The Odin Mission Concept

A Mission to the Ice Giant Planets to Study the History of our Solar System

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The Odin Mission and Cosmic Vision

The Odin mission concept aims to address the first theme of the Cosmic Vision:

1. What are the conditions for planetary formation and the emergence of life?

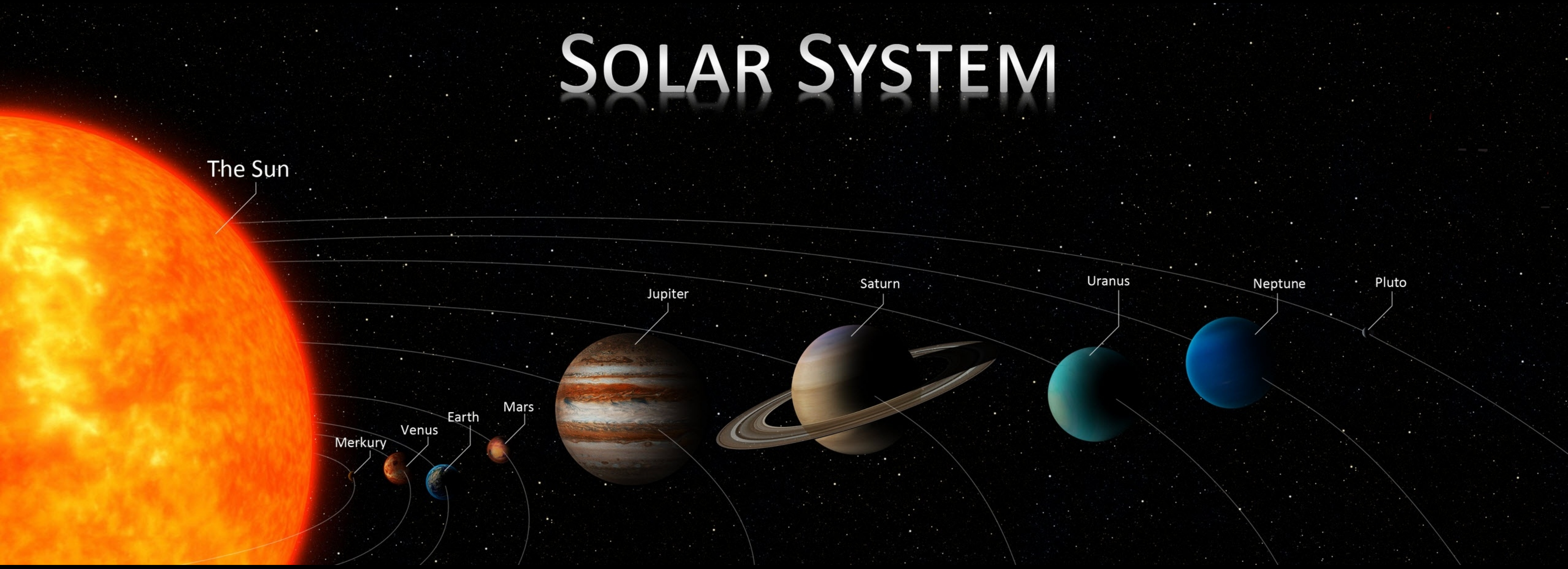
In doing so, the Odin mission will also address the second and third themes of Cosmic Vision:

2. How does the Solar System work?

3. What are the fundamental physical laws of the Universe?

Planetary Formation and the Solar System

The **original idea**, derived from the observations of the Solar System, was that **planetary formation** was a **local, orderly process** that produced regular and stable planetary systems.



Planetary Formation and Extrasolar Planets

As we discover more and more planetary systems through ground-based and space-based observations, it is becoming evident that **planetary formation can result in a wide range of outcomes**. Our Solar System may be the exception and not the rule.

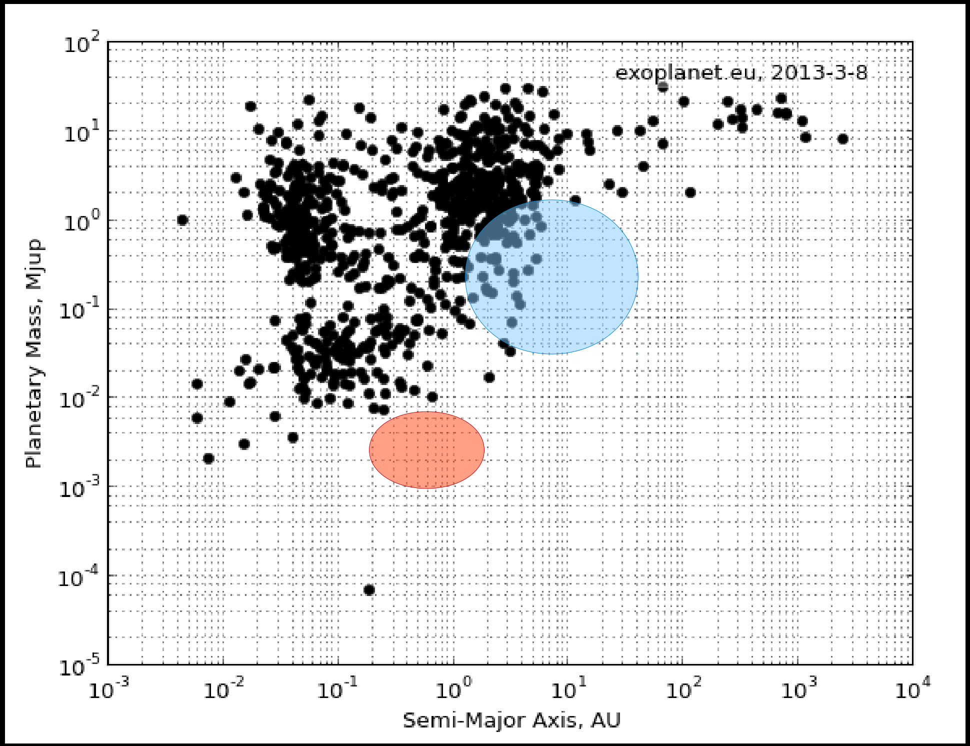
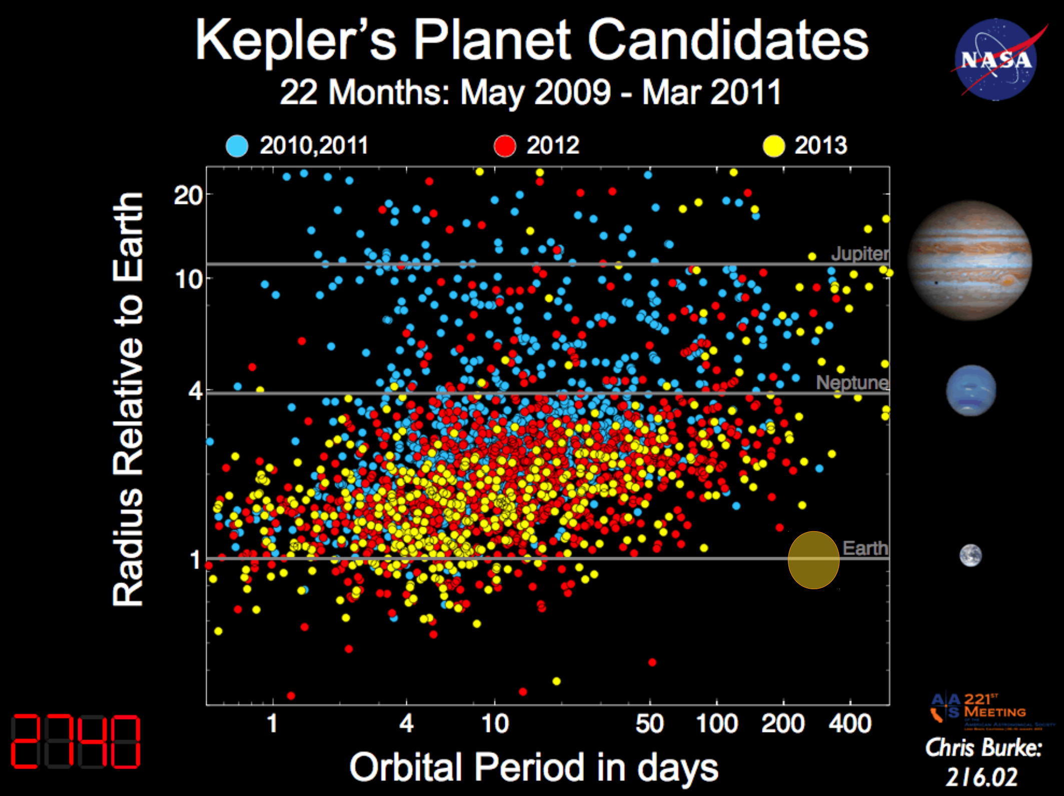


Image credits: The Extrasolar Planets Encyclopaedia (www.exoplanet.eu)



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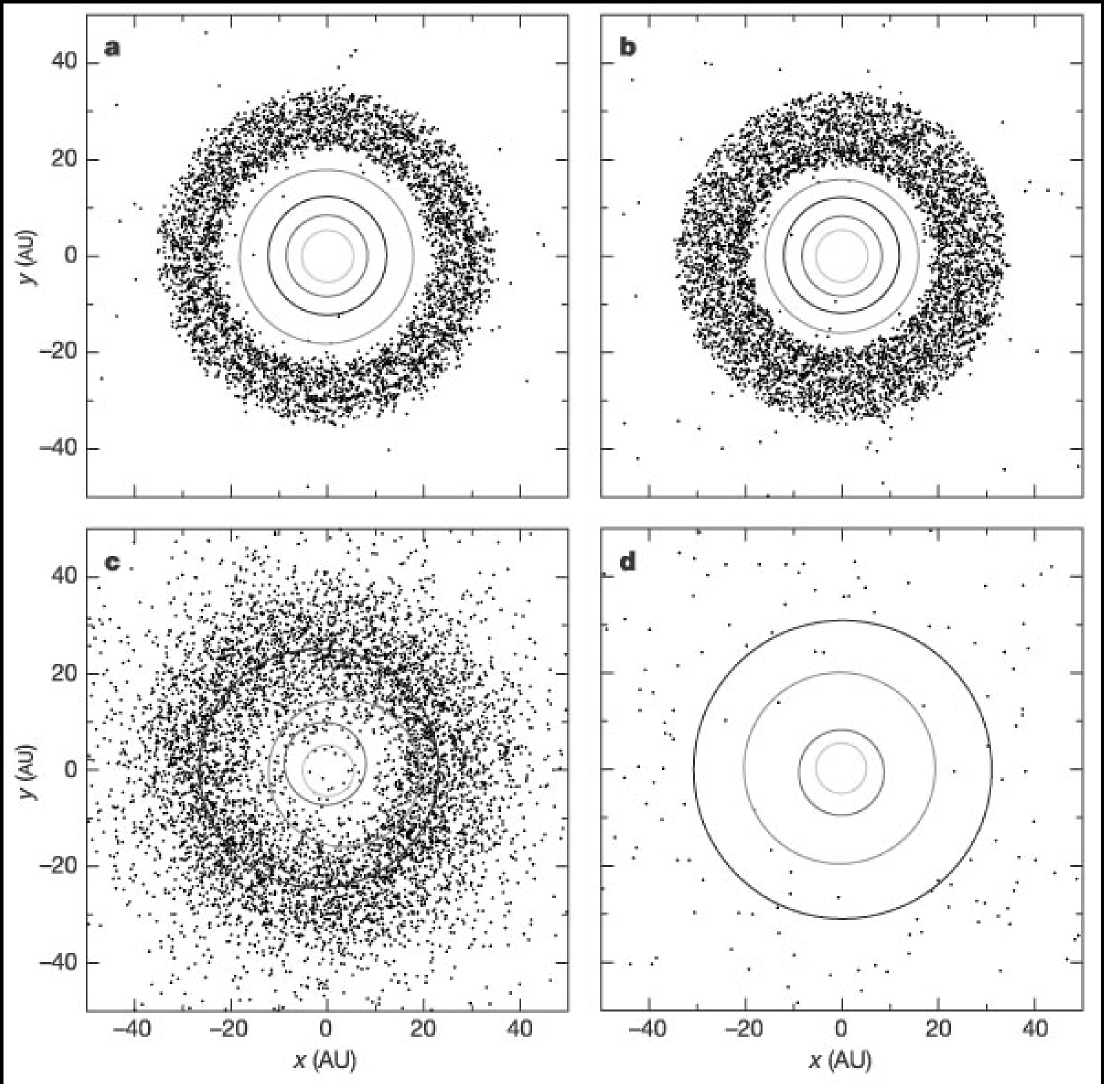
Uranus, Neptune and the Late Heavy Bombardment

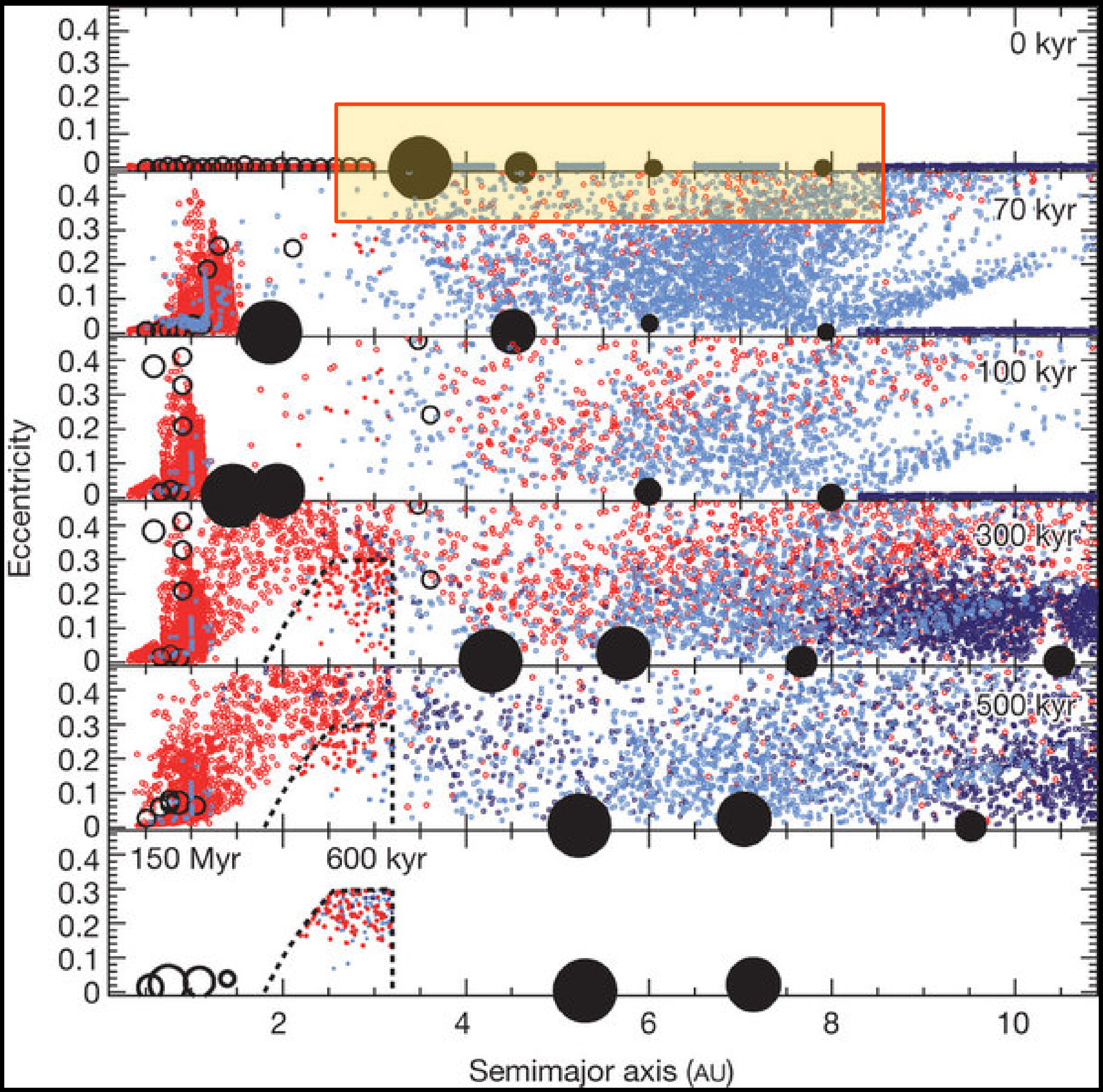


Evolution of the early Solar System (figure from Gomes et al. 2005)

A **"Jumping Jupiters" scenario** (Weidenschilling & Marzari 1996) proposed to explain the Late Heavy Bombardment and the present day structure of the Solar System is the **"Nice Model"** (Tsiganis et al. 2005; Gomes et al. 2005; Morbidelli et al. 2005).

The importance of the "**Nice Model**" lies in that it strongly supports the idea that the **giant planets did not form where we see them today**.

Uranus, Neptune and the Evolution of the Solar Nebula



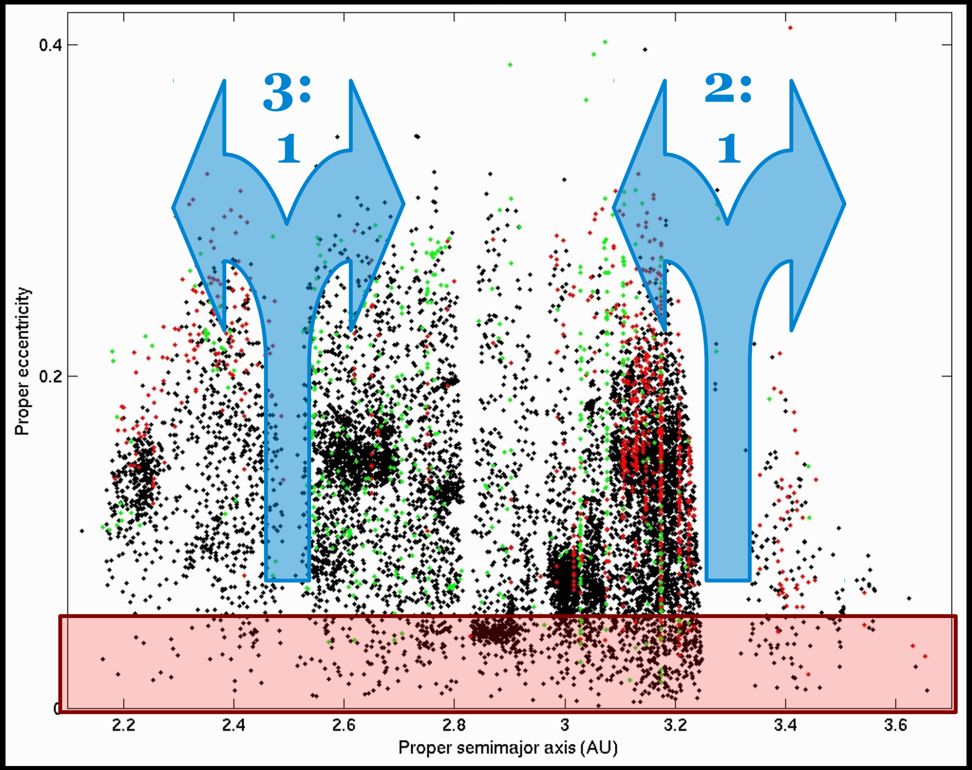
Evolution of the early Solar System (figure from Walsh et al. 2011)

Building on the success of the Nice Model, more **dramatic scenarios** have been proposed for the evolution of the **early Solar System** (Walsh et al. 2011, Nesvorny et al. 2011).

These scenarios have a **low probability to produce the Solar System** we know (D'Angelo & Marzari 2012), yet the **richness of orbital configurations of the extrasolar planets** does not allow to rule out **we may be a "lucky case"**.

Uranus, Neptune and the Primordial Bombardments

Safronov (1969) originally proposed that the formation of **Jupiter** should **scatter planetesimals from its formation region** outward, **supplying material to** the forming cores of **Neptune and Uranus**.



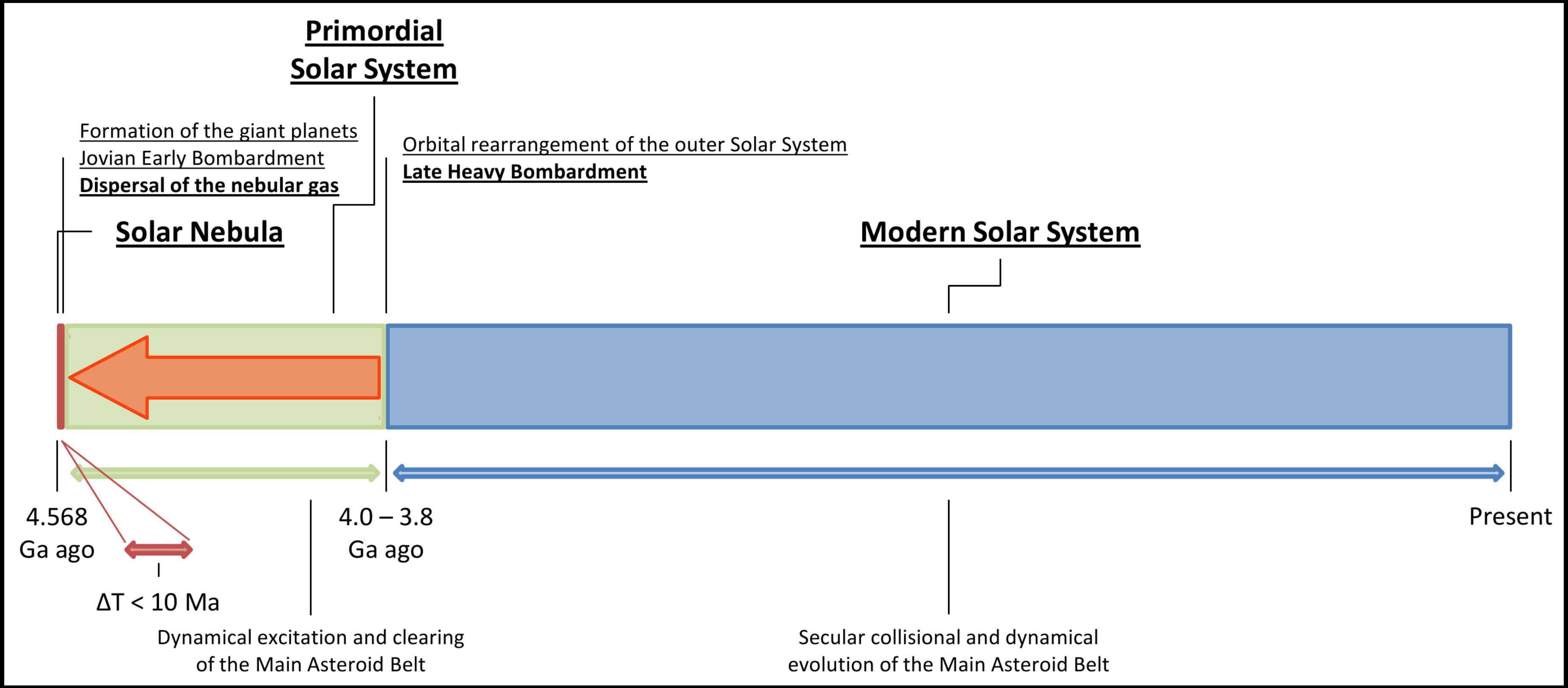
The **formation of Jupiter** also causes the **appearance of orbital resonances** in the asteroid belt and triggers a **primordial bombardment** (Turrini et al. 2011, 2012).

Scattering and resonances then cause the **reshuffling of planetesimals** in the disk.

The sequence of bombardments and reshuffling events due to the **formation of Jupiter, Saturn, Uranus and Neptune** can significantly **affect the rock/ice ratio in the Solar System**.

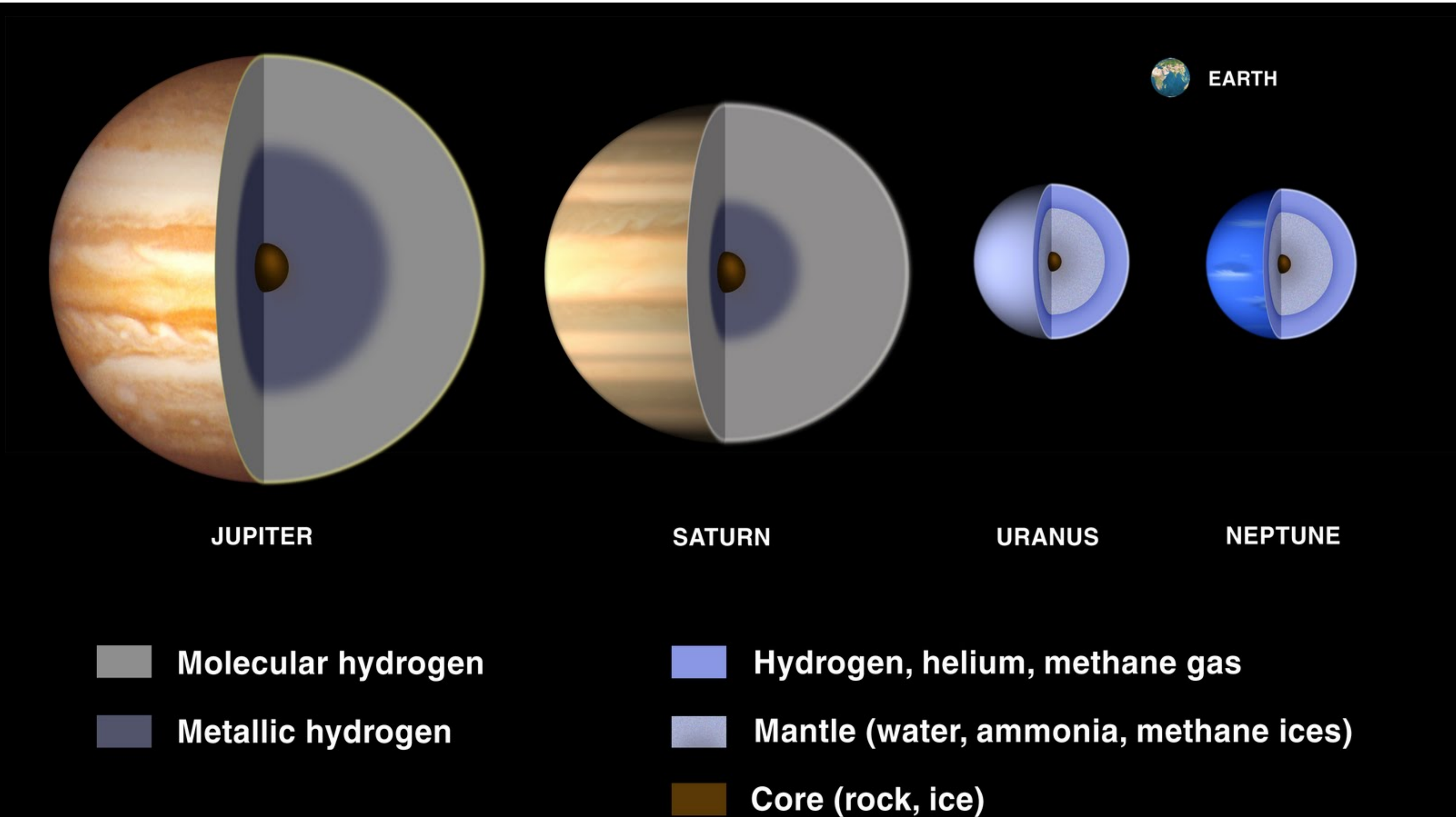
A First Look to the History of the Solar System

The history of Solar System can be divided in three phases: the **Solar Nebula**, the **Primordial Solar System** and the **Modern Solar System** (Coradini et al., 2011).



Giant planets formed in the **Solar Nebula** and **played** an important **role in** the **evolution of the Primordial and Modern Solar Systems**.

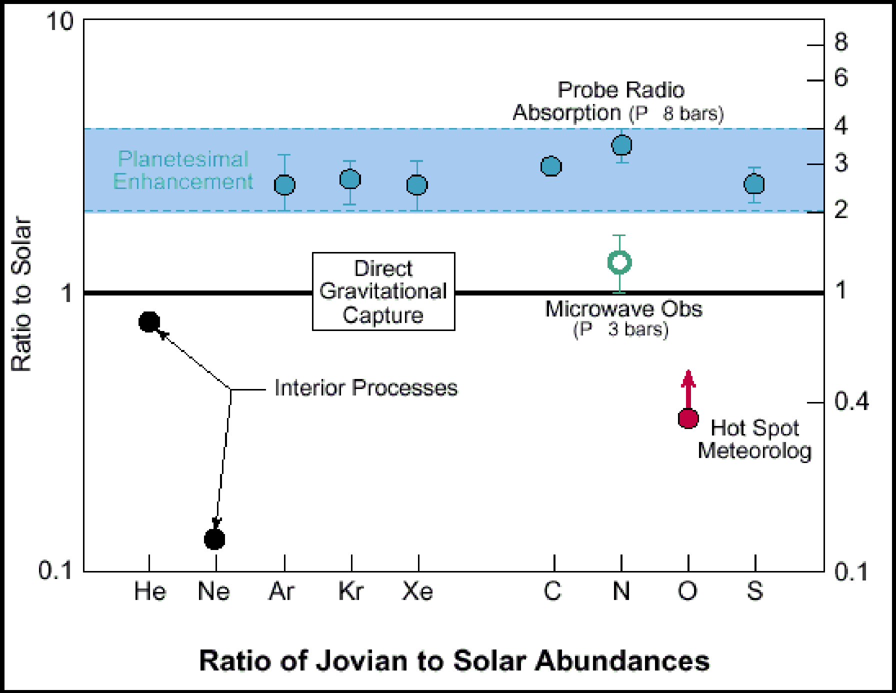
Understanding the Giant Planets



Giant planets in Solar System are assumed to have formed from planetary cores of 10 $M_\oplus$ made of rock and ice (analogous to SuperEarths), which captured different amounts of nebular gas (~300 $M_\oplus$ for Jupiter, ~80 $M_\oplus$ for Saturn, ~3 $M_\oplus$ for Uranus and Neptune).

Understanding the Giant Planets: Enrichment

The Galileo mission revealed that the **Jovian atmosphere** is characterized by a **factor 3 enhancement of C, N, S and Ar, Kr and Xe** (Owen et al. 1999). Jupiter's bulk composition in enriched (3%-13%) in high-Z elements respect to solar (2%) composition (Lunine et al. 2004).



Elemental abundances in the Jovian atmosphere, compared to solar abundances. Figure from Coradini et al. (2011).

Also the other giant planets of the Solar System are enriched in high-Z elements, but the **enrichment factor varies from planet to planet and possibly from element to element**.

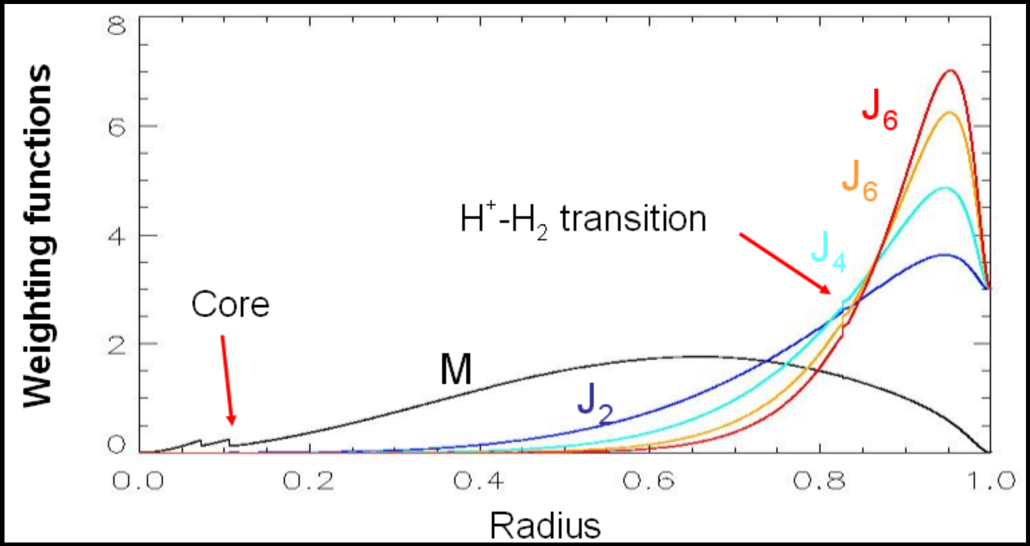
For, e.g., C/H we have:

- **Saturn: 10.4±0.4** (Fouchet et al. 2009);
- **Uranus & Neptune: 45±20** (Guillot & Gautier 2007).

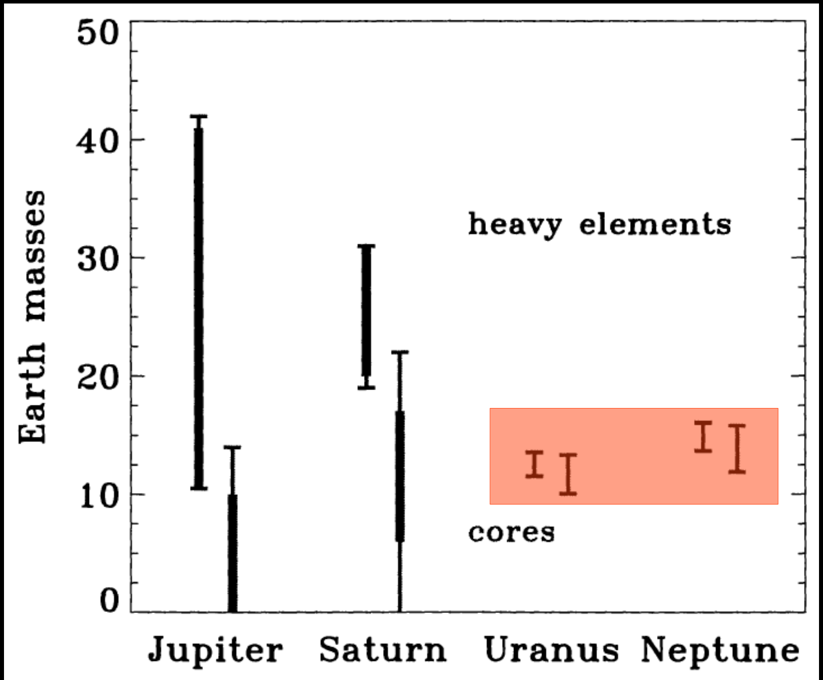
Giant Planets: Interiors and Compositions

Atmospheric enrichment is only the tip of the iceberg: the exact amount of high-Z elements in the core and the mantle are still poorly constrained.

In the most extreme cases, Jupiter's interior models are consistent with the absence of a planetary core.



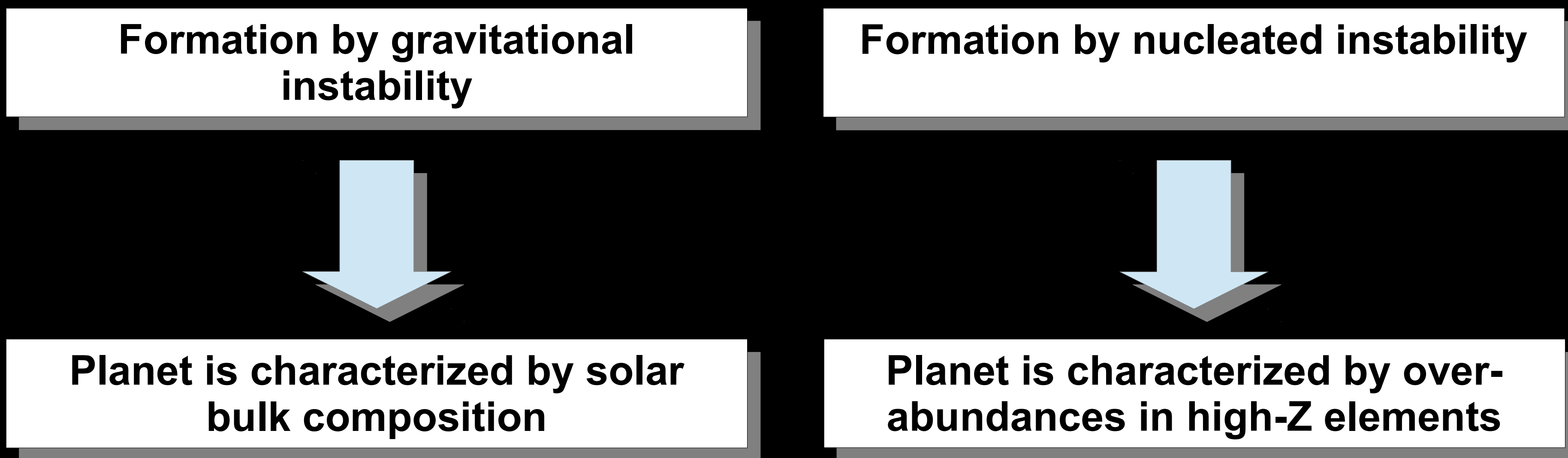
Weighting functions for different gravitational momenta J_{2n} (colour lines). Black line: Jupiter's mass as a function of the radius. (Coradini et al., EJSM Origins White Paper).



Abundance of high-Z elements in the giant planets (left bars) and in their cores (right bars). Figure from Guillot & Gladman (2000).

Giant Planets: Composition and Formation

For a long time it was thought that **enrichment** could be used to **assess whether** giant planets **formed by core accretion or gravitational instability** (see e.g. Coradini et al. 2010 for a discussion). The basic idea was the following:



A nice and simple idea, which unfortunately does not work (at least for Jupiter and Saturn): the erosion of the core, an inefficient mixing inside the envelope or the capture and dissolution of planetesimals in the atmosphere can produce (alone or in conjunction) the same outcomes from both scenarios (see e.g. Helled et al. 2011).

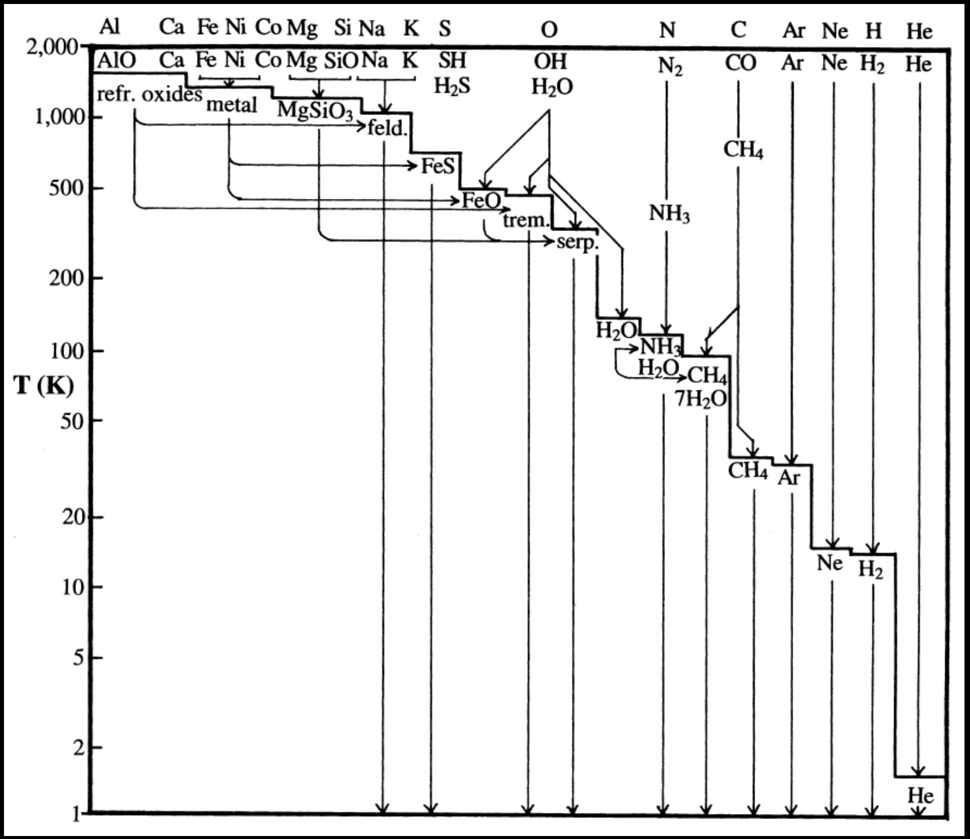
Giant Planets: Composition and Formation

Atmospheric enrichment and composition, however, can tell us about the **formation environment** of the giant planets (see e.g. Helled et al. 2011).

Enrichment in noble gases was suggested to be due to the accretion of nebular gas from a **H- and He-depleted circumsolar disk** (Guillot & Hueso 2006).

To explain the C (and O,N,S) enrichment of Jupiter, a **late accretion of planetesimals** has been suggested (Owen et al 1999; Gautier et al. 2001; Mousis et al. 2012).

Late accretion is implicitly assumed as a "local" process, i.e. it tracks the region where the giant planet formed.



Condensation sequence of the Solar Nebula from Lewis (1996).

Giant Planets: Composition and Evolution

To complicate things, we know from Solar System that giant planets can:

4.568 Ga ago

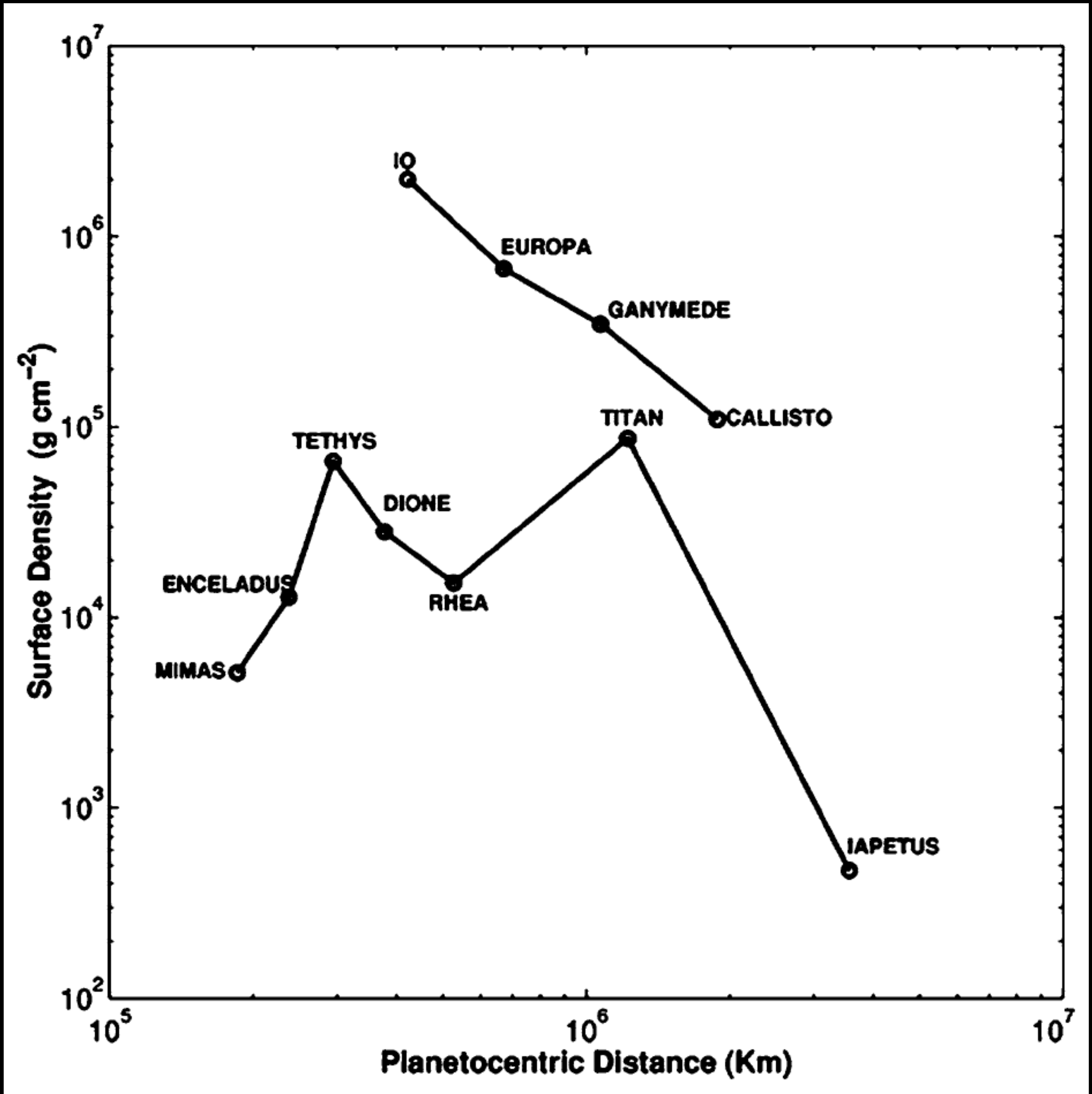
Capture planetesimals from far away regions due to resonances (e.g. Jovian Early Bombardment)	τ = 1-10 Ma
Secularly capture planetesimals while terrestrial planets are forming (e.g. Guillot & Gladman 2000)	τ = 10-100 Ma
Capture planetesimals during late migration events (e.g. Late Heavy Bombardment)	τ = 0.1-1 Ga
Secularly capture planetesimals in stationary planetary systems (e.g. comets hitting Jupiter)	τ > 1 Ga

Now

The Regular Satellites of the Giant Planets

Regular satellites formed in circumplanetary disks from material captured from the Solar Nebula. The fact that **all satellite systems have a mass ratio to their primaries of about 10^{-4}** suggests a **common mechanism** to produce them (Canup & Ward 2002).

Looking at the **Jovian system**, the satellite formation process appears **regular and orderly**. However, a look to the **Saturnian system** immediately shows that **stochastic processes played an important role** (see e.g. Coradini et al. 2010).



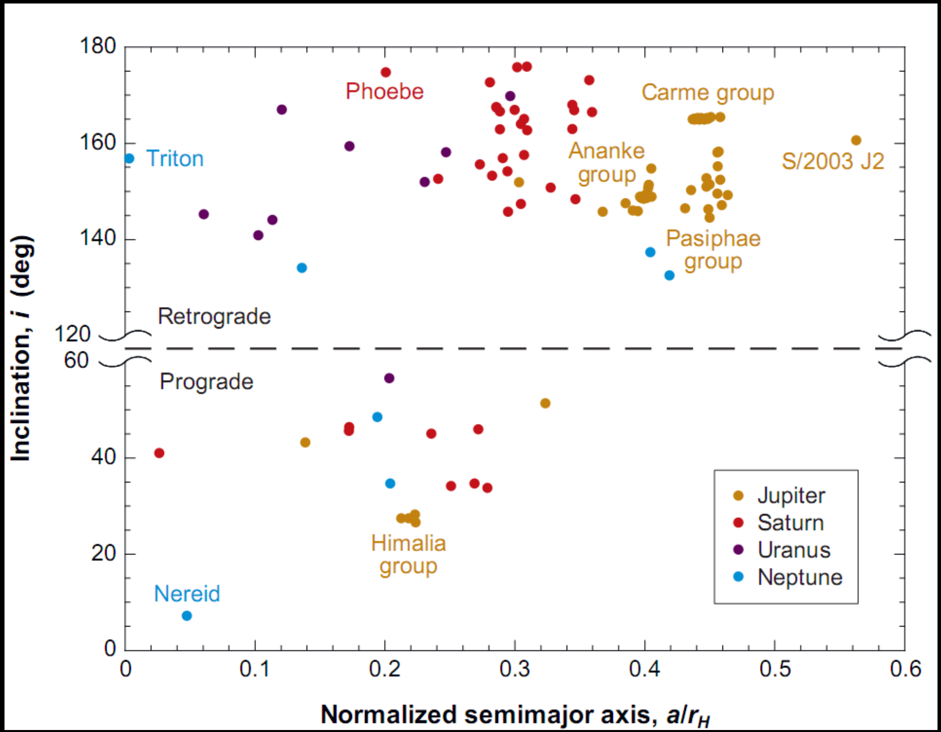
The Irregular Satellites of the Giant Planets

Irregular satellites are objects that were captured from heliocentric orbits across the first 600 Ma of the lifetime of the Solar System: they don't supply us information on the local material but they can constrain the dynamical evolution of the giant planets.

Triton, the major satellite of Neptune and one of the largest in the Solar System, belongs to the family of the irregular satellites.

GIANT PLANET	IRREGULAR SATELLITES	REGULAR SATELLITES
JUPITER	55	8
SATURN	38	21
URANUS	9	18
NEPTUNE	7	6
TOT.	109	53

Right: irregular satellites of the giant planets in the a-i plane (Jewitt & Haghighipour 2007).



The Exploration of Uranus and Neptune

The systems of **Uranus and Neptune** were respectively **visited in 1986 and 1989 by the Voyager 2 mission**.

Voyager 2 performed **flybys of the two giant planets**, imaged some of their major satellites and discovered several new ones.

Data from the Voyager 2 allowed the **first characterization** of these two systems, both in terms **of** the **giant planets and** in terms of **their satellites**.

Coverage of the satellites, however, **was partial** and the **uncertainty on the measurements** of atmospheric composition was **large** (e.g. C enrichment was estimated 45 ± 20, i.e. 50% error).

Uranus, Neptune and the Odin Mission

The primary information that the Odin mission wants to gather by exploring the Uranian and Neptunian systems are:

- What is the **atmospheric composition and enrichment** respect to solar abundances of the two planets?
- What are the **bulk densities and** the **masses** of the two planets and their satellites?
- What are the **interior structures and density profiles** of the two planets and the satellites?
- What is the **surface composition of** the (regular and irregular) **satellites**?
- Which satellites are **fully/partially differentiated and** which ones are **undifferentiated**?

Uranus, Neptune and the Odin Mission

Using these data, the questions Odin aims to answer are:

- **When and wher**e did the **planets formed**?
- **Did they migrate**? How much?
- **Did** the two **planets swap their positions** as hypothesized by the Nice Model?
- **Are the satellites of Uranus primordial** or they reformed after the planet tilted its spin axis?
- What were the effects of the **capture of Triton** for the Neptunian satellites?
- **How much "non-local" material** was available to the Uranian and Neptunian satellites when they formed? **Where did it originated from**?
- **Where** did the **irregular satellites originate**? Can they be used to **constrain the dynamical evolution** of the two ice giants?

Fundamental Physics, Solar Wind and TNOs

During the cruise and the duration of the mission, we plan to collect information on:

- The **mass of the trans-neptunian region**;
- The **atmospheric circulation and dynamics** on Uranus and Neptune;
- The **interplanetary medium and the solar wind** at large distances from the Sun;
- The **magnetic fields** of the two giant planets and their satellites;
- The **ring systems** of the two ice giant planets.

In addition, during the cruise and after insertion in the planetocentric orbits we also plan to perform tests and experiments on:

- **Gravitation at large distances from the Sun**;
- **Relativity in the very-weak field regime**;
- **Non-gravitational forces and drag effects** in the atmospheres of the planets.

Last but not the least, during the cruise we plan to study the **behaviour of the spectral features** of the two ice giant planets as a function of the **relative distances from the spacecraft** (range: ~30-0 AU) and **FOV fill factor**.

The Focus of the ODIN mission concept

The Odin concept is different from the classic approach of Solar System exploration

Classical approach

Explore one planet and (possibly) its satellite system at a time with **focus on** their **characterization** or on few specific aspects

Build up data **across decades** and do comparative planetology

Odin's approach

Explore two planets and their satellites with focus on their origin and evolution

Do comparative planetology **now** and open road for future, in-depth exploration

PRO

More thorough investigation of the target system

CON

Exploration of the ice giants is going to **require 50 years**

The Focus of the ODIN mission concept

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Classical approach

Explore one planet and (possibly) its satellite system at a time with **focus on** their **characterization** or on few specific aspects

Build up data **across decades** and do comparative planetology

PROS

Exploration of the ice giants with a single space mission

Can constrain the history of Solar System

Europe first to explore the two systems

CON

Less complete investigation of the target systems

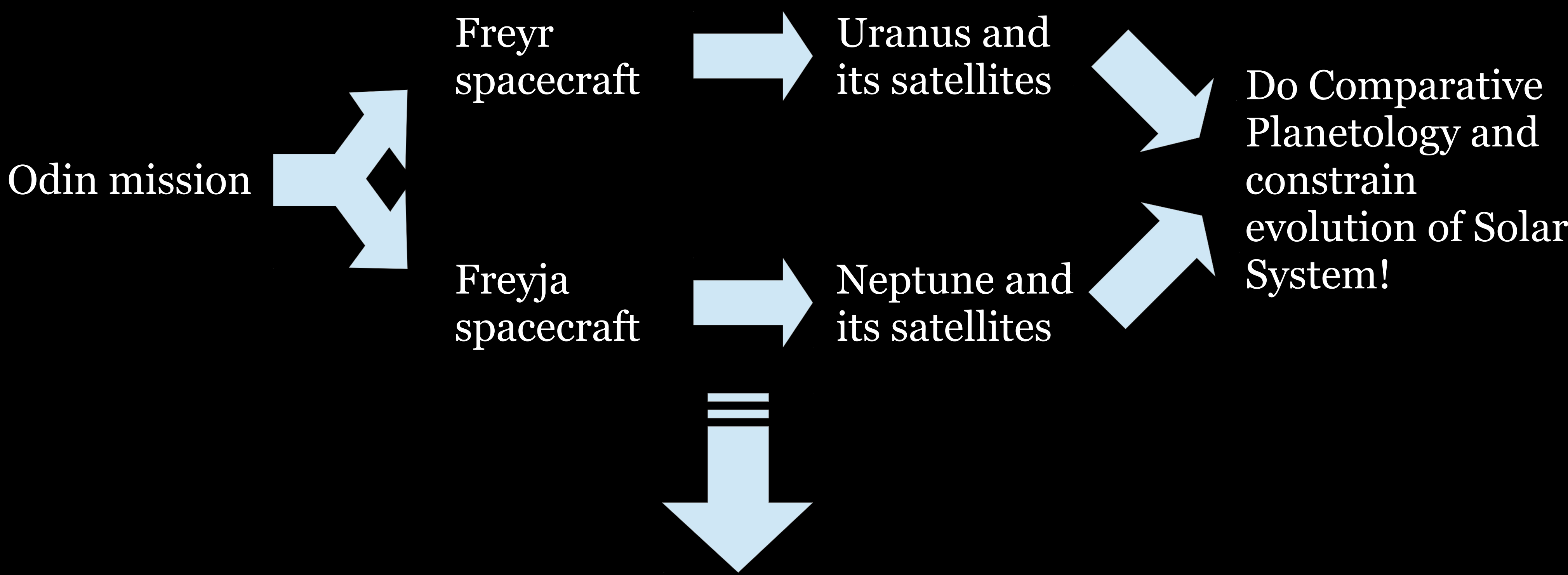
Odin's approach

Explore two planets and their satellites with focus on their origin and evolution

Do comparative planetology **now** and open road for future, in-depth exploration

The Design of the ODIN mission concept

In order to achieve its goals, the Odin mission concept propose the use of two twin spacecraft (here dubbed Freyr and Freyja from the twin gods of the Norse pantheon) to be put in orbit of Uranus and Neptune.



During the cruise(s) Odin can perform fundamental physics experiments (gravitation and general relativity in the very-weak field regime) and measurements of the interplanetary medium and solar wind.

The Straw-man Design for the ODIN mission

In order to fit the budget of an L-class mission, a conservative, strawman configuration for the Odin mission could be based on two New Horizons-like spacecrafts, i.e.:

- About 6 instruments in the scientific payload + radio science;
- About 500-600 km of dry mass of each spacecraft;
- Hybrid (ionic and chemical) propulsion;
- Radioisotope-powered spacecrafts.

A similar mission is already marginally doable with today technology:

Direct transfer from Earth to Uranus + Direct transfer from Earth to Uranus ⇒ Wet/Dry mass ratio = 4.7 ⇒ Total mass fit into Soyuz payload (2 launches) or Ariane V (1 launch)

Expected cost of New Horizons is about 500 Meuro ⇒ Expected cost of Odin can fit into the L-class mission budget

The Straw-man Payload & Orbit for the ODIN mission

A straw-man payload for the two spacecrafts is composed by:

- Camera;
- VIS-NIR Image Spectometer;
- Magnetometer;
- Mass Spectrometer (Ions and Neutrals);
- Doppler Spectro-Imager (for seismic measurements) or Microwave Radiometer;
- Radio-science package.

Presently, the idea would be to insert on a distant and highly eccentric orbit (irregular satellite-like) and take advantage of the ionic propulsion to spiral inward to the regular satellites and then the planets.

A fascinating possibility would be to use the spacecrafts as entry probes at the end of the mission by spiralling them inside the upper atmospheres of the two ice giant planets (possible Venus Express know-how heritage).