Identification of a primordial asteroid family constrains the original planetesimal population

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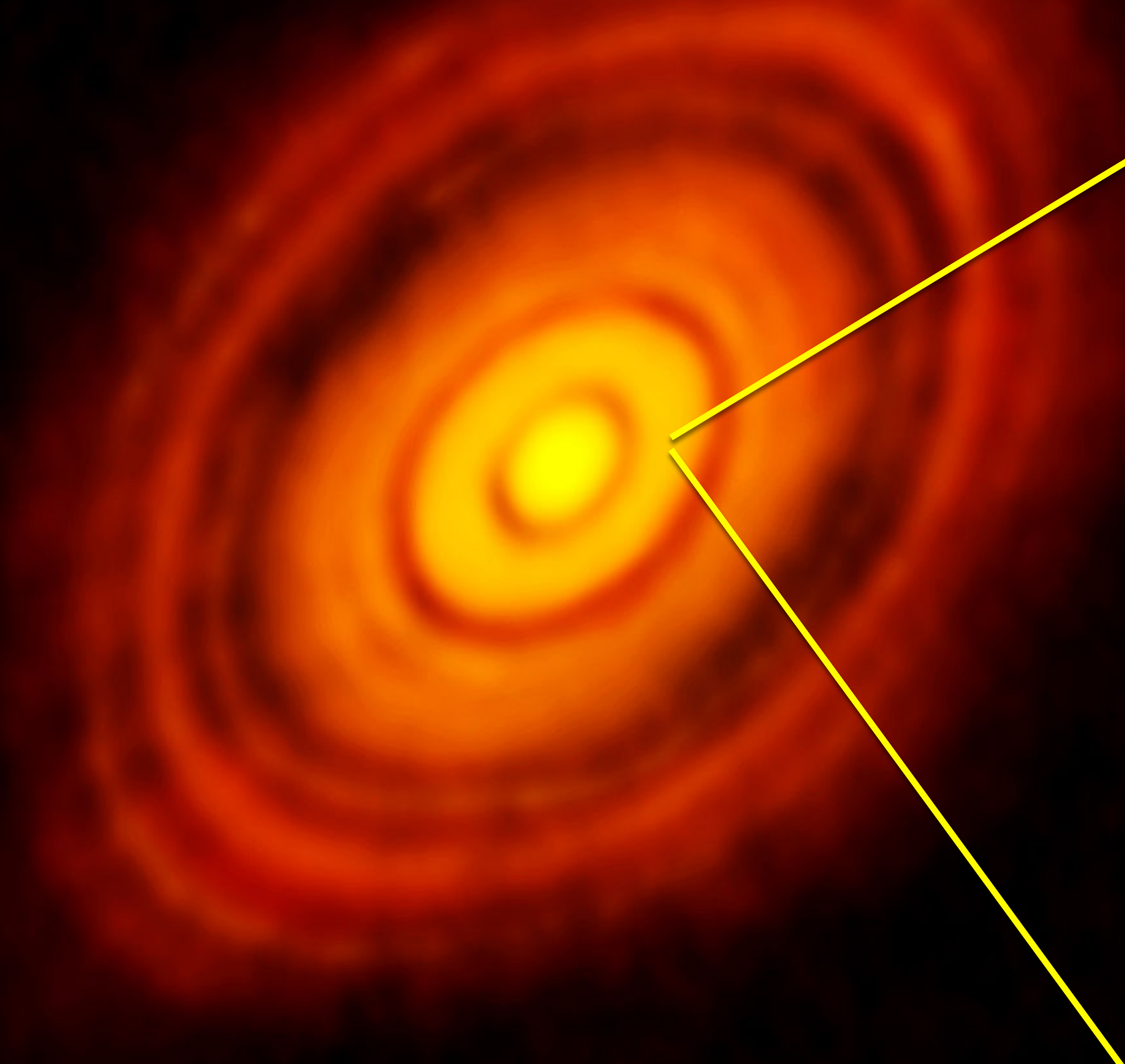
A seminar of the Institut d'Astrophysique Spatiale - Université Paris-Sud

Delbo' et al., Science 357, 1026–1029 (2017)

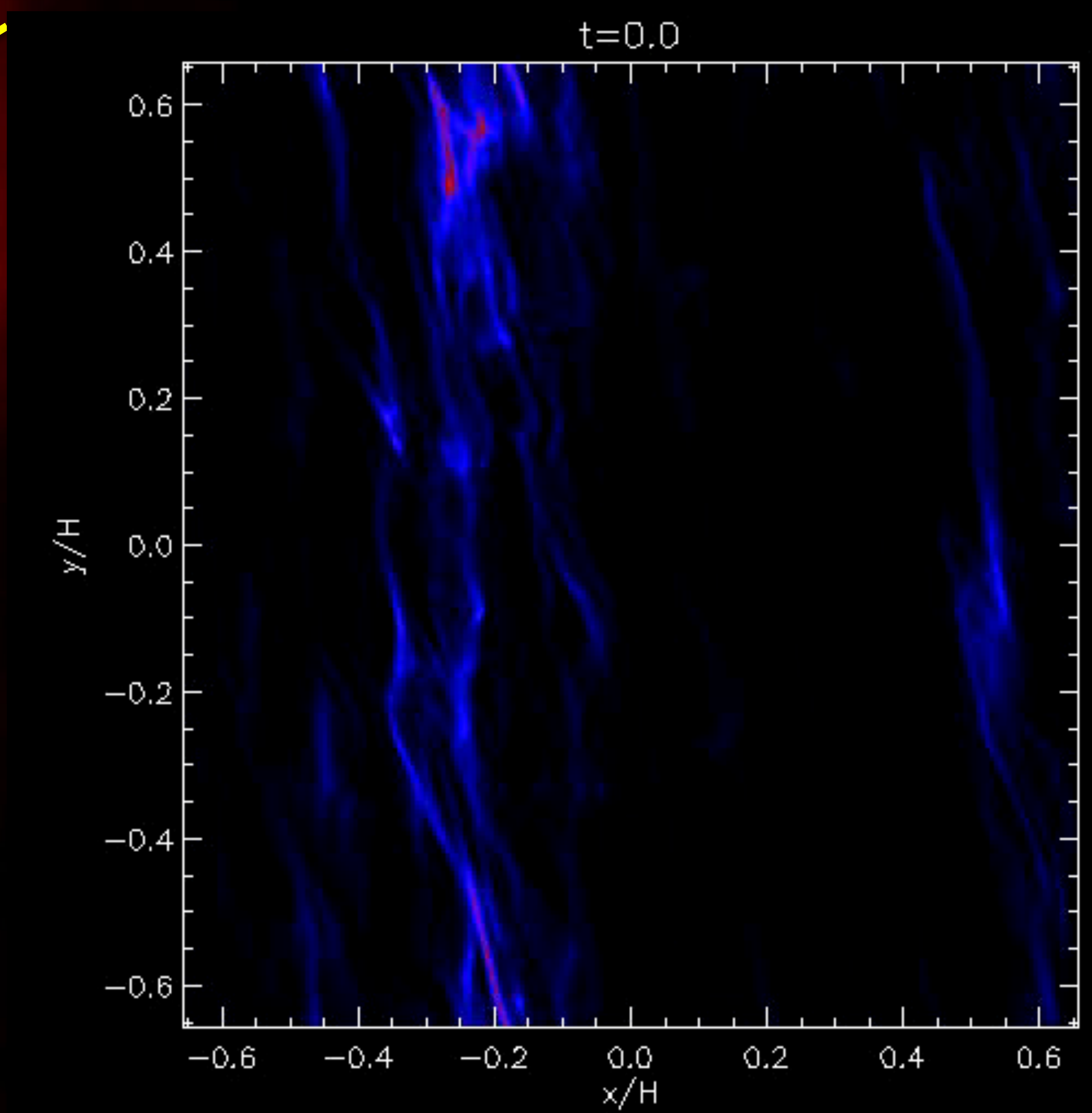
Formation of gravitational aggregates (planetesimals) within protoplanetary disks

Observations



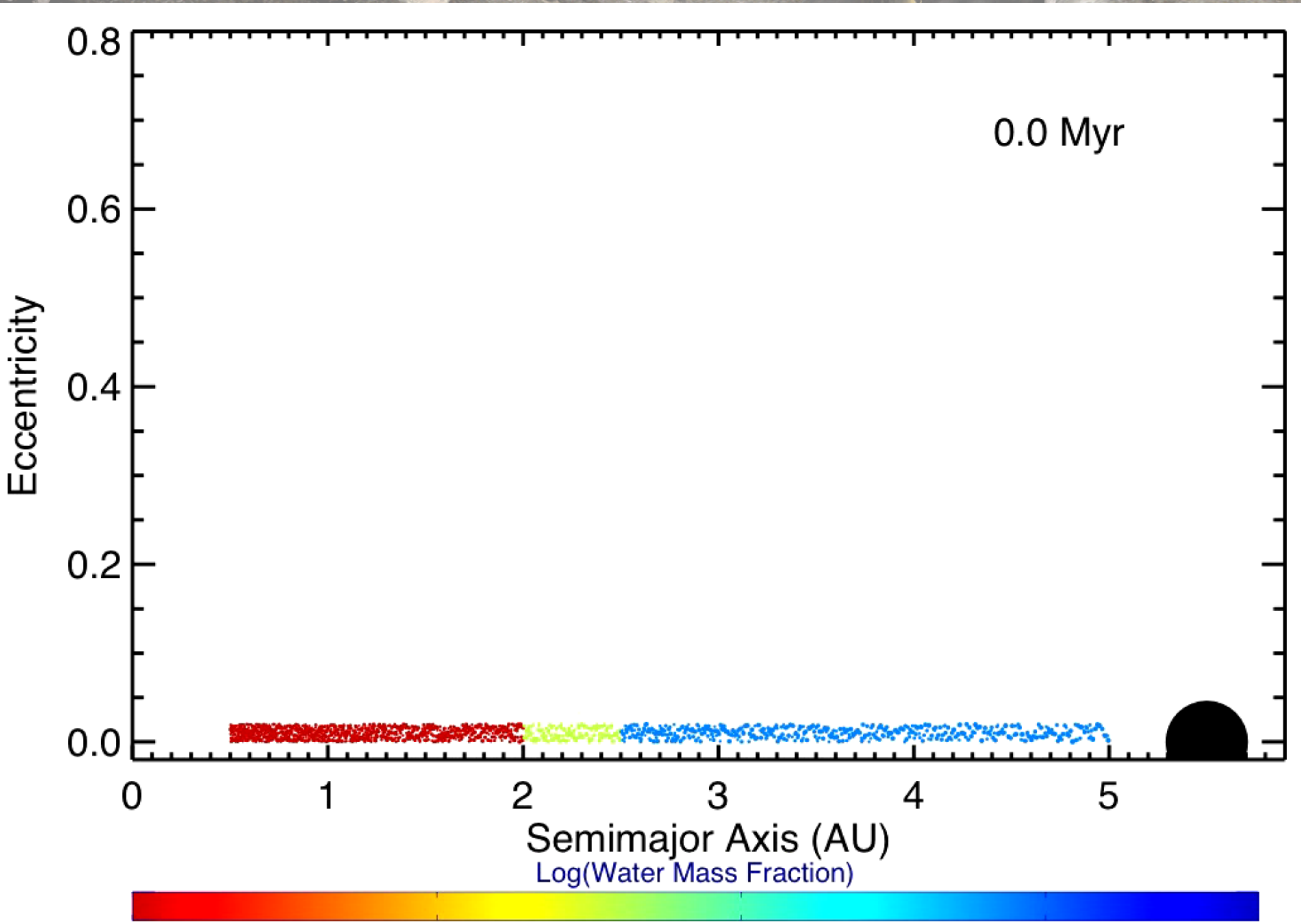
The protoplanetary disk around HL Tauri seen by ALMA
APOD 2014-Nov-10
Paper: arxiv.org/pdf/1503.02649.pdf & Akiyama +2015

Simulations



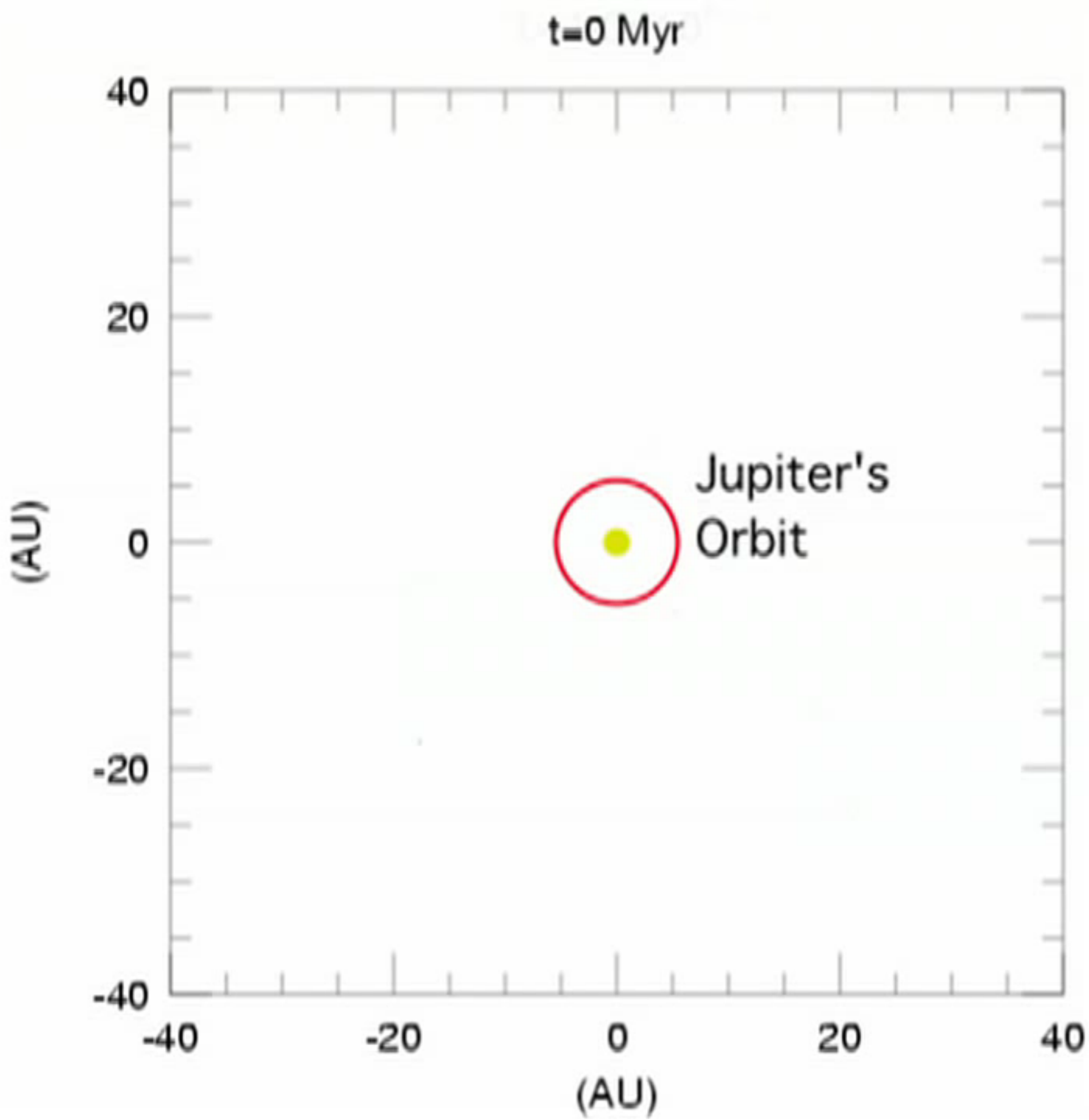
Johansen, Oishi, Mac Low, Klahr, Henning, & Youdin (2007)

Planetesimals: formation of and water delivery to the terrestrial planets



Raymond, Quinn & Lunine (2006).

Planetesimals as the cause of the giant planet orbital instability (Nice model)



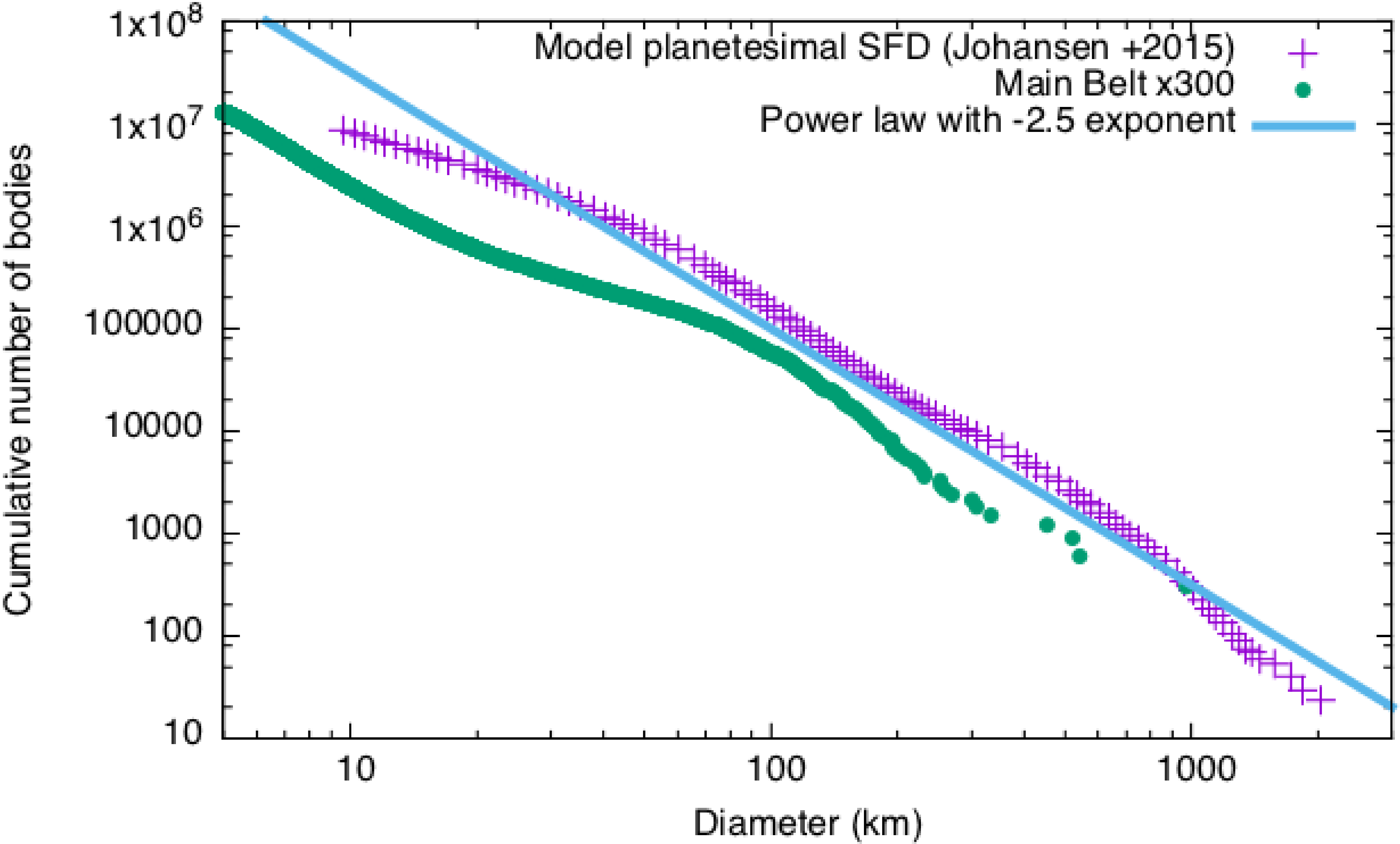
Credits: Hal Levison (youtube)

Planetesimals perturbed the orbits of giant planets (and viceversa)

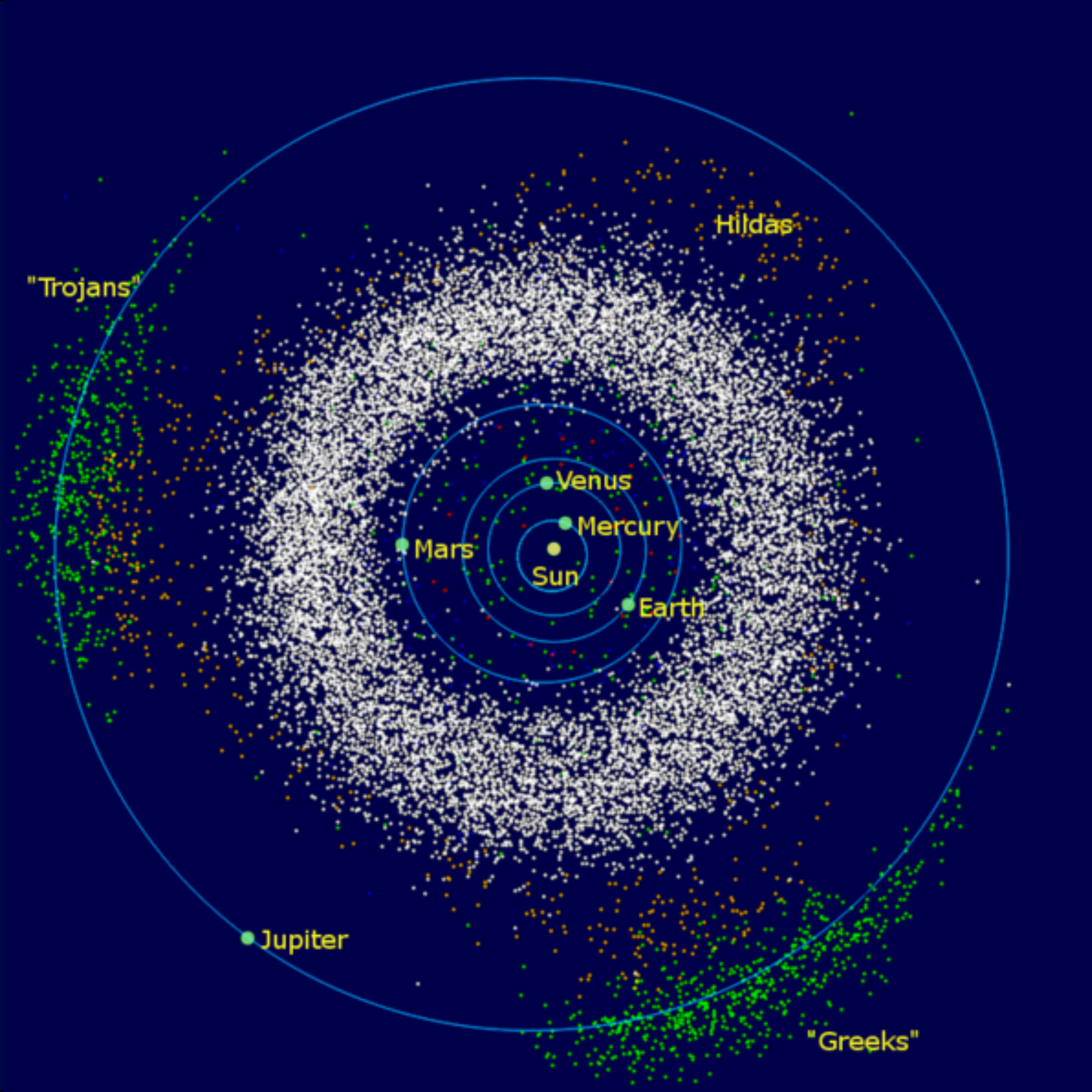
The giant planet instability resulted in excitiaiton of the eccentricity and inclination of the orbits of planetesimals in the Main Belt.

Izidoro+ 2016 ApJ
Nesvorny+ 2013 ApJ
Morbidelli+ 2010 AJ
Gomes+ 2005 Nature
Morbidelli+ 2005 Nature
Tsiganis+ 2005 Nature

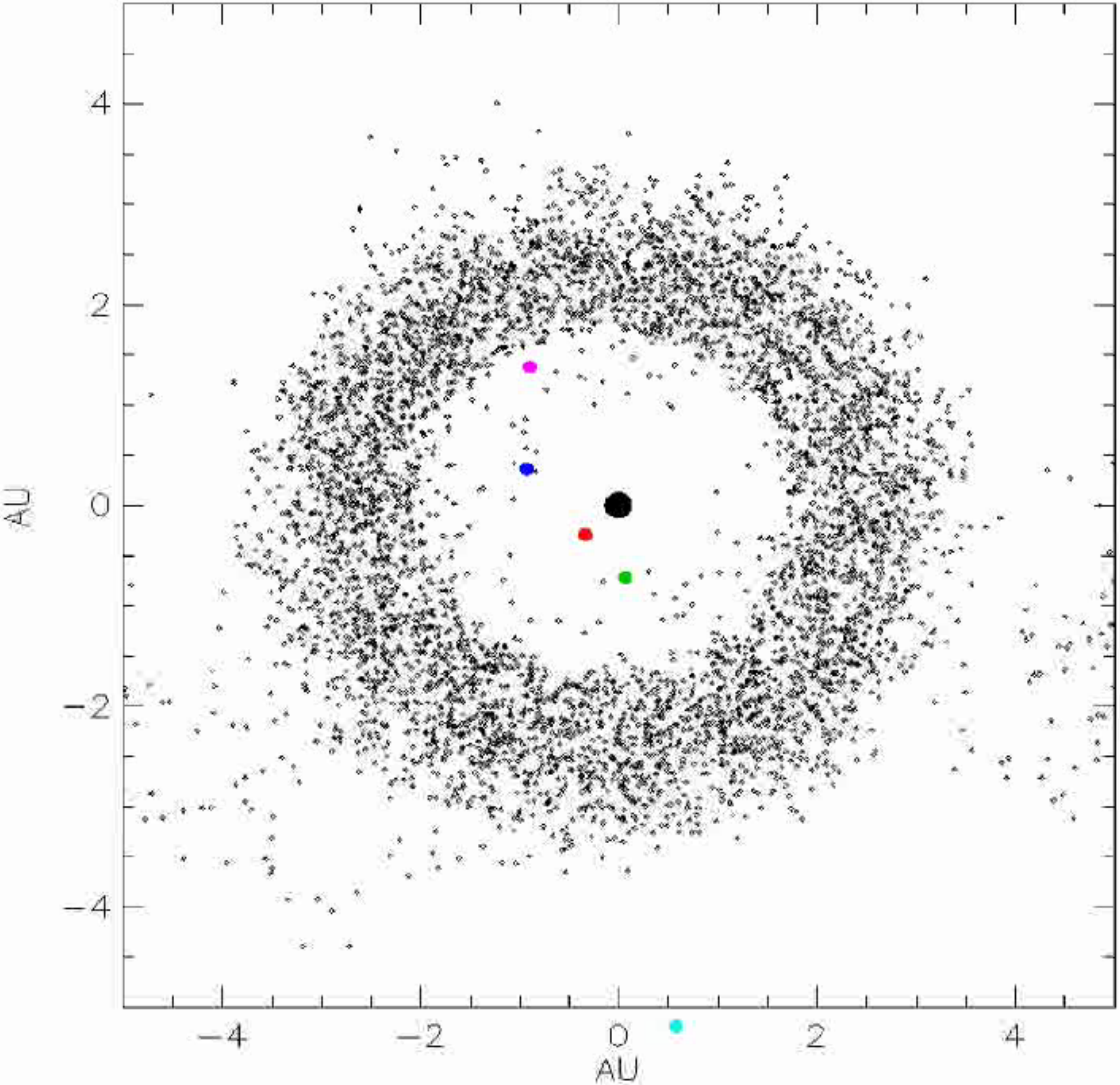
Planetesimal Initial Size Frequency Distribution (SFD)



[Johansen et al., 2015b, Johansen et al., 2015a, Cuzzi et al., 2008, Klahr and Schreiber, 2016]

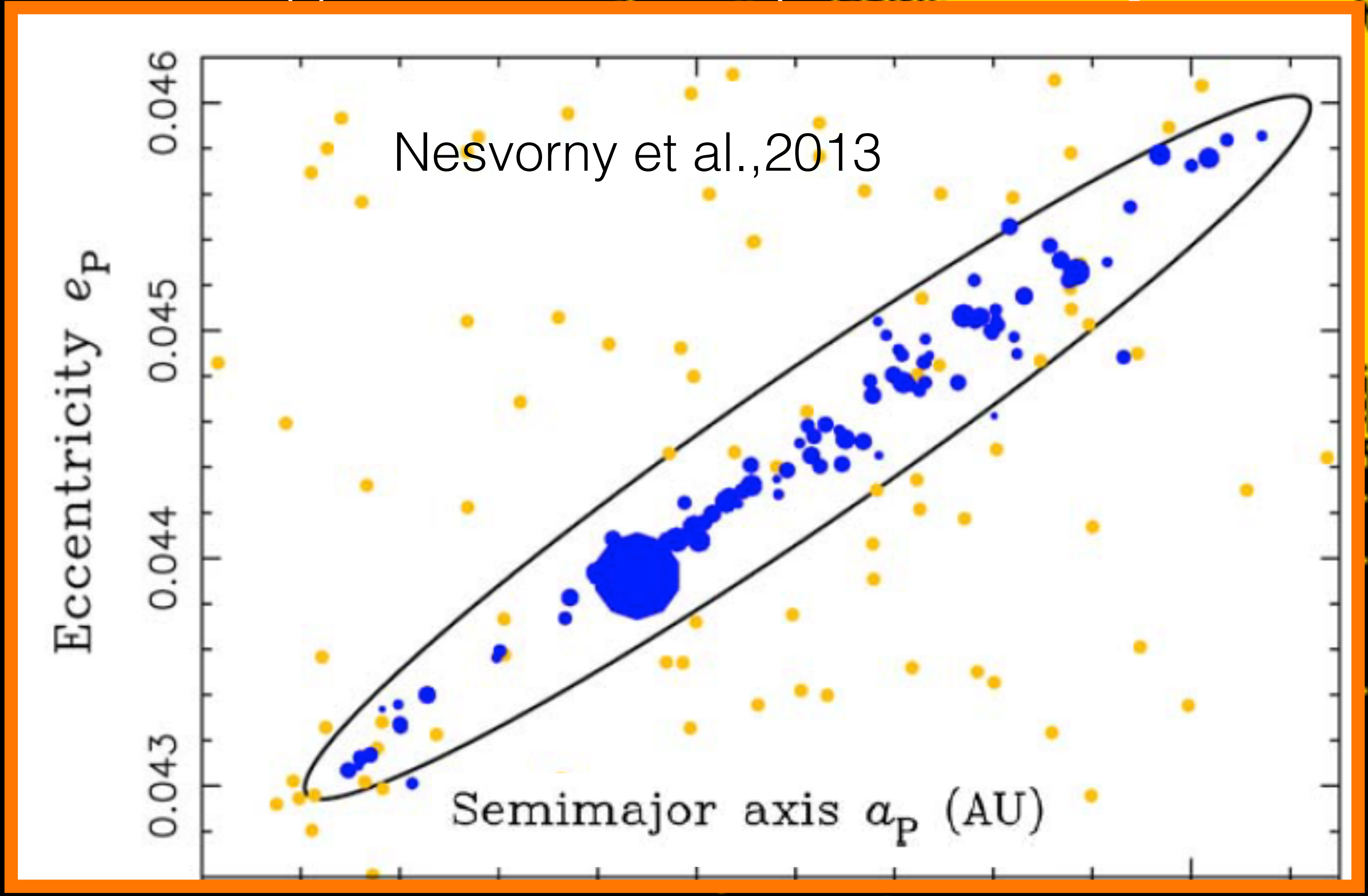


Hildas
"Trojans"
Venus
Mercury
Mars
Sun
Earth
Jupiter
"Greeks"

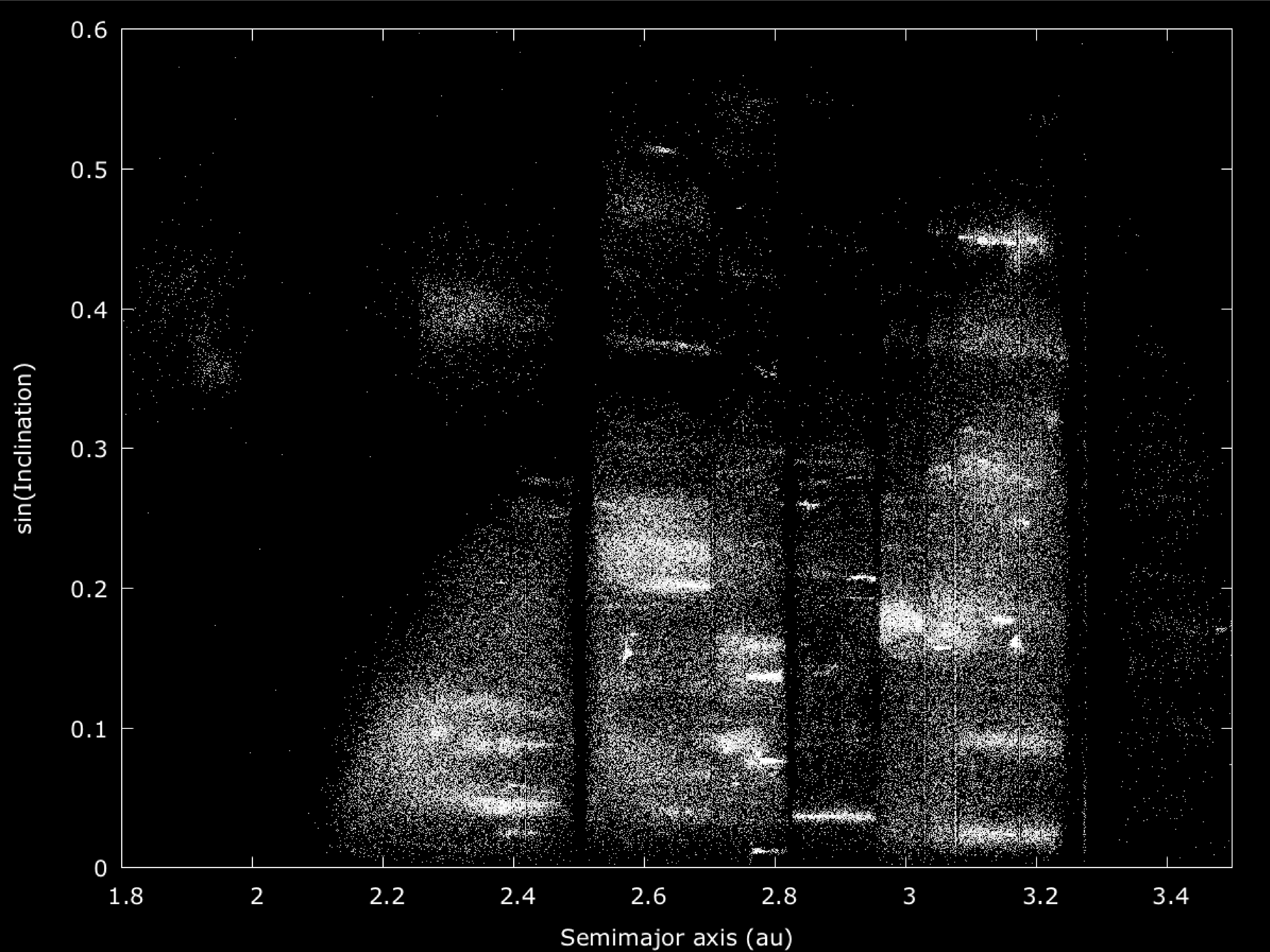

4
2
0
−2
−4
AU
−4
−2
0
2
4
AU

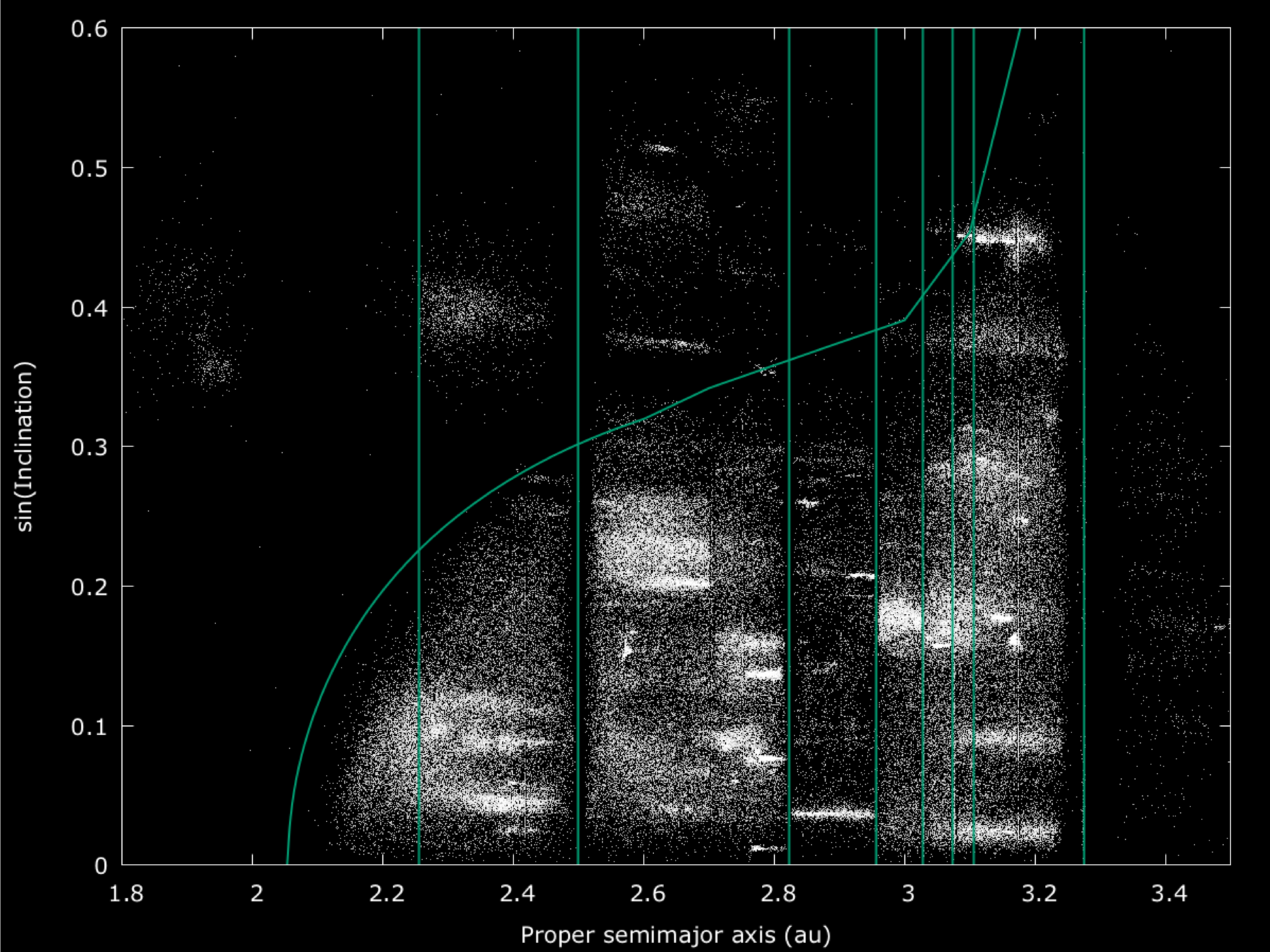
Collisional families

- Created during catastrophic and cratering disruptions of asteroids
- Fragments disperse in space, but have closely related semi-major axes (*a*), eccentricities (*e*) and inclinations (*i*) to that of the parent body

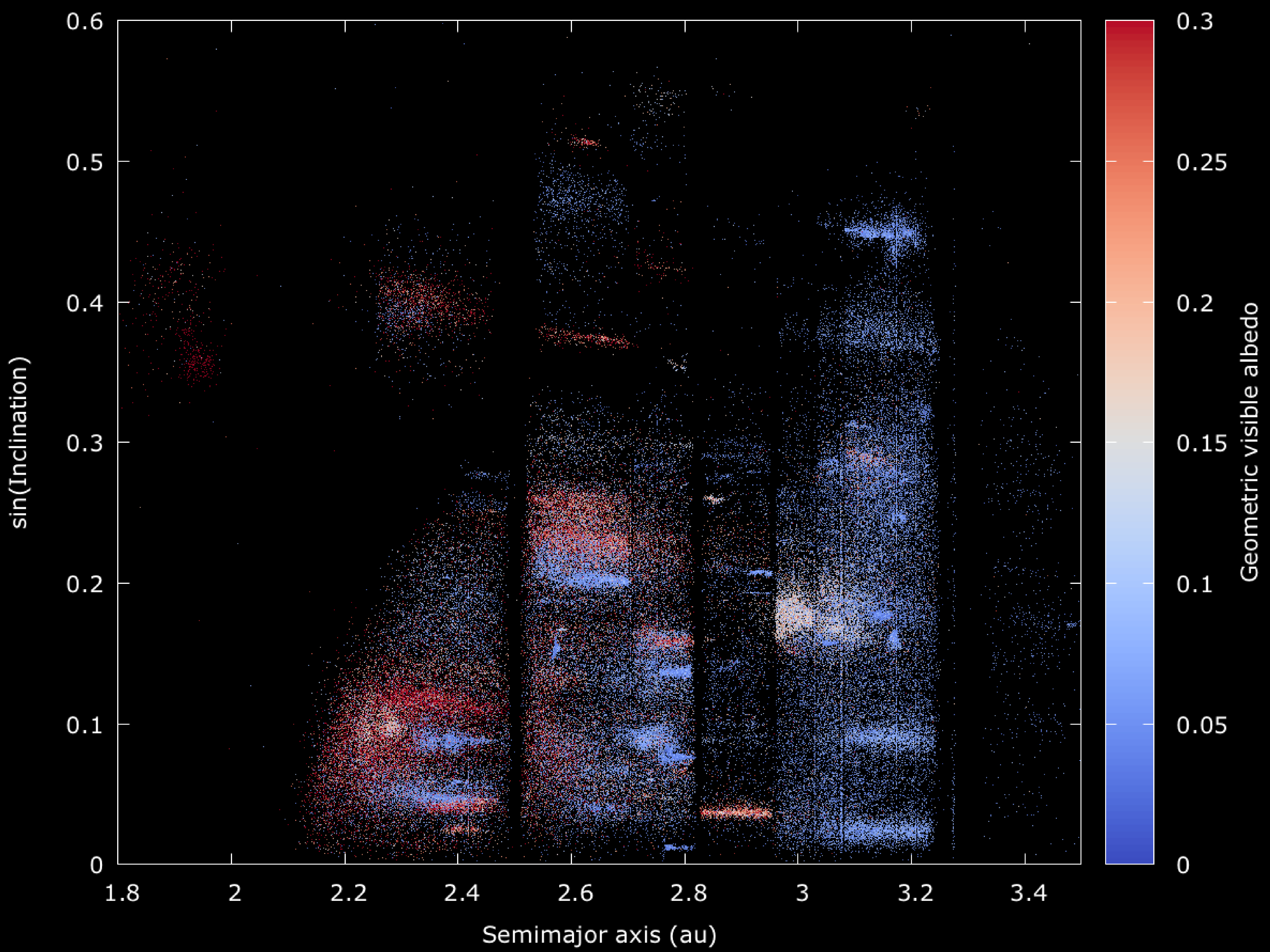


Michel et al., 2013

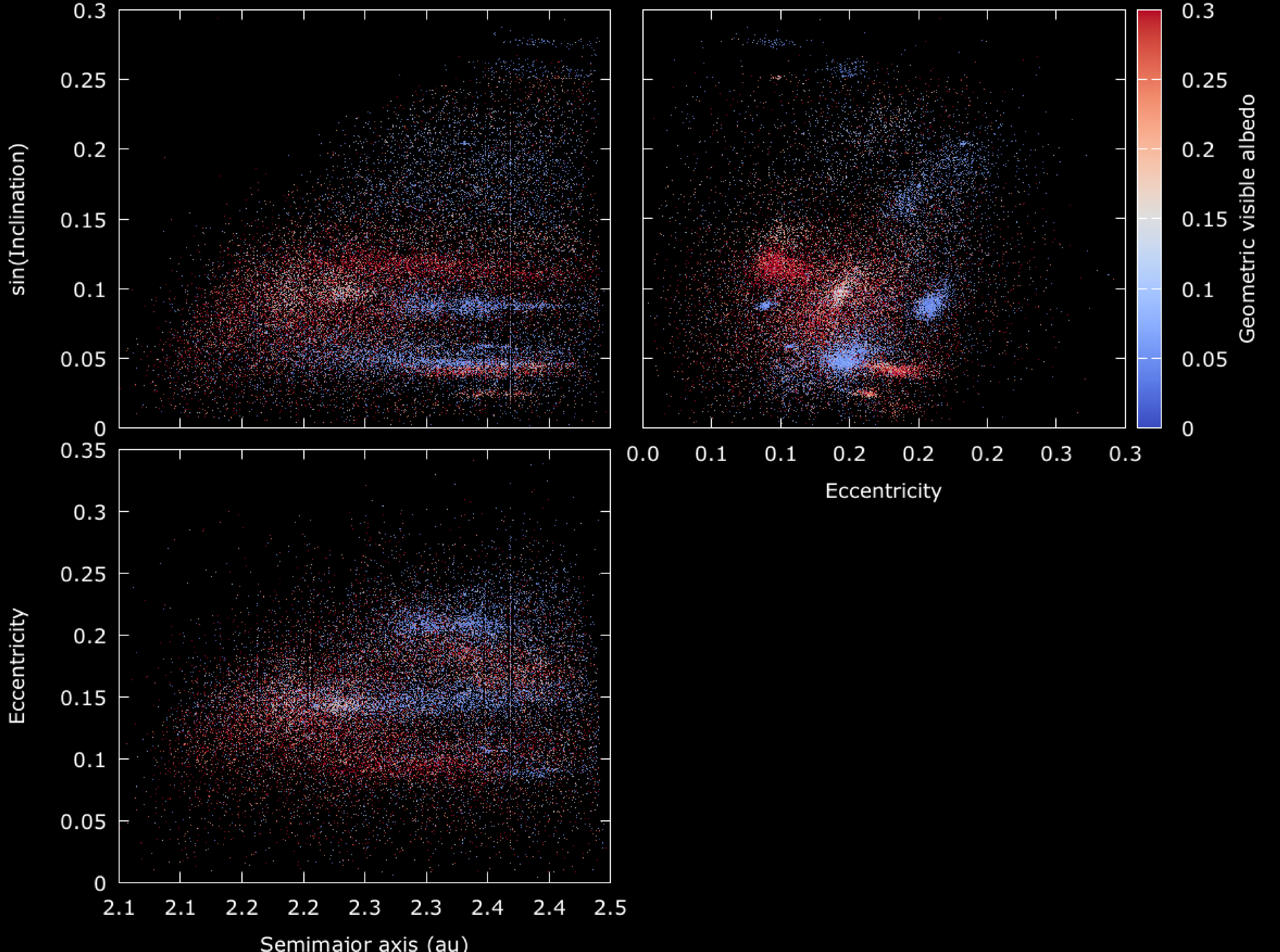

0.6
0.5
0.4
0.3
0.2
0.1
0
sin(Inclination)
1.8
2
2.2
2.4
2.6
2.8
3
3.2
3.4
Semimajor axis (au)



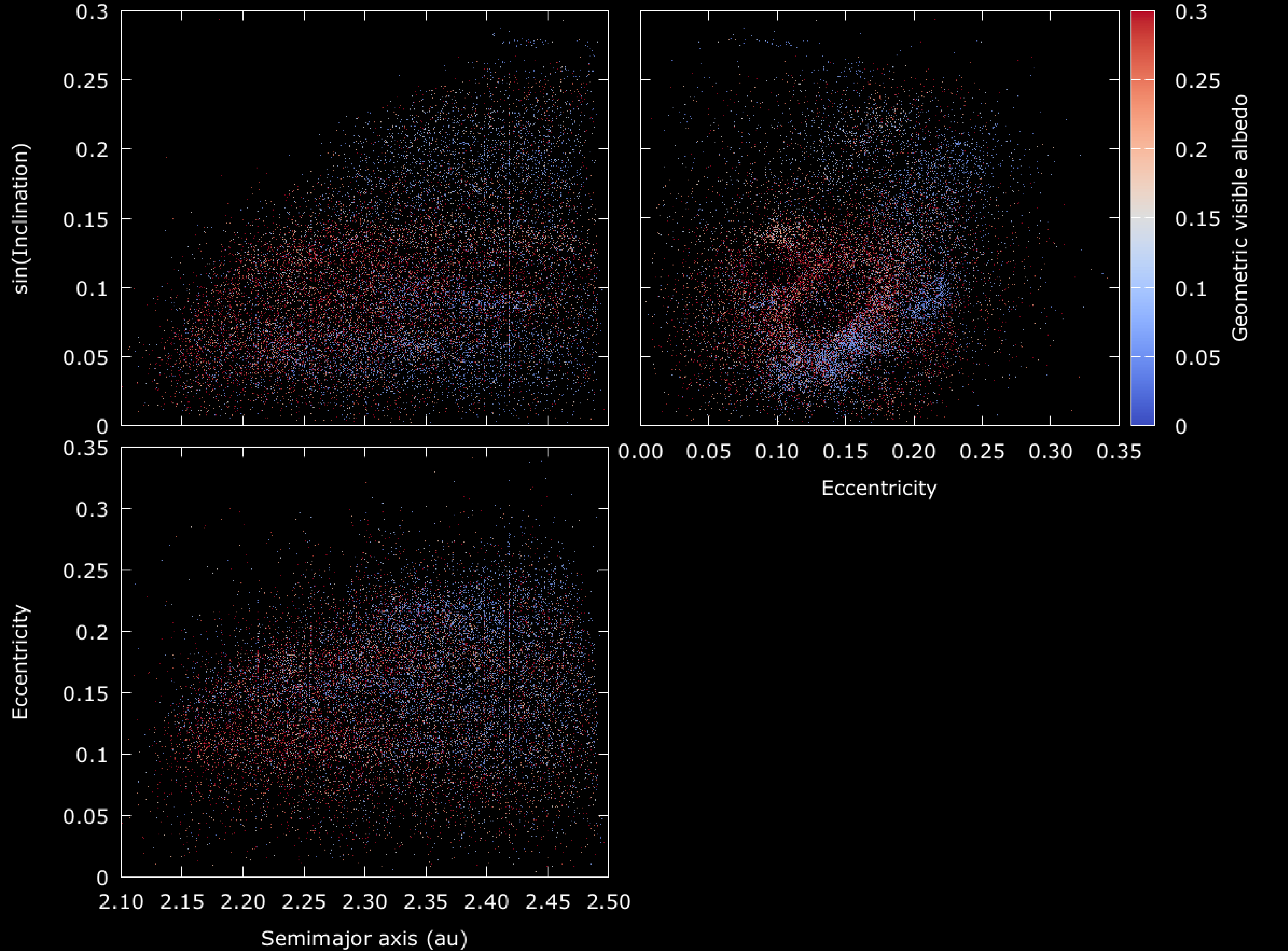
0.6
0.5
0.4
0.3
0.2
0.1
0
sin(Inclination)
1.8
2
2.2
2.4
2.6
2.8
3
3.2
3.4
Proper semimajor axis (au)



0.6
0.5
0.4
0.3
0.2
0.1
0
sin(Inclination)
1.8
2
2.2
2.4
2.6
2.8
3
3.2
3.4
Semimajor axis (au)
0.3
0.25
0.2
0.15
0.1
0.05
0
Geometric visible albedo



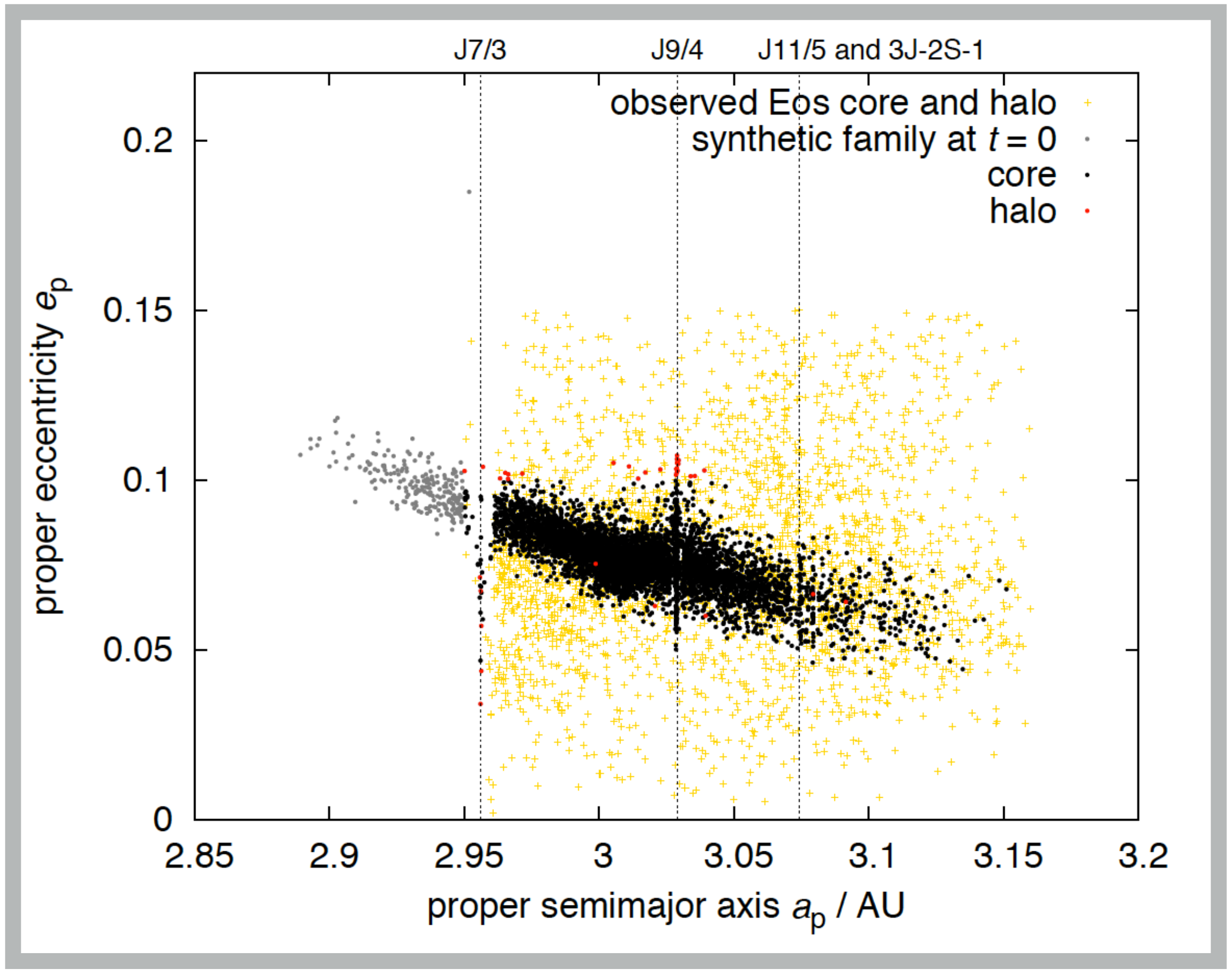
sin(Inclination)
0.3
0.25
0.2
0.15
0.1
0.05
0
0.0 0.1 0.1 0.2 0.2 0.2 0.3 0.3
Eccentricity
Geometric visible albedo
0.35
Eccentricity
2.1 2.1 2.2 2.2 2.3 2.3 2.4 2.4 2.5
Semimajor axis (au)

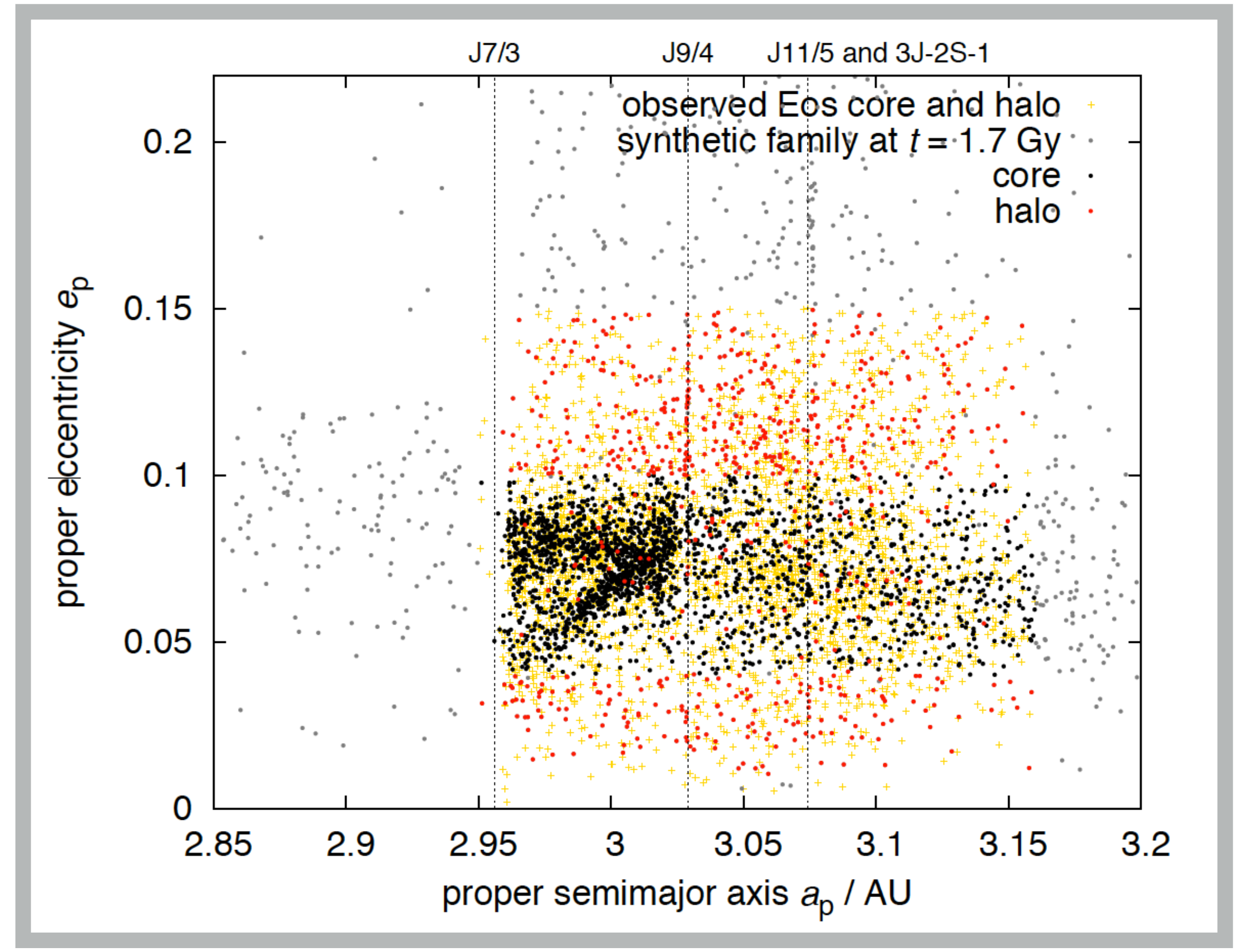


sin(Inclination)
Eccentricity
Semimajor axis (au)
Geometric visible albedo
0.3
0.25
0.2
0.15
0.1
0.05
0
0.35
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
2.10
2.15
2.20
2.25
2.30
2.35
2.40
2.45
2.50

Diffusion of orbital elements

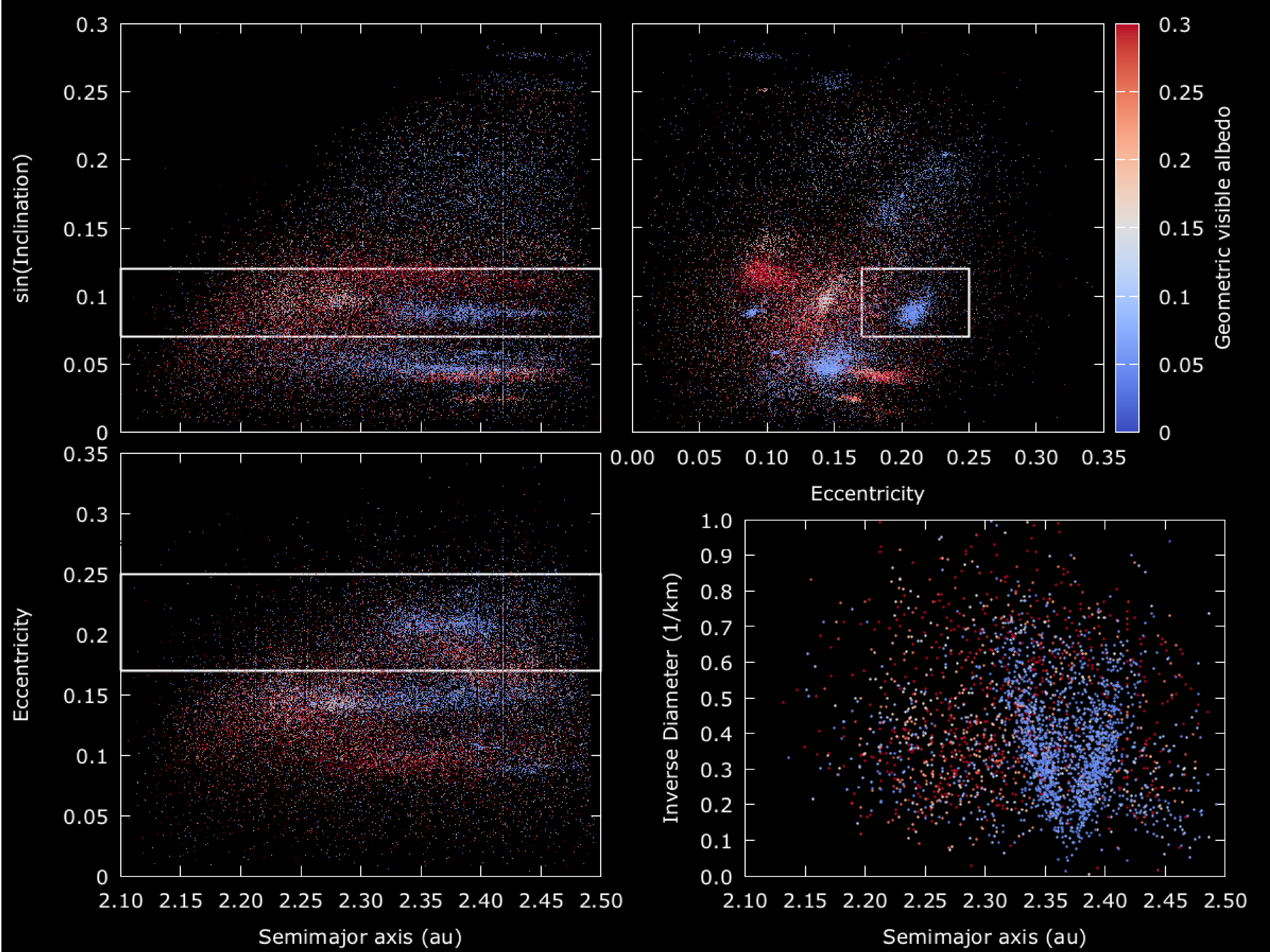
- Family fragments diffuse in (e,i) due to secular and mean motion resonances (MMR).



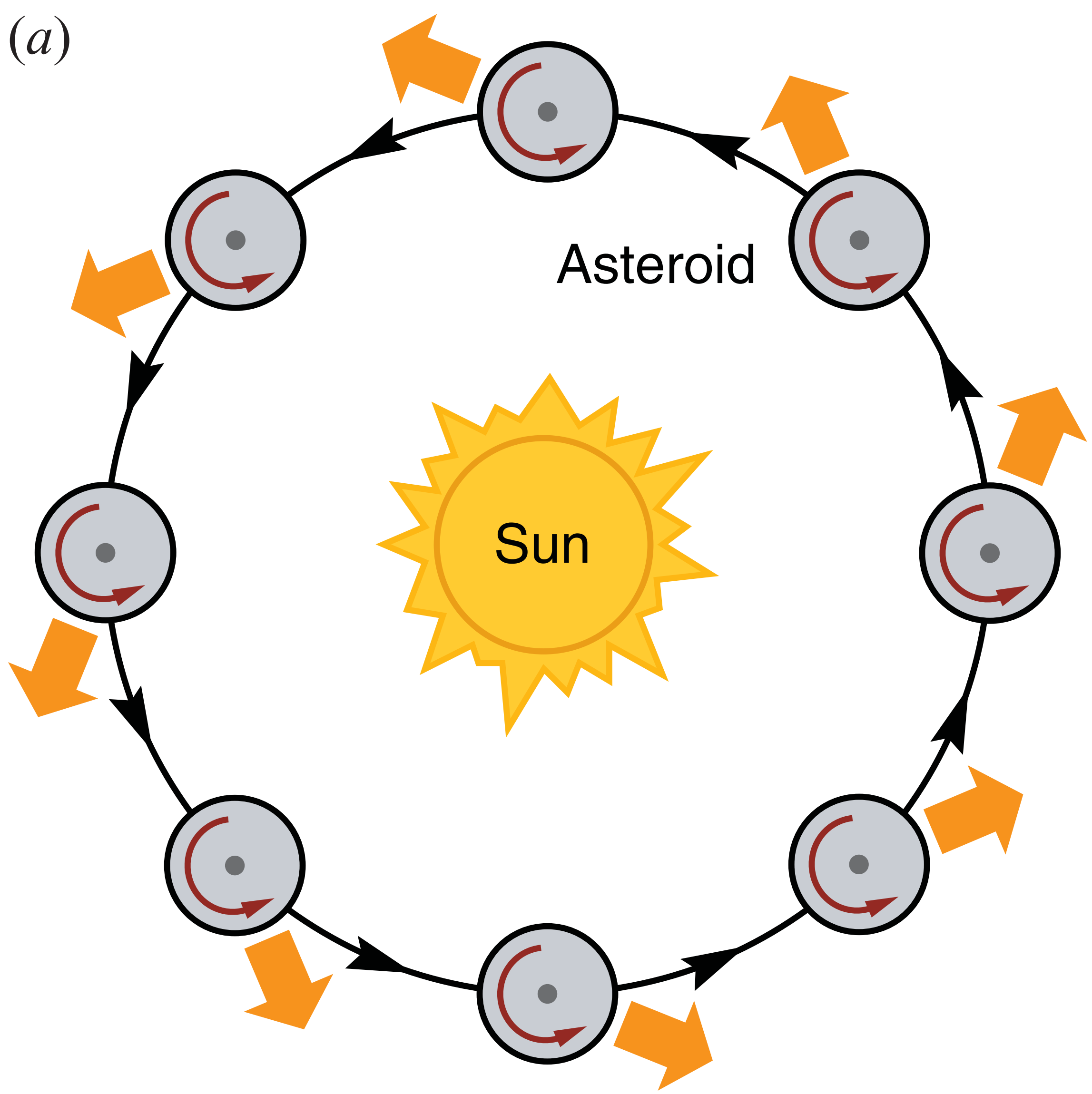


1.7 Gyr

Brož and Morbidelli, 2013

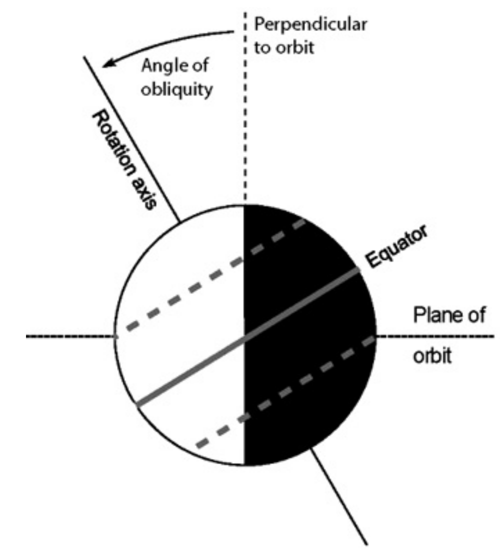

sin(Inclination)
Eccentricity
Geometric visible albedo
Semimajor axis (au)
Inverse Diameter (1/km)
Semimajor axis (au)
0 0.05 0.1 0.15 0.2 0.25 0.3
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
2.10 2.15 2.20 2.25 2.30 2.35 2.40 2.45 2.50
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

The V-shape is due to the Yarkovsky-Effect



from [Bottke et al., 2006]

$\frac{da}{dt} = \left(\frac{da}{dt}\right)_{1\ km} \frac{1}{D} \cos\gamma,$
[Vokrouhlický et al., 2006], where γ is the obliquity and $(da/dt)_{1\ km}$ is the rate of change of the orbital semi-major axis with time for an



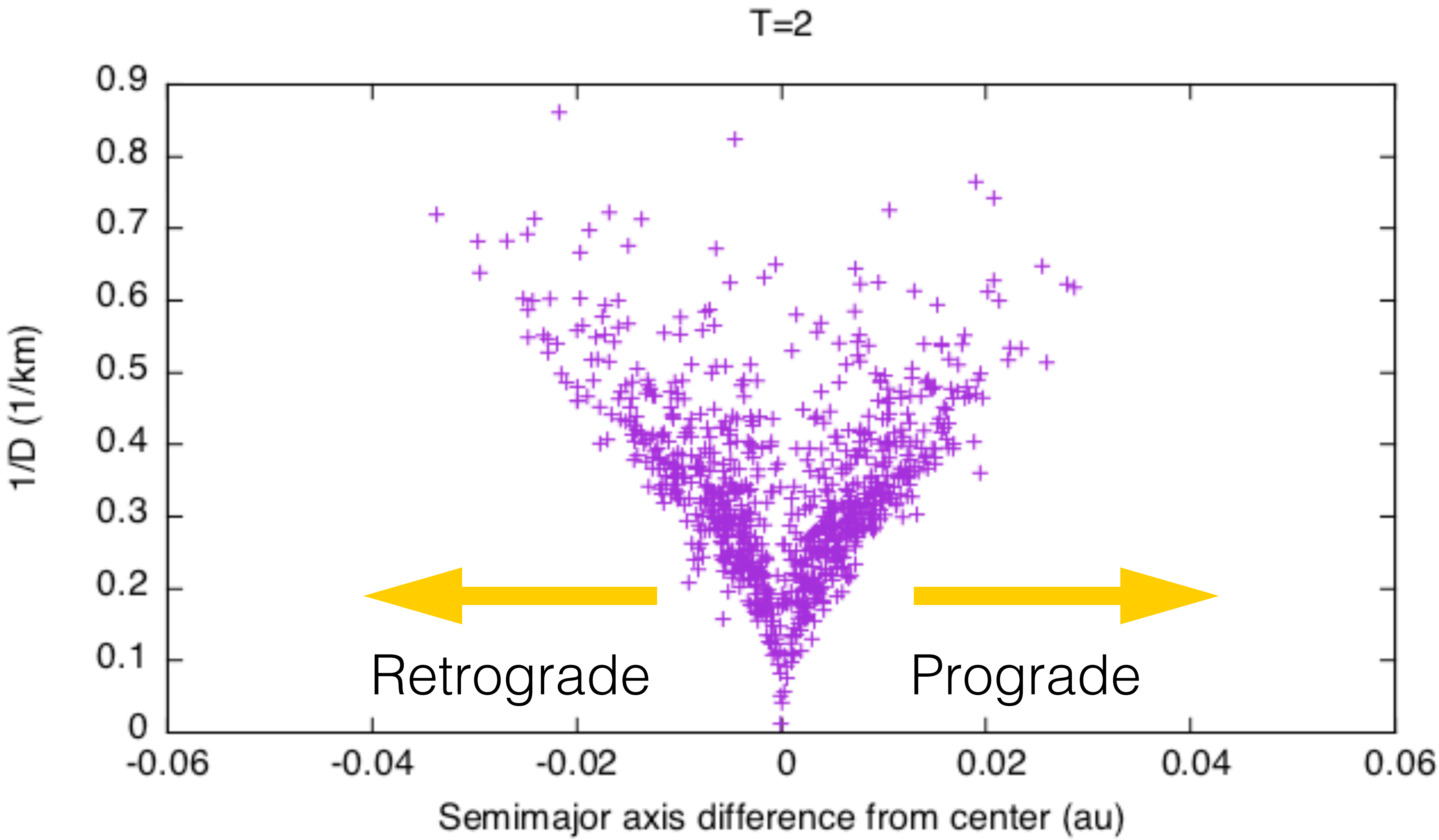
asteroid of 1 km

The age of the family, ΔT, is derived from the inverse slope of the V-shape [Spoto et al., 2015] :

$1/K = (da/dt)_{1\ km} \cos\gamma\ \Delta T$

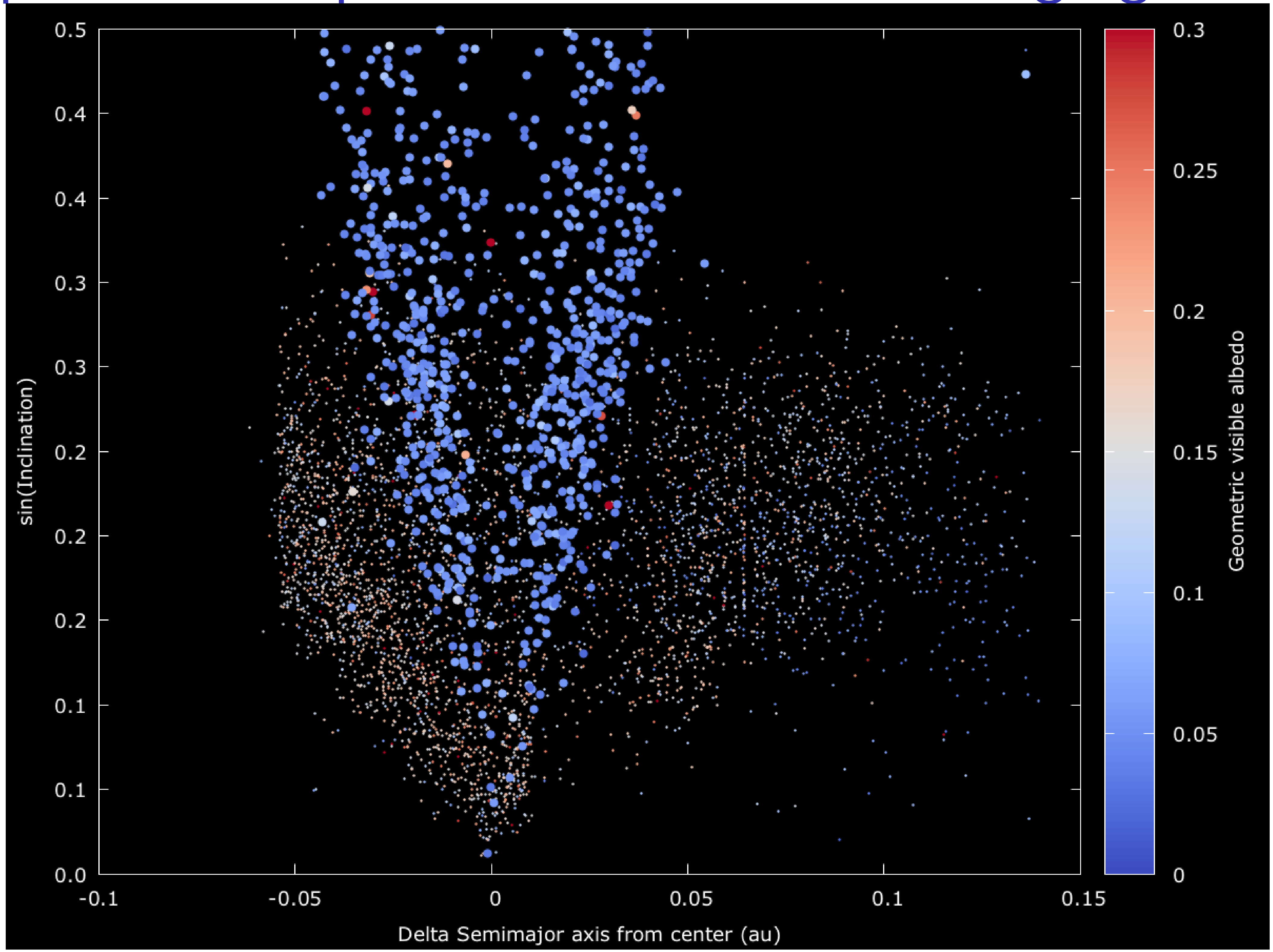
for more fun with Yarkovsky effct, see: https://www.youtube.com/watch?v=DQtj0RhimZY&t=33s

Yarkovsky V-shape



da/dt prop.to 1/D

Slopes of V-shape decrease with increasing age

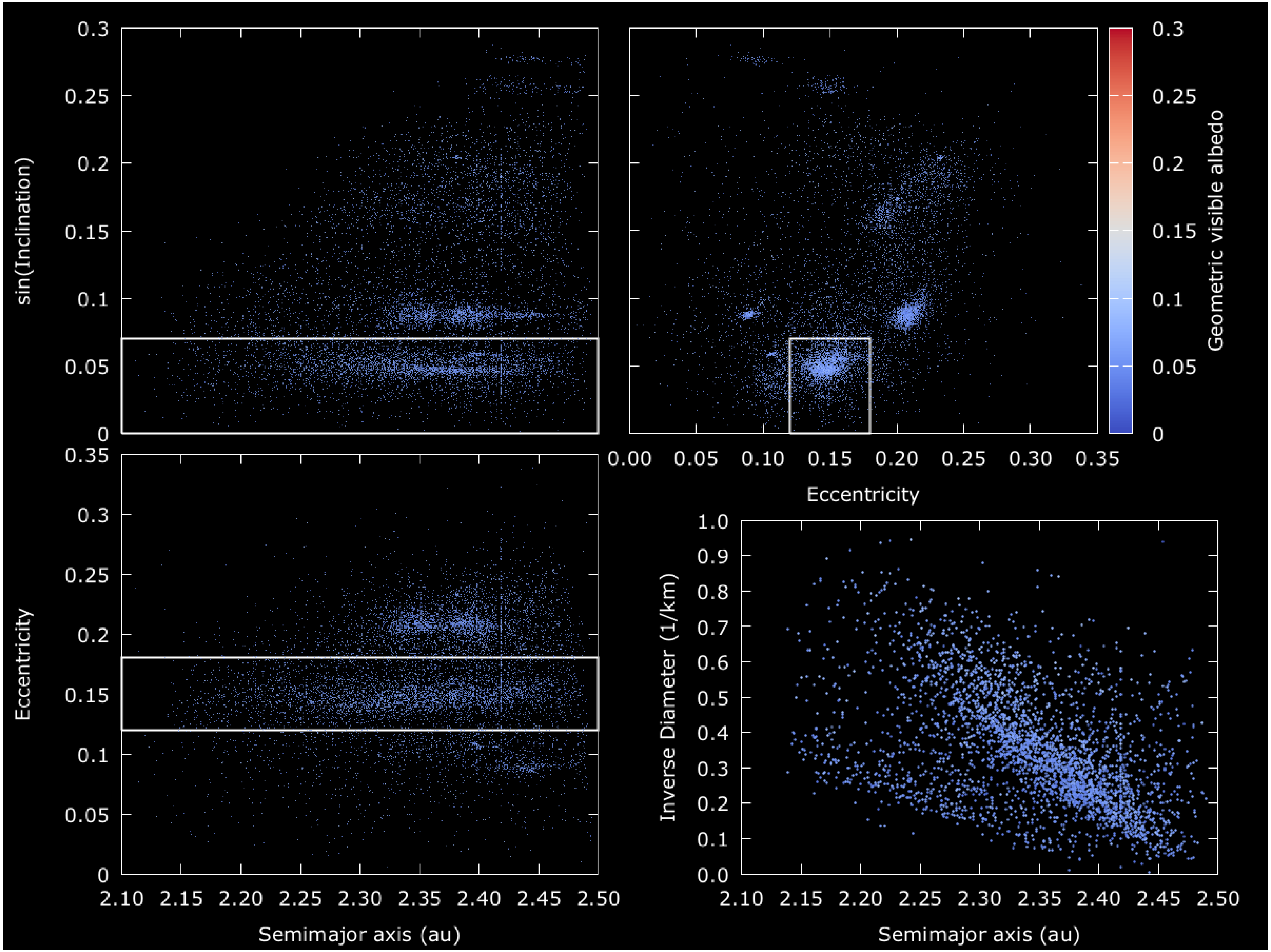


Erigone's age = 210 – 230 My [Spoto et al., 2015];

= 300 +/- 200 My [Brož et al., 2013]

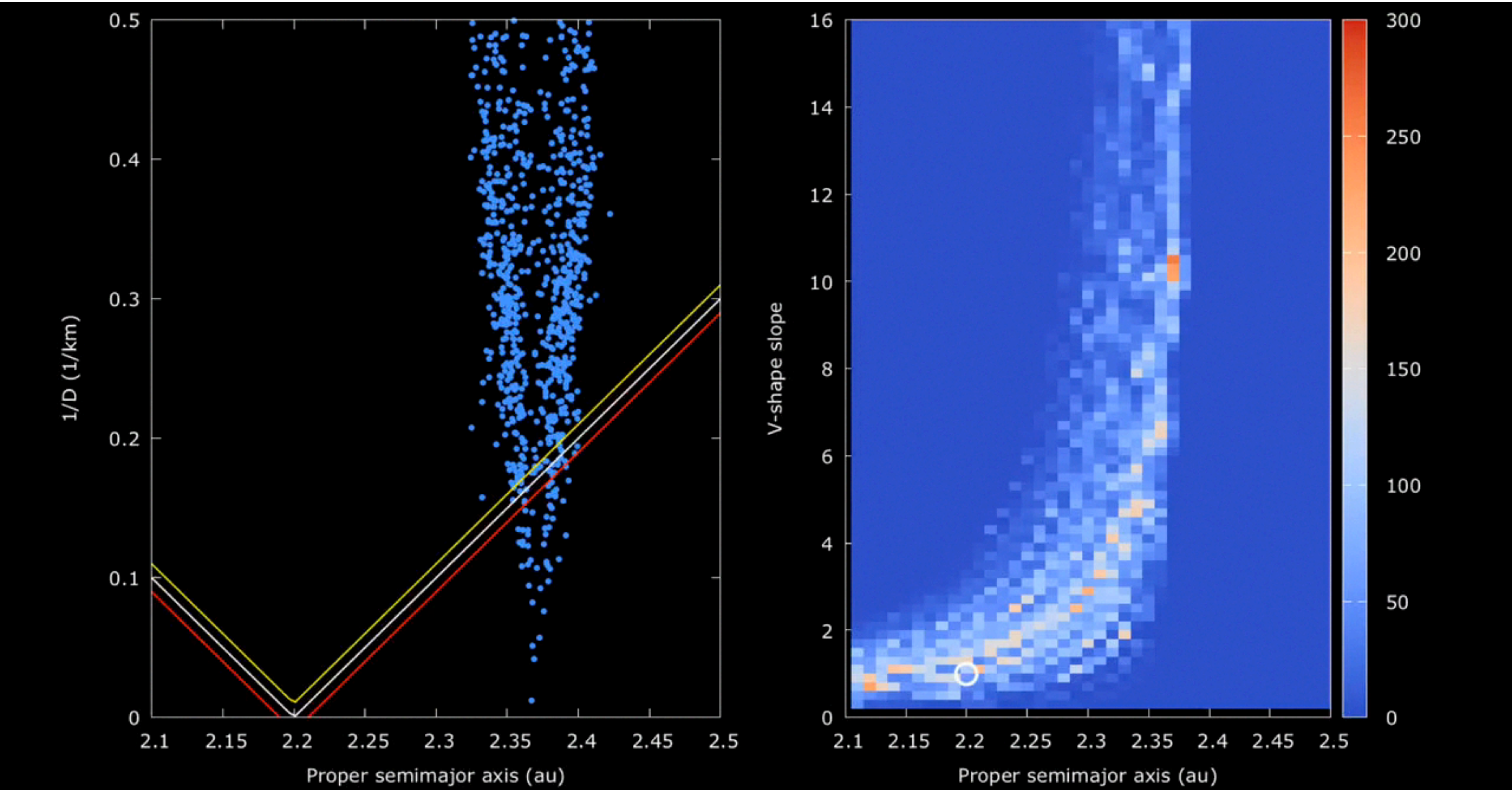
Eos age 1300 +/- 200 My [Brož et al., 2013]

Half V-shapes



New Polana age 1500 My and Eulalia family age 1000 My
[Walsh et al., 2013, Bottke et al., 2015]

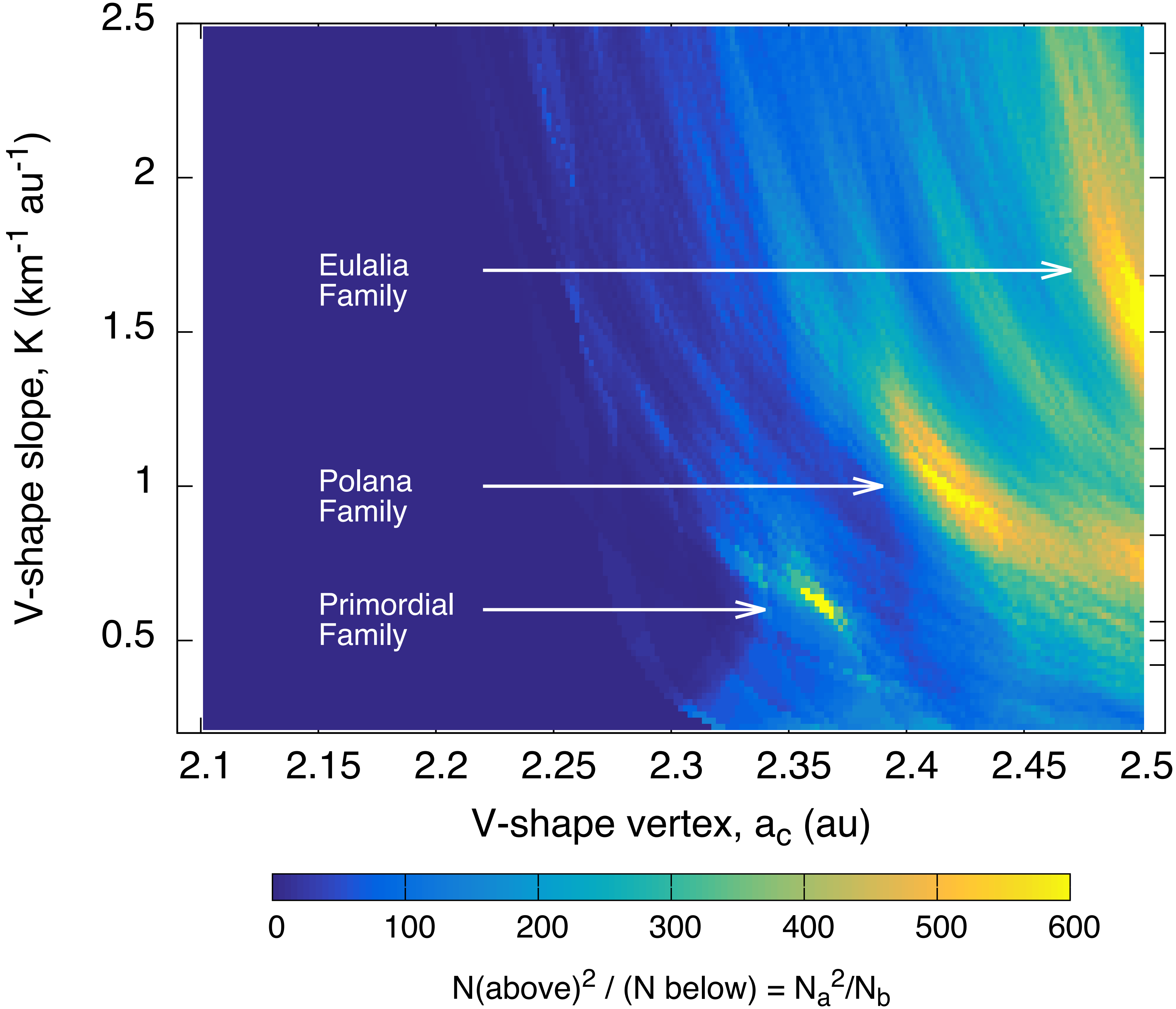
V-shape searching method



Bolin+ 2017

Identification of a previously unknown family

- We searched for V-shapes amongst low-albdeo ($p_V<0.12$) in the inner Main Belt ($2.1<a<2.5$ au)
- The value of N^2_a/N_b is shown as a function of the slope (K) and semimajor axis of the vertex of a V shape (a_c).
- Maxima in this quantity correspond to probable families.

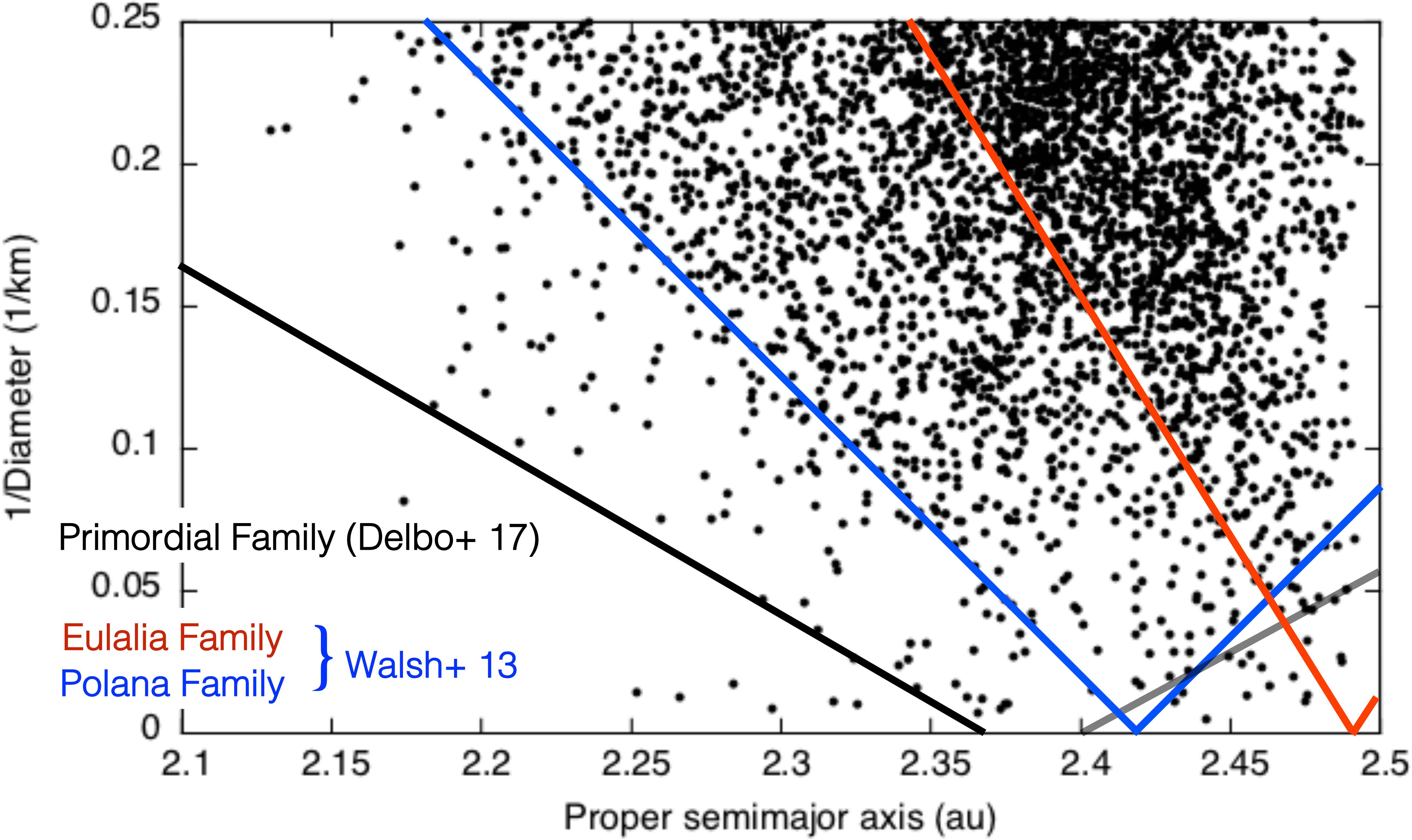


Delbo+ 2017;

see also Walsh+ 2013; Bolin+ 2017; DeMeo 2017.

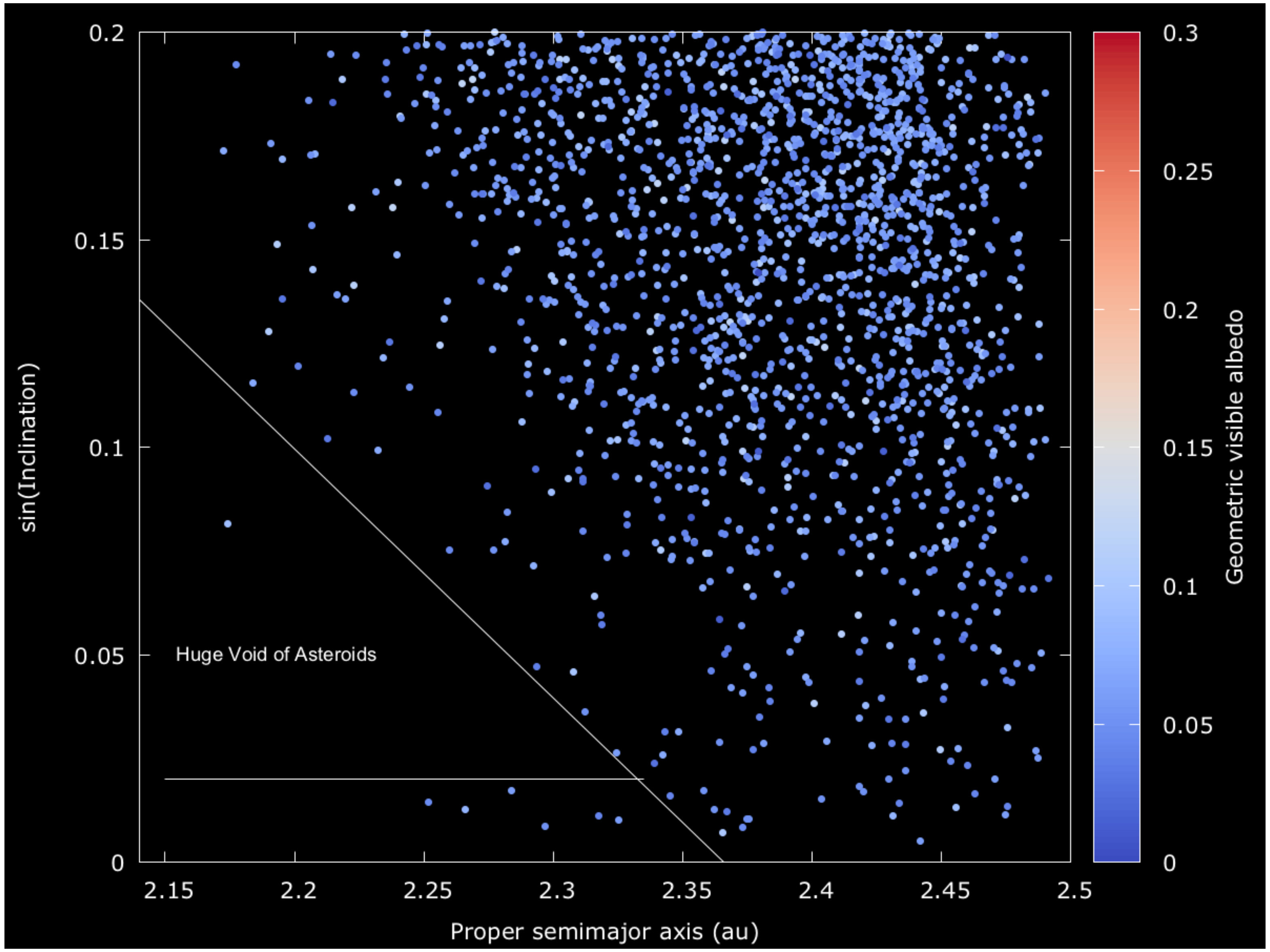
The entire inner Main Belt makes a V-shape

for the low-albedo asteroids



- The V-shape slope of the primordial family is ~ 0.6 $km^{-1}au^{-1}$ corresponding to an age $t = 4.0^{+1.7}_{-1.1}$ Gyr

The primordial family and the big asteroid void !



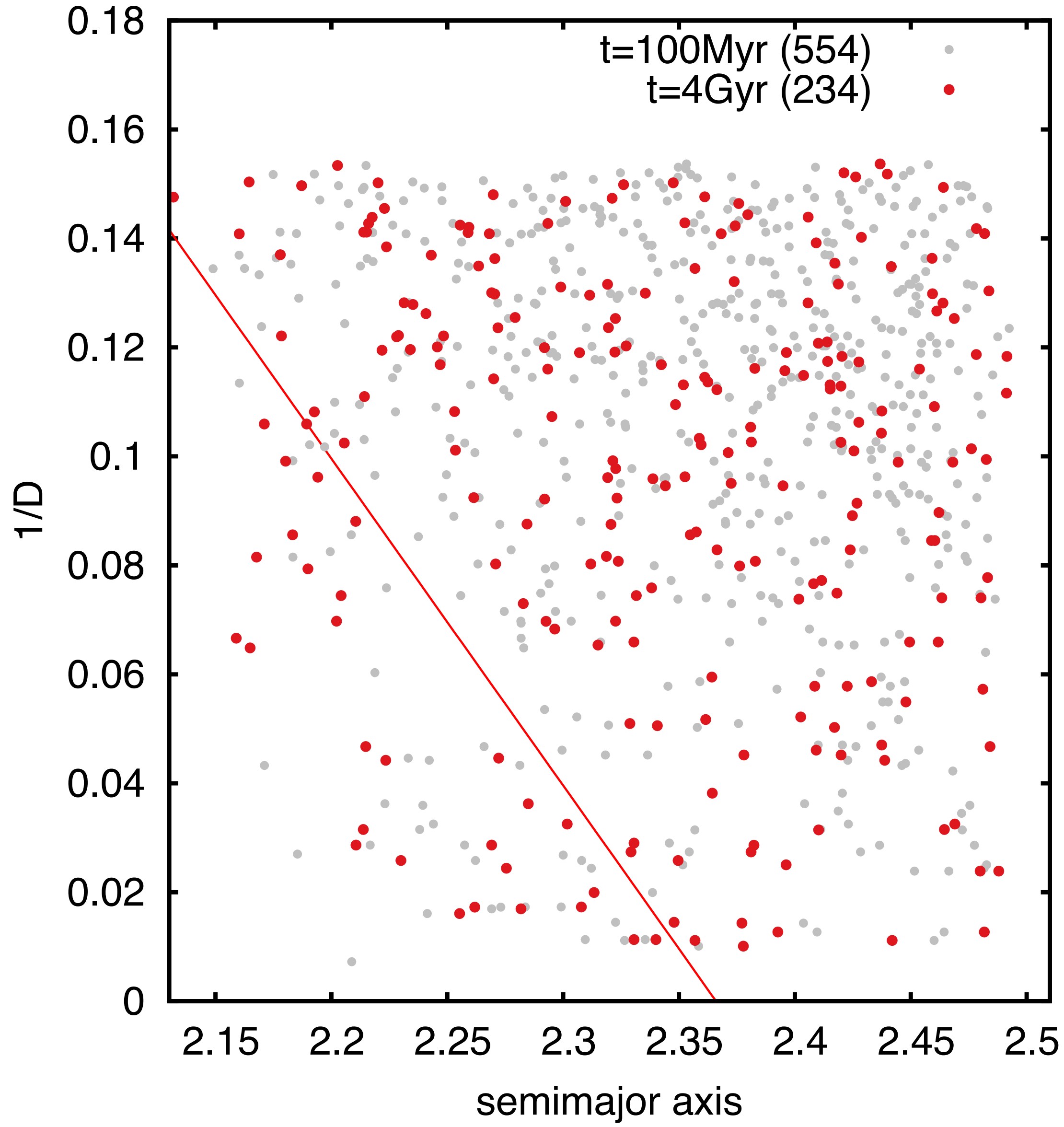
The primordial V-shape is that it is not constituted by an over-density of asteroids above a diffuse background, which is typical for younger families [Milani et al., 2014]:

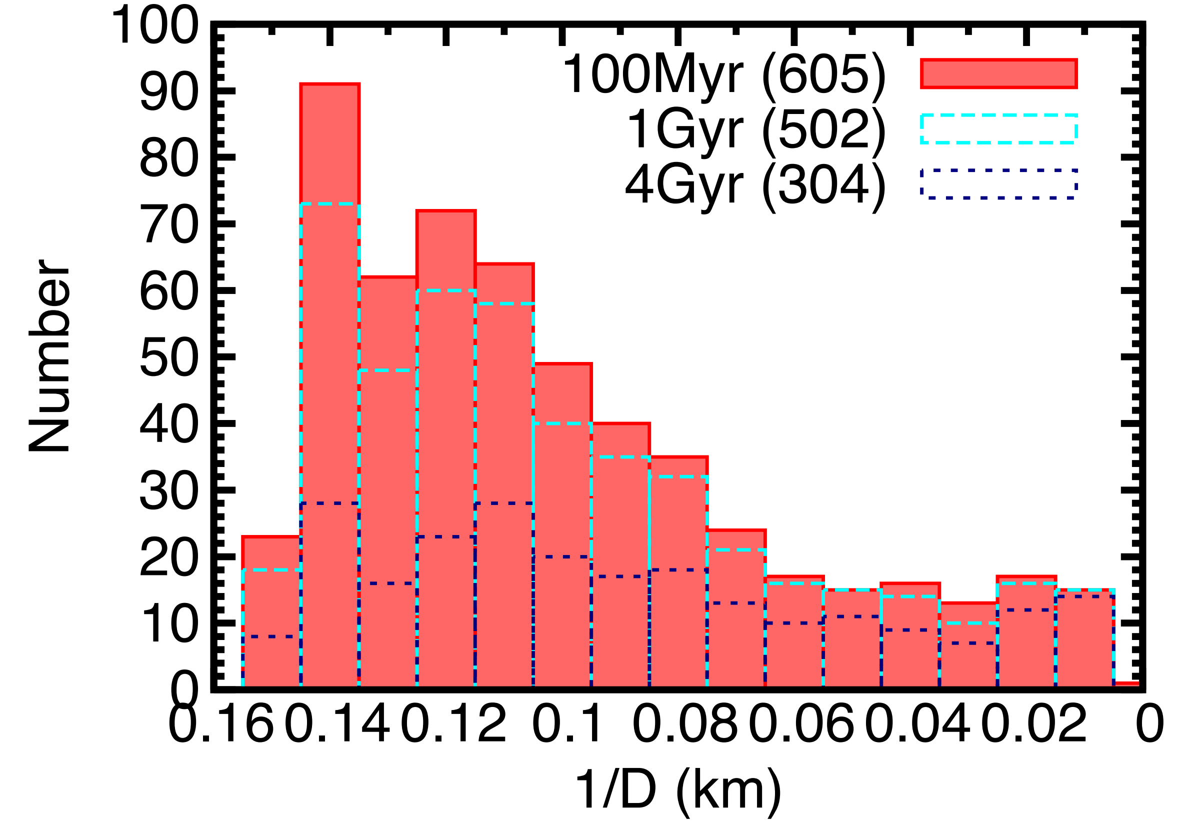
Instead the inward edge of the V-shape marks the border of a huge triangular void of dark asteroids with $2.15 < a < 2.3$ au and $0.2 < 1/D < 0.125$ km^{-1} (i.e. $50 > D > 8$ km), with only one (questionable) low-albedo asteroid assigned to an almost-absent background

- We calculated probability to have a V-shape by coincidence and a void similar to those formed by low-albedo asteroids from random distributions of objects, is smaller than 10^{-6}.

Could the void of asteroids be due to 4 Gy evolution ?

- test whether the void of asteroids and the primordial V-shape could be the results of 4 Gyr dynamical evolution of a initially random distribution of bodies.
- We carry out numerical integrations of orbital evolution of asteroids for 4 Gyr, including the Yarkovsky effect and the planets on their current orbits



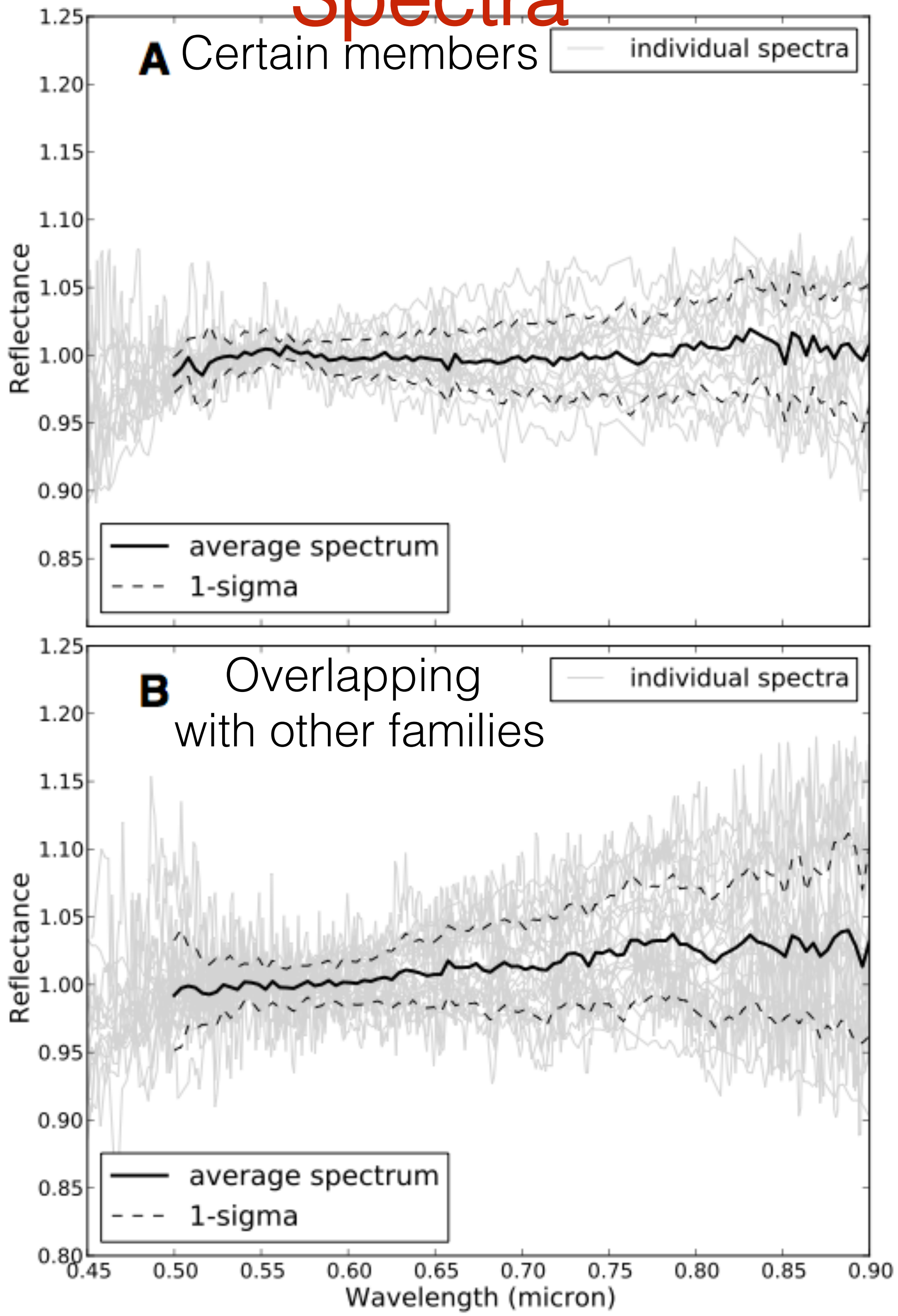


- We find that only about 50% of the initial asteroids are removed, with no removal preference from where the void is found, so that said process is not able to reproduce the observations, implying that there is no dynamical reason for the presence of the void.

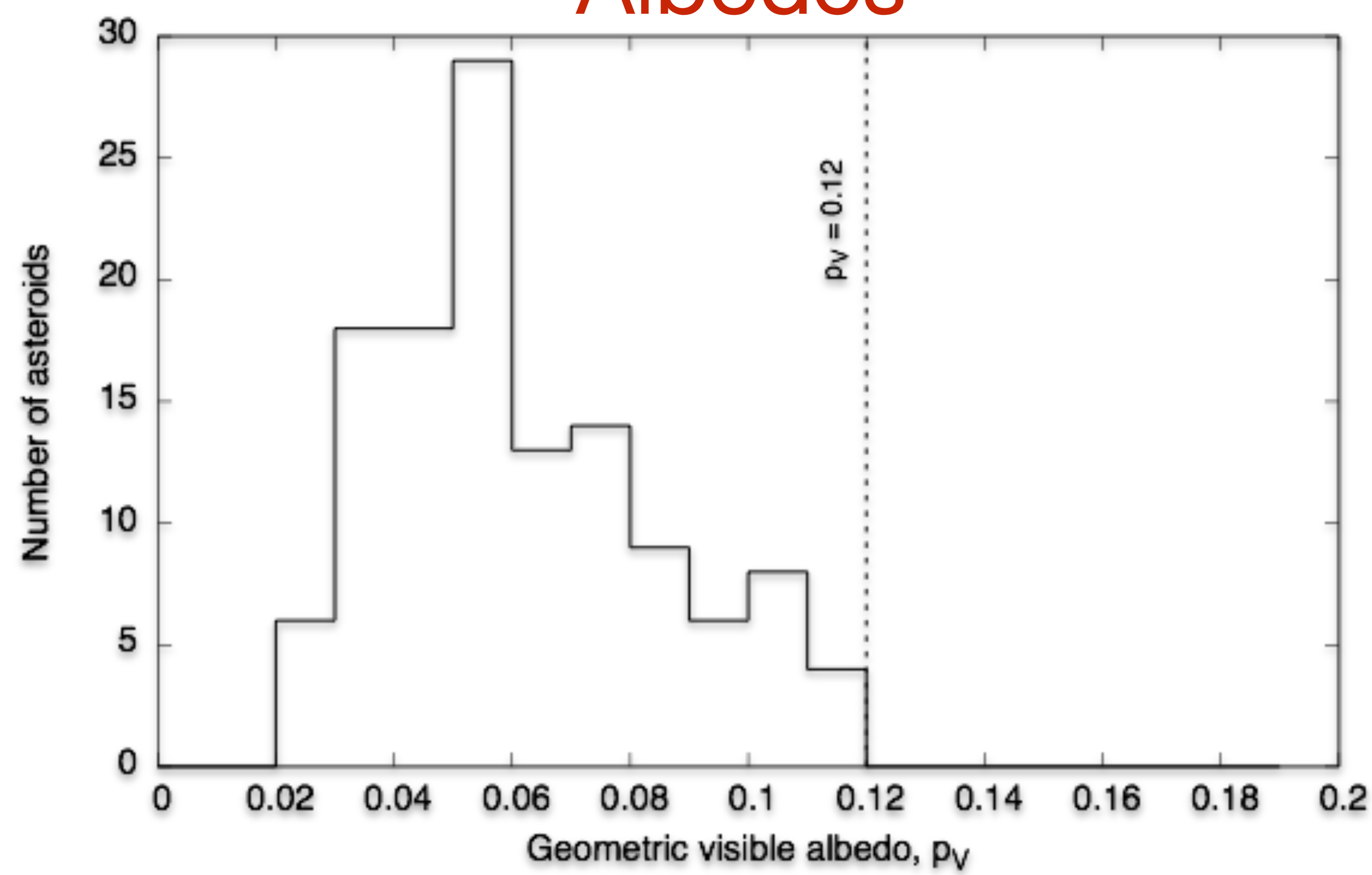
Physical properties

Homogeneity of the physical properties of its members (albedo and spectra are expected to be similar for asteroids sharing origin from a common parent body)

Spectra



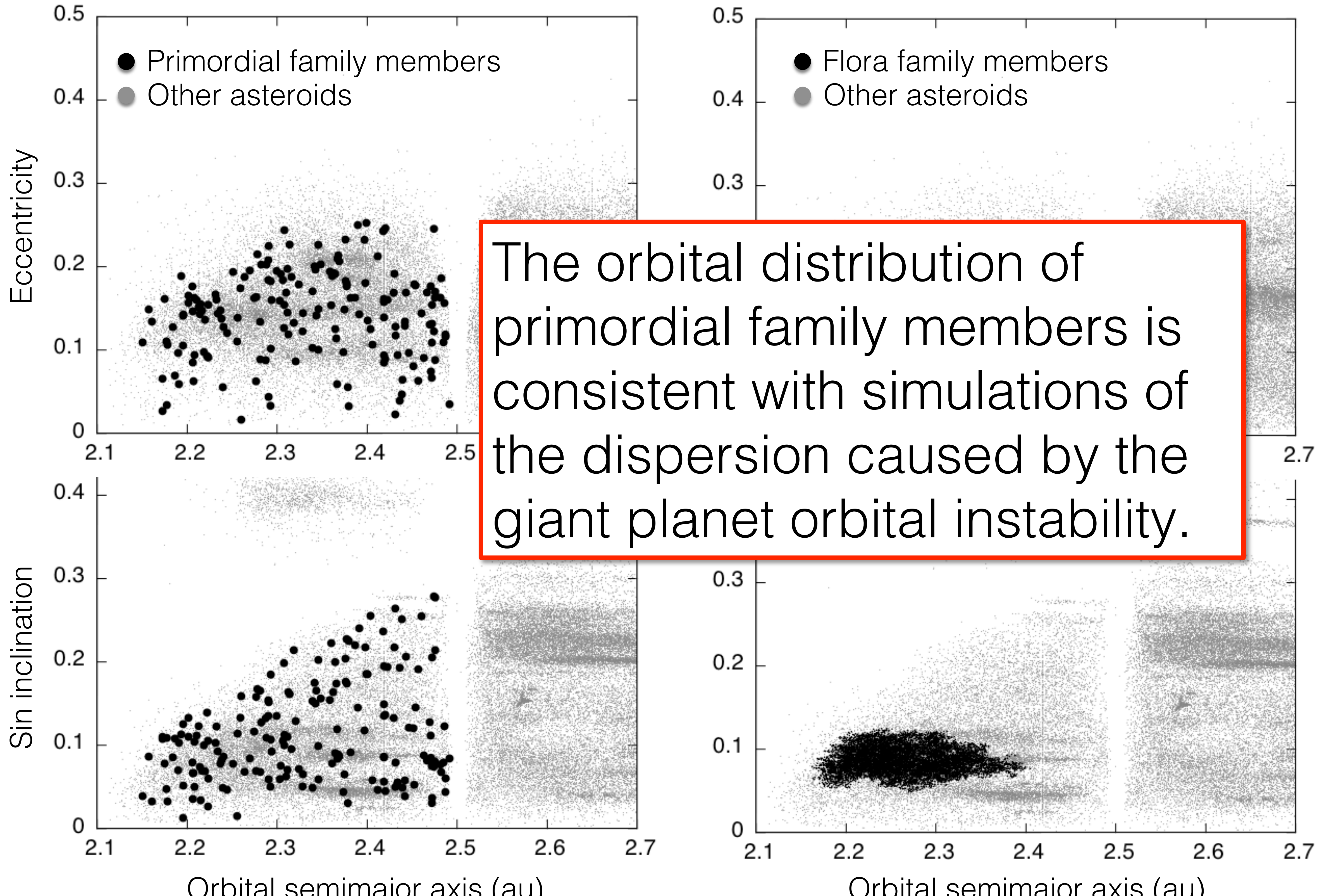
Albedos



- Homogenous albedos and spectra, similar other low-albedo families of the inner Main Belt (Walsh+2013; Pinilla-Alonso+2016; DeLeon+2016; Masiero+2013,2015; Nesvorny +2015;)

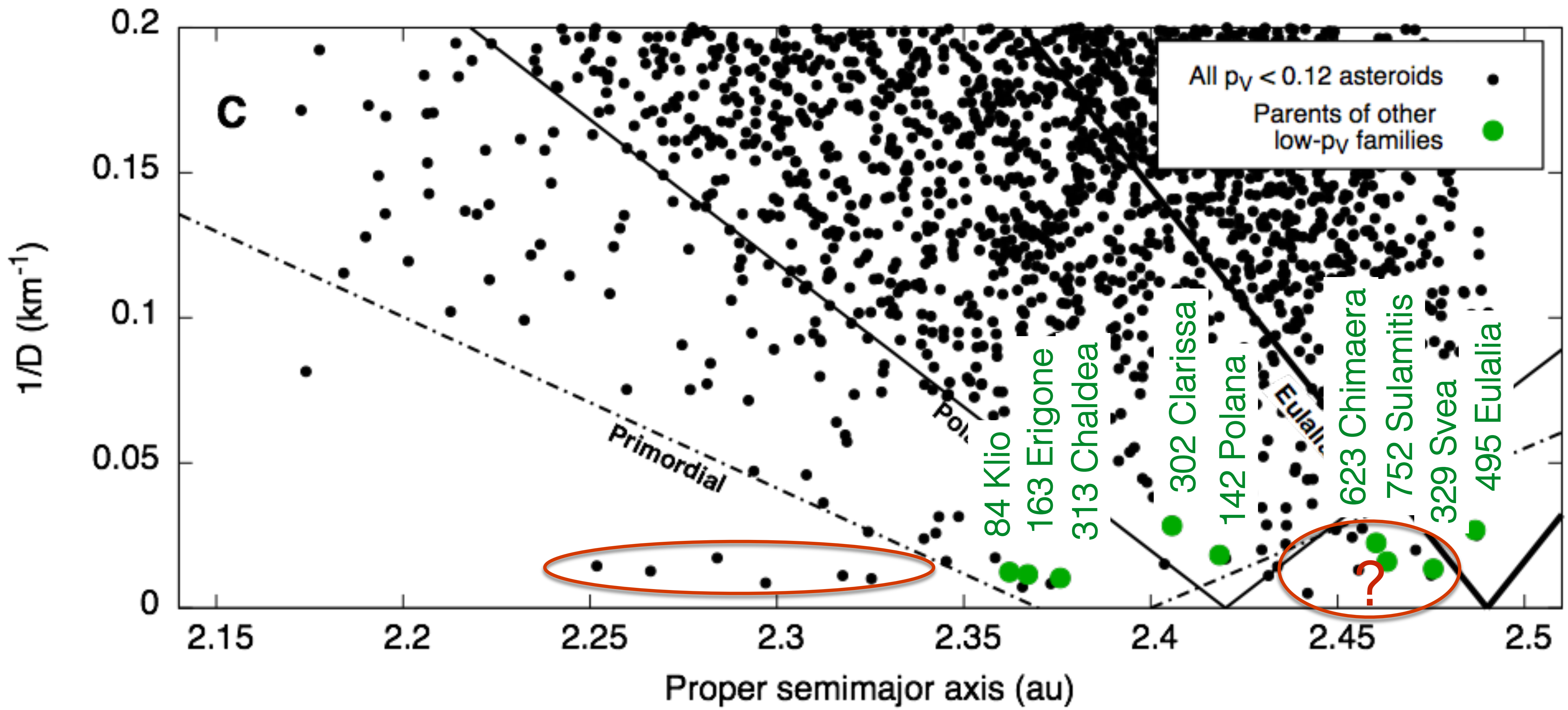
Orbital distribution

Compare the dispersion in orbital elements of our primordial family with the old but less dispersed Flora family.



The orbital distribution of primordial family members is consistent with simulations of the dispersion caused by the giant planet orbital instability.

The family tree of the inner Main Belt



- We have weak detection of the outward border of the primordial family.
- Some of the parents of known low-albedo families are within the boundary of the primordial family. They could be members of the primordial family that suffered further family forming impacts.
- There are very few low-albedo asteroids non affiliated to a family. And they are all big.

Origin of notable near-Earth asteroids

- The most likely parent families for **Bennu** – the target of NASA OSIRIS-Rex – are Eulalia and Polana [Bottke+ 2015, Campins+ 2010]

- Polana and Eulalia families have a 70% and 30% probability of producing Bennu, respectively.

- (162173) **Ryugu** – target of JAXA Hayabusa2 – has similar probabilities for both families [Bottke+ 2015], but Campins+ 2013 calculate that Ryugu could also come from the primordial family (once called the background)

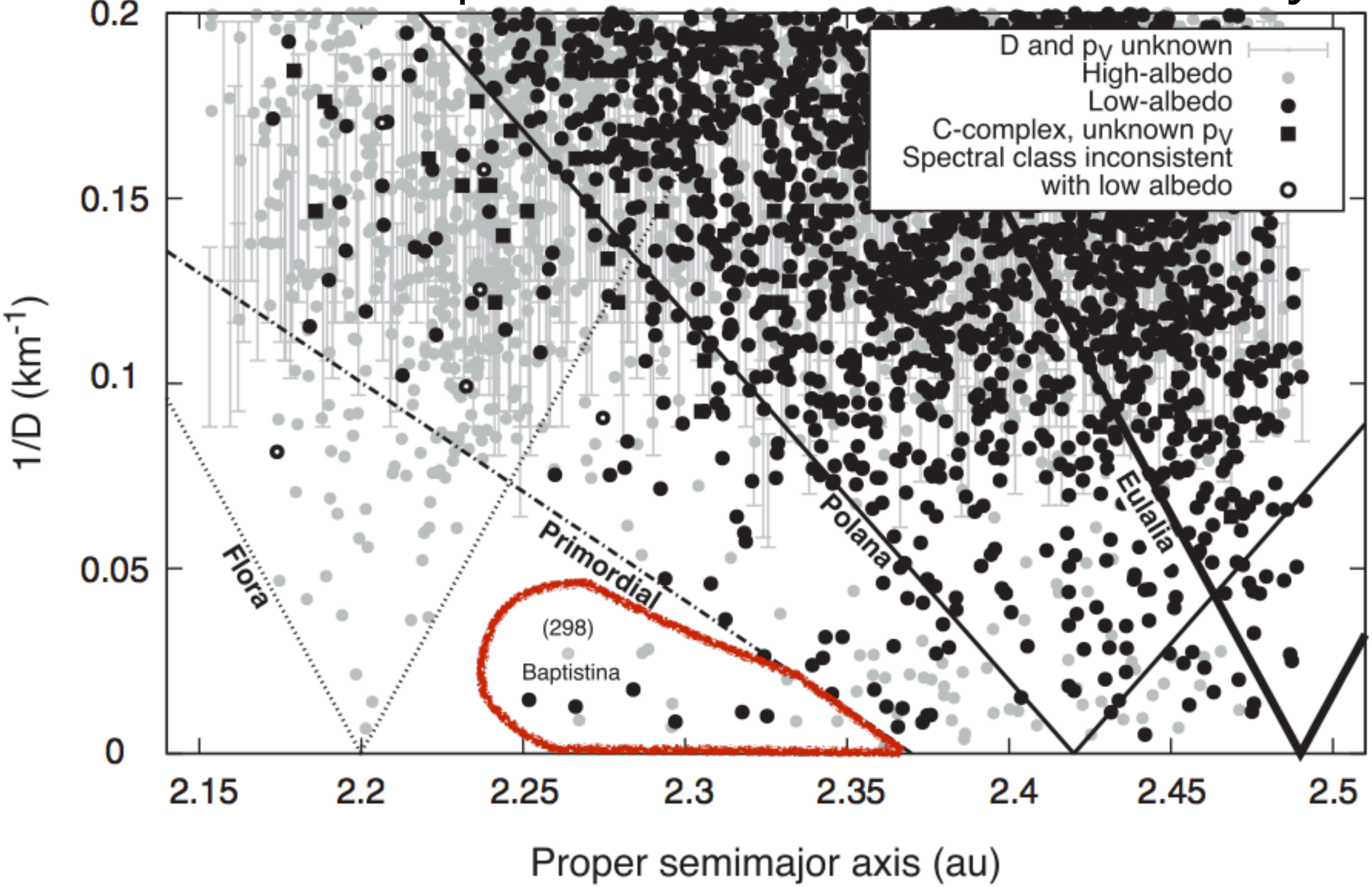
Implication ⟹ two asteroid populations

We conclude that the inner Main Belt contains asteroids of two different origins:

those that are collisional fragments of other asteroids and are inside V-shapes.

those that are outside V-shapes, indicating that were not created as collisional fragments in the Main Belt and therefore are planetesimals accreted the protoplanetary disk phase.

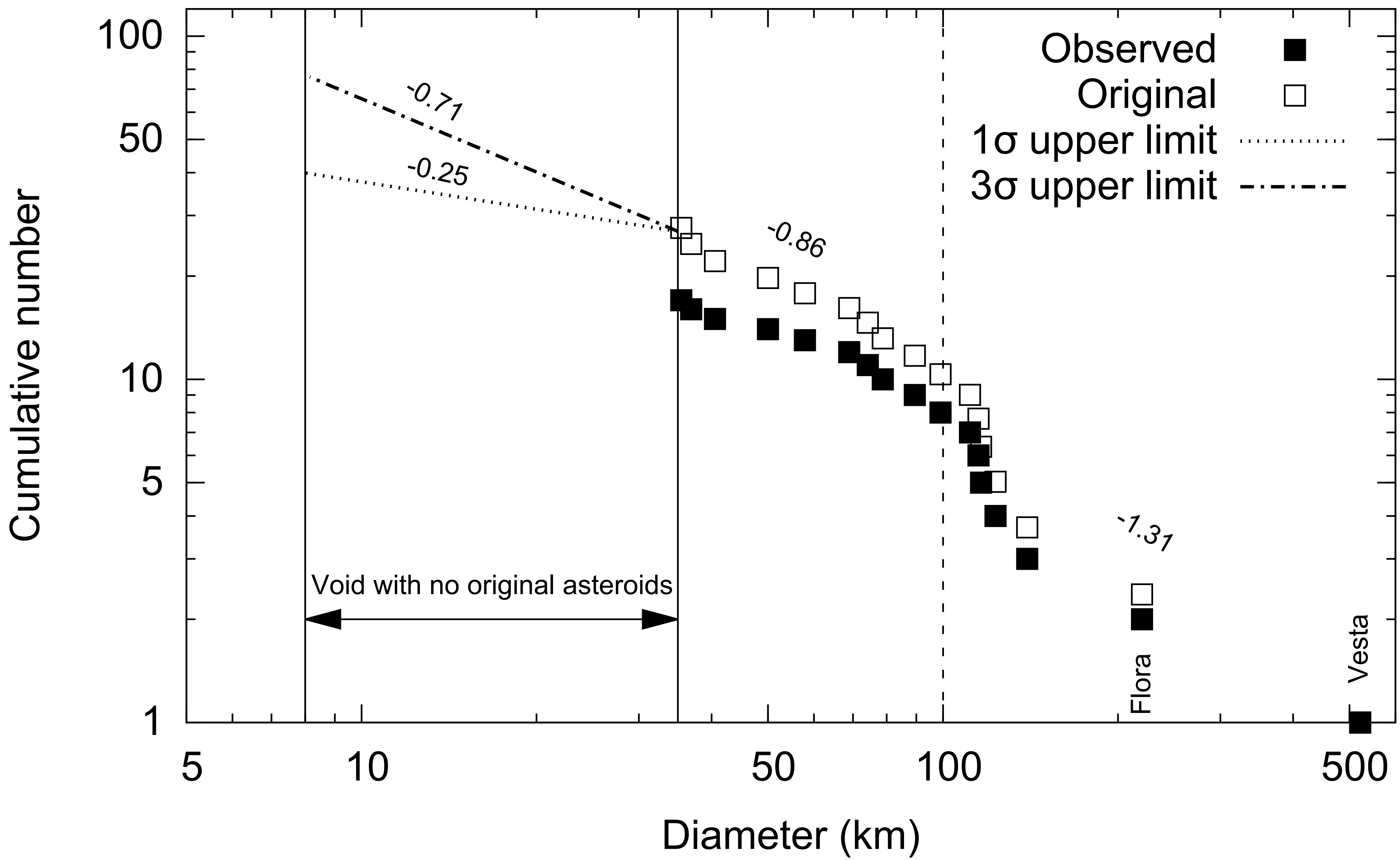
Meet the primordial asteroid family



The V-shape slope ~ 0.6 km^{-1}au^{-1} corresponds to an age $t = 4.0^{+1.7}_{-1.1}$ Gyr

Two populations of asteroids: those inside V-shapes and those that cannot be inside V-shapes. The former are family members; the latter the original ones.

Observed size distribution of the planetesimals



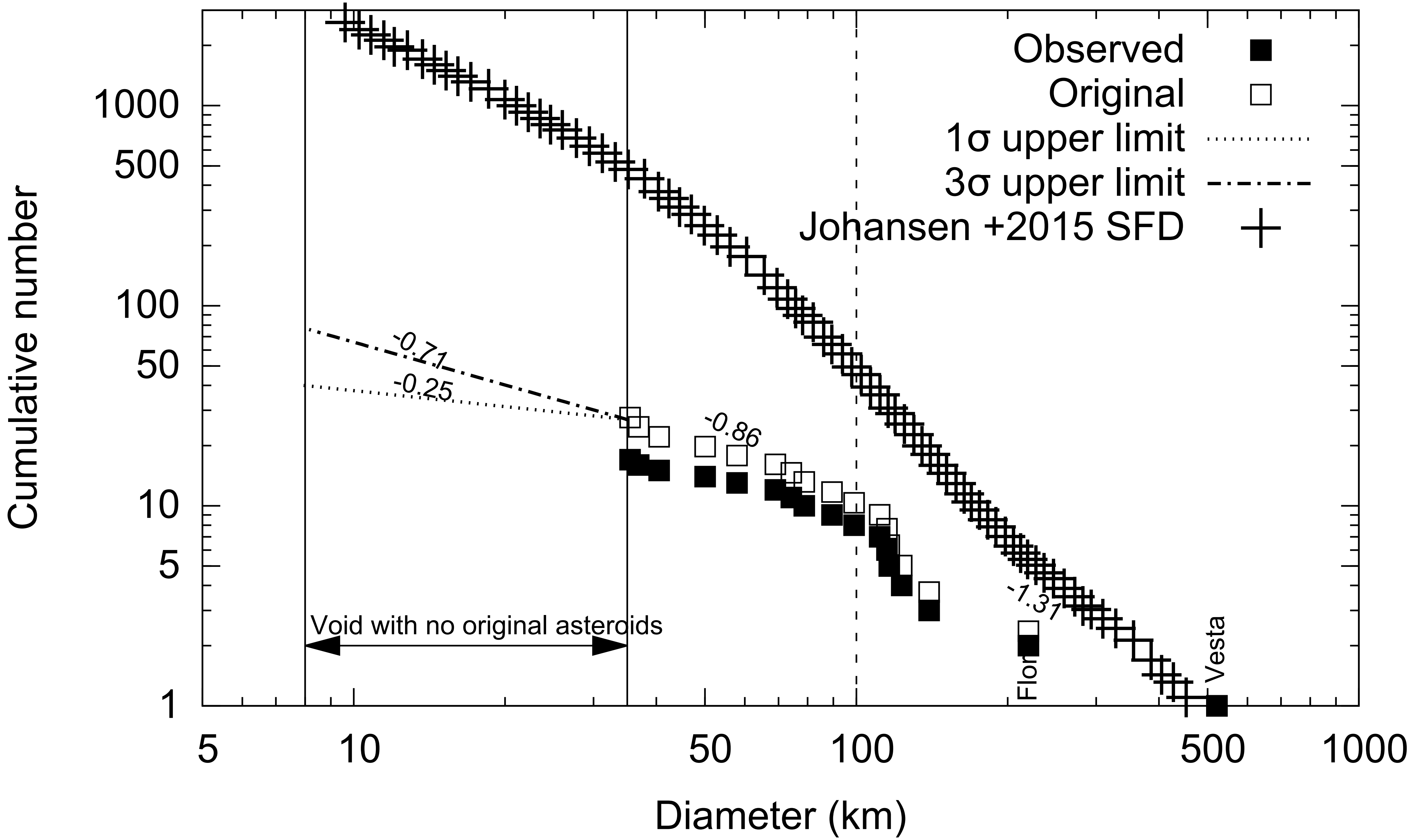
Cumulative size distribution of the observed primordial asteroids (filled squares) corrected for the maximum number of objects that were lost, due to the collisional and dynamical evolution (open squares).

(10 Gy collisional evolution; 4 Gy of dynamical loss)

The resulting original size distribution is still shallower compared to some of the current accretion model predictions [Johansen et al., 2015b, Simon et al., 2016]

Observed size distribution of the planetesimals

Comparision with (some) model predictions



Cumulative size distribution of the observed primordial asteroids (filled squares) corrected for the maximum number of objects that were lost, due to the collisional and dynamical evolution (open squares).
(10 Gy collisional evolution; 4 Gy of dynamical loss)
The resulting original size distribution is still shallower compared to some of the current accretion model predictions [Johansen et al., 2015b, Simon et al., 2016]

Database for this work is available online

Not Secure https://www-n.oca.eu/delbo/astphys/astphys.html

mp3c.oca.eu

List of Objects :

Number/Designation:

Example: Pallas Ceres Diotima 3200 1950DA

Submit

Orbital elements range:

a [au] : between 2.1 and 2.5

e : between 0 and 0.3

sin(i) : between 0 and 0.3

q [au] : between and

Physical Data range :

H : between and

D [km] : between 3 and 1000

pV : between 0 and 0.12

Spectral Class :

Include (comma separated) :

Example: B,C,Cb,Ch,Cg,Cgh will select asteroids of the C-complex

Exclude (comma separated) :

Output :

(•) List ( ) NEA ( ) SpinPole ( ) Blocks

Submit

Input example

development

Delbo

Tanga

Carry

Ordenovich

Output example

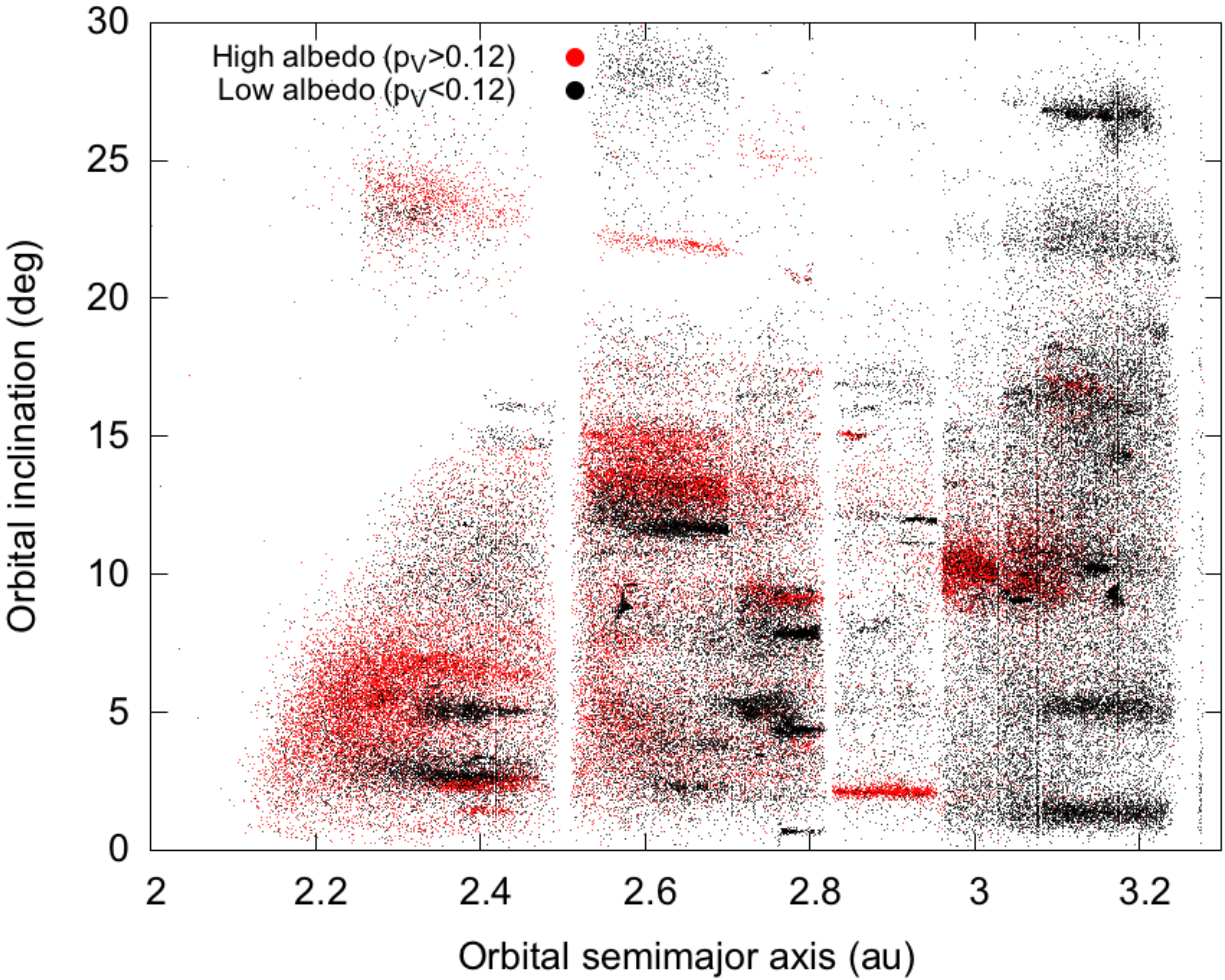
# Number	Designation	H	G	prop.a	.e	.sini	D (km)	D_unc	pV	pV_Unc	Period	Spectroscopic Classes	Family	a*	i-z	Ref.
000019	Fortuna	7.13	0.10	2.4420	0.1345	0.0388	196.370	0.300	0.060	0.010	7.44	Ch----------G-----------------	000000	0.00	0.00	39
000051	Nemausa	7.35	0.08	2.3657	0.1140	0.1740	138.160	0.970	0.100	0.030	7.78	Cgh---------CU----------------	000000	0.00	0.00	39
000072	Feronia	8.94	0.15	2.2662	0.0741	0.1037	78.800	2.000	0.080	0.010	8.10	----s---STD-TDG---------------	000000	0.00	0.00	39
000083	Beatrix	8.66	0.15	2.4315	0.1174	0.0794	89.640	2.650	0.080	0.010	10.16	------------X-----------------	000000	0.00	0.00	39
000084	Klio	9.32	0.15	2.3622	0.1928	0.1637	79.000	4.867	0.053	0.017	23.56	Ch----------G---Caa-----------	000084	0.00	0.00	38
000112	Iphigenia	9.84	0.15	2.4339	0.0941	0.0557	69.820	1.820	0.040	0.010	31.47	------------DCX-Caa-----------	000000	0.00	0.00	39
000142	Polana	10.27	0.15	2.4184	0.1576	0.0561	54.810	0.280	0.050	0.010	9.76	------------F-----------------	000044	0.00	0.00	39
000163	Erigone	9.47	0.04	2.3671	0.2096	0.0837	81.579	3.062	0.033	0.004	16.14	------------C-----------------	000163	0.00	0.00	38
000207	Hedda	9.92	0.15	2.2840	0.0656	0.0589	57.880	0.150	0.060	0.010	30.10	------------C---Caa-----------	000000	0.00	0.00	39
000220	Stephania	11.20	0.15	2.3486	0.2030	0.1560	31.740	0.220	0.070	0.020	18.20	------------XC--X---C---X-----	000000	-0.03	-0.01	39
000248	Lameia	10.20	0.15	2.4709	0.0744	0.0849	50.120	0.310	0.060	0.010	11.91	----s---X---------------------	000000	0.00	0.00	39

Conclusions

- We discovered a primordial asteroid family whose members are almost all low-albedo asteroids of the inner Main Belt previously unlinked to families.
- The age of the family is ~4 Gyr, but it could be as old as the Solar System.
- The orbital distribution of the family members is consistent with the asteroid being dispersed by resonance sweeping/moving during the giant planet orbital instability.

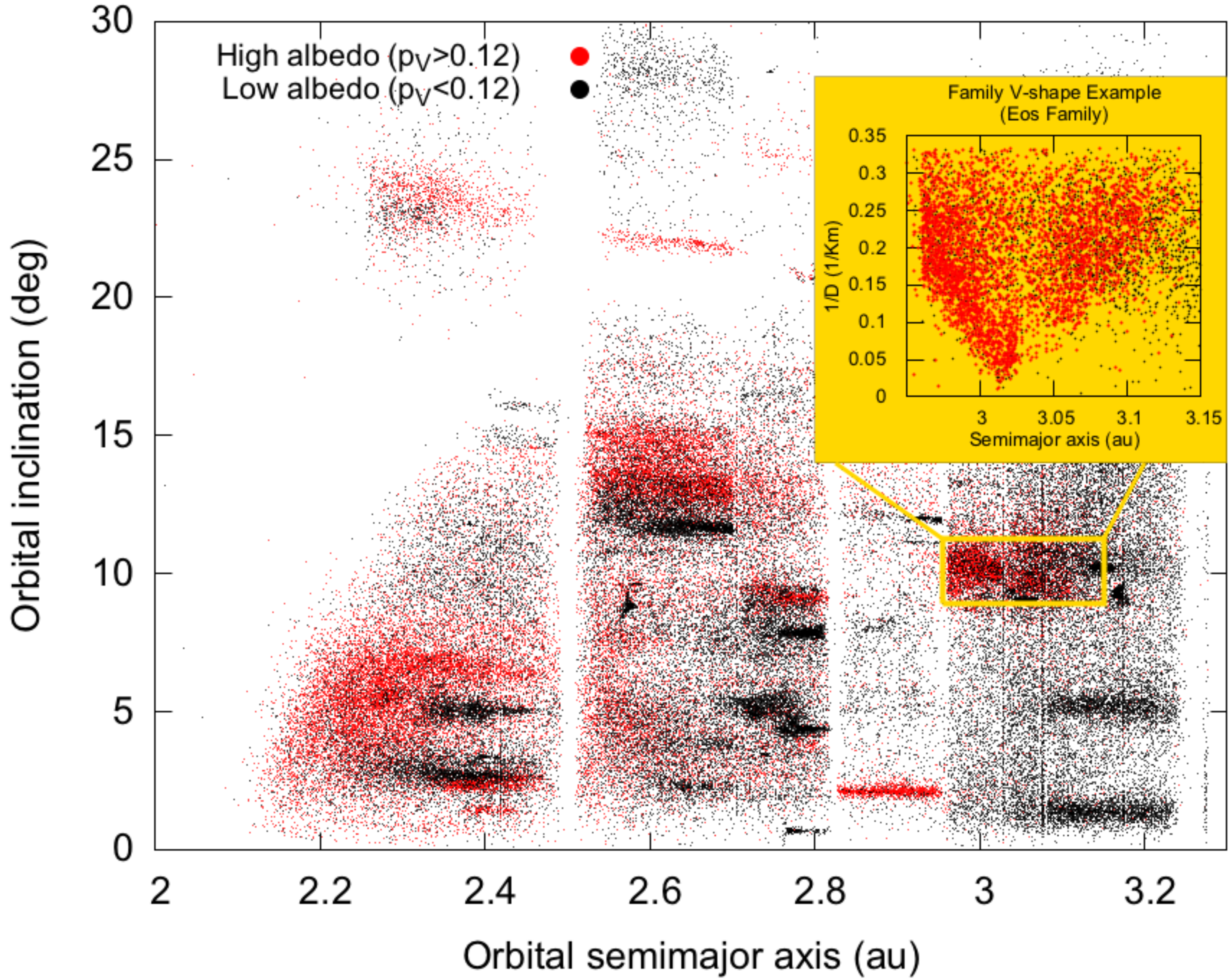
- The very few asteroids that cannot be associated to families are all big (>50 km for low-albedo, >35 km for high albedo).
- These are those planetesimals that are still intact today.
- Their size distribution is very shallow, confirming that planetesimals were born big.

Backup slides



High albedo (p_V>0.12)
Low albedo (p_V<0.12)
Orbital inclination (deg)
Orbital semimajor axis (au)
0
5
10
15
20
25
30
2
2.2
2.4
2.6
2.8
3
3.2

The V-shape of asteroid families



Diameters & Albedos: Masiero+11,12,14; Nugent+15,16; Usui+11; Ryan&Woodward+10; Tedesco+02

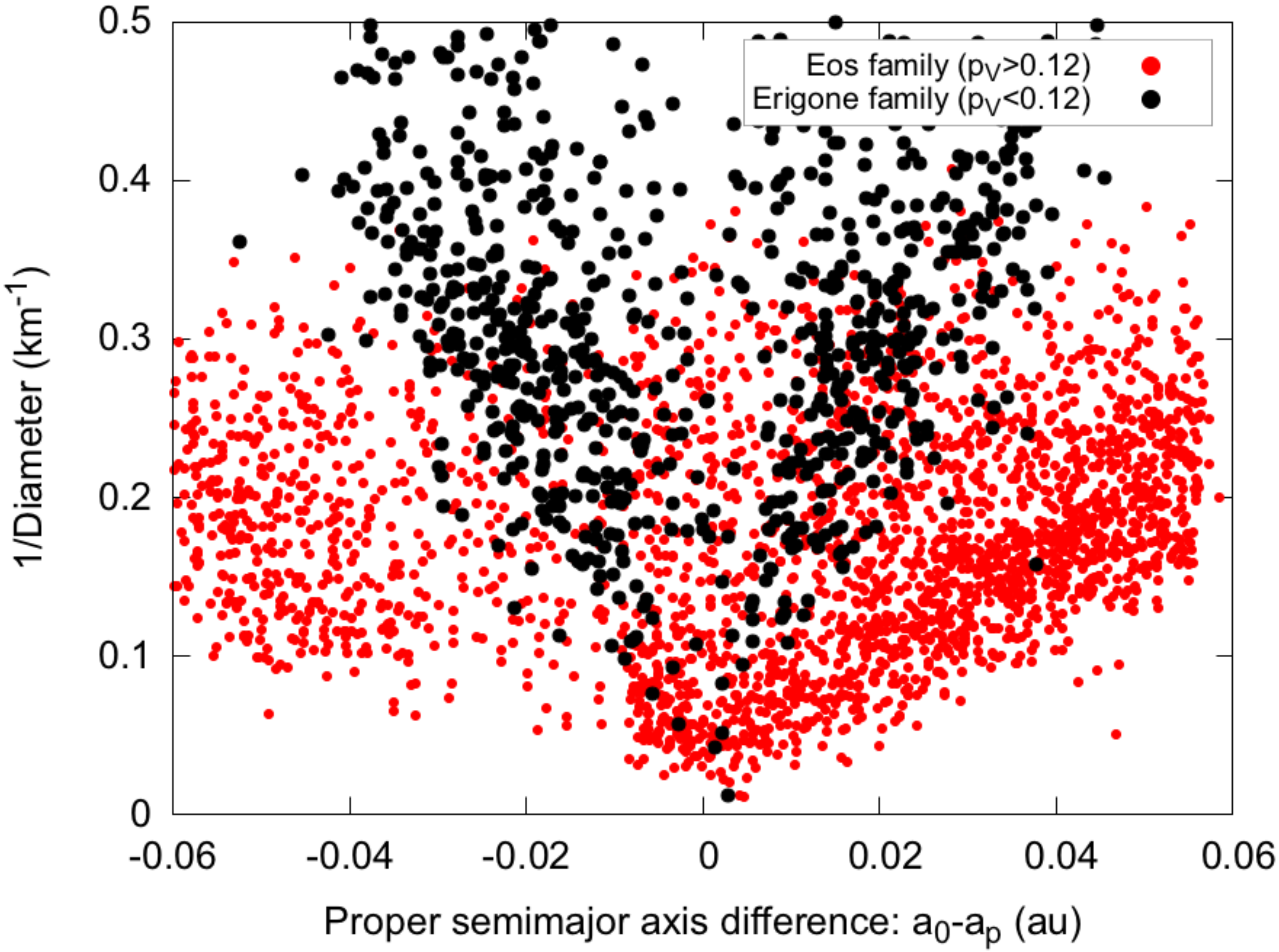
V-shape slopes show family age

Erigone

T= 210 – 230 My
[Spoto+ 2015]
T= 300 +/- 200 My
[Broz+ 2013]

Eos

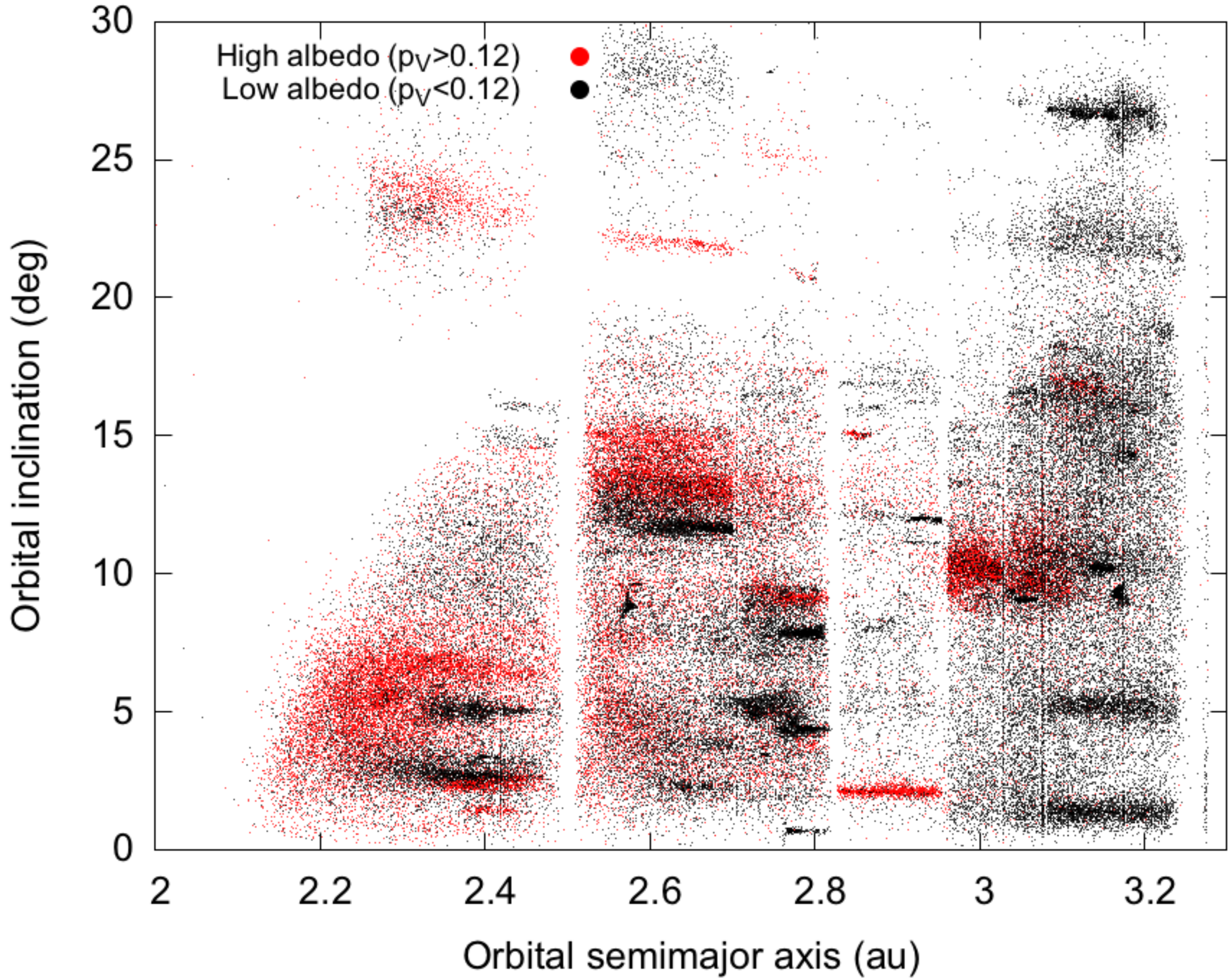
T=1300 +/- 200 My
[Broz+ 2013]



A narrow V shows a young family
A wide ⌵ shows an old family

Vokrouhlicky+ 2006
Spoto+ 2015
Bolin+ 2017, 2018

Asteroids and asteroid families

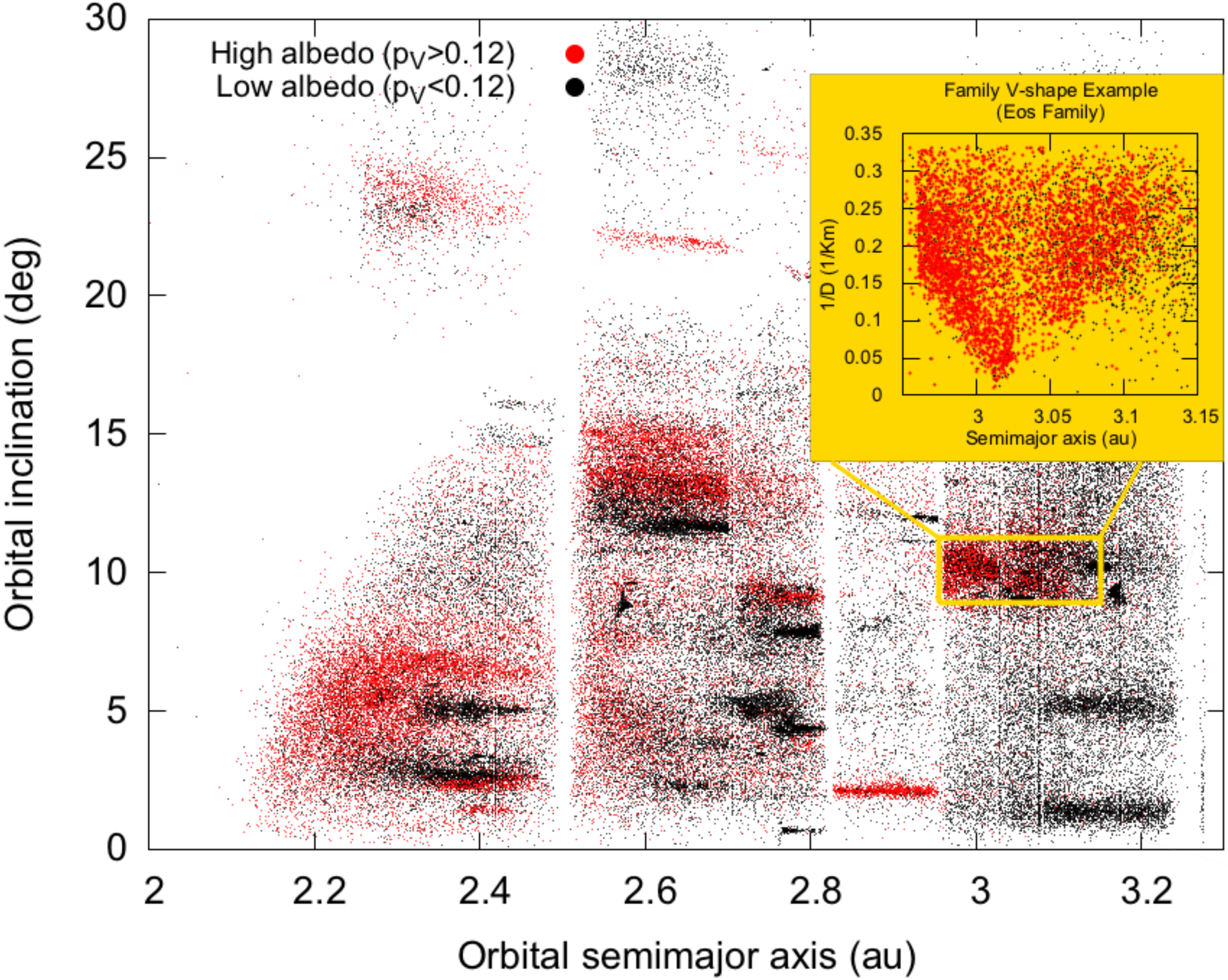


Diameters & Albedos: Masiero+11,12,14; Nugent+15,16; Usui+11; Ryan&Woodward+10; Tedesco+02

Asteroid and family formation

DeMeo 2017

Asteroids and asteroid families



Diameters & Albedos: Masiero+11,12,14; Nugent+15,16; Usui+11; Ryan&Woodward+10; Tedesco+02

More on Yarko

$$\frac{da}{dt} = \frac{(1-A)}{\rho\ R}\frac{1}{3}\frac{S_\odot}{c\ \ n\ \ r^2}\frac{0.5\Theta}{1+\Theta+0.5\Theta^2}\cos\gamma \tag{1}$$

$$with\ \Theta = \Gamma\sqrt{2\pi}/(\sqrt{P}\epsilon\sigma T_\star^3) \tag{2}$$

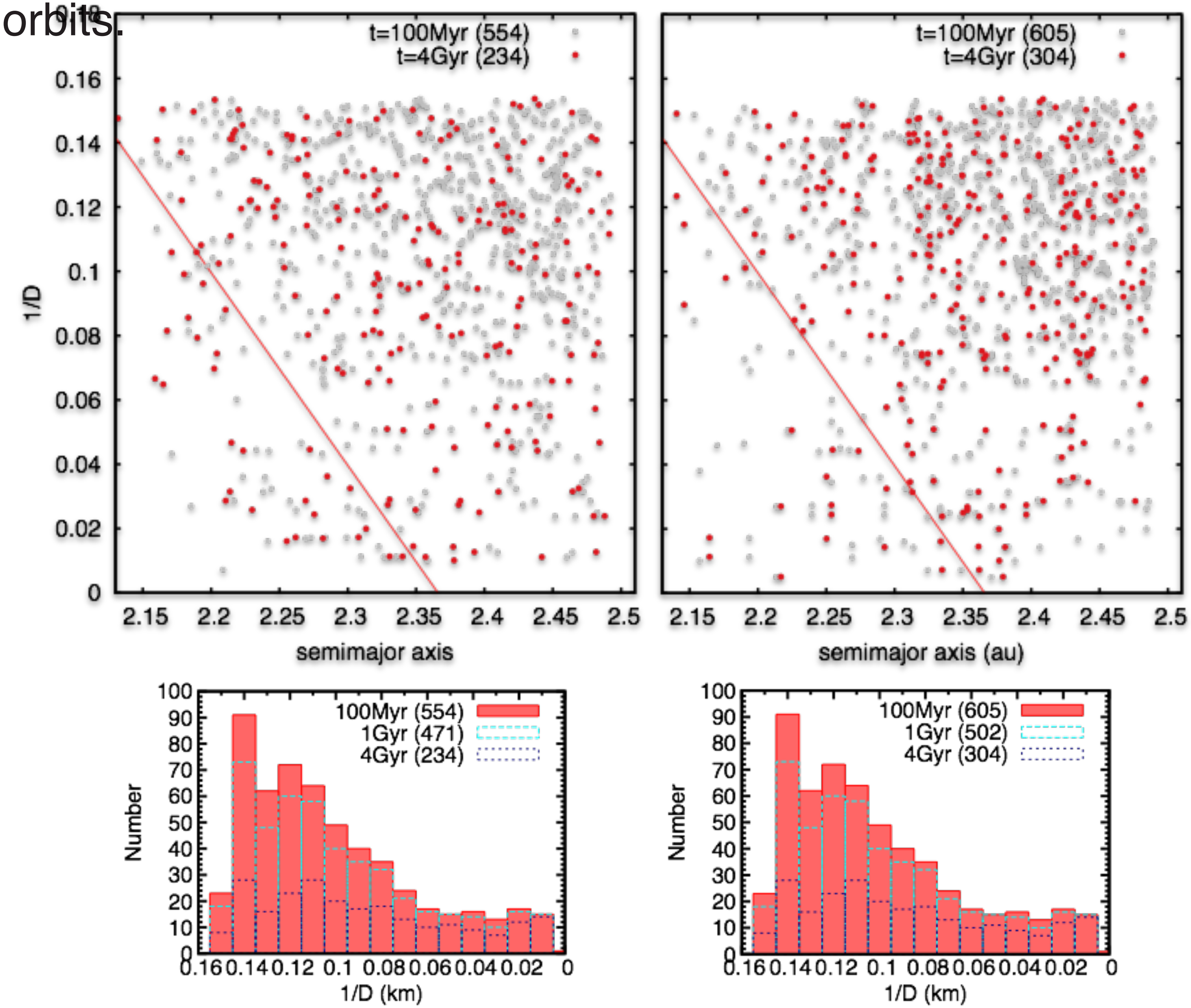
where $S_\odot$, c, n, r, A, γ, P, ϵ, $T_\star$, are the solar flux at 1 au, the speed of light, the mean orbital motion, the heliocentric distance in au, the bolometric Bond albedo, the spin axis obliquity, the rotational period, the emissivity, and the subsolar temperature, respectively.

Reality of the primordial family (2)

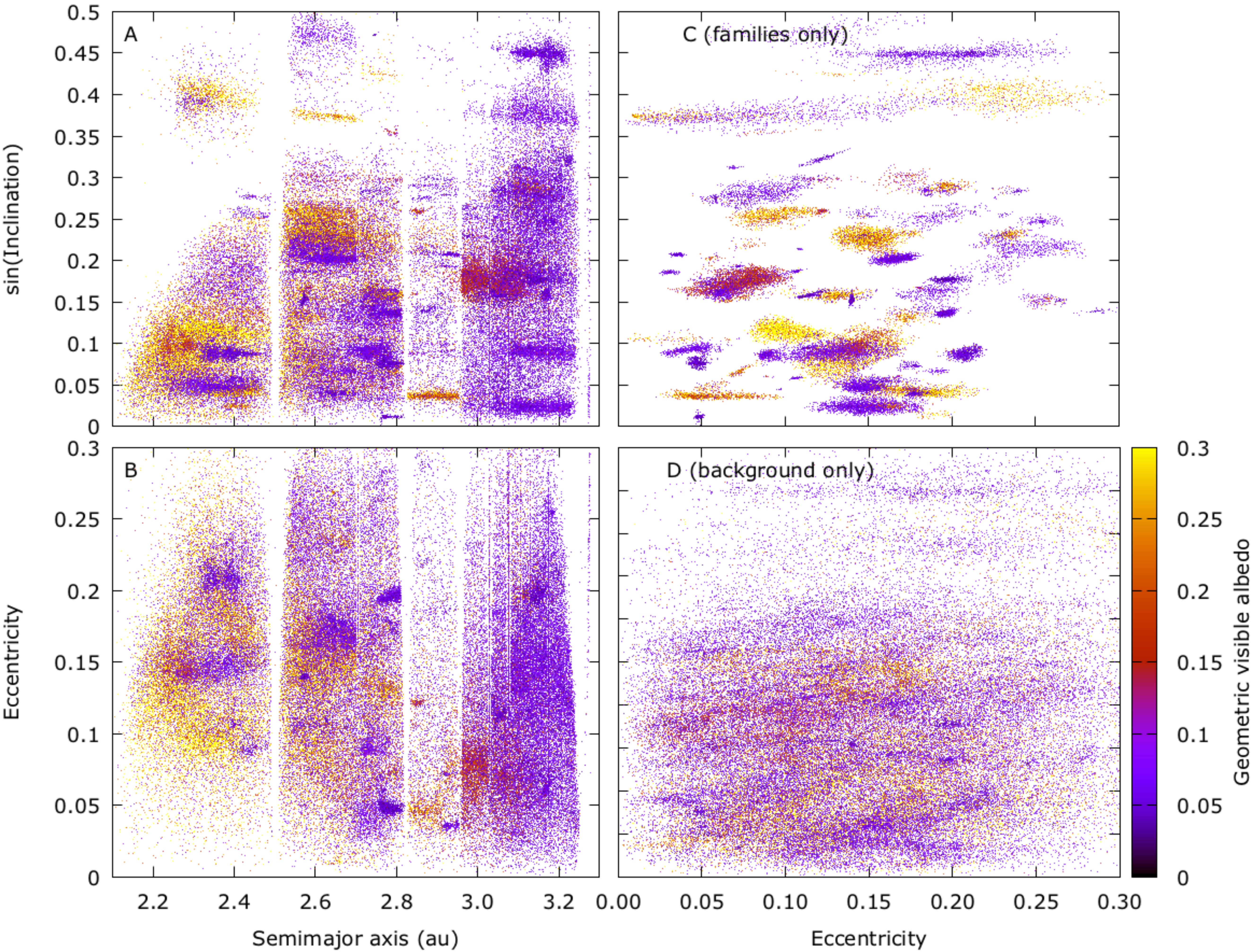
- Carried out numerical integrations of orbital evolution of asteroids over 4 Gyr, including the Yarkovsky effect, the planets, and the major asteroids on their current orbits.

Results

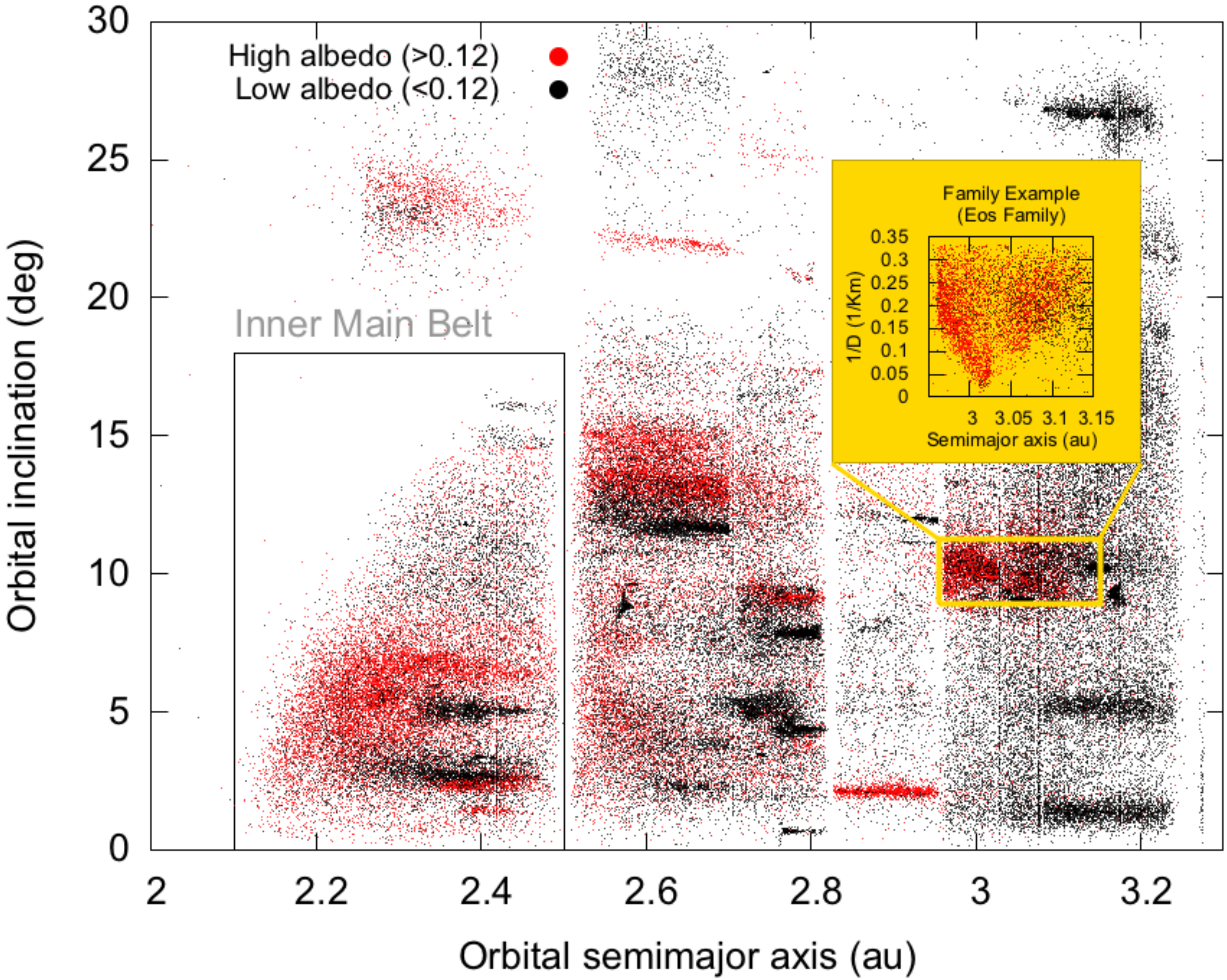
- Asteroids depletion consistent with Minton&Malothra09 (histograms). About 50% of the initial population is lost.



- No preference for removing asteroids inward of the primordial family’s border (red line in the figure).
- No dynamical reasons to


A
B
C (families only)
D (background only)
sin(Inclination)
Eccentricity
Semimajor axis (au)
Eccentricity
Geometric visible albedo
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2.2
2.4
2.6
2.8
3.0
3.2
0.00
0.05
0.10
0.15
0.20
0.25
0.30

Asteroids and asteroid families



Non-family

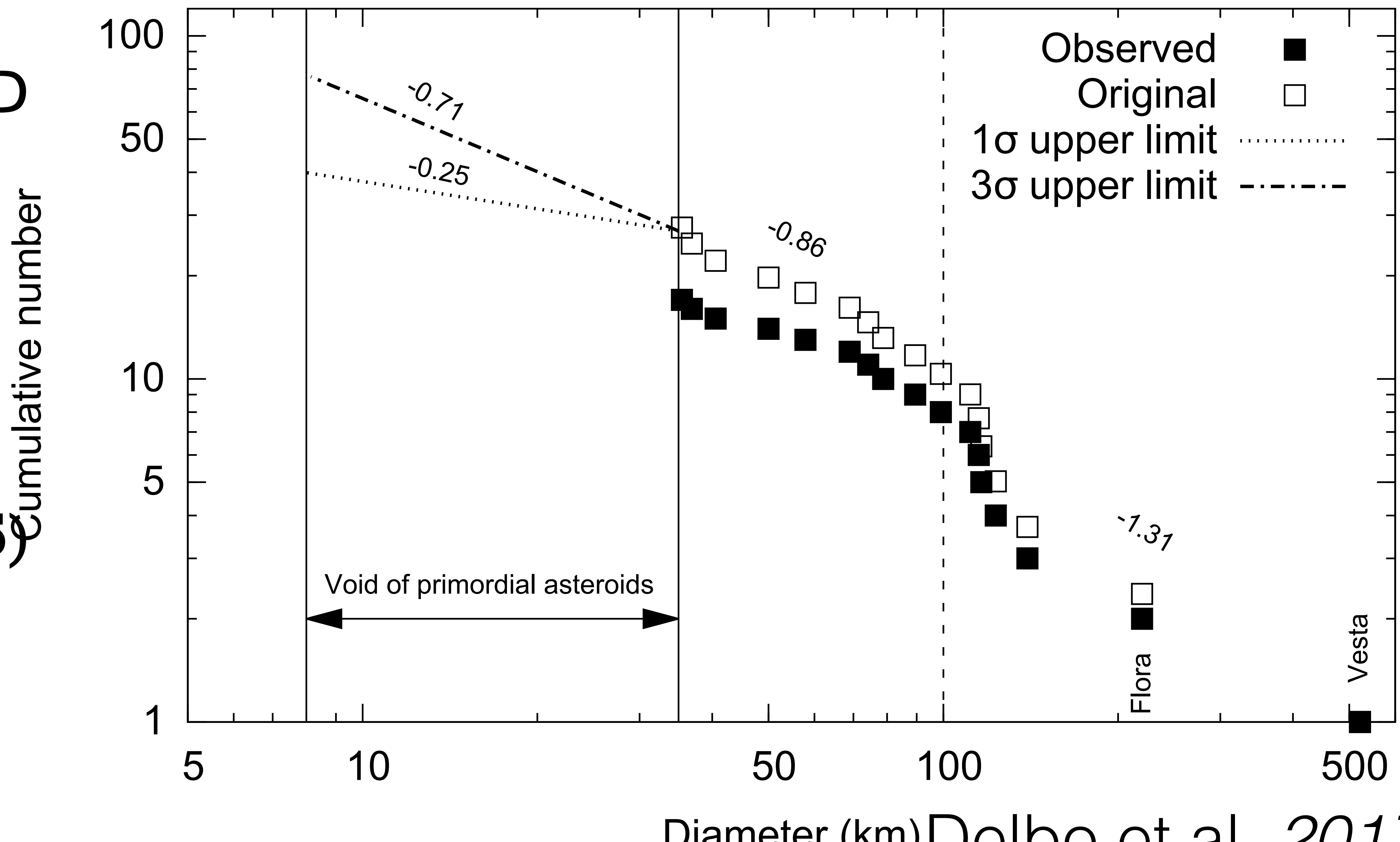
The objects not in any family (filled squares) can be analyzed as a population of original planetesimals

Corrected for collisional and dynamical loss (open squares)

Cumulative SFD is shallower than current planetesimal formation models

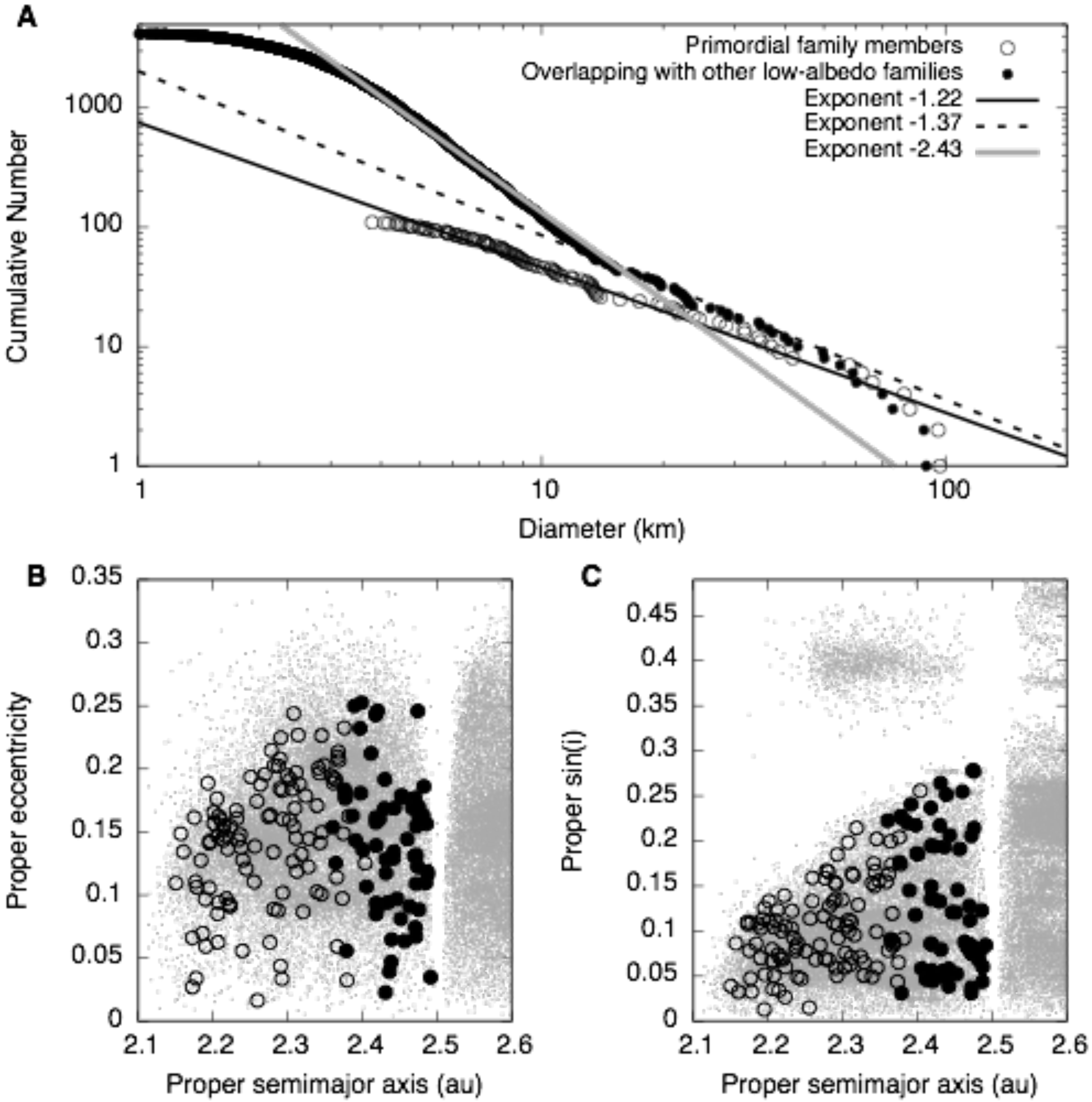
Johansen (2015)

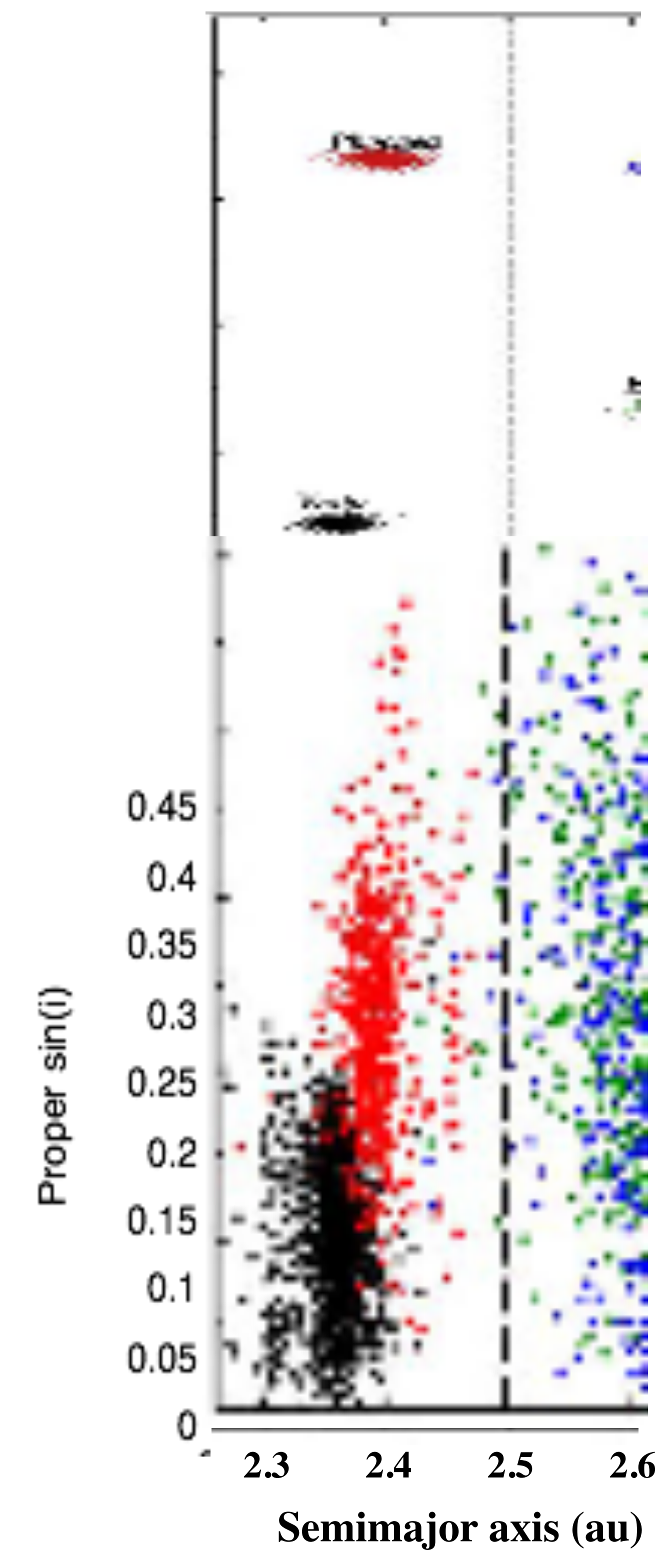
Simon (2016)



Delbo et al. *2017*

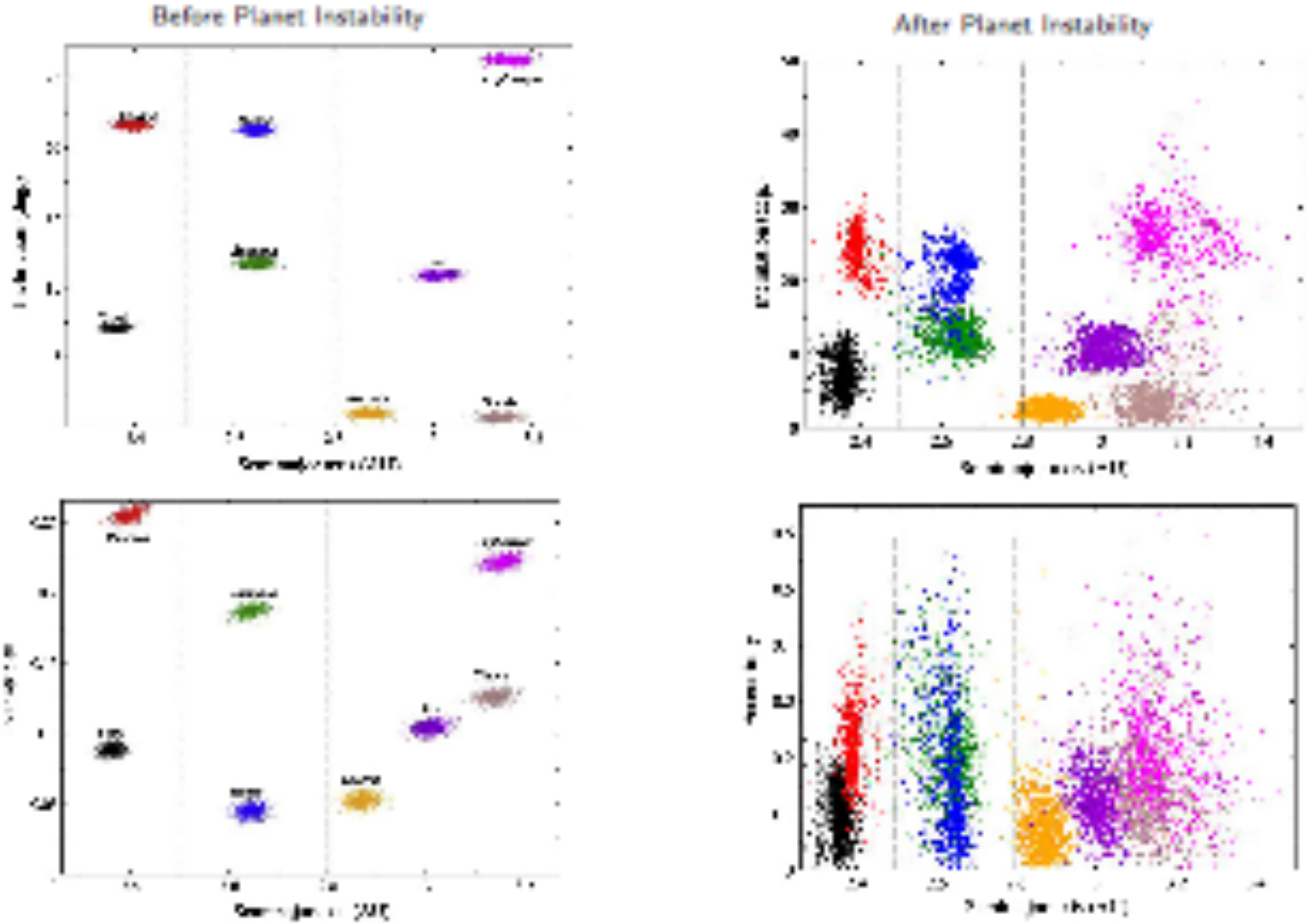
Size (A) and orbital (B,C) distributions





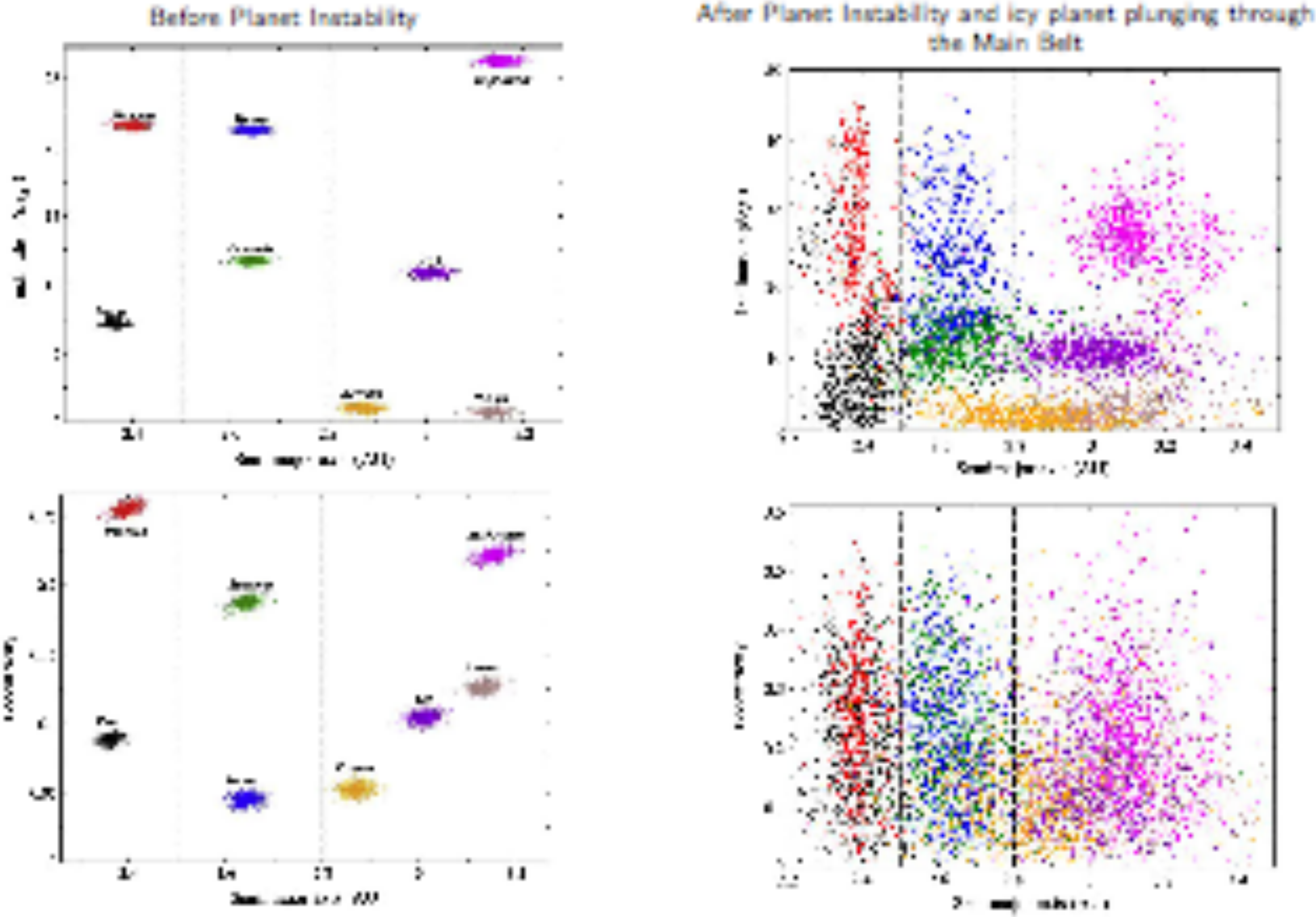
spread over the whole inner main belt

Dynamical dispersal of primordial asteroid families



[Brasil et al., 2016]

Dynamical dispersal of primordial asteroid families (2)

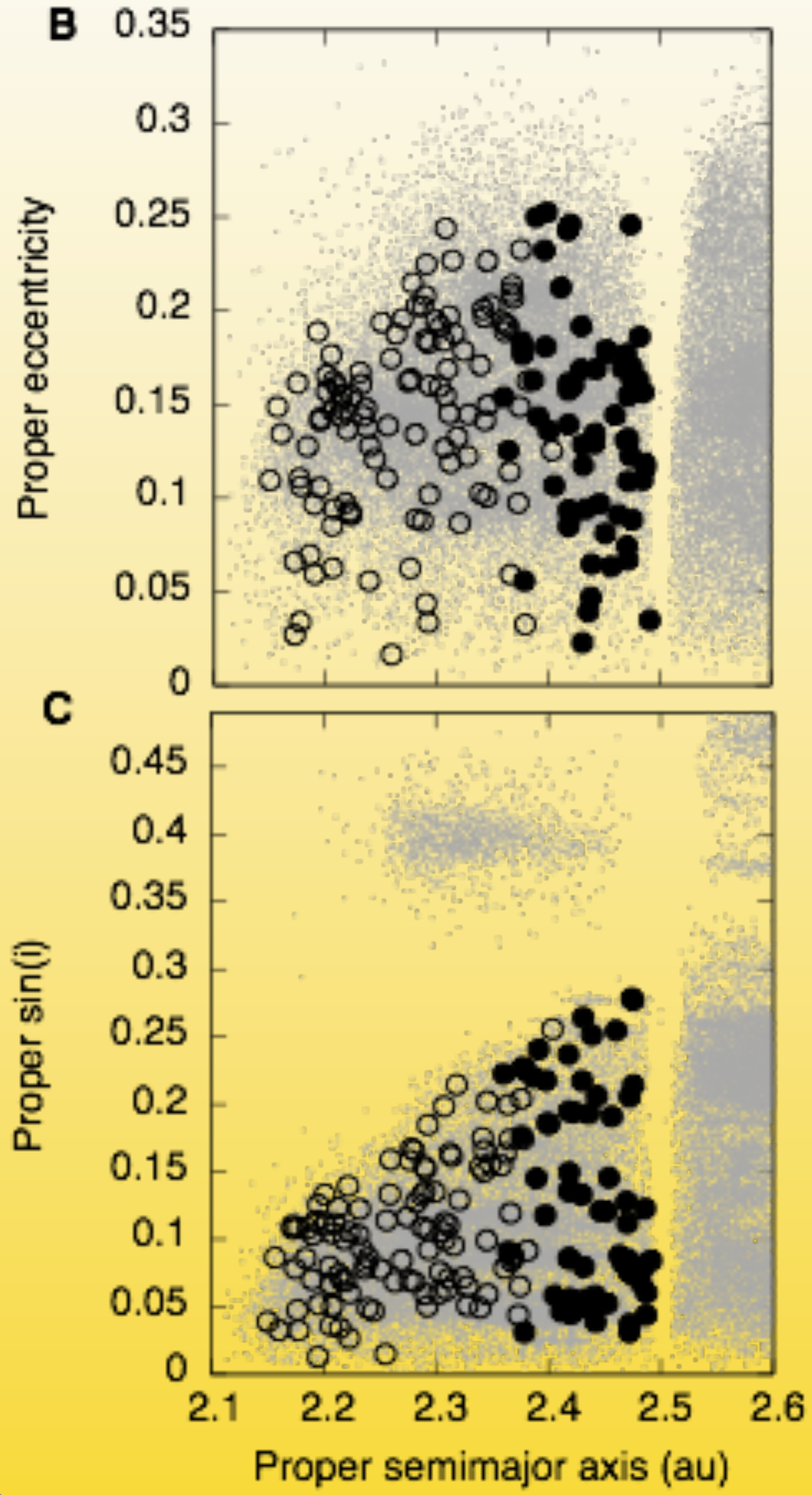


[Brasil et al., 2016]

Orbital distribution

Observations

Primordial Family

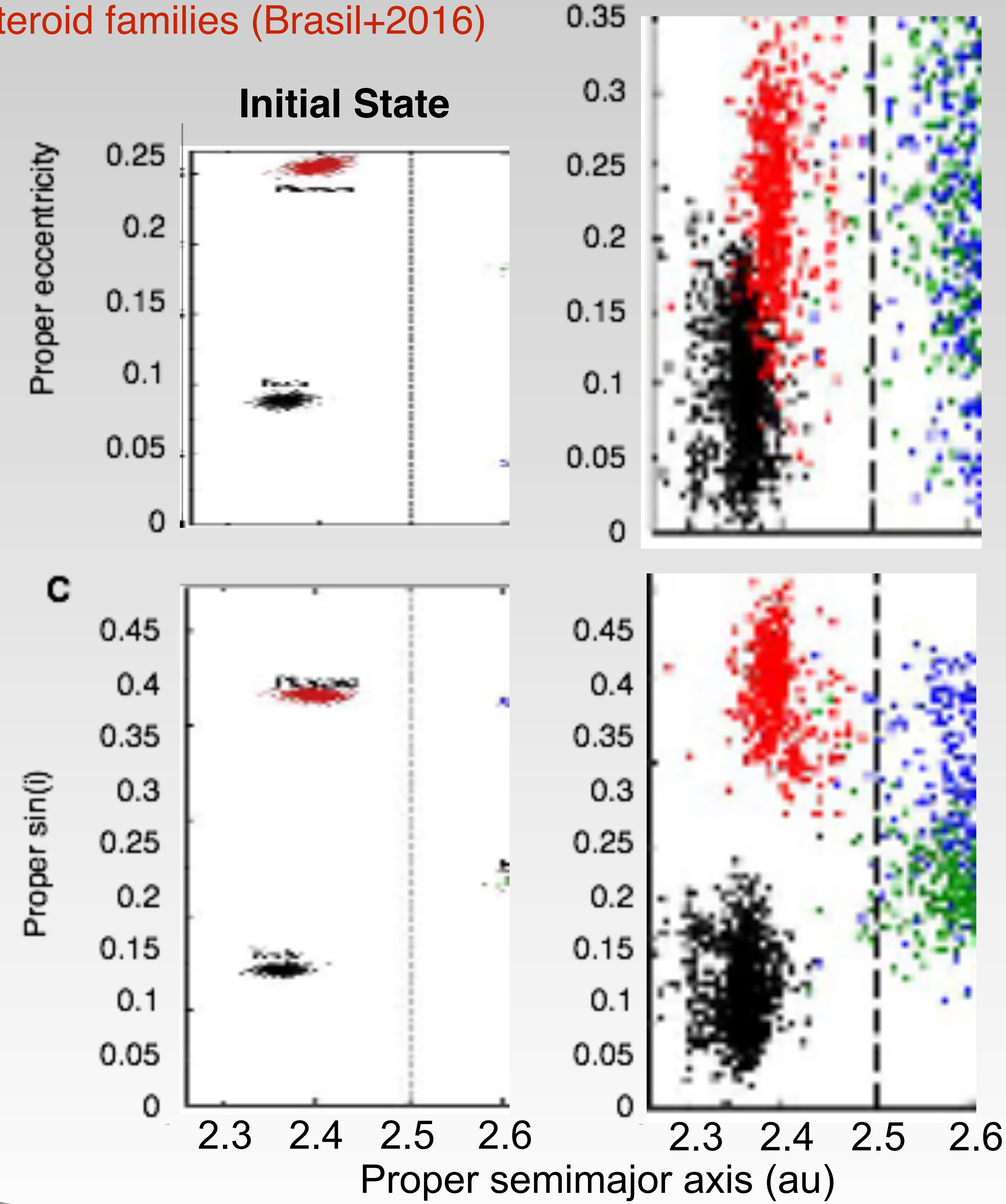


Simulations

Dynamical dispersal of primordial asteroid families (Brasil+2016)

Initial State

After the giant planets orbital instability



Conclusions

- We discovered a primordial asteroid family whose members are almost all low-albedo asteroids of the inner Main Belt previously unlinked to families.
- The age of the family is ~4 Gyr, but it could be as old as the Solar System.
- The orbital distribution of the family members is consistent with the asteroid being dispersed by resonance sweeping/moving during the giant planet orbital instability.
- The very few asteroids that cannot be associated to families are all big (>50 km for low-albedo, >35 km for high albedo) (Kevin Walsh's talk)

Further information

- Delbo, M., Walsh, K., Bolin, B., Avdellidou, C. & Morbidelli, A. Identification of a primordial asteroid family constrains the original planetesimal population. *Science* **357**, 1026–1029 (2017).
- DeMeo, F. Meet the primordial asteroid family. *Science* **357** (2017).
- Bolin, B. T., Delbo, M., Morbidelli, A. & Walsh, K. J. Yarkovsky V-shape identification of asteroid families. *Icarus* **282**, 290–312 (2017).