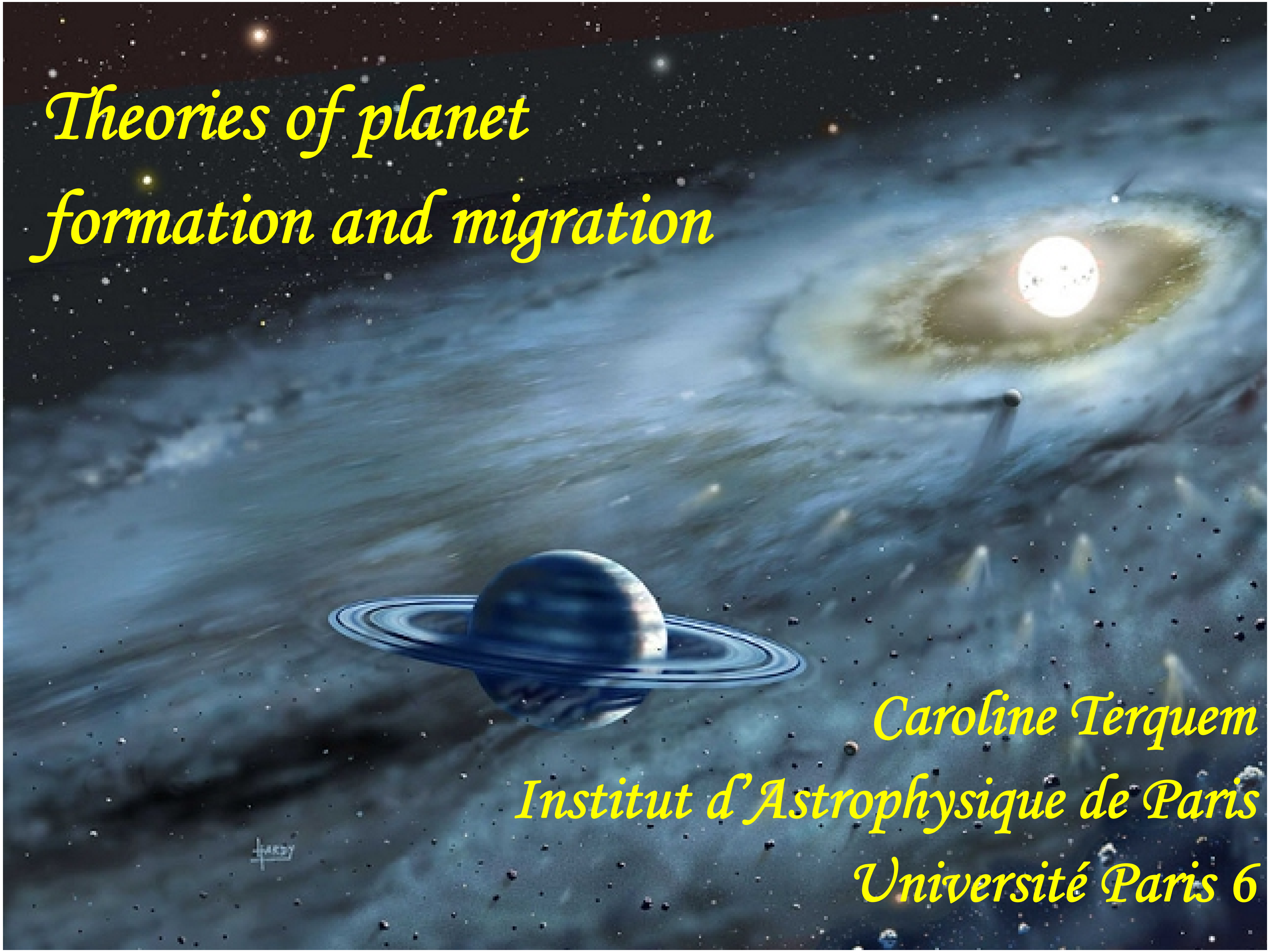

Theories of planet formation and migration

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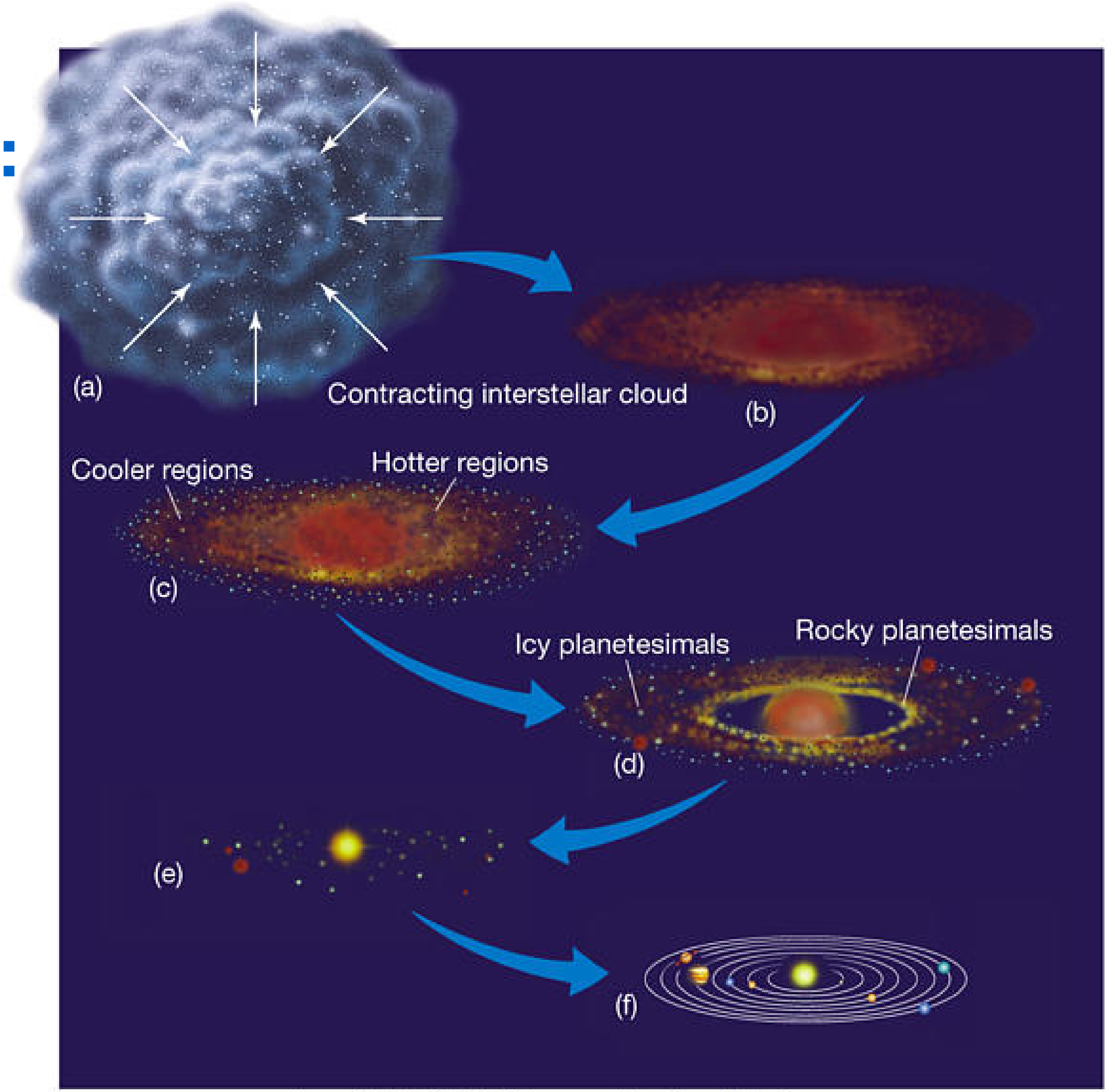
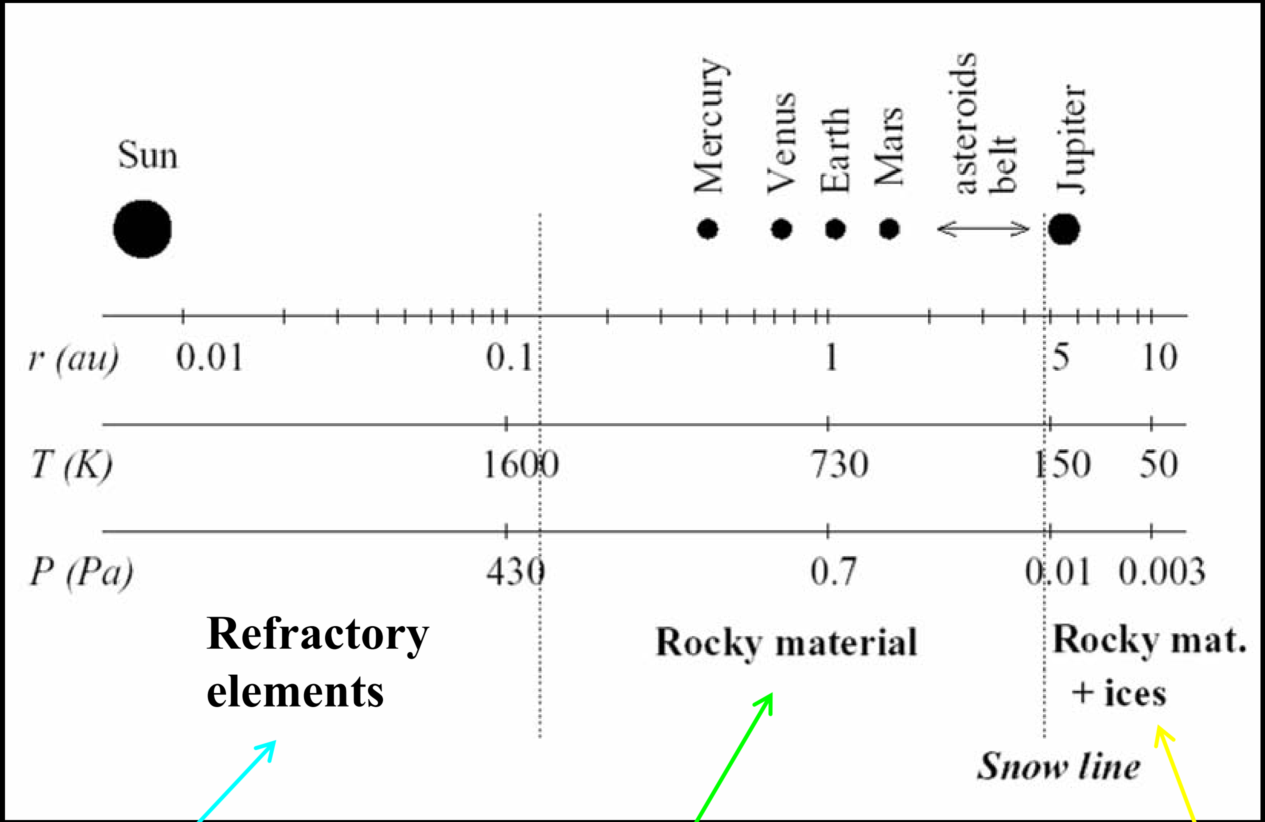
Planet Formation: Overview



α-Disk Models

$dM/dt = 10^{-7}\ M_\odot\ /\ yr$
$\alpha = 10^{-2}$

(Papaloizou & Terquem 1999)

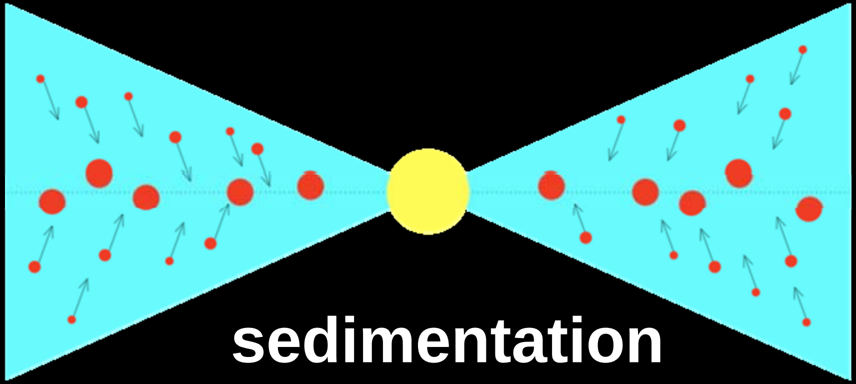


Ca and Al Oxydes

Solids containing Fe, Mg, Si and S combined with themselves and with O

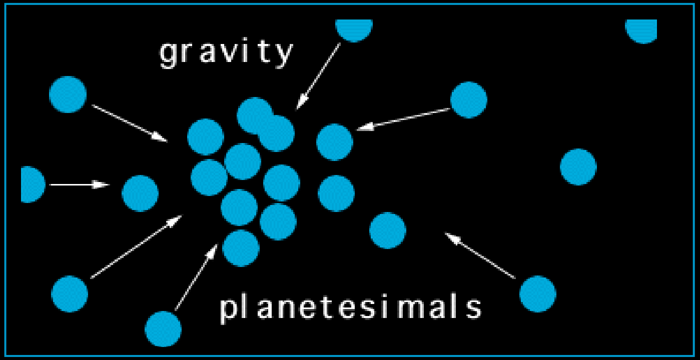
H_2O, CH_4 , NH_3 , CO_2 , CO
Gaseous Hydrates

Formation of terrestrial planets / cores

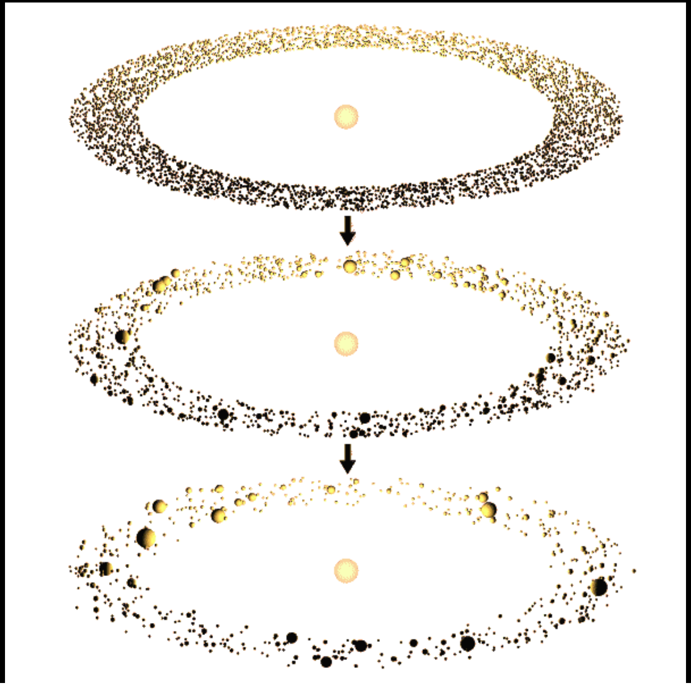


sedimentation
grain size ~ cm

cm → 0.1 - 1 km

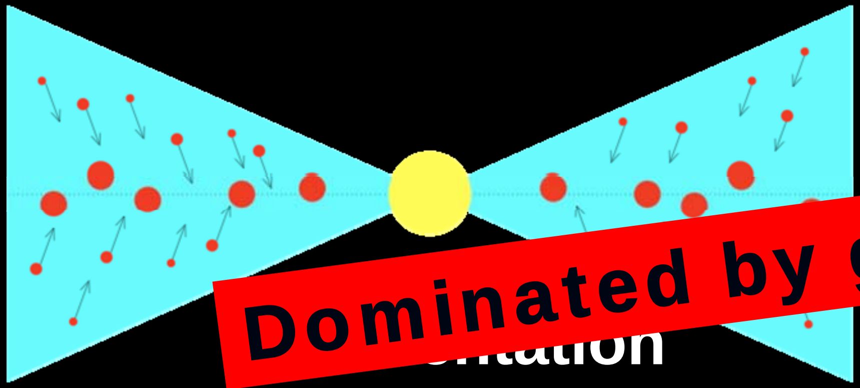


1 km → few 100 km,
i.e. 10^{-3} - 10^{-2} $M_\oplus$



(Tanaka et al. 2000)

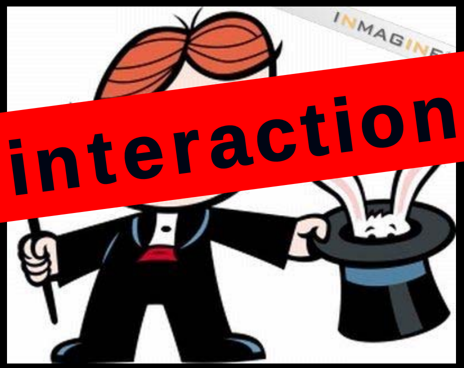
Formation of terrestrial planets/cores



Dominated by grain-gas interaction

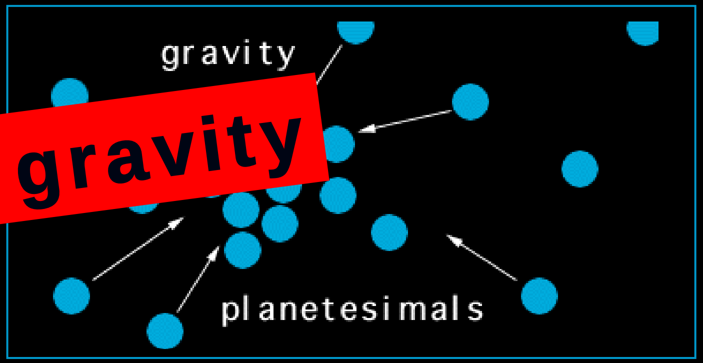
ntation

grain size ~ cm



cm → 0.1 - 1 km

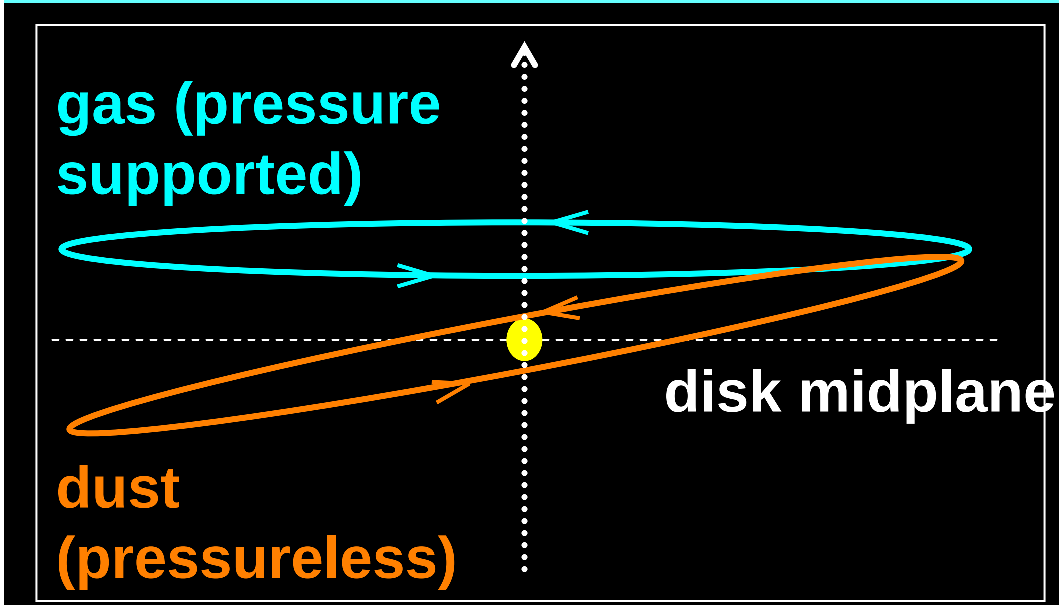
(Tanaka et al. 2000)



Dominated by gravity

1 km → few 100 km,
i.e. 10^{-3} - 10^{-2} $M_{\oplus}$

Sedimentation



In the rotating frame, the dust oscillates around the disk midplane with the frequency = orbital frequency

Drag between the dust and the gas → damping of the oscillations (τ_{damp} ~ 10 s)

→ Sedimentation toward the disk midplane

Collisions between grains → growth to ~ cm-m size

Sedimention timescale ~ 10^5 years at 1 au with no turbulence

Radial drift

Dust: not pressure supported → Keplerian velocity

Gas: pressure supported → sub-Keplerian velocity

→ Drag → the dust drifts inward

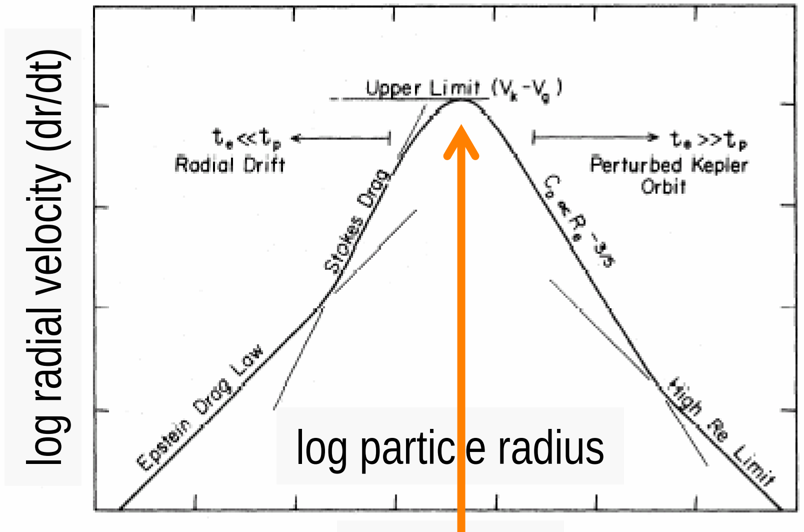


Figure 1. Radial velocity versus particle size (schematic). The shape of the curve is determined by the drag laws, but the peak value depends only on the nebular structure.

(Weidenschilling 1977)

Formation of planetesimals

Growth from cm-m to 0.1-1 km:

???

but has to be fast since radial drift most efficient (τ ~ 100 years, or 10^3 years for collective drag) for m-sized bodies.

Solution = Turbulence?

Particles concentrate at pressure maxima
Streaming instabilities → reinforce the concentration
Growth faster than the drift (Johansen et al.)

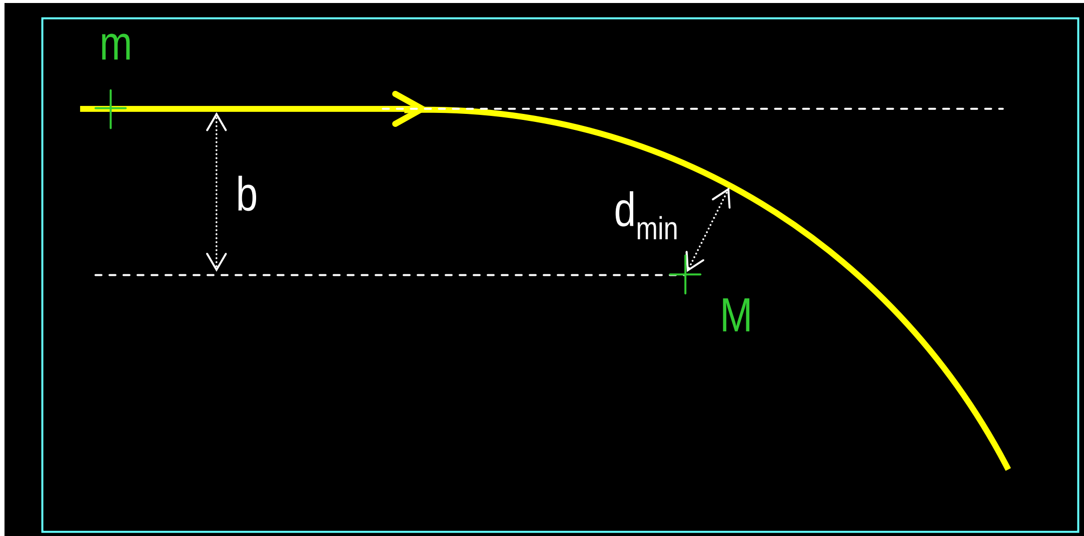
Protoplanet formation

0.1-1 km → 100 km (10^{-2} - 10^{-3} $M_{\oplus}$): « particles in a box »

collissions and sticking → **growth**

runaway accretion

Runaway accretion



Energy: $E^* = \frac{1}{2}\mu v^2 - GMm/r$

Angular momentum:

$$\mathbf{L^* = r \times \mu v}$$

$L^* = \text{cst} \rightarrow \mu b v_{-\infty} = \mu d_{min} v(d_{min})$

$E^* = \text{cst} \rightarrow \frac{1}{2}\mu b v_{-\infty} = \frac{1}{2}\mu v^2(d_{min}) - GMm/d_{min}$

$$\Rightarrow \sigma_{col} = \pi b^2 = \underbrace{\pi\left(r_m + r_M\right)^2}_{\sigma_{geom}}\left[1 + \frac{M+m}{M}\frac{v_e^2}{v_{-\infty}^2}\right]$$

v_e: escape velocity at the contact point

"gravitational focussing" ~ 10^3 !

Si $r_M \gg r_m$, $\boldsymbol{\sigma_{col}}$ □ $\mathbf{r_M^2}$ → **"runaway accretion"**

Runaway growth

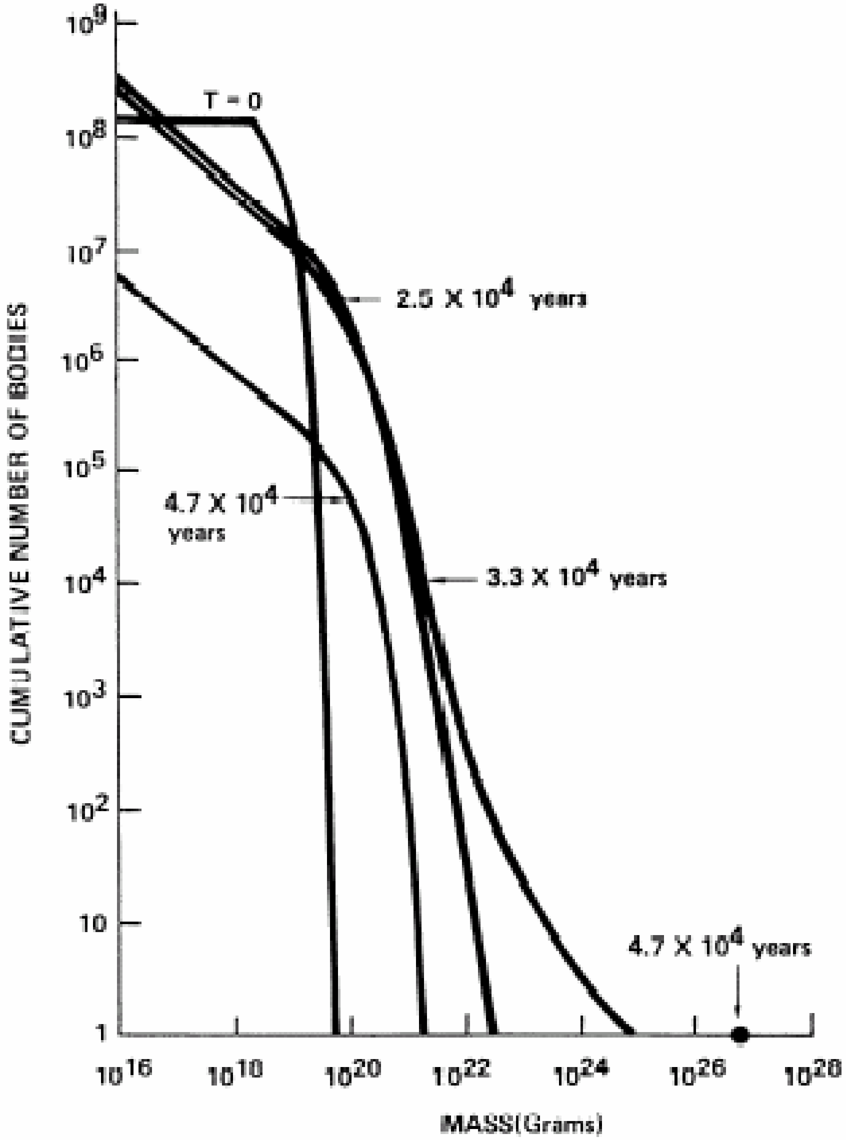
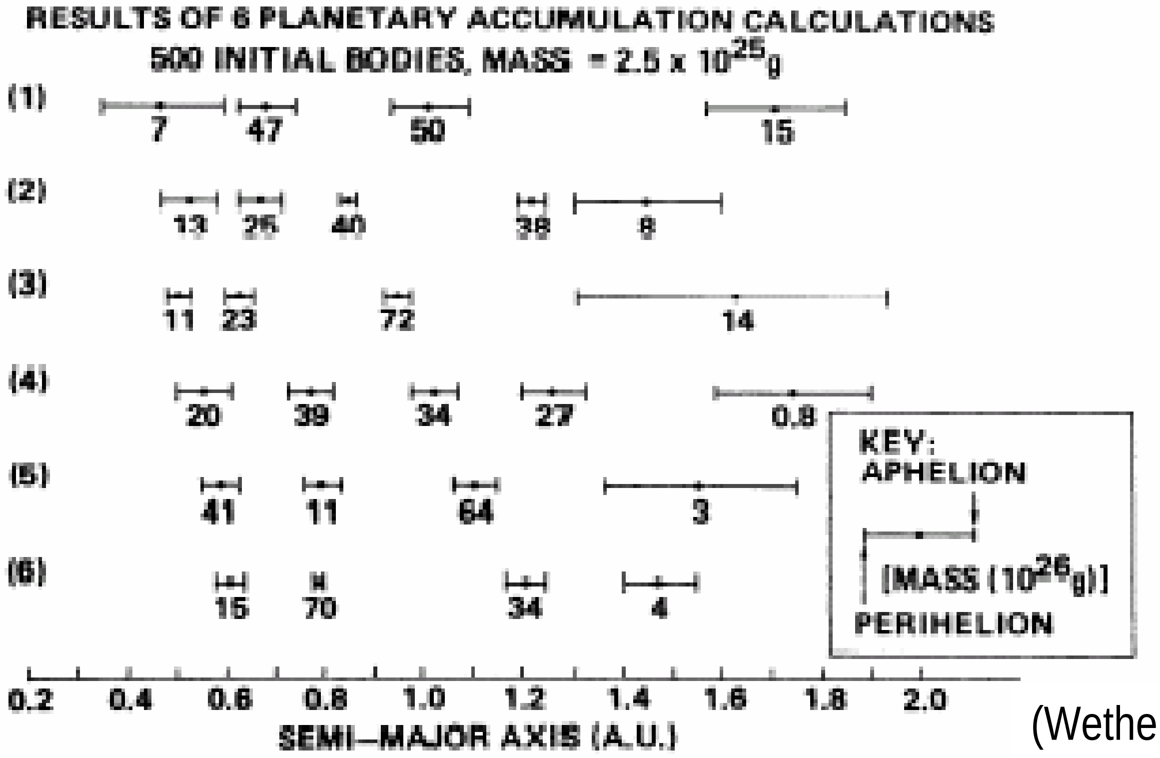


Figure 3 The evolution of the size distribution of a swarm of planetesimals distributed between 0.99 and 1.01 AU using the velocity evolution equations of Stewart & Wetherill (1988). This simulation includes fragmentation, a reduction of gravitational perturbations of runaway bodies from the uncorrelated encounters approximation, and the 3-body gravitational enhancement in accretion cross-sections for low velocity bodies. Note the rapid runaway growth of the largest bodies, with the most massive planetary embryo becoming detached from the remainder of the swarm. Figure adapted from Wetherill & Stewart (1989), courtesy G. Wetherill.

(Wetherill & Stewart 1989
Lissauer 1993)

Planet / core formation

N-body simulations

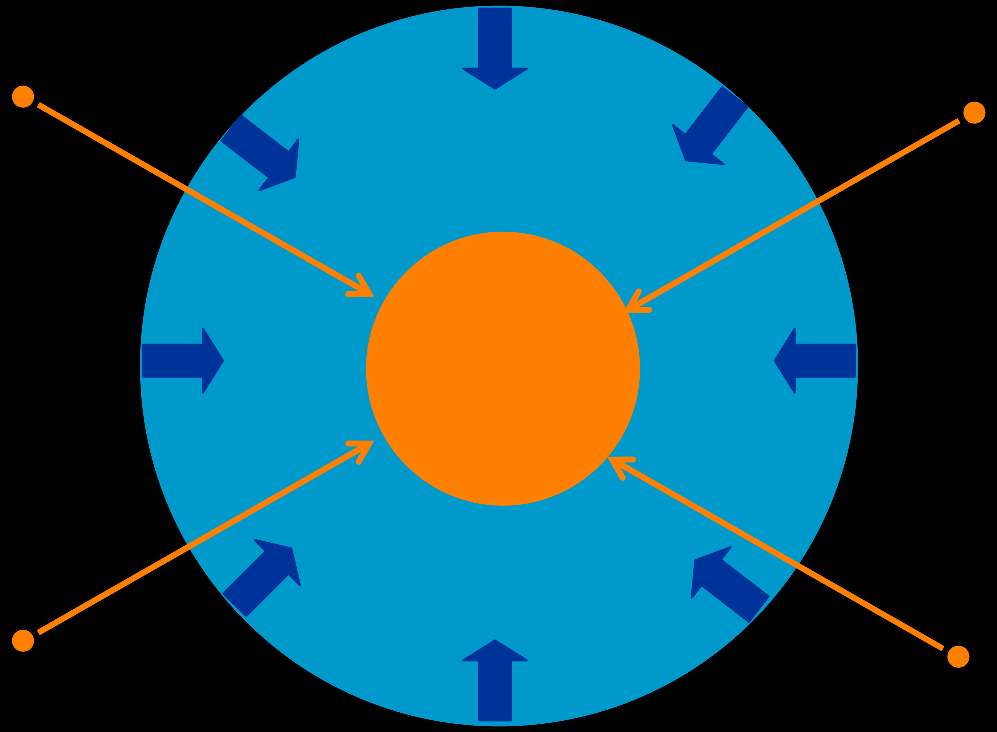


(Wetherill 1989)

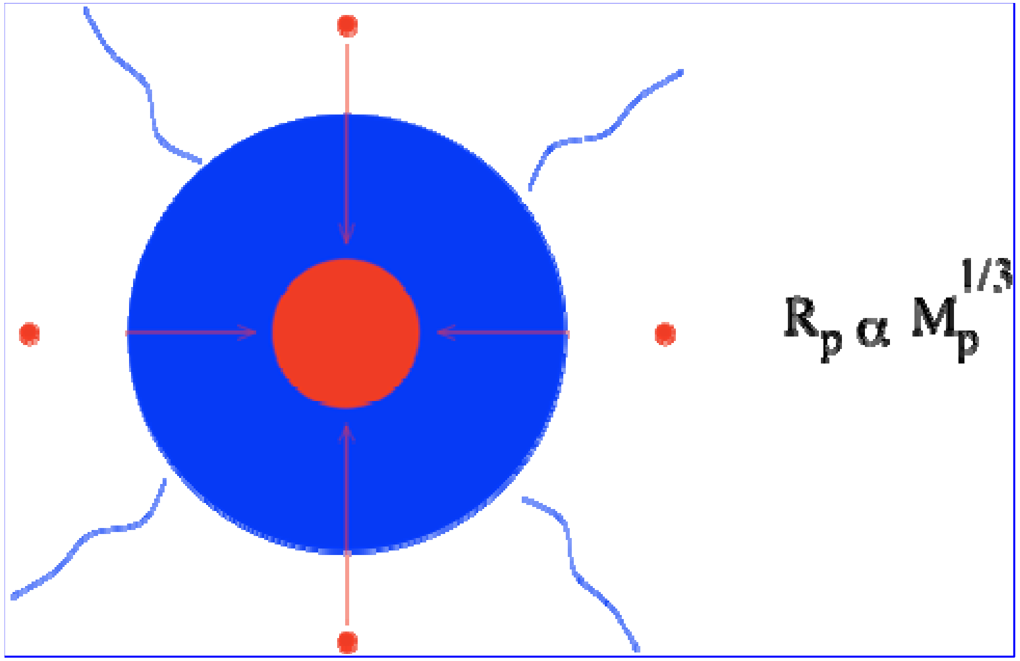
Figure 4 Final outcome of 6 terrestrial planet accumulation calculations by Wetherill (1988). The simulations began with 500 bodies each of mass 2×10^{25} g. The semimajor axes of the final planets are indicated by points; the line through each point extends from the perihelion to the aphelion of the planet. The numbers under each point indicate the final mass of the body in units of 10^{24} g.

Giant planet formation

Capture of a gaseous envelope:



→ Critical core mass



Capture of an envelope

Energy sources:

- (S1) accretion of planetesimals
- (S2) gravitational contraction of the gas

Energy losses:

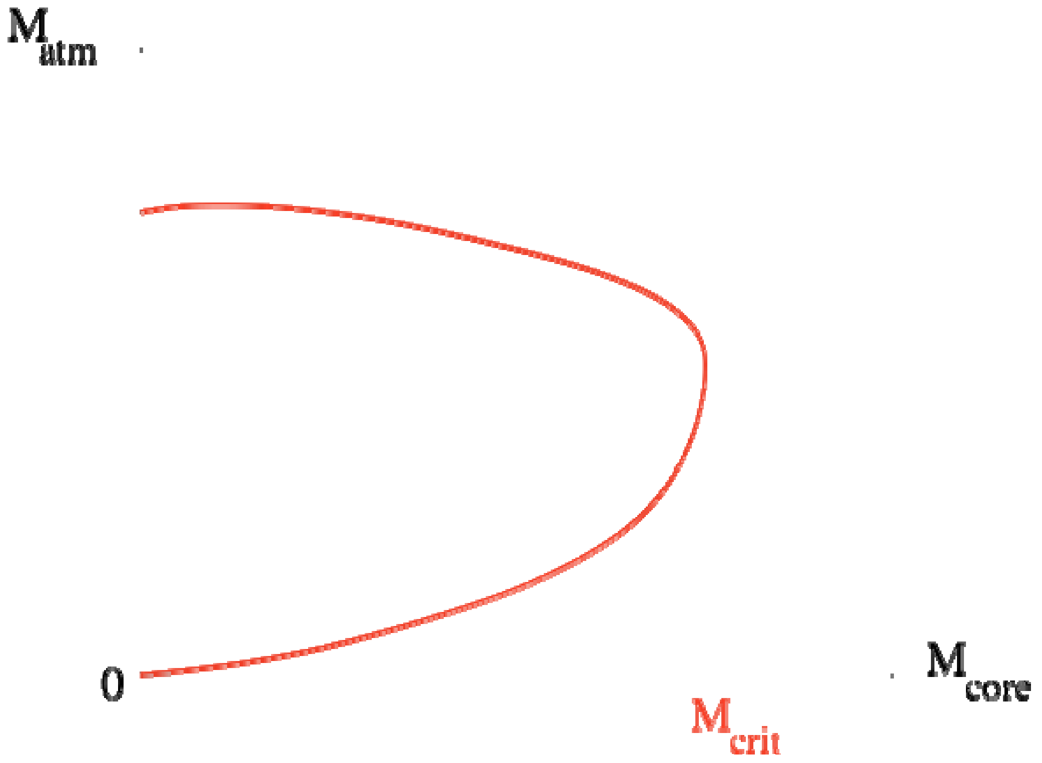
- (P1) Radiative transport
- (P2) Convective transport

Energie conservation: (S1)+(S2)=(P1)+(P2)

If (S1) » (S2): atmosphere at thermal and hydrostatic equilibrium

(Perri & Cameron 1974, Mizuno 1980)

Capture of an envelope



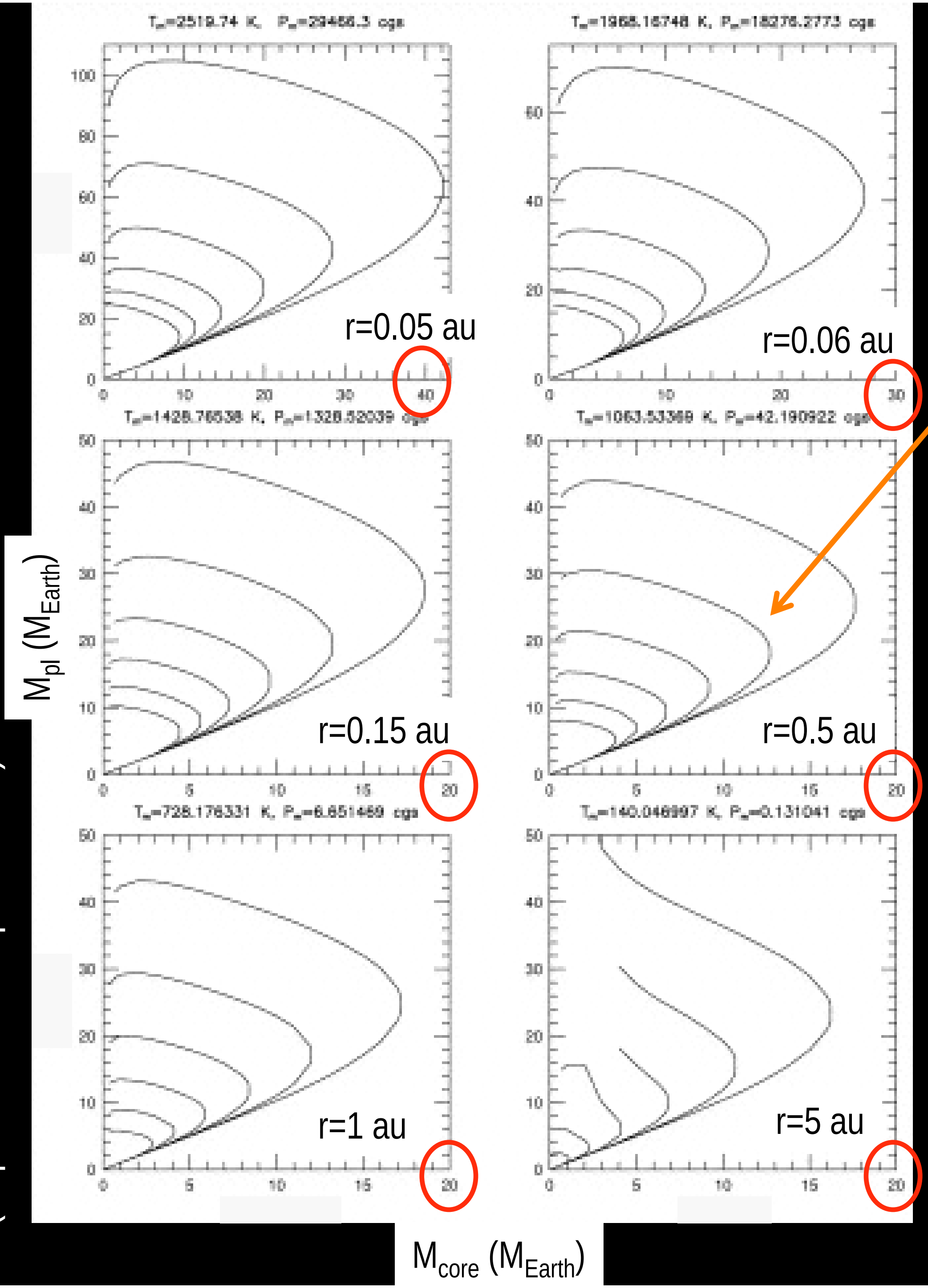
- $M_{core} < M_{crit}$: (S1) large enough to support the atmosphere

- $M_{core} > M_{crit}$: (S1) not large enough

→ collapse of the atmosphere

M_{crit} increases with dM_{plan}/dt

Giant planet formation



(Papaloizou & Terquem 1999)

$dM_{plan}/dt = 10^{-7}\ M_\oplus/yr$

$M_{crit} = 10 - 15\ M_\oplus$

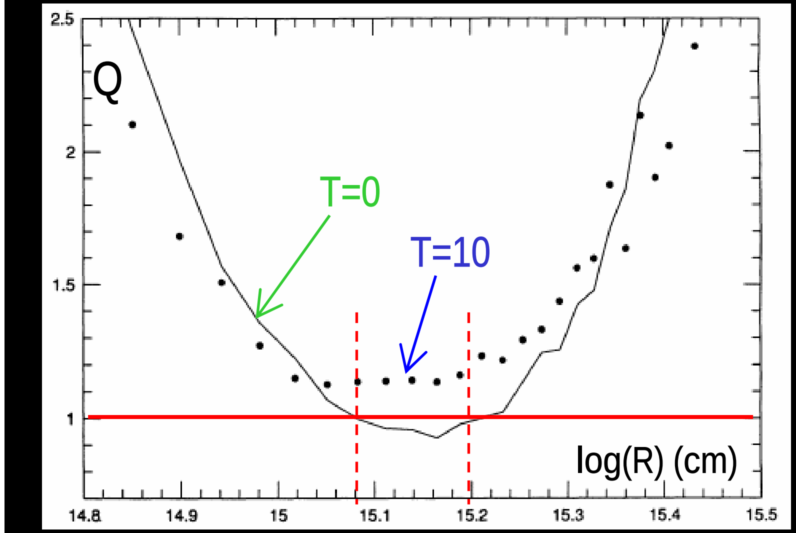
BUT…

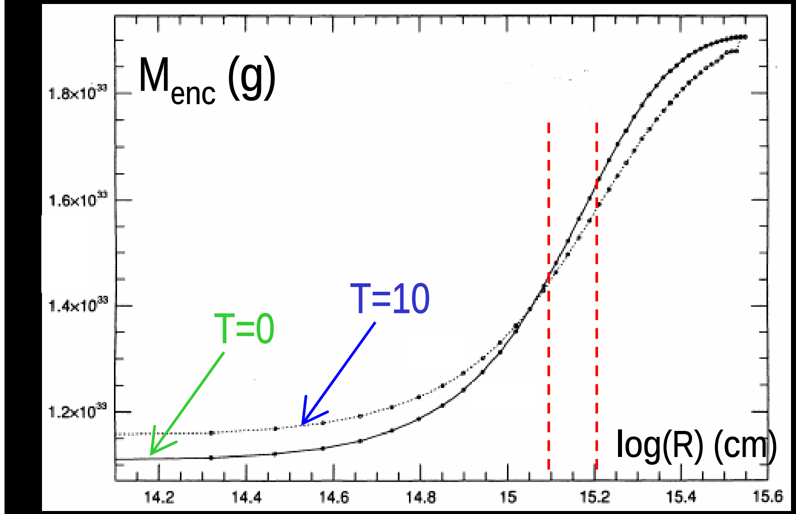
$M_{core} \sim 5\ M_\oplus$ for Jupiter!

(Galileo data)

Solution = smaller dM_{plan}/dt and opacities?

Gravitational instabilities





(Laughlin & Bodenheimer 1994)

Important when $Q = \frac{\kappa c}{\pi G \Sigma} \approx \frac{M_*}{M_d(R)} \frac{H}{R} \approx 1$

i.e. $M_d(R) \sim 0.1 M_*$

Instability timescale: a few Ω^{-1}

Probably help pushing a significant amount of mass onto the star in the early stages.

Planet migration

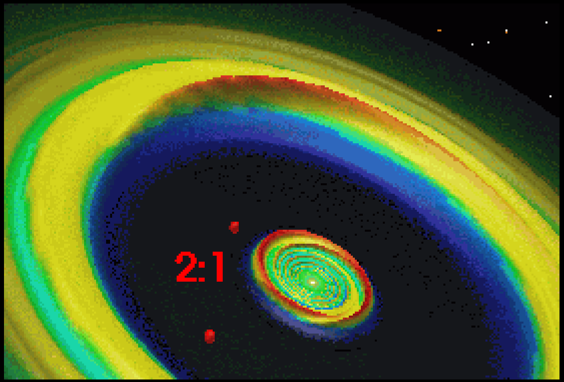
(L. Cook)

Hot Jupiter and Neptunes:

in situ formation:

too hot

(not enough material)



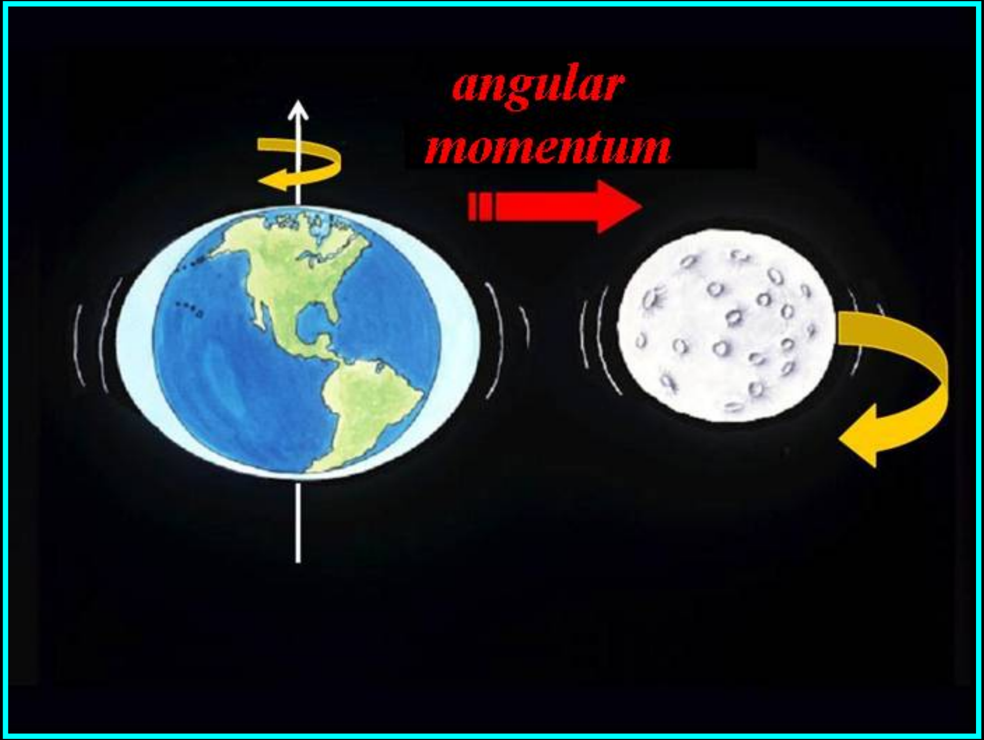
(G. Bryden)

Resonant planets:

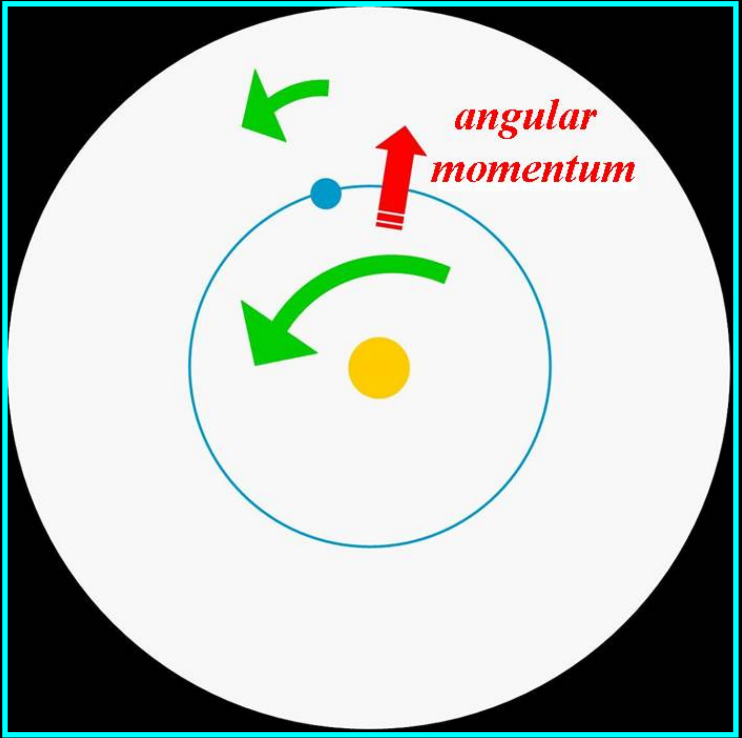
capture

Tidal torques

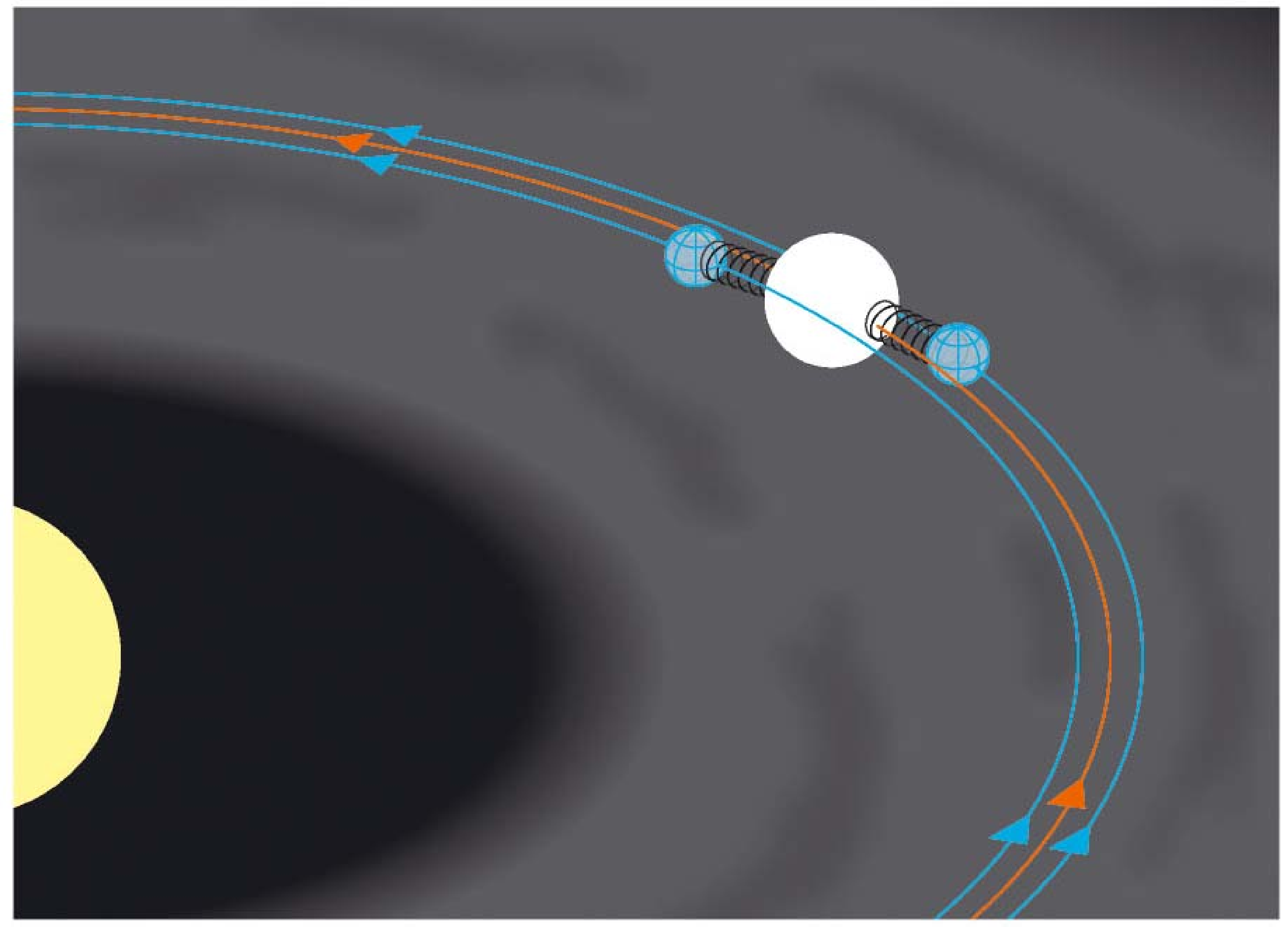
Earth-Moon system



Keplerian disk



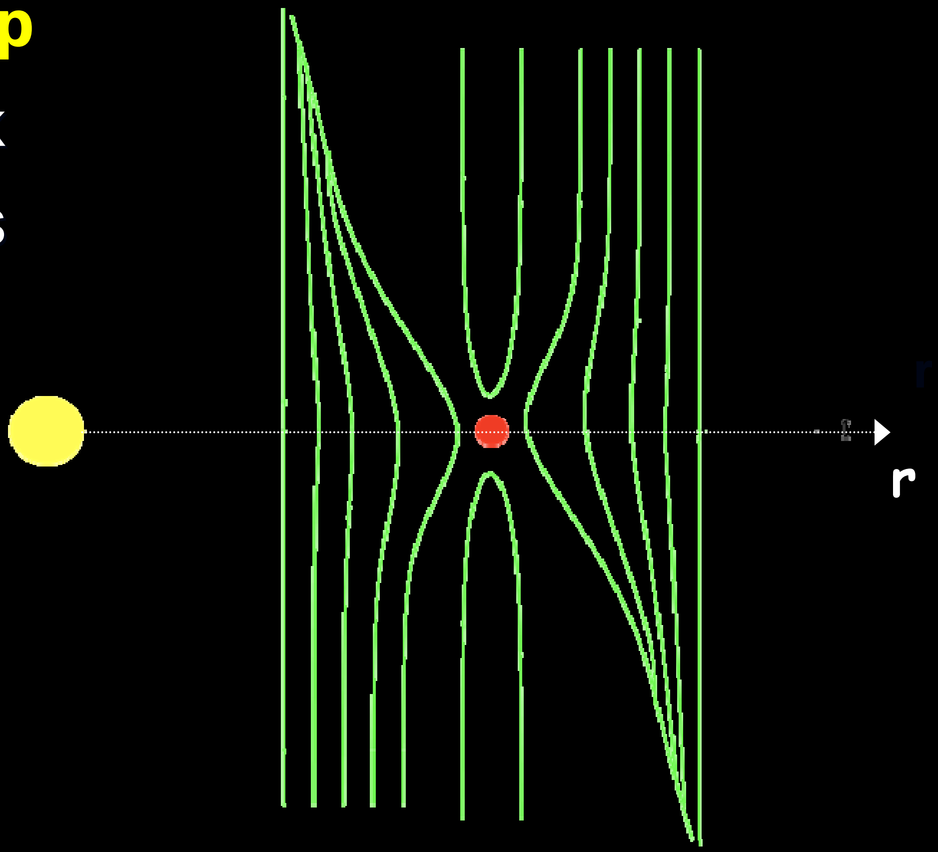
Tidal torques



(Goldreich & Tremaine '79)

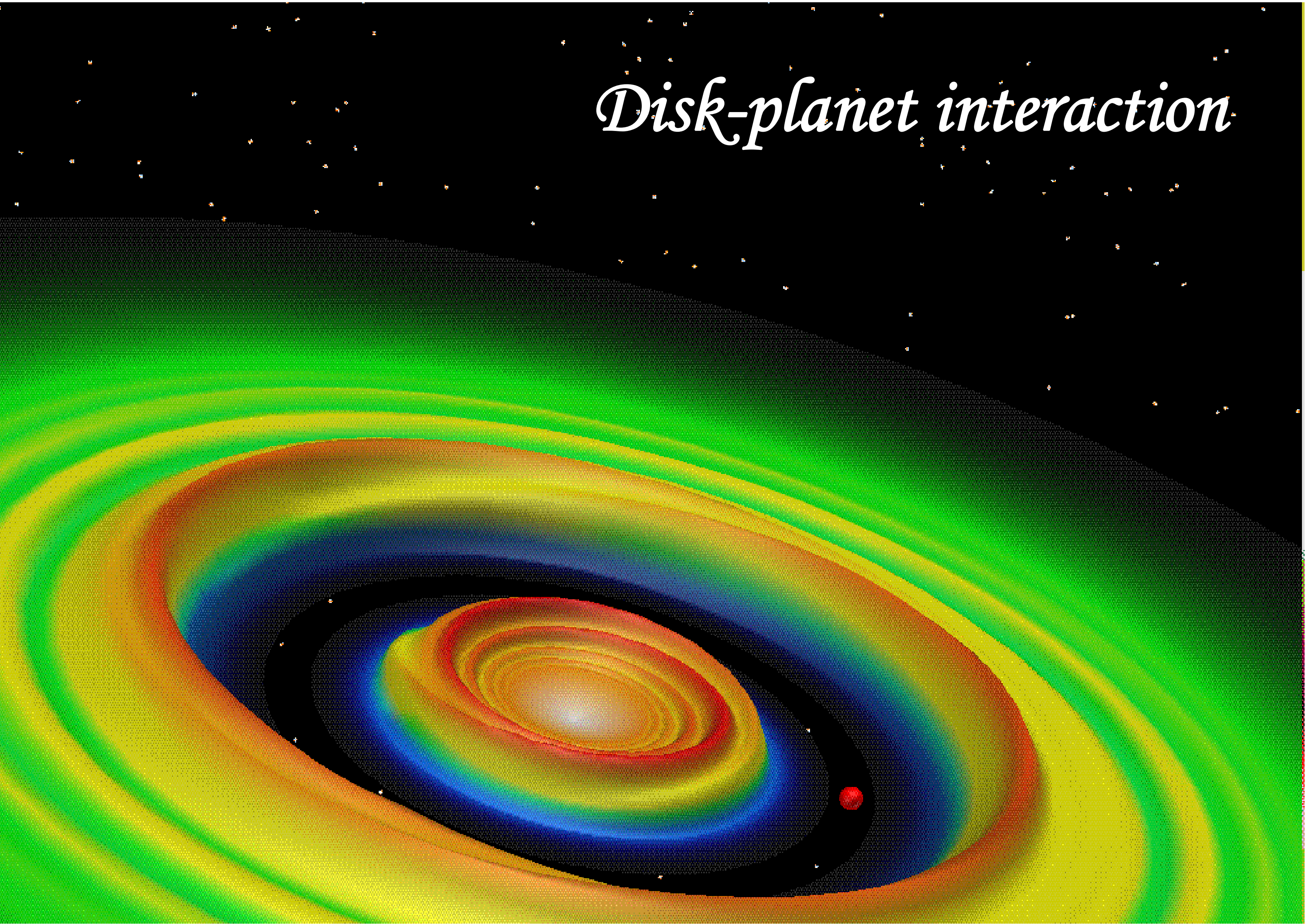
Type II migration ($M>100\ M_{\oplus}$)

The planet opens up a **gap** and is locked into the disk viscous evolution process

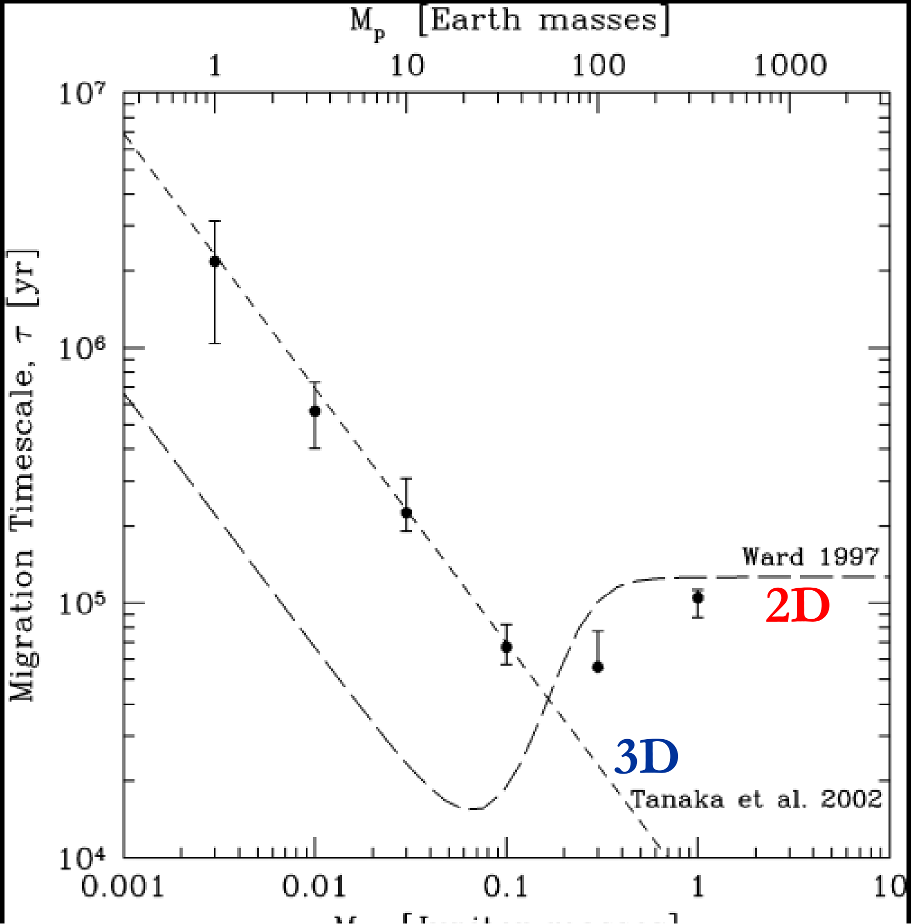


(Goldreich & Tremaine ’80, Papaloizou & Lin ‘84)

Disk-planet interaction



Migration rate



Is migration inevitable?

e I migration:

y not be that efficient (turbulence, magnetic field, entric orbits...)

e II migration:

pends on the disk mass: efficient only in massive ks?

Conclusions

anet formation:

ill lots of uncertainties (planetesimal formation, mescales, critical core mass)

igration:

o much? and what about the solar system?

e do understand mechanisms, but we still lack a obal view

ogress in theory and modelling is fast, but servations progress even faster!