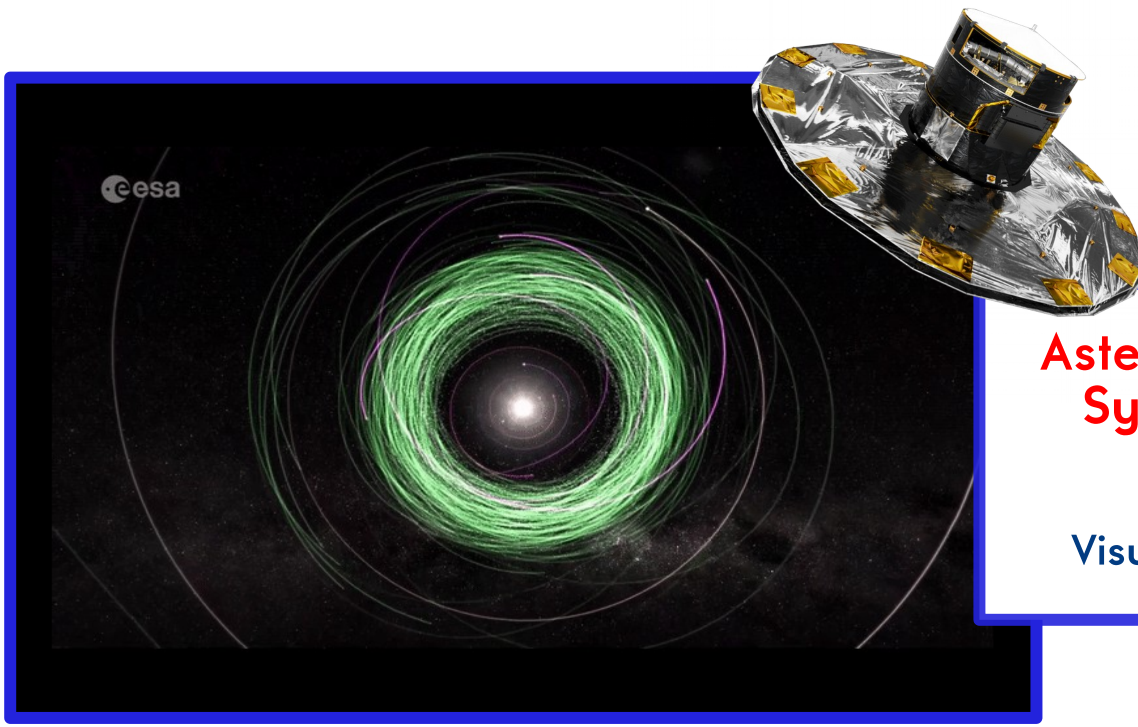
How Gaia has changed our view of asteroid astrometry

Gaia & ground-based asteroid observations to understand our Solar System

F. Spoto

Observatoire de la Côte d'Azur, Laboratoire Lagrange



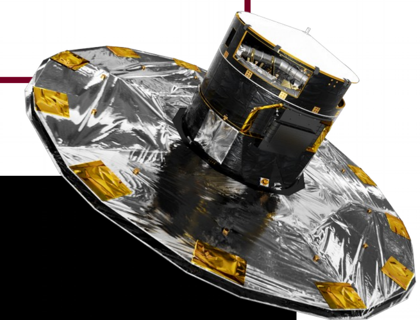
Asteroid in our Solar System observed by Gaia

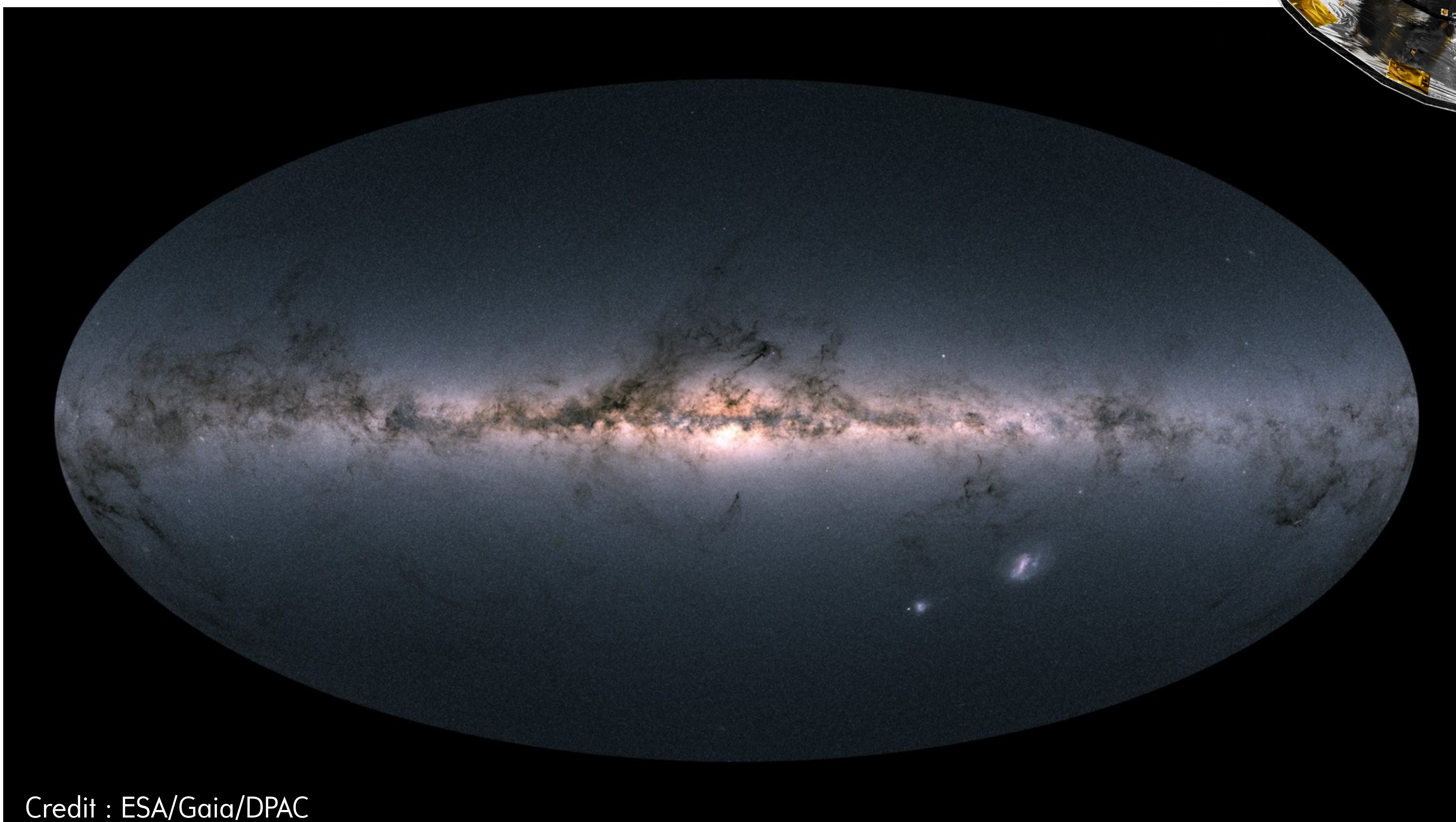
Visualization: Gaia Sky

Lagrange seminary

Nice, 15/10/2019

Gaia is a mission to **chart a three-dimensional map of our Milky Way**, in the process revealing the composition, formation and evolution of the Galaxy. **Gaia will provide unprecedented positional and radial velocity measurements** with the accuracies needed to produce a stereoscopic and kinematic census of about one billion stars in our Galaxy and throughout the Local Group.





Open questions

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Dœs Gaia discover asteroids ?

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What can we do with Gaia asteroid observations ?

Answer n. 1

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Answer n. 1

Dœs Gaia discover asteroids ? $\boxed{\text{YES !}}$

Answer n. 1

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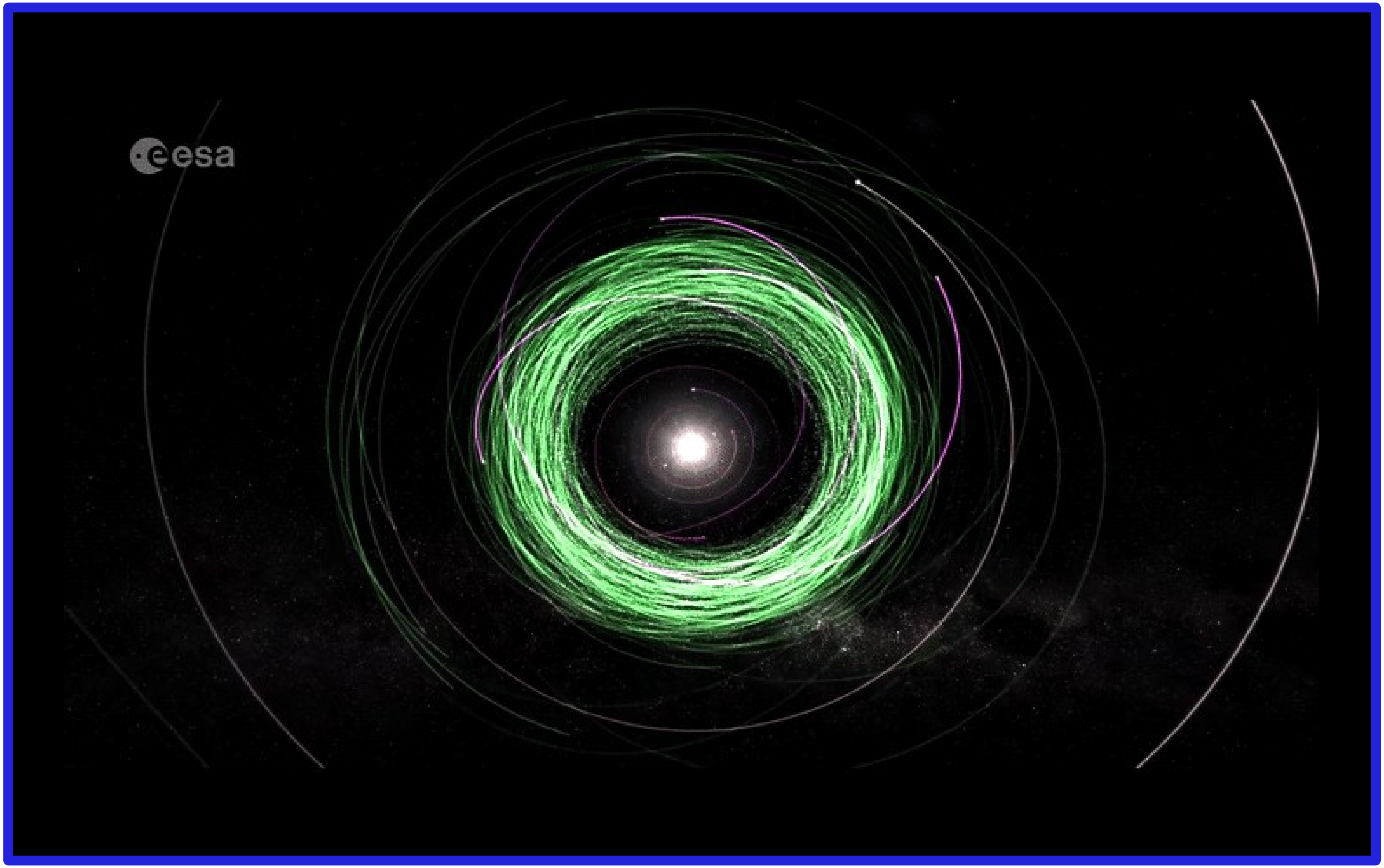


Gaia FUN SSO : https://gaiafunsso.imcce.fr/
Spoto et al. 2018 (A&A)
https://sci.esa.int/web/gaia/-/61433-gaia-s-asteroid-discoveries

Answer n. 2

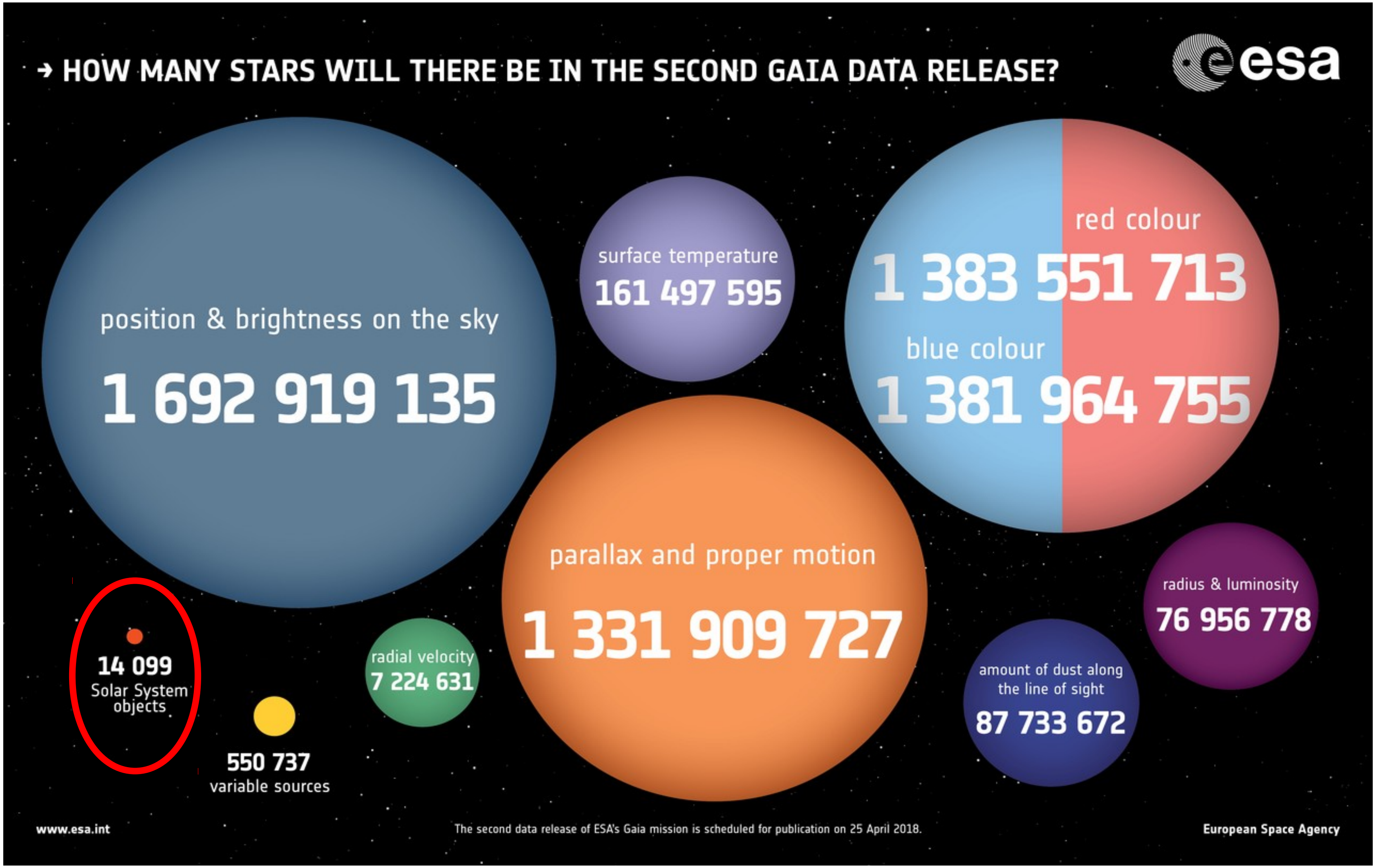
Dœs Gaia observe asteroids ?

Answer n. 2

Dœs Gaia observe asteroids ? $\boxed{\text{YES !}}$

Answer n. 2

Dœs Gaia observe asteroids ? YES !



Gaia Collaboration : Spoto et al. 2018 (A&A)

Answer n. 3

What can we do with Gaia asteroid observations ?

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Outline

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- Main goal :
  Understanding the origin and formation
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Answer n. 3

What can we do with Gaia asteroid observations ?

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- Main goal :
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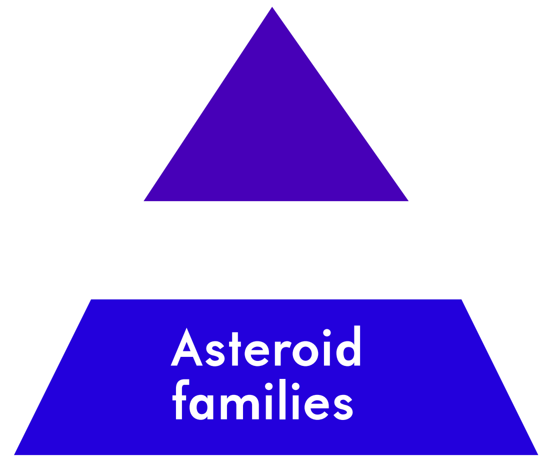
- Why do we study asteroids ?
  How do we study asteroids ?



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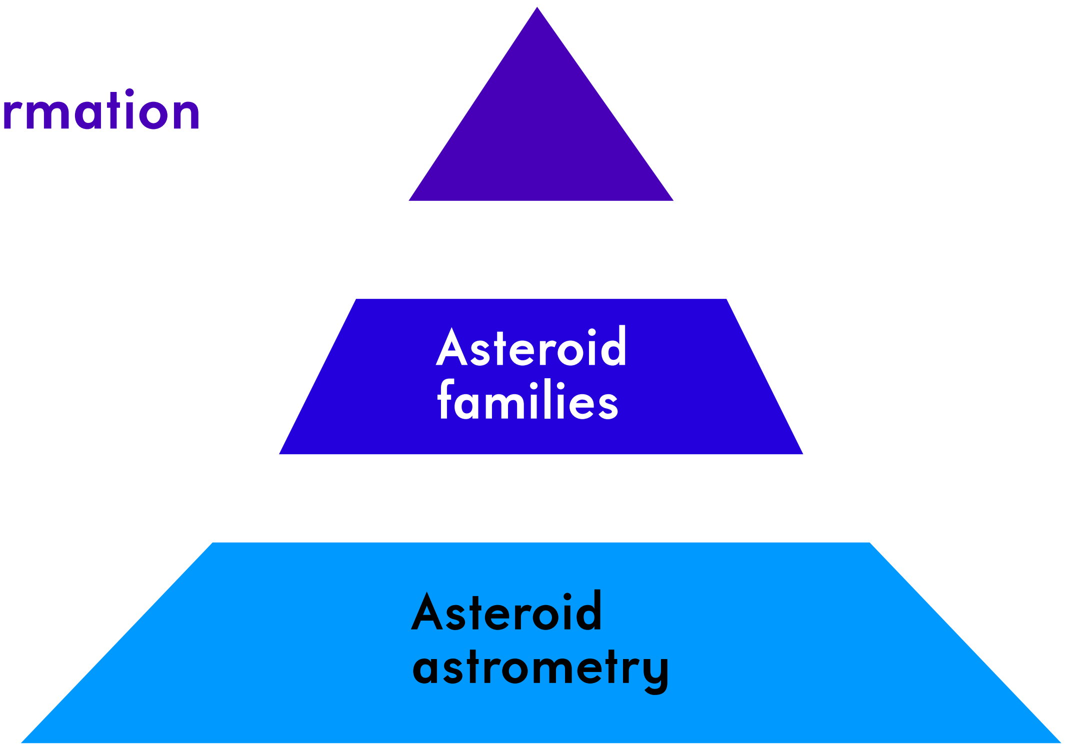

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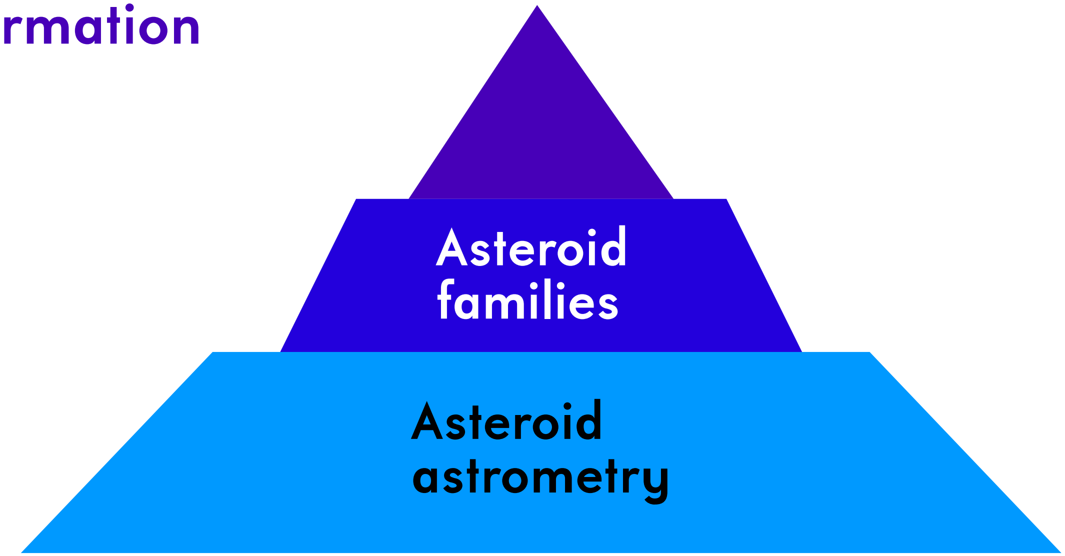

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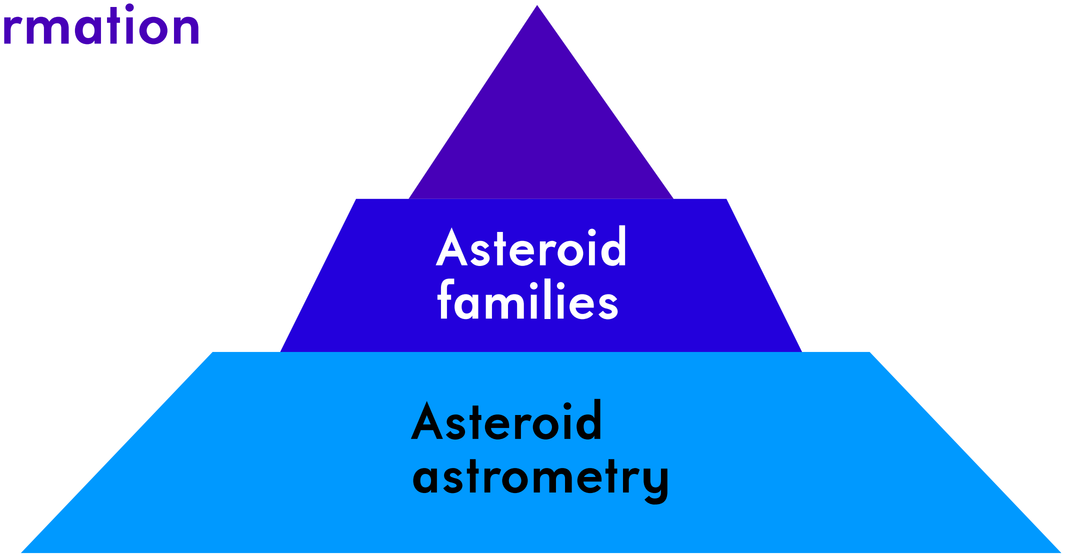
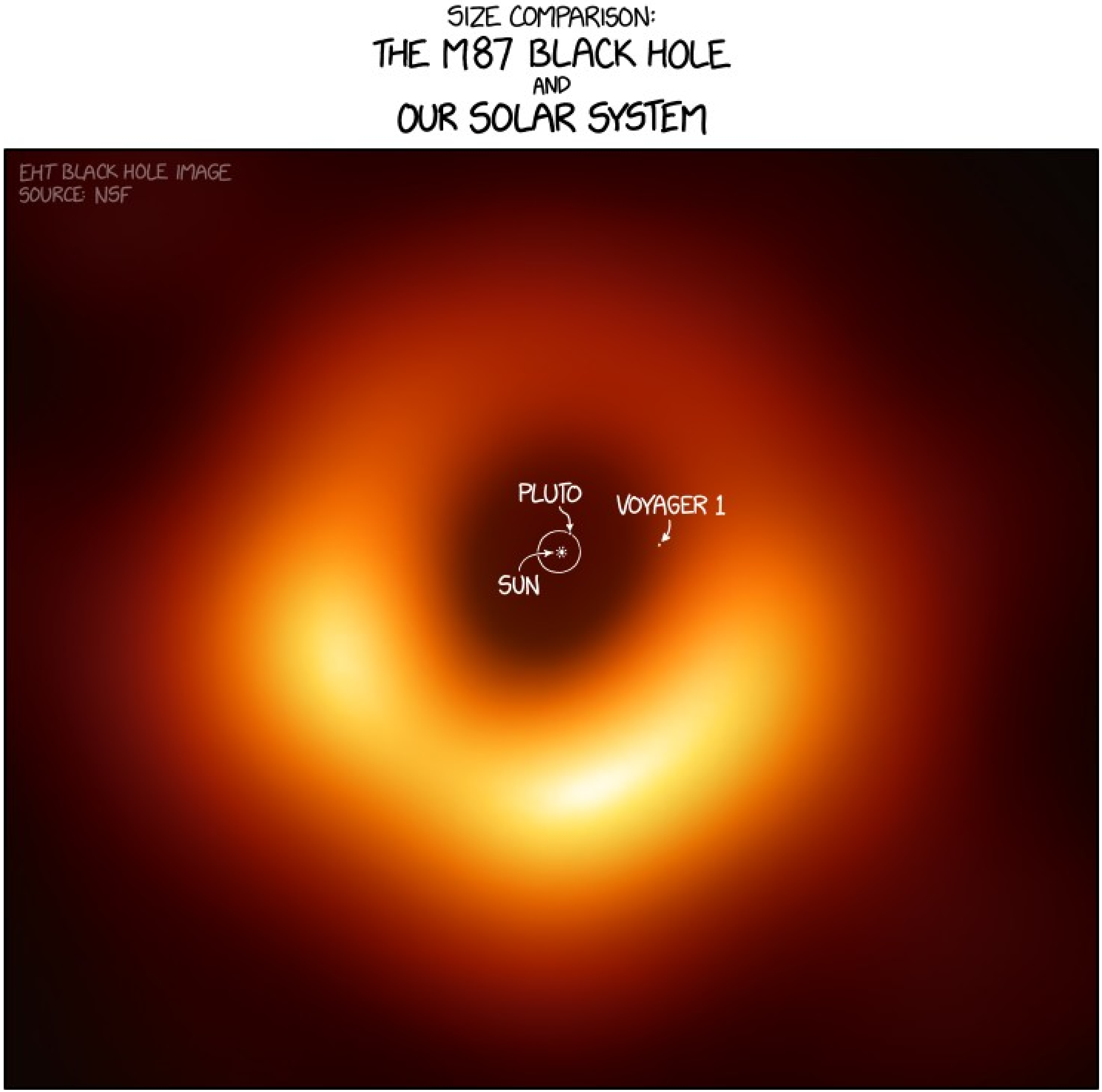
  How do we study asteroids ?

- Why do we need Gaia ?

- Results obtained with Gaia DR2

- Future perspectives



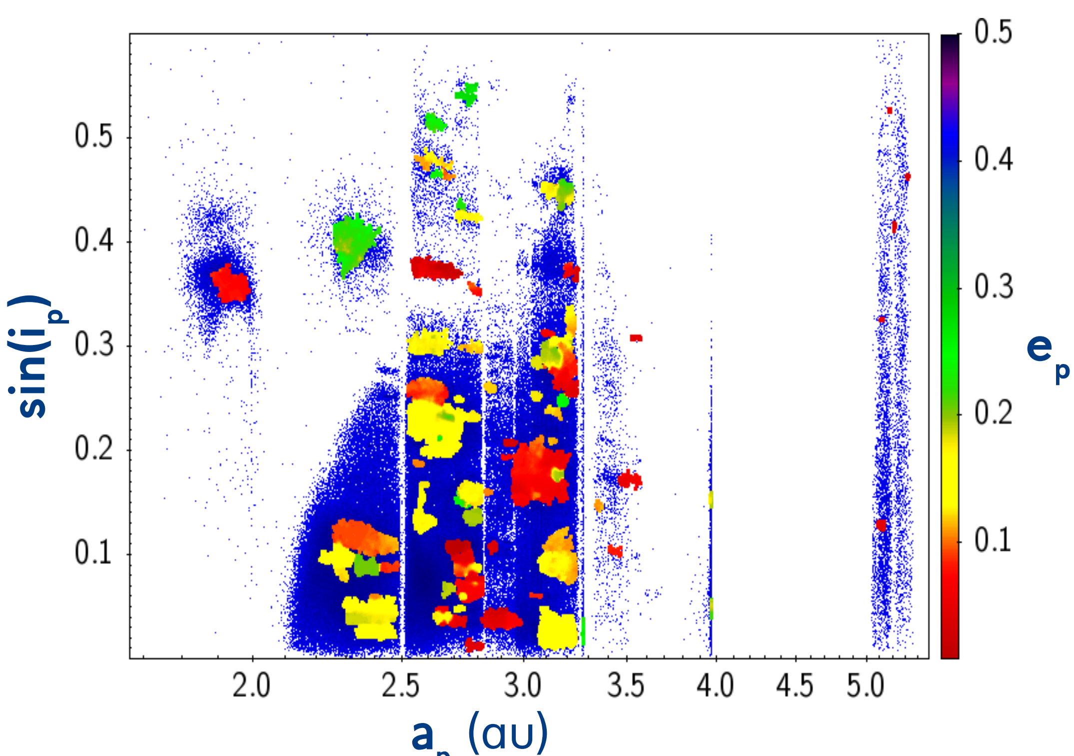


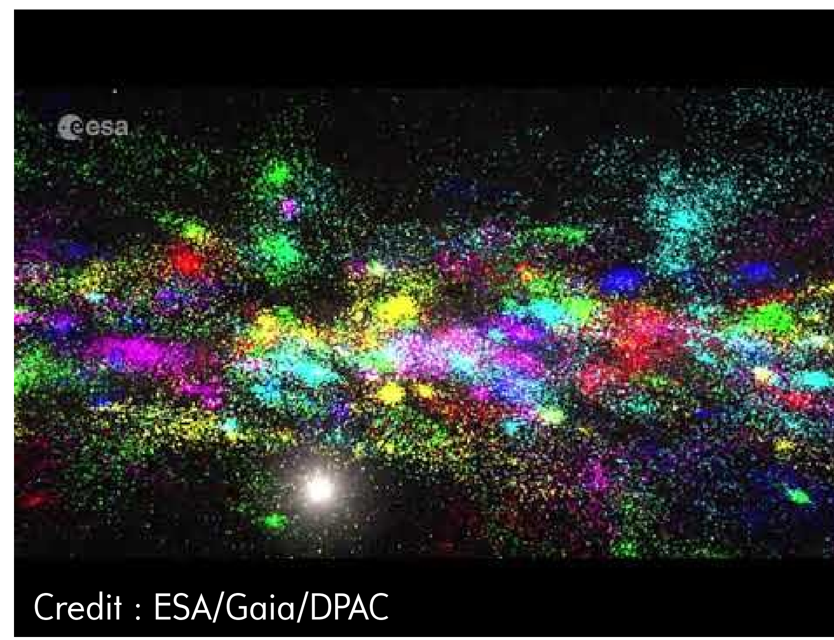
Credit: M87 Black Hole Size Comparison https://xkcd.com/2135/

Tracing the history of our Solar System

Asteroid families

Groups of asteroids sharing the same dynamical / physical properties and the same collisional history (initial collision)





Credit : ESA/Gaia/DPAC

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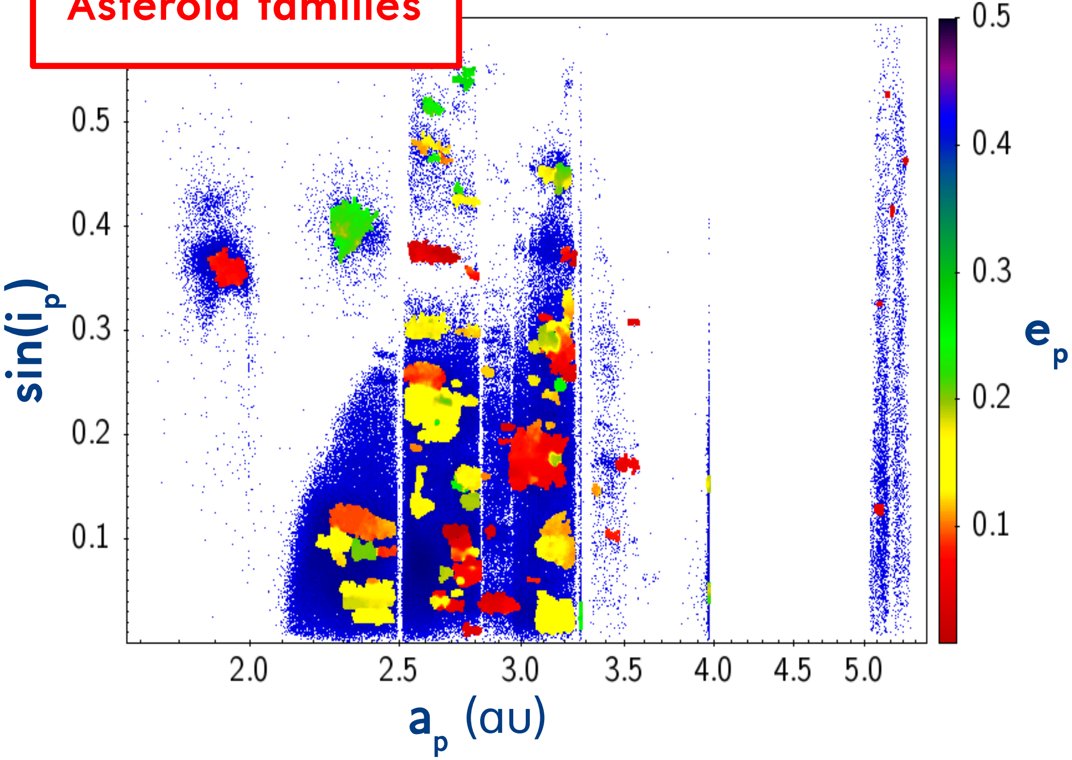

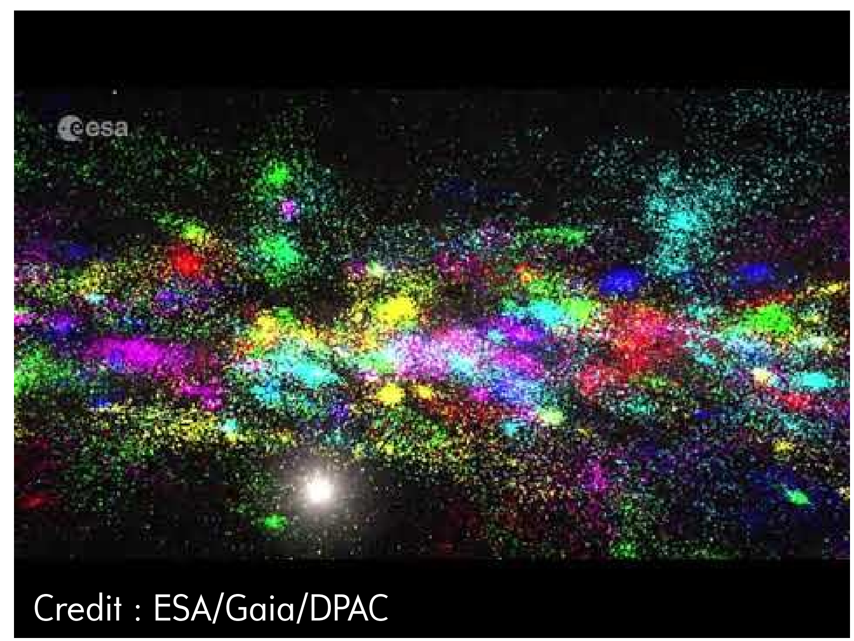

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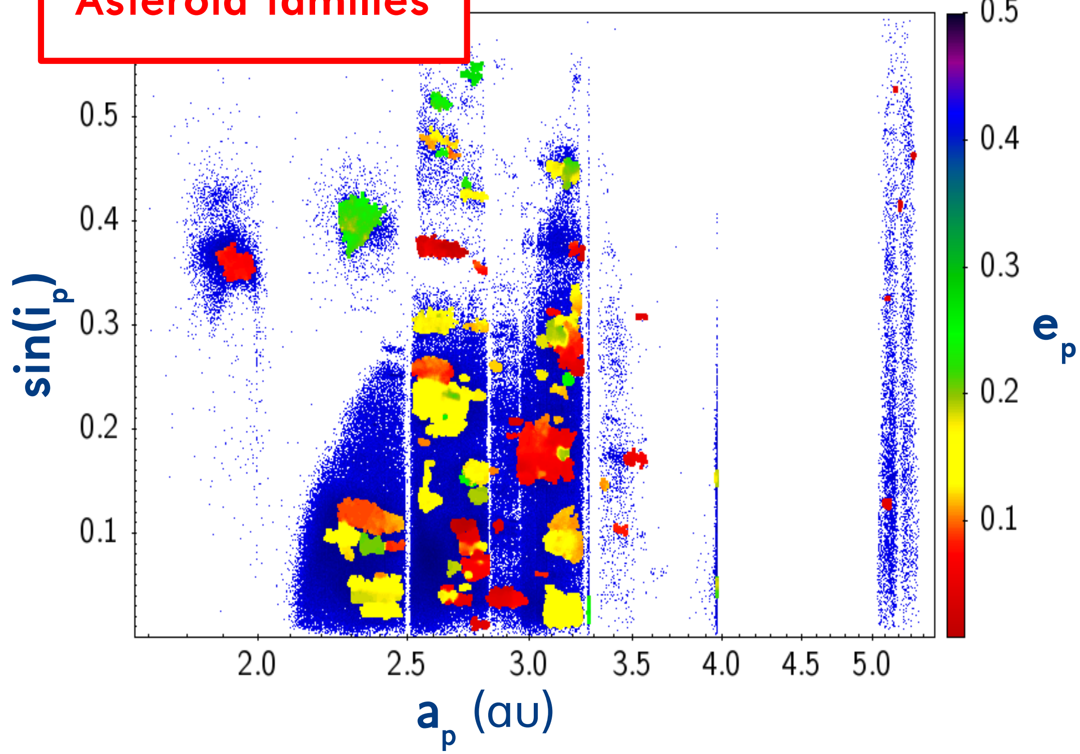
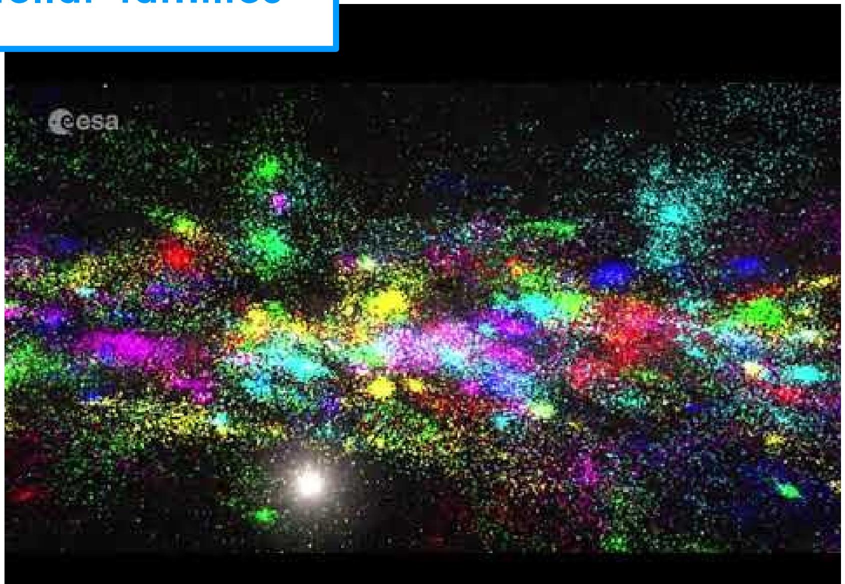


Stellar families



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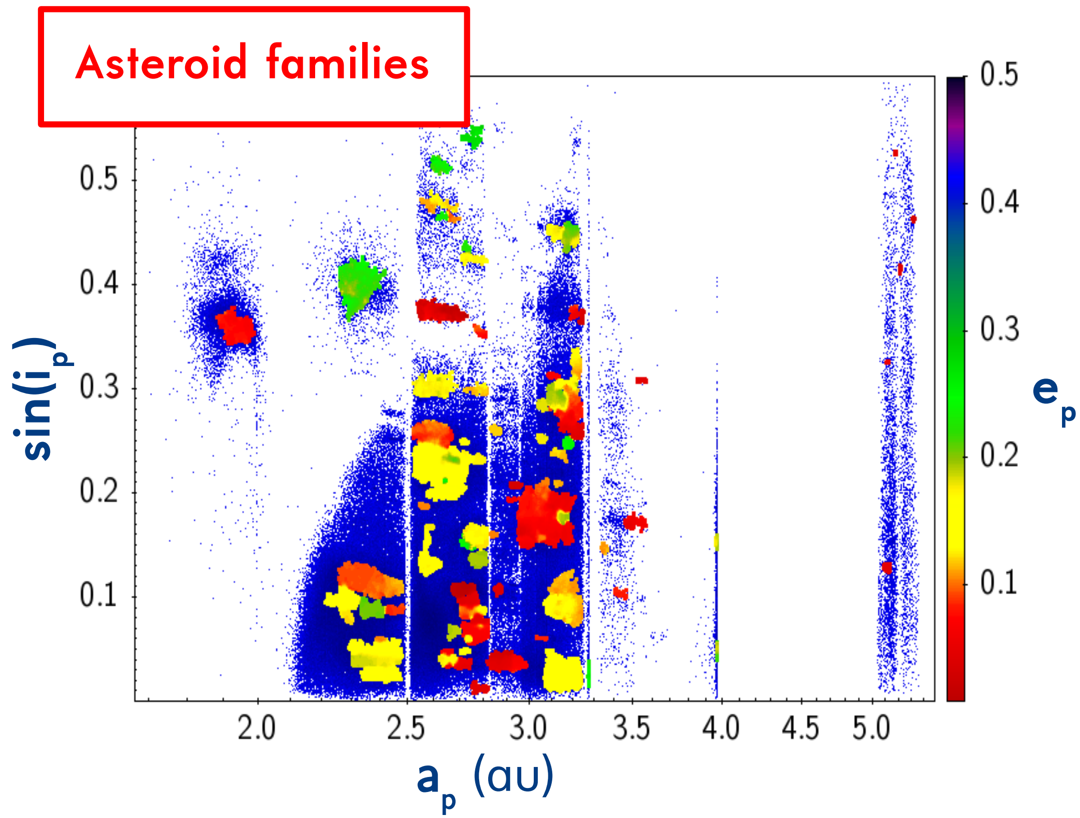

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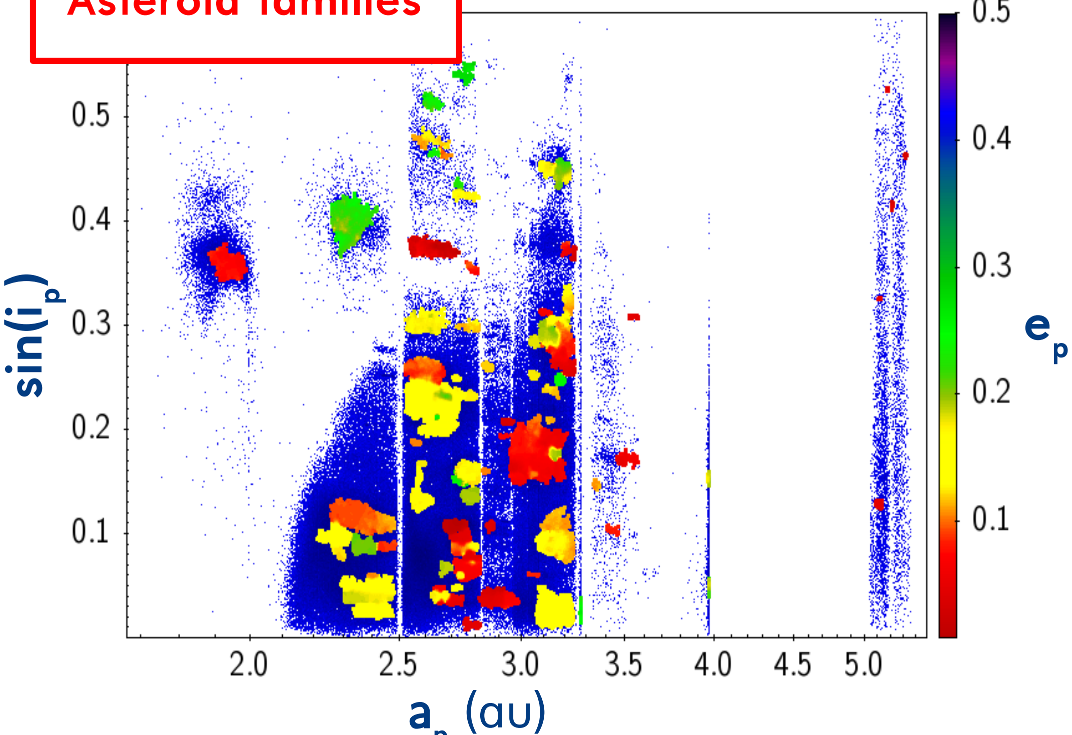

First step : Identification

- Quasi-integrals of the motion
- We need « accurate » orbits

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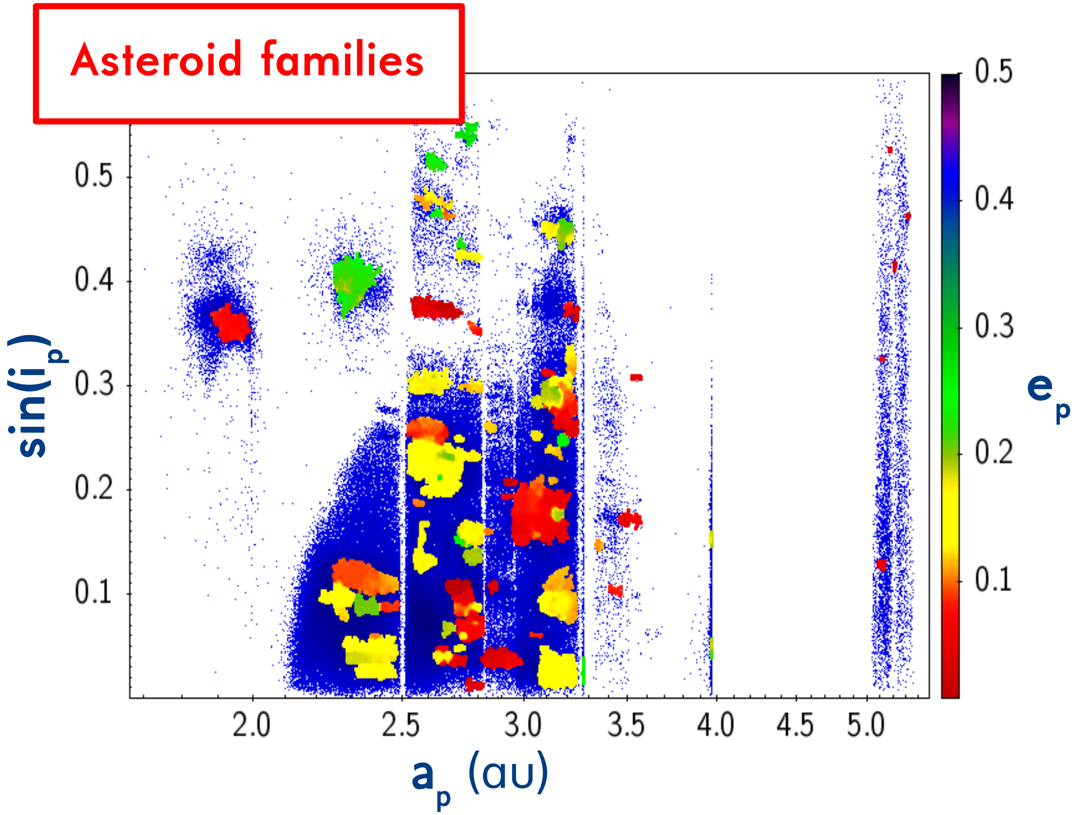


First step : Identification

- Quasi-integrals of the motion
- We need « accurate » orbits

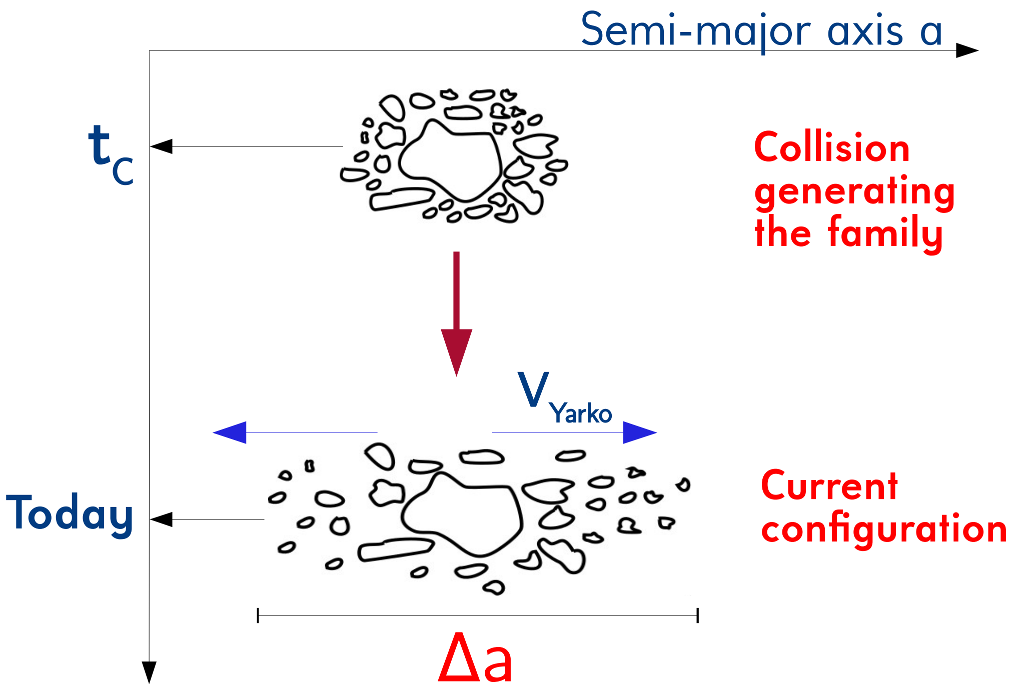
Second step : age of the family

- Connection between the family and the collision
- We need «very accurate » orbits

Tracing the history of our Solar System

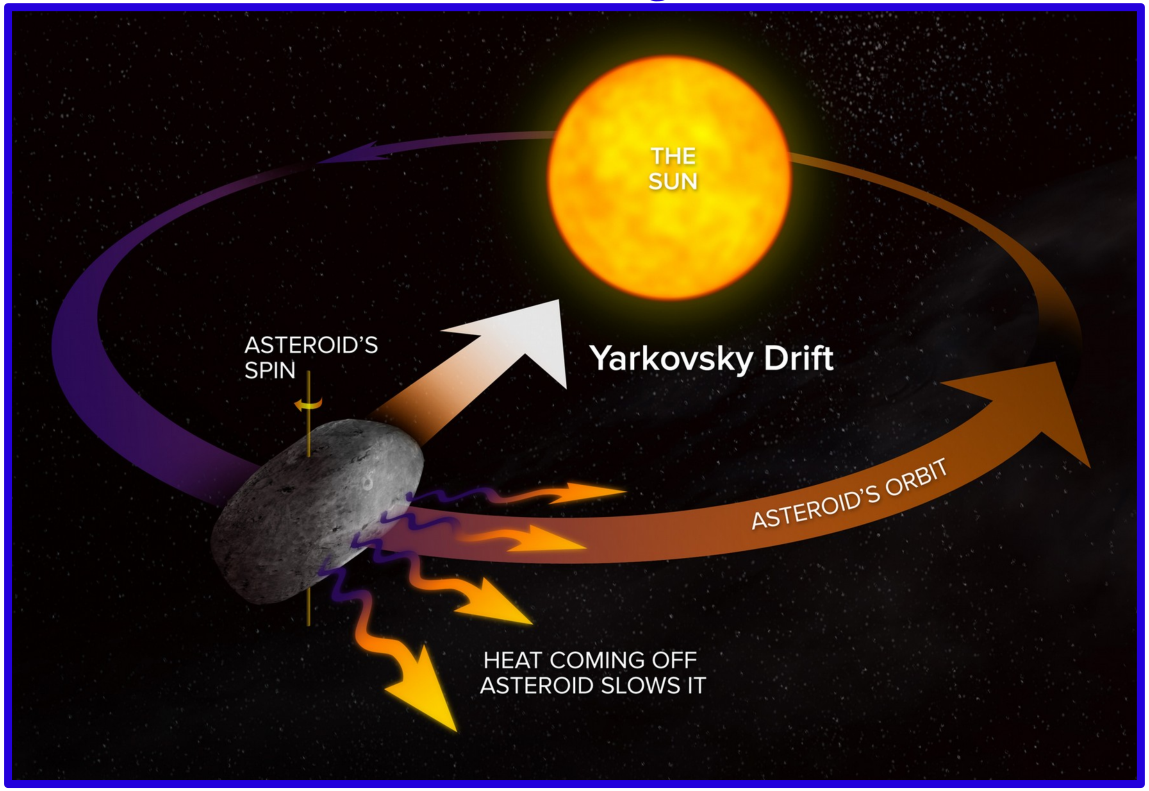
Age of the family

$$\boxed{t_C = \Delta a \,/\, V_{Yarko}}$$



How the configuration changes ?

The Yarkovsky effect



Description

- Subtle **non-gravitational** perturbation
- Resulting from the **anisotropic thermal emission** of the solar radiation
- Dependence on **physical parameter** usually unknown

Consequences

- **Secular semi-major axis drift**
- Necessary to **understand** the **evolution of our Solar System**
  - **Collisional history**
  - **Delivery of NEAs from the Main Belt**

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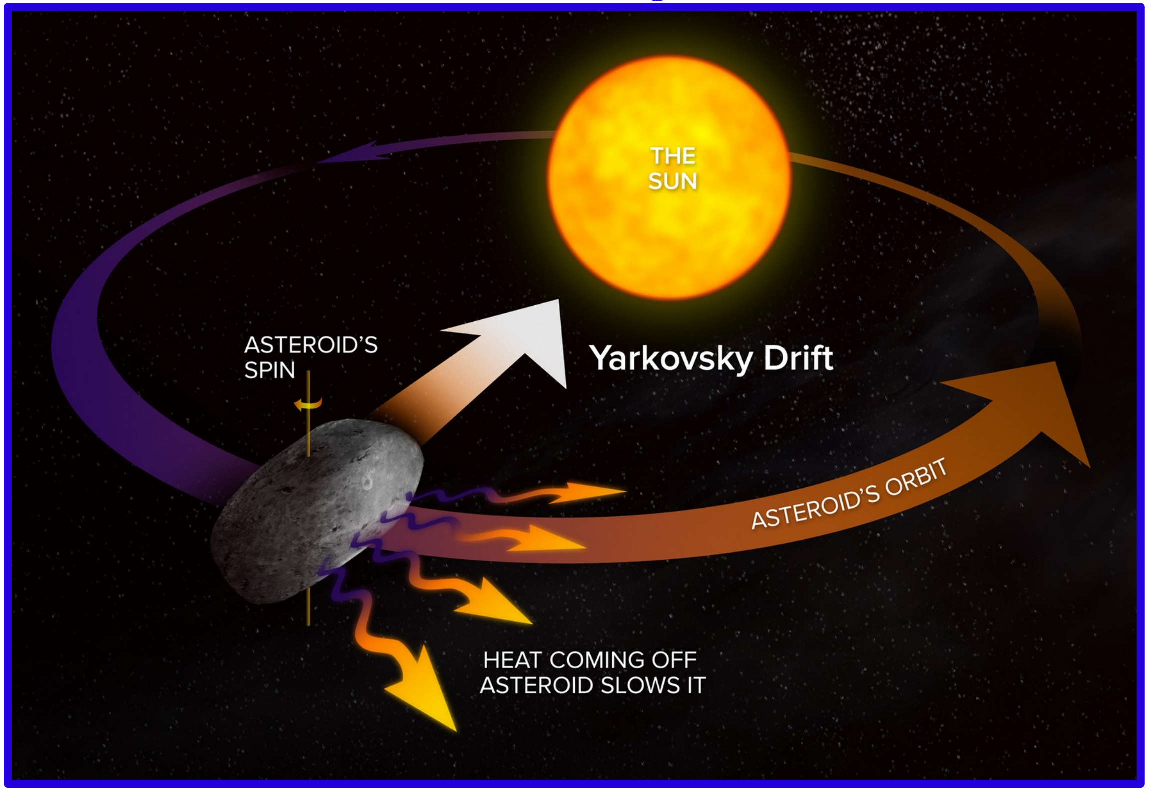

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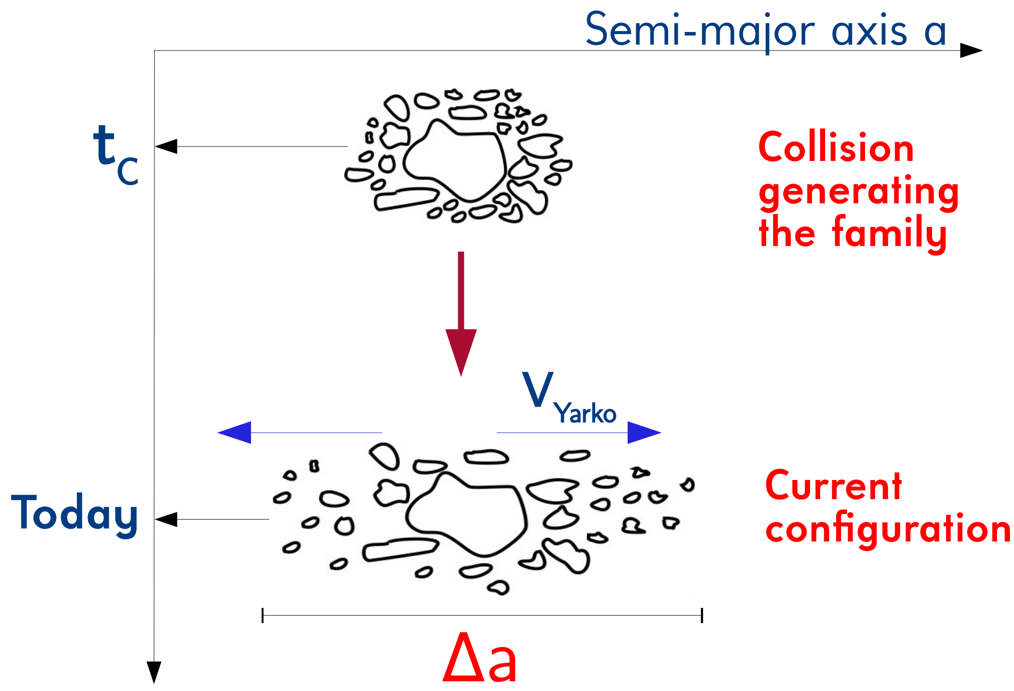
Detections

- **Detected from the astrometry:** least-square orbit determination (6 orbital elements + Yarkovsky parameter)
- **Very accurate orbits & long time span**
- **Small objects** (proportional to 1/D)

Tracing the history of our Solar System

Age of the family

$$\boxed{t_C = \Delta a \, / \, V_{Yarko}}$$



Tracing the history of our Solar System

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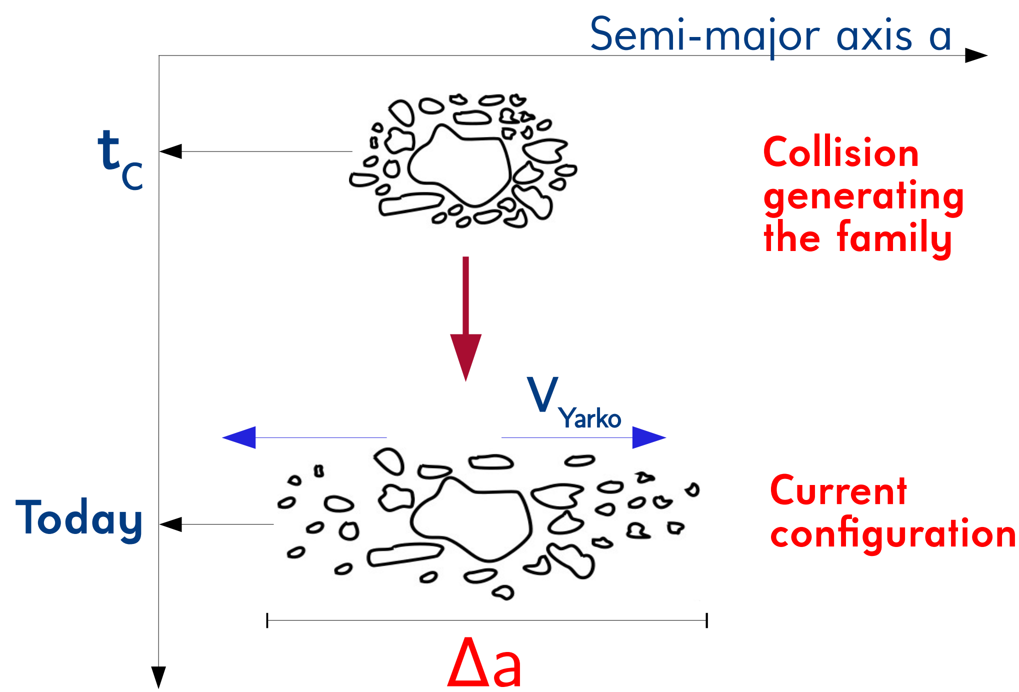

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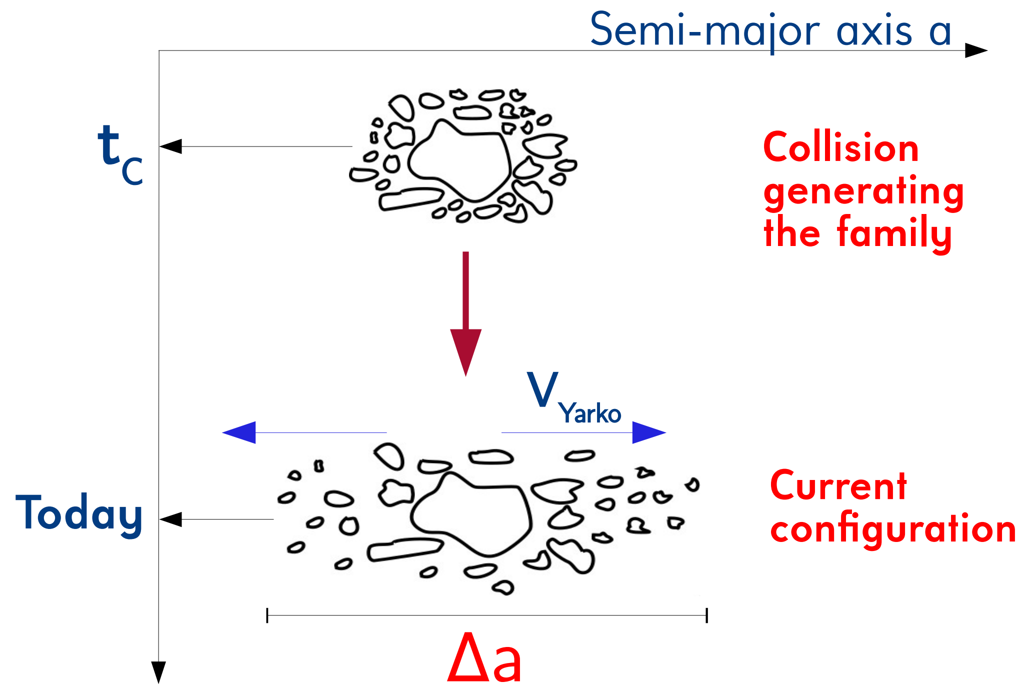

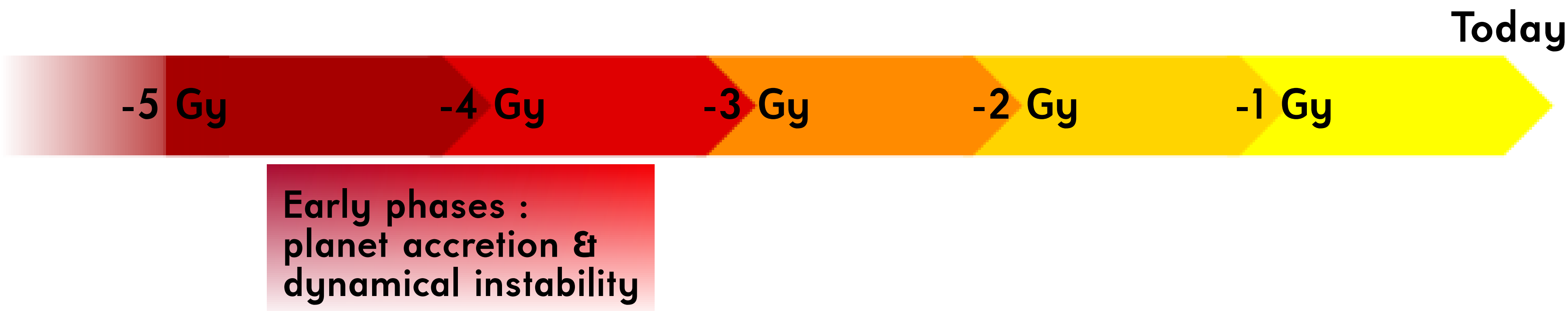

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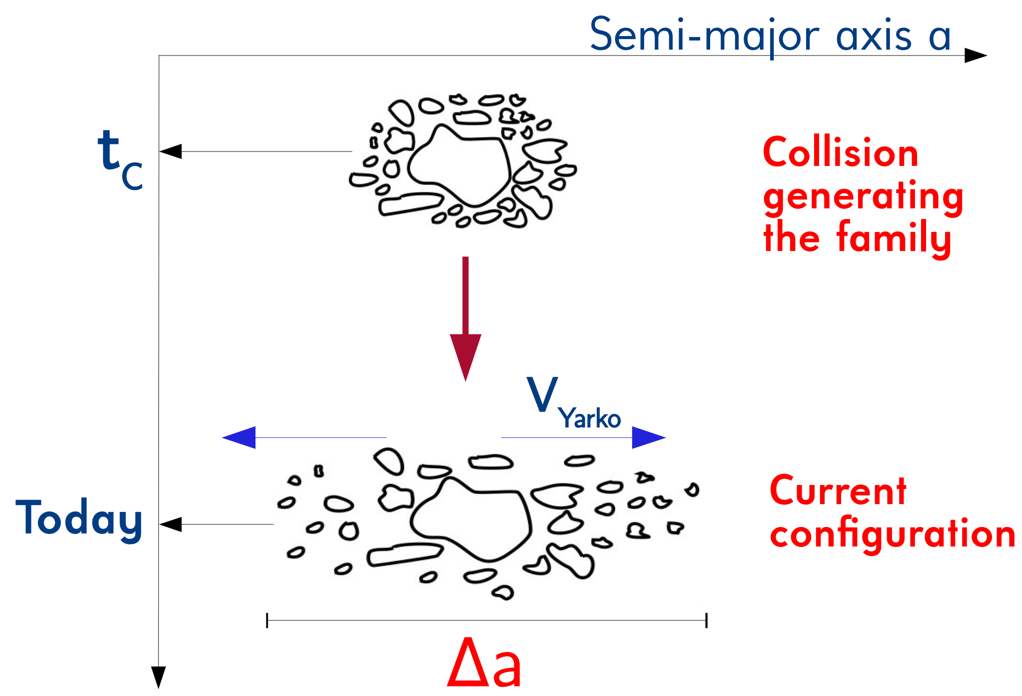

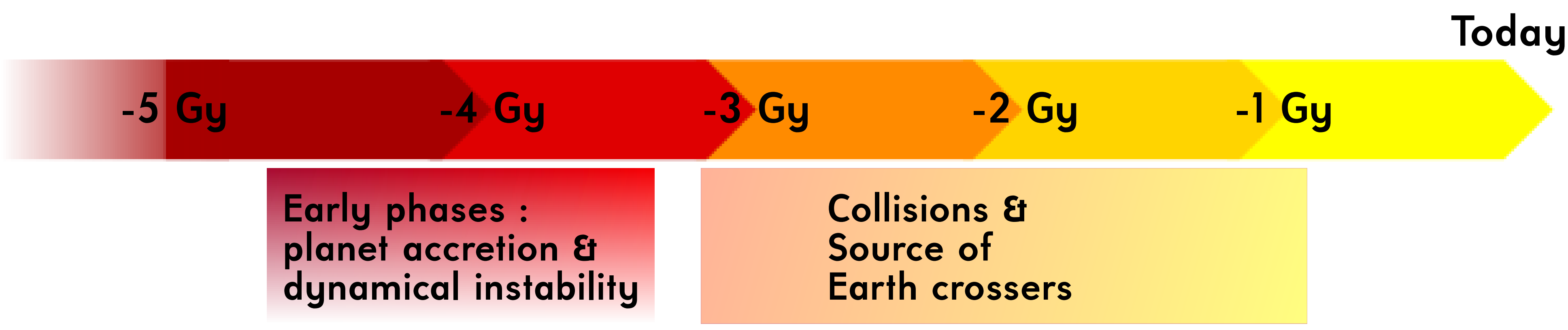

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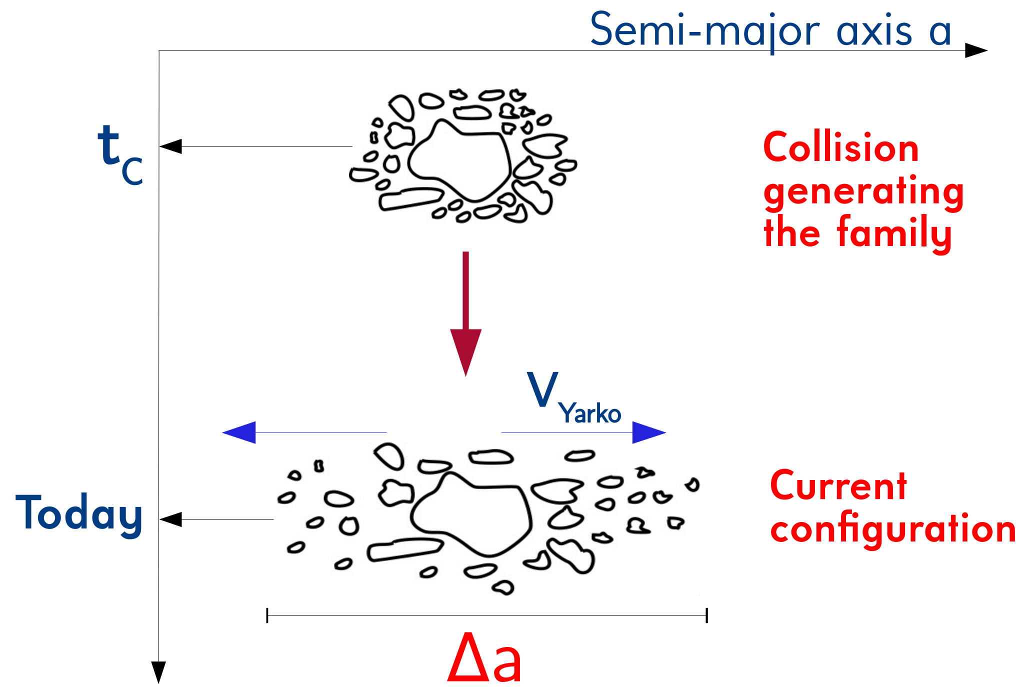


Early phases :
planet accretion &
dynamical instability

Collisions &
Source of
Earth crossers

Source of
meteorites

Summary 1.

Understand the origin and evolution of the Solar System

- Constraints to the formation models
- Main Belt

Asteroid families

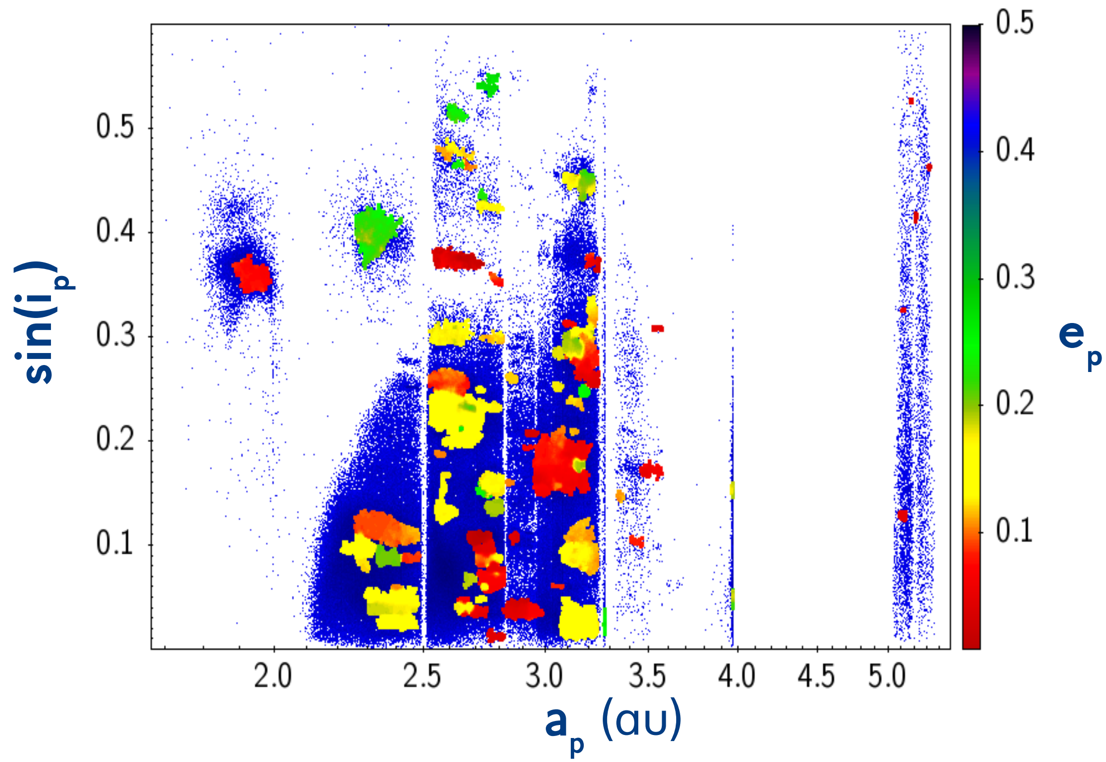
- Identification : proper elements and clustering method
- Determination of their ages : connection with the initial collision

The Yarkovsky effect

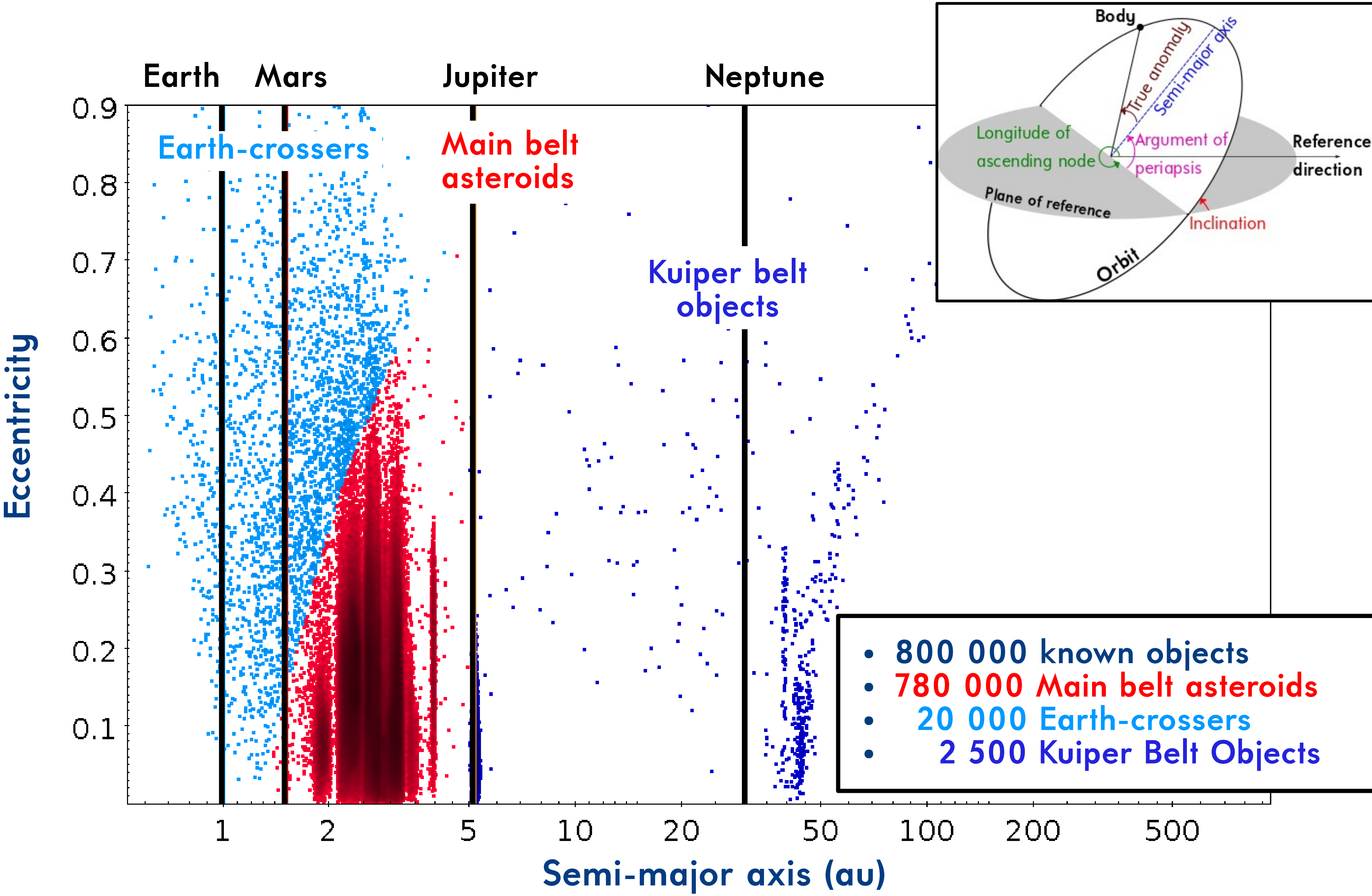
- Changes the orbit of small asteroids over long time
- Can be detected from astrometry

What do we need ?

- **To know physical and dynamical properties of asteroids**
- **Very accurate orbits**



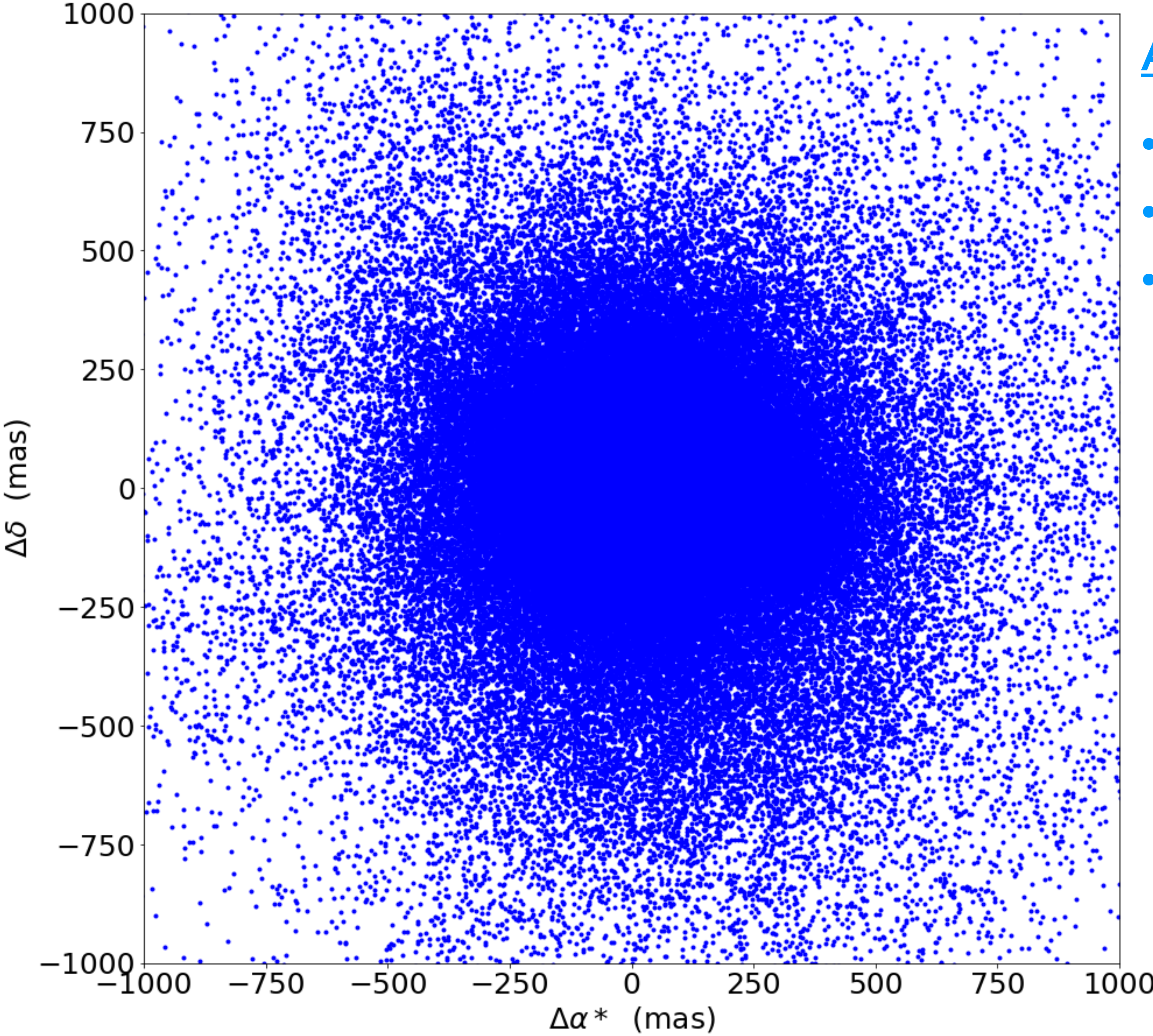
Our knowledge of the asteroid population



- 800 000 known objects
- 780 000 Main belt asteroids
- 20 000 Earth-crossers
- 2 500 Kuiper Belt Objects

Typical asteroid observation residuals

Post -fit residuals on the sky : Observed - Computed



Available ground-based astrometry

- **200 millions** of observations
- Typical accuracy: **400 / 500 mas**
- **2 000** accurate observations (mostly radar)

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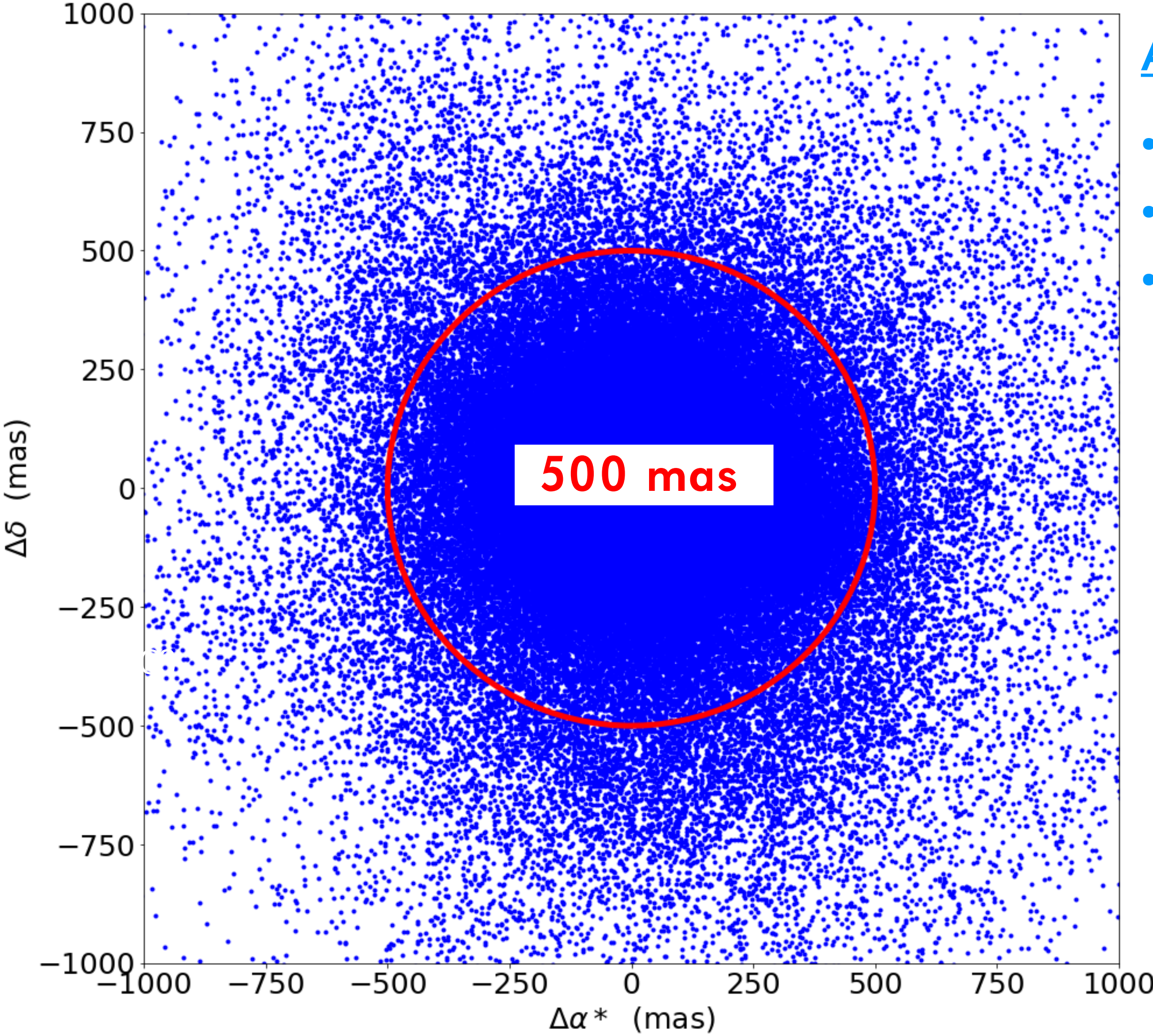

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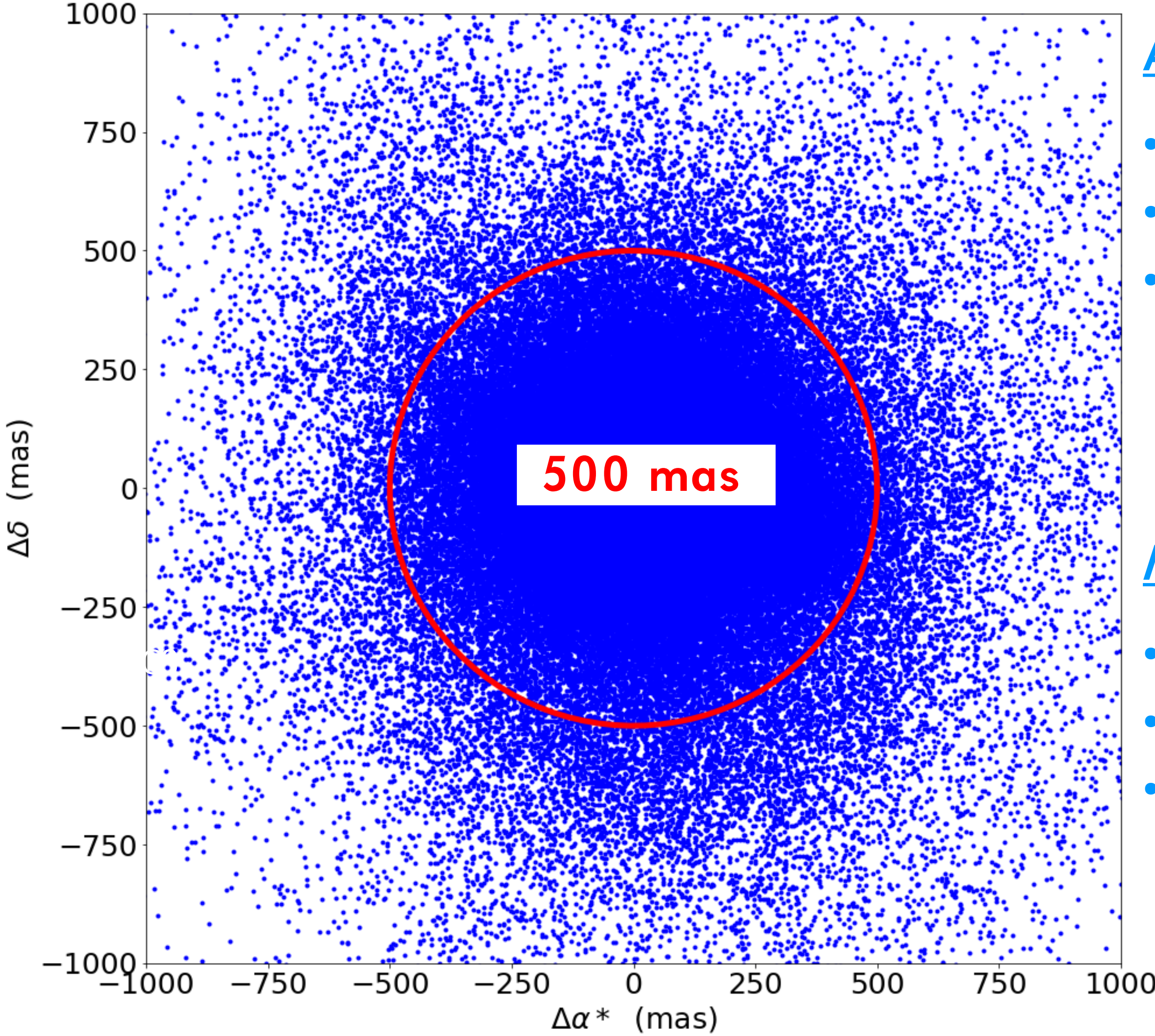

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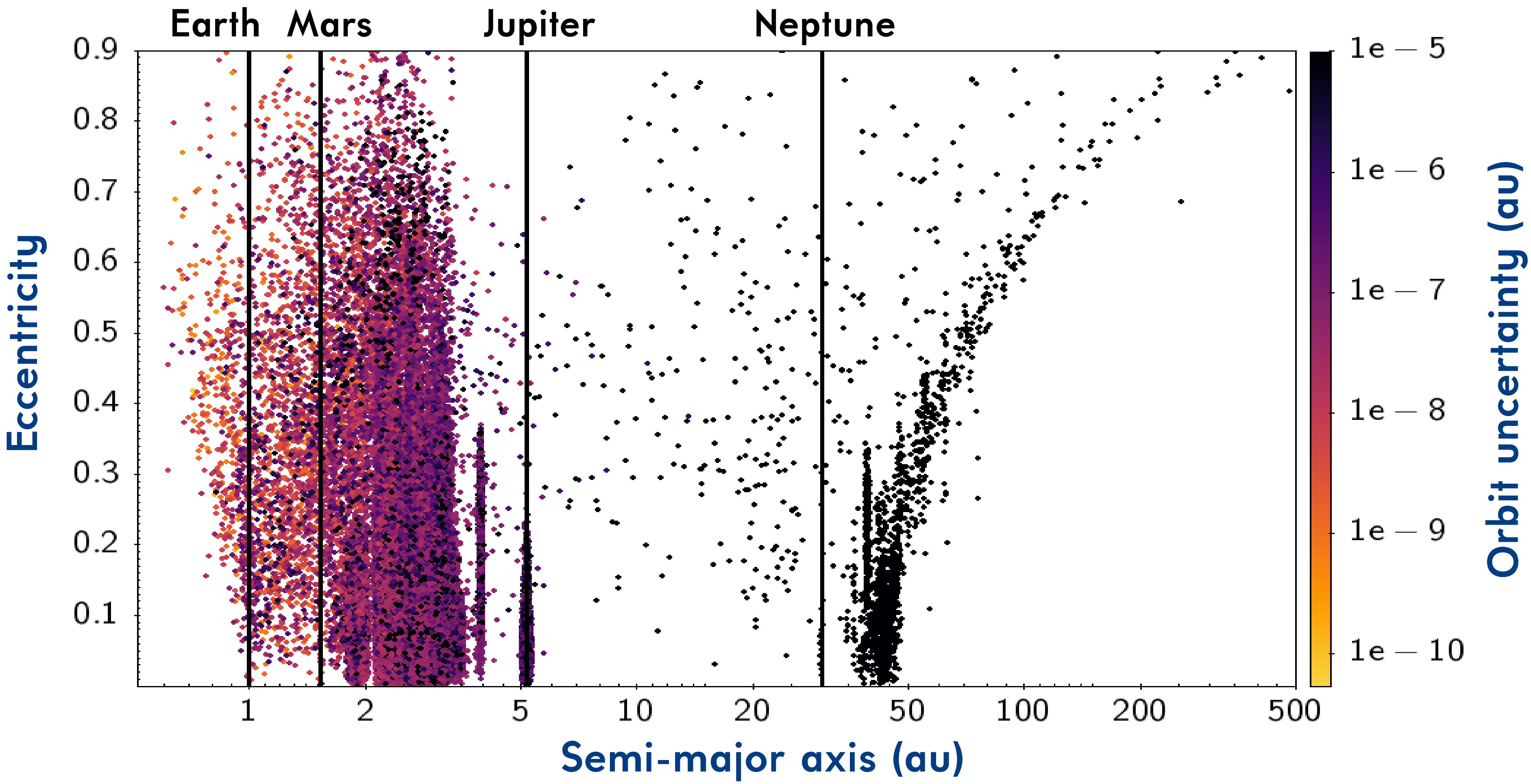
Main consequences

- **Orbital elements : large uncertainties**
- **Poorly known orbits**
- Observations focused **on NEAs**

Yarkovsky detections (before Gaia)



800 000 asteroids

900 small with « good » orbits
uncertaintity < 3e-9 au (~ 450 m)

87 detections
(Del Vigna et al. 2018)
All Earth-crossers &
No Main Belt asteroids

Summary 2.

Current knowledge of the asteroid population

- 800 000 asteroids
- < 1000 (0.1%) have accurate orbits (all Earth-crossers)
- A very poor knowledge of the physical properties

Astrometry

- 200 millions of observations available
- Typical accuracy of 400/500 mas

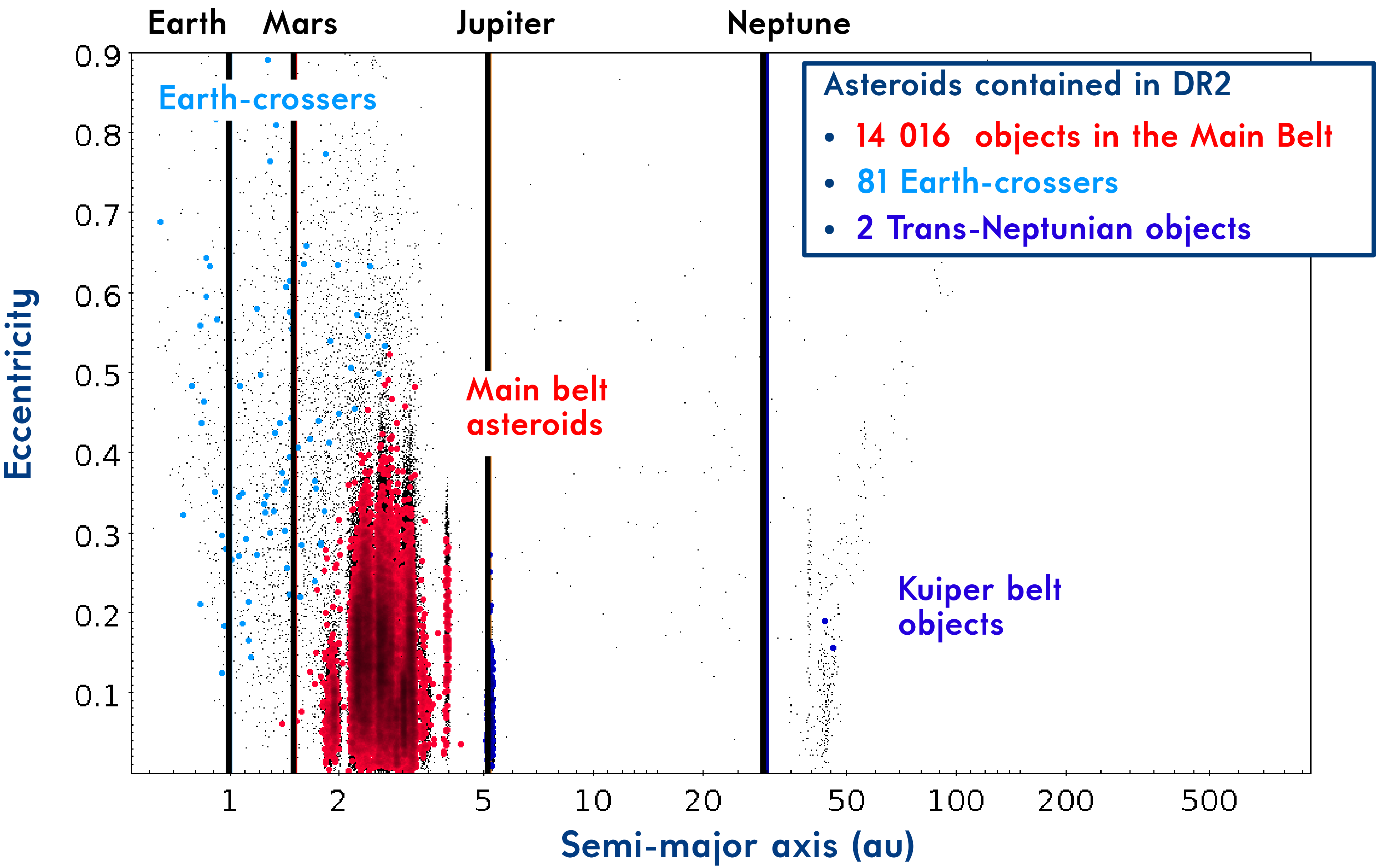
The Yarkovsky effect

- 87 detections : all Earth-crossers
- Bennu detection has been validated by the OSIRIS-Rex mission

What do we need ?

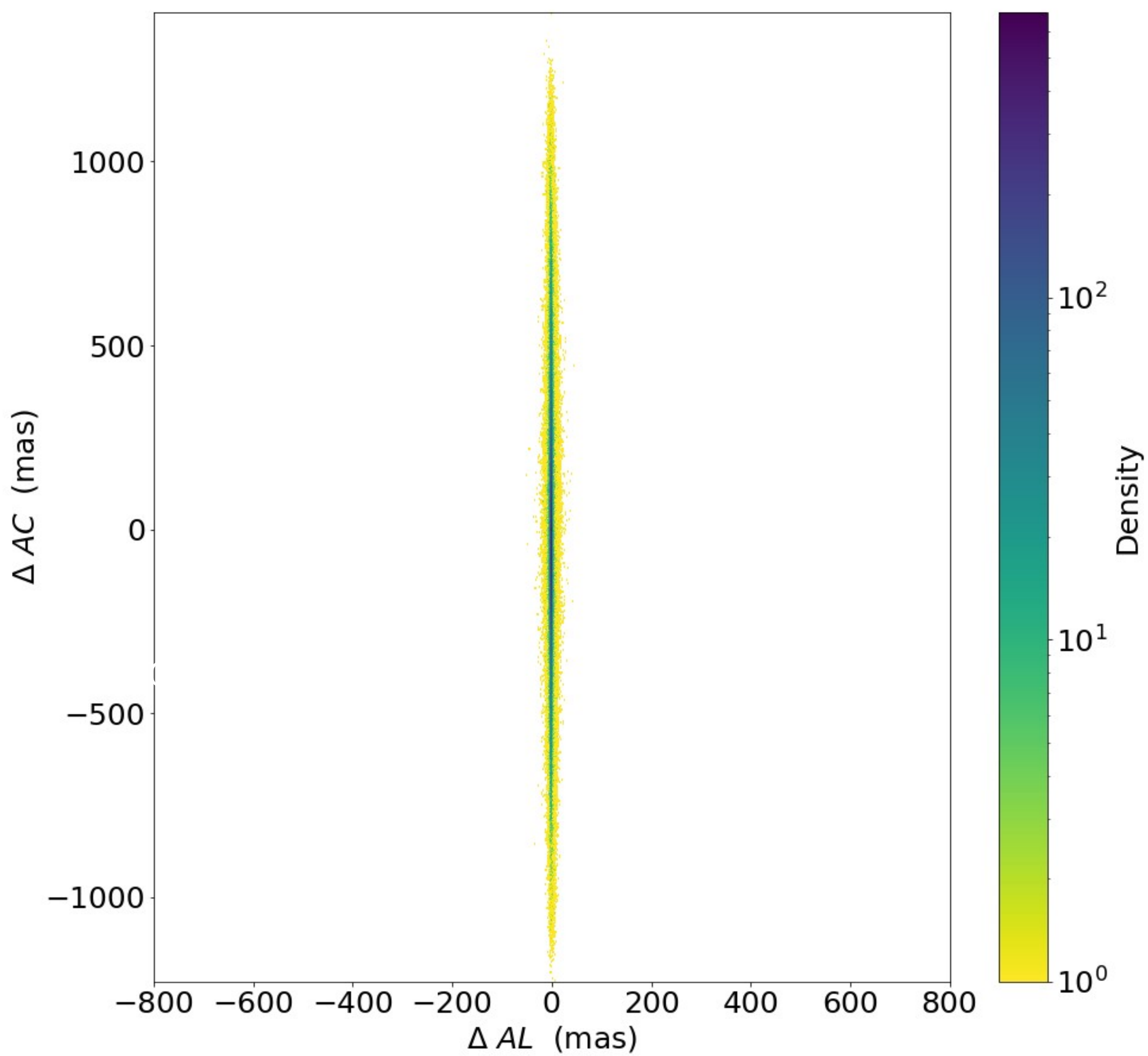
- **Very accurate astrometry**
- **Physical / Spectral properties**

Gaia Data Release 2



Gaia DR2 asteroid observation residuals

Post -fit residuals in the **ALong** scan – **ACross** scan **plane**



Gaia asteroid astrometry

- **~ 2 millions** of observations
- 22 months
- Accuracy is in the **ALong** scan direction

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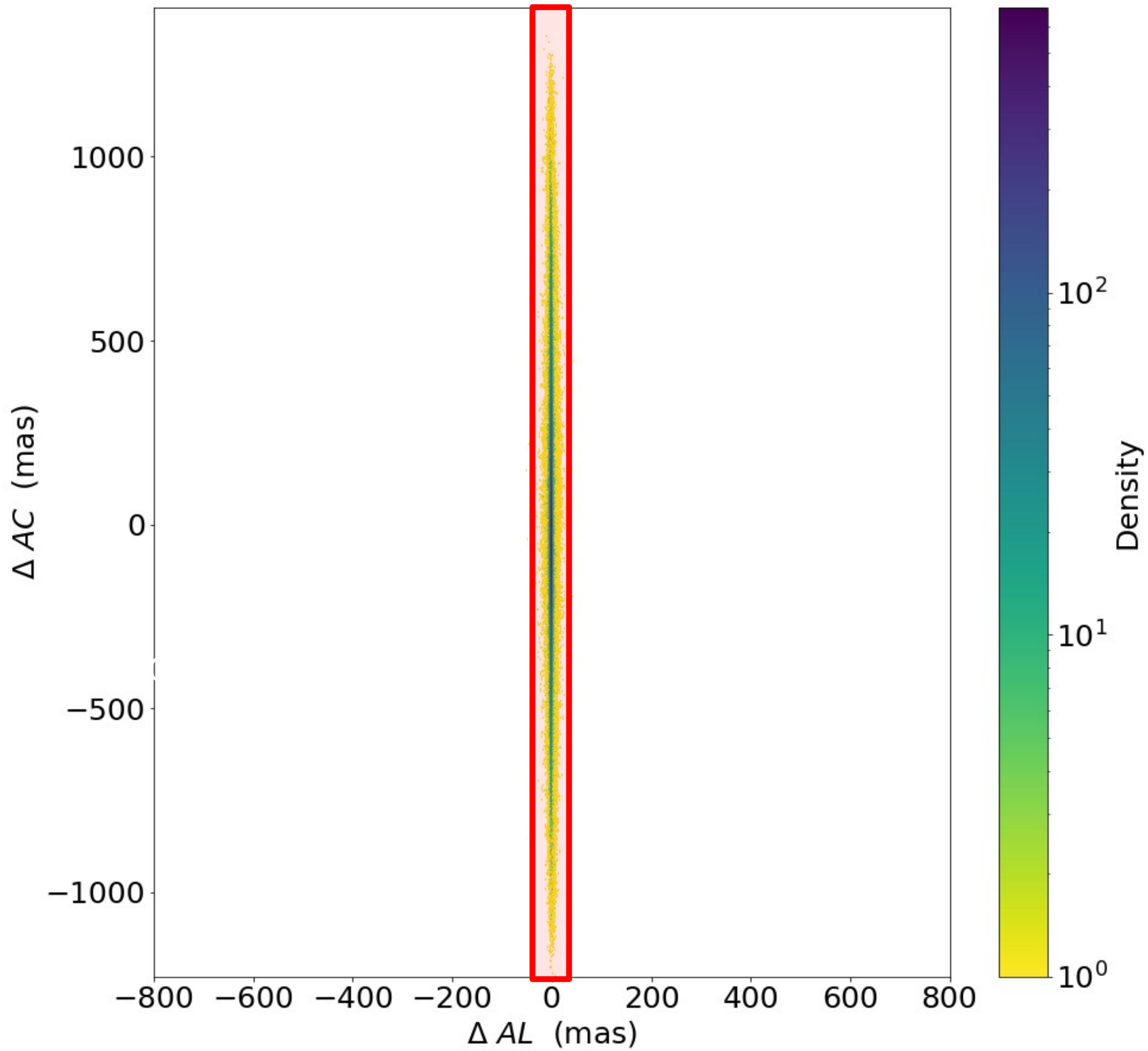

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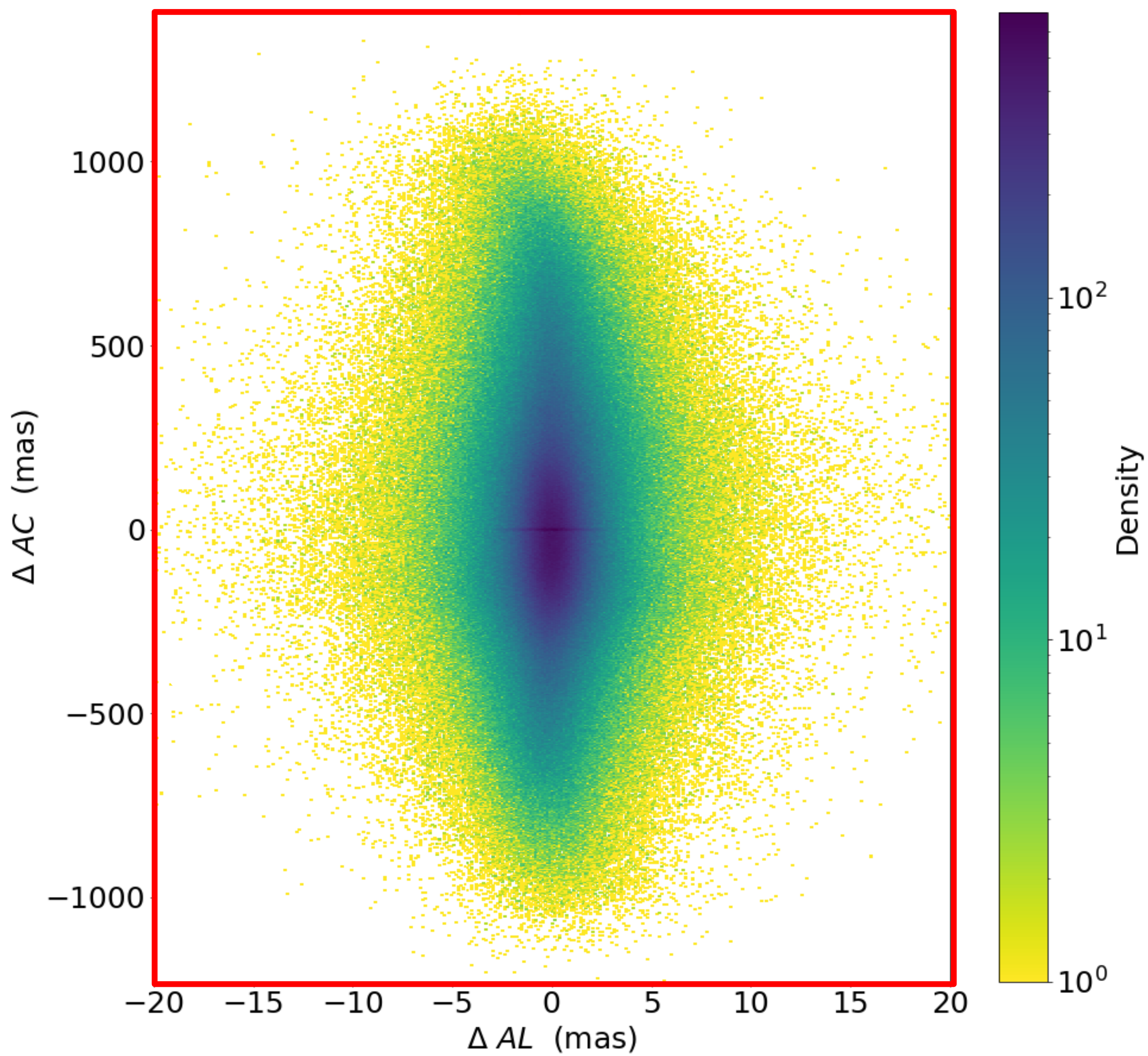

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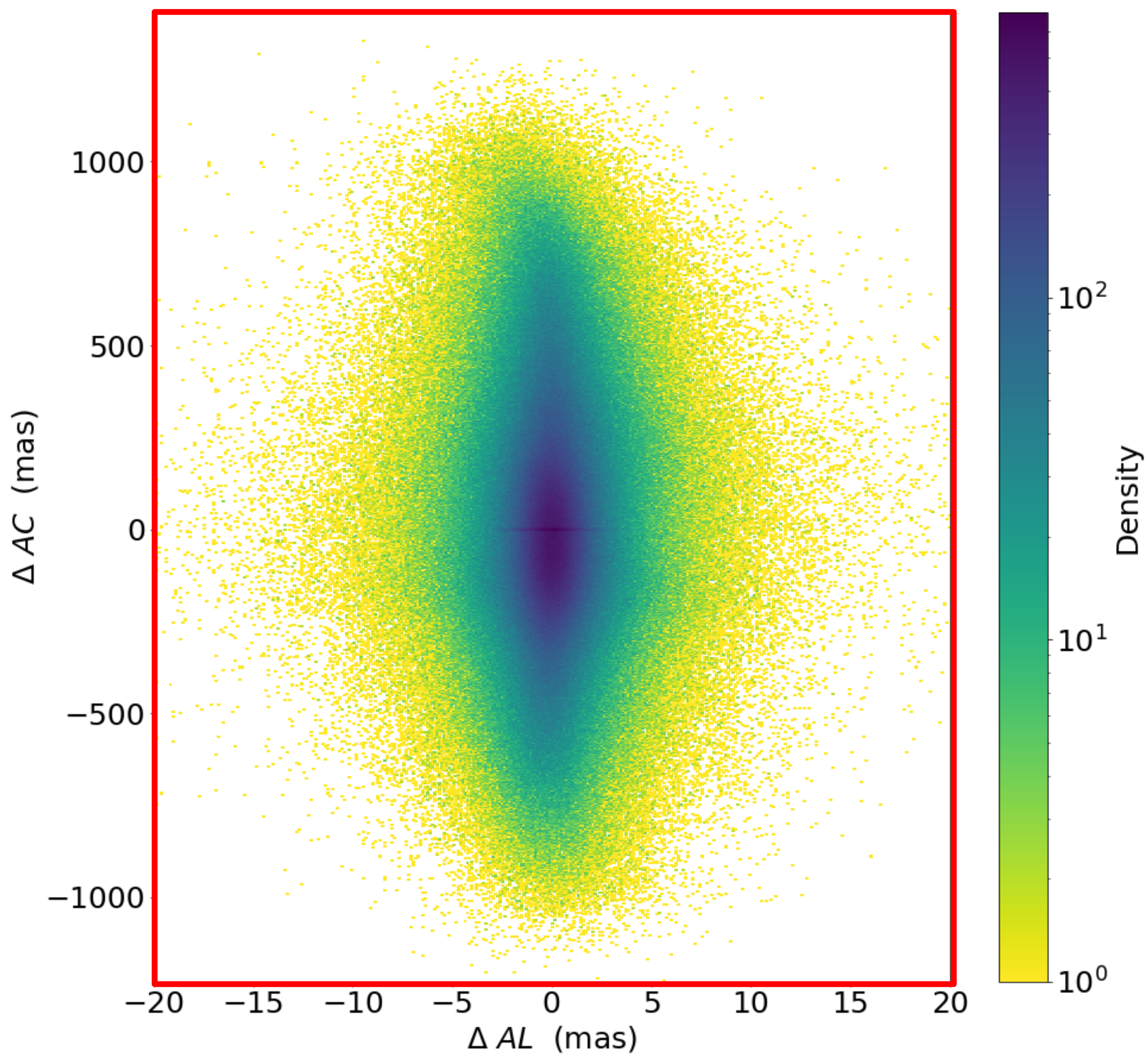

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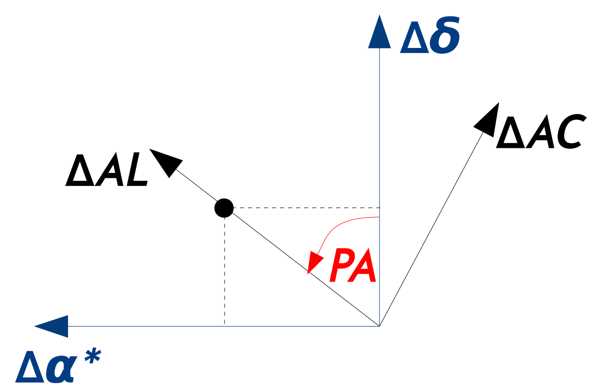
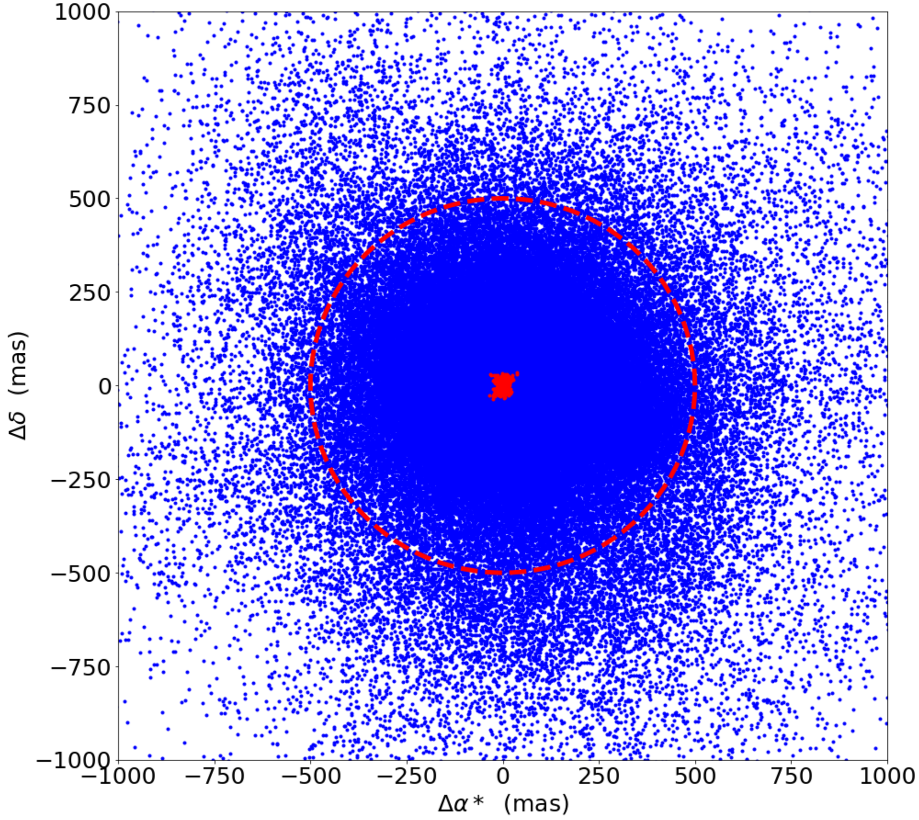
How can we make a comparison between Gaia and ground-based astrometry ?



Gaia DR2 vs ground-based asteroid astrometry

Post – fit residuals on the sky



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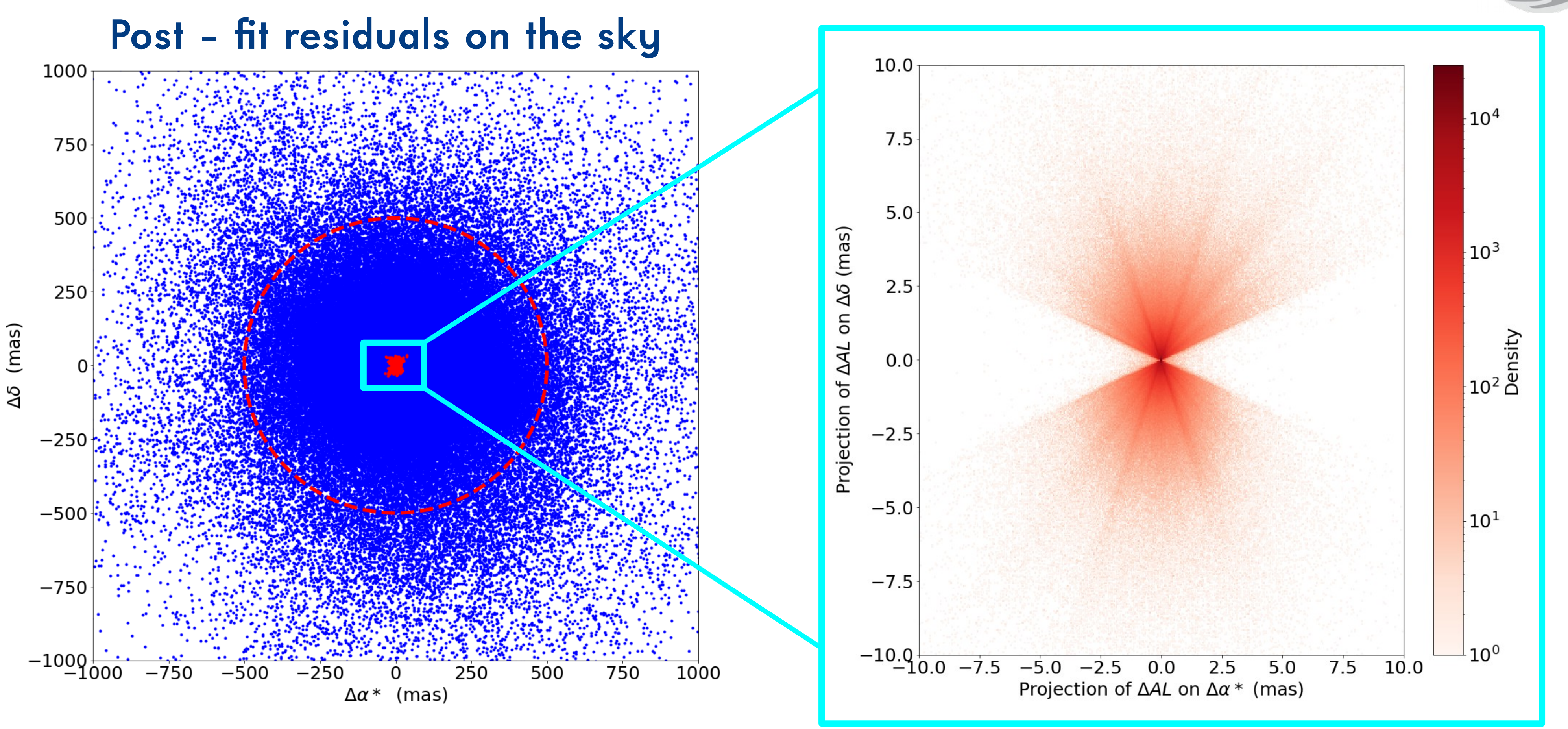
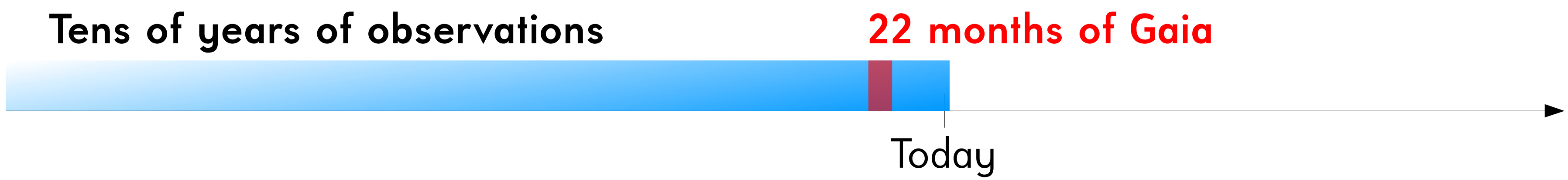


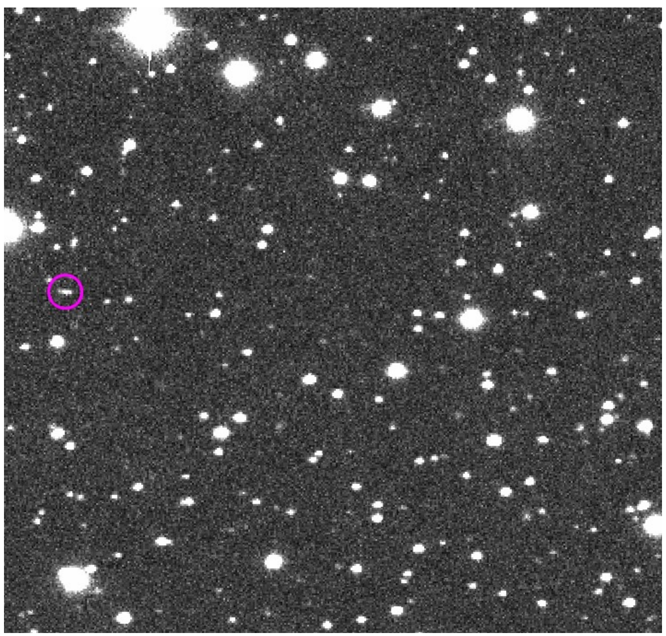
Gaia is amazing and challenging at the same time :

- 2 millions of very accurate observations
- New vision of asteroid astrometry
- Short observational arc

How to combine Gaia and ground-based observations?



Debiasing of old stellar catalogs



Discovery observations
of an asteroid

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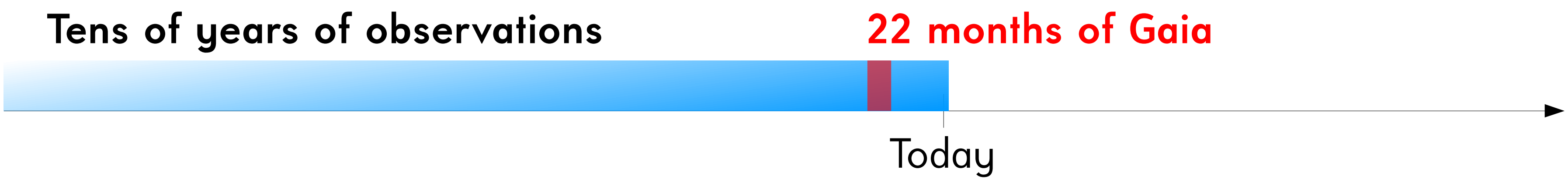

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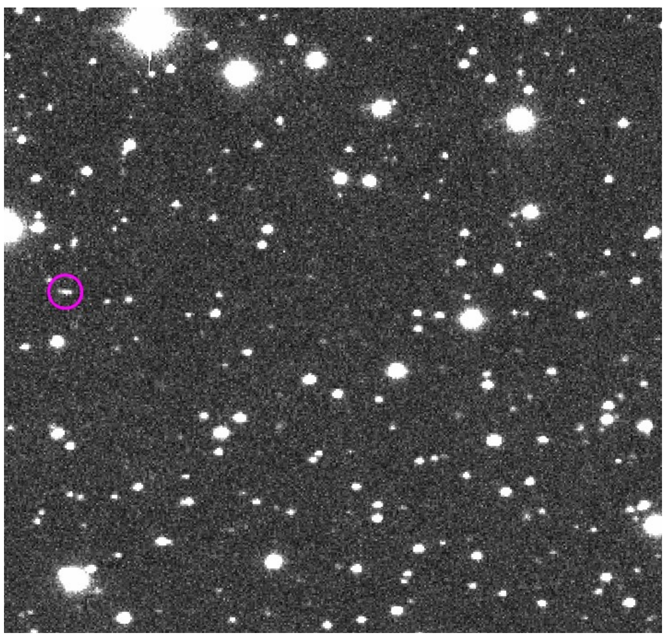

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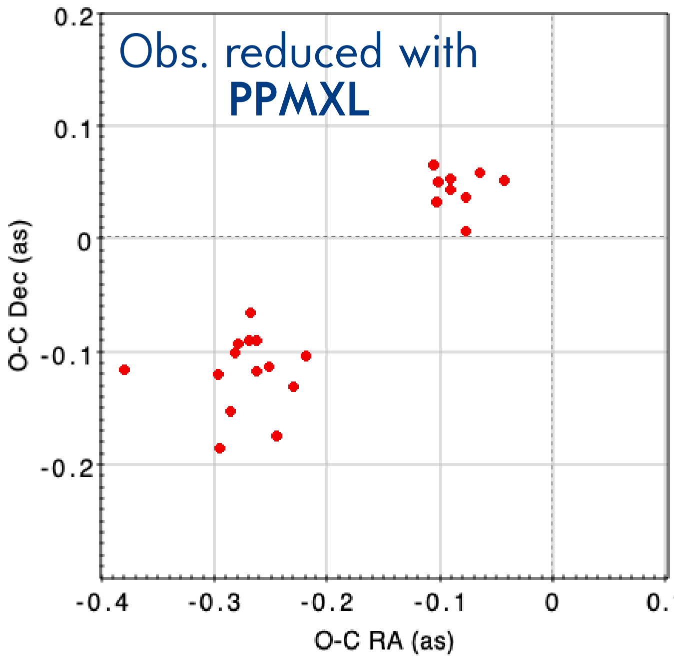
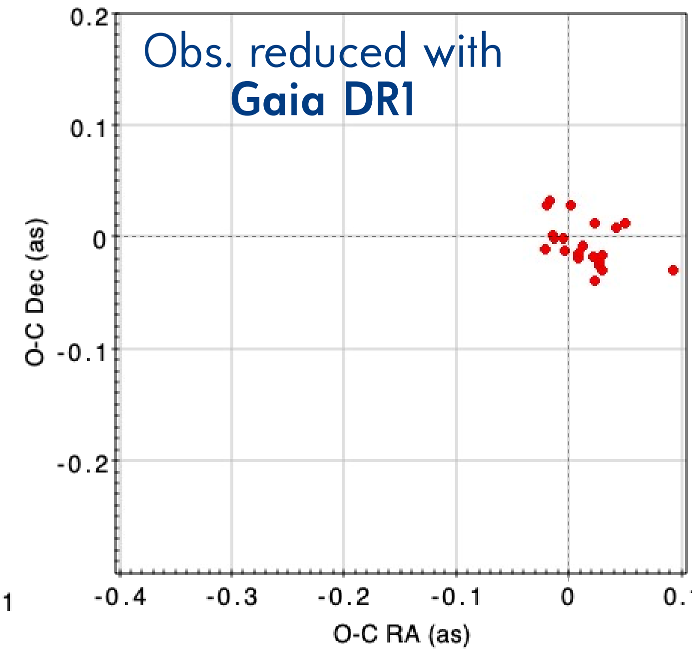
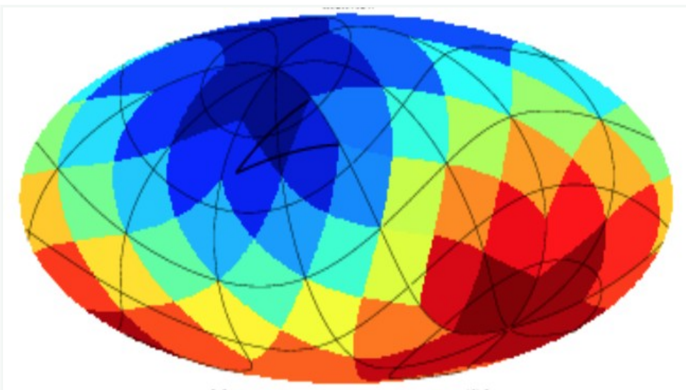


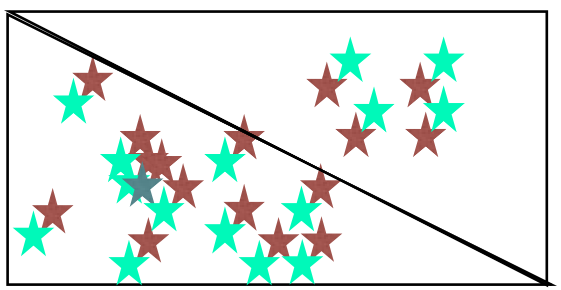


Credit : GBOT Team, Spoto et al. 2017 (A&A)

How to combine Gaia and ground-based observations?

A new approach to debiasing





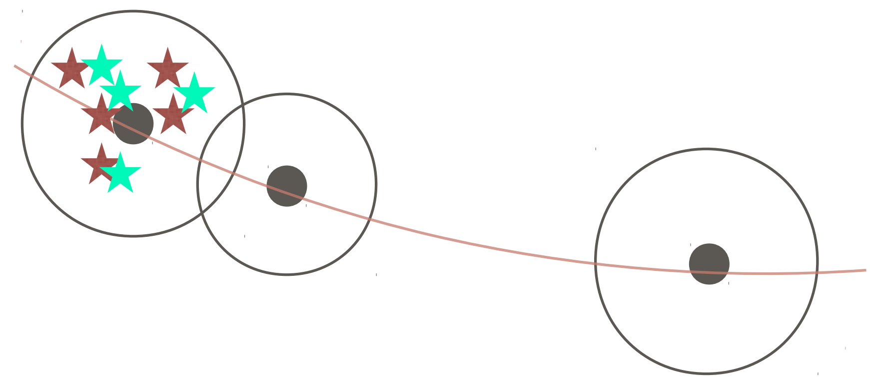
Method 1 (used up to now):

Corrections of catalogs

Computed on a healpix tassellation of the sky

(Farnocchia et al. 2015

Referred to PPMXL & SMASS)



Method 2 :

Corrections of single archive position with Gaia DR2

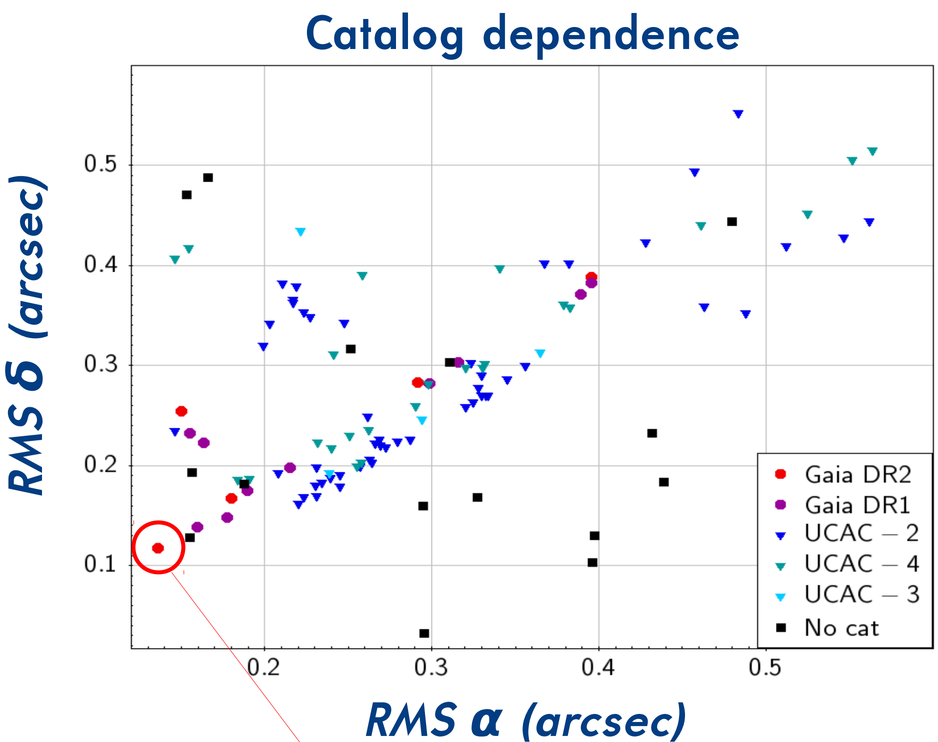
No discontinuities

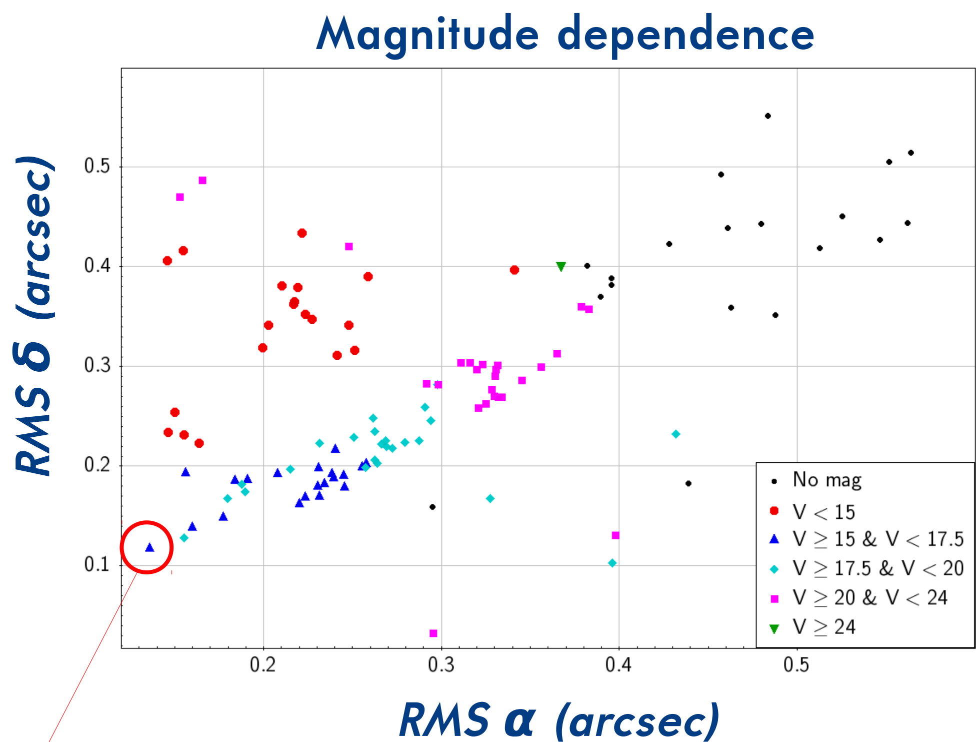
(Tanga & Spoto, in preparation)

Credit : P. Tanga

How to combine Gaia and ground-based observations?

Error model : weights to give to each observatory





(Observatory, year, catalog, magnitude class)
(G96, 2019, V, 2)

How to combine Gaia and ground-based observations?

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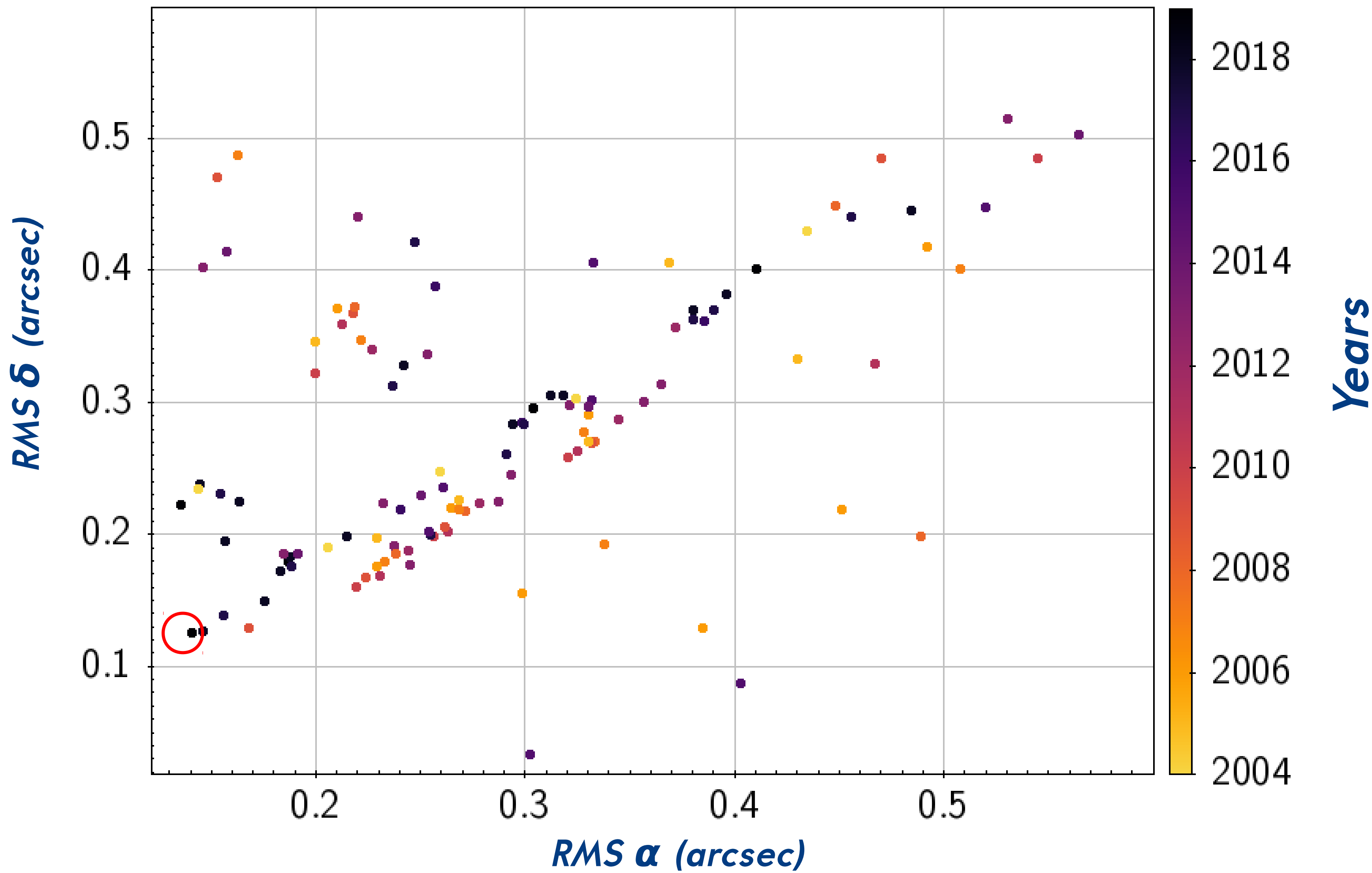
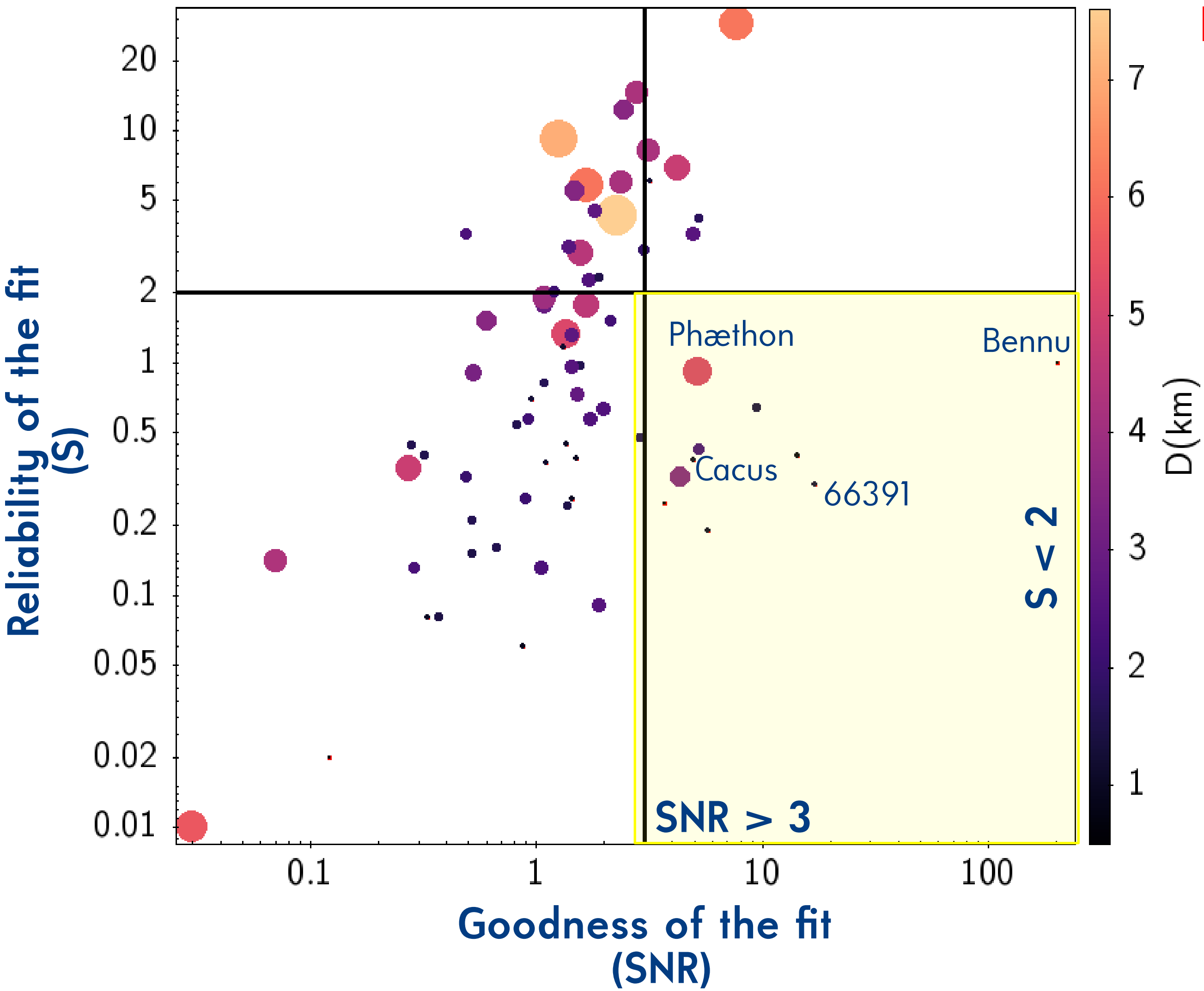


New Yarkovsky detections



Initial sample from Gaia DR2

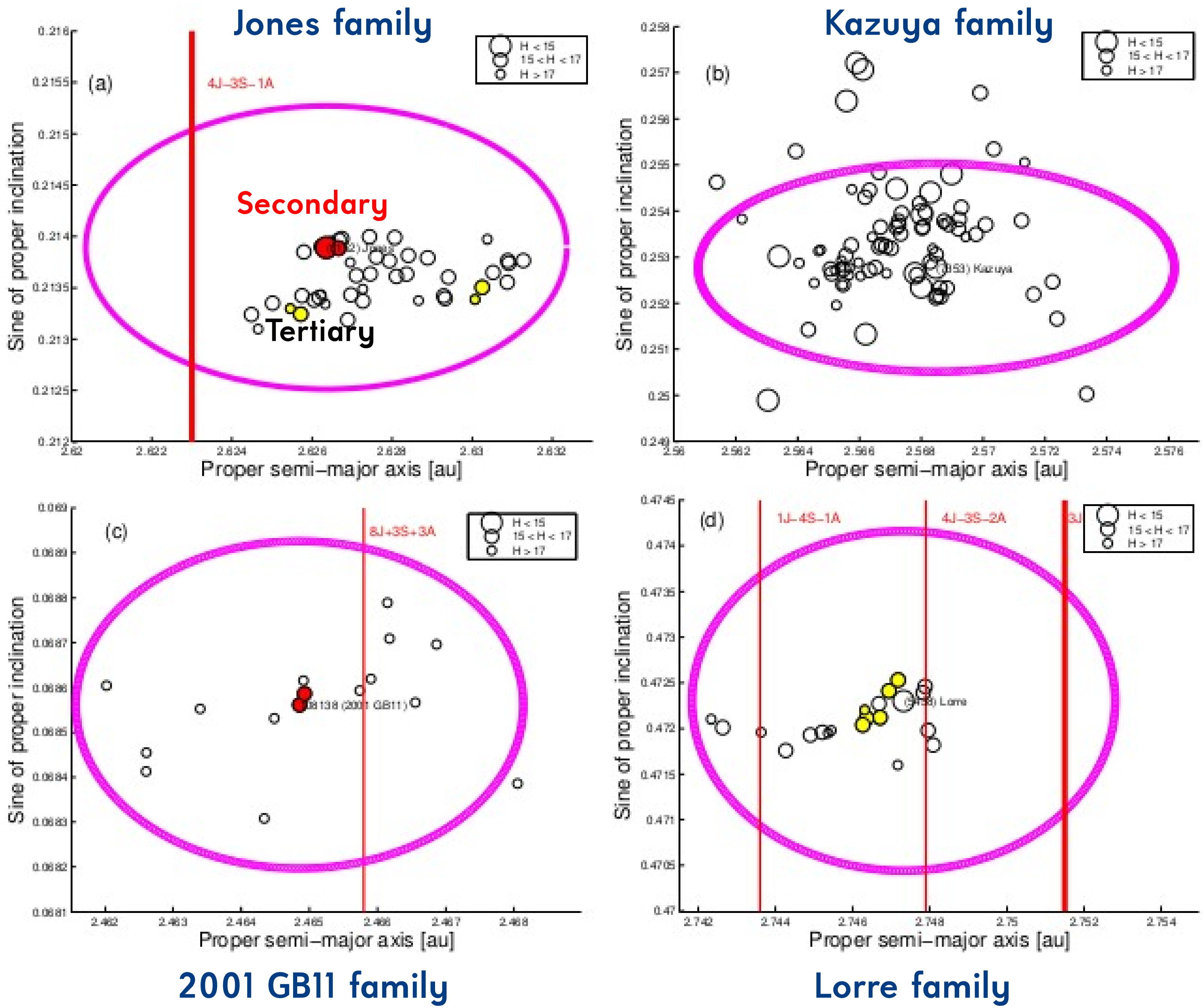
- ~ 60 objects
- Diameter < 10 km
- Orbit uncertainty < 1 km

Detections

- 10 new + densities
- Cases not possible before Gaia

Spoto et al. 2019, in preparation

Young fission clusters inside collisional families

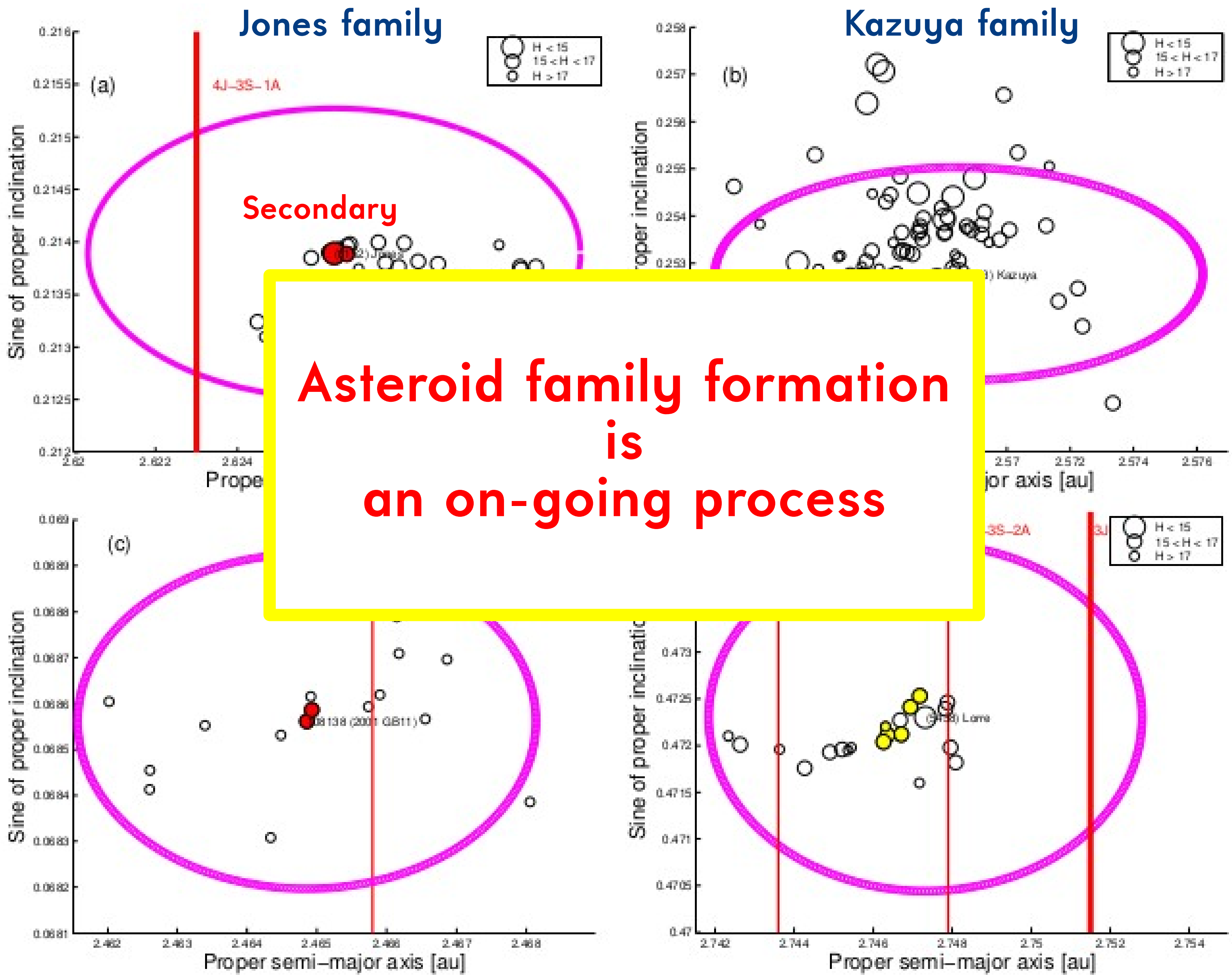


Carruba, Spoto et al. 2019 (Nature Astronomy)

Young fission clusters inside collisional families

Jones family

Kazuya family



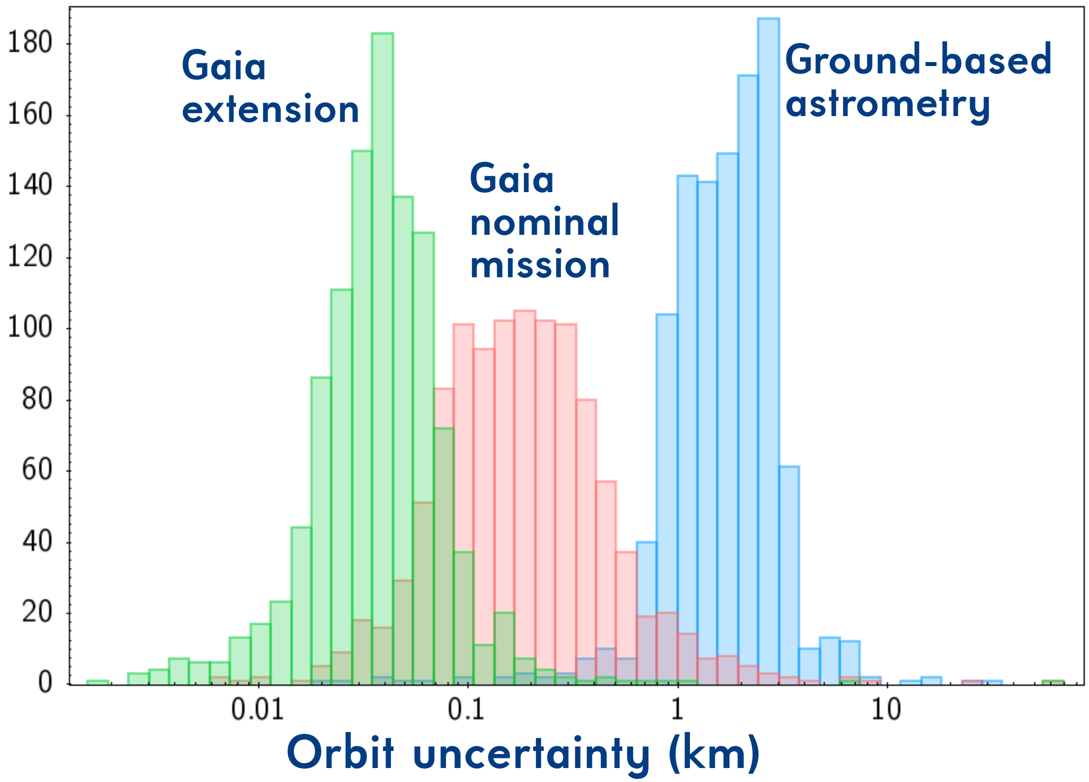
Asteroid family formation is an on-going process

2001 GB11 family

Lorre family

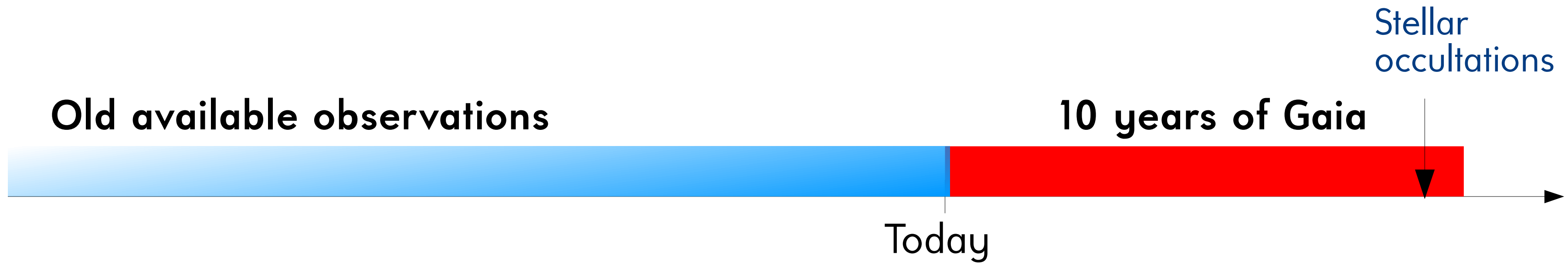
Carruba, Spoto et al. 2019 (Nature Astronomy)

Future perspectives

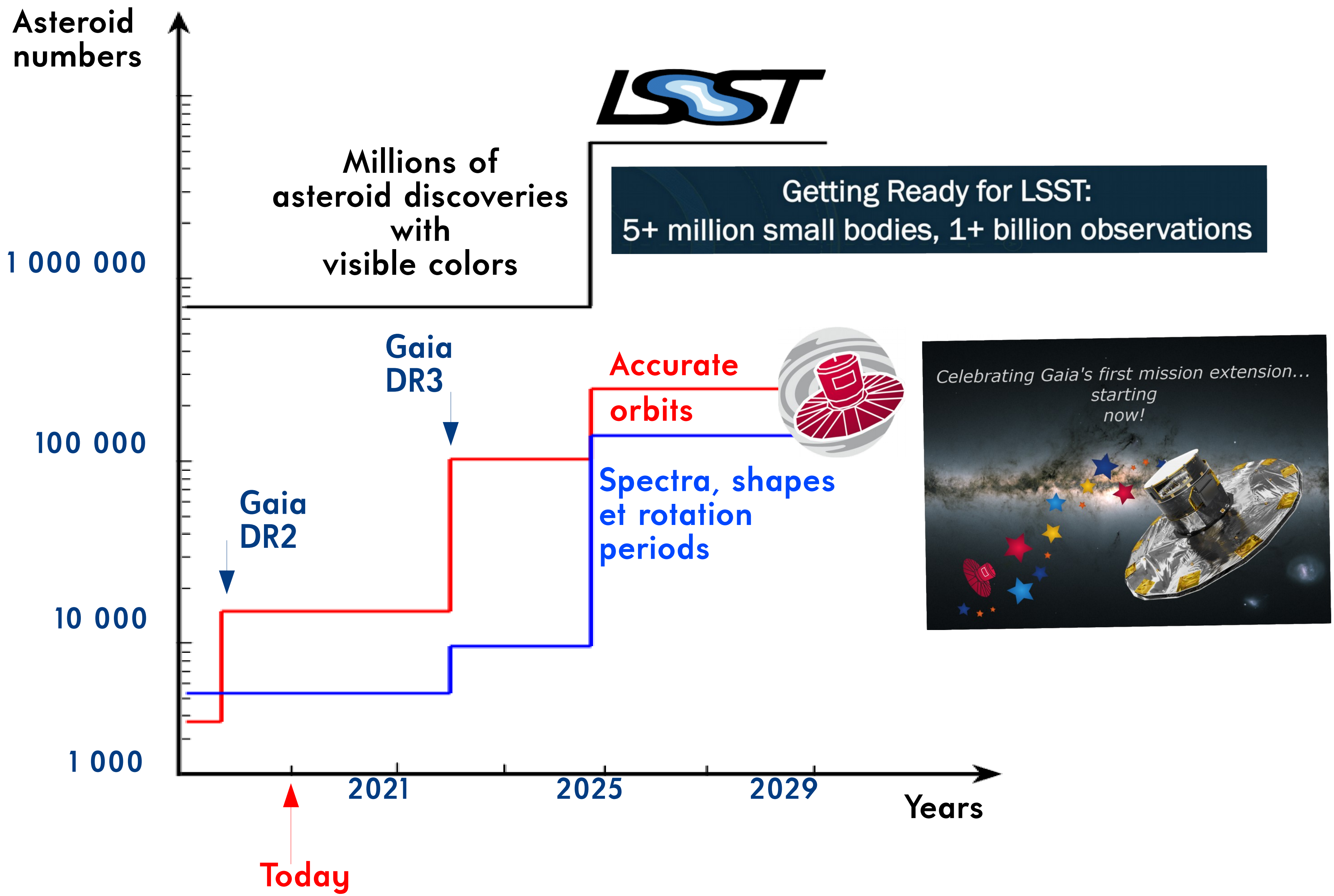


Asteroid orbit accuracy after 5 and 10 years of the Gaia mission

Simulation for the mission extensions (F. Spoto & F. Mignard)



Future perspectives



Conclusions

- Gaia has already changed our view of the asteroid astrometry
- Our knowledge of the Main Belt is still very limited:
  we are missing quantity and quality
- We are on the verge of a revolution : Gaia is producing ultra-accurate astrometry for millions of observations
- We need to combined Gaia and tens of ground-based observations to detect subtle non-gravitational perturbations like the Yarkovsky effect
- We have analyzed and corrected all the available astrometry
- The combination has already produced amazing results, but moreover it shows that now we are ready for the next Gaia releases
- To the Main Belt and beyond.

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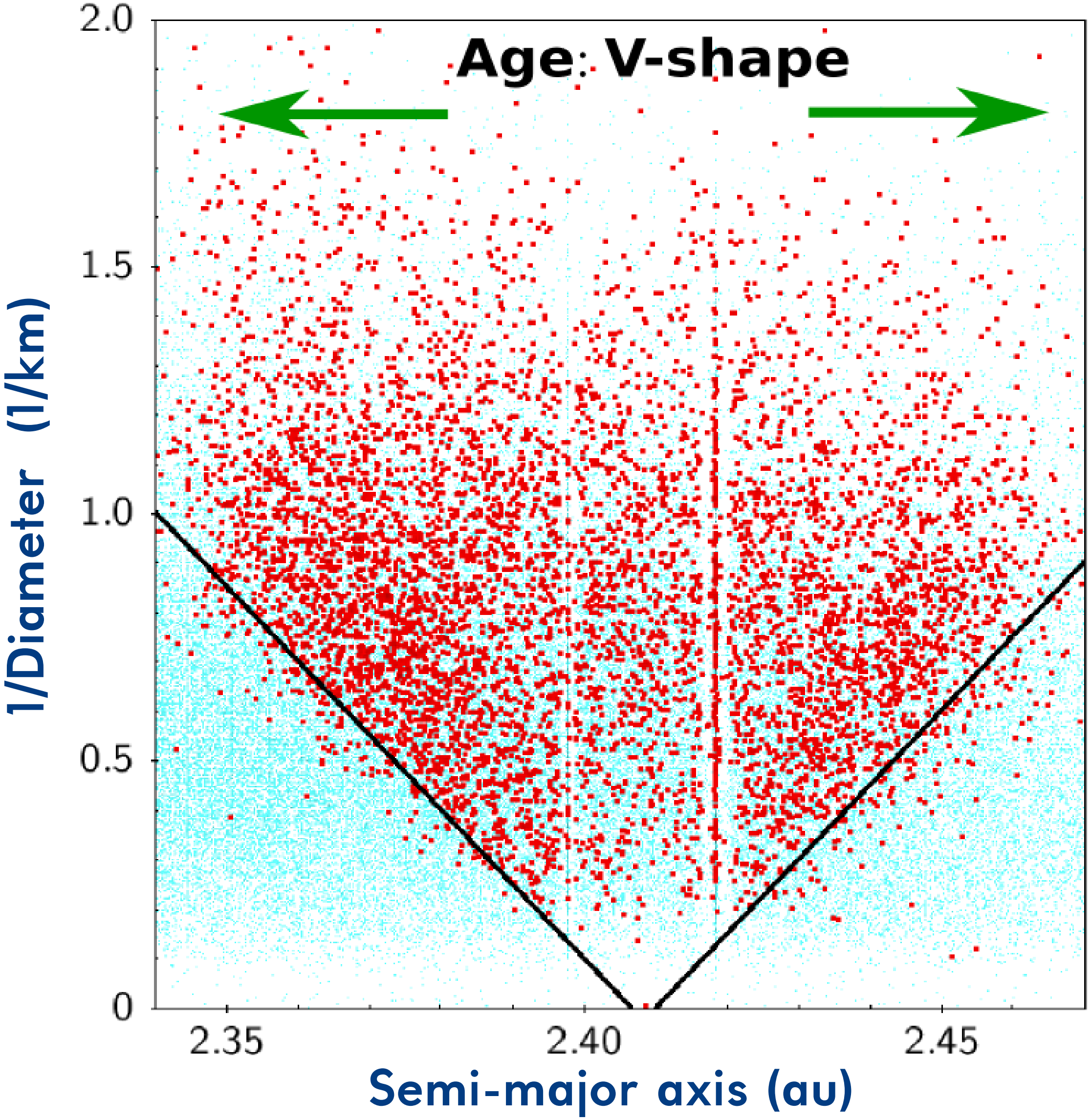
Thank you.

V-shape



Space :

Computation of the inverse slope

$$1/S = \Delta a \text{ (1 km)}$$

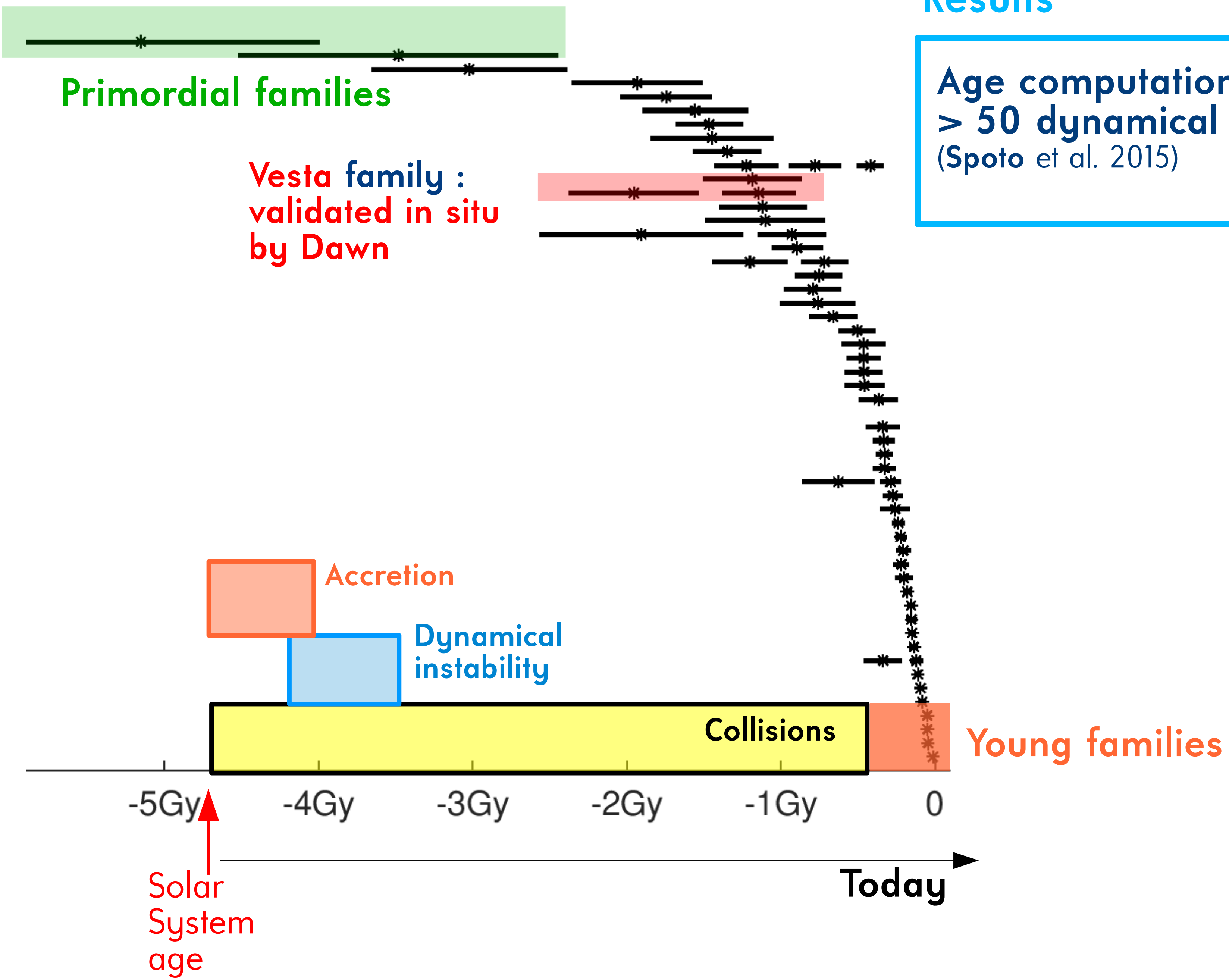
Velocity :

Calibration of the Yarkovsky Effect for each family (V_{Yarko})

Time of the initial collision :

$$t_C = \Delta a \; / \; V_{Yarko}$$

First collisional history of the Main Belt

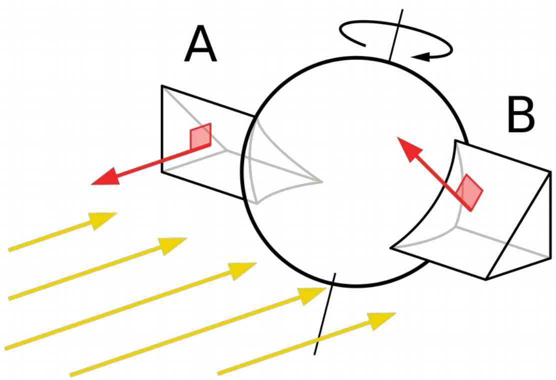


Results

Age computation for > 50 dynamical families
(**Spoto** et al. 2015)

Rotational fissions : models

- Asteroid pairs
- Binaries



YORP effect:
- Fast rotating body
- Repeated accelerations
- Break-up

(Bottke et al. 2002)

Spin-orbit coupling:
- Nearly identical solar orbits
- Inter-related past
- High mass-ratio systems

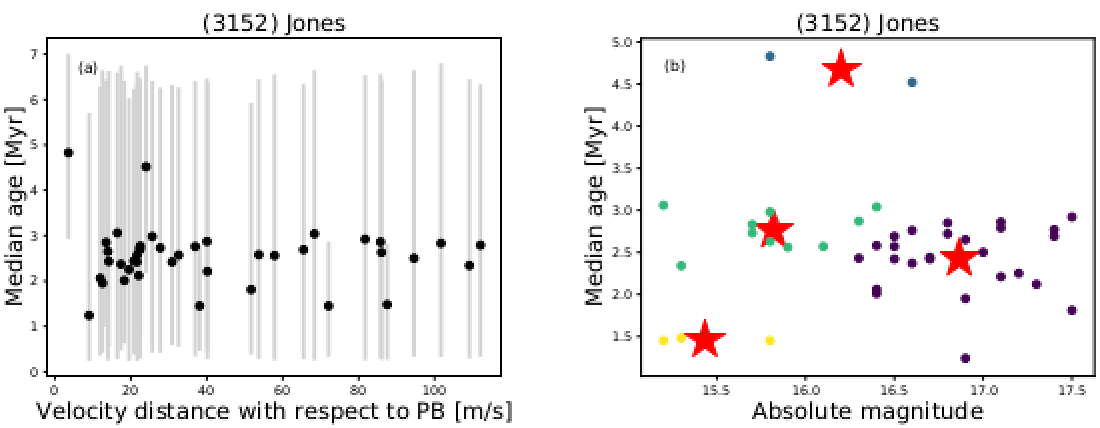
(Jacobson et al. 2011)

Low energy collision:
- Fast rotating primary

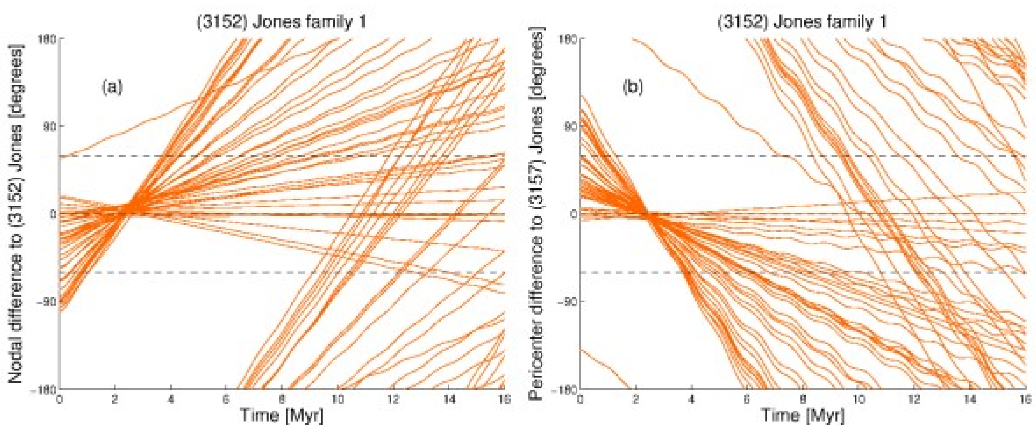
(Vokrouhlický et al. 2011)

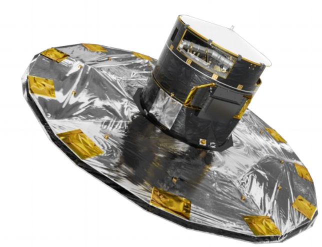
Age estimation method

- **CEM: close-encounters method**
  - Clones of the parent body and the asteroids are integrated into the past
  - The times of close encounters between clones is registered
  - Median value: estimation of the age of asteroid pairs
- **BIM: backward integration method**
  - Family formation: pericenters and ascending nodes of the asteroids in the family are aligned
  - Back in time to reconstruct the setting in which the parameters were aligned



CEM + machine learning



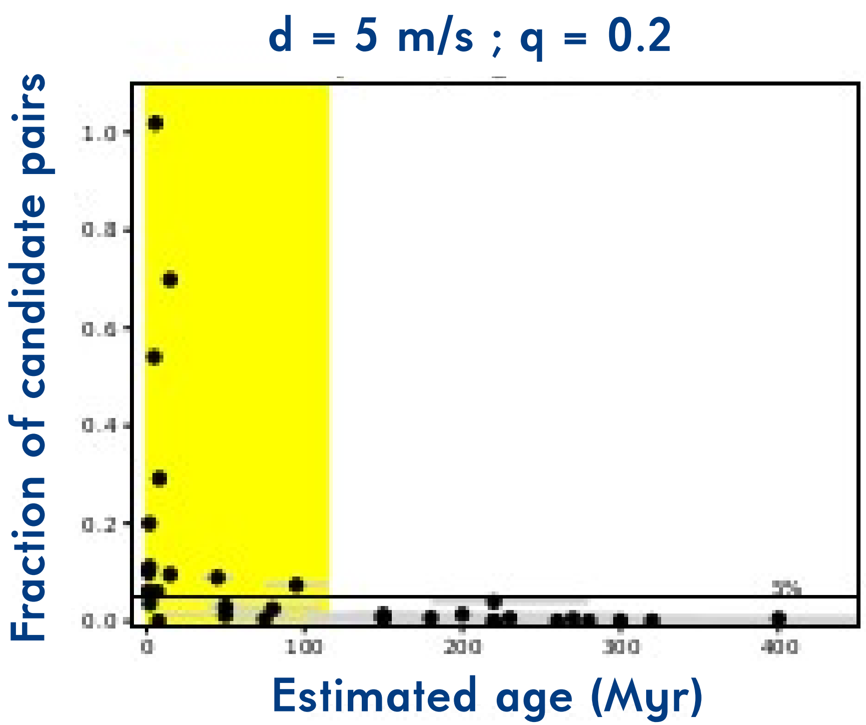


BIM

Young fission clusters

The sample

- All the families within 300 Myr
- Fraction of number of pairs larger than 5%
  - Distance (d) = 5 m/s
  - Mass ratio (q) = 0.2 (upper limit for fission clusters)



Results

- **12 families** inside the 5%
- **Younger than 120 Myr**
  - **9/12** are **cratering** families
  - **5/12 S-type** families

Implications

- **Initial collision → highly rotating states**
  - **Fission clusters**
- **Normal production rate**

Asteroid family formation:
an on-going process