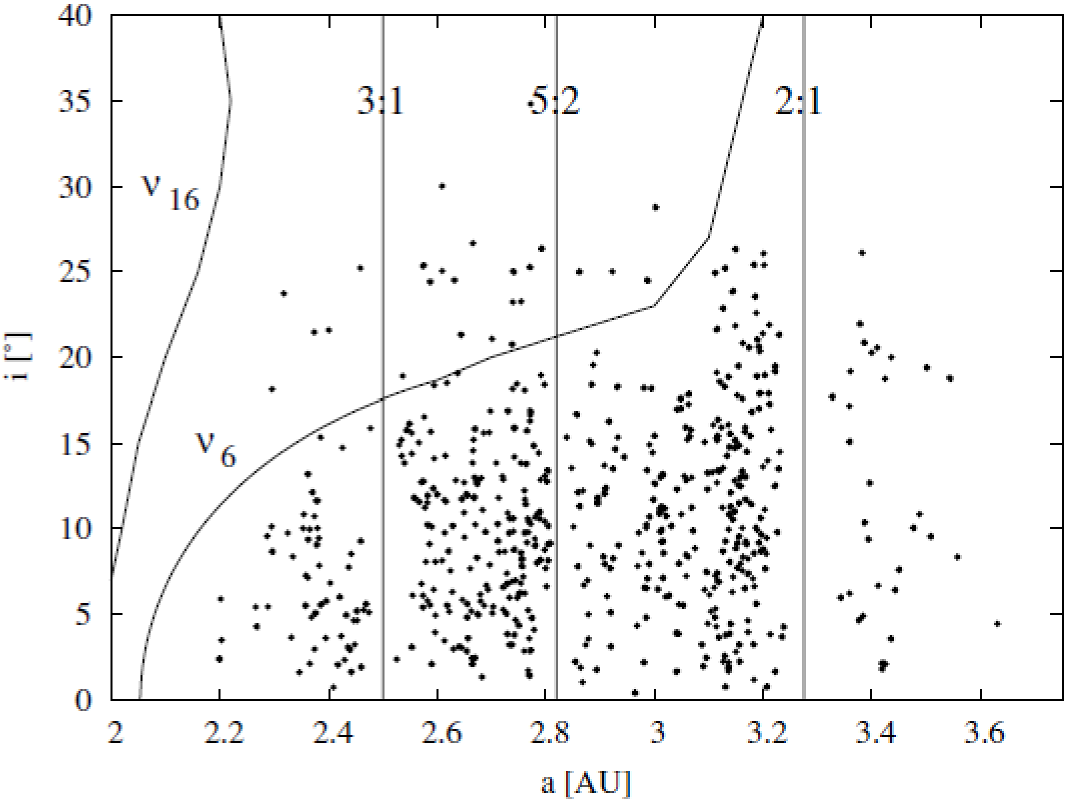
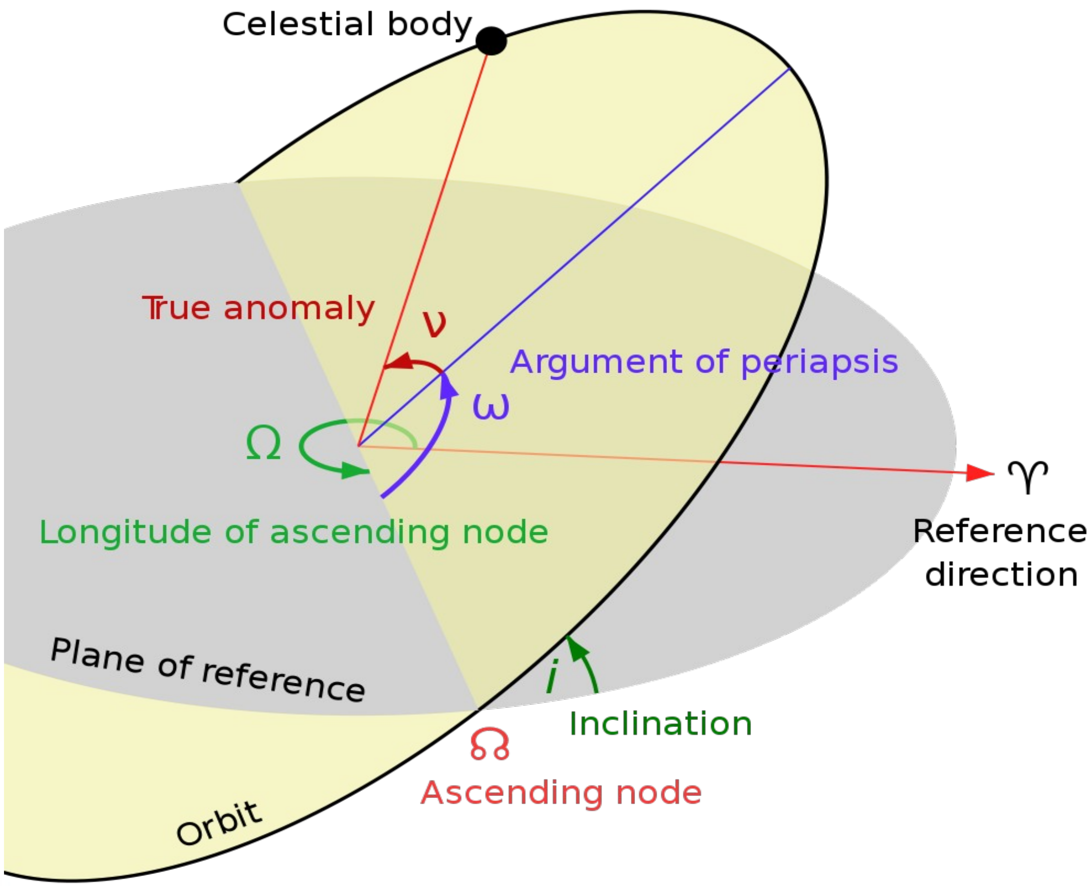
Origin of the orbital distribution of the main-belt asteroids

Kleomenis Tsiganis

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



Overview



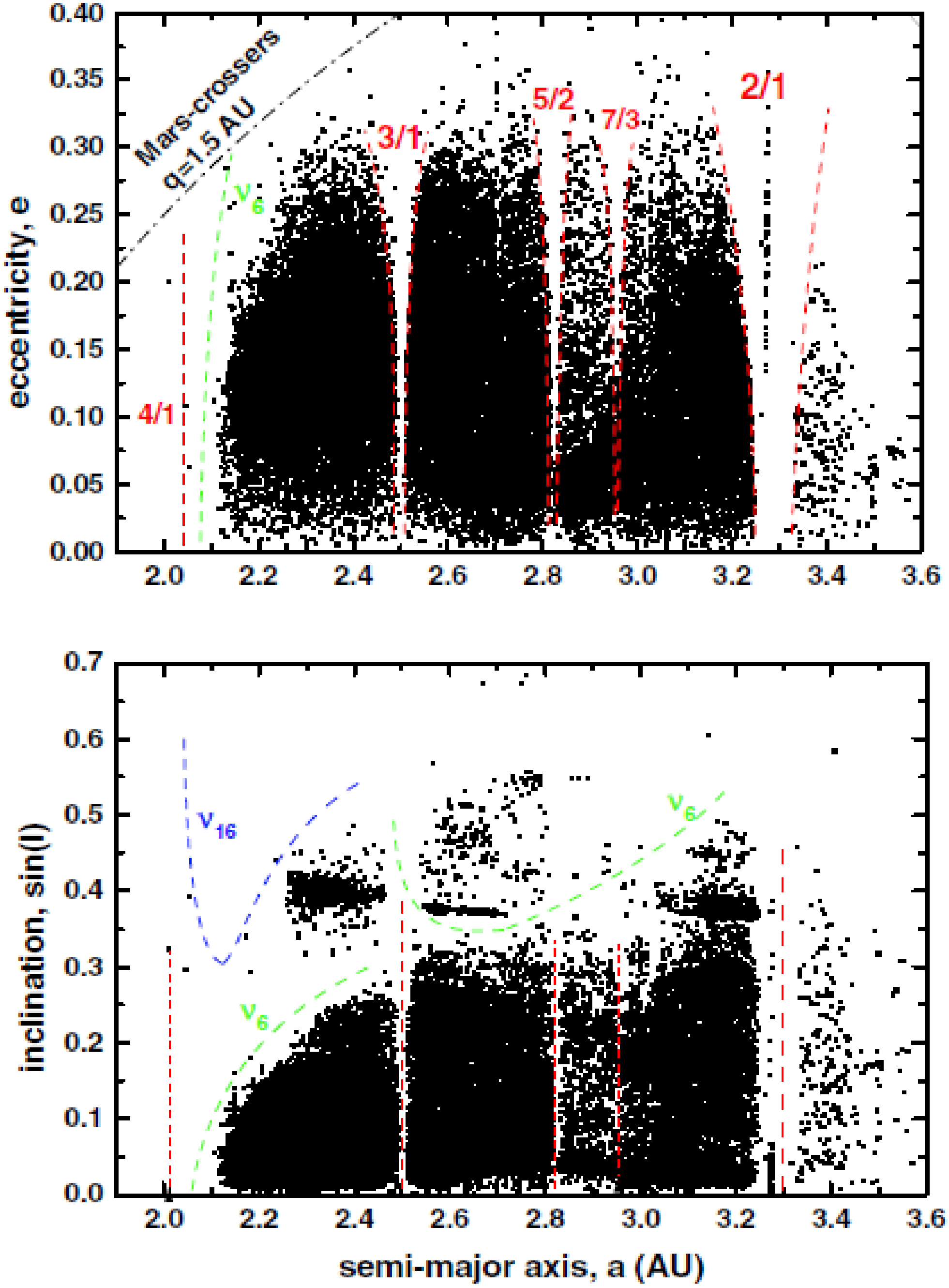
- Orbits characterized by the elliptic orbital elements:

$[a,e,i,\Omega,\omega,\nu(t)]$

→ only constant in the Keplerian approximation

- The orbital distribution of *main-belt asteroids* ($D>50$ km) contains much of the information related to the early dynamical evolution of the solar system

Orbital distribution in (a,e,i)



Boundaries (and gaps) are related to the main ***resonances***

- Kirkwood gaps → mean motion resonances:

$$n/n_j = k/q$$

- Outer boundaries carved by secular resonances:

$$g = \frac{d\omega}{dt} = \langle \omega_{J,S} \rangle \longrightarrow \nu_{5,6}$$

$$s = \frac{d\Omega}{dt} = \langle \Omega_S \rangle \longrightarrow \nu_{16}$$

What do we need to explain?

- **Fact 1:** a "flat disk" cannot evolve into what we observe today
  → need for planet migration!

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

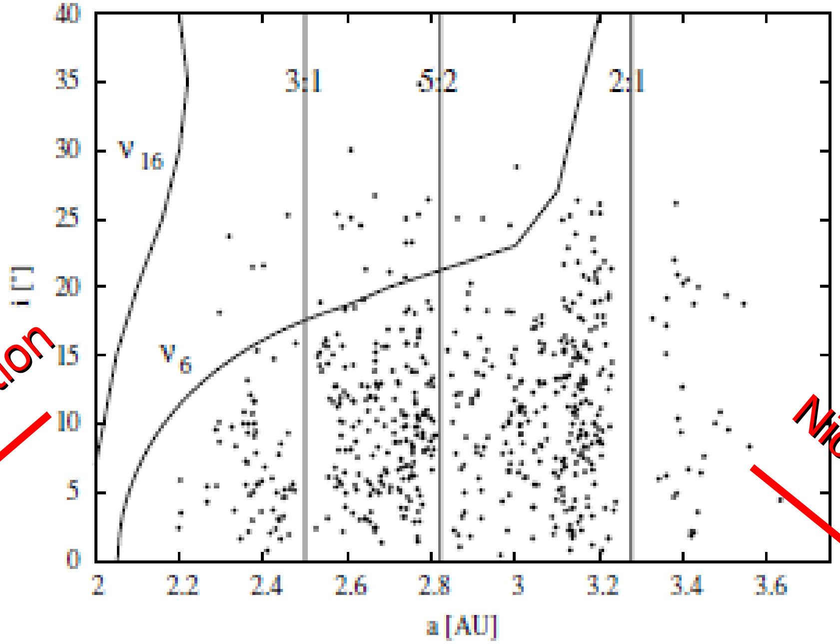
  → Excitation is due to Secular Resonance Sweeping: $g=g(a/a_J)$, $s=s(a/a_J)$ and a_J changes with time, the main secular resonances "sweep" through the belt, exciting asteroid orbits (if the time-scale is of ~10 My)

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

→ We need to find a pre-migration process to do this!!

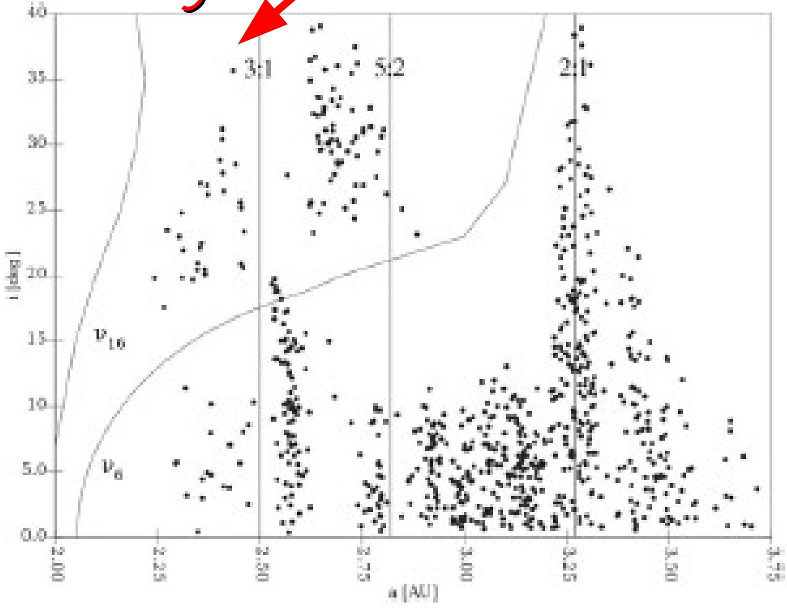
(a,i) distribution

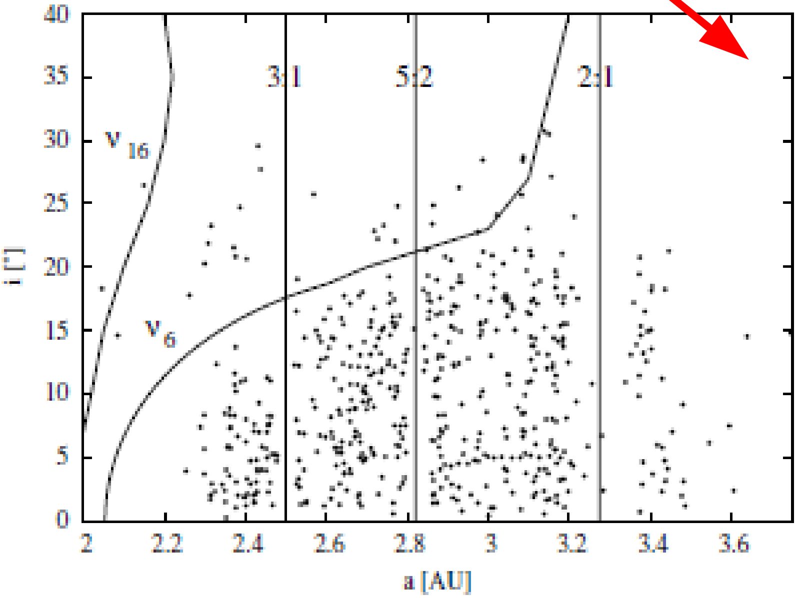
Main-belt asteroids with
D>50 km



Smooth (slow) migration

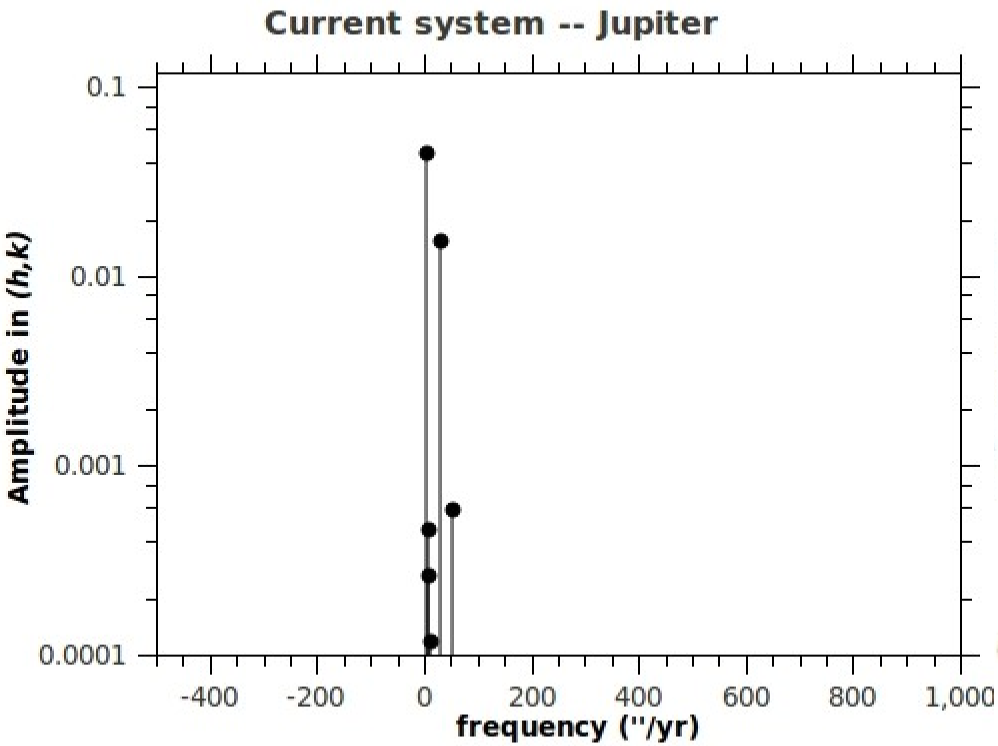
Nice-model (fast)

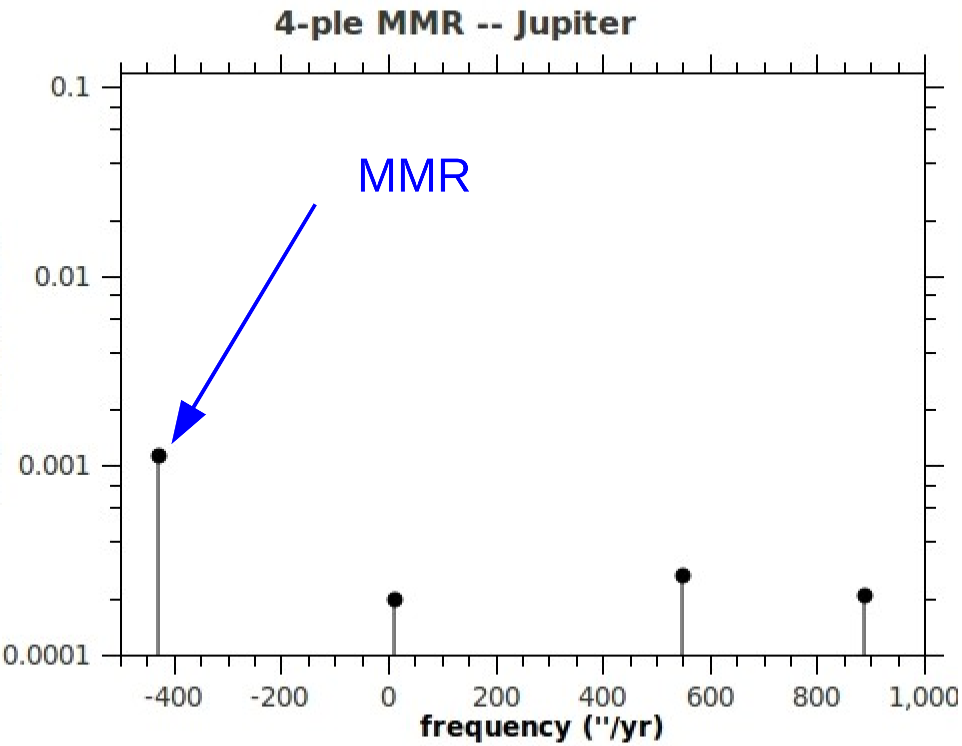




Pre-migration planetary history

- 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


Current system -- Jupiter


4-ple MMR -- Jupiter

Adding a ~5 M_J gas disk

- The pericentre frequency of an asteroid (i.e. test-particle) inside a massive disk becomes negative (regression)

$$n = \frac{1}{a}\left(\frac{\partial\Phi}{\partial r}\right)$$

$$\kappa = \frac{3}{a}\left(\frac{\partial\Phi}{\partial r}\right) + \left(\frac{\partial^2\Phi}{\partial r^2}\right) \longrightarrow g = n - \kappa < 0$$

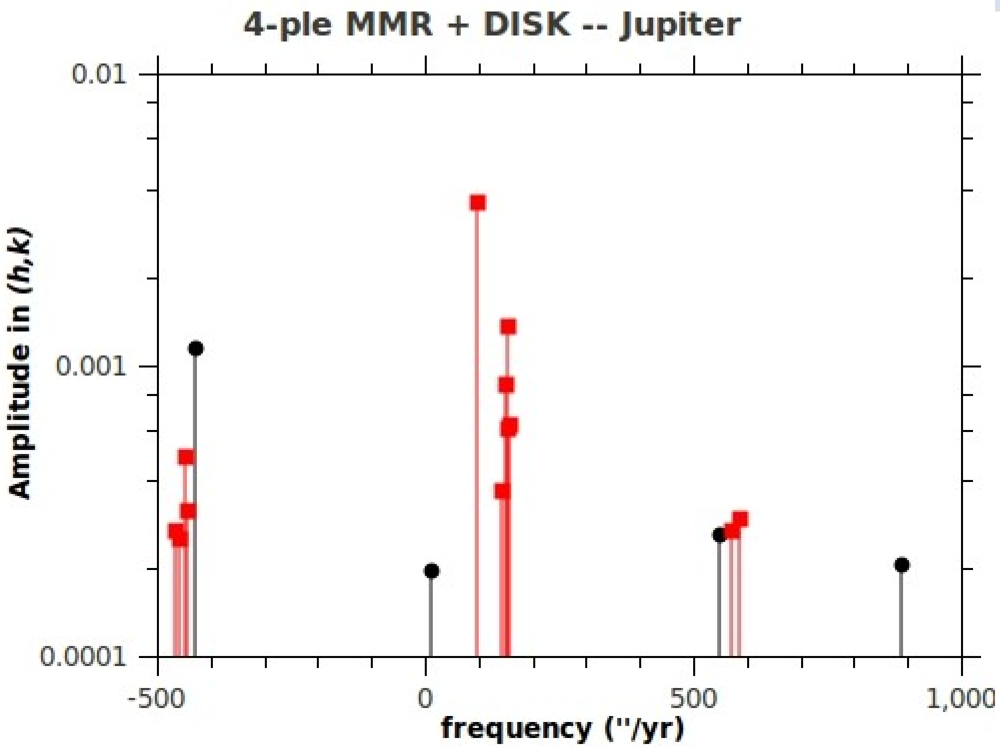
- assume a simple exponential evaporation model for the disk, with a characteristic e-folding time of $\tau = 0.5 - 10$ My

→ planets must go from precession (due to the massive disk) to regression (due to the resonance), as the disk evaporates

→ asteroids must go from regression to (slow) positive precession (only planets)

- → frequencies on "collision course" → secular resonances (SR) sweeping

Adding a ~5 M_J gas disk

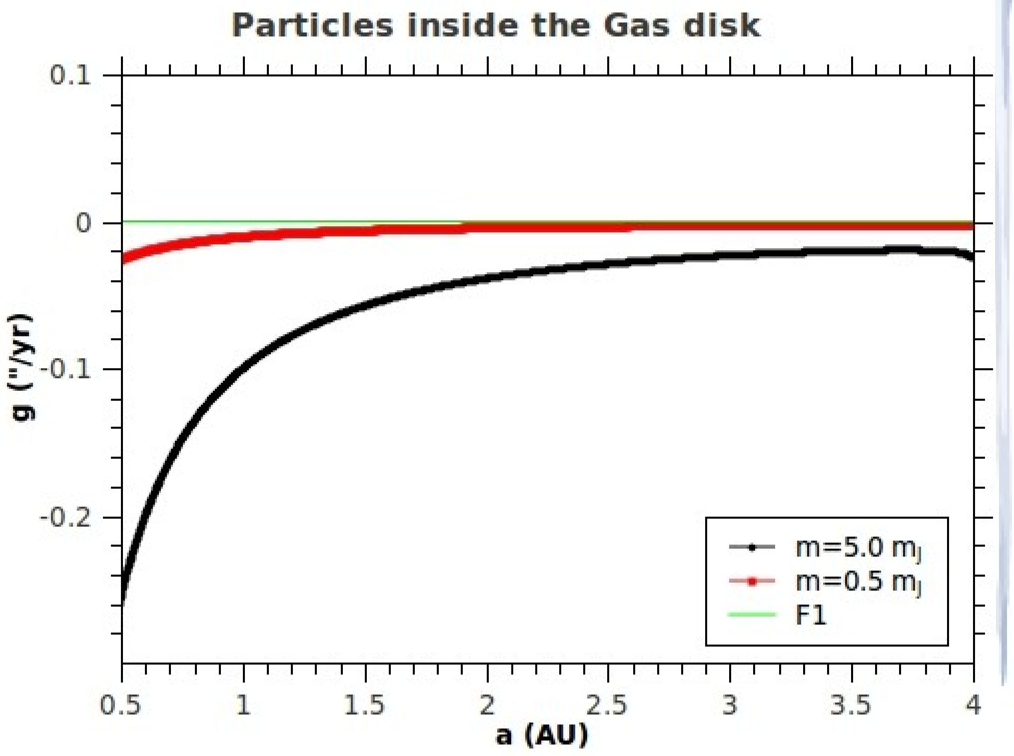


MMSN suggests ~5 M_J within ~ 4 AU

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

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

→ forcing by the planets dominates orbital precession



The experiments

- We use the SWIFT symplectic integrator, adding the radial and vertical components of the force exerted by a thin disk:

$$\rho(R,z)=\rho_0 R^{-a}\exp[-(z/H)^b] \quad , \quad H\sim 0.01$$

- We included tidal eccentricity damping and gas drag → orbits of *D*~100 km asteroids are not much affected
- Two different disk models gave very similar results

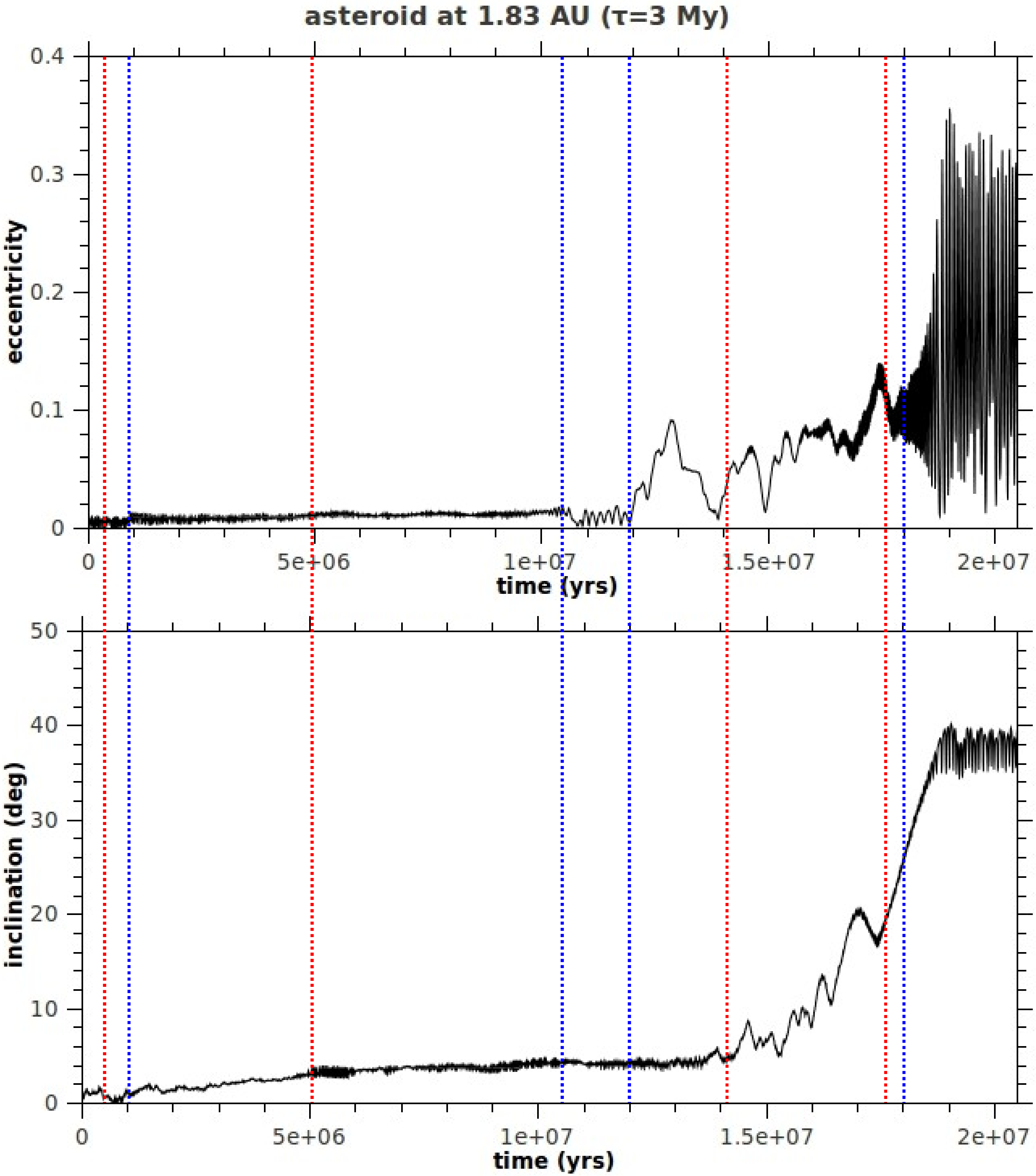
a) a razor-thin disk (*b*=2, *a*=3/2) for which F_z is given by:

$$4\pi G\rho(R,z)=\nabla^2\Phi\approx\frac{\partial^2\Phi}{\partial z^2}$$

b) a thin exponential disk (*b*=1) for which a full 2-D computation of *Φ*(*R*,*z*) was done

- Critical quantity is the evaporation time-scale:

→ if too fast, excitation but no mixing in e,i



Results (1)

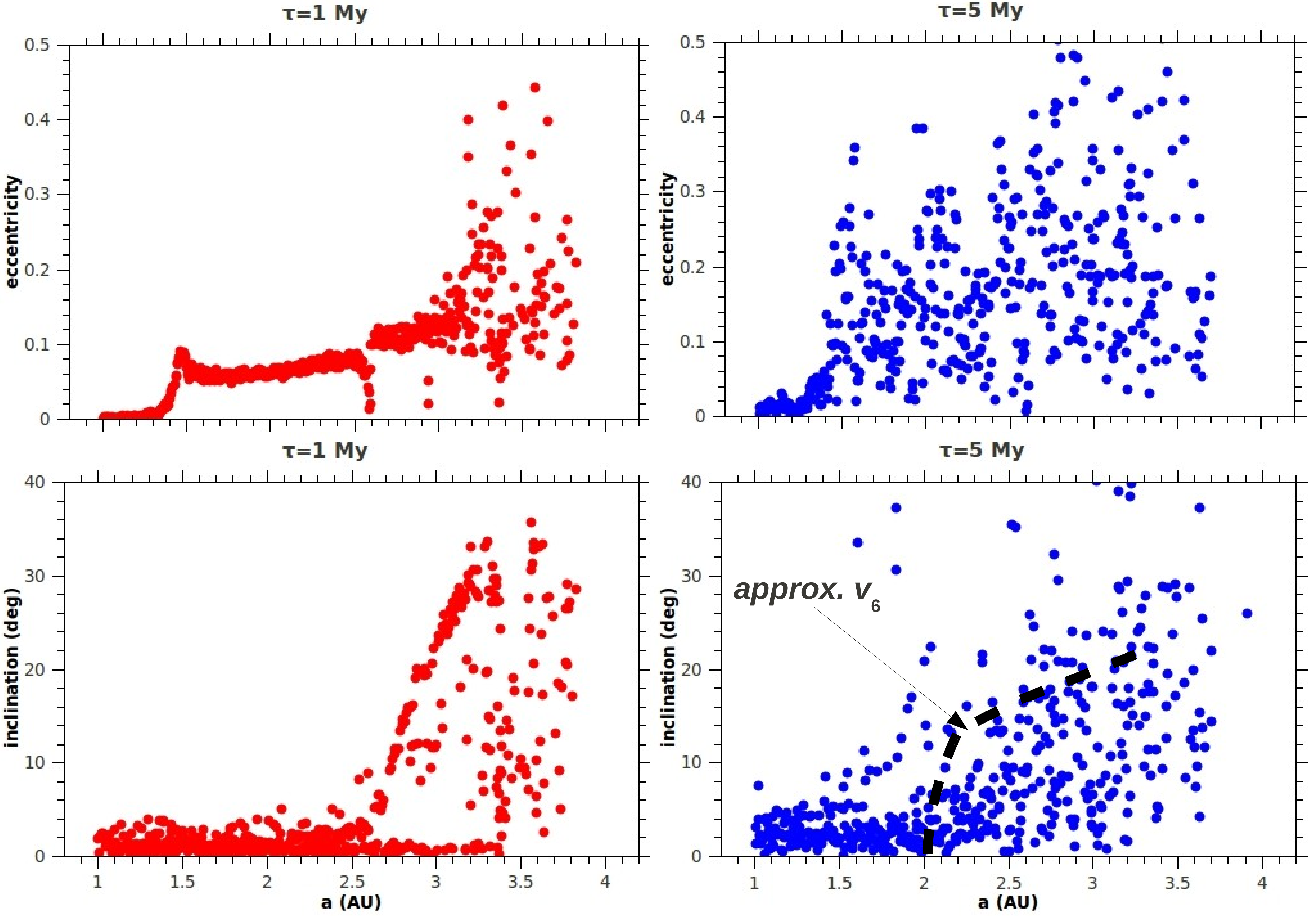
- Several episodes of pericentric and nodal SRs

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

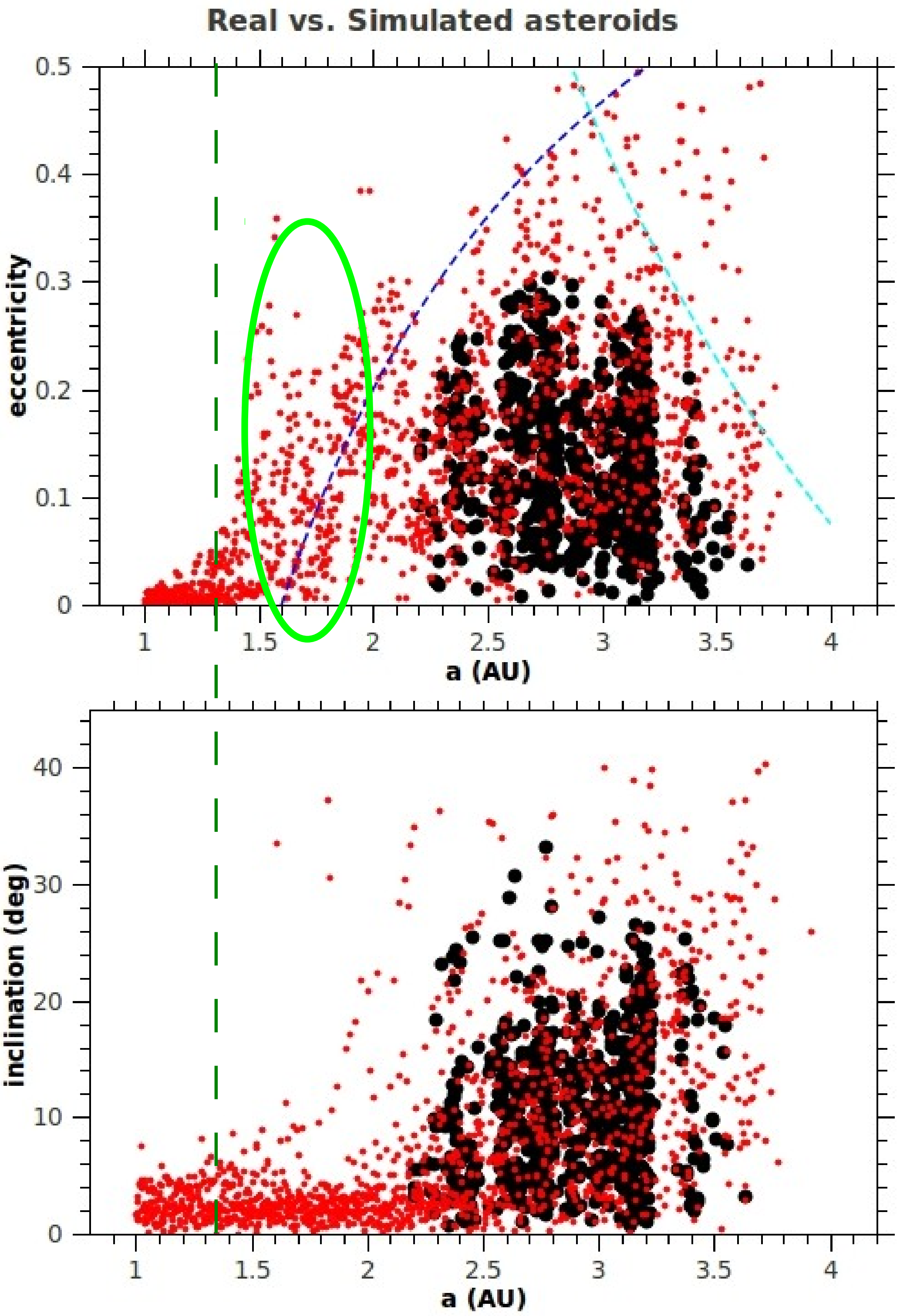
- Strongest eccentricity forcing when *g*~16 "/yr

- Inclination increases strongly when *e*>0.1

Results (2)


τ=1 My
τ=5 My
eccentricity
0.5
0.4
0.3
0.2
0.1
0
τ=1 My
τ=5 My
inclination (deg)
40
30
20
10
0
1
1.5
2
2.5
3
3.5
4
a (AU)
approx. ν_6

Results (3)



- (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 (ν6 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

Conclusions

- The orbital distribution of main-belt asteroids could be the result of the slow evaporation of the proto-solar nebula

  → multiple SR crossings scramble the eccentricities and inclinations of asteroid orbits

  → these SRs are directly related to the initial configuration of the planets (and the disk mass/geometry) **

- An excited, Extended (E-)belt is created (a<2 AU) → maybe needed as a source of LHB projectiles

- The disk of solids is truncated at ~1.2 AU → important for explaining the small mass of Mars in terrestrial planet formation simulations