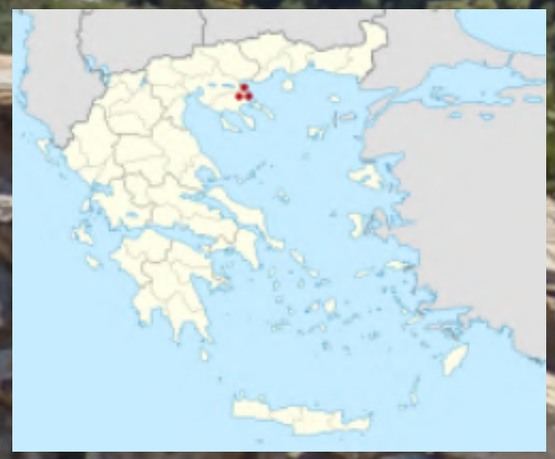
Asteroidi più antichi: alla ricerca delle origini del nostro sistema solare

Marco Delbo'
CNRS - Observatoire de la Côte d'Azur

The formation of planets

One of the most ancient and unresolved fundamental mysteries

<u>Στάγειρα</u>
Ancien Greek city of Stagira, birth place of Aristotle [384-322 BC]



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- How big is Earth, the Sun and the Moon ?
- How far is the Sun, the Moon, and how far are other planets and stars ?
- How did the cosmos formed and within it Earth came to be?

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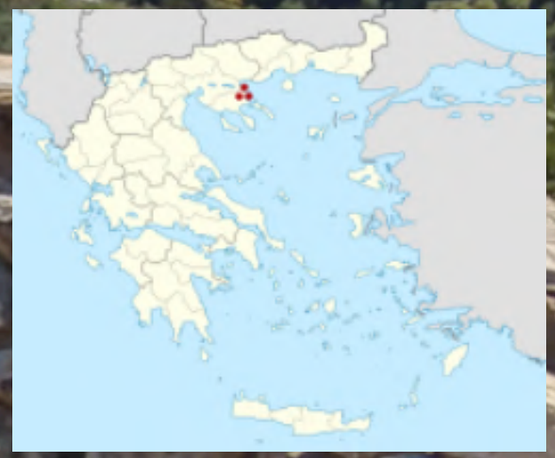

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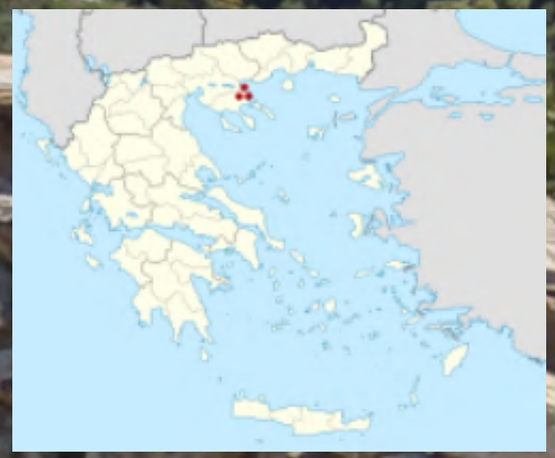
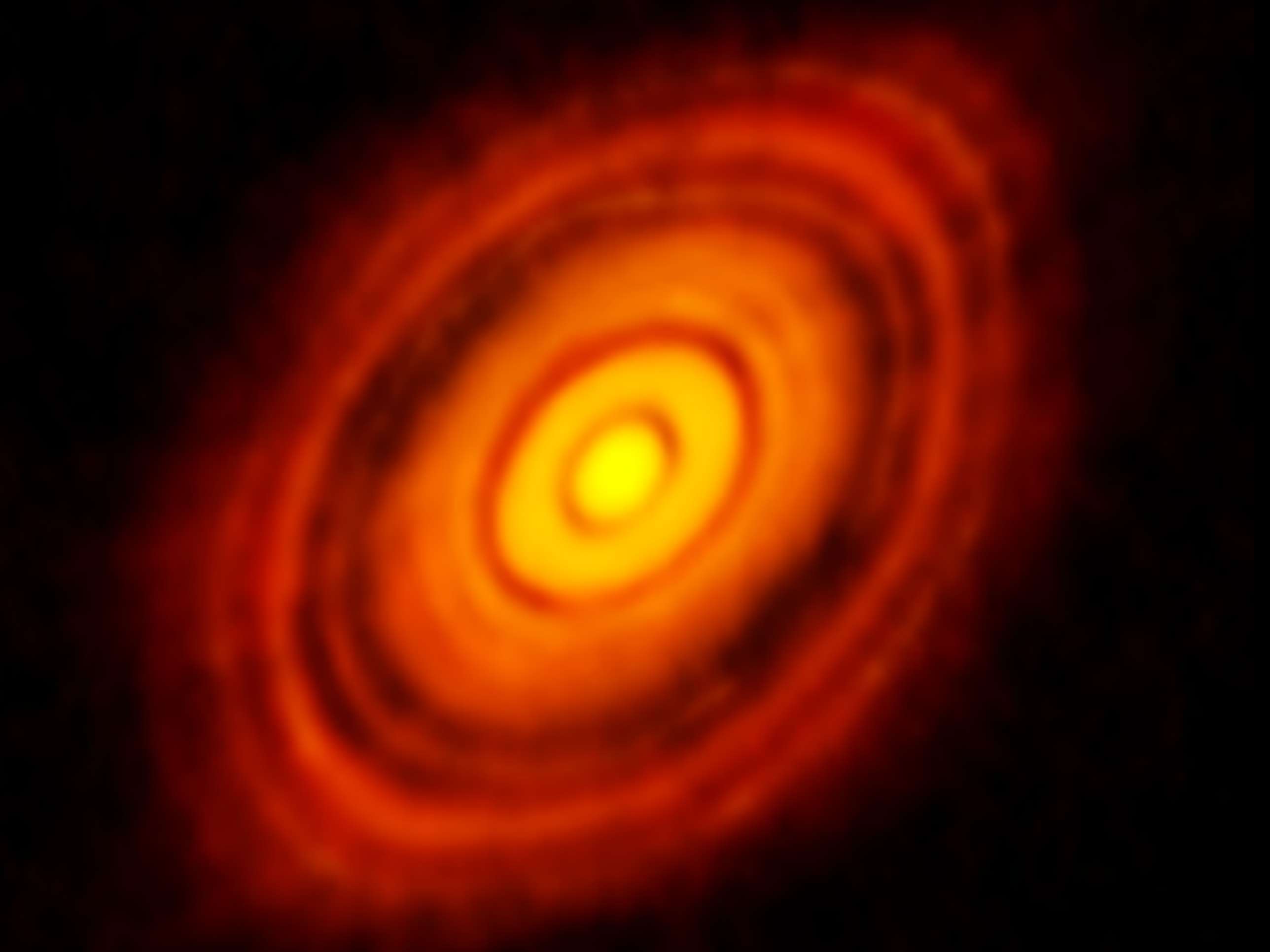




SPHERE images a zoo of dusty discs around young stars

Eso1811 — Photo Release

https://www.eso.org/public/news/eso1811/

PROTOPLANETARY DISKS

Specimens exhibiting rings, gaps, & spirals

RX J1615

Light-years from Earth: 600
Instrument: SPHERE

HD 163296

Light-years from Earth: 600
Instrument: SPHERE

HD 169142

Light-years from Earth: 380
Instrument: ALMA

TW HYDRAE

Light-years from Earth: 194
Instrument: ALMA

AS 209

Light-years from Earth: 400
Instrument: ALMA

ELIAS 2-27

Light-years from Earth: 450
Instrument: ALMA

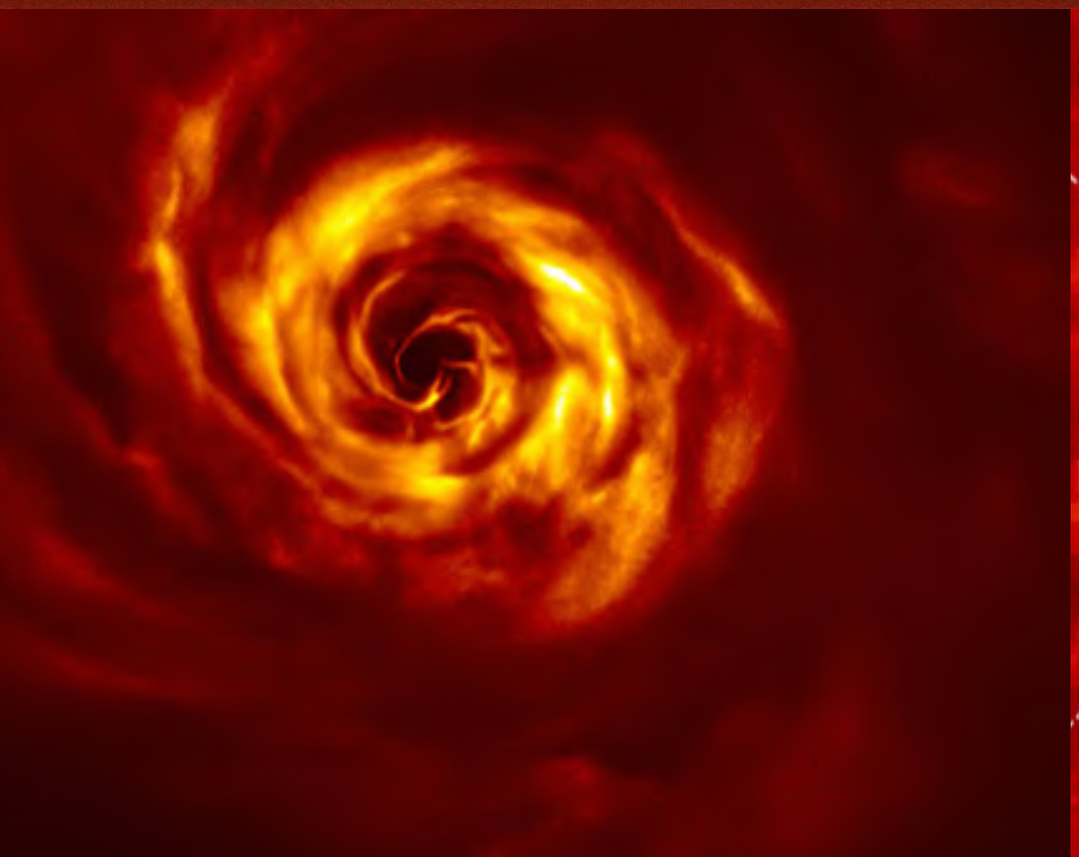
HD 135344B

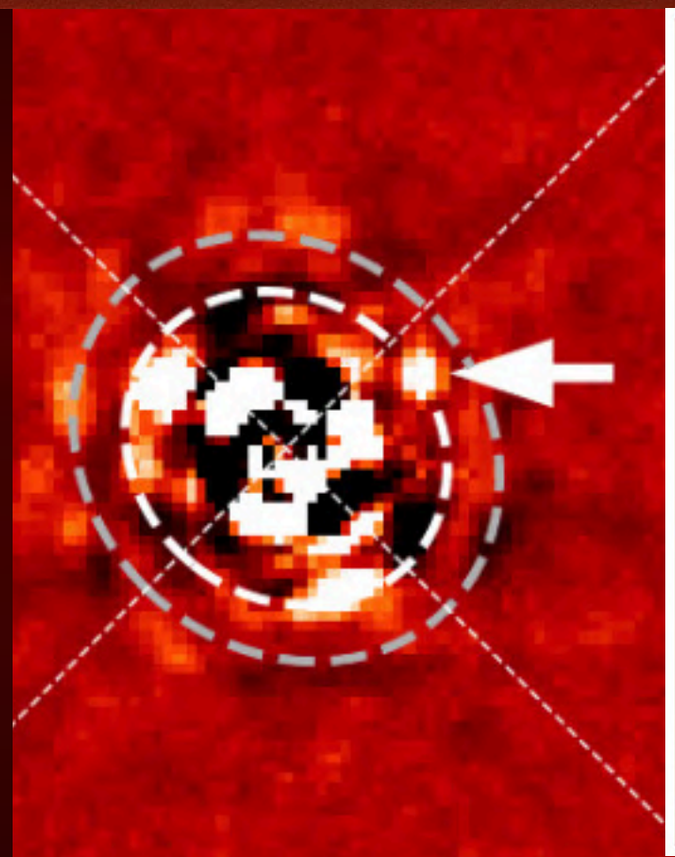
Light-years from Earth: 450
Instrument: SPHERE

HL TAURI

Light-years from Earth: 450
Instrument: ALMA

WARNING: OBJECTS NOT TO SCALE





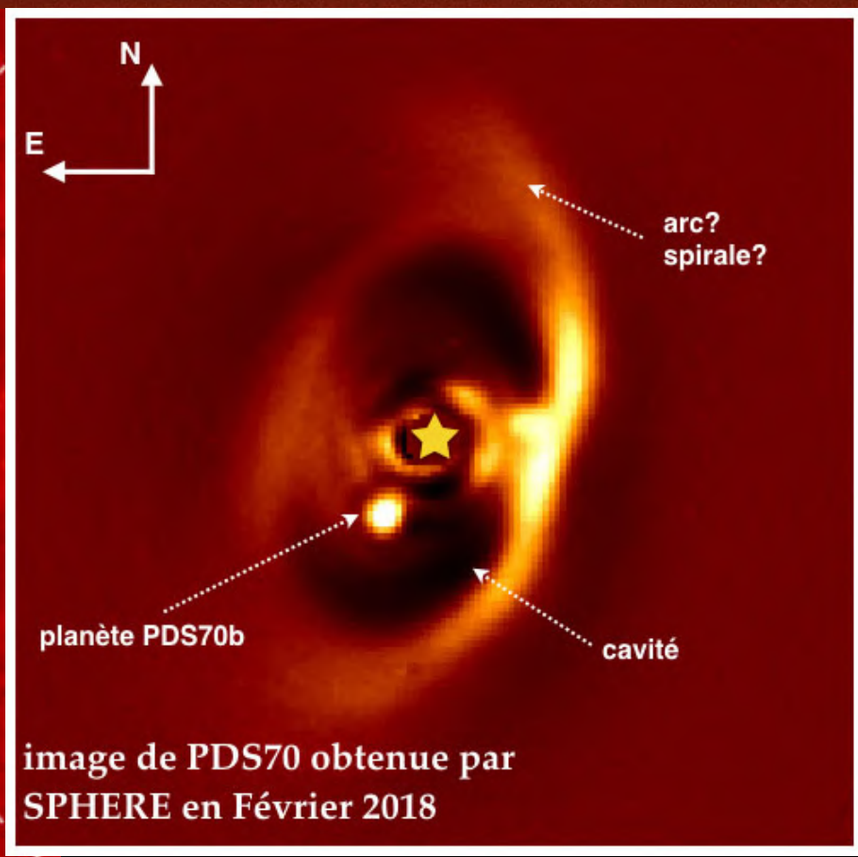
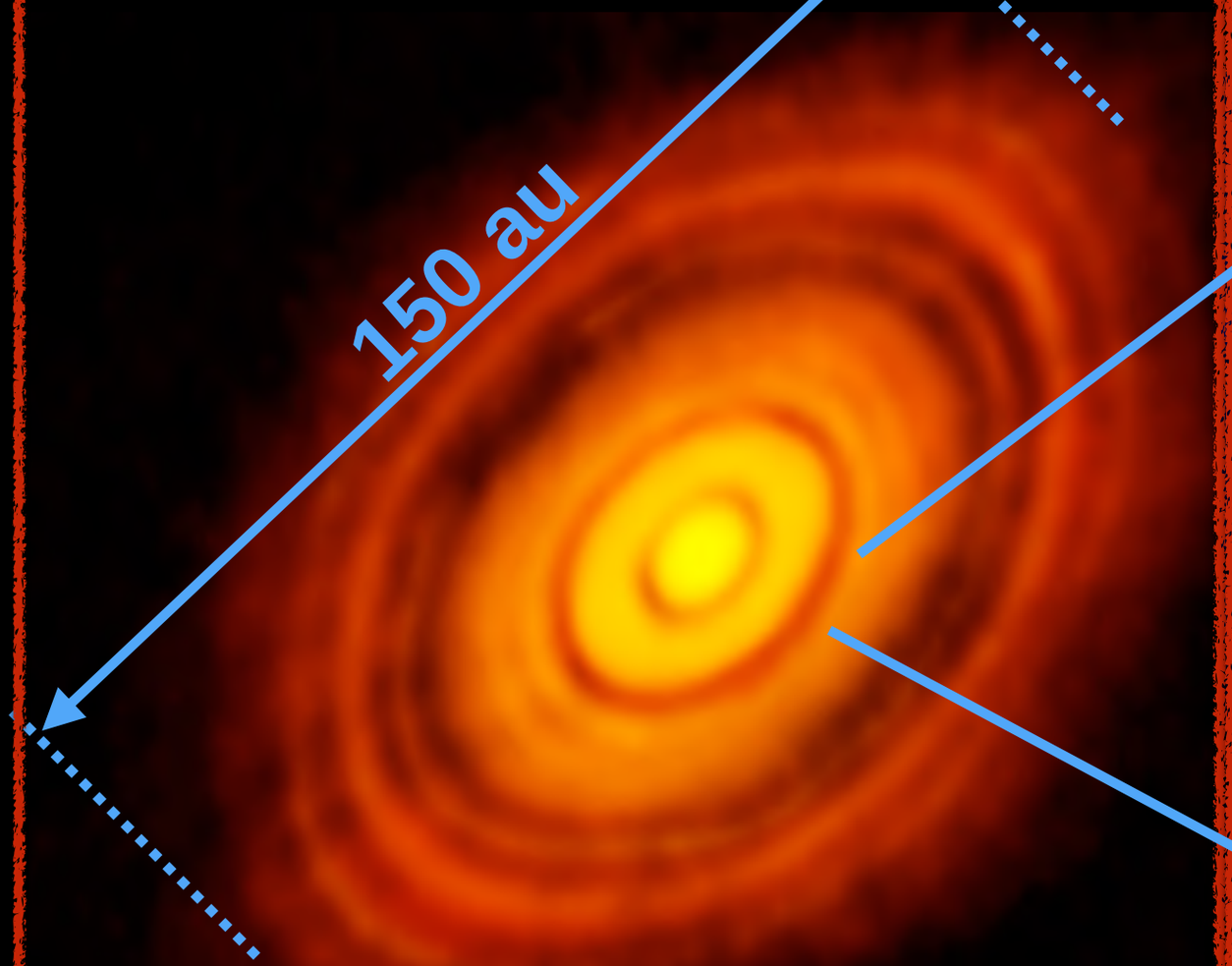


image de PDS70 obtenue par SPHERE en Février 2018

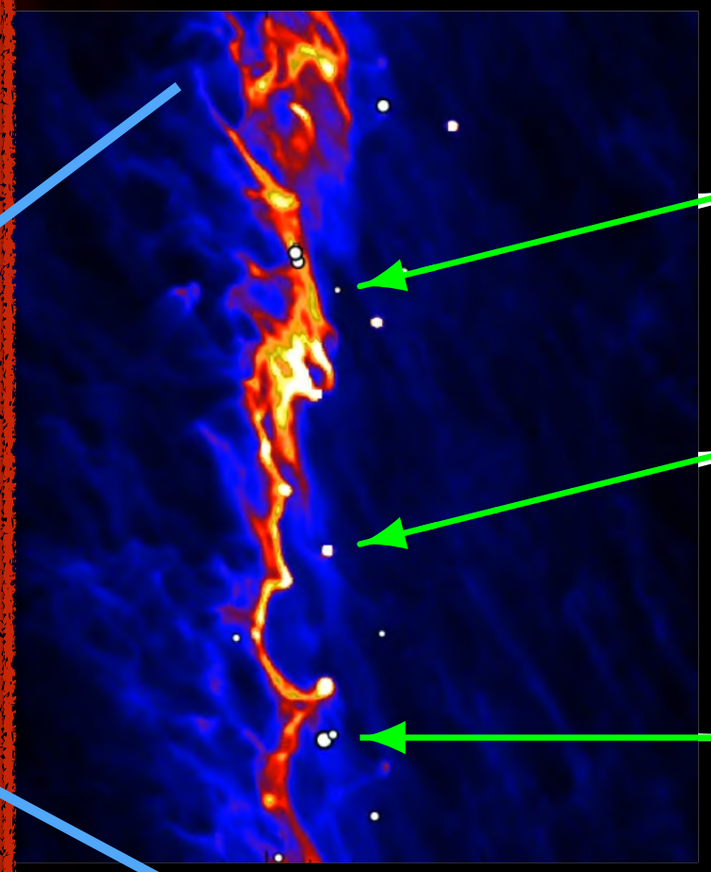
From dust to planets in protoplanetary disks

Observations



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

Simulations



Simulation of planetesimal formation by
“streaming instability”

Questions

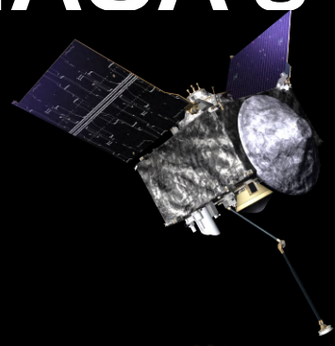
What are the typical sizes of planetesimals?
What is their composition?
Where can we find them today in the Solar System?

Youdin & Goodman, ApJ, 2005
Johansen+2007
Bai & Stone, ApJ, 2010

Planetesimals

- the precursors of planets
- the most primordial smallest objects bound by their own self-gravity instead of their material binding forces
- **in the asteroid main belt**, planetesimals = **original asteroids**, i.e. those asteroids that formed by accretion in the protoplanetary disk
- There are other type of asteroids, which are younger, i.e. those that formed as collisional fragments of more primitive (older) asteroids (likely the original asteroids = planetesimals)

NASA’s OSIRIS-



JAXA’s
Hayabusa2

Bennu
560 m

Ryugu
870 m

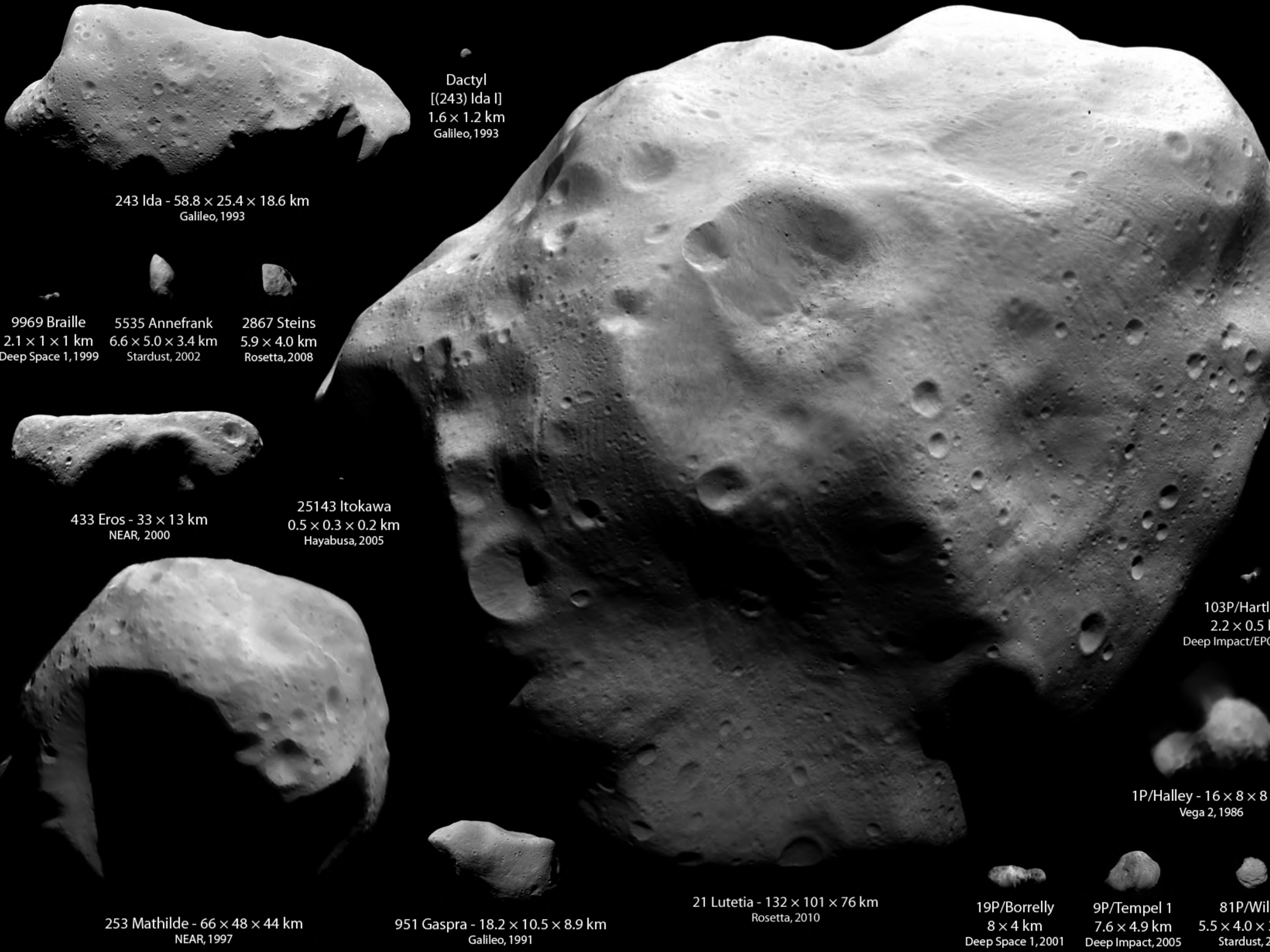
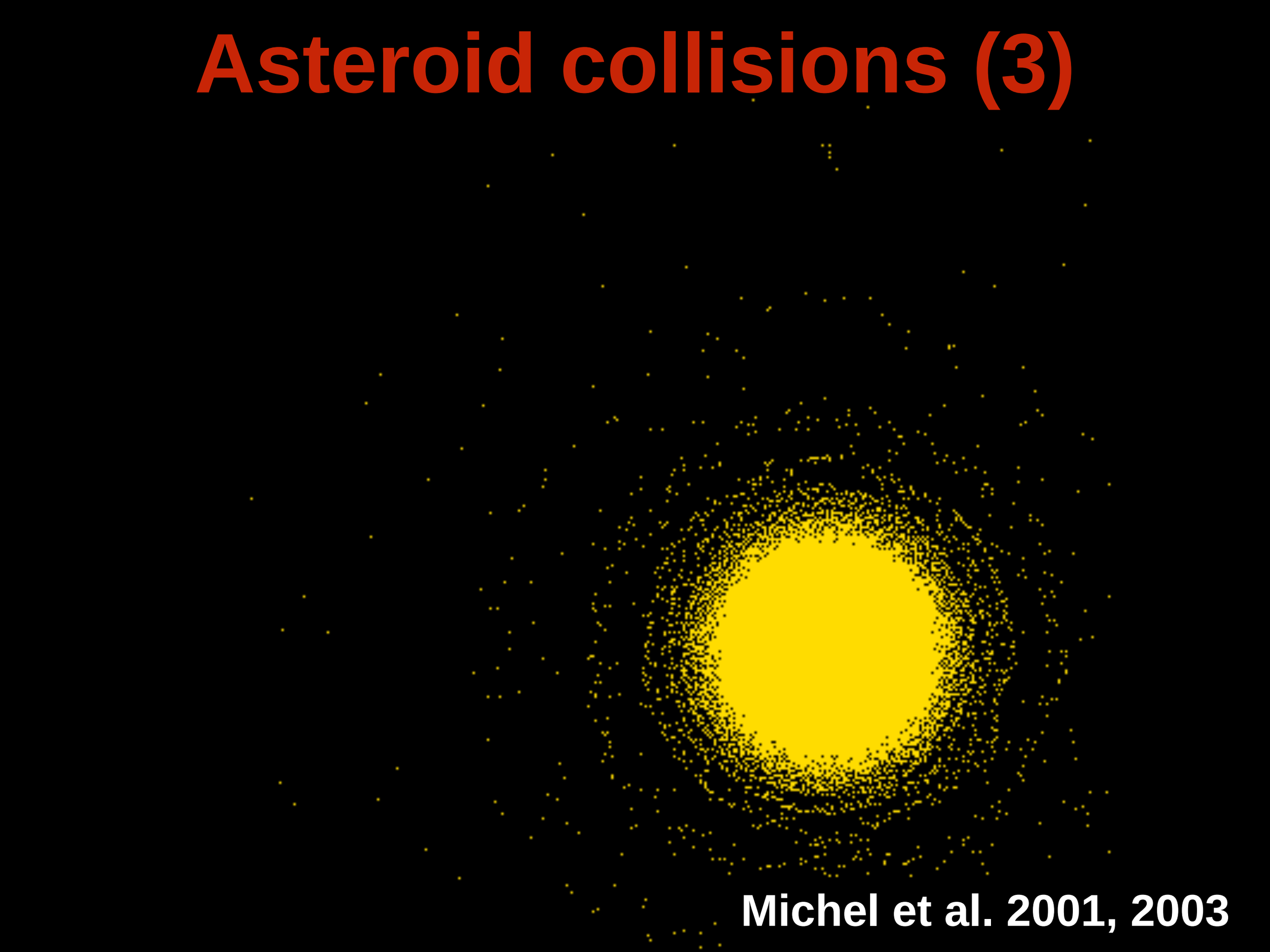

Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993
9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
433 Eros - 33 × 13 km
NEAR, 2000
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
253 Mathilde - 66 × 48 × 44 km
NEAR, 1997
951 Gaspra - 18.2 × 10.5 × 8.9 km
Galileo, 1991
21 Lutetia - 132 × 101 × 76 km
Rosetta, 2010
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
1P/Halley - 16 × 8 × 8
Vega 2, 1986

Image of the surface of (4)Vesta from the NASA Dawn

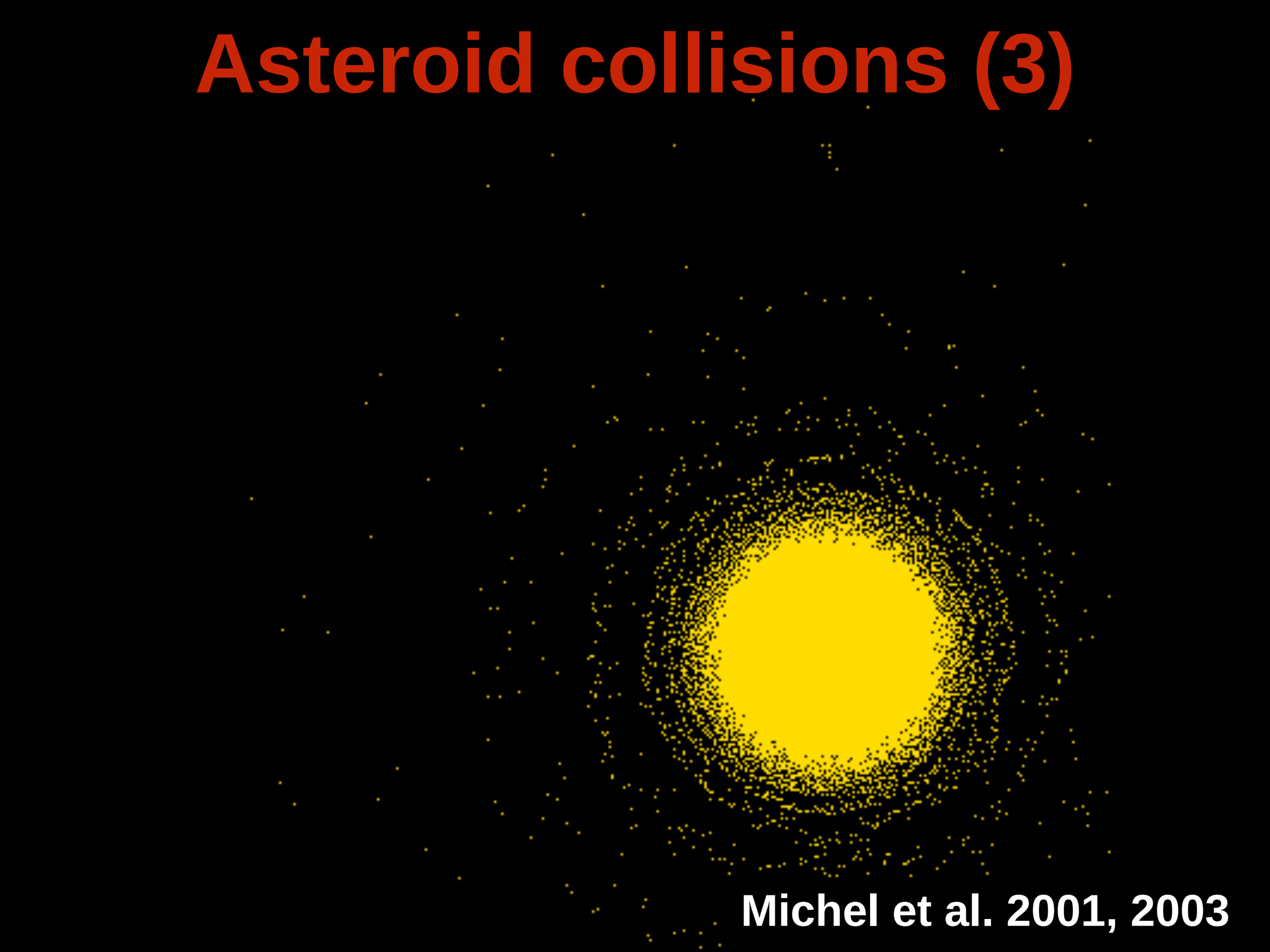
Image: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/ASU

Asteroid collisions (3)



Michel et al. 2001, 2003

Asteroid collisions (3)



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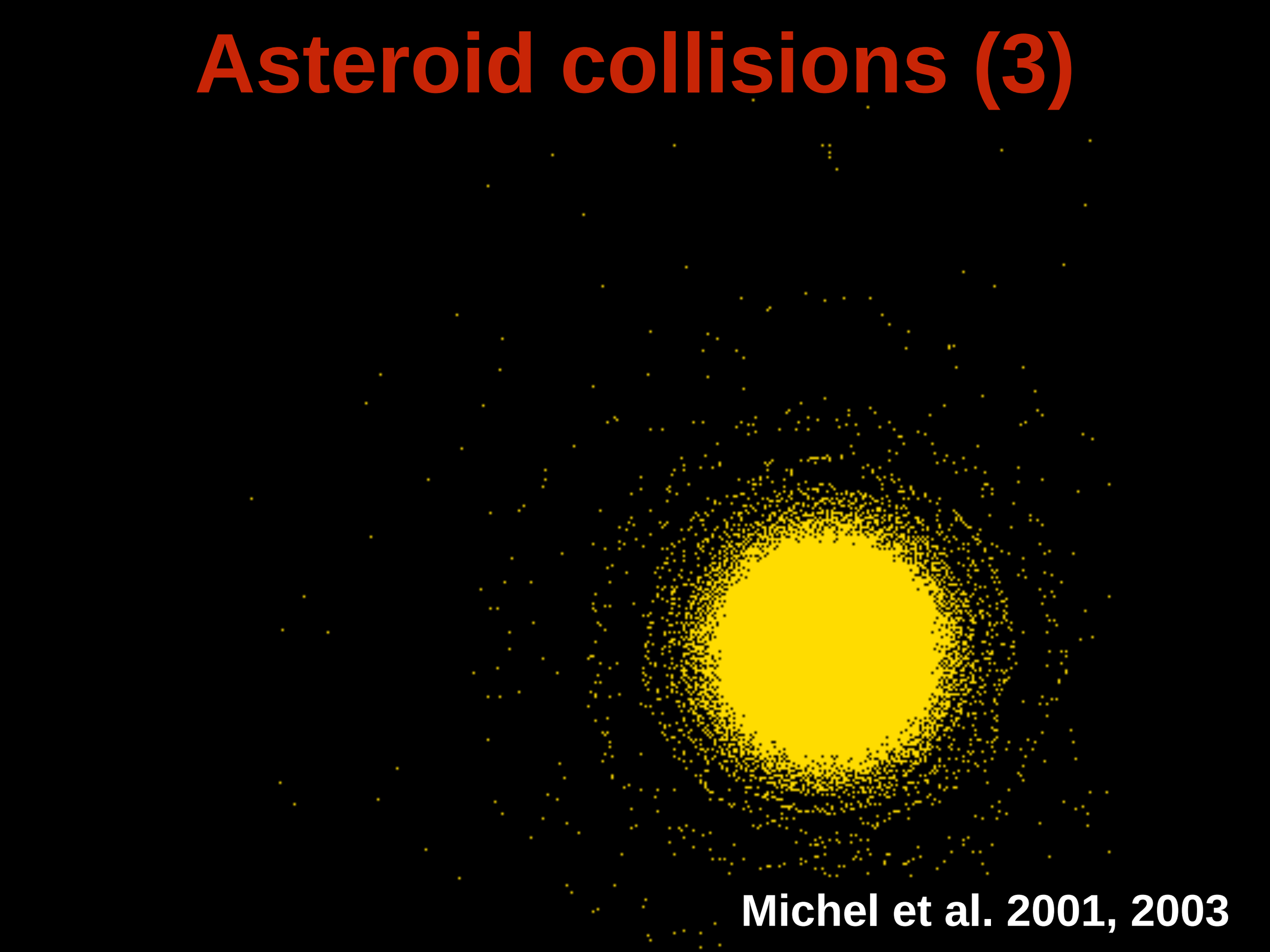

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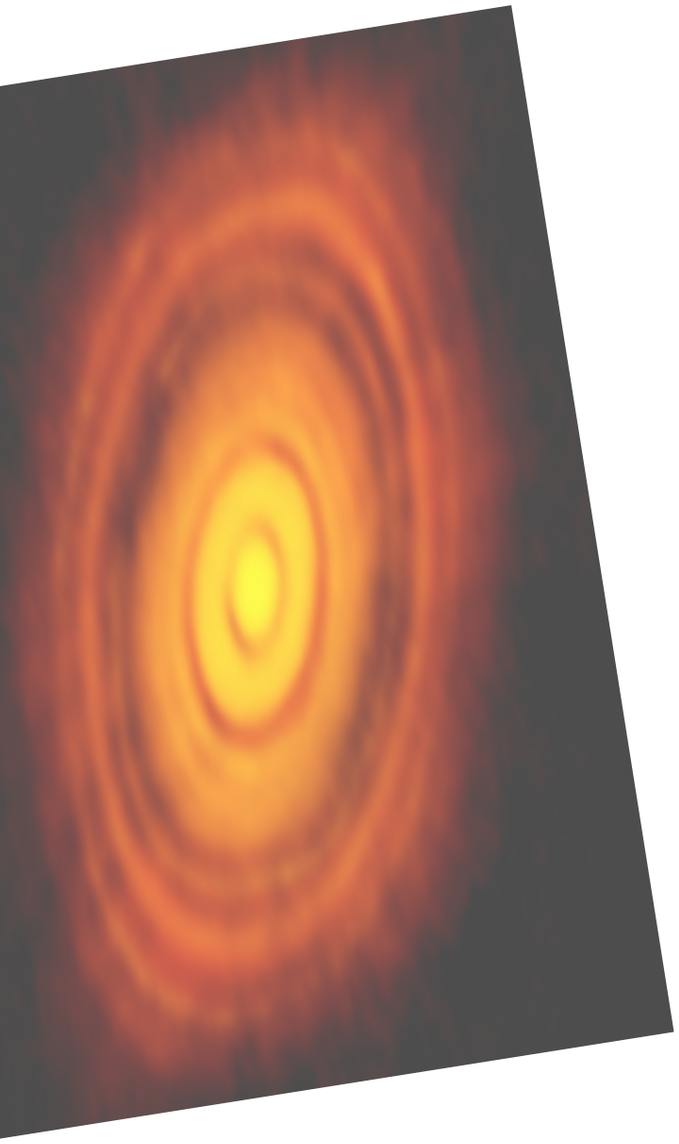
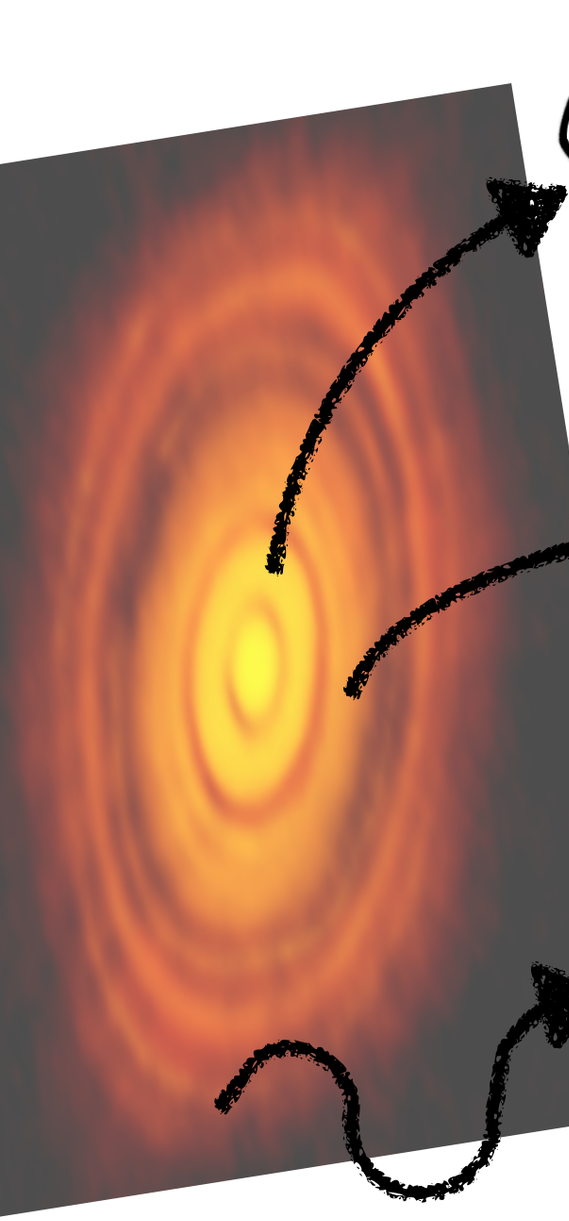
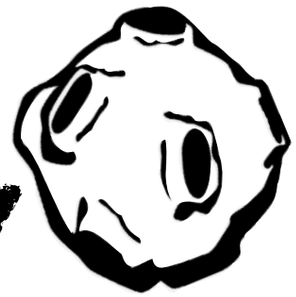
Asteroid Formation



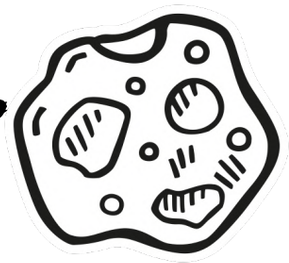
Asteroid Formation

This asteroid may have formed from accretion of dust from in the protoplanetary nebula...

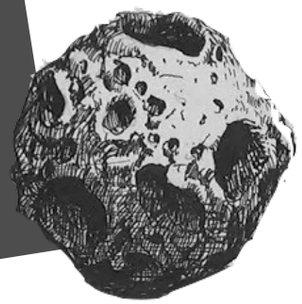




...this asteroid too



... and also this asteroid.



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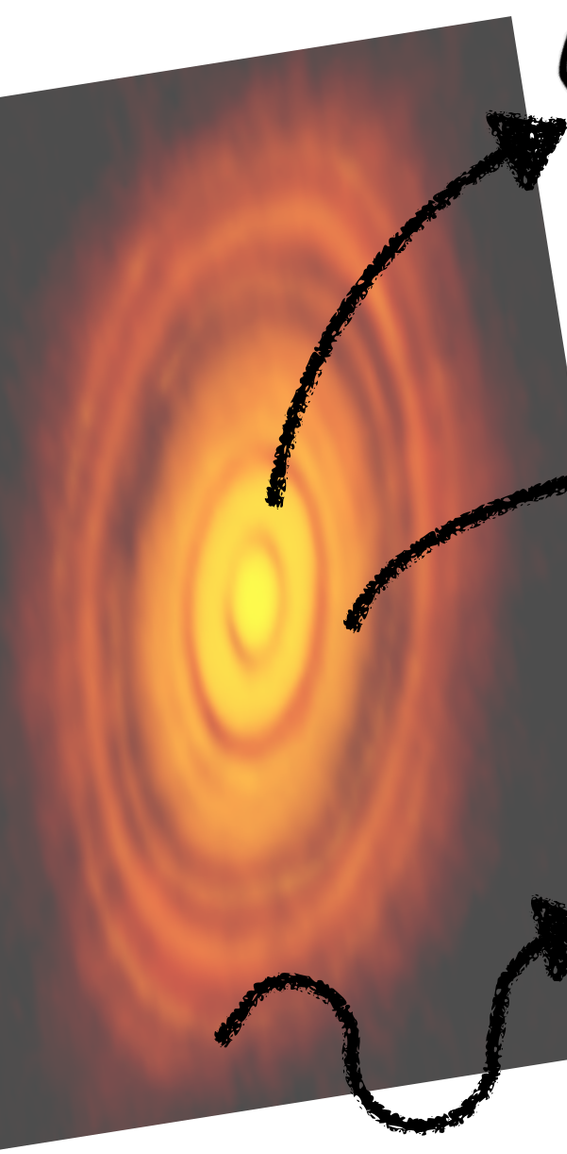
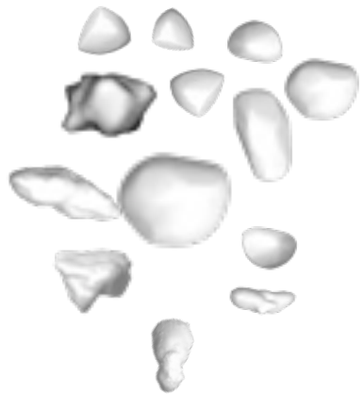


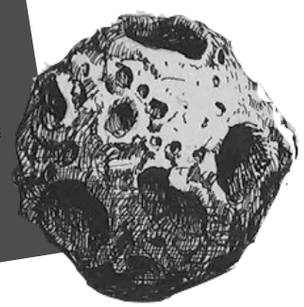
First asteroid broke-up and formed a family of asteroid fragments



...this asteroid too

2nd asteroid did not break up

... and also this asteroid.



3rd asteroid broke-up and formed a family of asteroid fragments too

Asteroid Formation

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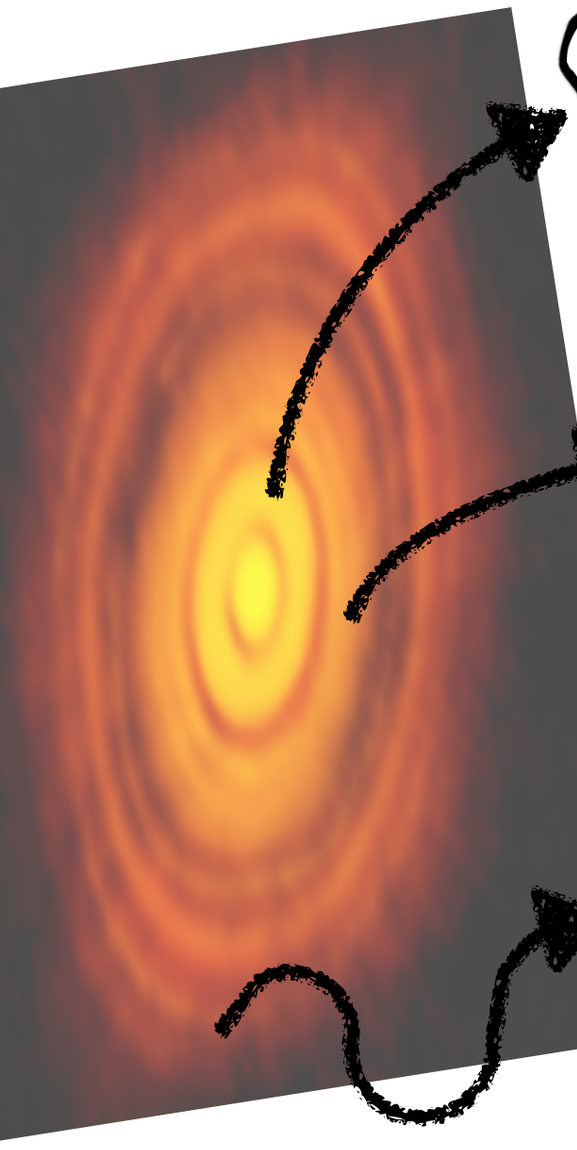
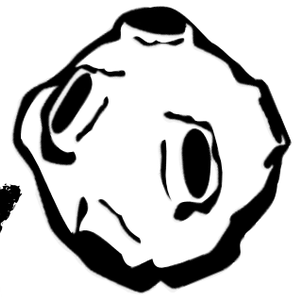


…this asteroid too



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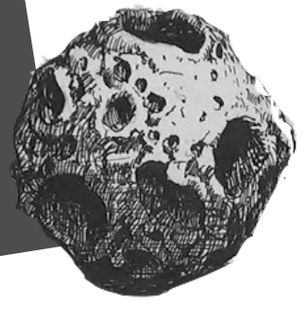

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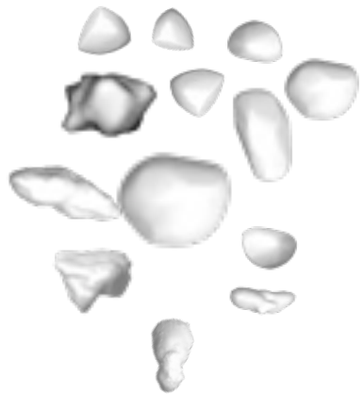


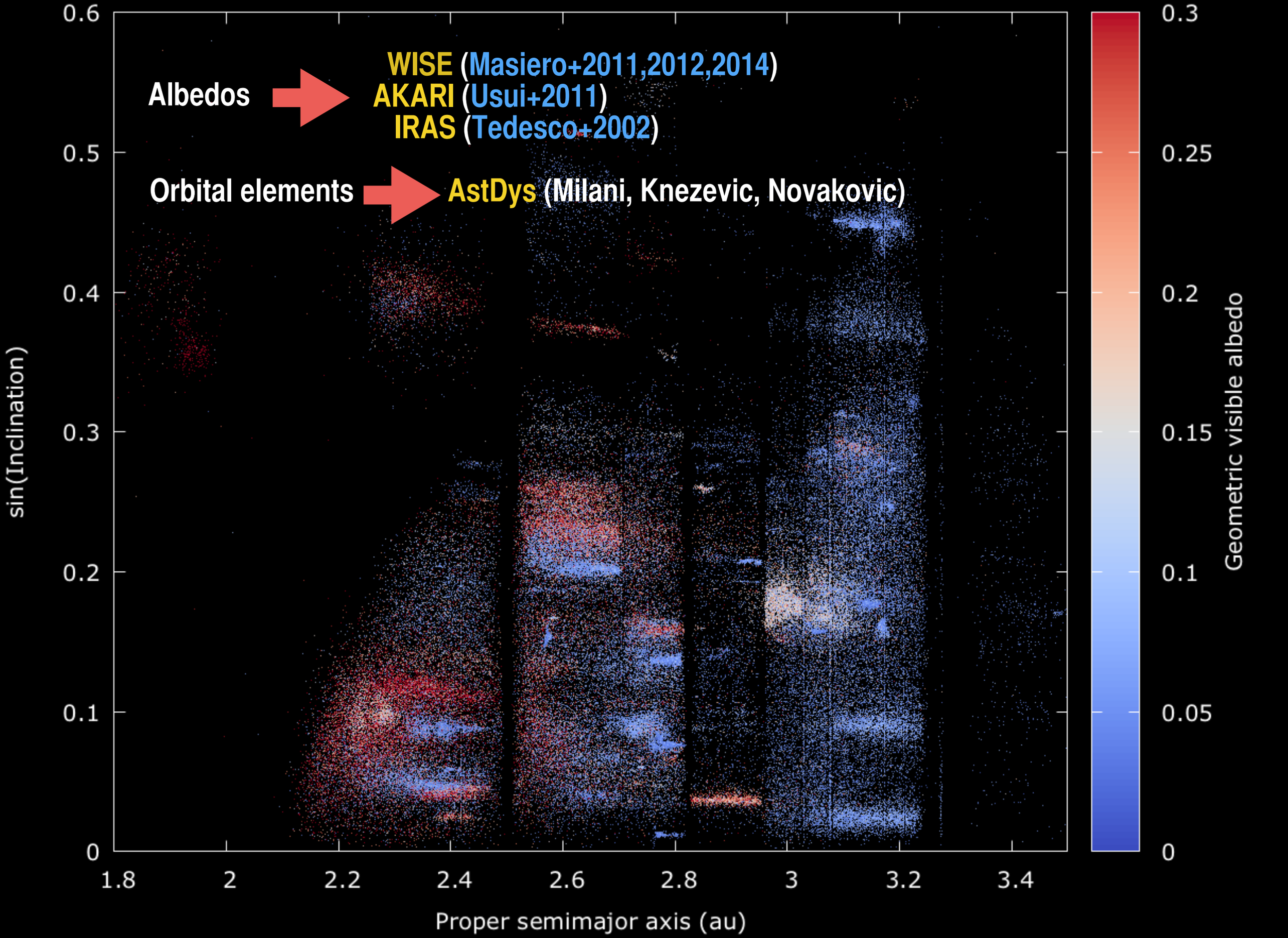
2nd asteroid did not break up

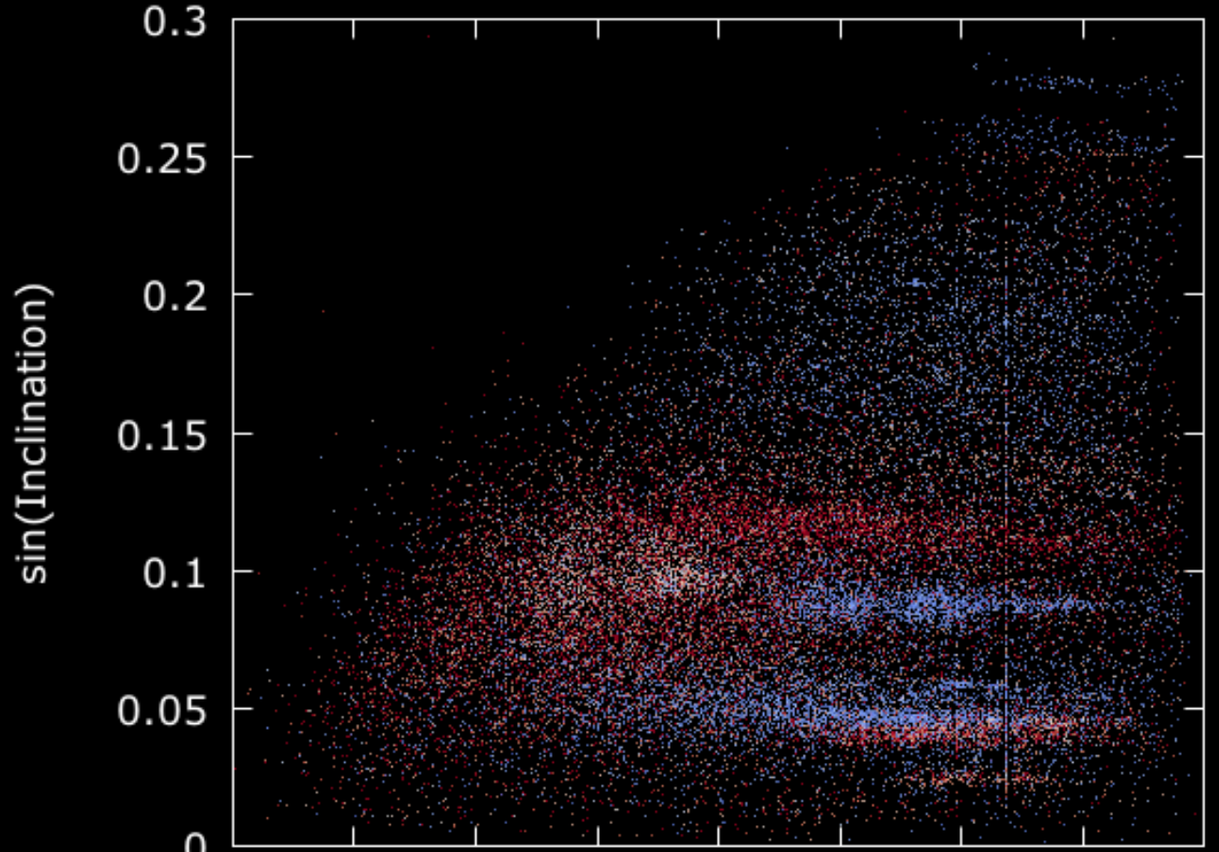
3rd asteroid broke-up and formed a family of asteroid fragments too

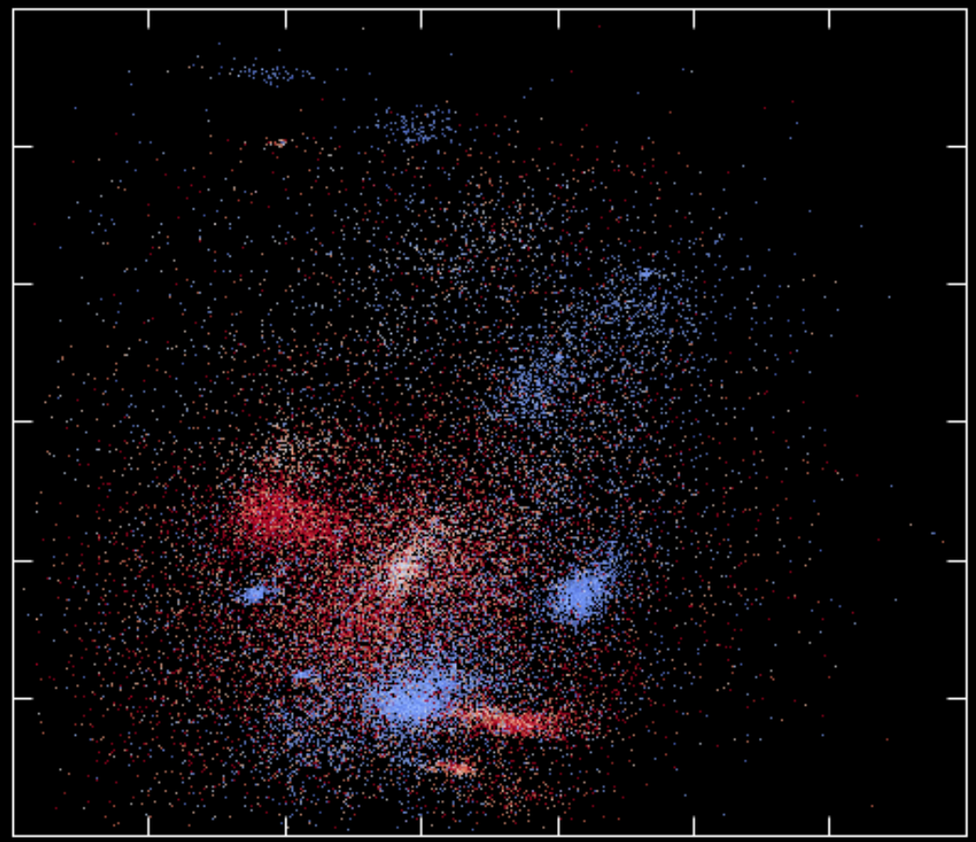
Orbital elements of asteroid family members diffuse with time. Families may overlap among themselves and over the original asteroids

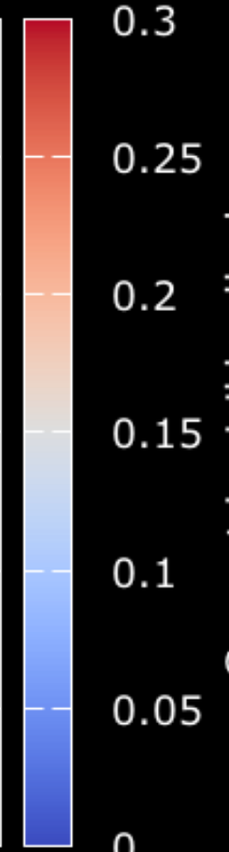
Albedos → WISE (Masiero+2011,2012,2014)
AKARI (Usui+2011)
IRAS (Tedesco+2002)

Orbital elements → AstDys (Milani, Knezevic, Novakovic)

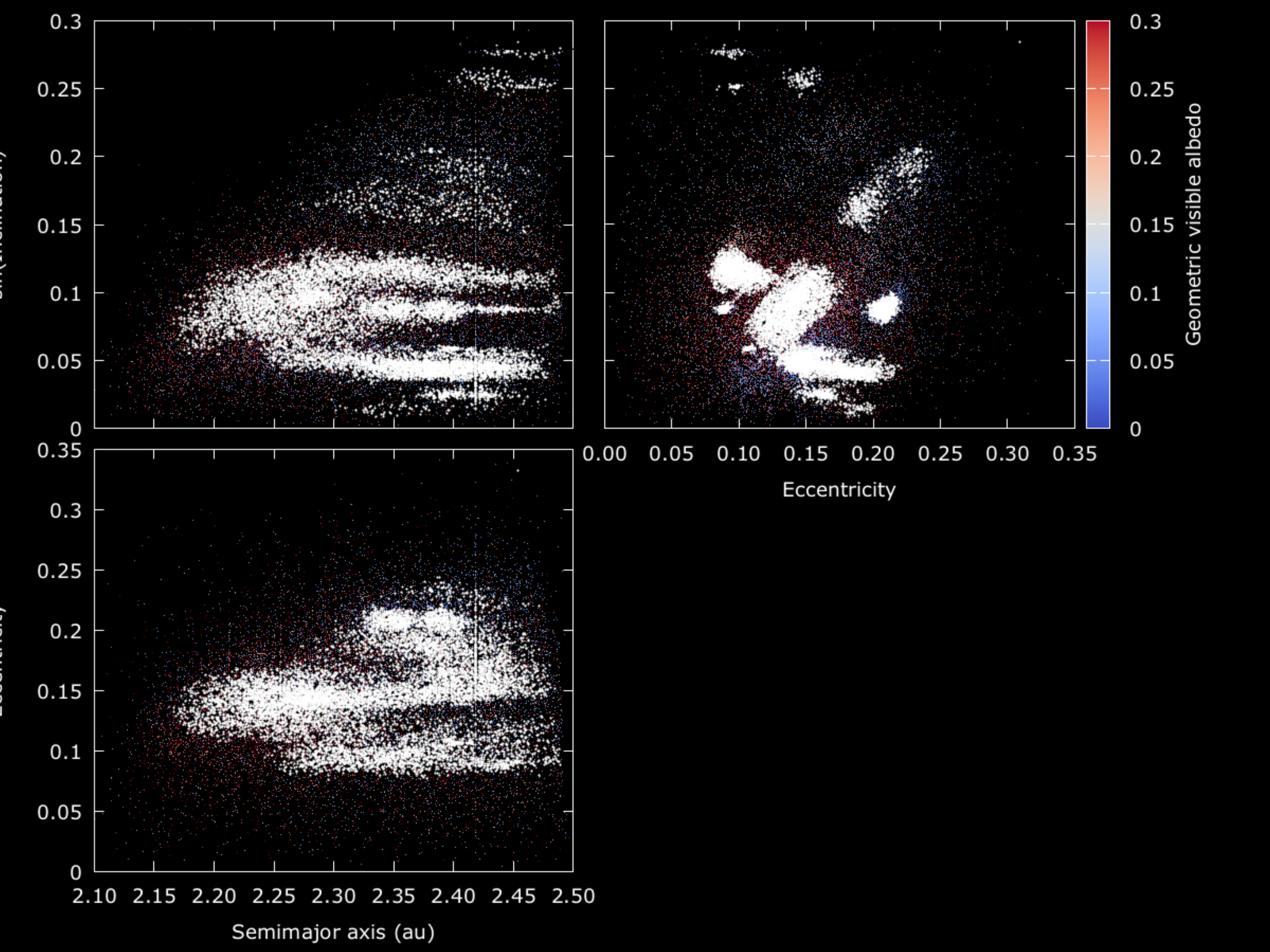



0.3
0.25
0.2
0.15
0.1
0.05
0
sin(Inclination)


0.0
0.1
0.1
0.2
0.2
0.2
0.3
0.3
Eccentricity


0.3
0.25
0.2
0.15
0.1
0.05
0
Geometric visible albedo

0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Eccentricity
2.1
2.1
2.2
2.2
2.3
2.3
2.4
2.4
2.5
Semimajor axis (au)


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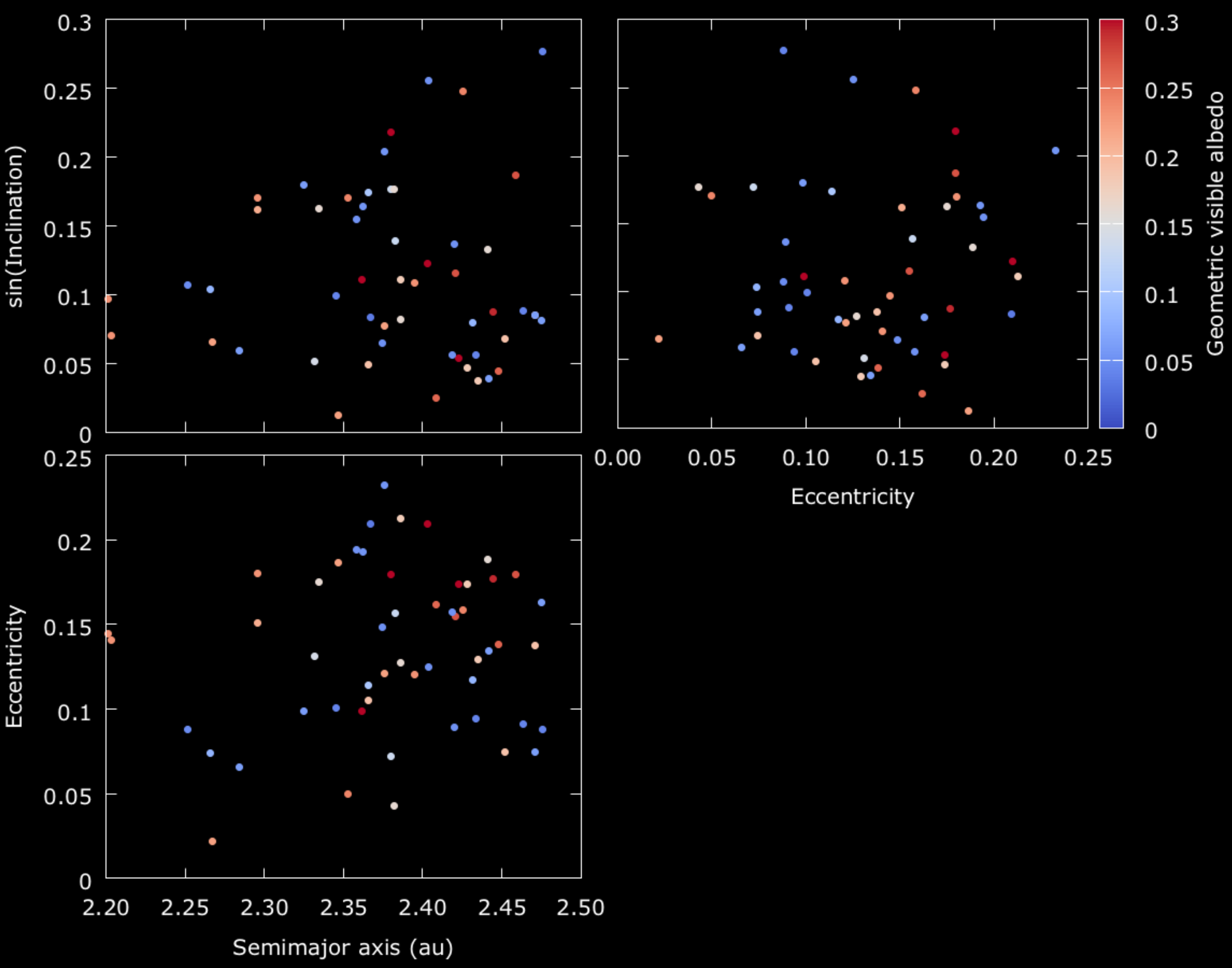
Eccentricity
2.10 2.15 2.20 2.25 2.30 2.35 2.40 2.45 2.50
Semimajor axis (au)


sin(Inclination)
0.3
0.25
0.2
0.15
0.1
0.05
0
0.00
0.05
0.10
0.15
0.20
0.25
Eccentricity
Geometric visible albedo
0.3
0.25
0.2
0.15
0.1
0.05
0
Eccentricity
0.25
0.2
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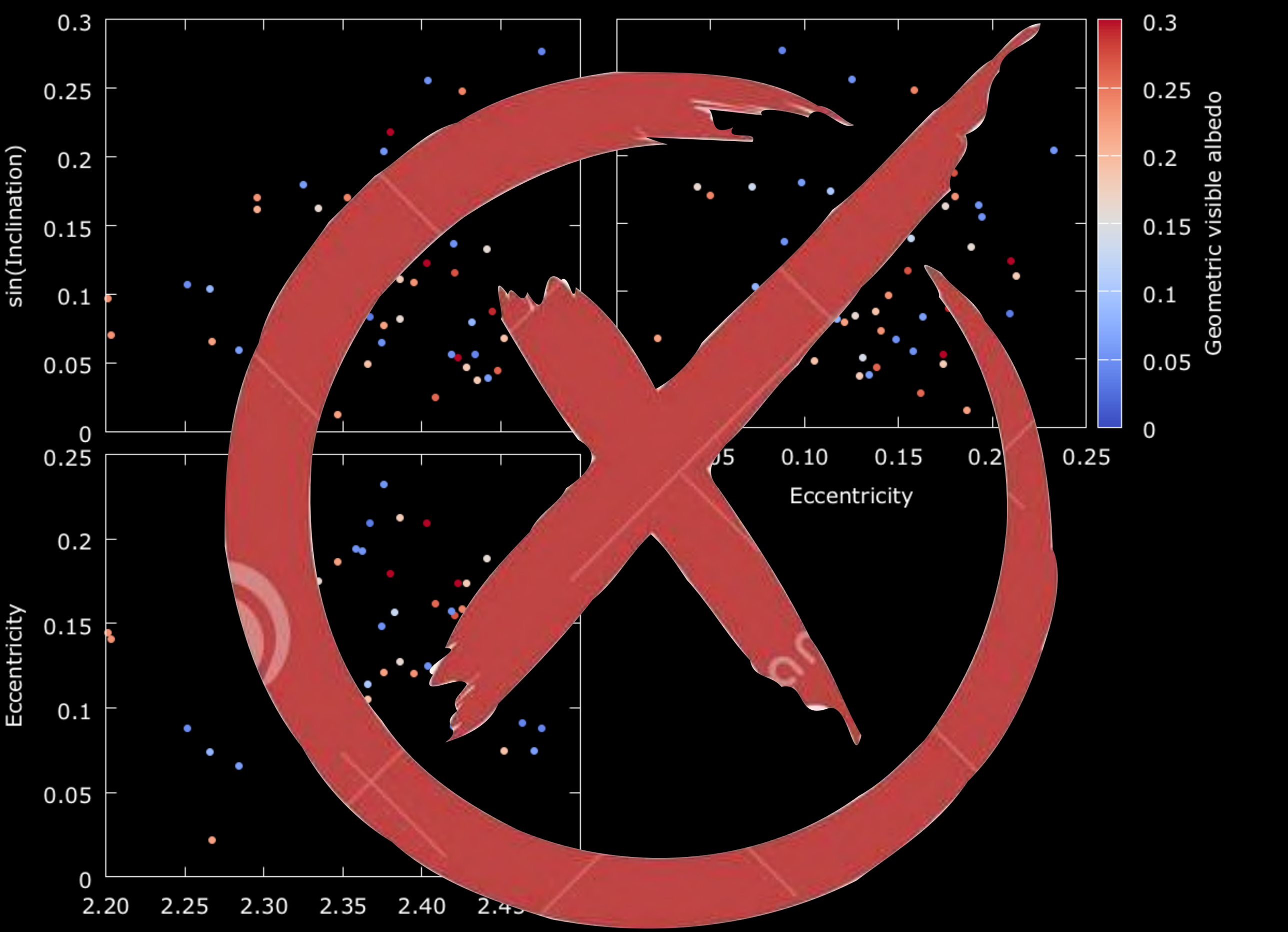
2.40
2.45
2.50
Semimajor axis (au)


0.3
0.25
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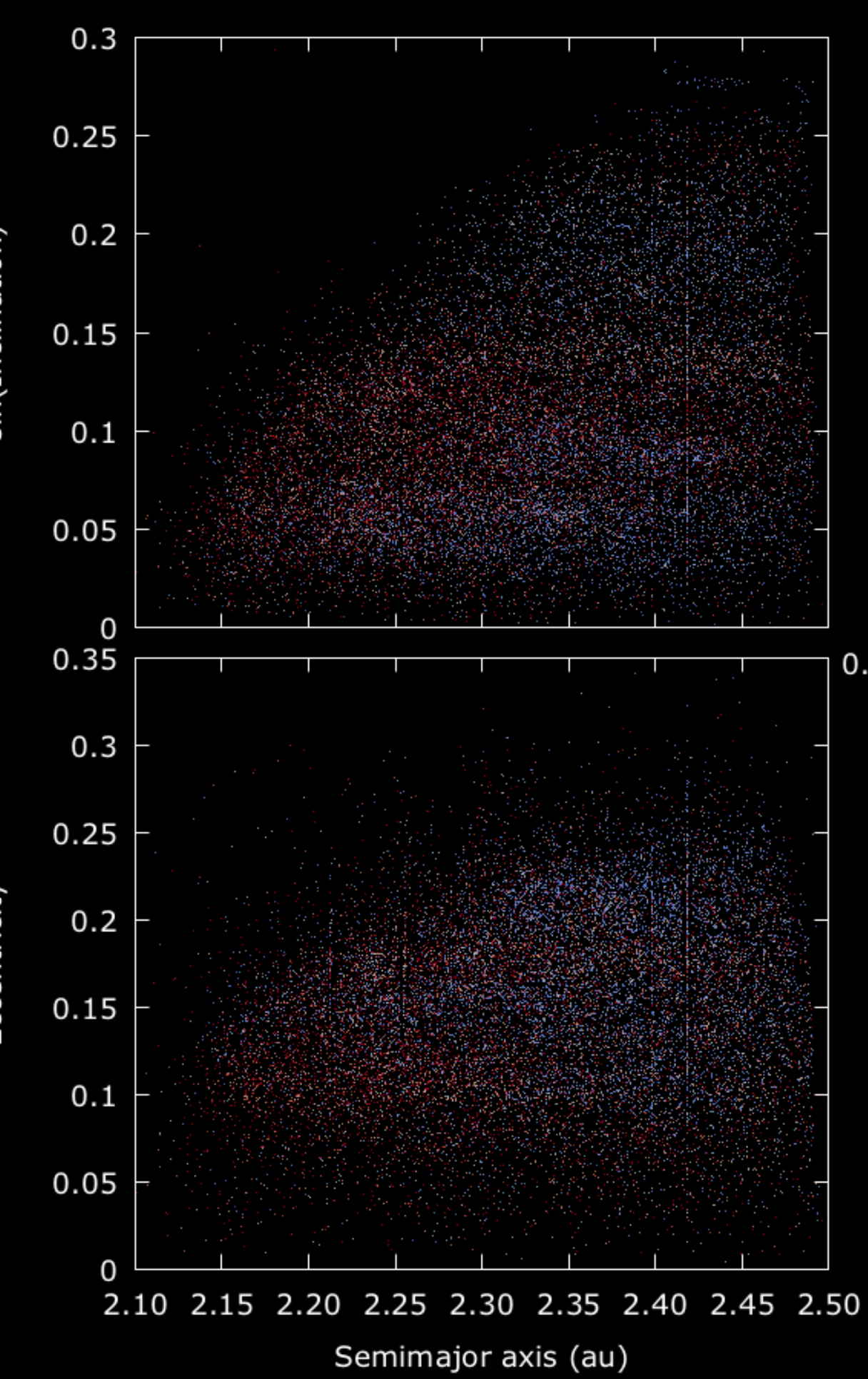
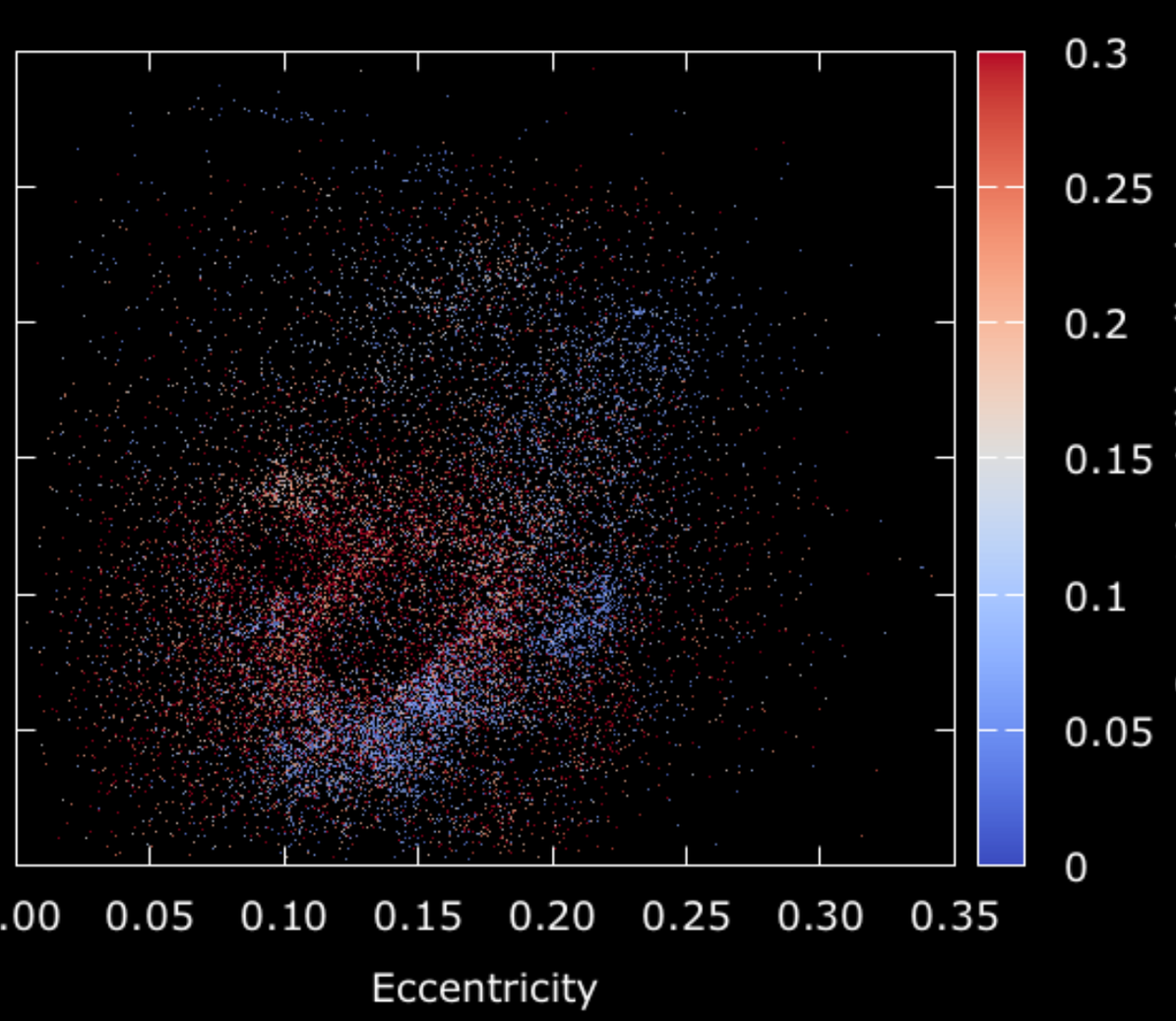
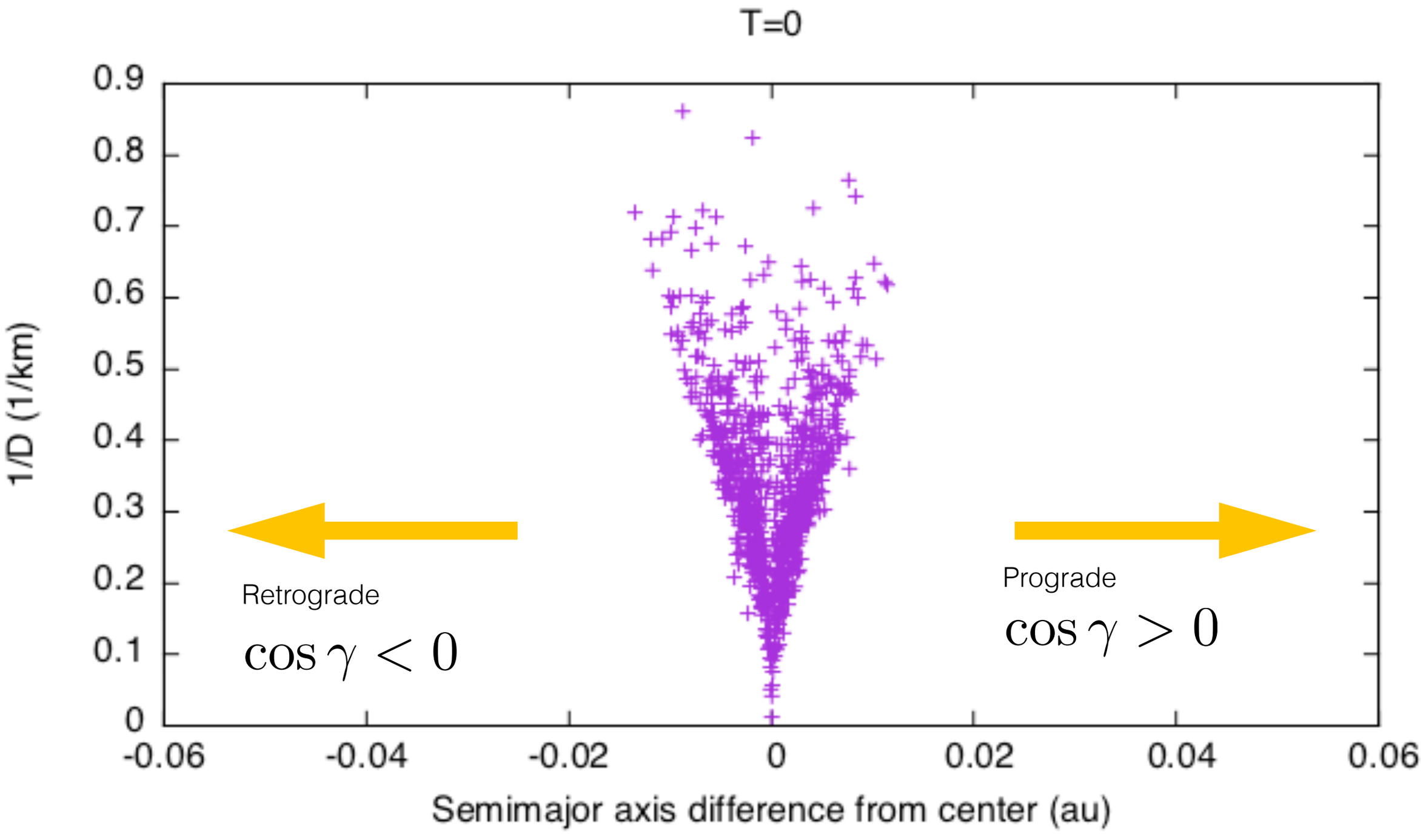
0.15
0.1
0.05
0
sin(Inclination)
0.25
0.2
0.15
0.1
0.05
0
Eccentricity
2.20
2.25
2.30
2.35
2.40
Semimajor axis (au)
0.10
0.15
0.2
0.25
Eccentricity
0.3
0.25
0.2
0.15
0.1
0.05
0
Geometric visible albedo



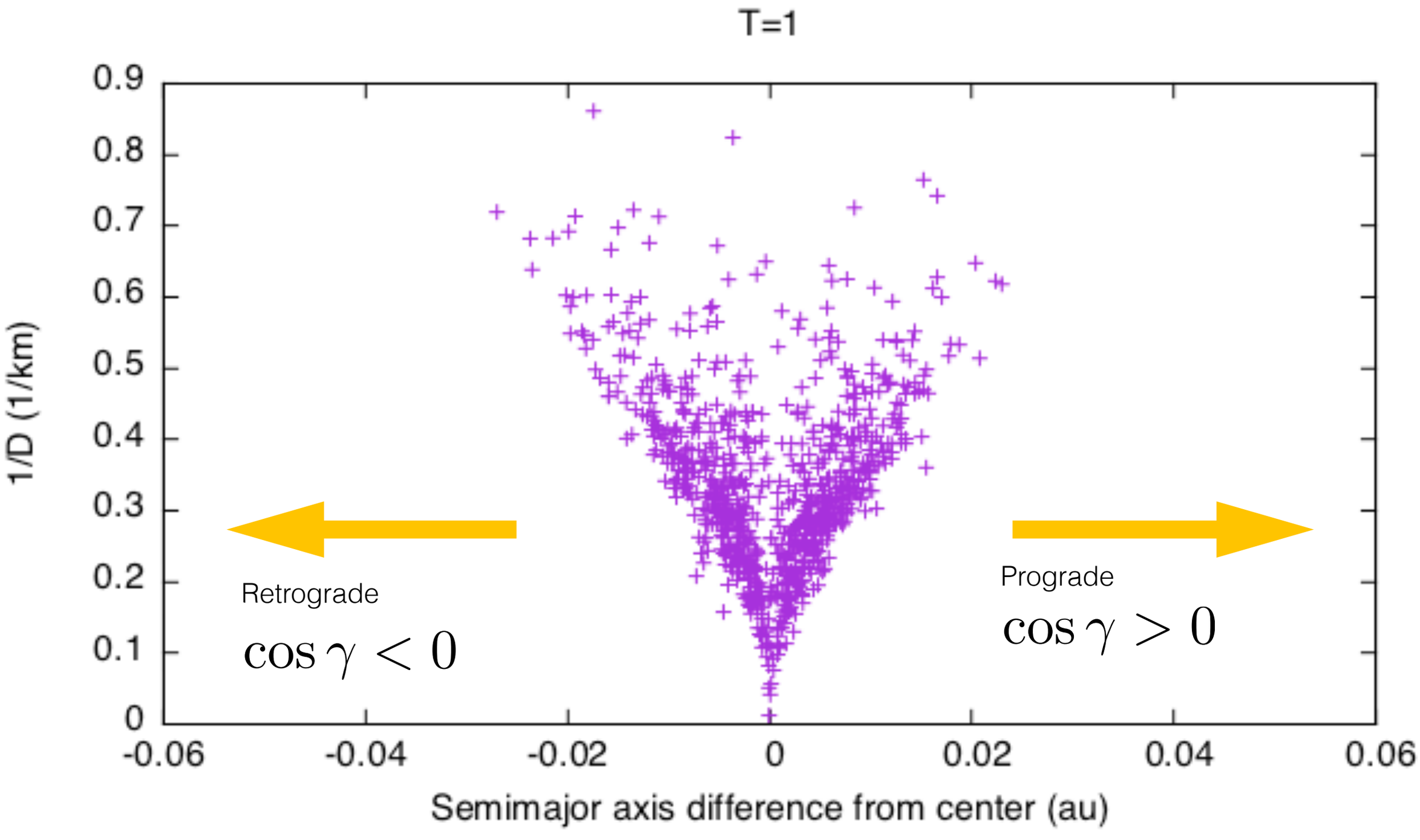


The background has structures:
- Halos of families (**Parker+2009**)
- Undetected ancient families ?

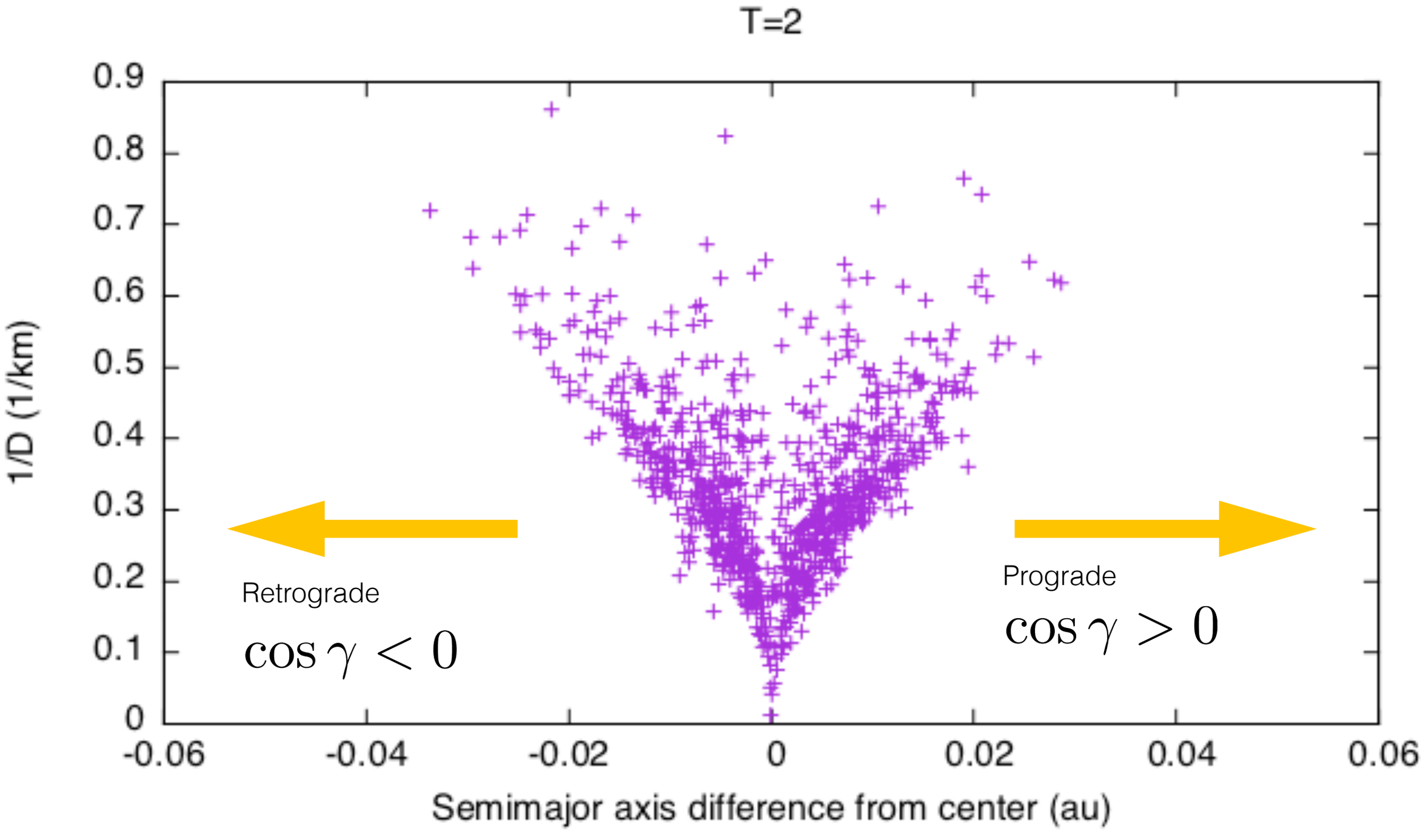
Yarkovsky V-shape



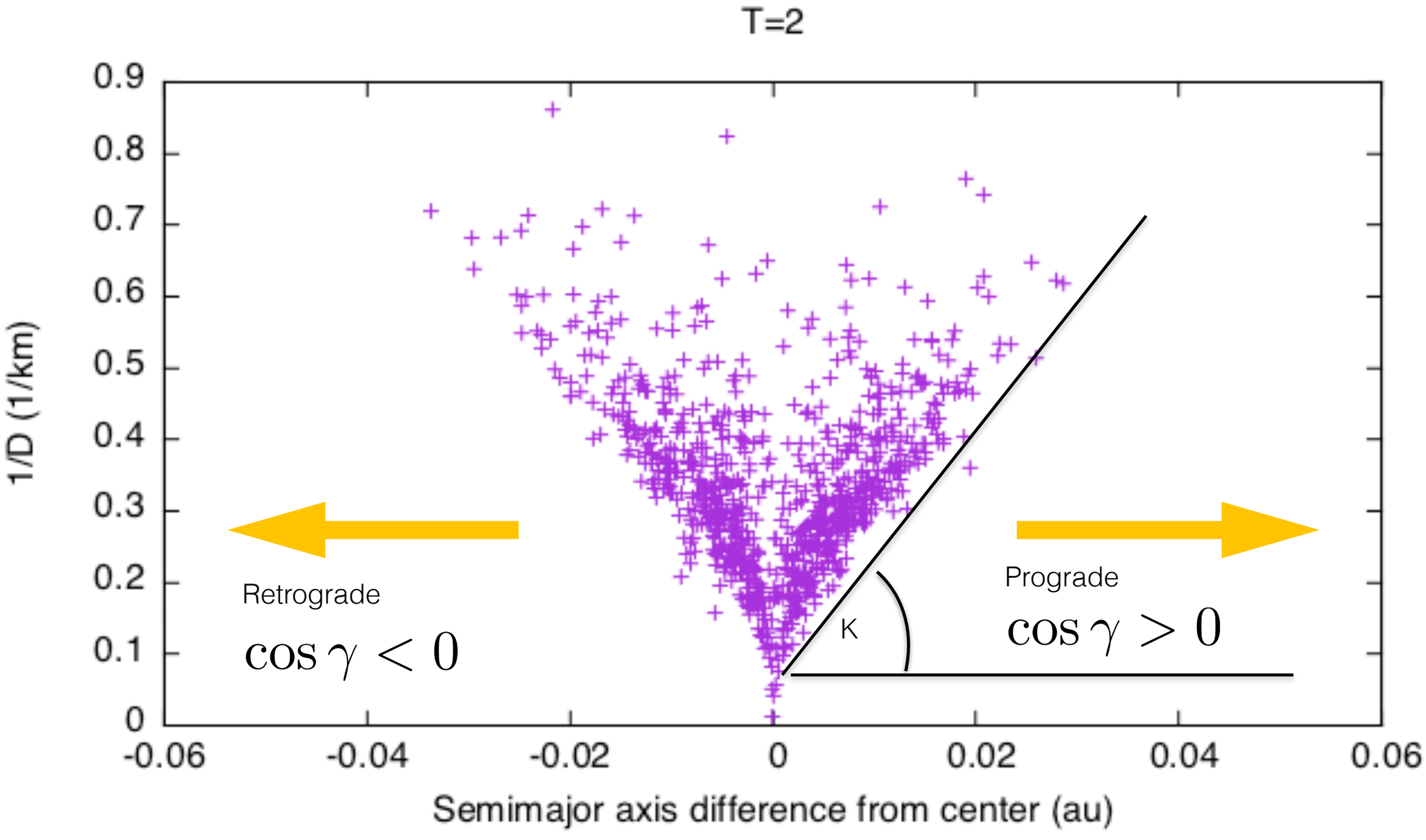
Yarkovsky V-shape



Yarkovsky V-shape



Yarkovsky V-shape



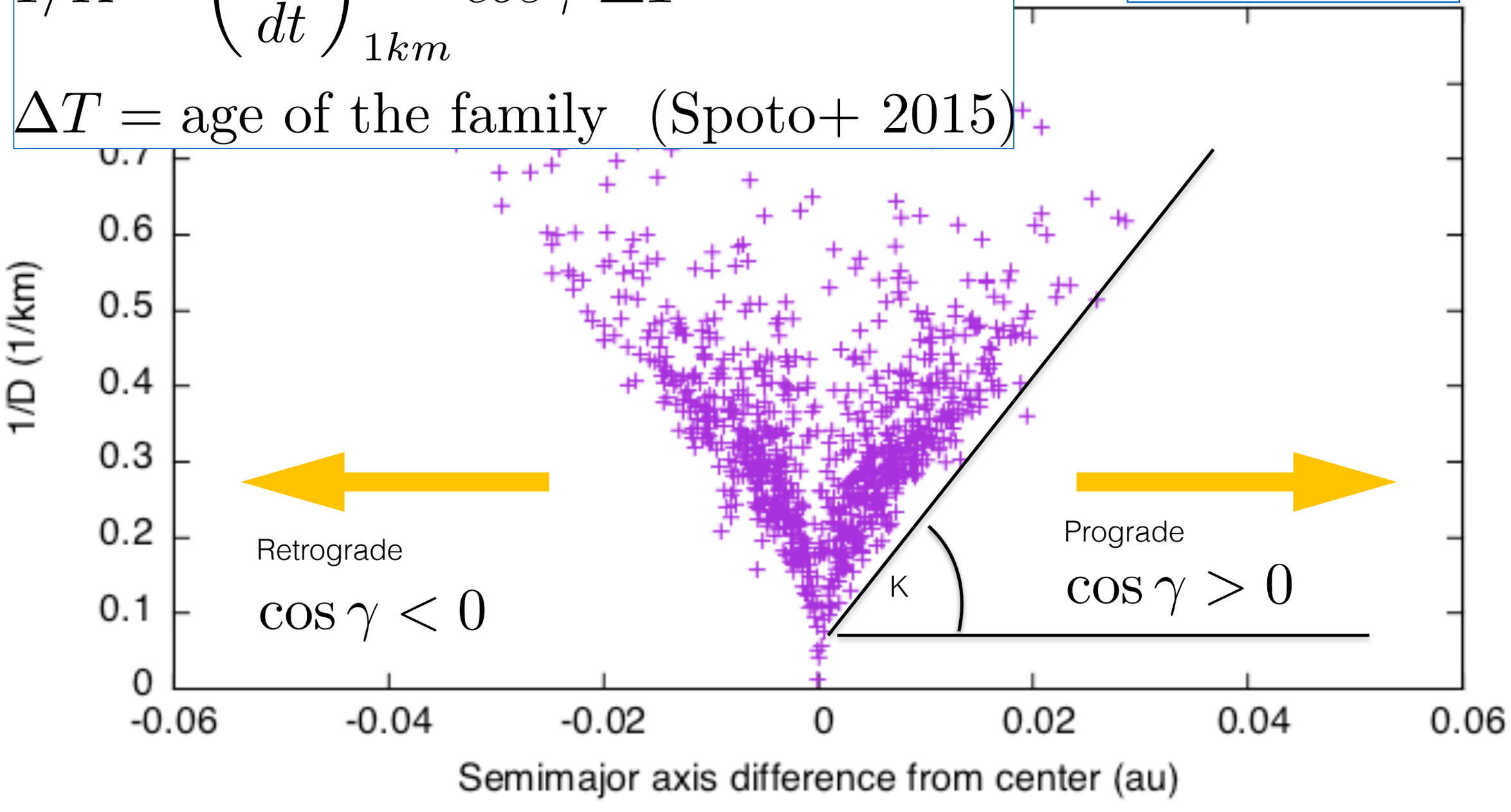
Yarkovsky V-shape

$$\frac{da}{dt} \propto 1/D$$

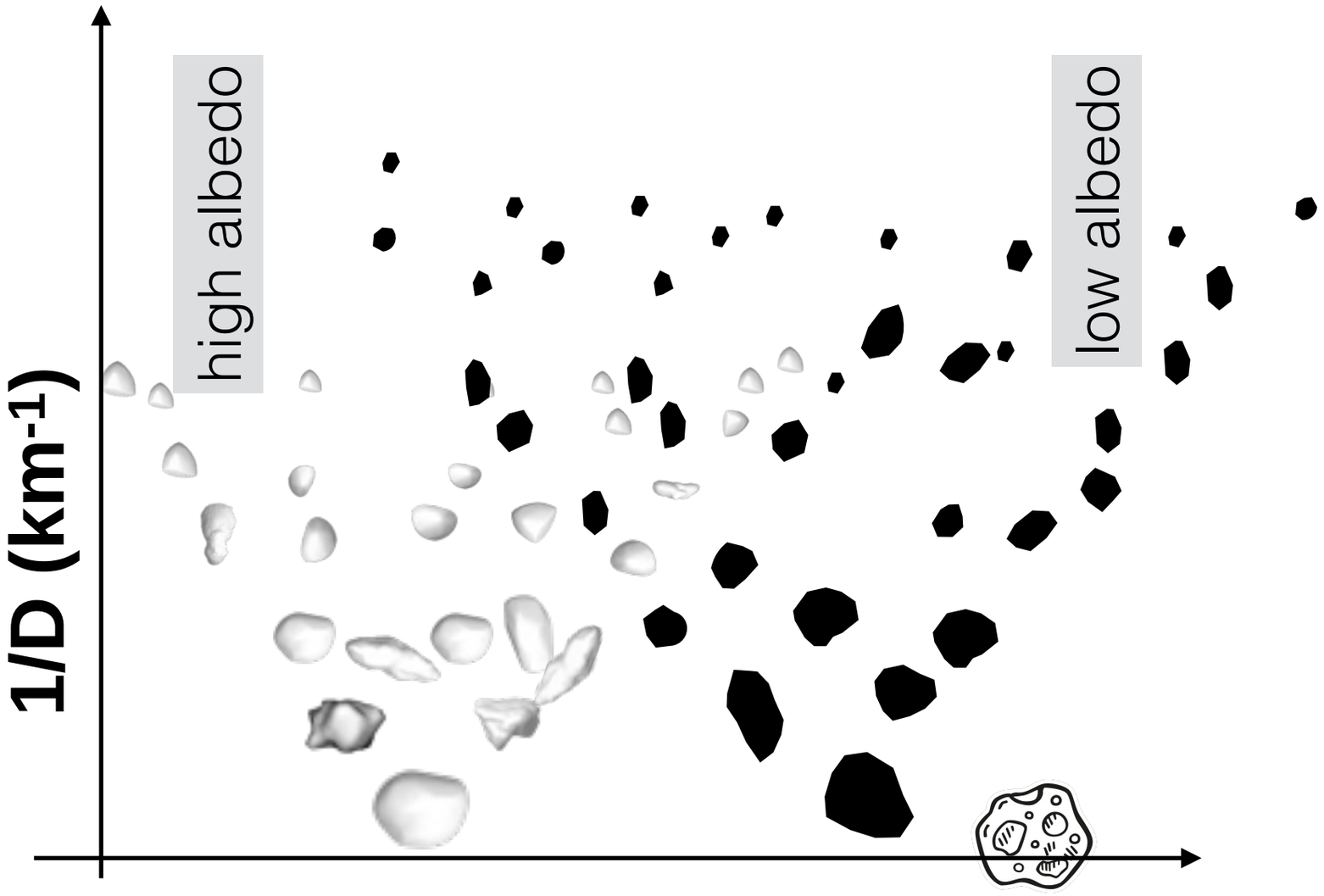
$$1/K = \left(\frac{da}{dt}\right)_{1km} cos\gamma\ \Delta T$$

ΔT = age of the family (Spoto+ 2015)

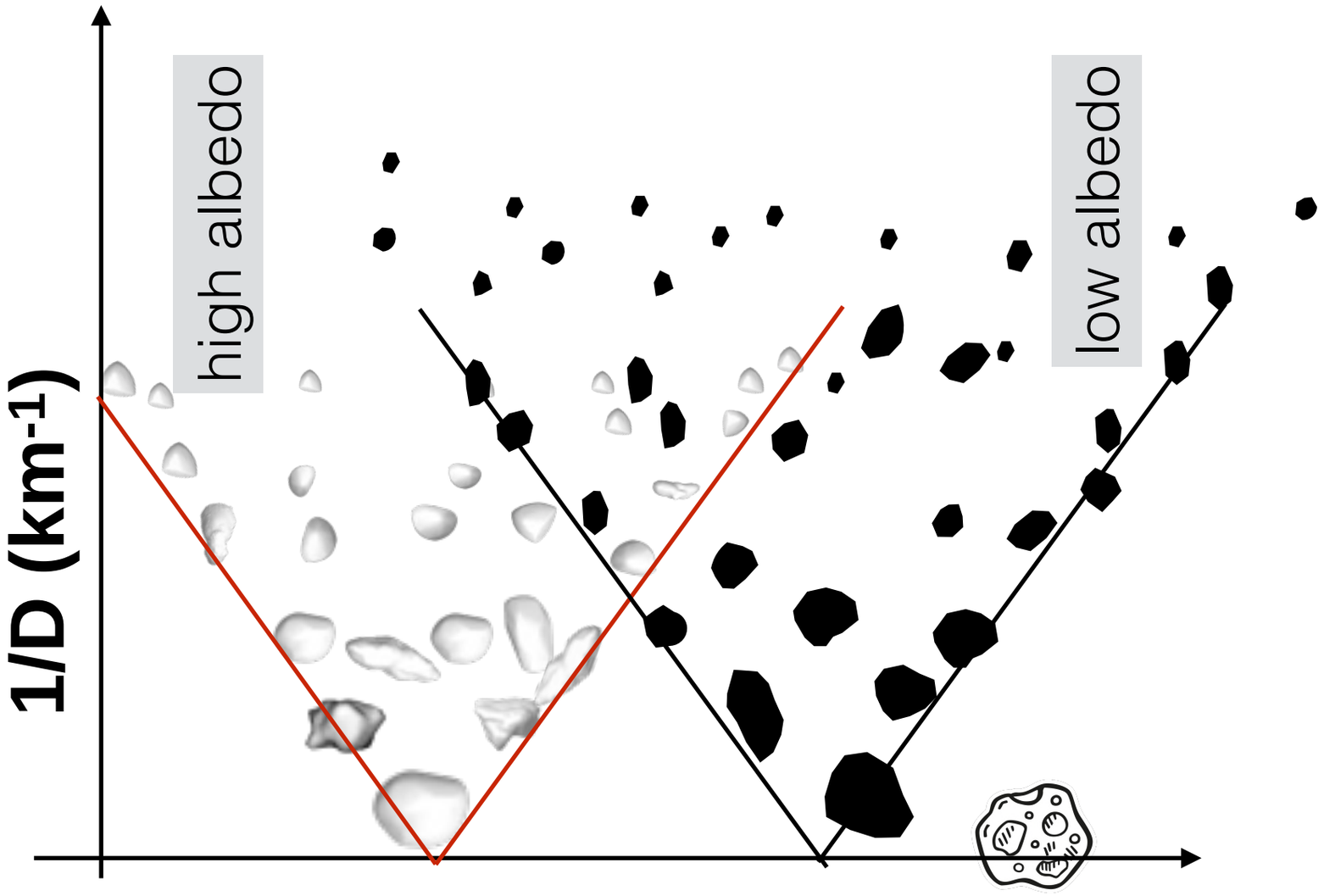
Vokrouhlický+2006
Broz+2013
Bottke+2015
Nesvorny+2015
Carruba+2016



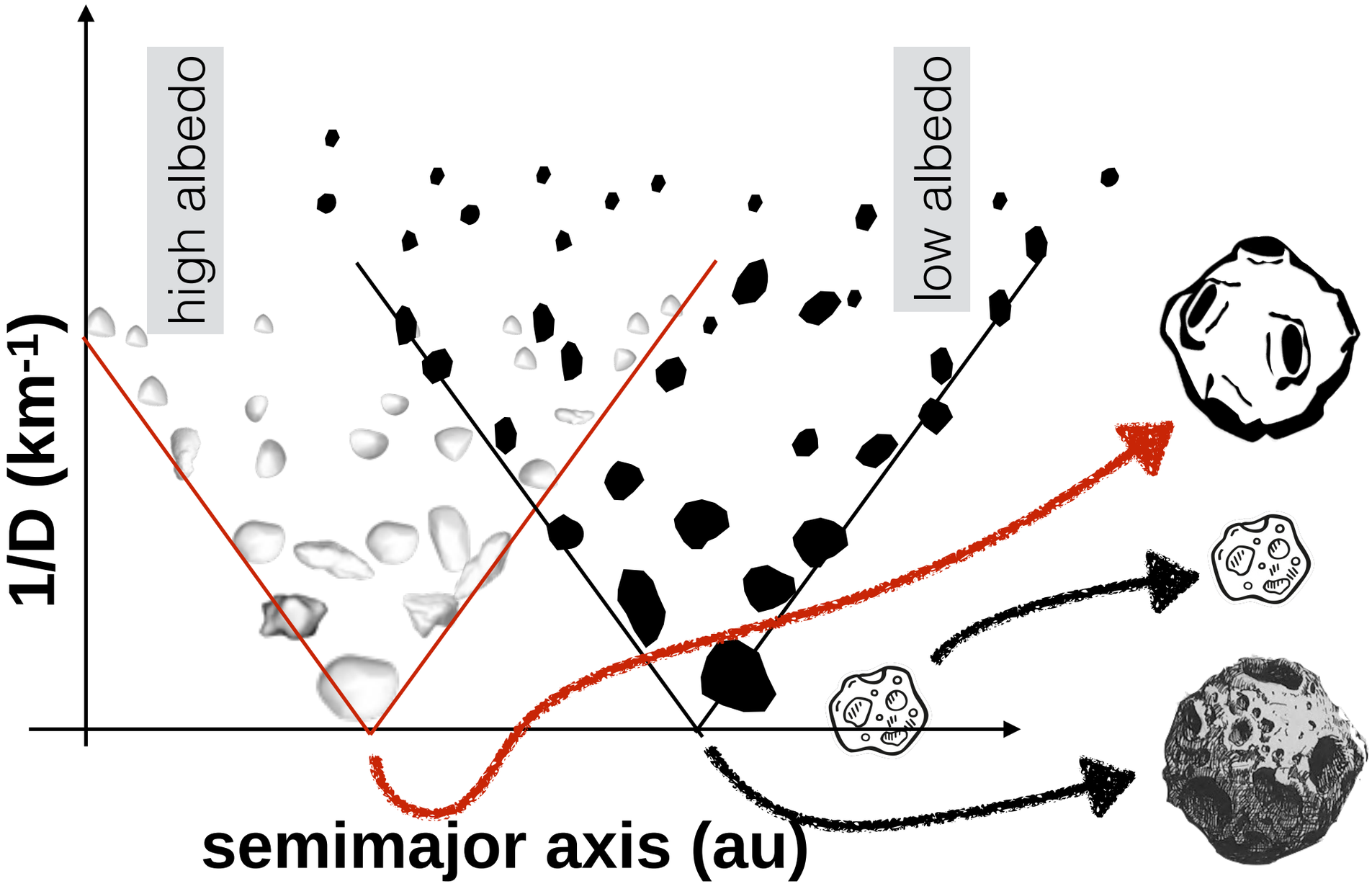
Family separation by physical properties & V-shapes



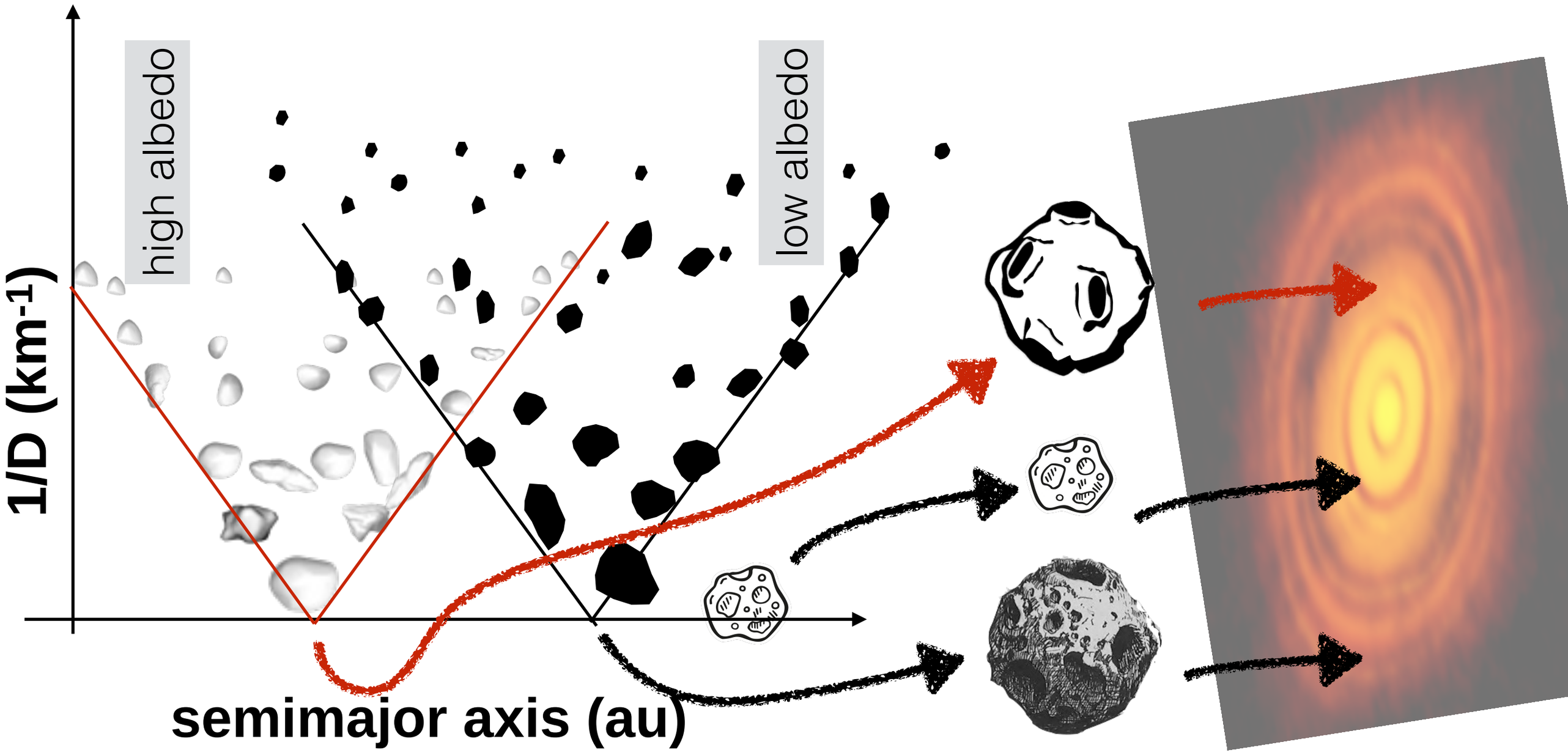
Family separation by physical properties & V-shapes



Family separation by physical properties & V-shapes

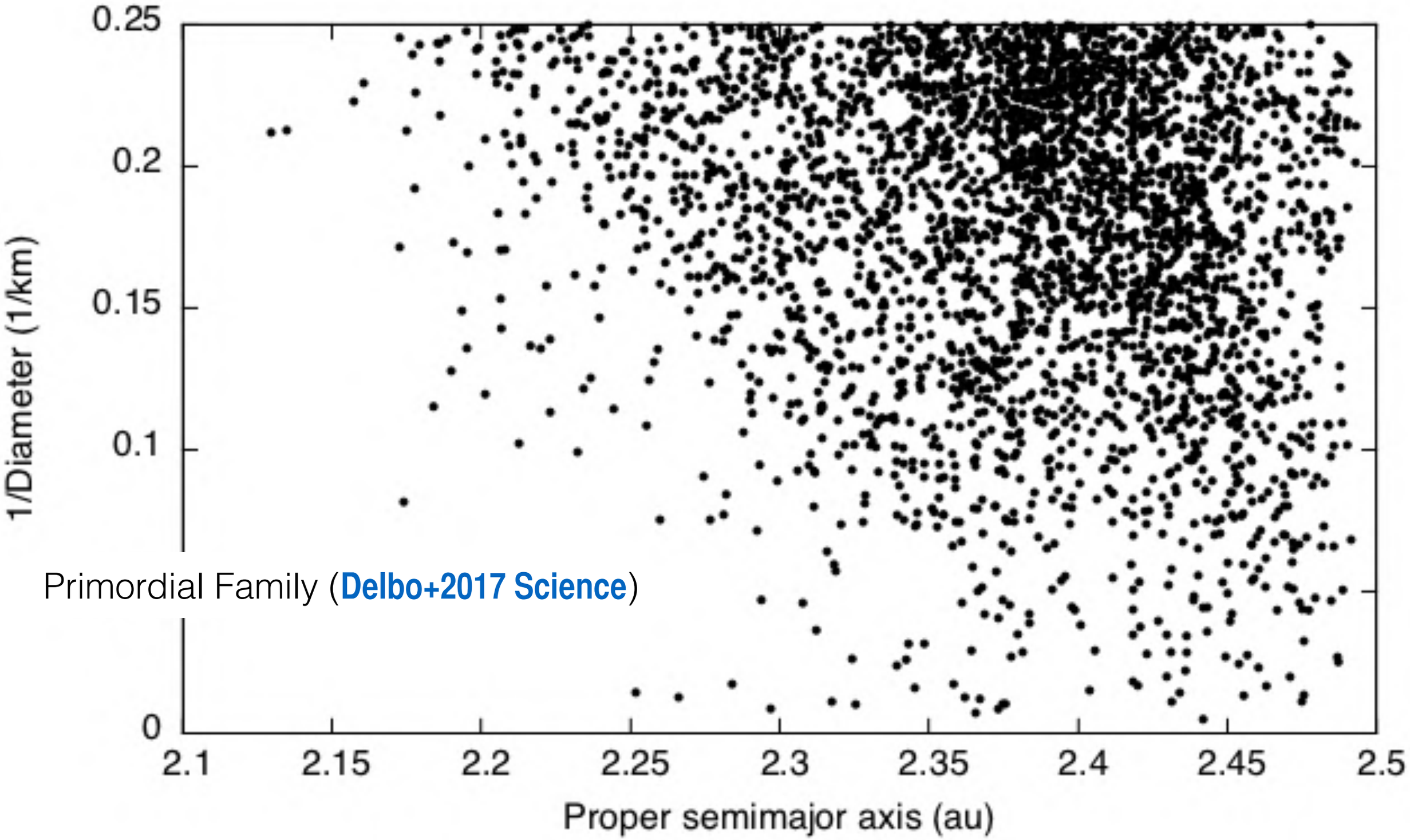


Family separation by physical properties & V-shapes



The entire inner-Main Belt in a V-shape

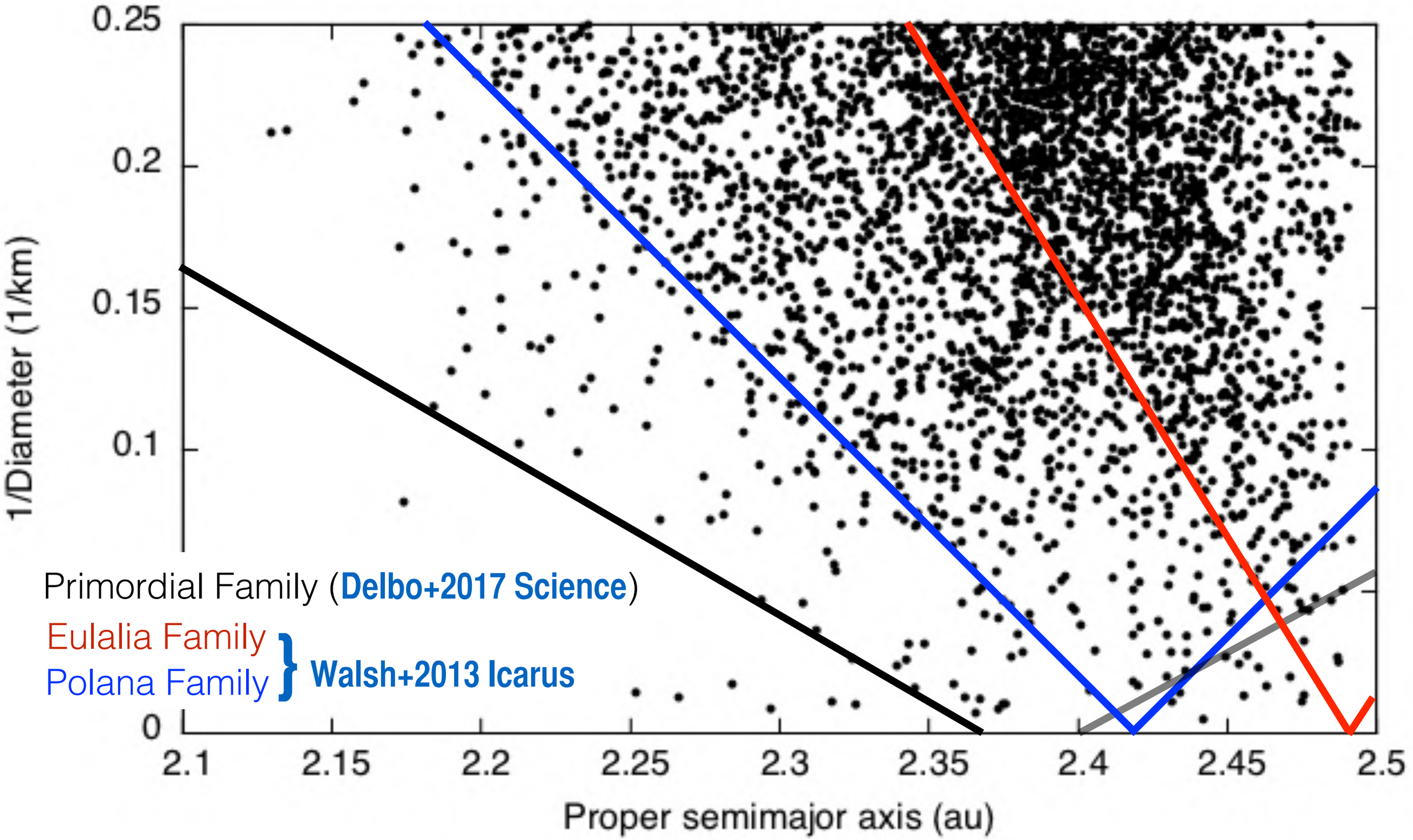
for the **low-albedo** asteroids



Primordial Family (**Delbo+2017 Science**)

The entire inner-Main Belt in a V-shape

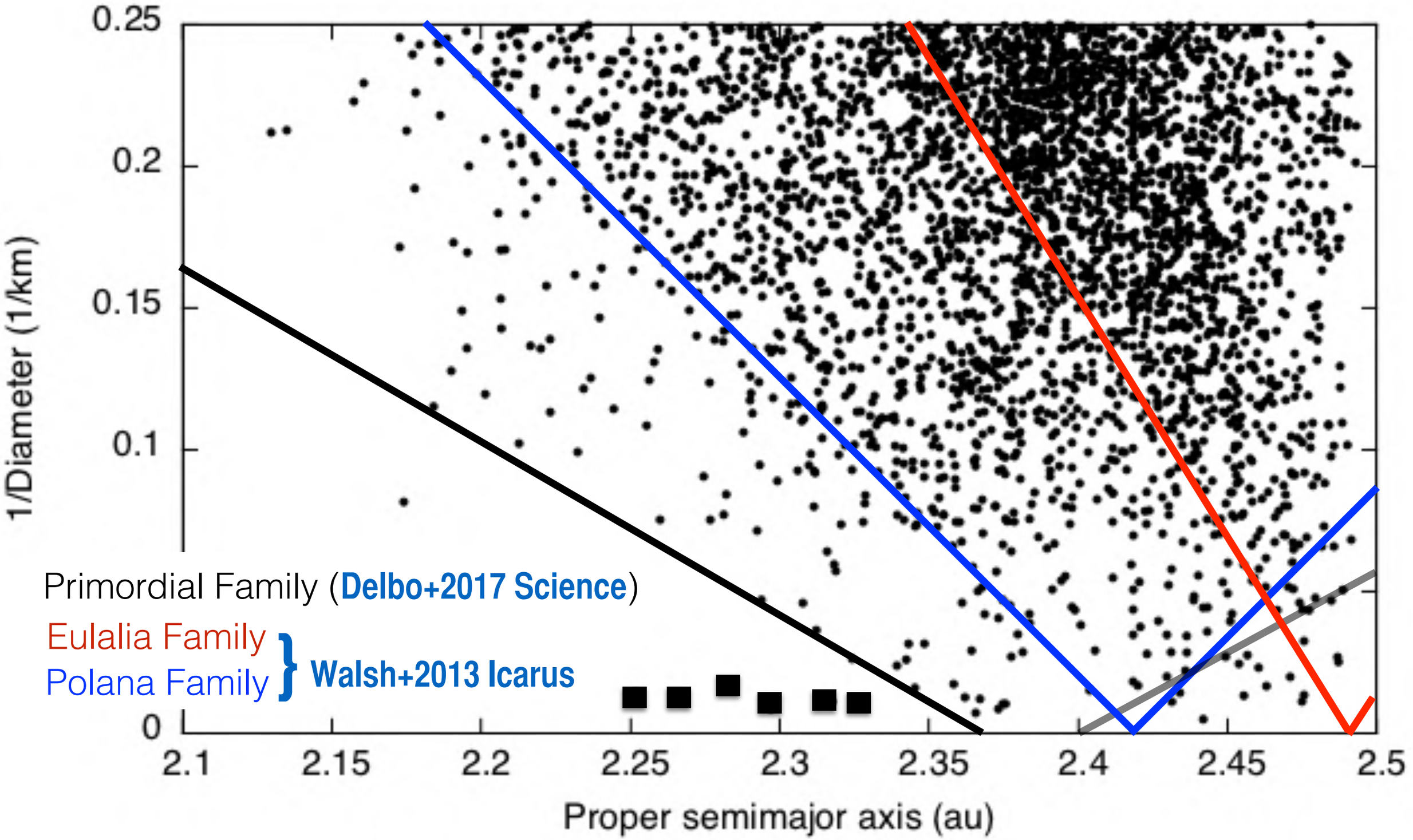
for the **low-albedo** asteroids



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 entire inner-Main Belt in a V-shape

for the **low-albedo** asteroids

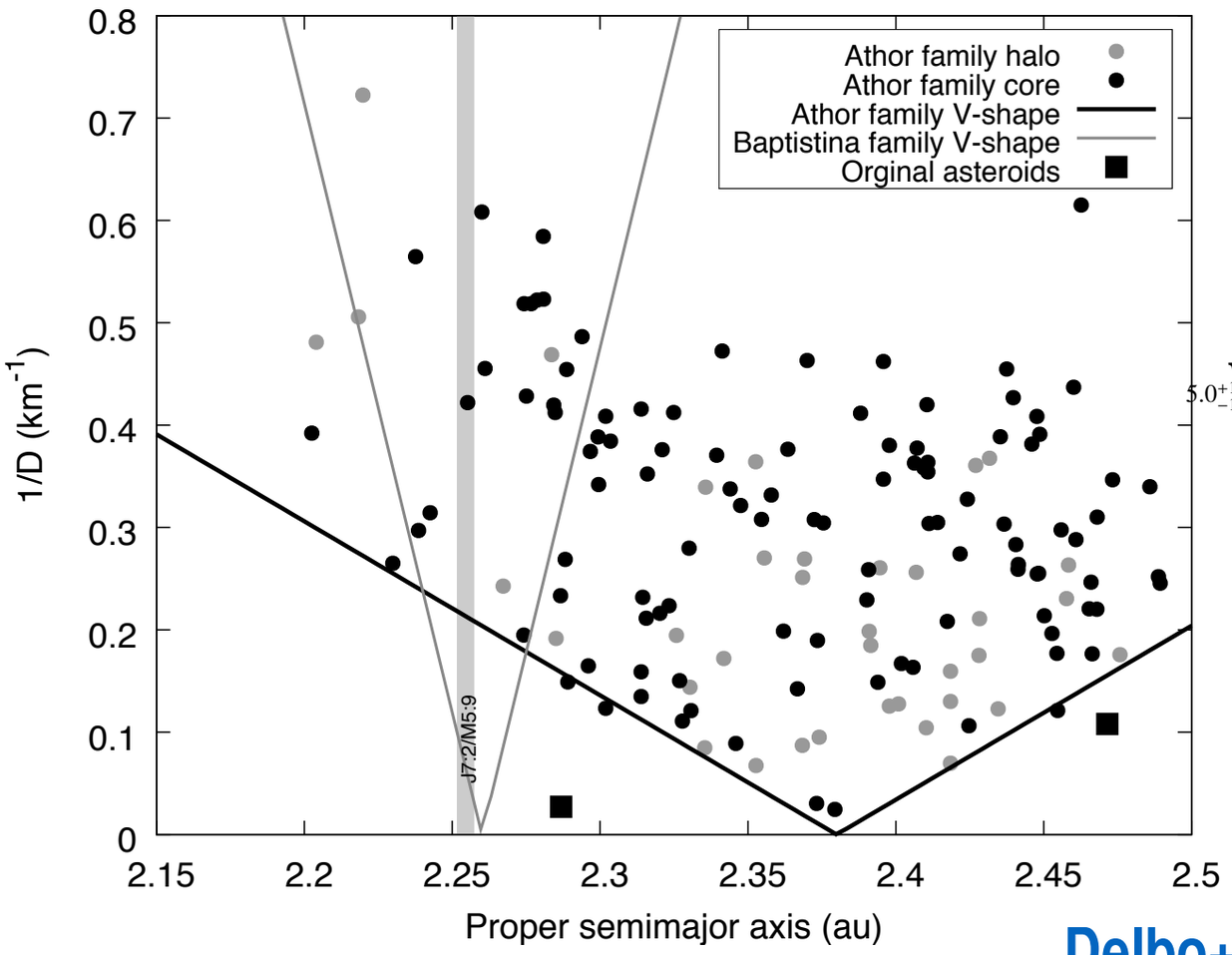


The V-shape slope of the primordial family is ~ 0.6 $km^{-1}au^{-1}$ corresponding to an age $t = 4.0^{+1.7}_{-1.1}$ Gyr

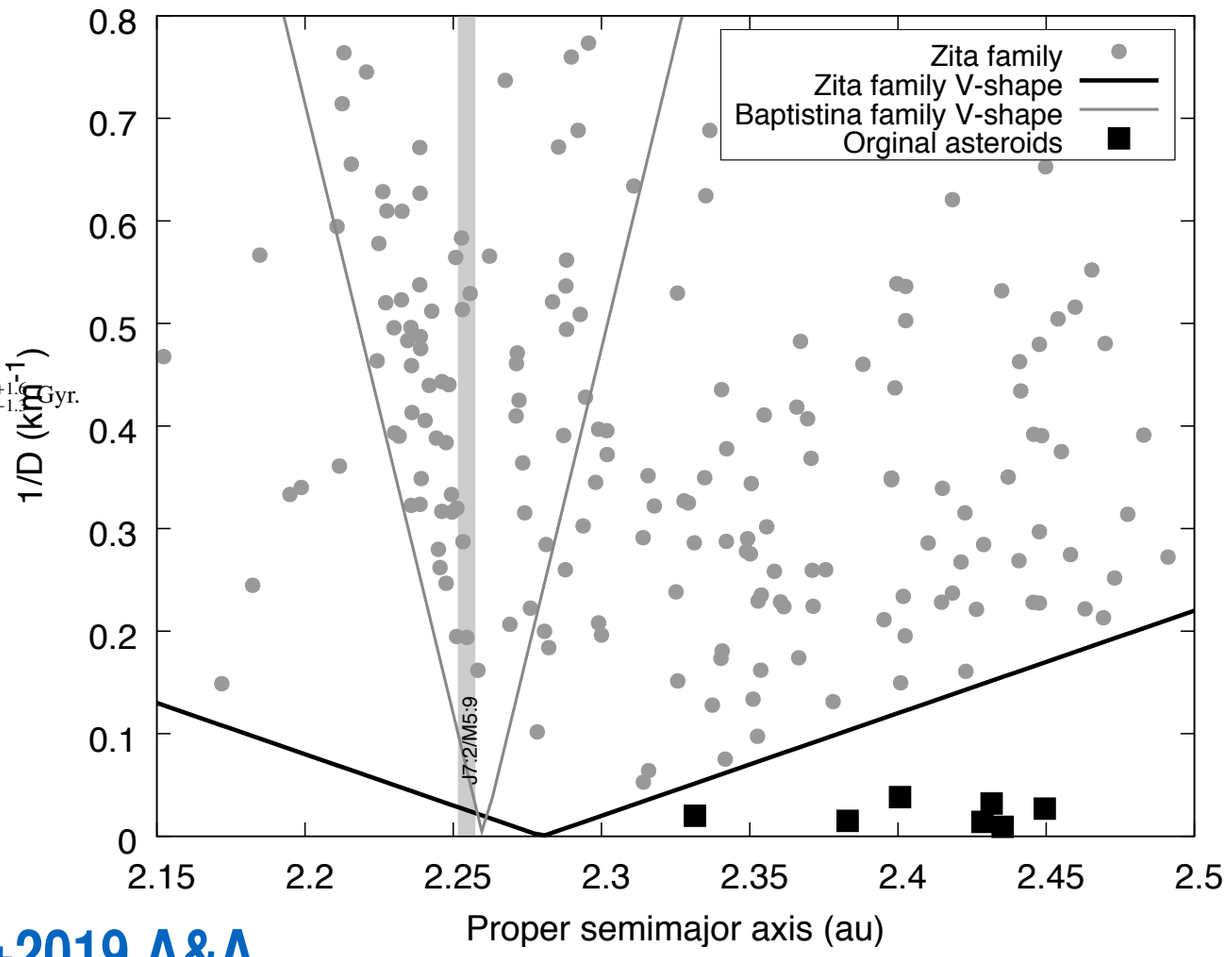
The entire inner-Main Belt makes V-shapes

for the **intermediate-albedo** asteroids of the **X-complex**

(161) Athor



(689) Zita

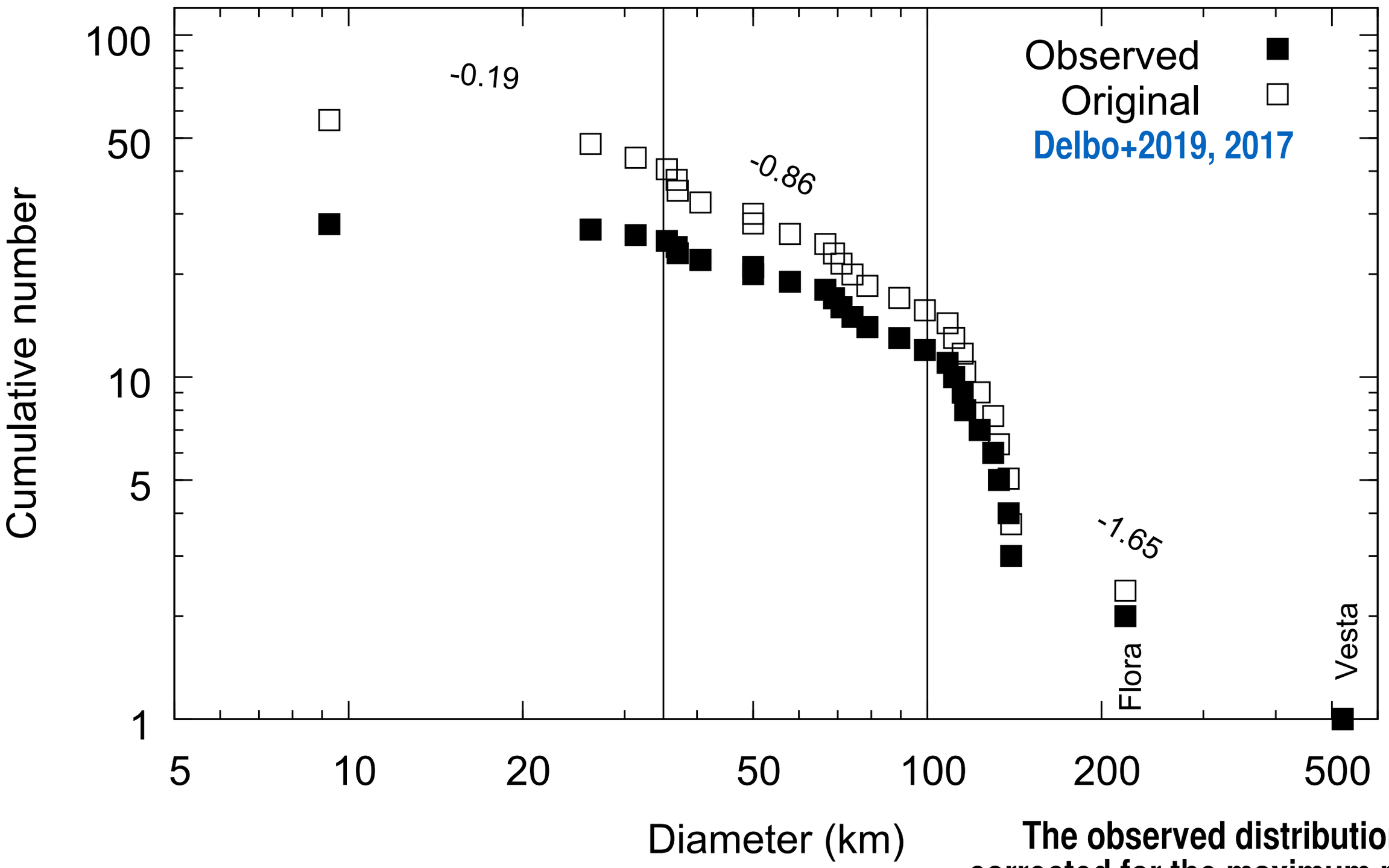


Delbo+2019 A&A

age = $3.0^{+0.5}_{-0.4}$ Gyr.

age = $5.0^{+1.6}_{-1.3}$ Gyr.

Planetesimal size-frequency distribution



The observed distribution is corrected for the maximum number of objects that were lost due the collisional and dynamical evolution

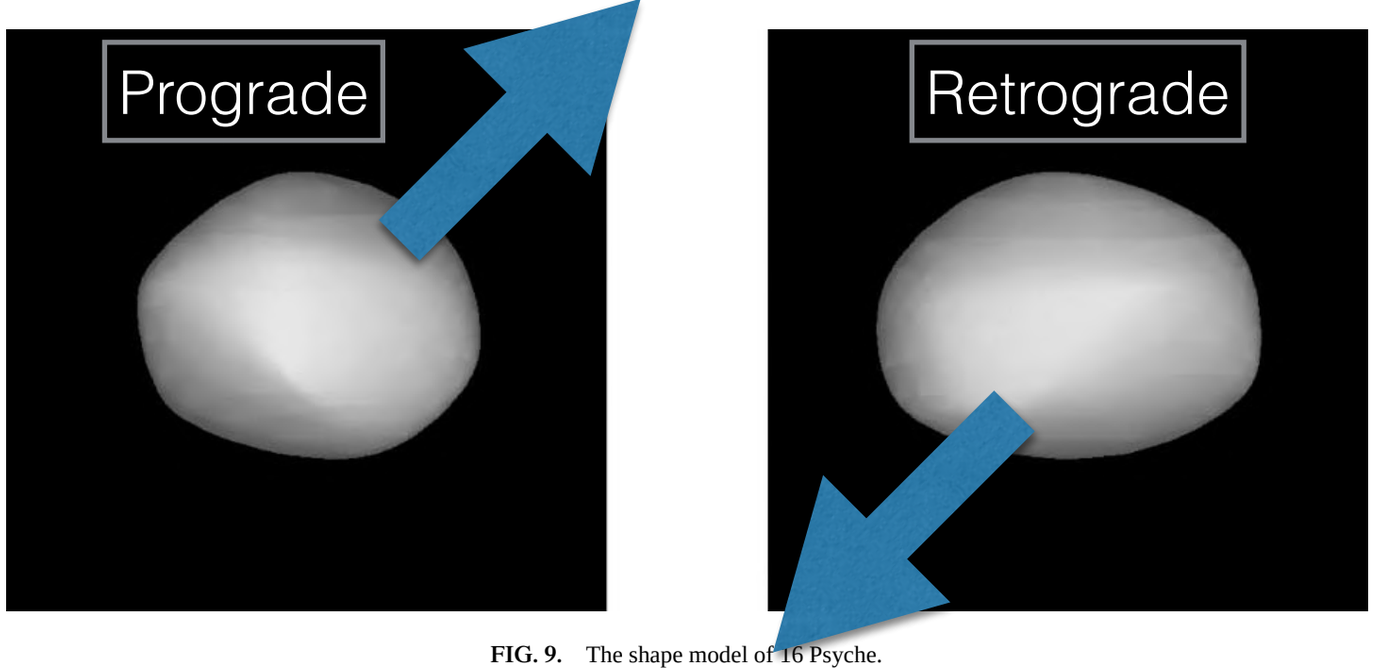


FIG. 9. The shape model of 16 Psyche.

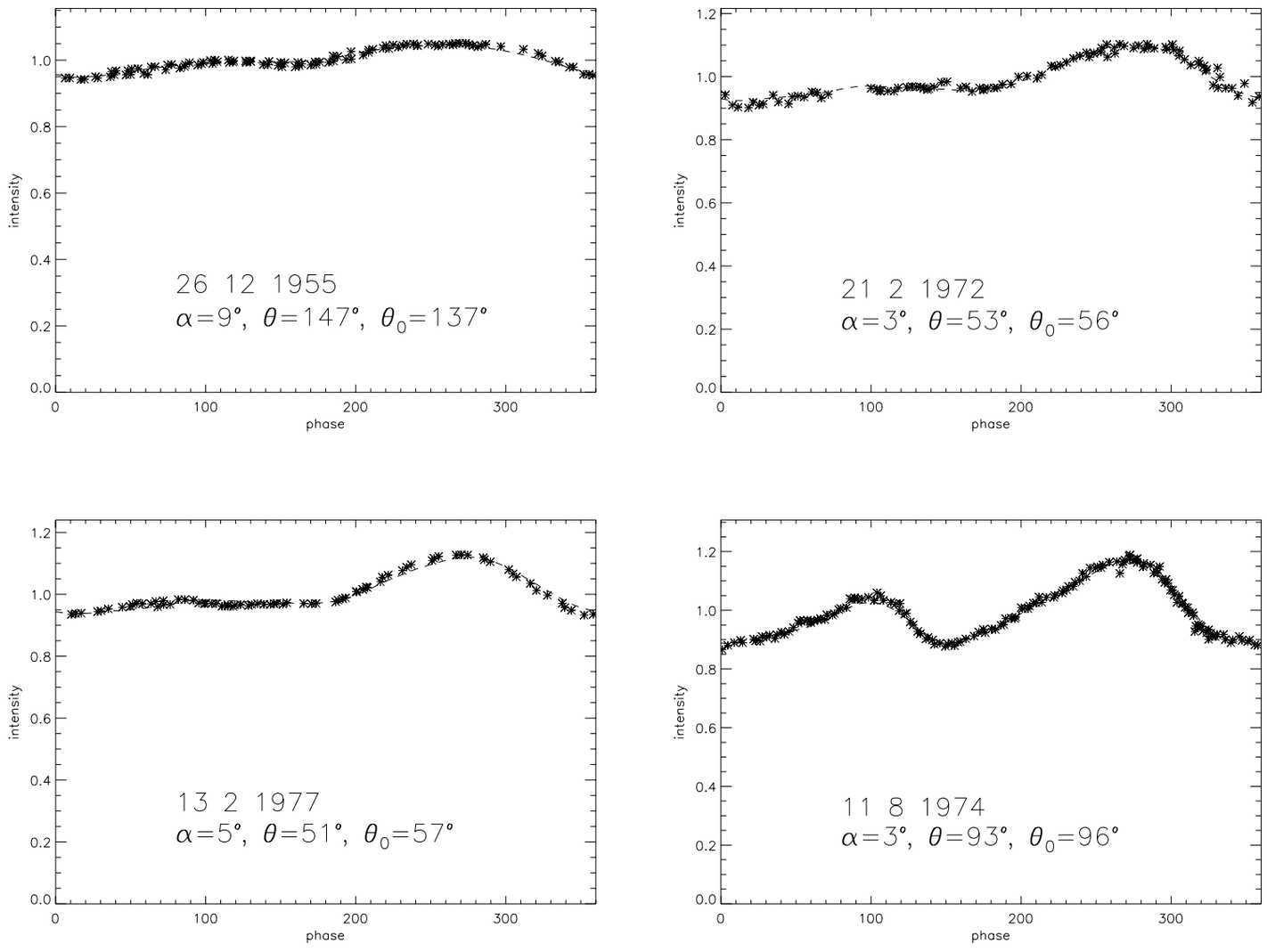
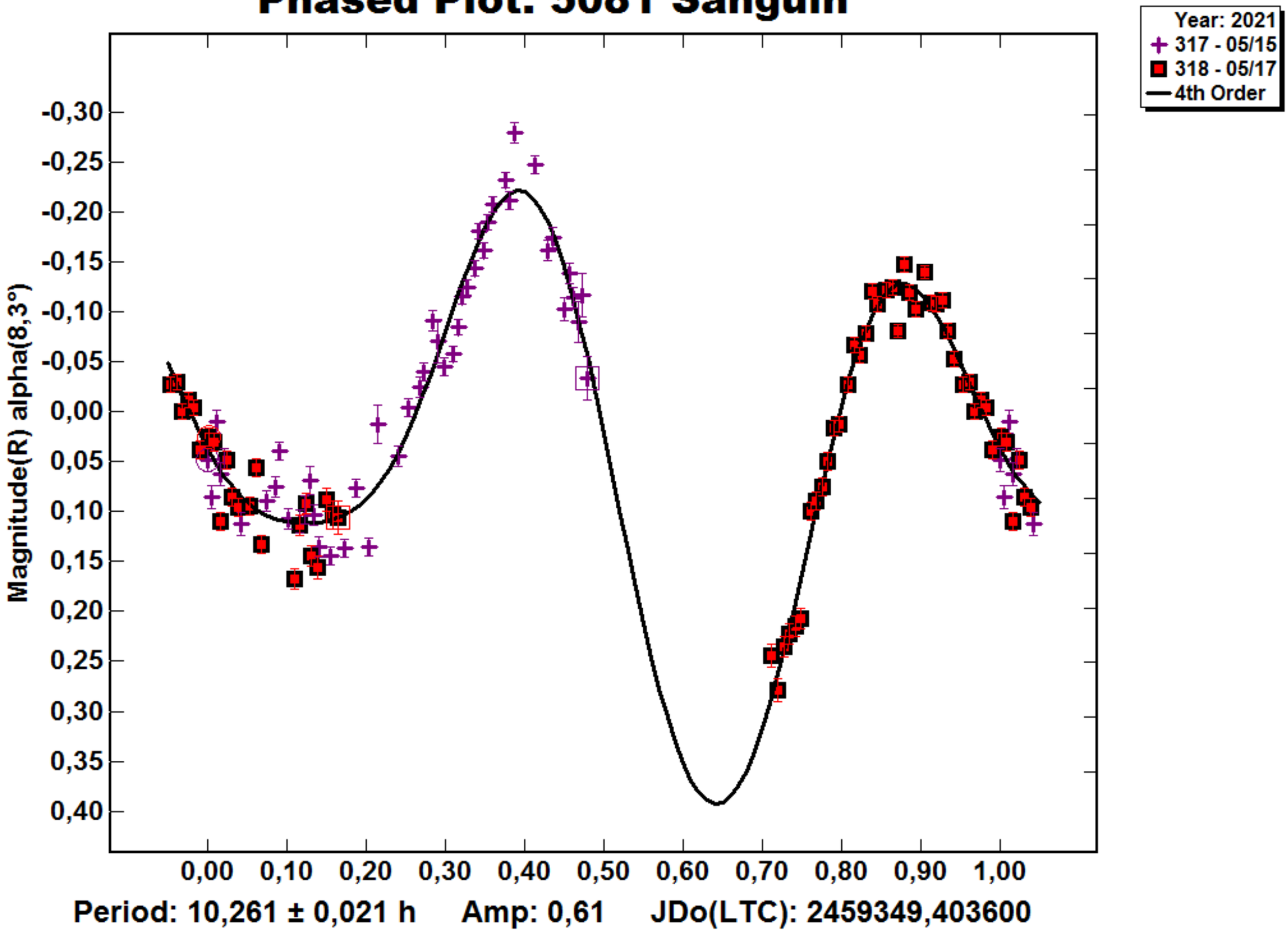


FIG. 10. Four lightcurves and the corresponding fits for 16 Psyche.

Asteroid shape models and spin vector from photometric lightcurves

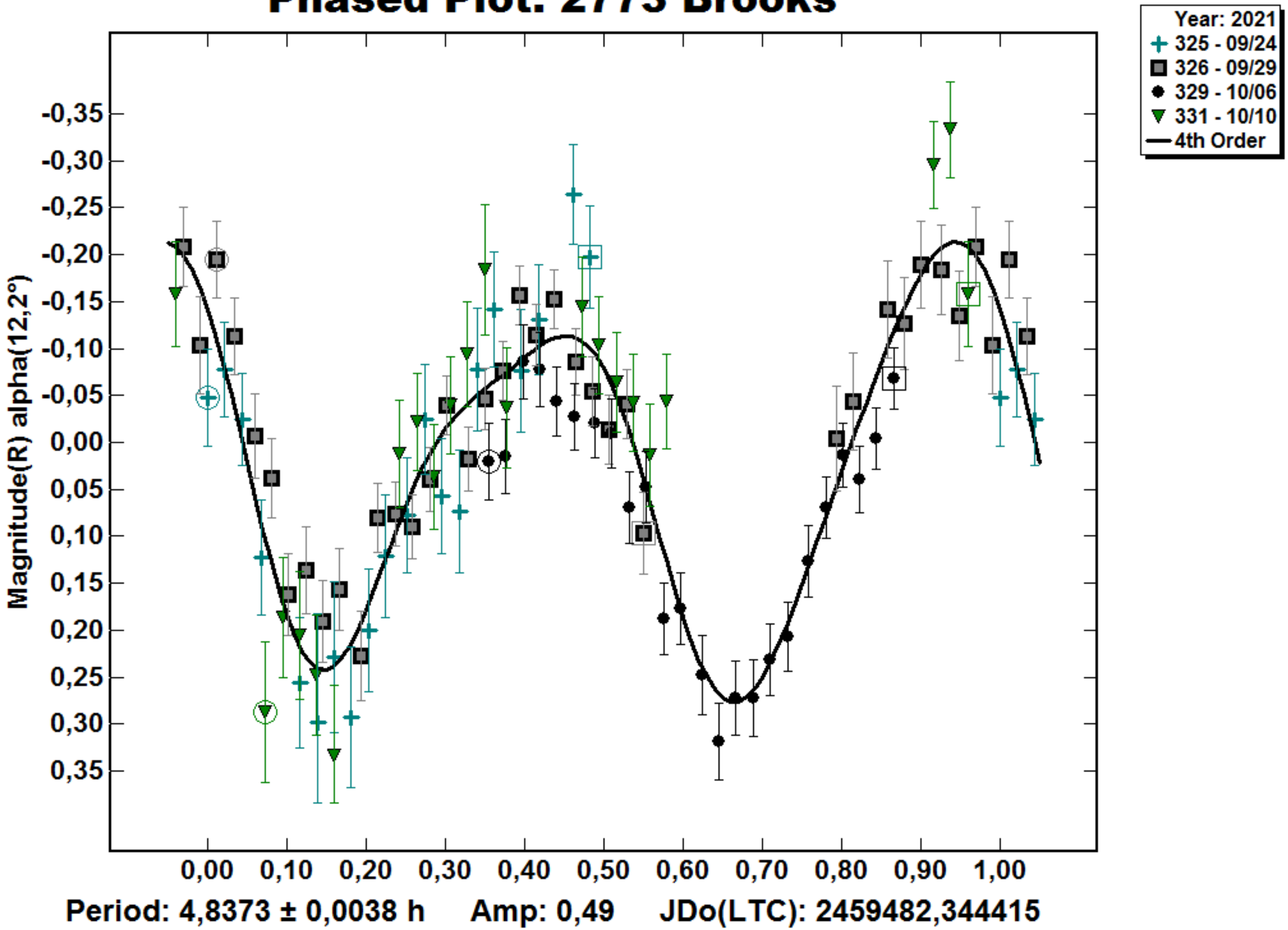
Kaasalainen et al. 2002, 2010 etc

Phased Plot: 5081 Sanguin



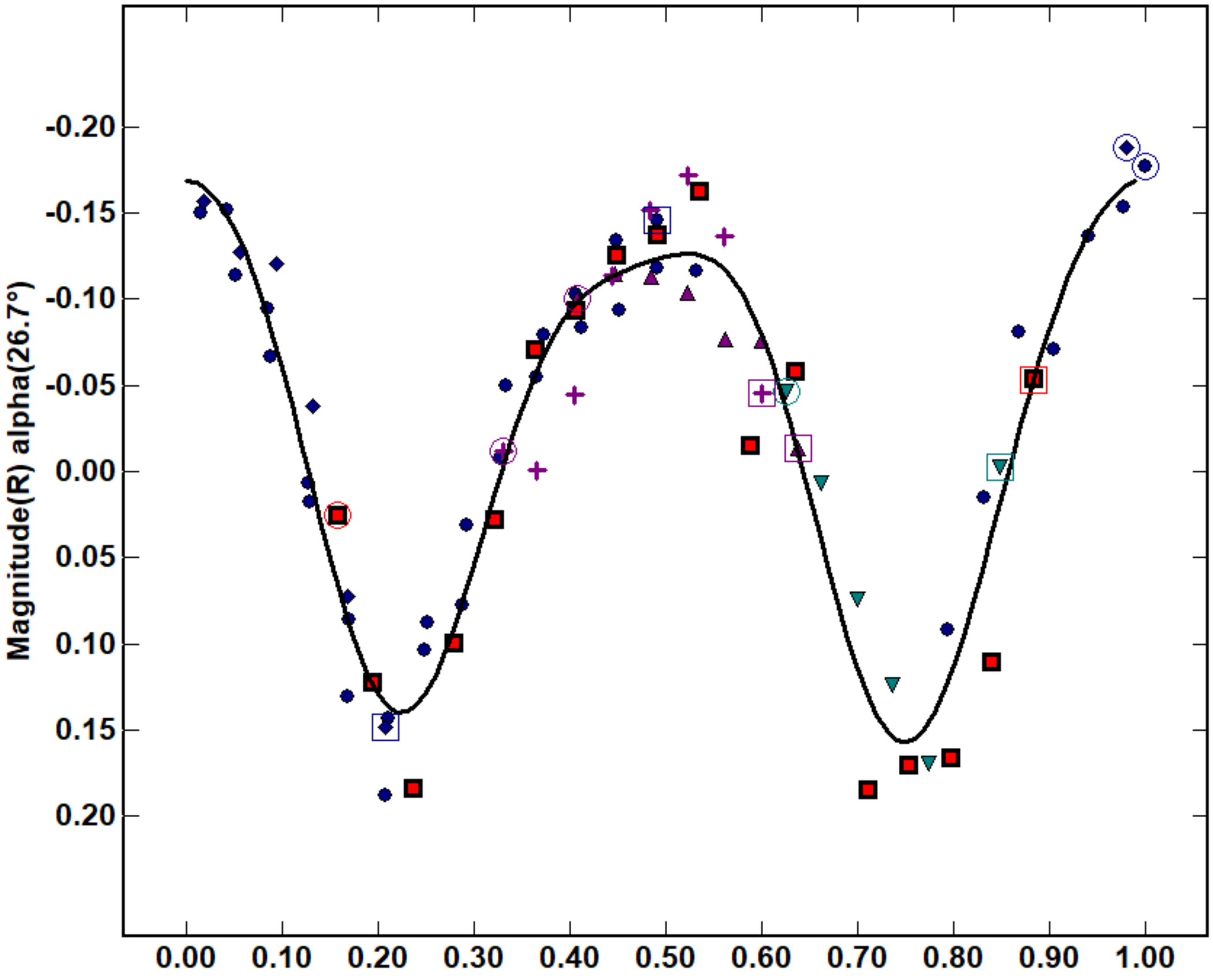
Period: 10,261 ± 0,021 h Amp: 0,61 JDo(LTC): 2459349,403600

Phased Plot: 2773 Brooks

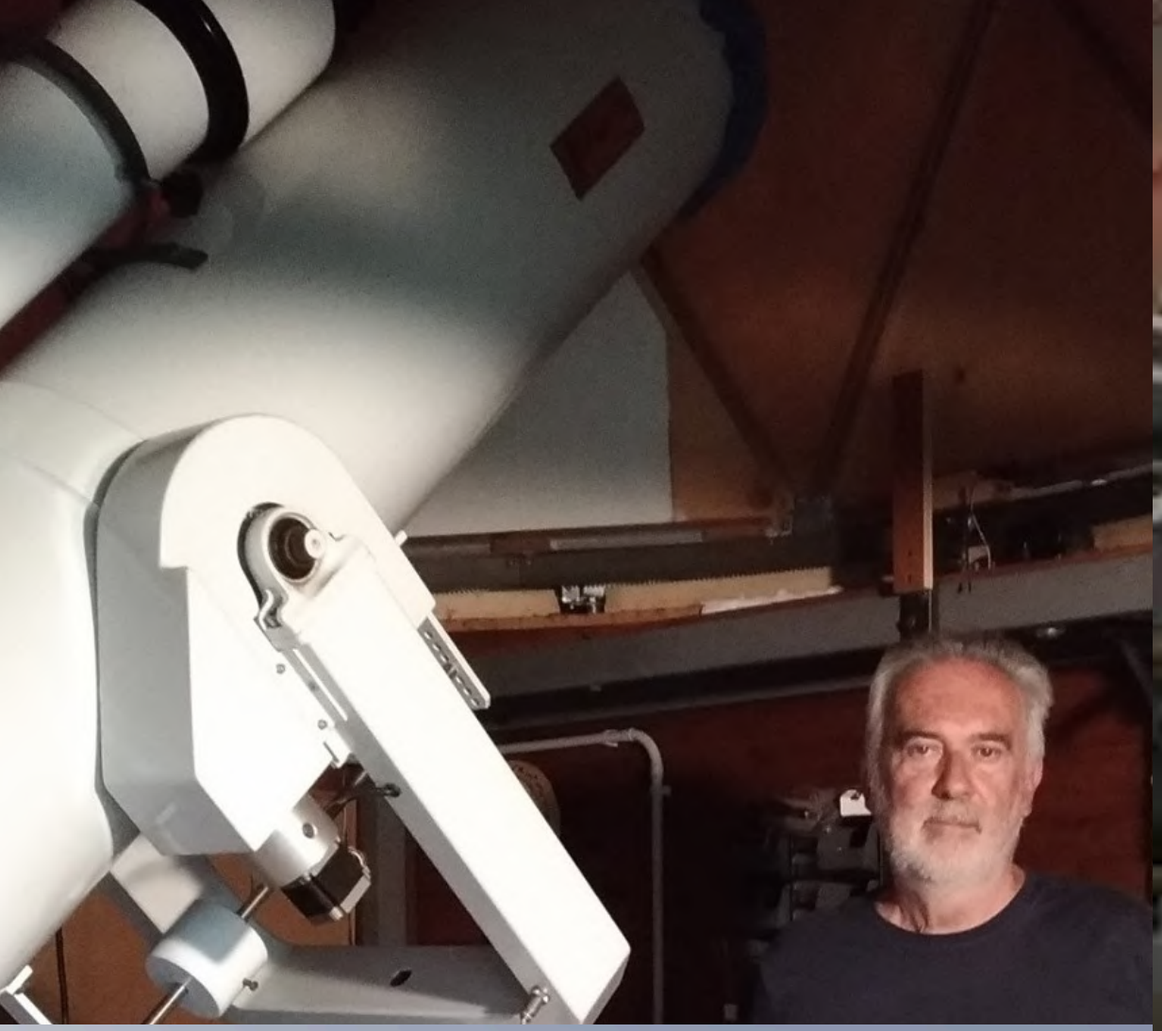


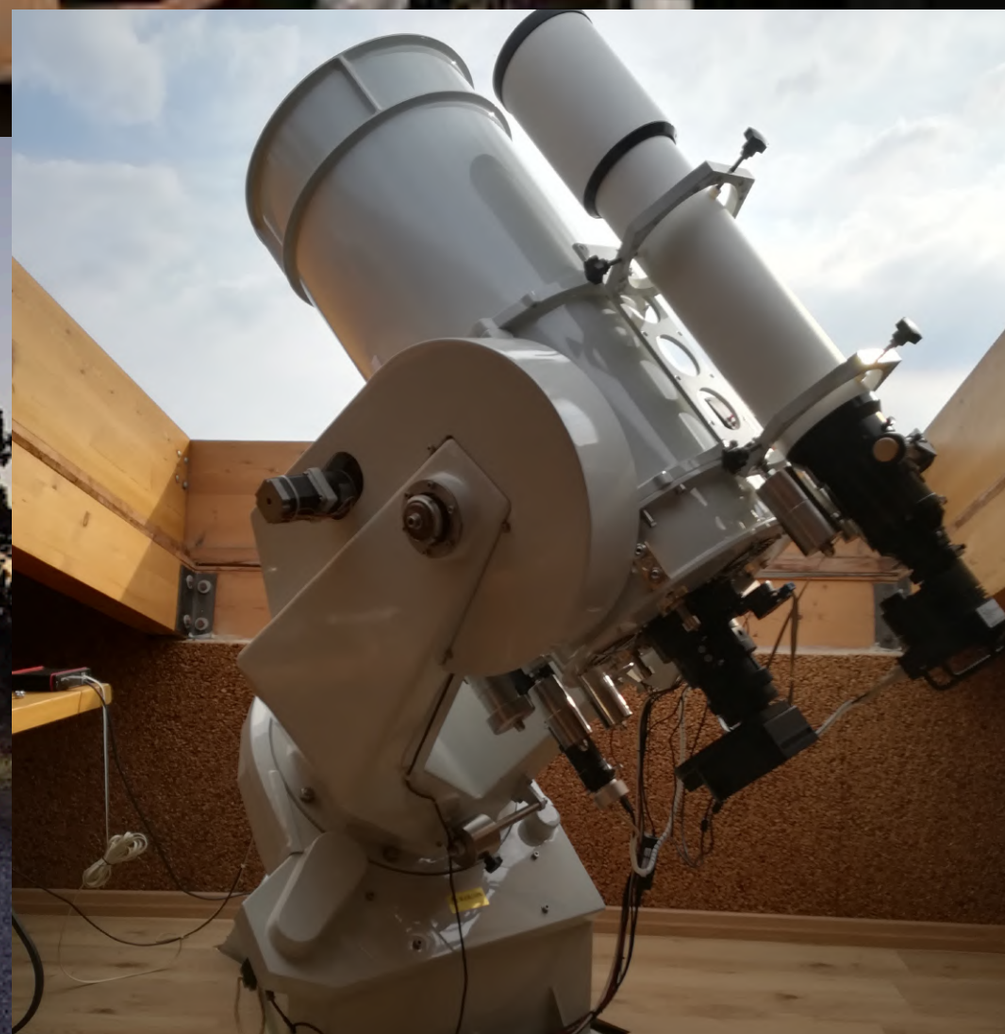
Period: 4,8373 ± 0,0038 h Amp: 0,49 JDo(LTC): 2459482,344415

Phased Plot: 2778 Tangshan_Lowell



Period: 3.460 ± 0.001 h Amp: 0.33 JDo(LTC): 2459224.592121

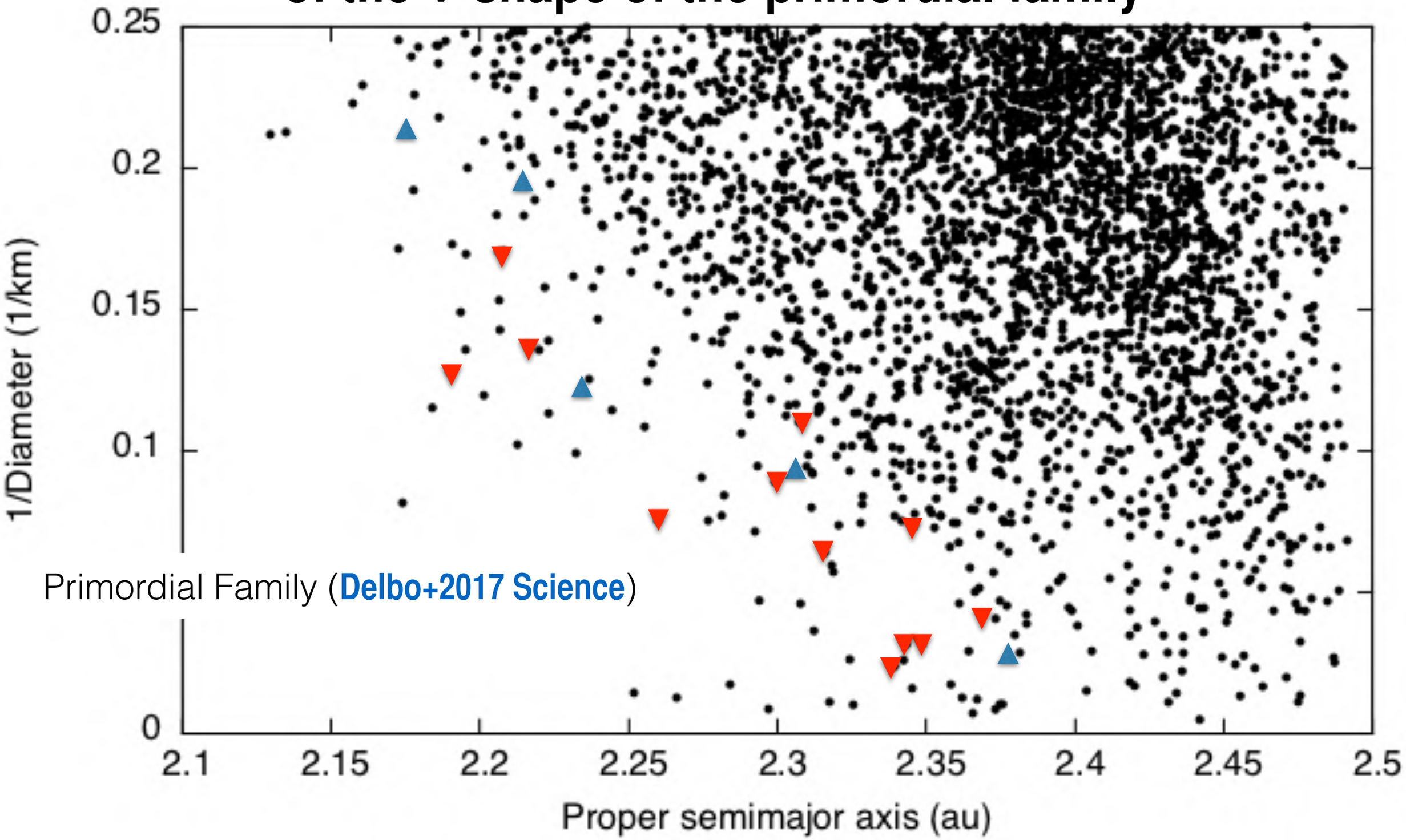




Number	Observatory
67	BSA-Lowell
282	BSA-Lowell
370	NOAK (Ancient Asteroids)
853	BSA-Lowell
933	BSA-Lowell
1700	BSA-Lowell
2322	BSA-Lowell
2768	BSA-Lowell-UOAO
2778	BSA-Lowell
4231	BSA-Lowell
4422	BSA-Lowell-UOAO
25543	BSA-Lowell
TBD 2259	BSA
TBD 1806	BSA
9086	UOAO

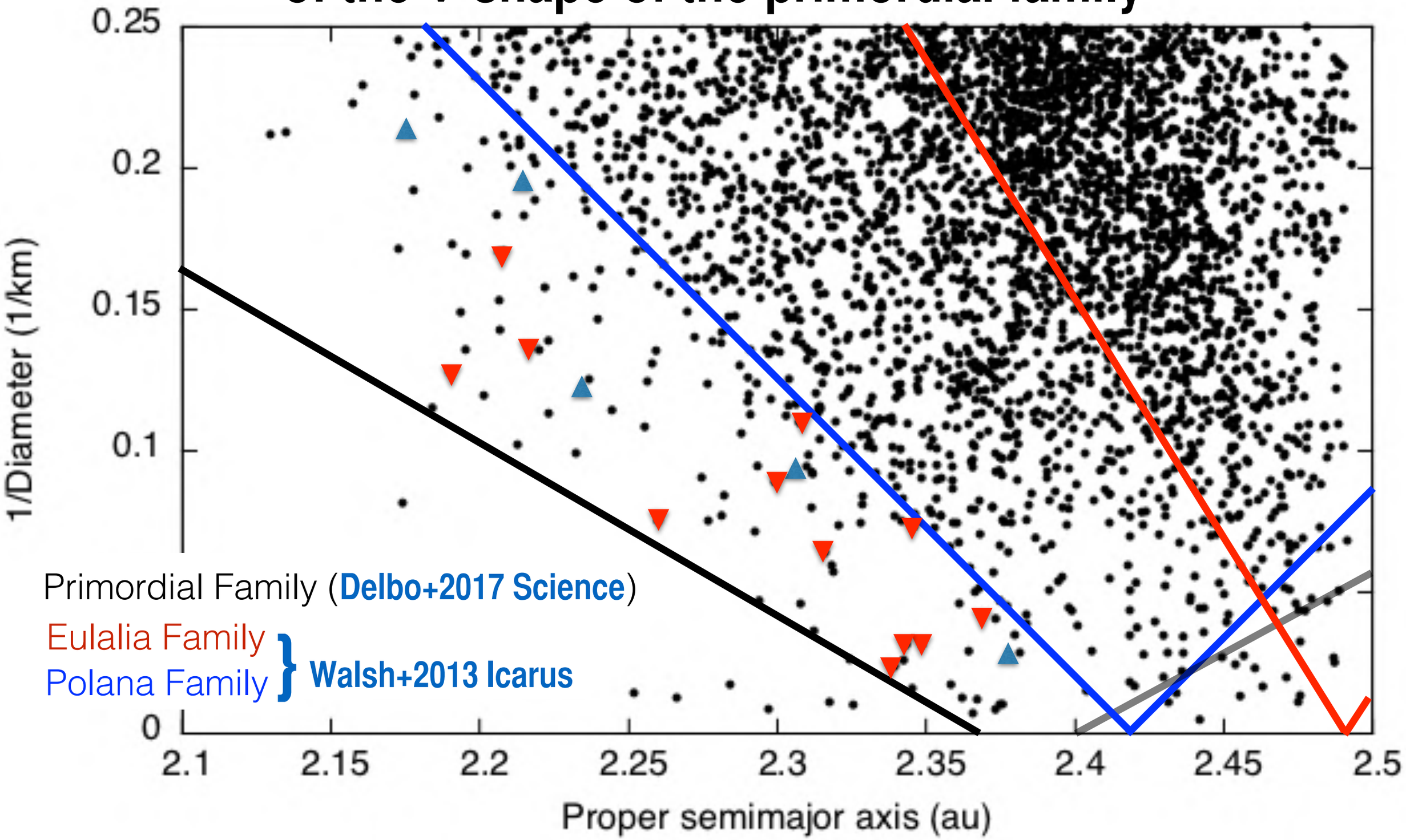
Table 2: Asteroids that have been observed by us.

Predominance of retrograde asteroids in the inward part of the V-shape of the primordial family

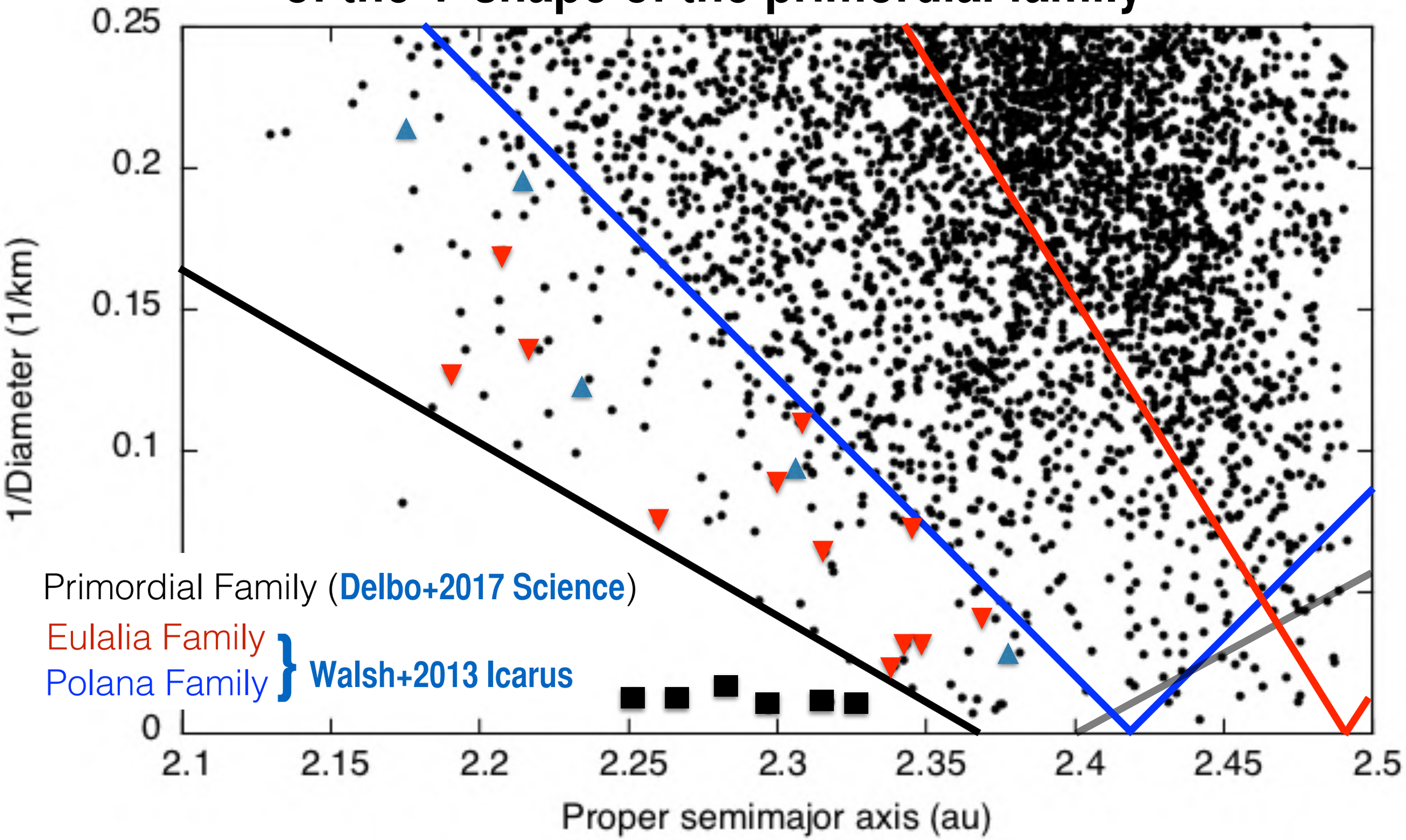


Primordial Family (**Delbo+2017 Science**)

Predominance of retrograde asteroids in the inward part of the V-shape of the primordial family



Predominance of retrograde asteroids in the inward part of the V-shape of the primordial family



Athanasopoulos, **Bonamico**, …., & **Delbo**, Astronomy & Astrophysics, in preparation, 2022

Conclusions

- The study of asteroids can shed light on one of the most obscure phases of planetary formation, i.e. planetesimal accretion.

- Ancient collisional families needs non-classical methods of identification

- Ancient families needs to be confirmed by light curve observations. Small (0.3-1m) telescopes are perfect for this research.