Long-term evolution of asteroid families among Jovian Trojans

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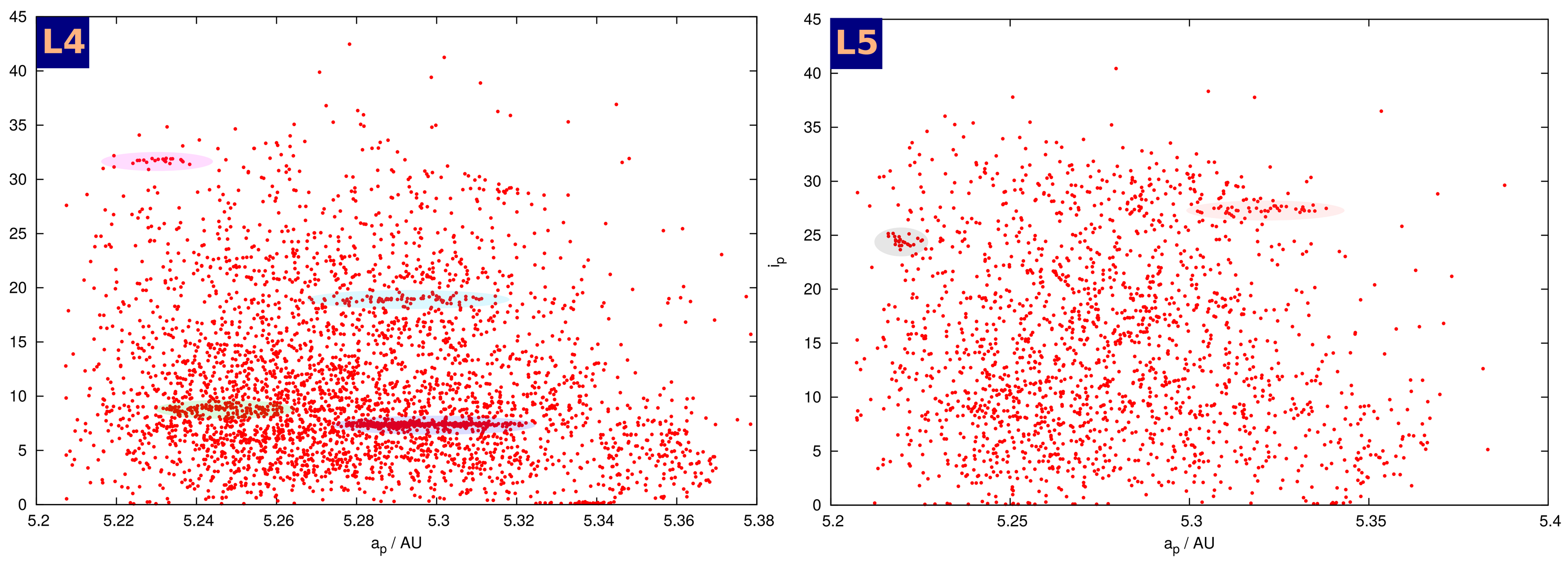
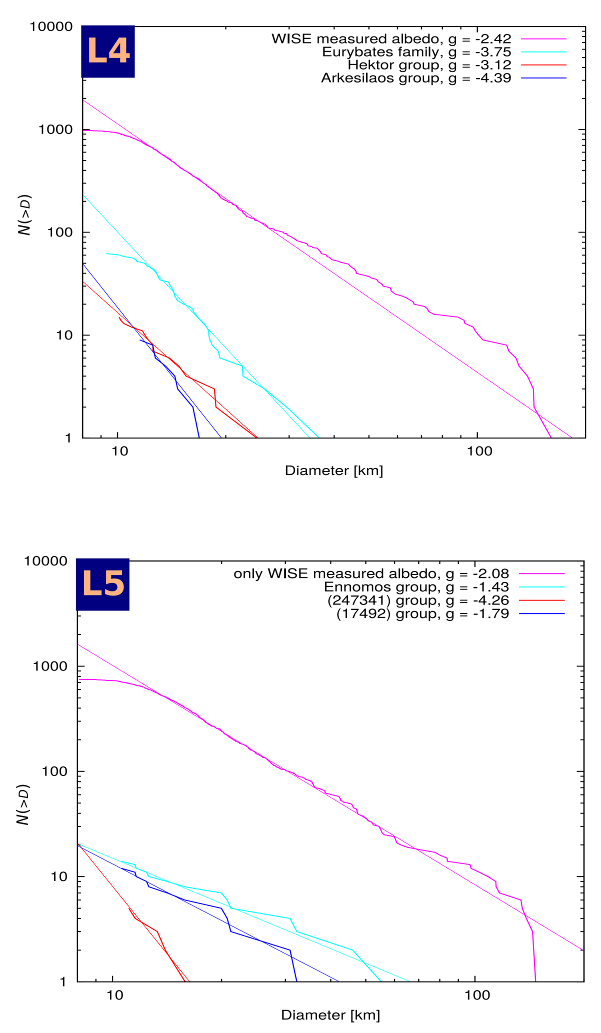
Abstract: We updated the database of resonant elements (i.e. the libration amplitude Δ, eccentricity *e*, inclination *I*) of Jupiter Trojans and we identified and verified clusters by both the Hierarchical Clustering Method and Monte Carlo simulations, which allow us to assess the statistical significance of the asteroid families. Apart from the Eurybates family (Brož & Rozehnal 2011), we also found five clusters of potentially collisional origin — namely families around asteroids (20961) Arkesilaos, (624) Hektor and (9799) 1996 RJ in L4 cloud and (17492) Hippasos and (247341) in L5 cloud. Using the WISE albedos and diameters (Grav et al. 2011, 2012), we constructed size-frequency distributions of Trojans in both the leading/trailing clouds which we compared to SFDs of the families. As these clusters fulfill our criteria for collisional families (i.e. statistical significance, albedo homogeneity, steeper SFD than that of background), we tried to explain their origin and consequential orbital evolution (using the SWIFT code, Levison and Duncan, 1994) in the frame of the five planet scenario (Nesvorný 2011). We also tried to constrain ages of the families.



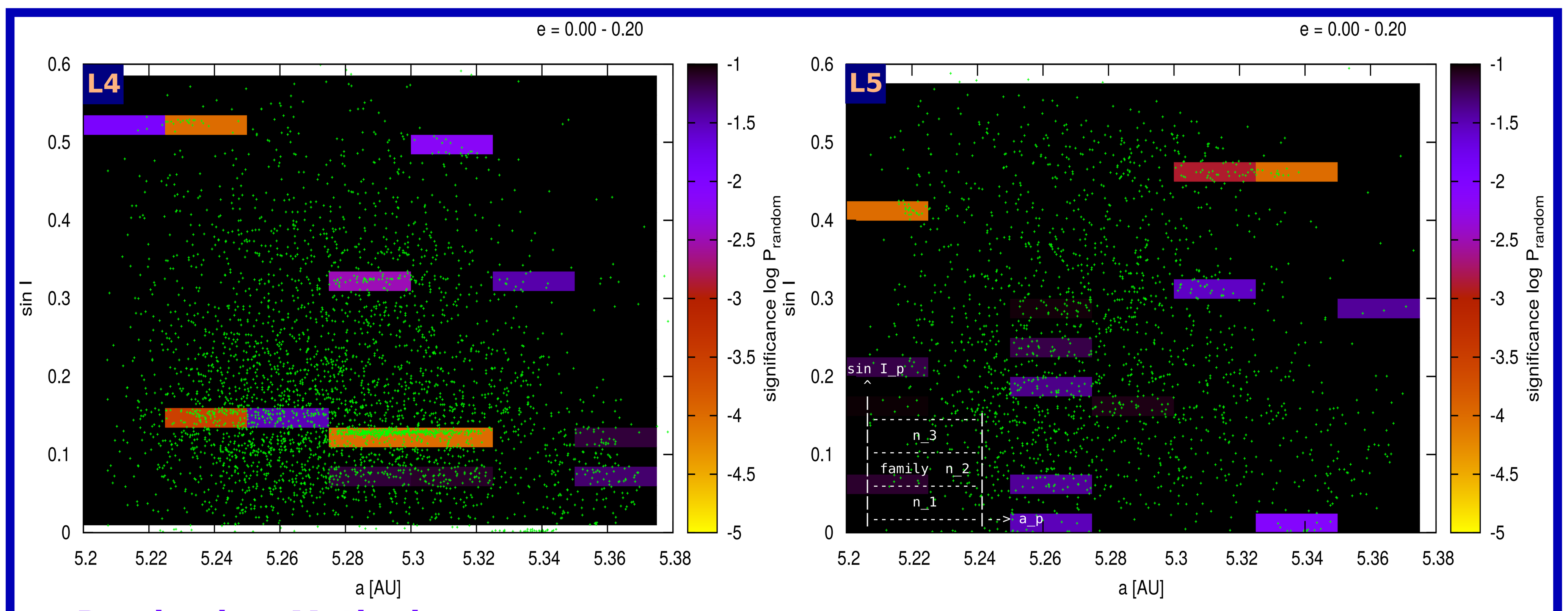
Resonant elements computation

Resonant elements of 3773 Trojans in the leading (L4, left) and 1917 in the trailing (L5, right) cloud listed in the MPCORB database were computed with the SWIFT integrator (Levison et al. 1994) as described in Brož & Rozehnal (2011). This is approximately a twice larger sample than previously analysed.
There are 4 (relatively) compact groups visible in L4 and 2 in L5, which we further analyse with the help of the HCM, "Randombox", SFDs and albedo data.



Size-frequency Distributions

We used diameters derived from WISE albedo measurements (Grav et al., 2011) to construct the size-frequency distributions for L4 and L5 Trojans. To avoid bias, we assumed the mean albedo for the objects which were not observed by WISE.
The SFDs of compact groups (potential families) detected in the space of proper elements are usually steeper than that of the background population.



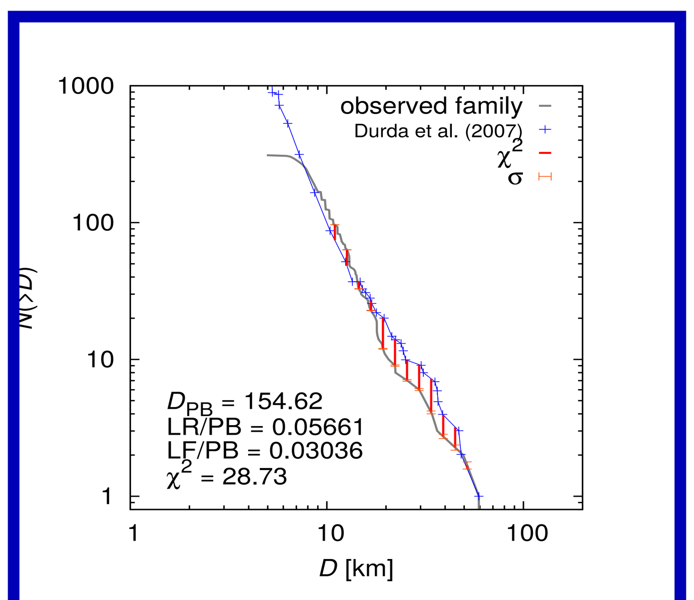
Randombox Method

Besides the commonly-used Hierarchical clusterring method, we used a "Randombox method", based on the Monte Carlo simulations. This method allows us to compute the **statistical significance** of the concentrations of bodies in the space of proper elements (*a*, *e*, sin *I*). We can also use an analytical formula:

$$p = \frac{\sum_{k=n_2}^{n} C(n,k)\, V'(n_{\mathrm{box}}-1, n-k)}{V'(n_{\mathrm{box}}, n)}$$

n ... the total number of bodies
n_{box} ... the number of boxes
C(*k*, *n*) ... combinations (without repetitions; *n* choose *k*)
V'(*k*, *n*) ... variations with repetitions

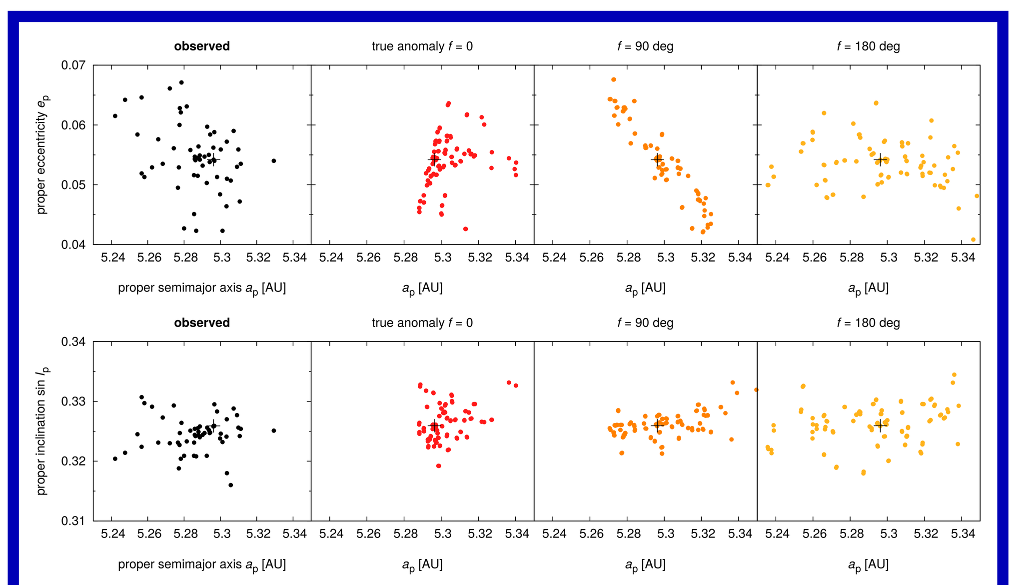
We plot the results on the picture above for both the L4 (left) and L5 (right) clouds. Probabilities *p* that clusters of bodies in the space of proper elements (green dots) are random, are marked by boxes of different colours, ranging from the dark blue (i.e. low significance) to yellow (high significance, see the scale next to the pictures). Using this method, we evaluated all families identified by HCM, what makes our decision wheather the cluster is real family or not **much more objective**.



SFD Fitting by SPH

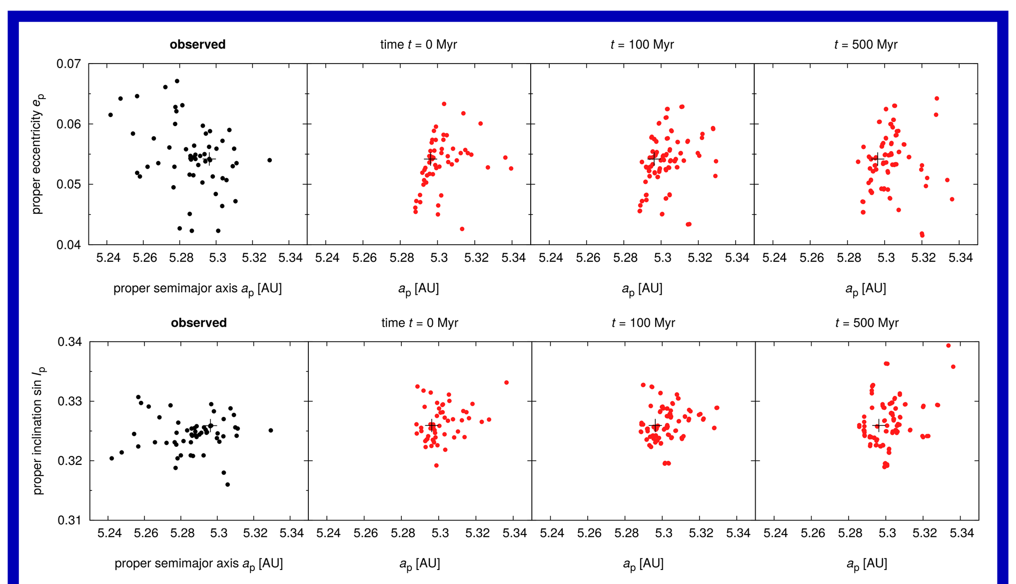
We tried to estimate the parent body sizes by the method described in Durda et al. (2007). To this point, we calculated a "pseudo-chi-square" for the whole set of size-frequency distributions as given by the **SPH simulations results**. We will use these as initial conditions for simulations of collisonal evolution. The parent body size for the Eurybates family (see the picture above) is about (150 ± 20) km.

designation	V_{cutoff} [m/s]	N_{members}	p_V (WISE)	tax.	diameter [km]	$D_{\mathrm{PB\_Min}}$	D_{Durda}	LF/PB	v_{esc} [m/s]	age [Gyr]	notes, refs
(624) Hektor	110	90	0.087 ± 0.016	D	164 ± 7	171	216	0,0005	73	0 to 3.8	L4, cratering, satellite (Marchis et al. 2014)
(3548) Eurybates	60	310	0.060 ± 0.016	C/P	59.4 ± 1.5	100	155	0,03	46	1.0 to 3.8	L4, old?
(9799) 1996RJ	140	17	0.082 ± 0.014	-	58.3 ± 0.9	61	88	0,006	26	-	L4, young? very compact, Broz & Rozehnal (2011)
(20961) Arkesilaos	55	35	n/a	-	24 ± 5	37	87	0,01	16	-	L4
(17492) Hippasos	100	104	0.064 ± 0.012	-	55.2 ± 0.9	67 – 154	95 – 168	0,06	29 – 66	1 to 2	L5, PB size strongly influenced by possible interlopers
(247341) 2001UV209	120	30	0.088 ± 0.023	-	16.3 ± 1.1	32	80	0,005	14	-	L5, Rozehnal & Broz (2013)



Simulation of cratering (Hektor family)

Since (624) Hektor is a close binary with a sattelite (Marchis et al. 2014), i.e. an exceptional object, we want to address its association with the family. To constrain the age of the Hektor family, we first created a synthetic family, assuming an isotropic velocity field with a typical velocity of 70 m/s, corresponding to the escape velocity (Farinella et al. 1993). We studied **three impact geometries**, differing in the true anomaly *f*, see the picture above. For *f* = 180 deg the shape of the syntetic family can be compatible with the observed one, even at *t* = 0, which is the lower limit of the family age.

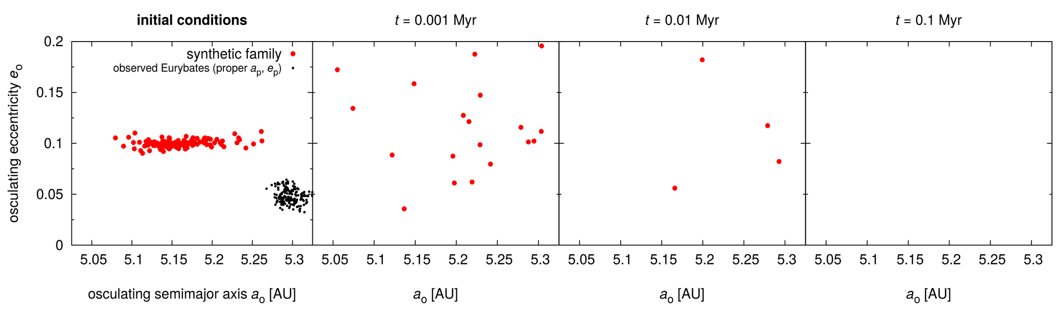


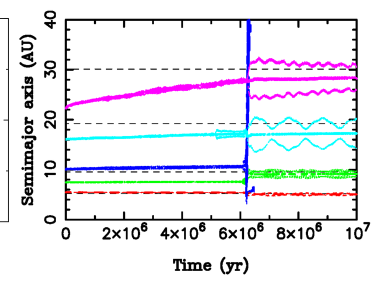
Simulation of orbital evolution (Hektor family)

To get an upper limit of the Hektor family age, we simulated a long-term evolution of the synthetic family. Our model included four giant planets on current orbits, integrated by the symplectic integrator SWIFT (Levison and Duncan 1994) modified according to Robutel and Lascar (2001), with the timestep of 91 days. The structures in the space of proper elements may dissapear only after approximately 1 Gyr. We think the sructure will persist up to 4 Gyr, so we can exclude this initial geometry (*f* = 0 deg).

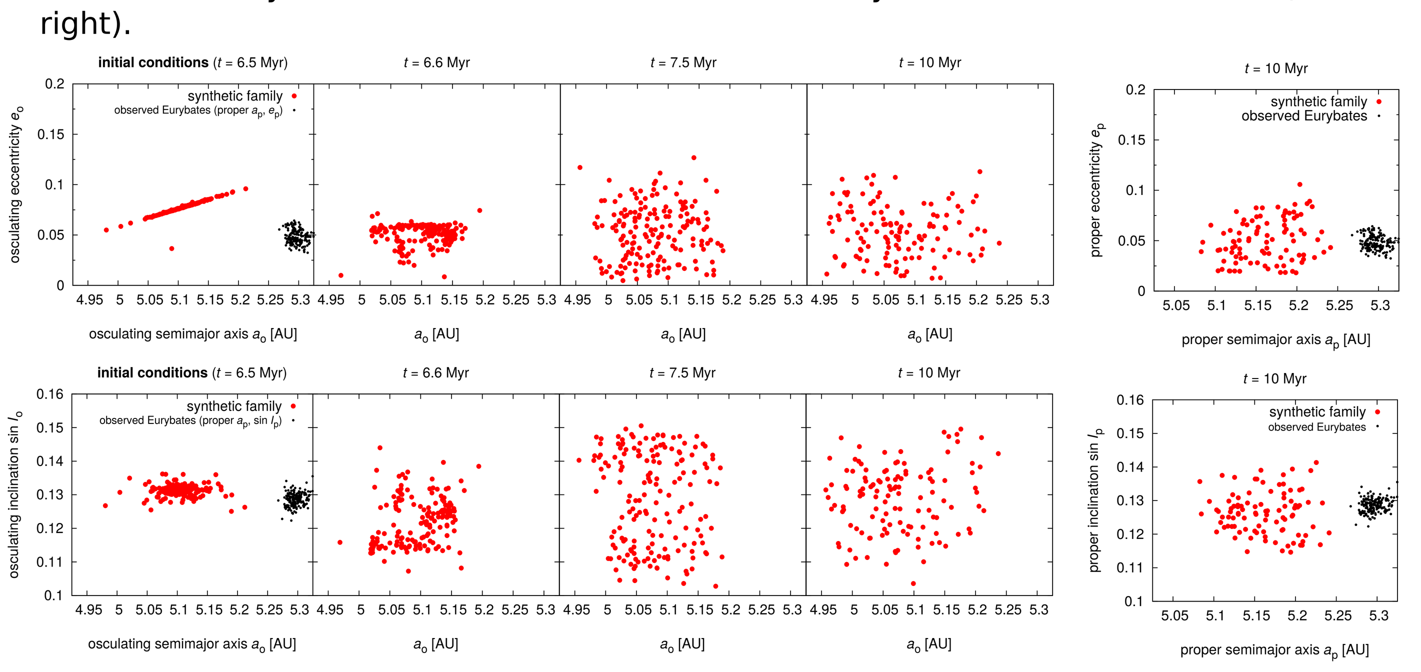
Simulation of the orbital evolution during the planetary instability (Eurybates family)

In order to find the upper limit for the Eurybates family age, we simulated a disruption and consequential evolution of a synthetic family during planetary migration as given by a **fifth planet scenario** (Nesvorný 2011). We set the initial conditions by the similar way as for the synthetic Hektor family.
The left picture below shows an evolution of osculating elements starting before the jump of the Jupiter (t = 6.2 Myr of "artificial time", see the right picture below). As one can see on time-series snapshots, nothing can survive the jump.





The pictures below shows a time series of the later-phase evolution (again, of osculating elements) starting *after* the Jupiter jump. Initially, the synthetic family is compact, but perturbations by (still eccentric) planets **increased its dispersion too much** in both the eccentricity and inclination. This is confirmed by the resonant elements (on the right).



Summary and Conclusions

- We used a rather objective "randombox" method for identification of asteroid families in the space of proper (resonant) elements, which is based on a Monte Carlo approach. Using this method, we computed statistical significance of the families (including those previously indentified in Rozehnal and Brož 2013).
- We updated the table of orbital/physical properties of the families among Jupiter Trojans.
- We compared the observed size-frequency distributions of the families with synthetic SFDs resulting from SPH simulations of Durda et al. (2007).
- We simulated a long-term evolution the Hektor family. We realised that the age of the family strongly depends on the initial geometry - if the (isotropic) disruption occured at *f* = 180 deg, the family could be very young, while at *f* = 0 deg, even a 4 Gyr of orbital evolution is not sufficient to produce a family compatible with observations.
- We also simulated an evolution of a synthetic family during giant-planet migration as given by a fifth planet scenario (Nesvorný 2011). We realised that: a) nothing can survive the Jupiter jump, and b) even immediately after the jump and ejection of the ice giant the perturbations by planets are too strong to save a compact structure of young families. It means that observable families were likely formed later, i.e. after the associated late heavy bombardment (LHB) has ended.

References and Acknowledgements

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Brož M., Rozehnal J., 2011, MNRAS, 414, 565-574
Durda D. D. et al., 2007, Icarus, 186, 498-516
Farinella P. et al., 1993 in Milani A., Di Martino M., Cellino A. (editors): Asteroids, Comets, Meteors, p. 205, Kluwer, Dordrecht, 1993
Grav T. et al., 2011, ApJ, 742, 40-80
Grav T. et al., 2012, ApJ, 759, 49
Levison H. F., Duncan M., 1994, Icarus, 108, 18-36
Marchis F. et al., 2014, ApJL, 783, L37
Nesvorný D., 2011, ApJL, 742, L22
Rozehnal J., Brož M., 2013, DPS meeting, 112.12