Formation of Giant Planets

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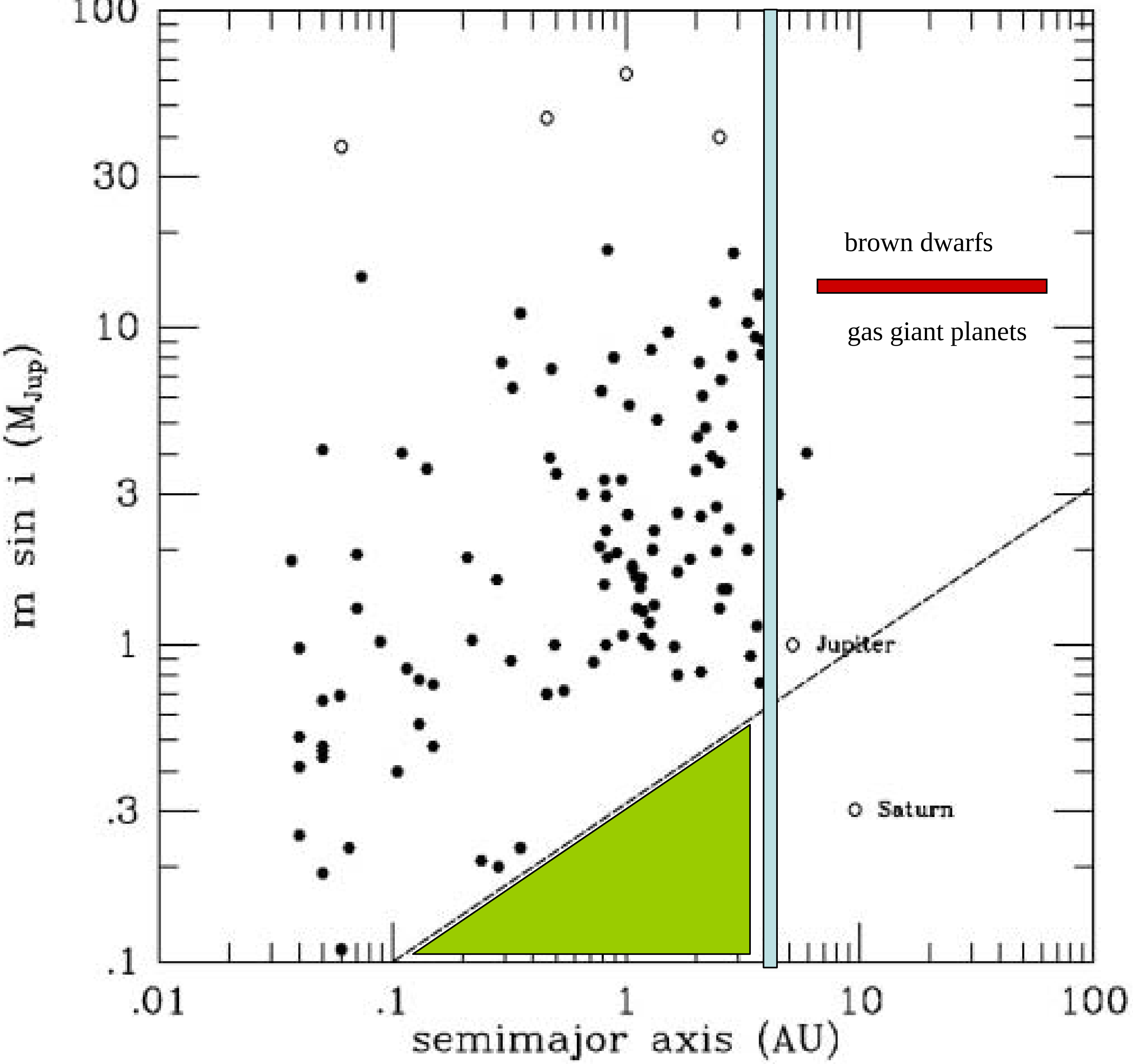
Outline:

- Conventional scenario for Solar System formation:
  - region of low mass star formation (Taurus)
  - collisional accumulation of terrestrial planets
  - formation of giant planets by core accretion
- Heretical scenario for Solar System formation:
  - region of high 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: pros and cons for both mechanisms

Extrasolar Planet Discovery Space



brown dwarfs

gas giant planets

Extrasolar Gas Giant Planet Census: Frequency

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

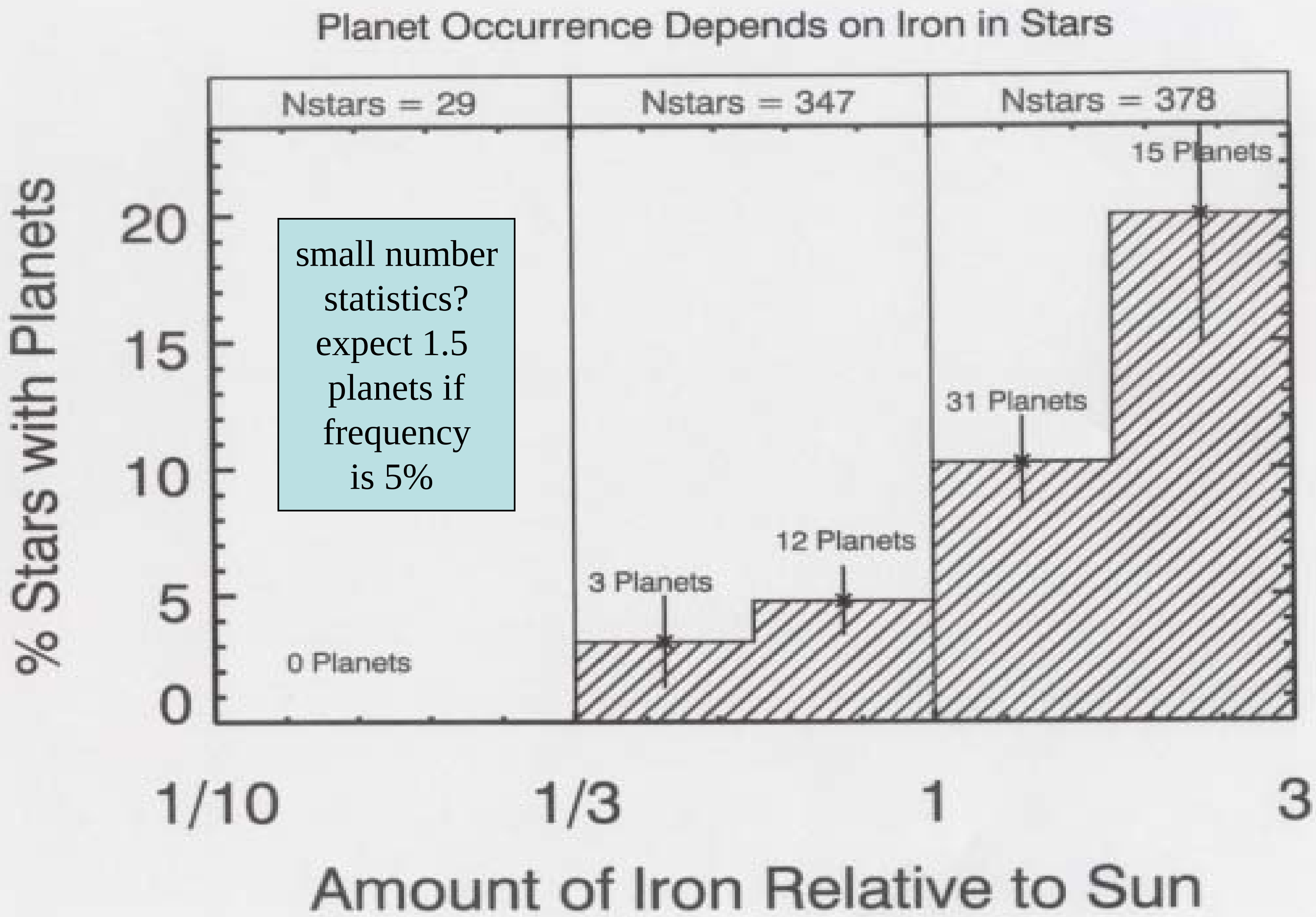
* Approximately 15% of nearby G-type stars have gas giant planets with short orbital periods – hot and warm Jupiters

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

* 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

Fischer et al. 2004 (planets with periods < 3 yrs)



small number statistics? expect 1.5 planets if frequency is 5%

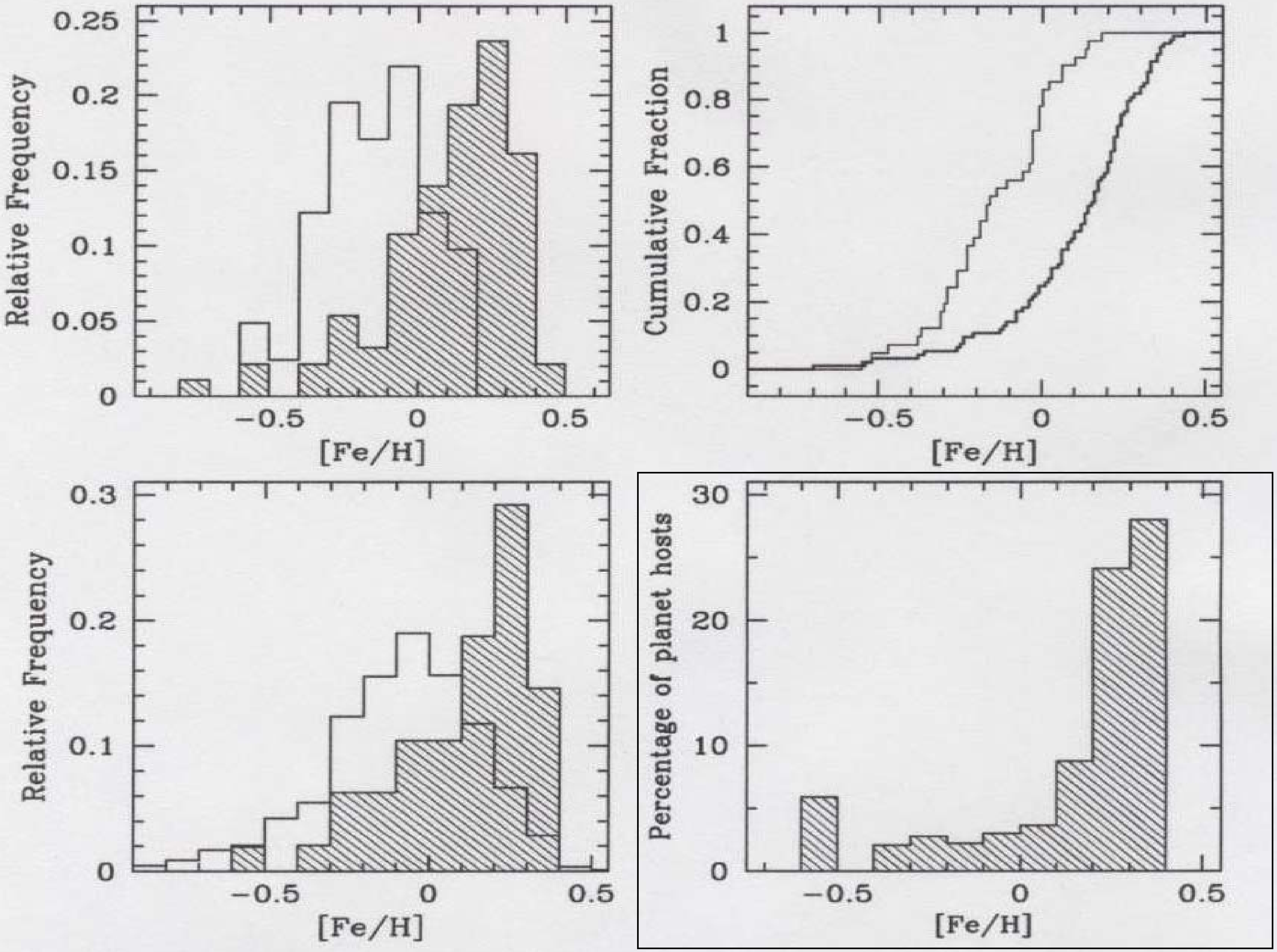
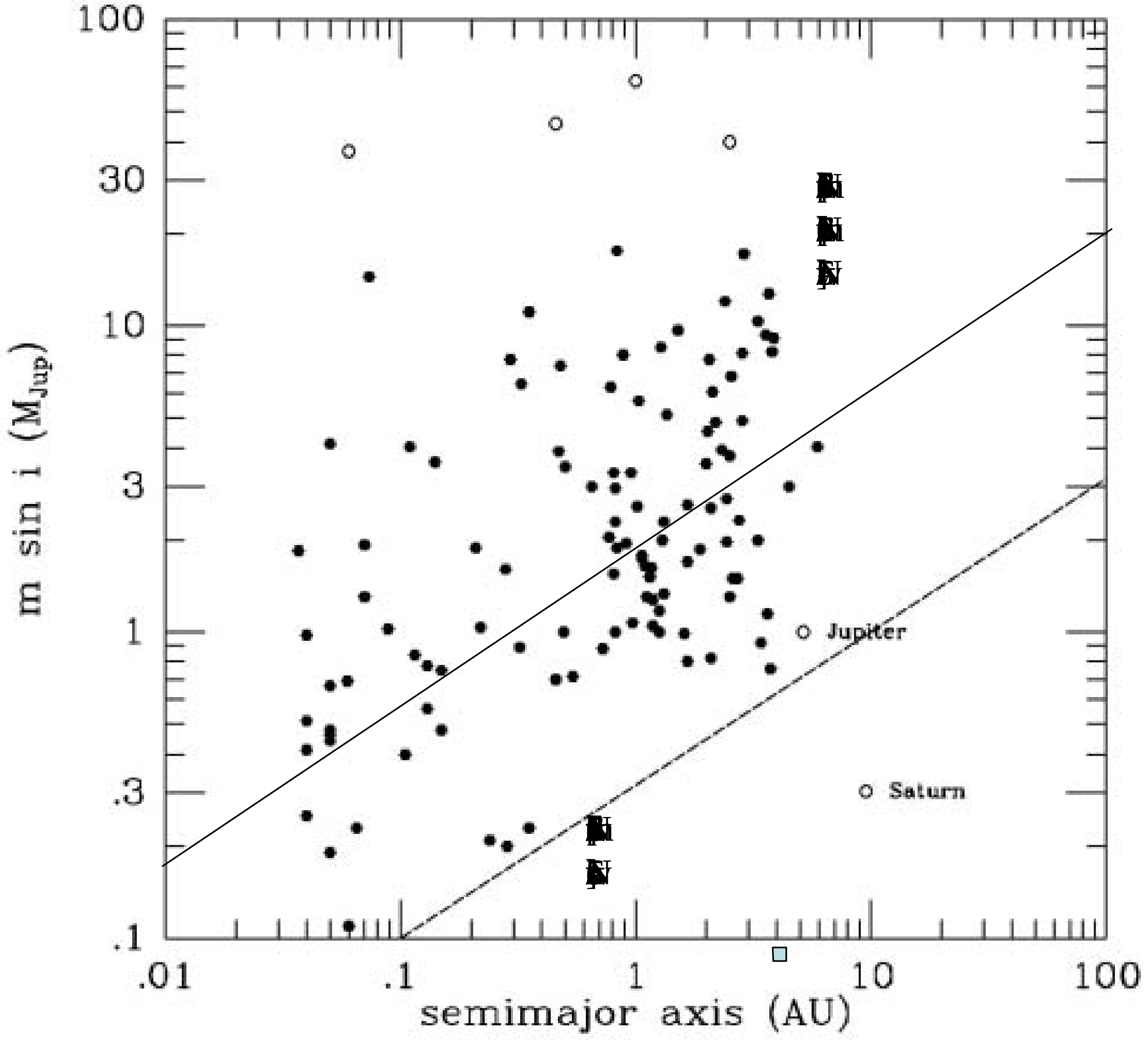


Fig. 6. *Upper panels*: [Fe/H] distributions for planet host stars (hashed histogram) and for our volume-limited comparison sample of stars (open bars). The average difference between the [Fe/H] of the two samples is of ~0.25 dex. A Kolgomorov-Smirnov test shows that the probability that the two samples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


100
30
10
3
1
.3
.1
.01
.1
1
10
100
m sin i (M_{Jup})
semimajor axis (AU)
Jupiter
Saturn

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

* Swiss group finds roughly flat distribution with strong peak at highest 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

* 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 l

ricity of greater than 0.1. HD

system and has been omitted from this plot.

Jones et al. 2004

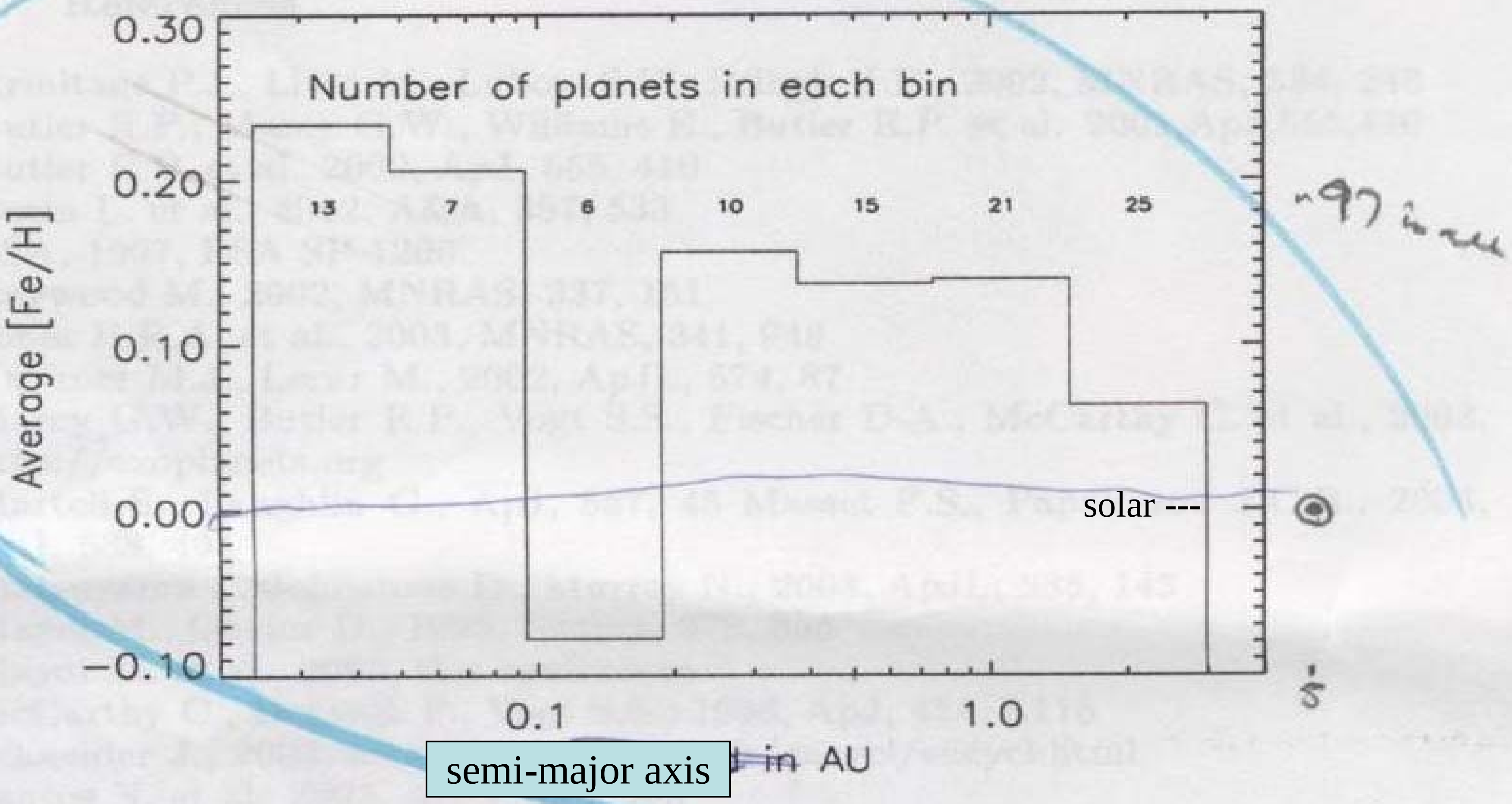


Figure 7. Average spectroscopic metallicities of the primaries of exo-planets plotted as a function of period. The overall featues of this distribution are similar whether plotted for spectroscopic or Stromgen metallicities (Haywood 2002; Martell & Laughlin 2002).

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])

Extrasolar Gas Giant Planet Census: Low-mass Host Stars

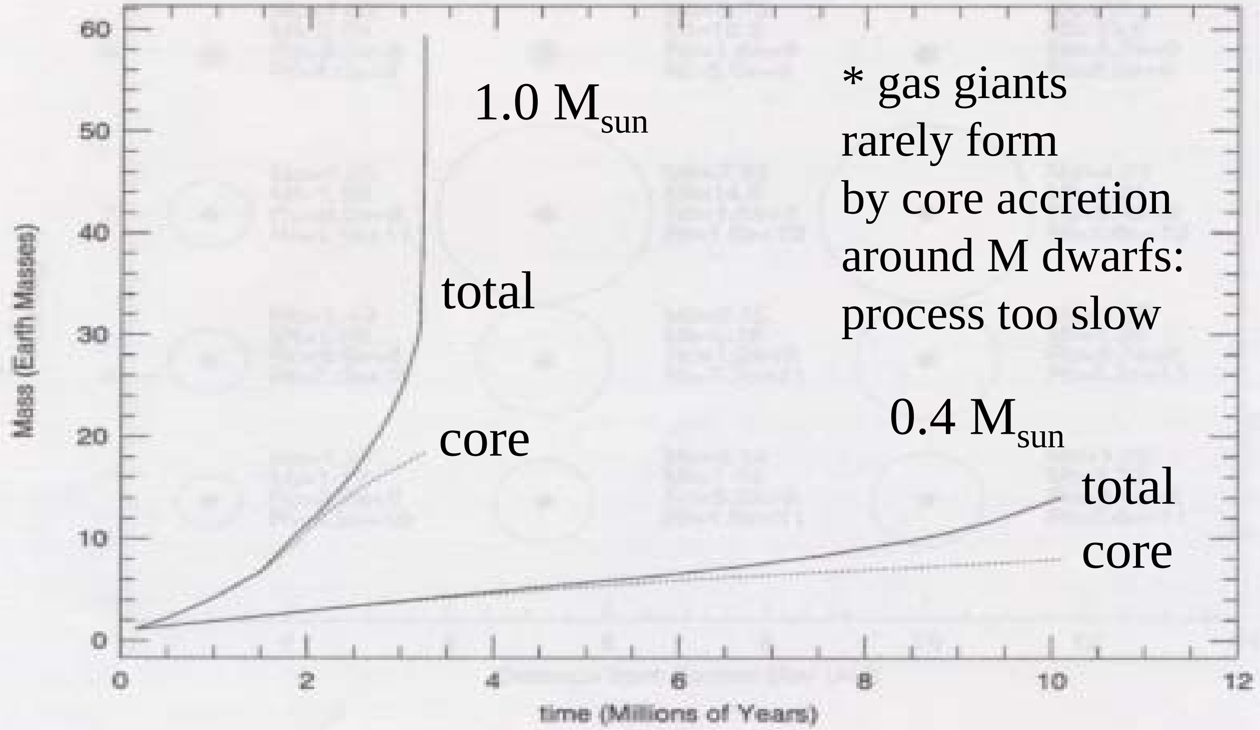
* Most planet-host stars are G-type stars – G-type stars have dominated the target lists

* M4 dwarf star GJ876 (0.32 M_{sun}) has two known gas giant planets

* 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 $M \approx 14M_\oplus$.

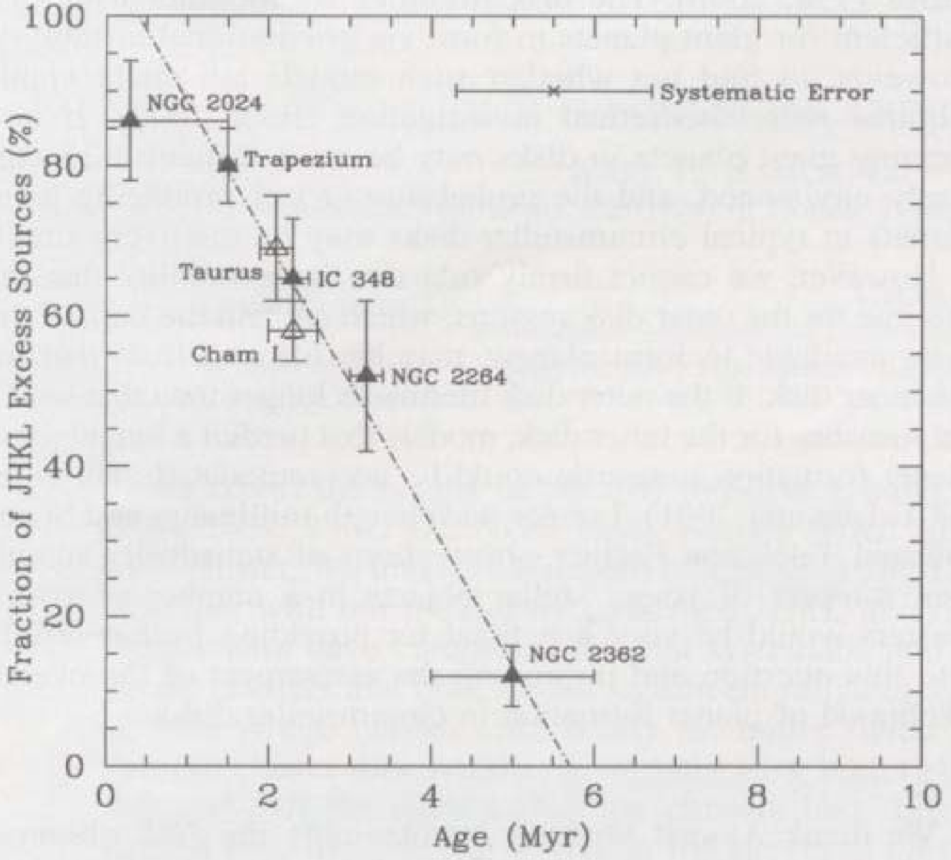


FIG. 1.—*JHKL* excess/disk fraction as a function of mean cluster age. Vertical error bars represent the statistical $\sqrt{N}$ errors in our derived excess/disk fractions. For all star-forming regions except NGC 2024 and NGC 2362, the horizontal error bars represent the error in the mean of the individual source ages derived from a single set of PMS tracks. The age error for NGC 2362 was adopted from the literature. Our estimate of the overall systematic uncertainty introduced in using different PMS tracks is plotted in the upper right corner and is adopted for NGC 2024. The decline in the disk fraction as a function of age suggests a disk lifetime of 6 Myr.

(0.3–30 Myr) to enable a meaning
scale for disk evolution within
characterized by a very high ini
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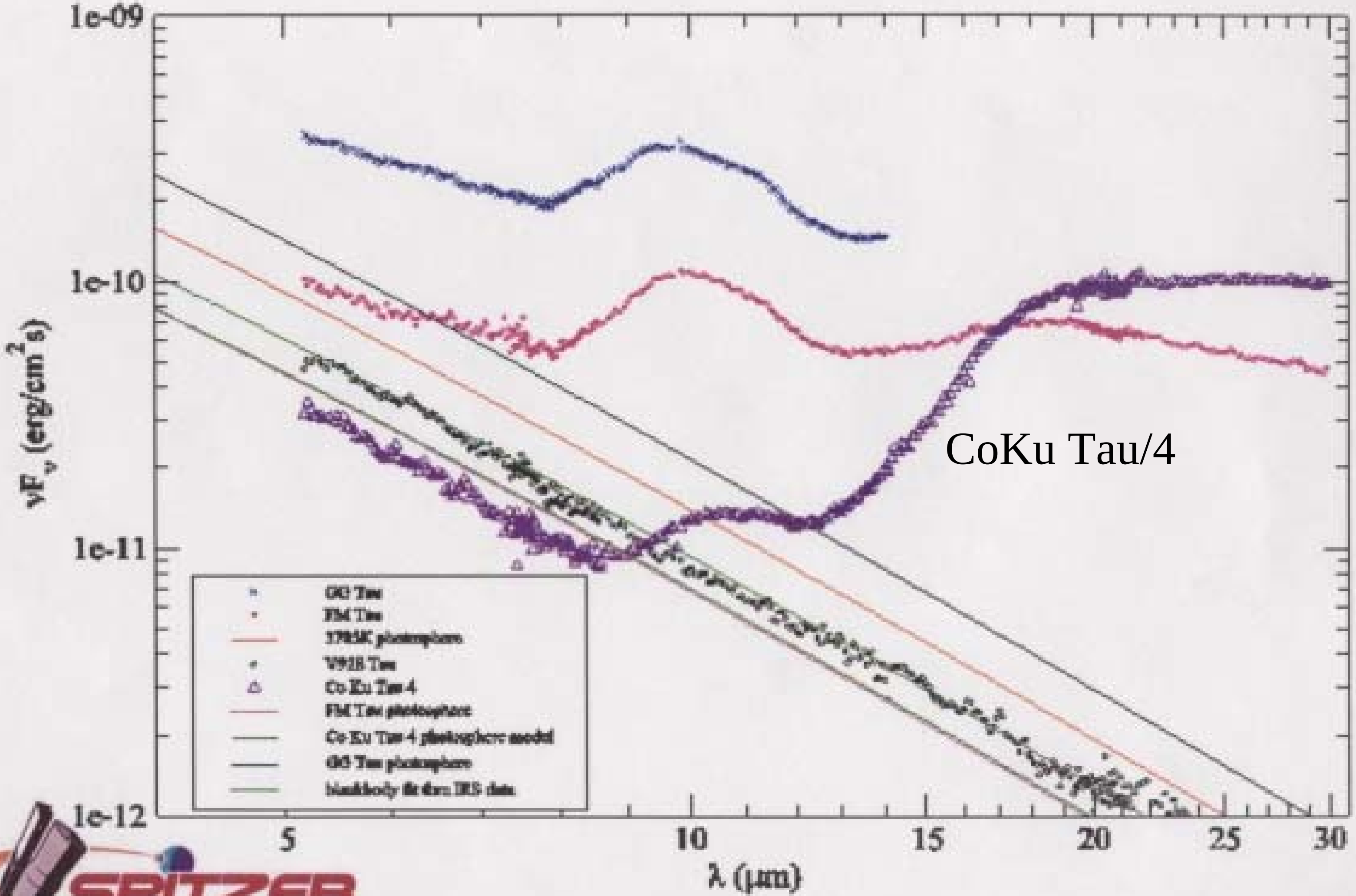
τ CMa. This star is a multiple sy
signment on the H-R diagram is sc
wen & van Genderen 1997). Corr
lead to a slightly older age. How
in its age likely reflects the magni
ona & Laney 1996). On the othe
errors were twice as large as quot
age between 3 and 7 Myr. The
overall disk lifetime derived from

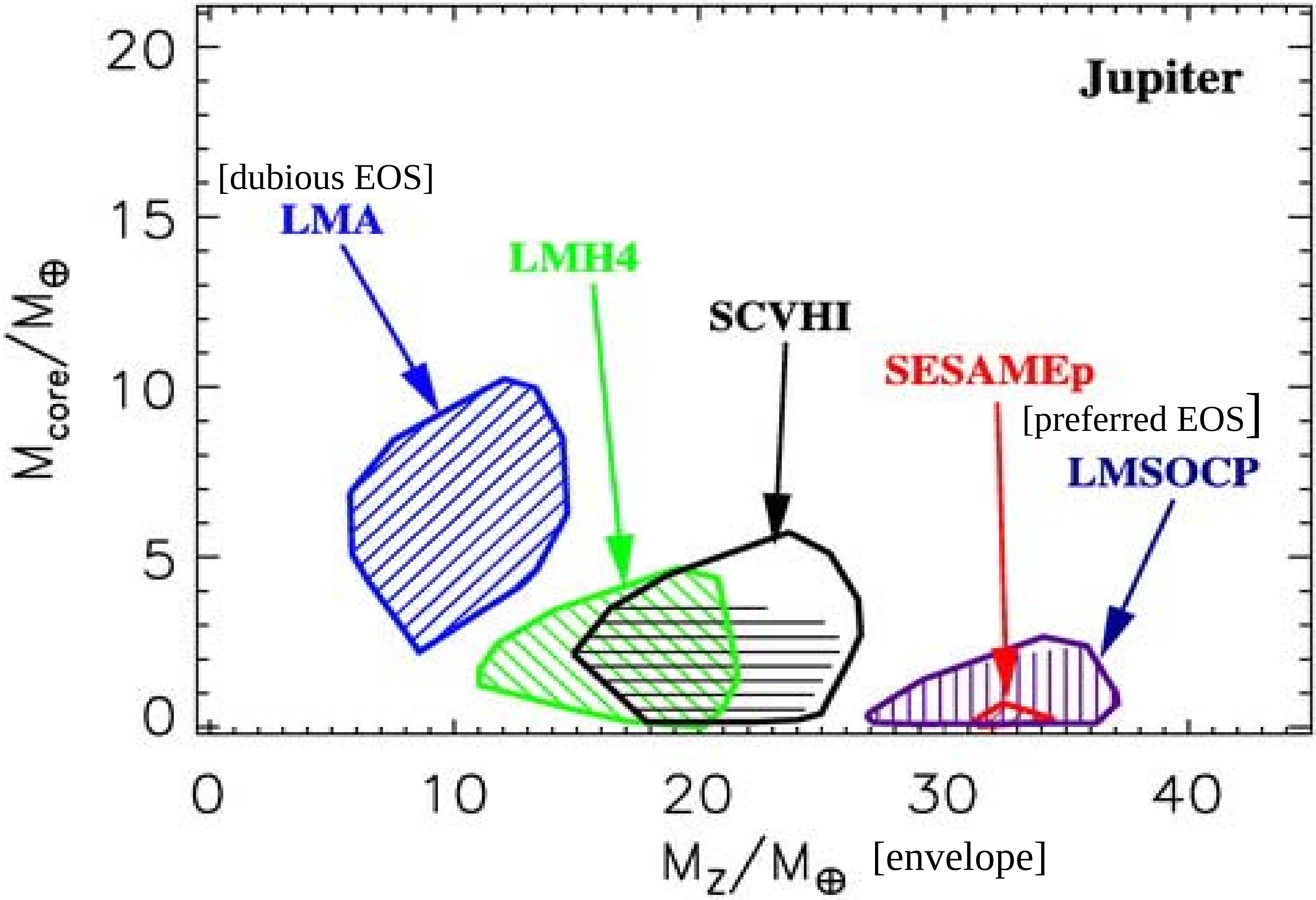
Typical disk lifetimes are three million years or less, though a fraction of disks persist for longer periods of time

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

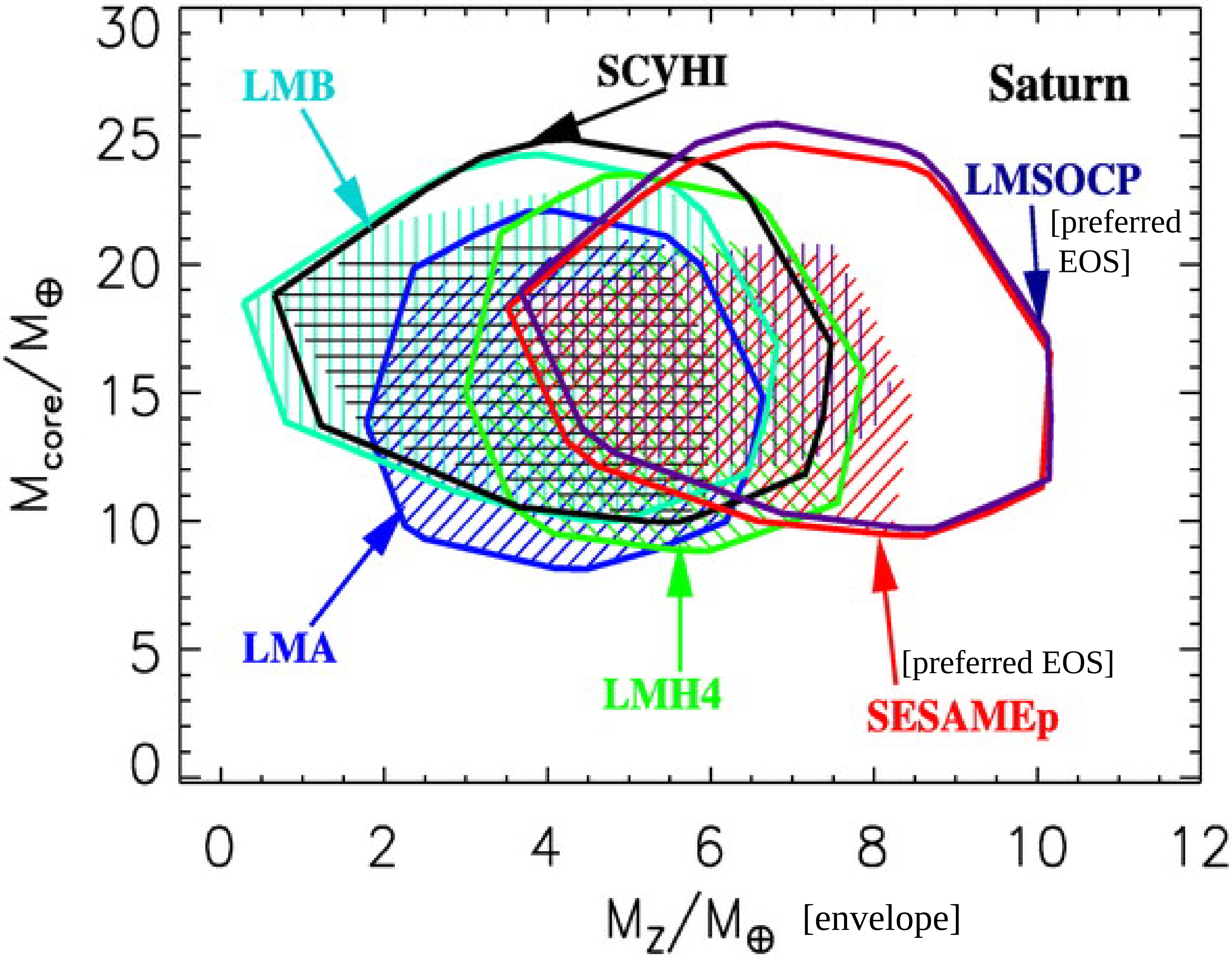


Planetary formation within 1 Myr of star formation? *Spitzer*-IRS spectrum of CoKu Tau/4 – with a disk void of dust for 11 AU around the star – compared to that of 1 Myr-old stars with full disks (FM Tau) and no disk at all (V928 Tau).

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?)

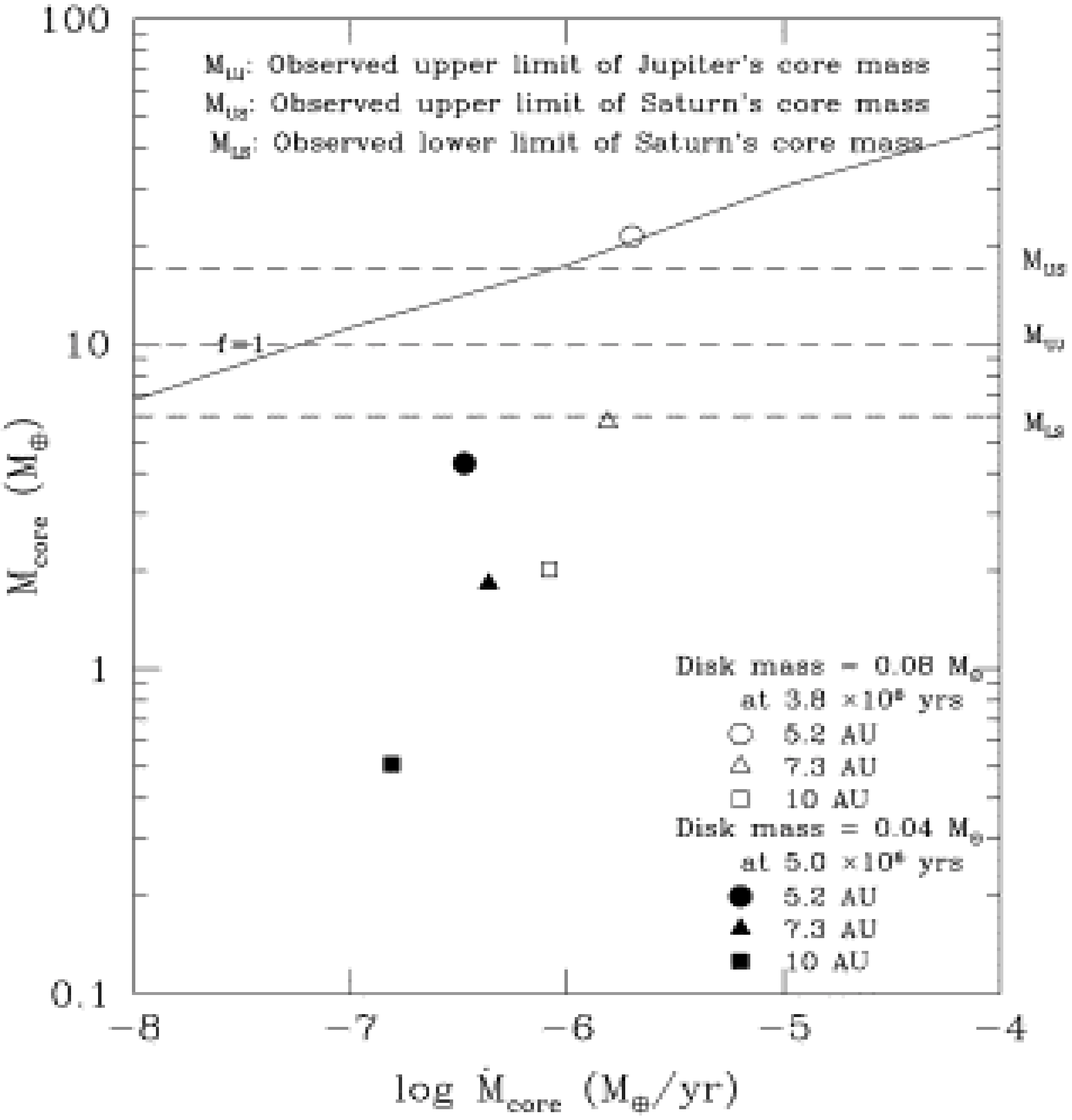
* Saturn's core mass is about 10 to 20 Earth masses, sufficient to initiate dynamic gas accretion

* 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)

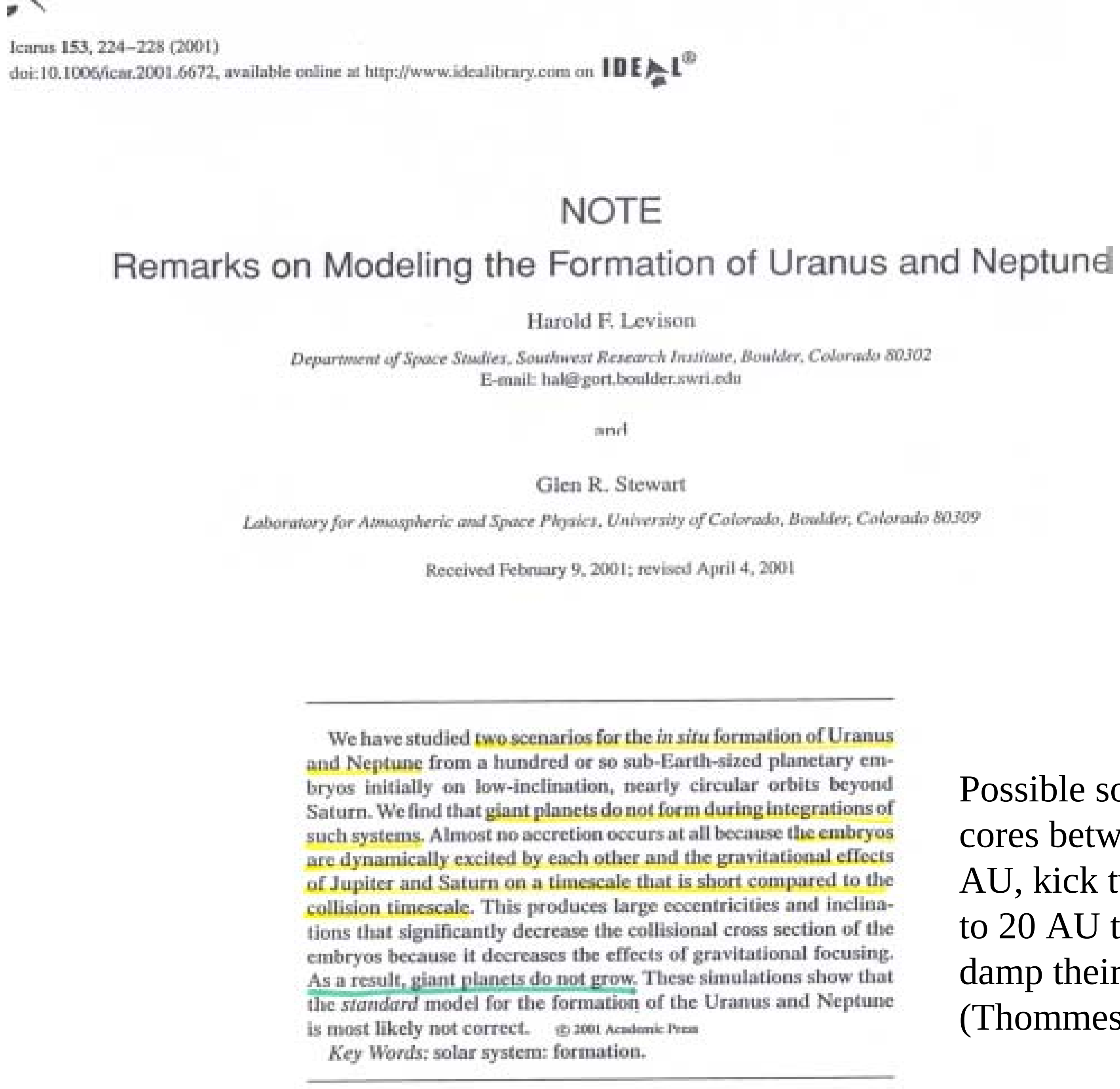
* If Saturn's core is more massive than Jupiter's, why did it not become the more massive planet?

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



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NOTE

Remarks on Modeling the Formation of Uranus and Neptune

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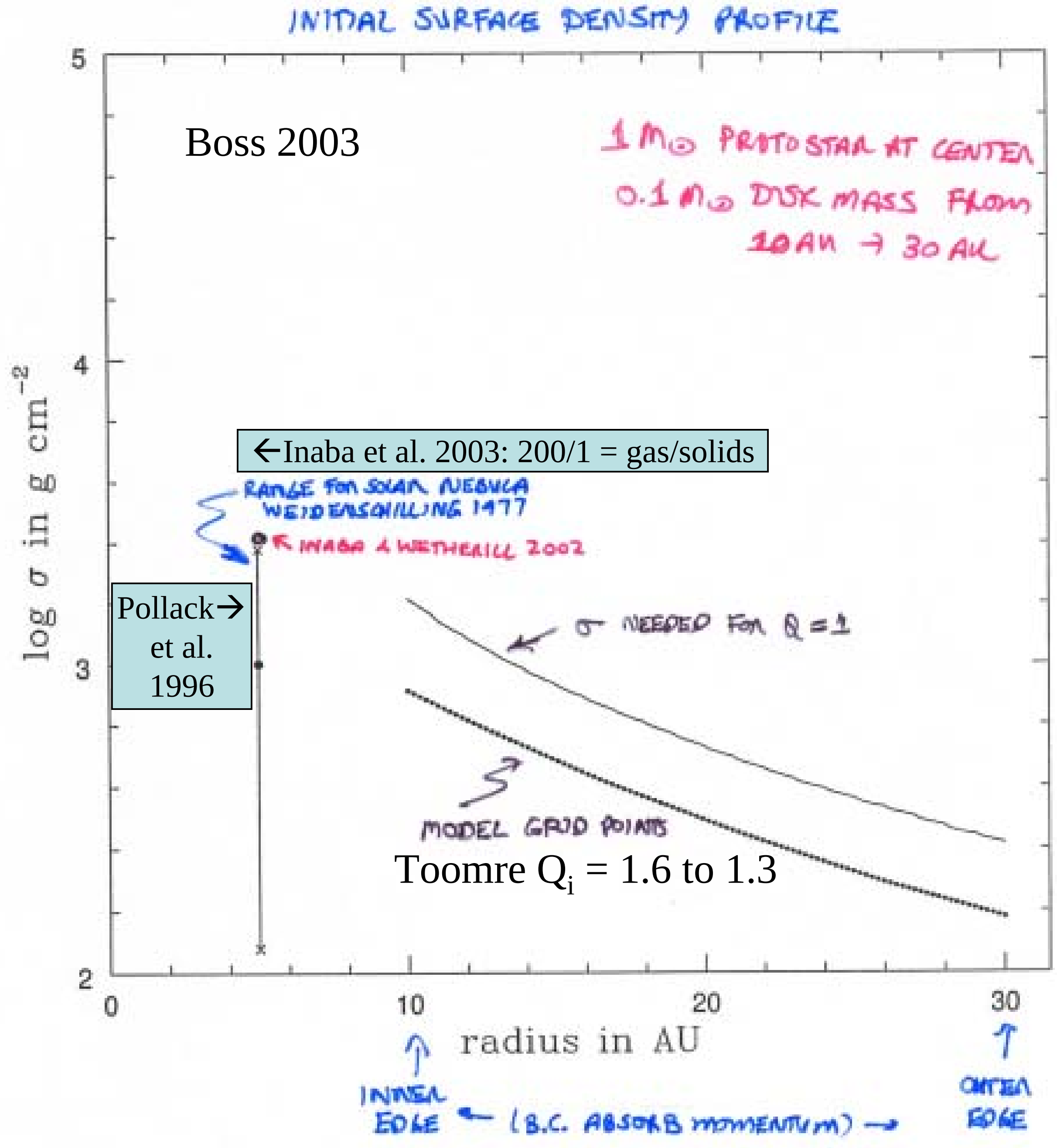
We have studied two scenarios for the *in situ* formation of Uranus and Neptune from a hundred or so sub-Earth-sized planetary embryos initially on low-inclination, nearly circular orbits beyond Saturn. We find that giant planets do not form during integrations of such systems. Almost no accretion occurs at all because the embryos are dynamically excited by each other and the gravitational effects of Jupiter and Saturn on a timescale that is short compared to the collision timescale. This produces large eccentricities and inclinations that significantly decrease the collisional cross section of the embryos because it decreases the effects of gravitational focusing. As a result, giant planets do not grow. These simulations show that the *standard* model for the formation of the Uranus and Neptune is most likely not correct. © 2001 Academic Press

Key Words: solar system: formation.

Possible solution: form four cores between 5 AU and 10 AU, kick two of them out to 20 AU to 30 AU and then damp their eccentricities (Thommes et al. 2002)



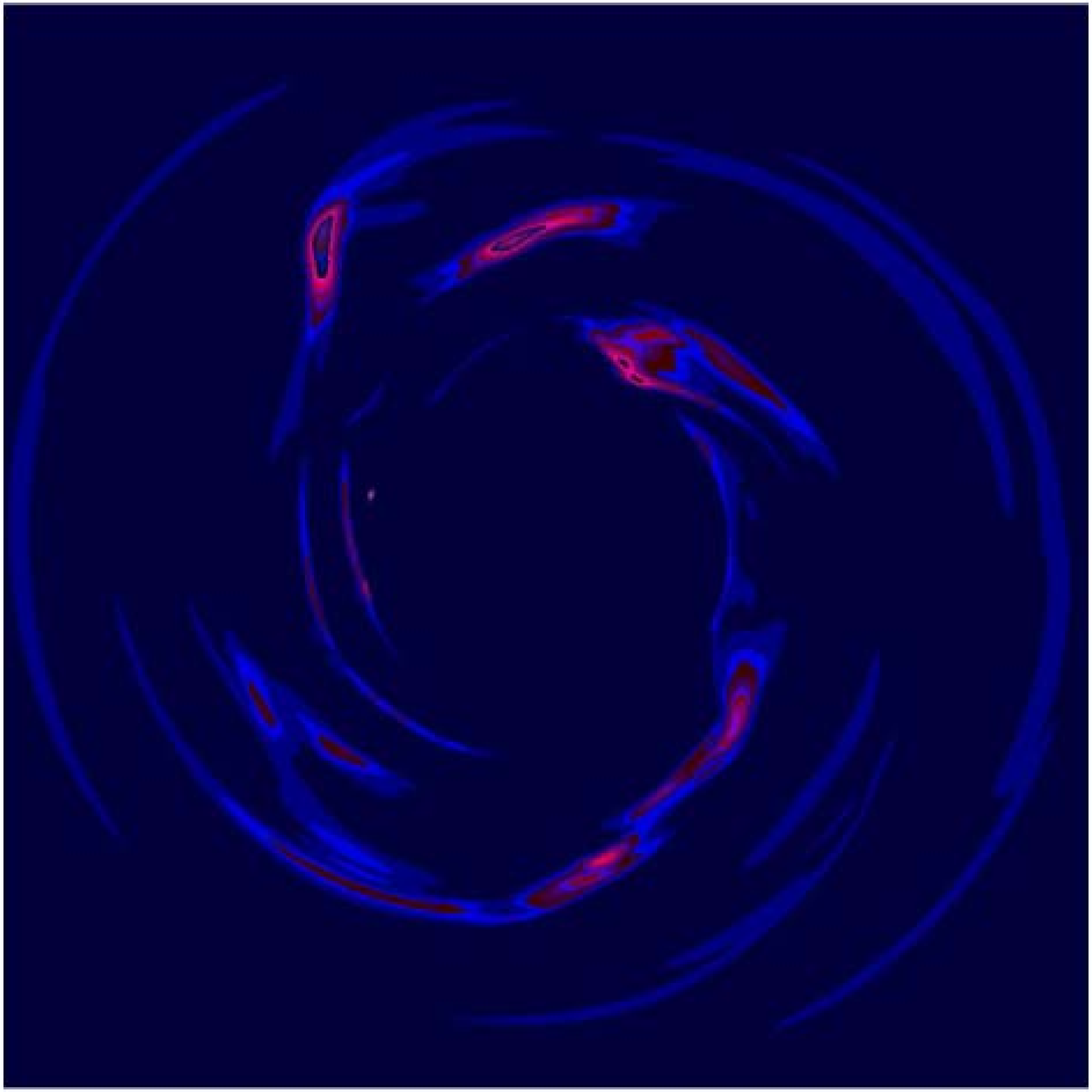
Boss 2003

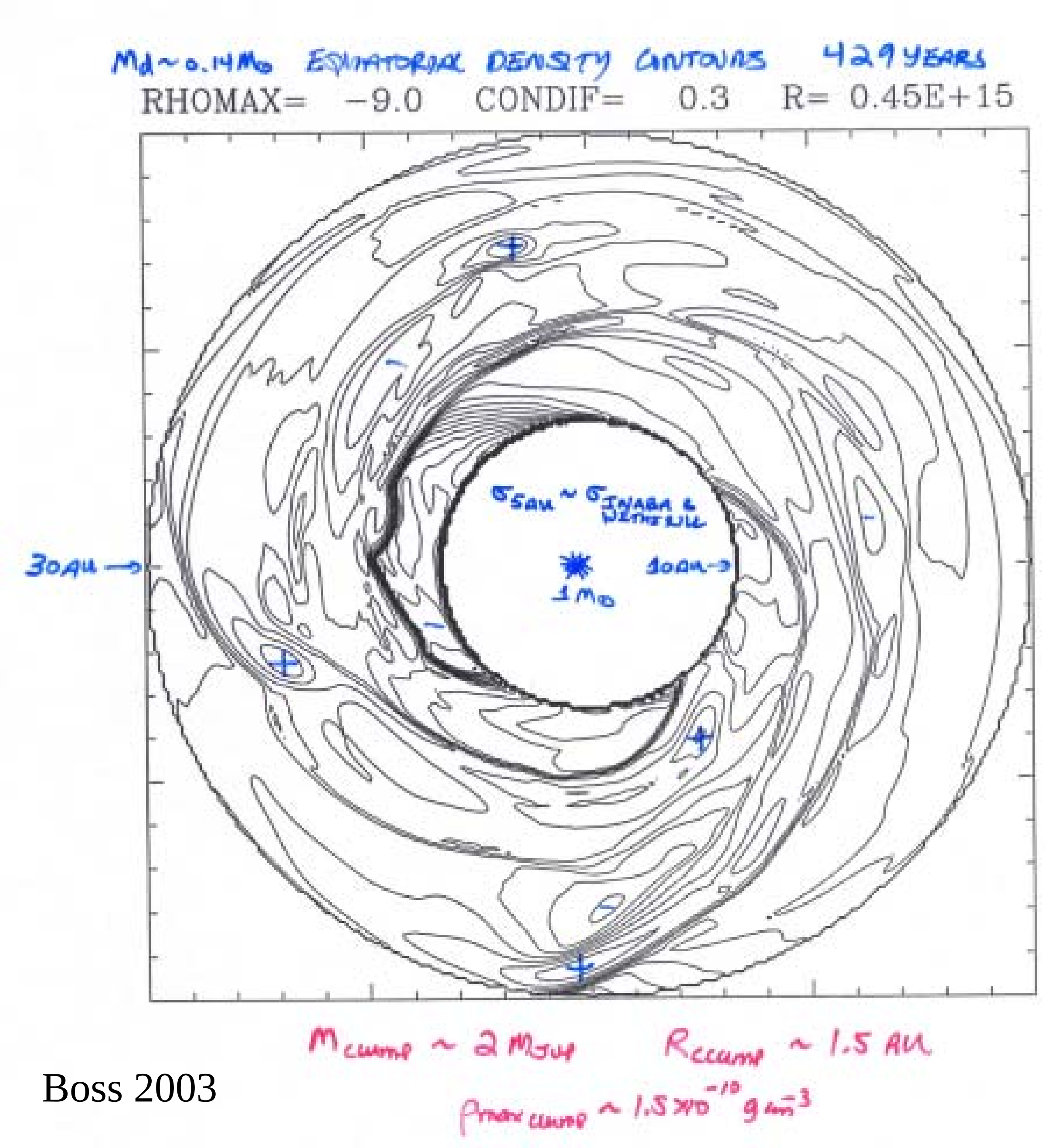
←Inaba et al. 2003: 200/1 = gas/solids

Pollack→
et al.
1996

Toomre Q_i = 1.6 to 1.3

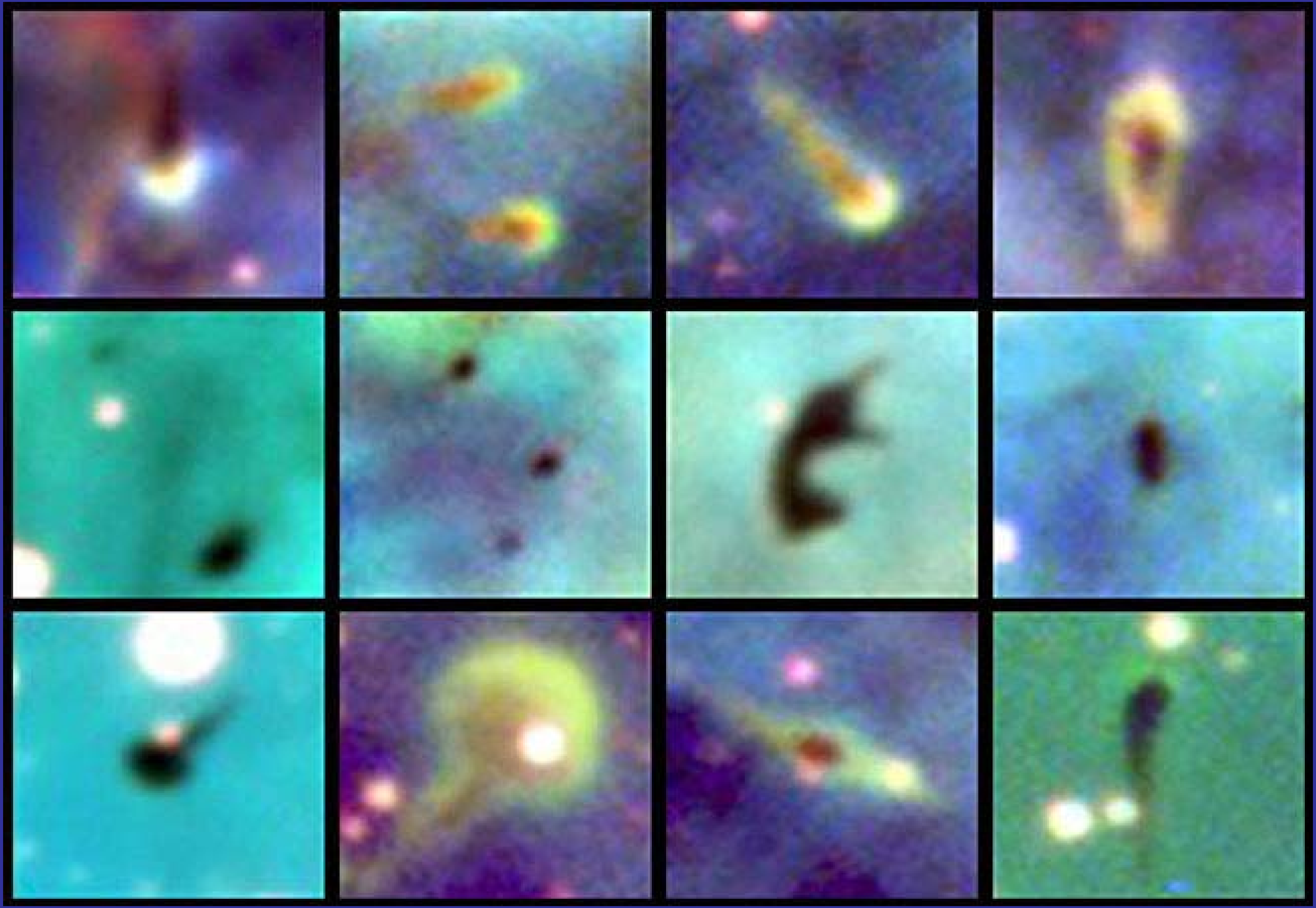
Boss 2003 disk instability model after 429 yrs, 30 AU radius





$M_d \sim 0.14 M_\odot$ EQUATORIAL DENSITY CONTOURS 429 YEARS
RHOMAX= −9.0 CONDIF= 0.3 R= 0.45E+15
$\sigma_{5AU} \sim \sigma_{Inaba\ \&\ Wetherill}$
30AU →
10AU →
$1 M_\odot$
+
−
$M_{clump} \sim 2 M_{Jup}$
$R_{clump} \sim 1.5$ AU
$\rho_{max\ clump} \sim 1.5 \times 10^{-10}$ g cm^{-3}

Boss 2003



A new paradigm for forming the giant planets rapidly:

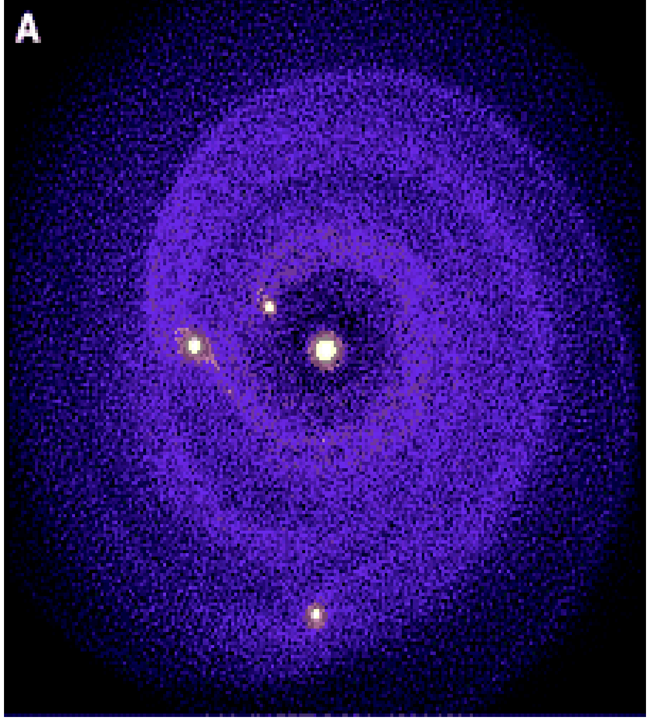
- Marginally gravitationally-unstable protoplanetary disk forms four or more giant gaseous protoplanets within about 1000 years, each with masses of about 1 to 3 Jupiter-masses
- Dust grains coagulate and sediment to centers of the protoplanets, forming solid cores on similar time scale, with core masses of no more than about 6 Earth-masses per Jupiter-mass of gas and dust ($Z=0.02$)
- Disk gas beyond Saturn’s orbit is removed in a million years by ultraviolet radiation from a nearby massive star (Orion, Carina, ...)

Continued…

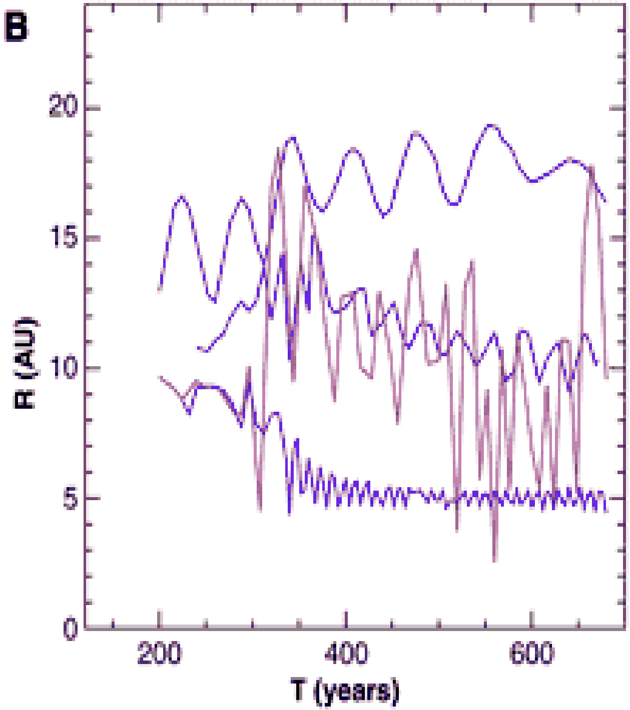
- Outermost protoplanets are exposed to FUV/EUV radiation, which photoevaporates most of their envelope gas in about a million years or less
- Outermost planets' gas removal leads to roughly 15-Earth-mass solid cores with thin gas envelopes: Uranus, Neptune
- Innermost protoplanet is sheltered by disk H gas gravitationally bound to solar-mass protosun and so does not lose any gas: Jupiter
- Protoplanet at transitional gas-loss radius loses only a portion of its gas envelope: Saturn
- Terrestrial planet region largely unaffected by UV flux [TPF/Darwin targets]

Mayer et al. 2002
disk instability
model after 800 yrs

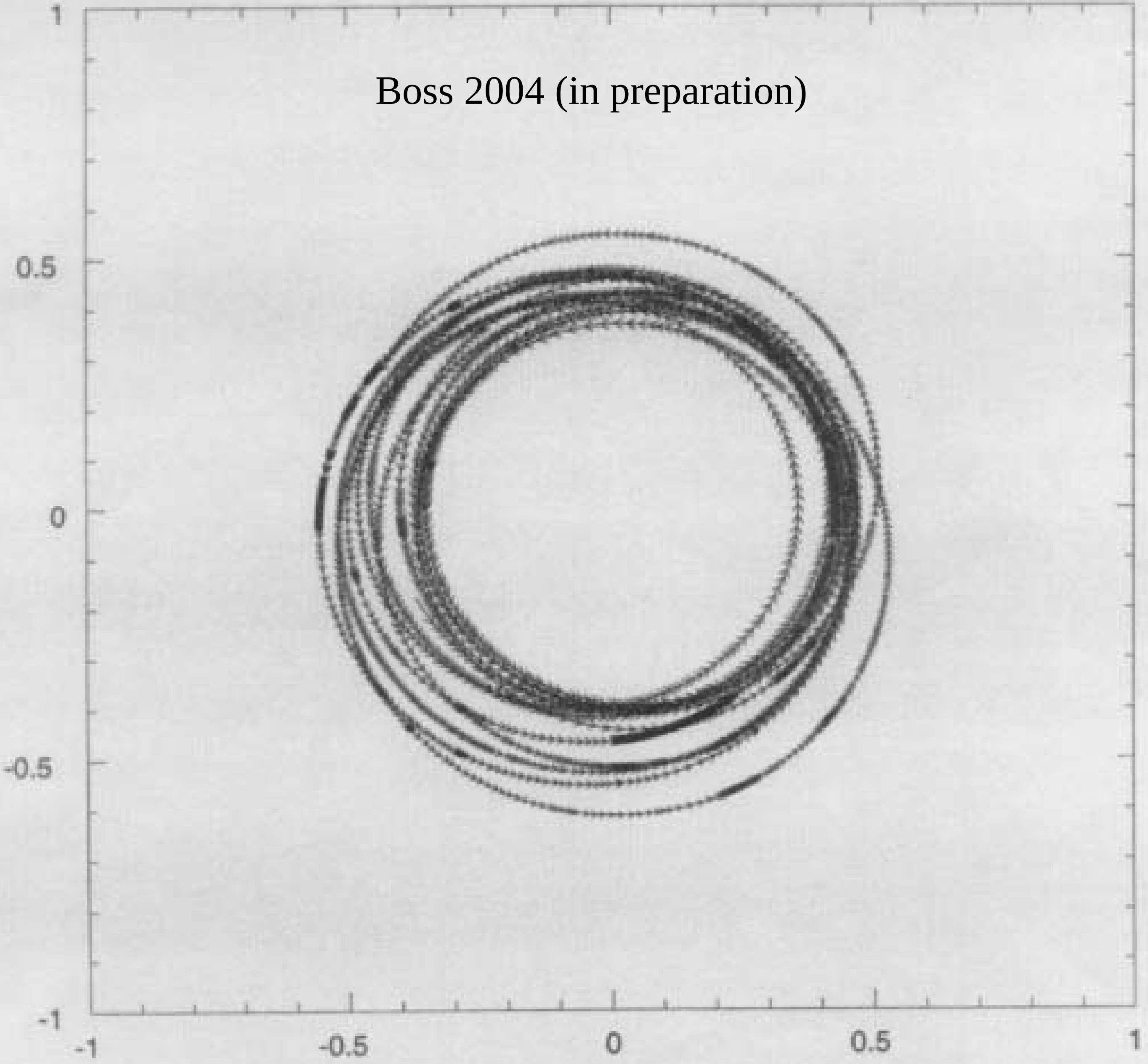
[SPH with simple
thermodynamics]



time evolution of
clump orbits

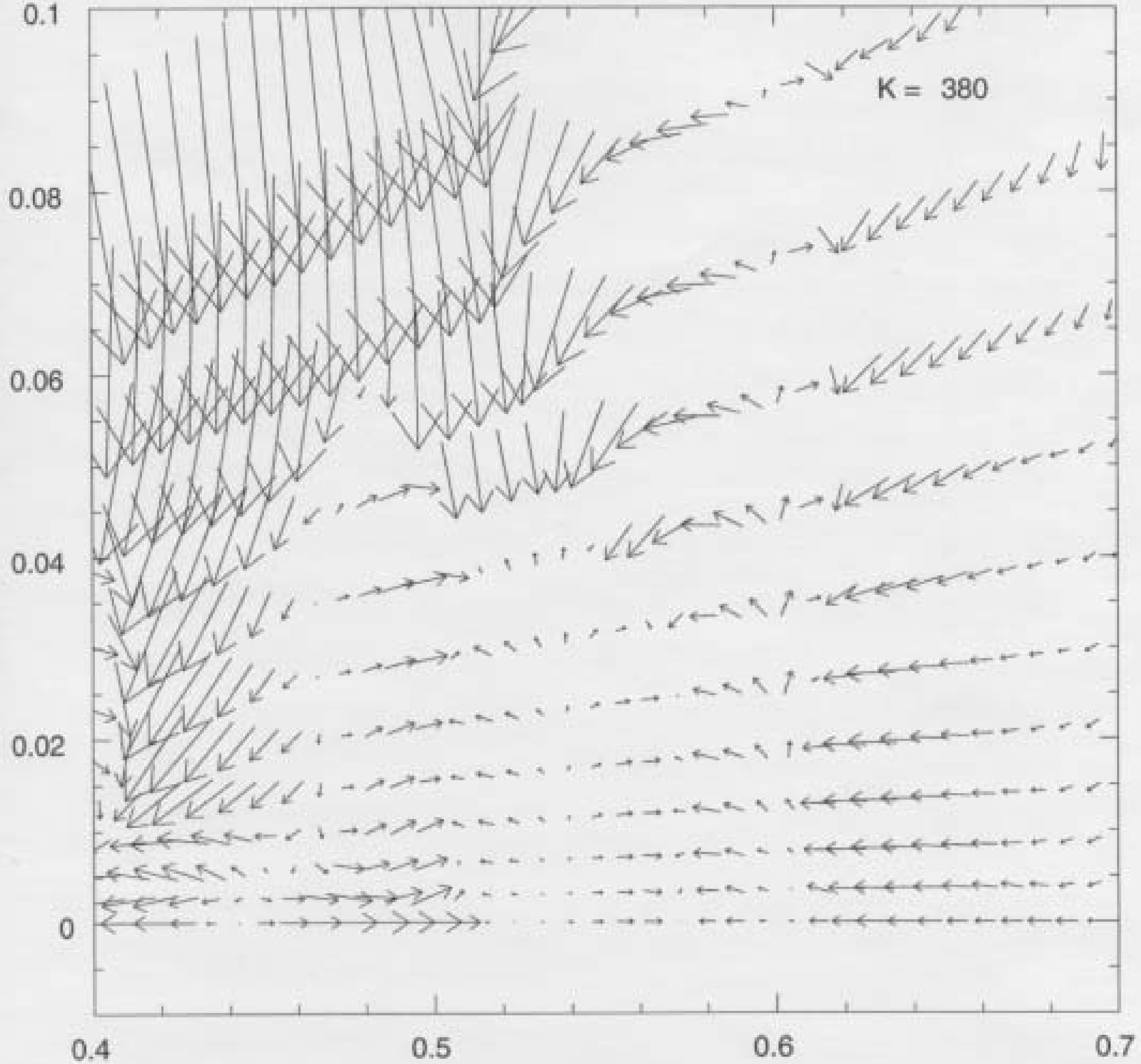


Boss 2004 (in preparation)



[Virtual protoplanet orbits for at least 1000 years, at least 30 orbits]

Boss 2004 disk instability models: cooling by convection



Core Accretion Mechanism

- Pro:
- Leads to large core mass, as in Saturn
- Higher metallicity speeds 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
- Gas disks dissipate before critical core mass reached → "failed Jupiters" usually
- Cannot form giant planets around M dwarfs or 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:
- Explains 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)
- Self-gravitating clumps form quickly (CoKu Tau/4?) and efficiently in shortest-lived disks
- Likely to work for M dwarfs
- Sidesteps Type I orbital migration danger
- Works in Taurus or Orion, implying Solar System analogues are common [TPF/Darwin]

- Con:
- May 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 high spatial resolution (AMR)
- Requires large UV dose to make ice giant planets – in Taurus would make only gas giant planets