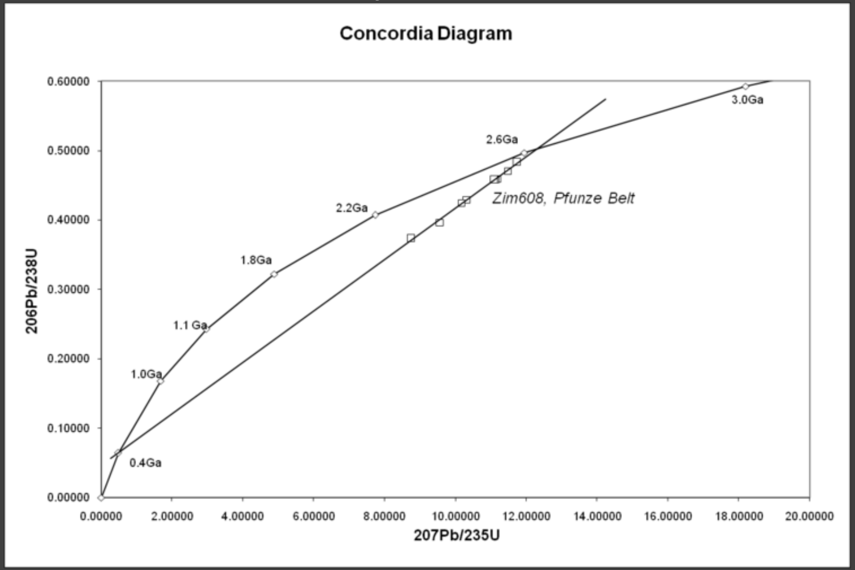
Solar system

SERGEI POPOV

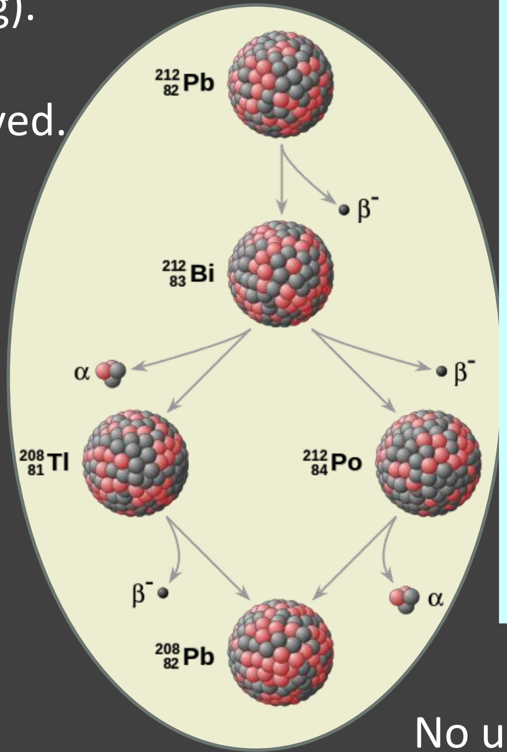
Solar system age

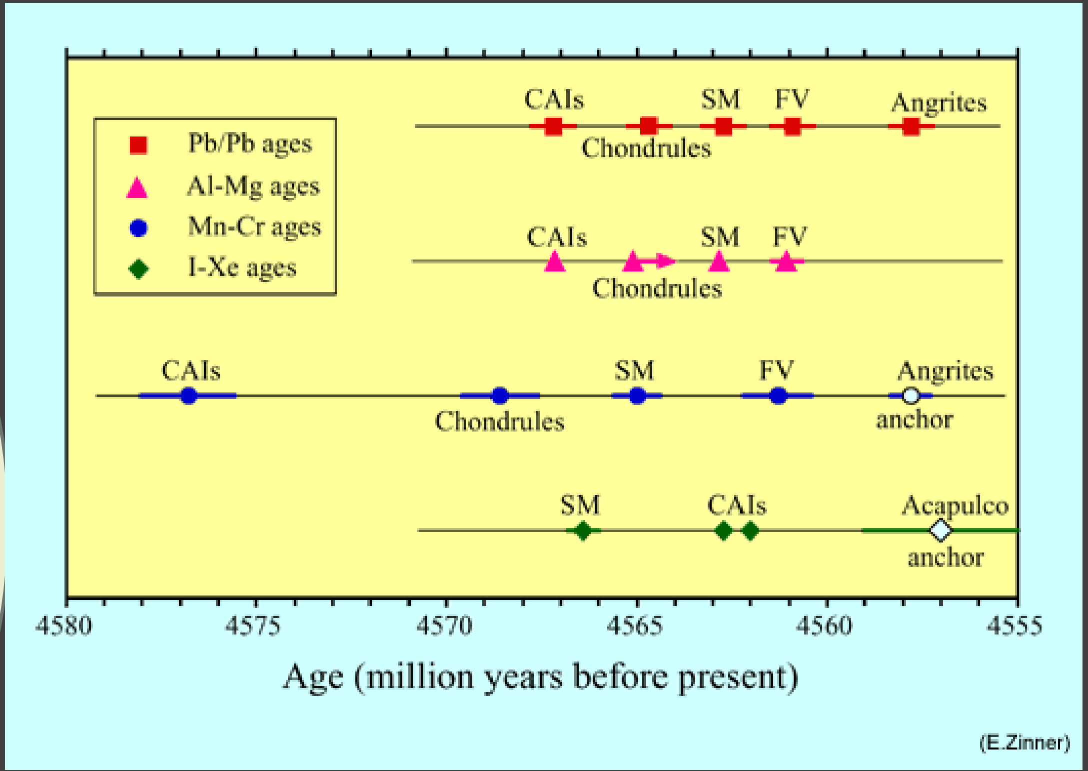
http://www.nhm.ac.uk

The age is determined due to meteorite studies.
Some 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


Concordia Diagram

wikipedia.org





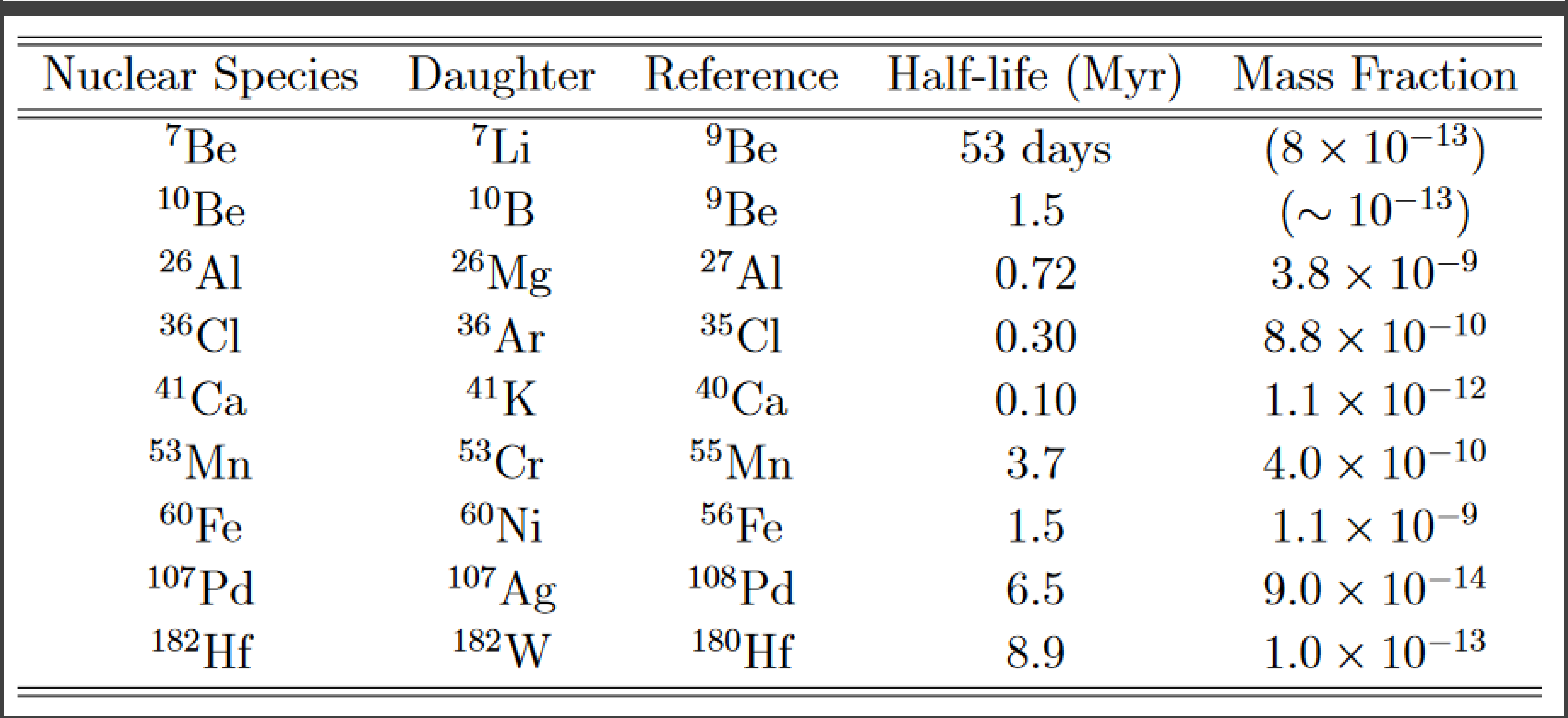
(E.Zinner)

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

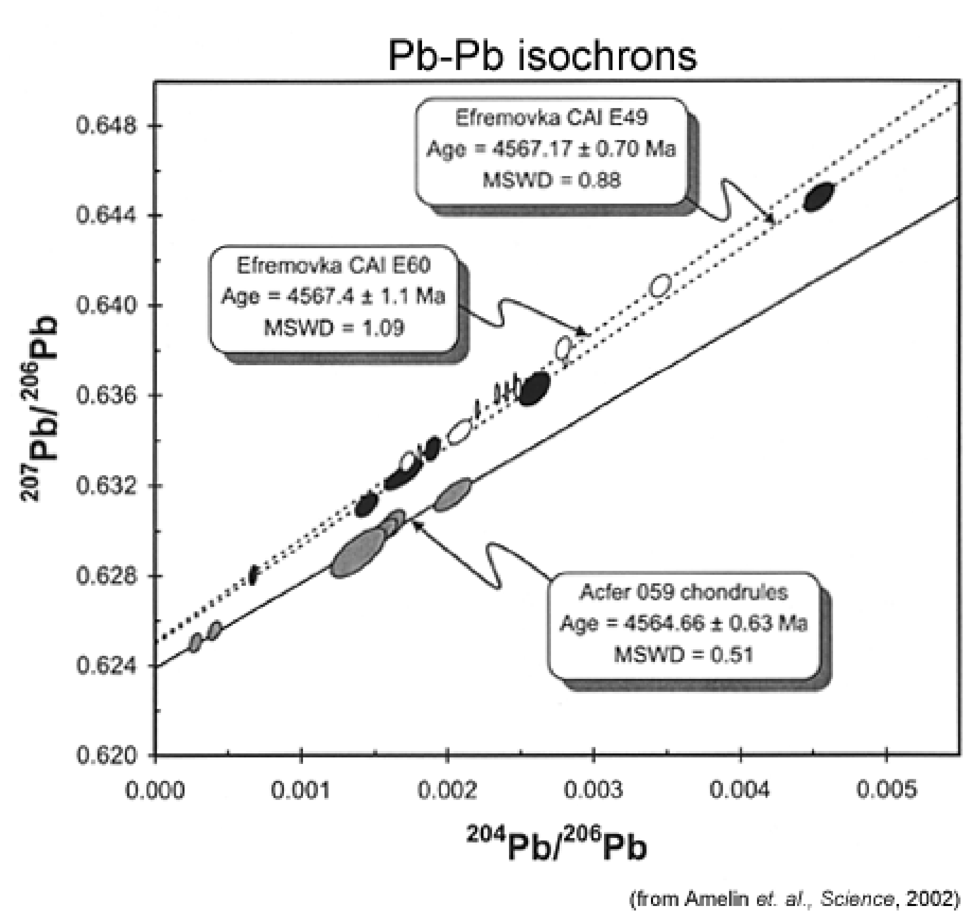


Nuclear Species	Daughter	Reference	Half-life (Myr)	Mass Fraction
^{7}Be	^{7}Li	^{9}Be	53 days	(8×10^{-13})
^{10}Be	^{10}B	^{9}Be	1.5	$(\sim 10^{-13})$
^{26}Al	^{26}Mg	^{27}Al	0.72	3.8×10^{-9}
^{36}Cl	^{36}Ar	^{35}Cl	0.30	8.8×10^{-10}
^{41}Ca	^{41}K	^{40}Ca	0.10	1.1×10^{-12}
^{53}Mn	^{53}Cr	^{55}Mn	3.7	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}

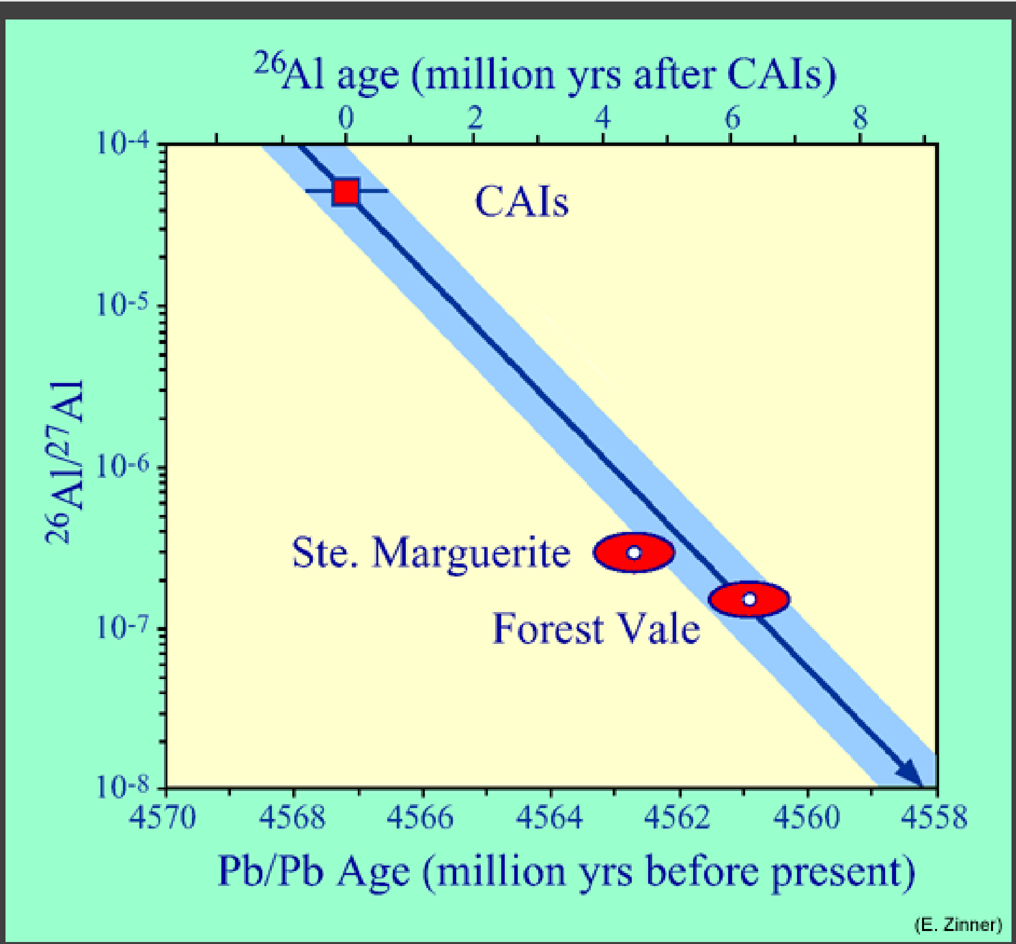
1001.5444

Two approaches complete each other

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



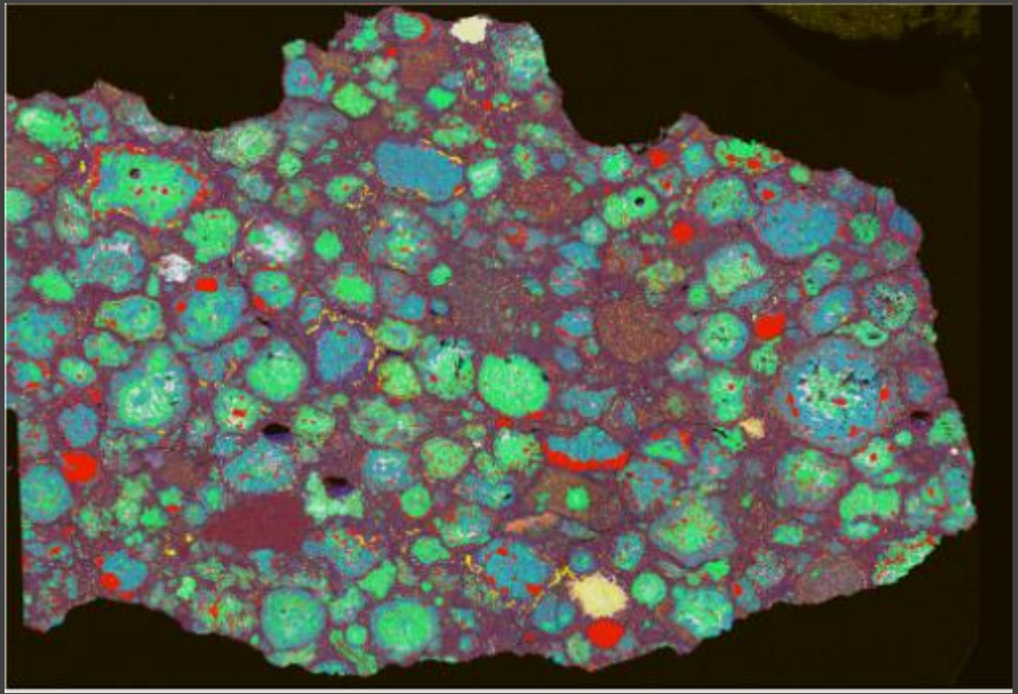
(from Amelin *et. al.*, *Science*, 2002)



(E. Zinner)

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

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

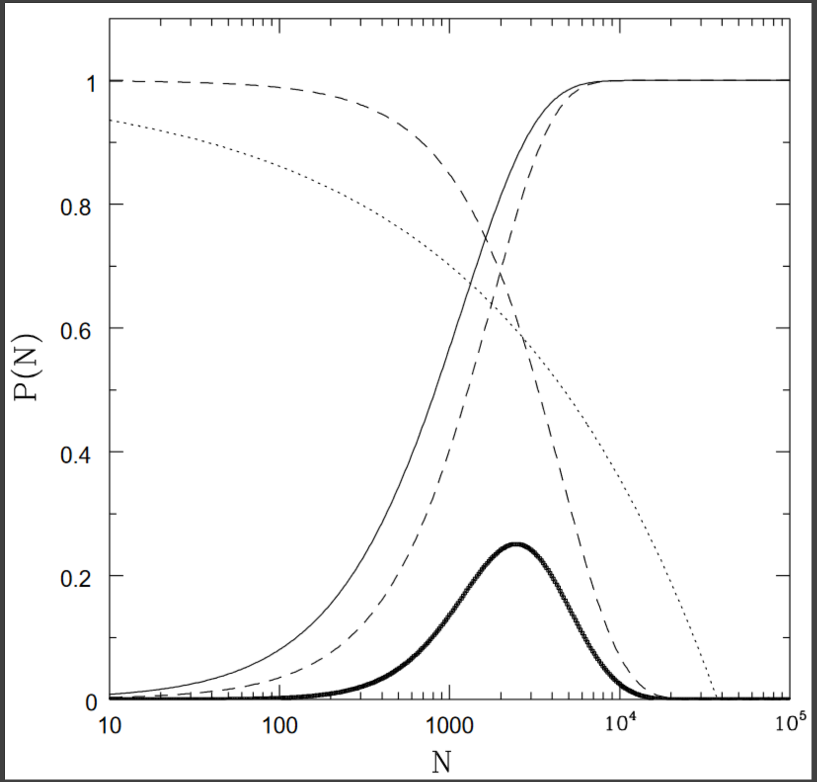


aluminum (white), magnesium (green), silicion (blue), calcium (yellow), iron (red)

1501.03101

Near-by supernova or an AGB/WR star.

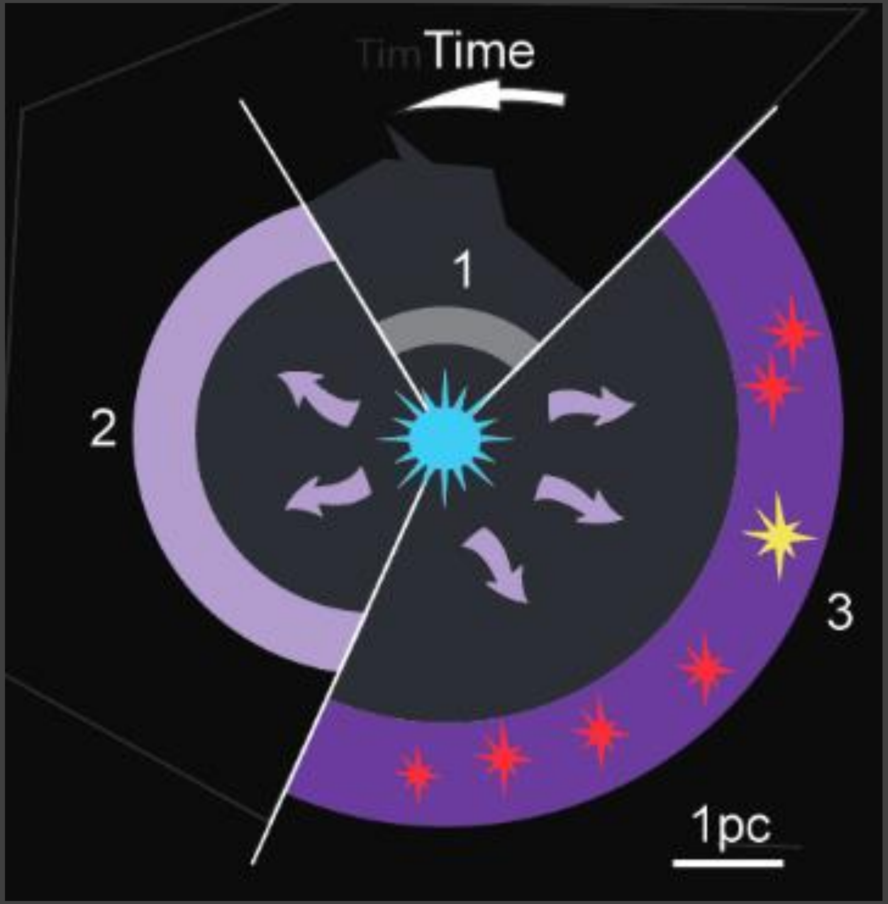
Cluster cannot be too rich, otherwise EUV and FUV emission of massive stars can significantly influence protoplanetary disc within 30 AU due to photoevaporation.



Number of stars in the Sun cluster

1001.5444

Supernova vs. evolved star



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

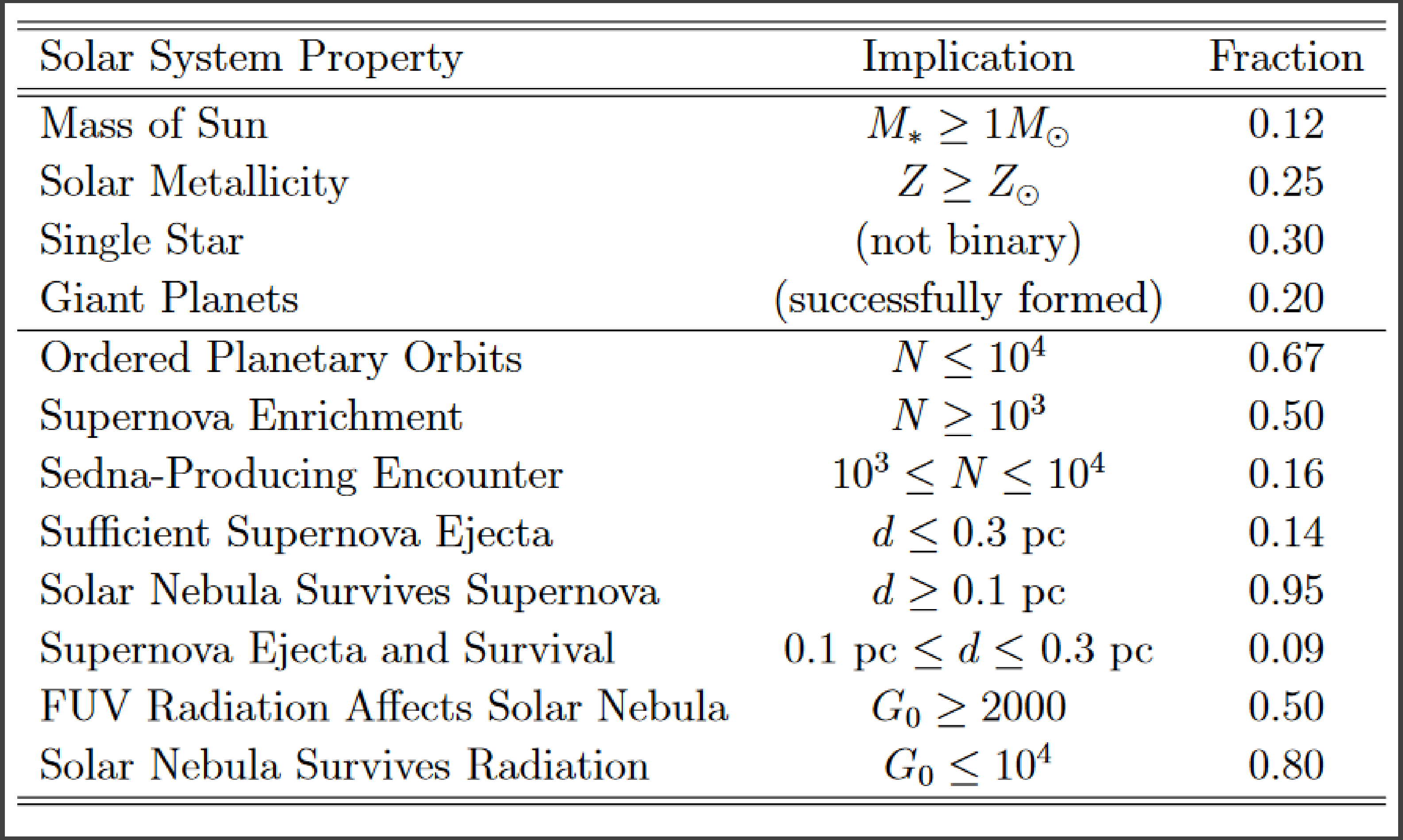
Thus, the exact origin is not known, yet.
It seems that Fe-60 has been formed due to a SN (on larger time scale), and Al-26 – appeared from wind of a near-by evolved star.

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

However, influence of the cluster cannot explain orbital inclinations (see 2002.05656).

About other aspects of cluster influence on a forming planetary system see 2007.07890

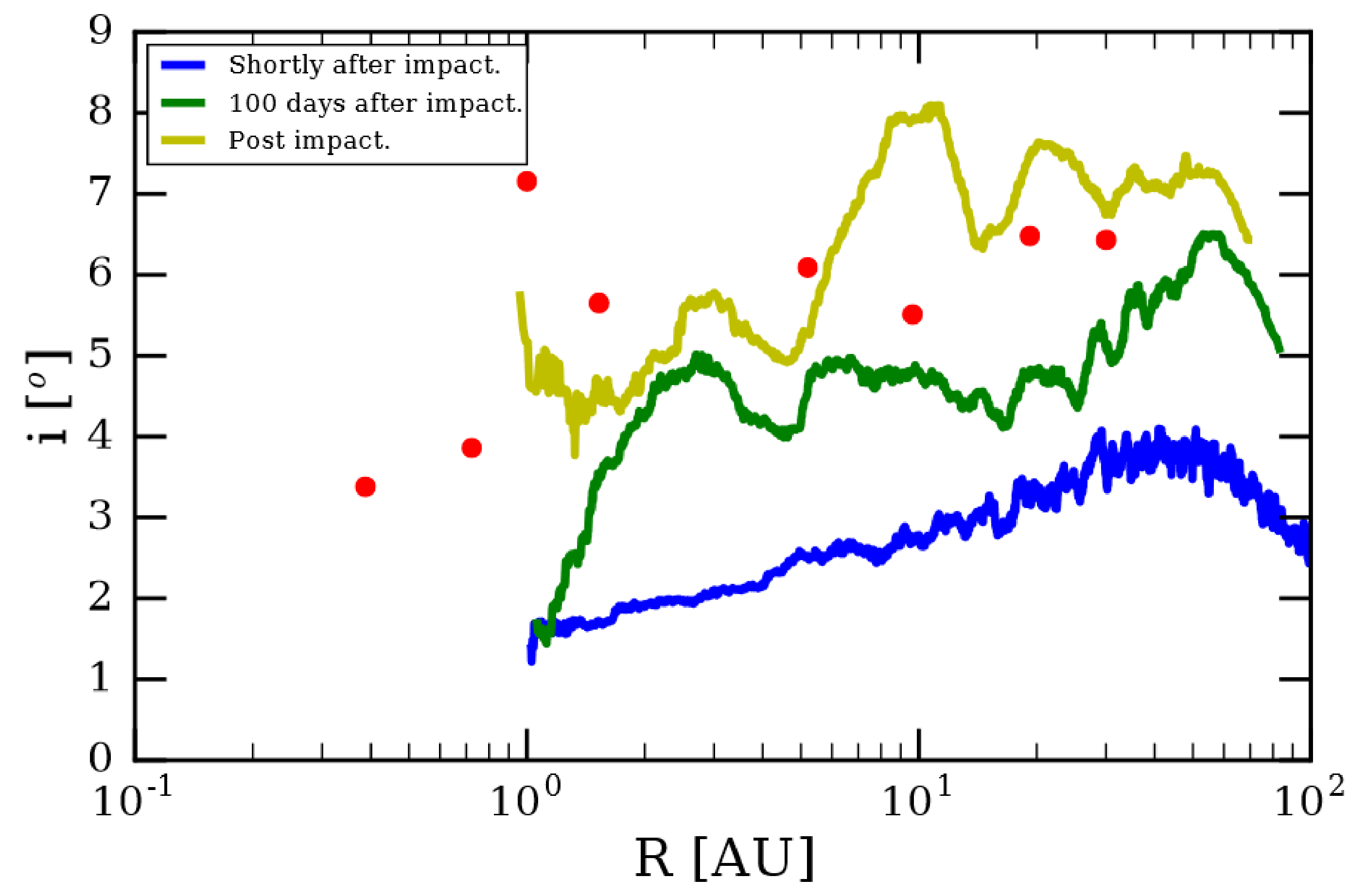
1001.5444

Supernova influence on the SoSys

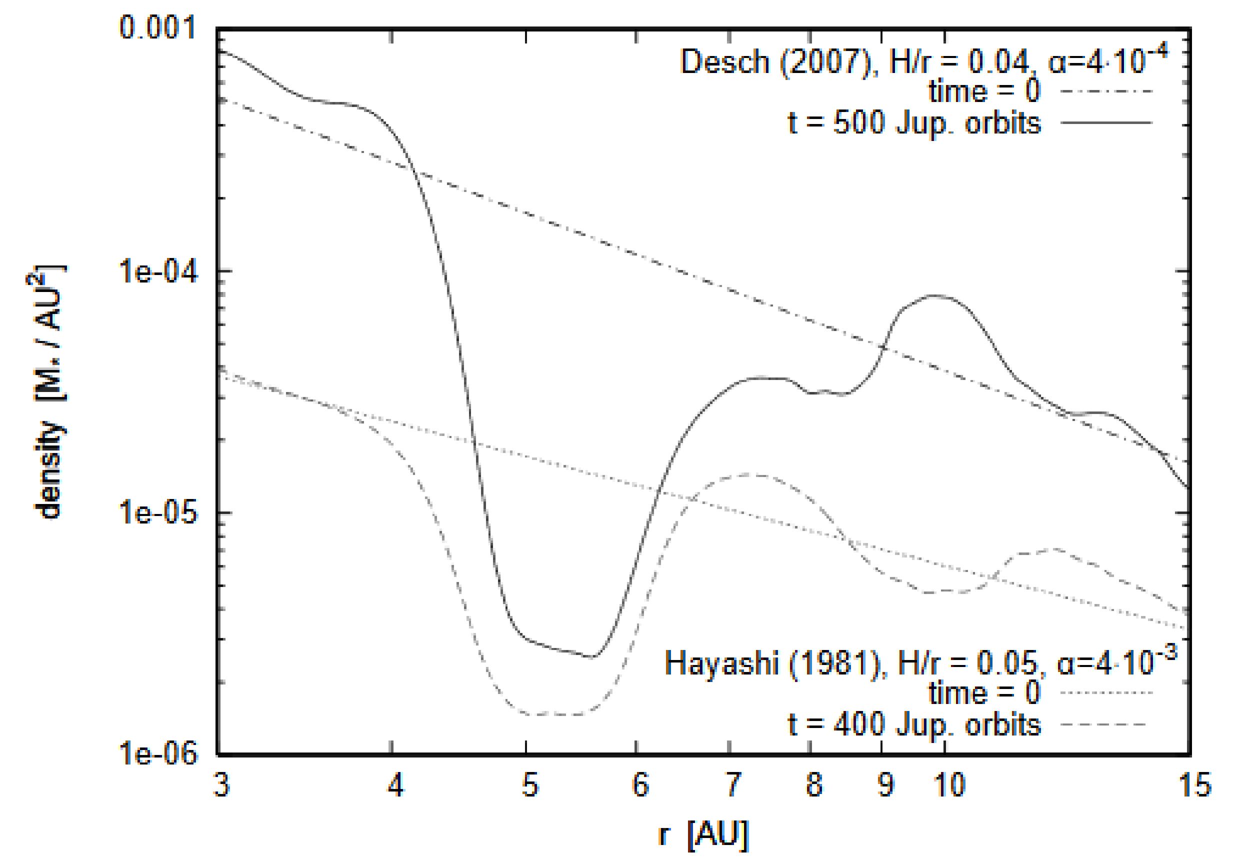
Distance 0.15-0.4 pc

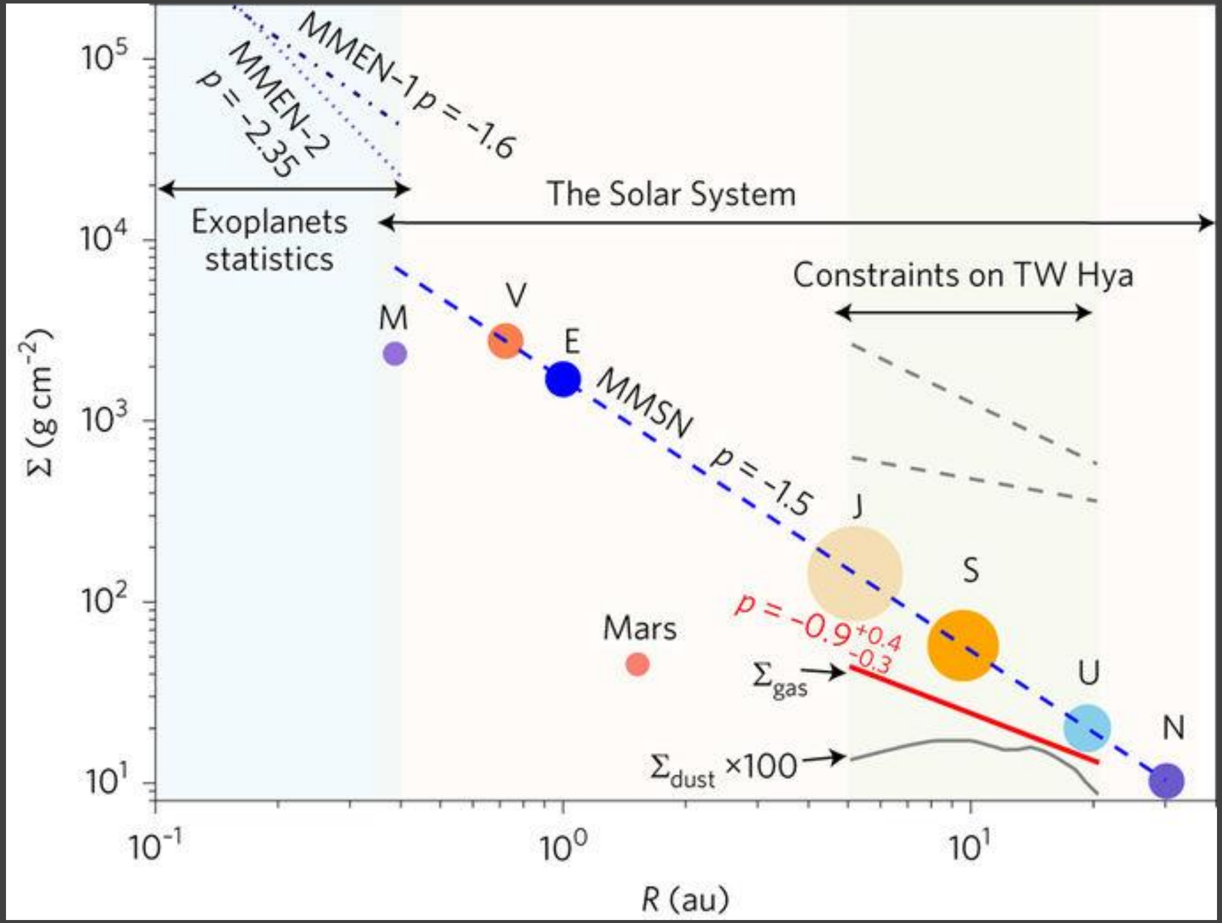
- heating (dust melting)
- enrichment
- blast wave
  - stripping
  - tilting

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

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

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

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

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

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

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

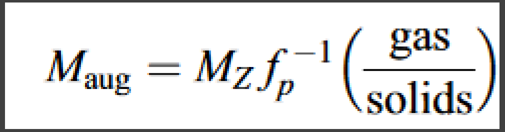
Desch 2007
Planets at initial positions
in the NICE model

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.

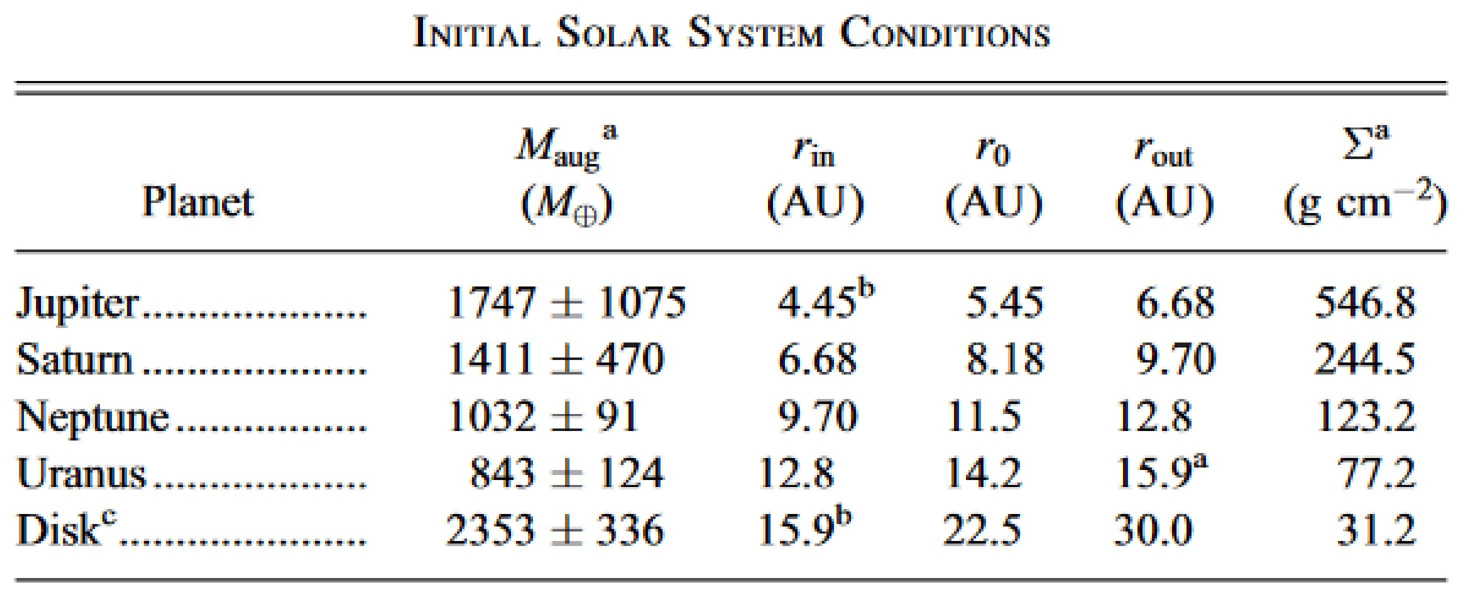
New MMSN model

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!

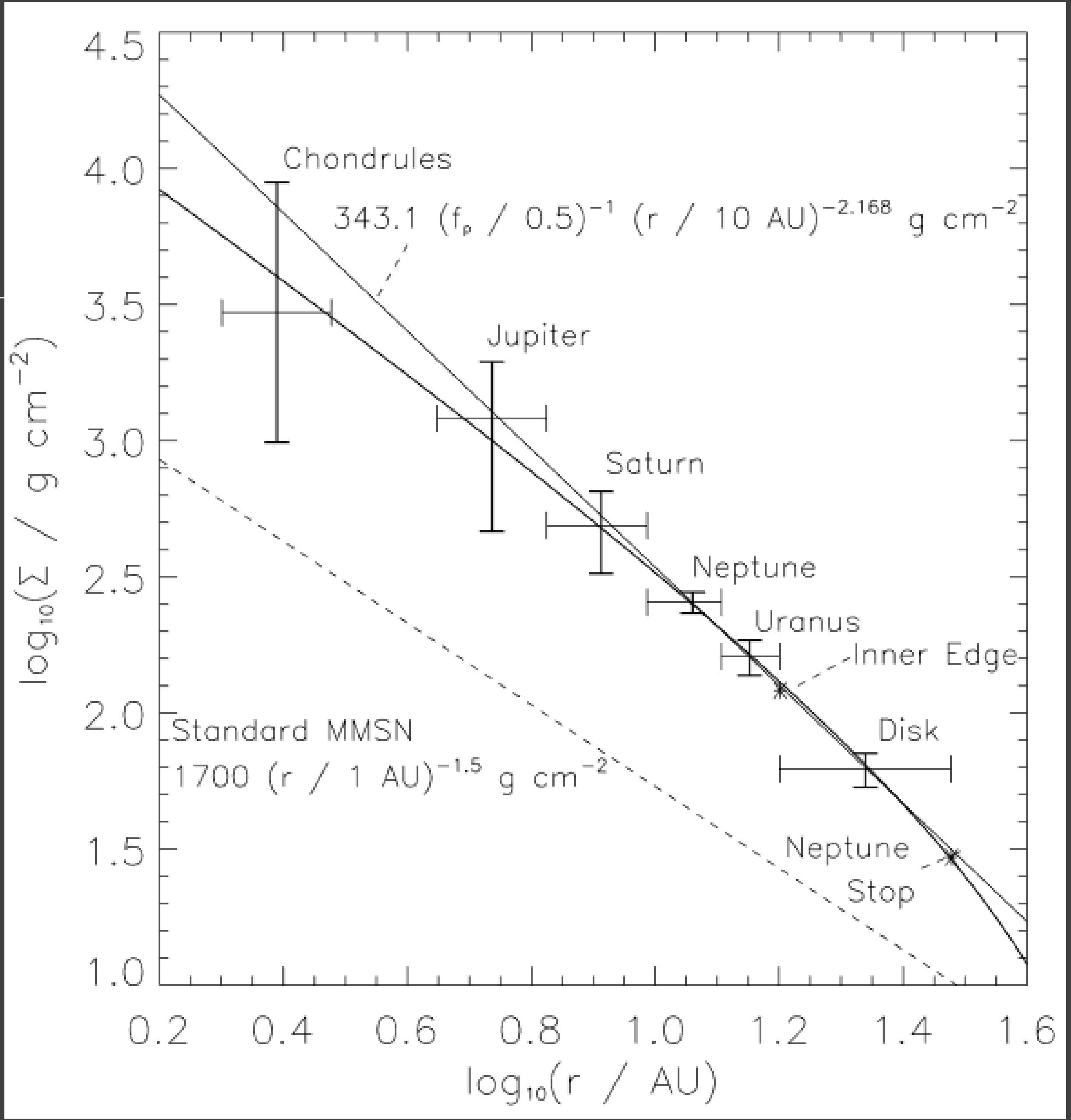
Desch 2007

Surface density

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

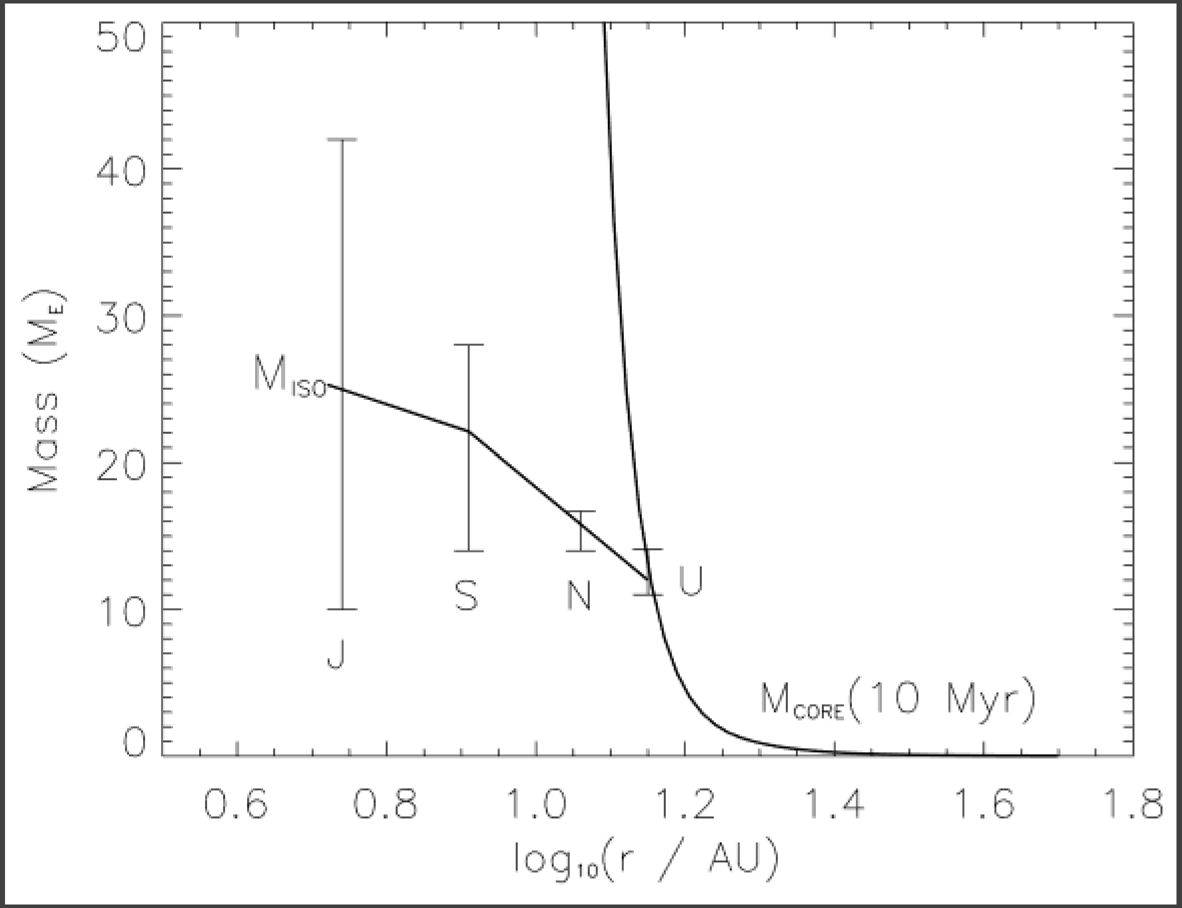
$$\rho_{\mathrm{gas}}(r,0) = 1.93\times10^{-11}\left(\frac{f_p}{0.5}\right)^{-1}\left(\frac{r}{10\ \mathrm{AU}}\right)^{-3.4537}\ \mathrm{g\ cm^{-3}}$$

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.



Desch 2007

Comparison with the isolation mass

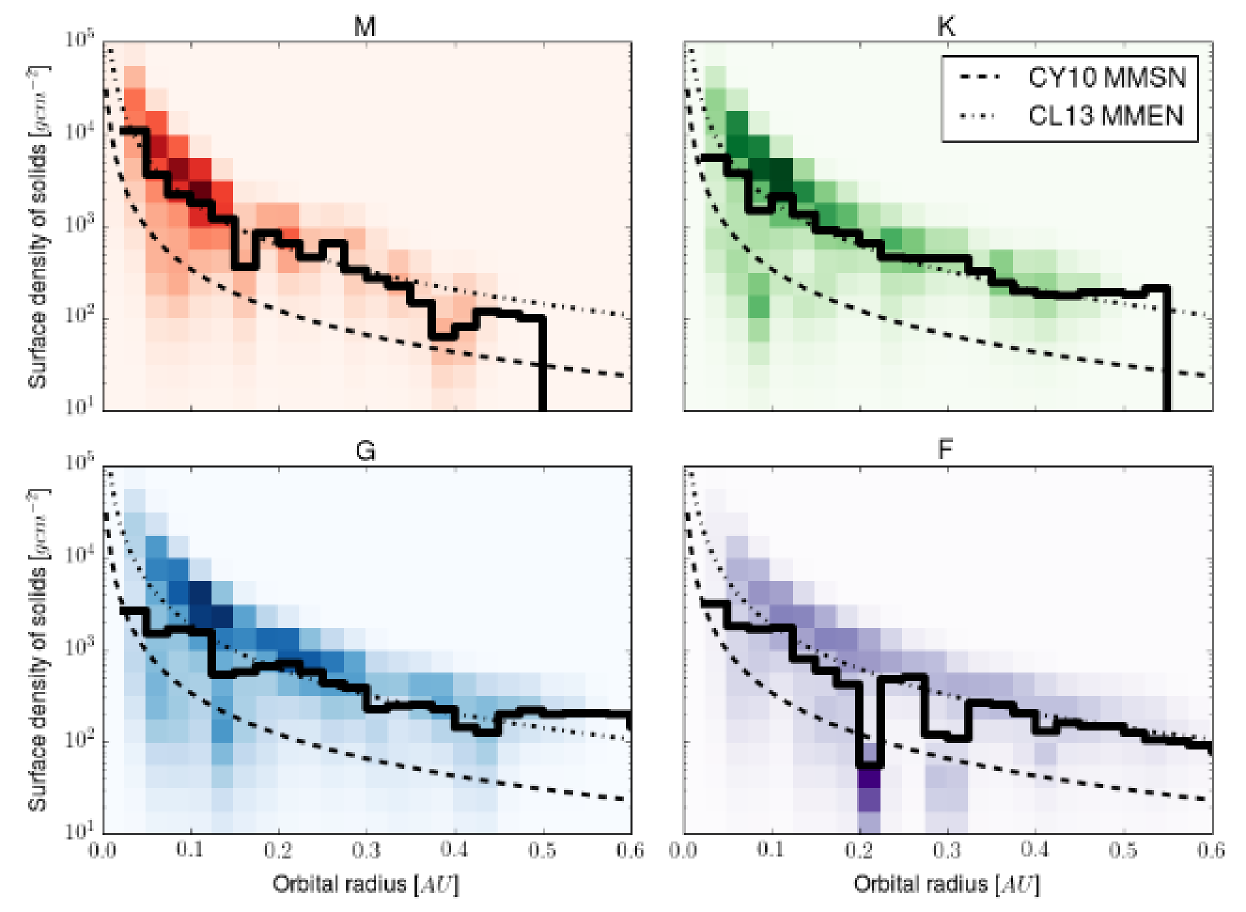


Vertical lines – total amount of solids in each planet.

Planets collect almost all available solids
in their feeding zones.

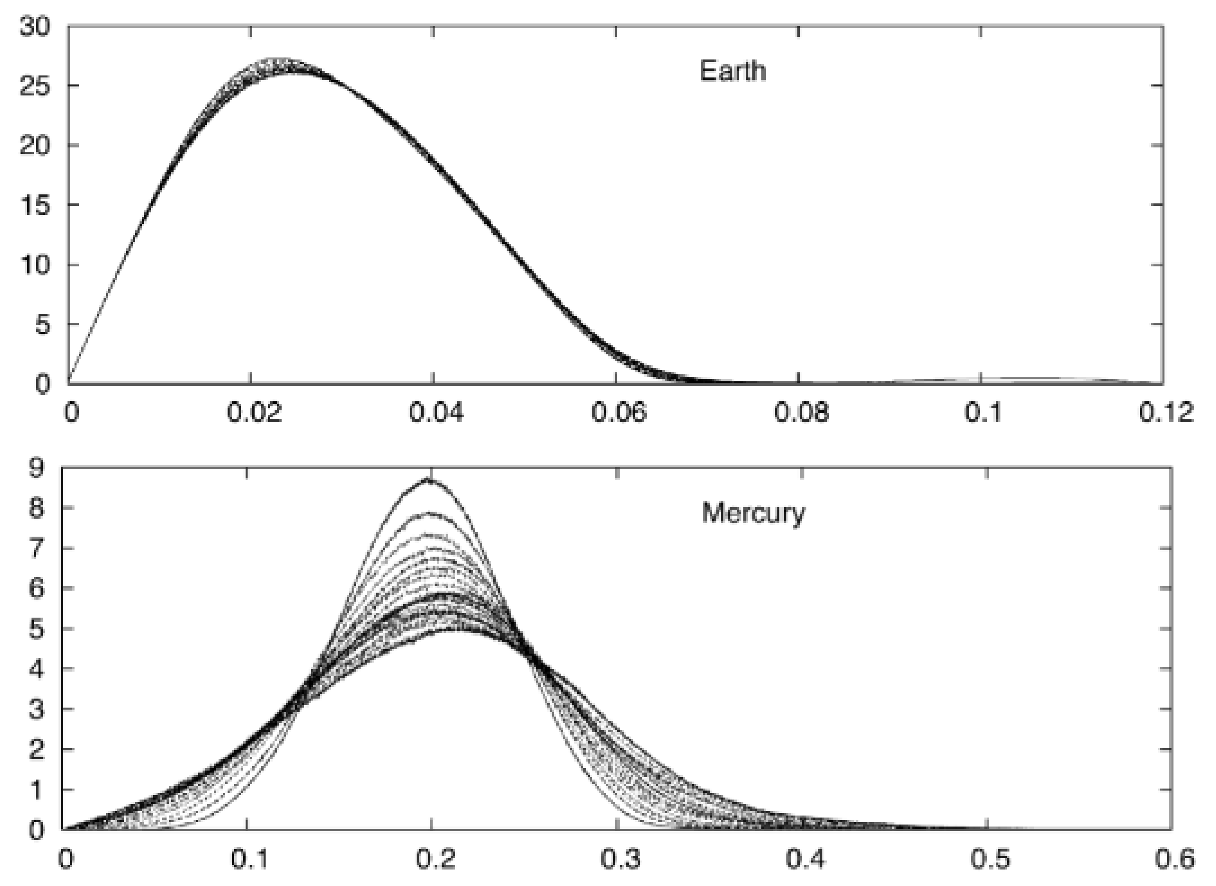
Desch 2007

MMEN and data



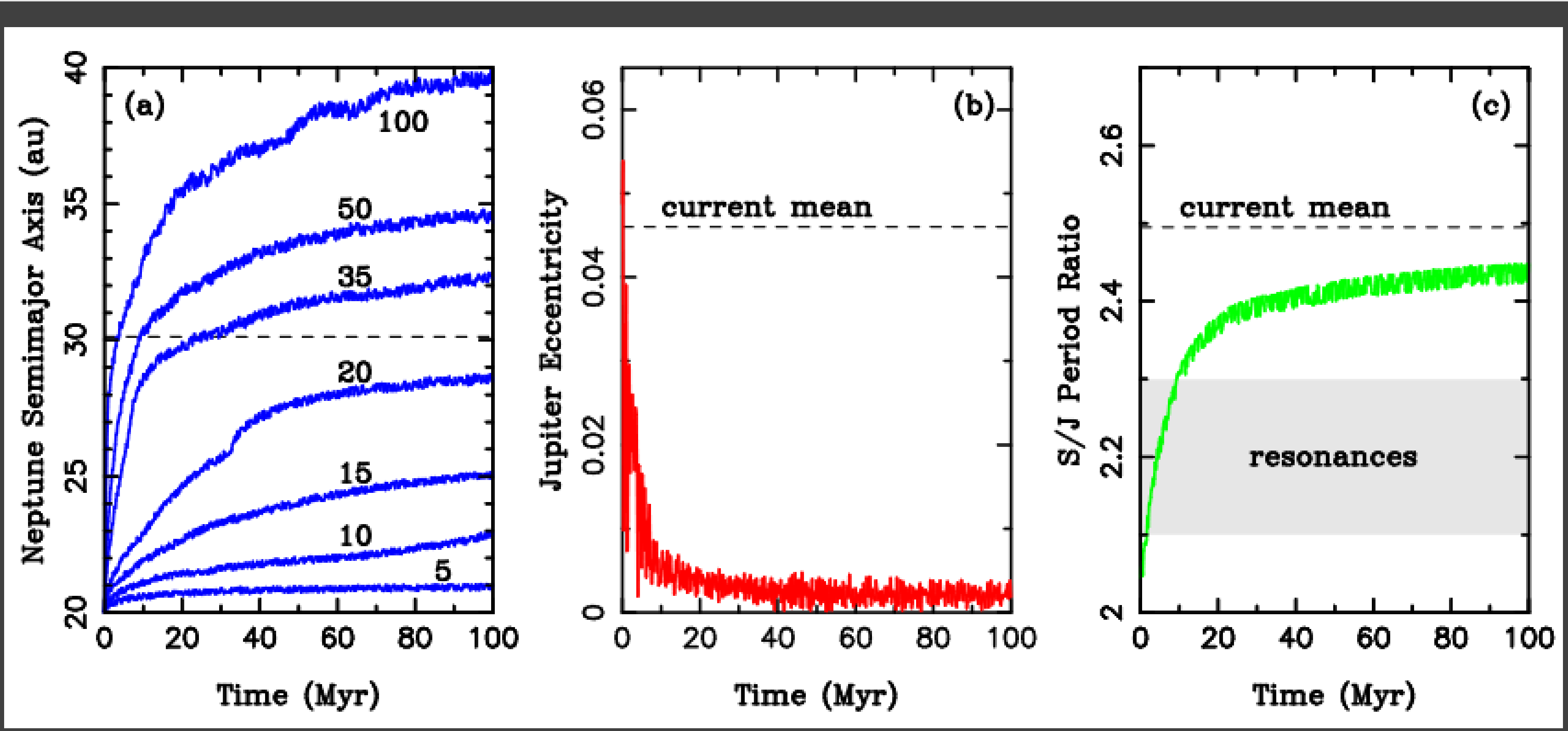
1911.03579

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



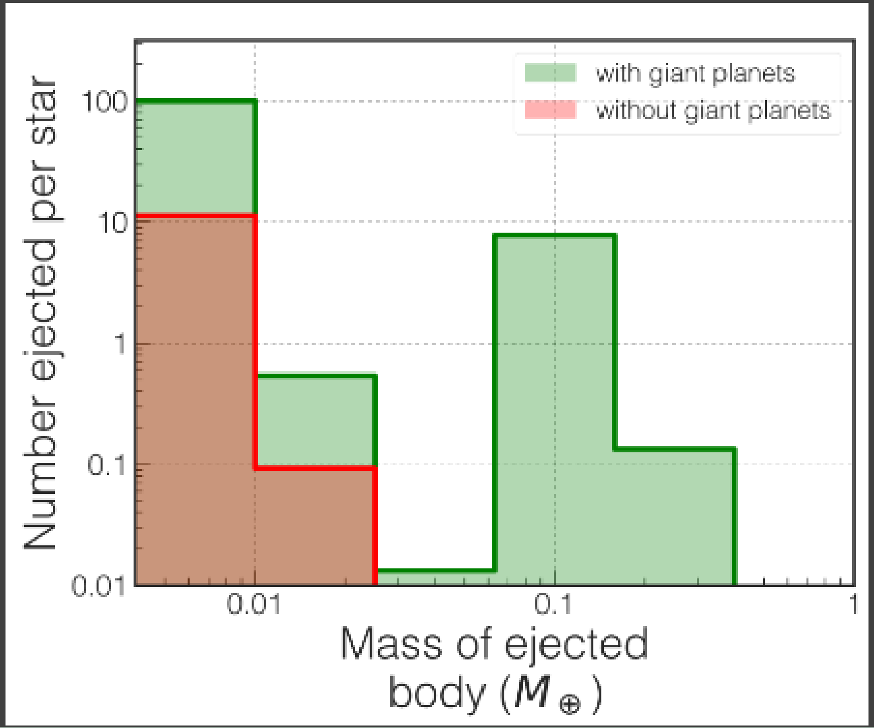
Jupiter migrates inward, other giants – outward.

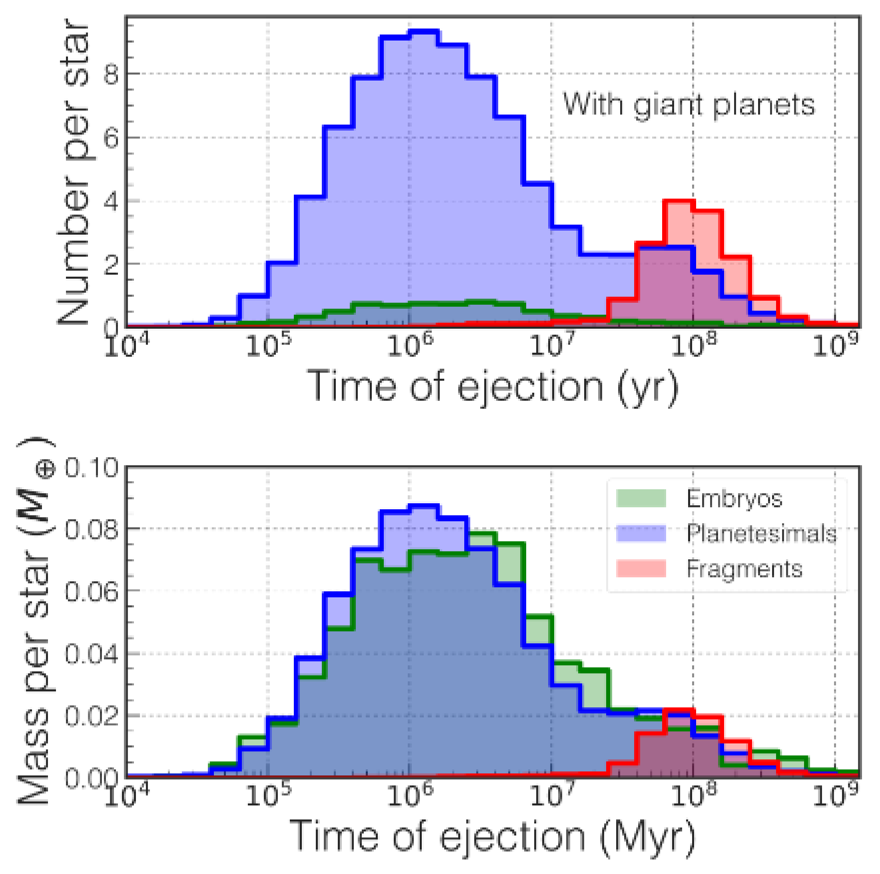
Ejection of 15 M_{earth} by Jupiter results in migration by 0.2 au. $\delta r/r \approx m/M$

1807.06647

Planetesimals ejection

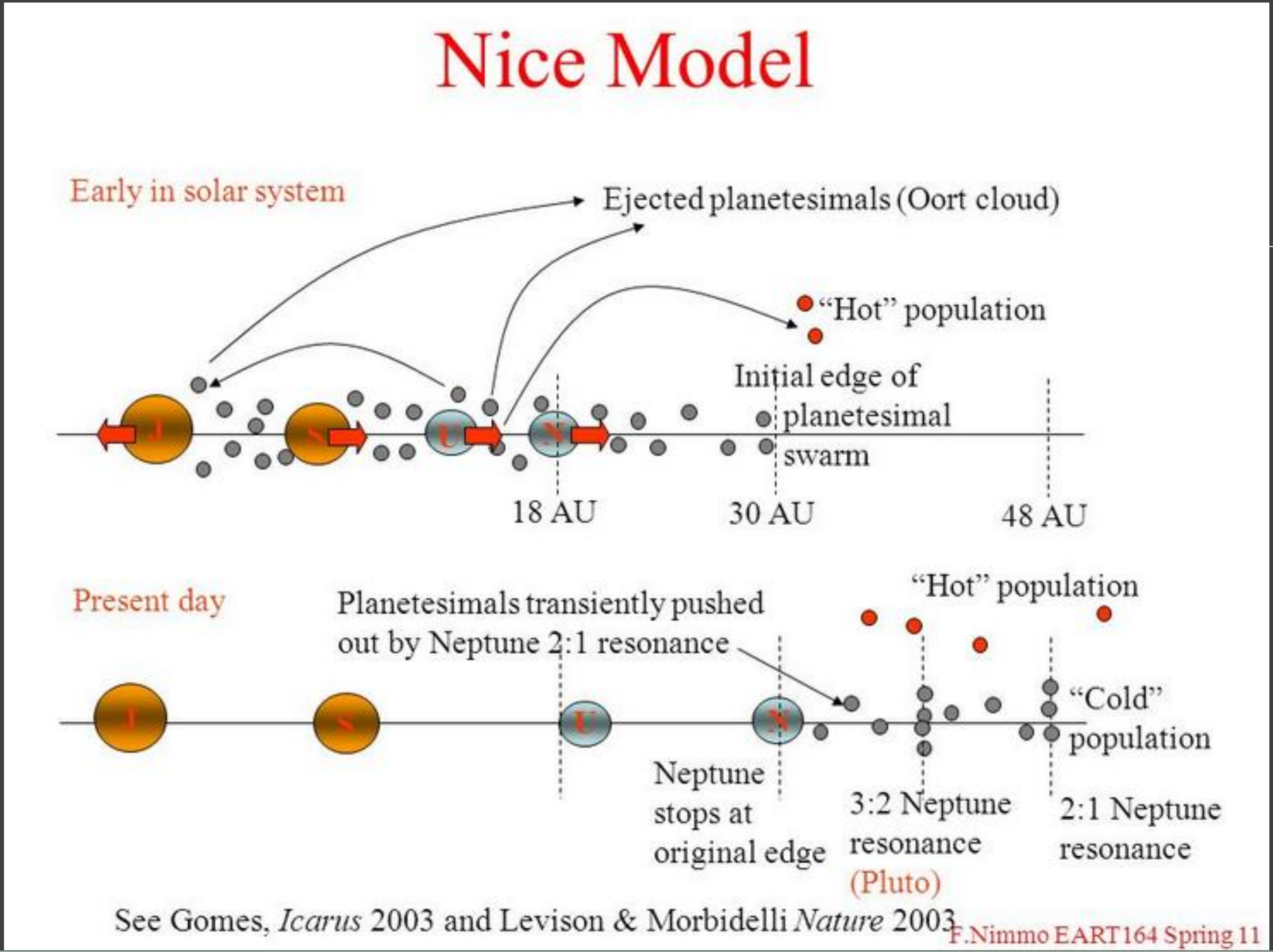
Giant planets are crucially important for ejection.
With two (Jupiter and Saturn-like giant planets)
~1/3 of 5 earth mass disk was ejected
and ~1/5 fall onto the star.





About 2.5 terrestrial mass planet is ejected per star.

1704.08749



Nice Model

Early in solar system

Ejected planetesimals (Oort cloud)

"Hot" population

Initial edge of planetesimal swarm

18 AU

30 AU

48 AU

Present day

Planetesimals transiently pushed out by Neptune 2:1 resonance

"Hot" population

"Cold" population

Neptune stops at original edge

3:2 Neptune resonance (Pluto)

2:1 Neptune resonance

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

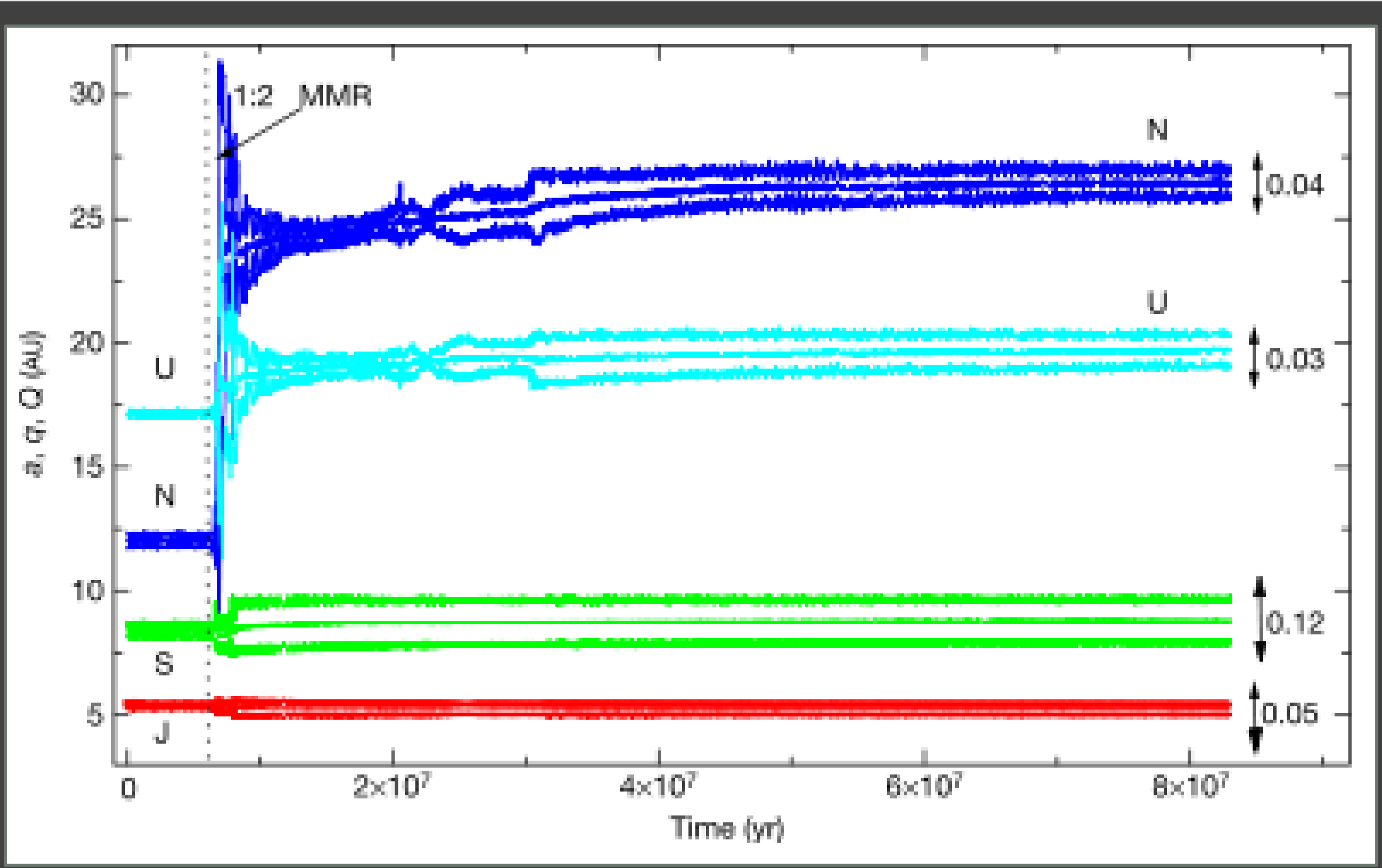
F.Nimmo EART164 Spring 11

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}

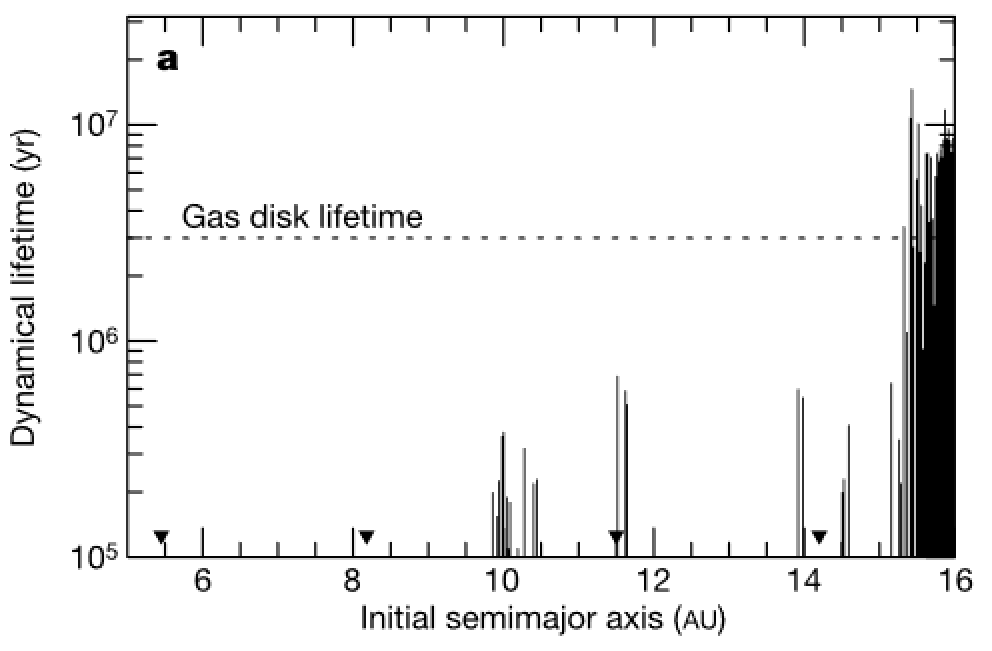
Planet migration in the Nice model



wikipedia.org

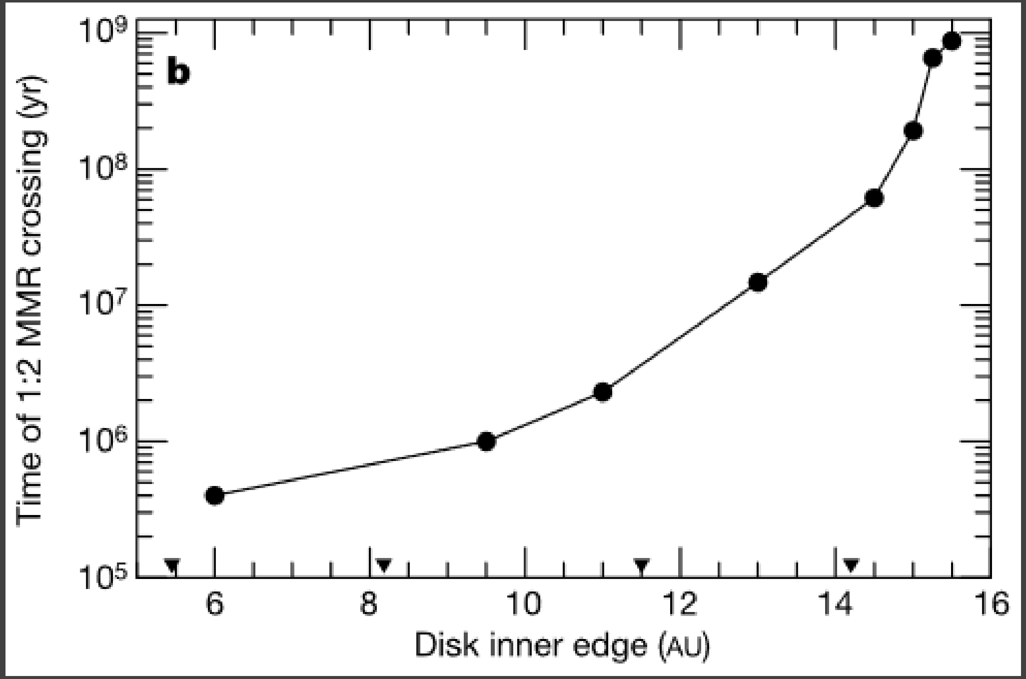
Tsiganis et al. 2005

Late heavy bombardment



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.

Gomes et al. 2005

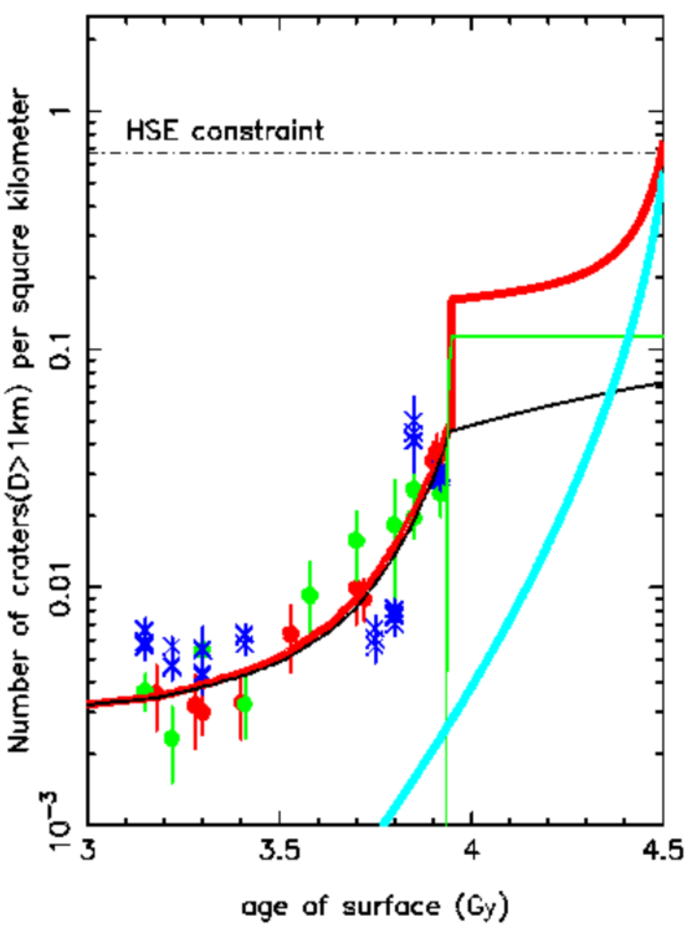
Revisiting the timeline of the LHB

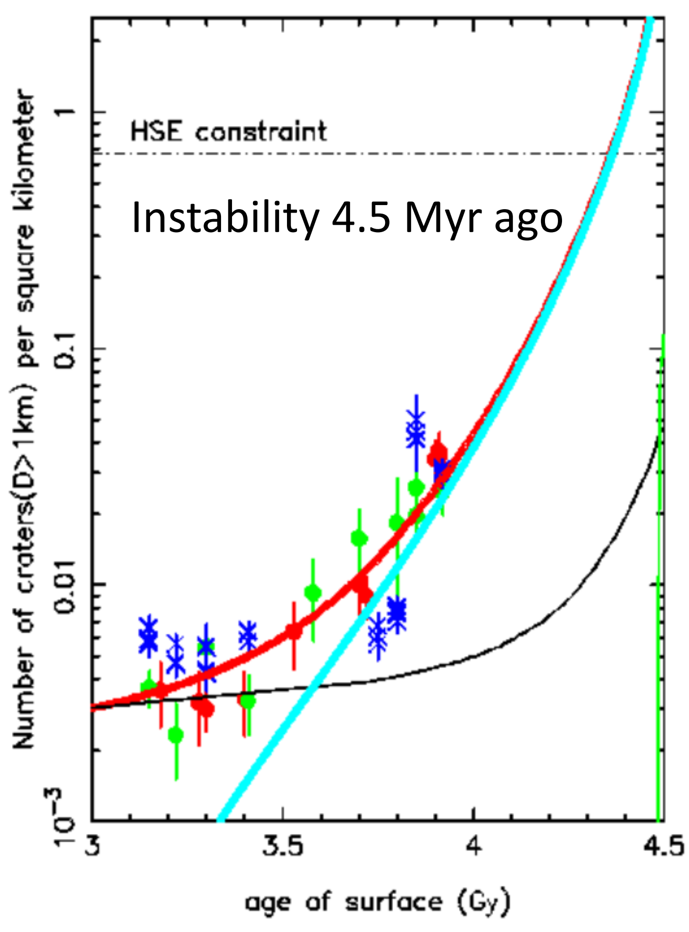
asteroids (thin black curve),
comets (thin green curve),
leftover planetesimals (thick cyan curve).

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.



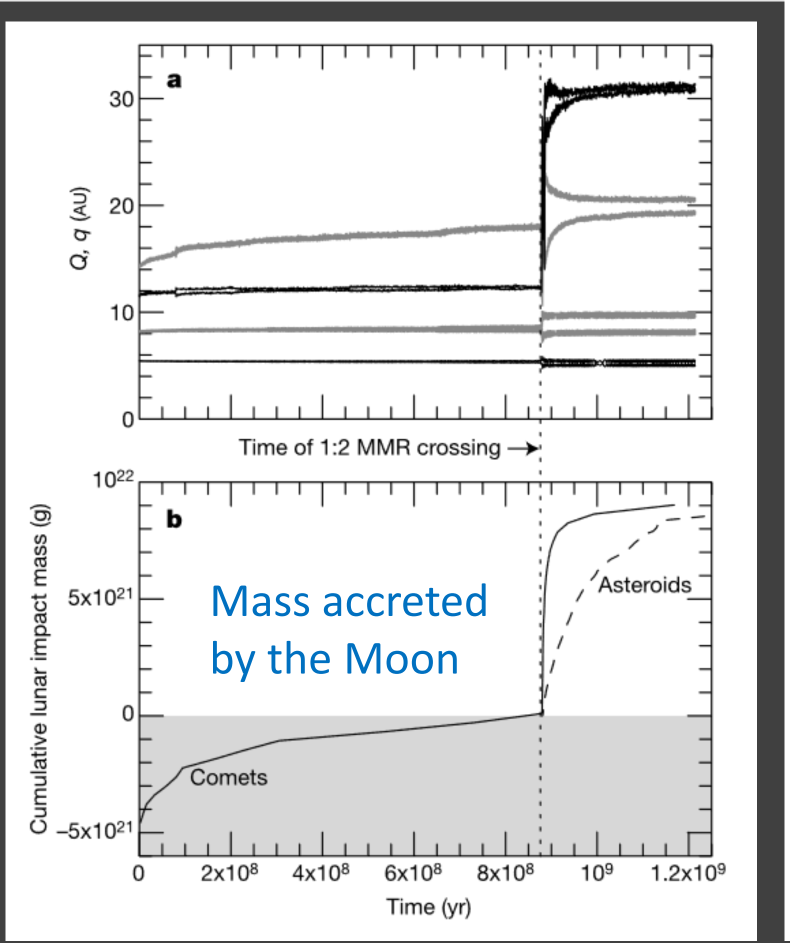


1801.03756

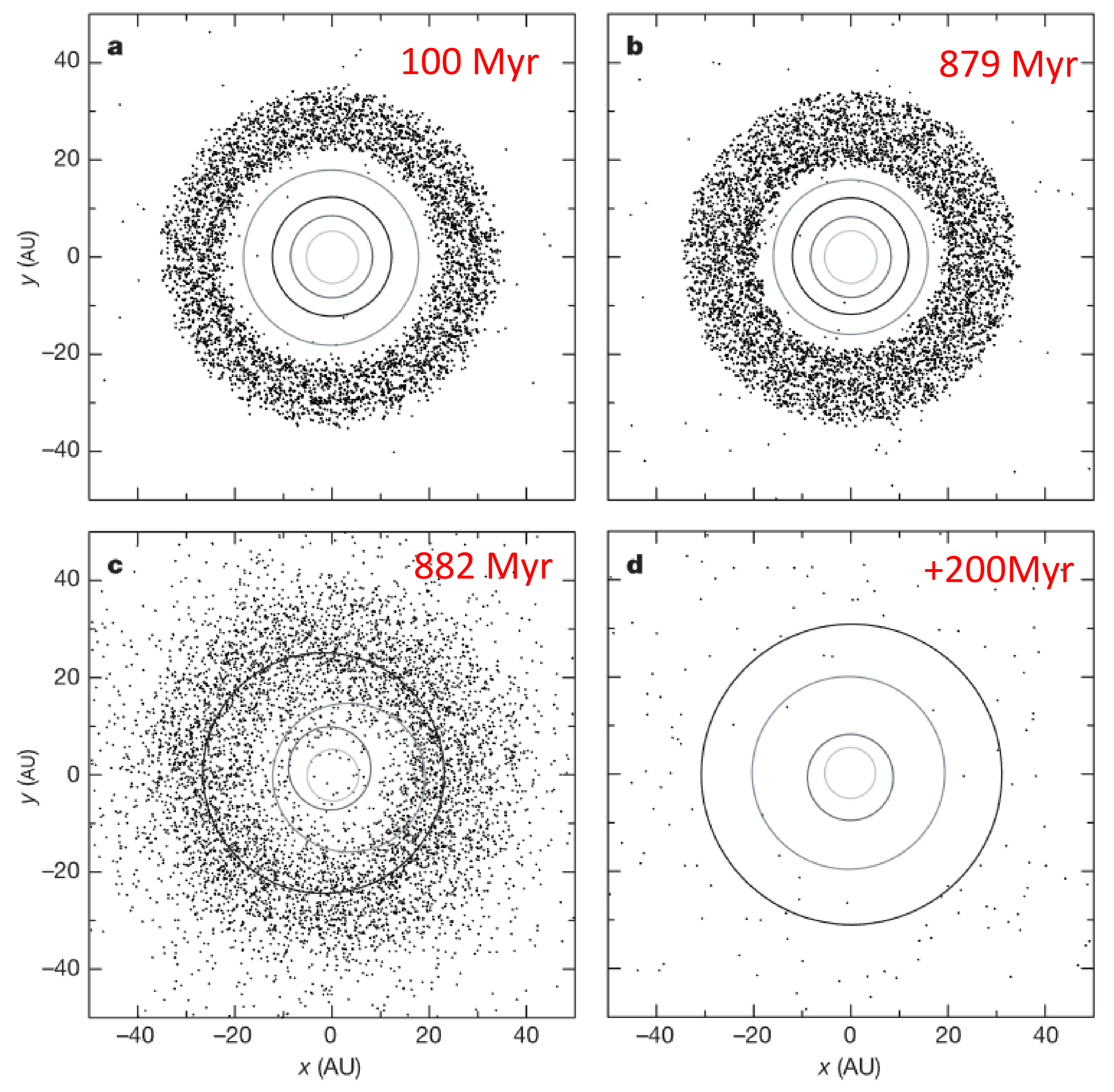
See also 2011.13686 and 2011.13682

Dynamics

LHB lasted
for ~100 Myr



Mass accreted by the Moon



100 Myr

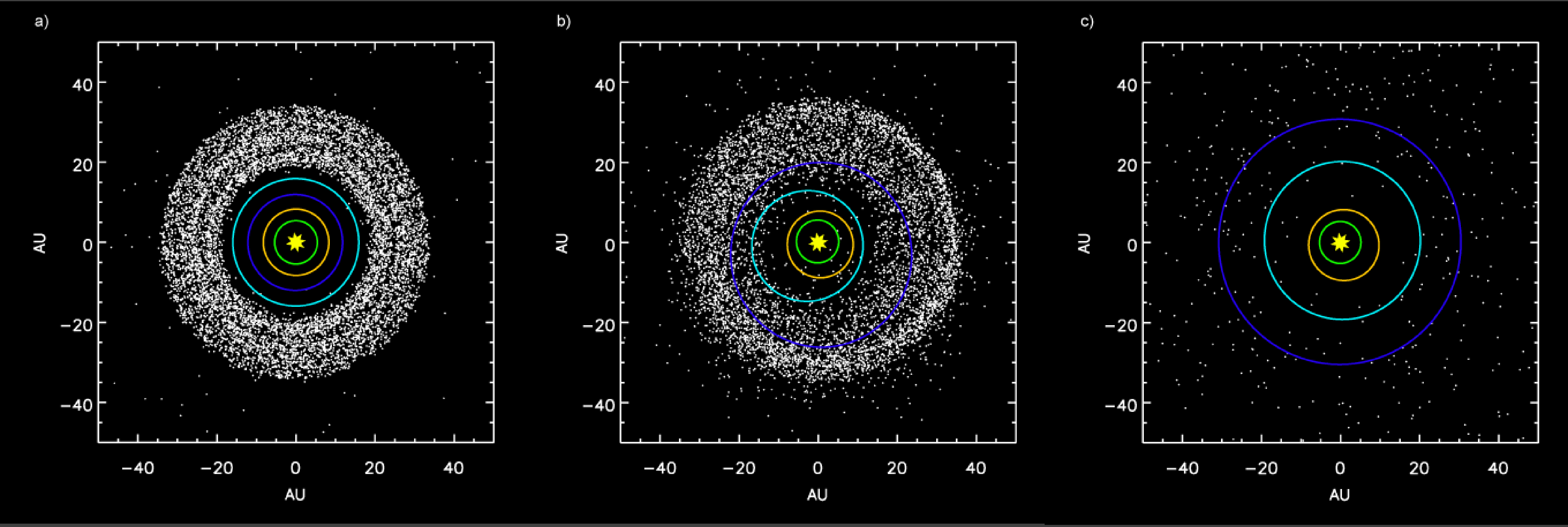
879 Myr

882 Myr

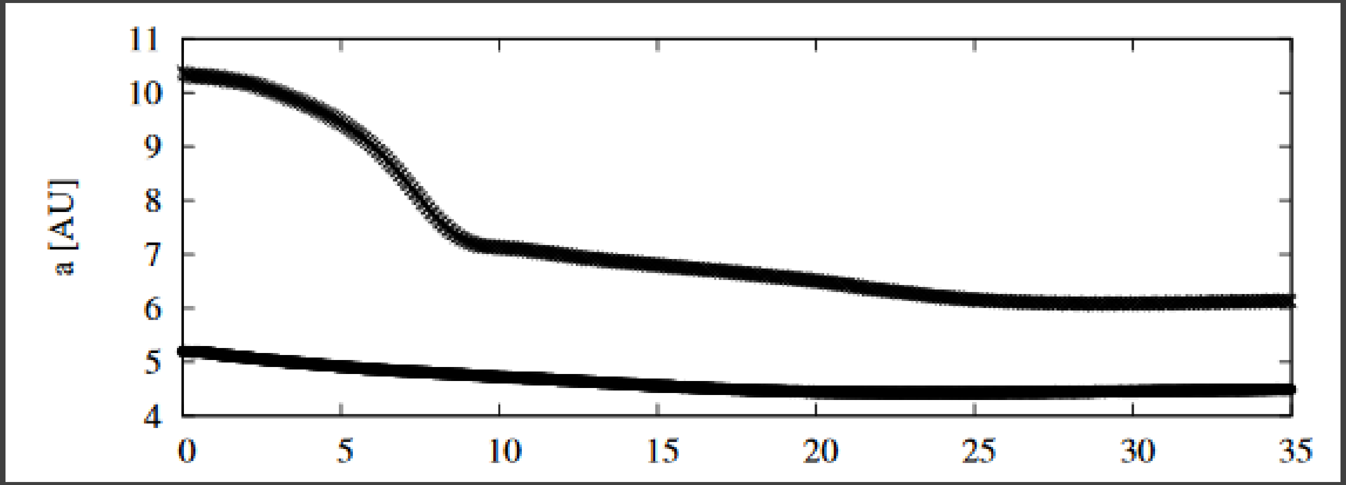
+200Myr

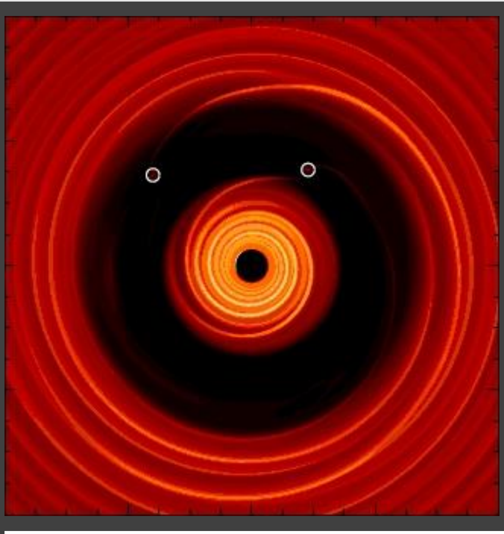
Gomes et al. 2005

Nice model

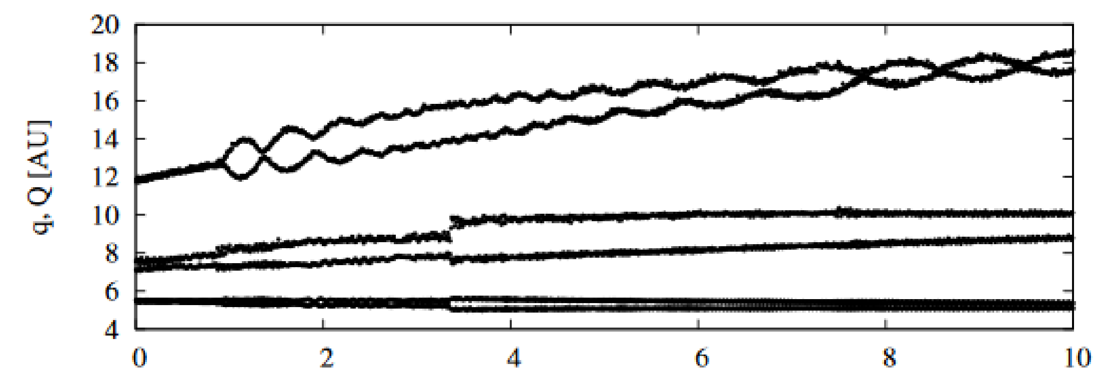


Solar system secular evolution: resonance crossing




planetplanet.net

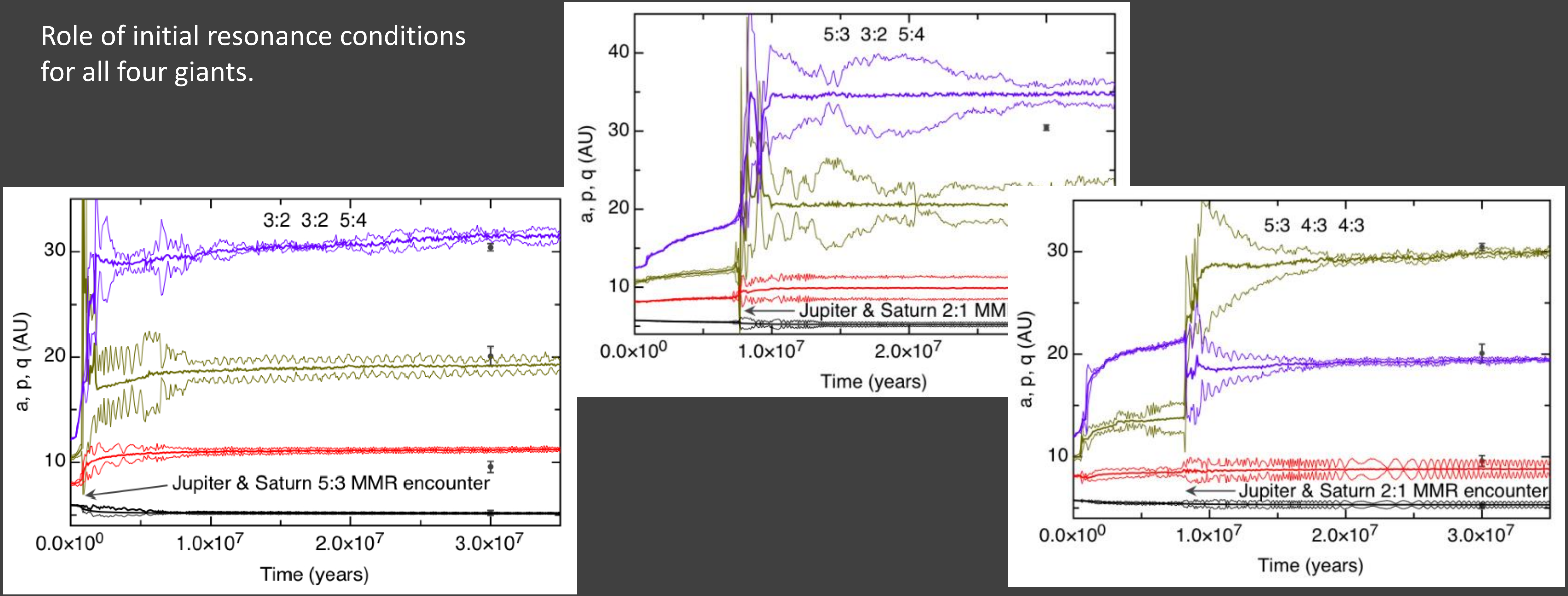
After evolution in the gas disc Jupiter and Saturn are in 3:2 resonance.
At this stage eccentricities and inclinations are low.
It is non-trivial to explain present-day eccentricities and inclinations.
It was proposed that it can be potentially solved
if these planets crossed resonances
and interacted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



Morbidelli et al. 2009

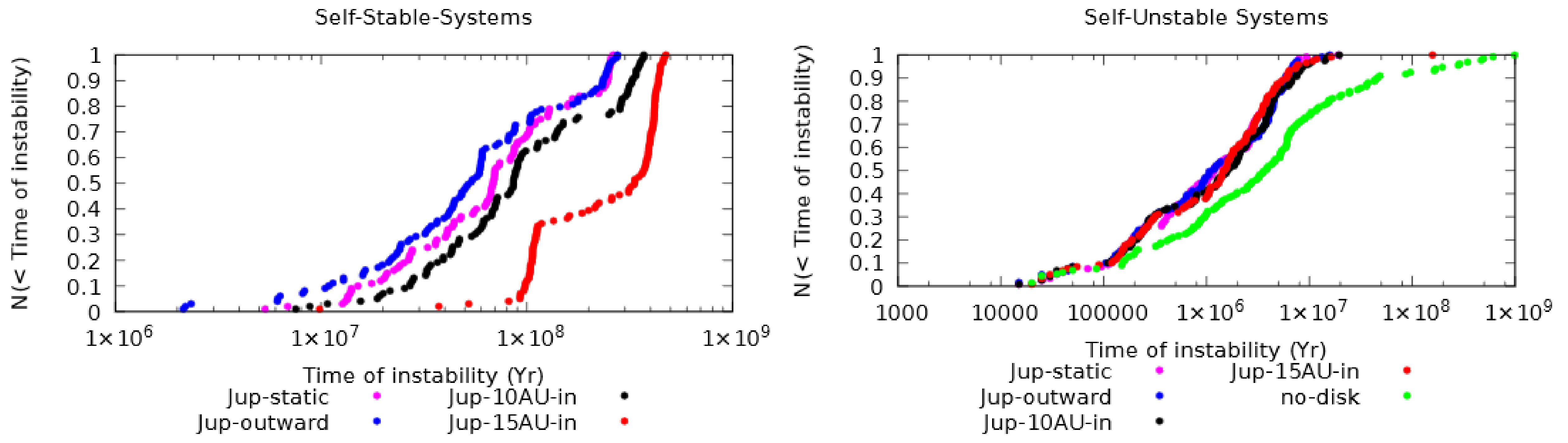
Further studies

Role of initial resonance conditions for all four giants.



1004.5414

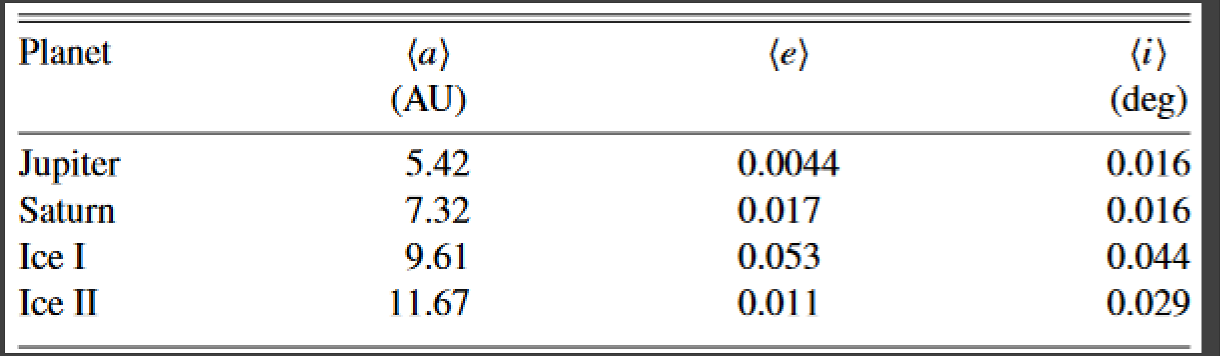
Early giant planets instability?



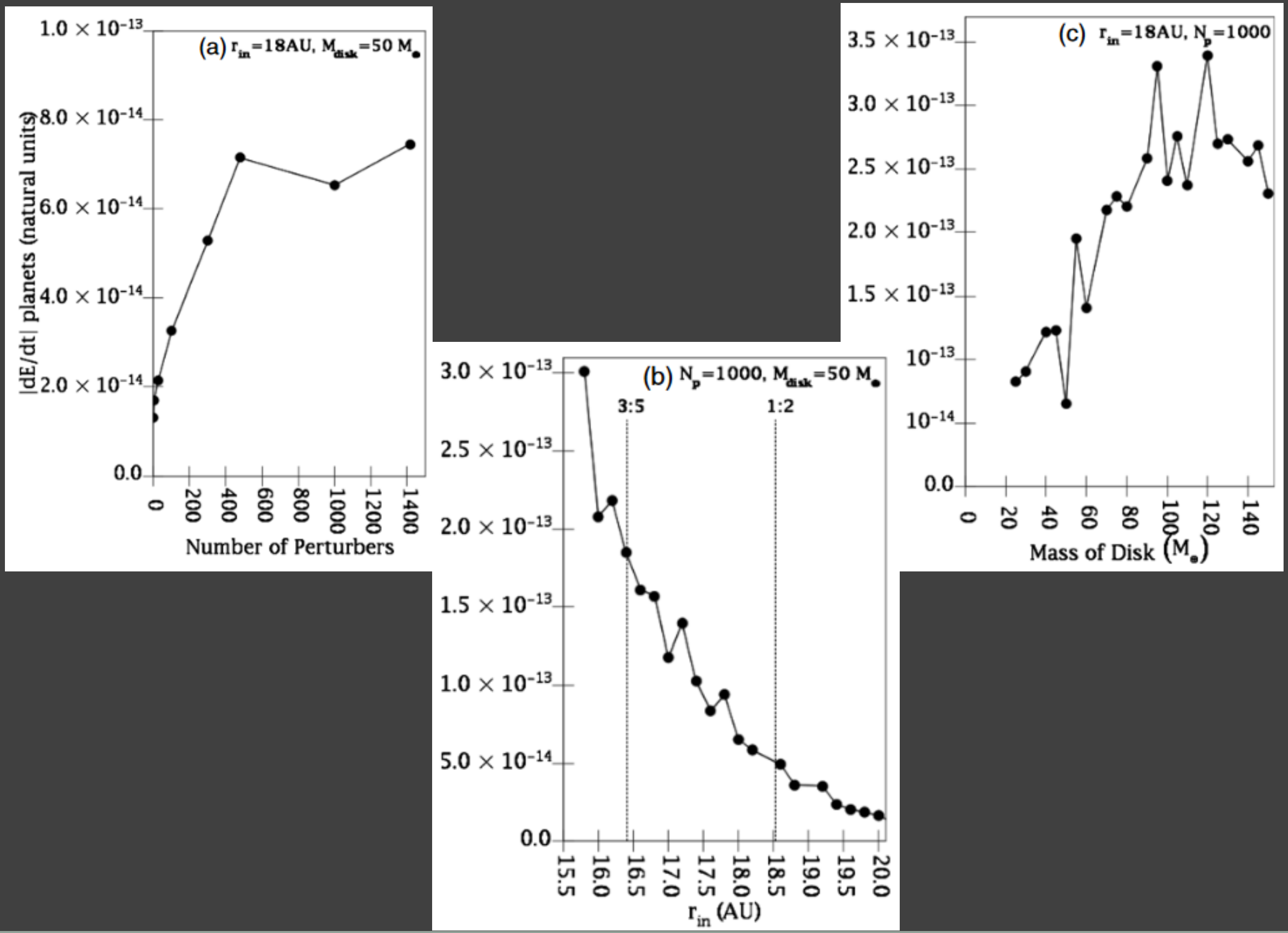
1912.10879

Modifications of the original Nice model

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



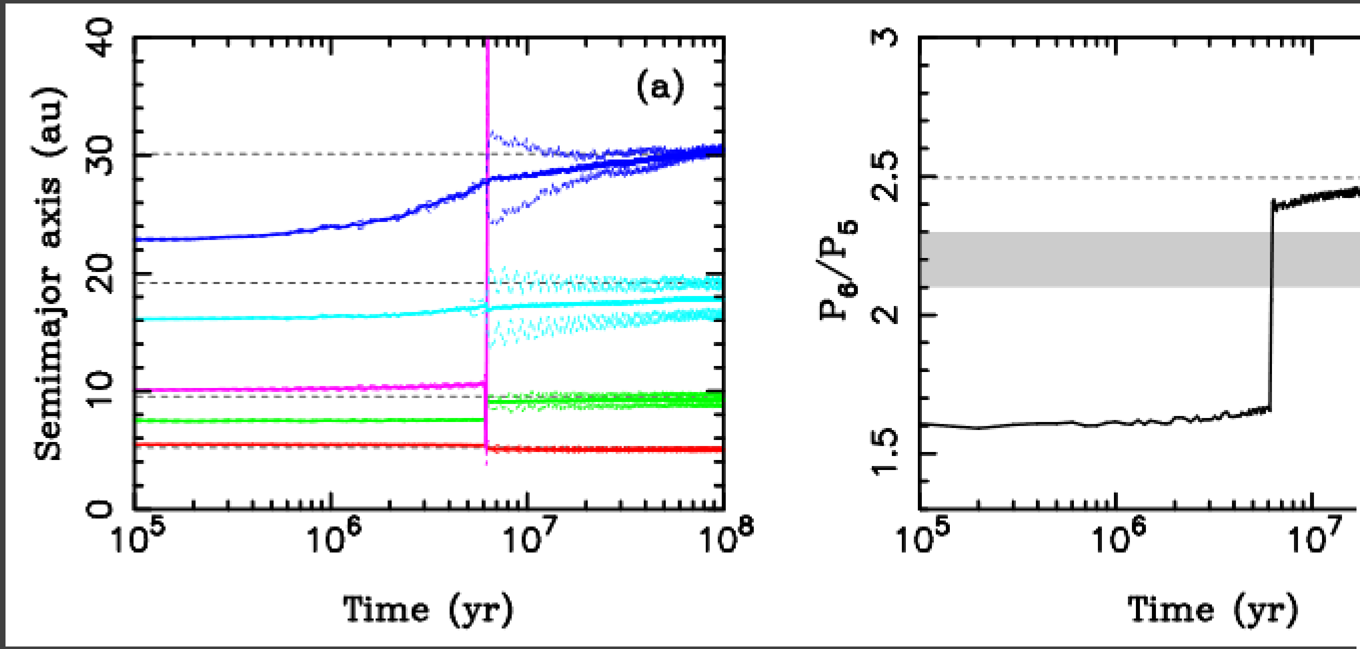
Planet	$\langle a \rangle$ (AU)	$\langle e \rangle$	$\langle i \rangle$ (deg)
Jupiter	5.42	0.0044	0.016
Saturn	7.32	0.017	0.016
Ice I	9.61	0.053	0.044
Ice II	11.67	0.011	0.029



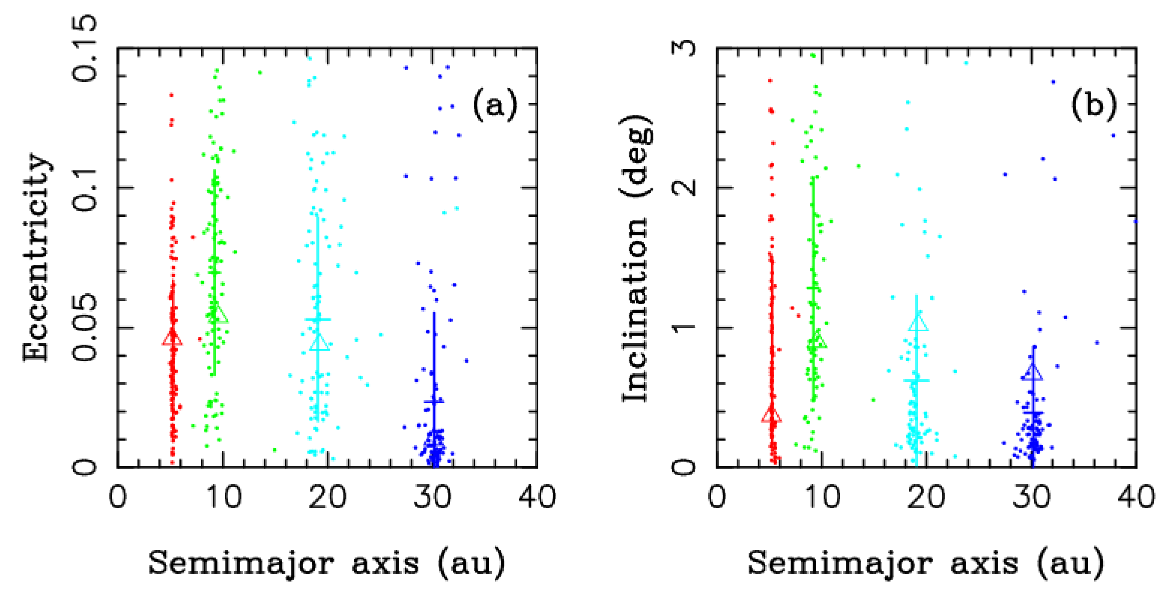
Interaction between disc particles (stirring) and eccentricity of planets are important factors for planets-disc interaction.
Internal ice giant might have larger eccentricity after evolution in the gas disc.
Interaction of this planet with the disc of planetesimals can result in the instability in the planetary system.

Levison et al. 2011 (AJ 142, 152)

Jumping Jupiter



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



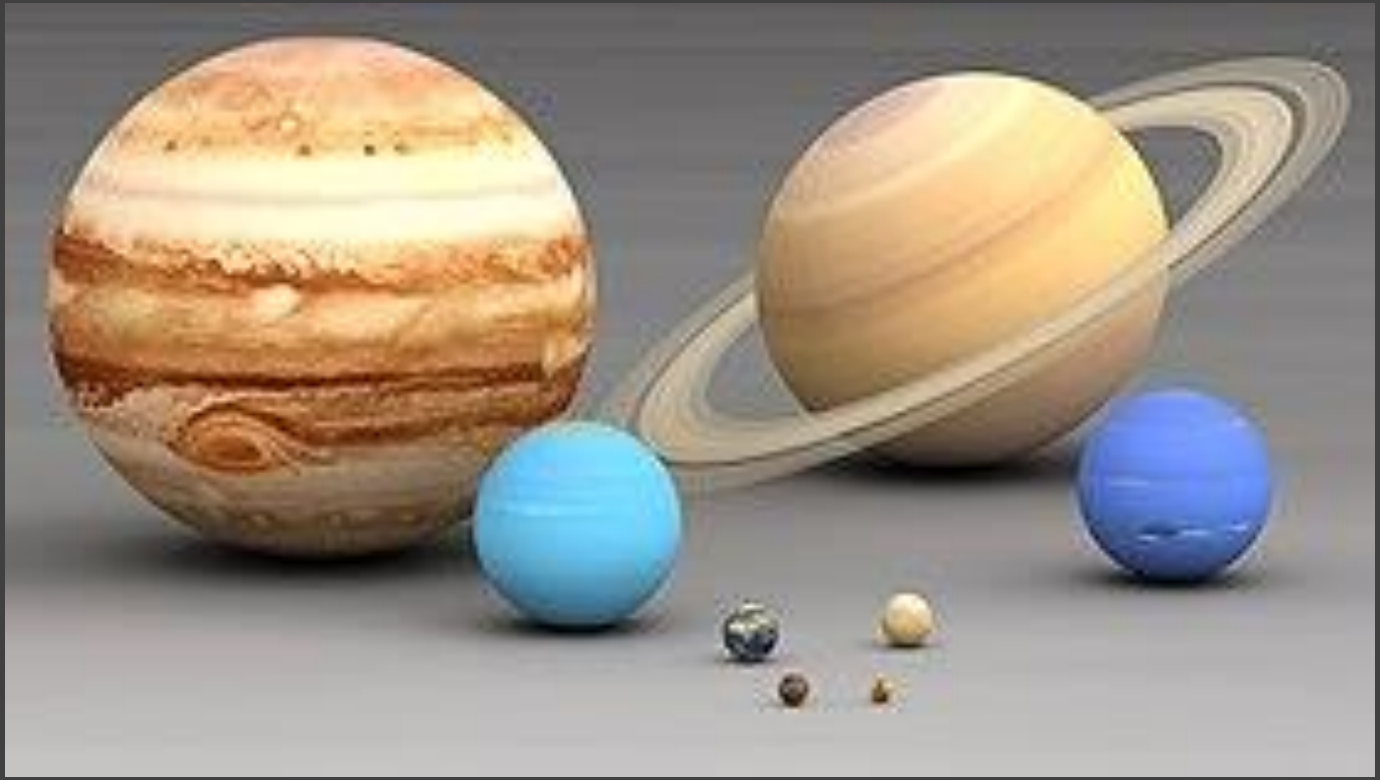
Five planets configuration.

The instability was triggered when the inner ice giant crossed an orbital resonance with Saturn and its eccentricity was pumped up.

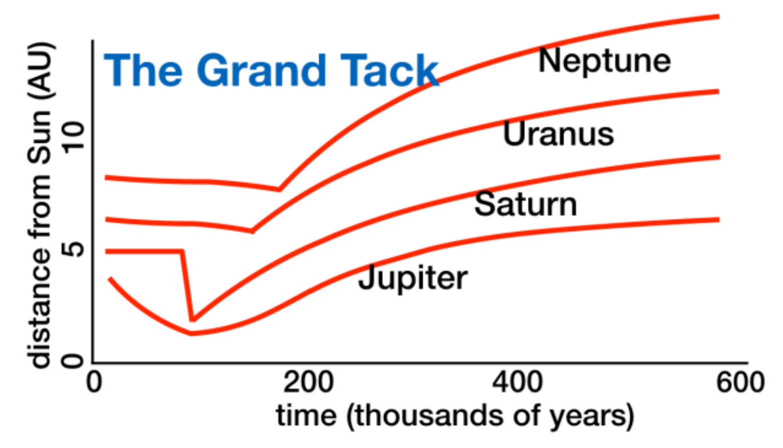
1807.06647

More problems (and solutions?)

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

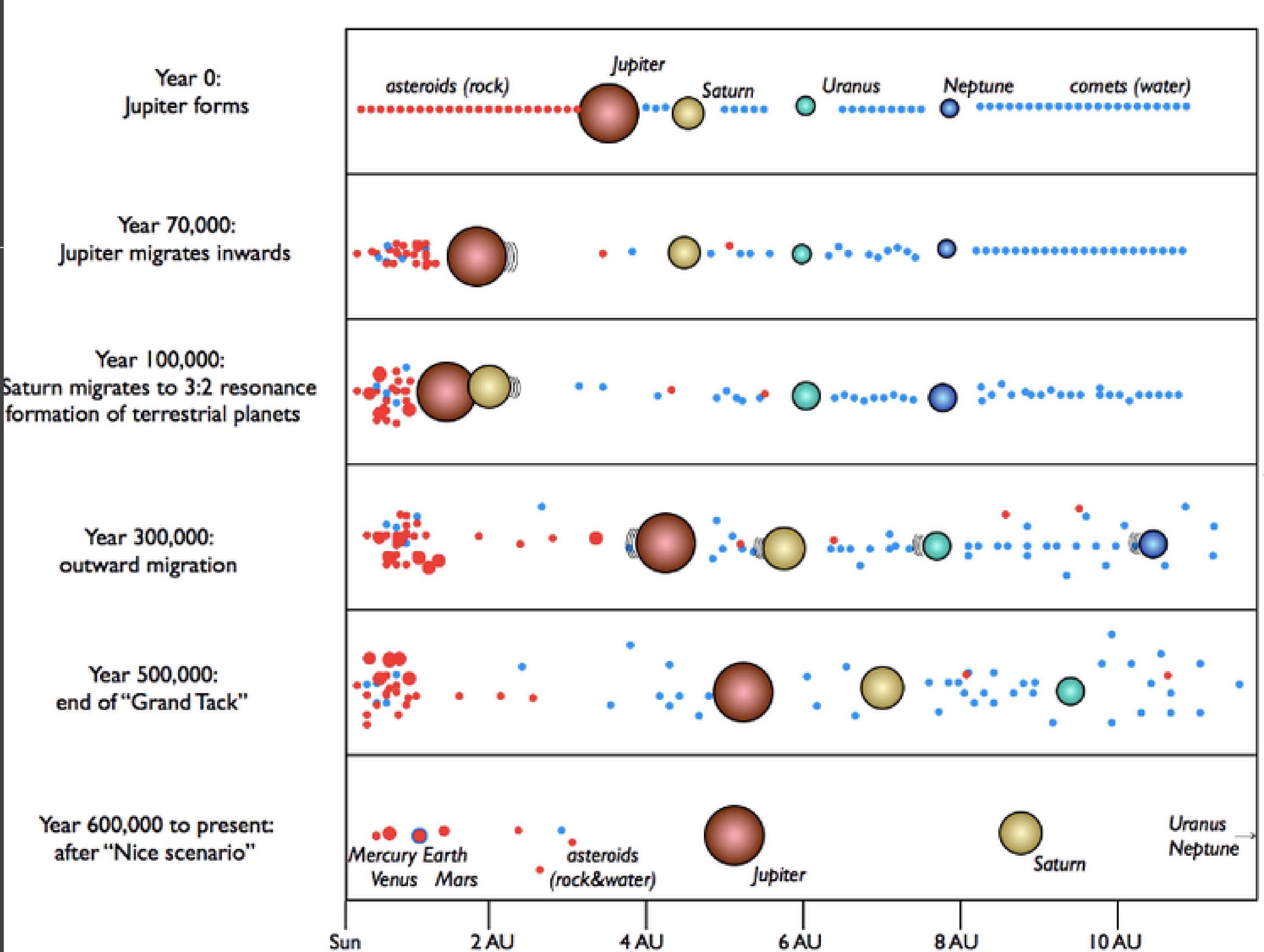


Grand tack



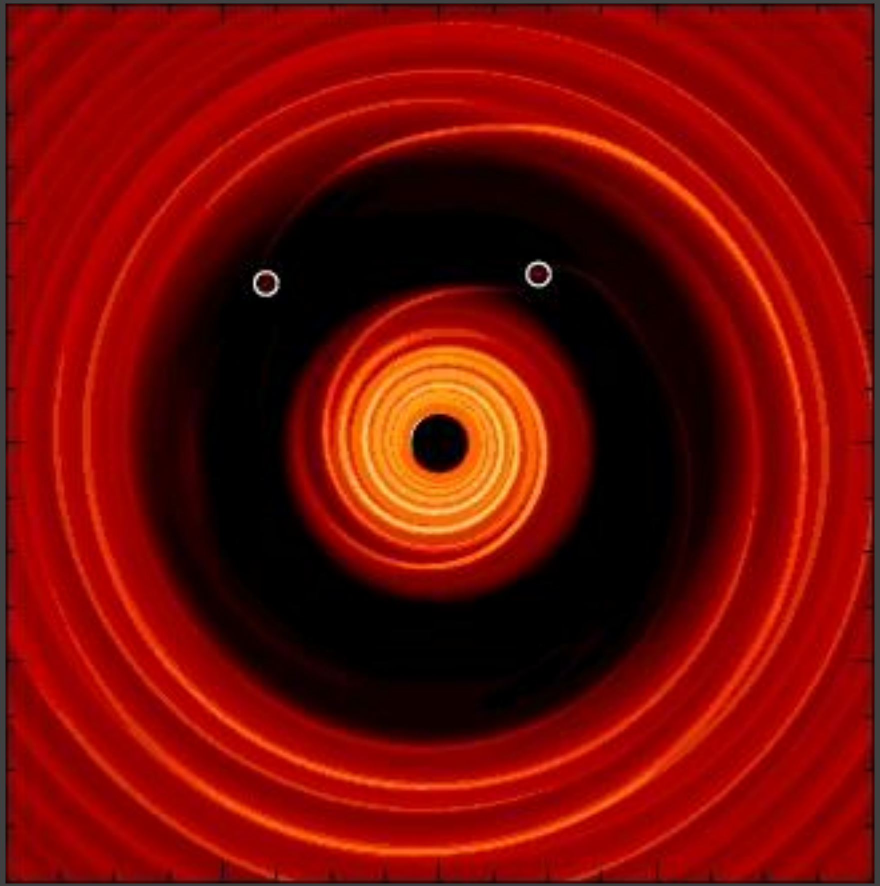
Proposed by Walsh et al. (2011).

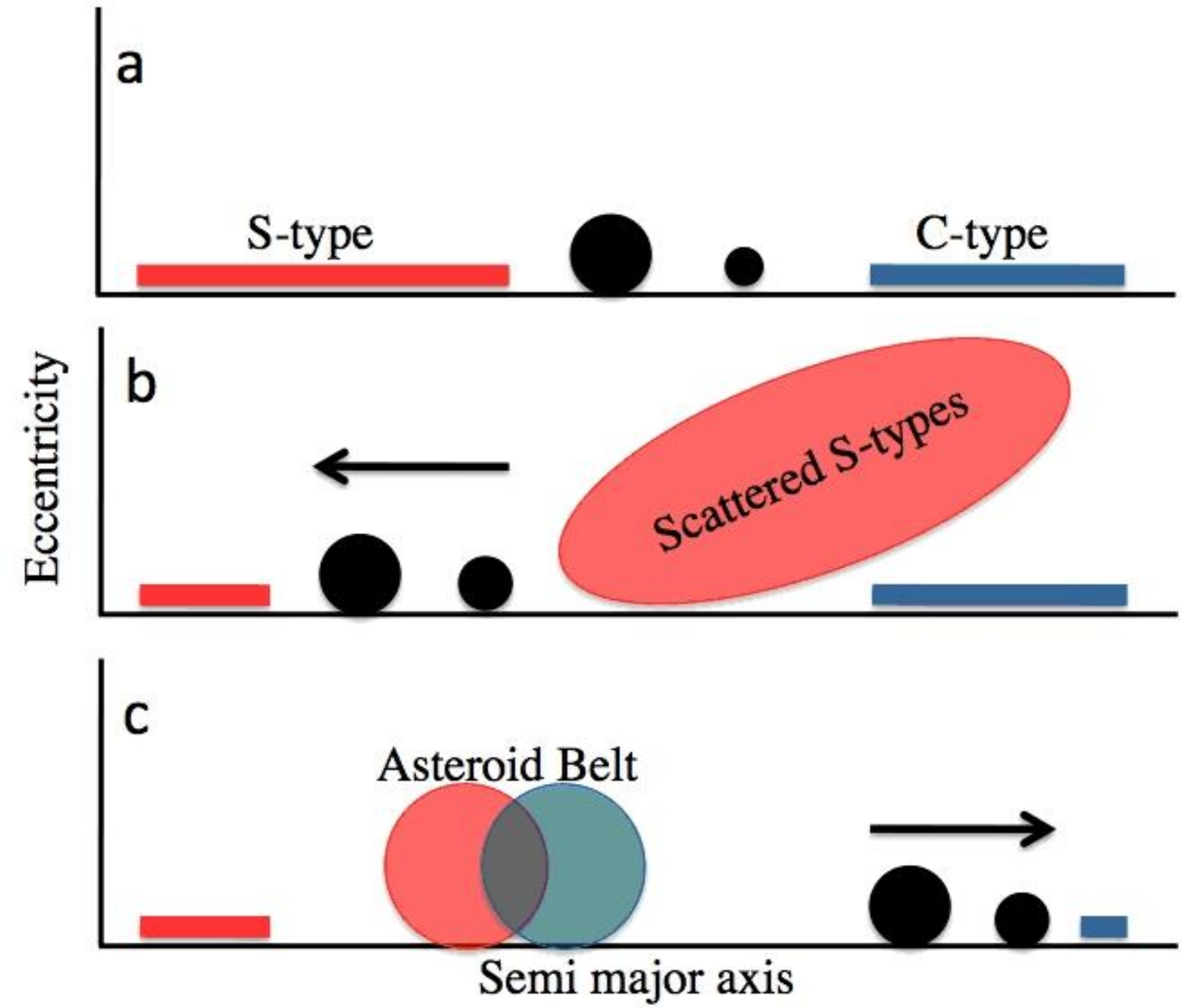
Explains why Mars is small
(truncation of planetesimals disc).



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

Grand tack

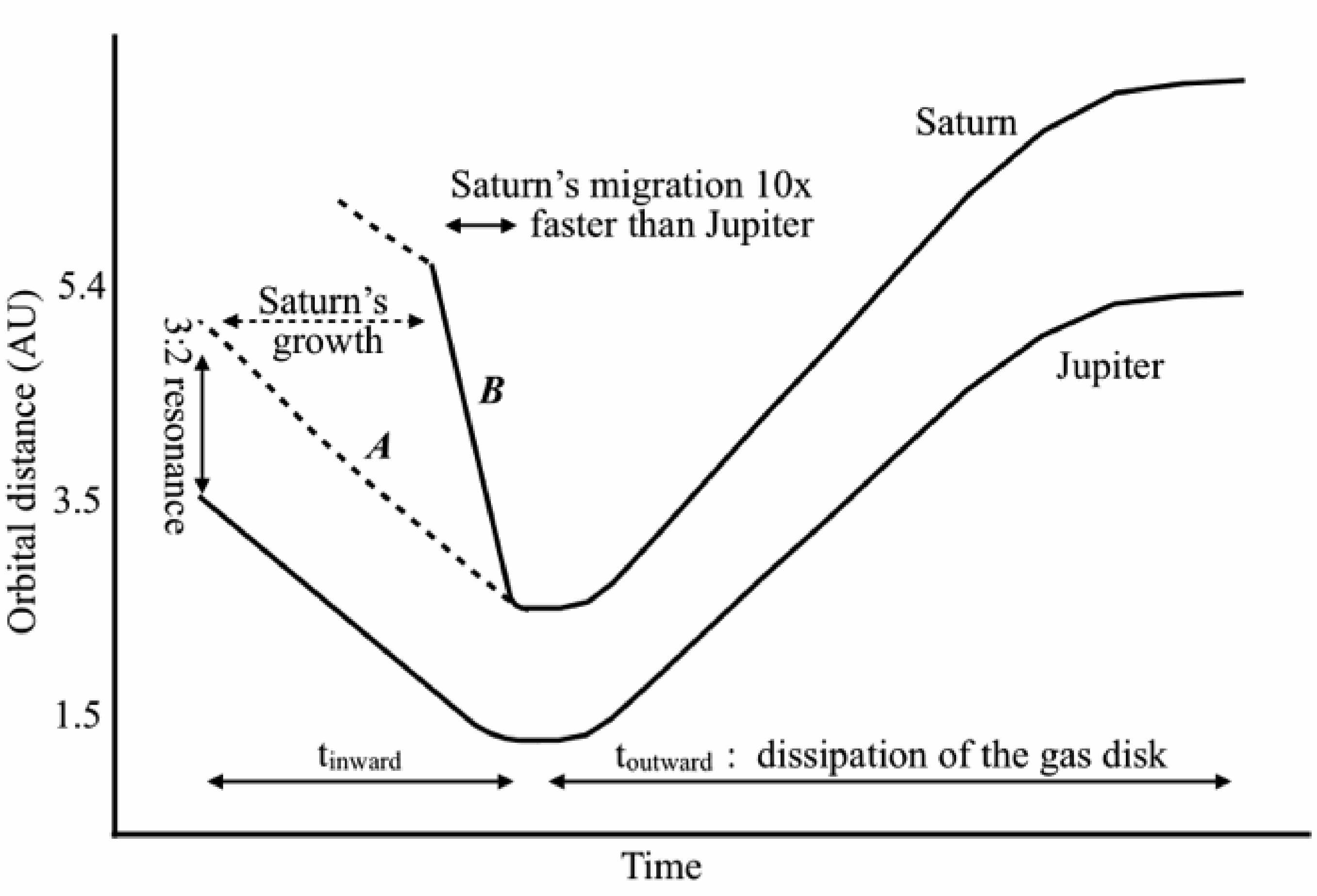




https://planetplanet.net/2013/08/02/the-grand-tack

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

Phases of the Grand tack

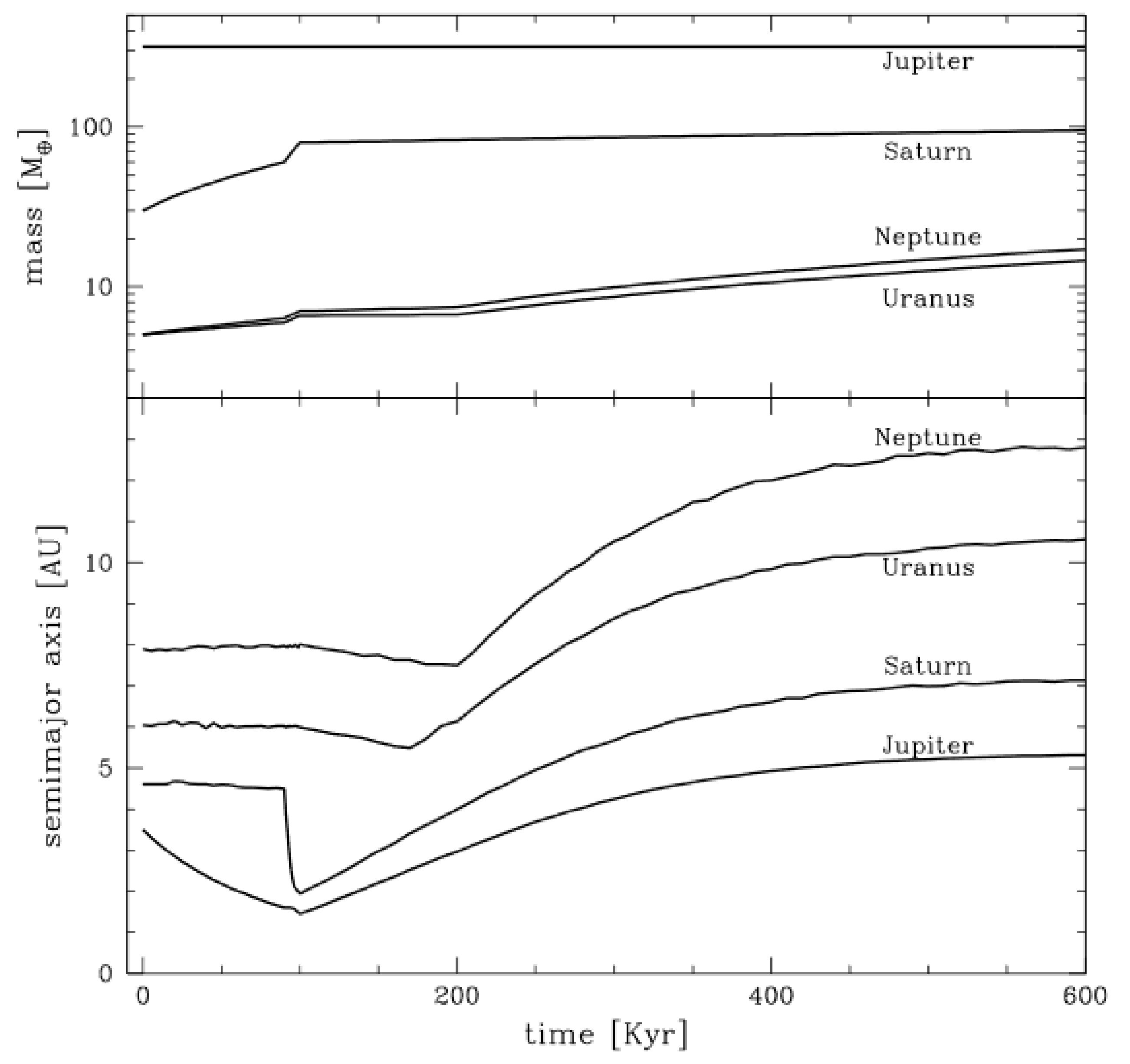


Jupiter and Saturn form earlier than terrestrial planets.
Thus, it is possible to influence the disc of planetesimals (embryos for terrestrial planets) with giants,
if they can migrate closer to the region of solid planets formation.

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

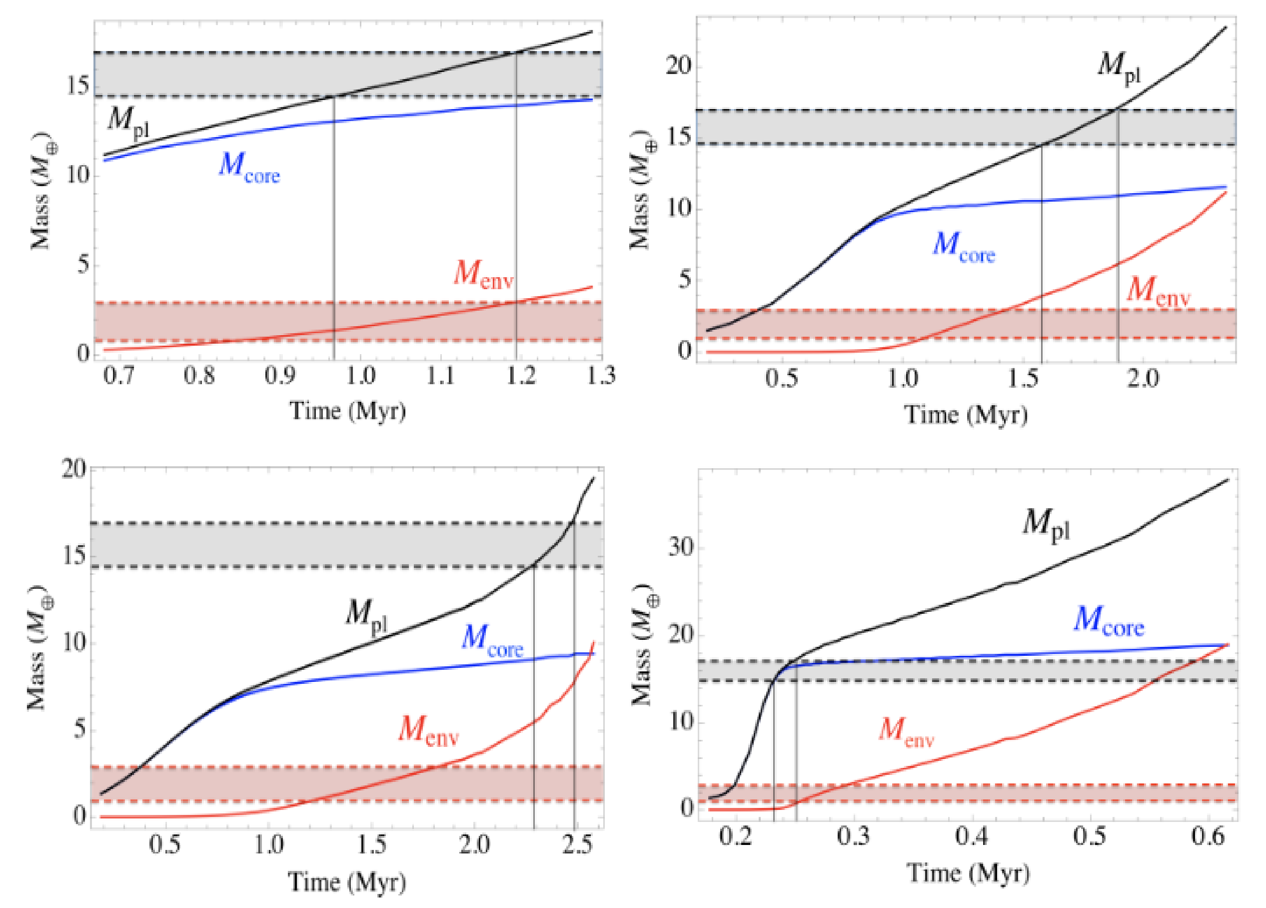
Grand Tack

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

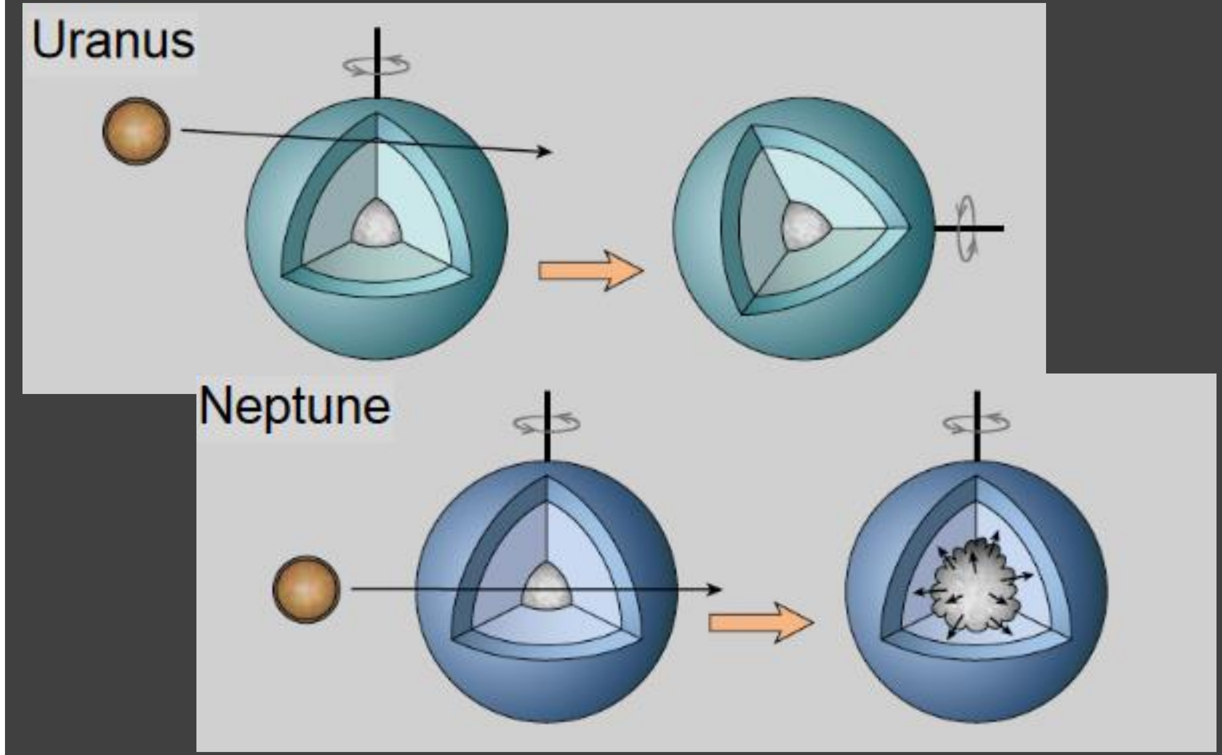


1201.5177

Problems with Uranus and Neptune



Fine tuning is necessary to fit core and envelope masses.
Gas disc might disappear in a specific moment.

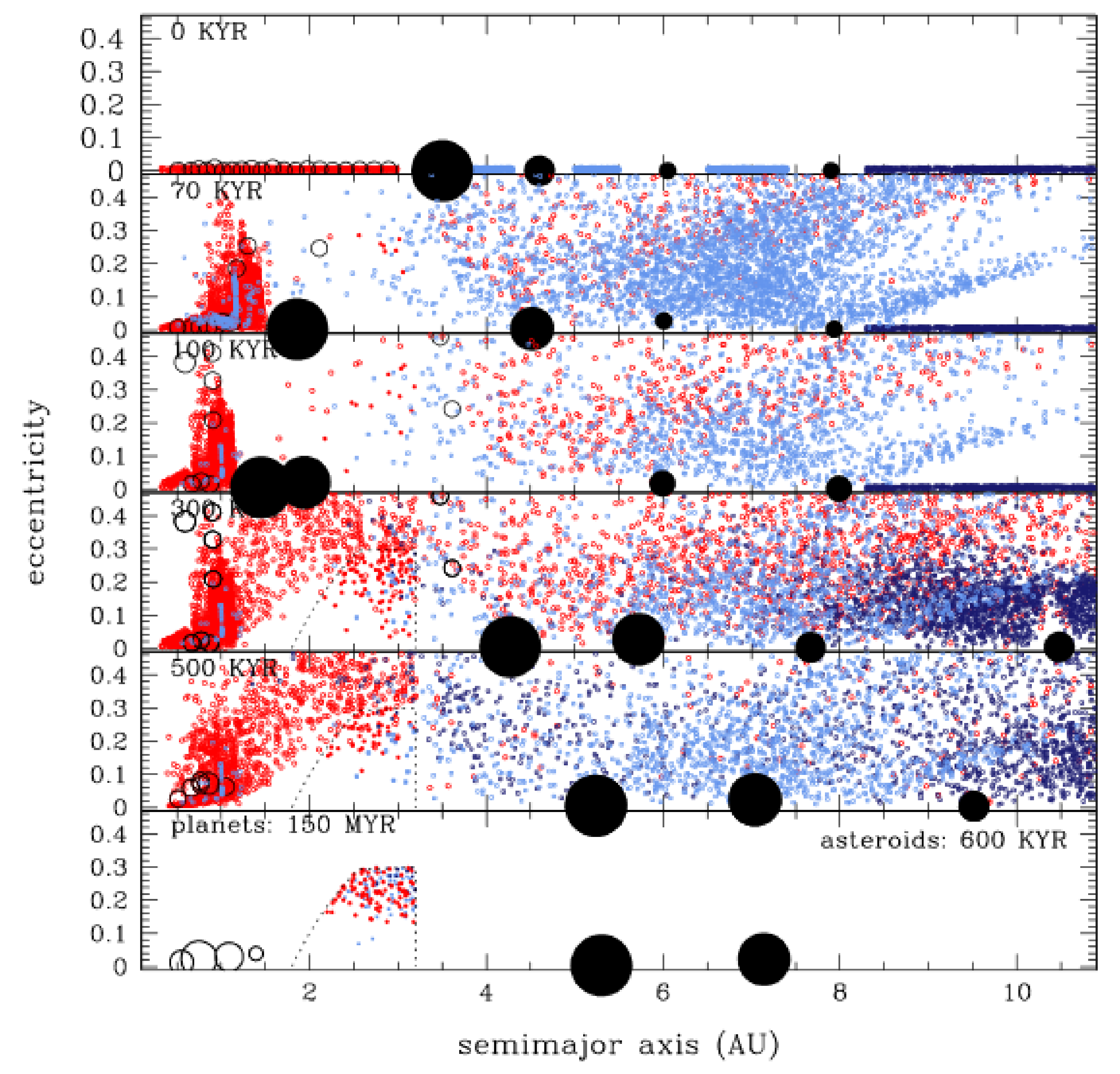


Both planets might have experience collisions.

1909.04891

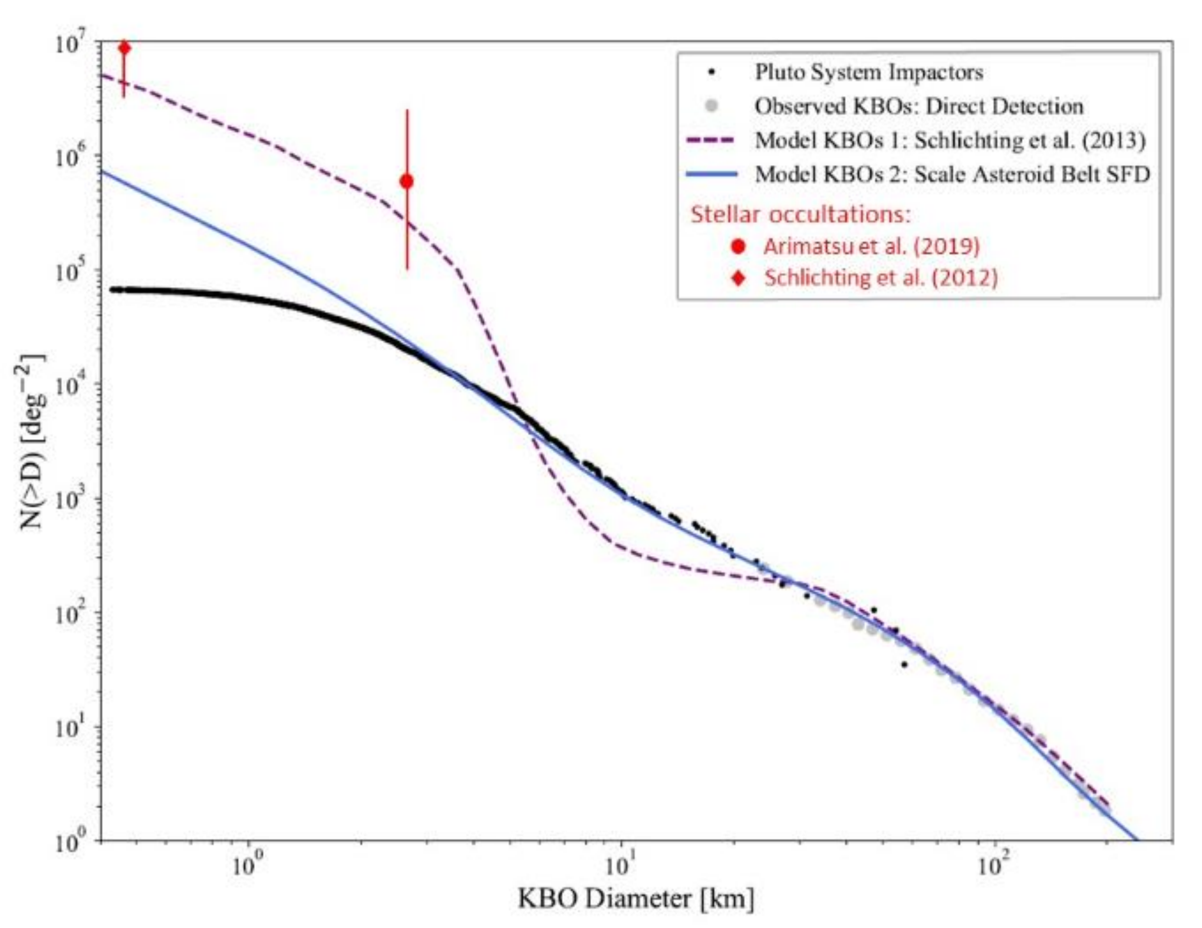
Small bodies

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



1201.5177

Kuiper belt formation



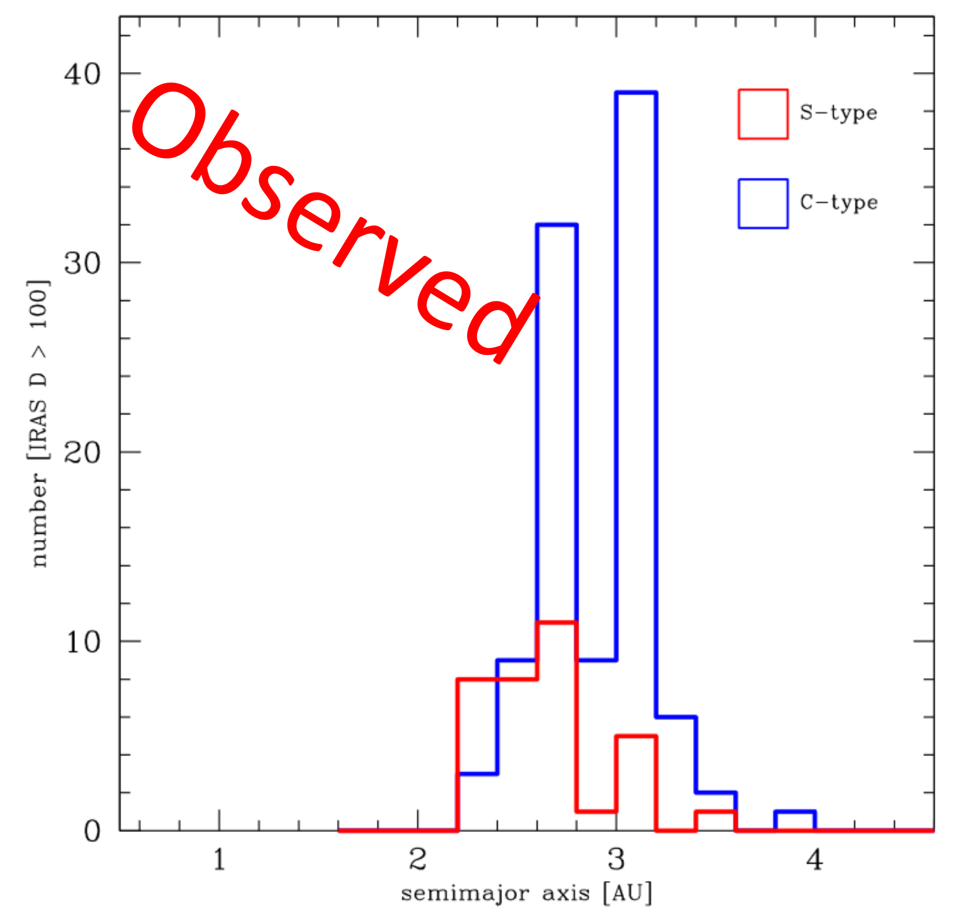
Initial mass of the disk was ~15-20 Earth masses.

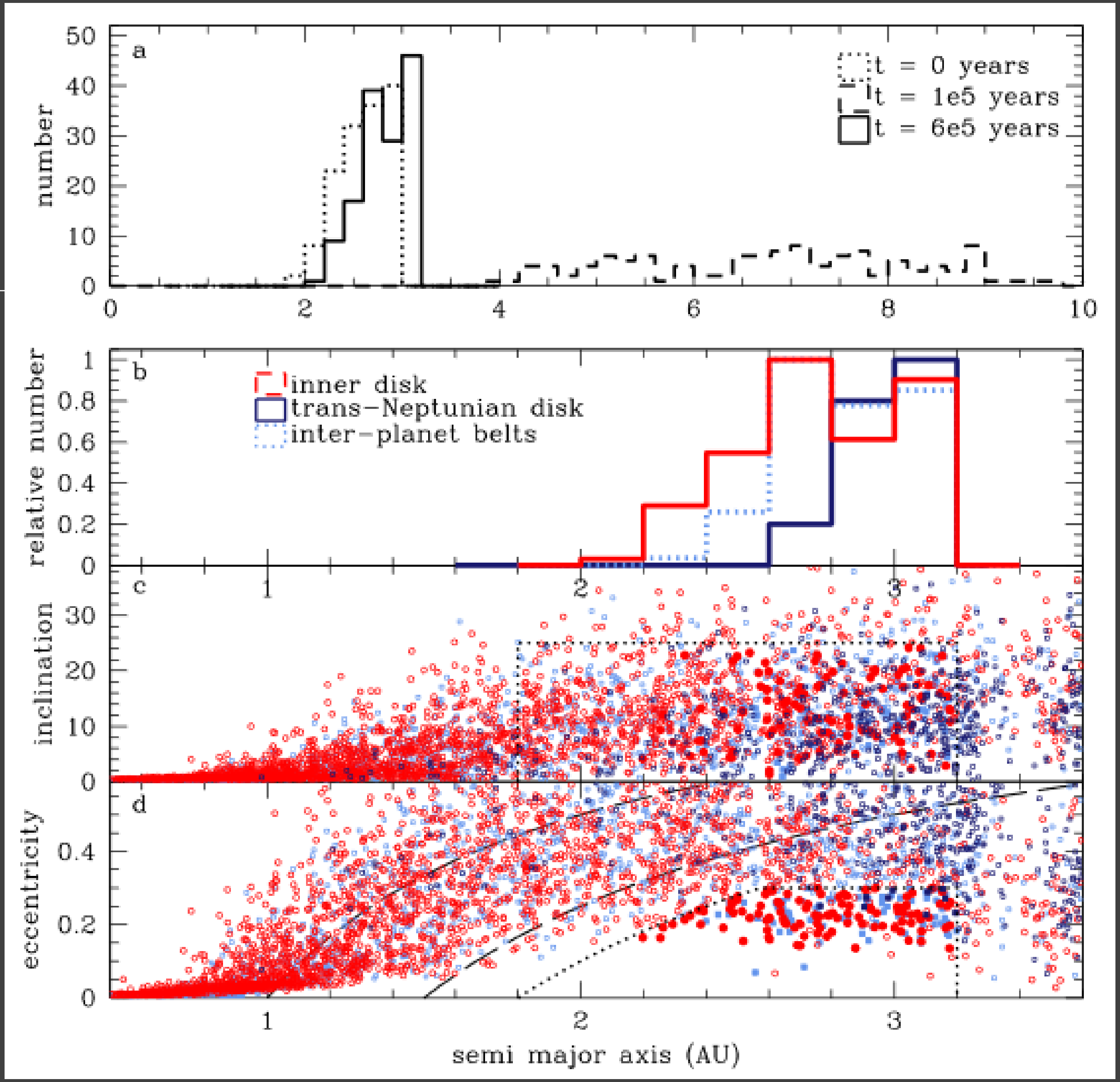
The disk contained ~2 10^{11} objects with D>2 km and several thousands Pluto-mass objects.

About extrasolar Kuiper belts see arXiv:1909.12312

1904.02980

Asteroids

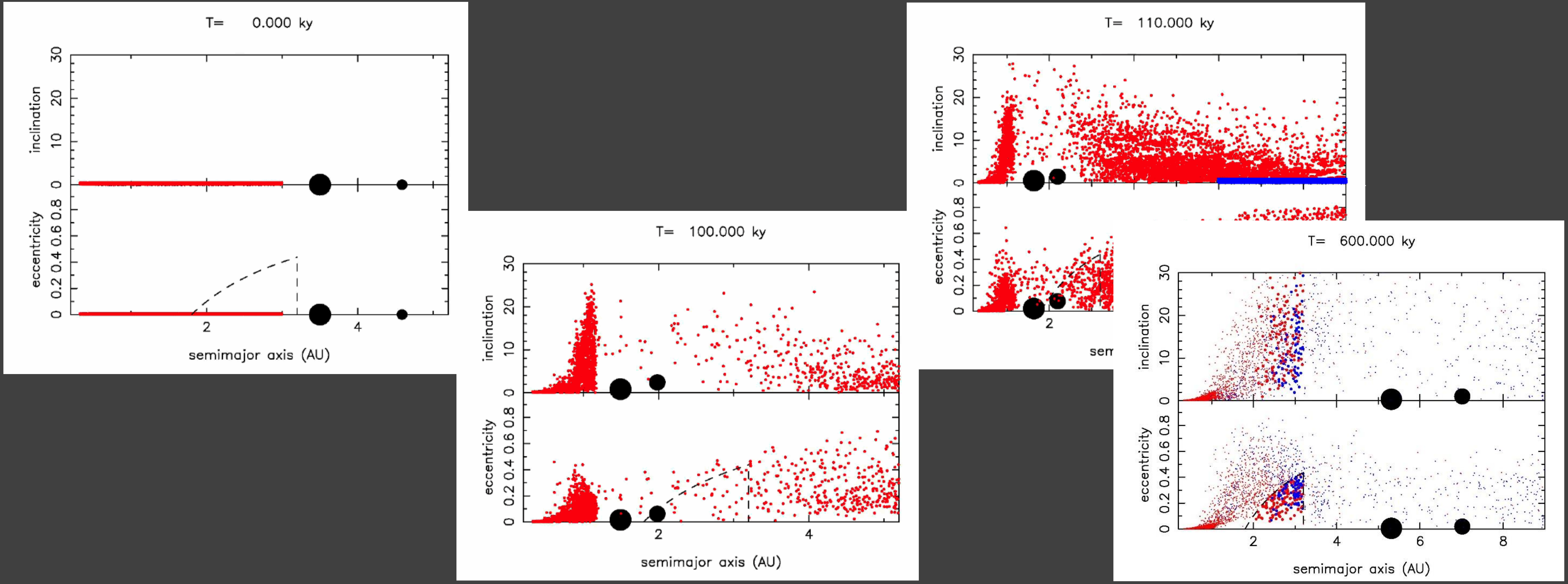

Observed



1201.5177

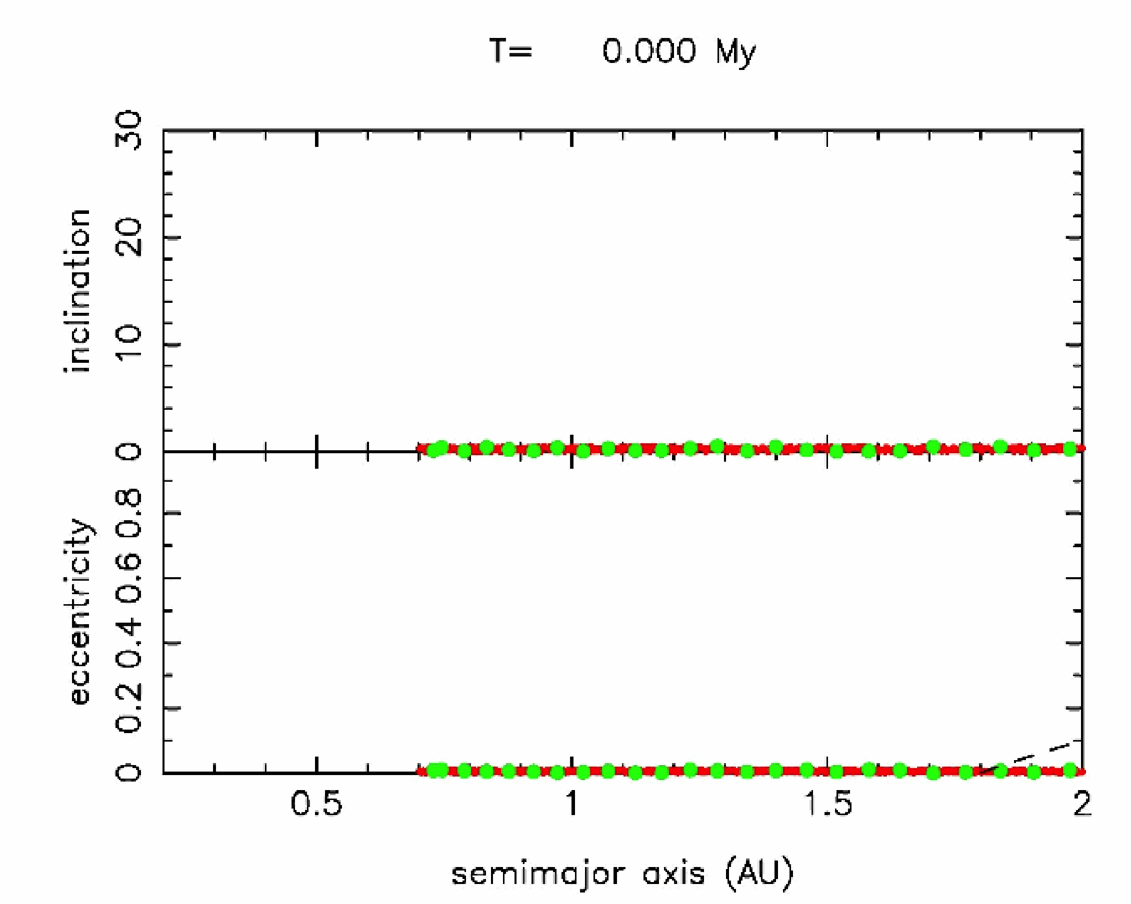
Distributions of 100 km planetesimals Grand Tack model.

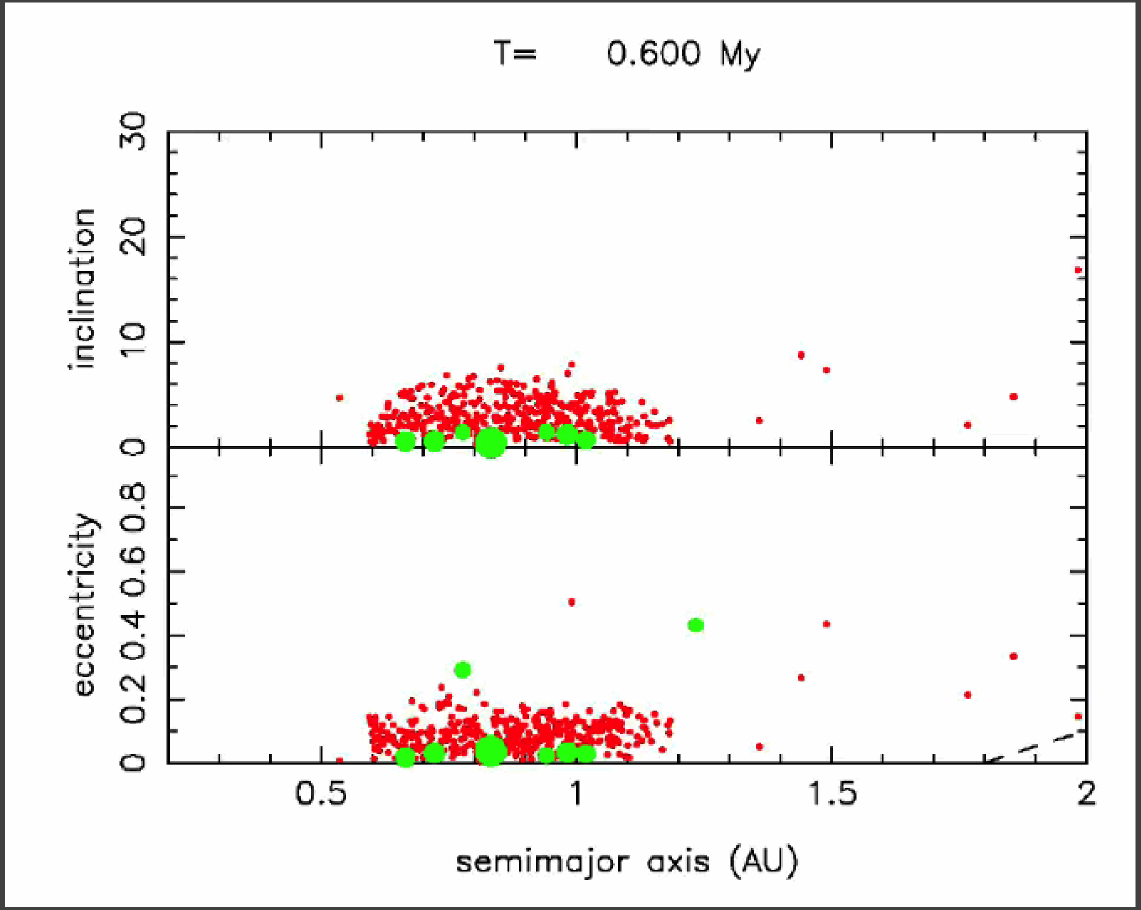
Sequence of events



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

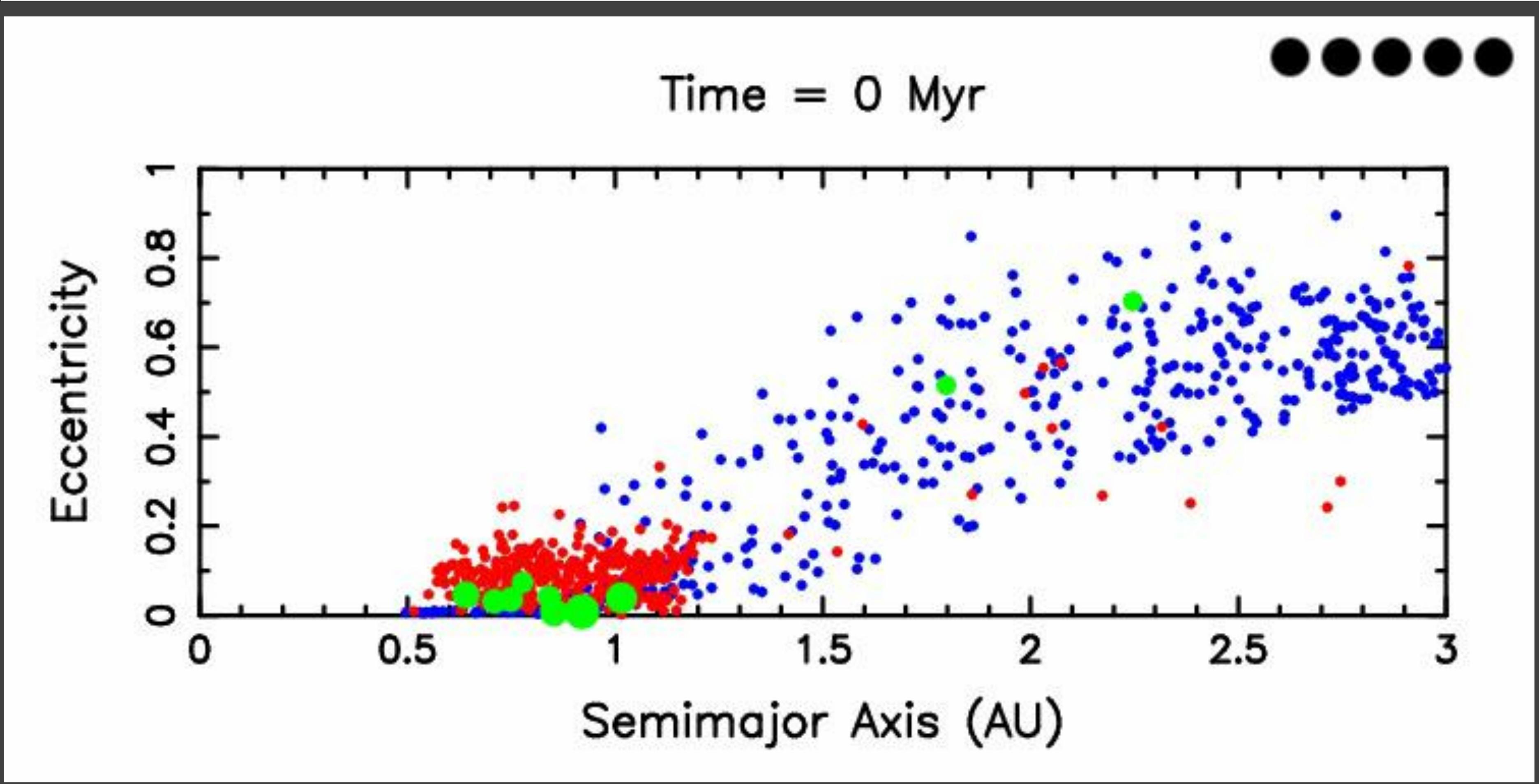
Disc of planetesimals: truncation





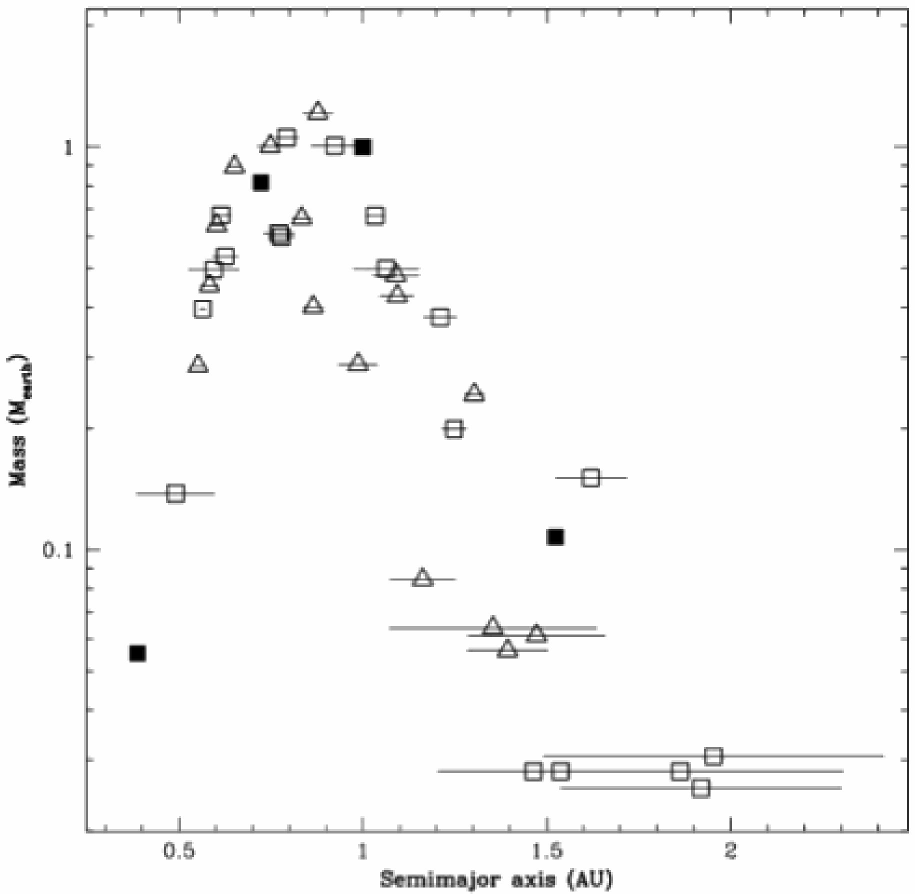
http://perso.astrophy.u-bordeaux.fr/SRaymond/movies_grandtack.html

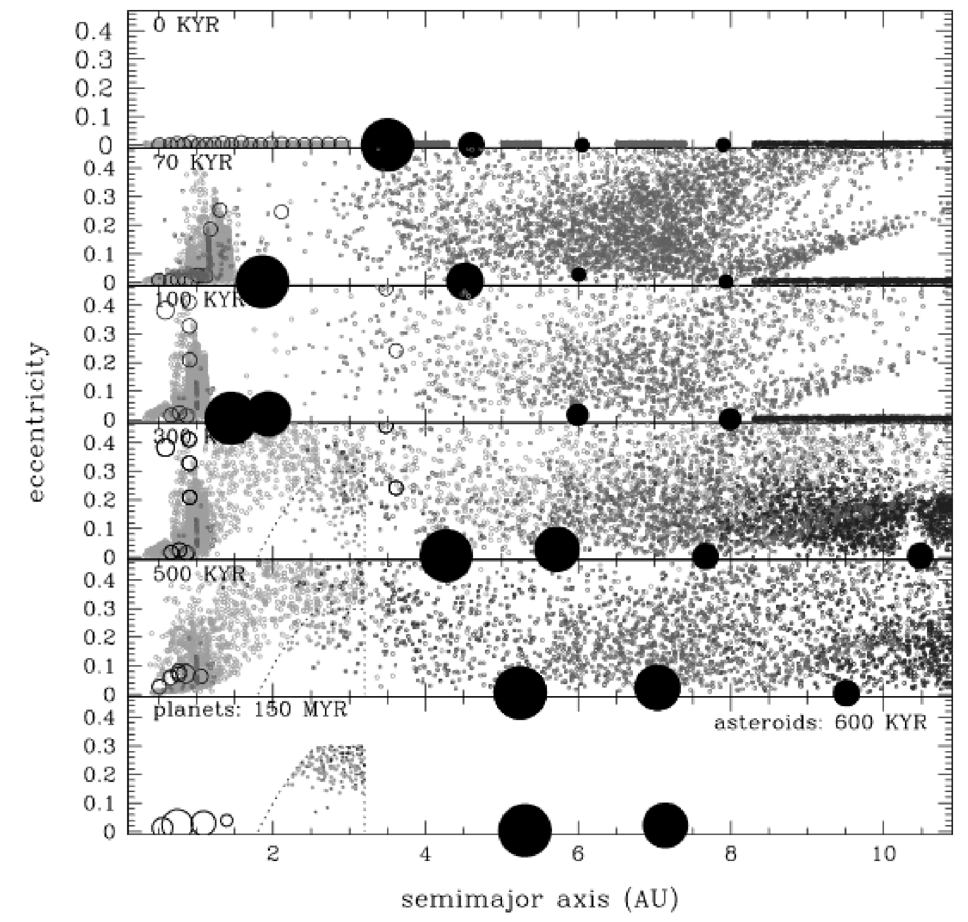
Water on Earth from C-type asteroids



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

Mass distribution

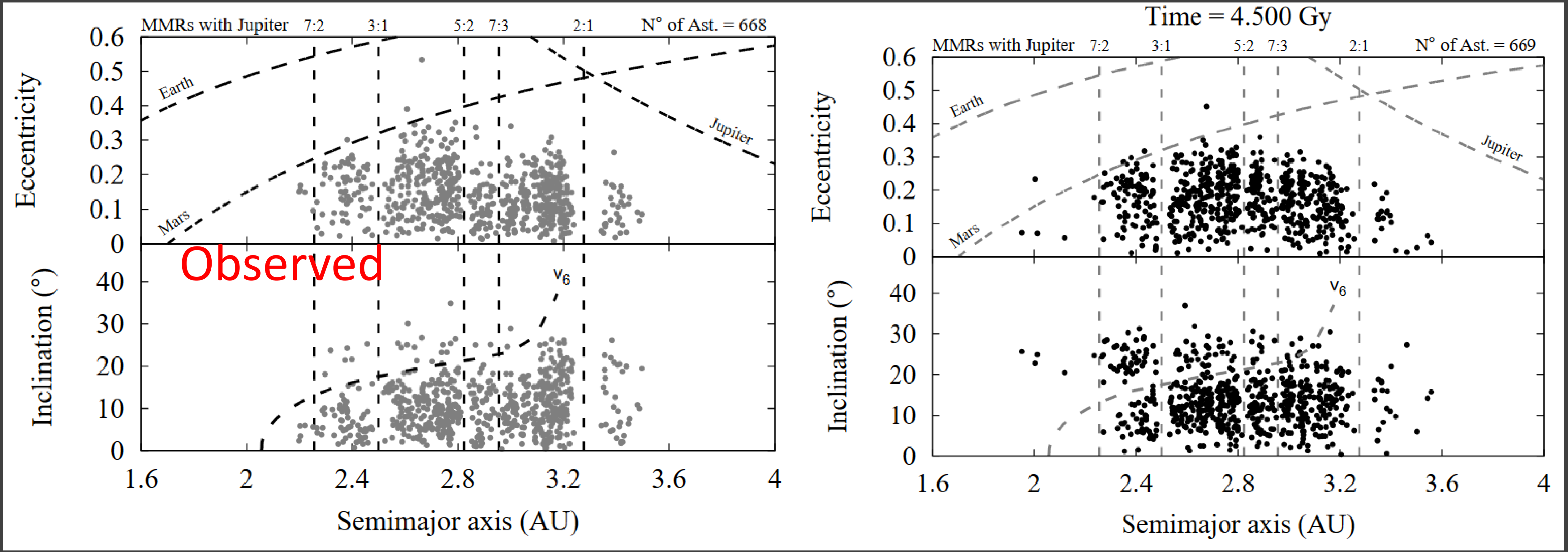




http://perso.astrophy.u-bordeaux.fr/SRaymond/movies_grandtack.html

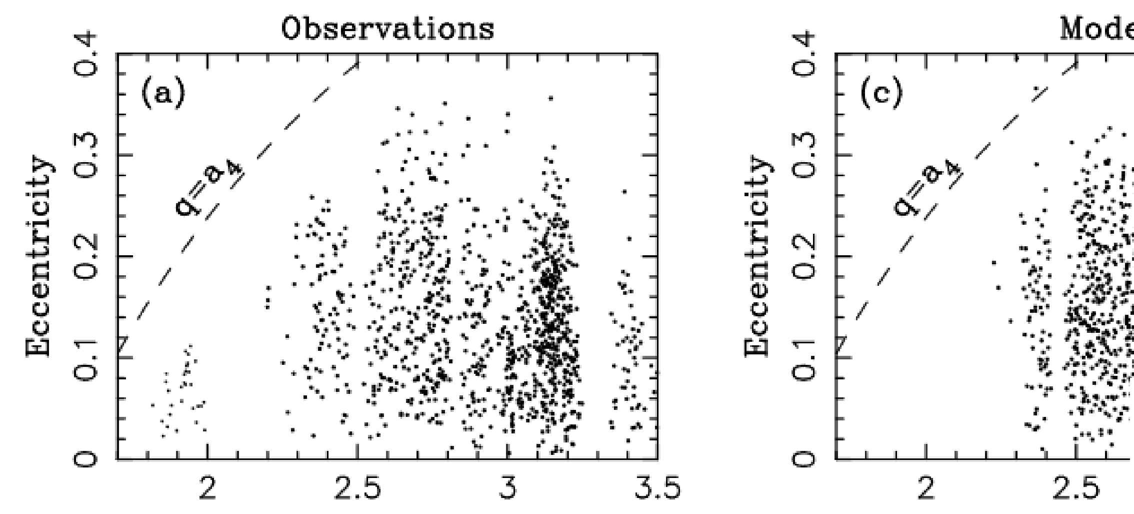
1409.6340

Asteroids and Grand Tack: details



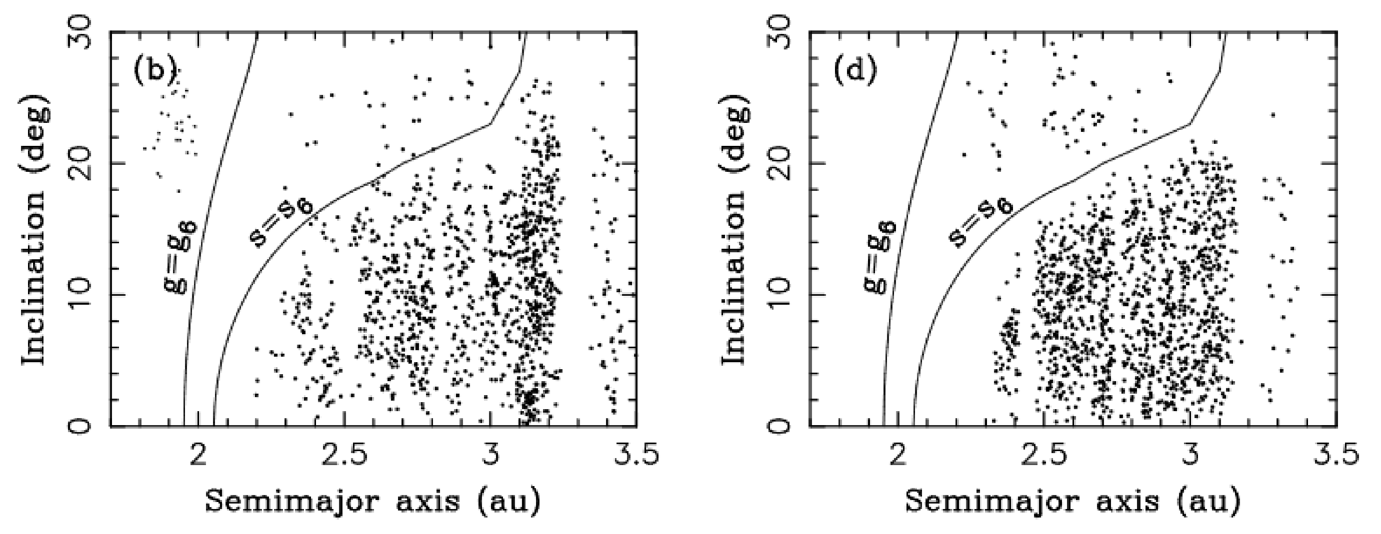
1701.02775

Asteroids in the jumping Jupiter model



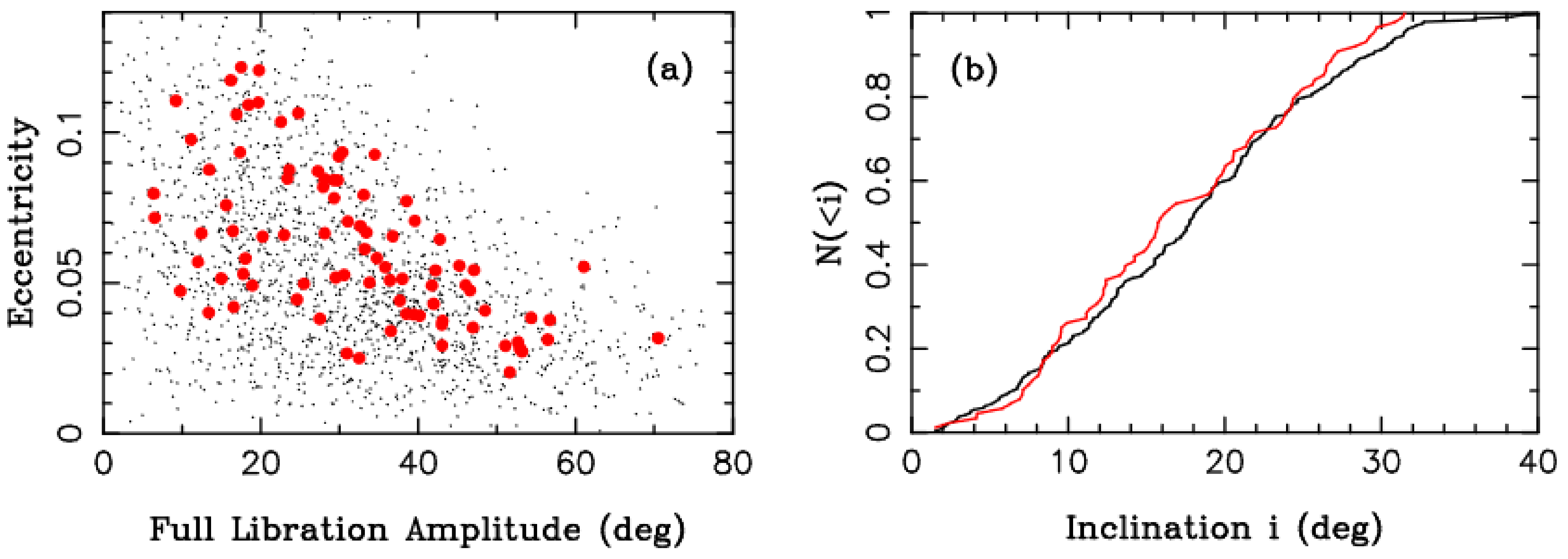
Solid line – secular resonances.
Dashed lines – Mars crossing.

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.



1807.06647

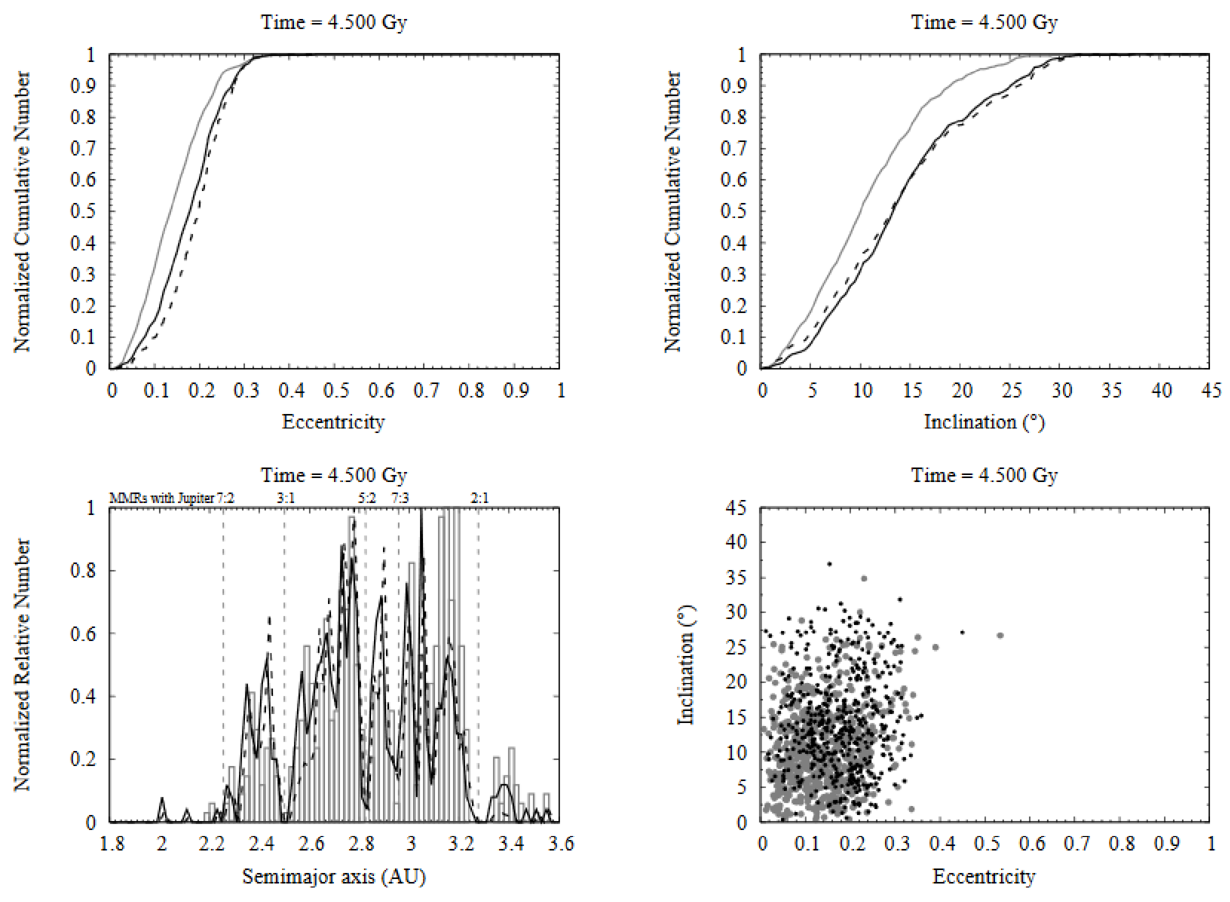
Trojans of Jupiter in the jumping model



Red symbols and line – modeling, black – observations.

1807.06647

Detailed comparison (Grand Tack)

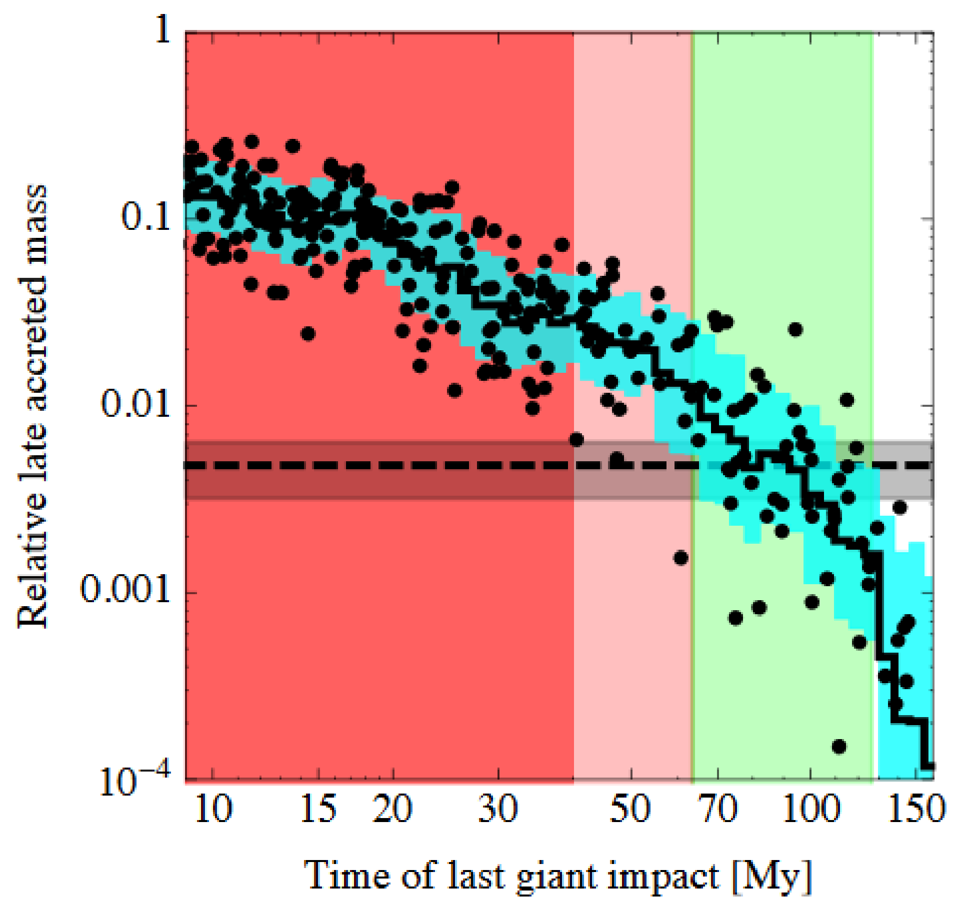


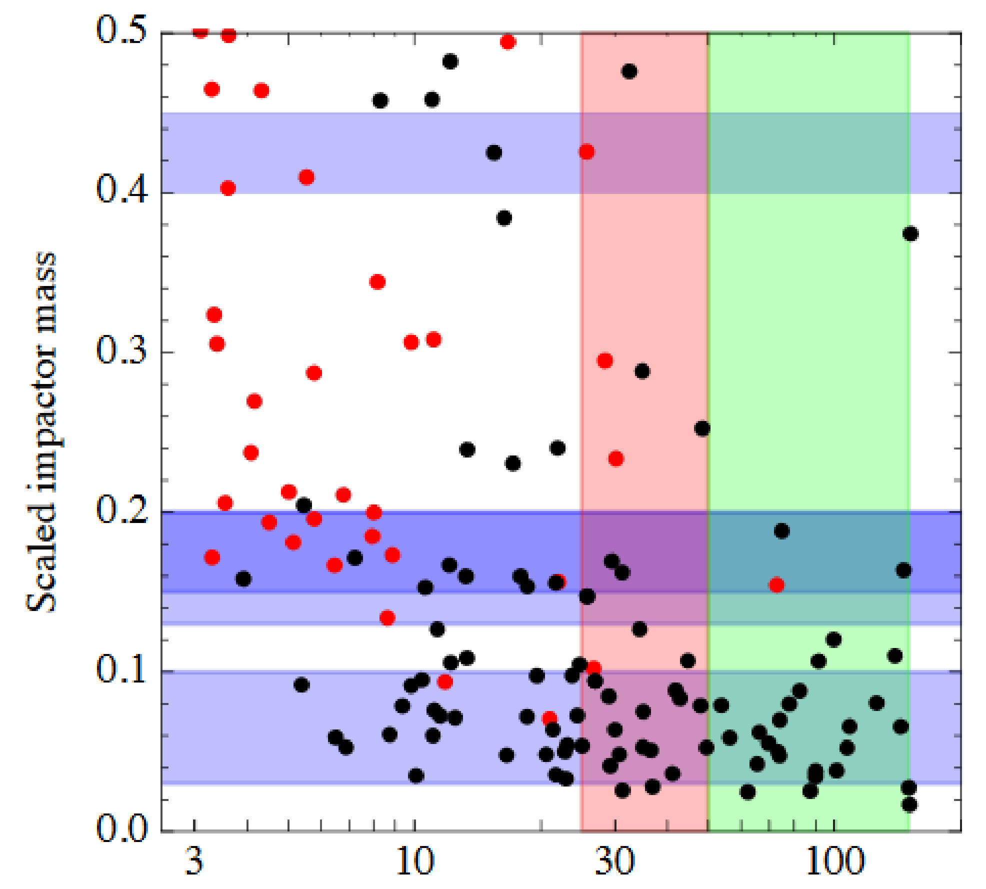
$\sim 1.6\times10^{-3}\ M_{\oplus}$

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

1701.02775

Moon formation and Grand Tack

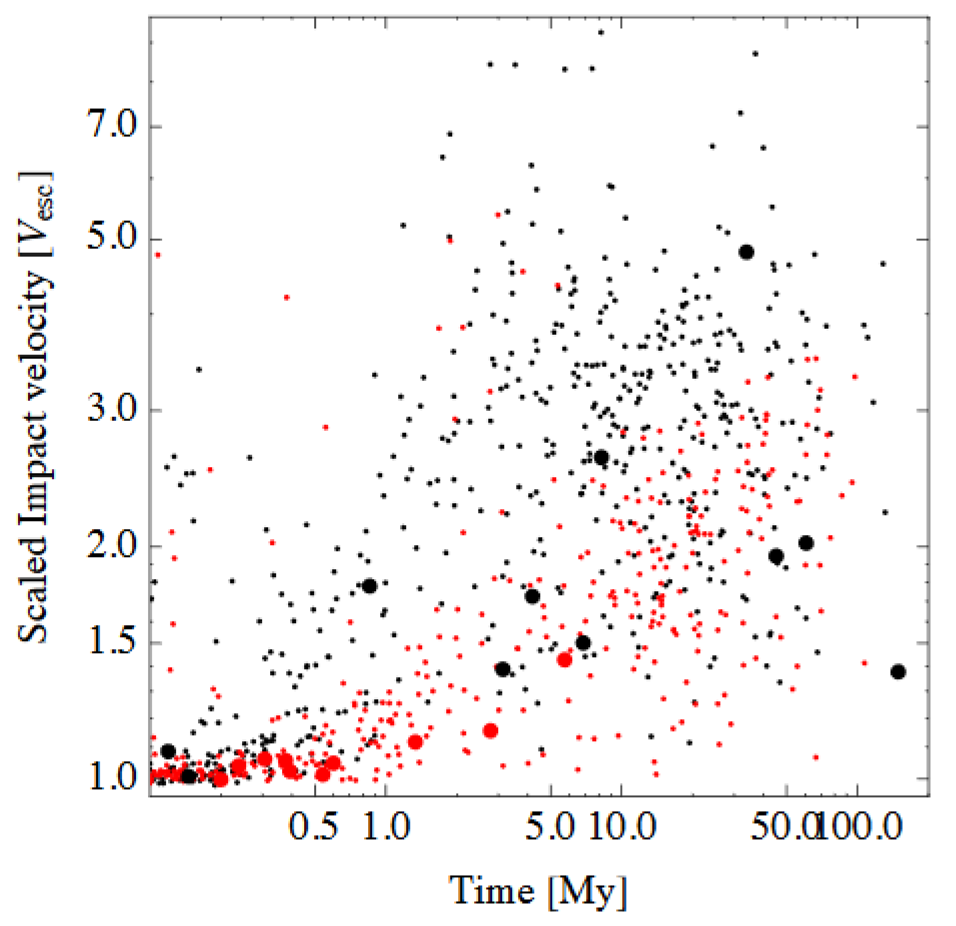


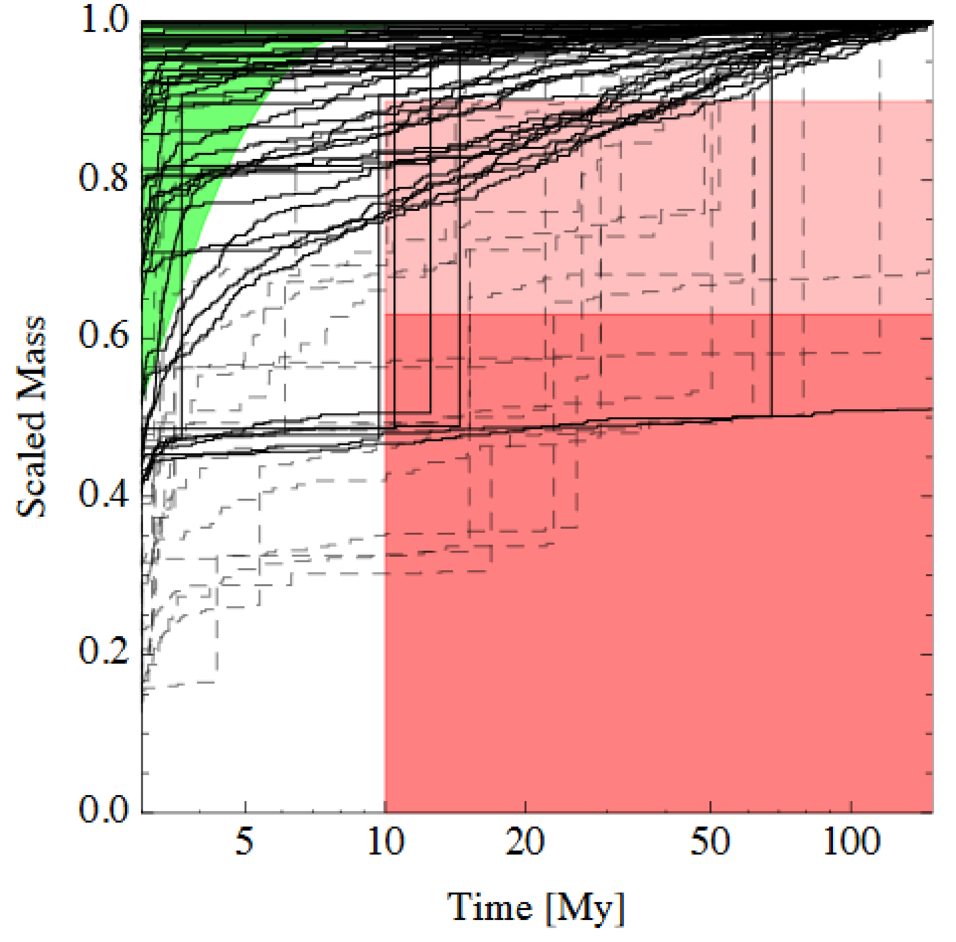


About the age of Moon formation see also Thiemens et al. *Nature Geoscience* (2019) **Vol. 12**, p. 696–700. The authors suggest that the age is ~50 Myrs.

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

Mars and Venus in Grand Tack

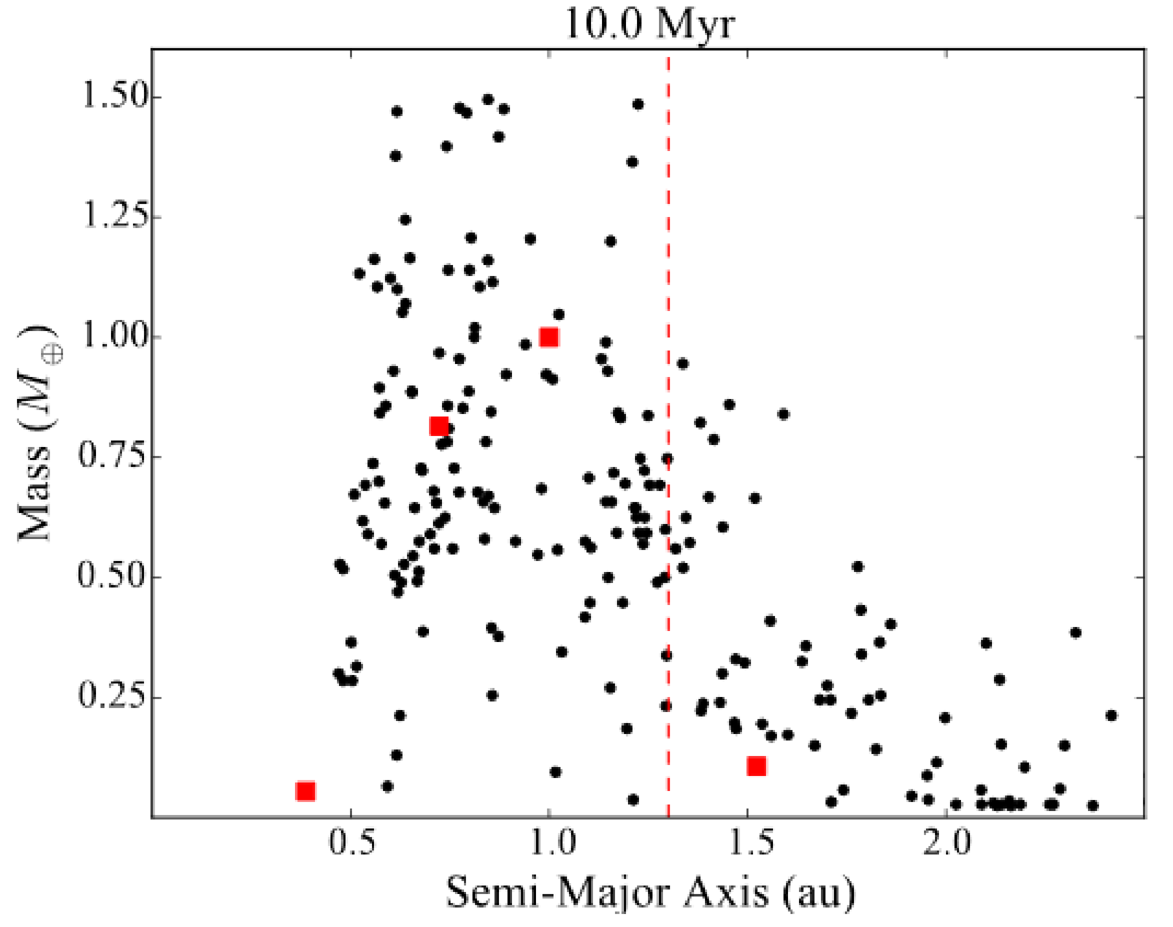


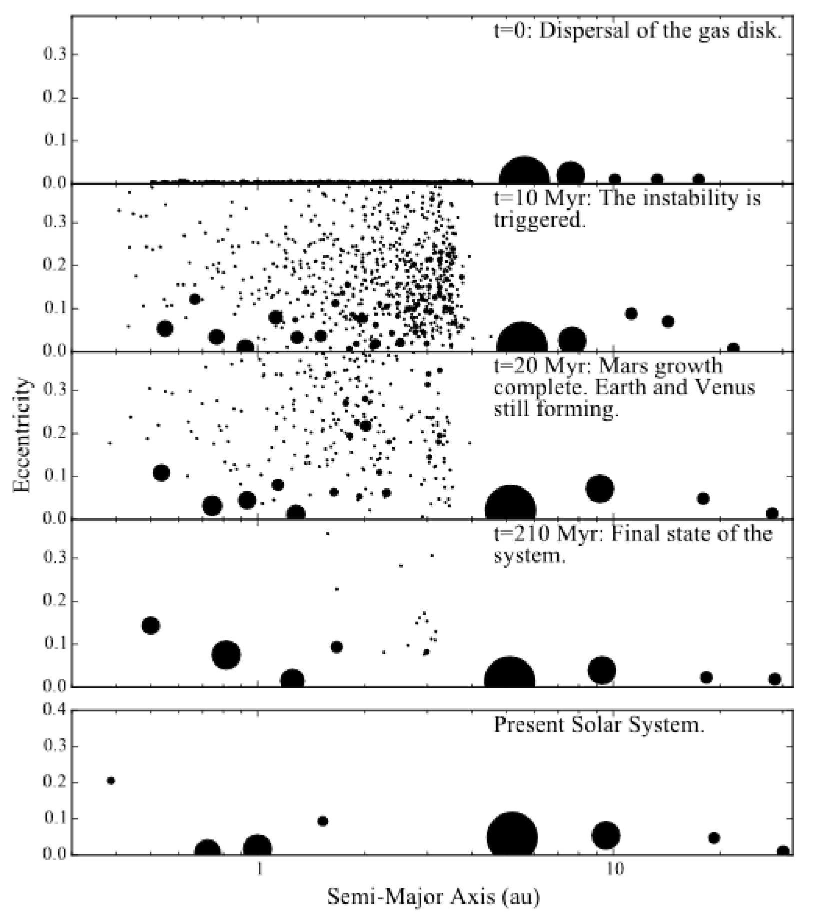


https://www.hou.usra.edu/meetings/lpsc2014/pdf/2274.pdf

New calculations

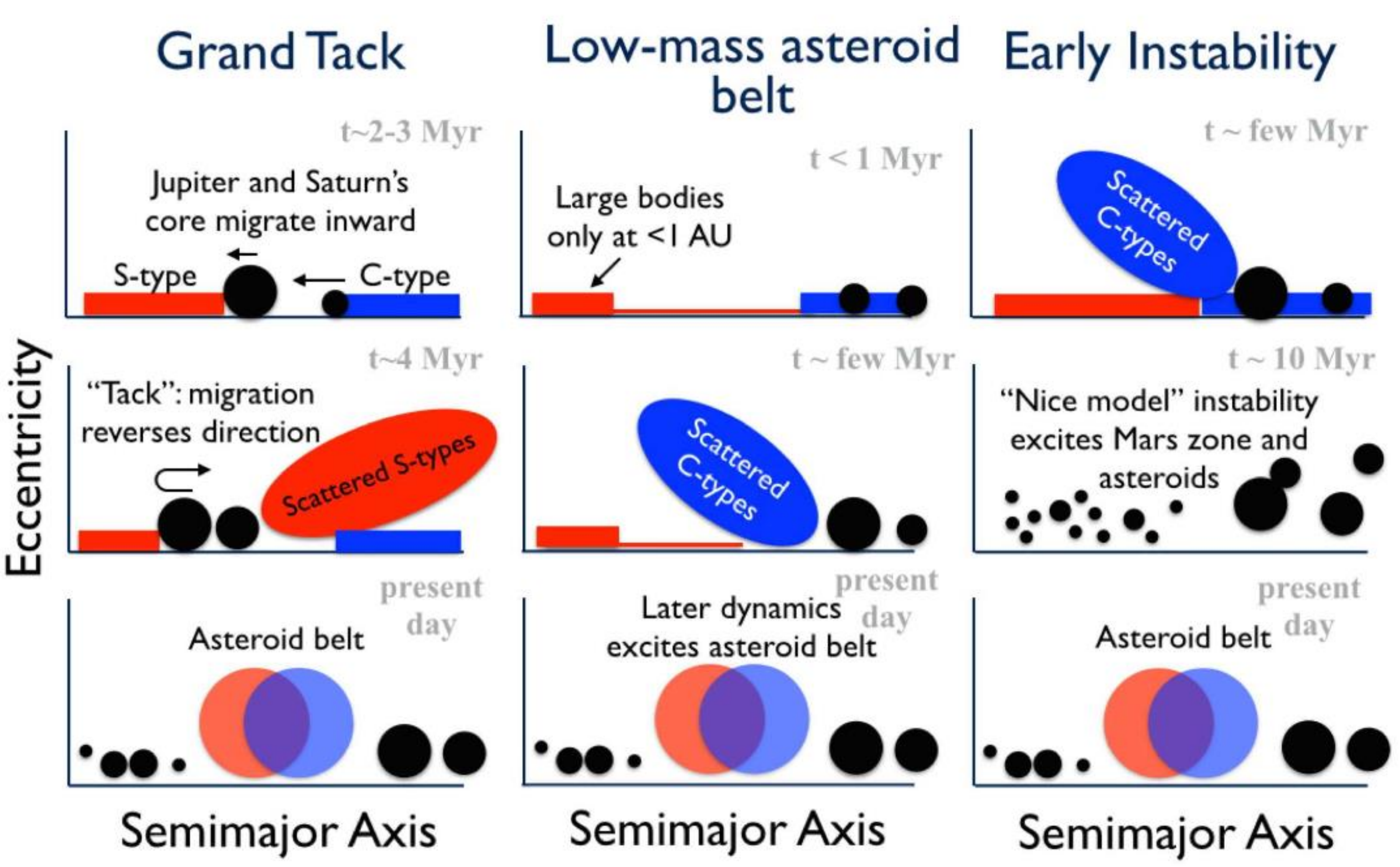
Slightly different model, but consistent with the Grand Tack and Nice.





1804.04233

Model comparison



1812.01033

About structure and formation of Uranus and Neptune see 1909.04891

Literature

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• 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 (review)	1807.06647 Dynamical evolution of the early Solar System D. Nesvorny
• General properties	2004.13209 Solar System Physics for Exoplanet Research Horner et al.