

Solar system

SERGEI POPOV

Solar system age

The age is determined due to meteorite studies.
Chondrites are made of non-processed matter.

^{26}Al half life-time 730 kyrs (\rightarrow ^{26}Mg).

CAI – Ca-Al Inclusions.

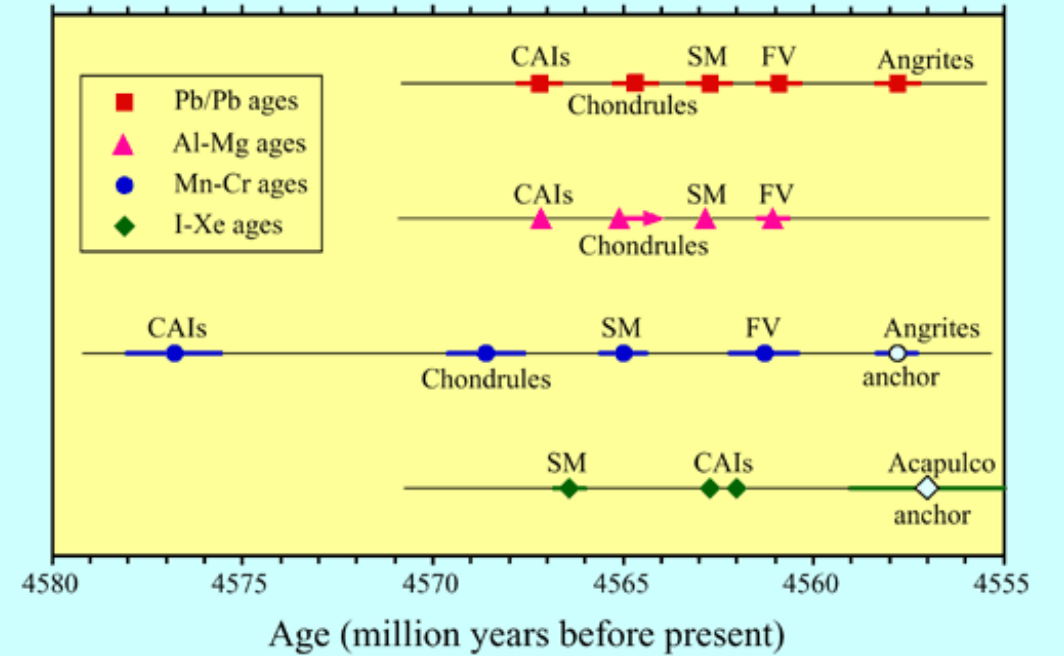
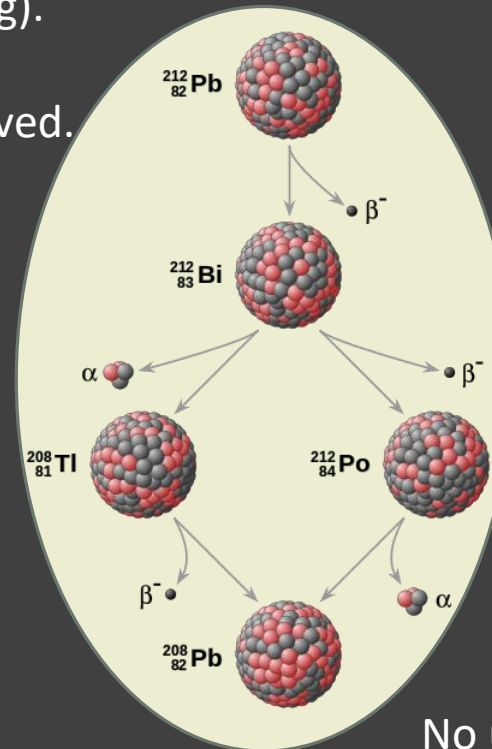
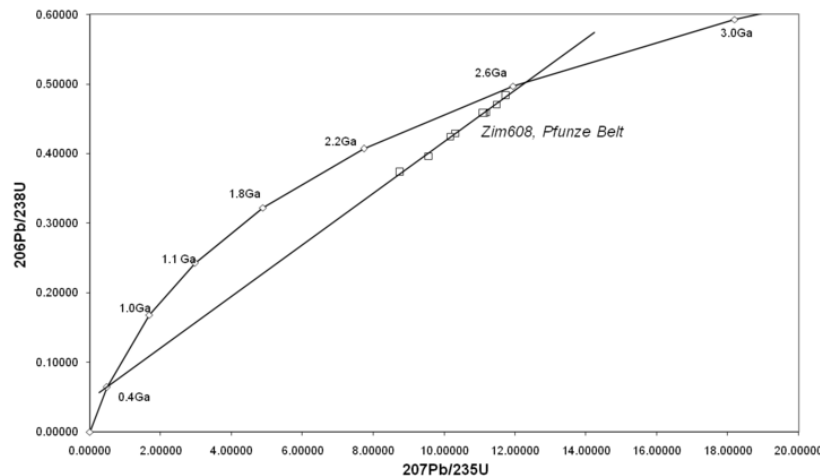
Al-Mg – short lived, U-Pb – long lived.

4.567 Gyrs



<http://www.nhm.ac.uk>

Concordia Diagram



(E.Zinner)

No uranium in CAIs \rightarrow Pb-Pb.

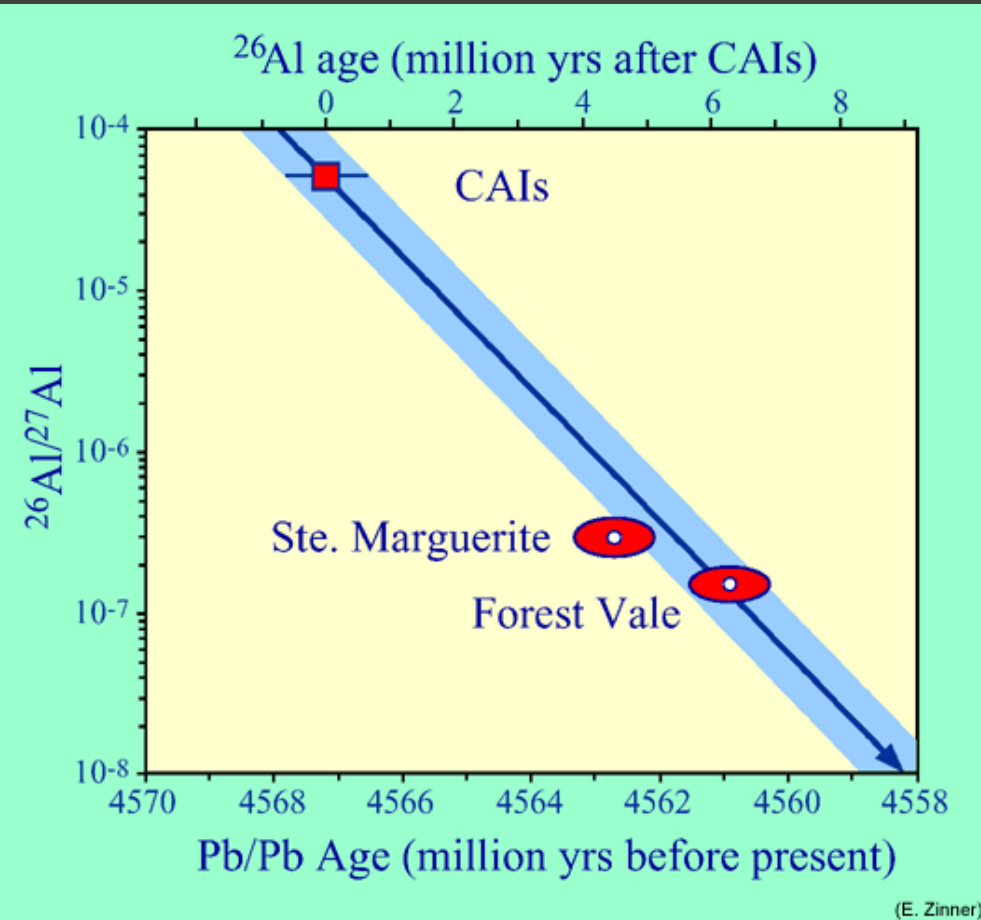
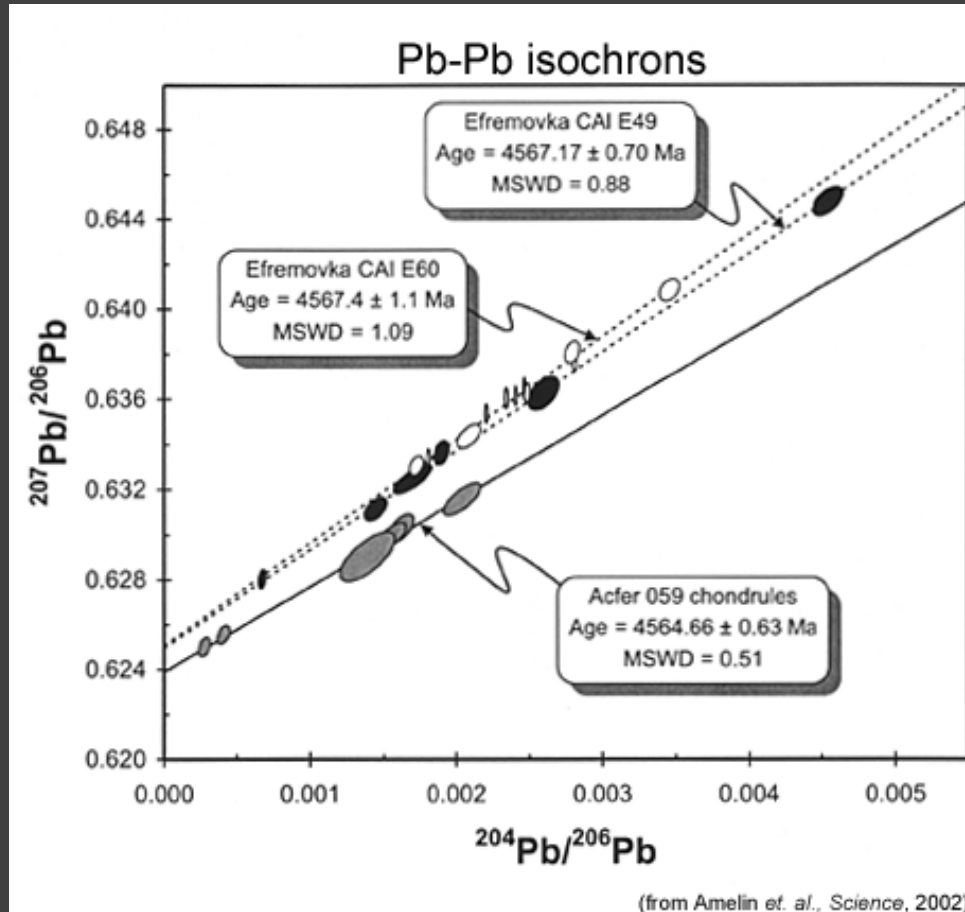
See details at <http://www.geo.cornell.edu/geology/classes/Geo656/656notes03/656%2003Lecture09.pdf>

<http://www.psrhawaii.edu/Sept02/Al26clock.html>

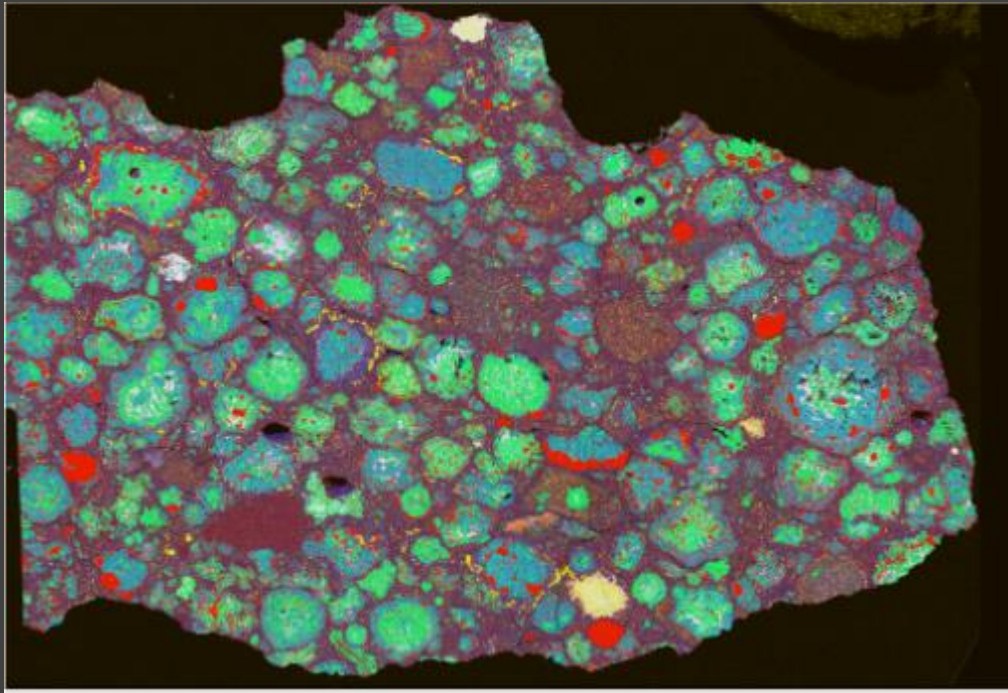
Short lived isotopes

Nuclear Species	Daughter	Reference	Half-life (Myr)	Mass Fraction
${}^7\text{Be}$	${}^7\text{Li}$	${}^9\text{Be}$	53 days	(8×10^{-13})
${}^{10}\text{Be}$	${}^{10}\text{B}$	${}^9\text{Be}$	1.5	$(\sim 10^{-13})$
${}^{26}\text{Al}$	${}^{26}\text{Mg}$	${}^{27}\text{Al}$	0.72	3.8×10^{-9}
${}^{36}\text{Cl}$	${}^{36}\text{Ar}$	${}^{35}\text{Cl}$	0.30	8.8×10^{-10}
${}^{41}\text{Ca}$	${}^{41}\text{K}$	${}^{40}\text{Ca}$	0.10	1.1×10^{-12}
${}^{53}\text{Mn}$	${}^{53}\text{Cr}$	${}^{55}\text{Mn}$	3.7	4.0×10^{-10}
${}^{60}\text{Fe}$	${}^{60}\text{Ni}$	${}^{56}\text{Fe}$	1.5	1.1×10^{-9}
${}^{107}\text{Pd}$	${}^{107}\text{Ag}$	${}^{108}\text{Pd}$	6.5	9.0×10^{-14}
${}^{182}\text{Hf}$	${}^{182}\text{W}$	${}^{180}\text{Hf}$	8.9	1.0×10^{-13}

Two approaches complete each other



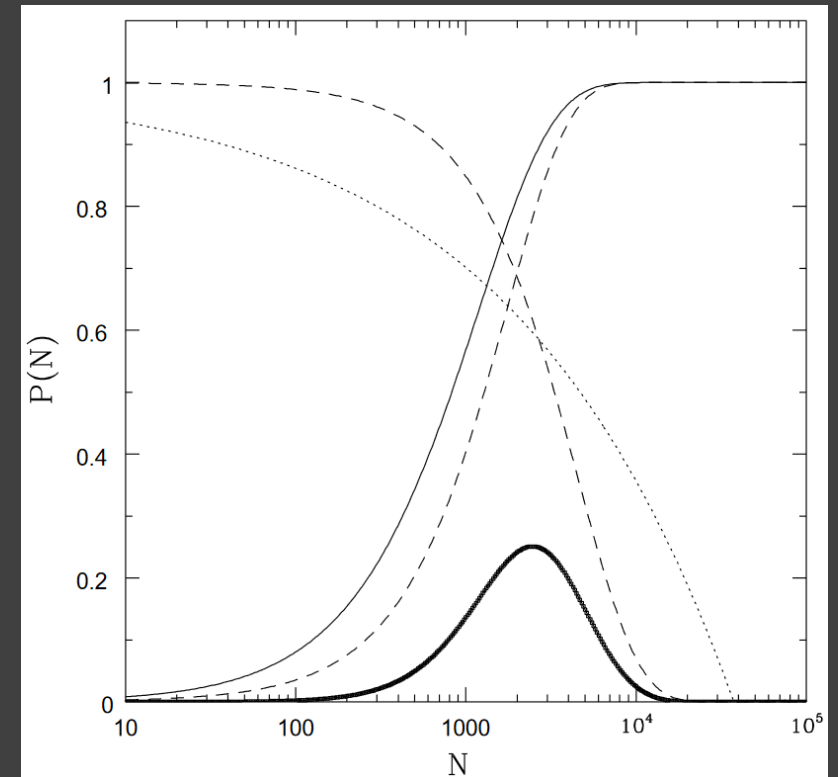
Origin of ^{26}Al and other short lived elements



aluminum (white), magnesium (green),
silicon (blue), calcium (yellow), iron (red)

Near-by supernova or
an AGB/WR star.

Cluster cannot be too rich,
otherwise EUV and FUV
emission of massive stars
can significantly influence
protoplanetary disc
within 30 AU due to
photoevaporation.

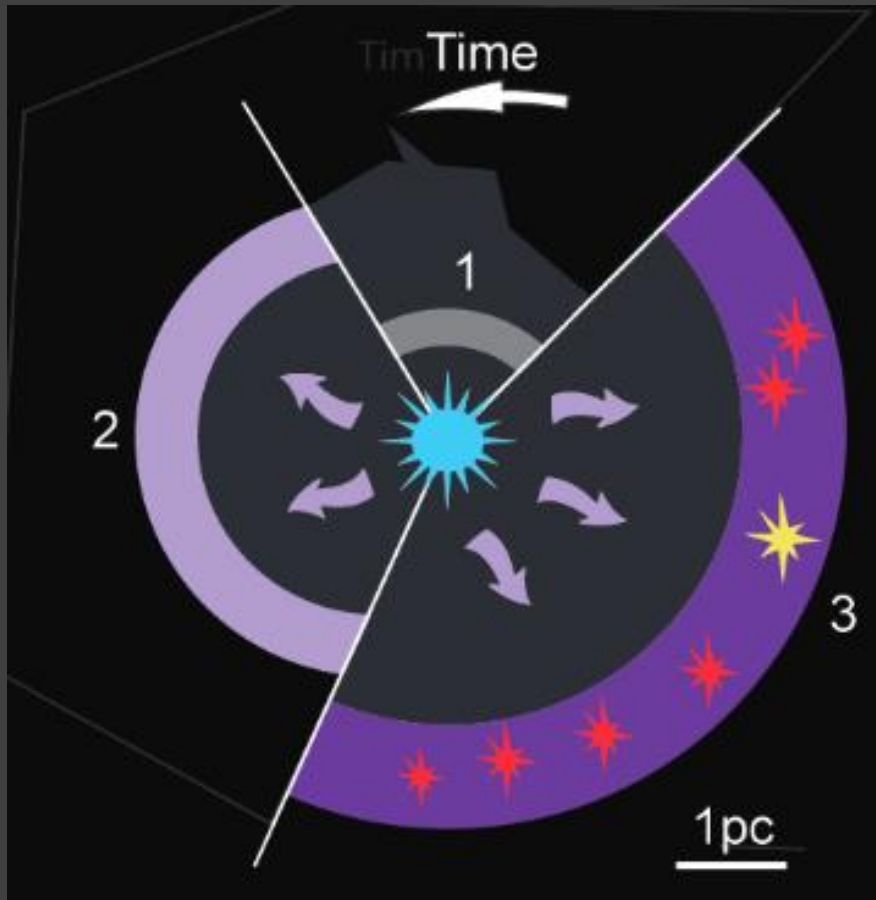


Number of stars in the Sun cluster

1001.5444

1501.03101

Supernova vs. evolved star



SN overproduce ^{60}Fe in comparison with ^{26}Al .

Thus, the exact origin is not known, yet.
It seems that Fe-60 has been formed due to a SN
(on larger time scale), and Al-26 – appeared from
wind of a near-by evolved star.

Distribution of small-body's orbits also put constraints
on properties of the solar cluster (see 1001.5444).

Model of Al-26 “logistic” by a stellar wind.
A dense envelope is continuously enriched in Al-26,
and the Sun is formed from this material.

Constraints on the solar cluster

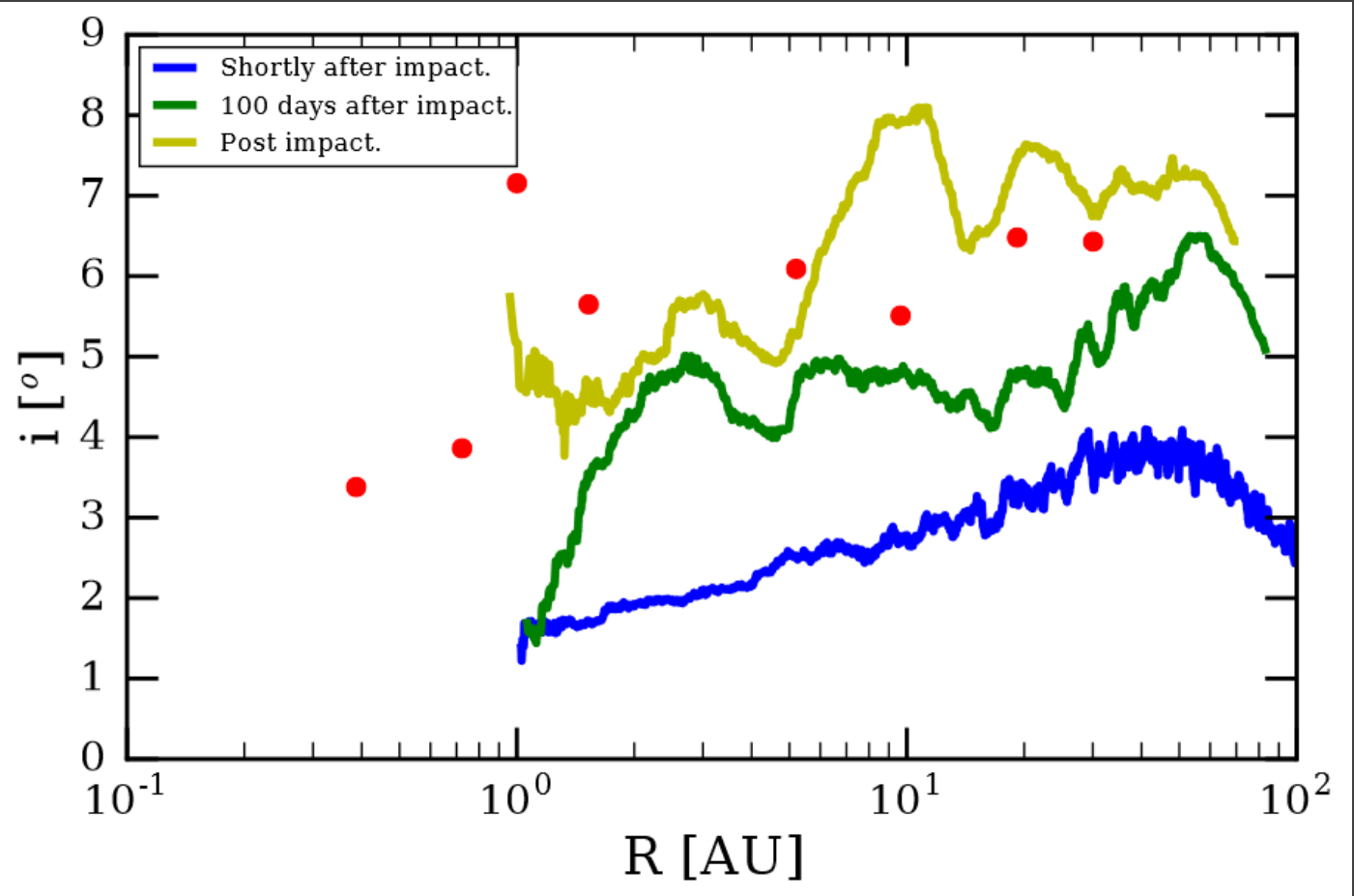
Solar System Property	Implication	Fraction
Mass of Sun	$M_* \geq 1M_{\odot}$	0.12
Solar Metallicity	$Z \geq Z_{\odot}$	0.25
Single Star	(not binary)	0.30
Giant Planets	(successfully formed)	0.20
Ordered Planetary Orbits	$N \leq 10^4$	0.67
Supernova Enrichment	$N \geq 10^3$	0.50
Sedna-Producing Encounter	$10^3 \leq N \leq 10^4$	0.16
Sufficient Supernova Ejecta	$d \leq 0.3 \text{ pc}$	0.14
Solar Nebula Survives Supernova	$d \geq 0.1 \text{ pc}$	0.95
Supernova Ejecta and Survival	$0.1 \text{ pc} \leq d \leq 0.3 \text{ pc}$	0.09
FUV Radiation Affects Solar Nebula	$G_0 \geq 2000$	0.50
Solar Nebula Survives Radiation	$G_0 \leq 10^4$	0.80

Supernova influence on the SoSys

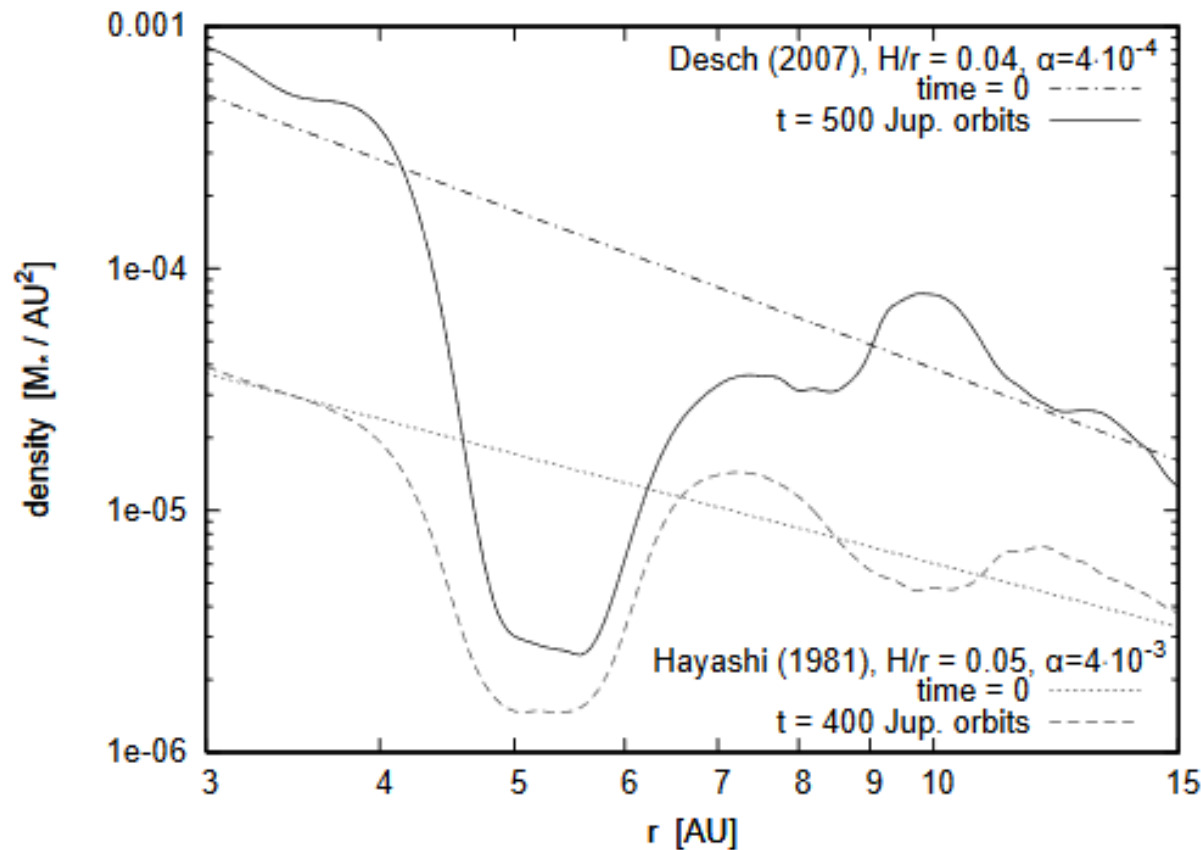
Distance 0.15-0.4 pc

- heating (dust melting)
- enrichment
- blast wave
- stripping
- tilting

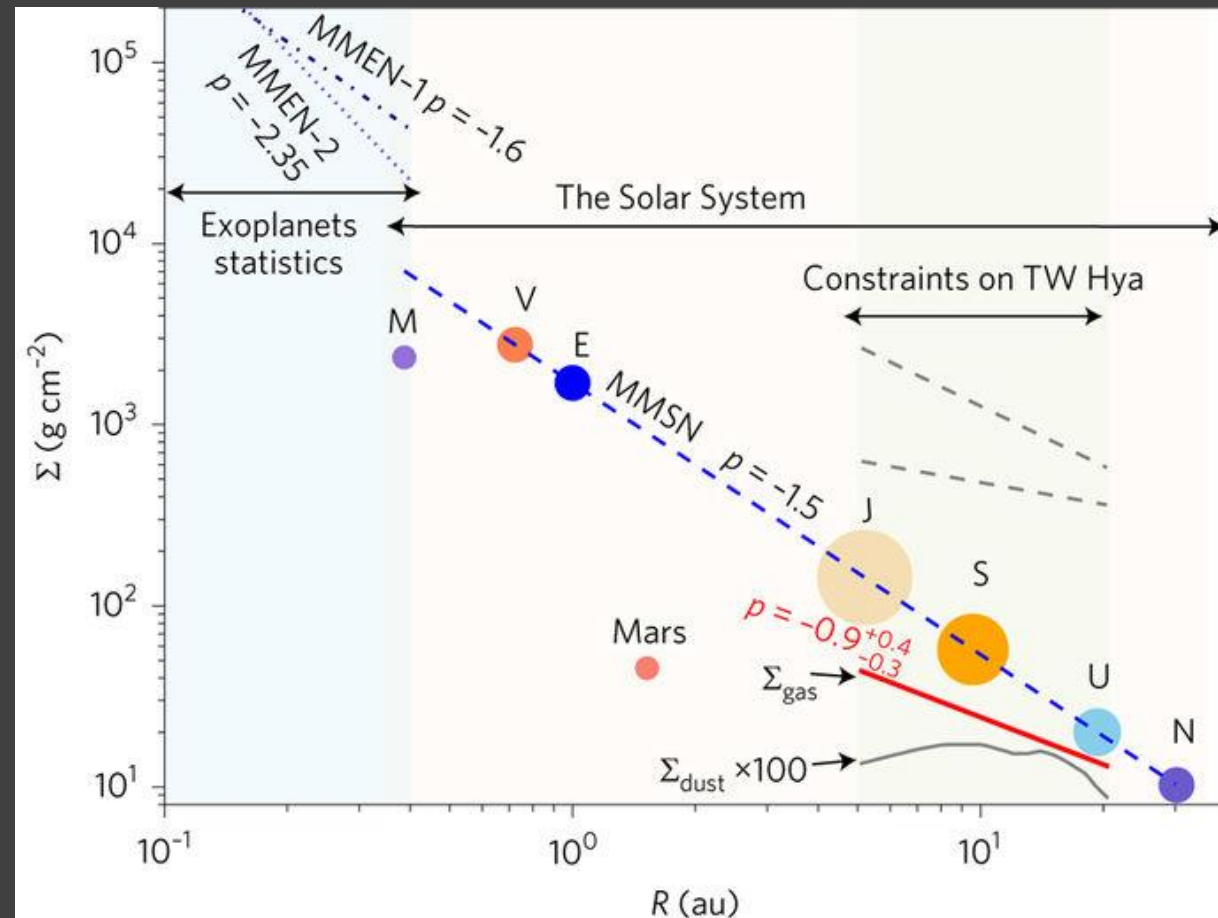
Difficulties in explaining all data in one framework with a single SN (in particular, difficult to explain the abundance of Al-27).



Minimum mass solar nebula



0903.5077



Zhang et al. (2017). 1705.04746 Nature Astronomy v. 1

Different variants of the MMSN

$$\Sigma(r) = 1700(r/1 \text{ AU})^{-3/2} \text{ g.cm}^{-2}$$

$$\Sigma(r) = 1.9125 \times 10^{-4} (r/1 \text{ AU})^{-3/2} M_{\odot} \text{ AU}^{-2}$$

Hayashi 1981

Normalized by the estimate
of Jupiter formation $1.55 < r < 7 \text{ AU}$
(mass of solids = 15 Earth masses)

$$\Sigma \approx 50500(r/1 \text{ AU})^{-2.168} \text{ g.cm}^{-2}$$

$$\Sigma(r) = 343(f_p/0.5)^{-1} (r/10 \text{ AU})^{-2.168} \text{ g cm}^{-2}$$

$$\begin{aligned} \Sigma_0(r) &= 343(r/10 \text{ AU})^{-2.168} \text{ g.cm}^{-2} \\ &= 5.68 \times 10^{-3} (r/1 \text{ AU})^{-2.168} M_{\odot} \text{ AU}^{-2} \end{aligned}$$

Important: nebula parameters might allow
proper regime of planetary migration (0903.5077).

Desch 2007

Planets at initial positions
in the NICE model

In the classical MMSN mass of the disc is ~ 0.01 solar mass between 2 and 30 AU.

New MMSN model

Based on the Nice model

$$M_{\text{aug}} = M_Z f_p^{-1} \left(\frac{\text{gas}}{\text{solids}} \right)$$

Gas/solid = 67 (i.e. solids = 1.5%)

INITIAL SOLAR SYSTEM CONDITIONS					
Planet	$M_{\text{aug}}^{\text{a}}$ (M_{\oplus})	r_{in} (AU)	r_0 (AU)	r_{out} (AU)	Σ^{a} (g cm ⁻²)
Jupiter.....	1747 ± 1075	4.45 ^b	5.45	6.68	546.8
Saturn	1411 ± 470	6.68	8.18	9.70	244.5
Neptune	1032 ± 91	9.70	11.5	12.8	123.2
Uranus	843 ± 124	12.8	14.2	15.9 ^a	77.2
Disk ^c	2353 ± 336	15.9 ^b	22.5	30.0	31.2

Initial positions: Jupiter – 5.45 AU; Saturn – 8.18 AU; Neptune – 11.5 AU; Uranus – 14.2 AU
Uranus and Neptune change places during migration!

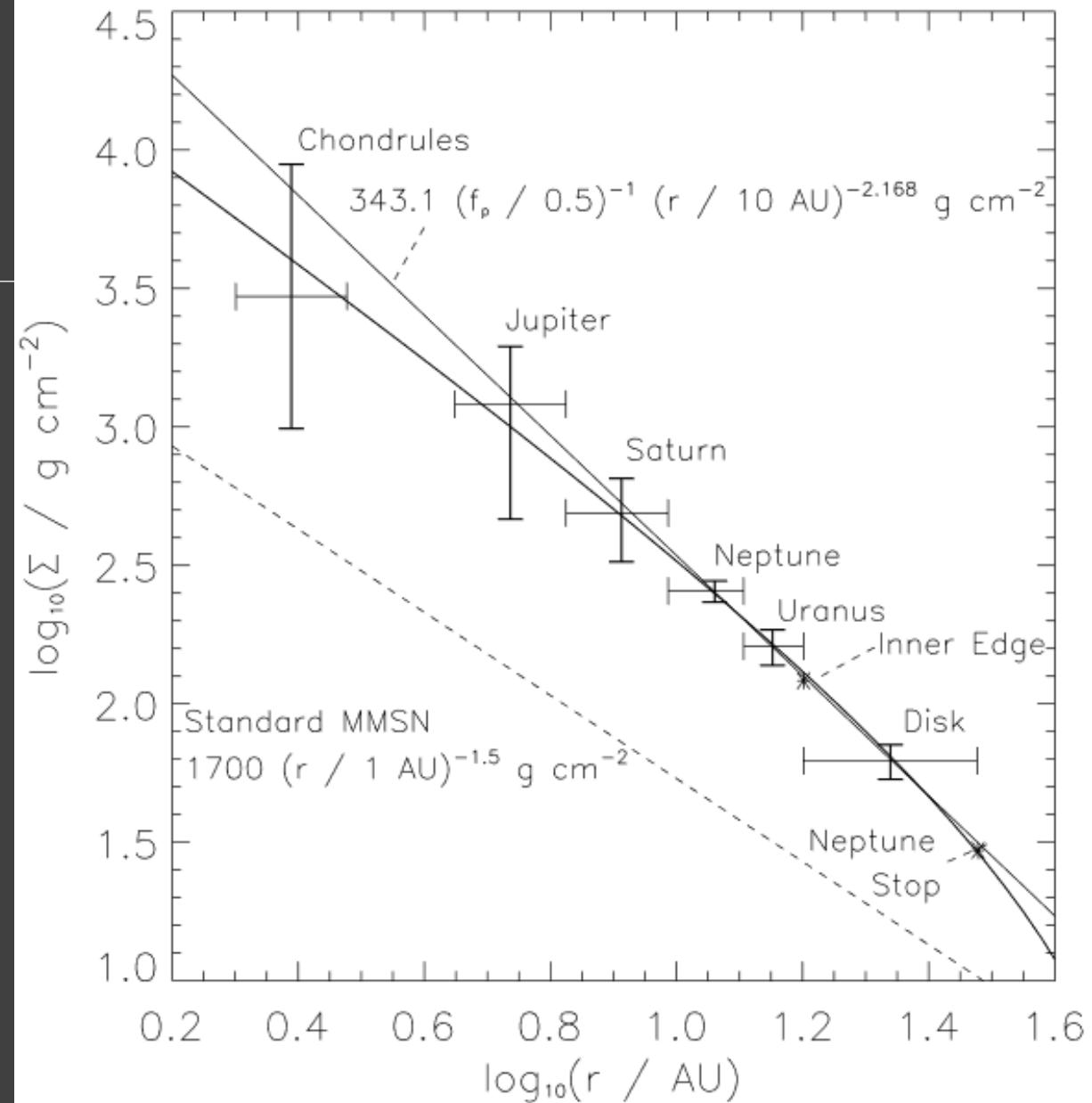
Surface density

$$\Sigma(r) = 343 \left(\frac{f_p}{0.5} \right)^{-1} \left(\frac{r}{10 \text{ AU}} \right)^{-2.168} \text{ g cm}^{-2}$$

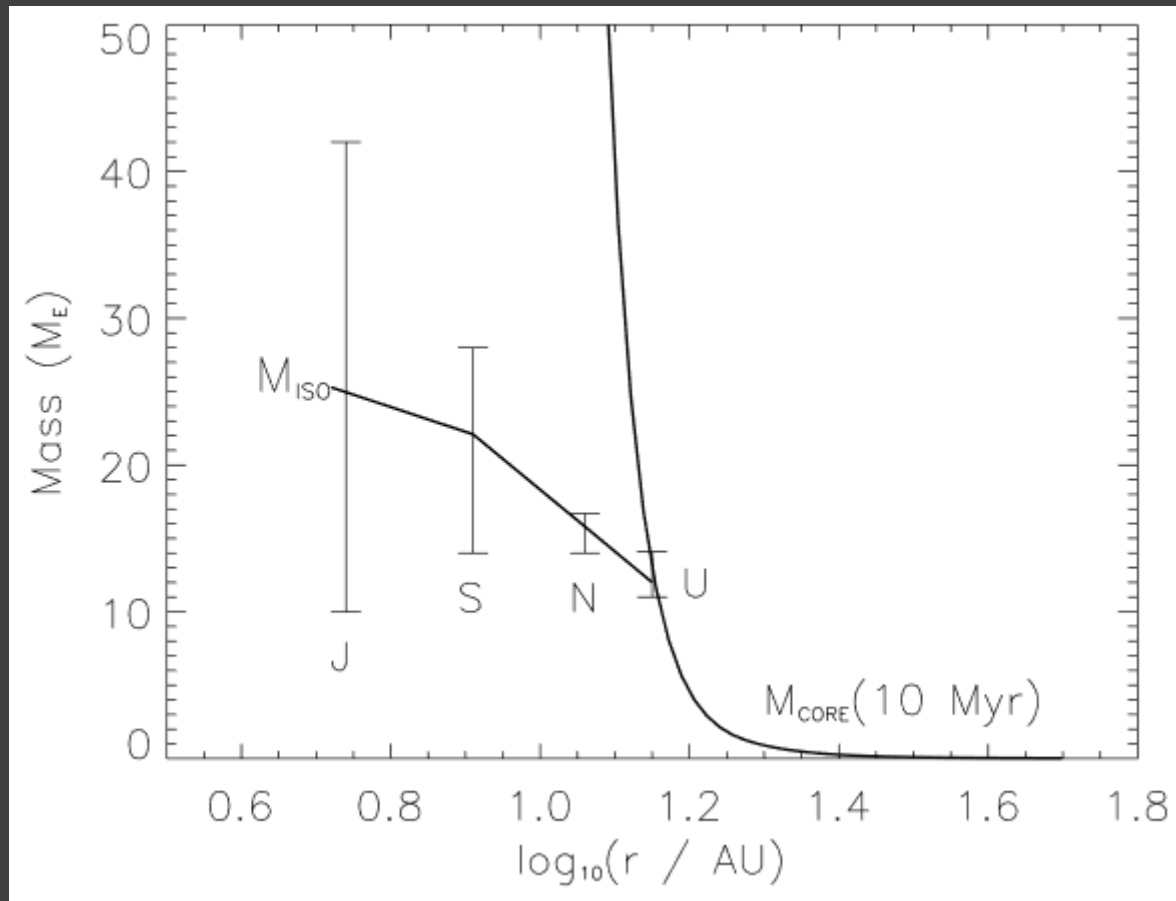
$$\rho_{\text{gas}}(r, 0) = 1.93 \times 10^{-11} \left(\frac{f_p}{0.5} \right)^{-1} \left(\frac{r}{10 \text{ AU}} \right)^{-3.4537} \text{ g cm}^{-3}$$

Steep profile is achieved thanks to photoevaporation of the outer parts of the disc due to influence of a massive star.

Mass partly flows out to compensate losses.



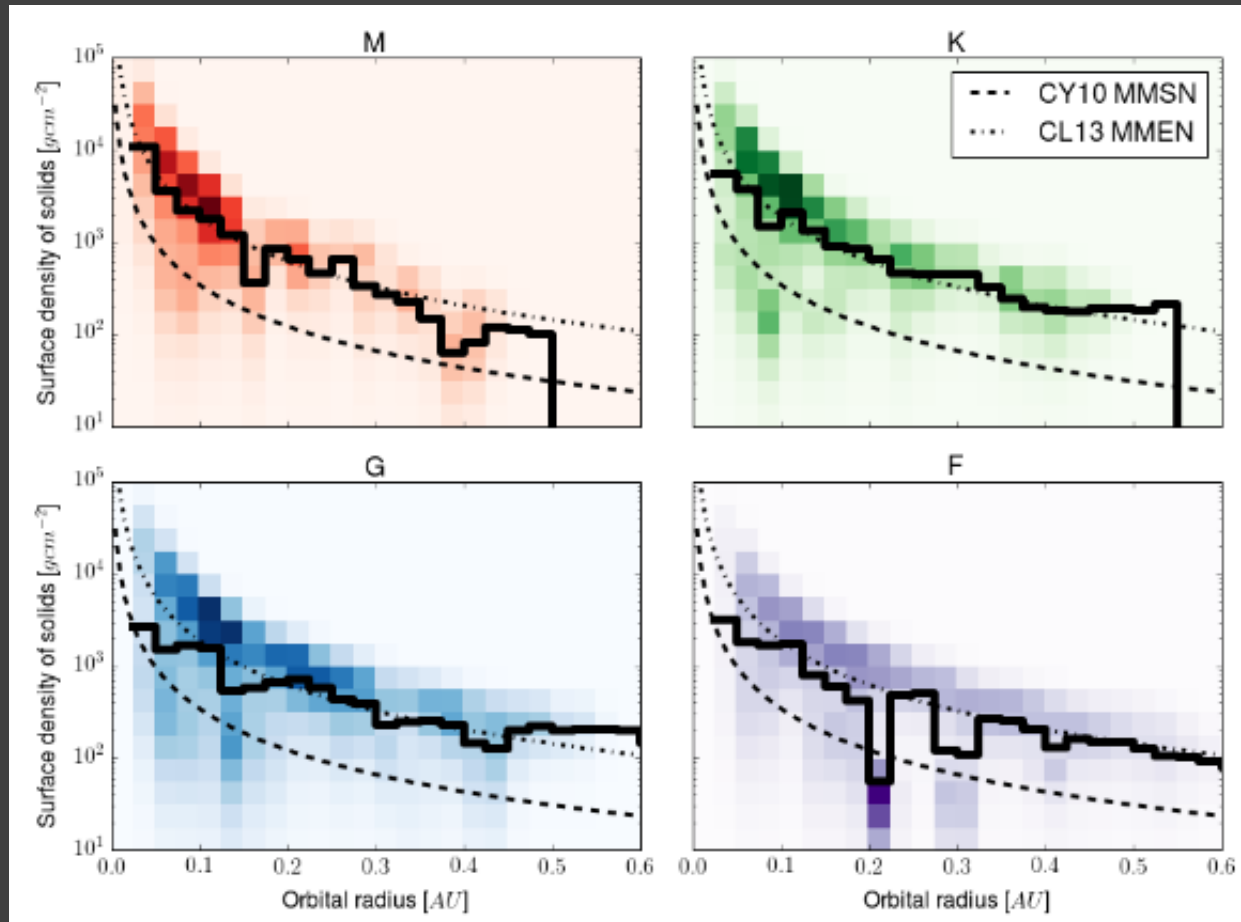
Comparison with the isolation mass



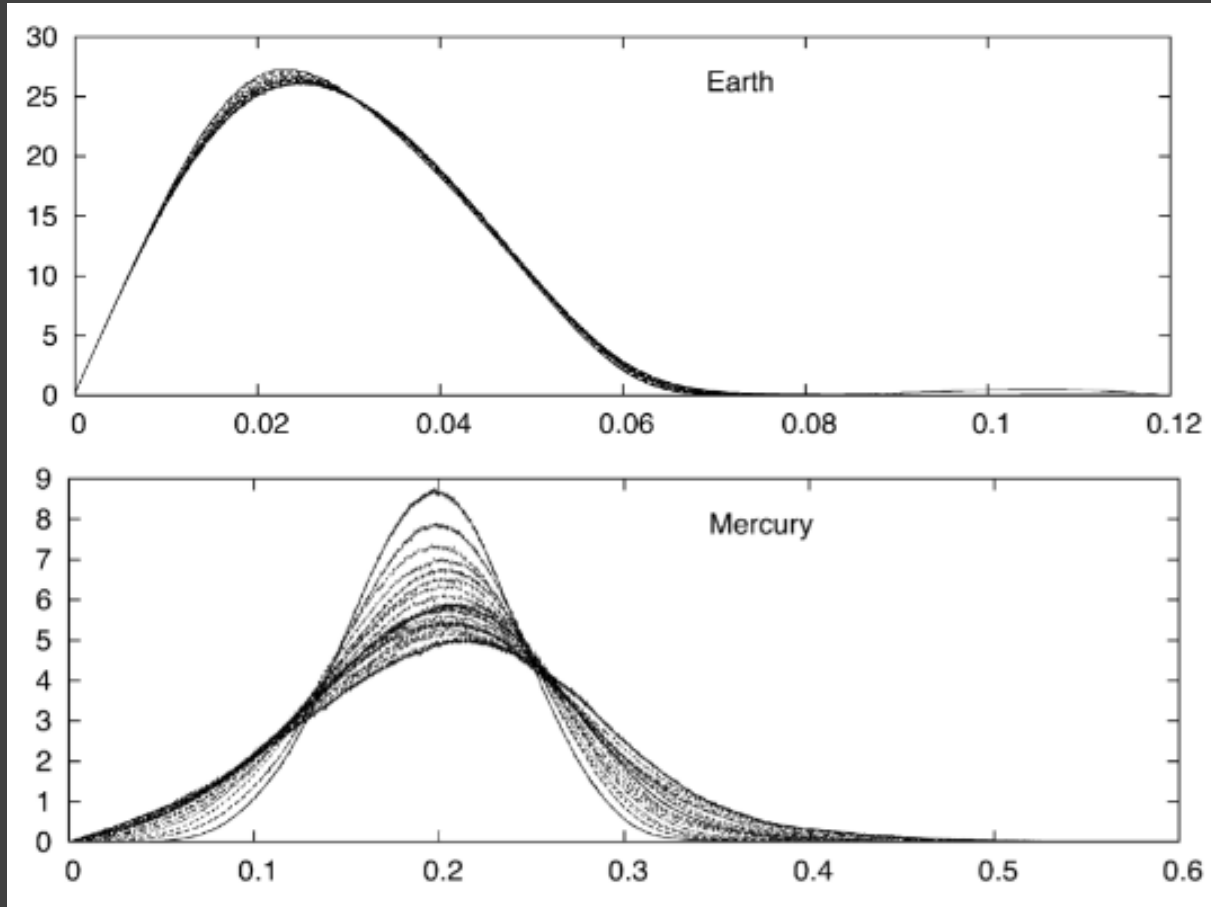
Vertical lines – total amount of solids in each planet.

Planets collect almost all available solids in their feeding zones.

MMEN and data

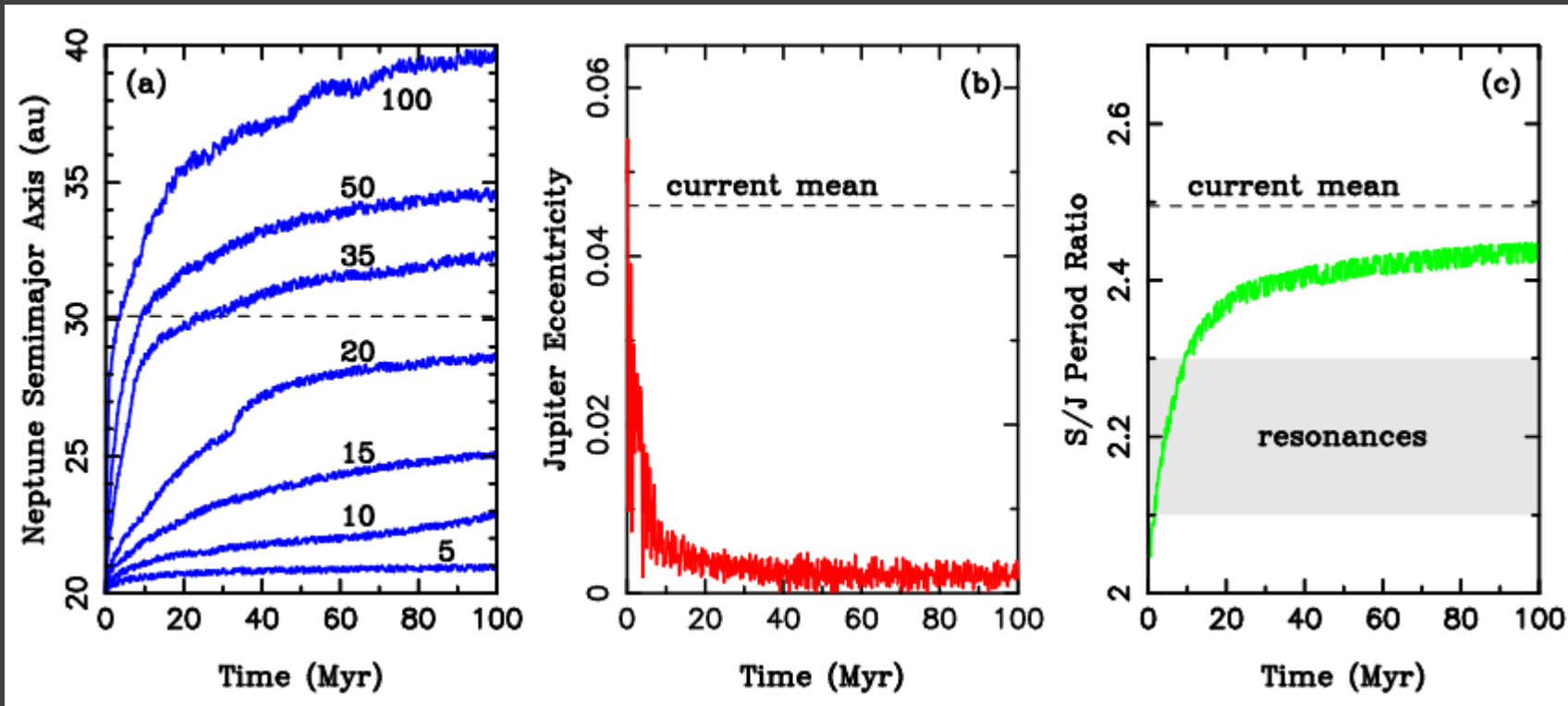


Long term evolution of the Solar system



On each plot the 19 curves represent intervals of 250 Myr. Each curve is based on 1001 solutions with very close initial conditions. The variation of these curves reflects the chaotic diffusion of the solutions (Laskar 2008, see arXiv: 0802.3371).

Planetesimal-driven migration

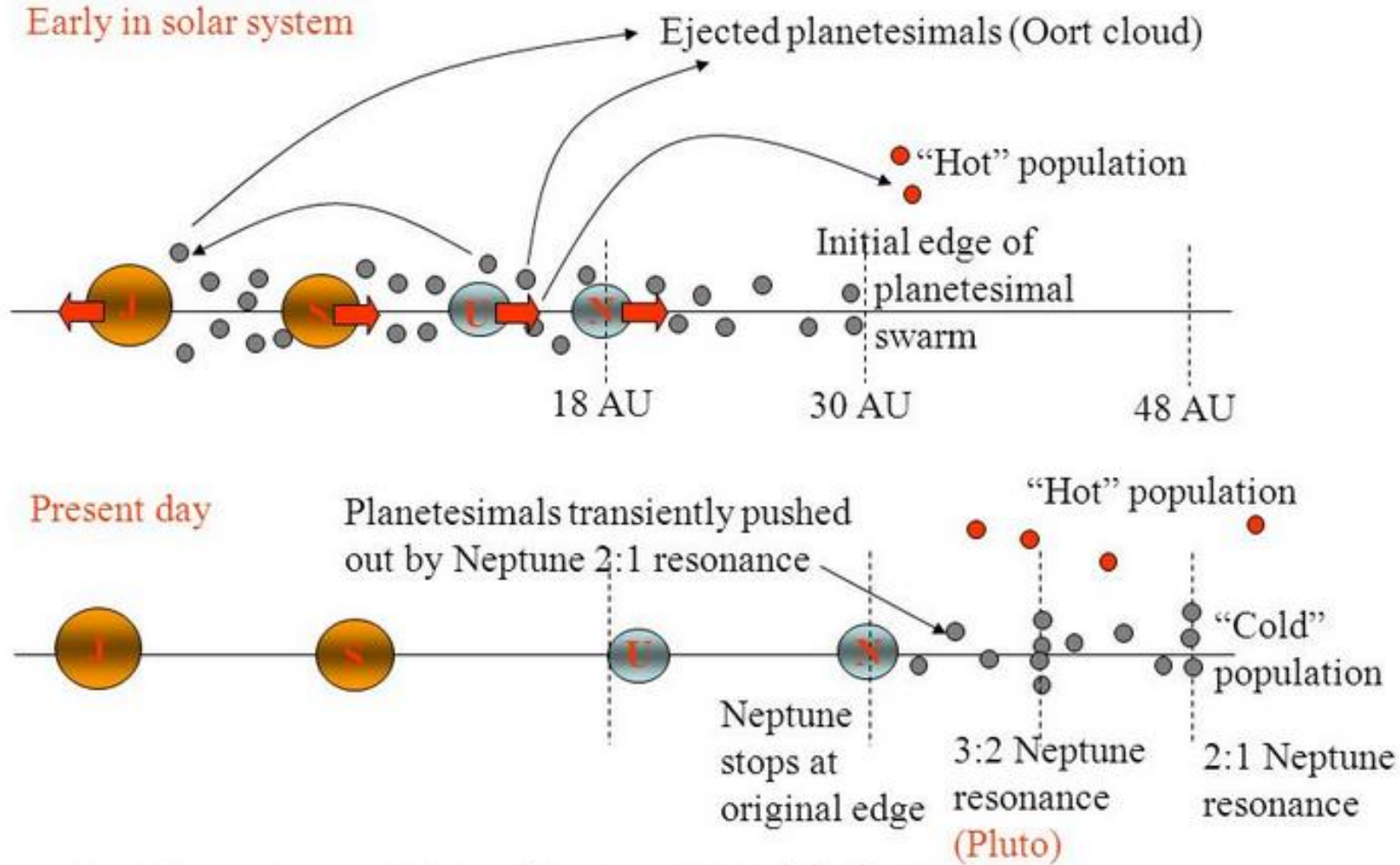


Jupiter migrates inward, other giants – outward.

Ejection of $15 M_{\text{earth}}$ by Jupiter results in migration by 0.2 au.

$$\delta r/r \approx m/M$$

Nice Model



Three papers in Nature in 2005:

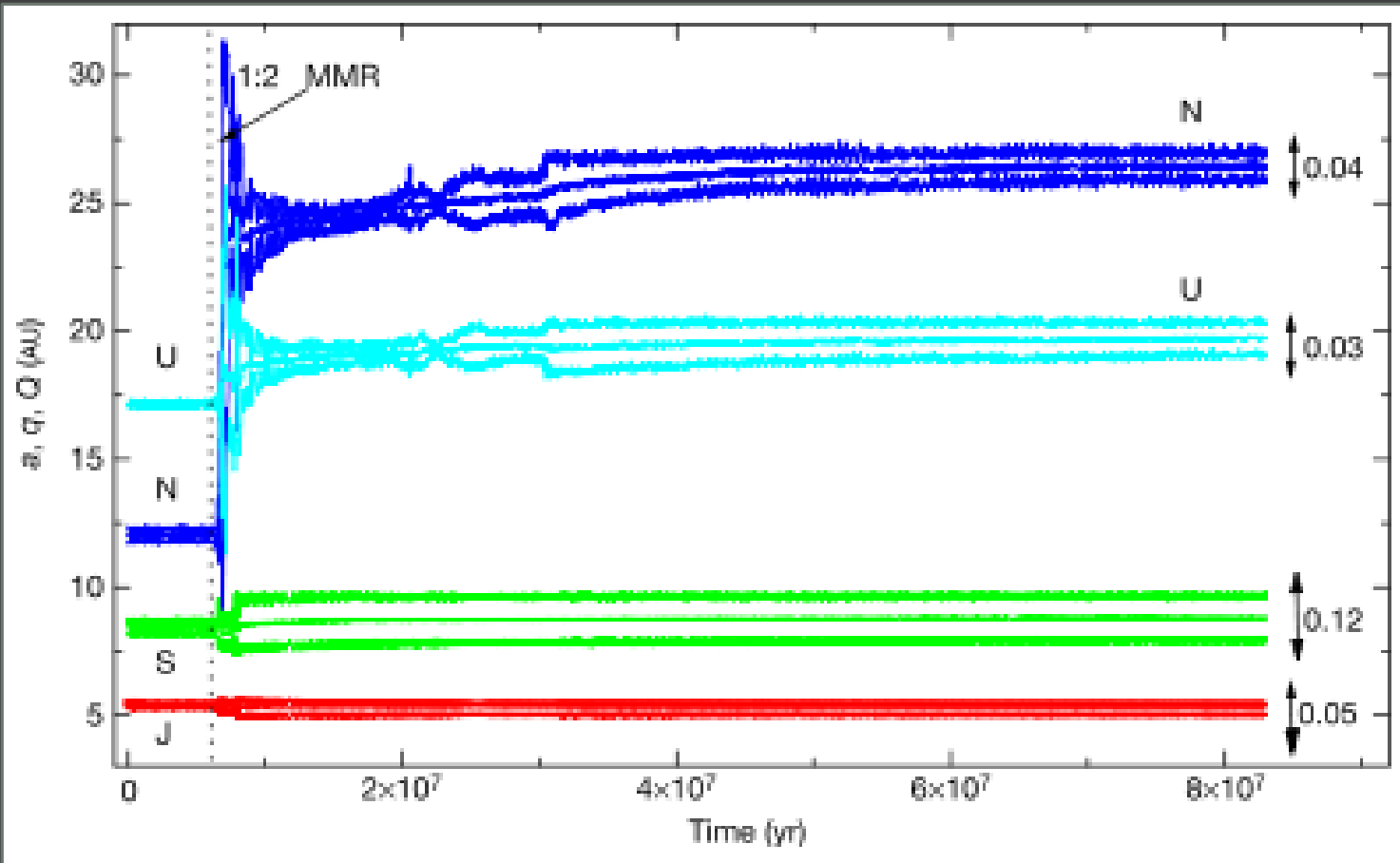
- Planet migration
- Late heavy bombardment
- Jupiter Trojans

Four giant planets +
a disc of planetesimals
with the mass $35 M_{\text{Earth}}$

See Gomes, *Icarus* 2003 and Levison & Morbidelli *Nature* 2003

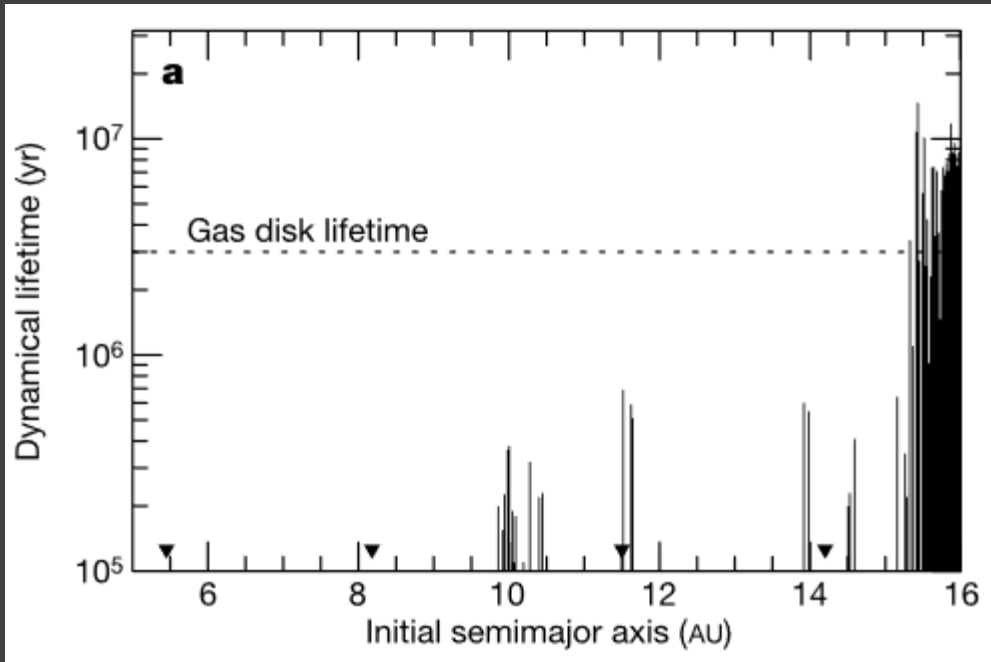
F.Nimmo EART164 Spring 11

Planet migration in the Nice model



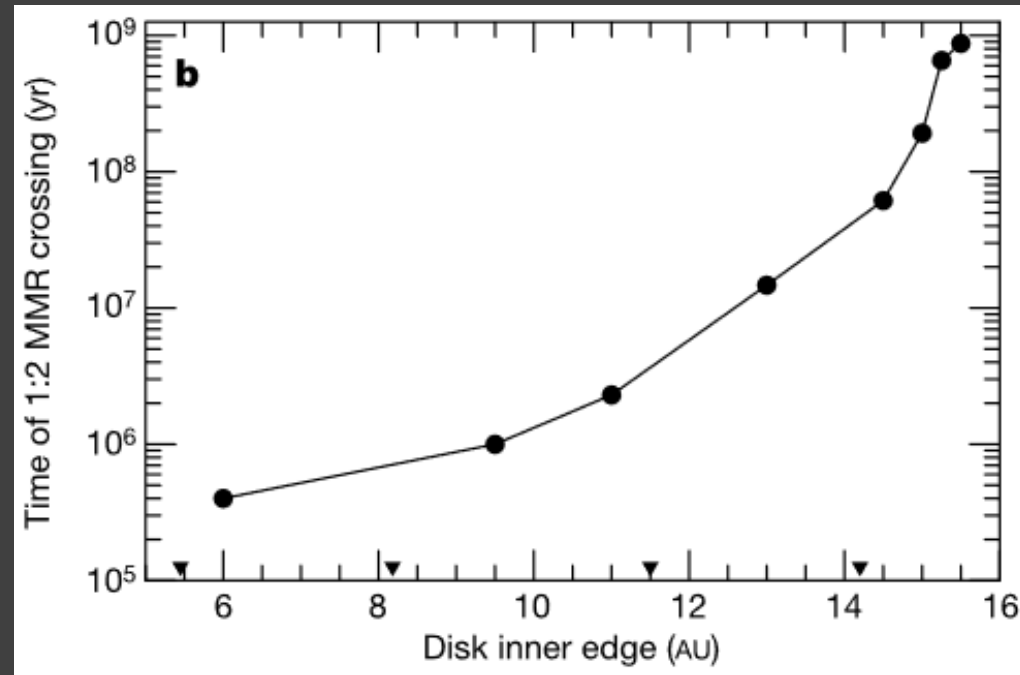
wikipedia.org

Late heavy bombardment



While the gas disk is still existing not all particles can survive long enough. Thus, the inner edge of the planetesimals disc appears at ~15-16 AU.

Position of the disc of planetesimals determines the rate of planet migration. Thus, the time of 1:2 resonance crossing depends on the position of the disc's edge.



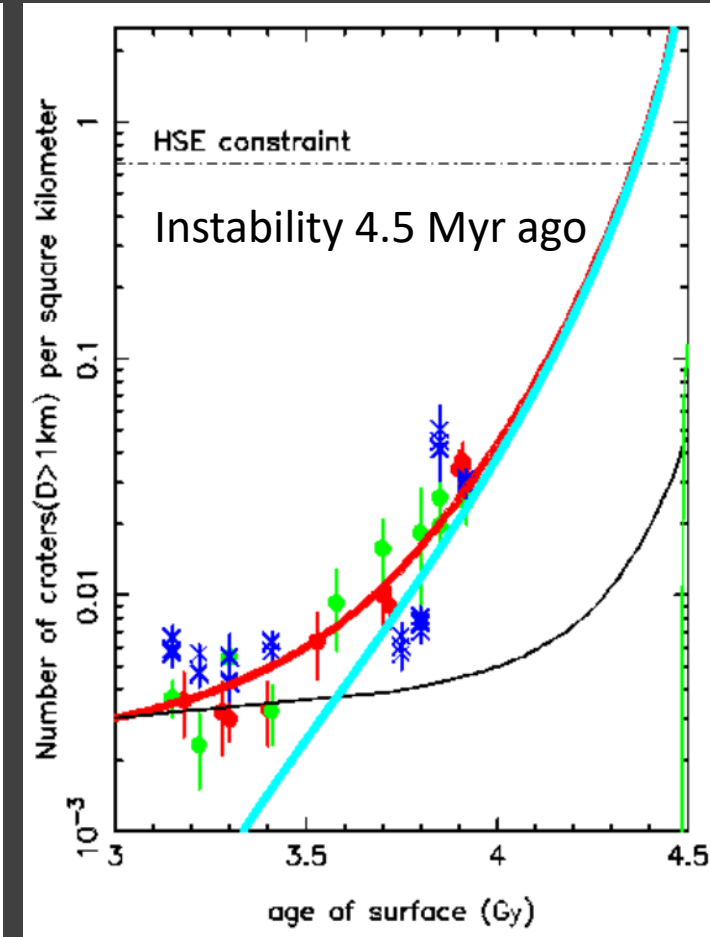
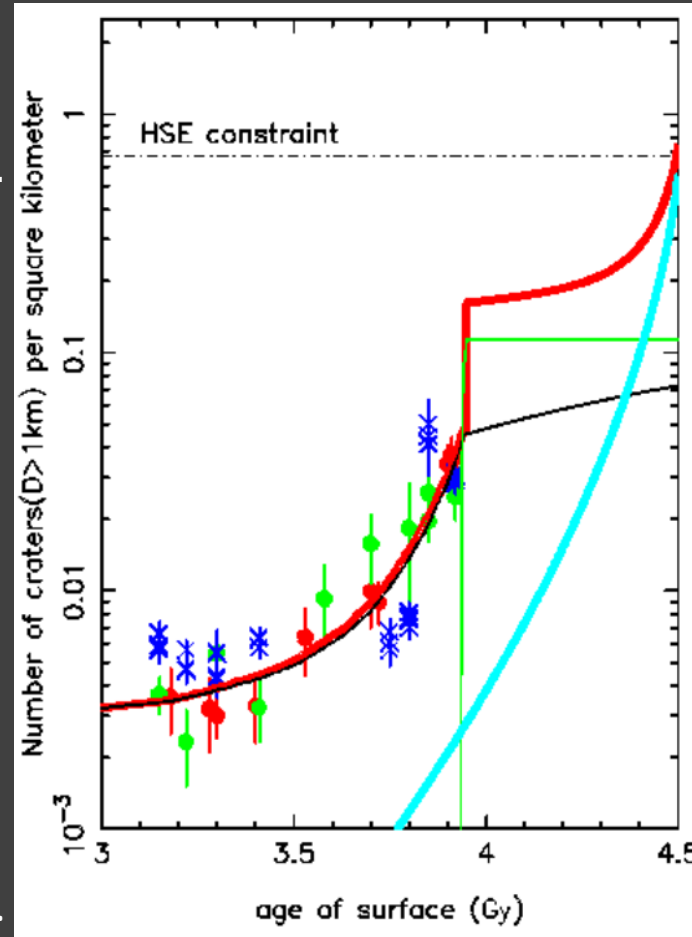
Jupiter-Saturn 1:2 resonance is crossed at ~600-900 Myrs after formation.

Revisiting the timeline of the LHB

asteroids (thin black curve),
comets (thin green curve),
leftover planetesimals (thick cyan curve).

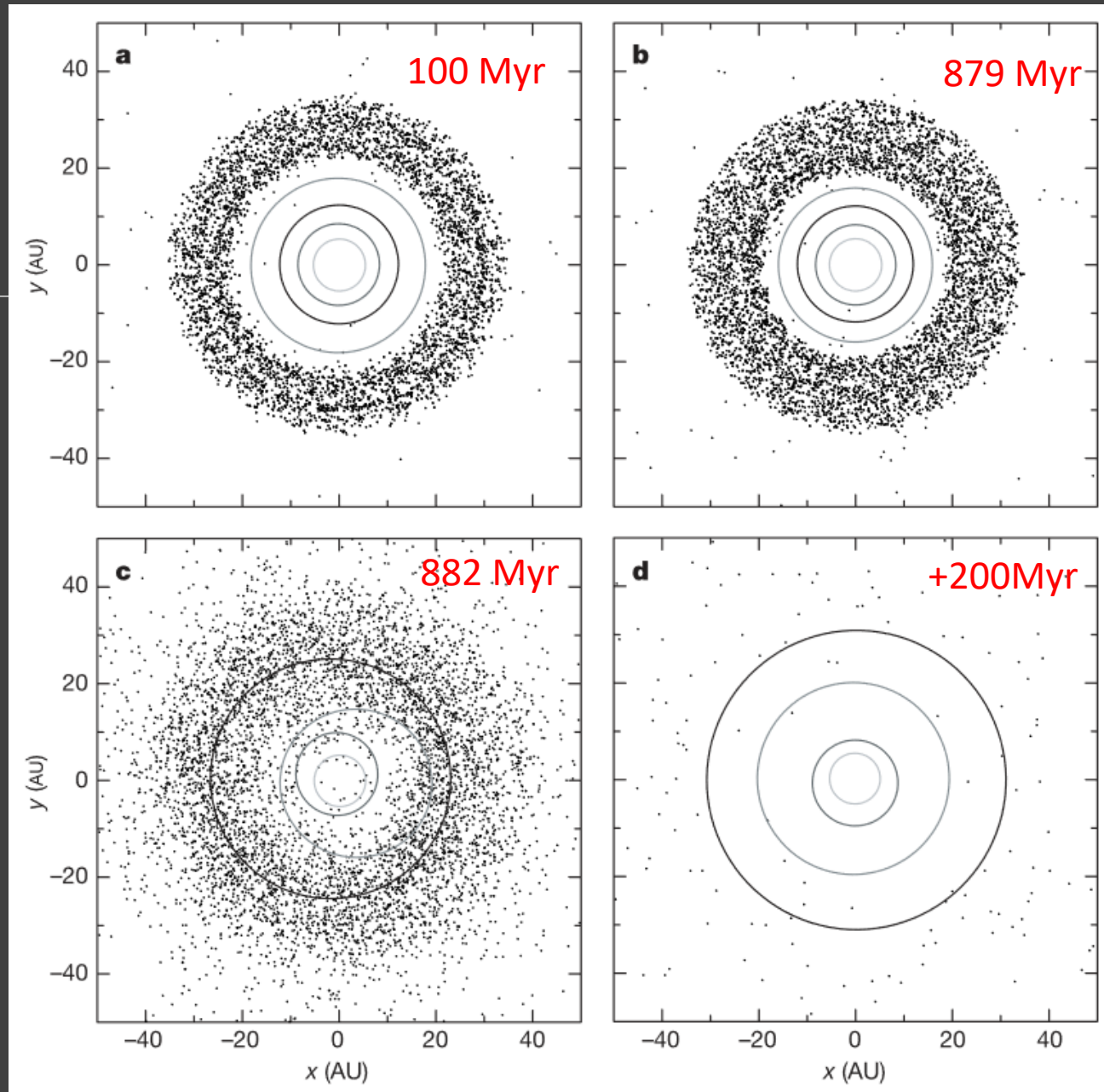
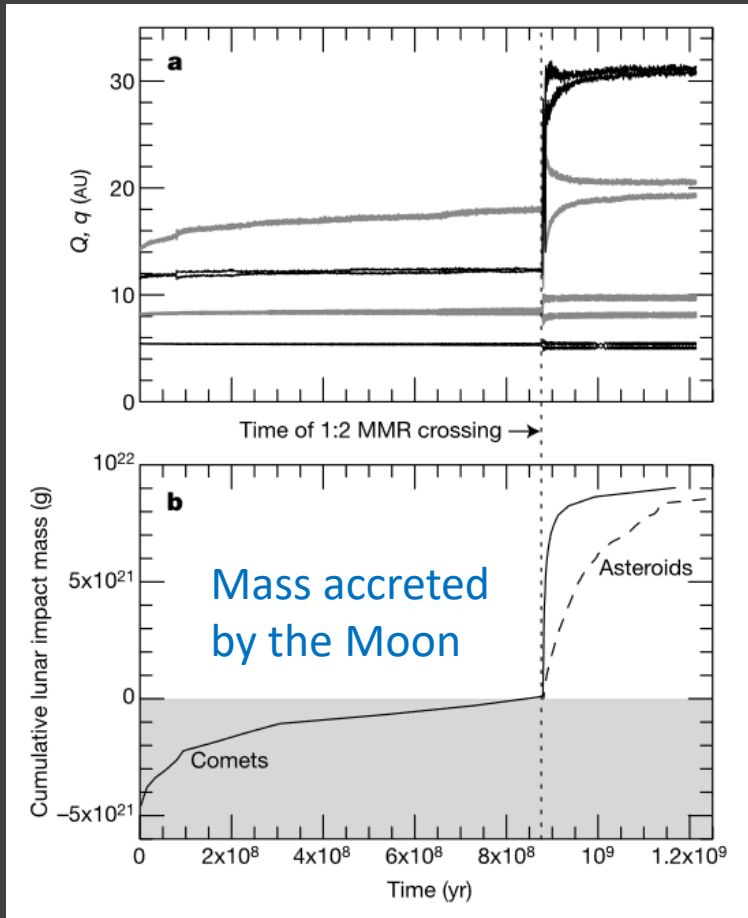
1. If HSE indicate the amount of accreted matter, then earlier results are confirmed: cataclysmic LHB 3.95 Gyr ago
2. If HSE were transported to the core (in the cases of Moon and Mars), then all the data can be explained by an accretion tail.

HSE - highly siderophile elements:
transition metals which tend
to sink into the core
because they dissolve readily in iron.

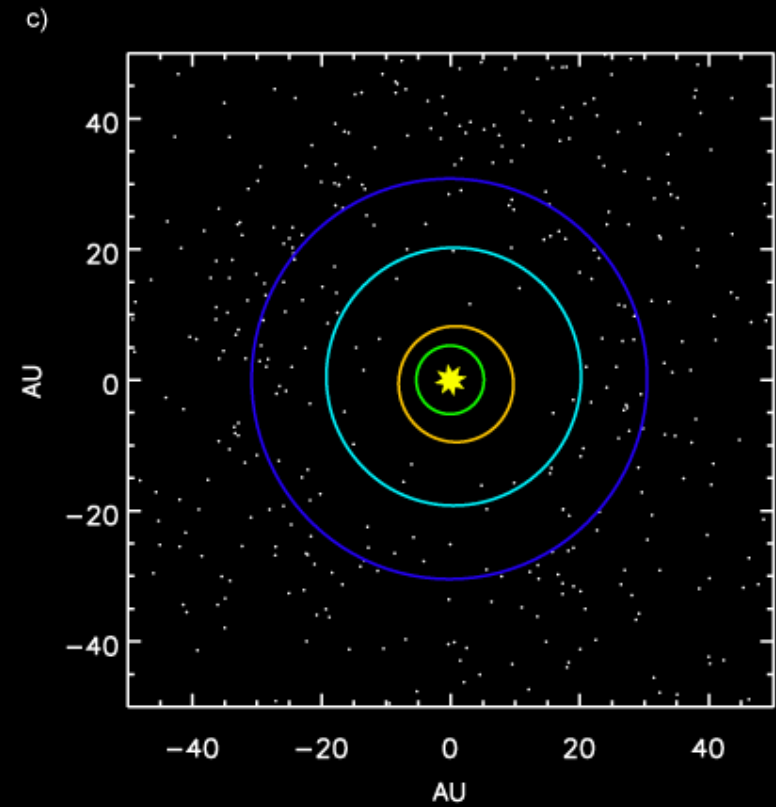
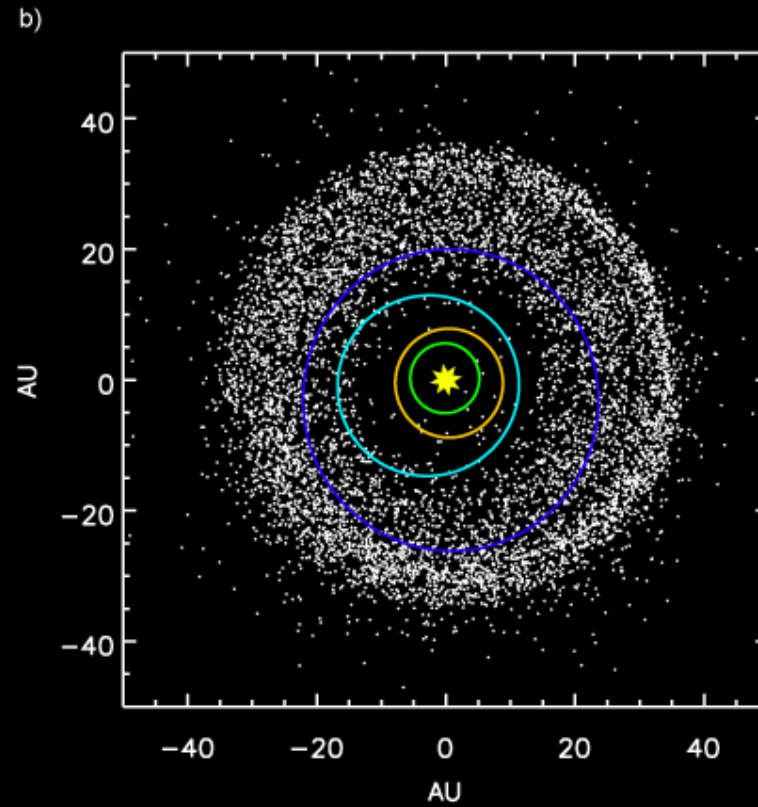
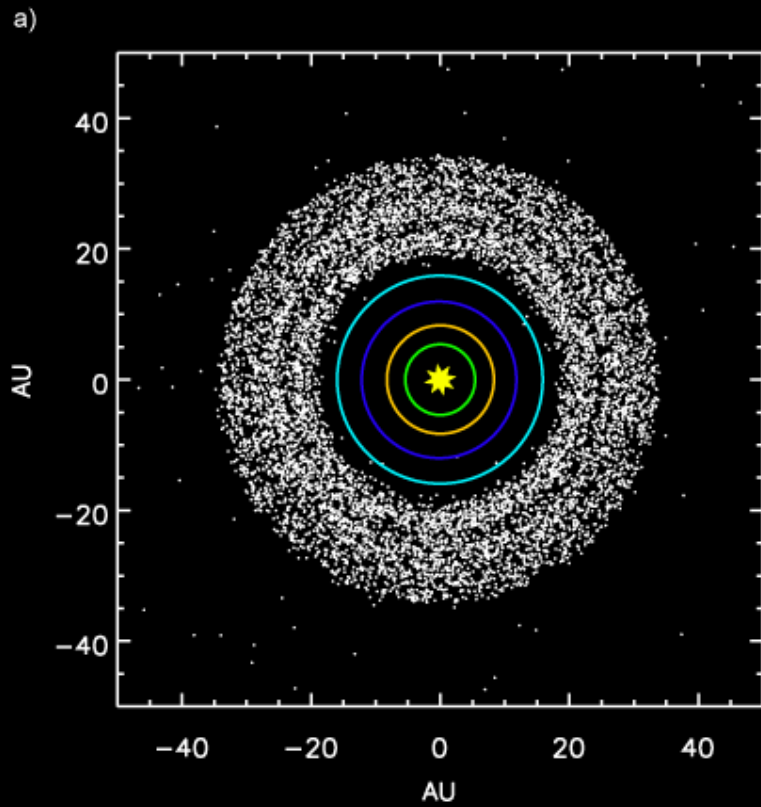


Dynamics

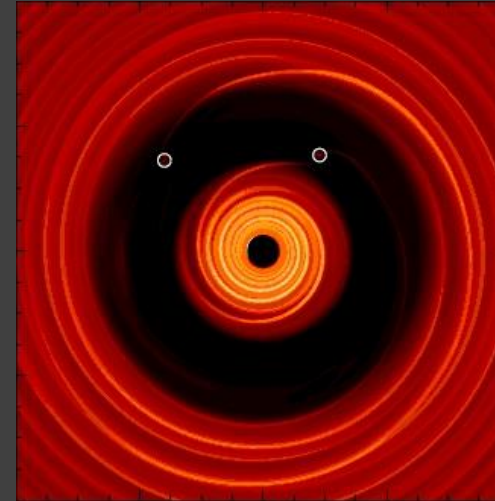
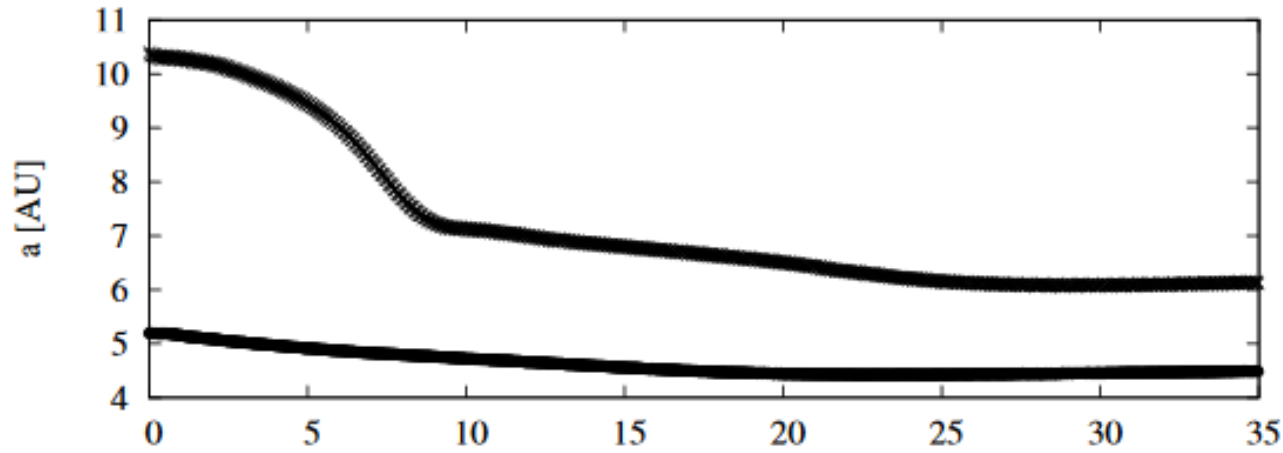
LHB lasted
for ~ 100 Myr



Nice model

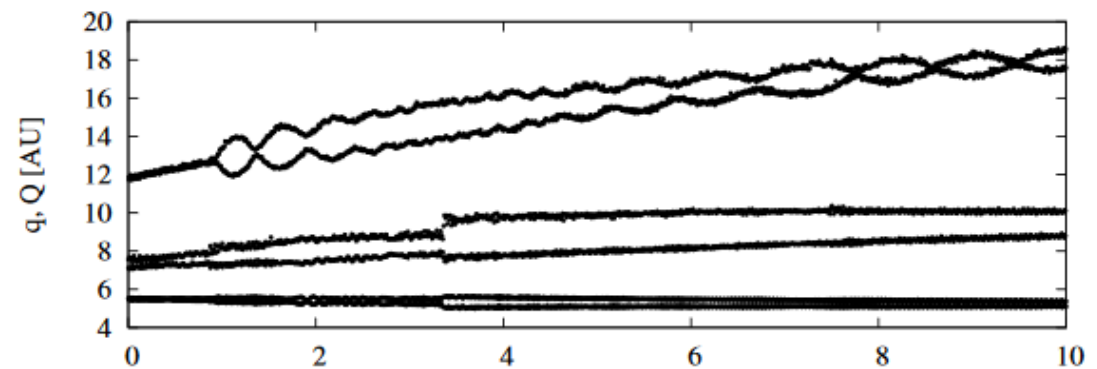


Solar system secular evolution: resonance crossing



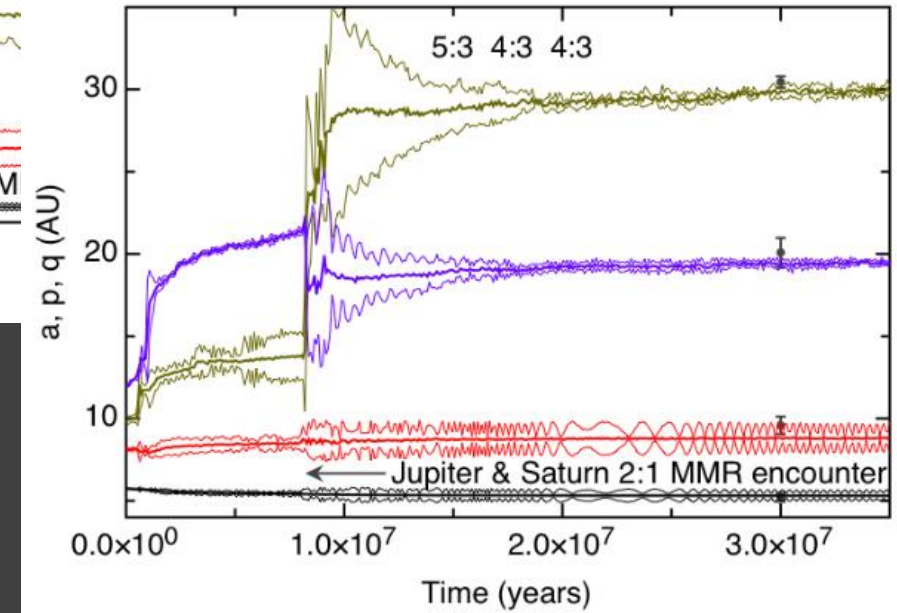
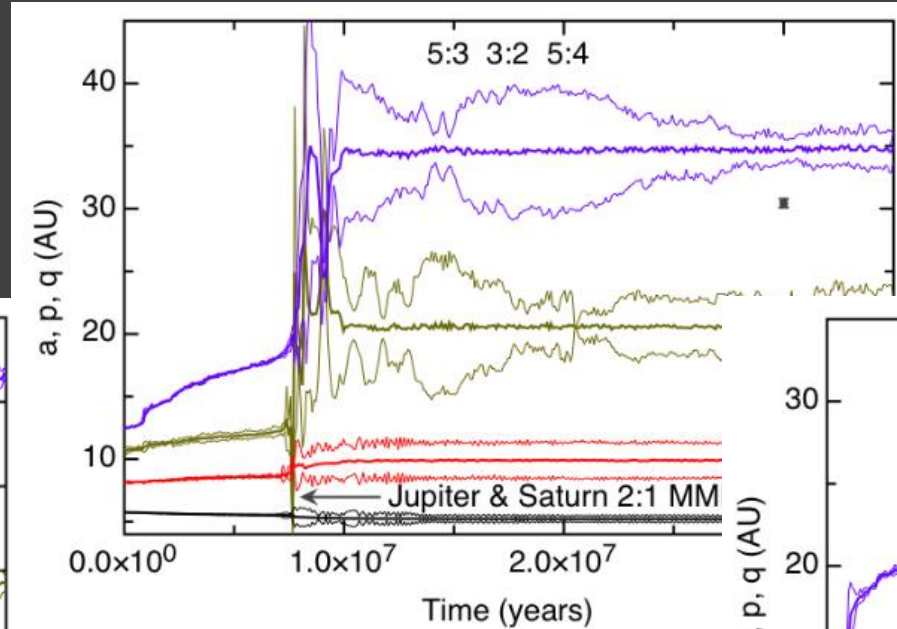
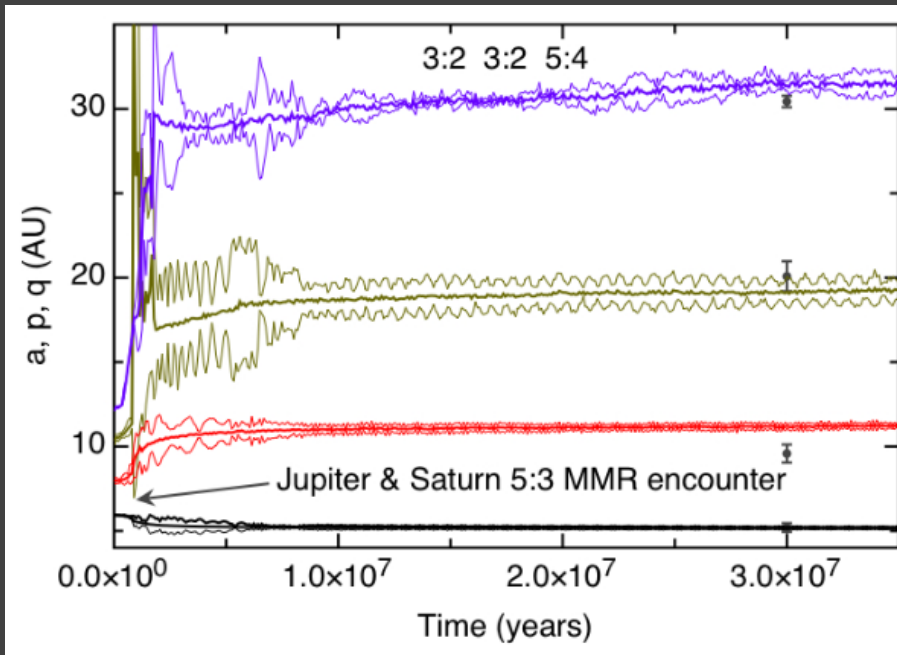
planetplanet.net

After evolution in the gas disc Jupiter and Saturn are in 3:2 resonance. At this stage eccentricities and inclinations are low. It is non-trivial to explain present-day eccentricities and inclinations. It was proposed that it can be potentially solved if these planets crossed resonances and interacted with ice giants on eccentric orbits. But strong interaction of an ice giant with Saturn is a better option.



Further studies

Role of initial resonance conditions
for all four giants.



Modifications of the original Nice model

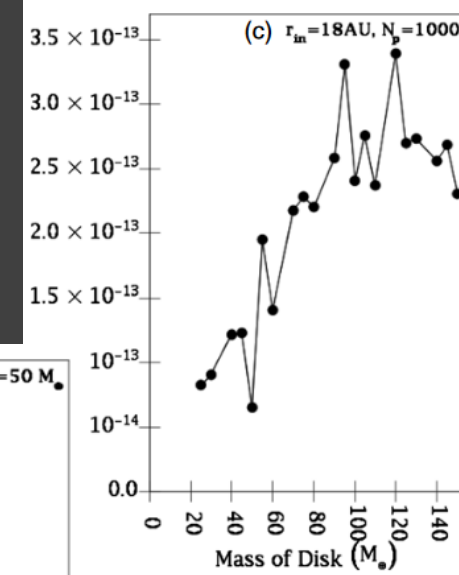
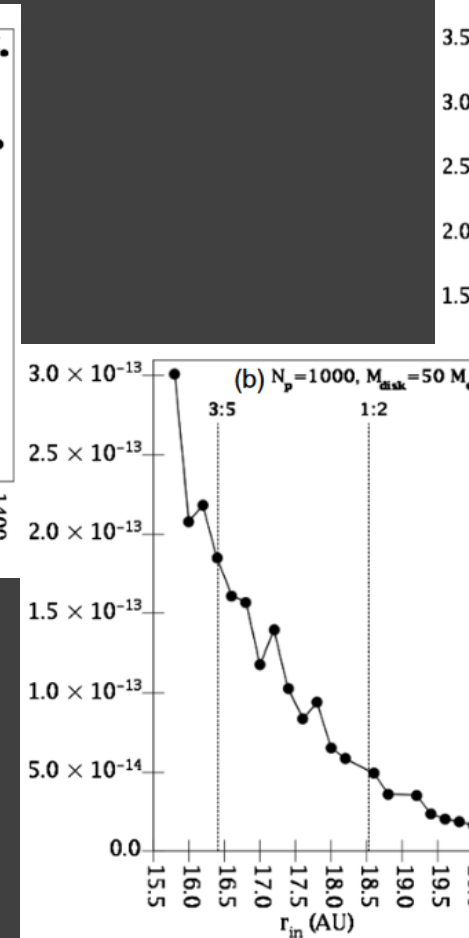
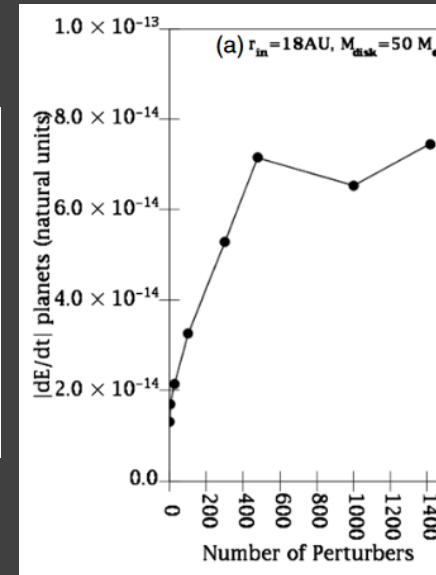
Initial (resonant) conditions in the Nice II model.
+ a disc which is now more massive $50 M_{\text{Earth}}$

Planet	$\langle a \rangle$ (AU)	$\langle e \rangle$	$\langle i \rangle$ (deg)
Jupiter	5.42	0.0044	0.016
Saturn	7.32	0.017	0.016
Ice I	9.61	0.053	0.044
Ice II	11.67	0.011	0.029

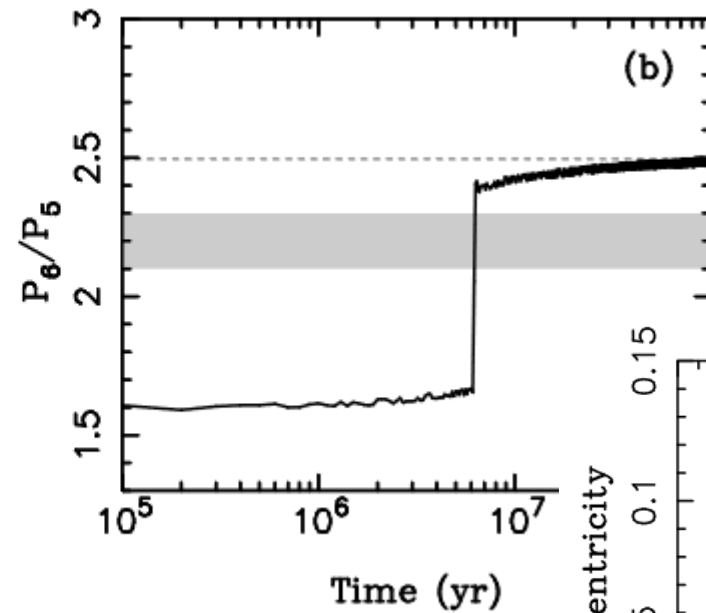
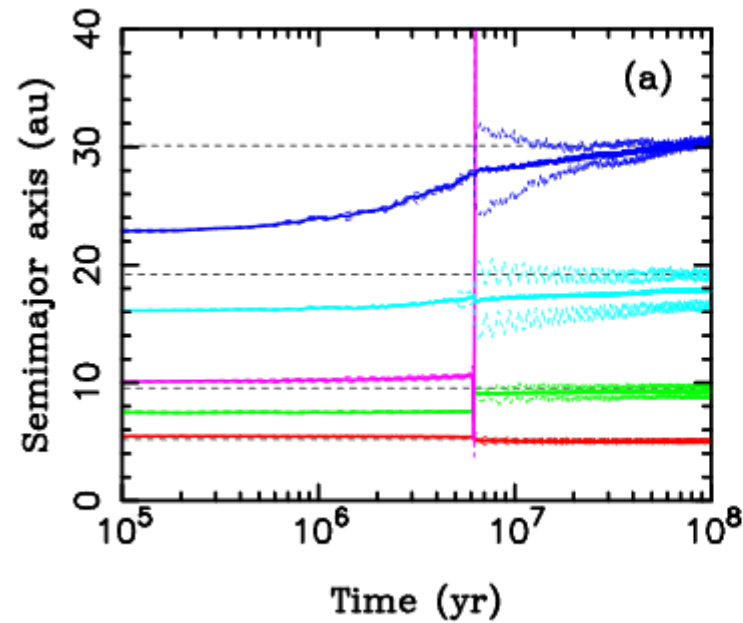
Interaction between disc particles (stirring) and eccentricity of planets are important factors for planets-disc interaction.

Internal ice giant might have larger eccentricity after evolution in the gas disc.

Interaction of this planet with the disc of planetesimals can result in the instability in the planetary system.

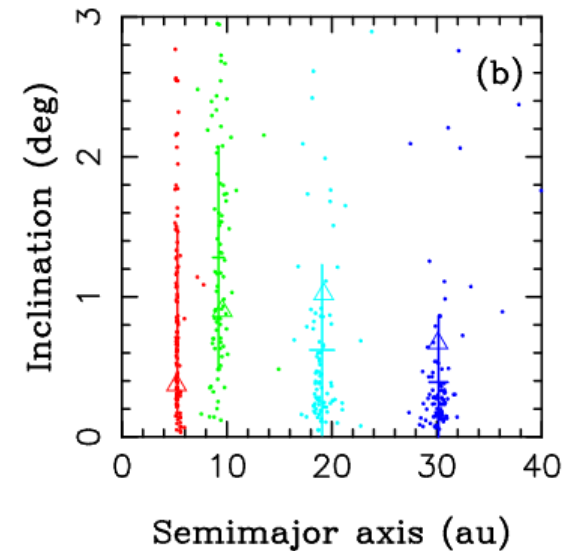
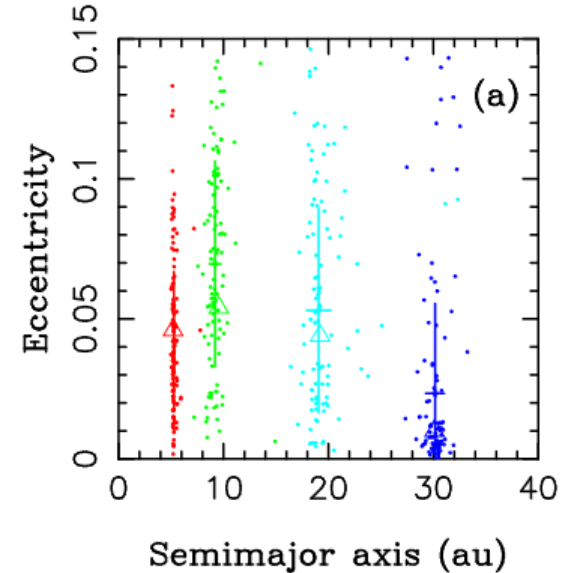


Jumping Jupiter



500 simulations with 5 planets.
Initial resonances 3:2,3:2,2:1,3:2

Five planets configuration.

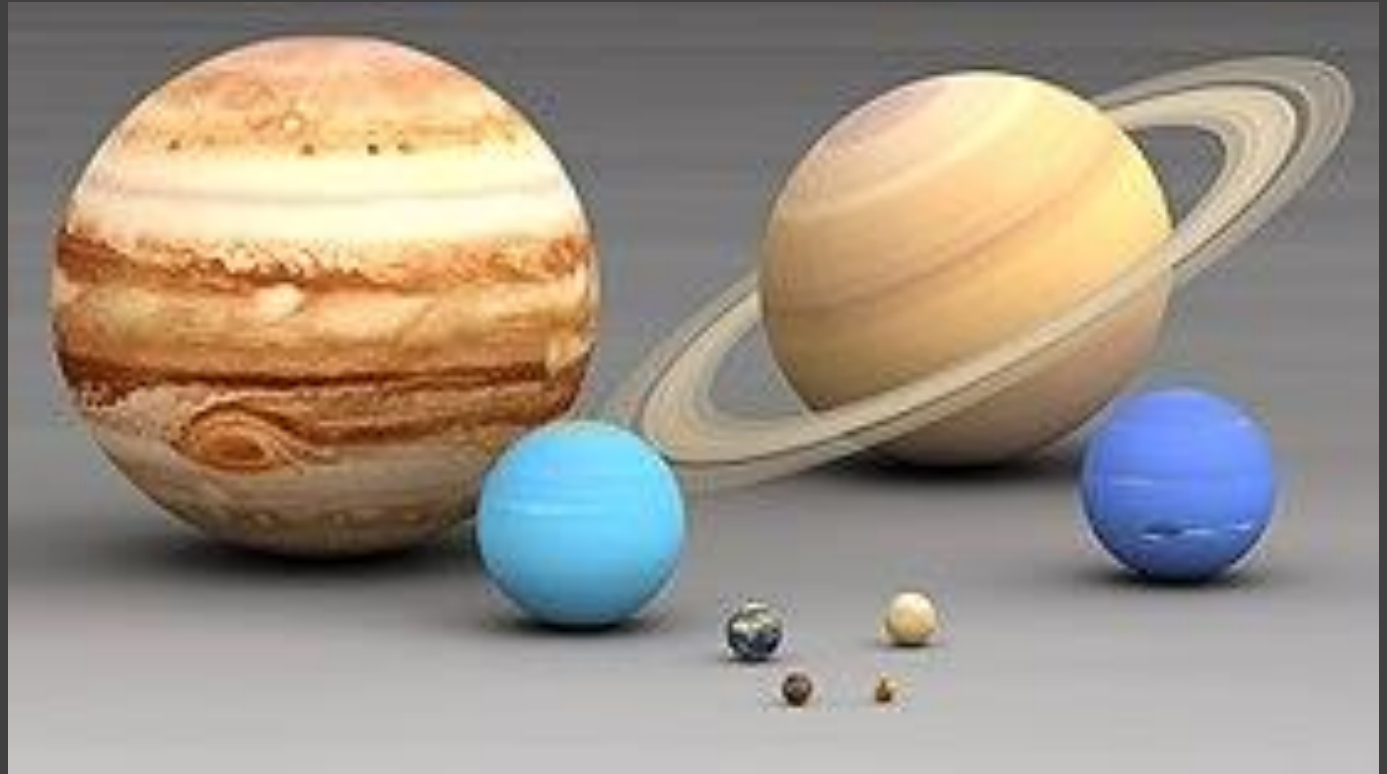


More problems (and solutions?)

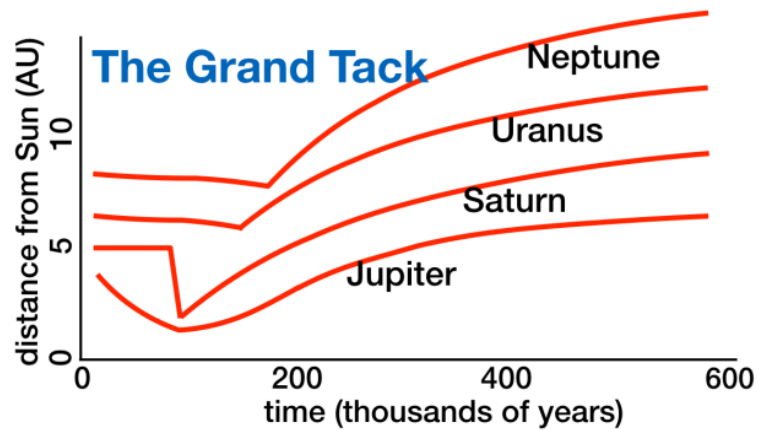
Problem: light Mars

Solution: cut planetesimal disc at 1 AU

How: Jupiter!

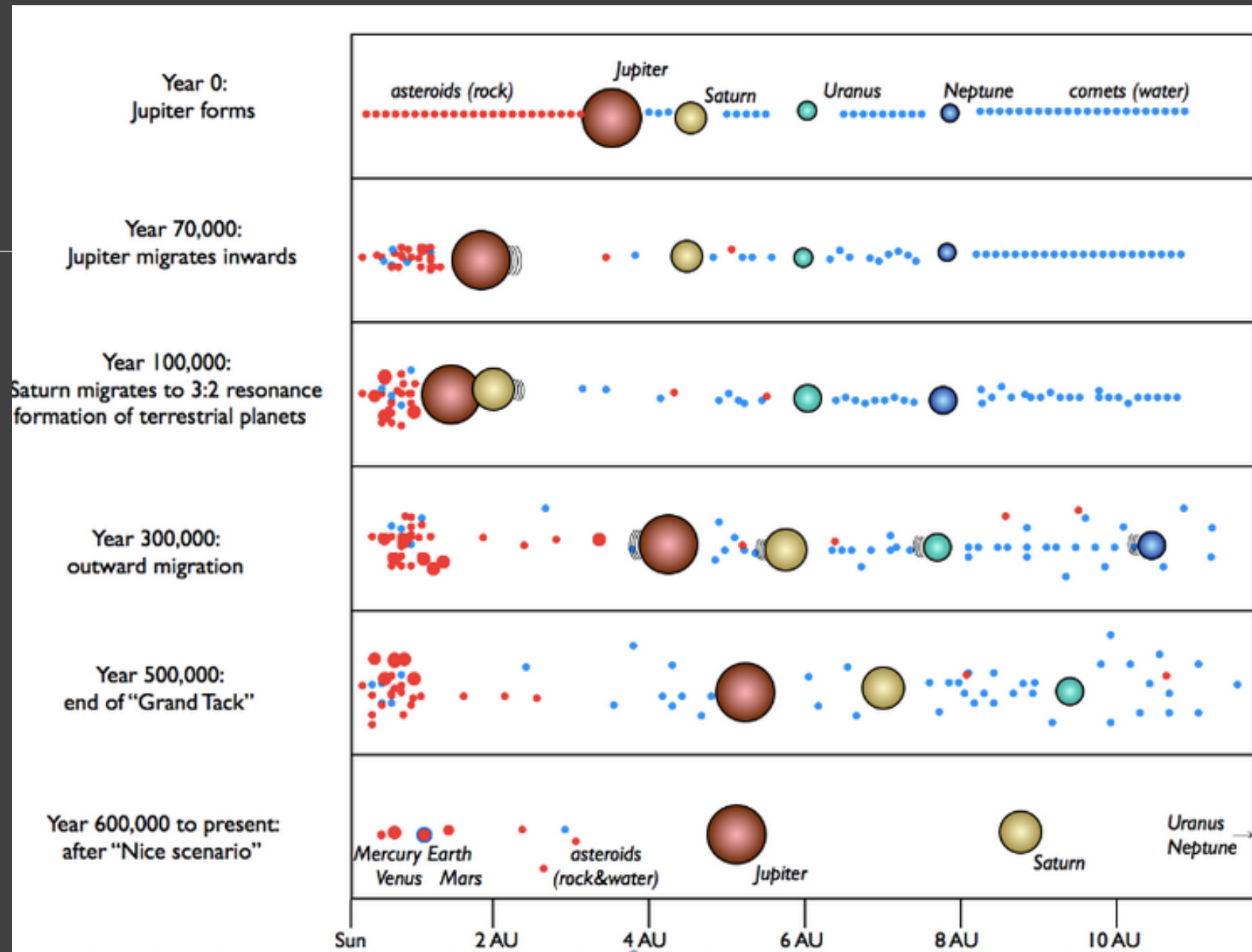


Grand tack



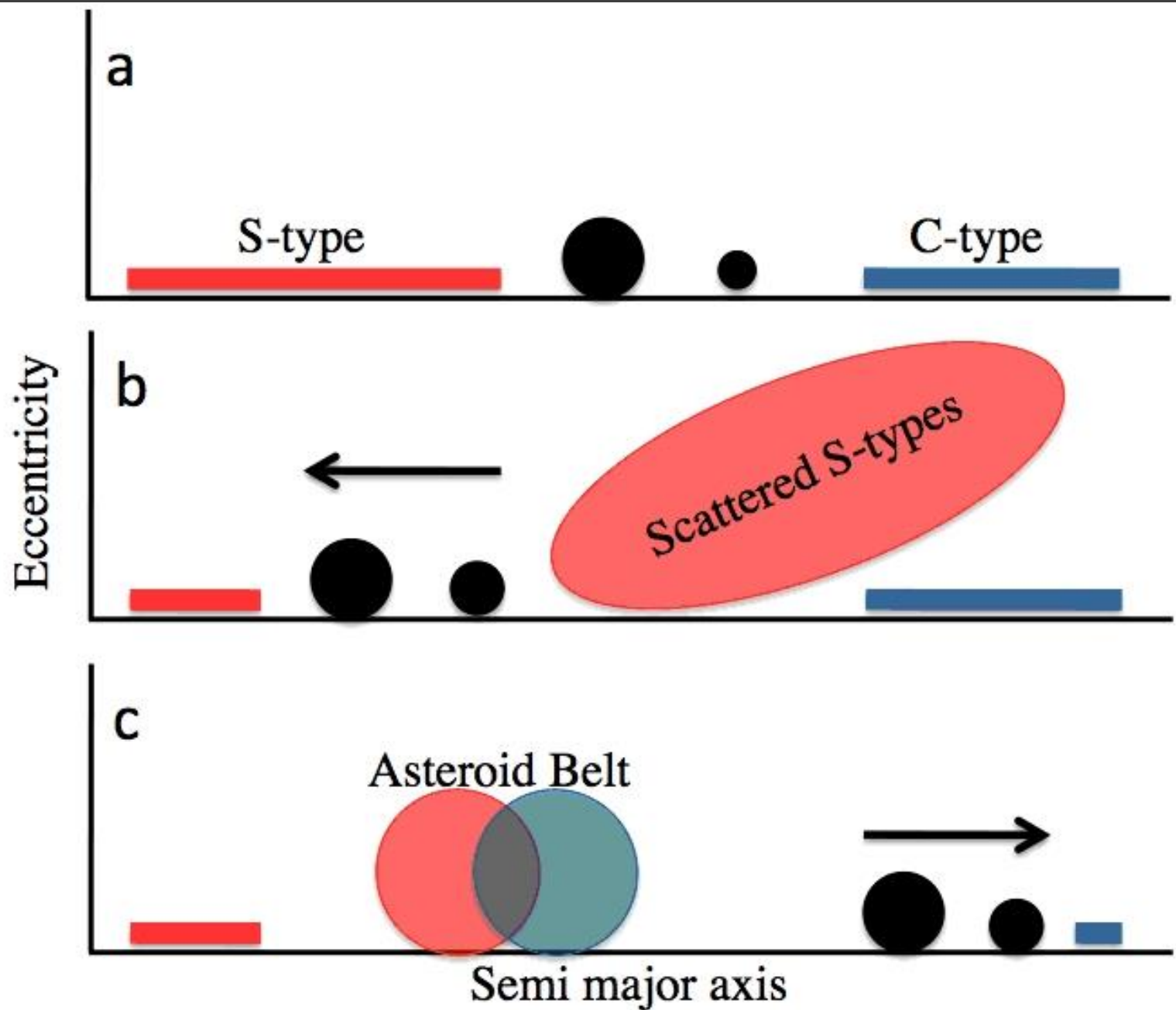
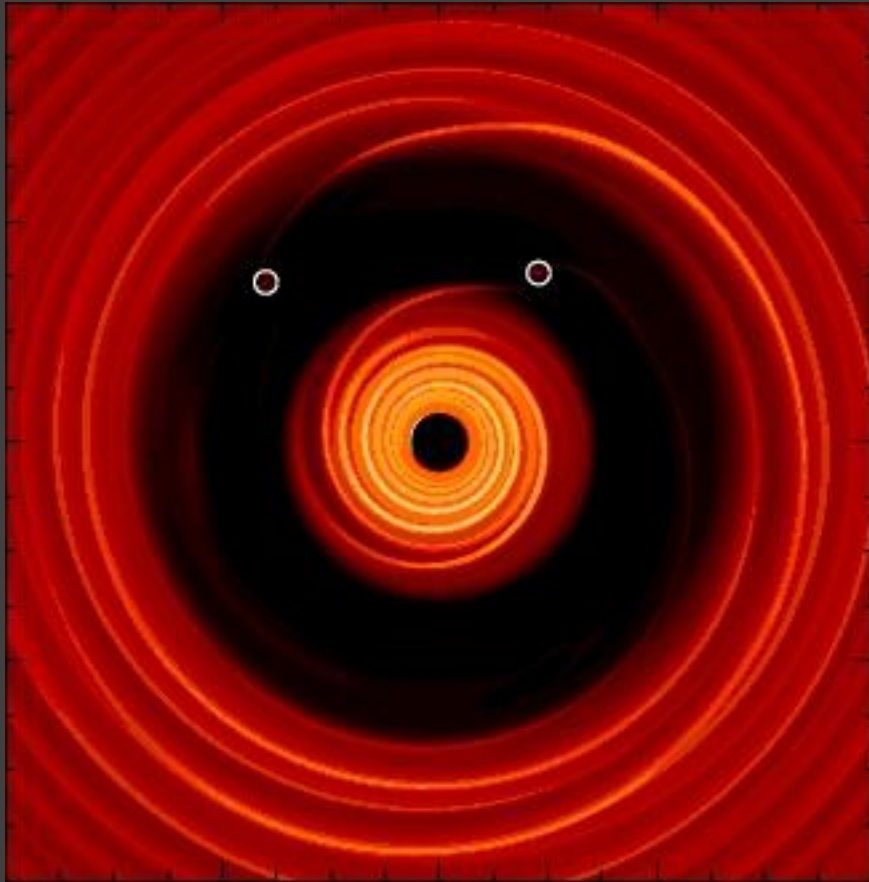
Proposed by Walsh et al. (2011).

Explains why Mars is small
(truncation of planetesimals disc).



See a simple introduction at <https://planetplanet.net/2013/08/02/the-grand-tack/>

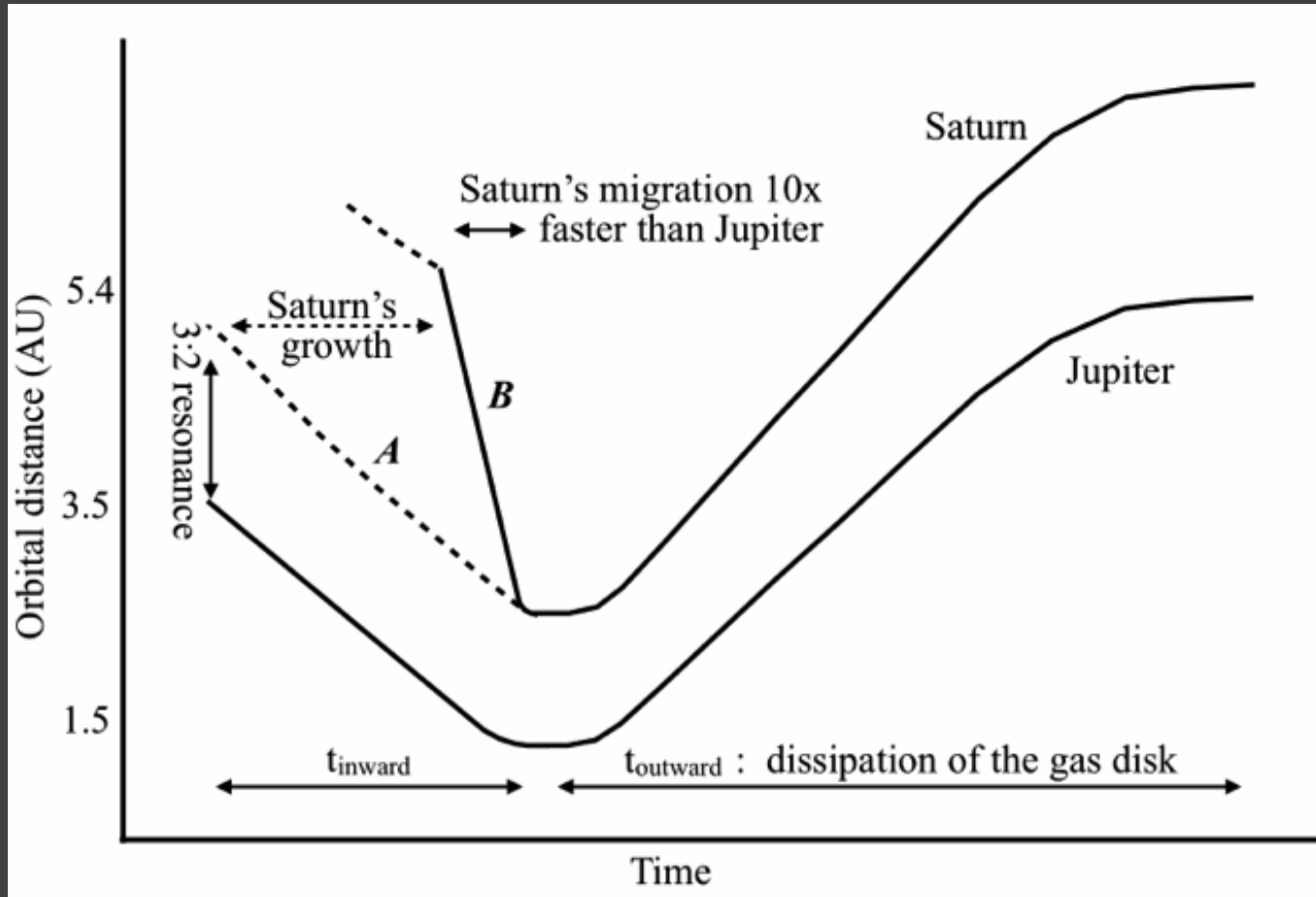
Grand tack



<https://planetplanet.net/2013/08/02/the-grand-tack>

see movies at http://perso.astrophy.u-bordeaux.fr/SRaymond/movies_grandtack.html

Phases of the Grand tack

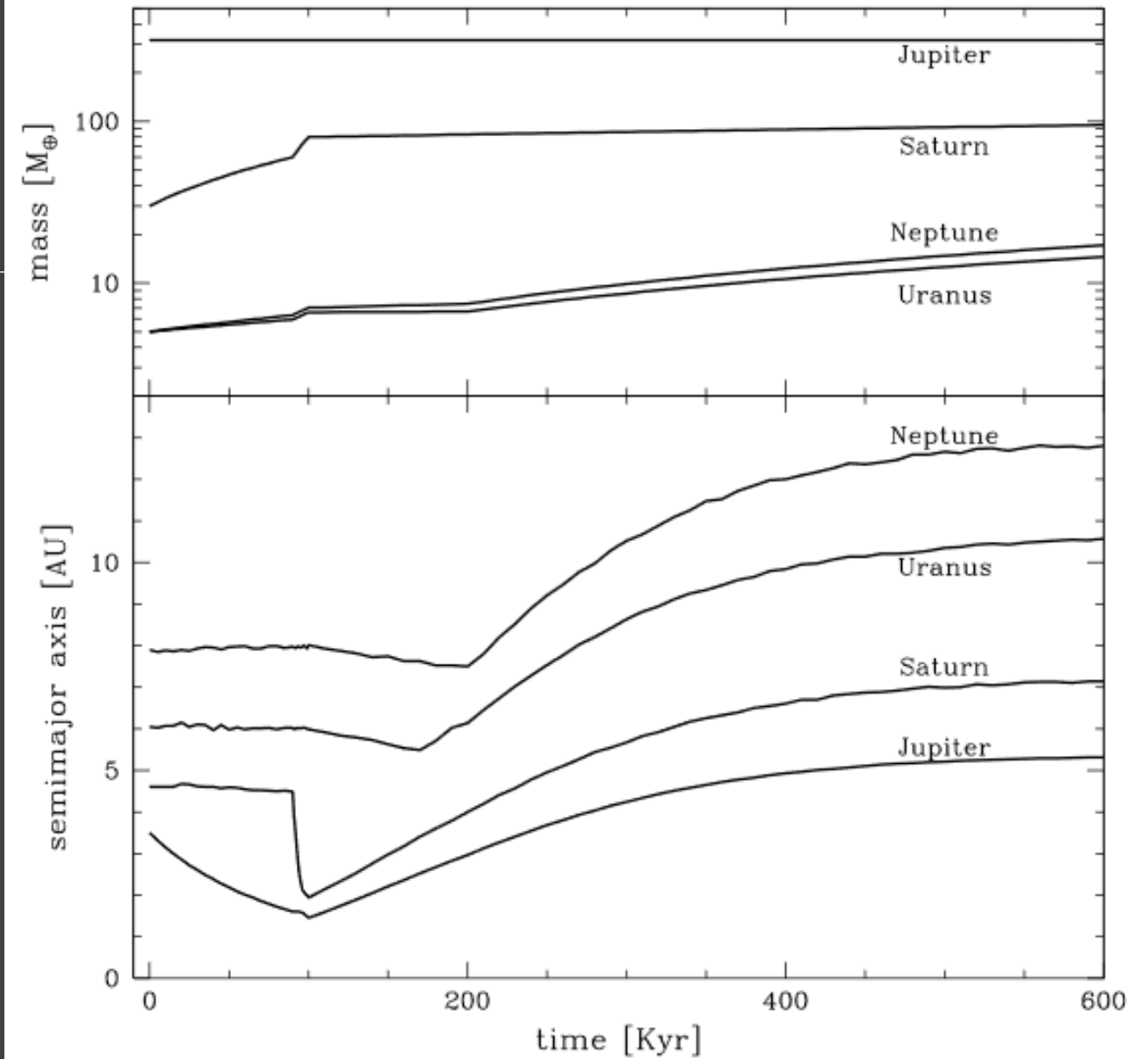


Jupiter and Saturn form earlier than terrestrial planets.

Thus, it is possible to influence the disc of planetesimals (embryos for terrestrial planets) with giants, if they can migrate closer to the region of solid planets formation.

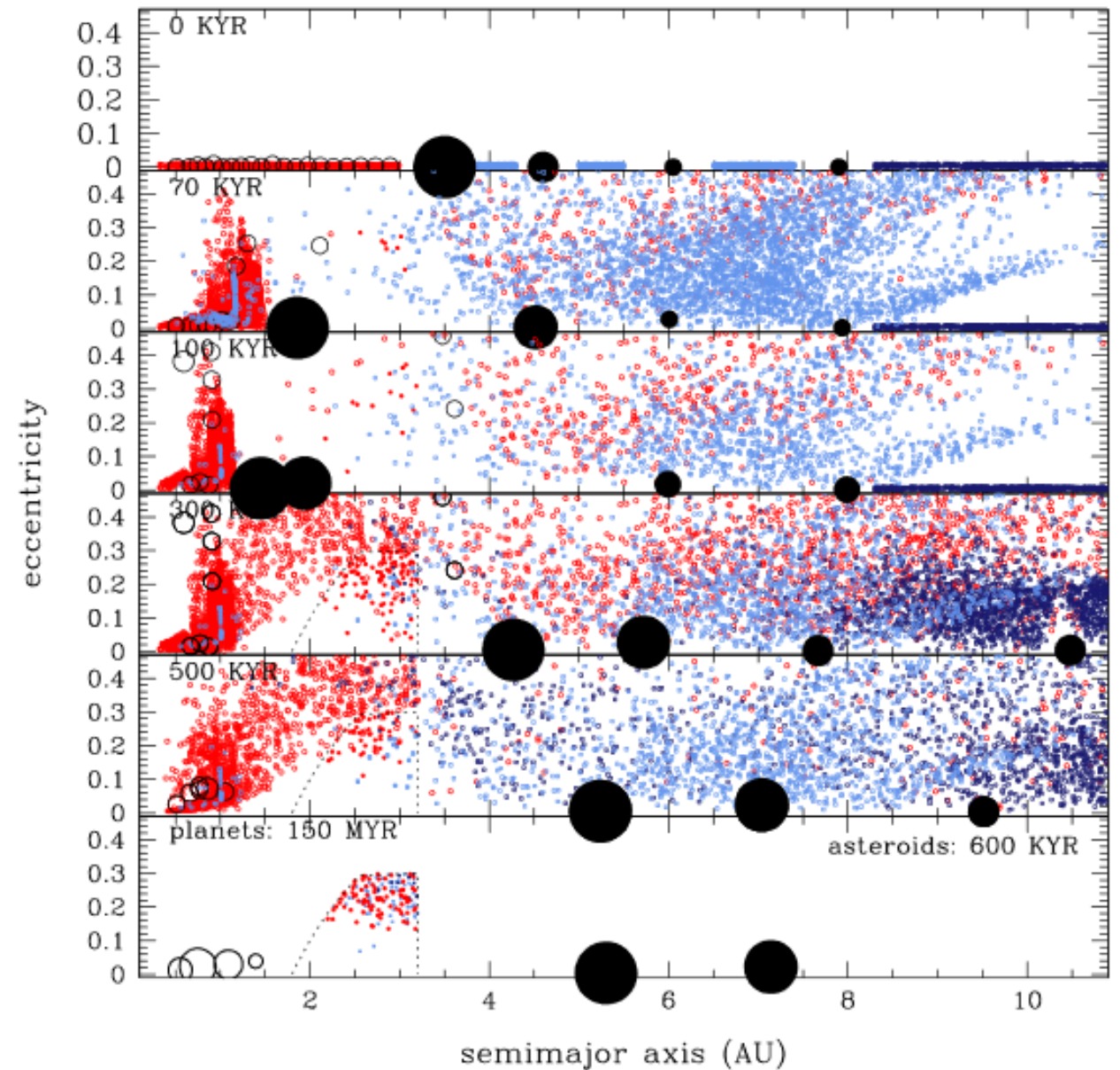
Grand Tack

Results of calculation of planet migration
from the original paper Walsh et al. (2011)

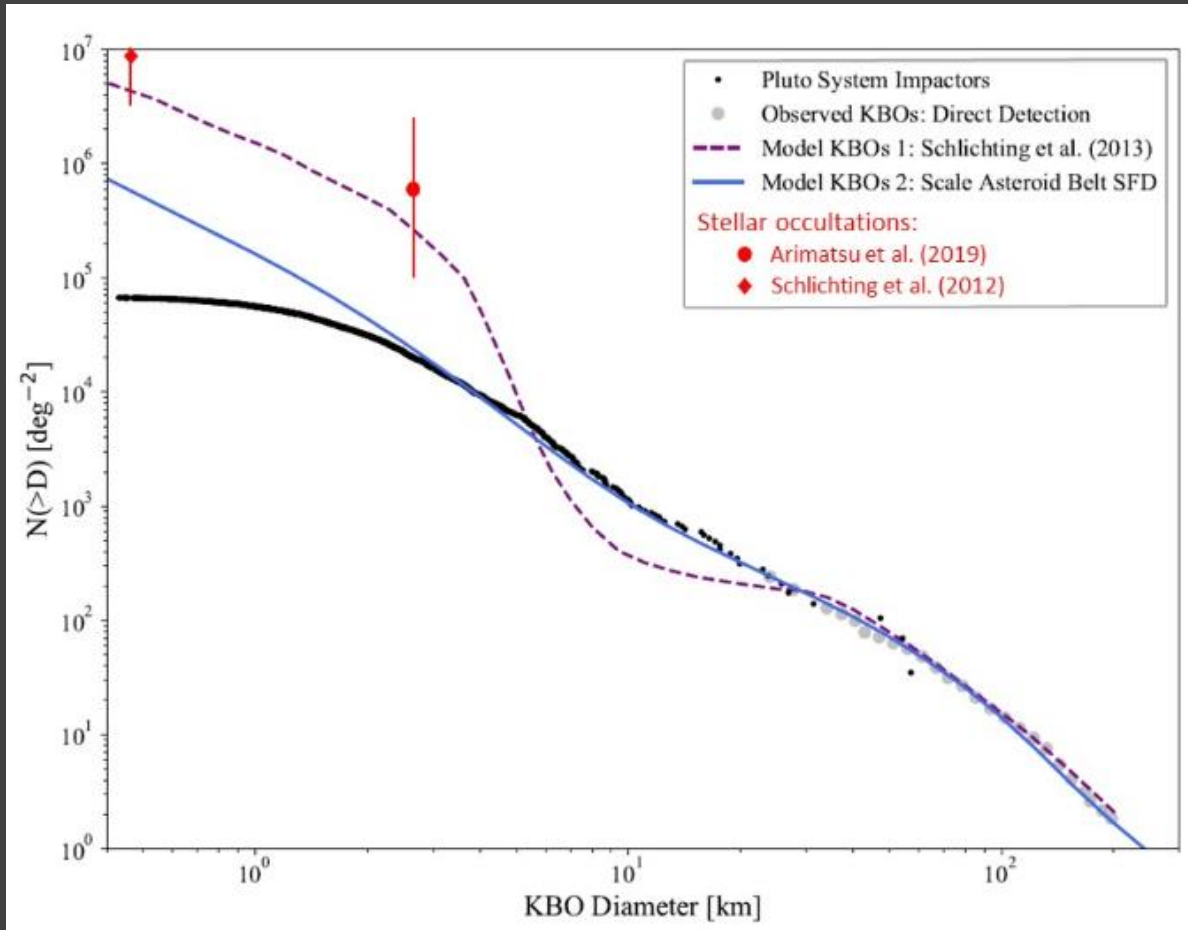


Small bodies

Evolution of orbits of small bodies
from the original paper Walsh et al. (2011).



Kuiper belt formation

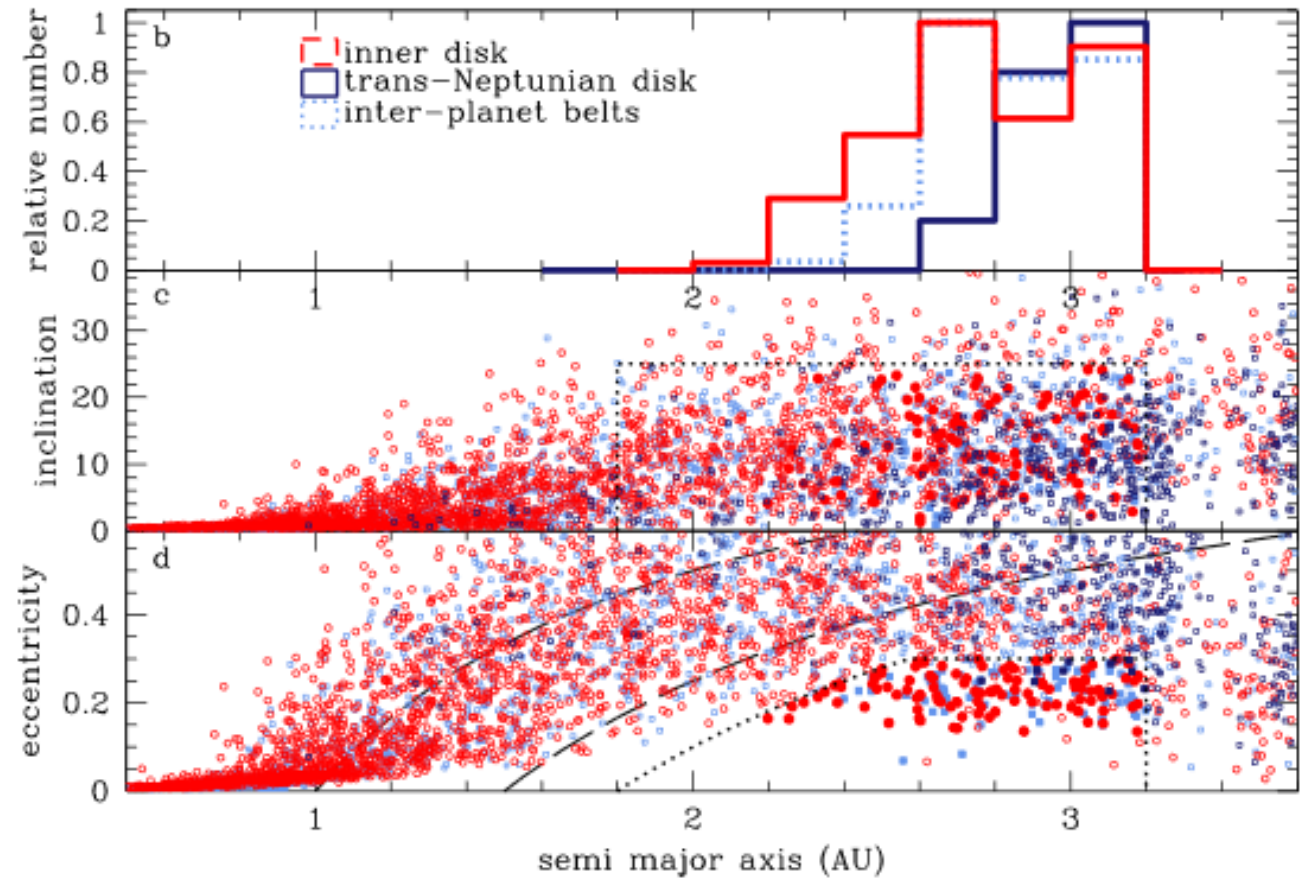
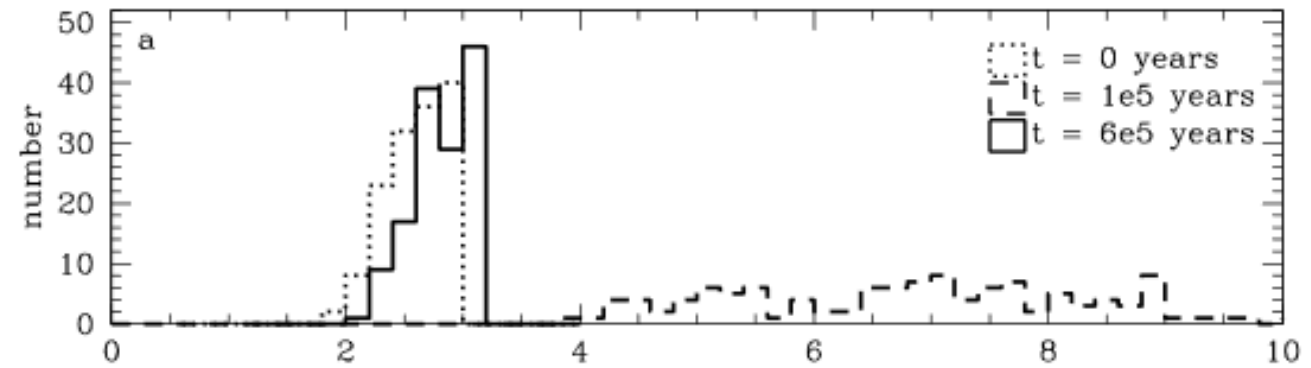
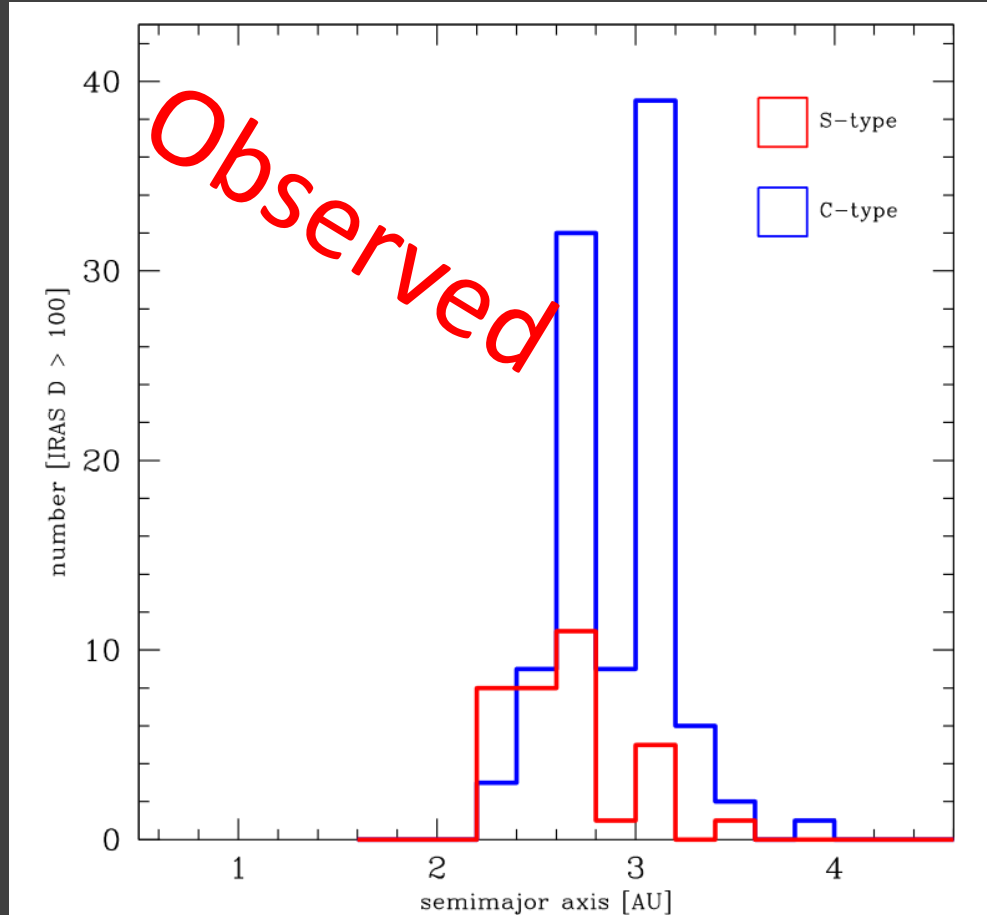


Initial mass of the disk was ~ 15 -20 Earth masses.

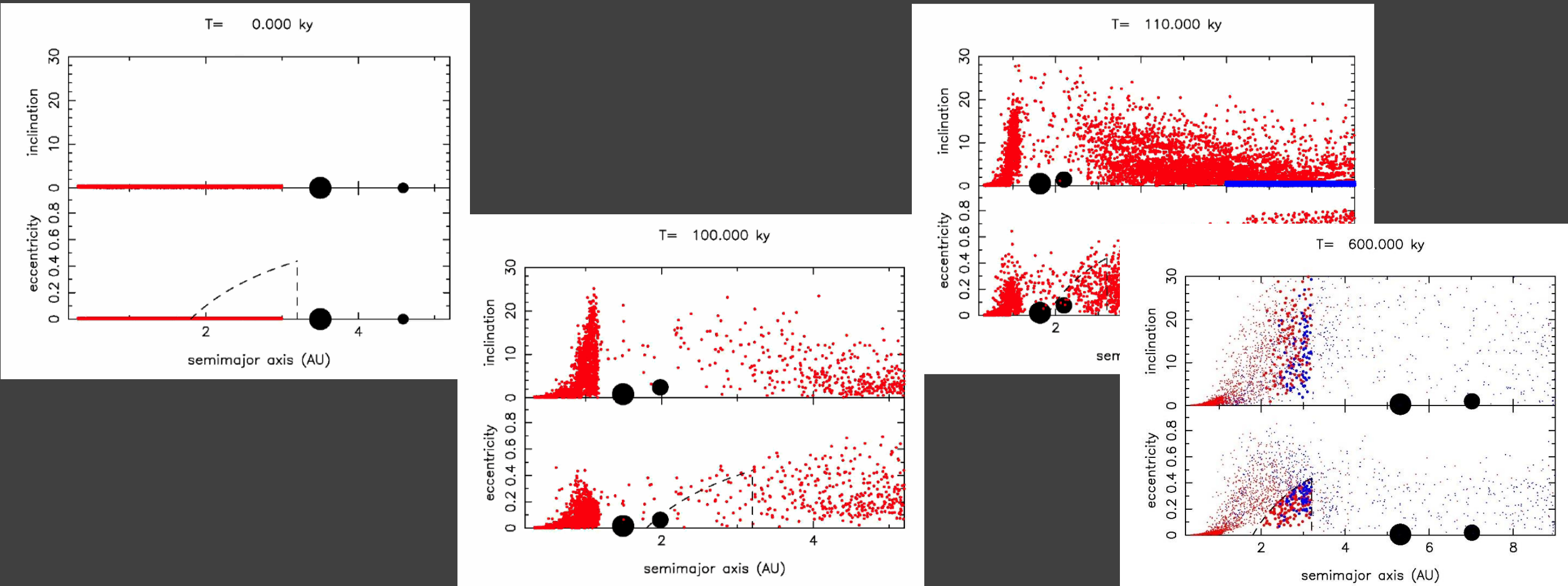
The disk contained $\sim 2 \times 10^{11}$ objects with $D > 2$ km and several thousands Pluto-mass objects.

About extrasolar Kuiper belts see [arXiv:1909.12312](https://arxiv.org/abs/1909.12312)

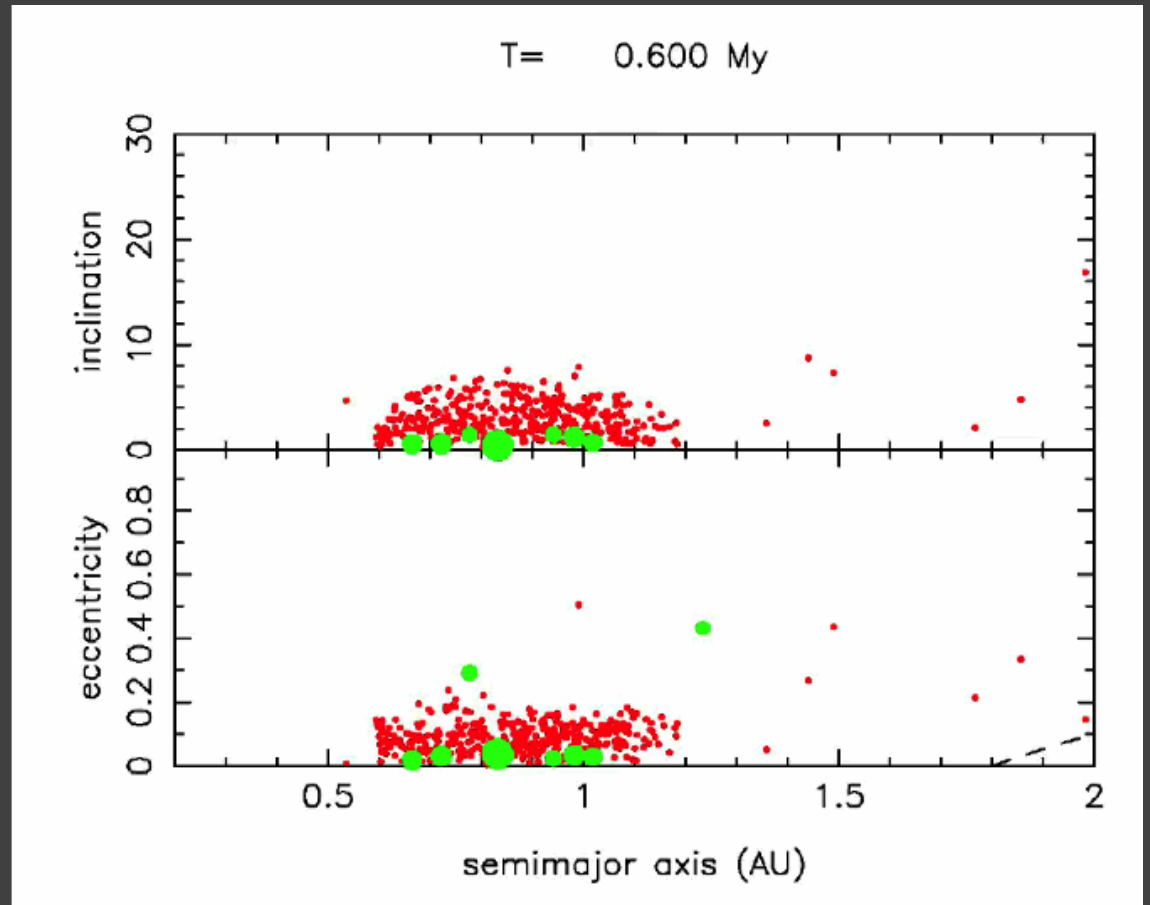
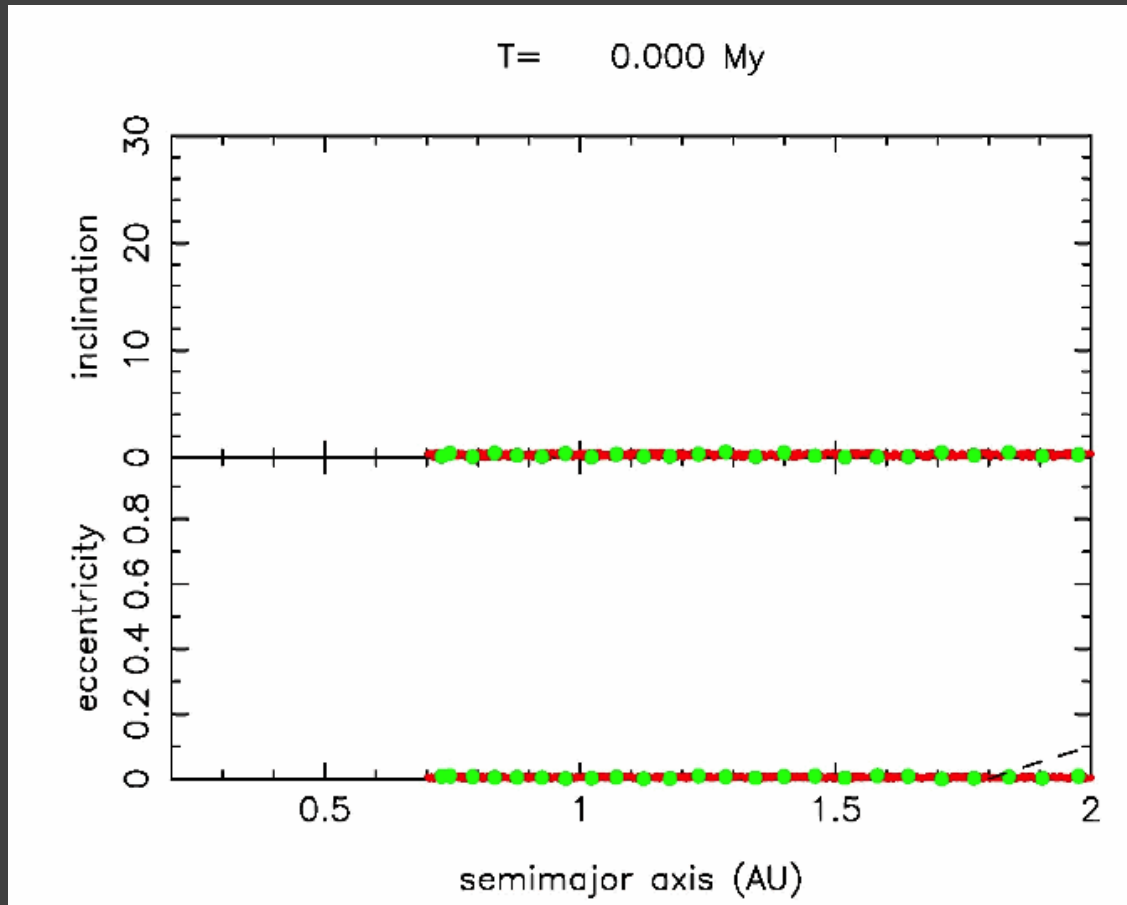
Asteroids



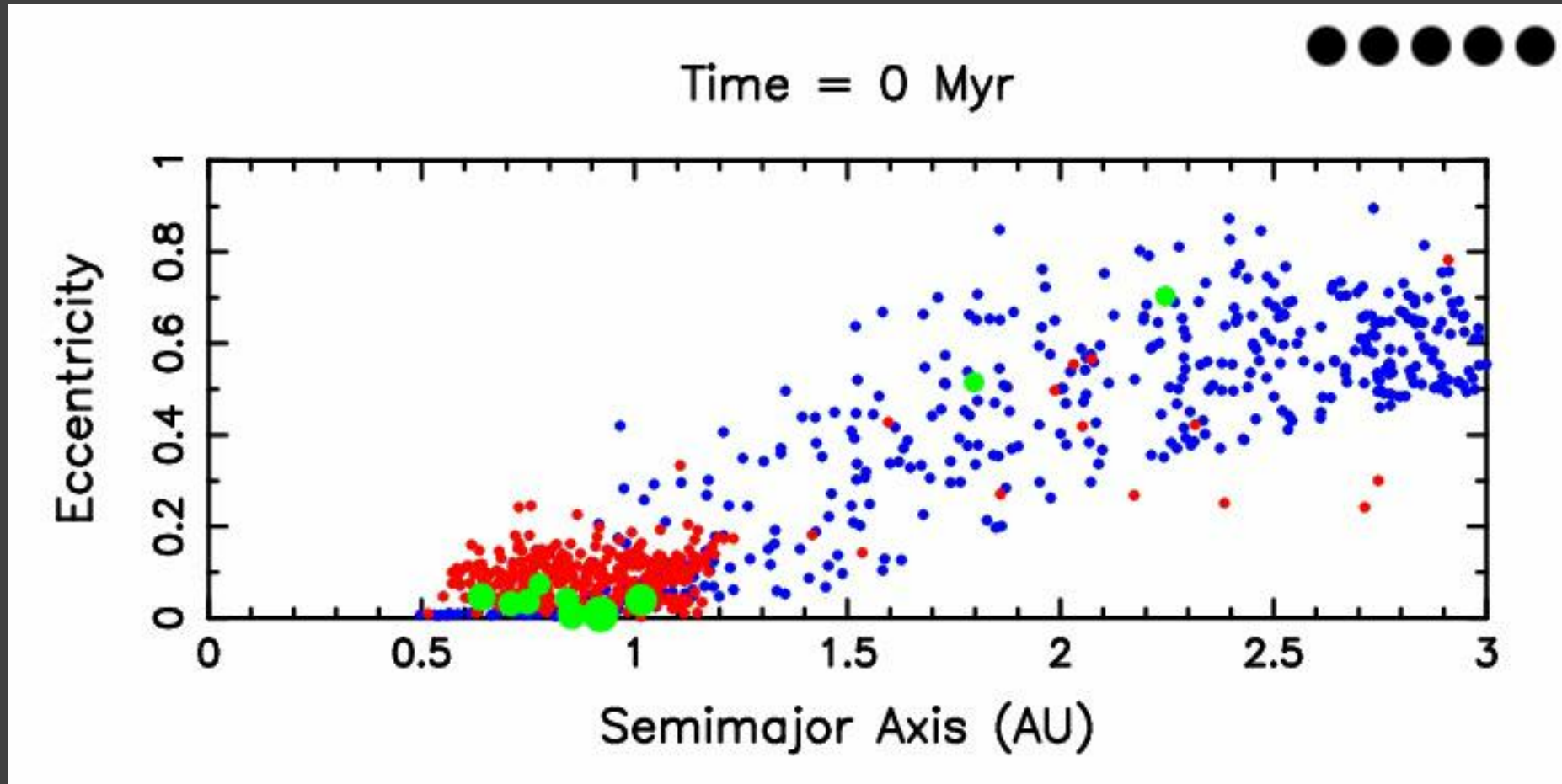
Sequence of events



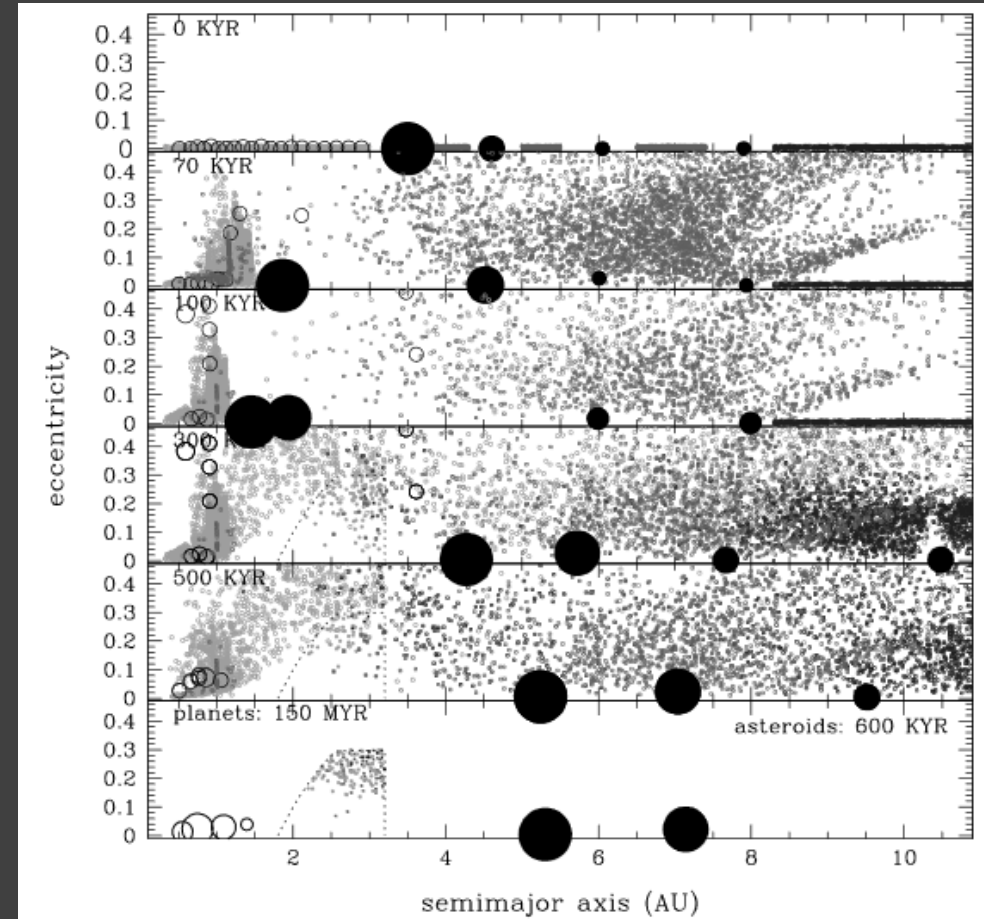
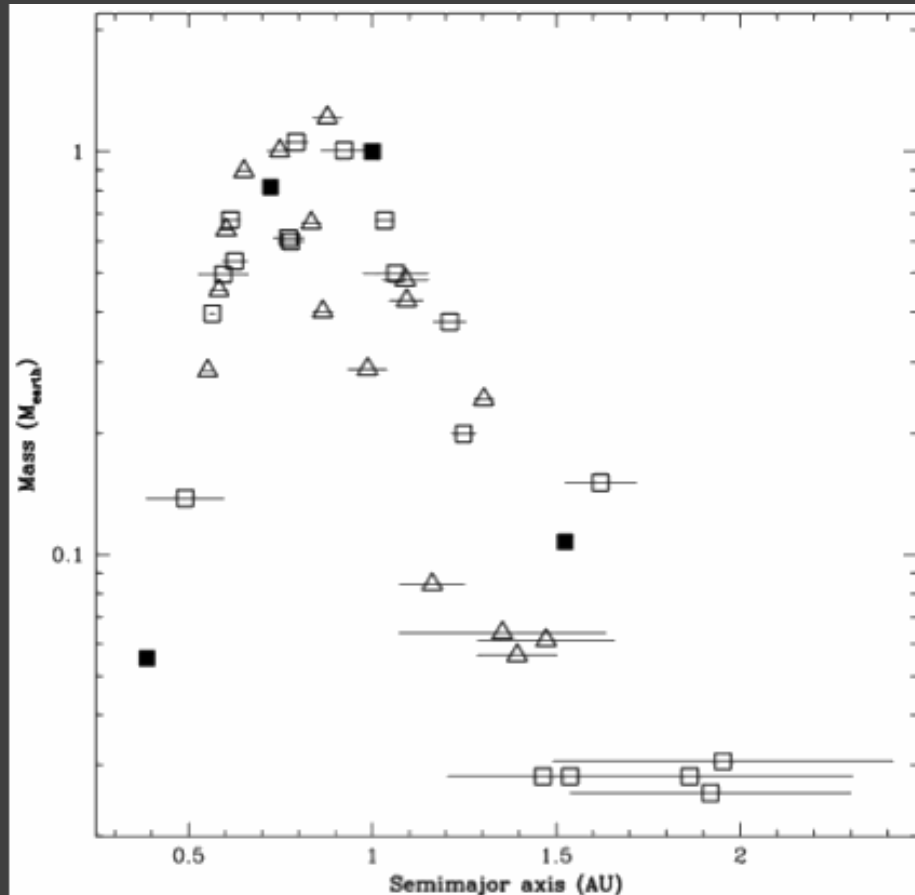
Disc of planetesimals: truncation



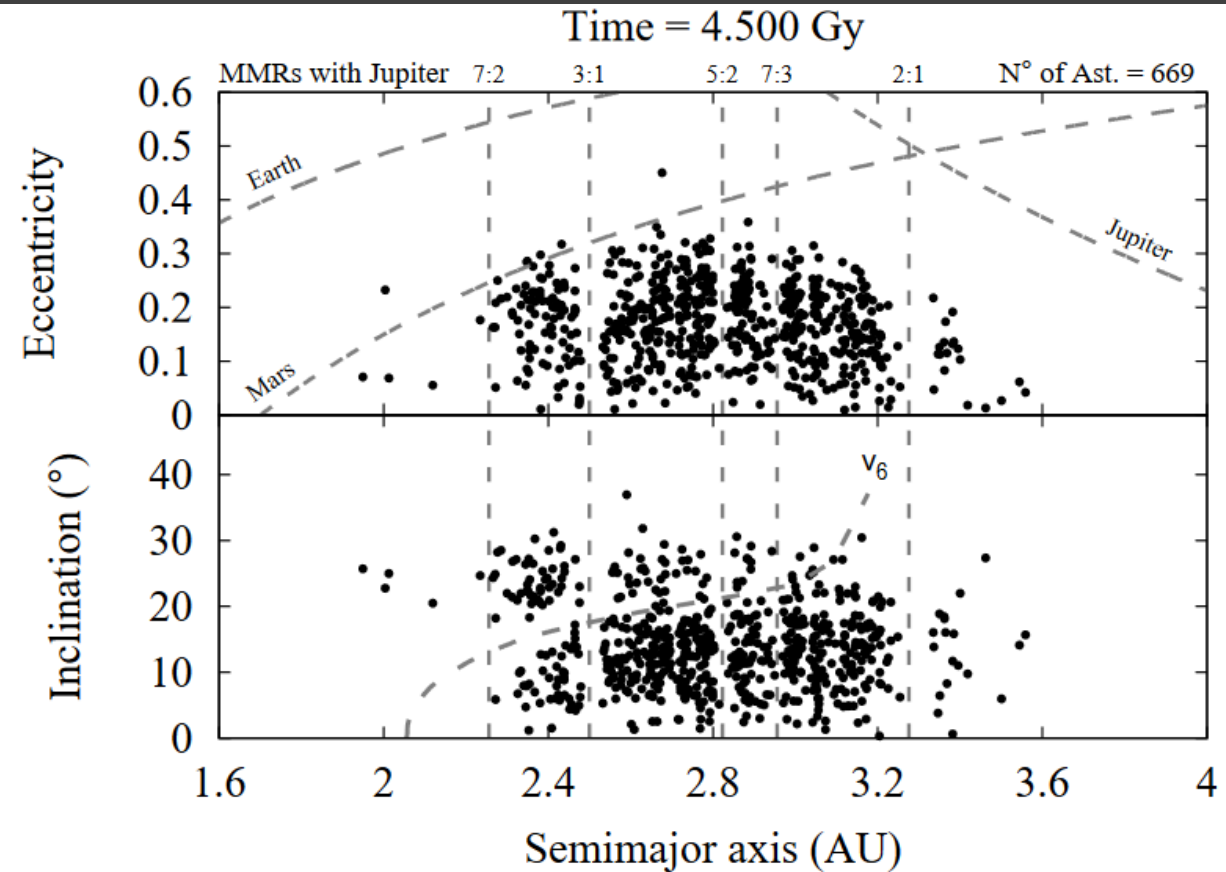
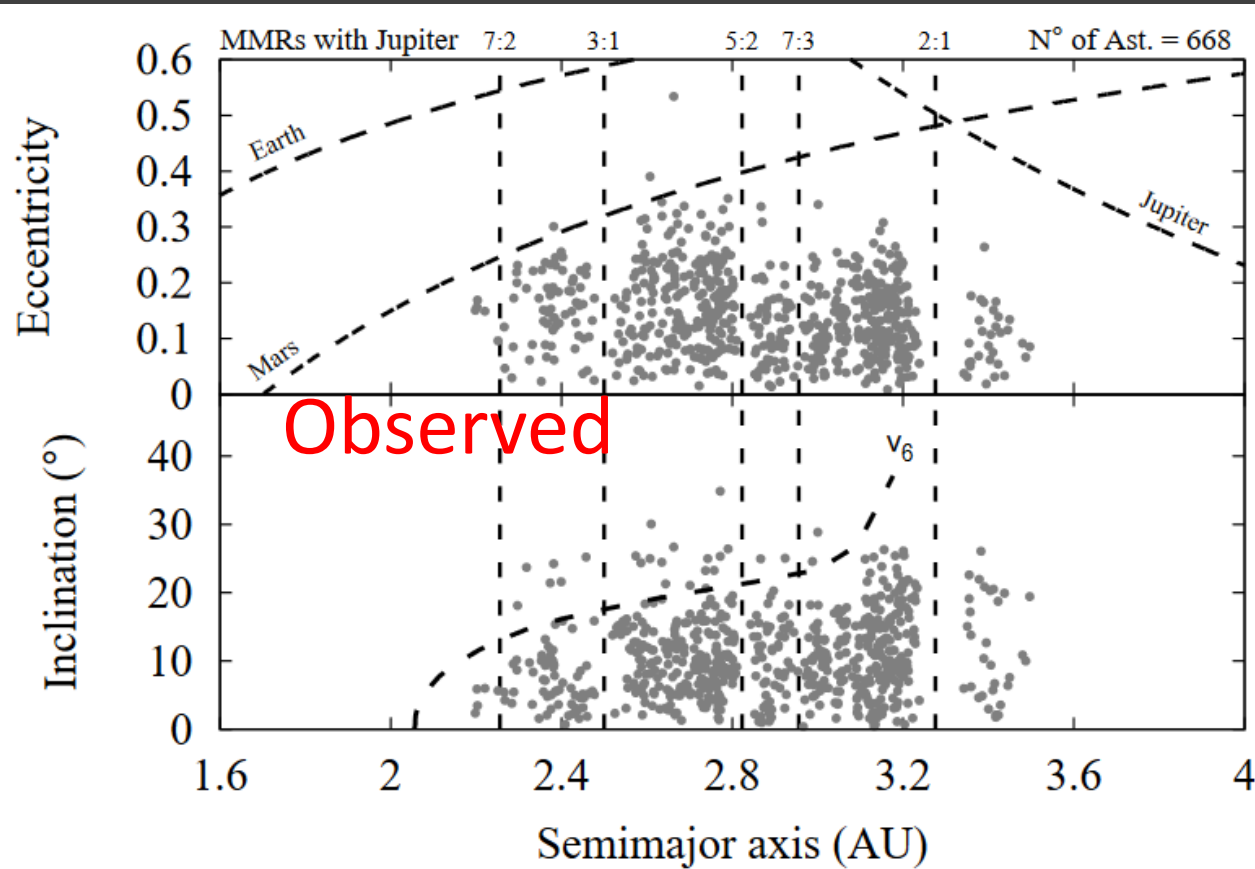
Water on Earth from C-type asteroids



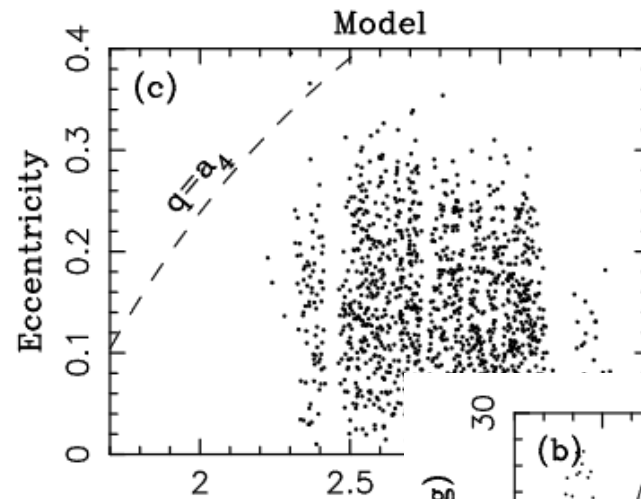
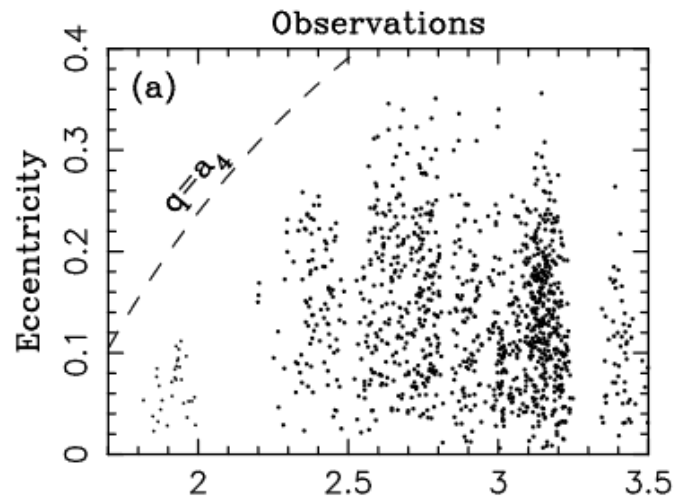
Mass distribution



Asteroids and Grand Tack: details

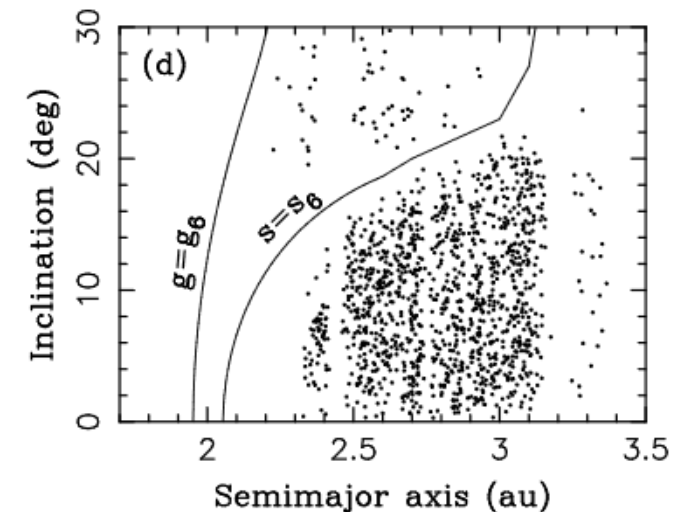
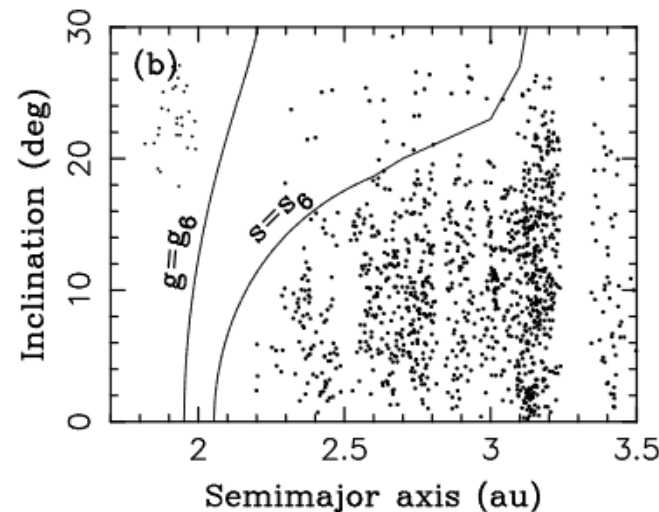


Asteroids in the jumping Jupiter model

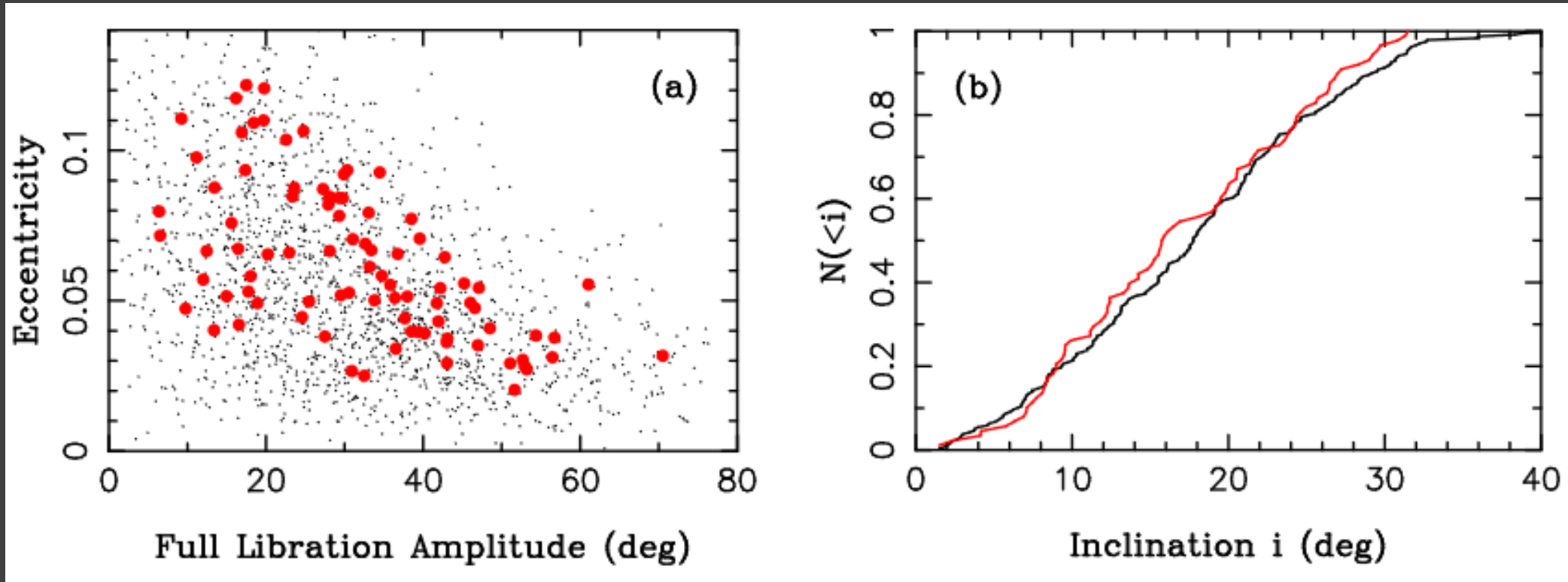


Solid line – secular resonances.
Dashed lines – Mars crossing.

The orbital distribution of main belt asteroids with diameters $D > 30$ km for $a > 2$ au and $D > 5$ km for $a < 2$ au in the case of Hungarians.

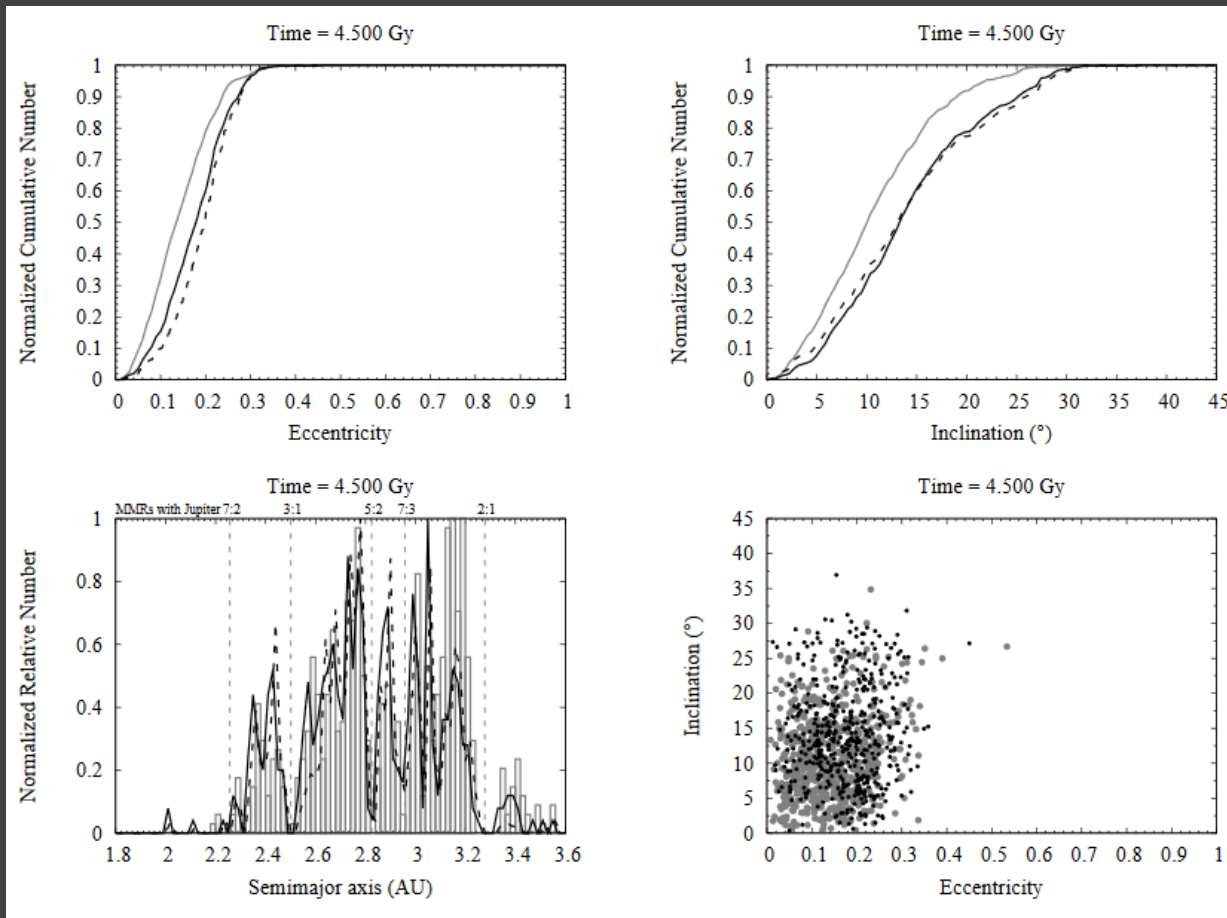


Trojans of Jupiter in the jumping model



Red symbols and line – modeling, black – observations.

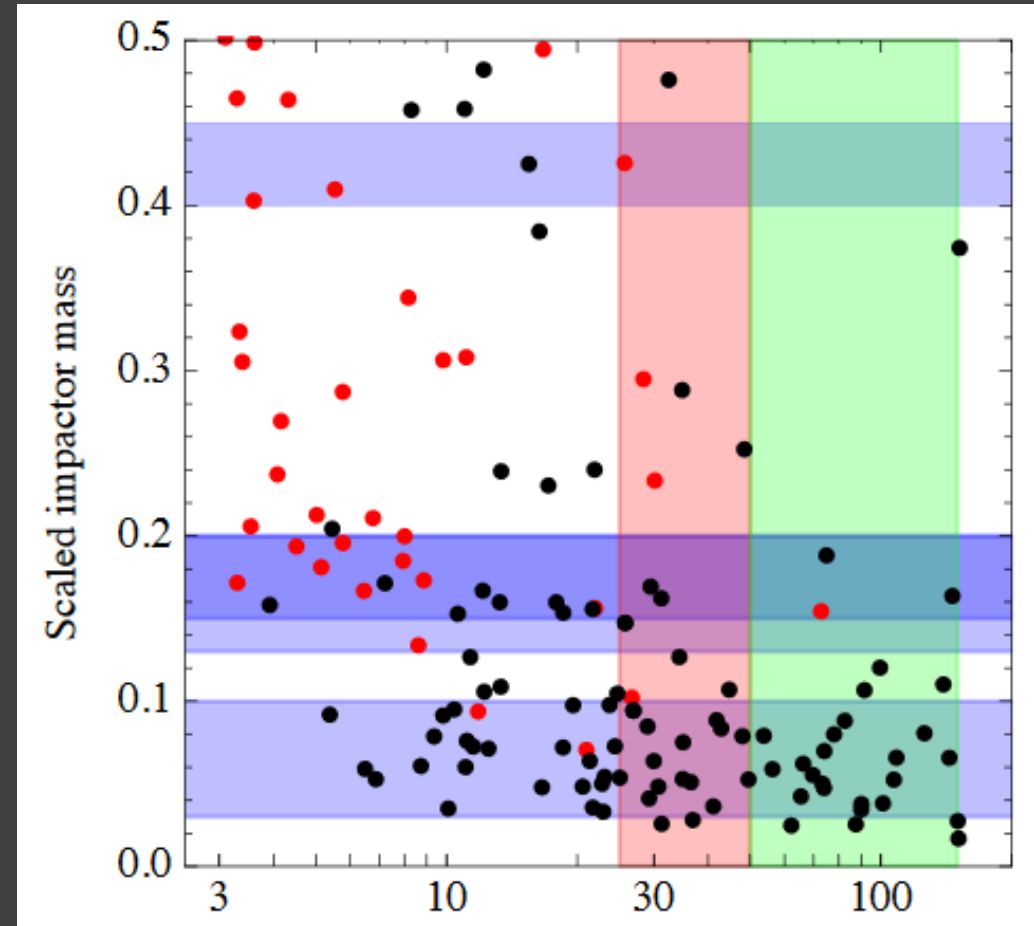
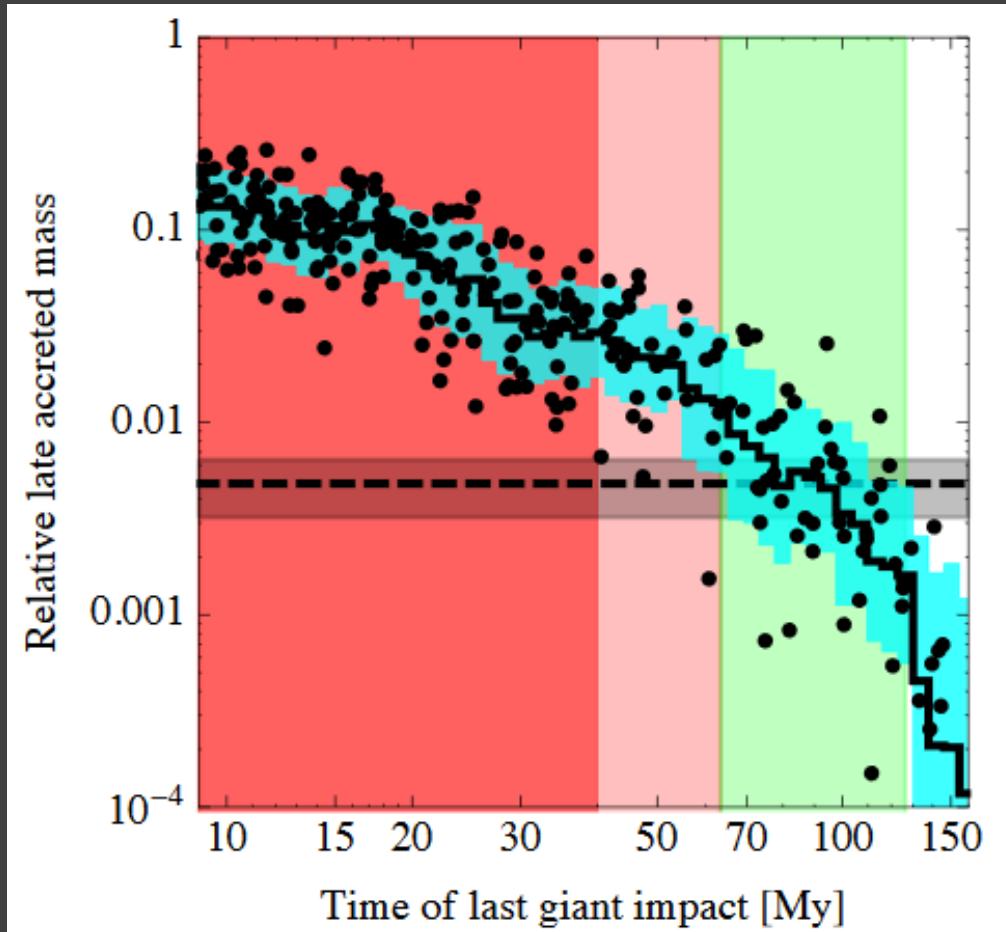
Detailed comparison (Grand Tack)



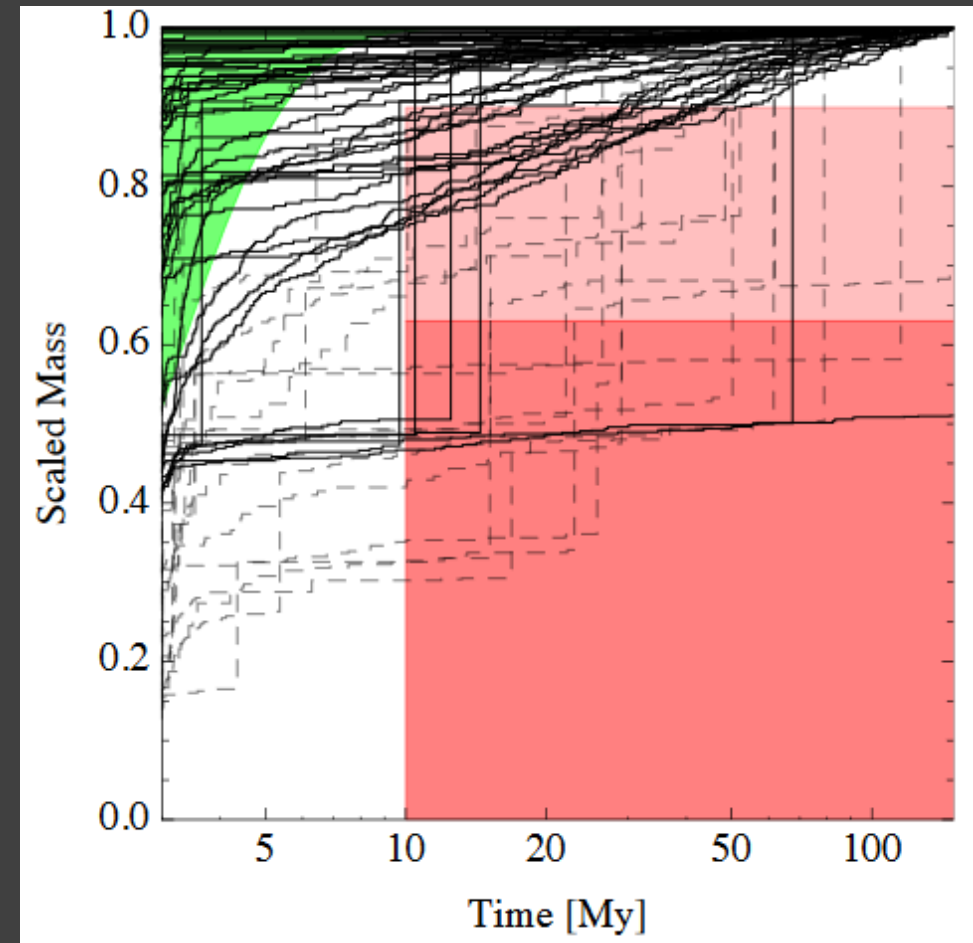
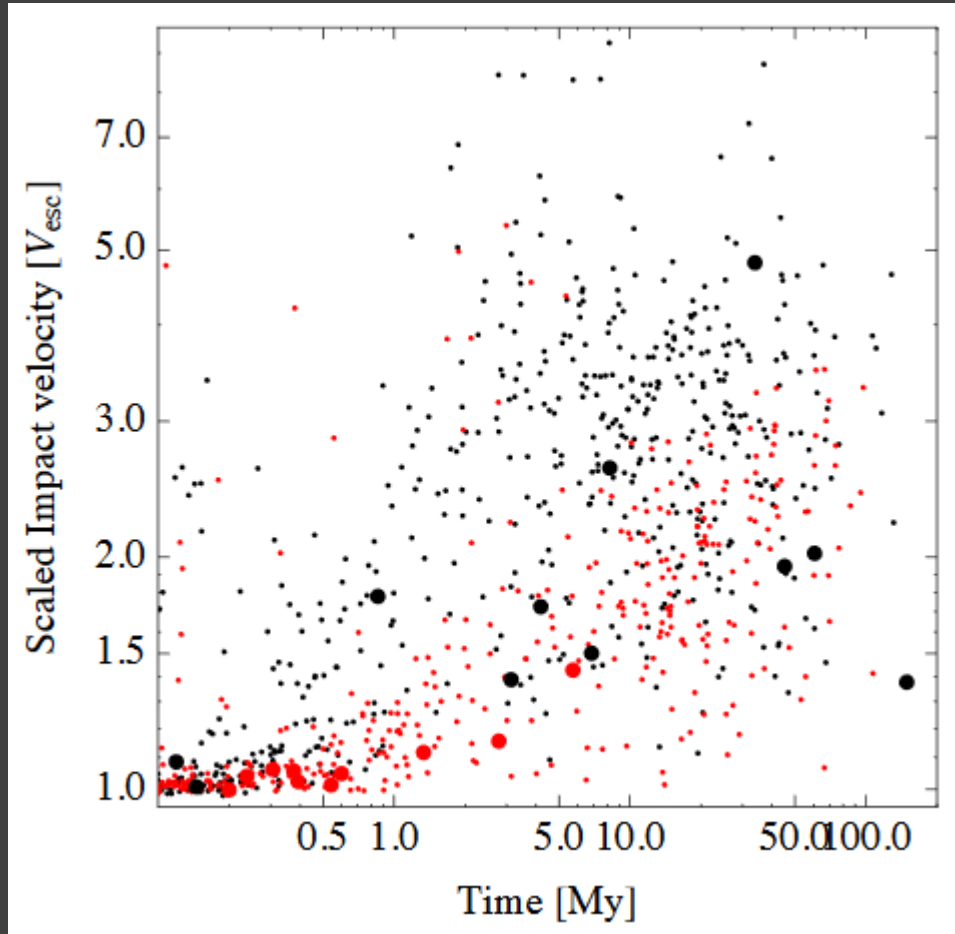
$$\sim 1.6 \times 10^{-3} M_{\oplus}$$

Slightly larger than the observed value,
but reasonable considering uncertainties.

Moon formation and Grand Tack

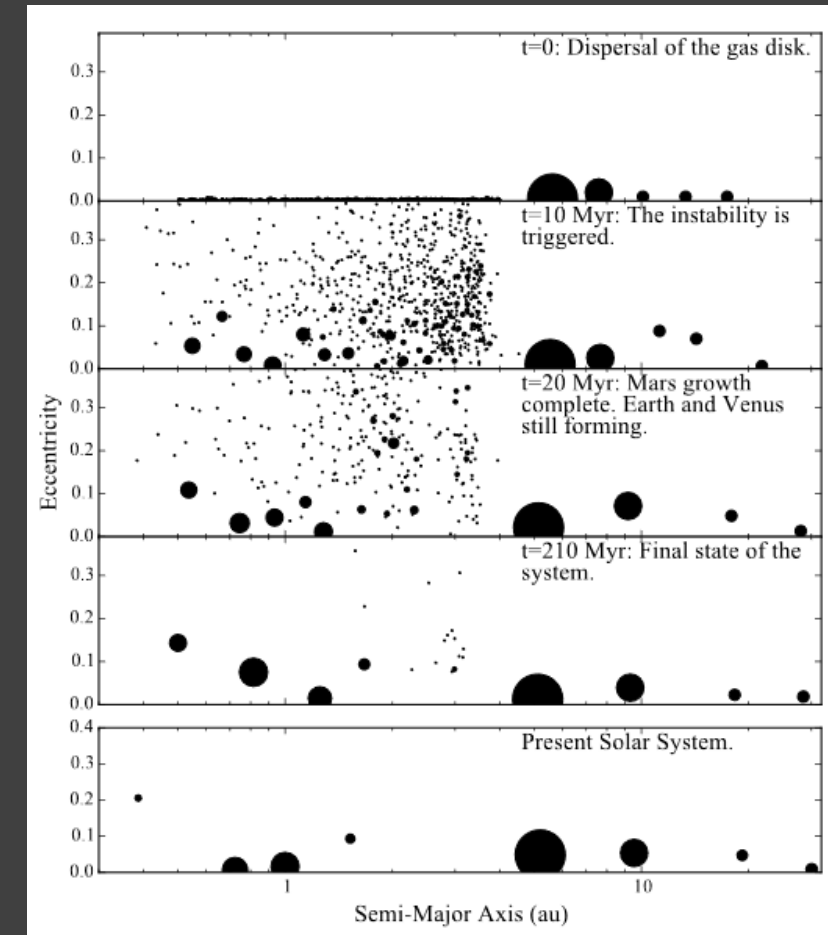
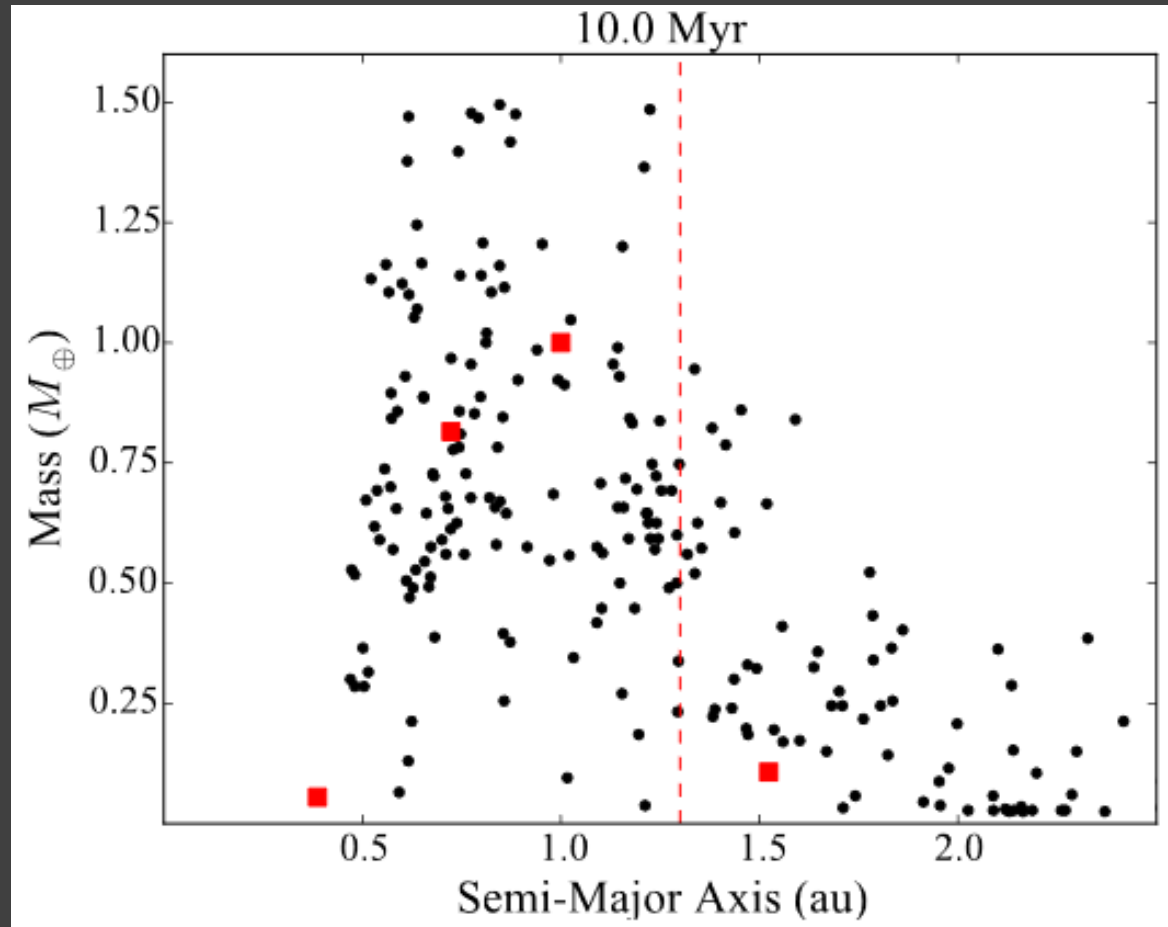


Mars and Venus in Grand Tack

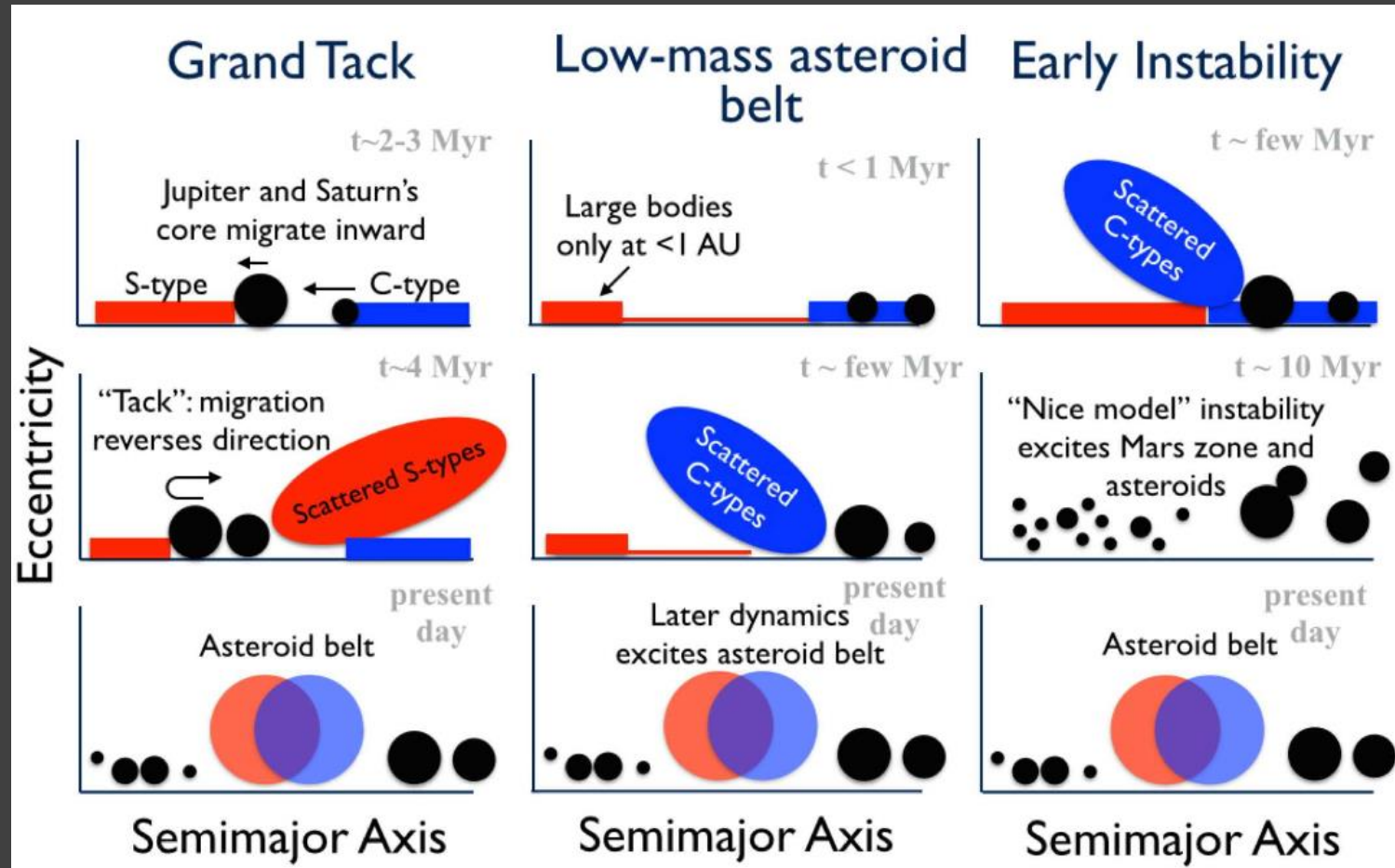


New calculations

Slightly different model,
but consistent with the
Grand Tack and Nice.



Model comparison



Literature

- Solar system formation 1501.03101 The formation of the solar system S. Pfalzner et al.
- Radioisotopes dating 1005.4147 The Early Solar System M. Busso
- MMSN 0903.5077 Minimum mass solar model Crida
- Nice model Nature 435, 459 (2005) Tsiganis, K. et al.
- Grand Tack 1409.6340 The Grand Tack model: a critical review
Sean N. Raymond, Alessandro Morbidelli
- 1406.2697 Lunar and Terrestrial Planet Formation in the Grand Tack Scenario
Seth A. Jacobson et al.
- Review of models 1812.01033 Solar system formation Raymond, Izidoro, Morbidelli
- Dynamical evolution 1807.06647 Dynamical evolution of the early Solar System
(review) D. Nesvorny