Origin of Super-Earths & Prospects of Habitable Planets

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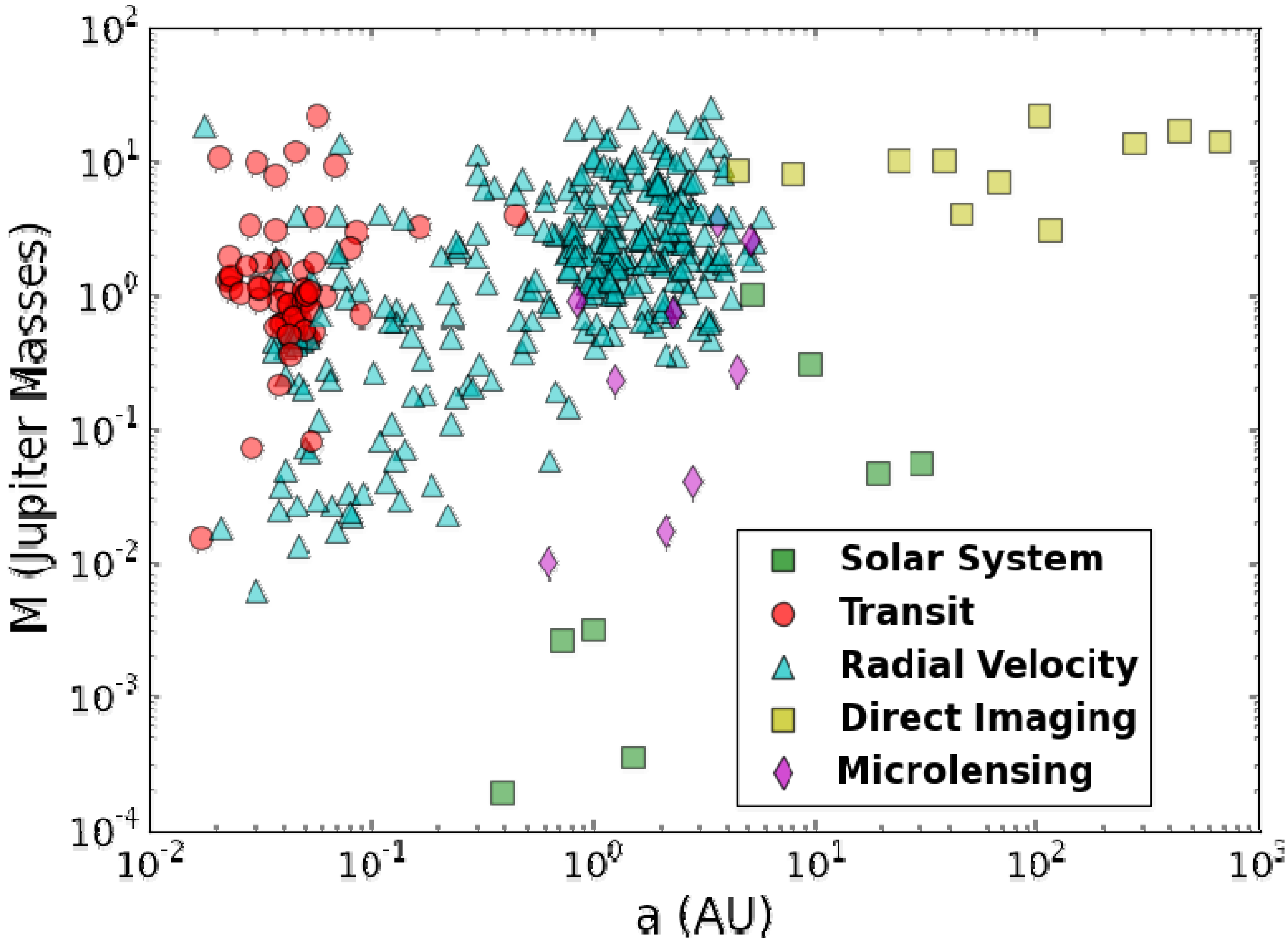
b

37slides

Known Planets

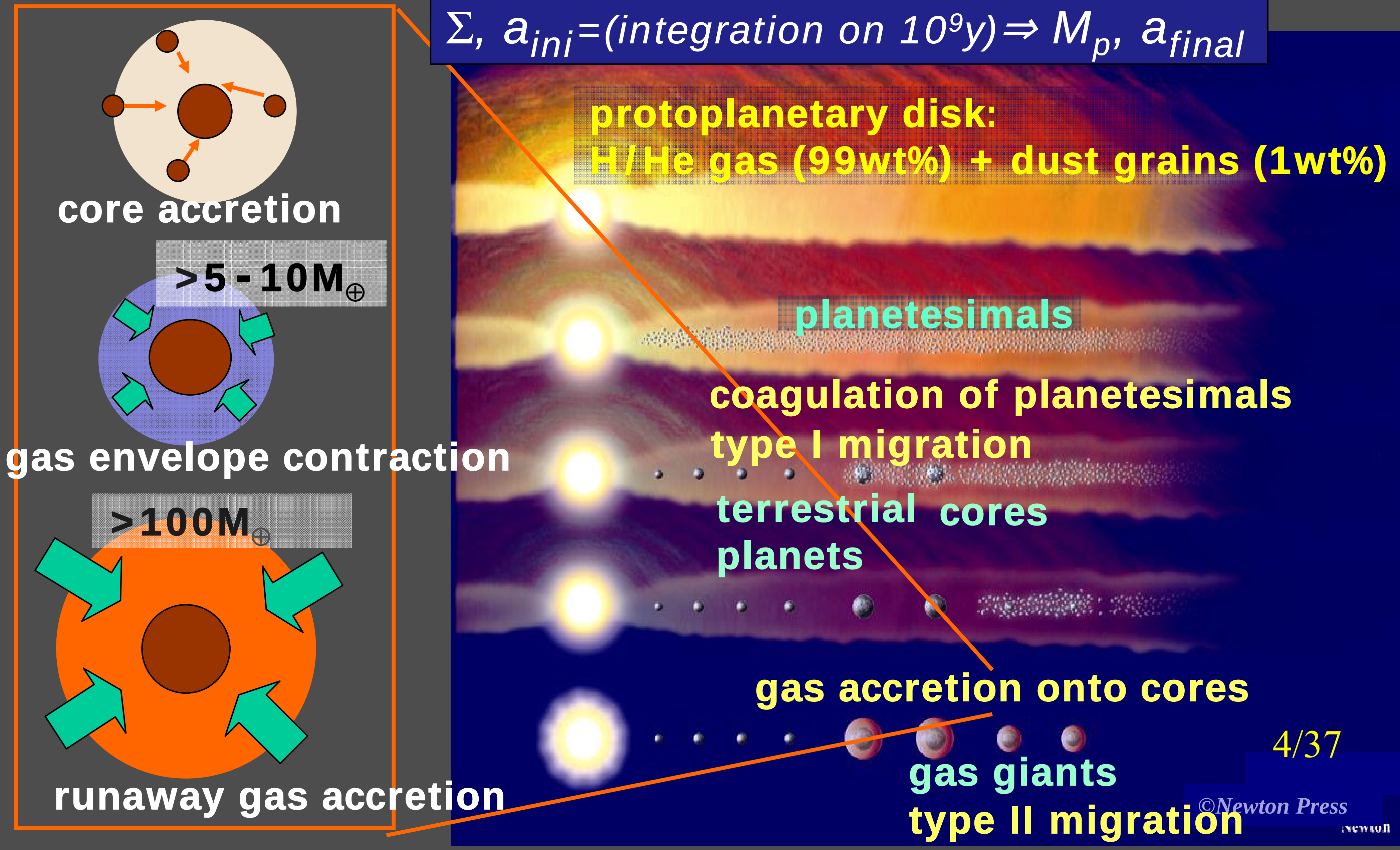


Key Theoretical Issues

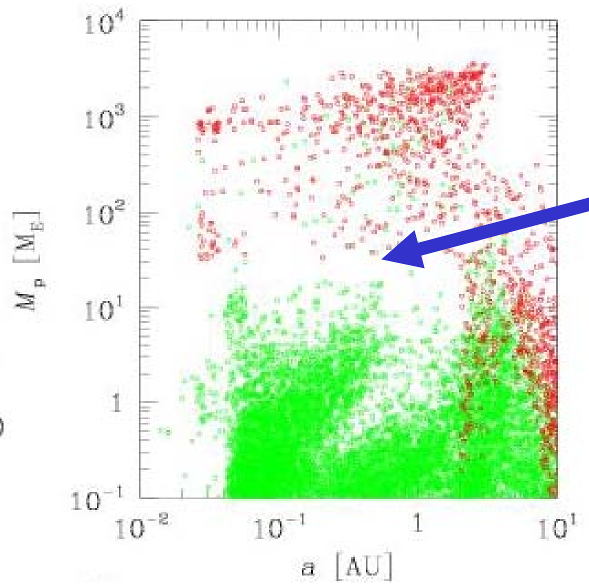
1) What physical processes determine their mass-period and size-period distribution?
2) How do dynamical architecture emerge around any host star?
3) Why is there no super-Earth in the solar system?

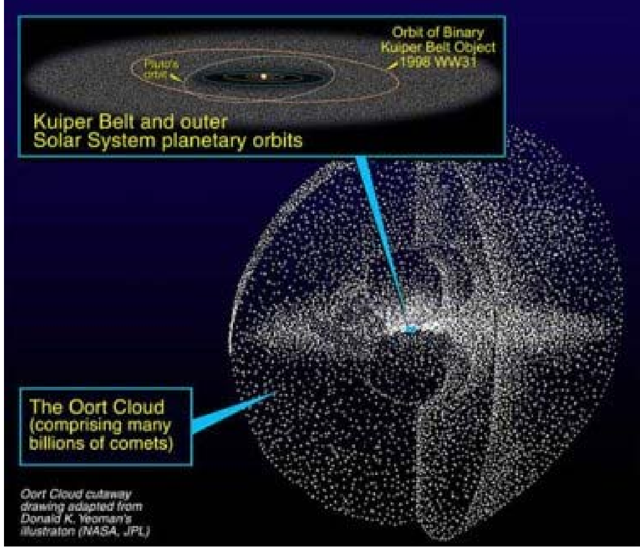
Population synthesis model (PS1.1)
With planet formation & disk evolution

$\Sigma,\ a_{ini}$=(integration on 10^9y)$\Rightarrow M_p,\ a_{final}$



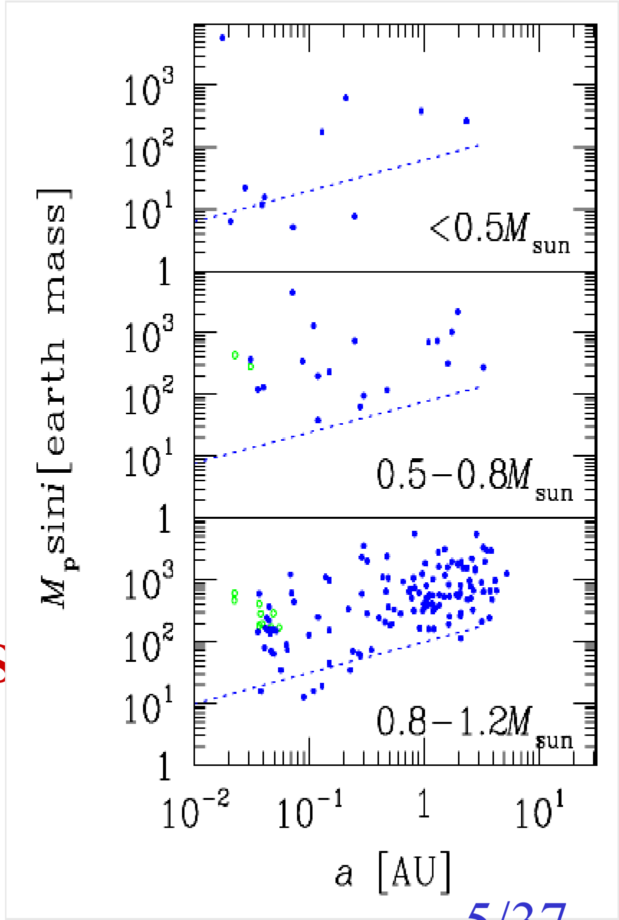
Observable predictions: test





1. Planetary desert

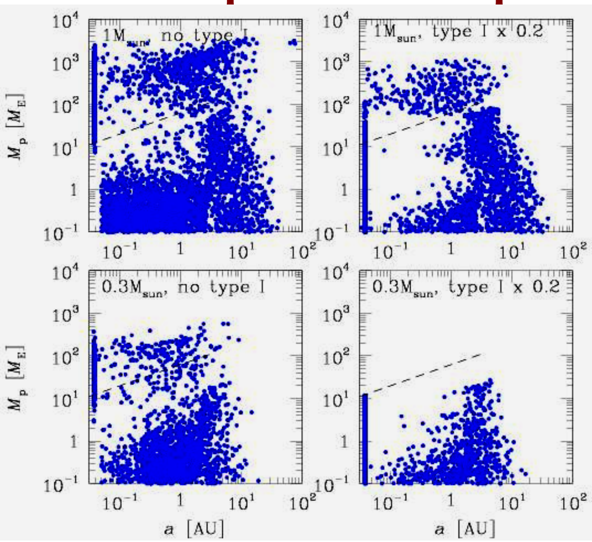
2. rare brown dwarfs & many super-earths



3. Cradle of gas giants: bimodal periods

4.Domains of gas giants: period boundary

5. Epoch of planet formation (1-10 Myr)



6. Dependence on stellar mass: K giants & M dwarfs and metallicity

Why do greater fraction of metal-rich stars have gas giants

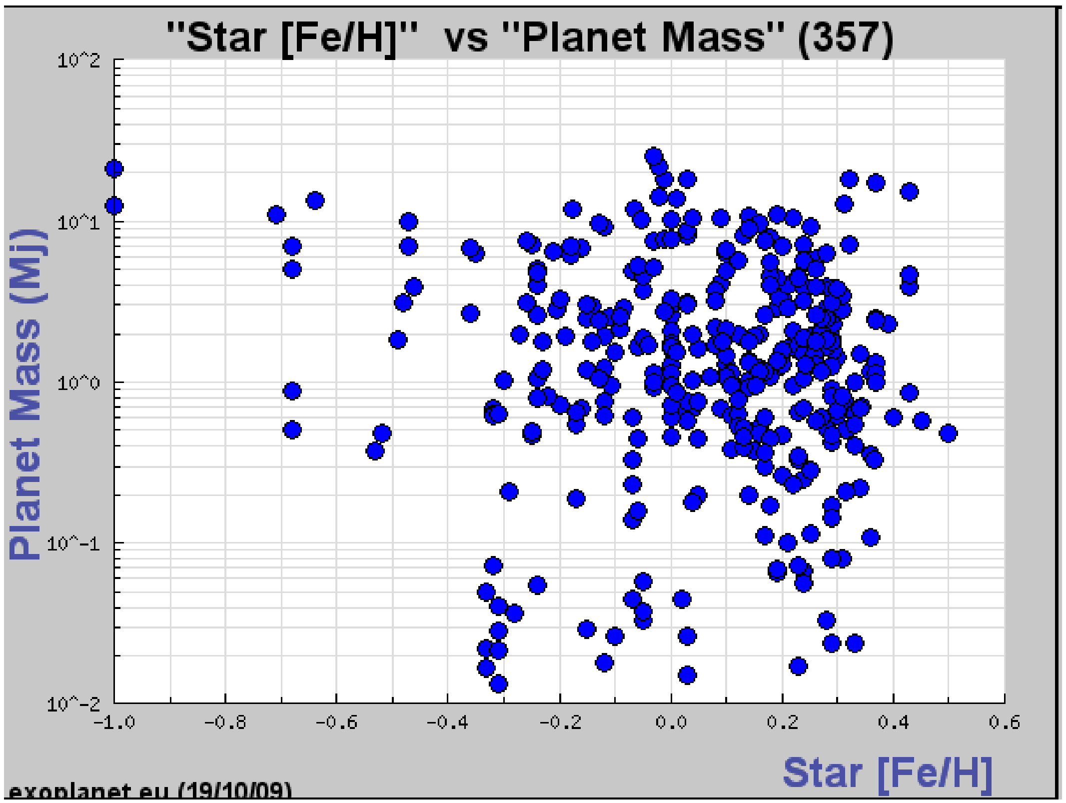


TABLE 5

SME Mean Abundances for Pleiades Stars

Element	Mean log N^a (SME)	log N^b	
		Solar	Meteoritic
Li...	2.51 ± 0.513	1.16	3.31
Na...	6.23 ± 0.042	6.33	6.31
Si...	7.54 ± 0.054	7.55	7.55
Ca...	6.33 ± 0.025	6.36	6.34
Sc...	3.00 ± 0.094	3.10	3.09
Ti...	4.93 ± 0.044	4.99	4.93
V...	4.02 ± 0.038	4.00	4.02
Cr...	5.61 ± 0.037	5.67	5.68
Fe...	7.44 ± 0.021	7.54	7.51
Co...	4.81 ± 0.051	4.92	4.91
Ni...	6.13 ± 0.031	6.25	6.25

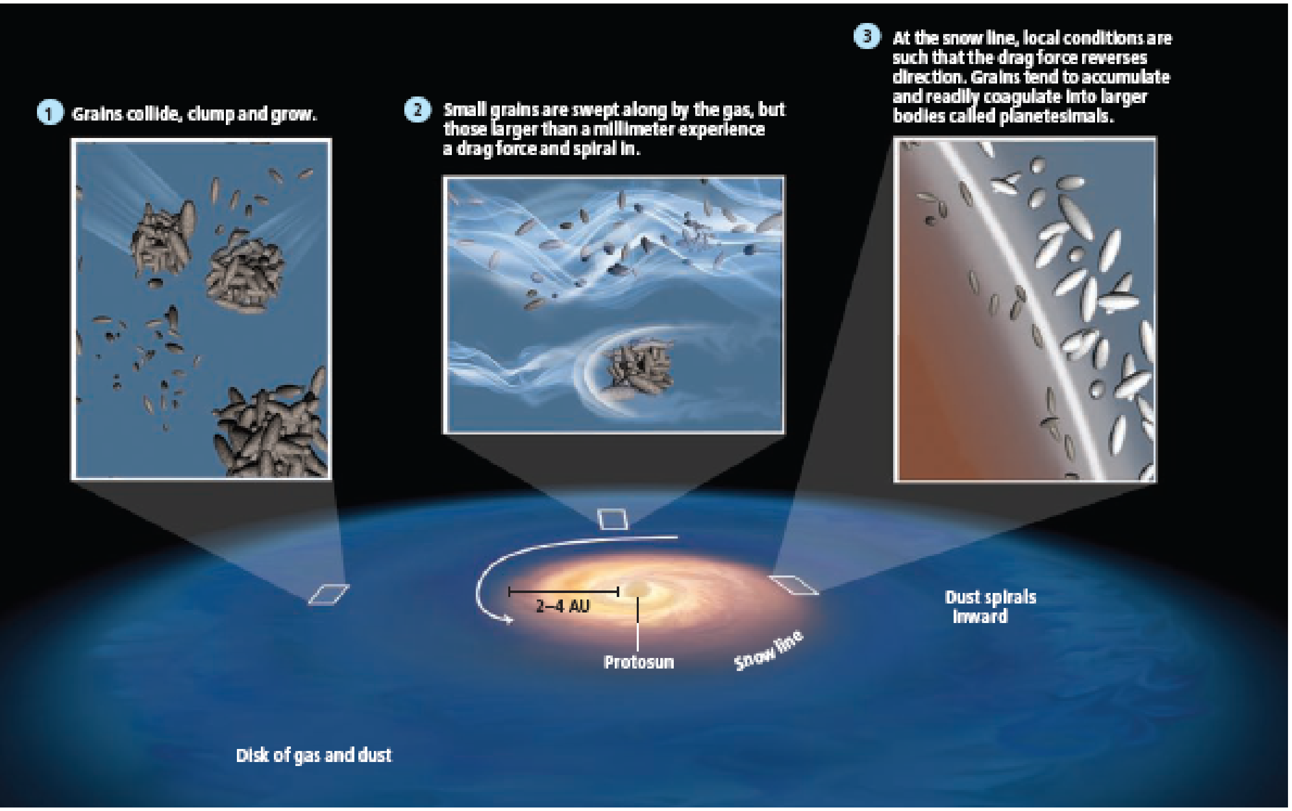
Population Synthesis PS2.1

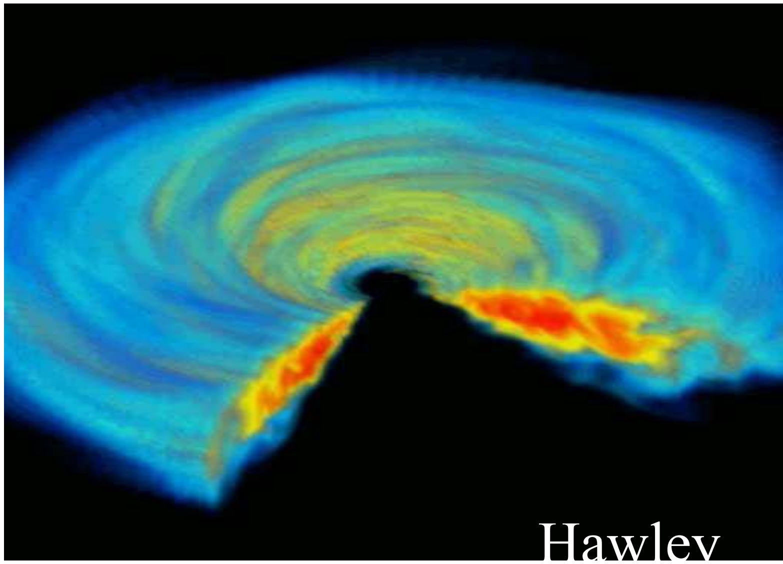
Self-regulated clearing process

Restricted formation region

Homogenous ΔF_e<5%G dwarfs in Pleiaides stars (100 Myr old).

Paradox: building blocks are mobile

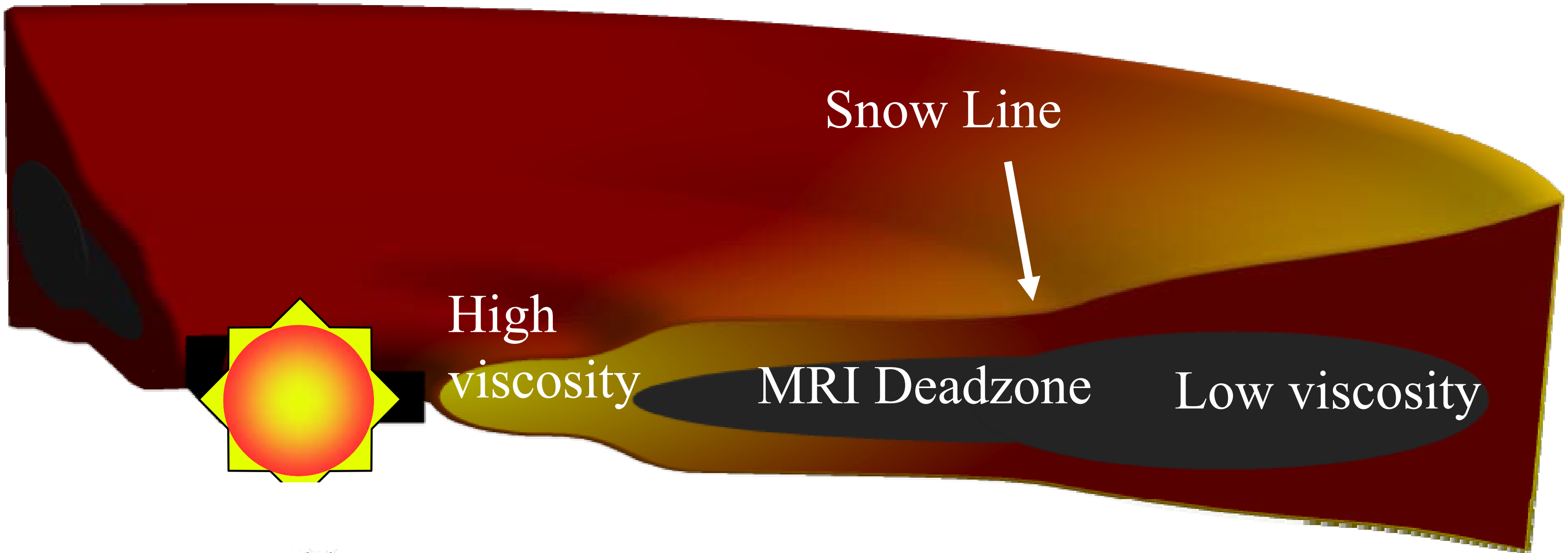


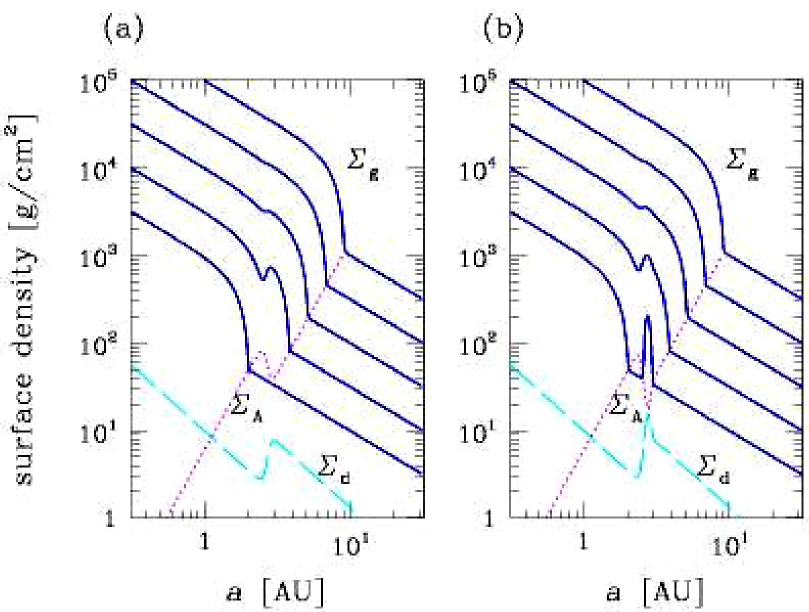


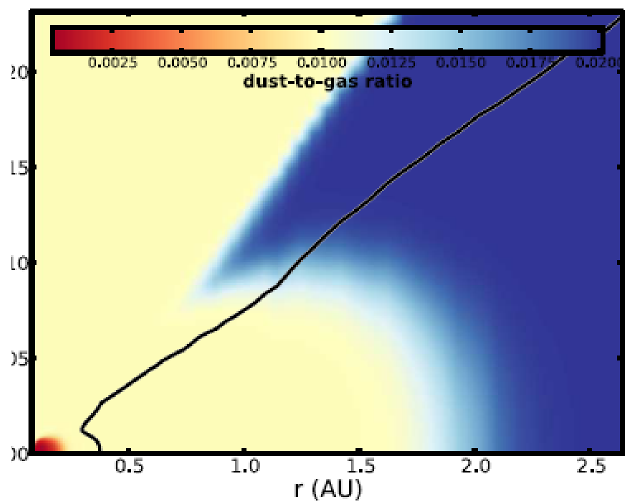
Hydrodynamic **drag & drift** towards the Sun

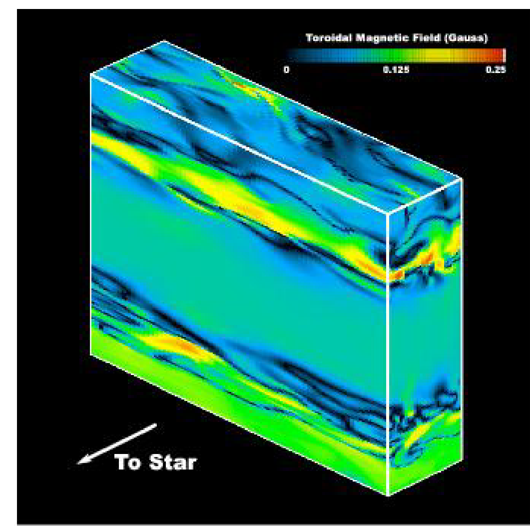
Snow Line barrier during late evolution (**PS 2.2)**

Magento-Rotational Instability

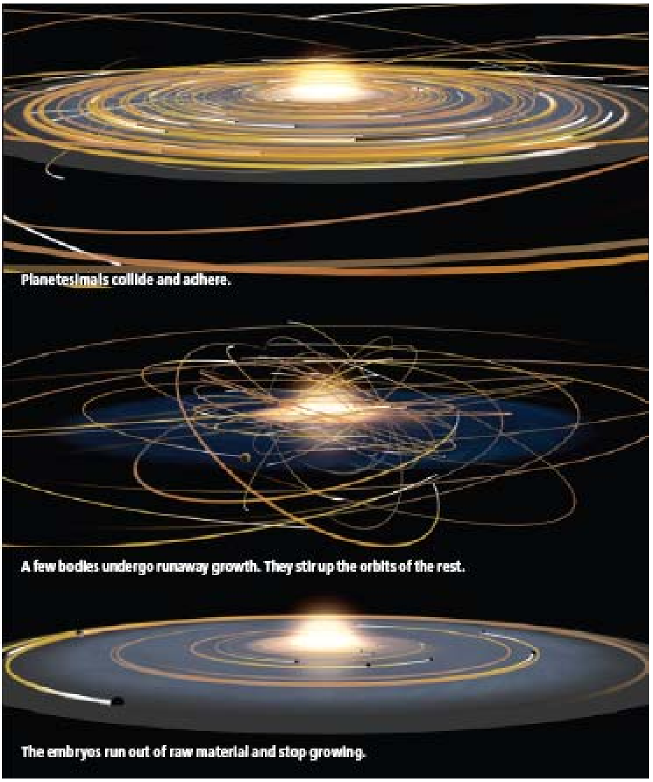








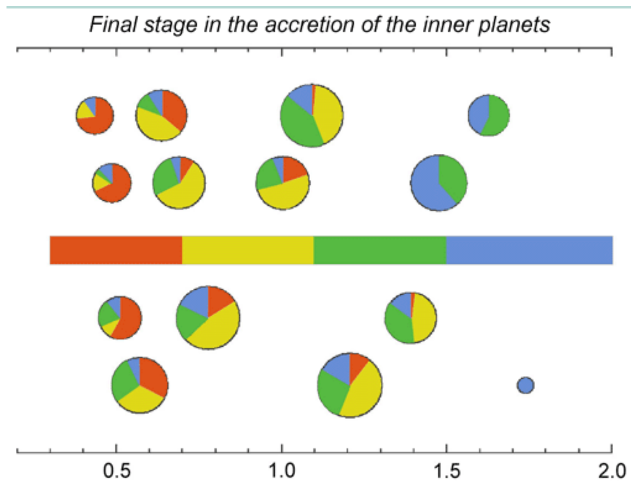
Back to the **core accretion** theory

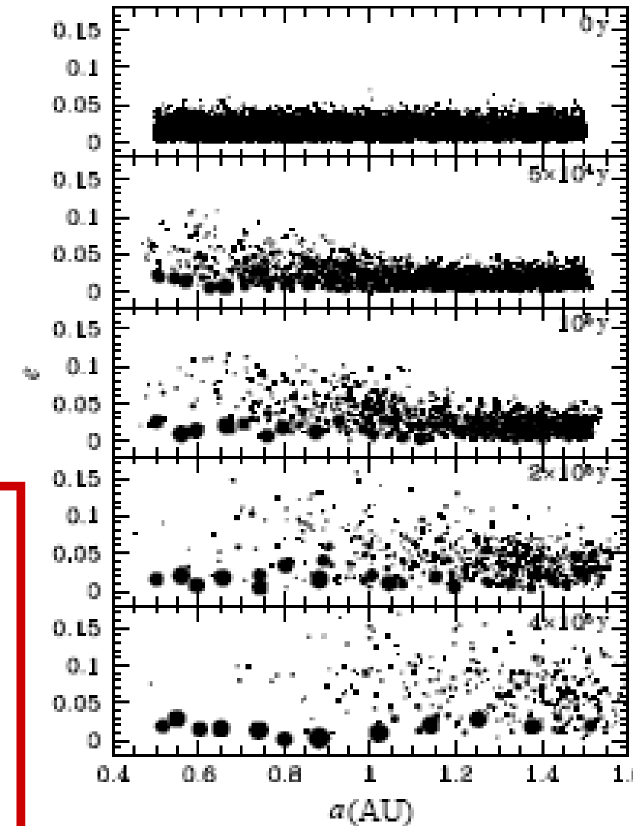


Grains => **planetesimals =>embryos**

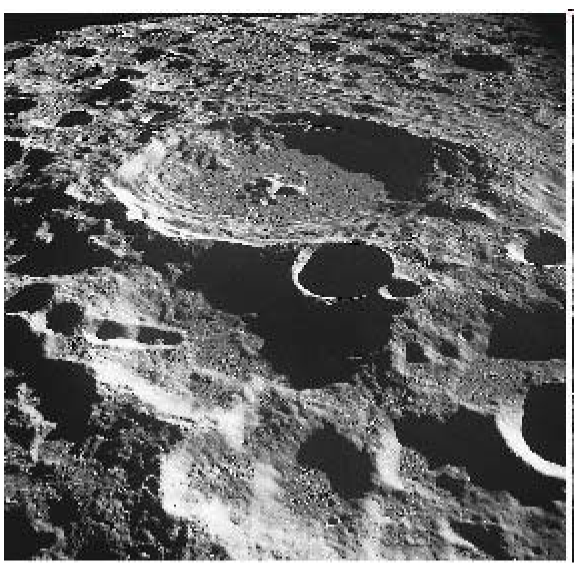
relaxation, **coagulation**, & fragmentation

Isolation Mass: ~ Mars' mass in NMSN





Kokubo& Ida



Feeding zones:

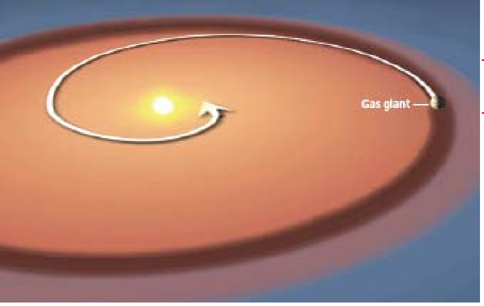
$\Delta \sim 10\ r_{Hill}$

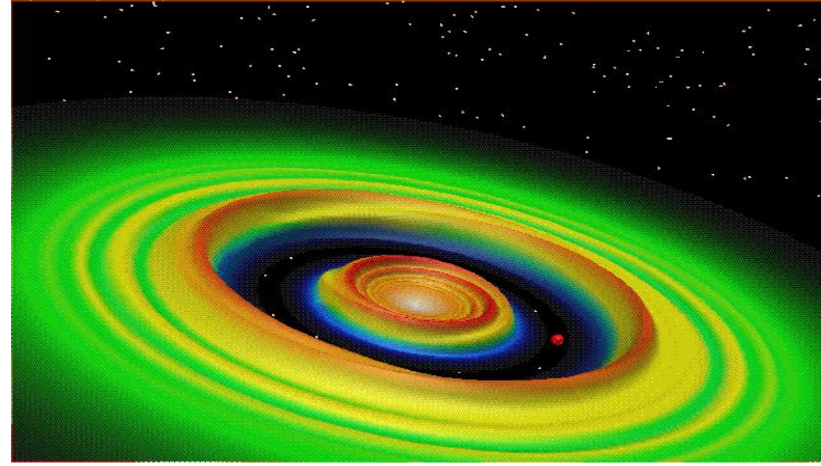
Isolation mass:

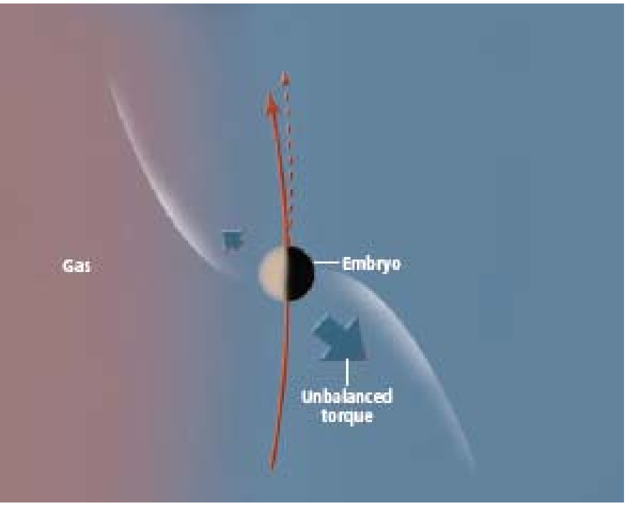
$\mathbf{M_{isolation} \sim \Sigma^{1.5}\, a^3 M_*^{-1/2}}$

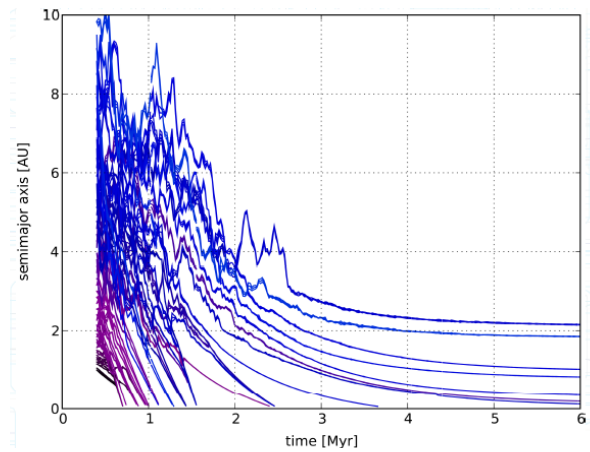
Challenge: how to form **close-in super-Earths**

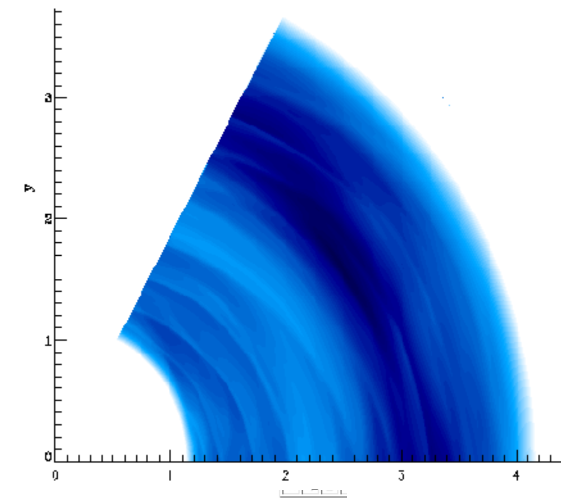
Migration & retention

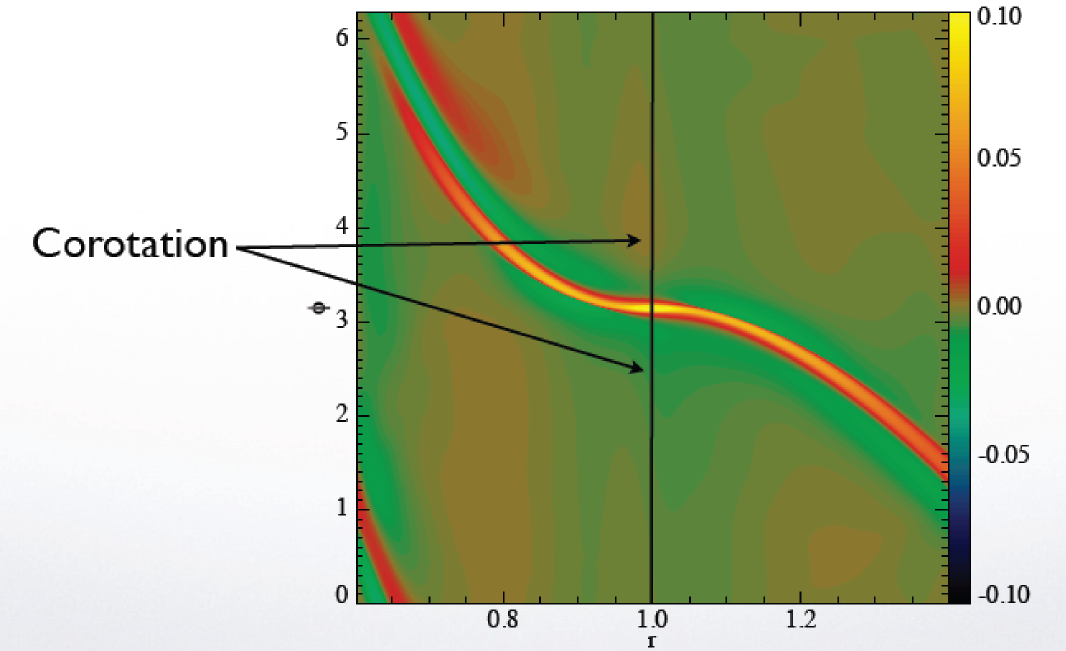


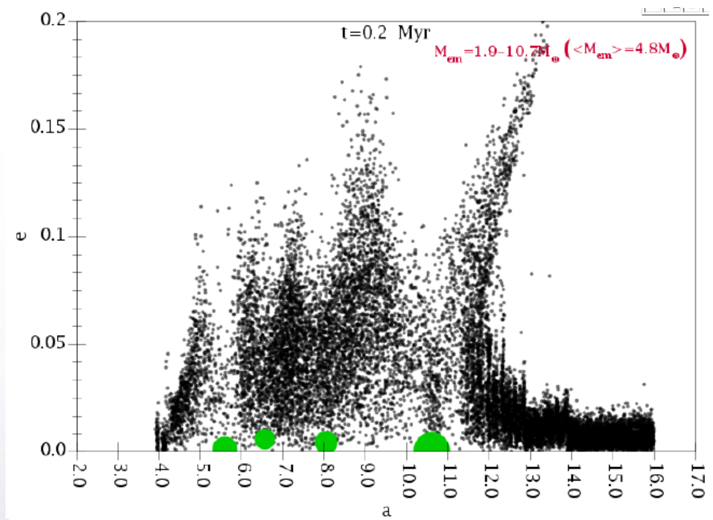




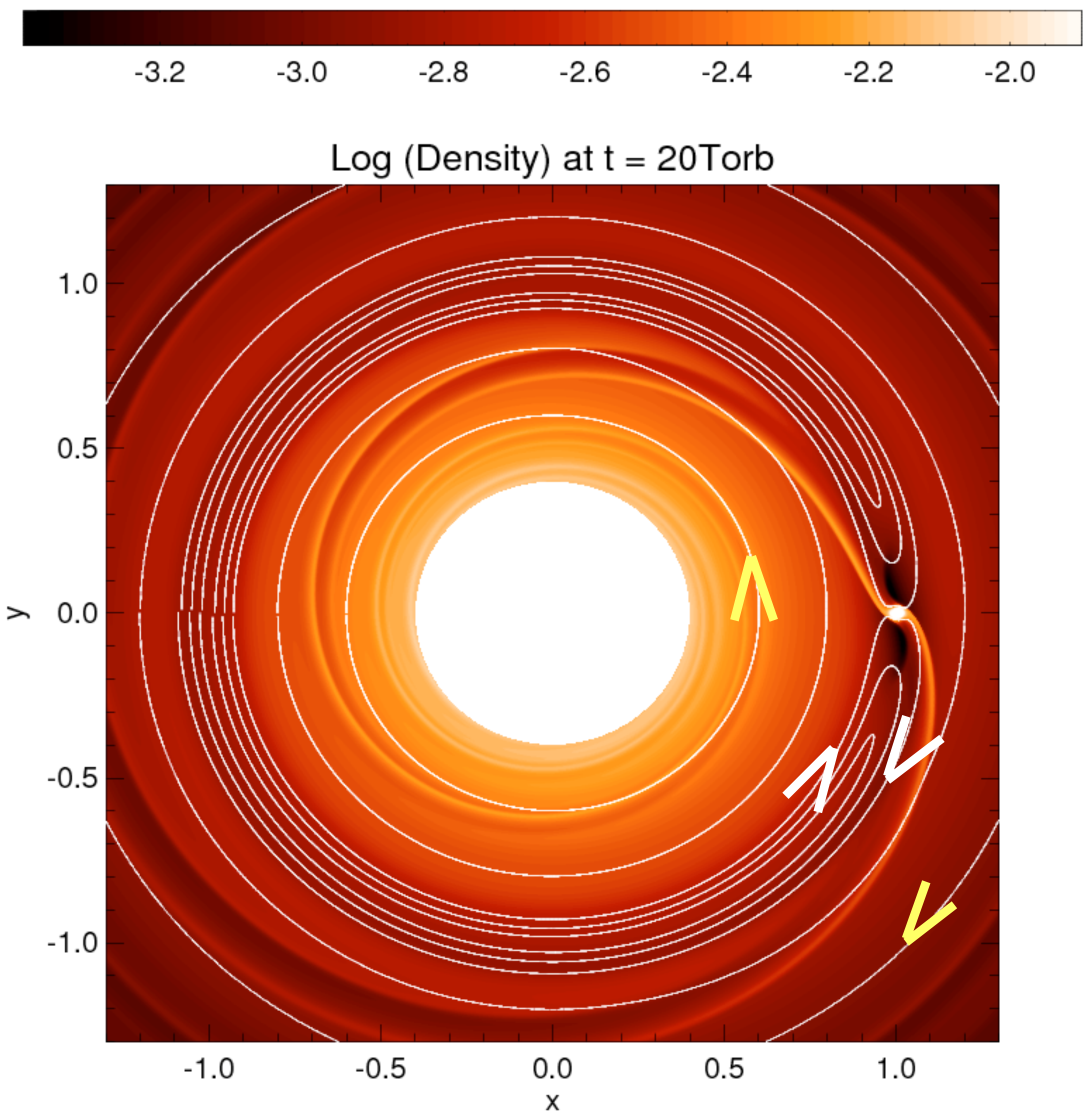






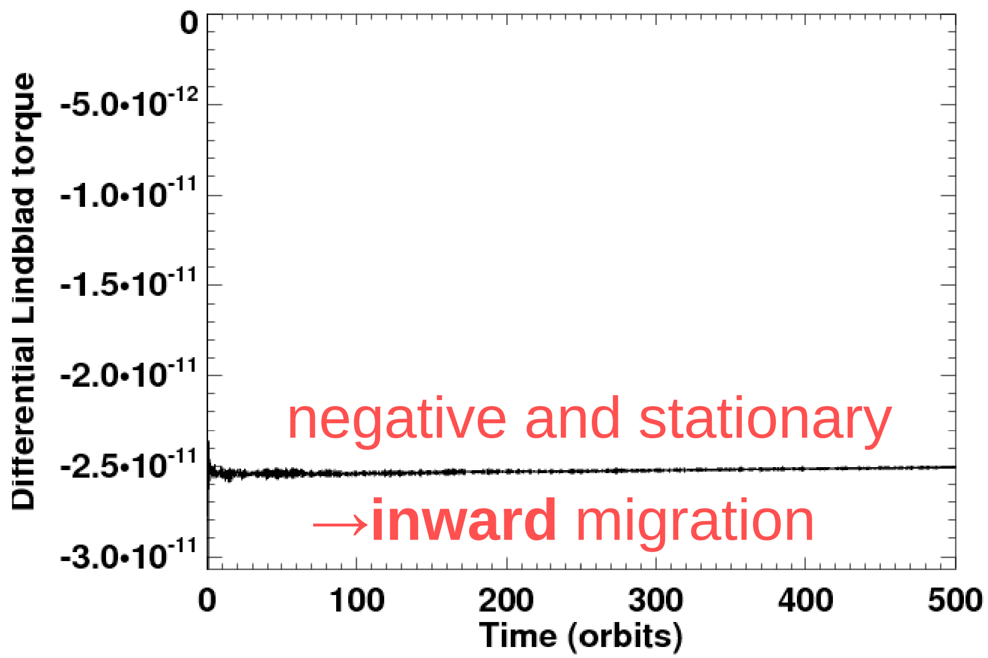


Type I migration in isothermal disks



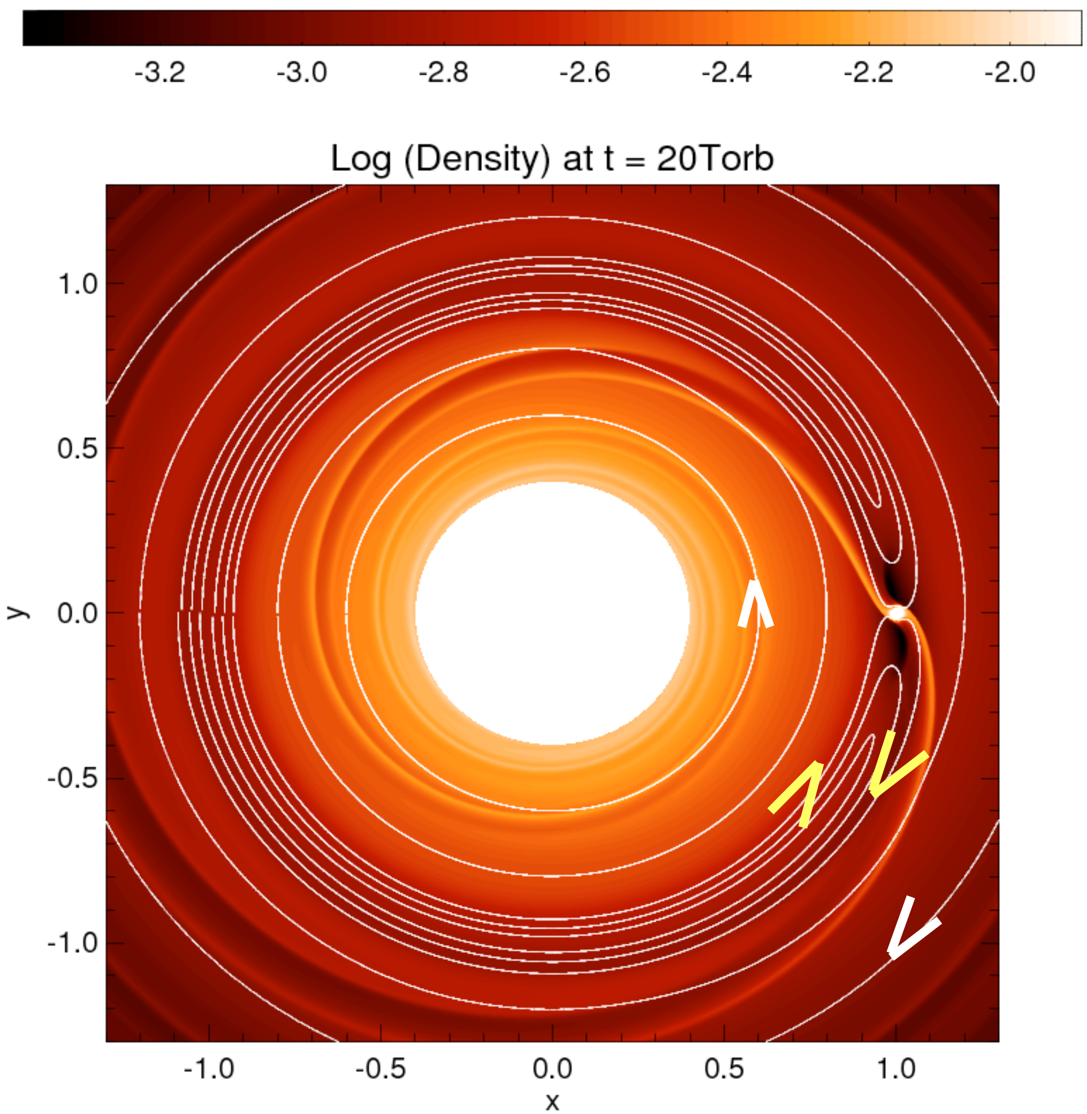
The planet exchanges angular momentum with:

- **circulating** fluid elements:
  →**differential Lindblad torque**
- **librating** fluid elements:



e.g. Goldreich & Tremaine (1980), Ward (1997)

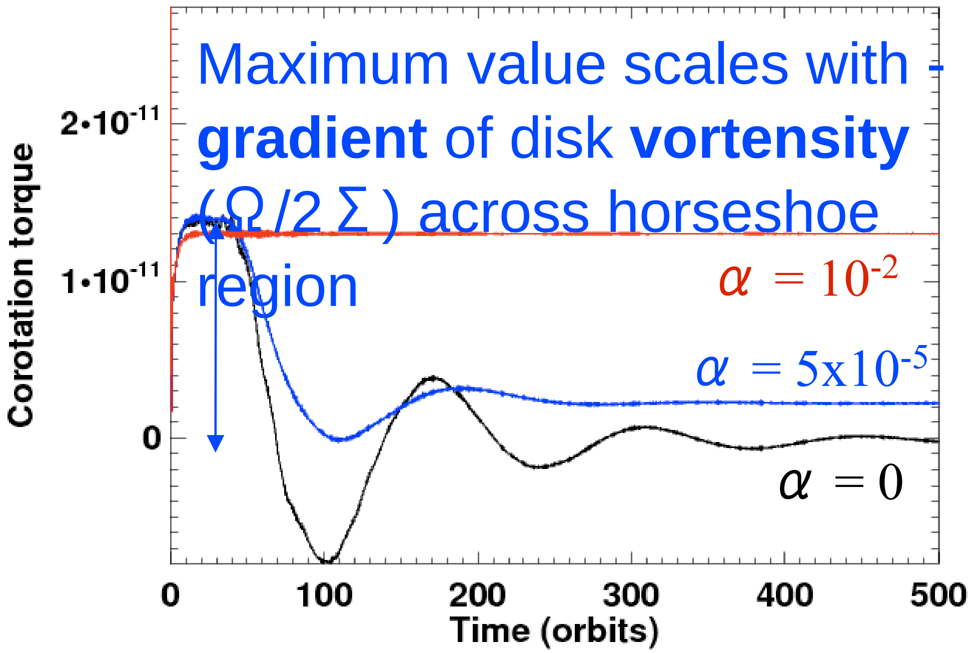
Type I migration in isothermal disks



The planet exchanges angular momentum with:

- **circulating** fluid elements:
  →**differential Lindblad torque**

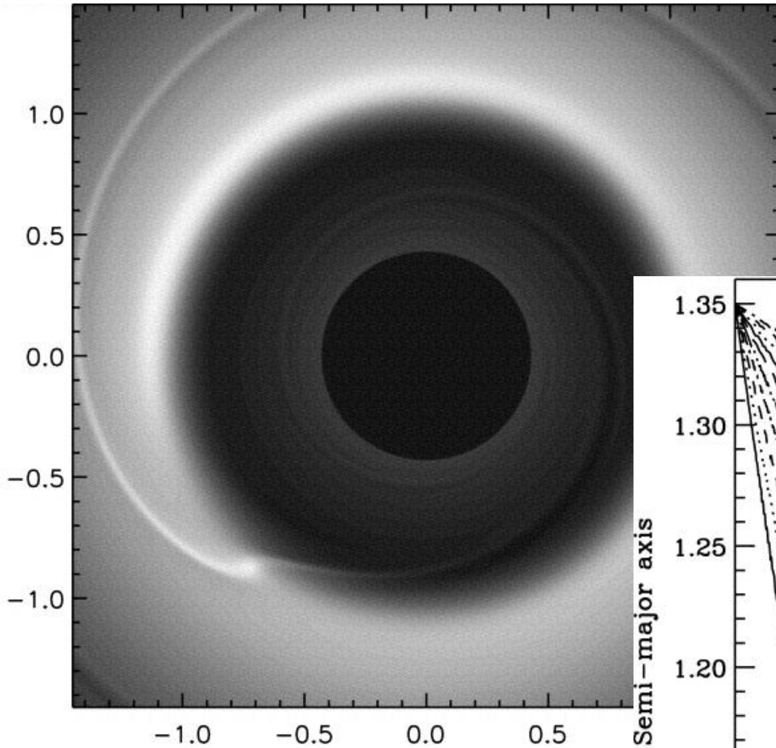
-**librating** fluid elements:
  →**corotation torque**



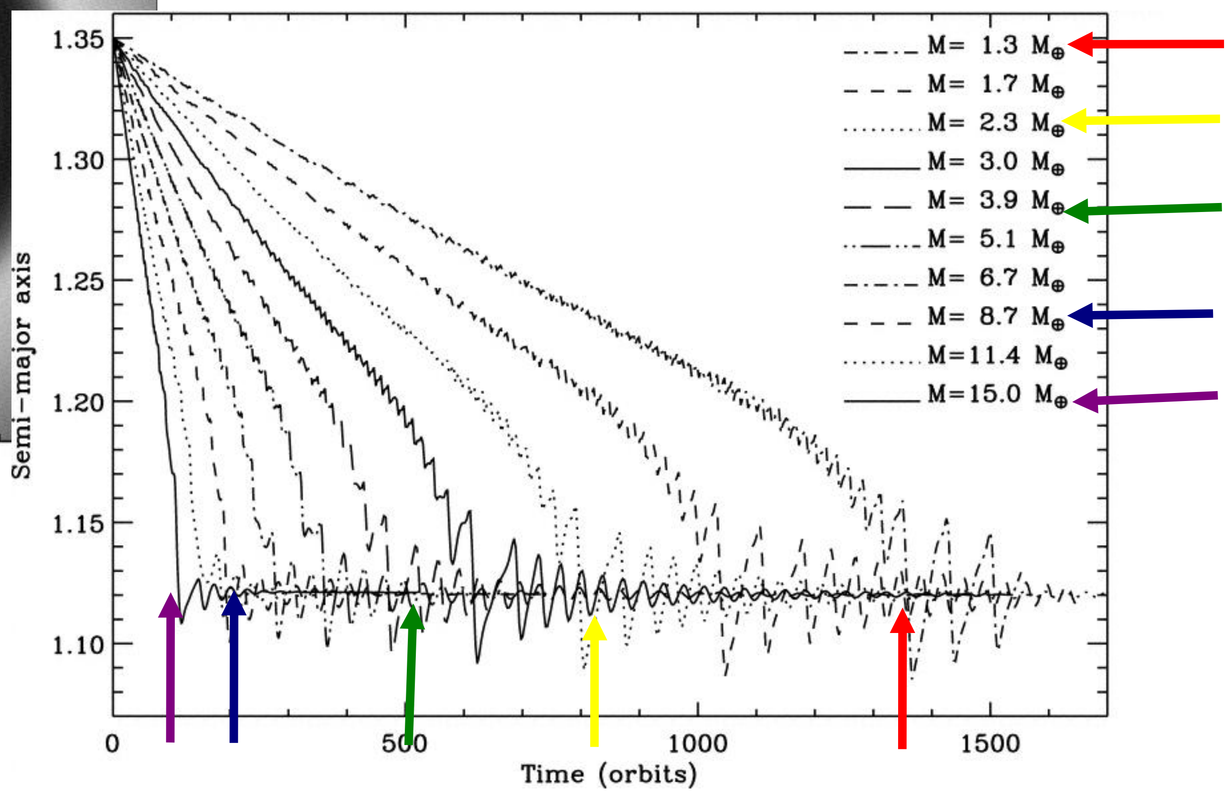
e.g. Ward (1992), Masset (2001)

! Long-term evolution of the corotation torque is related to the disk viscosity

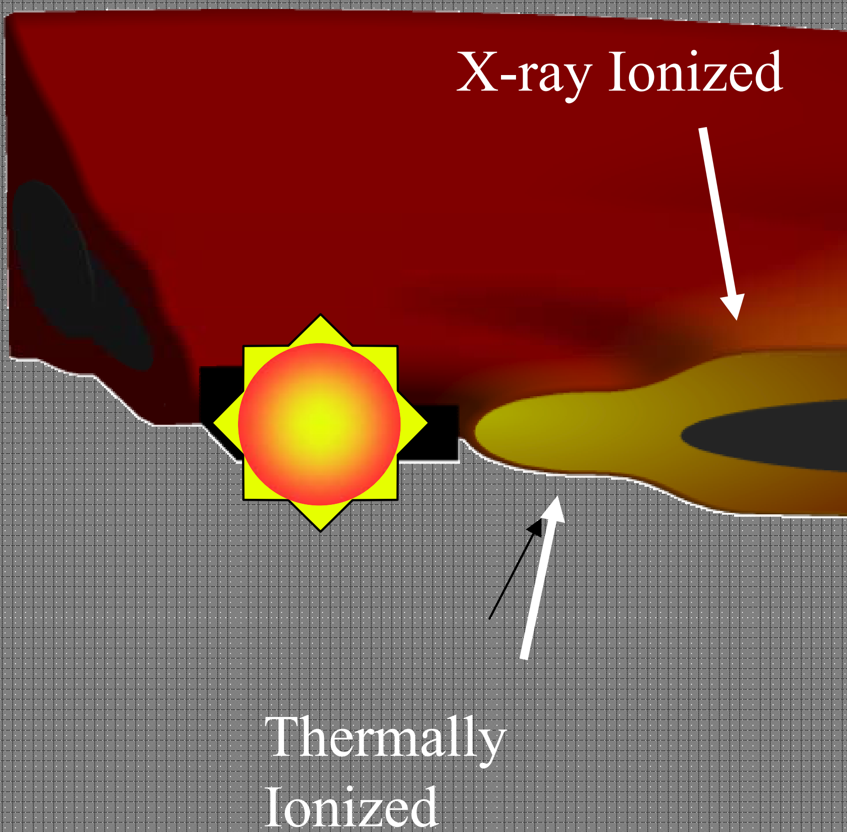
Type I Migration

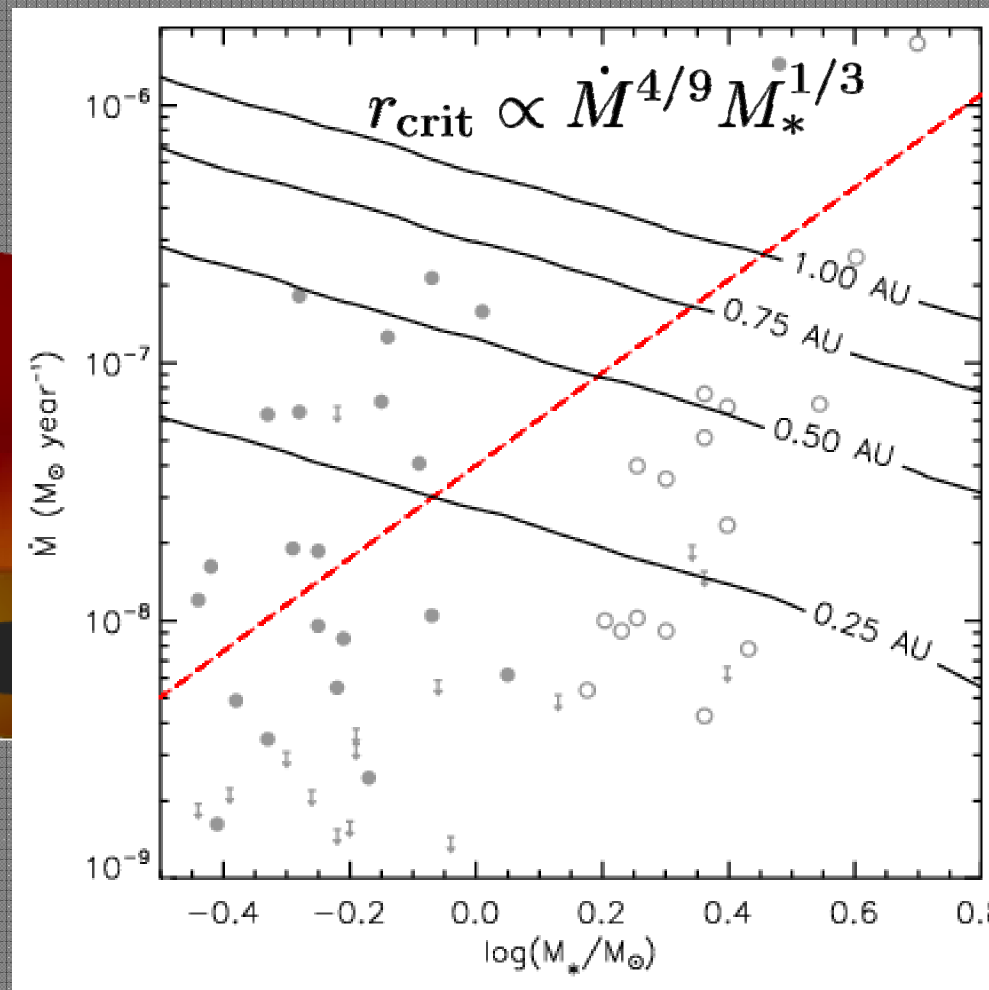


Masset et al. 2006



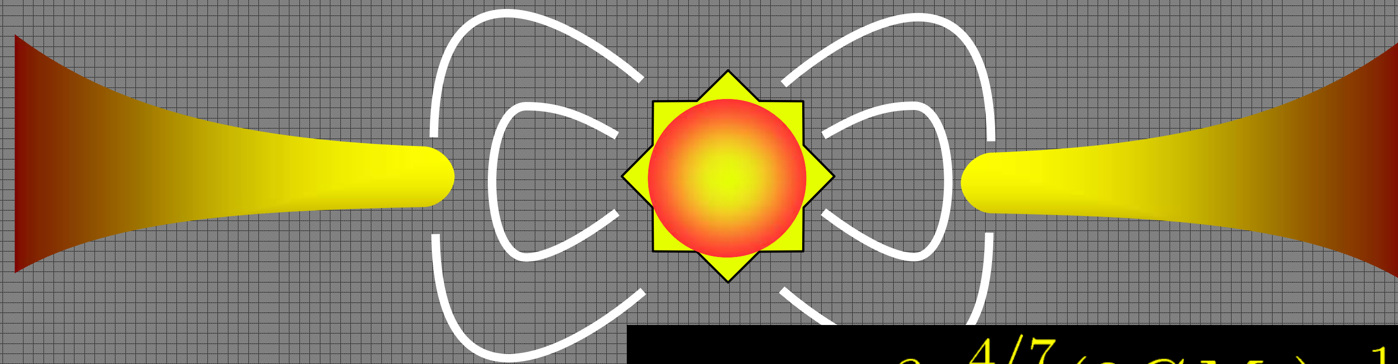
Inner Edge of the Deadzone $r_{\rm crit}$



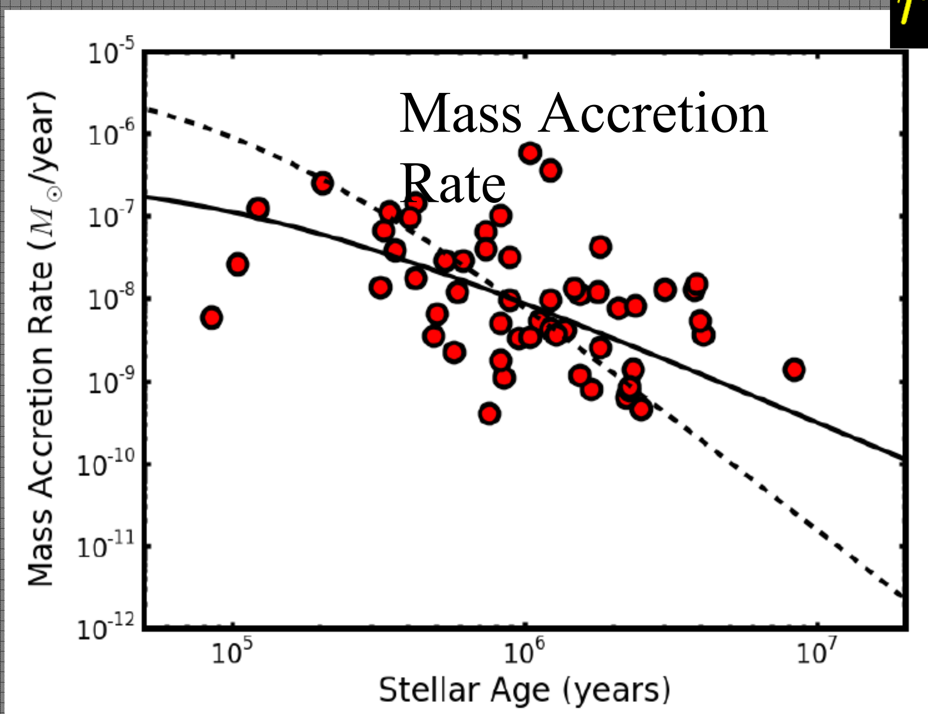


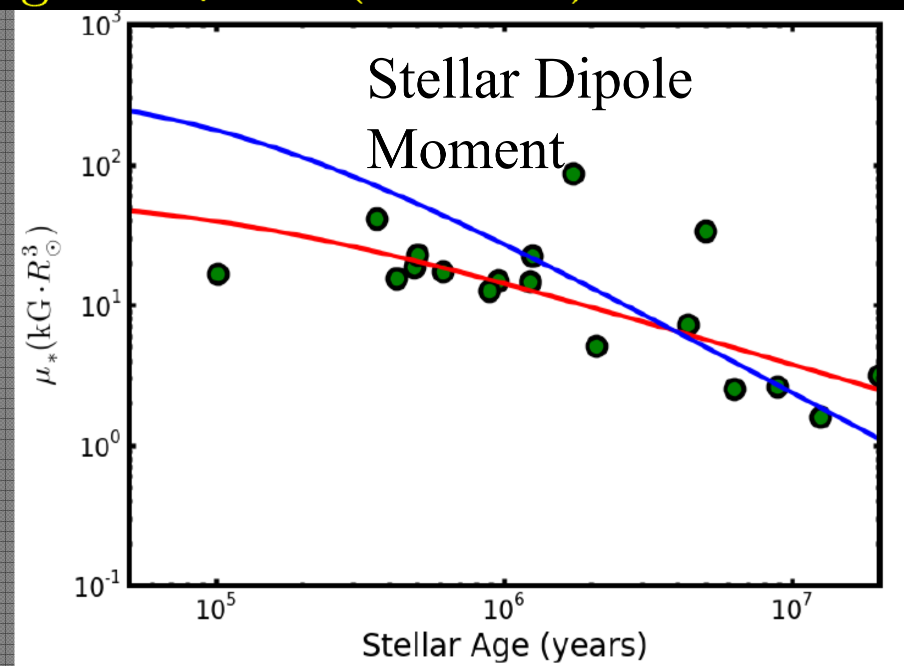
Kretke et al. 2009
(Observations Natta et al 2006)

Magnetospheric Truncation Radius



$$r_{\mathrm{mag}} = \beta \mu_*^{4/7} (2GM_*)^{-1/7} \dot{M}^{-2/7}$$

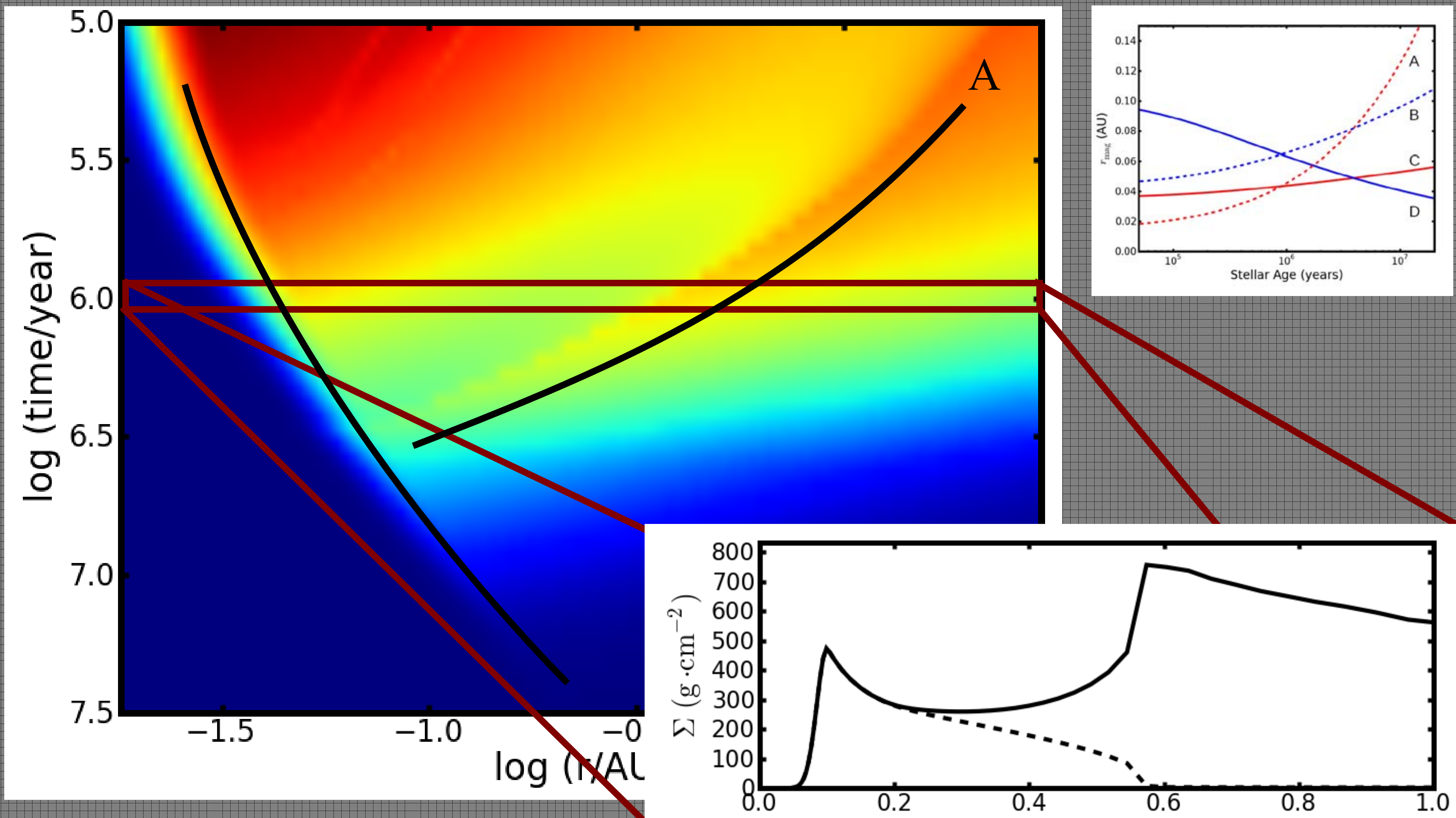




Hartmann et al. 1998

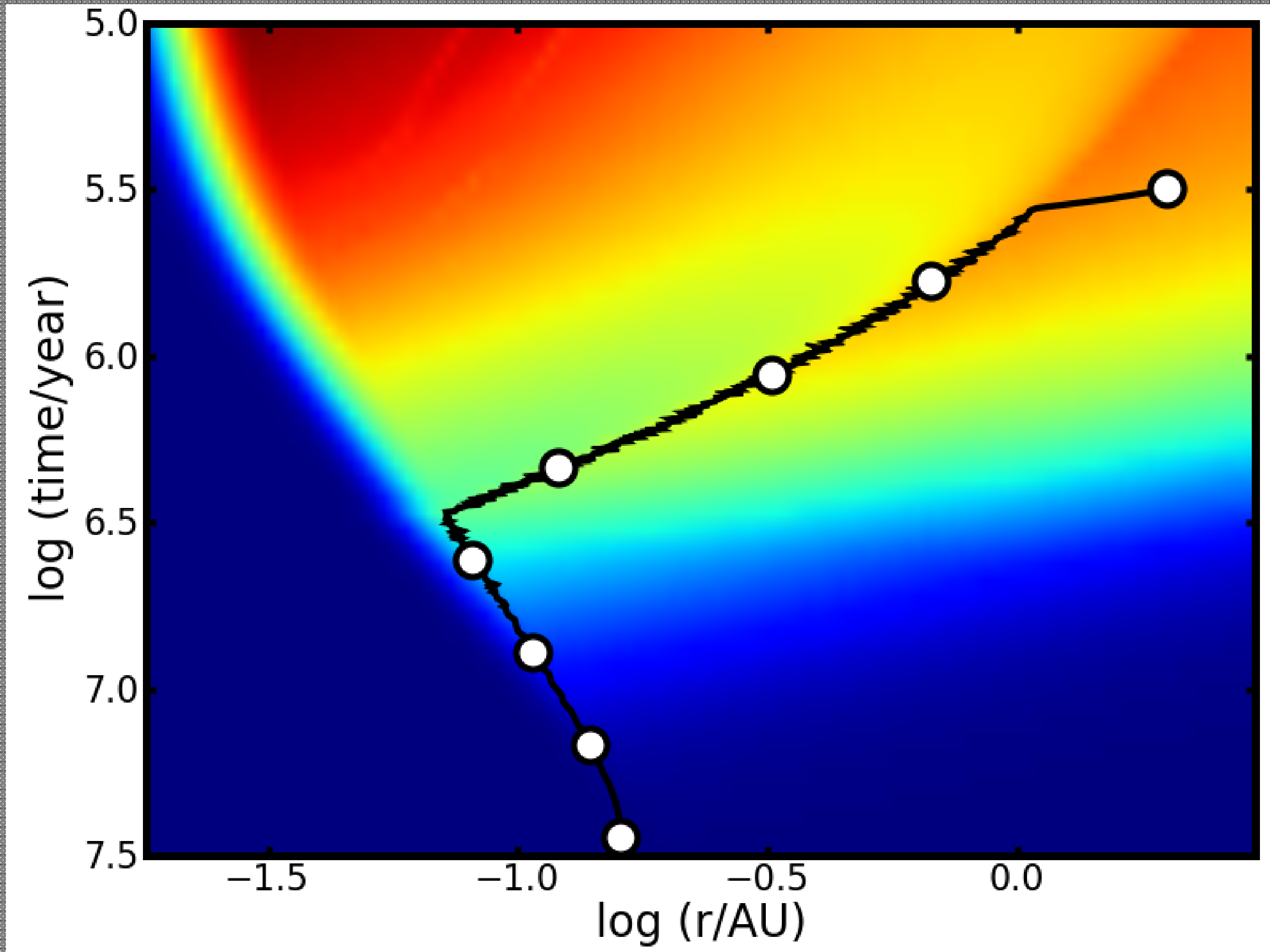
Johns-Krull 2007; Yang et al. 2008

Evolution of Disk



Kretke & Lin (2010)

Planet Migration



Kretke & Lin (2010)

Unipolarinduction

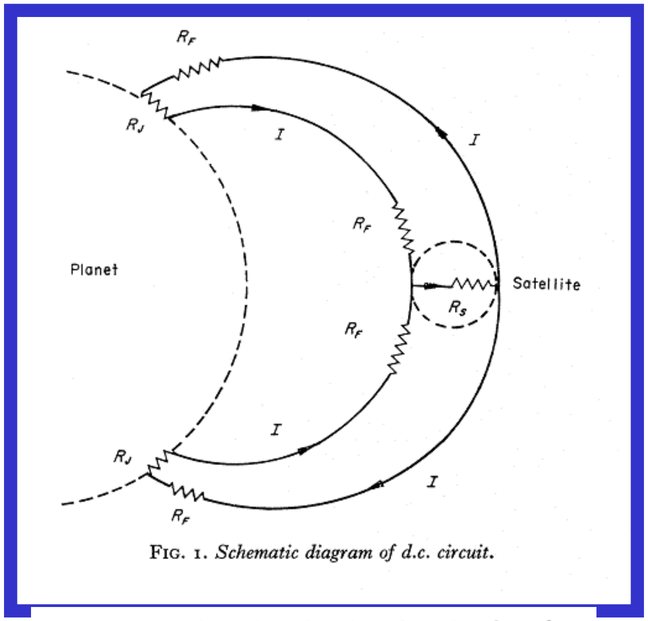
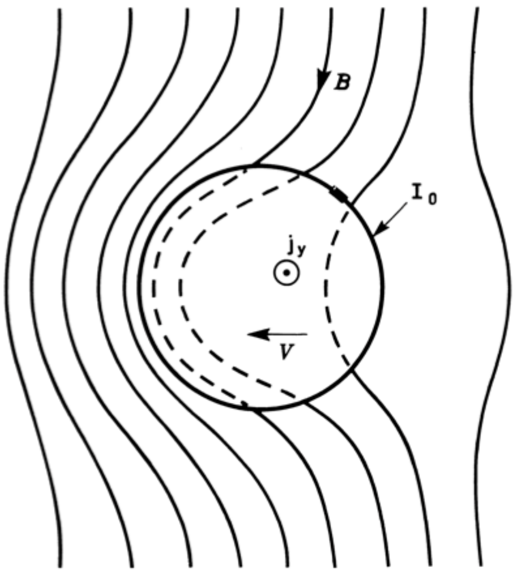
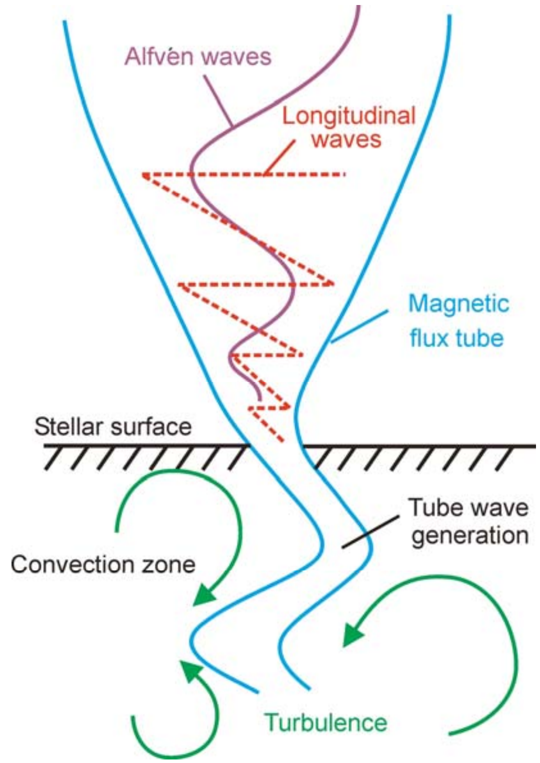
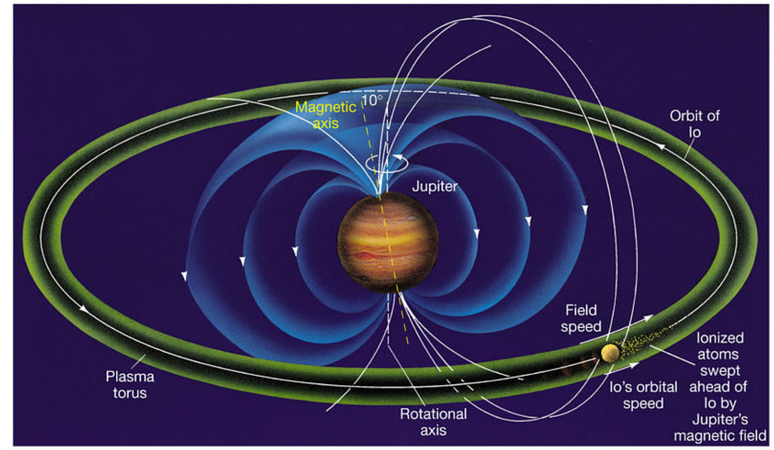


FIG. 1. *Schematic diagram of d.c. circuit.*



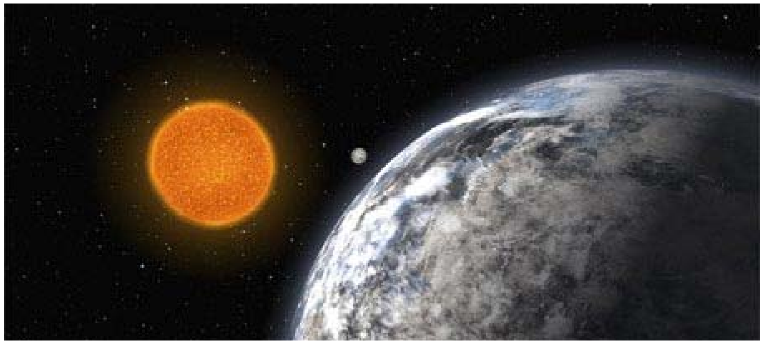


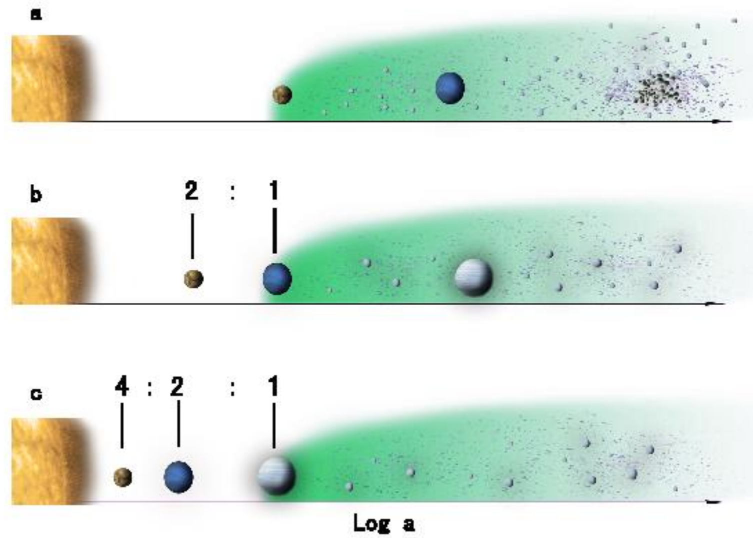


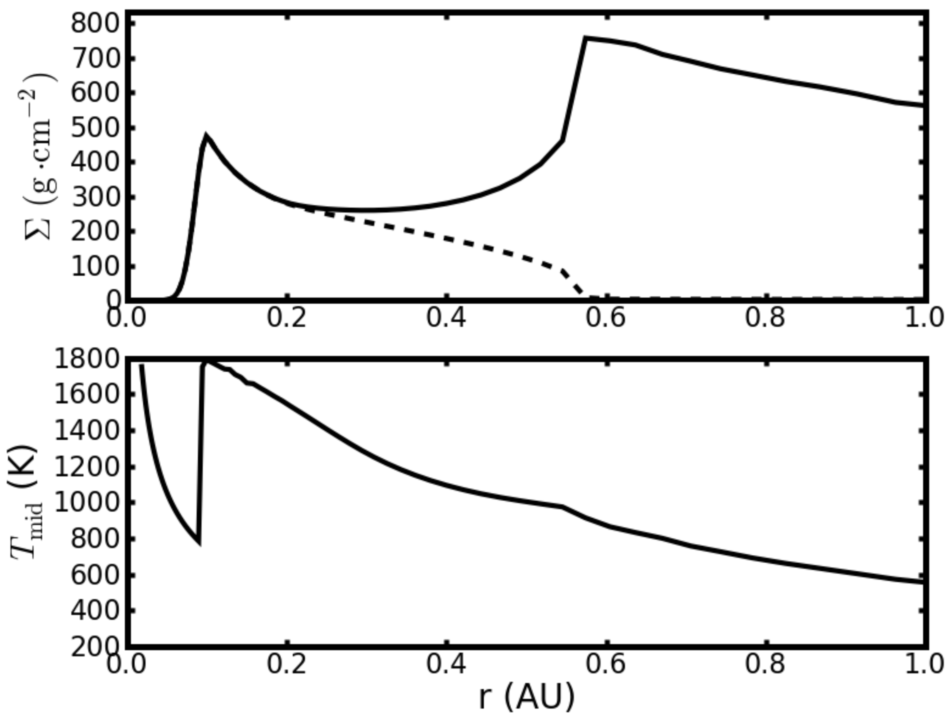
Induced field drags the planet to co-rotate. A planet's orbit would decay/expand if it is inside co-rotation radius.

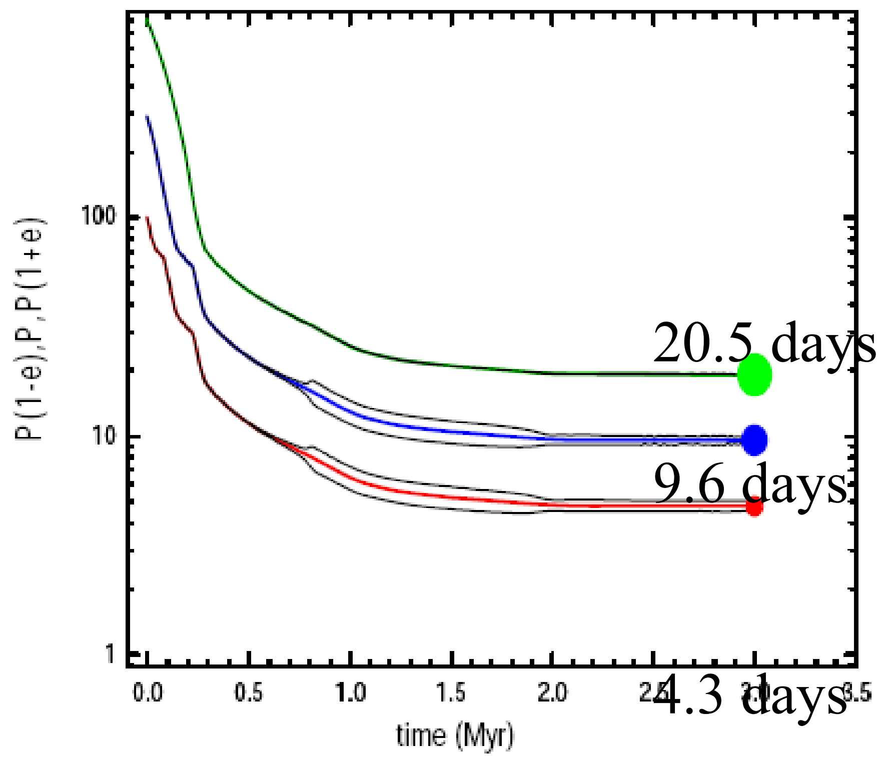
Good conductivity on the planet's atmosphere is needed! Stellar UV flux provides an ionization source.

HD 40307b,c,d as failed cores

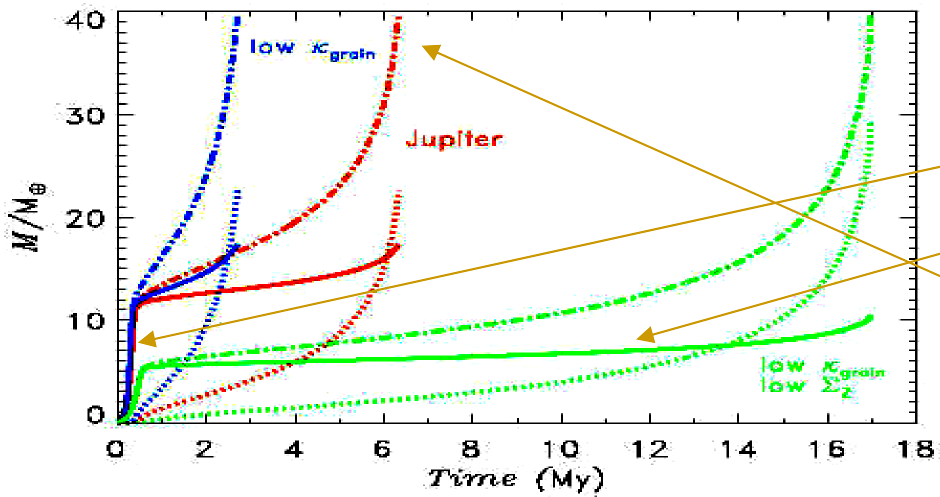








Zhou, Lin, Kretkesubmitted



Accretion onto cores

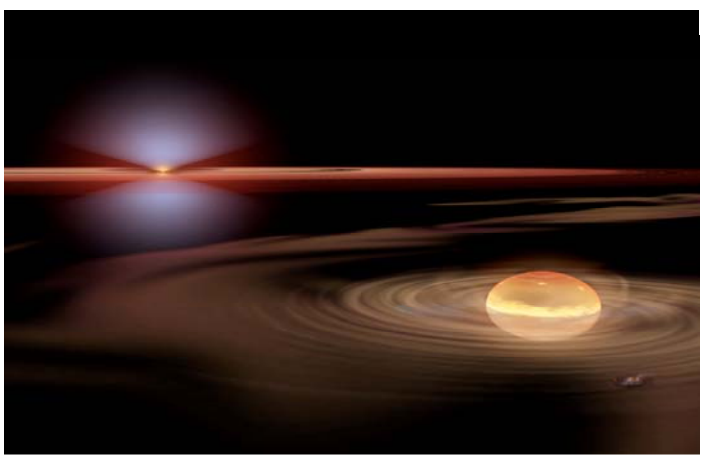
1. **Phase 1:** runaway solid accretion
2. **Phase 2:** solid and gas accretion rates are small and time independent; gas rate > solid rate
3. **Phase 3:** runaway gas accretion
4. Cooling and contraction

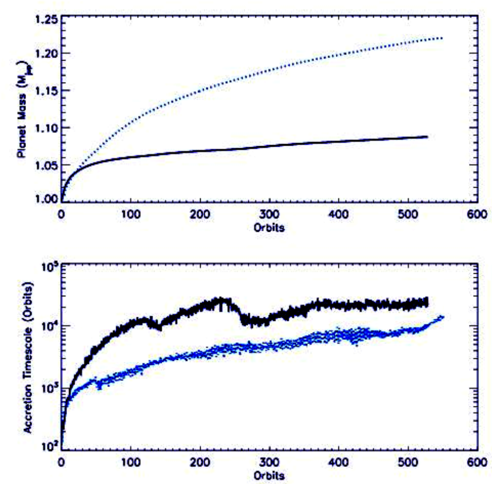
Cameron, Pollack, Bodenheimer:

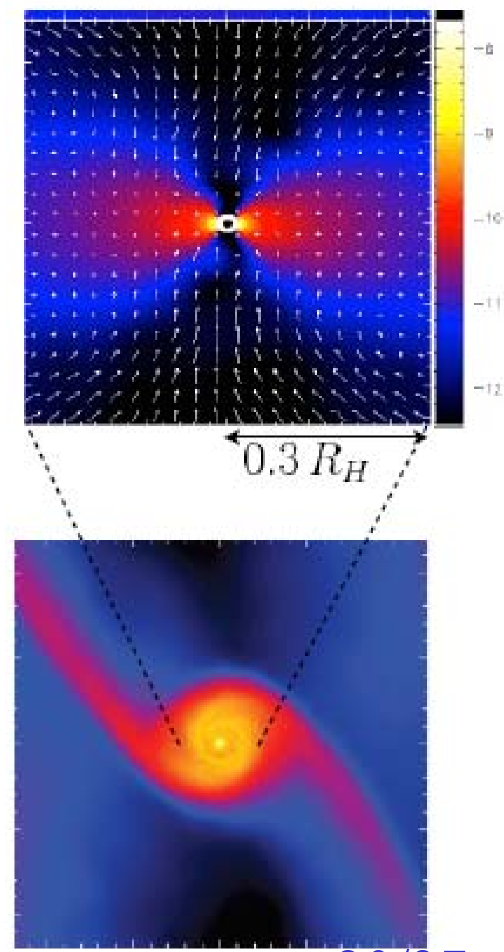
10 M_{Earth} cores needed to **accrete gas**

Lin, Papaloizou

M_J needed to **open gap**& stop growth



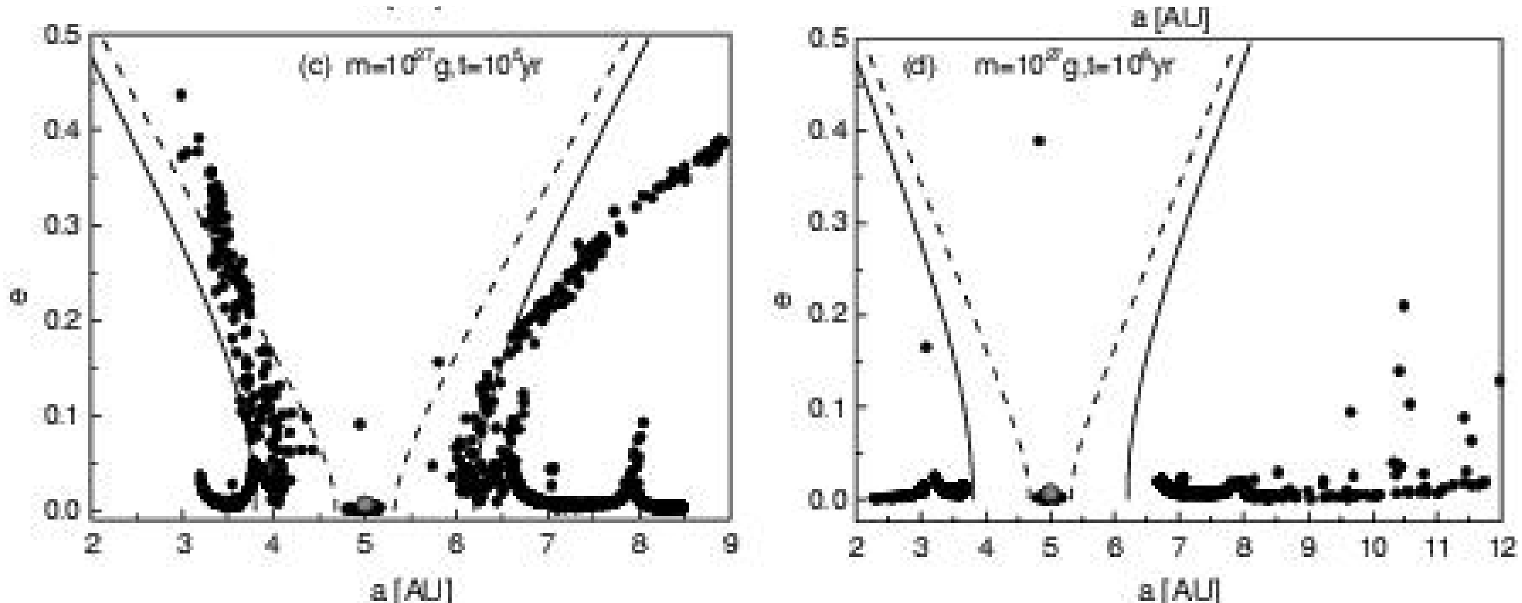




Challenge: how to **retain 10 M_{Earth} cores**

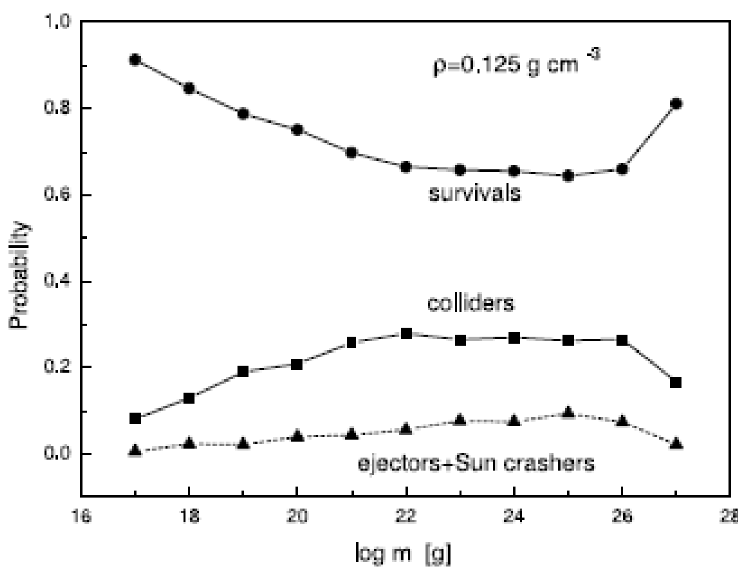
Kley, Bate

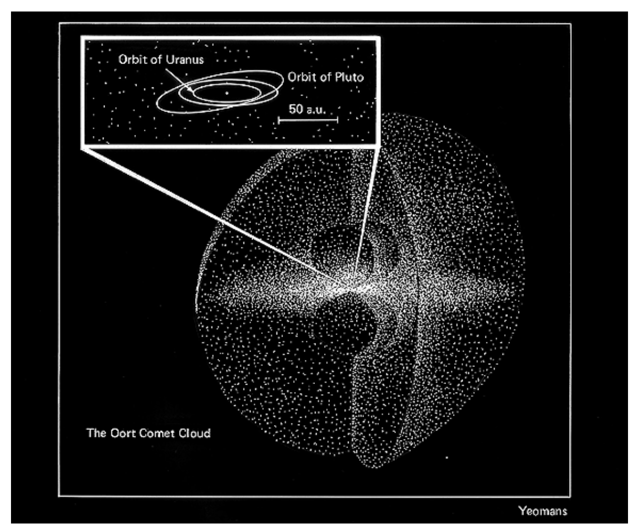
Environmental impact of gas giants



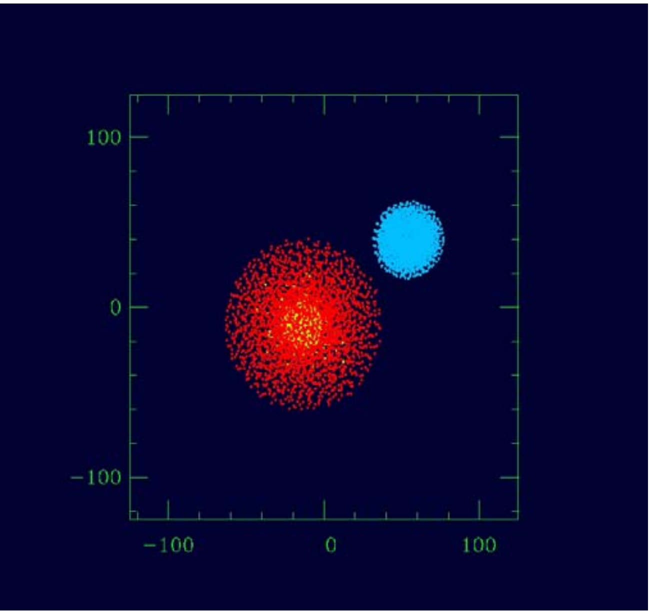
Early slow-growth phase: clearing of **planetesimal gap**

Late rapid-growth phase: **orbit crossing of embryos**

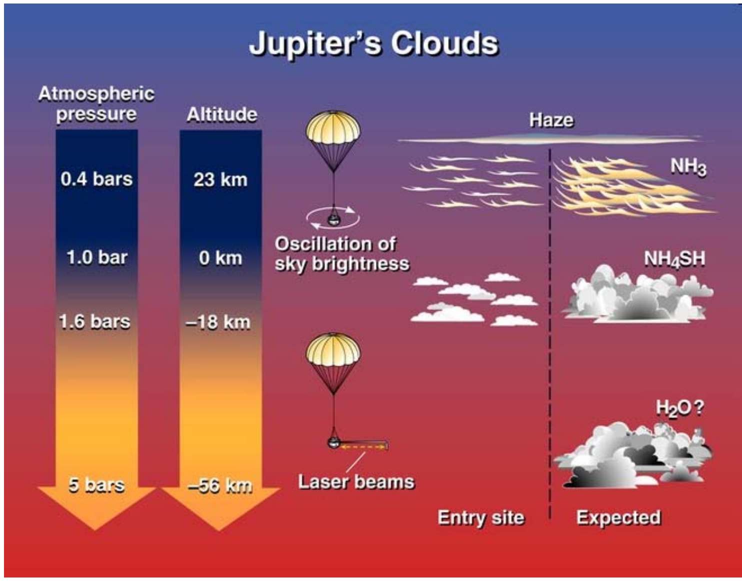


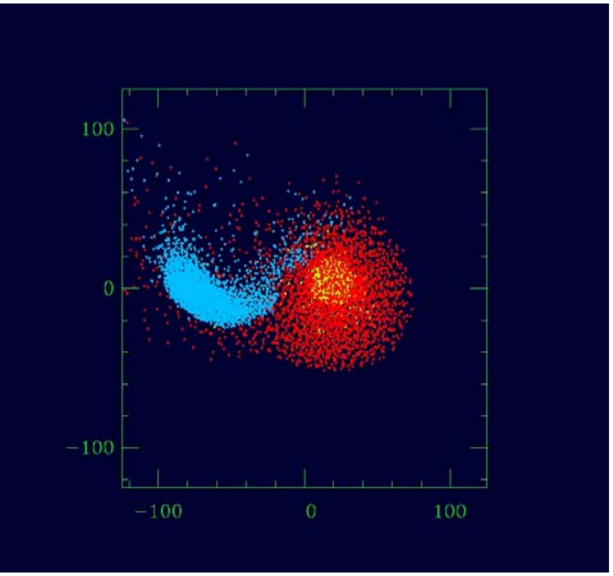


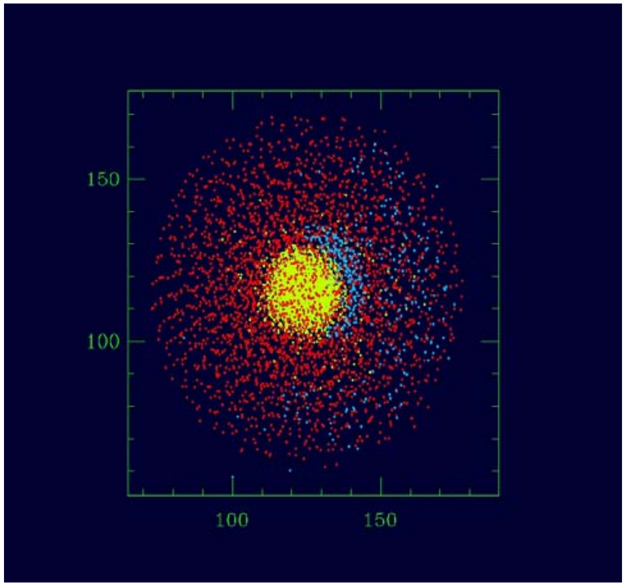
Role of giant impacts: isolated gas giants: PS3.1

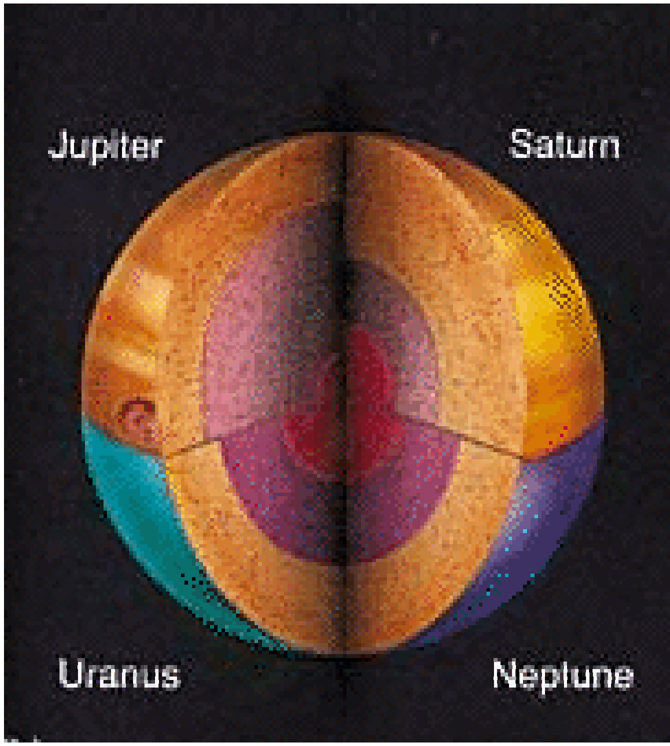


Metal-rich envelope
Diverse cores
Oort's clouds

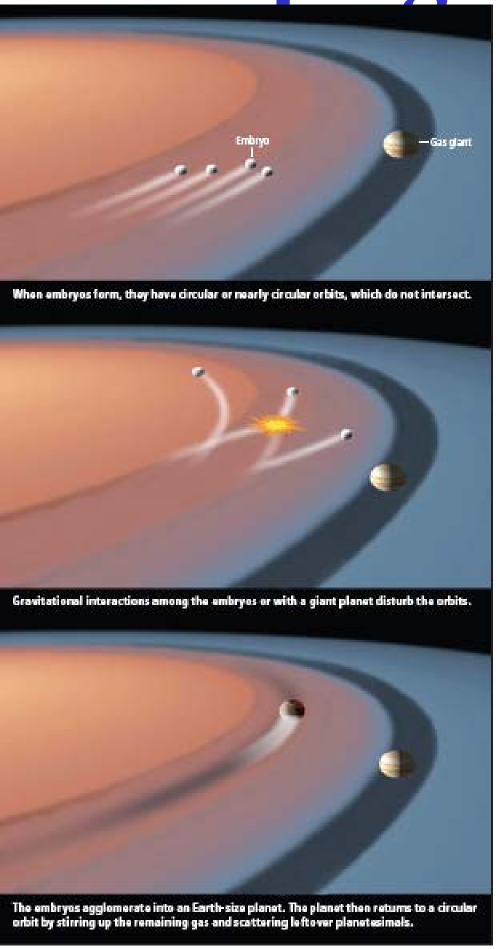








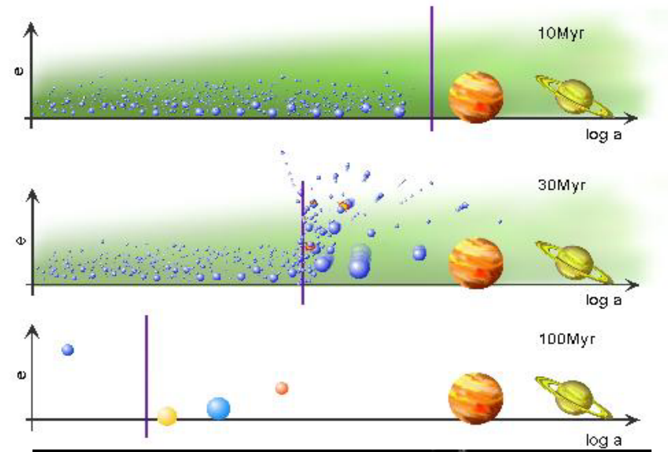
Sweeping secular resonance of eccentric gas giants

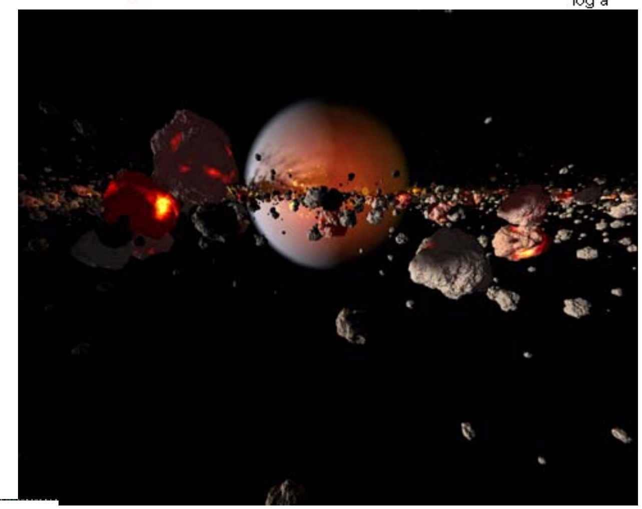


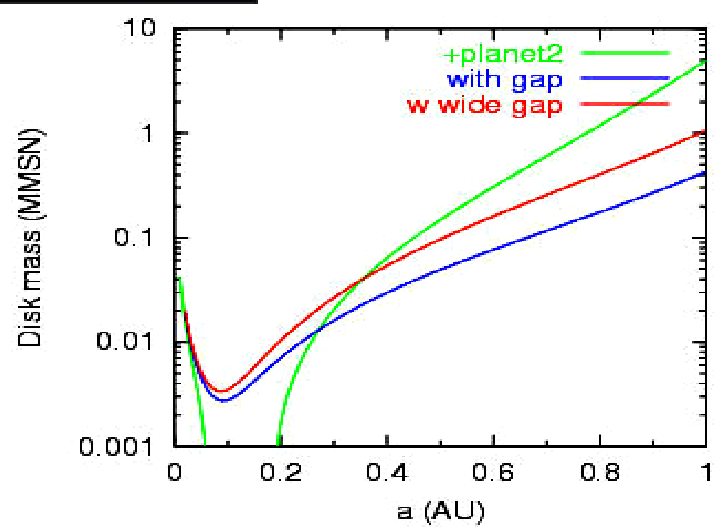
Secular resonances sweep during gas removal: **PS3.3**

Angular momentum exchange, e-excitation, damping & migration

Planets need initial angular momentum deficit







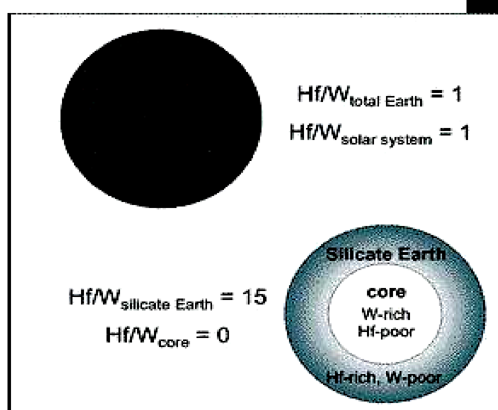


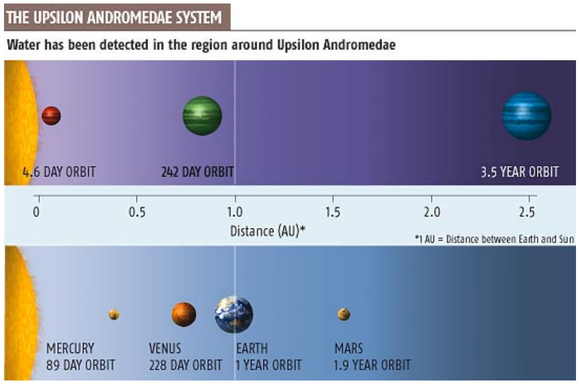
Fig. 2. Schematic showing the fractionation of Hf from W in the early solar system.

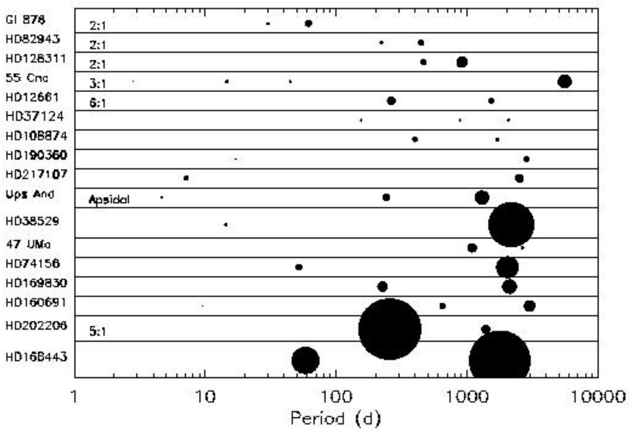
After Halliday et al. (2000)

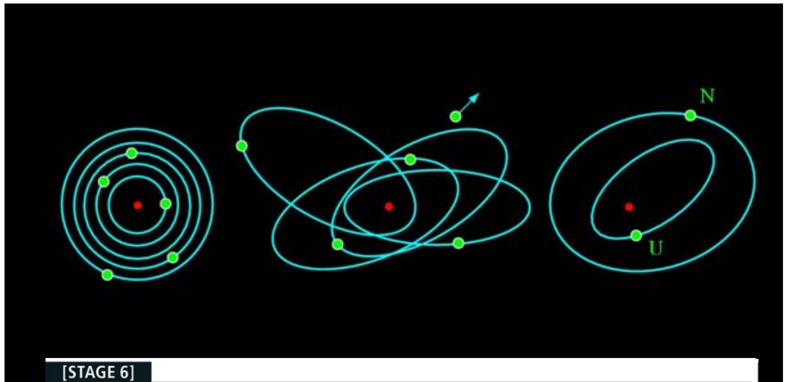
Formation after 60 Myr

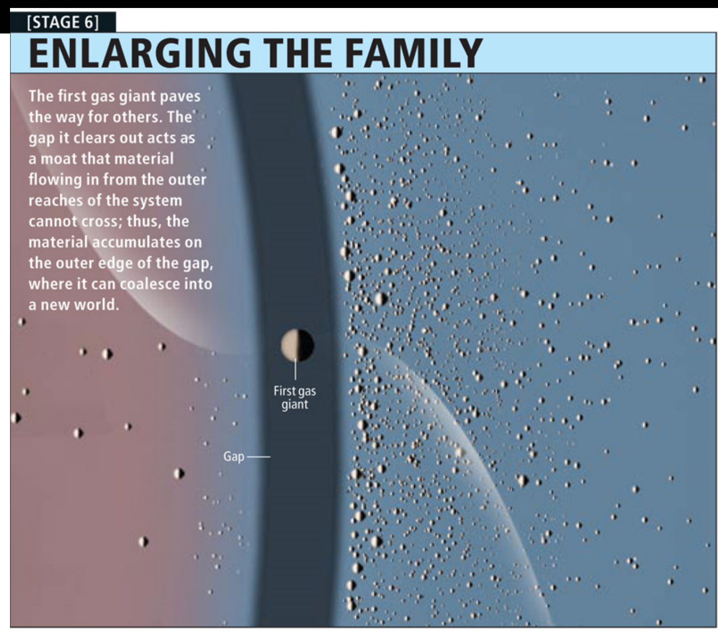
Formation on 30-60 Myr

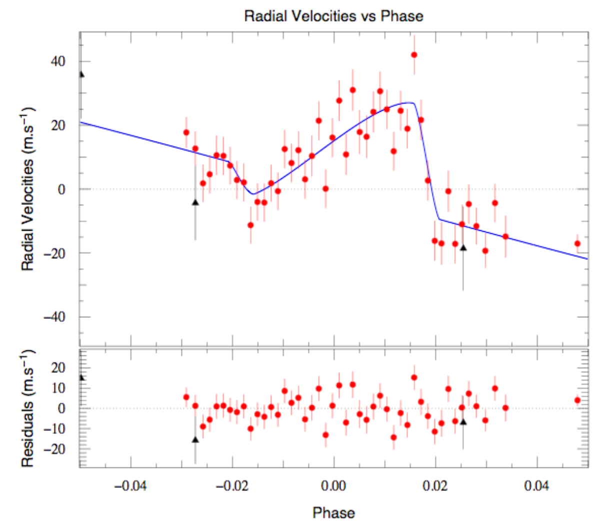
Formation of multiple planets: PopSyn3.4

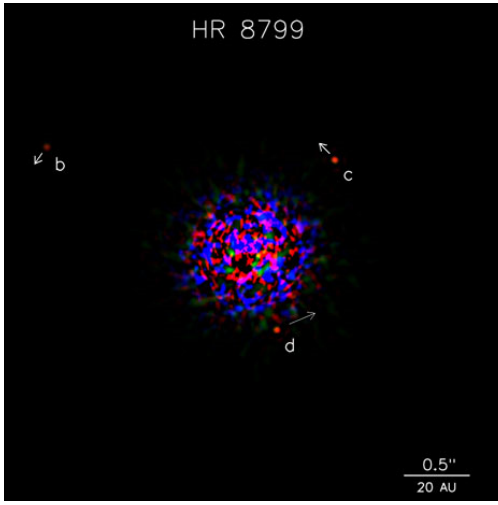


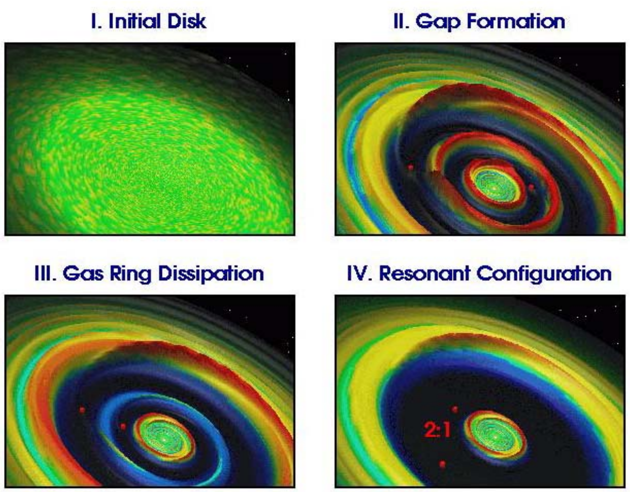












Induced formation &**proliferation**

Emergence of **metastable systems**

Limited extent of **relaxation**

Consequence of **dynamical instability**

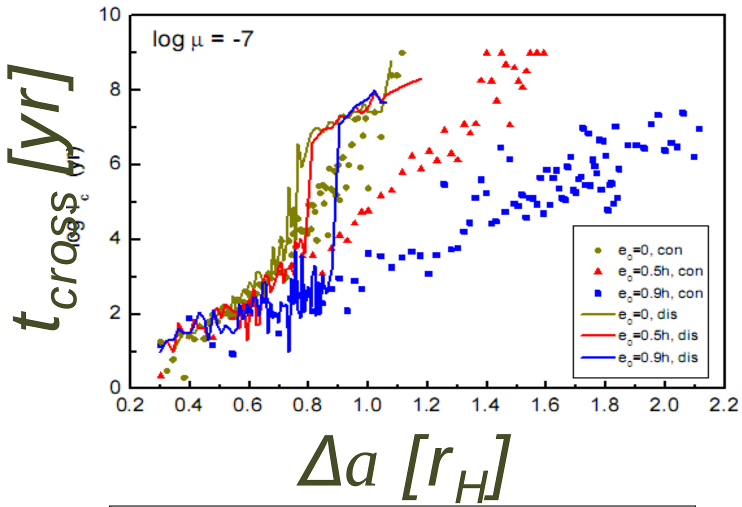
Origin of eccentric planets: jumping jupiter: PS 3.5

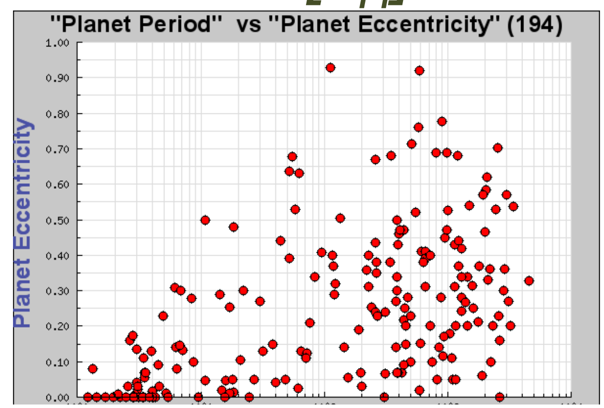
Weidenschilling & Marzari (1996), Lin & Ida(1997),Zhou et al (2007)

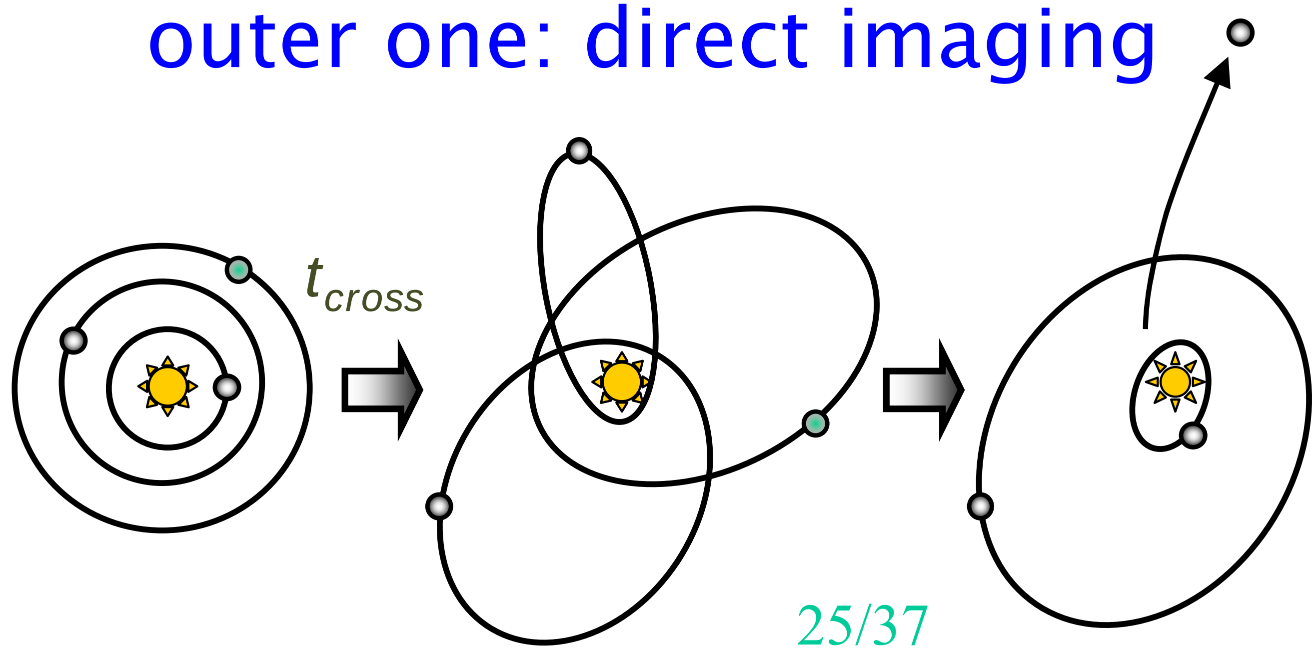
- If more than 3 giant planets form on circular orbits
- Orbit crossing starts on t_{cross}
- One is ejected. The others remain in stable eccentric orbits.

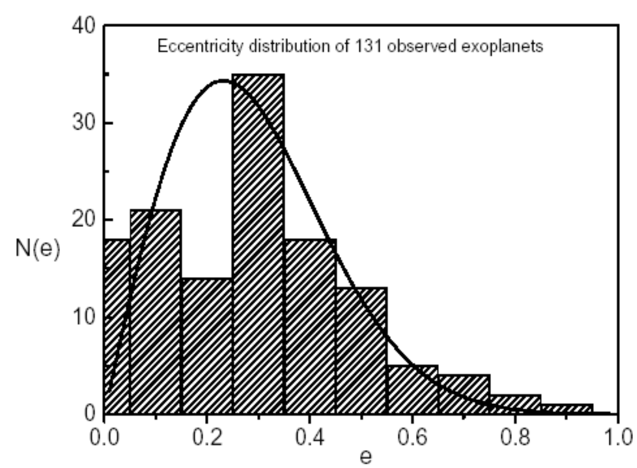
→ inner one: radial velocity

outer one: direct imaging

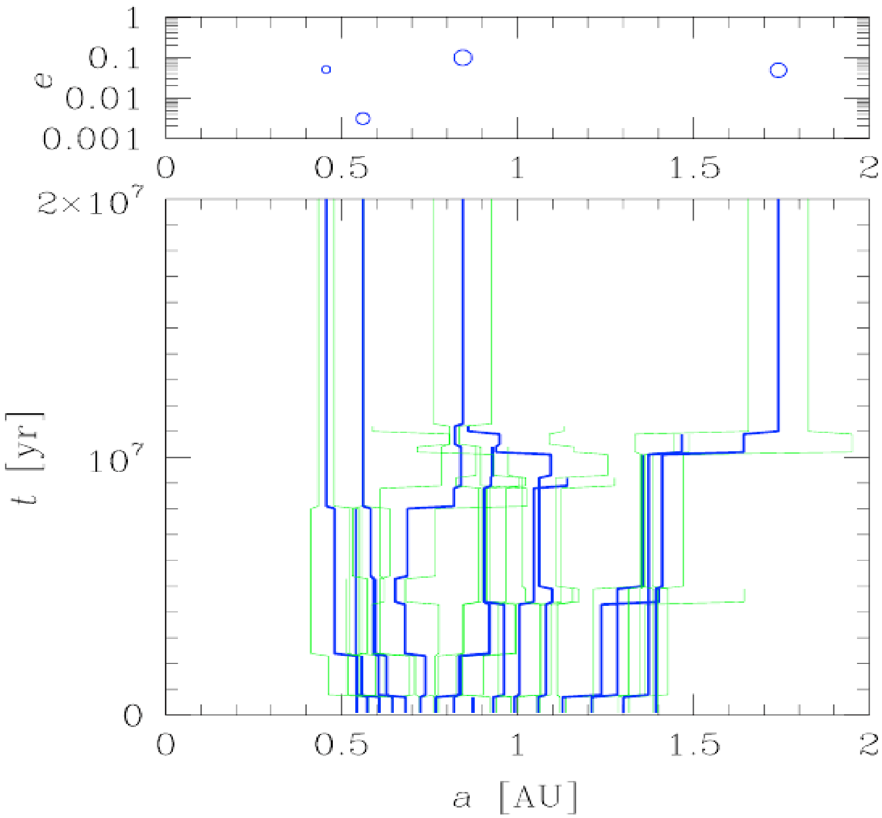


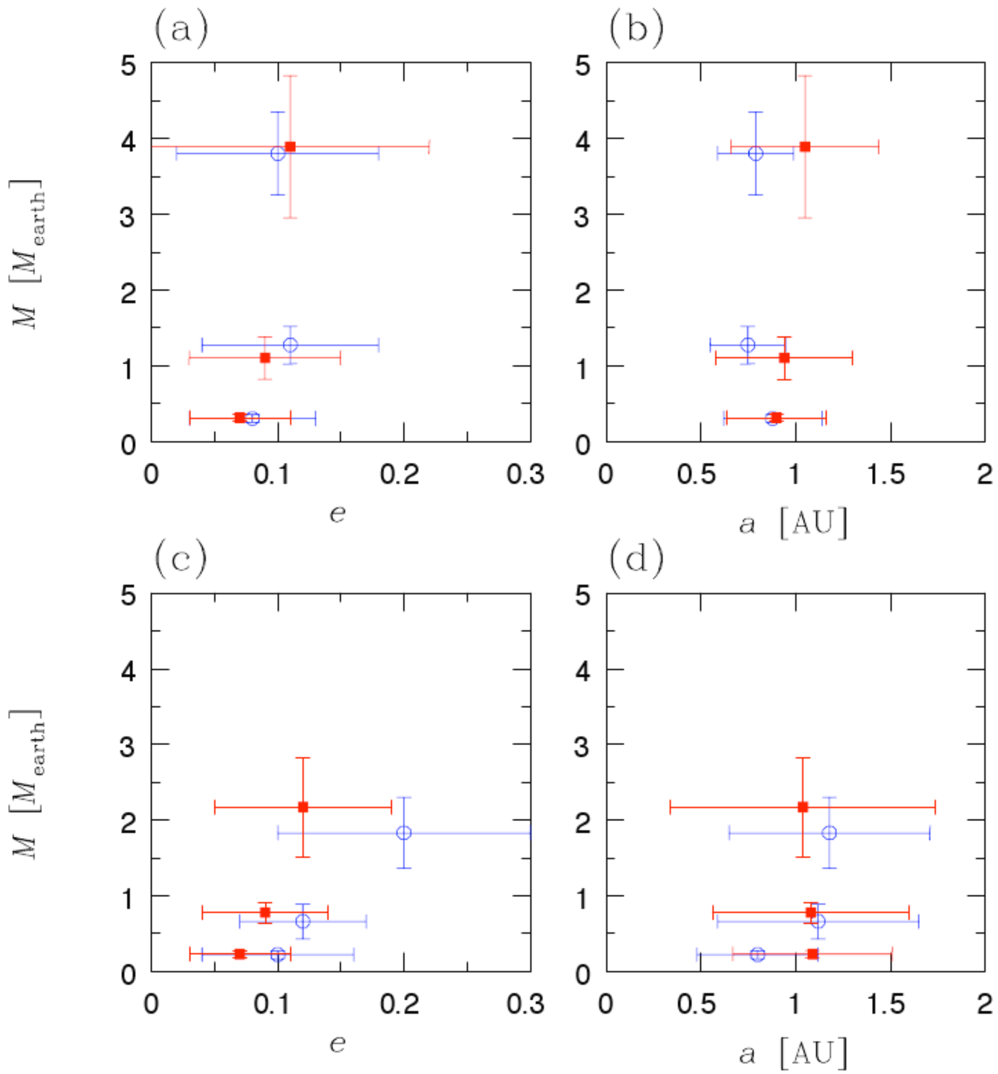




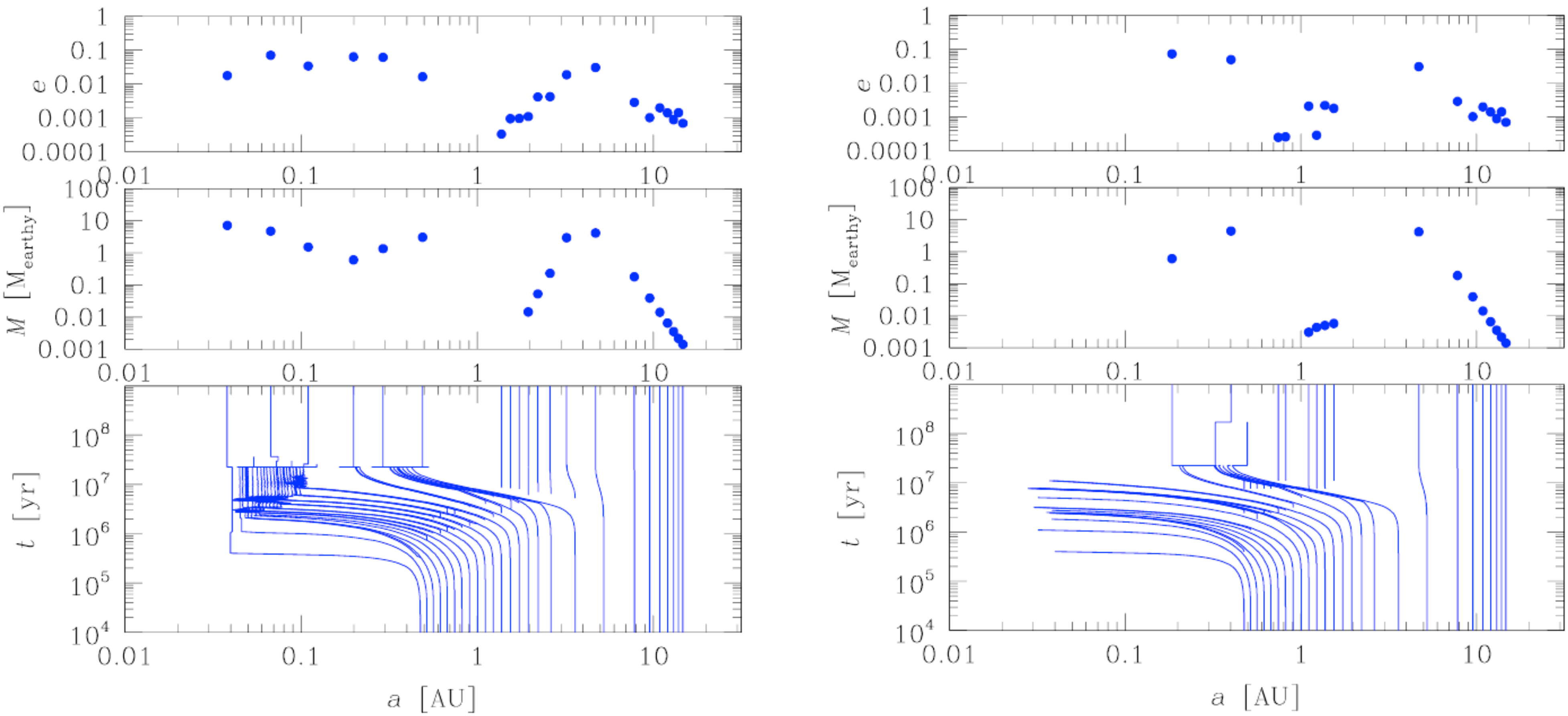


New version of population synthesis models

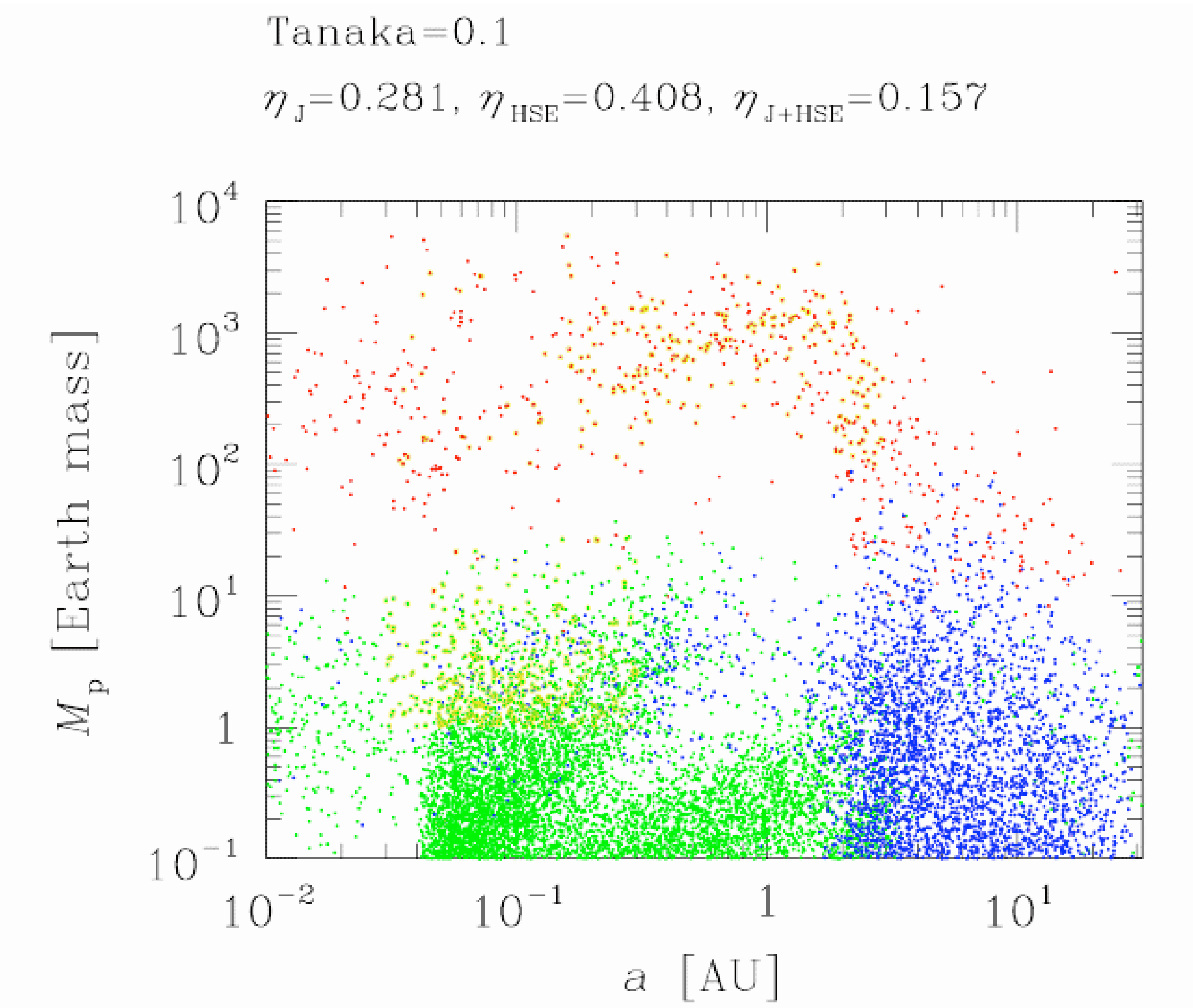




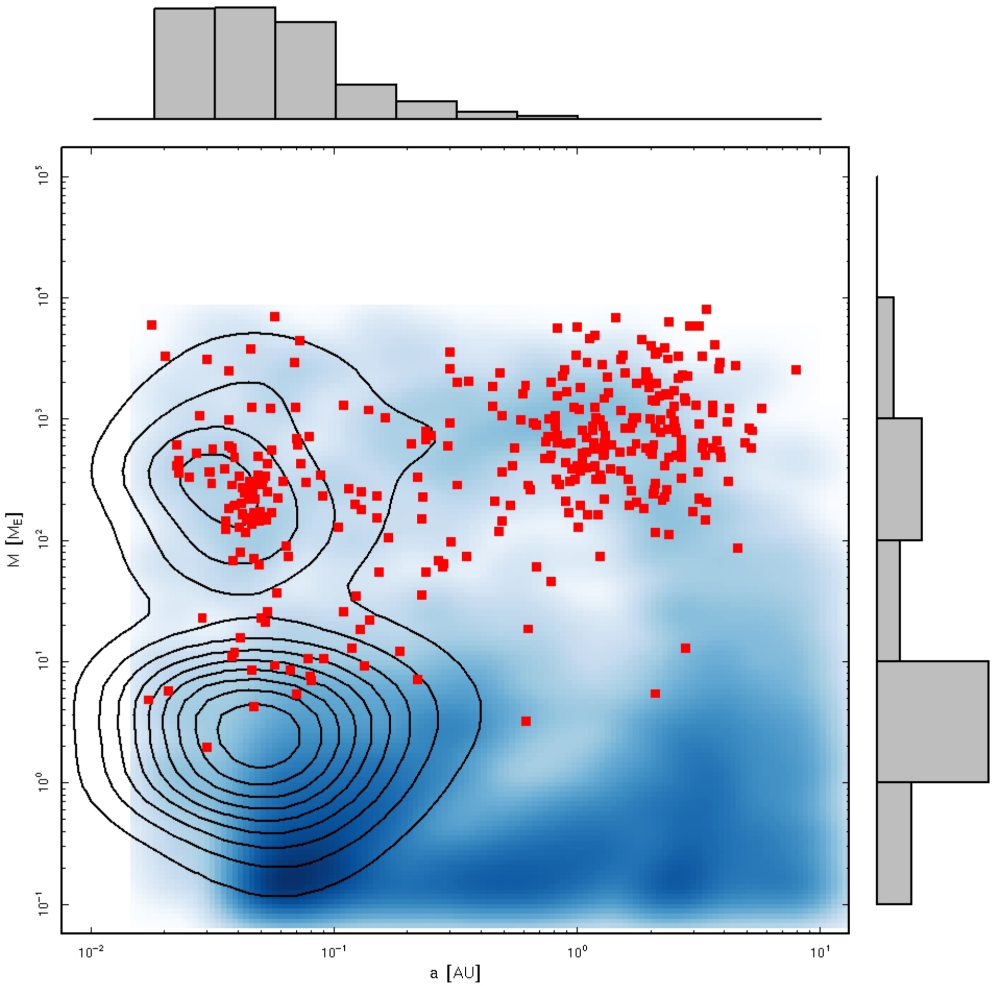
Effect of inner halting radii

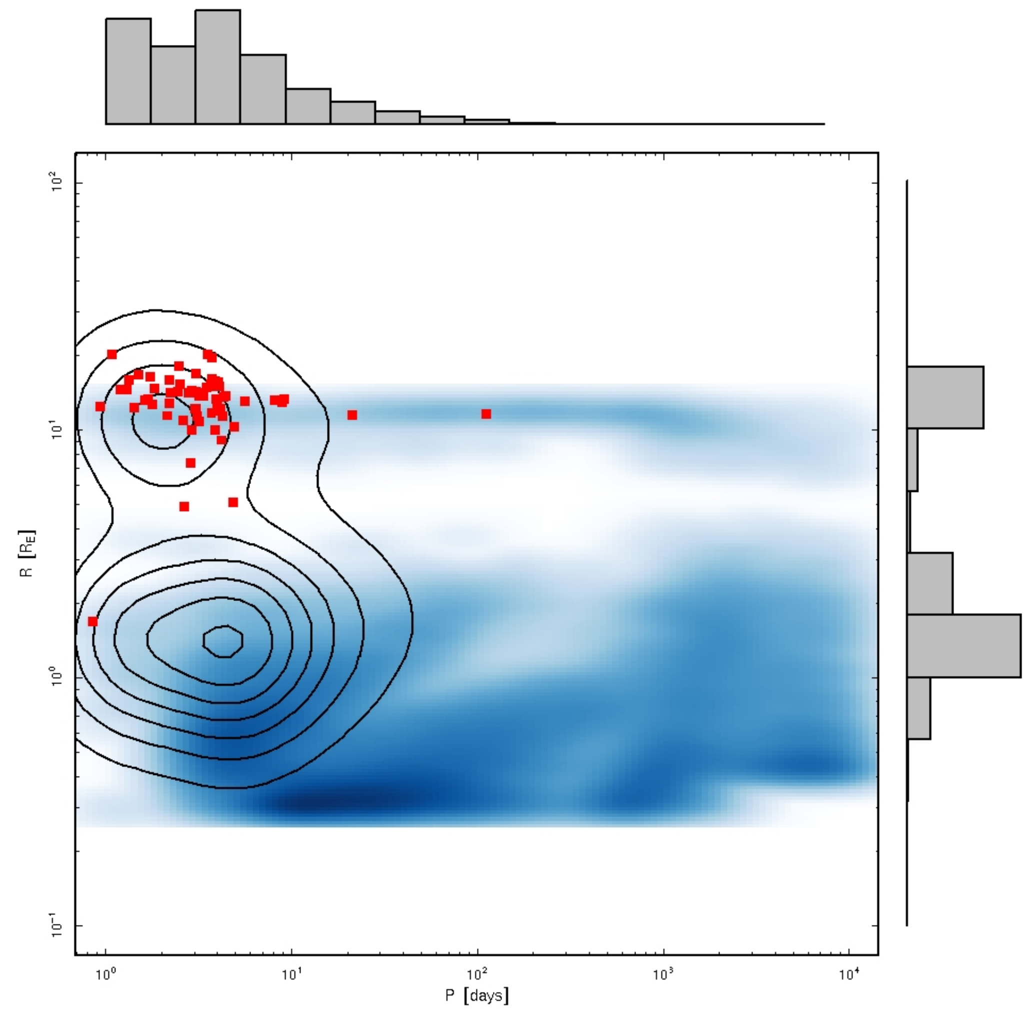


New population synthesis models I

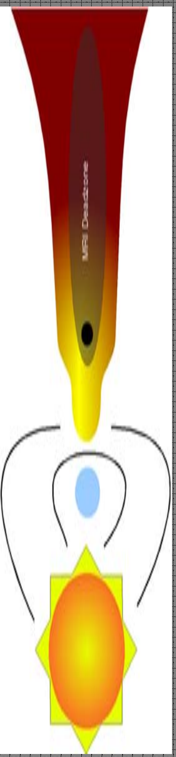


Comparison with observations





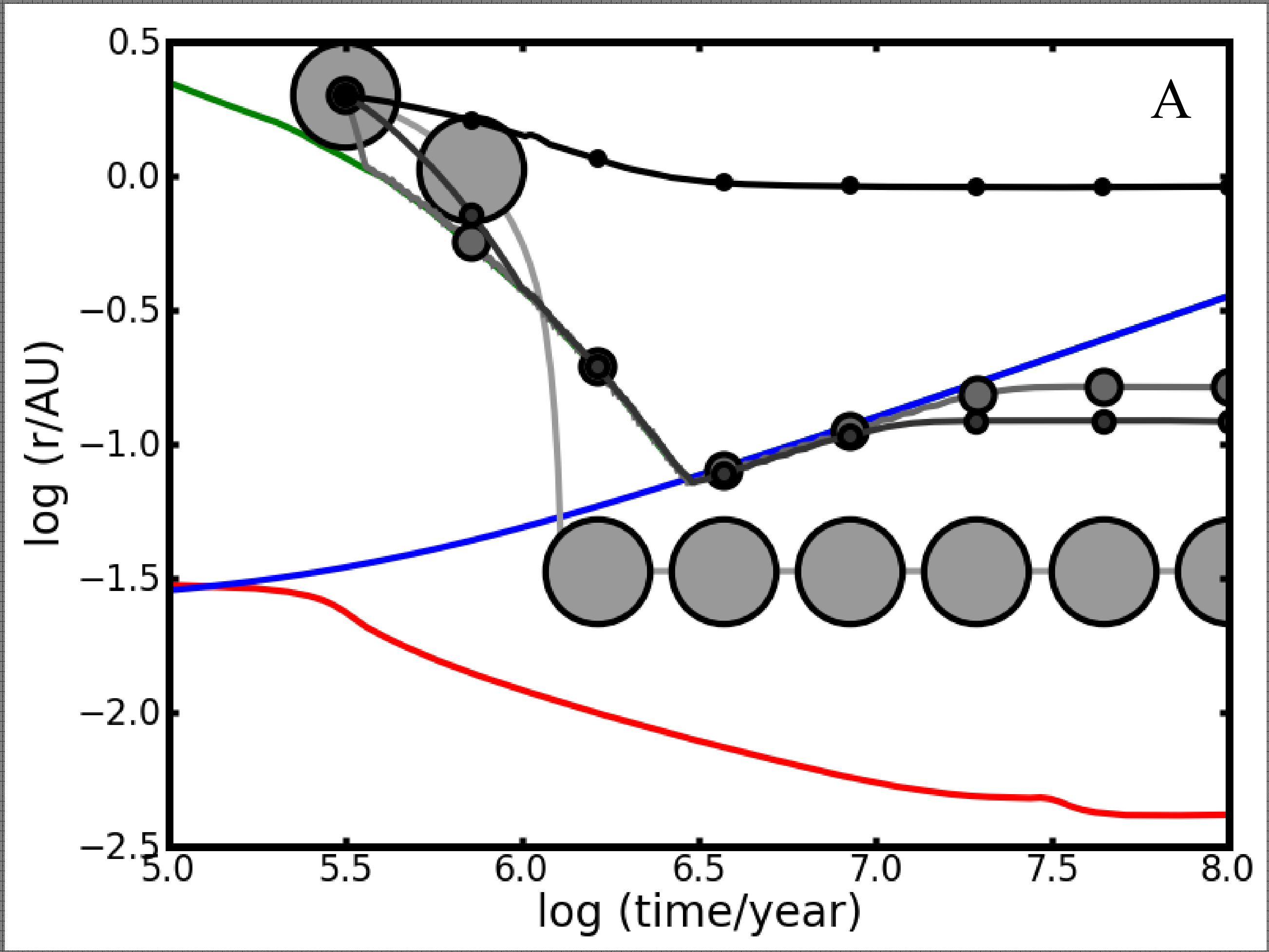
Migration of Various Mass Planets



$r_{\rm crit}$

$r_{\rm mag}$

Stellar Radius



½ Earth

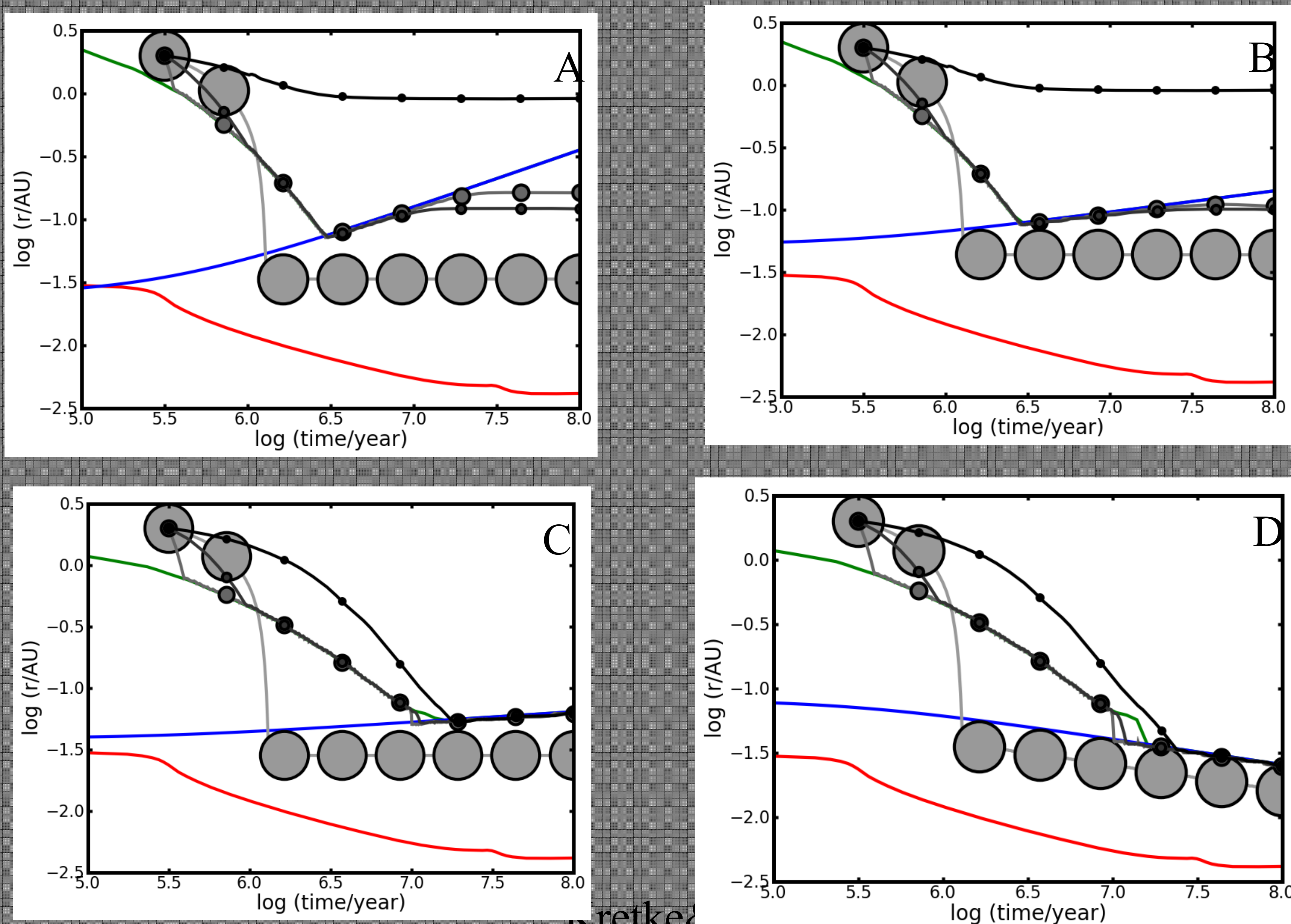
5 Earth

2 Earth

Jupiter

Kretke& Lin (in prep)

Diversity of Systems

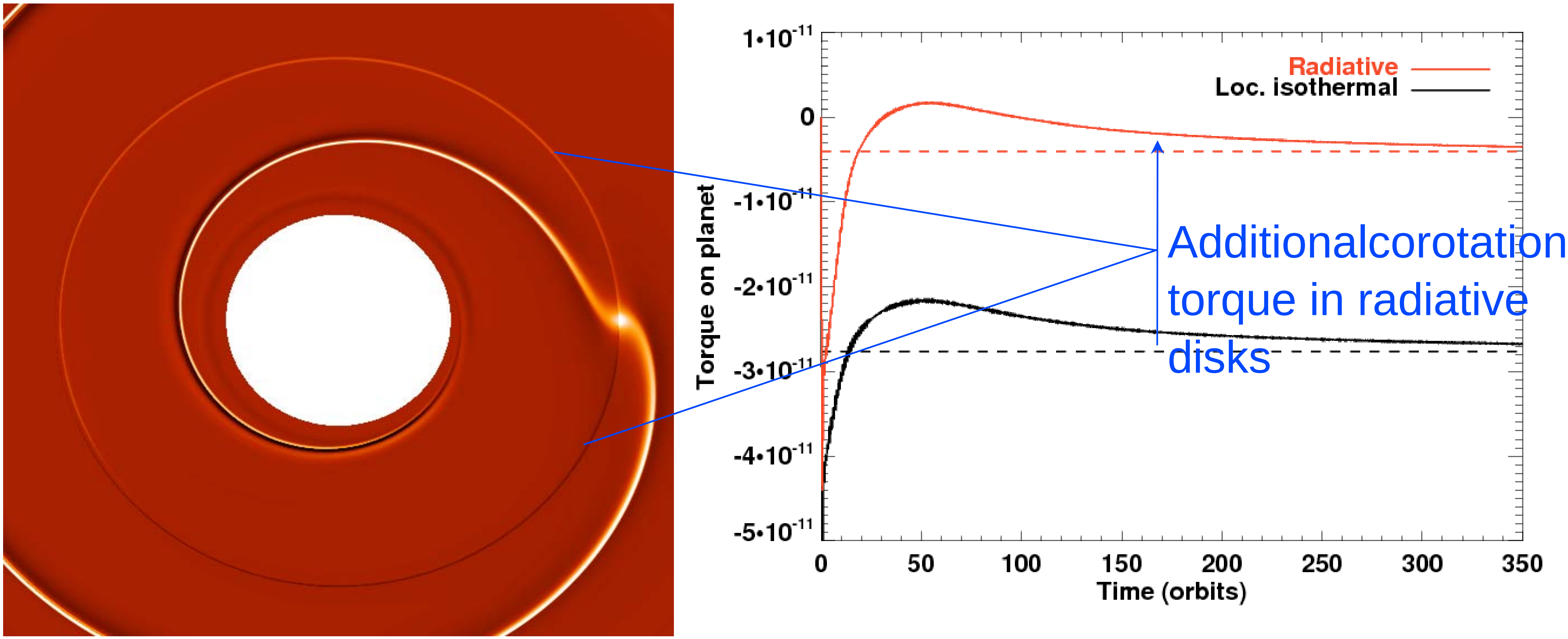


Kretke&

Type I migration in ***radiative*** disks

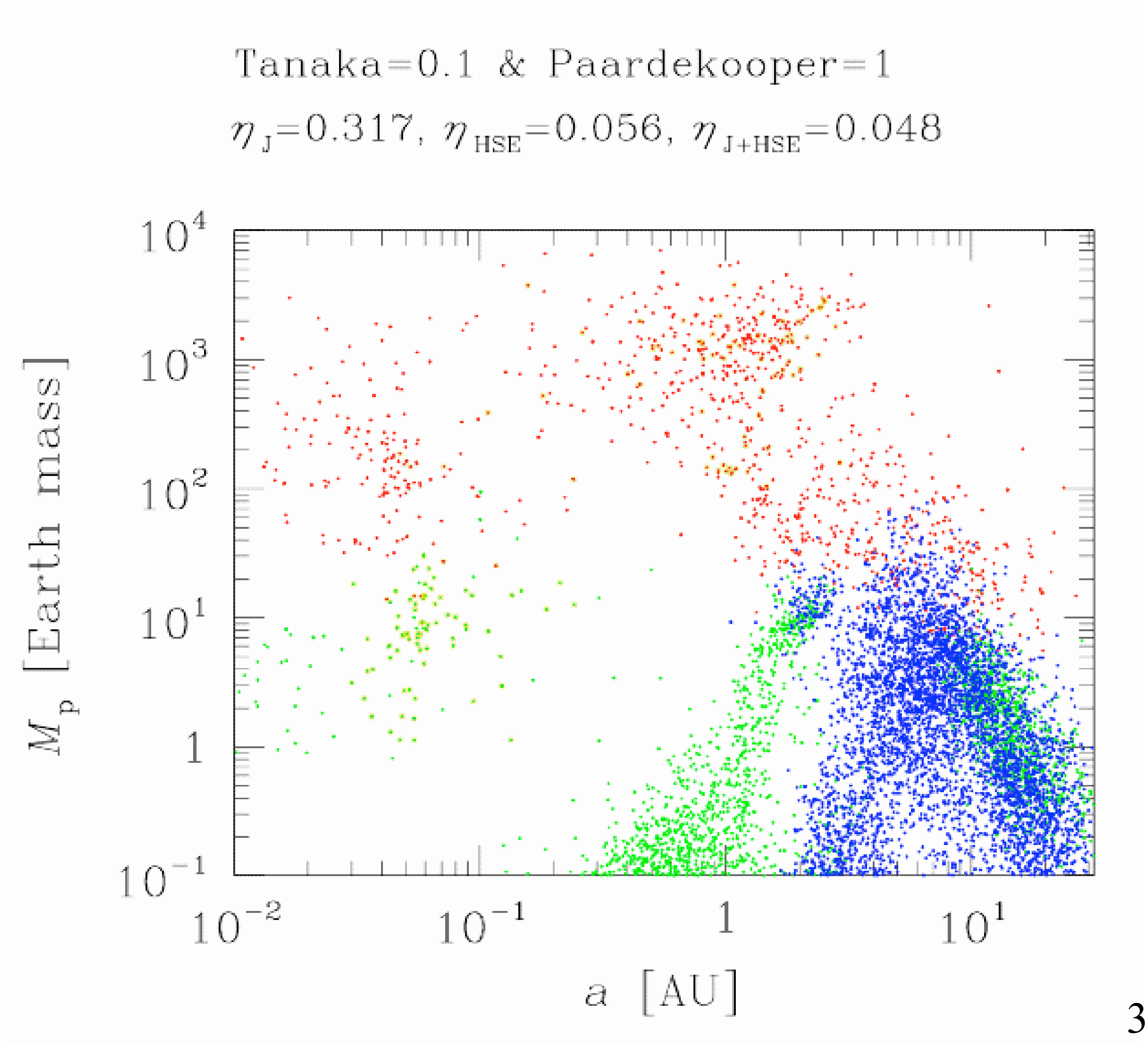
Additional contribution to the corotation torque, scalingwith the radial gradient of the gasentropy

Baruteau&Masset (2008), Paardekooper&Papaloizou (2008)

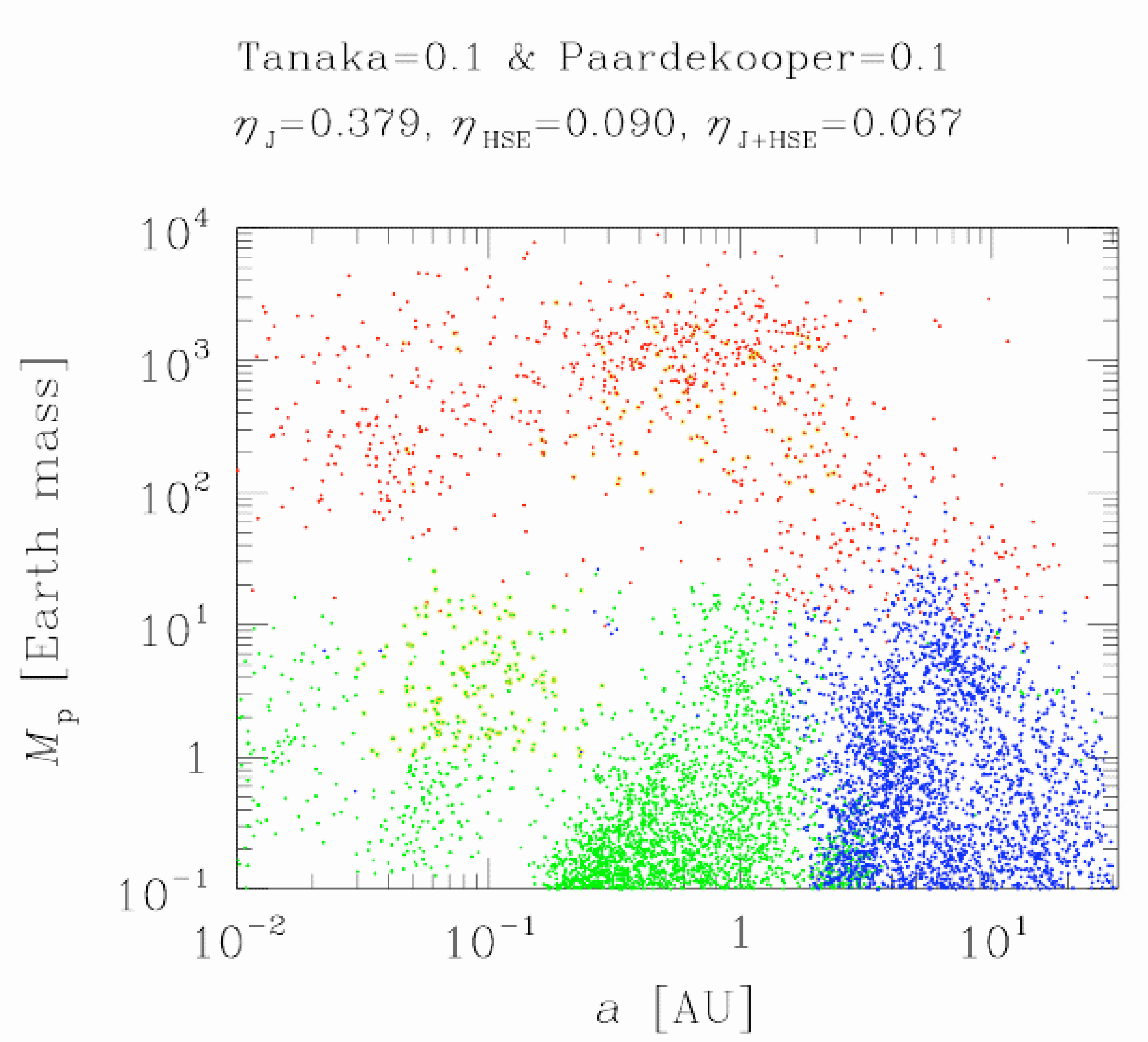


Depending on the gas**entropy gradient** (density and temperature gradients), and on **dissipation processes** (viscosity and thermal diffusion), the additionalcorotation torque can**slow down, stall or even reverse type I migration**!

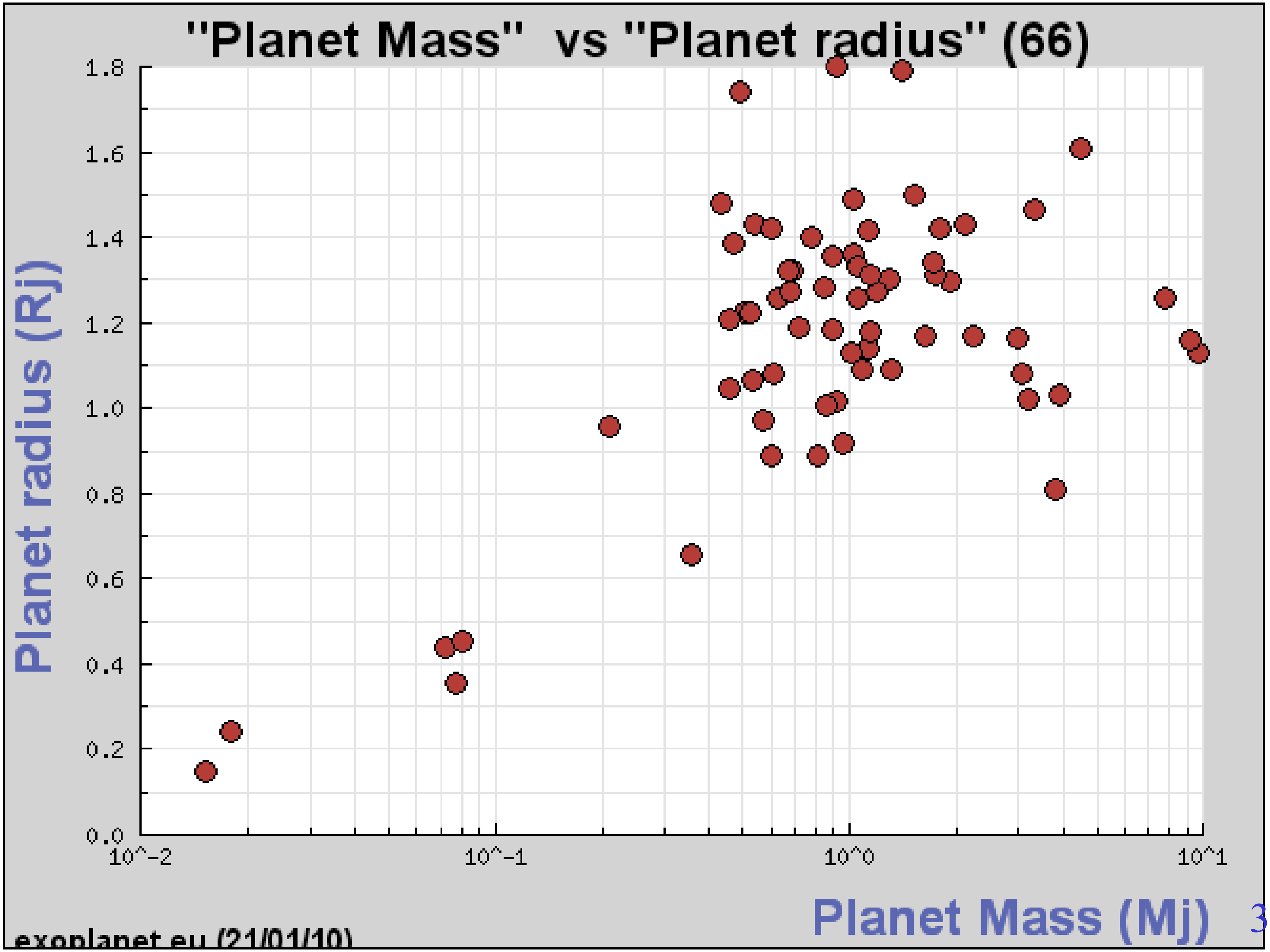
New population synthesis II



New population synthesis 1.5



Rocky versus icy worlds



Some preliminary results

- **Prolific** production of super & habitable Earths
- **Bimodal mass distribution**: super-Earths mass less than critical core mass.
- **Born again embryos** have refractory composition and tend to associate with gas giants
- **Failed cores** have volatile composition and tend to be by themselves
- Super-Earths' period distribution is less peaked due to disk evolution and giant impacts
- Very **few resonant** super-Earth systems
- **Bimodal period distribution** signifies the extent of type I migration

Outstanding issues:

- Fraction of stars with super-earths but no gas giants
- Fraction of stars with gas giants but no super-earths
- Eccentricities of gas giants in systems contain both
- Eccentricity of super-Earth only systems
- Long-term (non linear) stability and statistical mechanics of multiple super-Earth systems
- Stellar spin-orbit alignment for super-Earths
- Tidal evolution, atmospheric circulation & evolution
- Volatile retention during giant impacts