Migration and Growth of Protoplanetary Embryos: Emergence of Gas giant cores vs Super Earth Progenitors

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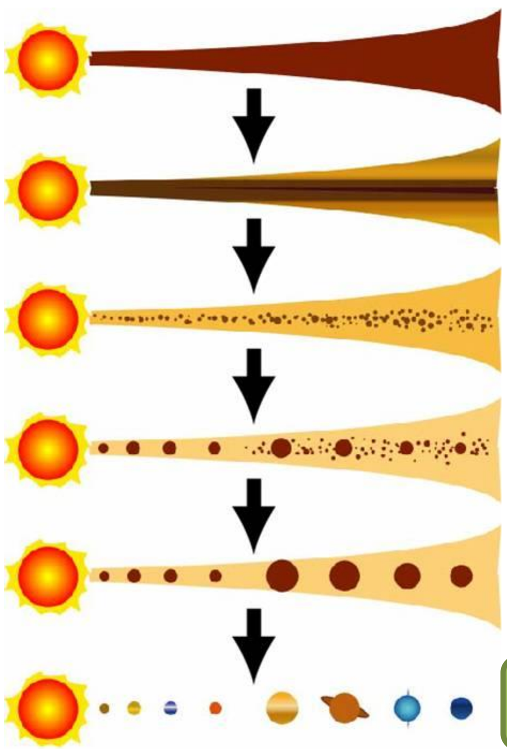
The fundamental and unsolved topics in field of exoplanet

- How the planets form? What's the difference between gas giant formation and terrestrial planet formation?

- What's role of protoplanetary disks? Do they have a significant effect on the formation and evolution of planetary systems?

Planet Formation

Core accretion scenario



Dust grains (sub)um-mm

Condensation coagulation

Planetesimals ~km

Runaway/oligarchic growth

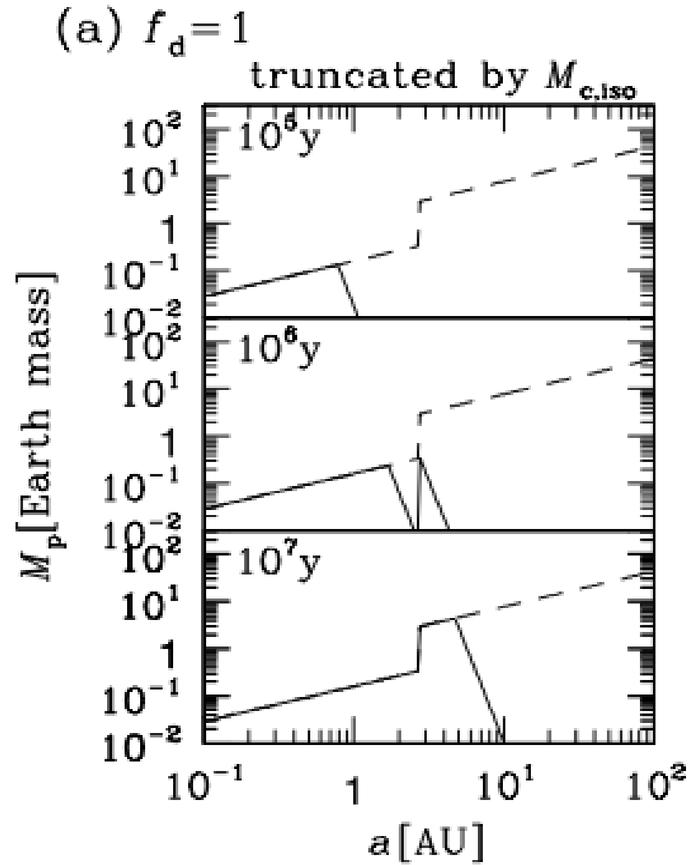
Planetary embryos ~Earth size

$M_C \sim 10 M_\oplus$

$\tau_{KH} \simeq (M_\oplus/M_p)^3$ Gyr

$\tau_g = 10^6 - 10^7$ yrs

Gas giant planet/terrestrial planet



too long growth time from Earth mass to critical core mass

Ida & Lin 2004

Growth barrier for gas giant planet

Planet Migration

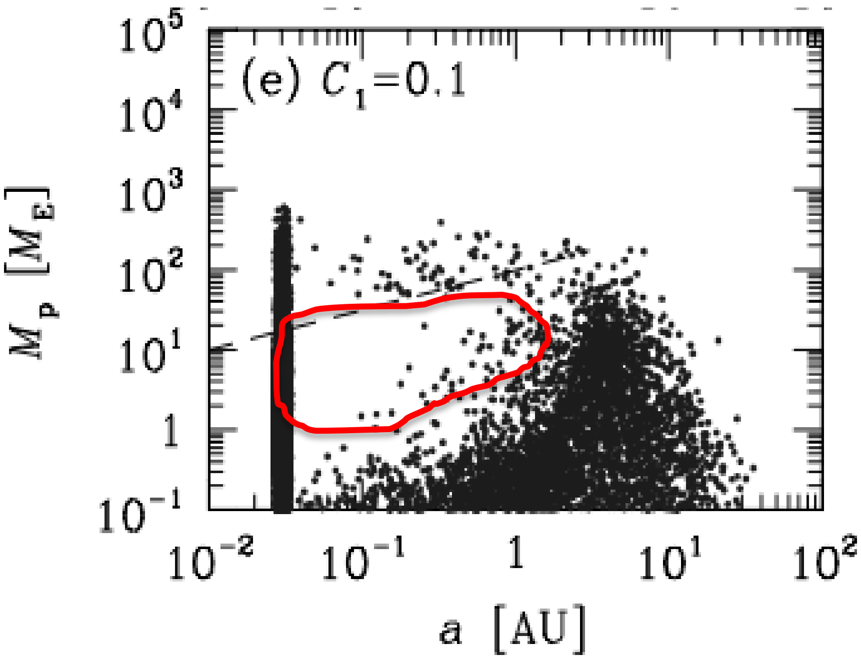
Type I migration

$M_p <$ 10-30 $M_\oplus$

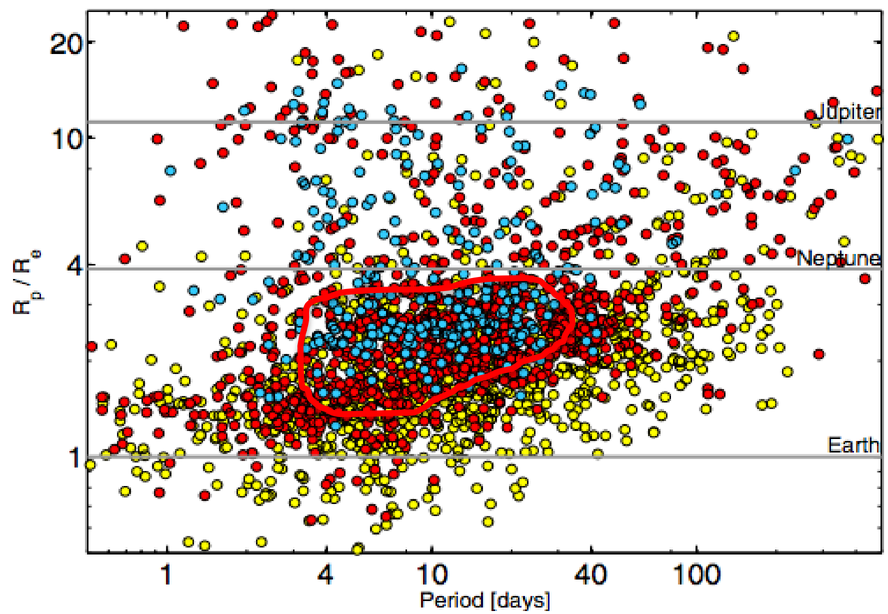
Goldreich & Tremaine 1979,1980; Lin & Papalozou 1979

$$\tau \propto (\frac{M_*}{M_p})(\frac{M_*}{\Sigma r^2})(\frac{H}{r})^2 P_{orb} \text{ years}$$

→ **too fast**



Ida &Lin 2008



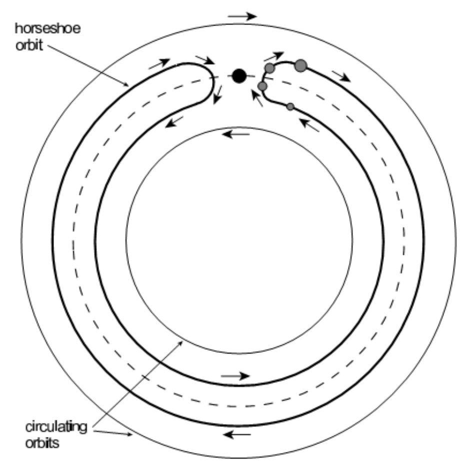
Batalha et al. 2013

Embarrassment for the retention of super Earth/Neptune mass planets

Type I migration

$$\frac{dr}{dt} = f(p, q, p_\nu, p_\chi)\frac{M_p}{M_*}\frac{\Sigma r^2}{M_*}\left(\frac{r\Omega_K}{c_s}\right)^2 r\Omega_K$$

Paardekooper et al. 2011



f

- Direction → Surface and temperature gradient
- Magnitude → Viscous and thermal diffusion (unsaturation)

unsaturation criterion

$$\tau_{\rm U-turn} \le \tau_{\rm visc} \le \tau_{\rm lib}/2$$

↓

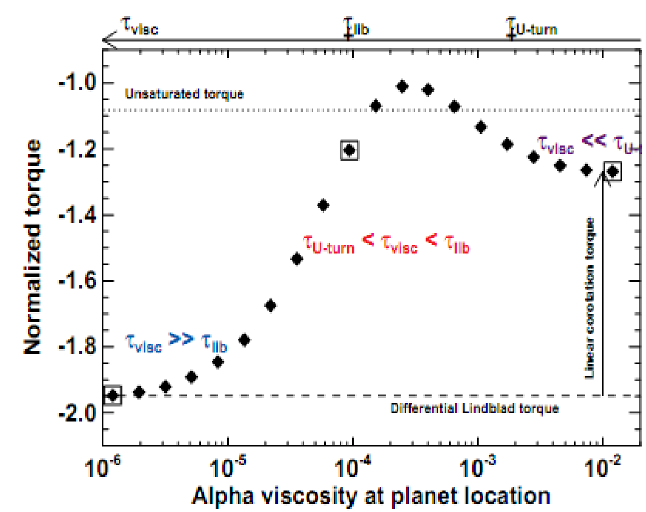
$$0.32q^{3/2}h_p^{-7/2} \le \alpha_{\rm v,p} \le 0.16q^{3/2}h_p^{-9/2}$$

$M_{\rm p,min}$ $M_{\rm p,max}$

↓

A range mass of embryos satisfy the unsaturated type I torque and corresponds to outward migration

Baruteau & Masset 2012



Methodology

- HERMITE-EMBRYO code

HERMIT4 package (Aarseth) + Type Ⅰ torque Paardekooper et al.2011

$$\frac{dv_\theta}{dt} = \frac{\Gamma_{\rm tot}}{M_p r} \qquad \frac{dv_r}{dt} = -\frac{v_r}{\tau_e}$$

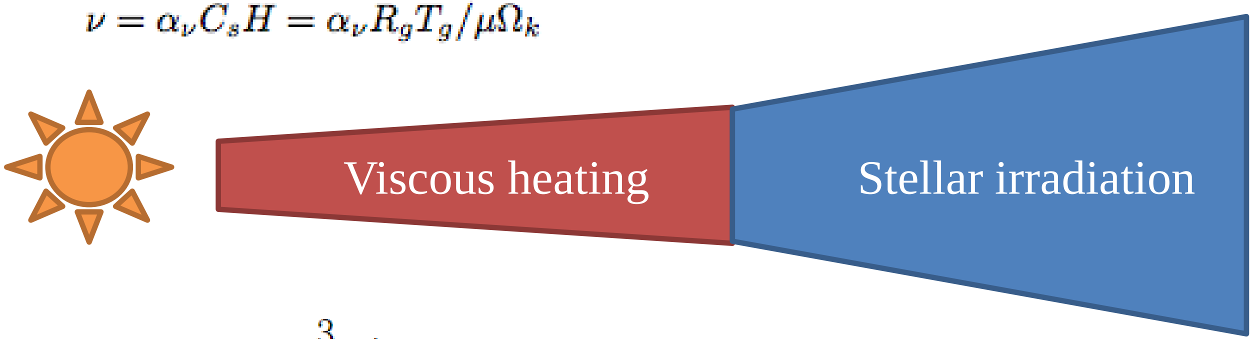
$$\tau_a \simeq \frac{a}{\dot{a}} = M_p\sqrt{(GM_* a)}/(2f_a\Gamma_0)$$

$$\tau_e \simeq \frac{e}{\dot{e}} = h^2 M_p\sqrt{(GM_* a)}/(2f_e\Gamma_0)$$

- Disk structure (steady state)

Garaud & Lin 2007

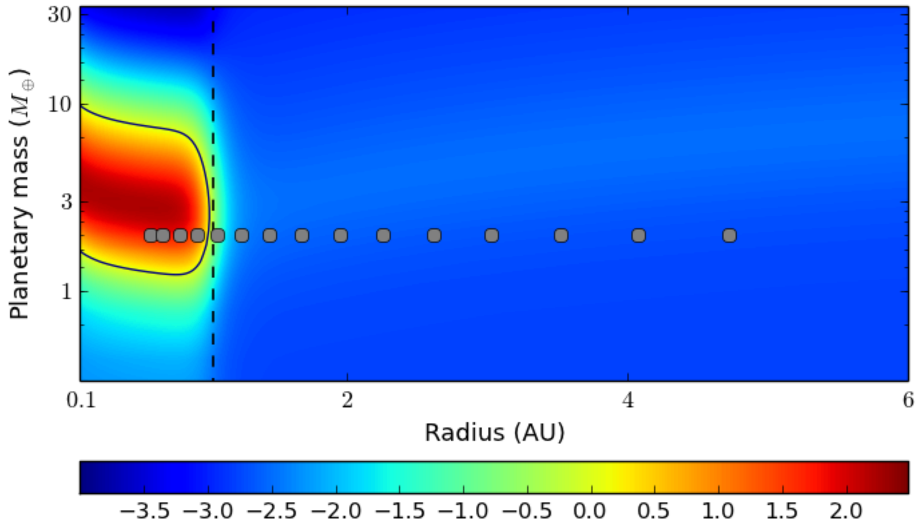
$$\nu = \alpha_\nu C_s H = \alpha_\nu R_g T_g/\mu\Omega_k$$

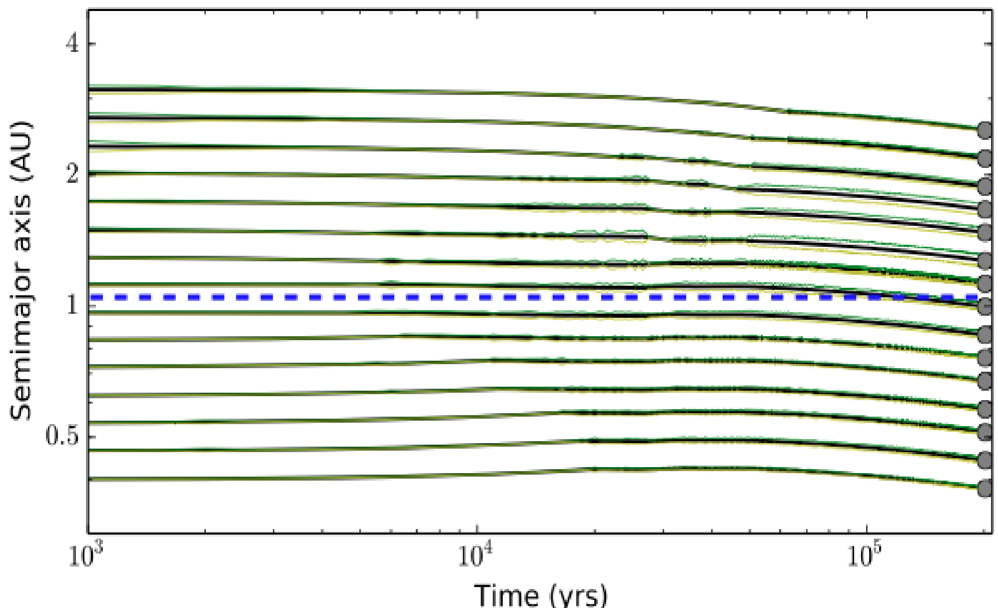


$$\frac{3}{4\pi}\dot{M}\Omega_k^2 = 2\left(\sigma T_e^4\right) \qquad \frac{A_s}{2}\frac{L_*}{4\pi r^2} = \sigma T_e^4$$

Results I: Gas Giant Cores vs Super Earths

$$\dot{M} = 7 \times 10^{-9} M_{\odot}/\mathrm{yr},\ \alpha_{\nu} = 10^{-3}$$





Trapping radius

$$r_{\mathrm{trans}} \simeq 0.26 m_*^{0.74} l_*^{-0.41} \dot{m}_9^{0.72} \alpha_3^{-0.36} \kappa_0^{0.36} \mathrm{AU}$$

Optimum mass of outward migration

$$p_{\nu} \sim 1 \ (\text{or } p_{\xi} \sim 1)$$

↓

$$M_{\mathrm{opt}} \simeq m_*^{13/48} \dot{m}_9^{7/12} \alpha_3^{3/8} \kappa_0^{7/24} r_{AU}^{-7/48} M_{\oplus}.$$

low disk accretion rate $\dot{M}_g$

↓

capture into mean motion resonance (MMR)

Results I：Gas Giant Cores vs Super Earths

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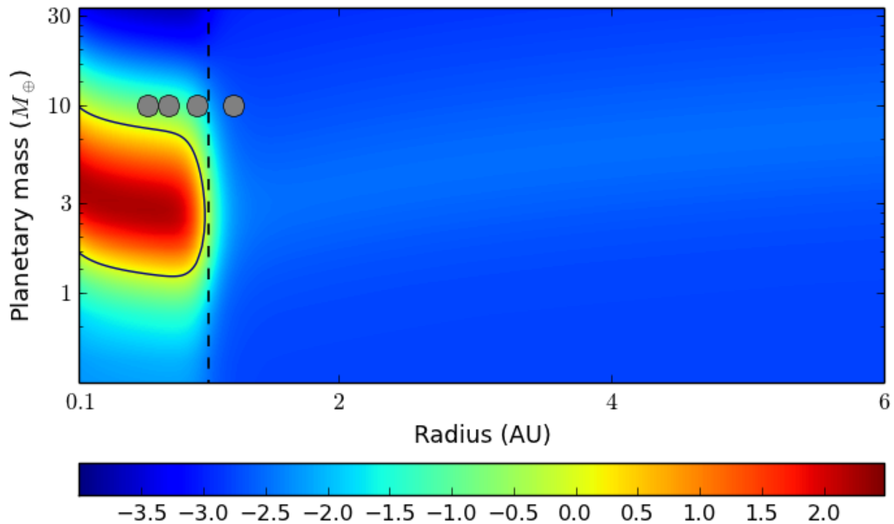

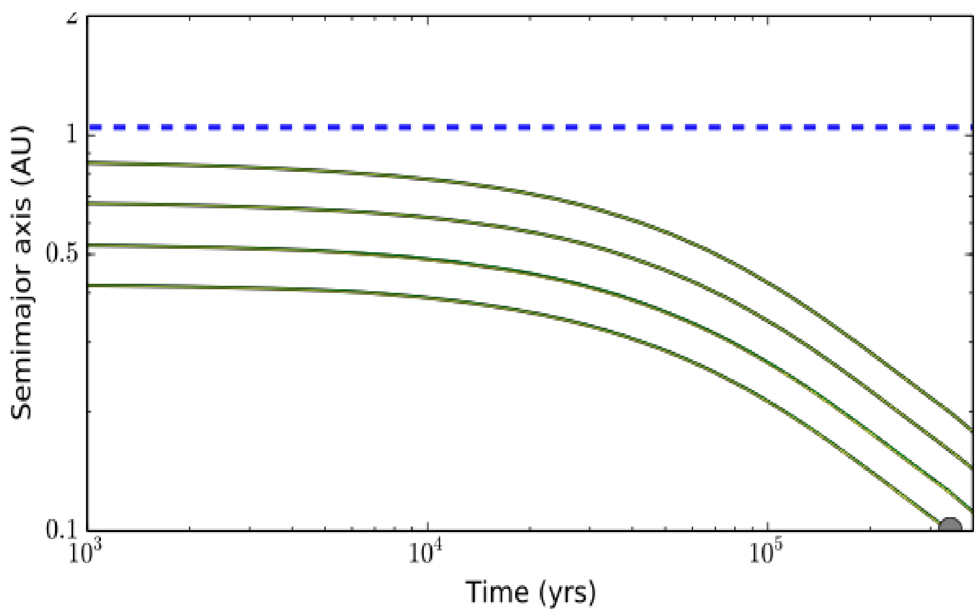

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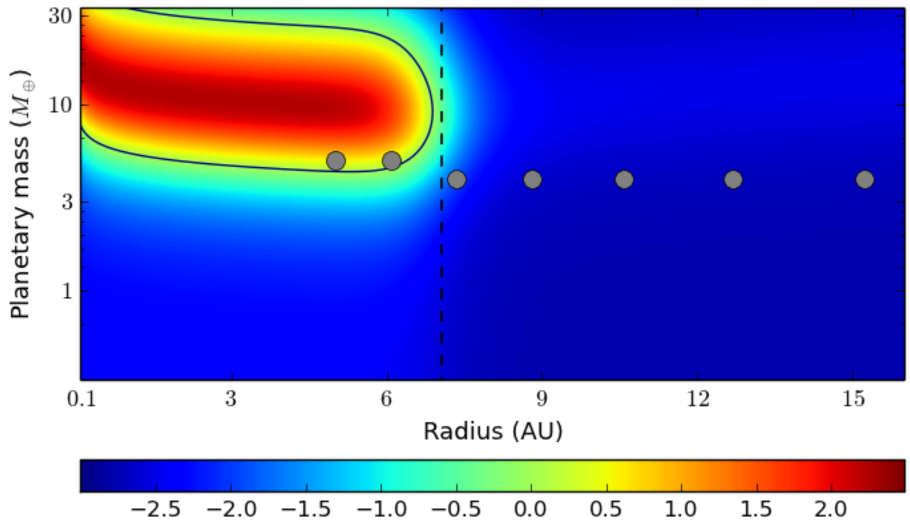
low disk accretion rate $\dot{M}_g$

↓

cannot retain massive embryos

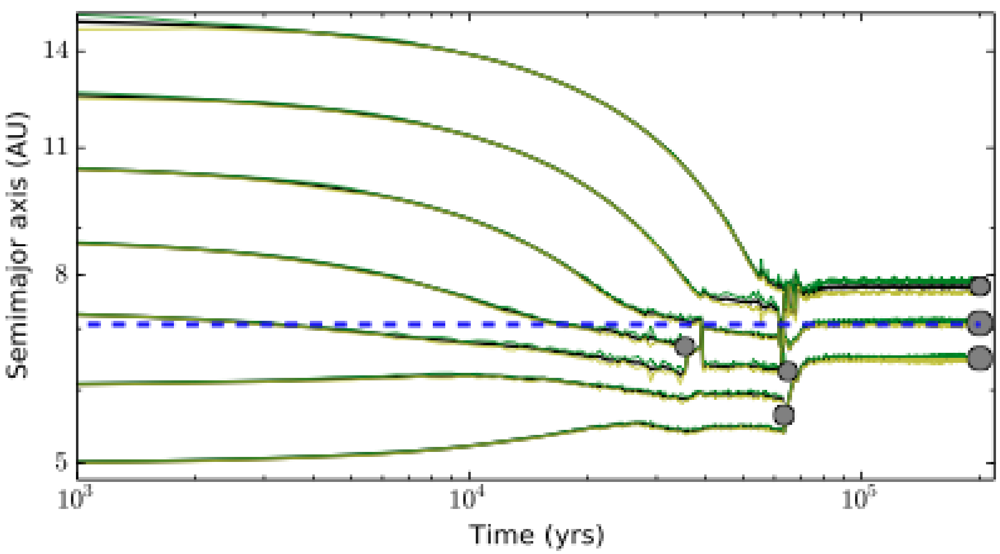
Results I: Gas Giant Cores vs Super Earths

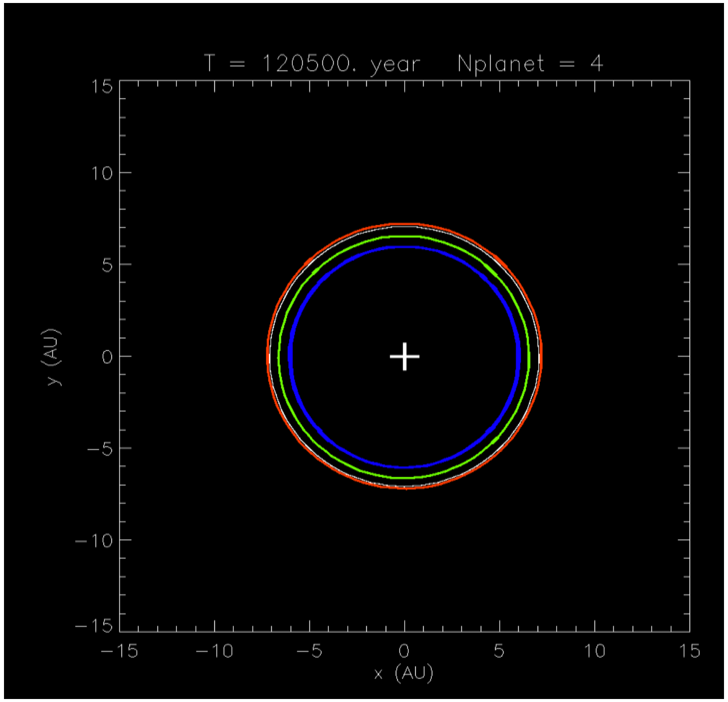
$\dot{\mathrm{M}} = 1 \times 10^{-7} \mathrm{M}_{\odot}/\mathrm{yr},\ \alpha_{\nu} = 10^{-3}$



high disk accretion rate $\dot{M}_g$

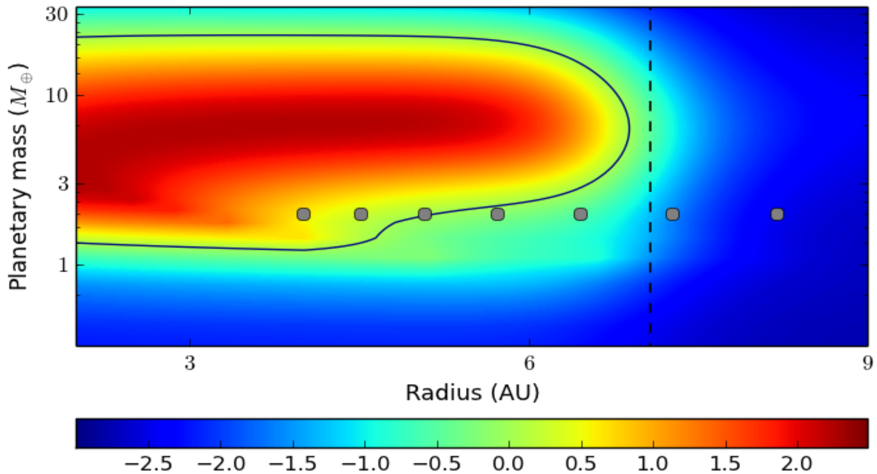
Strong convergent migration feature
Orbital crossing and close encounters
leads to embryo-embryo collision

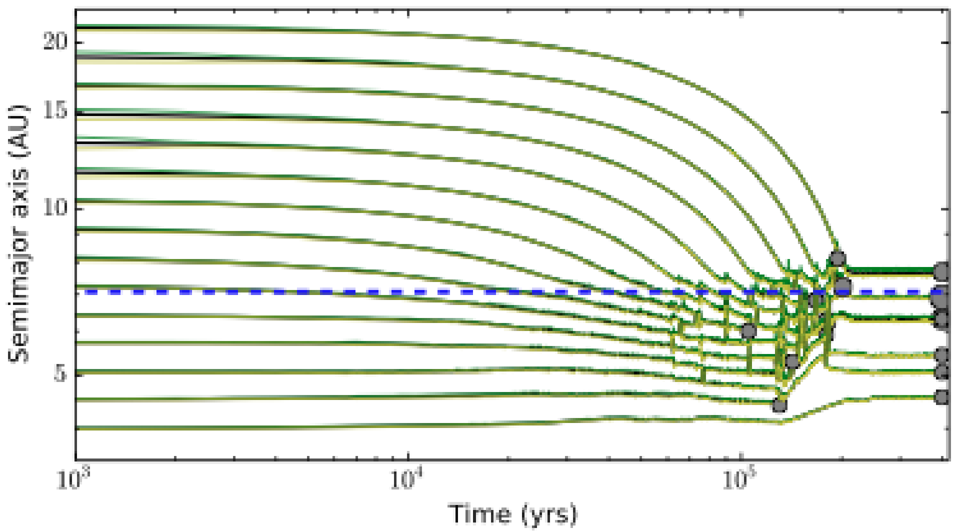




Results I: Gas Giant Cores vs Super Earths

$\dot{M}_g = 10^{-7} M_\odot \ \mathrm{yr}^{-1}$ Layered disk, varied alpha vertically





Results I: Gas Giant Cores vs Super Earths

MMR capture condition

$$\tau_{\Delta a} > \tau_{\rm lib}$$

Murray & Dermott 1999

$$\dot{n} \sim \partial R/\partial\lambda/a^2,\ \dot{e}_{\rm exc} \sim \partial R/\partial\tilde{\omega}/(na^2e)$$

$$e\dot{e}_{\rm exc} \sim \dot{a}/a \sim 1/\tau_a \qquad \dot{e}_{\rm damp} \sim e/\tau_e$$

$$e_{\rm res} \sim (\tau_e/\tau_a)^{1/2} \sim h \qquad \tau_{\rm lib} \sim (qf_{\rm res}e_{\rm res})^{-1/2}n^{-1} \qquad \tau_{\Delta a} \sim \Delta a_{\rm res}/\dot{a} \simeq \tau_a \Delta a_{\rm res}/a$$

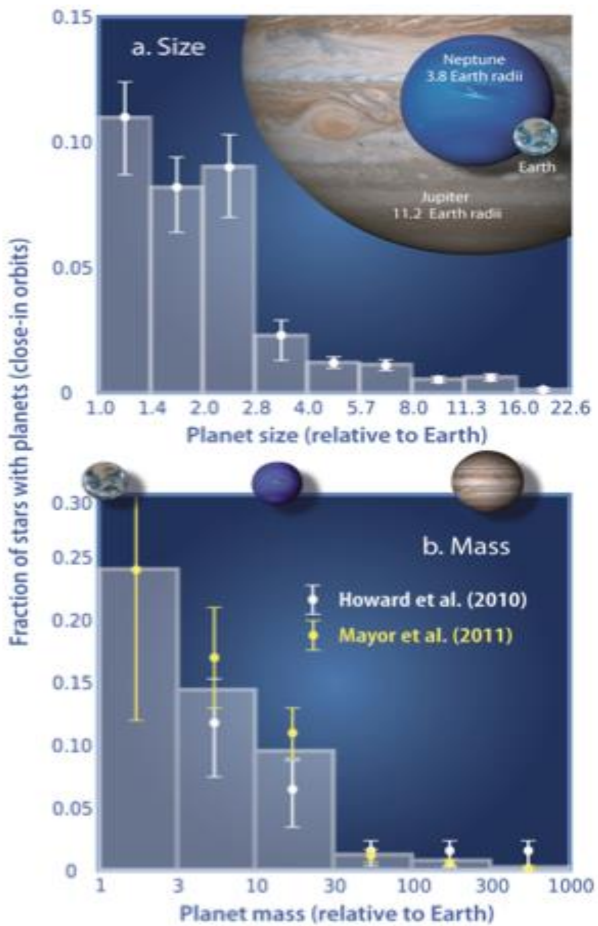
$$\dot{m}_{9\ \rm res} \simeq 6.02 f_{\rm res}^{0.95} m_*^{-1.33} \alpha_3^{0.97} \kappa_0^{-0.026} l_*^{0.70}$$

critical accretion rate to bypass the MMR barrier

2:1 MMR → $\dot{M}_g \gtrsim 1-2\times10^{-8} M_\odot\ \rm yr^{-1}$

6:5 MMR or higher → $\dot{M}_g \gtrsim 10^{-7} M_\odot\ \rm yr^{-1}$

Observation Implication



- 15%-20% of solar type stars harbor at least one gas giant planet.

Cumming et al. 2008;
Marcy et al. 2008

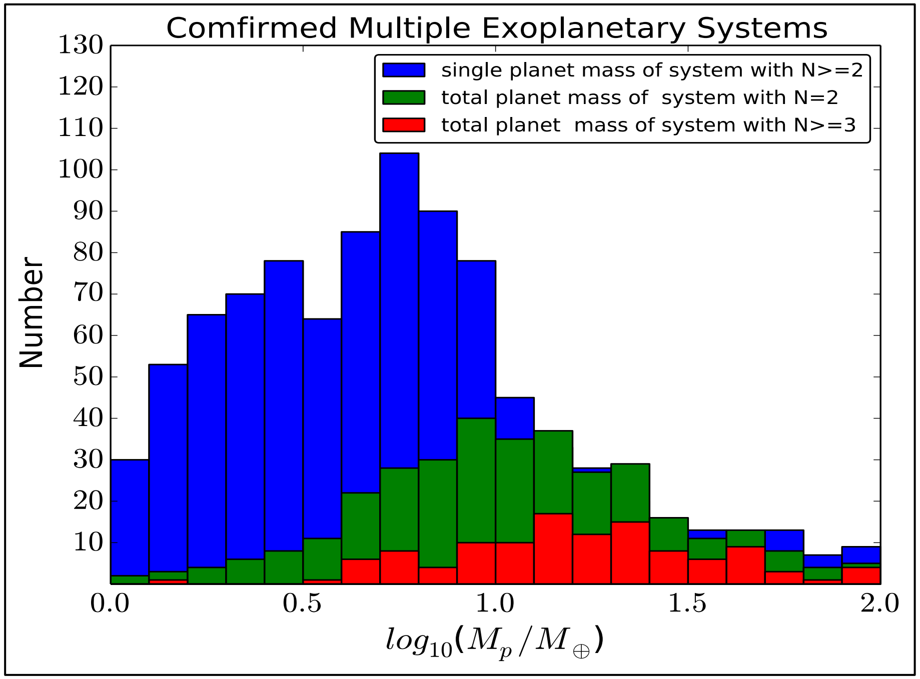
- ~50% of these stars contain at least one super earth up to 100 days.

Mayor et al. 2011

Observation Implication

Gas giant formation → abundance of total heavy elements in disks

$\eta_J \propto M_{disk} Z_d$



- In known multiple systems, the medium mass of single planet is less than M_C(~$10M_E$), the total mass of those systems around individual stars are larger than M_C.

$M_{disk} Z_d$ ← necessary but not sufficient

Our Explanation

- The shortage of gas giants around most solar type stars may be due to the inability for small mass embryos to be collected into a few cores (with $M_p \geq M_c$) rather than the lack of heavy elements in disks.

$$\eta_J \propto \eta_c \times M_{disk} Z_d$$

Disk property $\dot{M}_g$ → Probability of forming gas giants

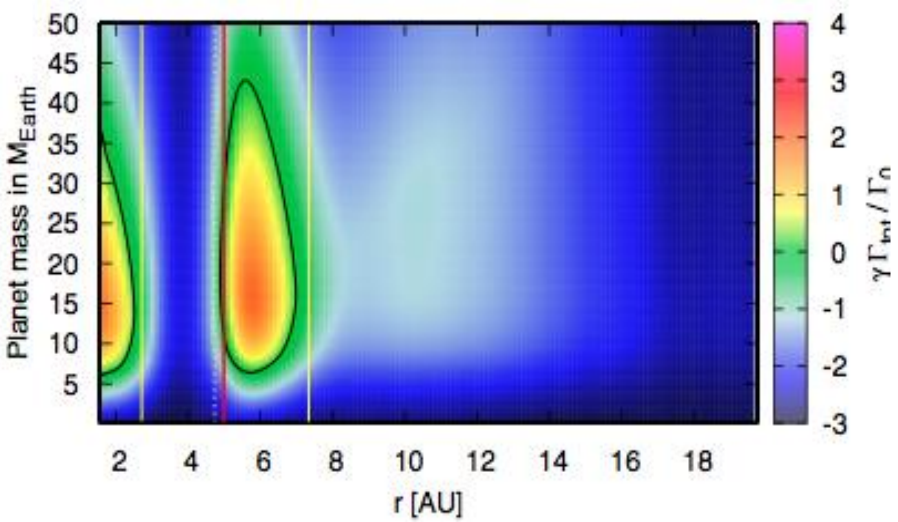
In high disk accretion $\dot{M}_g \gtrsim 10^{-7} M_\odot\ \mathrm{yr}^{-1}$ → 1. Embryos overlap their orbits and collide with each other 2. massive cores can be retained → Gas giant planets

In low disk accretion $\dot{M}_g < 10^{-7} M_\odot\ \mathrm{yr}^{-1}$ → Approach slowly and capture into MMR → Multiple super earths systems

Liu Zhang Lin & Aarseth 2014

Inhomogeneity & Diversity of disk structures

- Our simulations base on one disk model. Similar work (Kretke & Lin 2012; Bitsch et al. 2014; Cossou et al. 2014) presented with different disk models help to test the validity of our work and confirm the robustness of this convergent migration scenario.



Bitsch et al. 2014

- We should also bear in mind that the diverse architecture and final fate of planetary systems come from their inhomogeneous disk structure, which needs further investigation and comparison of theory, simulation and observation.

Summary

Disk Migration do play a significant role on the formation and evolution of planetary systems.

- We build HERMITE-Embryo code and present simulation to show the possible mechanism for embryos ($\sim M_E$) to attain massive cores ($>M_C$) by this convergent type I migration.

- Our theoretical analysis and numerical simulations suggest that the common existence of super earths but lack of gas giants is determined by disk accretion rate.