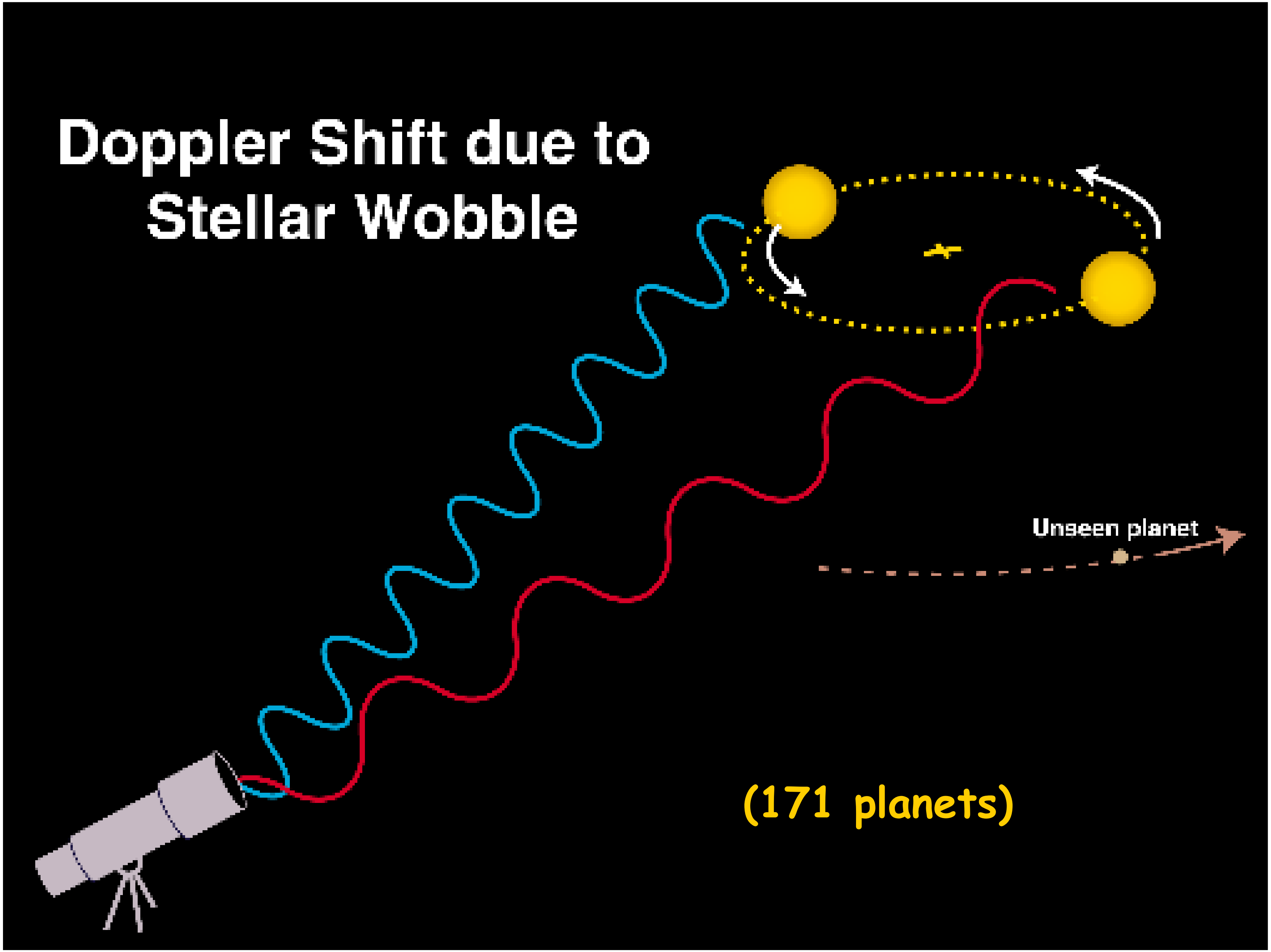
2. Extrasolar planets

Frontiers of Astronomy Workshop/School
Bibliotheca Alexandrina
March-April 2006


Doppler Shift due to
Stellar Wobble
Unseen planet
(171 planets)

For a planet of mass m on a circular orbit of semi-major axis a around a star of mass M >> m,

$$v_{\rm planet} = \sqrt{\frac{GM}{a}} \sin \frac{2\pi(t-t_0)}{P}, \qquad v_{\rm star} = -\frac{m}{M} v_{\rm planet}$$

prove!

where $P=2\pi\,(a^3/GM)^{1/2}$. This neglects

- inclination (assumes orbit is edge-on)
- eccentricity

Radial velocity is

$$v_{\rm star} = \frac{m \sin I}{M}\sqrt{\frac{GM}{a}}(1-e^2)^{-1/2}[\cos(f+\omega)+e\cos\omega]$$

where

$$\tan^{-1}\frac{1}{2}f = \sqrt{\frac{1+e}{1-e}}\tan^{-1}\frac{1}{2}u, \qquad u-e\sin u = \frac{2\pi}{P}(t-t_0).$$

$$P = \sqrt{\frac{GM}{a^3}}$$

m = planet mass

M = star mass

I = inclination of orbit

a = semi-major axis

e = eccentricity

ω = argument of pericenter

f = true anomaly

u = eccentric anomaly

Radial velocity is

$$v = \frac{m \sin I}{M} \sqrt{\frac{GM}{a}} (1 - e^2)^{-1/2} [\cos(f + \omega) + e \cos \omega]$$

where

$$\tan^{-1} \frac{1}{2} f = \sqrt{\frac{1+e}{1-e}} \tan^{-1} \frac{1}{2} u, \qquad u - e \sin u = \frac{2\pi}{P}(t - t_0).$$

$$P = \sqrt{\frac{GM}{a^3}}$$

Given the star mass M (known from spectral type), radial-velocity observations yield a, m sin I, e, ω

Observational techniques

- spectrograph with resolving power of 100,000 has pixel scale 3 km/s. Best observers can now measure Δ v~ 3 m/s or 1/1000 of a pixel and are stable over many years.
  - use many lines in spectrum
  - very high signal-to-noise (200-500)
  - pass light through iodine cell, so calibration lines are distorted in the same way as the data
- error sources:
  - photon noise (use largest telescopes, bright stars)
  - weak or broad spectral lines (focus on old G stars)
  - stellar activity (convection, p-modes)

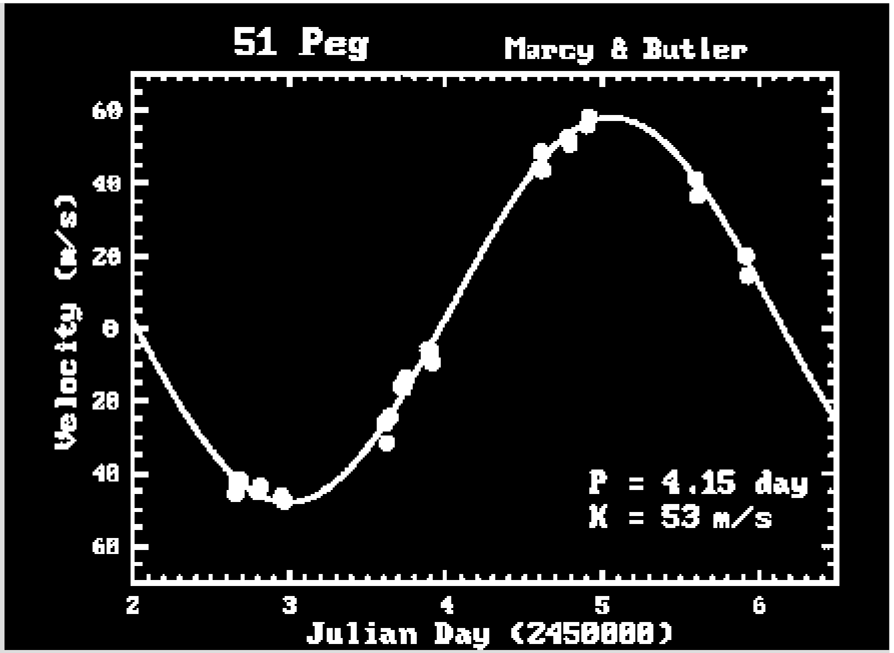
51 Peg:

m sin I = 0.46 M_J

P = 4.23 d

a = 0.05 AU

e = 0.01



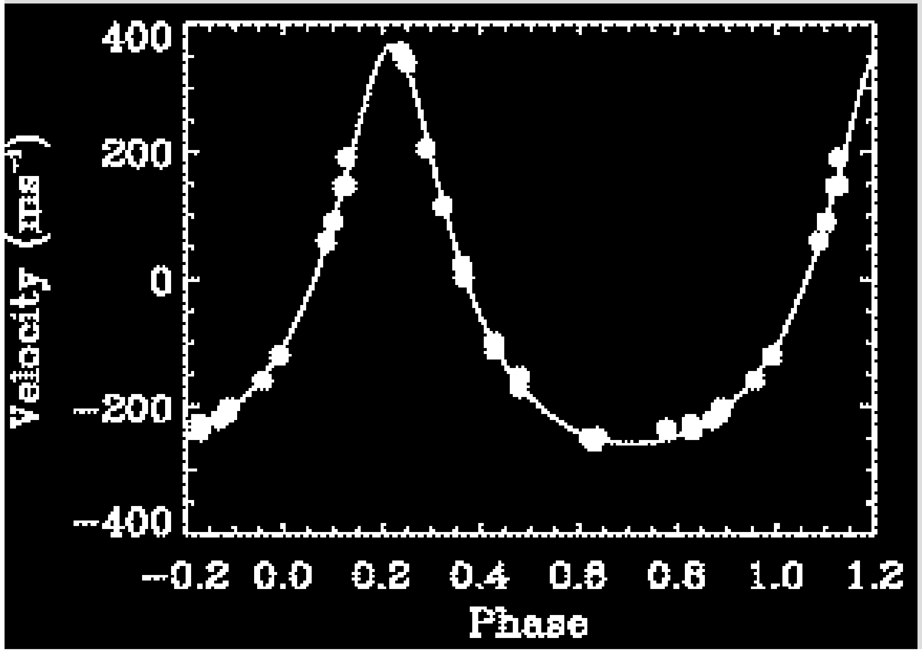
70 Vir:

m sin I = 7.44 M_J

P = 116.7 d

a = 0.48 AU

e = 0.40



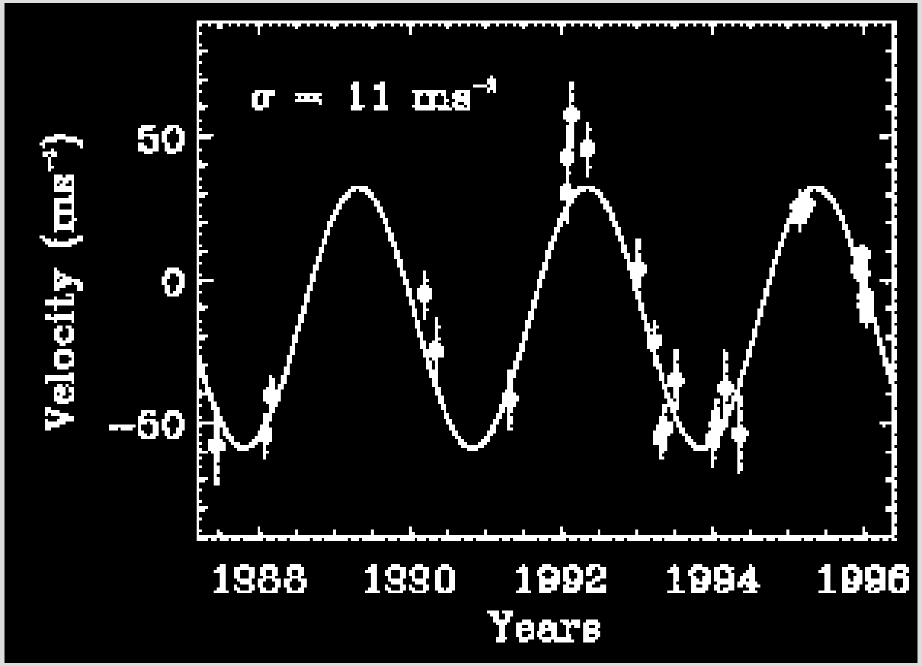
47 UMa:

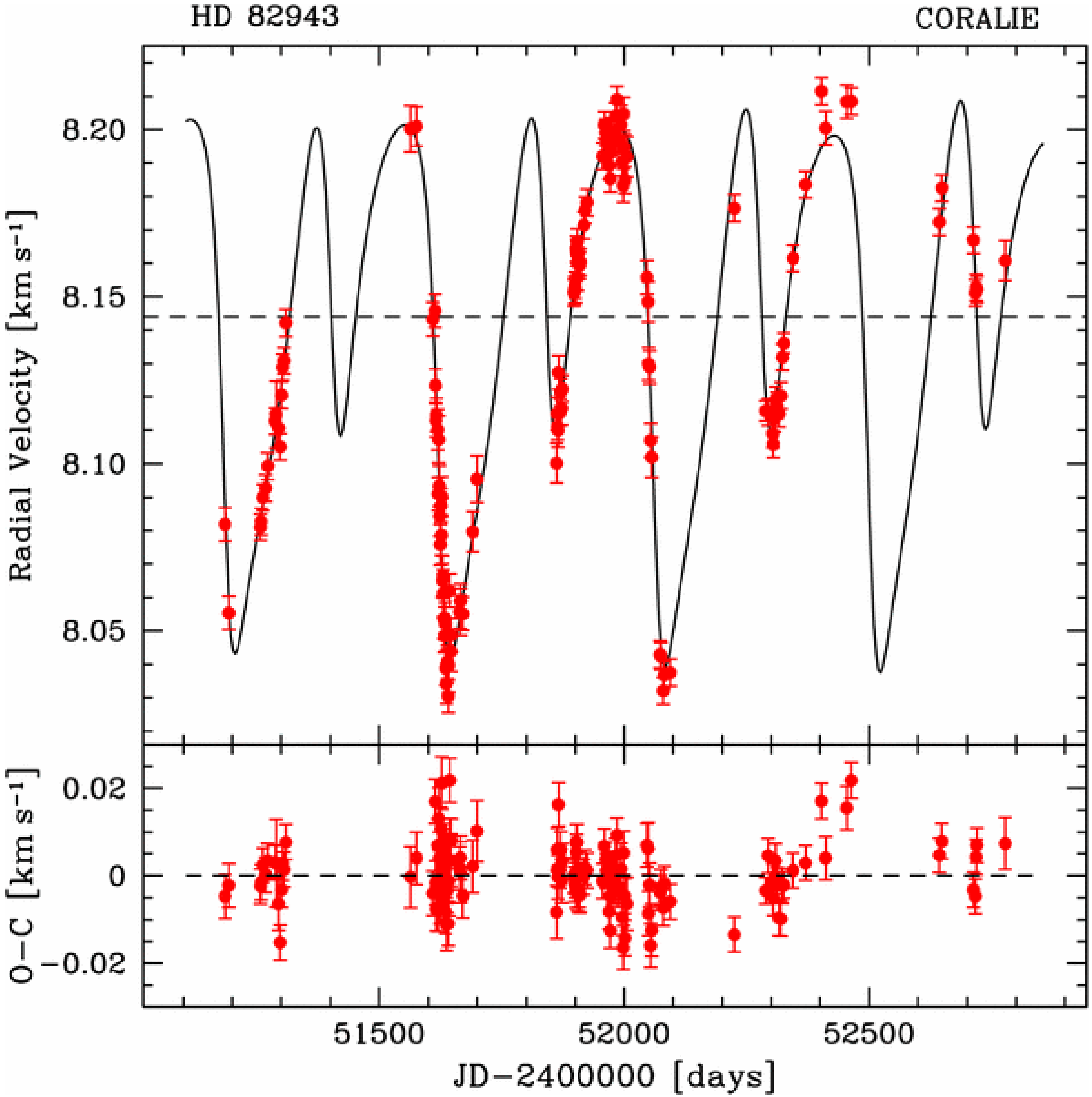
m sin I = 2.54 M_J

P = 1089 d

a = 2.09 AU

e = 0.06





HD 82943

planet 1:

$m \sin I = 1.84 m_J$

$P = 435$ d

$e = 0.18 \pm 0.04$

planet 2:

$m \sin I = 1.85 m_J$

$P = 219$ d

$e = 0.38 \pm 0.01$

(Mayor et al. 2003)

Pulsar planets

Arrival time is related to emission time by

$$t = t_e + cr$$

where r is the distance to the pulsar. Observed pulsar period is

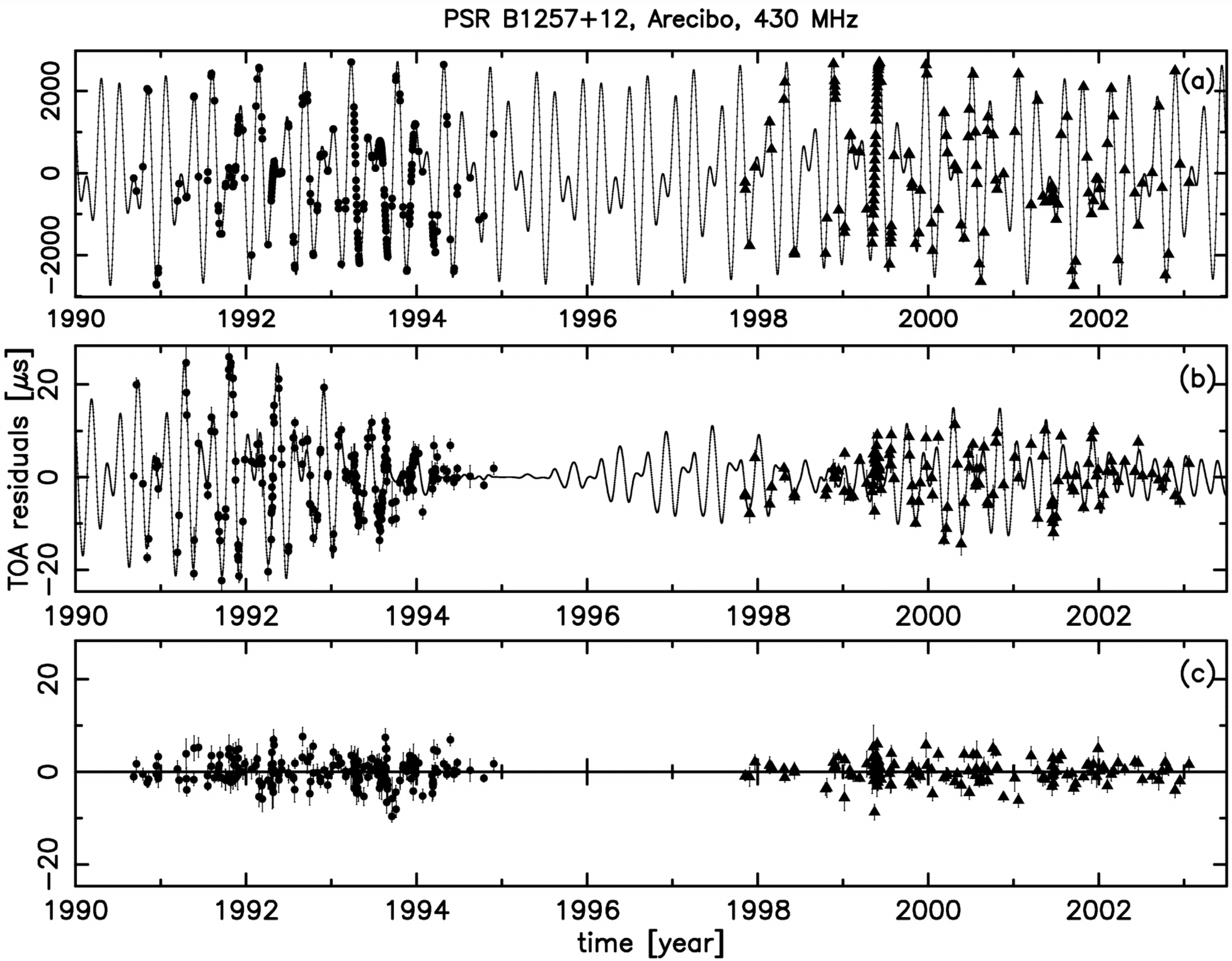
$$\Delta t = \Delta t_e + \Delta r/c = \Delta t_e + v_r \Delta t_e/c = \Delta t_e(1 + v_r/c)$$

where Δt_e is the period of the pulsar in its rest frame. Rate of change of observed period is

$$\frac{d\Delta t}{dt} = \frac{\Delta t_e}{c}\frac{dv_r}{dt}.$$

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)	...

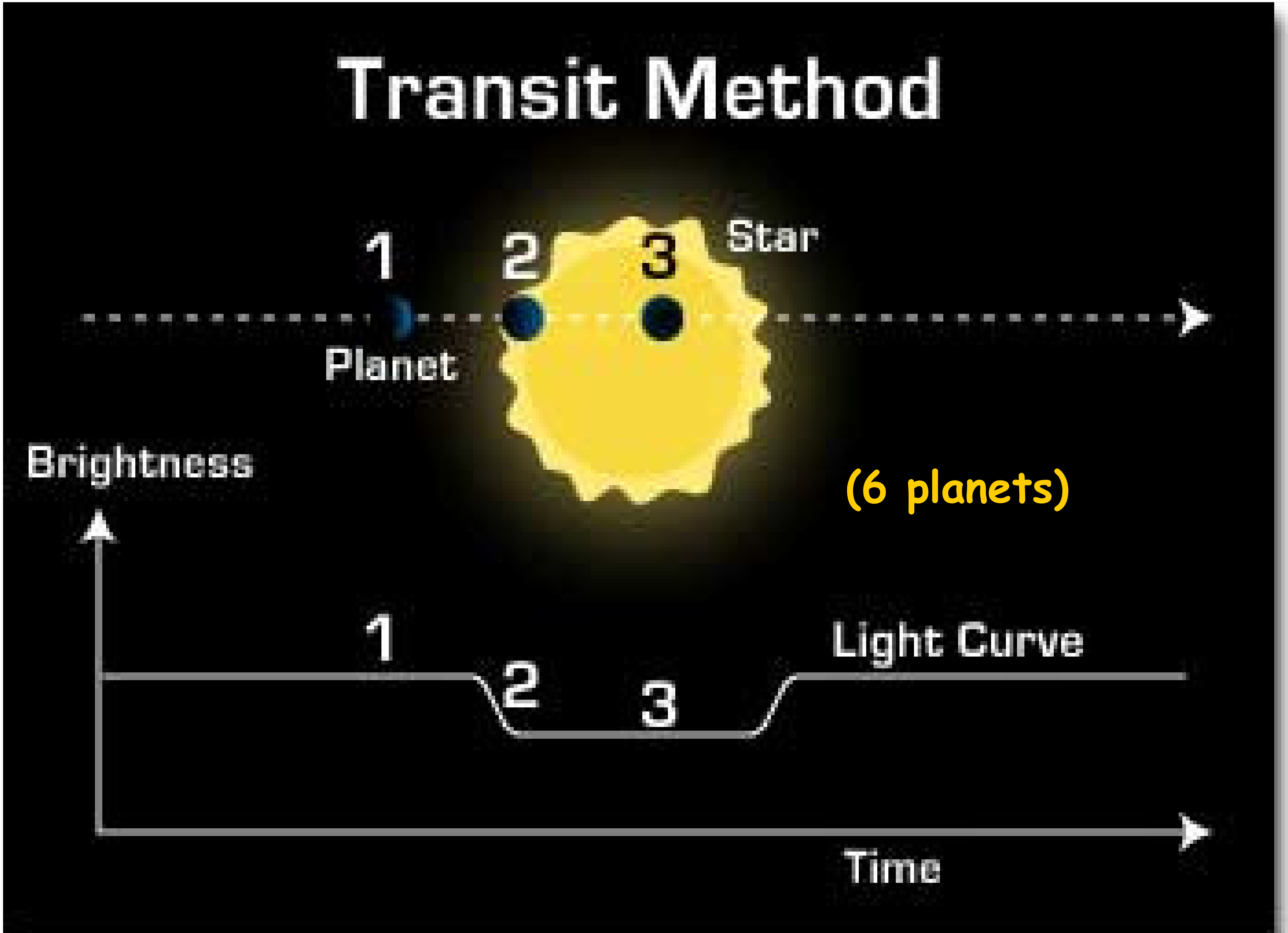
[a] Figures in parentheses are the formal 1 σ uncertainties in the last digits quoted.

Konacki & Wolszczan (2003)

Radial-velocity surveys - summary

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

- sensitive to high-mass planets, small semi-major axes, short orbital periods
- give only m sin I, not m
- maximum sensitivity $\Delta v \sim 2$ m/s
- Jupiter $\Delta v \sim 13$ m/s, P = 11.9 yr – just detectable
- Earth $\Delta v \sim 0.1$ m/s, P = 1 yr – not detectable


Transit Method
1
2
3
Star
Planet
Brightness
(6 planets)
1
2
3
Light Curve
Time

Transit surveys

Primary eclipse:

- planet passes in front of the star
- flux from star is reduced by $(R_{planet}/R_{star})^2$. For a solar-type star this is 1% for Jupiter or 0.01% for Earth

prove!

Secondary eclipse:

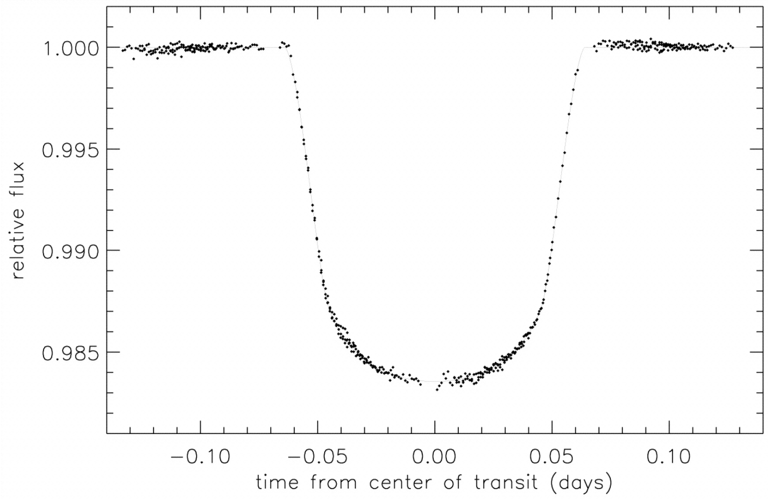
- planet passes behind the star and flux is decreased by eclipse of light from planet
- in visible light, planet emits by reflection from surface: total flux is reduced by $p(R_{planet}/a)^2$ where p is albedo (0.4-0.6 for giant planets in solar system)

prove!

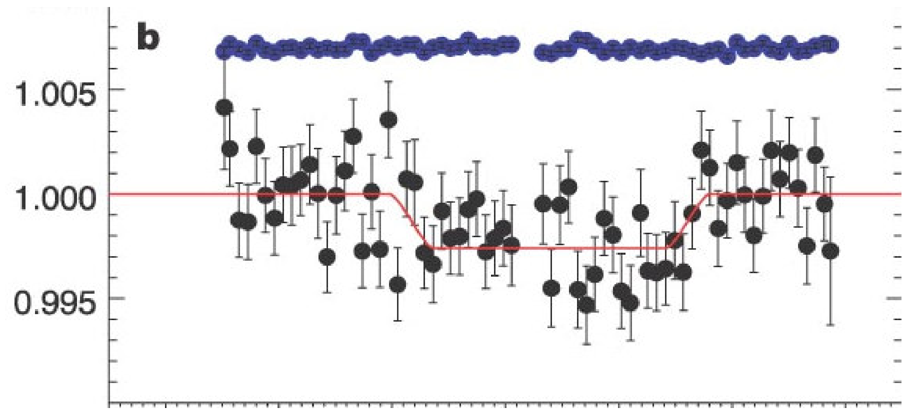
- in infrared, planet emits thermally as black body. If planet and star are black bodies in Rayleigh-Jeans limit (λ > $3\mu(1000\ K/T)$) then flux reduced by $(R_{planet}/R_{star})^2(T_{planet}/T_{star})^2$

prove!

primary (visible)



secondary (infrared)



- mass = 0.69 Jupiter masses
- radius = 1.35 Jupiter radii ("bloated")
- orbital period 3.52 days, orbital radius 0.047 AU or 10 stellar radii
- stellar obliquity < 10^{o}
- T = 1130 ± 150 K
- sodium, oxygen, carbon detected from planetary atmosphere

HD 209458

Brown et al. (2001), Deming et al. (2005)

Transit searches

Ground-based:

ASP, BEST, GITPO, HATNetwork, MONET, OGLE, PASS, PISCES, STARE, STEPSS, TAPT, TEP, Transitsearch.org, UstAPS, Vulcain, Vulcain South, WHAT, STELLA, SuperWASP

Space missions:

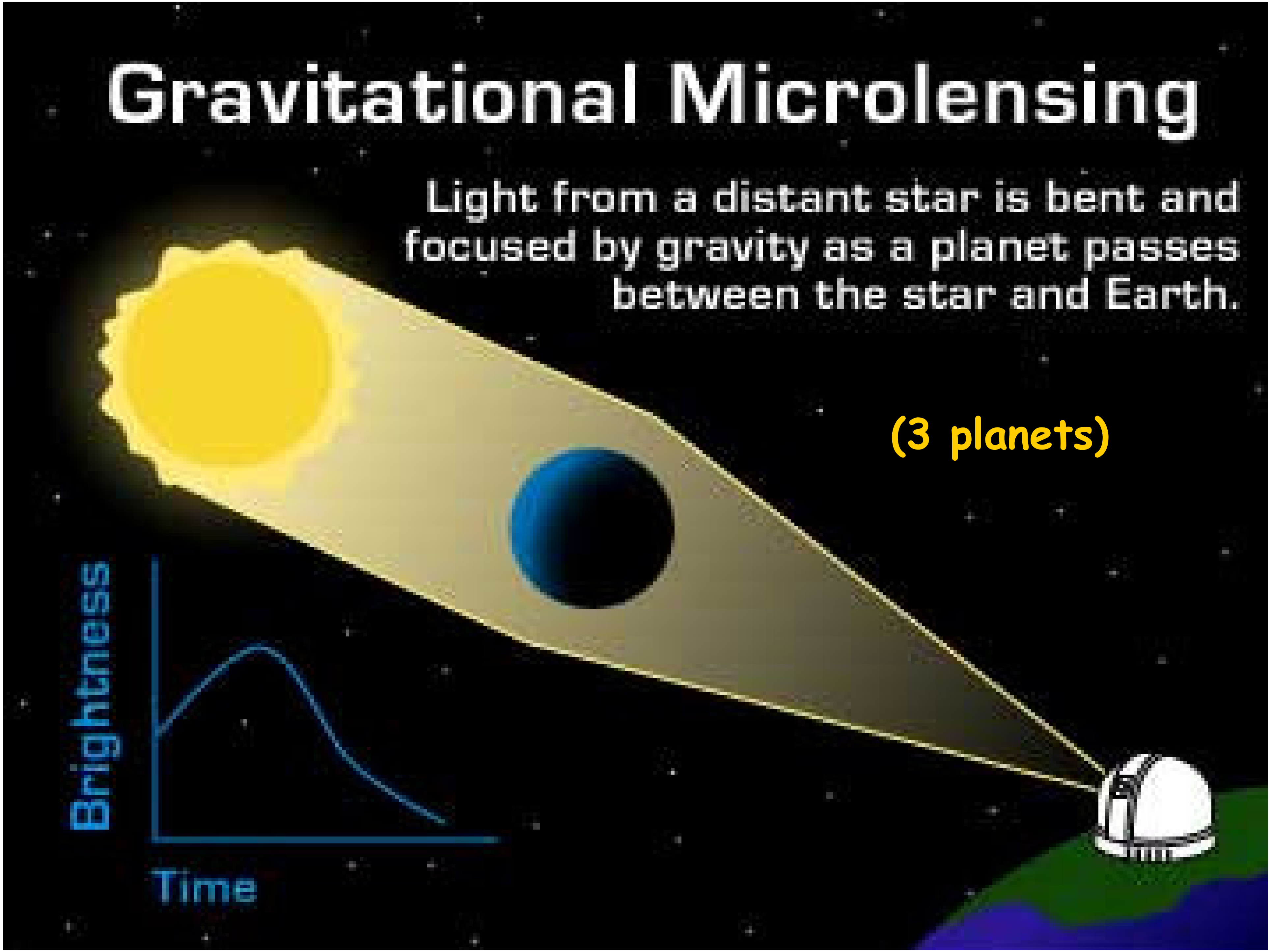
COROT (2006), GAIA (2011), GEST, Kepler (2008)

current record: 5 from OGLE, 1 from STARE, 3 from radial-velocity surveys

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) **prove!**
- transit duration is $(R_{star}/a)P/\pi$ **prove!**
- transit depth is small, <1%
- confusion from grazing eclipsing binary stars
- star spots, stellar pulsations, stellar flares

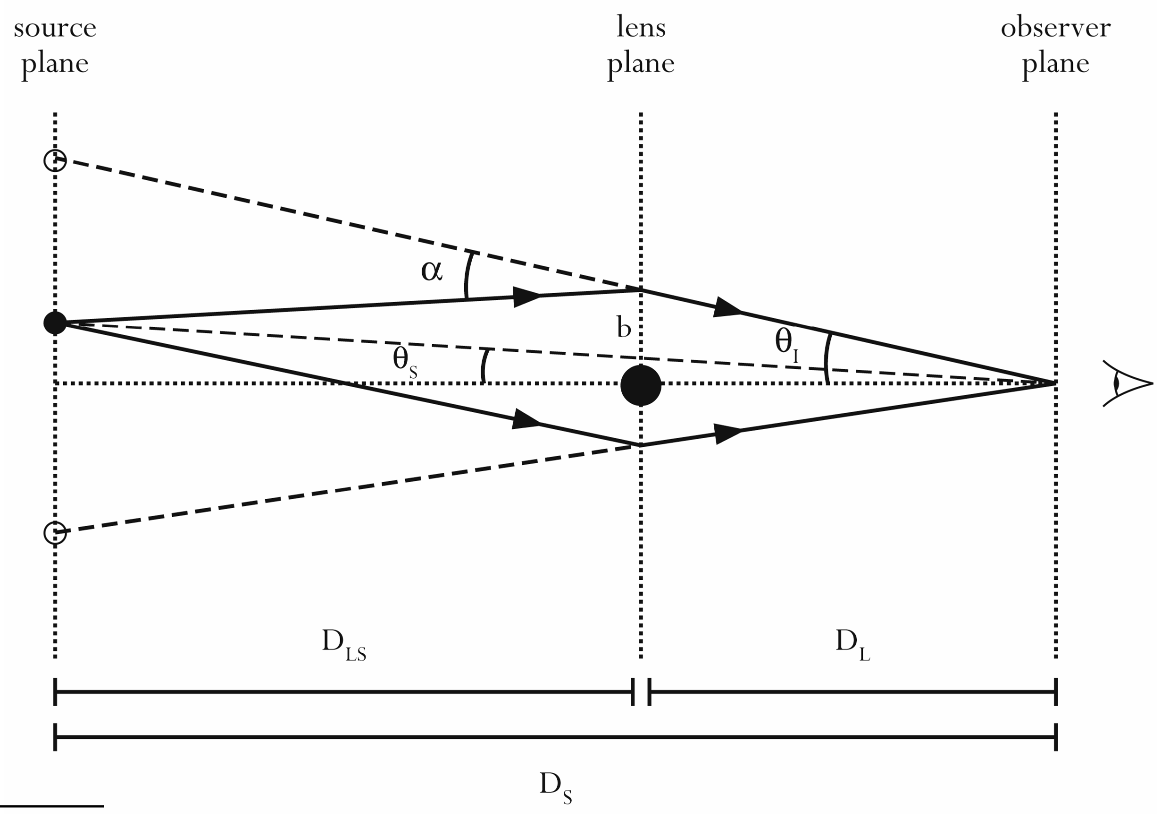

Gravitational Microlensing
Light from a distant star is bent and focused by gravity as a planet passes between the star and Earth.
(3 planets)
Brightness
Time

Gravitational lensing

- first proposed by Einstein in 1936
- a particle travelling 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:

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

Gravitational lensing



Einstein ring radius

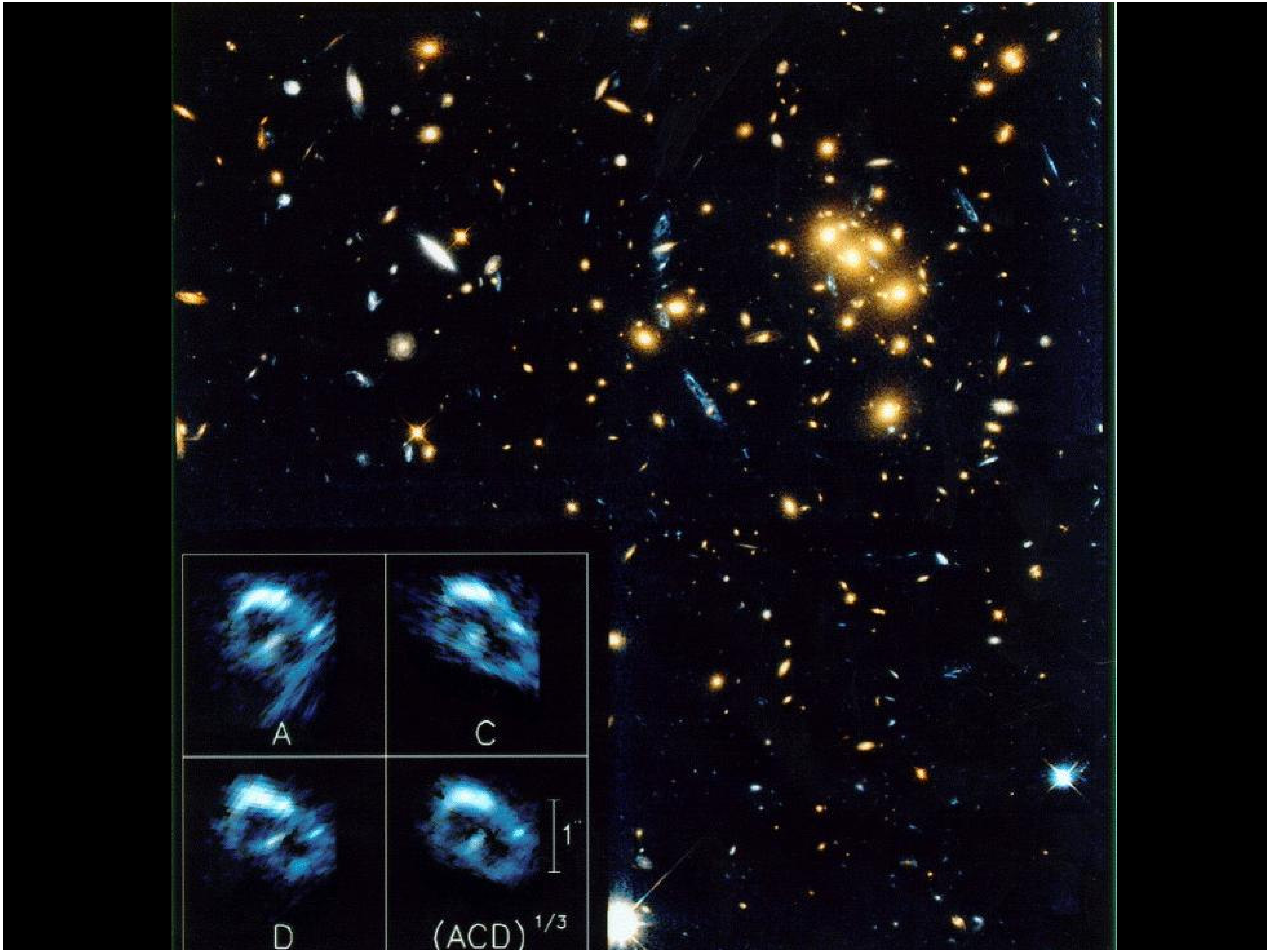
$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{SL}}{D_L D_S}}$$

Then observed angle θ is related to true source angle θ_S by the lensing equation

$$\theta_S = \theta - \frac{\theta_E^2}{\theta}.$$

prove!

If $\theta_S = 0$ (observer, lens and source are collinear) then $\theta = \theta_E$.

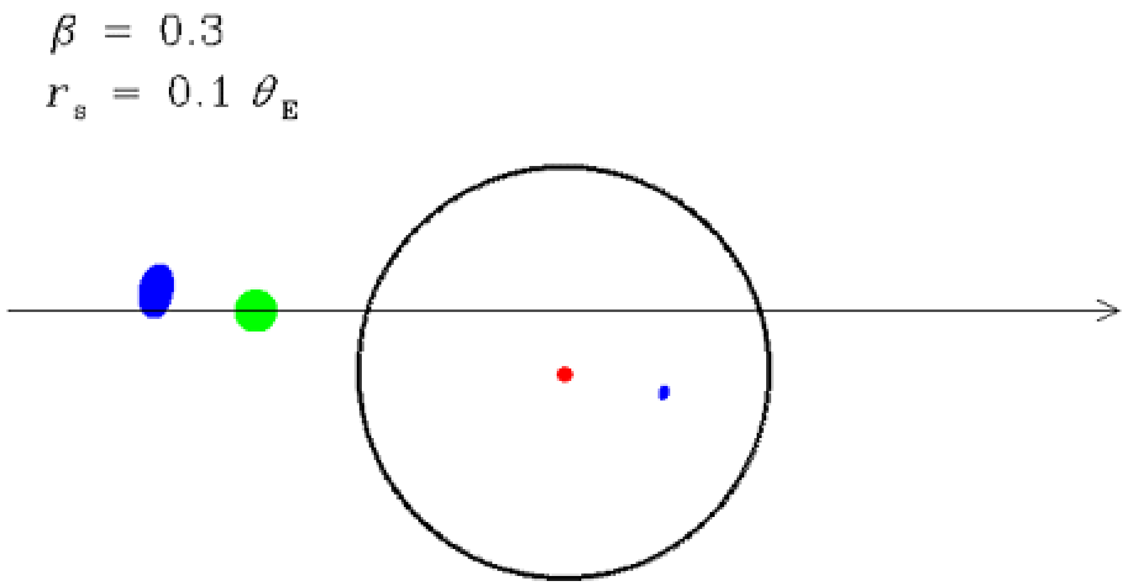

A
C
D
1"
(ACD) 1/3

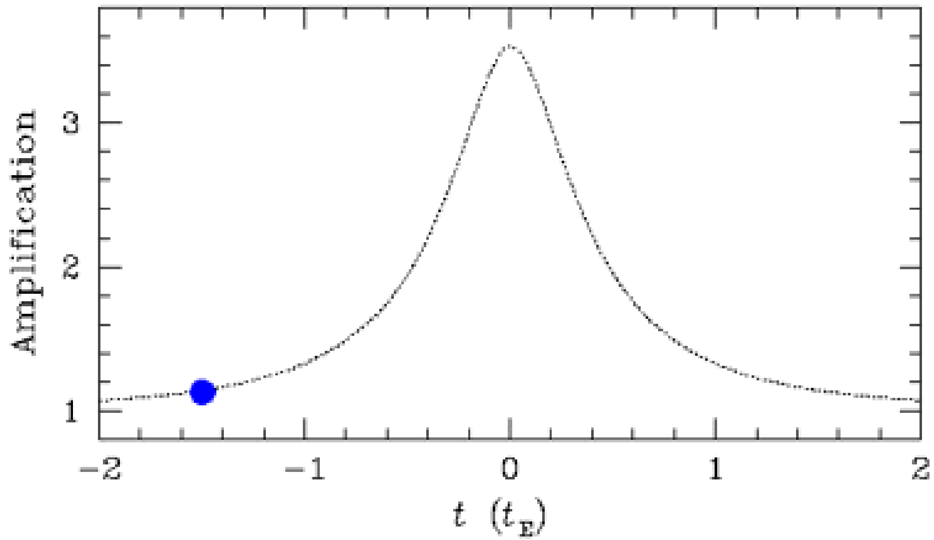
Gravitational lensing

surface brightness is conserved so distortion of image of source across larger area of sky implies magnification

$$A = \frac{u^2 + 2}{u\sqrt{u^2+4}},$$

$$u \equiv \frac{\theta_S}{\theta_E}$$





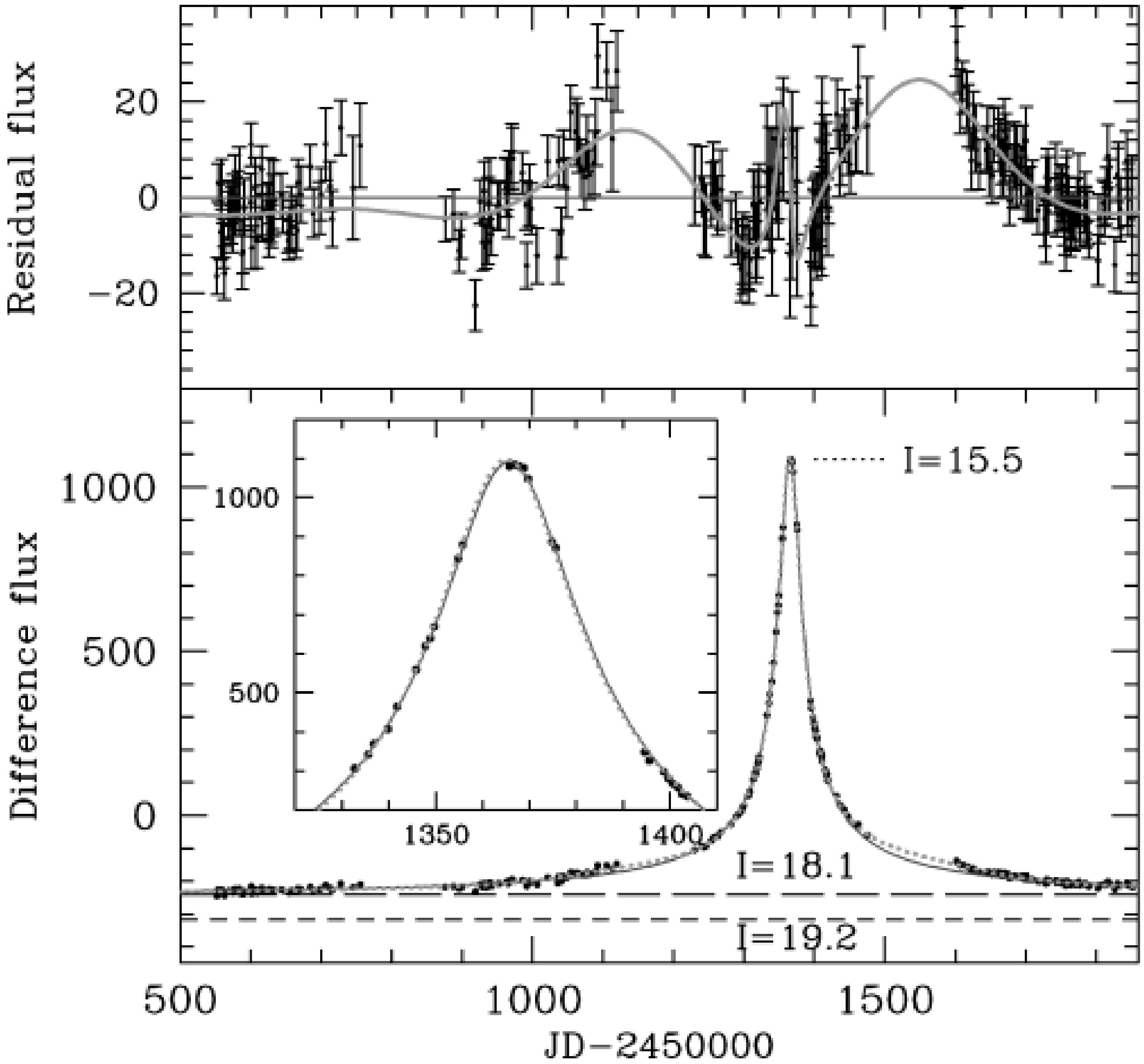
prove!

Gravitational microlensing

Consider a source star in the Galactic bulge at $D_S \sim 7$ kpc, lensed by an intervening star at $D_L \sim 4$ kpc. For solar-type lens star, θ_E=0.001 arcsec ~ 4 AU.

prove!

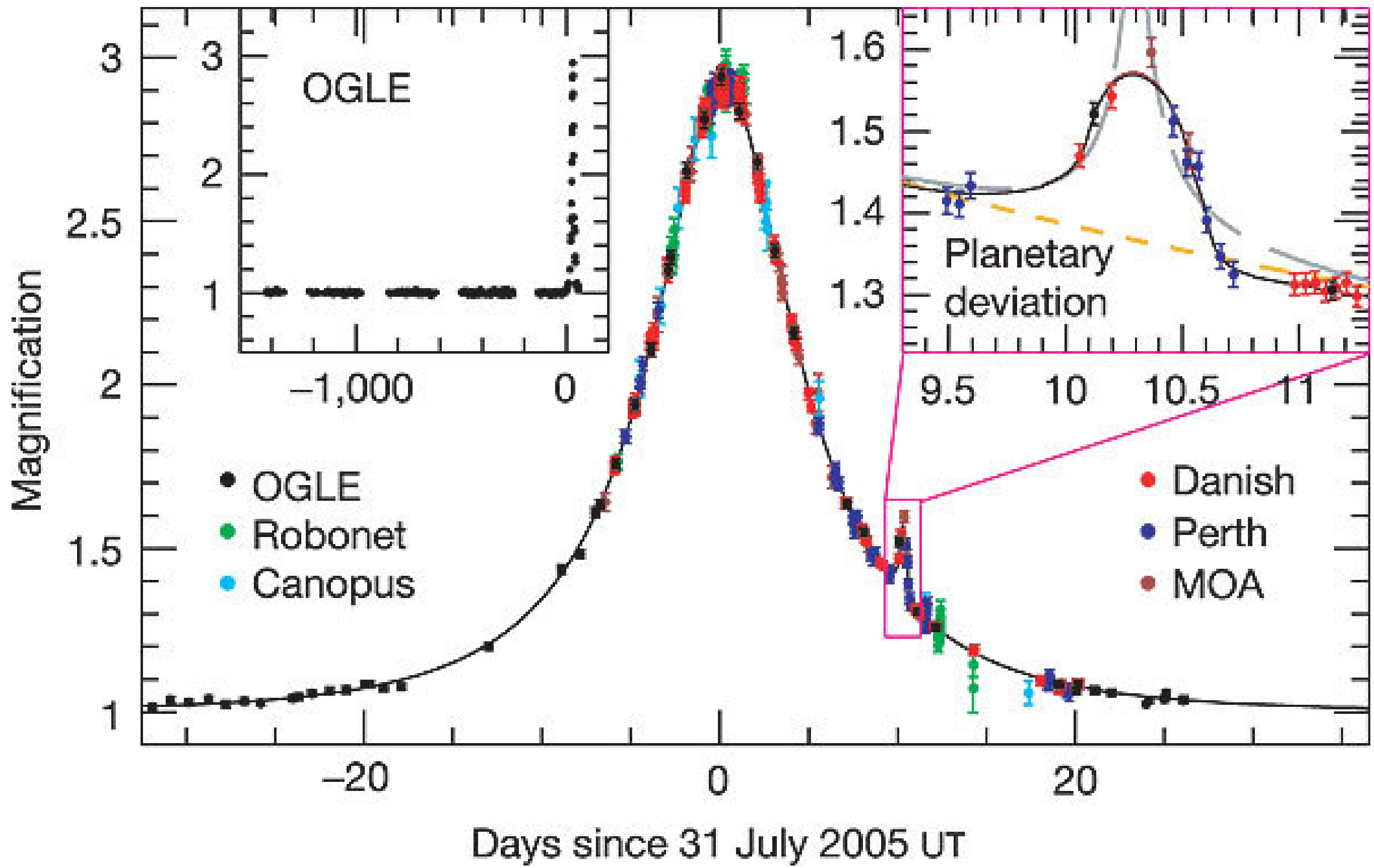
- image splitting or shift is impossible to see
- image magnification is easy to see
- time required to transit Einstein ring $\sim D_L \theta_E / v \sim 0.2$ yr, for $v \sim 100$ km/s **prove!**
- substantial magnification if and only if impact parameter less than Einstein radius
- chance that any given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



Mao et al. (2002)

Gravitational microlensing of planets

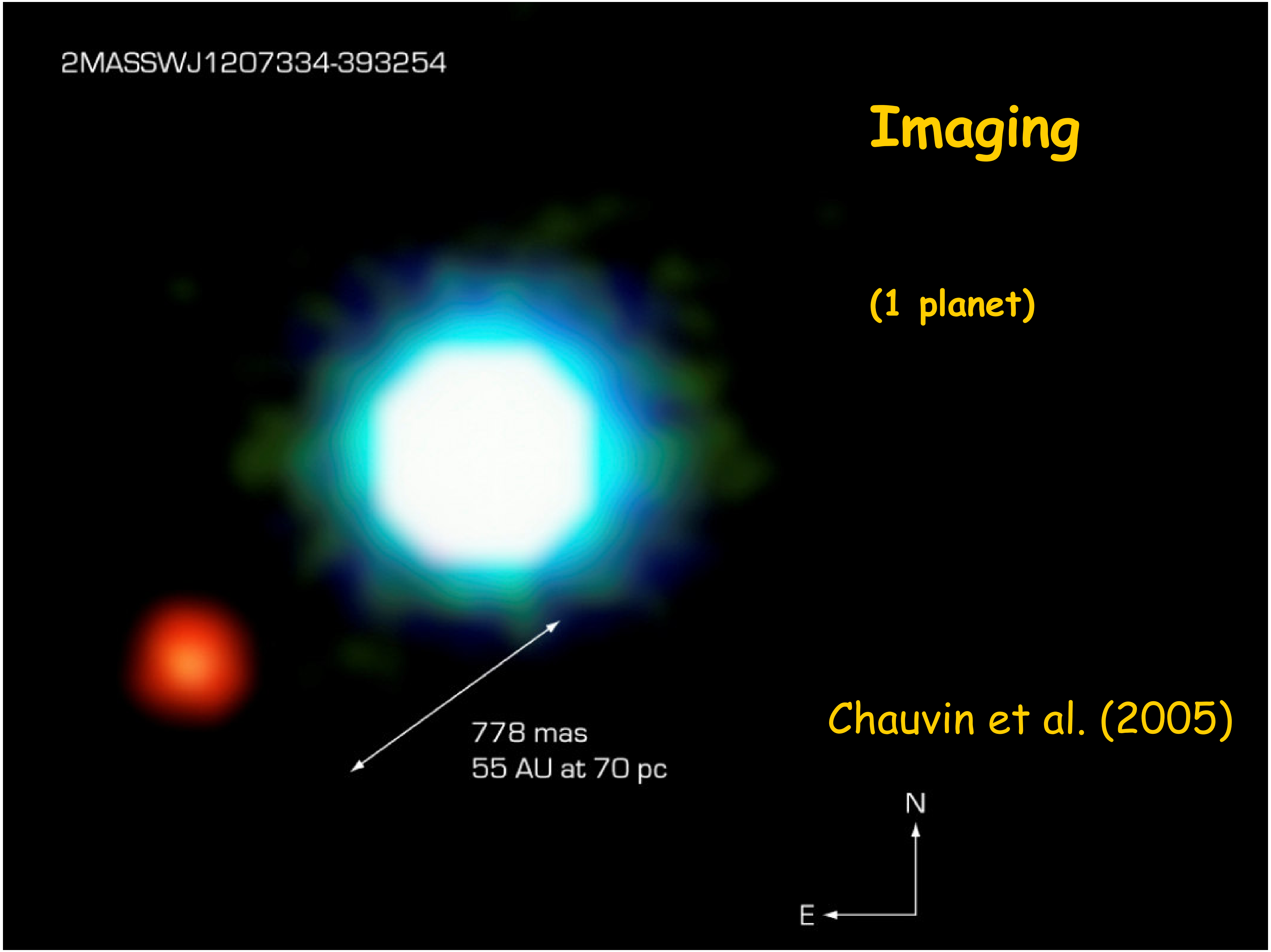
- Einstein radius scales as $M^{1/2}$ so cross-section and expected duration scale as $M^{1/2}$~ 0.03 for Jupiter, i.e. duration ~ 1 day for Jupiter, ~1 hour for Earth
- image magnification is the same
- Einstein ring radius ~ typical planet orbital radius
- use two-step strategy:
  1. wide-angle surveys find microlensed stars with coarse time resolution
  2. small telescopes monitor microlensed stars constantly



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

Imaging

(1 planet)



Chauvin et al. (2005)

What have we learned?

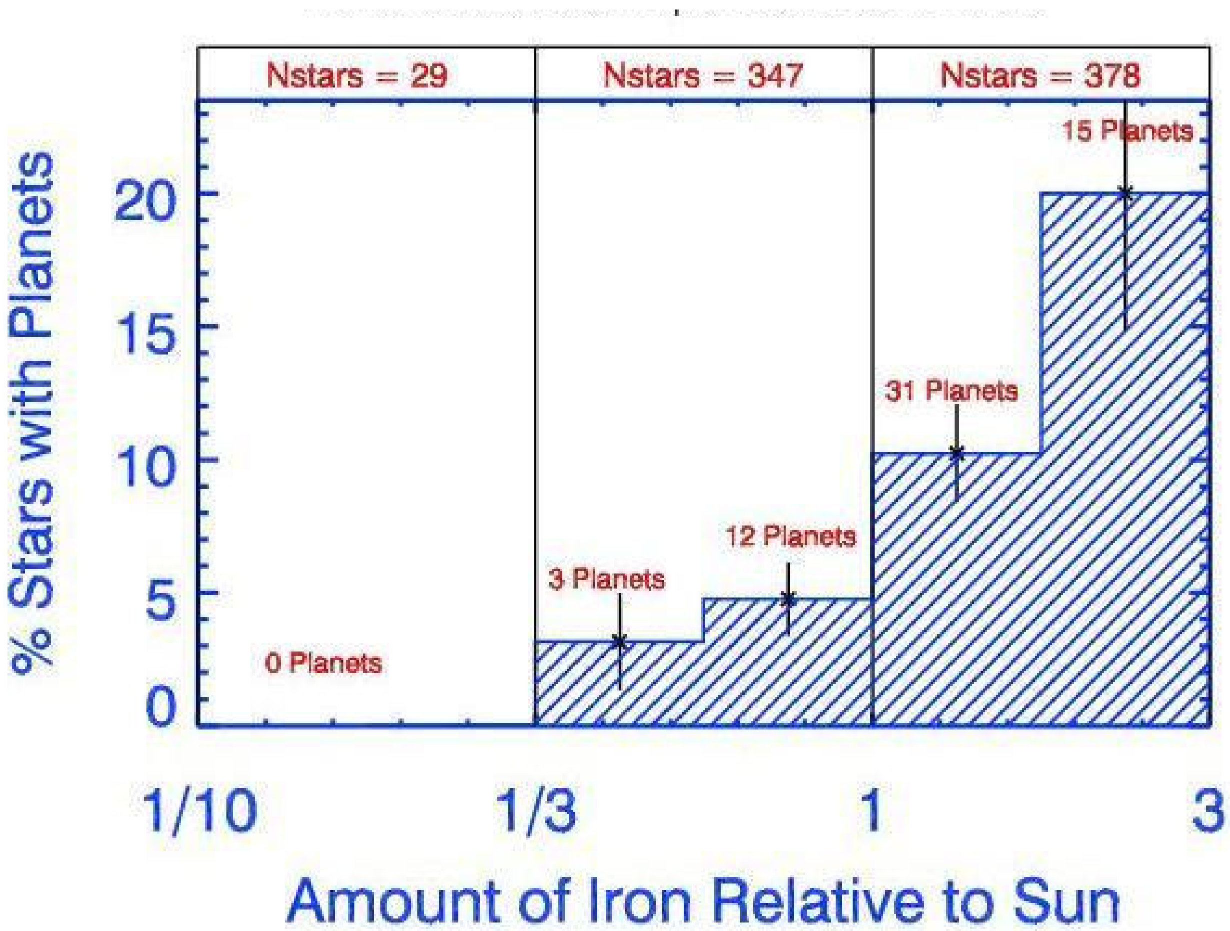
- 185 extrasolar planets known (March 2006)
  - 171 from radial-velocity surveys
  - 6 from transits
  - 4 around pulsars
  - 3 by microlensing
  - 1 by imaging

(see http://vo.obspm.fr/exoplanetes/encyclo/encycl.html)

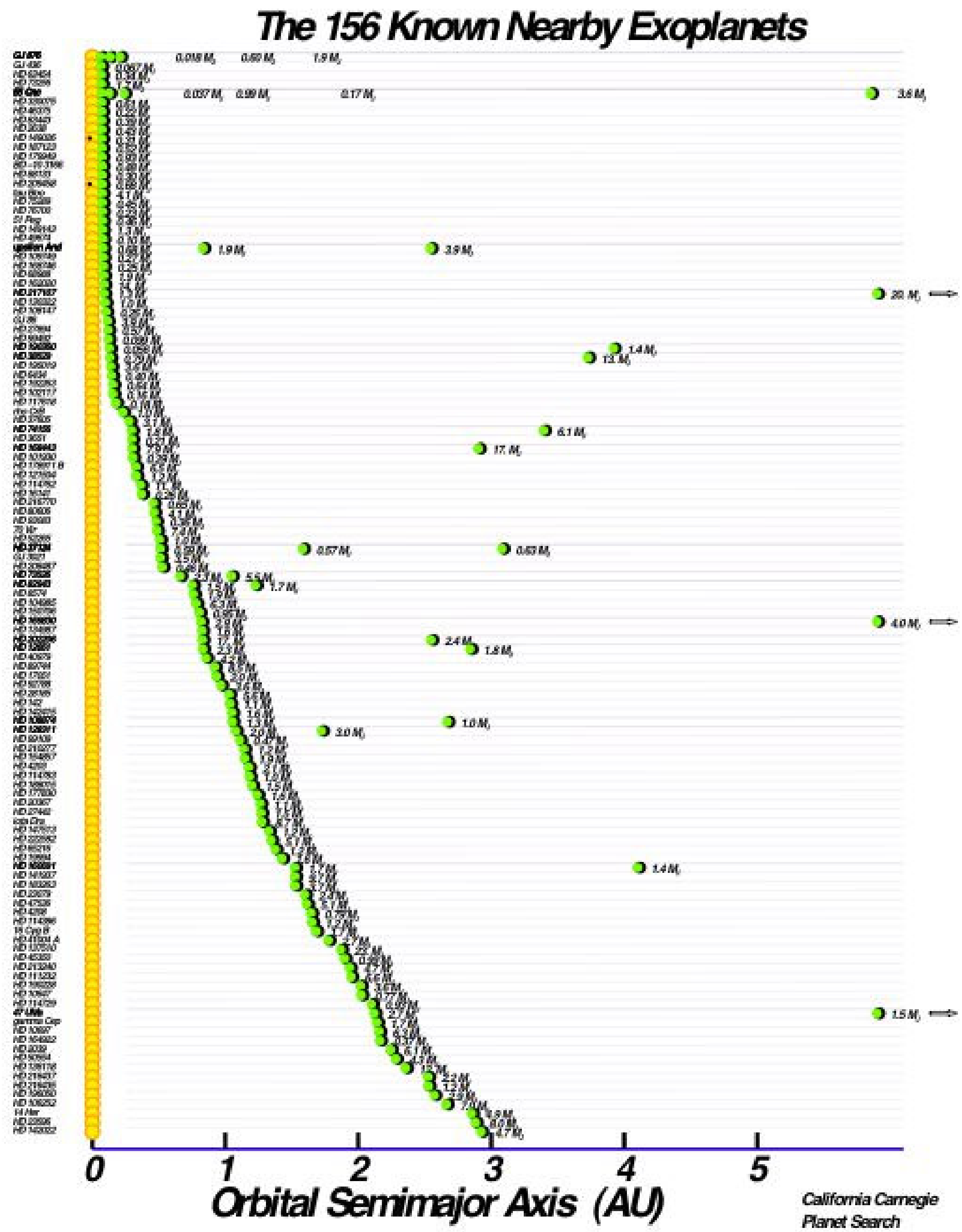
What have we learned?

- smallest semi-major axis a = 0.021 AU = 4.5 R_{Sun}
- largest semi-major axis a=5.26 AU (Jupiter = 5.2 AU)
- biggest eccentricity e = 0.93
- smallest eccentricity e = 0
- smallest mass 0.018 $M_{Jupiter}$ = 5.7 M_{Earth}
- biggest mass 15 $M_{Jupiter}$

What have we learned?



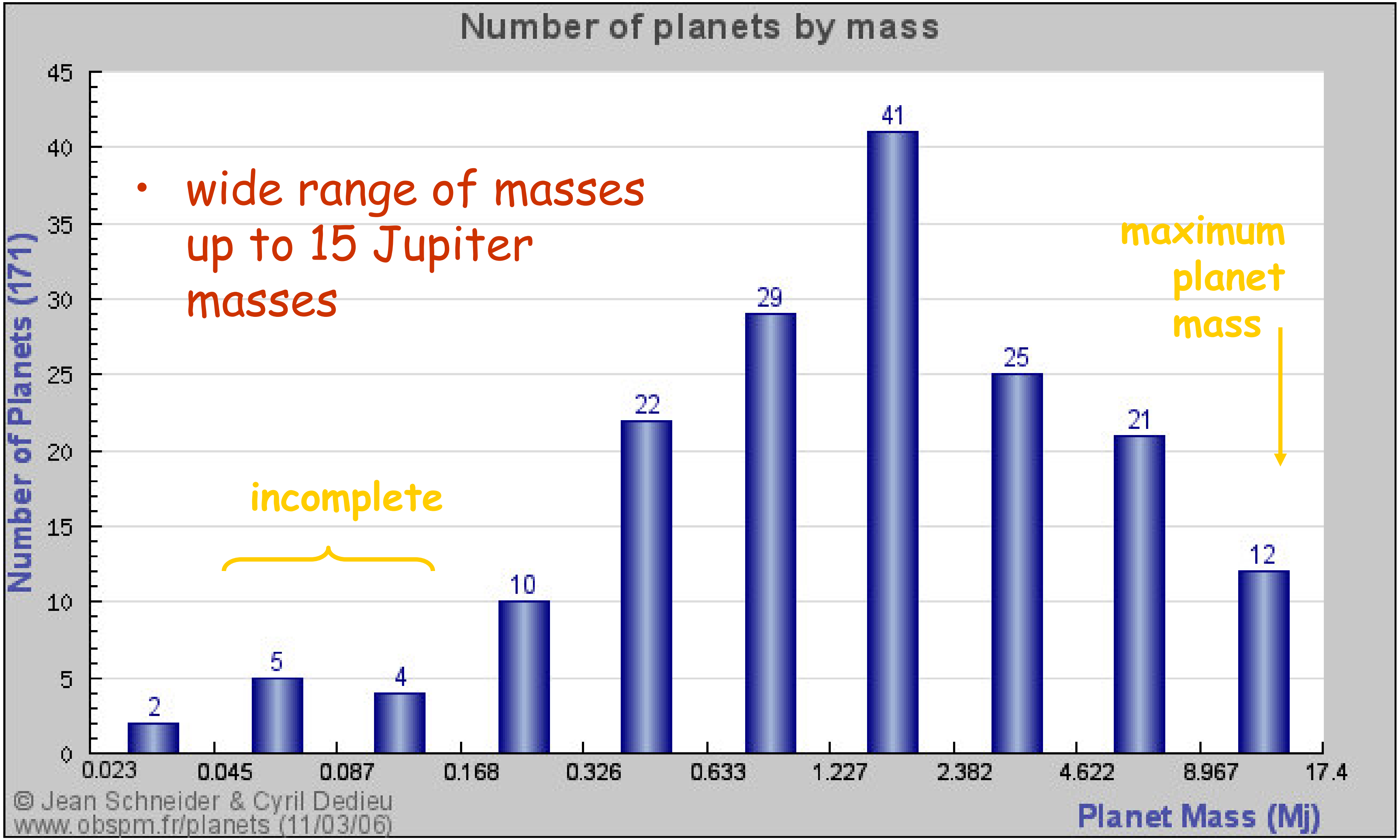
- planets are remarkably common, especially around metal-rich stars
- probability of finding a planet $\propto$ mass in metals in the star



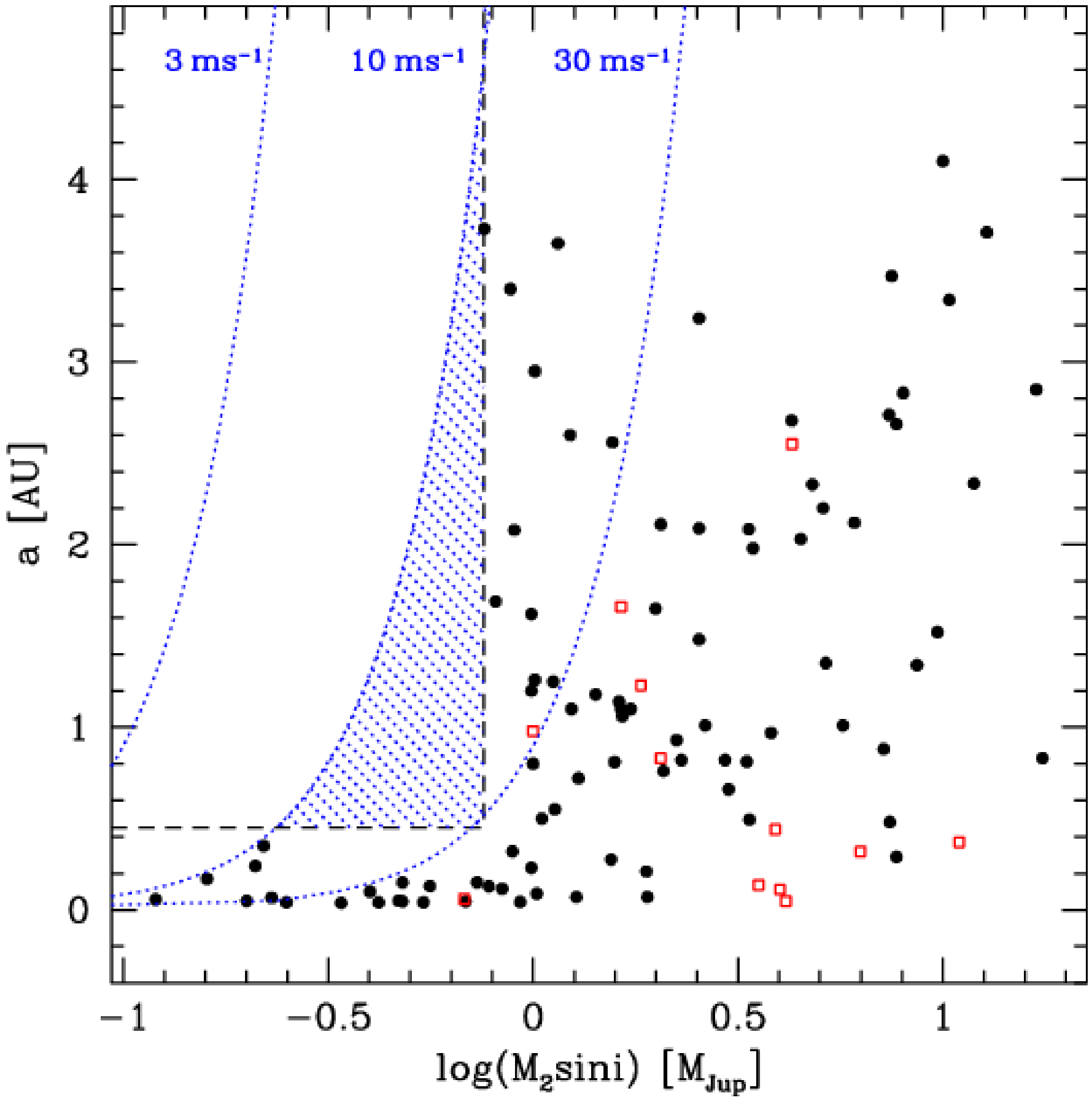
What have we learned?

- giant planets like Jupiter and Saturn are found at *very* small orbital radii
- Gliese 876d: $M \sin I = 0.0023\ M_{Jupiter}$, $P = 1.94$ days, $a = 0.0208$ AU

What have we learned?



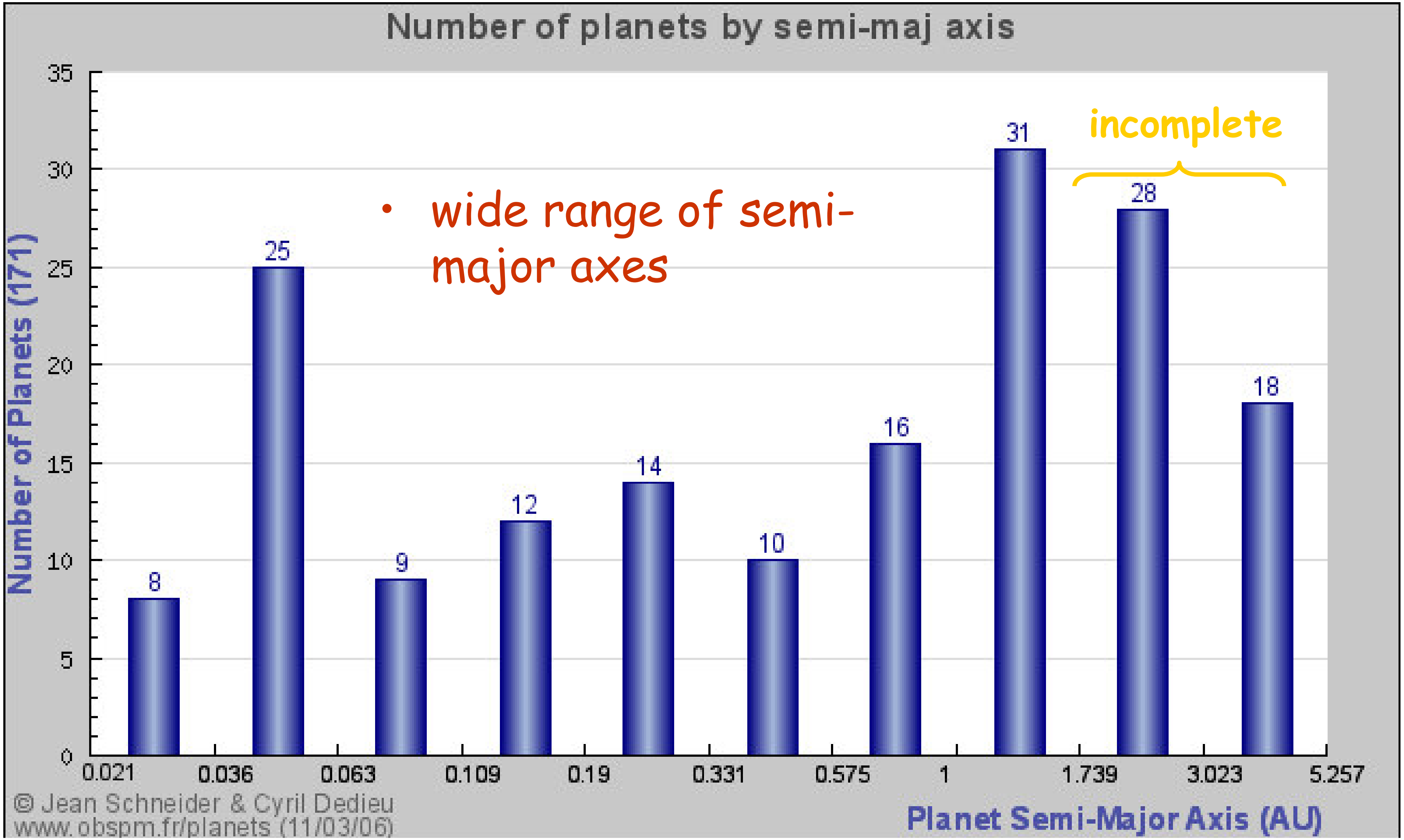
What have we learned?



- wide range of masses up to 10 Jupiter masses

Udry et al. (2003)

What have we learned?



- wide range of semi-major axes

Mass and semi-major axis distribution

To a first approximation,

$$dn \propto M^{-\alpha}\, dM, \quad M < 10\, M_J$$

$$\alpha = 1.1 \pm 0.1$$

Planets are uniformly distributed in log M

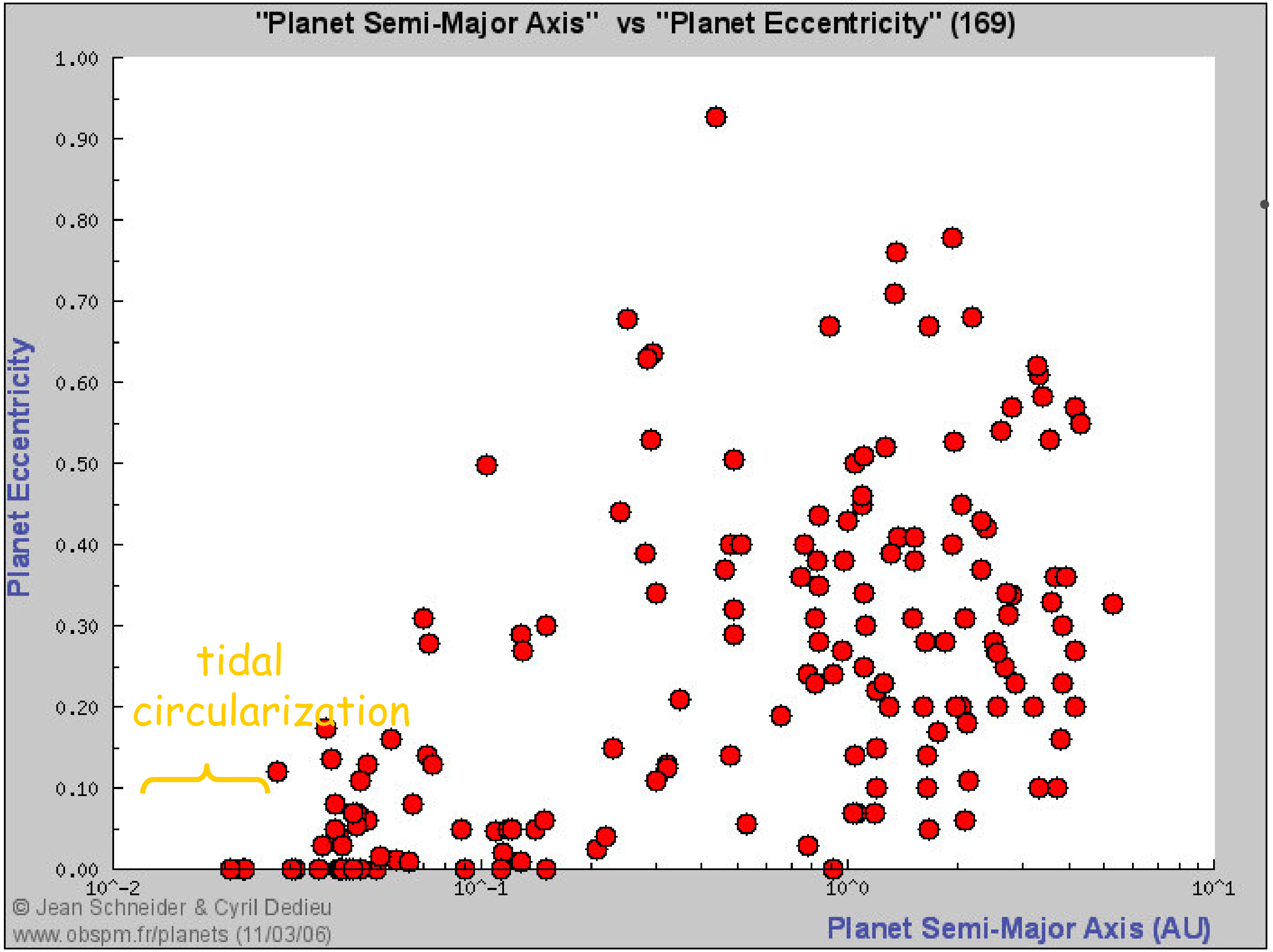
To a first approximation,

$$dn \propto a^{-\beta}\, da$$

$$\beta = 0.6 \pm 0.1$$

(Tabachnik & Tremaine 2002)

What have we learned?



- eccentricities are much larger than in the solar system