The Solar System from formation to habitability

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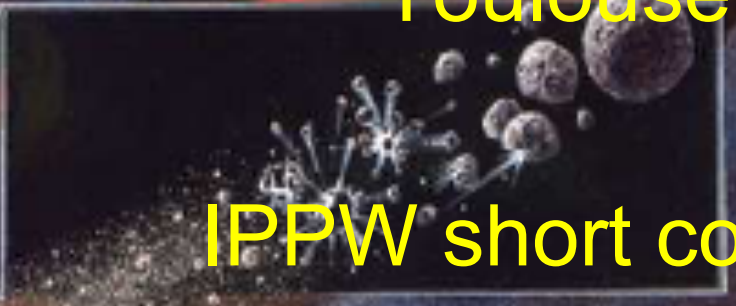
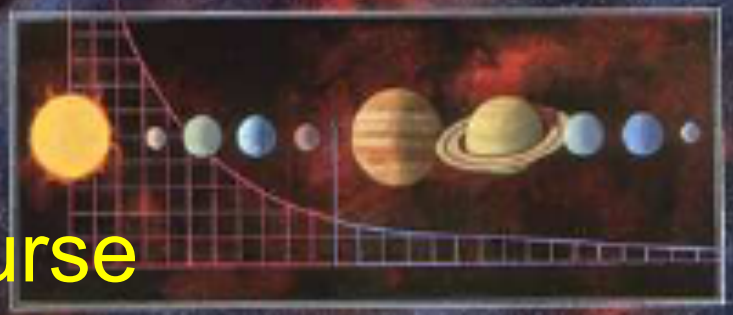




IPPW short course

June 16, 2012

Outline

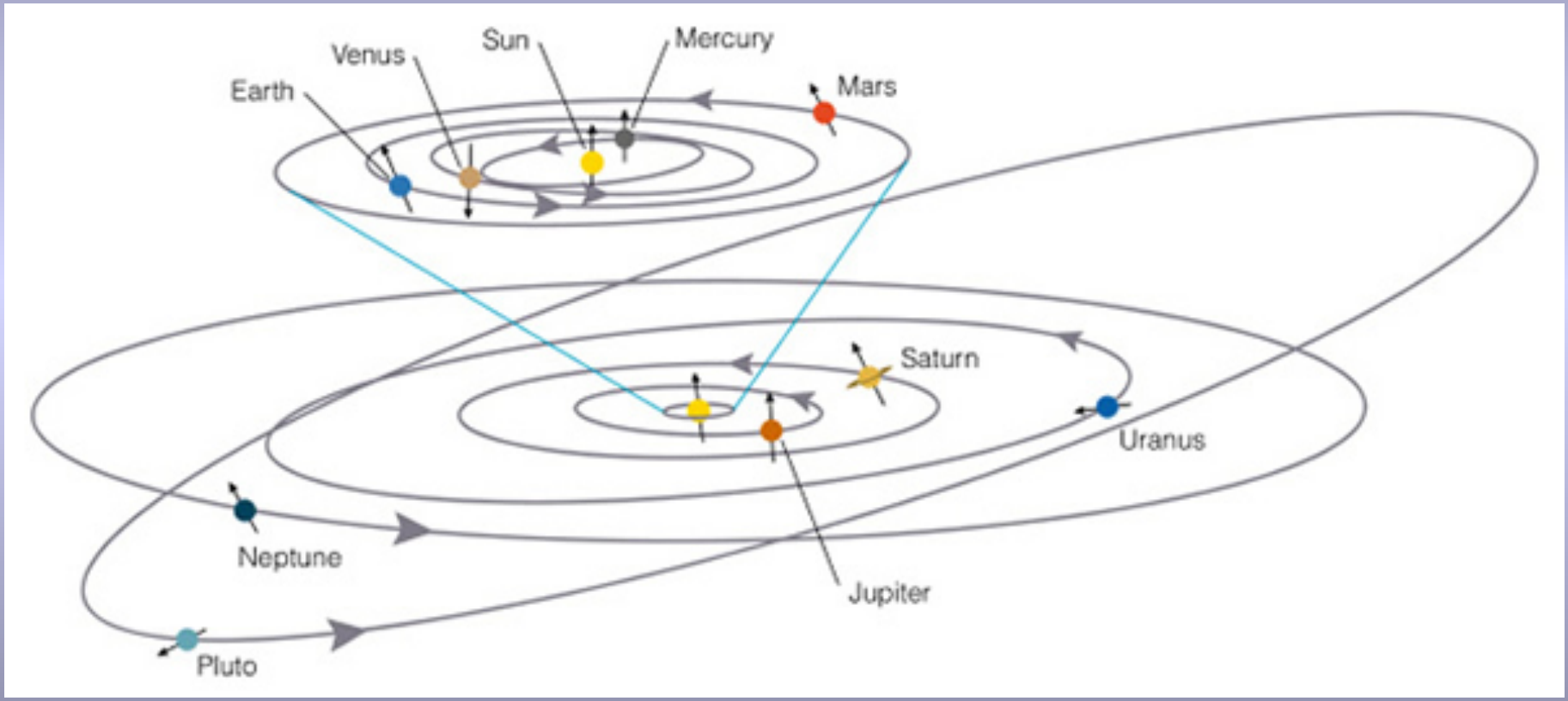
1 – Architecture of the Solar System

2 – Formation of planets, satellites and small bodies

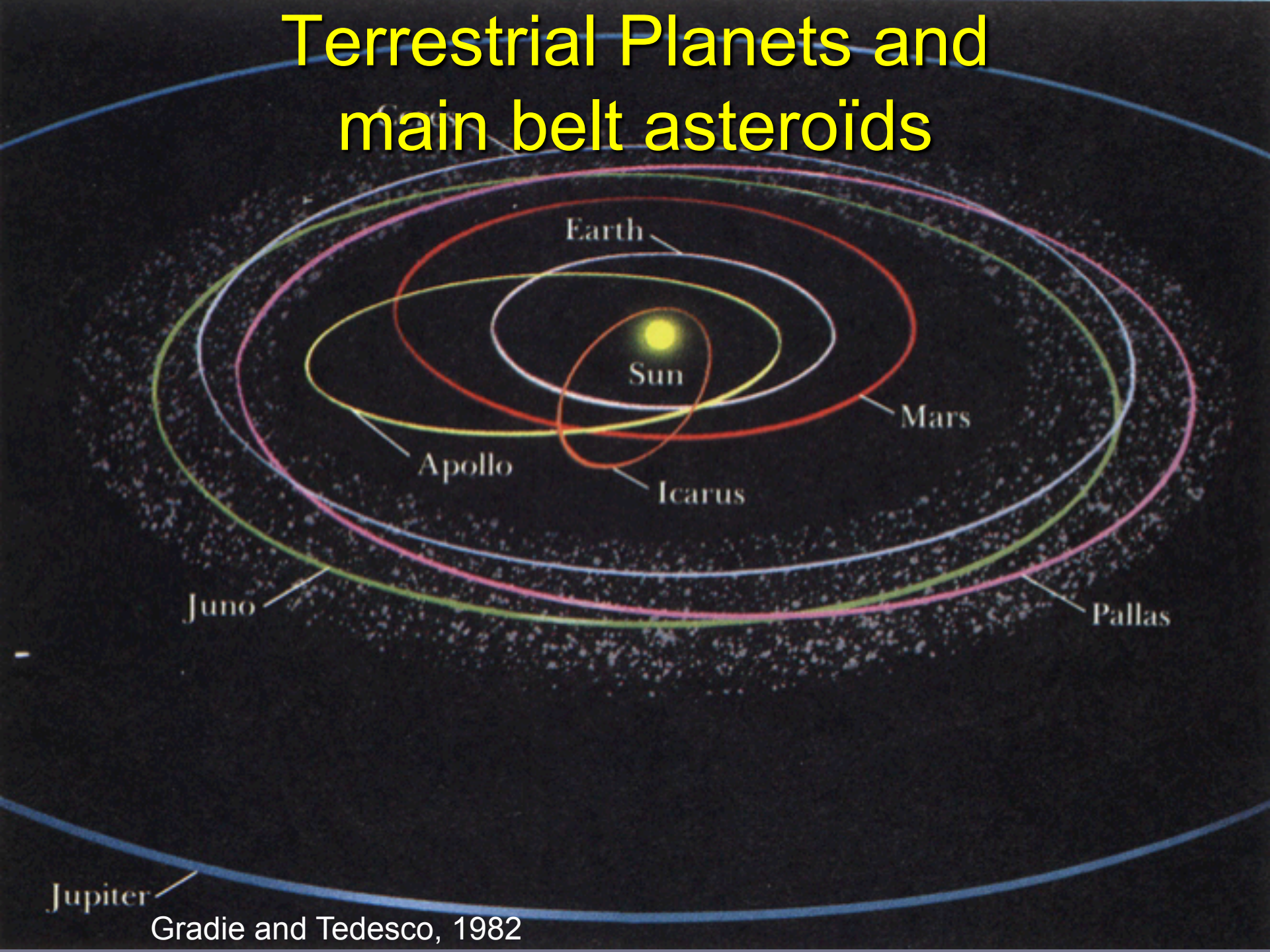
3 – The study of planets as complex systems

4 – Habitability in the solar system

1 – Architecture of the Solar System

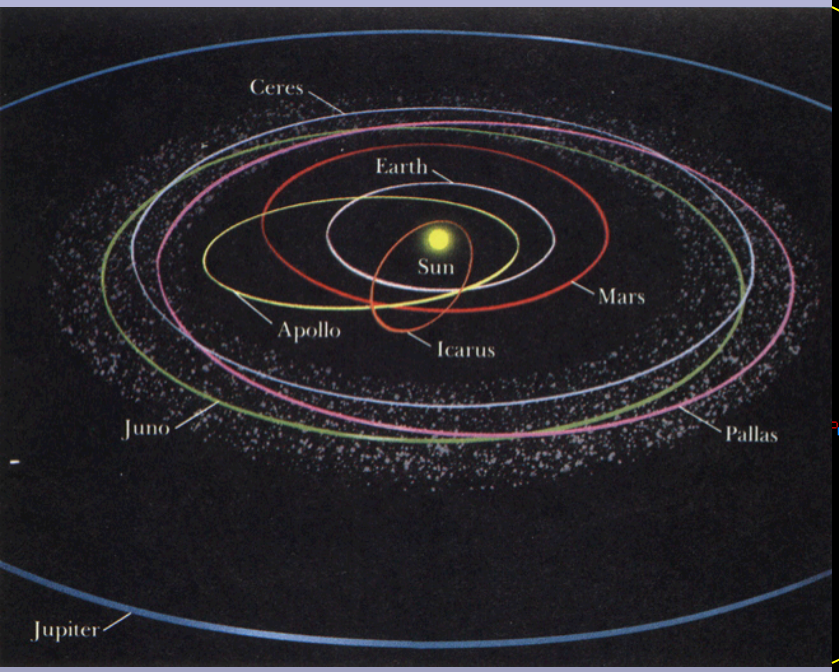


Terrestrial Planets and main belt asteroïds

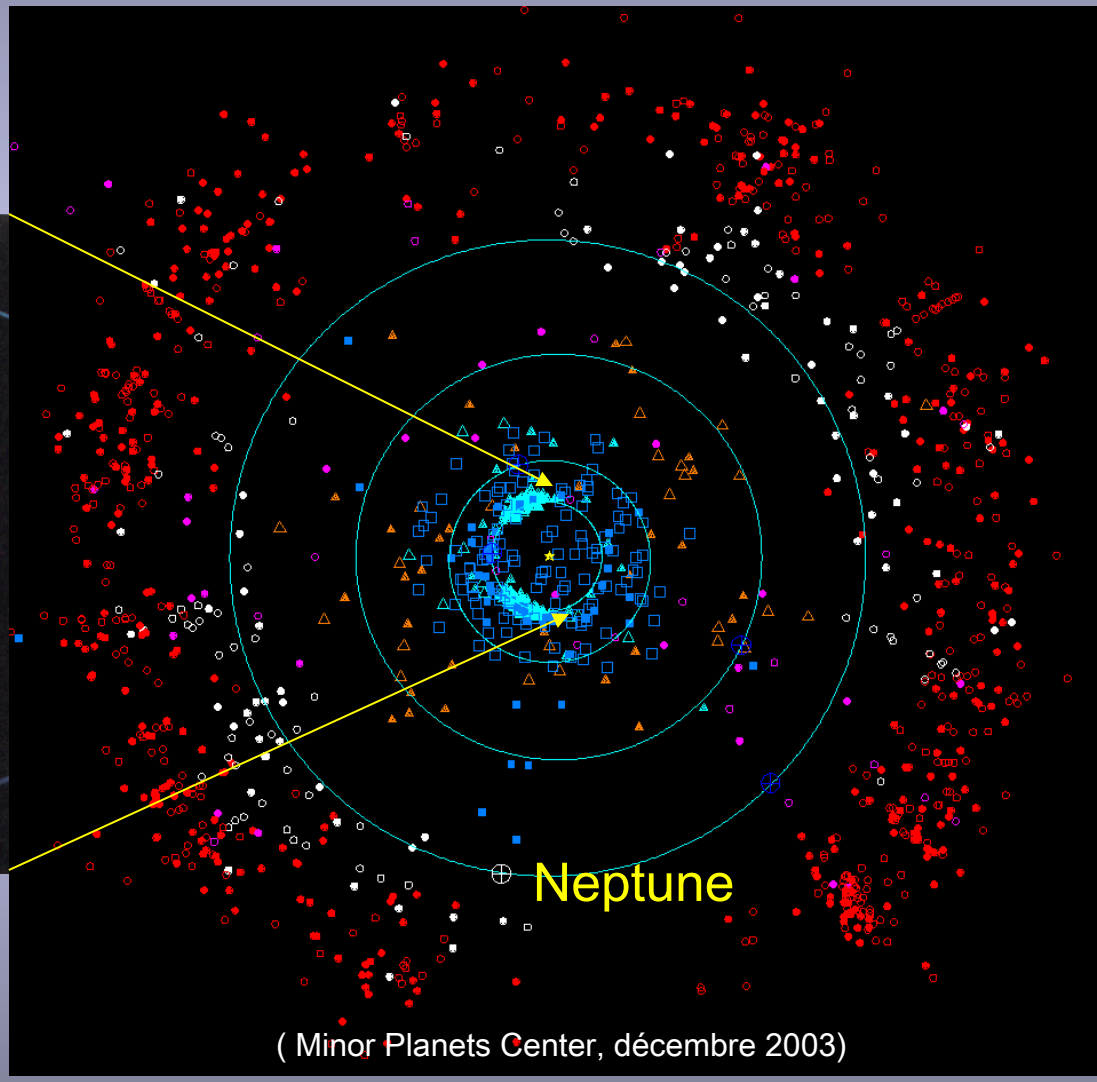


Gradie and Tedesco, 1982

Outer solar system

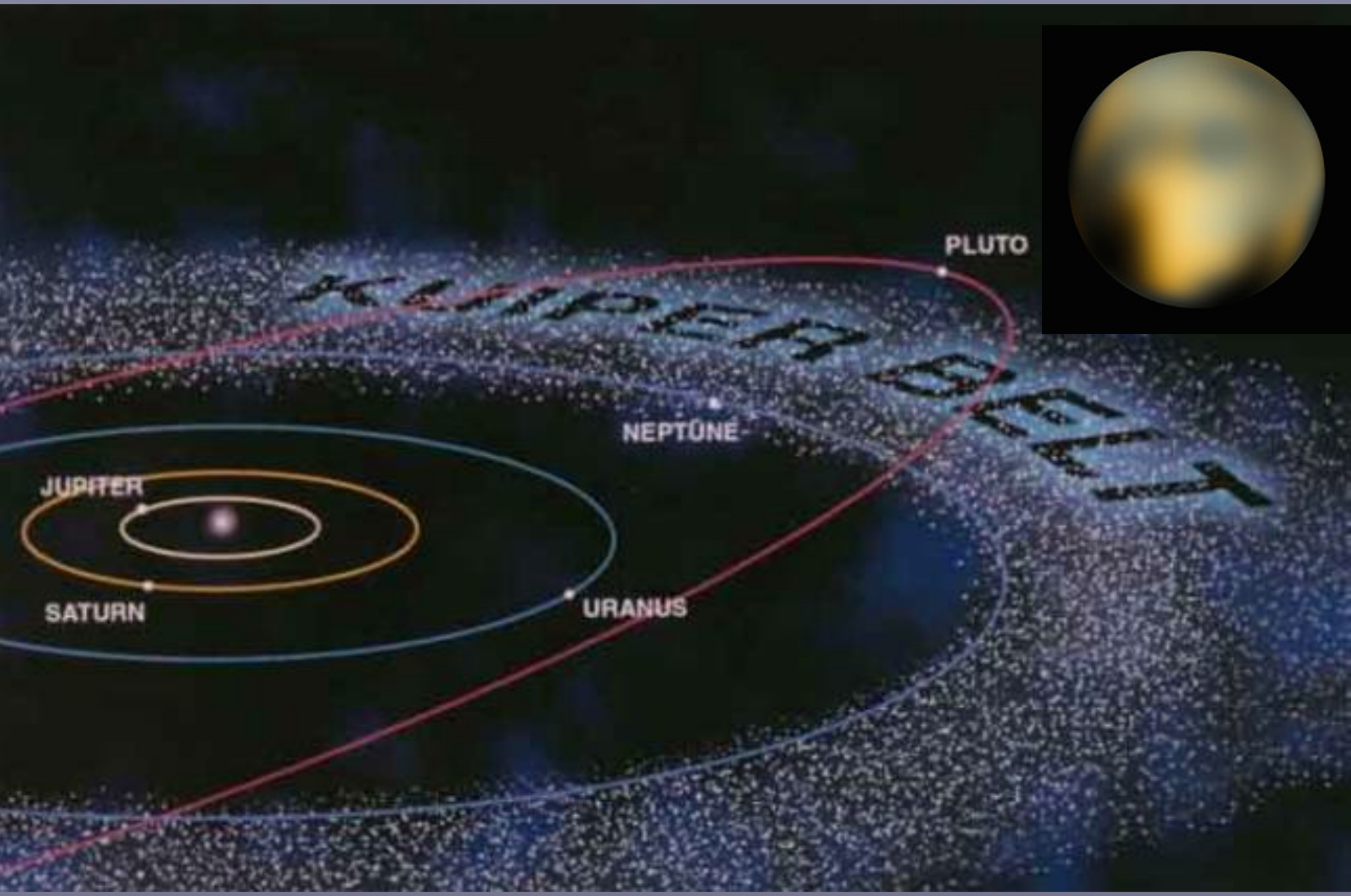


Inner solar system

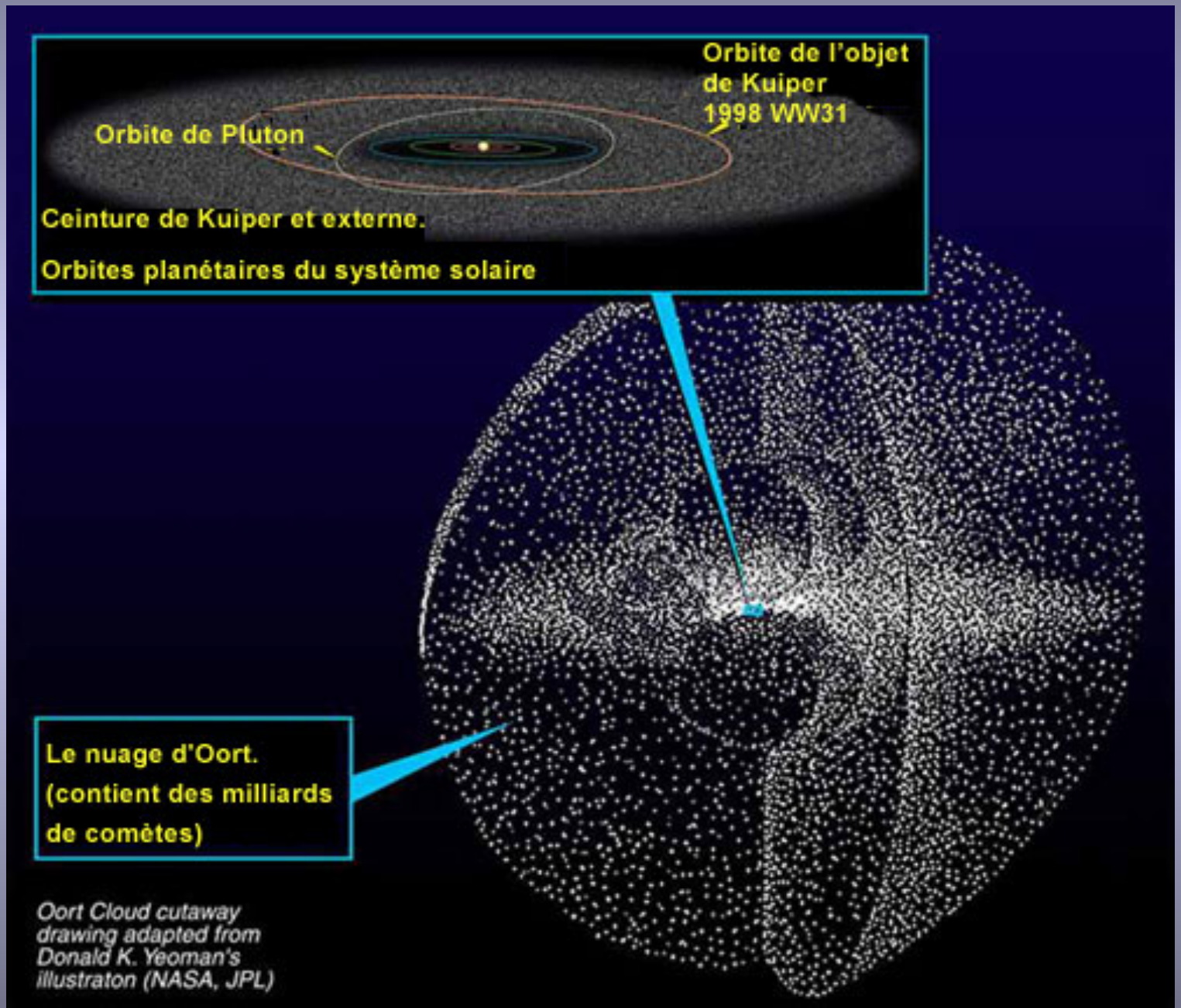


(Minor Planets Center, décembre 2003)

Beyond Neptune, the Kuiper belt

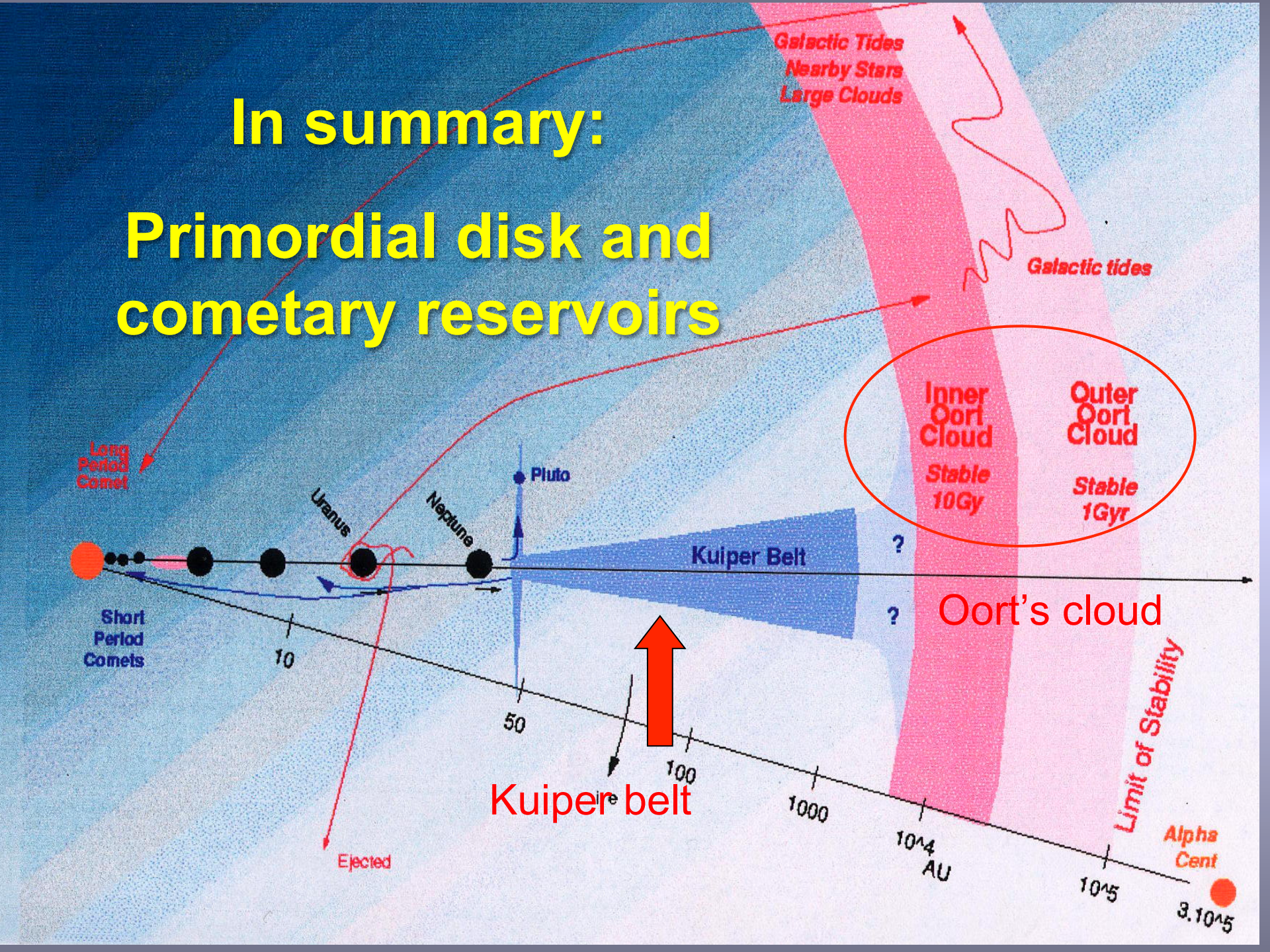


Still beyond, Oort's cloud

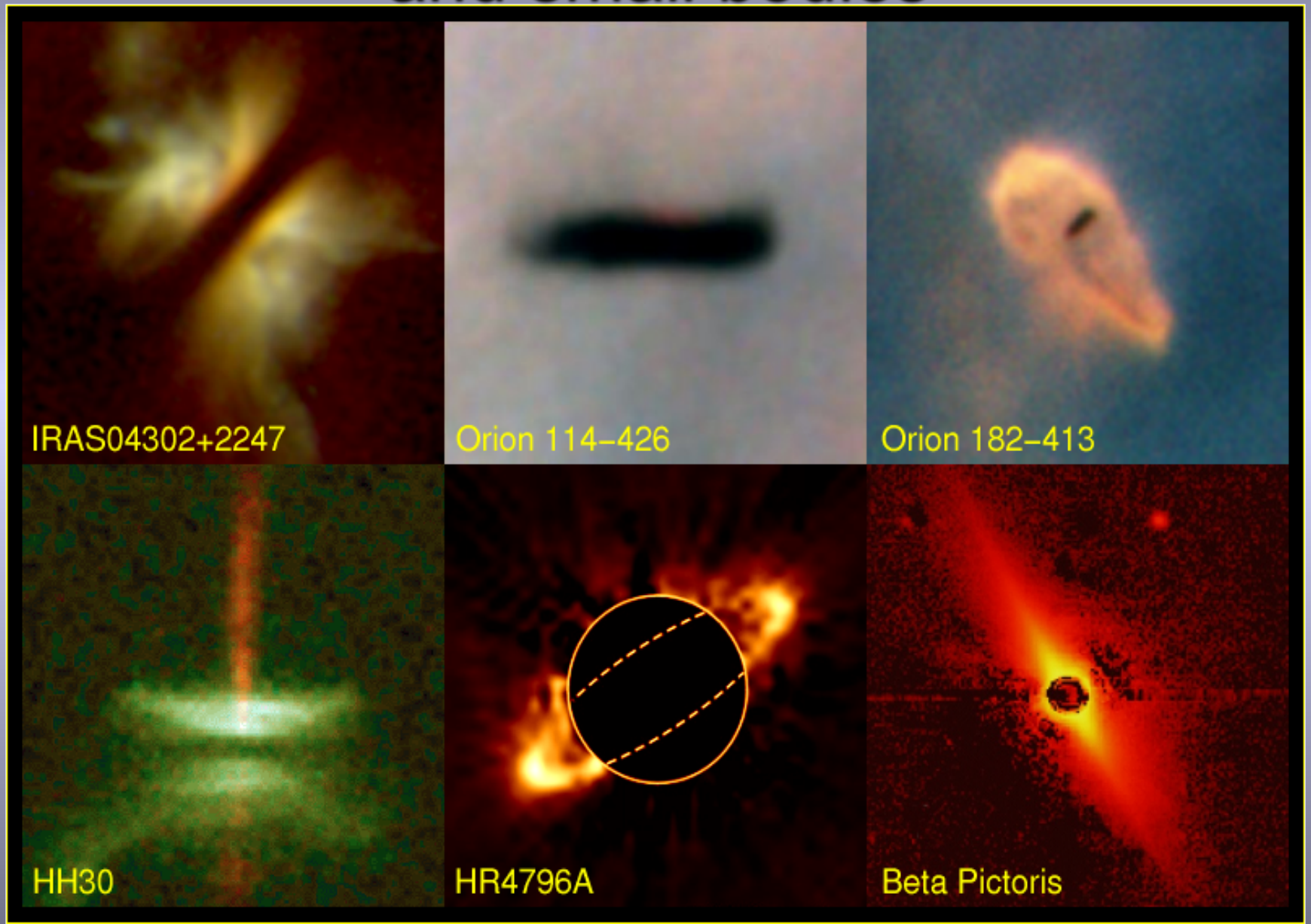


In summary:

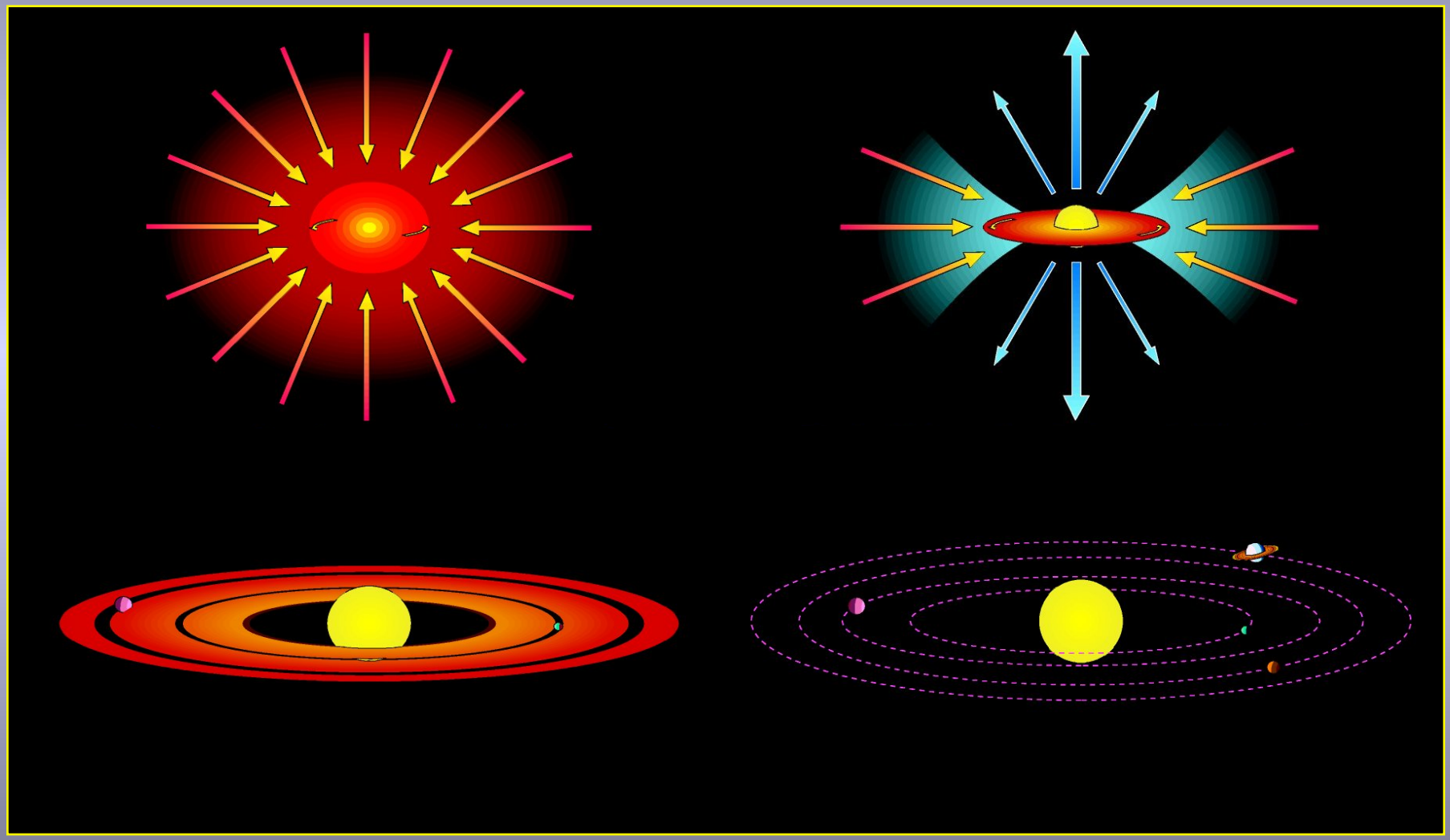
Primordial disk and cometary reservoirs



2 – Formation of planets, satellites and small bodies



The four phases of planetary formation



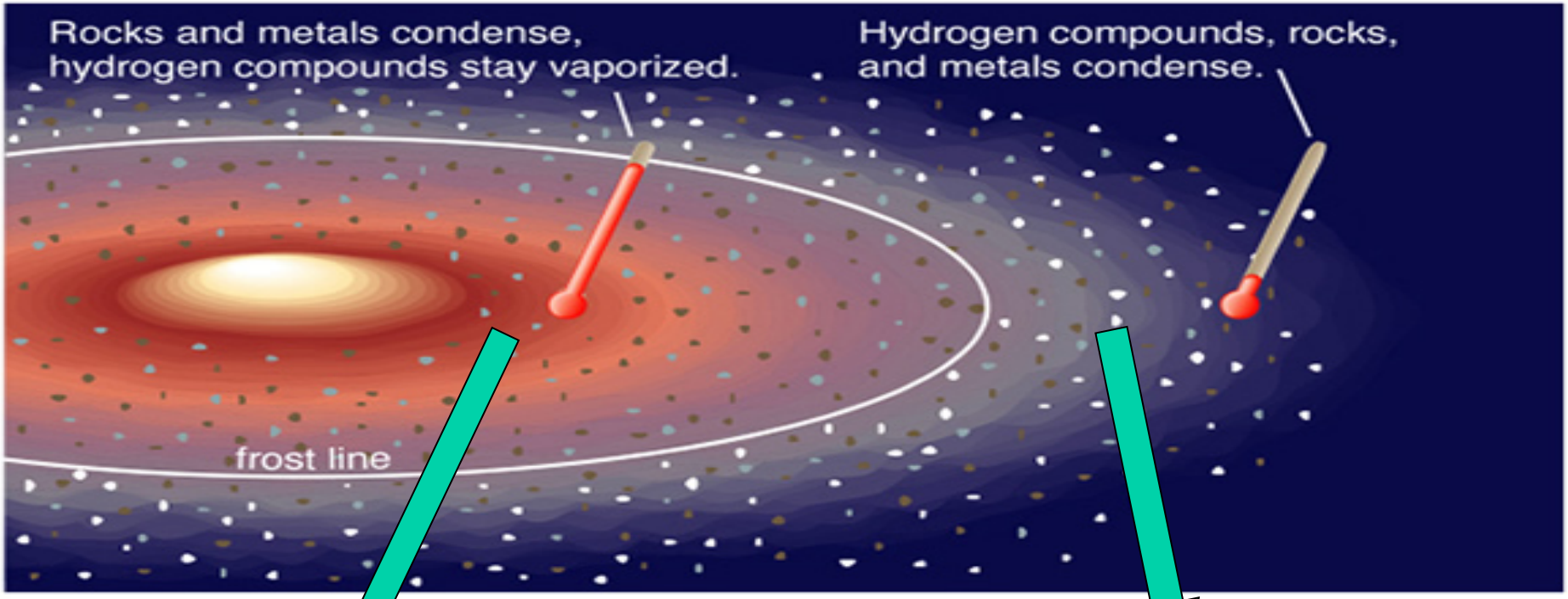
The basic ingredients of planet-forming

Materials in the Solar Nebula

	Metals	Rocks	Hydrogen Compounds	Light Gases
				
Examples	iron, nickel, aluminum	silicates	water (H_2O) methane (CH_4) ammonia (NH_3)	hydrogen, helium
Typical Condensation Temperature	1,000–1,600 K	500–1,300 K	<150 K	(do not condense in nebula)
Relative Abundance (by mass)	•	■	■	
	(0.2%)	(0.4%)	(1.4%)	(98%)

… + a few percent organic matter !

Condensation of the Solar Nebula



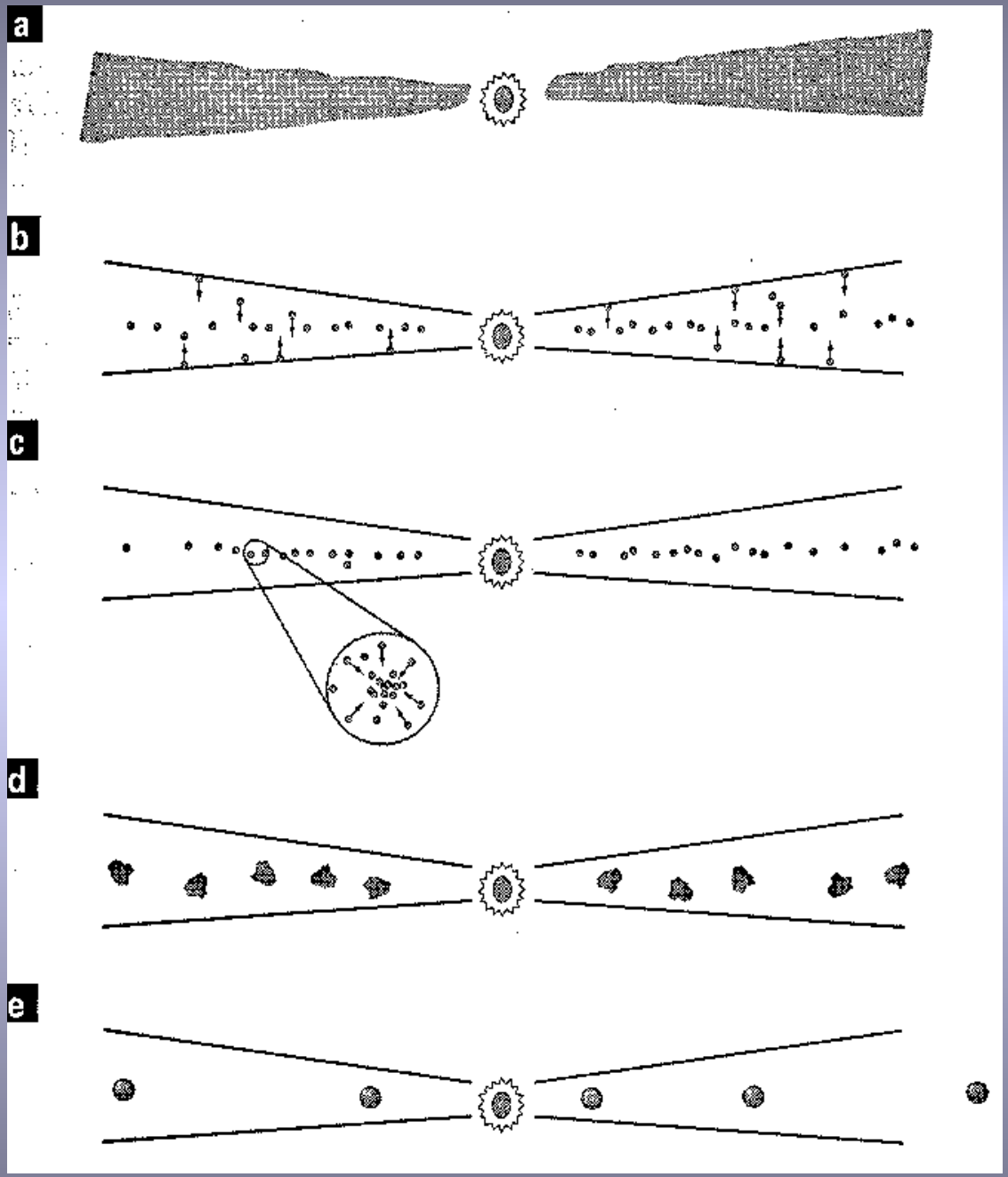
Rocky Planetesimals

Icy Planetesimals

Accretion of solid bodies from dust to planetesimals finally leads to the formation of:

- **Solid/rocky planets;**

- **The cores of giant planets**



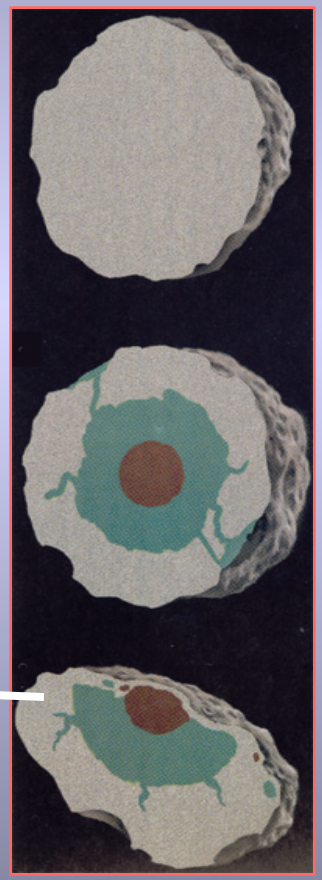
In the inner solar system :

Accretion of condensates of metals and silicates

Dust

Accretion

Proto-Planets



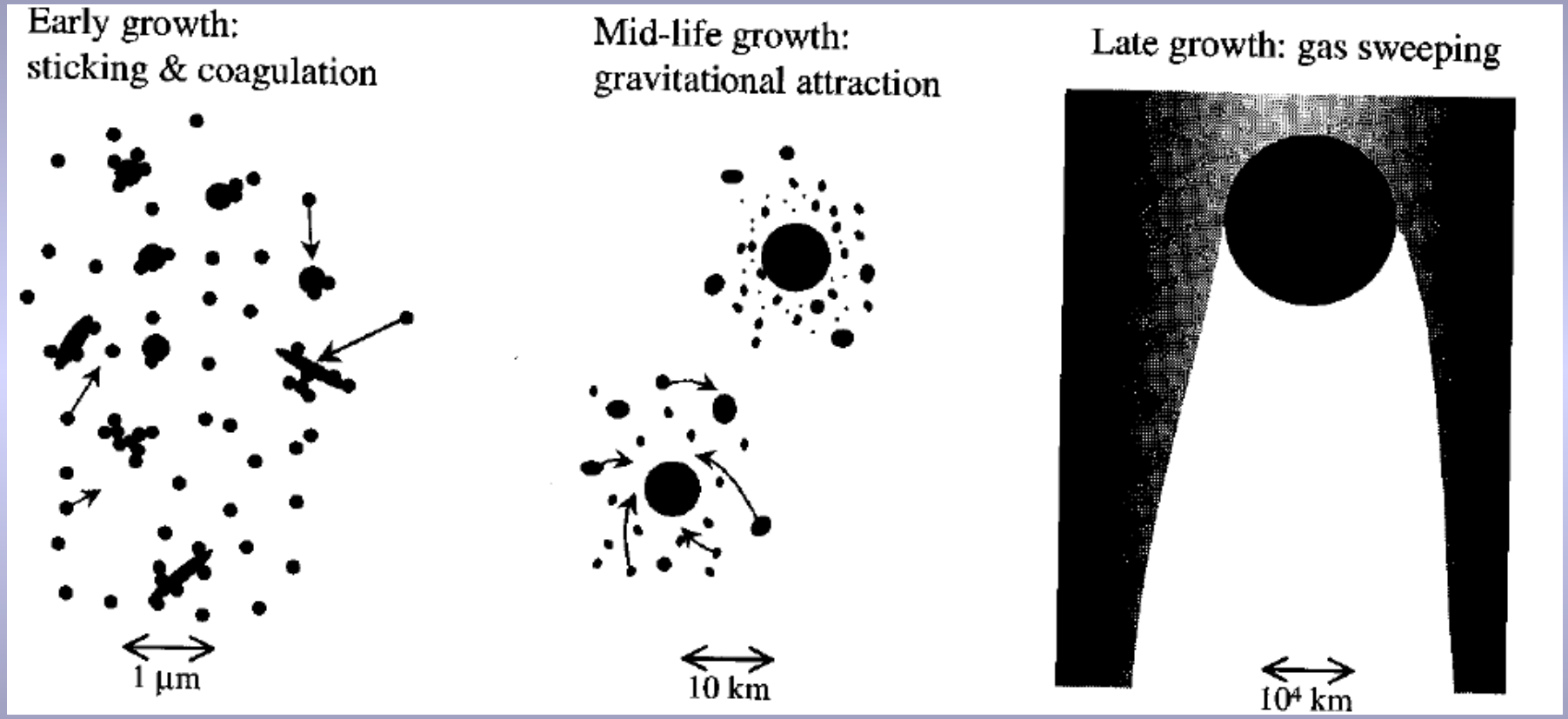
differenciation

Terrestrial Planets

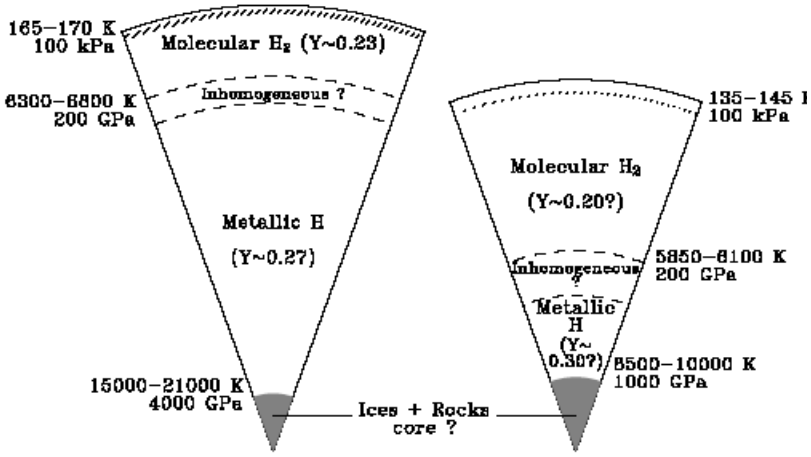
Asteroïds

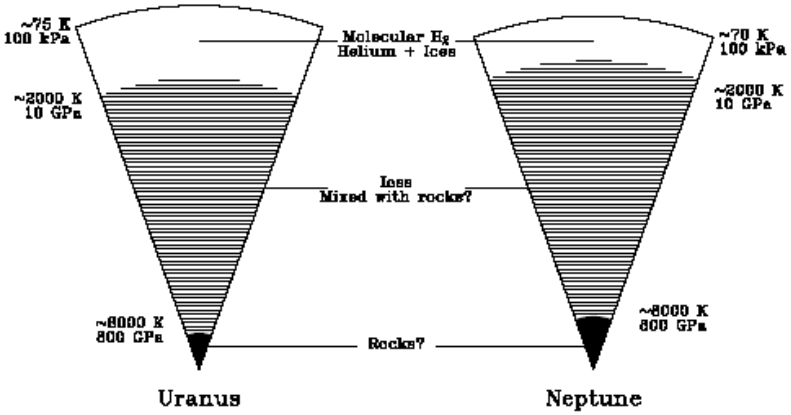
fragmentation

In the outer solar system ices condense too

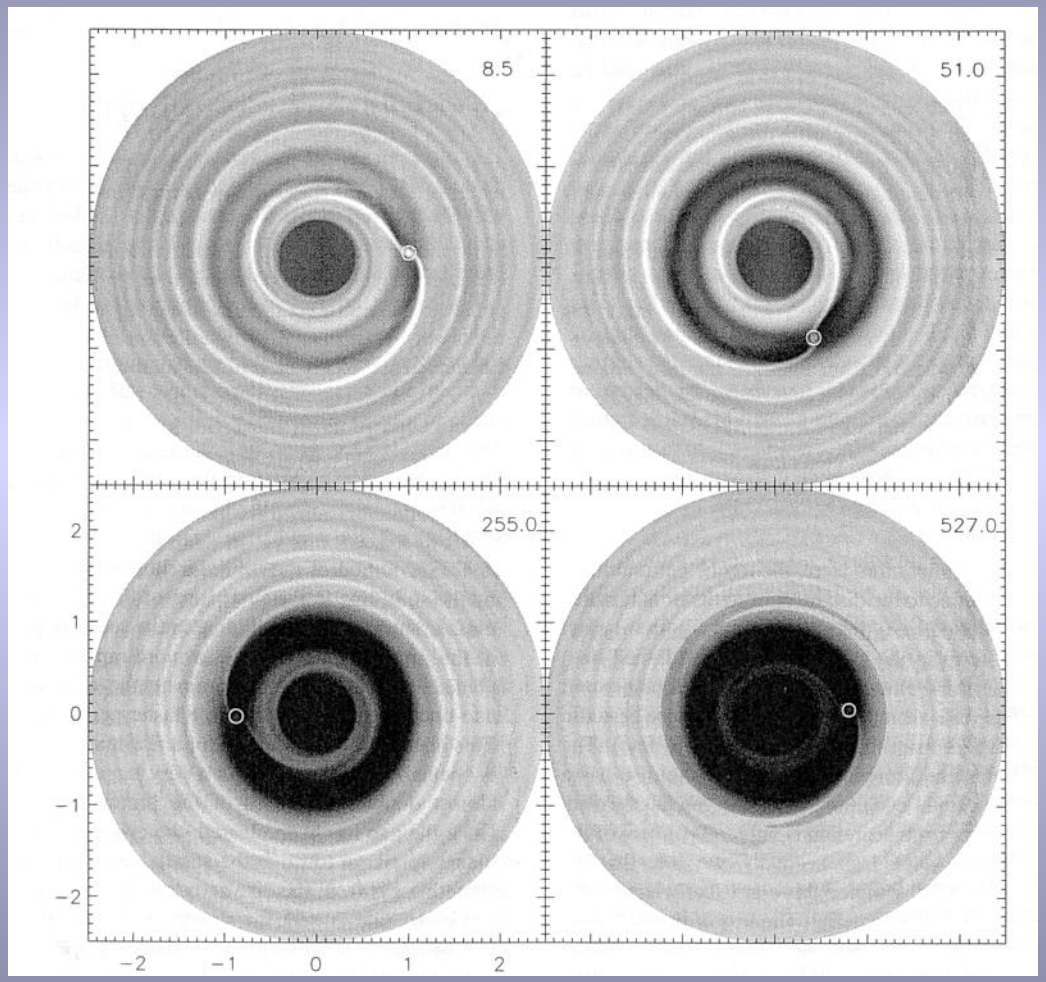


… then gas is accreted on giant planets cores by gravitational collapse

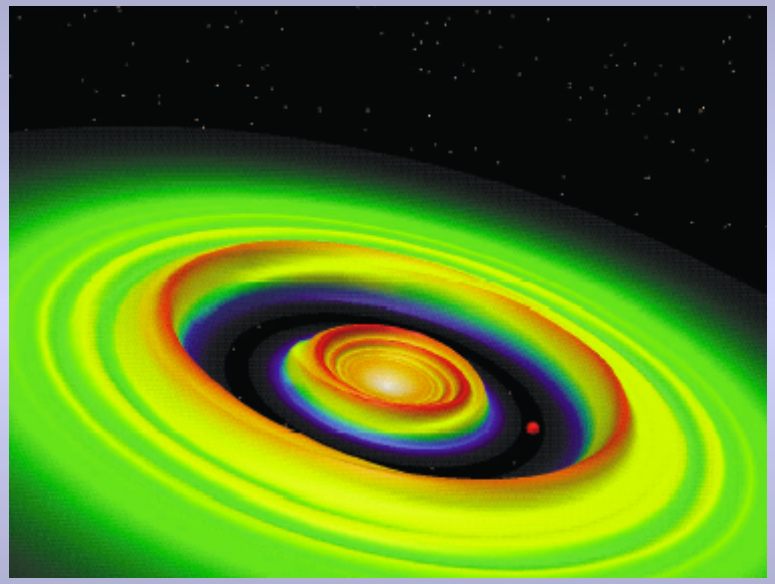

165–170 K
100 kPa
Molecular H_2 (Y~0.23)
6300–6800 K
200 GPa
Inhomogeneous ?
Metallic H
(Y~0.27)
15000–21000 K
4000 GPa
Ices + Rocks
core ?
Jupiter
135–145 K
100 kPa
Molecular H_2
(Y~0.20?)
5850–6100 K
200 GPa
Inhomogeneous
Metallic H
(Y~0.30?)
8500–10000 K
1000 GPa
Saturn


~75 K
100 kPa
Molecular H_2
Helium + Ices
~2000 K
10 GPa
Ices
Mixed with rocks?
~8000 K
800 GPa
Rocks?
Uranus
~70 K
100 kPa
~2000 K
10 GPa
~8000 K
800 GPa
Neptune

Gas accretion on core and orbital migration



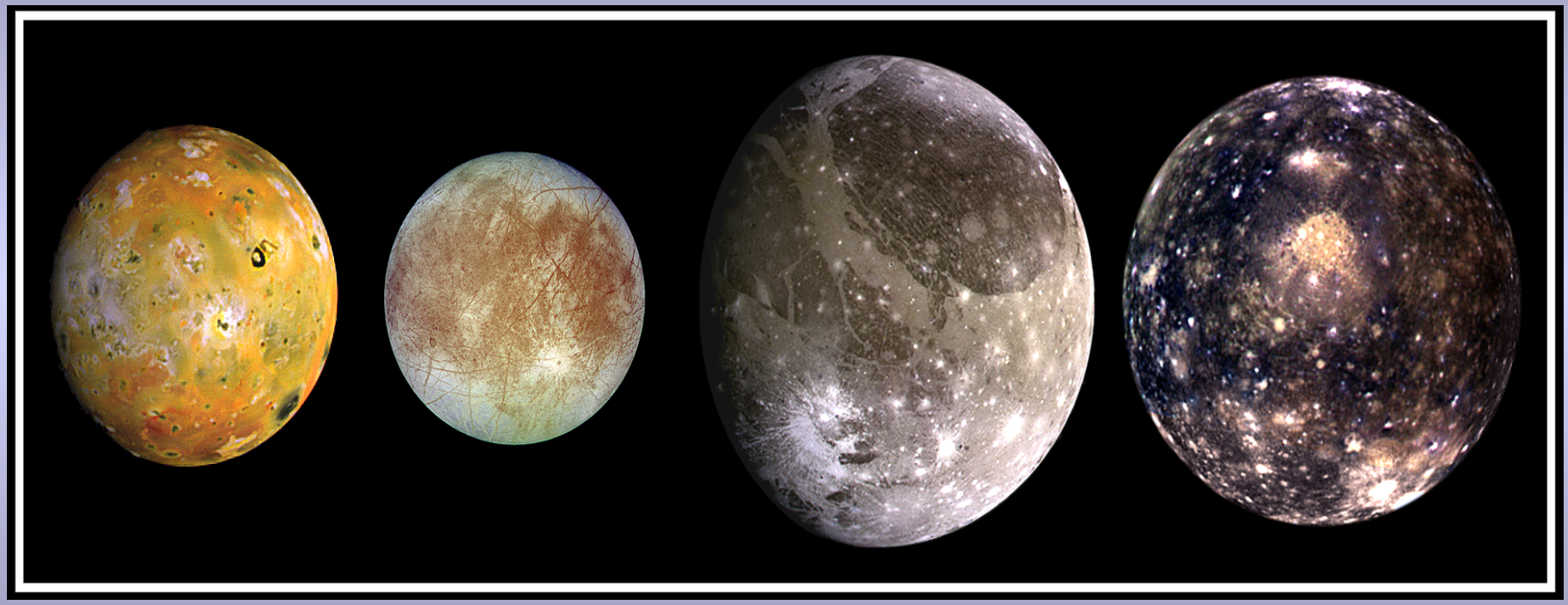
Nelson et al., 2000



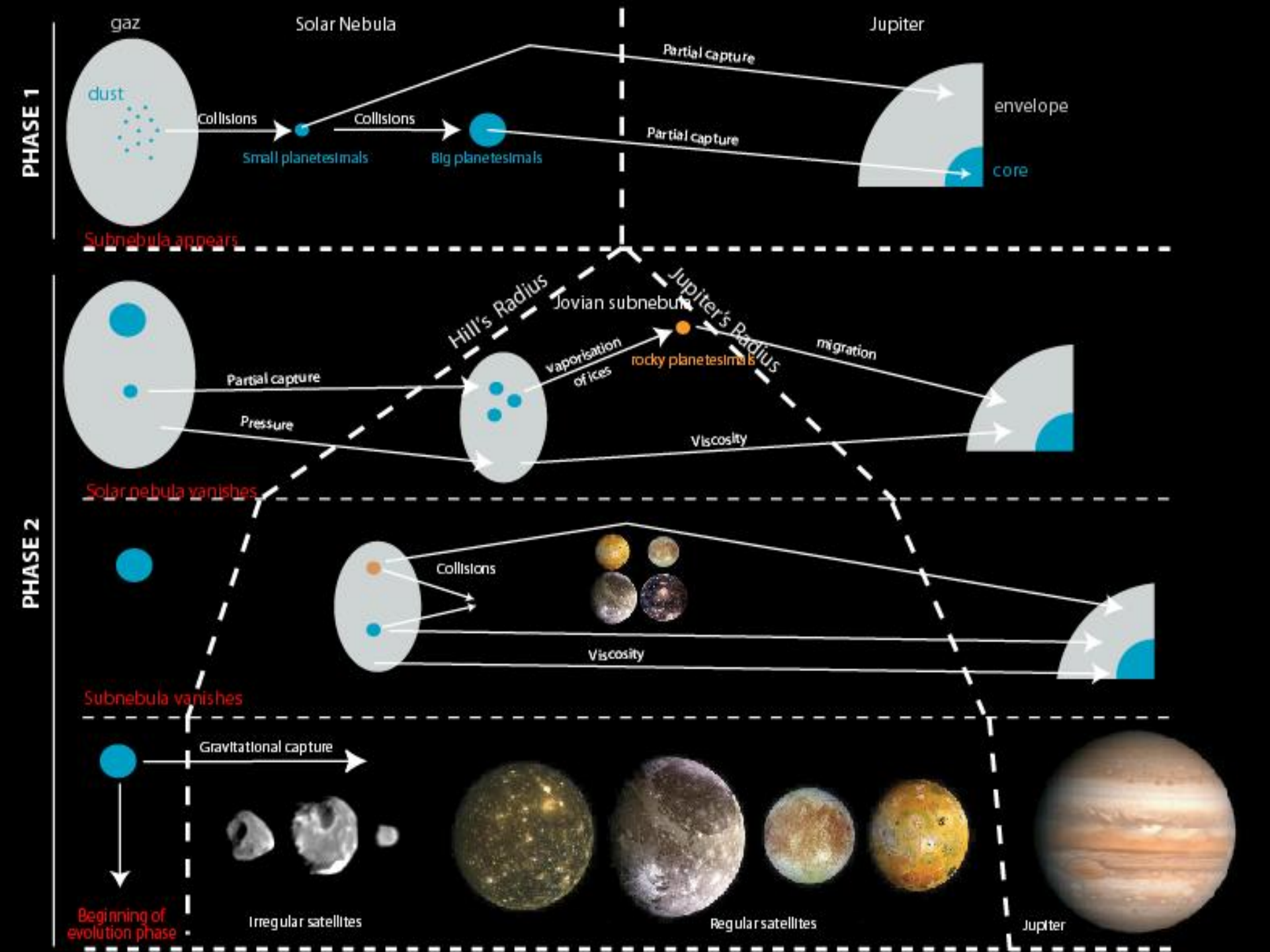
Bryden et Lin

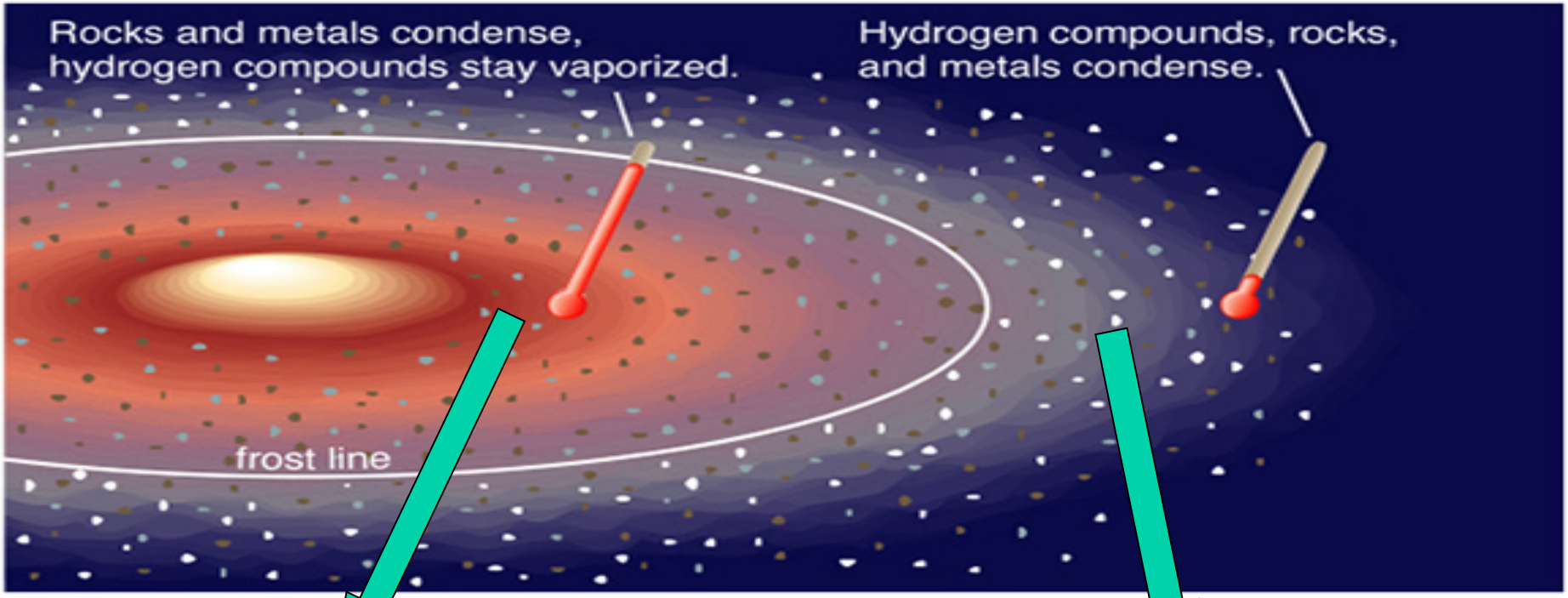
The satellites

The four Galilean satellites



Io Europe Ganymede Callisto


PHASE 1
gaz
Solar Nebula
Jupiter
dust
Collisions
Small planetesimals
Collisions
Big planetesimals
Partial capture
envelope
Partial capture
core
Subnebula appears
PHASE 2
Hill's Radius
Jovian subnebula
Jupiter's Radius
Partial capture
Pressure
vaporisation of ices
rocky planetesimals
migration
Viscosity
Solar nebula vanishes
Collisions
Viscosity
Subnebula vanishes
Gravitational capture
Beginning of evolution phase
Irregular satellites
Regular satellites
Jupiter



Rocky planetesimals

Terrestrial planets

Asteroids

Icy planetesimals

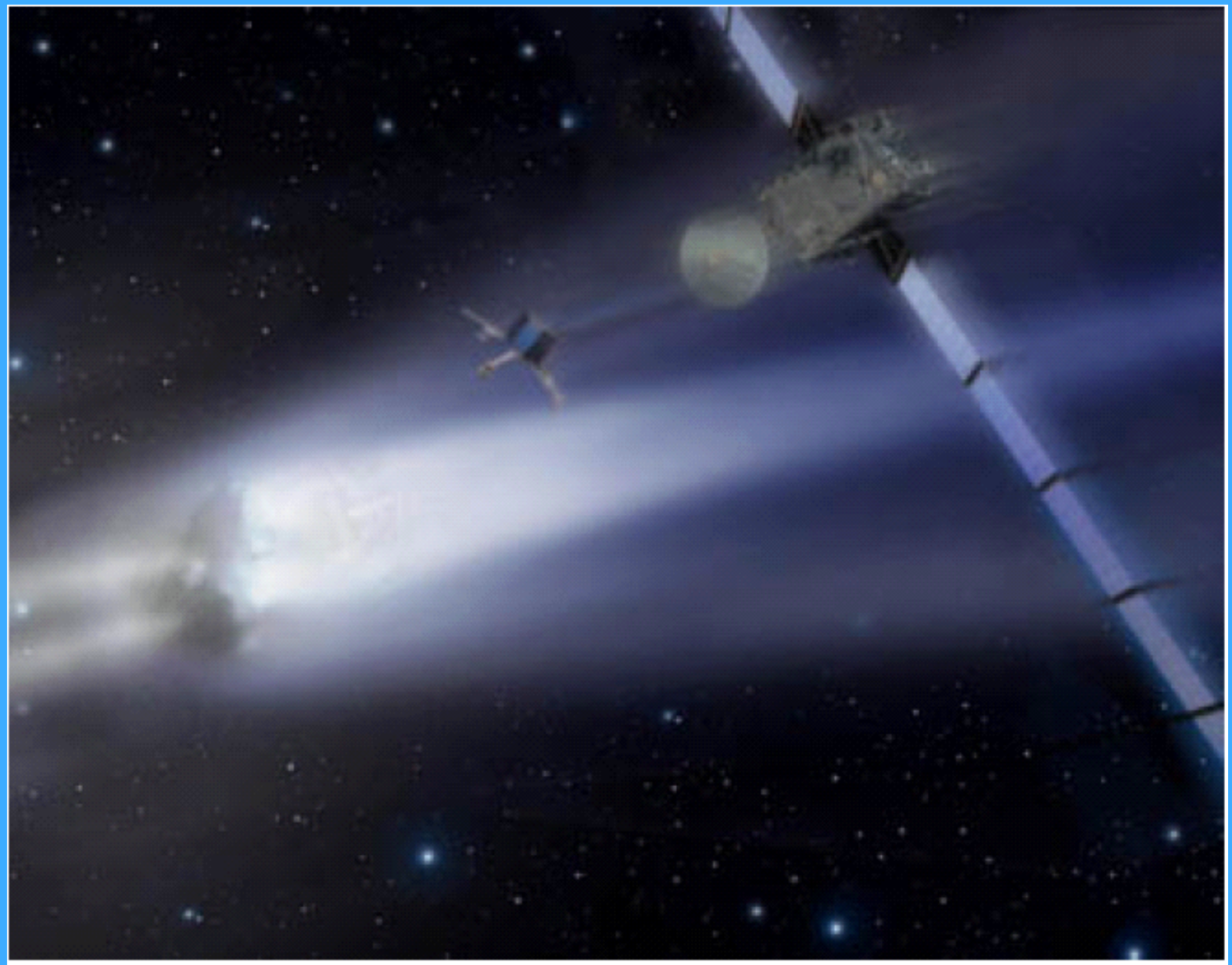
Giant planets

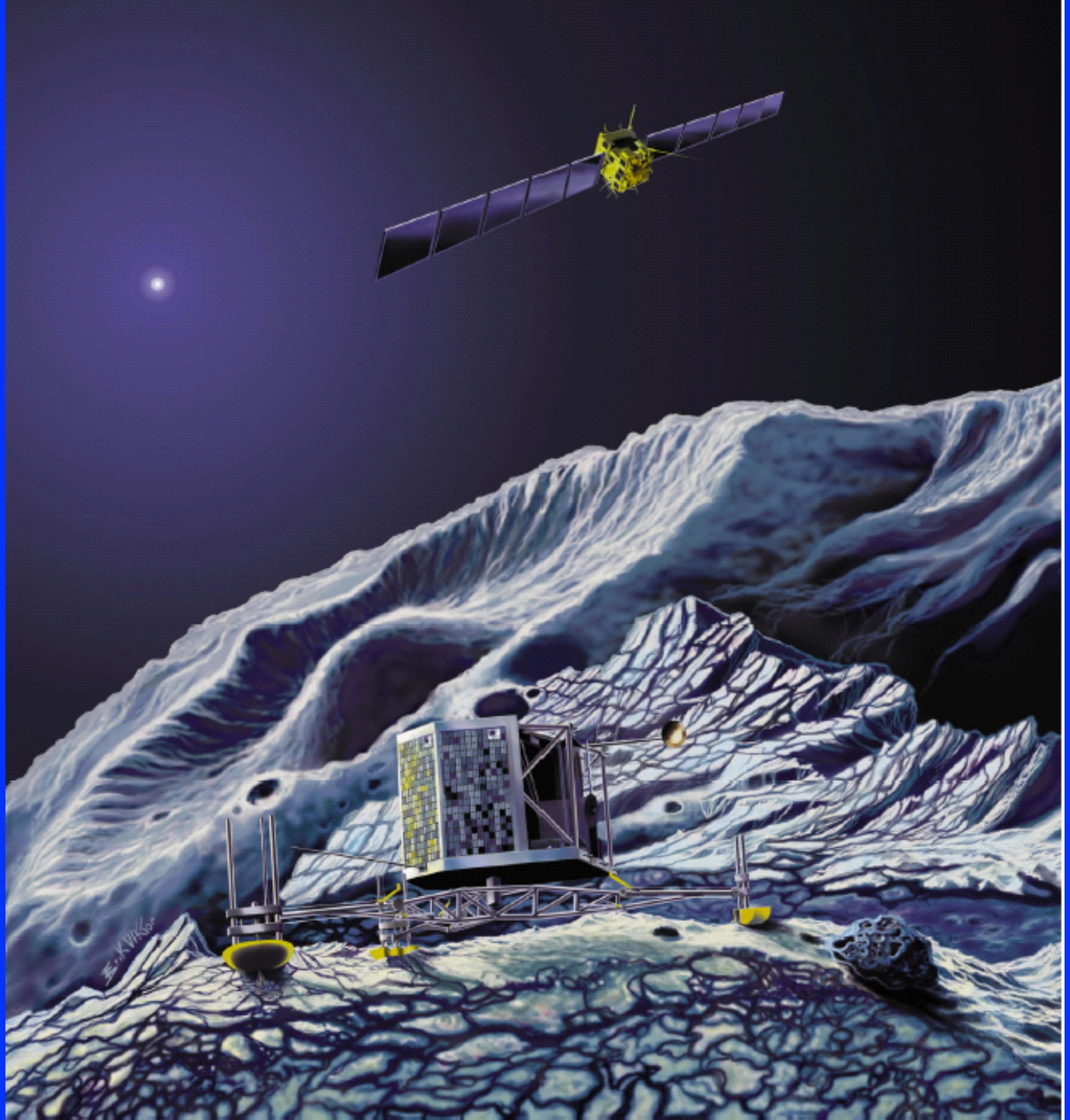
Rings and disks

Satellites

Kuiper objects, Comets

The Rosetta mission





3 – Planets as complex systems

3 examples:
Jupiter system
Titan
Enceladus

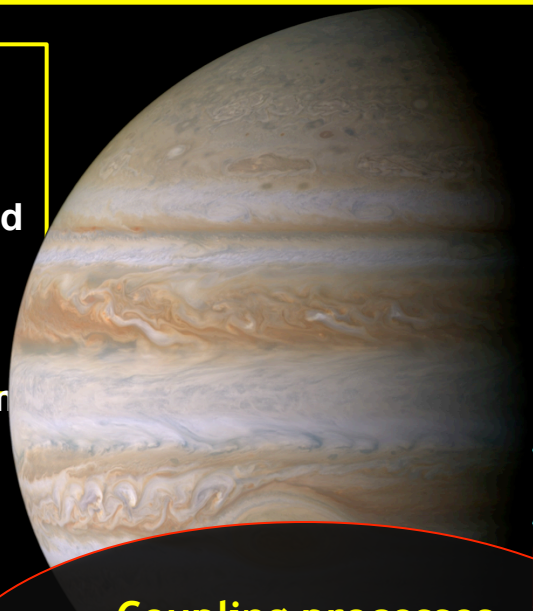
Exploration of the Jupiter system

JUICE

The biggest planet, the biggest magnetosphere, and a mini solar system

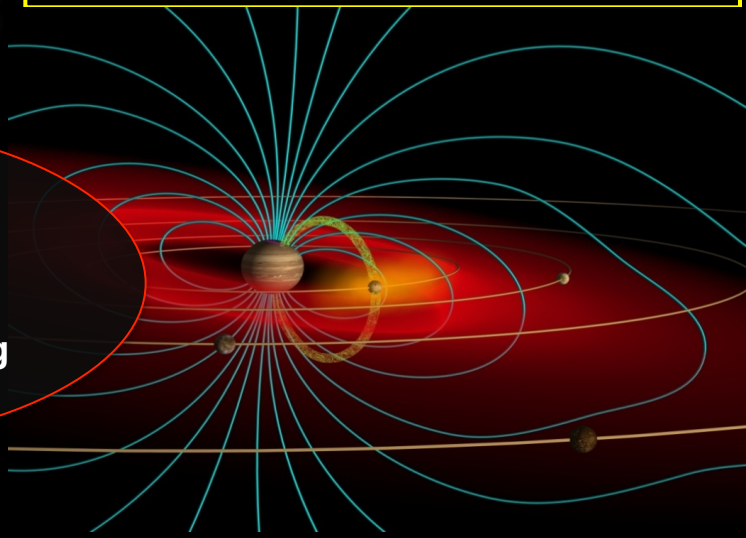
Jupiter

- Archetype for giant planets
- Natural planetary-scale laboratory for fundamental fluid dynamics, chemistry, meteorology,...
- Window into the formational history of our planetary system



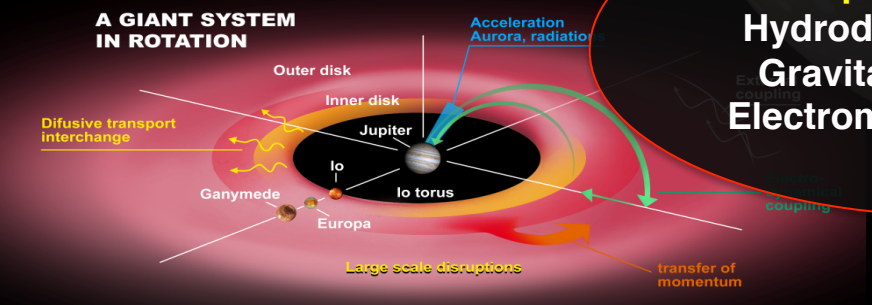
Magnetosphere

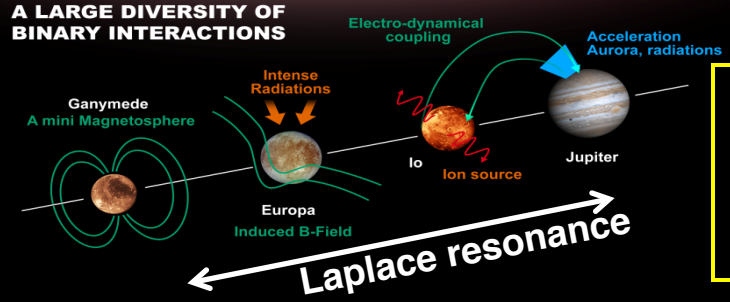
- Largest object in our Solar System
- Biggest particle accelerator in the Solar System
- Unveil global dynamics of an astrophysical object



Coupling processes

Hydrodynamic coupling
Gravitational coupling
Electromagnetic coupling

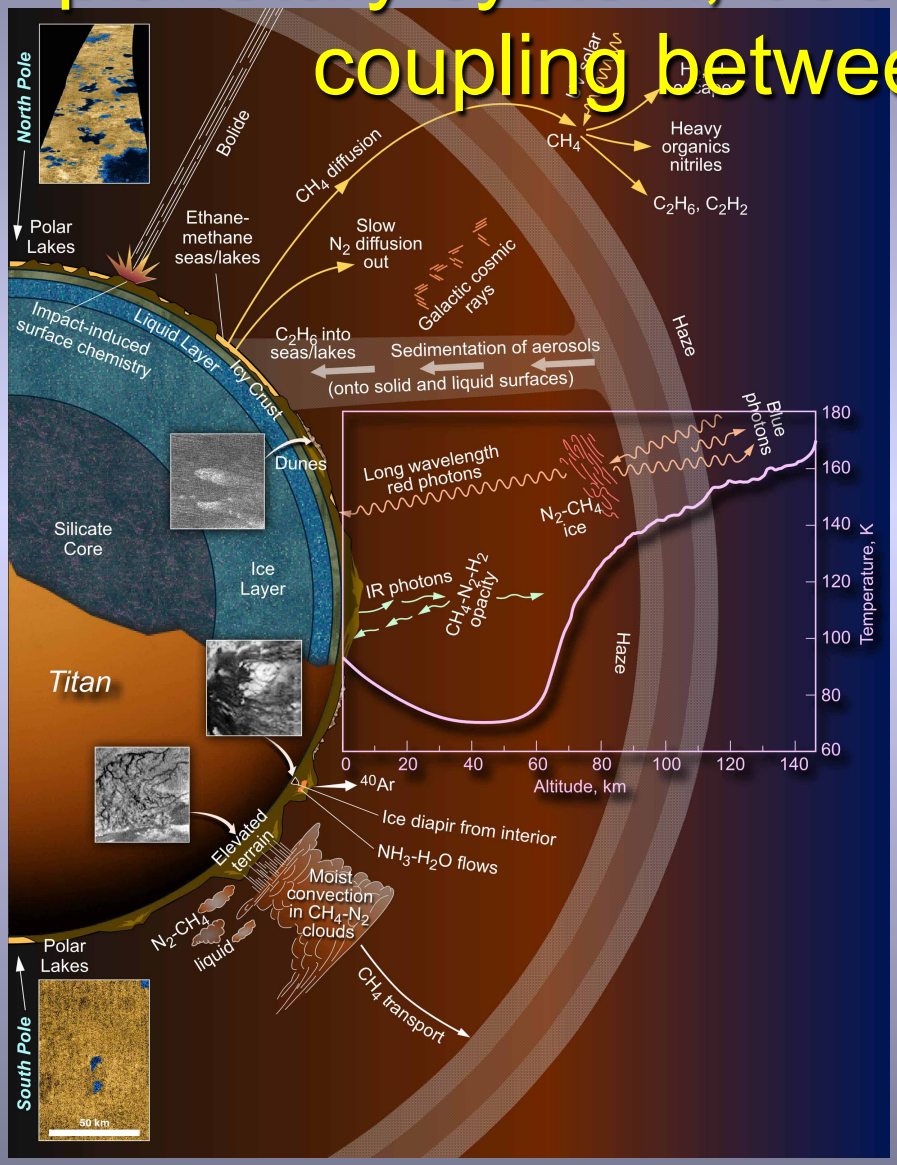




Satellite system

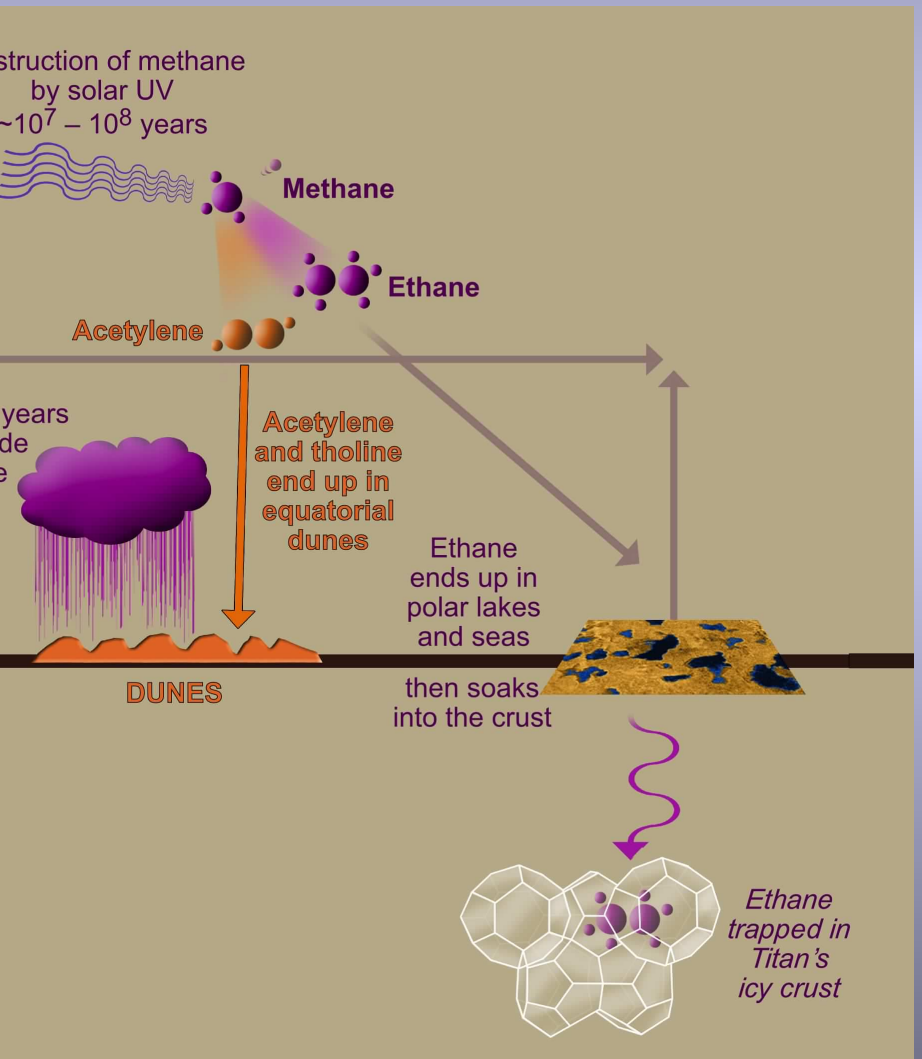
- Tidal forces: Laplace resonance
- Electromagnetic interactions to magnetosphere and upper atmosphere of Jupiter

Titan is a perfect example of a complex planetary system, because of the strong coupling between all layers



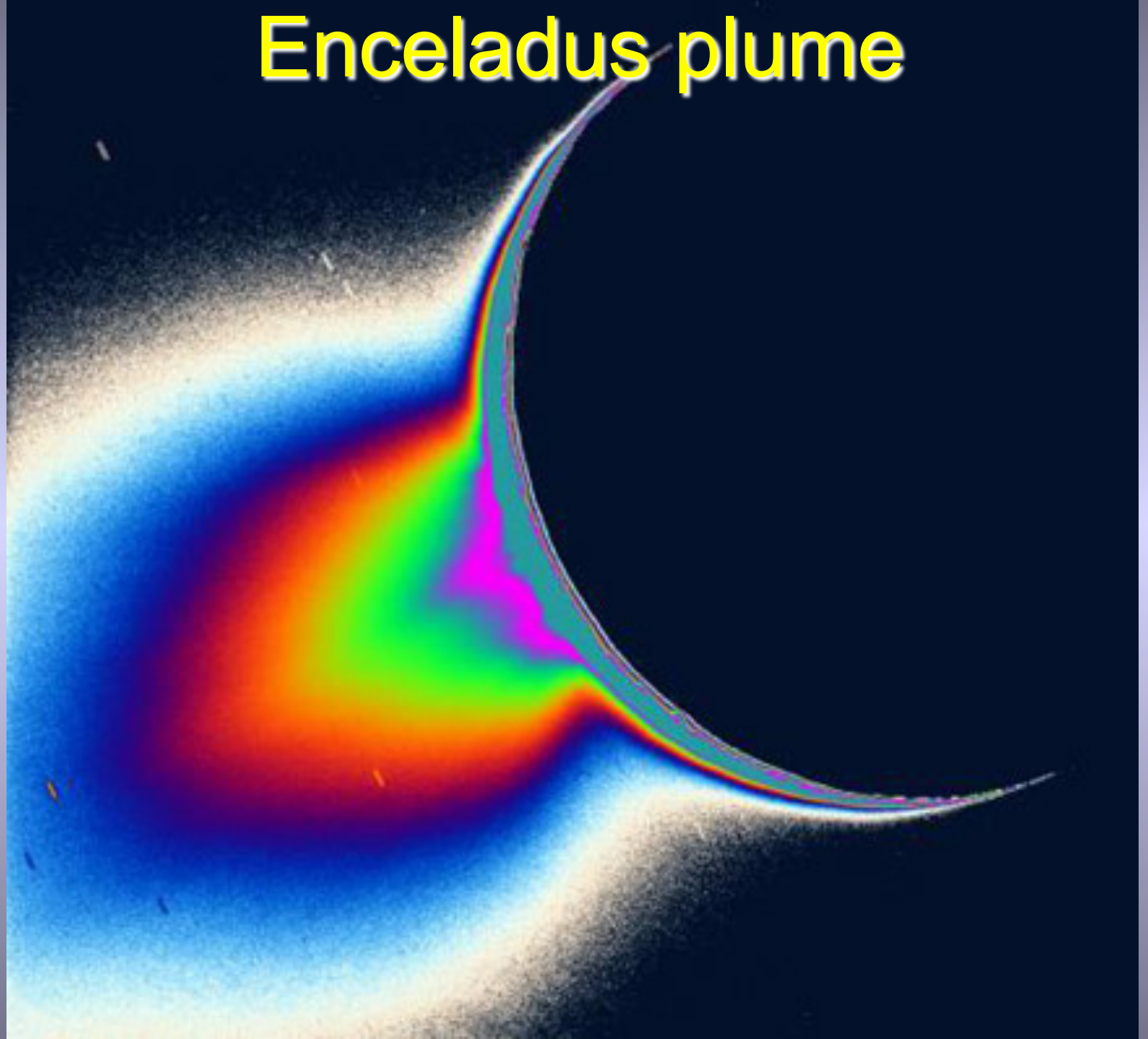
Titan's study is extremely interdisciplinary and involves : atmospheric physics, geology, meteorology, circulation, astrobiology, cryovolcanism, etc

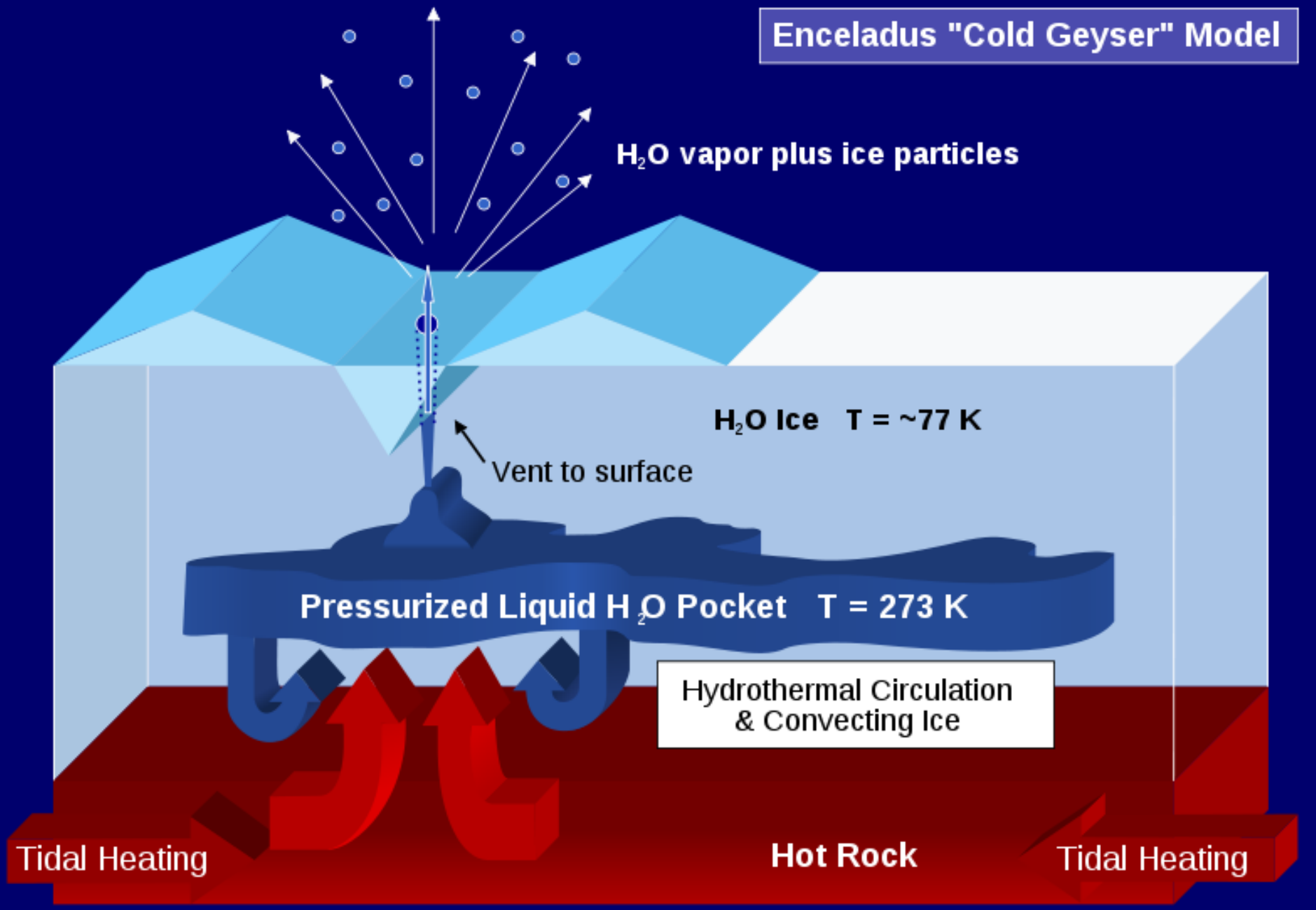
Titan's methane cycle



Enceladus, another complex system

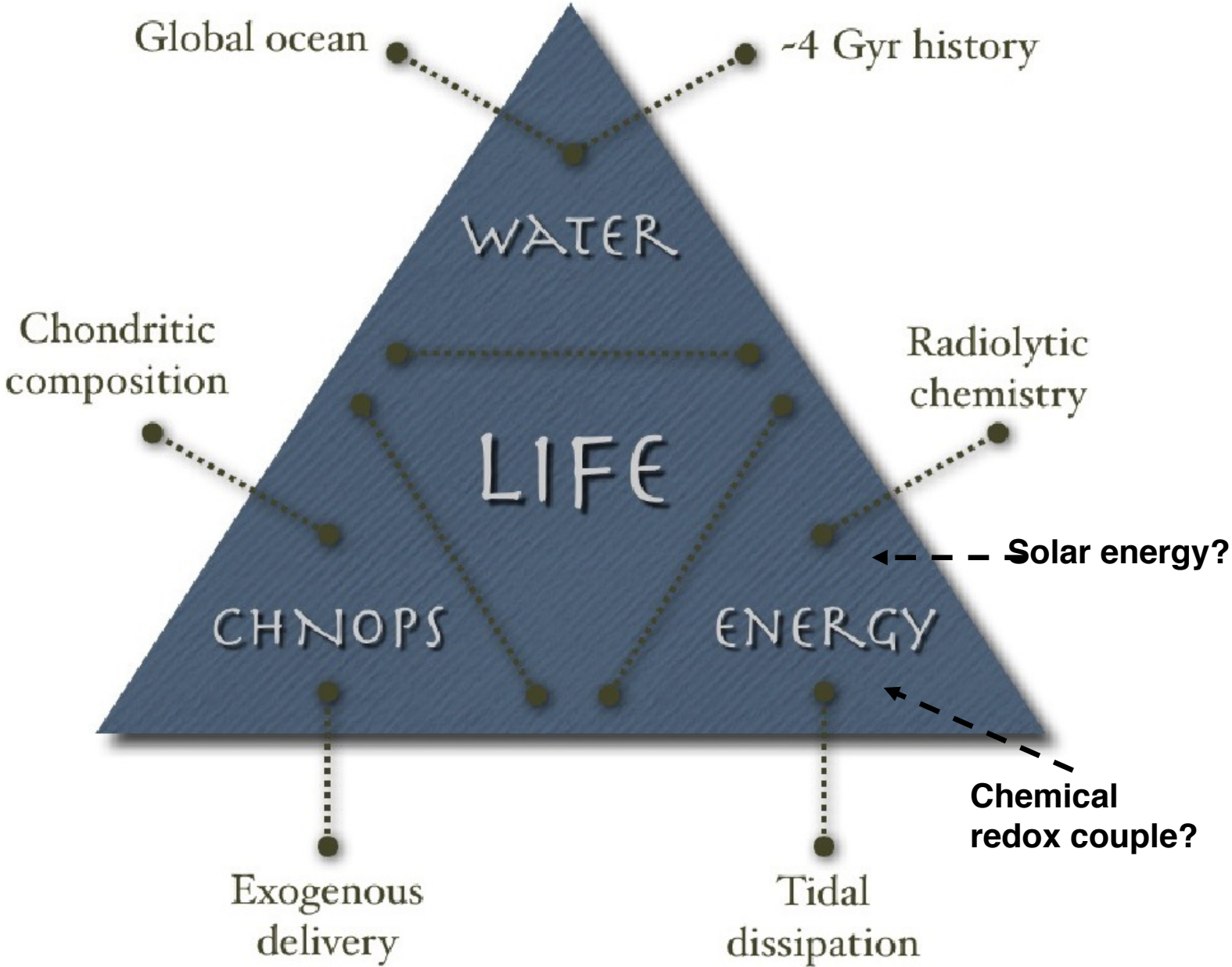
Enceladus plume




Enceladus "Cold Geyser" Model
H2O vapor plus ice particles
H2O Ice T = ~77 K
Vent to surface
Pressurized Liquid H2O Pocket T = 273 K
Hydrothermal Circulation
& Convecting Ice
Tidal Heating
Hot Rock
Tidal Heating

4 – Habitability in the solar system

The triangle of habitability



Where can liquid water exist?

1 - At the surface of solid bodies when their temperature is between freezing and boiling water

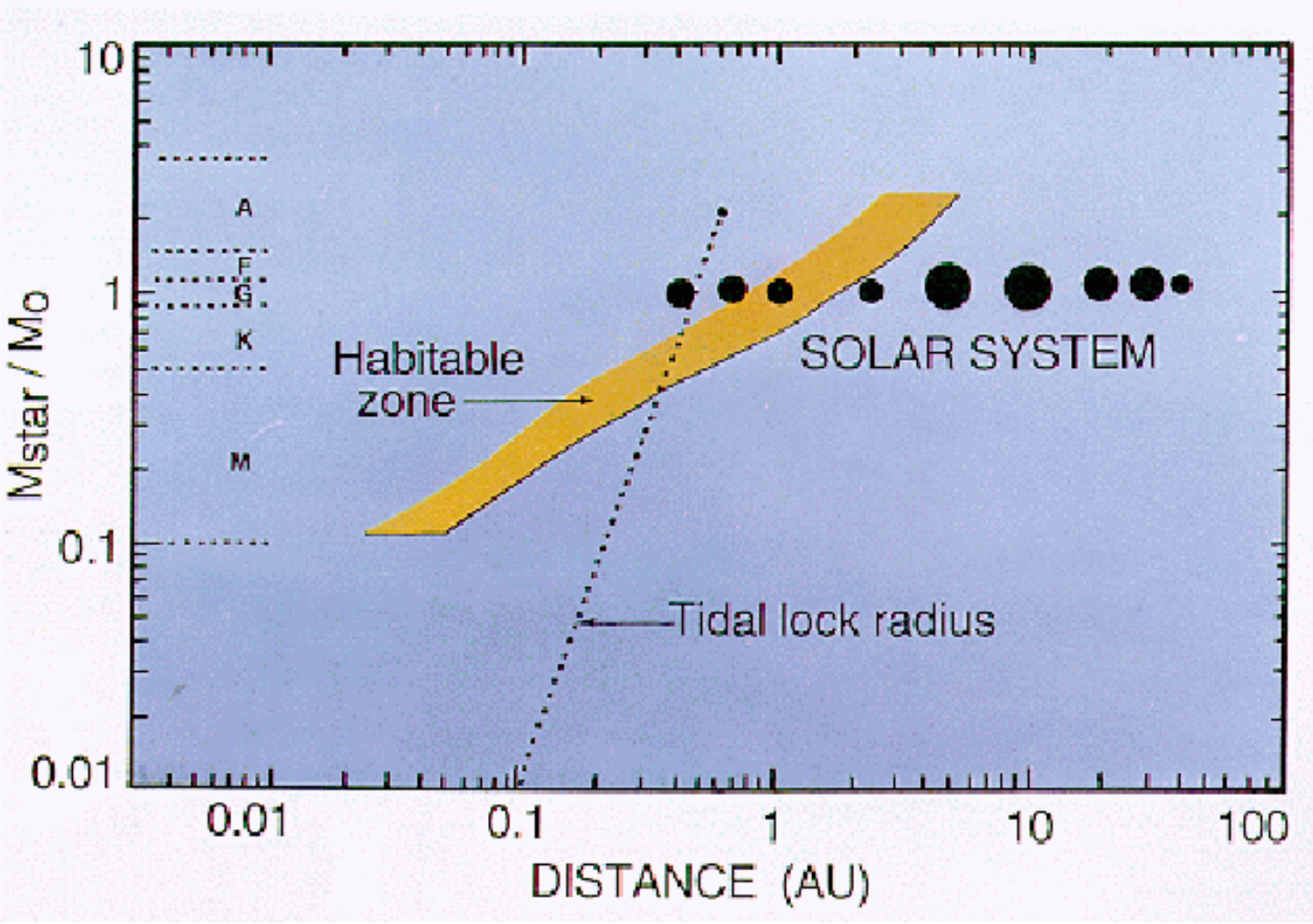
→ **At a certain distance of the star (Earth, early Mars)**

2 – Inside solid bodies made of water ice, when the pressure and temperature meet the conditions for liquid water

→ **At a certain depth inside icy satellites (Europa, Ganymede, Titan, Enceladus…)**

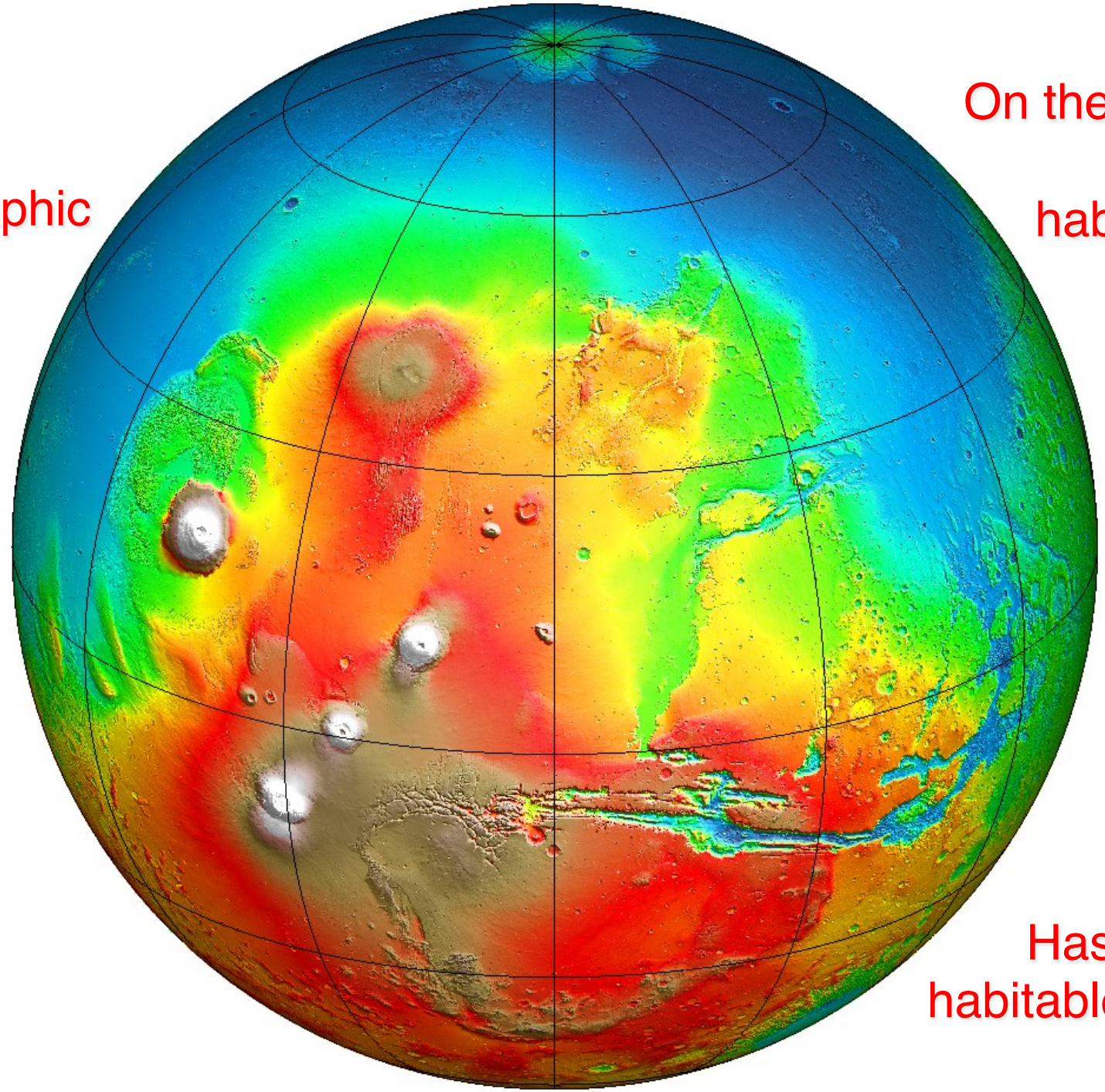
Habitability of terrestrial planets

The Habitable Zone around a Star



Mars

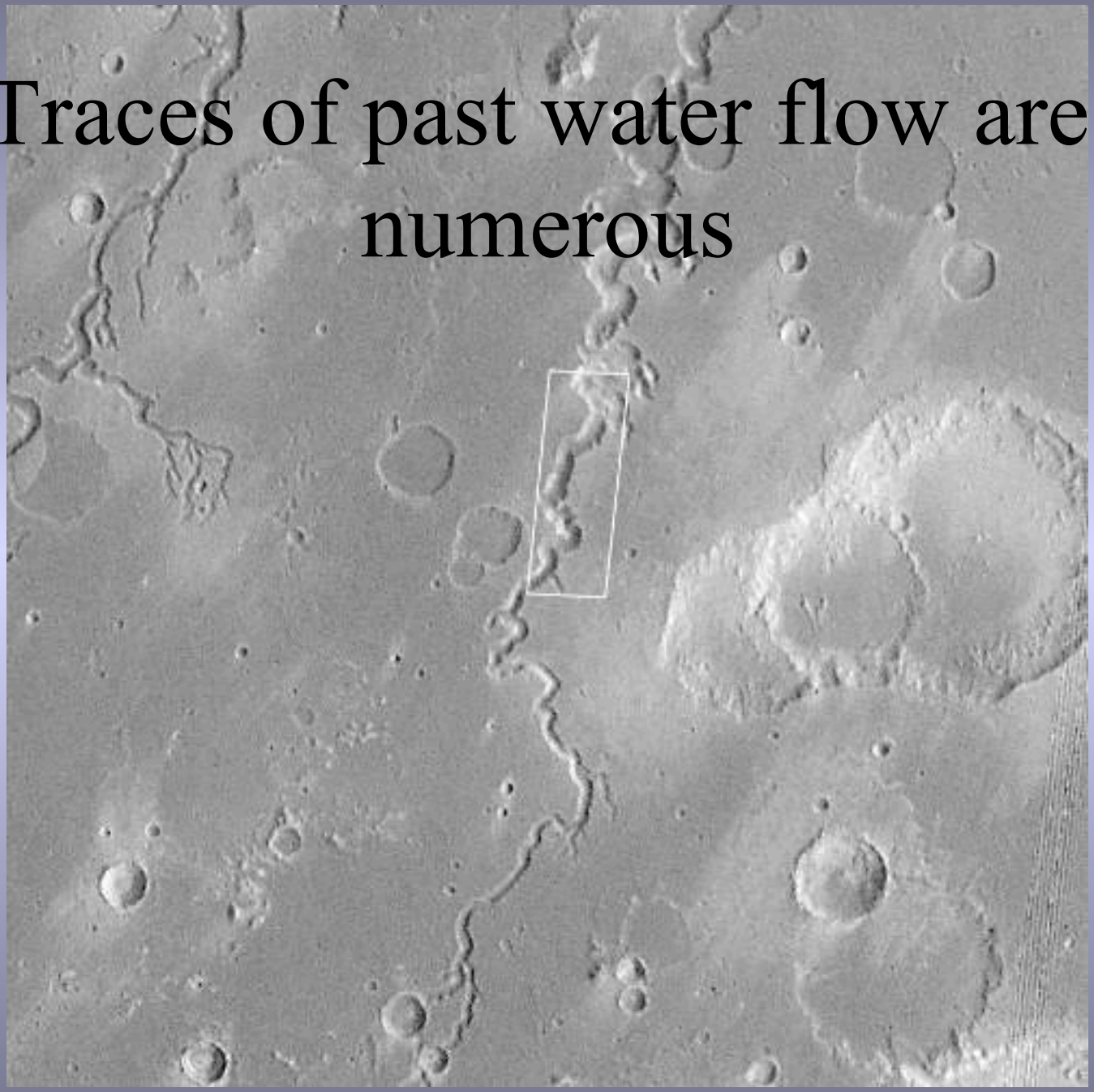
Topographic map



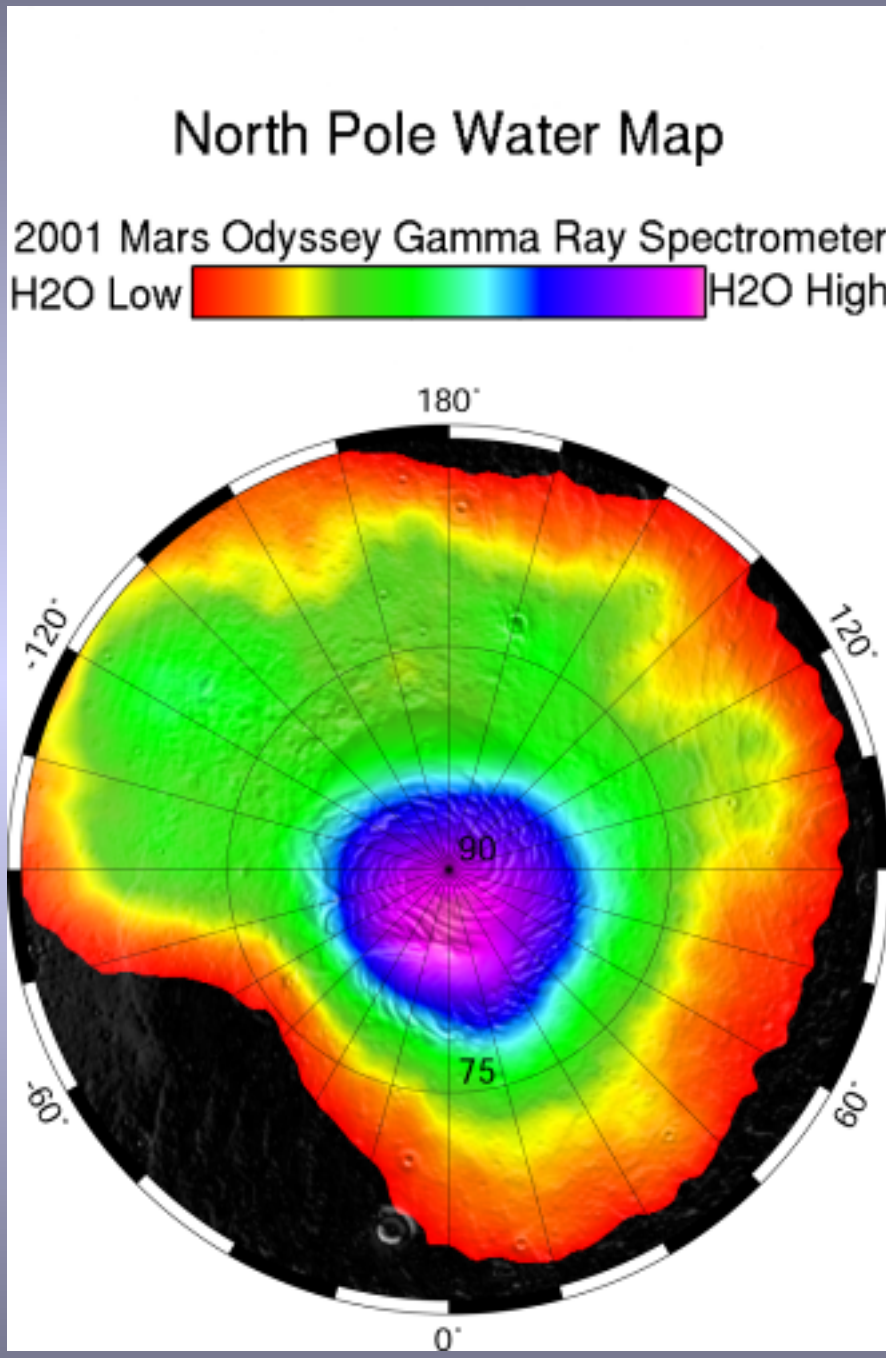
On the edge of the habitable zone

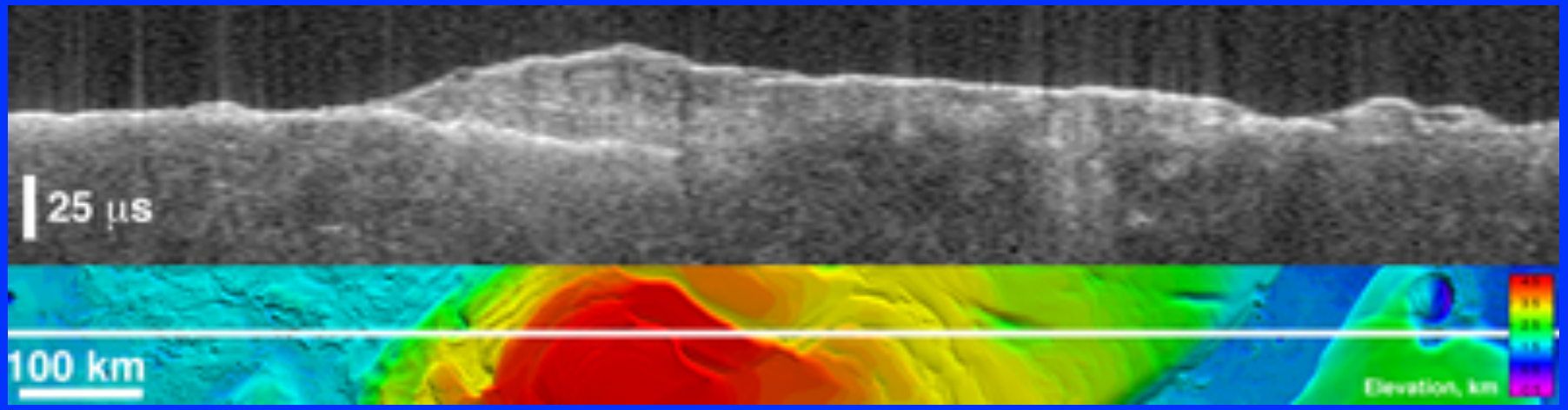
Has it been habitable in the past?

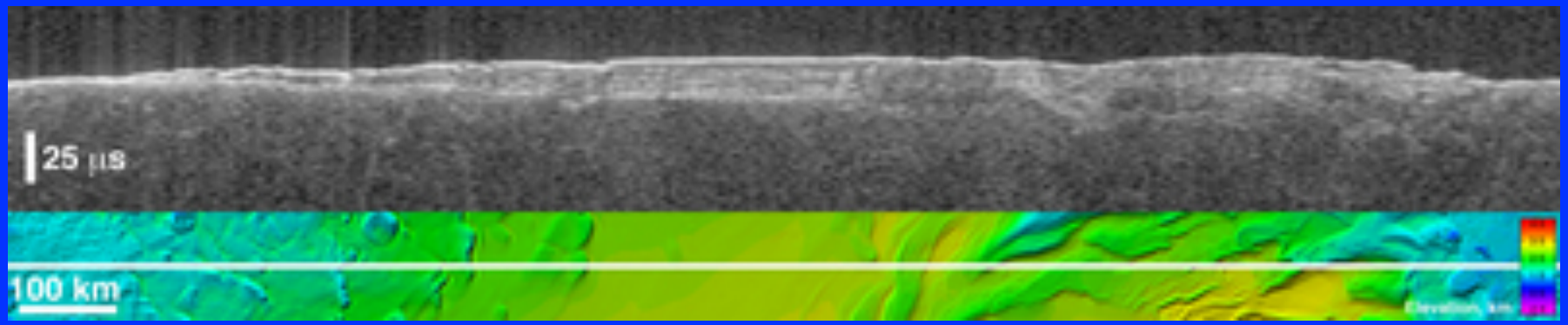
Traces of past water flow are numerous



Presence of water (ice) to-day



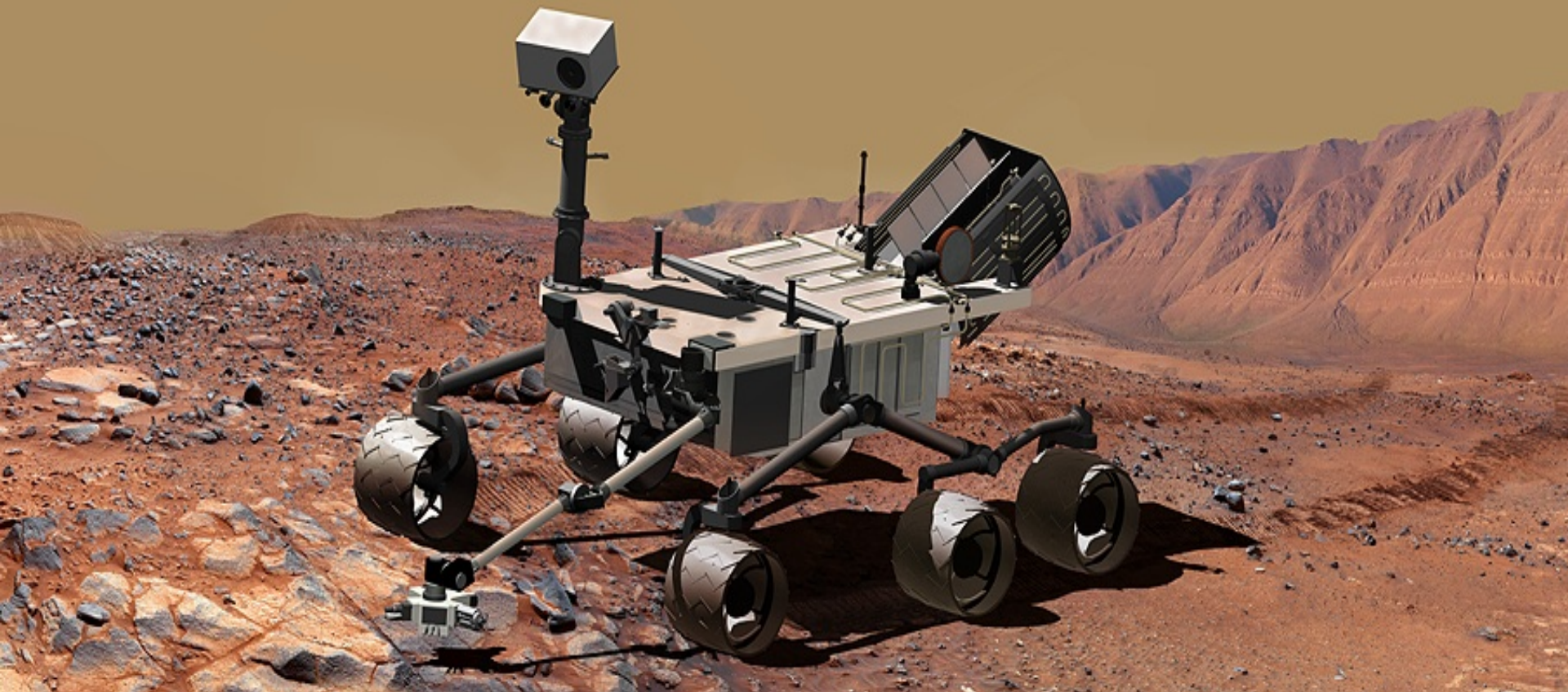




Mars cryosphere from MARSIS radar

Goals of future Mars exploration (NASA)

NASA's 2011
Mars Science Laboratory



Scientific Objectives for MSL

Explore and quantitatively assess a local region on Mars' surface as a potential habitat for life, past or present.

A. Assess the biological potential of at least one target environment.

1. Determine the nature and inventory of organic carbon compounds.
2. Inventory the chemical building blocks of life (C, H, N, O, P, S).
3. Identify features that may represent the effects of biological processes.

B. Characterize the geology and geochemistry of the landing region at all appropriate spatial scales (i.e., ranging from micrometers to meters).

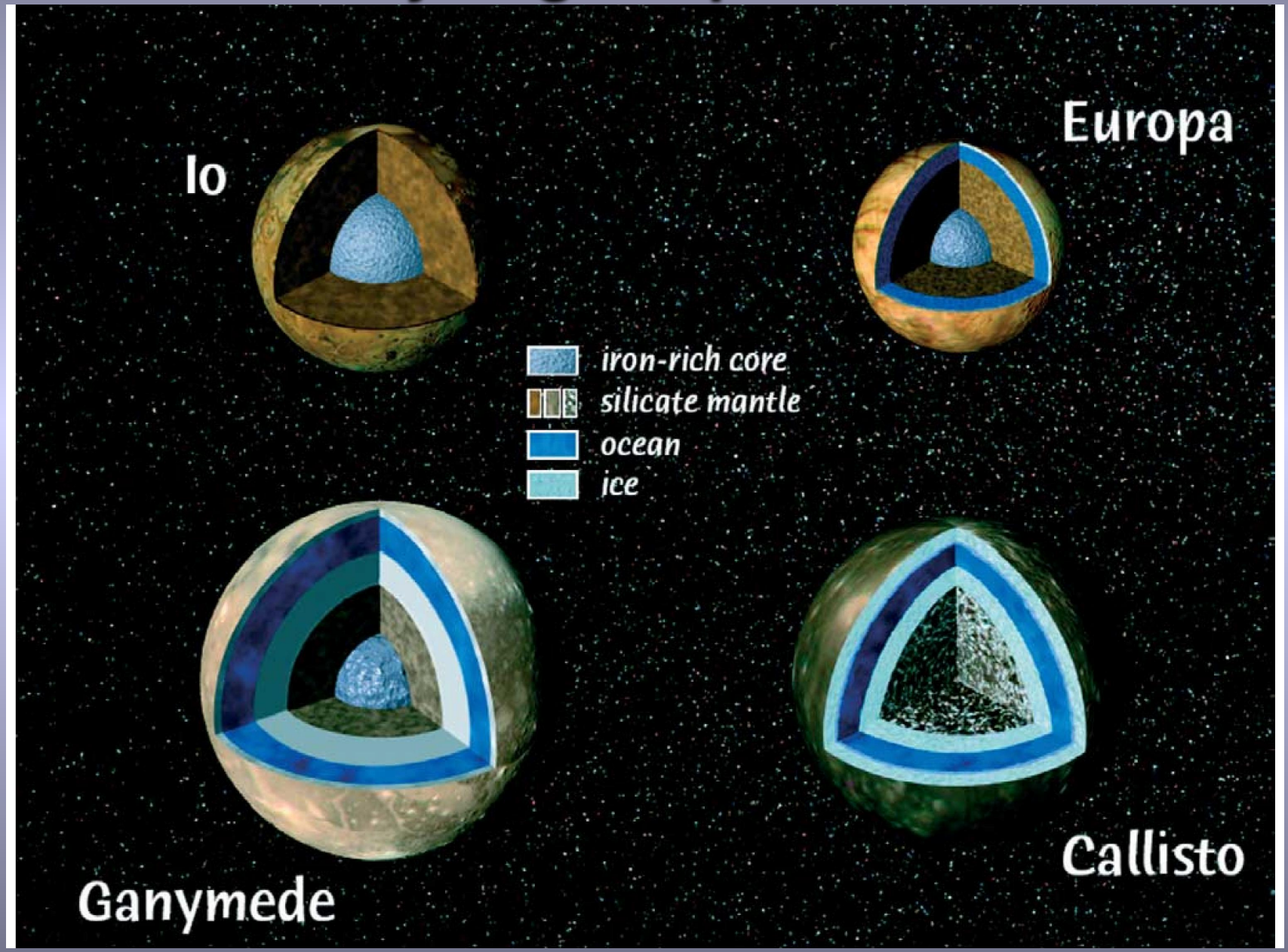
1. Investigate the chemical, isotopic, and mineralogical composition of martian surface and near-surface geological materials.
2. Interpret the processes that have formed and modified rocks and regolith.

C. Investigate planetary processes of relevance to past habitability, including the role of water.

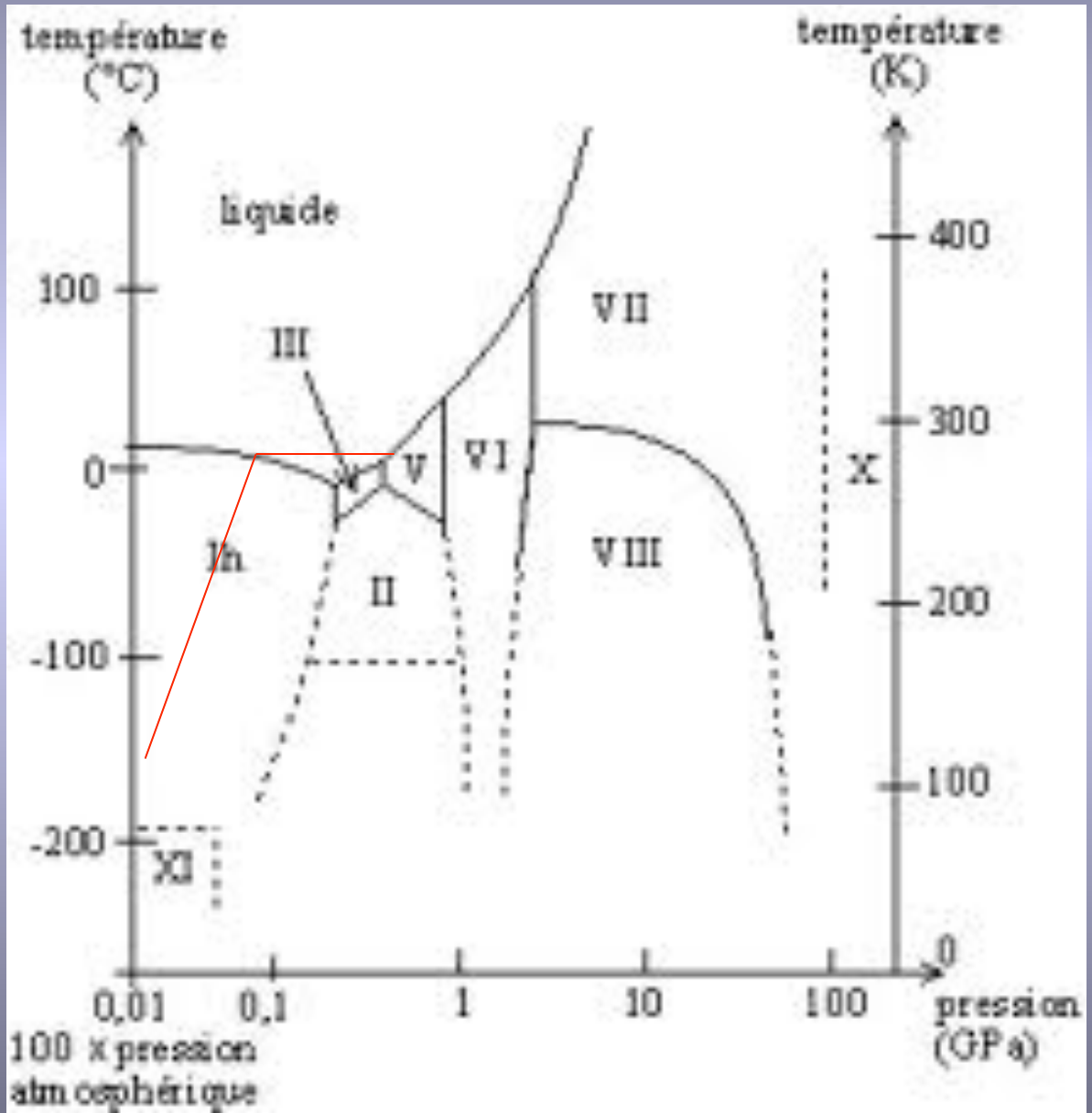
1. Assess long-timescale (i.e., 4-billion-year) atmospheric evolution processes.
2. Determine present state, distribution, and cycling of water and CO_2.

D. Characterize the broad spectrum of surface radiation, including galactic cosmic radiation, solar proton events, and secondary neutrons.

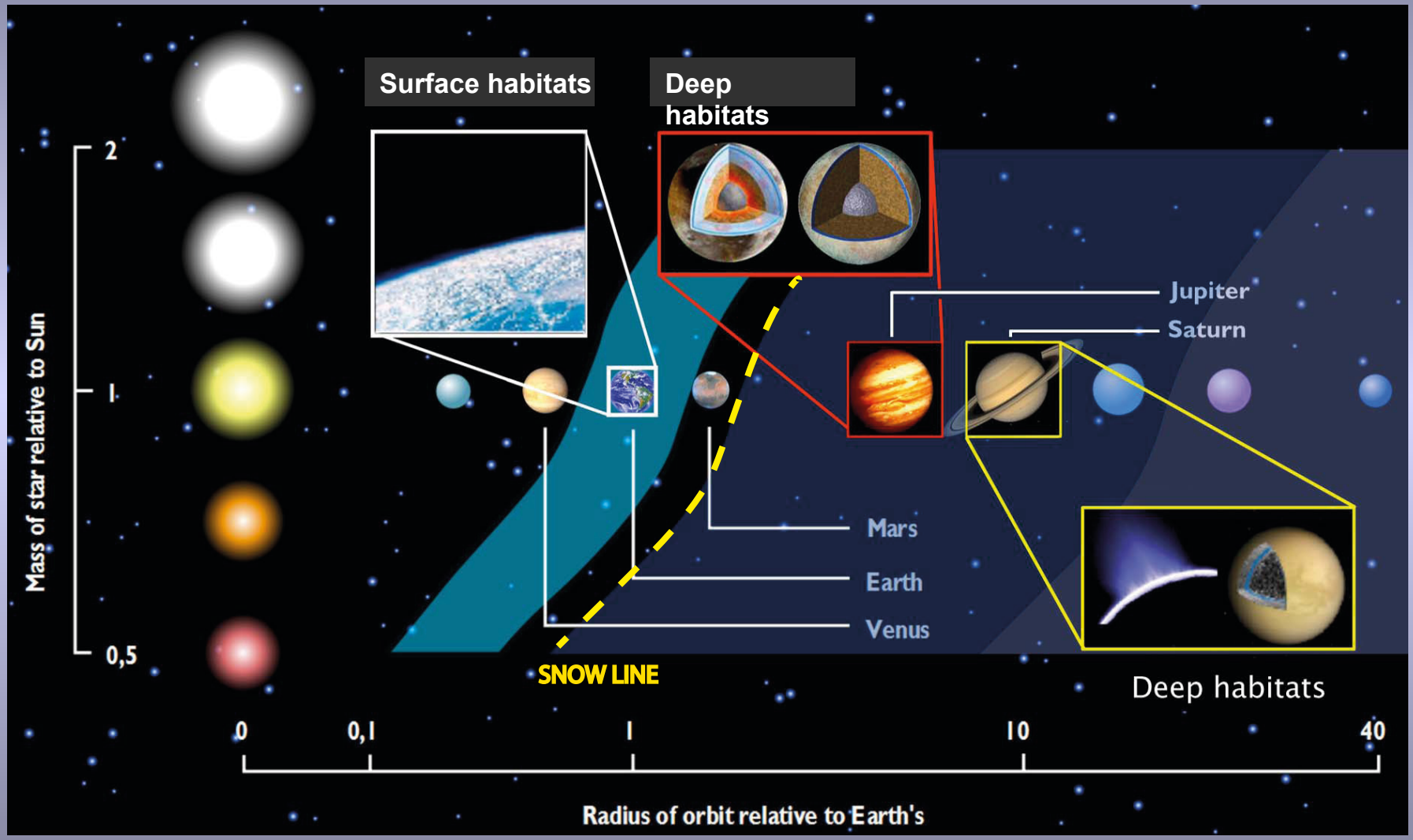
Habitability of giant planets satellites



The phase diagram of water (ice)



The habitable zone(s) in the Solar System … and beyond



Thank you for your attention