# Giant Planet Formation: Theory 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 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

2004



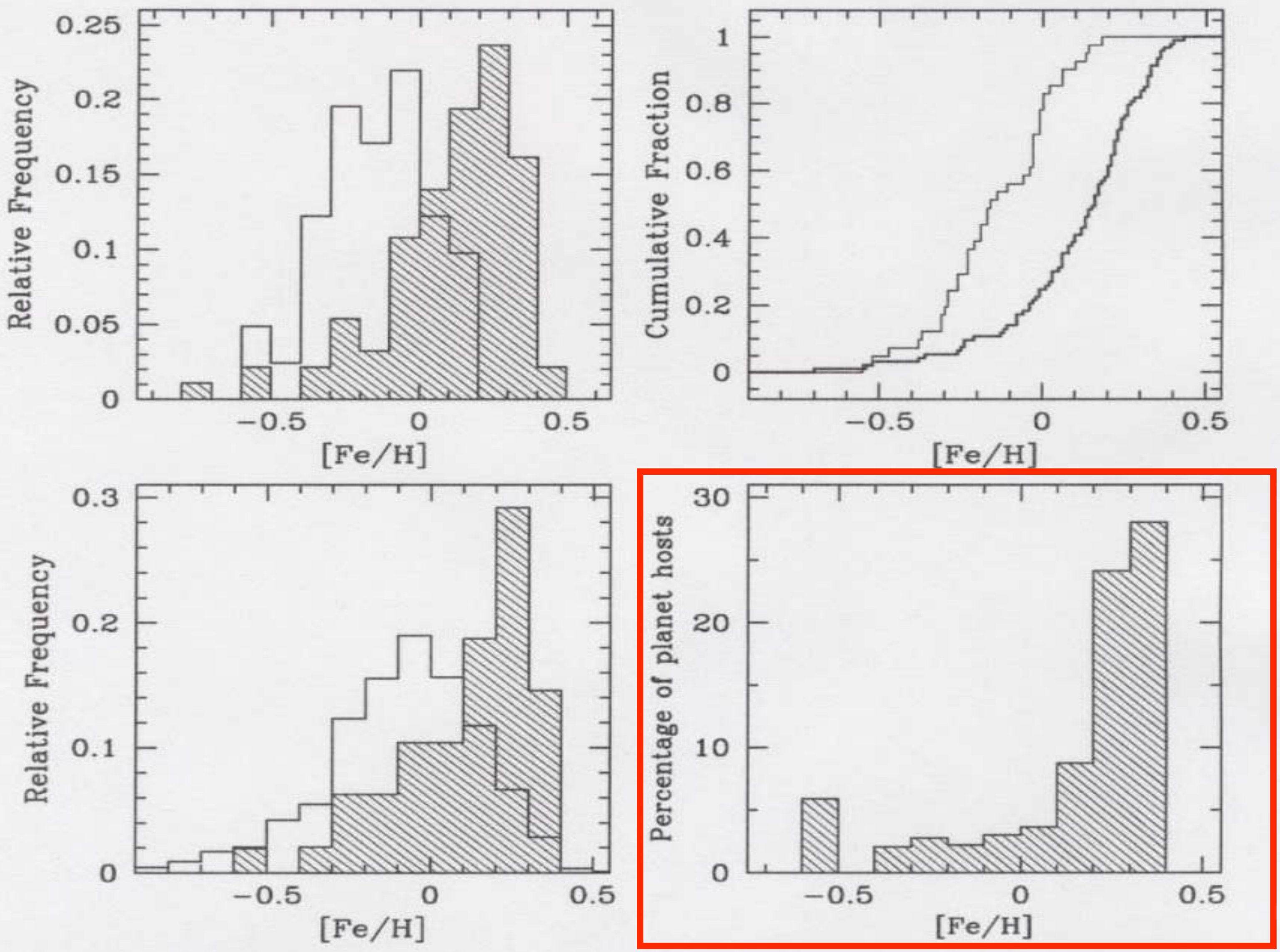
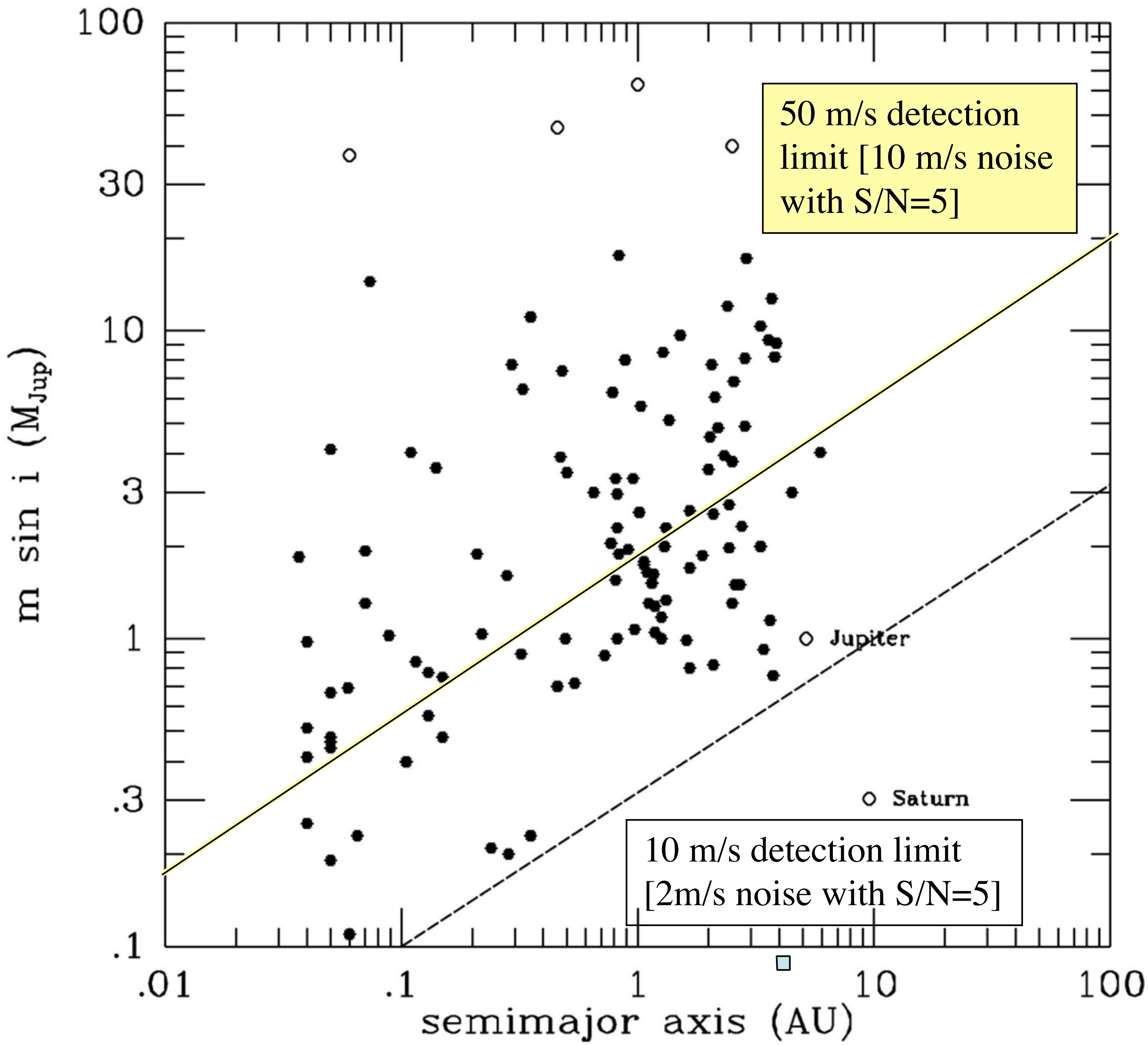
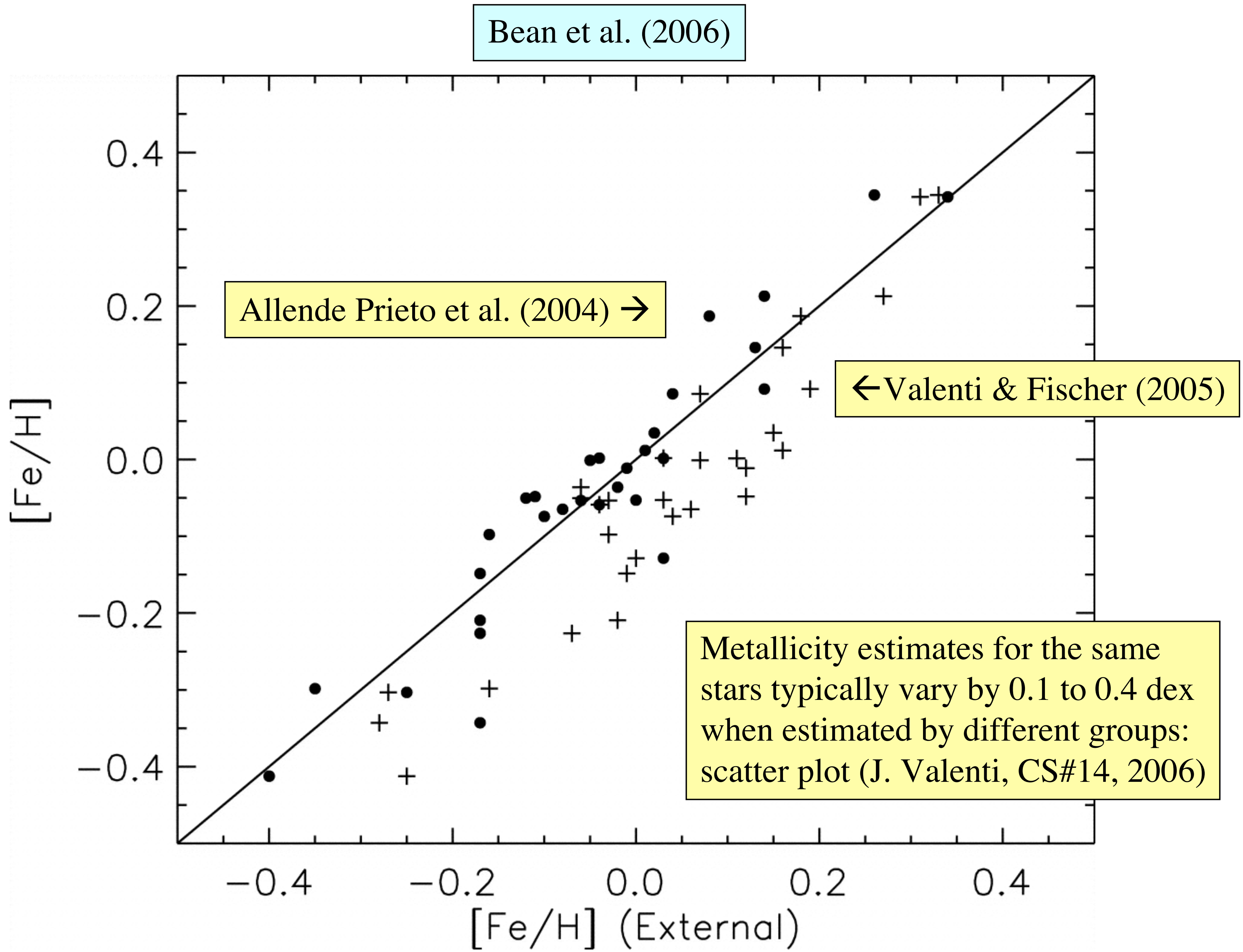



**Fig. 6.** *Upper panels*: [Fe/H] distributions for planet host stars (hashed histogram) and for our volume-limited comparison sample of stars (open bars). The average difference between the [Fe/H] of the two samples is of ~0.25 dex. A Kolgomorov-Smirnov test shows that the probability that the two 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)




Bean et al. (2006)
Allende Prieto et al. (2004) →
←Valenti & Fischer (2005)
Metallicity estimates for the same stars typically vary by 0.1 to 0.4 dex when estimated by different groups: scatter plot (J. Valenti, CS#14, 2006)
[Fe/H]
[Fe/H] (External)
0.4
0.2
0.0
−0.2
−0.4

# 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 or of debris disks (Beichman et al. 2006) with metallicity
* 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
* Long-period planets found around ~ ten K giants, which are all metal-poor (Hatzes et al. 2005)
* 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?

metallicity-period correlation

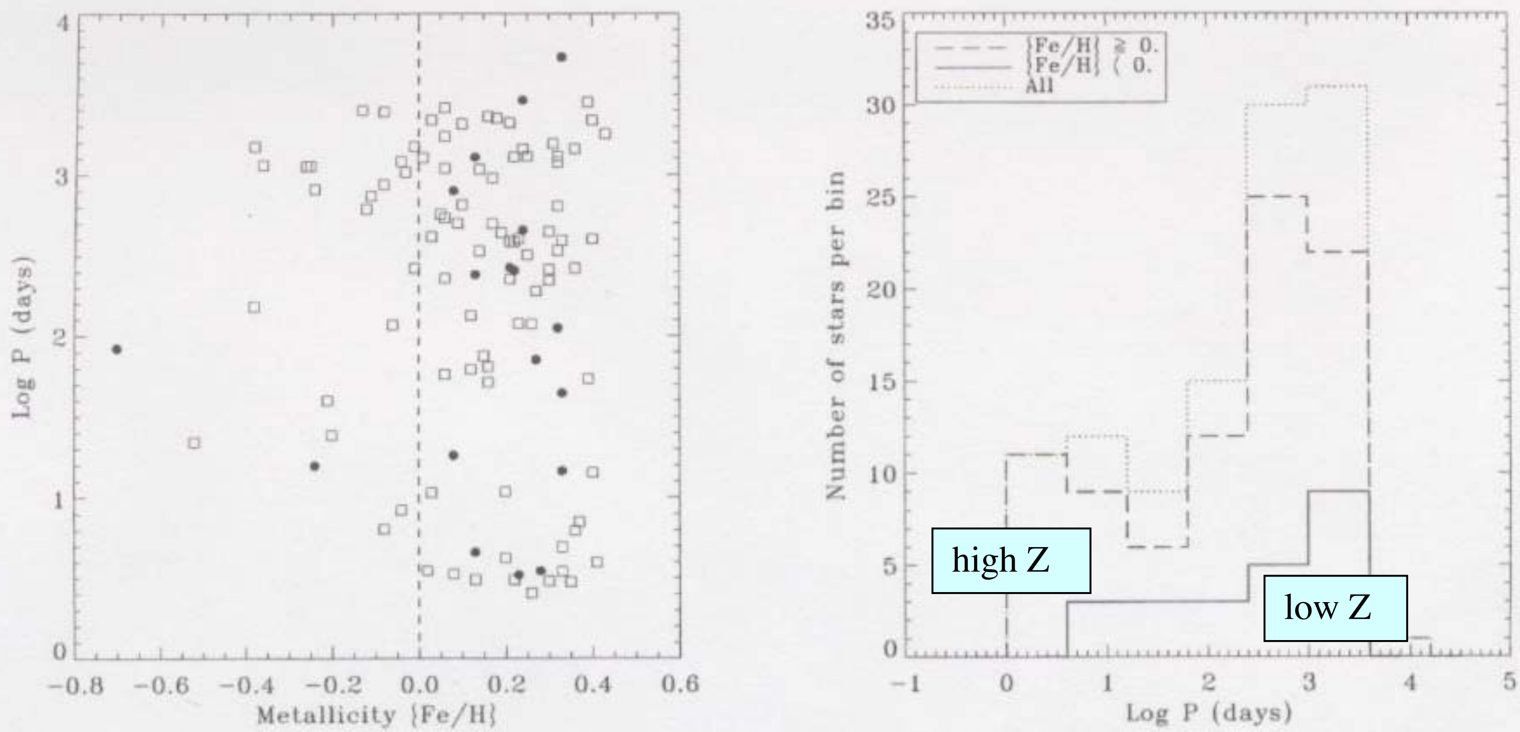



**Figure 1.** Left panel: orbital periods of extrasolar planets as a function of the metallicity of the host stars. Planets identified by solid circles are orbiting know members of binary systems. Right panel: distribution of orbital periods for the stellar sample with [Fe/H] < 0.0 (solid line), with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

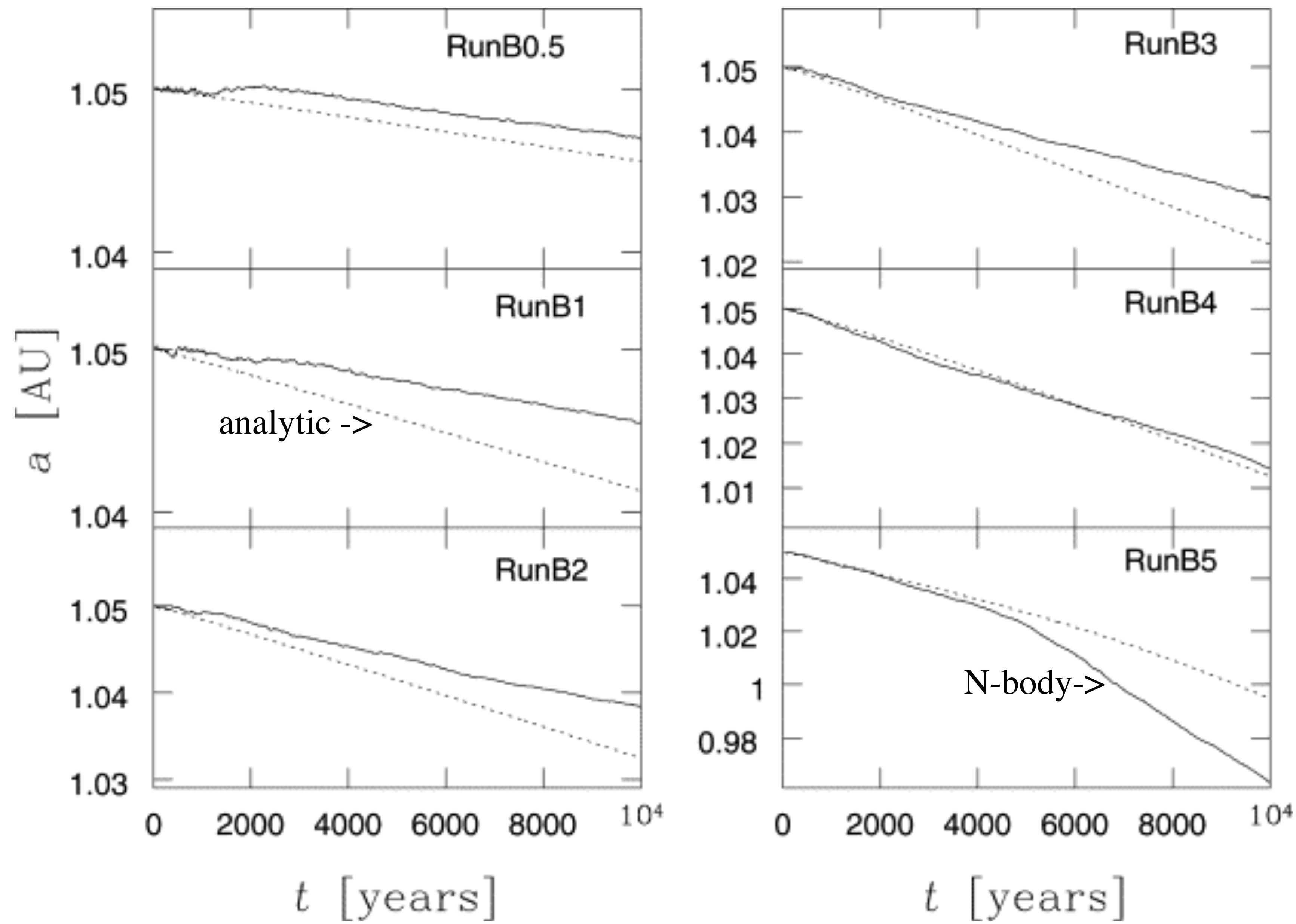
have used a more relaxed version of the Oppenheimer, Kulkarni & Stauffer (2000) theoretical deuterium-burning threshold of 13 $M_J$ (where $M_J$ is the mass of Jupiter), which establishes both the lower limit to the mass of a brown dwarf and the upper bound to the mass of a planet (assuming solar metallicity). 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 refe ence, the full distribution of orbital periods for all metallicities i

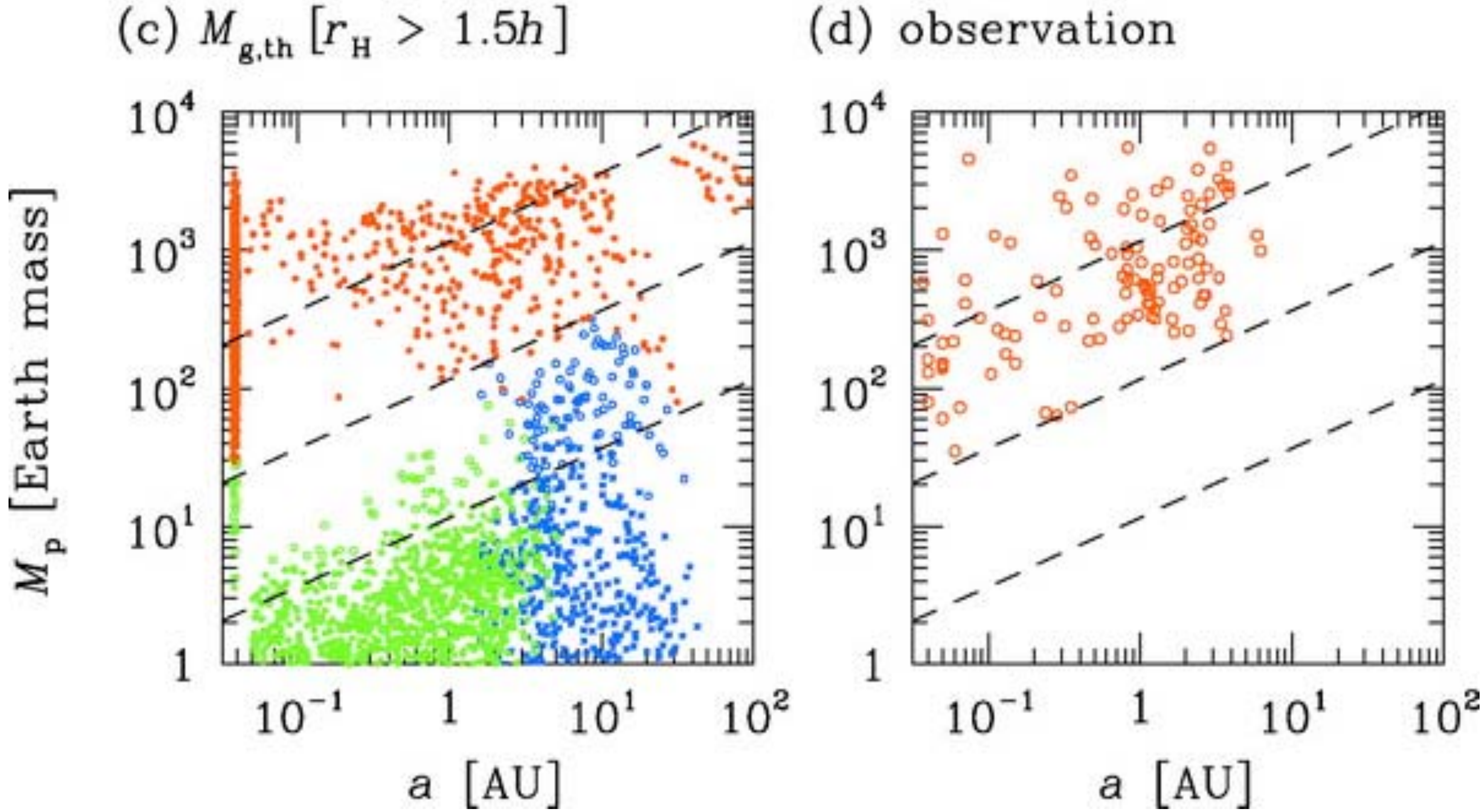
# Highest Metallicities Correlation: Migration or Formation?

* 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])

Type I migration – Kominami, Tanaka, & Ida 2005



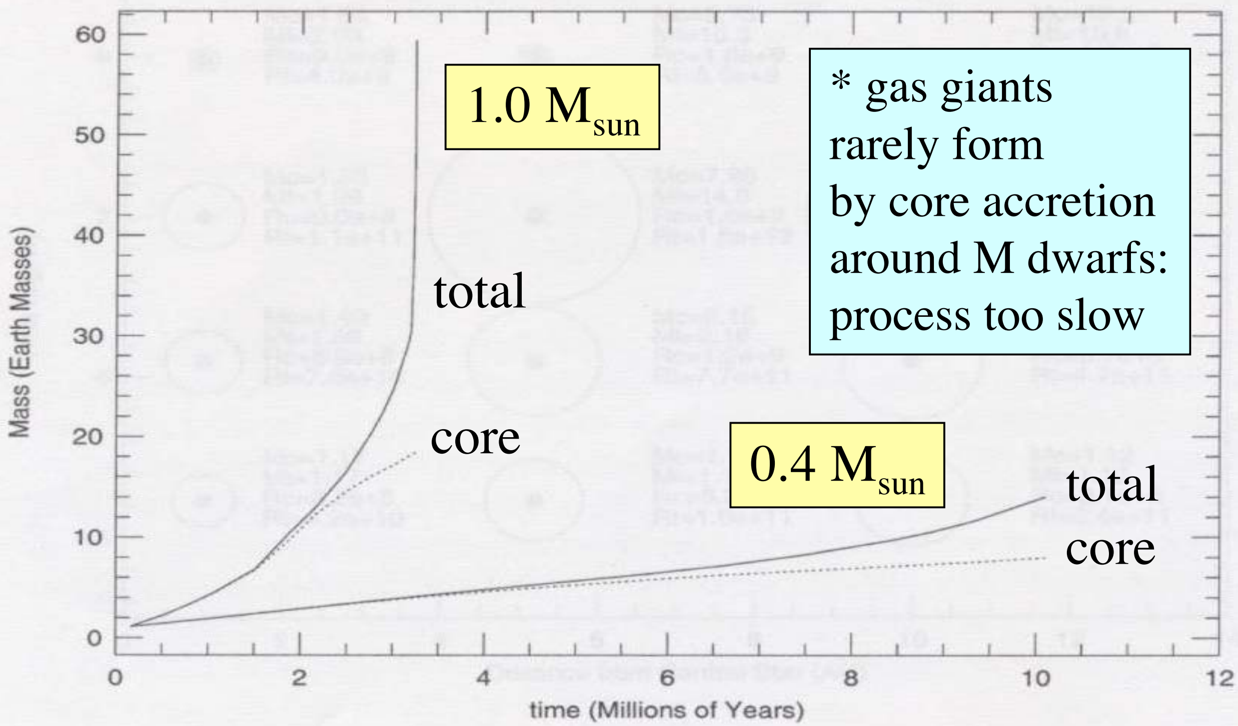
Prediction of a ‘planet desert’ from 10 to 100 Earth masses and for semi-major axes less than 3 AU, based on core accretion models of gas and ice giant planet formation (figure from S. Ida and D. N. C. Lin, 2004, ApJ, 604, 388-413). Includes the effects of Type II migration, but not Type I or Type III,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



# Giant Planet Census: Low-mass Host Stars

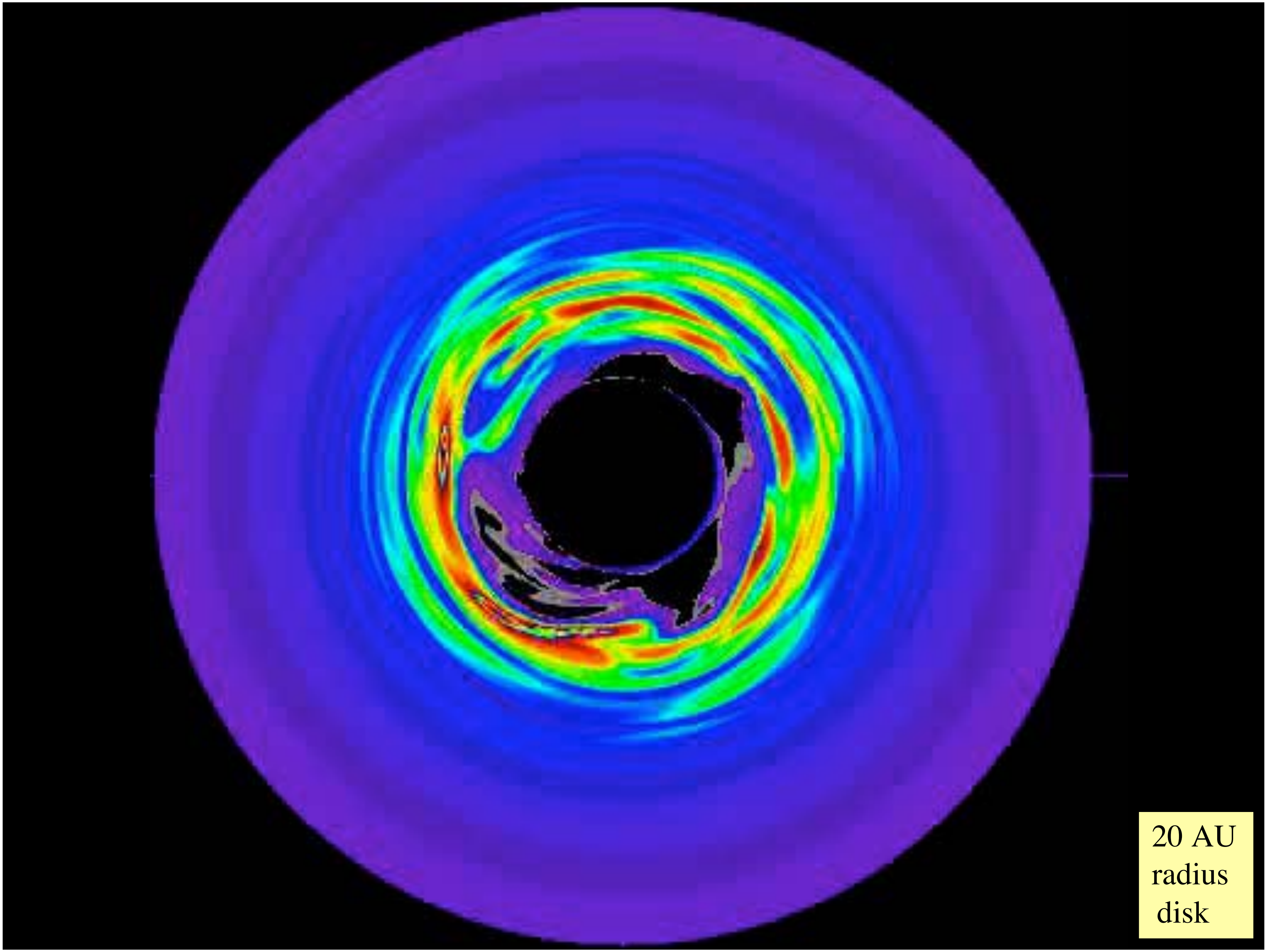
* Most planet-host stars are G dwarf stars like the Sun, while most nearby stars are M dwarfs, less massive than the Sun
* Frequency of RV gas giant planet companions to M dwarfs appears to be smaller than for G dwarfs
* M4 dwarf star Gl876 (0.32 $M_{Sun}$) has two known gas giant planets (and one sub-Neptune-mass planet: more later…)
* Microlensing surveys have found two Jupiter-mass planets orbiting distant M dwarfs
* While the frequency of giant planets around M dwarfs is uncertain, it is clearly not zero
* The three nearby M dwarfs with known planets (Gl 876, Gl 436, Gl 581) have metallicities less than solar (Bean et al. 2006): -0.12, -0.32, and –0.33 respectively

# Laughlin et al. 2004 core accretion models

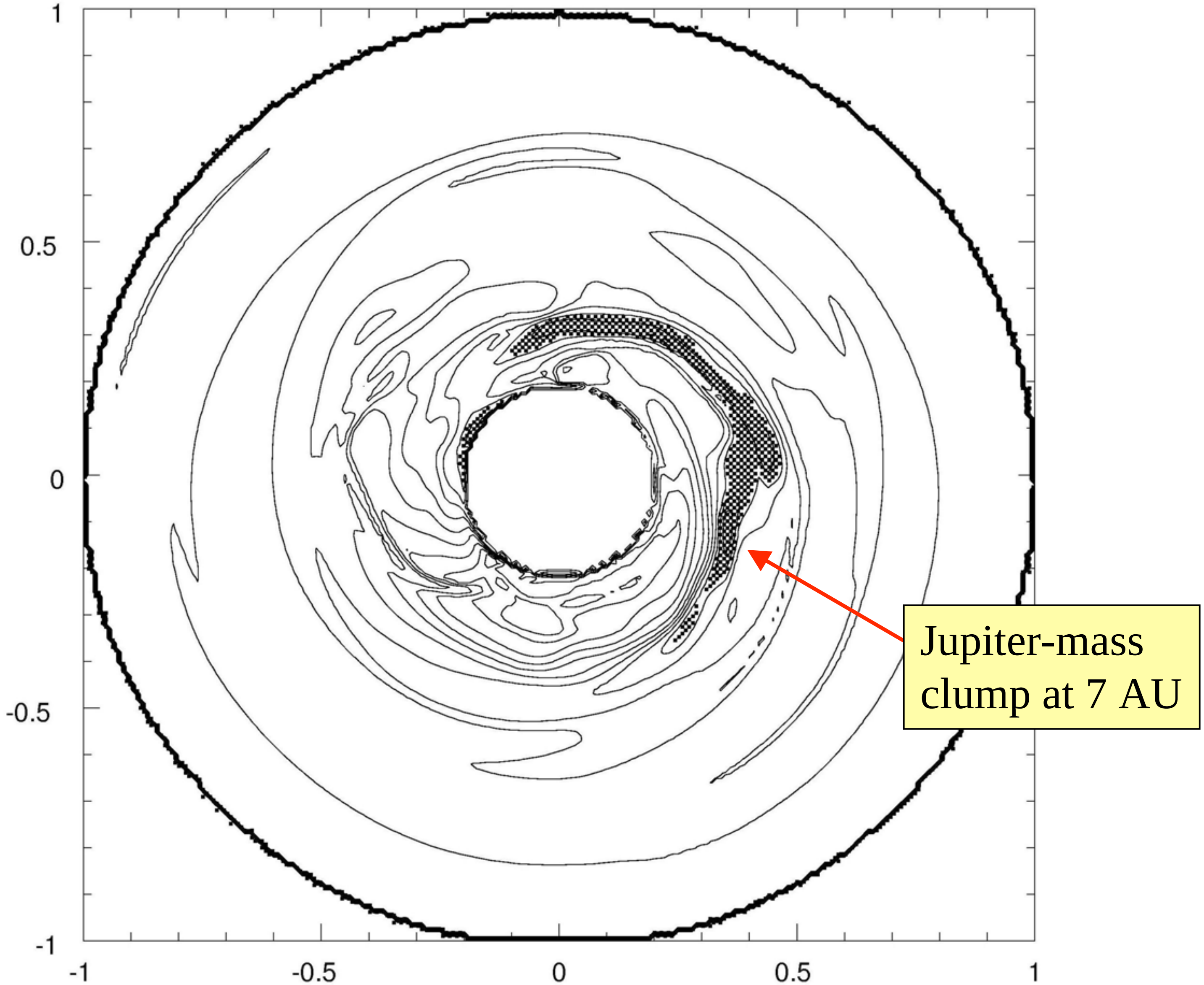



(vs. Kornet et al. 2006: more gas giants as stellar mass decreases)

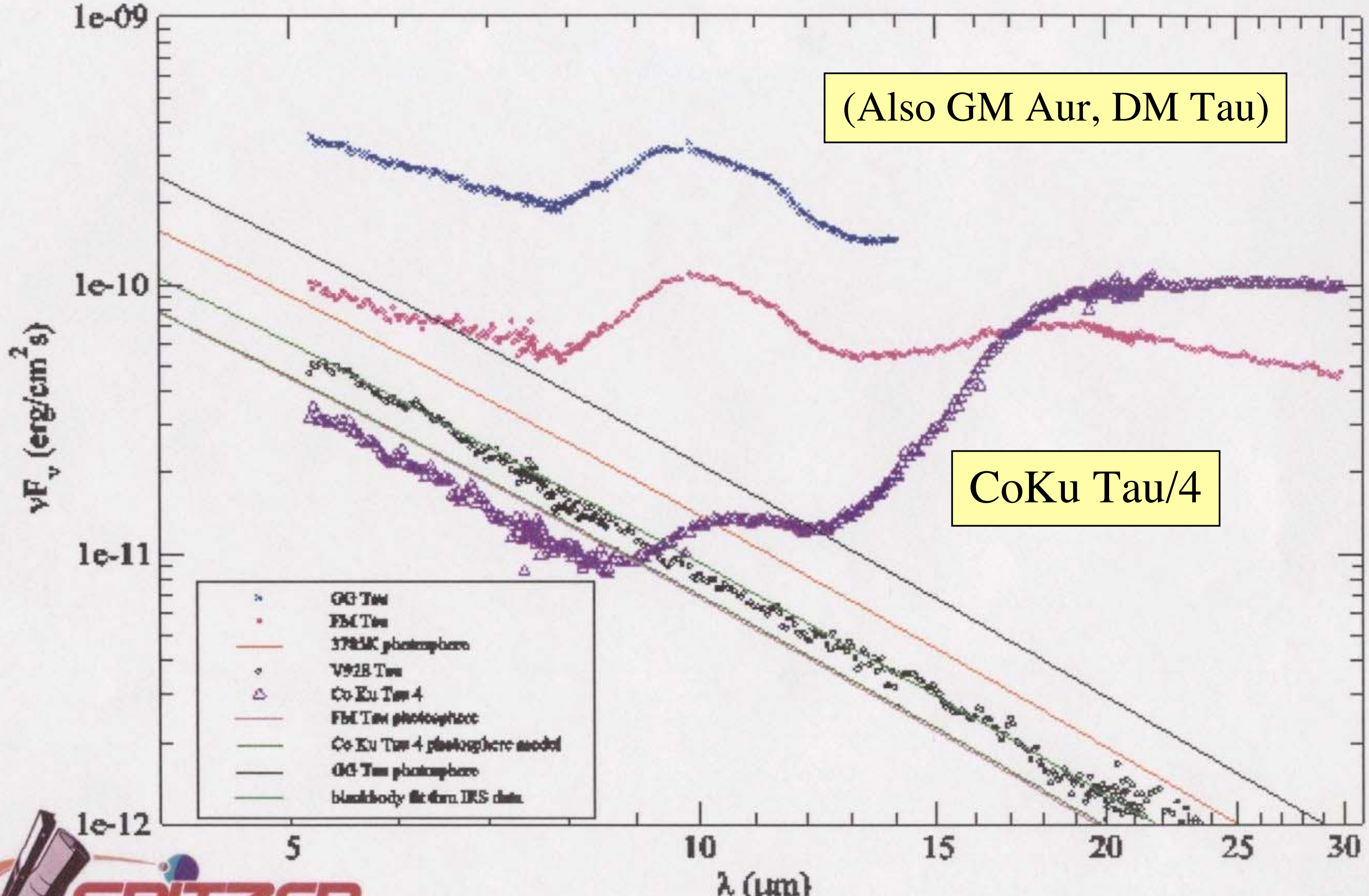
Fig. 1.— Growth of the core and envelopes of planets at 5.2 AU in disks orbiting stars of two different masses. The upper curves show the time-dependent core mass (dotted curve) and total mass (solid curve) for a planet forming in a disk surrounding a $1 M_\odot$ star. The lower curves show the time dependence of the core mass (dotted curve) and total mass (solid curve) for a planet forming in a disk around a $0.4 M_\odot$ 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 $M \approx 14 M_\oplus$.


20 AU
radius
disk

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



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).

# 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

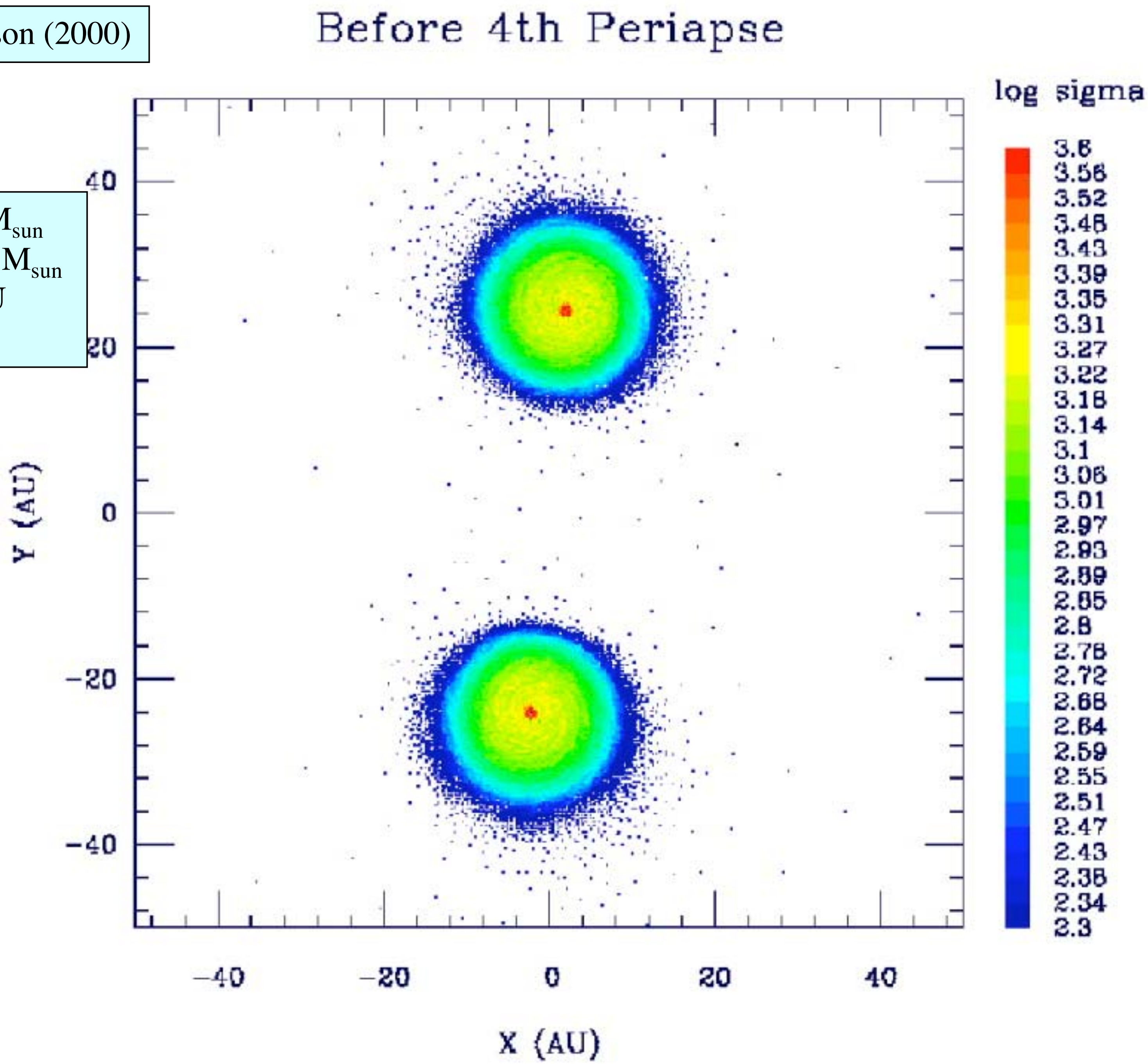
  Gamma Cephei – about 20 AU separation

  Gl 86 – about 20 AU separation

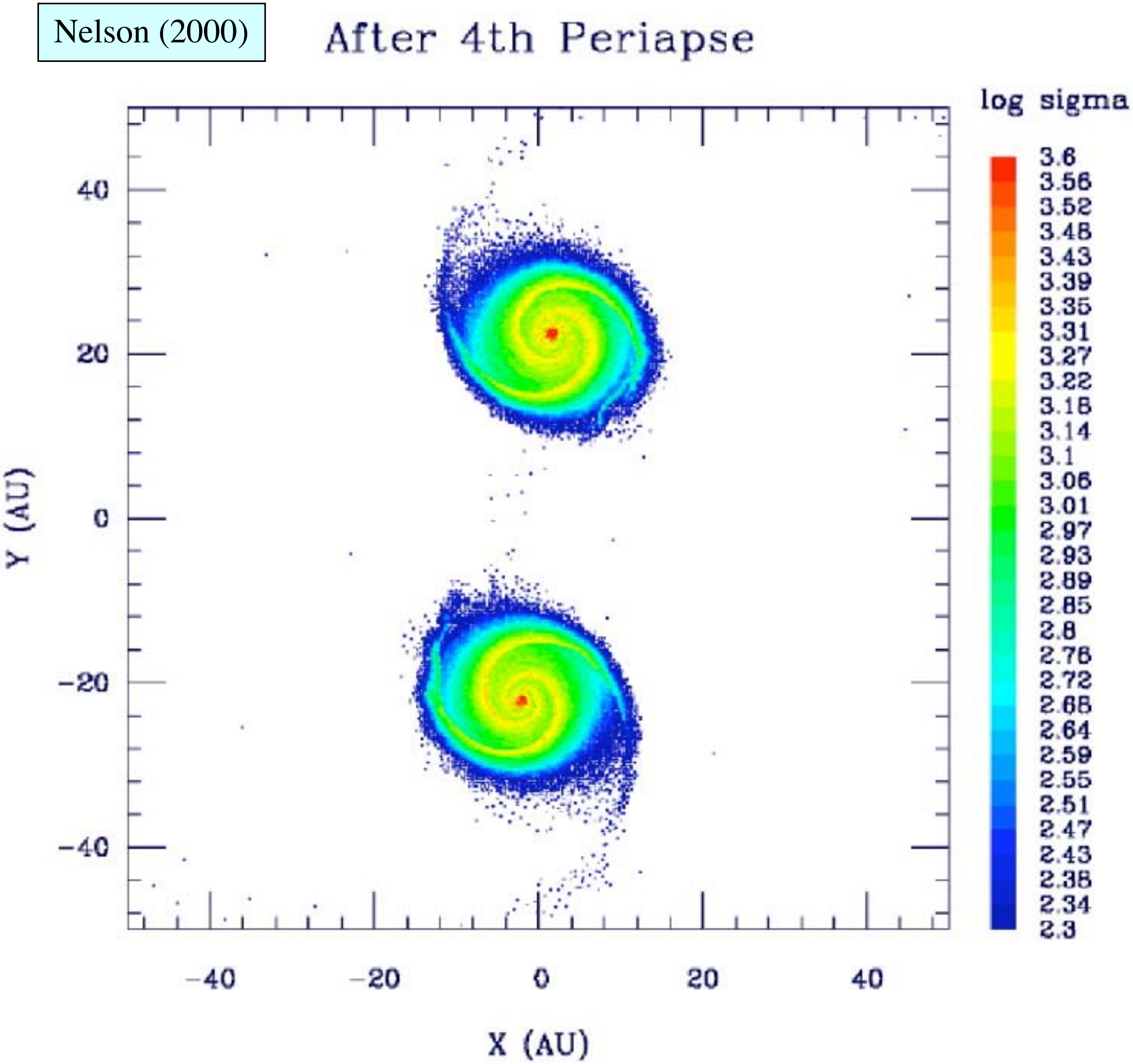
[ At least ~ 29 multiple stars have planets to date (M. Mugrauer, 2004)]

Nelson (2000)

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



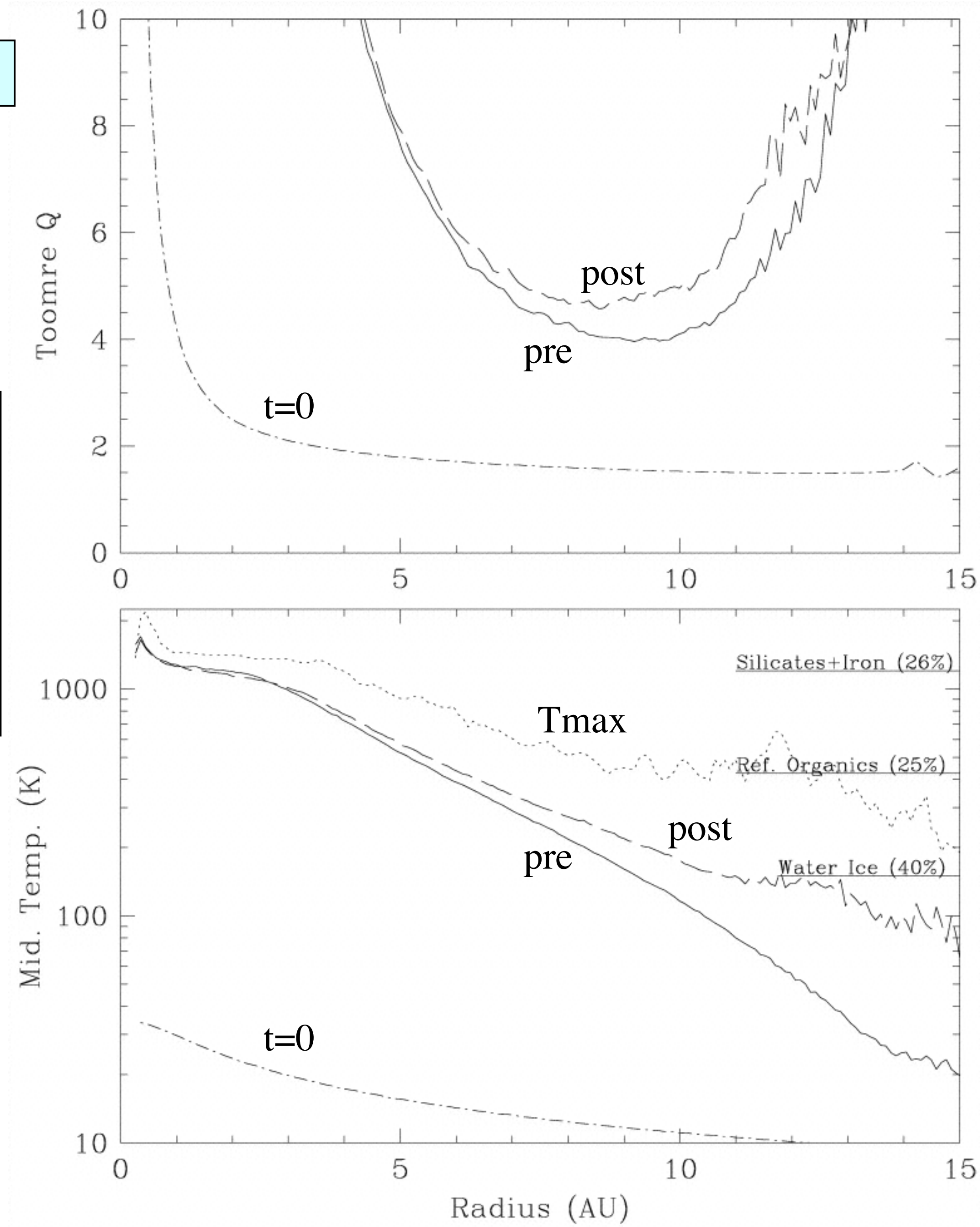
Nelson (2000)

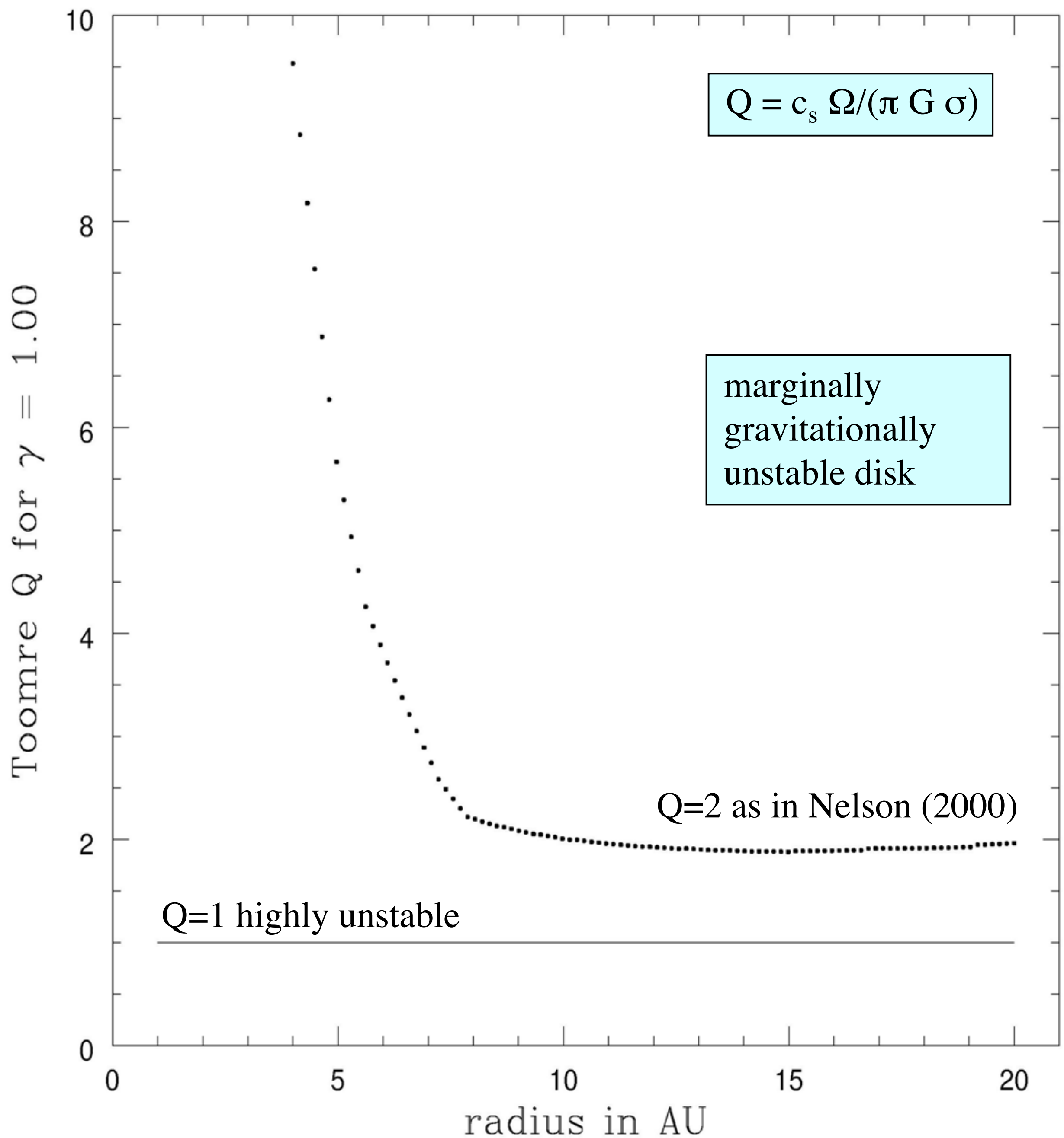


After 4th Periapse
log sigma
3.6
3.56
3.52
3.48
3.43
3.39
3.35
3.31
3.27
3.22
3.18
3.14
3.1
3.06
3.01
2.97
2.93
2.89
2.85
2.8
2.76
2.72
2.68
2.64
2.59
2.55
2.51
2.47
2.43
2.38
2.34
2.3
Y (AU)
40
20
0
−20
−40
X (AU)
−40
−20
0
20
40

Nelson (2000)

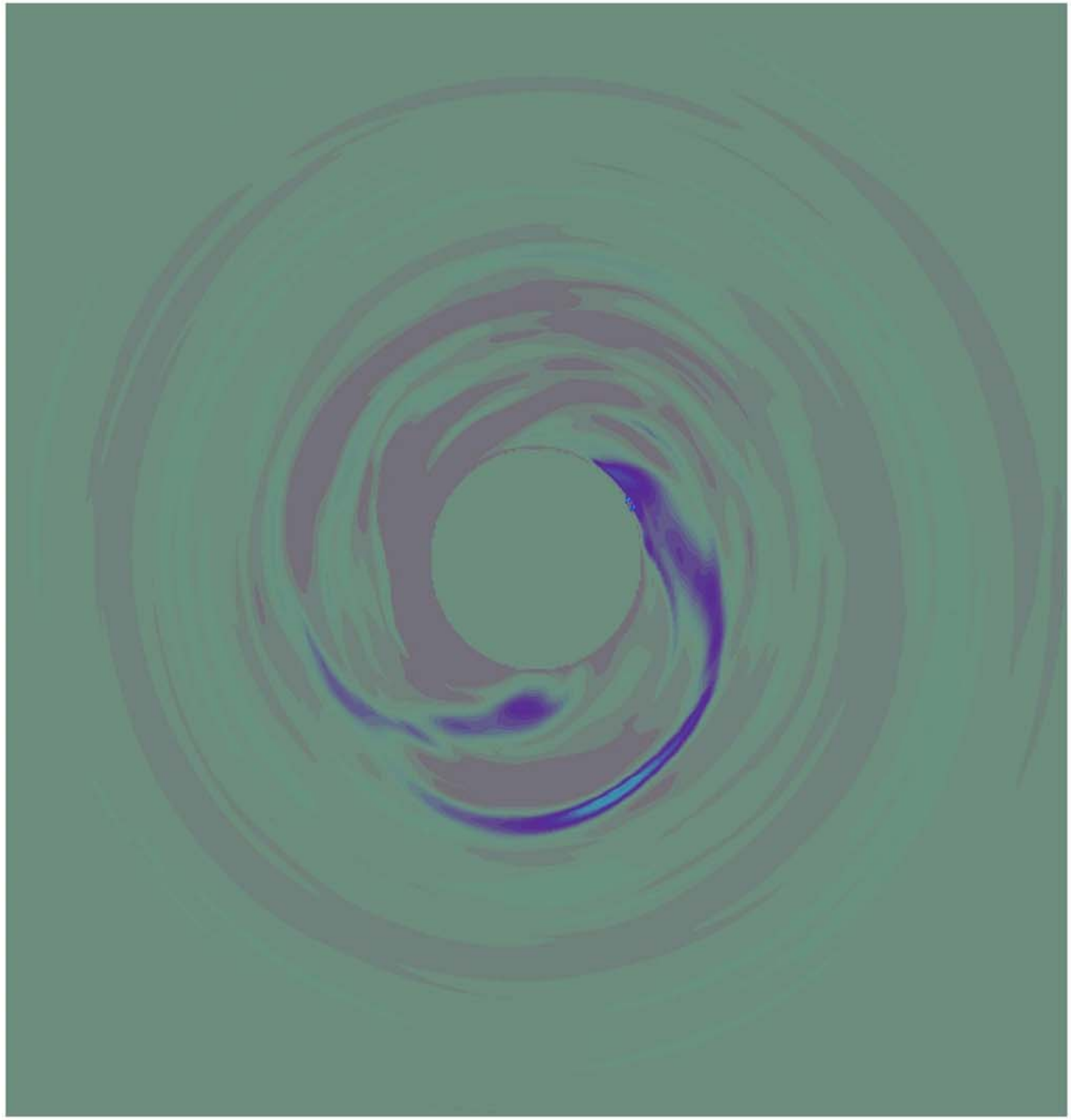
"Planet formation is unlikely in equal-mass binary systems with a = 50 AU"





Q = $c_s$ Ω/(π G σ)
marginally gravitationally unstable disk
Q=2 as in Nelson (2000)
Q=1 highly unstable
Toomre Q for γ = 1.00
radius in AU
0
2
4
6
8
10
0
5
10
15
20

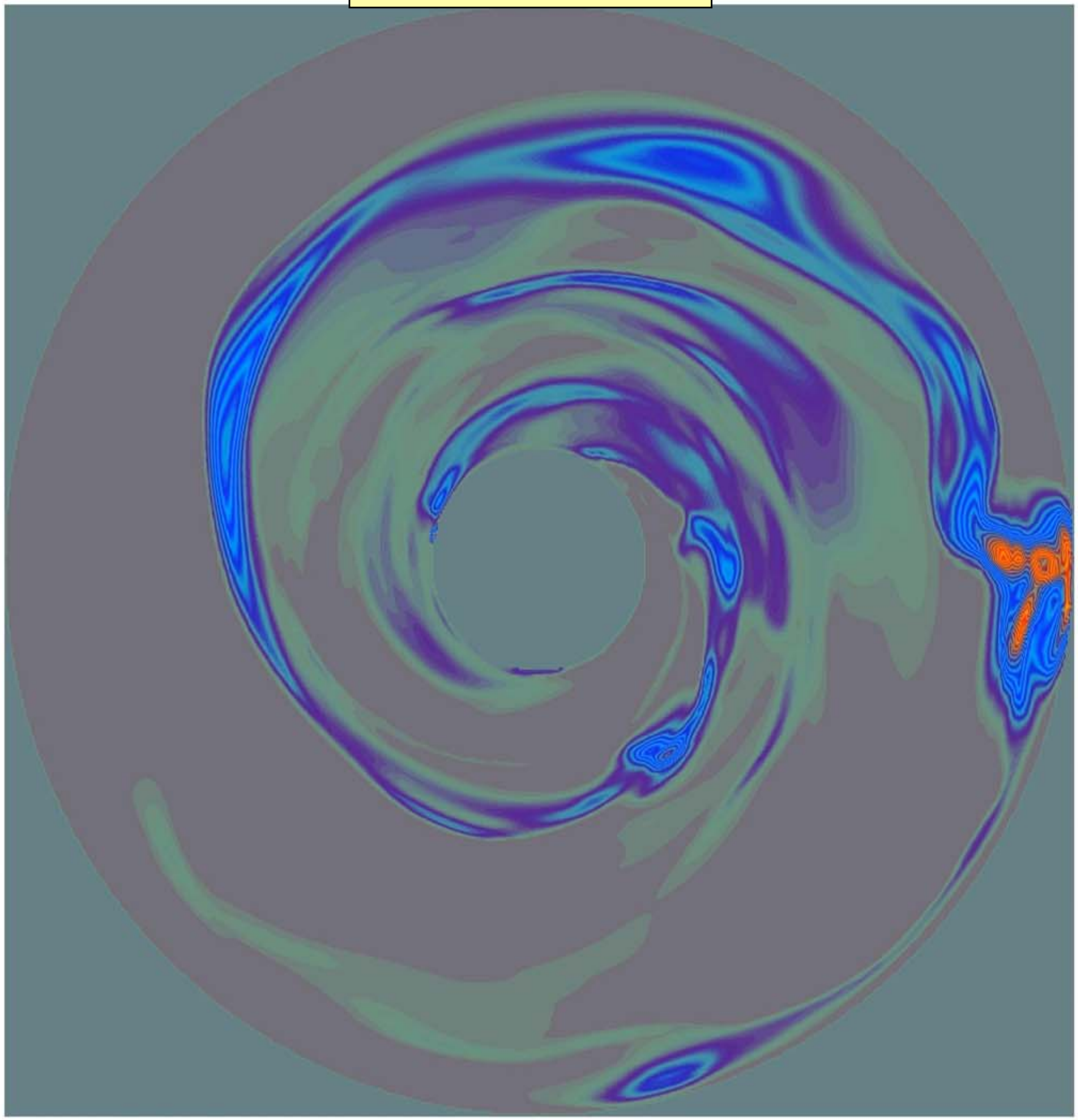
20 AU
radius
disk



no binary
245 years

to binary ^ at apastron

20 AU radius disk



after one binary rotation period: 239 years

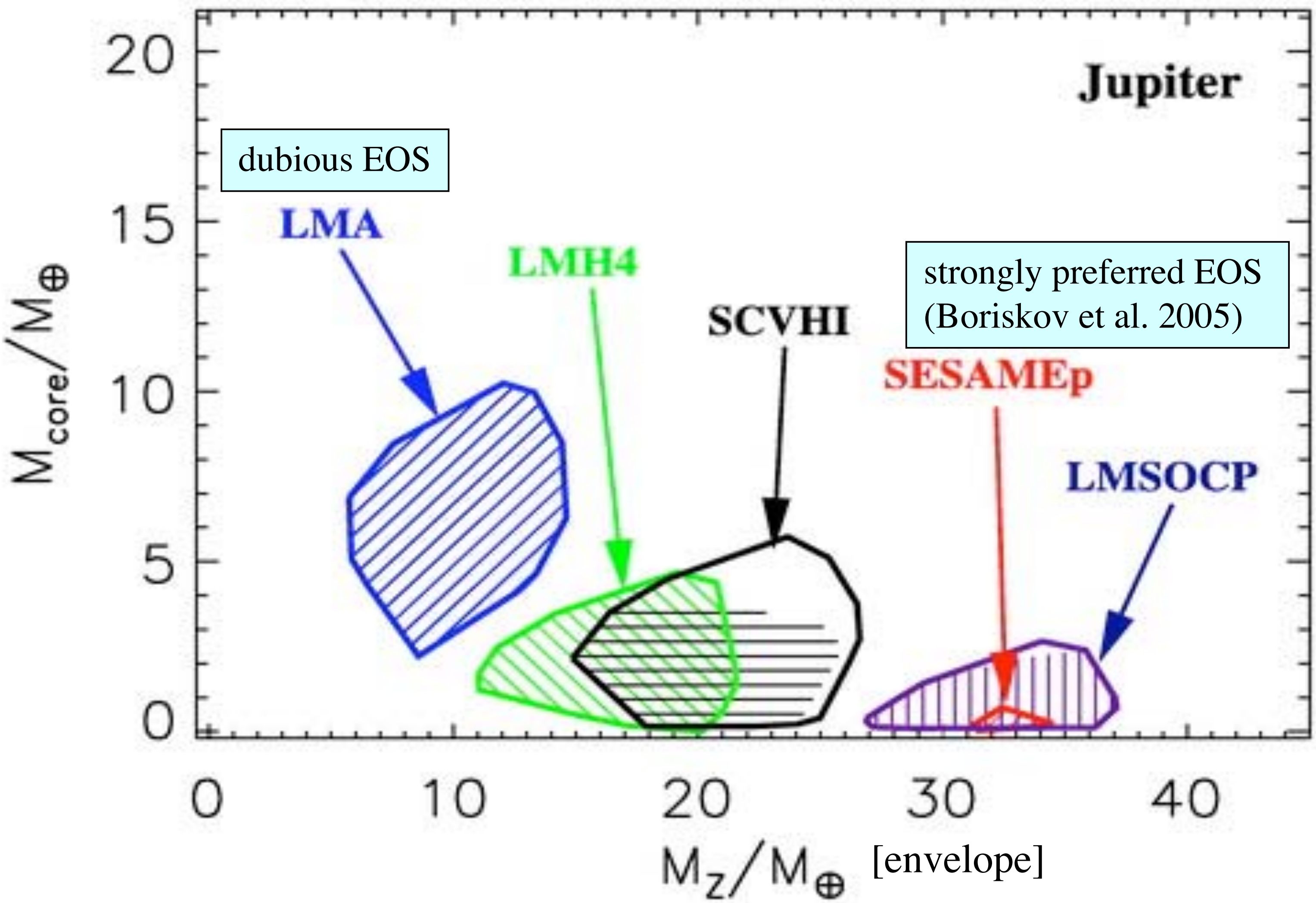
$M_s$= 1 $M_{sun}$
$M_d$= 0.09 $M_{sun}$
a = 50 AU
e = 0.5

# Differences between Nelson (2000) and present models

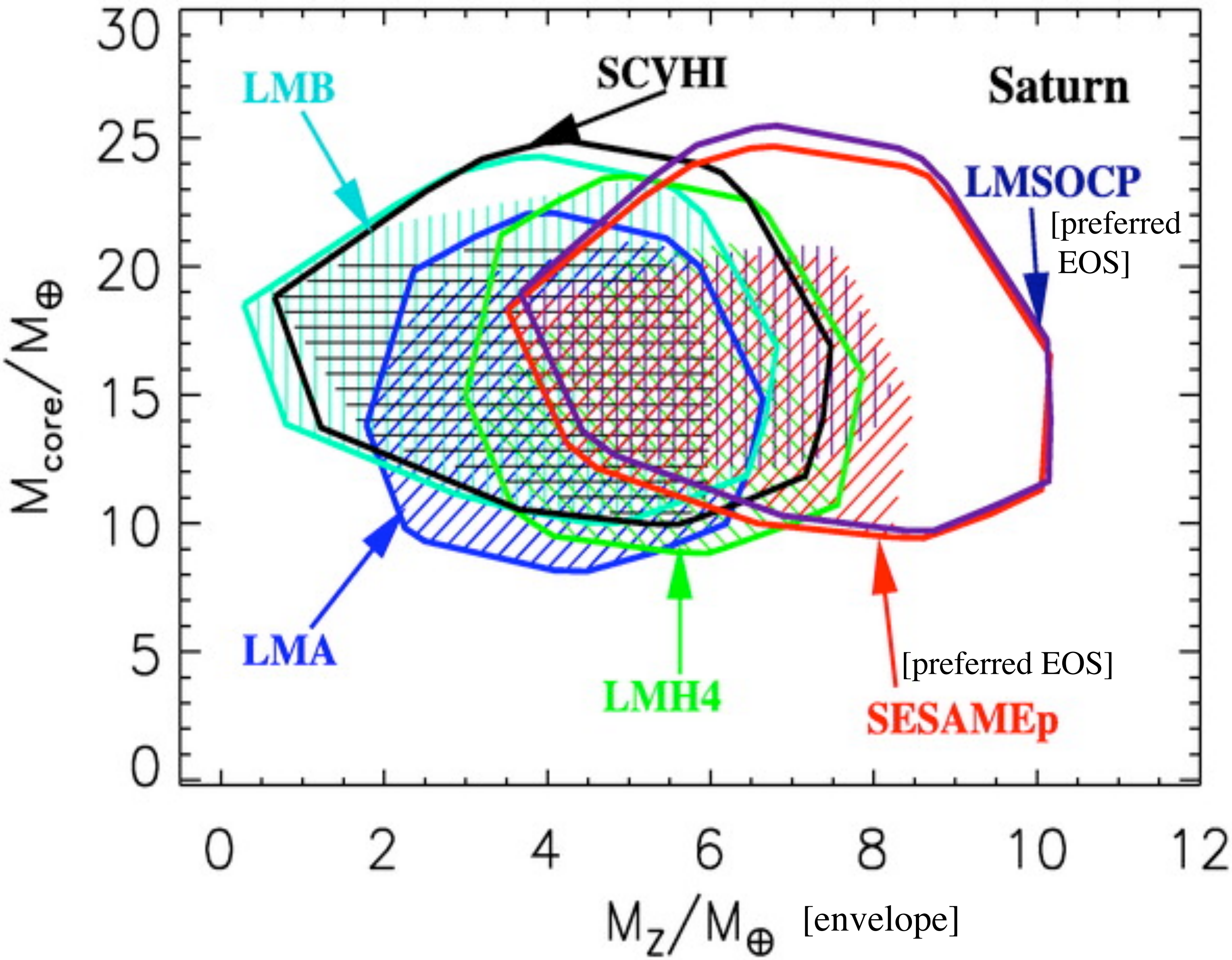
- Nelson (2000) used 60,000 SPH particles
- Thin disk so adiabatic gradient assumed in vertical direction, as if cooled by convection
- Surface T > 100 K means higher midplane T
- Artificial viscosity converts KE into heat in shock fronts and elsewhere ($\alpha = 0.002$ to 0.005)
- Cooling time ~ 10 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

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



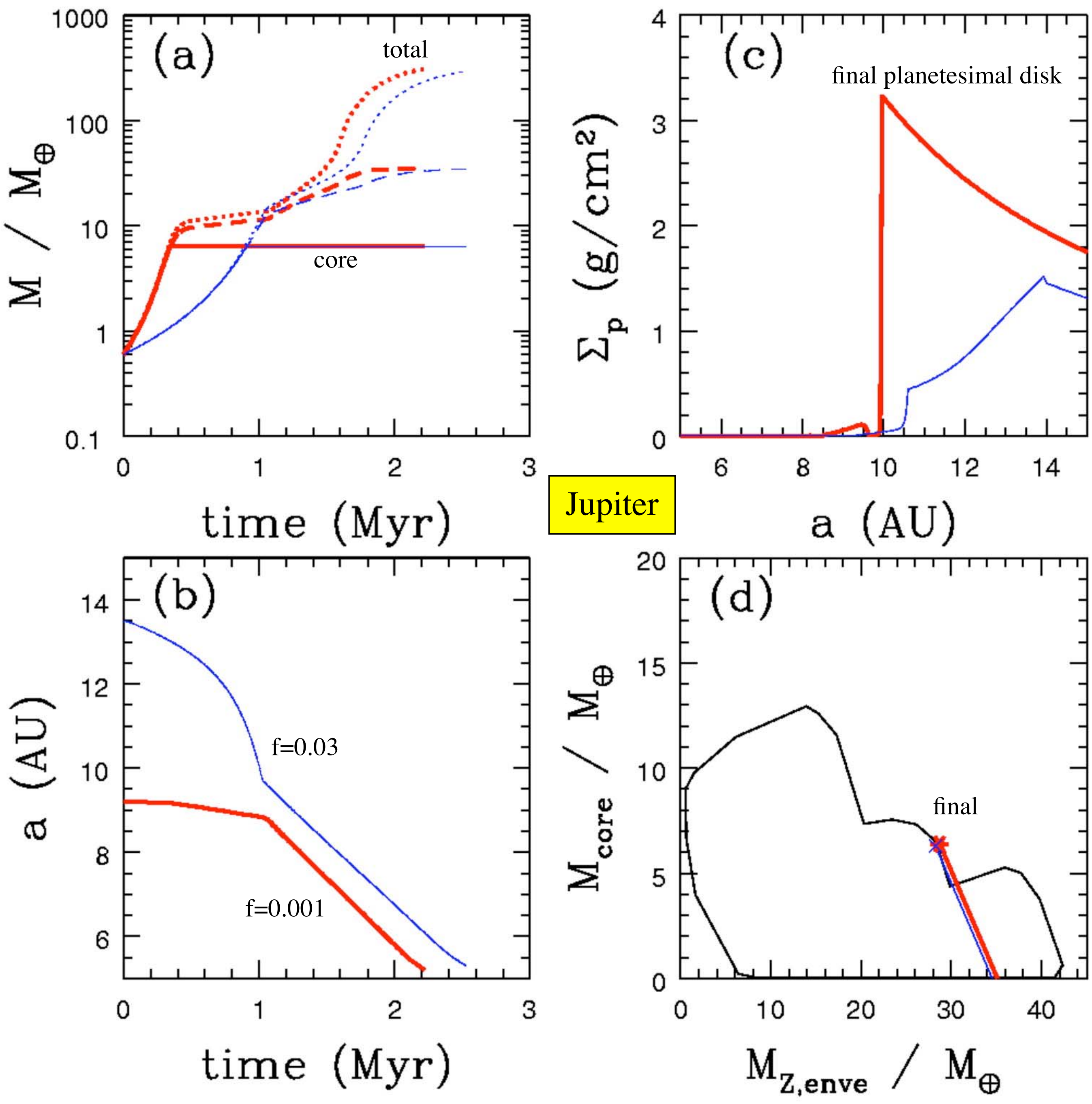
Saumon & Guillot 2004 core mass constraints based on EOS



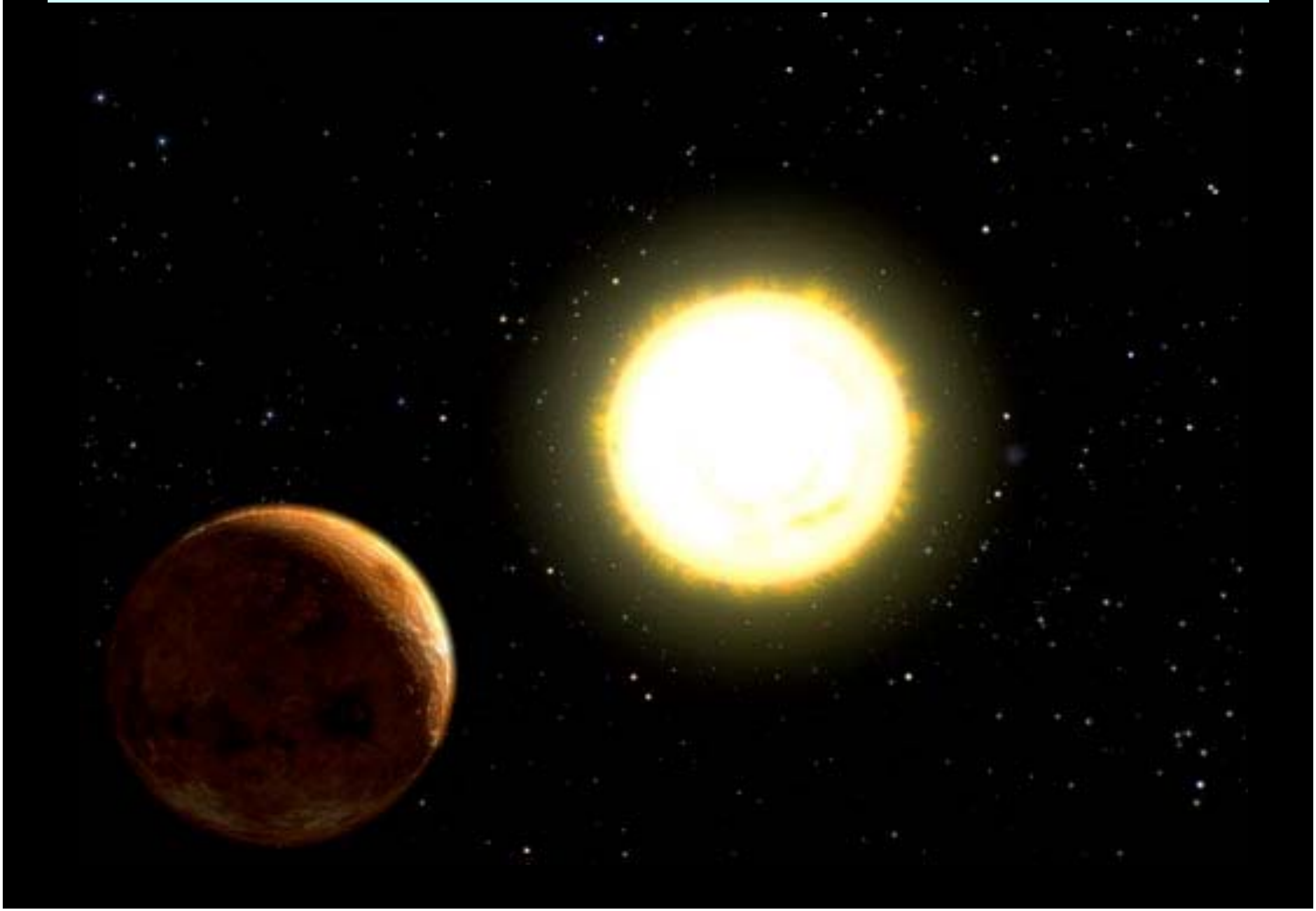
# Constraints from the Solar System's Gas Giant Planets

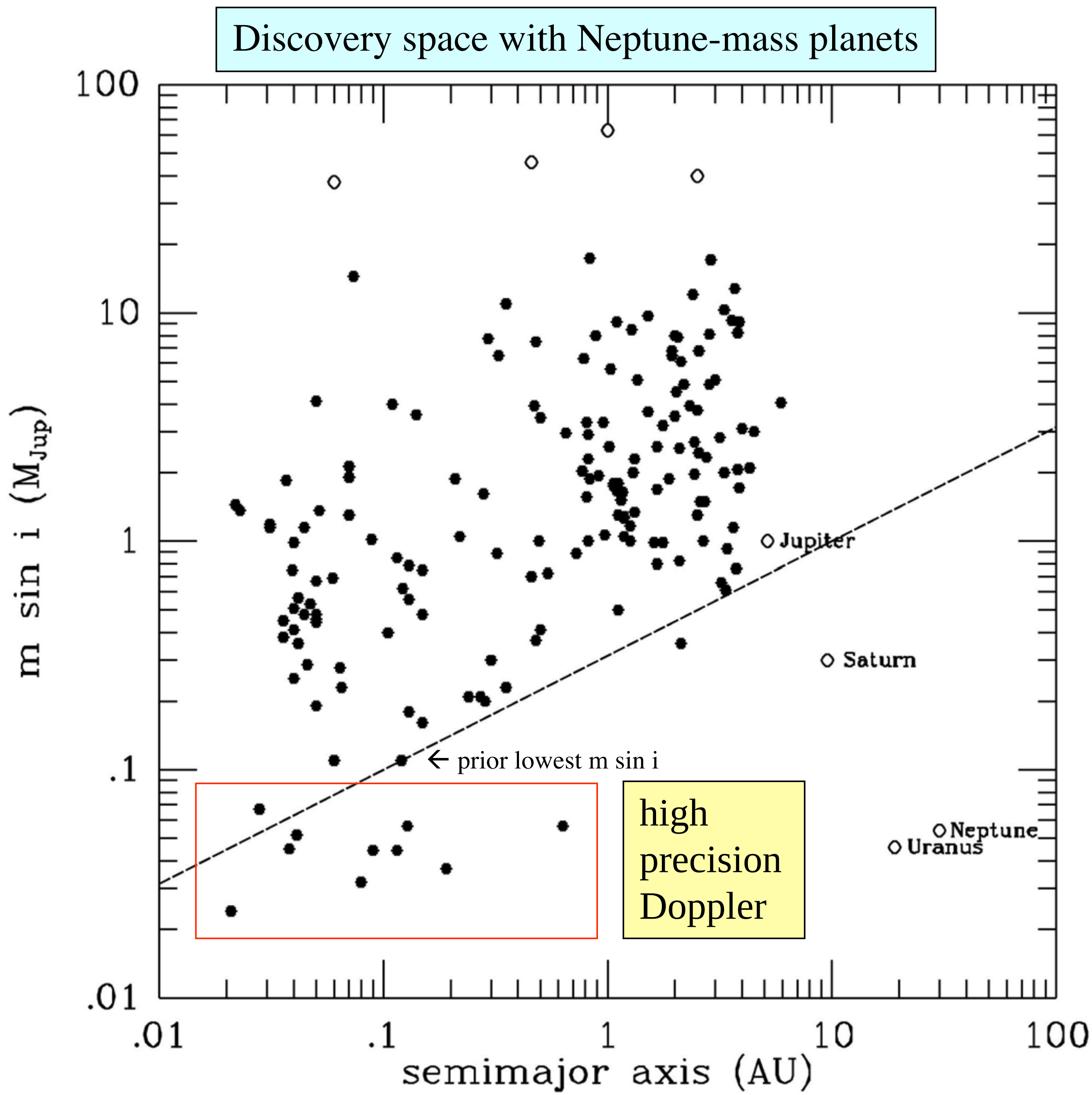
* Jupiter's core mass is 3 Earth masses or less, too small to initiate dynamic gas accretion (erosion?)
* Saturn's core mass is about 10 to 20 Earth masses, sufficient to initiate dynamic gas accretion
* Envelopes of both planets contain substantial amounts of heavy elements
* Envelope enrichments presumably arose from ingestion of planetesimals/cometesimals during and shortly after the planets formed (multiple Comet S/L 9 impacts) [Helled et al. 2006]
* Saturn's core is more massive than Jupiter's, yet it did not erode or become the more massive planet

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



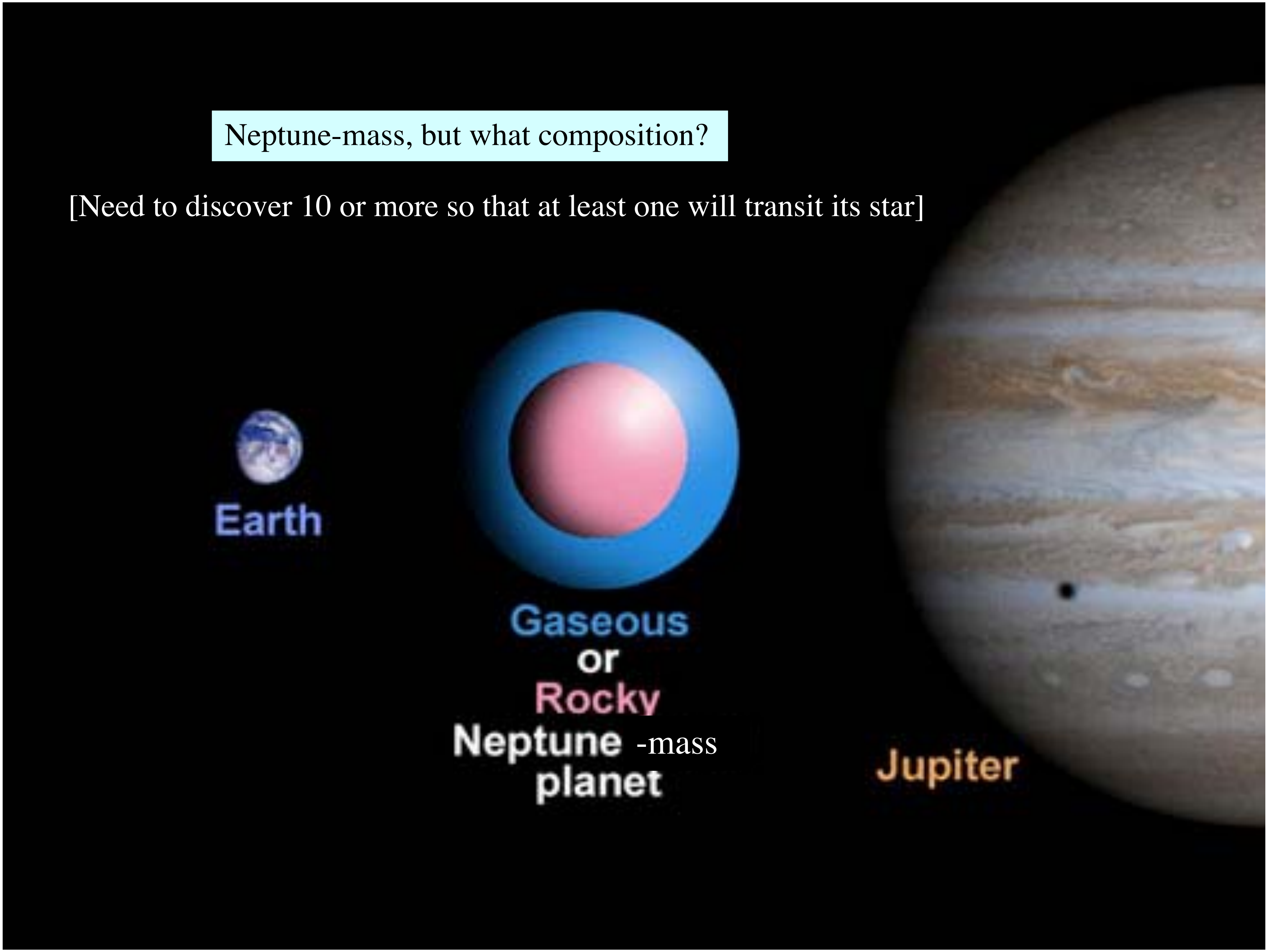
55 Cancri's fourth planet with a minimum mass of 14 Earth masses (McArthur et al. 2004)



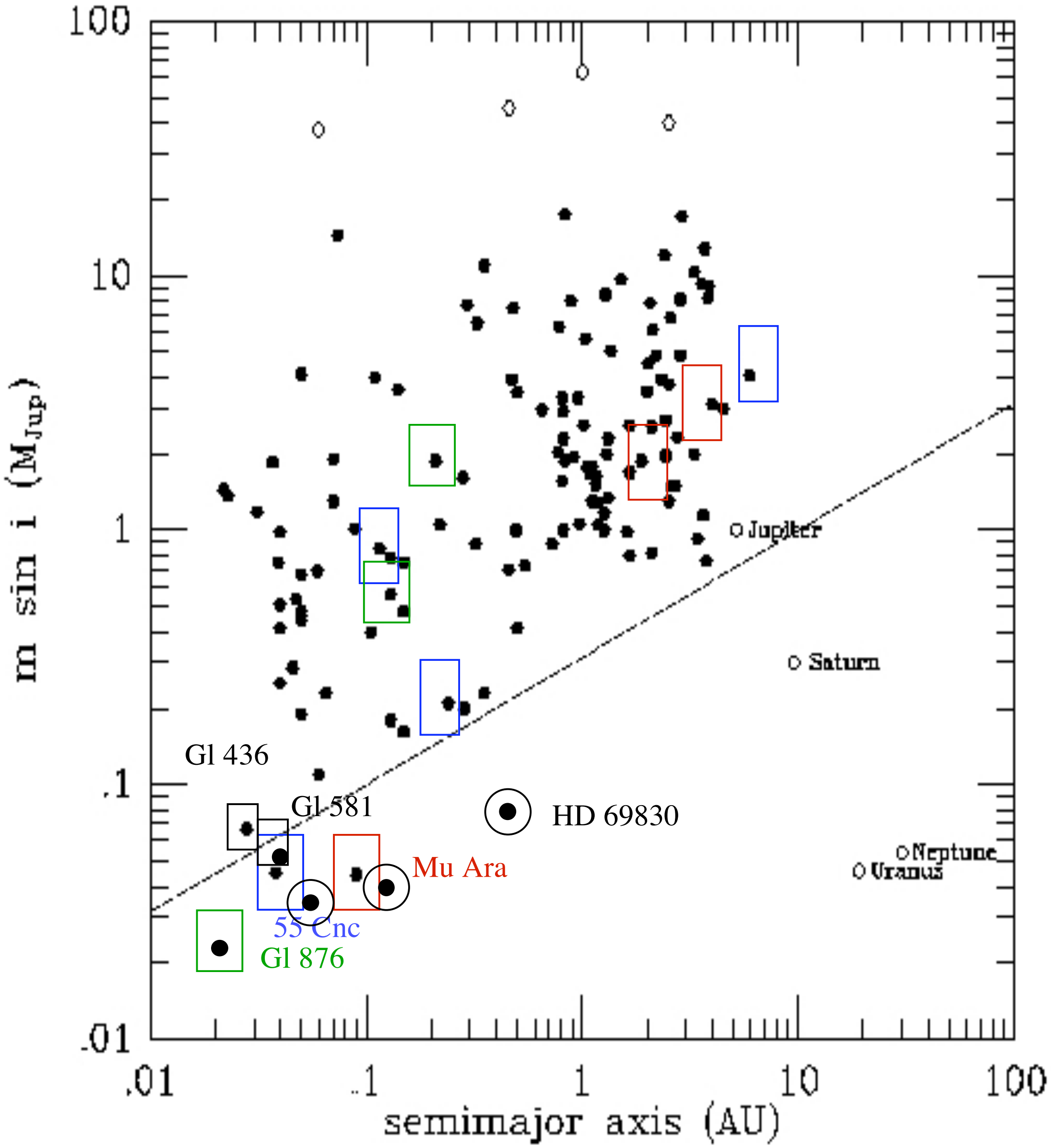

Discovery space with Neptune-mass planets
100
10
1
.1
.01
m sin i ($M_{Jup}$)
.01
.1
1
10
100
semimajor axis (AU)
Jupiter
Saturn
Neptune
Uranus
prior lowest m sin i
high precision Doppler

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 Doppler 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)

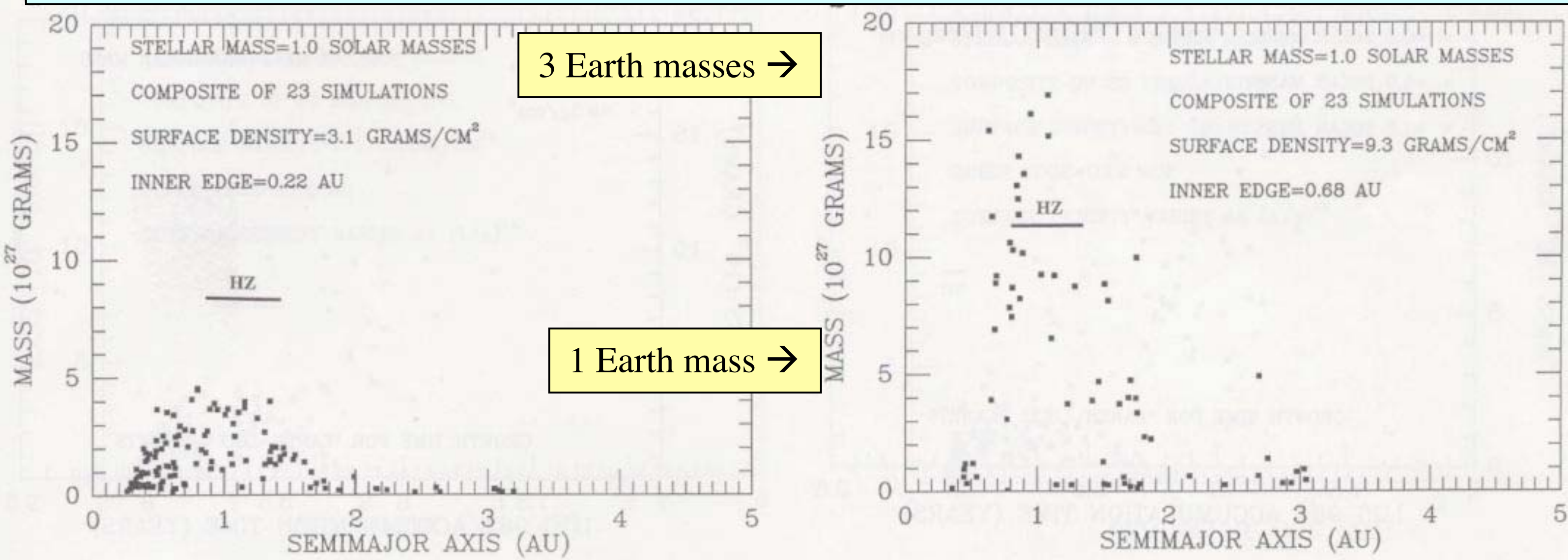


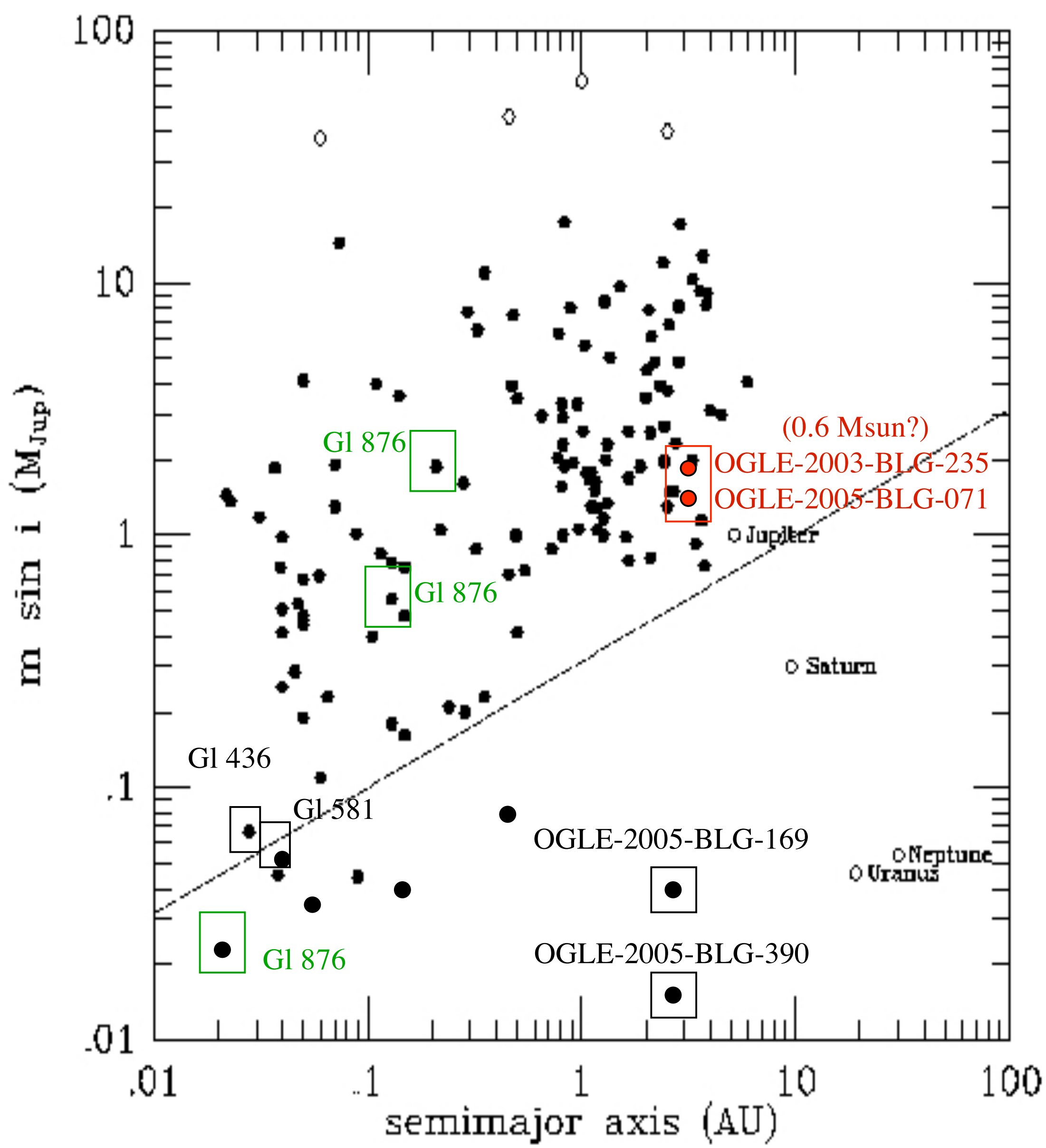

FIG. 4. Effect of varying surface density with constant stellar mass. The positions of the final planets remain similar. Their mass is dependent on the surface density, particularly for lower surface densities. The nominal case is again Fig. 1a. (a) Stellar mass, 1.0 $M_{\odot}$. Surface density half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

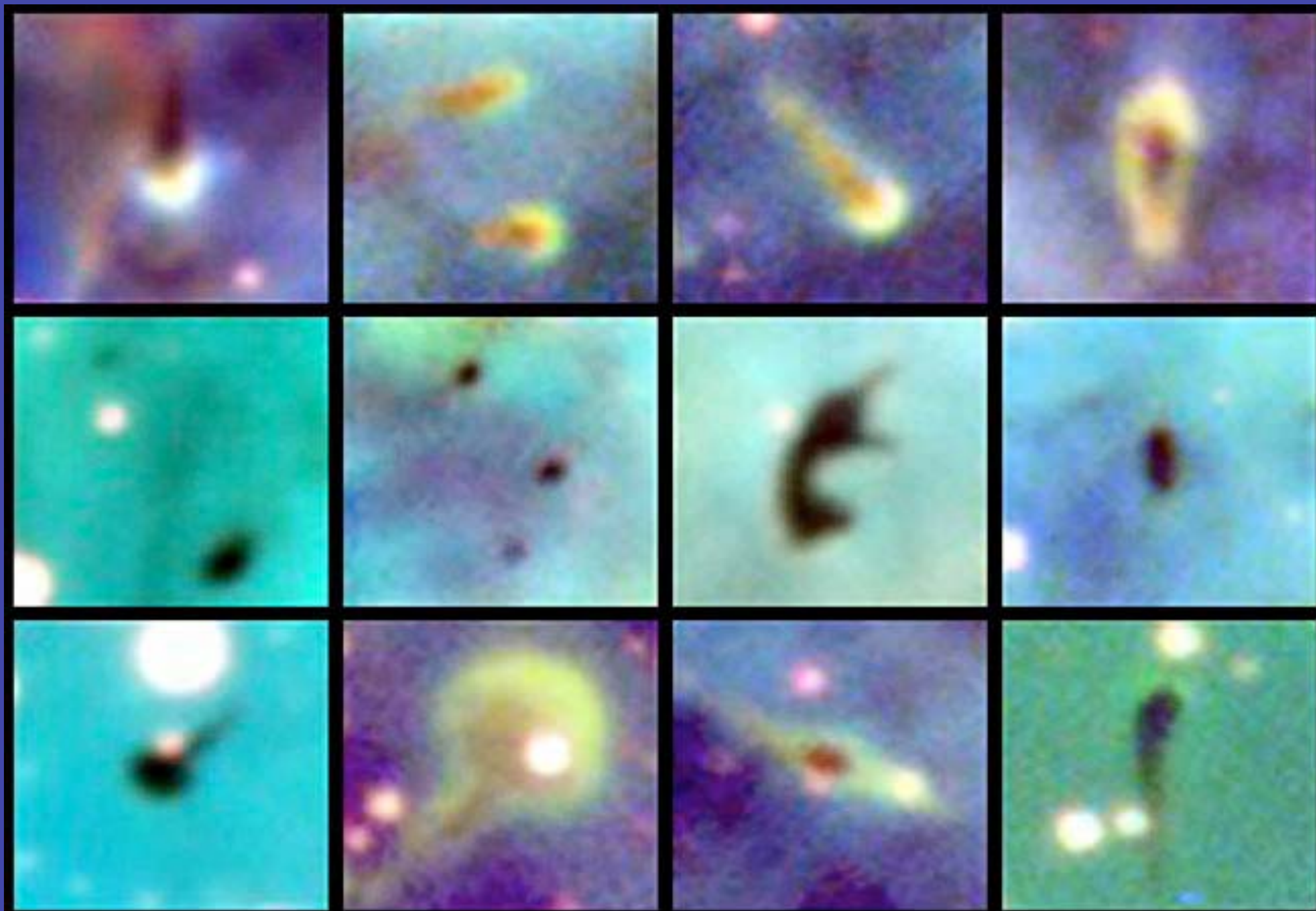
Since mass of the terrestrial planets is roughly proportional to the surface density of solids, raising the solid surface density by a factor of about 7 should result in the formation of rocky planets with masses as high as about 21 Earth masses

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 $a^{-3/2}$*

# Discovery space with planets around M dwarf stars highlighted





# Heretical Explanation for Microlensing Planets

- Most stars form in regions of high-mass star formation (e.g., Orion, Carina) where their protoplanetary disks can be photoevaporated away by nearby O stars.
- Photoevaporation converts gas giant protoplanets into ice giants if the protoplanet orbits outside a critical radius, which depends on the mass of the host star.
- For solar-mass stars, the critical radius is > 5 AU, while for a 0.3 $M_{Sun}$ M dwarf star, the critical radius is > 1.5 AU.
- If M dwarfs have disks massive enough to undergo disk instability, then their gas giant protoplanets orbiting outside ~1.5 AU will be photoevaporated down to super-Earth mass, for M dwarfs in regions of high-mass star formation.
- In low-mass star formation regions (e.g., Taurus), their gas giant protoplanets will survive to become gas giant planets.

# 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 to make ice giants, so works in Taurus
- HD 149026: 70 Earth-mass core plus 40 Earth-mass gaseous envelope? Formed by collision between two giant planets (Ikoma et al. 2006)?

- **Con:**
- Jupiter's core mass is too small
- Higher metallicity makes even larger mass cores
- Saturn should be largest planet
- 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?)
- 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:**
- Can 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?) and efficiently even in short-lived disks
- Works for M dwarf primaries
- Sidesteps Type I (and III) orbital migration danger
- Works in Taurus or Orion, implying Solar System analogues are common
- Efficient giant planet formation

- **Con:**
- Requires efficient cooling of midplane (e.g., convection), coupled with efficient cooling from the surface of the disk: subject of work in progress
- Clump survival uncertain: need for models with detailed disk thermodynamics and higher spatial resolution (e.g., 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 dwarfs (Geneva, California/Carnegie, Texas groups)
- RV and astrometric searches for long period Jupiters around M, L, T dwarfs (HET/Texas, JPL & Carnegie groups)
- RV searches for long period Jupiters around low metallicity dwarfs (CfA group) and K giants (Texas group)
- 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 (GMT, SIM, TPF-C, TPF-I/Darwin)
- Jupiter/Saturn core masses (Juno mission to Jupiter)