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Evoluzione termofisica dei corpi minori del Sistema Solare

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Definition of Small Solar System Bodies

(1) A **PLANET** IS A CELESTIAL BODY THAT:

a) IS IN ORBIT AROUND THE SUN;

b) HAS SUFFICIENT MASS FOR ITS SELF-GRAVITY TO OVERCOME RIGID BODY FORCES SO THAT IT ASSUMES A HYDROSTATIC EQUILIBRIUM (NEARLY ROUND) SHAPE;

c) HAS CLEARED THE NEIGHBOURHOOD AROUND ITS ORBIT.

(2) A "**DWARF PLANET**" IS A CELESTIAL BODY THAT:

a) IS IN ORBIT AROUND THE SUN;

b) HAS SUFFICIENT MASS FOR ITS SELF-GRAVITY TO OVERCOME RIGID BODY FORCES SO THAT IT ASSUMES A HYDROSTATIC EQUILIBRIUM (NEARLY ROUND) SHAPE;

c) HAS NOT CLEARED THE NEIGHBOURHOOD AROUND ITS ORBIT;

d) IS NOT A SATELLITE.

(3) All other objects, except satellites, orbiting the Sun shall be referred to collectively as "**Small Solar System Bodies**".

Why studying small bodies?

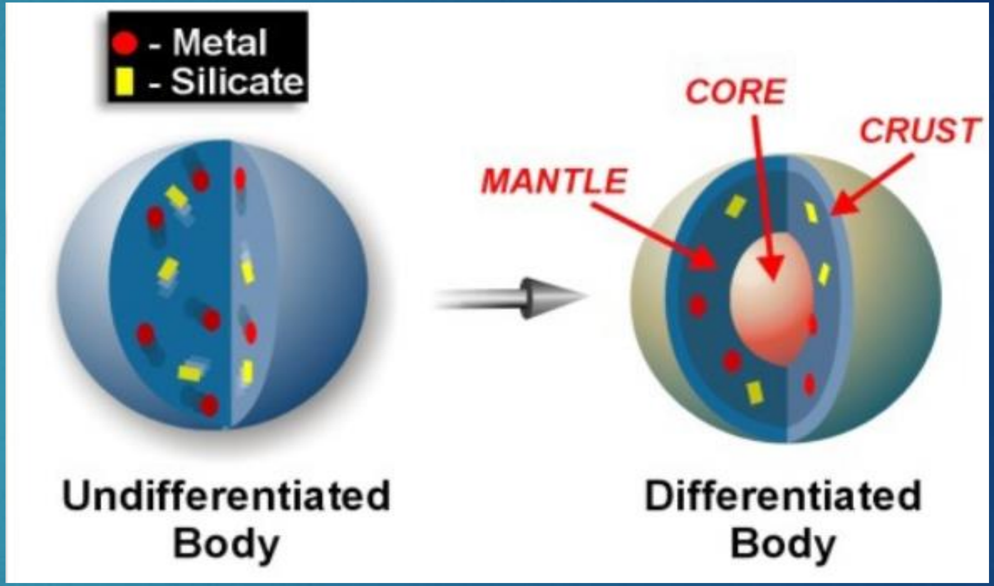
SMALL BODIES ARE OBJECTS THAT HAVE PRESERVED INFORMATION ABOUT THE PRIMORDIAL PHASES OF OUR SOLAR SYSTEM.

↓

*Information about the **primordial processes** of the **planetary formation**, **water origin** on Earth, **water role** in the thermophysical evolution of planets, role of the **organics**, etc...*

What is the planetary differentiation?

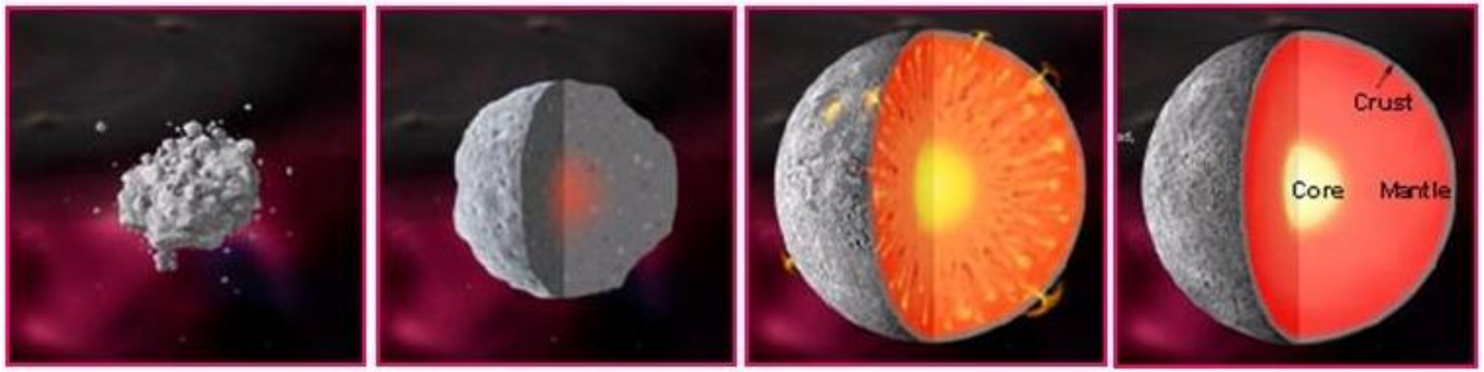
- DIFFERENTIATION MEANS TO MAKE A HOMOGENOUS BODY HETEROGENEOUS.
- IT IS THE PROCESS THAT LEADS TO THE STRATIFICATION OF THE ASTEROID/PLANET BASED ON ITS PHYSICAL AND/OR CHEMICAL PROPERTIES.



DIFFERENTIATION → MINIMIZATION OF GRAVITATIONAL POTENTIAL ENERGY

Main stages of the life of a small body

- ***Accretion***
- ***Sintering***
- ***Core Formation***
- ***Mantle convection***
- ***Cooling phase***



Minimum Size for Differentiation

The **minimum size** for the **differentiation** will be set by the rate of **conductive heat loss**.

The **characteristic timescale** for the **thermal conduction** into a body of radius R is **R^2/K**, where K is the thermal diffusivity.

The **minimum size** for the **differentiation** will occur when the heat flux is maximum (i.e.instantaneous accretion). The approximate conductive cooling time for a planetesimal with **instanenous accretion** is given by (Moskovitz & Gaidos 2011):

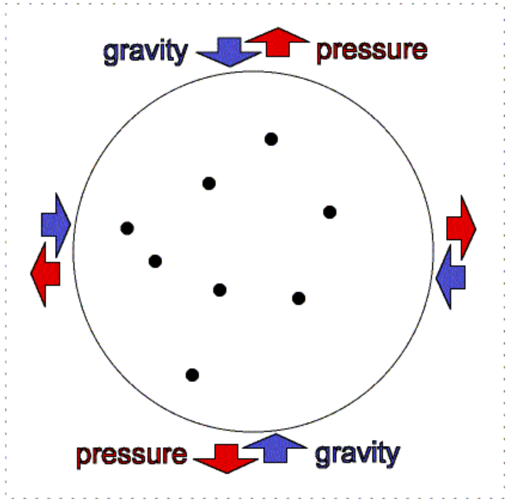
$$\boxed{\tau_{cool} = 0.014Ma\left(\frac{R}{1km}\right)^2}$$

Planetesimals with **τ_{cool}** longer than the most important heating timescale (**τ_{Al26}**) will sustain melting temperatures and differentiate. The minimum size is **18 km**.

Hydrostatic equilibrium & Differentiation

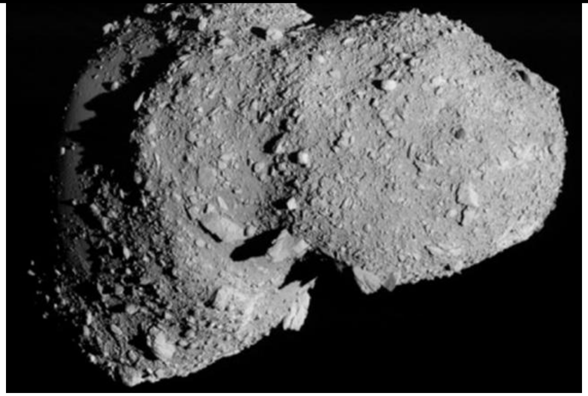
Can we assume that a **differentiated body** is also in **hydrostatic equilibrium** (HE)?

HE implies that the body has a spherical shape (neglecting the rotation) to minimize gravitational potential. We can not assume that all differentiated bodies achieved HE, even if small asteroids are differentiated, it is unlikely they have sufficient mass to reach spherical form.



HYDROSTATIC EQUILIBRIUM

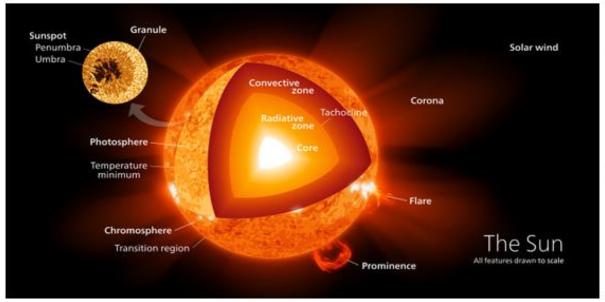
NOT HYDROSTATIC EQUILIBRIUM



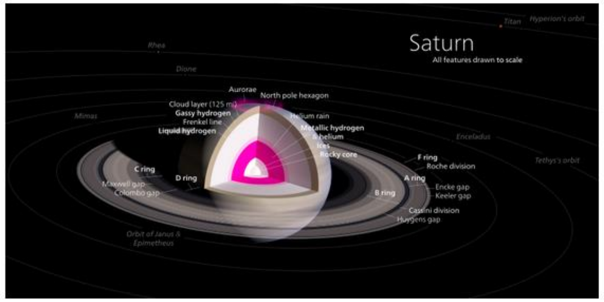
DIFFERENTIATION ↛ **HYDROSTATIC EQUILIBRIUM**

Moment of Inertia Factor & Differentiation

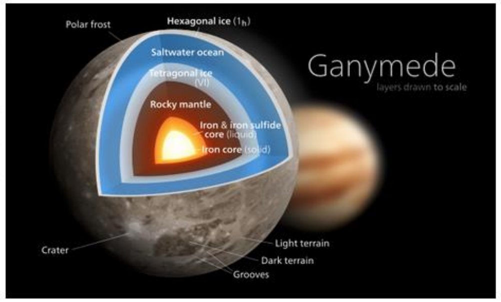
- In Planetary Science, **momentum** of **Inertia** factor (MoI) is linked to the **radial distribution** of **mass** inside a celestial body. For a **differentiated** planet or satellite, where there is an increase of density with depth, **$C/MR^2 < 0.4$** (which corresponds to the **homogeneous sphere**).



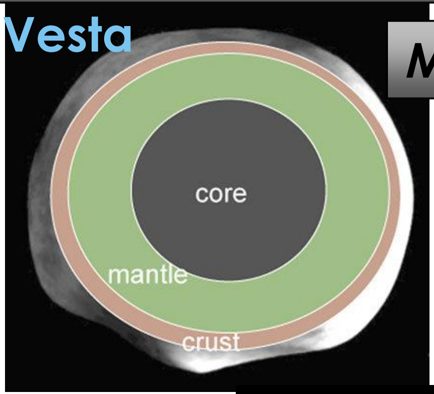
MoI = 0.070



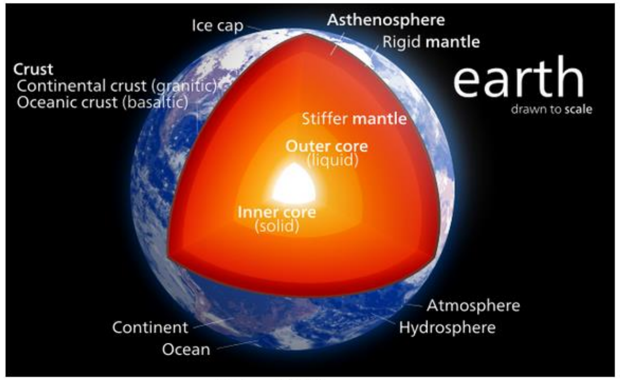
MoI = 0.22



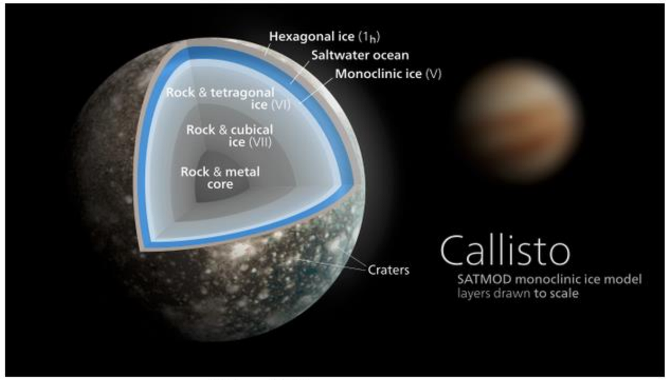
MoI = 0.31



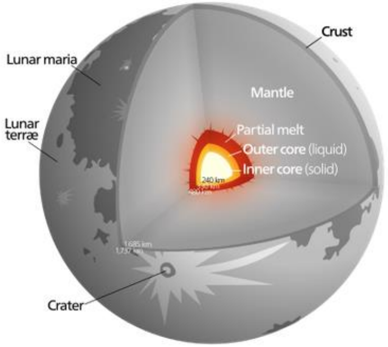
MoI = 0.33



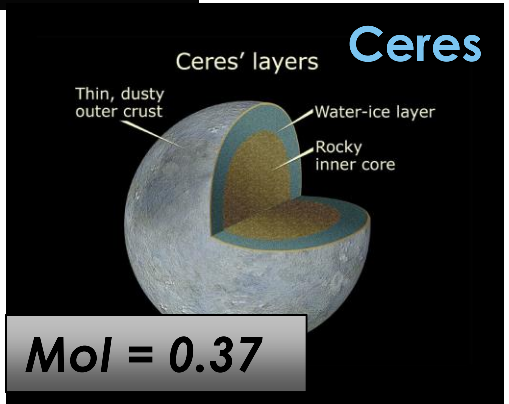
MoI = 0.33



MoI = 0.25

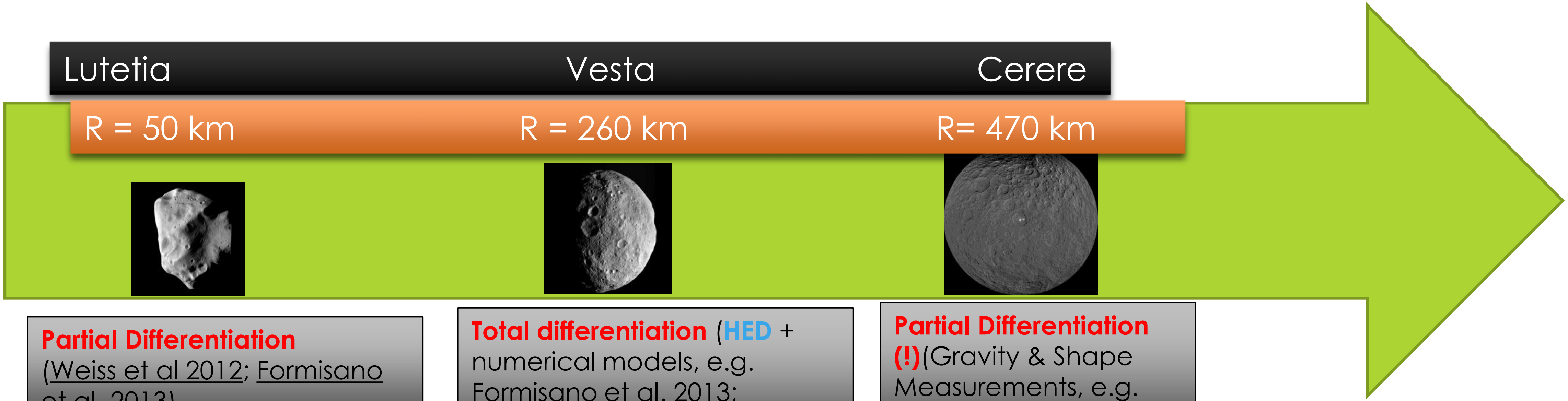


MoI = 0.39



MoI = 0.37

Size & Differentiation



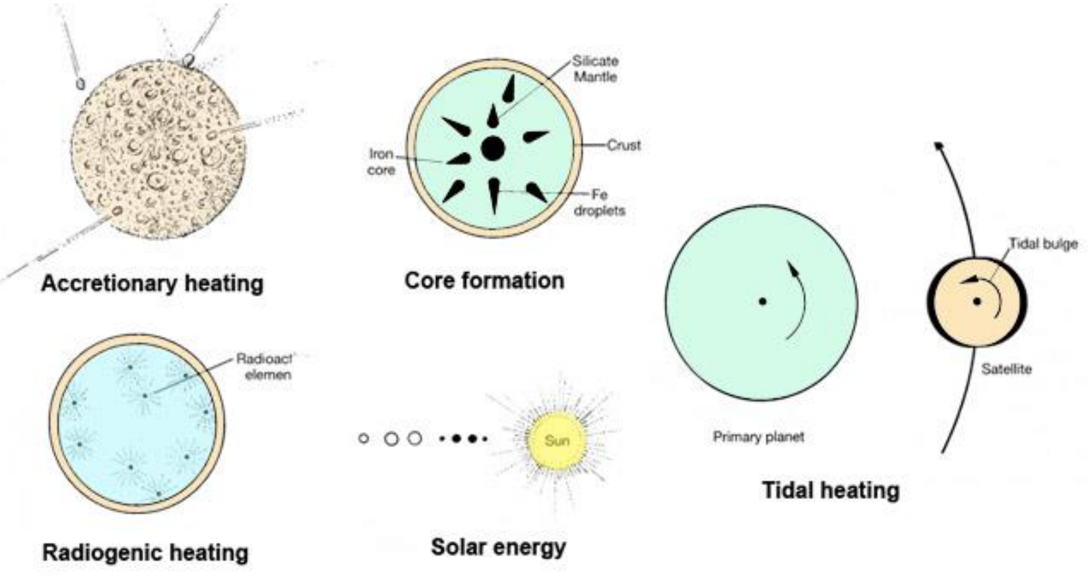
Partial Differentiation (Weiss et al 2012; Formisano et al. 2013)

Total differentiation (**HED** + numerical models, e.g. Formisano et al. 2013; Neumann et al. 2014.)

Partial Differentiation **(!)**(Gravity & Shape Measurements, e.g. Park et al. 2016)

Sources of Energy

- The **decay** of **short-lived radioactive** elements such as **26Al** (primary heat source), 60Fe or of **long-lived radioactive** elements such as 40K, 232Th, 235U and 238U;
- **Accretion process**;
- The **differentiation process**, i.e. the separation of the metallic component to the silicatic one;
- **Tidal heating**;
- The **impacts** with other bodies;
- **Electrical induction** by an early T-Tauri like solar wind;



Energy Source Requirements

I) POWERFUL, since small bodies have a high surface/volume ratio;

II) FAST, as suggested by the measurements on Hf – W ratio in iron meteorites (Kleine 2002);

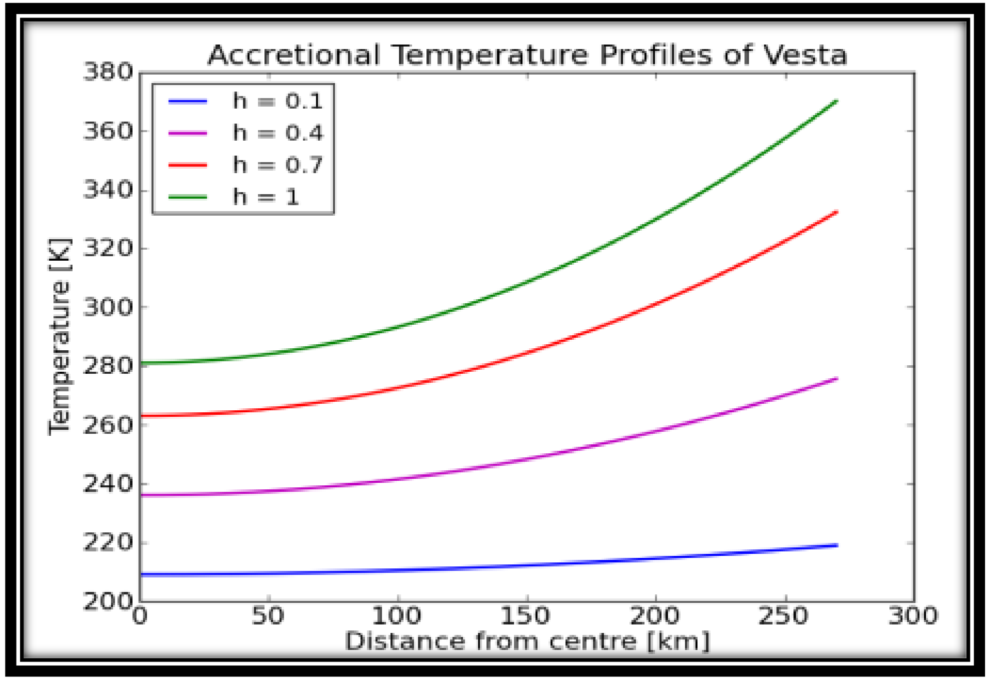
III) **UNIFORMLY DISTRIBUTED** in our galaxy

Accretional Heating

- The **fraction** (h) of heat retained during **accretion** is very poorly known. In terms of h, we can approximate the **accretional temperature T_A** at radius r within an accumulating planetesimal as (Schubert et al. 1986):

$$T_A(r) = \frac{hGM(r)}{c_v r}\left[1+\frac{rv^2}{2GM(r)}\right]+T_E$$

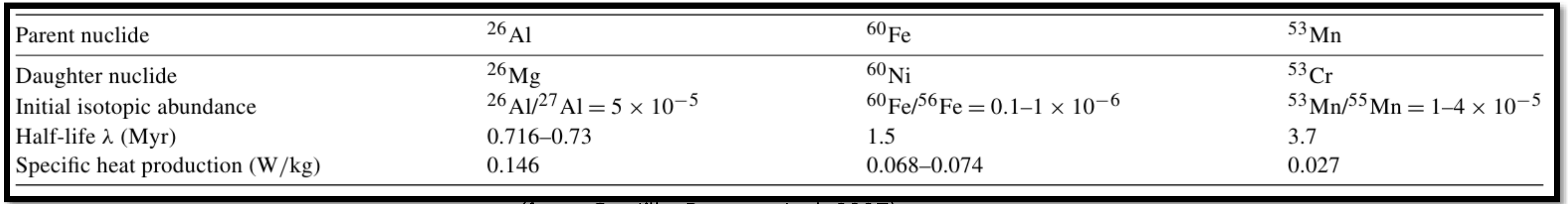
- If **accretion** is **slow**, heat will be **radiated into space** faster than it is delivered and the body will not heat up. If accretion is **fast**, heat will be **stored** and the temperature of the body will increase. Depending on the amount stored heat and on the size of the body, the **accretion profile** can rise the **melting temperature** of **iron** and possibly of **silicate**.
- In the optimistic case in which the **50%** of the **energy** is **converted** in **heat** and stored in the asteroid, i.e. h = 0.5, the **temperature increase** is only about **50K**.



For the **Earth**, **accretion** is the main source of energy: **ΔT ≥ 1000 K** (Solomon 1989)

C_v = specific heat;
T_E = ambient temperature;
$V^2/2$ = approach kinetic energy per unit of mass;
M(r) = mass of the accreting asteroid internal to r;
h = efficiency.

Short-lived Radionuclides



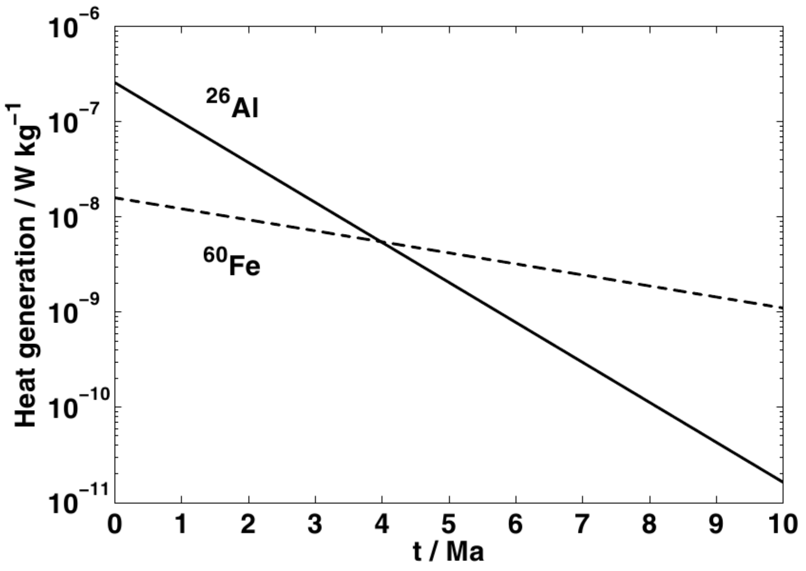
Parent nuclide	^{26}Al	^{60}Fe	^{53}Mn
Daughter nuclide	^{26}Mg	^{60}Ni	^{53}Cr
Initial isotopic abundance	$^{26}\mathrm{Al}/^{27}\mathrm{Al} = 5 \times 10^{-5}$	$^{60}\mathrm{Fe}/^{56}\mathrm{Fe} = 0.1\text{–}1 \times 10^{-6}$	$^{53}\mathrm{Mn}/^{55}\mathrm{Mn} = 1\text{–}4 \times 10^{-5}$
Half-life λ (Myr)	0.716–0.73	1.5	3.7
Specific heat production (W/kg)	0.146	0.068–0.074	0.027

(from Castillo-Rogez et al. 2007)

26Al is uniformly distributed in our Galaxy (MacPherson 1995); 🙂

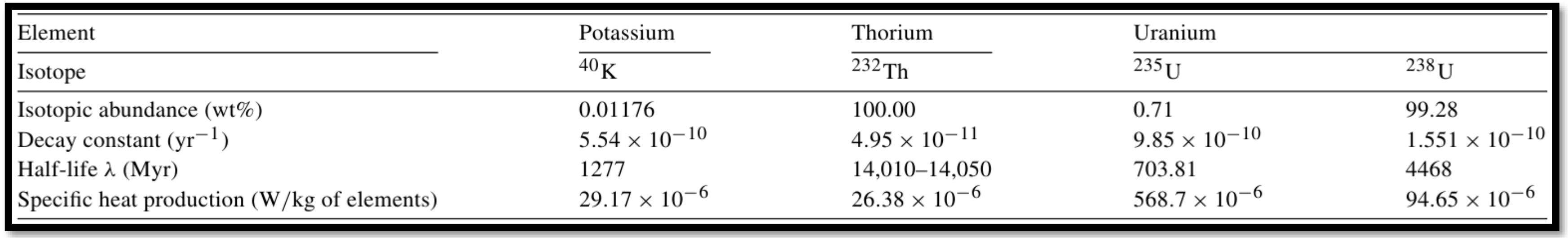
It is a strong source (3 MeV per decay);🙂

Short half-life (0.7 Ma) 🙂



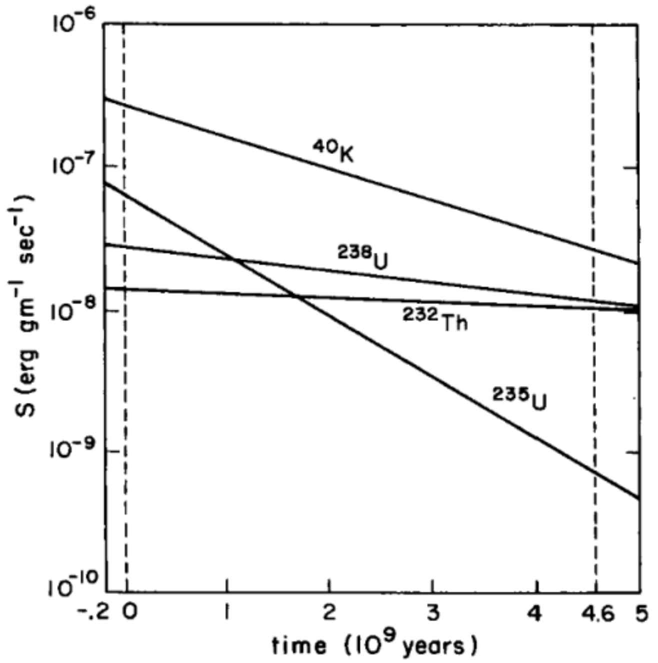
Long-lived Radionuclides

The most important **long-lived radionuclides** are **238U**, **235U**, **232Th** and **40K**: decay information about these elements are reported in the following table (Castillo-Rogez et al. 2009) :

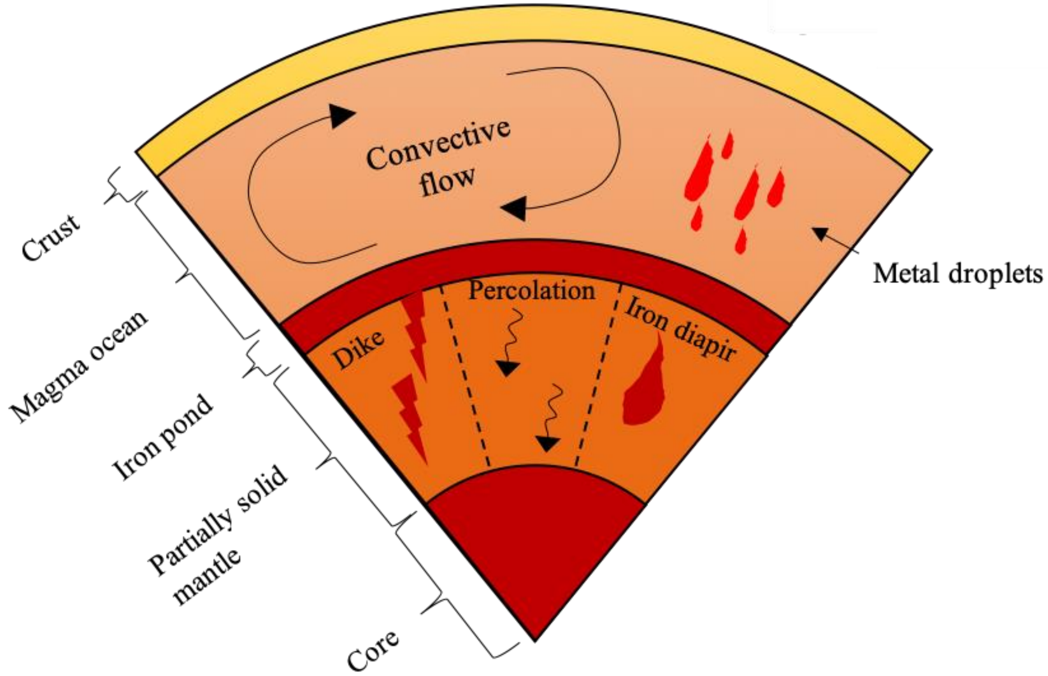


Element	Potassium	Thorium	Uranium	
Isotope	^{40}K	^{232}Th	^{235}U	^{238}U
Isotopic abundance (wt%)	0.01176	100.00	0.71	99.28
Decay constant (yr^{-1})	5.54×10^{-10}	4.95×10^{-11}	9.85×10^{-10}	1.551×10^{-10}
Half-life λ (Myr)	1277	14,010–14,050	703.81	4468
Specific heat production (W/kg of elements)	29.17×10^{-6}	26.38×10^{-6}	568.7×10^{-6}	94.65×10^{-6}

These long-lived radionuclides are still present in the Earth and other planetary bodies, although in lower abundances with respect to the Solar System formation. This allows for sustained **long-term heating** during planetary evolution.



Magma Ocean & Core Formation

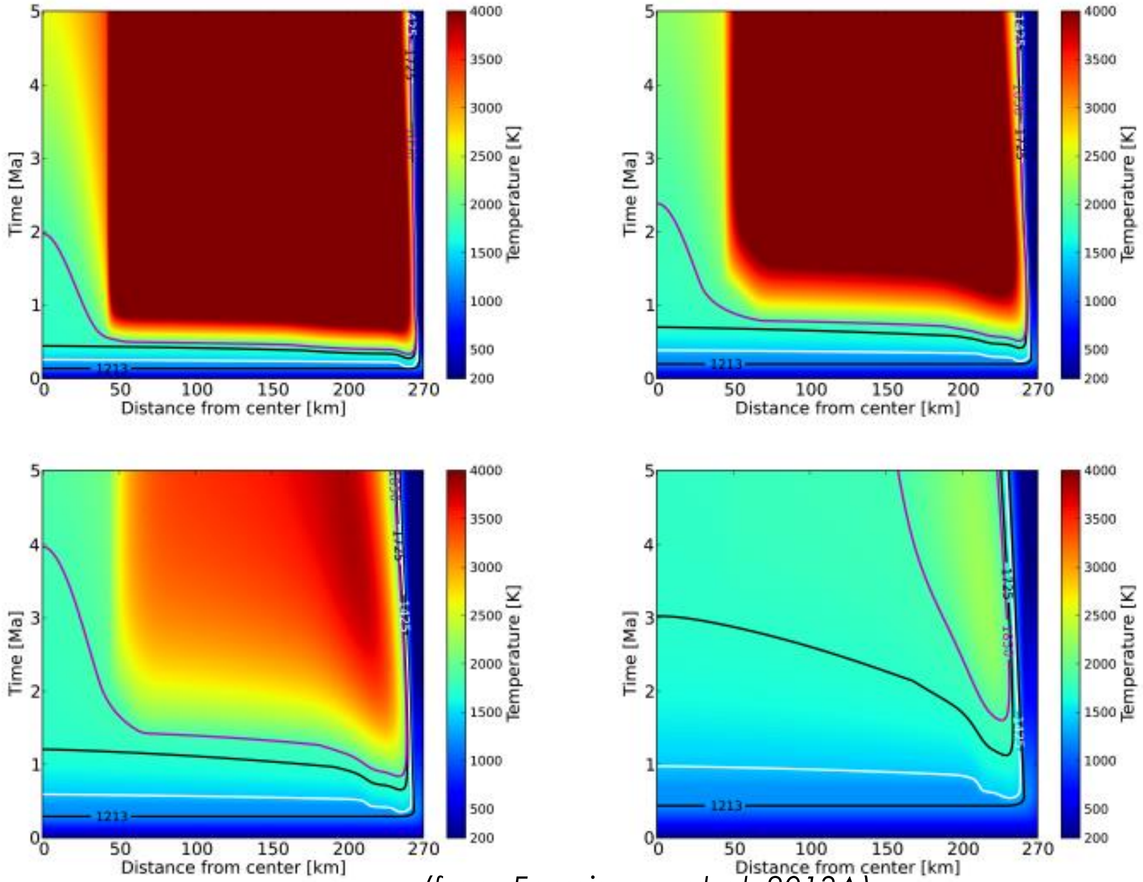


If **T > 1400 K** (Neumann et al. 2013) -> **Magma Ocean** (Righter & Drake 1997) in which iron drops migrates at the bottom creating a core (Stevenson 1990).

The **velocity** of **iron drops** is directly proportional to the density difference with the silicate matrix and to the radius^2 and inverse proportional to the viscosity (**Stoke law**).

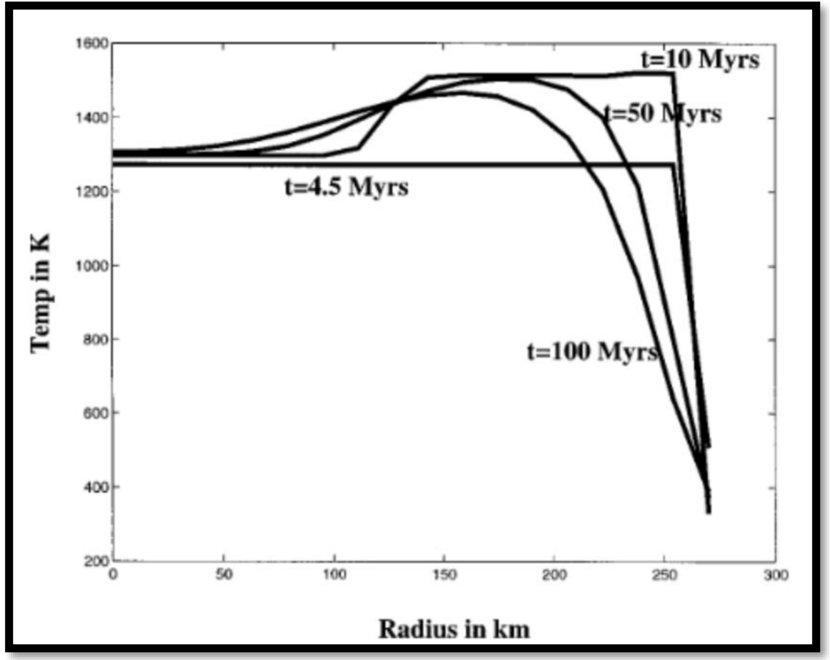
Crystallization sequence in the magma ocean follows the **Bowen's series**.

Some Results: Vesta



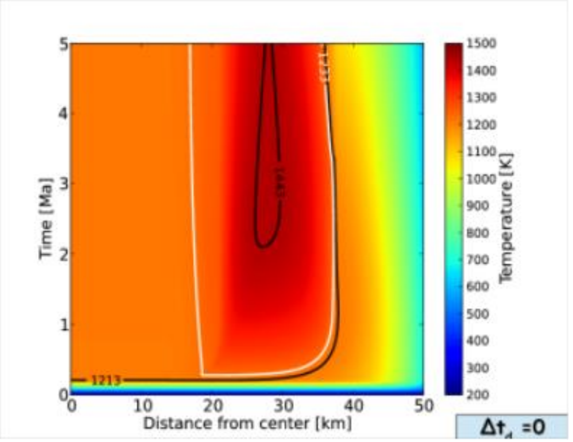
(from Formisano et al. 2013A)

26Al affinity with **silicates** leads to the formation of a peculiar **temperature** profile, with the **peak** in the **mantle** (Ghosh & McSween 1998, Formisano et al. 2013A).

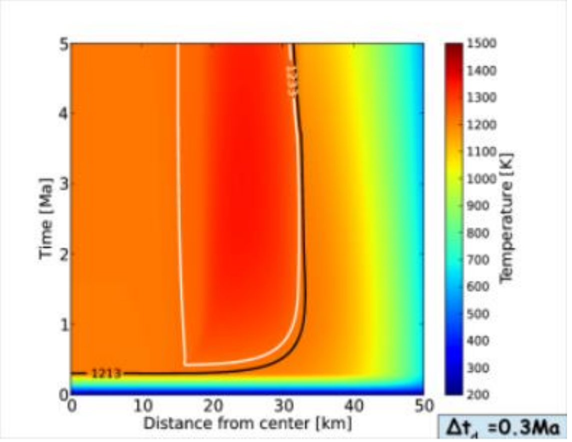


(from Ghosh & McSween 1998)

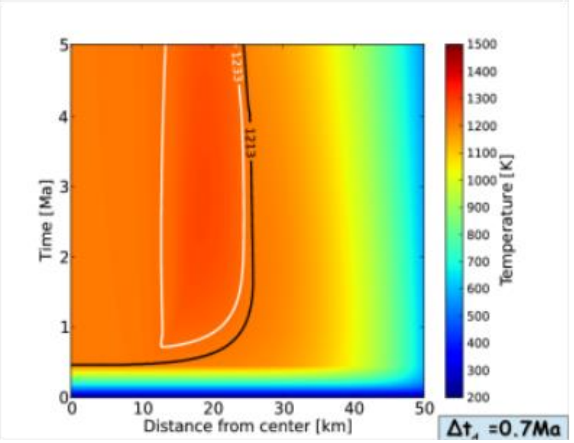
Some Results: Lutetia



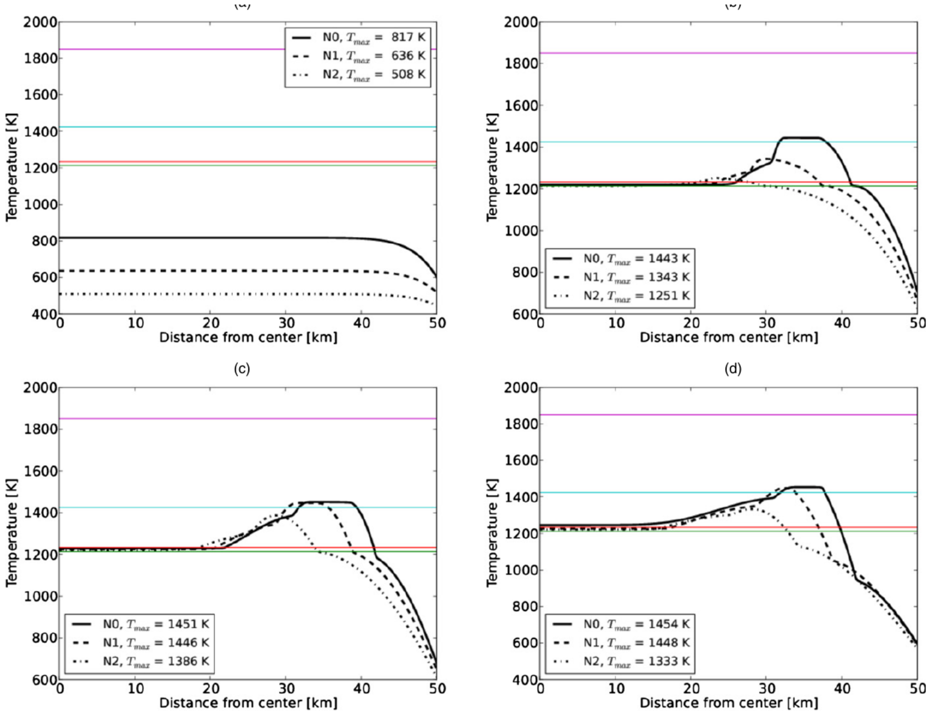
Δt_d =0



Δt_d =0.3Ma



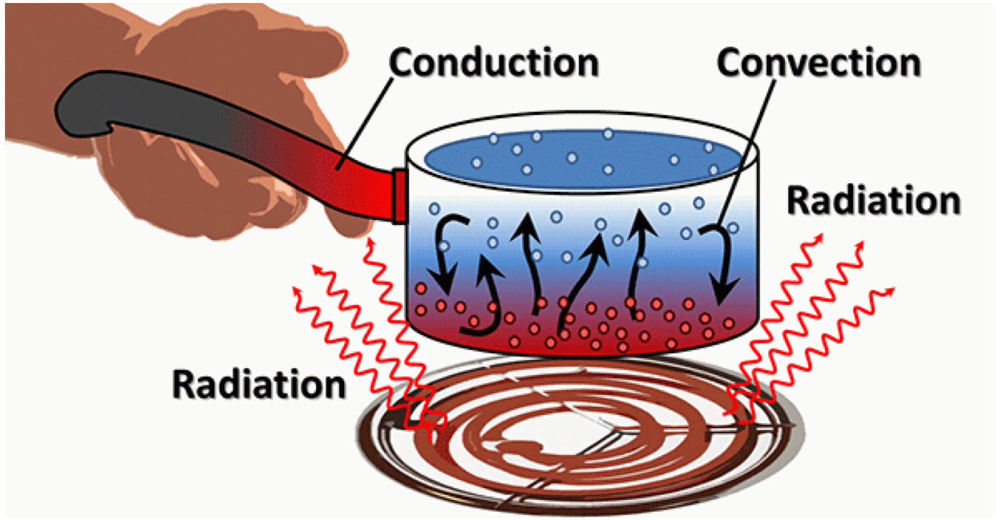
Δt_d =0.7Ma



(from Formisano et al. 2013B)

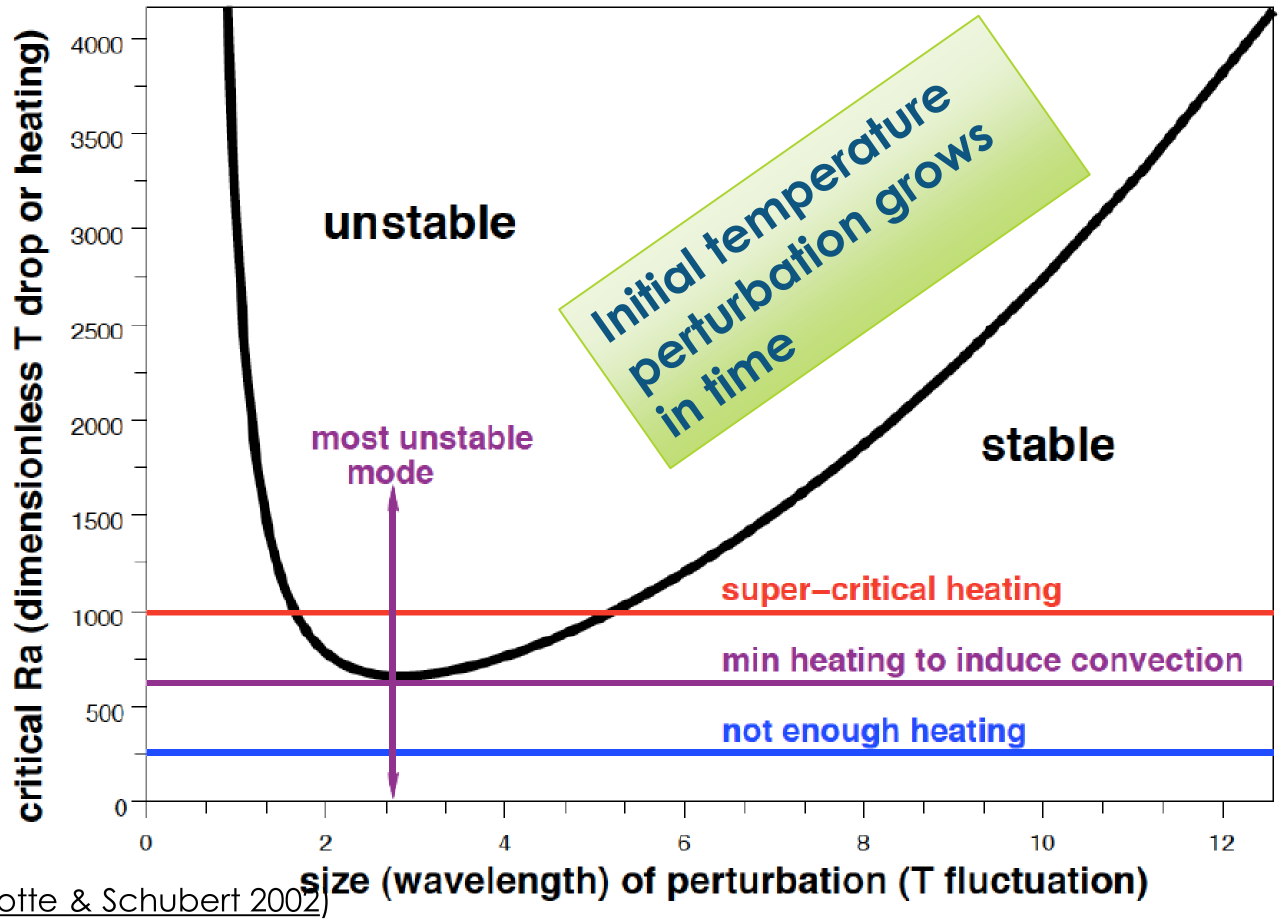
Heat transfer mechanisms

- CONDUCTION (the most diffused);
- CONVECTION
- RADIATION



- Most materials…
  - Get less dense when heated
  - More dense when cooled
- Hot stuff buoyant relative to surroundings: rises
- Cold stuff relatively heavy: falls

Thermal Convection



(from Turcotte & Schubert 2002)

The **Rayleigh number** characterizes the competition between forcing by thermal bouyancy and damping by viscosity and thermal diffusion

Ra must exceed a certain value called the **critical Rayleigh number** (**Ra_c**) for convection to occur.
For **$Ra < Ra_c$** -> the layer is stable and trasports heat by conduction
For **$Ra > Ra_c$** -> the layer will be **convectively unstable** and trasports heat more rapidly **via convection.**

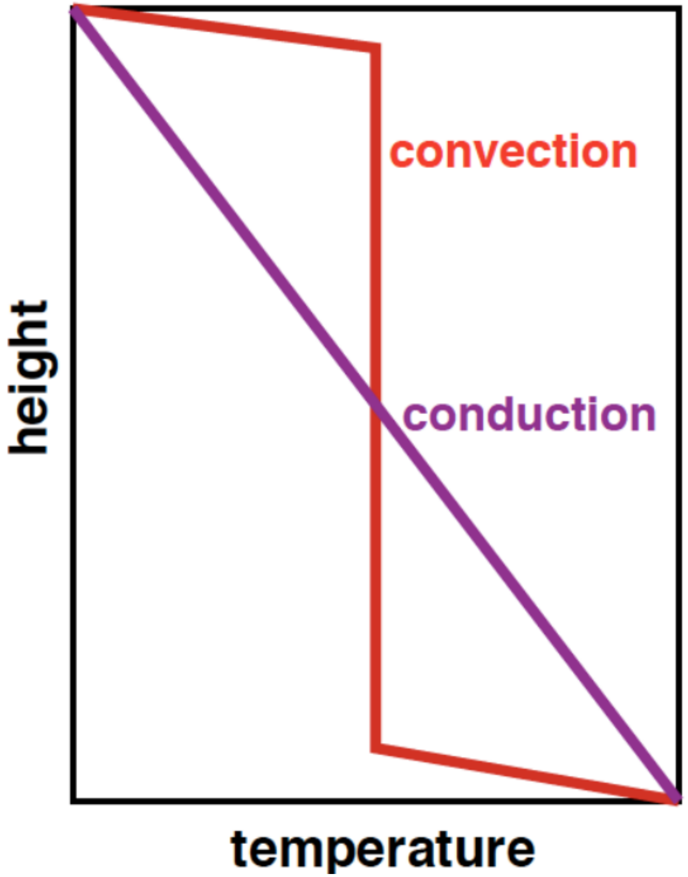
Thermal Boundary Layers & Nusselt Number

With **very large Ra** and vigorous mixing most of the **layer** is largely **uniform** and **isothermal**. Most of the fluid is at the mean temperature between the two boundary temperatures.
However the **temperature** still must **drop** from the well-mixed warm interior to the cold temperature at the top, and to the hotter temperature at the bottom. The **narrow regions** accommodating these jumps in temperature are called **thermal boundary layers**.

Nu = Nusselt number= Heat transfer across layer in convective regime/ Heat transfer across layer by conduction

Nu = $q_{convection}/k\Delta T/d$

(from Turcotte & Schubert 2002)



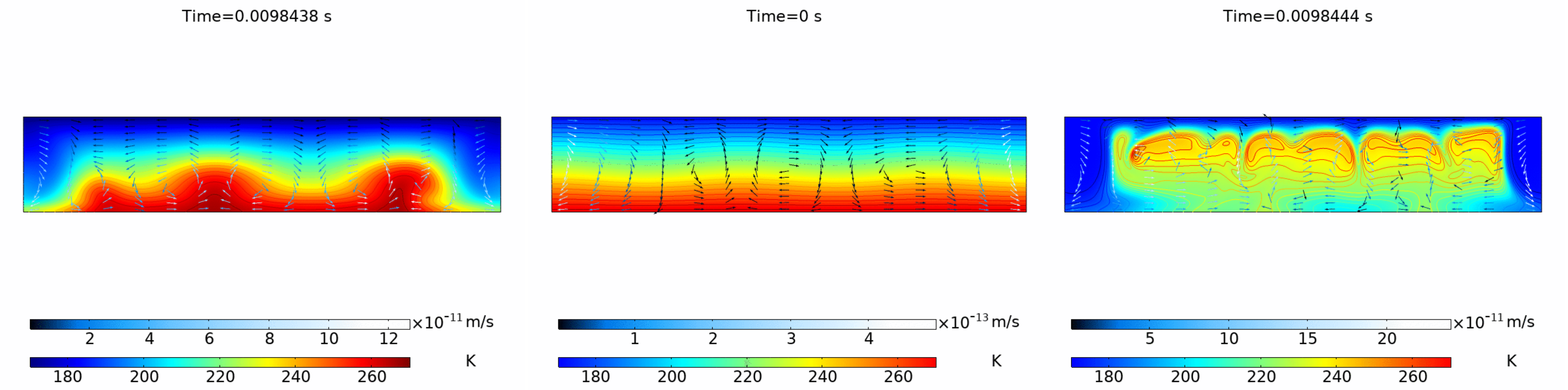
Thermal Convection "typologies"

$$Ra = \frac{\Delta T\, \rho^2\, g\, c_p\, L^3}{\mu_{dyn}\, \kappa}$$

If the **viscosity** is high (> **10^{19} Pa s**, as in the asthenosphere – Schubert 1979) -> "**Sub-Solidus Convection**"

If the **viscosity** is low (**few Pa s**) -> **Core convection**

Sub-solidus Convection: Ceres' crust



note that **time** is **dimensionless**

(from Formisano et al. 2019, JGR, submitted)

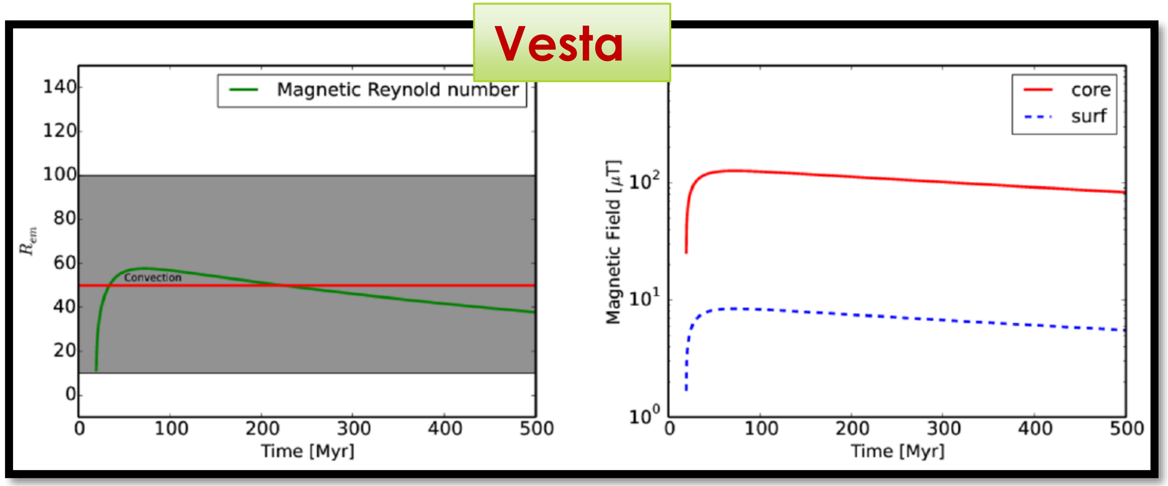
Core Dynamo as a consequence of the Differentiation

- **Three conditions** are required to drive a **dynamo** on a growing planet (Monteux et al. 2011) and so to have a magnetic field:
- 1) The **heat flow** out of the core must exceed the adiabatic value such that convection can occur (Stevenson et al. 1983).
- 2) The **ratio** of the **rate** at which **gravitational potential energy** is **released** by **convection** to the **rate** of **ohmic dissipation** must exceed a critical value (Buffett 2002).
- 3) The **structure** of the **convective motions** carrying magnetic field lines must be sufficiently **complicated** to favor self-sustaining dynamo action, i.e. if magnetic **Reynolds number** overcomes a **critical value** (typically in the range **10-100** (Monteux et al. 2011 and reference therin)).

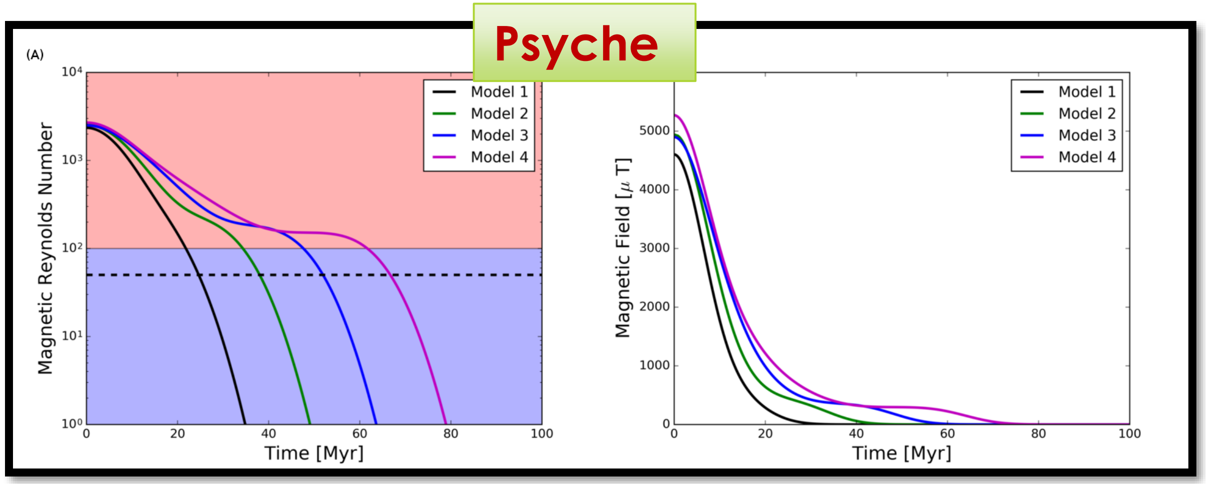
Typical timescale of **core dynamo** is < **100 Ma** (Elkins-Tanton et al. 2011)

Core Convection: Vesta & Psyche

- **Vesta** probably had a magnetic field as suggested by the studies on the residual magnetization on an eucritic meteorite (Fu et al. 2012) and suggested by theoretical models (Formisano et al. 2016);
- **Psyche** could have been characterized by a core dynamo (Bryson et al. 2015), appearing to be an **exposed metallic core** or a **fragment** of a **metallic core** from a **larger differentiated parent body** some 500 kilometers in diameter. Its origin is still matter of debate.



(from Formisano et al. 2016)



(from Formisano et al. 2019, in preparation)

Why studying magnetic fields?

- Information about:

i. The **physics** of the **interior** of the celestial bodies;

ii. Past **geological activities**;

iii. **Mathematically interesting** since it is a problem of **complex system**

ALL THE **EFFECTS** OF THE **PAST MAGNETIC FIELDS** ARE RECORDED IN THE ROCK IF THE LOCAL TEMPERATURE DOES NOT OVERCOME THE **CURIE TEMPERATURE**.

Conclusions

- **Small bodies** are important to understand the **main stages** of the **evolution** of our Solar System;
- **Numerical models** offer a **theoretical support** to the observations, in order to select the most plausible physical scenarios:
- **New models** (and new computers) are required to simulate more and more **complicated physical situations**, in particular **turbulent convection** and **core dynamos generation**.