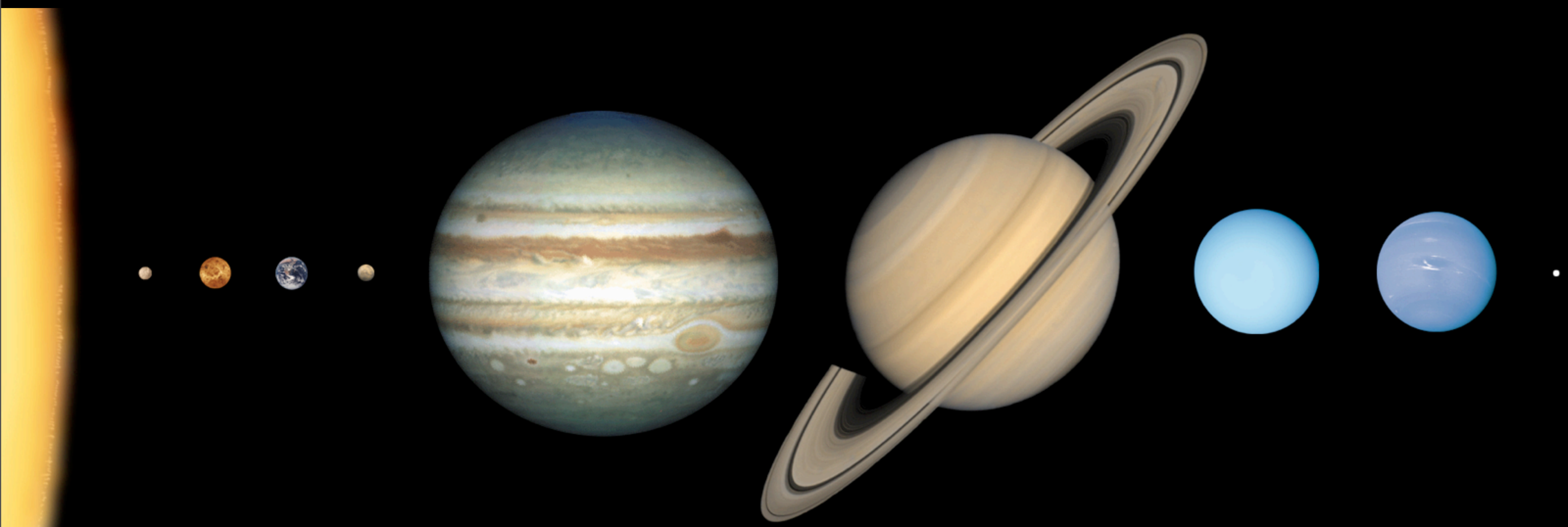
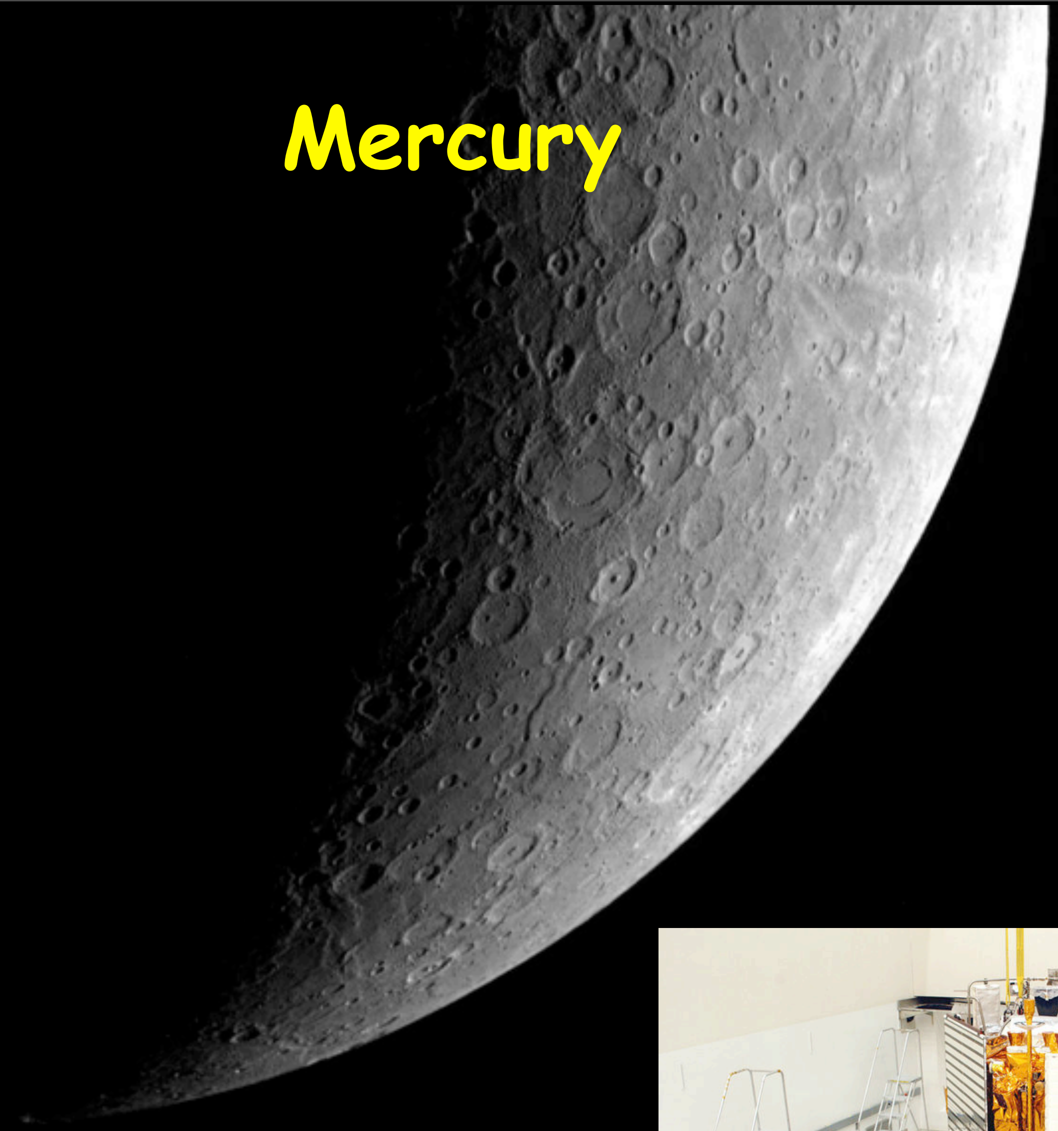
Observations of extrasolar planets

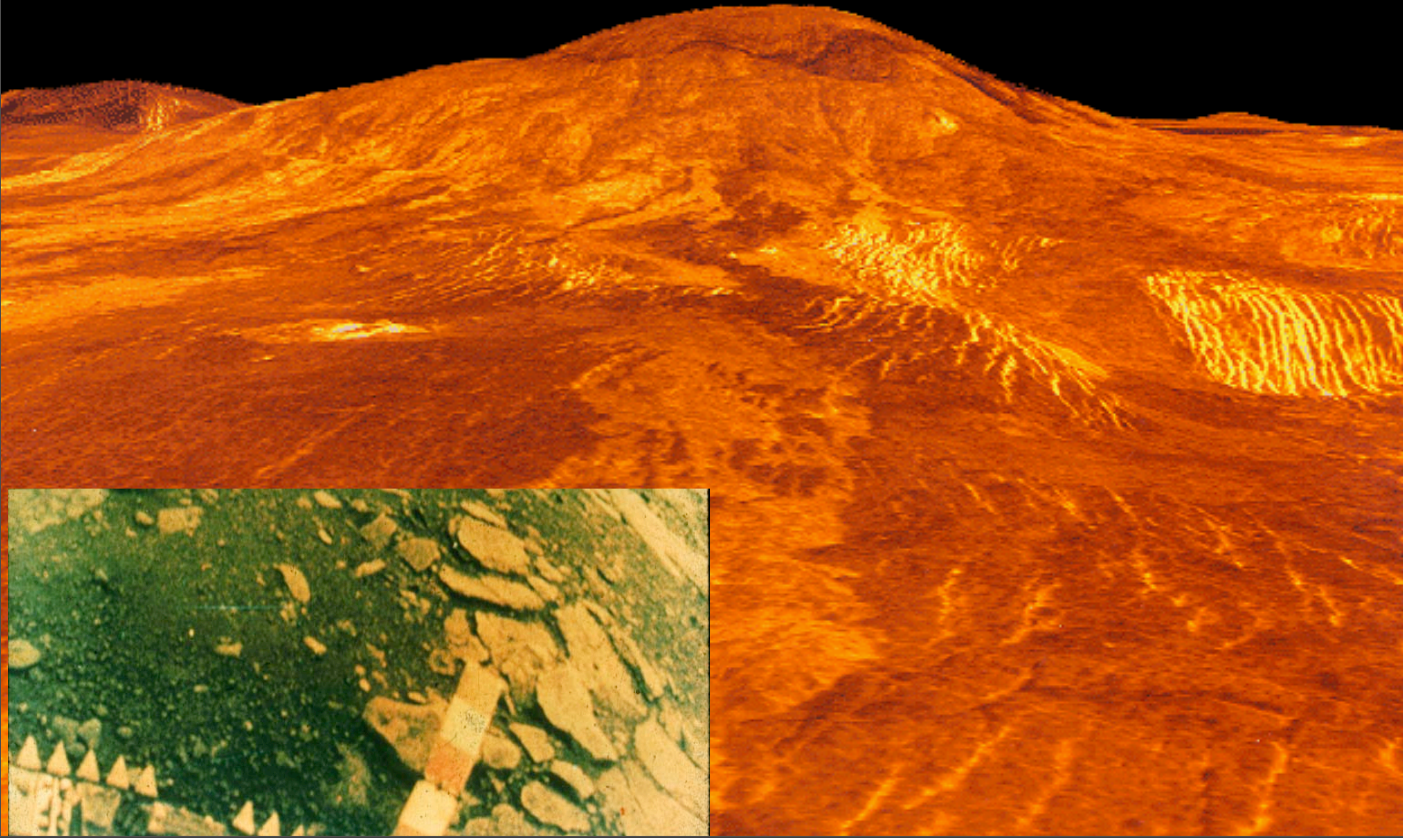


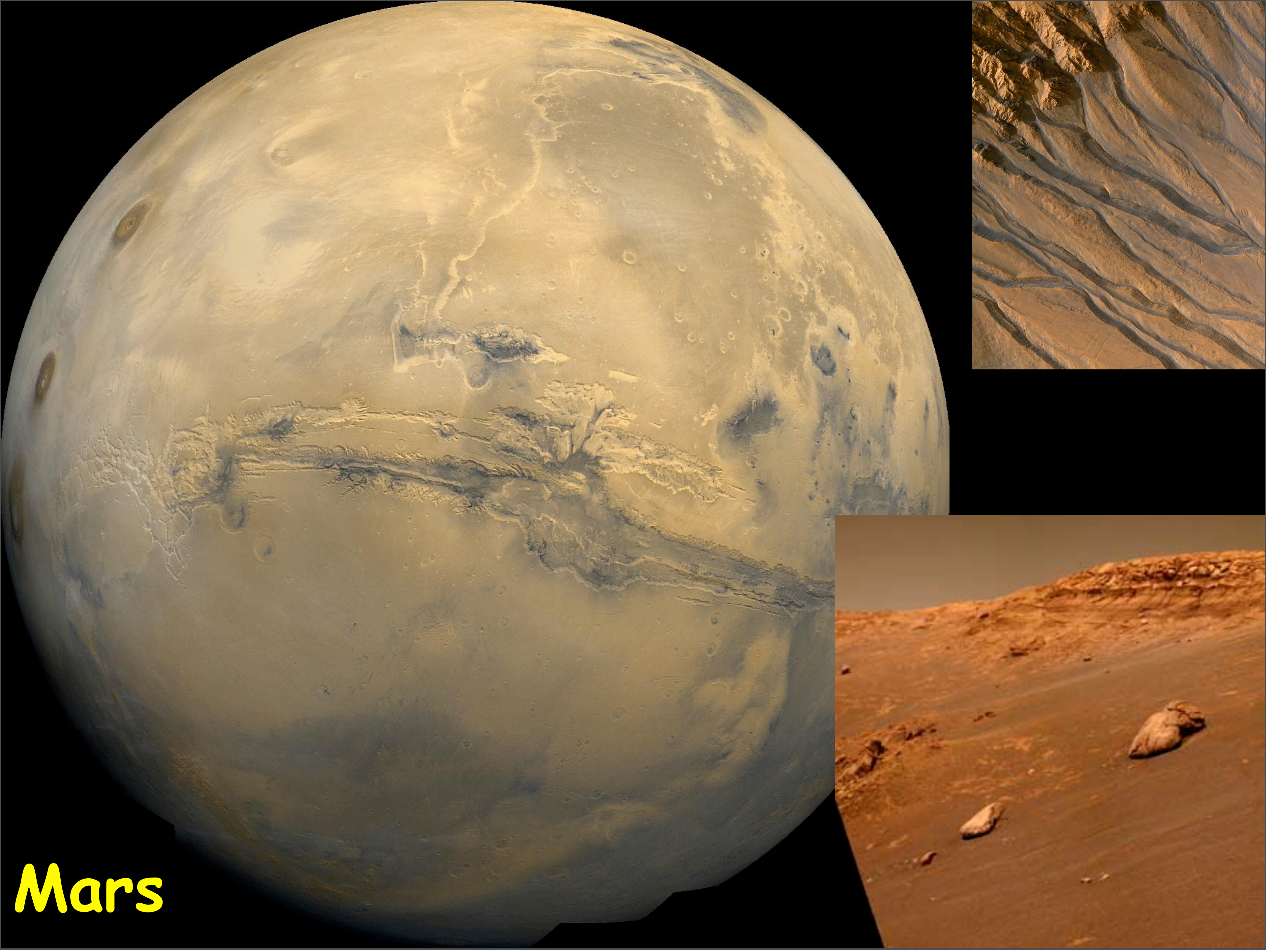
Mercury

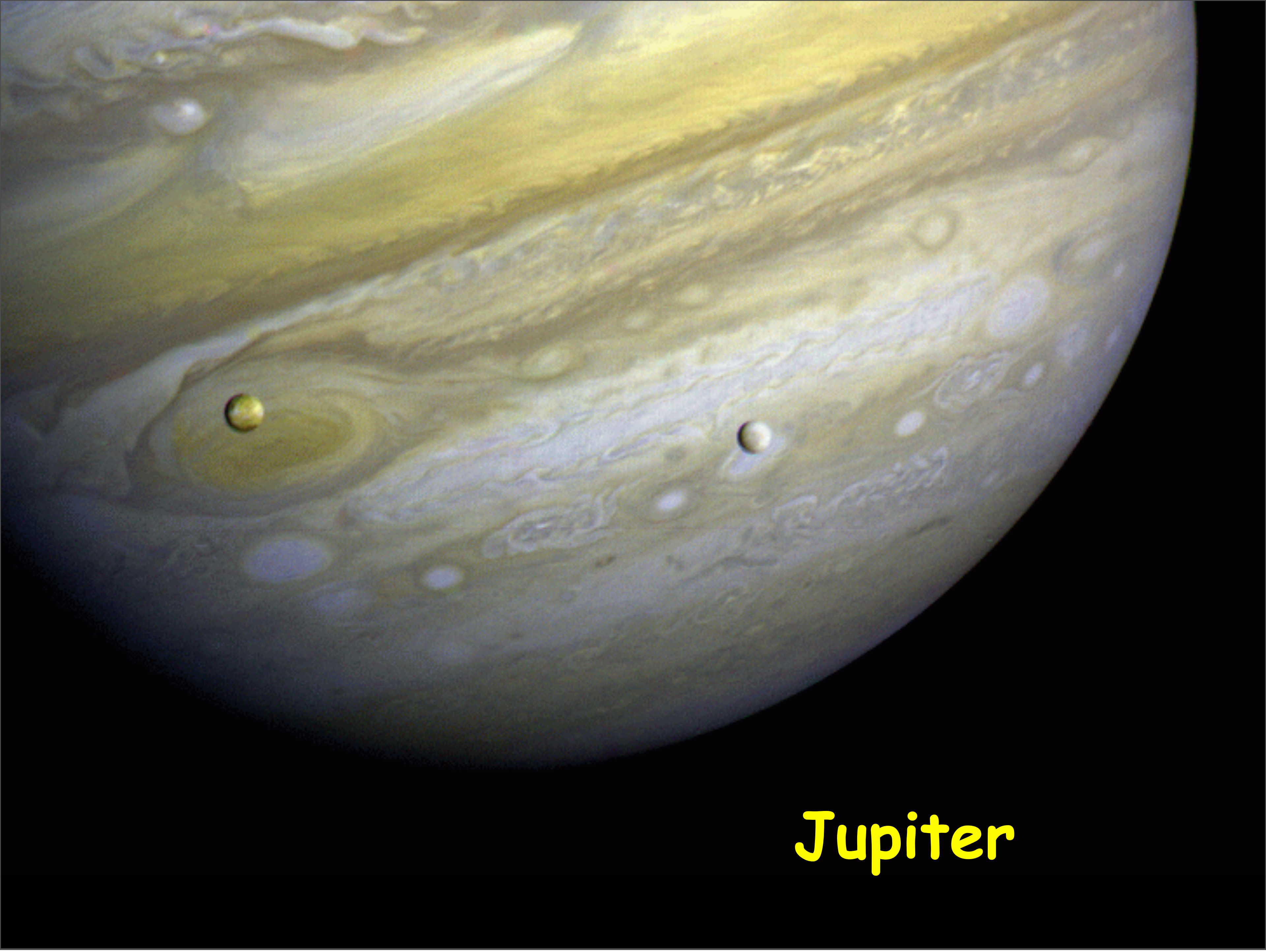


radar image from Magellan (vertical scale exaggerated 10 X)

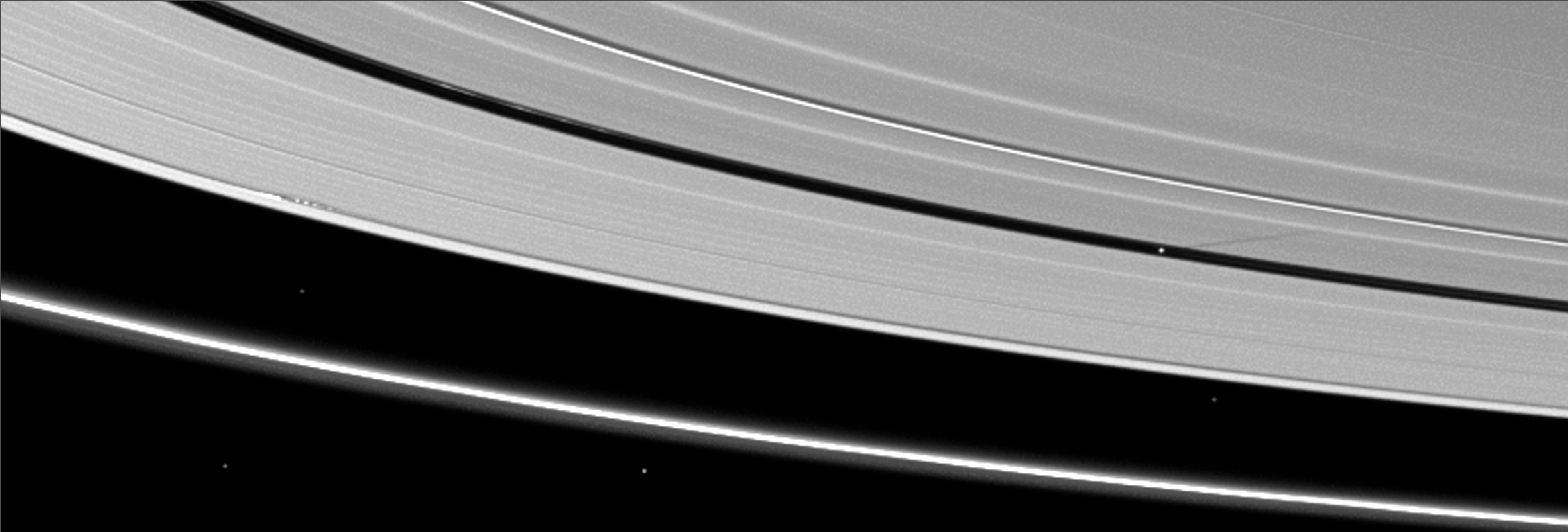
Venus

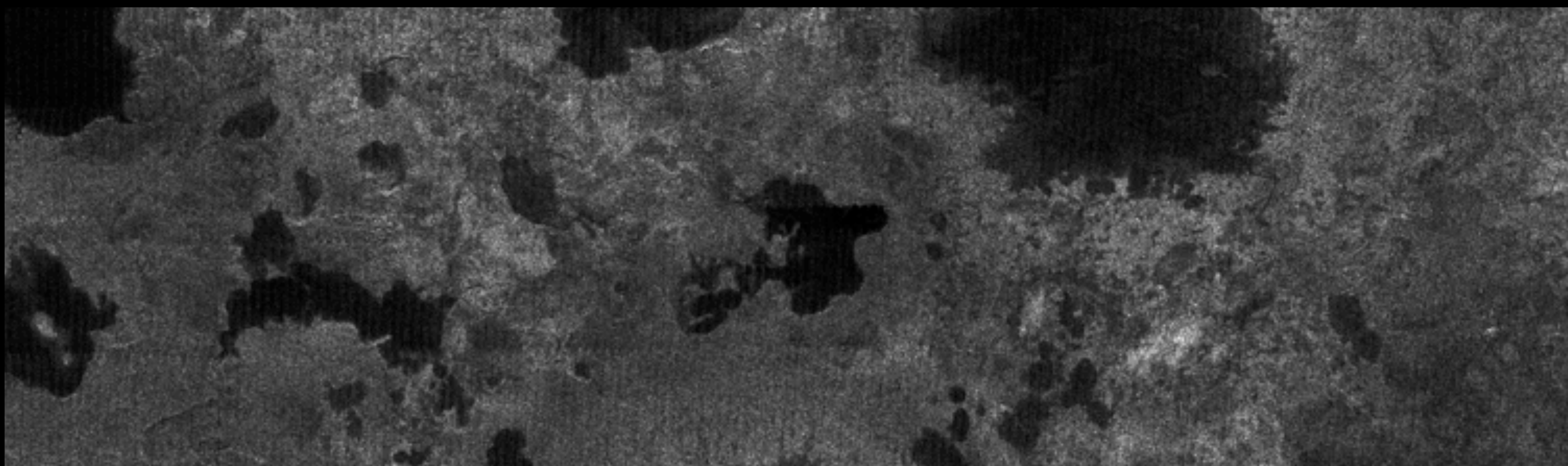



Mars

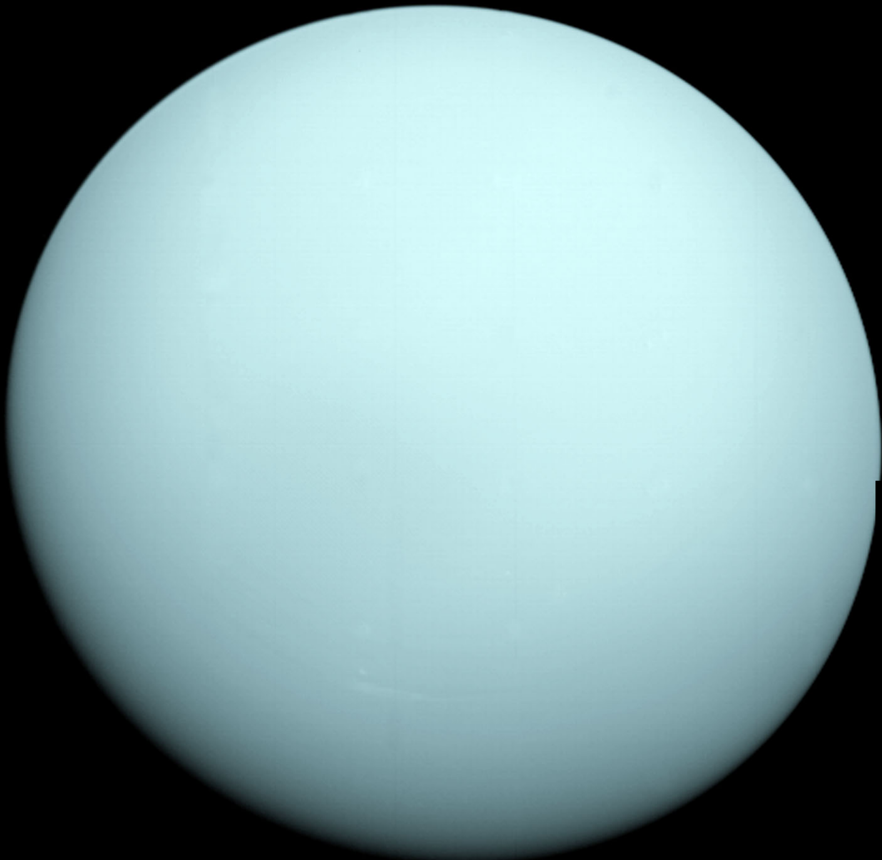

Jupiter

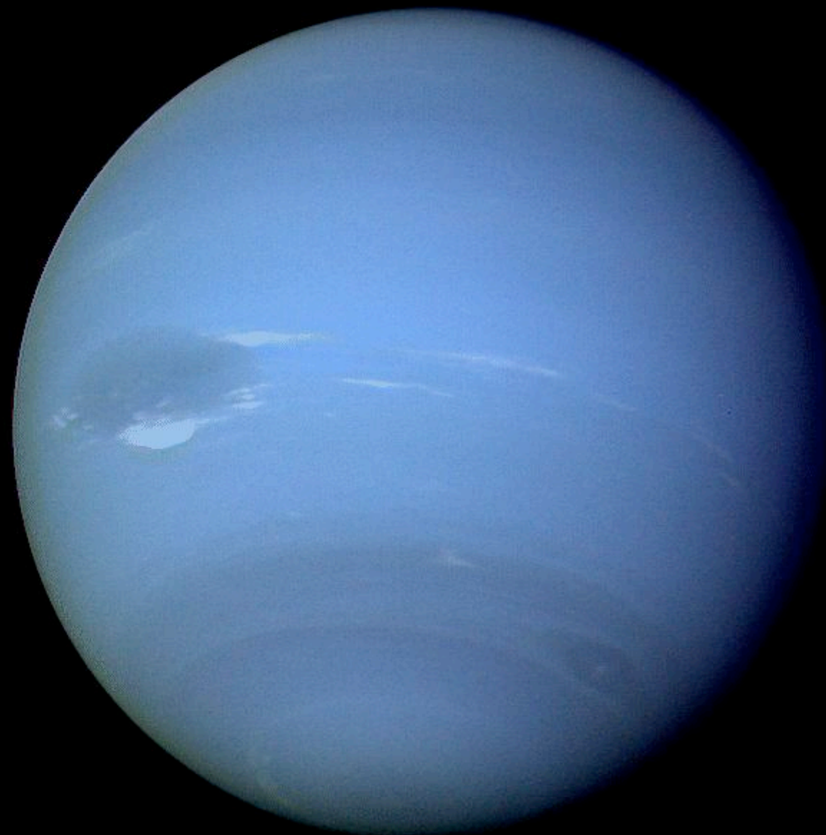
Saturn

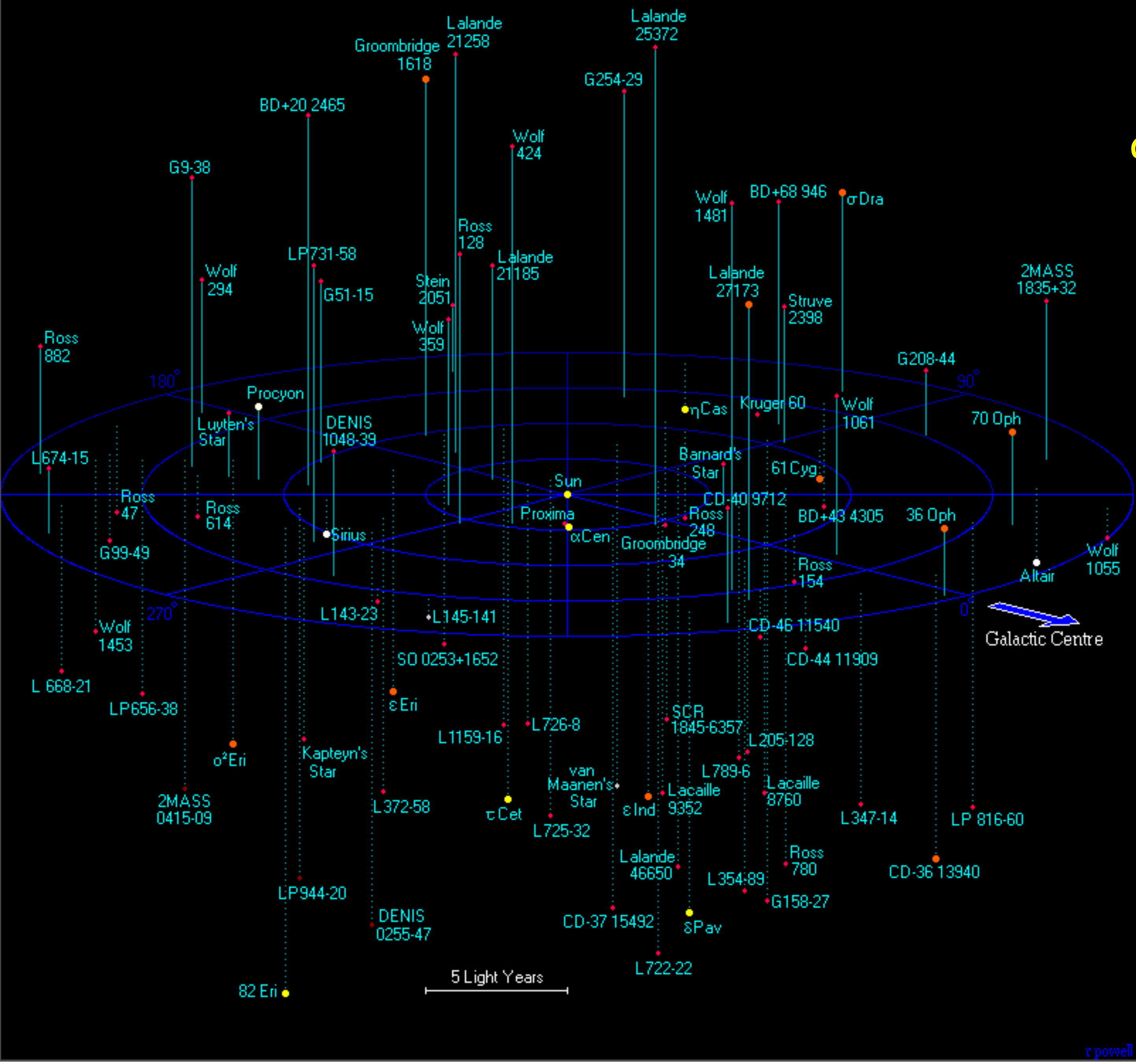




Uranus and Neptune







we need to look out about 10 parsecs or 2 million astronomical units to examine 100 stars for planets

why is finding planets hard?

- the Earth is visible in reflected light from the Sun
- the total light reflected by Earth is about 10^{-9} of the light emitted by the Sun
- Jupiter is bigger but more distant so only about 4X brighter than Earth

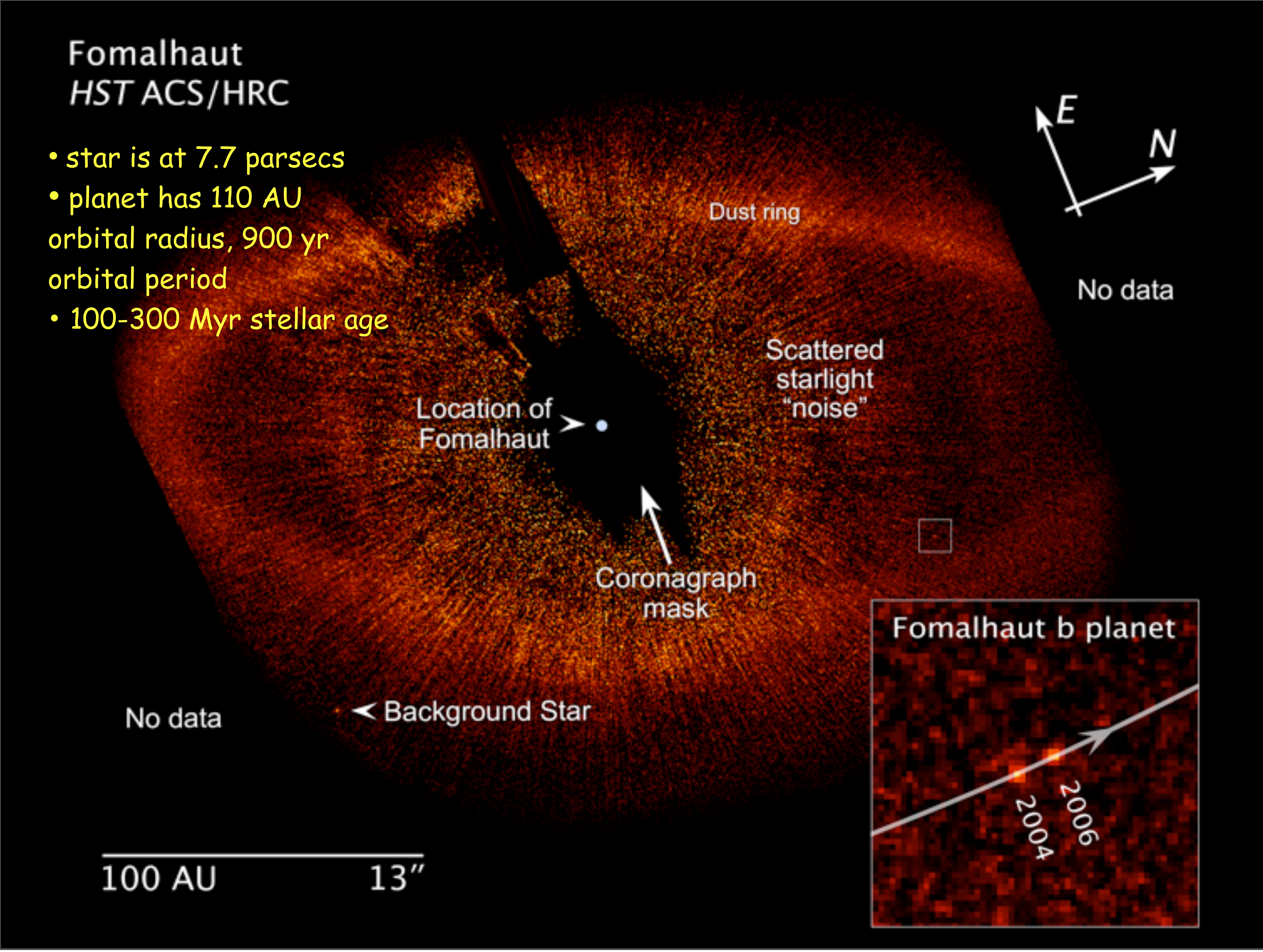
These would be easy to see with modern telescopes at 10 parsecs if the star were not right beside them

(imagine looking at a lighthouse 1000 km away and trying to detect a firefly flying 1 meter from the light)

With current technology direct imaging requires one or more of:

- planet with a large orbital radius (e.g. 100 AU vs. 30 AU for Neptune)
- observations in the infrared (for a black body in thermal equilibrium at 100 AU around the Sun, emission peaks at 100 microns)
- young planet (Jupiter's internal luminosity falls at 1/age)

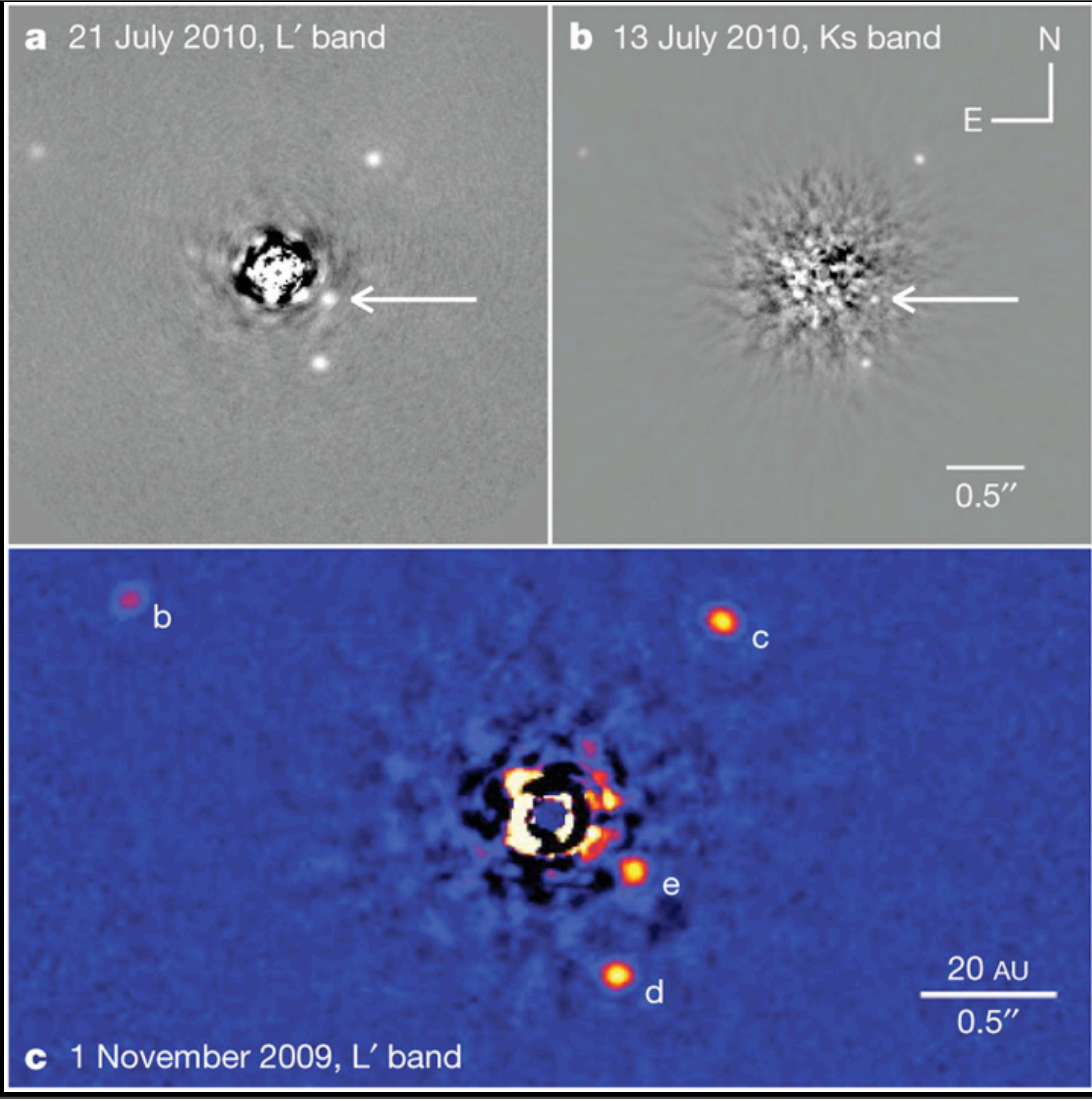
- star is at 7.7 parsecs
- planet has 110 AU orbital radius, 900 yr orbital period
- 100-300 Myr stellar age

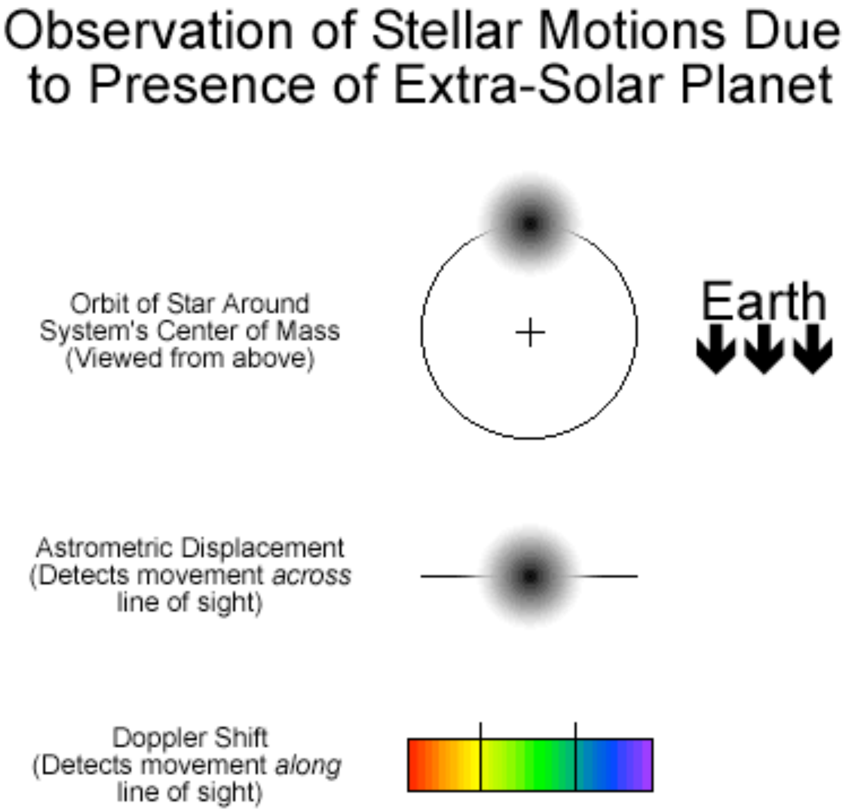


HR 8799

• star is at 39 parsecs
• planets have masses of 7-10 Jupiter masses and projected separations of 14-68 AU
• 30-160 Myr age

Marois et al. (2008, 2010)



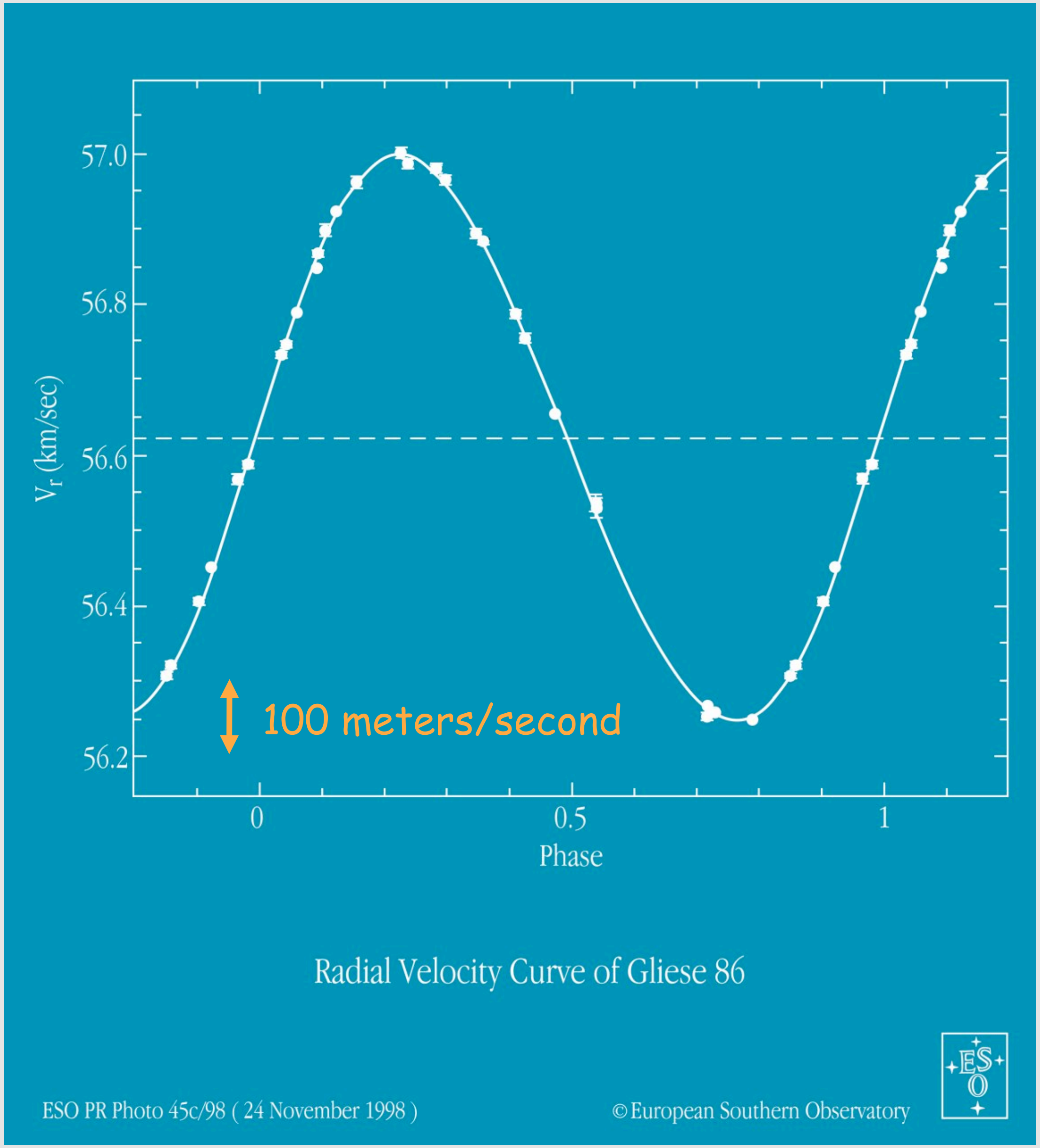


- current accuracy: velocity of 1 meter/sec (3 parts in 10^9)
  - cross-correlation uses all lines in spectrum
  - high S/N (bright stars, big telescopes)
  - iodine absorption cell
  - old stars (less rotation, less activity)
  - G stars
- Jupiter: orbital period of 12 yr, reflex velocity of Sun 13 meter/sec
- Earth: orbital period of 1 yr, reflex velocity of Sun 0.1 meter/sec

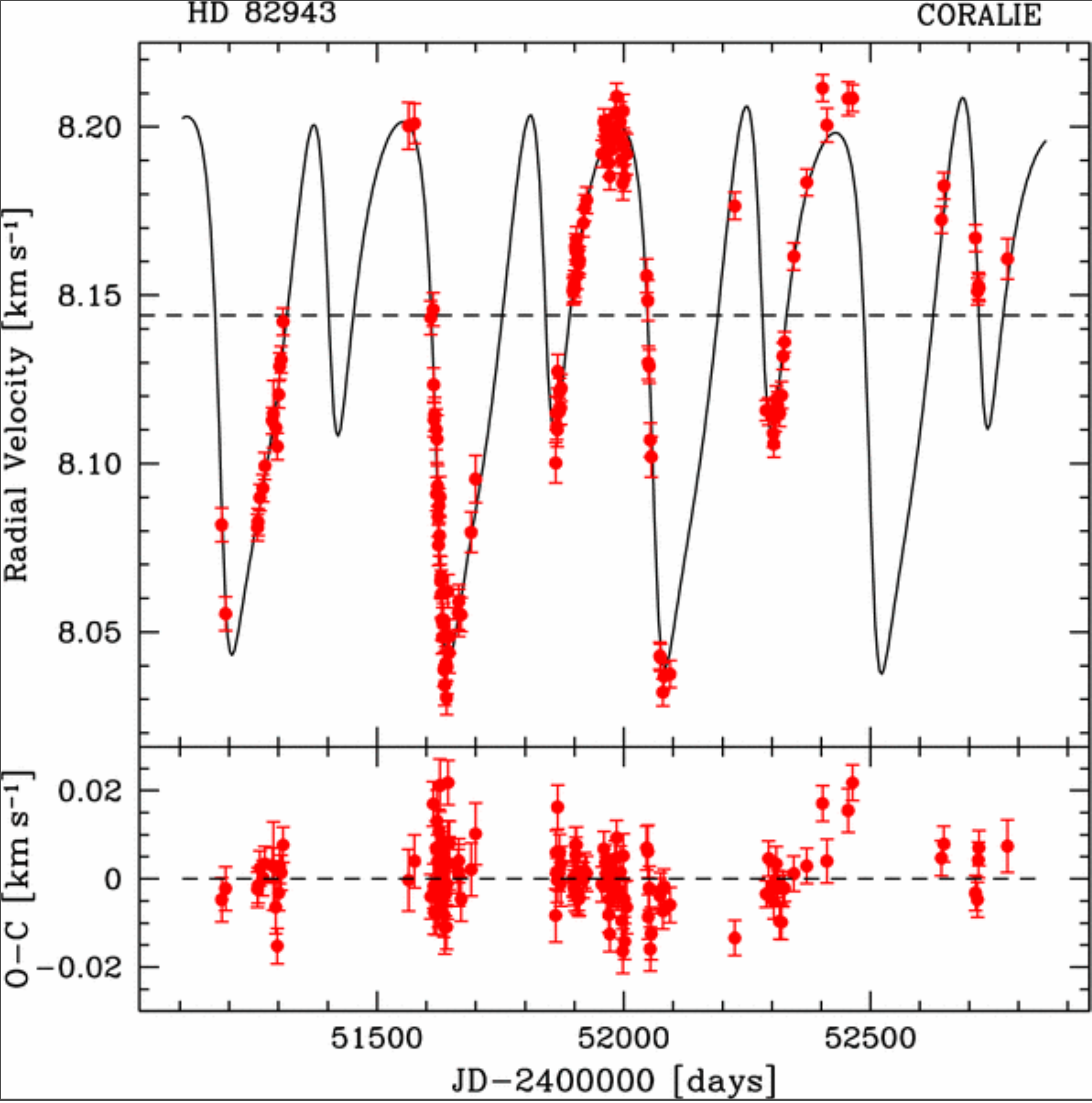
$$\Delta v \propto \frac{m \sin I}{M}\sqrt{\frac{GM}{a}}$$

Given the star mass M (known from spectral type), radial-velocity observations yield:

- orbital period P
- semi-major axis a
- combination of planet mass m & inclination I, m sin I
- orbit eccentricity e



- the star is similar to the Sun and 11 parsecs away
- the planet orbits once every 15.8 days, has a mass 4 X that of Jupiter (if edge-on orbit), and is 0.11 AU from the star



HD 82943

planet 1:

m sin I = 1.84M_J

P = 435 d

e = 0.18 ± 0.04

planet 2:

m sin I = 1.85M_J

P = 219 d

e = 0.38 ± 0.01

(Mayor et al. 2003)

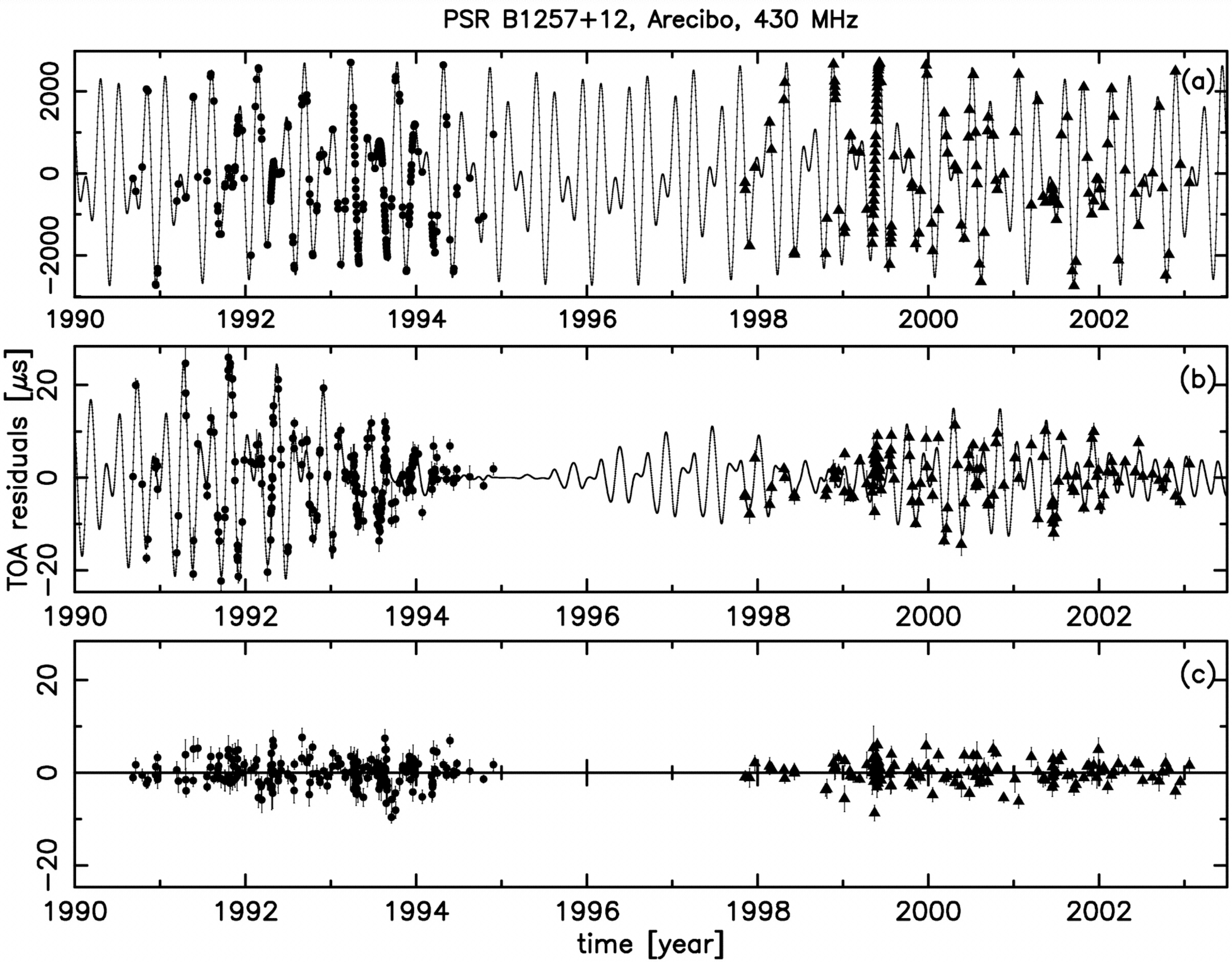
Timing

- works for pulsars, pulsating stars, eclipsing binaries
- observed period is $P=P_0(1+v/c)$ so

$$\frac{dv}{dt} = c\frac{d\log P}{dt}$$

Pulsar planets

- three planets discovered orbiting PSR B1257+12 by Wolszczan & Frail (1992)
- orbital parameters can be determined far more accurately than for radial-velocity measurements of nearby stars
- two planets near 3:2 resonance which enhances mutual perturbations, so these can be measured
- remarkably similar to the inner solar system



(a) no planets

(b) three planets

(c) three planets + mutual interactions

Konacki & Wolszczan (2003)

TABLE 2

ORBITAL AND PHYSICAL PARAMETERS OF PLANETS[a]

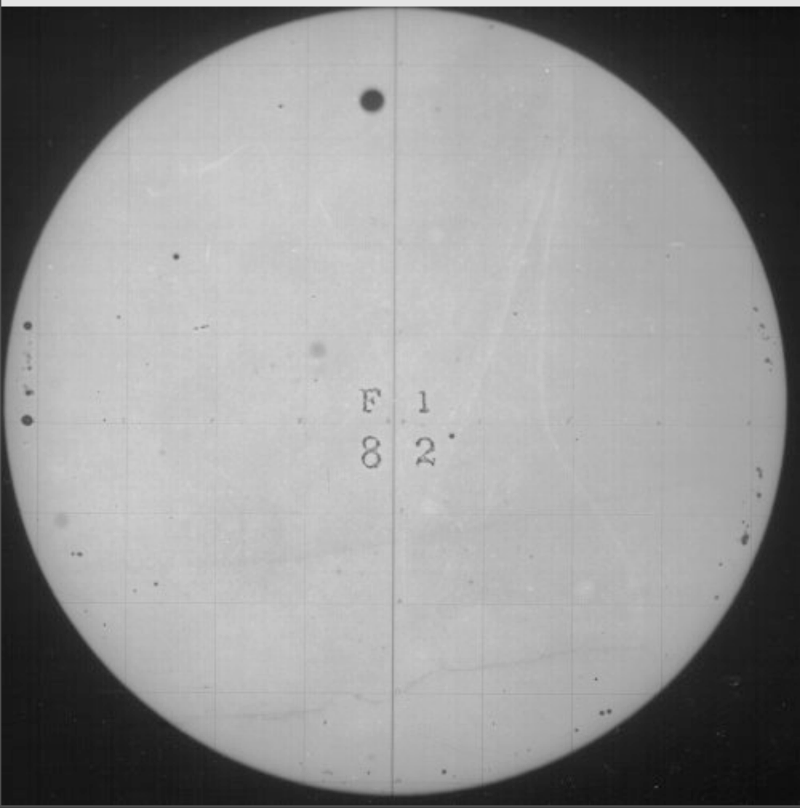
Parameter	Planet A	Planet B	Planet C
Projected semimajor axis, x^0 (ms)	0.0030 (1)	1.3106 (1)	1.4134 (2)
Eccentricity, e^0	0.0	0.0186 (2)	0.0252 (2)
Epoch of pericenter, T_p^0 (MJD)	49765.1 (2)	49768.1 (1)	49766.5 (1)
Orbital period, P_b^0 (day)	25.262 (3)	66.5419 (1)	98.2114 (2)
Longitude of pericenter, ω^0 (deg)	0.0	250.4 (6)	108.3 (5)
Mass ($M_\oplus$)	0.020 (2)	4.3 (2)	3.9 (2)
Inclination, solution 1, i^0 (deg)	...	53 (4)	47 (3)
Inclination, solution 2, i^0 (deg)	...	127 (4)	133 (3)
Planet semimajor axis, a_p^0 (AU)	0.19	0.36	0.46
Non-Keplerian dynamical parameters	...	...	...
γ_B ($\times 10^{-6}$)	...	9.2 (4)	...
γ_C ($\times 10^{-6}$)	...	8.3 (4)	...
τ (deg)	...	2.1 (9)	...

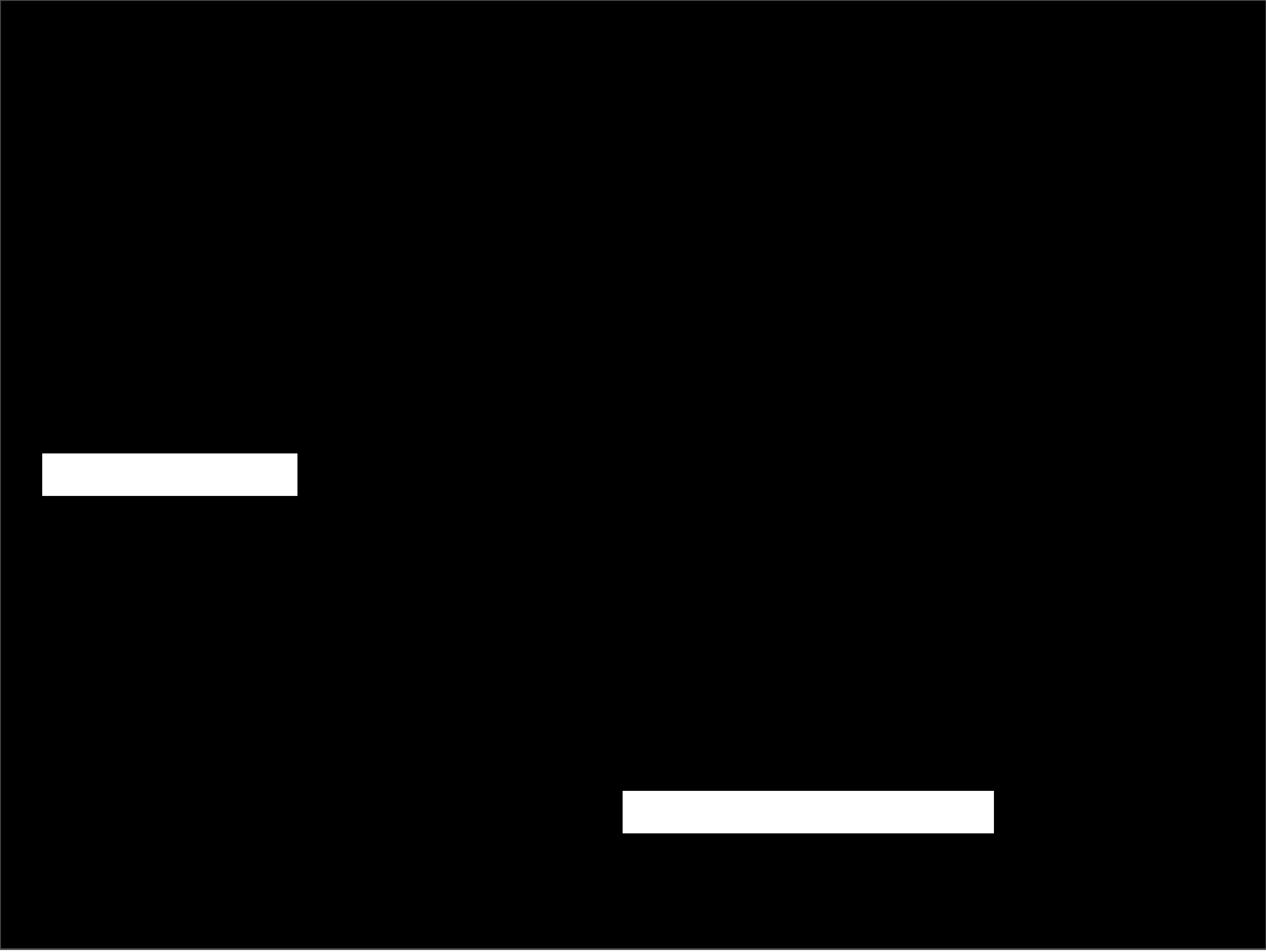
[a] Figures in parentheses are the formal 1 σ uncertainties in the last digits quoted.

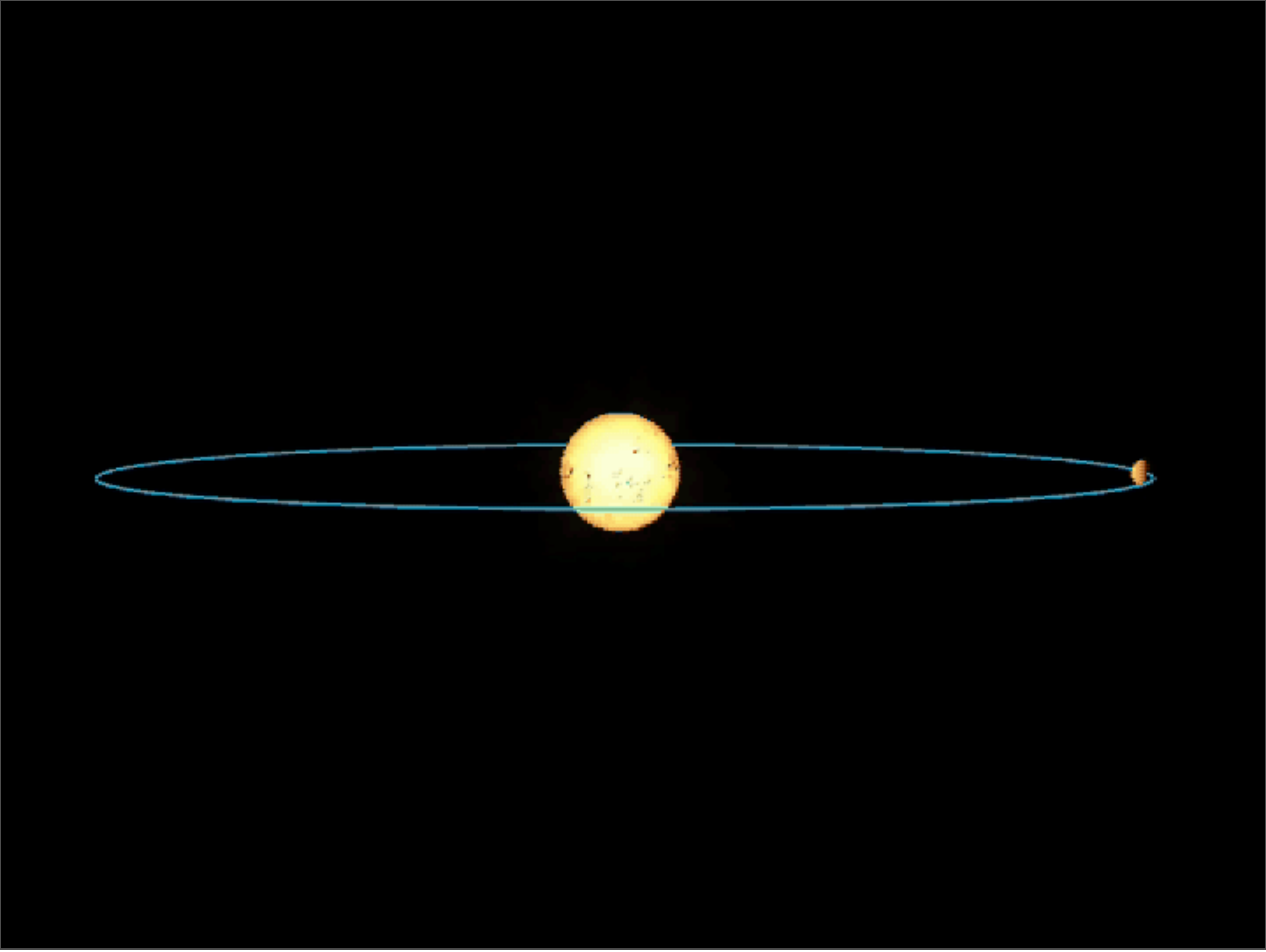
Konacki & Wolszczan (2003)

Transit of Venus

- next June 6, 2012, 22:10 UTC at Tokyo





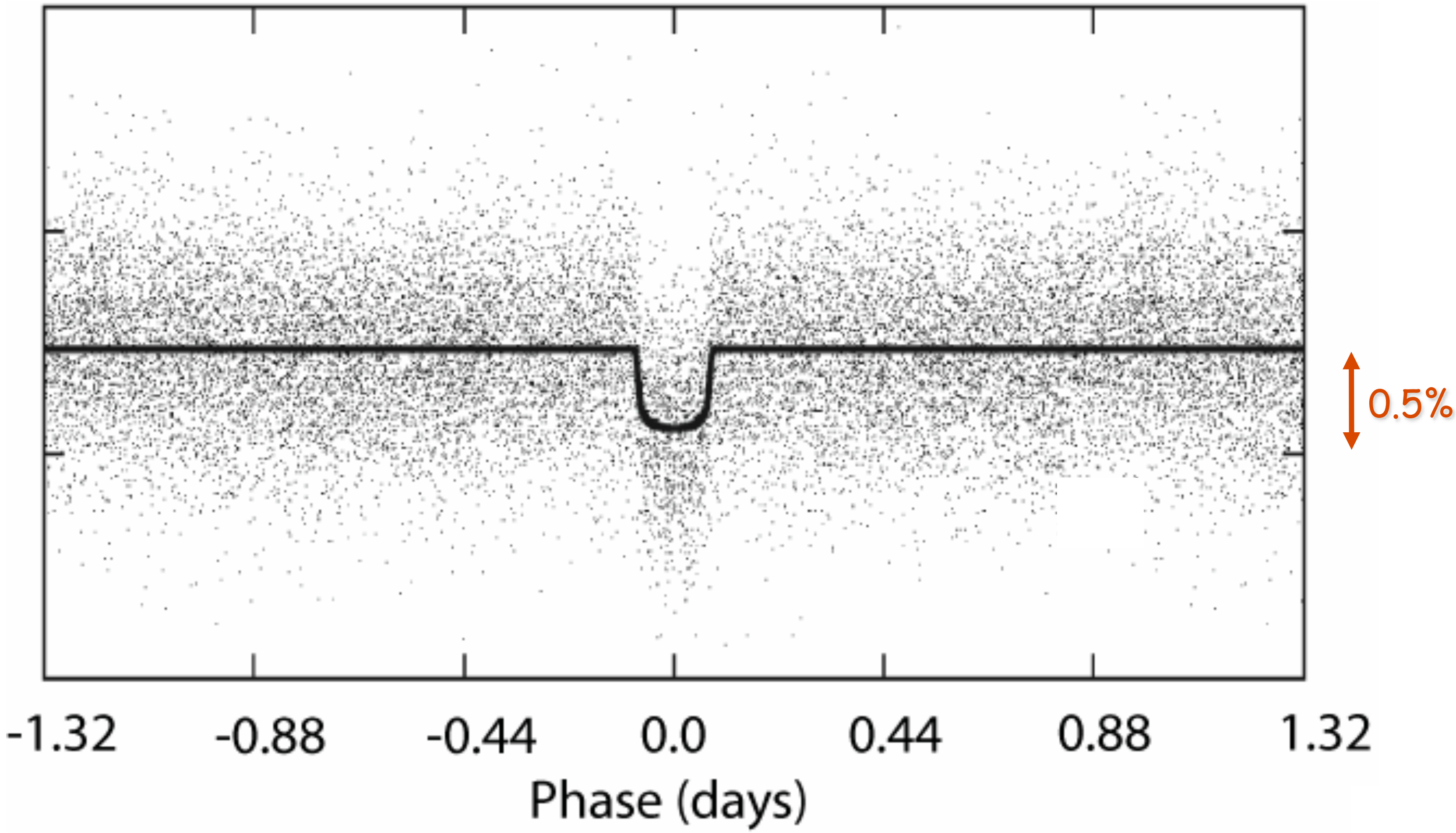


Transit searches

Why are these so hard?

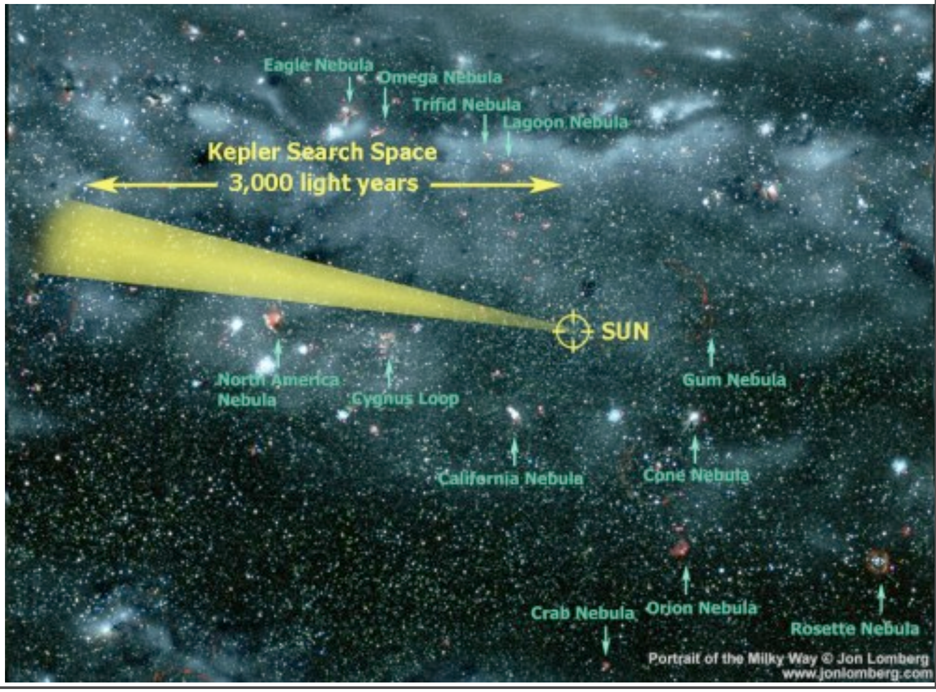
- probability that a given planet will transit is small, ~ r_{star}/a (only 0.5% at a = 1 AU)
- transit duration is short, $\sim(r_{star}/a)P/\pi$
- transit depth is small, <1% *
- confusion from grazing eclipsing binary stars
- star spots, stellar pulsations, stellar flares
- incomplete sampling (daytime, weather, observing schedules, etc.)*

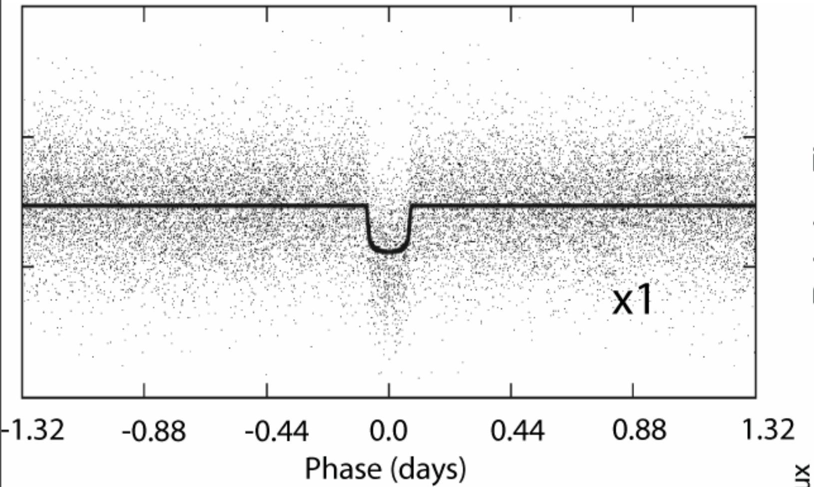
* much easier in space


0.5%
-1.32
-0.88
-0.44
0.0
0.44
0.88
1.32
Phase (days)

Kepler (NASA)

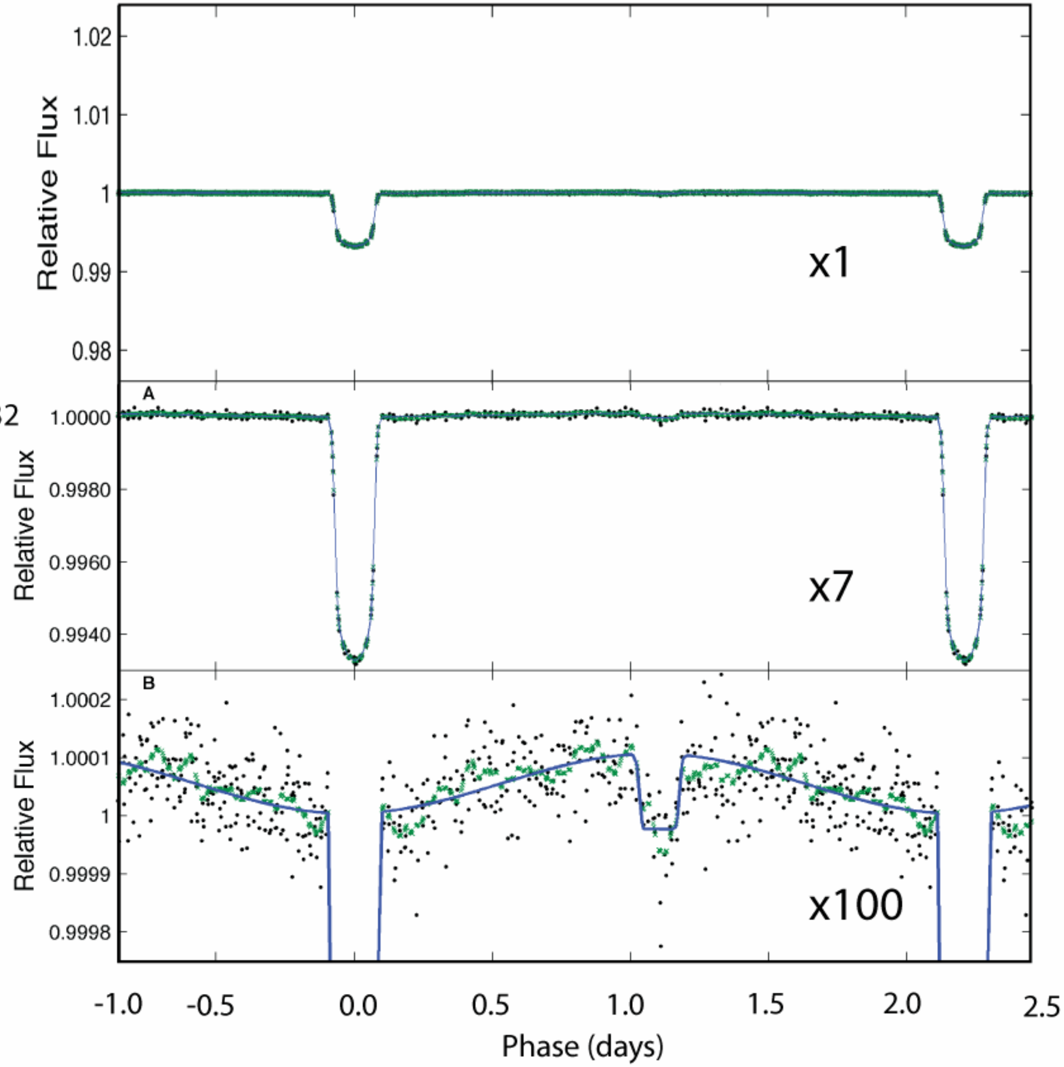
- launch March 6 2009
- stare 24/7 for five years at a single patch of sky
- monitor 200,000 stars for transits
- ppm precision





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

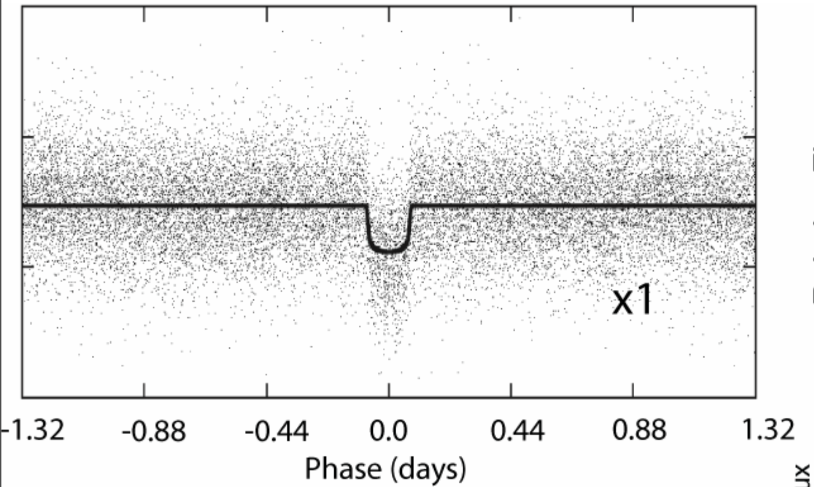
HAT-P-7b data from the ground



Kepler Commissioning data (10 days)

transit: planet moves in front of the star; U-shape because of limb darkening in star

occultation: planet moves behind the star; square shape



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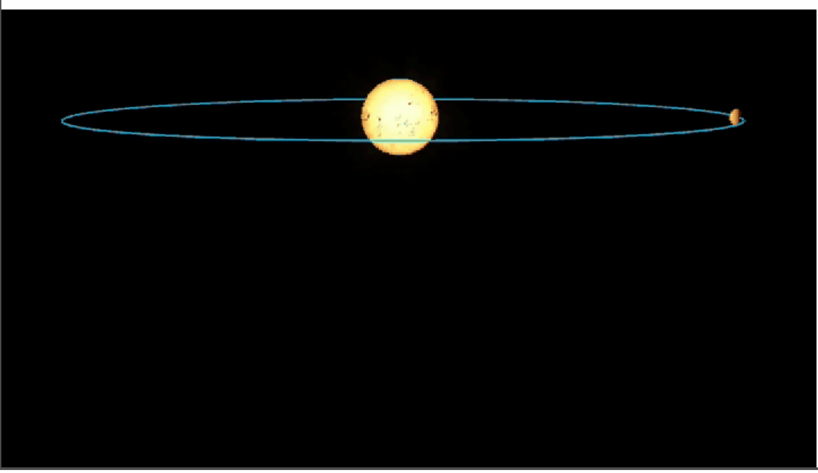
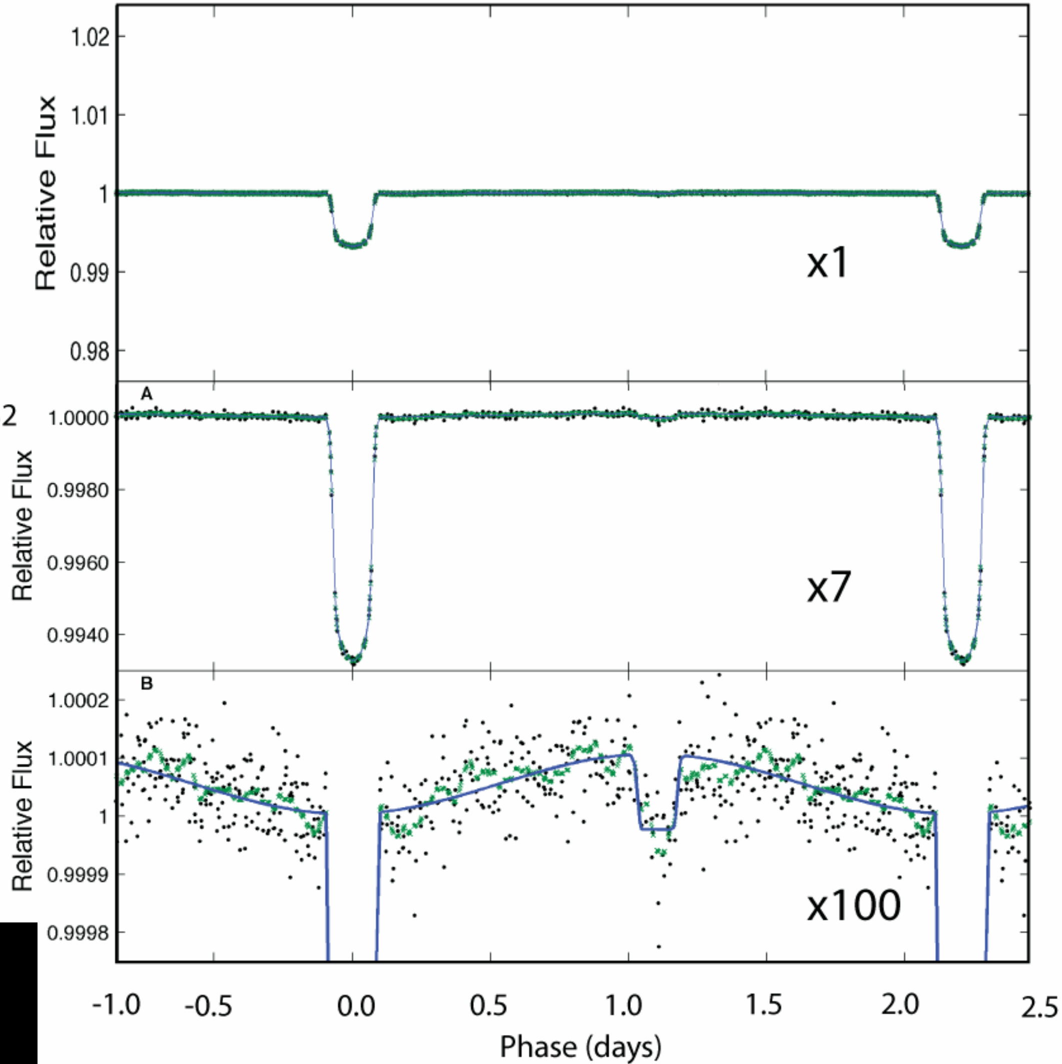
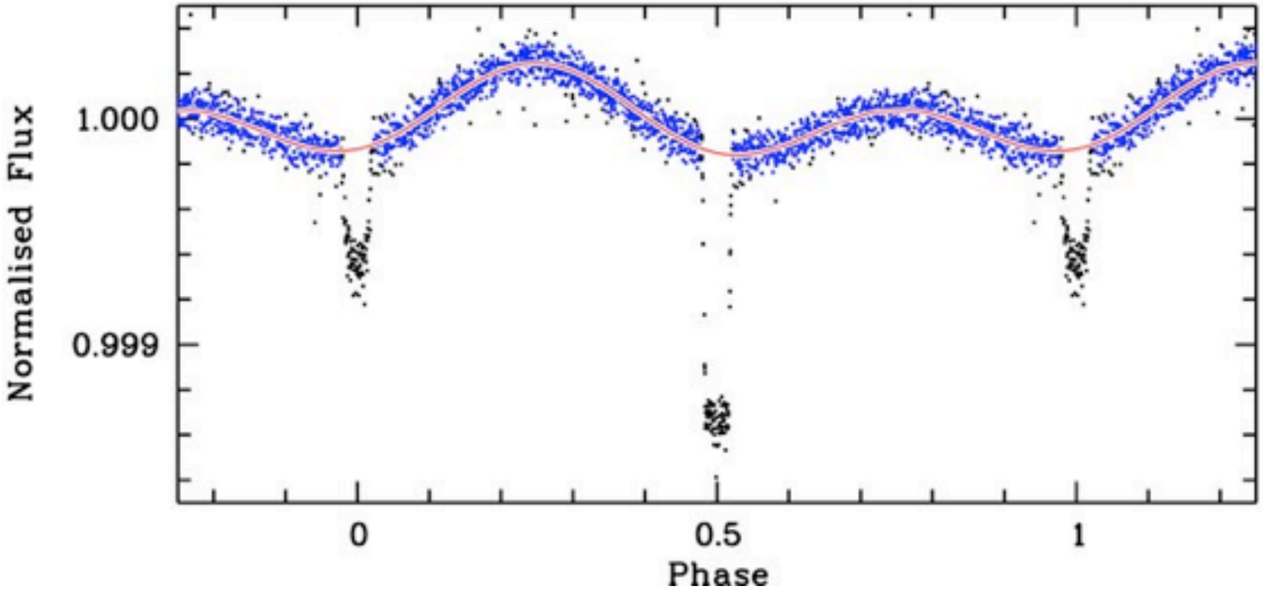


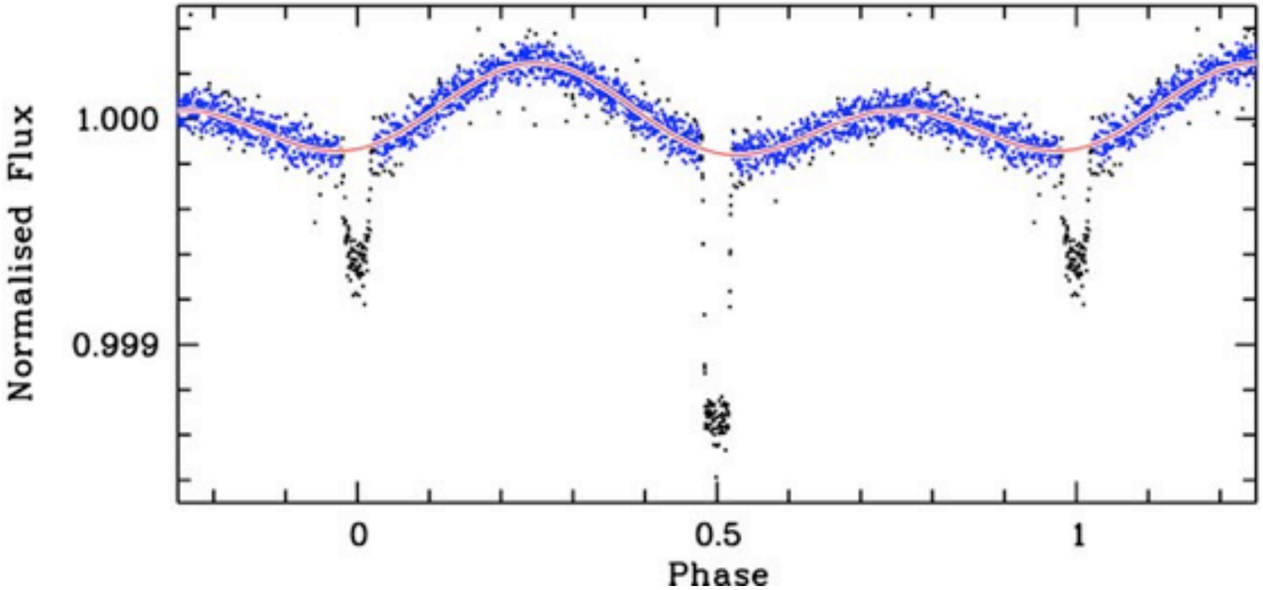


Kepler Commissioning data (10 days)



van Kerkwijk et al. (2010)

- orbital period P = 5.2 days
- two curious features:
    - sinusoidal brightness variations at fundamental and first harmonic
    - transit (U shape) is shallower than occultation (square well)



van Kerkwijk et al. (2010)

- orbital period P = 5.2 days
- two curious features:
  - sinusoidal brightness variations at fundamental and first harmonic
  - transit (U shape) is shallower than occultation (square well)
- both can be explained if the companion is a white dwarf rather than a planet:
  - occultation is deeper because the white dwarf is hotter than the primary (T=13,000 K vs. 9,400 K)
  - first harmonic due to tidal distortion of the primary by the white dwarf
  - fundamental due to Doppler boosting
  - white dwarf has mass 0.22±0.03 $M_\odot$; radius 0.043±0.004 $R_\odot$

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 $V^2 \sim \frac{1}{P}$. 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.

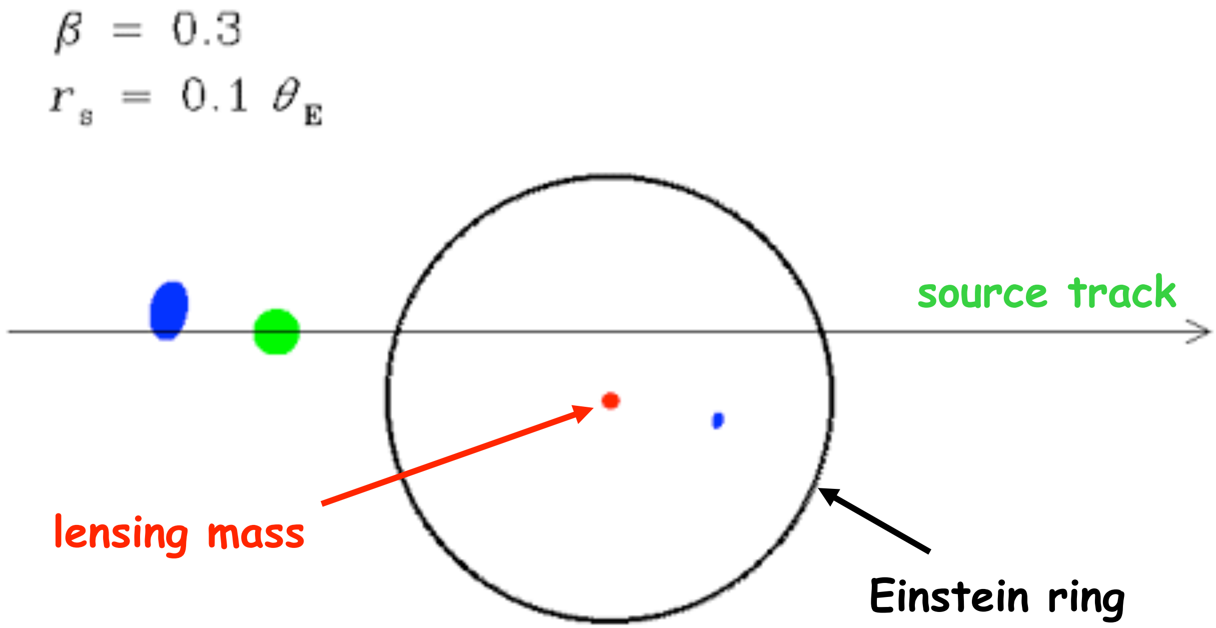
Gravitational lensing

- a particle traveling at high speed v past a mass M with impact parameter b suffers angular deflection $\alpha = 2GM/v^2b$
- in general relativity, deflection of a photon is obtained by replacing v by c and multiplying by 2:

$$\alpha = \frac{4GM}{c^2 b}$$

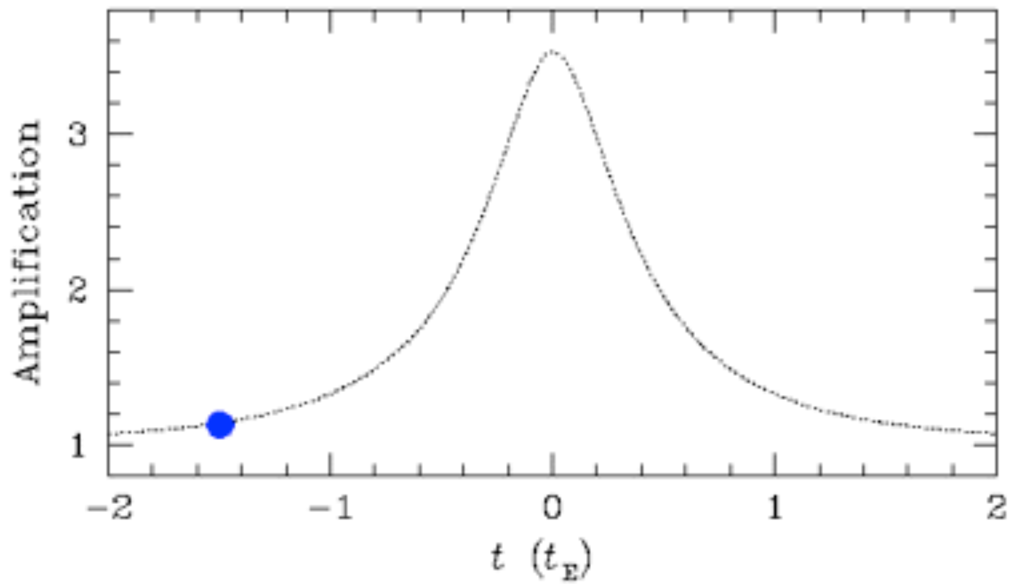
- three effects: position shift, image splitting, image magnification

Gravitational lensing



the gravitational field from the lensing star:

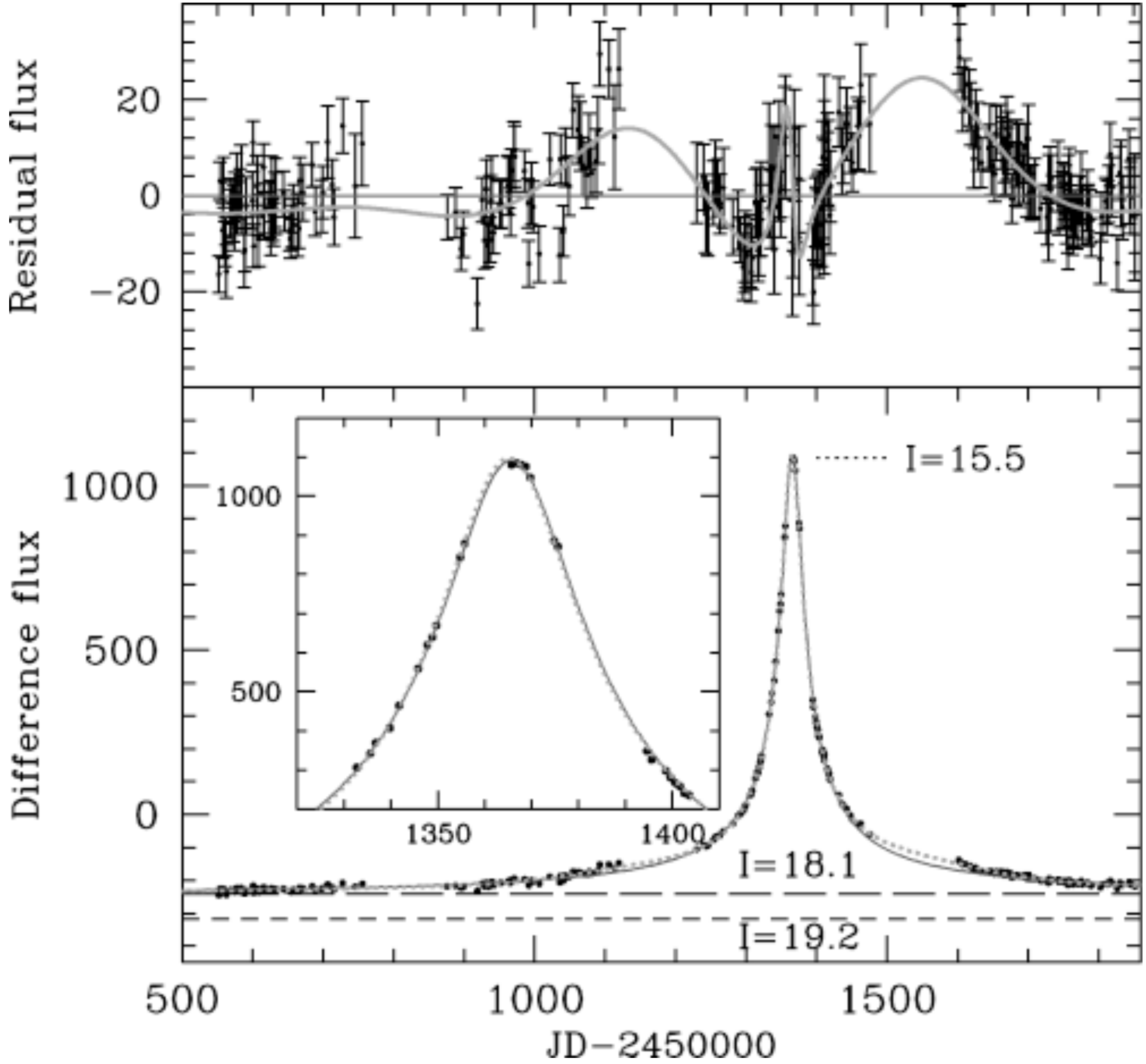
- splits image into two
- magnifies one image and demagnifies the other
- if source, lens and observer are exactly in line the image appears as an Einstein ring



Gravitational microlensing

Consider a source star near the center of the Galaxy, lensed by an intervening star at half that distance. Then θ_E=0.001 arcsec ~ 4 AU.

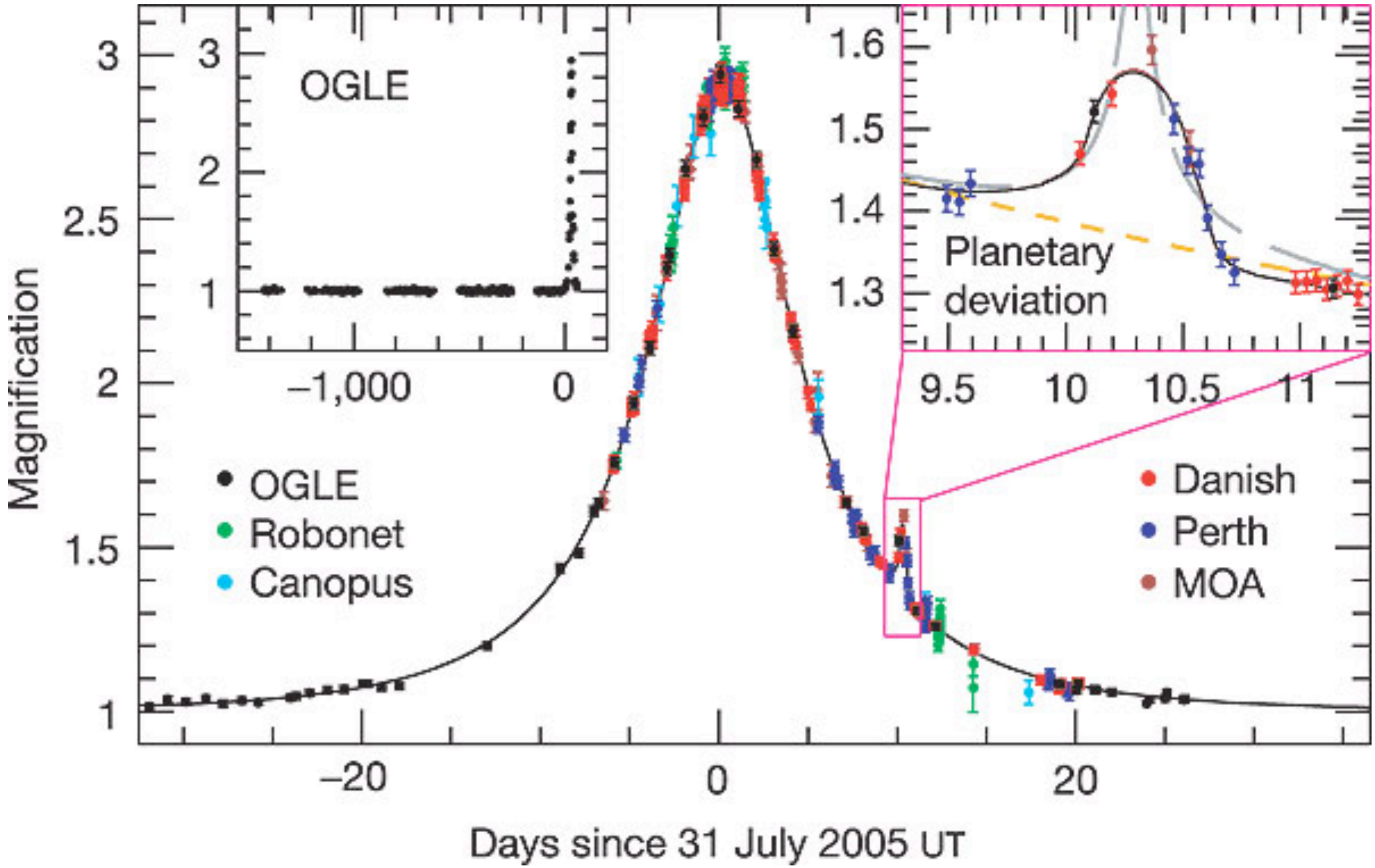
- image splitting or shift is impossible to see
- image magnification is easy to see
- time required to transit Einstein ring $\sim D_L\theta_E/v \sim 0.2$ yr, for $v \sim 100$ km/s
- substantial magnification if and only if impact parameter less than Einstein radius
- chance that any given star is microlensed is only $\sim 10^{-6}$



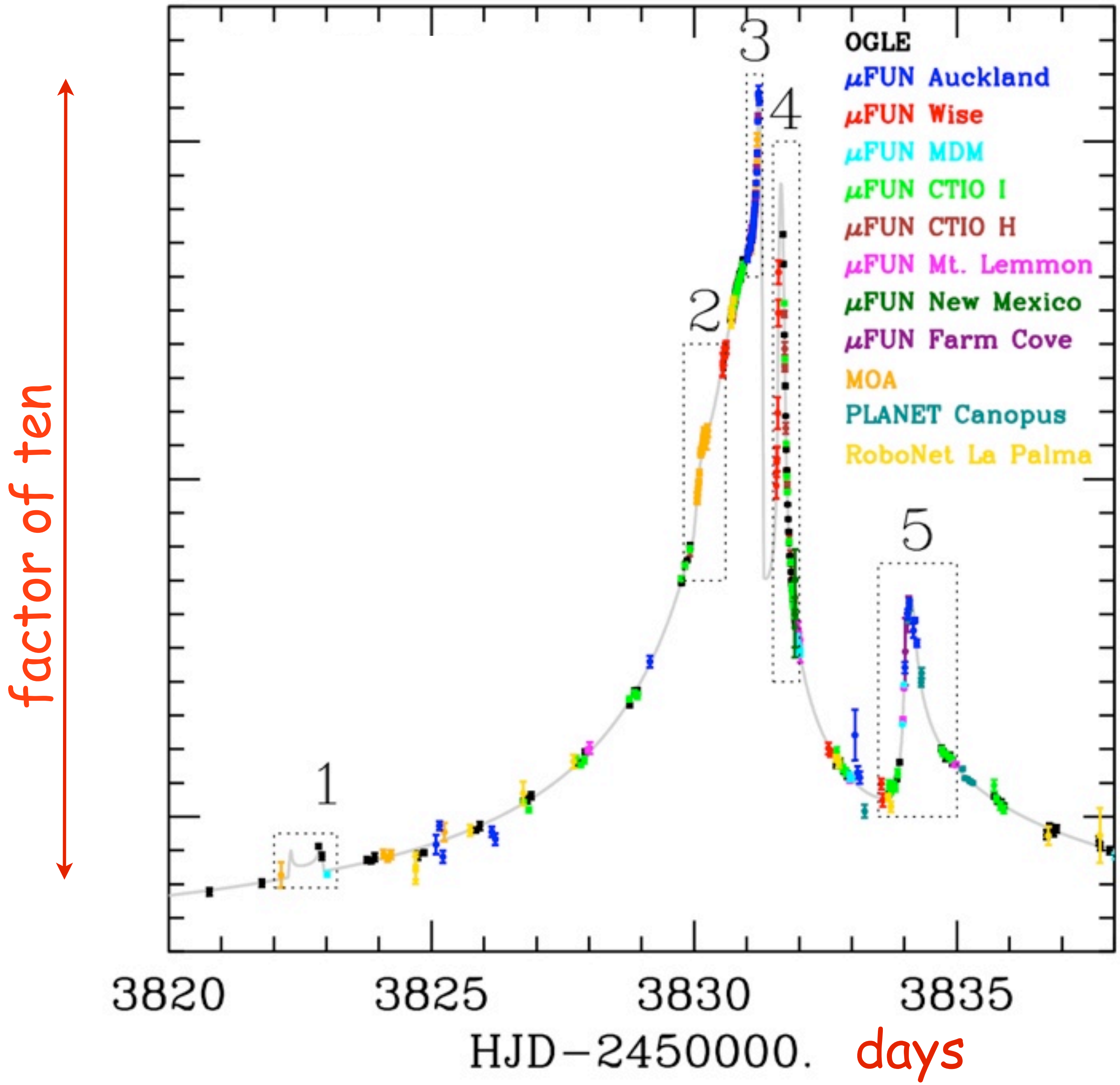
Mao et al. (2002)

Gravitational microlensing of planets

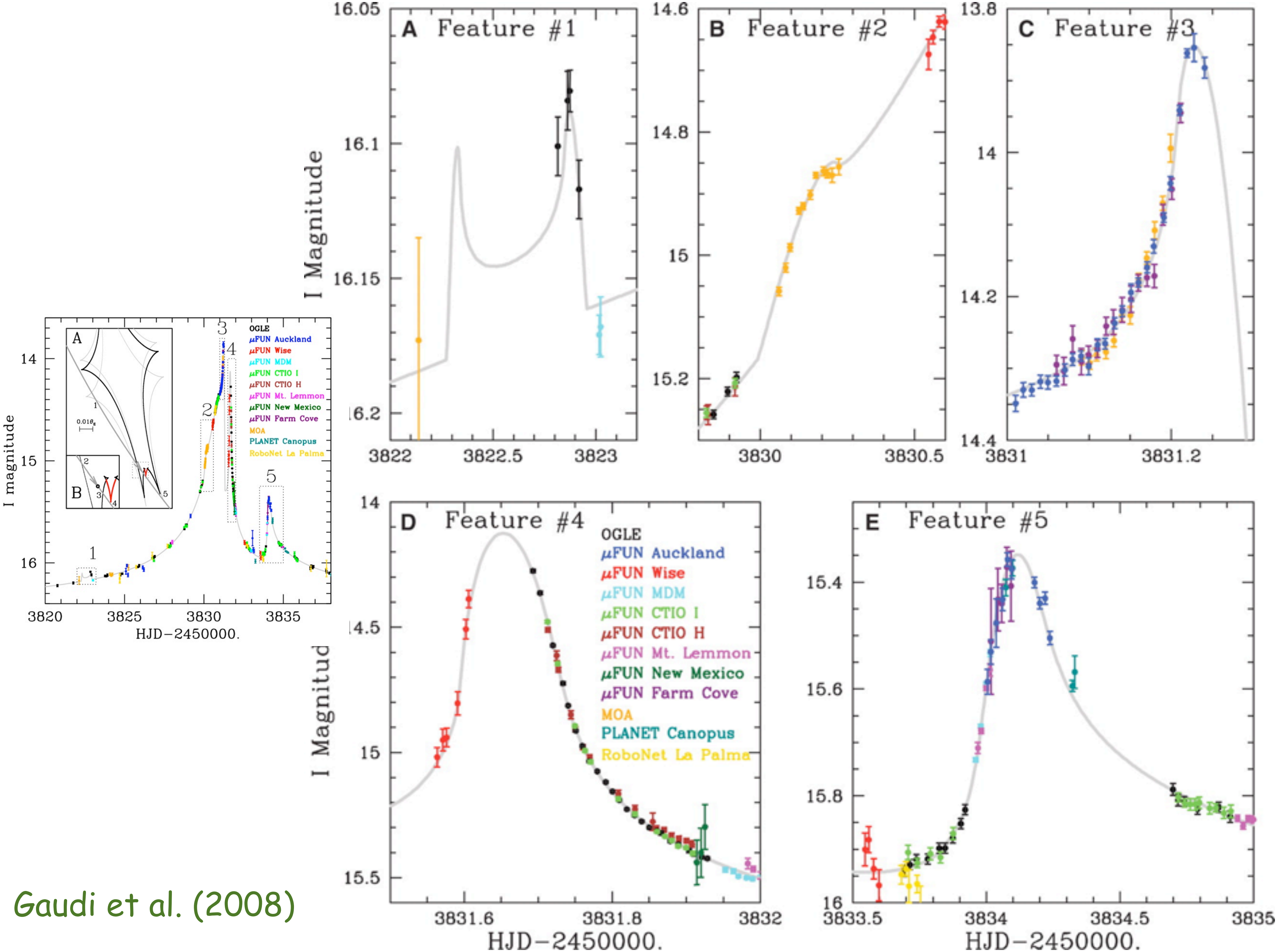
- Einstein radius scales as $M^{1/2}$ so cross-section and expected duration scale as $M^{1/2}$~ 0.03 for Jupiter, i.e. duration ~ 1 day for Jupiter, ~1 hour for Earth
- image magnification is the same
- Einstein ring radius ~ typical planet orbital radius



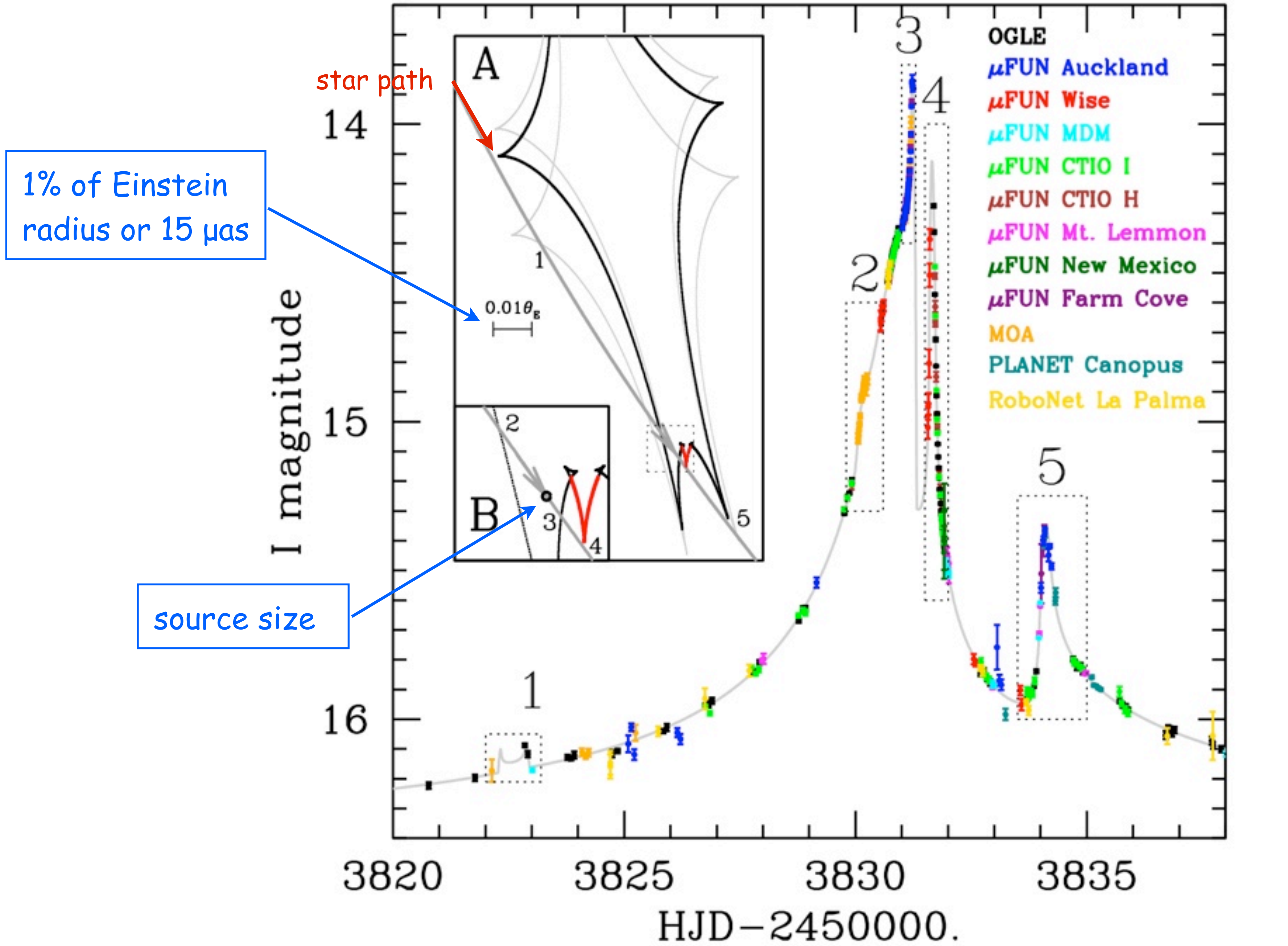
Beaulieu et al. (2006): 5.5 (+5.5/-2.7) M_{Earth}, 2.6 (+1.5/-0.6) AU orbit, 0.22(+0.21/-0.11) M_{Sun}, D_L=6.6±1.1 kpc



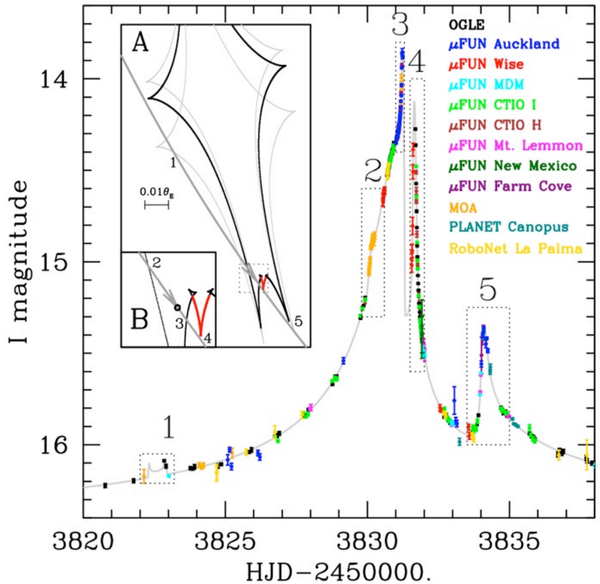
Gaudi et al. (2008)



Gaudi et al. (2008)

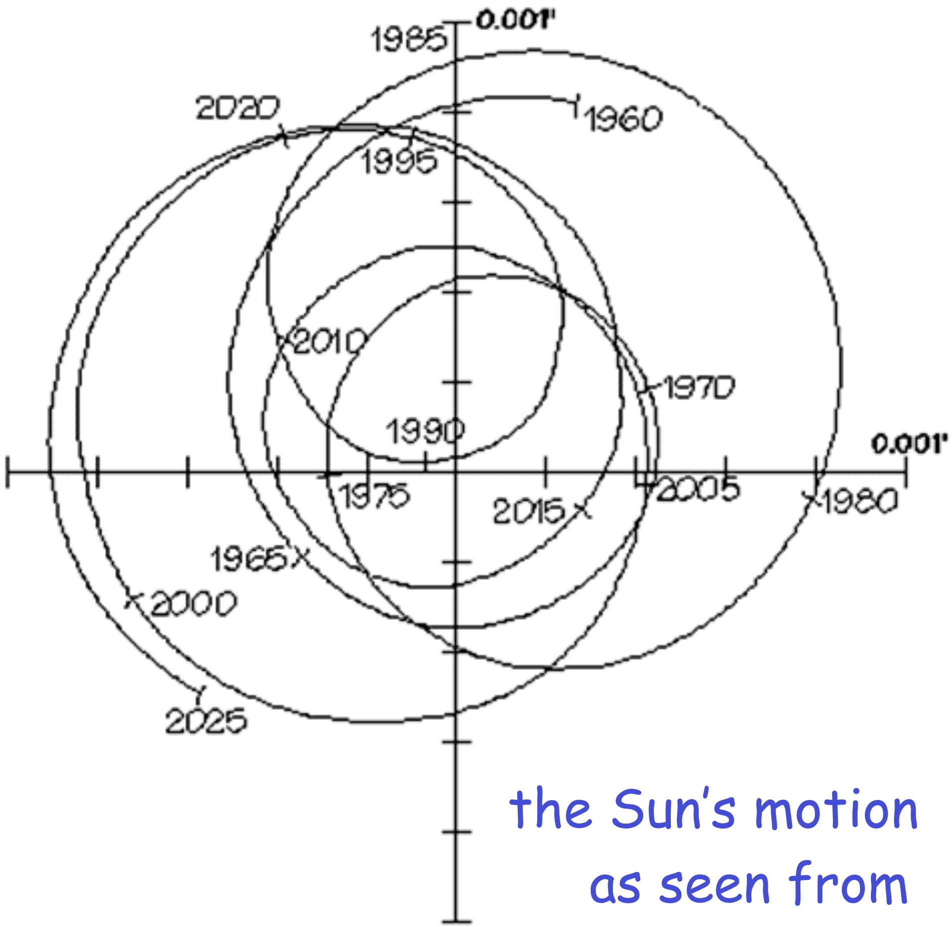

star path
1% of Einstein radius or 15 μas
source size
A
B
0.01θ_E
1
2
3
4
5
14
15
16
I magnitude
3820
3825
3830
3835
HJD−2450000.
OGLE
μFUN Auckland
μFUN Wise
μFUN MDM
μFUN CTIO I
μFUN CTIO H
μFUN Mt. Lemmon
μFUN New Mexico
μFUN Farm Cove
MOA
PLANET Canopus
RoboNet La Palma

- two planets, b and c
- can detect orbital motion of Earth and planet c
- $m_b = 0.71 \pm 0.08\ M_{Jupiter}$, $m_c = 0.27 \pm 0.03\ M_{Jupiter}$
- assuming coplanar, circular orbits $a_b = 2.3 \pm 0.2$ AU, $a_c = 4.6 \pm 0.5$ AU
- distance 1.49 ± 0.13 kpc
- $M_* = 0.50 \pm 0.05\ M_\odot$



Gaudi et al. (2008)

Astrometry



the Sun's motion as seen from 10 pc

why this is hard:

- typical motions << 0.001 arcsec ~ 10^{-8} radians
- not many nearby stars
- confusion from outer planets: maximum radial velocity is $(m/M)(GM/a)^{1/2}$ but maximum wobble is $(m/M)a$

space missions:

- GAIA (ESA)
    - launch 2013
    - every Jupiter analog within 50 pc
    - 10^4 - 5×10^4 planets
    - also transits via photometry

the current track record:

• imaging:	26
• radial velocity:	644
• transits:	185
• gravitational lensing:	13
• timing:	12
• astrometry:	0

see
http://www.exoplanet.eu,
http://exoplanets.org/

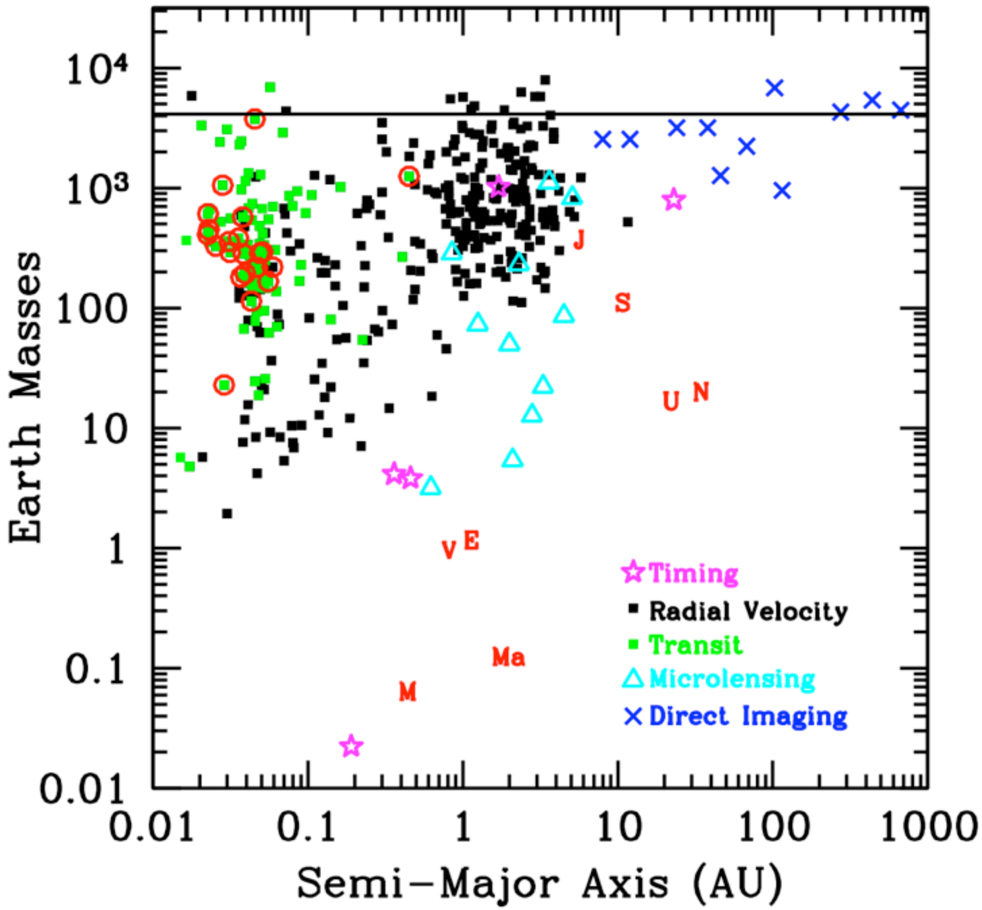
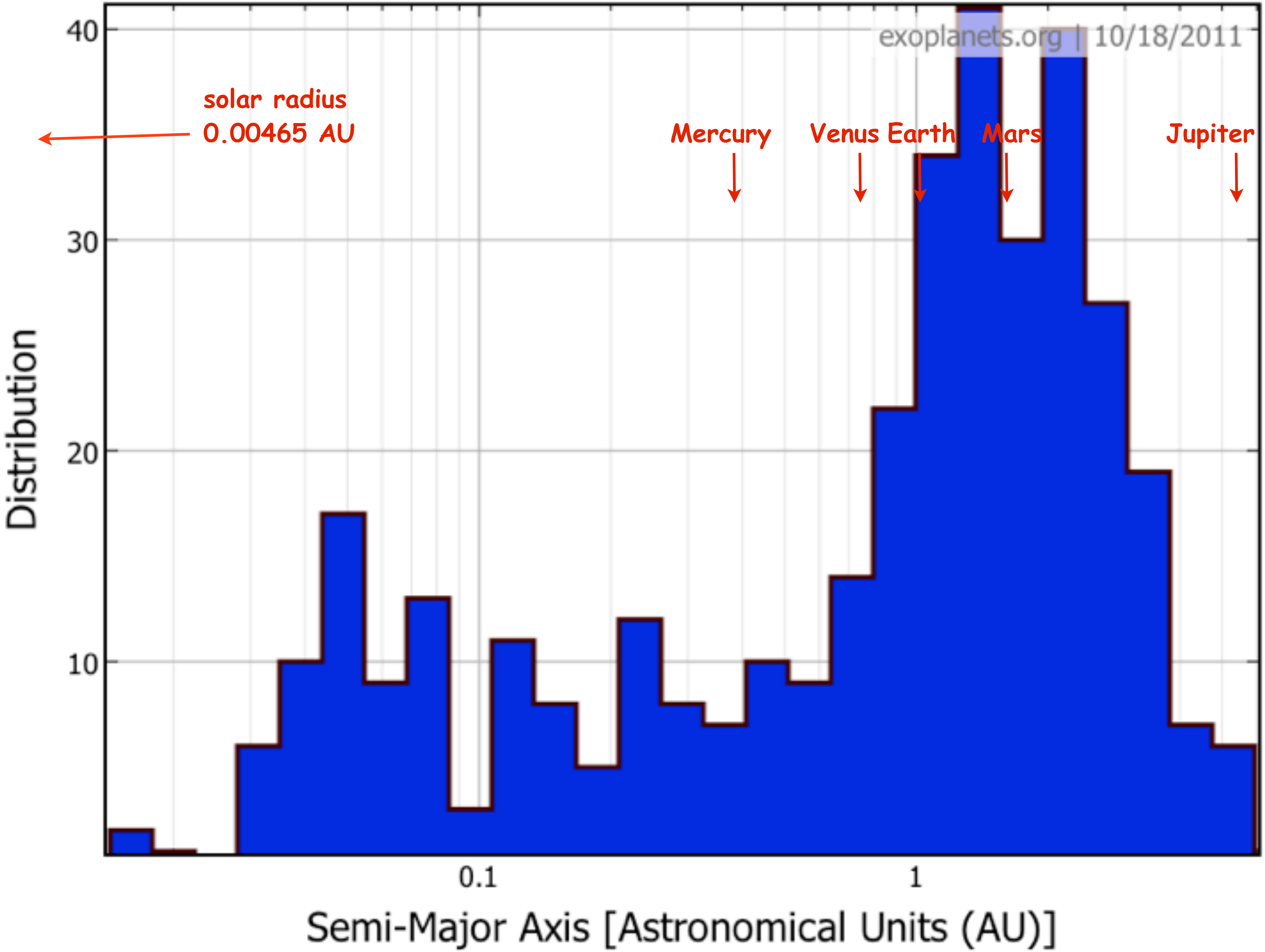
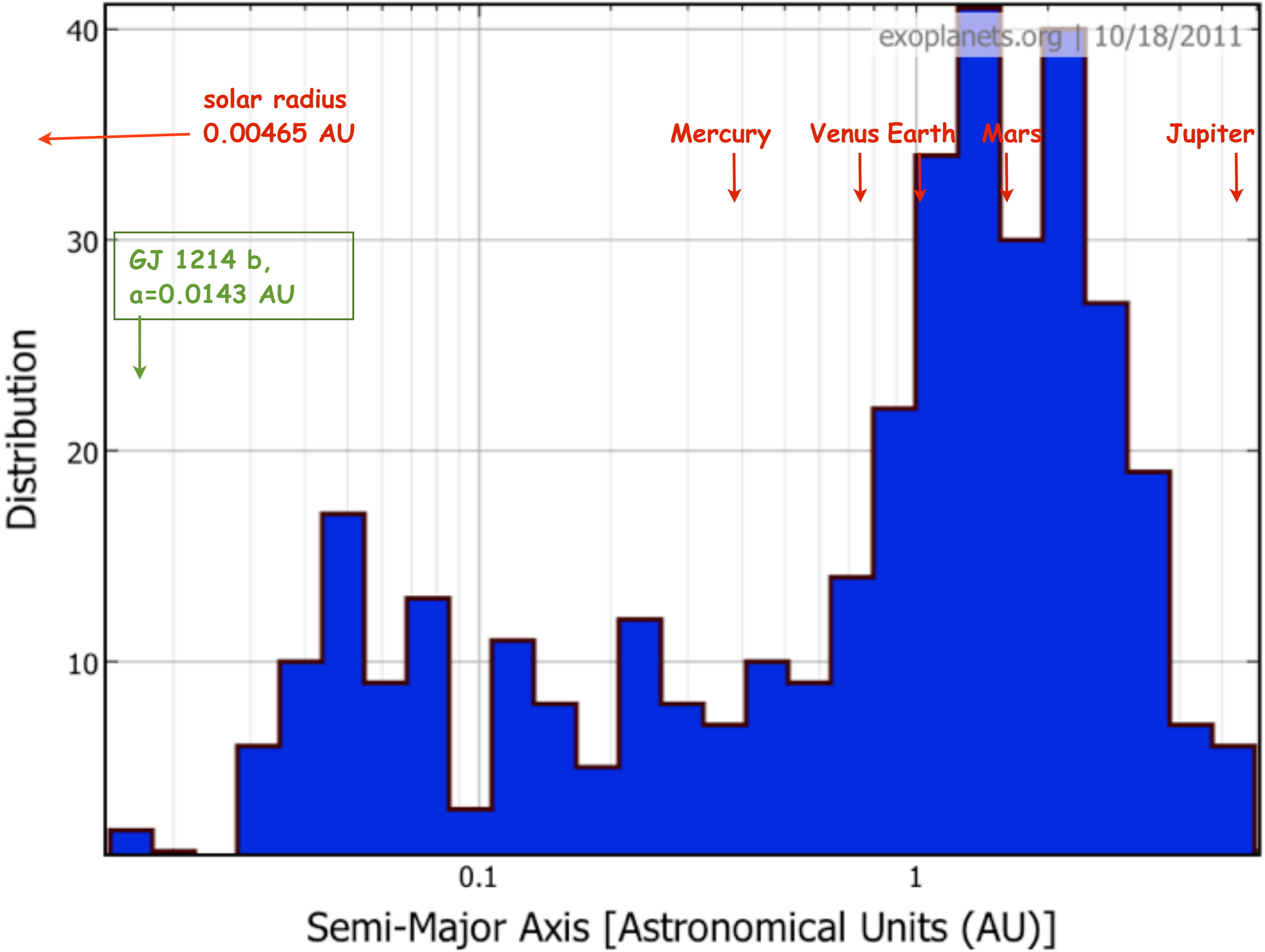


figure from
Seager (2011)

Current record-holders (RV surveys)

- smallest semi-major axis a = 0.0143 AU = 3.06 R_{Sun}
- largest semi-major axis a=11.6 AU (Jupiter = 5.2 AU)
- biggest eccentricity e = 0.94
- smallest eccentricity e = 0
- smallest mass 0.0061 $M_{Jupiter}$ = 1.9 M_{Earth}


exoplanets.org | 10/18/2011
solar radius
0.00465 AU
Mercury
Venus
Earth
Mars
Jupiter
40
30
20
10
Distribution
0.1
1
Semi-Major Axis [Astronomical Units (AU)]


exoplanets.org | 10/18/2011
solar radius
0.00465 AU
Mercury
Venus Earth
Mars
Jupiter
GJ 1214 b,
a=0.0143 AU
40
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20
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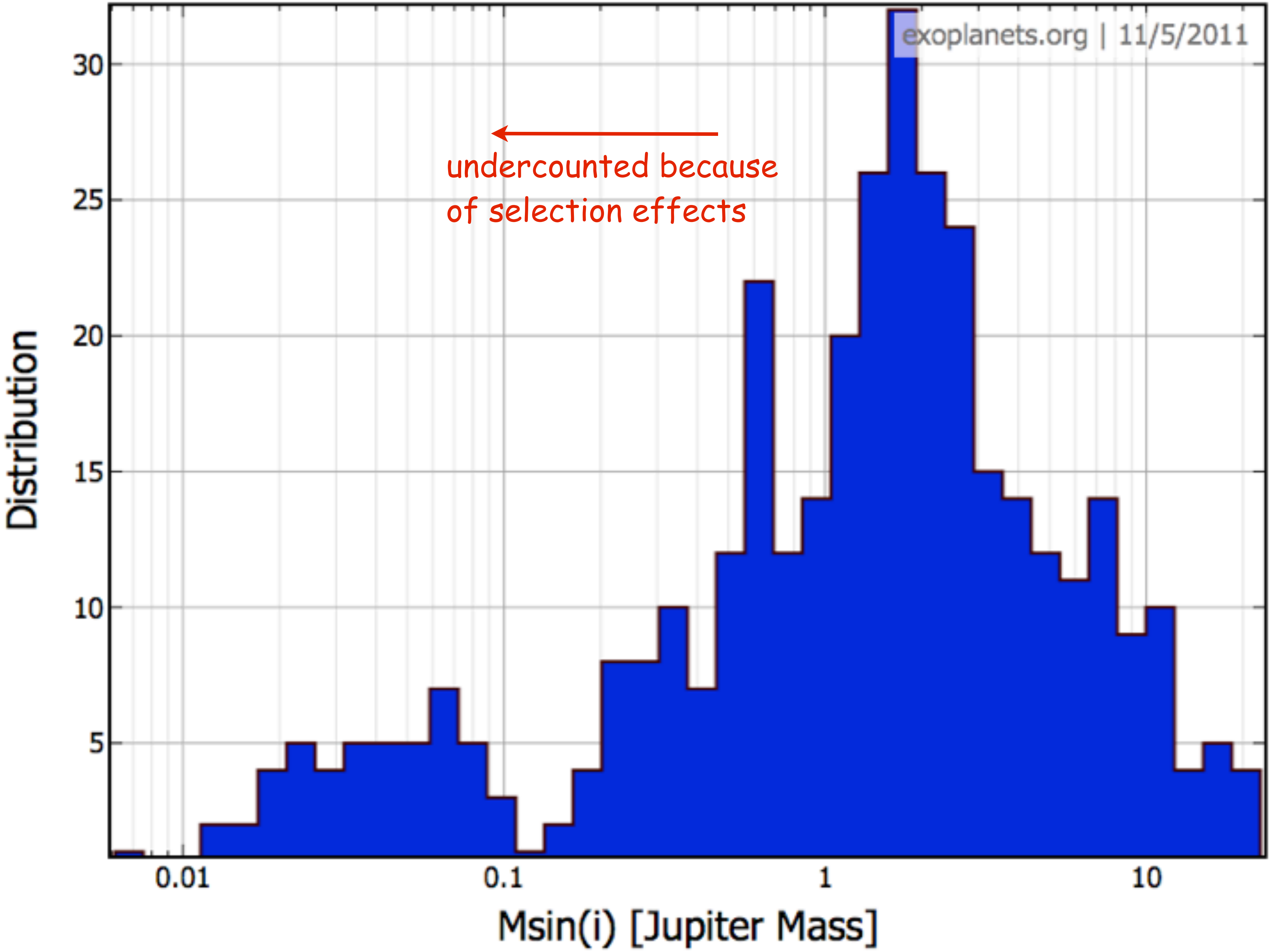
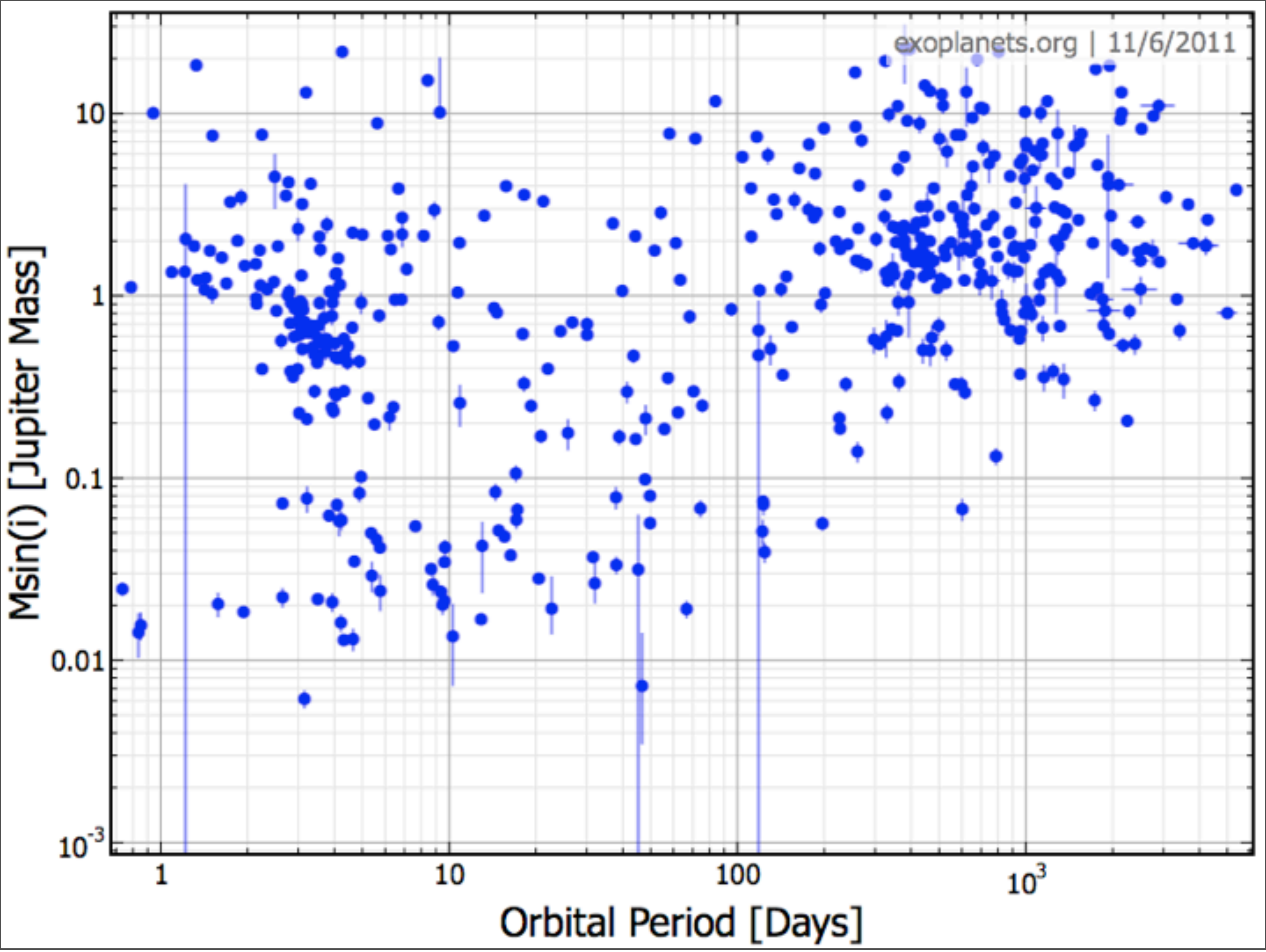
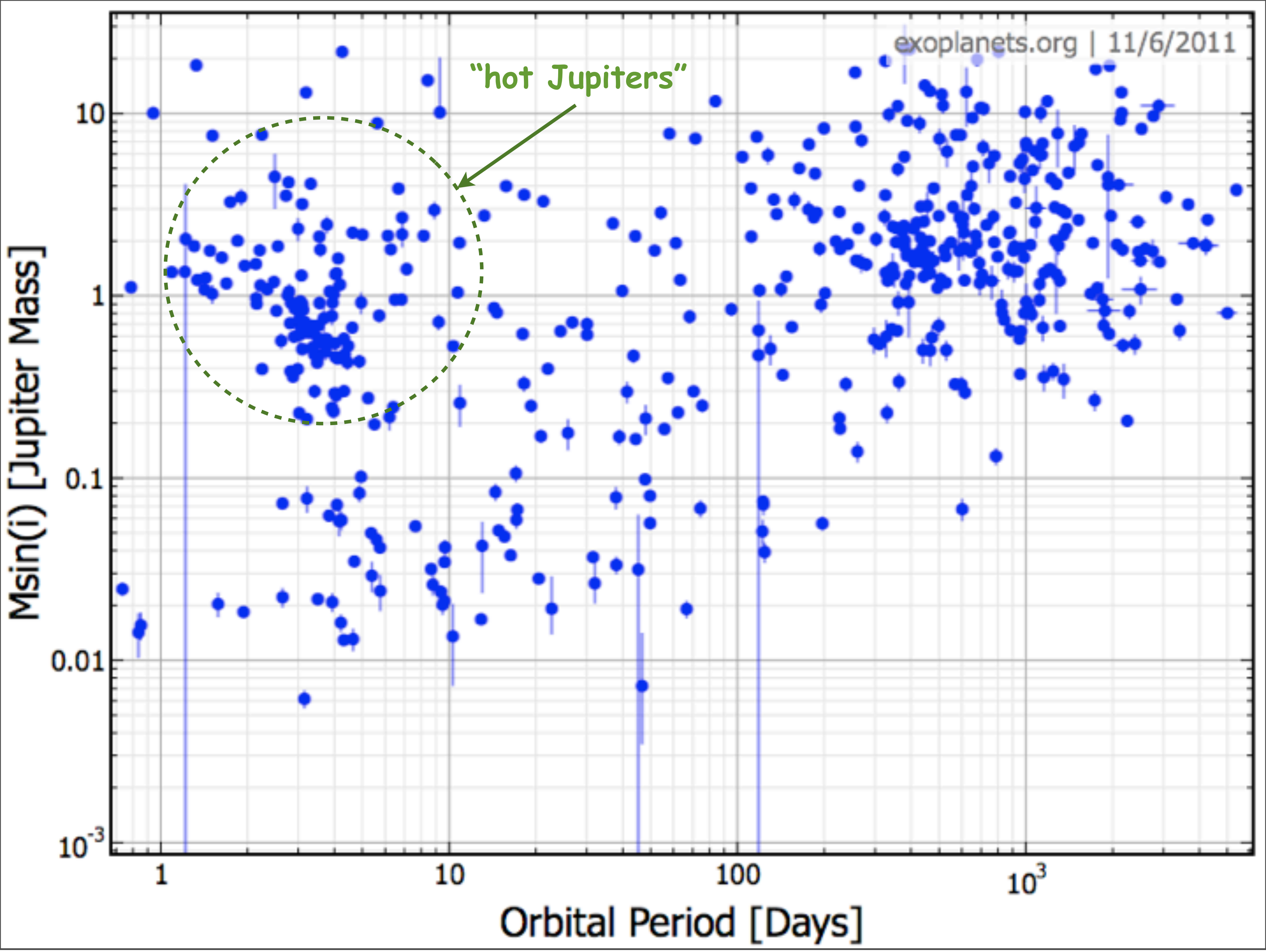
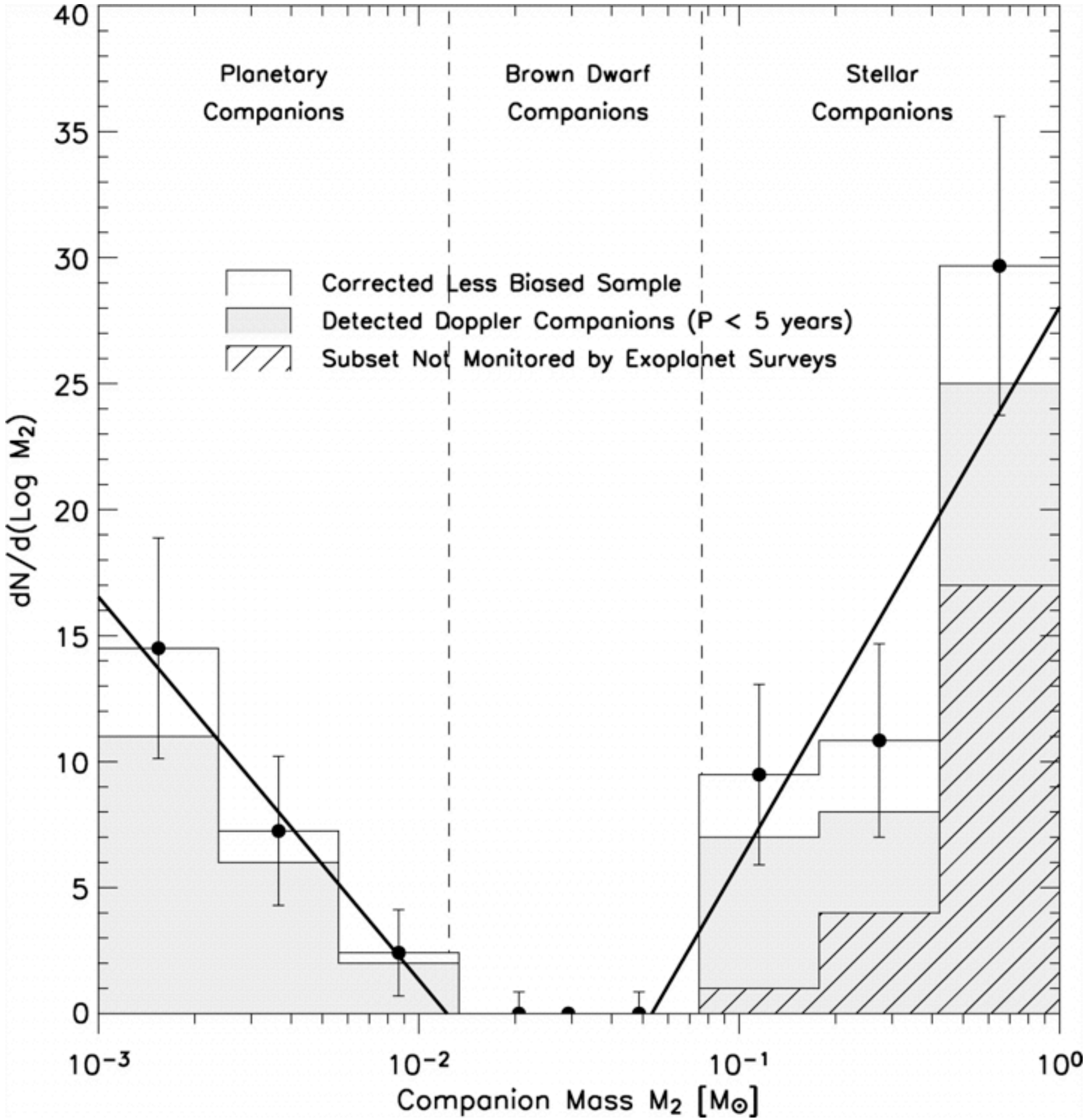
Distribution
0.1
1
Semi-Major Axis [Astronomical Units (AU)]

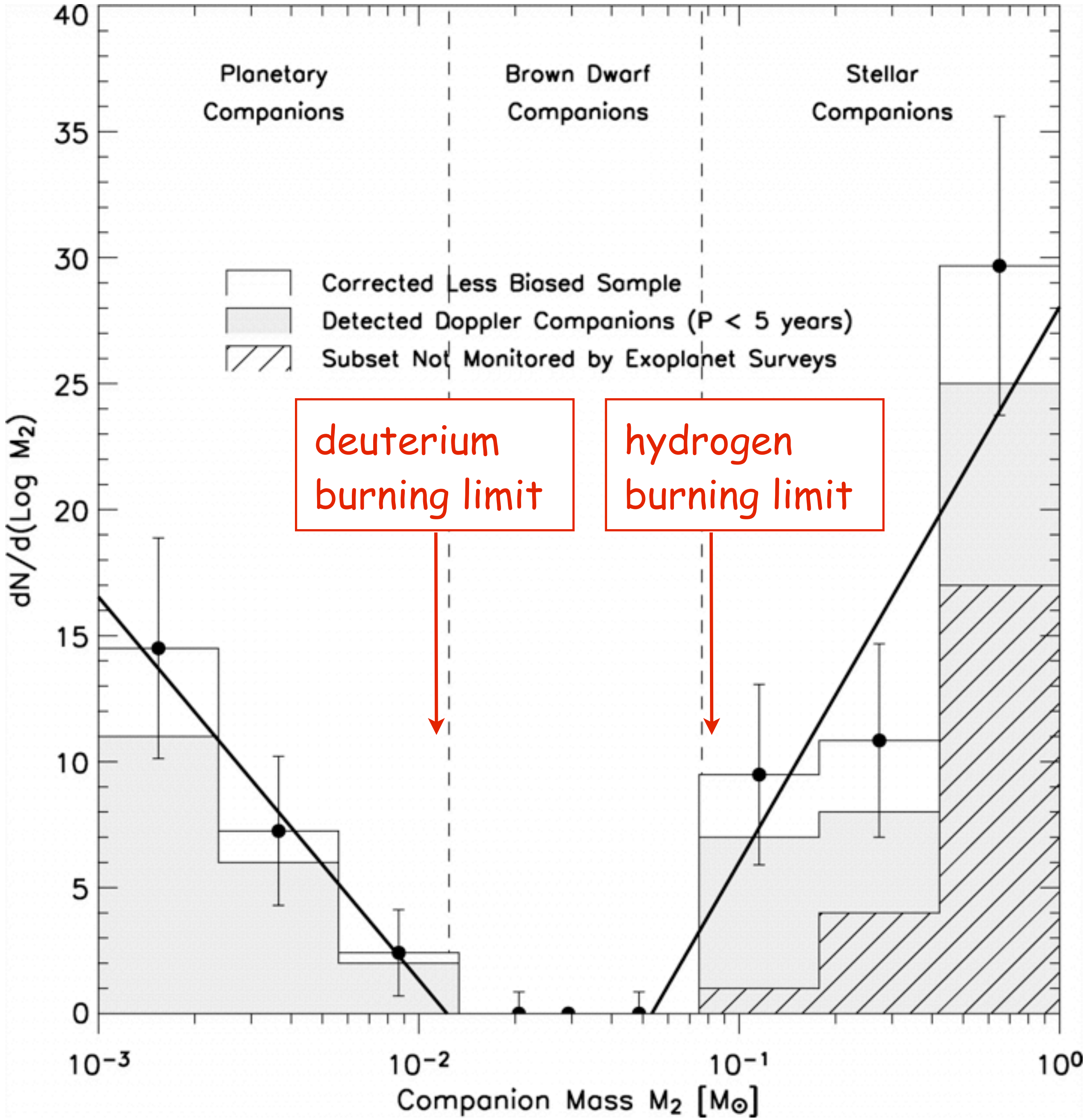

exoplanets.org | 11/5/2011
undercounted because
of selection effects
Distribution
30
25
20
15
10
5
0.01
0.1
1
10
Msin(i) [Jupiter Mass]


exoplanets.org | 11/6/2011
Msin(i) [Jupiter Mass]
10
1
0.1
0.01
10^-3
1
10
100
10^3
Orbital Period [Days]

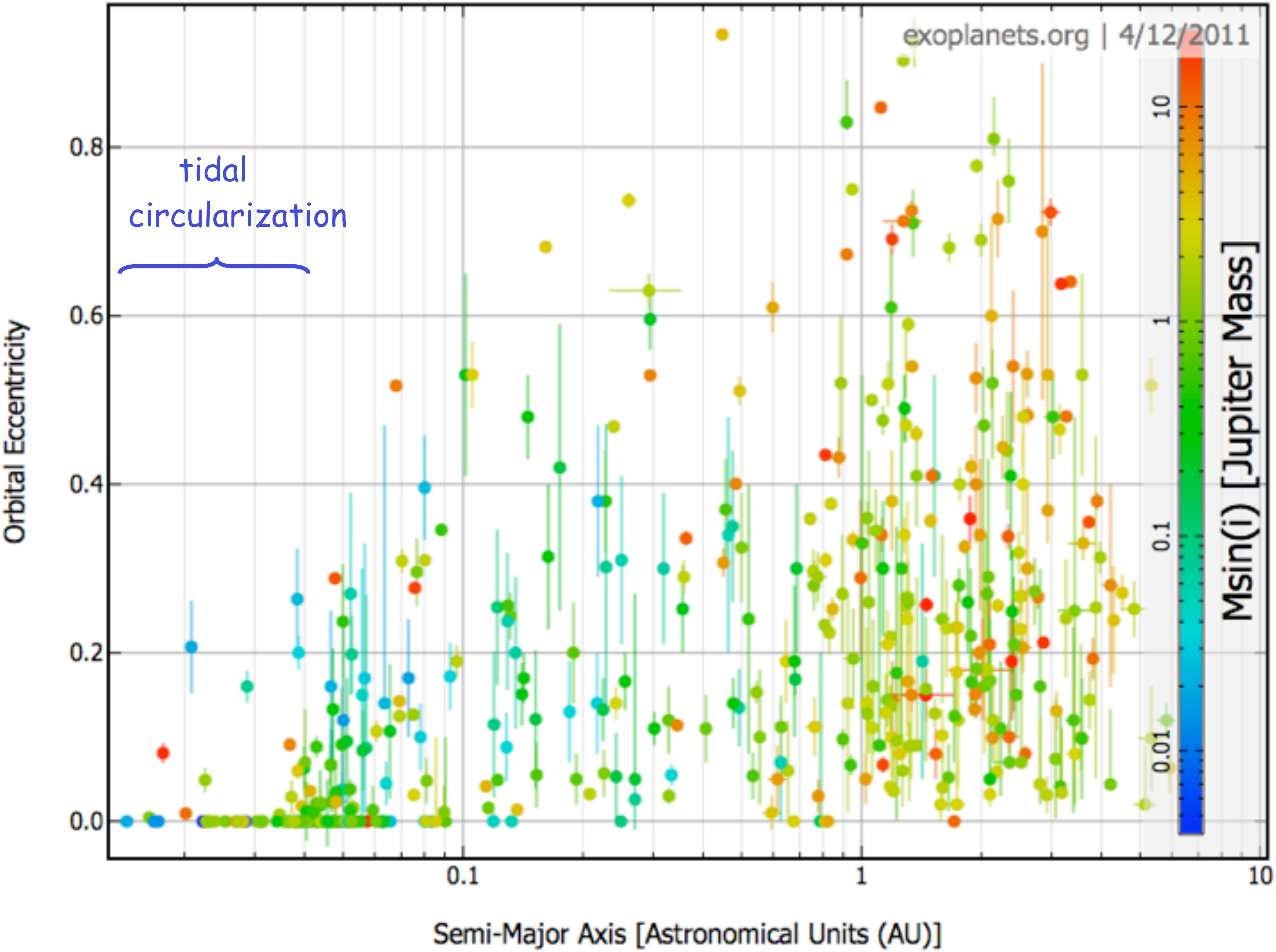

exoplanets.org | 11/6/2011
"hot Jupiters"
Msin(i) [Jupiter Mass]
10
1
0.1
0.01
10^-3
1
10
100
10^3
Orbital Period [Days]



Grether & Lineweaver (2006)



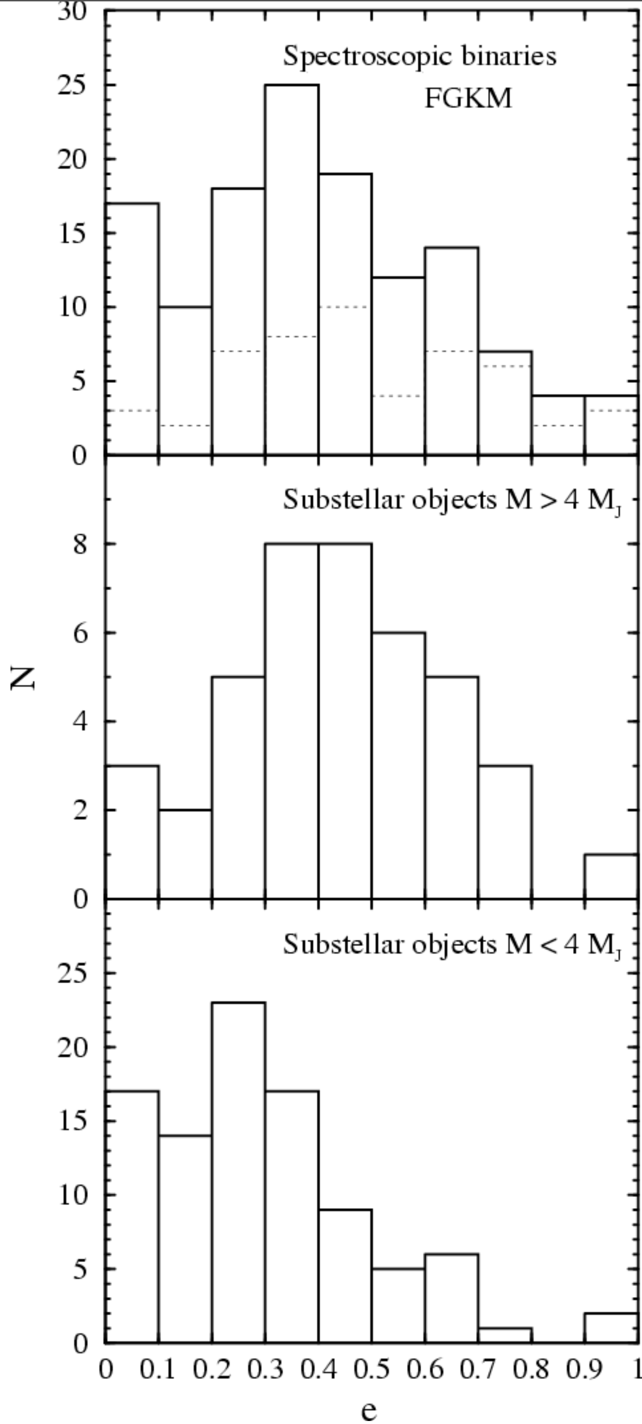
Grether & Lineweaver (2006)


exoplanets.org | 4/12/2011
tidal
circularization
Orbital Eccentricity
0.8
0.6
0.4
0.2
0.0
0.1
1
10
Semi-Major Axis [Astronomical Units (AU)]
Msin(i) [Jupiter Mass]
10
1
0.1
0.01

binary stars

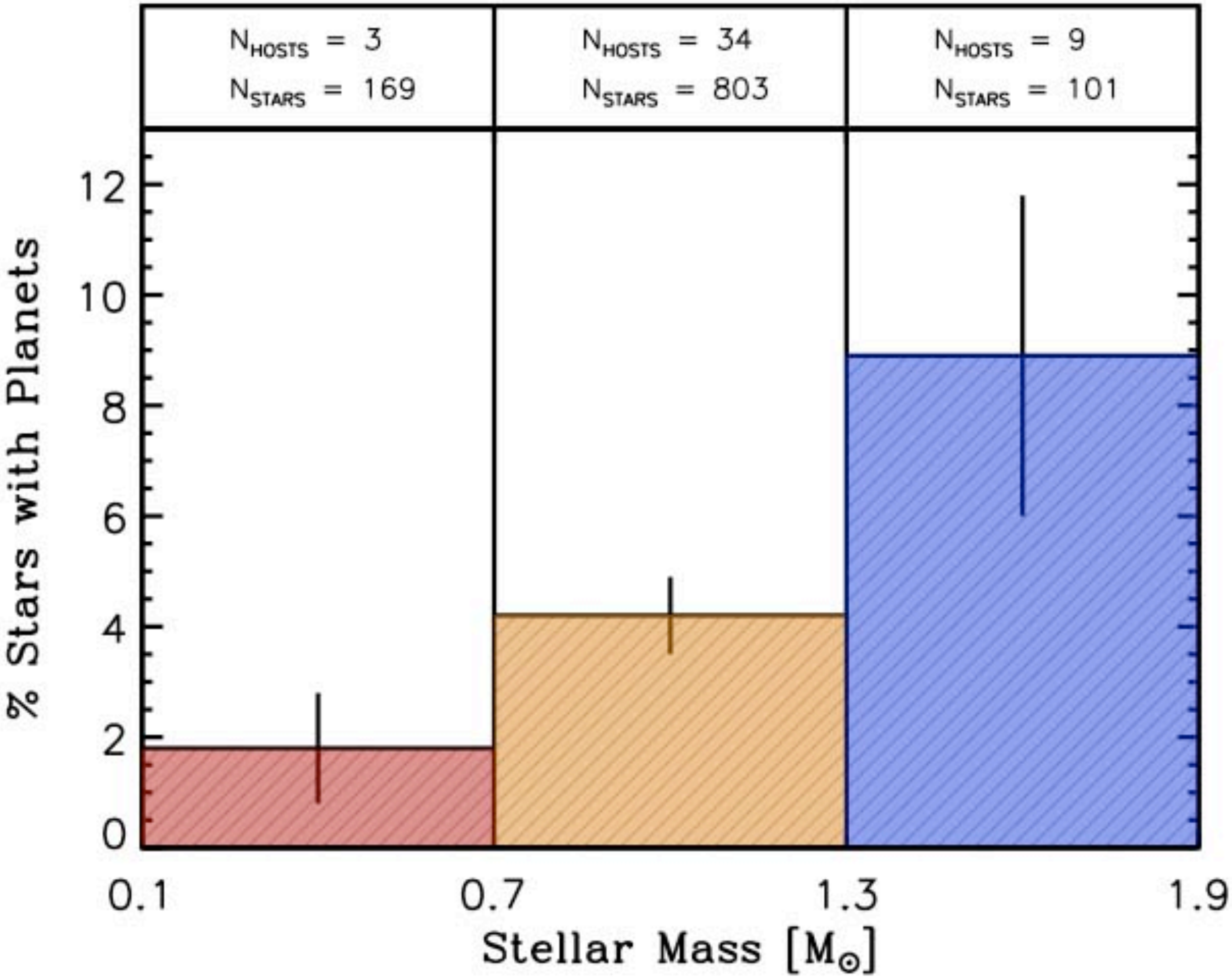
massive planets (M > 4 Jupiter masses)

planets (M < 4 Jupiter masses)



eccentricity distribution of massive planets is similar to that of binary stars

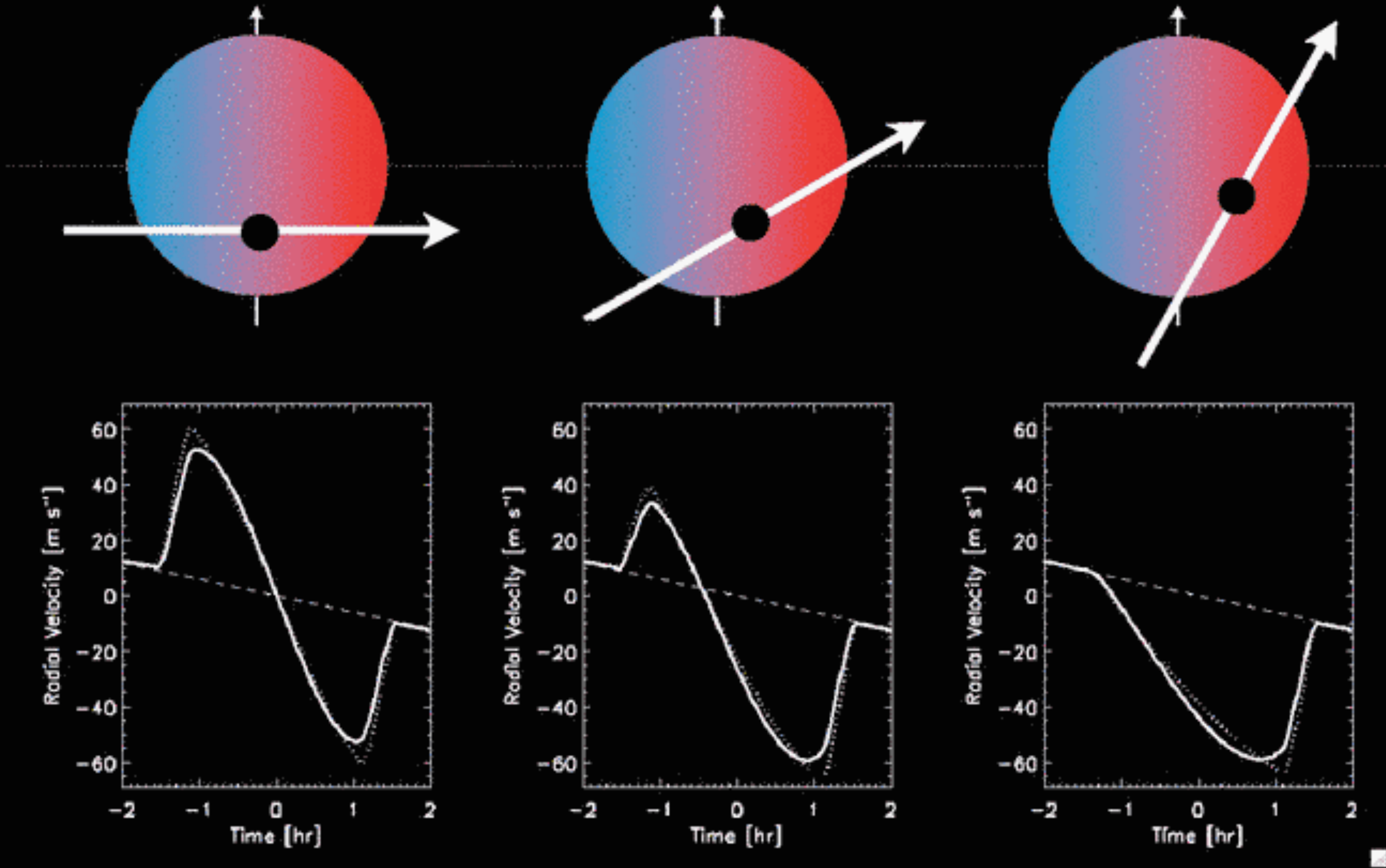
Ribas & Miralda-Escudé (2007)



high-mass stars are more likely to host planets

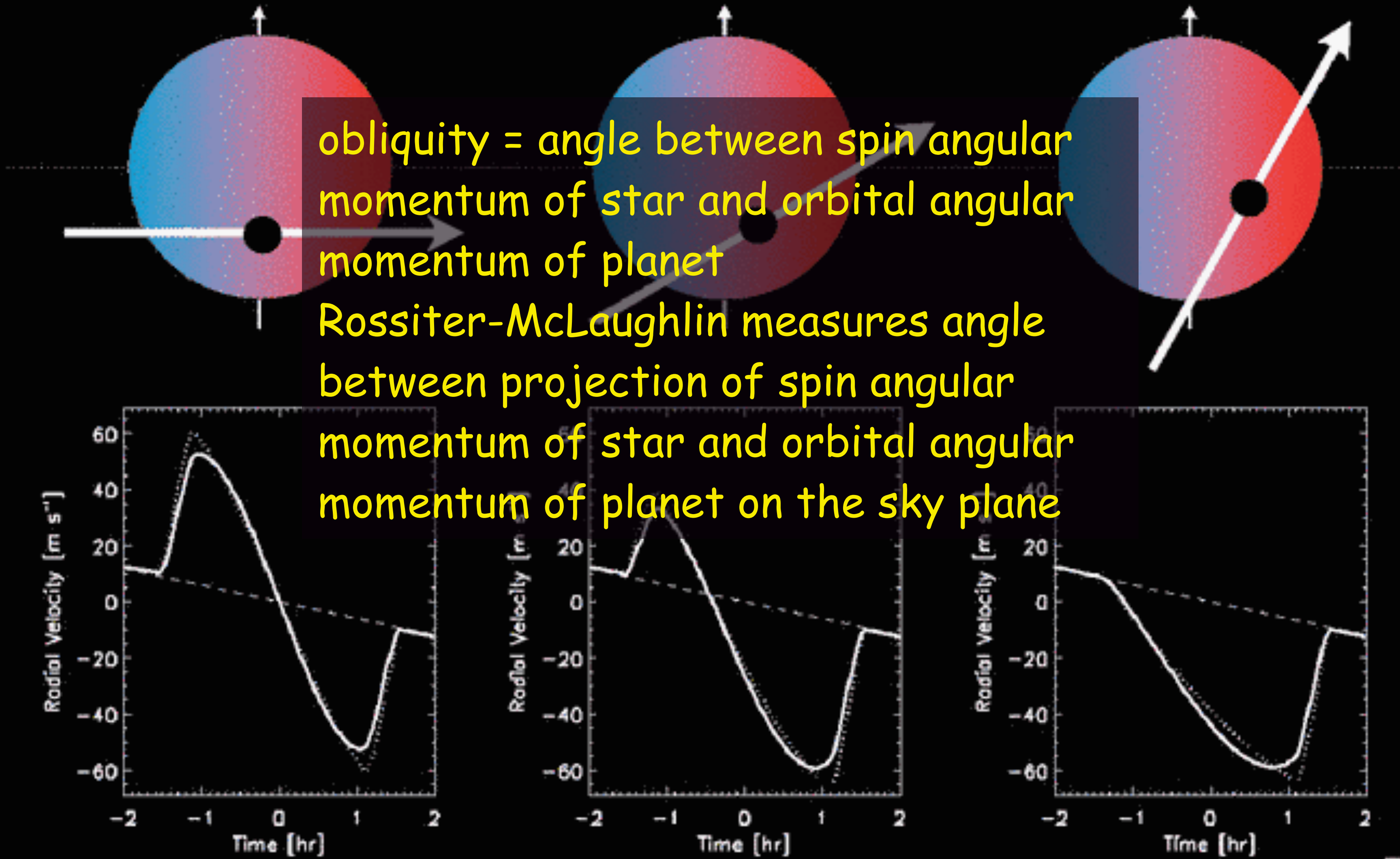
Johnson (2007)

The Rossiter-McLaughlin Effect



(from J. Winn)

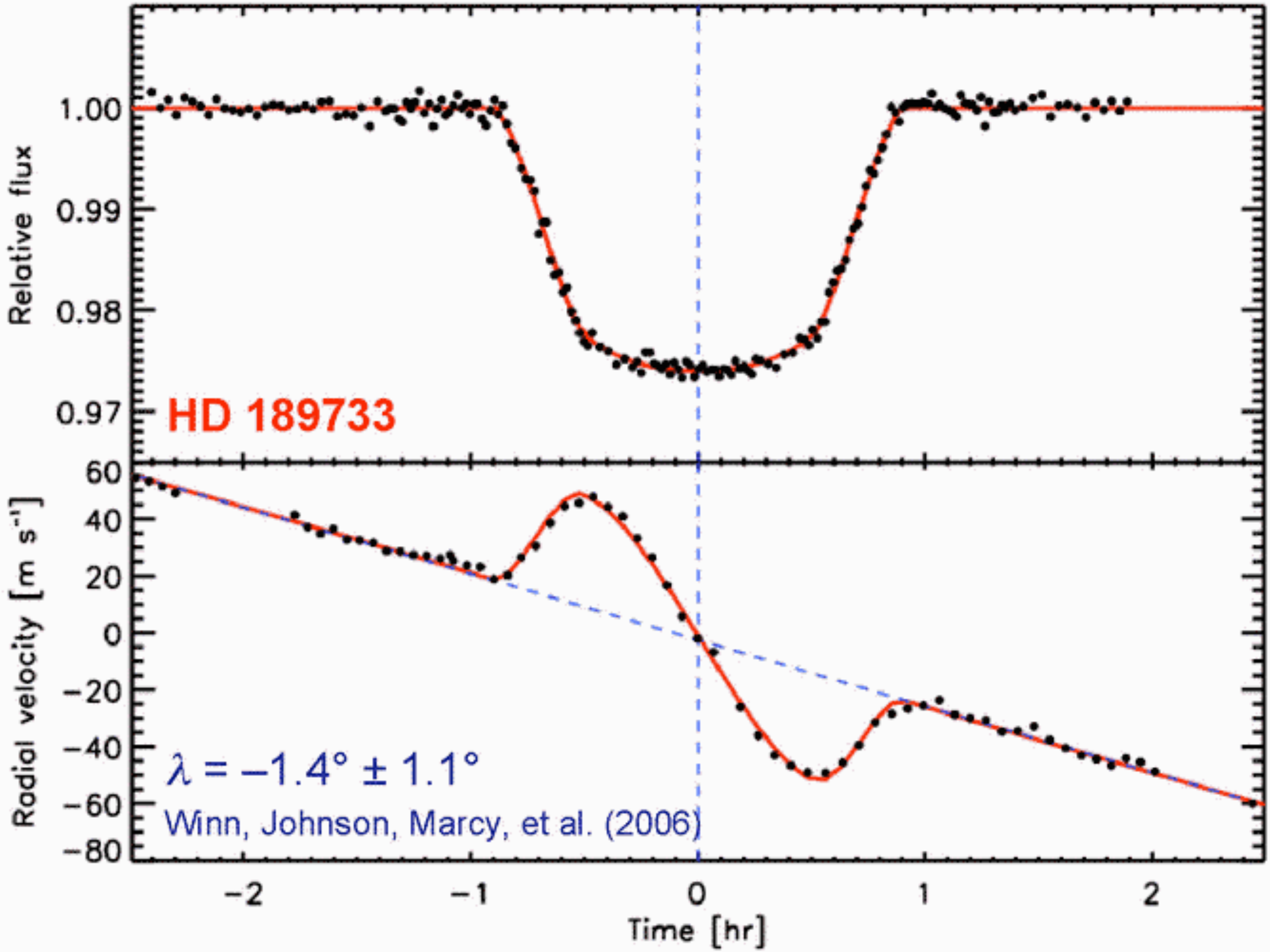
The Rossiter-McLaughlin Effect



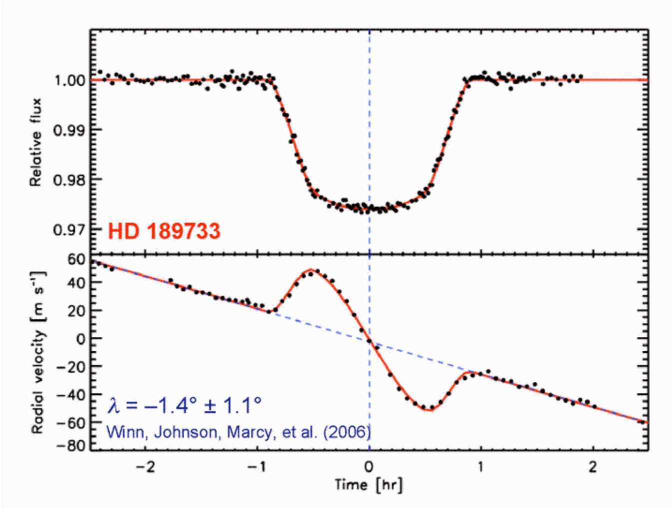
obliquity = angle between spin angular momentum of star and orbital angular momentum of planet

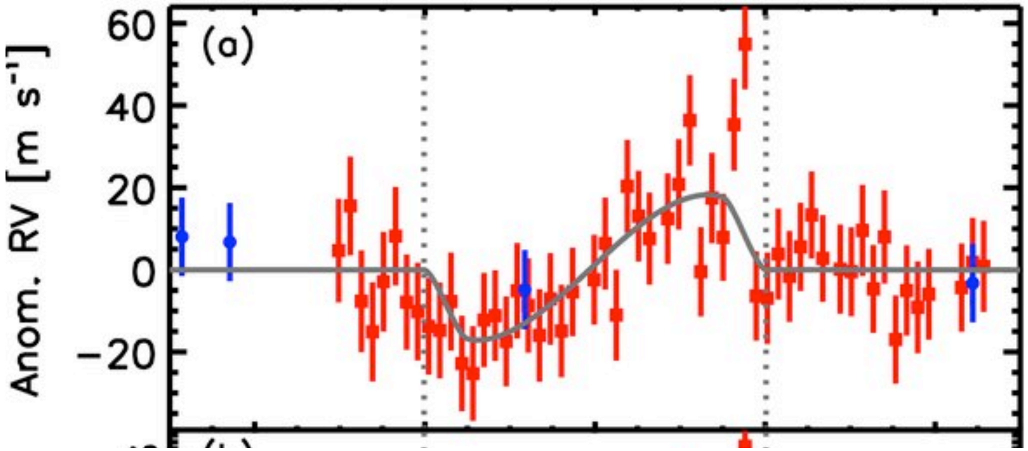
Rossiter-McLaughlin measures angle between projection of spin angular momentum of star and orbital angular momentum of planet on the sky plane

(from J. Winn)



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]

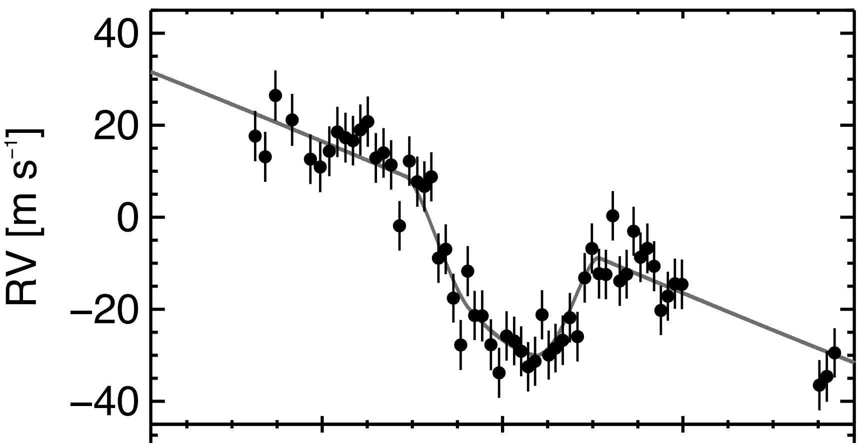


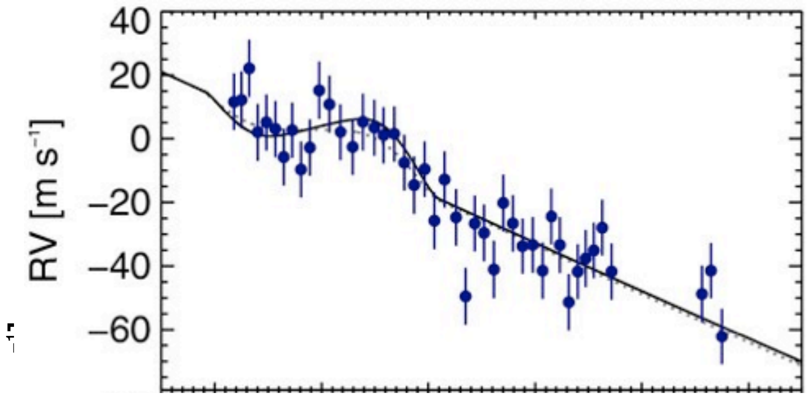


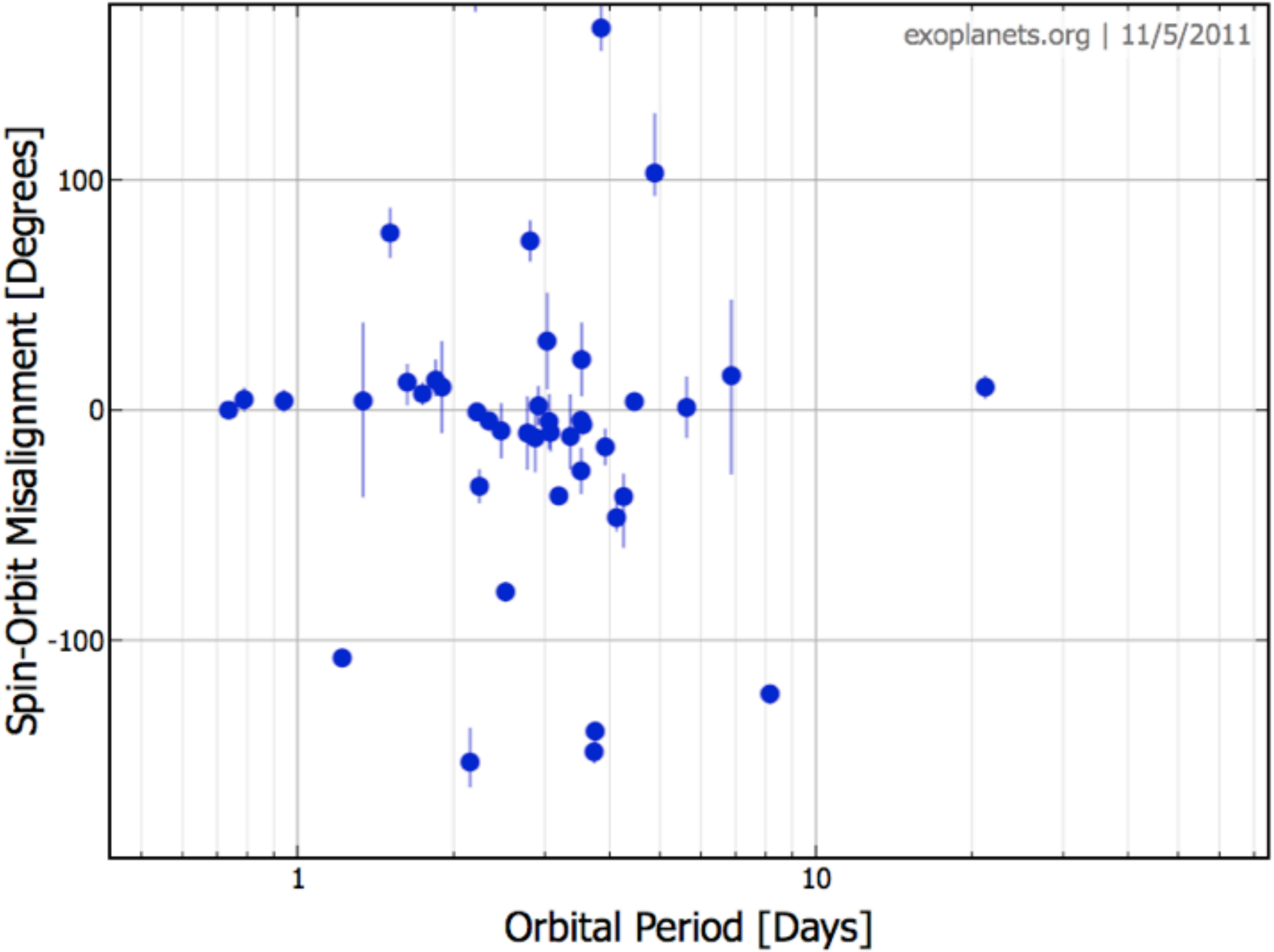
HAT P-7b
λ = 183±9°
Winn et al. (2009)

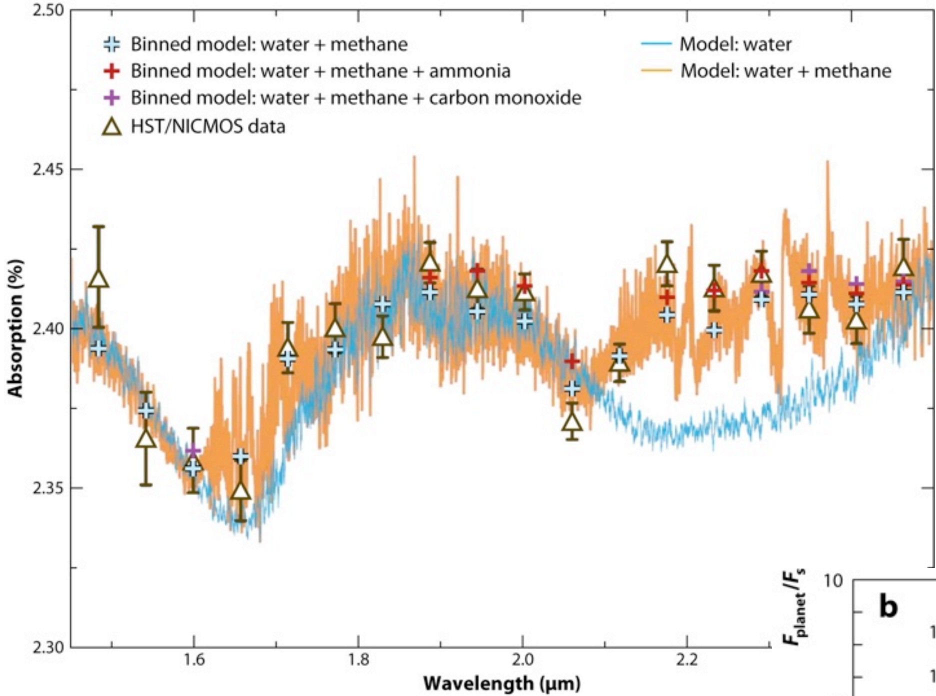
HAT P-30b
λ = 74 ± 9°
Winn et al. (2009)

HAT P-14b
λ = 189 ± 5°
Winn et al. (2011)

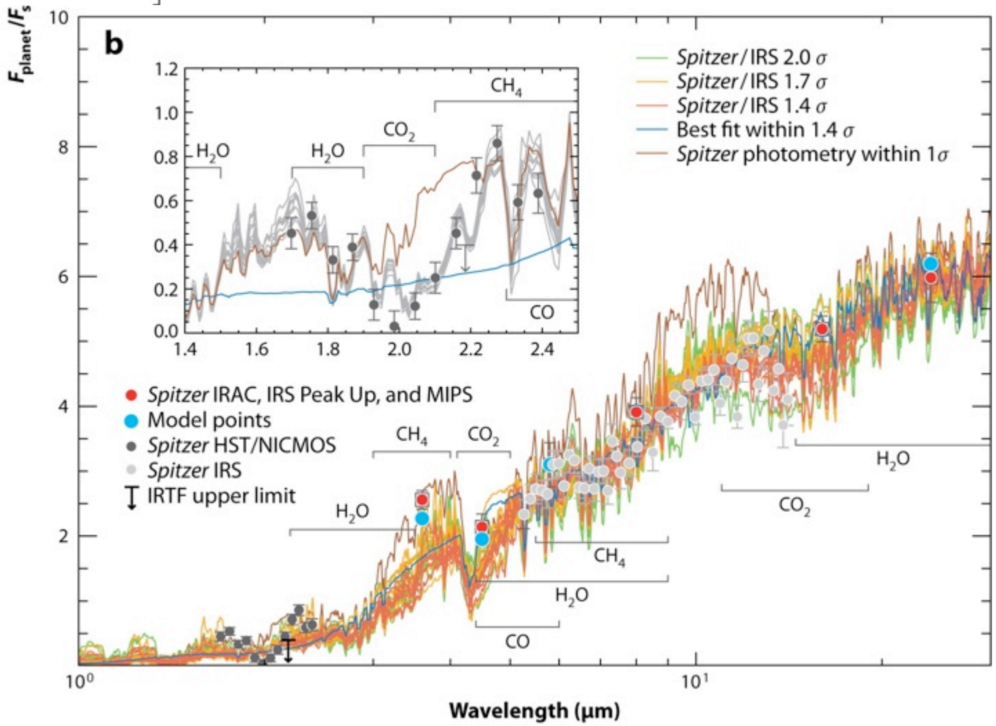





exoplanets.org | 11/5/2011
Spin-Orbit Misalignment [Degrees]
100
0
-100
1
10
Orbital Period [Days]



detection of CH_4, H_2O, Na, CO, CO_2



Seager & Deming (2010)