Formation of Planetary Systems
II. Theories vs. Observations

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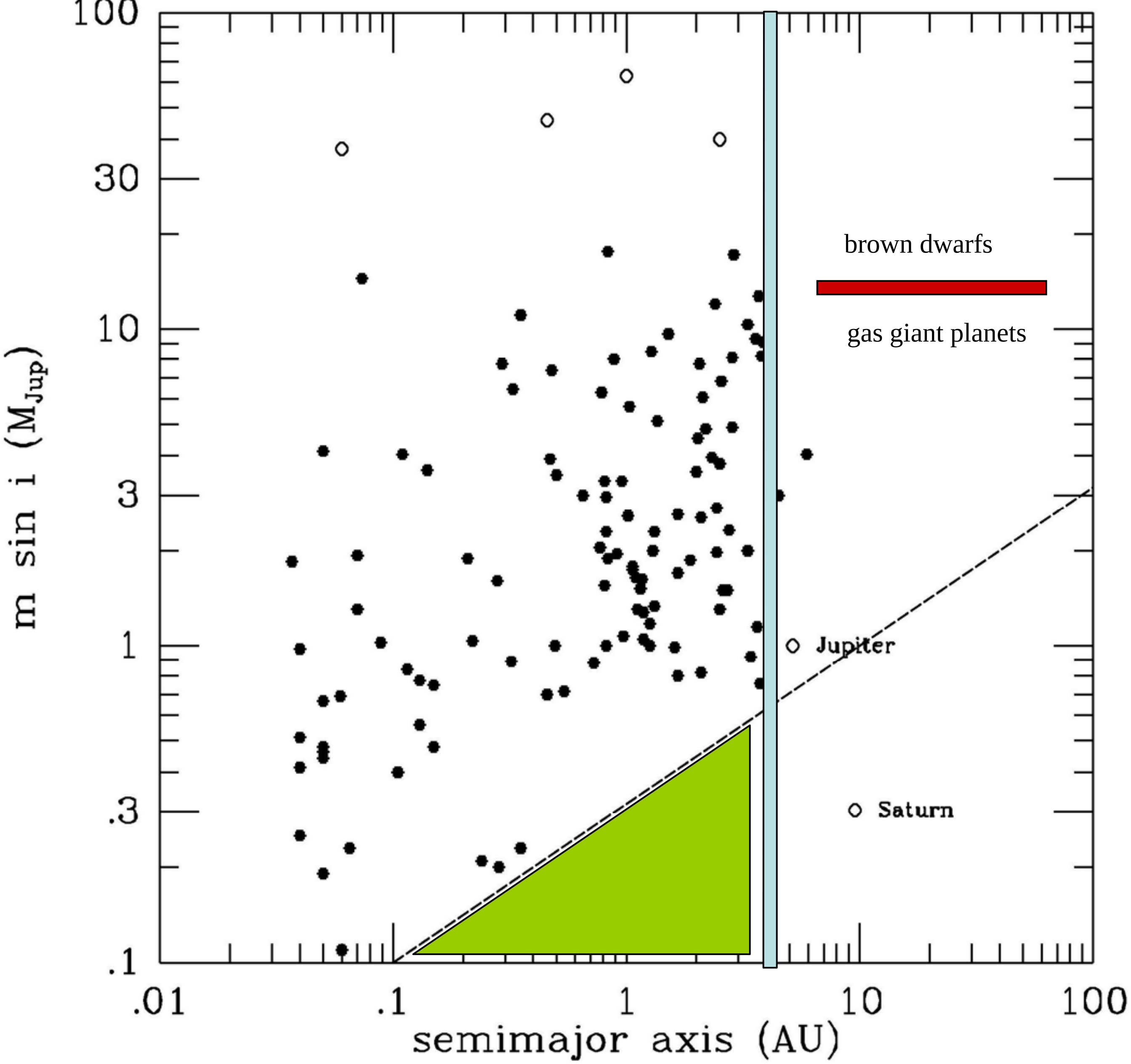
Context:

- Conventional scenario for planetary system formation:
  - region of low mass star formation (Taurus)
  - collisional accumulation of terrestrial planets
  - formation of giant planets by core accretion
- Heretical scenario for planetary system formation:
  - region of high (or low) mass star formation (Orion)
  - collisional accumulation of terrestrial planets
  - formation of giant planets by disk instability
- Apply constraints from our Solar System, star-forming regions, and extrasolar planetary systems
- Conclusions: lists of pros and cons for both scenarios and of future observational tests

Extrasolar Planet Discovery Space



Extrasolar Gas Giant Planet Census: Frequency

[15 yrs of observations, A. Hatzes, 2004]

* Approximately 15% of nearby G-type stars have gas giant planets with short orbital periods – hot and warm Jupiters

* Approximately 25% of nearby G-type stars appear to have gas giant planets with long orbital periods – Solar System analogues

* Hence at least 40% of nearby G-type stars appear to have gas giant planets inside about 10 AU

* Gas giant planet formation mechanism must be relatively efficient and robust

N. C. Santos et al.: Spectroscopic [Fe/H] for 98 extra-solar planet-host stars 2004 1163

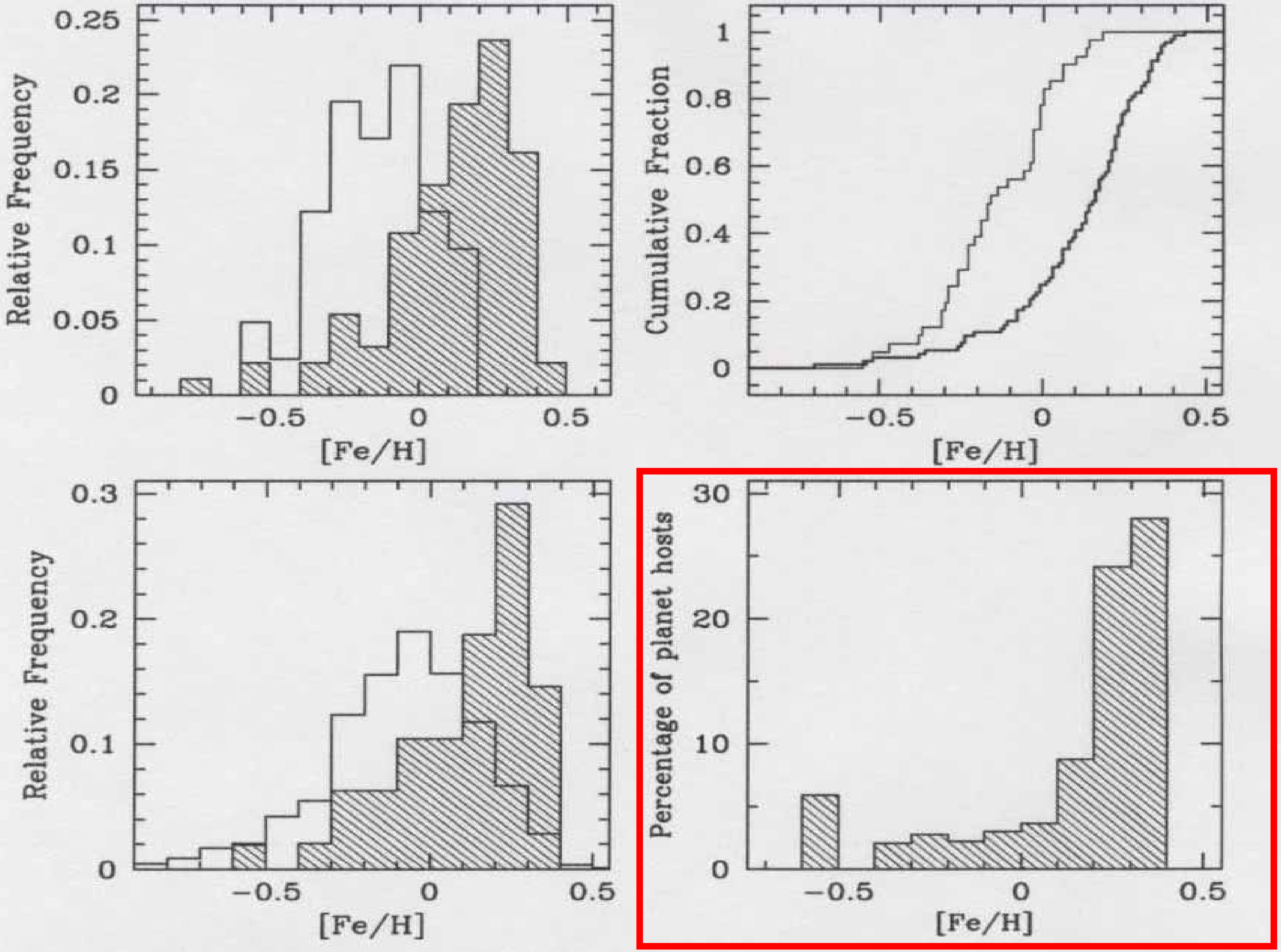
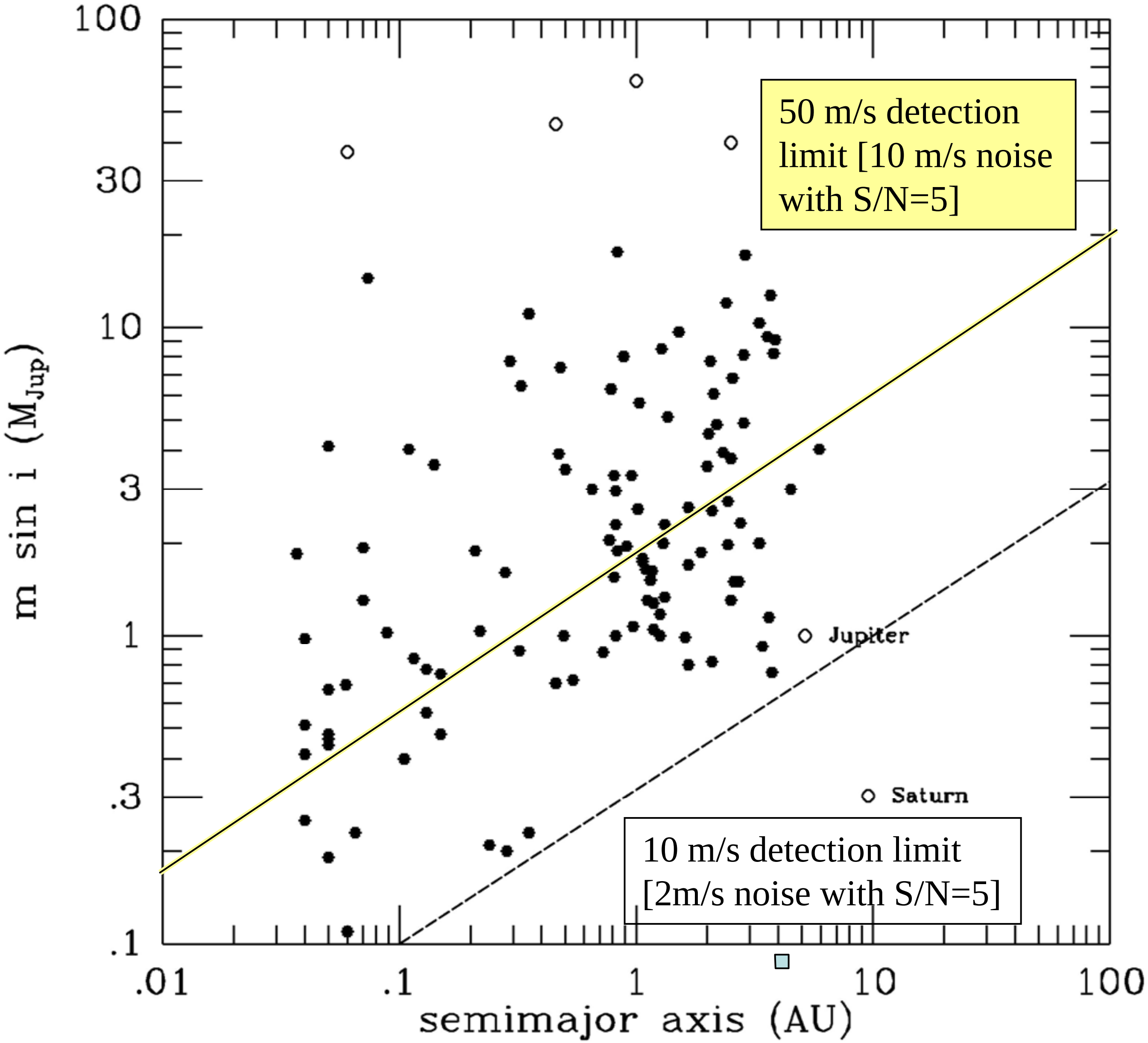


Fig. 6. *Upper panels*: [Fe/H] distributions for planet host stars (hashed histogram) and for our volume-limited comparison sample of stars (open bars). The average difference between the [Fe/H] of the two samples is of ~0.25 dex. A Kolgomorov-Smirnov test shows that the probability that the two samples are part of the same population is of the order of 10^{-9}. See text for more details. *Lower panel, left*: [Fe/H] distributions for planet host stars (hashed histogram) included in the CORALIE planet-search sample, when compared with the same distribution for all the 875 stars in the whole CORALIE program for which we have at least 5 radial-velocity measurements (solid-line open histogram). *Lower panel, right*: percentage of planet hosts found amid the stars in the CORALIE sample as a function of stellar metallicity.

RV precision for –1.0 < [Fe/H] < –0.6 stars with high S/N is 5 to 16 m/s (D. Fischer, 2004)



50 m/s detection limit [10 m/s noise with S/N=5]

10 m/s detection limit [2m/s noise with S/N=5]

Extrasolar Gas Giant Planet Census: Metallicity

* Observational bias in favor of metal-rich host stars because of stronger absorption lines, shorter integration times, lower velocity residuals

* No correlation of planet masses with metallicity (N. Reid) or of debris disks (G. Bryden)

* Hyades cluster ([Fe/H]=0.13) RV search of 98 stars found no short period planets (Paulson et al. 2004), whereas about 10 should have been found

* Nevertheless, there seems to be a correlation with the highest host star metallicities, at least for short period (P < 3 yrs, a < 2 AU) planets

* Is this caused by formation or by migration?

Figure 6. Eccentricity versus period for exo-planets. In the Solar System I ricity of greater than 0.1. HD system and has been omitted from this plot.

Jones et al. 2004

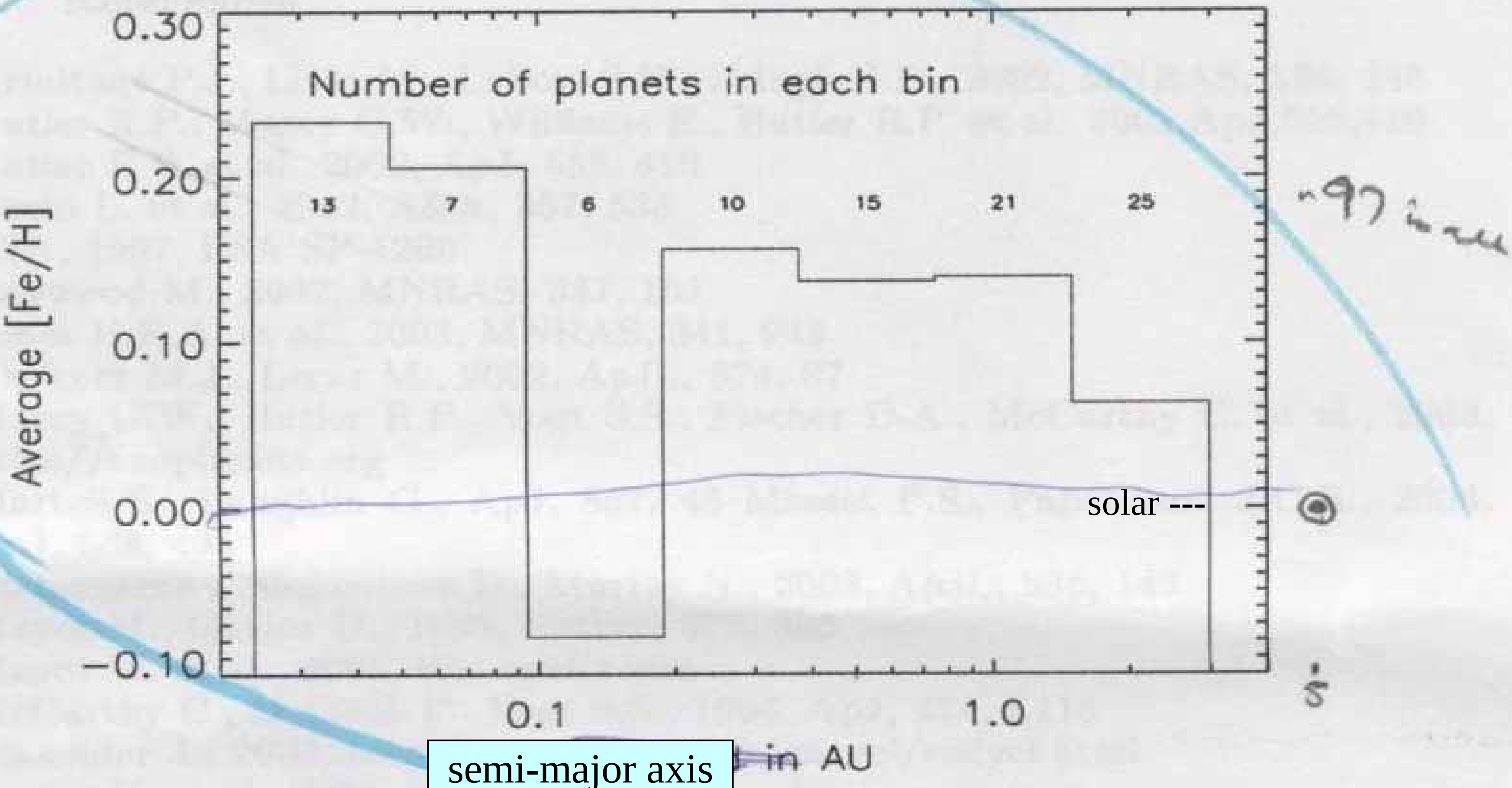
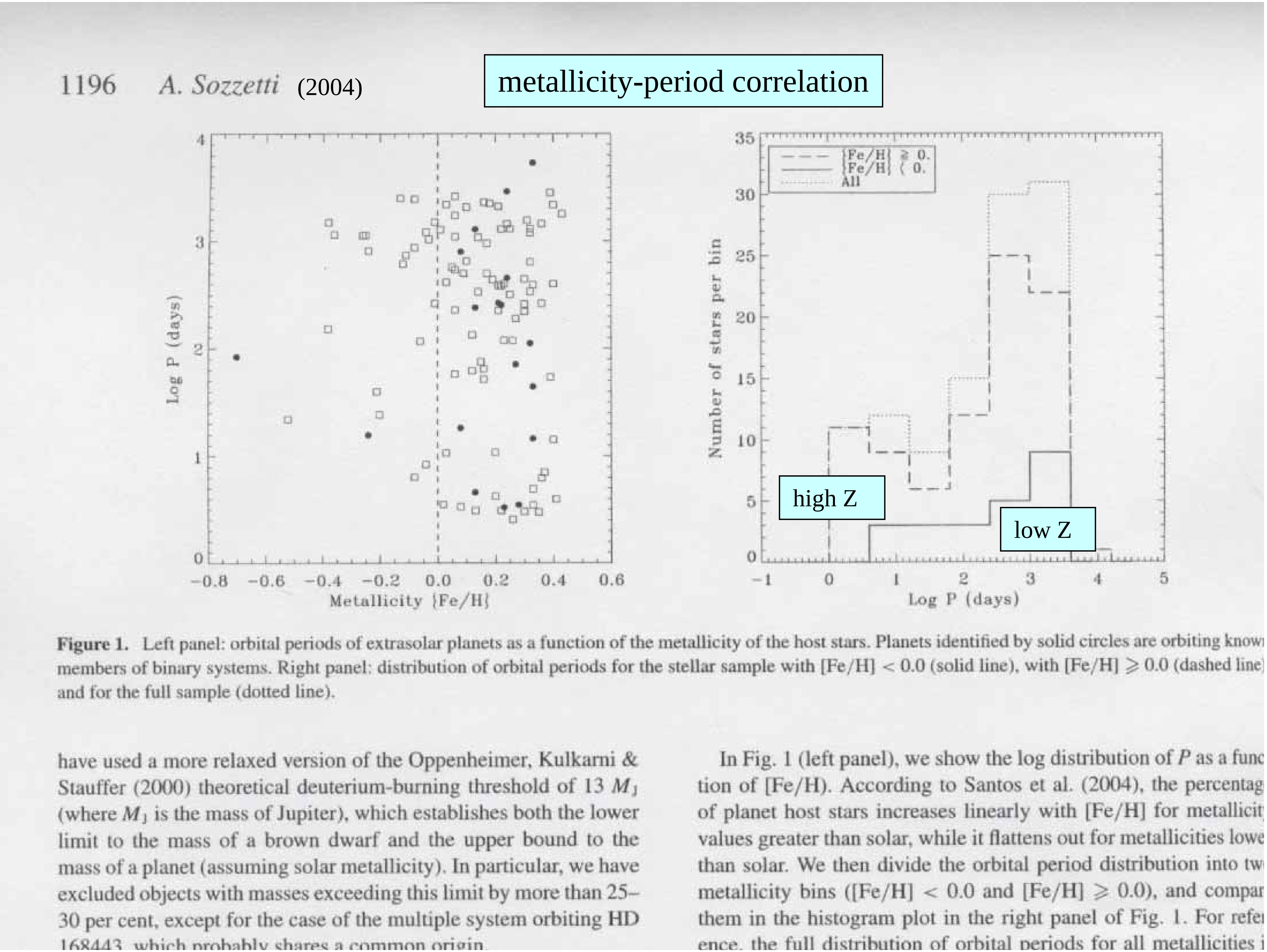


Figure 7. Average spectroscopic metallicities of the primaries of exo-planets plotted as a function of period. The overall featues of this distribution are similar whether plotted for spectroscopic or Stromgen metallicities (Haywood 2002; Martell & Laughlin 2002).

metallicity-period correlation

1196 *A. Sozzetti* (2004)



high Z

low Z

Figure 1. Left panel: orbital periods of extrasolar planets as a function of the metallicity of the host stars. Planets identified by solid circles are orbiting know
members of binary systems. Right panel: distribution of orbital periods for the stellar sample with [Fe/H] < 0.0 (solid line), with [Fe/H] ⩾ 0.0 (dashed line
and for the full sample (dotted line).

have used a more relaxed version of the Oppenheimer, Kulkarni & Stauffer (2000) theoretical deuterium-burning threshold of 13 M_J (where M_J is the mass of Jupiter), which establishes both the lower limit to the mass of a brown dwarf and the upper bound to the mass of a planet (assuming solar metallicity). In particular, we have excluded objects with masses exceeding this limit by more than 25–30 per cent, except for the case of the multiple system orbiting HD 168443, which probably shares a common origin.

In Fig. 1 (left panel), we show the log distribution of *P* as a func
tion of [Fe/H]. According to Santos et al. (2004), the percentag
of planet host stars increases linearly with [Fe/H] for metallicit
values greater than solar, while it flattens out for metallicities lowe
than solar. We then divide the orbital period distribution into tw
metallicity bins ([Fe/H] < 0.0 and [Fe/H] ⩾ 0.0), and compar
them in the histogram plot in the right panel of Fig. 1. For refer
ence, the full distribution of orbital periods for all metallicities i

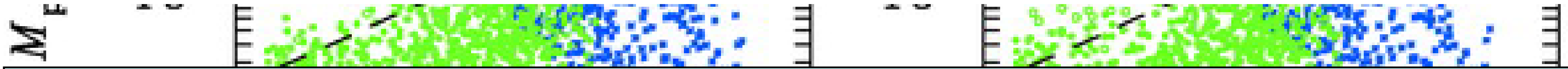
Highest Metallicities Correlation: Migration or Formation?

* Higher metallicity → higher opacity → hotter disk midplane → higher sound speed (c_s) → thicker disk (h) → higher disk kinematic viscosity ($\nu = \alpha c_s h$) →shorter time scale for Type II inward migration → more short period giant planets

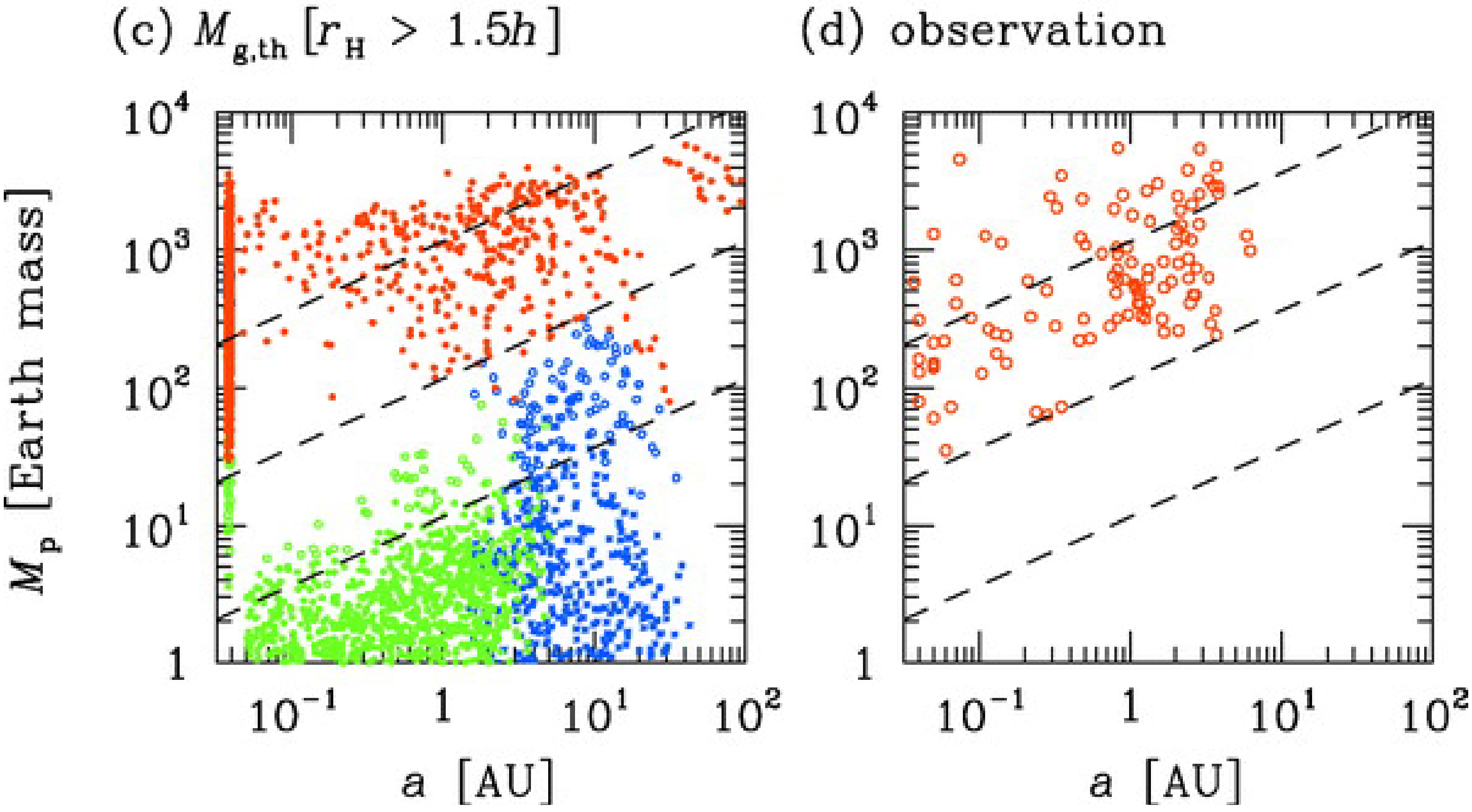
* Uncertain magnitude of migration effect, but goes in the right direction to explain the correlation

* Migration consistent with absence of short-period giants in low-metallicity globular cluster 47 Tuc

* Migration consistent with long-period pulsar giant planet in M4 globular cluster (1/30 solar [Fe/H])



Prediction of a ‘planet desert’ from 10 to 100 Earth masses and for semi-major axes less than 3 AU, based on core accretion models of gas and ice giant planet formation (figure from S. Ida and D. N. C. Lin, 2004, ApJ, 604, 388-413). Includes the effects of Type II migration, but not Type I or Type III, appropriate for disk instability giants.



(c) $M_{g,th}$ $[r_H > 1.5h]$

(d) observation

Extrasolar Gas Giant Planet Census: Low-mass Host Stars

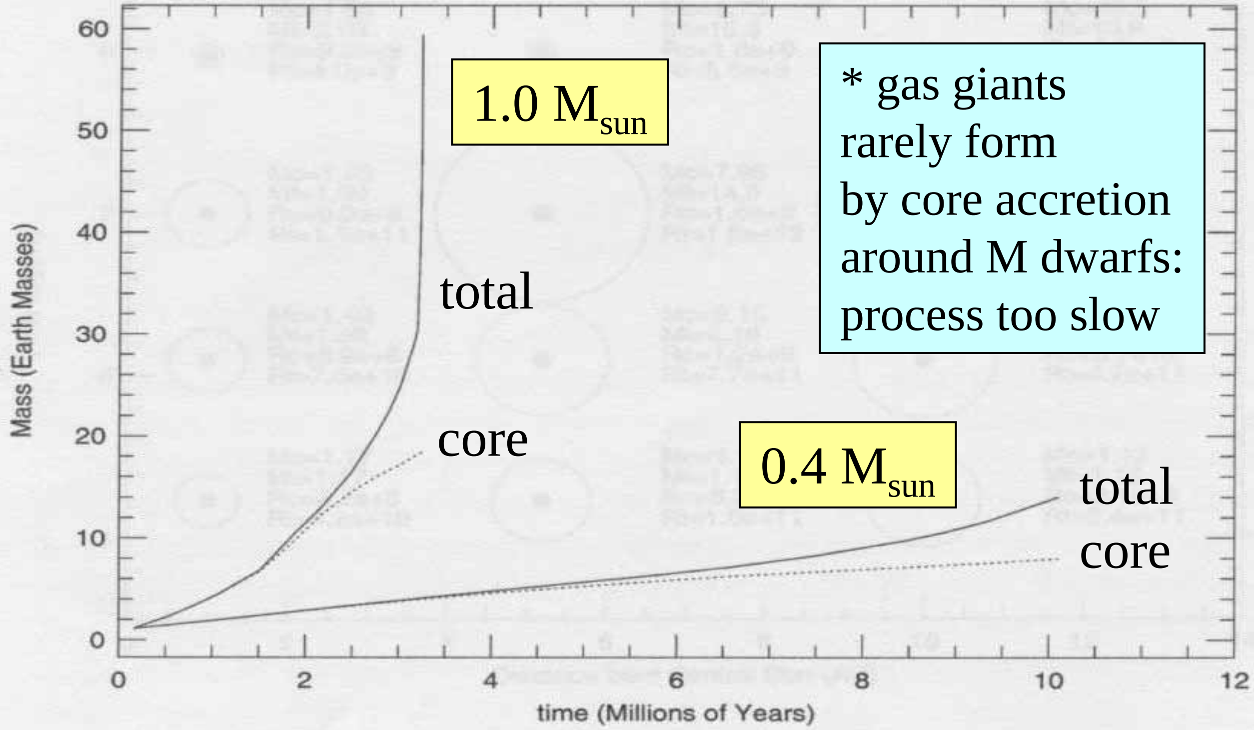
* Most planet-host stars are G-type stars – G-type stars have dominated the target lists

* M4 dwarf star GJ876 (0.32 M_{sun}) has two known gas giant planets and one sub-Neptune-mass planet

* Ongoing radial velocity surveys have evidence for at least several more giant planets orbiting M dwarfs in a relatively small sample of stars

* While frequency of giant planets around M dwarfs is uncertain, it is clearly not zero

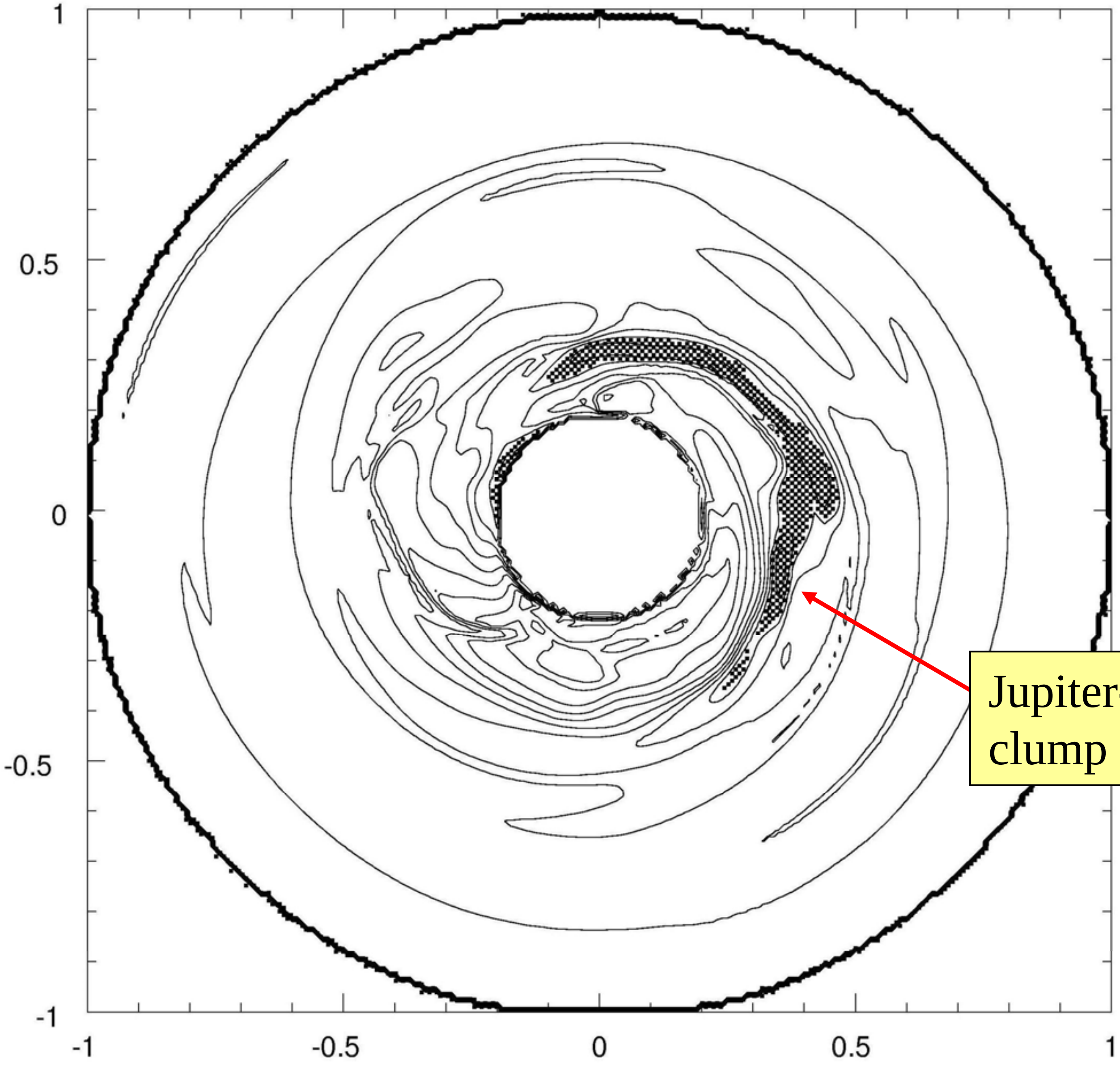
Laughlin et al. 2004 core accretion models



* gas giants
rarely form
by core accretion
around M dwarfs:
process too slow

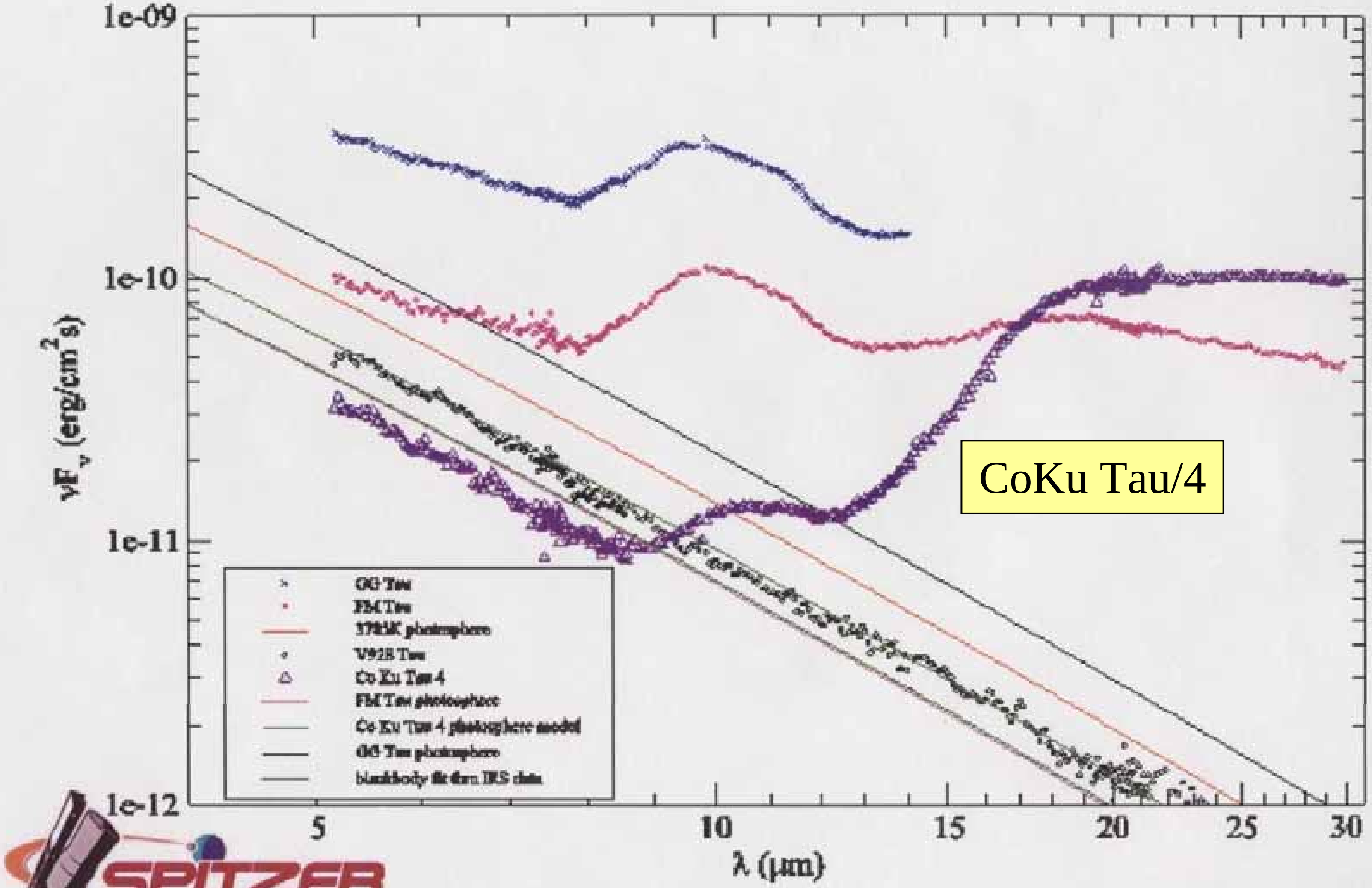
Fig. 1.— Growth of the core and envelopes of planets at 5.2 AU in disks orbiting stars of two different masses. The upper curves show the time-dependent core mass (dotted curve) and total mass (solid curve) for a planet forming in a disk surrounding a $1M_{\odot}$ star. The lower curves show the time dependence of the core mass (dotted curve) and total mass (solid curve) for a planet forming in a disk around a $0.4M_{\odot}$ star. After 10 Myr, the disk masses become extremely low, which effectively halts further planetary growth. The planet orbiting the M star gains its mass more slowly and stops its growth at a relatively low mass $M \approx 14M_{\oplus}$.

Clump formation by disk instability after 445 yrs in a 0.02 M_{sun} disk orbiting a 0.1 M_{sun} star (Boss 2005).



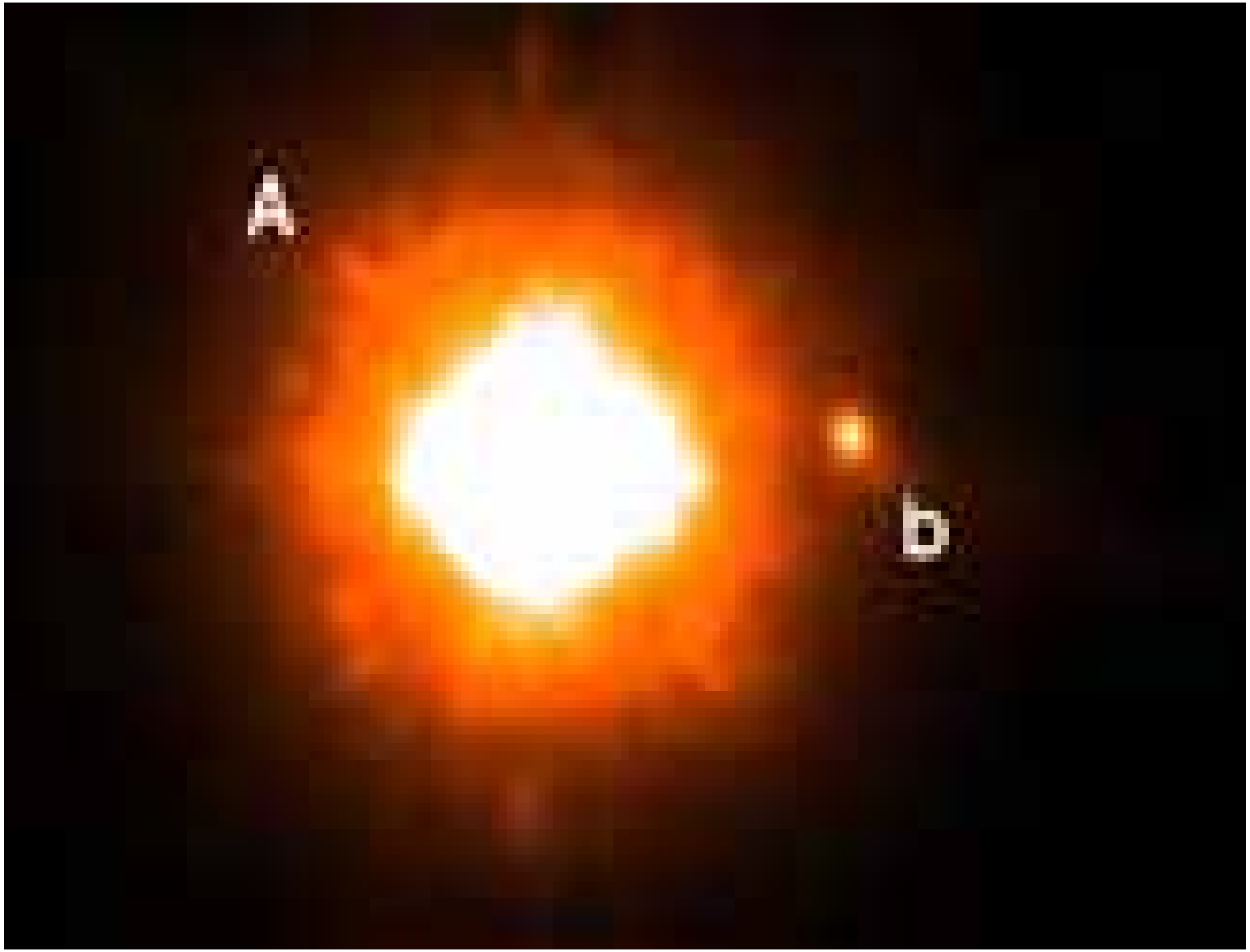
Jupiter-mass clump at 7 AU

Forrest et al. 2004 evidence for rapid gas giant planet formation



Planetary formation within 1 Myr of star formation? *Spitzer*-IRS spectrum of CoKu Tau/4 – with a disk void of dust for 11 AU around the star – compared to that of 1 Myr-old stars with full disks (FM Tau) and no disk at all (V928 Tau).

GQ Lup b – 1 Myr-old gas giant planet at 100 AU? (Neuhauser et al. 2005)



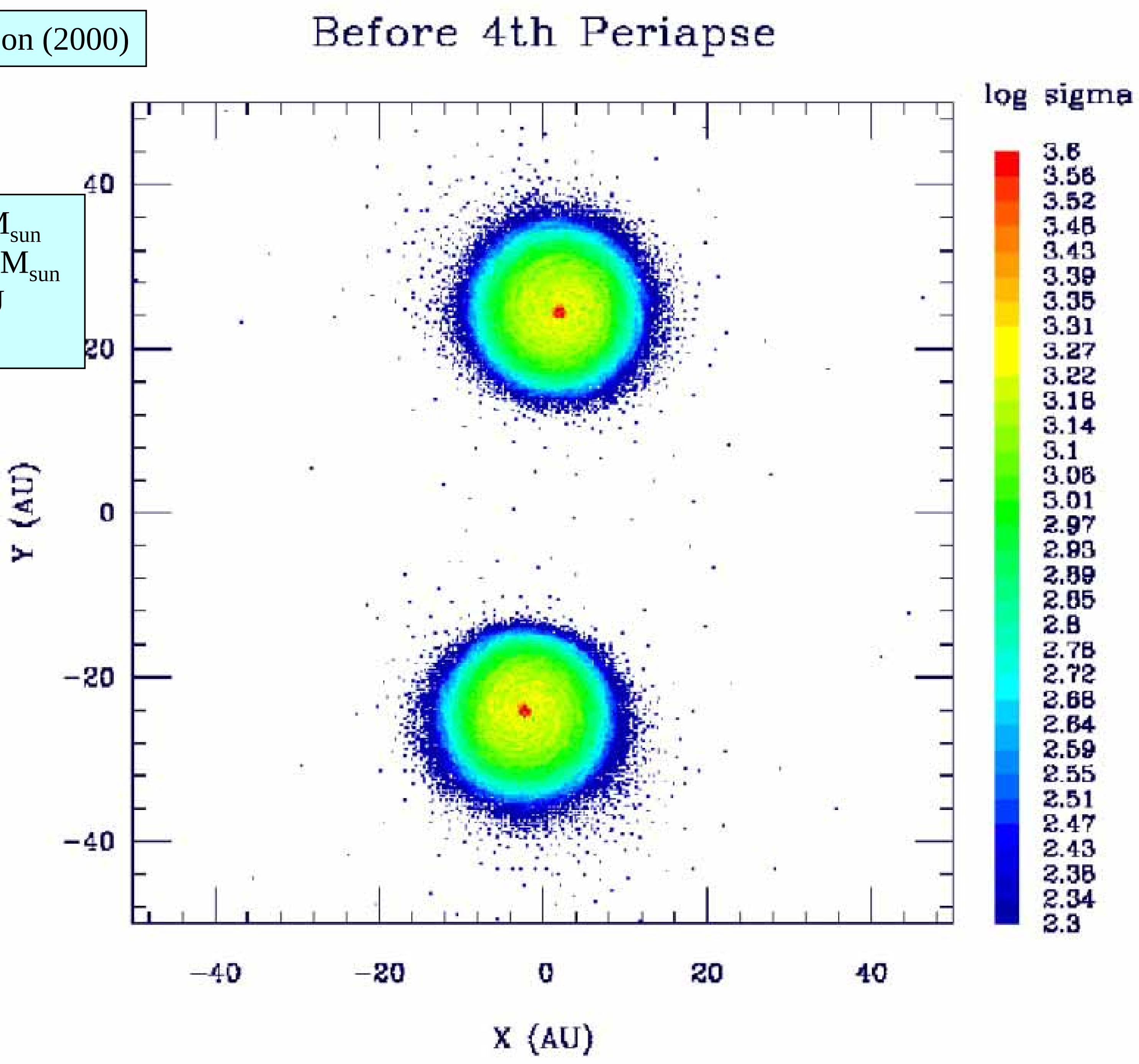
Gas Giant Planets in Multiple Star Systems

- Hierarchical triple star systems (planet orbits the single member of the triple):
  - 16 Cygni B – about 850 AU separation
  - HD 178911 B – about 640 AU separation
  - HD 41004 A – about 23 AU separation
- Binary star systems:
  - HD 195019 – about 150 AU separation
  - HD 114762 – about 130 AU separation
  - HD 19994 – about 100 AU separation
  - Gamma Cephei – about 20 AU separation
  - Gl 86 – about 20 AU separation

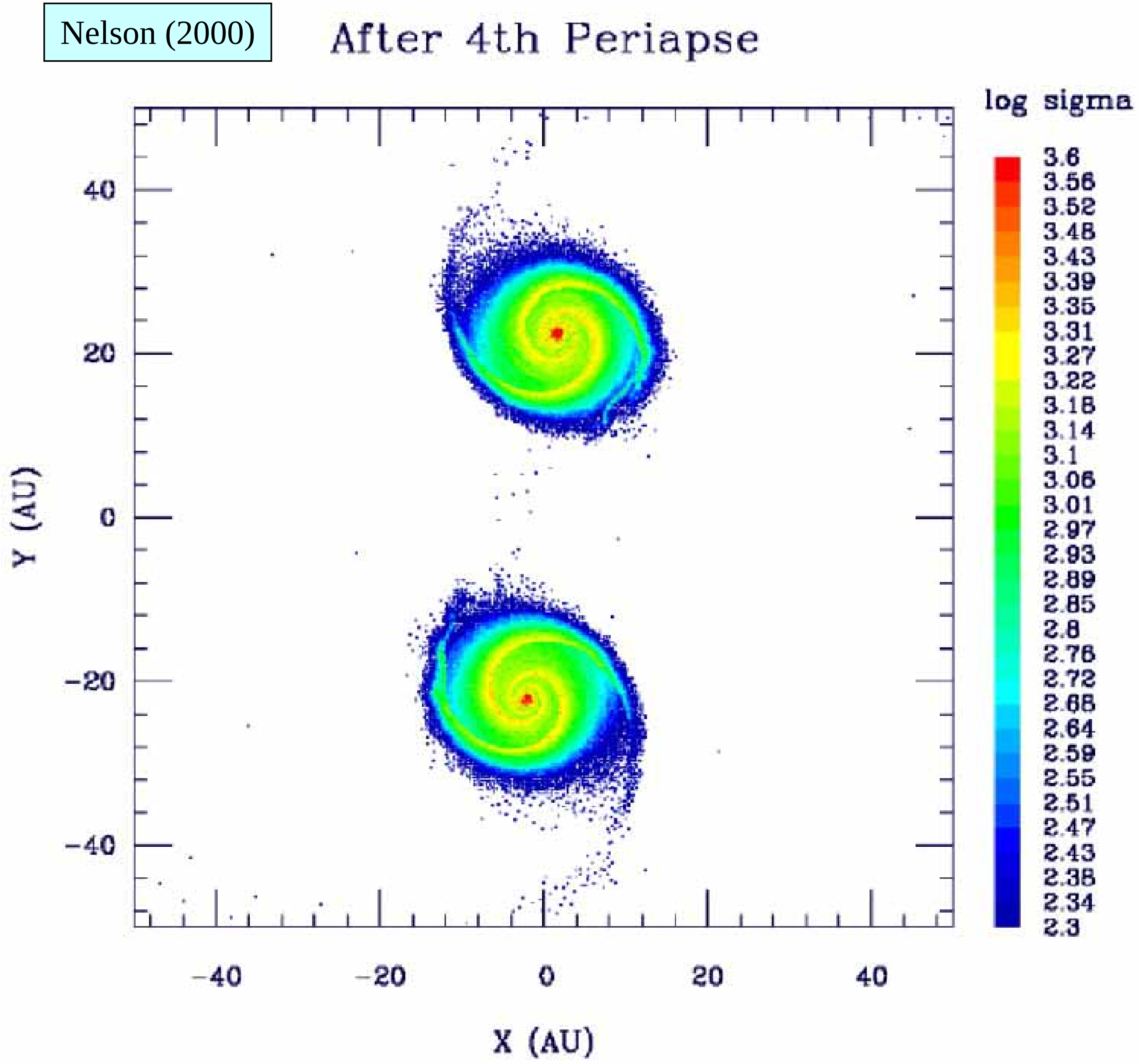
[A total of ~ 15 multiple stars have planets to date (Eggenberger et al.2004)]

Nelson (2000)

$M_s = 0.5\ M_{sun}$
$M_d = 0.05\ M_{sun}$
$a = 50$ AU
$e = 0.3$

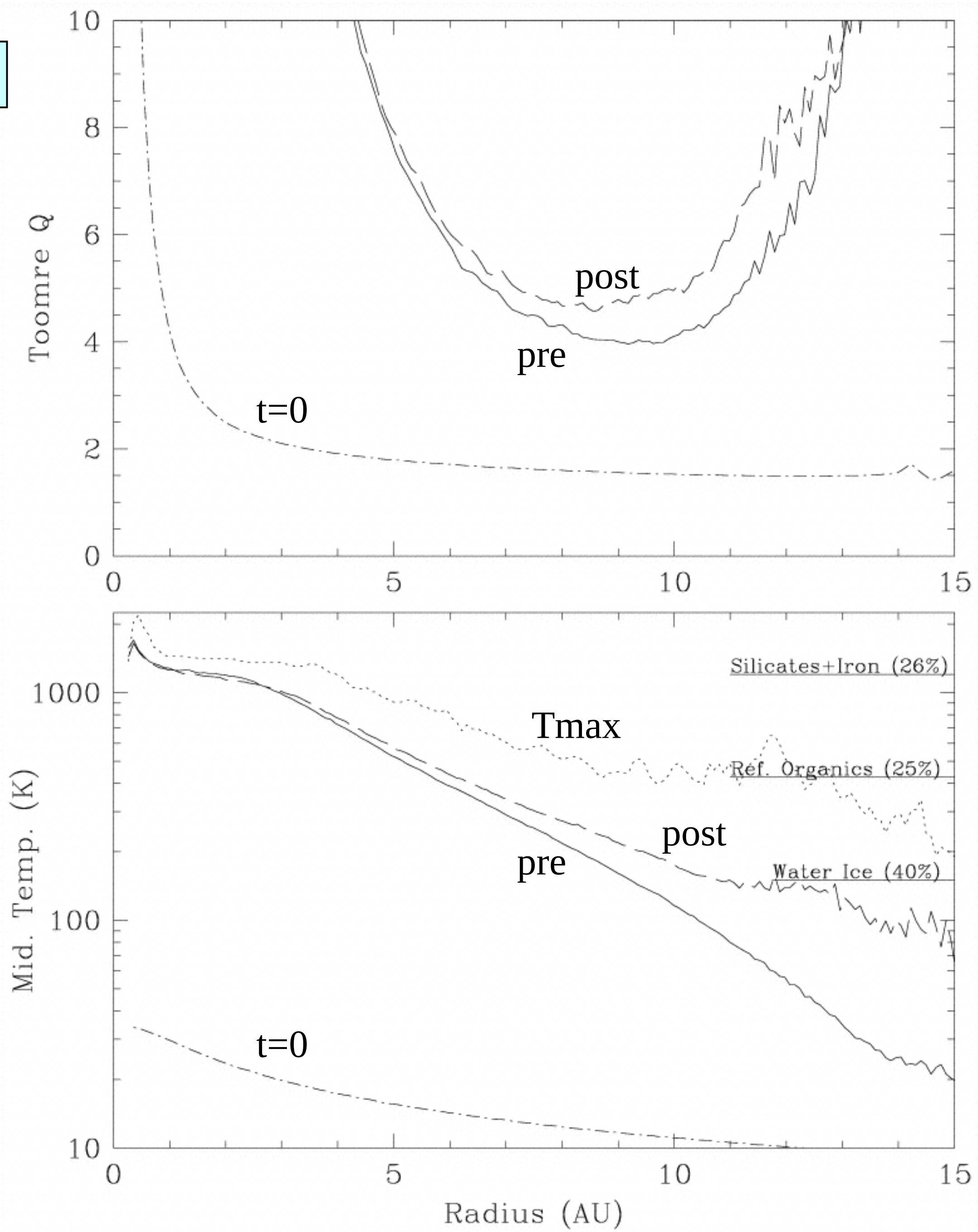


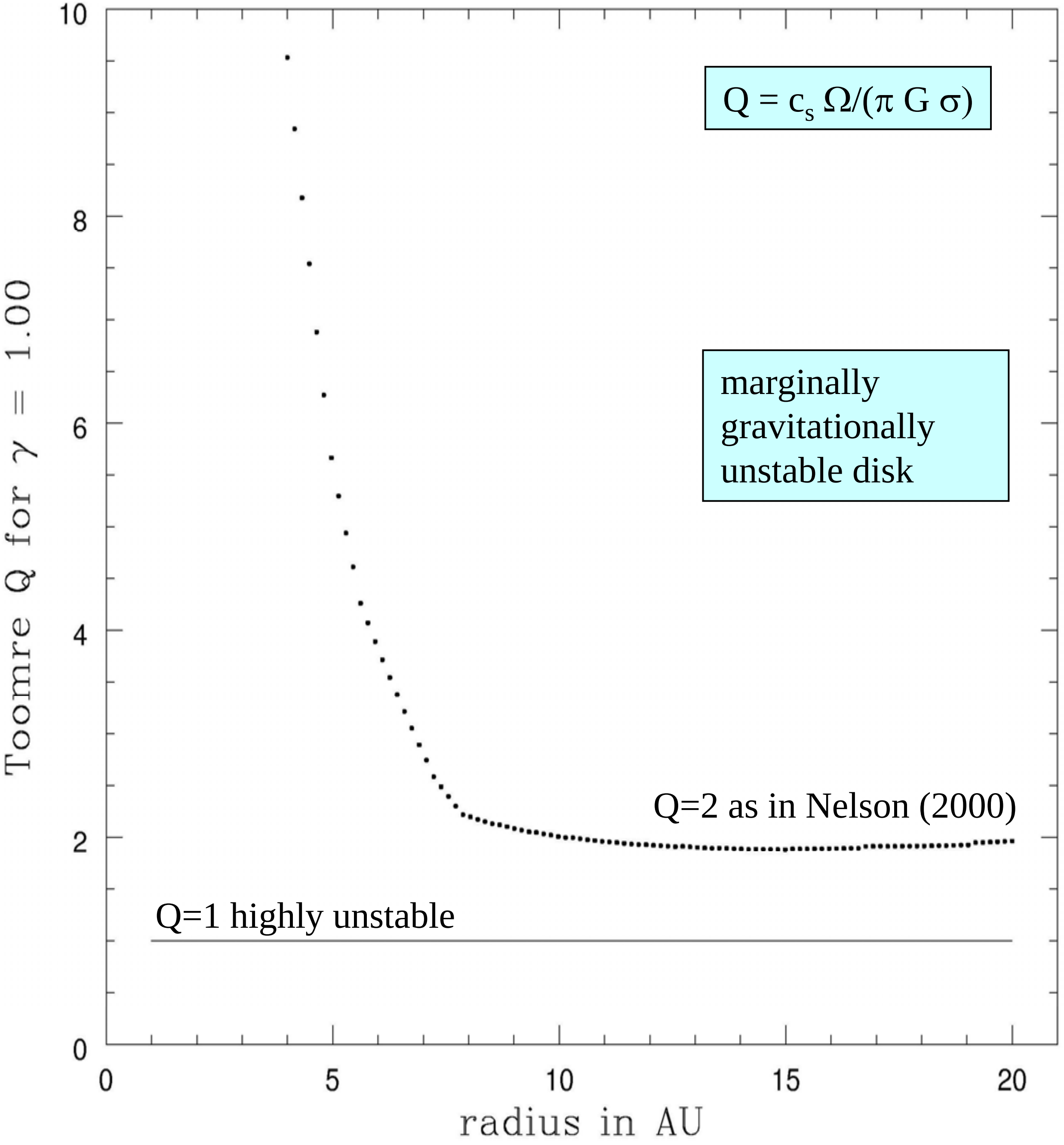
Nelson (2000)


After 4th Periapse
log sigma
3.6
3.56
3.52
3.48
3.43
3.39
3.35
3.31
3.27
3.22
3.18
3.14
3.1
3.06
3.01
2.97
2.93
2.89
2.85
2.8
2.76
2.72
2.68
2.64
2.59
2.55
2.51
2.47
2.43
2.38
2.34
2.3
40
20
0
−20
−40
Y (AU)
−40
−20
0
20
40
X (AU)

Nelson (2000)

“Planet formation is unlikely in equal-mass binary systems with a = 50 AU”





$Q = c_s\,\Omega/(\pi\, G\, \sigma)$

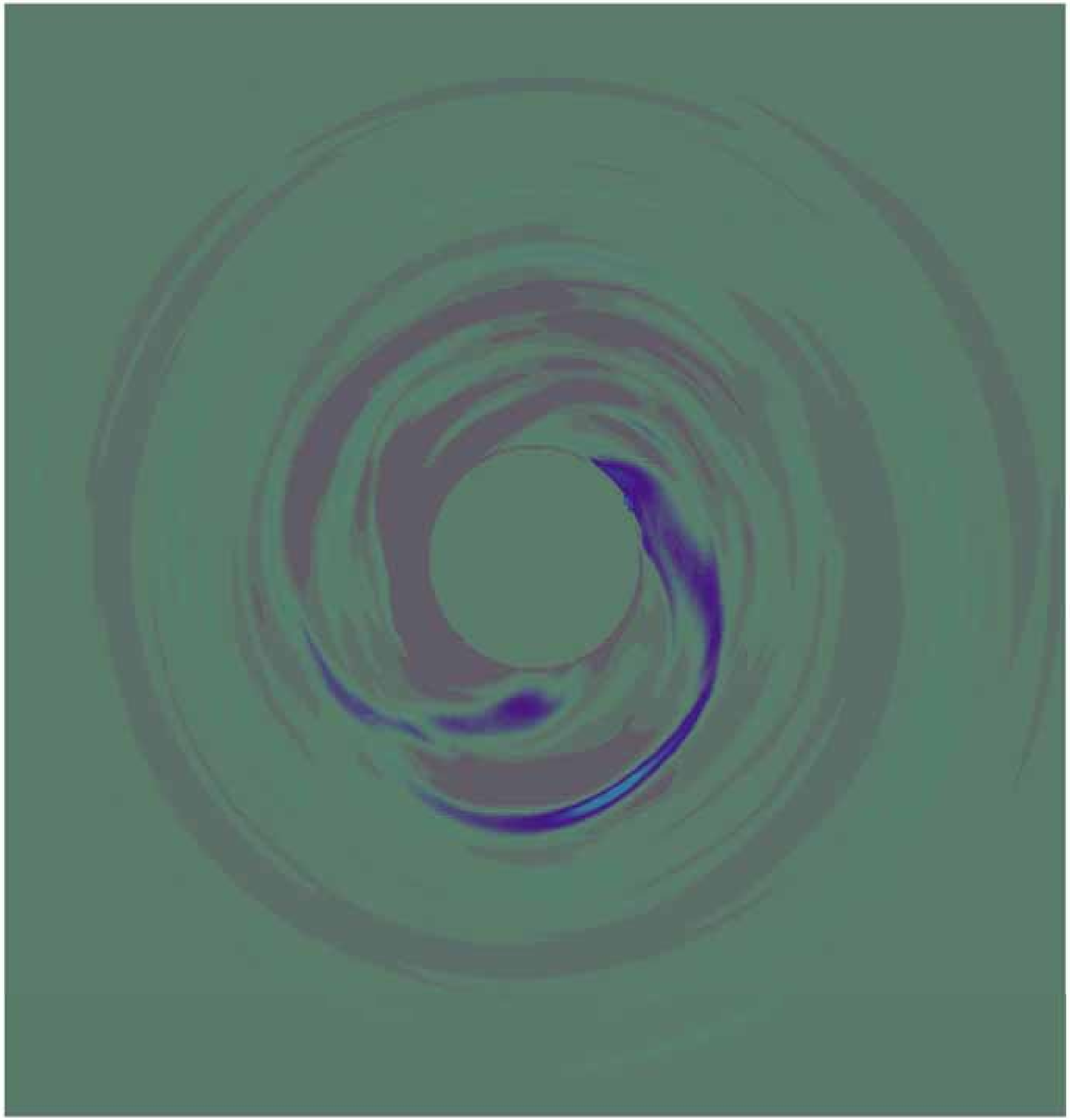
marginally gravitationally unstable disk

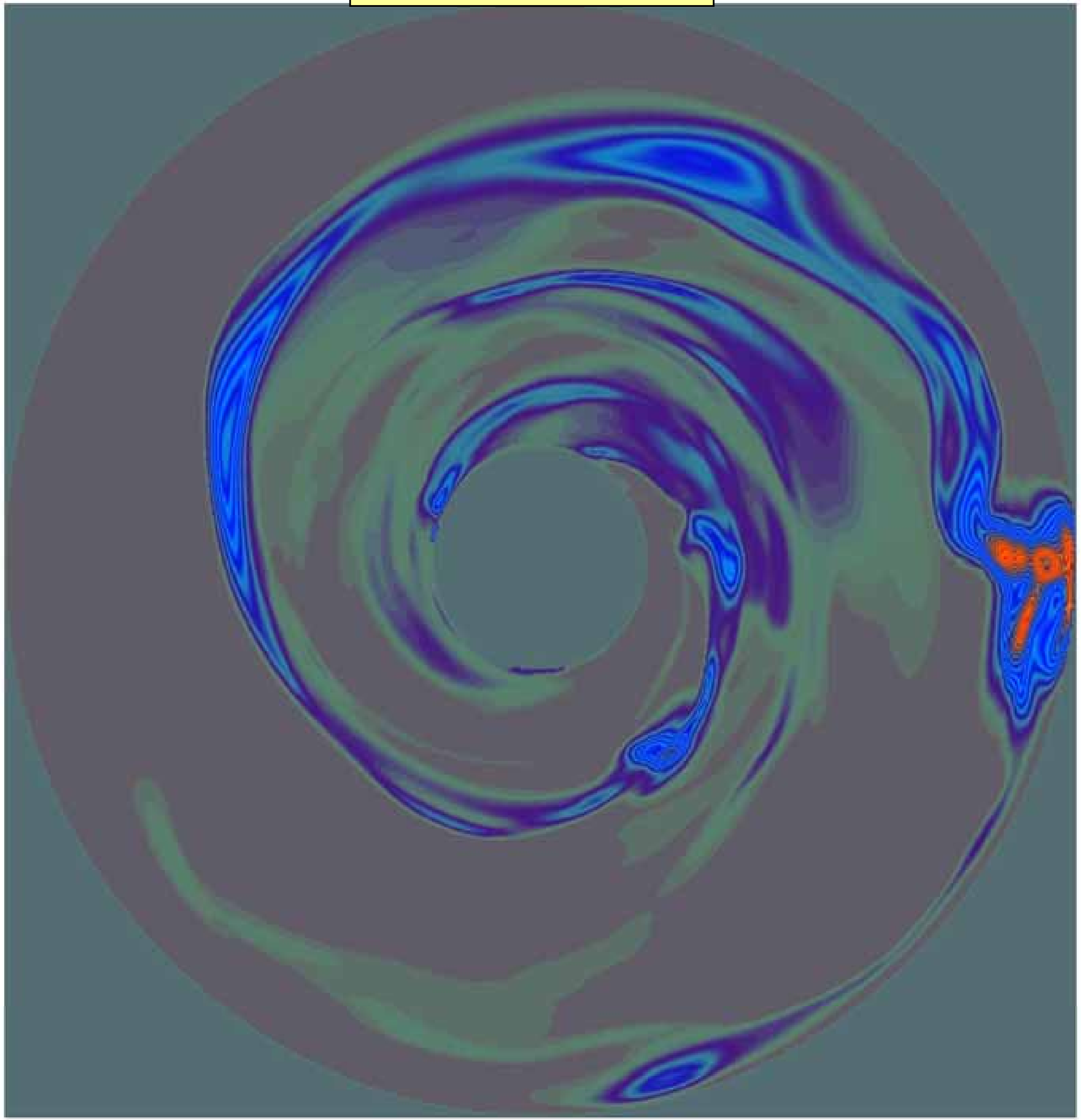
Q=2 as in Nelson (2000)

Q=1 highly unstable

20 AU
radius
disk

no binary
245 years



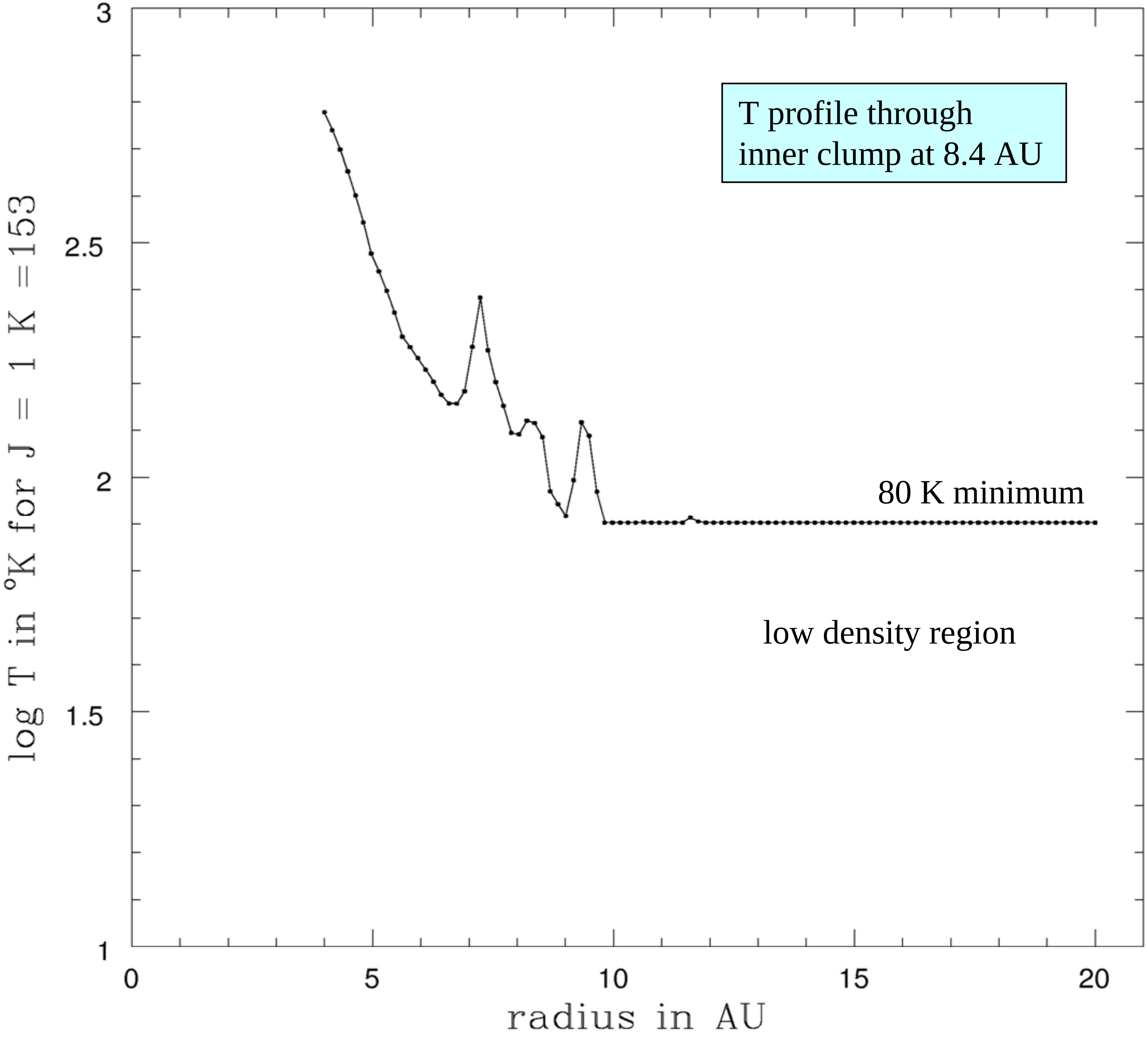


to binary △ at apastron

20 AU
radius
disk

after one
binary
rotation
period:
239 years

M_s= 1 M_{sun}
M_d= 0.09 M_{sun}
a = 50 AU
e = 0.5



T profile through
inner clump at 8.4 AU

80 K minimum

low density region

Differences between Nelson (2000) and present models

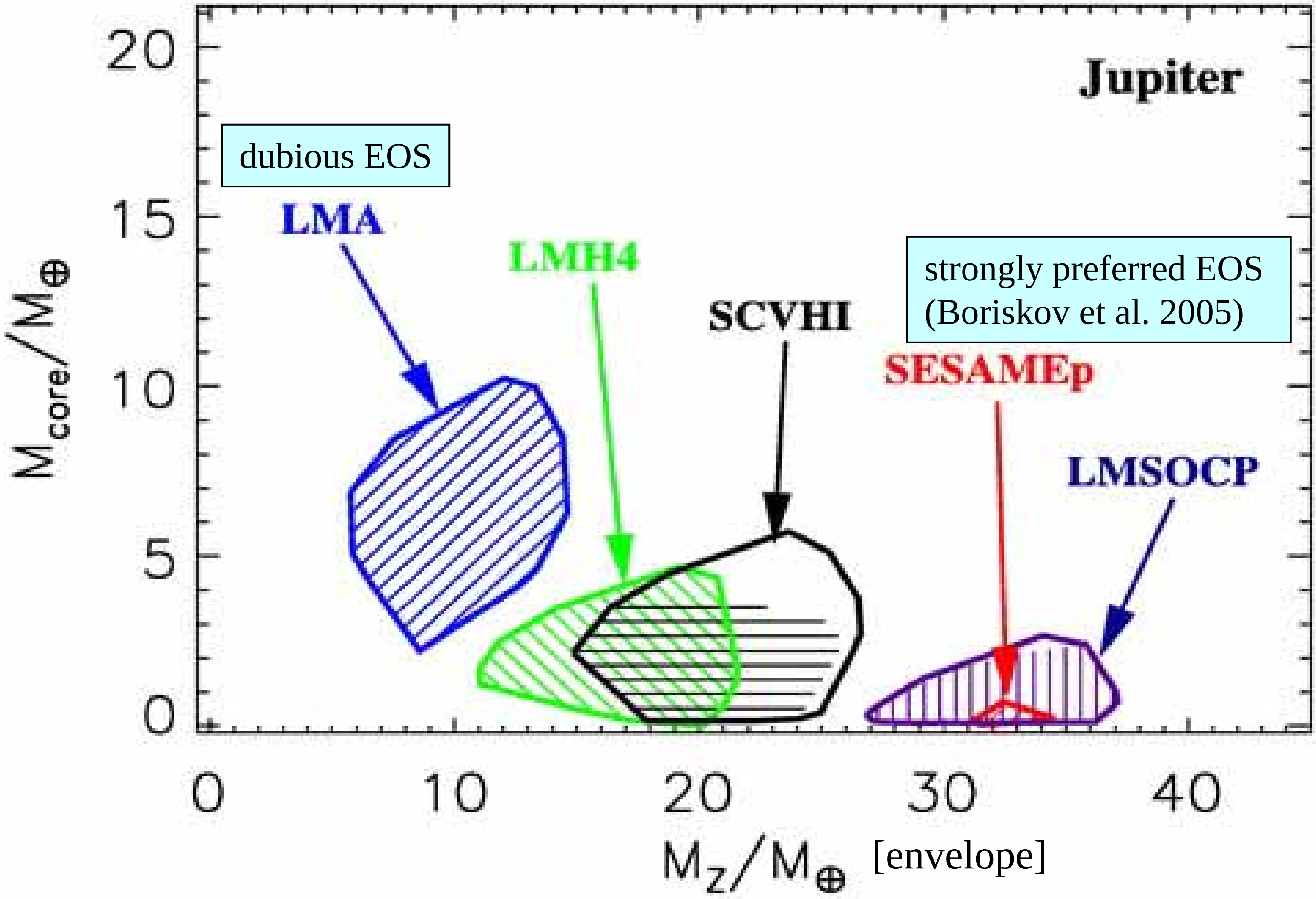
- Nelson (2000) used 60,000 SPH particles
- Thin disk so adiabatic gradient assumed in vertical direction, as if cooled by convection
- Surface T > 100 K means higher midplane T
- Artificial viscosity converts KE into heat in shock fronts and elsewhere ($\alpha = 0.002$ to 0.005)
- Cooling time ~ 40 P

- Present models used over 1,000,000 grid points
- Fully 3D so vertical convection cools disk midplane in optically thick regions, radiation cools in optically thin regions
- Surface T = 50 K means lower midplane T
- No artificial viscosity so no irreversible heating in shock fronts and $\alpha = 0$ assumed
- Cooling time ~ 1-2 P

Planet Formation in Binary Star Systems?

- Tidal forces from a binary star companion can trigger the formation of dense clumps in a marginally gravitationally unstable disk
- Convection keeps disk midplanes relatively cool
- Giant planet formation should proceed in binary stars with periastrons as small as ~ 25 AU
- Terrestrial planet formation should occur as well
- Most binary stars should be excellent targets for planet hunting – as the RV surveys have found

Saumon & Guillot (2004) core mass constraints based on EOS

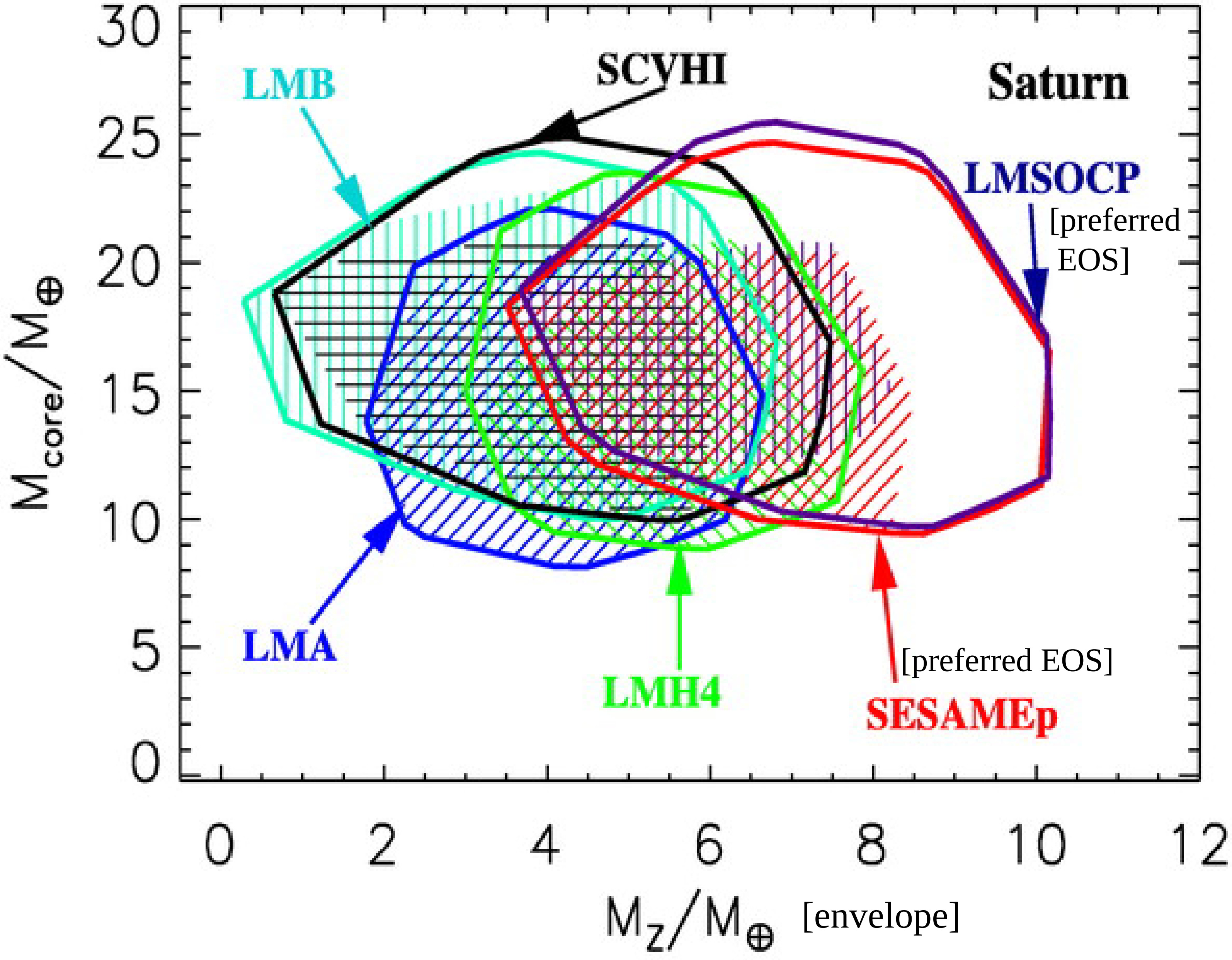


dubious EOS

strongly preferred EOS
(Boriskov et al. 2005)

[envelope]

Saumon & Guillot 2004 core mass constraints based on EOS



[preferred EOS]

[preferred EOS]

[envelope]

Constraints from the Solar System’s Gas Giant Planets

* Jupiter’s core mass is 3 Earth masses or less, too small to initiate dynamic gas accretion (erosion?)

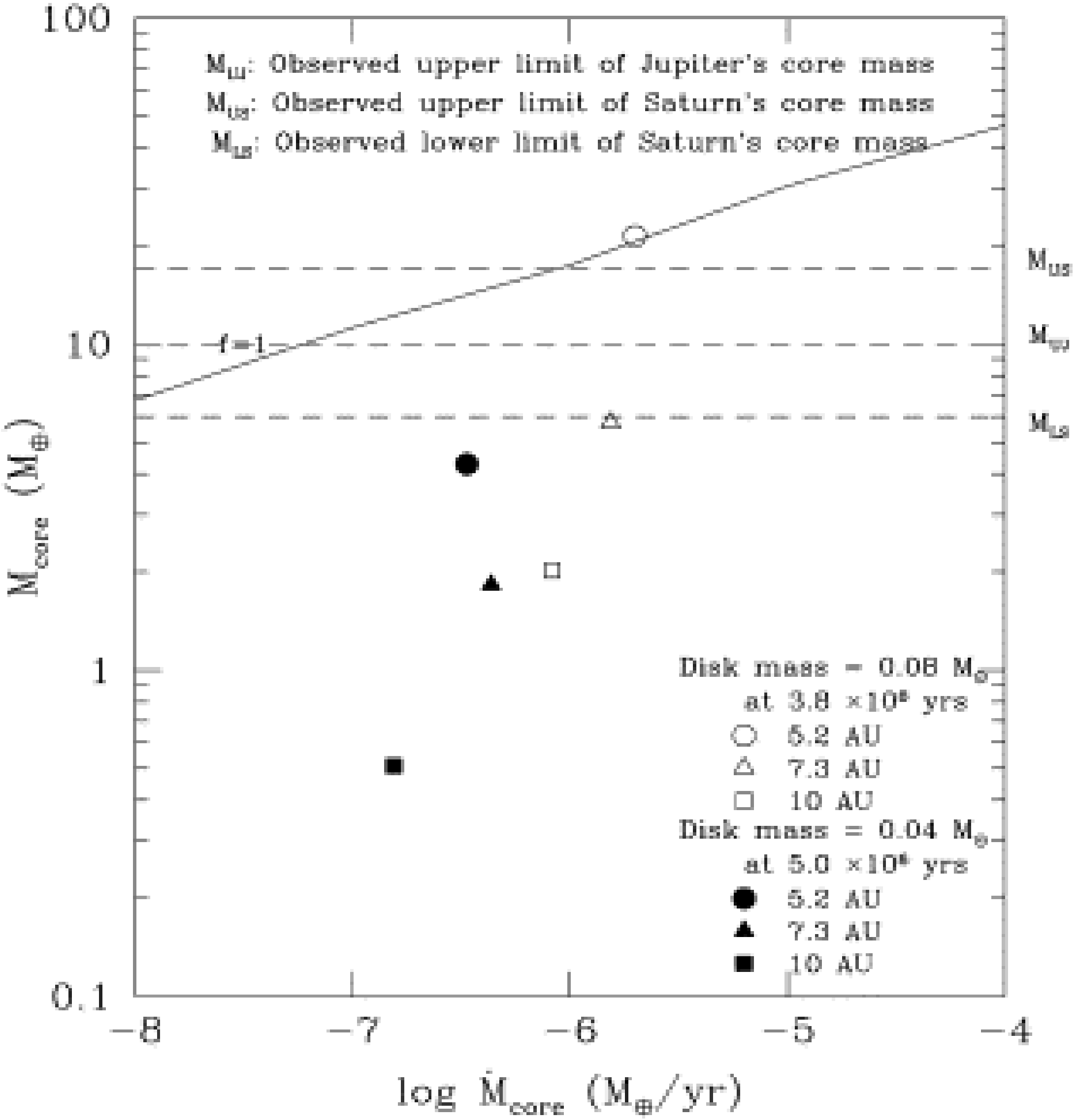
* Saturn’s core mass is about 10 to 20 Earth masses, sufficient to initiate dynamic gas accretion

* Envelopes of both planets contain substantial amounts of heavy elements

* Envelope enrichments presumably arose from ingestion of planetesimals/cometesimals during and shortly after the planets formed (multiple Comet S/L 9 impacts)

* Saturn’s core is more massive than Jupiter’s, yet it did not erode or become the more massive planet

Inaba, Wetherill, & Ikoma (2003) core accretion model

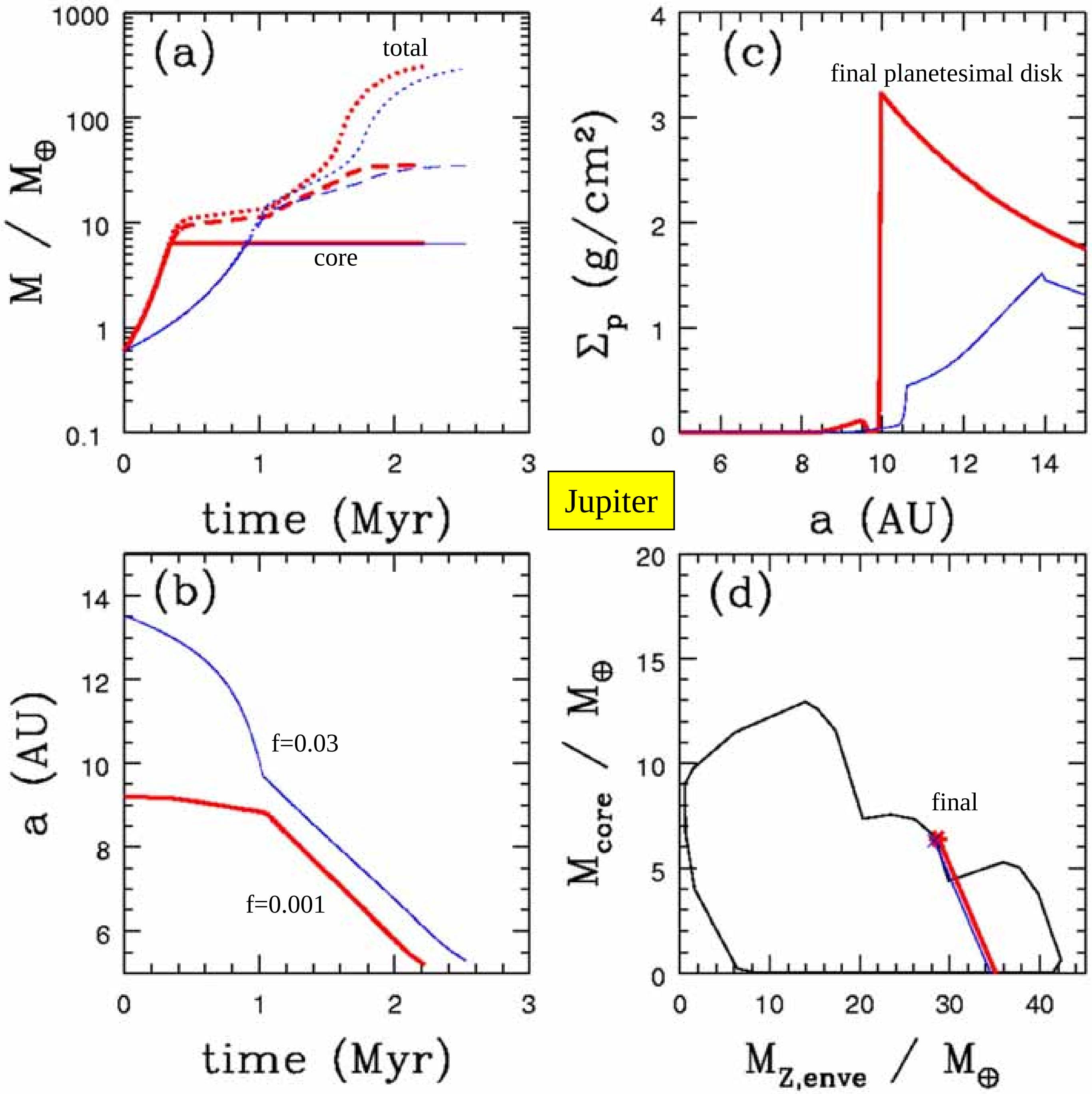


← Critical mass for onset of gas accretion

- * first model which included effects of planetesimal fragmentation and loss by orbital migration as well as capture by protoplanet's gas envelope
- * 21 Earth-mass core forms at 5.2 AU in 3.8 Myr
- * no Saturn formed
- * disk mass = 0.08 solar masses

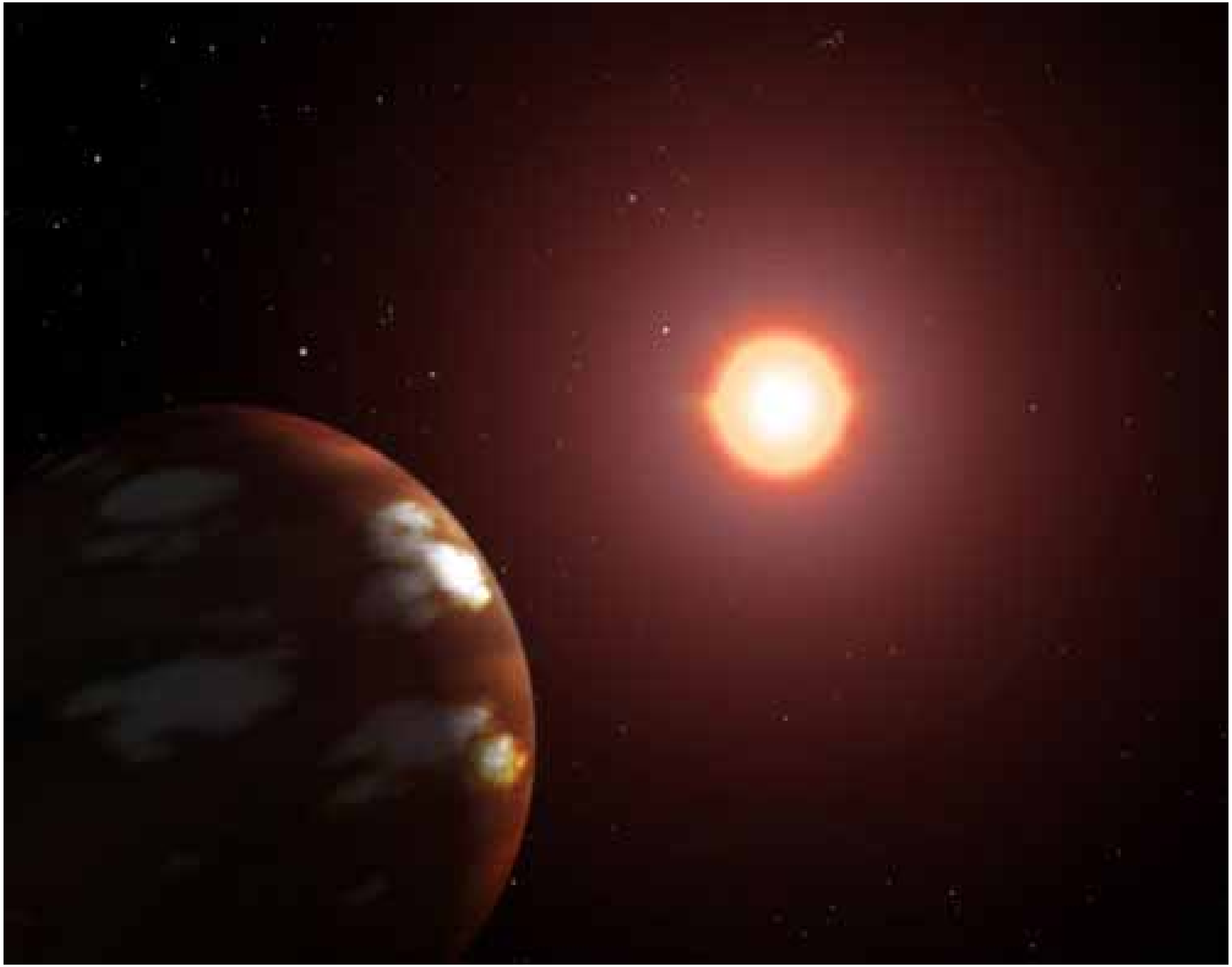
Alibert et al. (2005):

- Migration of cores included to speed planet growth
- Viscous alpha disk evolution
- Type I migration rate slowed by arbitrary factor f
- Planetesimal migration neglected
- Monarchical growth of cores
- Final Saturn core mass about the same as Jupiter's

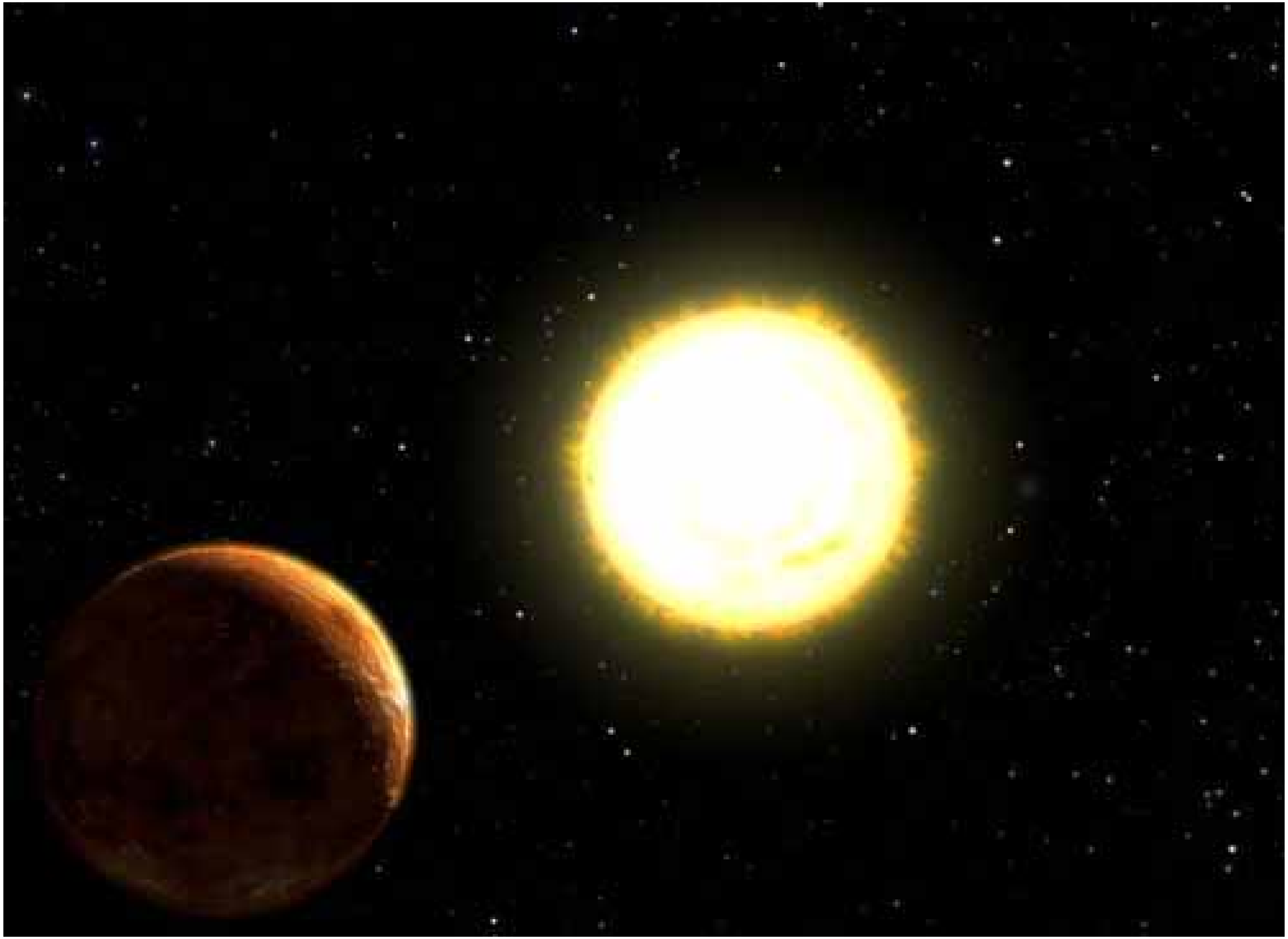


Jupiter

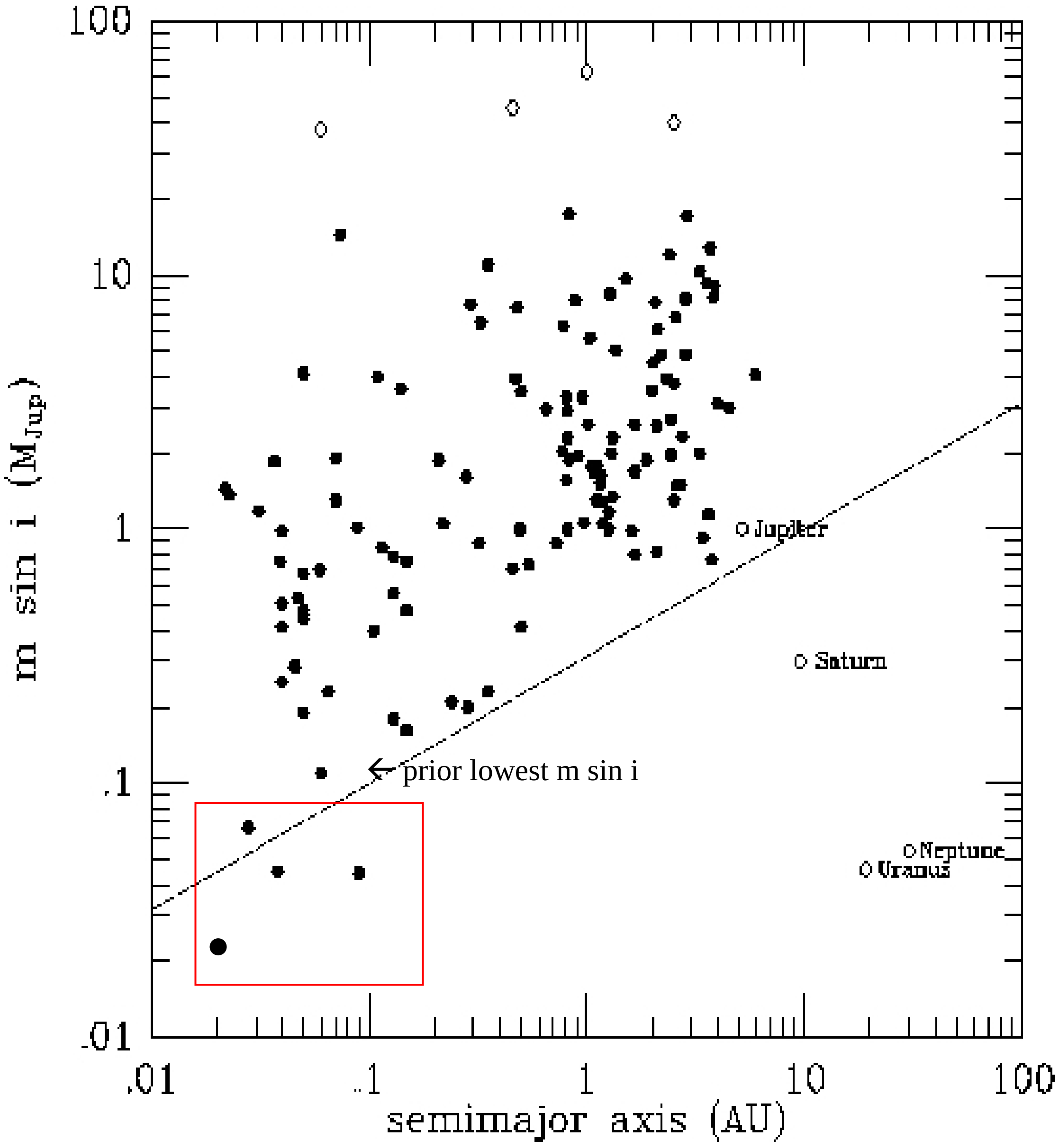
Gl 436’s planet with a minimum mass of 21 Earth masses



55 Cancri’s fourth planet with a minimum mass of 14 Earth masses

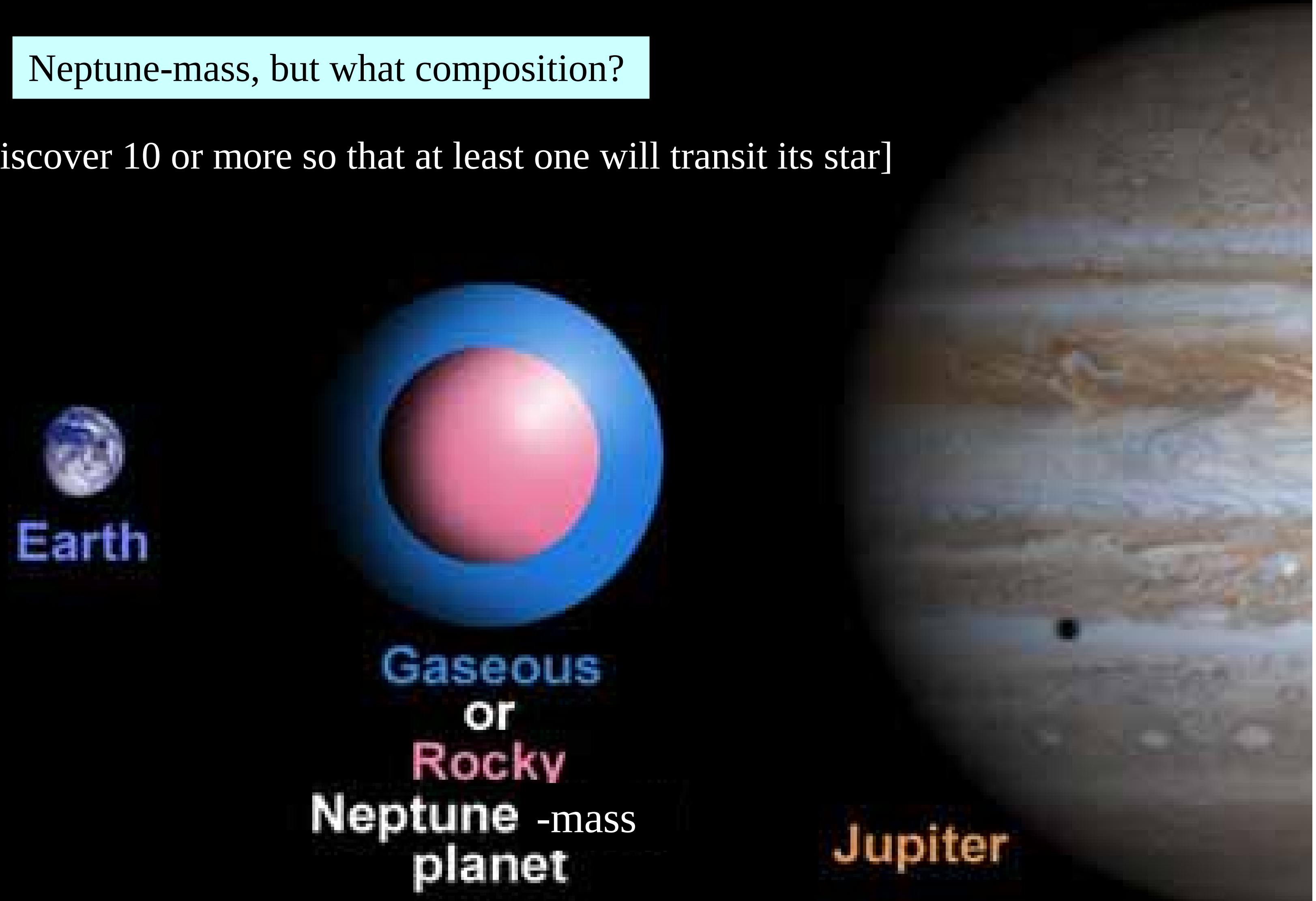


Discovery space with Neptune-mass planets

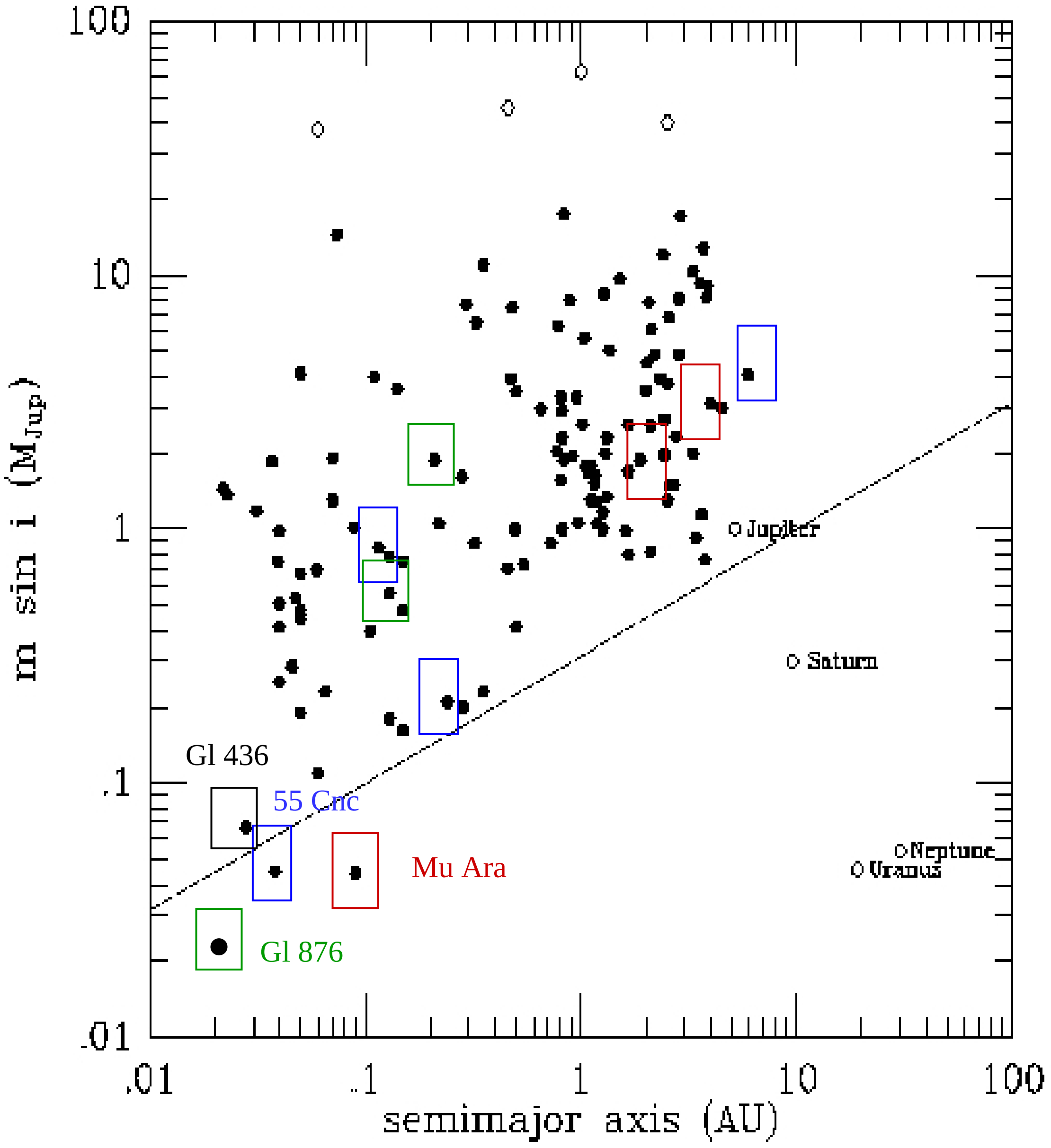


Neptune-mass, but what composition?

[Need to discover 10 or more so that at least one will transit its star]

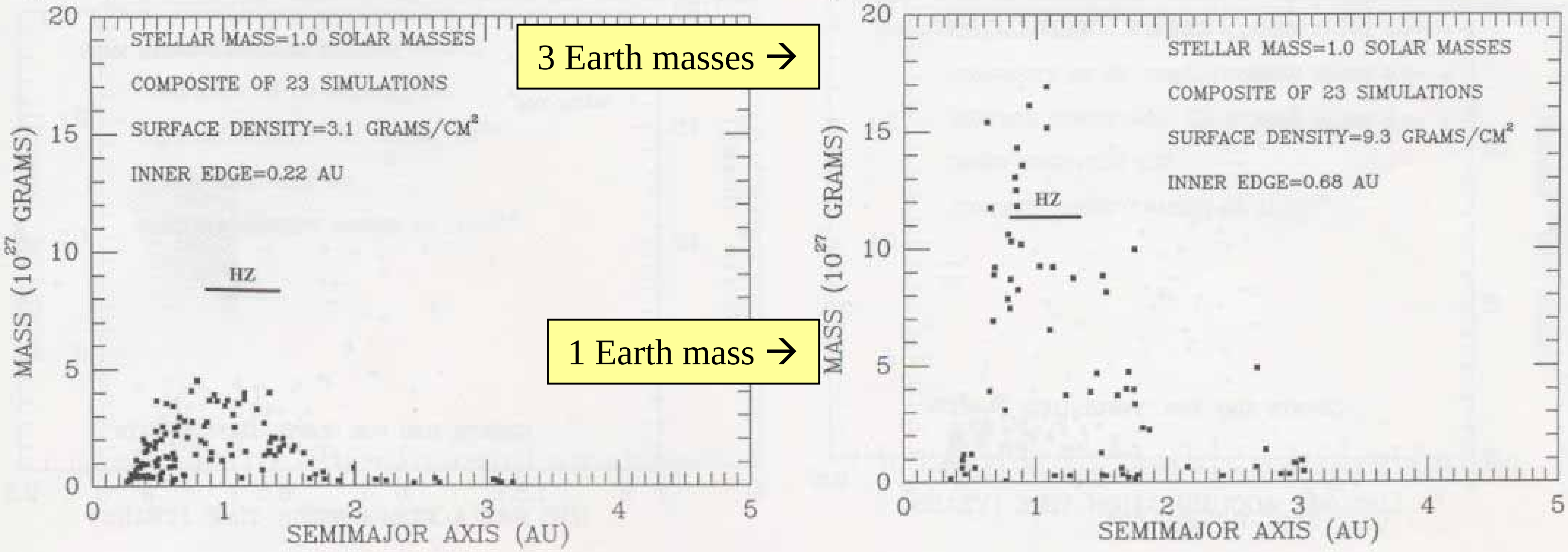


Discovery space with Neptune-mass planets and their siblings



Wetherill (1996)

Assuming surface density proportional to 1/radius, rock surface density of 9.3 g cm^{-2} at 1 AU should be increased by a factor of about 7 to account for rock/ice surface density needed at 5 AU of 25 g cm^{-2} to form Jupiter by core accretion (Inaba et al. 2003)



3 Earth masses →

1 Earth mass →

FIG. 4. Effect of varying surface density with constant stellar mass. The positions of the final planets remain similar. Their mass is dependent on the surface density, particularly for lower surface densities. The nominal case is again Fig. 1a. (a) Stellar mass, 1.0 $M_\odot$. Surface density half the nominal value. (b) Stellar mass, 1.0 $M_\odot$. Surface density 3/2 the nominal value.

Since mass of the terrestrial planets is roughly proportional to the surface density of solids, raising the solid surface density by a factor of about 7 should result in the formation of rocky planets with masses as high as about 21 Earth masses

those of the bodies in Fig. 1a (column c of table II). The more distant cutoff at the inner edge of the disk probably results in somewhat fewer smaller planets near the inner

D. Changing the Power Law Dependence of Surface Density to $a^{-3/2}$

Core Accretion Mechanism

- **Pro:**
- Leads to large core mass, as in Saturn
- Higher metallicity may speed growth of core
- Based on process of collisional accumulation, same as for the terrestrial planets
- Does not require external UV flux, so works in Taurus

- **Con:**
- Jupiter's core mass is too small
- Higher metallicity makes even larger mass cores
- Saturn should be largest planet
- No Saturn in Inaba et al. (2003)
- If gas disks dissipate before critical core mass reached → "failed Jupiters" are usual result
- Cannot form gas giant planets for M dwarfs, low metallicity stars (M4), or form planets rapidly (CoKu Tau/4? GQ Lup?)
- Loss of growing cores by Type I migration prior to gap formation
- Needs disk mass high enough to be gravitationally unstable
- No *in situ* ice giant formation

Disk Instability Mechanism

- **Pro:**
- May explain core masses, bulk compositions, and radial ordering of gas and ice giant planets in Solar System
- Requires disk mass no more than that assumed by core accretion
- Forms gas giants in either metal-rich or metal-poor disks (M4)
- Clumps form quickly (CoKu Tau/4? GQ Lup?) and efficiently even in short-lived disks
- Appears to work for M dwarfs
- Sidesteps Type I (and III) orbital migration danger
- Works in Taurus or Orion, implying Solar System analogues are common

- **Con:**
- Might require a trigger (magnetically dead zone, episodic infall, binary companion, or close protostar encounter)
- Clump survival uncertain: need for models with detailed disk thermodynamics and higher spatial resolution (AMR)
- Requires large UV dose to make ice giant planets – in Taurus would make only gas giant planets

Future Observational Tests

- RV searches for long period Jupiters around G, K, M dwarfs (Geneva, California/Carnegie, Texas, … groups)
- Astrometric search for long period Jupiters around late-M, L, T dwarfs (Carnegie group/Las Campanas)
- RV search for long period Jupiters around low metallicity stars (CfA group/Keck HIRES)
- RV and transit searches for “hot Neptunes” [failed cores with lower mean density than “hot Earths”] (ground-based, Corot, Kepler)
- Determine epoch of giant planet formation from disk gaps or astrometric wobble of YSOs (SST, ALMA, SIM)
- Planetary system architectures as $f(r)$: terrestrial - gas - ice Solar-System-like order or … (SIM, TPF-C, TPF-I/Darwin)
- Jupiter/Saturn core masses (Juno mission to Jupiter)

My thanks to the Kobe International Summer School, and especially to Yoshi Nakagawa!

DTM, Carnegie Institution, Washington, DC, 1988