Planet formation mini-course

Leiden University
June 2007

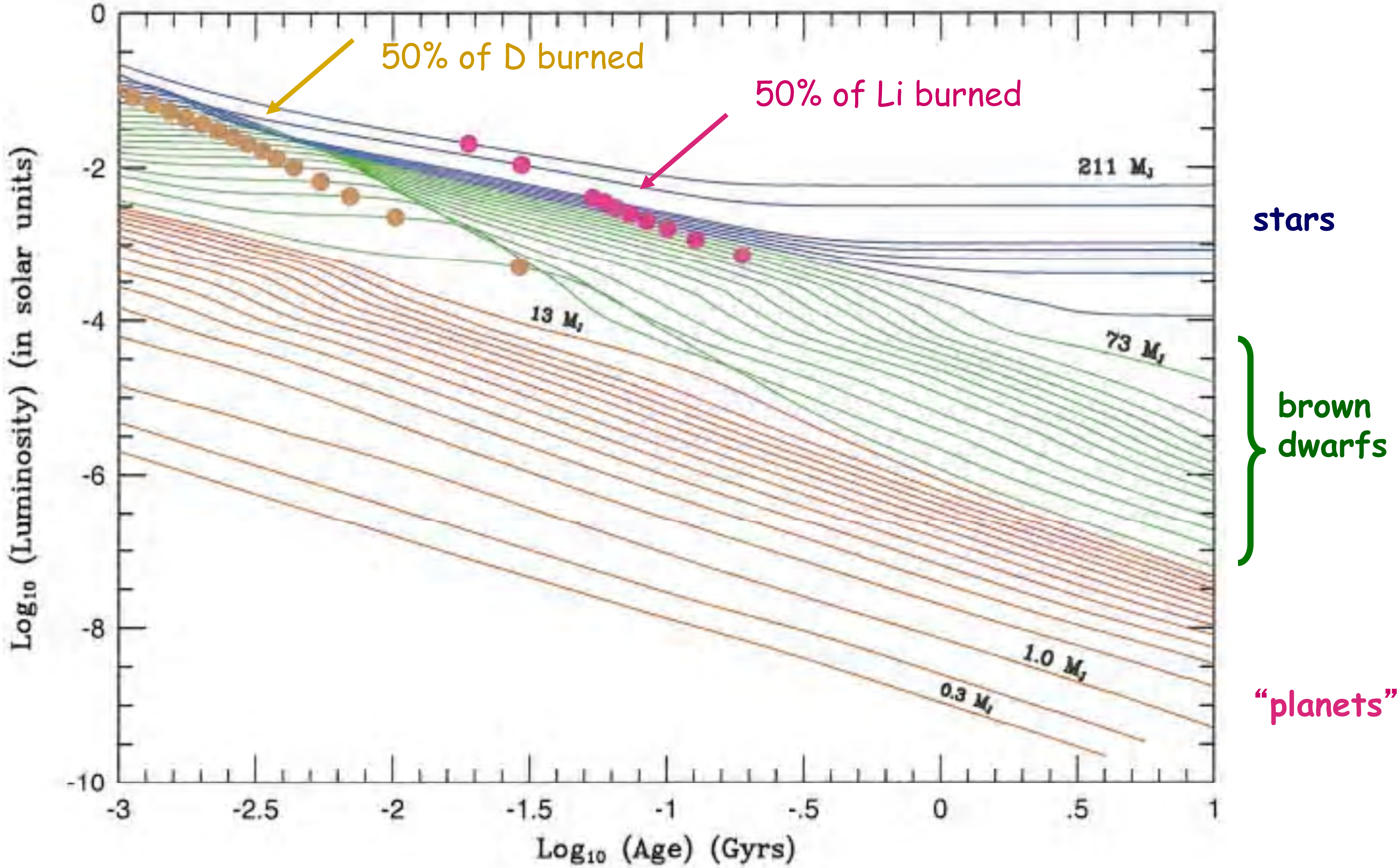
Units and characteristic numbers

1 astronomical unit = mean Earth-Sun distance = 1.496×10^{13} cm

solar mass = $M_\odot = 1.99\times10^{33}$ gm
Earth mass = $M_\oplus = 5.97\times10^{27}$ gm = $3.00\times10^{-6} M_\odot$
Jupiter mass = $M_J = 1.90\times10^{33}$ gm = $0.001 M_\odot$ = 318 $M_\oplus$

minimum hydrogen-burning mass = lower end of the main sequence
= 0.08 $M_\odot$ = 80 M_J (smallest "star")
minimum deuterium-burning mass = 0.013 $M_\odot$ = 13 M_J
brown dwarfs: 13 $M_J < M <$ 80 M_J

JPL Solar System Dynamics: ssd.jpl.nasa.gov/



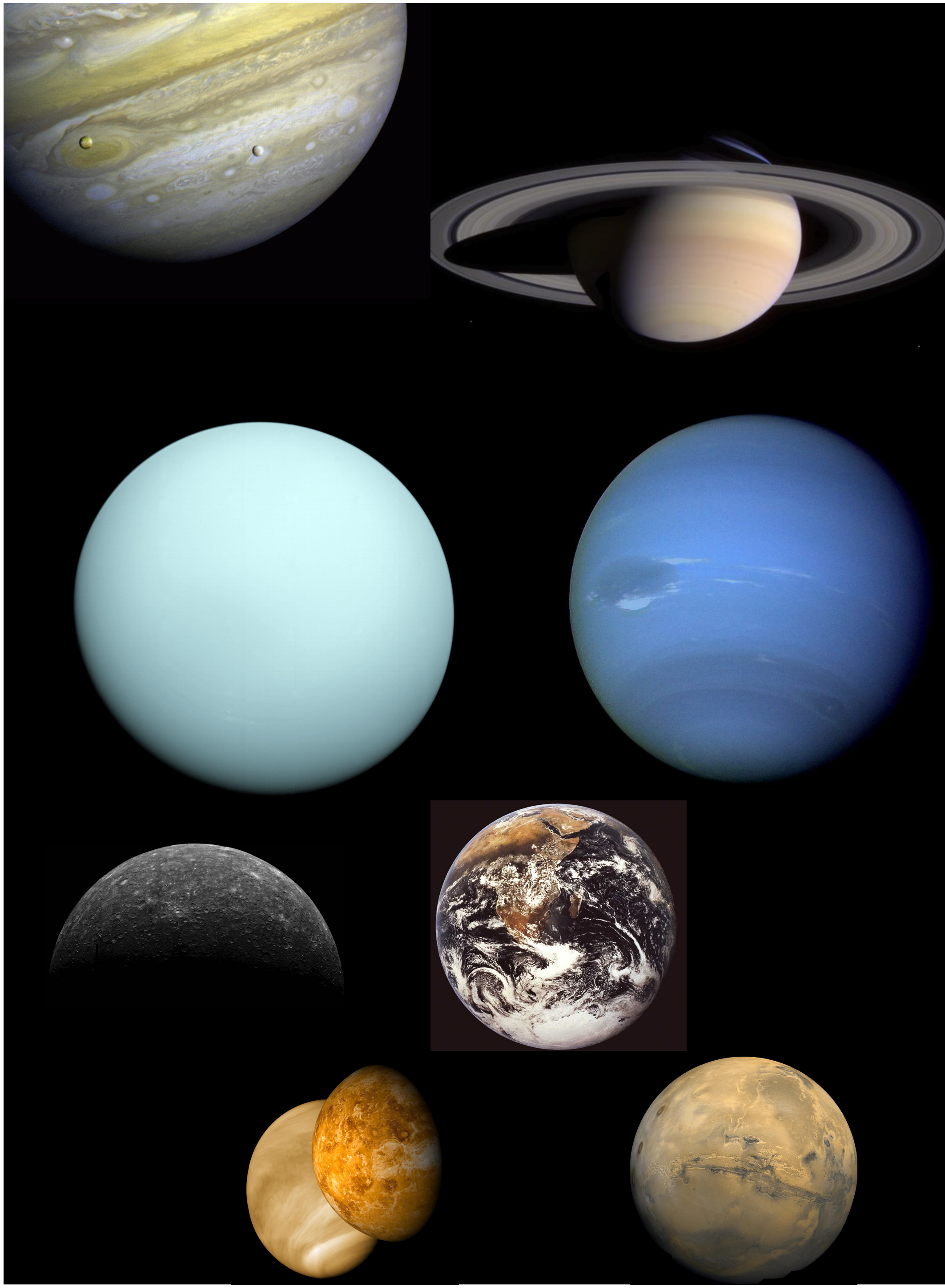
Burrows et al. (2001)

planet	semi-major axis a (AU)	eccentricity e
Mercury	0.387 (0.4)	0.206
Venus	0.723 (0.7)	0.007
Earth-Moon barycenter	1	0.017
Mars	1.524 (1.5)	0.093
Jupiter	5.203 (5)	0.048
Saturn	9.537 (10)	0.054
Uranus	19.19 (20)	0.047
Neptune	30.07 (30)	0.009

biggest

second biggest

typically < 0.05



giant planets (Jupiter, Saturn)

- composed mostly of H and He but enriched in metals and appear to have rock-ice core comprising 10-20 Earth masses

intermediate or "ice" planets (Uranus, Neptune)

- rock-ice core comprising most of mass surrounded by a gas envelope ; 5-20% H and He

terrestrial planets (Mercury, Venus, Earth, Mars)

- composed of rocky, refractory (high condensation temperature) material

planet	density (g/cm^3)	Mass ($M_\oplus$)
Mercury	5.4	0.055
Venus	5.2	0.82
Earth	5.5	1
Mars	3.9	0.11
Jupiter	1.3	318
Saturn	0.7	95
Uranus	1.3	14
Neptune	1.6	17

terrestrial planets ~ 1 $M_\oplus$ or less

giant planets > 100 $M_\oplus$

intermediate or ice planets ~ 20 $M_\oplus$

Properties of the solar system

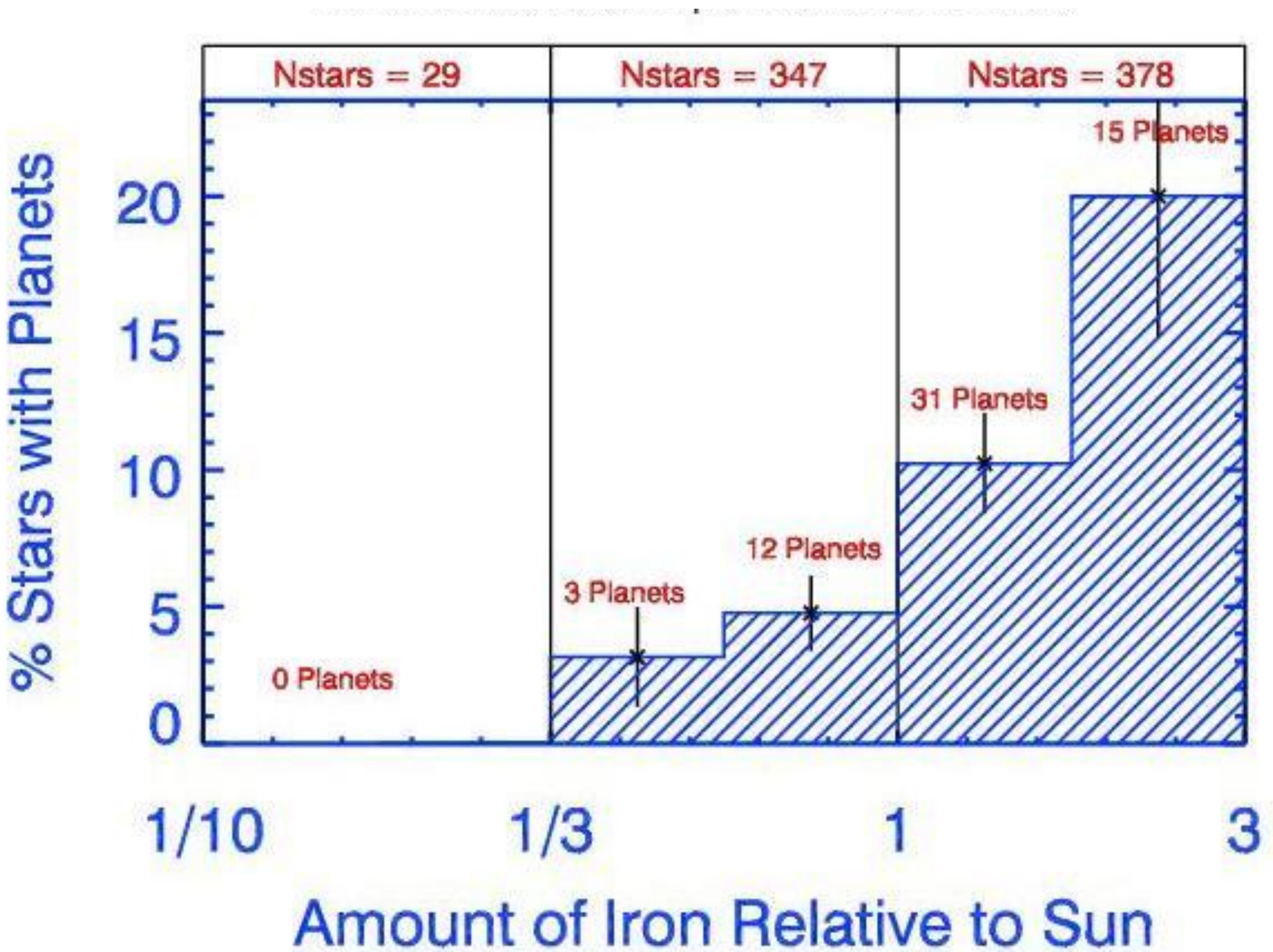
- most planets have satellites

planet	number	M_{max}/M_{planet}
Earth	1	0.012
Mars	2	1.7×10^{-8}
Jupiter	61	7.8×10^{-5}
Saturn	31	2.4×10^{-4}
Uranus	27	4.1×10^{-5}
Neptune	13	2.1×10^{-4}

Properties of the solar system

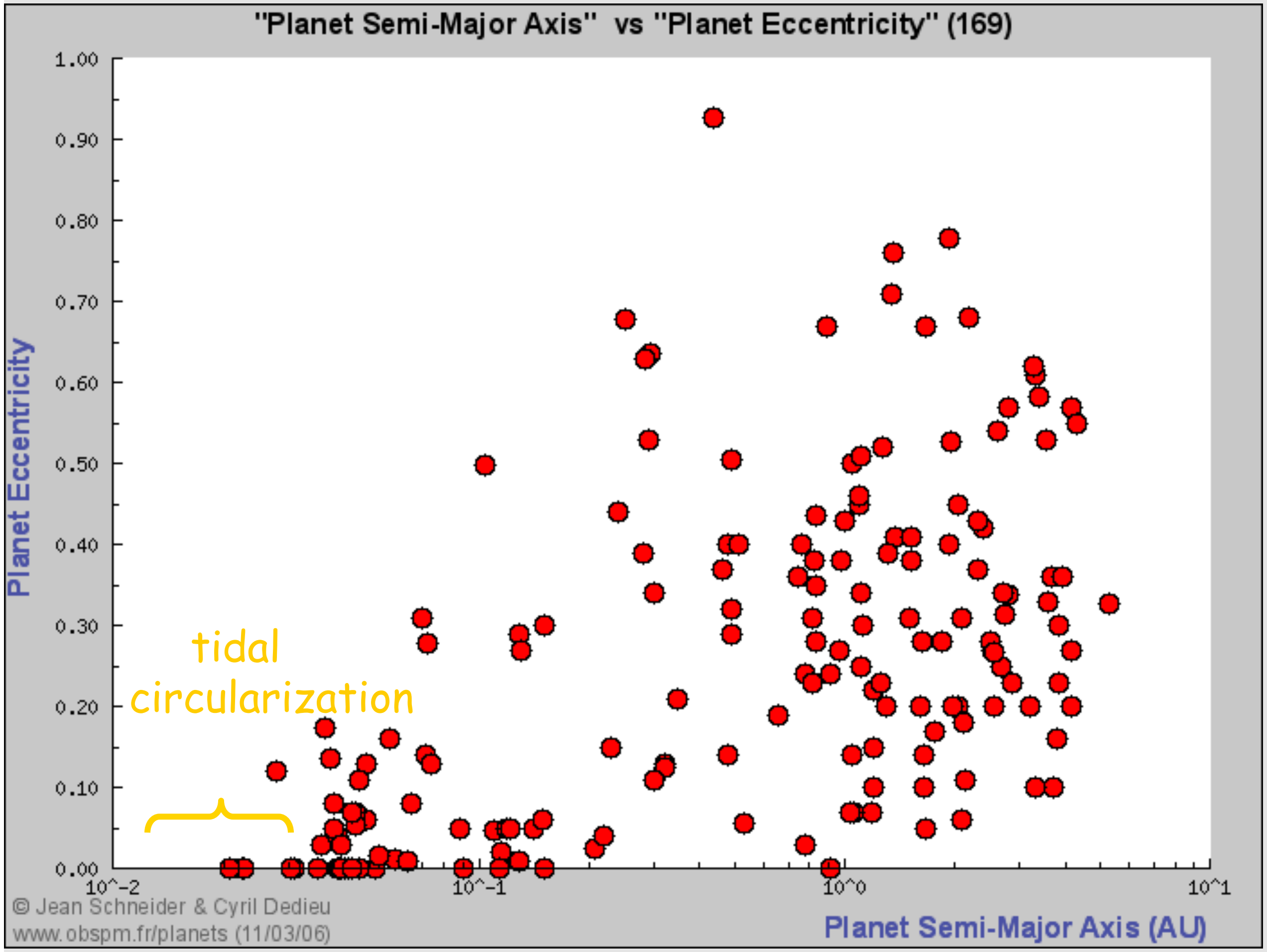
- planetary orbital angular momentum is close to direction of Sun's spin angular momentum (within 7^o)
- 3 of 4 terrestrial planets and 3 of 4 giant planets have obliquities (angle between spin and orbital angular momentum) $< 30^o$; but Uranus is tipped at 98^o
- interplanetary space is virtually empty, except for the asteroid belt and the Kuiper belt
- planets account for < 0.2% of mass of solar system but > 98% of angular momentum
- solid planetary and satellite surfaces are heavily cratered; cratering rate must have been far greater in first 10^9 yr of solar system history than it is now ("late heavy bombardment")
- age of solar system is $4.56 \pm 0.02 \times 10^9$ yr
- typically protoplanetary gas disks disperse in 1-10 Myr, so outer planets must have formed in less than this time

Properties of extrasolar planetary systems



- probability of finding a planet is proportional to mass of metals in the star

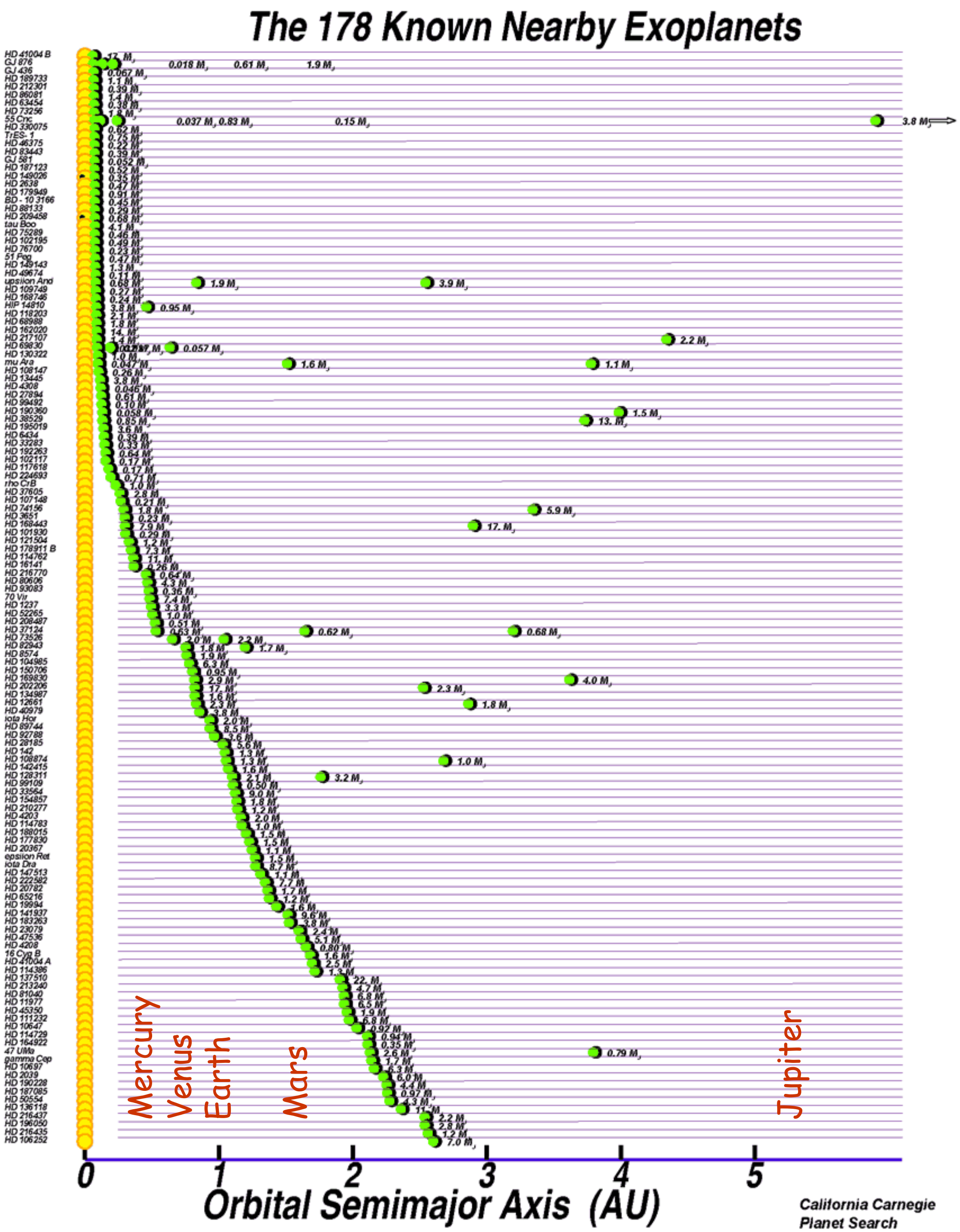
Properties of extrasolar planetary systems



- orbits of major planets in solar system are nearly circular ($e_{Mercury}$=0.206, e_{Mars}=0.09, typically < 0.05); orbits of extrasolar planets are *not* (e_{median}=0.28)
- biggest eccentricity e = 0.93

Extrasolar Planets Encyclopedia

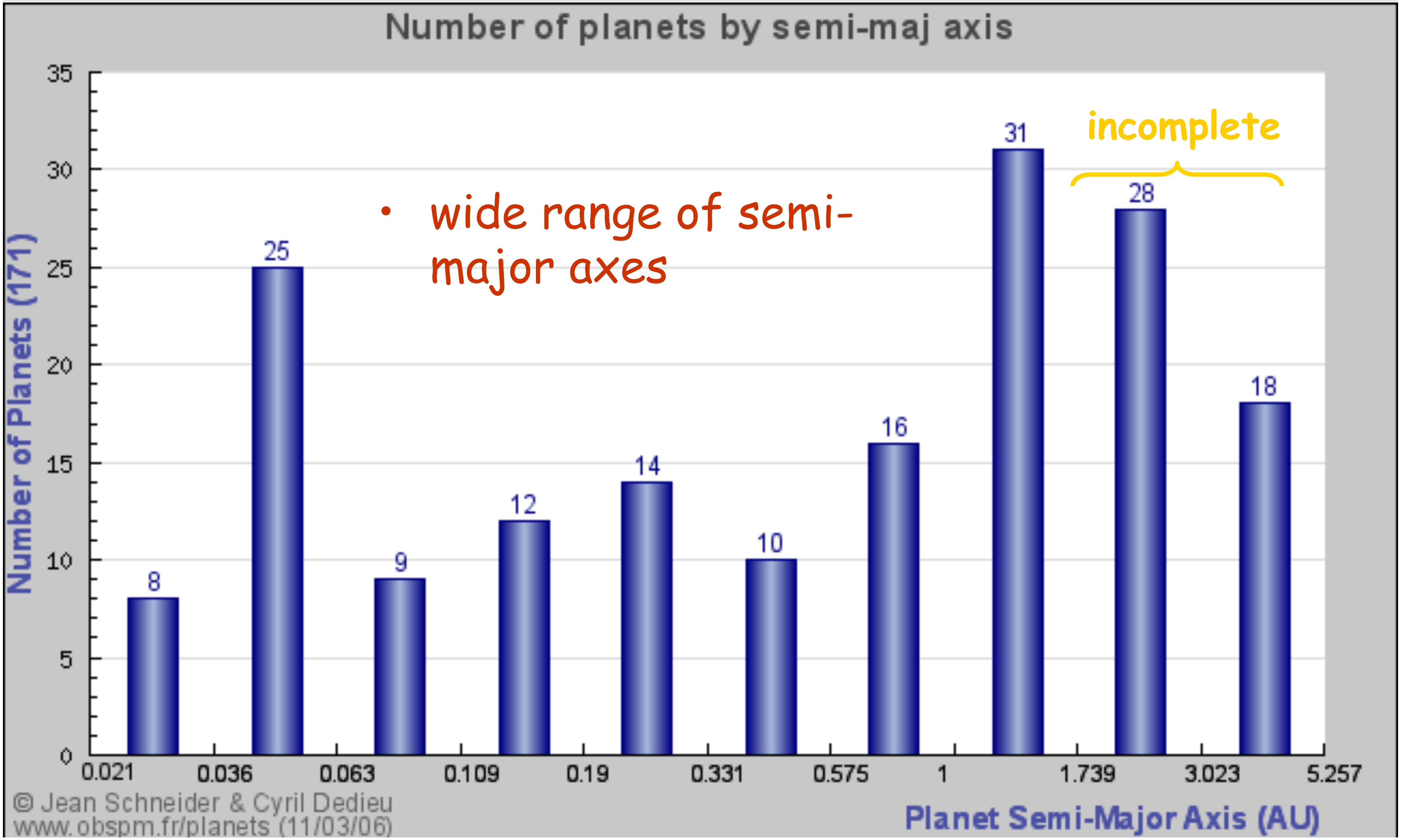
www.exoplanet.eu



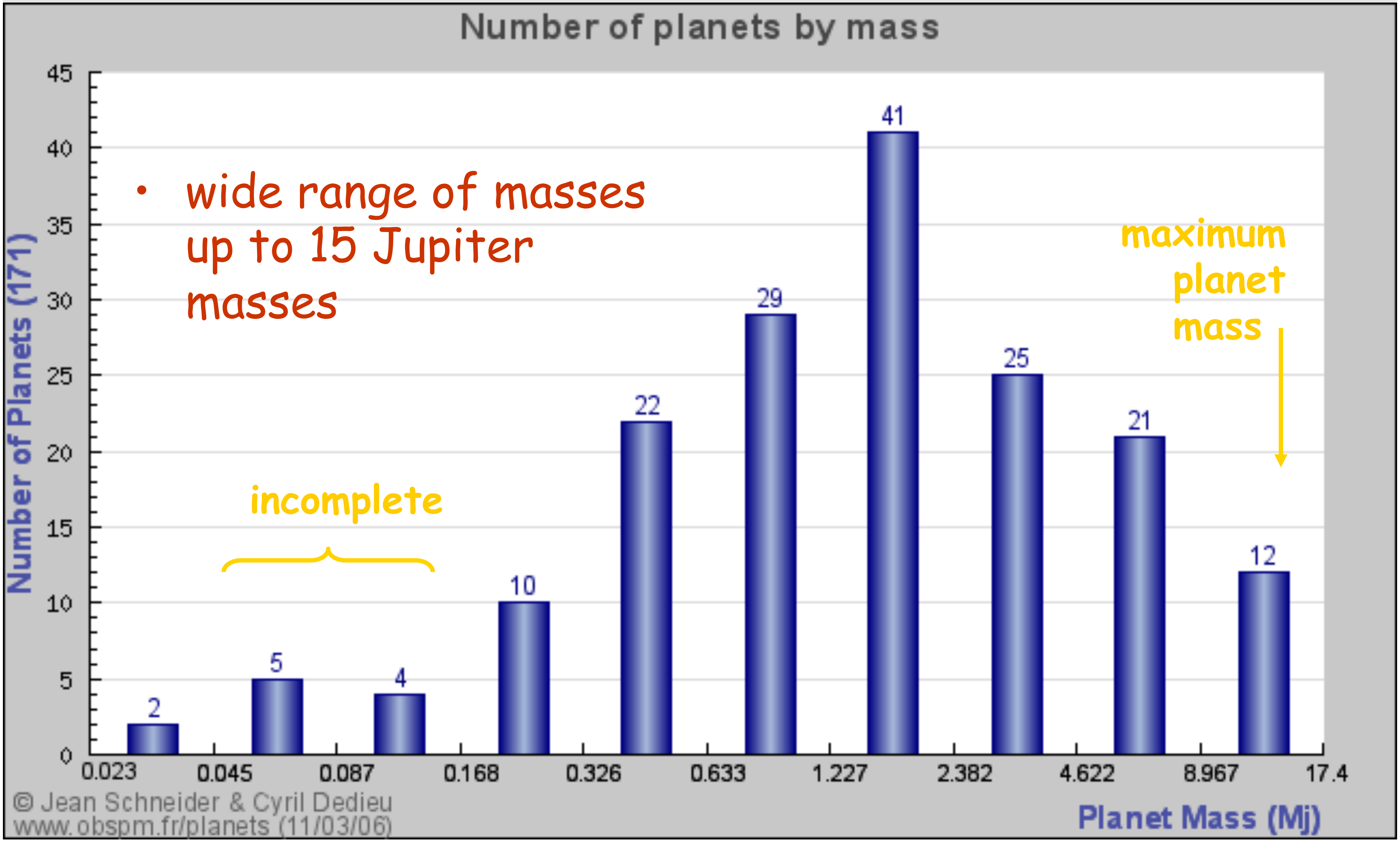
Properties of extrasolar planetary systems

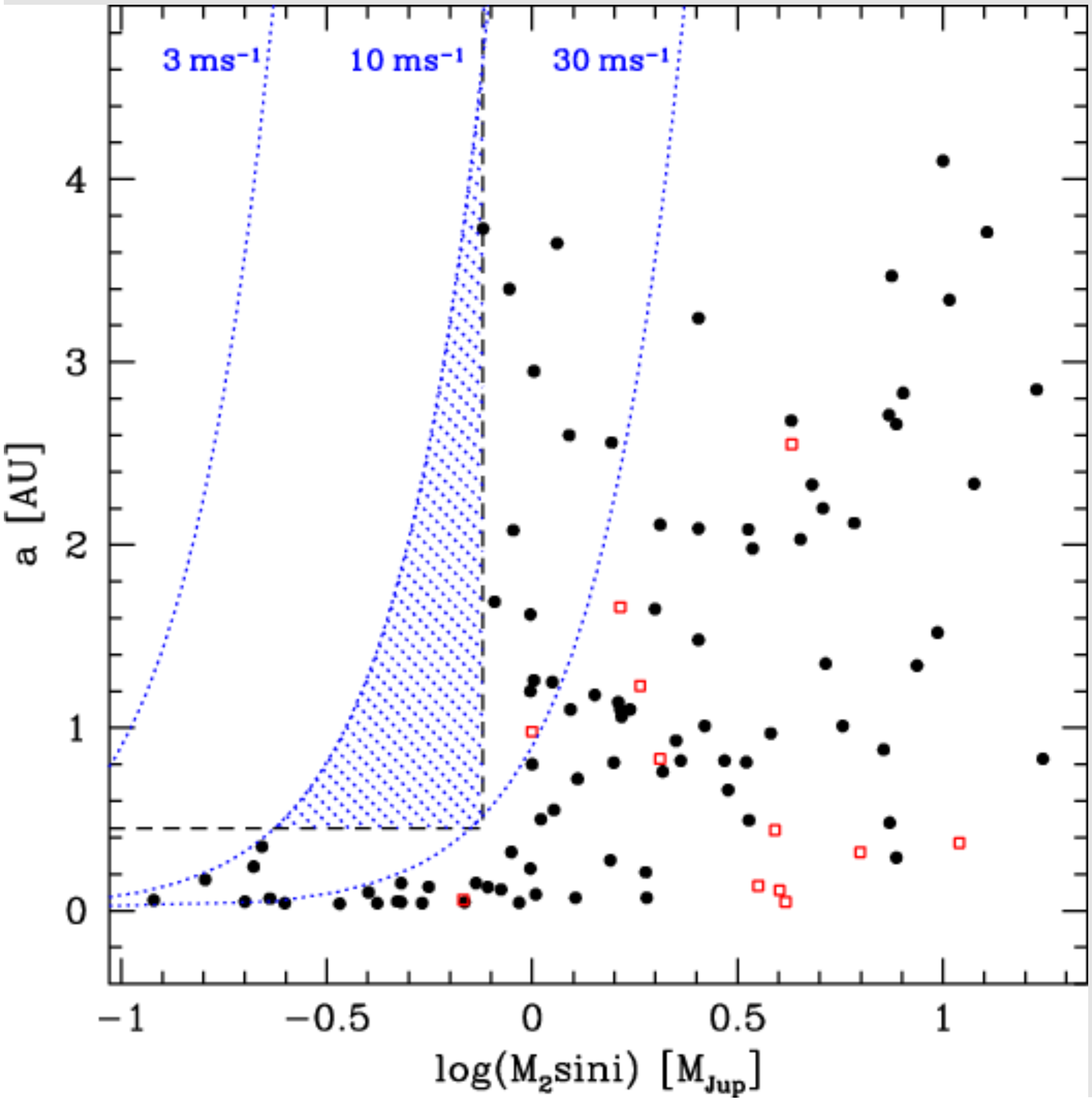
- giant planets like Jupiter and Saturn are found at *very* small orbital radii – up to a factor 200 less than Jupiter
- OGLE-TR-56b: mass = 1.45 Jupiter masses, orbital period = 1.21 days, orbital radius = 0.0225 AU

Properties of extrasolar planetary systems



Properties of extrasolar planetary systems

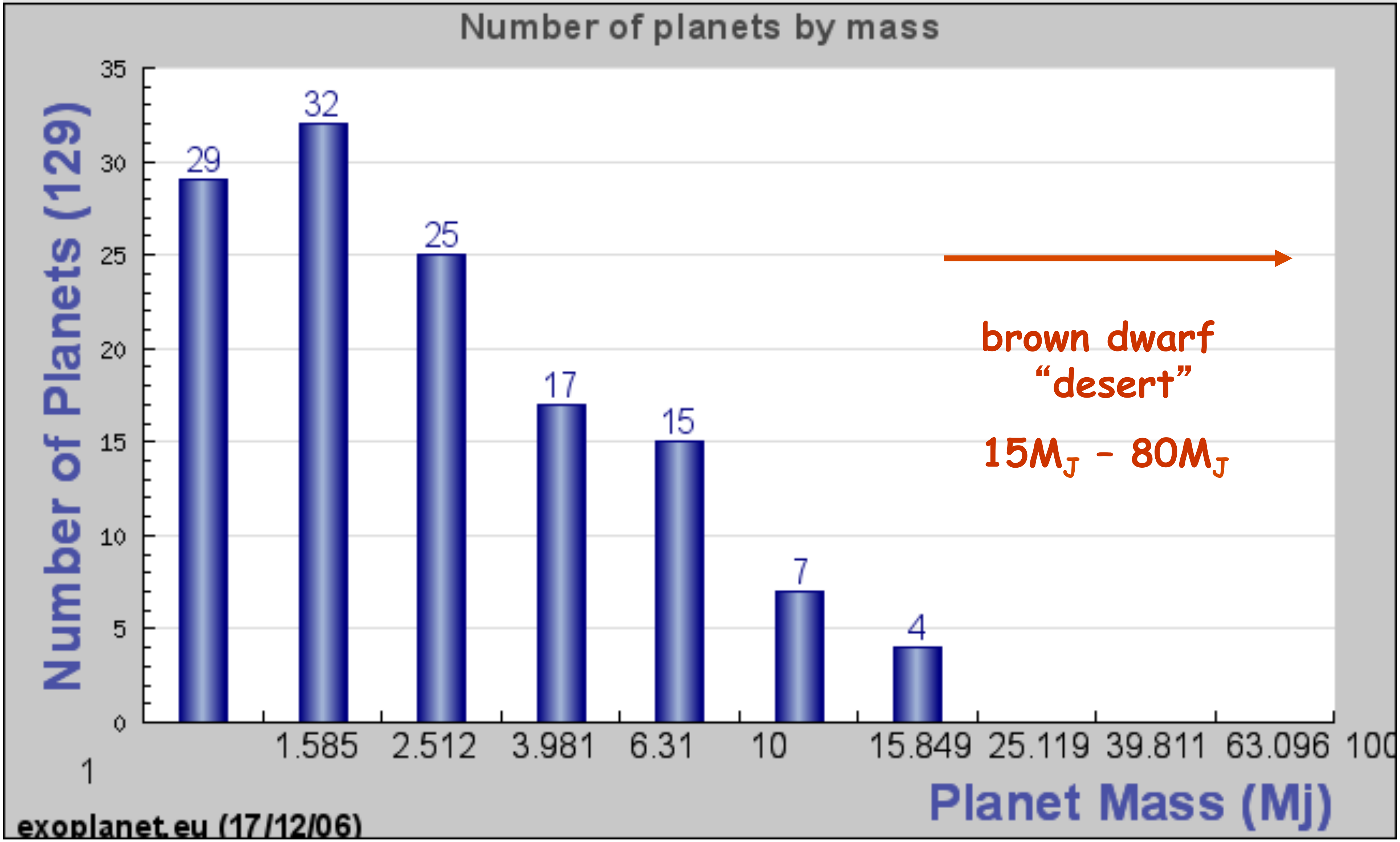




- wide range of masses up to 15 Jupiter masses
- lower cutoff to masses is determined entirely by observational selection

Udry et al. (2003)

Properties of extrasolar planetary systems



Mass distribution

- to a first approximation,

$$dn \propto M^{-\alpha}\, dM, \quad M < 15\ M_J$$

$$\alpha = 1.1 \pm 0.1$$

Planets are uniformly distributed in log M

- the brown dwarf desert: at separations < 5 AU, very few companion objects are found in the range 15 M_J to 80 M_J corresponding to brown dwarfs
- i.e., planets are *not* simply the extrapolation of the stellar mass distribution

What have we learned?

- 242 extrasolar planets known, most from radial velocity surveys (as of June 1 2007)
- smallest semi-major axis $a = 0.018$ AU = 3.9 R– (Mercury is 0.4 AU)
- largest semi-major axis $a = 7.73$ AU (Jupiter = 5.2 AU)
- biggest eccentricity $e = 0.93$
- smallest eccentricity $e = 0$
- smallest mass 0.016 M_J = 5 $M_{©}$
- biggest mass » 15 M_J
- big selection effects against small mass and large semi-major axis or period

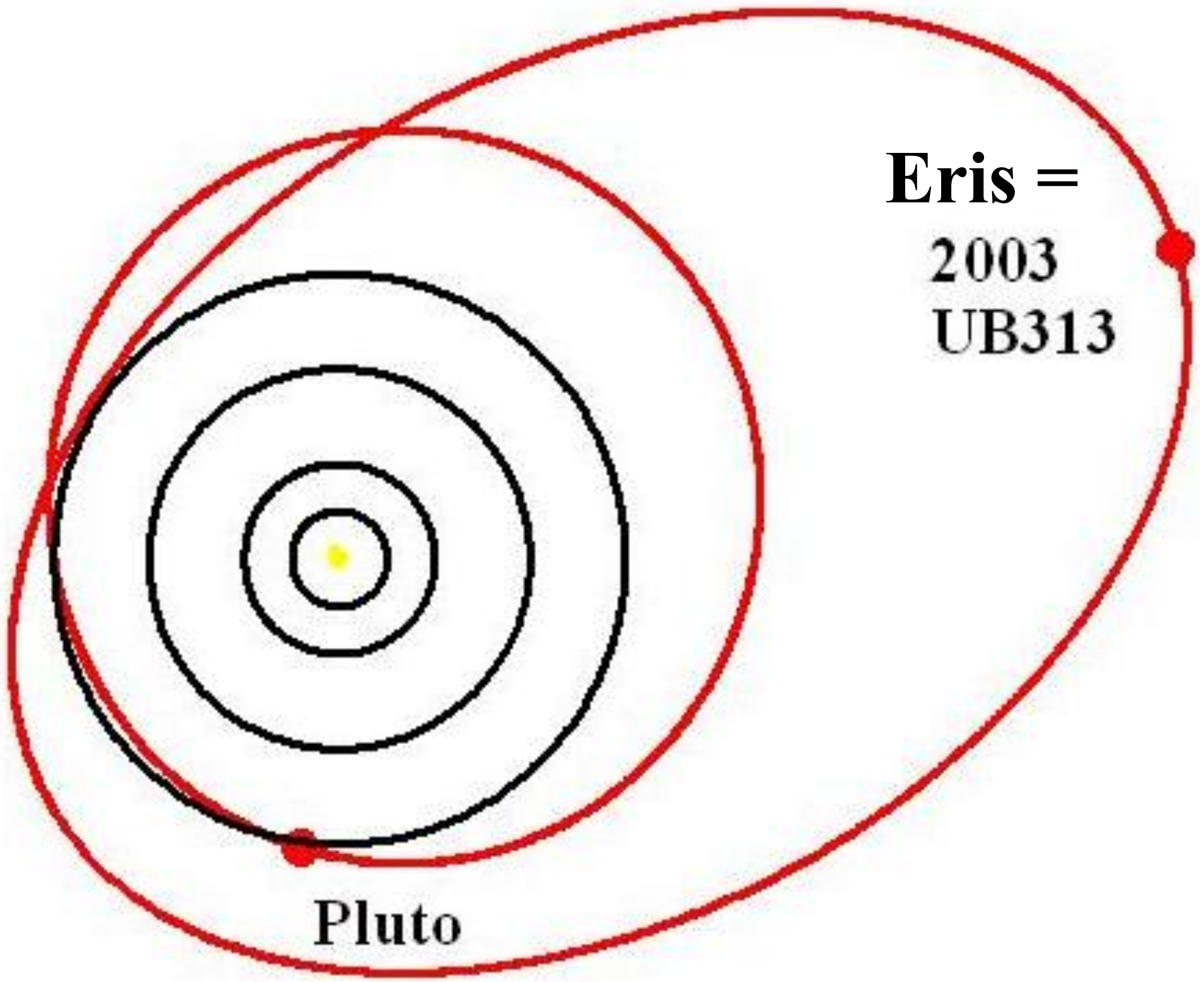
What is a planet?

Bad definition 1:

- main-sequence stars burn hydrogen ($M > 0.08\ M_\odot = 80\ M_J$)
- brown dwarfs have masses too low to burn hydrogen but large enough to burn deuterium ($80\ M_J > M > 13\ M_J$)
- planets have masses $< 13\ M_J$
- Good points:
  - mass is easy to measure
  - maximum mass of close companions to stars is around 15 M_J (brown-dwarf desert)
- Bad points:
  - deuterium burning has no fundamental relation to the formation or properties of a planet
  - what is the lower limit?

Bad definition 2:

- planets are objects similar to the planets in our own solar system
- Bad points:
  - is a Jupiter-mass object at a=0.02 AU a planet?
  - is Pluto a planet?
  - is our solar system special?
  - Eris and her sisters



Brown et al. (2005)

• diameter 2400 § 100 km or 5% bigger than Pluto

• has a moon

• albedo 80-90%

What is a planet?

Bad definition 3:

- anything formed in a disk around a star is a planet
- Bad points:
  - figuring out how something is formed is really hard, and what do we call them until we do?

Bad definition 4 (IAU):

- A "planet" is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighbourhood around its orbit.

- A "dwarf planet" is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, (c) has not cleared the neighborhood around its orbit, and (d) is not a satellite.

- All other objects except satellites orbiting the Sun shall be referred to collectively as "Small Solar-System Bodies".

- Bad points:
  - really complicated
  - only works for the solar system
  - hydrostatic bodies are not necessarily spherical (e.g., many asteroids)

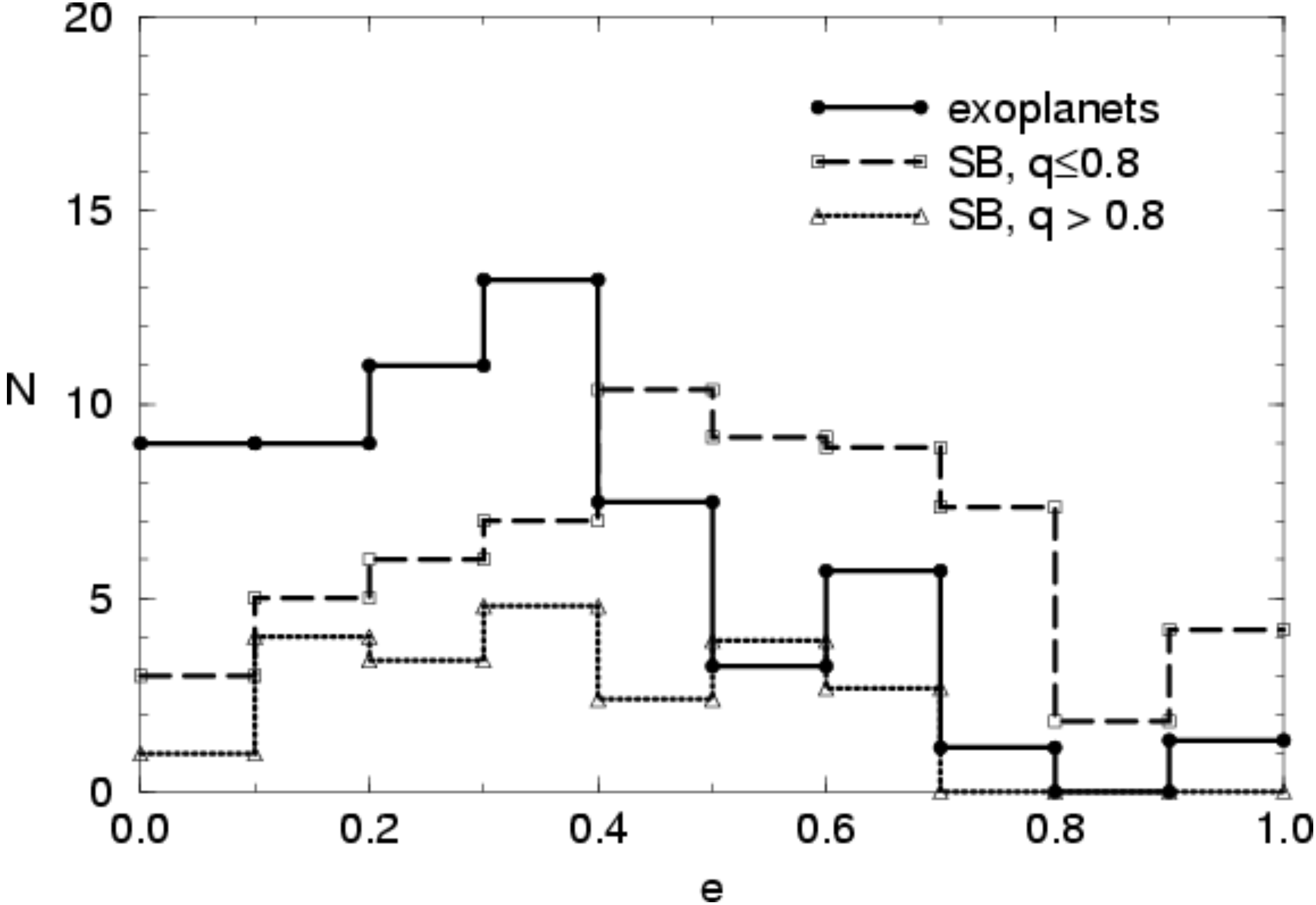
The encounter hypothesis

Close encounter with a passing star rips material off the Sun that spreads into a long filament and condenses into planets (Buffon 1745, Jeans 1928, Jeffreys 1929)

- bad points:
  - specific angular momentum of order $(GM_\odot R_\odot)^{1/2}$ not $(GM_\odot a_J)^{1/2}$; factor 30 too small (Russell 1935)
  - 1 Jupiter mass of material requires digging to $R \sim 0.1\ R_\odot$ where temperature $\sim 5 \times 10^5$ K and resulting blob will have positive energy, and cooling time $\sim 10^{10}$ sec. Blob expands adiabatically and disperses (Spitzer 1939)
  - where did Jupiter's deuterium come from – D/H approximately consistent with Big Bang
  - very rare event - no extrasolar planets
- good points:
  - predicts giant gaseous planets at very small radii

The brown dwarf hypothesis

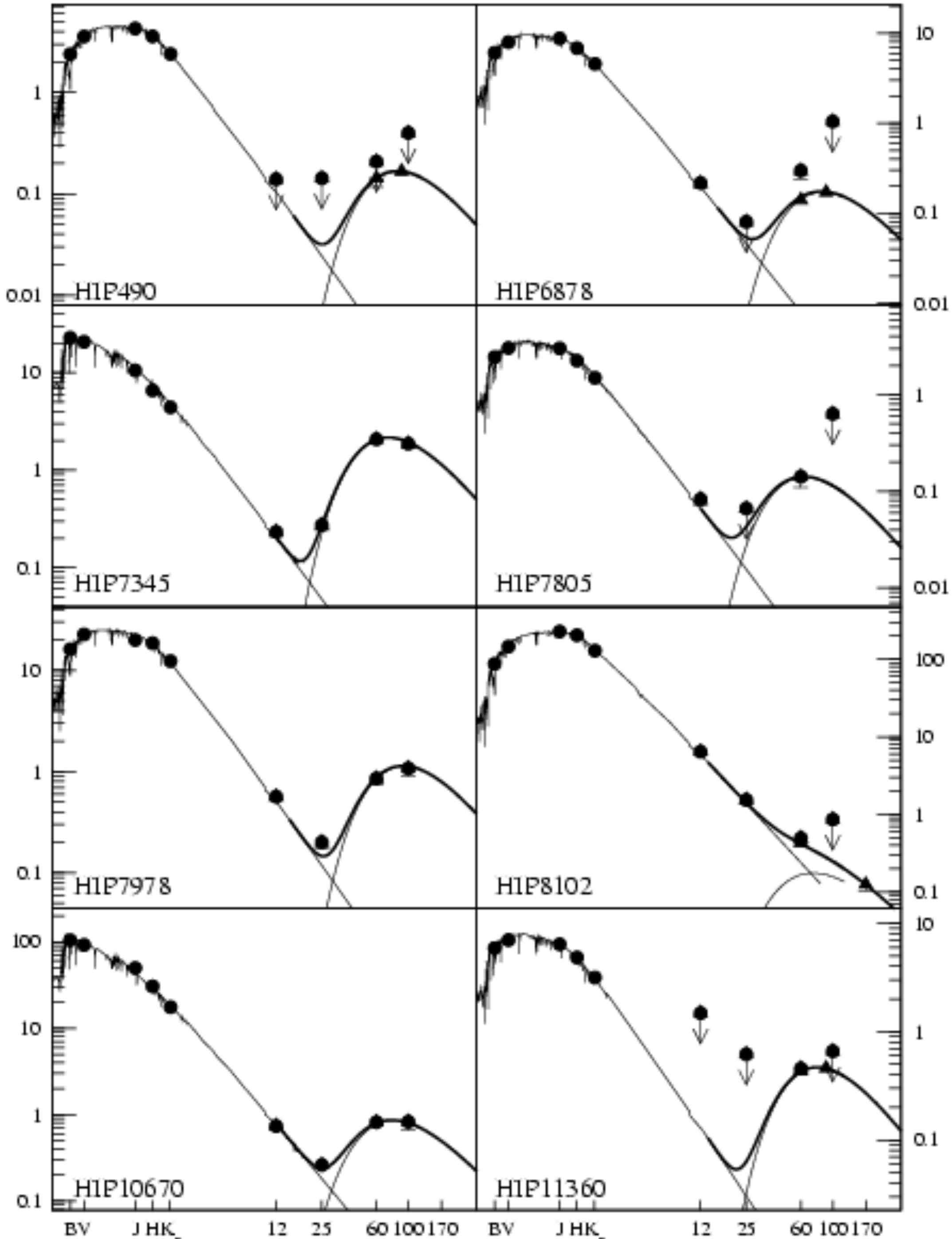
- extrasolar “planets” are simply very low-mass stars that form from collapse of multiple condensations in protostellar clouds
- good points:
  - distribution of eccentricities and periods of extrasolar planets very similar to distributions for binary stars
- bad points:
  - why is there a brown-dwarf desert?
  - how did planets in solar system get onto circular, coplanar orbits?
  - how do you make planets with solid cores, or terrestrial planets?
  - theory suggests that it is hard to make objects as small as Jupiter by fragmentation of a gas cloud
- maybe the most massive extrasolar planets are made this way



From Halbwachs et al. (2005)

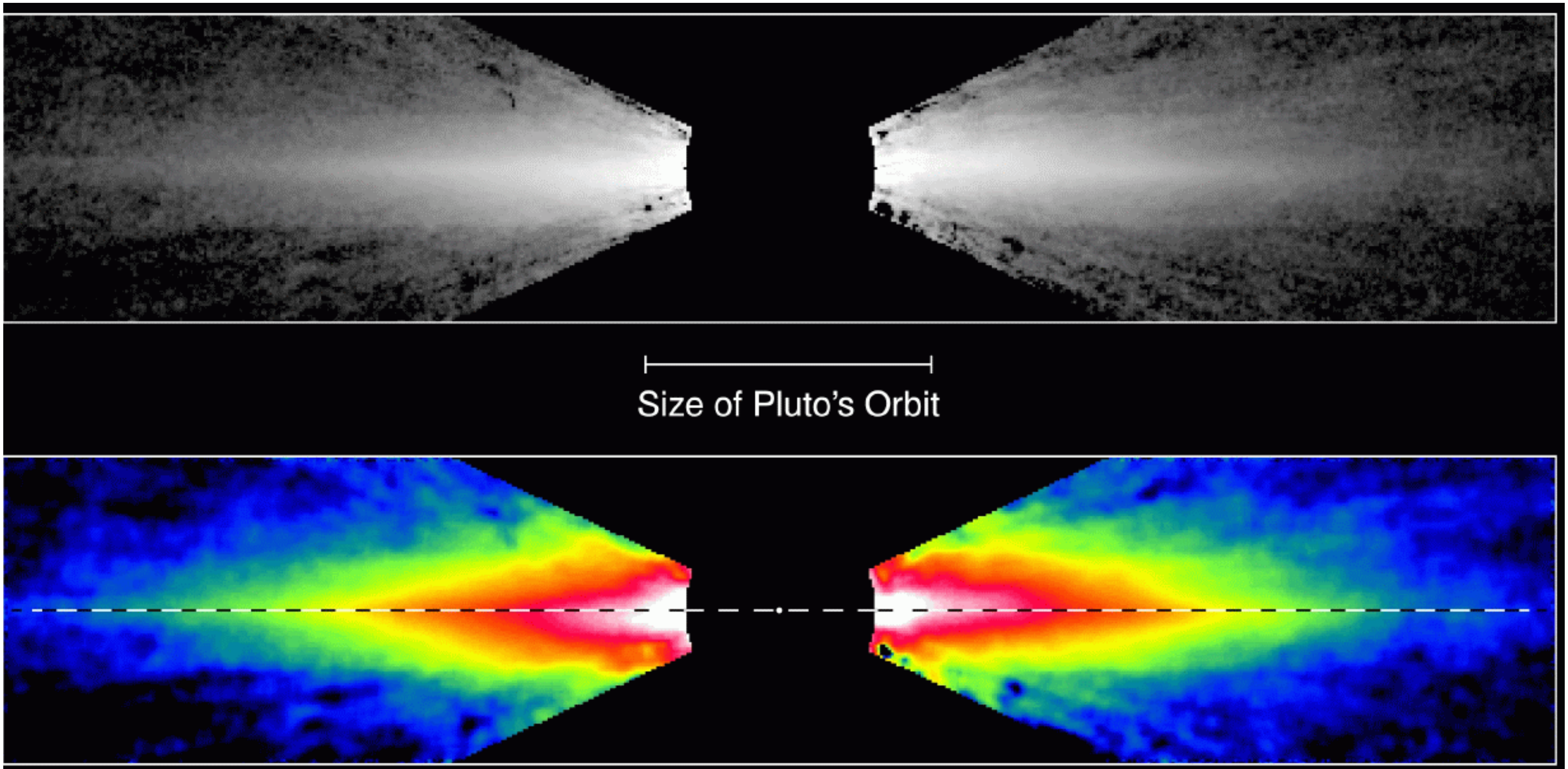
The "nebular" or "disk instability" hypothesis

- the Sun and planets formed together out of a rotating cloud of gas (the "solar nebula")
- gravitational instabilities in the gas disk condense into planets (Kant 1755)
- Good points:
  - correctly predicted that stars are surrounded by rotating gas disks after they are born

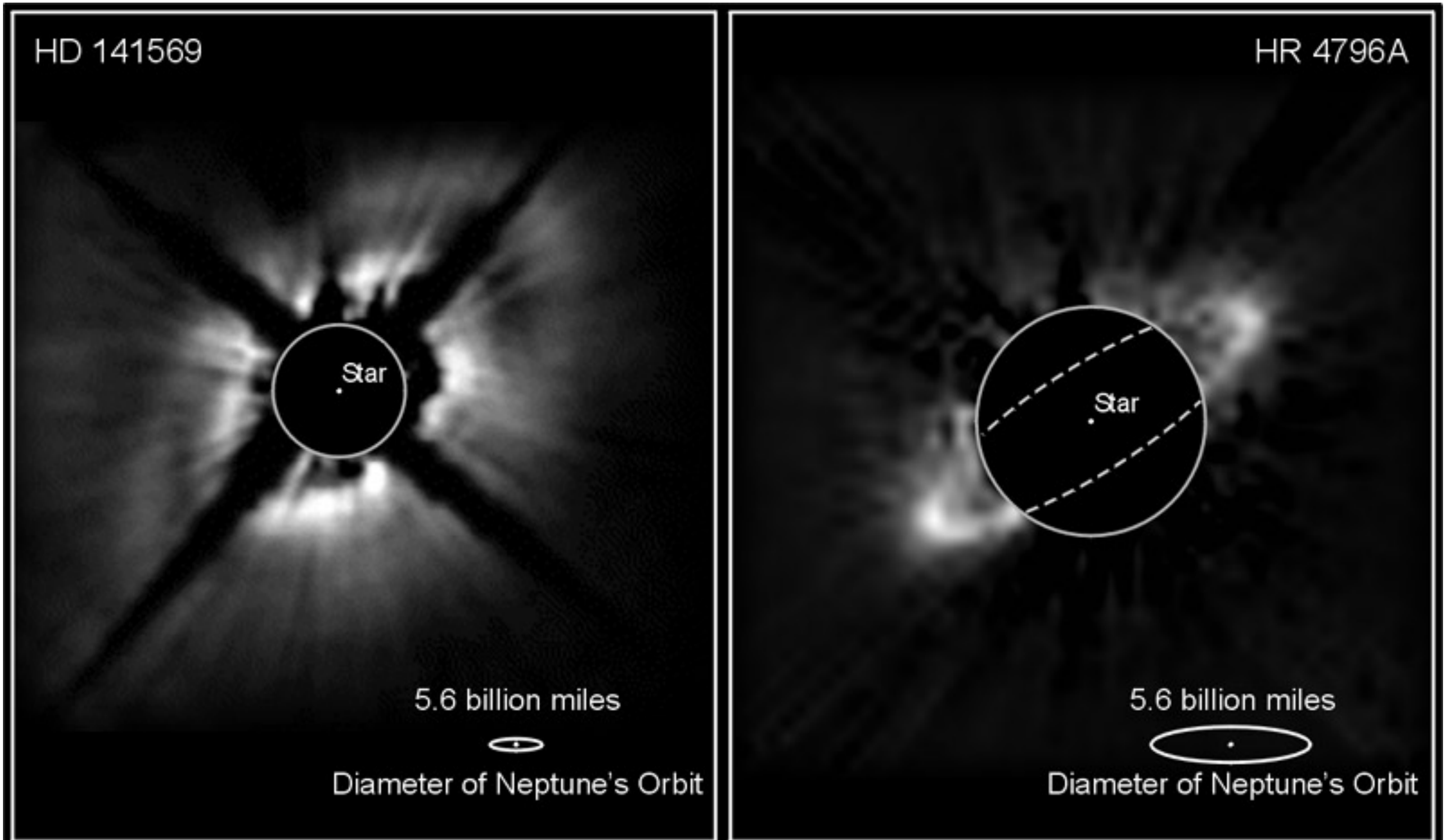


the “Vega phenomenon”

(Zuckerman & Song 2003)



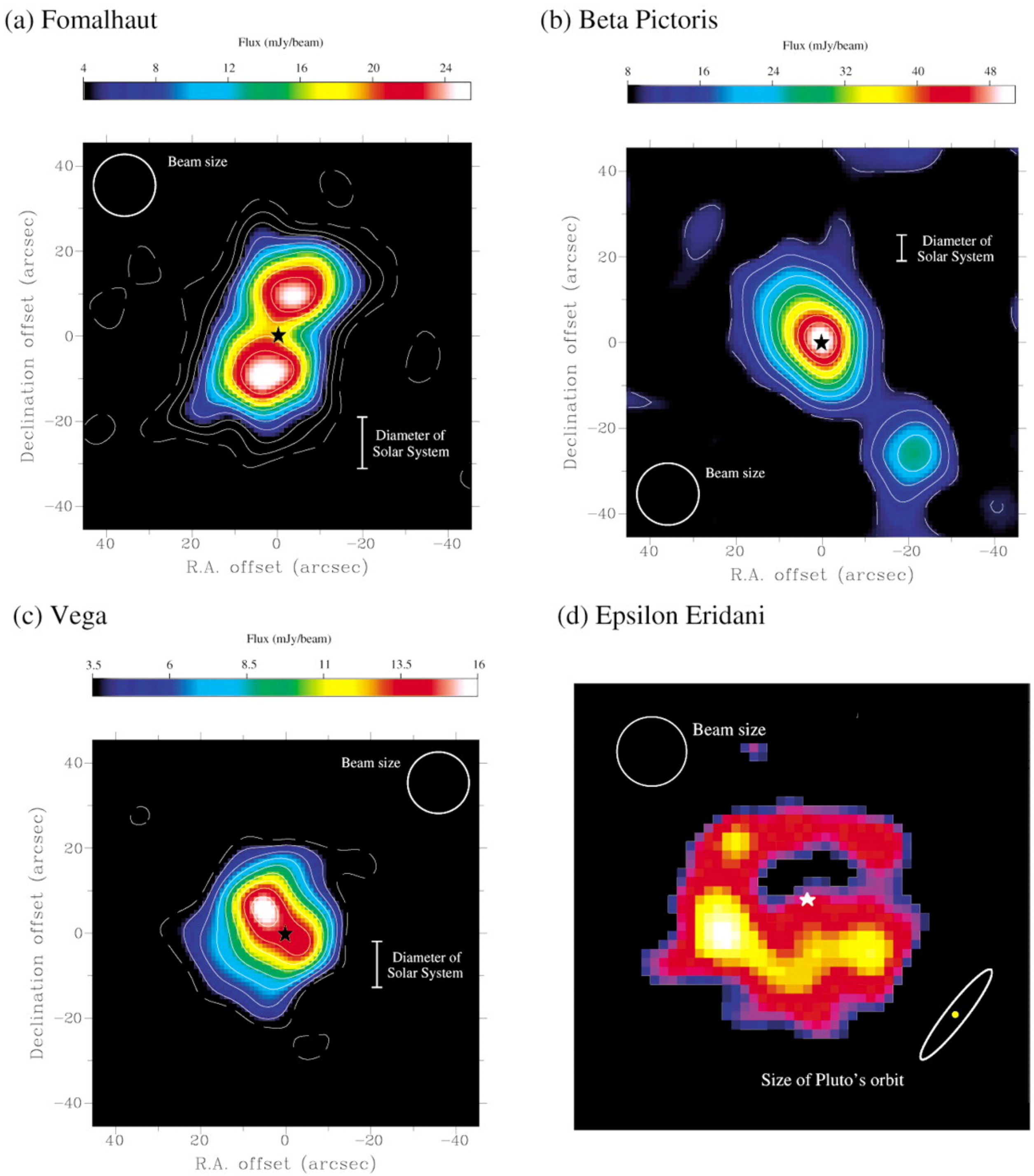
beta Pictoris disk



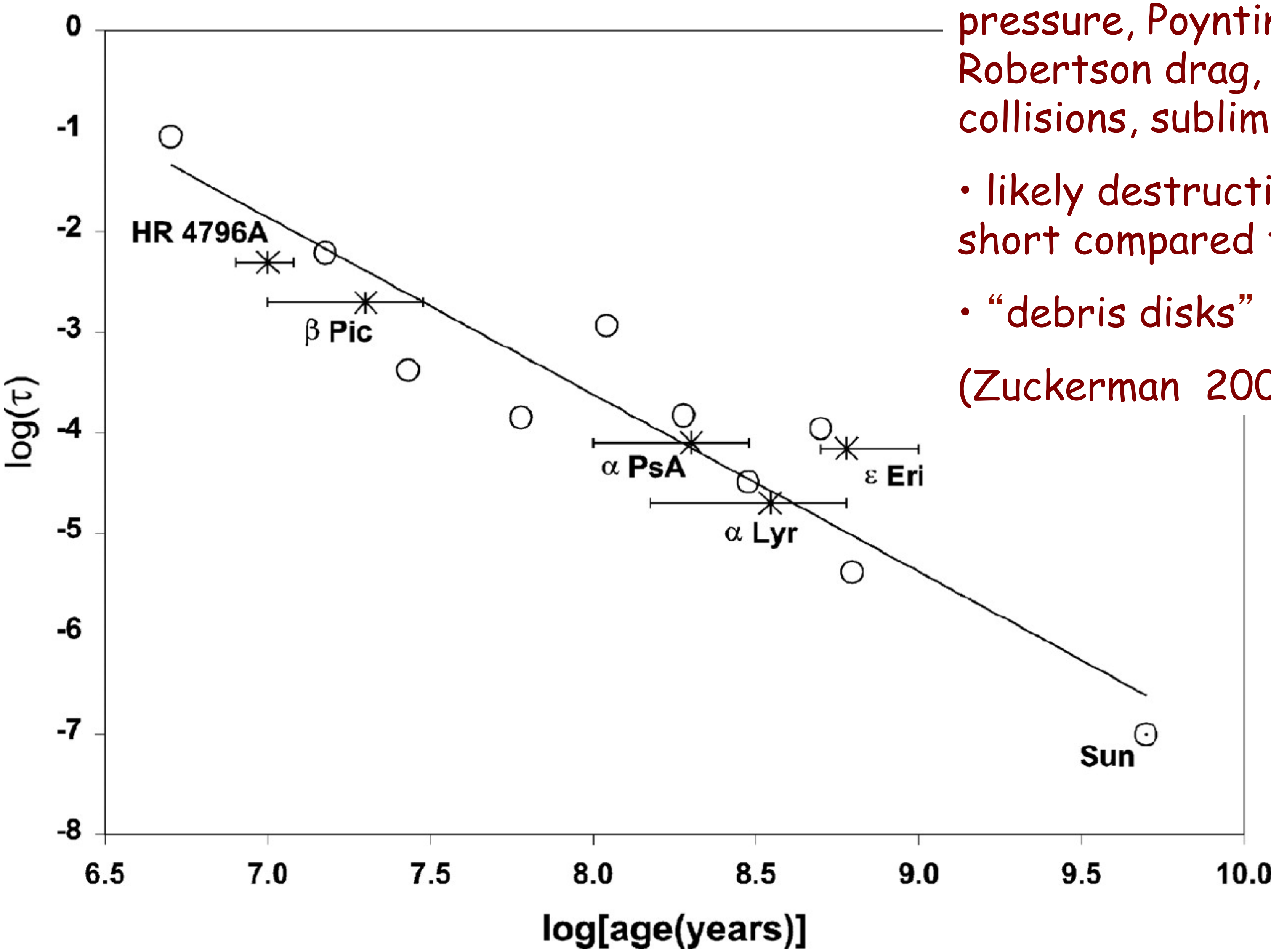
Dust Disks around Stars **HST • NICMOS**

PRC99-03 • STScI OPO • January 8, 1999

B. Smith (University of Hawaii), G. Schneider (University of Arizona),
E. Becklin and A. Weinberger (UCLA) and NASA



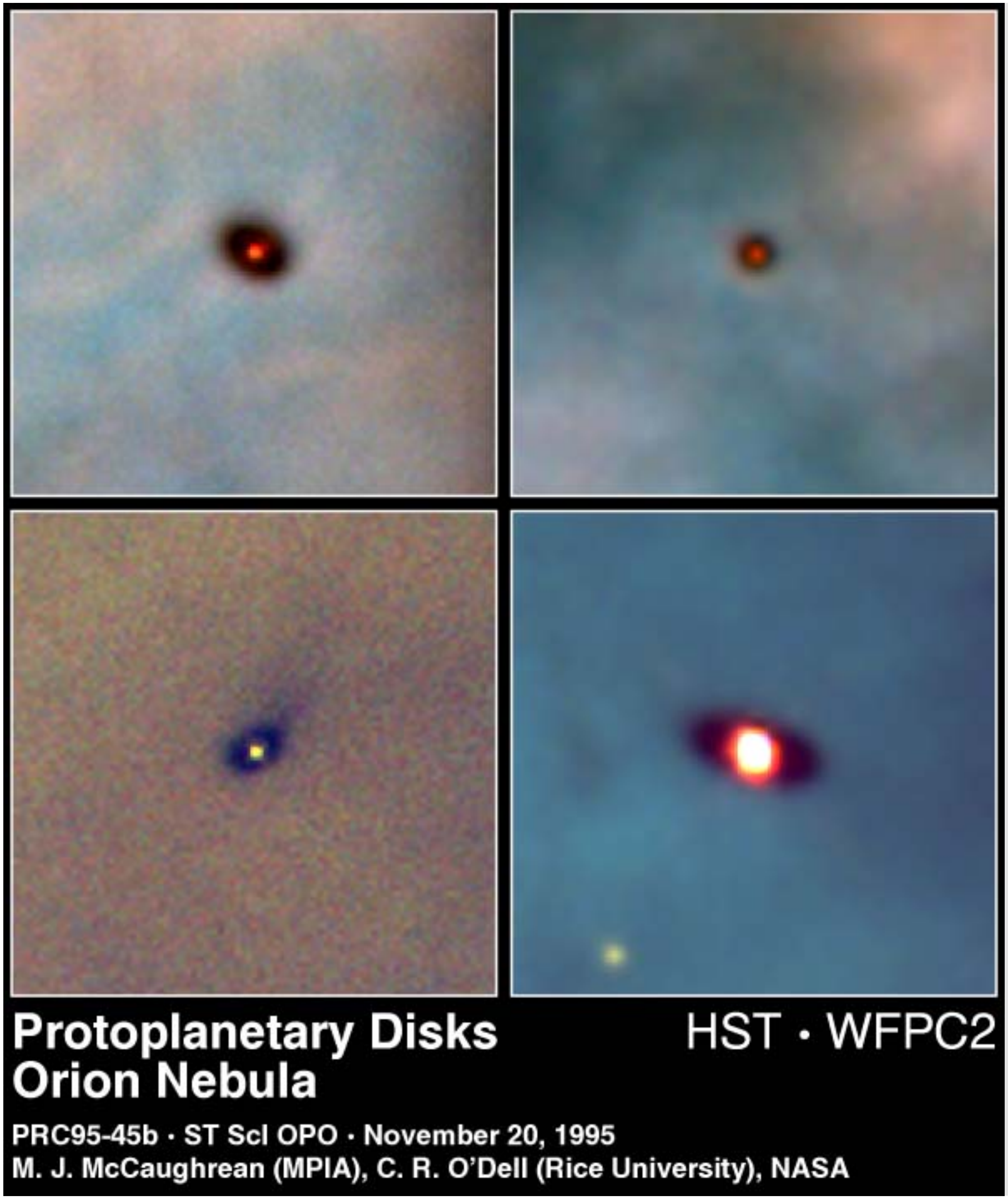
dust emission at 850 μ from SCUBA on JCMT. From Zuckerman (2001)



- destruction mechanisms include radiation pressure, Poynting-Robertson drag, collisions, sublimation
- likely destruction times short compared to age
- "debris disks"

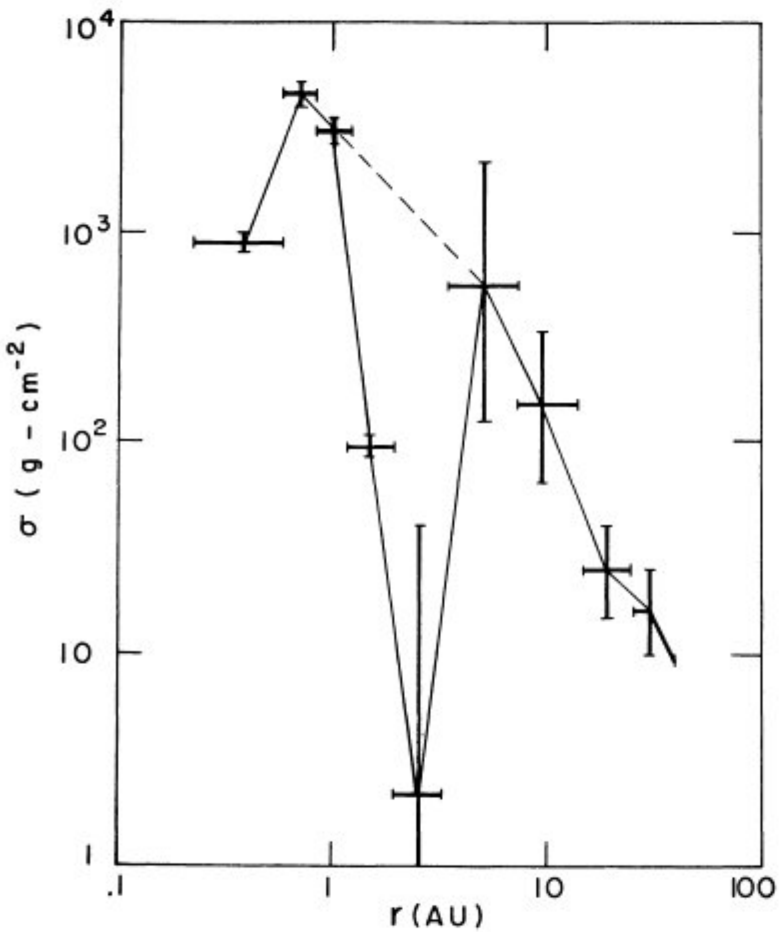
(Zuckerman 2001)

Orion nebula



PROtoPLanetarY DiskS
= "proplyds"

Minimum solar nebula



- add volatile elements to each planet to augment them to solar composition
- spread each planet into an annulus reaching halfway to the next planet
- smooth the resulting surface density:

$\Sigma(R) \approx 3 \times 10^3$ g cm $^{-2}$ $(1 \text{ AU}/R)^{1.5}$

Minimum solar nebula

- surface density $\Sigma(R) \approx 3 \times 10^3$ g cm^{-2} (1 AU/R)$^{1.5}$
- assume T = 500 K

⇒ sound speed:

$$c = 2\ \mathrm{km/s} \left(\frac{T}{500\ \mathrm{K}}\right)^{1/2} \left(\frac{2}{\mu}\right)^{1/2}$$

⇒ density:

$$\rho(R;z) = \rho_0(R) \exp\left(-\frac{z^2}{2h^2}\right) \quad \text{where} \quad \rho_0(R) = 2 \times 10^{-9}\ \mathrm{g/cm^3} \left(\frac{500\ \mathrm{K}}{T}\right)^{1/2} \left(\frac{1\ \mathrm{AU}}{R}\right)^{3}$$

⇒ scale height:

$$\frac{h}{R} = 0.05 \left(\frac{T}{500\ \mathrm{K}}\right)^{1/2} \left(\frac{R}{1\ \mathrm{AU}}\right)^{1/2} \left(\frac{2}{\mu}\right)^{1/2}$$

The disk instability hypothesis revisited

For standard parameters at 1 AU, Q= 60(1 AU/R)$^{1/4}$

Minimum solar nebula is *very* stable!

This is a big problem for the nebular hypothesis. How to fix it:

- "minimum solar nebula" is only a minimum
- consider only formation of giant planets at large radii, where temperature is lower

The disk instability hypothesis revisited

- the Sun and planets formed together out of a rotating cloud of gas (the "solar nebula")
- gravitational instabilities in the gas disk condense into planets (Kant 1755)
- good points:
  - correctly predicted that stars are surrounded by rotating gas disks after they are born
  - maybe this makes the most massive planets (1-15 M_J)
  - other models have problems too…
- bad points:
  - how do you make terrestrial planets, cores of giant planets, Kuiper belt, etc.
  - instability is not sufficient: need ***both*** $Q < 1$ ***and*** $\Omega t_{cool} < 3$ (Gammie 2001)
  - works best at *large* radii, but the extrasolar planets are found at *small* radii
  - why the strong correlation with metallicity of the host star?