Deciphering Meteorite Pathways in the Solar System

Patrick Shober
Marie Curie Fellowship Laureate

Patrick Shober

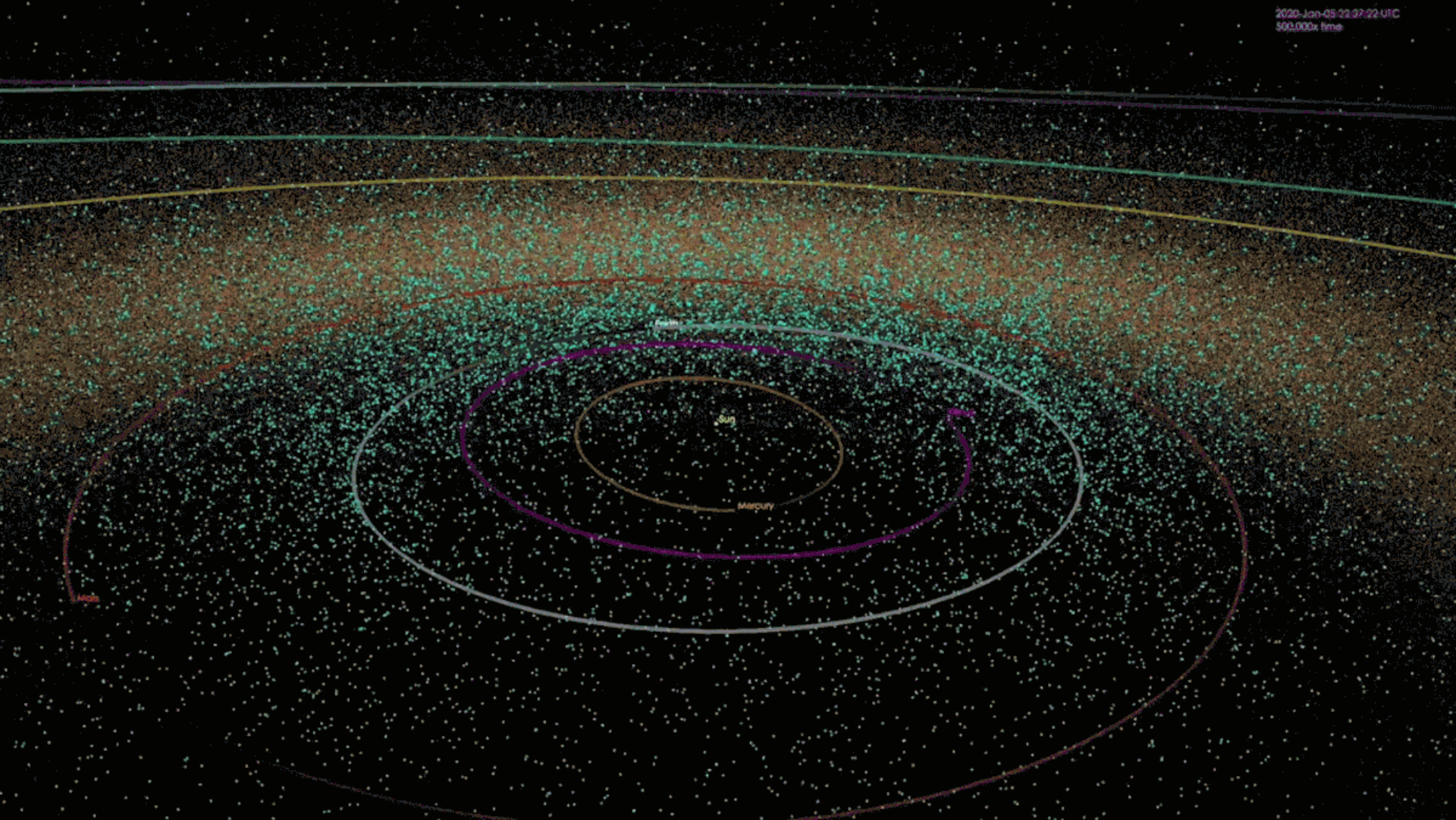
Education

2013-2017 **Case Western Reserve University**
B.S. Geological Sciences

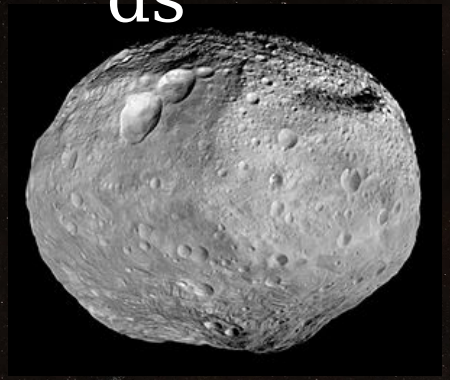
2017-2021 **Curtin University**
Ph.D. Planetary Science

2021-2022 **InTrack Solutions Pty Ltd**
Astrodynamics Specialist

2022-2024 **IMCCE - Paris Observatory**
Marie Curie Postdoctoral Fellow

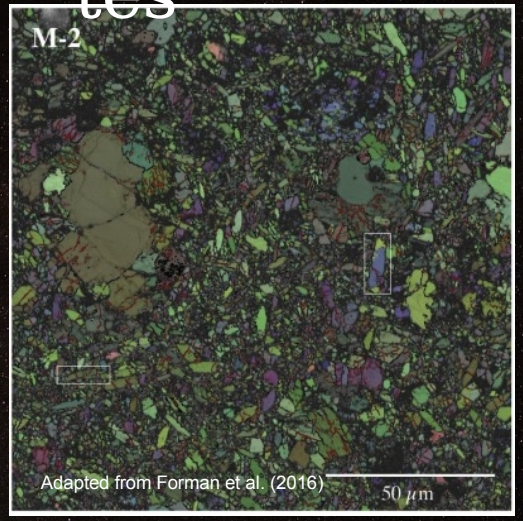

2020-Jan-05 22:07:22 UTC
500,000x time
Earth
Sun
Mercury
Mars

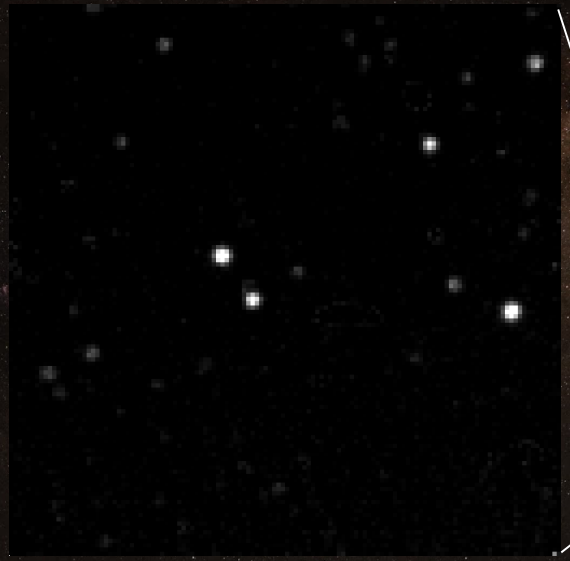
ds

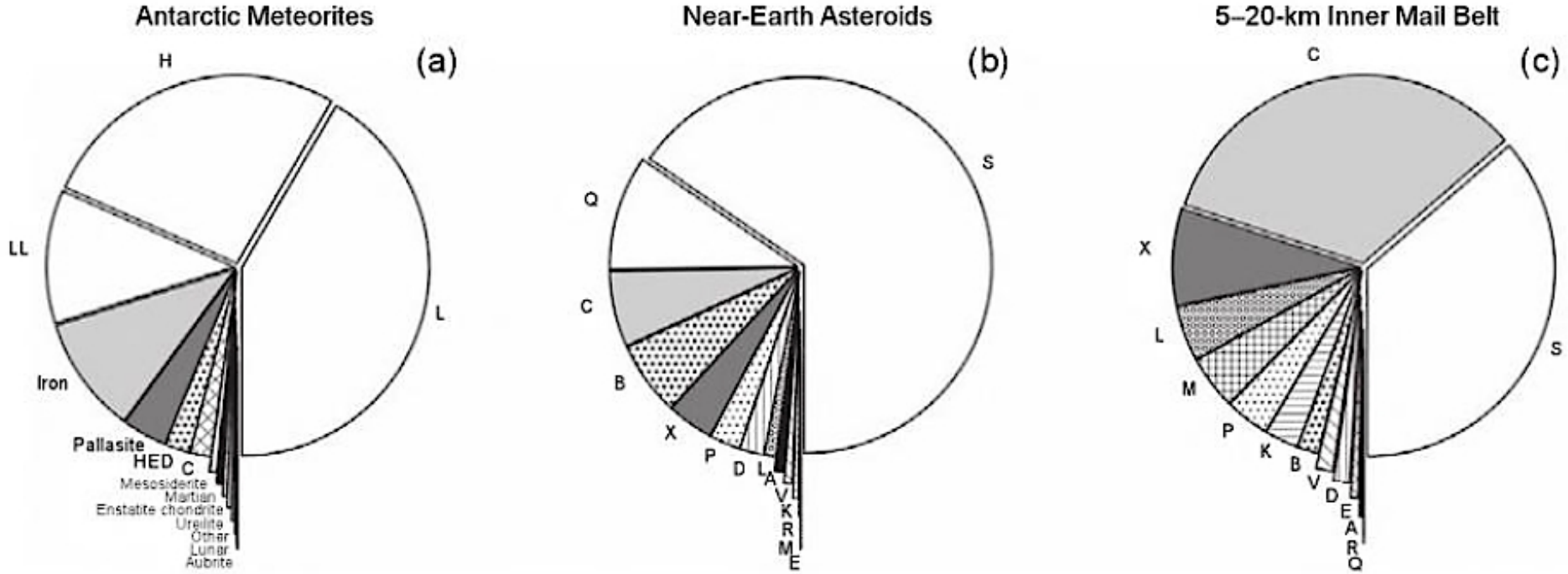


?

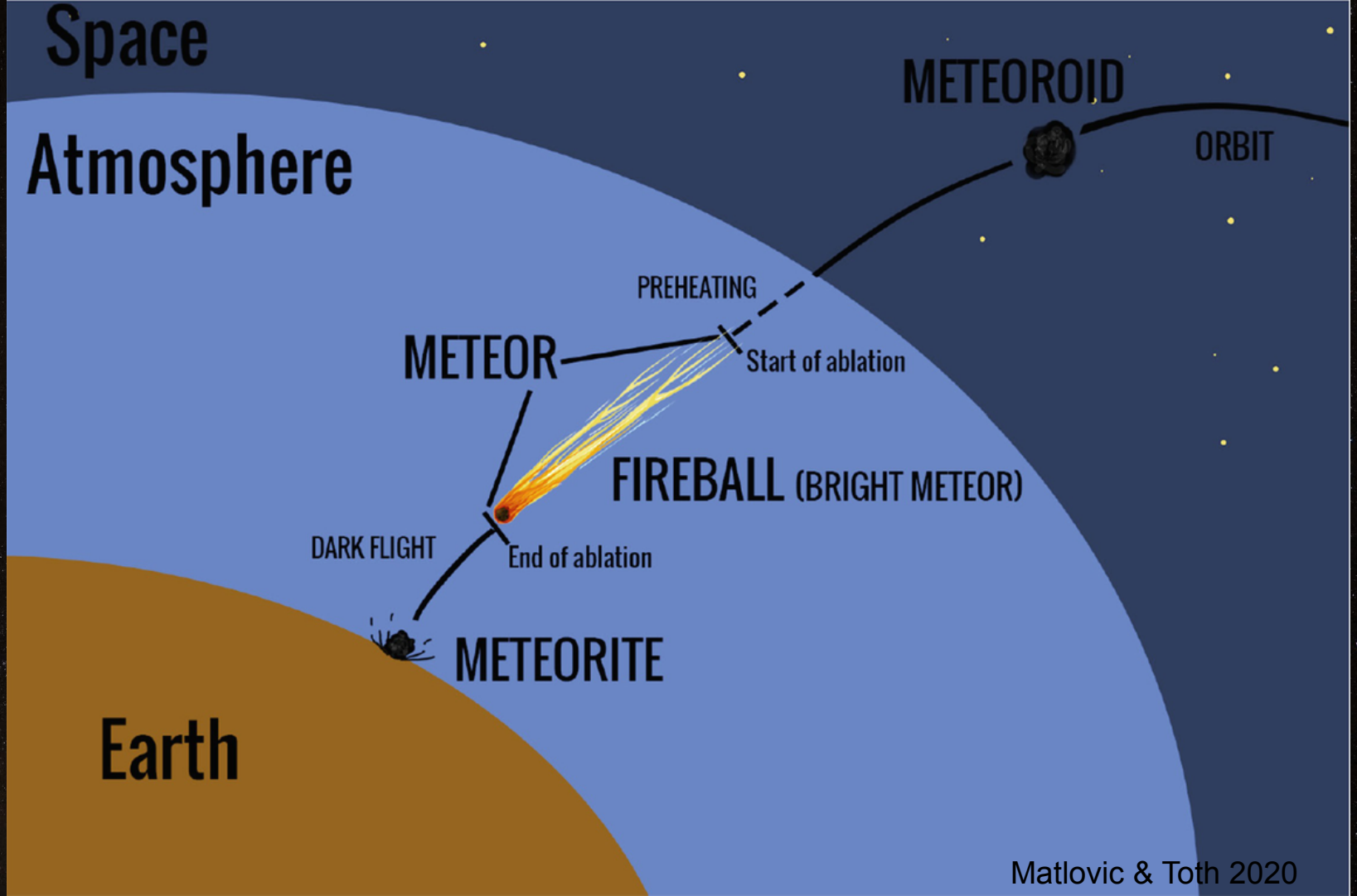
Meteori
tes







Mass distributions for Antarctic meteorites, near-Earth asteroids and the inner main belt. The two largest NEOs (433) Eros and (1036) Ganymed, both S-types, were not included because they dominate the NEO populations mass (Binzel et al. 2015).



Matlovic & Toth 2020

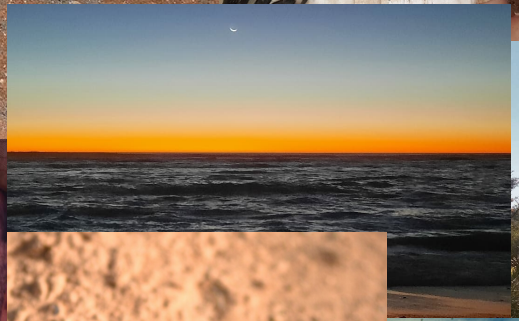

DESERT
FIREBALL NETWORK


Vigie Ciel
FRIPON

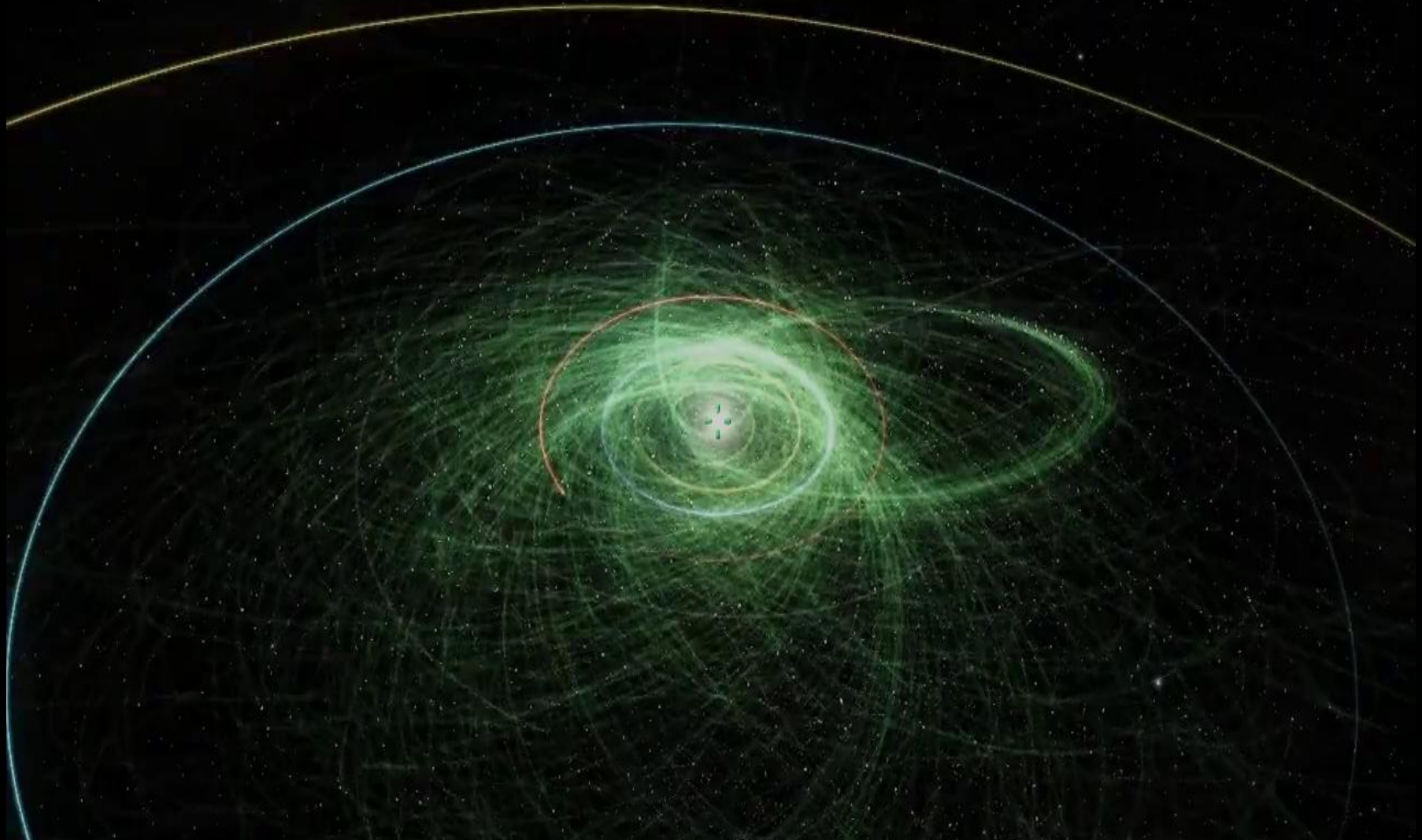

Lake Pravaa
Google Earth

IMAGE CREDIT: Curtin University and Desert Fireball Network



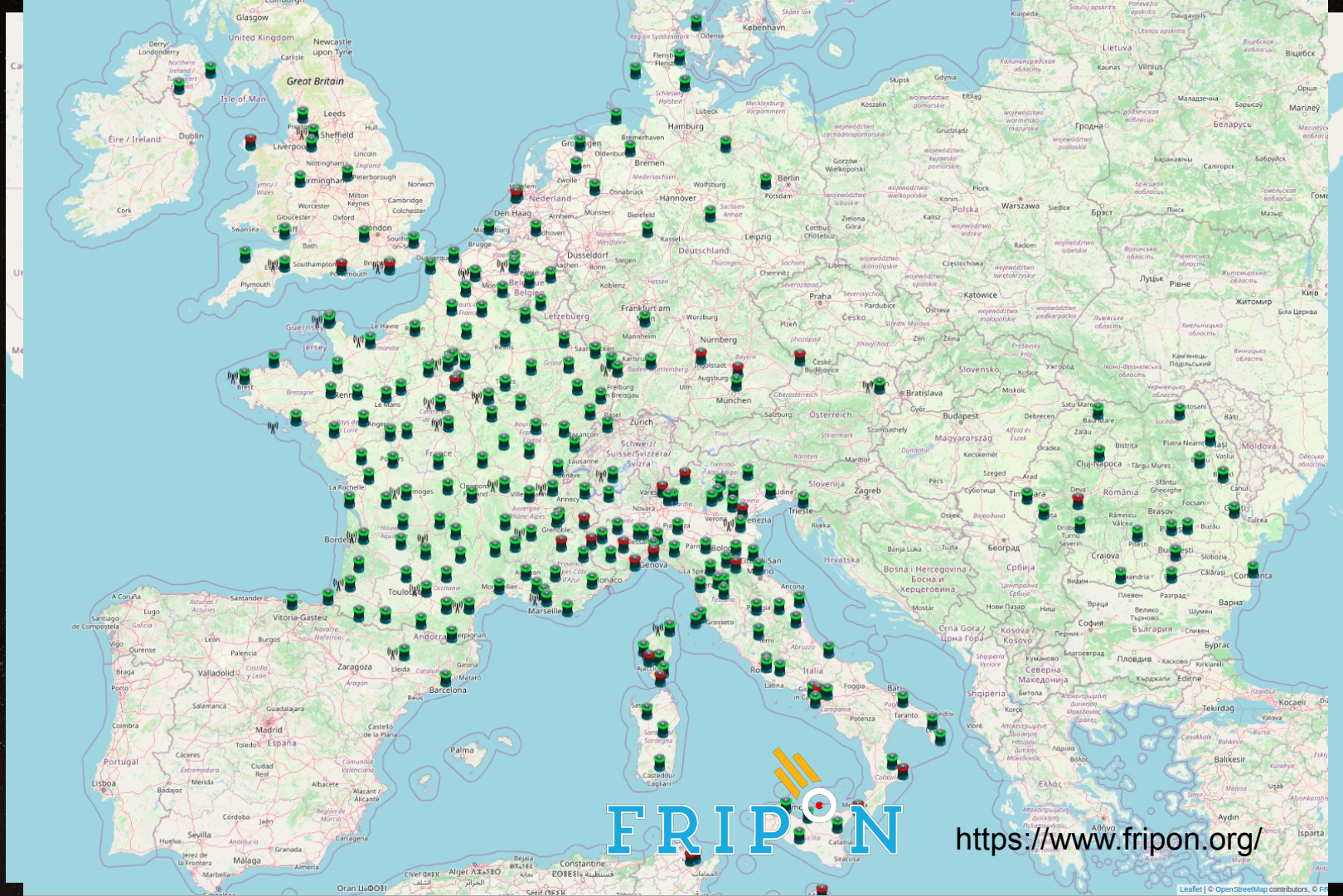


GLOBAL FIREBALL OBSERVATORY

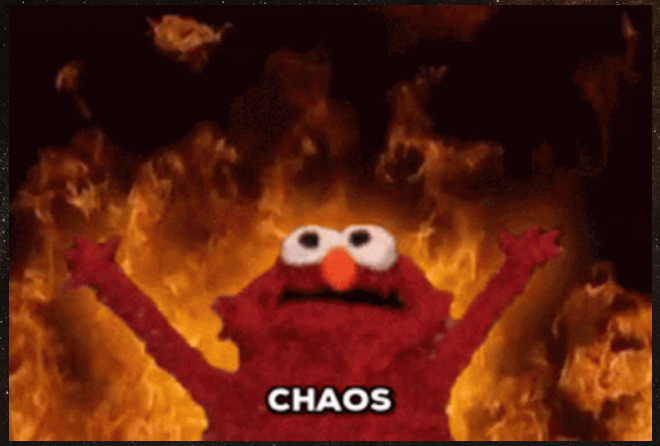
- 2% of Earth's surface
- 19 institutions
- 10 fireball networks


FRIP
www.fripon.org
1N-132

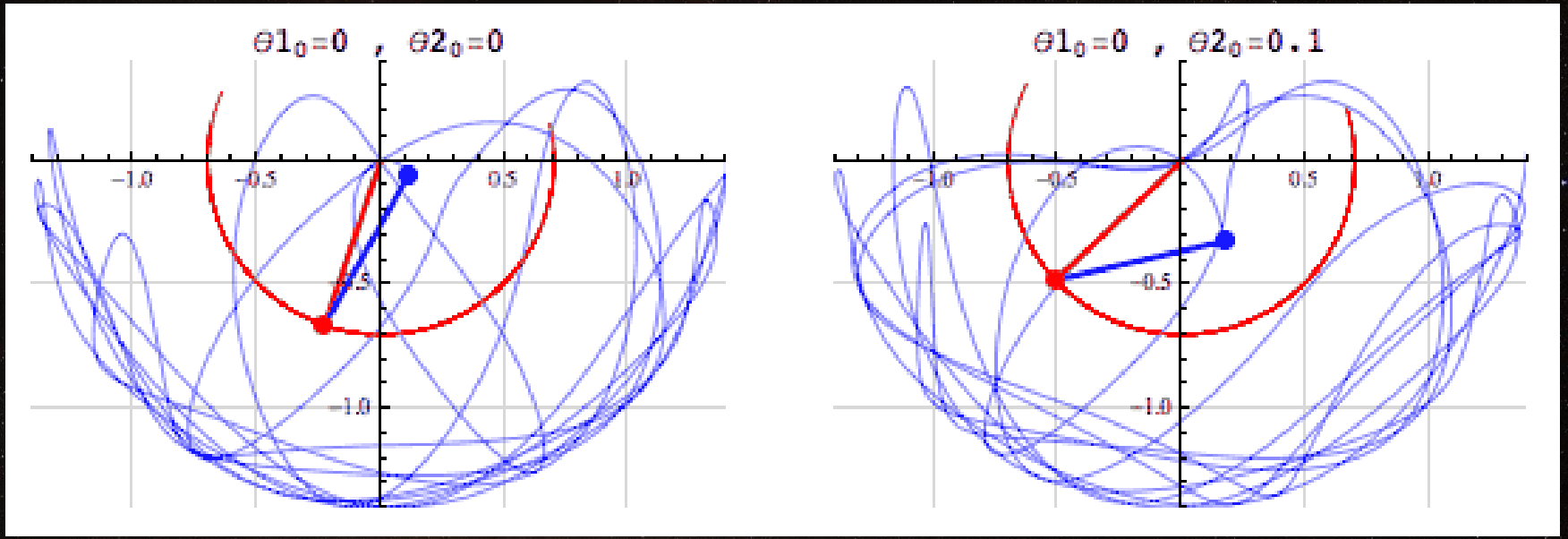

FRIPON
https://www.fripon.org/
Leaflet | © OpenStreetMap contributors, © FR

Problems…

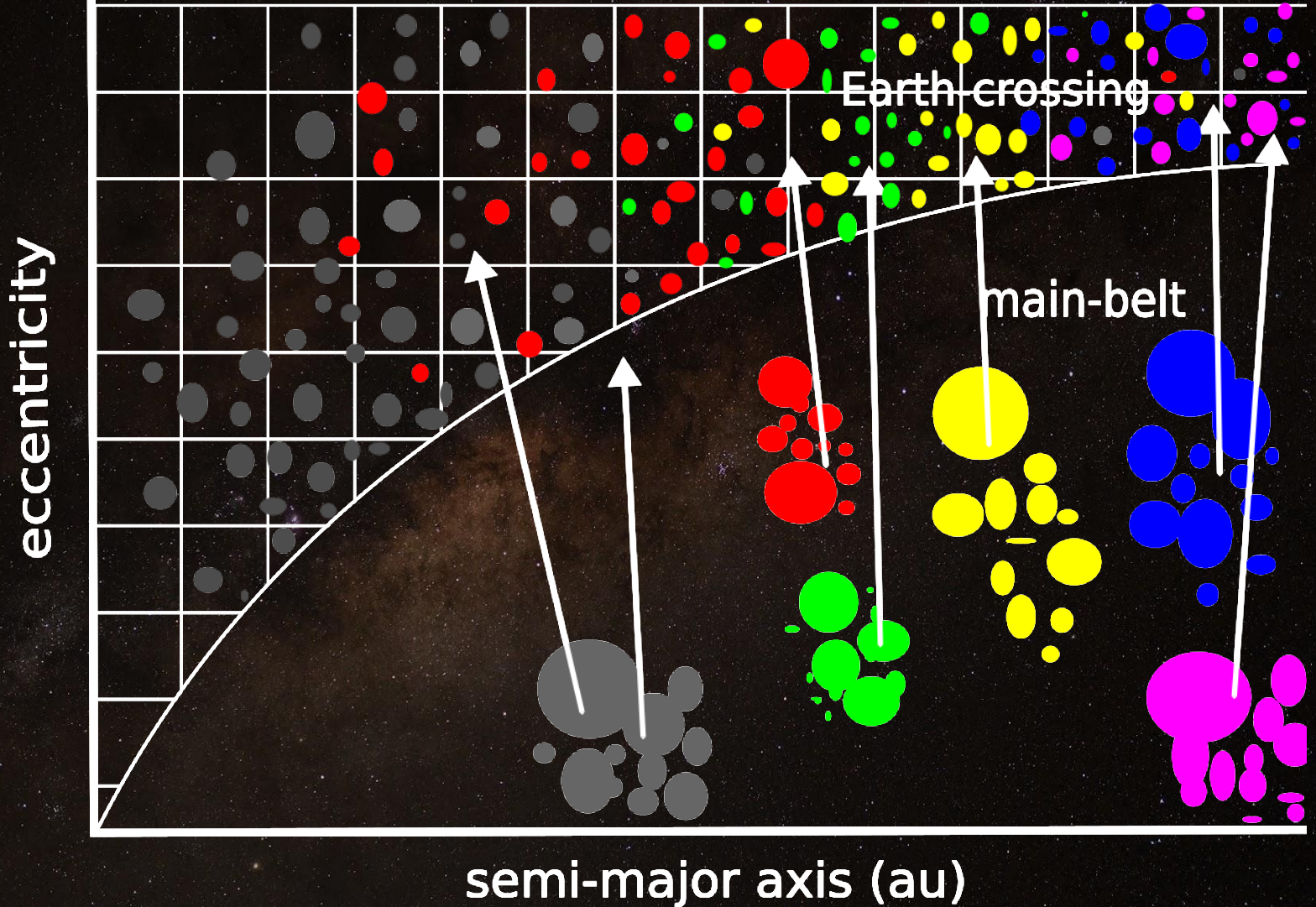
You cannot figure out where something can from exactly!

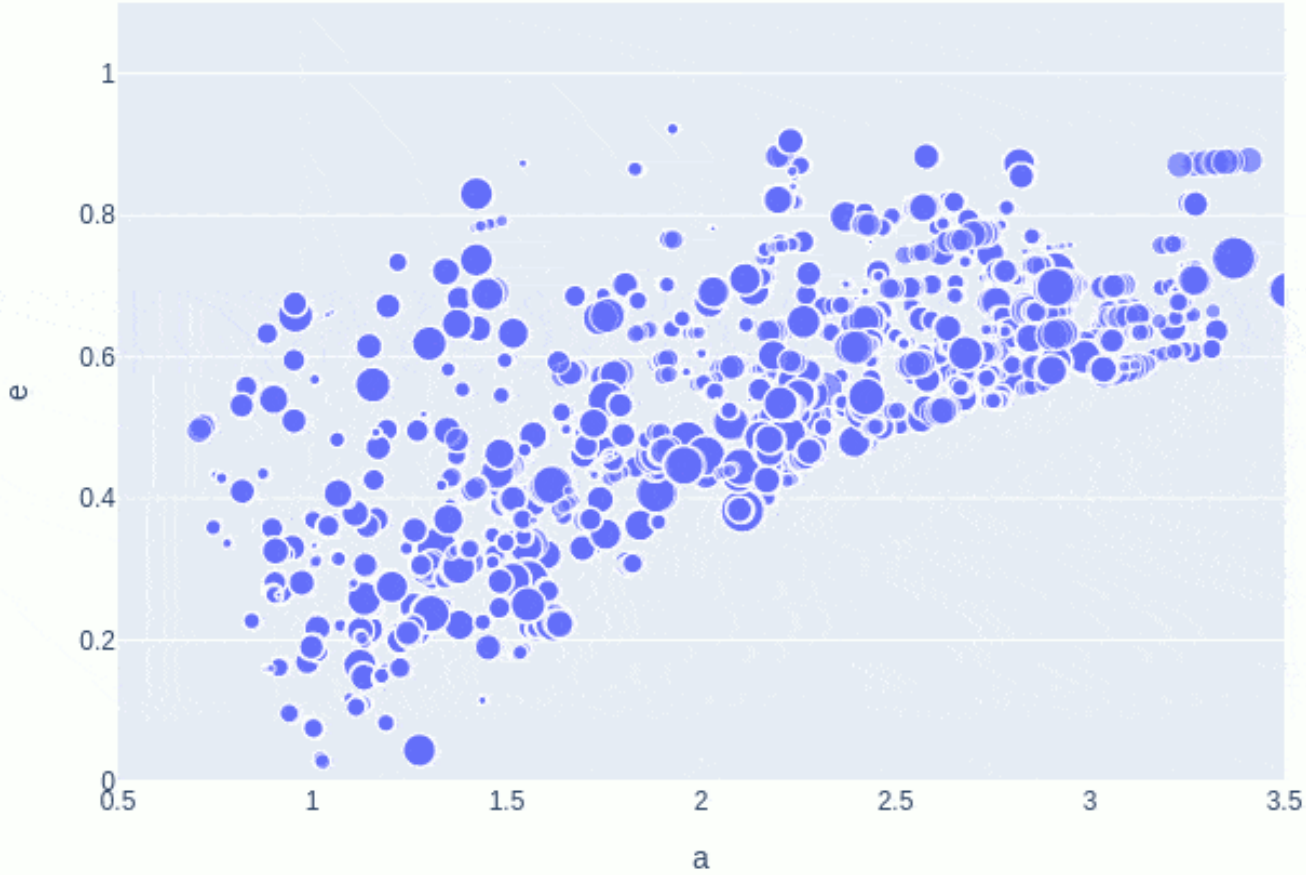


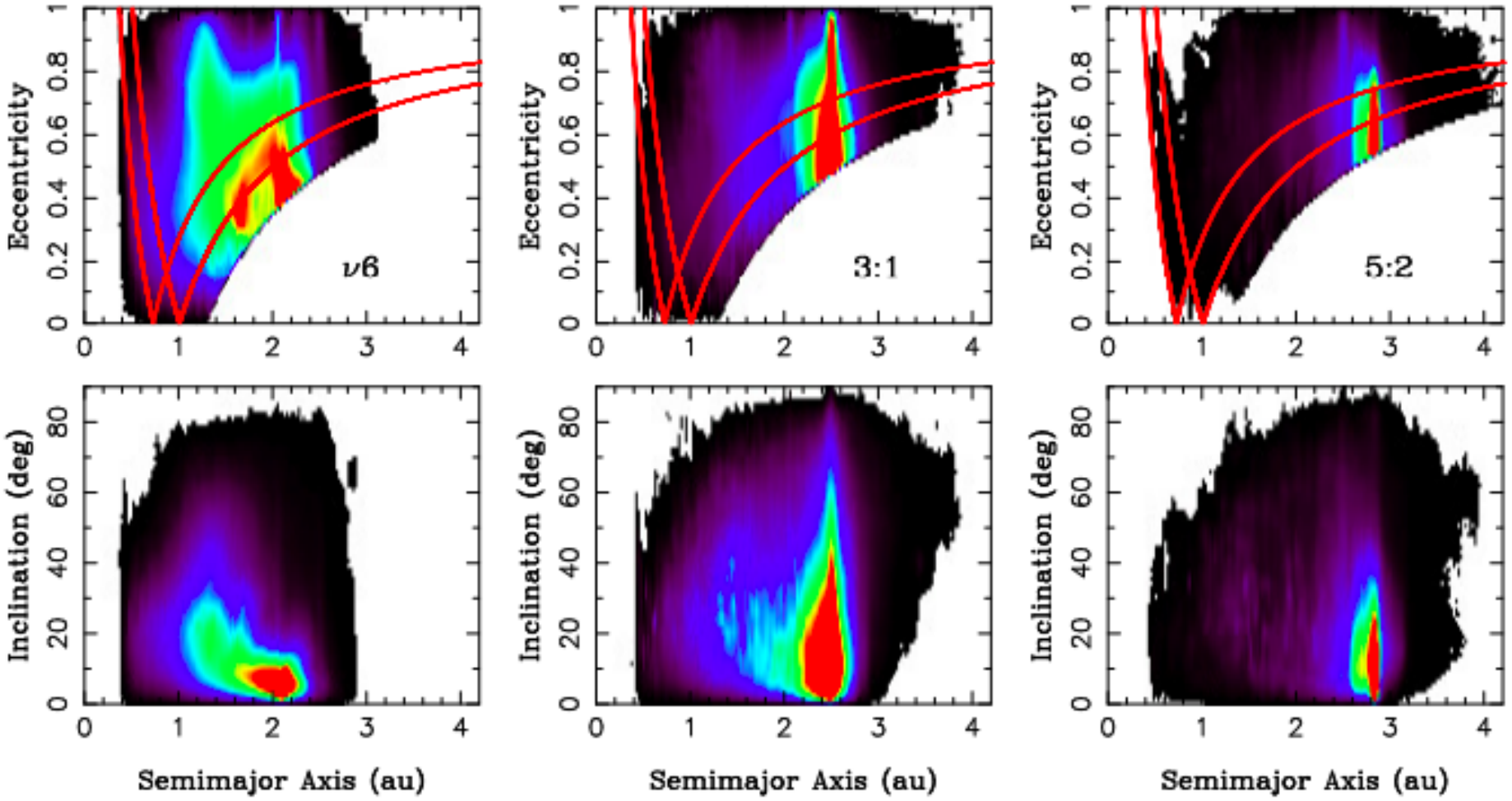
Because of **chaos**


θ1₀=0 , θ2₀=0
−1.0
−0.5
0.5
1.0
−0.5
−1.0
θ1₀=0 , θ2₀=0.1
−1.0
−0.5
0.5
1.0
−0.5
−1.0

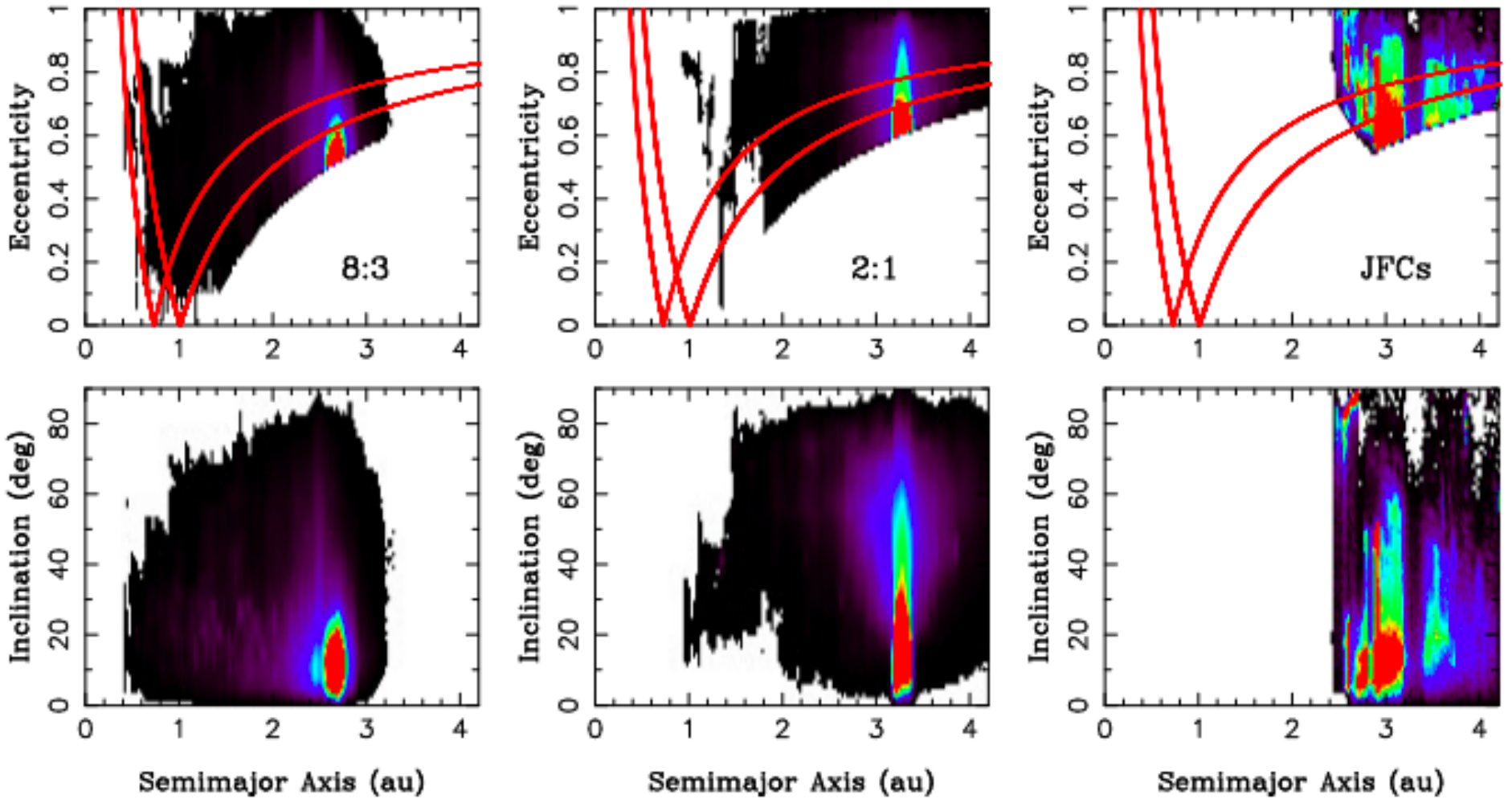
Debiased Near-Earth Object Models !


Earth-crossing
main-belt
eccentricity
semi-major axis (au)


1
0.8
0.6
0.4
0.2
0
e
0.5
1
1.5
2
2.5
3
3.5
a

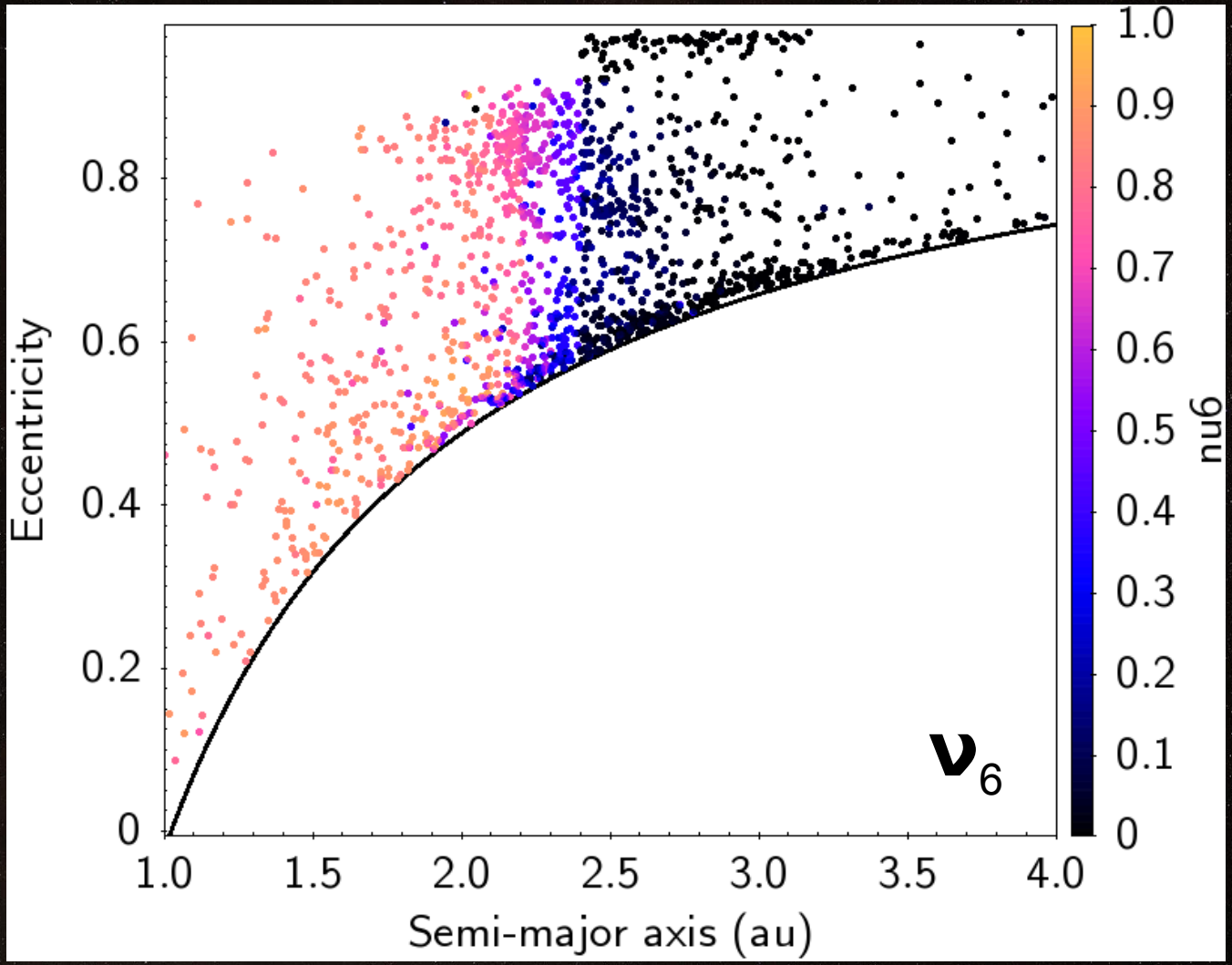


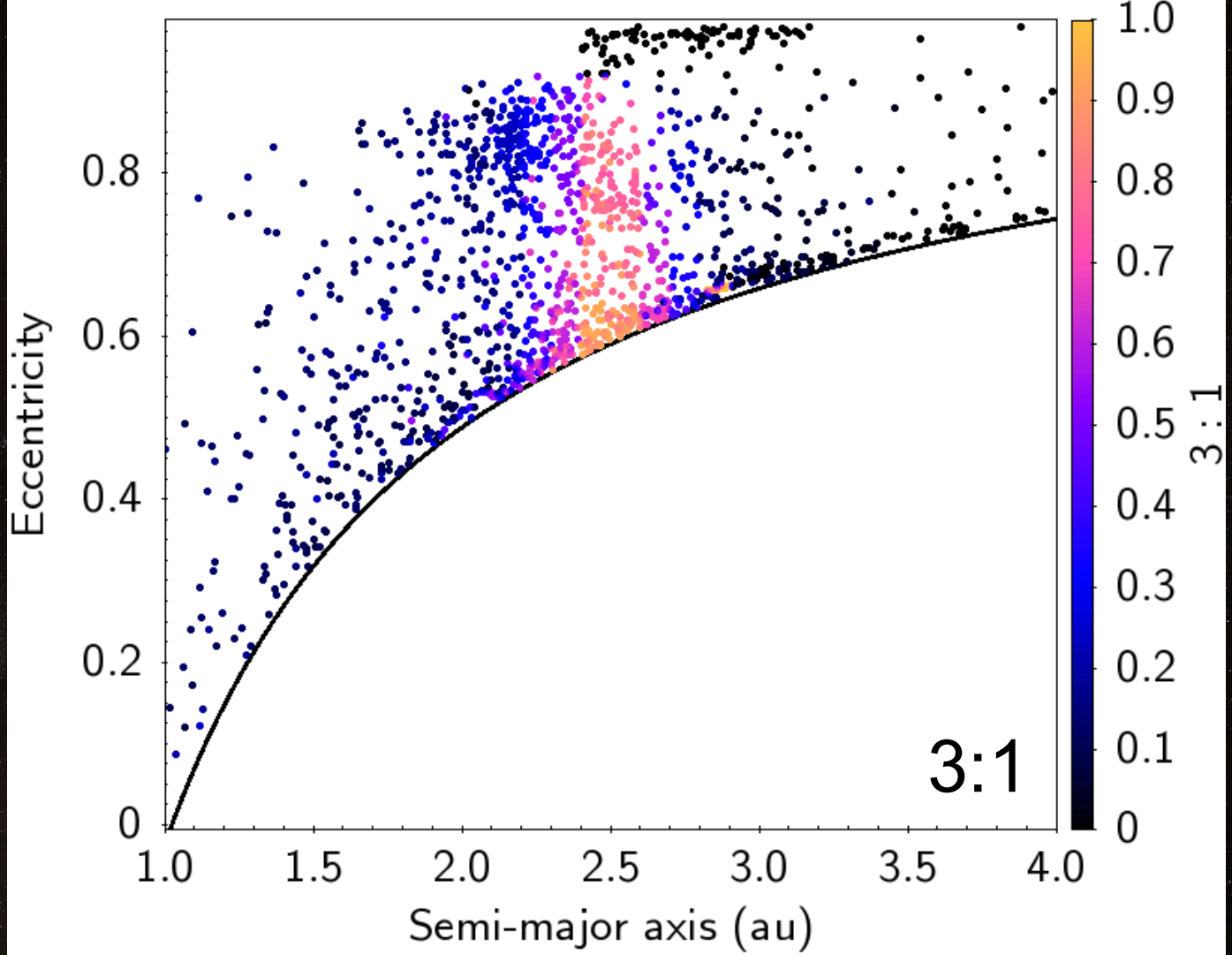
Nesvorny et al. 2024

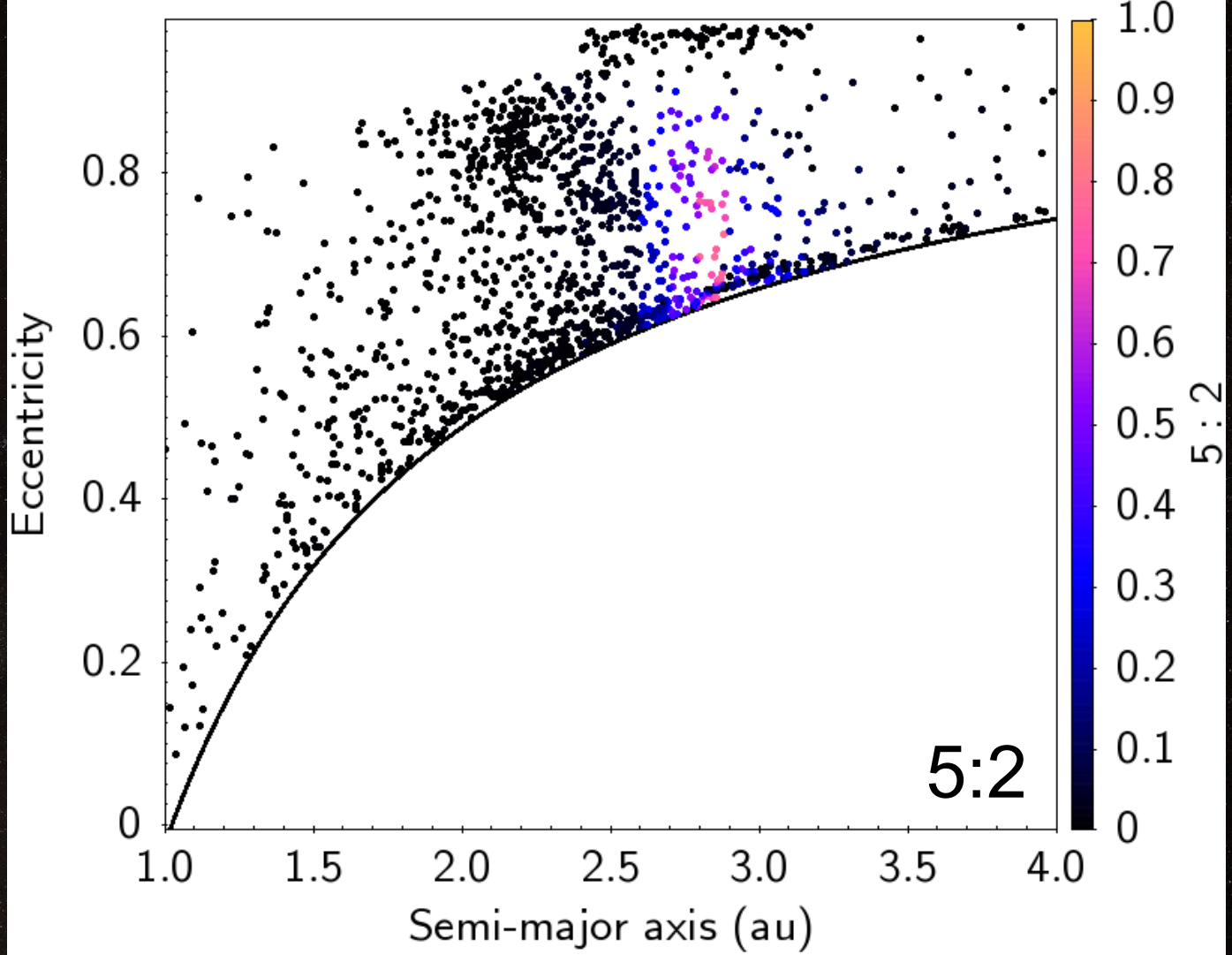


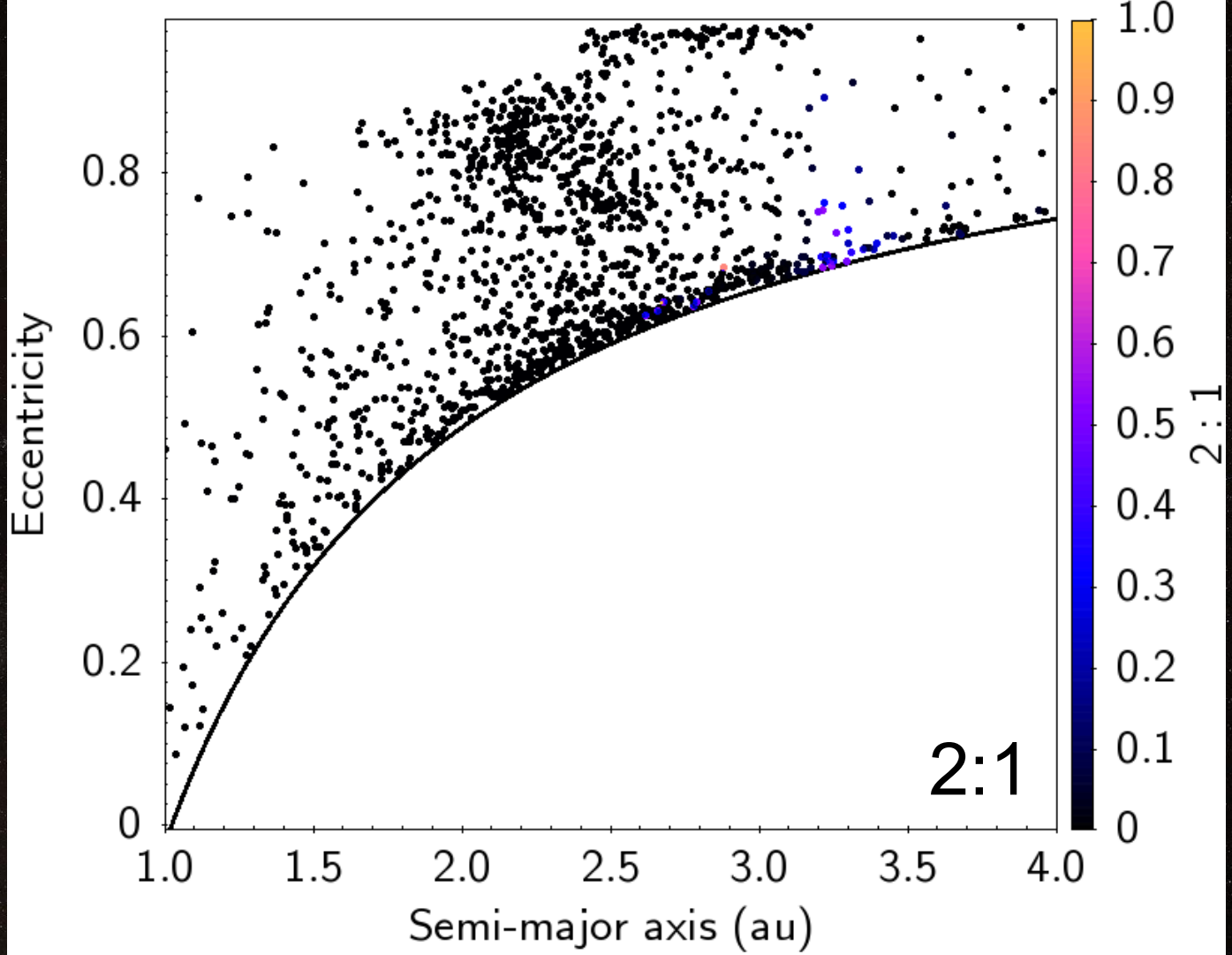
Nesvorny et al. 2024

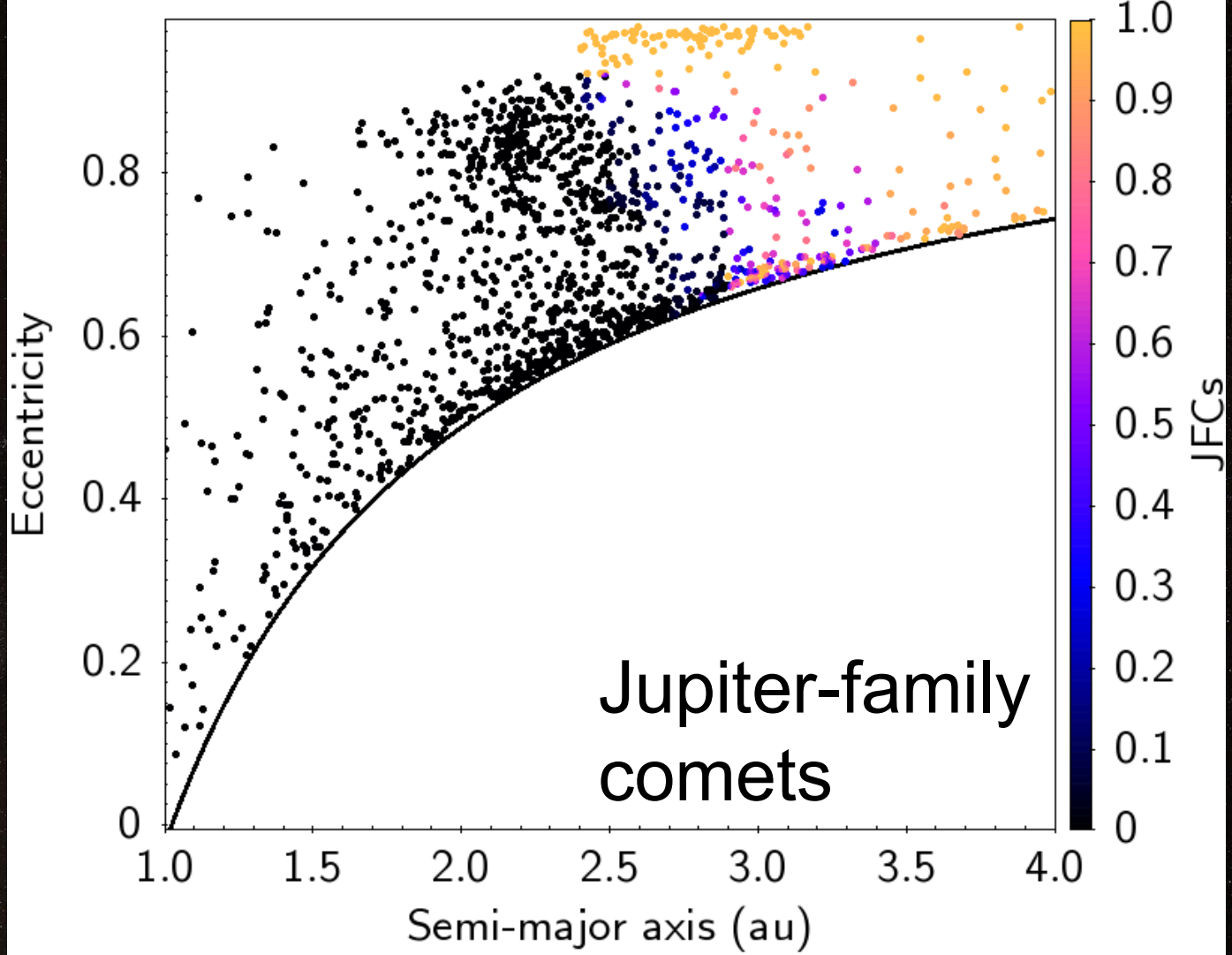
What happens when we apply these models to fireball data?


Eccentricity
0
0.2
0.4
0.6
0.8
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Semi-major axis (au)
ν_6
nu6
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0


Eccentricity
0
0.2
0.4
0.6
0.8
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Semi-major axis (au)
3:1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
3 : 1


Eccentricity
0
0.2
0.4
0.6
0.8
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Semi-major axis (au)
5:2
0.1
0.3
0.5
0.7
0.9
5:2


Eccentricity
0
0.2
0.4
0.6
0.8
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Semi-major axis (au)
2:1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
2:1


Eccentricity
0
0.2
0.4
0.6
0.8
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Semi-major axis (au)
JFCs
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Jupiter-family
comets

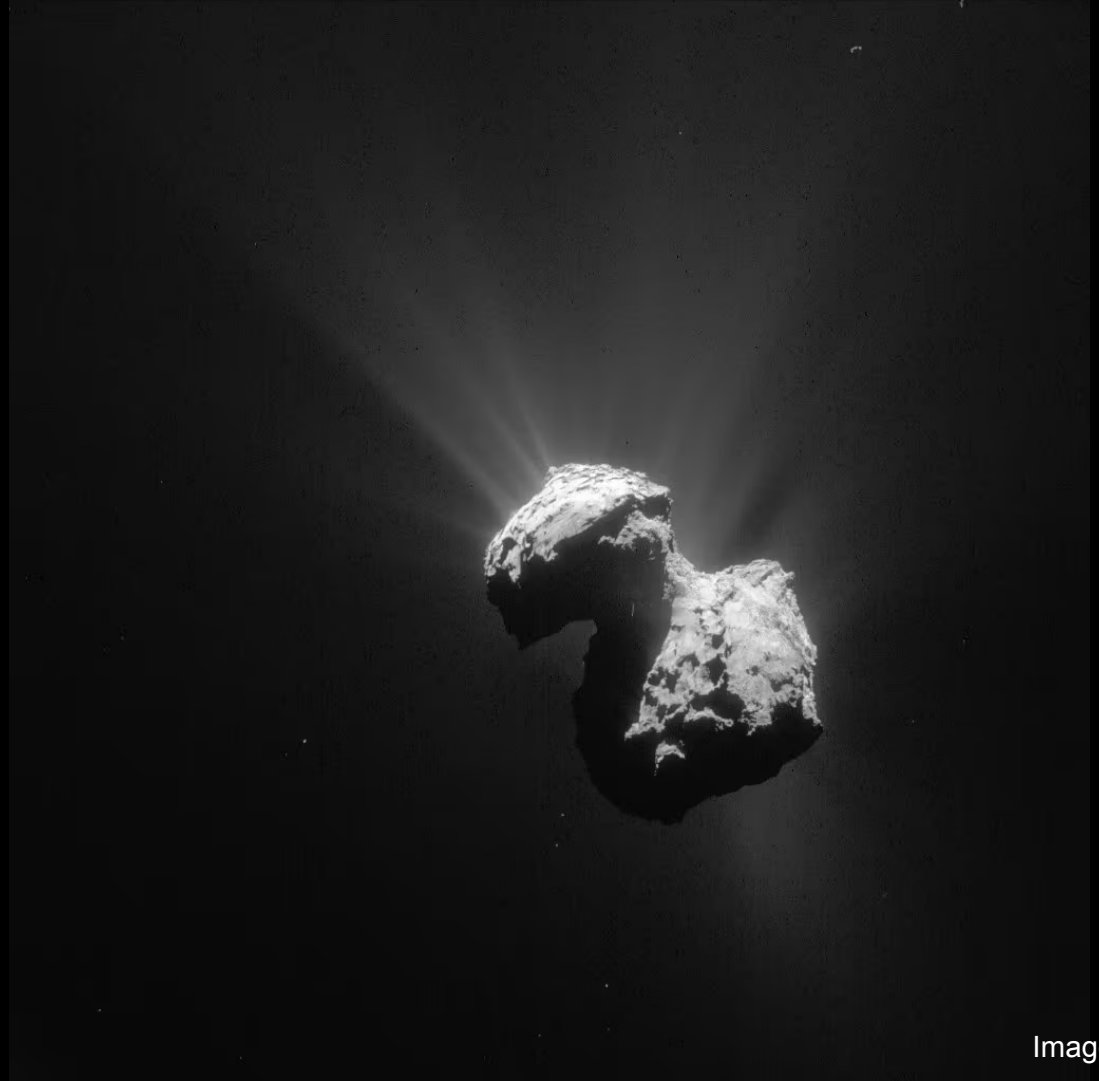
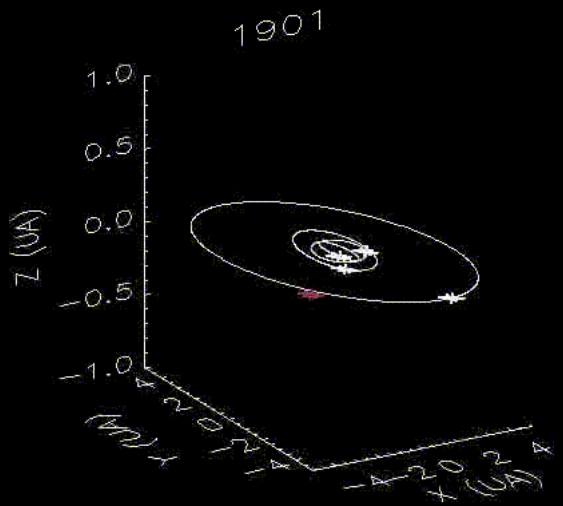
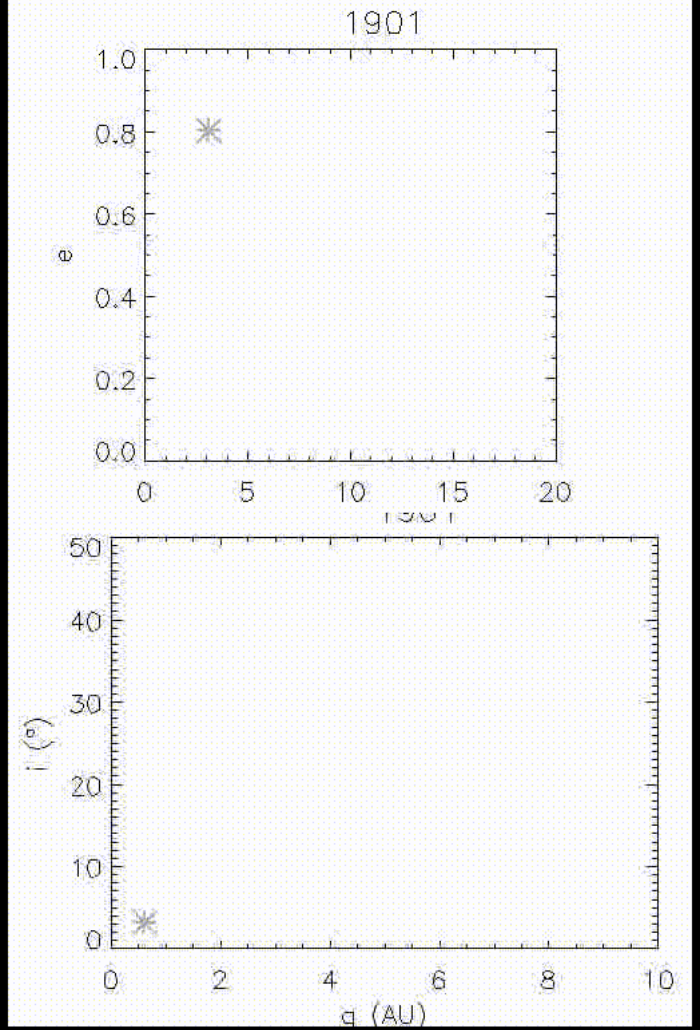
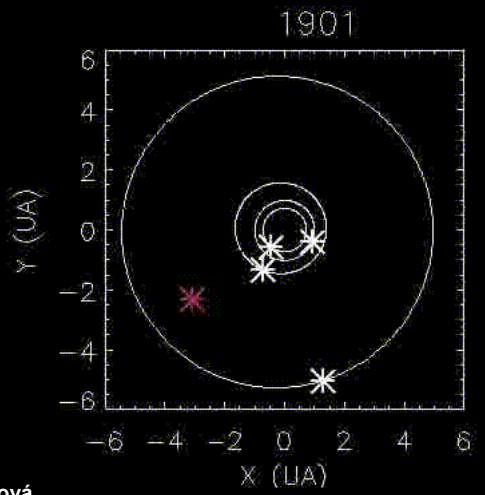


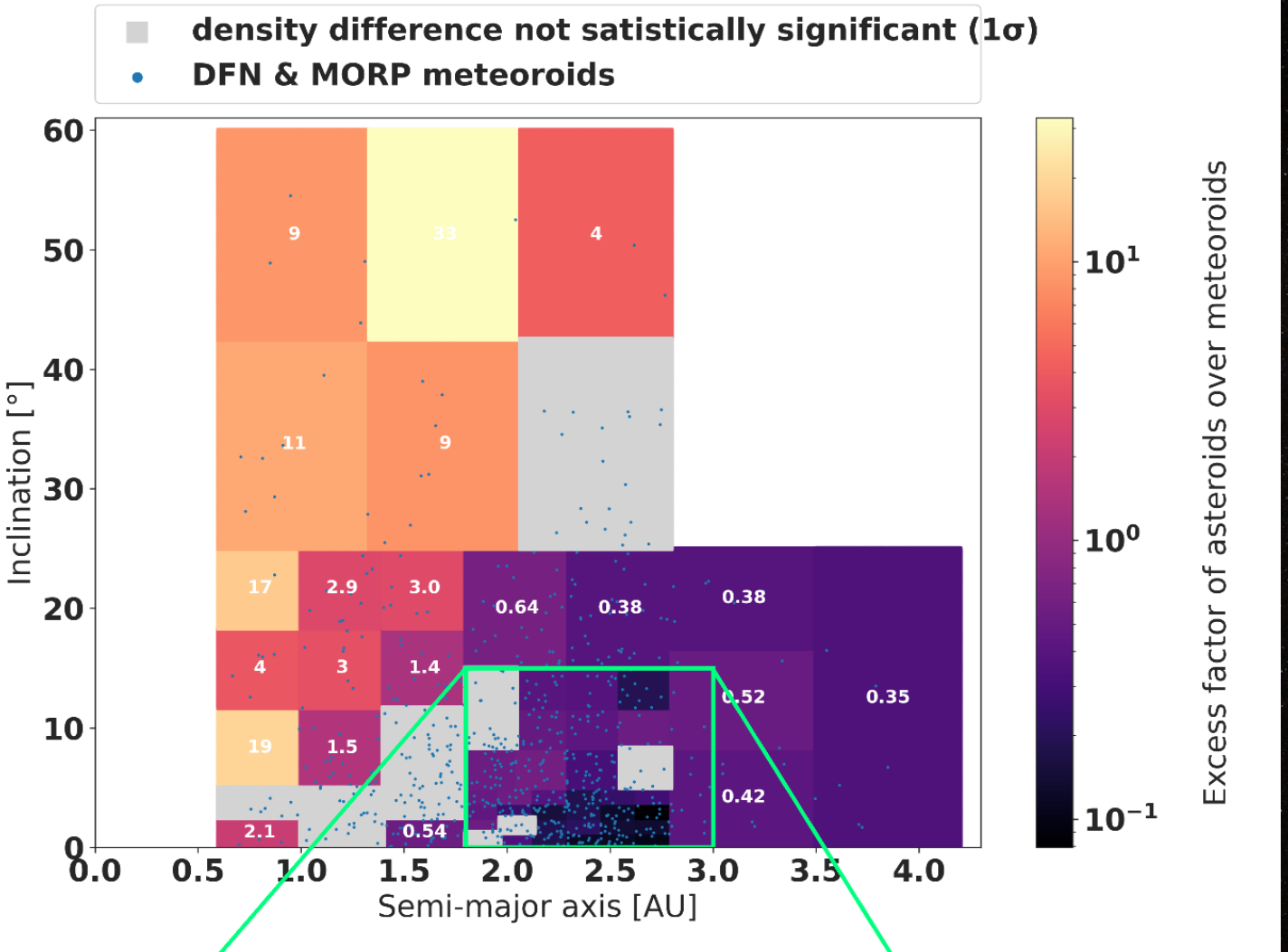
Image Credit: ESA Rosetta Mission

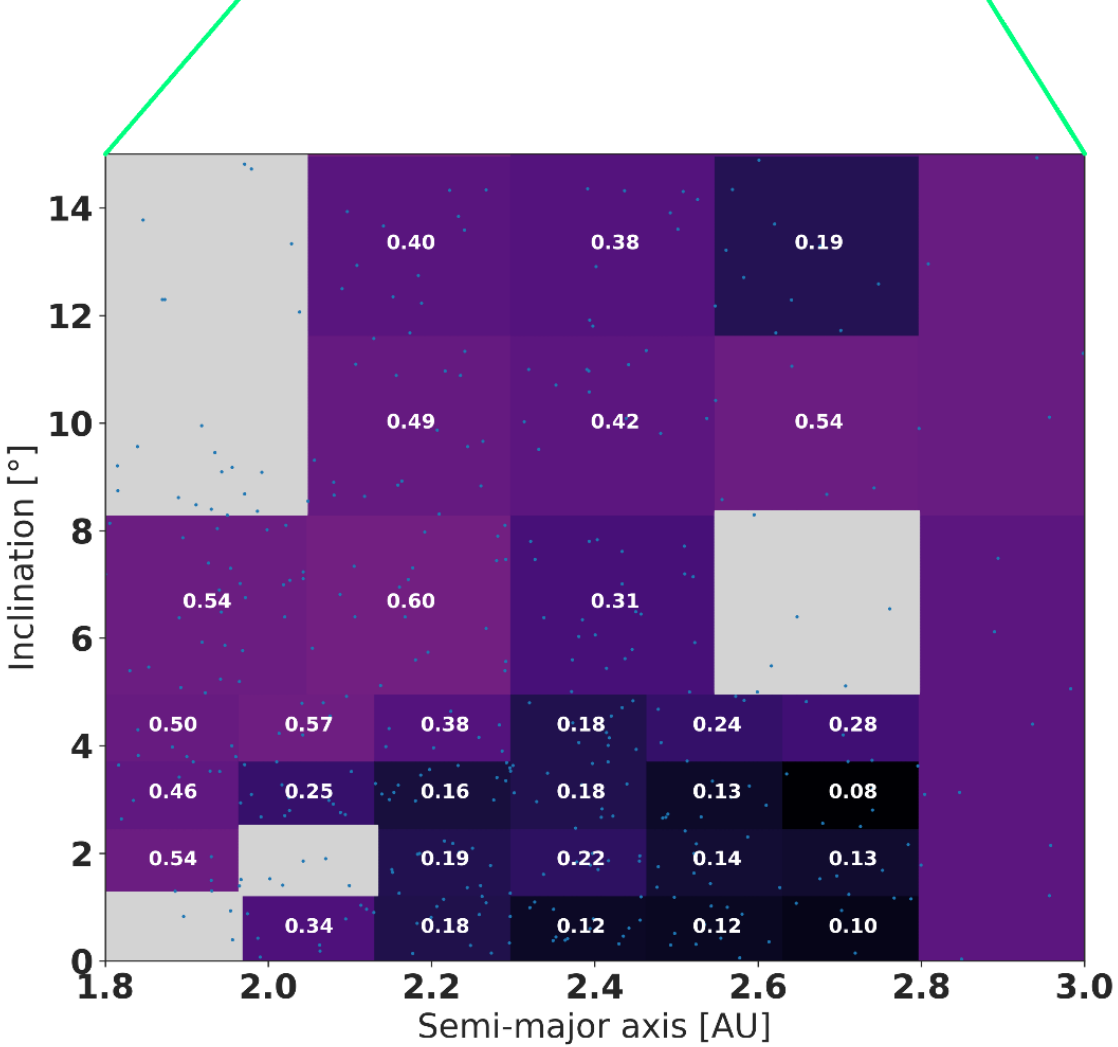






45P/Honda–Mrkos–Pajdušáková
Vaubaillon & Christou (2006)


density difference not satistically significant (1σ)
DFN & MORP meteoroids
Inclination [°]
Semi-major axis [AU]
Excess factor of asteroids over meteoroids
10^1
10^0
10^{-1}
9
33
4
11
9
17
2.9
3.0
0.64
0.38
0.38
4
3
1.4
0.52
0.35
19
1.5
0.42
2.1
0.54


0.40
0.38
0.19
0.49
0.42
0.54
0.54
0.60
0.31
0.50
0.57
0.38
0.18
0.24
0.28
0.46
0.25
0.16
0.18
0.13
0.08
0.54
0.19
0.22
0.14
0.13
0.34
0.18
0.12
0.12
0.10
Inclination [°]
Semi-major axis [AU]
0
2
4
6
8
10
12
14
1.8
2.0
2.2
2.4
2.6
2.8
3.0

21 Jan 2024 - Asteroid 2024 BX1 Impact

Probabilities	
nu6	0.881
3:1	0.109
5:2	0.002
7:3	0.000
8:3	0.000
9:4	0.000
11:5	0.000
2:1	0.000
Hungarias	0.001
JFCs	0.000

ELSEVIER

journal h e/icarus

ICARUS

Hungaria asteroid family as t orites

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[c] Southwest Research Institute, 1050 Walnut St., Suite 400, Bou

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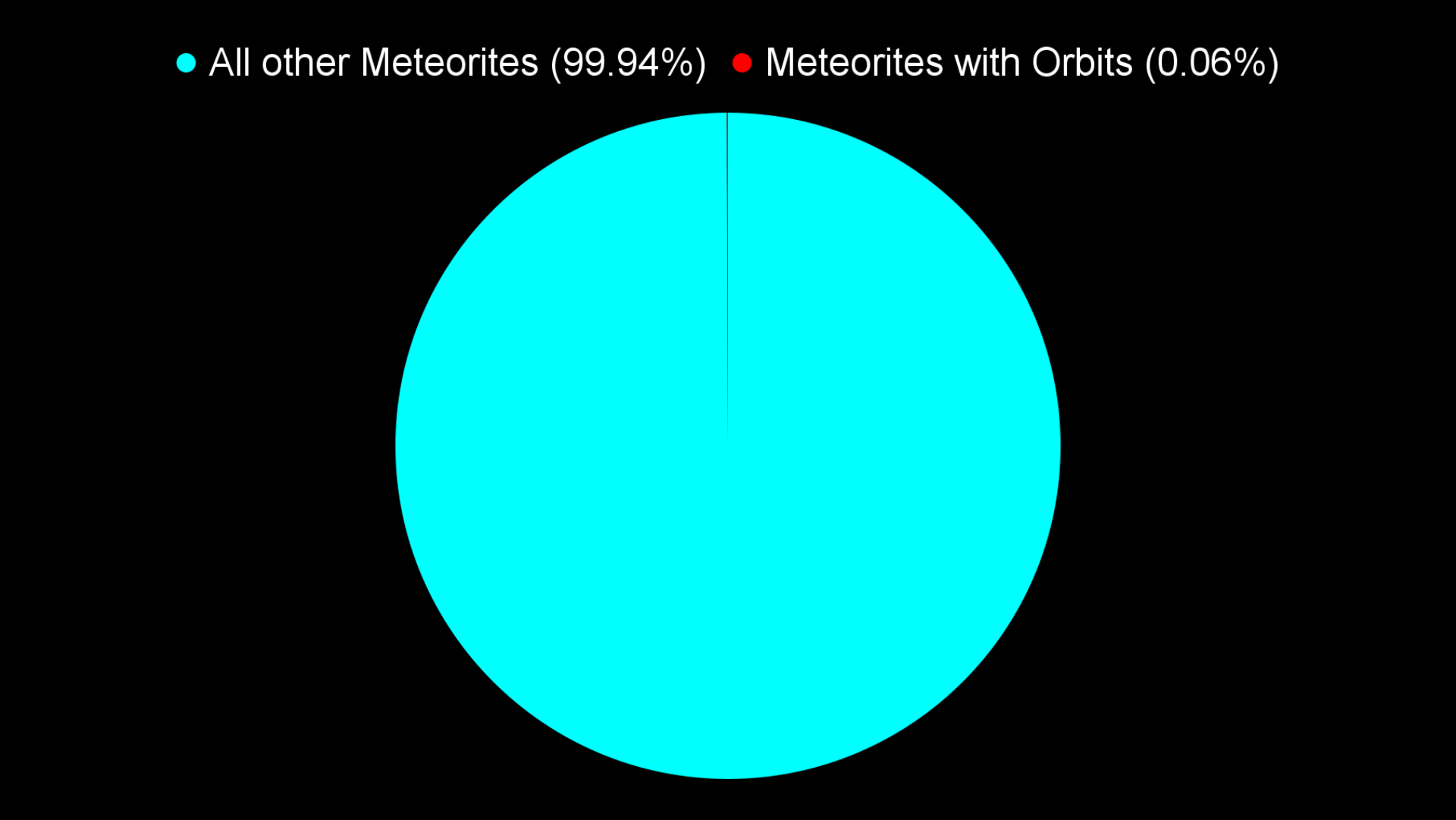
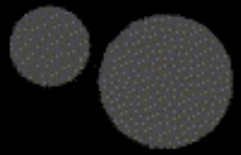
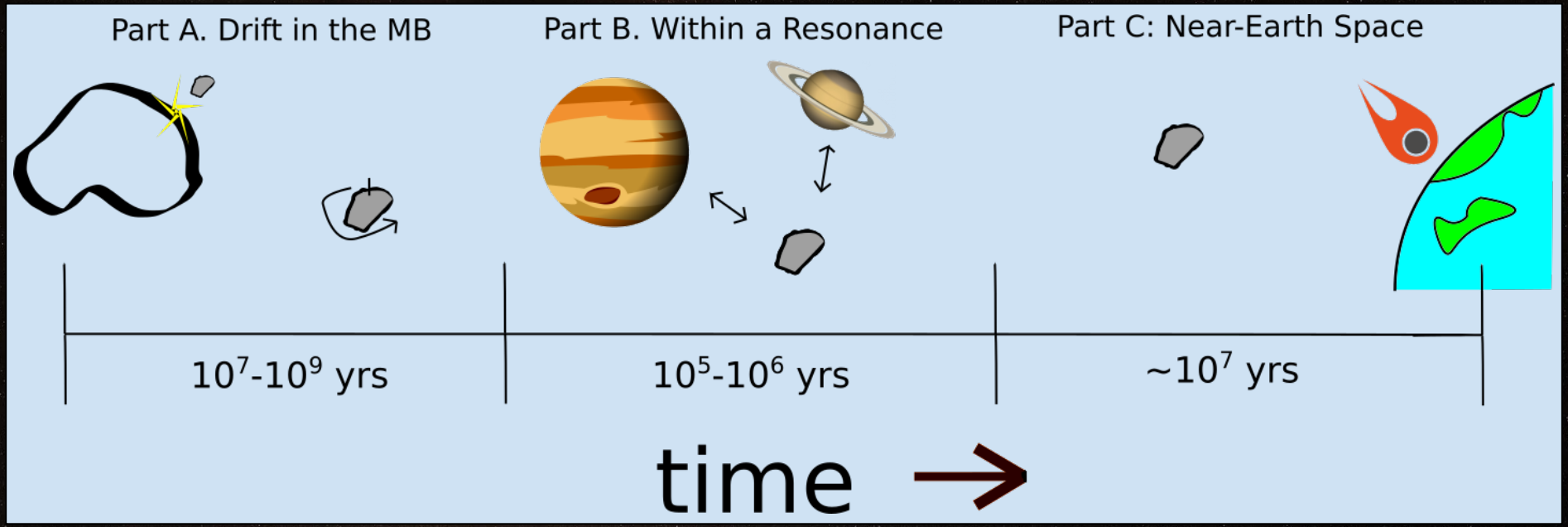
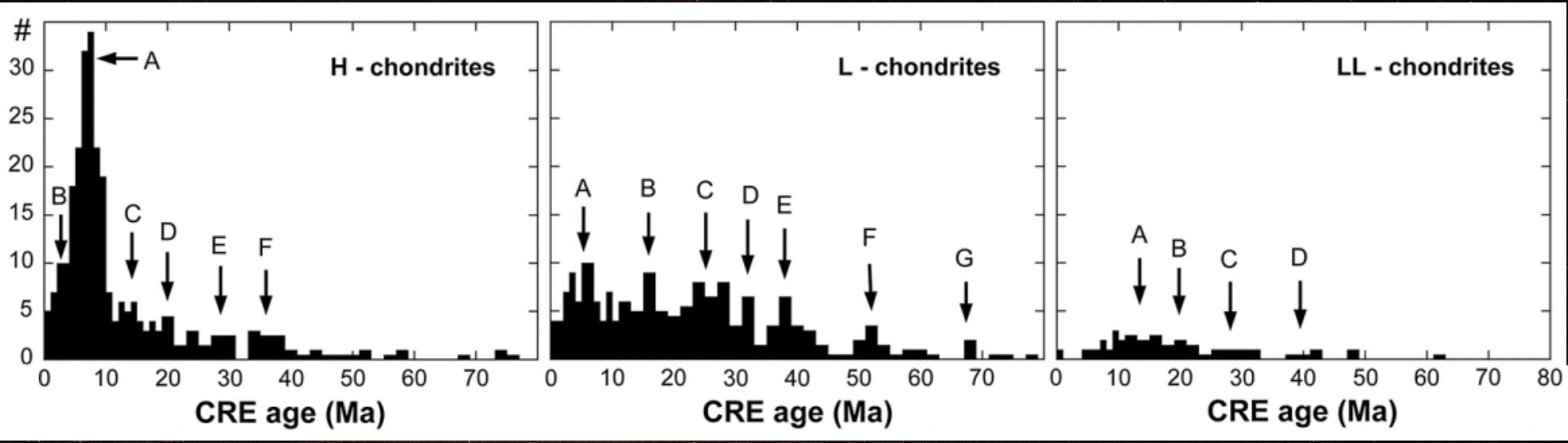
Keywords:
Asteroids

The H d belt, with semimajor axes between 1.8 and 2 AU, low e teroids in the Hungaria region are dominated by a collis dominant spectral type of the Hungaria group is the E 2–182), mostly due to the E-type composition of Hungaria and its genetic family. It is widely believed the E-type asteroids are related to the aubrite meteorites, also known as enstatite achondrites (Gaffey et al. [1992]. Icarus, 100, 95–109). Here we explore the hypothesis that aubrites originate in the Hungaria family. In order to test this connection, we compare model Cosmic Ray Exposure ages from orbital integrations of model meteoroids with those

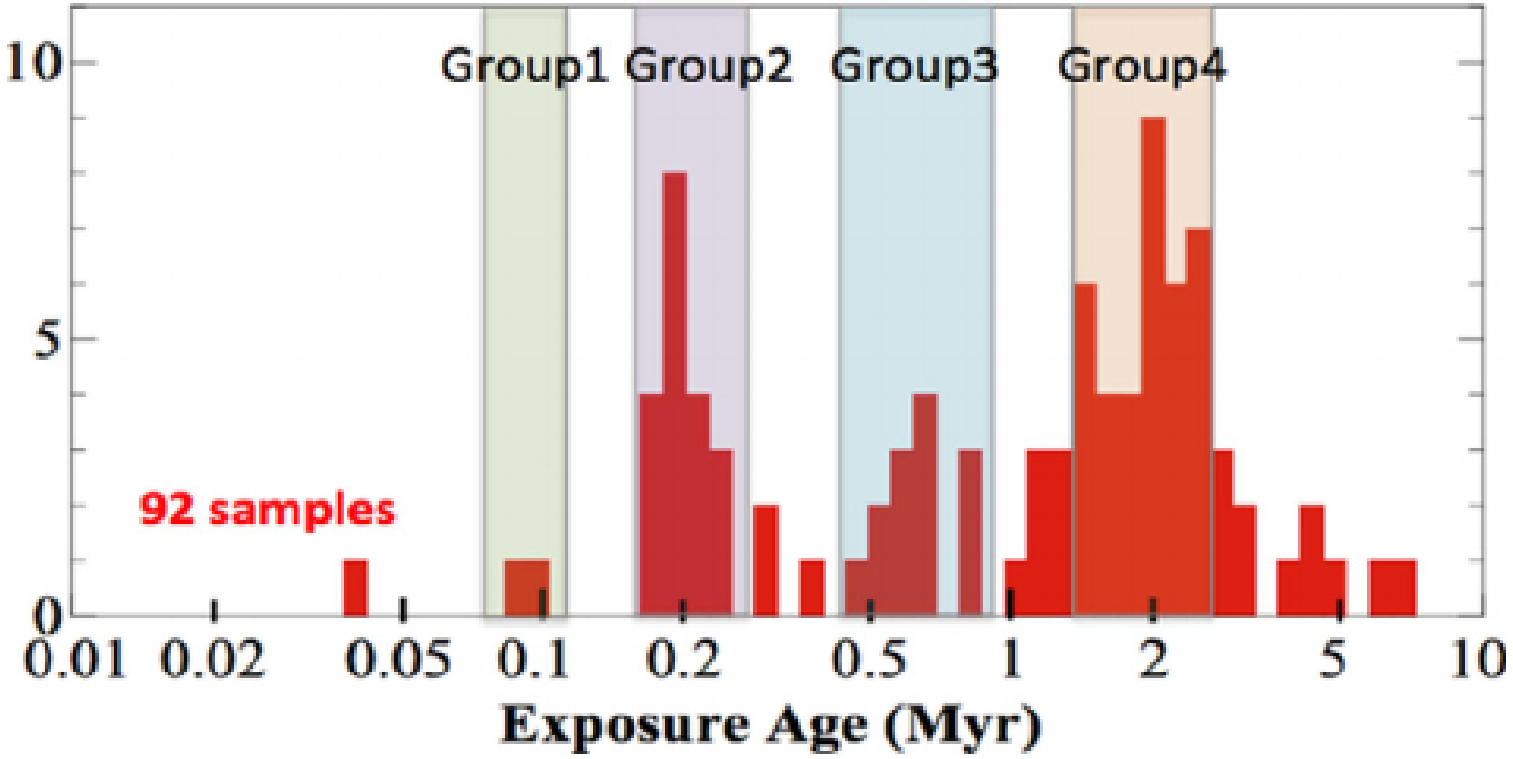

All other Meteorites (99.94%)
Meteorites with Orbits (0.06%)



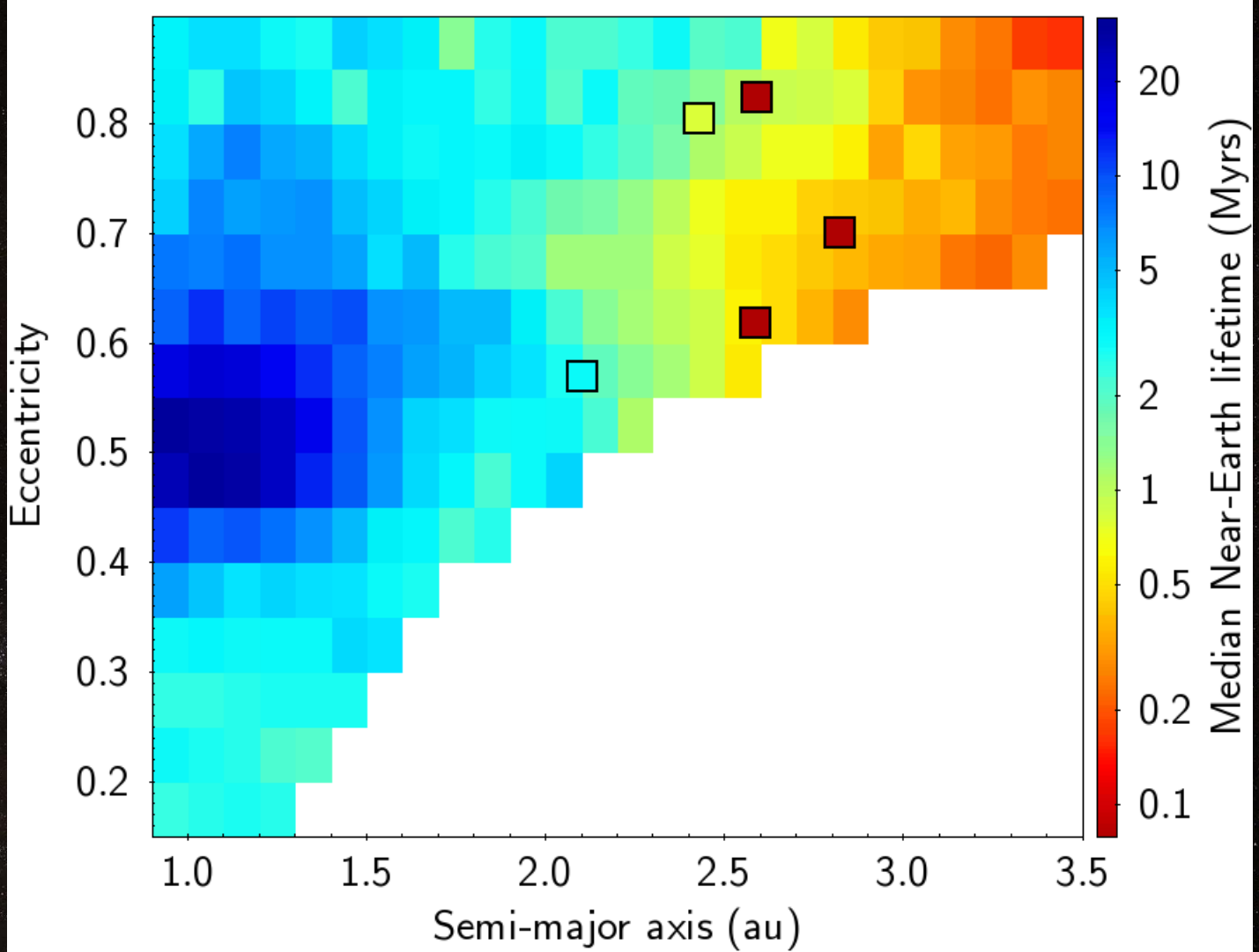

Part A. Drift in the MB
Part B. Within a Resonance
Part C: Near-Earth Space
10^7-10^9 yrs
10^5-10^6 yrs
~10^7 yrs
time

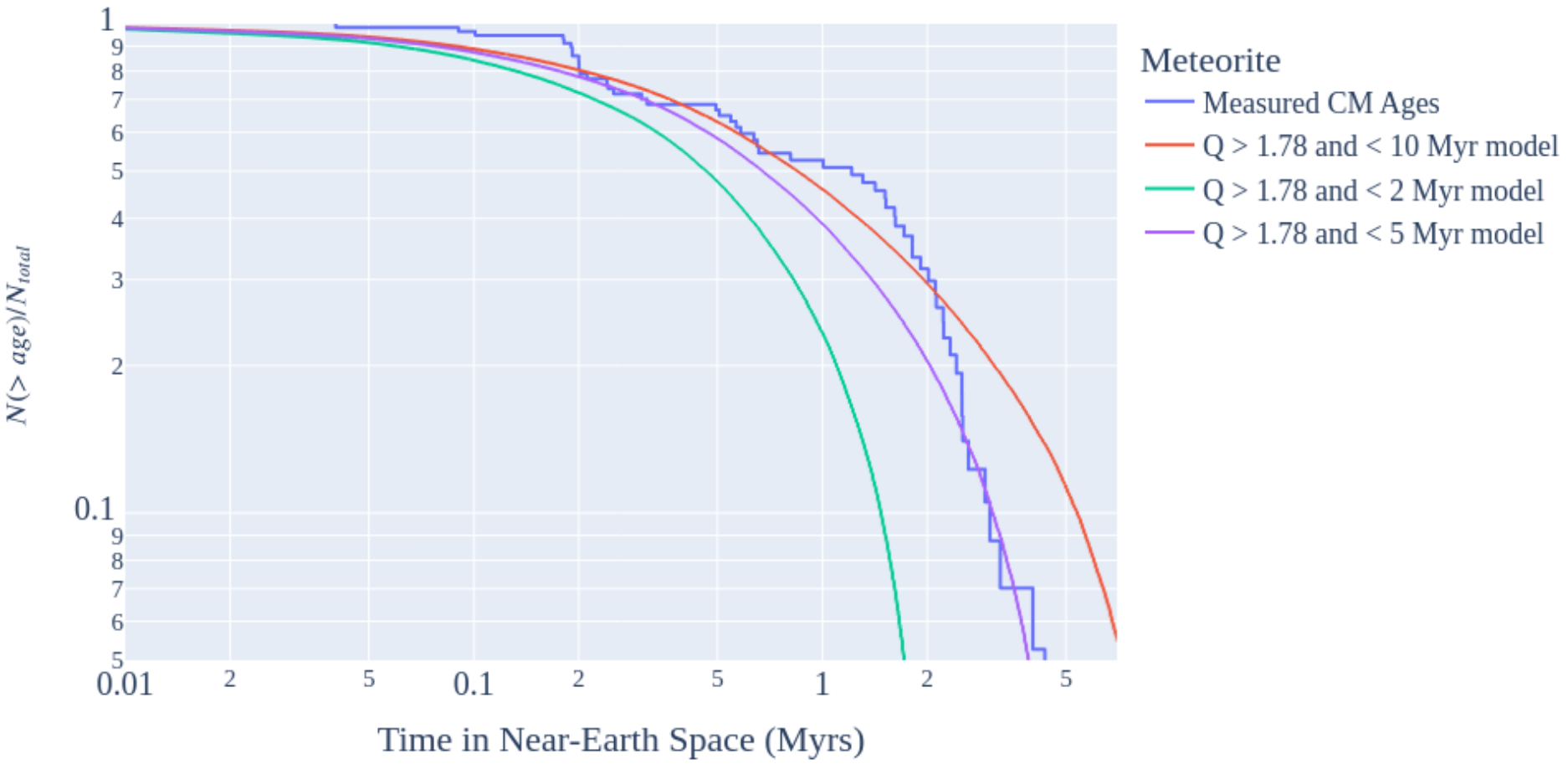


Jenniskens 2018



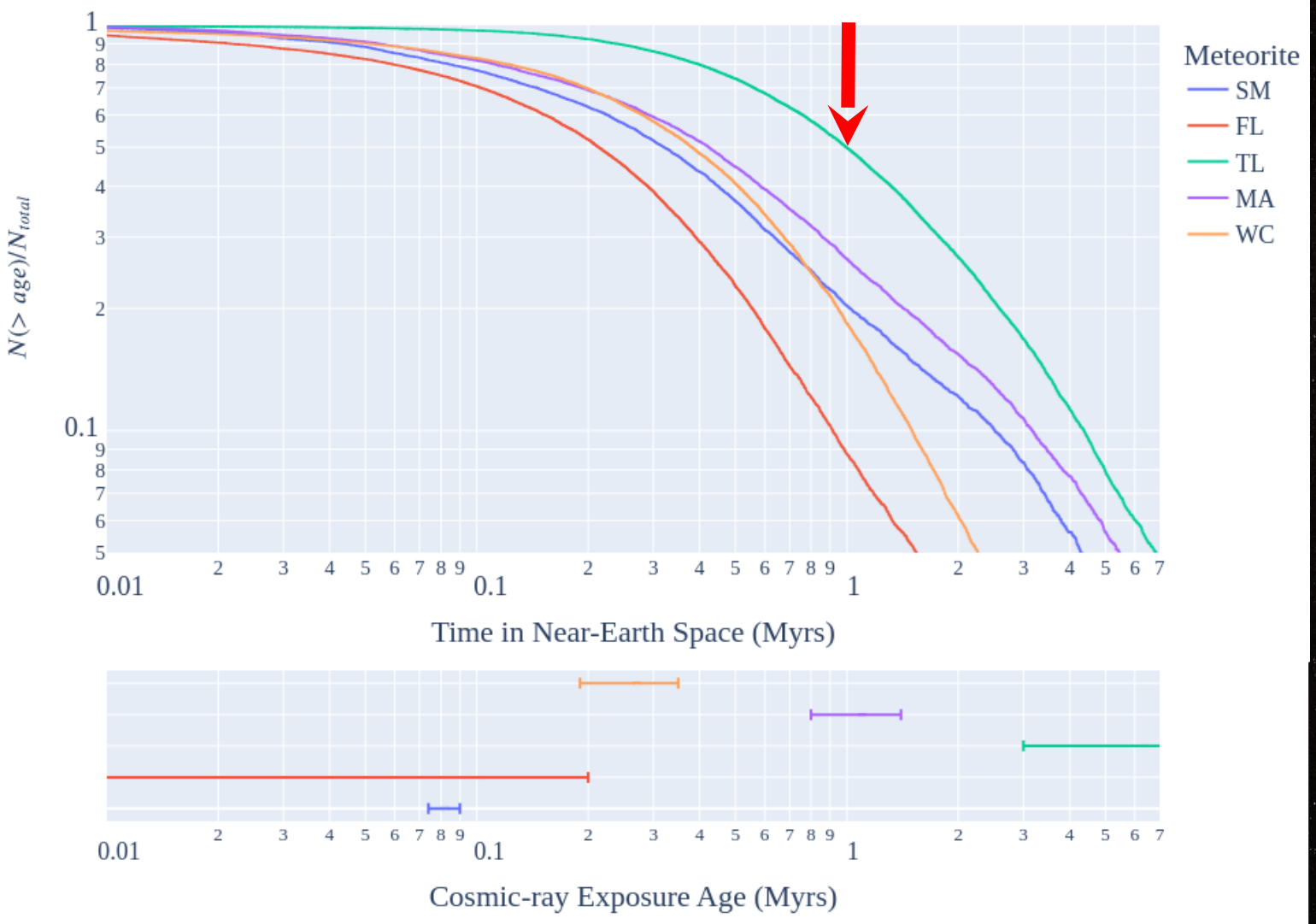
Nishiizumi and Caffee (2012)

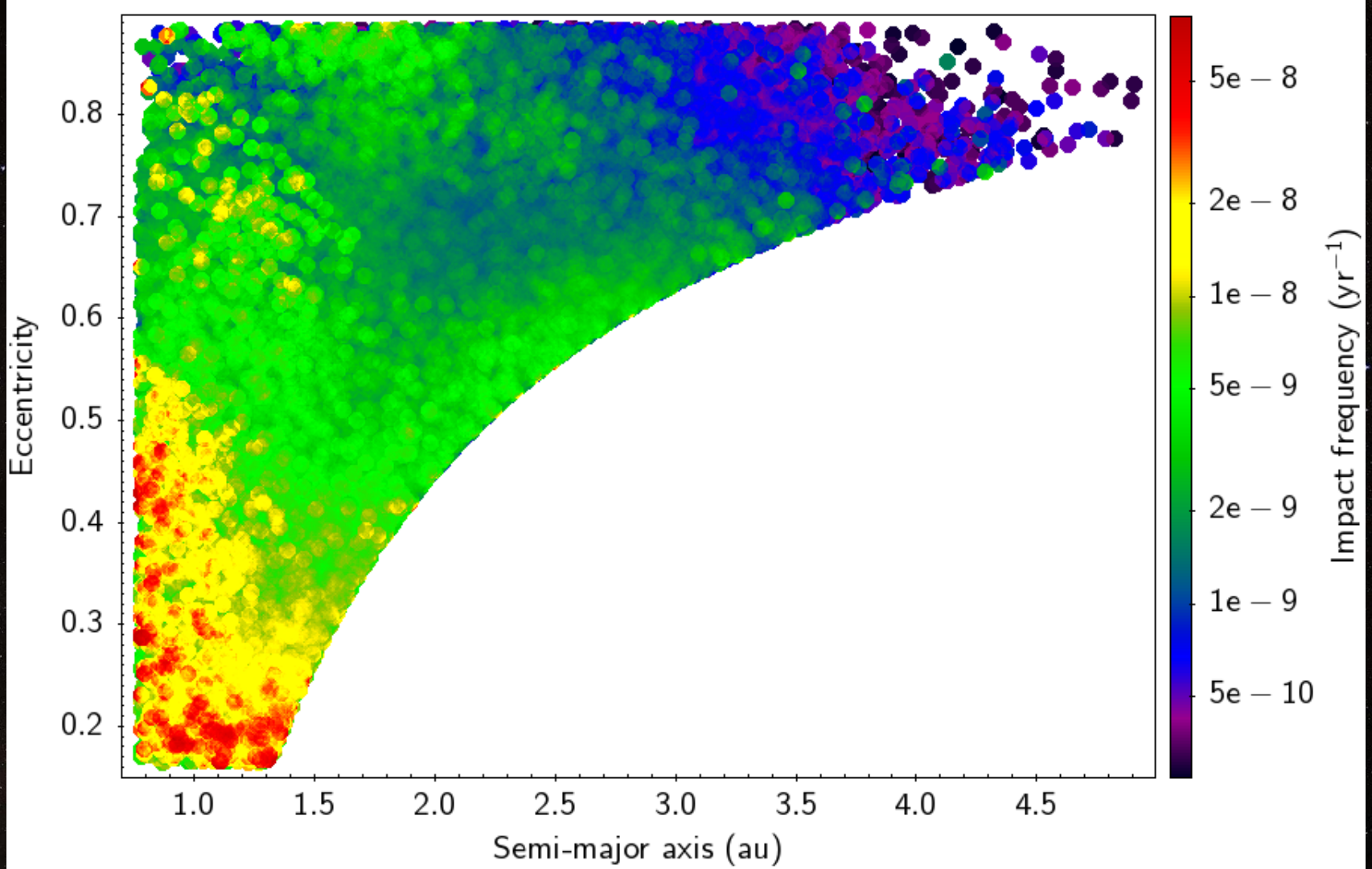

Eccentricity
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1.0
1.5
2.0
2.5
3.0
3.5
Semi-major axis (au)
20
10
5
2
1
0.5
0.2
0.1
Median Near-Earth lifetime (Myrs)


1
9
8
7
6
5
4
3
2
0.1
9
8
7
6
5
0.01
2
5
0.1
2
5
1
2
5
N(> age)/N_total
Time in Near-Earth Space (Myrs)
Meteorite
Measured CM Ages
Q > 1.78 and < 10 Myr model
Q > 1.78 and < 2 Myr model
Q > 1.78 and < 5 Myr model

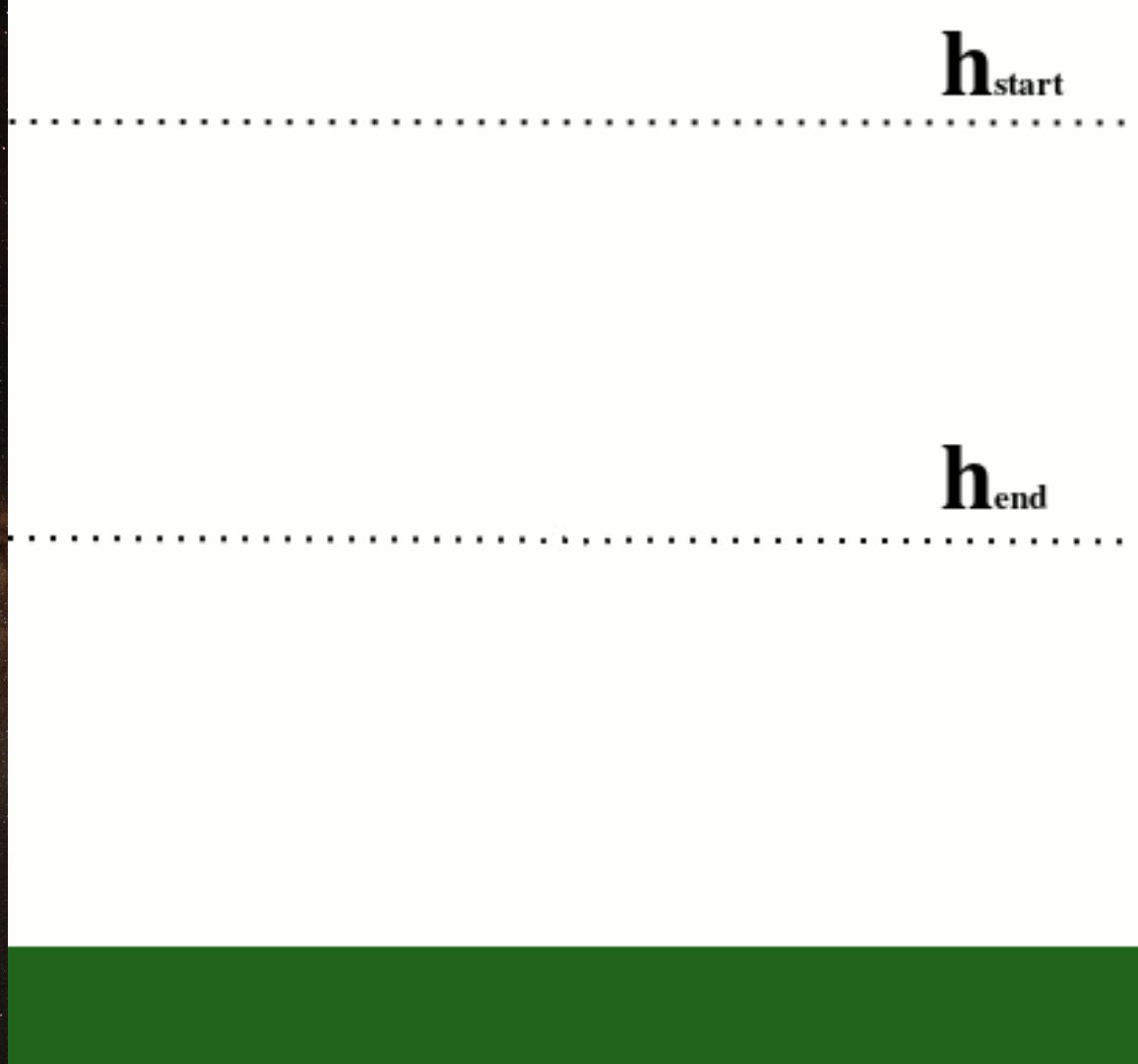
Thank you!

Email: patrick.shober@obspm.fr

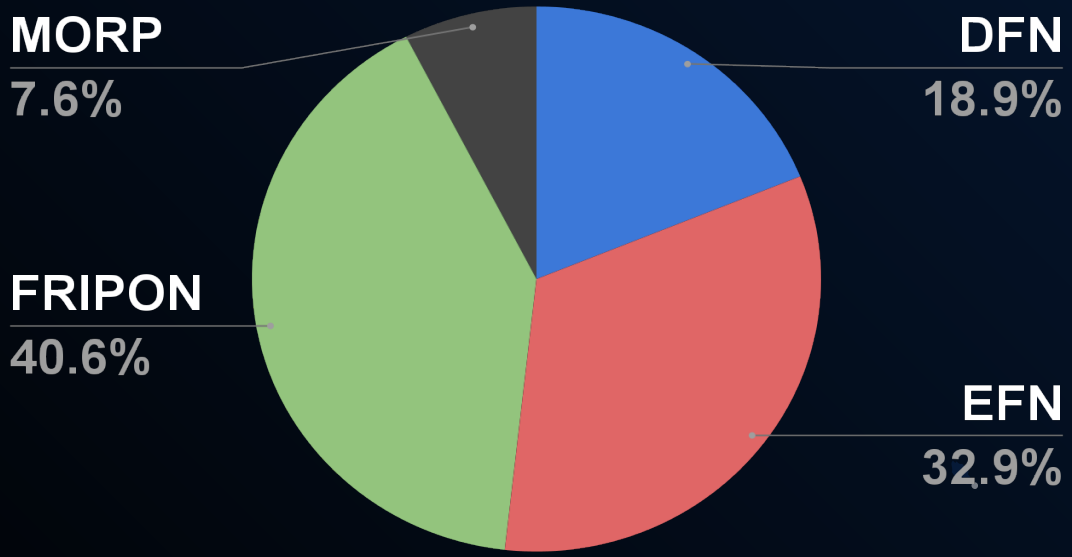

$N(>age)/N_{total}$
1
9
8
7
6
5
4
3
2
0.1
9
8
7
6
5
2 3 4 5 6 7 8 9
0.01
2 3 4 5 6 7 8 9
0.1
2 3 4 5 6 7
1
Time in Near-Earth Space (Myrs)
Meteorite
SM
FL
TL
MA
WC
2 3 4 5 6 7 8 9
0.01
2 3 4 5 6 7 8 9
0.1
2 3 4 5 6 7
1
Cosmic-ray Exposure Age (Myrs)

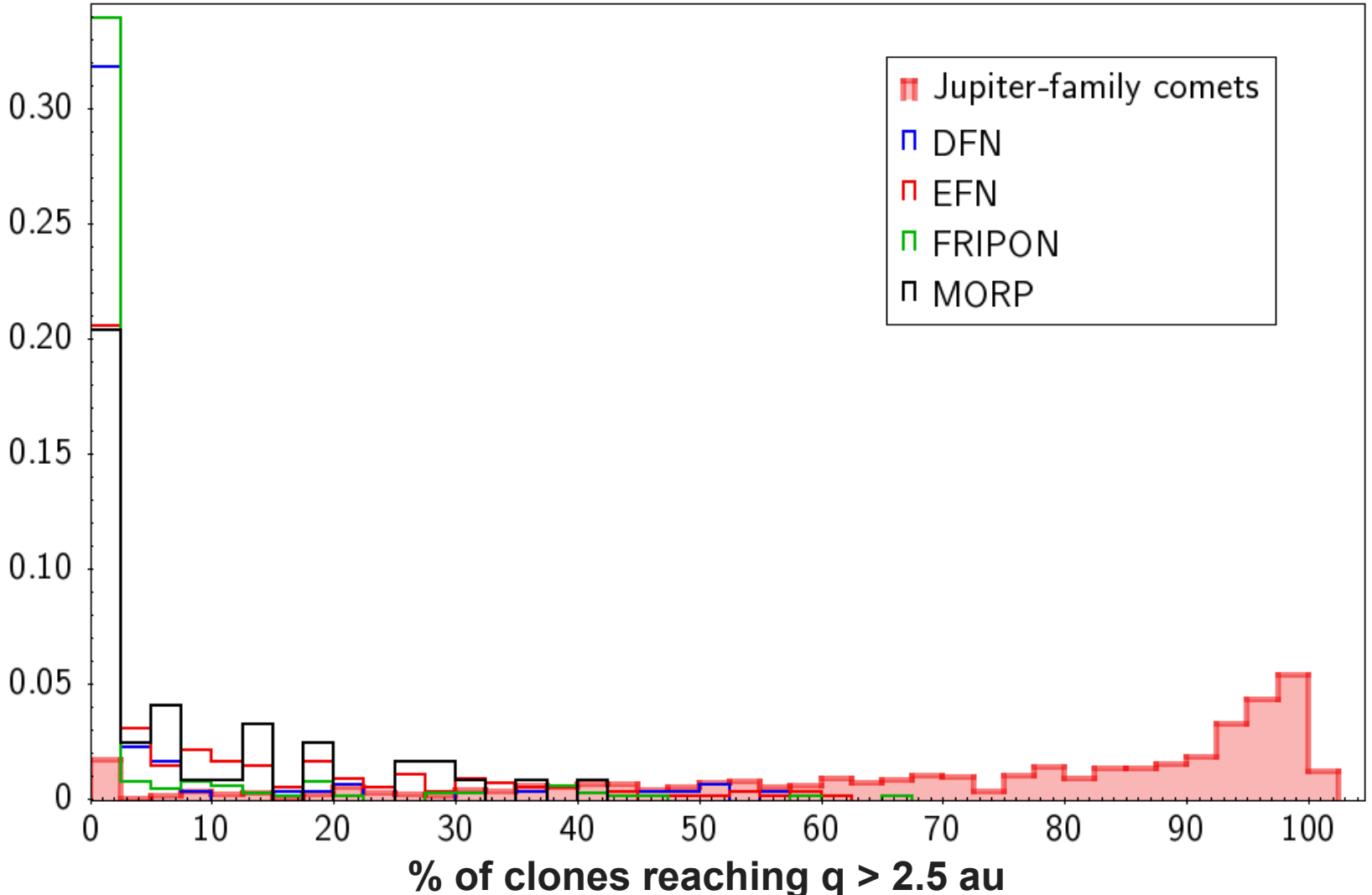

Eccentricity
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Semi-major axis (au)
5e − 8
2e − 8
1e − 8
5e − 9
2e − 9
1e − 9
5e − 10
Impact frequency (yr^{-1})

Physical characteristics of meteoroids using fireball observations?



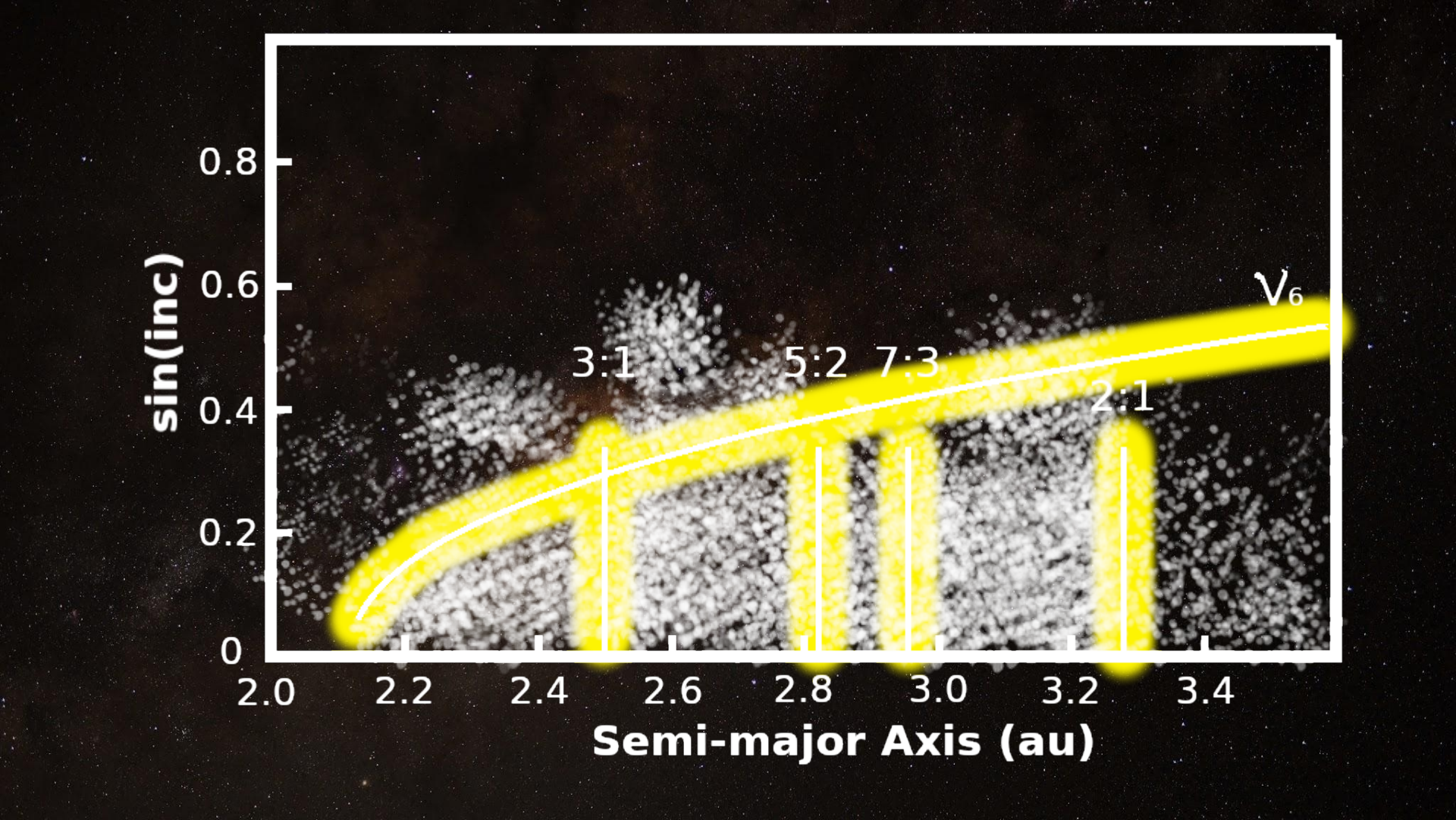
- 646 fireballs
- 661 JFCs

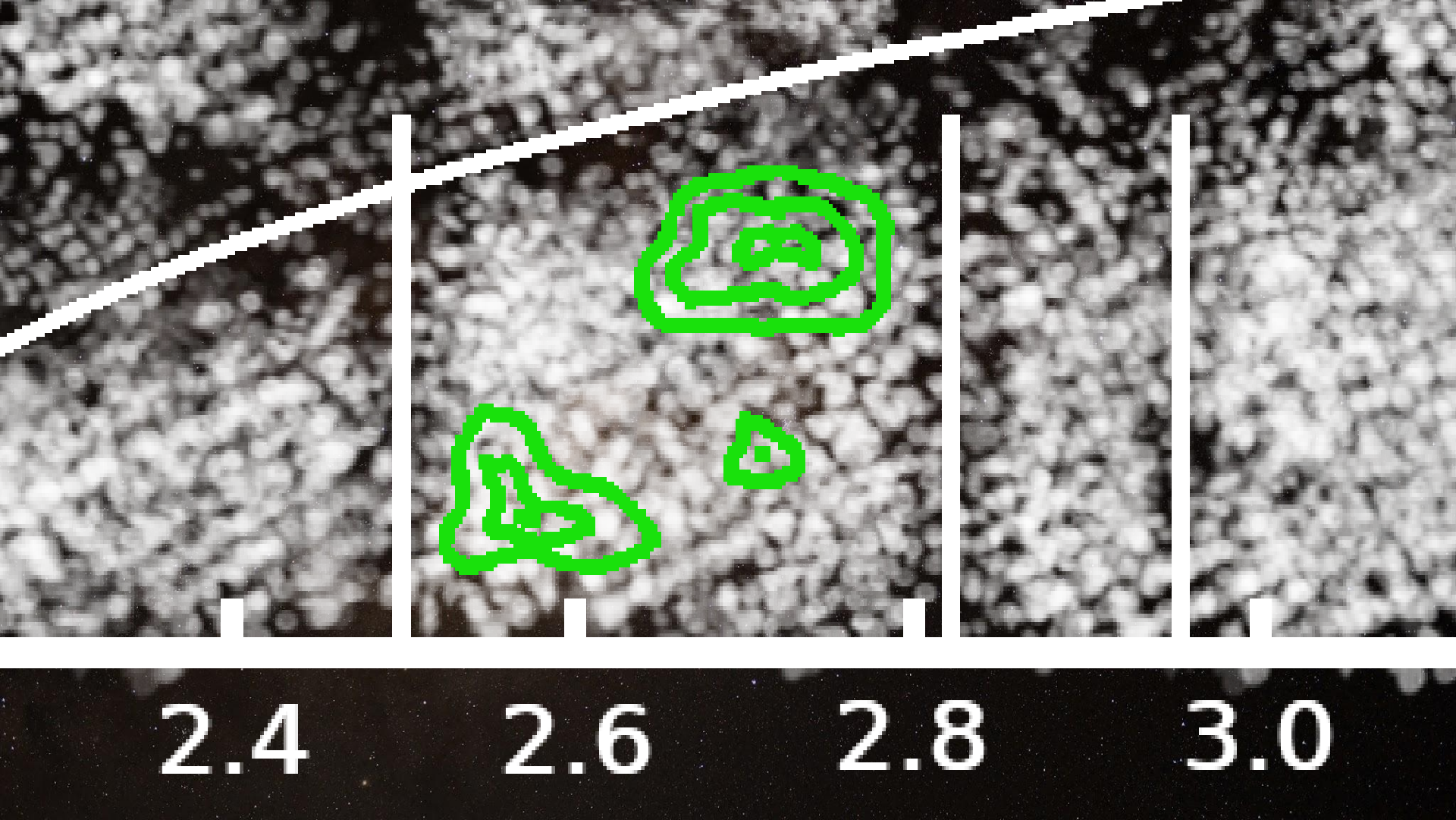


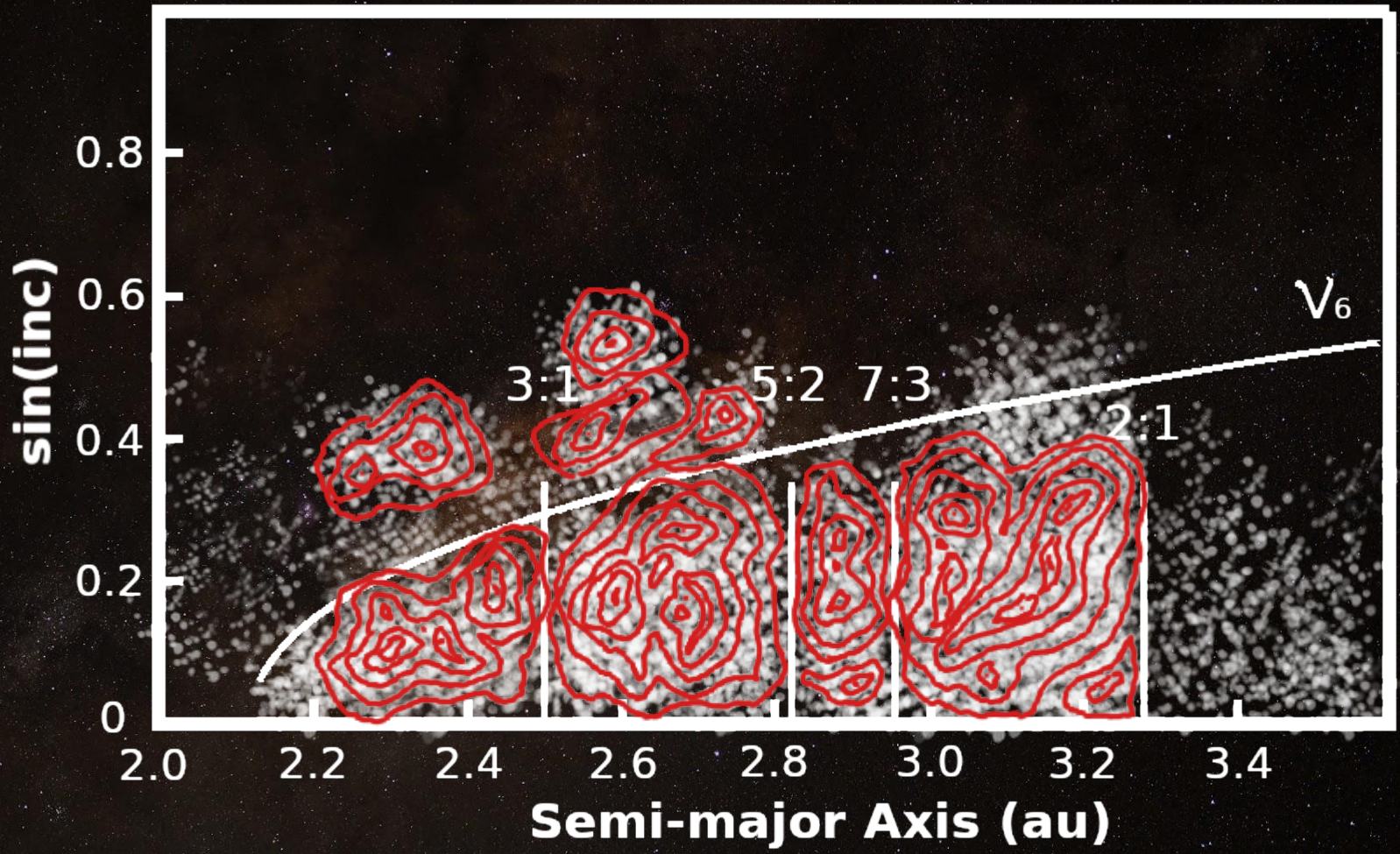

Jupiter-family comets
DFN
EFN
FRIPON
MORP
0.30
0.25
0.20
0.15
0.10
0.05
0
0
10
20
30
40
50
60
70
80
90
100
% of clones reaching q > 2.5 au

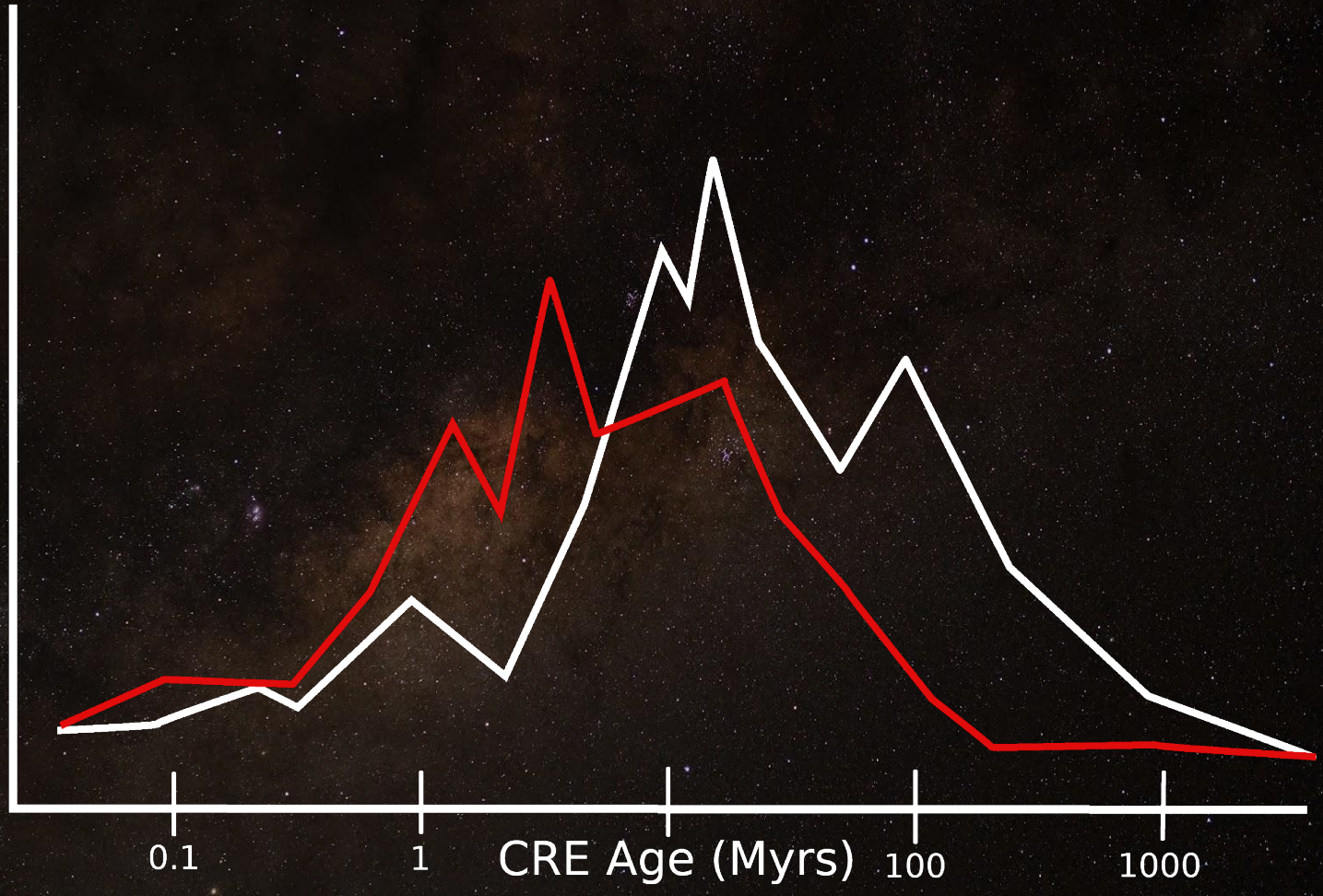
FIREBALL RESULTS

- Low levels of chaos
- Only 8-21% are likely to have experienced significant encounters with Jupiter
- 1-5% of the DFN, EFN, MORP, and FRIPON fireball datasets are dynamically consistent with JFCs
- The physical strengths alone is not a reliable indicator of discriminating between asteroidal and cometary source regions for fireball data


sin(inc)
0.8
0.6
0.4
0.2
0
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
Semi-major Axis (au)
ν6
3:1
5:2
7:3
2:1


2.4
2.6
2.8
3.0


sin(inc)
0.8
0.6
0.4
0.2
0
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
Semi-major Axis (au)
3:1
5:2
7:3
2:1
ν6


0.1
1
CRE Age (Myrs)
100
1000