Solar System formation

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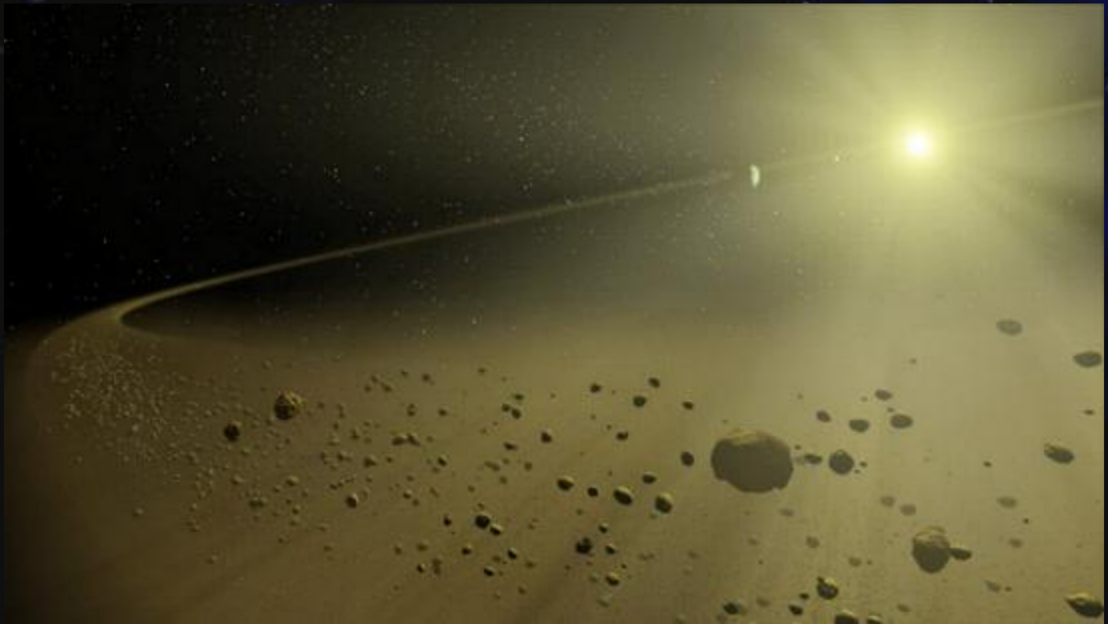


a vast and complex problem

REQUIRING NUMEROUS DIFFERENT SCIENTIFICAL COMPETENCES

- Stellar Physics
- Hydrodynamics
- Thermodynamics
- M.H.D
- Chemistry
- Dynamics
- Geophysics
- ….

OUTLINE

- Basic and not-so-basics facts & constraints
  - Planetary orbits, Masses and composition
  - Age of the Solar System
  - Extrasolar discs & planets
- The "standard" scenario
  - Cloud collapse/star+disc formation
  - Grain condensation
  - formation of planetesimals
  - Planetesimal & Embryo accretion
- Giant Planet formation
  - Can we form them in time?
  - Alternative formation by disc fragmentation?
- Asteroids and Kuiper Belt
  - getting rid of the mass

What is a (solar system!) planet?

Not an issue until the 1990s…

- **1992**: discovery of the first KBO
- **1995**: First exoplanet (around solar-type star)
- **2005**: Eris, a KBO nearly as massive as Pluto

⇒ Need for an ***upper limit***: Brown dwarf ≠ planet

=> Need for a ***lower limit***: small bodies ≠ planet

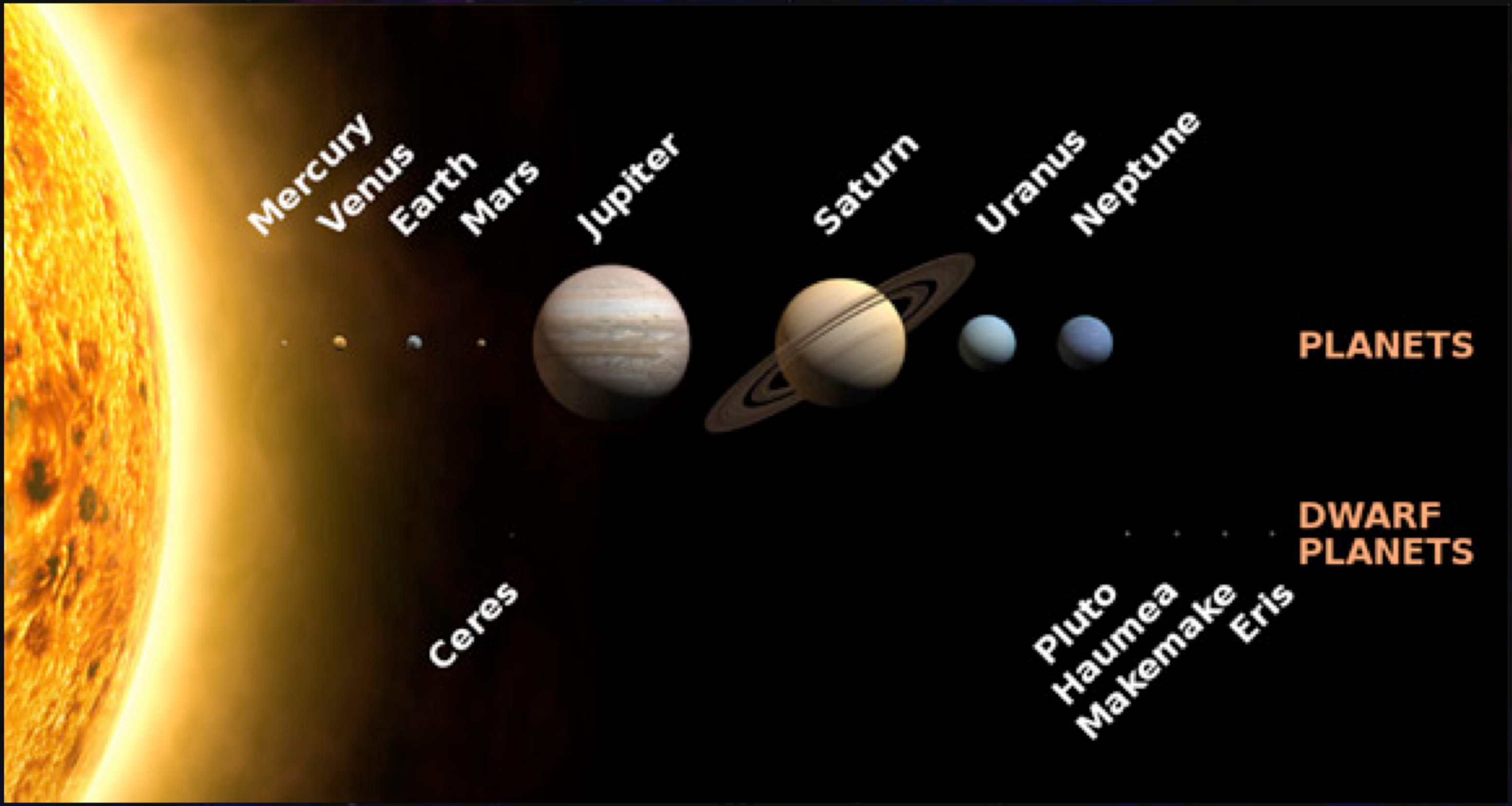
August 2006: IAU meeting, new definition

A ***solar system*** planet is a celestial body

1) orbiting the Sun (no satellites!)
2) massive enough to be spherical
3) Which is the « dominant » body in its orbital region

« dwarf planet »

The "new" Solar System



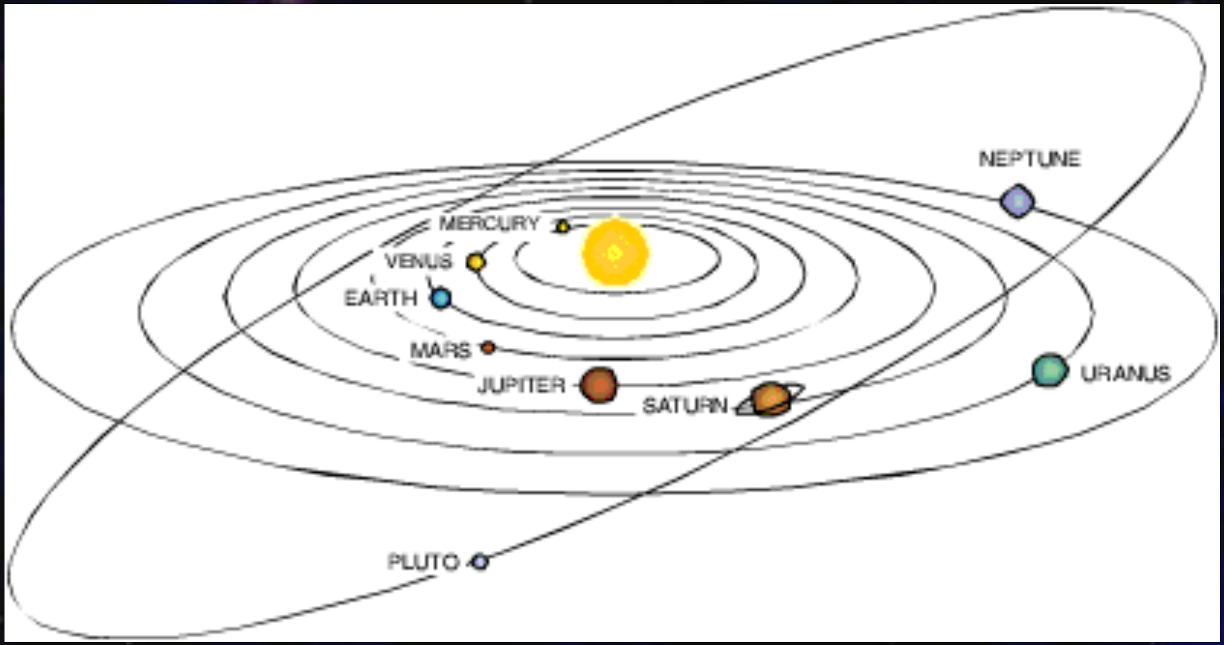
Solar System: basic constraints

- all planetary orbits are almost coplanar

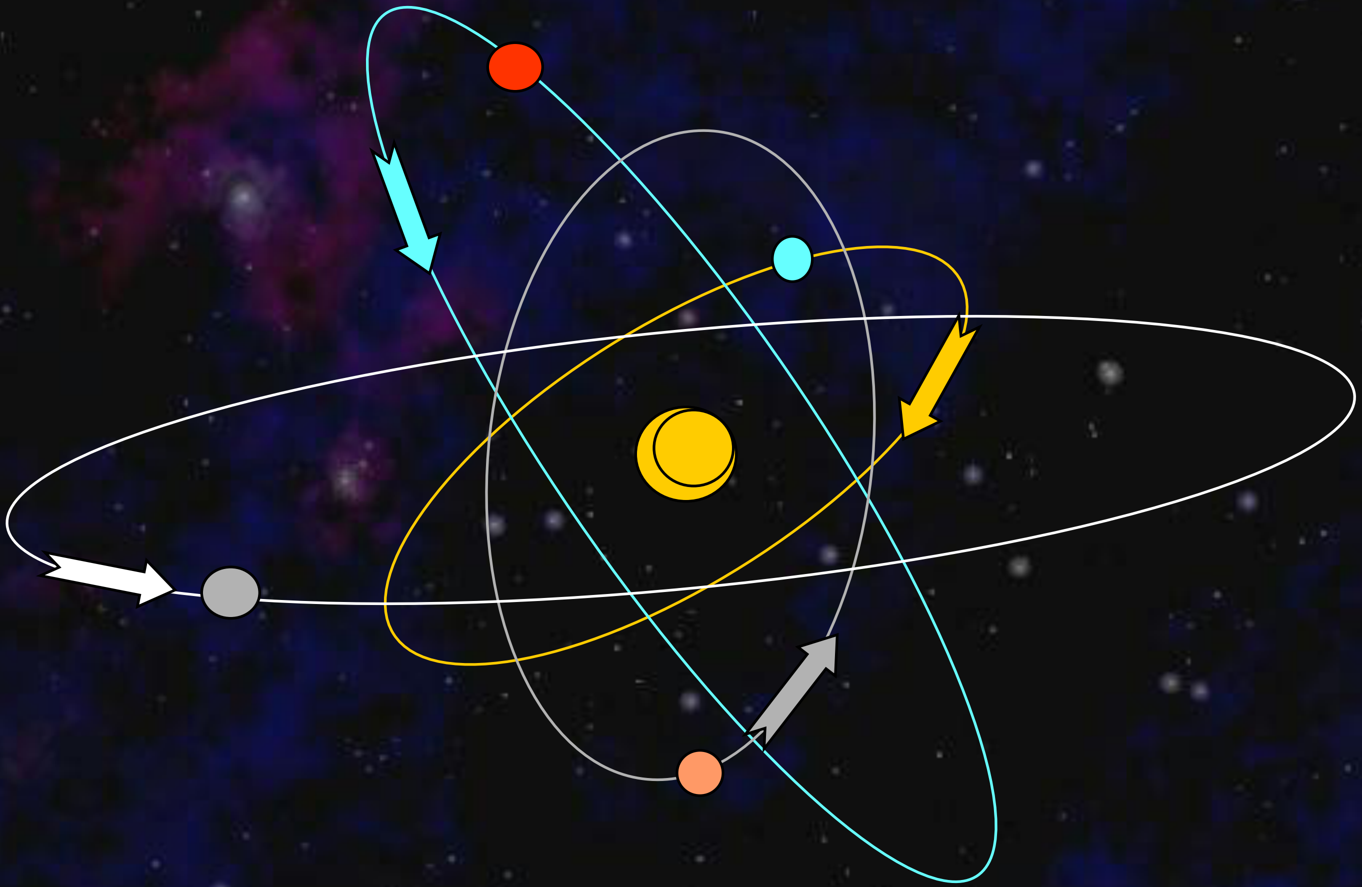
  $i_{max} < 7^\circ$ (Pluto: 17°)

- all planets orbit in the same direction

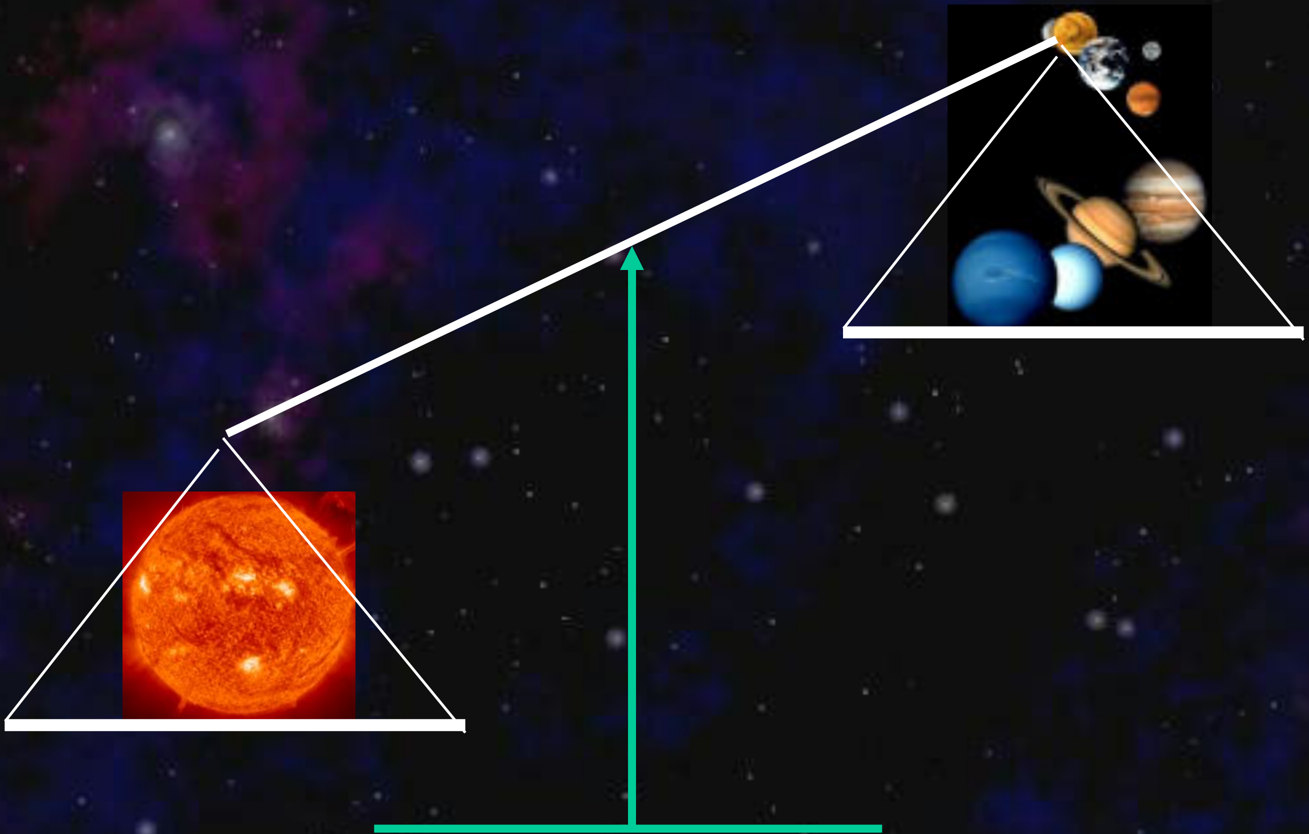
→ common origin for all planets



had planets been captured one by one…

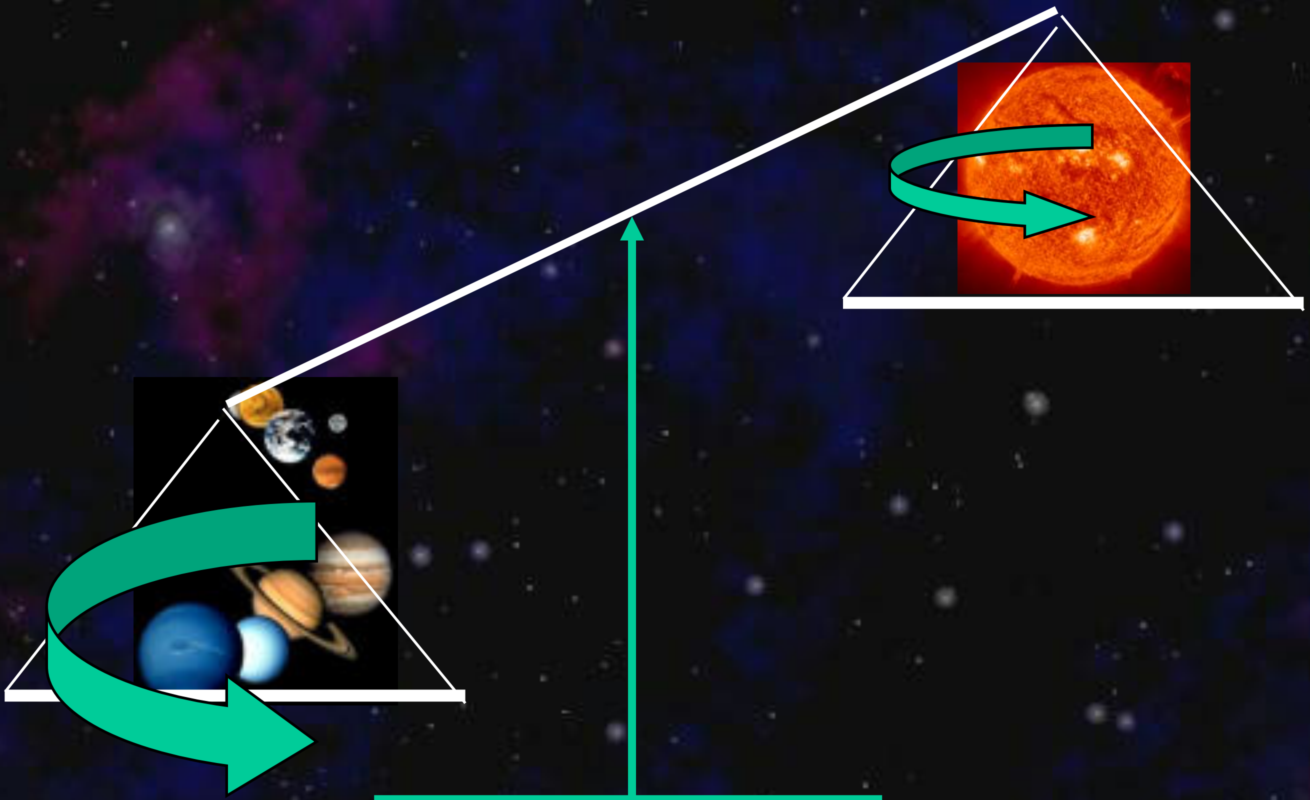


Solar System: basic constraints (2)



- 99,8 % of the mass is in the Sun !

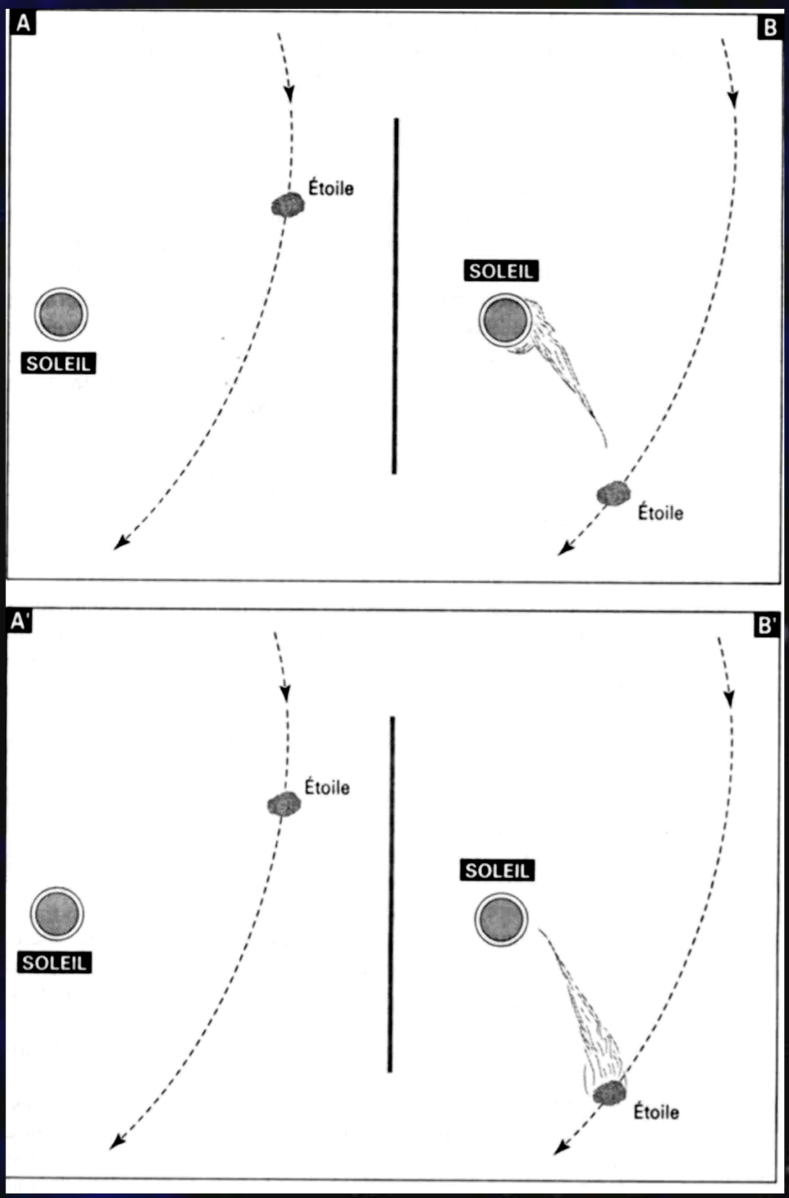
Solar System: basic constraints (3)



- 98% of the angular momentum is in the planets!!

→ Need for a mechanism able to redistribute angular momentum

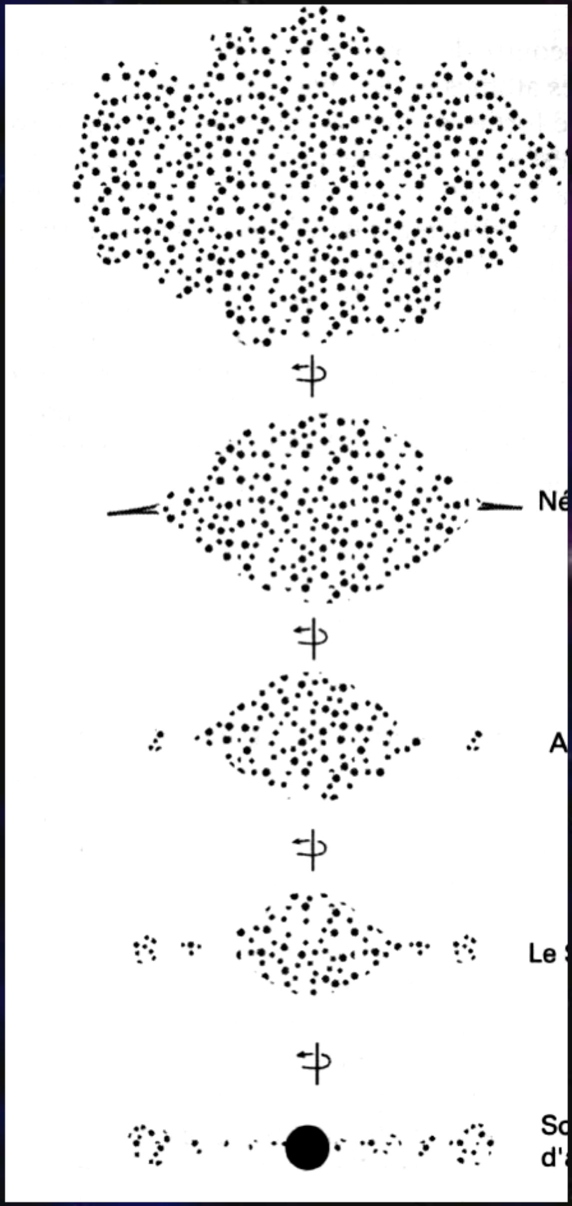
early models: *catastrophist* scenarios



Planets were formed thanks to an exceptional event:

-1741 **Buffon** : passing Comet
-1901 Arrénius : Impact of 2 « dead » stars
-1902 See : progressive capture of planets, inclination later diminishes due to friction
-1902 Belot : Encounter between “tubular vortex” and a cloud at rest
-1900 **Moulton & Chamberlin** : Critic of the Kant-Laplace model: angular momentum Problem
-1916 **Chamberlin** : close encounter with a star takes matter from the Sun=>Formation of a spiral nebulae=>cooling of the nebulae and collisional accretion of *planetesimals*
-1917 **Jeans** : another problem with Laplace : No accretion is possible in a collapsing nebulae … --- --
-1917-1922 **Jeans & Jeffreys** : Close encounter with a star pulls matter from the Sun. Its mass allows condensation of planets
-1935 **Russel** :Planets originate from the destruction of stellar companion of the sun.

early models: *evolutionist* scenarios



Planets formed along with the Sun

-1630 Descartes : dynamical evolution of a vortex

-1751 Kant & 1786 Laplace :
Collapse of an initial rotating cloud
Formation of a disc by centrifugal force
Separation of the disc in concentric annuli
Formation of inhomogeneities in annulii

Planets are common objects

PROBLEM!

Get rid of the sun's angular momentum

not so basic constraints: composition of the planets

- Terrestrial Planets

O, Fe, Si, … almost no H, no He at all

- Giant Planets

	Jupiter	Saturn	Uranus	Neptune
Total Mass	320 $M_\oplus$	95 $M_\oplus$	15 $M_\oplus$	17 $M_\oplus$
Rock & Ices	10-45 $M_\oplus$	20-30 $M_\oplus$	9-13 $M_\oplus$	12-16 $M_\oplus$
Core	0-12 $M_\oplus$	0-15 $M_\oplus$	0.5 $M_\oplus$ (?)	?
H2 et He Gas	275-310 $M_\oplus$	65-75 $M_\oplus$	0.5-1.5 $M_\oplus$	1-5 $M_\oplus$

- Total Masses

$M_{\text{terrestrial-planets}} \approx 6.10^{-6}\ M_\odot$ & $M_{\text{giant-planets}} \approx 1.5\ 10^{-3}\ M_\odot$

When extrapolating the « missing » H & He

↓

$M \approx 0.03\ M_\odot$

Minimum Mass Solar Nebulae

the M(inimum) M(ass) S(olar) N(ebula)

(*Weidenshilling, 1977*)

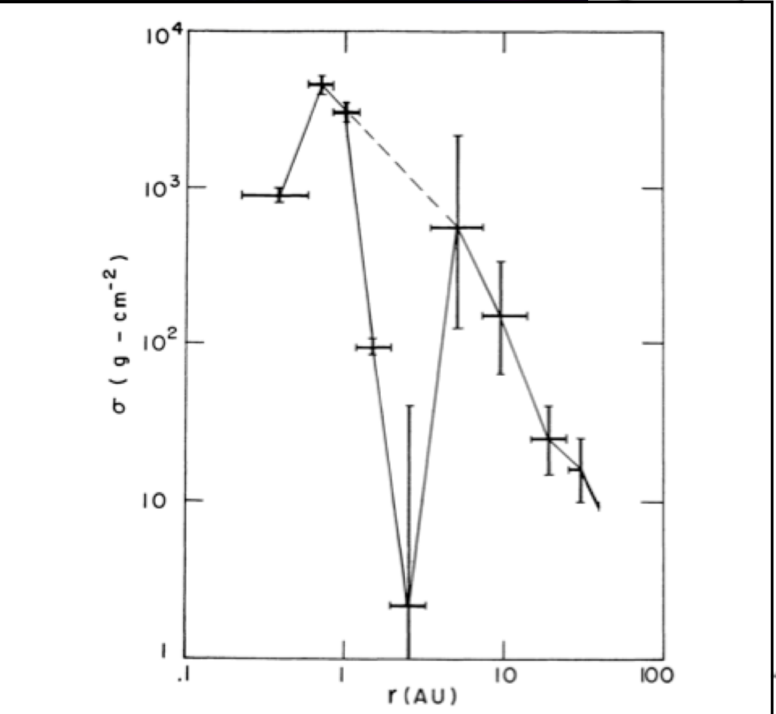
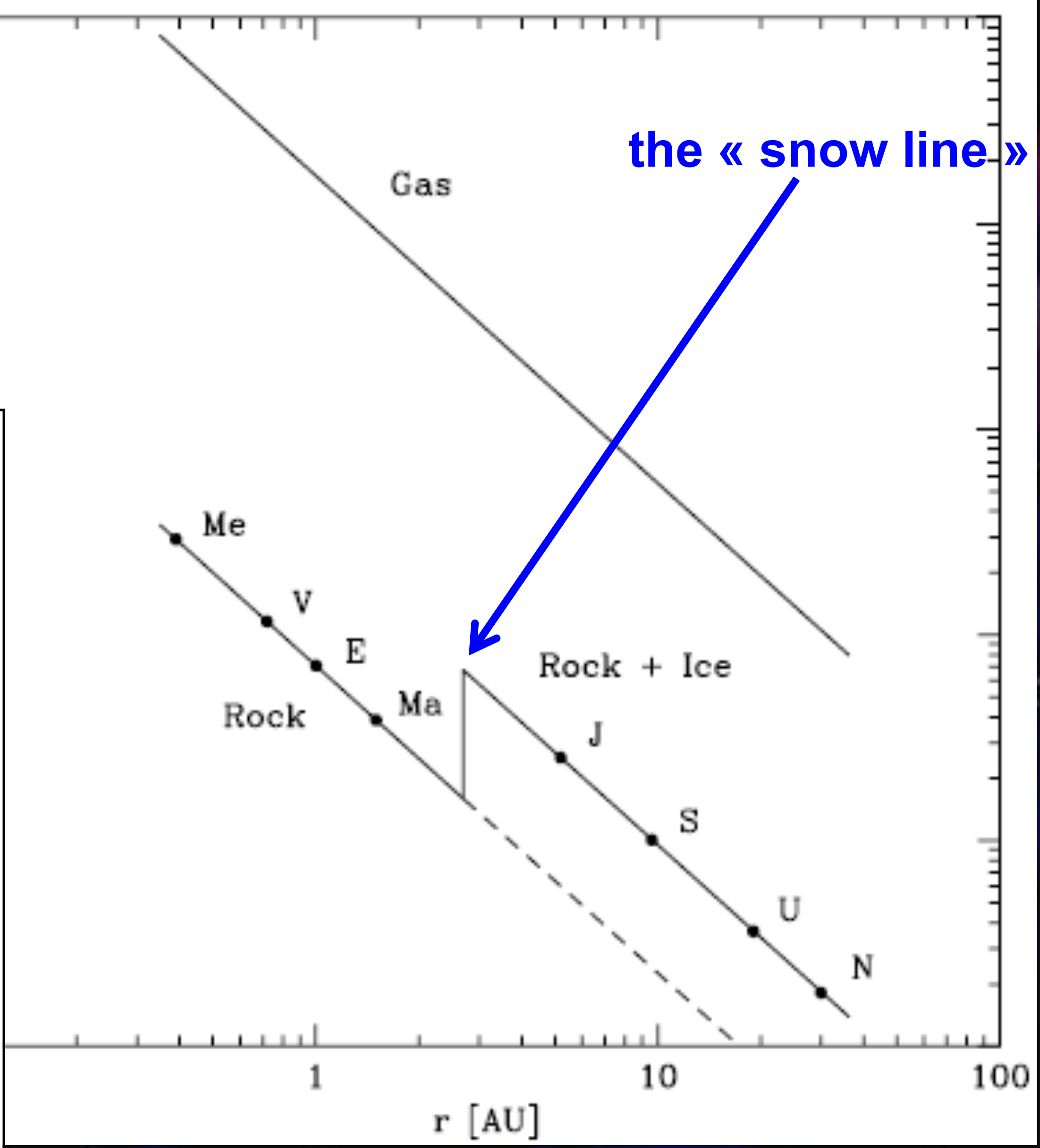


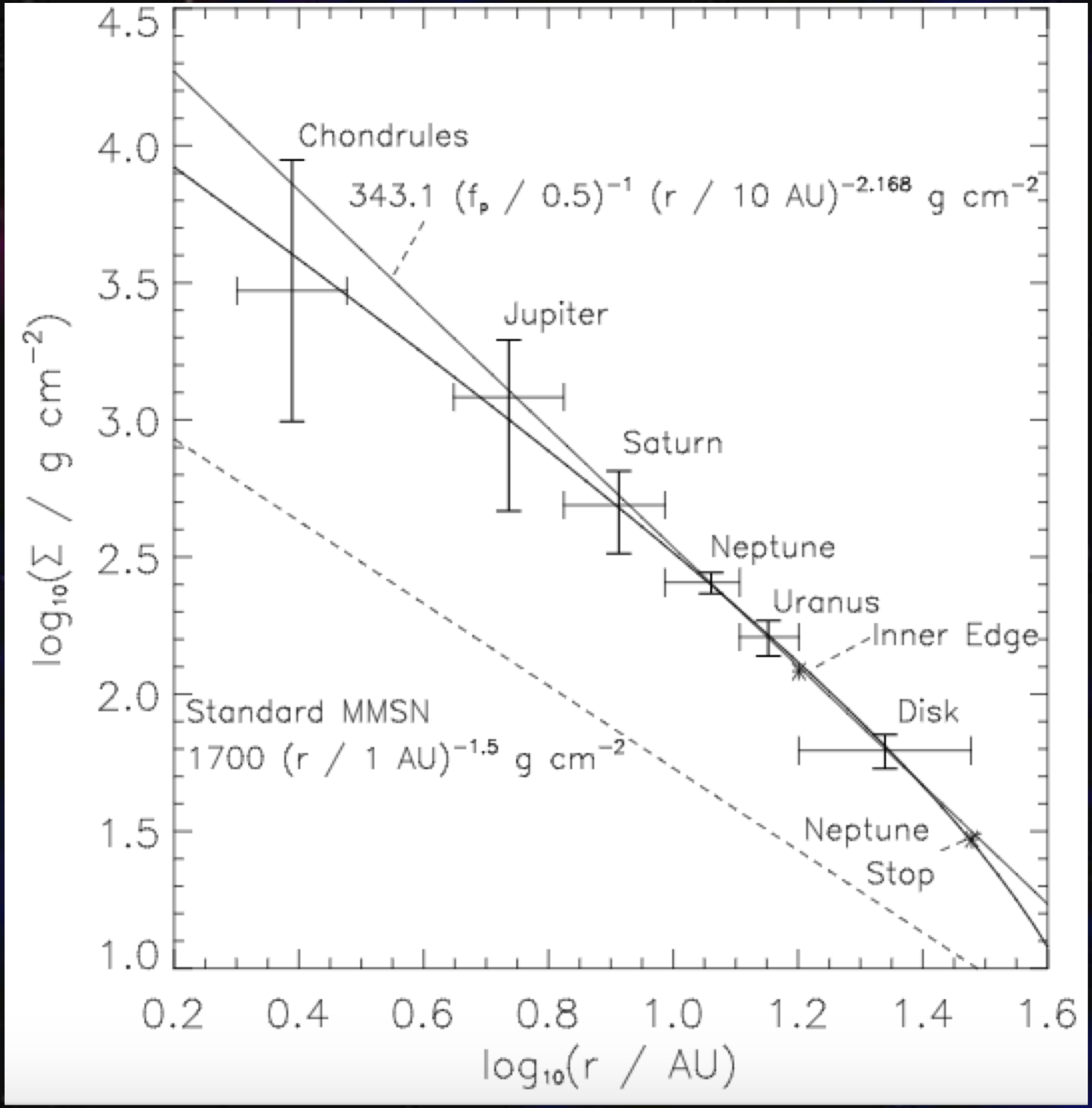
Fig. 1. Surface densities, σ, obtained by restoring the planets to solar composition and spreading the resulting masses through contiguous zones surrounding their orbits. The meaning of the 'error bars' is discussed in the text.



the « snow line »

(*Hayashi, 1981*)

MMSN with migration (?)



(*Desch, 2007*)

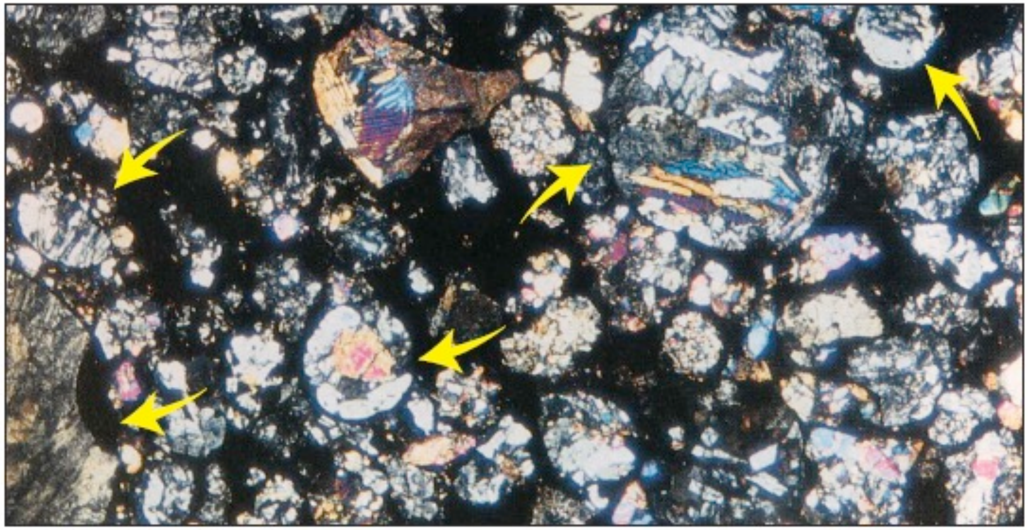
not so basic constraints: age of the solar system

Composition and Radioactivity of Meteorites

Decay of radioactive isotopes:

Absolute ages: Long-lived isotopes ^{235}U-^{238}U=>Pb

Relative ages: Short-Lived isotopes ^{26}Al=>^{26}Mg, …

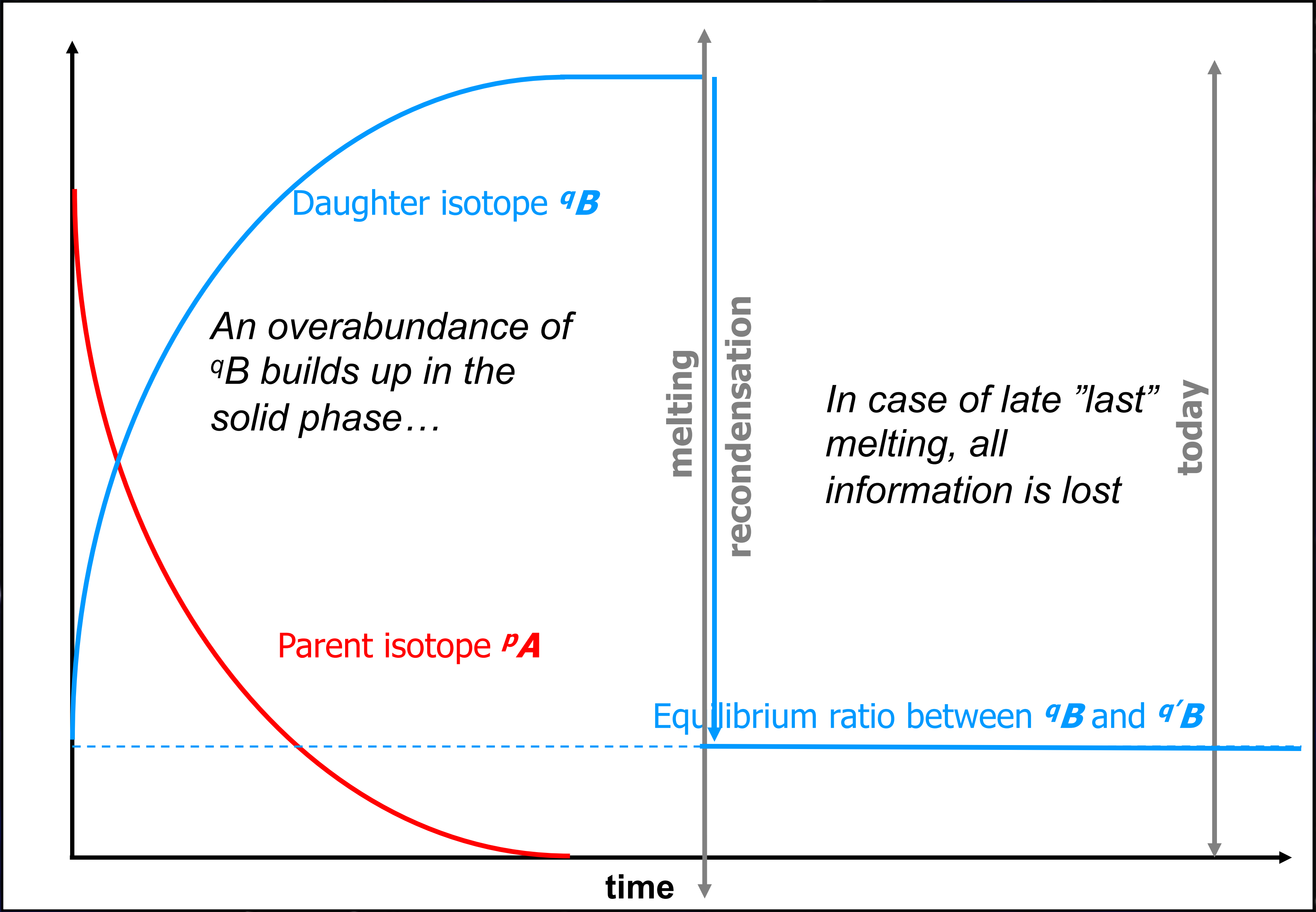


"Clocks" in meteorites. A thin section of the meteorite Tieschitz—some chondrules are indicated.

oldest meteorites
chondrites:

- -CAI
- -Chondrules
- -fine grain matrix

Melting resets daughter isotope abundance to its equilibrium ratio to other isotopes of its element => What we can estimate is the time since the ***last*** recondensation

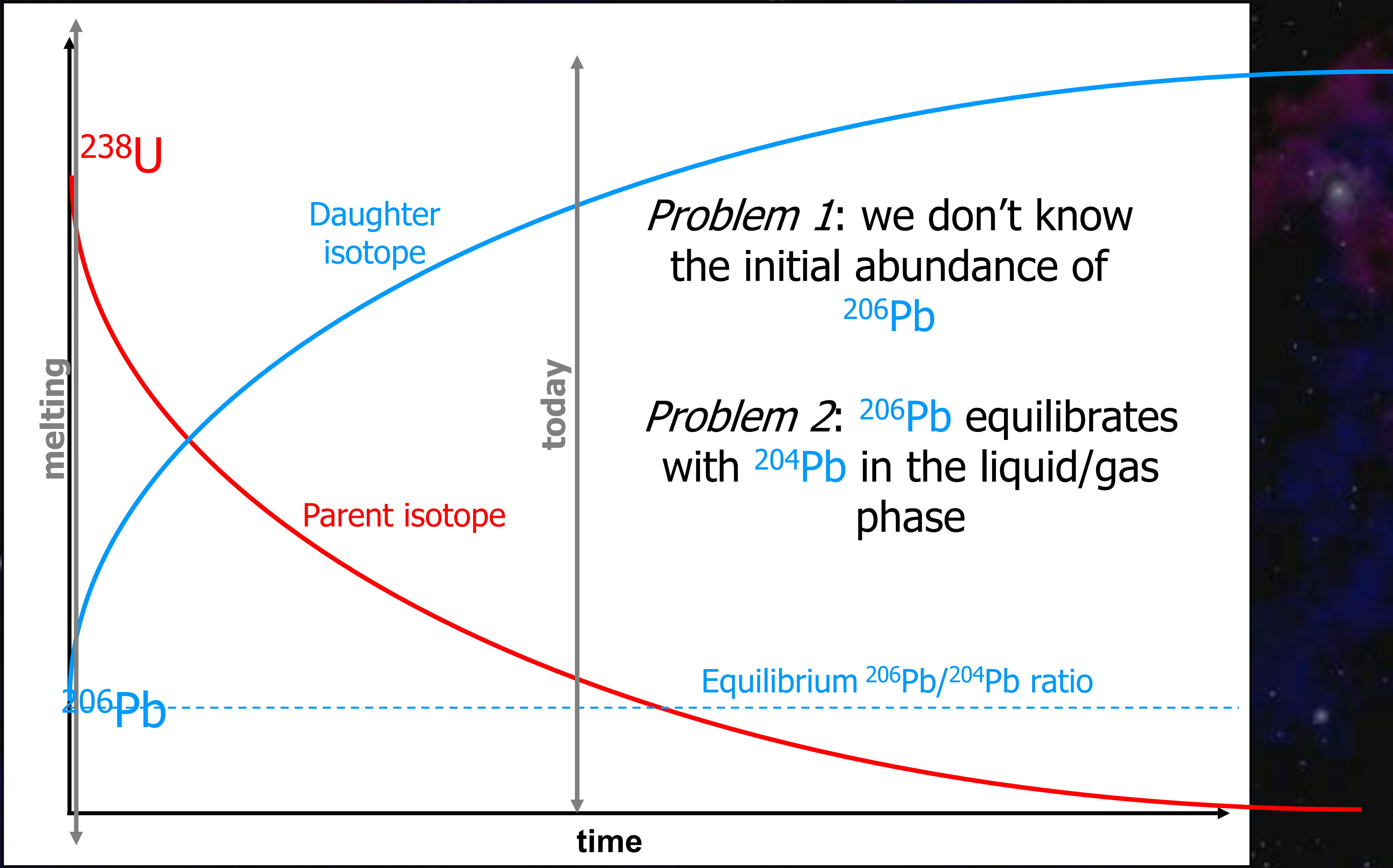


An overabundance of ^{q}B builds up in the solid phase…

In case of late "last" melting, all information is lost

Absolute datation by long-lived isotopes

^{238}U => ^{206}Pb (half-life = 4.47x10^{9} years)



Problem 1: we don’t know the initial abundance of ^{206}Pb

Problem 2: ^{206}Pb equilibrates with ^{204}Pb in the liquid/gas phase

We can *not* solve this equation alone

$$\left(\frac{^{206}Pb}{^{204}Pb}\right)_P = \left(\frac{^{206}Pb}{^{204}Pb}\right)_I + \left(\frac{^{238}U}{^{204}Pb}\right)_I \left(1 - e^{-\lambda_{238} t}\right)$$

luckily enough, there is *another* reaction:

^{235}U => ^{207}Pb (half-life = 0.706×10^9 years)

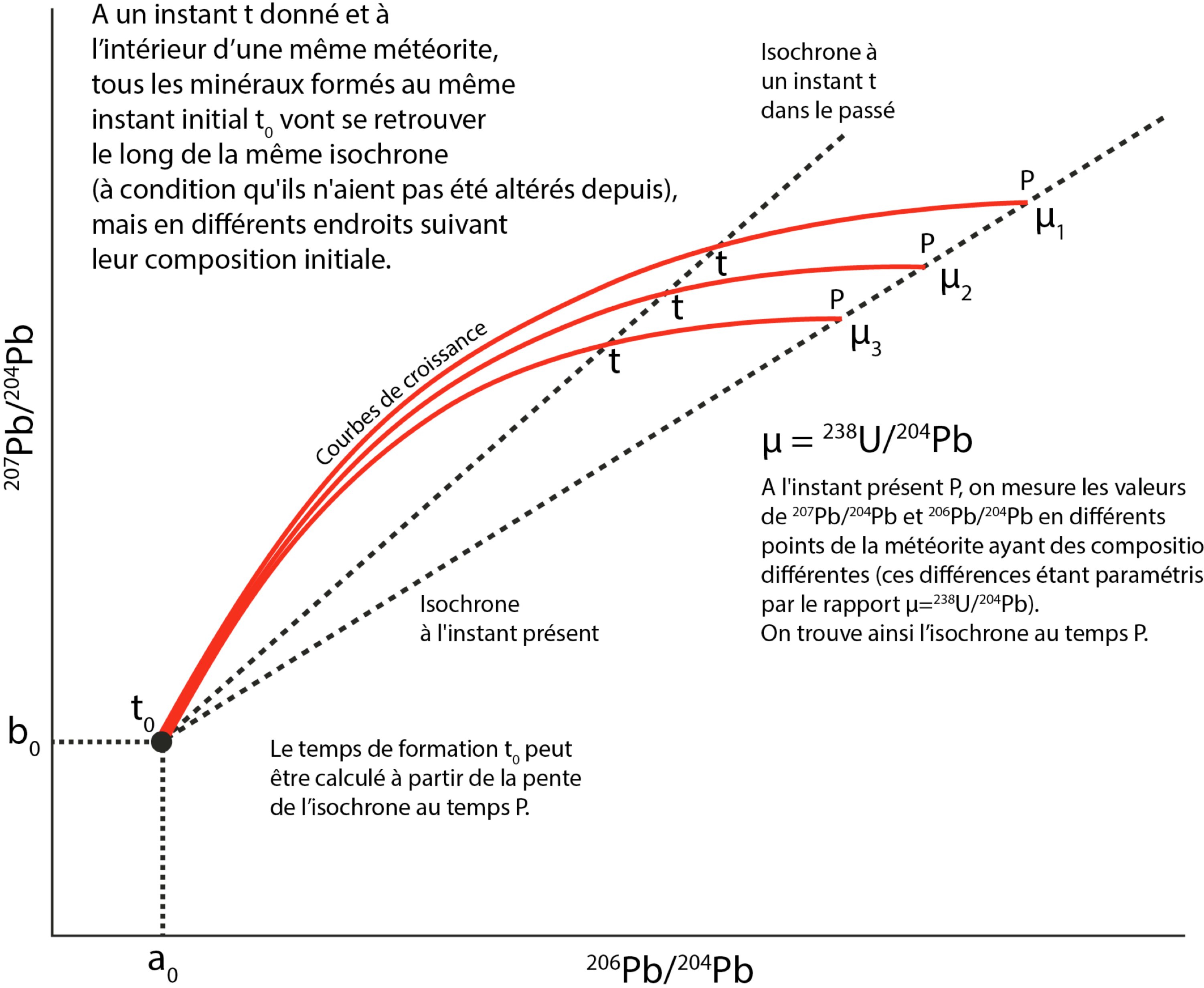
So if the meteorite was *initially inhomogeneous* but *condensed at the same time*, we can measure $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ at different locations and use:

$$\left(\frac{^{207}Pb}{^{204}Pb}\right)_P = \left(\frac{^{207}Pb}{^{204}Pb}\right)_I + \left(\frac{^{235}U}{^{204}Pb}\right)_P \left(e^{\lambda_{235} t} - 1\right)$$

$$\left(\frac{^{206}Pb}{^{204}Pb}\right)_P = \left(\frac{^{206}Pb}{^{204}Pb}\right)_I + \left(\frac{^{238}U}{^{204}Pb}\right)_P \left(e^{\lambda_{238} t} - 1\right)$$

Et donc: $\boxed{F = \left[\frac{\left(\frac{^{207}Pb}{^{204}Pb}\right)_P - \left(\frac{^{207}Pb}{^{204}Pb}\right)_I}{\left(\frac{^{206}Pb}{^{204}Pb}\right)_P - \left(\frac{^{206}Pb}{^{204}Pb}\right)_I}\right] = \left(\frac{1}{137.88}\right)\left(\frac{e^{\lambda_{235} t} - 1}{e^{\lambda_{238} t} - 1}\right)}$

Temporal isochrones on an inhomogeneous meteorite



A un instant t donné et à l'intérieur d'une même météorite, tous les minéraux formés au même instant initial t_0 vont se retrouver le long de la même isochrone (à condition qu'ils n'aient pas été altérés depuis), mais en différents endroits suivant leur composition initiale.

Isochrone à un instant t dans le passé

$\mu = {}^{238}U/{}^{204}Pb$

A l'instant présent P, on mesure les valeurs de ^{207}Pb/^{204}Pb et ^{206}Pb/^{204}Pb en différents points de la météorite ayant des compositions différentes (ces différences étant paramétrisées par le rapport $\mu = {}^{238}U/{}^{204}Pb$).
On trouve ainsi l'isochrone au temps P.

Isochrone à l'instant présent

Le temps de formation t_0 peut être calculé à partir de la pente de l'isochrone au temps P.

Relative datation with short-lived isotopes

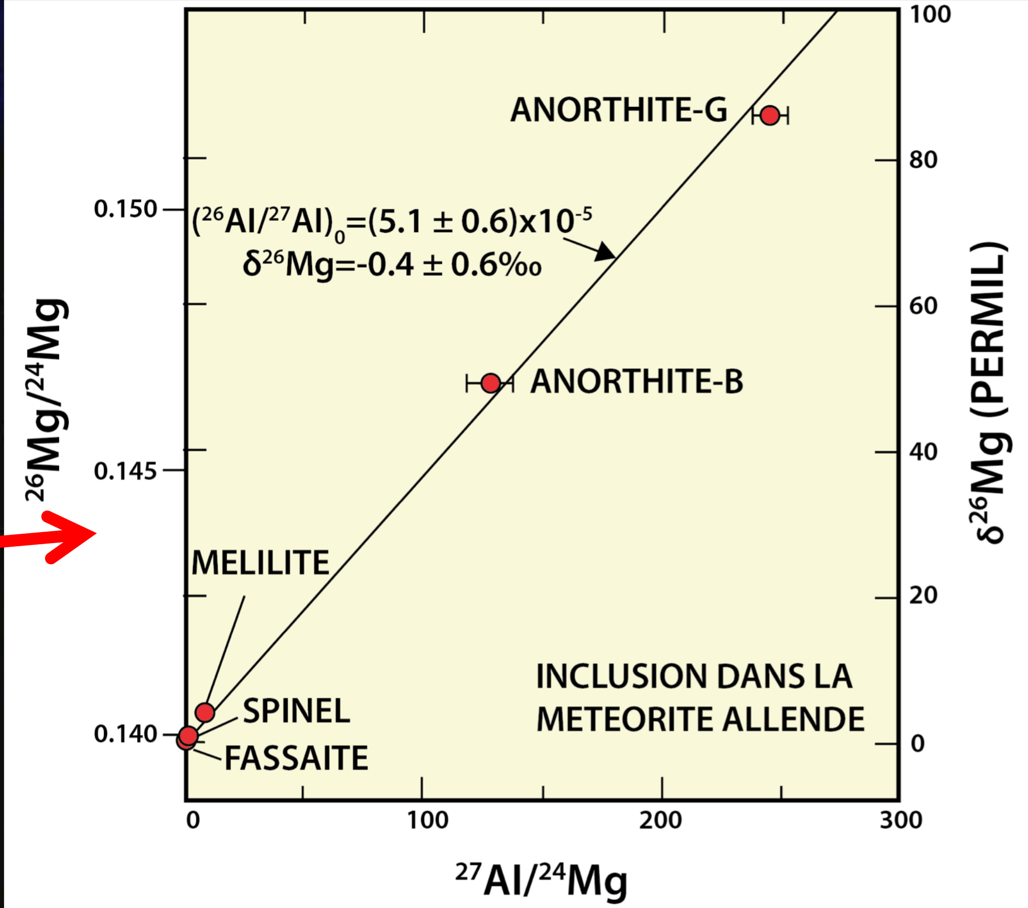
- ^{26}Al => ^{26}Mg (half-life = 0.720x10^{6} years) => all ^{26}Al is gone today
- But ^{27}Al and ^{24}Mg are the "natural" isotopes

$$(^{26}Mg)_P = (^{26}Mg)_I + (^{26}Al)_I$$

So if the meteorite was initially inhomogeneous but condensed at the same time, the initial ^{27}Al/^{26}Al ratio can be infered by using

$$\left(\frac{^{26}Mg}{^{24}Mg}\right)_P = \left(\frac{^{26}Mg}{^{24}Mg}\right)_I + \left(\frac{^{26}Al}{^{27}Al}\right)_I \left(\frac{^{27}Al}{^{24}Mg}\right)_P$$

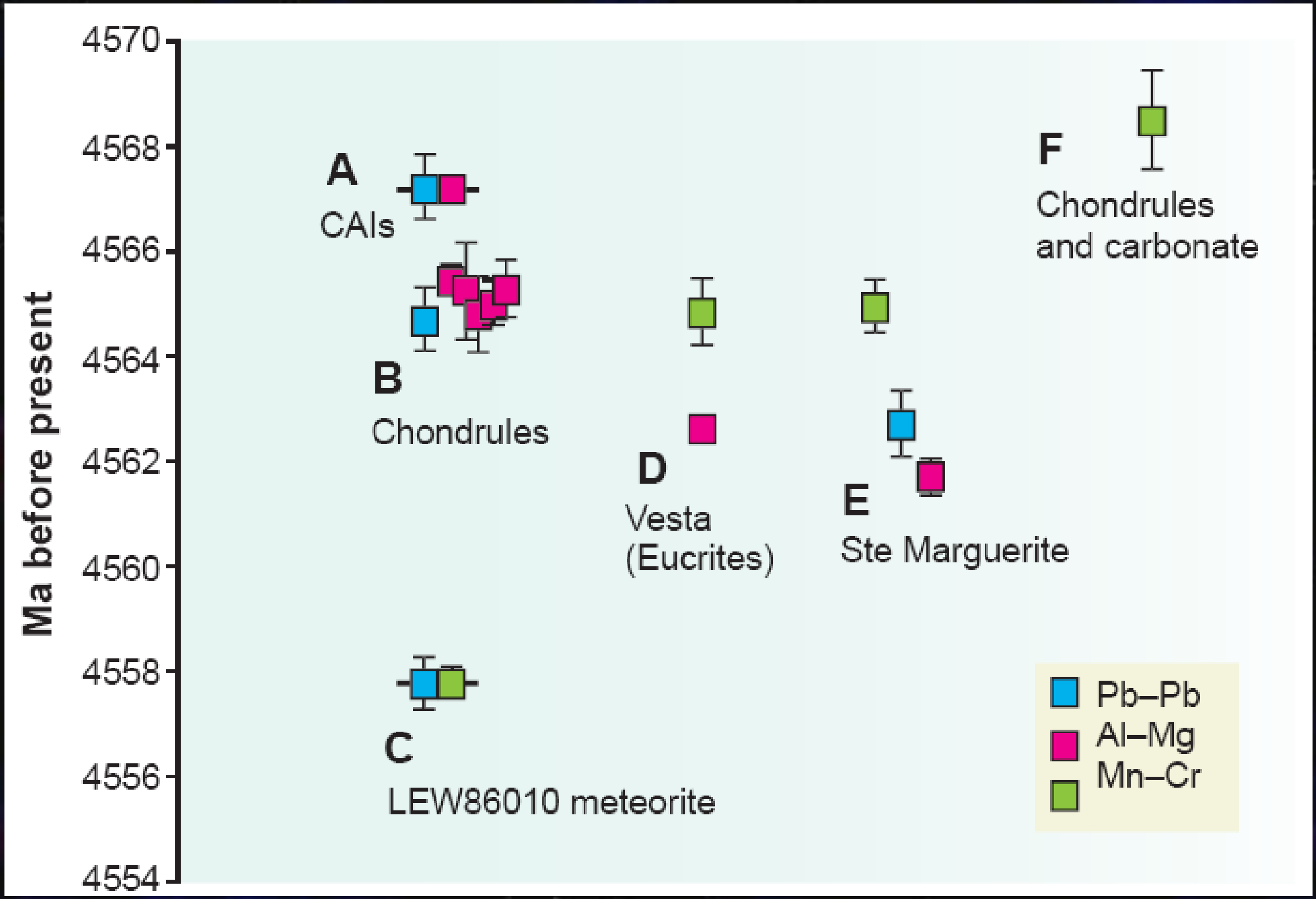
with measures of ^{26}Mg/^{24}Mg and ^{26}Al/^{27}Al at different locations



(Lee et al., *Geophys. Res. Lett.*, 1976

Relative datation between different meteorites using

$$\left(\frac{^{26}Al}{^{27}Al}\right)_I^1 = \left(\frac{^{26}Al}{^{27}Al}\right)_I^2 e^{-\lambda(t_1-t_2)}$$



Oldest rocks: CAIs (« Ca-Al rich Inclusions ») **4.5672±0.0004(!) 10^9yrs**

Oldest *differentiated* rocks: **4.5662±0.0001(!) 10^9yrs**

Maximum duration of formation < 10-100.10^6 yrs for the Earth

How to explain the presence of short-lived isotopes at the birth of the solar system?

overabundance of

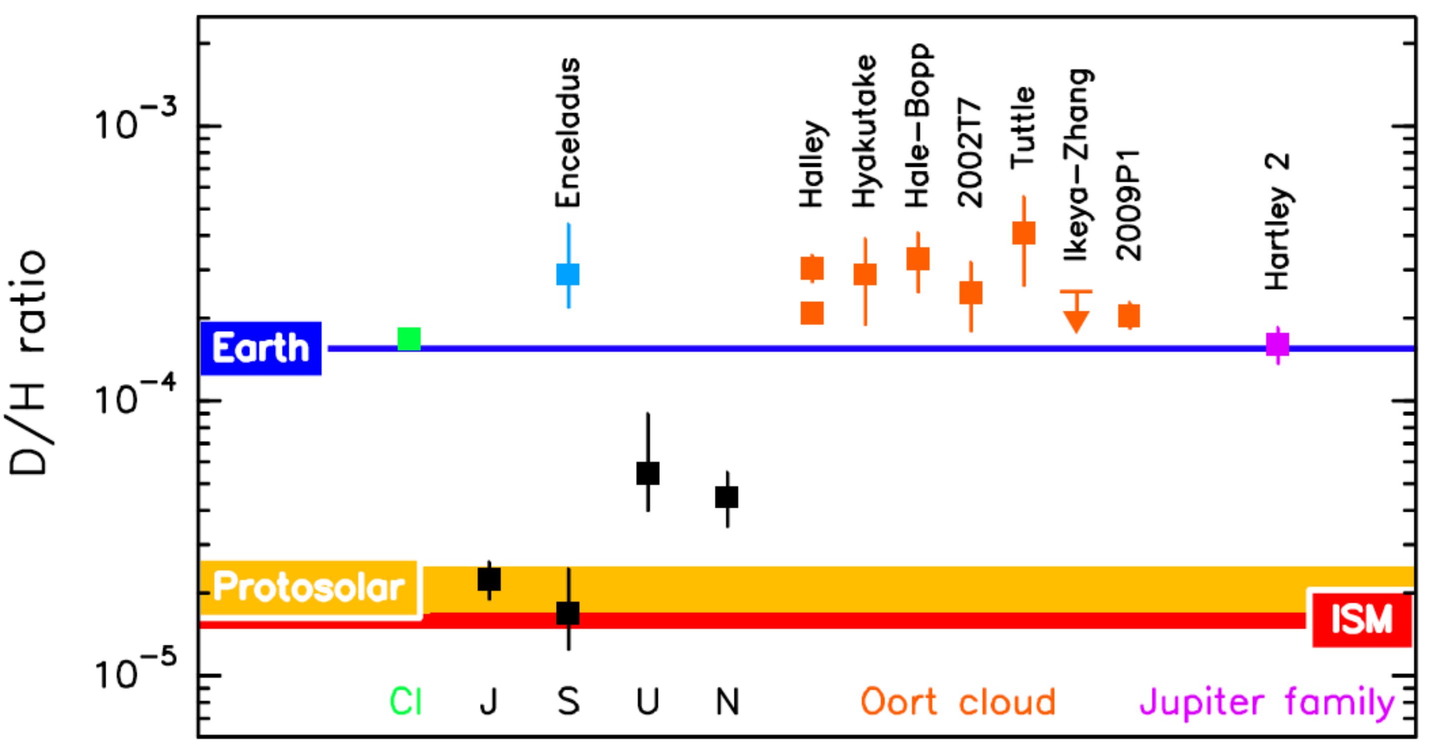
- ^{26}Al (τ=1.1 10^6yrs)
- ^{60}Fe (τ=3.7 10^6Myr)

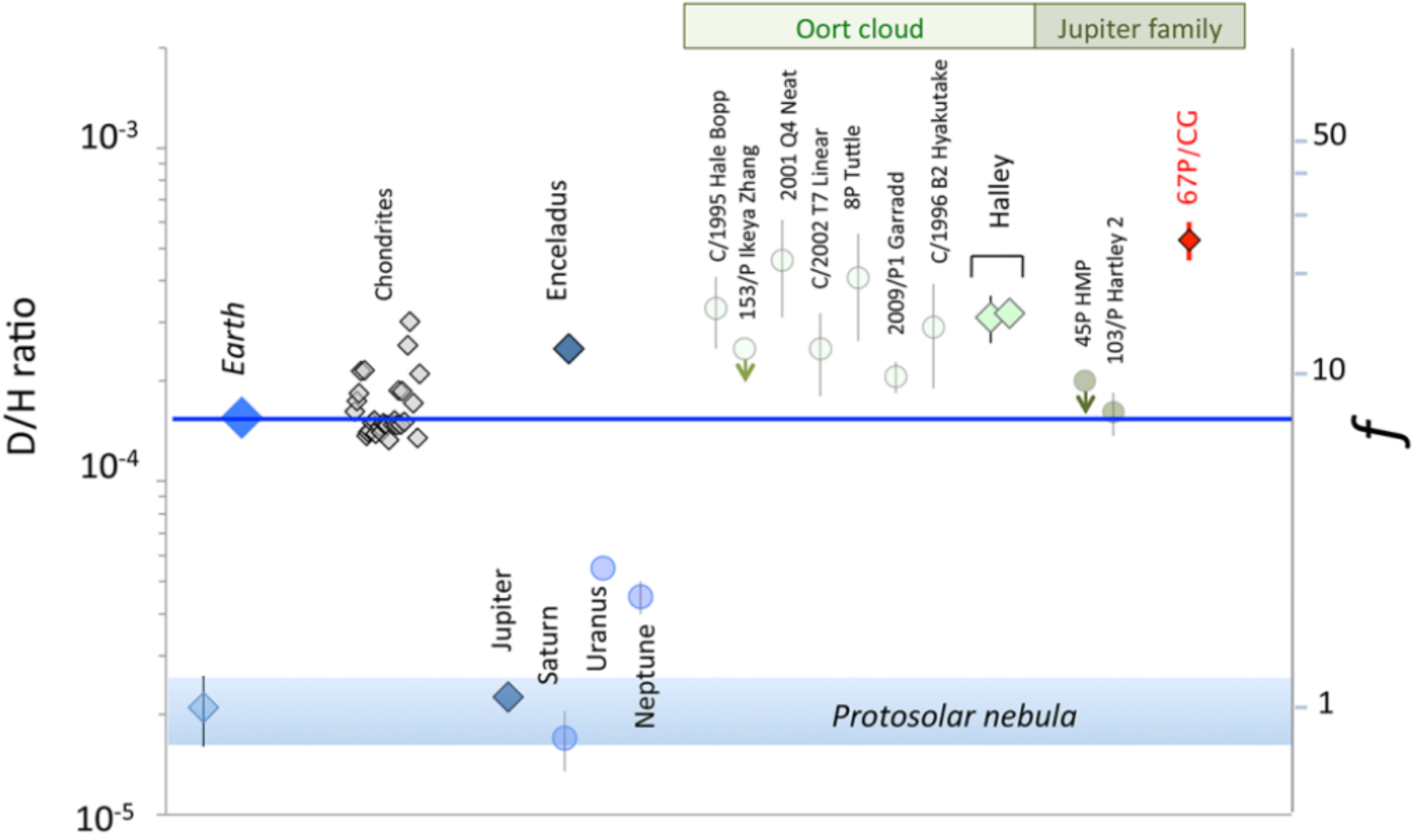
Did the solar system form close to an exploding supernovae?

Possible if the distance to the SN is <0.4pc

D/H ratio in water in the Solar System

Deuterium only produced by early nucleosynthesis.
D/H almost homogeneous throughout the Universe.
but D becomes concentrated in H_20 at low T.




Oort cloud
Jupiter family
D/H ratio
10^{-3}
10^{-4}
10^{-5}
f
50
10
1
Earth
Chondrites
Enceladus
C/1995 Hale Bopp
153/P Ikeya Zhang
2001 Q4 Neat
C/2002 T7 Linear
8P Tuttle
2009/P1 Garradd
C/1996 B2 Hyakutake
Halley
45P HMP
103/P Hartley 2
67P/CG
Jupiter
Saturn
Uranus
Neptune
Protosolar nebula

crater record on the moon

Evidence for a period of **Late Heavy Bombardment**

- spike in lunar rock resetting ages
- spike in ages of lunar impact melts
- impact basins Nectaris (3.9-3.92Gyr) and Orientale (3.82Gyr) imply quick decline (half life 50Myr)
- cratering on Mercury, Mars and Galilean satellites support LHB, but equivocally

not so basic constraints: observations of circumstellar discs

- Extrasolar Discs

50 % of Young.Stellar.Objects. are surrounded by discs

Class 0: $M_d \approx 0.5\ M_\odot$ lifetime $\approx 10^4$ yrs

Class I: $M_d \approx 0.1\ M_\odot$ lifetime $\approx 10^5$ yrs $R > 1000$ AU

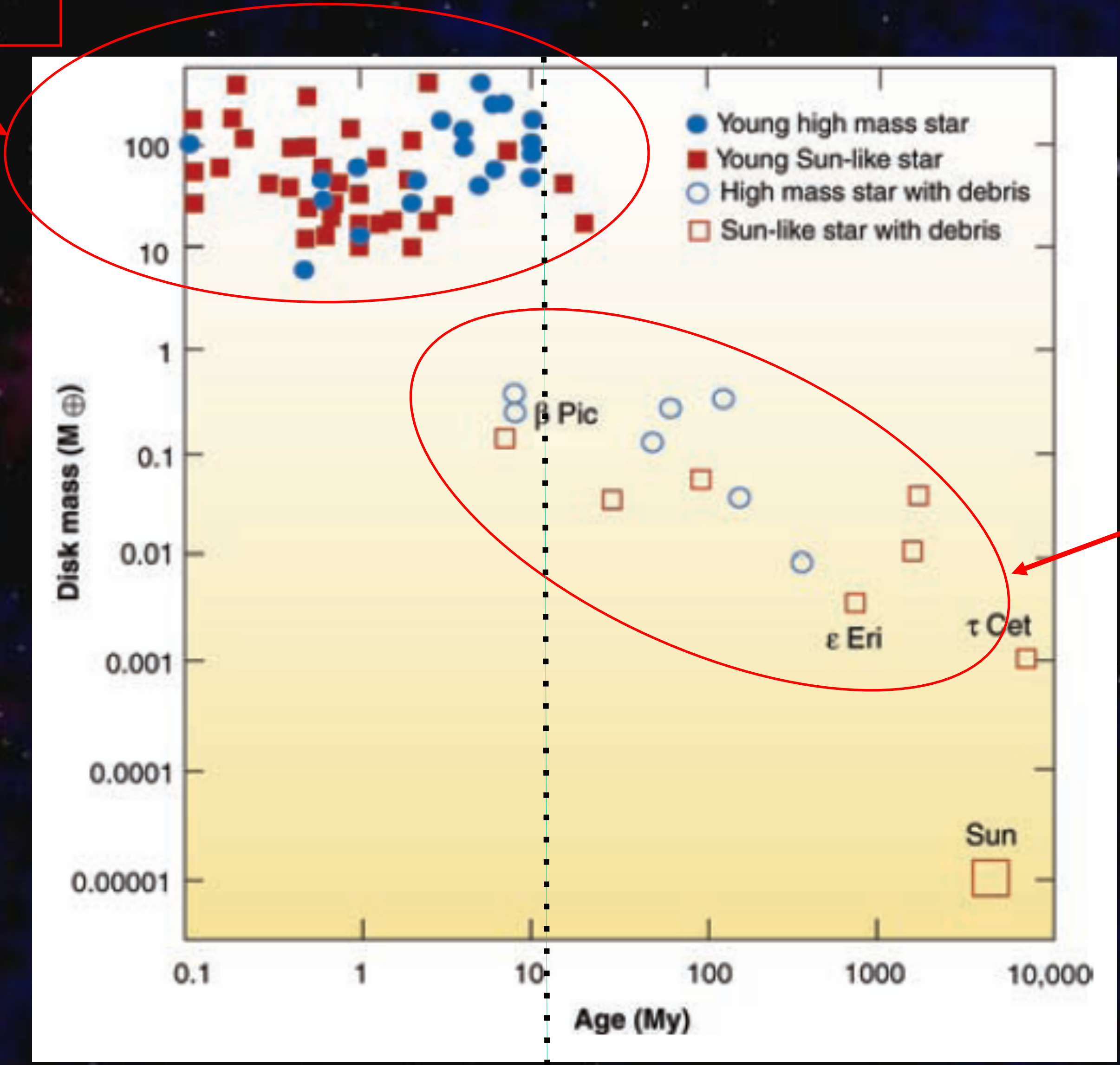
Class II: $M_d \approx 0.01\ M_\odot$ lifetime $\approx 10^6$ yrs

Class III: $M_d < 0.01\ M_\odot$ lifetime $\approx 10^7$ yrs $R \approx 100$ AU

(*Remember:* : $M_{\text{initial Solar-System}} > 0.03\ M_\odot$)

« protoplanetary » discs

Statistics of all detected extrasolar discs (Greaves, 2005)

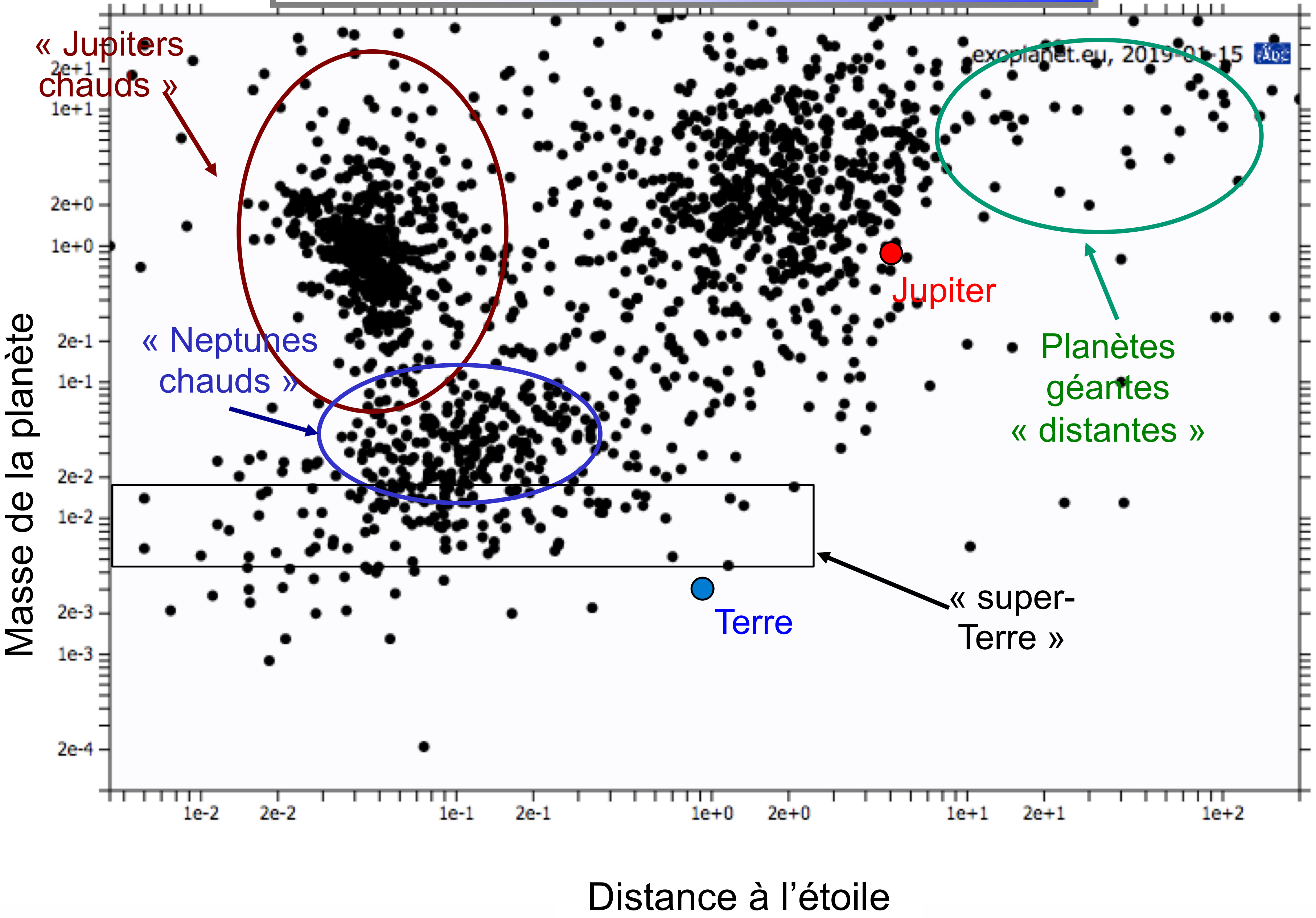


Debris discs

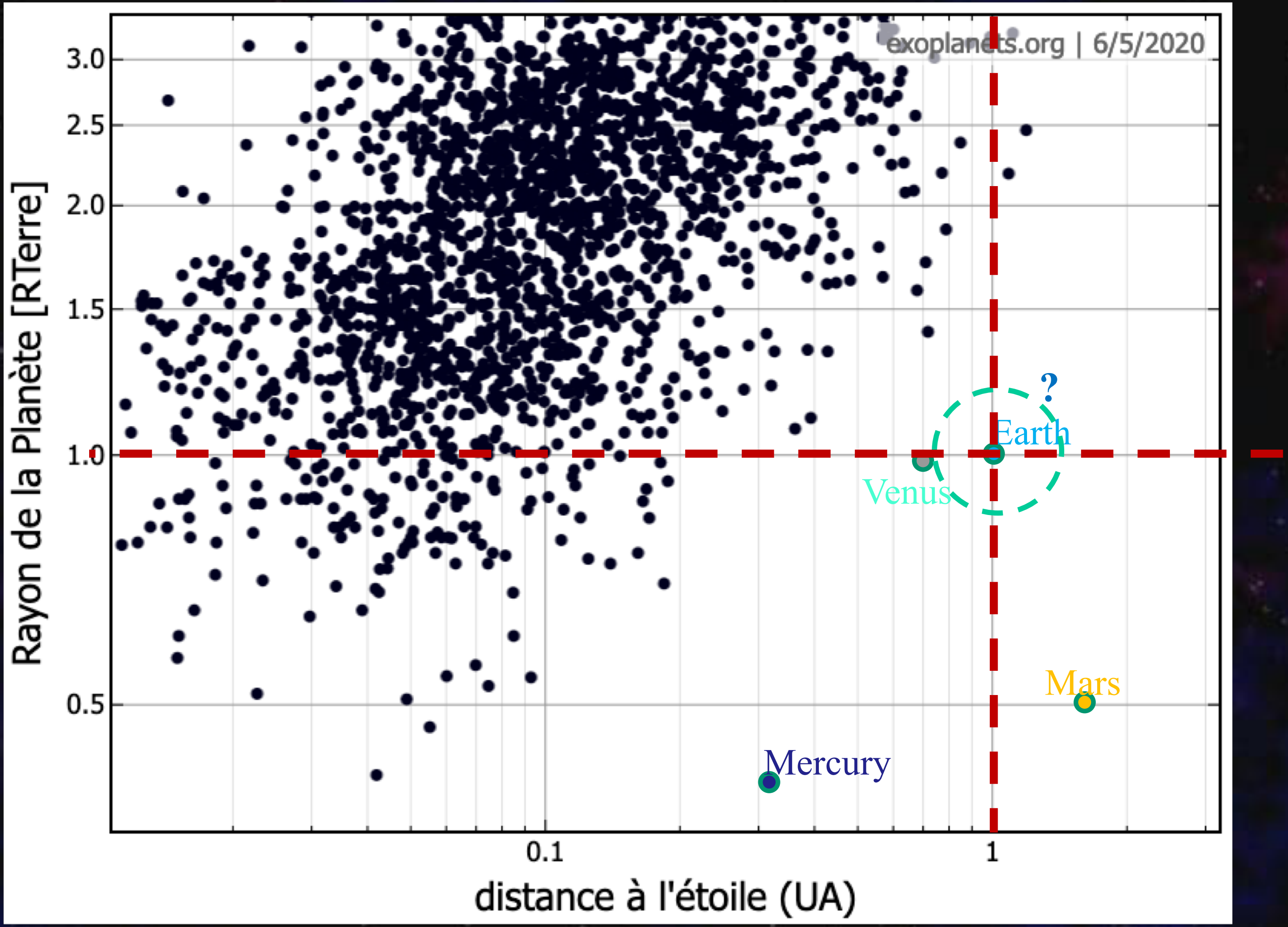
Massive primordial gas discs « disappear » after ≈10^7 years:

Maximum time to form giant gaseous planets

Over 4000 exoplanets!



terrestrial exoplanets



the “standard” scenario of planet formation

- 1751/86 Kant & Laplace
- 1969 Safronov
- 1978 Greenberg
- 1989 Wetherill & Stewart
- 1996 Pollack et al.
- 1997 Weidenschilling et al.
- 1998 Kokubo&Ida
- ……

in the beginning: a giant molecular cloud

Characteristics of a typical Cloud

$M_c \approx 1\ M_\odot$

$R_c \approx 0.1$ light year

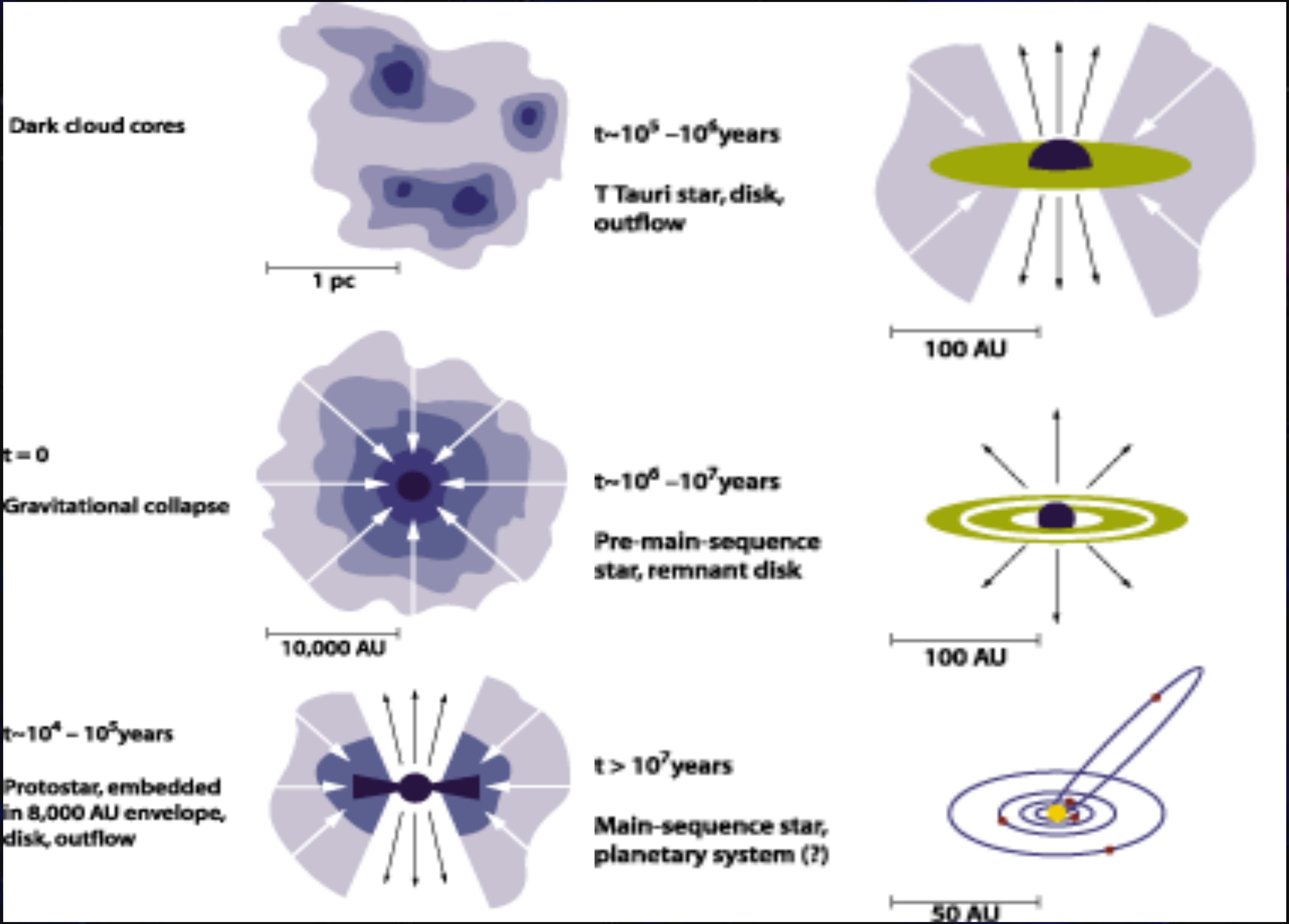
almost isothermal, $T_c \approx 10$ K

molecular density $\approx 10^4$ cm^{-3}

$\rho \alpha\ r^{-2}$ (hydrostatic isothermal spheres)

$\Omega \approx 10^{-14}$ s^{-1}

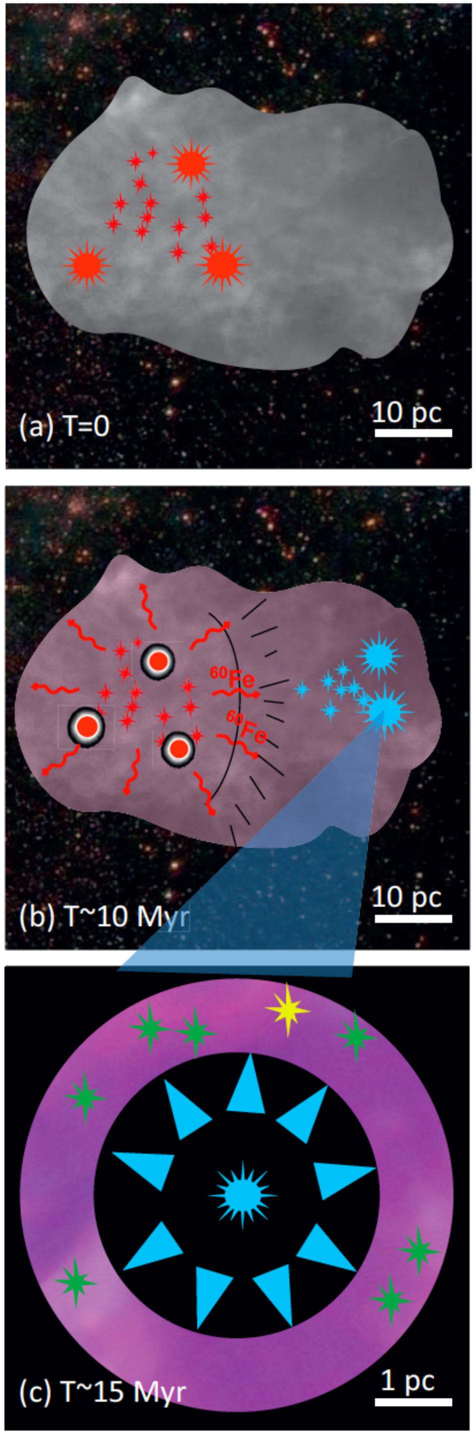
cloud collapse and disc formation



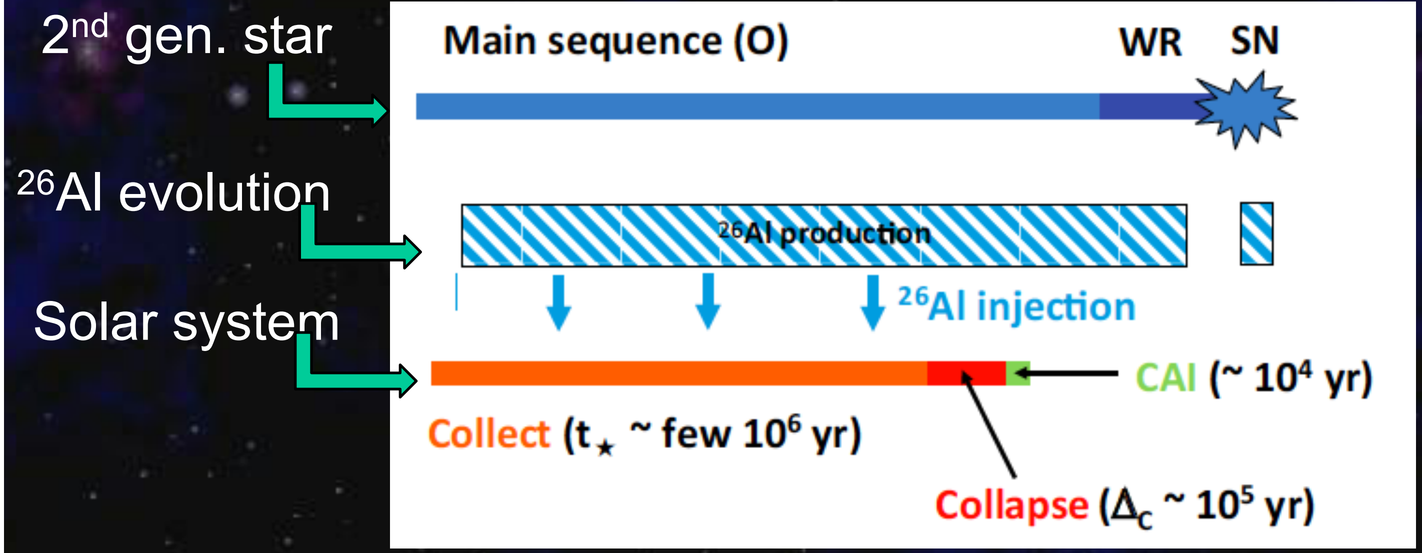
During collapse: cloud, star & disc co-exist!

A possible scenario to explain the ^{26}Al and ^{60}Fe enrichment in the early stages

(Gounelle et al., 2012)



timeline



2^{nd} gen. star

Main sequence (O)

WR

SN

^{26}Al evolution

^{26}Al production

^{26}Al injection

Solar system

Collect ($t_\star$ ~ few 10^6 yr)

Collapse (Δ_c ~ 10^5 yr)

CAI (~ 10^4 yr)

Global simulation of stellar formation

UK Astrophysical Fluids Facility

Stars are born in groups!

Matthew Bate

angular momentum transport: why?

- To transport most of ***J*** outward

  98% of ***J*** is in the planets

- To allow mass accretion towards the central proto-star

  otherwise direct cloud-collapse would be halted *before* star formation

  $$F_{centri.} = F_{grav} \quad \textit{for} \quad R = 2/5\, R_{Mercury}$$

  outward ***J*** flux ⇔ inward mass flux

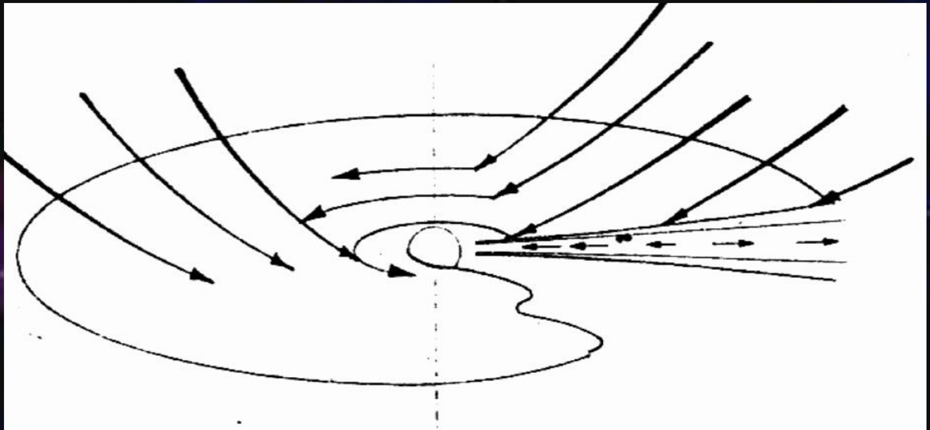
- Heat source

- Rapid dispersion of the disc ($<10^7$ yrs)

possible mechanisms for *J* transport

- Shear Turbulence
- Magnetic Winds
- Spiral Waves triggered by a companion
- Self-Gravitating Spiral-Waves
- Spiral Shocks
- One Armed Spiral, eccentric instabilities
- ….

structure of an accretion disc



- Mass

$$0.03\,M_{\odot} < M < 0.3\,M_{\odot}$$

M.M.S.N

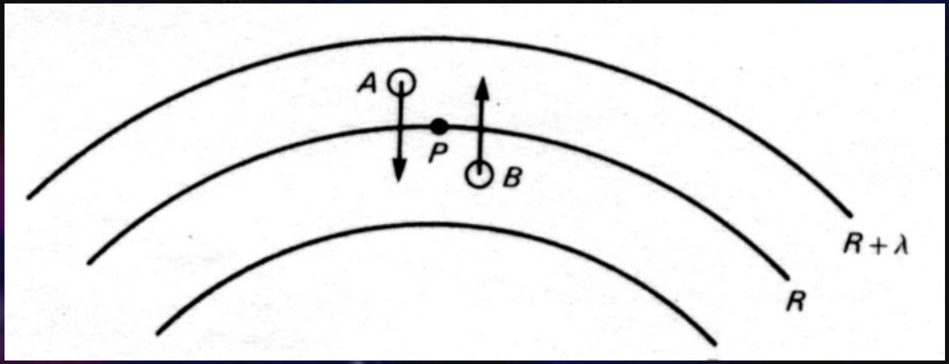
Limit for gravitational instabilities

- Density profile

$$\sigma \propto R^{-p} \quad \textit{with} \quad 1<p<1.7$$

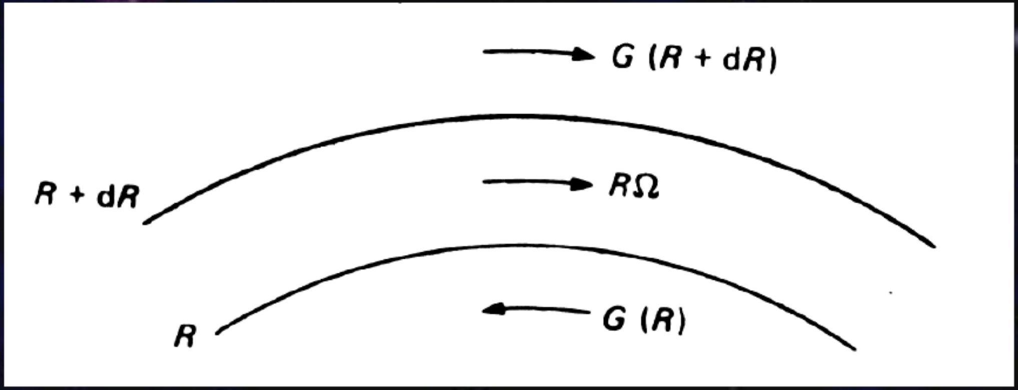
but density increase at the slow line

J transport by viscous torque (1)



$$G(R) = 2\pi \, R \upsilon \, \Sigma R^2 \, \frac{d\Omega}{dR}$$

with $\nu \approx \lambda v_{turb}$



G <0 if Ω decreases outwards (for ex:Keplerian discs)

↓

The inner parts lose angular momentum to the outer ones

J transport by viscous torque (2)

Mass+*J* conservation give:

$$R\Sigma \frac{\partial\left(R^2\Omega\right)}{\partial R} v_R = \frac{1}{2\pi}\frac{\partial G}{\partial R}$$

For a Keplerian stationary disc

$$v_R = -\frac{3}{\Sigma R^{1/2}}\frac{\partial}{\partial R}\left(\nu \Sigma R^{1/2}\right)$$

We can *assume*

$\nu \approx \alpha . c_s H$

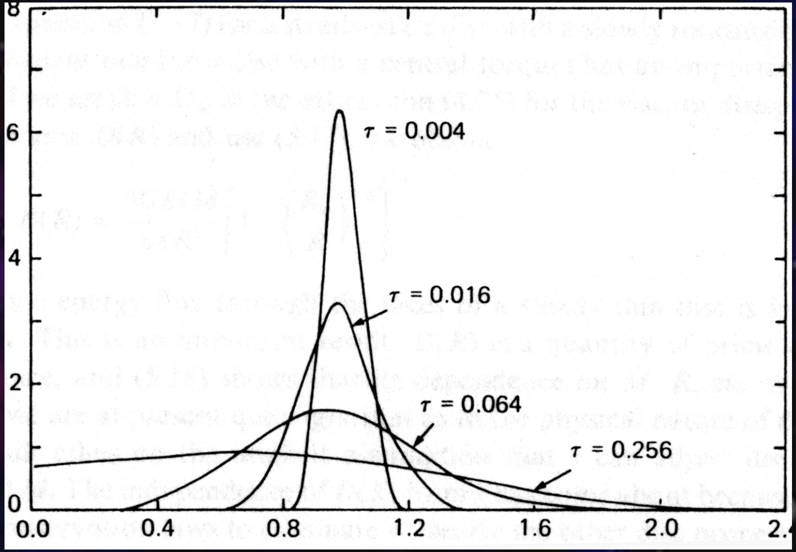
α depends on the source mechanism for turbulence

$10^{-10} < \alpha < 100$

pure molecular viscosity *Self-Gravitating Disc*

$\alpha = 0.005$ for shear turbulence

J transport by viscous torque (3)



$$v_R \approx \frac{3\nu}{R_0}\left(\frac{R_0}{4R} + 2\frac{R}{R_0}\frac{t_{visc}}{t} - 2\frac{t_{visc}}{t}\right) \quad \mathit{for} \quad 2\frac{R}{R_0} >> \frac{t}{t_{visc}}$$

the outer parts move outwards carrying ***J***
($t_{visc} = R/\nu R$)

$$v_R \approx -\frac{3\nu}{R_0}\left(\frac{1}{2}\frac{R_0}{R} - 2\frac{R}{R_0}\frac{t_{visc}}{t}\right) \quad \mathit{for} \quad 2\frac{R}{R_0} << \frac{t}{t_{visc}}$$

the inner parts move inwards

The limit radius between inward and ouward flows moves outward

At $t >> t_{visc}$:

- Nearly all ***J*** carried to large radii by a small fraction of the mass
- Nearly all initial mass accreted on the central Star

thermal structure of an accretion disc

- **Accretion releases Heat**

  rate of working of the viscous torque:

$$\Omega \frac{\partial G}{\partial R} dR = \left[\frac{\partial}{\partial R}(G\Omega) - G \frac{\partial \Omega}{\partial R} \right] dR$$

Convection of rotational energy

Heat

- **This Thermal dissipation is the main source of Disc heating**

  other Sources (Solar radiation, Back-heating from circumstellar material) are less efficient

- ***T*** increases during the Collapse of the Cloud and may > 1000 K

thermal structure of an accretion disc

- ***Effective* Temperature profile if all energy is released by *accretion* and *locally* dissipated**

  Effective temperature:

  $T_E \propto R^{-3/4}$

  Radiated energy distribution:

  $\lambda F_\lambda \propto \lambda^{-4/3}$

  For **observed T Tauri**: $\lambda F_\lambda \propto \lambda^{-N}$, with $0<N<4/3$

- ***Physical* Temperature in the Disc**

  Radiative vertical energy transport:

  Main parameter: **Opacity** of the Disc

  For an optically thick disc:

  $$\tau = \int_0^\infty \rho\kappa \, dz = \bar{\kappa}\Sigma/2$$

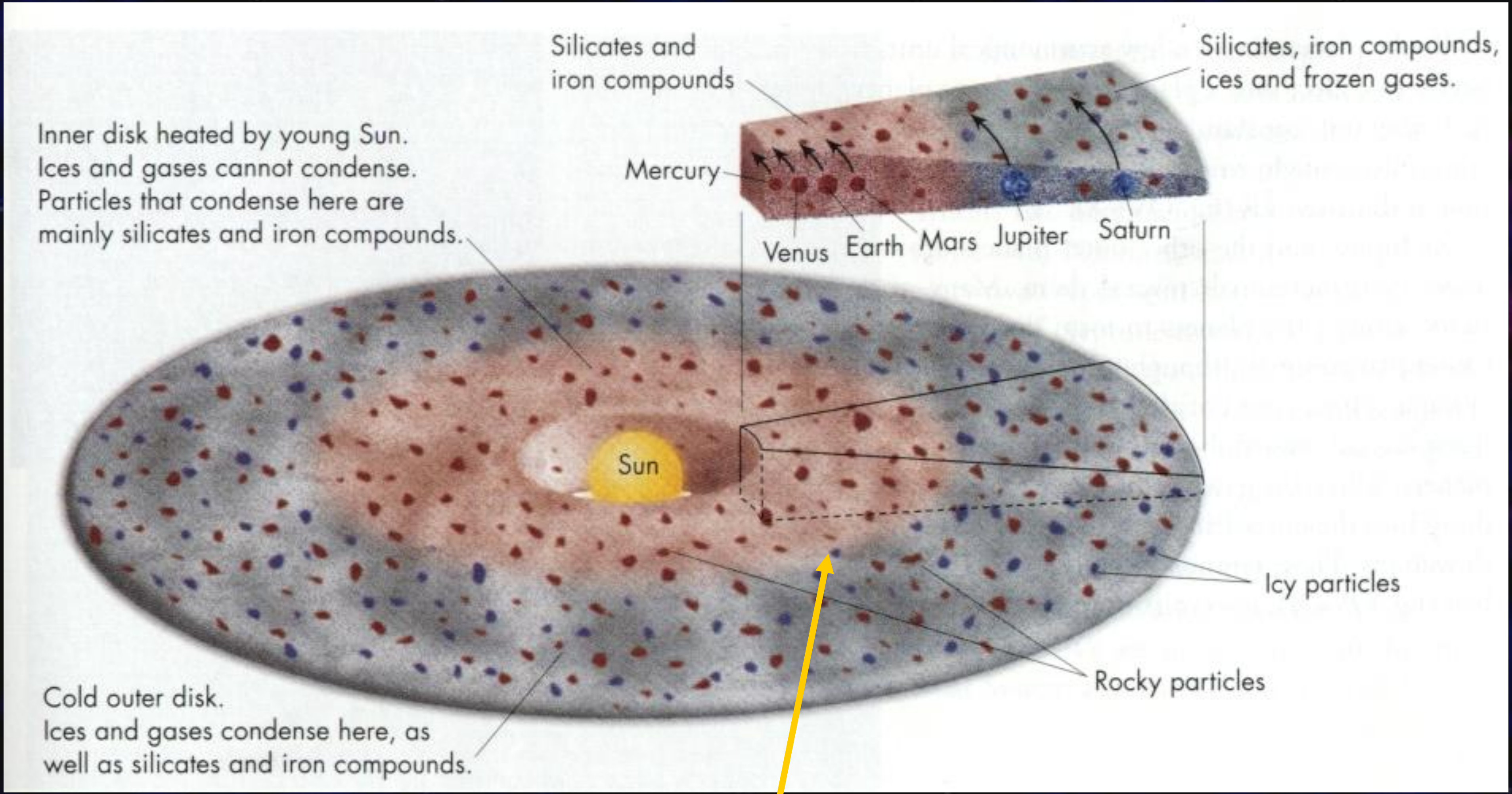
  $T_m = T_E (\eta\tau)^{1/4}$

  With

κ = 10^{-4} cm^{2}g^{-1} for gas T > 1350 K
κ = 5 cm^{2}g^{-1} for silicate grains 160 < T < 1350 K
κ = 5 (T/160)^2 cm^{2}g^{-1} for water ice T < 160 K

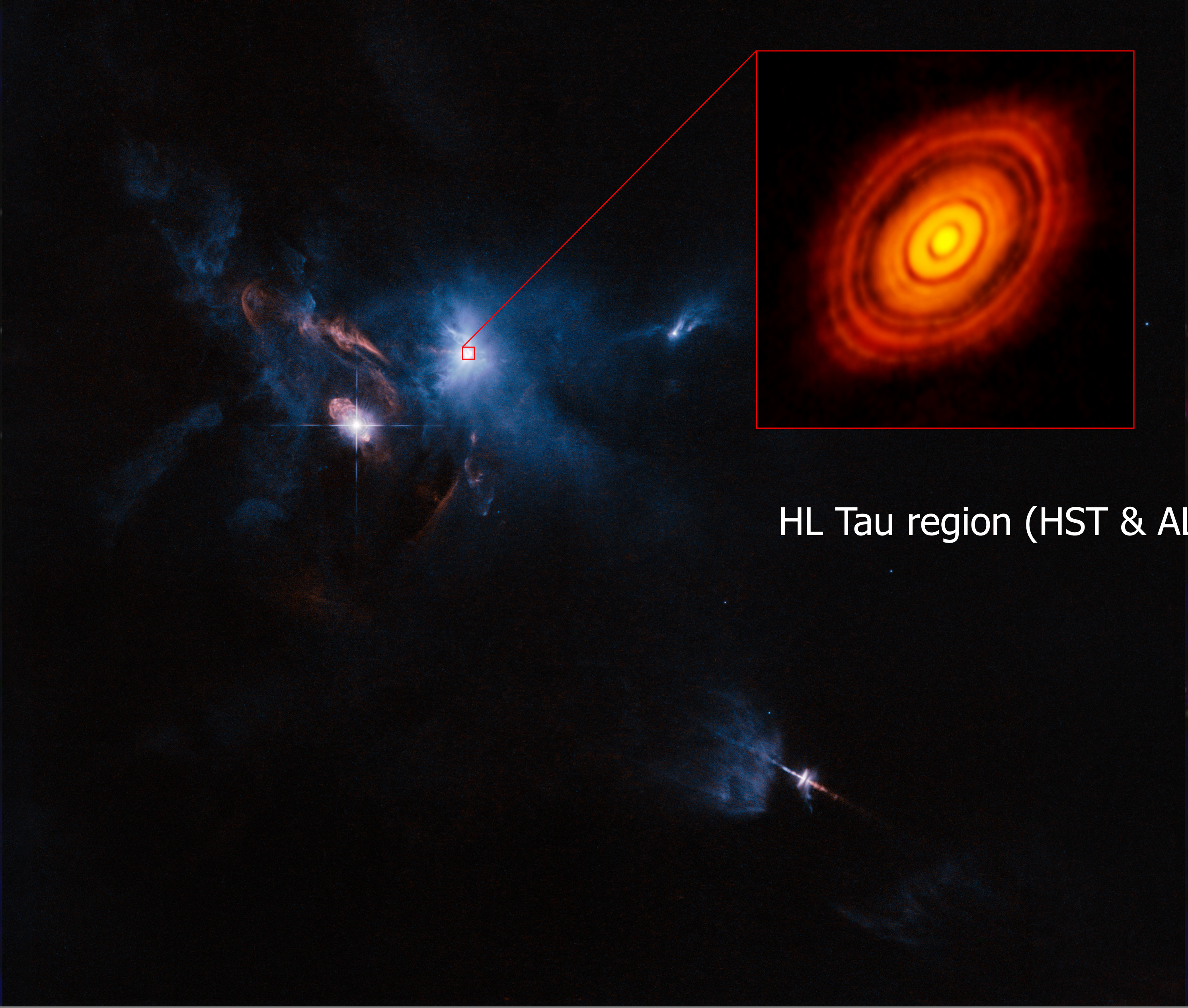
κ = 10^{-4}	cm^{2}g^{-1} for gas	T > 1350 K
κ = 5	for silicate grains	160 < T < 1350 K
κ = 5 (T/160)2	cm2g-1 for water ice	T < 160 K

Grain condensation in the disc



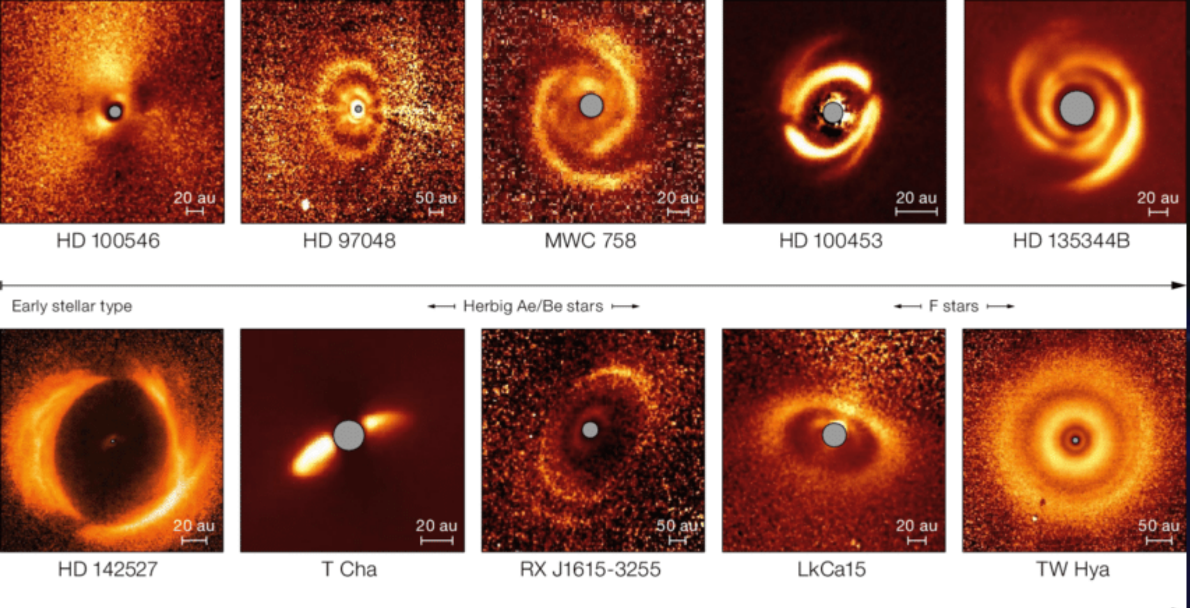
Fundamental limit 1 : T ~ 1350° K condensation of silicates

Fundamental limit 2: T ~ 160° K condensation of water-ice

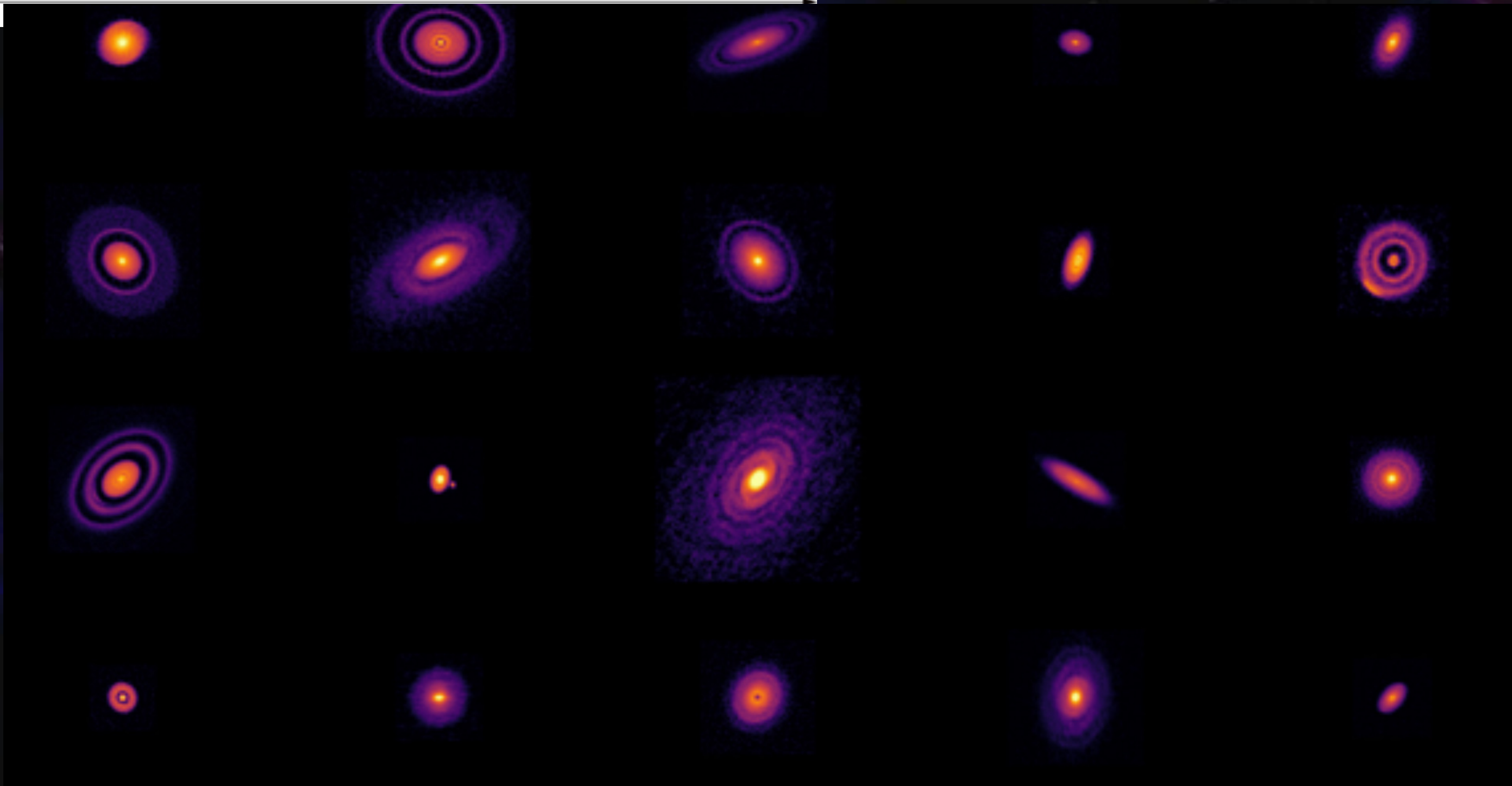


HL Tau region (HST & ALMA)

Protoplanetary discs ***exist***

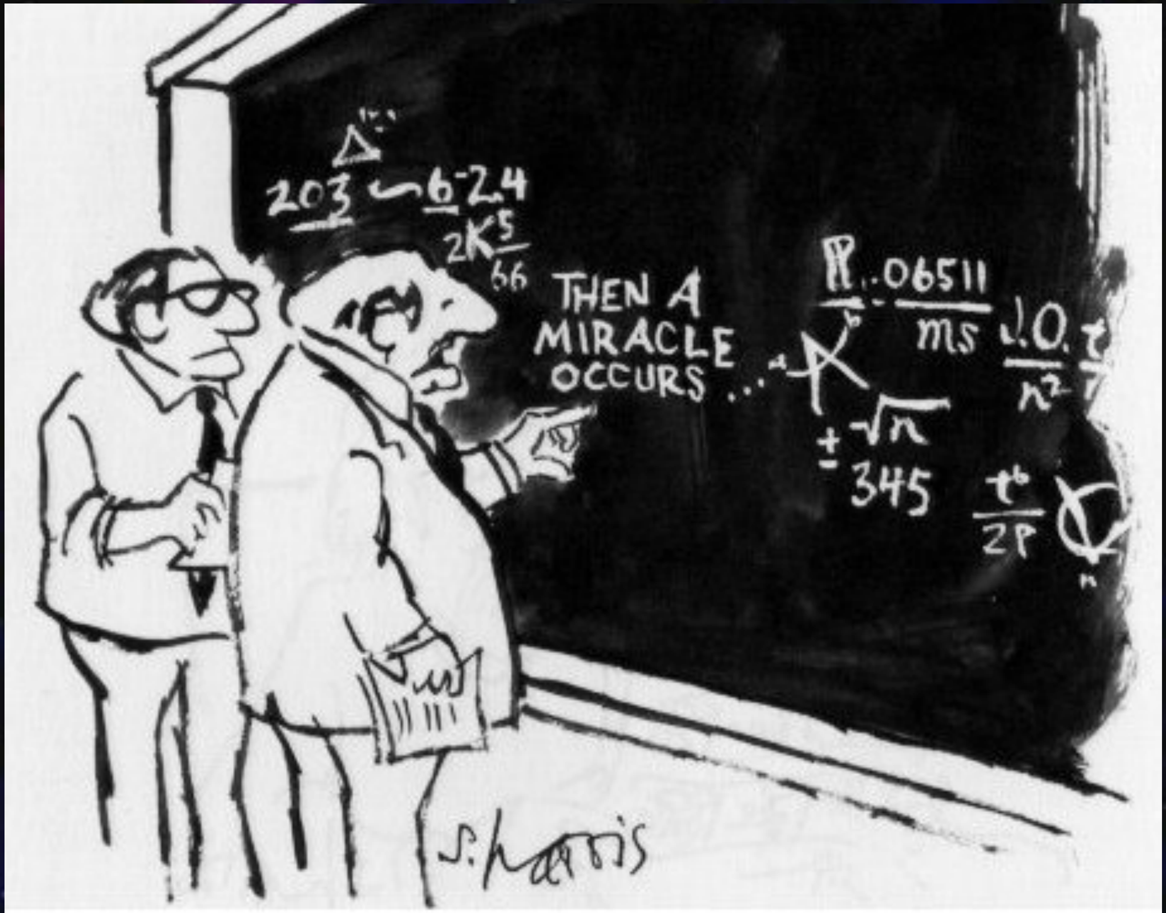


Discs imaged in the optical by the SPHERE instrument



Discs imaged in radio by ALMA

from grains to planetesimals…a miracle occurs

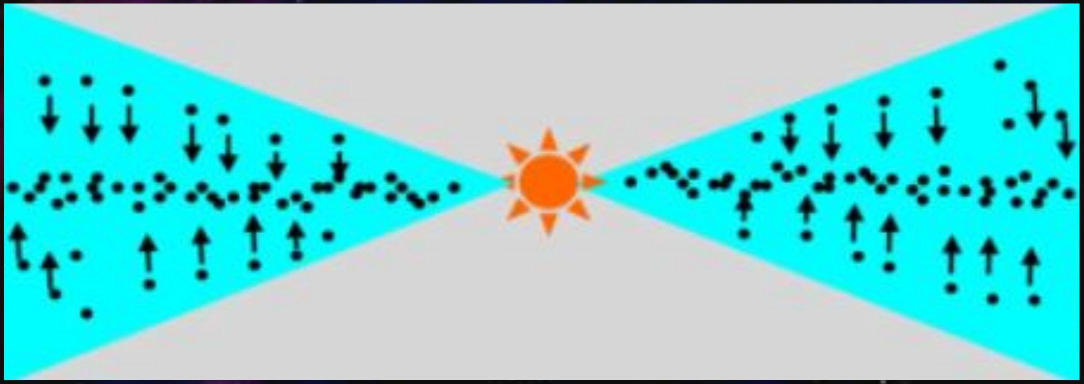


"I think you should be more explicit here in step two."

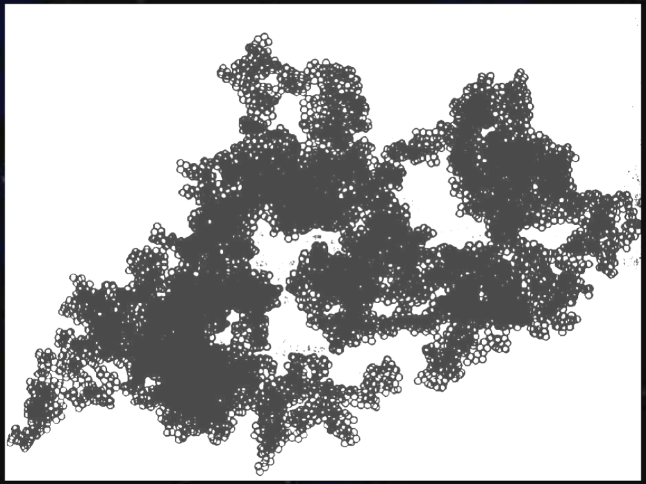
from *What's so Funny about Science?* by Sidney Harris (1977)

formation of planetesimals from dust

- In a « quiet » disc: gravitational instabilities



- In a turbulent disc: mutual sticking



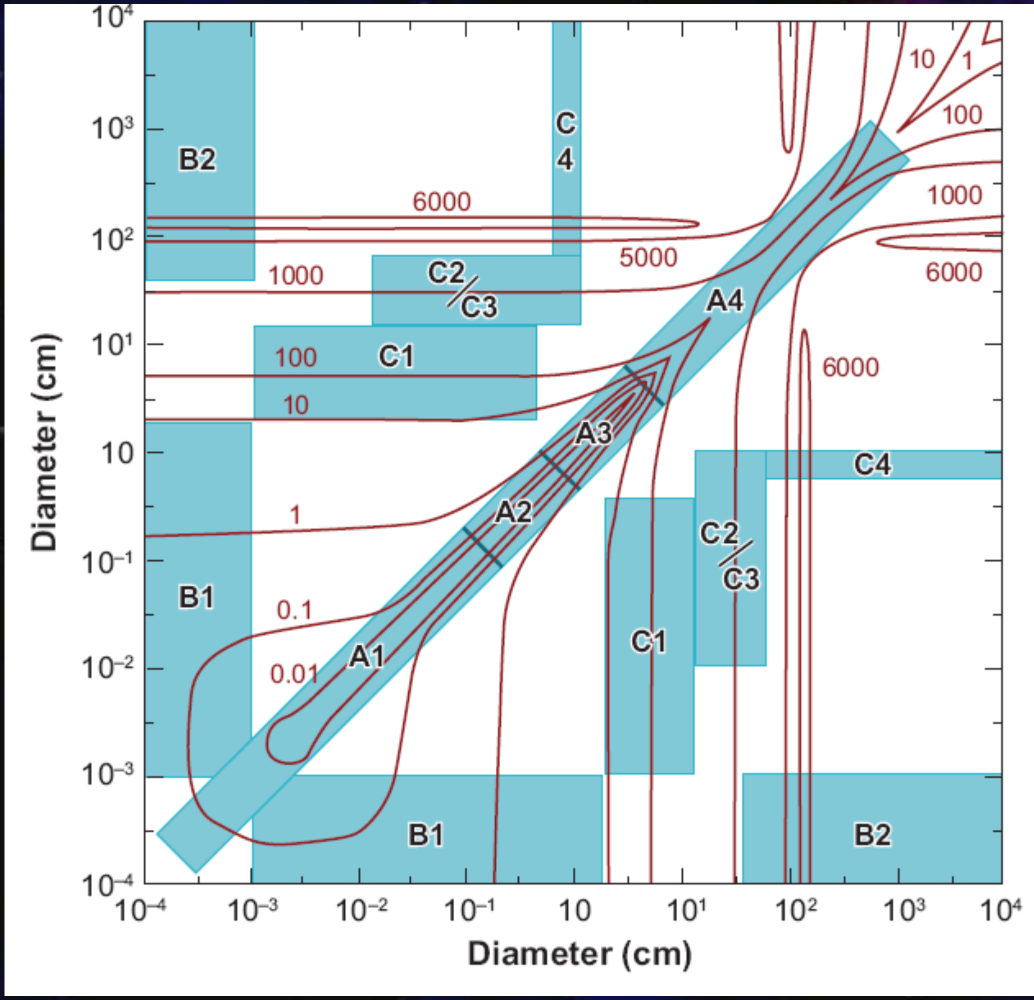
→ In any case: formation of~ 1 km objects

in a turbulent disc: growth by mutual sticking

- "sticking" by dipole-dipole interaction between molecules within the grains (Van der Wals)

- Sticking if $v_{coll} < v_{limit} \sim$ 1-5m/s

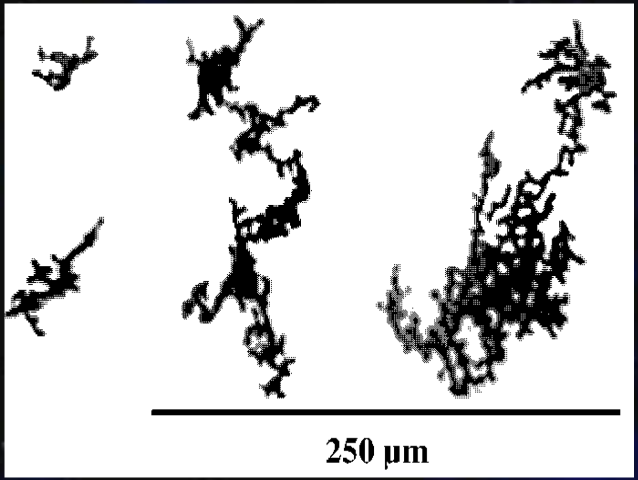
- But, in a protoplanetary disc, v_{coll} can be very high: gas friction, turbulence, etc...



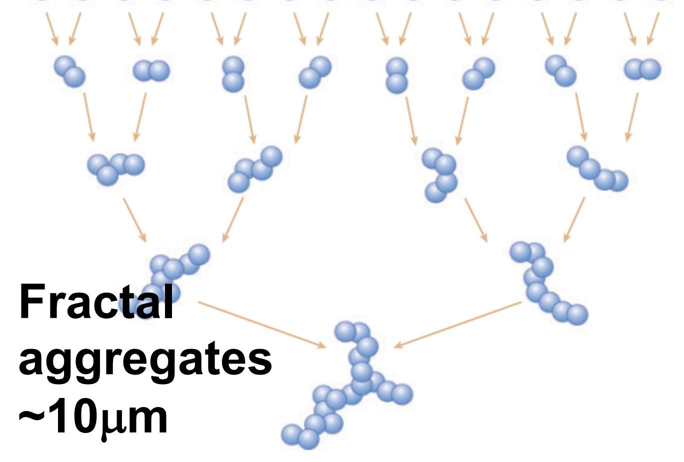
Laboratory experiments

(*Langowski et al., 2007*)

Or numerical

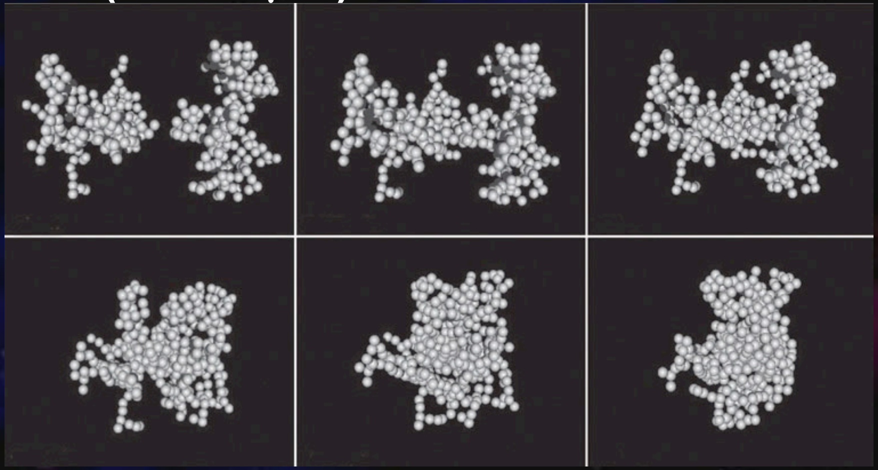


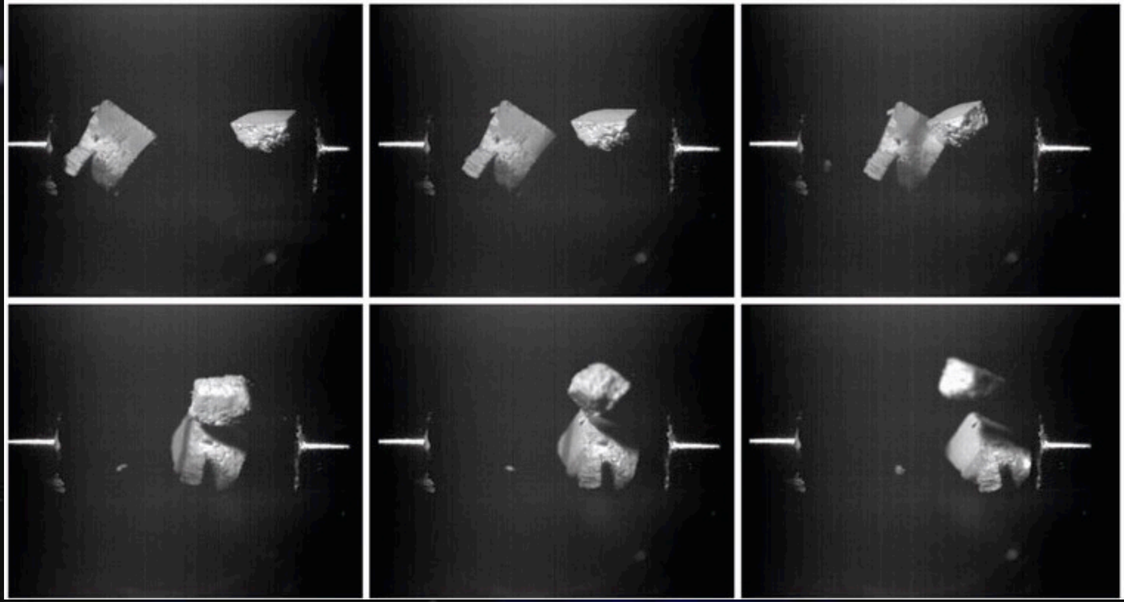
Initial grains : 0.1-1 µm.



Fractal aggregates ~10µm

Compacting of fractal aggragates (50-500µm)

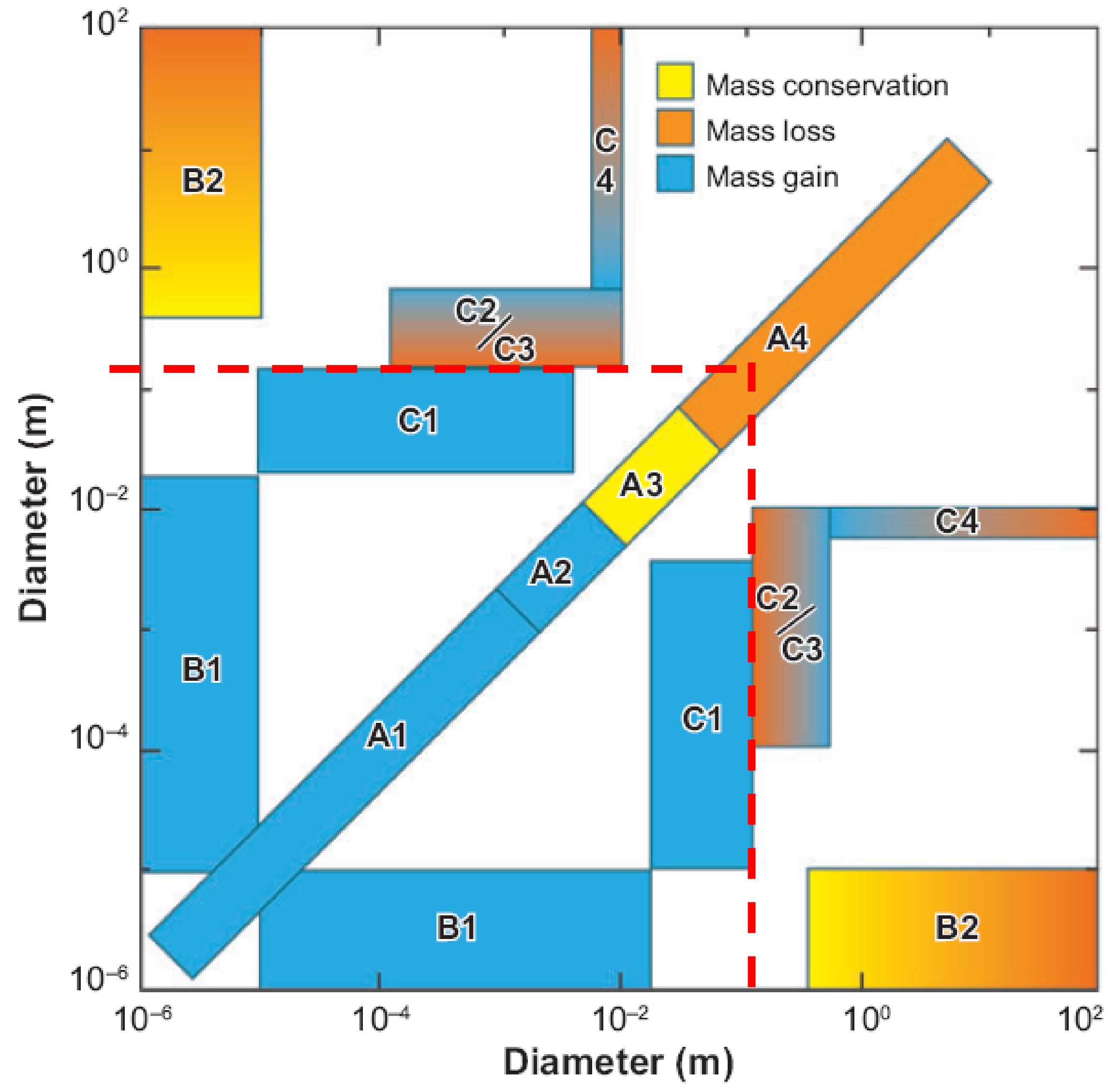




rebound between porous aggregates

fragmentation if r>10cm

SUMMARY



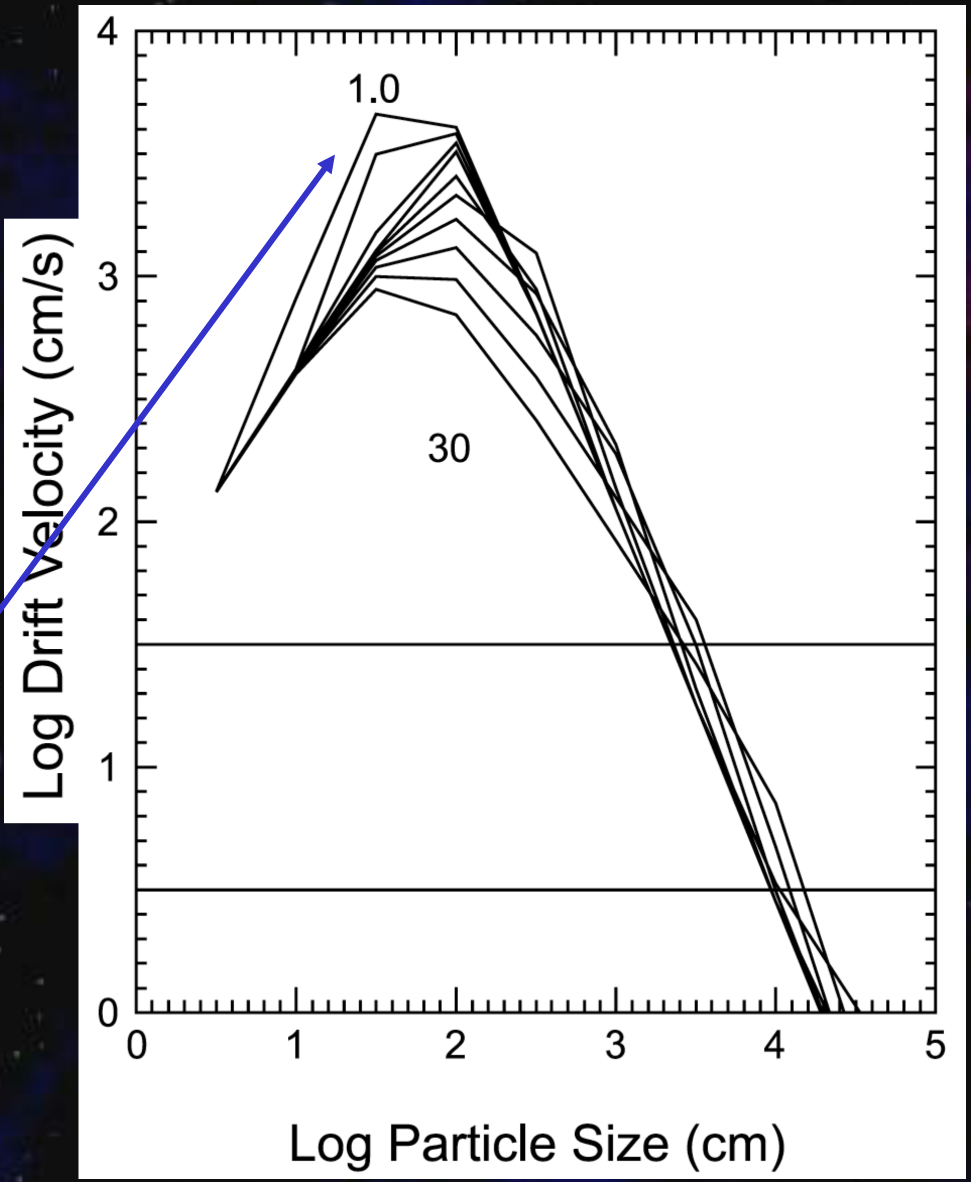
No growth possible for bodies > 10cm

The “meter barrier”

2 problems

- Bodies >10cm have high-dv impacts that are mostly destructive

- 1m particles are big enough to *decouple from the gas*, but not big enough to don’t care about it => They feel a strong gas drag that makes them drift toward the star in 100-1000 years!



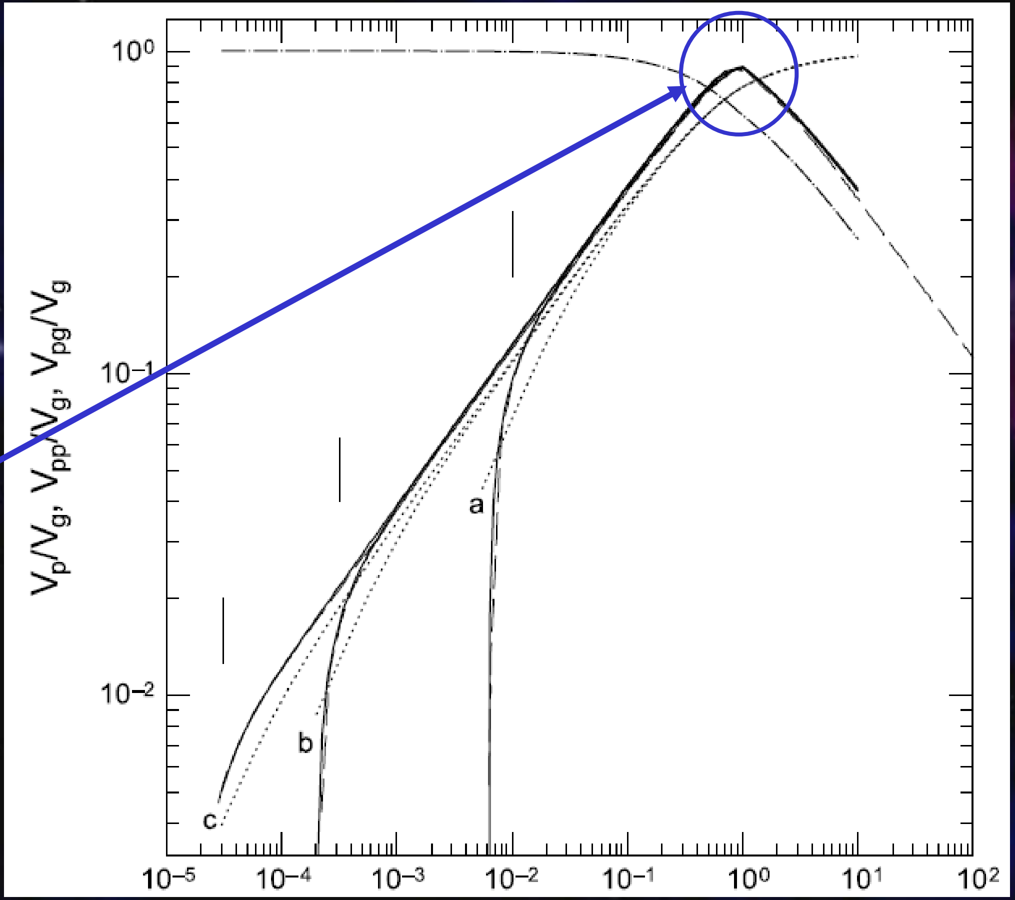
(Cuzzi&Weidenschilling, 2005)

growth by sticking

Crucial parameter: **Δv**, imposed by particle/gas interactions.

2 components:
- Δv differential vertical/radial drift
- Δv due to turbulence

- Small grains (μm-cm) are coupled to turbulent eddies of all sizes: Δv~0.1-1cm/s
- Big grains (cm-m) decouple from the gas and turbulence, and Δv_{max}~10-50m/s for 1m bodies



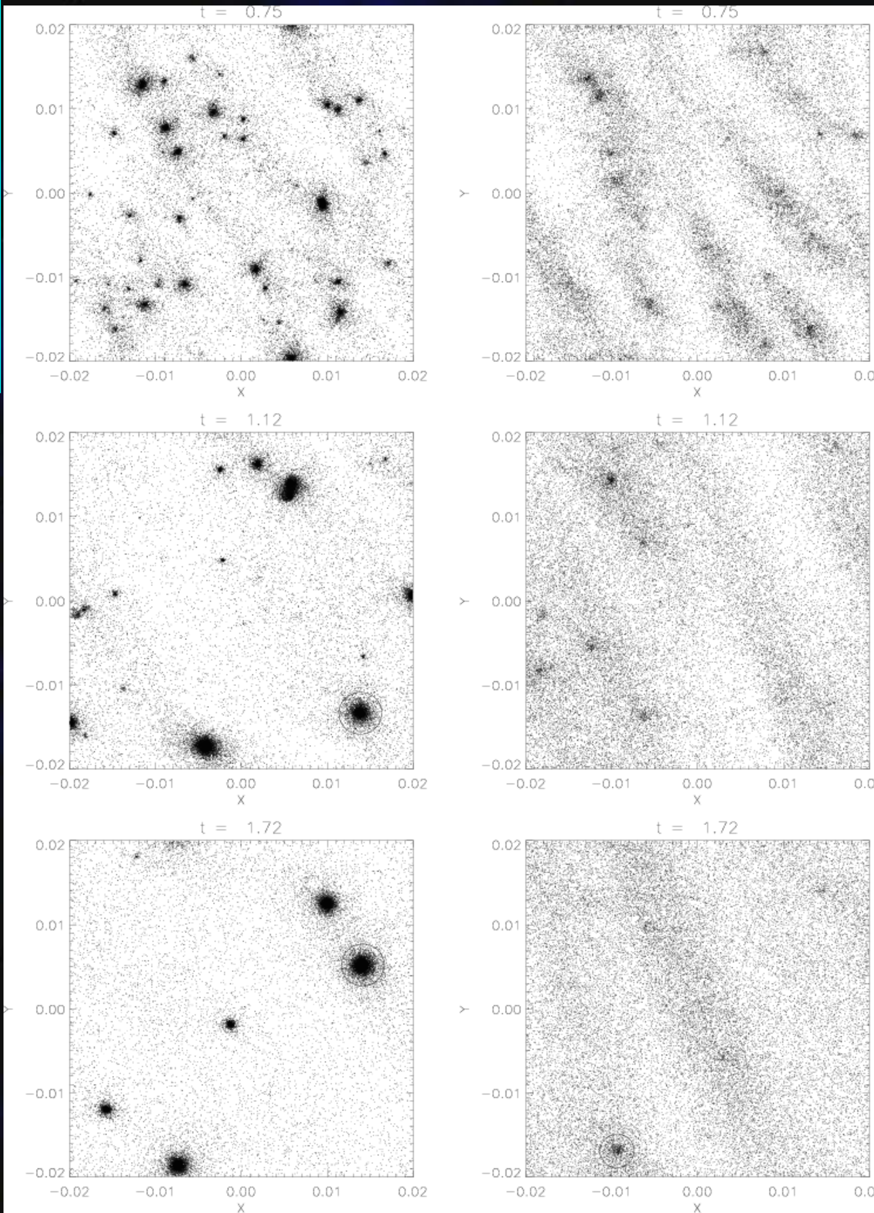
(Cuzzi&Weidenschilling, 2005)

alternative scenario: gravitational instability

if dust is sufficiently concentrated in mid-plane then gravitational instability which occurs when the Toomre parameter Q<1

$Q = \Omega_k c_d / (\pi G \Sigma_d)$

which for typical disks requires dust mass densities $>10^{-7}$ g/cm^3



Good: fragmentation fast (orbital time) and makes km-sized planetesimals

Bad: dust entrains gas causing vertical velocity shear and Kelvin-Helmholtz instability thus turbulence increasing velocity dispersion and stability

Comeback: GI possible if velocity shear doesn't lift all dust eg. if enhanced dust/gas

Ongoing debate: Weidenschilling (2003) said that turbulent stress on particle layer inhibits particle concentrations; Youdin & Chiang (2005) discussed method of concentrating particles due to drag rates…

concurrent scenarios: pros and cons

- gravitational instability

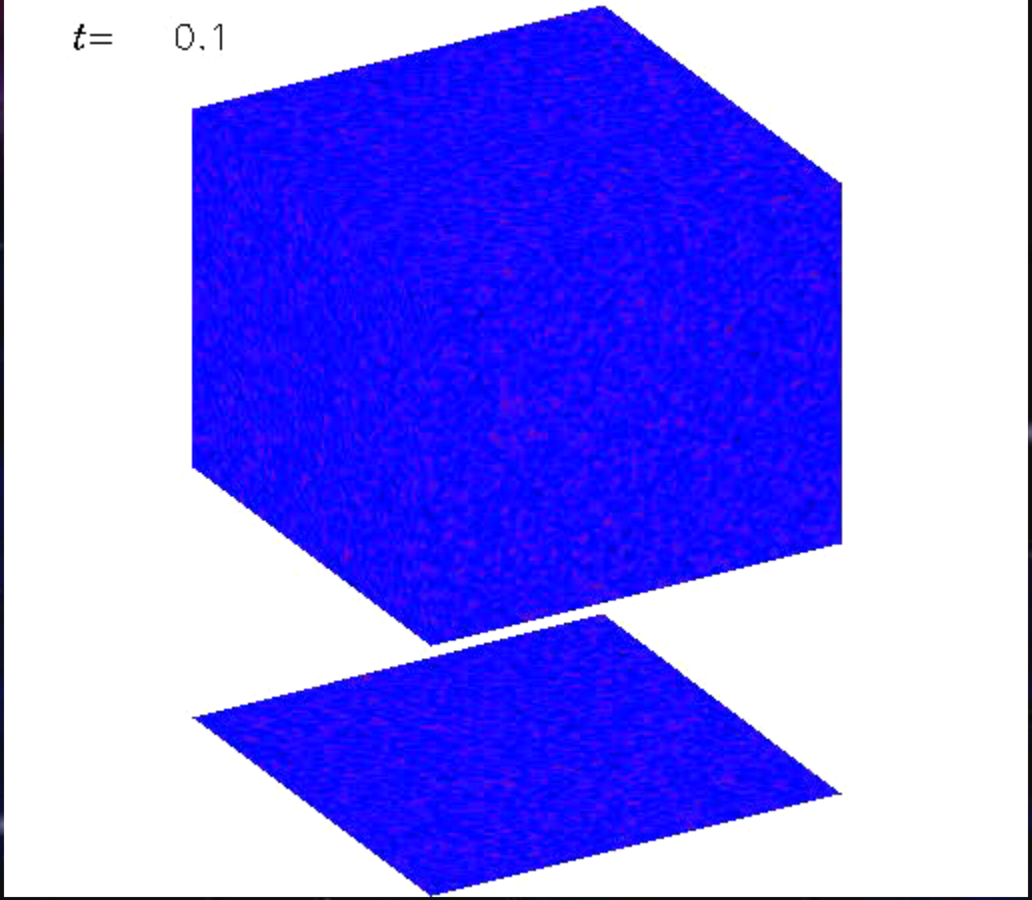
  - Requires unrealitisticaly low turbulence

- Turbulence-induced sticking

  - Particles with 1mm<R<10m might be broken up by dV>10-50m/s

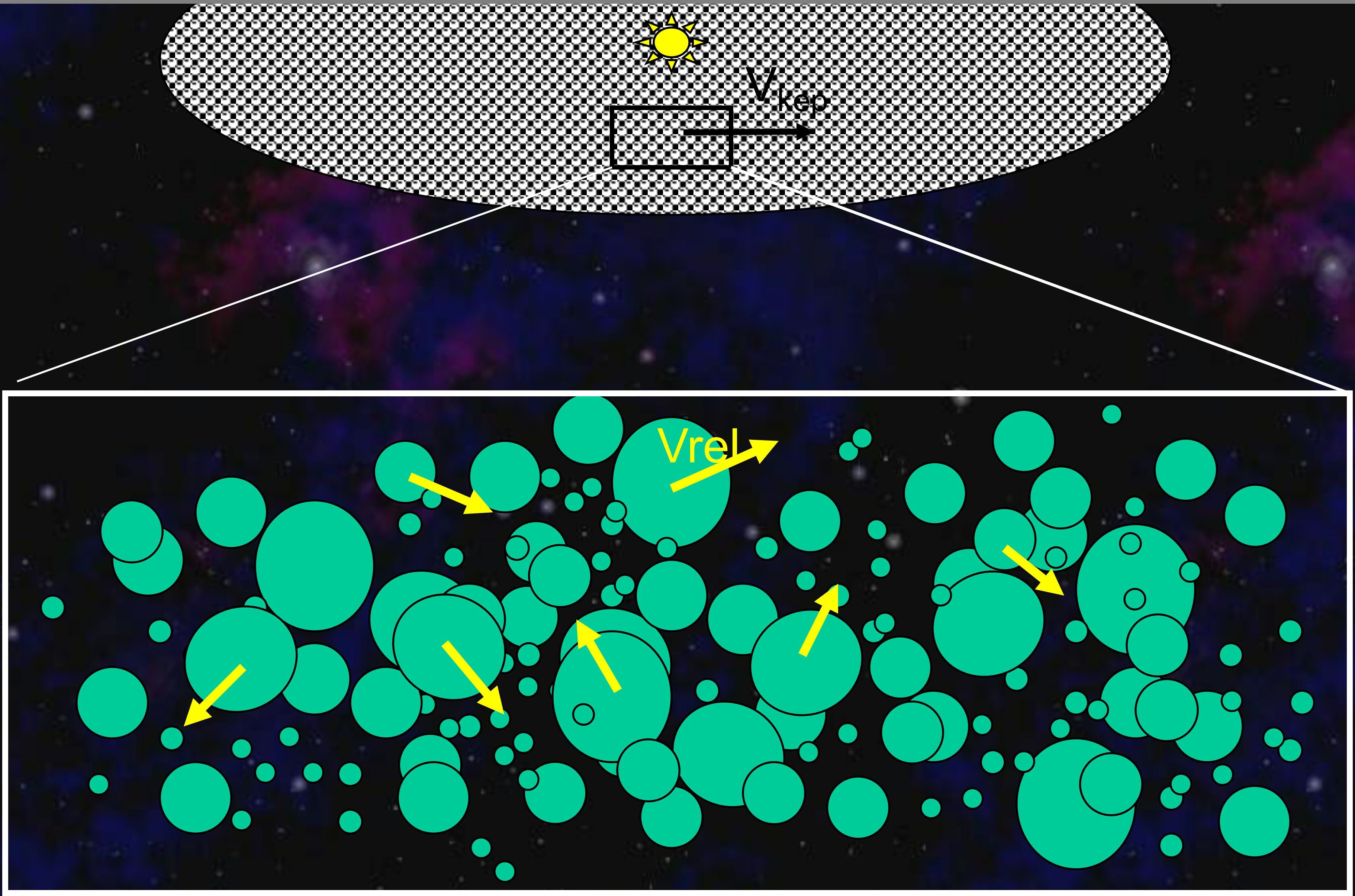
fierce debate going on...

Or.....Direct Formation of planetesimals by Shear instability (?)



Johansen (2007)

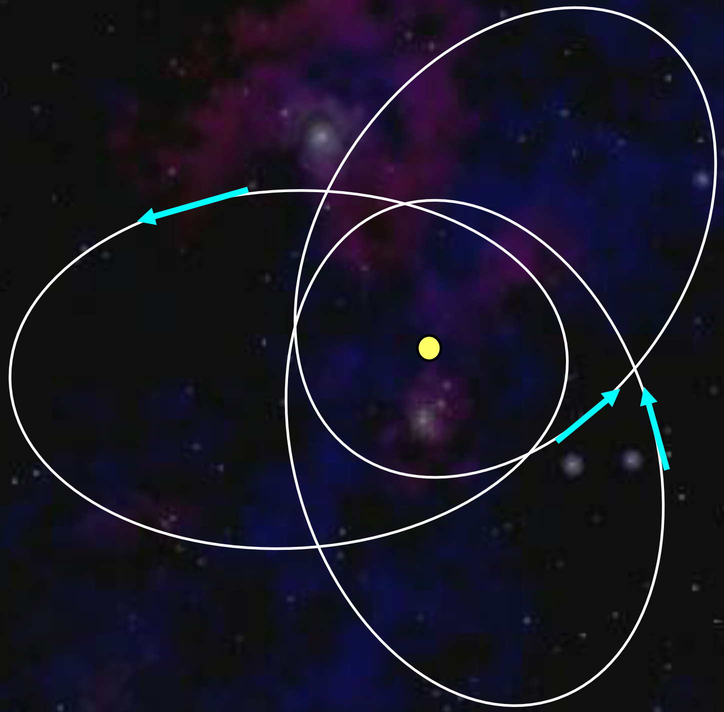
next step: mutual accretion of km planetesimals

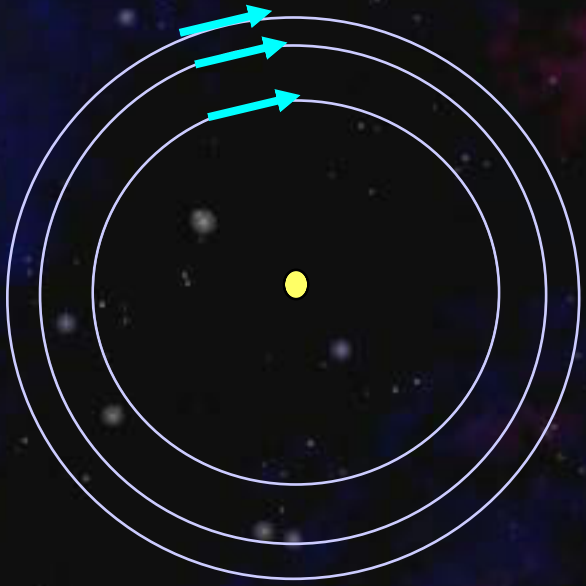


planetesimal accretion: a question of velocity

mutual planetesimal accretion: a tricky situation

Accretion criterion: $dV < c.V_{esc.}$





high-*e* orbits: high encounter rate but fragmentation instead of accretion

low-*e* orbits: low encounter rate but always accretion

physics of a planetesimal disc

Forces Acting

Mutual Gravitational stirring
Dissipative Collisions
Gas drag
External Perturbations? (Giant Planets)

Dynamical state

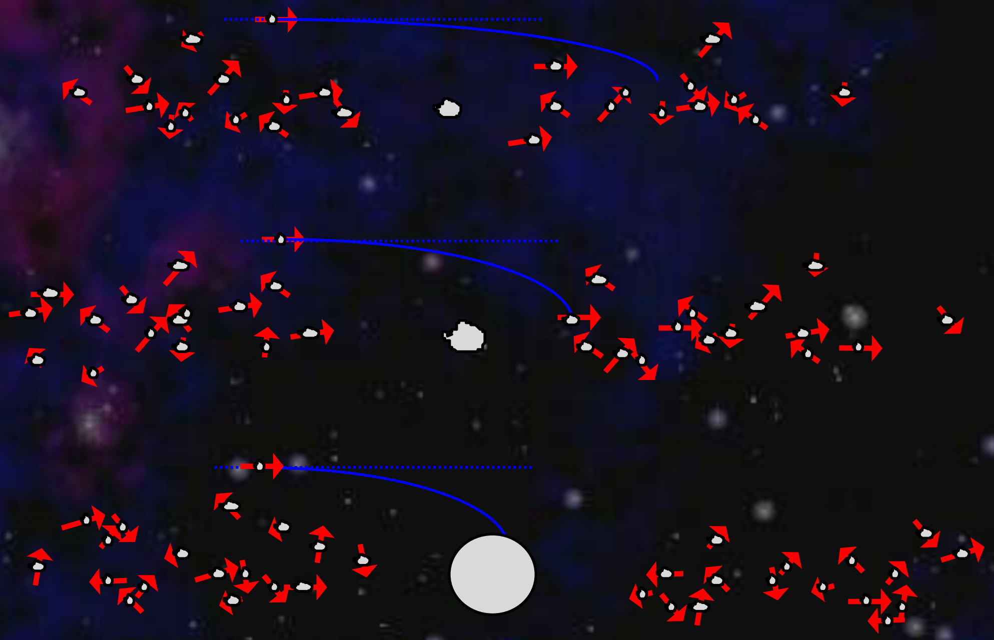
At equilibrium in a *homogeneous* disc:

$$<\Delta v> \approx \beta\, V_{escape}(r)$$

$$\boxed{V_{esc} = \sqrt{\frac{2G(m+m)}{r}} = \sqrt{\frac{8}{3} G \pi \rho . R}} = 1.3\, r_{(km)}\ m.s^{-1}$$

Corresponding to $<e> \approx 2<i> \approx 10^{-4}$ (!!!)

runaway growth



$$\sigma = 2\pi\left(R_1^2 + R_2^2\right)\left[1 + \left(\frac{v_{esc(R1,R2)}}{\Delta v}\right)^2\right]$$

gravitational focusing factor: $(v_{esc(\underline{\mathbf{R}})}/\Delta v)^2$

But if $\Delta v \sim v_{esc(\underline{\mathbf{r}})}$ then things get out of hand…

runaway growth: it is faaaaaast

Accretion rate increases with time

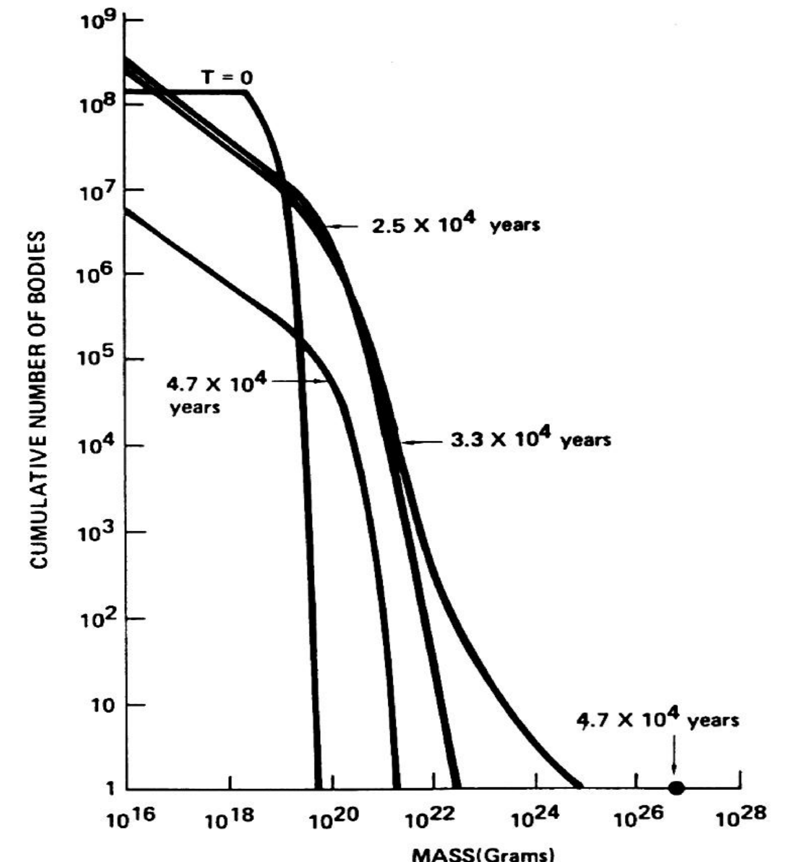
$dR/dt \propto K.(R/\langle r\rangle)^2 \Rightarrow 1/M(dM/dt) \propto M^{1/3}$

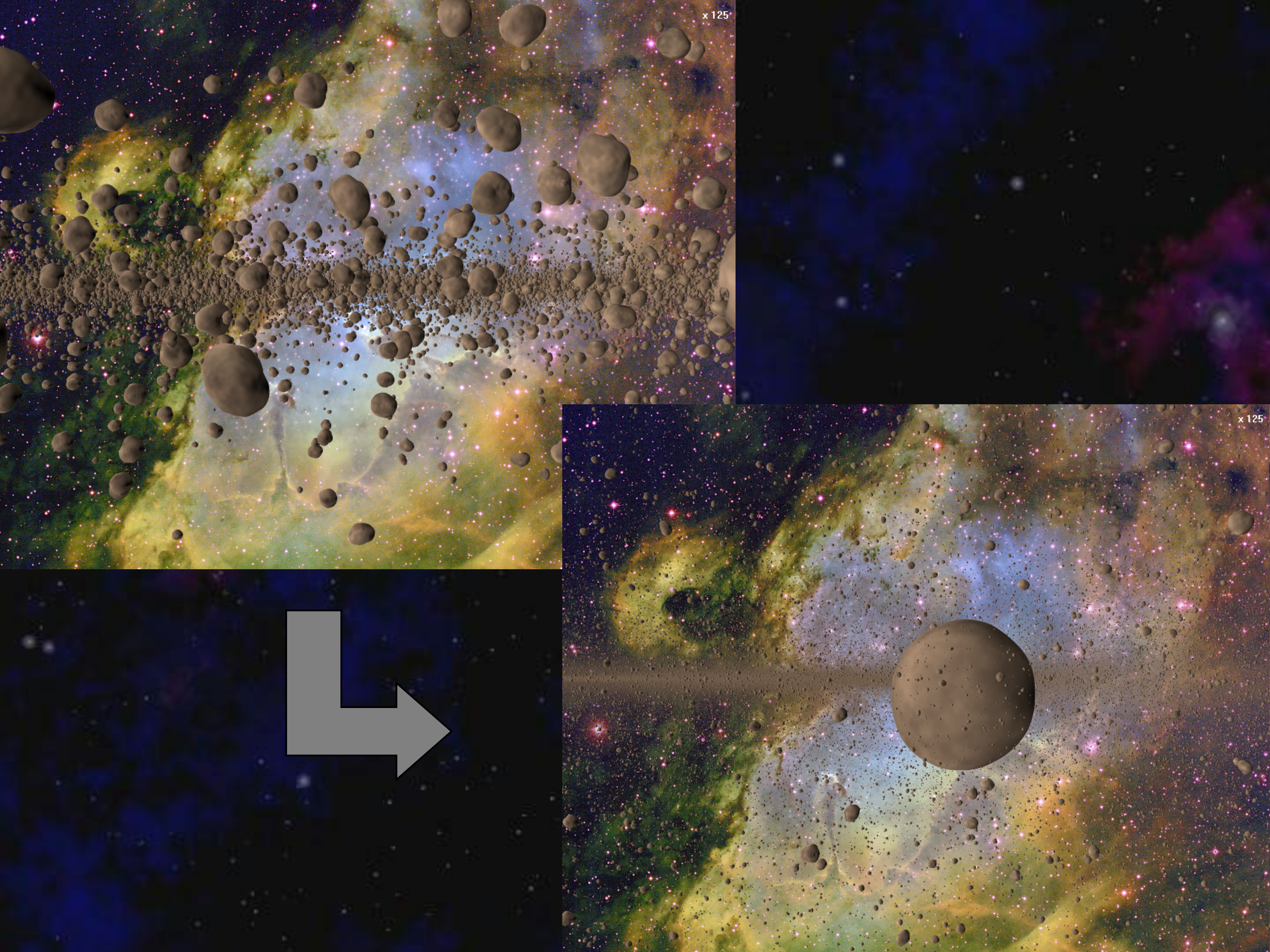
exponential growth of the biggest bodies

getting more and more isolated from the swarm

Size distribution evolution:

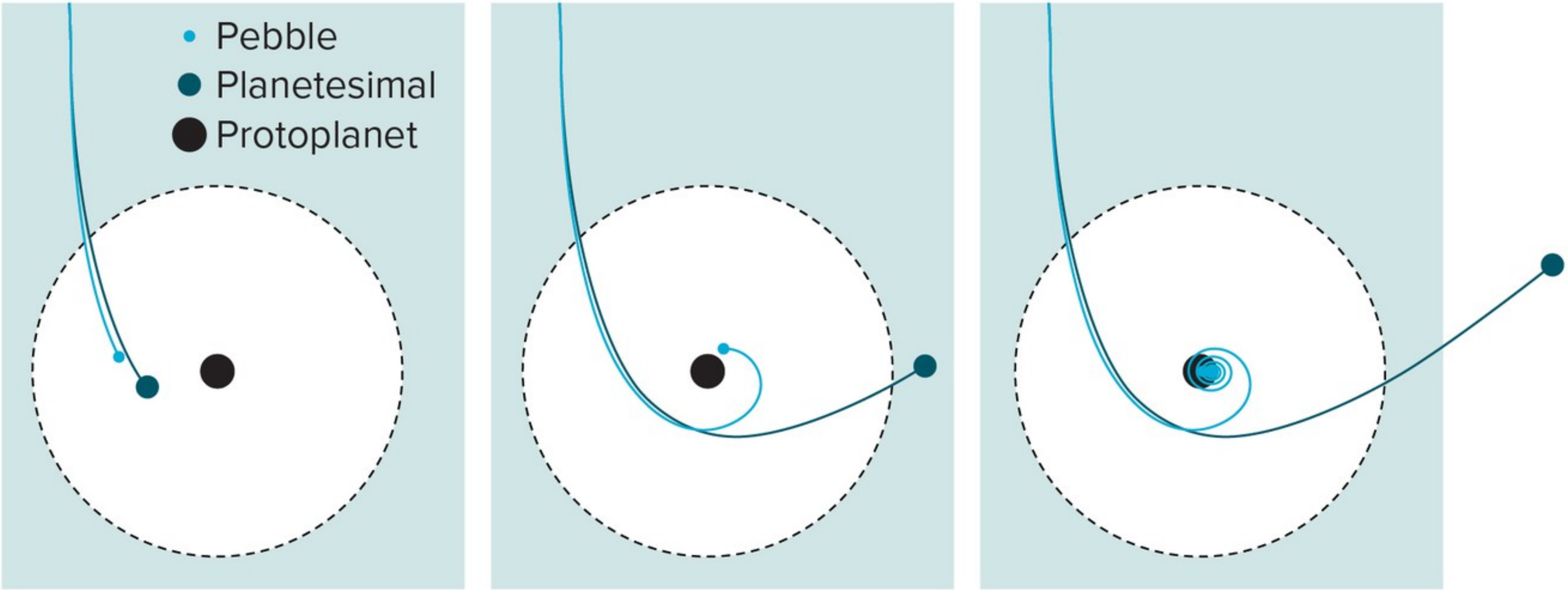
(Wetherill&Stewart, 1993)




x 125
x 125

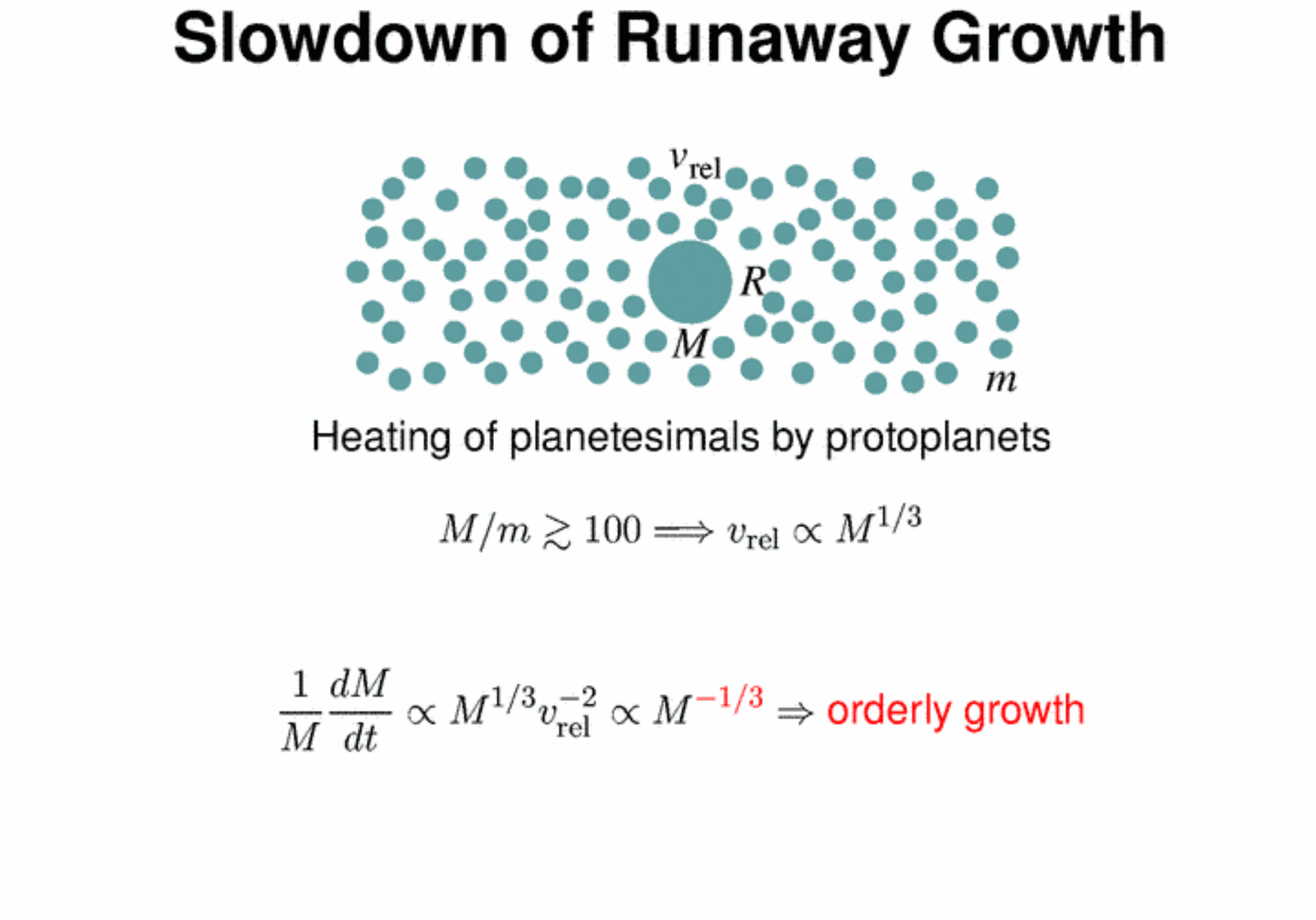
Speeding things up: Pebble accretion

A pebble flying past a protoplanetary body is slowed by friction from surrounding gas as it enters the protoplanet’s gravitational influence (dotted line). That slowdown allows the small pebble to be captured by the protoplanet’s gravity and spiral in for a smash-up, whereas a larger planetesimal just zips by. Over time, many pebbles will coalesce with the protoplanet, allowing it to grow large quickly.



(Lambrecht & Johanssen)

oligarchic growth



Slowdown of Runaway Growth

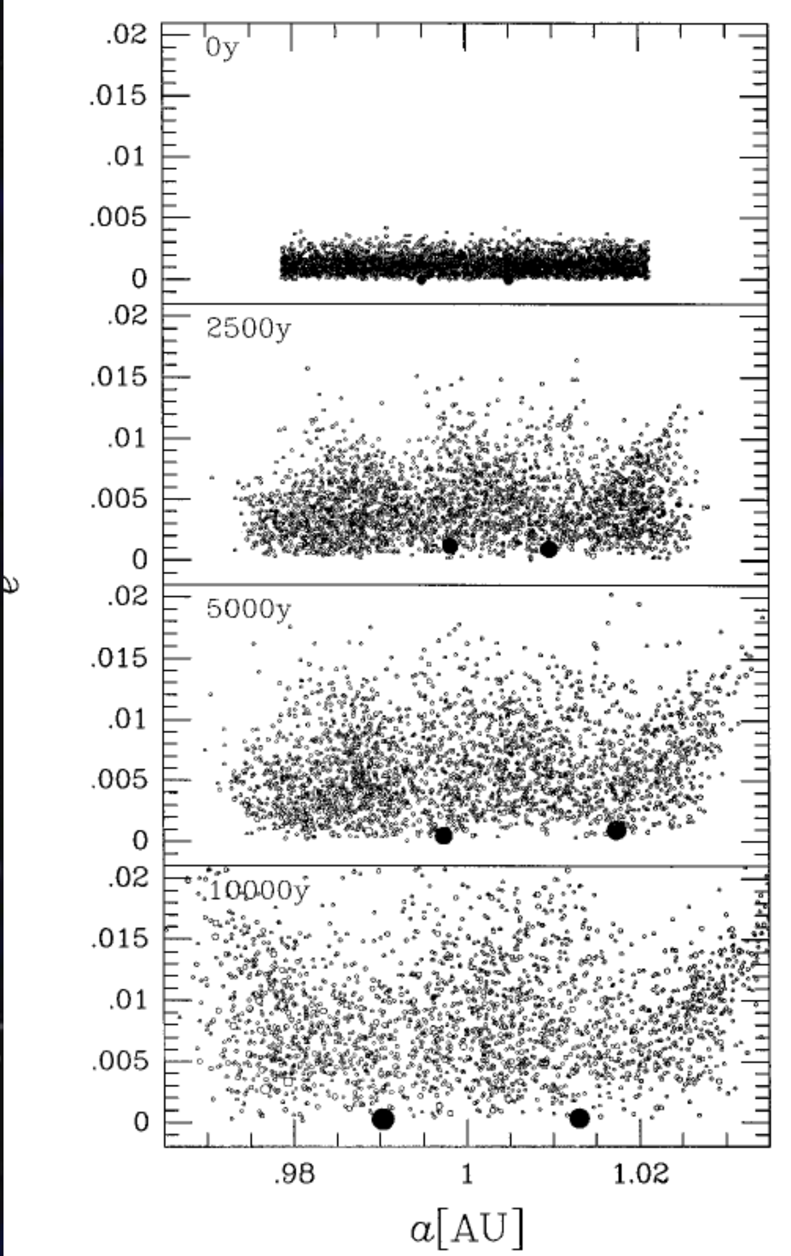
Heating of planetesimals by protoplanets

$$M/m \gtrsim 100 \Longrightarrow v_{\rm rel} \propto M^{1/3}$$

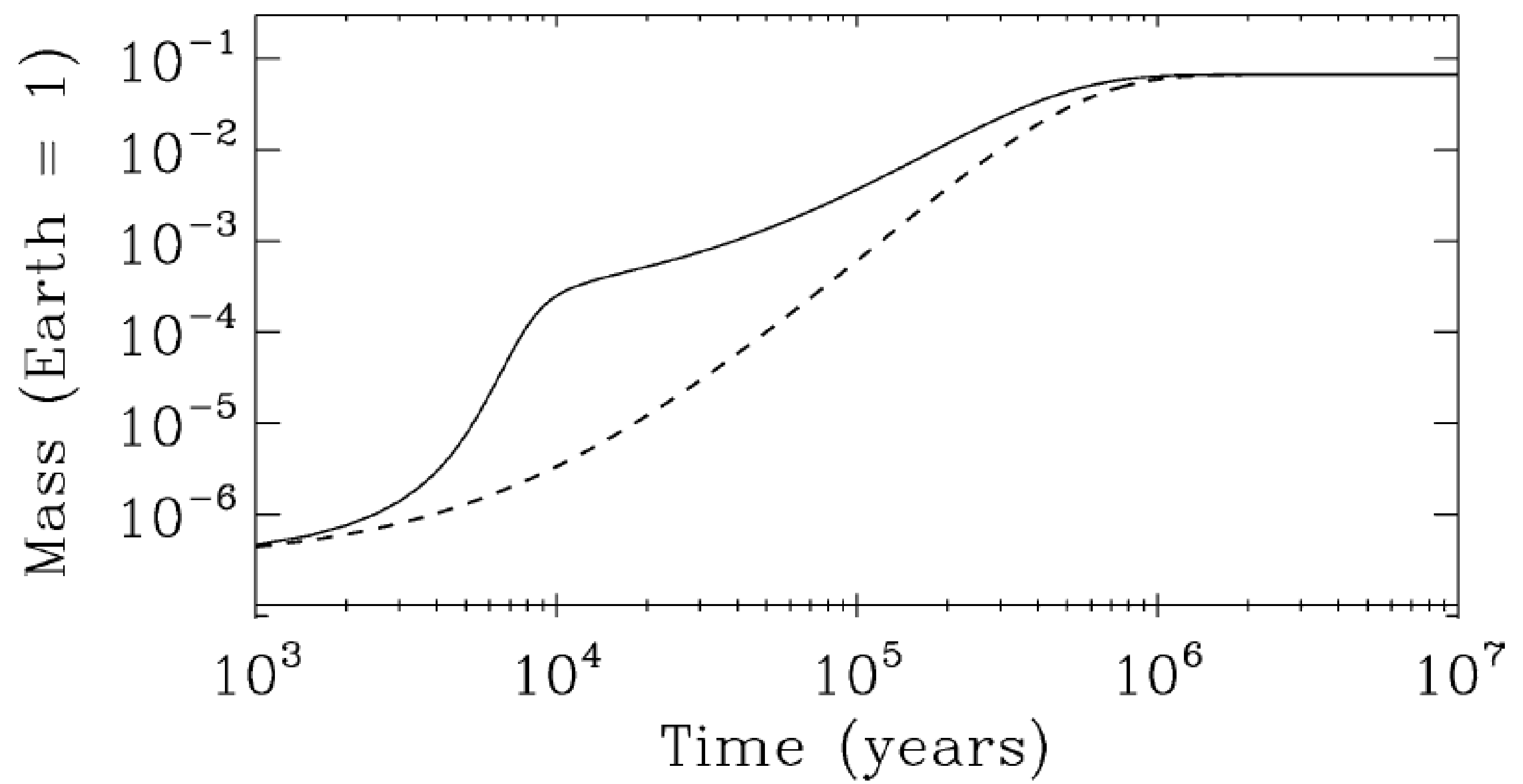
$$\frac{1}{M}\frac{dM}{dt} \propto M^{1/3} v_{\rm rel}^{-2} \propto M^{-1/3} \Rightarrow \text{orderly growth}$$

(Kokubo, 2004)

Numerical simulation of oligarchic growth



oligarchic growth: timescale



(Chambers, 2006)

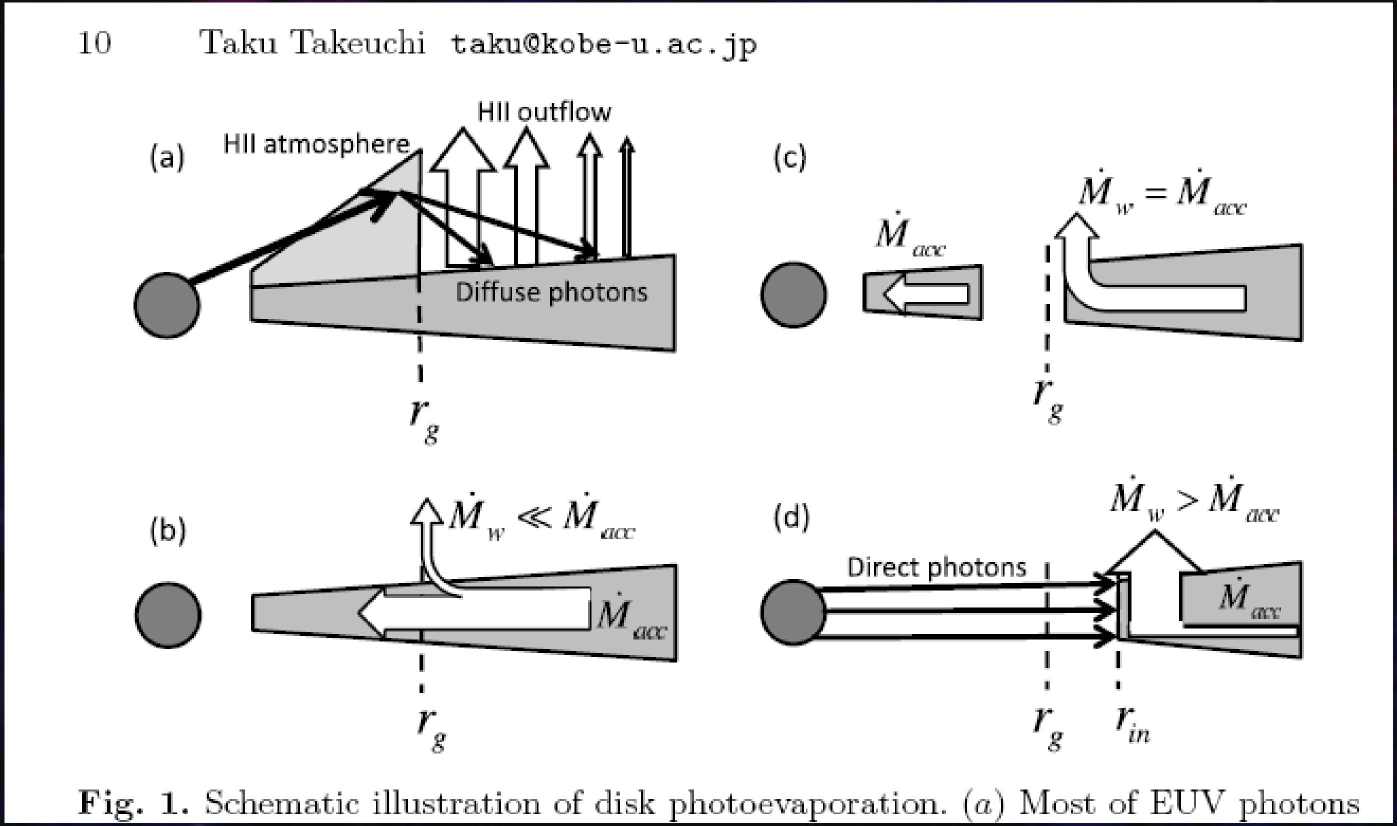
when does the gas disperse?

- After $t \leq 10^7$ years (circumstellar discs observations)

how does the gas disperse?

- Viscous evolution
- Truncation by Stellar Encounters
- Stripping by stellar Wind
- PhotoEvaporation
  - External Stars
  - Central Star

coupling between viscous evolution and photo-evaporation: GAS REMOVAL



10 Taku Takeuchi `taku@kobe-u.ac.jp`

Fig. 1. Schematic illustration of disk photoevaporation. (*a*) Most of EUV photons

Physics of Photoevaporation
Heating, Cooling, and Radiative Transfer

A. EUV ($h\nu > 13.6$ eV)

1. Heating by photoionization of H,
   Cooling like HII regions, $T=10^4$ K

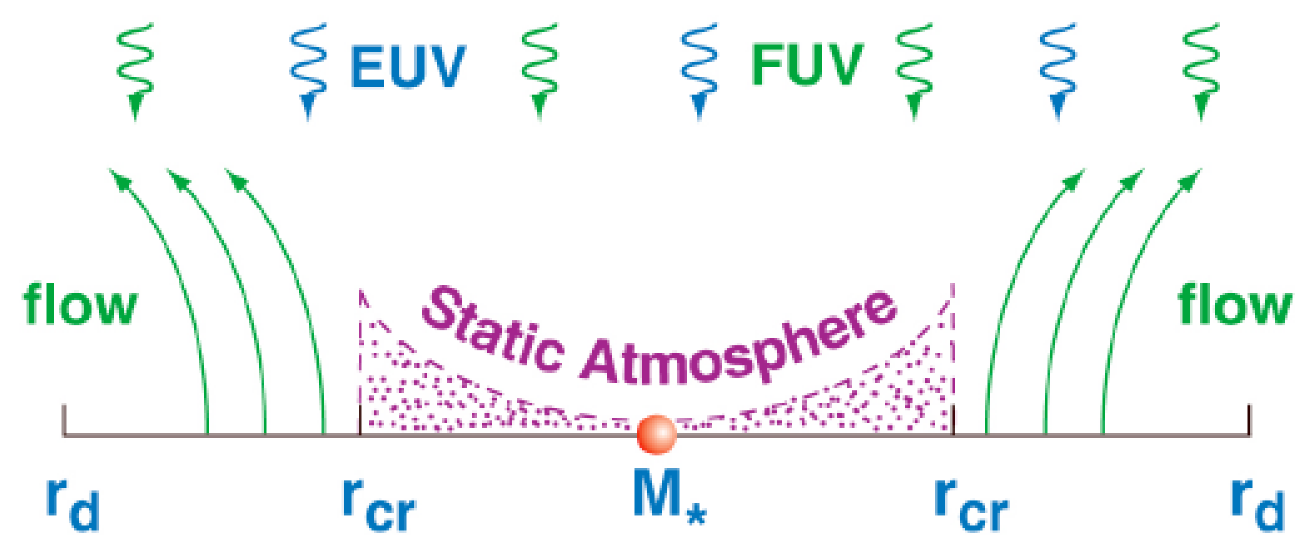
2. Opacity sources: H atoms or dust

B. FUV ($h\nu < 13.6$ eV)

1. Heating by grain photoelectric mechanism or FUV pumping of H_2. Cooling by O, C^+, H_2, grains.
   $T \sim 100 - 3000$ K.

2. Opacity source: dust

Physics of Photoevaporation



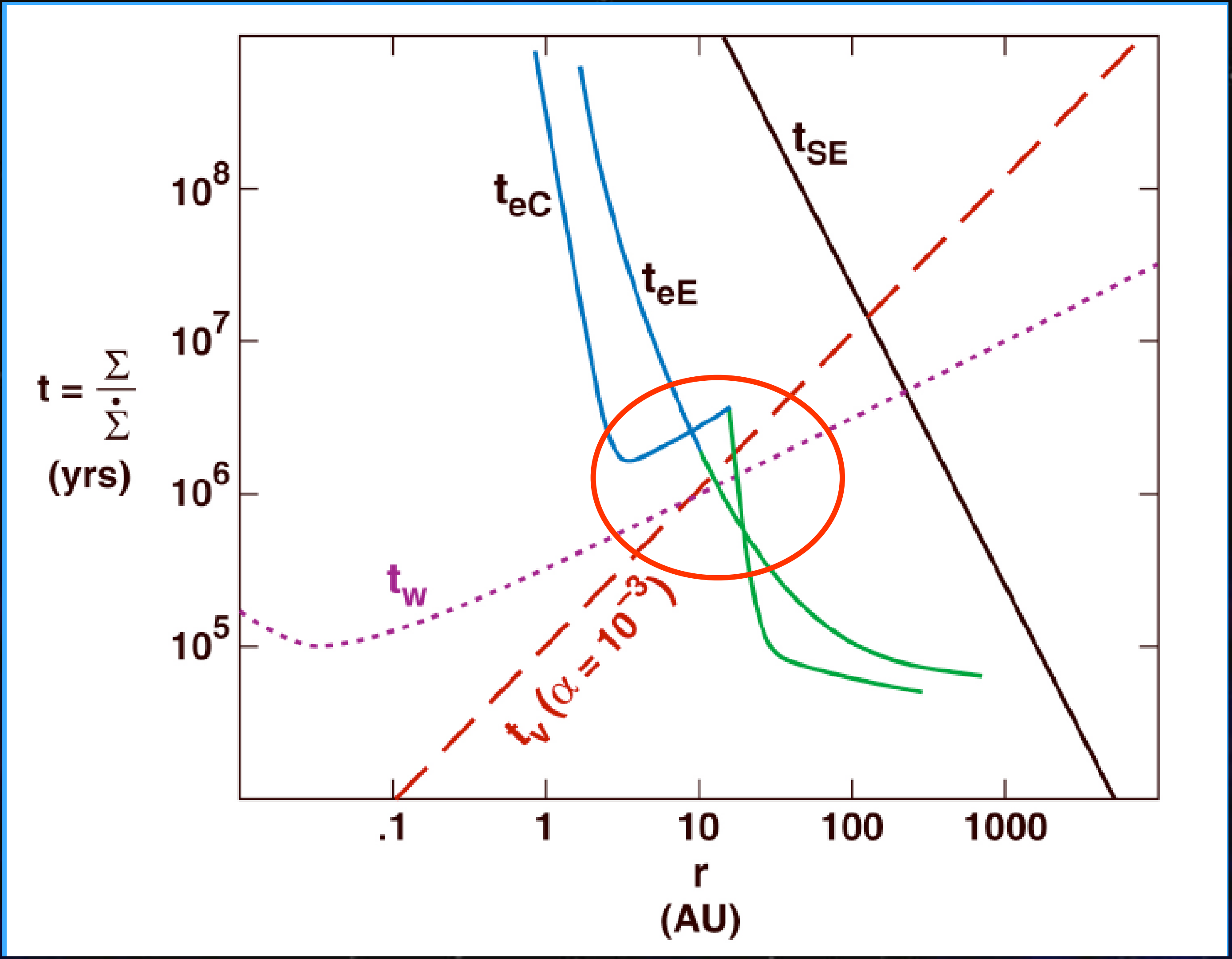
$$\text{escape speed} = \left(\frac{GM_*}{r_g}\right)^{1/2} \approx c = \text{sound or thermal speed}$$

$$r_{cr} \approx 0.2 r_g = 2 \left(\frac{M_*}{1M_\odot}\right)\left(\frac{10^4\ \mathrm{K}}{T}\right) \text{AU for EUV}$$

$$r_{cr} \approx 0.2 r_g = 30 \left(\frac{M_*}{1M_\odot}\right)\left(\frac{10^3\ \mathrm{K}}{T}\right) \text{AU for FUV}$$

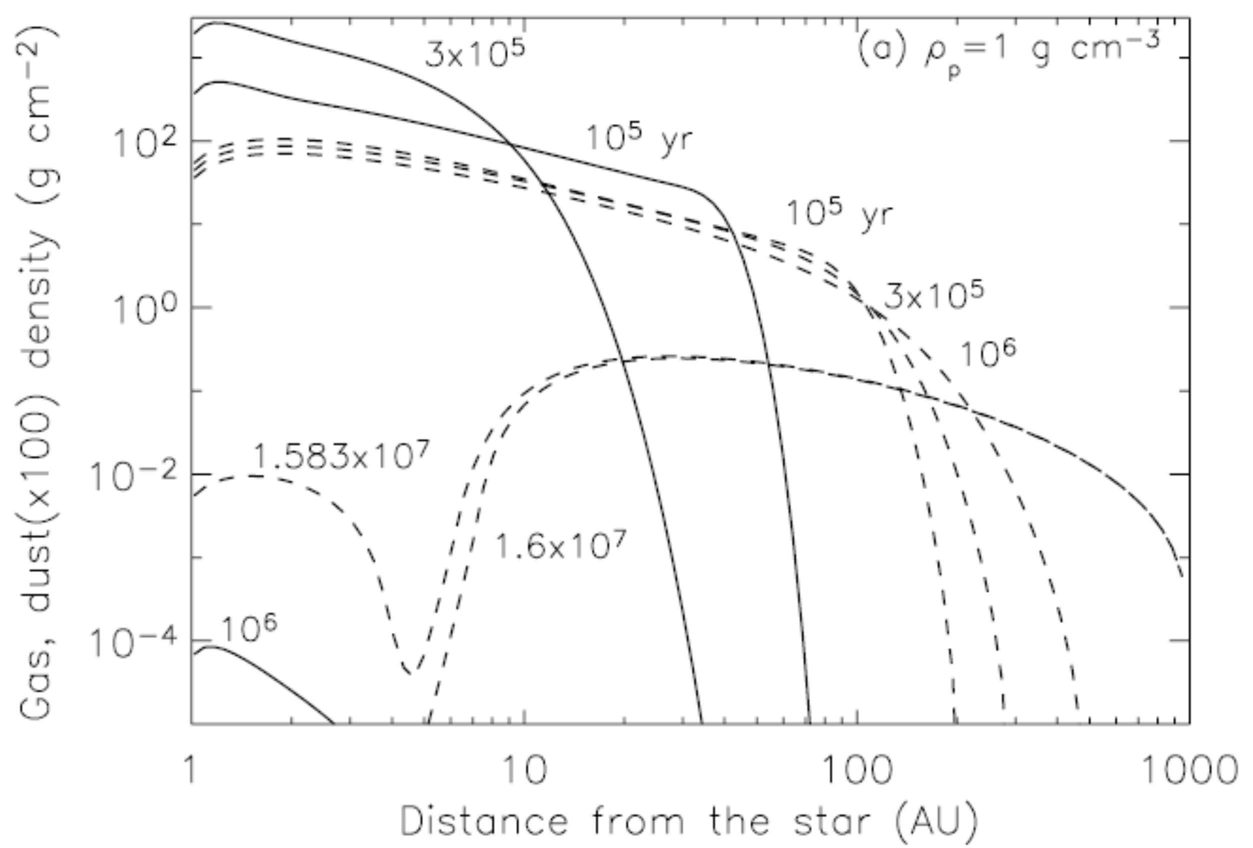
Adams, Hollenbach, Laughlin, & Gorti (2004)

disc dispersal mechanisms: time scales



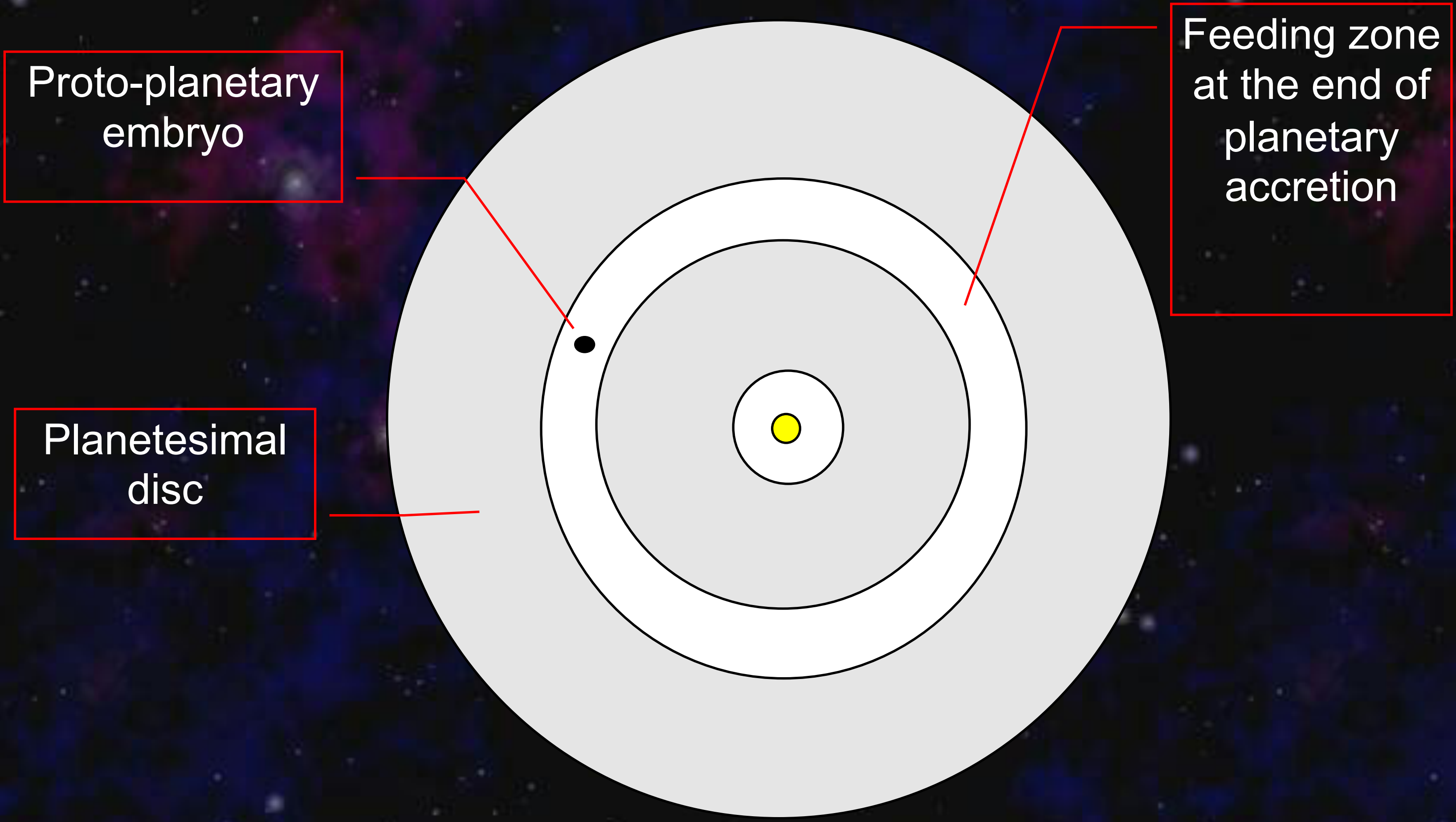
(Hollenbach, 2006)

Lifetime(s) of the gas and dust discs



(Takeuchi et al., 2005)

end of runaway/oligarchic growth (1)



Stops when growing embryo has eaten up its feeding zone

end of runaway/oligarchic growth (2)

Clearing of the feeding zone when

$$M(t) = \int_{R-\Delta R}^{R+\Delta R} 2\pi r \sigma(r) dr \approx 4\pi R \Delta R \sigma(R)$$

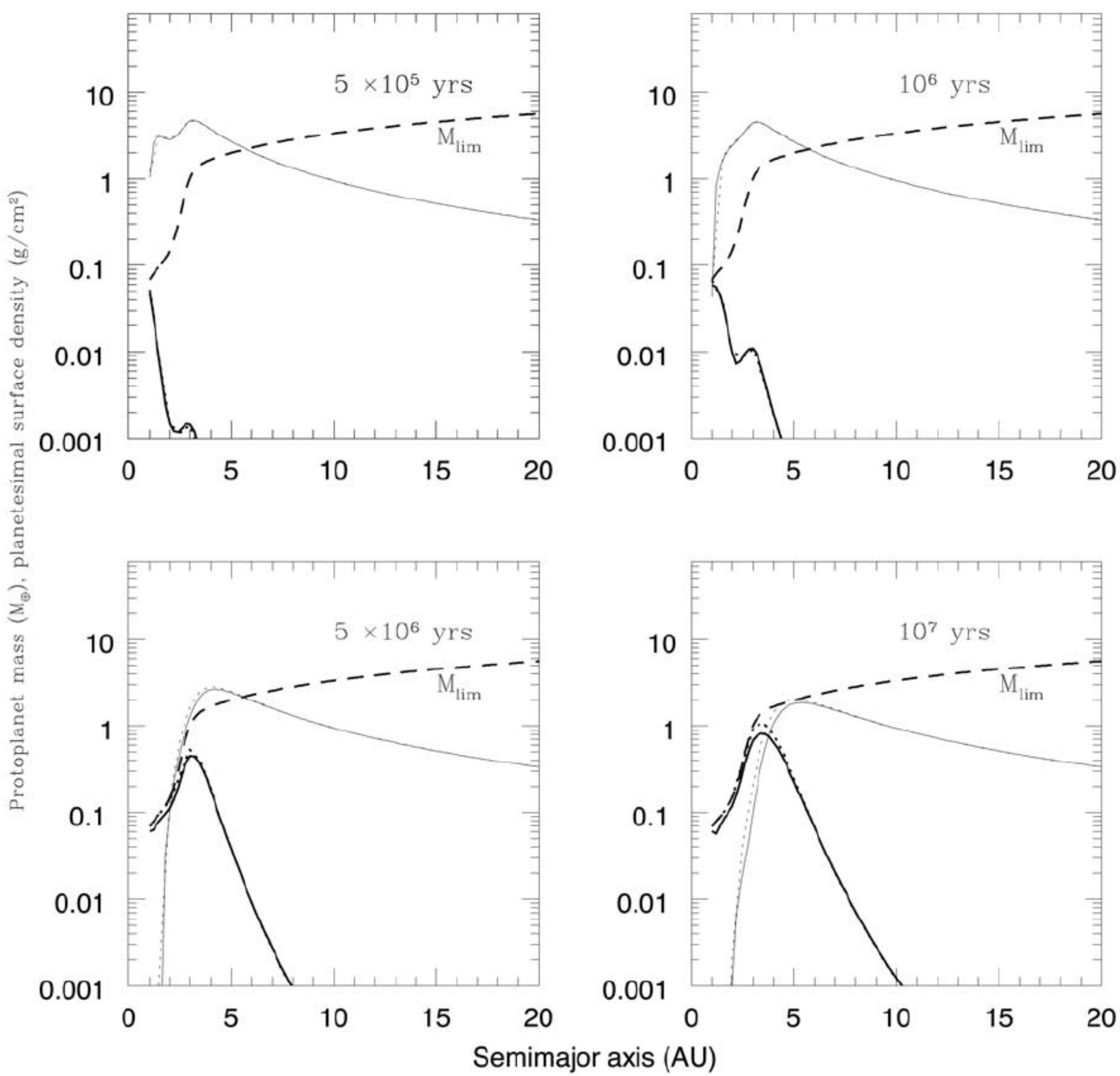
$$\Delta R \approx 3 R_{Hill} = 3 \left(\frac{m}{3M_*} \right)^{1/3} R$$

$$M_{Lim} = \frac{\left(12\pi R^2 \sigma\right)^{3/2}}{\left(3M_*\right)^{1/2}} \approx 2 \times 10^{-3} \left(\left(\frac{R}{1_{AU}} \right)^2 \frac{\sigma}{1_{g.cm^{-2}}} \right)^{3/2} M_\oplus \approx 0.05\, M_\oplus \ (at\ 1\ UA)$$

(Lissauer, 1993)

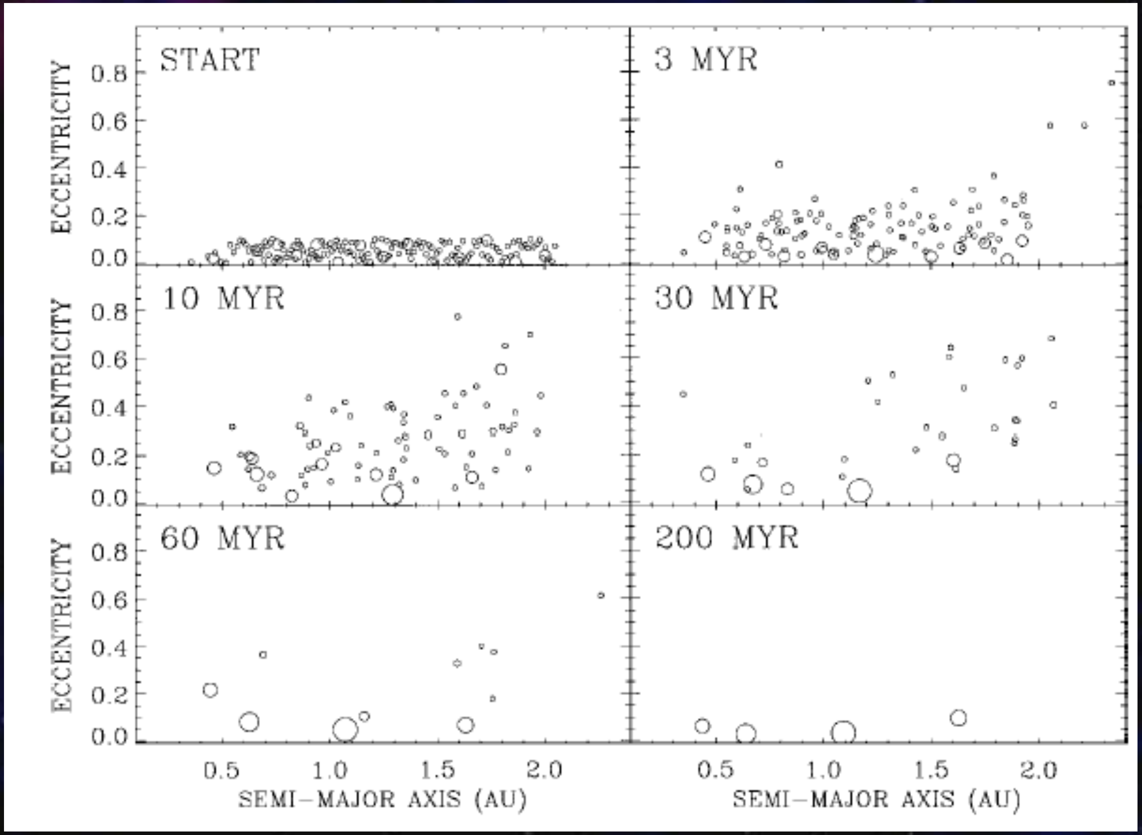
example of oligarchic growth

E.W. Thommes et al. / Icarus 161 (2003) 431–455



final stages

mutual interactions of proto-planetary embryos and clearing up



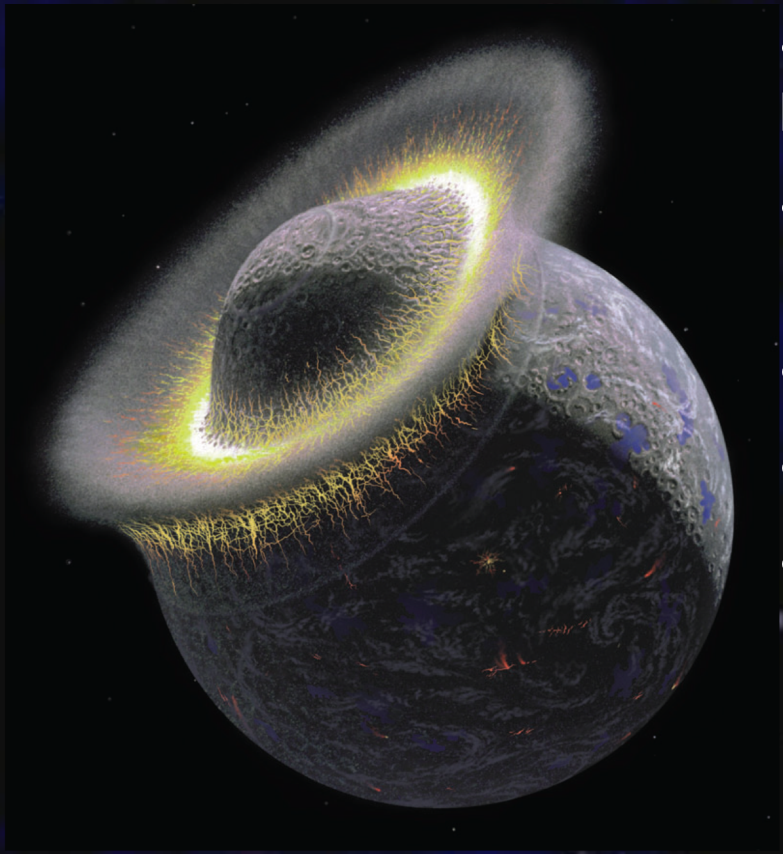
(Chambers, 2001)

Moon formation

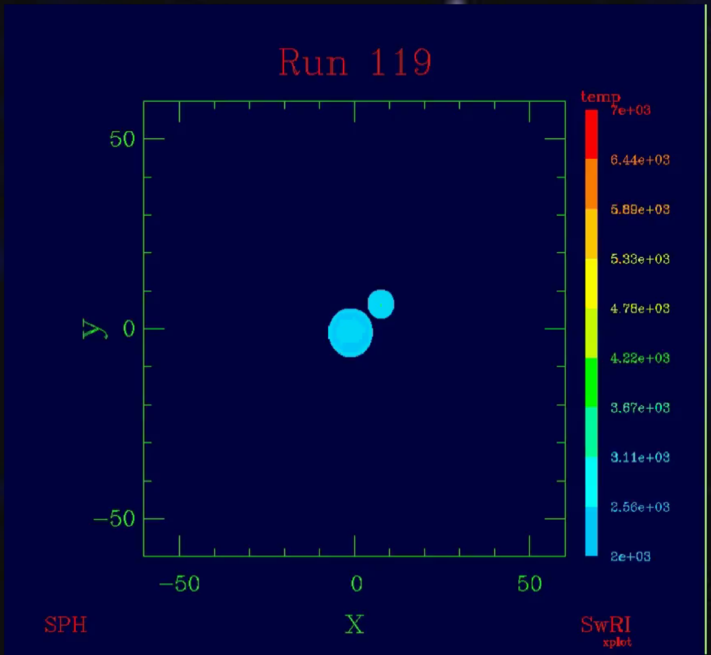
CONSTRAINTS

- The Moon is very big compared to the Earth
- The Moon is 30-200 Myr younger than the Earth (isotopes dating)
- The Moon is poor in iron and volatiles (H_20, CO_2, N_2,etc.)
- The Moon is rich in melted silicates
- The Moon has no (or a very small) core
- The Earth-Moon system has an anomalously large angular momentum
- Moon has the same isotopic composition (O, Fe, etc..) as the Earth mantle

Moon formation: the "Theia" impact scenario



- ≈50 Myrs after its birth, young Earth impacted by a Mars-sized planet (« Theïa »)
- Impact destroyed Theia and a fraction of the Earth
- Production of a debris ring orbiting the Earth
- Cloud mostly made of Theia fragments.
- Moon forms from the cooling debris ring



...but how can it explain the identical isotopic composition?

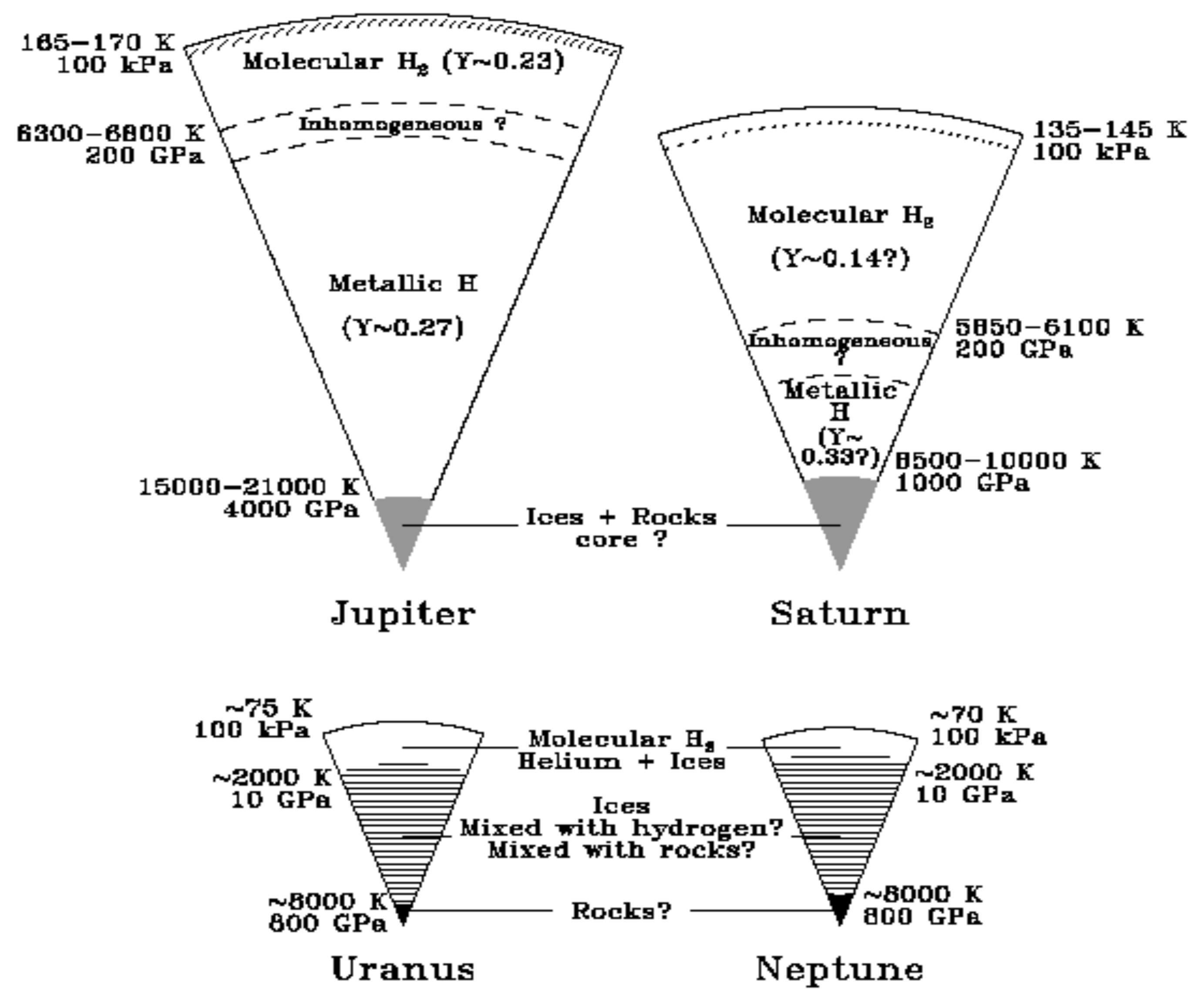
Giant Planet formation

Challenges:

- Accrete 10-15 $M_\oplus$ of solids (Rocks & ices)
- Accrete 70 and 280 $M_\oplus$ of gas for Jupiter & Saturn
- Accrete < 3 $M_\oplus$ of gas for Uranus & Neptune
- Accrete gas before the gaseous disc disapears at

  $t < 10^7$ years

constraint: composition



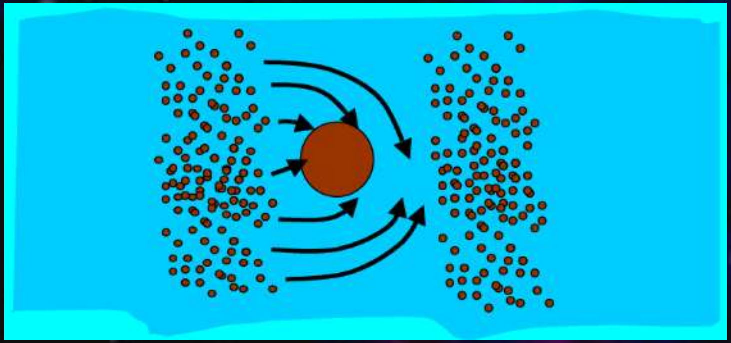
(from T. Guillot)

concurrent scenarios

- Solid Core in 2 steps (defending champion)

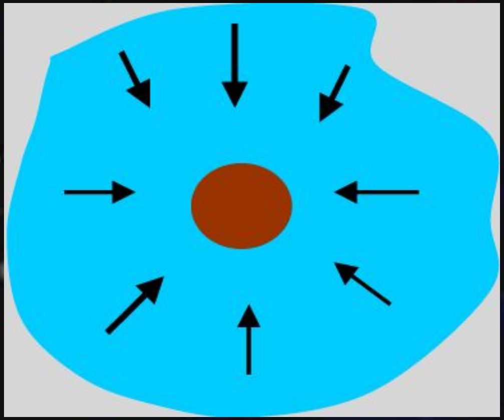
- Direct Instabilities/Gravitational collapse (challenger)

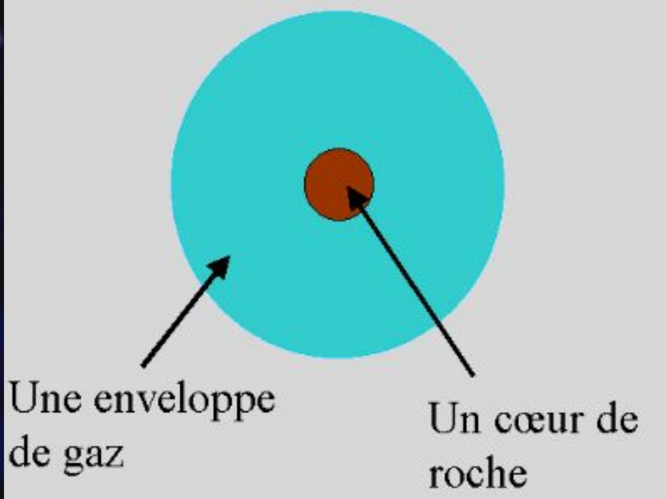
the “solid core” scenario: 2 stages



1) Formation of a solid core by runaway growth

2) when the core is massive enough, collapse of the surrounding gas

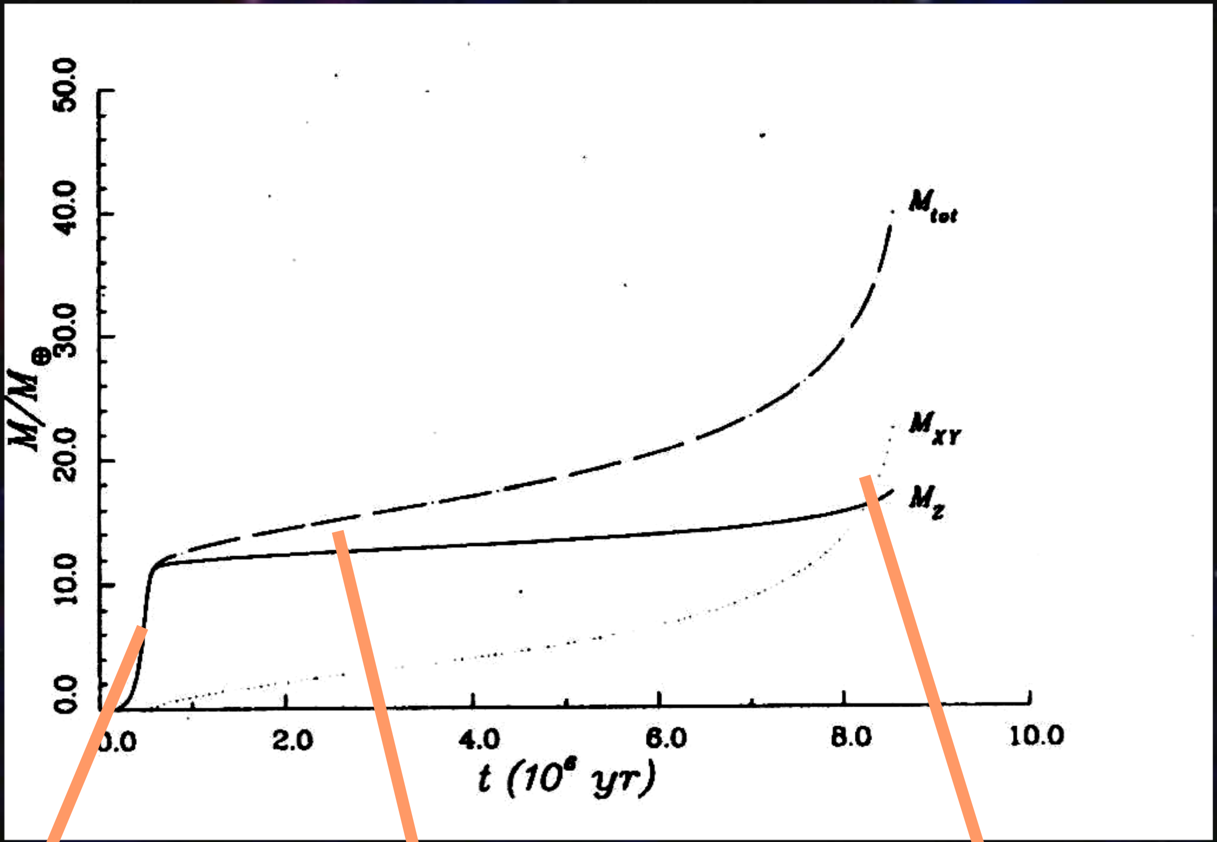




Final structure (?)

chronology

(numerical simulation; Pollack et al. 1996)



Progressive accretion of the gas

Collapse of the gas

Accretion of the solid core

the solid-core scenario: pros and cons

- We know that solid cores ***do*** exist: Uranus & Neptune
- Saturn (at least) has a core that agrees with the theory.
- Specificity of published models is artificial; shorter timescales are possible

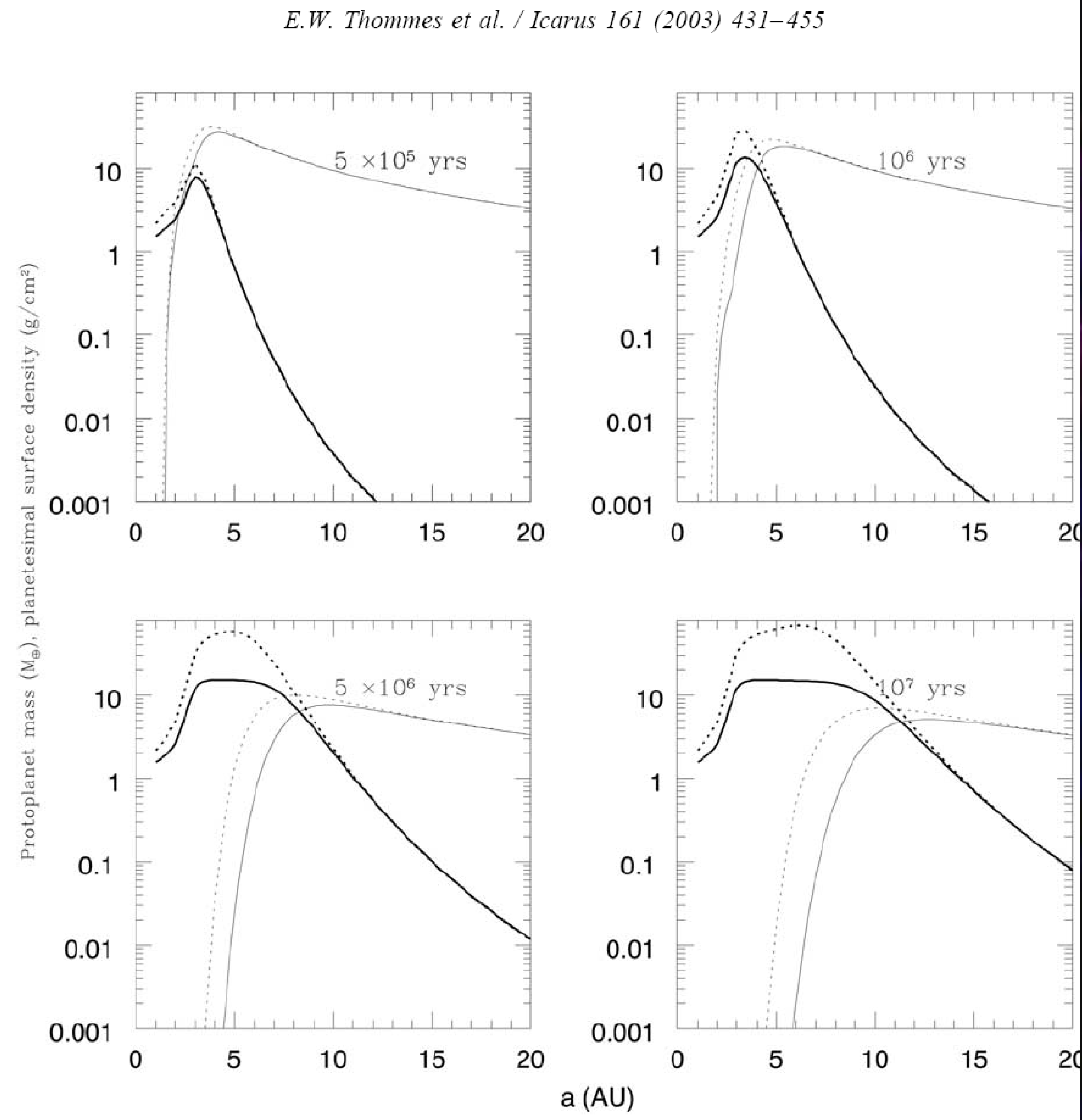
- ***Timescale problem***: do they form fast enough so that massive gas accretion takes place?
- A weak test, especially since so much heavy material is delivered *aside* from the core.
- More models needed

core-accretion: timescale problem

10x MMSN

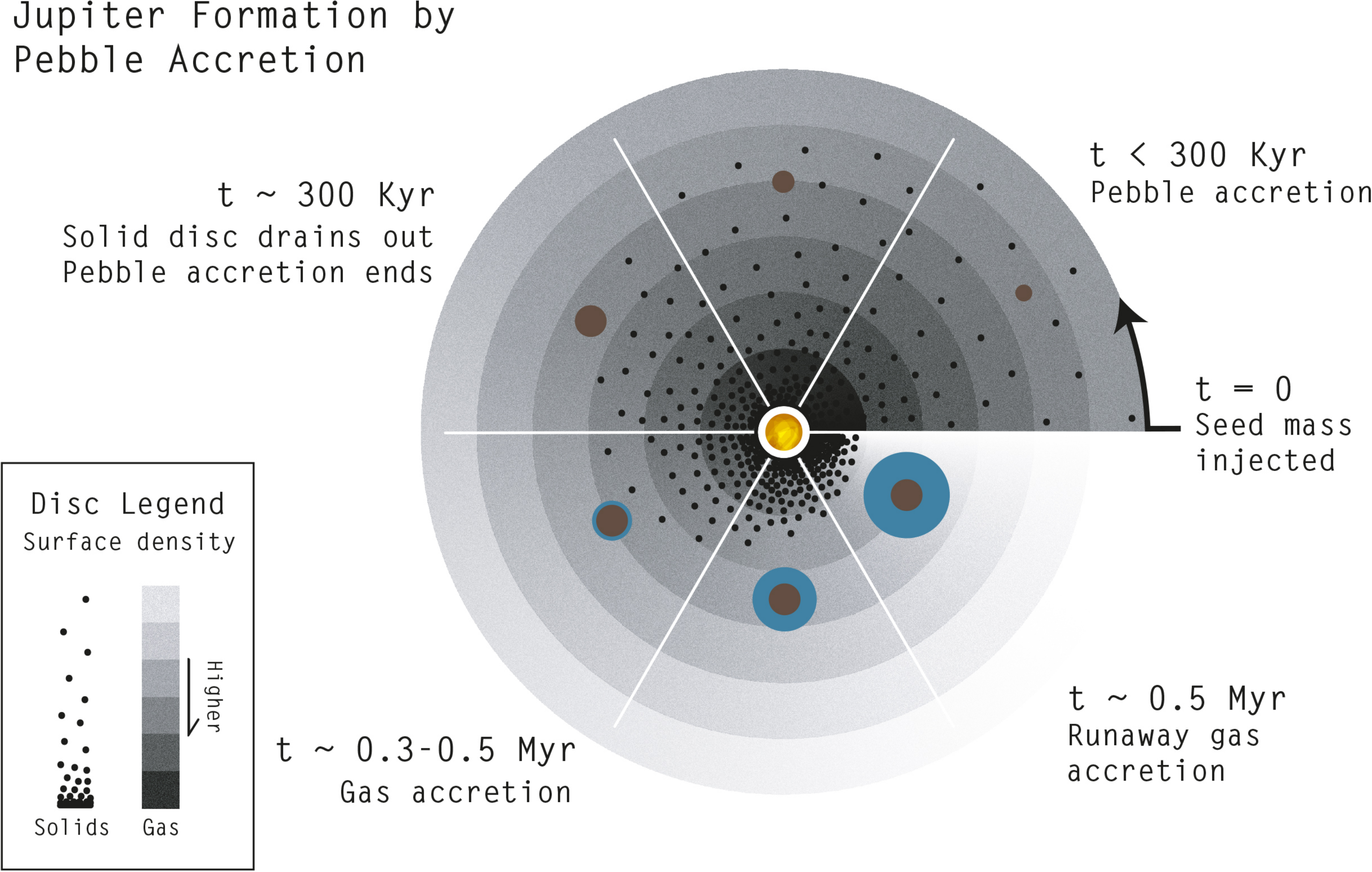
- *Difficult to form Saturn in time. Impossible to form Uranus and Neptune in-situ*

- *So, what?*



E.W. Thommes et al. / Icarus 161 (2003) 431–455

Pebble accretion for Jupiter?



Jupiter Formation by Pebble Accretion

t < 300 Kyr
Pebble accretion

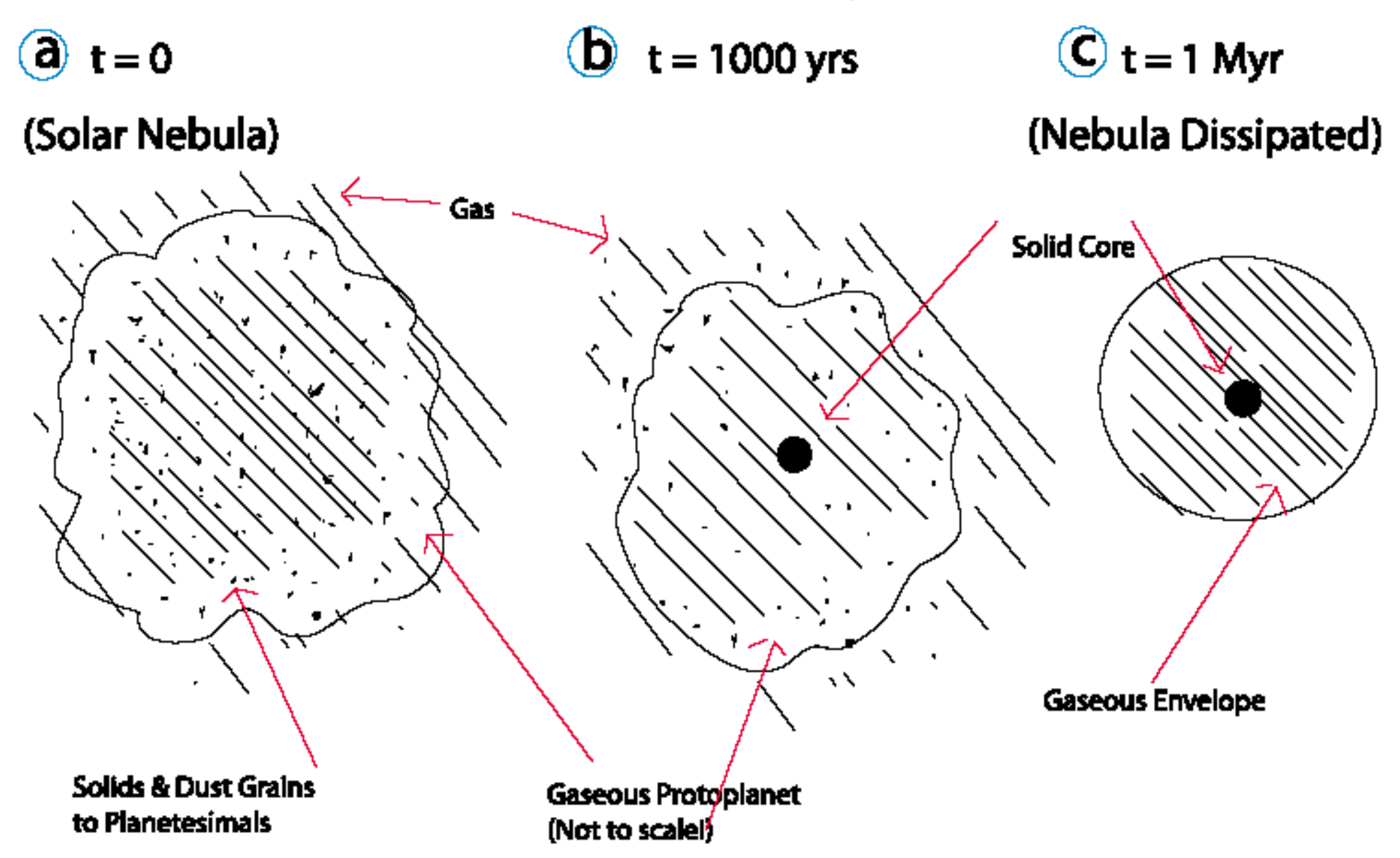
t = 0
Seed mass injected

t ~ 300 Kyr
Solid disc drains out
Pebble accretion ends

t ~ 0.3-0.5 Myr
Gas accretion

t ~ 0.5 Myr
Runaway gas accretion

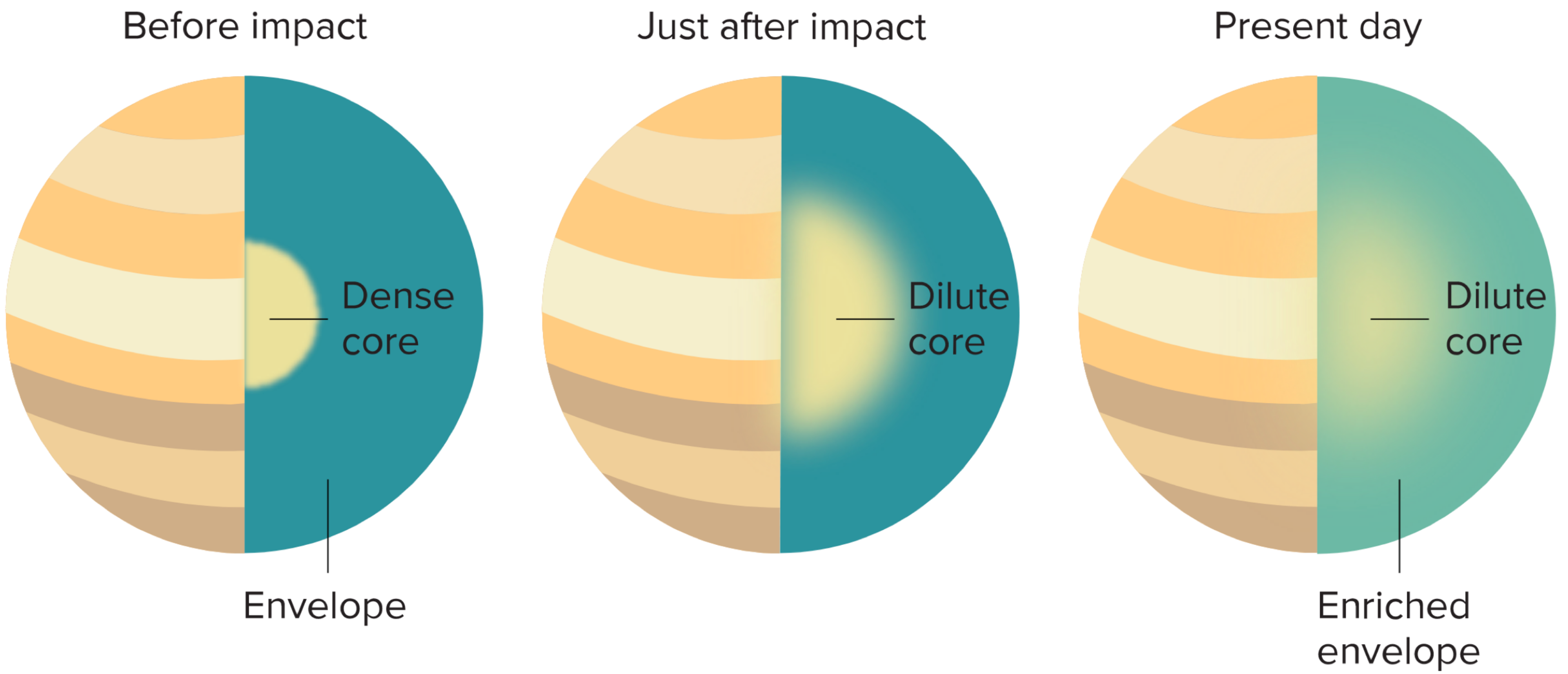
Alternative formation scenario: gravitational instability



(from Stevenson; 2004)

The Juno spacecraft has shown that Jupiter's is not small and compact but spread out across half of the planet's diameter
... how come?

A collision may have left Jupiter with a fuzzy core



SOURCE: T. GUILLOT / *NATURE NEWS & VIEWS* 2019

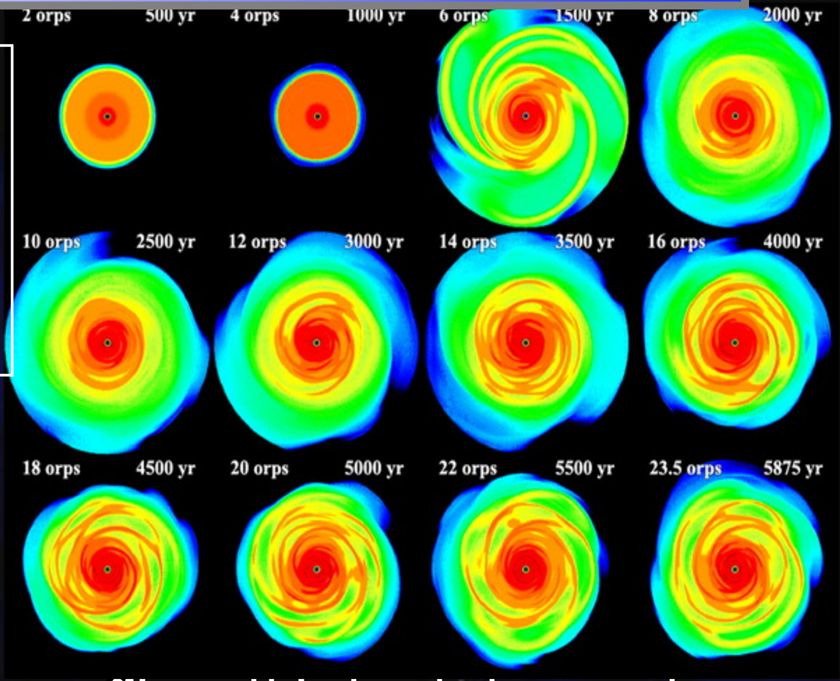
KNOWABLE MAGAZINE

gravitational instability

Self-gravity
vs
Keplerian shear + Thermal pressure

Gravitational instability: gas giant planets form when a part of the disk becomes unstable, i.e., when $Q \sim M_{star}H/(M_d r) < 1$ where M_d is disk mass within r (Kuiper 1949, Cameron 1978)

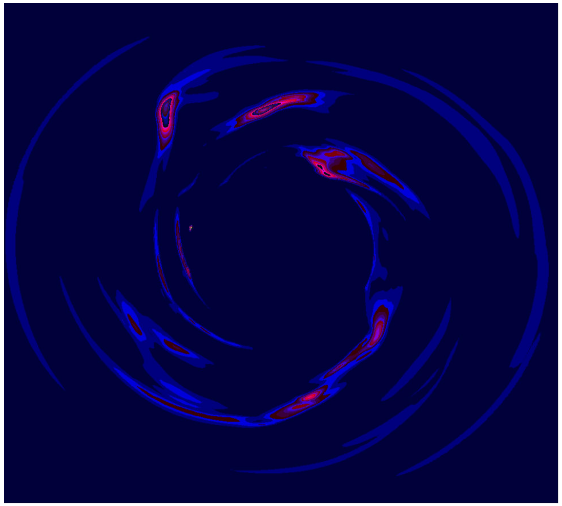
This would form planets very quickly (orbital timescales, or few hundred years) with a characteristic scale H and so with a mass of around $M_{jupiter}$ [$=(H/r)^3 M_*$ assuming $H/r=0.1$]



Since this leads to angular momentum transport on orbital timescales, Q can never reach 1 unless the disk is cooled down (so that v_t and H/r decrease) or matter added (so M_d increases) quicker than orbital timescales ($\tau_c<3\Omega_k^{-1}$, Gammie 2001)

grav. instability: pros and cons

- This process is fast!
- Can solve the timescale problem for Saturn
- Works well at large radial distances: can explain exoplanets detected by imagery

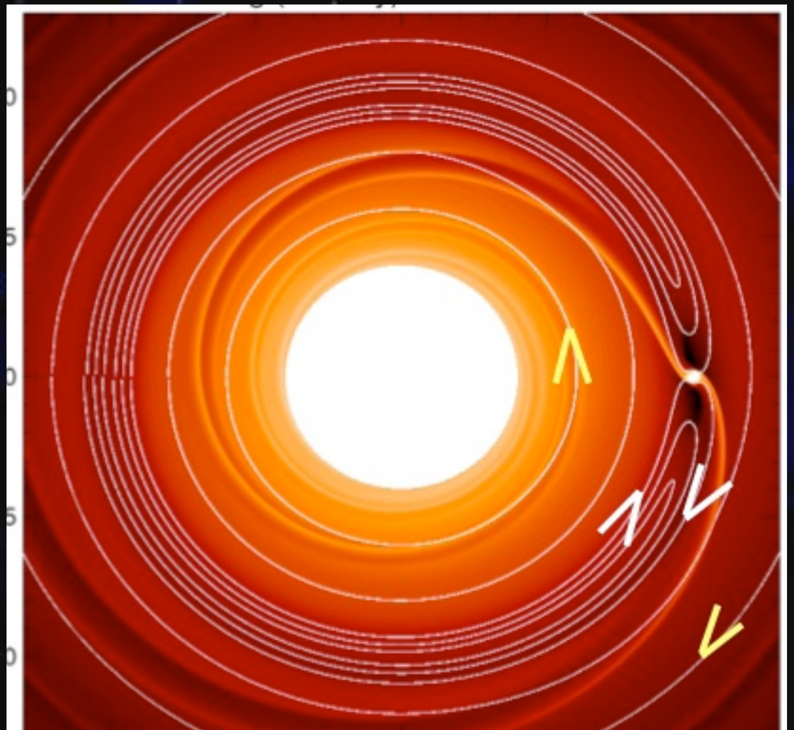


Alan Boss (2000)

- You don’t even know for sure if it happens! Depends on the rate at which you approach instability, etc.
- Cooling problem!
- May not have the right mass
- Still need to make Uranus and Neptune

Planetary migration

- ***Why?***: Explain the presence of « Hot-Jupiter » exoplanets, impossible to form in-situ in the « standard » scenario
- ***Cause***: Interaction between a proto-planet and the surrounding gas disc
- ***When?***: Just after the runaway/oligarchic growth phase, when $>1M_{\mathrm{Earth}}$ protoplanets have formed, but *before* the dispersion of the gas disc($<10^7$ years)

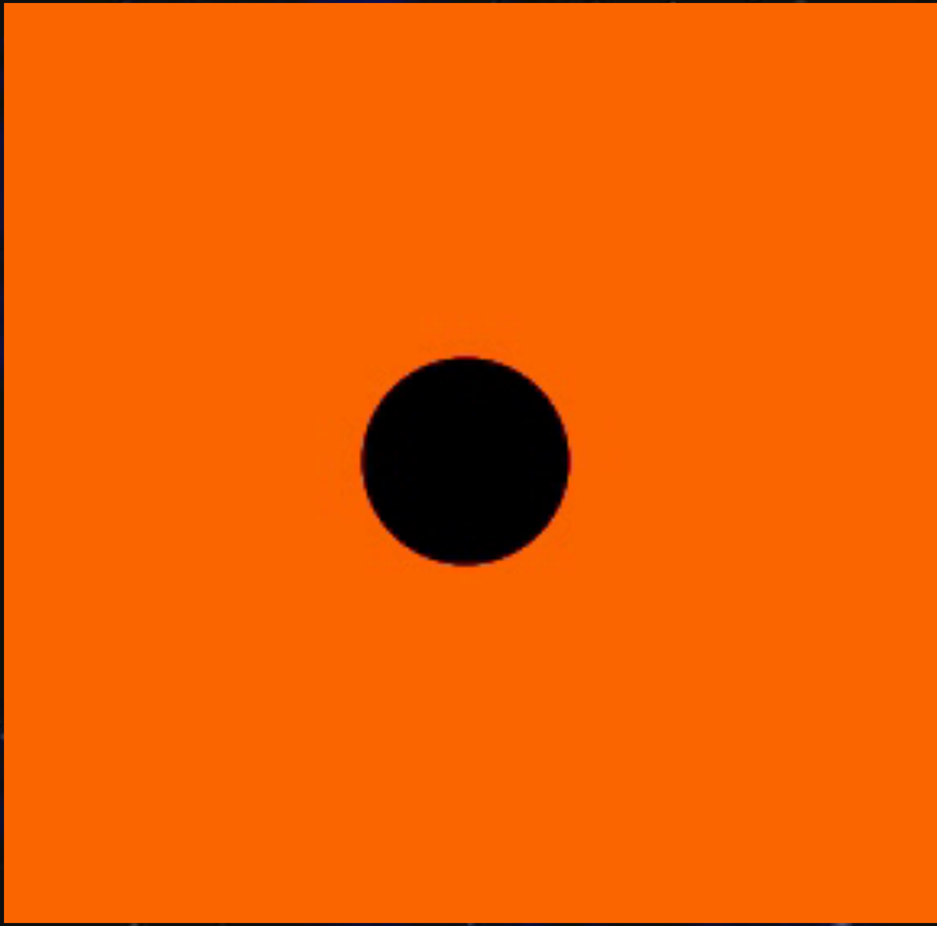


Planetary migration

- ***Type I migration***: Earth-sized planets imbedded in the disc: Differential couple between the disc parts inside and outside of the planet: very fast.

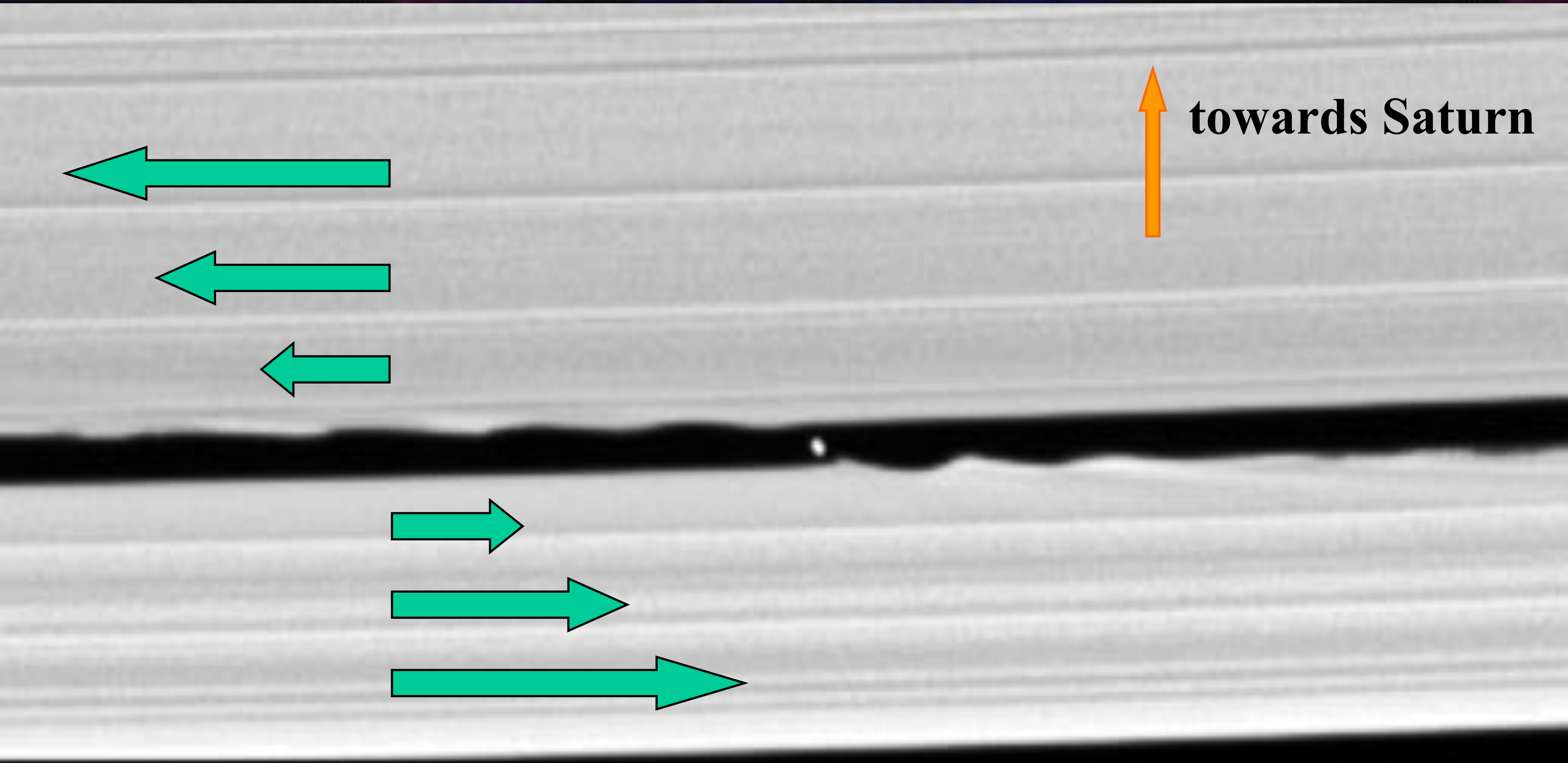
- ***Type II migration*** $>10M_{Earth}$ planets that can create a gap in the disc. Planet locked with the disc and migrates as the disc spirals inward due to its viscosity: slower but efficient

Example: Type I followed by type II



F.Masset (2002)

Migration in the real world: Saturn’s rings

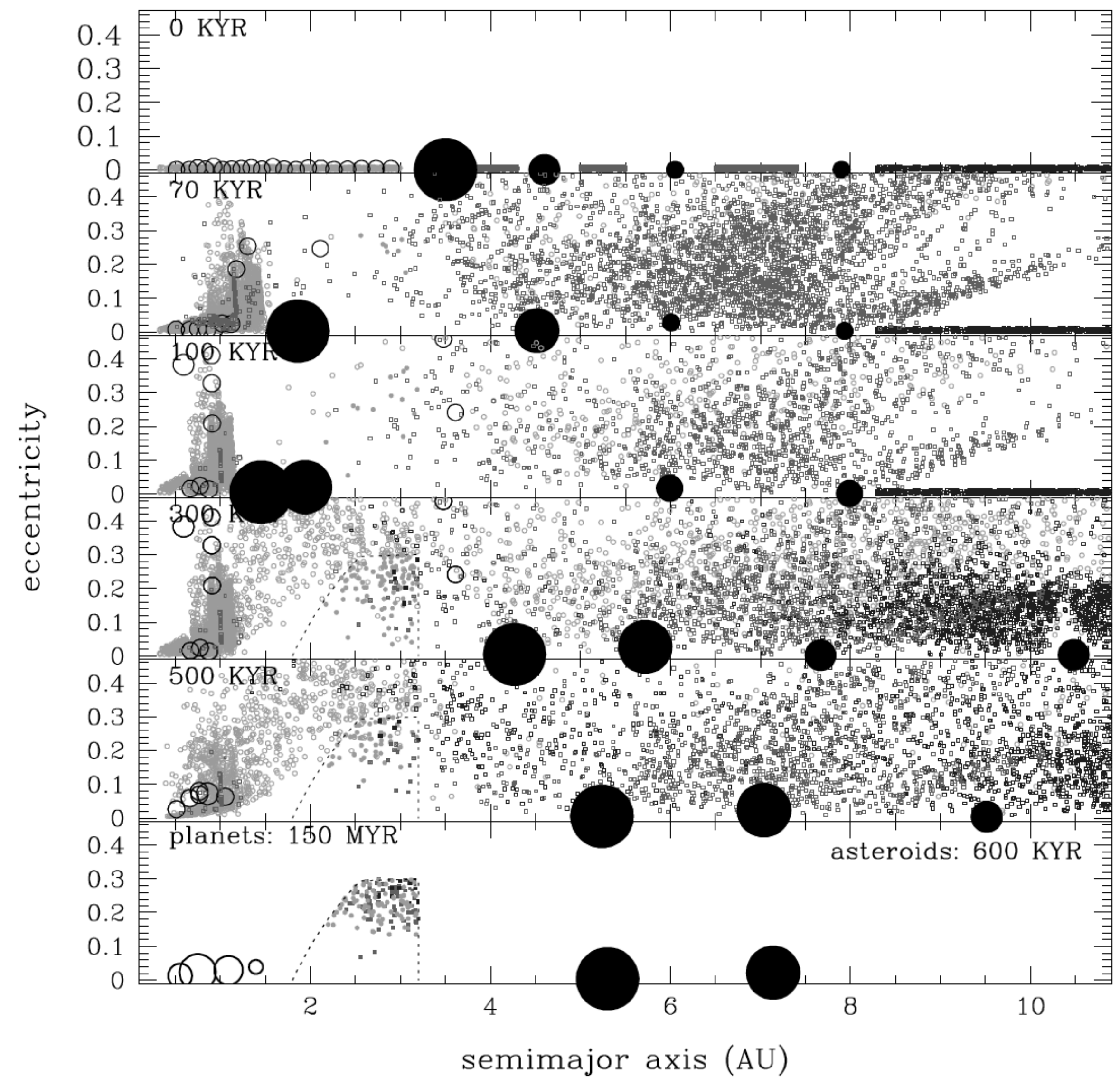


Keeler gap

Type I&II migrations work ***too*** good!

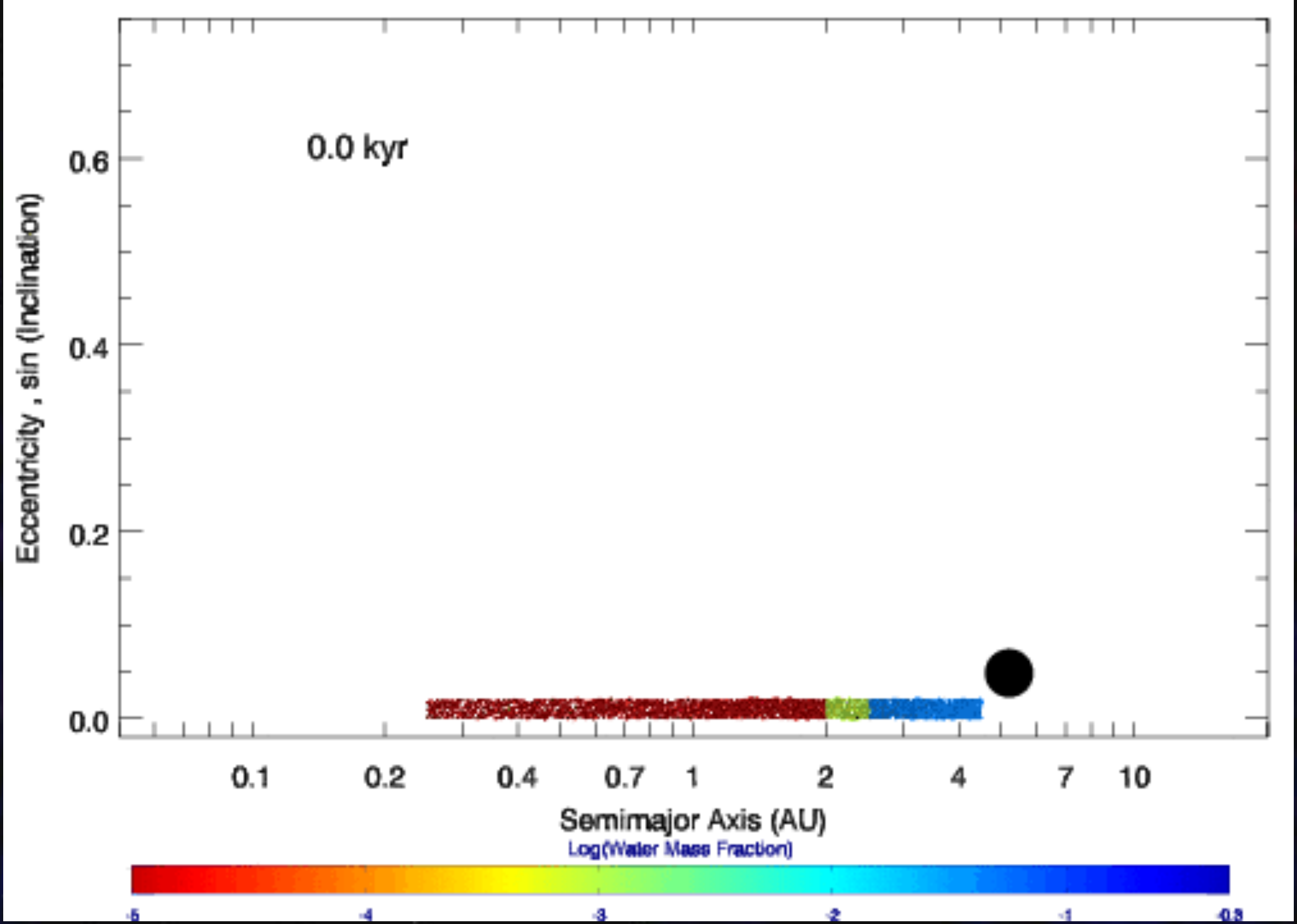
- How do you stop it and prevent planets from falling onto their star?
  - Stop at the inner edge of the protoplanetary disc?
  - Bump in the gas disc density profile?
  - Resonant interactions between *several* planets?
- Can you still have habitable planets once a giant planet has migrated through the inner regions?
- What happened to the solar system?
  - Limited migration because of Jupiter/Saturn interaction?

An example of a complex, multi-planet migration procedure: The "Grand Tack" model



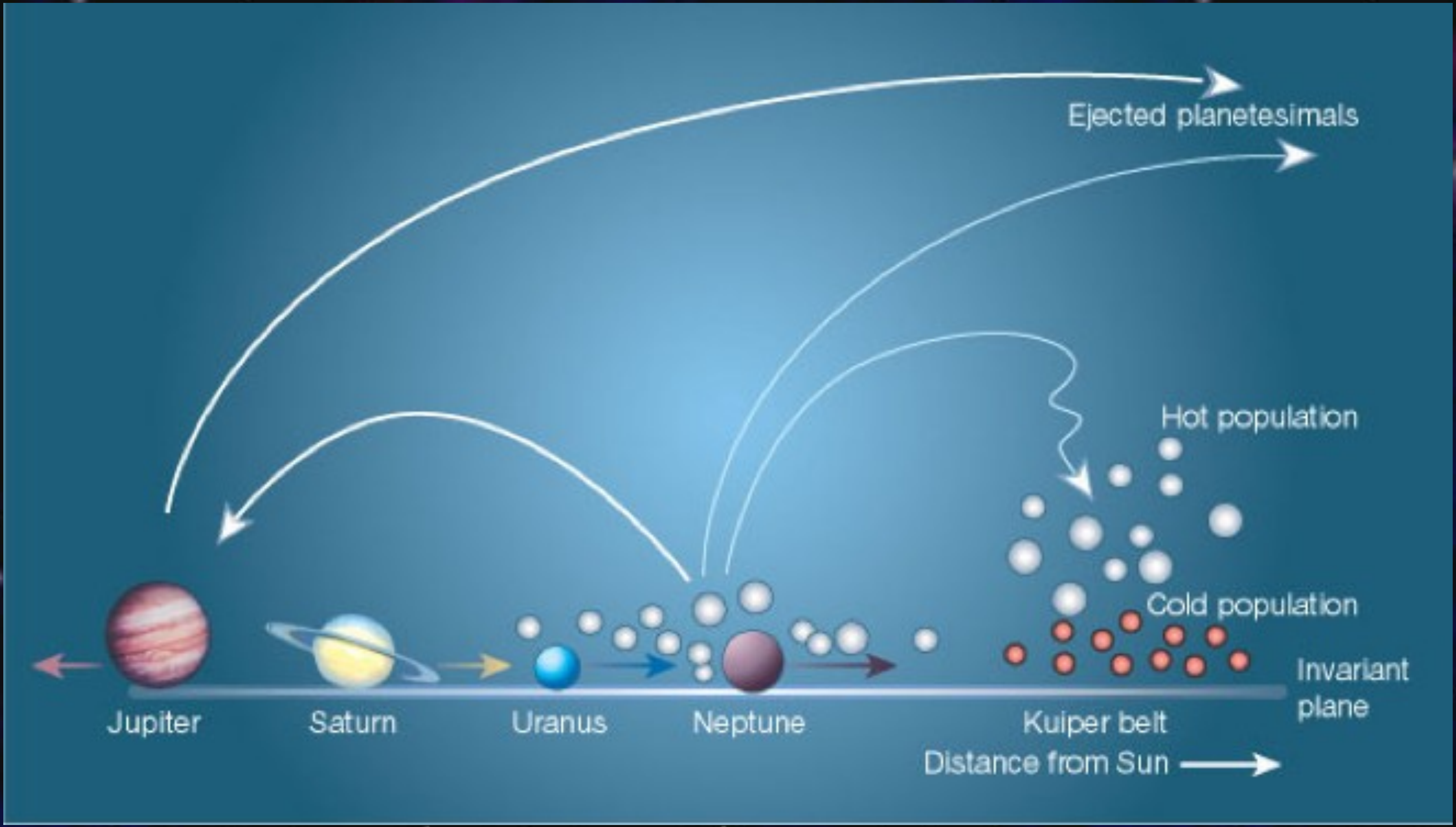
Raymond et al. (2014)

Forming terrestrail planets *after* the migration of a giant?

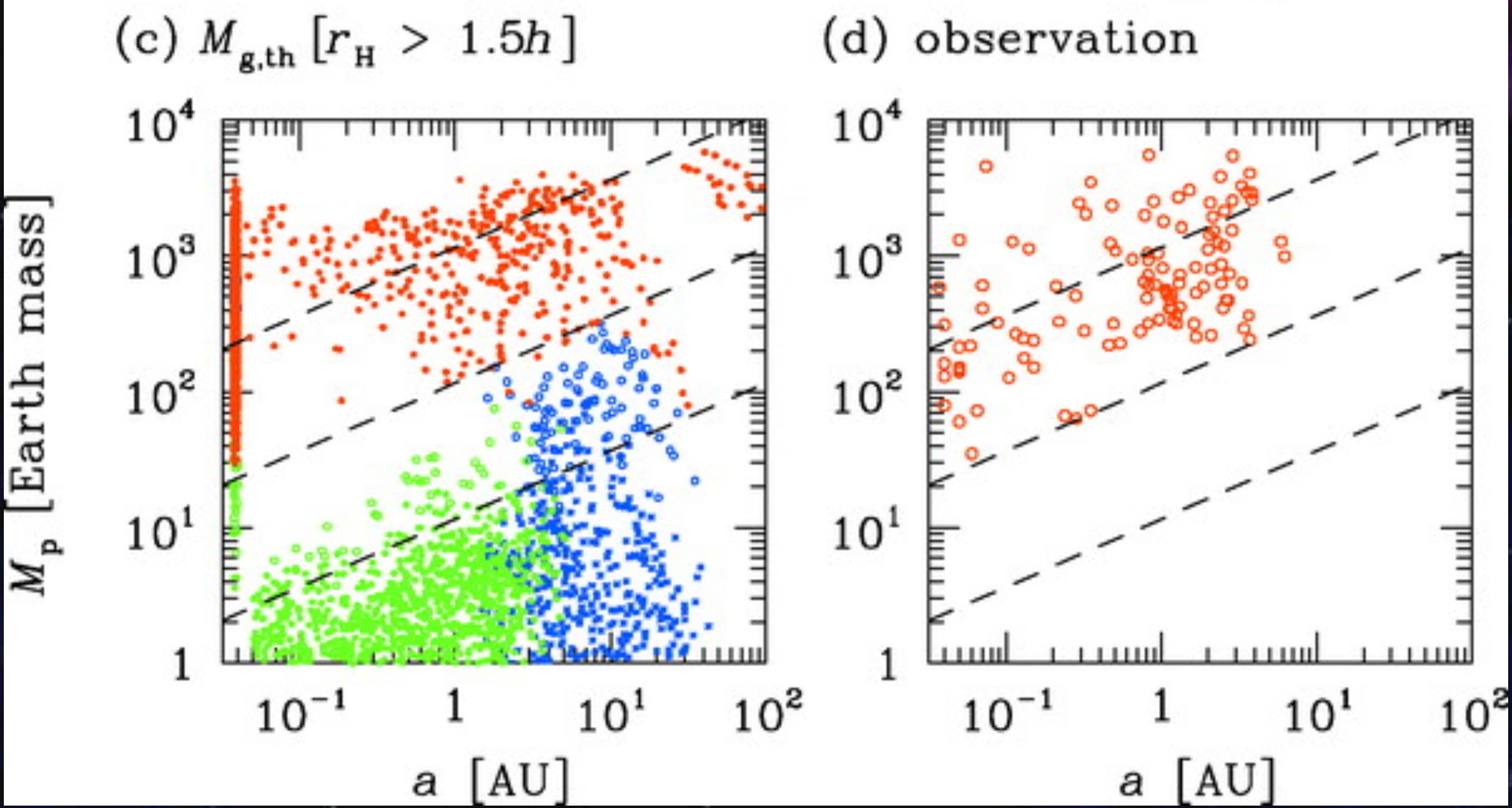


Raymond et al. (2006)

Late, planetesimal-driven migration: the (now abandoned) "Nice" model

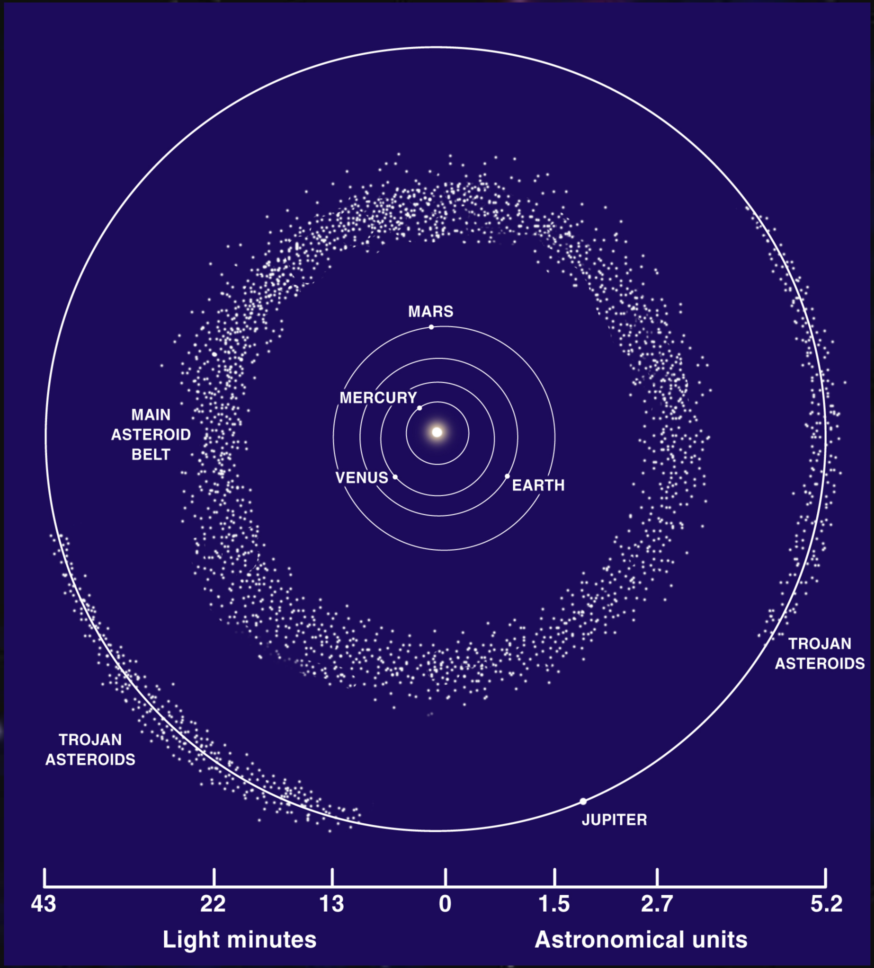


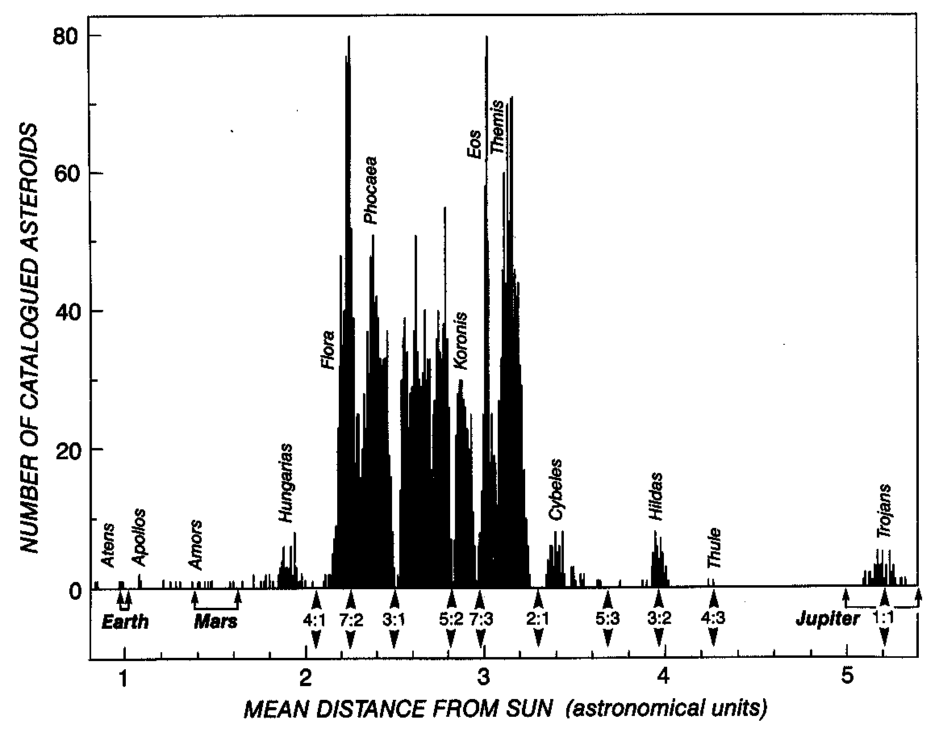
Global planet formation simulations



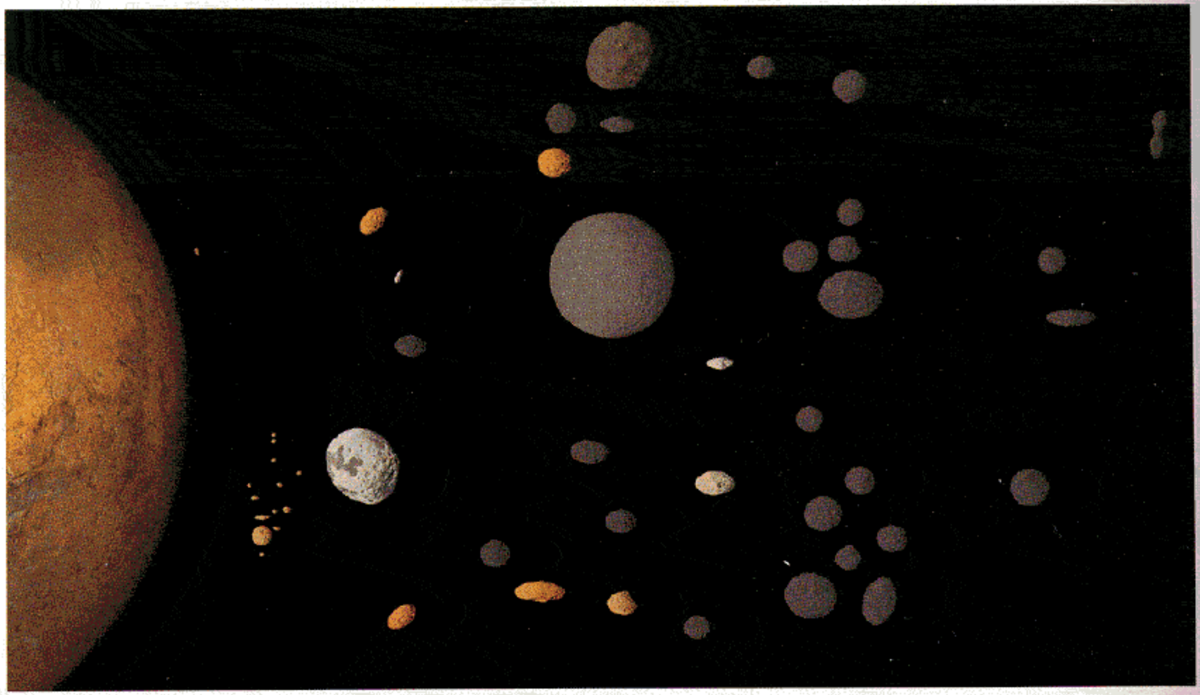
Ida & Lin (2004)

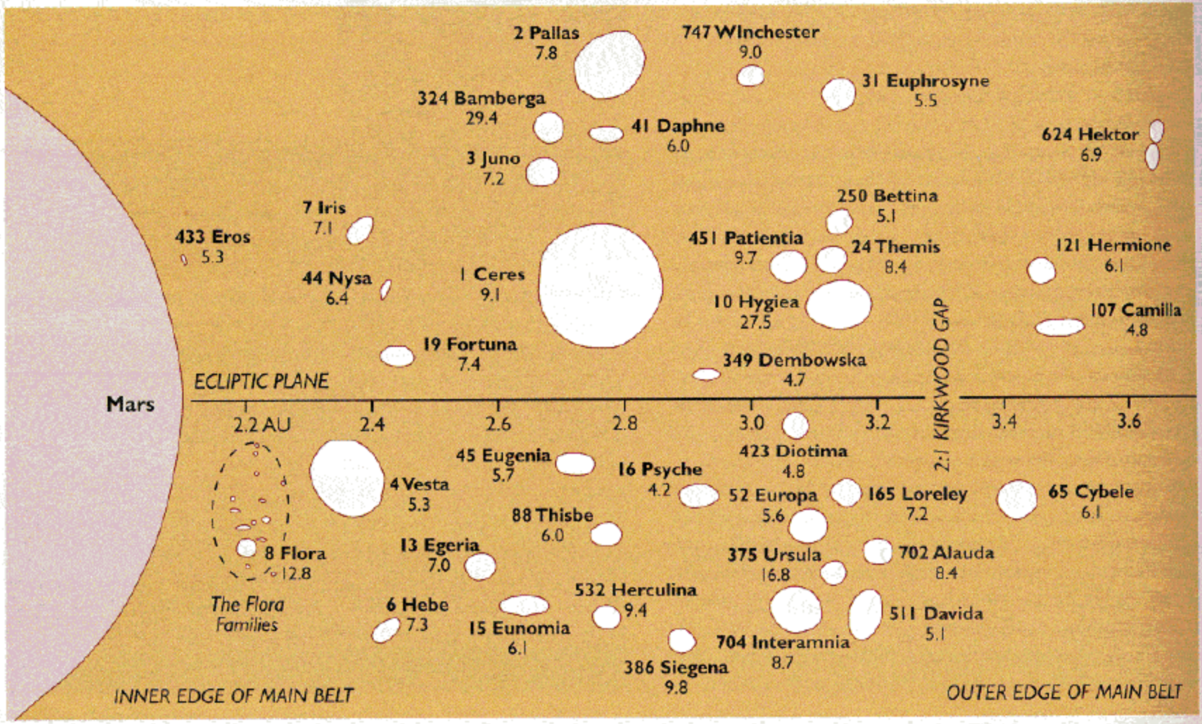
the asteroid belt



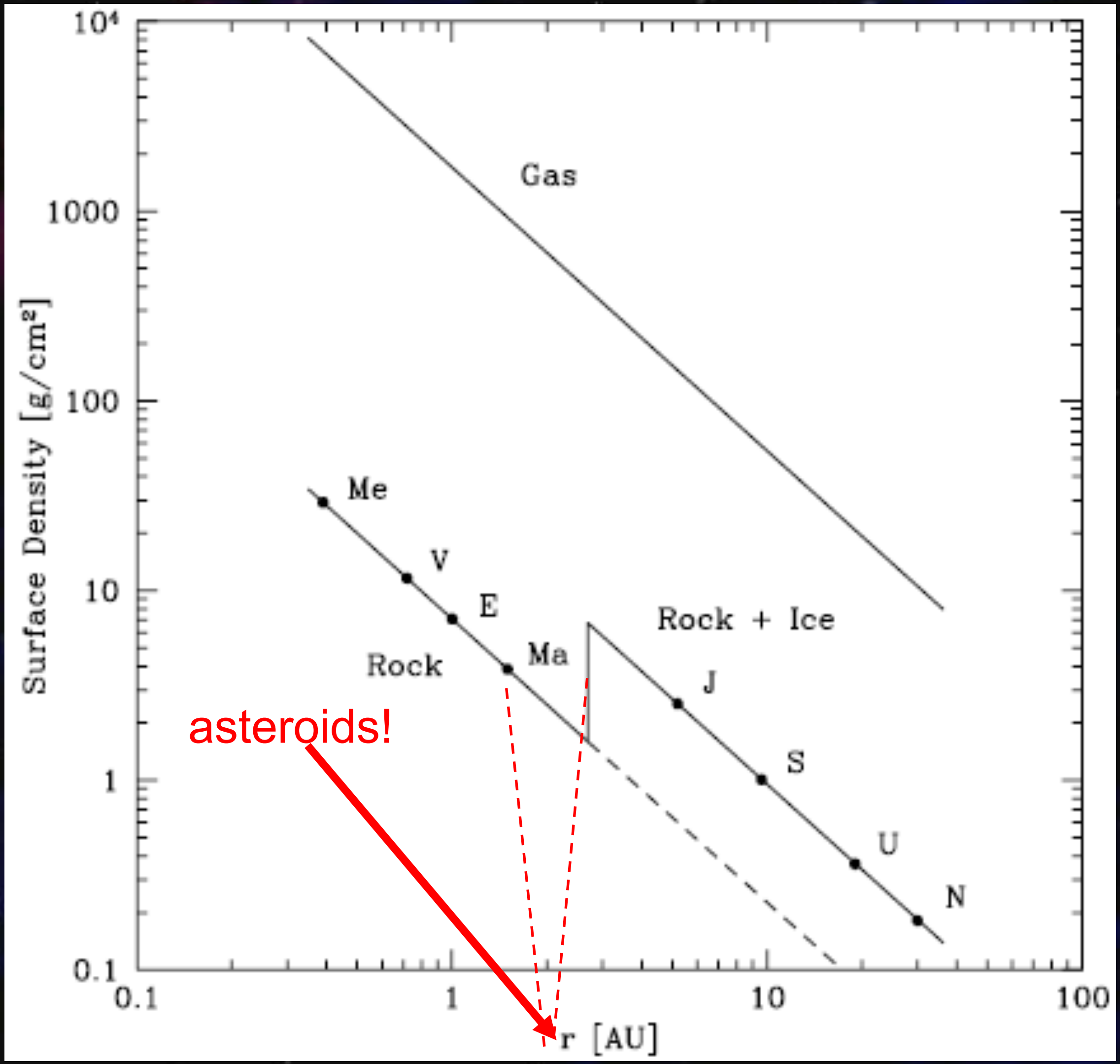


asteroid sizes





the asteroid belt: a factor 1000(!) mass deficit



Total mass: ~$0.0005M_{Earth}$

the asteroid belt:
problems to be solved by any formation scenario

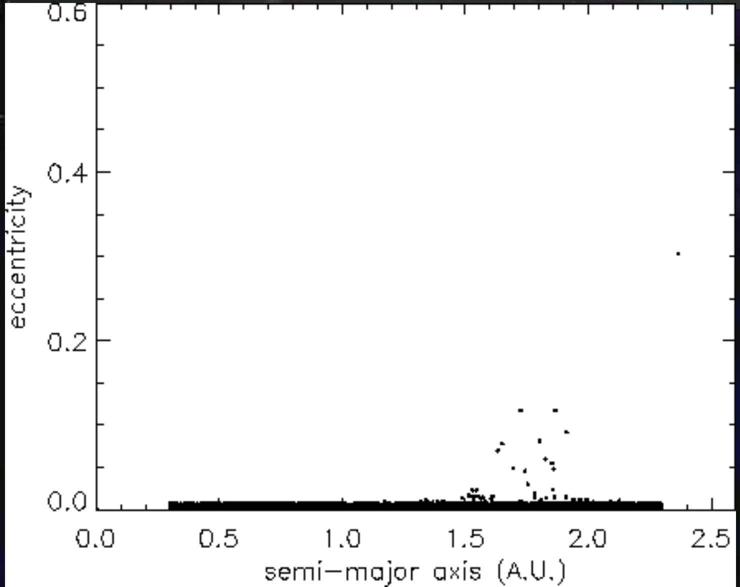
- Get rid of 99.9% of the mass initialy there
- Explain the present-day high-*e* & high-*i*
- Explain the current size distribution

the asteroid belt:

2 ways of getting rid of the mass

- Collisional erosion

- Dynamical ejection

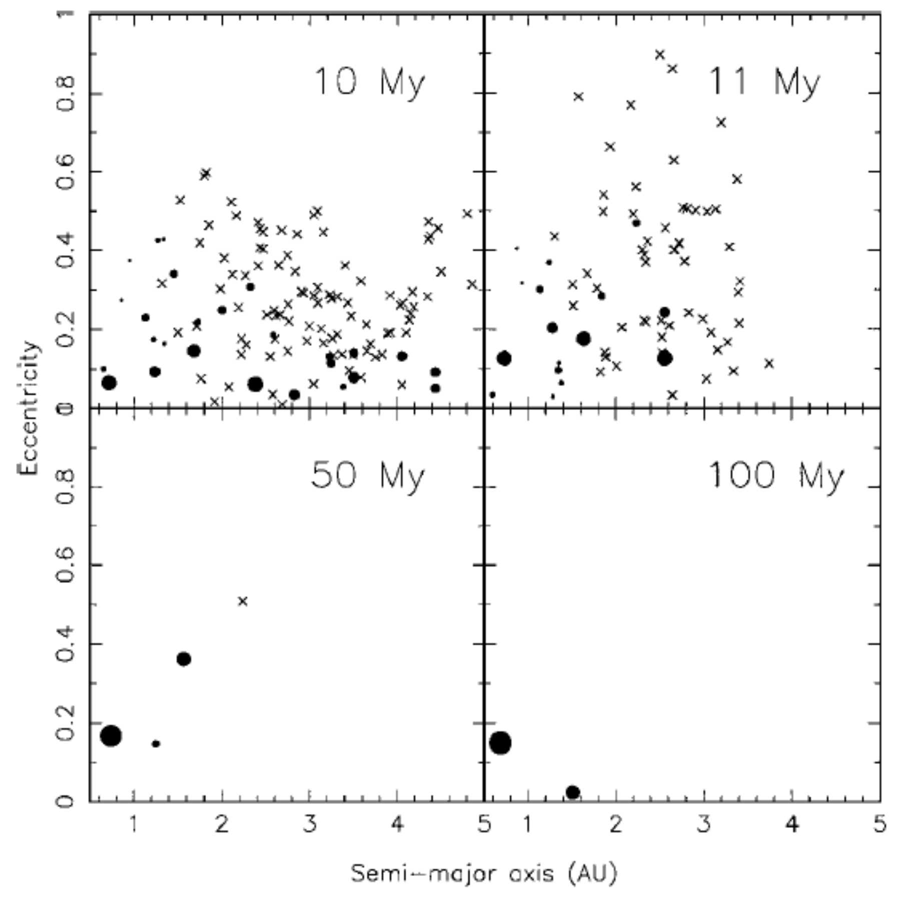


the asteroid belt:
a possible formation scenario (Petit et al.2001)

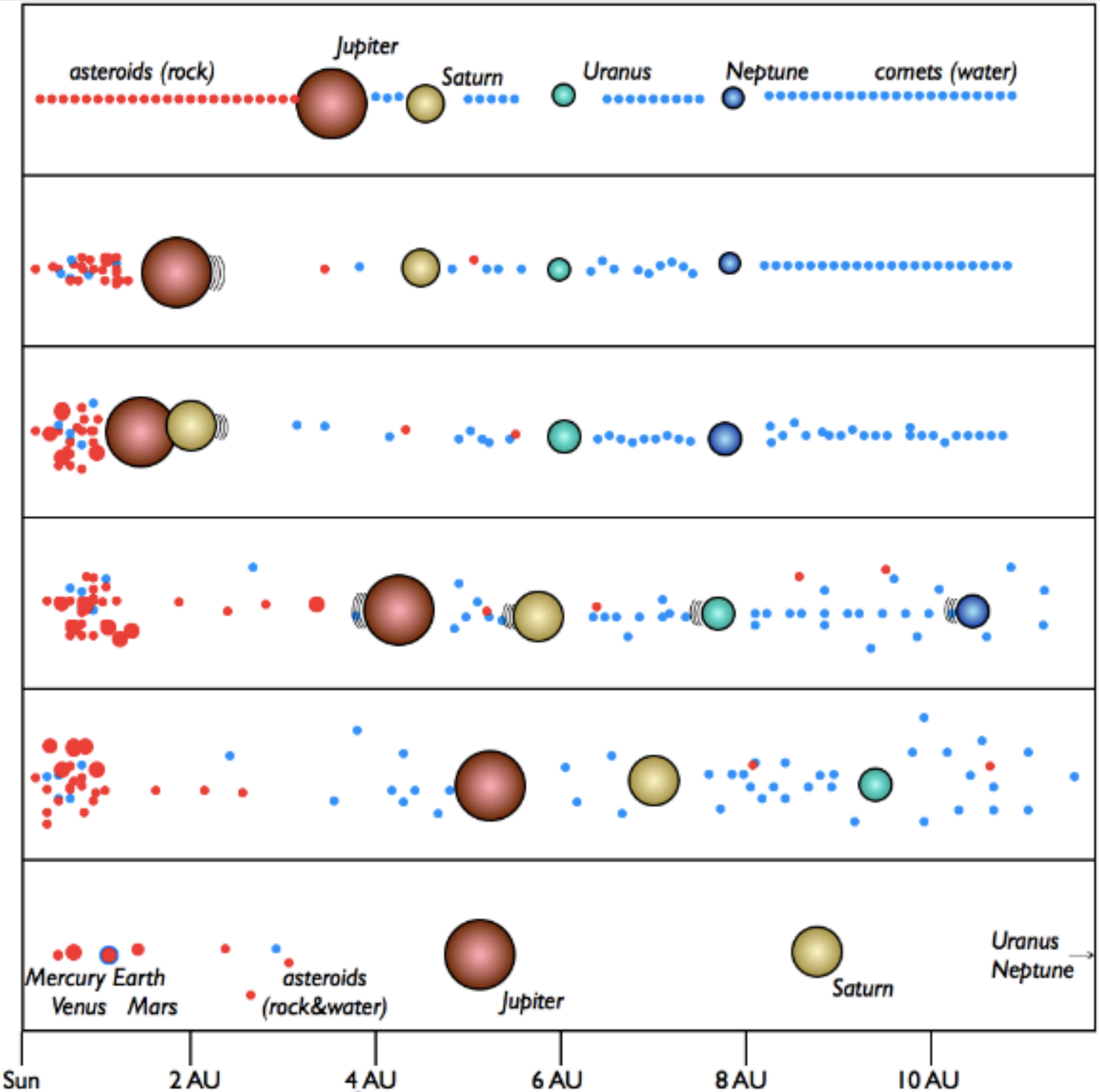
- **Step 1:** Lunar-sized planetary embryos form by runaway accretion. The asteroid region is moderately dynamicaly excited.

- **Step 2:** At $t \sim 10^7$ *yrs*, **Jupiter** arrives. Creates dynamically unstable regions in narrow chaotic Mean Motion Resonances

- **Step 3:** Small perturbations by the embryos regularly put bodies in the chaotic MMRs where they are rapidly ejected. After a few 10^6 years, 99.8% of objects are lost.



Forming the asteroid belt with the “Grand Tack”



Year 0:
Jupiter forms

Year 70,000:
Jupiter migrates inwards

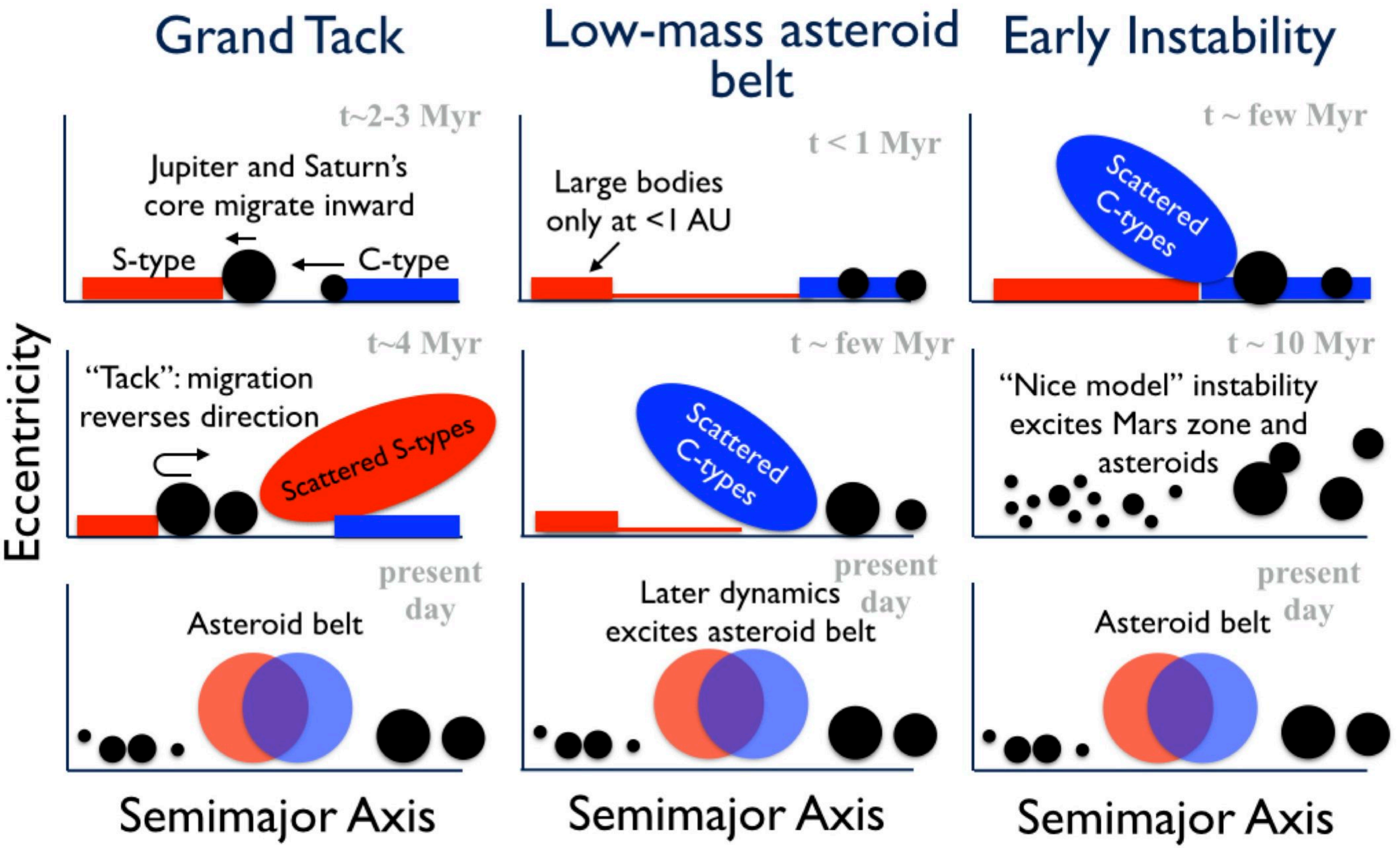
Year 100,000:
Saturn migrates to 3:2 resonance
formation of terrestrial planets

Year 300,000:
outward migration

Year 500,000:
end of “Grand Tack”

Year 600,000 to present:
after “Nice scenario”

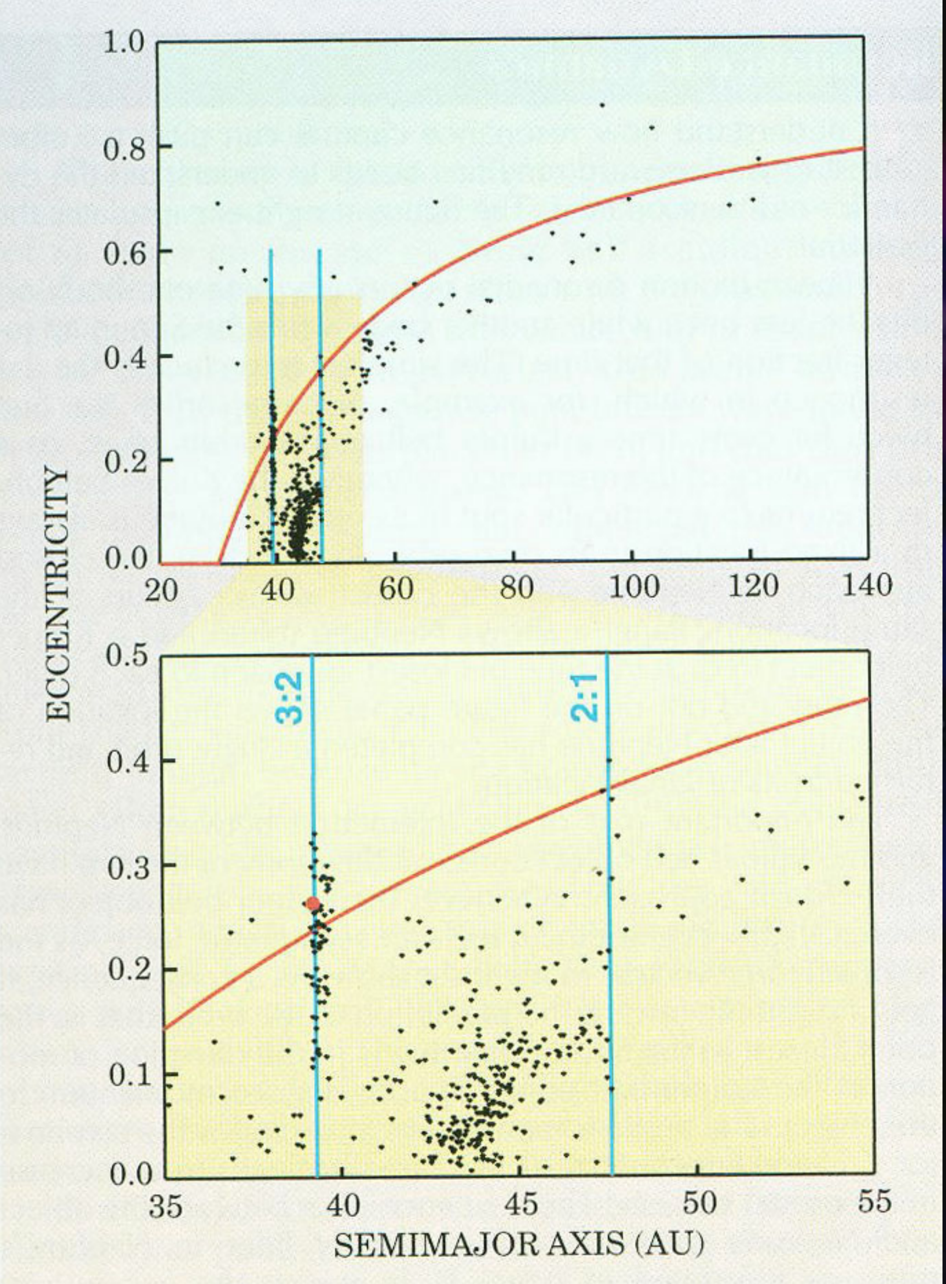
Alternative scenarios?



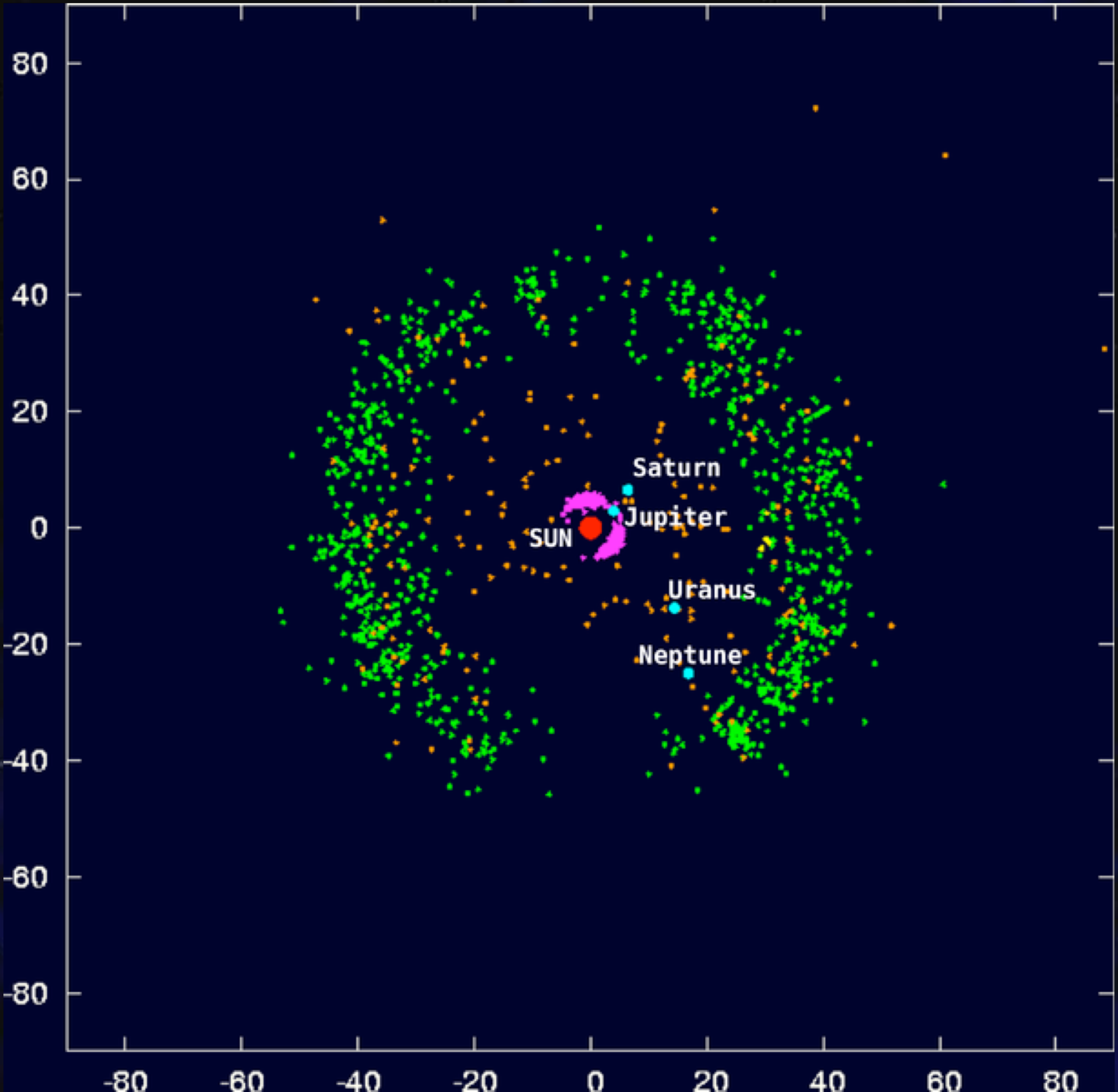
(Raymond et al., 2018)

the Kuiper belt

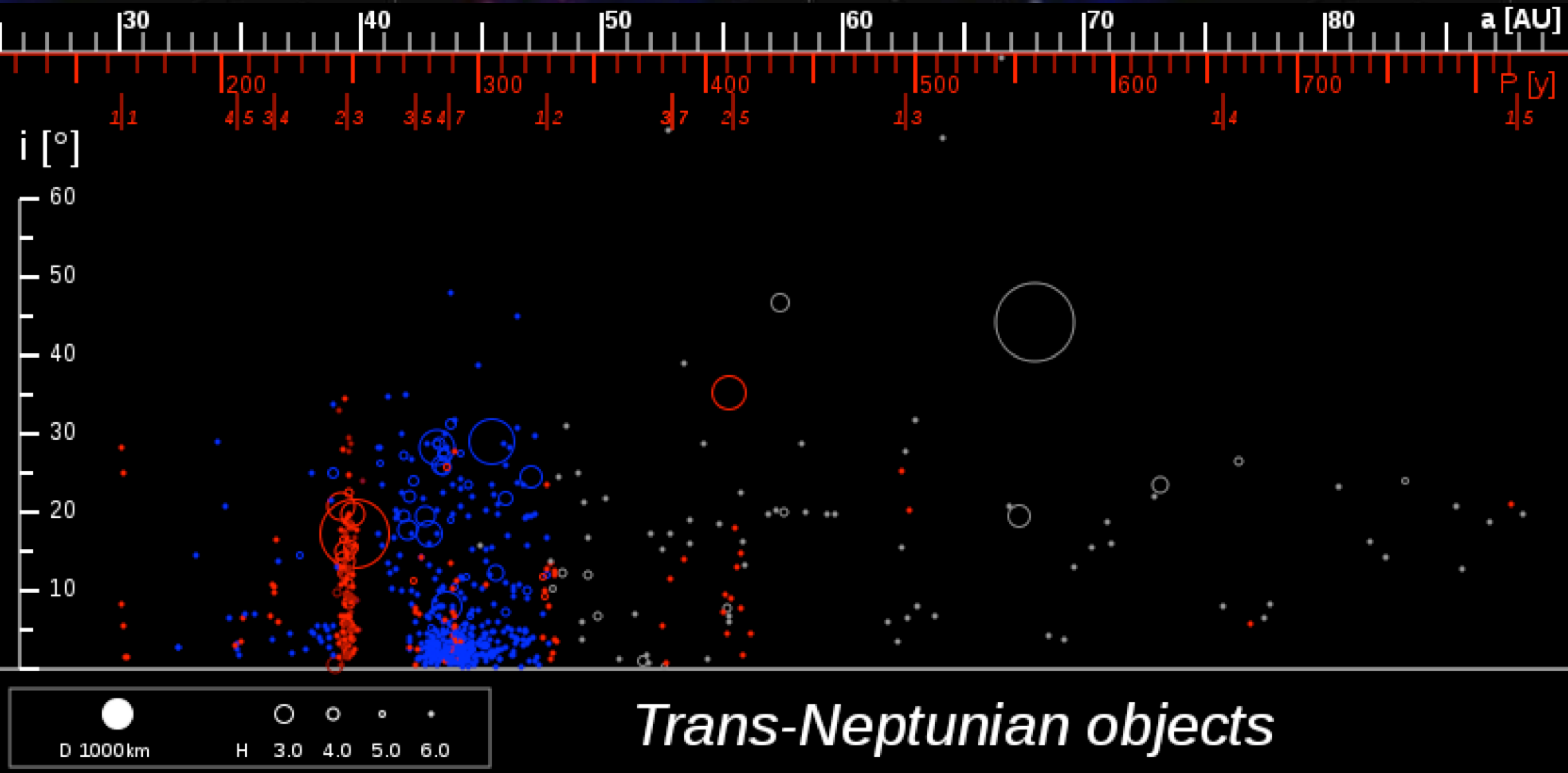
- •First suggested by Edgeworth (1949) and Kuiper (1951)
- •First object discovered in 1992 (Luu&Jewitt)
- •~1000 KBOs detected so far (2006)



the Kuiper belt: structure (1)



the Kuiper belt: structure (2)



Trans-Neptunian objects

Largest known KBOs (so far...)

the Kuiper belt: some puzzling facts

- ~10^4 objects>100km (?) Total mass ~$0.1M_{Earth}$ (?)

  => Mass deficit

- Highly structured spatial distribution

  => overdensity(?) of plutinos

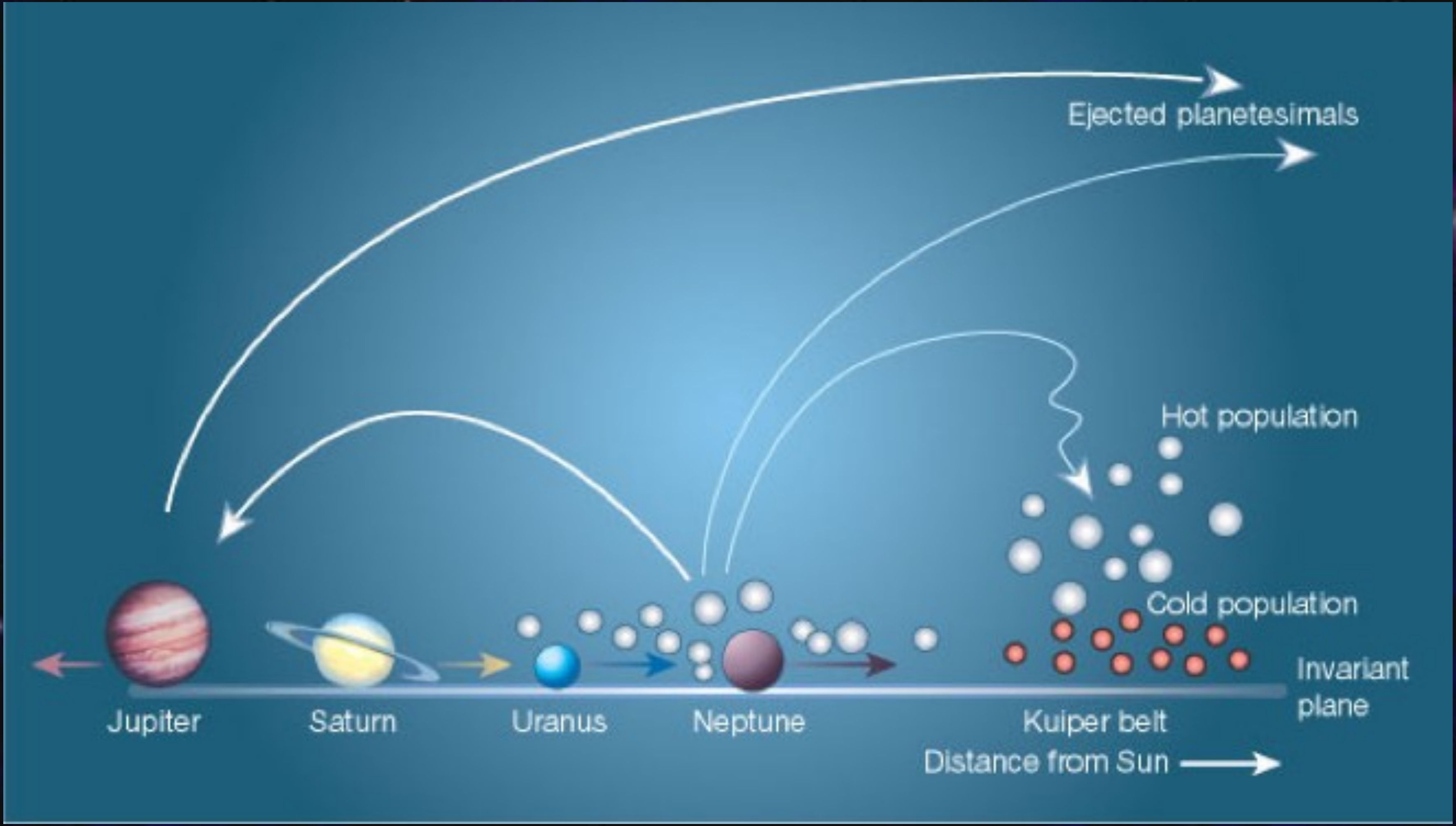
  => Outer edge at q=48 AU (1:2 Neptune res.)

- « Color gradient »: high excited « blue » objects & cold « red » objects => 2 different populations(?)

The Kuiper Belt paradox:

Need a massive disc (>10M_{Earth}) to built the KBOs, but how to get rid of it?

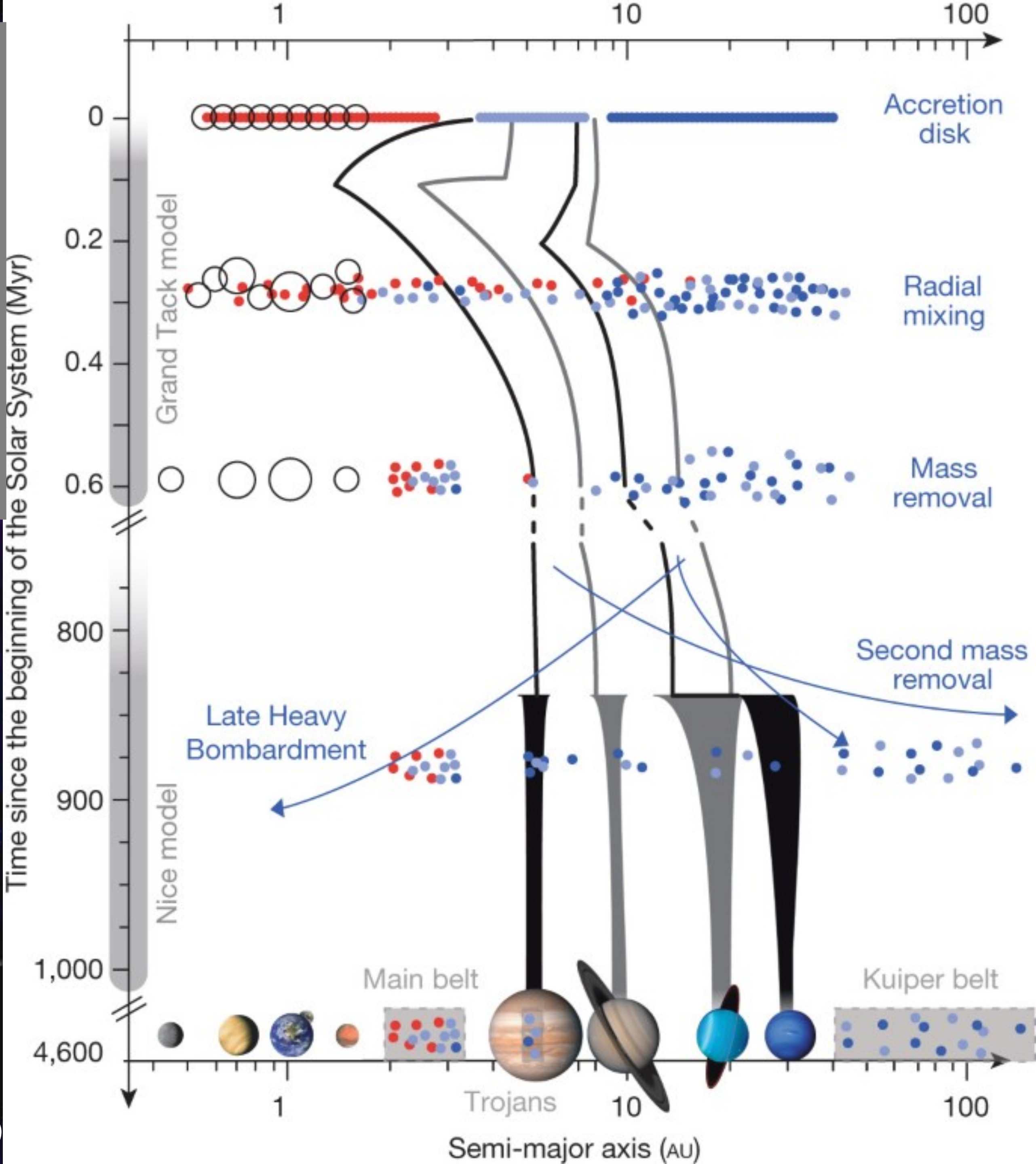
forming the Kuiper belt by Neptune's migration



(Gomes, 2003)

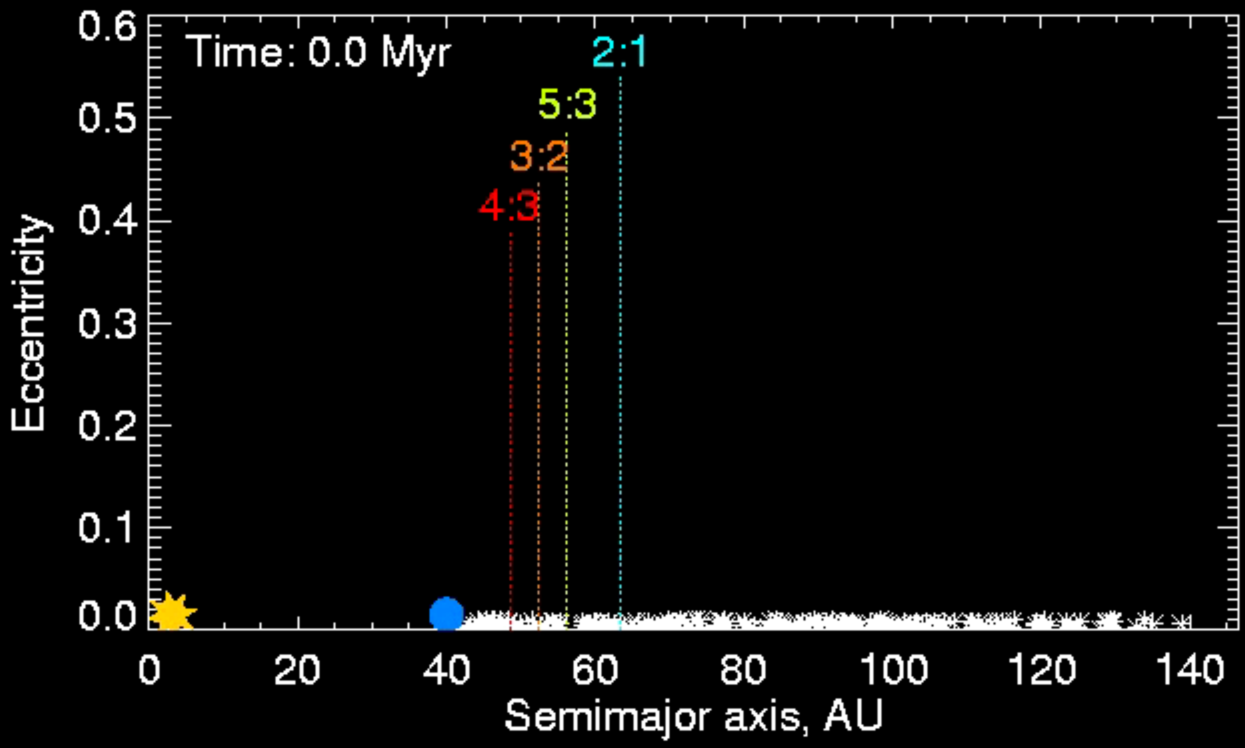
forming the Kuiper belt with the “Grand Tack” followed by the “Nice model”

?



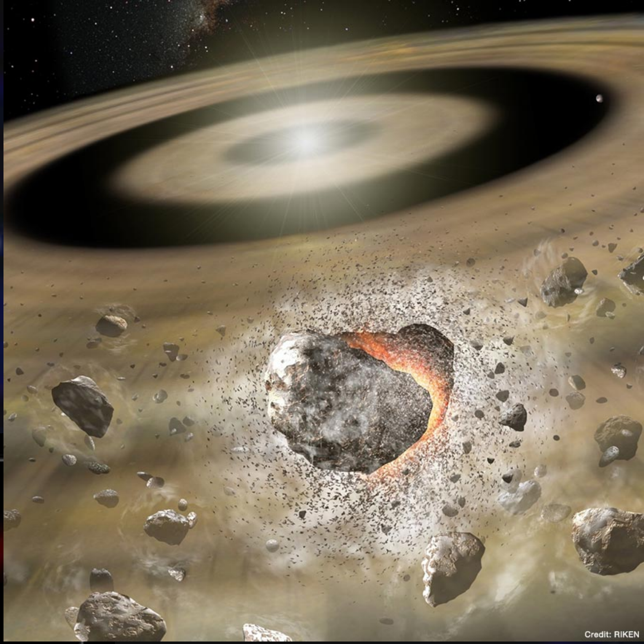
(DeMeo&Carry, 2014)

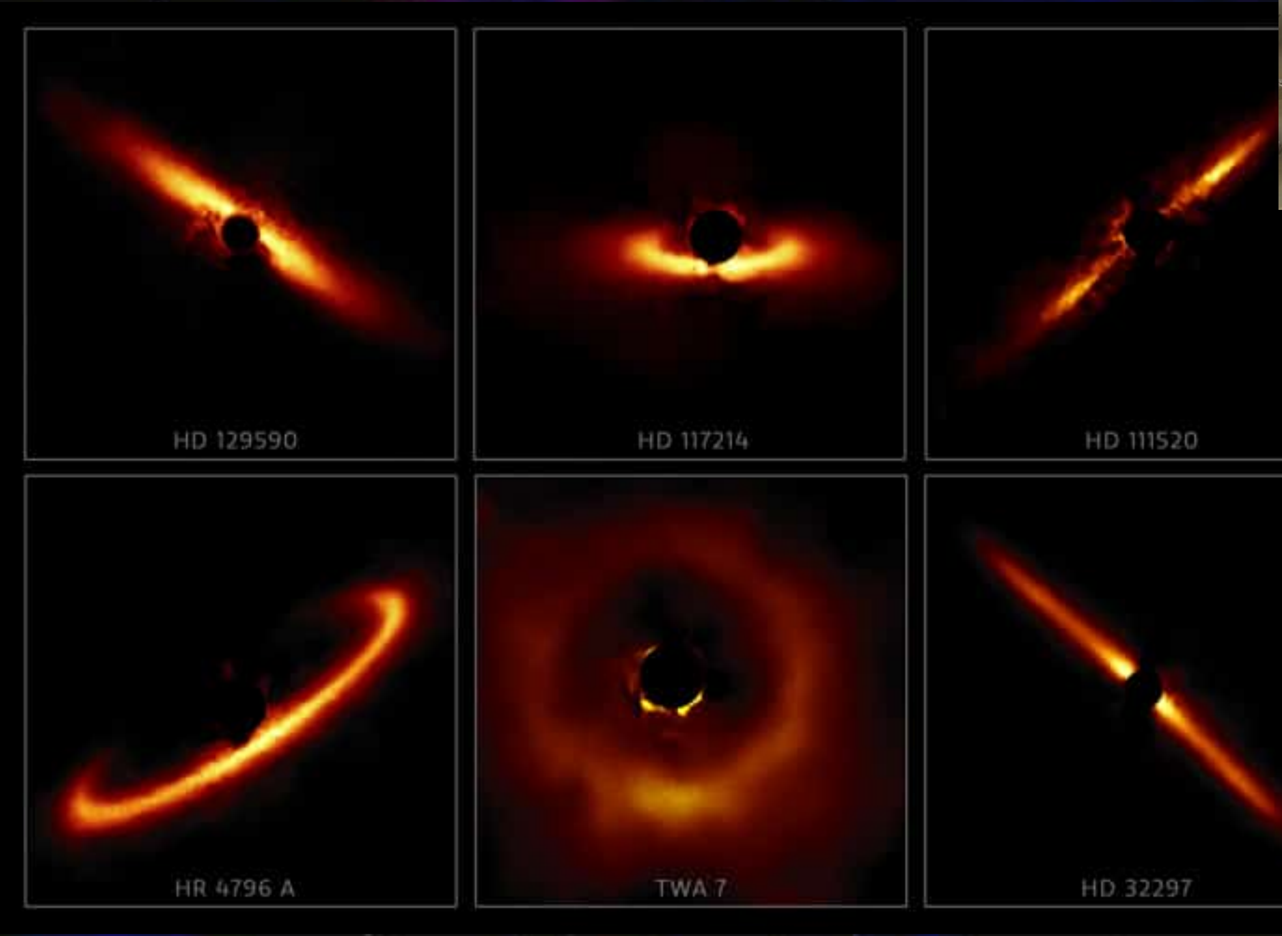
The outward migration of a Neptune mass planet (●) around Vega sweeps many comets (∗) into the planet's resonances



(from Wyatt, 2005)

« exo »-asteroid and Kuiper-belts

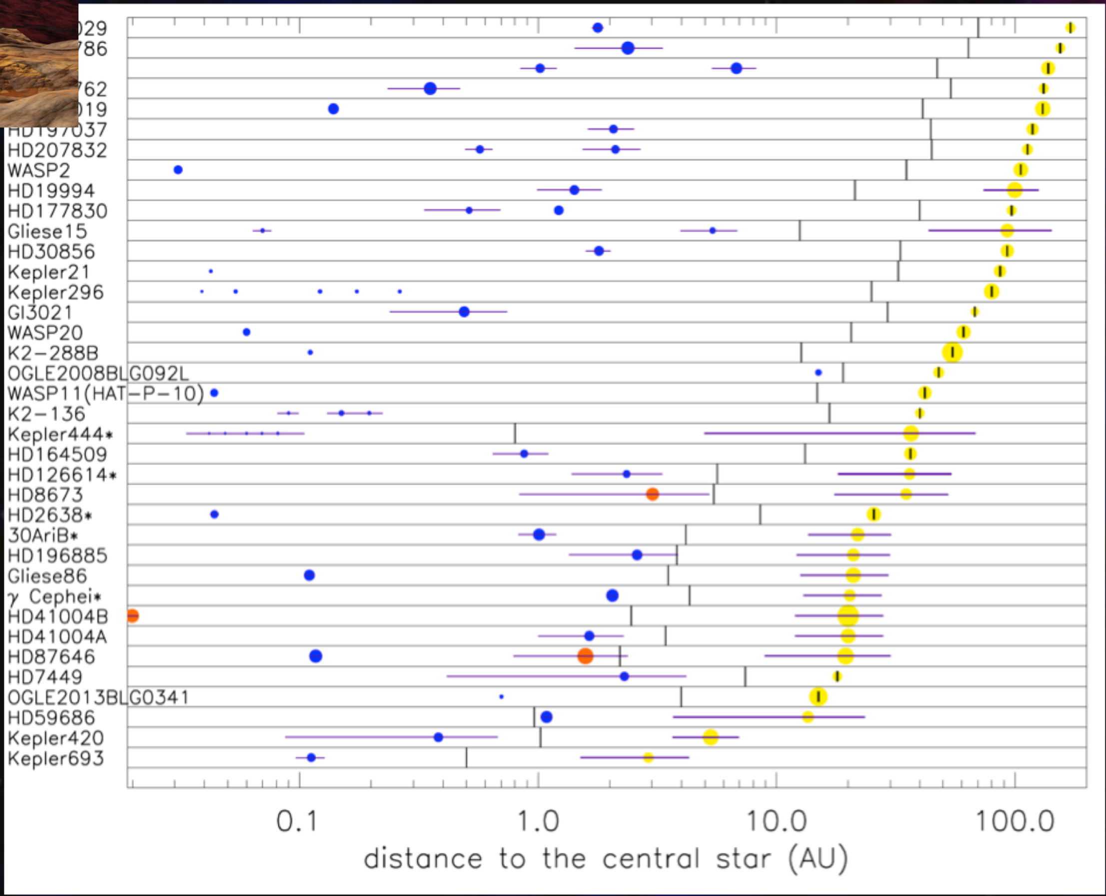

Credit: RIKEN



Debris discs!

Made of small fragments produced by destructive collisions in the belts

200 exoplanets in binaries



The greatest challenge to the « standard » model?