Tracing the origin of the Solar System

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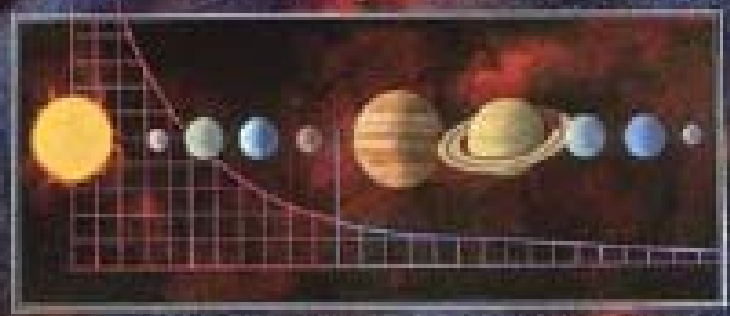
OAMP, Marseille



This talk was prepared with highly appreciated contributions from :

Yann Alibert, Antonella Barucci, Willy Benz, Dominique Bockelée-Morvan,Scott Bolton, Angioletta Coradini, Alain Doressoundiram, Michel Festou, Daniel Gautier, Tristan Guillot, Philippe Lamy, Alessandro Morbidelli, Toby Owen, Christophe Sotin.



A « Cosmic Vision » of the Solar System

Can one trace back this formation history along the paths of chemical compounds ?

The Solar Nebula

Circumstellar disks

Rocky planets

Small bodies

Jovian planets' nebulae

Pegasides

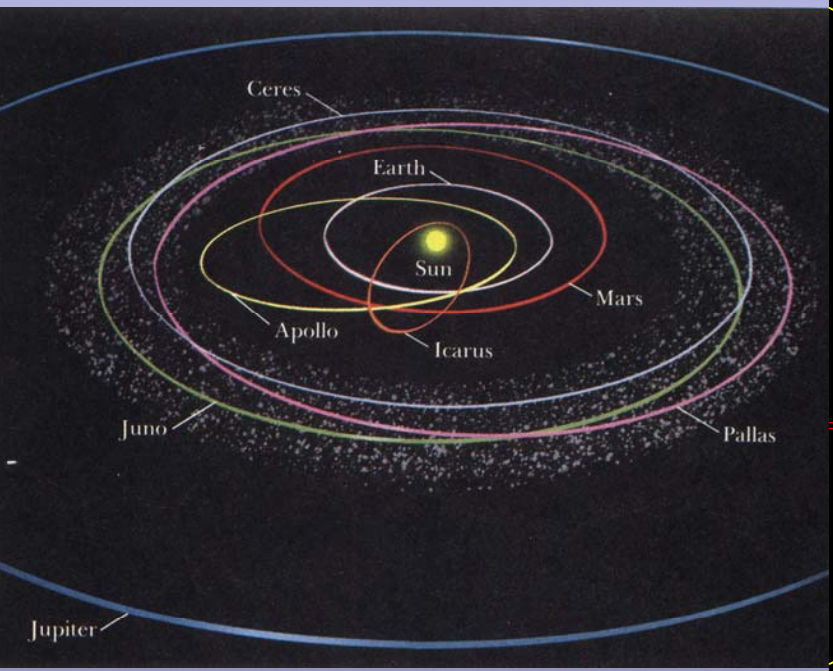
Terrestrial exoplanets ?

Icy satellites

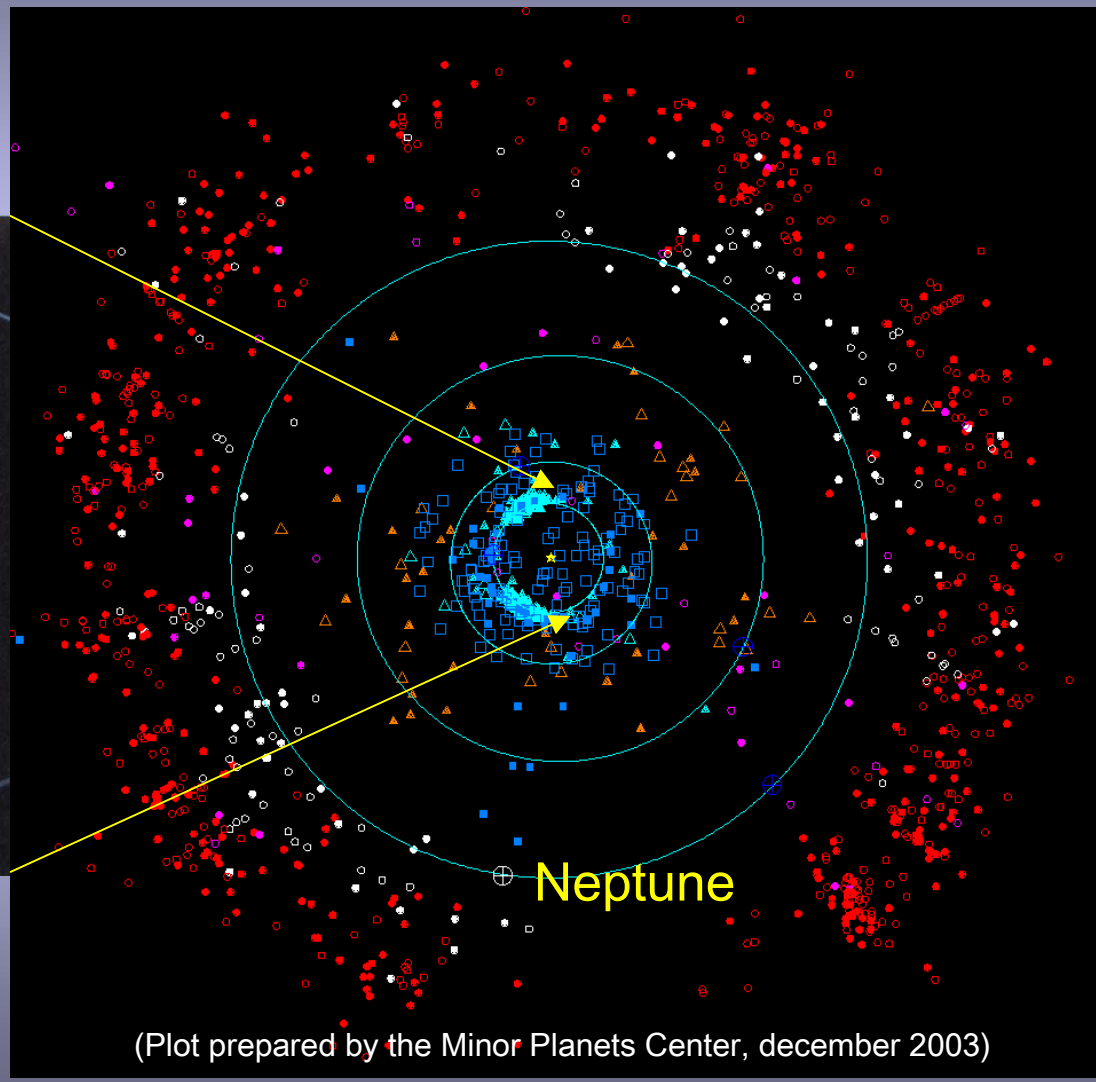
Rings and tori

Jovian planets

Our view of Solar System objects at the dawn of the XXIst century



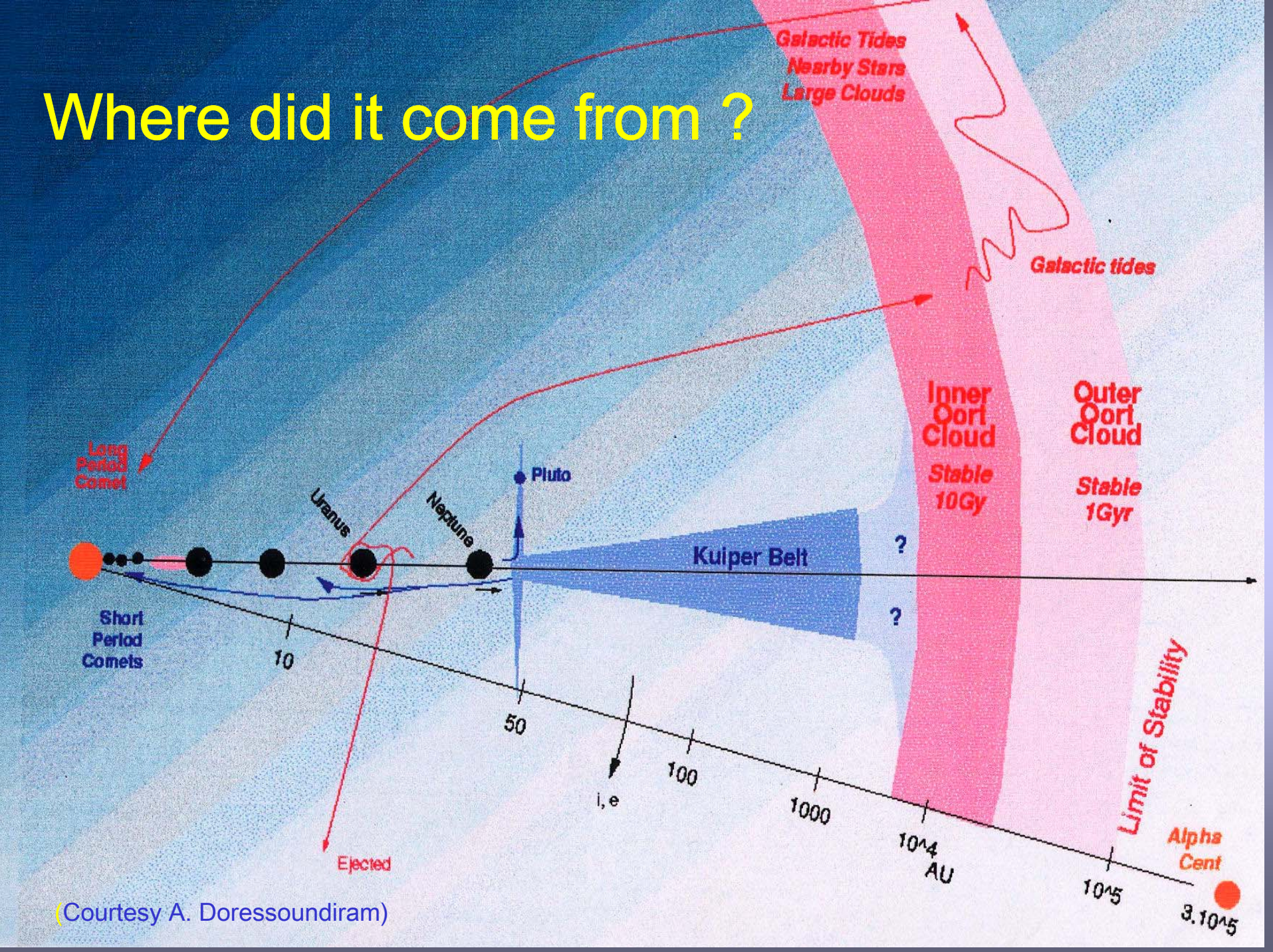
The inner solar system



(Plot prepared by the Minor Planets Center, december 2003)

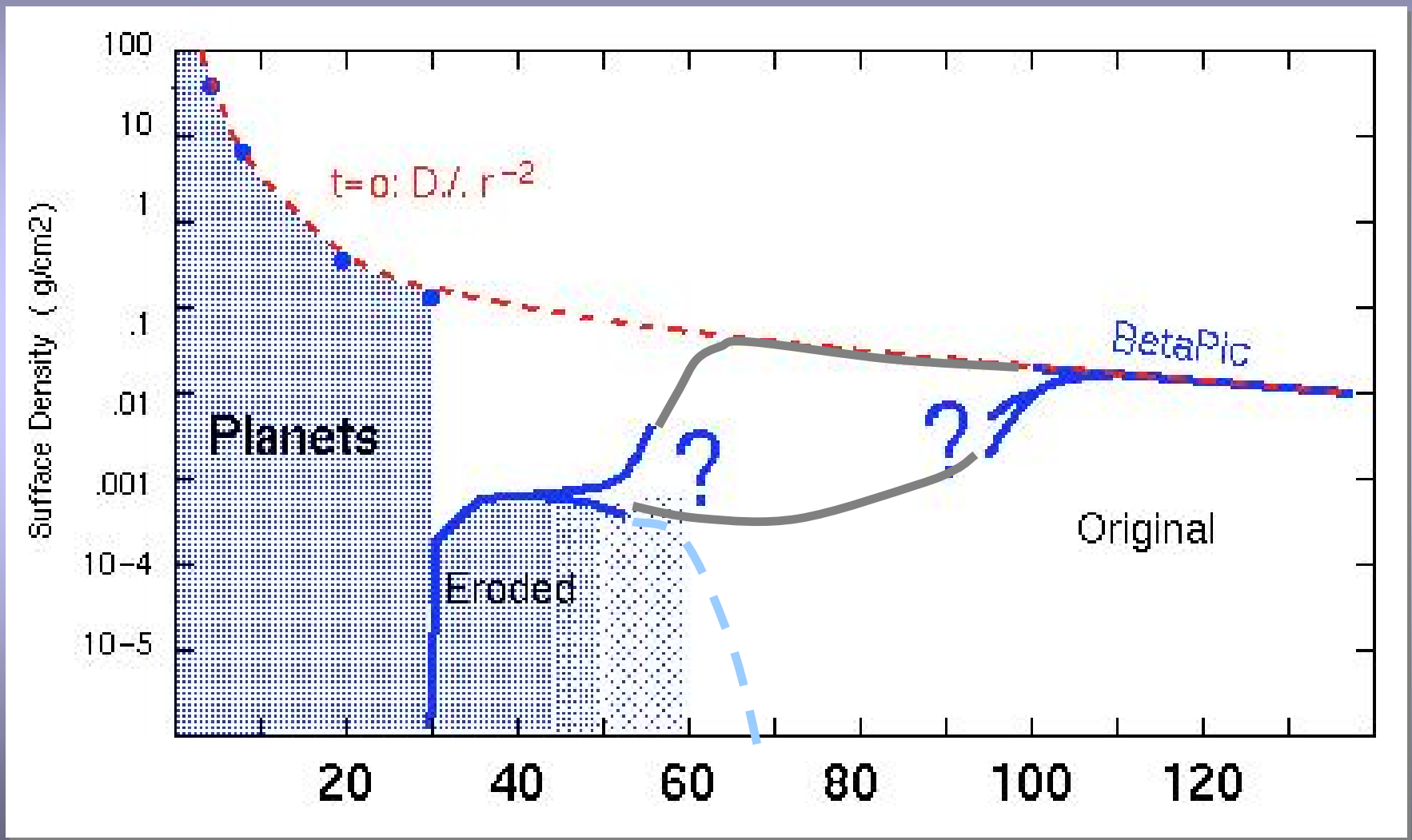
A large population of small bodies in the outer solar system

Where did it come from ?



(Courtesy A. Doressoundiram)

What radial density profile for the Nebula ?



1 – The Solar Nebula

- H and He throughout, lost to ISM after ~10 Myrs
- Volatiles : rare gases, N2,…

Hot inner nebula :

Condensates dominated by metal and silicate compounds

Cold outer nebula :

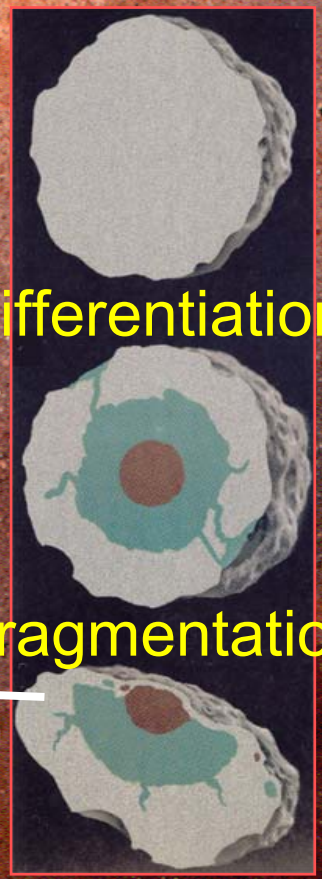
Condensates dominated by ices of H2O, hydrates of C and N

2 - The inner solar system : accretion of metal and silicate condensates

Dust

Proto-Planets

Accretion



differentiation

Rocky Planets

fragmentation

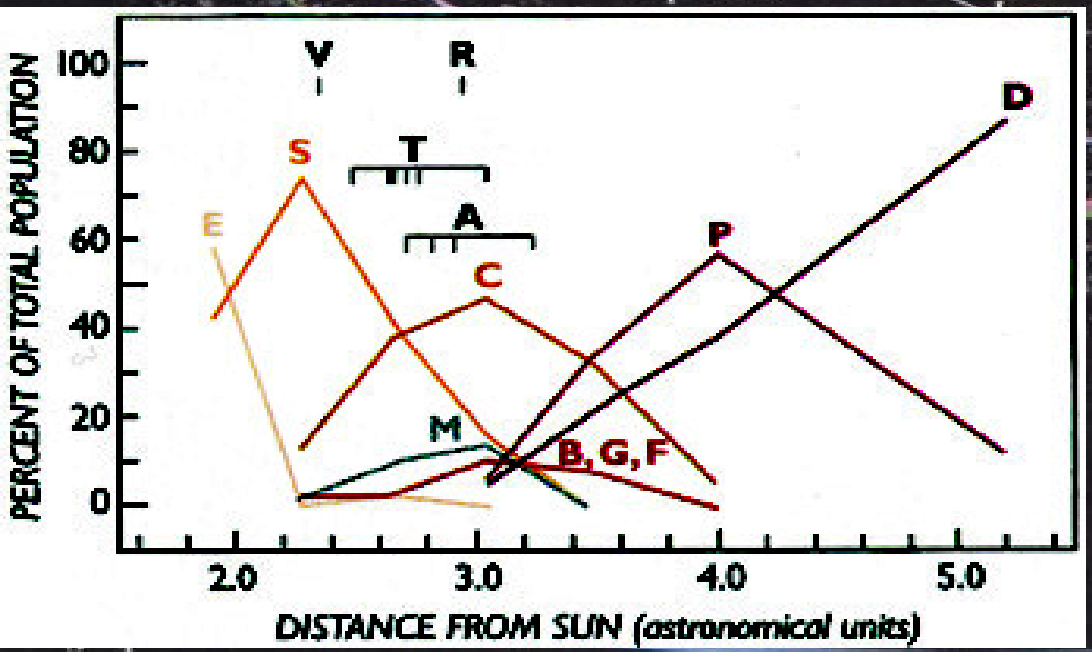
Asteroids

Gravitational dynamics

In the early solar nebula, the dust accreted to form rocks and the rocks accreted to form planetary embryos. In the asteroid belt this process was stopped when Jupiter formed.

(Kindly provided by A. Barucci)

The different classes of main belt asteroids (from the spectral types and albedos) have different radial distributions : a key to their chemical compositions ?



Gradie and Tedesco, 1982

Spectral signatures and albedos are connected to their composition but also affected by :

Shape

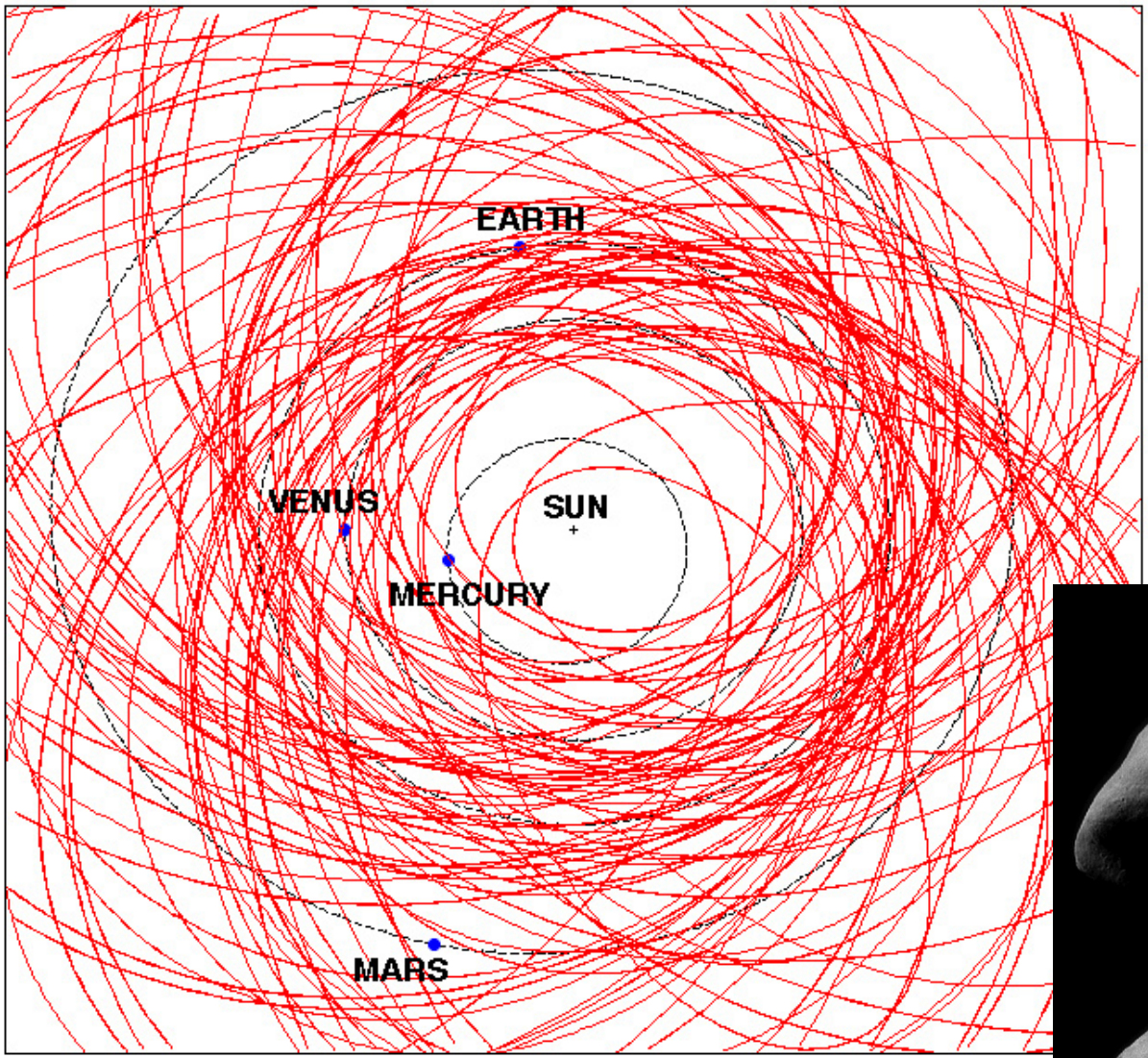
Bombardment history

Internal differenciation

Space weathering…

Need for site survey and sample analysis of a representative object in the most primitive classes

A unique opportunity : NEO's

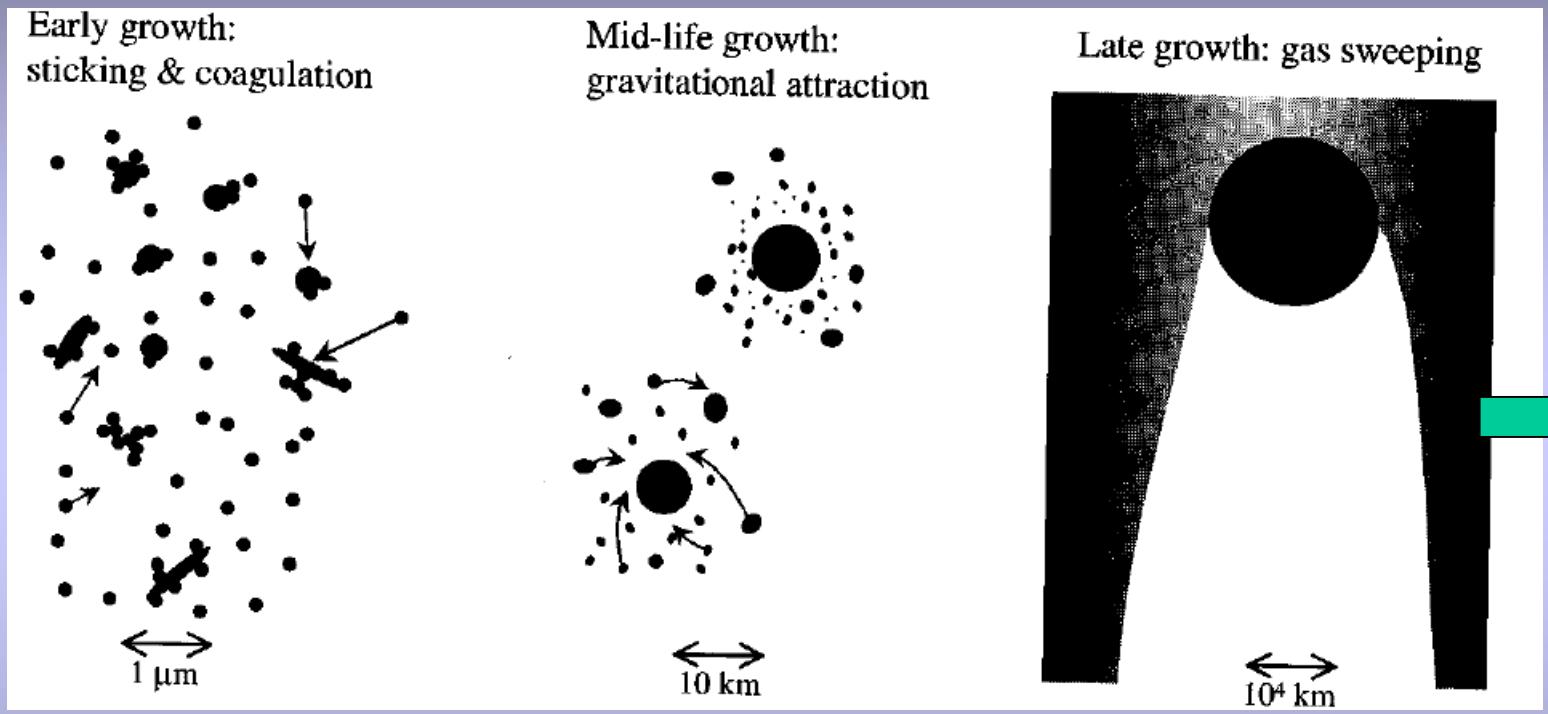


(Kindly provided by A. Barucci)

Critical space measurements on NEOs

1. Interior studies (internal structure, heterogeneity)
2. Elemental, mineralogical and isotopic data from in-situ and sample return mission to several different objects
3. Characterization of surface evolution processes
4. Return unaltered sample of primitive objects (C/D types)

3 - The outer solar system : formation of jovian planets and comet parents



Gas accretion extended to the full Hill sphere, run-away ?

- 1- Accretion acted on silicates, then on icy condensates to create the cometesimals and the cores of jovian planets ?

- **2 – continued accretion of ices, H, He by gravitational infall on the cores ?**
- **3 - Run-away growth fed by the nebular gas**
- **What degree of trapping of volatiles ?**

The « standard model » (Pollack, 1996) and its evolutions

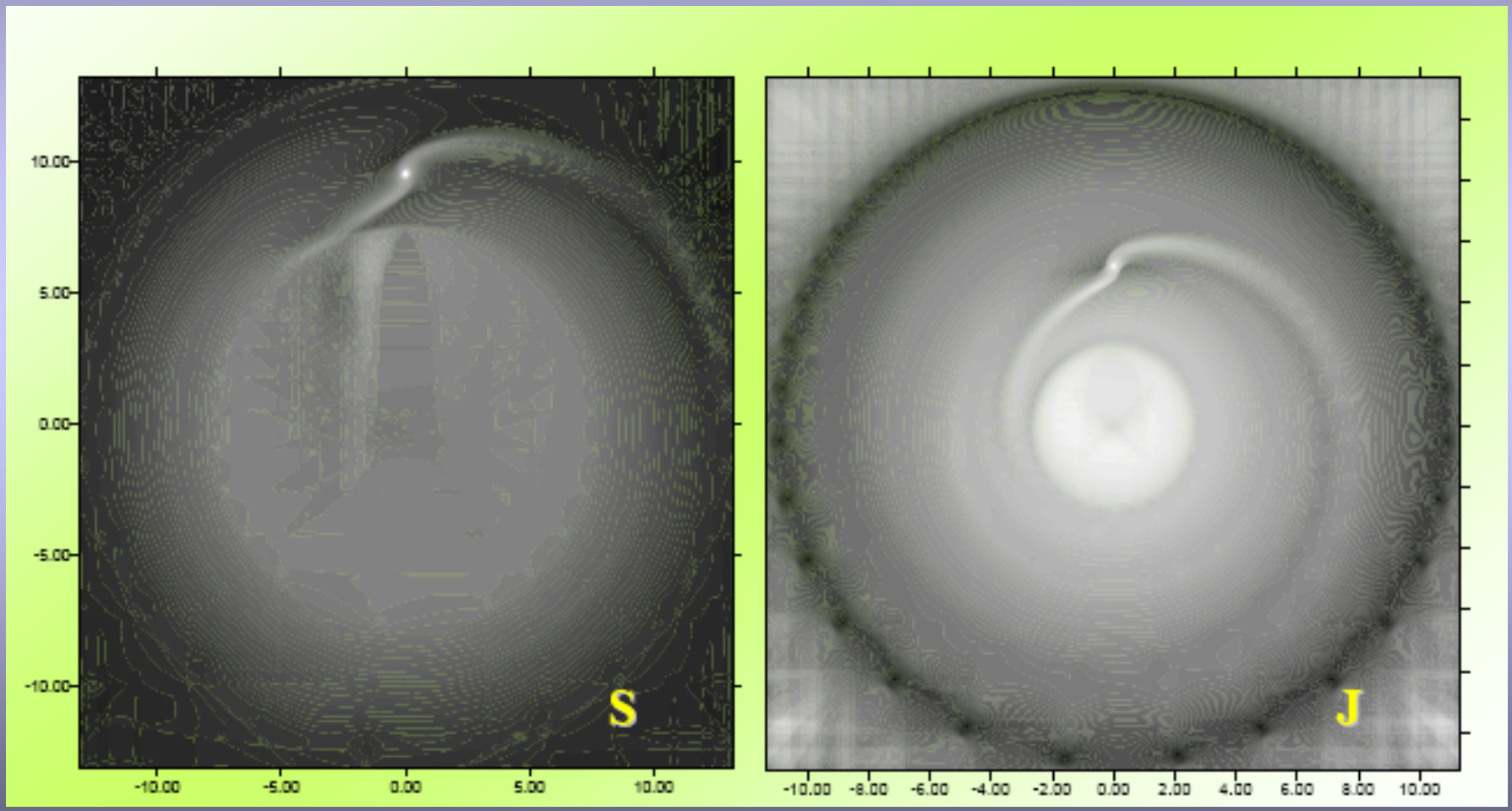
Central problem : Jupiter, Saturn to a lesser extent, must form before the nebular gas is dissipated by the T Tauri-phase solar wind.

Scenarios must take into account the interplay of :

- **Gas accretion and planet growth**
- **Evolution of the nebula**
- **Partial migration of the planet, displacing the feeding zone ?** (Alibert et al., 2004)

Example of a 3-D simulation of giant planet formation by core accretion

(Magni and Coradini, 2003)



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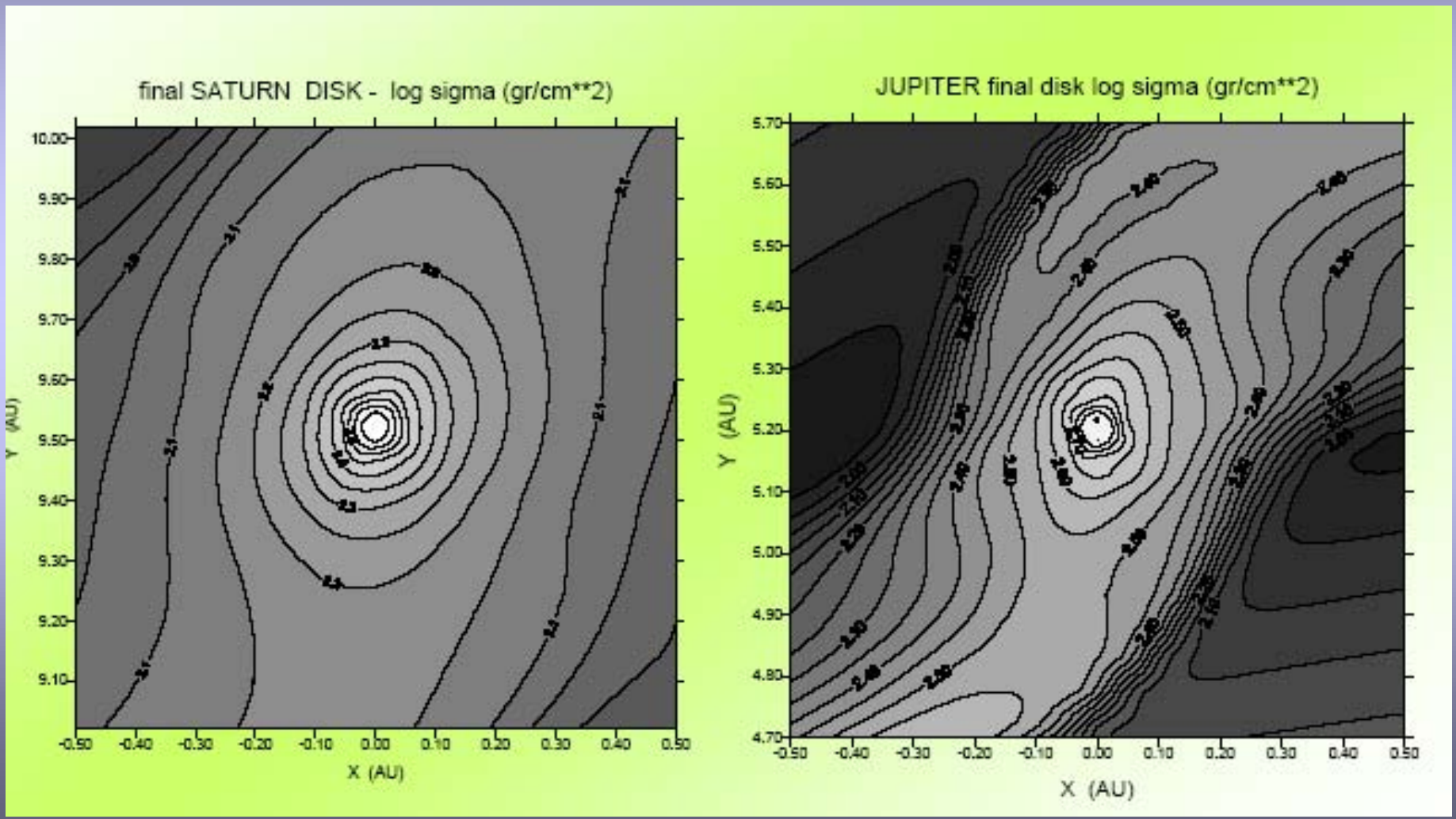
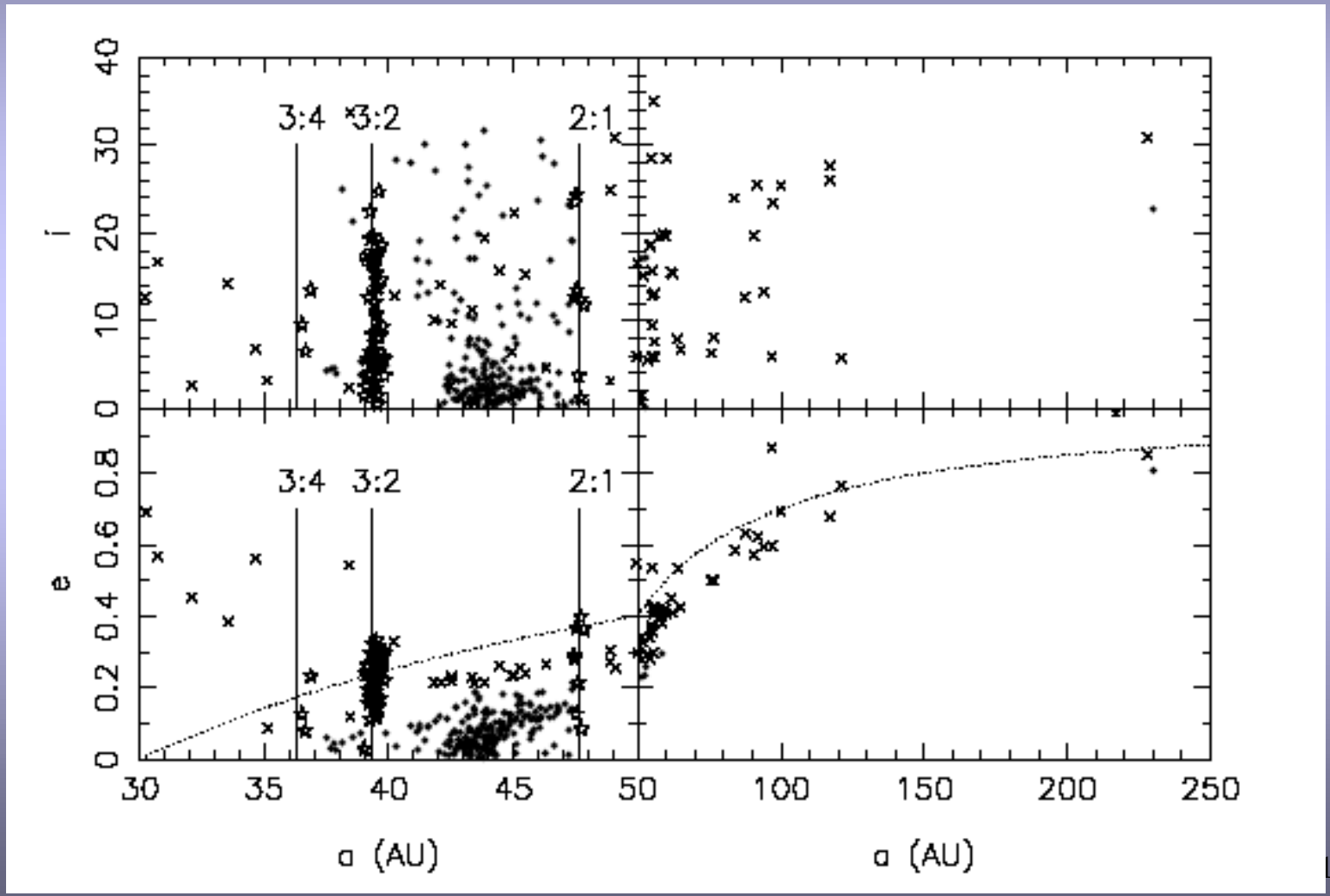


Planetary migration (of Neptune) also needed to explain the « sculpting » of the population of Trans Neptunian Objects ?



(Morbidelli et al., 2004)

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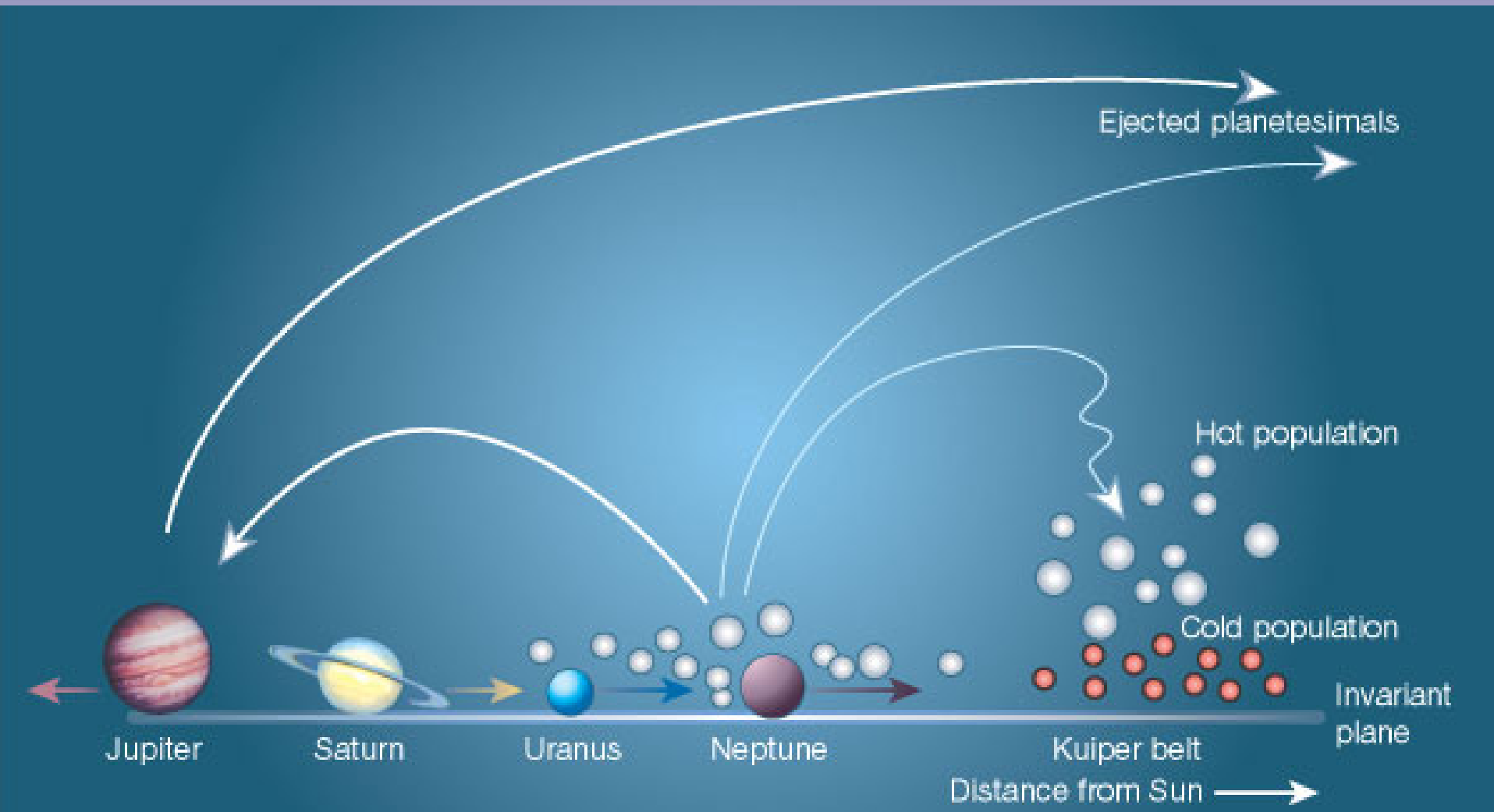
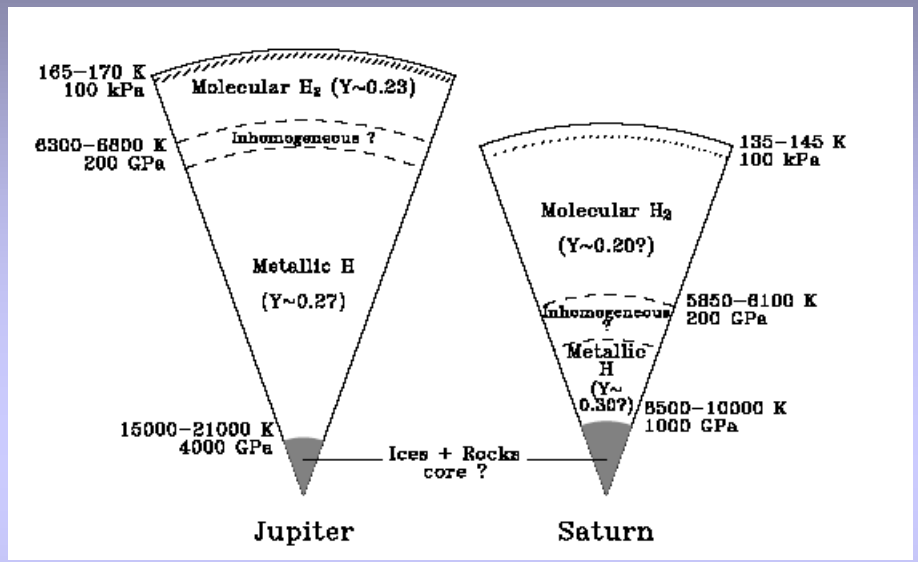


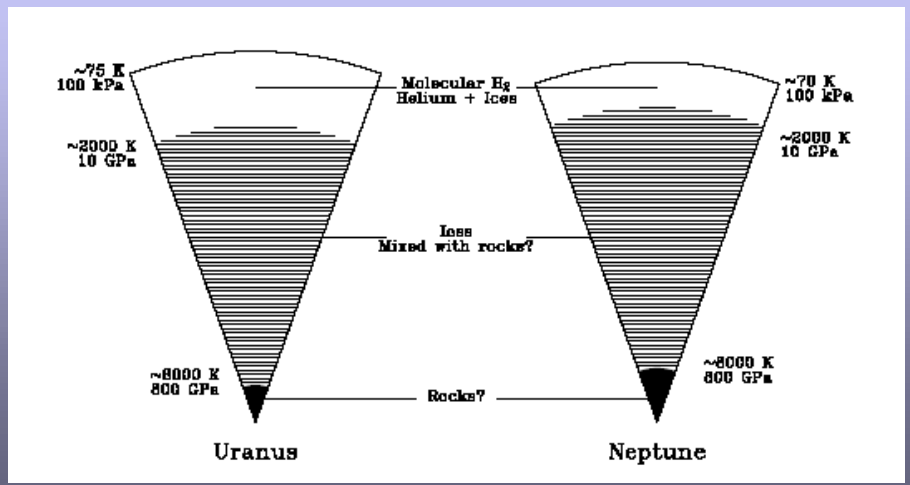
(Model, R. Gomes, 2003, Image by Morbidelli & Levison, 2003)

Giant planets internal structure :

Poorly constrained !



- Jupiter and Saturn have a thick H, He envelope, accreted before the nebula dissipated.
- At least 10 to 20 earth masses of heavy elements in their envelopes : degree of mixing, size of core ?



(T. Guillot, 1999, 2004)

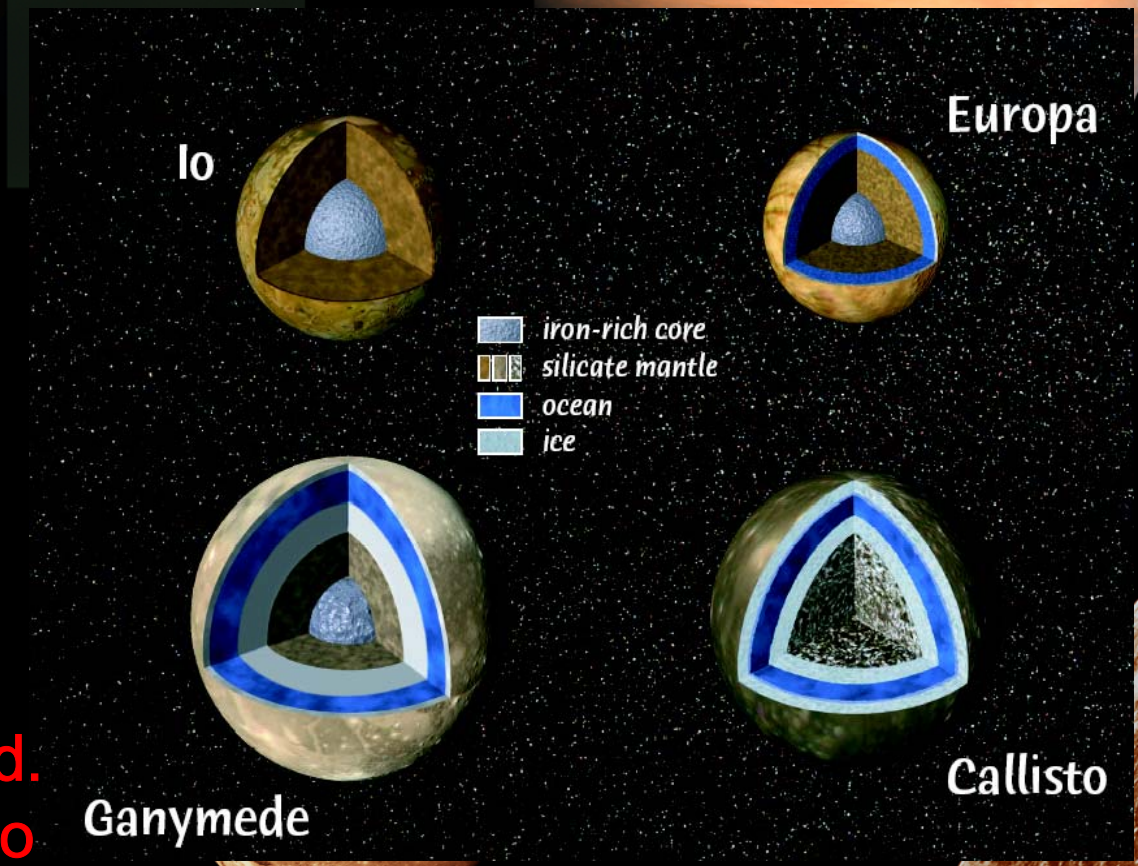
- Uranus and Neptune apparently completed their accretion long after the nebula dissipated.
- They have a « shallow » H, He envelope, and a dominant mantle of ices (and rocks ?)

Critical space measurements on giant planets internal structure :

- **Accurate measurements of gravity fields and magnetic fields : internal structure, rotation state.**
- **Abundance of water in the deep atmosphere of Jupiter : Deep microwave sounding ?(Bolton et al. 2003).**
- **Abundance of water and other species (especially volatiles) in the deep atmospheres of all four giant planets : atmospheric probe missions ?**
- **Detect new transiting extrasolar planets, and hopefully some that are further from their star : COROT (2006), Kepler (2007), Eddington ?**

4 - Icy satellites : outstanding targets for comparative planetology

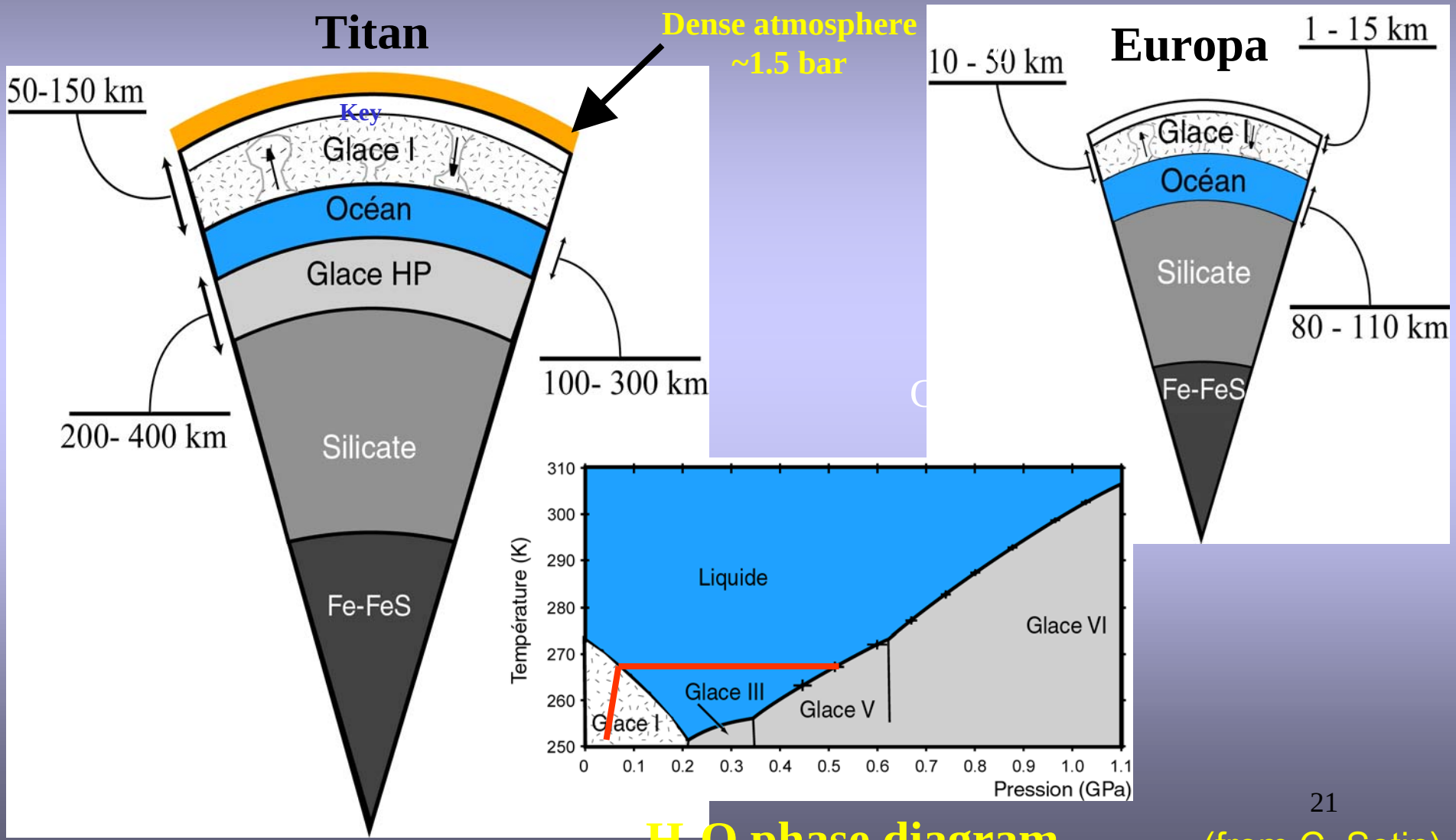
Volcanism !



Sub-surface ocean, dynamic sea-floor ?

Intrinsic magnetic field. What dynamo mechanism ?

Europe-Titan: similarities and differences



H_2O phase diagram

(from C. Sotin)

Critical measurements for icy satellites

- Improved average densities and constraints on internal mass distribution : gravity and magnetic fields
- Surface characterization, sub-surface sounding
- chemical composition of the surfaces,
- … a full characterization of these bodies with the eye of a geologist, a geophysicst, a geochemist…

Tracing back to their origins (jovian nebulae, solar nebula), is a long way ahead, but icy satellites are interesting enough as a very distinct class of planetary bodies !

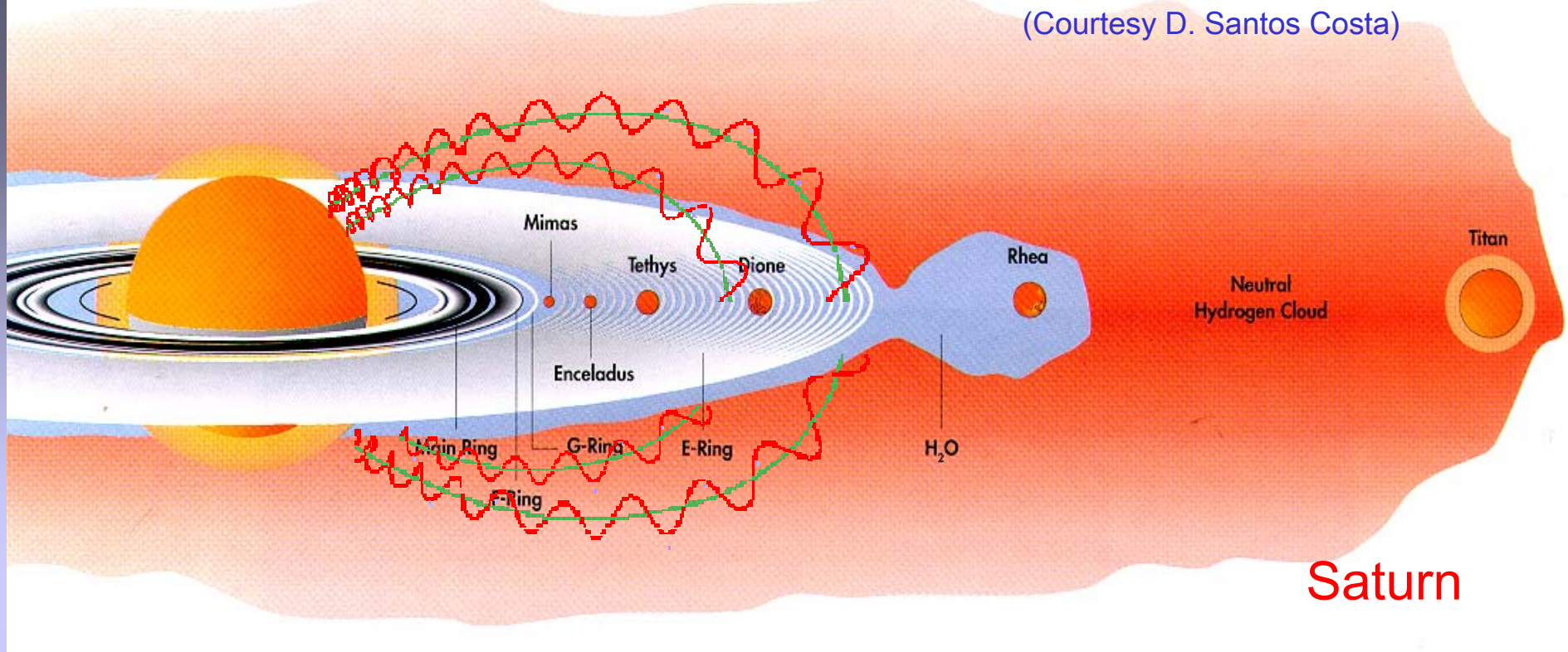
5 - Giant planets rings, dust and plasma environments

In situ study of momentum transfer between a magnetized central object and a partially ionized rotating disk

Rings studies

Jupiter

(Courtesy D. Santos Costa)



Saturn

- **Giant planets display interacting populations of ring particles, dust, gas, trapped radiation in strong interaction.**

- **A unique opportunity to study the dynamics and evolution of these complex systems**

- **… which may have connections with some of the mechanisms which were at work in the solar nebula.**

Conclusions :
1 – Major open questions

- **Initial structure and evolution of the Solar Nebula ?**
- **How did accretion work ? a complex interplay of processes…**
- **Formation history and chemical composition of small bodies populations. What connections to the primordial nebula ? How much do we understand of it ?**
- **How did giant planets form ? A question closely connected to :**
  - **The evolution of the outer solar nebula,**
  - **The internal structure, chemical composition and planetary fields of giant planets**
- **Internal structure, bulk composition, geodynamics of icy satellites ? Distribution of solid and liquid water ? What connection to the formation of giant planets' systems ?**
- **Outer planets coupling to their space environment, dusty plasmas, …**

Conclusions :
2 – Key measurements.

To solve the « big puzzle » of Solar System formation we need :

- **To sample all classes of objects in terms of elementary, isotopic, mineralogic composition, and to establish the budget of the different types of refractory and volatile compounds that contributed to their formation :**
  - **Small bodies (NEOs, Oort cloud comets, TNO's…)**
  - **giant planets atmospheres,**
  - **icy satellites surfaces and interiors**
- **To determine their internal structure :**
  - **Giant planets**
  - **Icy stellites**
- **To observe the mechanisms at work in contemporary planets' space environments : planetary rings, dust and gas tori……**