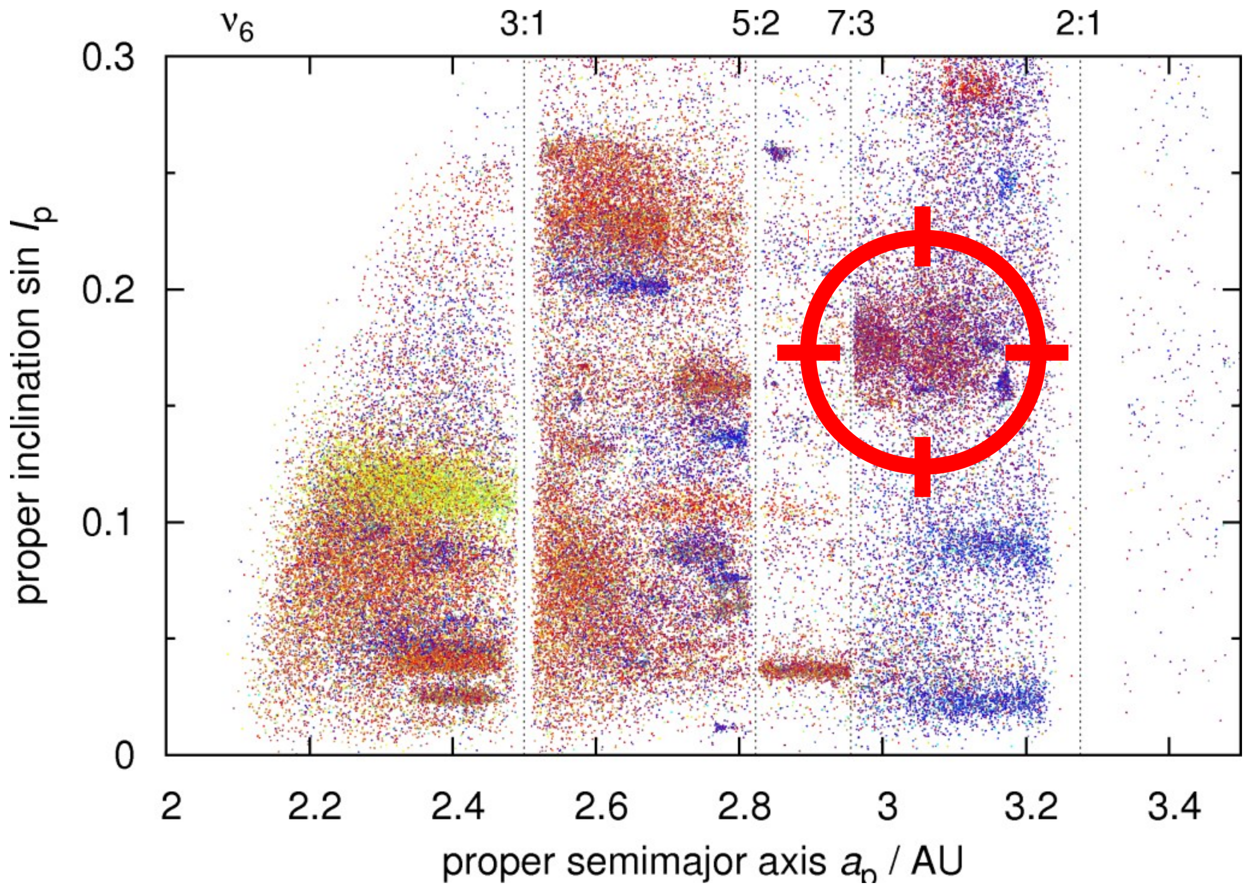
Dynamics of asteroid family halos

Miroslav Brož[1]

[1] Charles University, Czech Republic



Eos family

Milani & Kneževic (2003)
Ivezic et al. (2002)

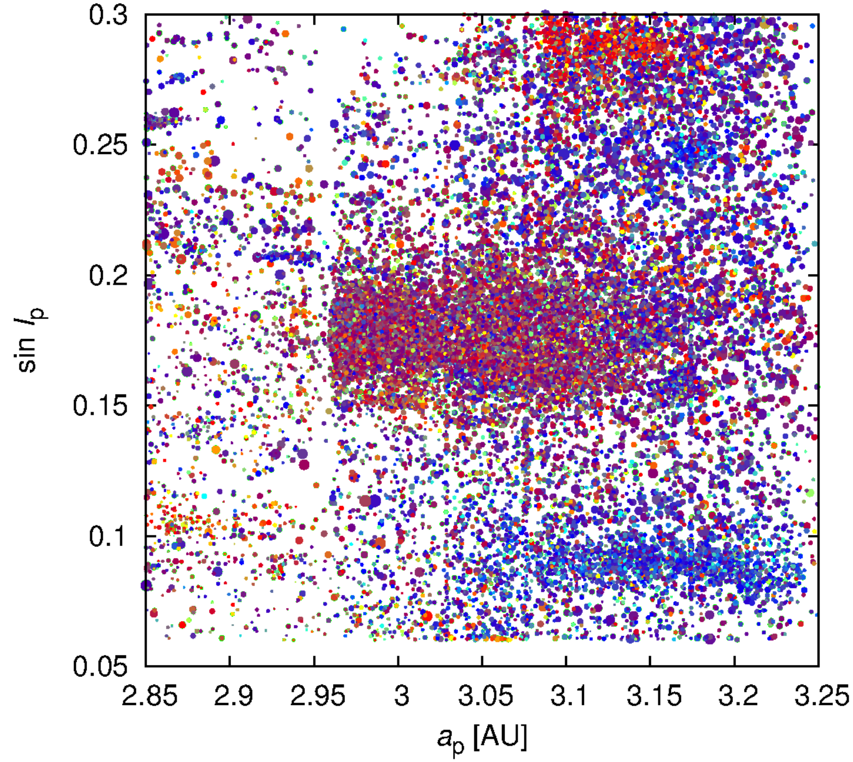
A lot of References...

Hirayama (1918), Gradie & Zellner (1977), Fujiwara (1982), Kozai (1983), Binzel (1988), Farinella etal. (1989), Marzari etal. (1995), Morbidelli etal. (1995), Grogan etal. (1997), Doressoundiram etal. (1998), Zappalà etal. (2000), Burbine etal. (2001), Ivezic etal. (2002), Tsiganis etal. (2003), Mothé-Diniz & Carvano (2005), Vokrouhlický etal. (2006), Durda etal. (2007), Carruba & Michtchenko (2007), Mothé-Diniz etal. (2008), Greenwood etal (2010), Hardersen etal. (2011), Brož & Morbidelli (2013), Hanuš etal. (2013), Novakovic & Tsirvoulis (2014), Masiero etal. (2014), Milani etal. (2014), Nesvorný etal. (2015), ...

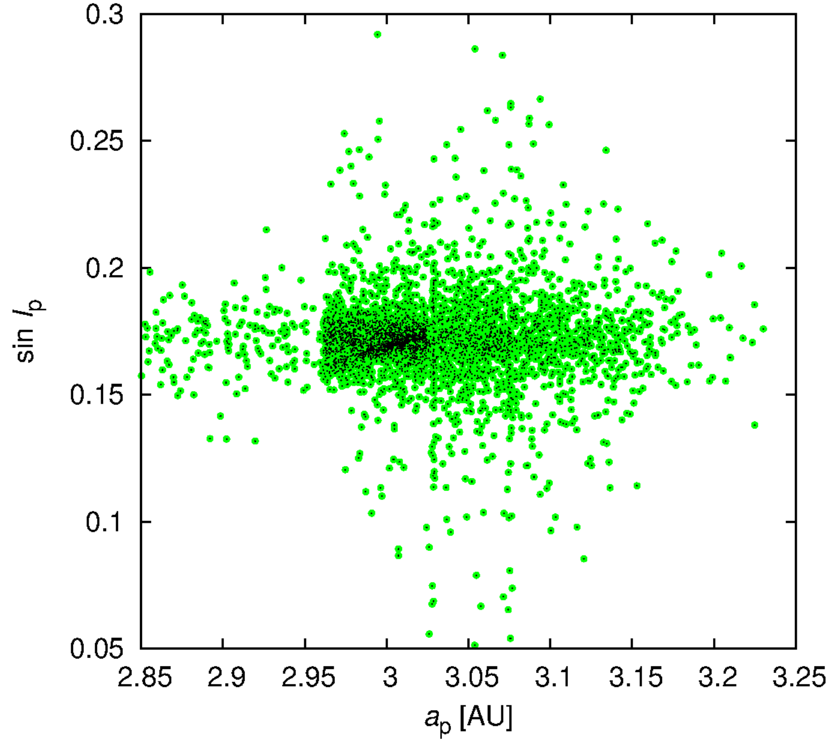
Observations vs simulations

of families

- observed proper elements a_p, e_p, $\sin I_p$, complicated shape, halo, neighbor families, background → HCM useless!
- synthetic (evolved) families: unknown & variable v_{cutoff}



vs



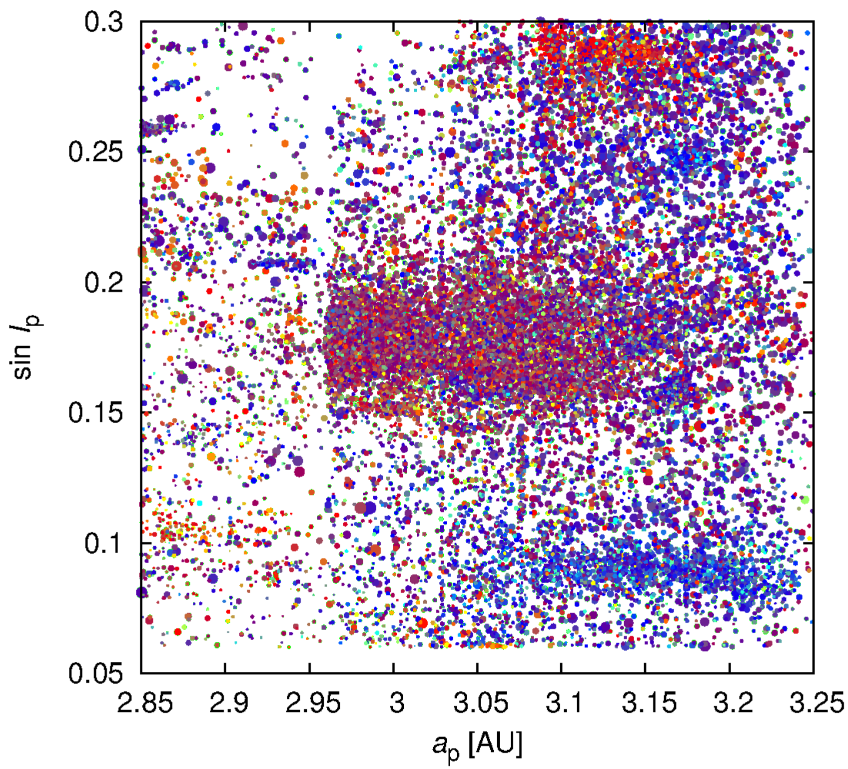
Dynamical model (Brož etal. 2011)

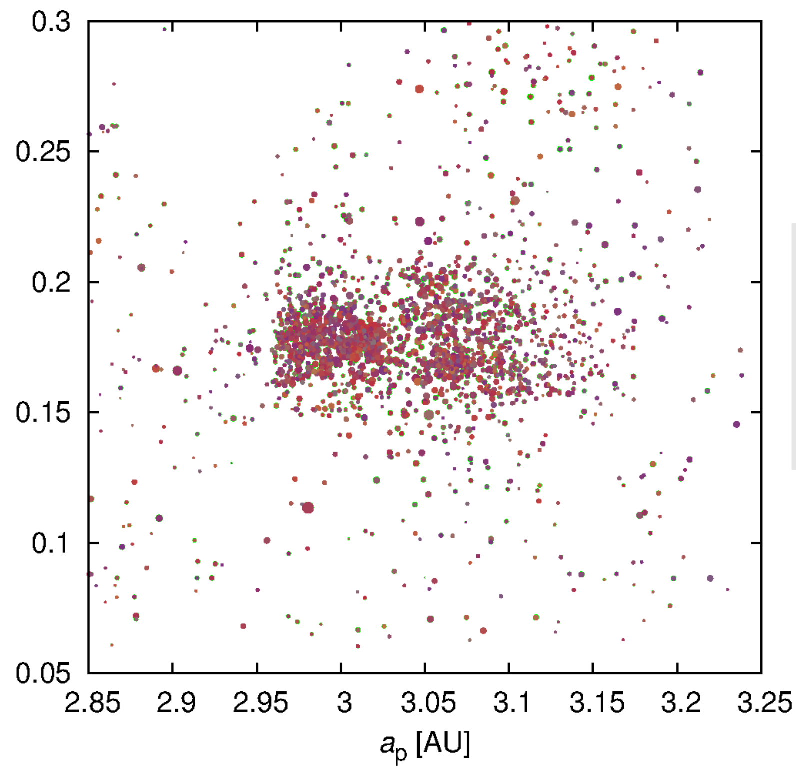
- modified SWIFT integrator (Levison & Duncan 1994)
- Yarkovsky thermal effect, da/dt
- captures in mean-motion and secular resonances, de/dt, dI/dt
- YORP effect, dω/dt, dγ/dt (Čapek & Vokrouhlický 2004)
- collisional reorientations (Farinella etal. 1998)
- mass shedding (Pravec & Harris 2000)

- digital filters for mean and proper elements “good-looking”

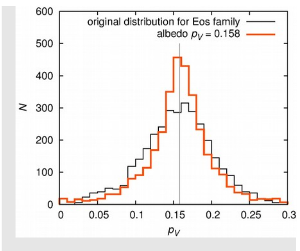
Problem 1: Selection of asteroids

- we can always select a subset (using SDSS, WISE data) to decrease a contamination by interlopers
- for Eos family it’s easy! (K-type), but only 1/10th of asteroids





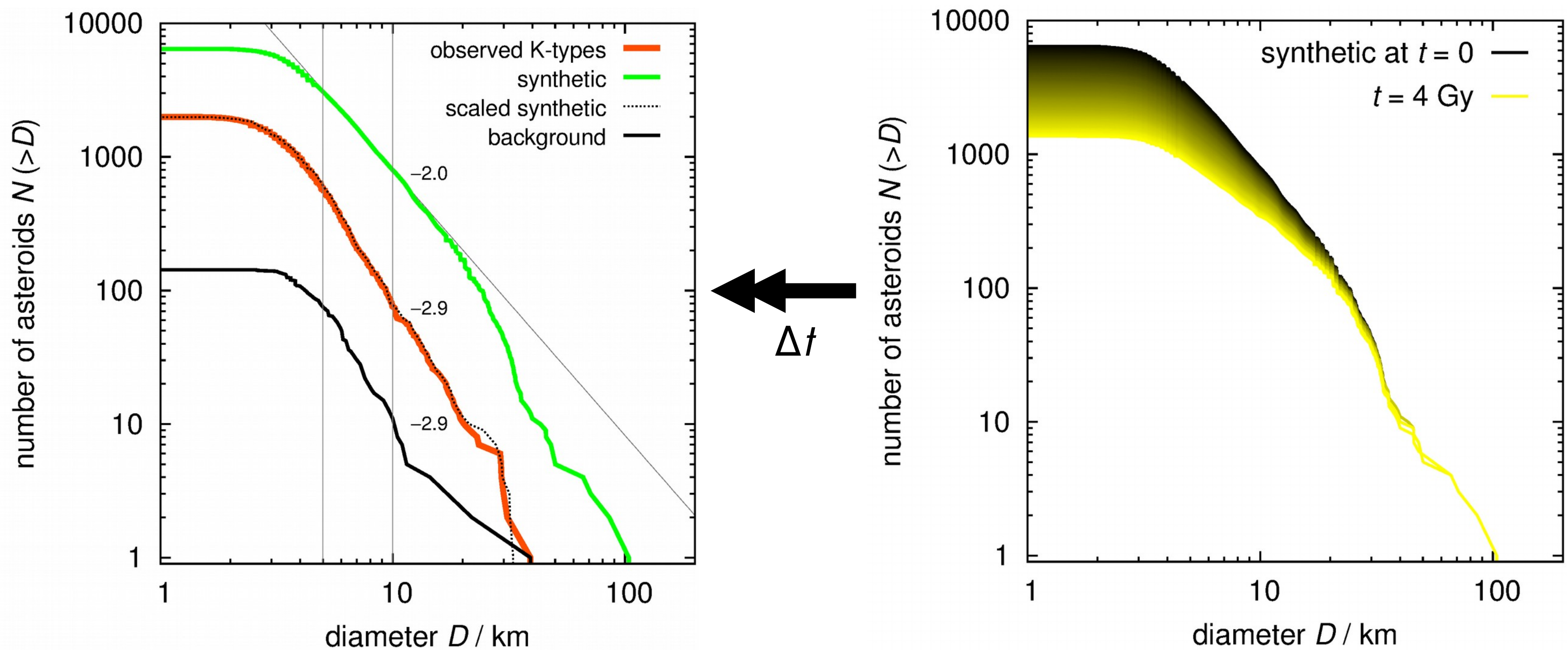
a^* = (0.0, 0.1)
i–z = (−0.03, 0.08)
p_V > 0.07



a note on WISE albedo distribution (Masiero etal. 2011)

2: Apples vs oranges (SFDs)

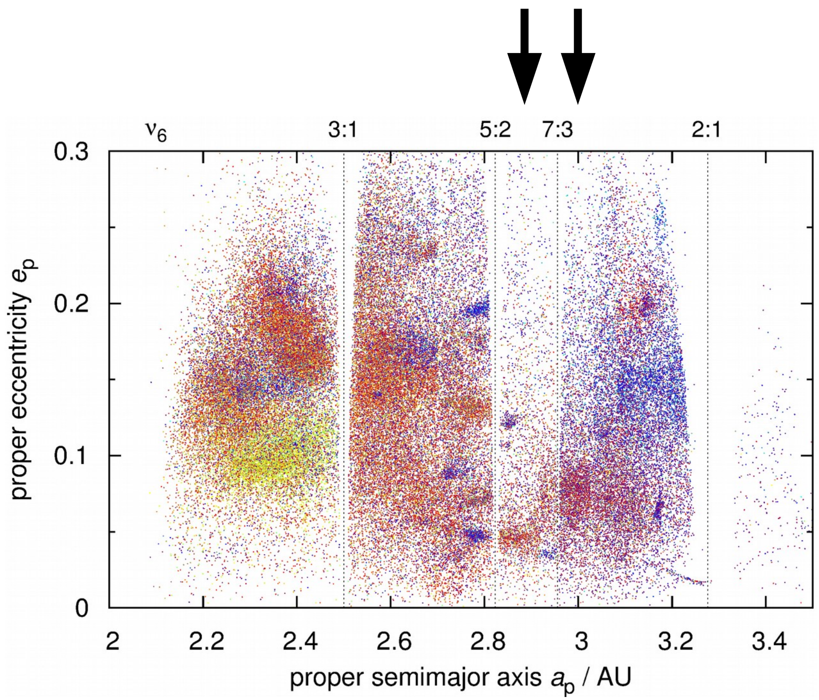
- the size-frequency distributions (SFDs) should match for both observed and synthetic populations ← rescaling
- random selection of synthetic asteroids *at every single timestep* of the simulation (or even multiple selections)



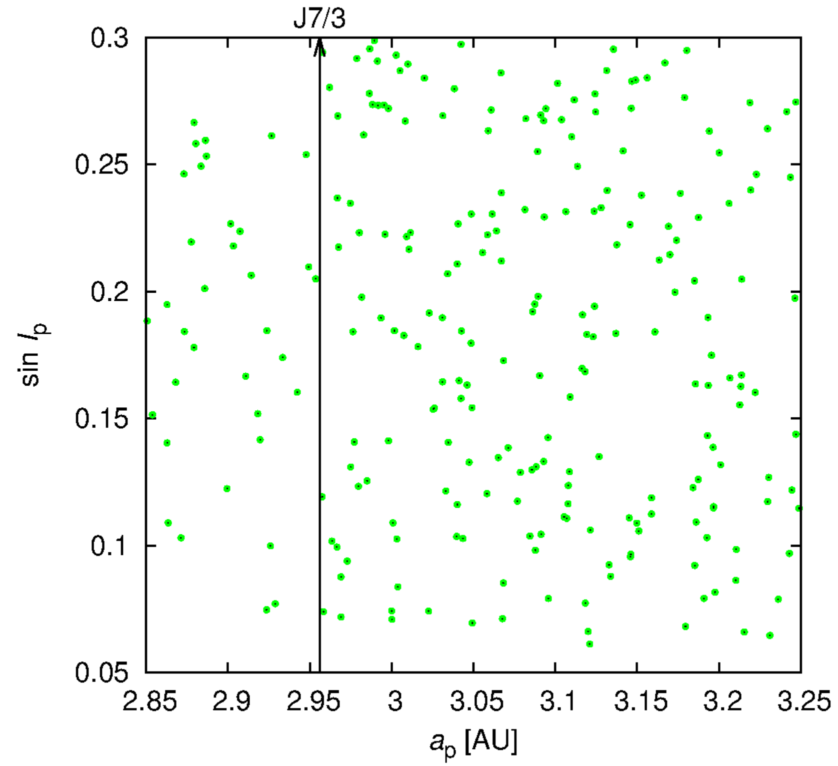
3: Non-uniform background

- background is *not* uniform in the MB (cf. boundaries)
- synthetic backgrounds with the same SFD as the observed...

cf. background



... and a_p, e_p, sin I_p generated randomly

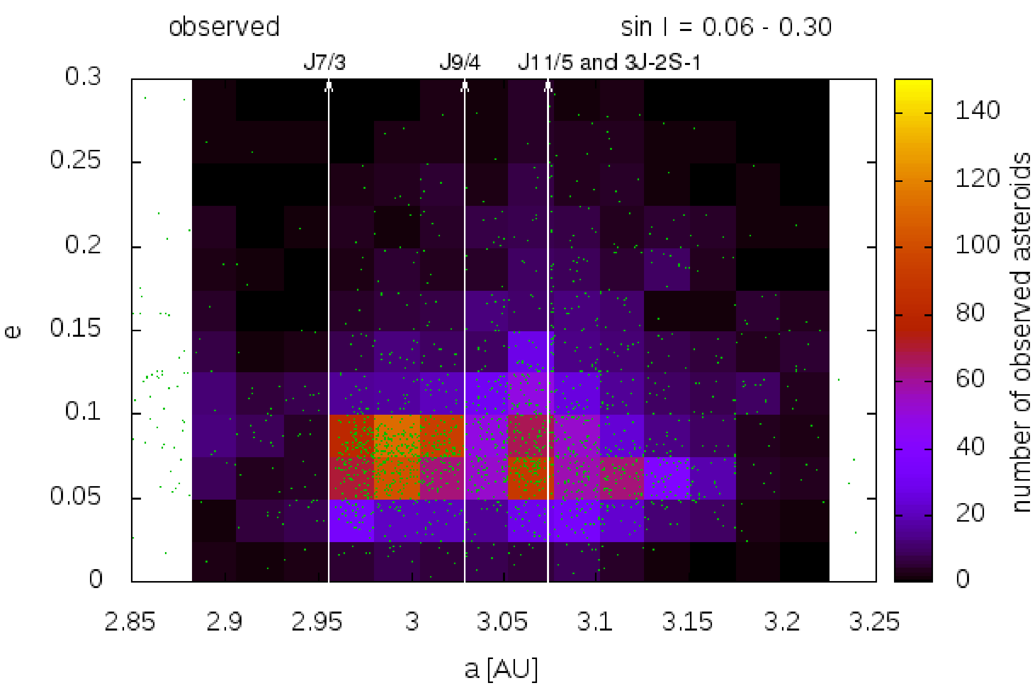


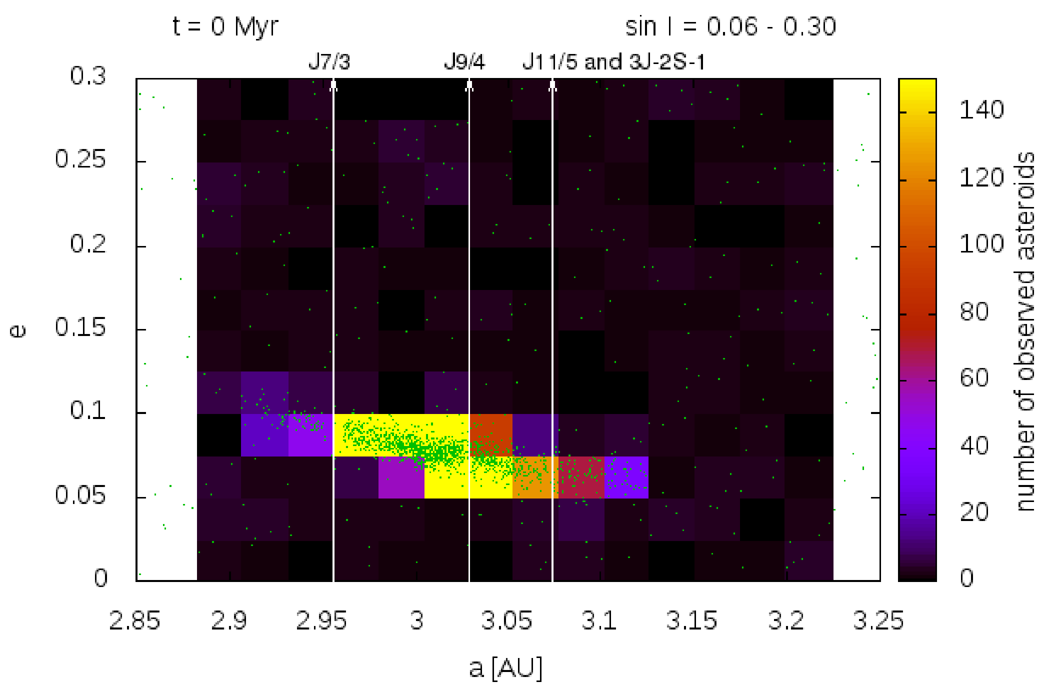
“Understandable Black Box”

observed family → the best fit ← synthetic family

Boxes and χ^2 metric

- boxes in (a_p, e_p, sin I_p), aligned with resonances, also in D
- initial conditions: isotropic disruption, velocities ~ $1/D$, D_{PB} = 380 km

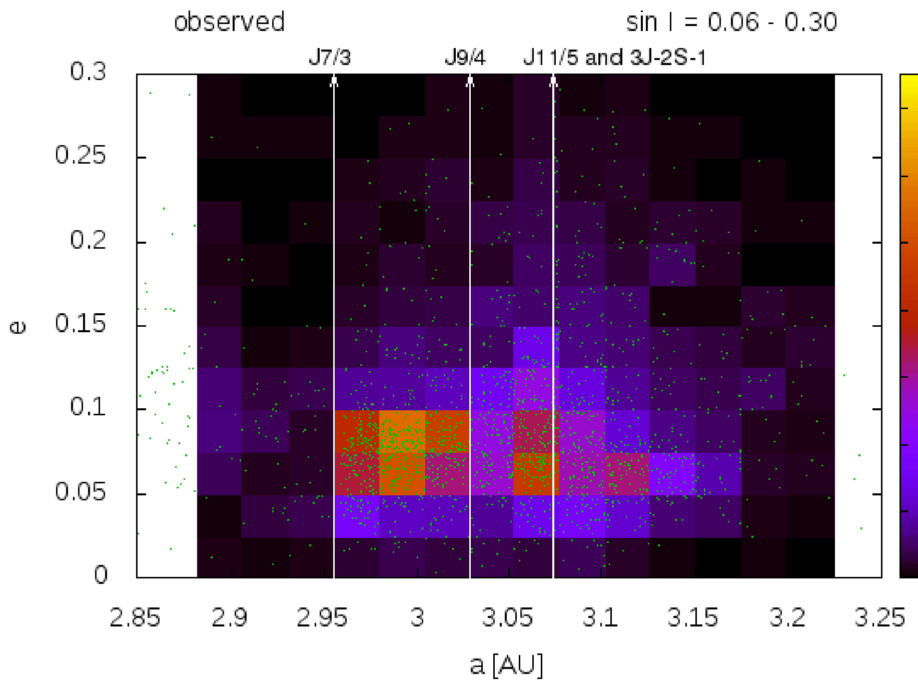


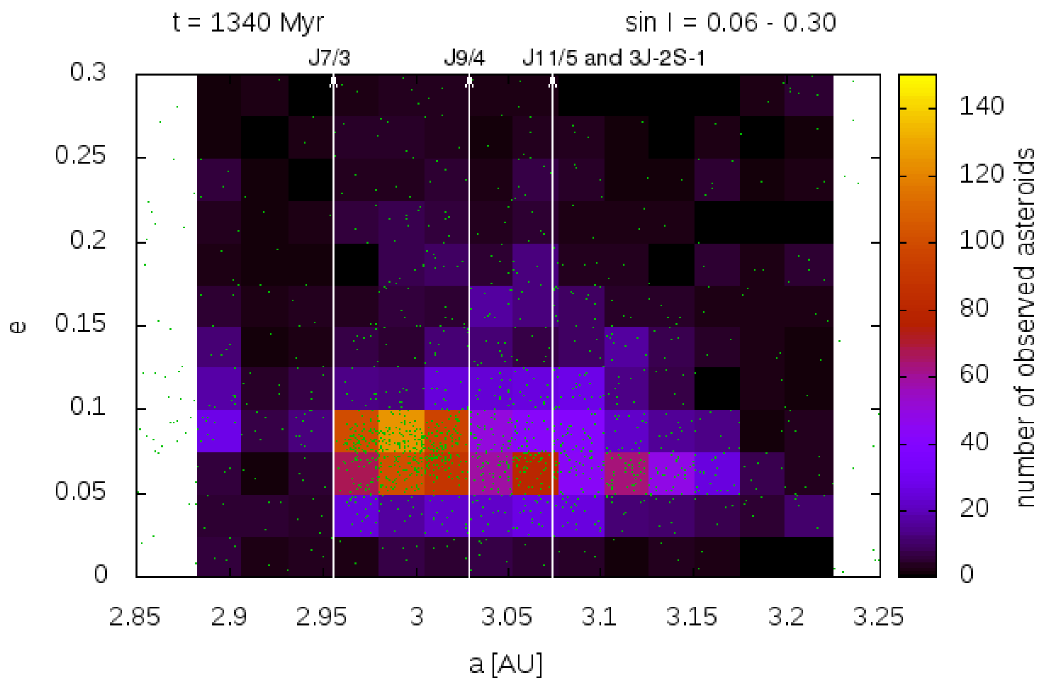


proper semimajor axis vs eccentricity

Boxes and χ^2 metric ← the best fit

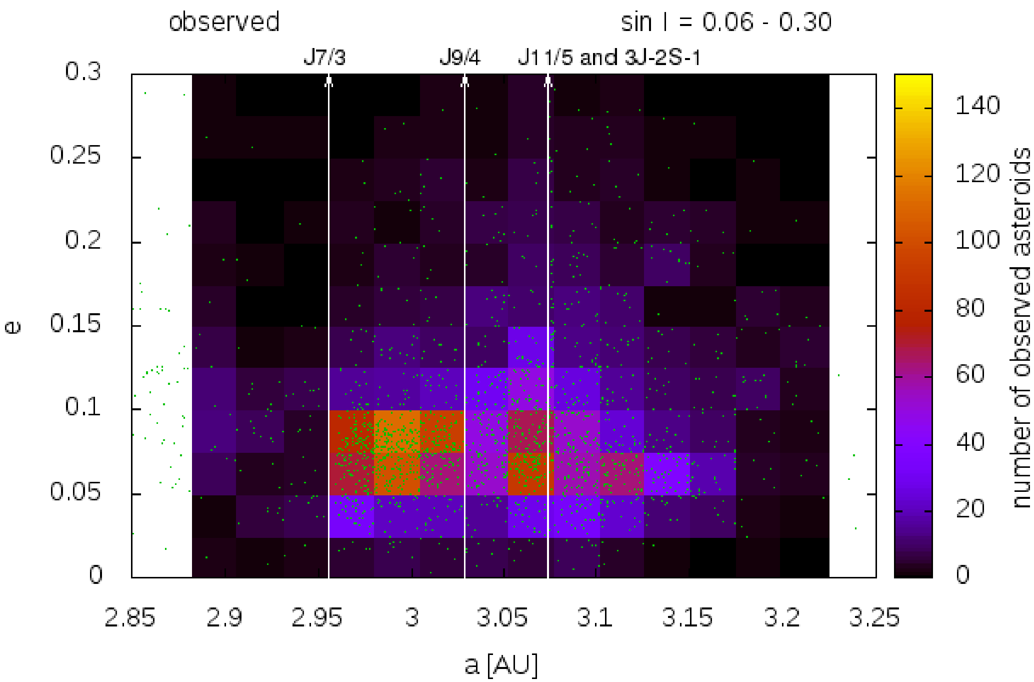
- boxes in (a_p, e_p, sin I_p), aligned with resonances, also in D
- not only upper, but also *lower* limit for t_{age} = (1.3 ± 0.2) Gy!

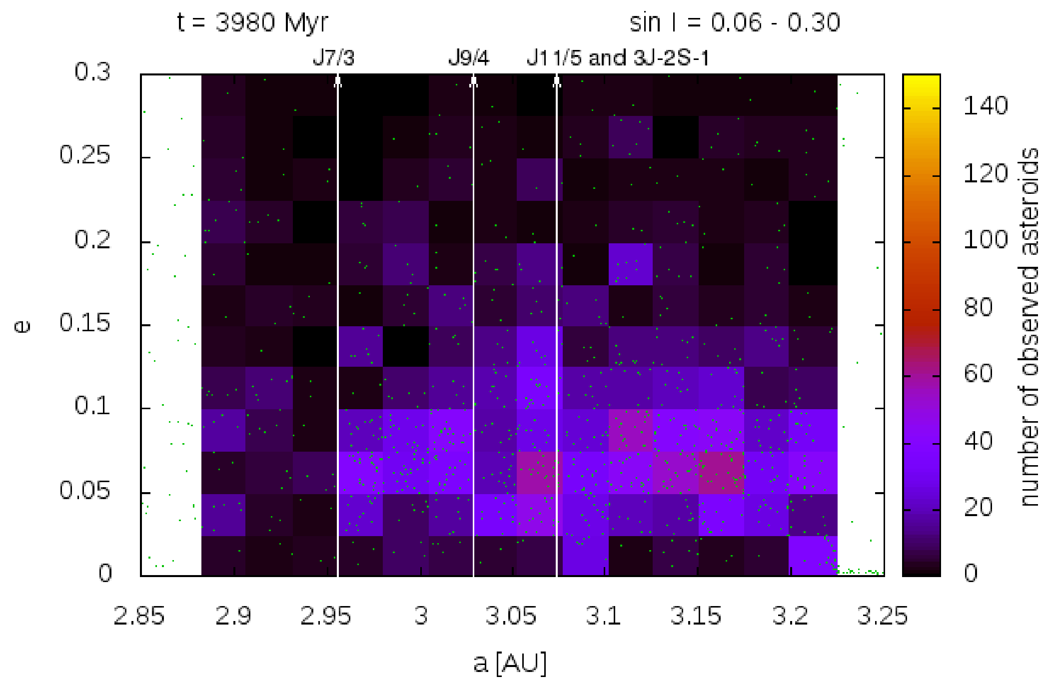




Boxes and χ^2 metric

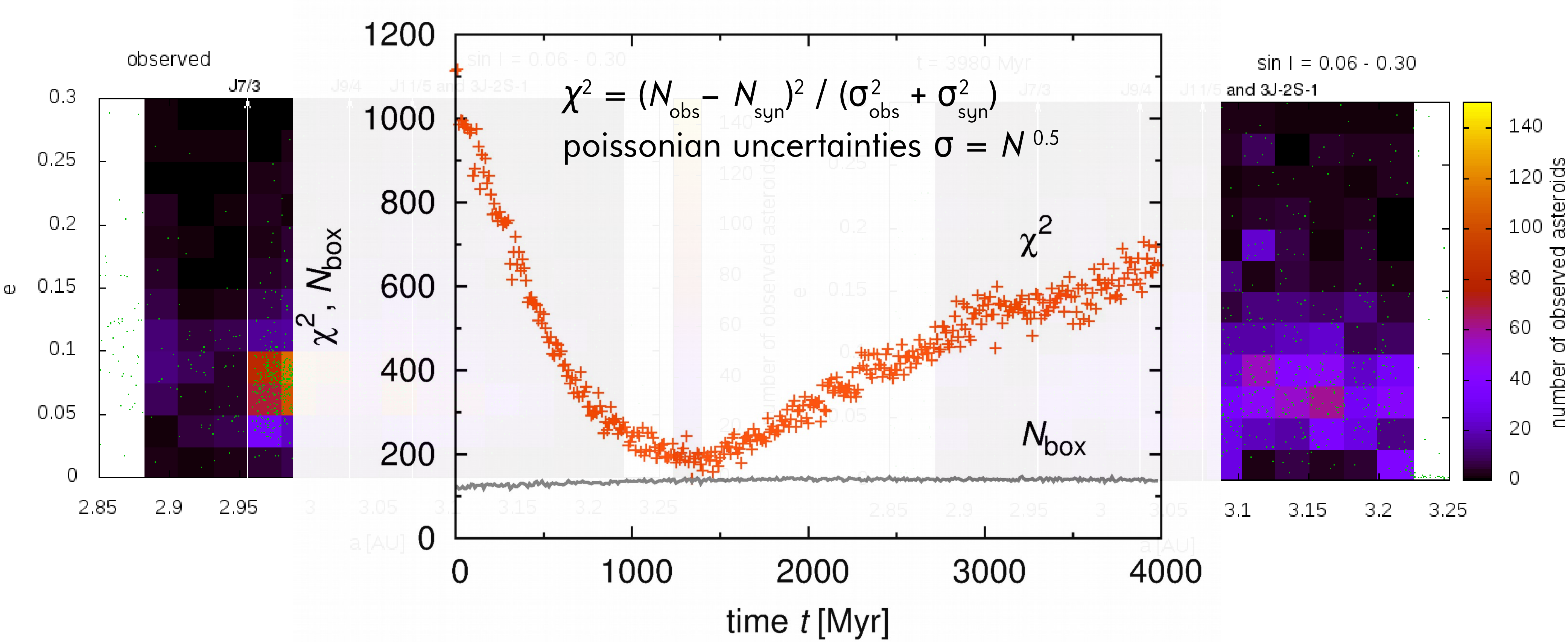
- boxes in (a_p, e_p, sin I_p), aligned with resonances, also in D
- not only upper, but also *lower* limit for t_{age} = (1.3 ± 0.2) Gy!





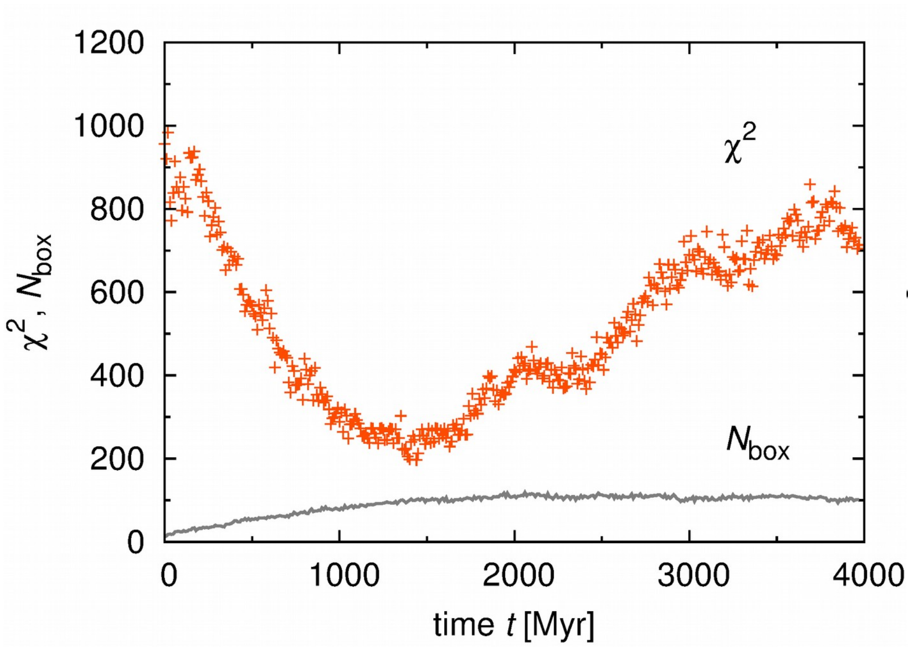
Boxes and χ^2 metric

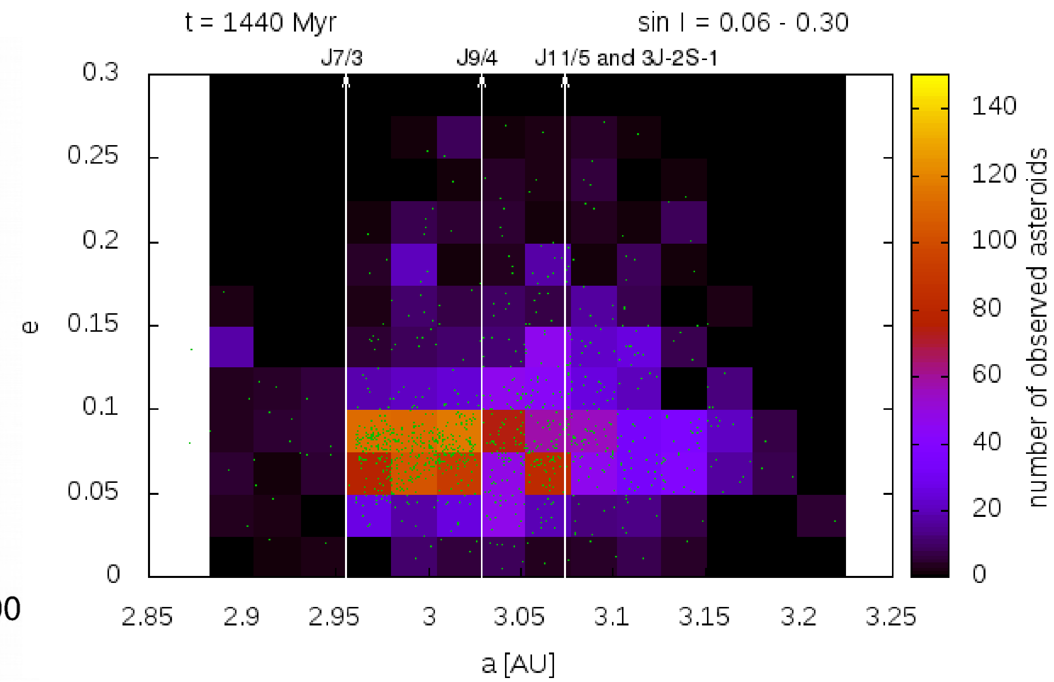
- boxes in (a_p, e_p, $\sin I_p$), aligned with resonances, also in D
- not only upper, but also *lower* limit for $t_{age} = (1.3 \pm 0.2)$ Gy!



Bad fit 1: Ejection velocity tail

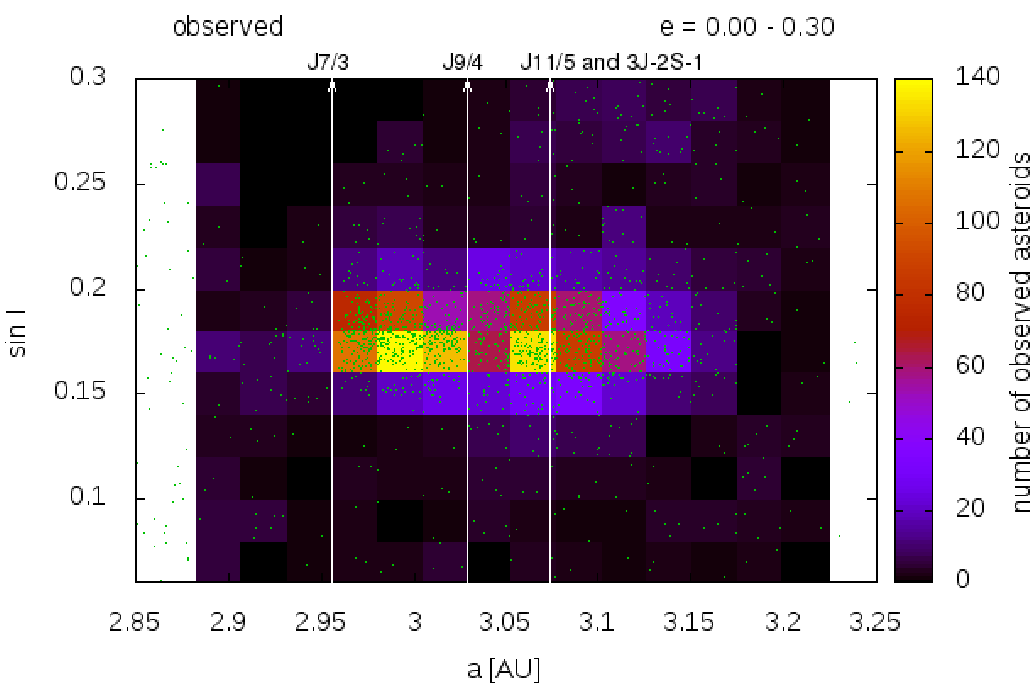
- for v_{ej} < 200 m/s we cannot explain K-types below J7/3 MMR
- **v_{ej} up to 400 m/s** is needed! (for *small* asteroids)

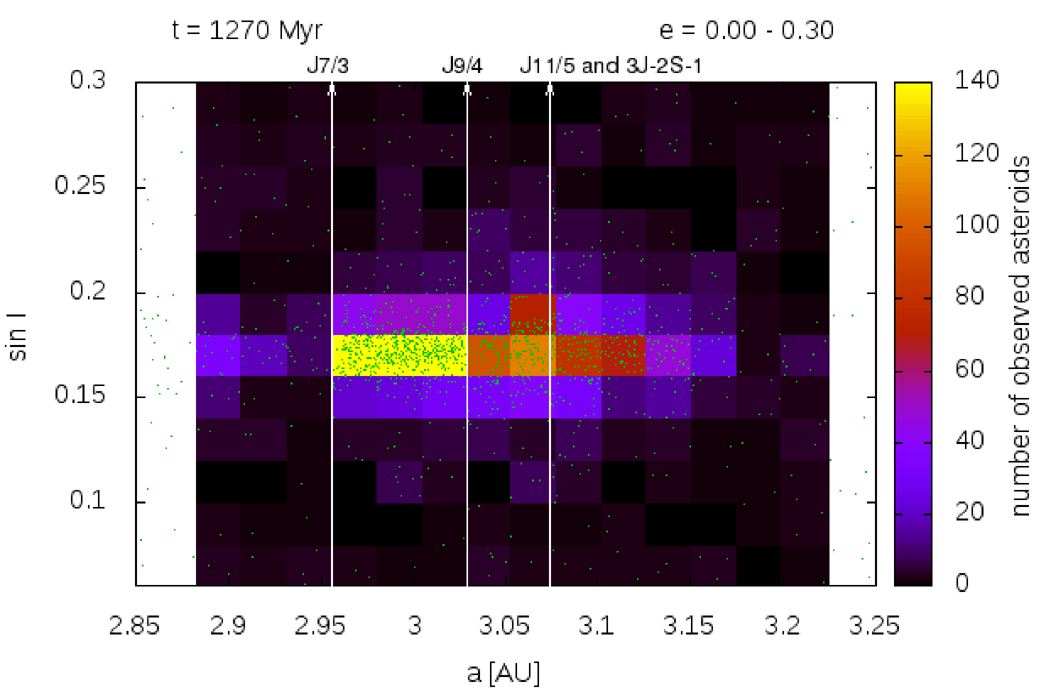




2: Parent body inclination

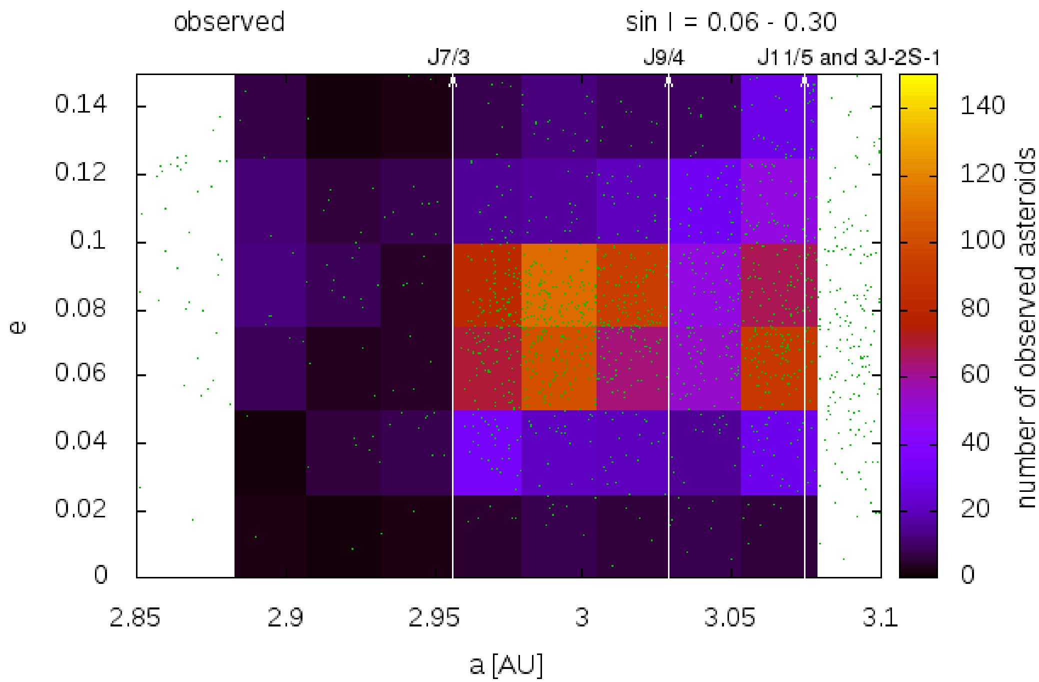
- for nominal inclination of Eos ($\sin I_p = 0.1726$) the best fit is rather poor ($\chi^2 \sim 240$)
- a shift **$\Delta \sin I_p \sim +0.005$** is needed

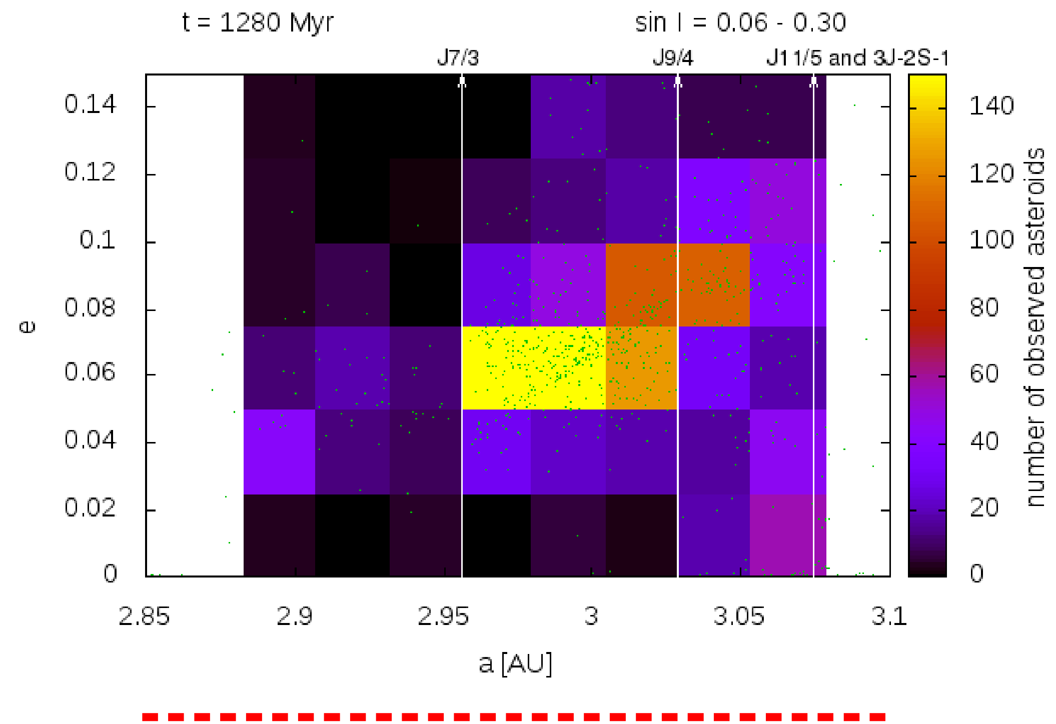




3: True anomaly f > 120 deg

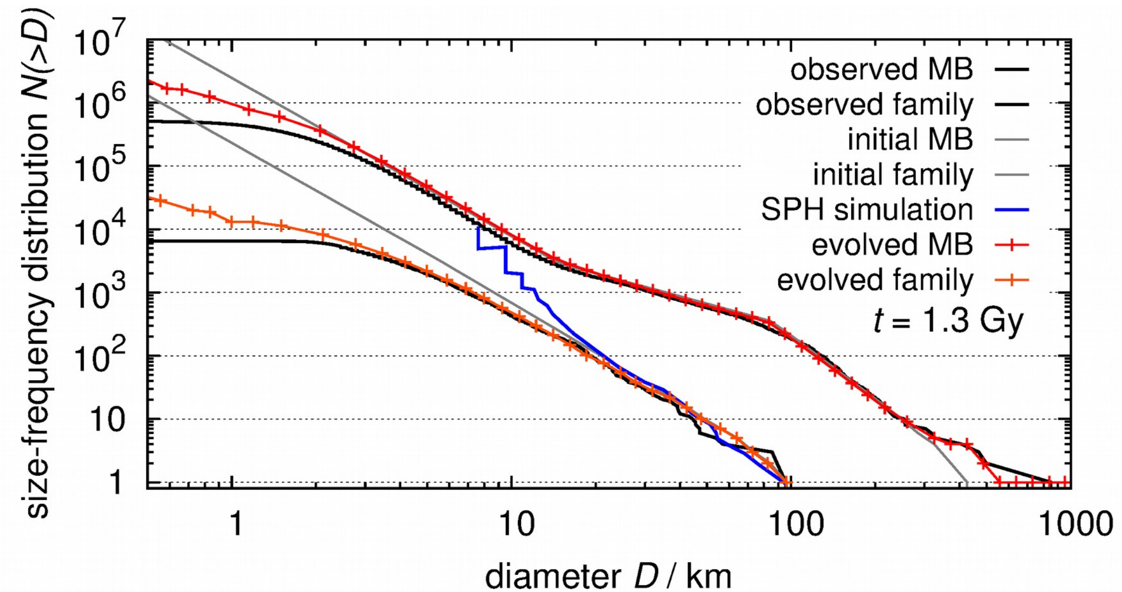
- for $f < 120$ deg, too many captures in z_1 secular resonance, consequently, wrong boxes are populated ($\chi^2 \sim 600$)
- **f > 120 deg** is needed ↓





Conclusions

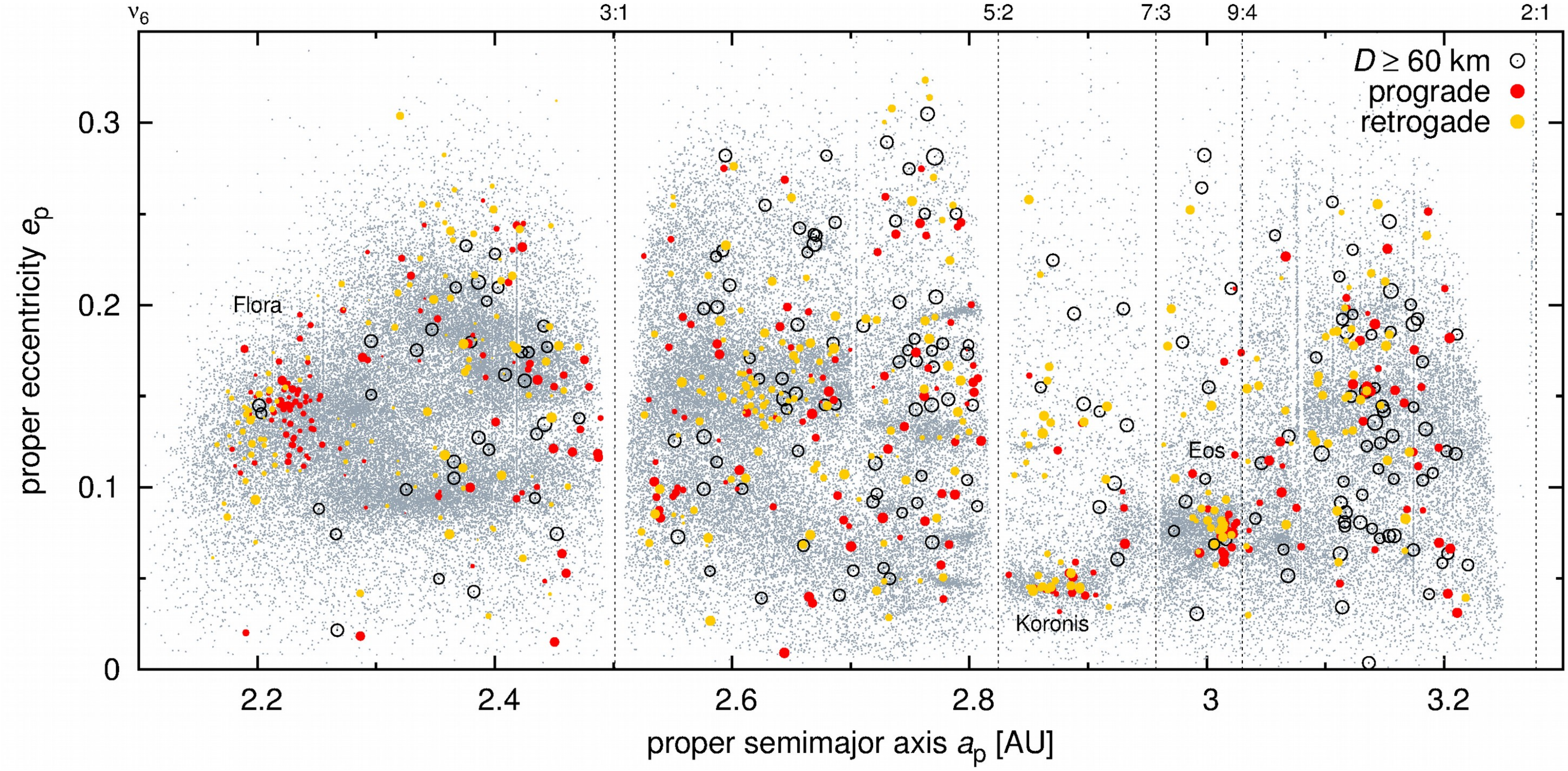
- it's important to account for: colours, SFDs & background
- for Eos it's possible to explain shape in a_p, e_p, $\sin I_p$ (in 3D)
- the age estimate still scales with the bulk density ρ
- *but* the collisional model also gives $t_{age} = (1.3 \pm 0.3)$ Gy



- Future work: other promising families (Flora, Koronis, ...)

DAMIT database

- 30 + 35 = 65 asteroids in Eos core + halo ← many more compared to Hanuš etal. (2013)



Dynamical evolution of spins

N-body Swift integrator

We use a symplectic integration scheme (Levison and Duncan 1994), denoted as kick–drift–kick, where the 'kick' (actually, a perturbation) is performed as:

$$\dot{\mathbf{r}}_{n+1} = \dot{\mathbf{r}}_n + \ddot{\mathbf{r}}\frac{\Delta t}{2}\,, \tag{3}$$

and the 'drift' corresponds to an analytical solution of the two-body problem (the Sun–asteroid), which involves a numerical solution of the transcendent Kepler equation:

$$\begin{aligned} M &= E - e\sin E\,, &(4)\\ \mathbf{r}_{n+1} &= p(E)\mathbf{r}_n + q(E)\dot{\mathbf{r}}_n\,, &(5)\\ \dot{\mathbf{r}}_{n+1} &= \dot{p}(E)\mathbf{r}_n + \dot{q}(E)\dot{\mathbf{r}}_n\,; &(6) \end{aligned}$$

we account for gravitational perturbations by planets, expressed in the heliocentric frame:

$$\ddot{\mathbf{r}}_j = \sum_i \left[-\frac{Gm_i}{r_i^3}\mathbf{r}_i - \frac{Gm_i}{r_{ji}^3}\mathbf{r}_{ji}\right]\,, \tag{7}$$

possibly, the planetary migration, in an analytical way (Malhotra 1995), and also eccentricity damping (Morbidelli et al. 2010):

$$\dot{\mathbf{r}}_{n+1} = \dot{\mathbf{r}}_n \left[1 + \frac{\Delta v}{\dot{r}}\frac{\Delta t}{\tau_{\mathrm{mig}}}\exp\left(-\frac{t-t_0}{\tau_{\mathrm{mig}}}\right)\right]\,, \tag{8}$$

Swift integrator (cont.) as of Brož et al. (2011)

the Yarkovsky thermal effect (Vokrouhlický 1998, Vokrouhlický and Farinella 1999):

$$f_X(\zeta) + \mathrm{i} f_Y(\zeta) = -\frac{8}{3\sqrt{3\pi}} \Phi\, t'_{1-1}(R'; \zeta)\,, \tag{9}$$

$$f_Z(\zeta) = -\frac{4}{3}\sqrt{\frac{2}{3\pi}} \Phi\, t'_{10}(R'; \zeta)\,, \tag{10}$$

$$\Phi \equiv \frac{(1-A)\mathcal{E}_\star \pi R^2}{m_j c_{\mathrm{vac}}}\,, \tag{11}$$

the YORP effect (Čapek and Vokrouhlický 2004):

$$\dot{\omega} = c f_k(\gamma)\,, \tag{12}$$

$$\dot{\gamma} = \frac{c g_k(\gamma)}{\omega}\,, \tag{13}$$

$$c \equiv c_{\mathrm{YORP}} \left(\frac{a}{a_0}\right)^{-2} \left(\frac{R}{R_0}\right)^{-2} \left(\frac{\rho}{\rho_0}\right)^{-1}, \tag{14}$$

mass shedding beyond the critical angular frequency (Pravec and Harris 2000):

$$\omega_{\mathrm{crit}} = \sqrt{\frac{4}{3}\pi G \rho}\,, \tag{15}$$

and random collisional reorientations with the time scale (Farinella et al. 1998):

$$\tau_{\mathrm{reor}} = B \left(\frac{\omega}{\omega_0}\right)^{\beta_1} \left(\frac{R}{R_0}\right)^{\beta_2}. \tag{16}$$

Eos parent-body size

- a simplified scaling (Durda et al. 2007), cf. Tanga et al. (1999)
- uncertainties: multiple fits have low χ^2, interlopers
- systematics: number & distribution of SPH particles