Hot Earth around G and M dwarfs

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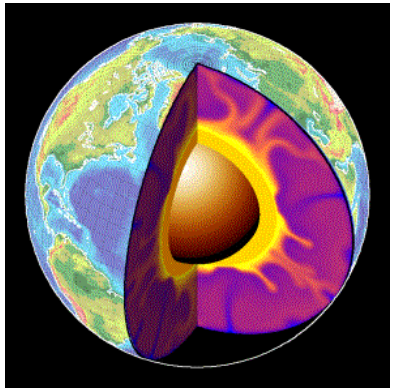
JPL Colloquium
Pasadena, California
Jan 31st, 2008

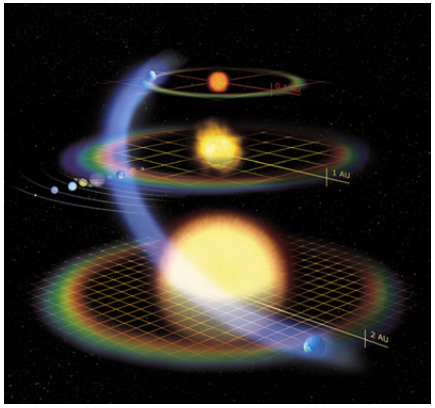
38 slides

Some relevant issues

Detectable habitable planets:



mass



environment

atmosphere

Theory:

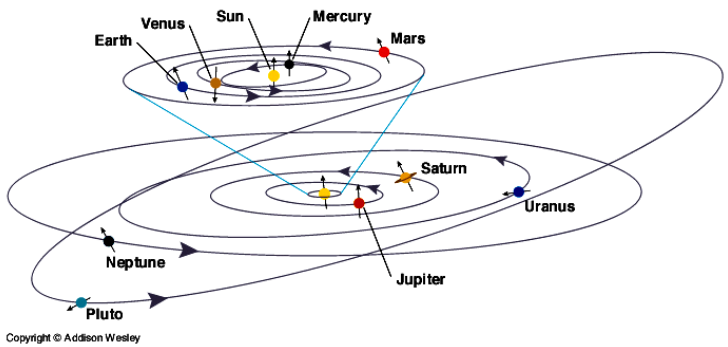
How did planets form ? **Core accretion vs gravitational instability**

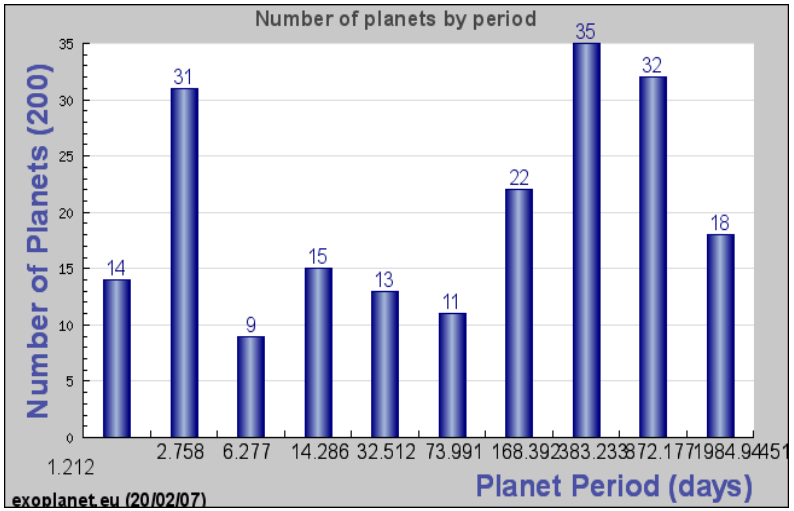
How prolific ? **Extrapolation from gas giant planets**

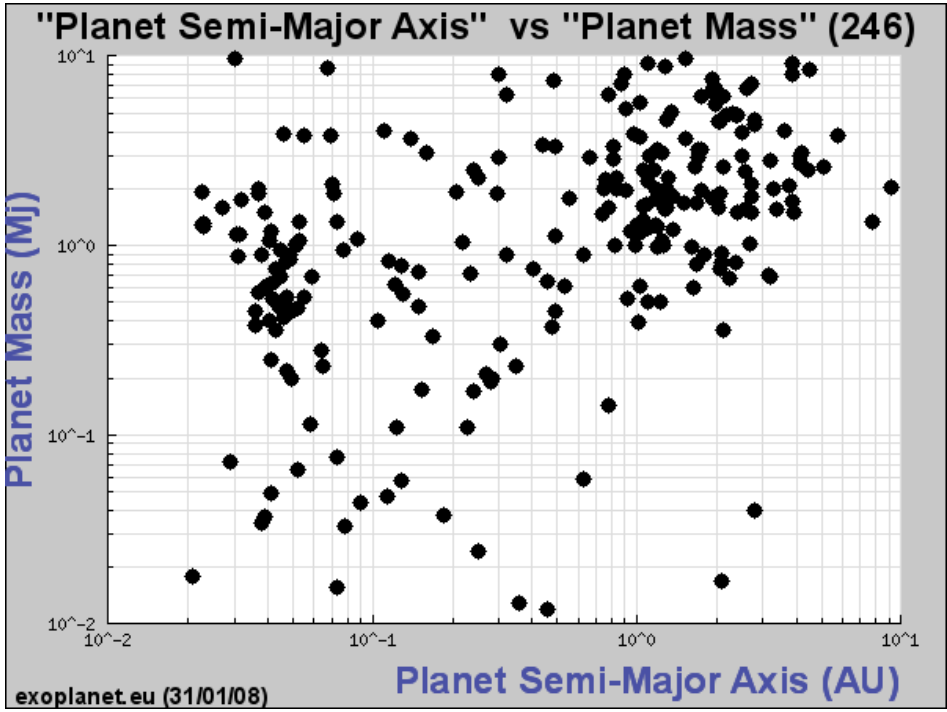
Where do we look for rocky planets? **Extreme, not necessarily habitable planets**

What are their dynamical properties? **Ubiquitous & diverse architecture: survival**

Observed M-P distribution around sun-like stars







A continuous logarithmic period distribution

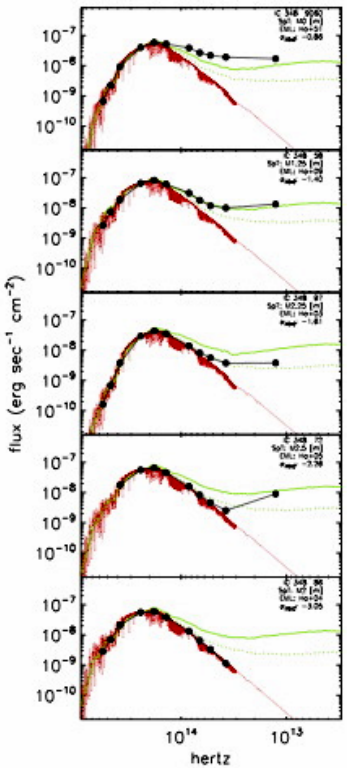
A pile-up near 3 days and another pile up near 2-3 years

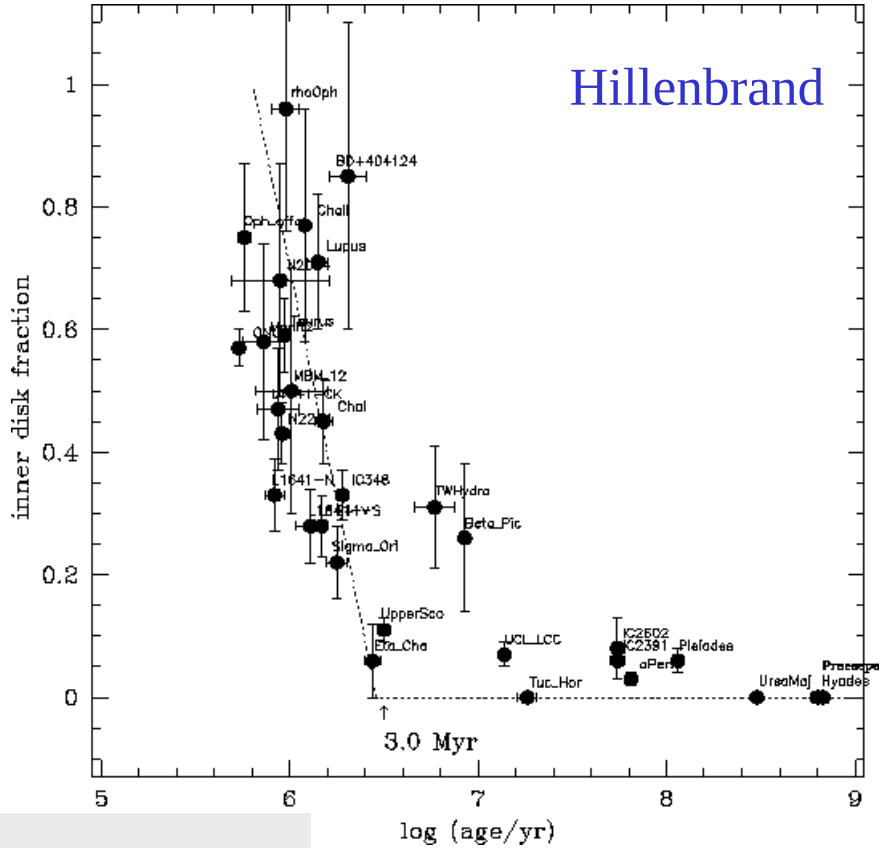
Does the mass function depend on the period?

Is there an edge to the planetary systems?

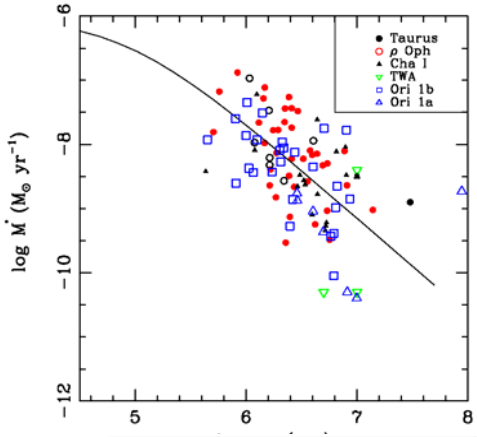
Does the mass function depend on the stellar mass or [Fe/H]?

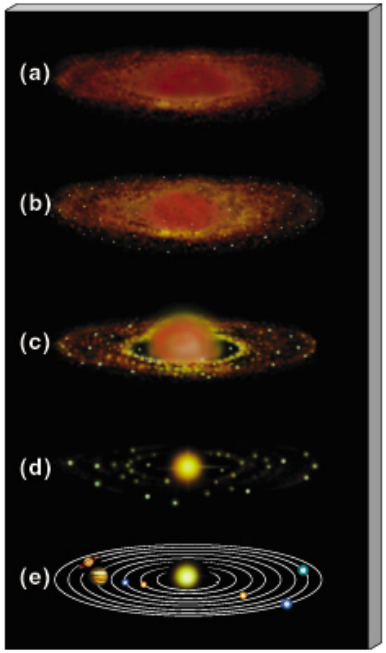
Disks' properties: mass and life span ~ 10 Myr

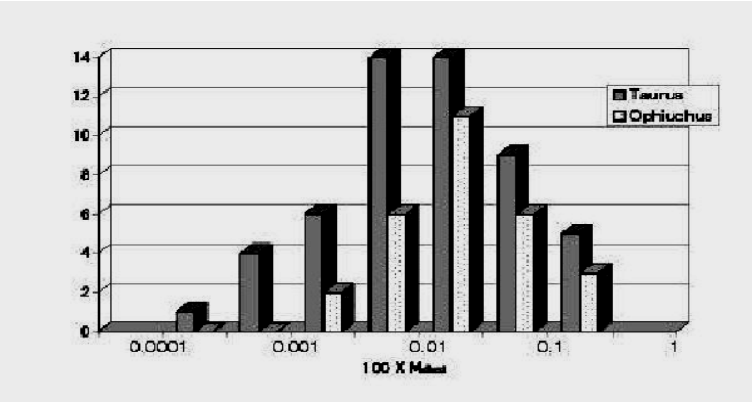


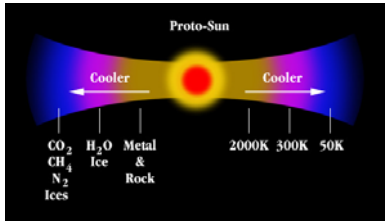


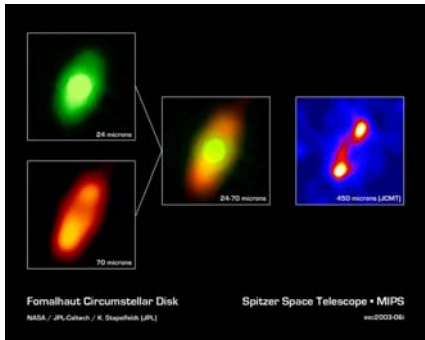
Gas accretion rate



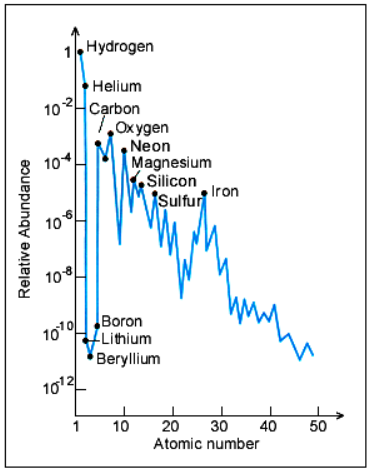


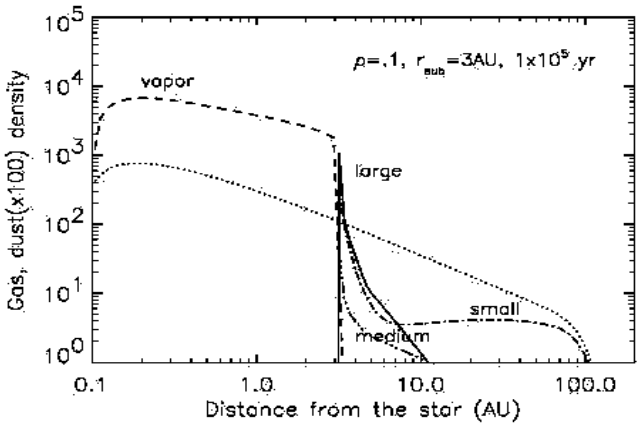




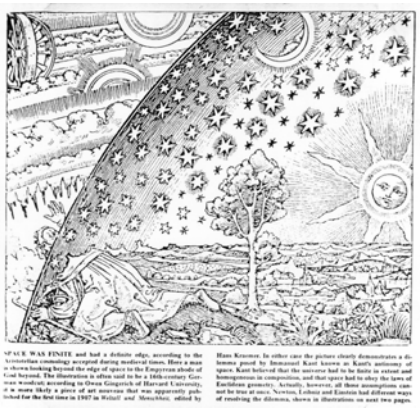


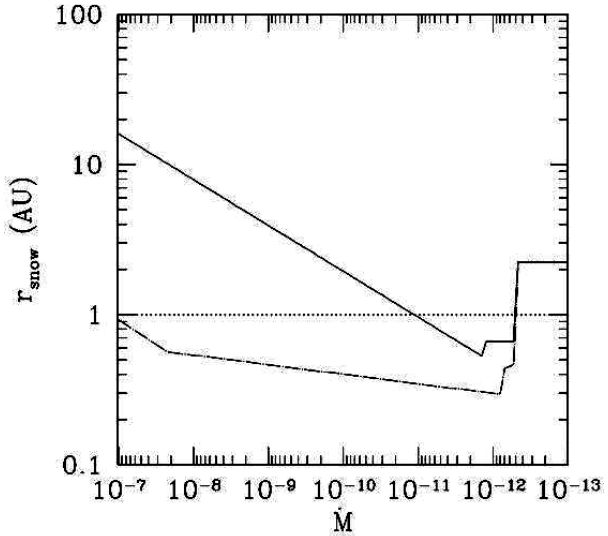
Preferred cradles of planetesimals: snow line

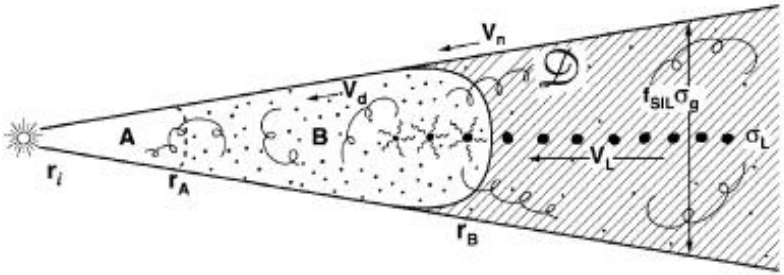




Cuzzi, Takeuchi

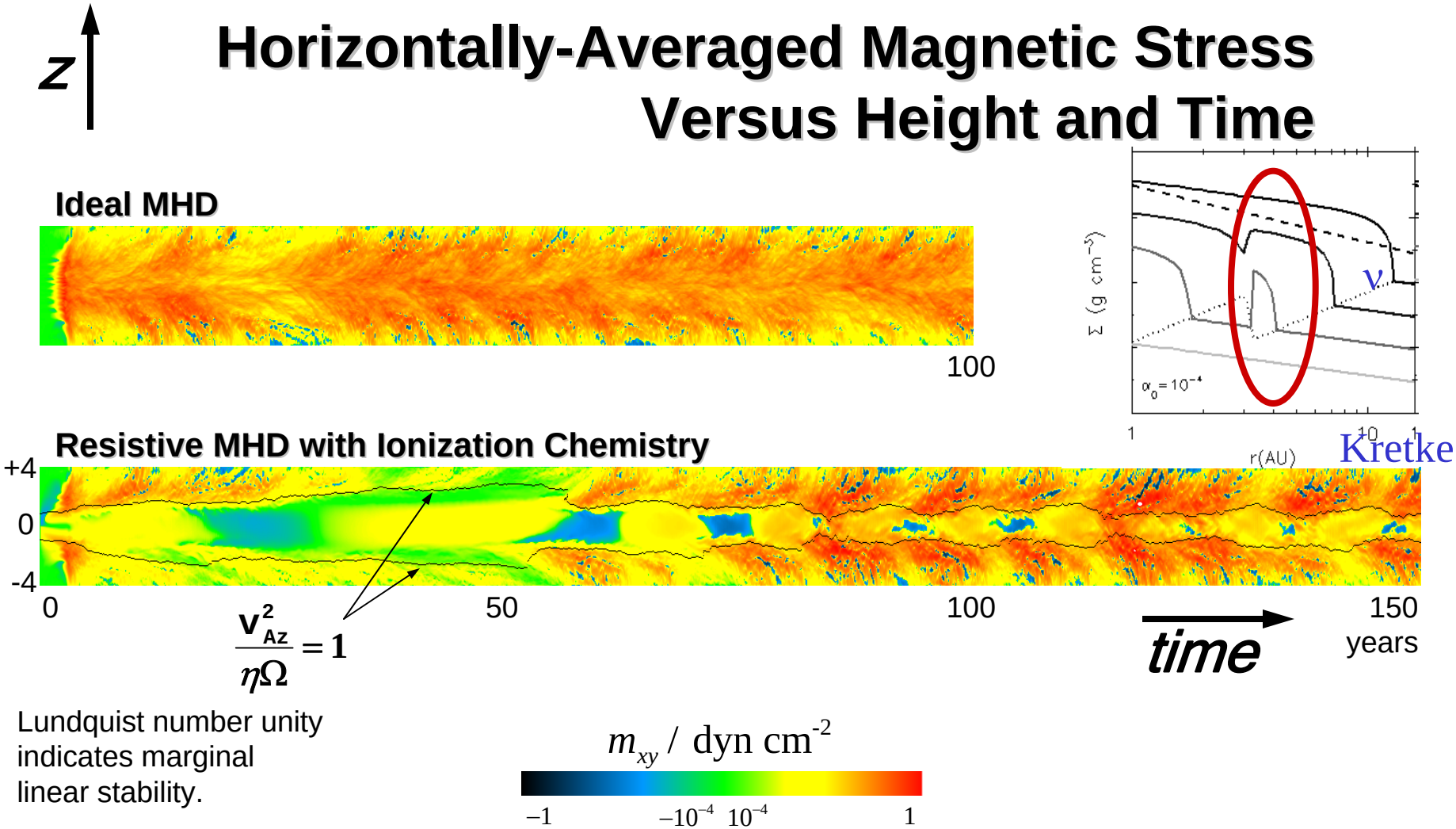






Lecar, Garaud, Lretle, Youdim
Brauer, Dullemond, Henning

The lively dead zone



Turner et al 07

Planetesimals can form and be retained around T Tauri stars at preferred sites

From planetesimals to embryos

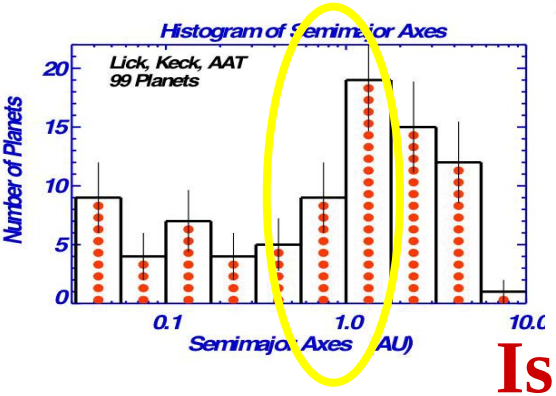
$$\dot{M}_c \sim \pi R_c^2 \rho_d \left(\frac{2GM_c}{R_c\sigma^2}\right)\sigma \sim 2\pi R_c^2 \Sigma_d \Omega_K \left(\frac{GM_c}{R_c\sigma^2}\right)$$

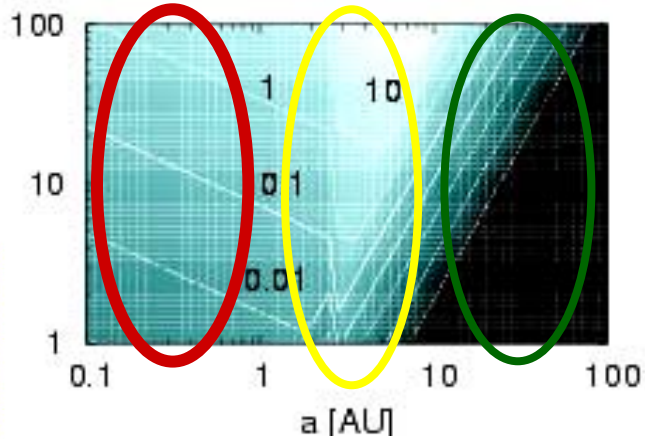
Feeding zones:

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

Isolation mass:

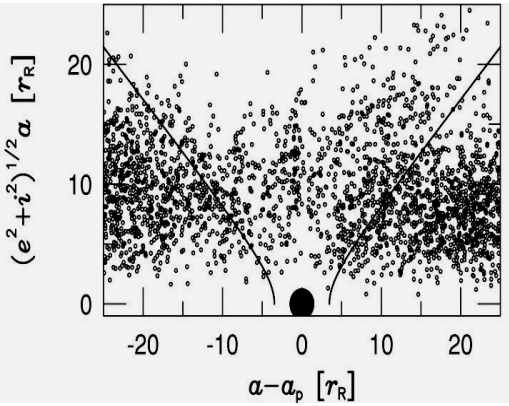
$M_{isolation} \sim \Sigma^{1.5}\ a^3$

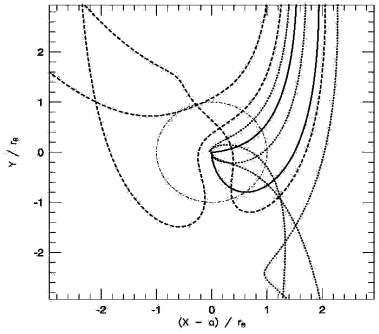




Limited by:

Isolation **slow growth**

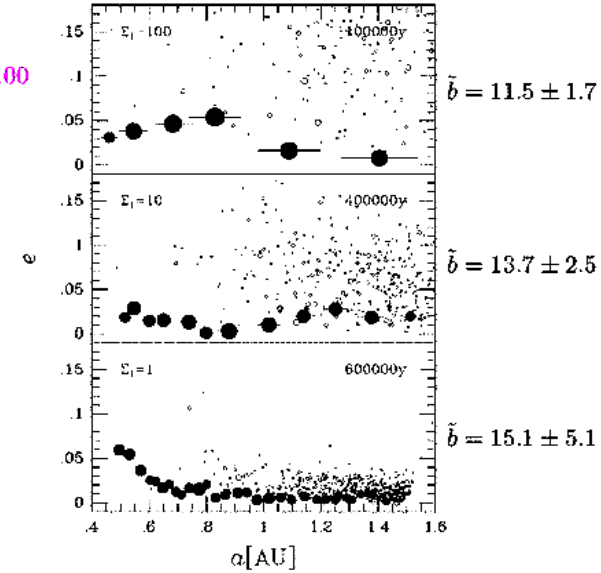




Disk Mass Dependence

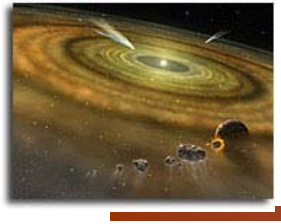
$= 3/2$

$\Sigma_1 = 1, 10, 100$



[Eiichiro Kokubo (National Astronomical University, Tokyo) 17] [NEXT> [last>

Safronov, Wetherill, Stewart, Aarseth, Kokubo, Ida, Leinhardt

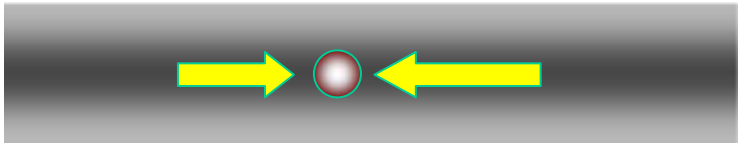


Survival of embryos under type I migration

type-I migration

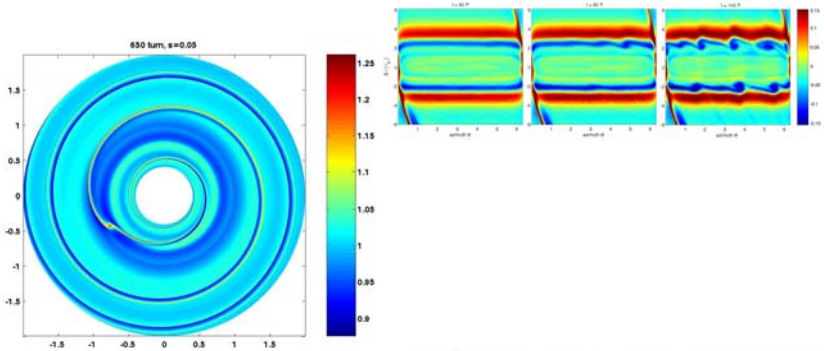
Goldreich & Tremaine (1979),
Ward (1986, 1997), Tanaka et al. (2002)

$$M > (0.1-1)M_{\oplus}$$

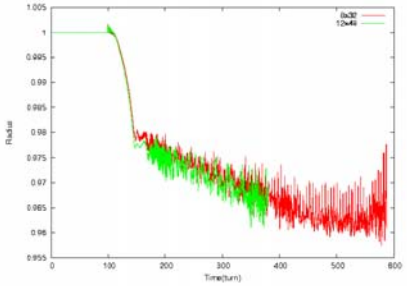


disk torque imbalance

$$\tau_{\mathrm{mig,I}} \approx 0.05\left(\frac{\Sigma_{\mathrm{g,SN}}}{\Sigma_{\mathrm{g}}}\right)\left(\frac{M_{\oplus}}{M_p}\right)\left(\frac{M_*}{M_o}\right)^{\frac{3}{2}}\left(\frac{a}{1\mathrm{AU}}\right)^{\frac{3}{2}}\mathrm{Myr}$$

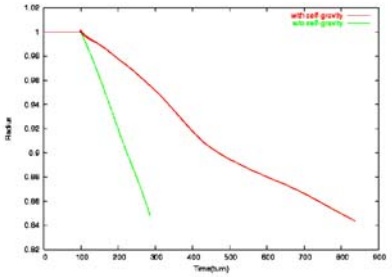


Invisic limit



$$\tau_{\mathrm{mig,II}} \approx \left(\frac{\Sigma_{\mathrm{g,SN}}}{\Sigma_{\mathrm{g}}}\right)\left(\frac{M_{\mathrm{p}}}{M_{\mathrm{J}}}\right)\left(\frac{10^{-3}}{\alpha}\right)\left(\frac{M_{\mathrm{o}}}{M_*}\right)^{\frac{1}{2}}\left(\frac{a}{1\mathrm{AU}}\right)^{\frac{1}{2}}\mathrm{Myr}$$

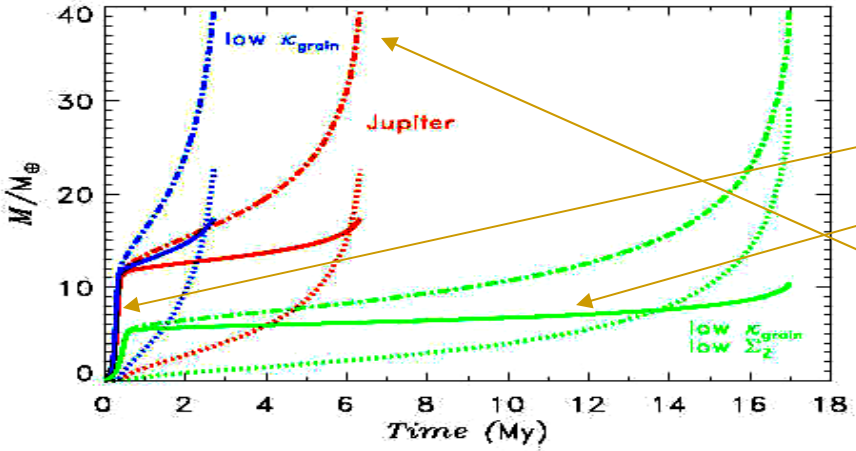
Self gravity



Korycanski, Nelson, Papaloizou, Kley, Masset, D'Angelo, Li, Dobbs-Dixon

Type I migration in T Tauri disks is ineffective

Accretion onto cores



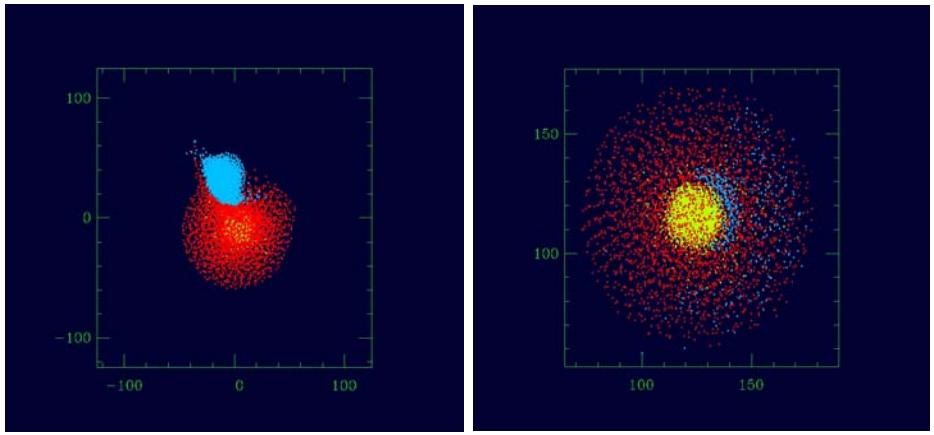
1. **Phase 1:** runaway solid accretion
2. **Phase 2:** solid and gas accretion rates are small and time independent; gas rate > solid rate
3. **Phase 3:** runaway gas accretion
4. Cooling and contraction

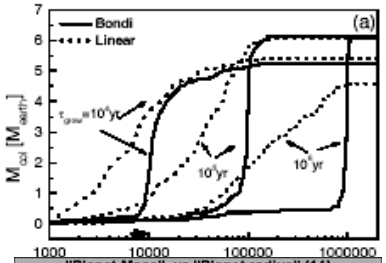
Challenges: Pollack et al

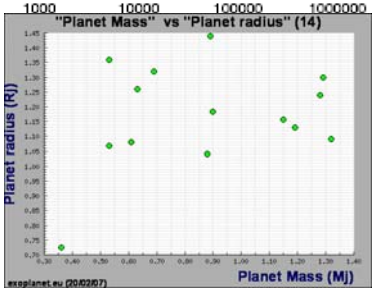
1) Core growth: perturbation slow down & planetesimal gaps (Ida)

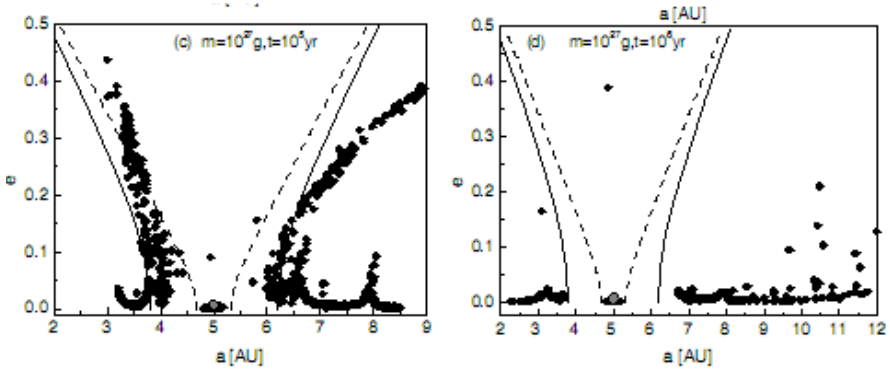
2) Radiation transfer efficiency grain survival & opacity (Podolak)

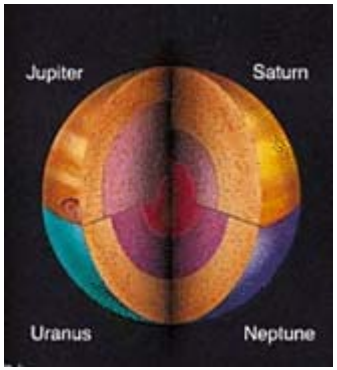
3) Low global Σ_{dust} (Bryden)

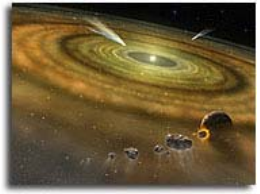




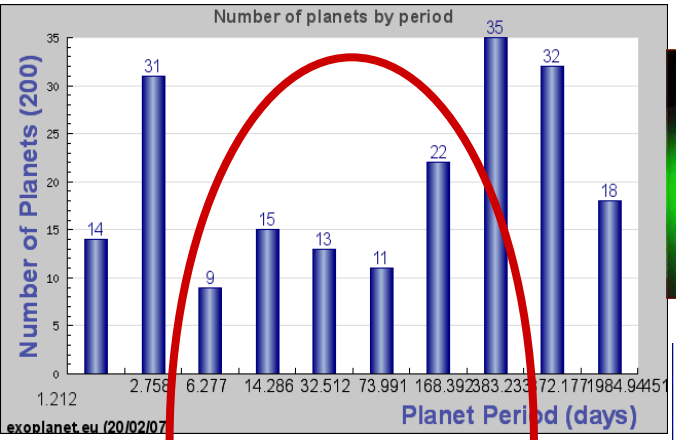


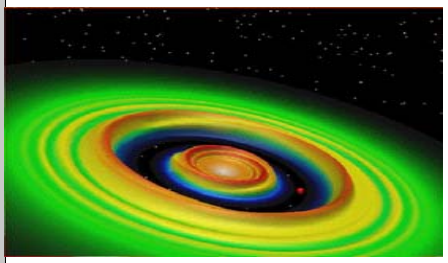






Disk-planet tidal interactions



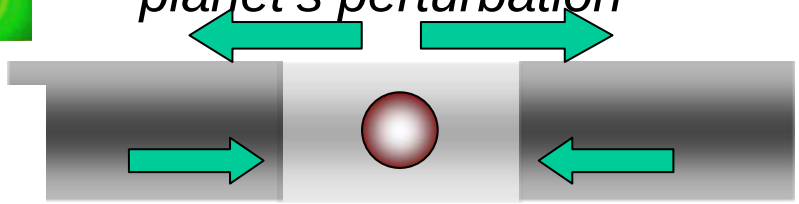


type-II migration

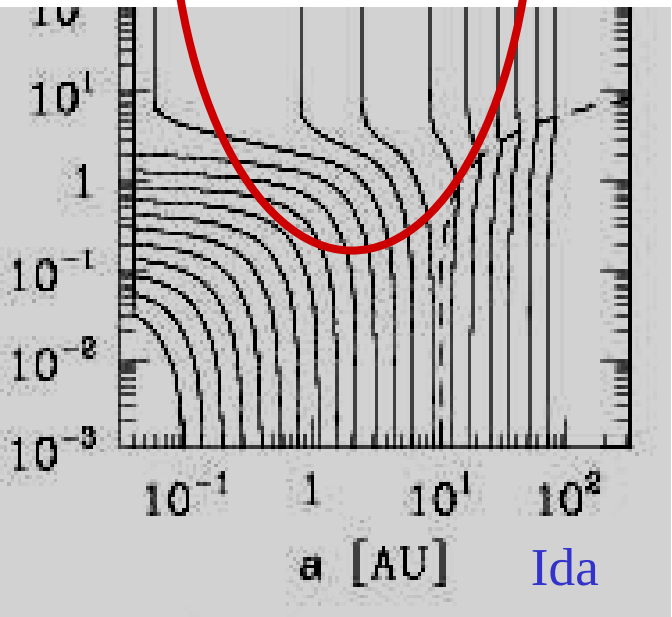
Lin & Papaloizou (1985),....

$$M > (10-100)M_{\oplus}$$

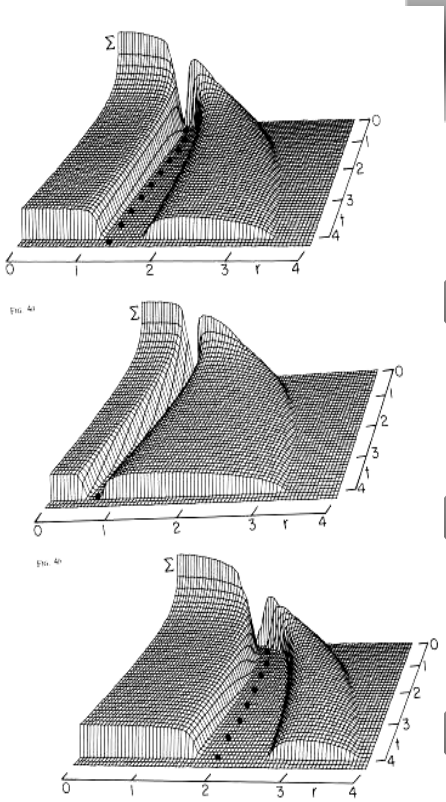
planet's perturbation

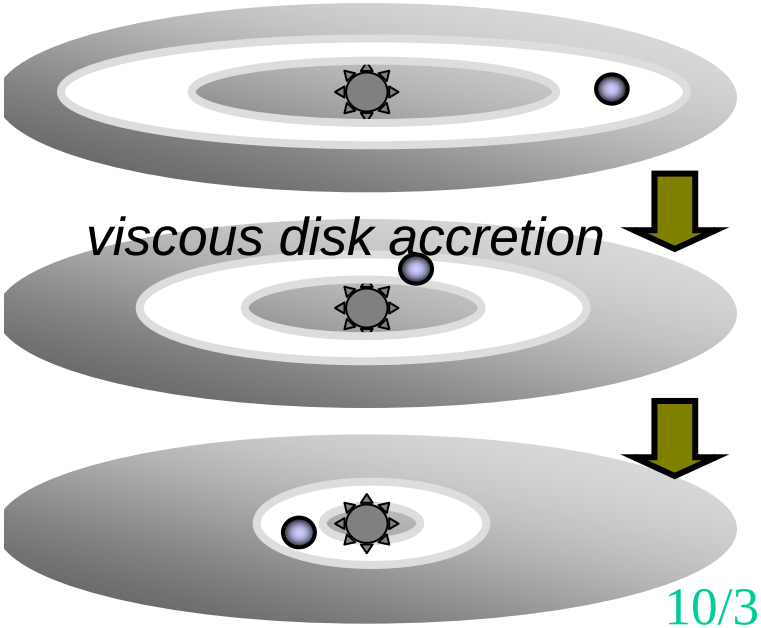


viscous diffusion



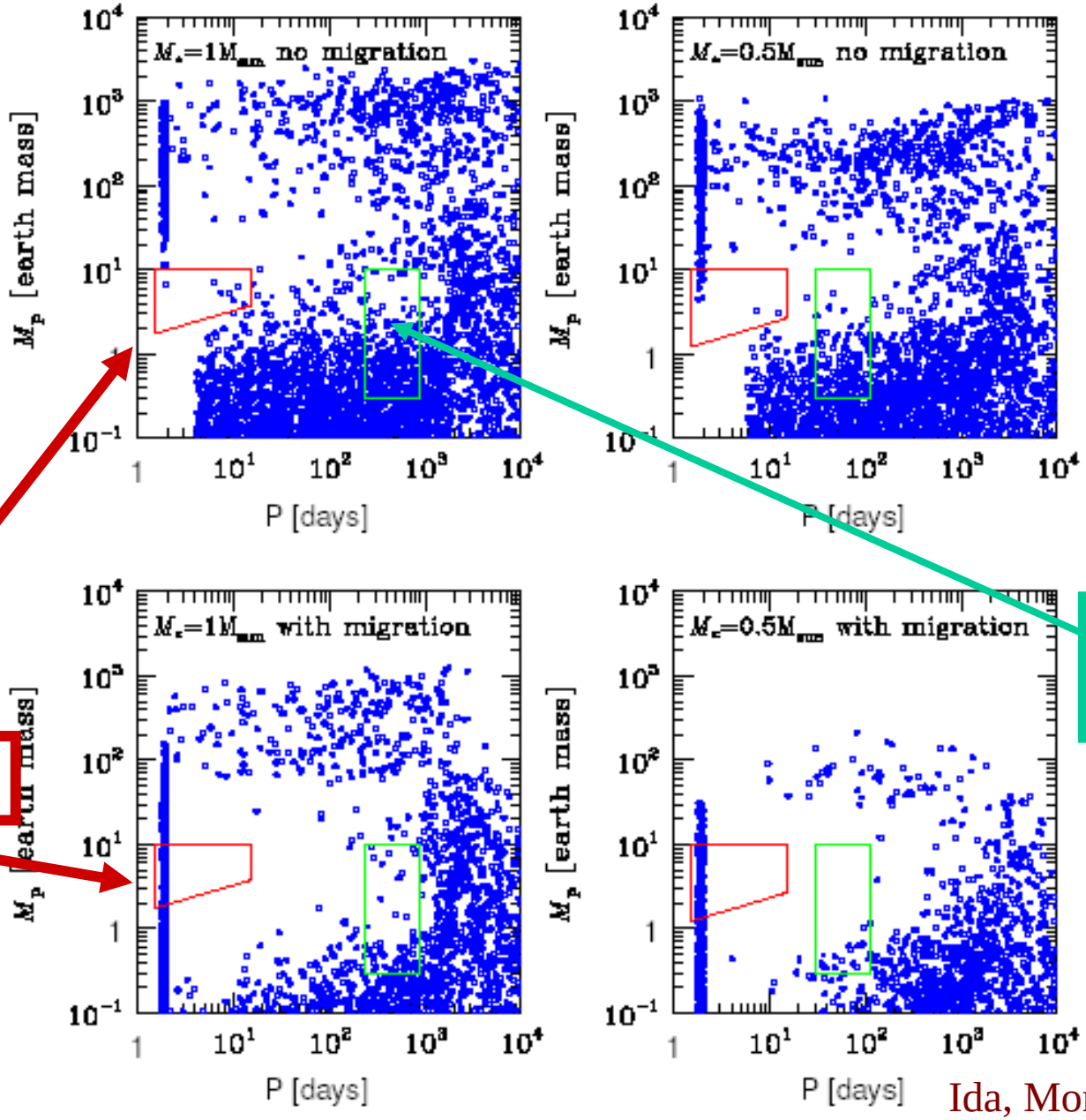
Ida





viscous disk accretion

Type I & II migration of isolated planets



Habitable planets

M/s accuracy

Ida, Mordasini

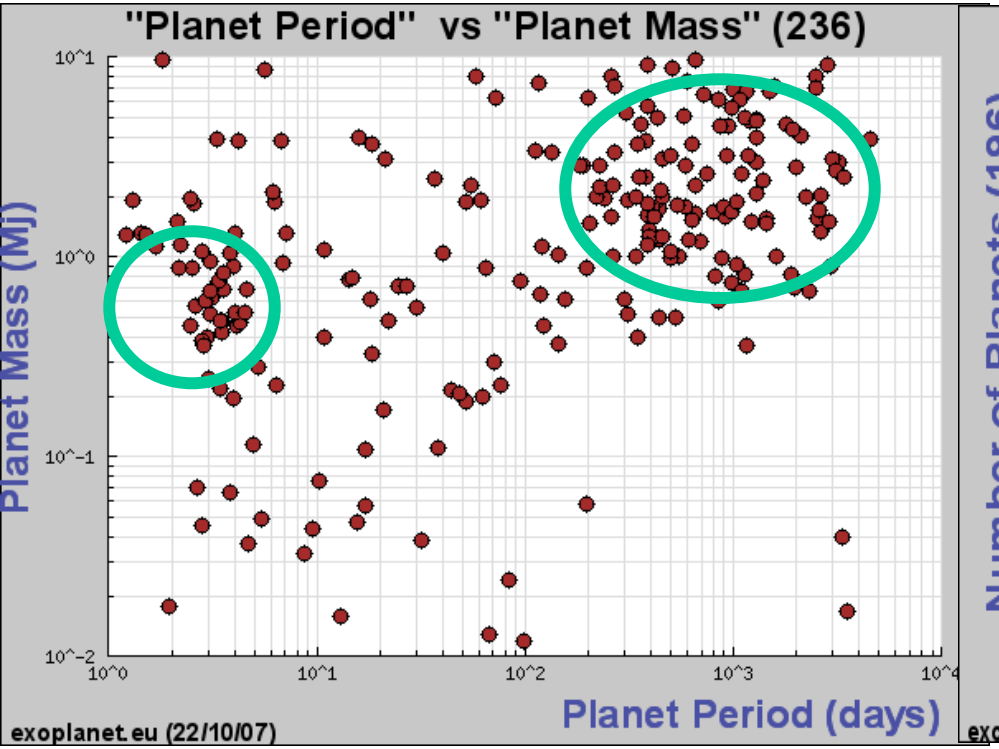
Challenges to planet formation theory

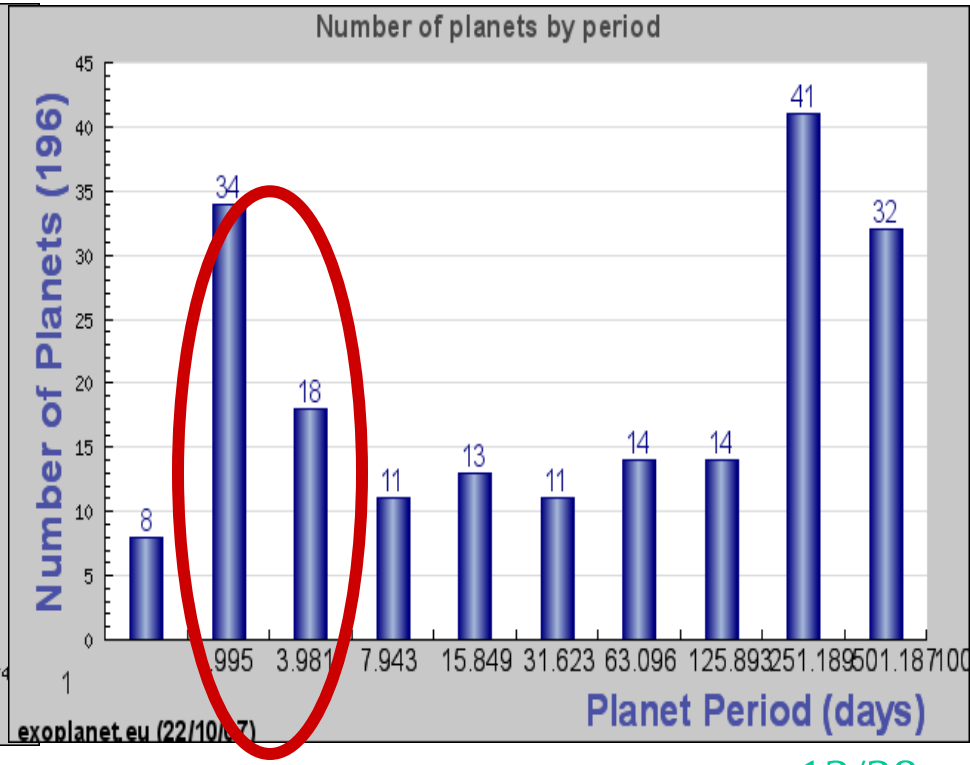
A) Halting Protoplanetary Migration

1) Tidal interaction

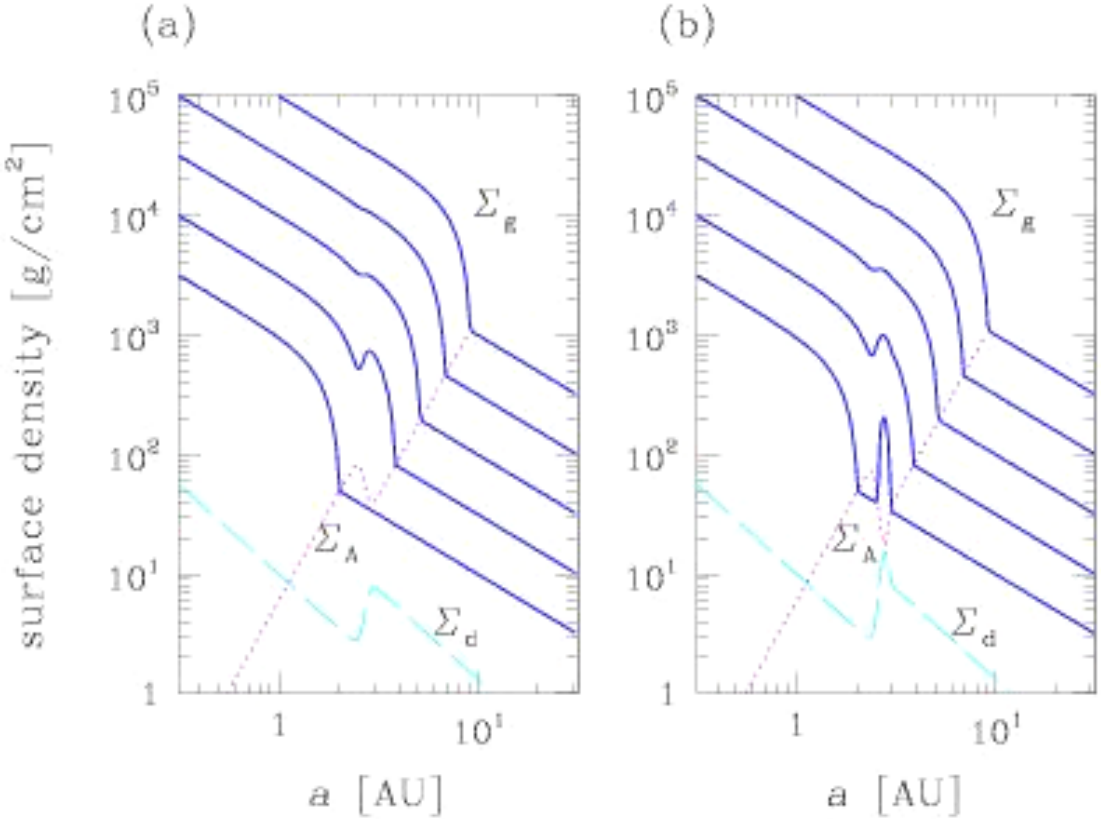
2) Magnetospheric cavity

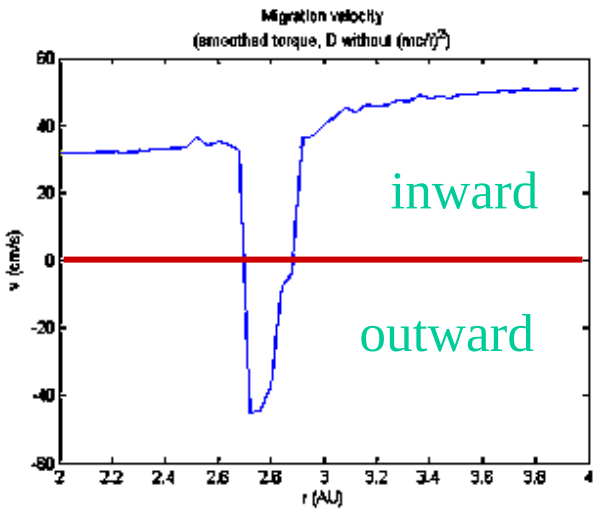
3) Protoplanetary mass loss (or accretion)





Stalling type I migration @ snow line

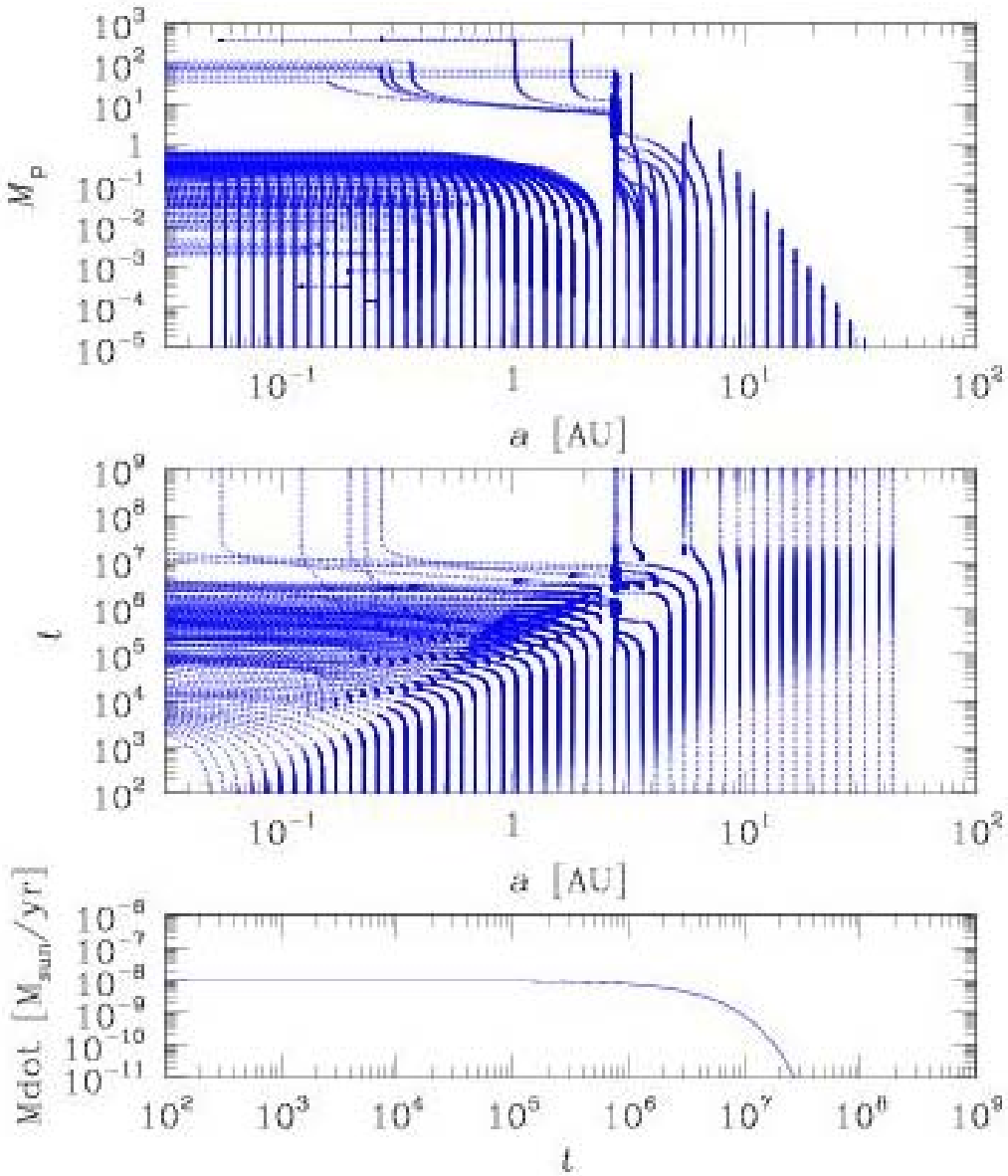




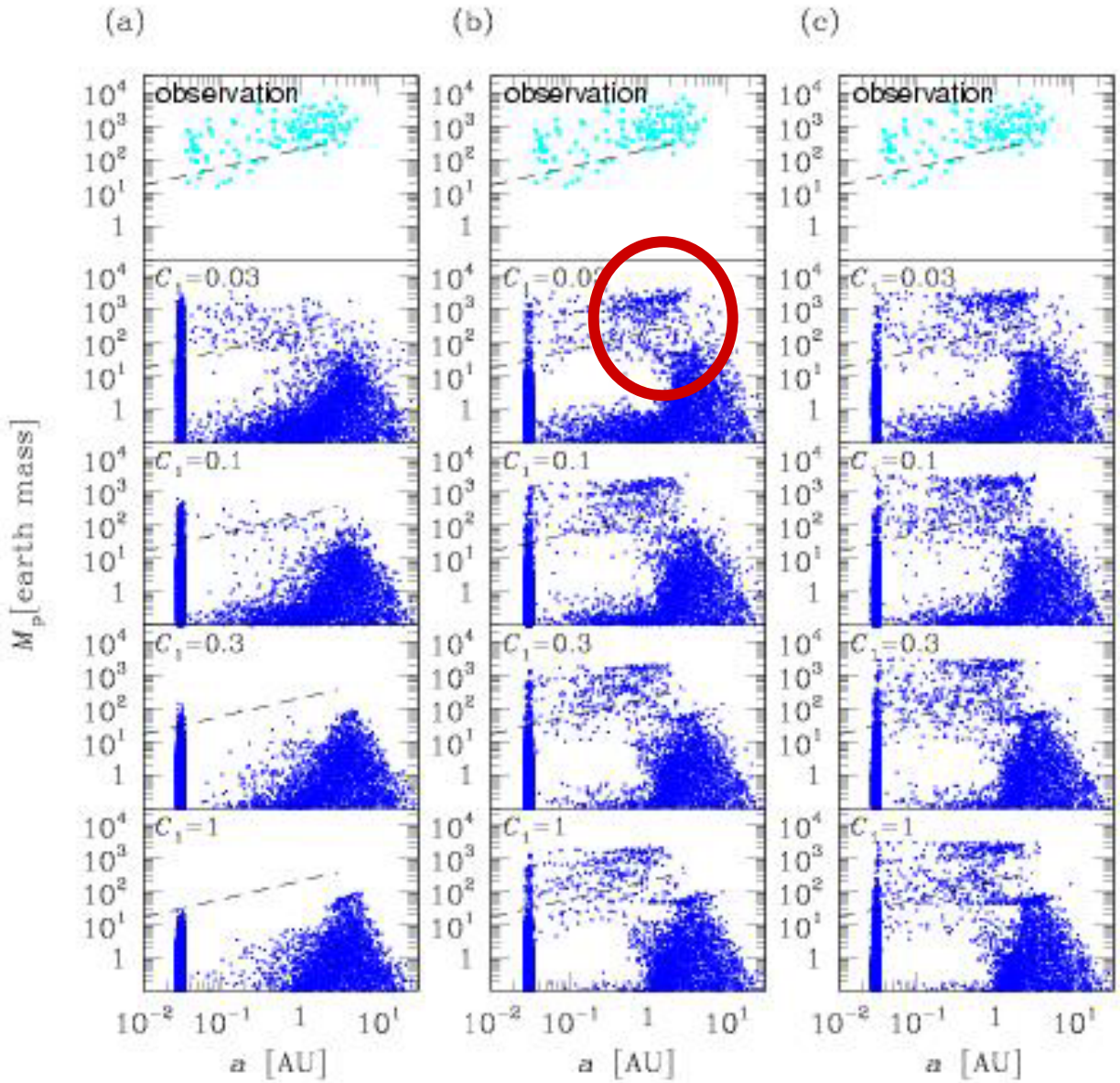
Corotation resonance

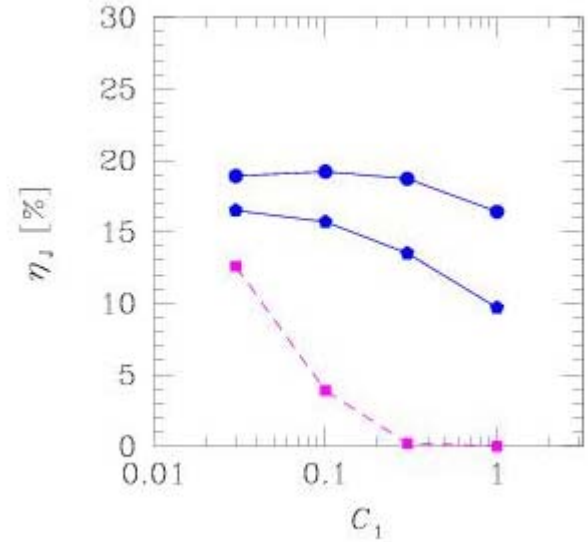
Viscous limit: Zhang

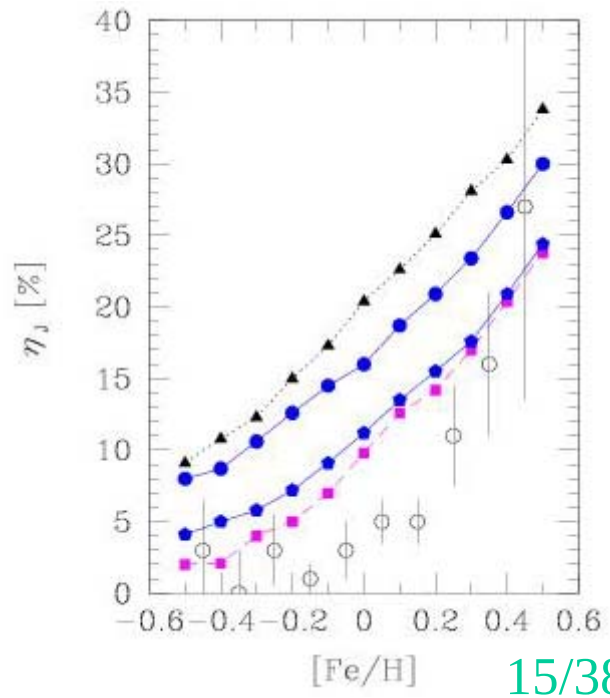
Retention of embryos



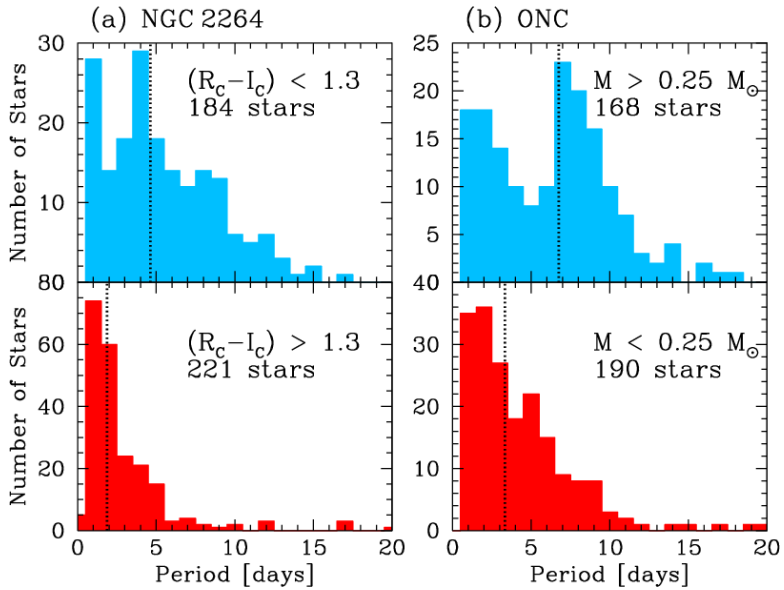
Influence of snow line



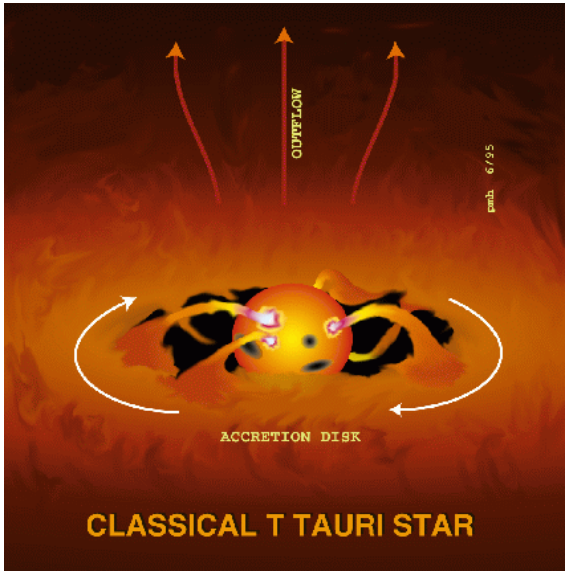


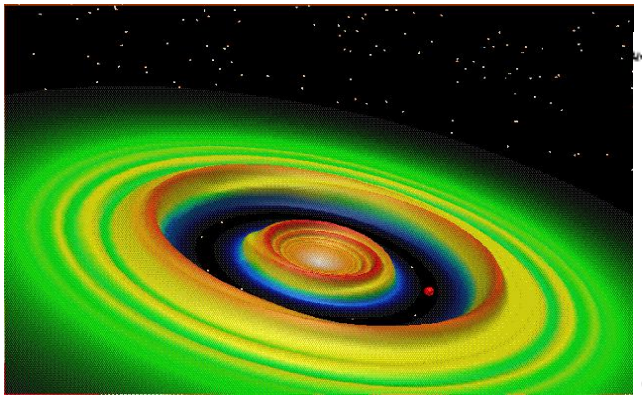


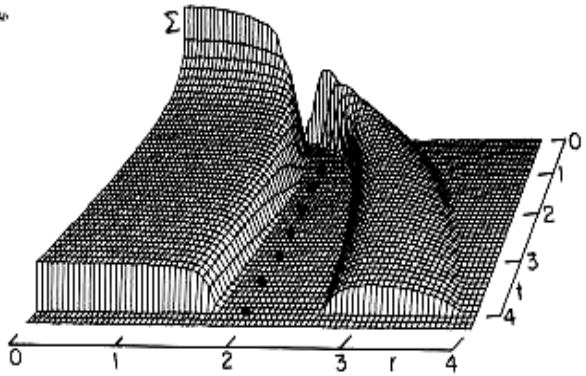
Magnetospheric cavity

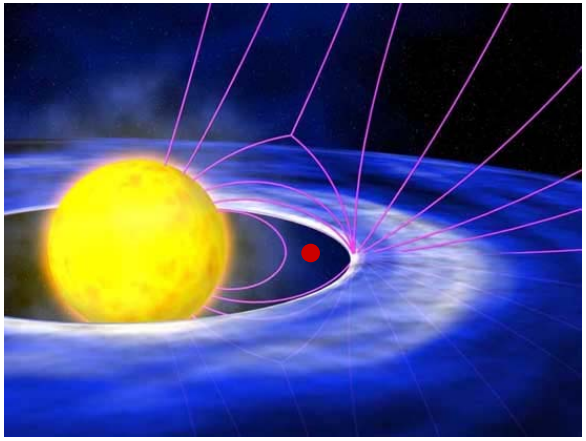


Spin distribution
Of T Tauri stars









Unipolar induction

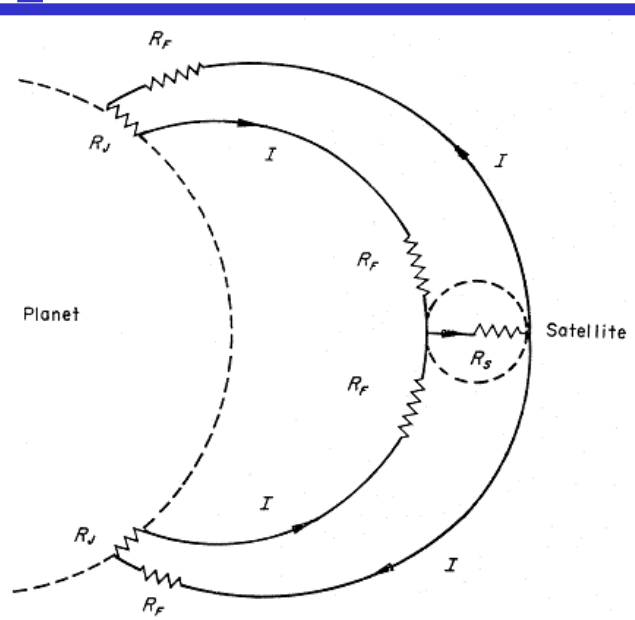
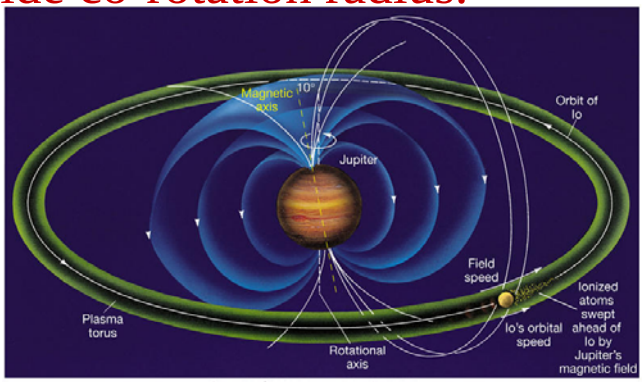


FIG. 1. *Schematic diagram of d.c. circuit.*

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



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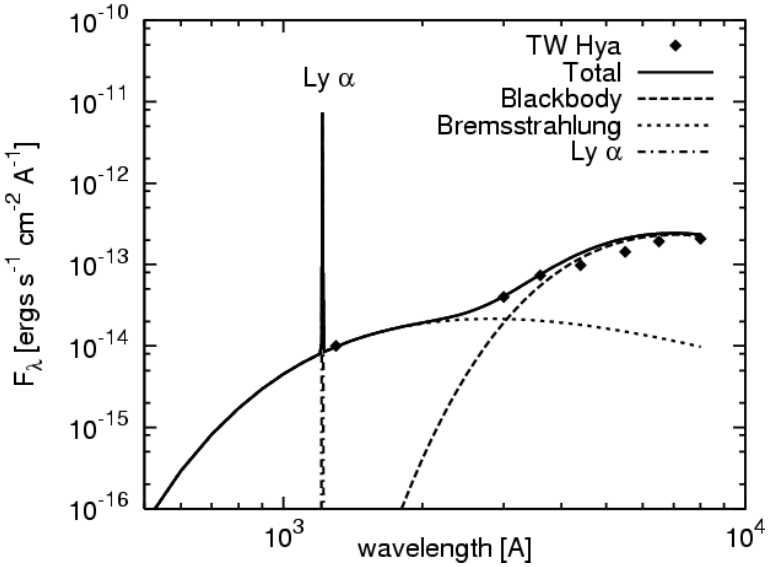
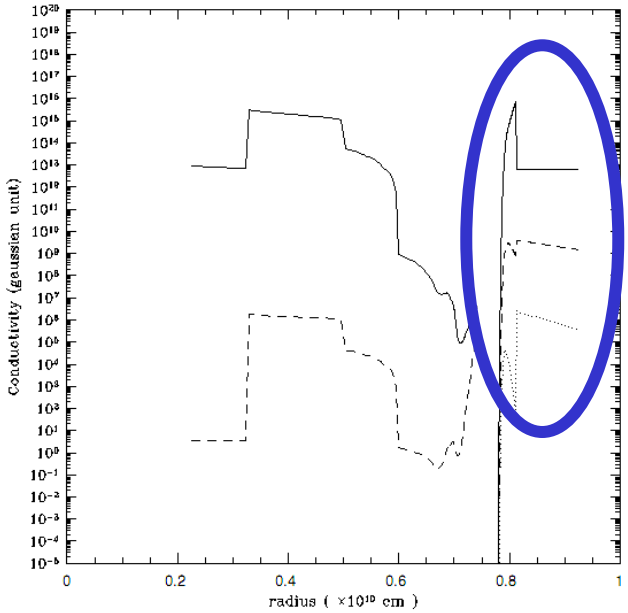
Io

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





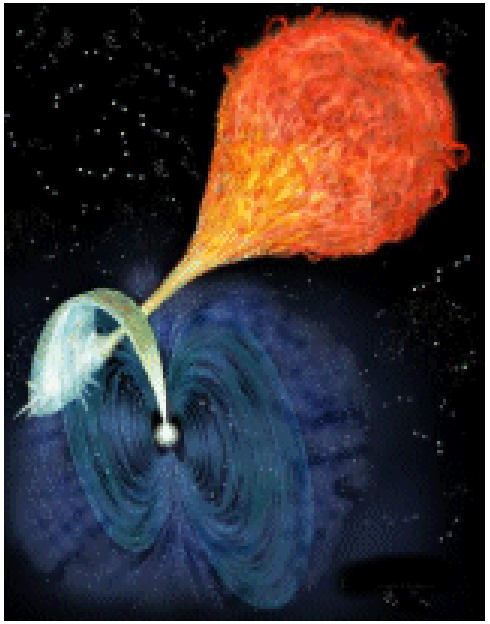
Skin depth & Ohmic dissipation

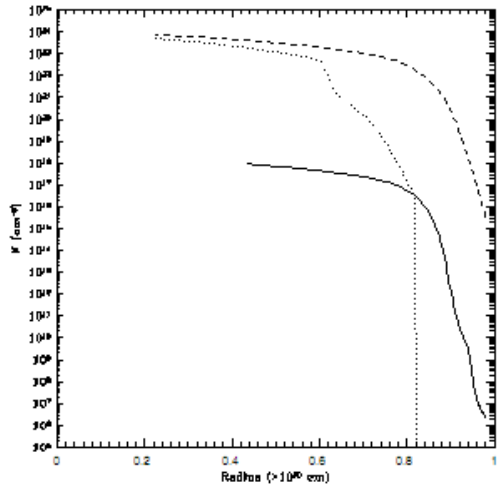
Laine

Modulated fields can penetrate into the planet's interior as in Am Her systems (Campbell)

Torque

$$\mathcal{P} = -\omega |T|$$





Internal conductivity
On the unexposed side

Induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \wedge (v \wedge \mathbf{B}) - \nabla \wedge (\eta \nabla \wedge \mathbf{B})$$

Magnetic diffusivity $\eta = 1/\mu_0 \sigma$

Synodic frequency

$$\omega = \omega_* - \Omega_p$$

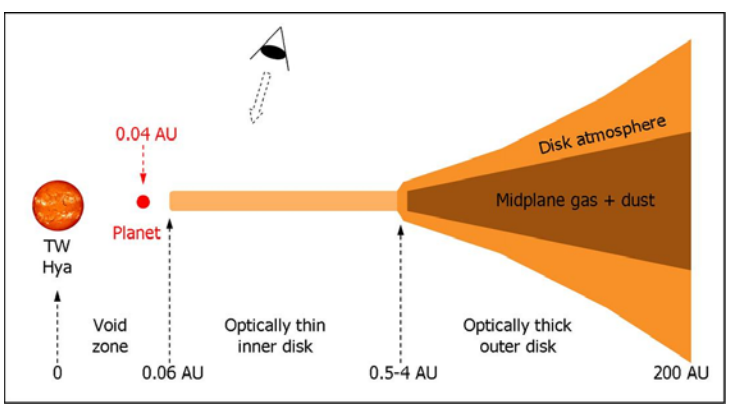
Planet's induced poloroidal field

$$\nabla \wedge \mathbf{B} = -\frac{i\omega}{\eta} \nabla \wedge (\phi\, \mathbf{e_r})$$

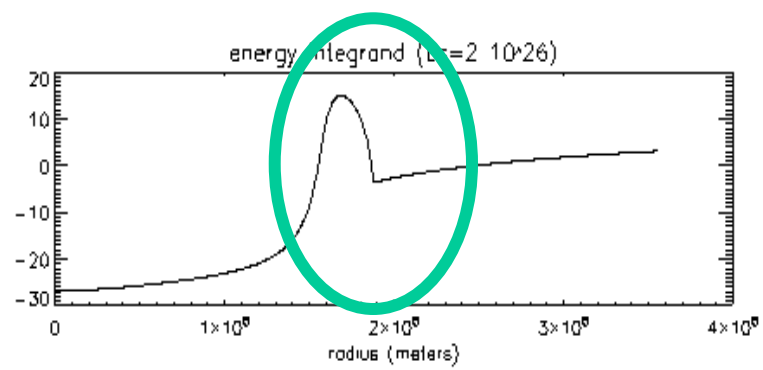
$$\phi(\mathbf{r}, t) = \mu_0 \left[\sum_{l,m} C_l^m\, G_l(r)\, Y_l^m(\theta, \varphi) \right] e^{i\omega t}$$

Ohmic energy dissipation rate

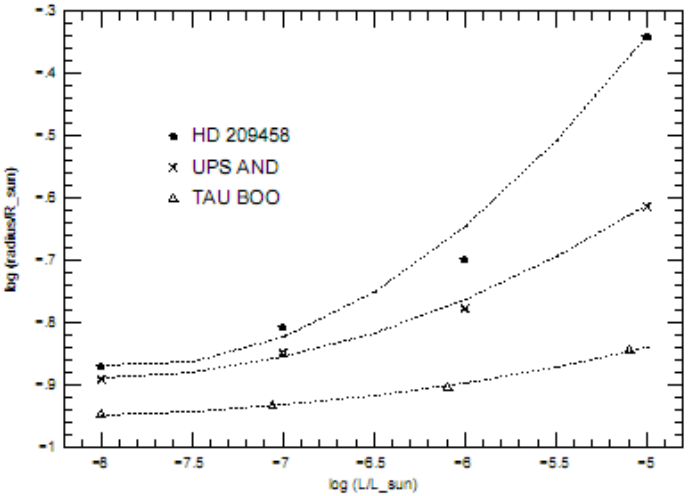
$$\mathcal{P} = \frac{\omega^2}{\mu_0} \int \frac{1}{\eta(r)} \left[\frac{1}{\sin\theta} \left(\frac{\partial Im(\phi)}{\partial \varphi}(r, \theta, \varphi) \right)^2 + \sin\theta \left(\frac{\partial Im(\phi)}{\partial \theta}(r, \theta\varphi) \right)^2 \right] dr\, d\theta\, d\varphi.$$



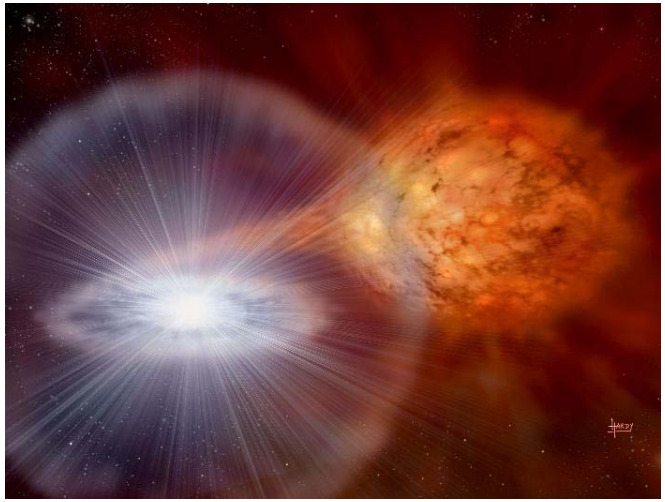
Setiawan

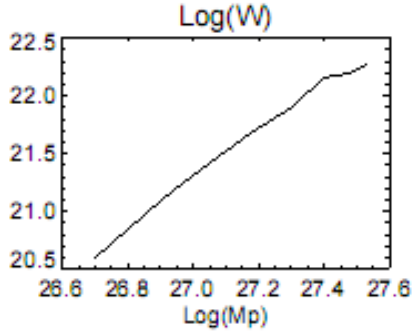


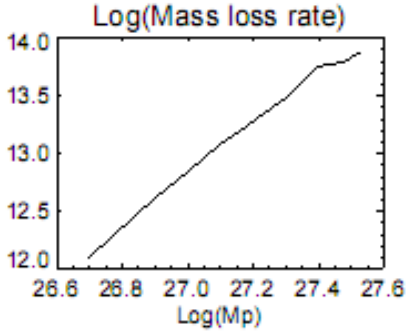
Planetary inflation & mass loss



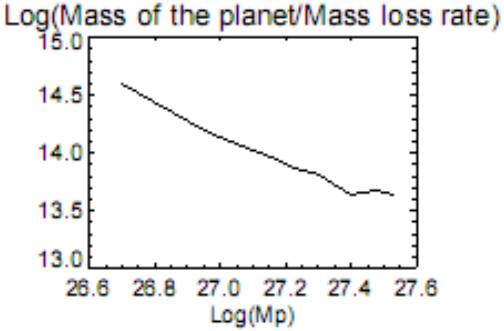
Inflation







Mass reduction, orbital expansion, and quasi-equilibrium configuration

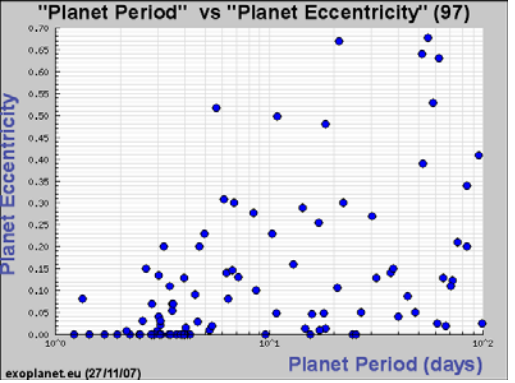


$$\tau_m = \frac{M_p}{\dot{\mathcal{M}}_{gen}} \simeq 3\mathrm{Mys}\left(\frac{0.63\ M_J}{M_p}\right)^{2.4}\left(\frac{a}{0.04\ AU}\right)^{3.8}\left[\left(\frac{|\omega|}{10^{-5}\mathrm{s}^{-1}} - 0.1\right)\right]^{-1}\left(\frac{m}{4\times 10^{34}\mathrm{Am}^2}\right)^{-2.3}$$

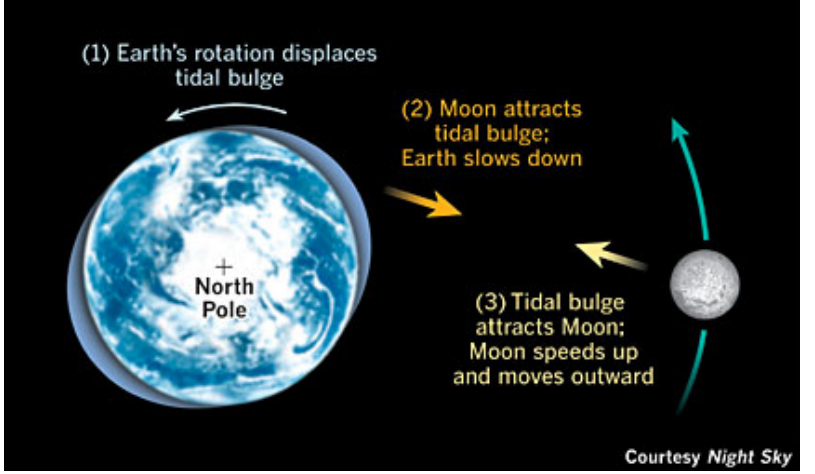
$$(\sin\ \alpha)^{-2.28}\left(\frac{M_\star}{M_\odot}\right)^{0.5}\left(\frac{L_\star}{1.5\ L_\odot}\right)^{0.8}$$

$$\frac{\dot{a}}{a} = -2\frac{\dot{M}}{Mp}$$

Mass loss



Stellar contribution



Inertial waves and Hough waves:

Can damp planet's eccentricity

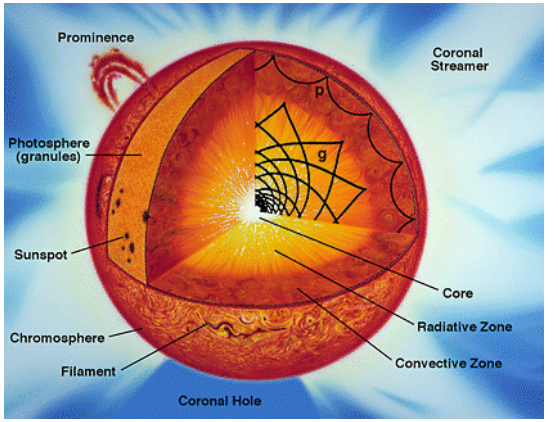
Can limit planet's orbital decay

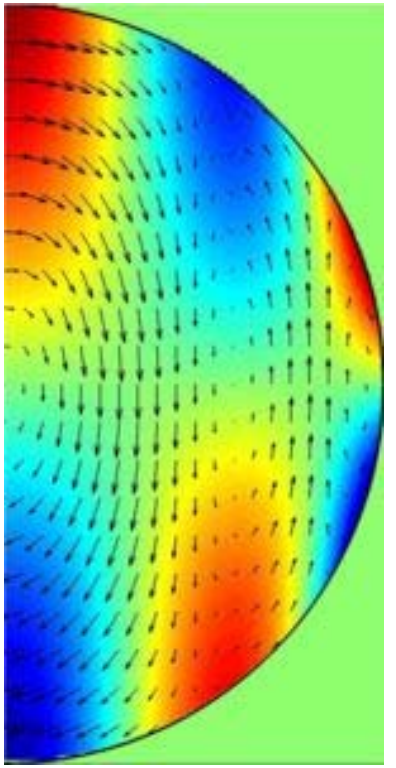
Frequency dependence:

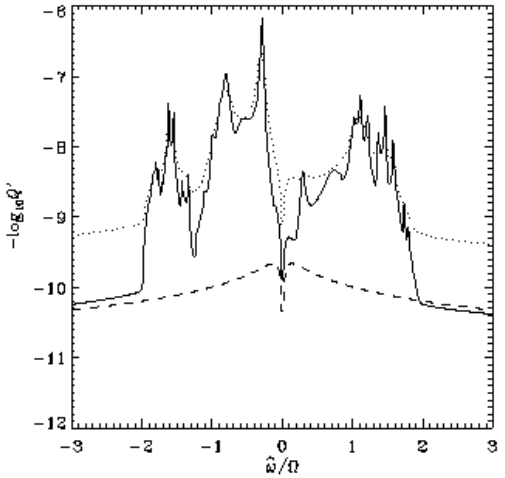
Diversity

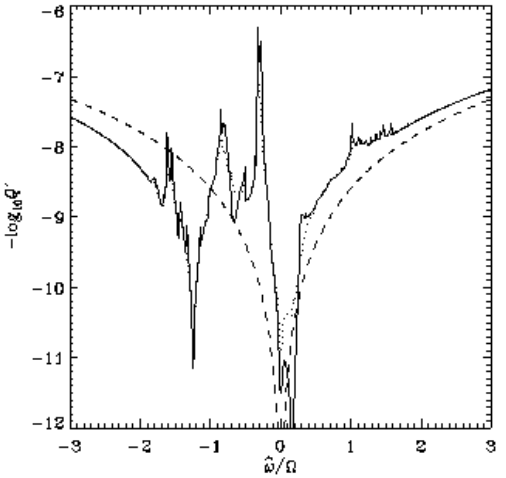
Possible circularization

Without synchronization

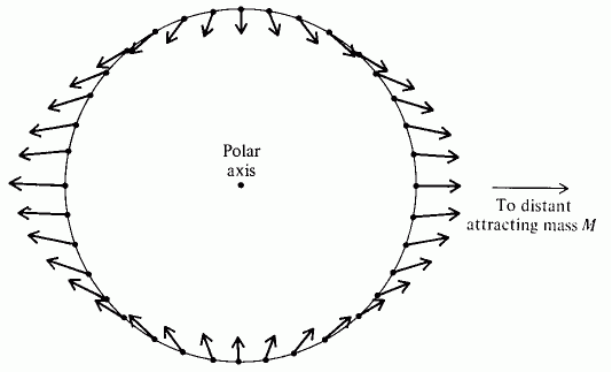


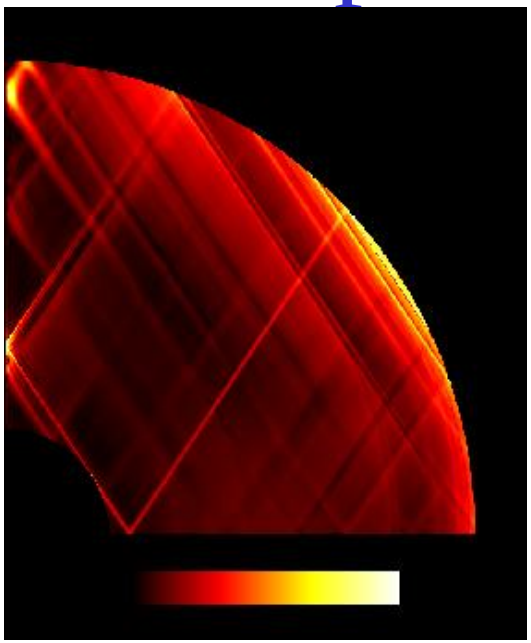


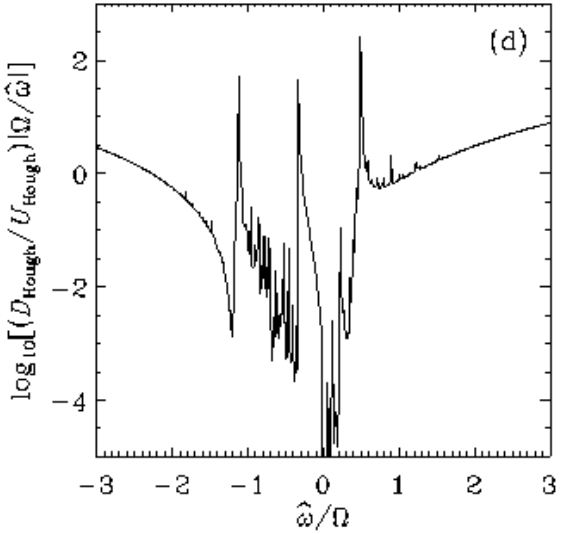




Wave excitation & planetary response

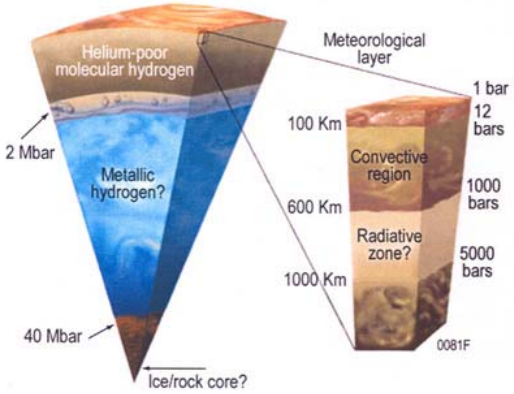


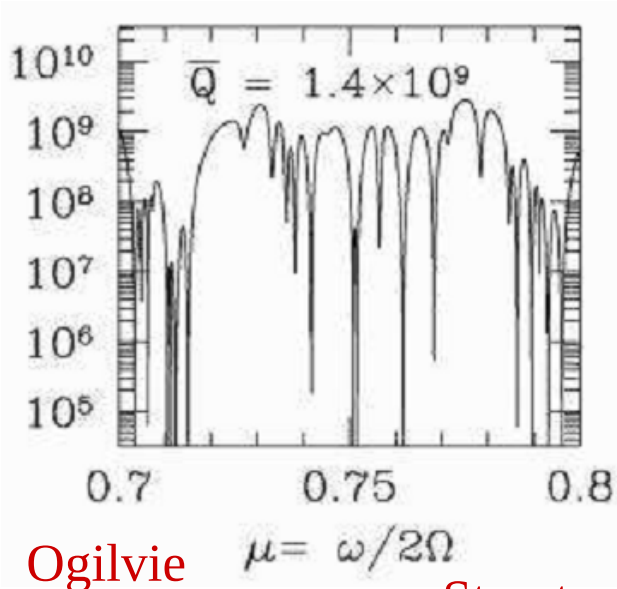


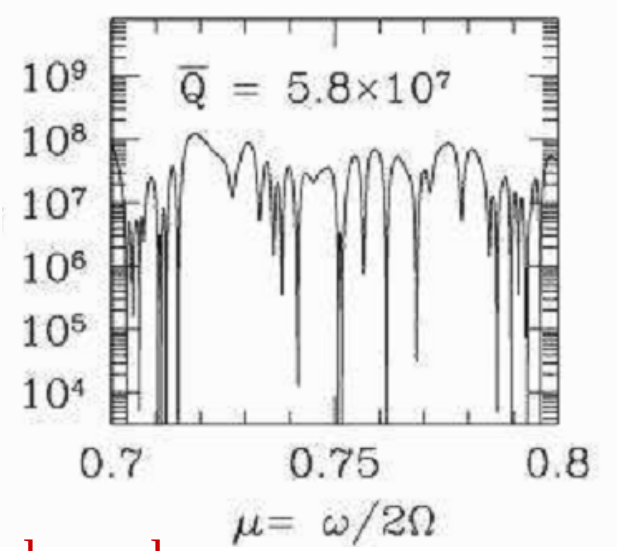


Equilibrium tide: convection is slow and nearly adiabatic

Frequency dependent Q value



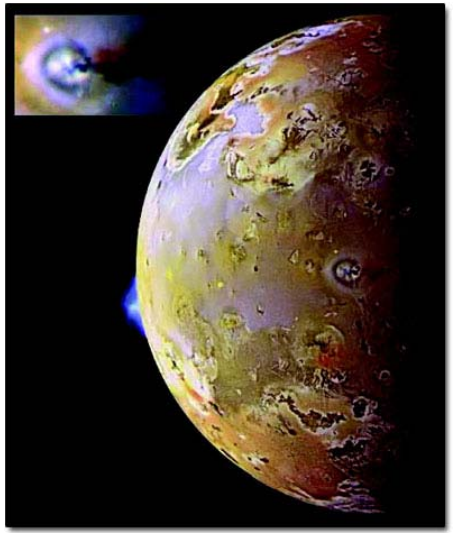


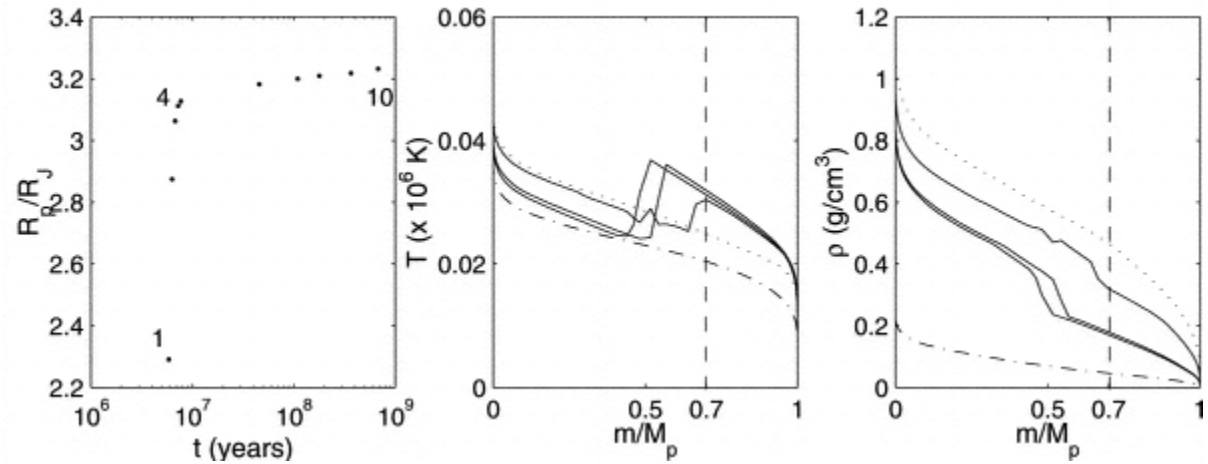


Ogilvie
Wu

Structural dependence

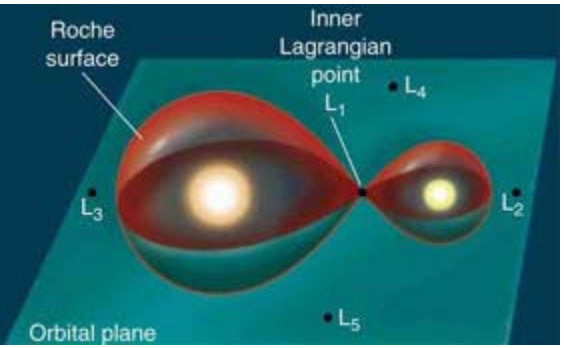
Runaway tidal heating

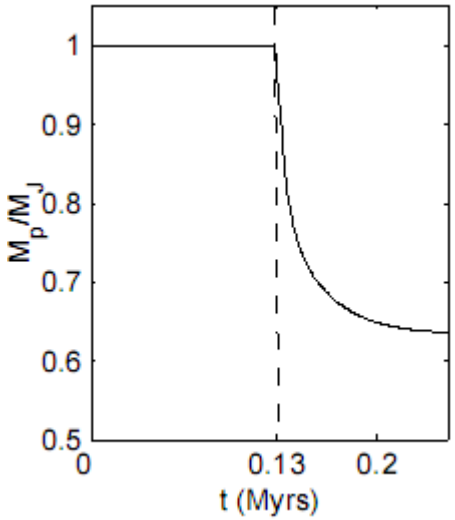


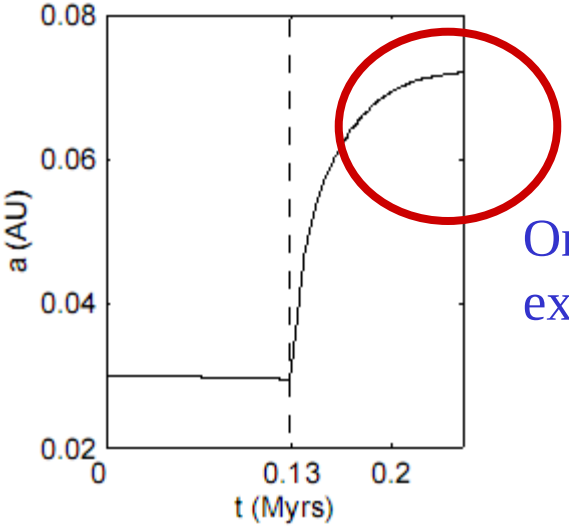


$$\dot{R}_p = \frac{-\mathscr{L} - \dot{E}_{\rm tide}}{q_p G M_p^2 / R_p^2 + \alpha_p M_p R_p \Omega_p^2}$$

Planetary radius adjustment: Gu, Bodenheimer

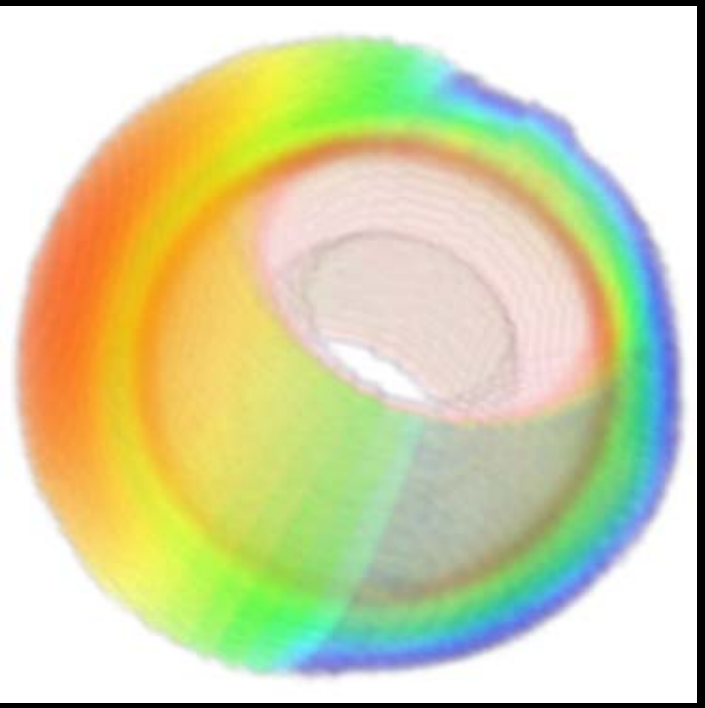


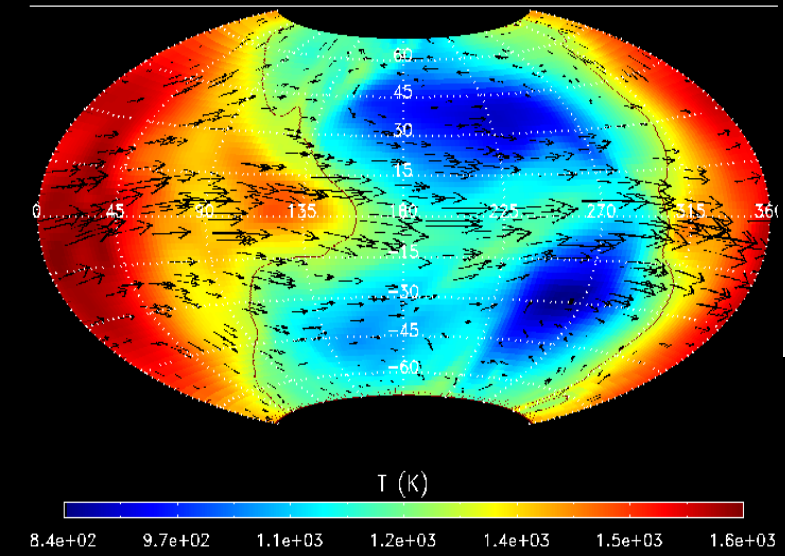


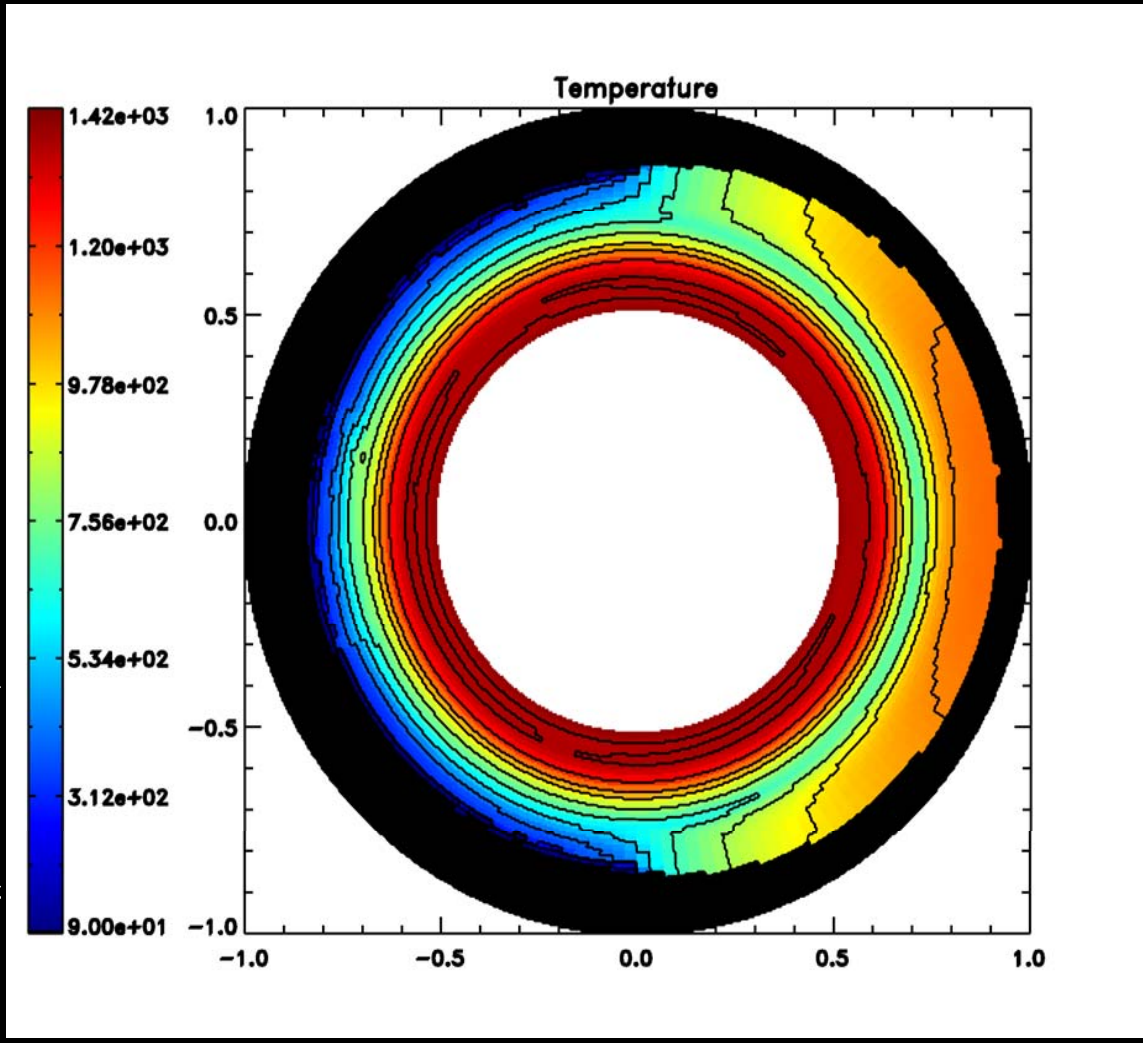


Orbital expansion

Stellar heating of close-in planets



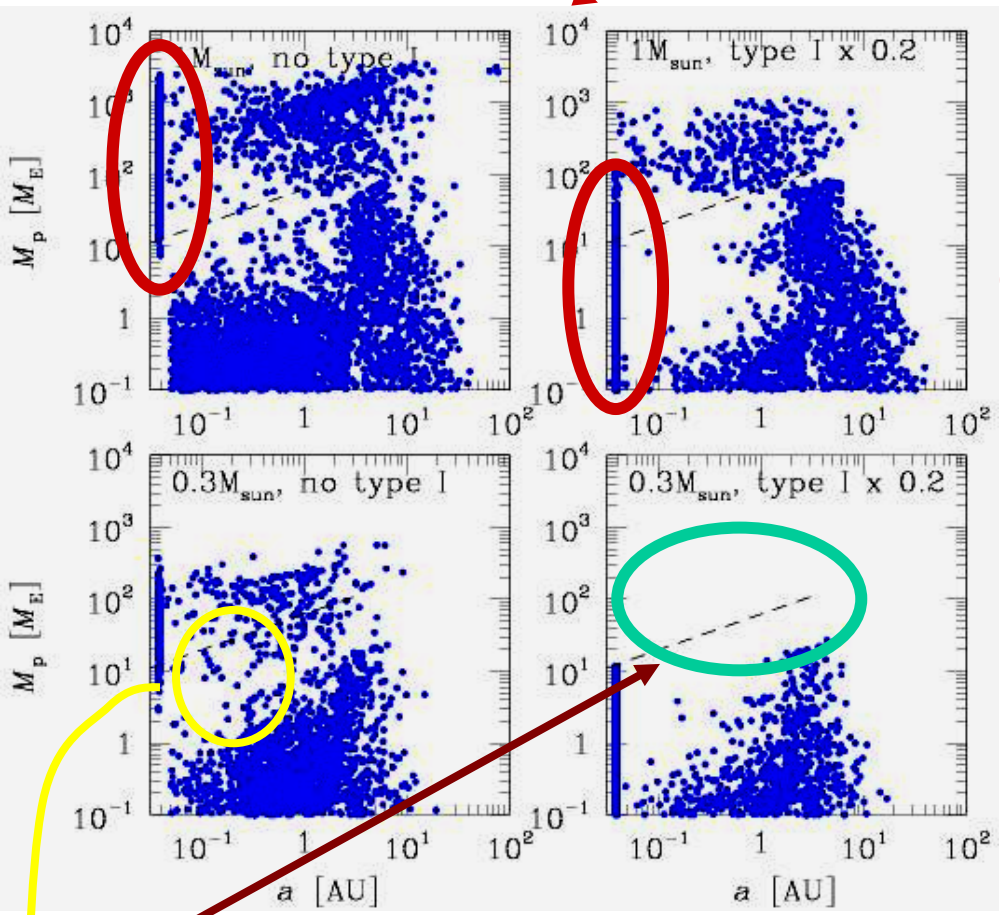




(Mass) growth vs (orbital) decay

Type II mig

Type I mig



Embryos' migration time scale

$$\tau_{\mathrm{mig,I}} \approx 0.04 \left(\frac{\Sigma_g(0)}{\Sigma_g(t)}\right)\left(\frac{M_o}{M_*}\right)\left(\frac{a}{1\mathrm{AU}}\right)^{\frac{3}{4}} \mathrm{Myr}$$

Outer embryos are better preserved only after significant gas depletion

$$\left(\frac{\tau_{\mathrm{embryo}}}{\tau_{\mathrm{mig,I}}}\right) \approx \left(\frac{\Sigma_g(t)}{\Sigma_g(0)}\right)\left(\frac{a}{1\mathrm{AU}}\right)^{\frac{11}{5}}$$

Ida

Critical-mass core: $M_p = 5M_{earth}$

$$\tau_{\mathrm{mig,I}} \approx 0.01 \left(\frac{\Sigma_g(0)}{\Sigma_g(t)}\right)\left(\frac{M_*}{M_o}\right)^{\frac{1}{2}}\left(\frac{a}{1\mathrm{AU}}\right)^{\frac{3}{2}} \mathrm{Myr}$$

Loss due to Type I migration

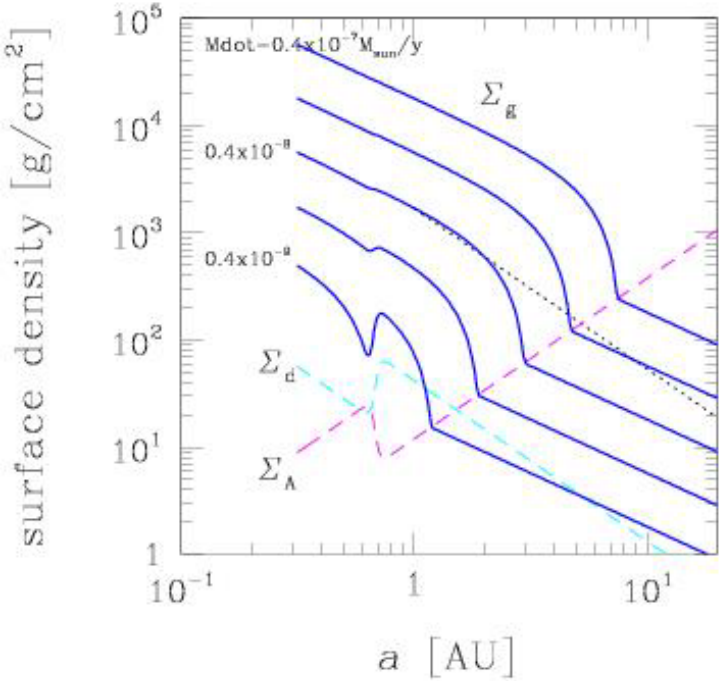
Jupiters are rare around late-type stars

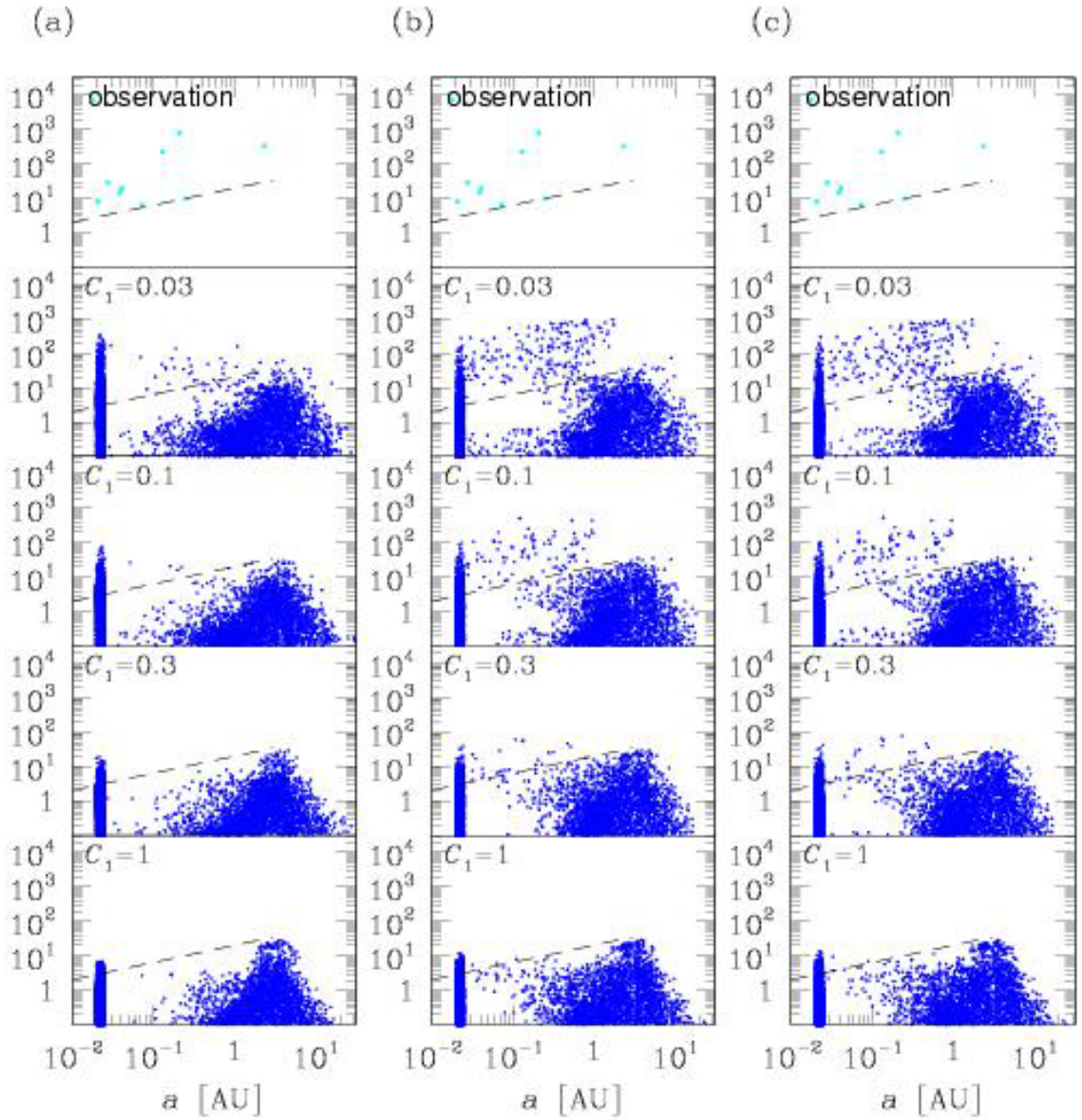
But, hot Neptune's and super-Earth are common!

$\eta_{habitable} > \eta_{Jupiter}$

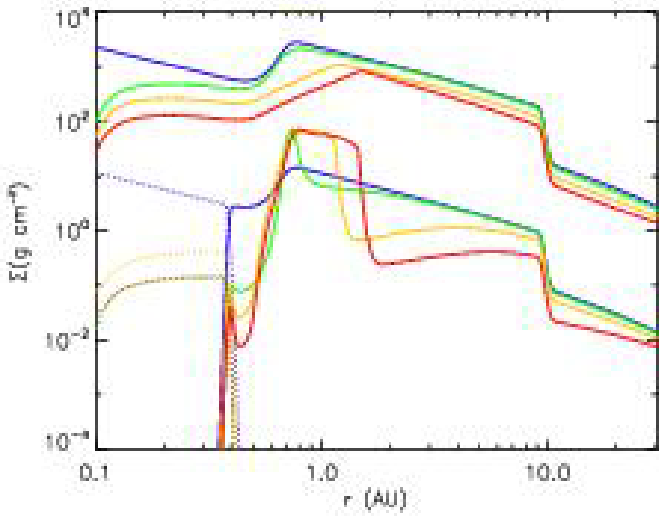
Around sun-like stars

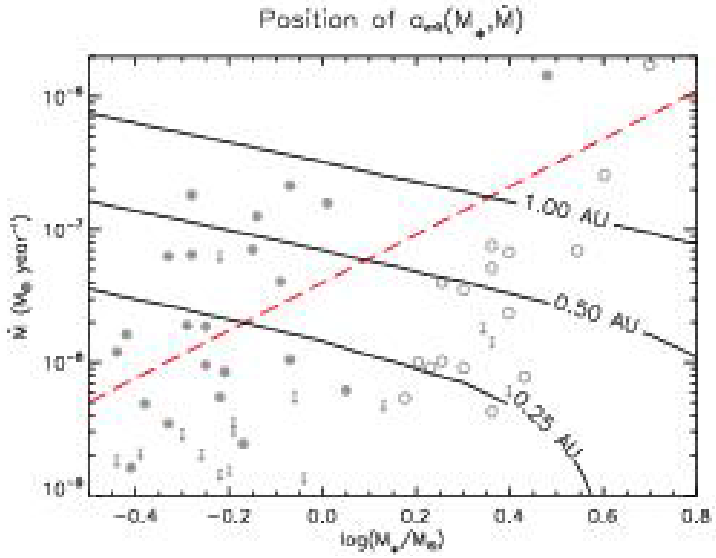
Rocky planets around M stars

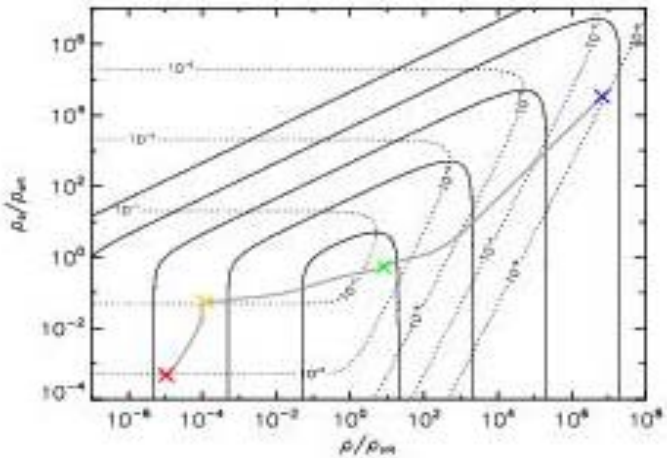


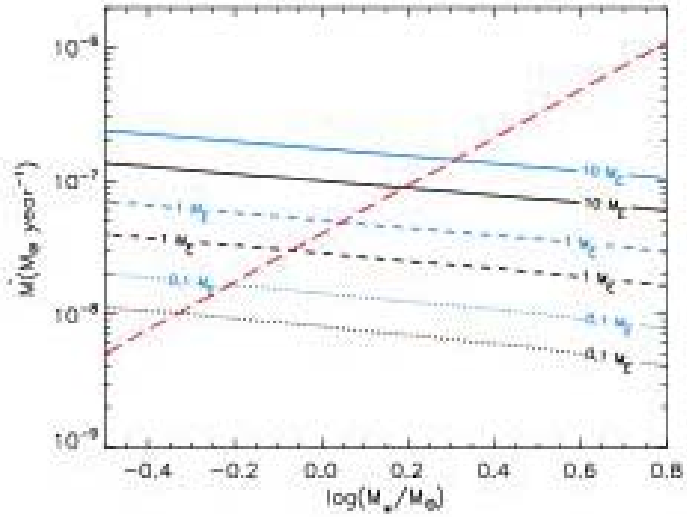


Dust destruction and ionization fronts around more massive stars

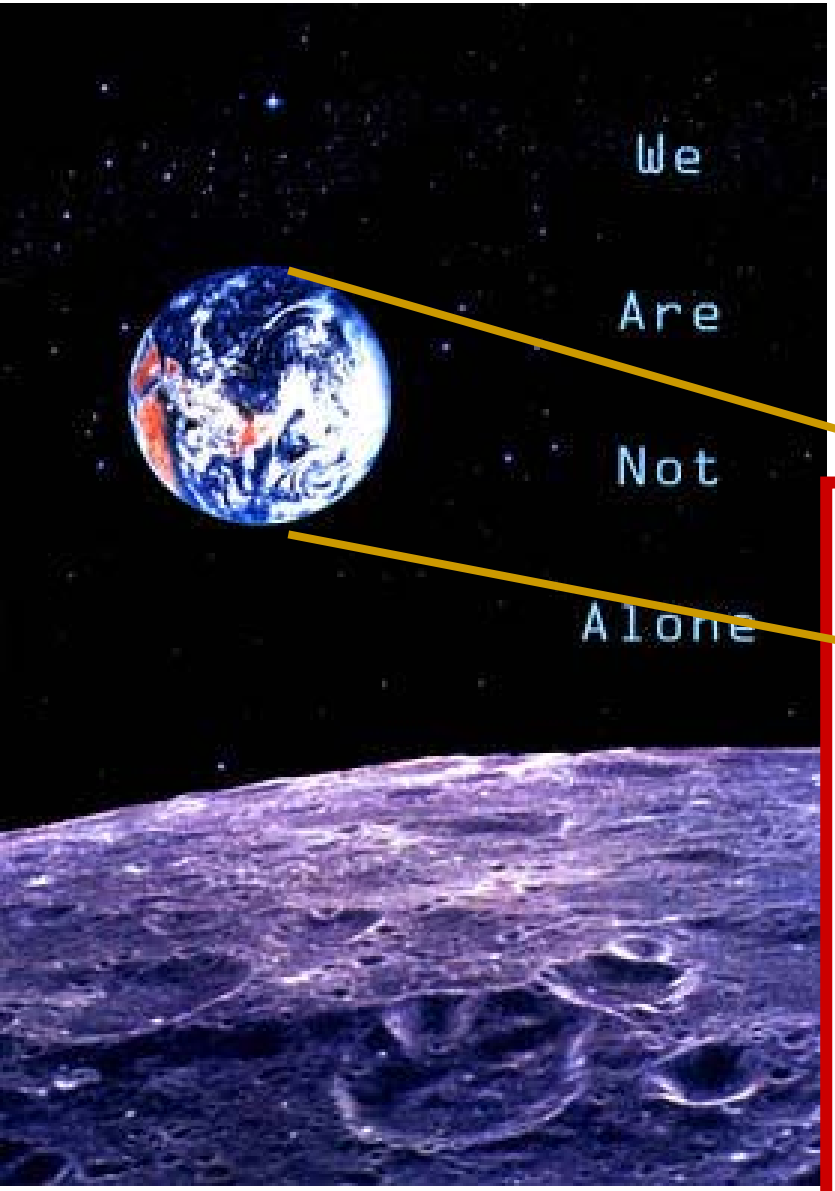


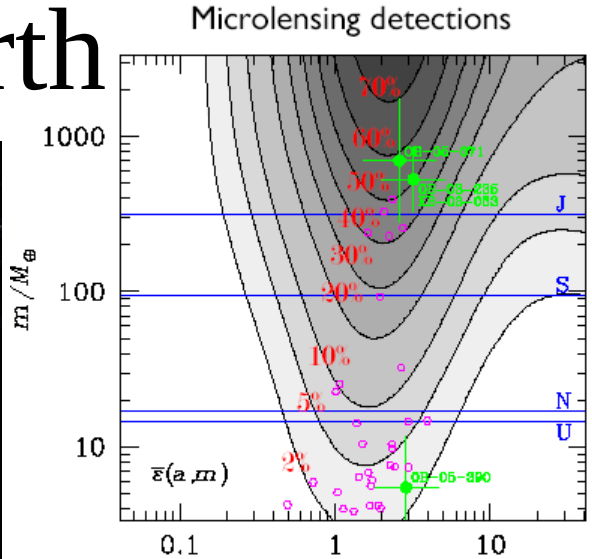


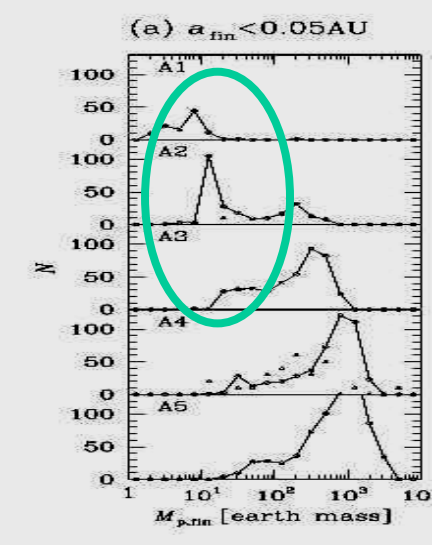




Frequency of Earth

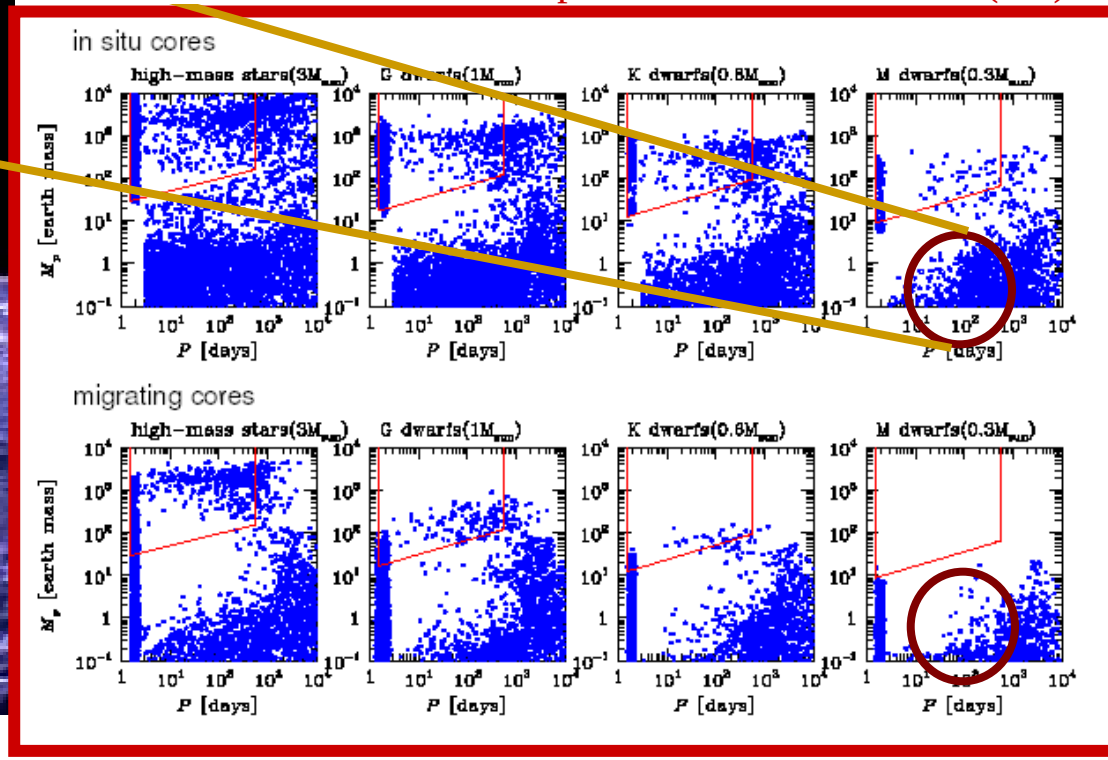




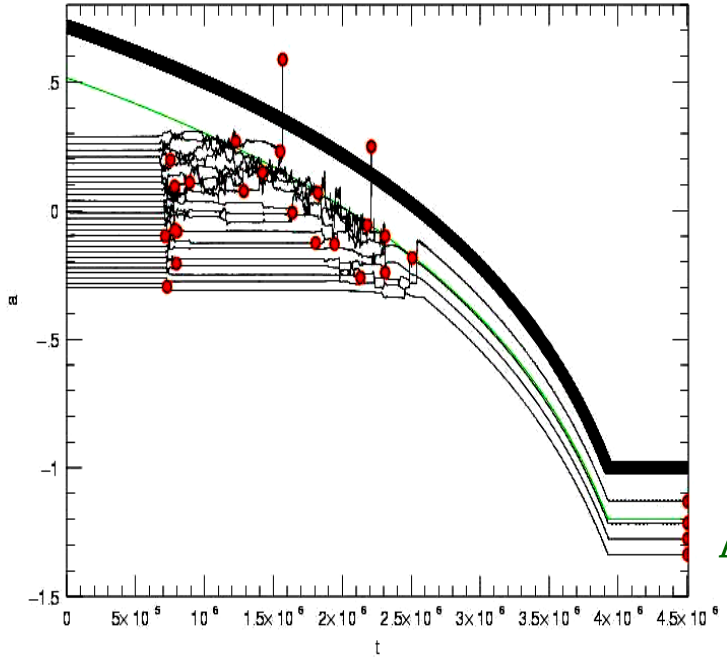


Gaudi

Hot Neptunes around M dwarfs (Ida)



Mean motion resonance capture

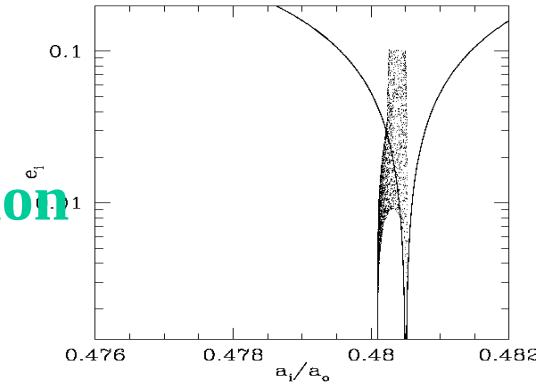


Migration of gas giants can lead
To the formation of hot earth
Implication for COROT

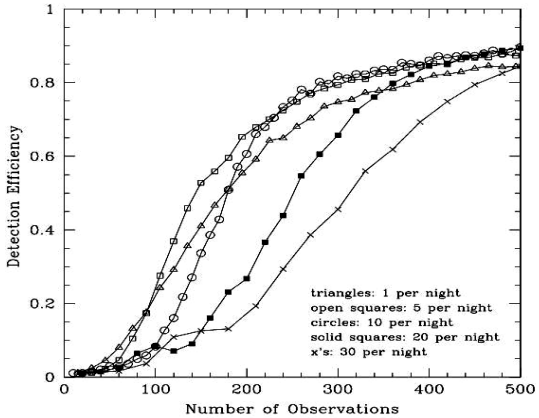
A definitive prediction of core accretion scenario

Zhou, Fogg, Mardling

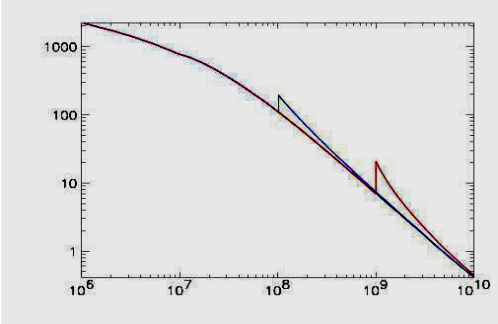
Hot earths closer to the host stars of hot Jupiters are common



Tidal decay out of mean motion resonance (Novak & Lai)

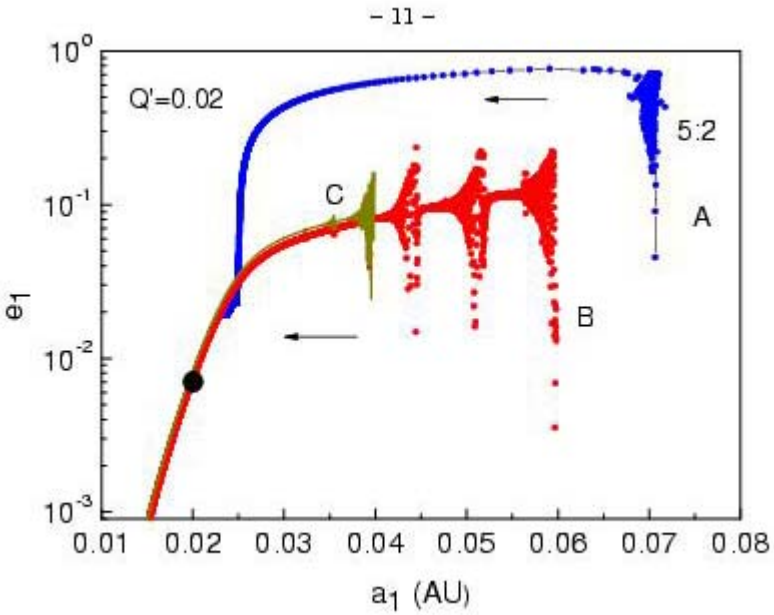


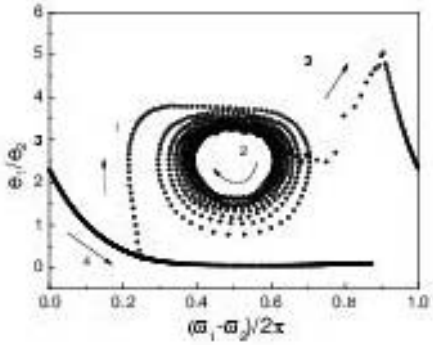
Impact enlargement
Rejuvenation of gas
Giant. HD 209458b
(Guillot)

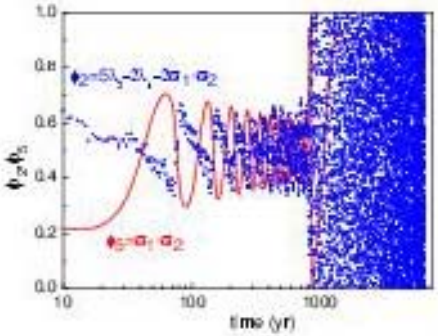


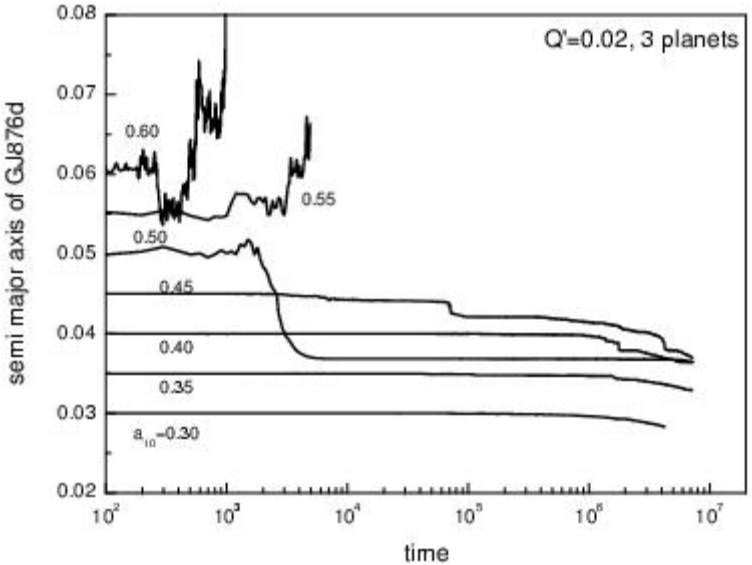
Detection probability of **hot Earth** Narayan, Cumming

Dynamical evolution of hot embryos

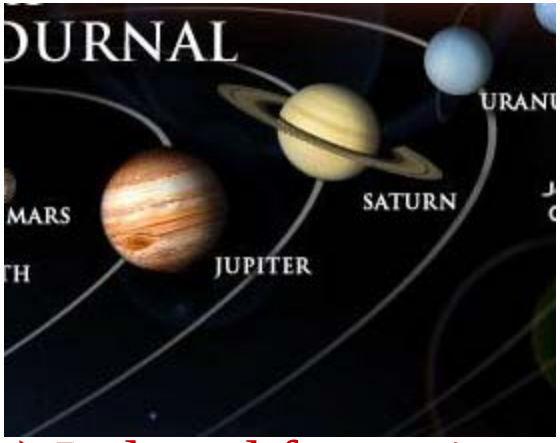


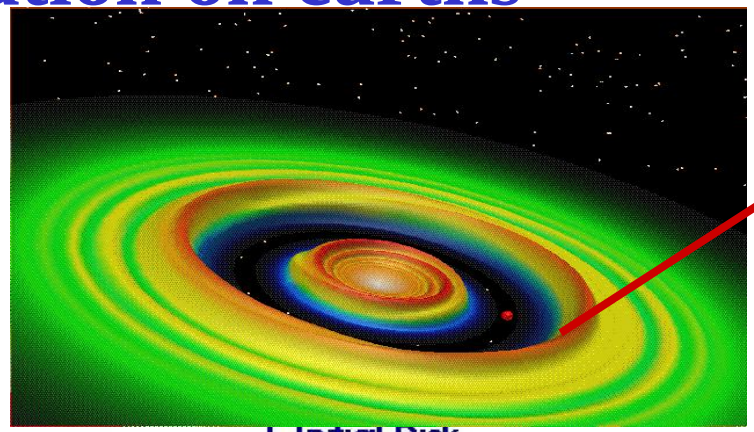


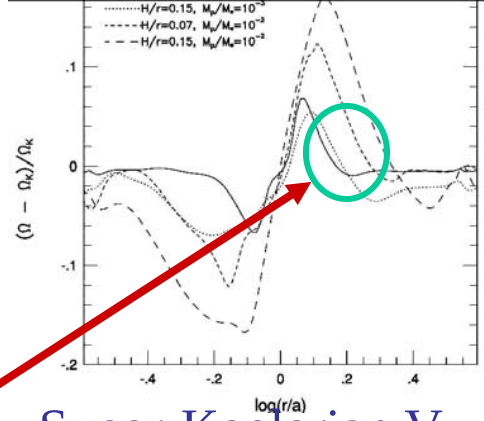




Multiple Jupiters' emergence & their perturbation on earths





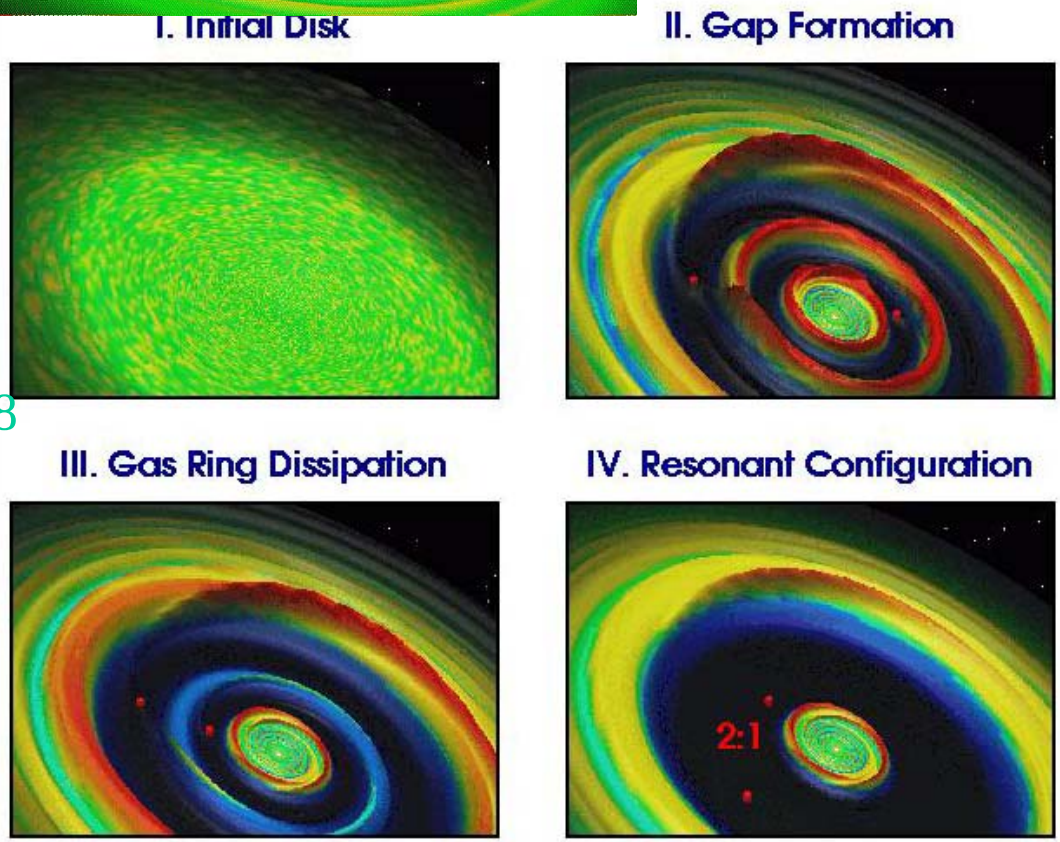


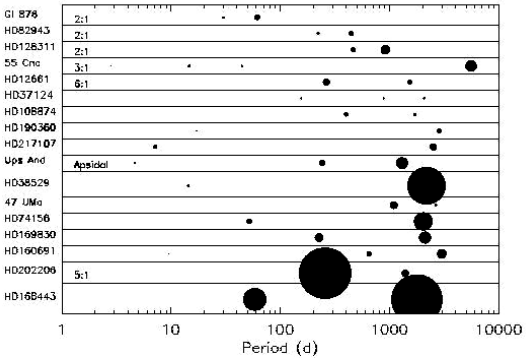
Super-Keplerian V_ϖ tail wind & halting Type I migration

a) Induced formation of multiple giants

b) Resonant planets

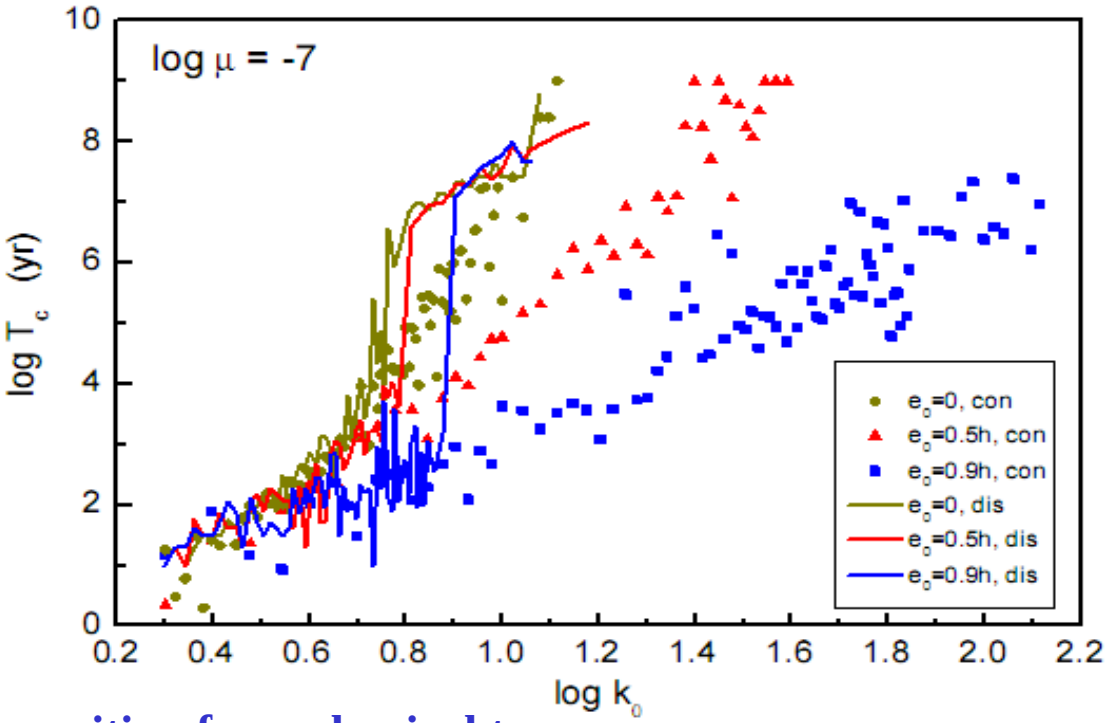
c) Formation time scale comparable to migration





Bryden, Masset, Kley, Papaloizou

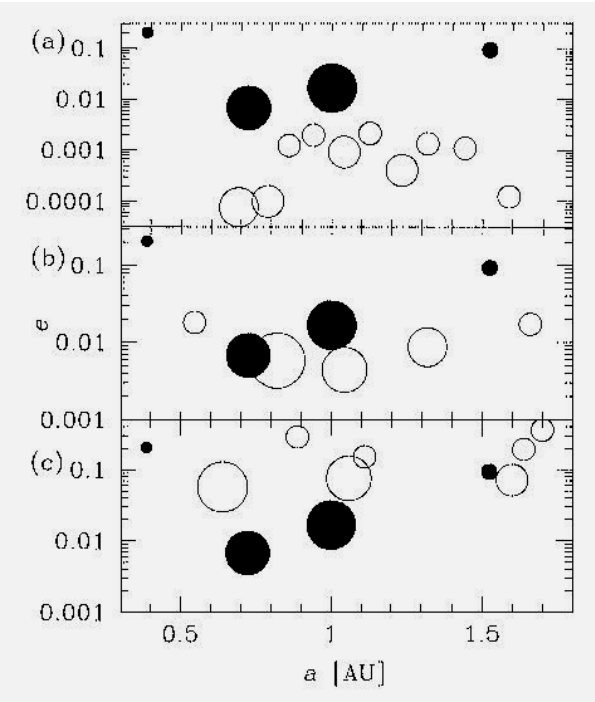
Growth of embryos beyond isolation



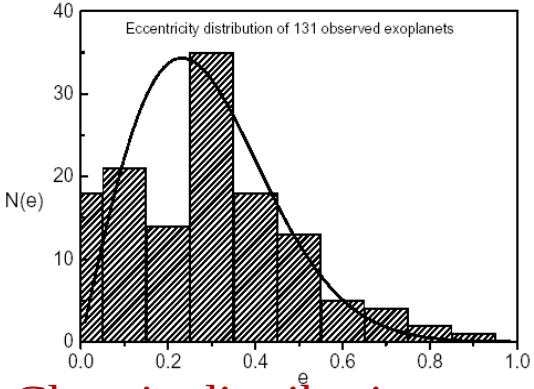
$$\log\left(\frac{T_c}{\mathrm{yr}}\right) = A + B\log\left(\frac{k_0}{2.3}\right). \quad (k_0 > 2.3, 10^{-4} \le \mu \le 10^{-10}) \tag{3}$$

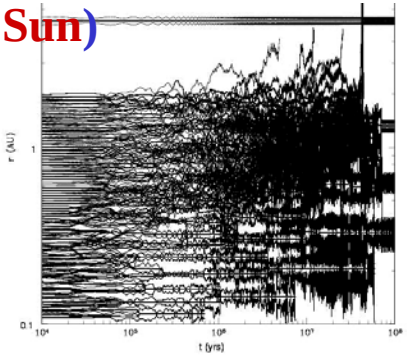
where

$$A = (-2 + \tilde{e}_0 - 0.27\log\mu)$$
$$B = (18.7 + 1.1\log\mu) - (16.8 + 1.2\log\mu)\tilde{e}_0. \tag{4}$$



Transition from classical to debris disk matters (Zhou, Sun)





$$P(e,t) = \frac{e}{\tilde{\sigma}^2}\exp\left(-\frac{e^2}{2\tilde{\sigma}^2}\right), \quad \tilde{\sigma} = \frac{\sqrt{2}\sigma}{na},$$

which has the form of a Rayleigh distribution

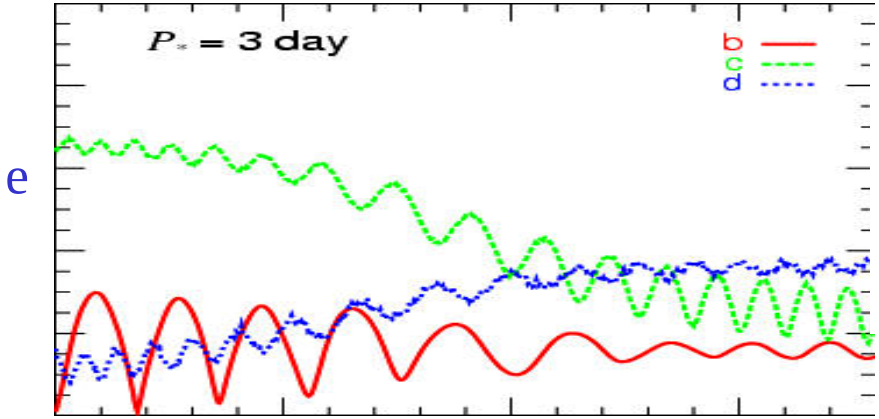
Delicate balance: Kominami & Ida

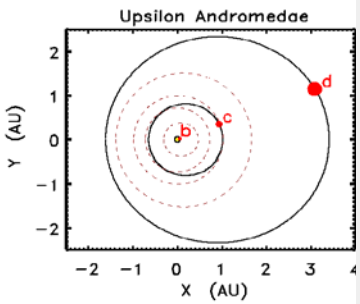
Chaotic distribution

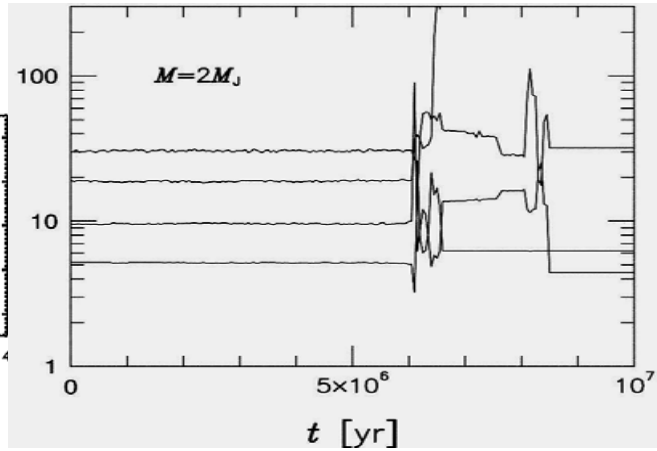
Rasio, Ford, Papaloizou, Terquem, Ida,Zhou, Sun, Fabrycky, Tremaine

Sweeping secular resonance in ESP's

Triple system around Ups And

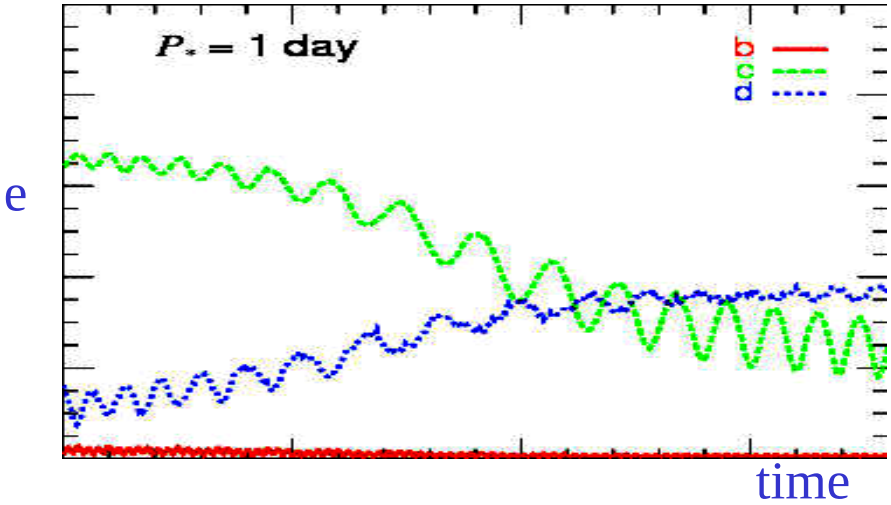


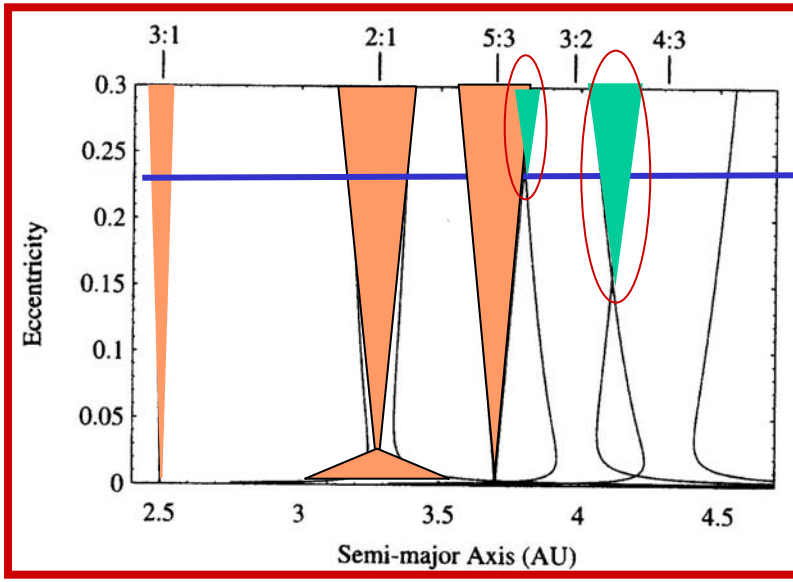




Rotational flattening & precession

Nagasawa, Mardling





Excitation of e & tidal inflation in HD209458 & disruption in 55 Can Gu, Mardling, Bodenheimer, Laughlin

Overlaping resonances Thommes

Migration-free sweeping secular resonances

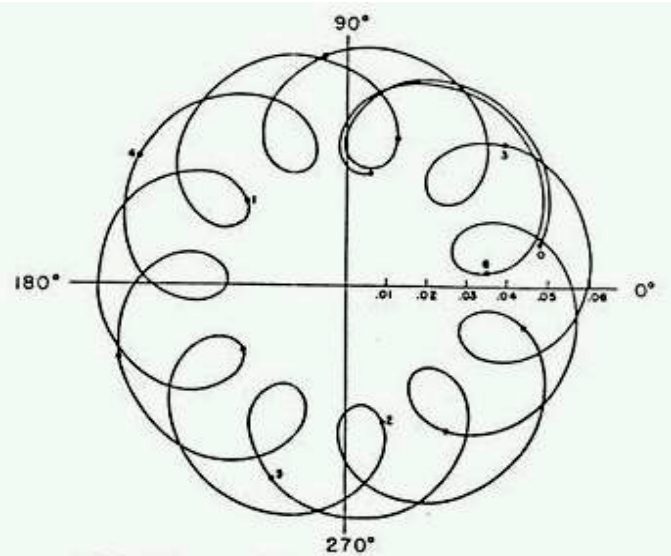


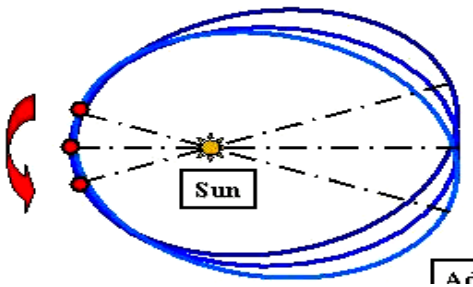
FIG. 3.—Jupiter's eccentricity and perihelion for 650 000 years

Resonant secular perturbation

$M_{disk} \sim M_p$

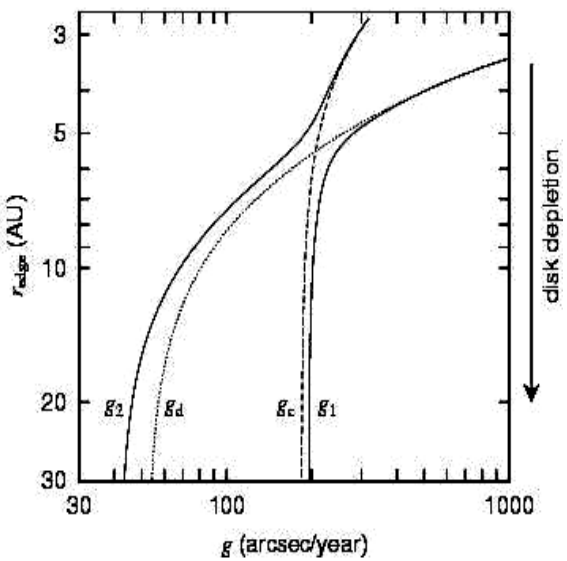
(Ward, Ida, Nagasawa)

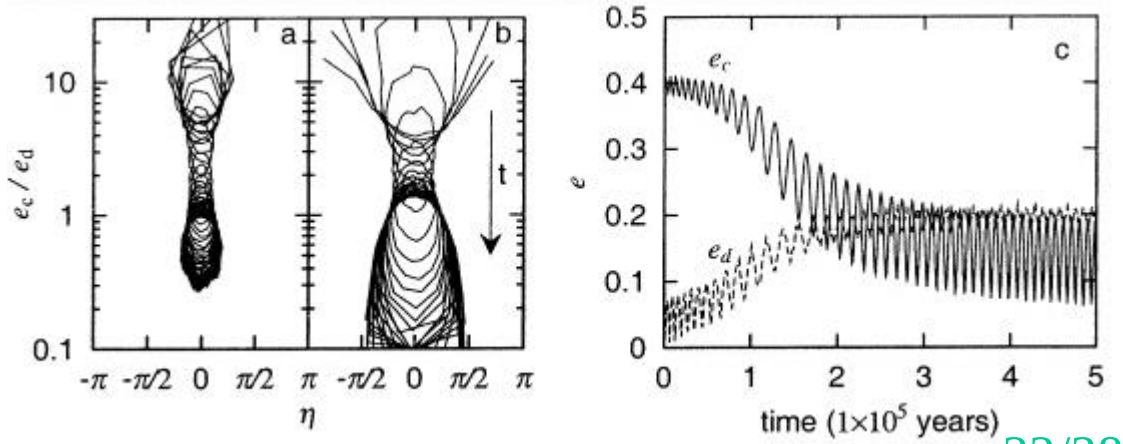
Ups And



Growth of additional gas giants

Gas depletion in transitional disks





Dynamical shake up (Nagasawa, Thommes)

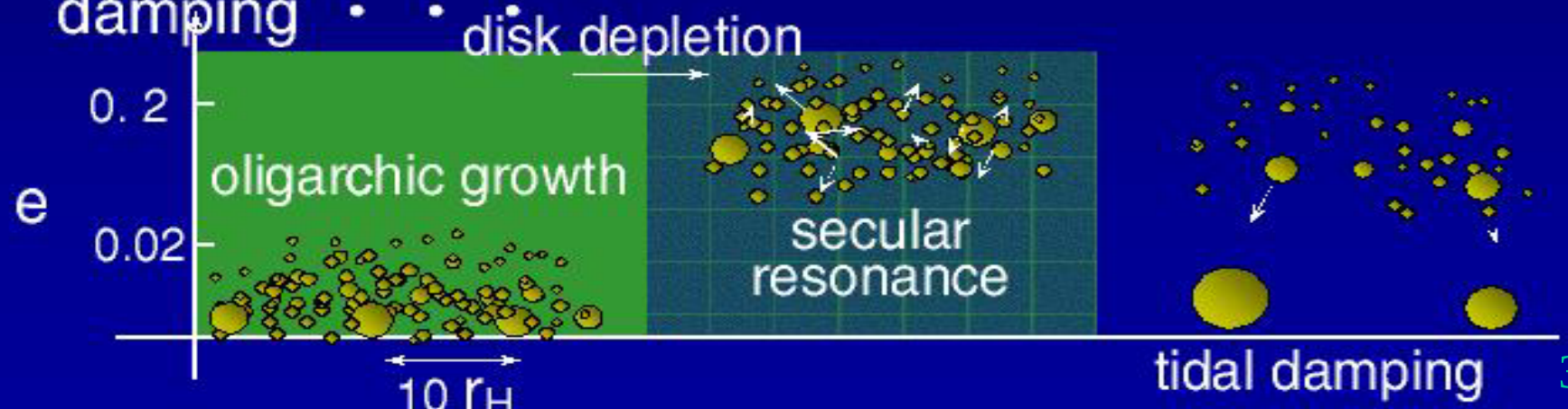
Bode's law: dynamically porous terrestrial planets orbits with low eccentricities with wide separation

Evolution of protoplanets

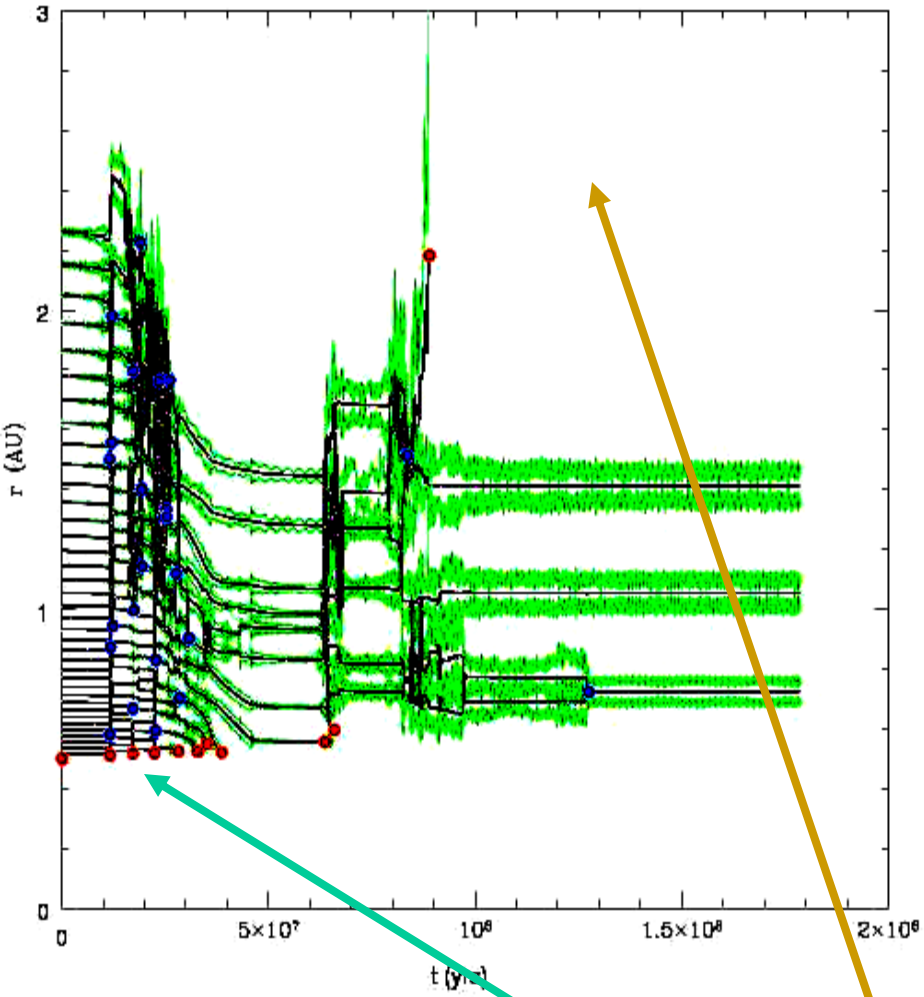
Making e~0 terrestrial planetary system

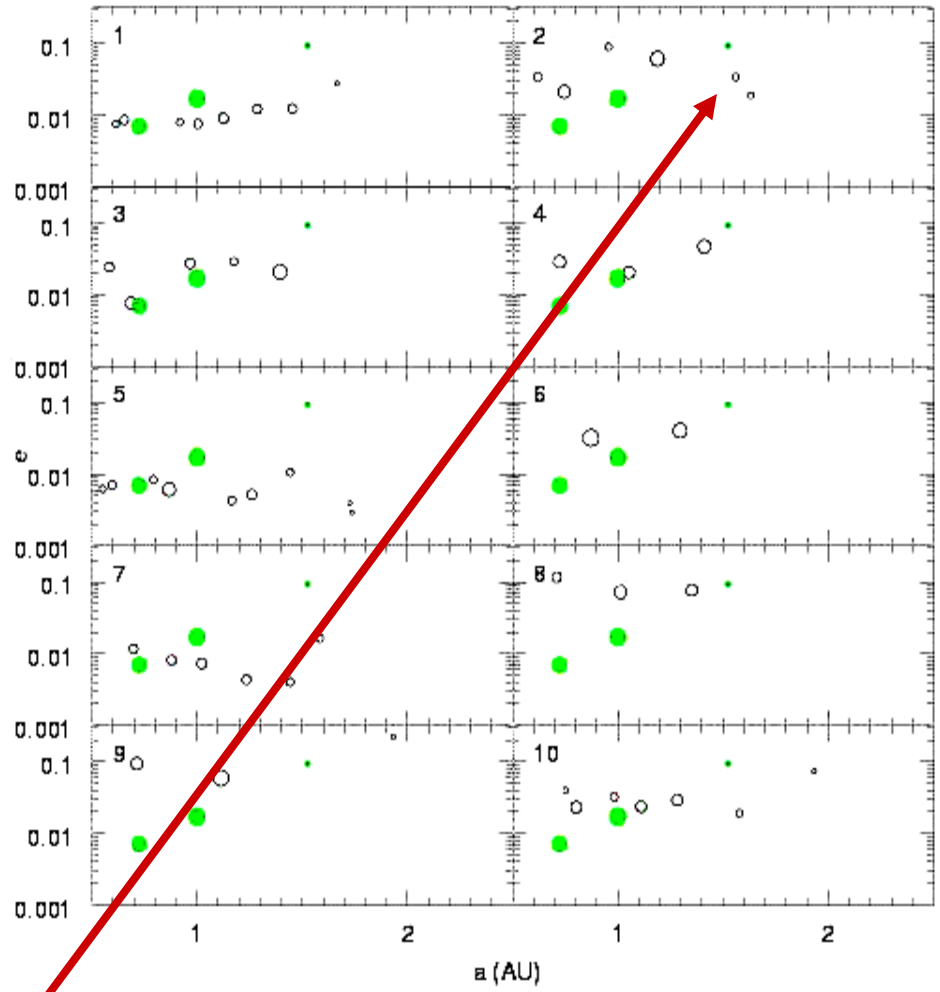
Next stage of the oligarchic growth

- Depletion of the protoplanetary disk ➡ secular resonance ➡ orbital crossings
- Tidal damping $\frac{1}{e}\frac{de}{dt} = -\frac{1}{\tau_e}$, $\tau_e \propto M^{-1}$ ➡ e_{planet} ↘



Migration, Collisions, & damping around the Sun



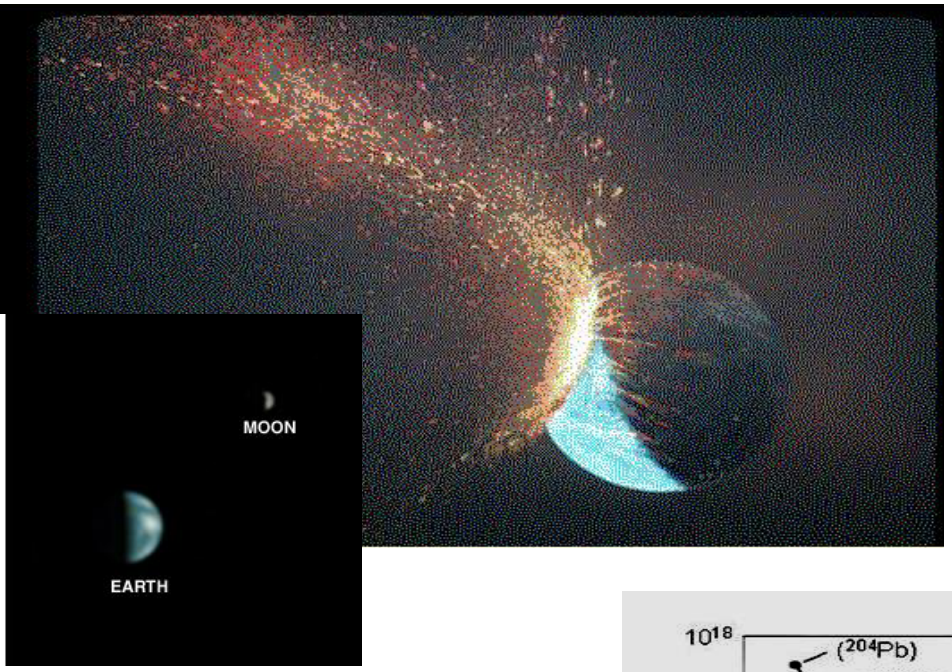


Nagasawa, Thommes

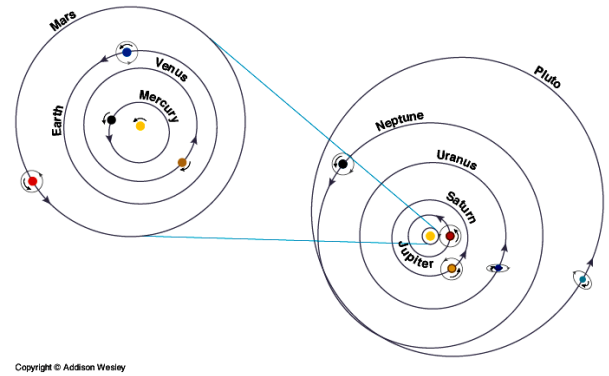
1. Clearing of the asteroid belt
2. Earlier formation of Mars
3. Sun ward planetesimals

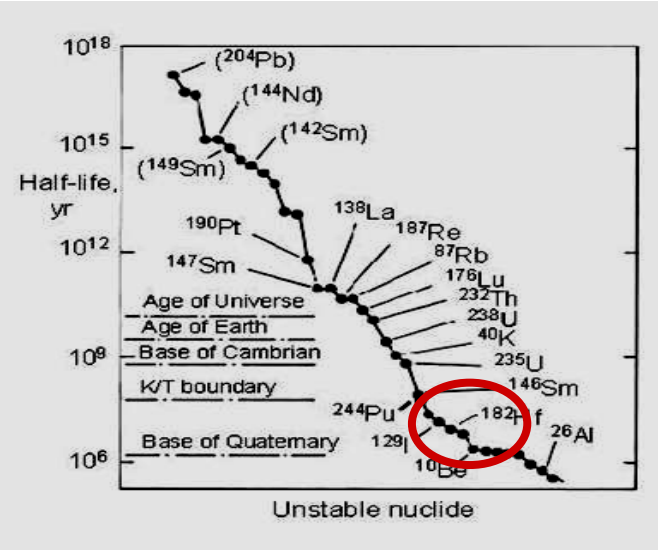
A. Late formation (10-50 Myr)
B. Giant-embryo impacts
C. Low eccentricities, stable orbits

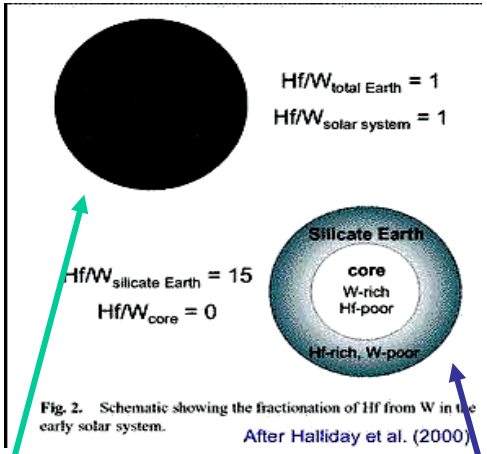
Giant impact & lunar formation



1) Lunar material similar to the Earth's crust.
2) Formation after the differentiation (30 Myr)
3) Mars-size impactor
4) Post impact circular orbit



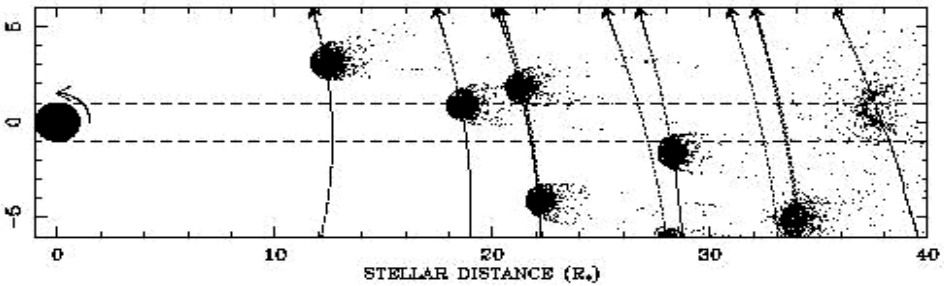


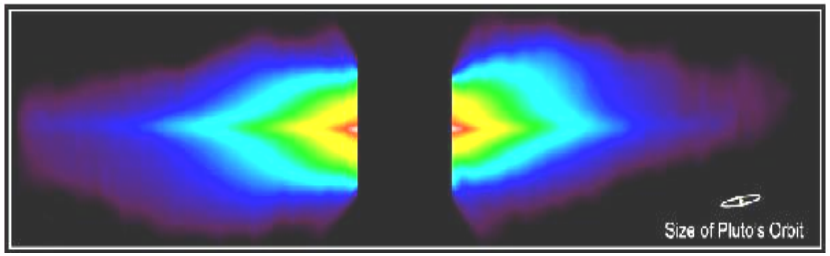


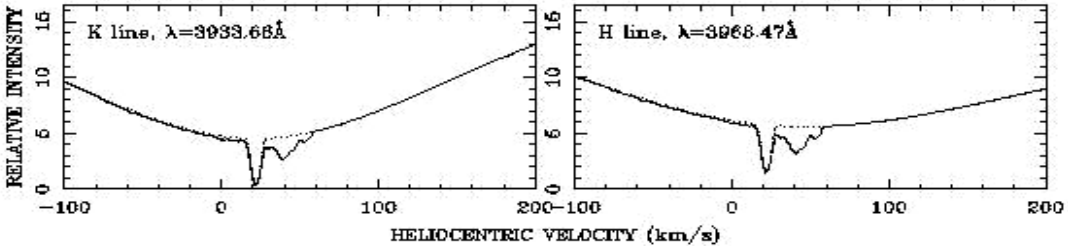
Formation after 60 Myr

Formation on 30-60 Myr

Sweeping clear of planetesimals

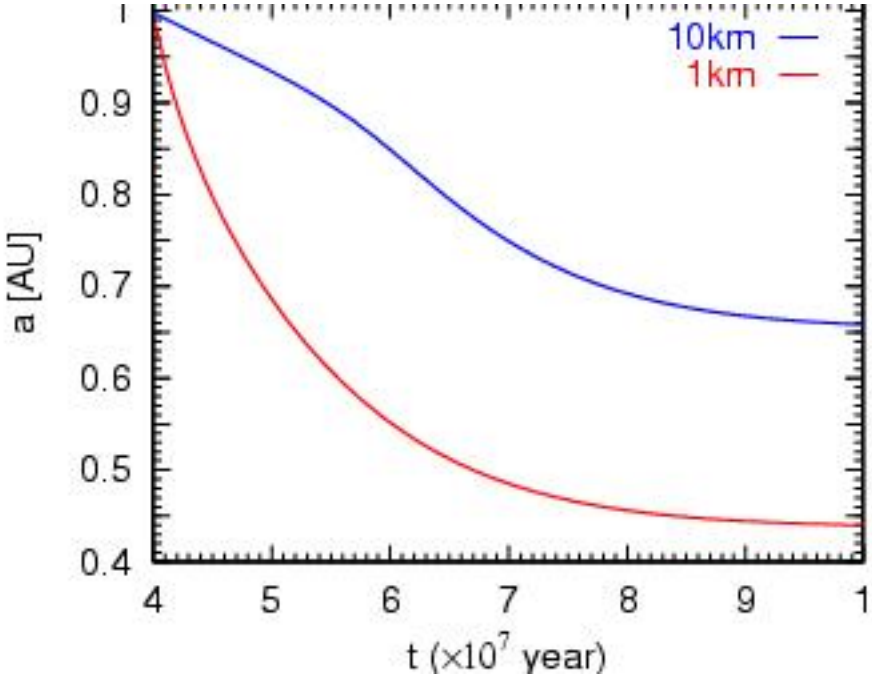


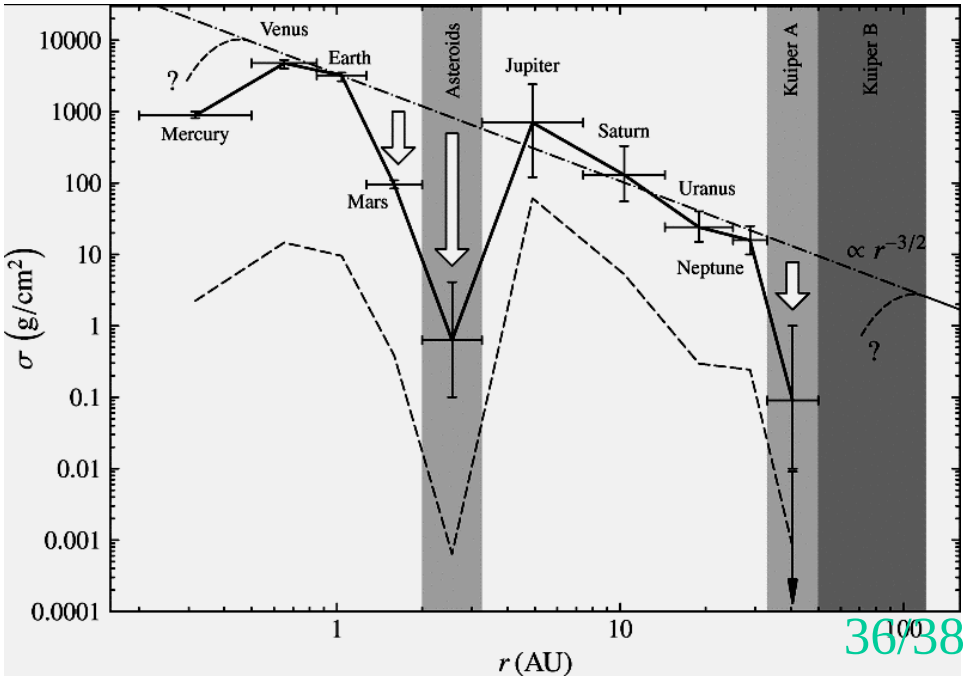




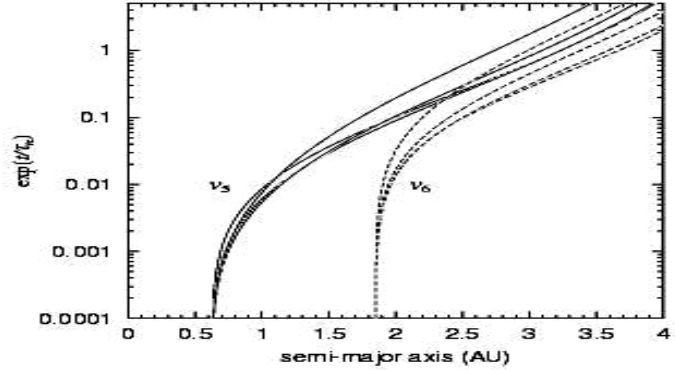
Sweeping secular resonance & gas drag

β Pic:Duncan, Nagasawa

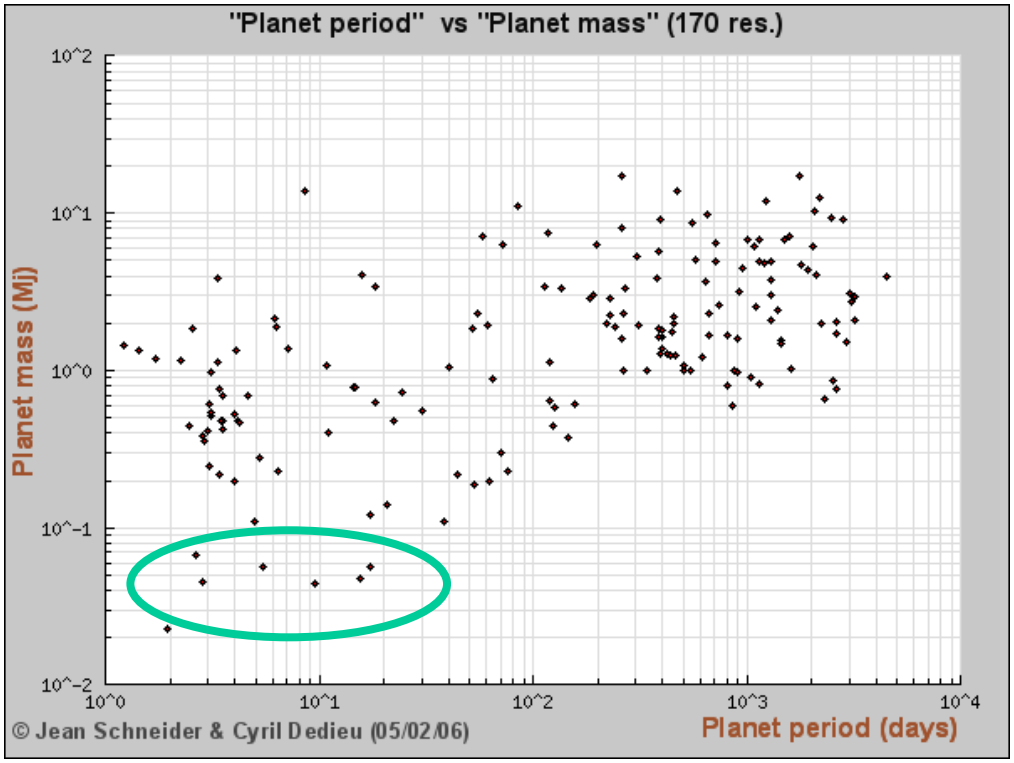


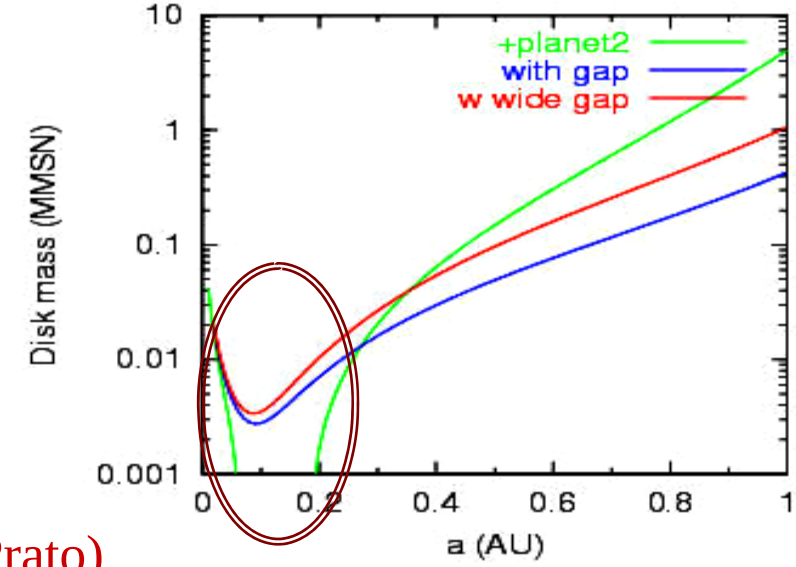


Formation of warm Neptunes around star with Jupiters



Jupiter-Saturn secular interaction & multiple extrasolar systems

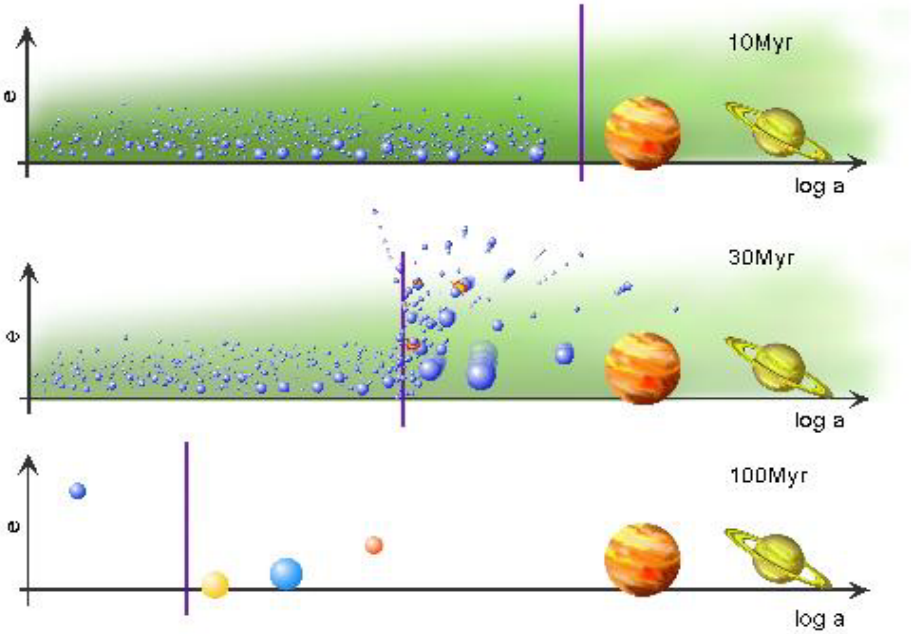




Prolific production of habitable planets in transition disks with embedded Jupiters
Ideal candidates for habitable planet formation (Prato)

Relativistic detuning in μ Arae

Zhou, Aarseth, Thommes, Marzari

Sequential accretion scenario summary

1) Snow line and dust destruction fronts are important traps against drag on grains and embryos' type I migration during the advanced stages of disk evolution.
2) There may be many prior generations of rocky planets which were lost to their host stars.
3) Gas giant formation is a sensitive function of the stellar mass, but rocky planets may be common around all stars.
4) There are hot earth associat
5) Shakeup led to the dynamic porous configuration of the inner solar system & the formation of the Moon.
6) Earths are common and detectable within a few yrs!