The Atmospheric Composition of Hot Jupiters: Insights from the History of the Solar System

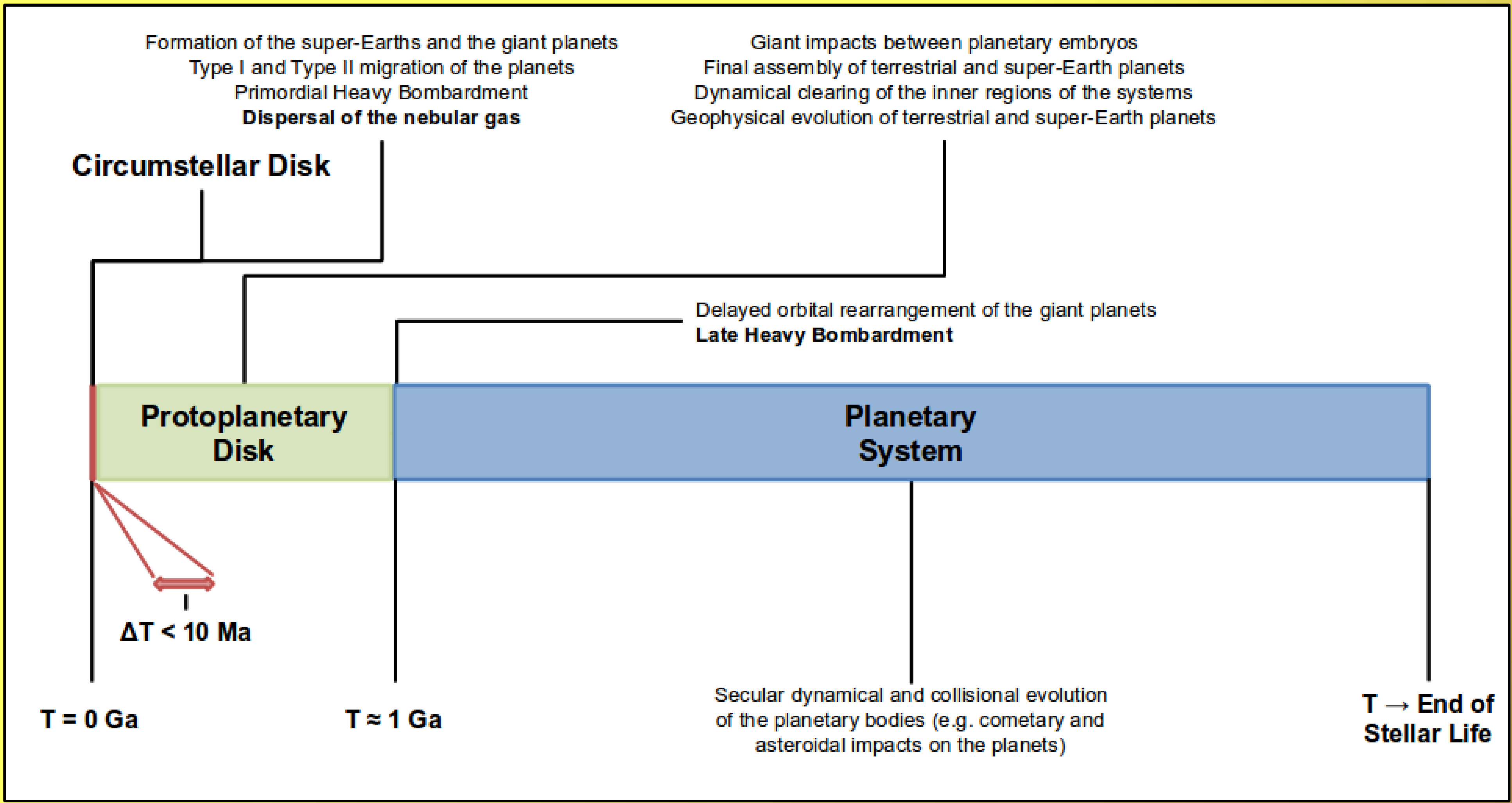
D. Turrini[1], M. Barbieri[2], D. Grassi[1], F. Altieri[1], A. Adriani[1], G. Piccioni[1]

+ the brainstorming contribution by G. Tinetti, R. Nelson and the ECHO-IT Consortium

[1] Institute for Space Astrophysics and Planetology INAF-IAPS
[2] Department of Physics and Astronomy, University of Padova

ECHO Open Workshop 2013 – ESA ESTEC

The Timeline of Planetary Systems



Formation of the super-Earths and the giant planets
Type I and Type II migration of the planets
Primordial Heavy Bombardment
Dispersal of the nebular gas

Giant impacts between planetary embryos
Final assembly of terrestrial and super-Earth planets
Dynamical clearing of the inner regions of the systems
Geophysical evolution of terrestrial and super-Earth planets

Circumstellar Disk

Delayed orbital rearrangement of the giant planets
Late Heavy Bombardment

Protoplanetary Disk

Planetary System

ΔT < 10 Ma

T = 0 Ga

T ≈ 1 Ga

Secular dynamical and collisional evolution
of the planetary bodies (e.g. cometary and
asteroidal impacts on the planets)

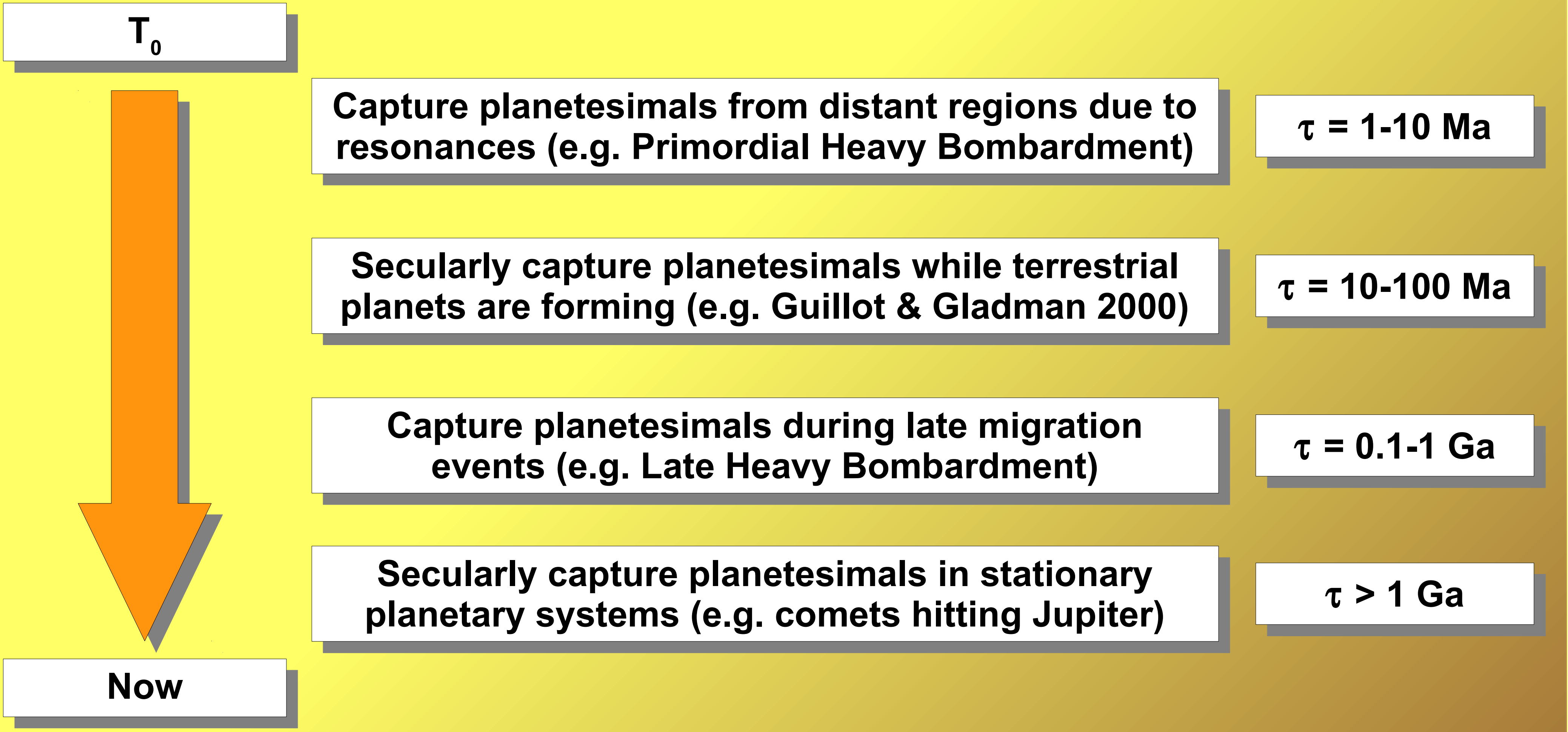
T → End of Stellar Life

Institute for Space Astrophysics and Planetology
Istituto di Astrofisica e Planetologia Spaziali

ECHO 2013

Post-Formation Accretion and Enrichment

After their formation, giant planets interact with the surrounding environment and can:



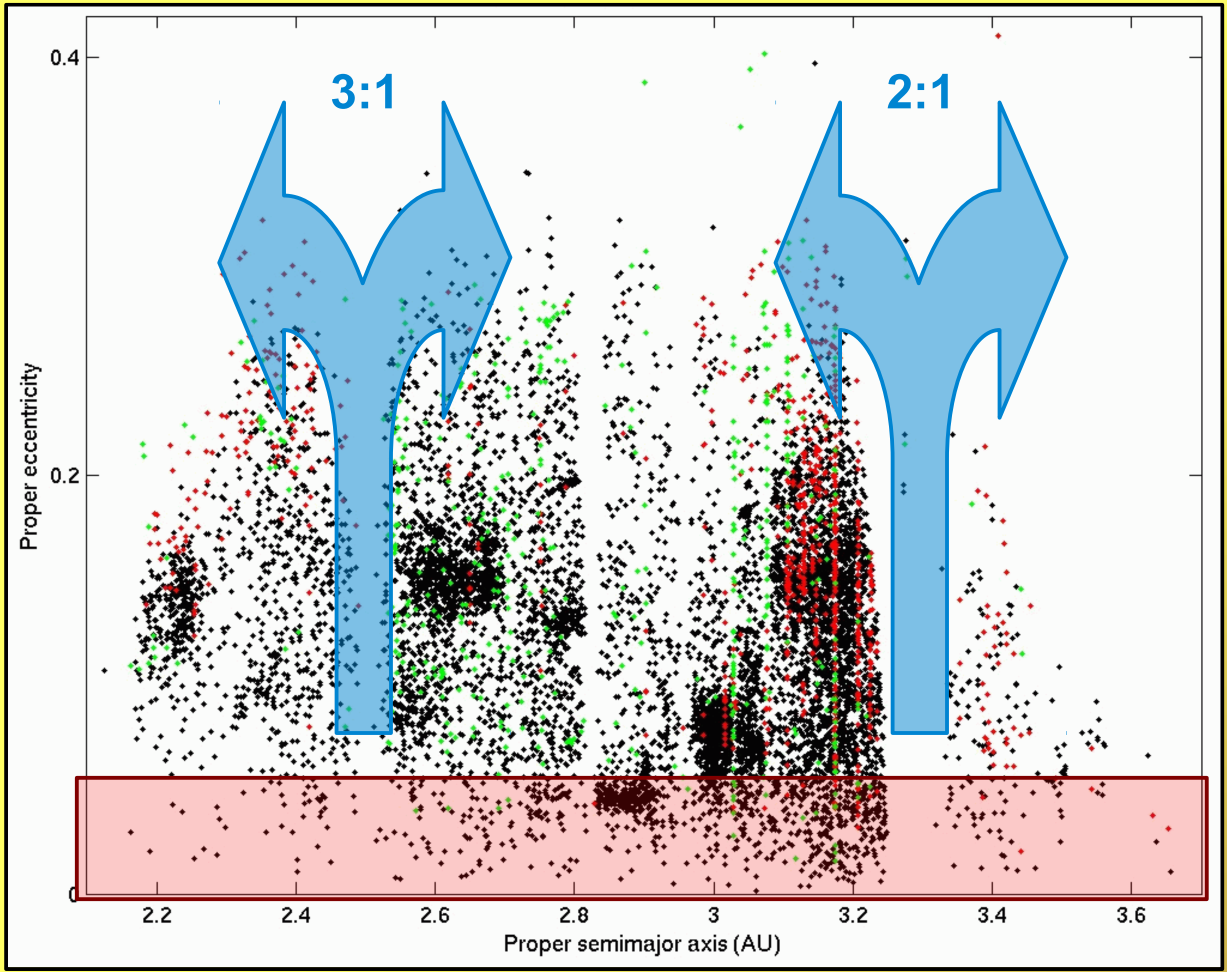
T_0

Capture planetesimals from distant regions due to resonances (e.g. Primordial Heavy Bombardment)	$\tau = 1\text{-}10$ Ma
Secularly capture planetesimals while terrestrial planets are forming (e.g. Guillot & Gladman 2000)	$\tau = 10\text{-}100$ Ma
Capture planetesimals during late migration events (e.g. Late Heavy Bombardment)	$\tau = 0.1\text{-}1$ Ga
Secularly capture planetesimals in stationary planetary systems (e.g. comets hitting Jupiter)	$\tau > 1$ Ga

Now

Late Accretion and Primordial Bombardments

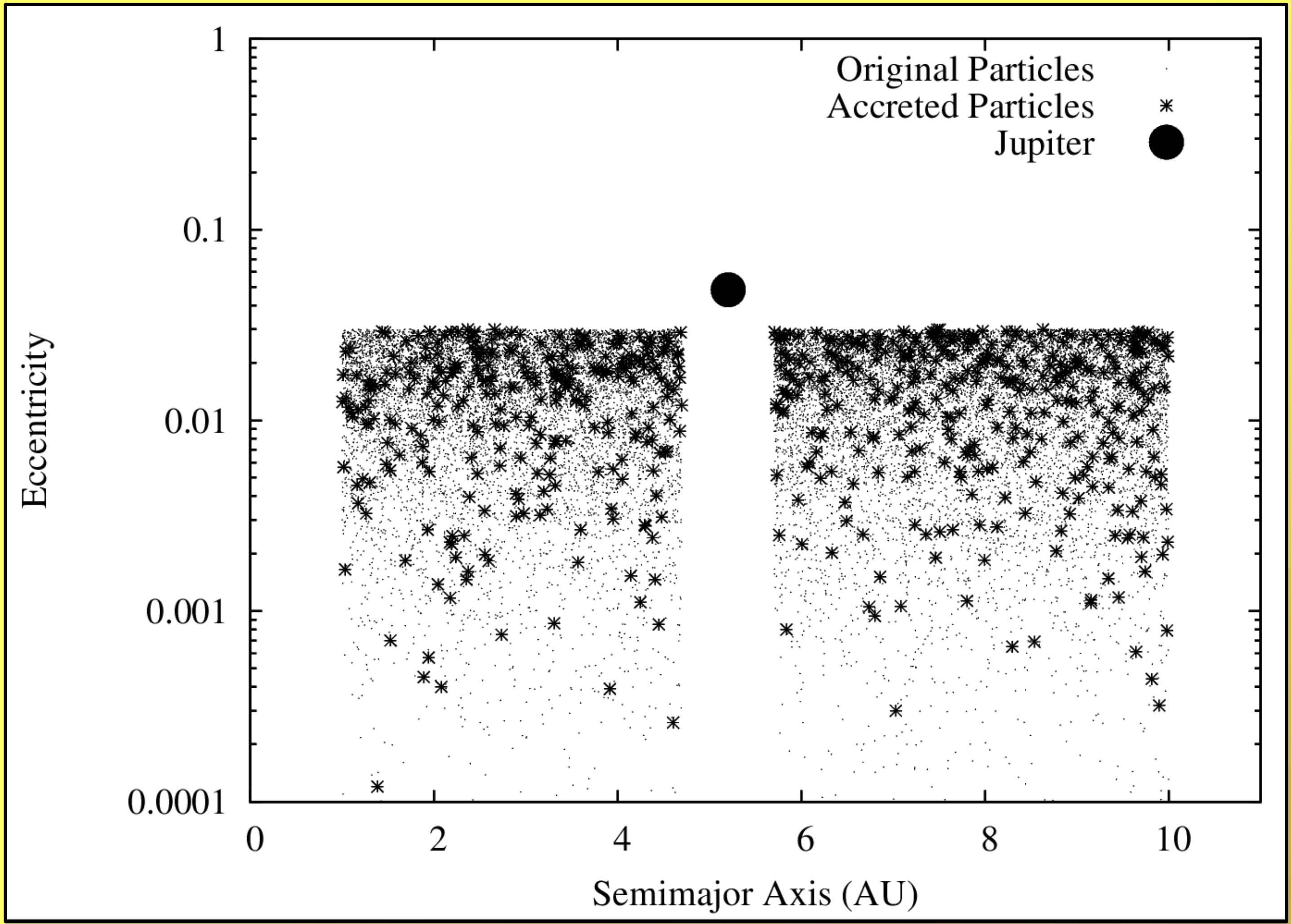
Safronov (1969) originally proposed that the formation of **Jupiter** should **scatter planetesimals from its formation region** outward, **supplying** further **material to** the forming cores of **Neptune and Uranus**.



The **formation of Jupiter** also causes the sudden **appearance of mean motion resonances** in the asteroid belt (Turrini et al. 2011, 2012) and in the outer Solar System (Weidenschilling et al. 2001).

The combined effects of scattering and resonances trigger a **primordial bombardment** through the planetary system (Safronov 1969, Weidenschilling 1975, Turrini et al. 2011, 2012).

Toy Model 1: Primordial Heavy Bombardment

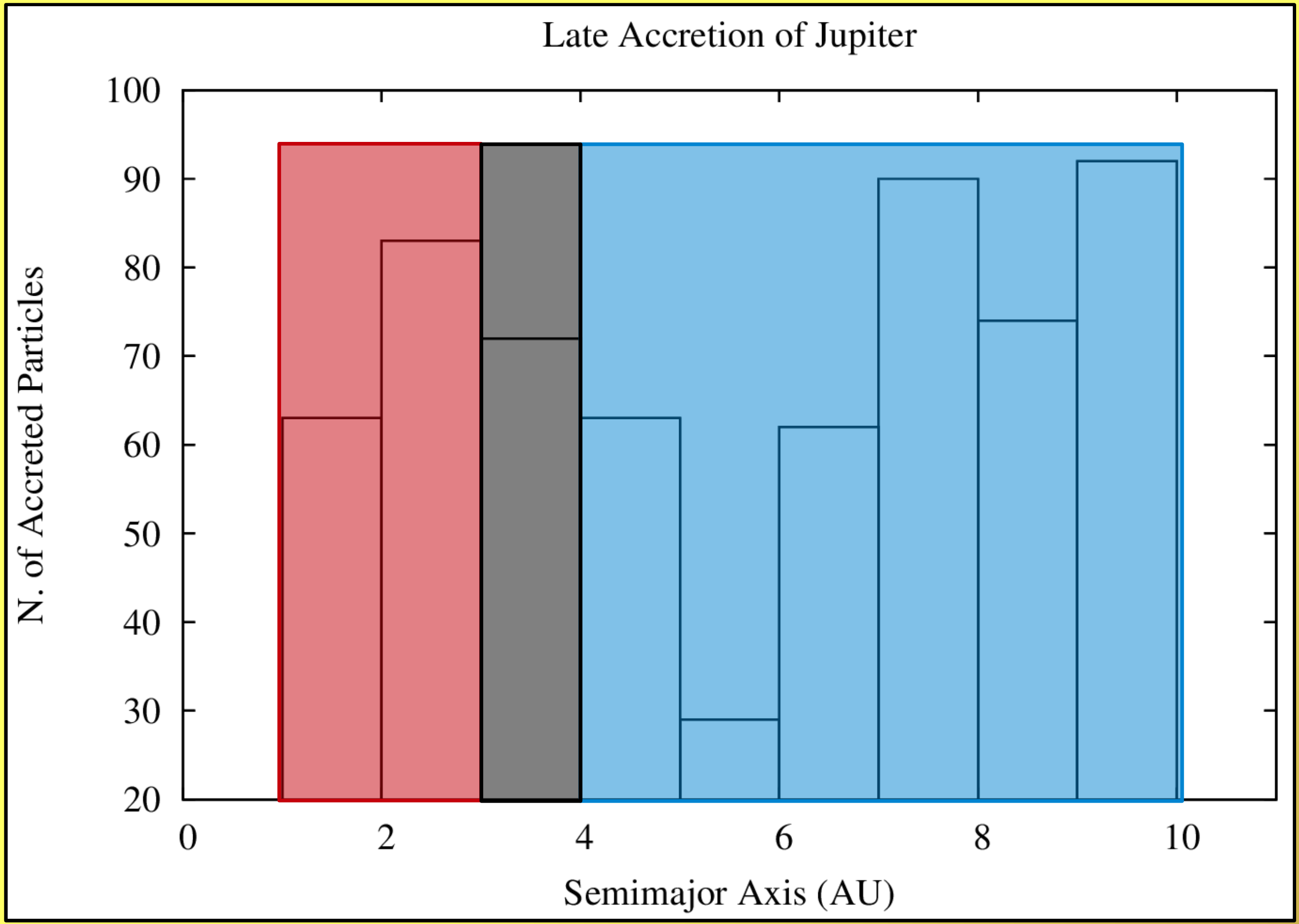


We simulated a **disk of $2x10^4$ test particles** (the planetesimals) under the influence of a **fully-formed Jupiter on its present orbit**.

The evolution of the system was followed for **2 Ma**.

To account for the formation of Jupiter's core, we **removed the particles between 4.7 AU and 5.7 AU**.

Toy Model 1: Primordial Heavy Bombardment



At the end of the simulation, **16.52% of the particles were ejected** from the Solar System.

3.14% of the particles were accreted by Jupiter.

About **34.7% of the particles** accreted by Jupiter **originated in the inner Solar System**.

Toy Model 1: Primordial Heavy Bombardment

If the accreted mass is distributed **over the whole Jupiter**, the **enrichment** is **of the order of 8%** only. However:

- If the accreted mass is distributed over an "atmospheric" **shell with thickness of 1000 km**, it produces a value of high-Z materials **a factor 3** over solar composition;
- If the accreted mass is distributed over an "atmospheric" **shell with thickness of 2000 km**, it produces a value of high-Z materials about **a factor 2** over solar composition.

Chemical Species	PHB-delivered mass (g)	PHB-delivered mass (units of solar abunances, Lodders 2012)
Fe	2.35E+026	2.44
Si	8.53E+026	15.17
C	5.72E+026	3.24
N	1.33E+025	0.24
S	1.59E+025	0.66
H_2O	1.59E+027	3.14

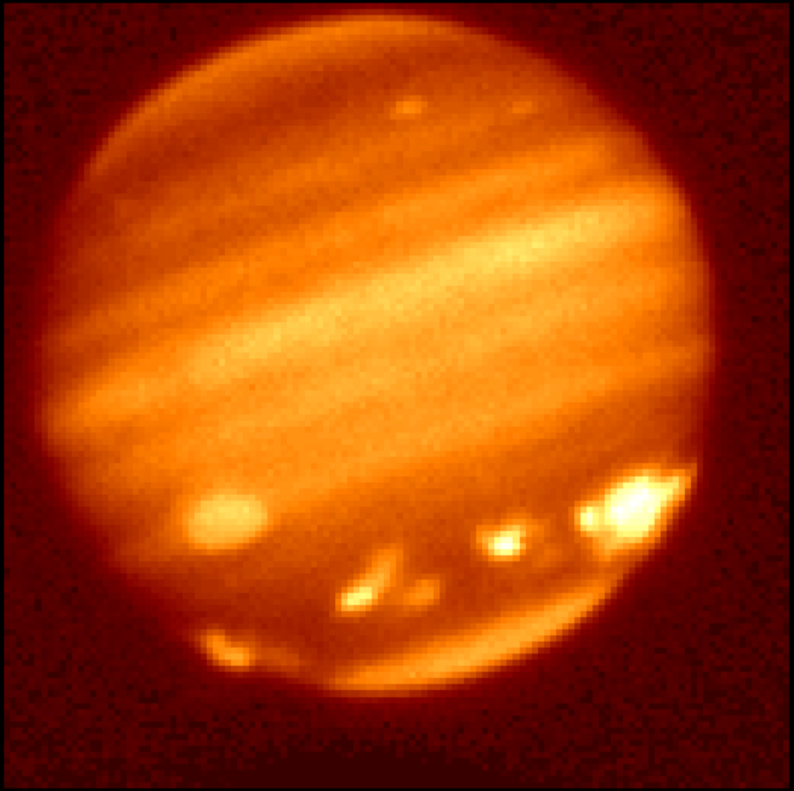
Late Accretion and Secular Delivery

Once planetary systems complete the most active and violent phases of their evolution, **impacts continue the remixing process** that acted across the earliest phases but **at a much lower rate**.

An example of this process in the Solar System is the impact of **comet Shoemaker-Levy 9 on Jupiter** in 1994. On average, across the last 19 years the **giant planet** has been **hit by one comet every four-five years.**

Results from the **Herschel mission** (Cavalié et al. 2013) indicate that the spatially-resolved **distribution of stratospheric water of Jupiter** is a **reflection of the impact(s) of SL9**.

The **contamination** by SL9 lasted **longer** than the **average time between impacts** → effects of **accumulation** are **possible**.



A necklace of Comet Shoemaker-Levy 9 impact sites on Jupiter
Infrared image in the 1.7 micron methane band taken using MAGIC
on the 3.5-m telescope, Calar Alto Observatory, Spain, 25/07/94 MPIA

Toy Model 2: Secular Delivery

We considered the planet **HD 189733 b** as our test case: orbital and physical parameters for star and planet were obtained from the Extrasolar Planets Encyclopaedia.

As impactors, we considered the **Sun-grazing comets** observed by SOHO: their orbital parameters were obtained from the JPL Small Bodies Database Search Engine.

Sun-grazing comets observed by SOHO have too high orbital inclination: a preliminary estimate gives 1 impact every 200 years.

Assuming an **ecliptic population of Sun-grazing comets**: a preliminary estimate gives 1 impact every 20 years.

In the latter case, **impact rate** is **comparable to survival** of contaminants in the atmosphere of HD 189733 b.

Toy Model 2: Secular Delivery

Using water as our tracer (72.8% of the cometary mass, Mumma & Charnley 2011) and assuming the dissolution and mixing of the cometary impactor in an atmospheric shell of thickness ΔR (in km) of a Jupiter-like planet, the resulting mixing ratio ξ can be approximated as:

$$\xi = 2.98\times10^{-6}\,\chi\left(\frac{D_c}{1\,km}\right)^{3}\left(\frac{\rho_{atm}}{2\times10^{-5}\,kg\,m^{-3}}\right)\left(\frac{\Delta R}{100\,km}\right)^{-1}$$

where D_c is the diameter of the comet in km, ρ_{atm} is the density of the atmospheric layer expressed in kg m^{-3} and χ is the fraction of the comet dissolved in the considered shell.

In principle, the **dissolution of a 5 km wide comet** (i.e. Shoemaker-Levy 9) into a **300 km thick atmospheric shell** (i.e. the Jovian stratosphere) could produce a **mixing ratio consistent** with the lower end (~10^{-5}) considered by Tinetti et al. (2007) for **HD 189733 b.**

Wrapping up...

…here are the two main points that these toy models want to drive.

First, the **interaction of a giant planet with the surrounding disk of planetesimals** can result in the **capture of metals and silicate-based refractory materials** (whether these materials can actually stay in the atmosphere for us to see them or not is a completely different question...)

Second, the **secular impacts** of comets or asteroids on an exoplanet **bring transient contaminants** in its atmosphere. If the delivery rate is comparable to the removal rate of the contaminants, in principle we **can have a prolonged non-equilibrium situation**.