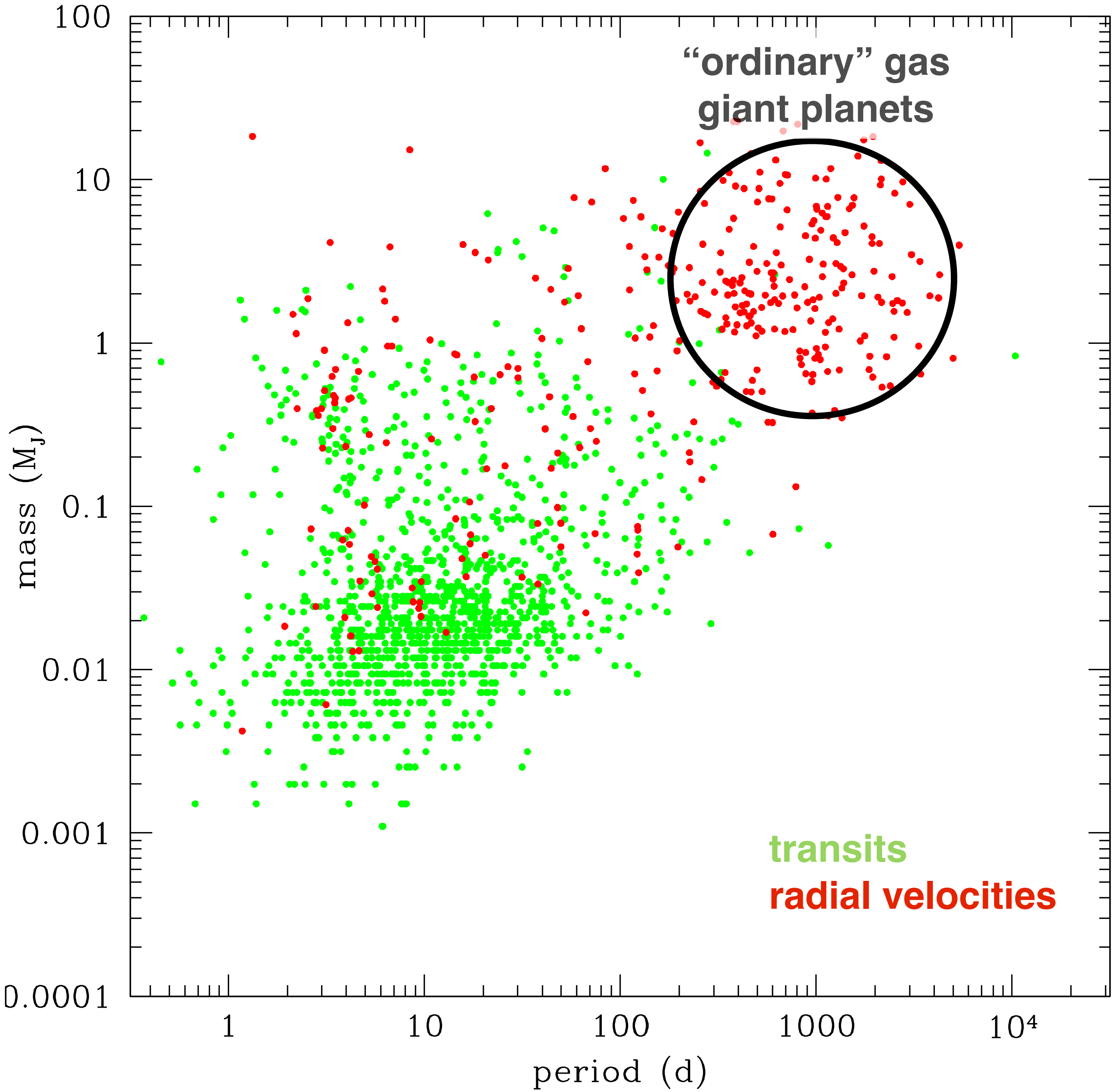
100
1000
10^4
period (d)
Jupiter
Saturn
Uranus
Earth
Venus
Mars
Mercury



"ordinary" gas
giant planets
transits
radial velocities
mass (M_J)
period (d)
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0.01
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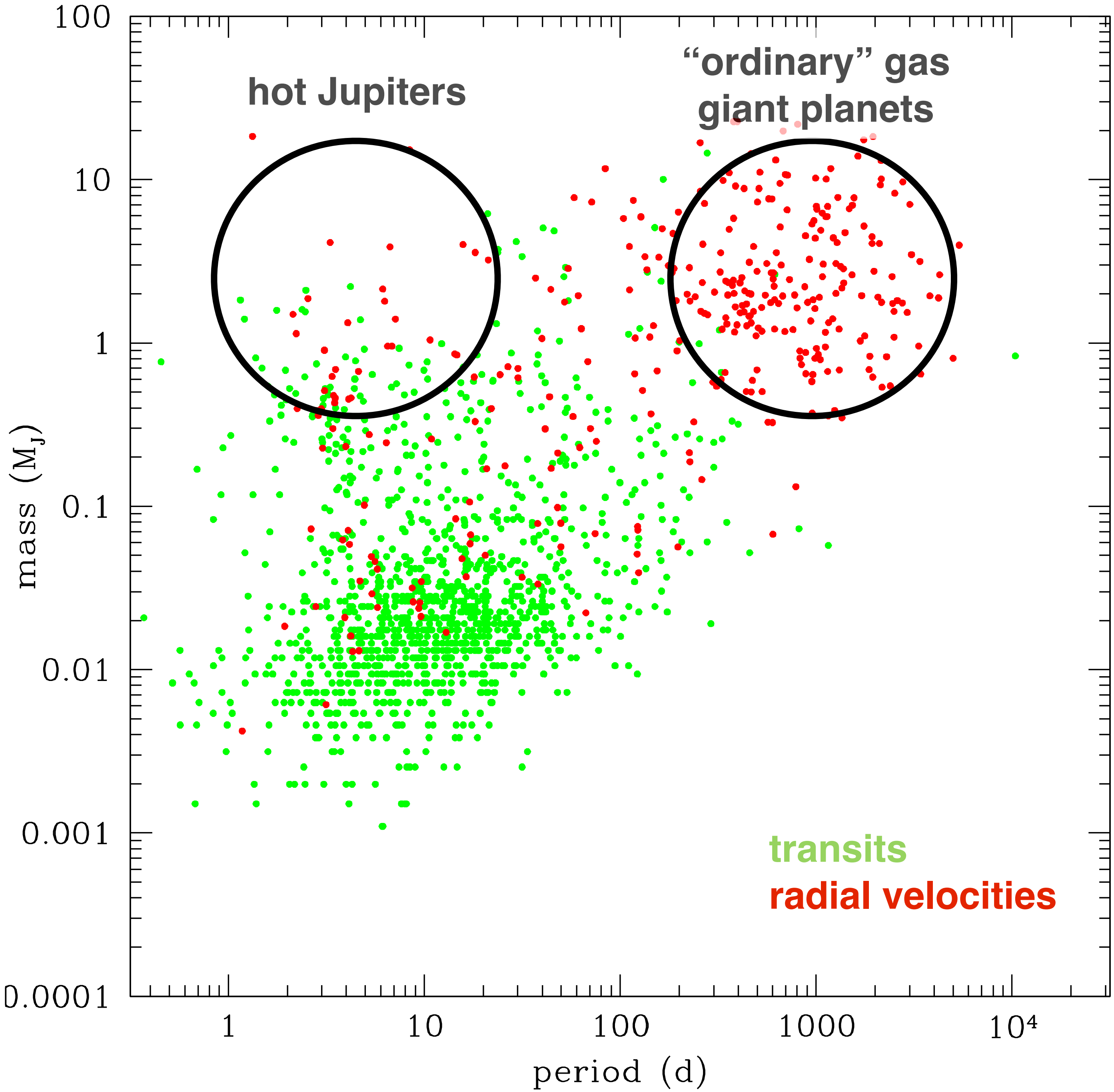
100
1000
10^4



hot Jupiters
"ordinary" gas giant planets
transits
radial velocities
mass (M_J)
period (d)
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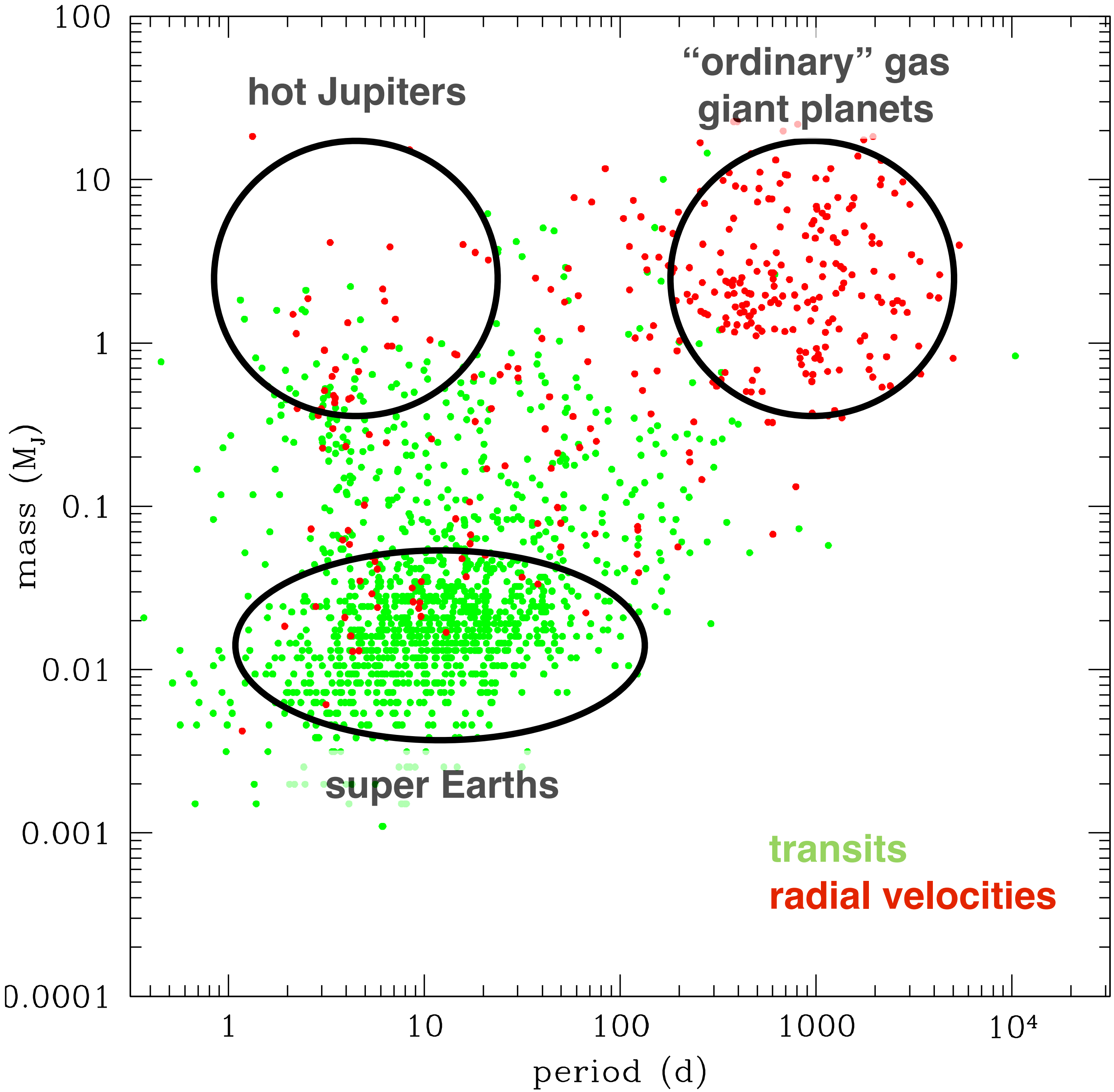
hot Jupiters
"ordinary" gas giant planets
super Earths
transits
radial velocities
mass (M_J)
period (d)
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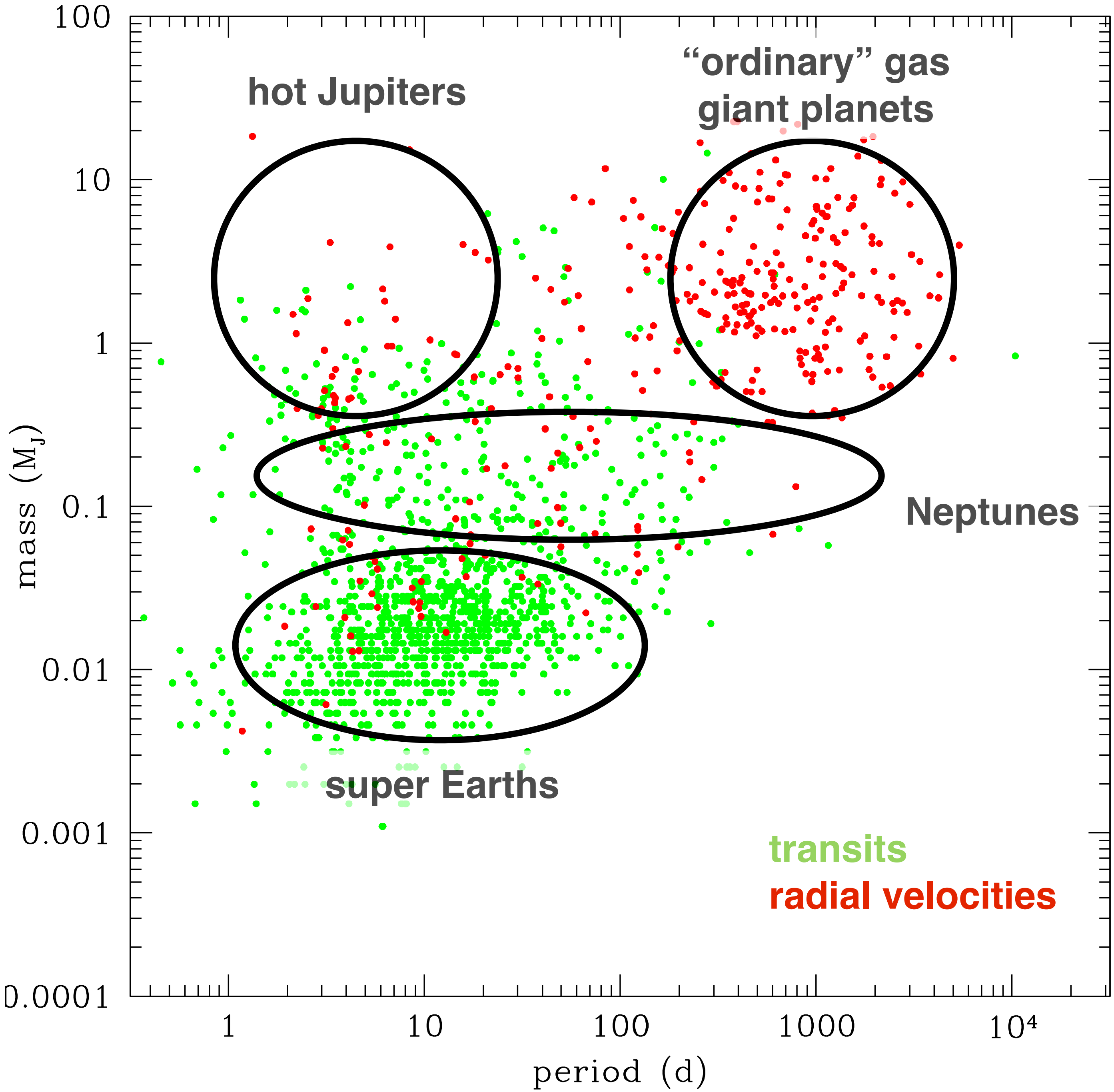

hot Jupiters
"ordinary" gas giant planets
Neptunes
super Earths
transits
radial velocities
mass (M_J)
period (d)
100
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0.0001
1
10
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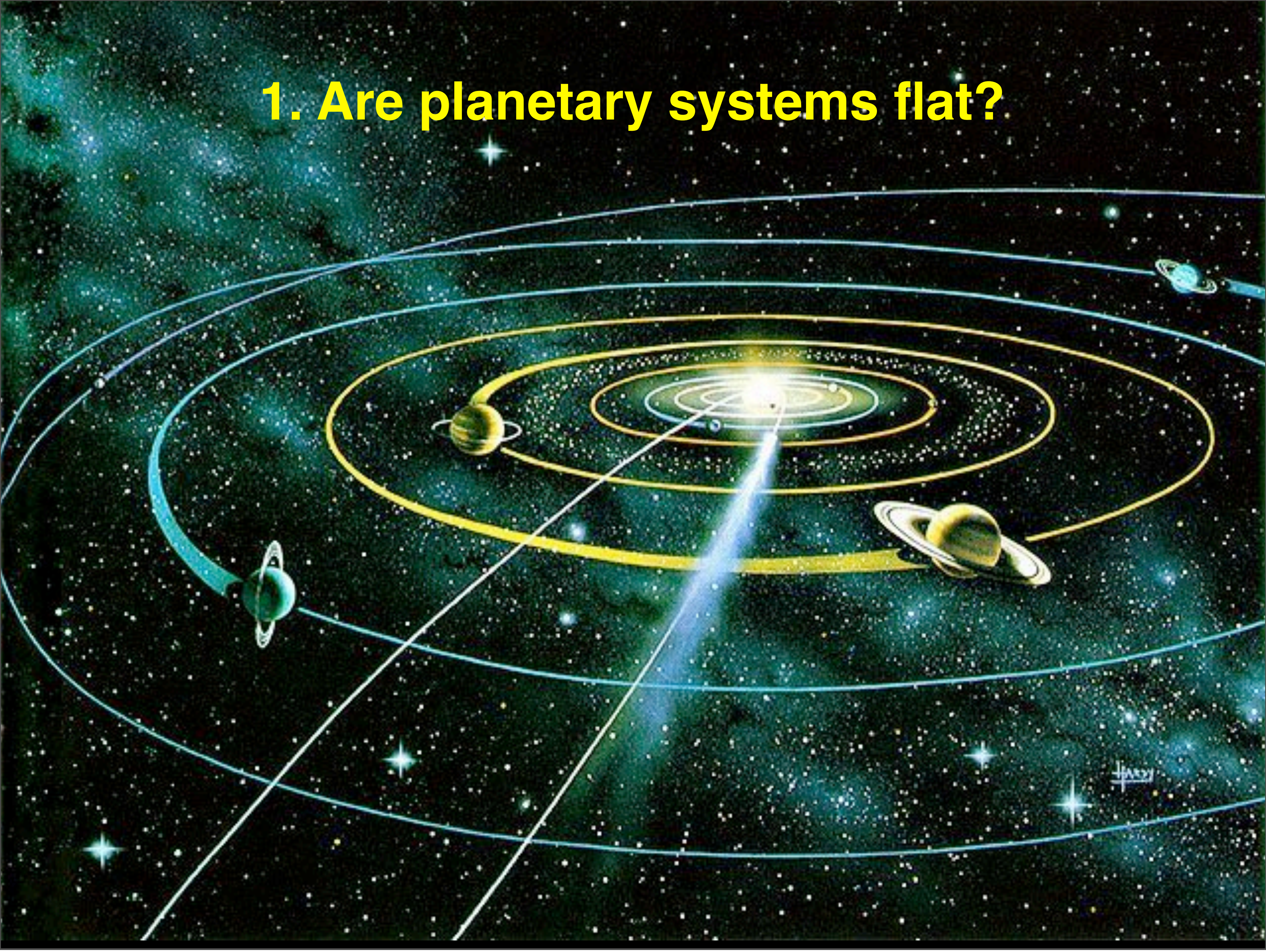
1000
10^4

Architecture and demographics of planetary systems

1. are planetary systems flat?
2. are there interstellar planets?
3. how common are planets?
4. is the solar system anomalous?

1. Are planetary systems flat?



Kepler has identified over 360 multi-planet systems (2- 6 transiting planets)

Flatness of Kepler planetary systems can be measured in two ways:

- compare the multiplicity distribution (fraction of systems with N planets) in radial-velocity surveys and *Kepler* survey; this comparison gives mean inclination < 6° (Tremaine & Dong 2012)
- compare transit durations in multi-planet *Kepler* systems; gives mean inclination between 1° and 2.5° (Fabrycky et al. 2012)
- for comparison the solar system has mean inclination 2.3°

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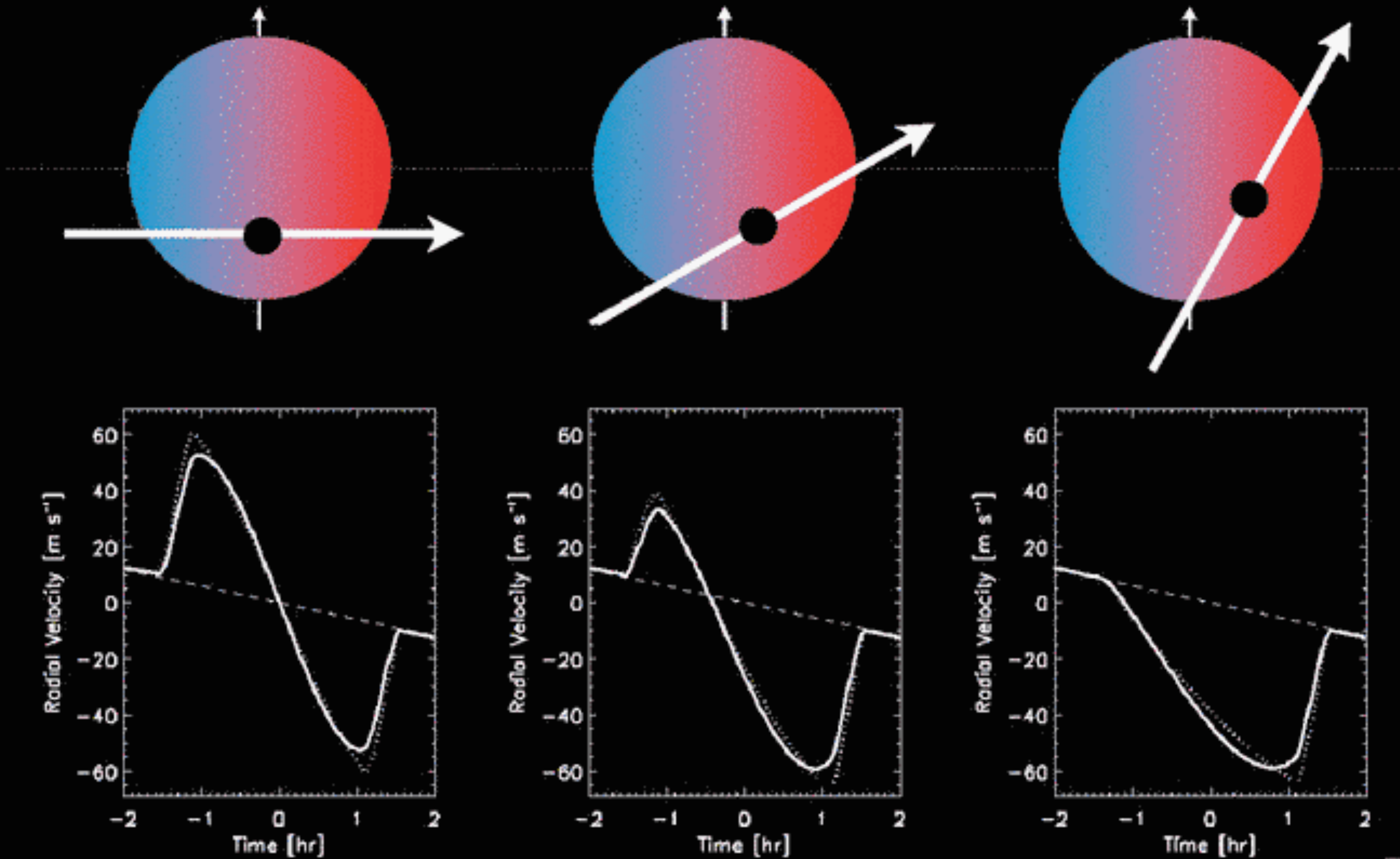
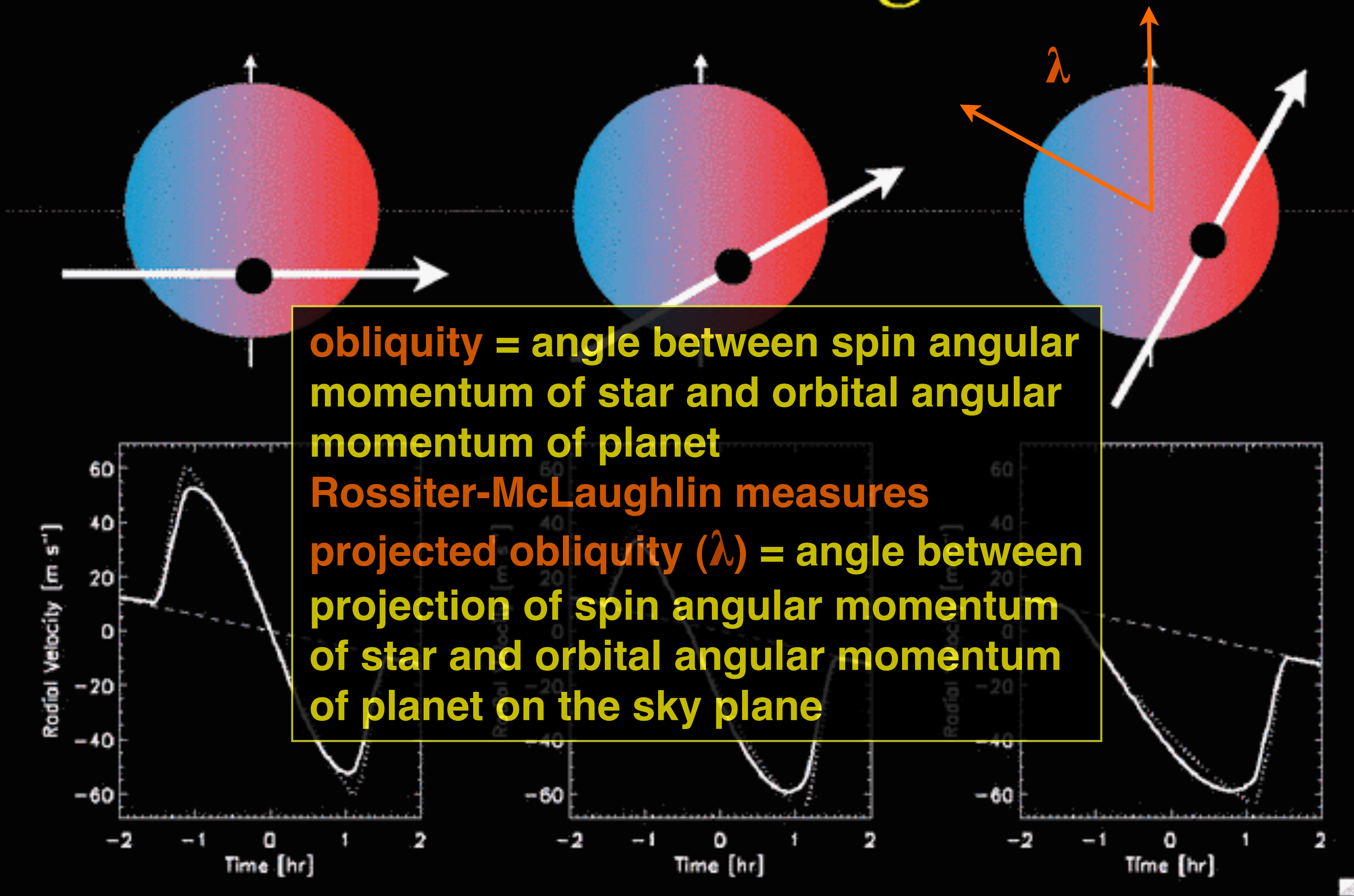
On average, the *Kepler* multi-planet systems are about as flat as the solar system

The Rossiter-McLaughlin Effect



from J. Winn, MIT

The Rossiter-McLaughlin Effect

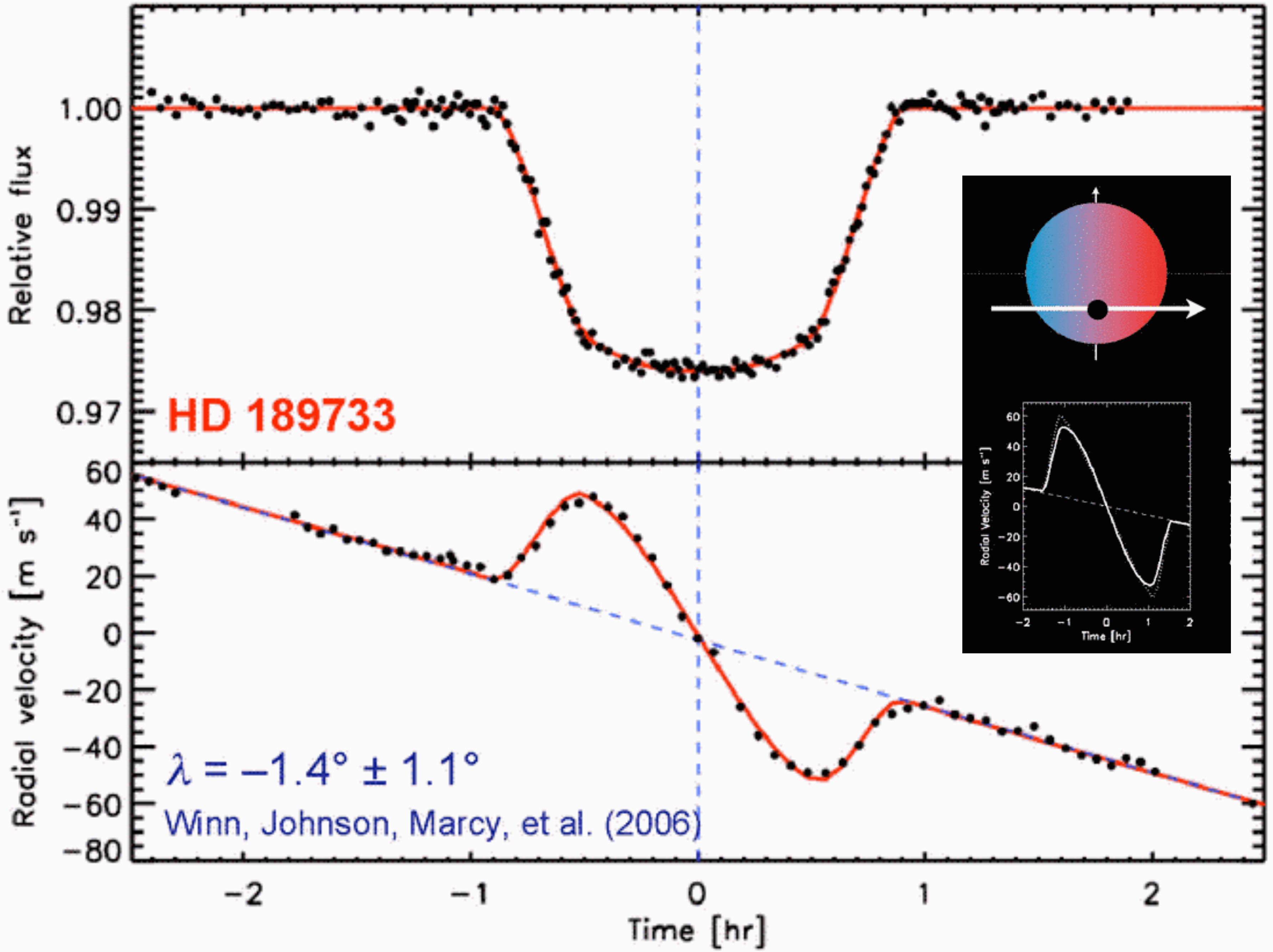


obliquity = angle between spin angular momentum of star and orbital angular momentum of planet

Rossiter-McLaughlin measures

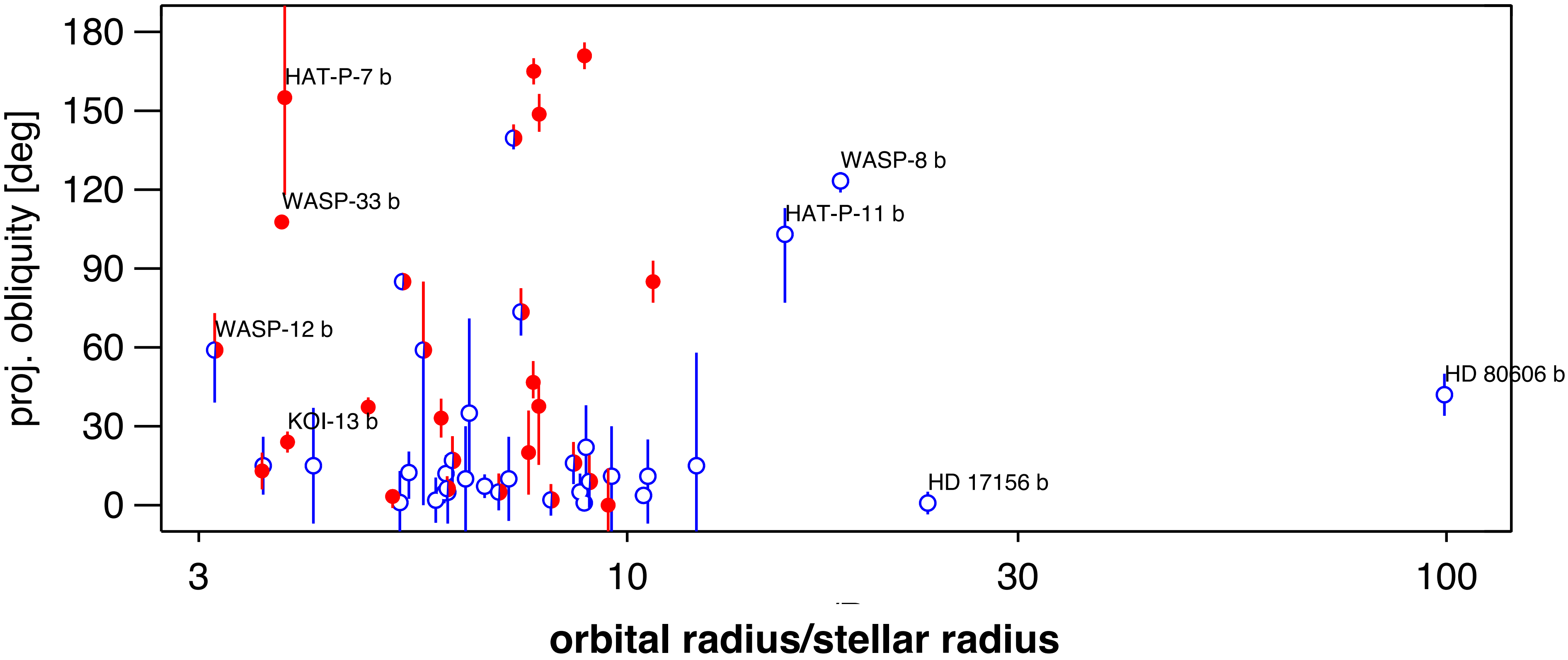
projected obliquity (λ) = angle between projection of spin angular momentum of star and orbital angular momentum of planet on the sky plane

from J. Winn, MIT



Relative flux
1.00
0.99
0.98
0.97
HD 189733
Radial velocity [m s⁻¹]
60
40
20
0
−20
−40
−60
−80
λ = −1.4° ± 1.1°
Winn, Johnson, Marcy, et al. (2006)
−2
−1
0
1
2
Time [hr]
Radial Velocity [m s⁻¹]
Time [hr]

Albrecht et al. (2012)



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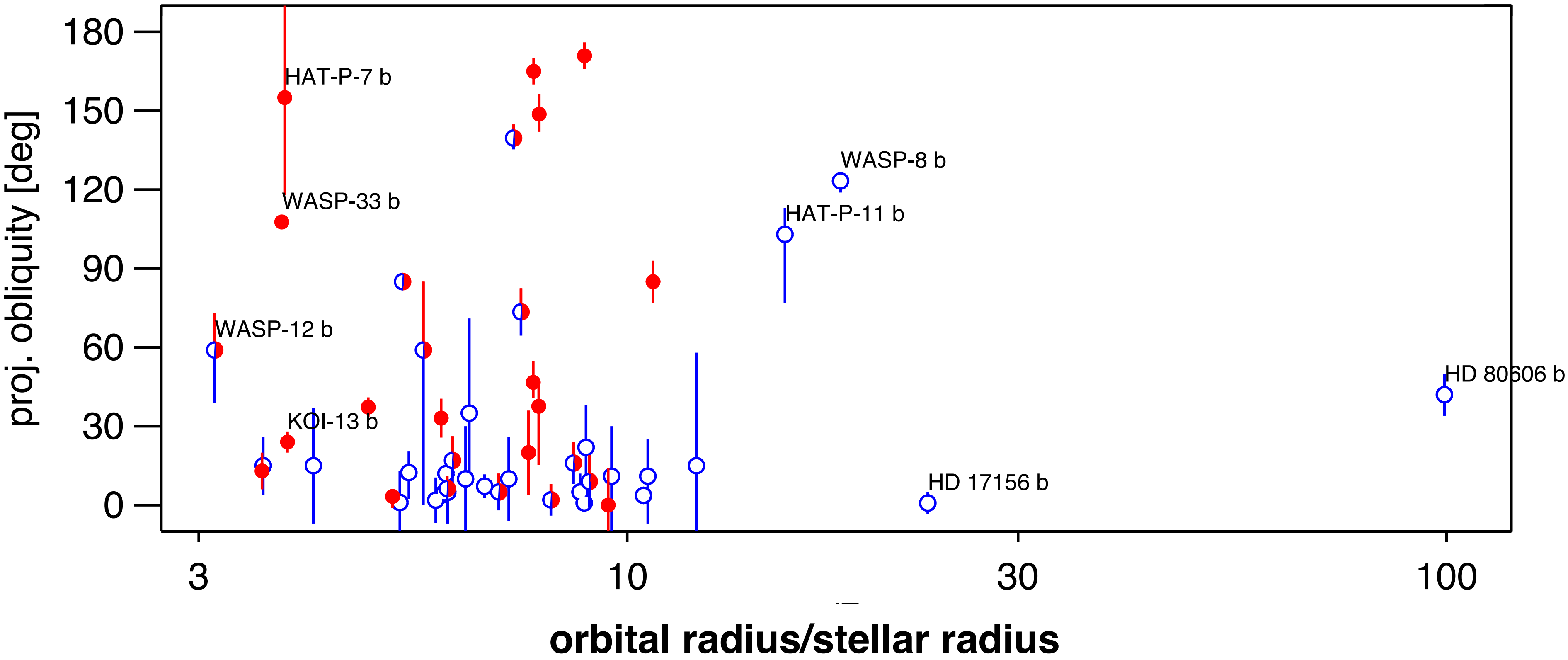

Roughly half of hot Jupiters have orbits that are aligned with the spins of their host star, and the other half of the orbits are oriented randomly

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Why?

- **planetary system is flat, but stellar equator is misaligned with *all* the planetary orbits:**
  - stellar spin has been tilted by a collision with a giant planet
  - planetary plane has been tilted by torques from the birth environment of the system

- **planetary system is not flat:**
  - hot Jupiters are formed like binary stars, from condensations in collapsing clouds
  - hot Jupiter orbits have been tilted by Kozai-Lidov oscillations

2. Are there interstellar planets?

- the solar system is surrounded by ~10^{11} comets orbiting at distances ~1000 X Neptune's orbit (the Oort comet cloud). In the standard model for its formation
    - comets are planetesimals of ~1-10 km that formed in the outer solar system on unstable orbits, and were later ejected by gravitational interactions with the giant planets
    - in this process at least 10^{11} comets were ejected into interstellar space
    - if comets can be ejected, why not planets?

- the outer solar system (Jupiter-Neptune) is "full", i.e., there are no stable orbits left

2. Are there interstellar planets?

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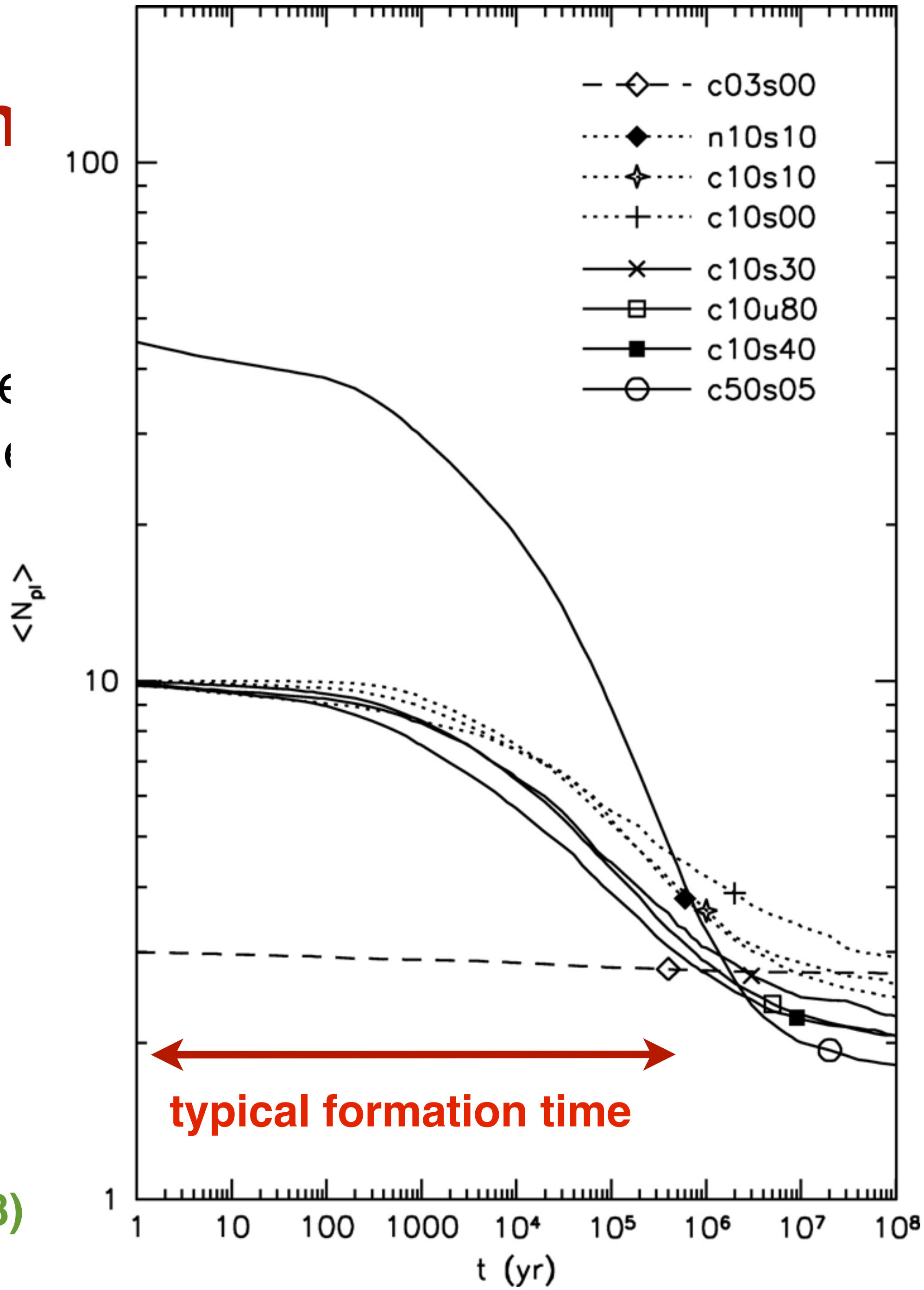
2. Are there in

• simulations of multi-plane
often unstable on timescal
formation time



Jurić & Tremaine (2008)

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- a good reference number is 1 interstellar Jupiter per star

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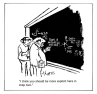
- interstellar planets can be detected by gravitational microlensing
    - Sumi et al. (2011) estimate 1.8 (+1.7/-0.8) interstellar Jupiters per star
- Earth-mass interstellar planets with thick hydrogen atmospheres can retain radioactive heat and therefore could have water oceans (Stevenson 1999)

3. How common are planets?

- until ~1970 the standard (Jeans-Jeffreys) theory of planet formation implied that planets are present around only ~10^{-9} of all stars
- the modern planetesimal (Safronov) theory still has serious gaps



3. Ho

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- the modern pl
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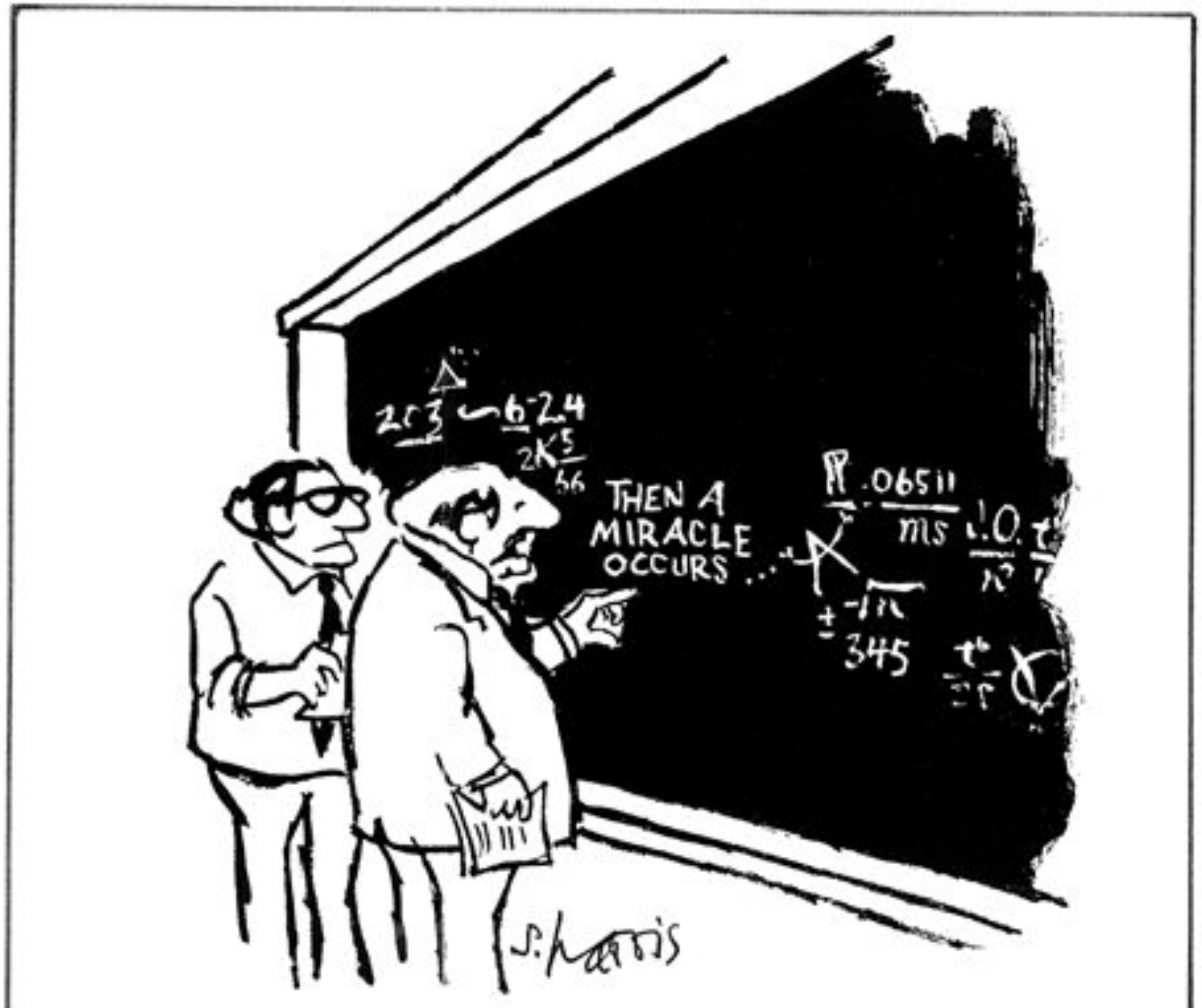

"I think you should be more explicit here in step two."

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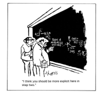
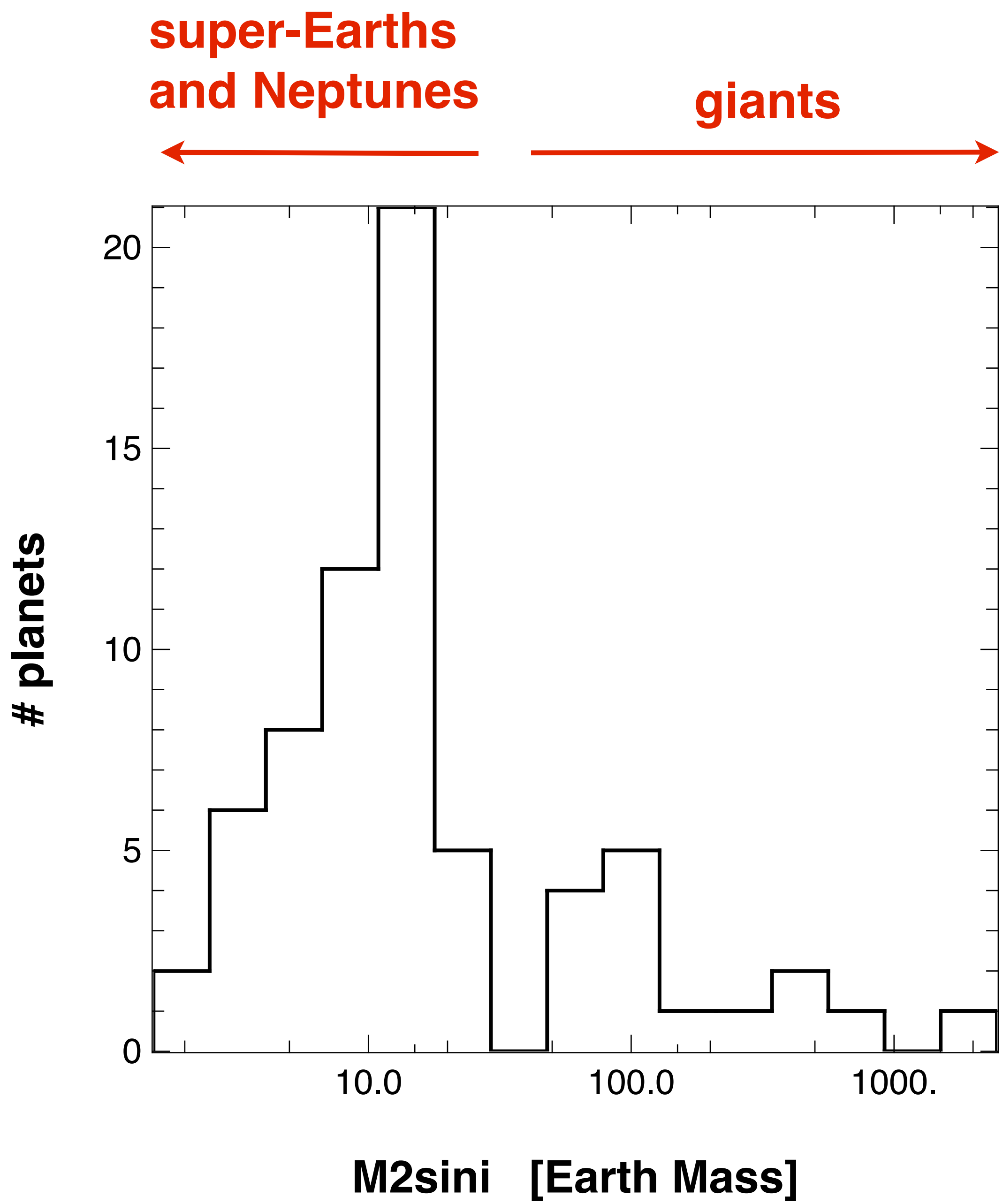


3. How common are planets?

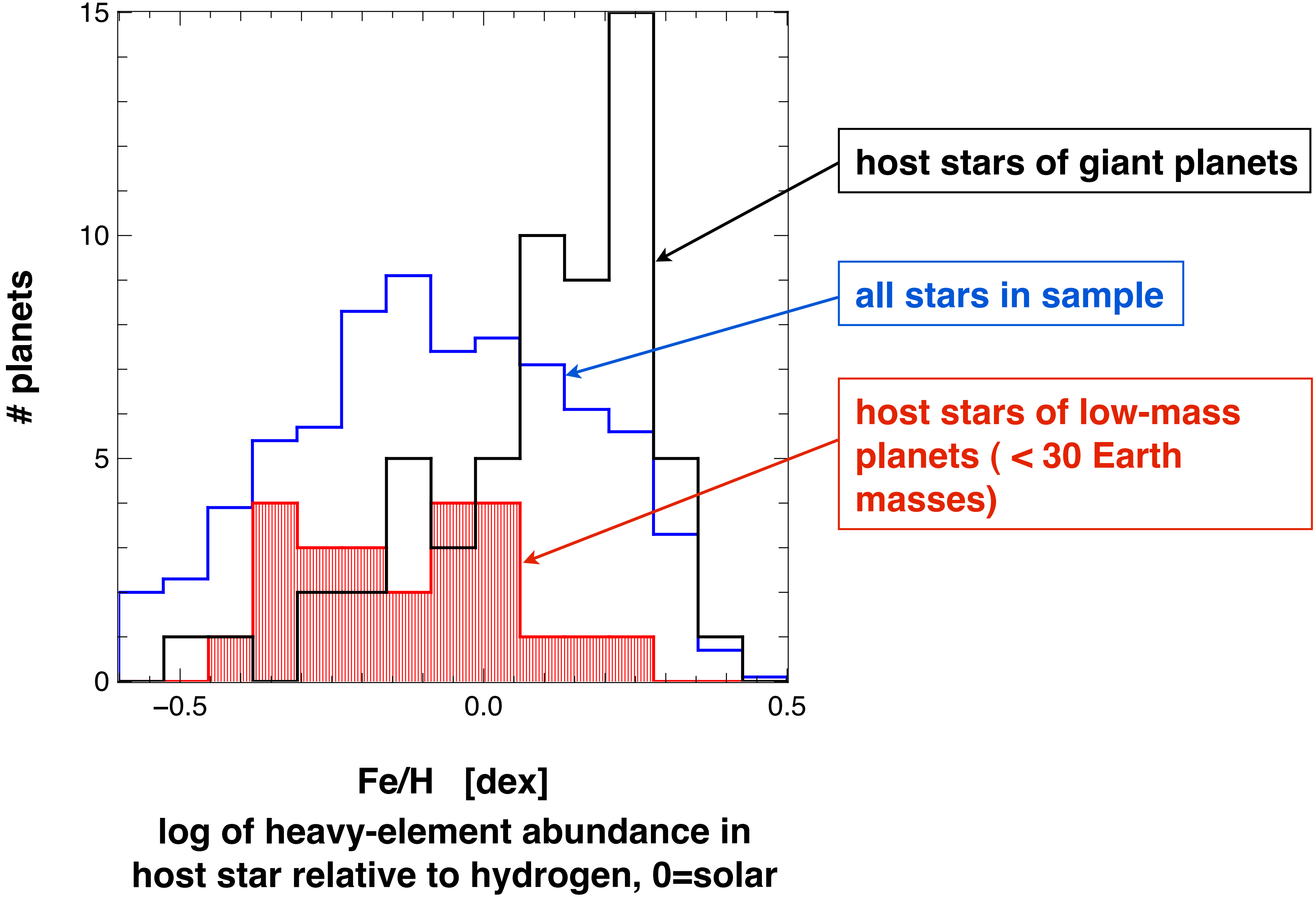
- most exoplanet searches have poorly specified search strategies and null detections are often not reported
- Cumming et al. (2008) using Keck planet search: for solar-type stars
    - 10% have planets with mass $M > 0.3$ Jupiter masses and orbital period $P < 2000$ days
    - 20% have gas giants within 20 AU
    - $dN \sim M^{-0.3} P^{0.26}\, d\log M\ \ d\log P$, i.e., roughly flat in log mass and log period
- Wright et al. (2012) find 1% of solar-type stars have hot Jupiters ($M > 0.1$ Jupiter masses, $P < 10$ days)

3. How common are planets?

- Mayor et al. (2011) using HARPS survey: for solar-type stars there are two distinct populations of planets:
- **giant planets:**
  - mass > 50 Earth masses
  - present in about 15% of stars (P < 100 days)
  - occur mostly in environments rich in heavy elements
- **super-Earths and Neptunes:**
  - present in at least 50% of stars
  - different radial distribution from giant planets
  - lower orbital eccentricities
  - no preference for environments rich in heavy elements



Mayor et al. (2011)



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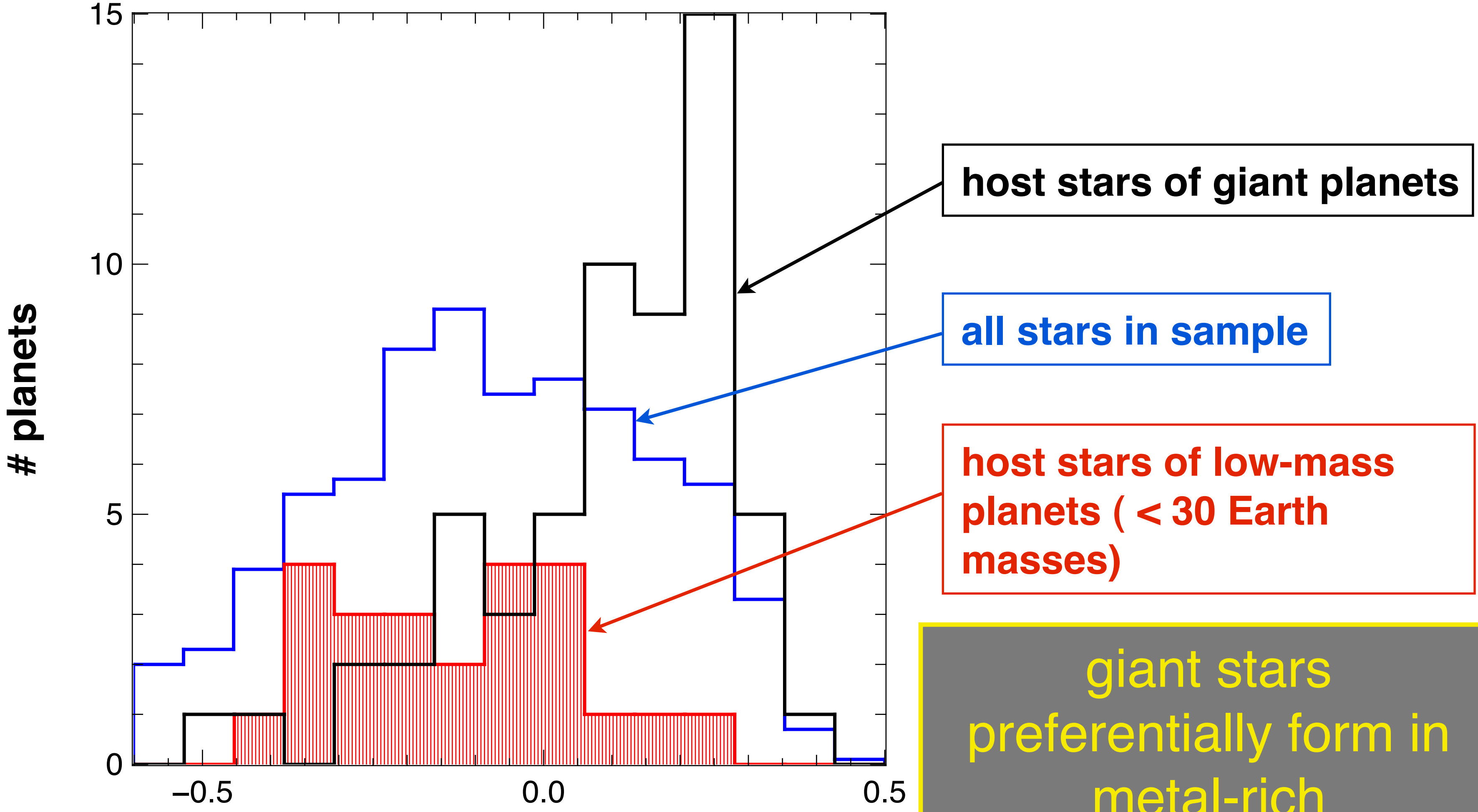
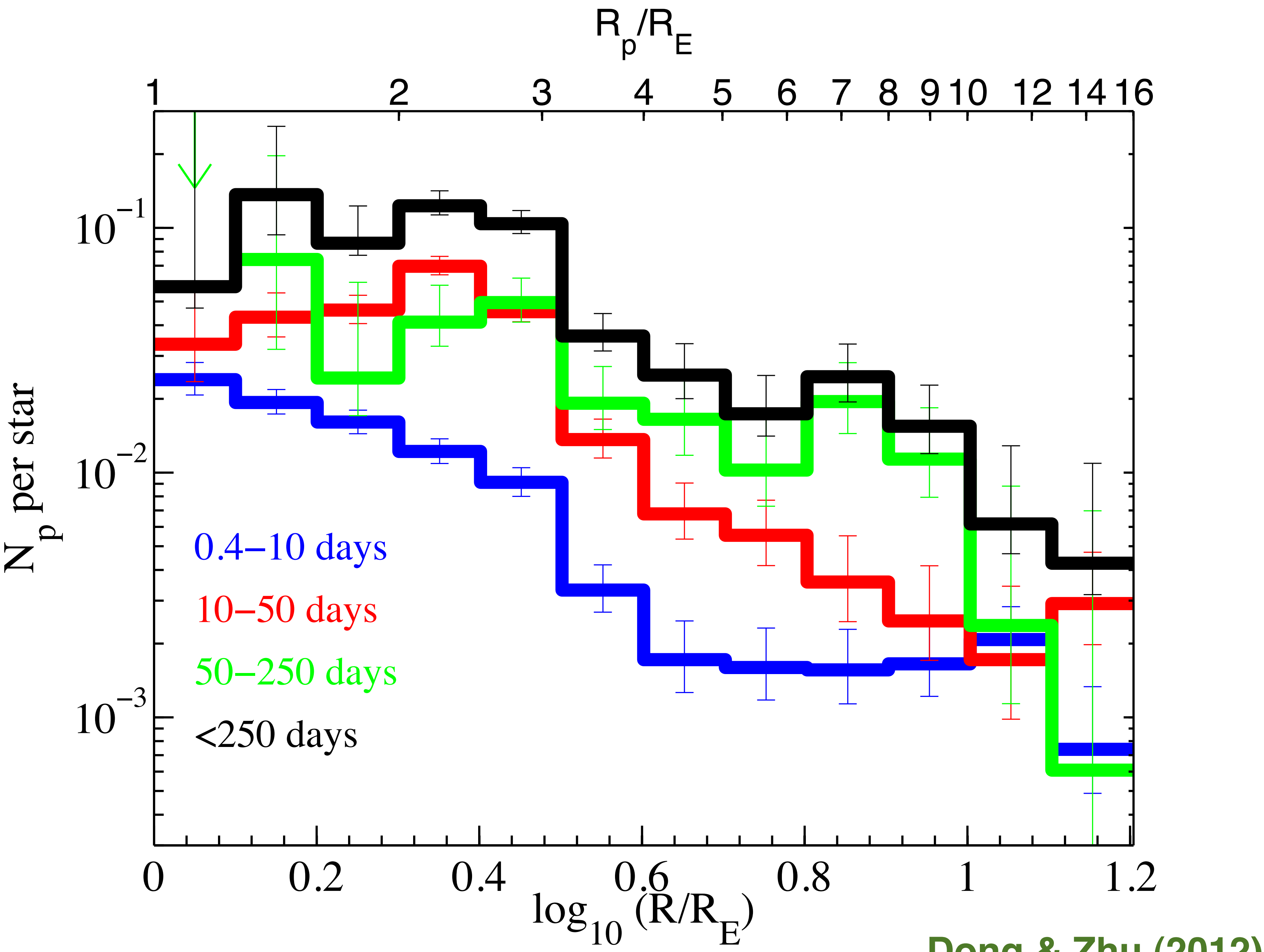


Fe/H [dex]

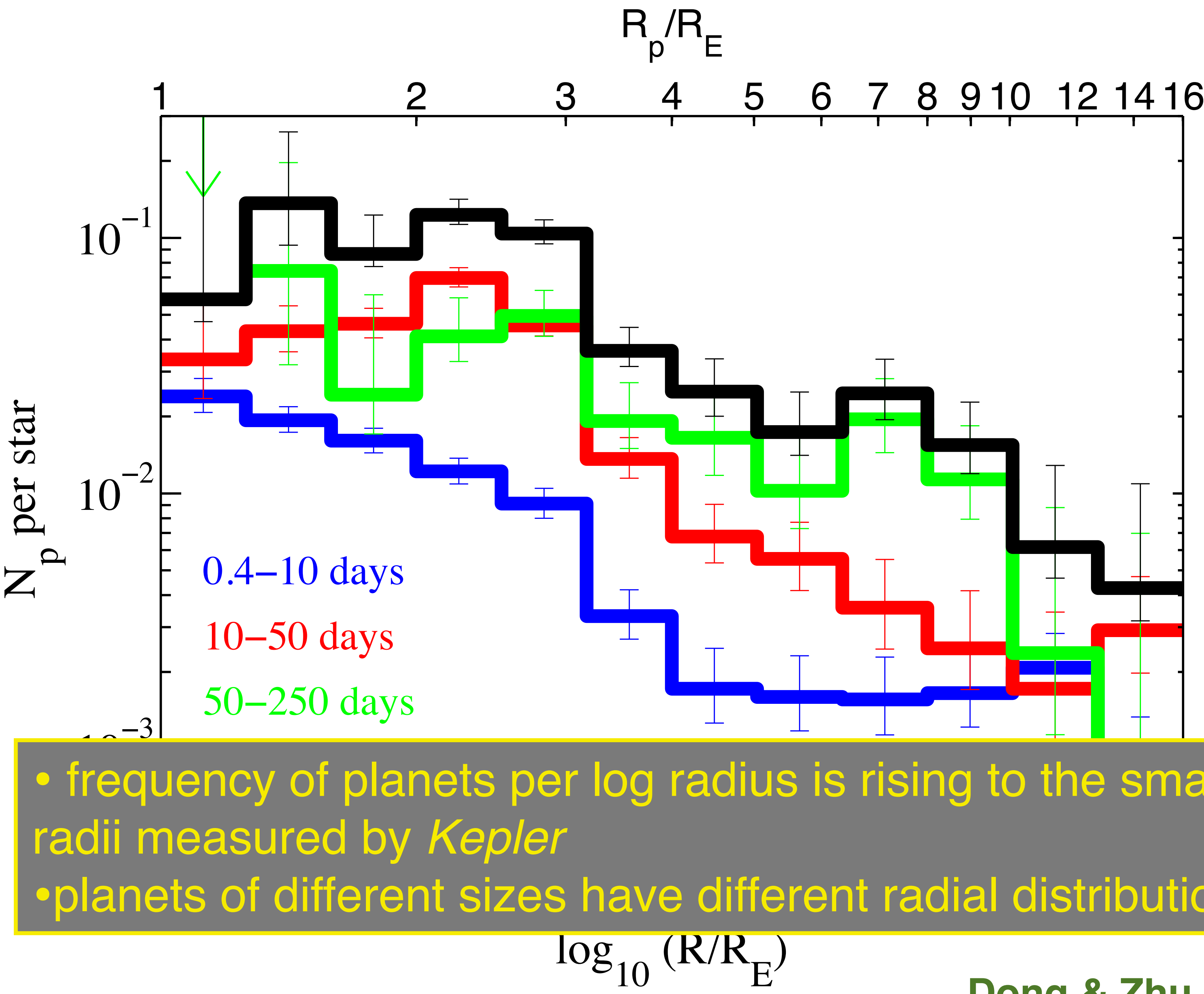
log of heavy-element abundance in host star relative to hydrogen, 0=solar

giant stars preferentially form in metal-rich environments

Mayor et al. (2011)



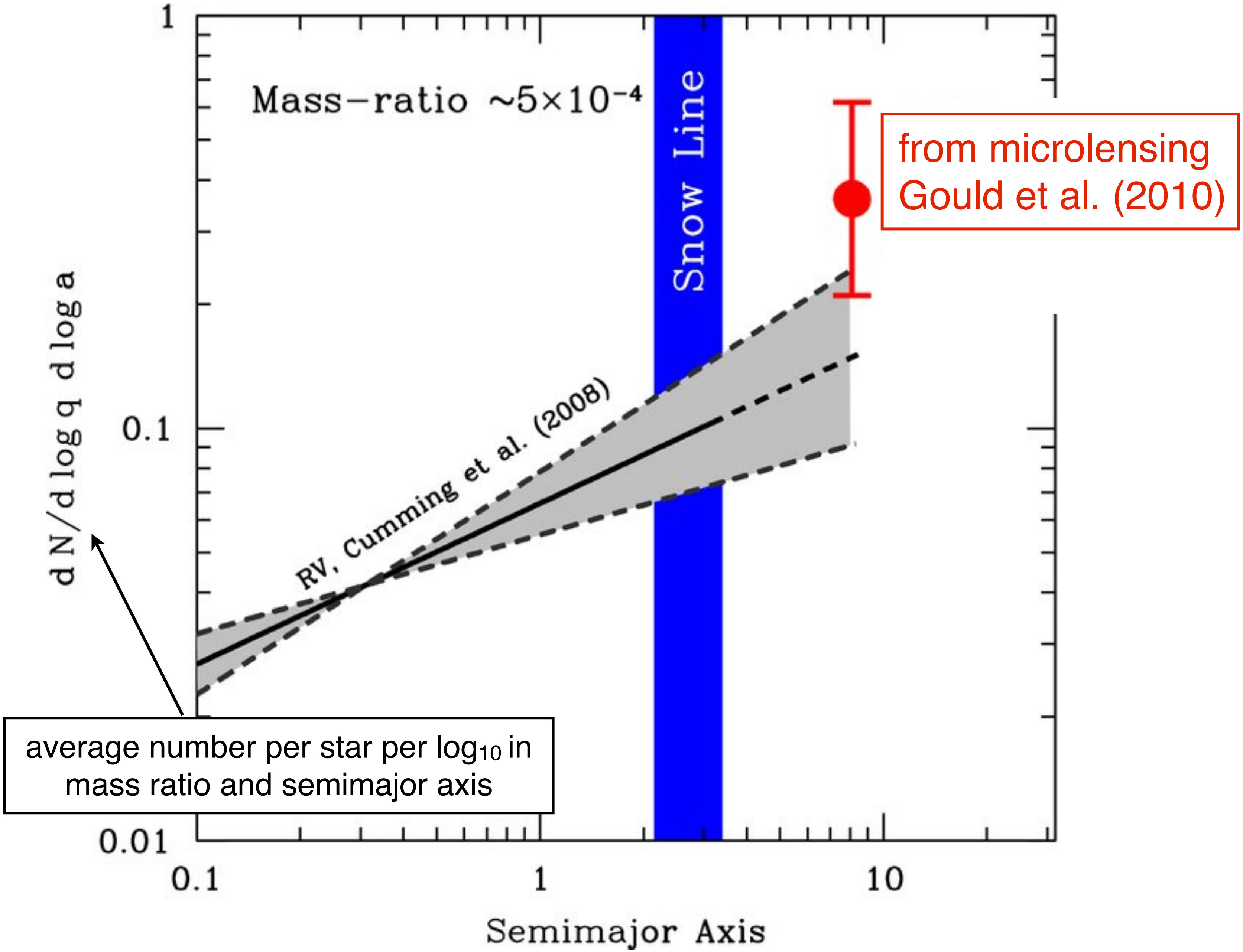
Wednesday, March 6, 2013



• frequency of planets per log radius is rising to the smallest radii measured by *Kepler*

•planets of different sizes have different radial distributions

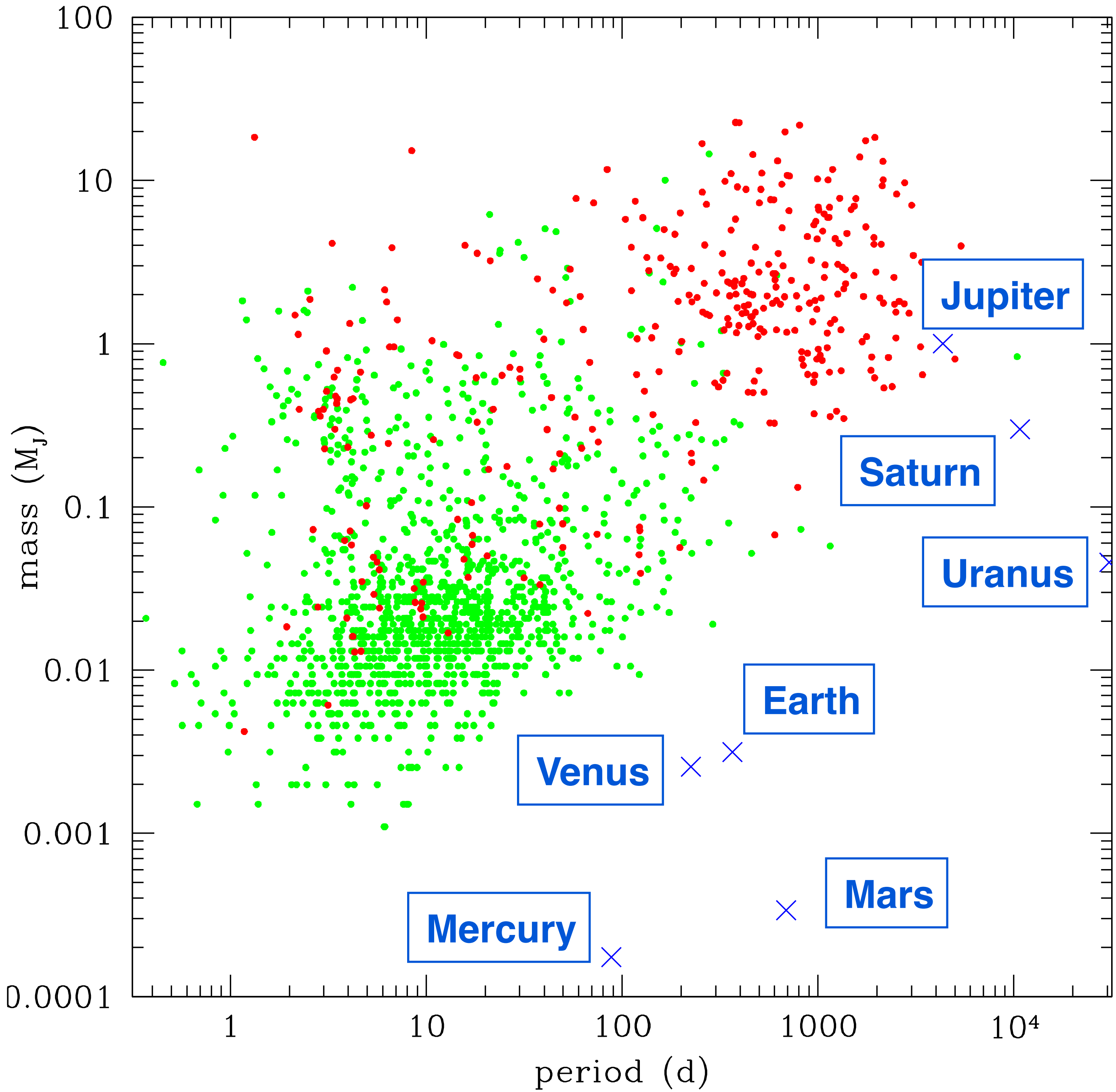
Dong & Zhu (2012)



Mass−ratio ~5×10⁻⁴
Snow Line
from microlensing
Gould et al. (2010)
RV, Cumming et al. (2008)
average number per star per log10 in mass ratio and semimajor axis
d N/d log q d log a
Semimajor Axis
1
0.1
0.01
0.1
1
10

4. Is the solar system anomalous?

- or, if we were carrying out a planet search with current technology, what would we detect around the Sun and would it look odd in any way?



100
10
1
0.1
0.01
0.001
0.0001
mass (M_J)
1
10
100
1000
10^4
period (d)
Jupiter
Saturn
Uranus
Earth
Venus
Mars
Mercury

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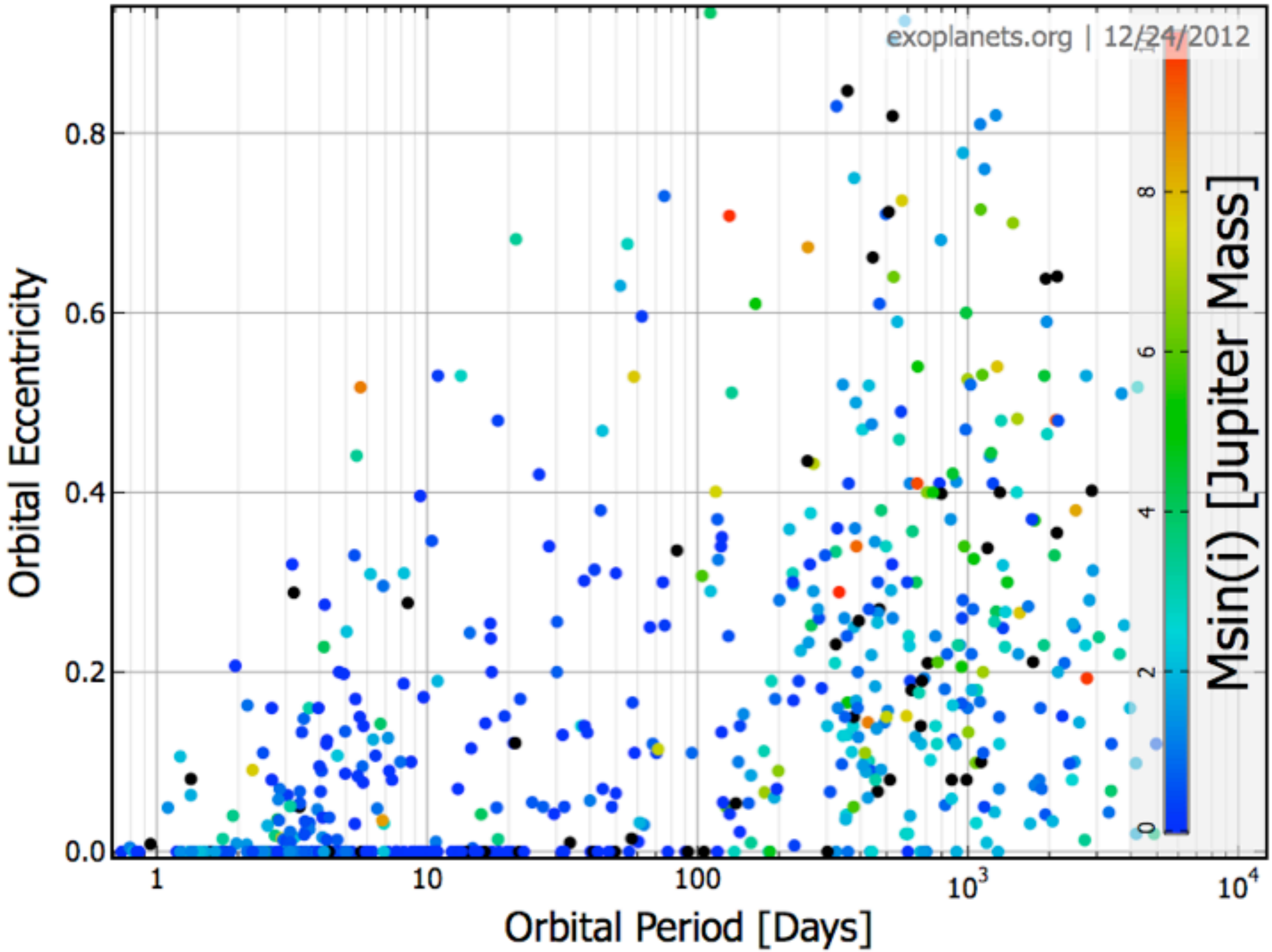
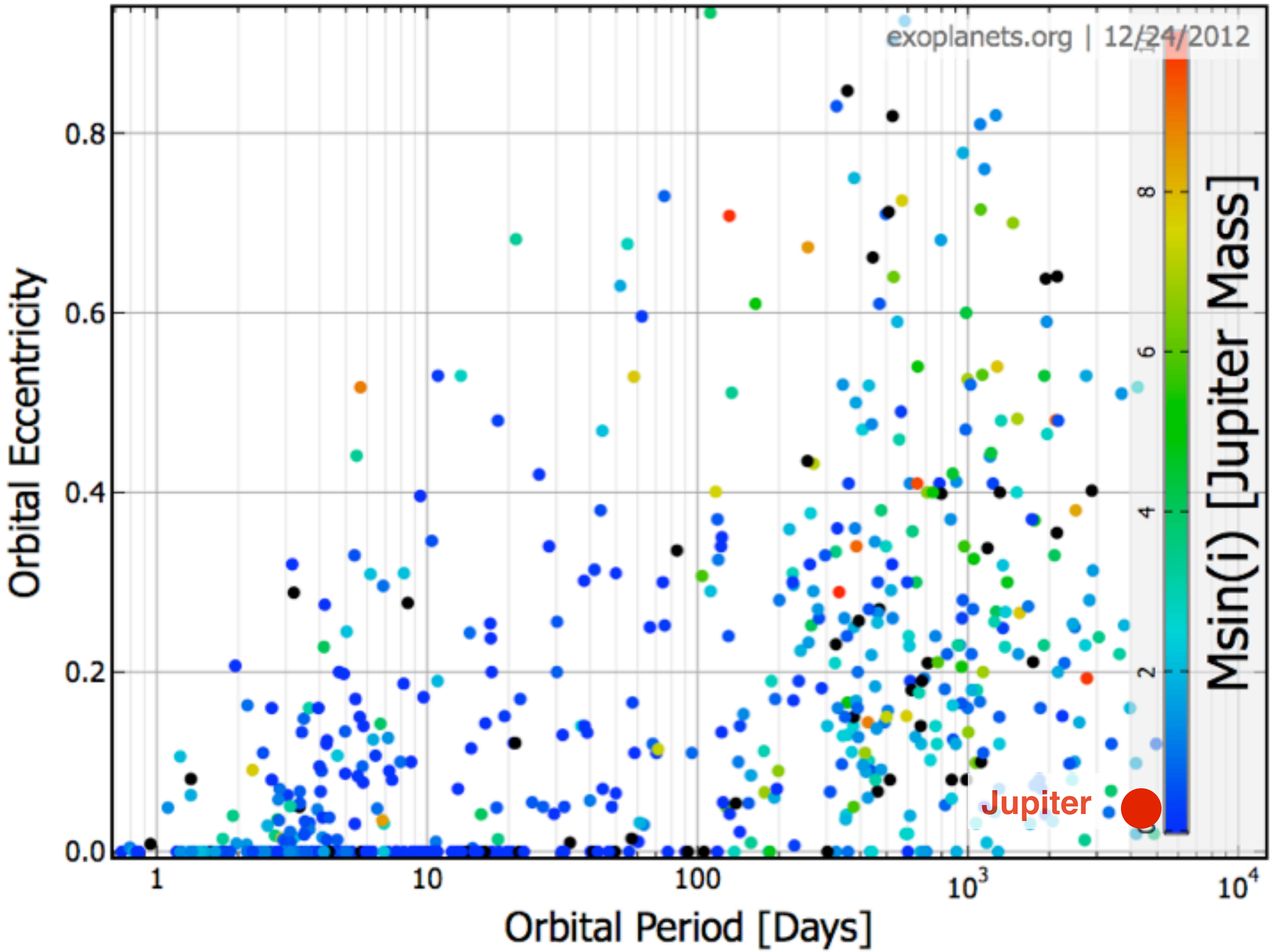
- about 8% of solar-type stars have a planet at least as large as Jupiter within Jupiter's orbit
- only 10% of these are hot Jupiters so it is not too surprising that Jupiter is at several AU


exoplanets.org | 12/24/2012
Orbital Eccentricity
0.8
0.6
0.4
0.2
0.0
1
10
100
10^3
10^4
Orbital Period [Days]
Msin(i) [Jupiter Mass]
0
2
4
6
8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Orbital Eccentricity
0.0
0.2
0.4
0.6
0.8
Orbital Period [Days]
1
10
100
10^3
10^4
Msin(i) [Jupiter Mass]
2
4
6
8
Jupiter

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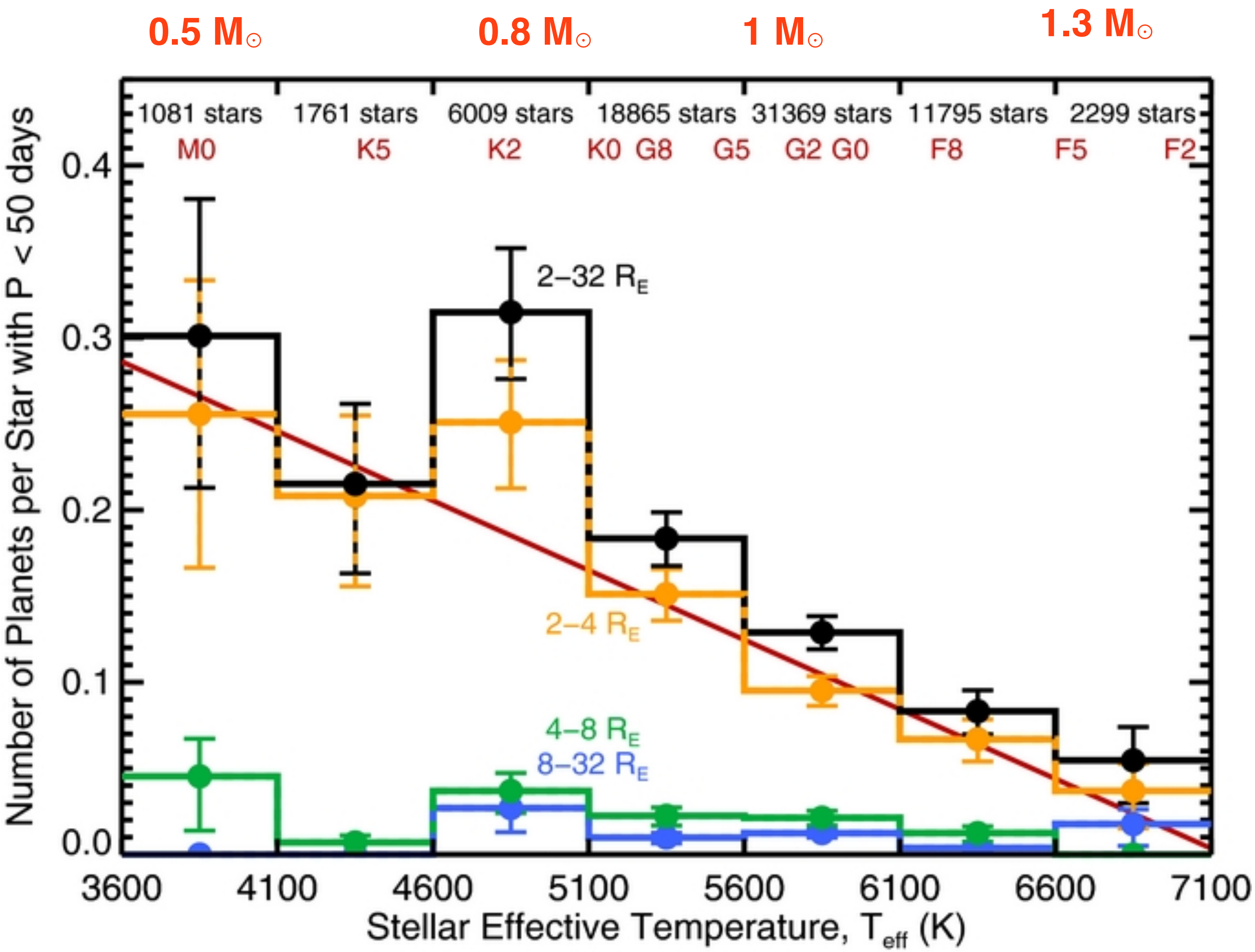
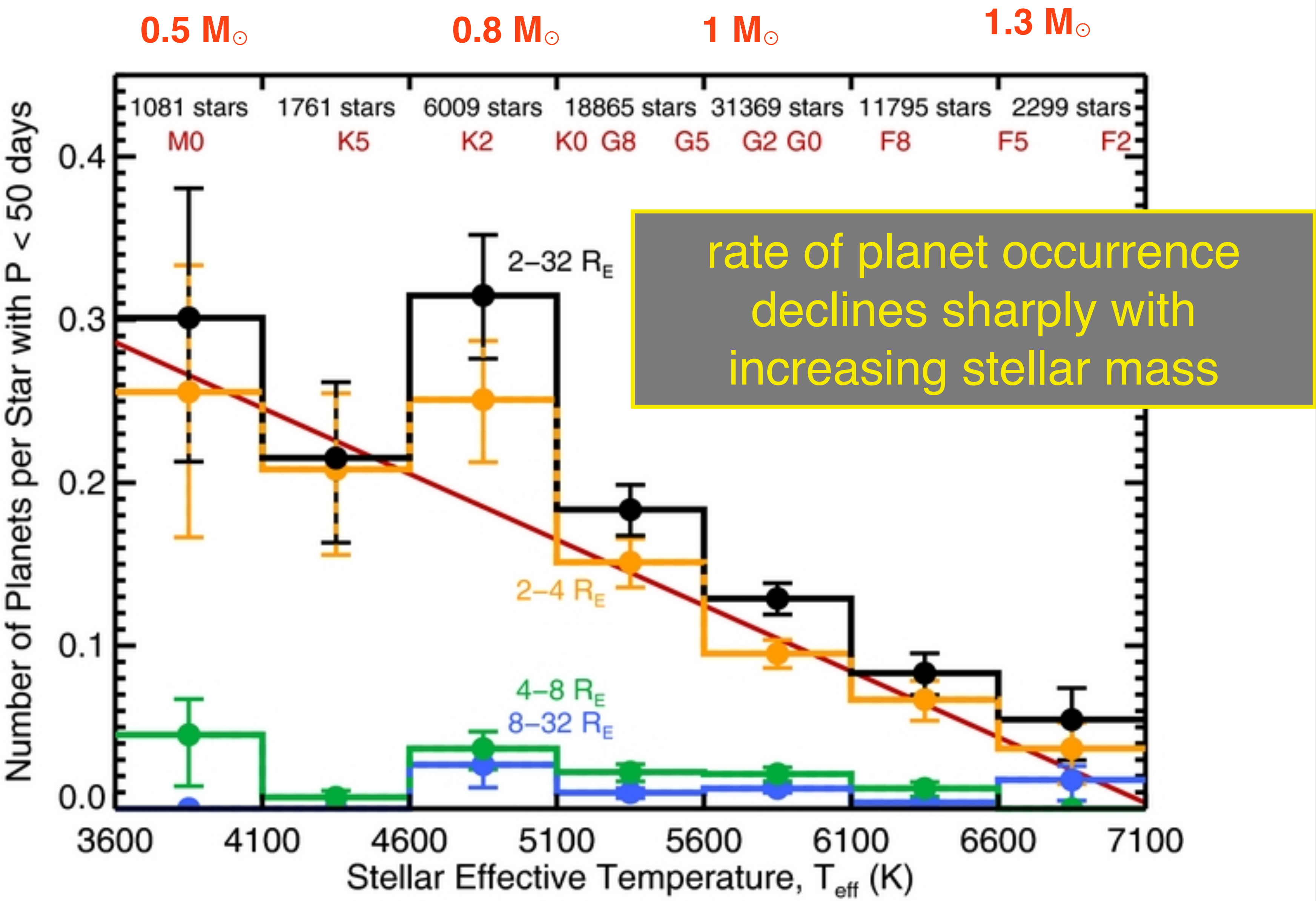
- only 10% of these are hot Jupiters so it is not too surprising that Jupiter is at several AU
- Jupiter's orbital eccentricity is smaller than 87% of exoplanets with $P > 1000$ days



Howard et al. (2012)



Howard et al. (2012)