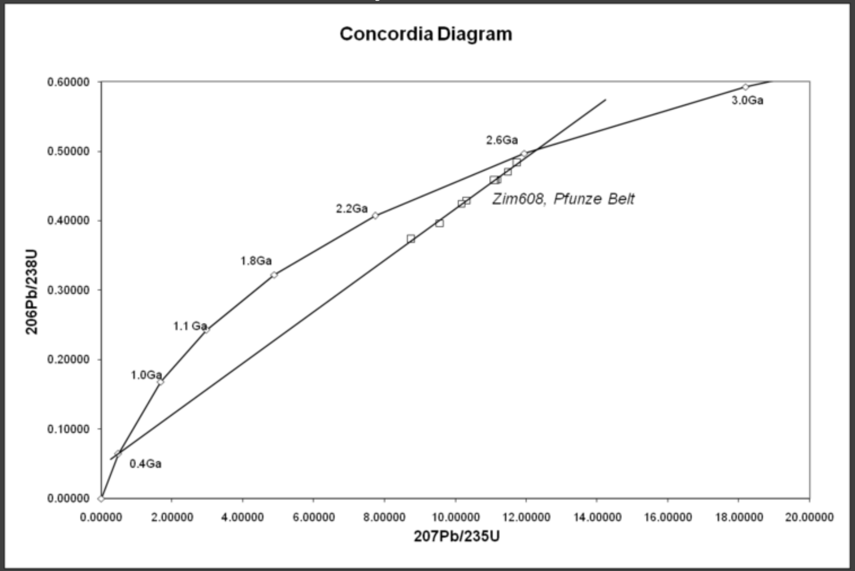
Solar system

SERGEI POPOV

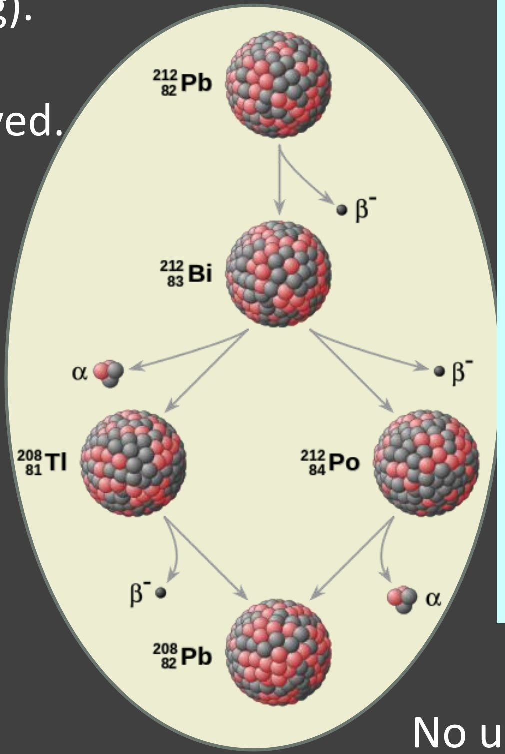
Solar system age

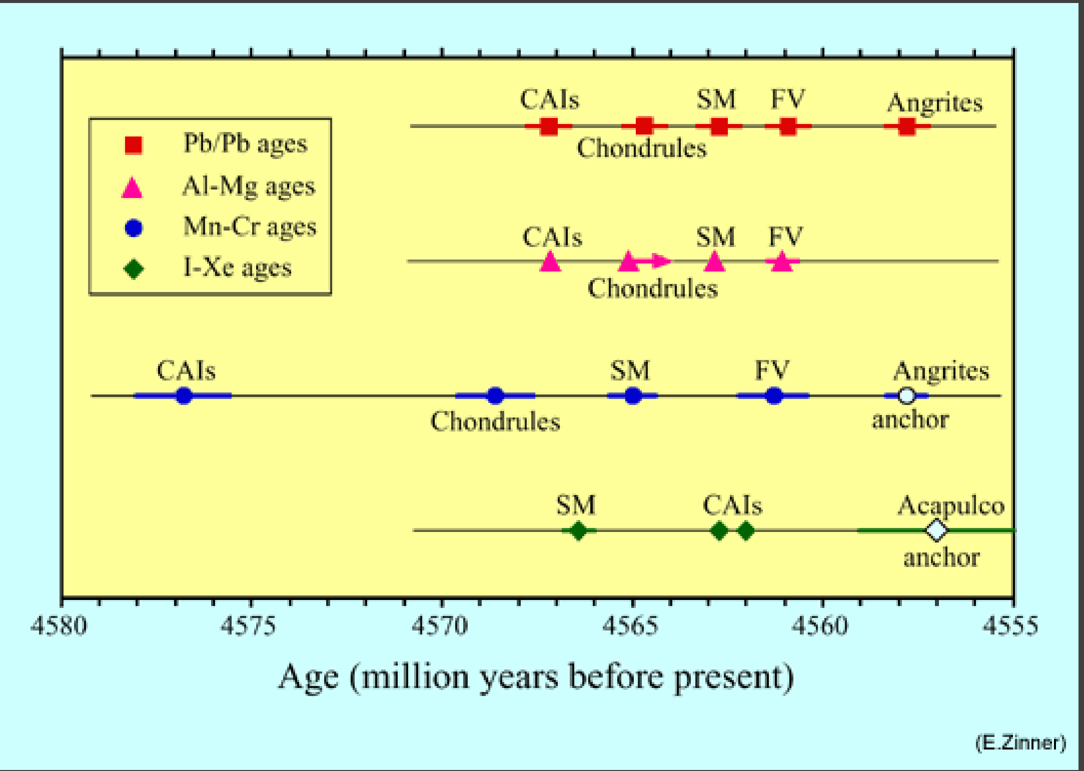
http://www.nhm.ac.uk

The age is determined due to meteorite studies.
Chondrites are made of non-processed matter.
^{26}Al half life-time 730 kyrs (-> ^{26}Mg).
CAI – Ca-Al Inclusions.
Al-Mg – short lived, U-Pb – long lived.
4.567 Gyrs



wikipedia.org





http://www.psrd.hawaii.edu/Sept02/Al26clock.html

No uranium in CAIs -> Pb-Pb.

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

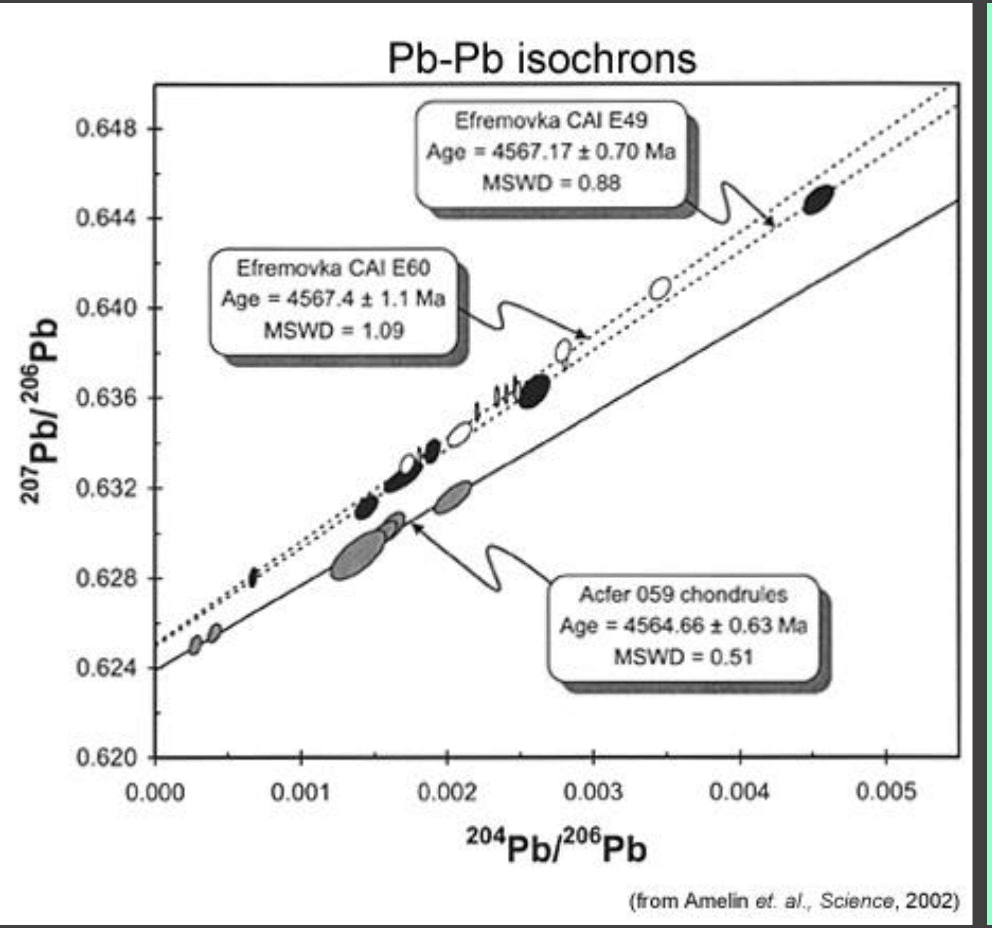
Short lived isotops

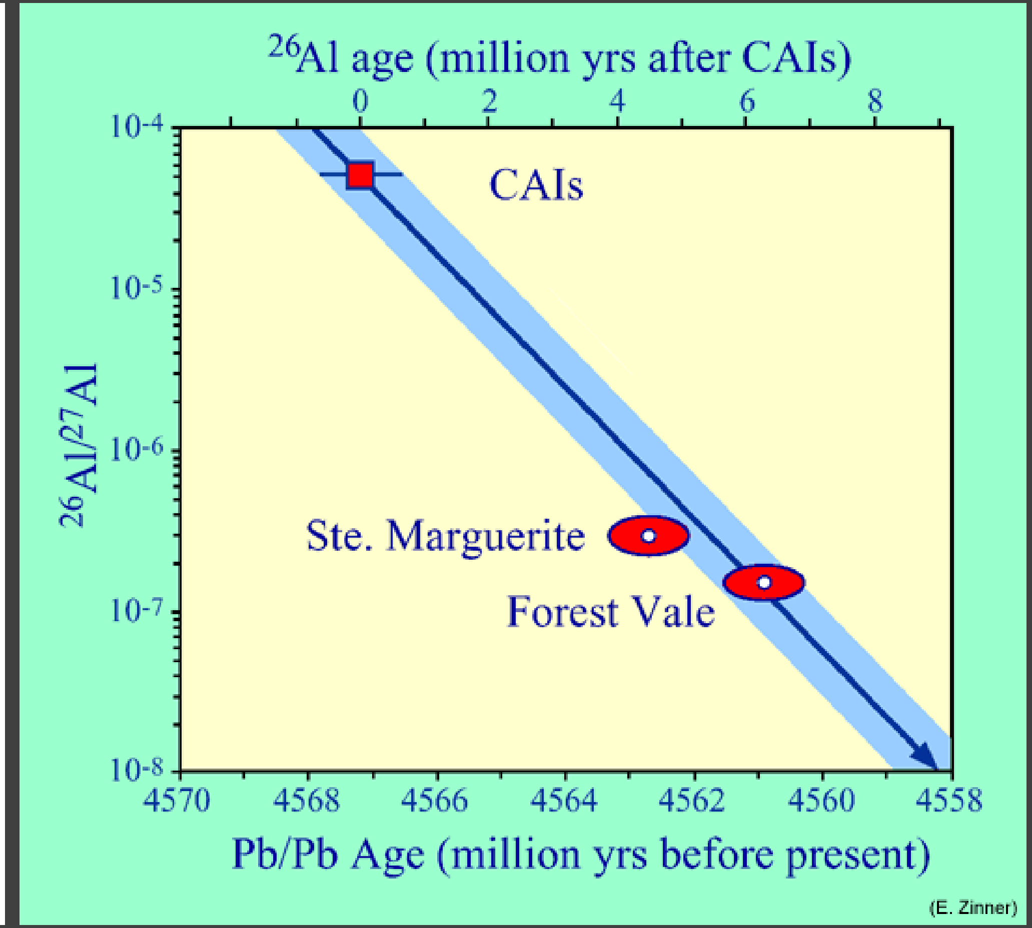
Nuclear Species	Daughter	Reference	Half-life (Myr)	Mass Fraction
^{7}Be	^{7}Li	^{9}Be	53 days	(8×10^{-13})
^{10}Be	^{10}B	^{9}Be	1.5	$(\sim 10^{-13})$
^{26}Al	^{26}Mg	^{27}Al	0.72	3.8×10^{-9}
^{36}Cl	^{36}Ar	^{35}Cl	0.30	8.8×10^{-10}
^{41}Ca	^{41}K	^{40}Ca	0.10	1.1×10^{-12}
^{53}Mn	^{53}Cr	^{55}Mn	3.7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

1001.5444

Two approaches complete each other

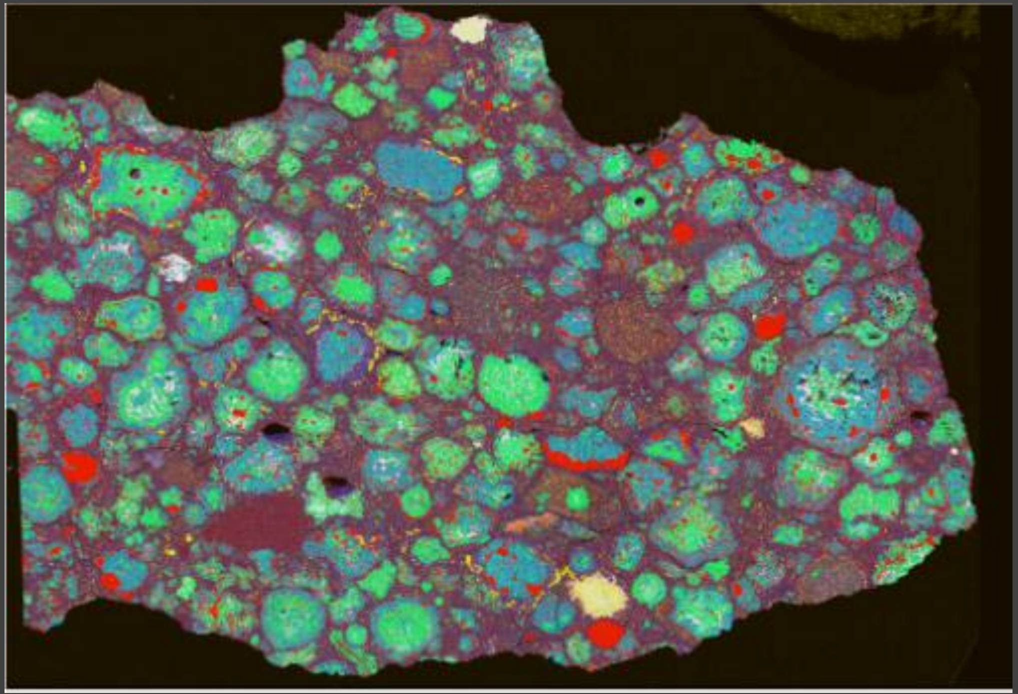
http://www.psrd.hawaii.edu/Sept02/isotopicAges.html





http://www.psrd.hawaii.edu/Sept02/Al26clock.html

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

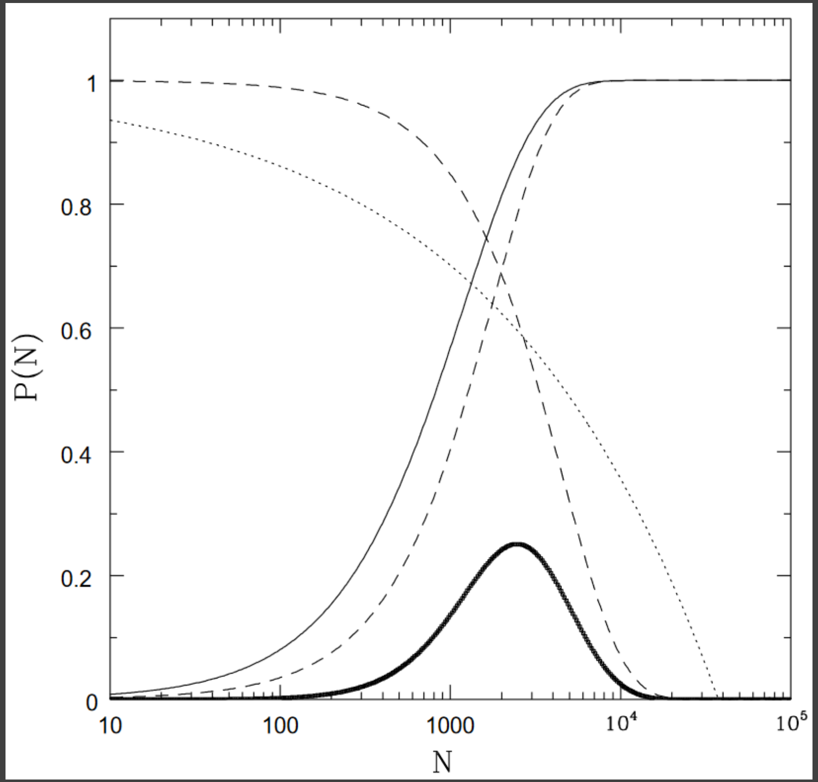


aluminum (white), magnesium (green), silicion (blue), calcium (yellow), iron (red)

1501.03101

Near-by supernova or an AGB/WR star.

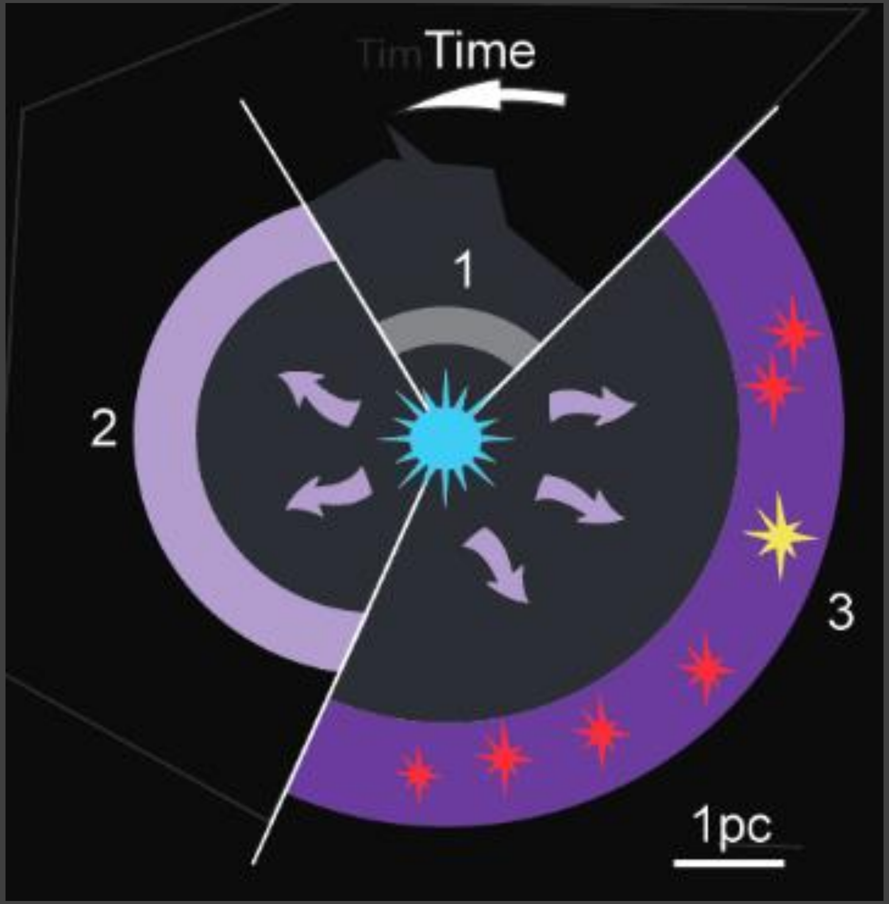
Cluster cannot be too rich, otherwise EUV and FUV emission of massive stars can significantly influence protoplanetary disc within 30 AU due to photoevaporation.



Number of stars in the Sun cluster

1001.5444

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.

1501.03101

Constraints on the solar cluster

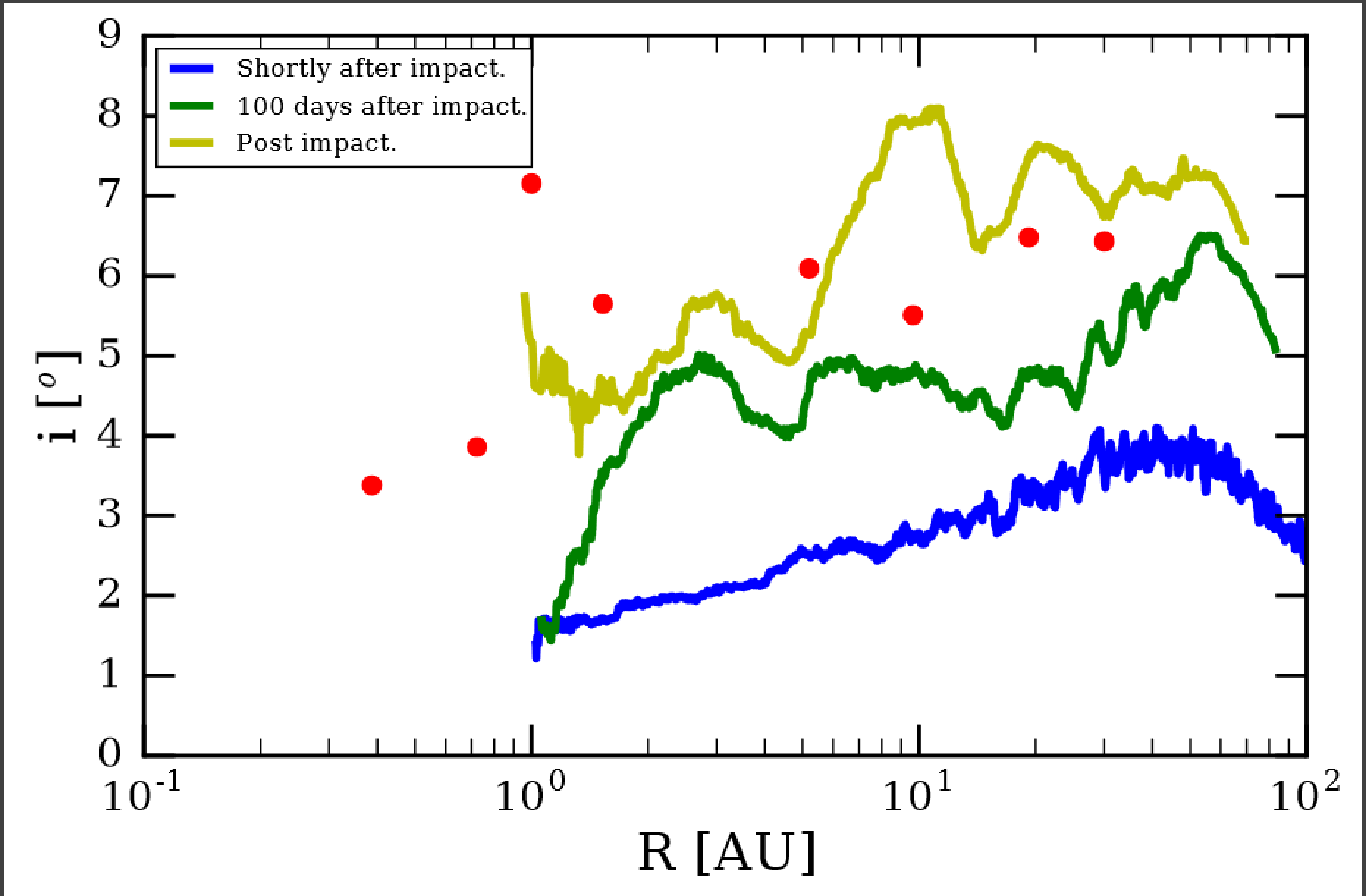
Solar System Property	Implication	Fraction
Mass of Sun	$M_* \geq 1 M_\odot$	0.12
Solar Metallicity	$Z \geq Z_\odot$	0.25
Single Star	(not binary)	0.30
Giant Planets	(successfully formed)	0.20
Ordered Planetary Orbits	$N \leq 10^4$	0.67
Supernova Enrichment	$N \geq 10^3$	0.50
Sedna-Producing Encounter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

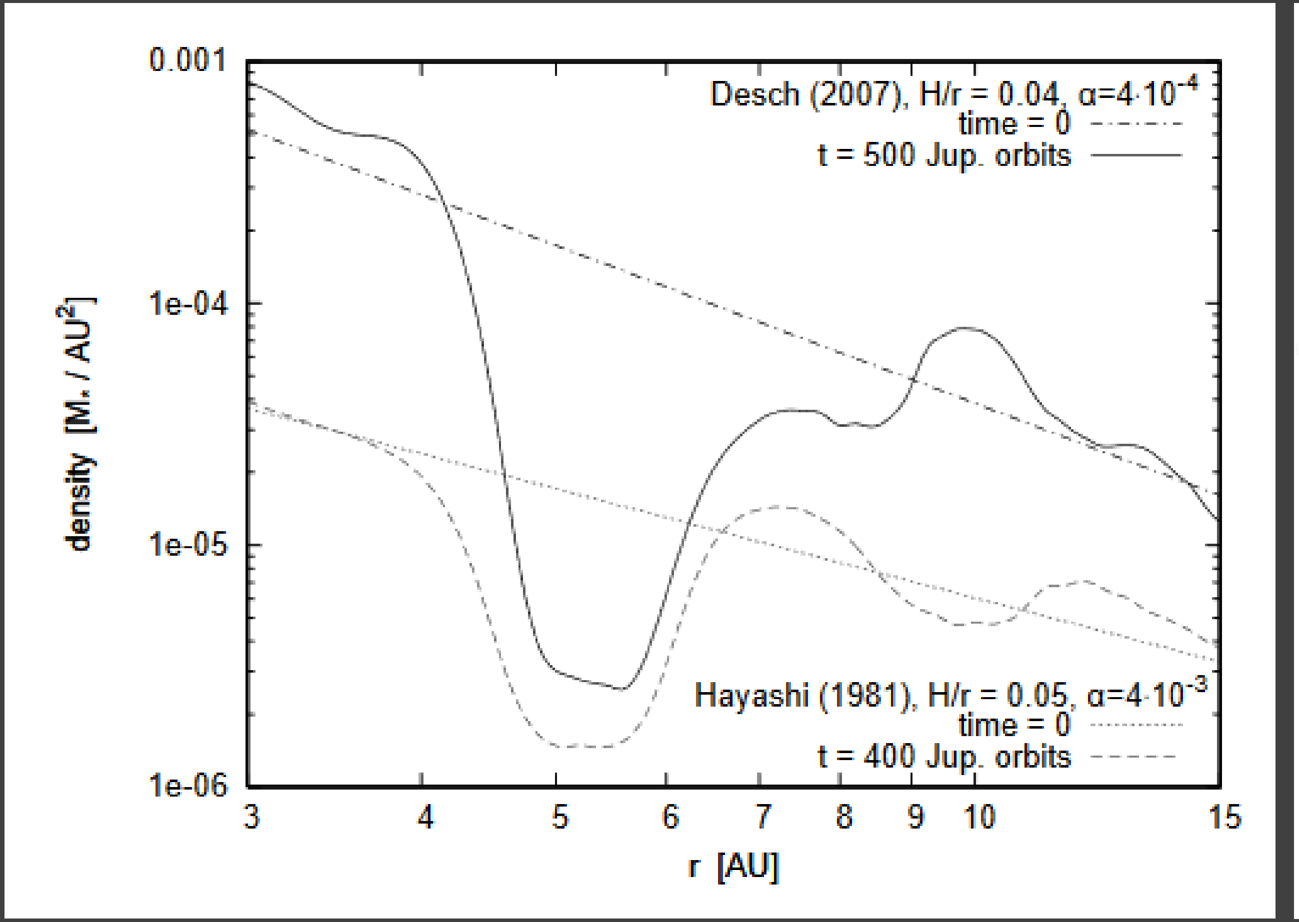
Distance 0.15-0.4 pc

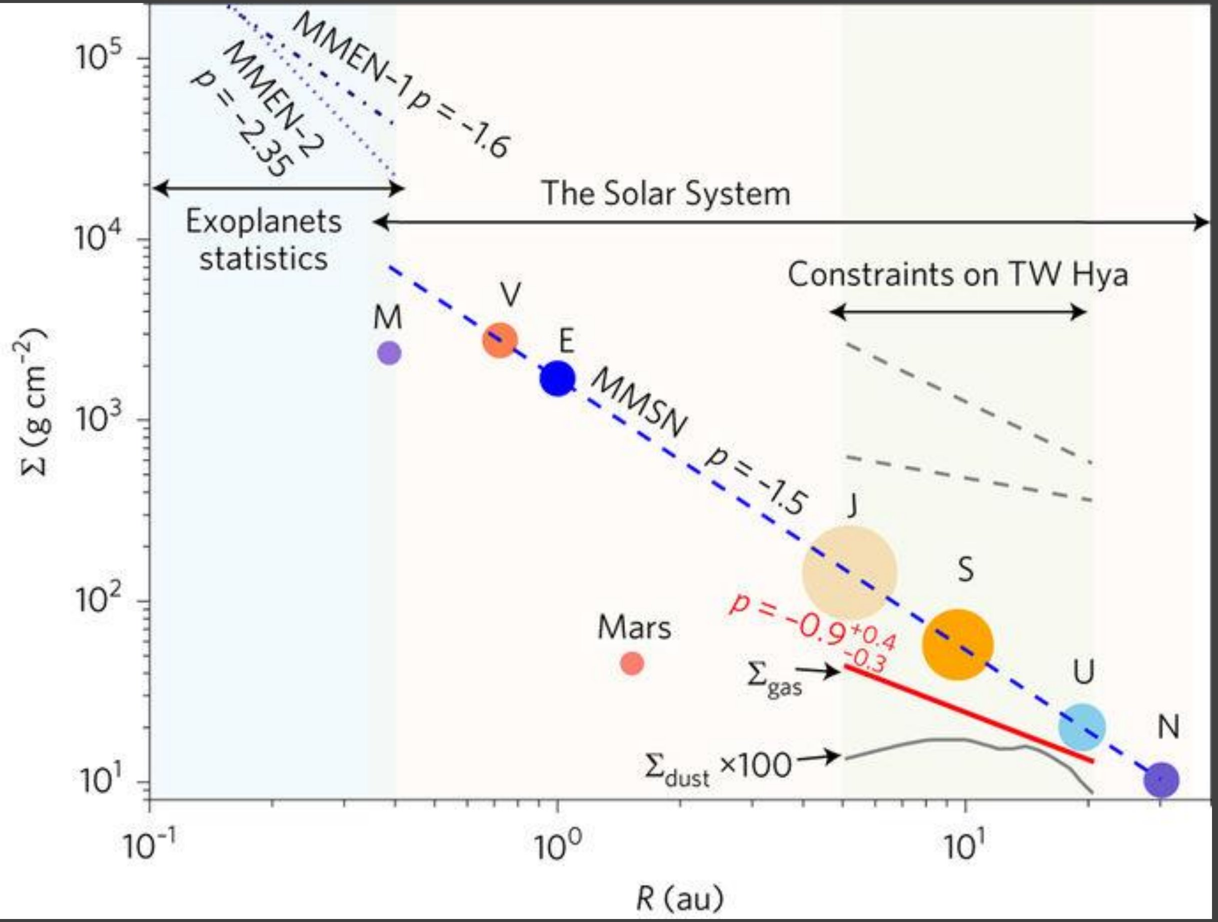
- heating (dust melting)
- enrichment
- blast wave
  - stripping
  - tilting

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





Different variants of the MMSN

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

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

Hayashi 1981
Normalized by the estimate
of Jupiter formation 1.55<r<7 AU
(mass of solids = 15 Earth masses)

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

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

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

Desch 2007
Planets at initial positions
in the NICE model

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

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

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

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

INITIAL SOLAR SYSTEM CONDITIONS

Planet	M_{aug} [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

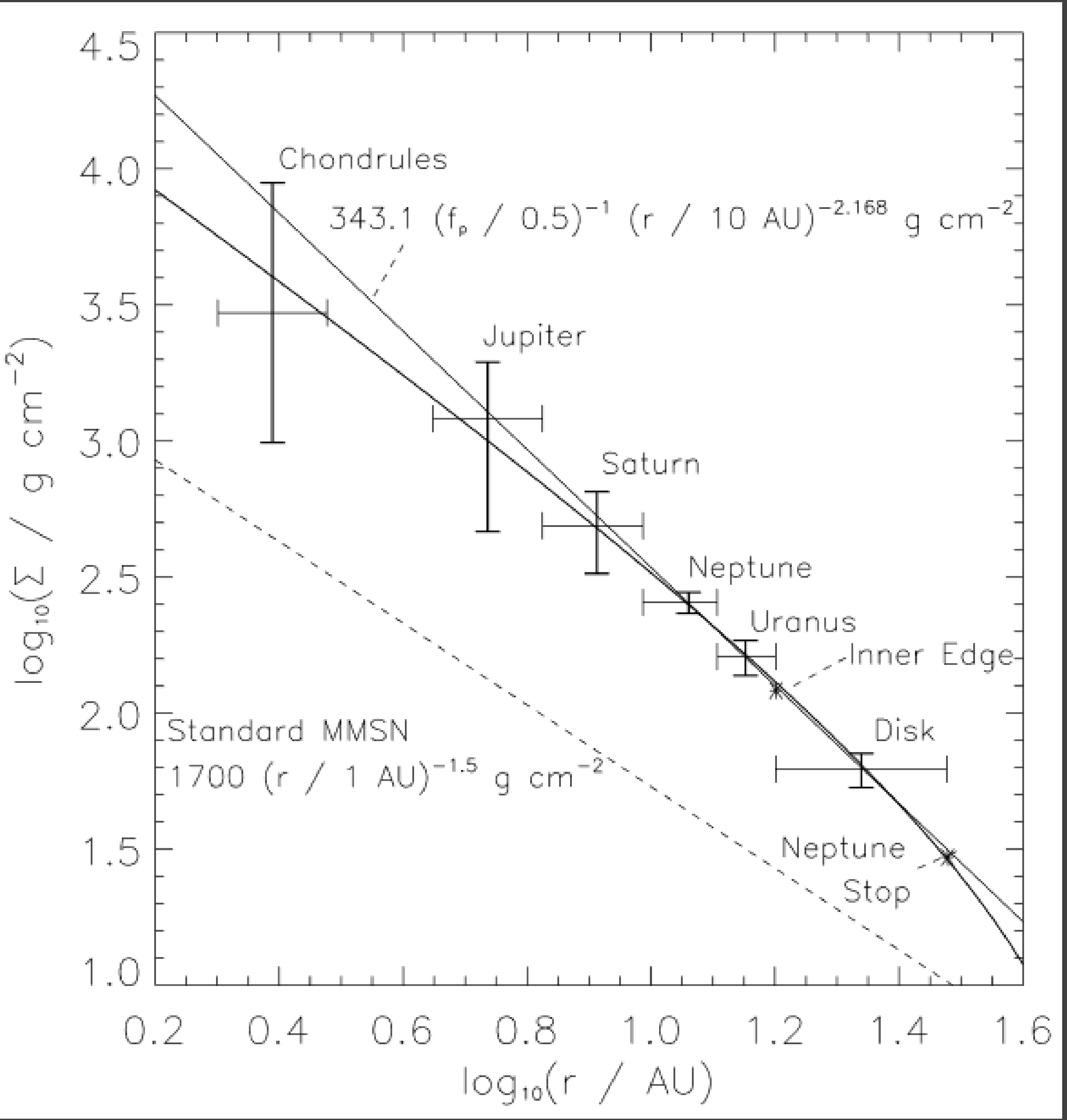
Initial positions: Jupiter – 5.45 AU; Saturn – 8.18 AU; Neptune – 11.5 AU; Uranus – 14.2 AU
Uranus and Neptune change places during migration!

Surface density

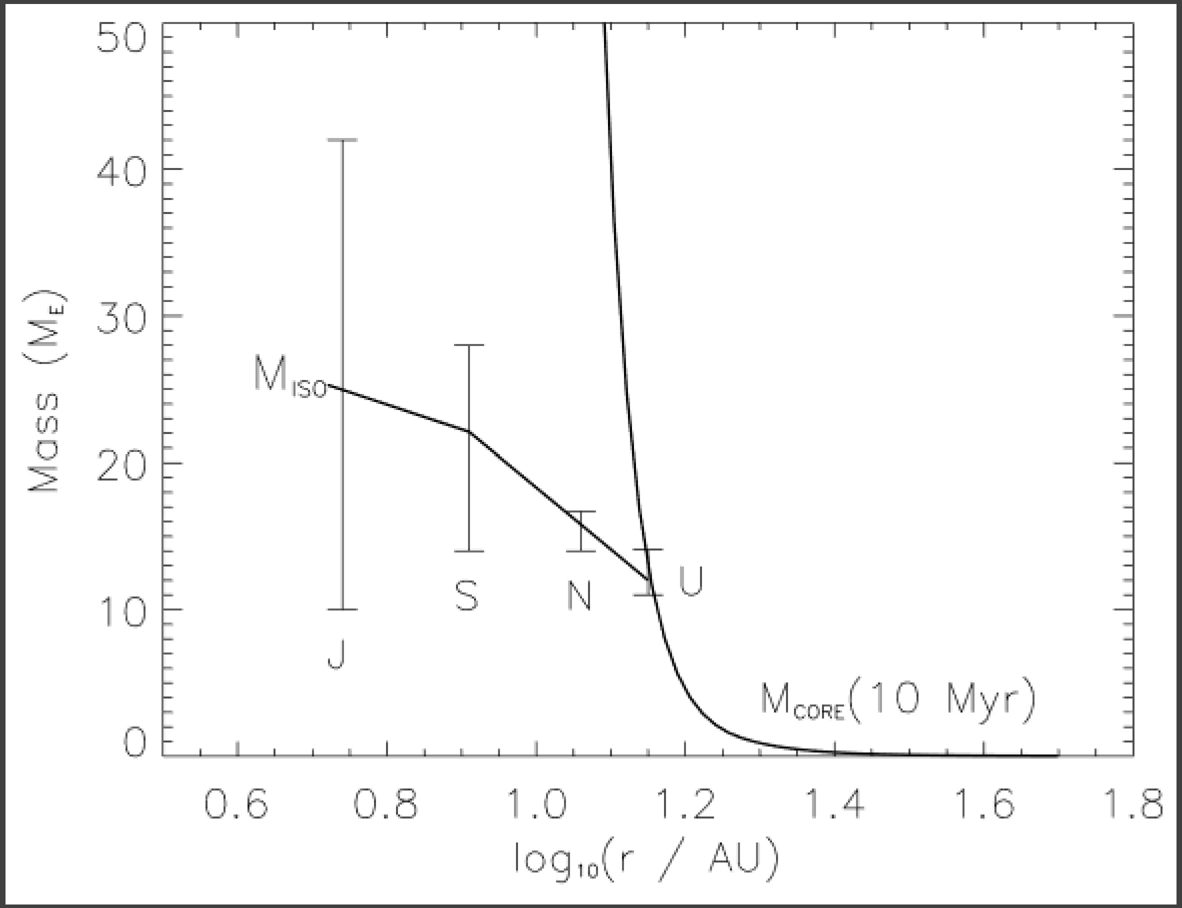
$$\Sigma(r) = 343\left(\frac{f_p}{0.5}\right)^{-1}\left(\frac{r}{10\ \mathrm{AU}}\right)^{-2.168}\ \mathrm{g\ cm^{-2}}$$

$$\rho_{\mathrm{gas}}(r,0) = 1.93\times10^{-11}\left(\frac{f_p}{0.5}\right)^{-1}\left(\frac{r}{10\ \mathrm{AU}}\right)^{-3.4537}\ \mathrm{g\ cm^{-3}}$$

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

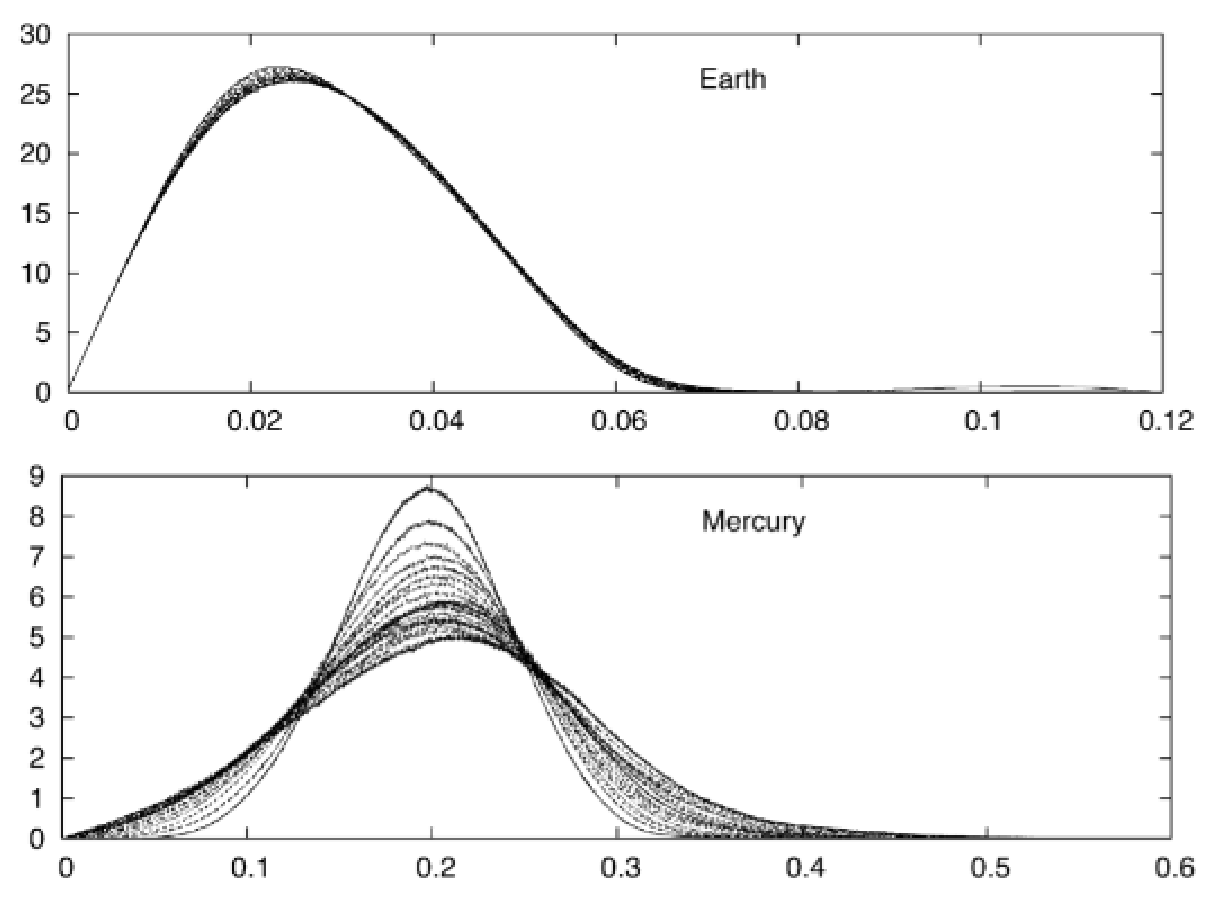


Vertical lines – total amount of solids in each planet.

Planets collect almost all available solids in their feeding zones.

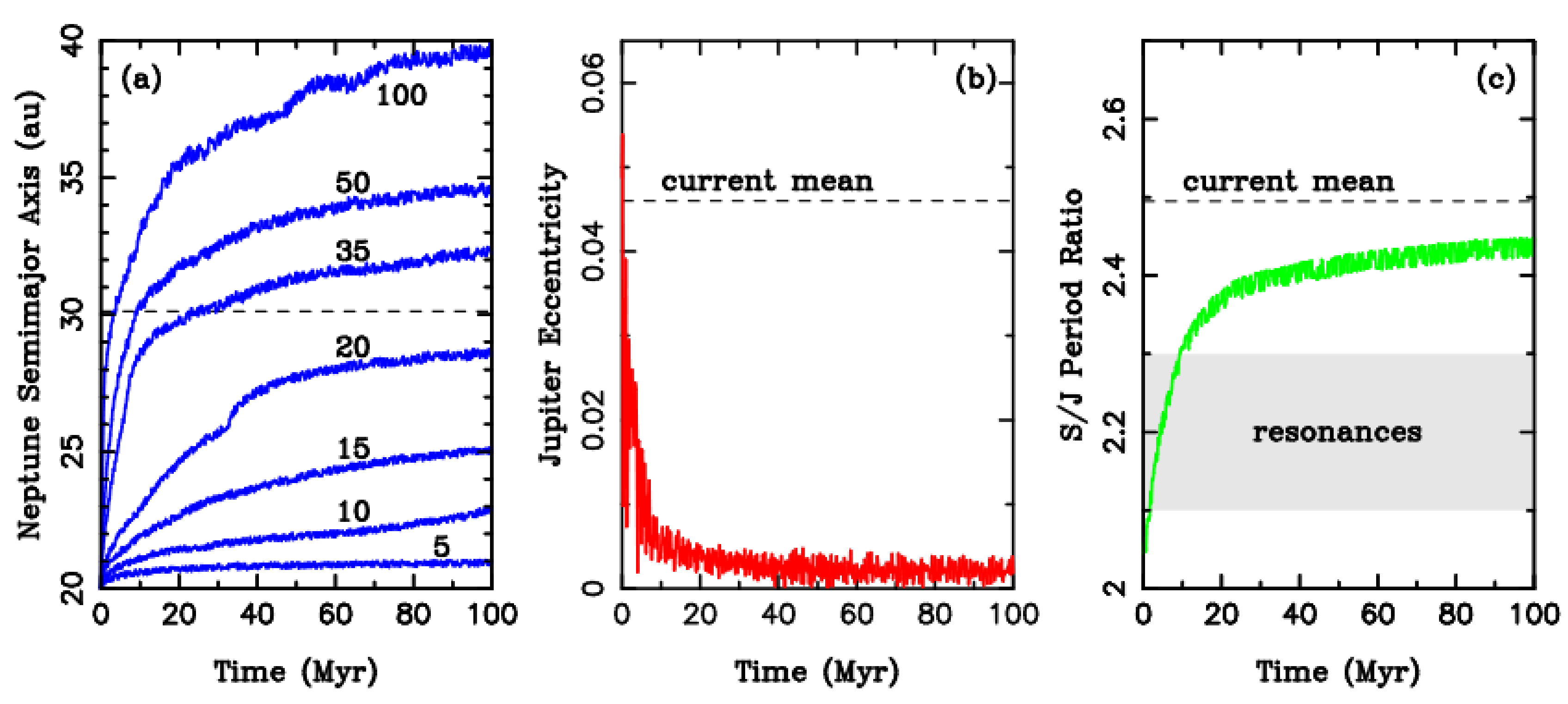
Desch 2007

Long term evolution of the Solar system



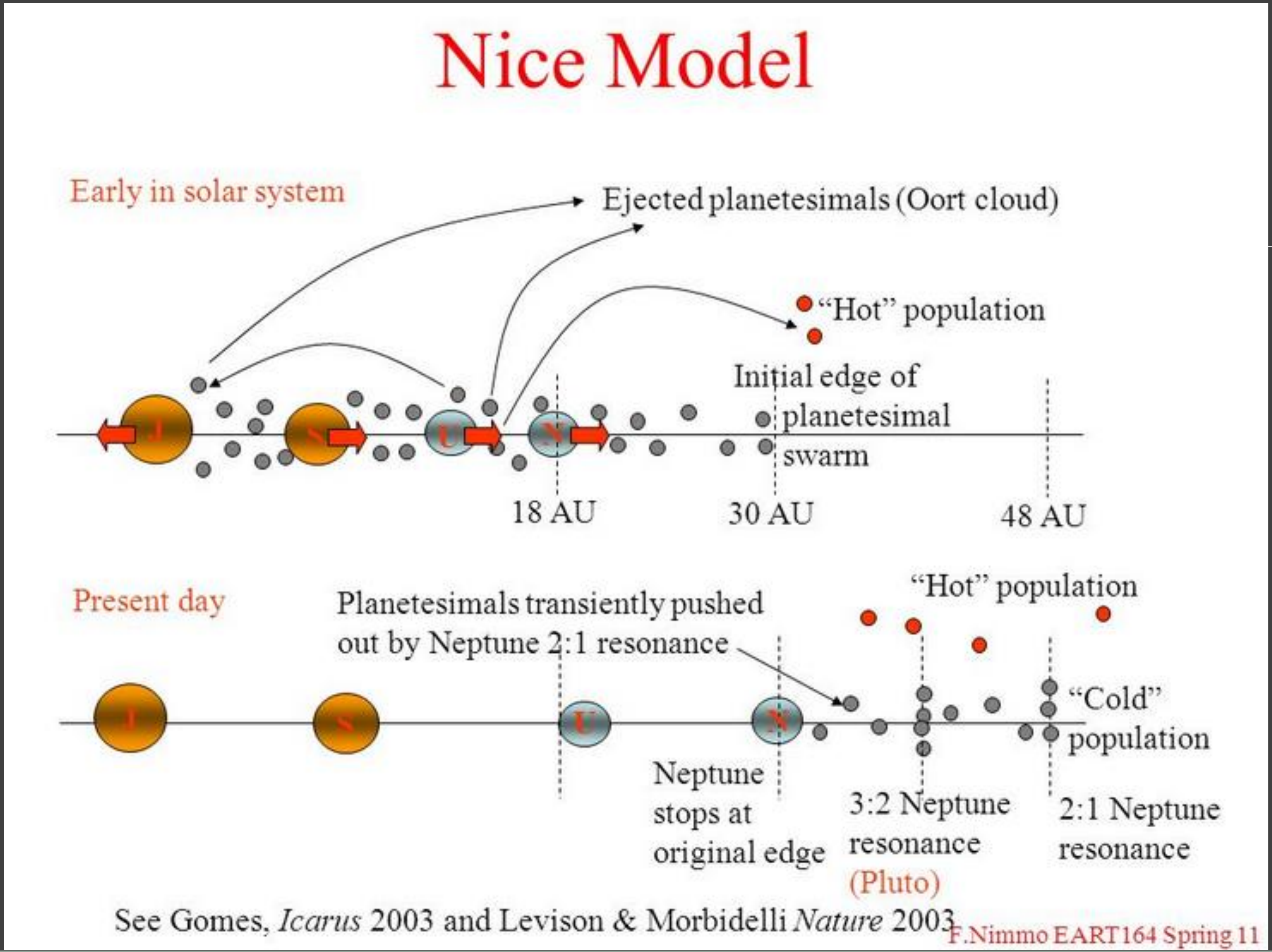
On each plot the 19 curves represent intervals of 250 Myr.
Each curve is based on 1001 solutions
with very close initial conditions.
The variation of these curves reflects
the chaotic diffusion of the solutions
(Laskar 2008, see arXiv: 0802.3371).

Planetesimal-driven migration



Jupiter migrates inward, other giants – outward.

Ejection of 15 M_{earth} by Jupiter results in migration by 0.2 au. $\delta r/r \approx m/M$

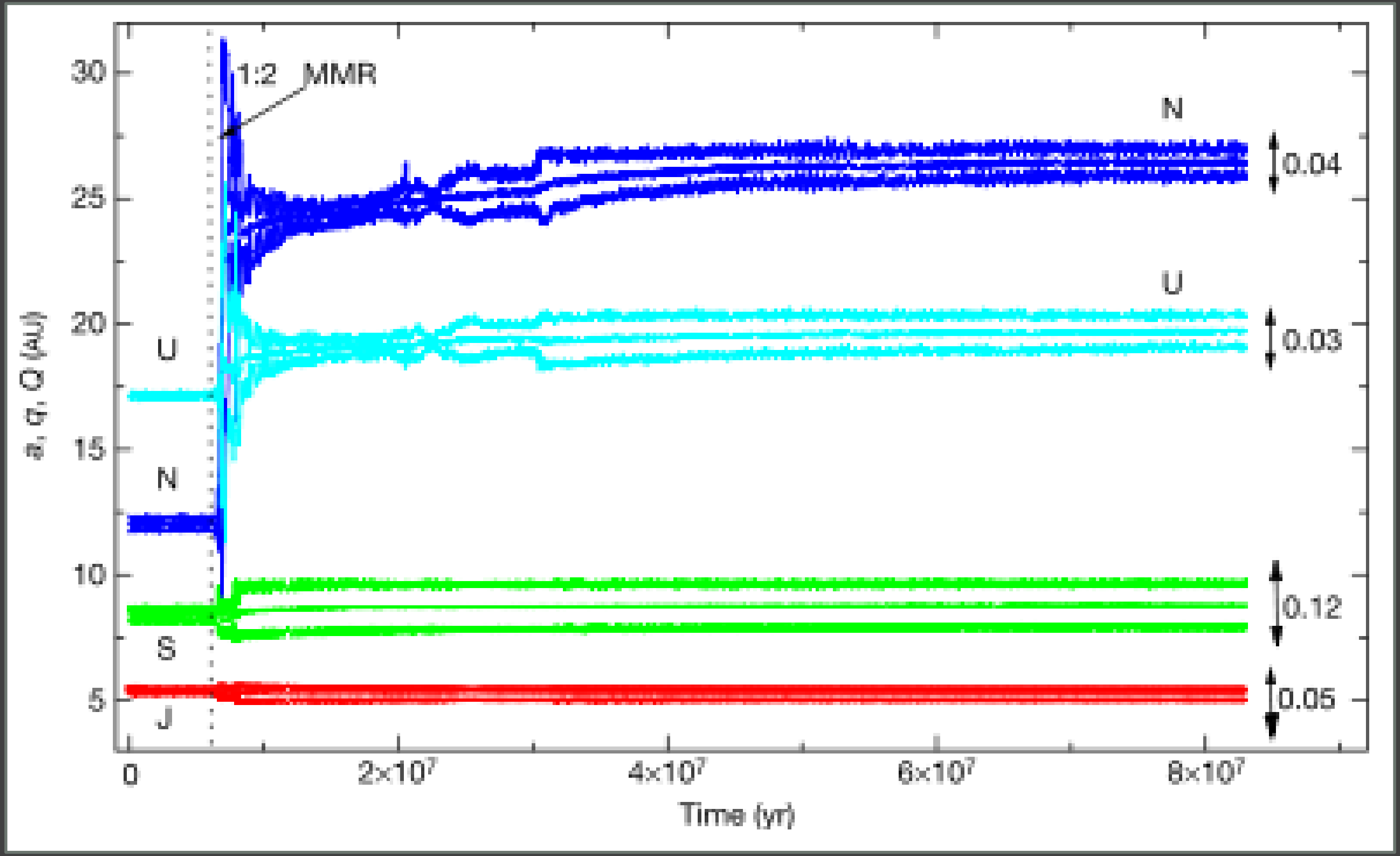


Three papers in Nature in 2005:

- Planet migration
- Late heavy bombardment
- Jupiter Troyans

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

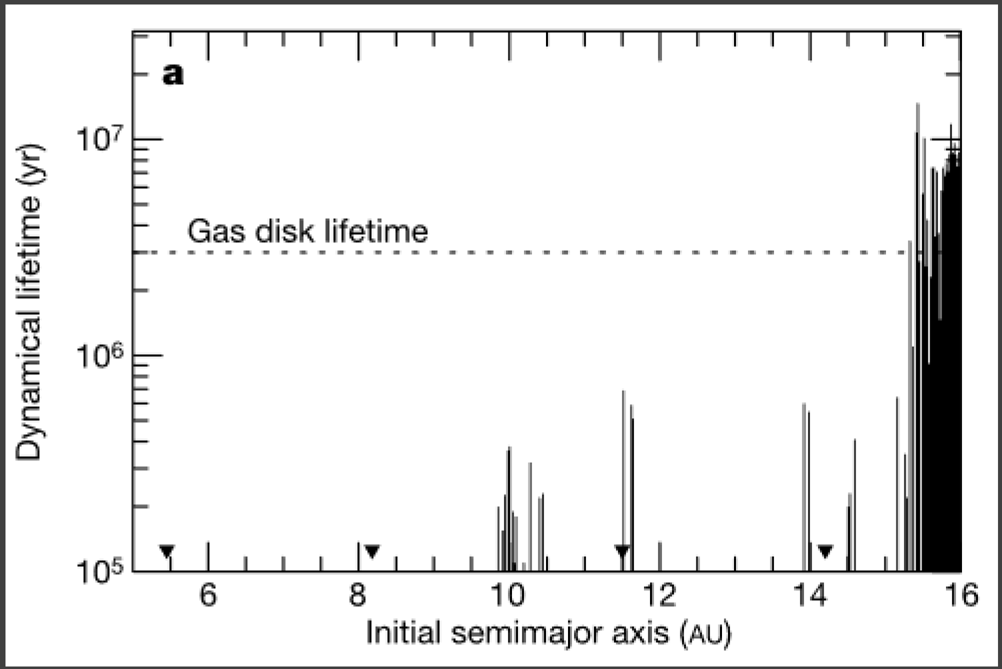
Planet migration in the Nice model



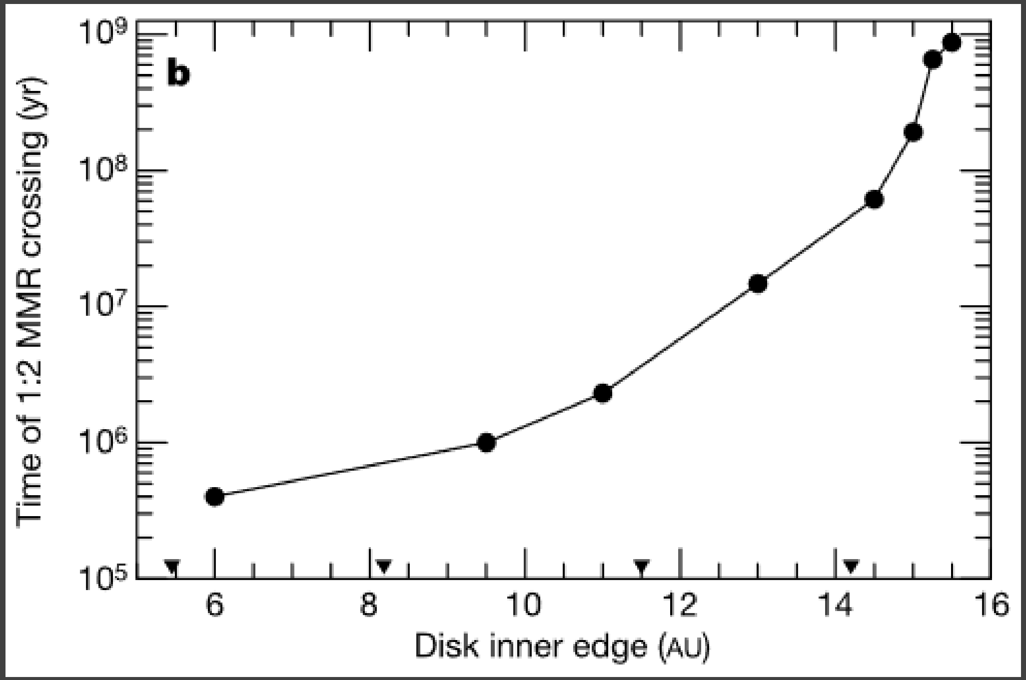
wikipedia.org

Tsiganis et al. 2005

Late heavy bombardment



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.

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.

Gomes et al. 2005

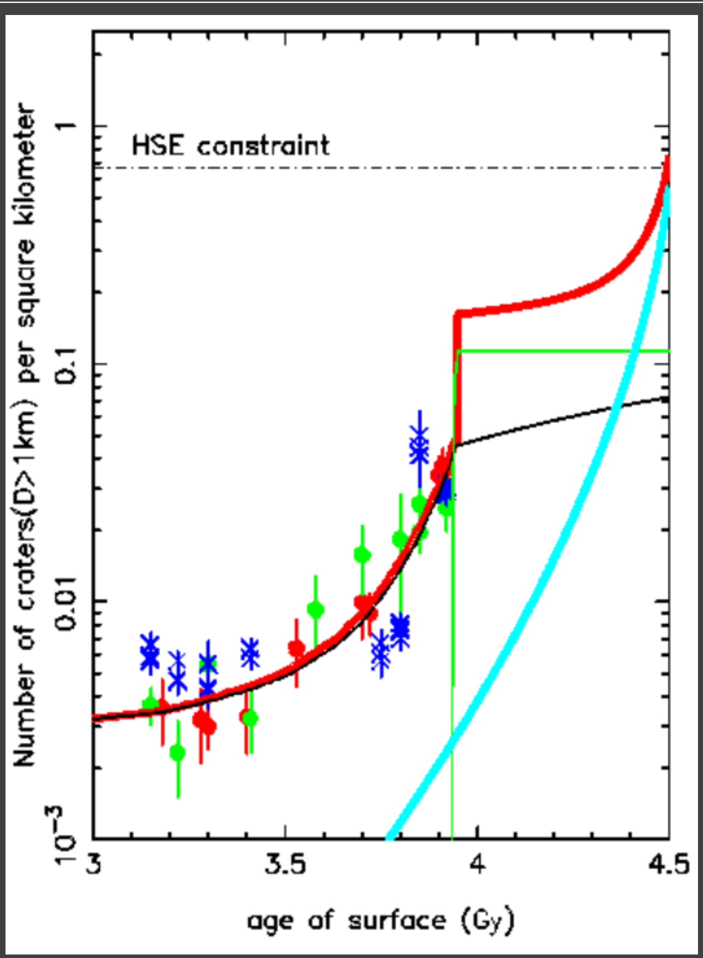
Revisiting the timeline of the LHB

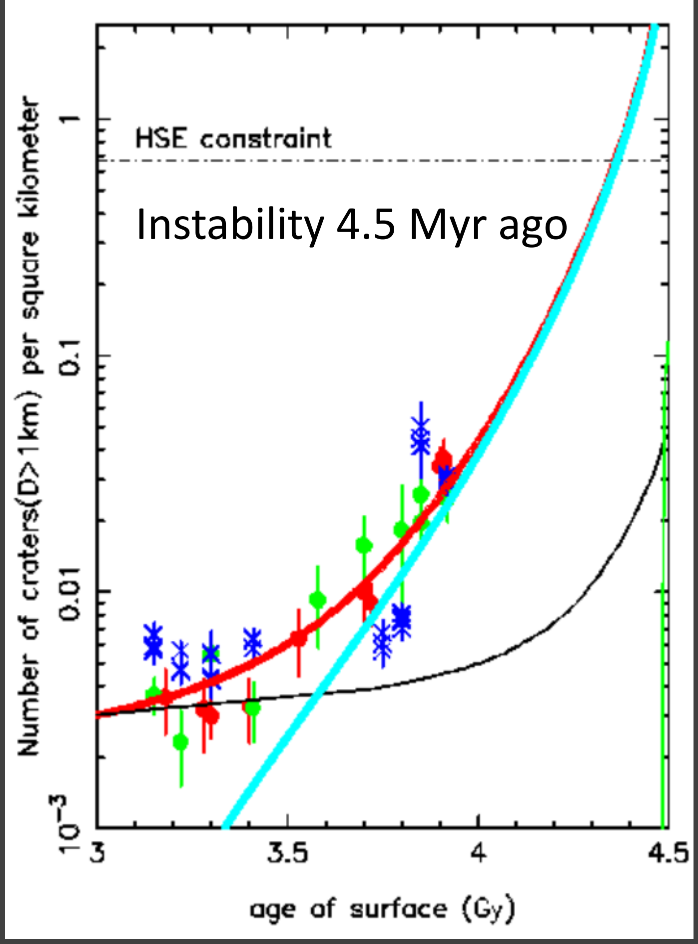
asteroids (thin black curve),
comets (thin green curve),
leftover planetesimals (thick cyan curve).

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.

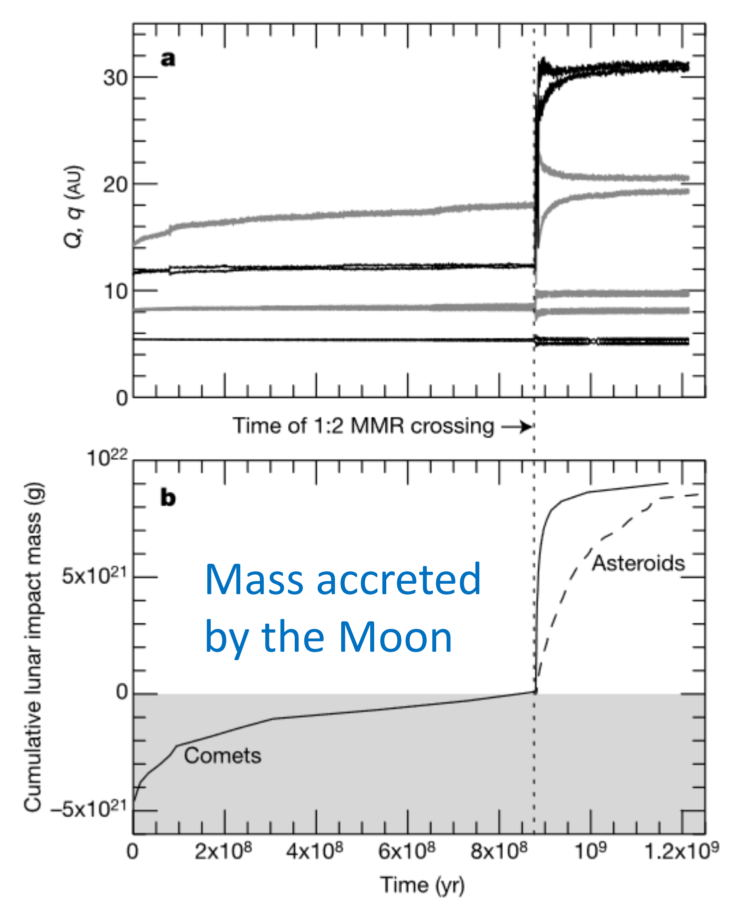
HSE - highly siderophile elements:
transition metals which tend
to sink into the core
because they dissolve readily in iron.

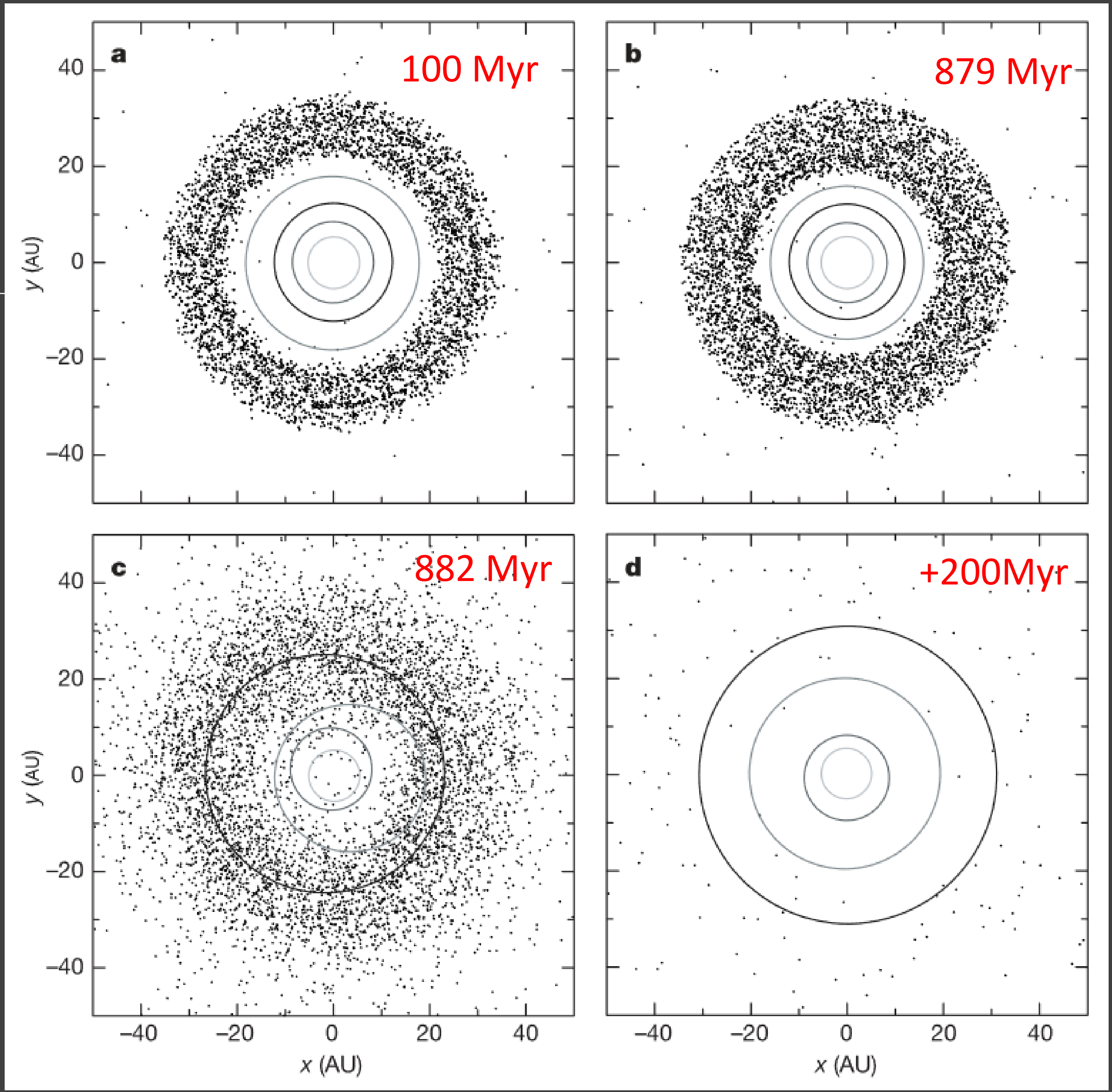




Dynamics

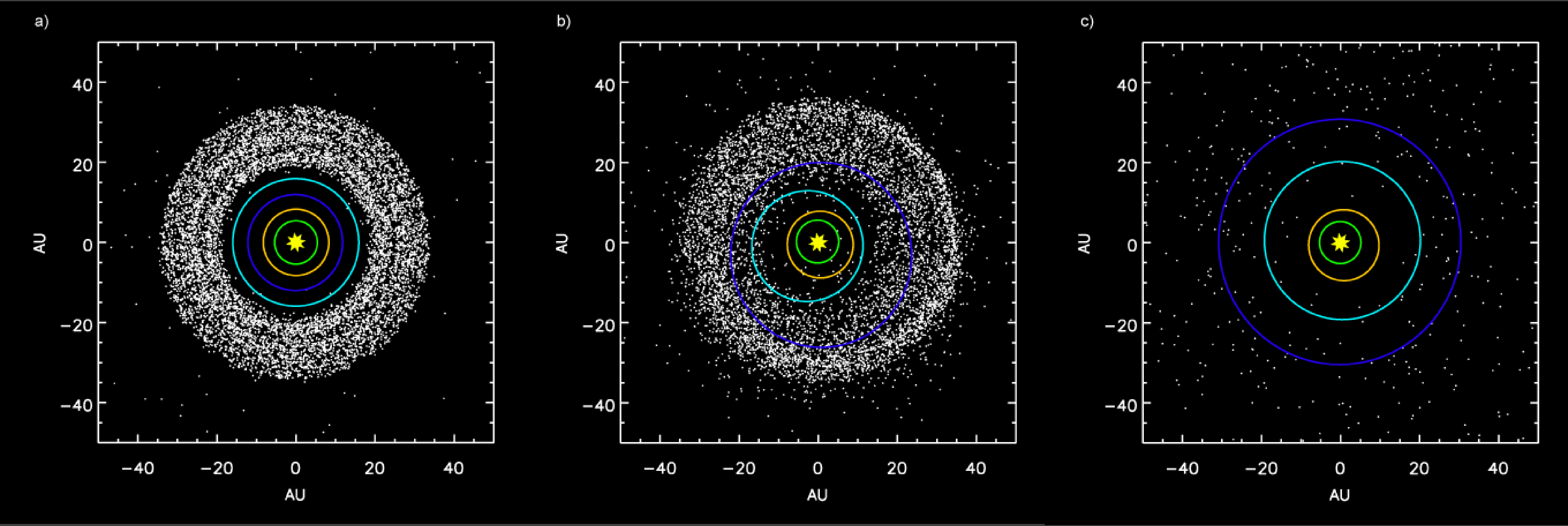
LHB lasted
for ~100 Myr



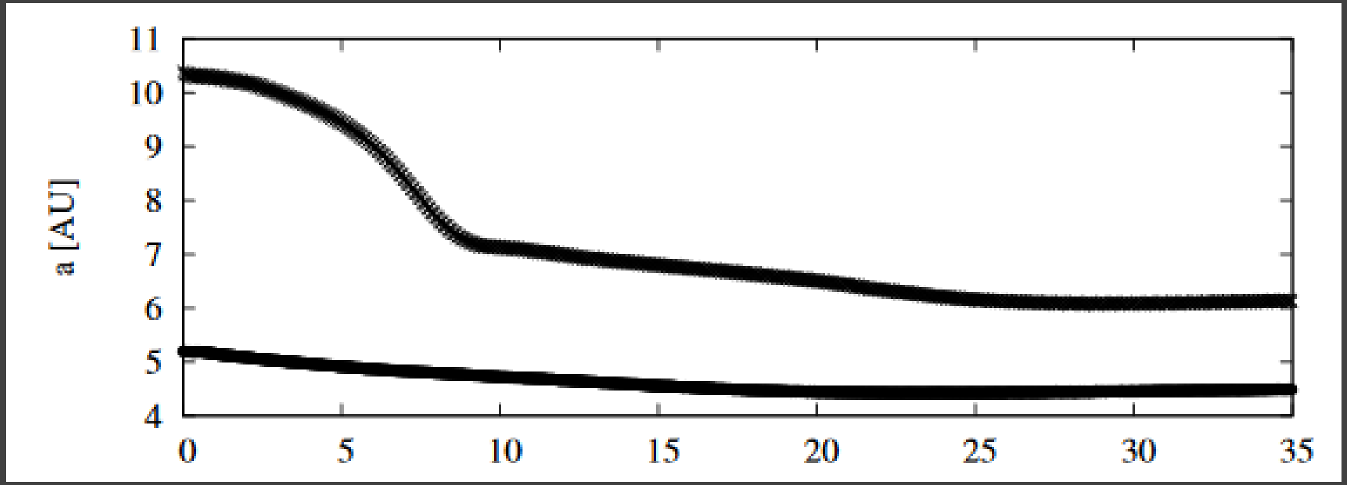


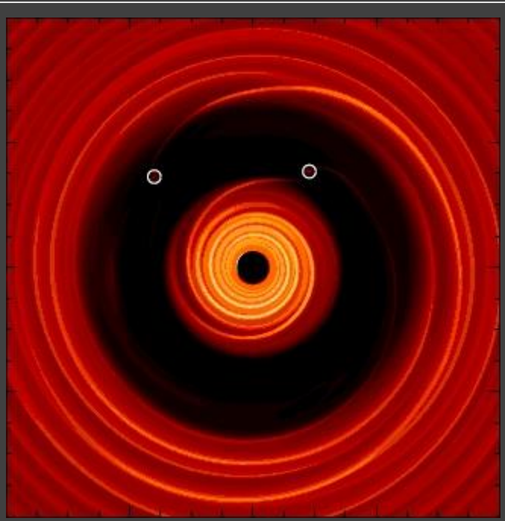
Gomes et al. 2005

Nice model



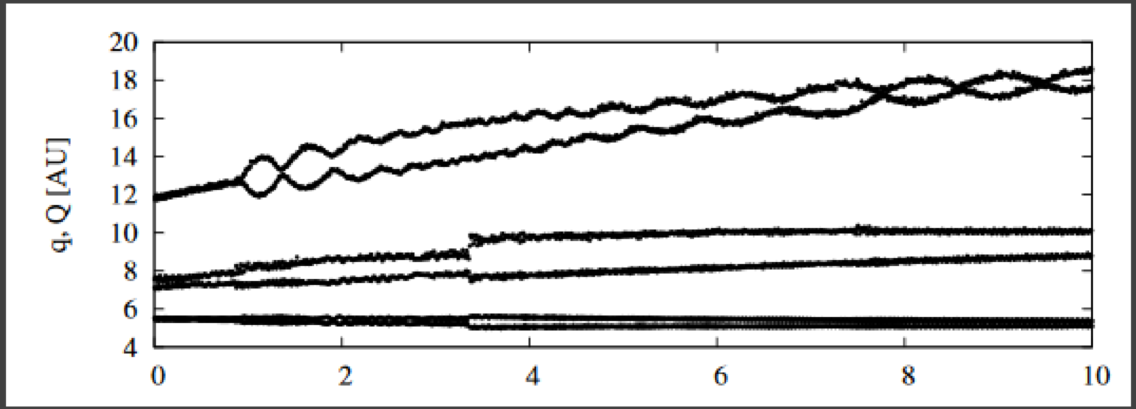
Solar system secular evolution: resonance crossing





planetplanet.net

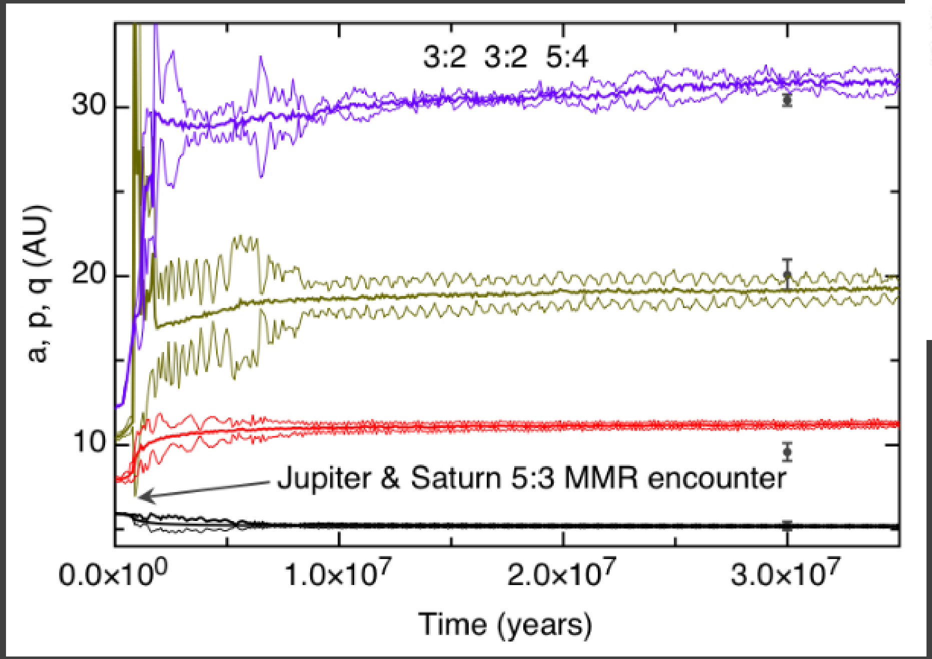
After evolution in the gas disc Jupiter and Saturn are in 3:2 resonance.
At this stage eccentricities and inclinations are low.
It is non-trivial to explain present-day eccentricities and inclinations.
It was proposed that it can be potentially solved
if these planets crossed resonances
and interacted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

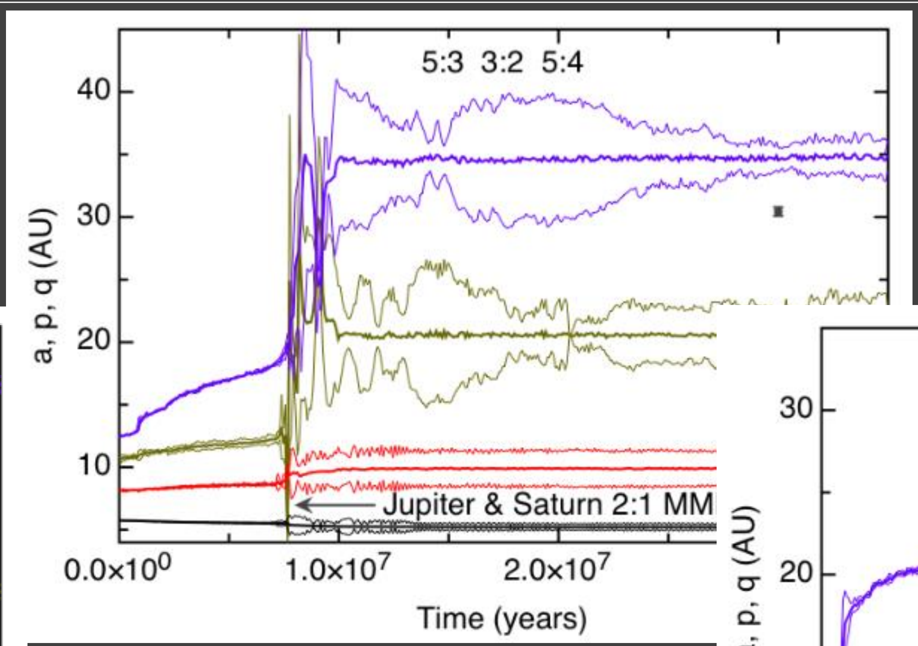


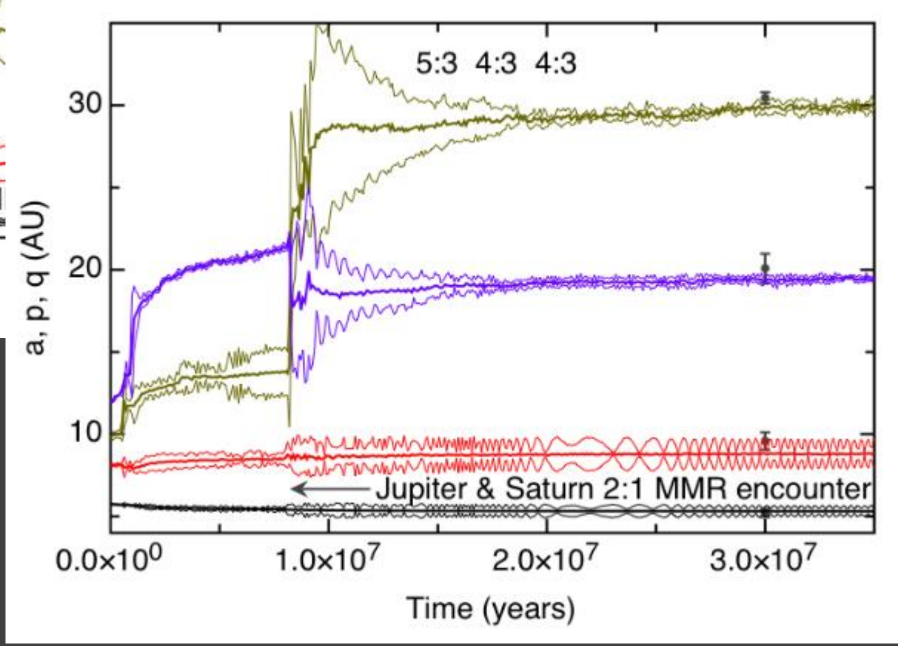
Morbidelli et al. 2009

Further studies

Role of initial resonance conditions for all four giants.



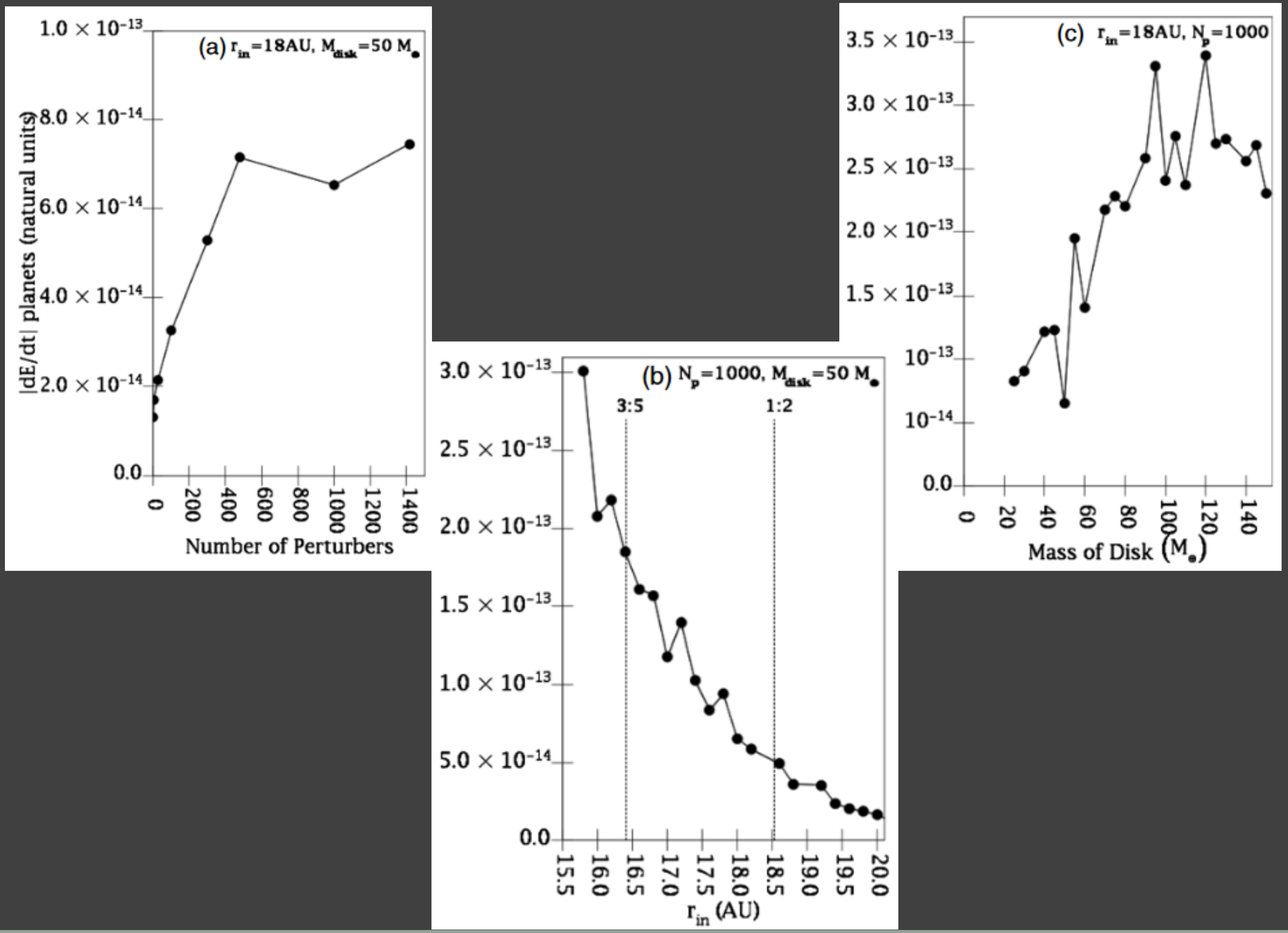




Modifications of the original Nice model

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

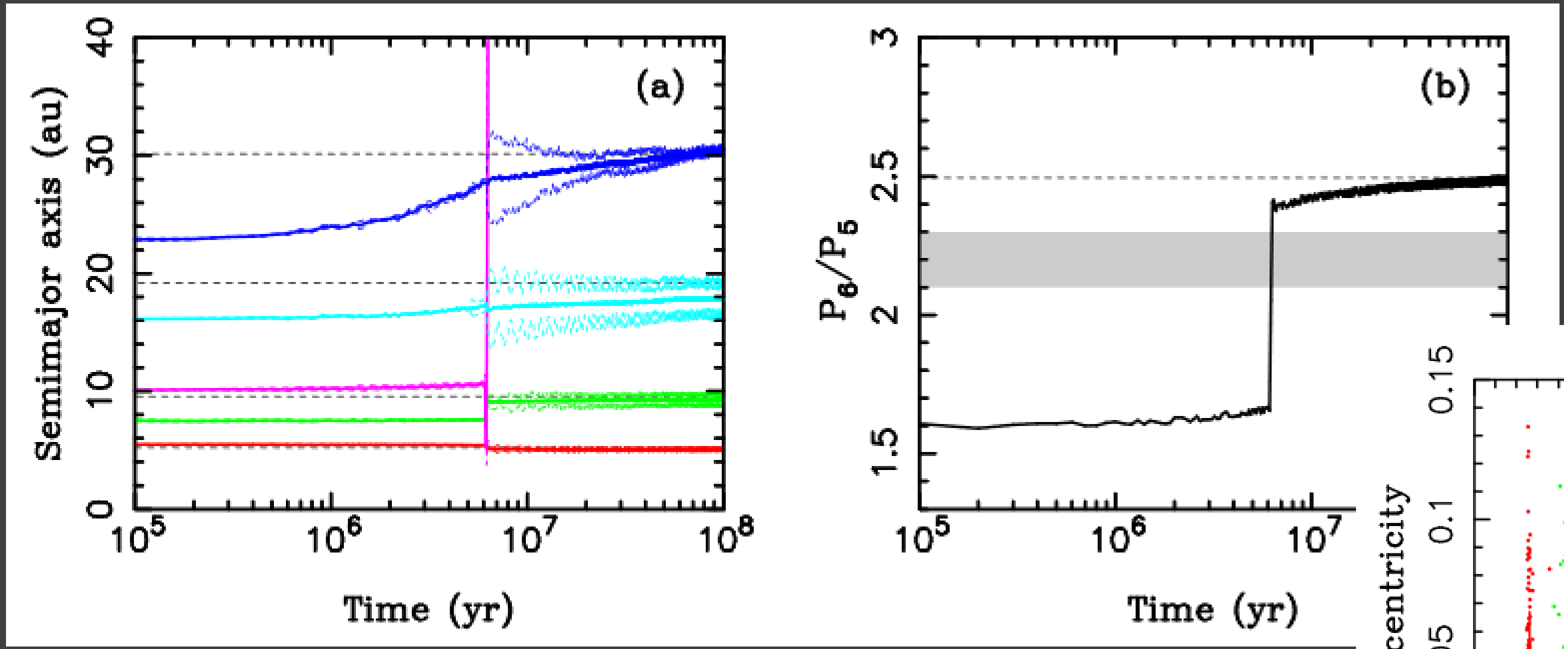
Planet	$\langle a \rangle$ (AU)	$\langle e \rangle$	$\langle i \rangle$ (deg)
Jupiter	5.42	0.0044	0.016
Saturn	7.32	0.017	0.016
Ice I	9.61	0.053	0.044
Ice II	11.67	0.011	0.029



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.

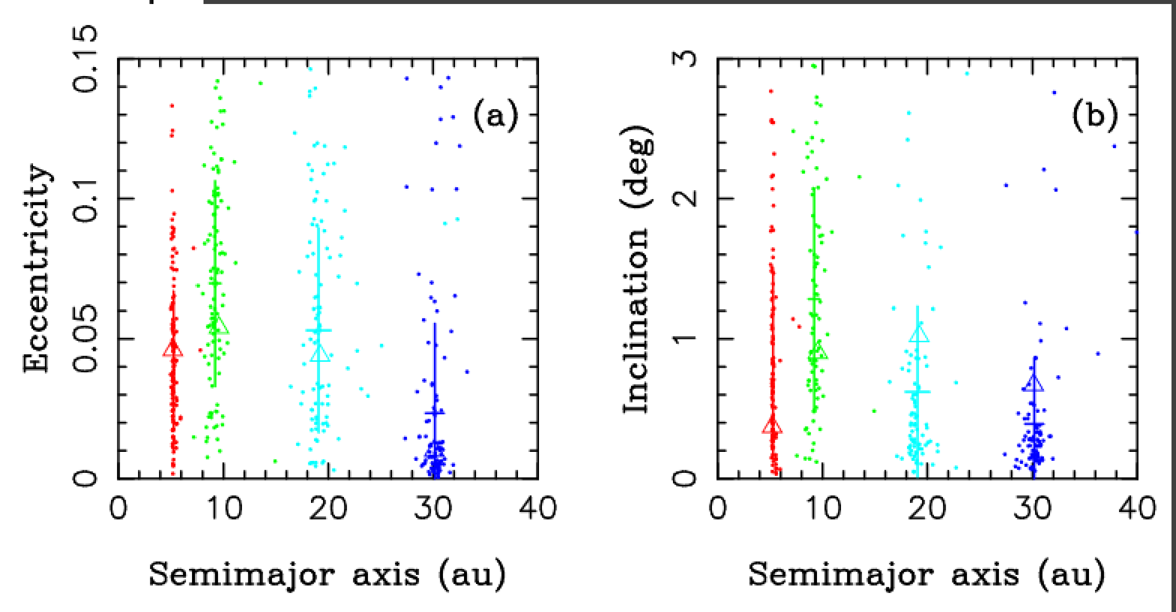
Levison et al. 2011 (AJ 142, 152)

Jumping Jupiter



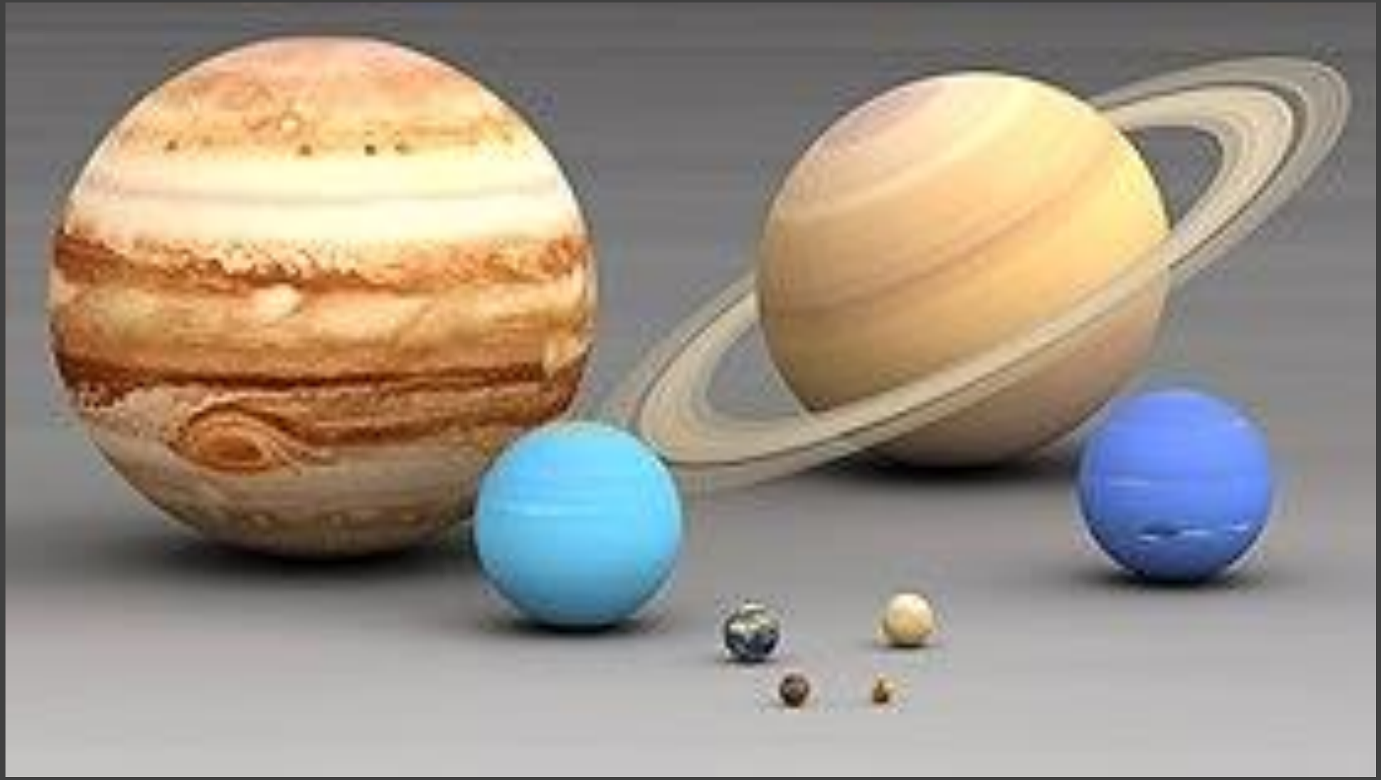
Five planets configuration.

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

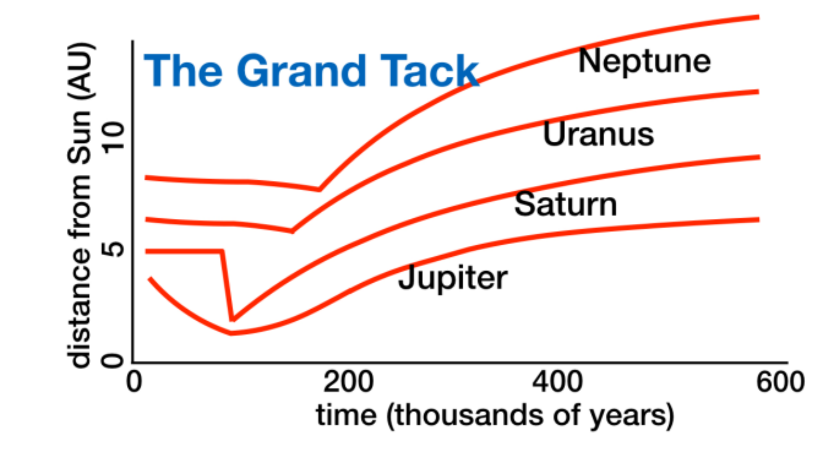


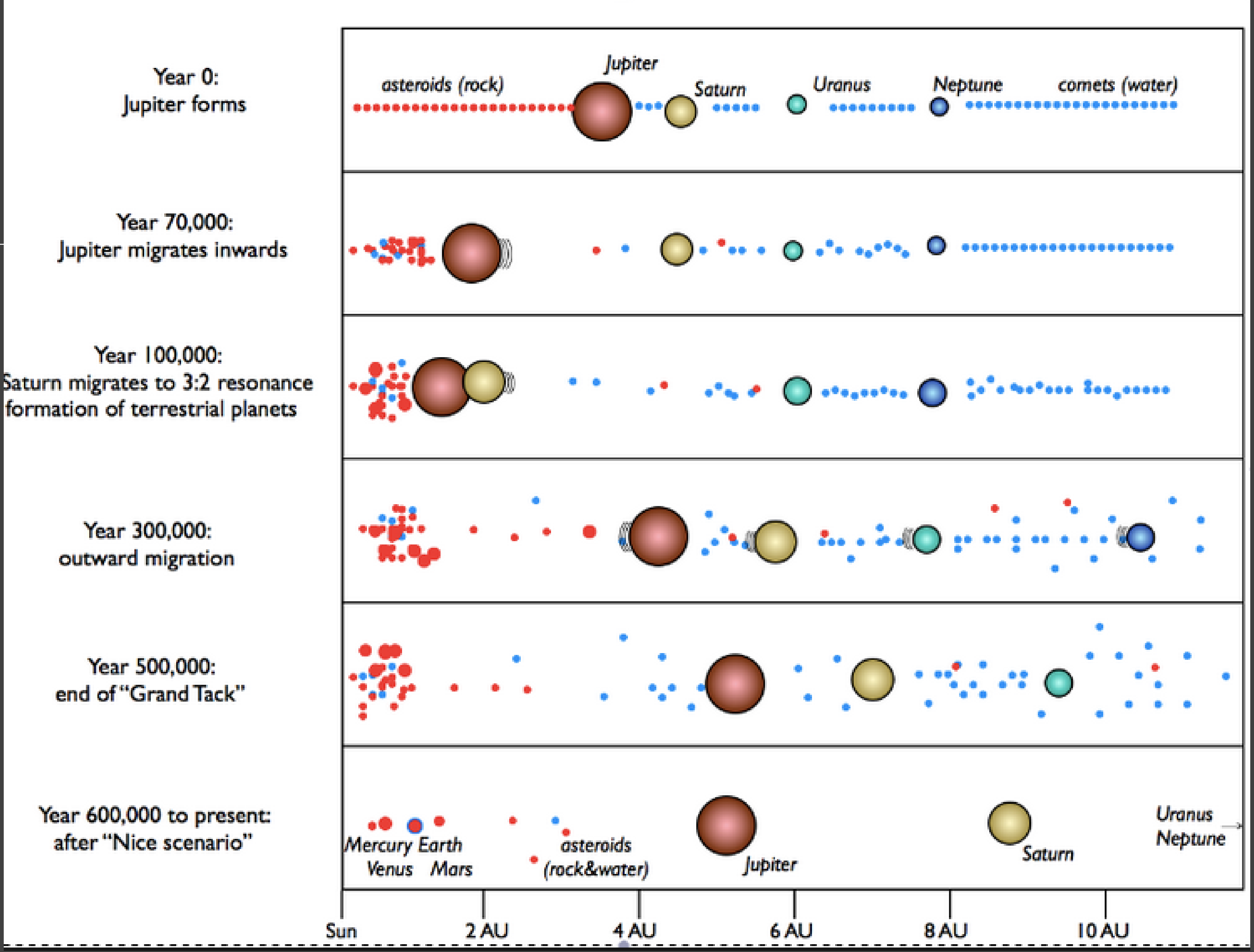
More problems (and solutions?)

Problem: light Mars
Solution: cut planetesimal disc at 1 AU
How: Jupiter!



Grand tack



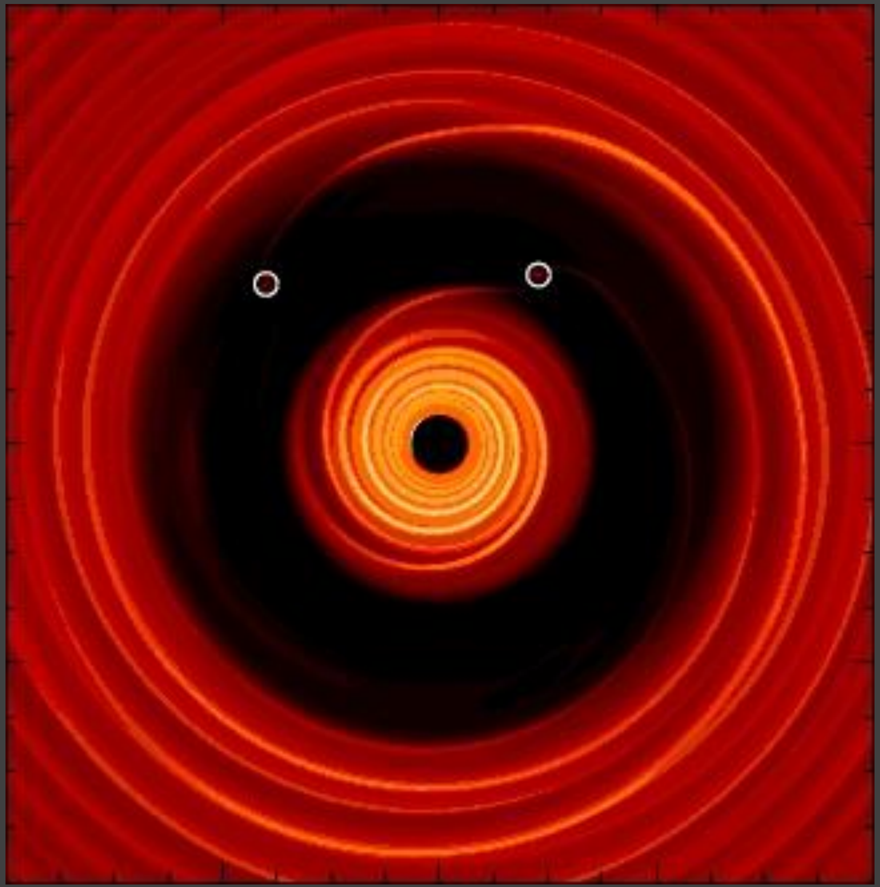


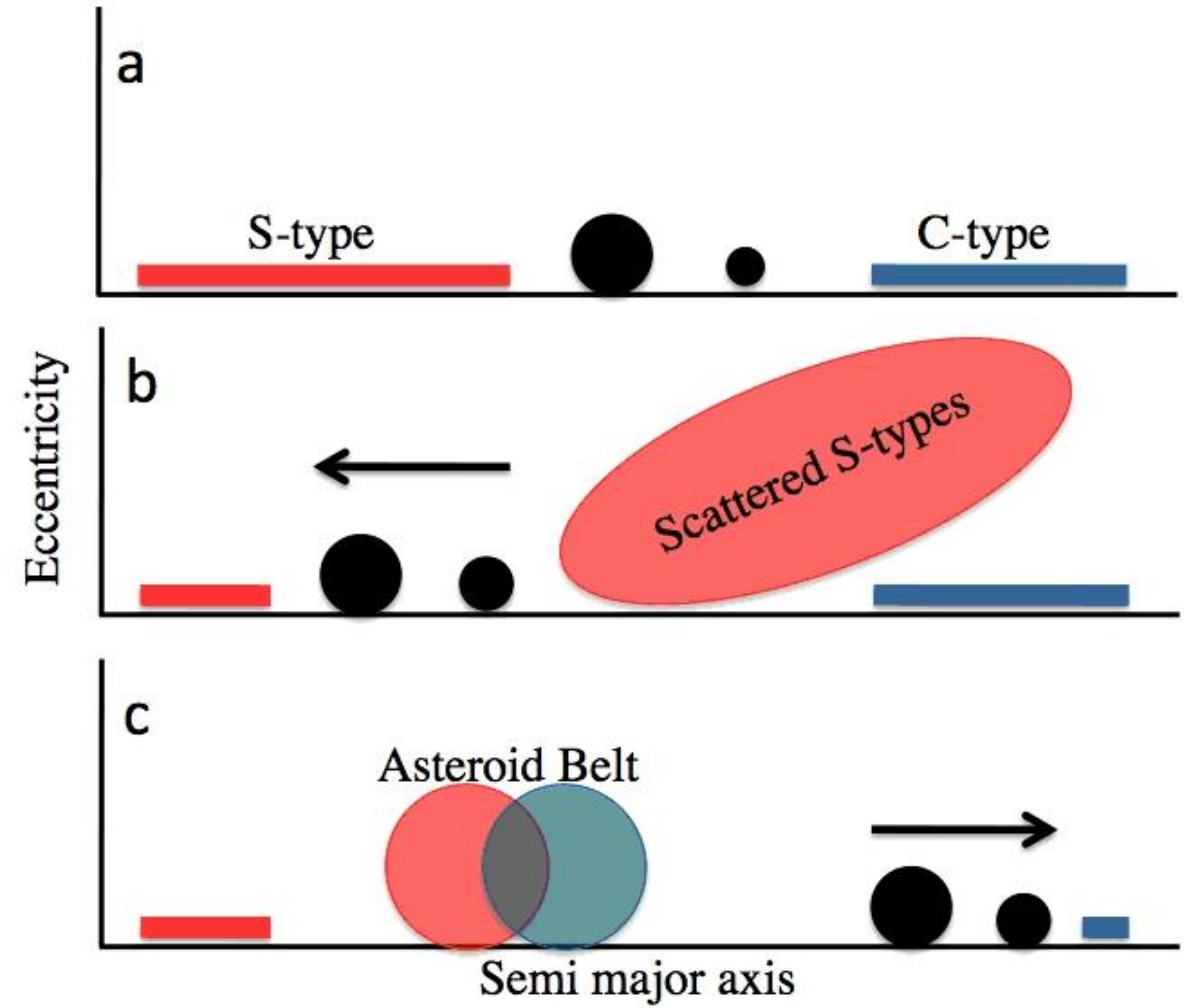
Proposed by Walsh et al. (2011).

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

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

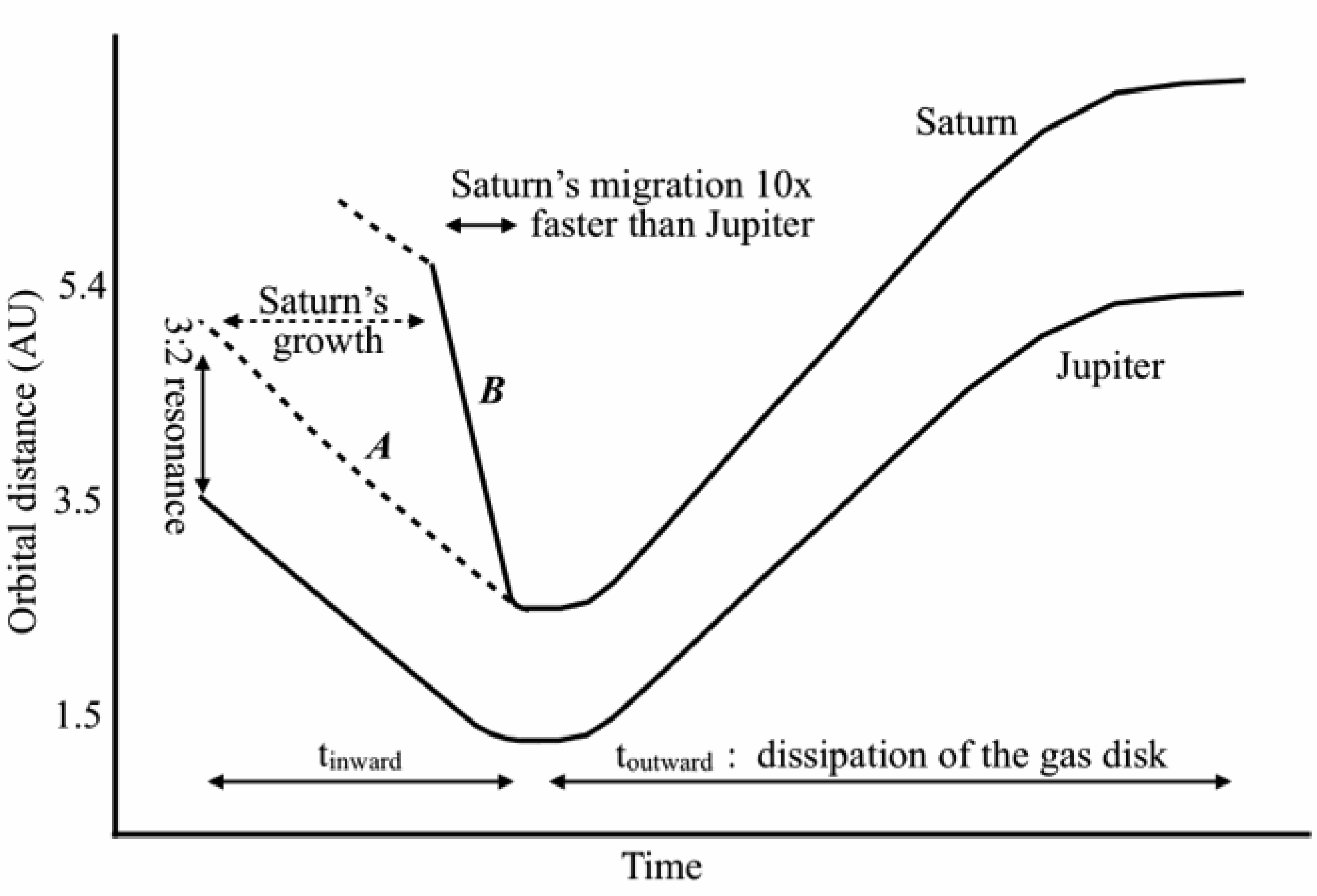
Grand tack





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

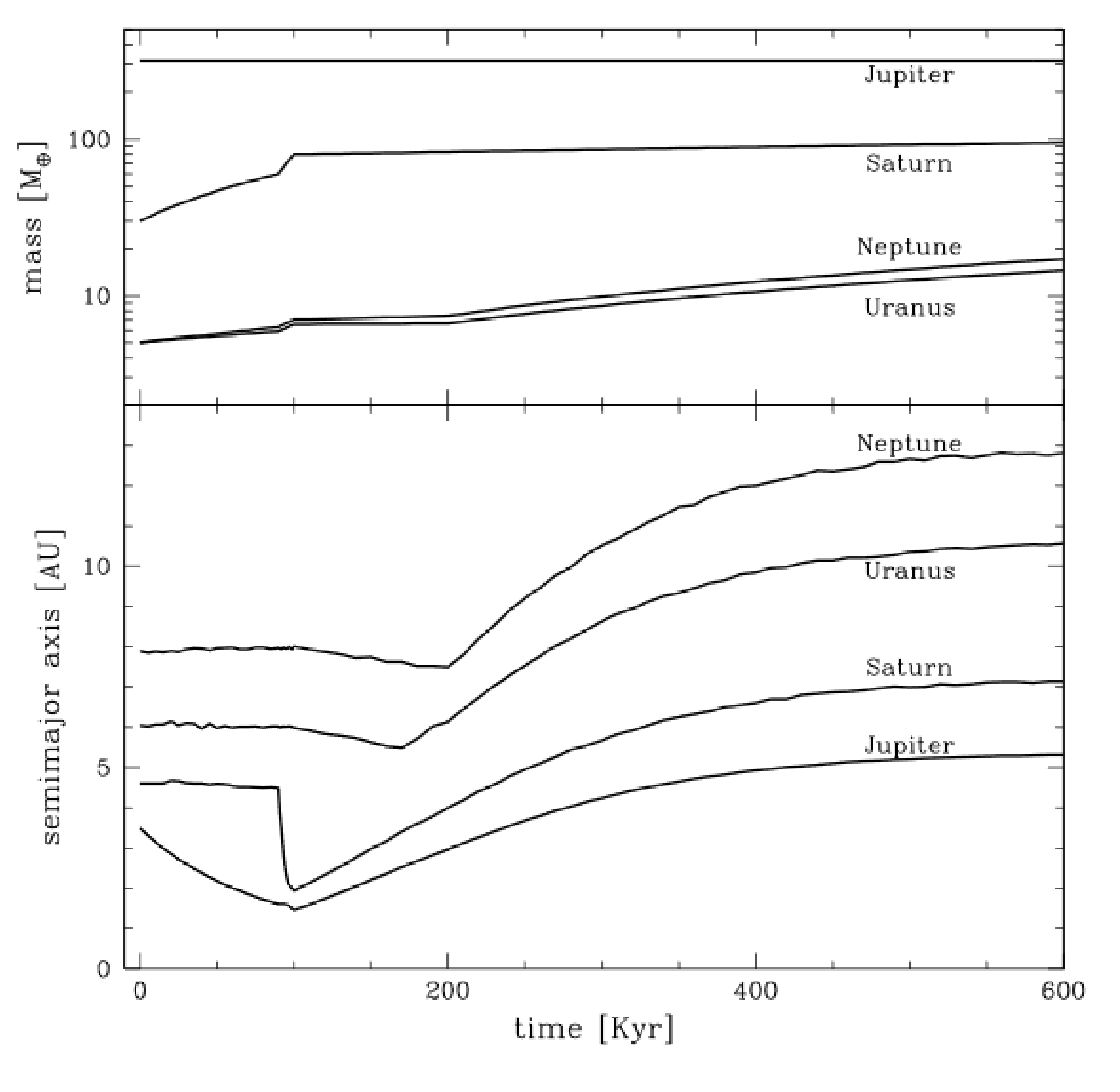


Jupiter and Saturn form earlier than terrestrial planets.
Thus, it is possible to influence the disc of planetesimals (embryos for terrestrial planets) with giants,
if they can migrate closer to the region of solid planets formation.

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

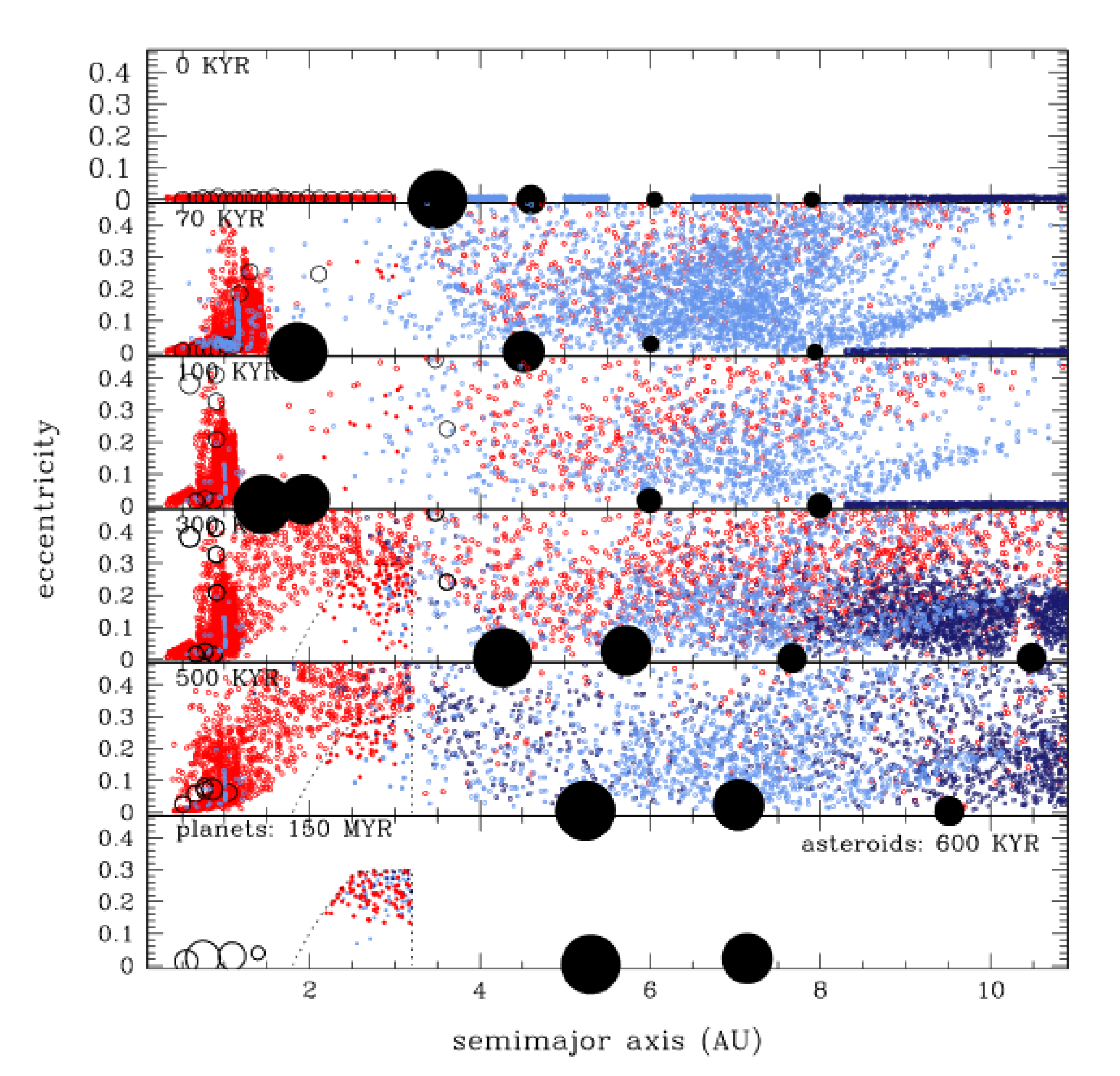
Grand Tack

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

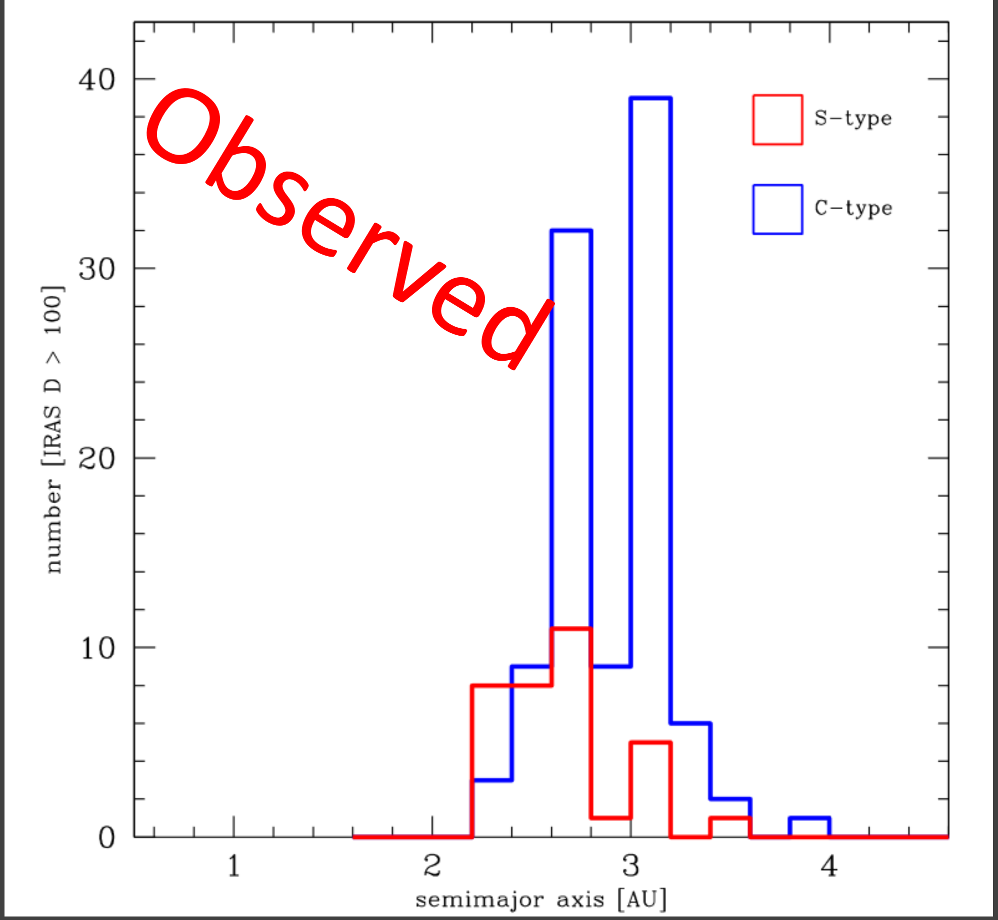


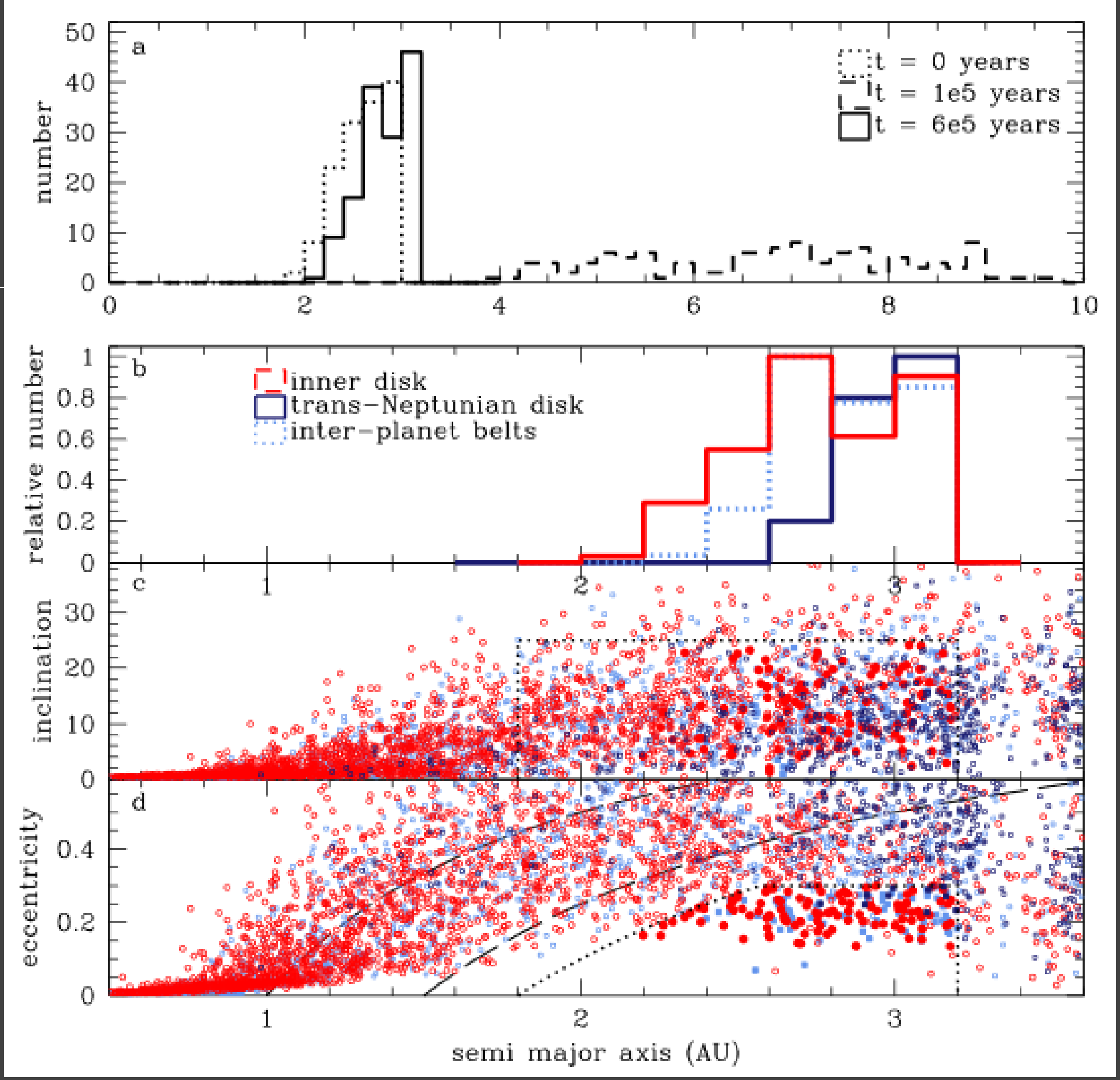
Small bodies

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



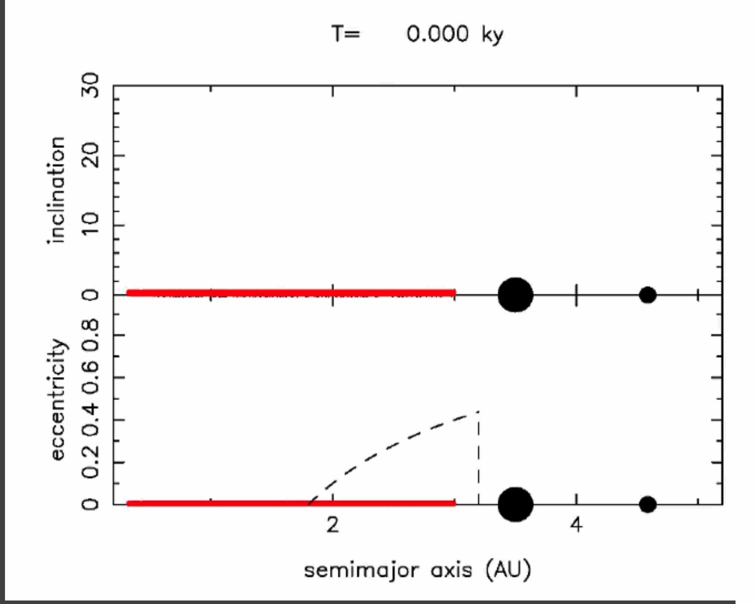
Asteroids

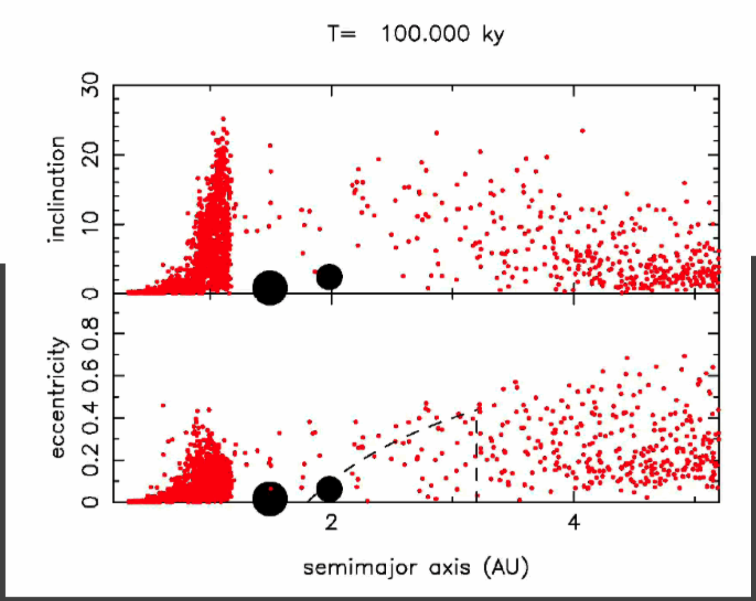


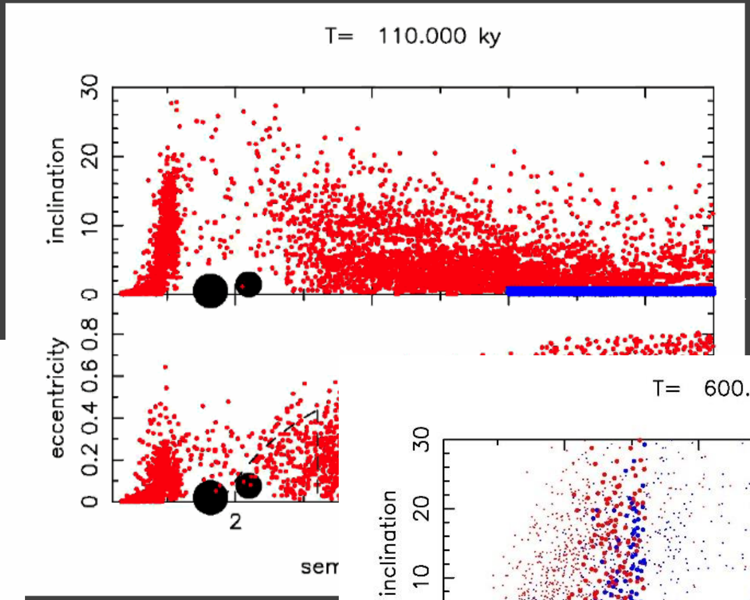


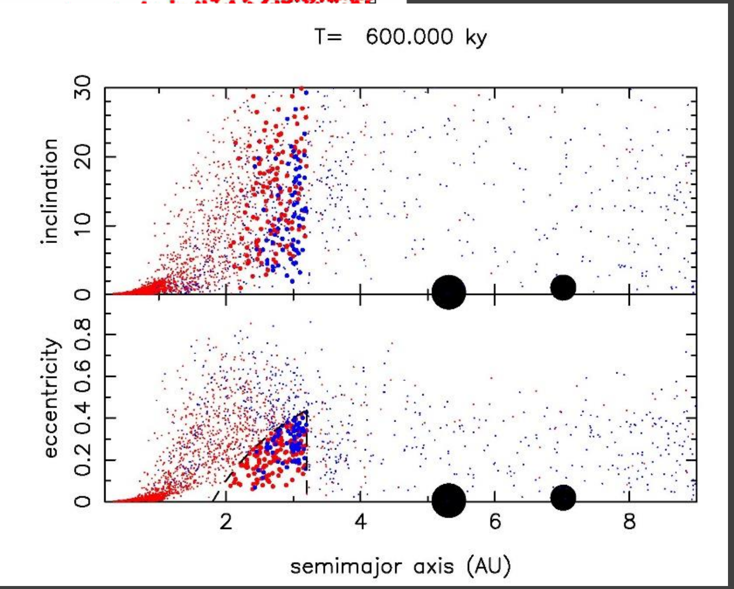
1201.5177

Sequence of events



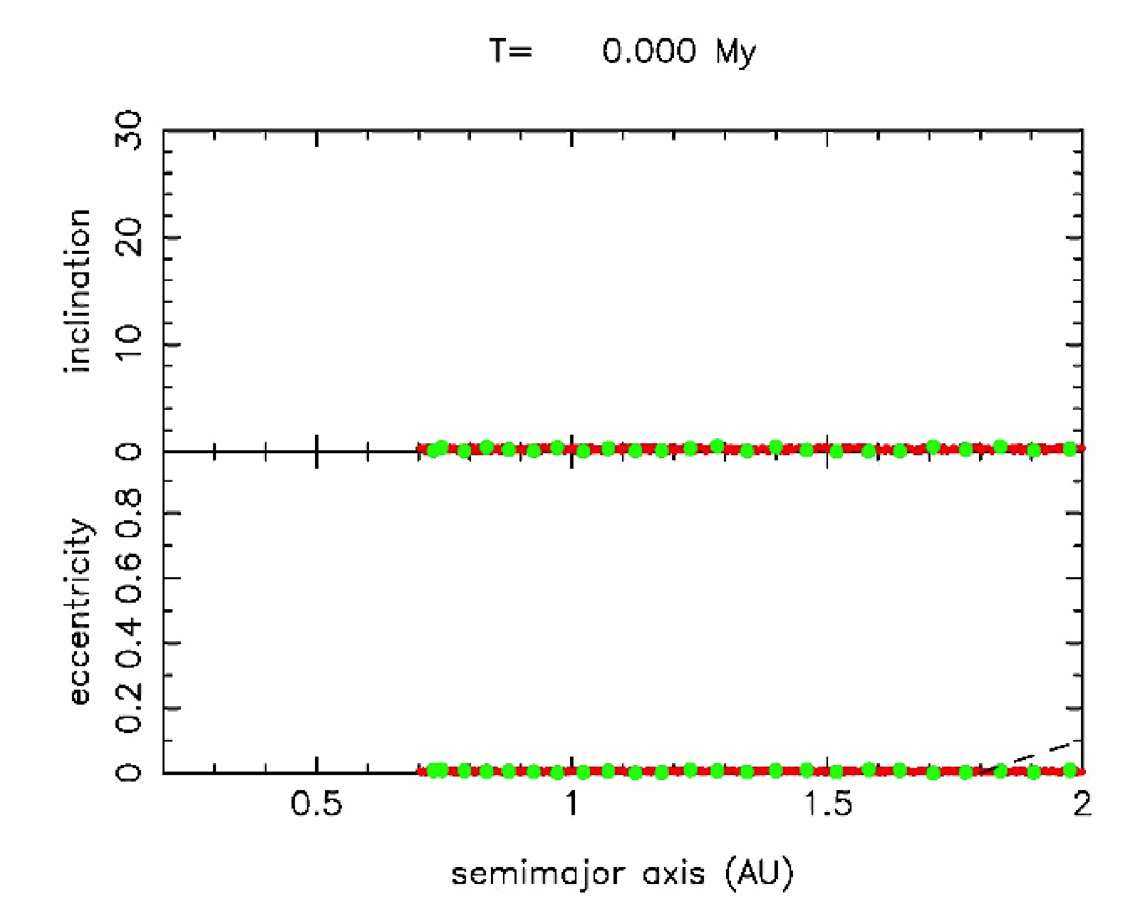


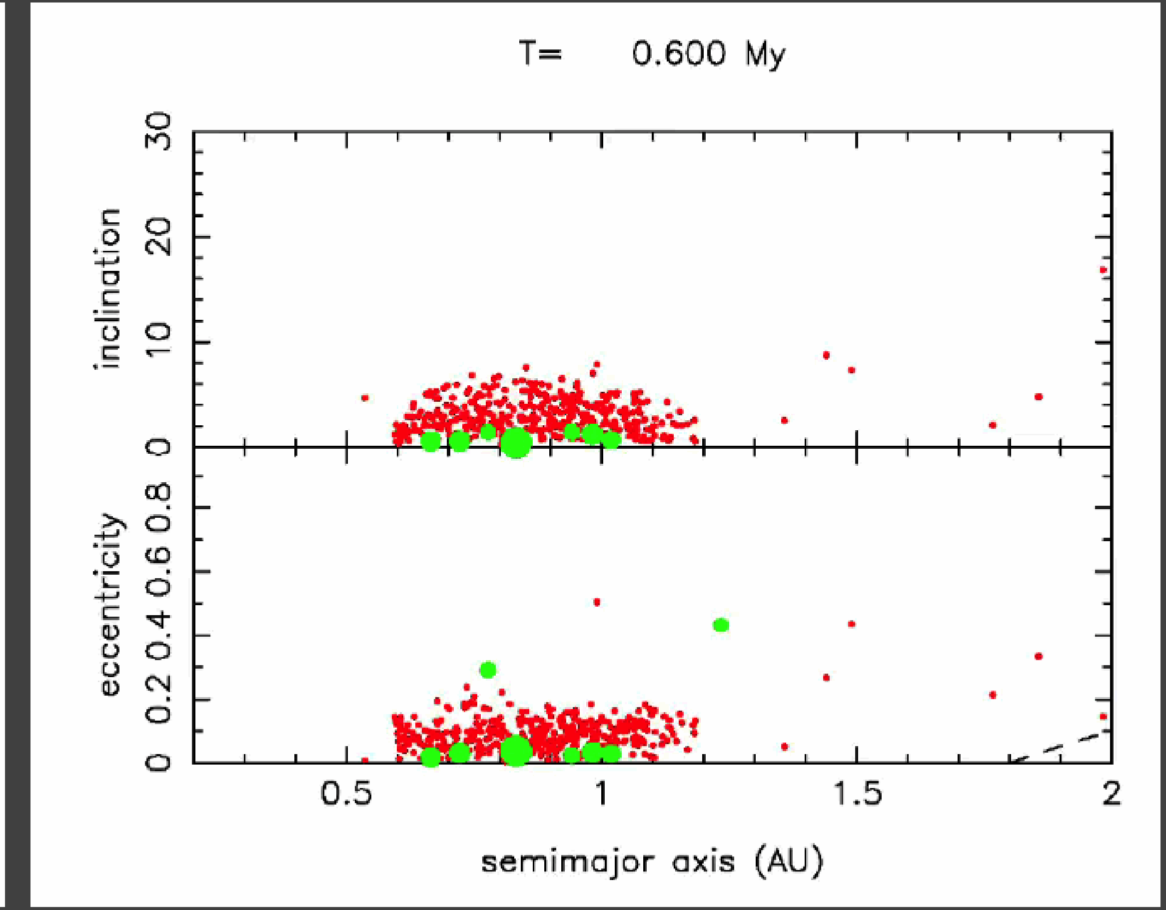




http://perso.astrophy.u-bordeaux.fr/SRaymond/movies_grandtack.html

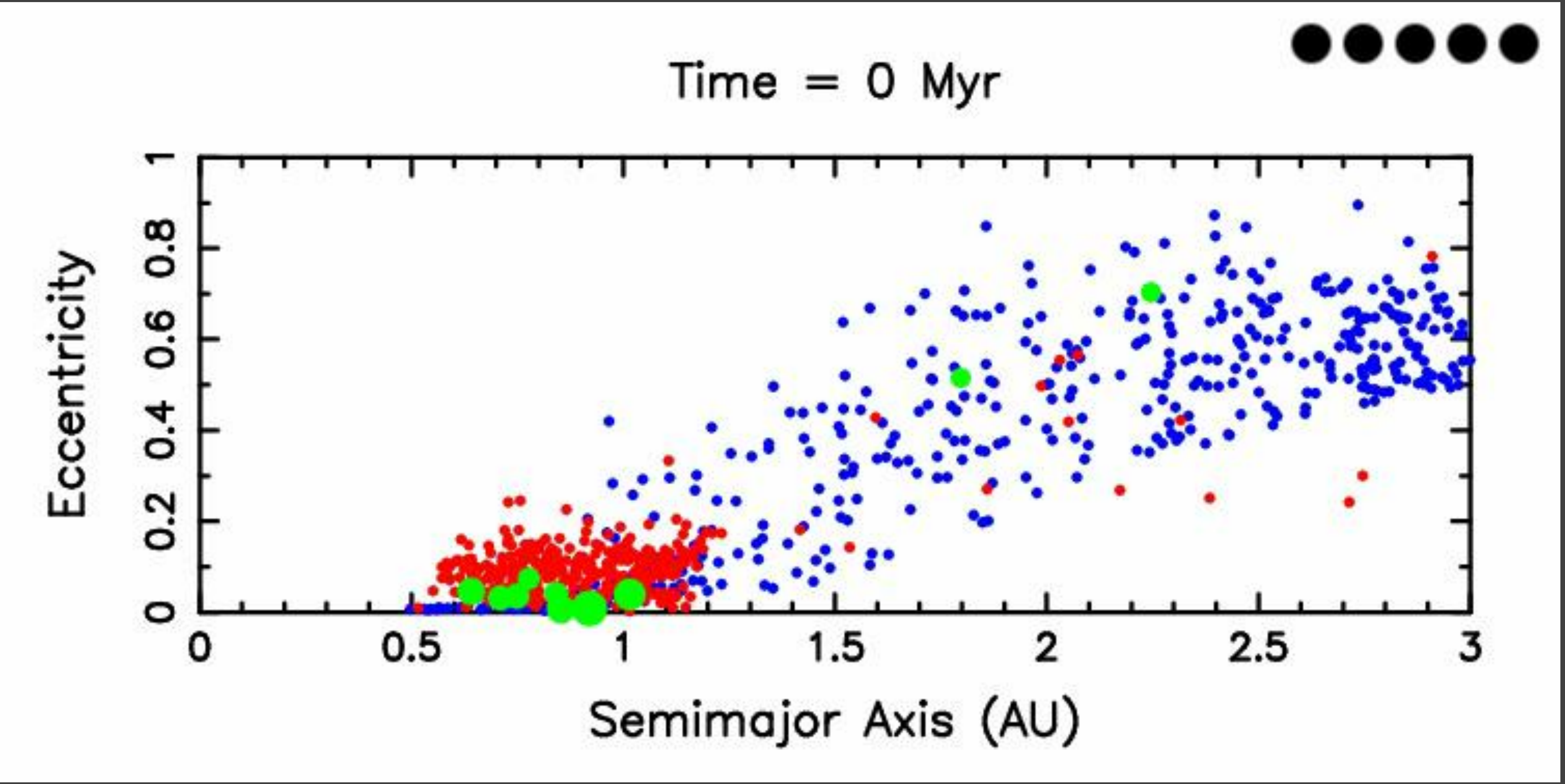
Disc of planetesimals: truncation





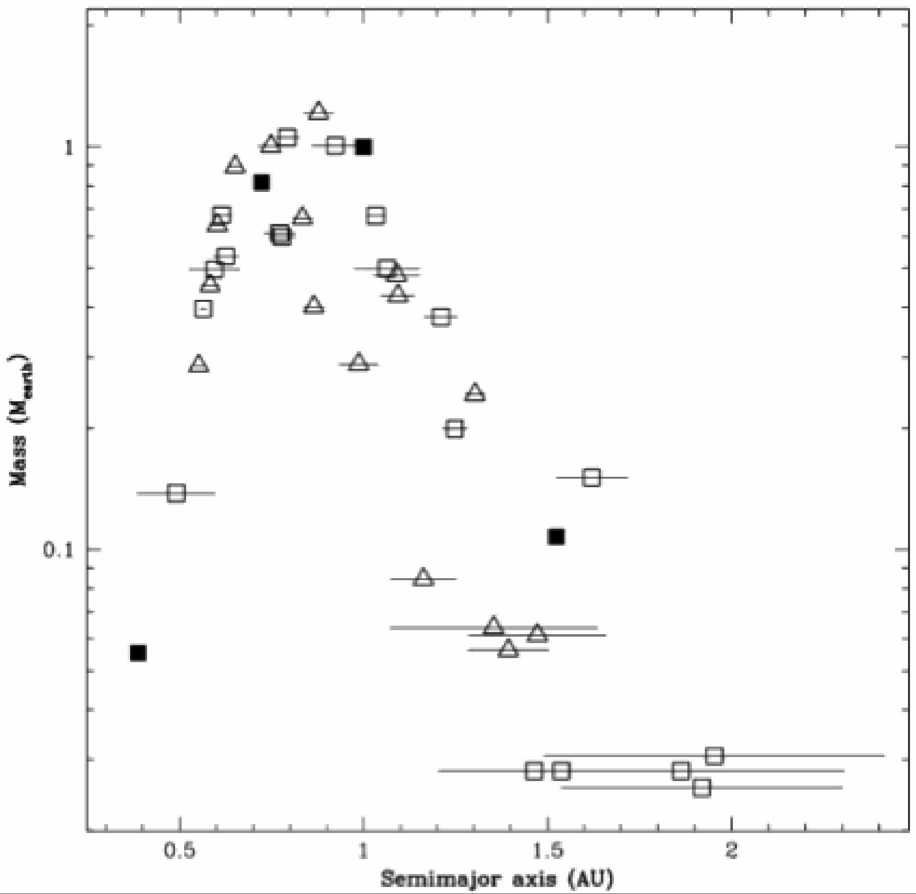
http://perso.astrophy.u-bordeaux.fr/SRaymond/movies_grandtack.html

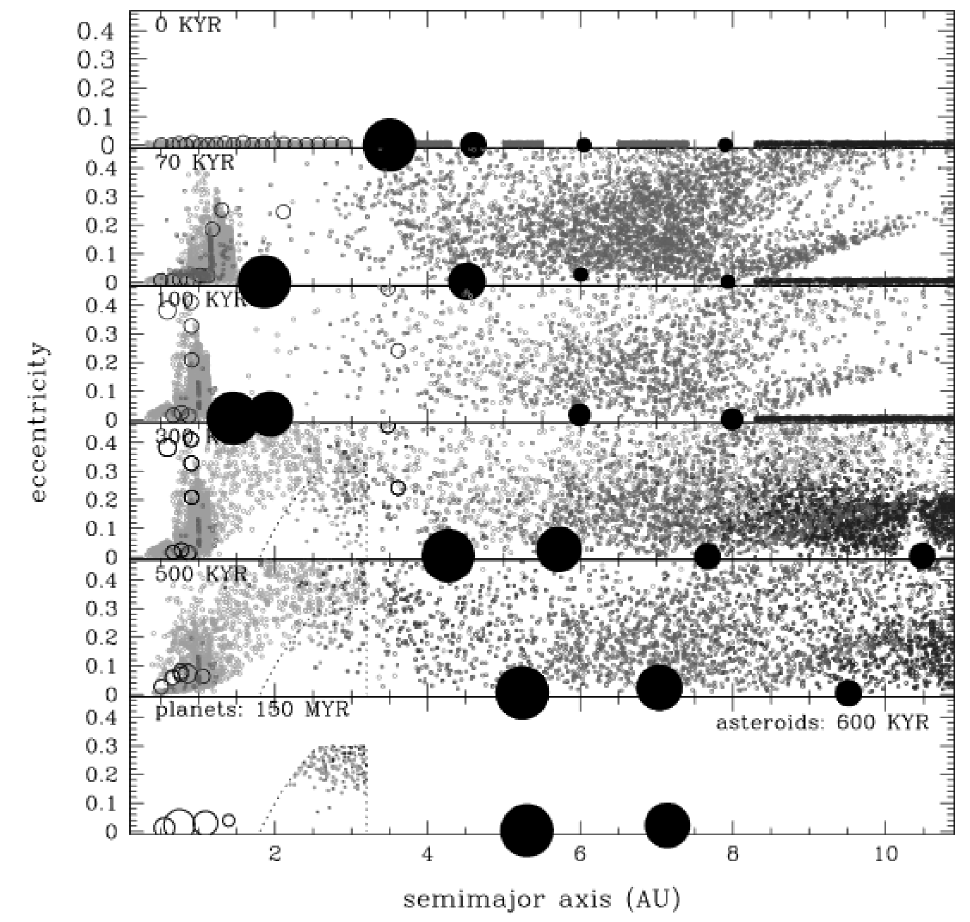
Water on Earth from C-type asteroids



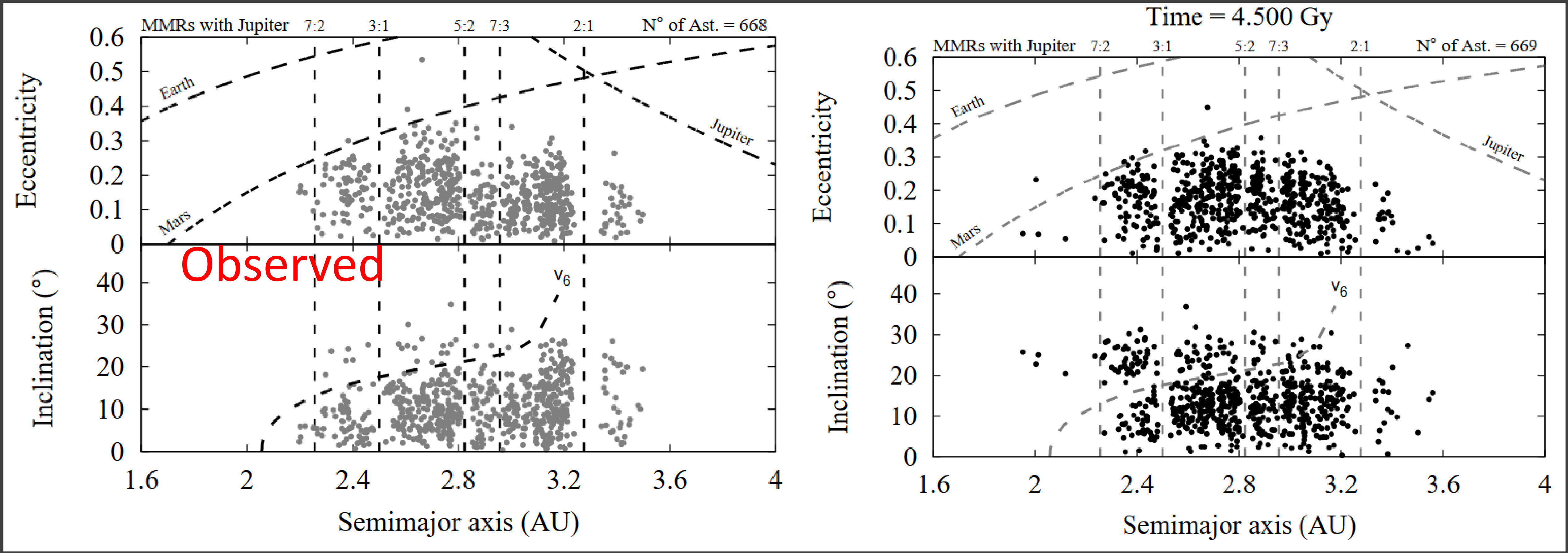
http://perso.astrophy.u-bordeaux.fr/SRaymond/movies_grandtack.html

Mass distribution

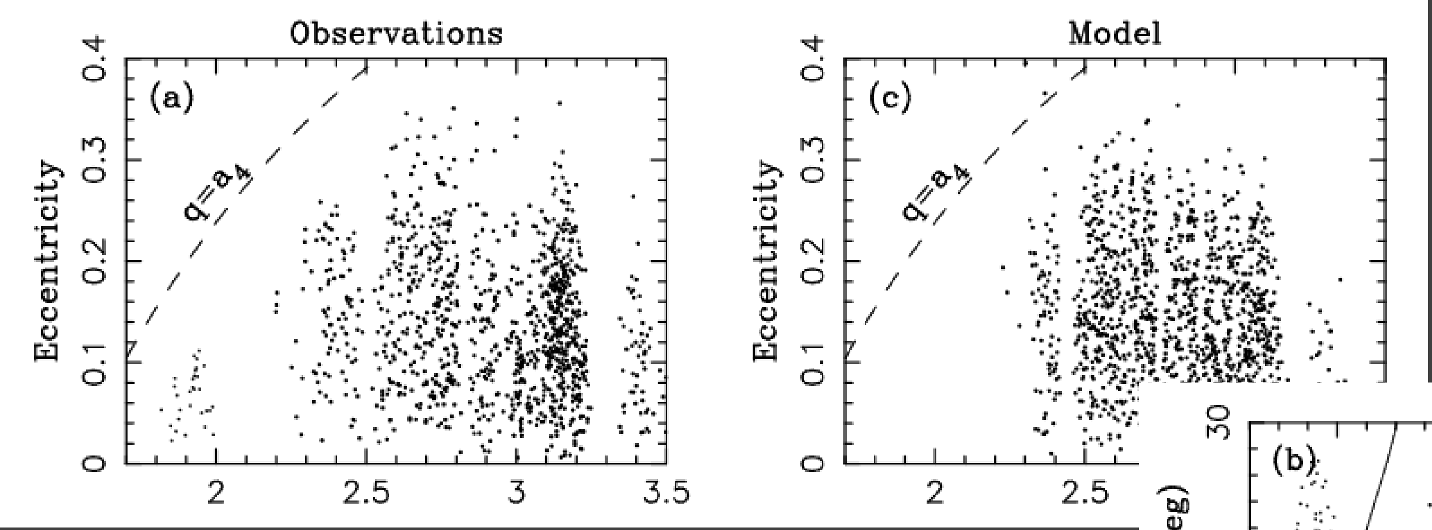




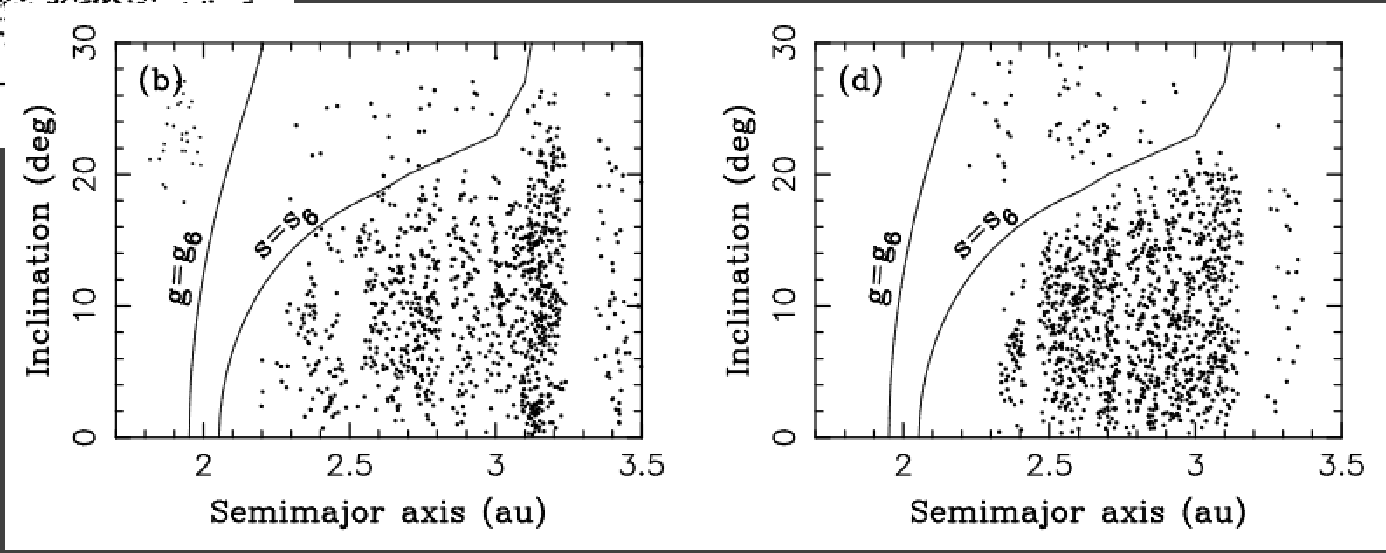
Asteroids and Grand Tack: details



Asteroids in the jumping Jupiter model

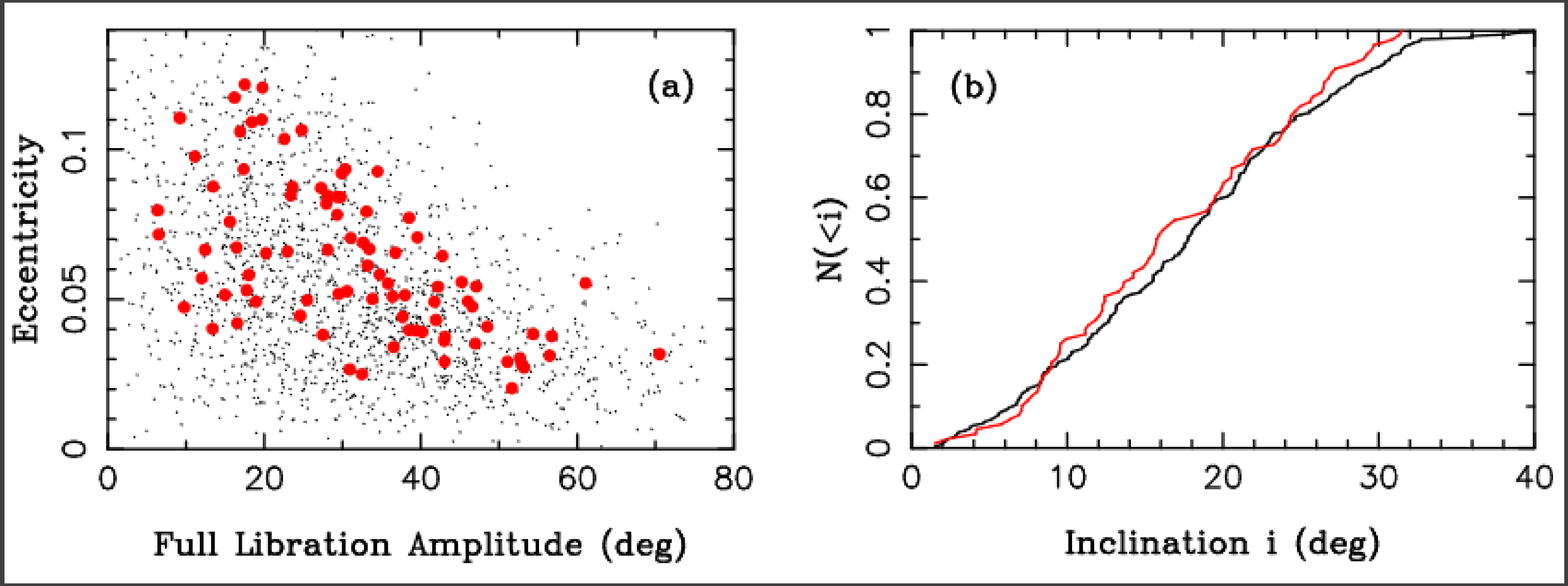


Solid line – secular resonances.
Dashed lines – Mars crossing.



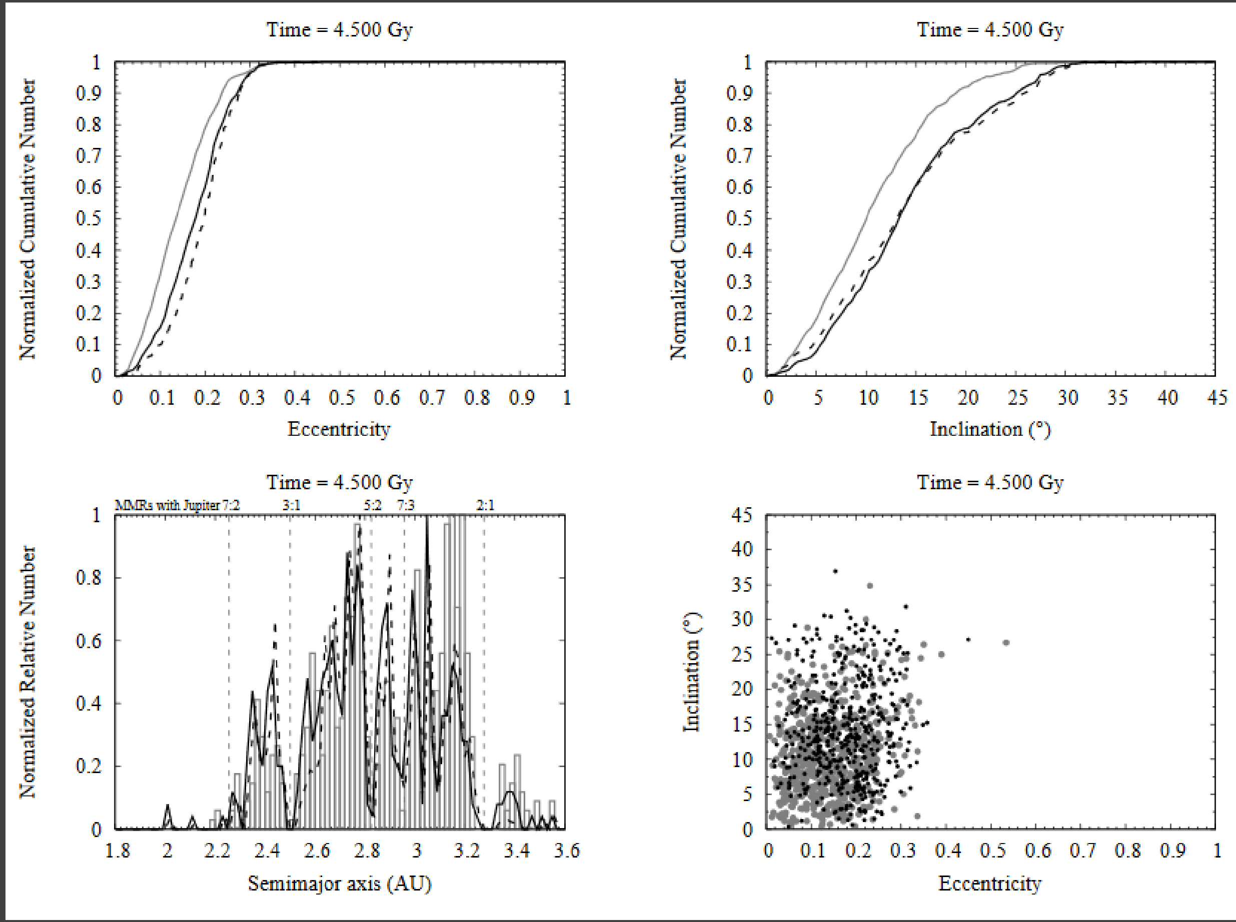
The orbital distribution of main belt asteroids
with diameters D>30 km for a>2 au
and D>5 km for a<2 au in the case of Hungarians.

Trojans of Jupiter in the jumping model



Red symbols and line – modeling, black – observations.

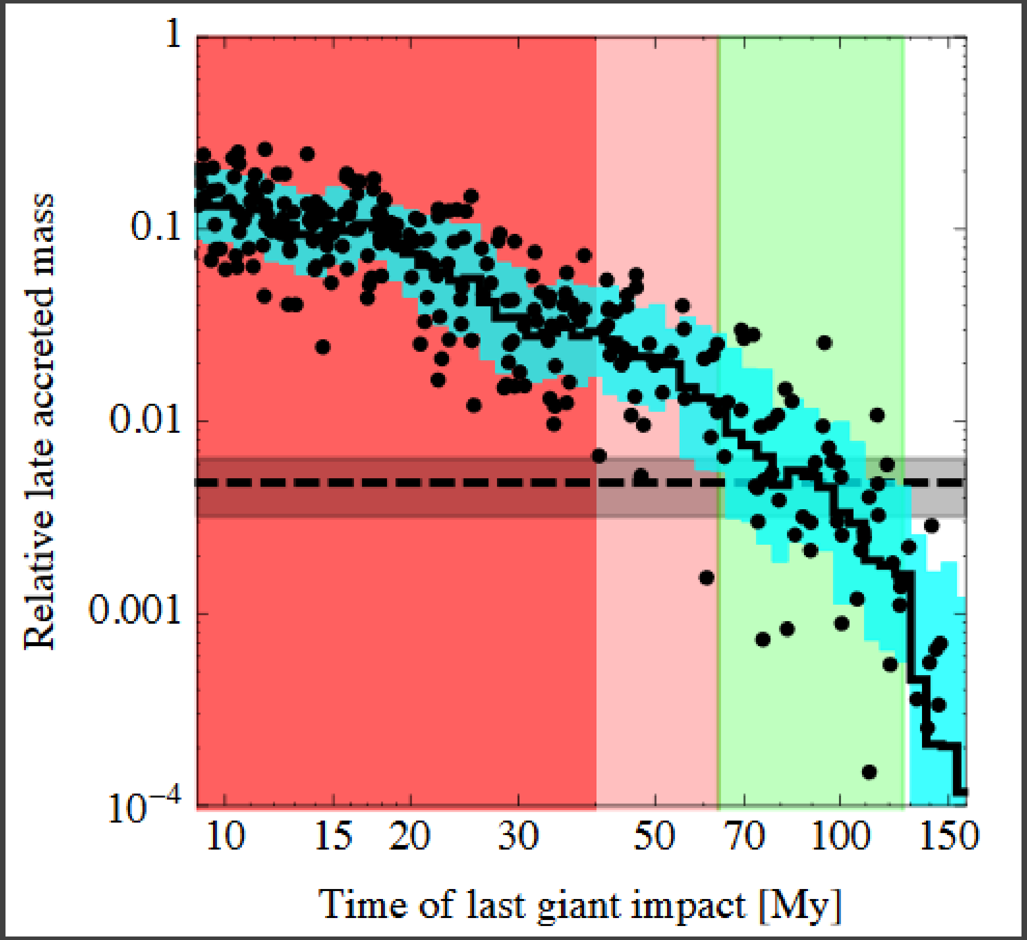
Detailed comparison (Grand Tack)

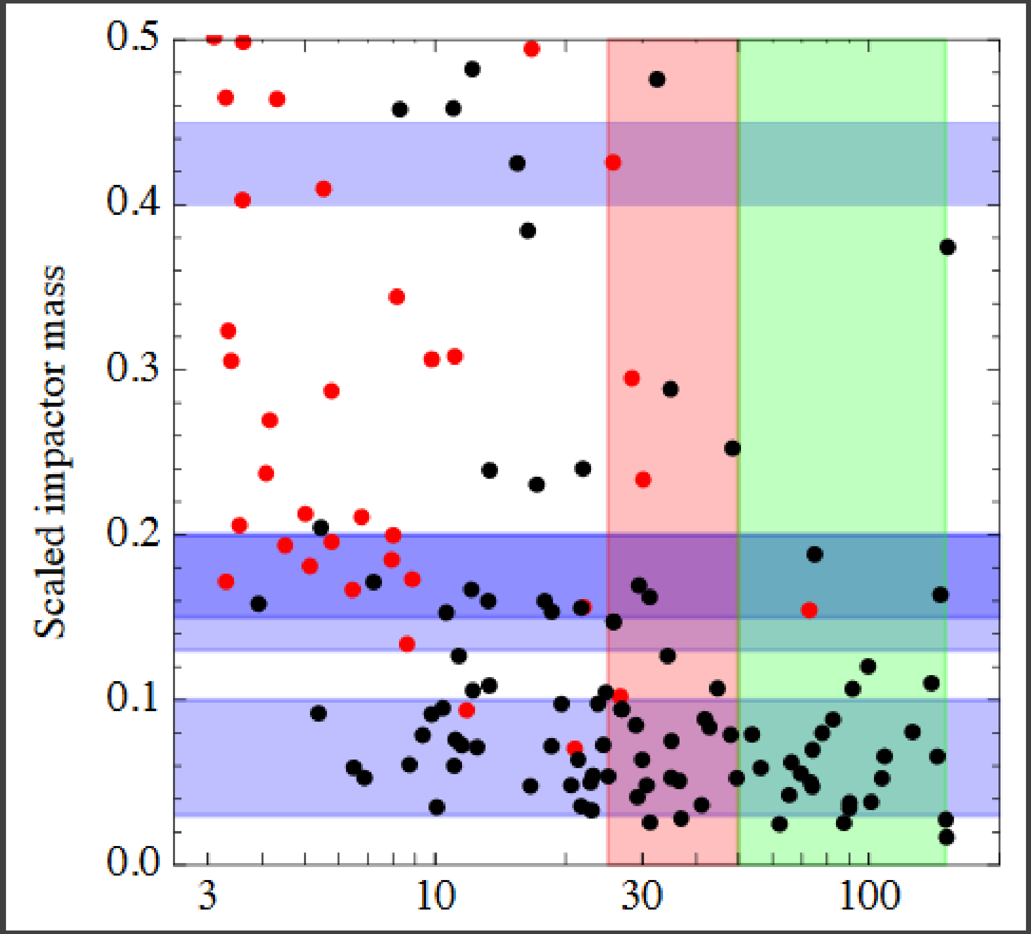


$\sim 1.6\times10^{-3}\ M_\oplus$

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

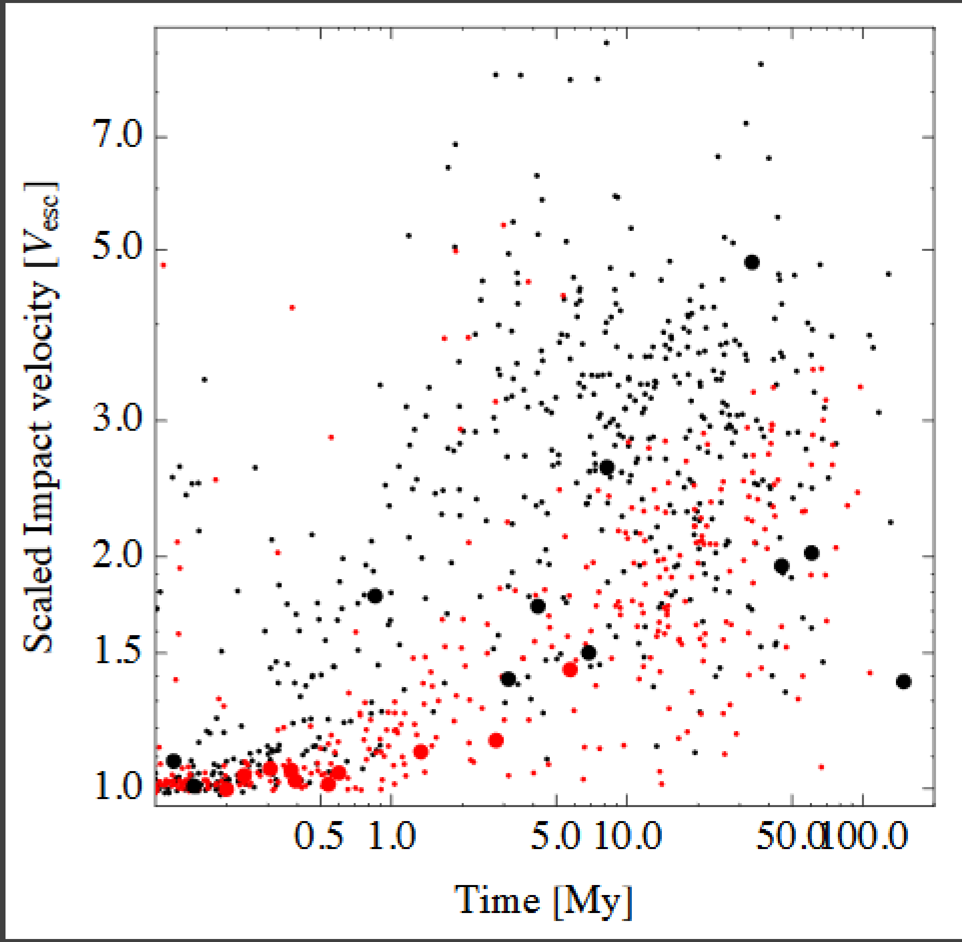
Moon formation and Grand Tack

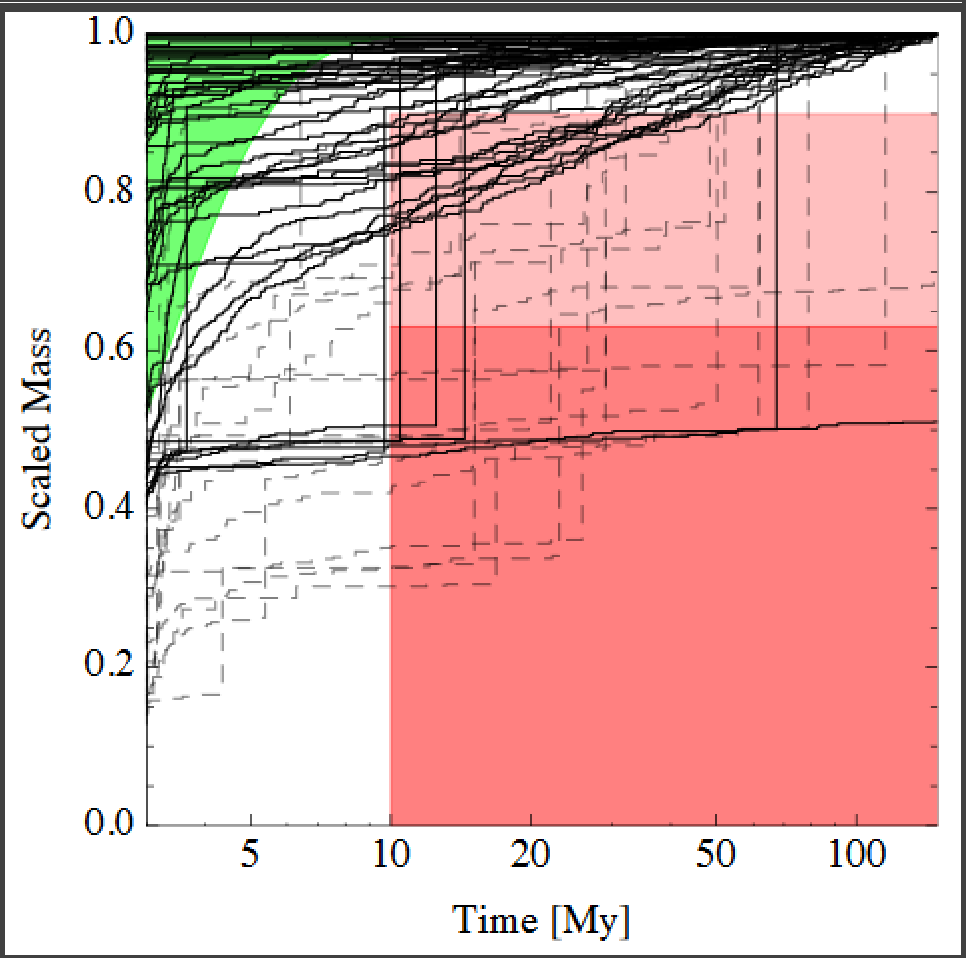




https://www.hou.usra.edu/meetings/lpsc2014/pdf/2274.pdf

Mars and Venus in Grand Tack

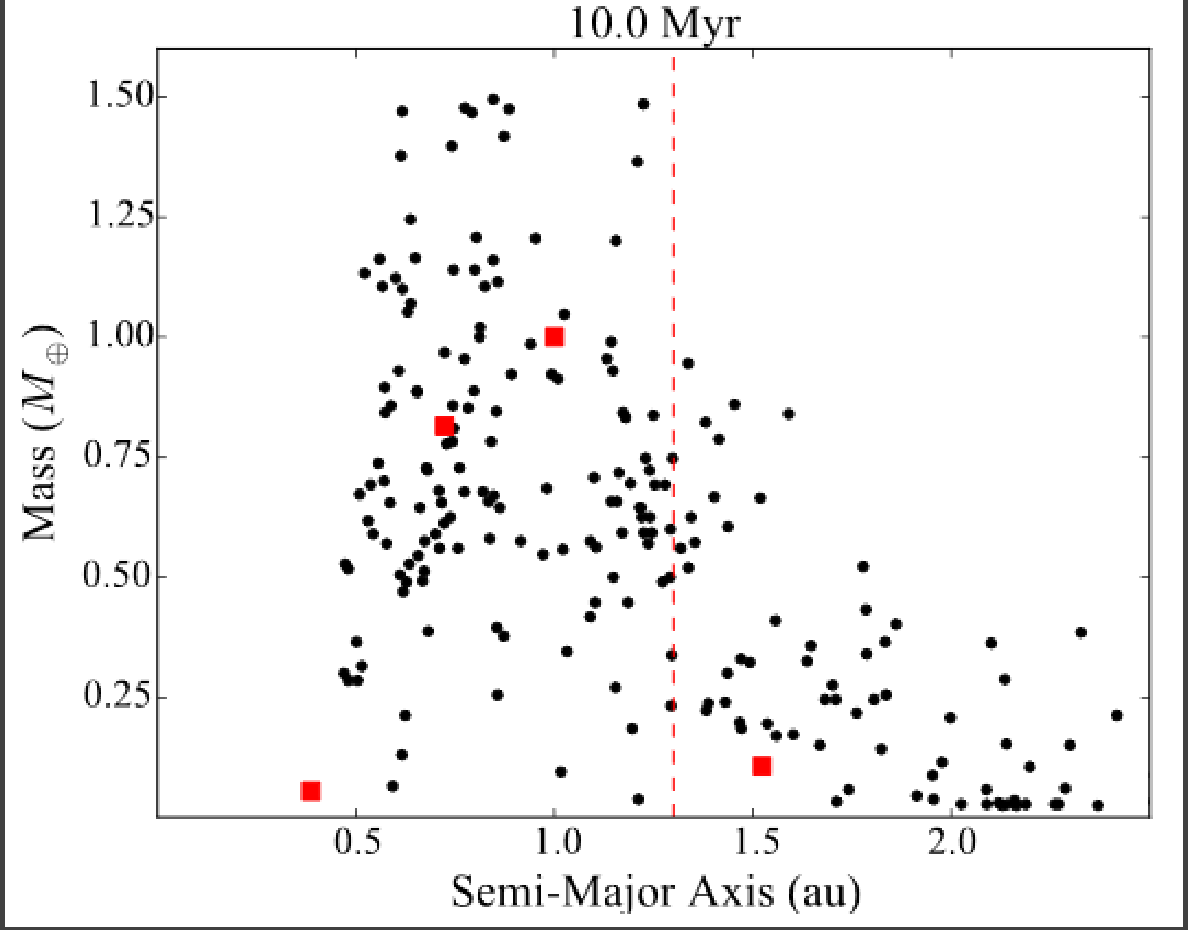


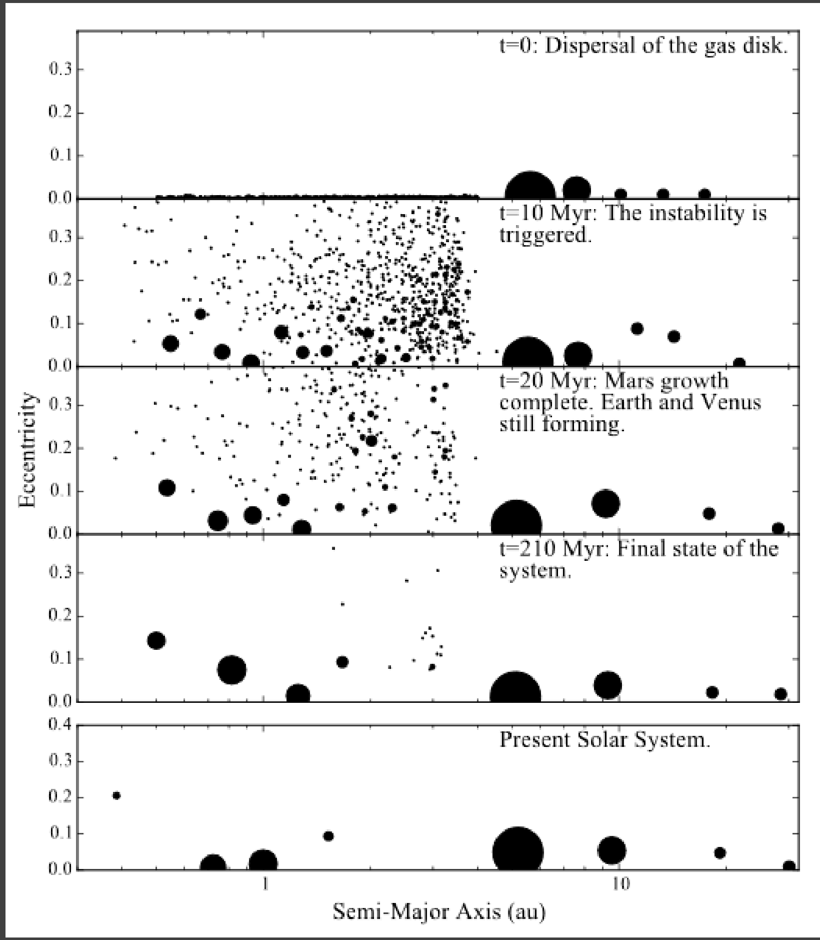


https://www.hou.usra.edu/meetings/lpsc2014/pdf/2274.pdf

New calculations

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





1804.04233

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.
- Dynamical evolution (review) 1807.06647 Dynamical evolution of the aerly Solar System
  D. Nesvorny