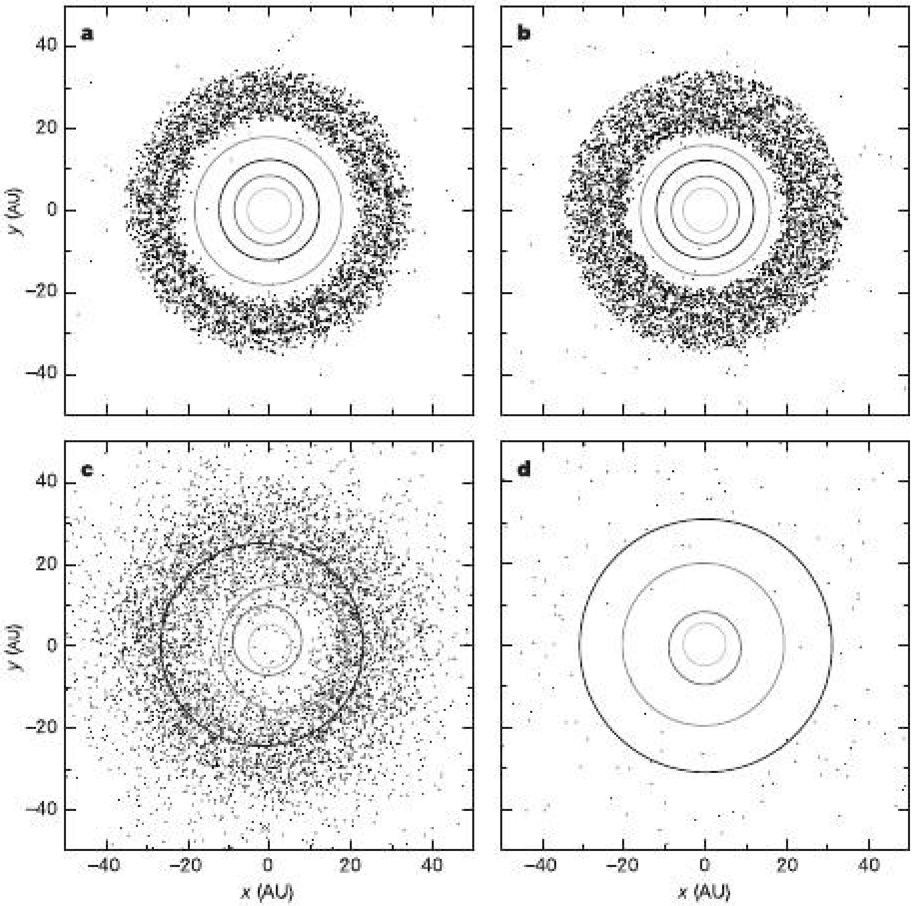
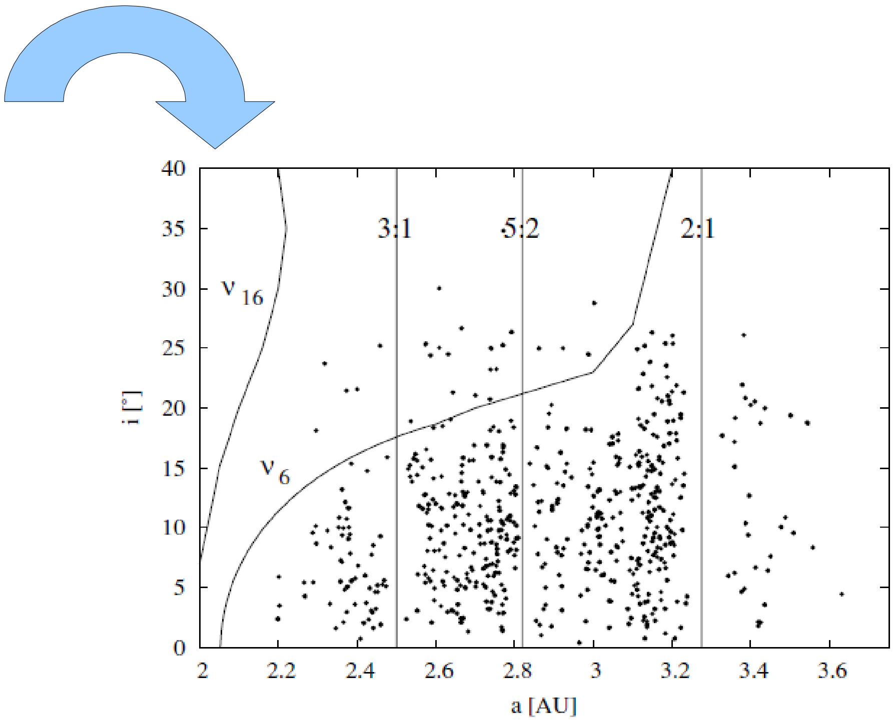
Unveiling the dynamical history of the young solar system

and building connections with extra-solar systems...

Kleomenis Tsiganis

Section of Astrophysics, Astronomy & Mechanics
Department of Physics, Aristotle University of Thessaloniki, Greece





Our research

• *Solar system dynamics* → formation history

[planet migration induced by gas/planetesimals → 'initial' dynamical state of giant planets → 2nd migration era → temporary instability and LHB → final configuration of planets, asteroid belt, KBOs, etc.]

Collaborators: the Nice-model team (A. Morbidelli, H. Levison, R. Gomes) and my students (S. Sotiriadis, A. Toliou, D.Skoulidou)

• *Extrasolar systems → dynamical formation*

[much richer set of solutions → initial configurations leading to resonant or non-resonant systems → dynamical break-up and ***trans***formation of systems]

Collaborators: G. Voyatzis, K. Antoniadou (AUTh) and A.S. Libert, S.Sotiriadis (Namur, BE)

• *NEOs / MBs / Trojans / KBOs and their interconnection*

[Current dynamics → interplay between chaotic diffusion and Yarkovsky → families evolution and NEO sub-populations → meteorites/asteroids connection → Trojan and KBOs connection → Evolution of the small-body reservoirs during the early stages of the solar system]

Collaborators: H. Campins, D. Turrini, Z. Knezevic & B. Novakovic ...

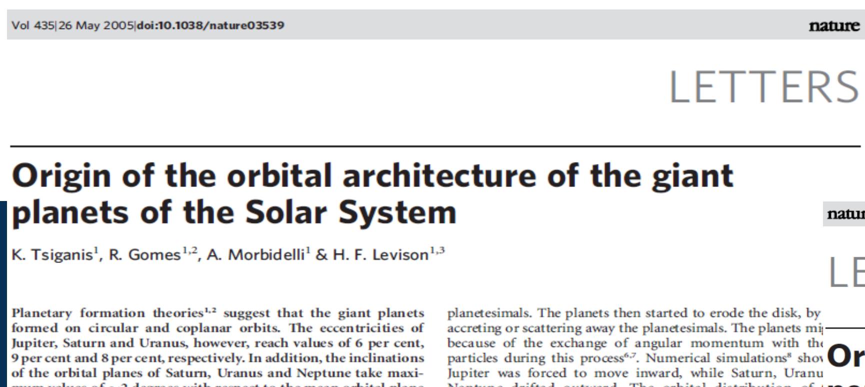
GOAL: *Understand the basic mechanisms that shaped our planetary system before it reached a mature state (and once there..). Identify which of these mechanisms are (a) generic to all planetary systems (b) crucial for the development of terrestrial planets, their habitability and the evolution of their biospheres*

The class of Nice-like planet migration models

•There has been a debate between *smooth migration* models and the *Nice-type models*

• What do we know from the *class* of models, known as the *“Nice model”*:

• ***Nice v1.0 (2005):*** smooth migration of the outer planets + resonance crossing → abrupt expansion of the system


Vol 435|26 May 2005|doi:10.1038/nature03539 nature

LETTERS

Origin of the orbital architecture of the giant planets of the Solar System

K. Tsiganis[1], R. Gomes[1,2], A. Morbidelli[1] & H. F. Levison[1,3]

Planetary formation theories[1,2] suggest that the giant planets formed on circular and coplanar orbits. The eccentricities of Jupiter, Saturn and Uranus, however, reach values of 6 per cent, 9 per cent and 8 per cent, respectively. In addition, the inclinations of the orbital planes of Saturn, Uranus and Neptune take maximum values of ~2 degrees with respect to the mean orbital plane

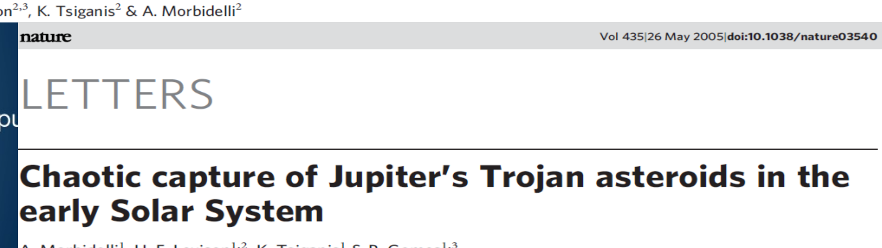
planetesimals. The planets then started to erode the disk, by accreting or scattering away the planetesimals. The planets mi because of the exchange of angular momentum with the particles during this process[6,7]. Numerical simulations[8] show Jupiter was forced to move inward, while Saturn, Uranu Neptune drifted outward. The orbital distribution of


nature Vol 435|26 May 2005|doi:10.1038/nature03676

LETTERS

Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets

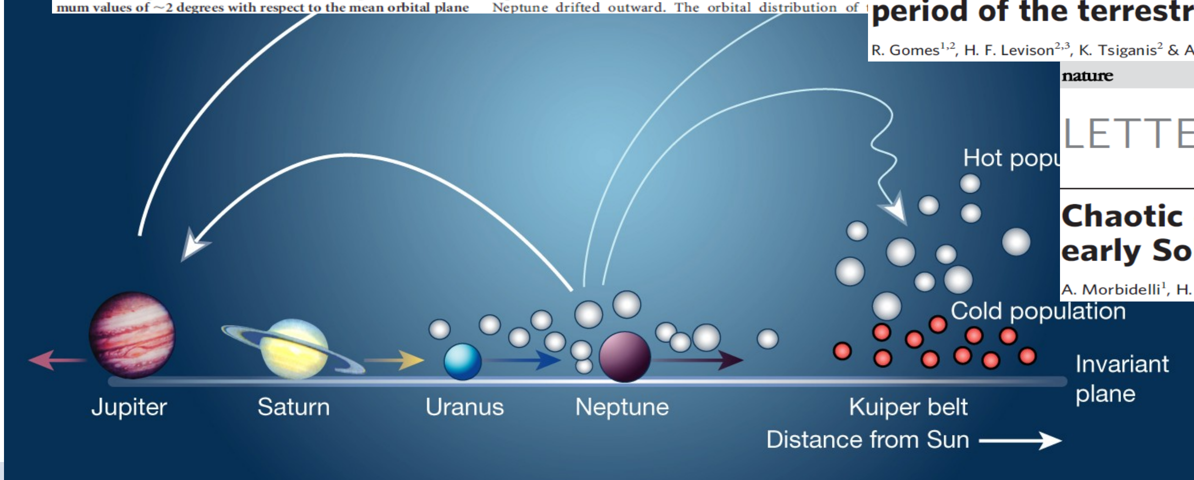
R. Gomes[1,2], H. F. Levison[2,3], K. Tsiganis[2] & A. Morbidelli[2]


nature Vol 435|26 May 2005|doi:10.1038/nature03540

LETTERS

Chaotic capture of Jupiter’s Trojan asteroids in the early Solar System

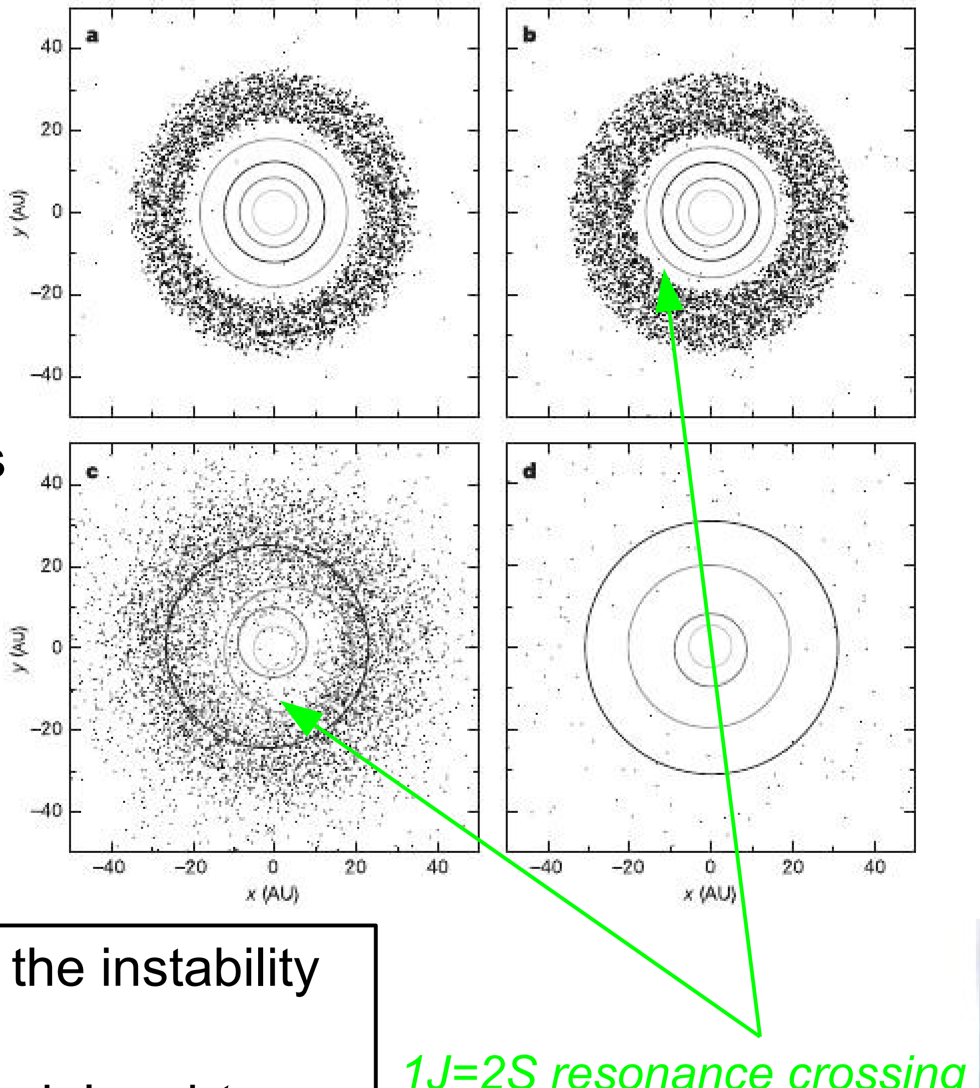
A. Morbidelli[1], H. F. Levison[1,2], K. Tsiganis[1] & R. Gomes[1,3]



10th-year anniversary on May 2015...

The Nice model (v1.0 - 2005)

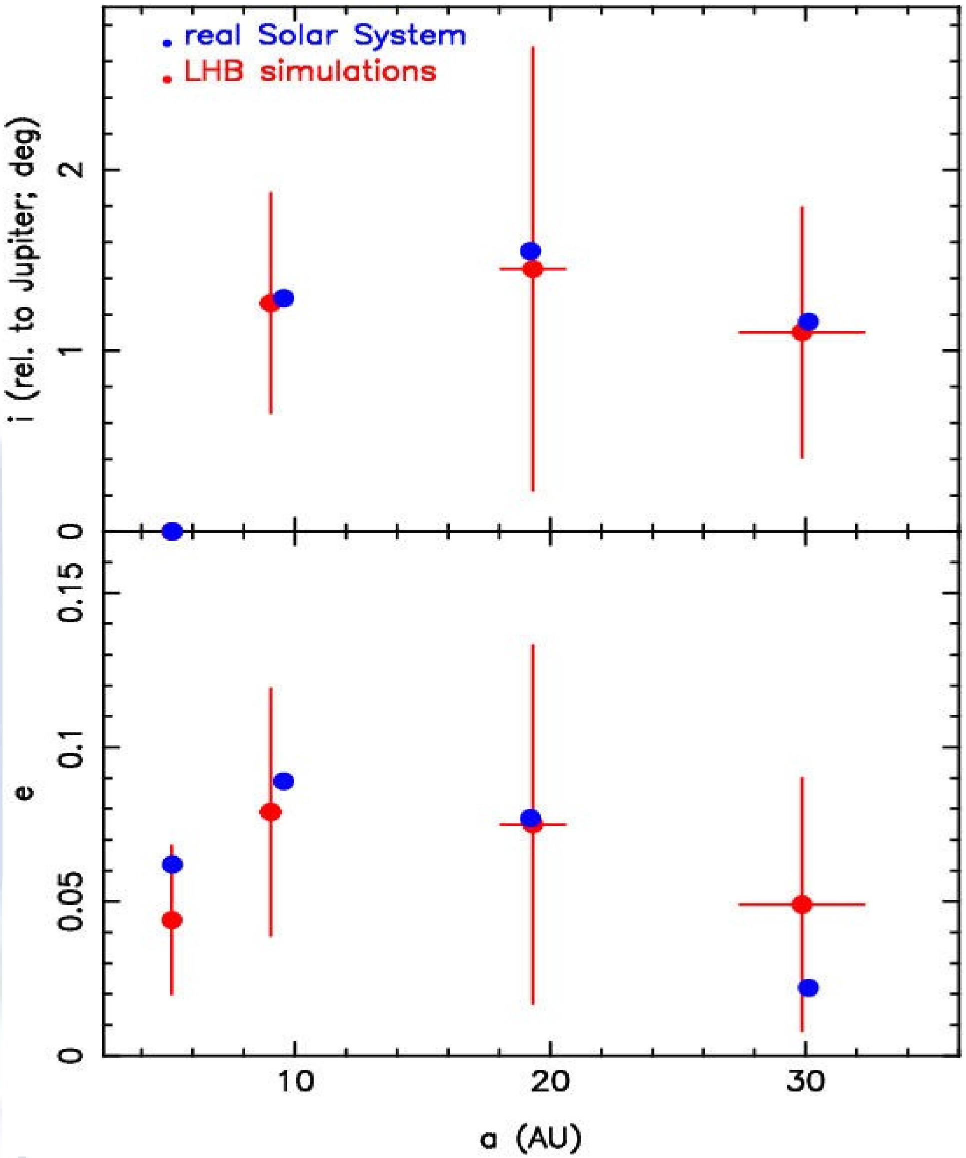
- Planets more closely packed than in smooth models → resonances come to play...
- an initially *stable* configuration → planet-disk interactions force smooth migration
- *resonance crossing* excites eccentricities → global instability
- Instability suppressed by dispersing the disk → mass depletion



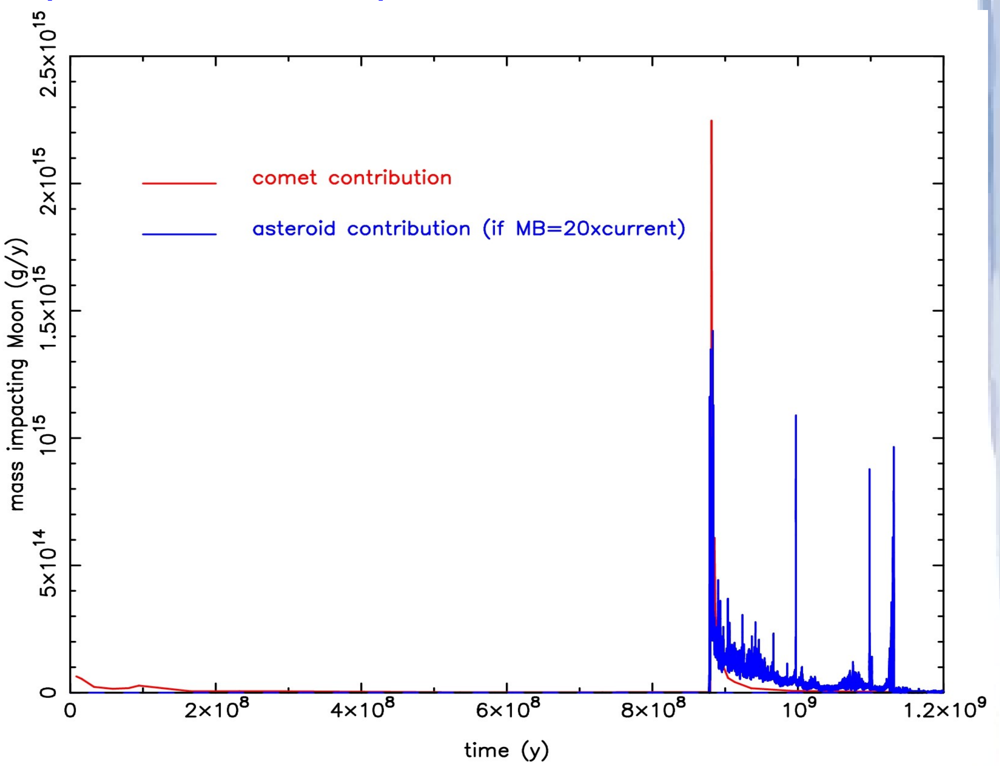
* Jup moves inwards by ~0.25 AU during the instability → actual $a_J(t_0)$ ~ 5.5 AU

* this value is better suited for the EJB model and t_0 means *after* formation and Type II migration

The Nice model (v1.0 - 2005)



reproduces the orbits of the planets...

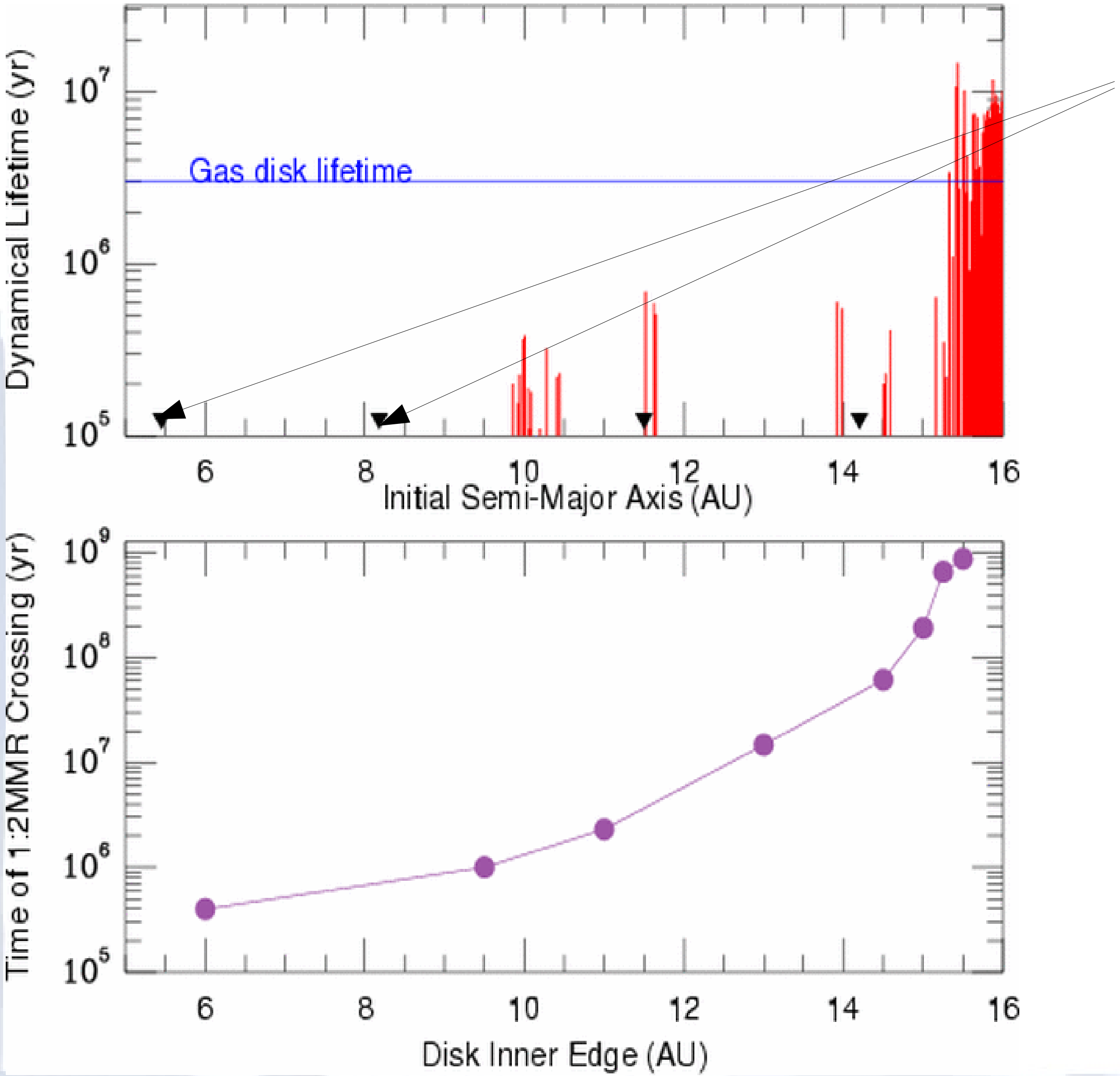


… and the LHB main constraints

- Several “success” stories since:

Ttrojans, irregular satellites, KBOs, primitive main-belt asteroids, ...

Main problems with Nice v1.0

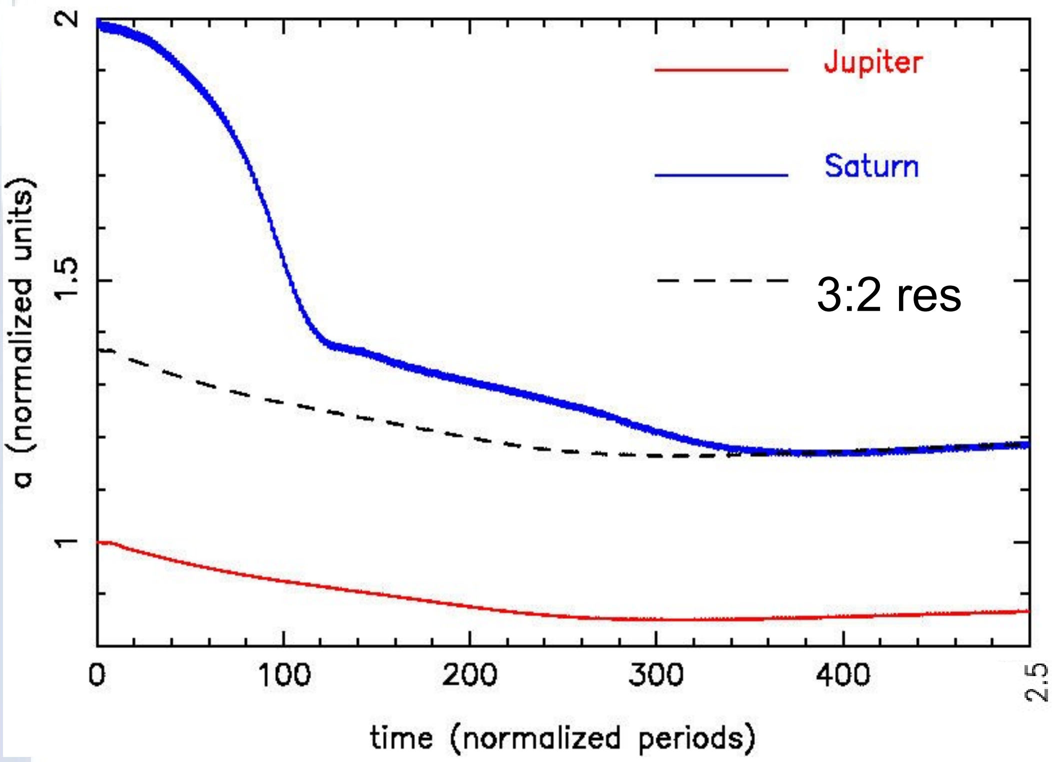


- Initial conditions for the planets were simply guessed ...

  … while they should represent the “final” conditions of a previous phase of gas-driven migration

- *Critical* (although monotonic) dependence on t_{crit} with disk parameters

The Nice model v1.5 (2007)

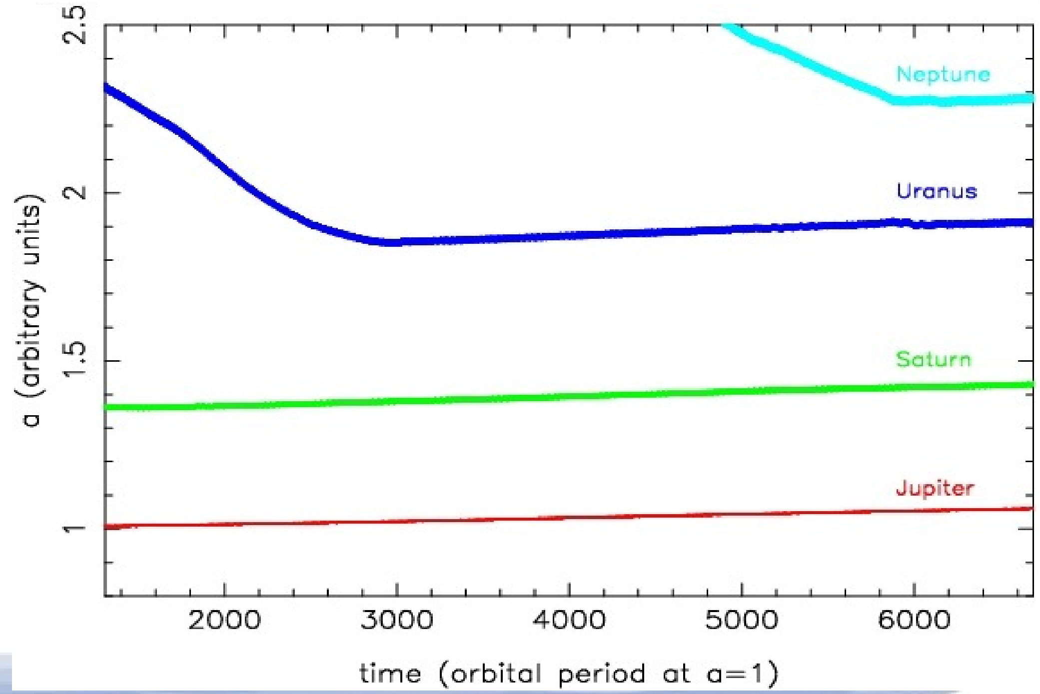


- J-S migration in a gas disk (first ~5 My) can lead to capture in a 3:2 MMR
- J-S can stop migrating after that, for a range of reasonable disk parameters

- … all four outer planets can be trapped in a multiple (Laplace-type) resonance

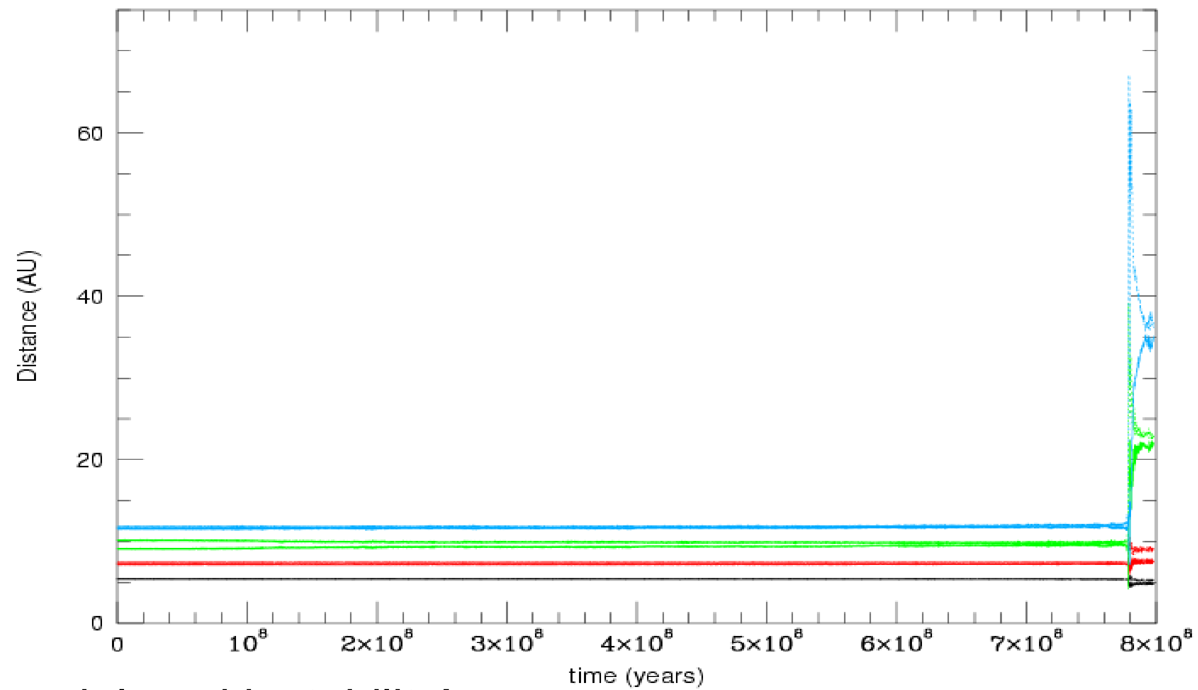
→ "proper" initial conditions

** Very important also for extra-solar systems → stable resonant systems OR a way to instability (**trans**formation of a system)**



- Planetesimals can then extract the planets from their resonance and force them to migrate, cross several MMRs → evolution similar to Nice v1.0

- **GREAT** initial conditions



- **WORSE** for having a delayed instability!

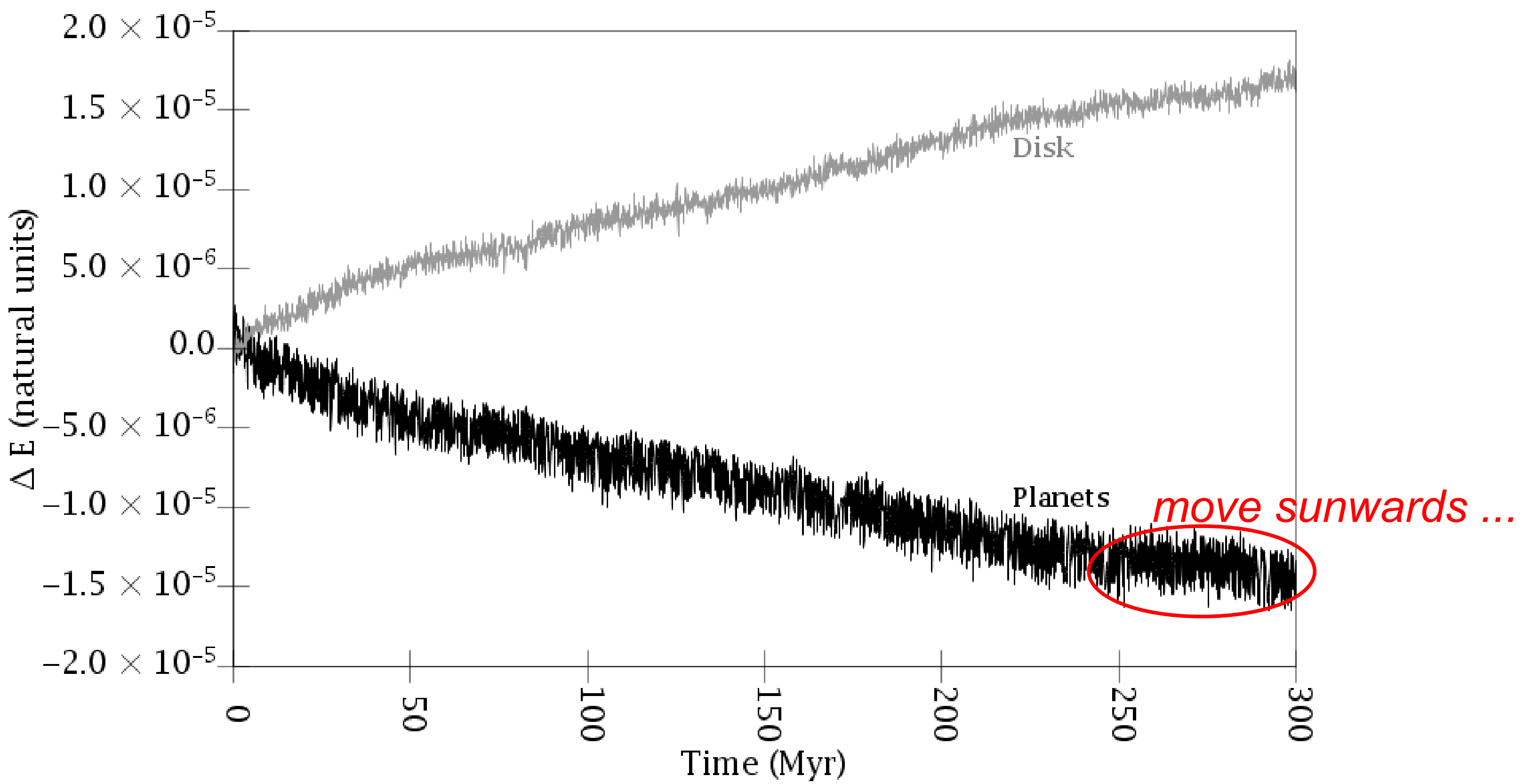
→ the planets are "pealing off" the inner edge of the disk but without moving freely in *a*

→ needs *extreme fine tuning* of the disk, to get t_{crit} ~ 500-700 My

Nice model v2.0 (2011)

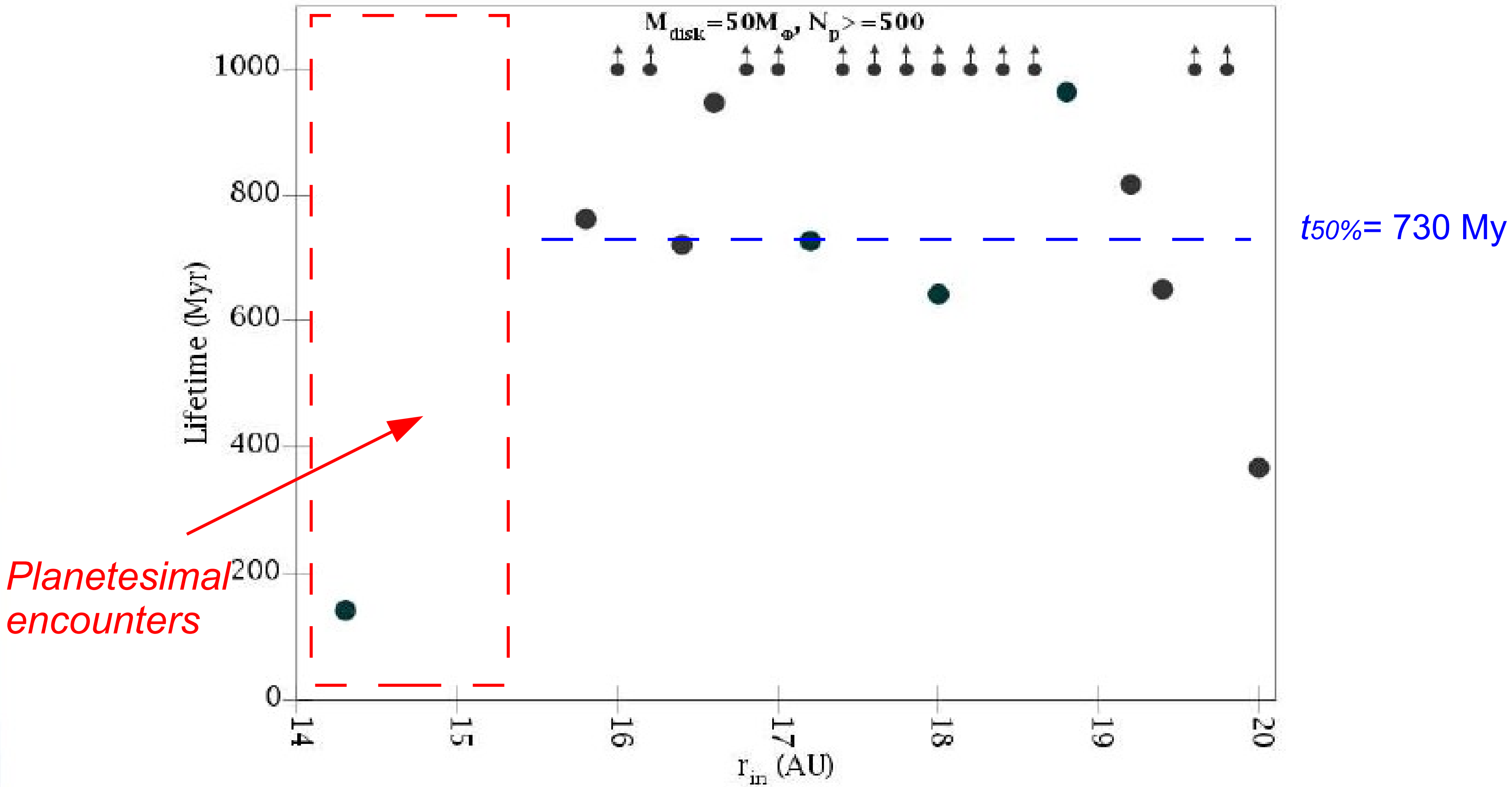
- What was missing in all these simulations ?
  → the disk's self-gravity → particle-particle velocity stirring

- Gives *secular energy exchange* between the disk and the planets!



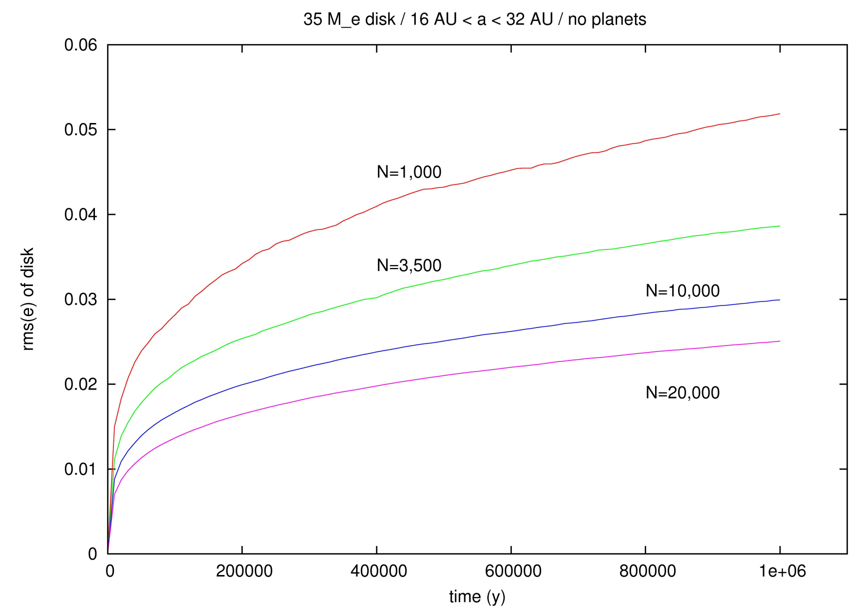
- leads to adiabatic eccentricity increase in resonance → *unstable!*

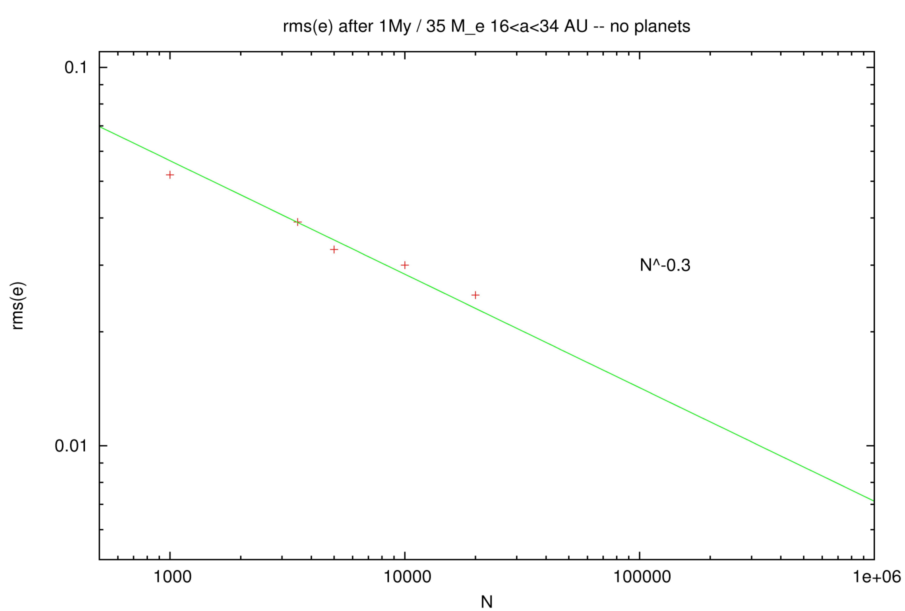
Instability Time (vs. LHB)



- Systems go unstable preferentially ***LATE***
- Not a sensitive dependence on the inner edge of the disk!
- Both “Proper” initial conditions and ***GREAT*** timing for the LHB.

* New results (full N^2 gravity – GPU Symba)





Disk excitation due to self-gravity goes like

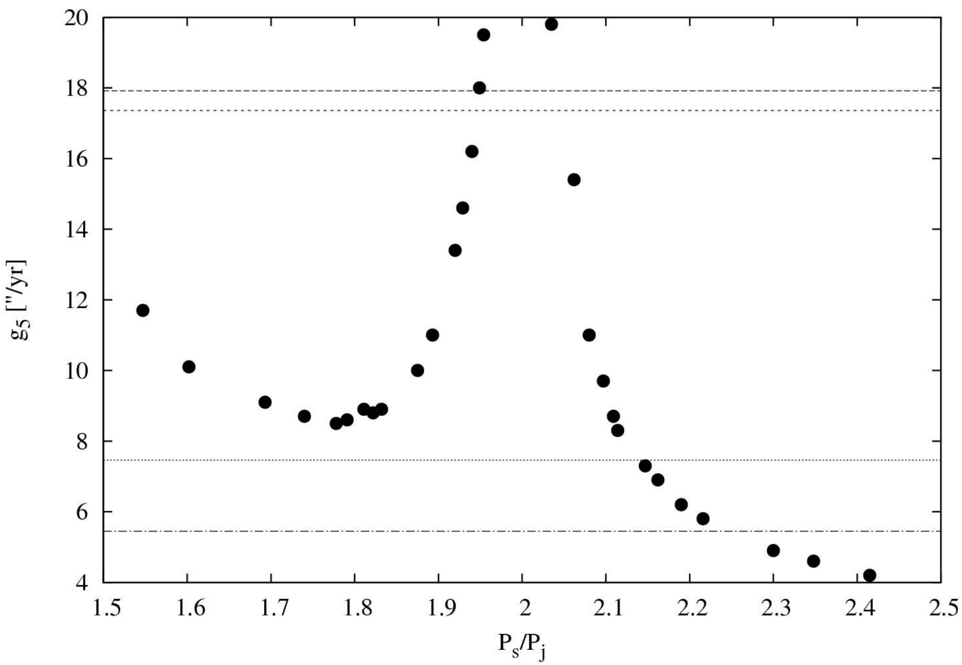
$$\text{rms}(e) \sim N^{-0.3}\, t^{1/2}$$

→ similar excitation to that given by the simplified model used in *“Nice v2.0”*

→ we will be able to do the 'real' problem

[needs a proper way of representing the real disk with a smaller collection of tp's]

a closer look to some ISS constraints...

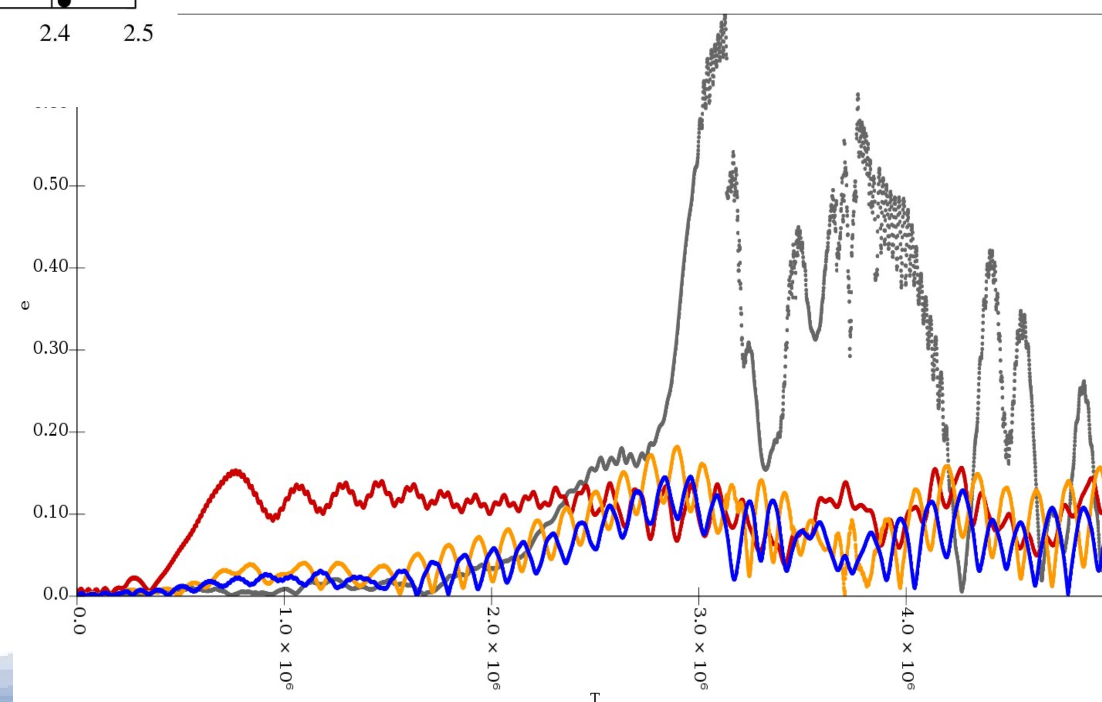


Divergent planet migration leads to variation of the secular frequencies

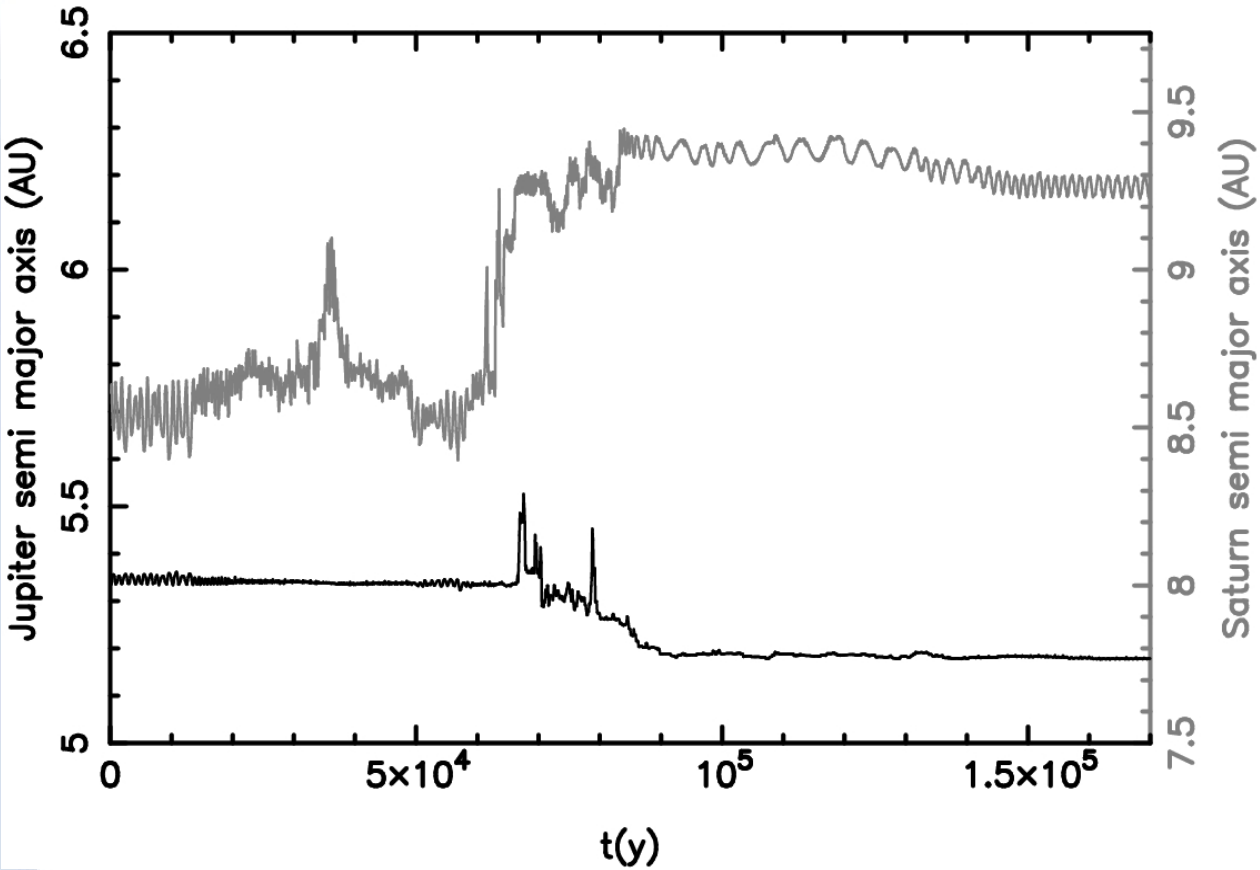
→ resonances between g5 and gi (i=2,4) are possible

If migration was slow (~ 10 My) or resonances were approached slowly

→ possibly *devastating effect on terrestrial planets* and asteroids



a closer look to some ISS constraints...



- This favors *fast* planet migration

  → dominated by *planet-planet encounters*

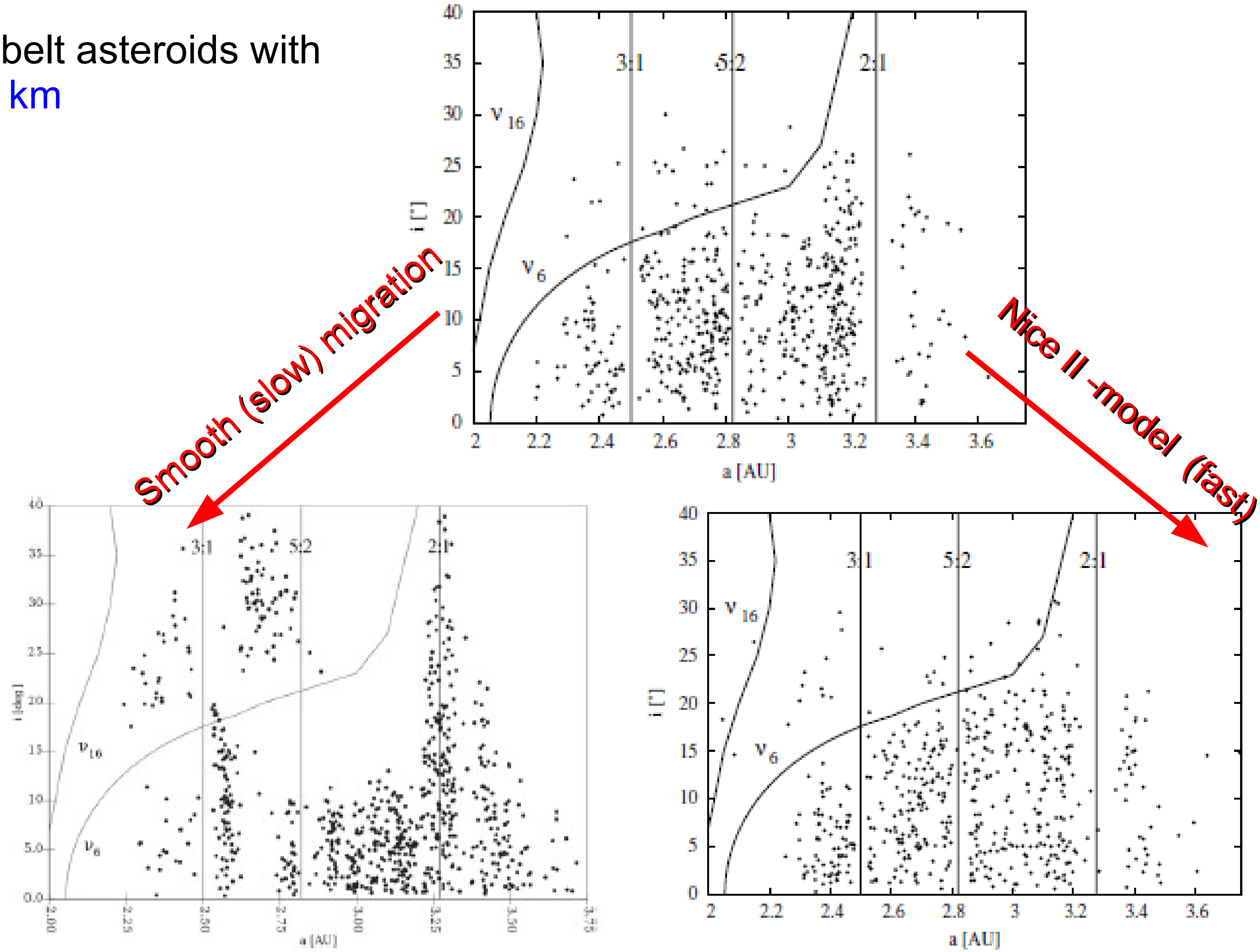
  → a subset of Nice-model runs

* may argue for a 5th outer planet (~ice giant) → escaped the system during this phase

… migration occurs on a much shorter time-scale ~10^5 y

What do these models give for the asteroid belt?

Main-belt asteroids with
D>50 km



Implantation of comet-like objects to the MB during the LHB

During the LHB event, comet-like objects penetrate not only the 'Trojans' but als the 'MB' outer regions

More fragile, may explain the μ-meteorites sample

Question: what part of the D/P types distribution is primordial ??

nature Vol 460|16 July 2009|doi:10.1038/nature08094

LETTERS

Contamination of the asteroid belt by primordial trans-Neptunian objects

Harold F. Levison[1,2], William F. Bottke[1,2], Matthieu Gounelle[3], Alessandro Morbidelli[4], David Nesvorný[1,2] & Kleomenis Tsiganis[5]

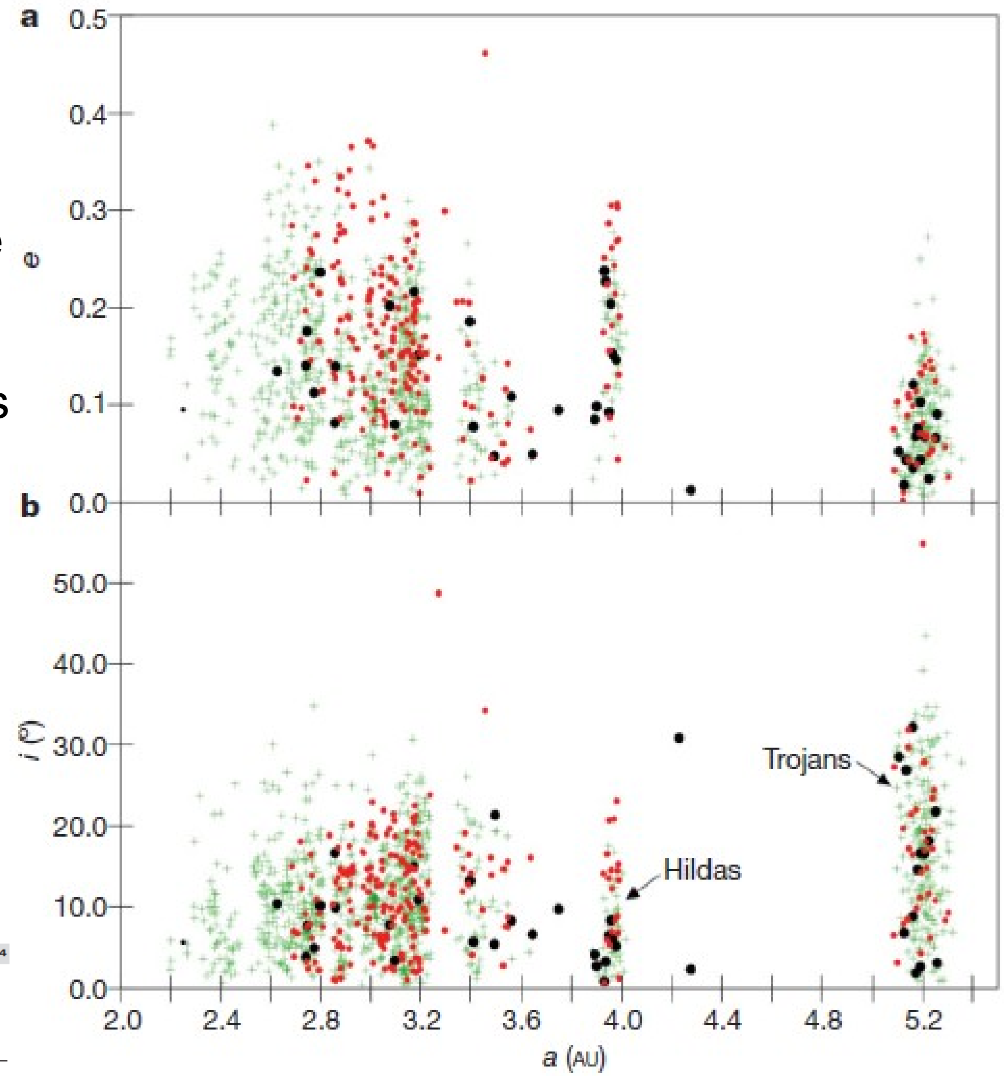
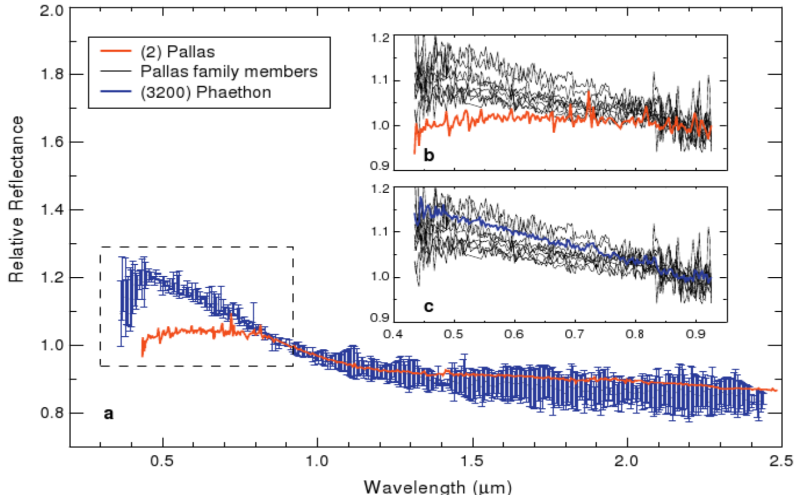


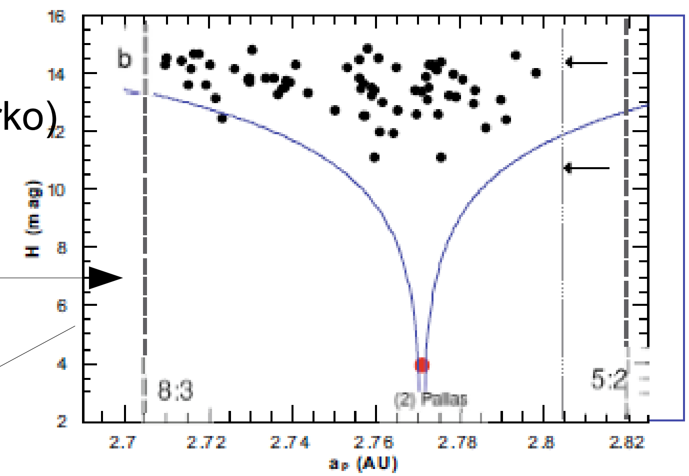
Figure 1 | The orbital element distributions of real and modelled asteroids.

Meteorite/Asteroid connection

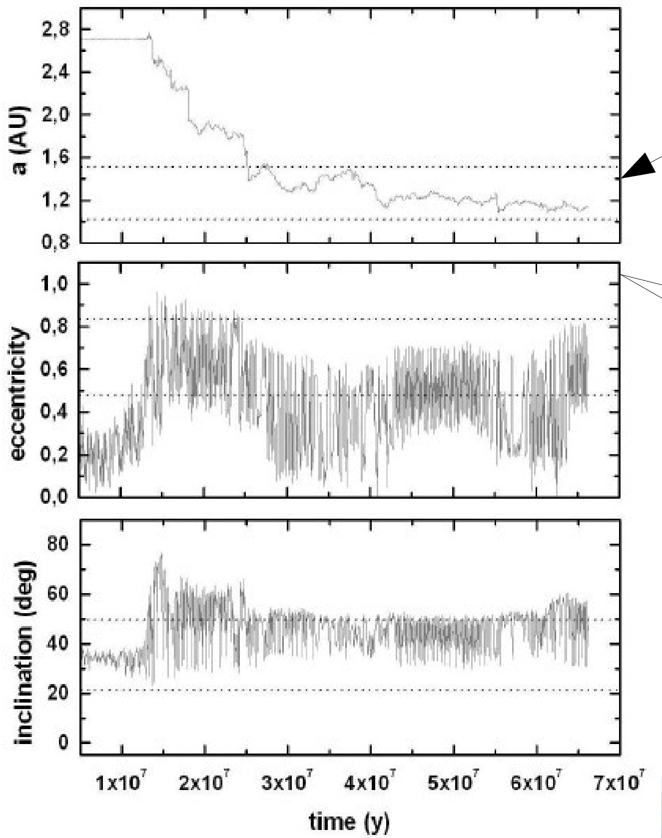
example: Geminids → Phaeton (NEA) → Pallas (MB)



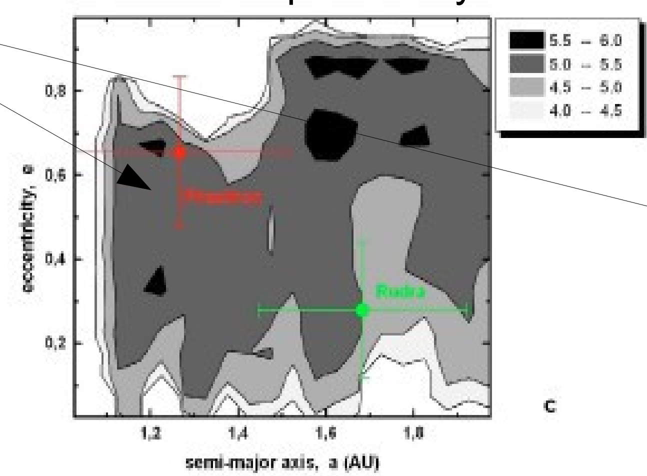
Pallas fragments enter MMRs (Yarko)

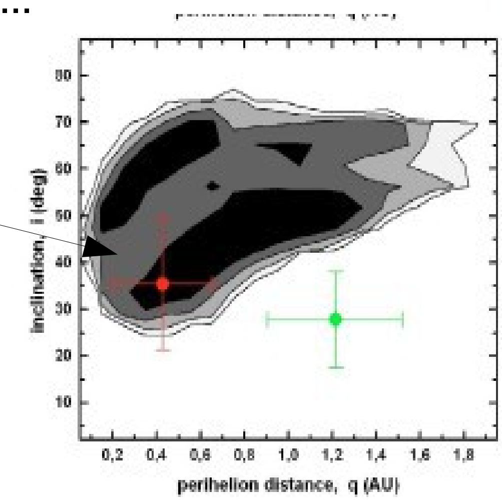


Travel to NEO region



… occupying the phase-space region spanned by Phaethon...





What we know/need to understand for the history of the MB

- Fact 1: a "flat" asteroids disk cannot evolve into what we observe today → need for planet migration! → (initial a_J <>5.2)

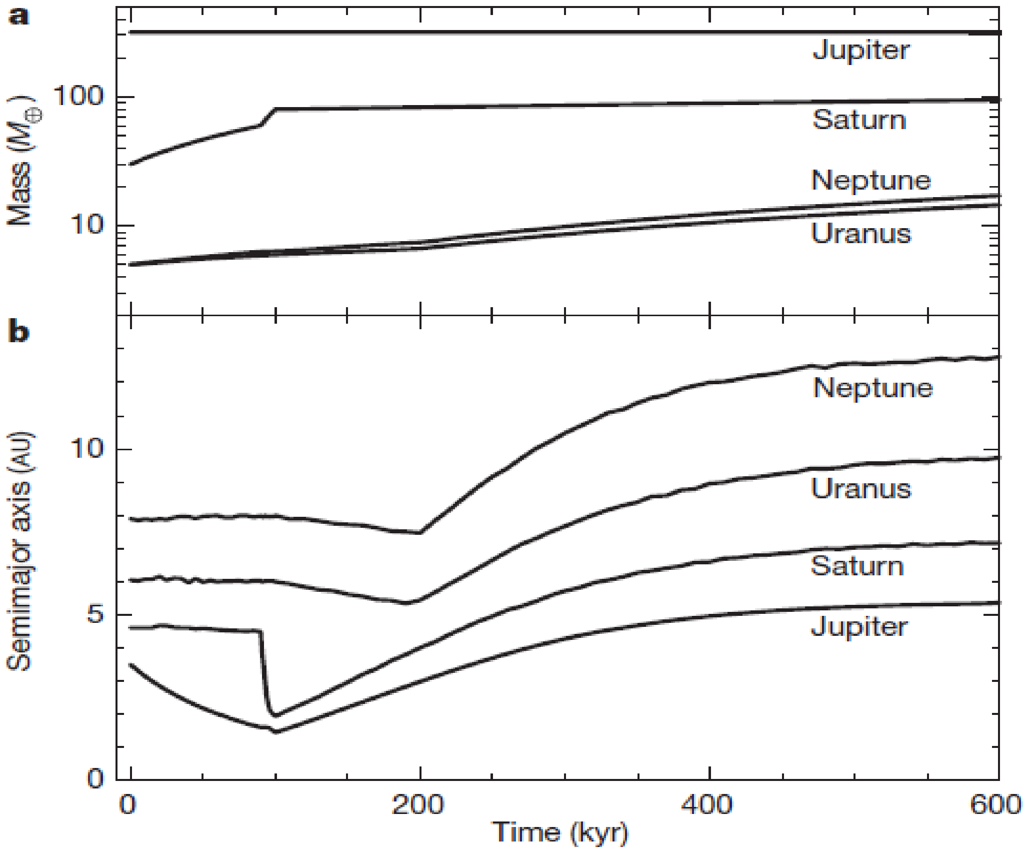
- Fact 2: "Smooth" migration can explain the (a,e) distribution but not the (a,i) distribution → need for fast migration

→ Excitation due to Secular Resonance Sweeping: $g=g(a/a_J)$, $s=s(a/a_J)$ and a_J changes with time, the main secular resonances "sweep" through the belt, exciting asteroid orbits (if the time-scale is of ~10 My)

- Fact 3: **Nice Model (v2.0)** suggests that ***(a,i) distribution is primordial*** since planetary orbits change so fast (t<1 My) that asteroids do not "see" the SRs

* Here "primordial" means before the final step of planet migration, i.e. *during* or *after* the Type II migration phase

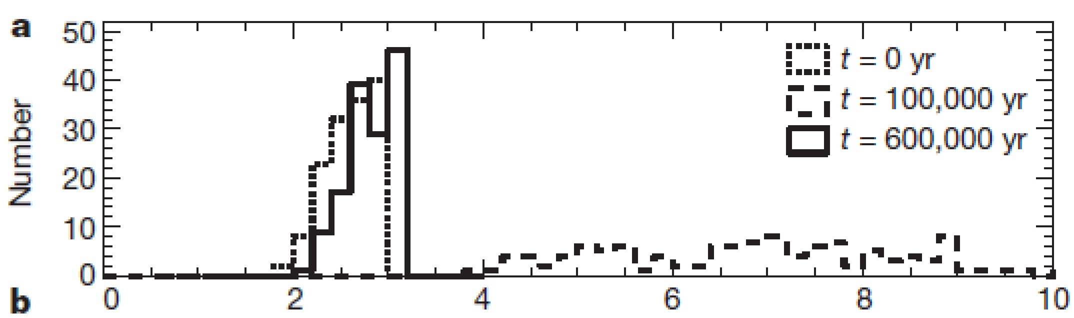
The Grand-Tack scenario



The planets migrate initially *inwards* (due to disk tides) but later move *outwards* due to resonance capture

Jupiter is initially between 3 and 5 AU, moves inwards to ~1.5 AU and then outwards to (near) its current location

(needs tuning...)



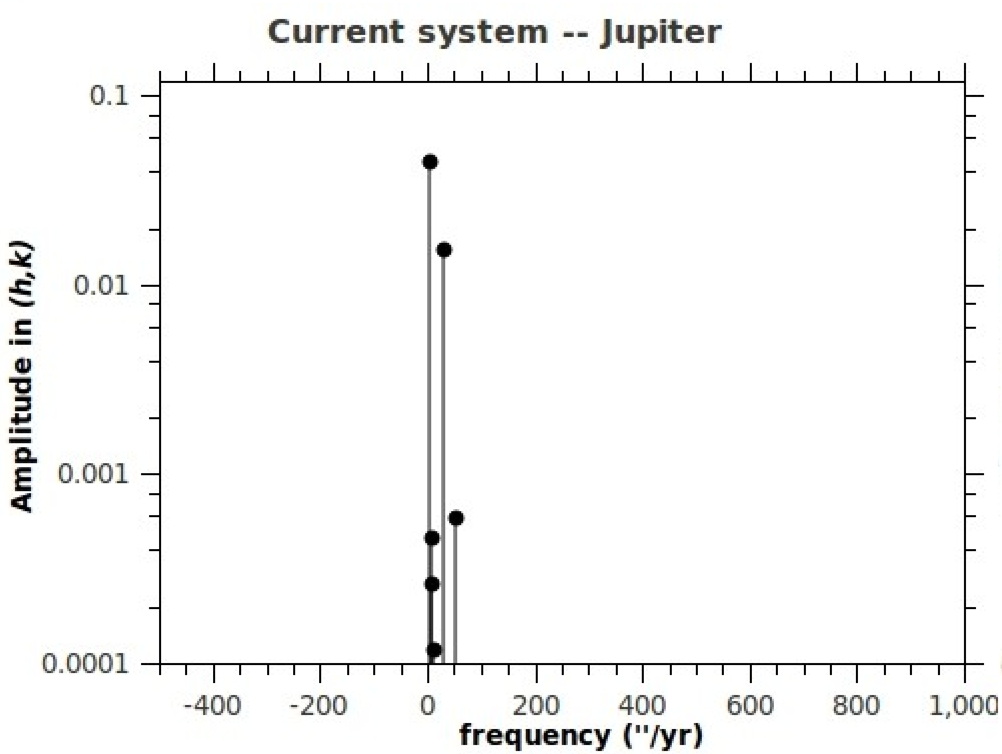
ISS planetesimals are scattered *twice* and are finally implanted in the belt, near their original location

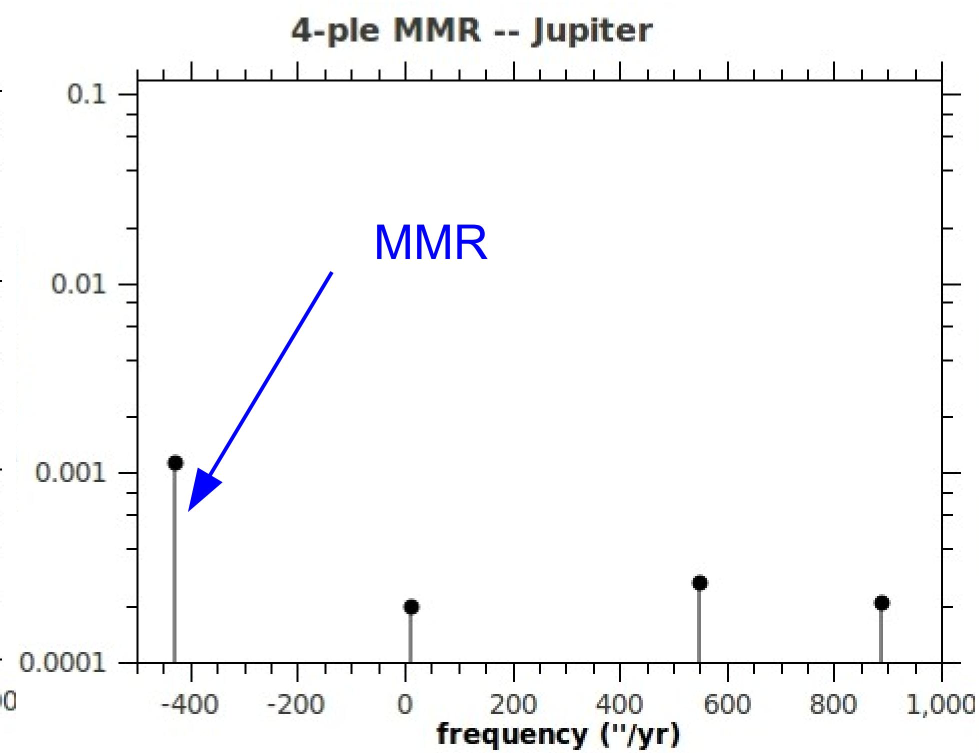
→ accounts for (a,i) and mixing of taxonomic types *(a,e is strange..)*

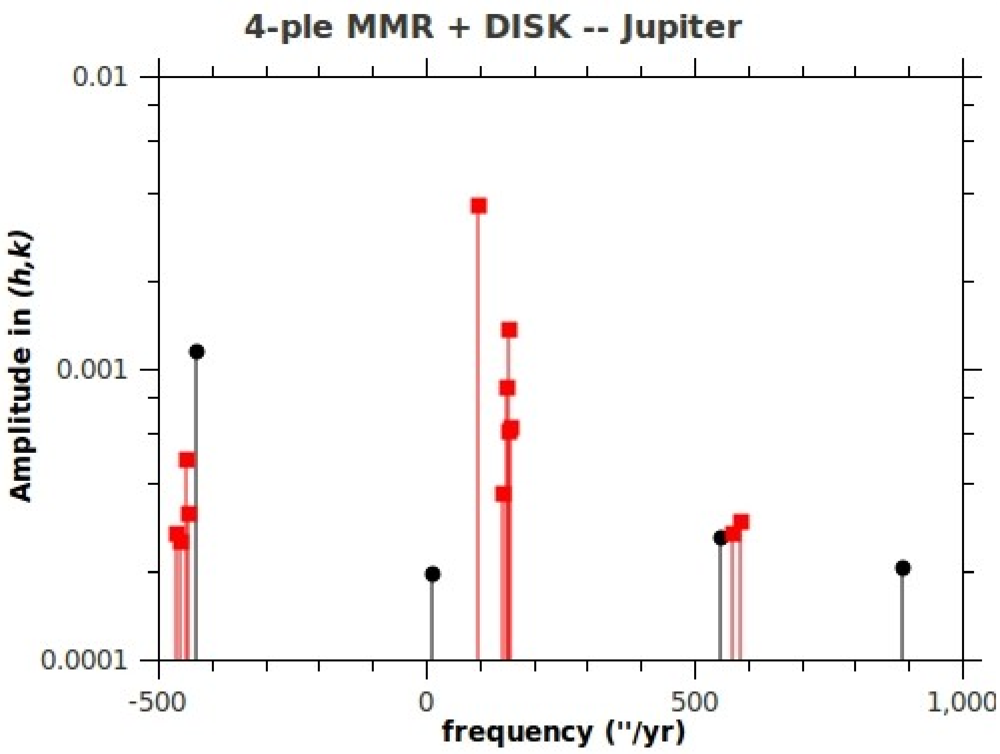
→ suggests truncation ~1.5 AU which fives a 'light' Mars

MB: the key to unveiling the pre-migration history

- Hydrodynamical simulations suggest that, during the gas-rich phase of the solar system, the planets migrate towards a quadruple mean motion resonance (3:2, 3:2, 4:3 /...)
- This configuration has a completely different set of fundamental secular frequencies w.r.t. the current system







Adding a gas disk

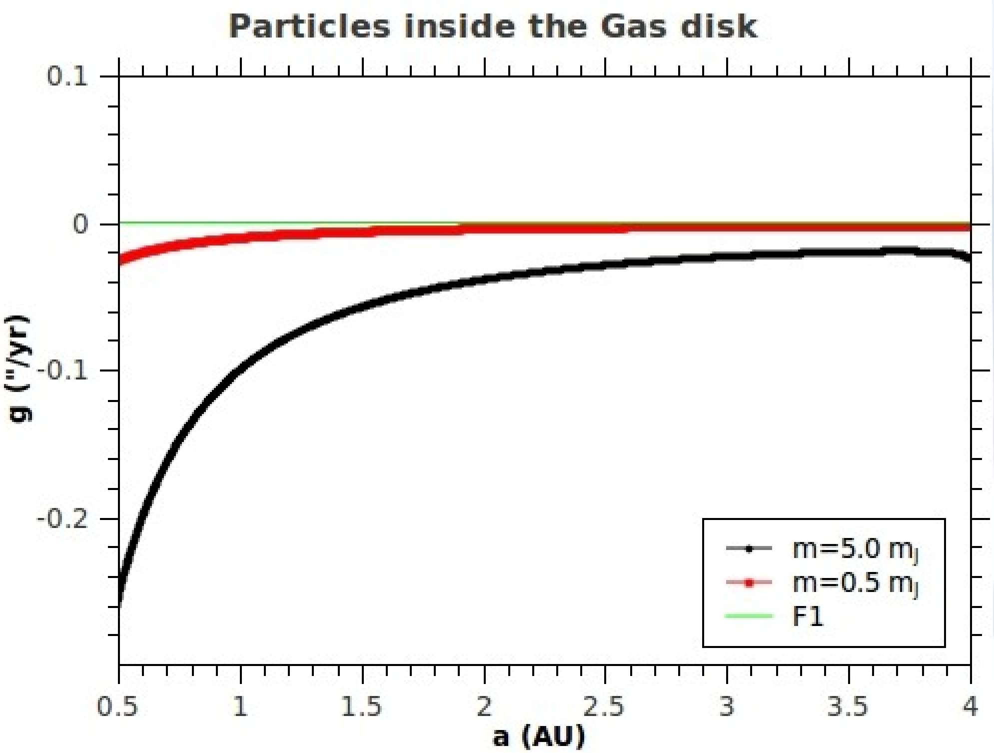
MMSN suggests ~5 M_J within ~ 4 AU (at t=0)

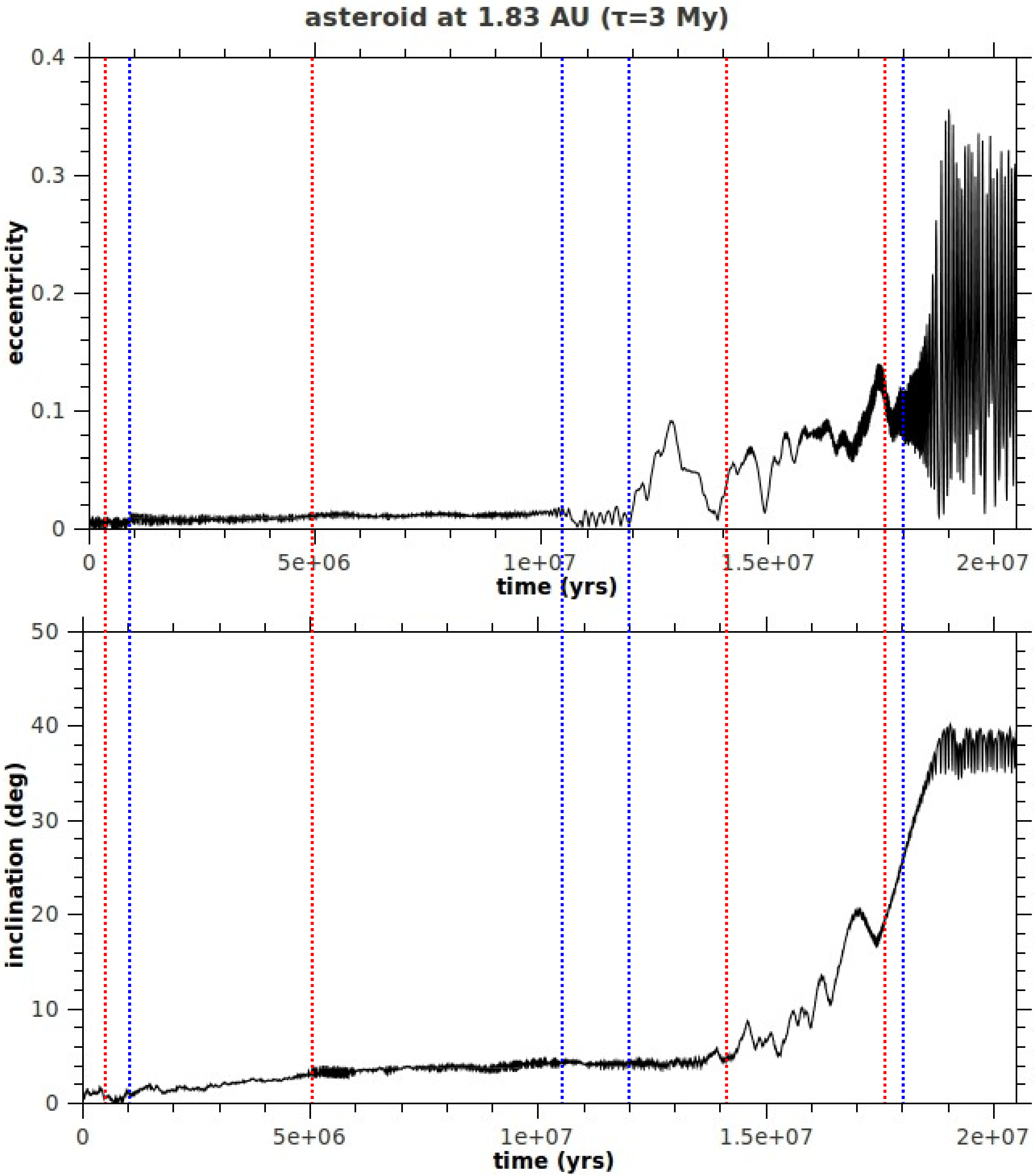
The spectra of the planetary orbits change as power shifts to g_i>0

As the disc evaporates:

→ asteroids regress (g<0), until the mass of the gas disk becomes very small

→ forcing by the planets dominates orbital precession





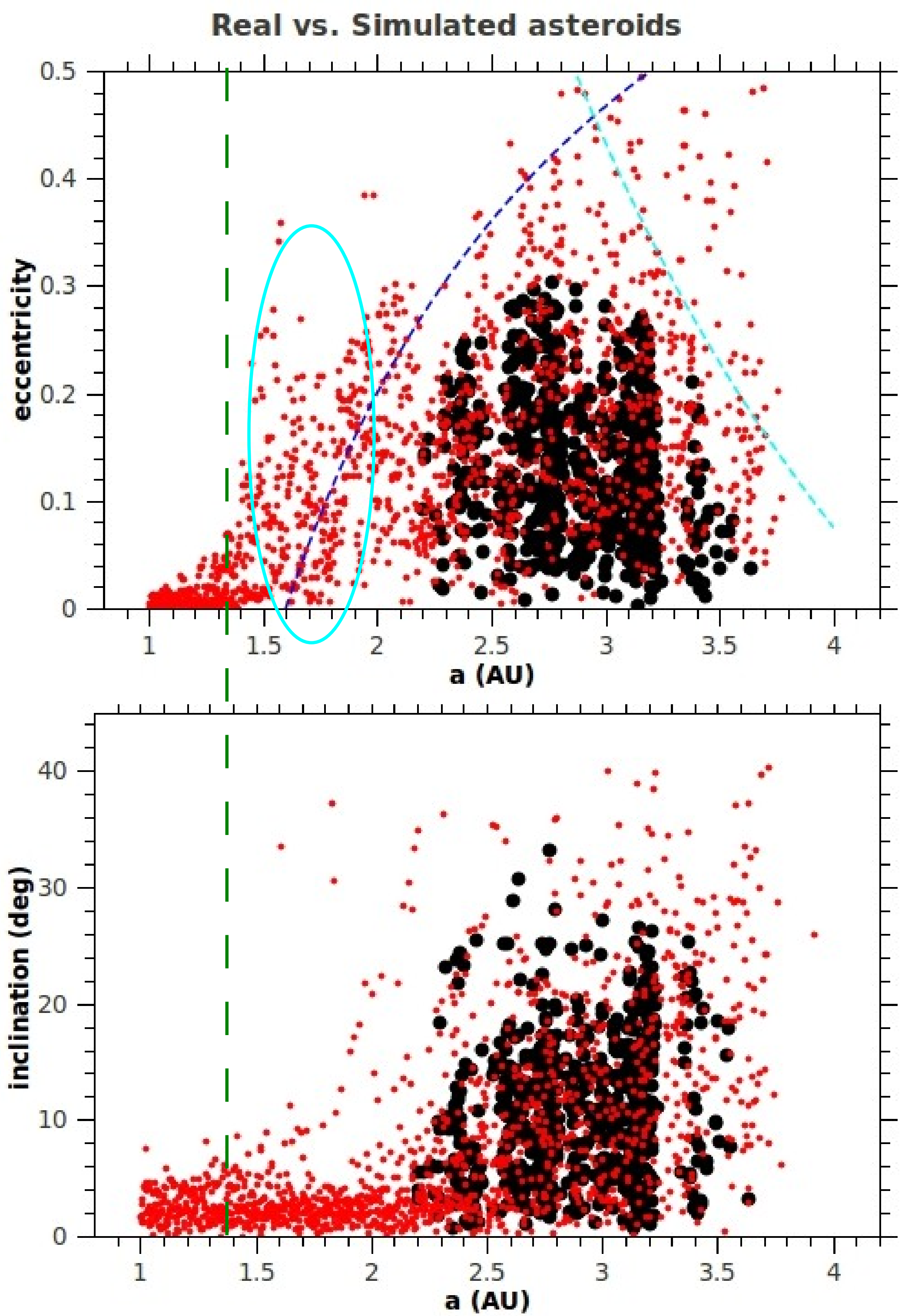
Simulations (1)

- Several episodes of pericentric and nodal SRs

→ asteroids can go "up and down" in *e*,*i*

- Strongest eccentricity forcing when *g*~16 "/yr

- Inclination increases strongly when *e*>0.1



Simulations (2)

- (a,e) and (a,i) distributions well reproduced
 →no spurious “gaps” or “clusters”

- Critical τ~3 My

- Very little mass loss (<9%)

- Regions near a=2 AU (v6 SR), outside the “wedge”, or inside the MMRs are unstable

- An excited Extended-belt is created

- The disk forms an outer edge
 ~ 1.3 AU → small-*q* orbits

*** A nice alternative (mixing?) or complement to GT (ecce) ***

*** May not be generic to all planetary configurations ***

Conclusions

- We need to understand the GT phase better...
- … together with the gas-evaporation phase

→ may give final answers as to how the MB came to what it is today and whether a 5th outer planet was necessary

→ sets-up the stage for terrestrial planet formation (+ water delivery, moon formation) and ...

→ … subsequent global-scale bombardment events (LHB-like)

- We need to know more about the physical properties of different populations and their inter-relations

[*can it be explained by an initial function of helioc distance* **+** *GT-like mixing* **+** *mixing / depletion during TP formation* **+** *LHB-like mixing ?*]

- We need to understand how to translate these mechanisms to extra-solar systems [*are they generic to all systems or not? How do they depend on star/planets/disk parameters?*]
- *Don't forget our poor knowledge on giant planets formation...*