A collisional model of the "pristine zone" of the Main Asteroid Belt and the dynamics of LHB families located there

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Abstract: Modifying the Boulder code (Morbidelli et al. 2009), we construct a new collisional model of the Main Asteroid Belt, which is divided to six parts (inner, middle, outer, pristine zone, Cybele region and high-inclination region) in order to study relations between them and check the number of observed families.
We extend our collisional models and include the effects of the Late Heavy Bombardment too. In the framework of the Nice model, the flux of comets during the LHB is mostly controlled by the original size-frequency distribution of the cometary disk beyond Neptune and the rate at which comets disrupt when they approach the Sun. To this point we provide a related discussion of various cometary disruption laws.
We focus on the so-called "pristine zone" between 2.825 and 2.955 AU - bounded by the 5:2 and 7:3 men-motion resonances with Jupiter - because this region is relatively empty and we may thus spot very old/eroded families. We model long-term dynamical and collisional evolution of the Itha family (around the asteroid (918) Itha) and we interpret it as an old, dispersed and comminutioned cluster, likely dated back to the LHB ~3.8 Gyr ago.

1. Observational data:

- AstOrb (Bowell 2008), AstDyS (Knežević & Milani 2003) and WISE (Masiero et al. 2011) catalogs
- five parts separated by mean-motion resonances with Jupiter, the sixth part formed by asteroids with high proper inclinations (Figure 1)
- their size-frequency distributions (Figure 2) are calculated from albedos available from WISE
- the individual SFDs differ significantly in terms slopes and total numbers of asteroids
- the up-to-date list of observed families is taken from Brož et al. (2012)

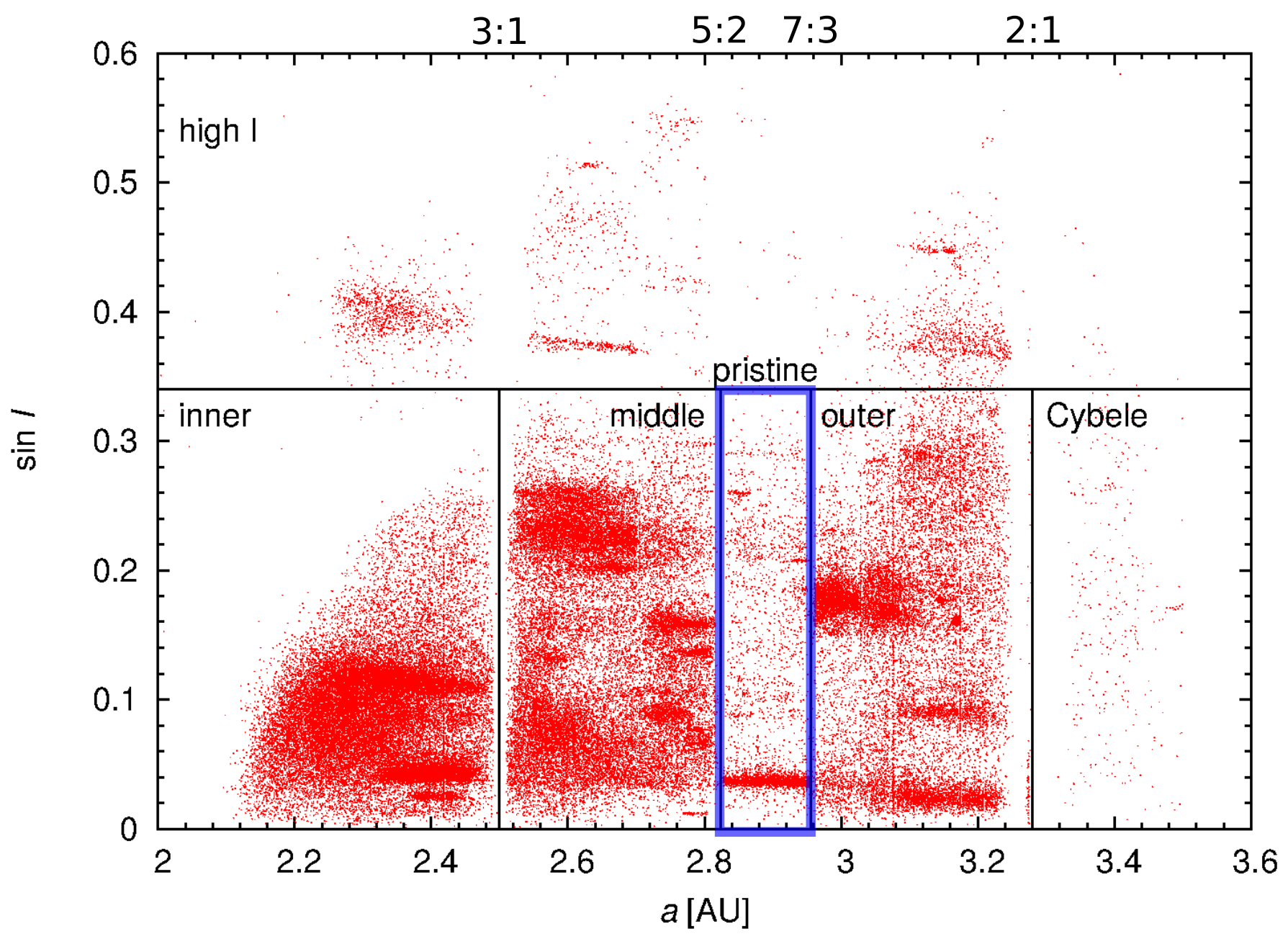


Figure 1: Six parts of the mail belt in the proper semimajor axis vs inclintion plane.

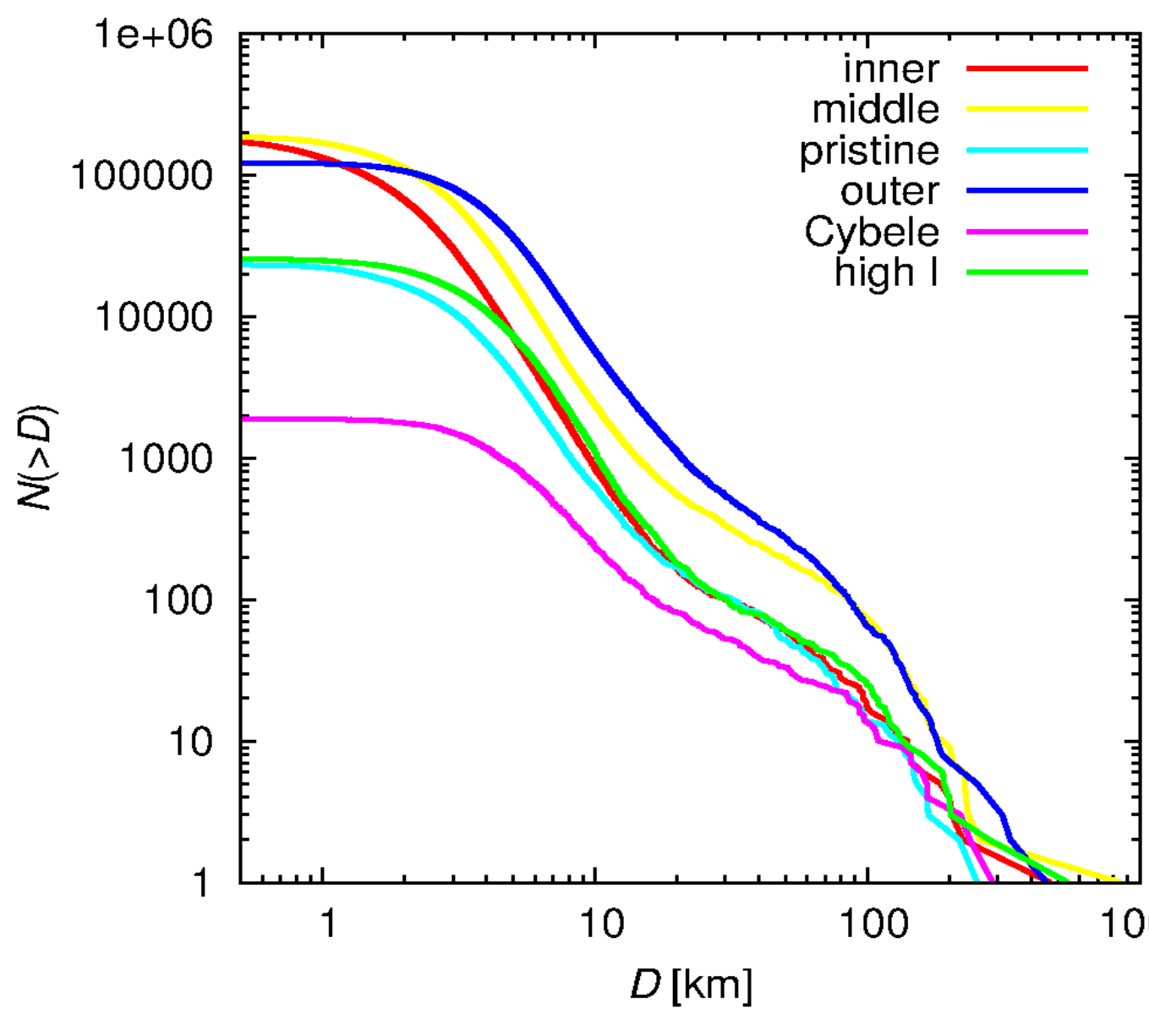


Figure 2: The observed SFDs of the six parts of the main belt.

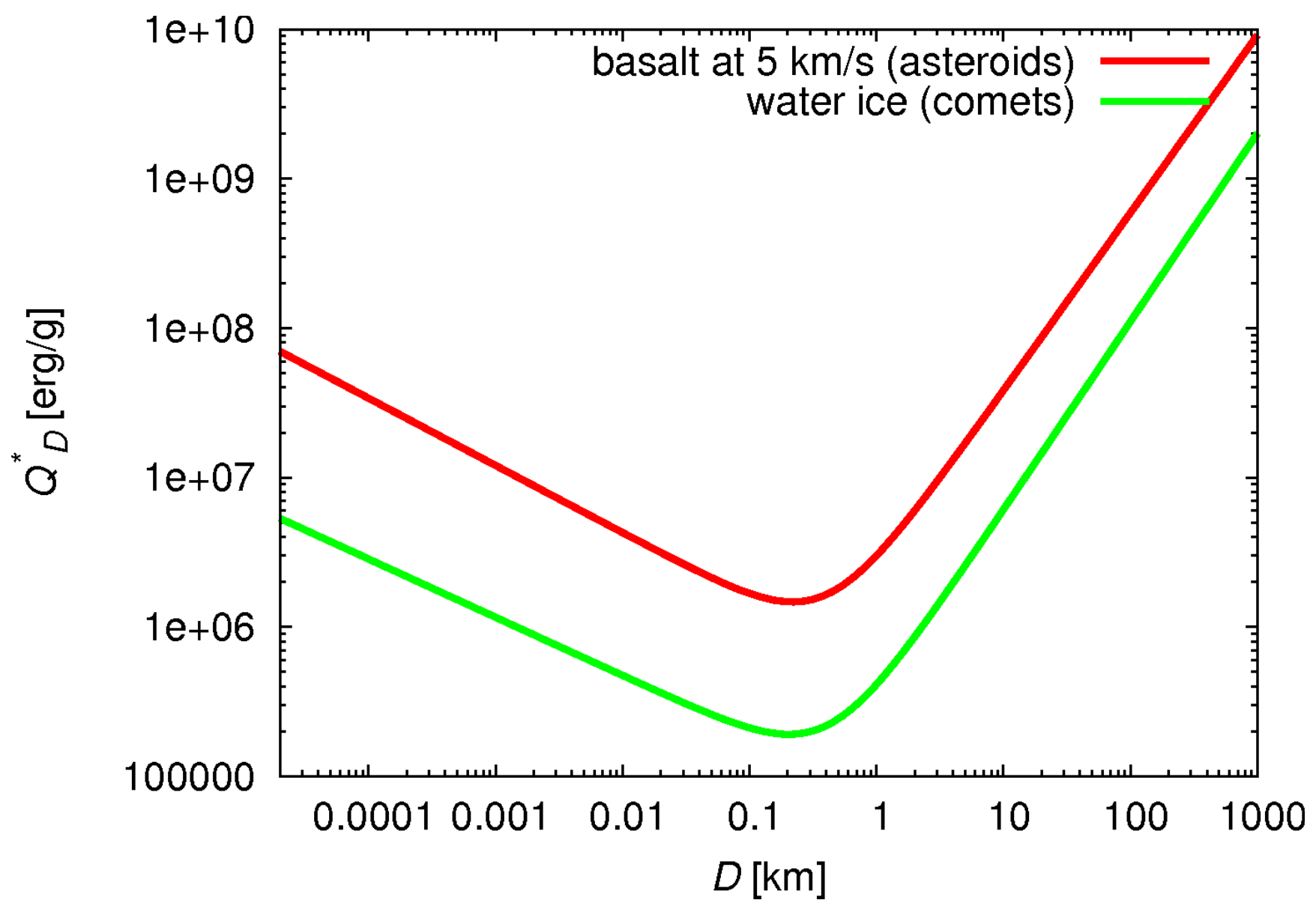


Figure 3: The nominal scaling law used in our simulations.

2. Initial conditions and parameters of collisional simulations

- mutual collision probabilities and impact velocities were calculated between each pair of populations
- to define the shape of initial SFDs (i.e. slopes in 3 size ranges and normalization) we fit currently observed SFDs
- scaling law parameters: Benz & Asphaug (1999) for basaltic material at 5 km/s (Figure 3)
- the Boulder collisional code operates with a random seed - for more reliable results we thus run 100 simulations

3. Results of 4 Gyr of collisional evolution (no LHB case)

- the final SFDs after 4 Gyr are shown in Figure 4, good fits for $D > 10$ km, but below $D < 5$ km are final SFDs often below the observed ones
- the most frequent number of families created in individual zones is shown in Figure 5 (we always choose only catastrophic disruptions with LF/PB < 0.5 and PB larger than 100 km)

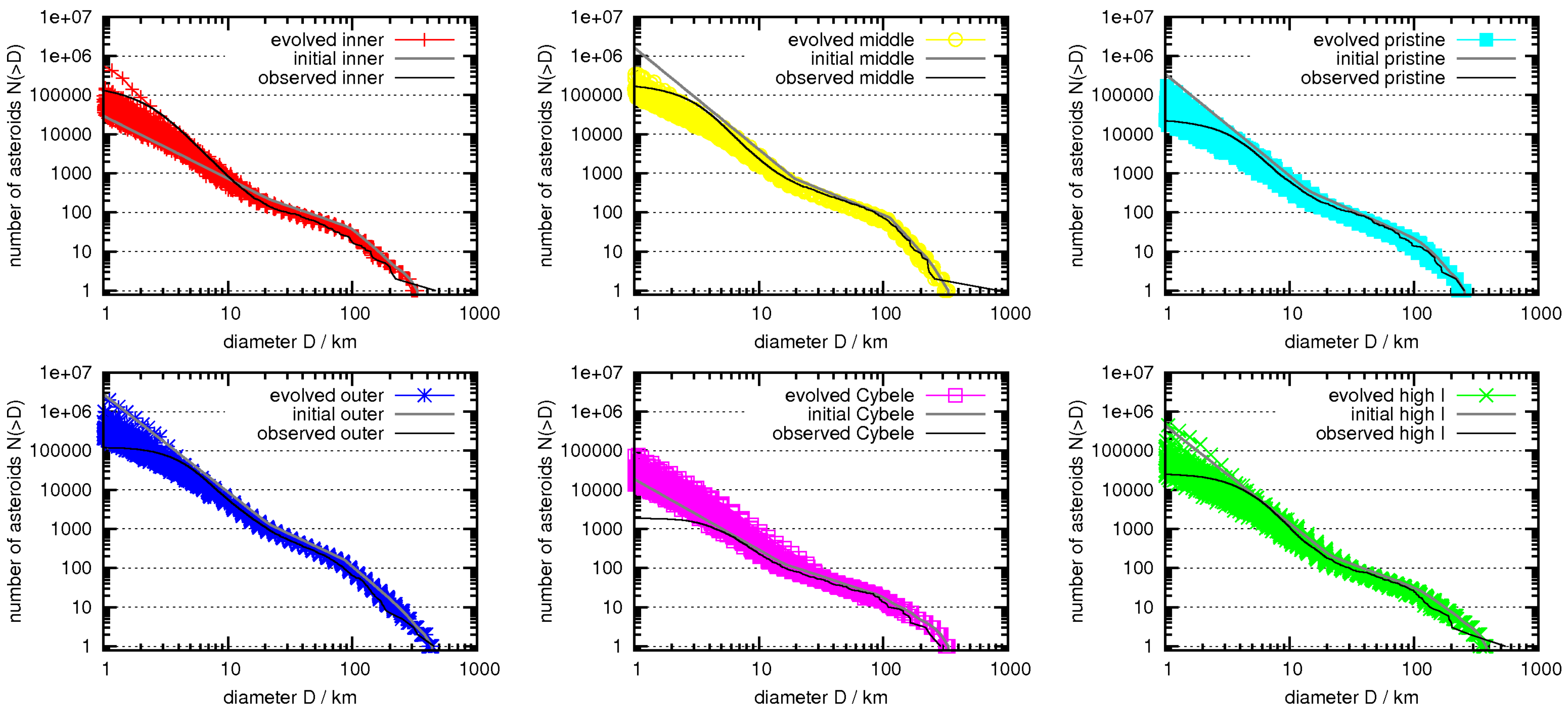


Figure 4: The final SFDs of individual parts of the main belt after 4 Gyr of collisional evolution. We show the currently observed SFD (black line) and the initial SFD (gray line) for comparison. A conservative completeness limit is D = 10 km.

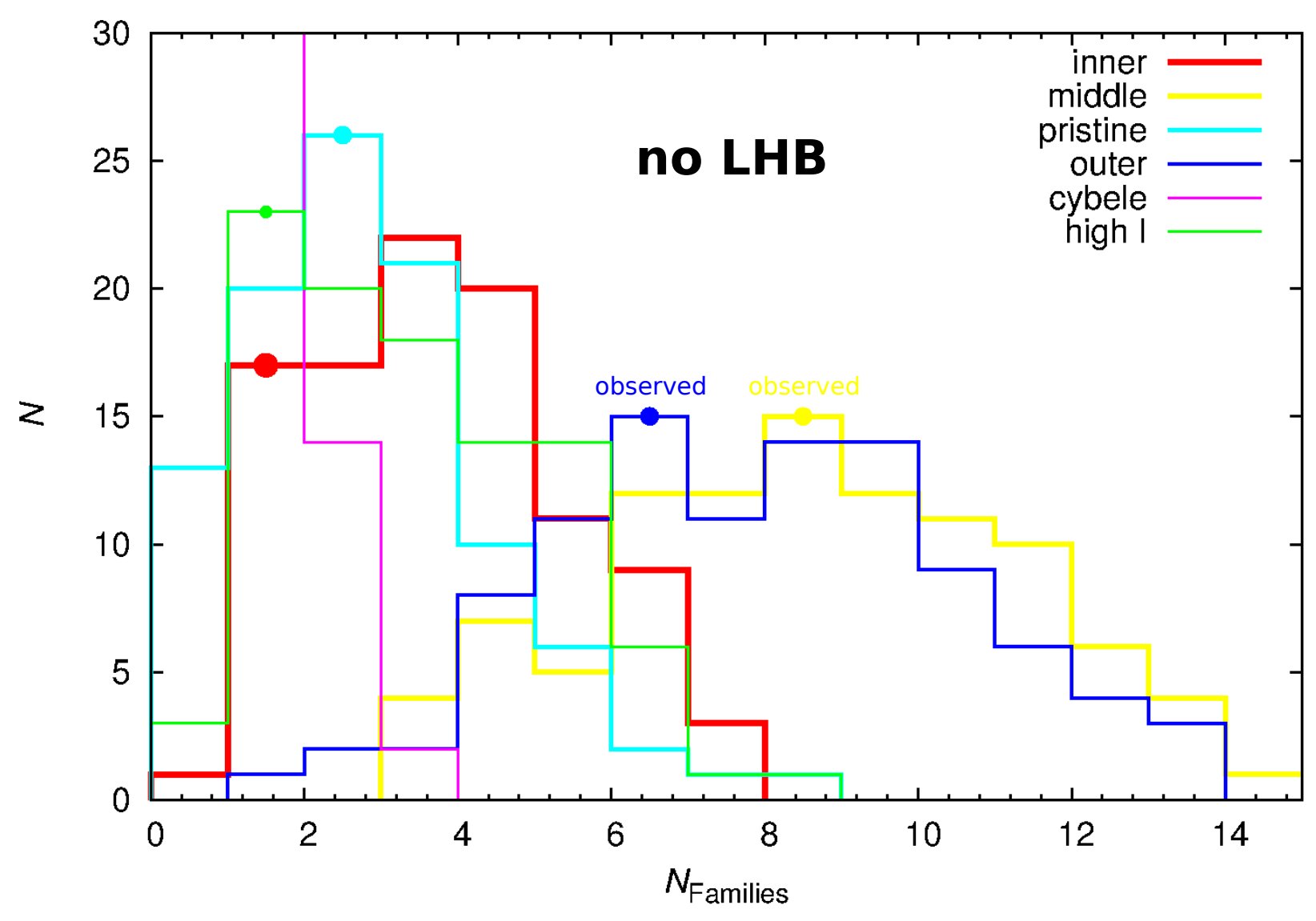


Figure 5: The histograms of number of families in individual zones. The currently observed numbers of families are displayed by points. Graph is trimed for better view, the most frequent number of families in the Cybele zone is 0.

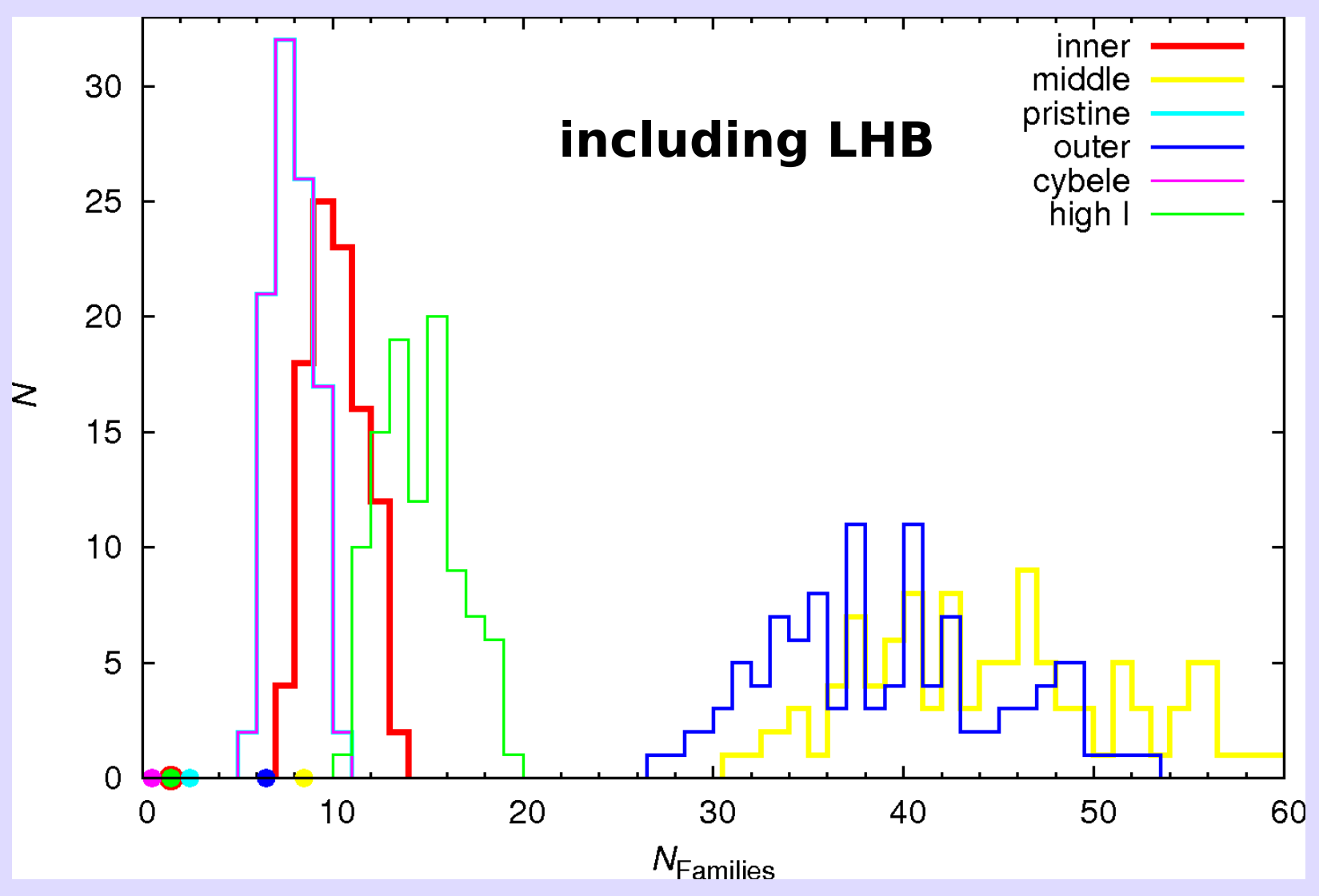


Figure 7: The histograms of number of families for the simulation which include the cometary LHB and the dynamical decay of the MB population. Majority of the D ~ 100 km families were 'erased' by secondary collisions.

4. Results including cometary Late Heavy Bombardment and dynamical decay

- a typical dynamical evolution of a cometary disk: data from Vokrouhlický et al. (2008), see Figure 6
- a dynamical decay of the main-belt population according to Minton & Malhotra (2010)
- we obtain the number of families in the whole main belt → families in individual zones are calculated as the ratio of the total number of bodies > 100 km to the number in the corresponding zone (Figure 7)

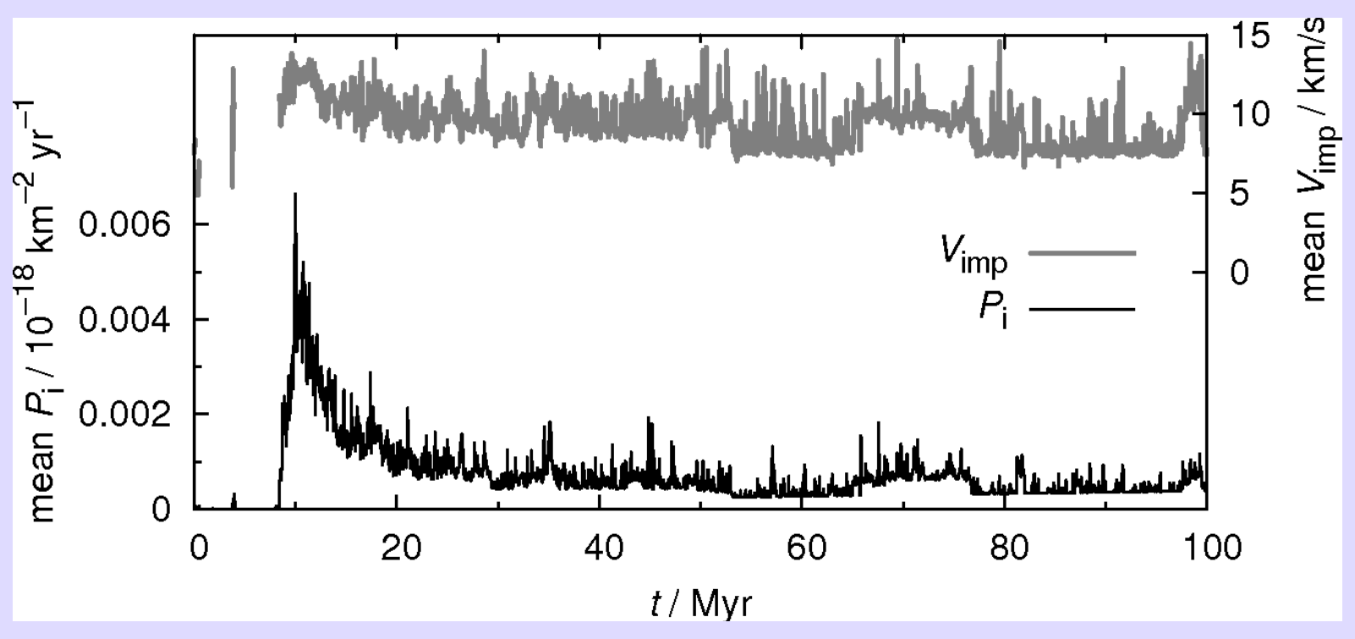
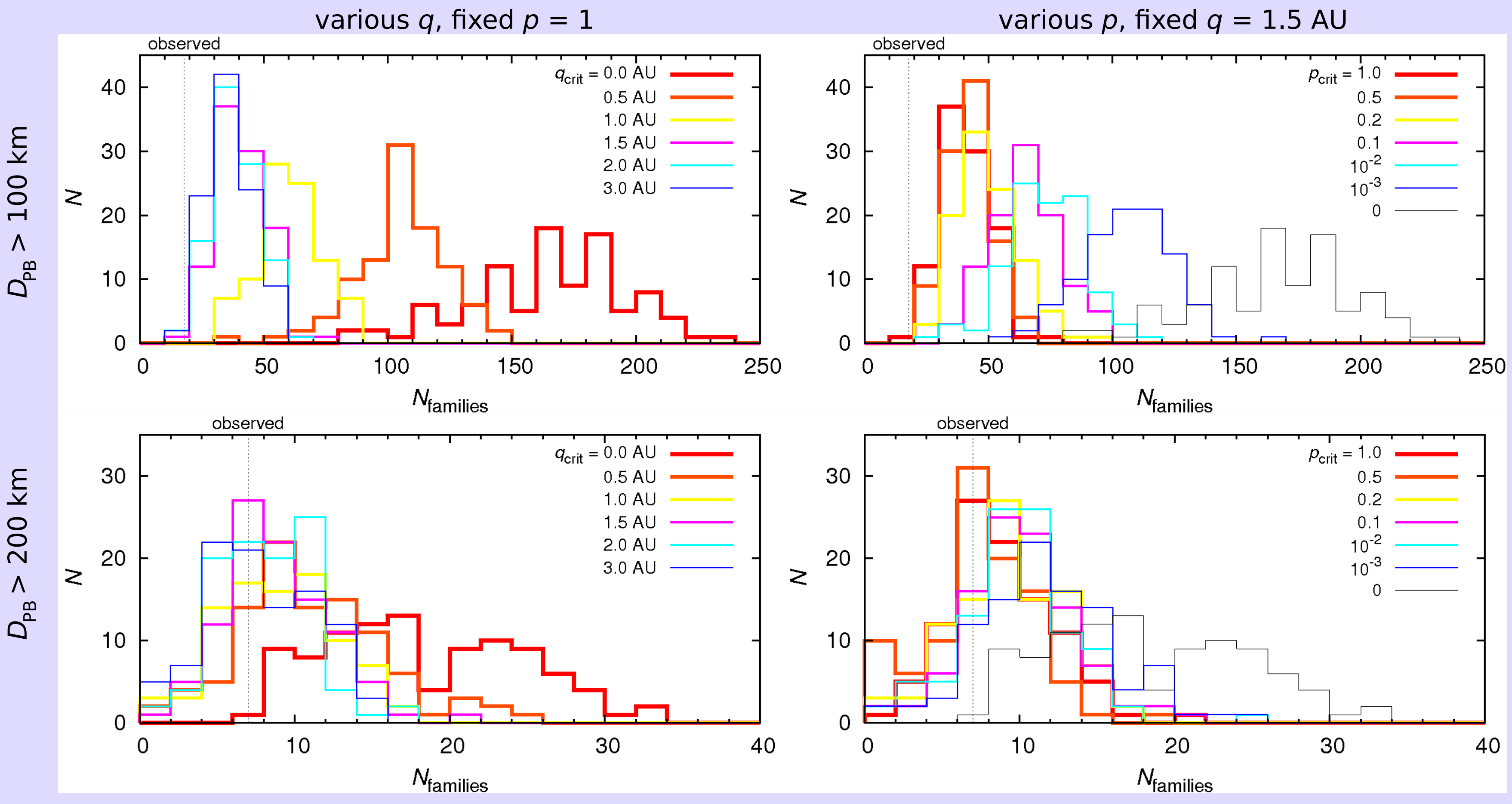


Figure 6: The temporal evolution of the intrinsic collisional probability (bottom) and mean collisional velocity (top) computed for collisions between cometary-disk bodies and the main-belt asteroids.

5. Important role of the cometary-disruption law!

- a simple criterion for physical disruptions of comets: perihelion distance q and probability p that the disruption occurs in one timestep (Δt = 500 yr in our case)
- results: the numbers of families in the whole MB (Figure 12) may significantly decrease (downto non-LHB case)


various q, fixed p = 1

various p, fixed q = 1.5 AU

Figure 12: The histograms of MB families for two different PB sizes and various cometary-disruption laws.

6. The "pristine zone" in the (e, sin I) plane

- up to 17 families were recognised (Figure 8), but most of them are either small or cratering events
- families confirmed by Sloan DSS colour indices (Parker et al. 2008) and WISE albedos (Masiero et al. 2011)

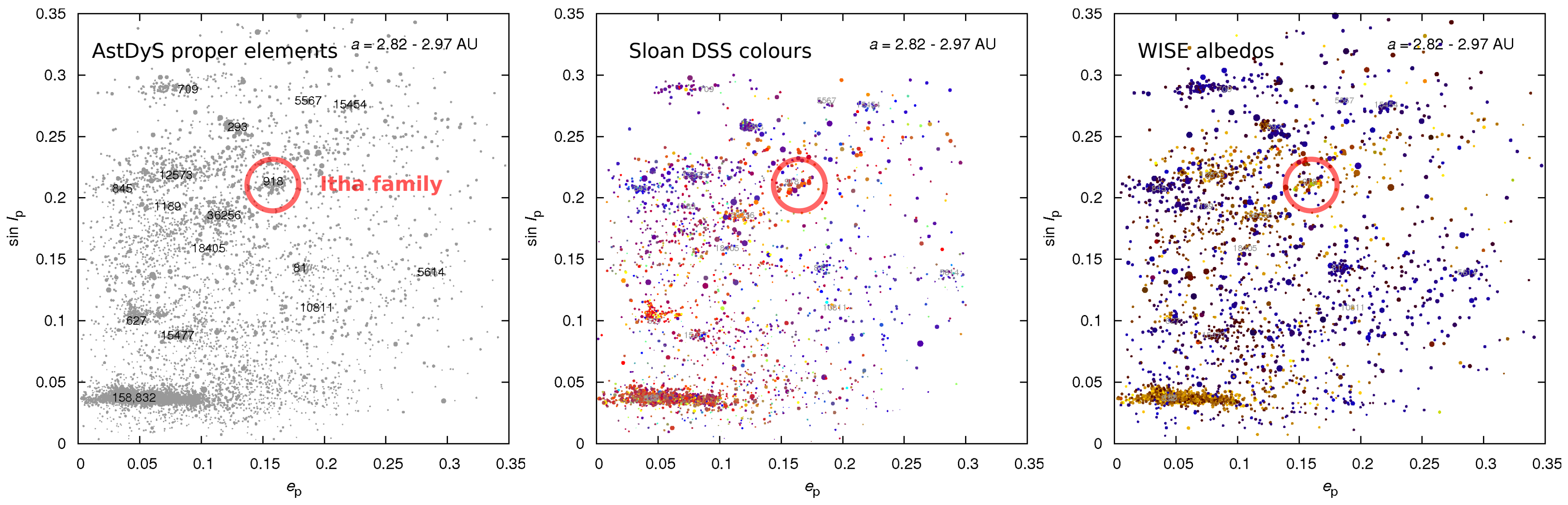
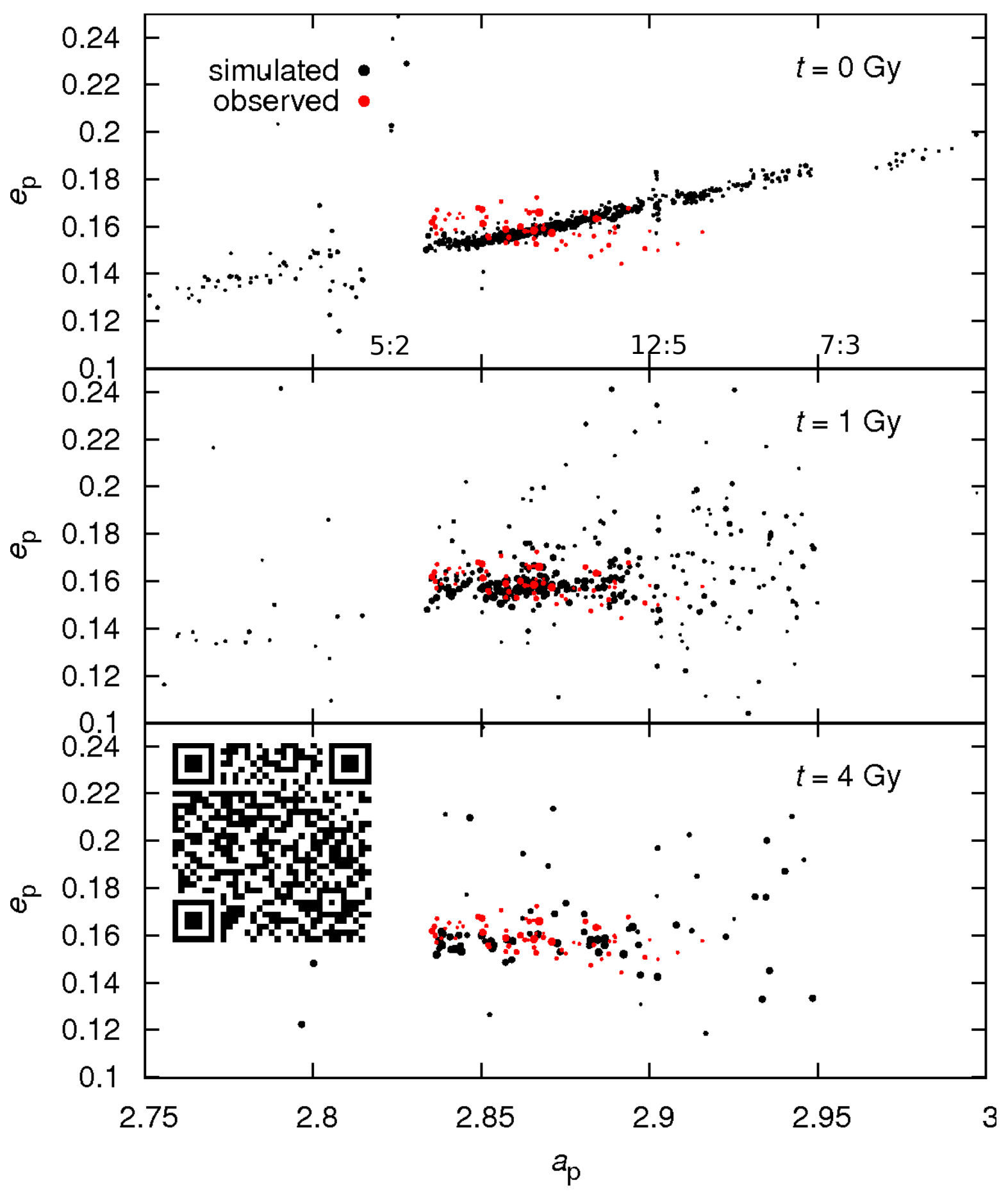


Figure 8: Proper eccentricity vs inclination for bodies in the pristine zone. Sizes of symbols correspond to actual diameters.

7. Itha family: a dynamical model



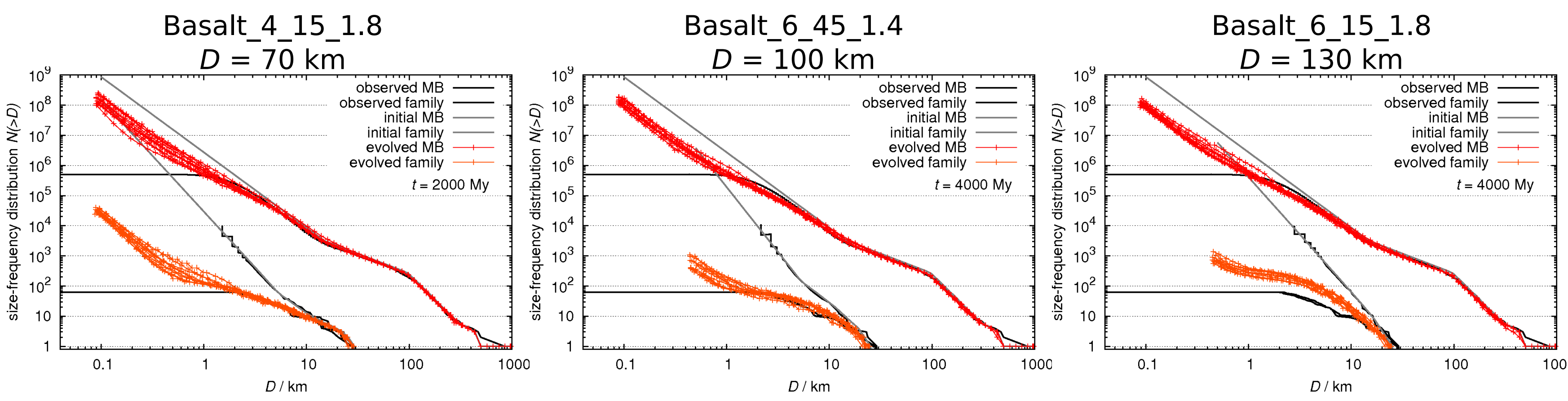
- initial conditions: isotropic velocity field with size-dependent $v \sim 1/D$, v = 90 m/s for D = 5 km
- random spin axes orientations
- N-body simulation: SWIFT by Levison & Duncan (1994), with Yarkovsky/YORP effect included
- thermal parameters: bulk density ρ = 2.5 g/cm³, surface ρ = 1.5 g/cm³, conductivity K = 0.001 W/m/K, C = 680 J/kg/K, Bond albedo A = 0.1, emissivity ε = 0.9
- spin evolution: YORP moments by Čapek & Vokrouhlický (2004), collisional reorientations

- results: synthetic family initially extends beyond J5:2 and J7:3 resonances (Figure 9)
- moreover, there is a weak 12:5 MMR at 2.9 AU present which is populated by family members
- none of these features is observed, we thus exclude a possibility that the Itha family is young
- a preliminary estimate of the lower limit for the age is 1 Gyr (to disperse family members sufficiently)

Figure 9: Proper semimajor axis vs eccentricity for the synthetic family (black) and observed members (red). The initial conditions as well as the situation at 1 and 4 Gyr are shown. Note that the number of synthetic bodies was selected 10 times larger.

8. Itha family: collisional evolution (without the LHB)

- parent body size: the method of Durda et al. (2007) based on a set of SPH simulations and fitting of $D > 10$ km part of the SFD (which is not evolved significantly); the best fits were from D = 70 to 130 km
- simulations with the Boulder code (with a similar setup as above)
- results: we can fit the observed SFD with a relatively small PB (D = 70 km), with a lower limit for the age 2 Gyr, but a larger PB (D = 100 km) is equally possible, with the age approching 4 Gyr (see Figure 10)

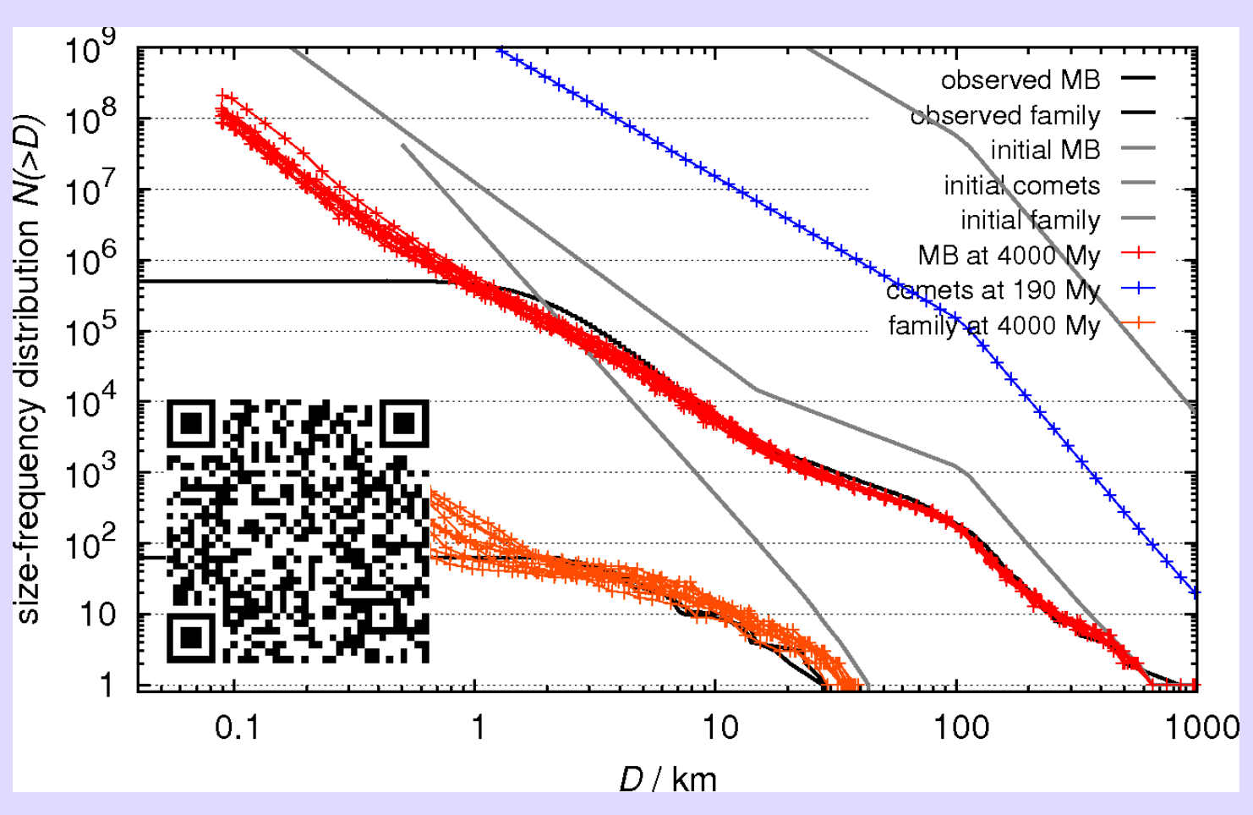

Basalt_4_15_1.8
D = 70 km

Basalt_6_45_1.4
D = 100 km

Basalt_6_15_1.8
D = 130 km

Figure 10: The final SFDs of the synthetic family (and the MB) for three different initial SFDs. Note that for the largest PB of D = 130 km we cannot fit the observed SFD within 4 Gyr (nevertheless, see below).

9. Itha family: a model including the Late Heavy Bombardment



- a synthetic family created at the beginning of the LHB
- no physical disruptions of comets in this simulation
- Durda et al. (2007) method cannot be used in this case

- a sufficiently large synthetic family (D > 200 km) can 'survive' the whole LHB and resemble the observed SFD.
- however, dynamical perturbations induced by planetary migration may destroy the compact family in the proper element space (Brož et al. 2012)
- it thus seems likely, that the Itha family was formed during the LHB 'tail'

Figure 11: The final synthetic SFDs for the simulation including the LHB.

Conclusions

- our collisional model of the MB seems consistent with the observed numbers of families in most parts of the MB, but we may be 'missing' some D > 100 km families in the inner belt and the high-inclination zone
- using a dynamical/collisional model we confirm that the Itha family may be 3.8 Gyr old and may have experienced the Late Heavy Bombardment

- future work: test if a single scaling law can be used for the whole MB or not
- studies of dynamical/collisional evolution of other families in the pristine zone
- *independent* models for physical disruptions of comets would be extremely useful to constrain collisional models

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