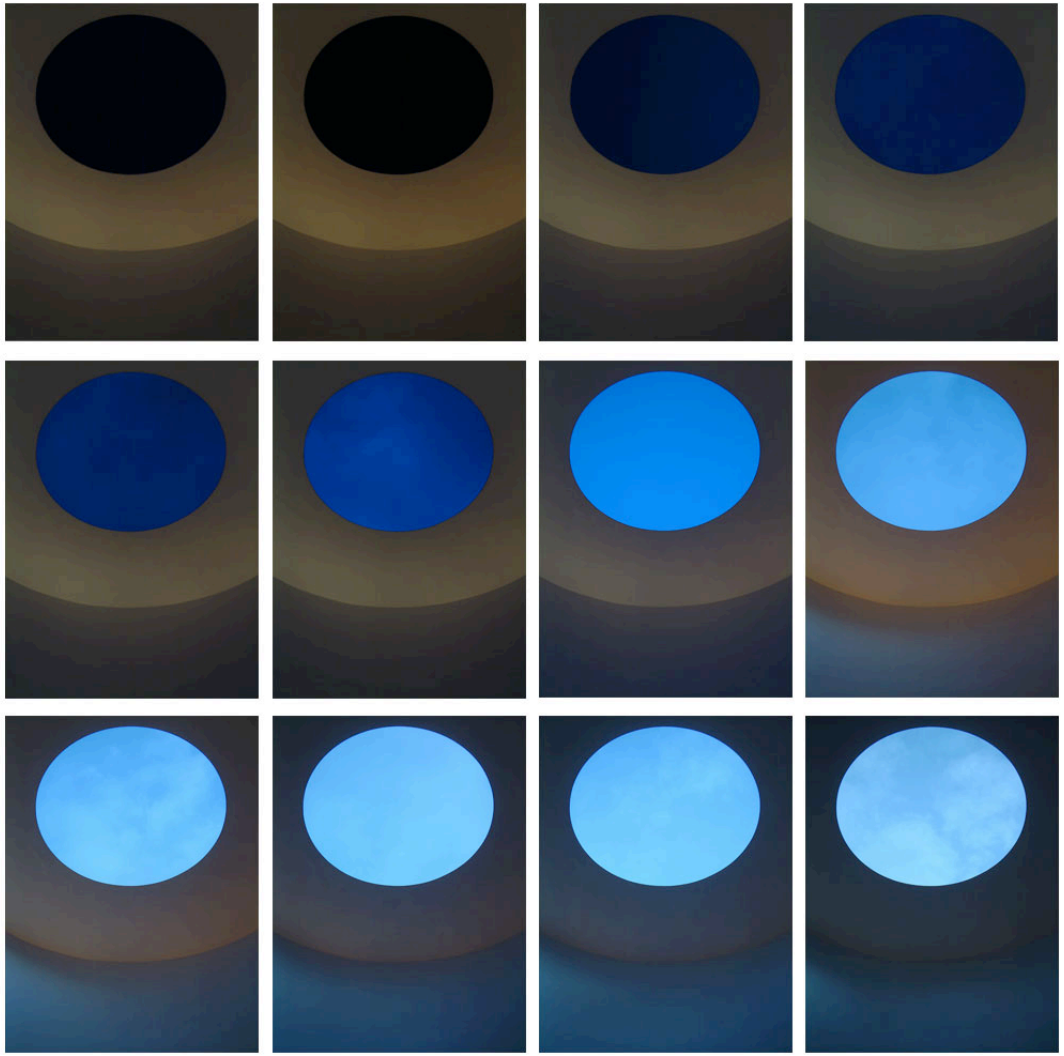


The Formation of Giant Planets

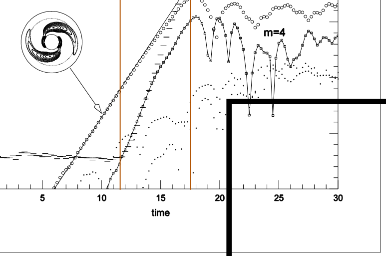
Greg Laughlin - UC Santa Cruz

The Gravitational Instability Paradigm

Kuiper 1951
Cameron 1978
DeCampli & Cameron 1979
Boss 1998
Boss 2000
Mayer et al. 2002
Pickett et al. 2003
Rice et al 2003a
Rice et al 2003b
Boss 2003
Cai et al 2004
Boss 2004
Mayer et al 2004
Mejia et al 2005

Two basic requirements for gravitational disk instability to work:

1. $Q = \dfrac{c_s \kappa}{\pi G \sigma} \sim 1$ somewhere in the disk
2. The cooling time for fragments must be less than half an orbital period (Gammie (2001).

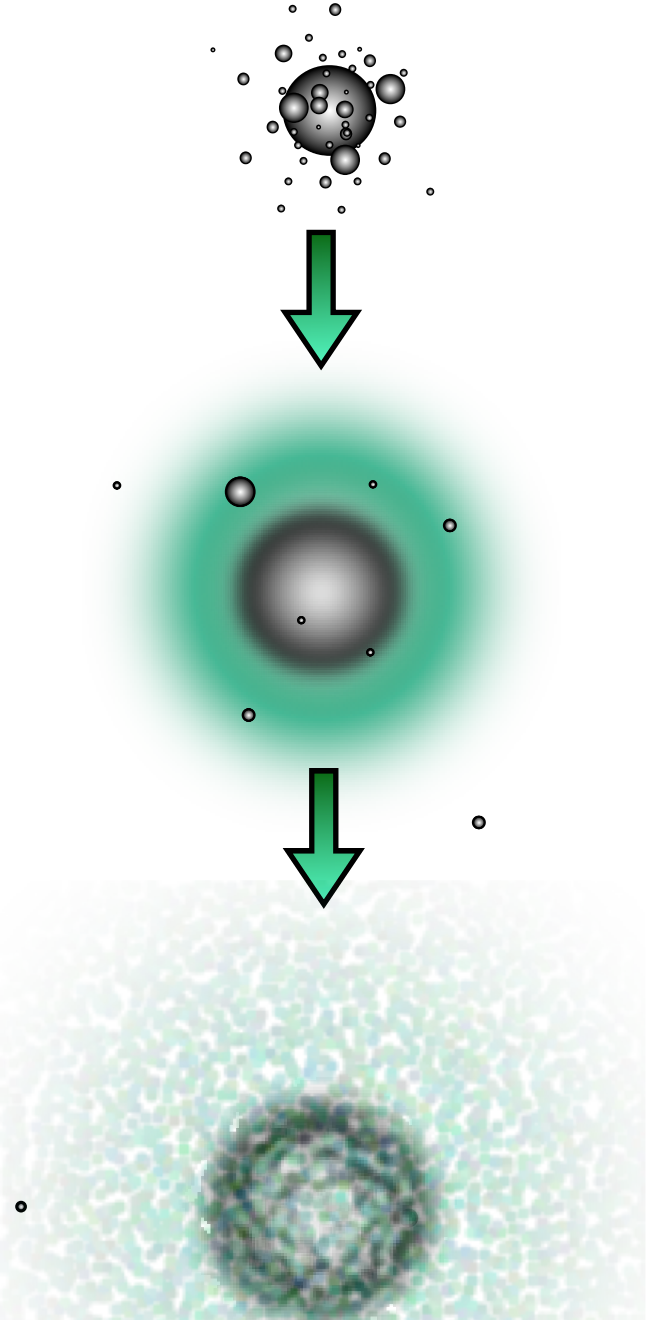


time

Another unresolved issue for G.I. is the feasibility of having a highly gravitationally unstable axisymmetric disk.

The Core Accretion Paradigm

Perri & Cameron 1974, Mizuno et al 1978, Mizuno 1980, Bodenheimer & Pollack 1986, Pollack et al 1996



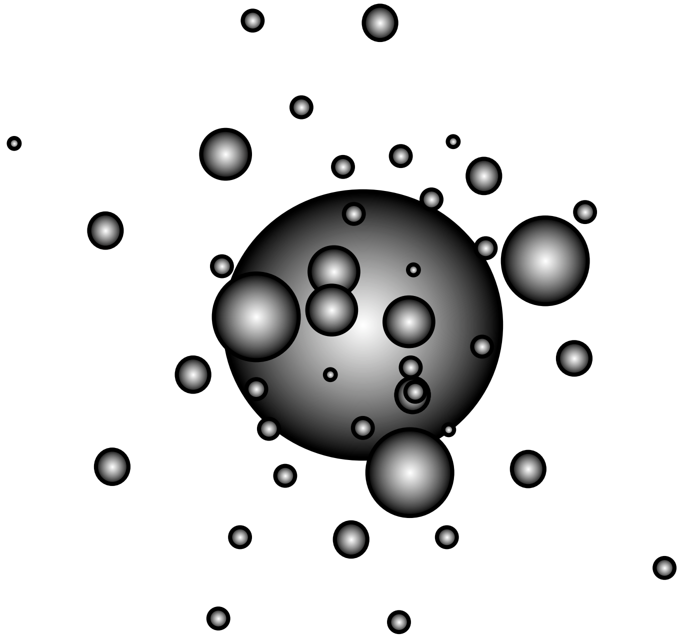
During Phase 1, the growing planet consists mostly of solid material. The planet experiences runaway accretion until the feeding zone is depleted. Solid accretion occurs much faster than gas accretion during this phase.

During Phase 2, both solid and gas accretion rates are small and are nearly independent of time. This phase dictates the overall evolutionary time-scale.

During Phase 3, runaway gas accretion occurs. Runaway gas accretion starts when the solid and gas masses are roughly equal.

The Core Accretion Paradigm

(Pollack et al 1996)



During Phase 1, the mass increase of the planet depends on the planetary radius, and the ratio of the gravitational to geometric cross section:

$$\frac{dM_p}{dt} = \pi R_c^2 \sigma \Omega F_g$$

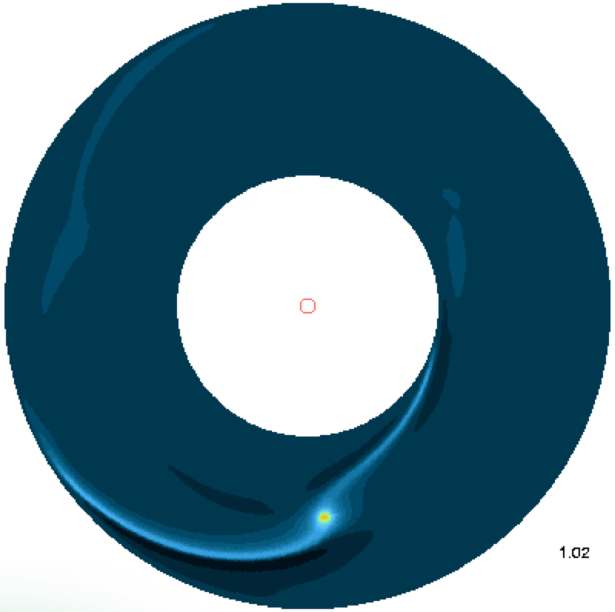
Because the escape velocity from the planetary surface is much faster than the relative velocity of planetesimals, this phase is characterized by a runaway growth of the solid core which ends when the core depletes its feeding zone, defined by:

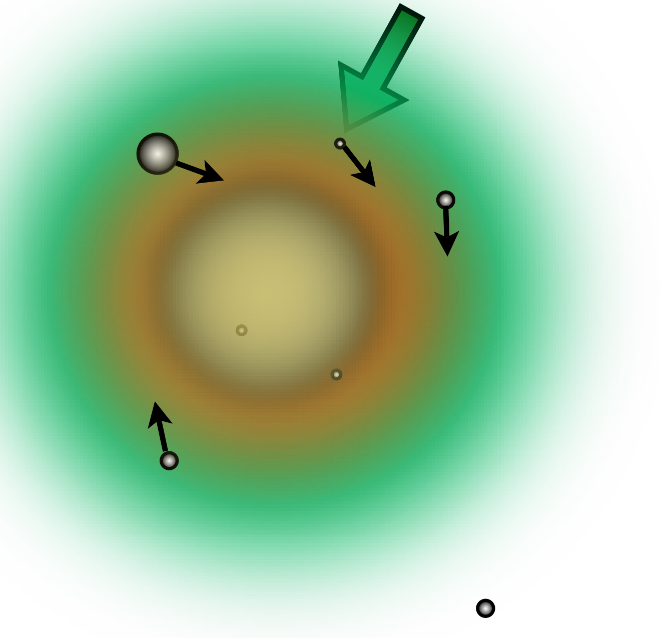
$$a_f = (\sqrt{12 + e_h^2}) R_H$$

Hill Radius →

$$R_H = a(\frac{M_P}{3M_\odot})^{1/3}$$

As runaway solid accretion proceeds through several Earth masses, the gas envelope becomes increasingly significant. Modeling of this stage requires computation of the hydrodynamic structure and effect of the gas envelope.





1. Stellar Evolution code for the quasi-equilibrium envelope:

$$\frac{dP}{dR} = -g\rho$$

$$\frac{dM}{dR} = 4\pi R^2 \rho$$

$$\frac{dT}{dR} = \frac{-3\kappa\rho}{16\sigma T^3}\frac{L}{4\pi R^2}$$

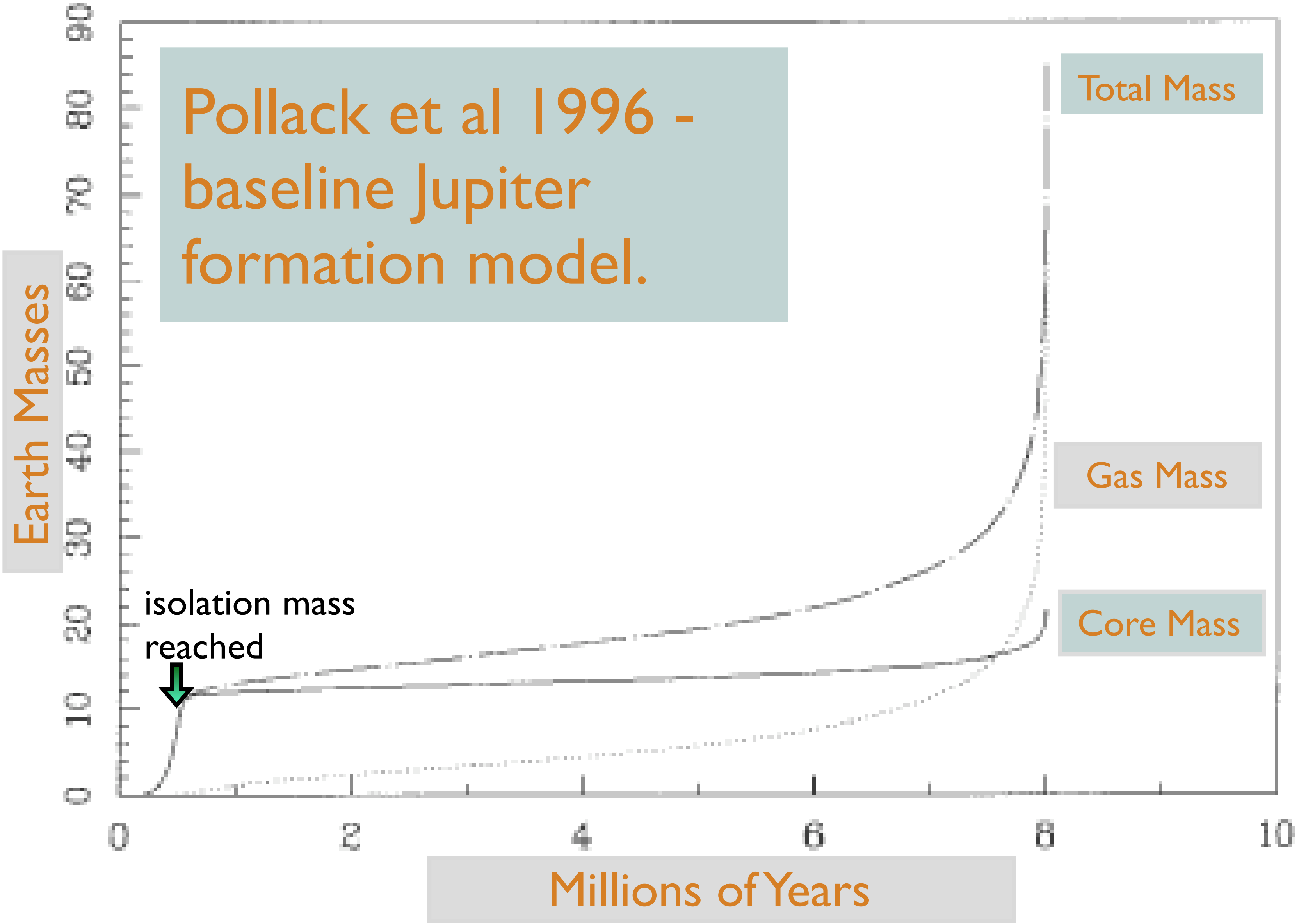
$$L_{core} = \frac{GM_{core}\dot{M}_{core}}{R_{core}}$$

2. Planetesimal dissolution routine:

$$v_{encounter} = (\sqrt{\frac{5e^2}{8} + i^2})v_{kepler}$$

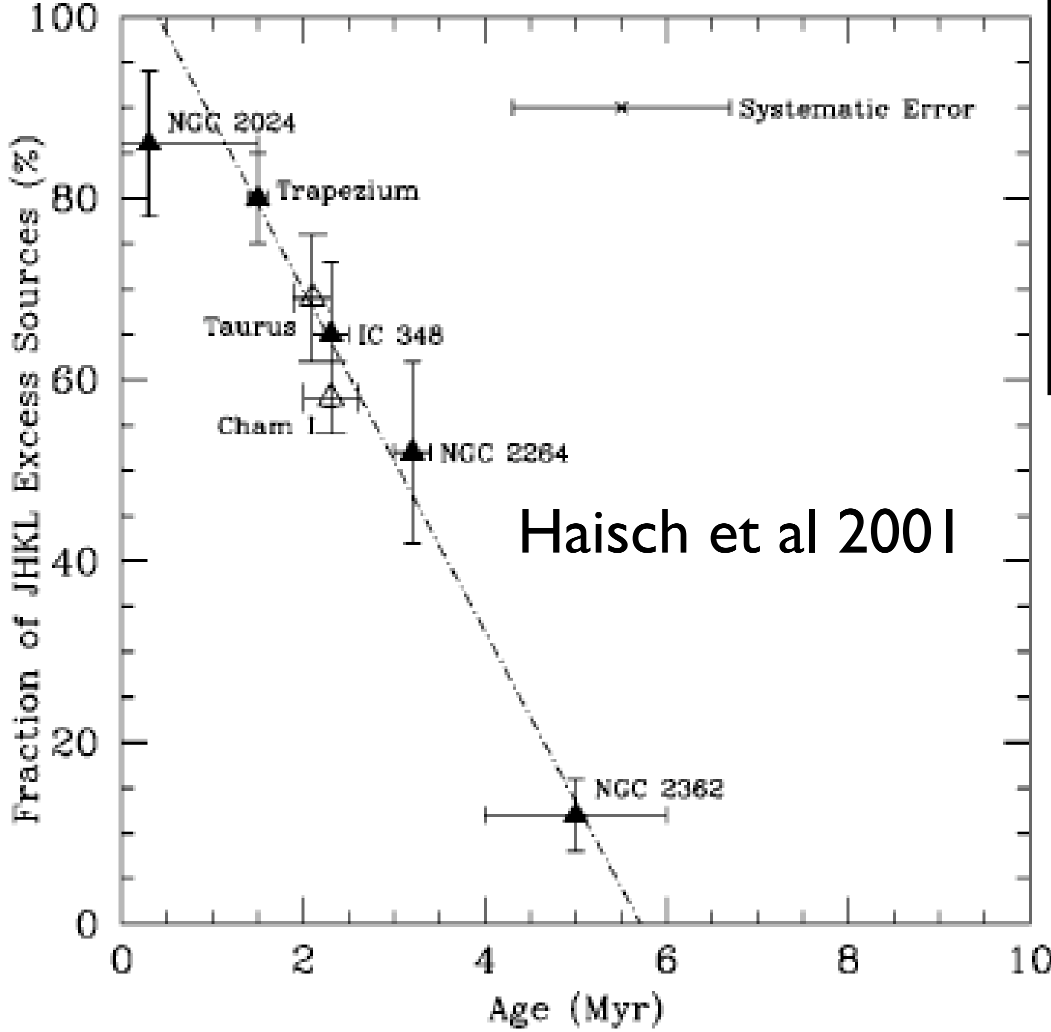
- numerical integration in envelope
- energy deposition into envelope

Pollack et al 1996 - baseline Jupiter formation model.

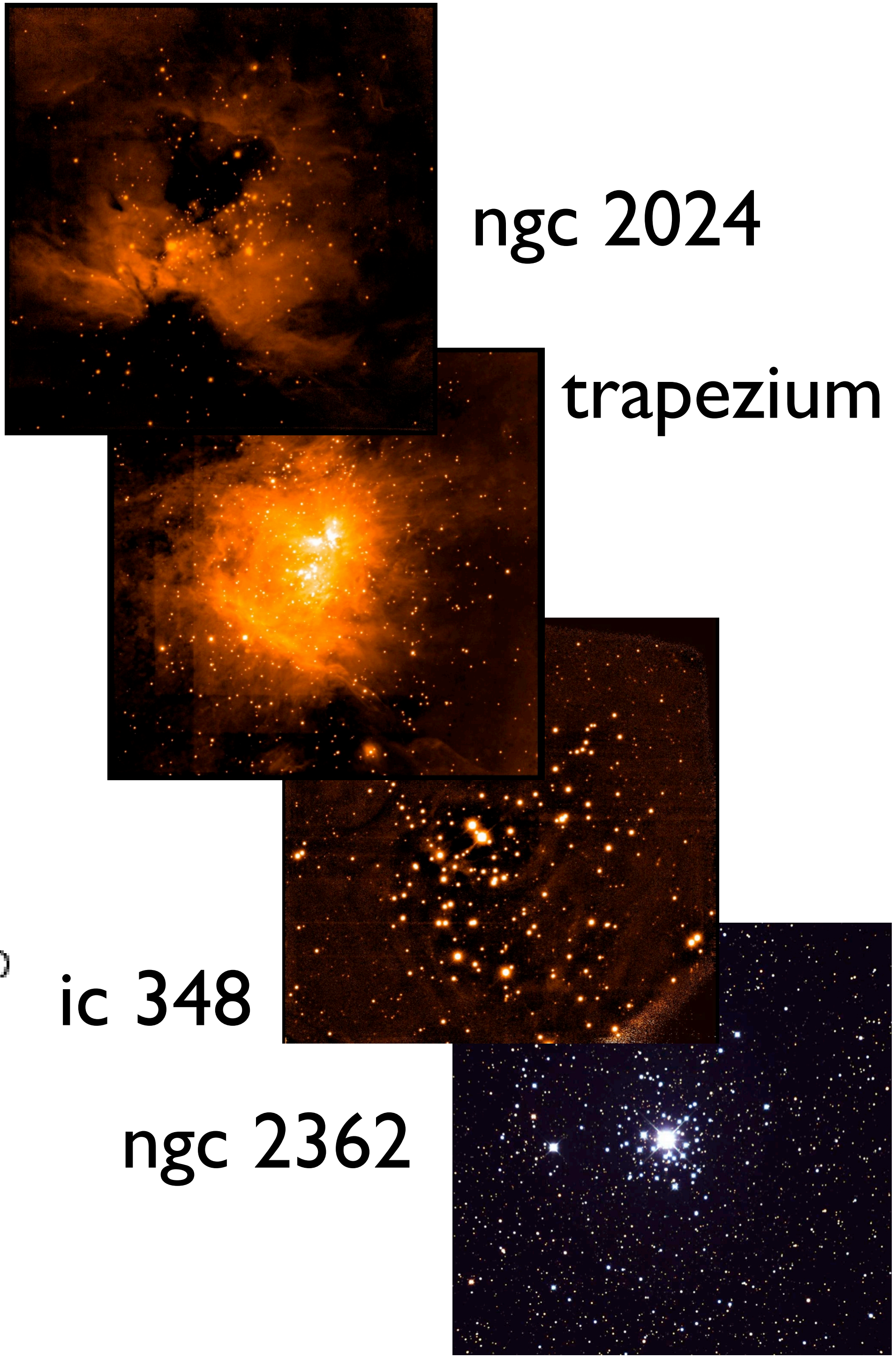


$$d = 5.2\,\mathrm{AU} \qquad \sigma_{solids} = 10\,\mathrm{g\,cm^{-2}}$$

$$T_{neb} = 150\,\mathrm{K} \qquad \rho_{neb} = 5 \times 10^{-11}\,\mathrm{gcm^{-3}}$$



Haisch et al 2001



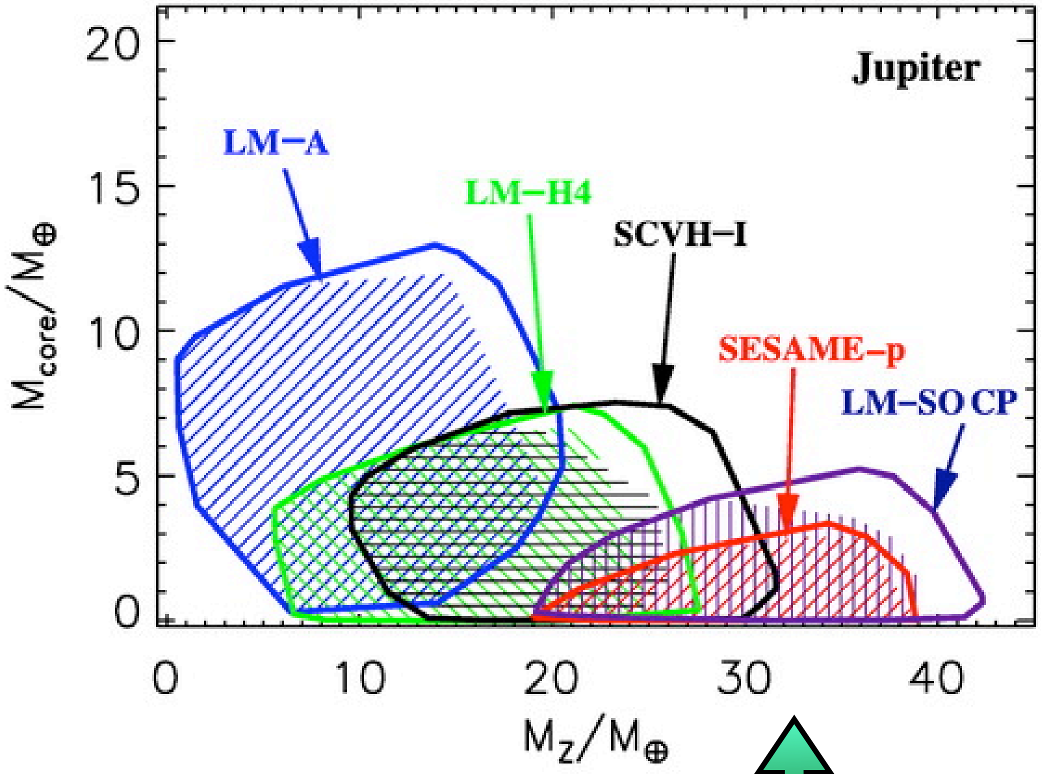
ngc 2024

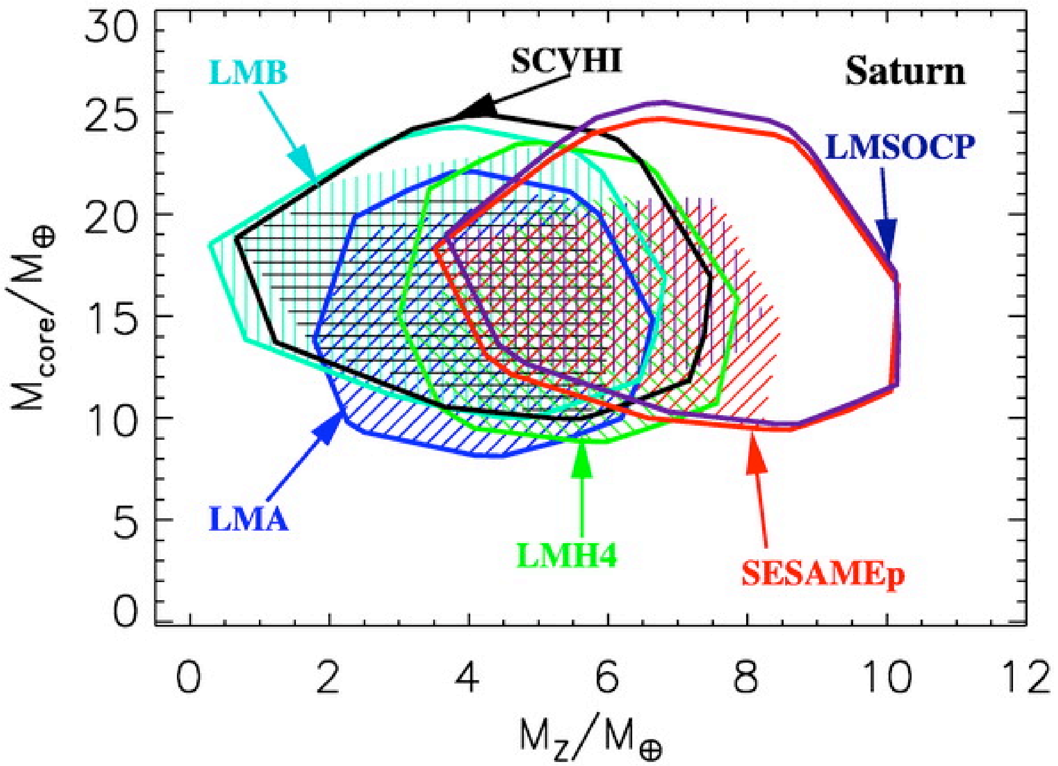
trapezium

ic 348

ngc 2362

Observed disk lifetimes tend to be shorter than the ~8 Myr required in the Pollack et al. (1996) standard case model





Saumon and Guillot (2004) compute the allowed ranges for Jupiter's core mass and the mass of heavy elements mixed into the envelope for which planetary models having different different H-He equations of state can match Jupiter's R_{eq}, J_2 and J_4 to 2-sigma.

Jupiter seems to have a small core.

The current list of planets with known radius and mass

observed properties

predicted properties

Planet	M/Mjup	Teq(K)	R/Rjup	core	no core	c+kh	nc+kh
Jupiter	1.00±0.00	113	1.00 ± 0.0	0.99	1.03	0.99	1.03
Ogle TR-111b	0.53±0.11	904	1.00 +.13 -.06	0.98	1.07	1.19	1.28
TrES-1	0.73±0.04	1011	1.08 ± 0.05	1.05	1.09	1.14	1.24
Ogle TR-113b	1.35±0.22	1144	1.08 +.07 -.05	1.05	1.09	1.15	1.20
HD 209458 b	0.69±0.05	1240	1.32 ± .05	1.04	1.09	1.23	1.35
Ogle TR-56 b	1.45±0.23	1686	1.23 ± .16	1.09	1.14	1.33	1.40
Ogle TR-132b	1.19±0.13	1821	1.13 ± .08	1.10	1.15	1.37	1.47

HD 209458 is an anomalous object

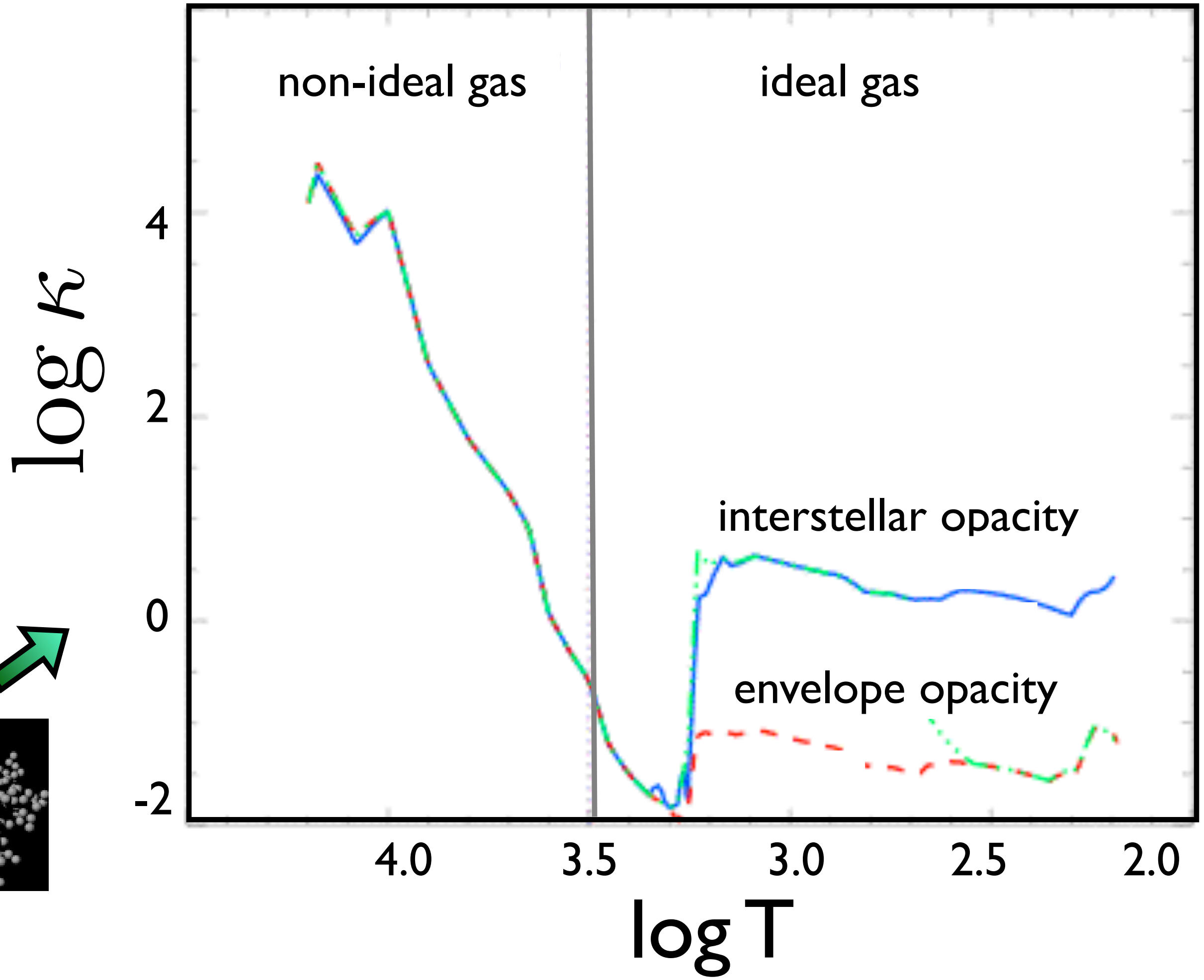
The “standard model” of Pollack et al 1996 predicts:

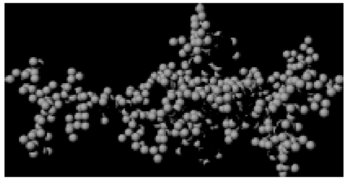
1. A planet with a core mass that seems too high.
2. A timescale to reach runaway gas accretion that seems too long.

A great deal of work has been done from 1996-2005 to refine core accretion. Examples include:

1. Improved physics:
    - equation of state (reviewed by Saumon & Guillot 2004)
    - envelope opacity (Ikoma et al 2000, Podolak 2003, Marley’s upcoming talk)

2. Additional physics:
    - migration of the cores (Papaloizou & Terquem 1999, Alibert et al 2004, Ida & Lin 2004)
    - turbulence in the disk (Rice and Armitage 2003)
    - competition between embryos (Hubickyj, Bodenheimer & Lissauer 2005)
    - time evolution of the disk (Alibert et al 2004, Ida & Lin 2004, Laughlin, Bodenheimer & Adams)



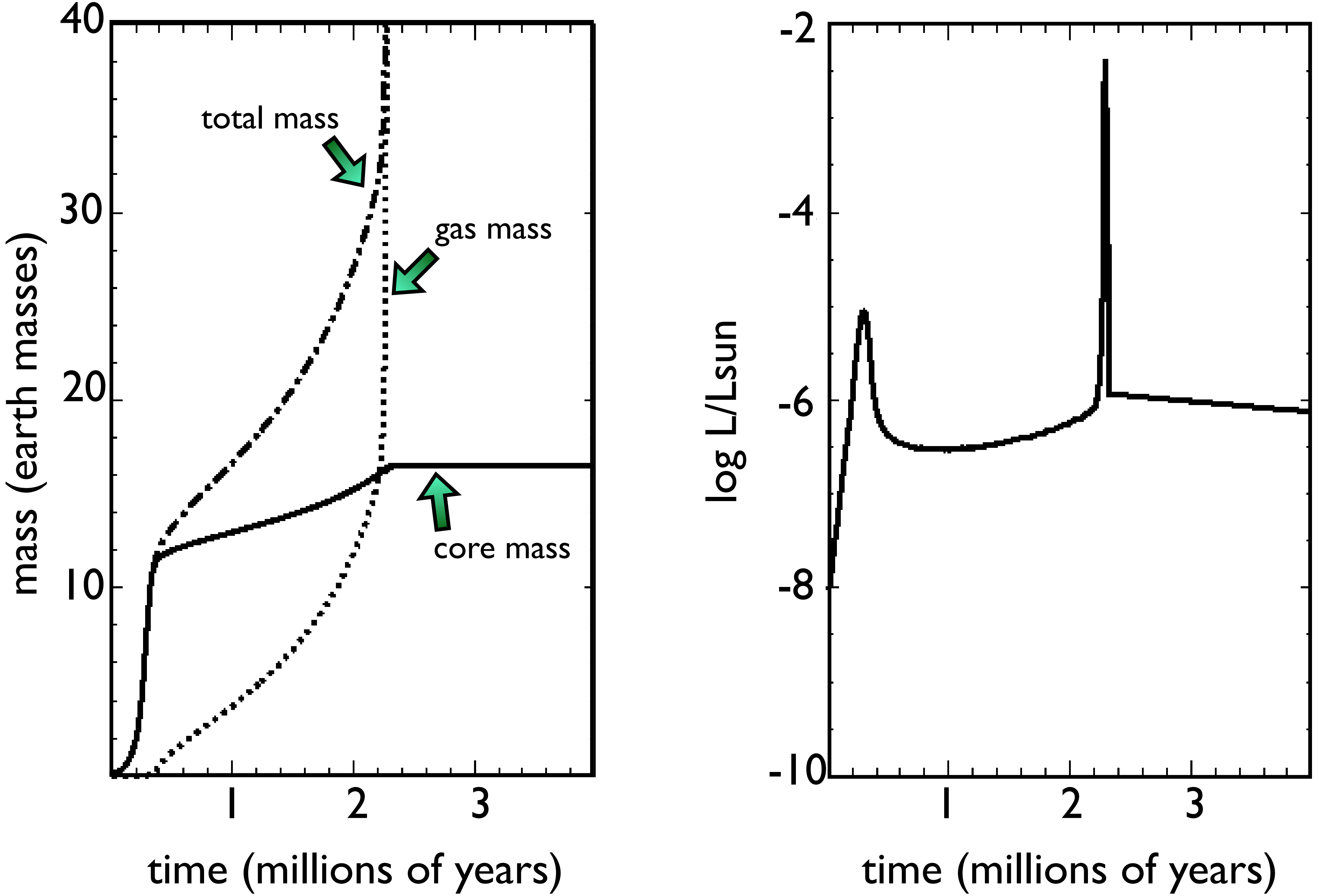


- Grain opacities are a key issue. Original studies (e.g Pollack et al 1996) used envelope opacities with an interstellar size distribution.

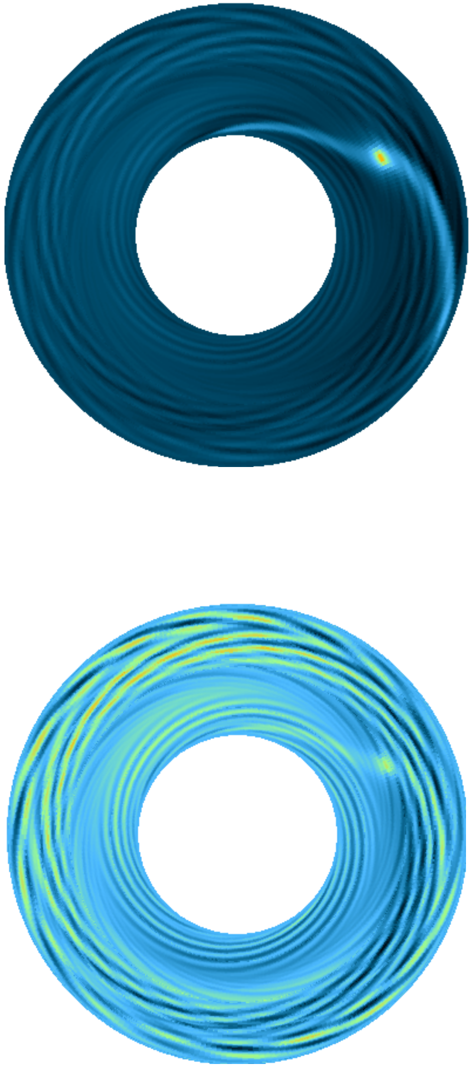
- But material that enters a giant planet envelope has been modified from the original interstellar grains by coagulation and fragmentation.

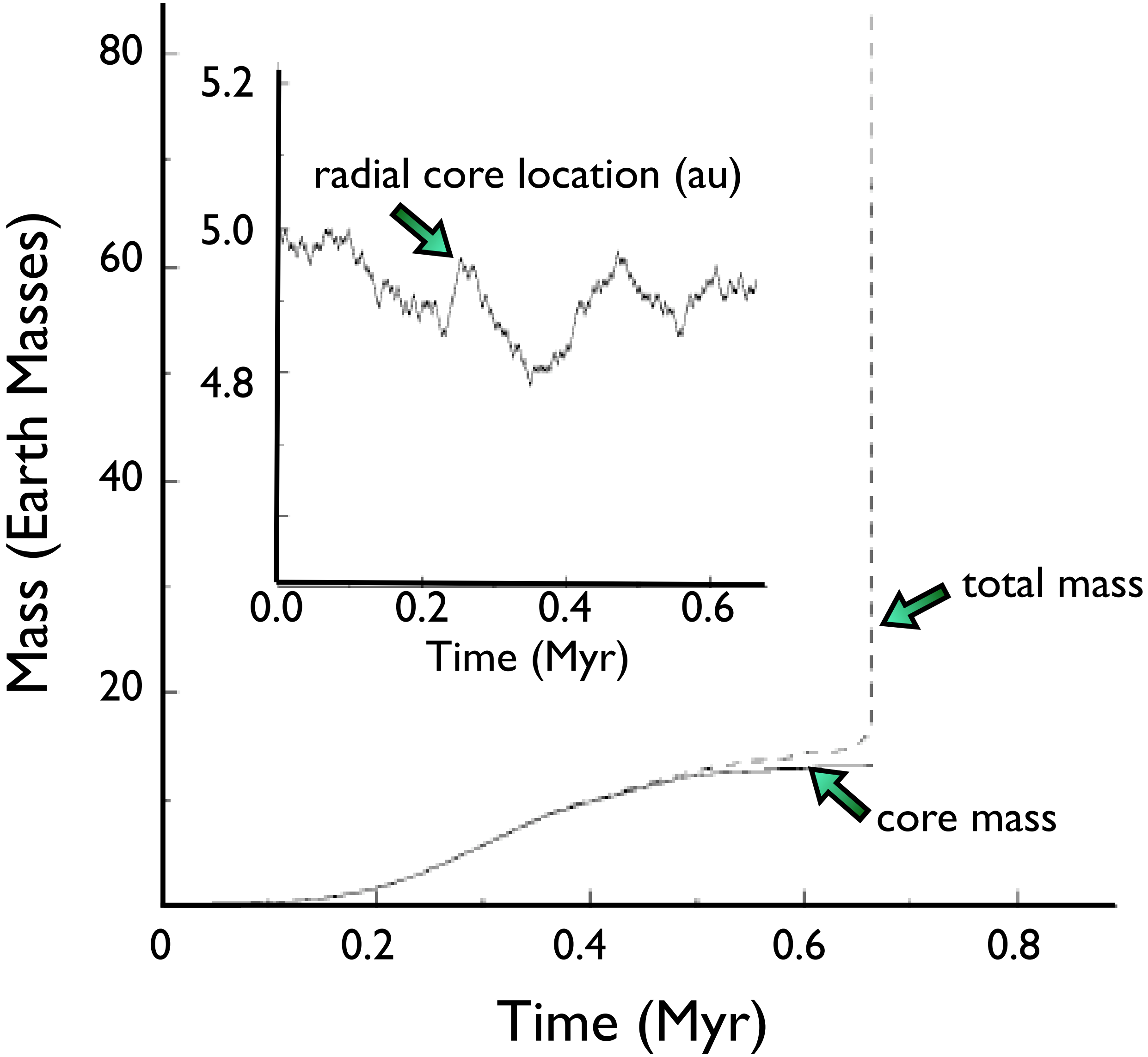
- Calculations by Podolak (2003) indicate that once grains enter the protoplanetary envelope, they coagulate and settle out quickly into warmer regions where they are destroyed. Podolak argues that true opacities are ~50x smaller than interstellar.

Reduced grain opacity greatly speeds up the gas accretion timescale.

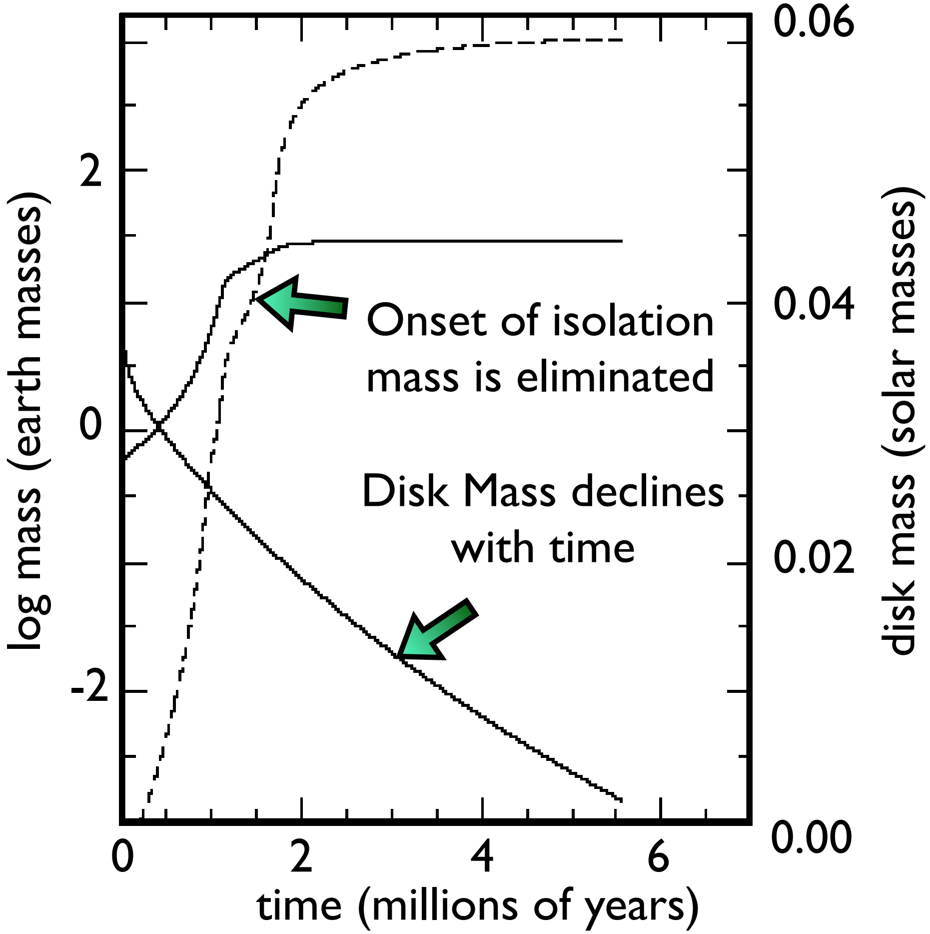


(Hubickyj et al. 2005)



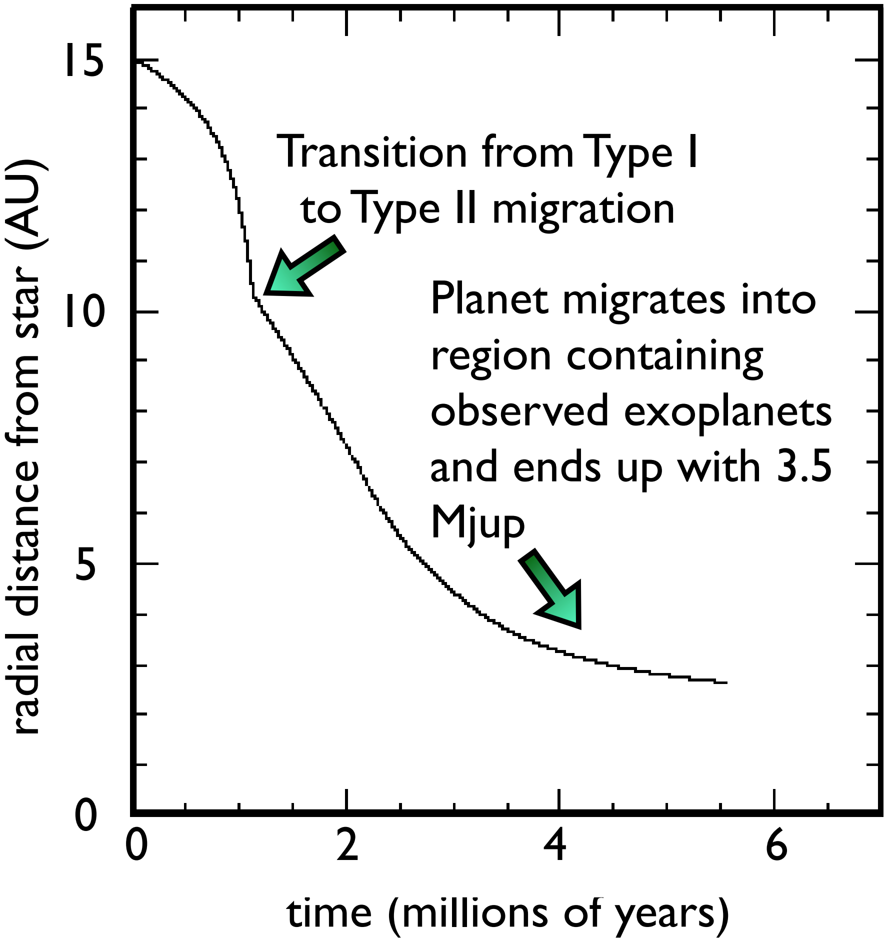


Turbulent fluctuations (such as those induced by the MRI) can generate surface density perturbations in the disk. The stochastic gravitational torques arising from such perturbations will cause an embedded core to execute a random walk. Rice and Armitage (2003) find that the random walk effectively eliminates the onset of core isolation, and allows a model Jupiter to form at 5AU in a disk with 10 gm cm^{-2} in less than 1 million years (albeit with a final core mass of ~17M_{Earth} that is rather large).



Onset of isolation mass is eliminated

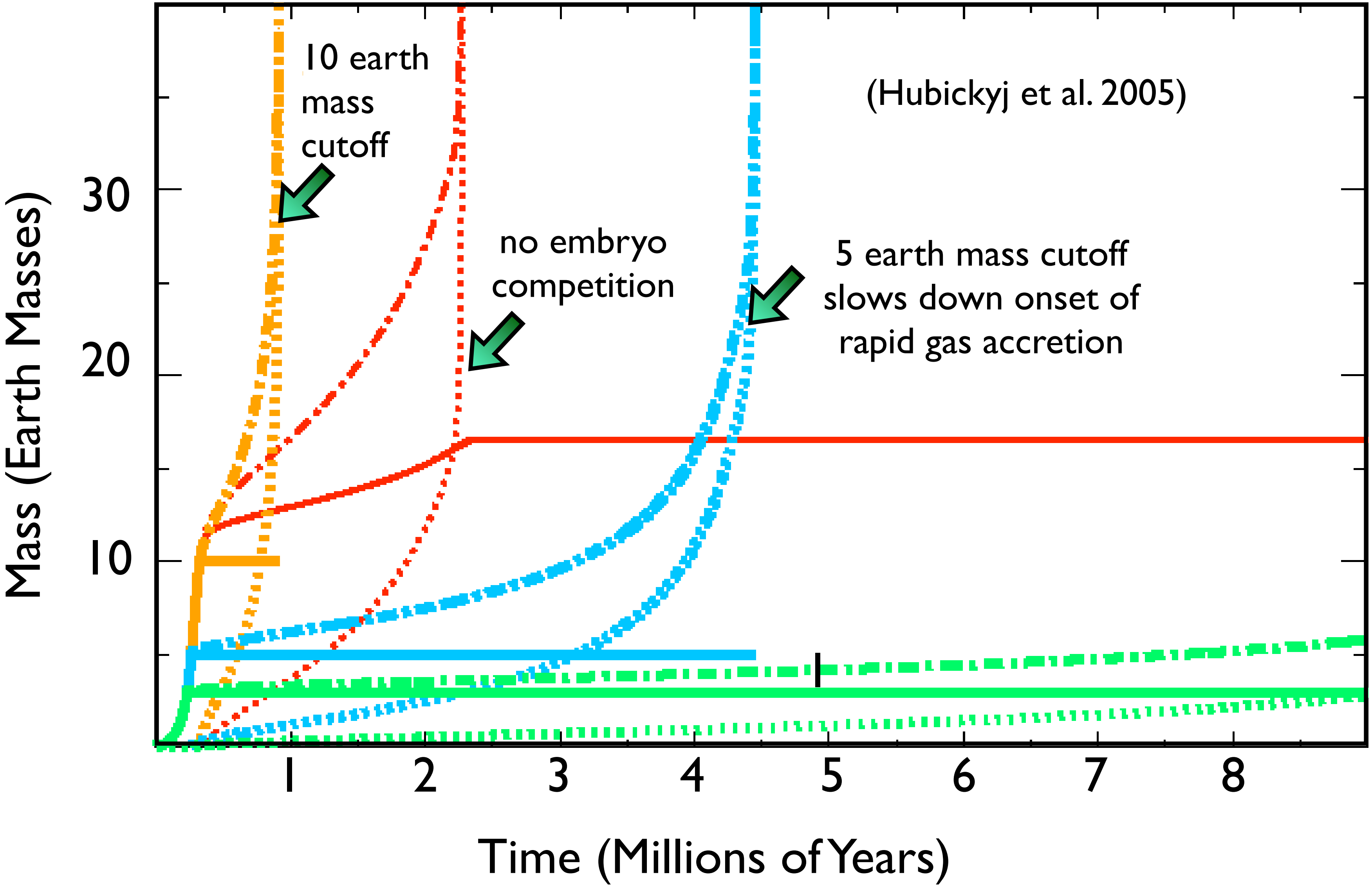
Disk Mass declines with time



Transition from Type I to Type II migration

Planet migrates into region containing observed exoplanets and ends up with 3.5 Mjup

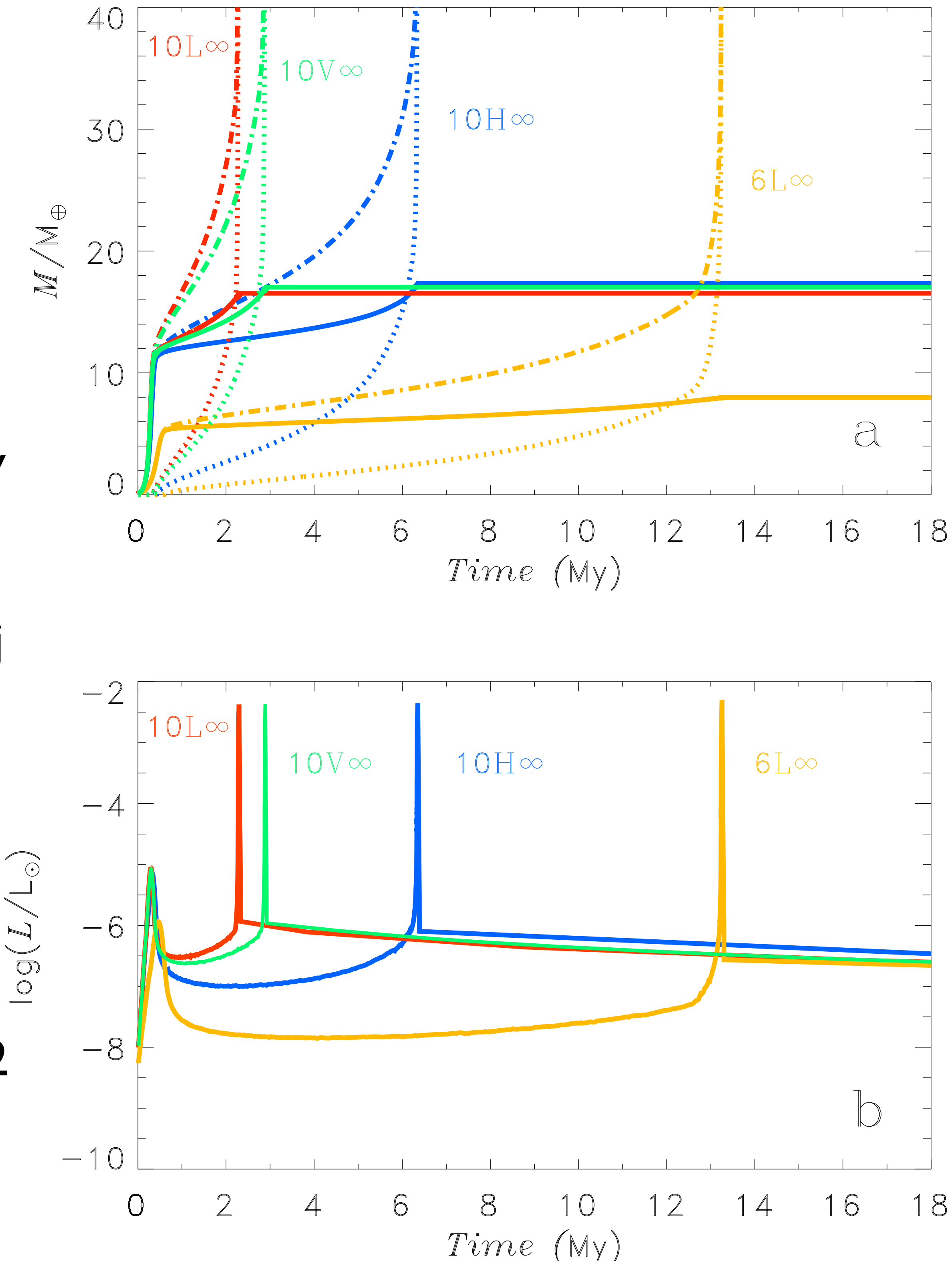
Alibert et al (2004) extended the Pollack et al (1996) model to include migration, disk evolution, and gap formation. They find much reduced timescales for the onset of rapid gas accretion. (Lin & Ida 2004) have a similar model (described later in the talk).

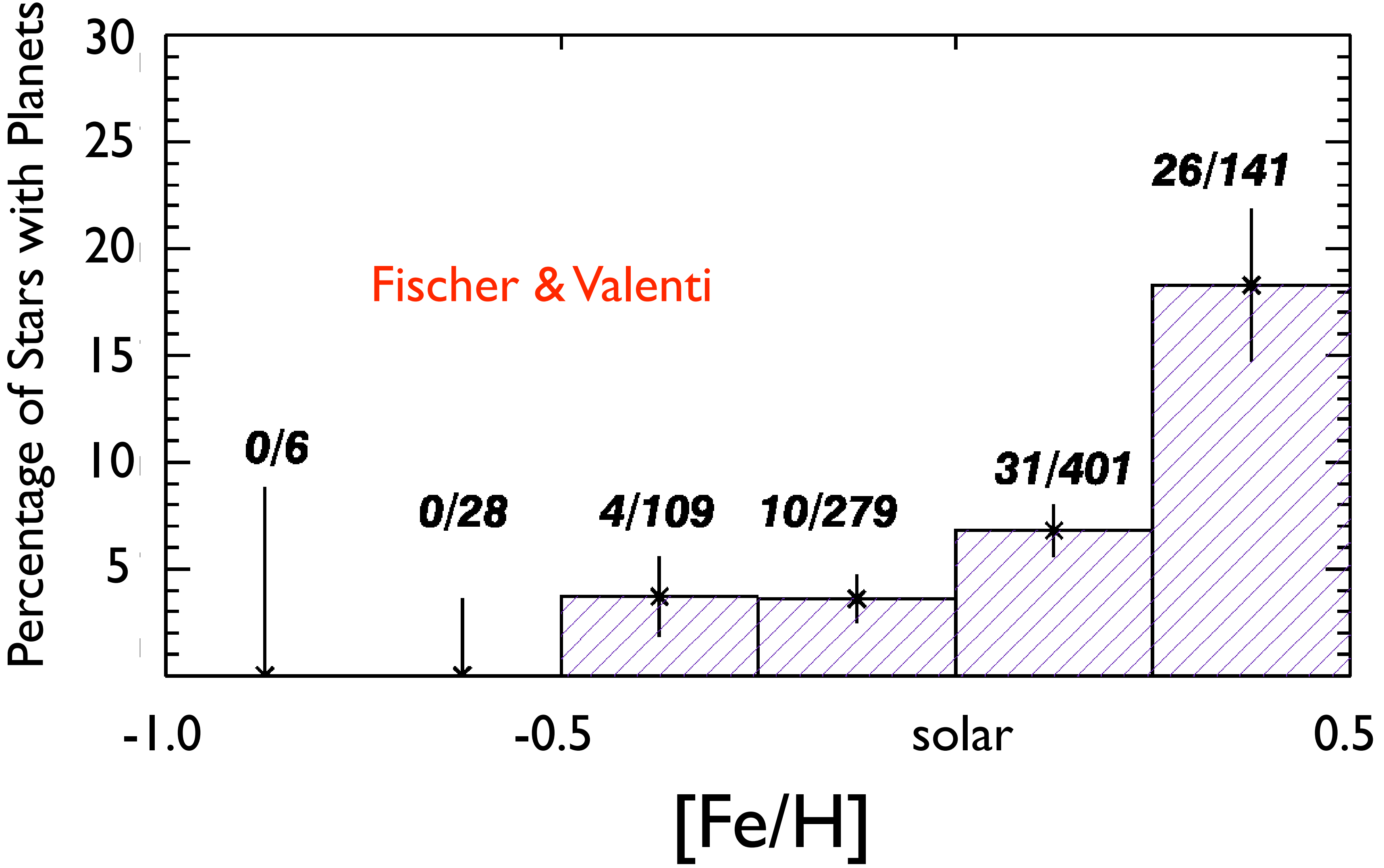


Competition between embryos can introduce a cutoff to solid body accretion prior to isolation mass being achieved. If this occurs at core masses of order 10 Earth masses, the onset of rapid gas accretion can occur much earlier. This effect also leads to an acceptably decreased core mass.

A key (and well established) result of standard core accretion theory is the extraordinary sensitivity of the time of onset of rapid gas accretion to the surface density of solids in the disk.

Recent calculations by Hubickyj et al (2005), illustrate that decreasing the solid surface density from 10 to 6 gm/cm2 causes a 12 Myr delay in the onset of rapid gas accretion. This solid surface density decrease corresponds to a ~0.2 dex decrease in metallicity.





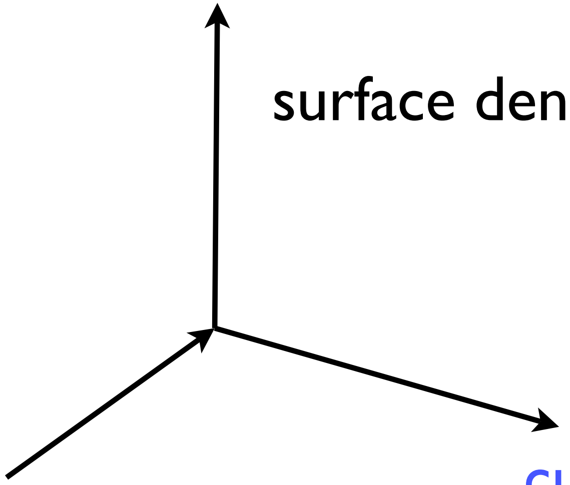
The extrasolar planet - host star metallicity connection (e.g. Santos 2003) is one of the most remarkable results to have emerged from the radial velocity surveys. This correlation certainly provides an important clue to the planet formation process.

The metallicity -- planet connection suggests that giant planet formation is a threshold phenomenon that depends sensitively on the surface density of solids (planetesimals) in the disk.

This is a characteristic and generic property of core-accretion.

The metallicity connection is very hard to understand within the gravitational instability paradigm (e.g. Boss 2002).

A Test of the Core Accretion Theory

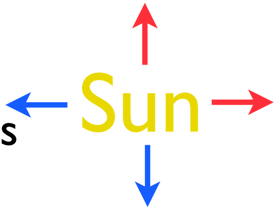


surface density of solids in disk

cutoff mass

opacity

The sensitive dependance of the core accretion timescale on surface density is independant of the other controlling parameters. If this effect is responsible for the observed metallicity correlation, one expects that Jovian-mass planet formation should also proceed more easily in higher mass disks. If disk-to-star mass ratios are relatively constant, then there should also be a stellar mass correlation with planet frequency.



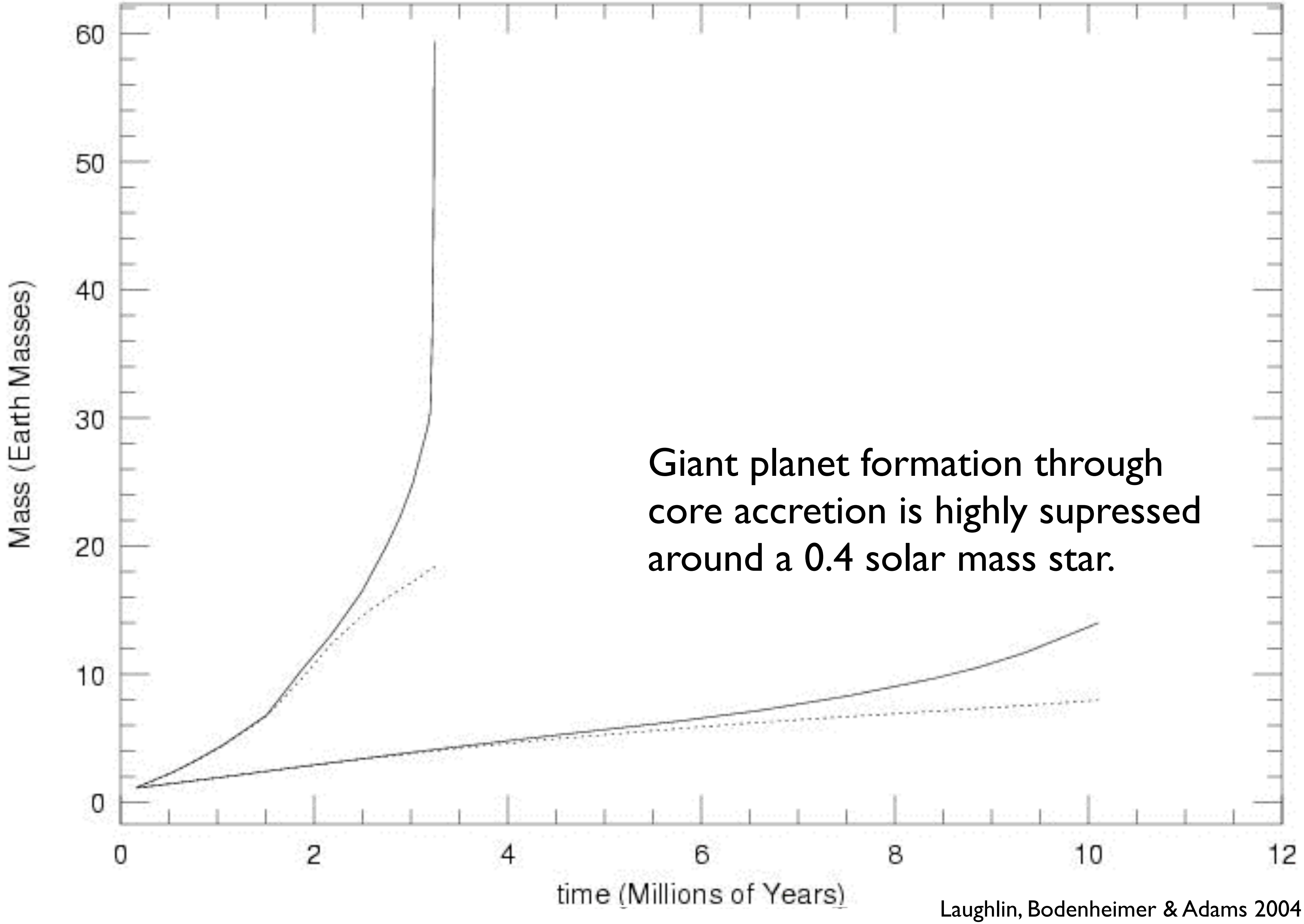
higher Fe/H
more planets

lower mass
fewer planets

Sun

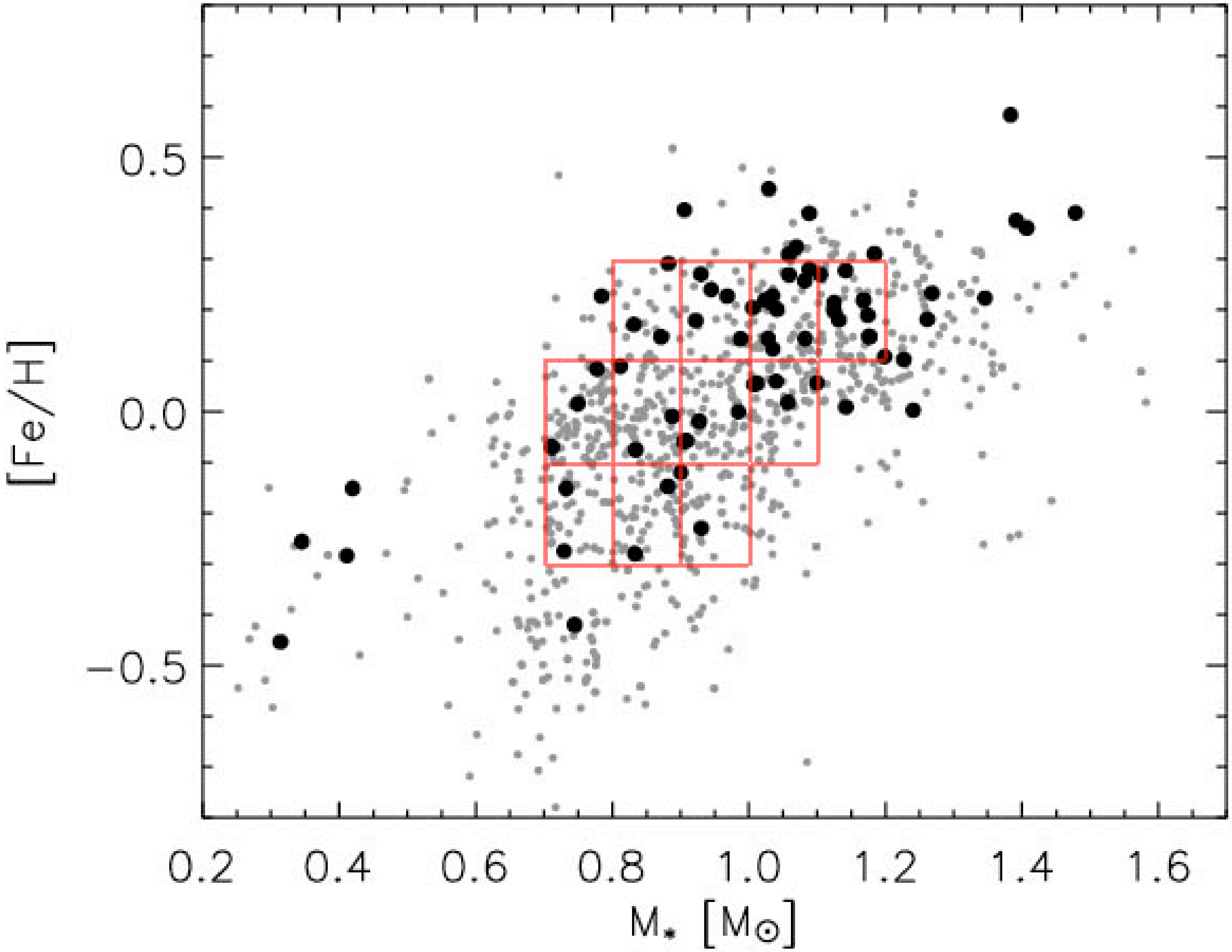
higher mass
more planets

lower Fe/H
fewer planets



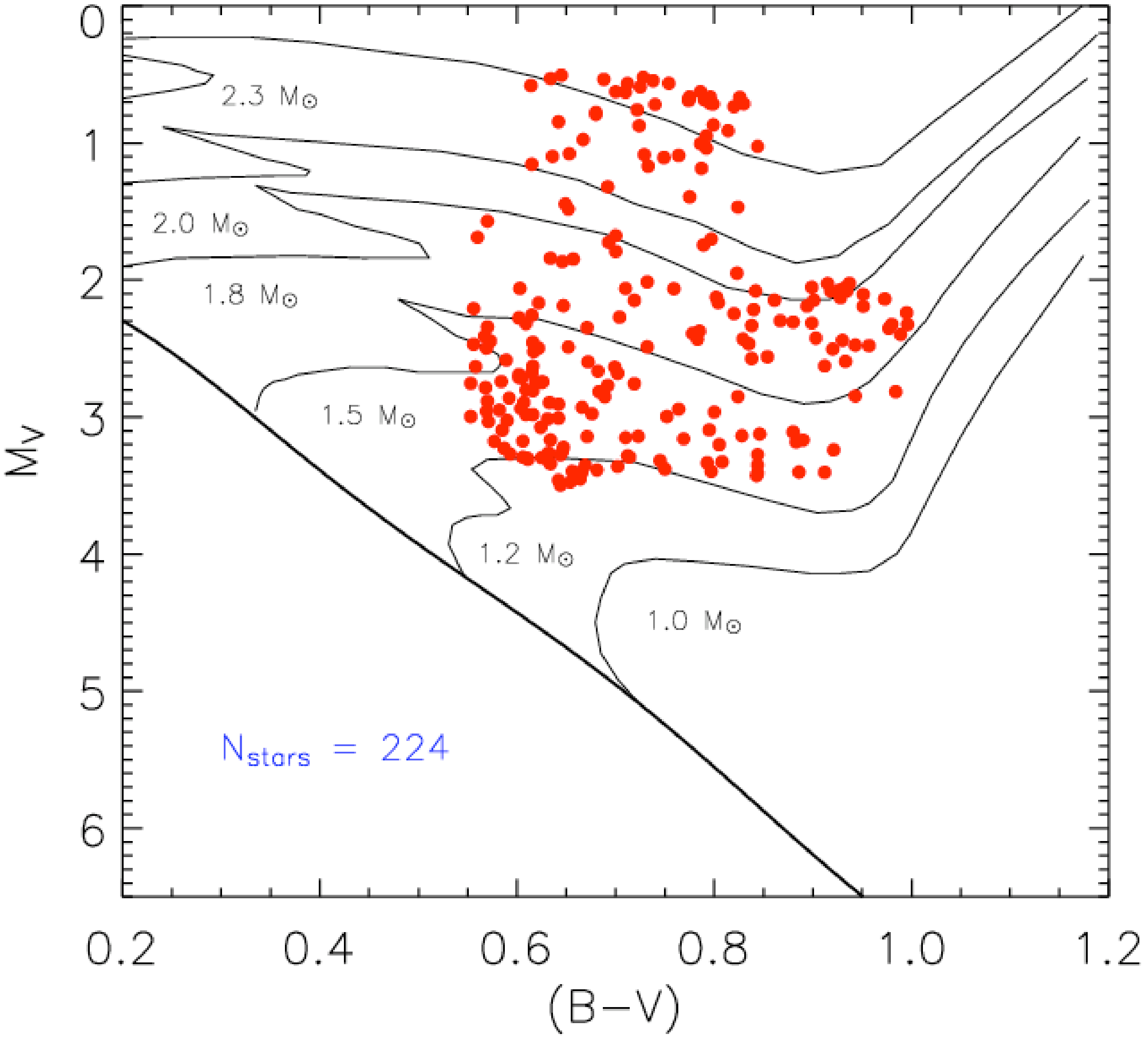
Giant planet formation through core accretion is highly supressed around a 0.4 solar mass star.

Laughlin, Bodenheimer & Adams 2004



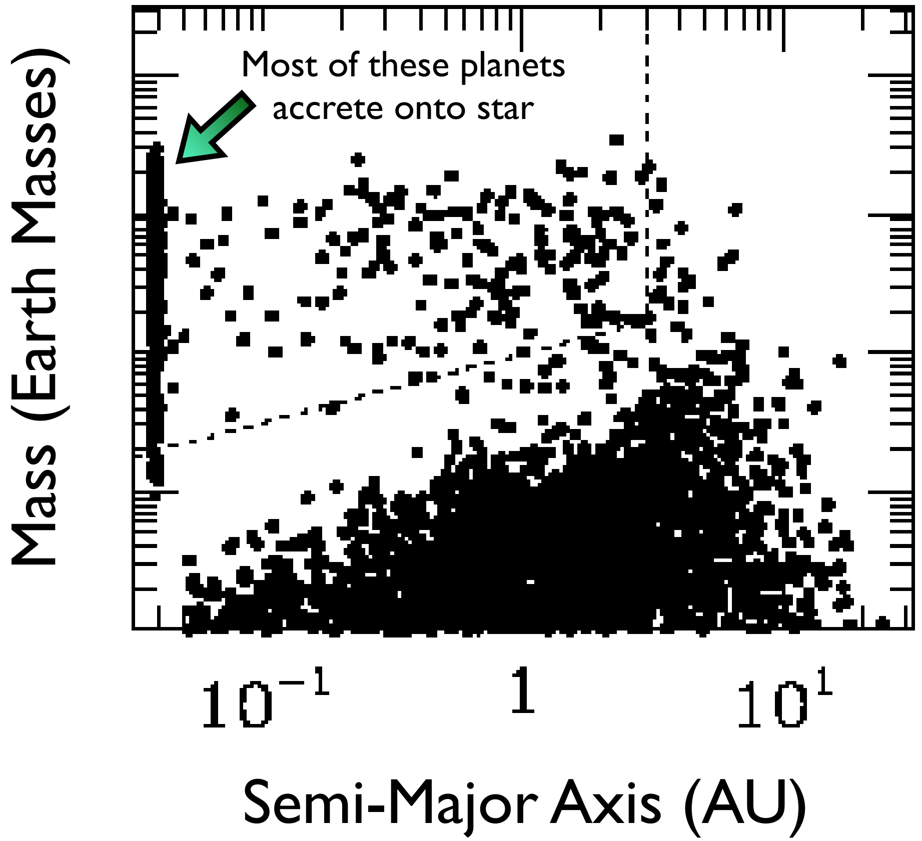
John Johnson fits a 2D power-law to the planet fraction in the current Keck Survey:

$$\mathcal{P} = 1.2 \times 10^{-3}([\mathrm{Fe/H}] + 1.9)^{6.2\pm0.6} M_\star^{0.7\pm0.6}$$

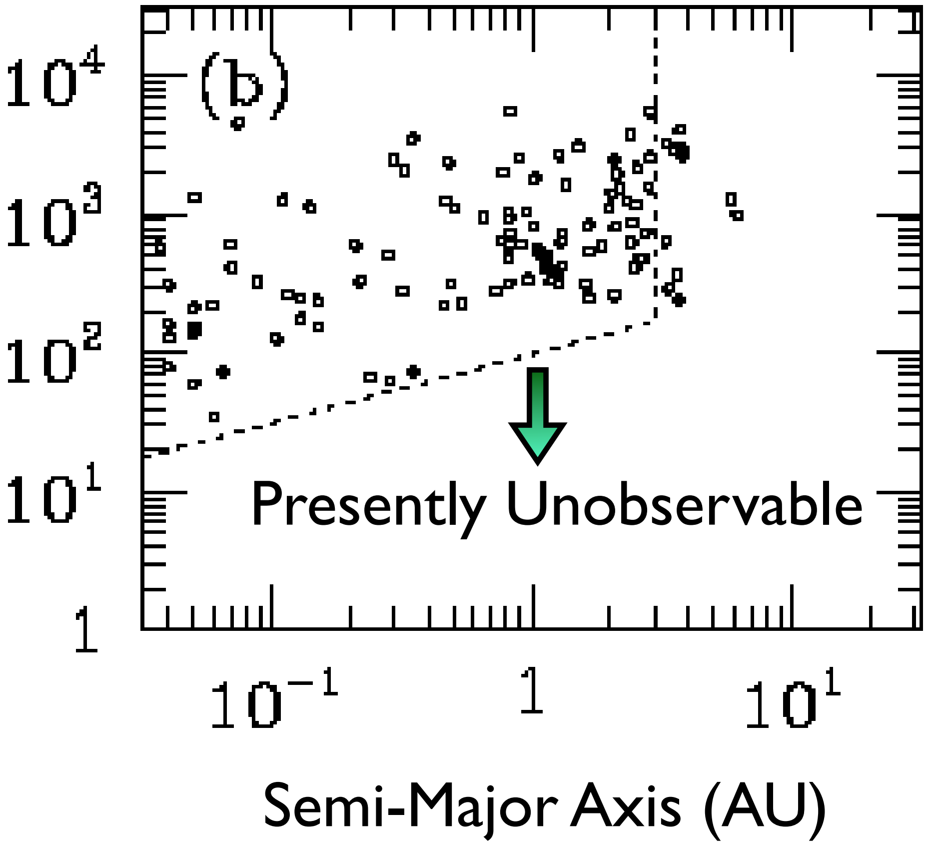


The relative planeticity of higher mass stars will soon be better constrained by John Johnson's thesis RV survey, and by Bunei Sato's ongoing RV survey.

Ida & Lin Model Distribution



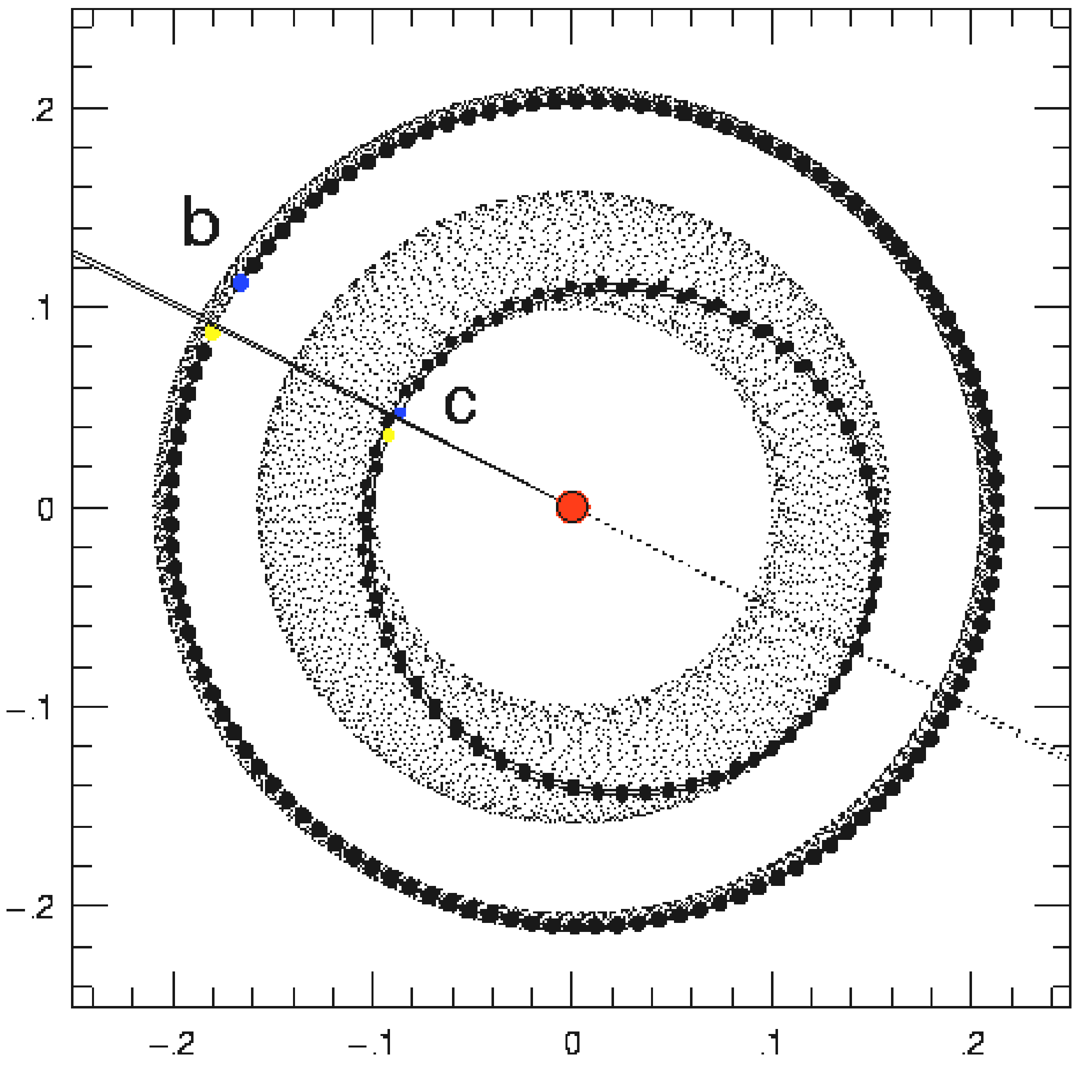
Observed Distribution



Ida and Lin (2004, 2005) carried out a large number of Monte-Carlo simulations which draw from distributions of disk masses and seed-planetesimals to model the process of core accretion in the presence of migration. These simulations reproduce the planet "desert", and predict a huge population of terrestrial and ice giant planets somewhat below the current detection threshold for radial velocity surveys.

$$\tau_{mig} = \frac{a}{\dot{a}} = 10^6 \frac{1}{f_{(}g,0)} \exp^{t/\tau_{dep}} (\frac{M_p}{M_J})(\frac{a}{1\mathrm{AU}})^{1/2} \,\mathrm{yr}$$

GJ 876 -- Evidence for Gravitational Instability?



GJ 876 presents a serious challenge to the core accretion paradigm. In the GJ 876 system, two Jovian-mass planets formed around a low metallicity (Fe/H~-0.4) low mass (0.32 Msun) star.