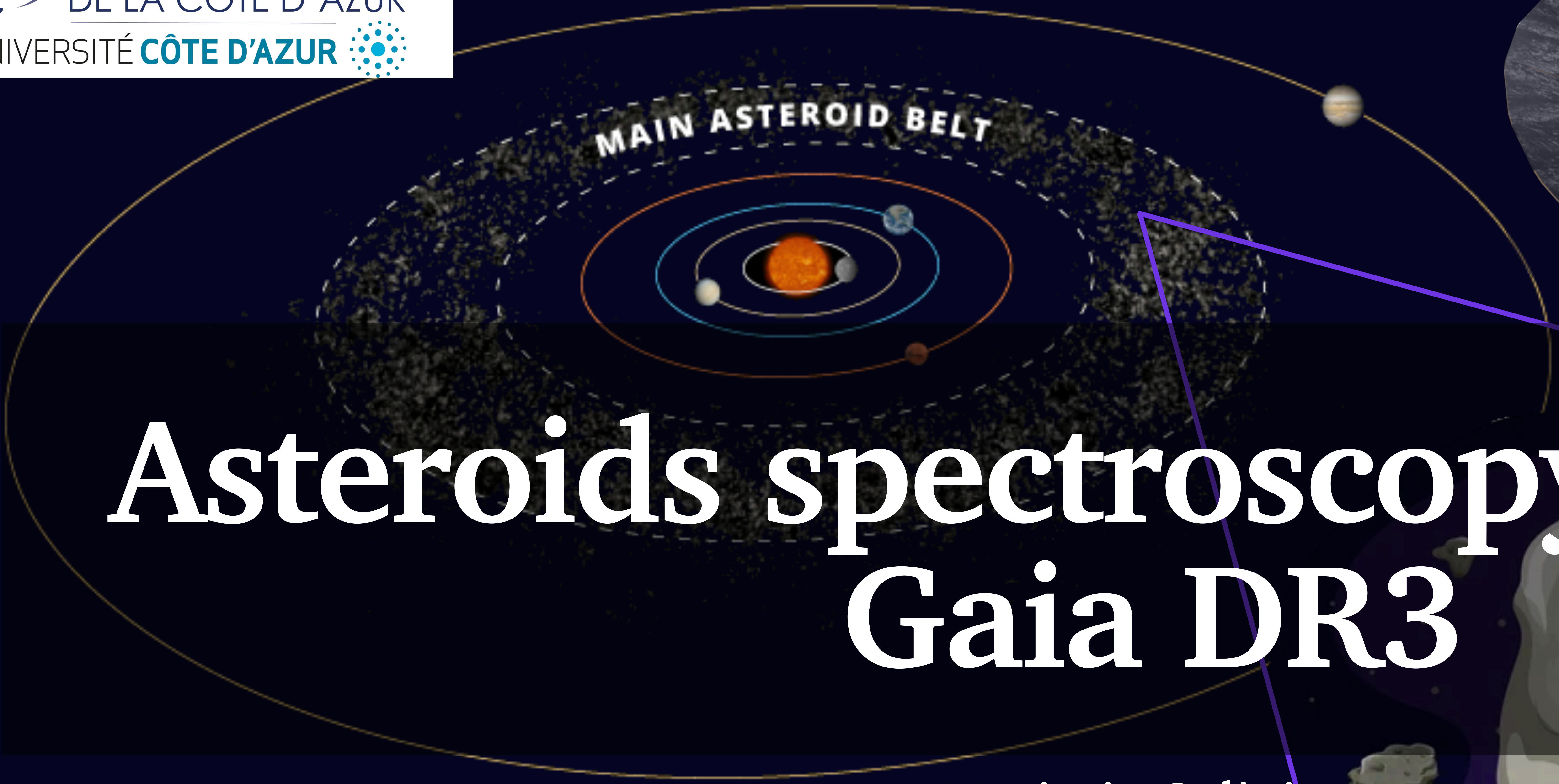
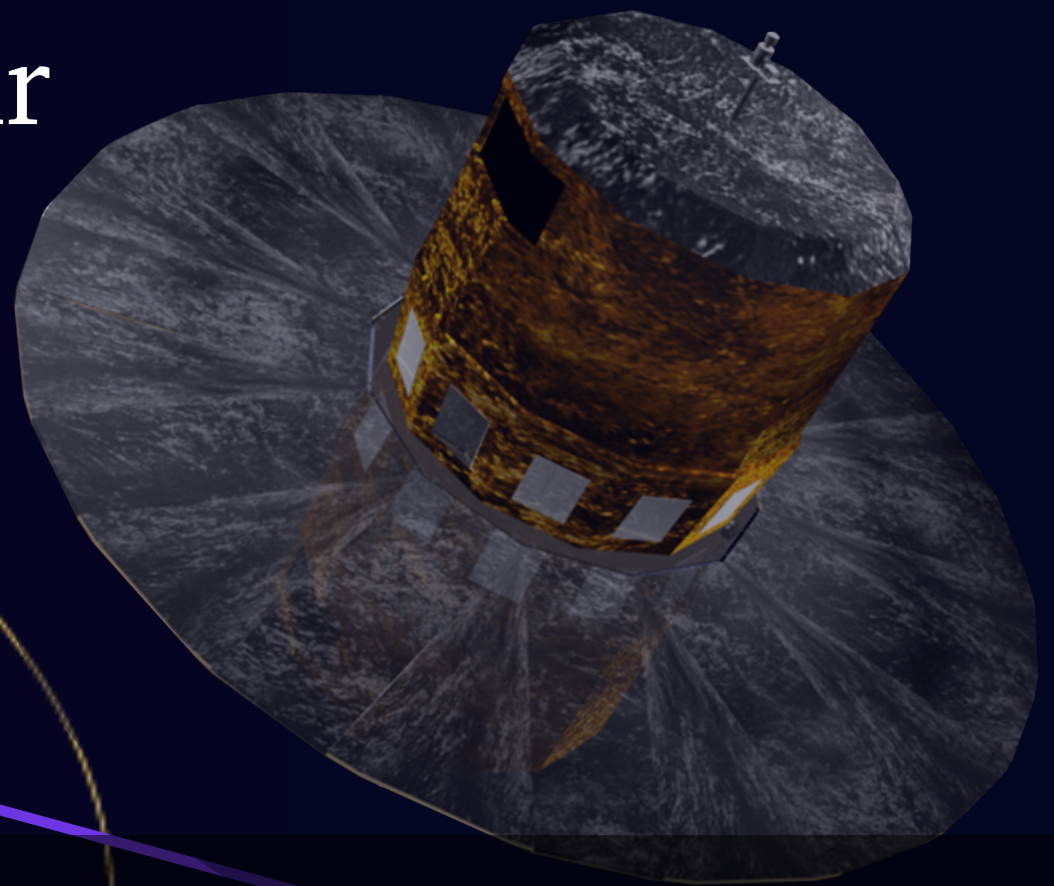
OBSERVATOIRE DE LA CÔTE D'AZUR
UNIVERSITÉ CÔTE D'AZUR

Astronomical Institute seminar

LAGRANGE





Asteroids spectroscopy with the Gaia DR3

Marjorie Galinier

3rd year PhD student of Marco Delbo & Laurent Galluccio

marjorie.galinier@oca.eu

cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

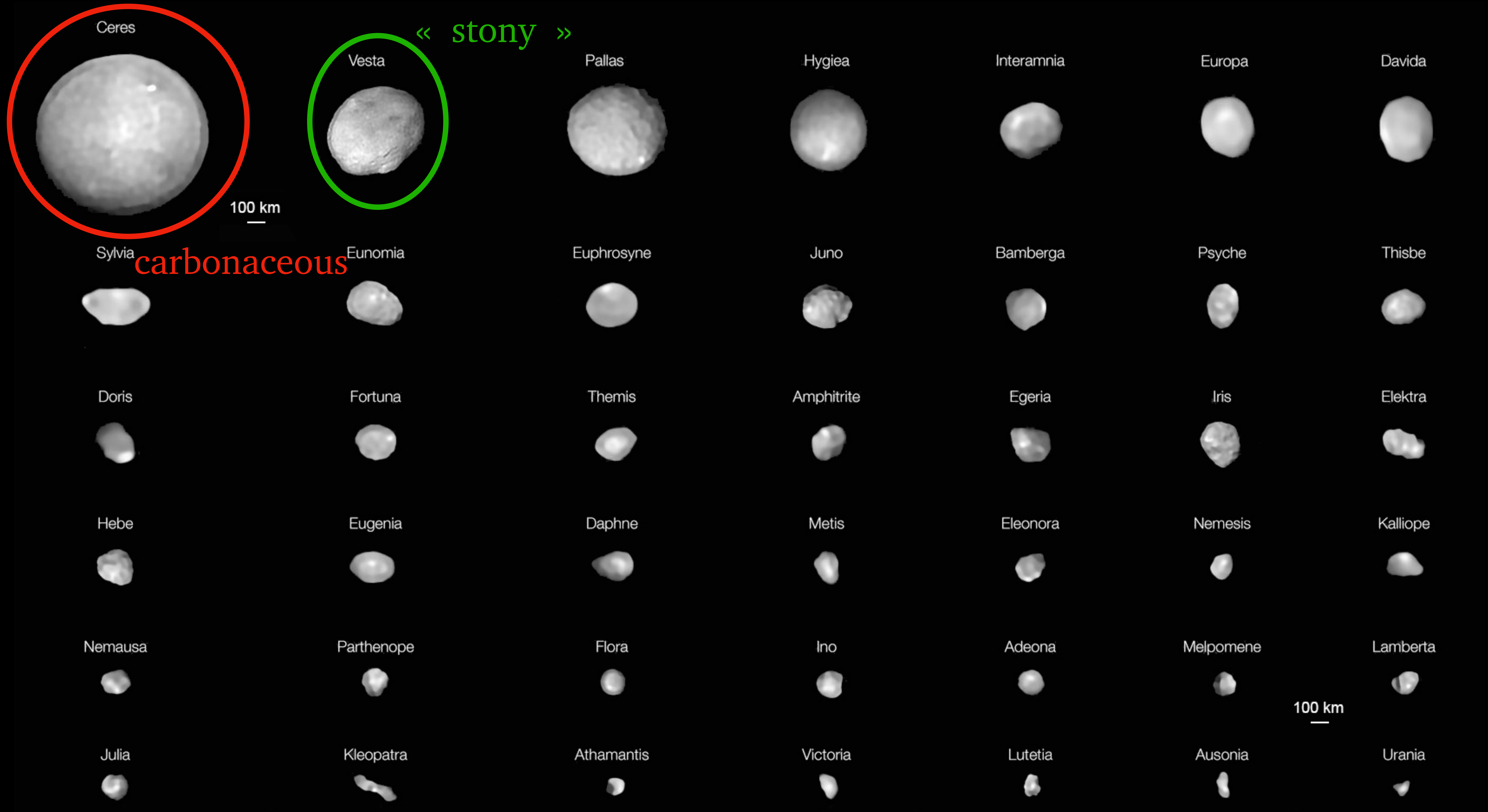
ANR
AGENCE NATIONALE DE LA RECHERCHE
ANR Origins

06/03/2024

Introduction

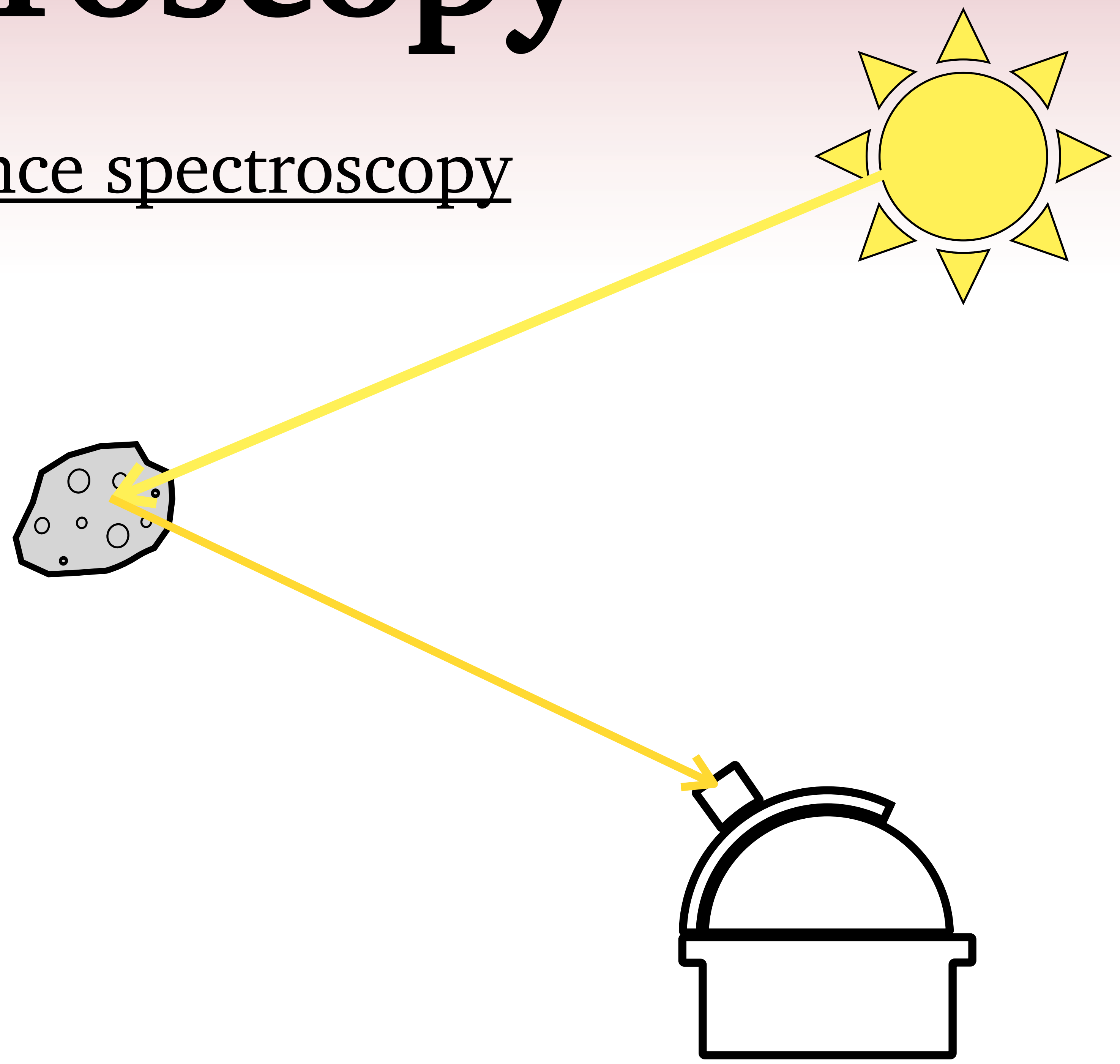
➡ Asteroids: what is left of the planetesimals, building blocks of planets.

VLT/SPHERE images of the 42 asteroids with D>210 km (Vernazza+2021)



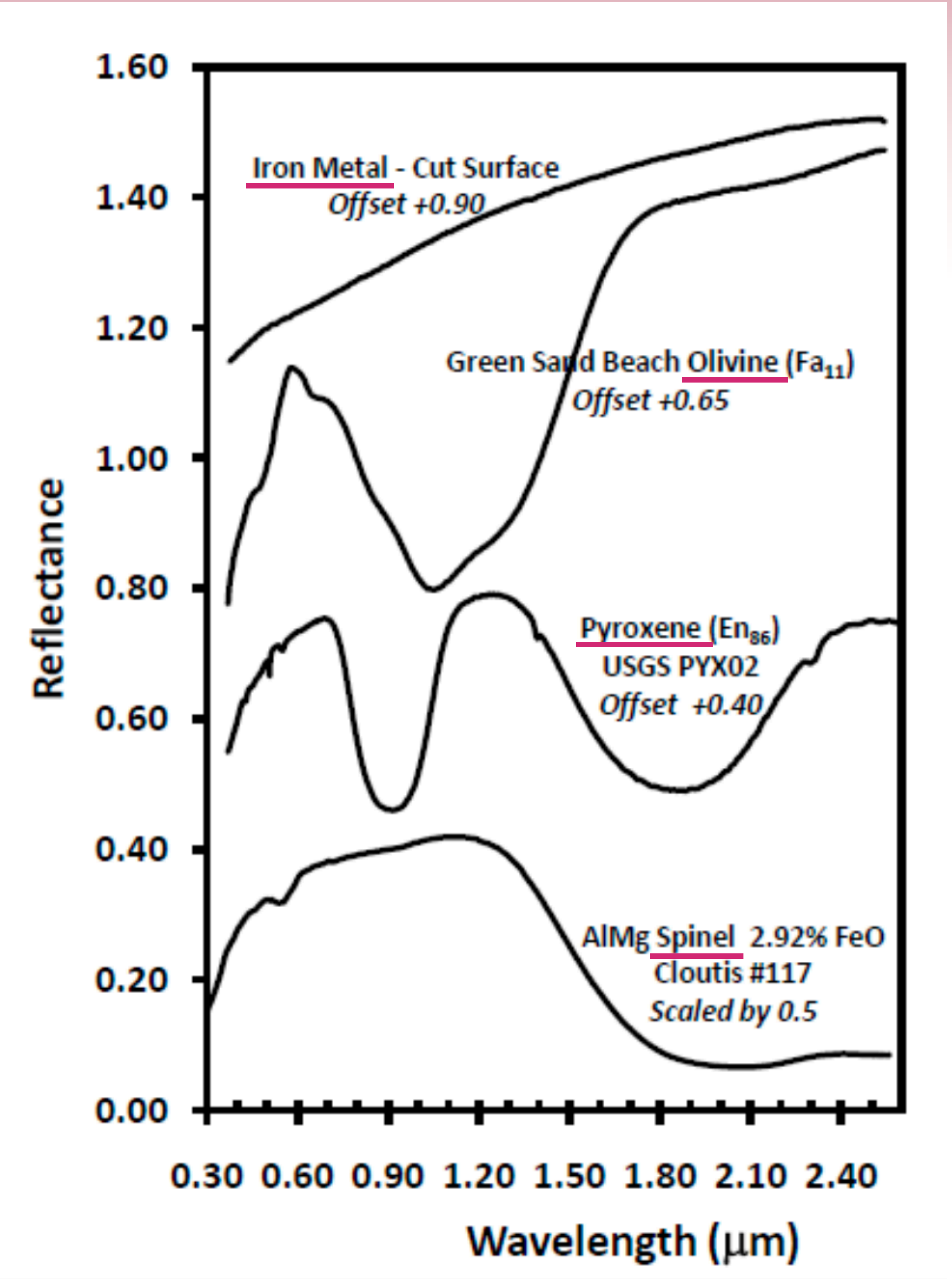
Spectroscopy

- Reflectance spectroscopy



- Spectrum characteristic of the mineralogic composition of objects

➡ **Powerful tool to probe the composition of asteroids surfaces**



Credit figure : Gaffey et al. 2011, Fig.3

The evolution of taxonomy

Chapman et al. 1975:

- Dataset: 110 asteroids
- Observables:
  - **polarimetry** over a range of solar phase angle
  - broad-band IR **radiometry**
  - **VISNIR spectrophotometry**
  - **albedo**

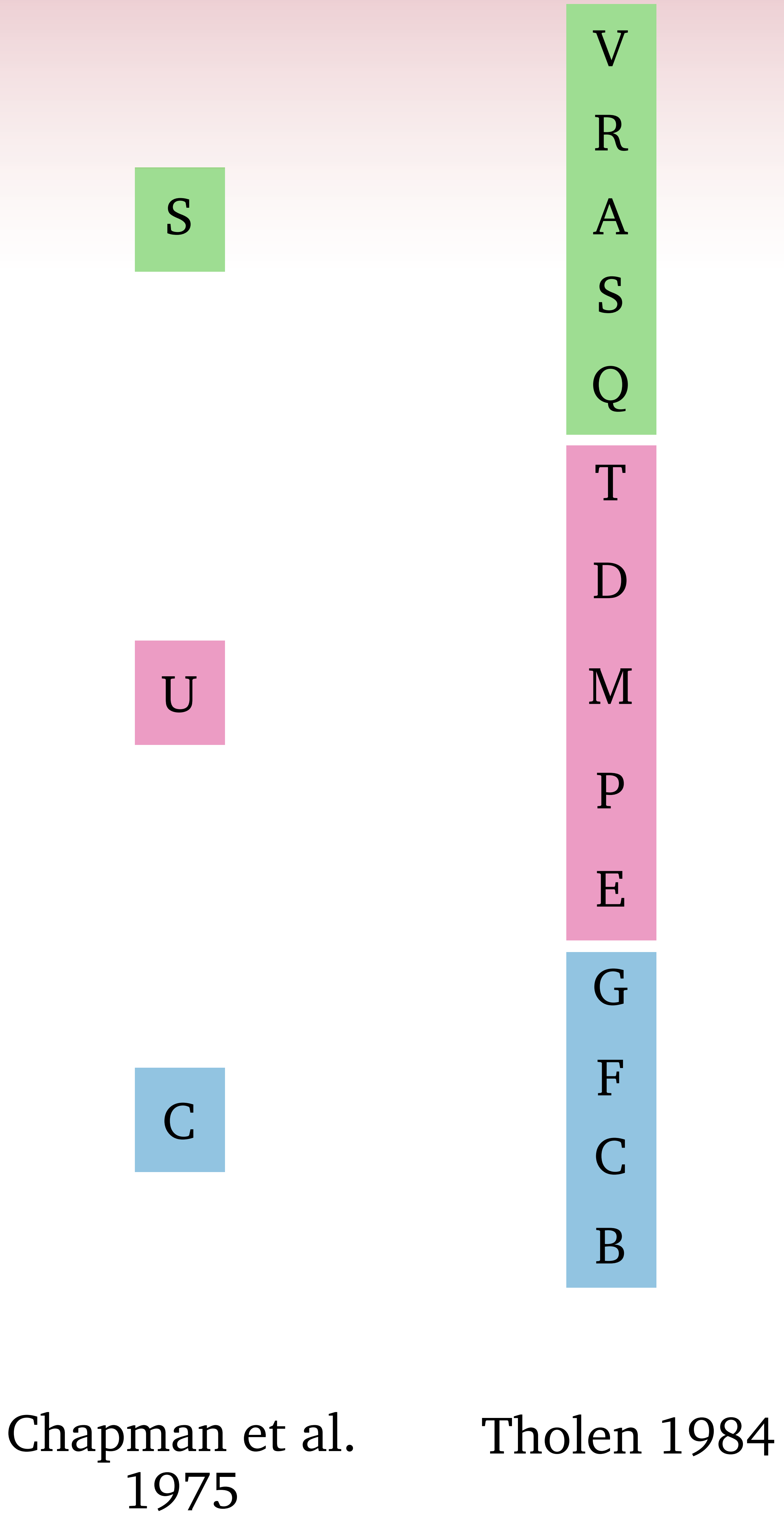
➡ More than 90 % of minor planets fall into 2 broad compositional groups: C and S

S ➡ stony

U

C ➡ carbonaceous

Chapman et al.
1975



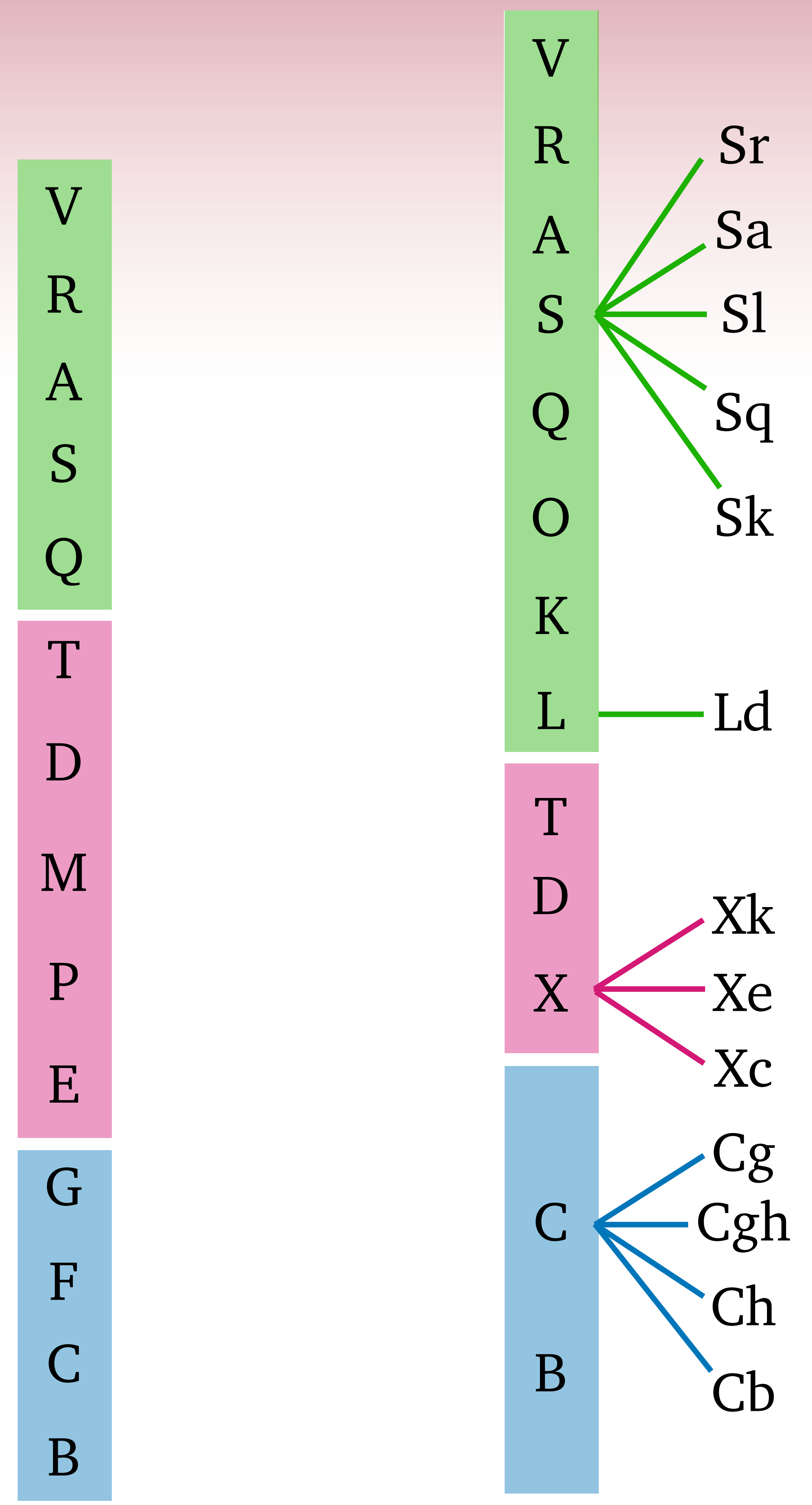
Tholen 1984:

- Dataset: 589 objects - 405 to define the taxonomy
- Observables:
  - **broad band photometry** based on the Eight-Color Asteroid Survey (ECAS), 0.3 to 1.1 microns wavelength range
  - **albedo** from the thermal radiometric survey

➡ 14 classes

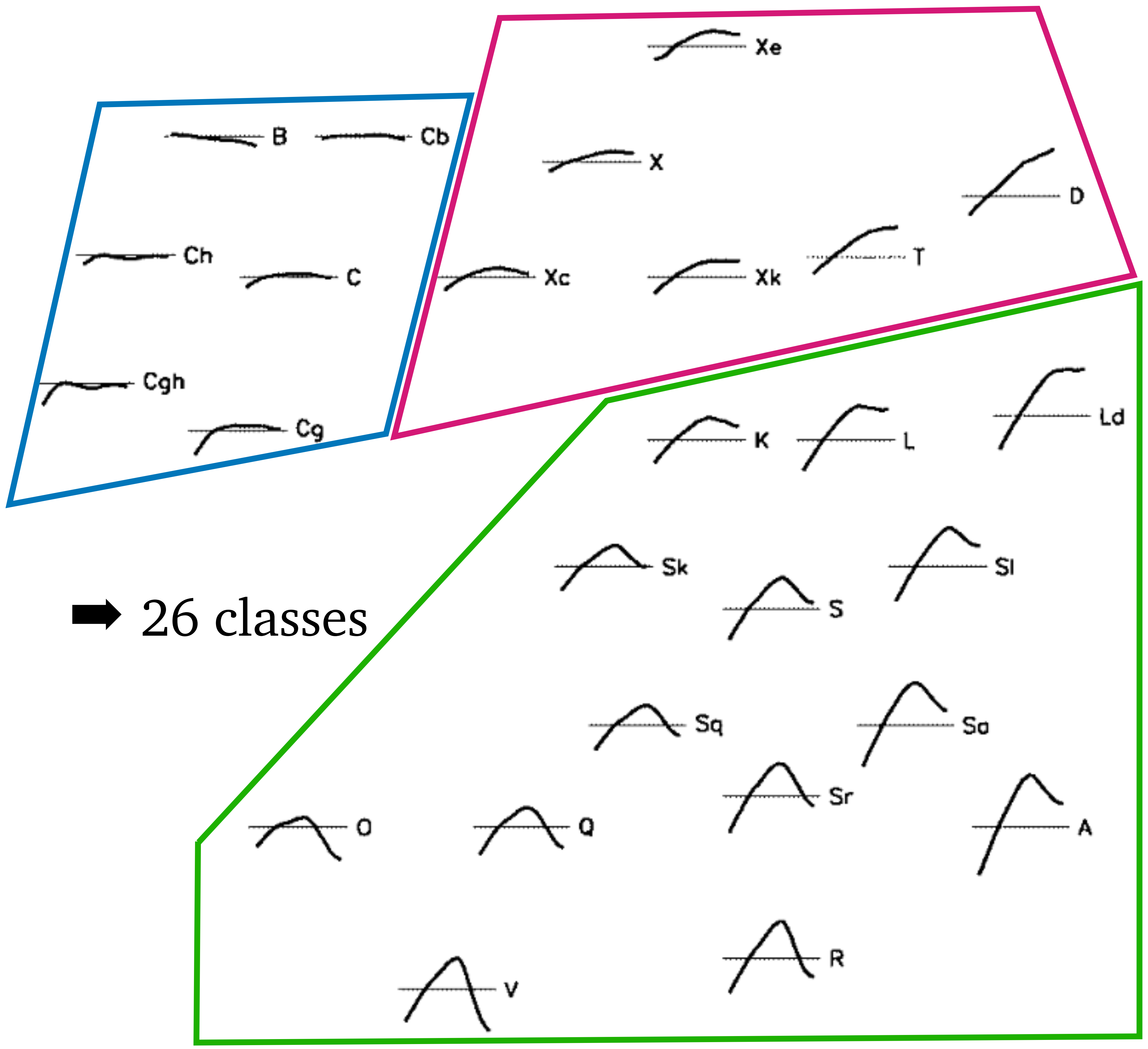
Bus & Binzel 2002

- Dataset: 1447 objects
- Observables: **VIS spectroscopy** from the Small Main belt Asteroid Spectroscopic Survey (SMASS)

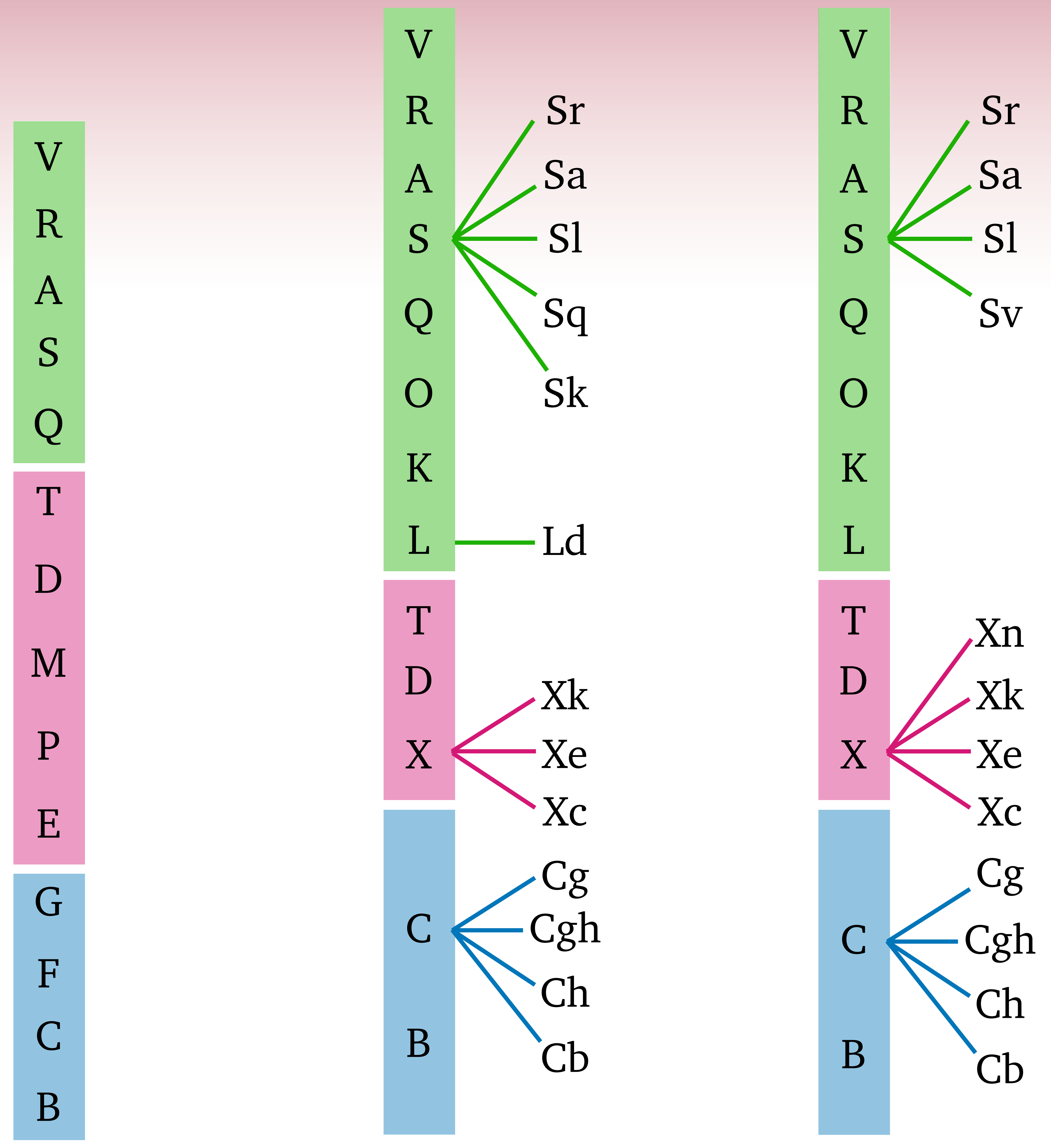


Tholen 1984

Bus & Binzel 2002



➡ 26 classes



Tholen 1984

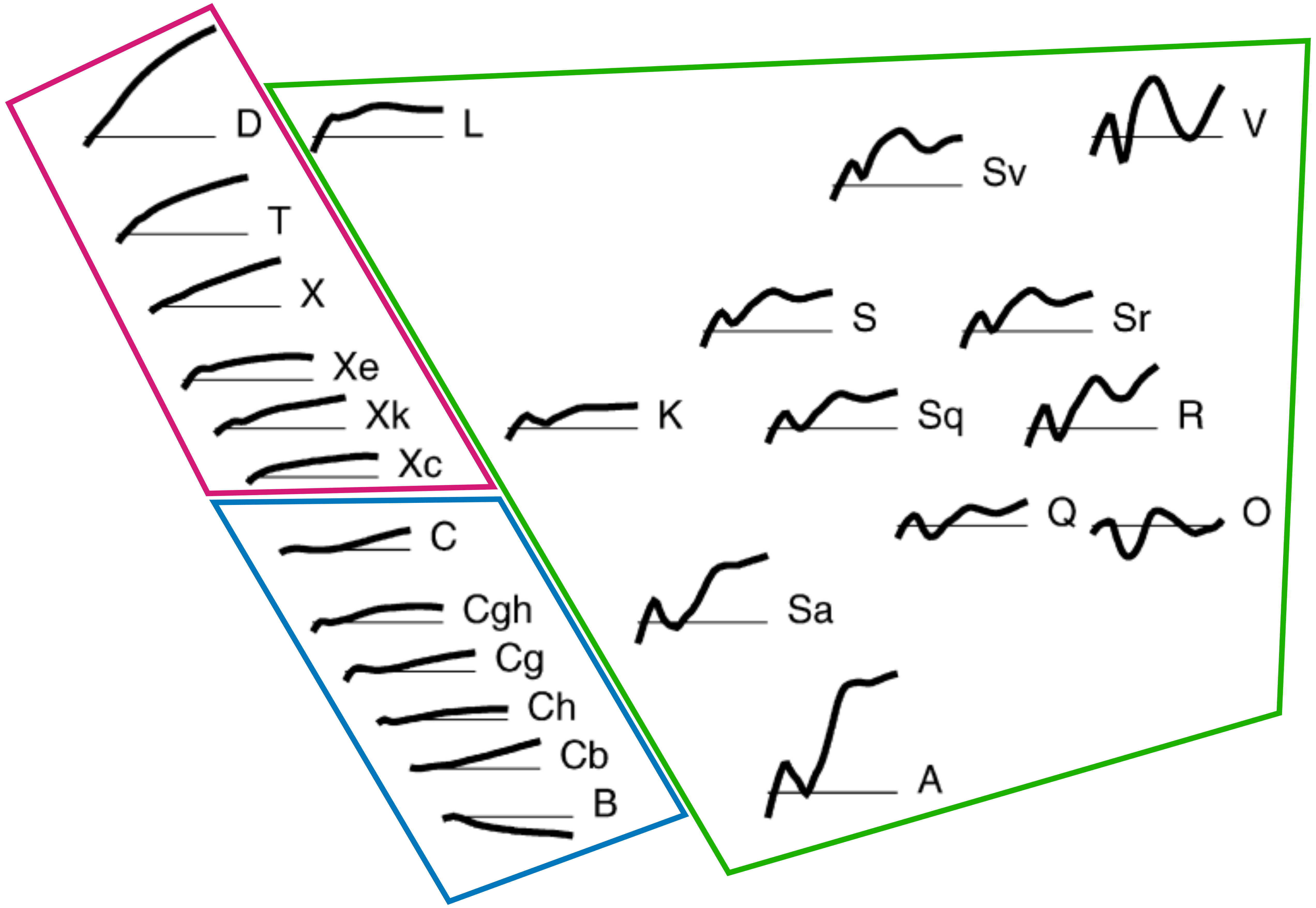
Bus & Binzel 2002

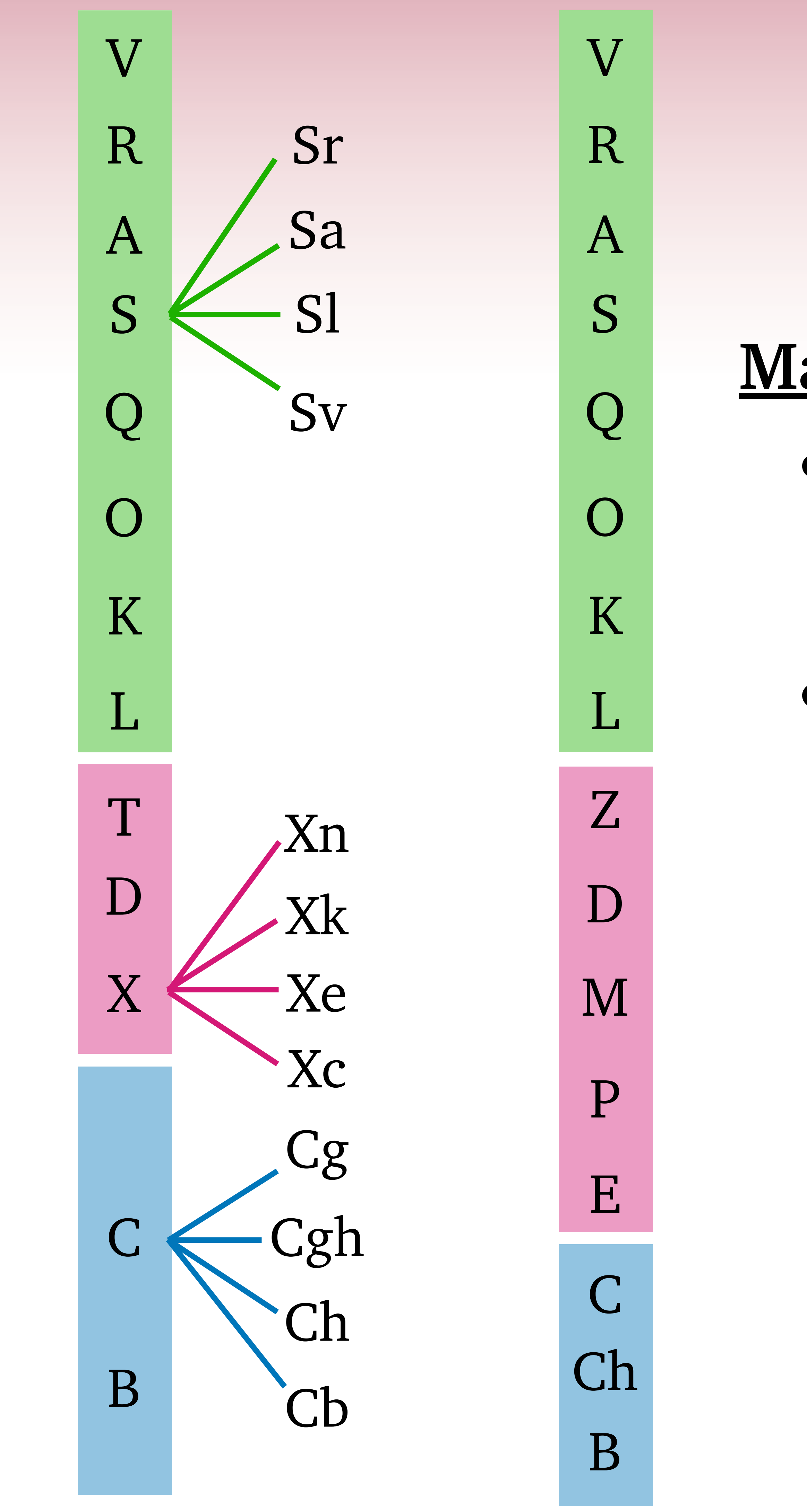
DeMeo et al. 2009

DeMeo et al. 2009

- Dataset: 371 objects
- Observables: **VISNIR spectroscopy**

➡ 24 classes





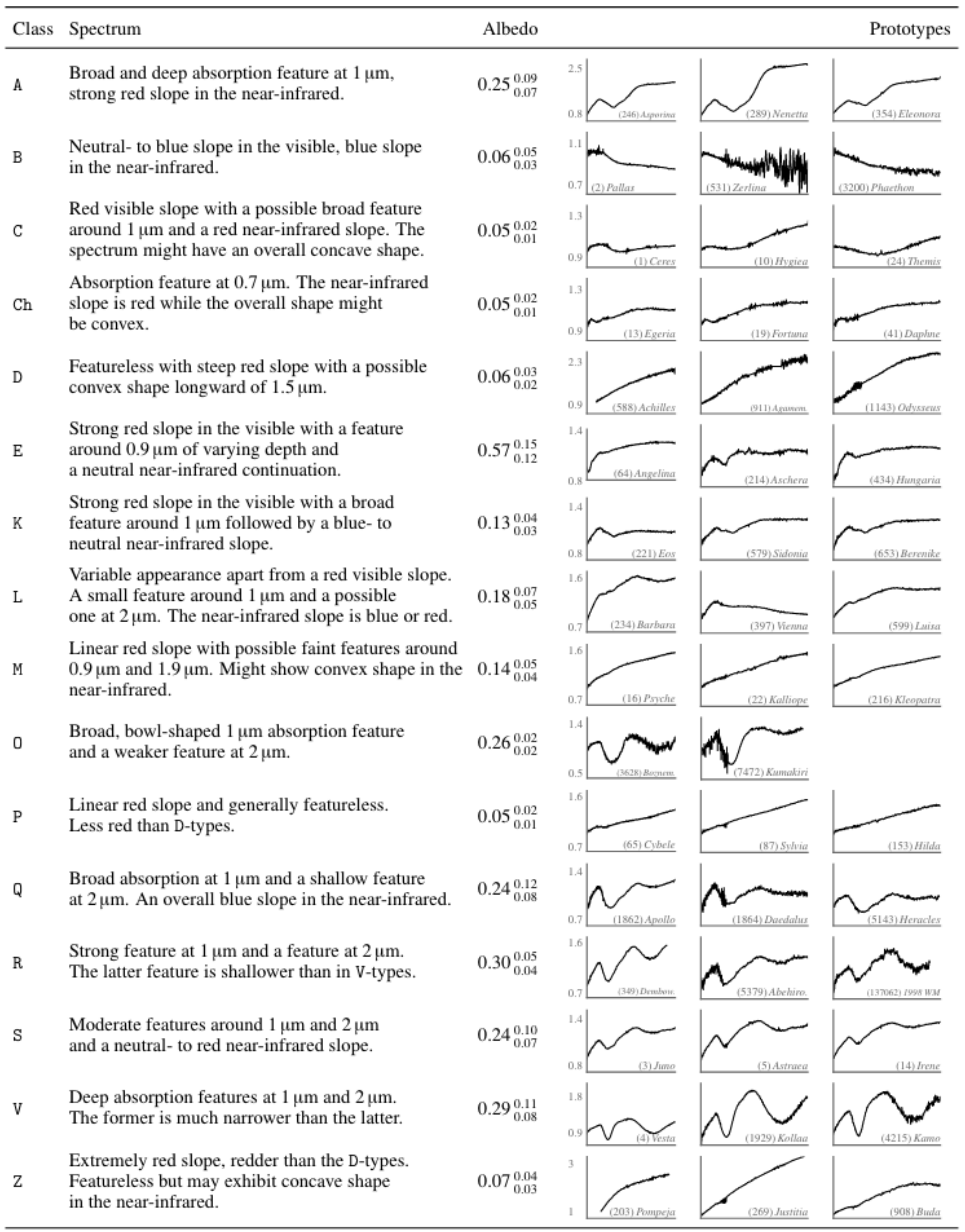
DeMeo et al. 2009

Mahlke et al. 2022

Mahlke et al. 2022

- Dataset: 2983 observations of 2125 asteroids
- Observables:
  - **VIS, NIR, and VISNIR spectroscopy**
  - **albedo**

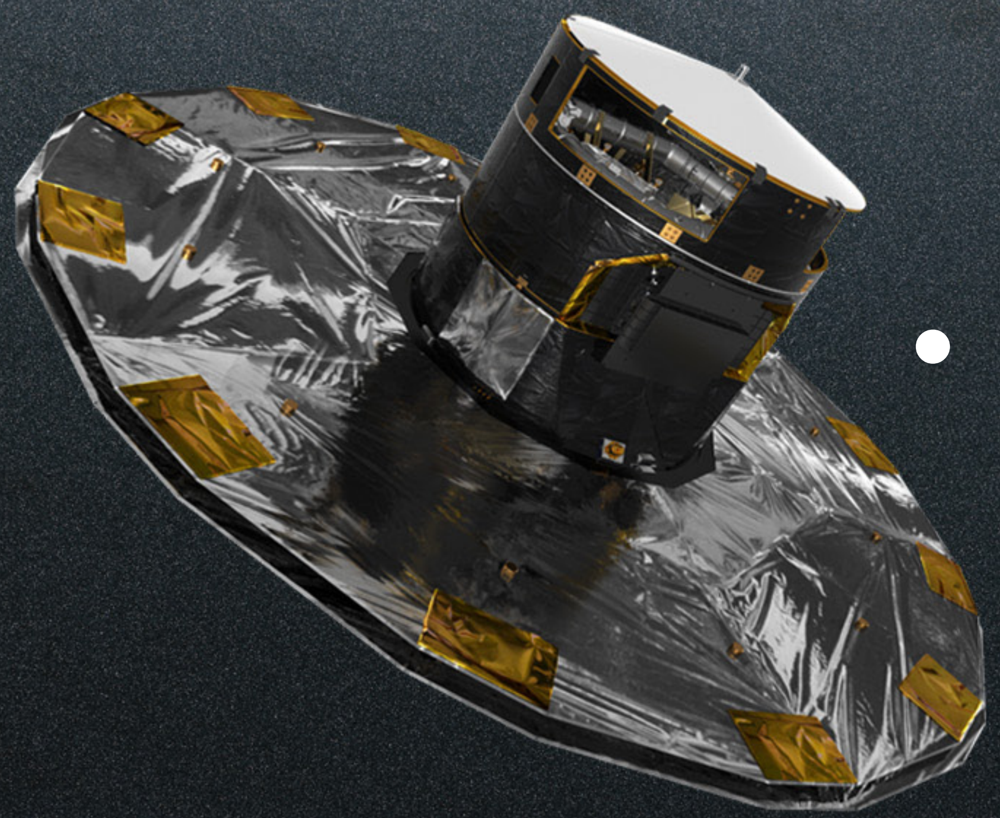
  ➡ 17 classes



Class	Spectrum	Albedo	Prototypes
A	Broad and deep absorption feature at 1 µm, strong red slope in the near-infrared.	$0.25^{0.09}_{0.07}$	(246) Asporina, (289) Nenetta, (354) Eleonora
B	Neutral- to blue slope in the visible, blue slope in the near-infrared.	$0.06^{0.05}_{0.03}$	(2) Pallas, (531) Zerlina, (3200) Phaethon
C	Red visible slope with a possible broad feature around 1 µm and a red near-infrared slope. The spectrum might have an overall concave shape.	$0.05^{0.02}_{0.01}$	(1) Ceres, (10) Hygiea, (24) Themis
Ch	Absorption feature at 0.7 µm. The near-infrared slope is red while the overall shape might be convex.	$0.05^{0.02}_{0.01}$	(13) Egeria, (19) Fortuna, (41) Daphne
D	Featureless with steep red slope with a possible convex shape longward of 1.5 µm.	$0.06^{0.03}_{0.02}$	(588) Achilles, (911) Agamem., (1143) Odysseus
E	Strong red slope in the visible with a feature around 0.9 µm of varying depth and a neutral near-infrared continuation.	$0.57^{0.15}_{0.12}$	(64) Angelina, (214) Aschera, (434) Hungaria
K	Strong red slope in the visible with a broad feature around 1 µm followed by a blue- to neutral near-infrared slope.	$0.13^{0.04}_{0.03}$	(221) Eos, (579) Sidonia, (653) Berenike
L	Variable appearance apart from a red visible slope. A small feature around 1 µm and a possible one at 2 µm. The near-infrared slope is blue or red.	$0.18^{0.07}_{0.05}$	(234) Barbara, (397) Vienna, (599) Luisa
M	Linear red slope with possible faint features around 0.9 µm and 1.9 µm. Might show convex shape in the near-infrared.	$0.14^{0.05}_{0.04}$	(16) Psyche, (22) Kalliope, (216) Kleopatra
O	Broad, bowl-shaped 1 µm absorption feature and a weaker feature at 2 µm.	$0.26^{0.02}_{0.02}$	(3628) Boznem., (7472) Kumakiri
P	Linear red slope and generally featureless. Less red than D-types.	$0.05^{0.02}_{0.01}$	(65) Cybele, (87) Sylvia, (153) Hilda
Q	Broad absorption at 1 µm and a shallow feature at 2 µm. An overall blue slope in the near-infrared.	$0.24^{0.12}_{0.08}$	(1862) Apollo, (1864) Daedalus, (5143) Heracles
R	Strong feature at 1 µm and a feature at 2 µm. The latter feature is shallower than in V-types.	$0.30^{0.05}_{0.04}$	(349) Dembow., (5379) Abehiro., (137062) 1998 WM
S	Moderate features around 1 µm and 2 µm and a neutral- to red near-infrared slope.	$0.24^{0.10}_{0.07}$	(3) Juno, (5) Astraea, (14) Irene
V	Deep absorption features at 1 µm and 2 µm. The former is much narrower than the latter.	$0.29^{0.11}_{0.08}$	(4) Vesta, (1929) Kollaa, (4215) Kamo
Z	Extremely red slope, redder than the D-types. Featureless but may exhibit concave shape in the near-infrared.	$0.07^{0.04}_{0.03}$	(203) Pompeja, (269) Justitia, (908) Buda

The *Gaia* mission

- ESA **astrometric** mission, launched in December 2013
- Objective: improve our knowledge of the structure, the formation and the evolution of the Milky Way
- Practical goals: measure the position, distance and motion of more than a billion of objects (stars, galaxies, asteroids…).
- Magnitude limit: 21



- 3 instruments

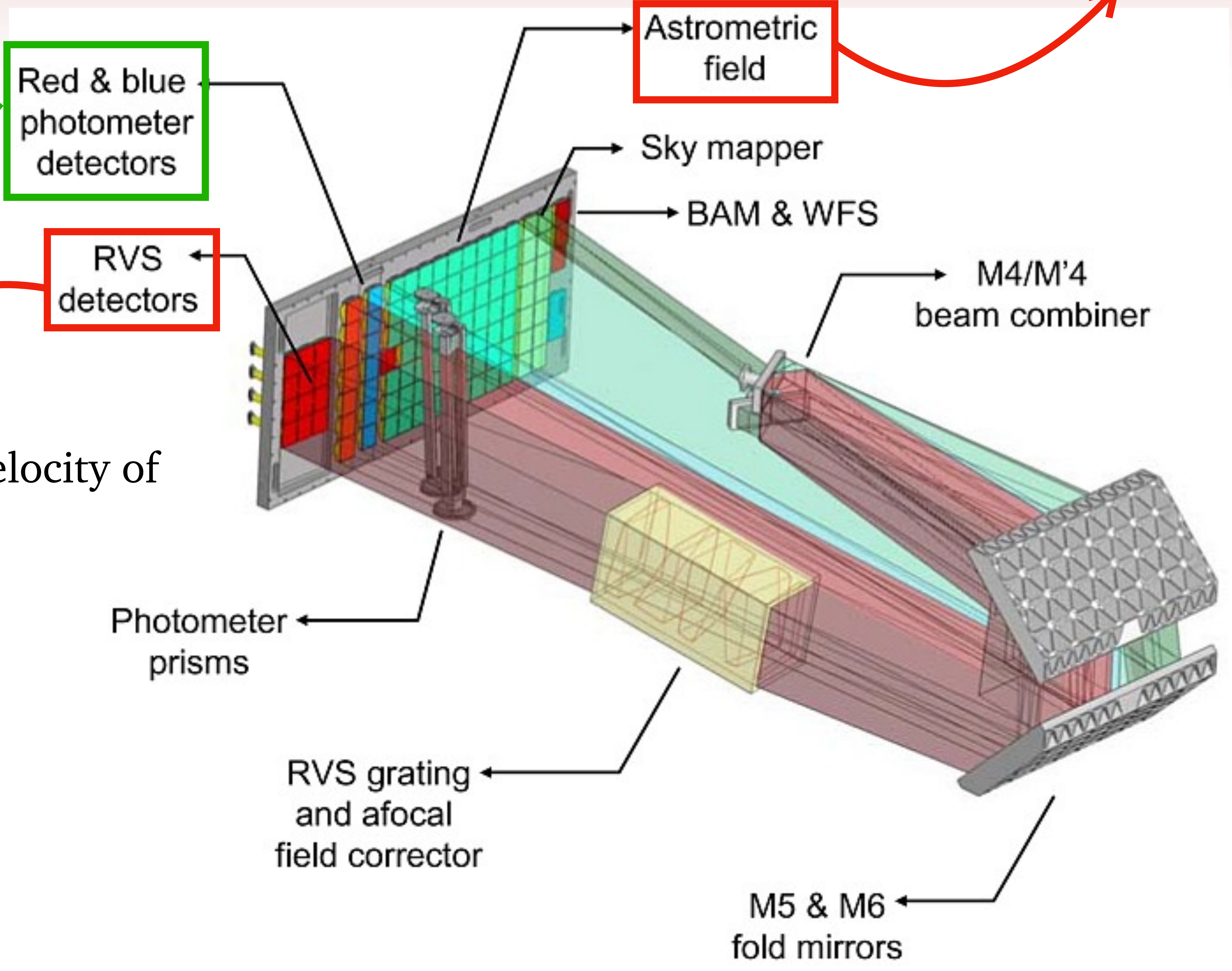
The *Gaia* mission

- **3 instruments**

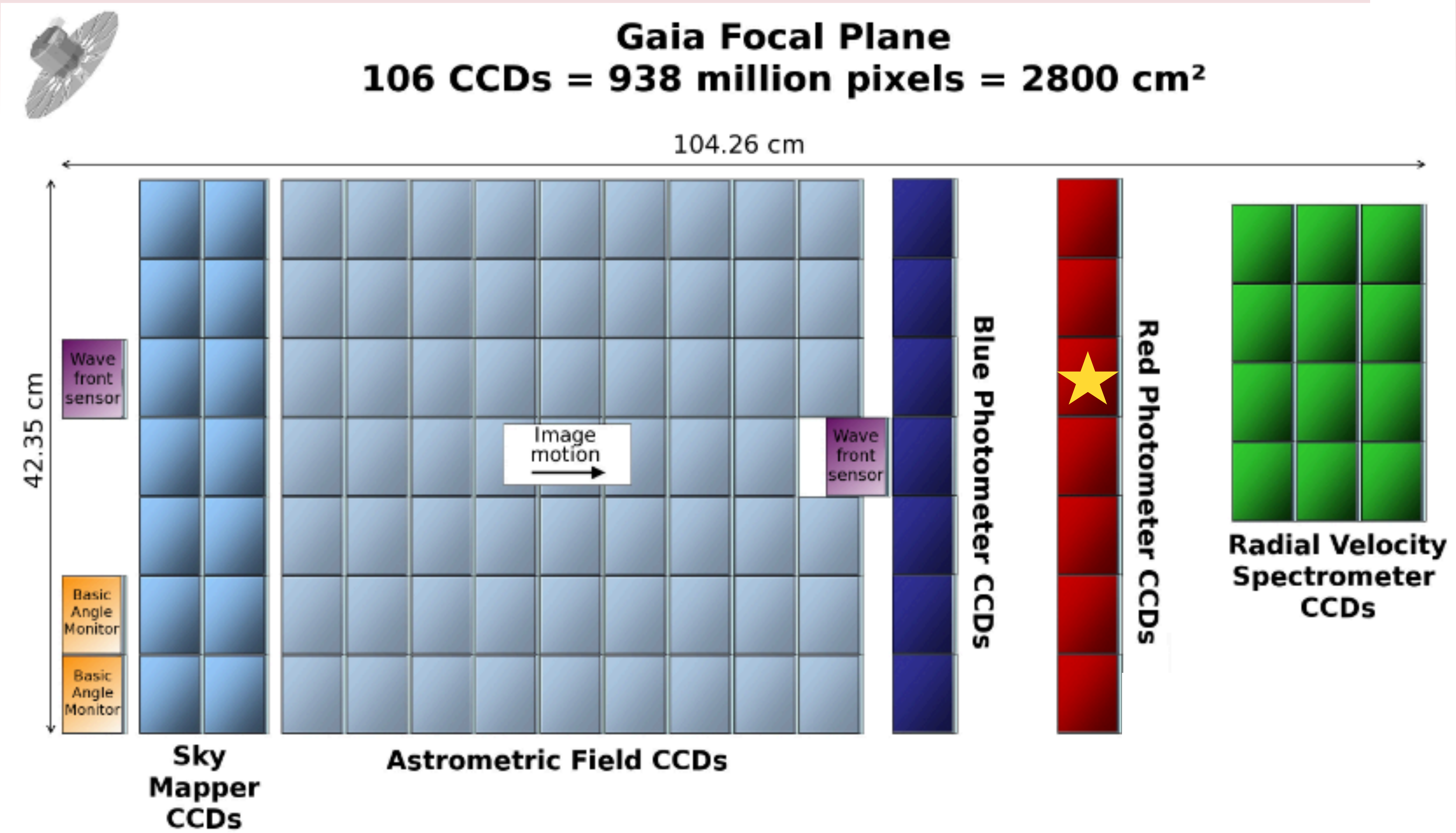
collect the light of objects in 2 distinct spectral bands

compute the radial velocity of the brightest objects

measures the position and proper motion of objects



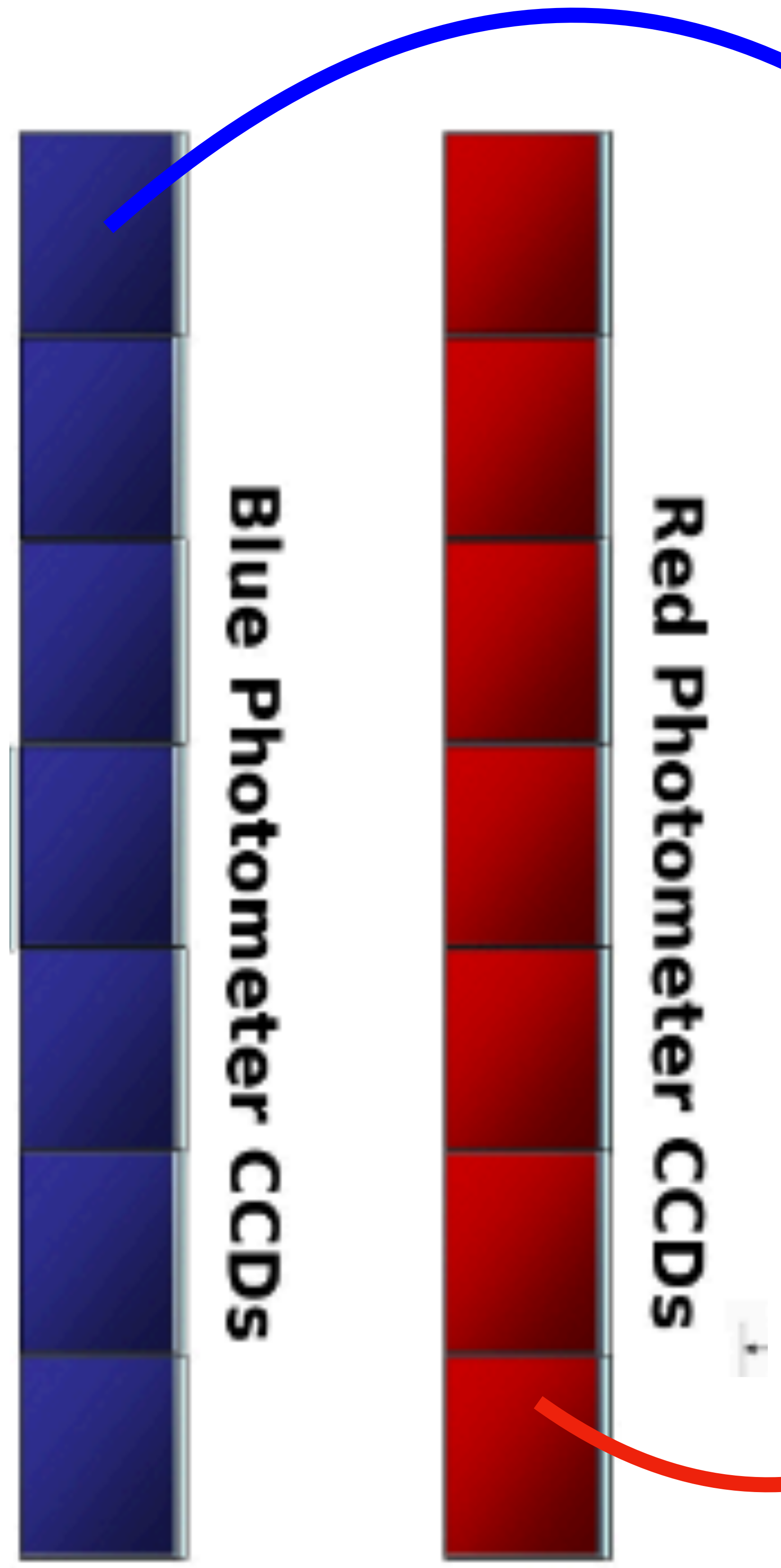
The *Gaia* mission



Credit figure : Carrasco et al. 2021

Production of mean reflectance spectra

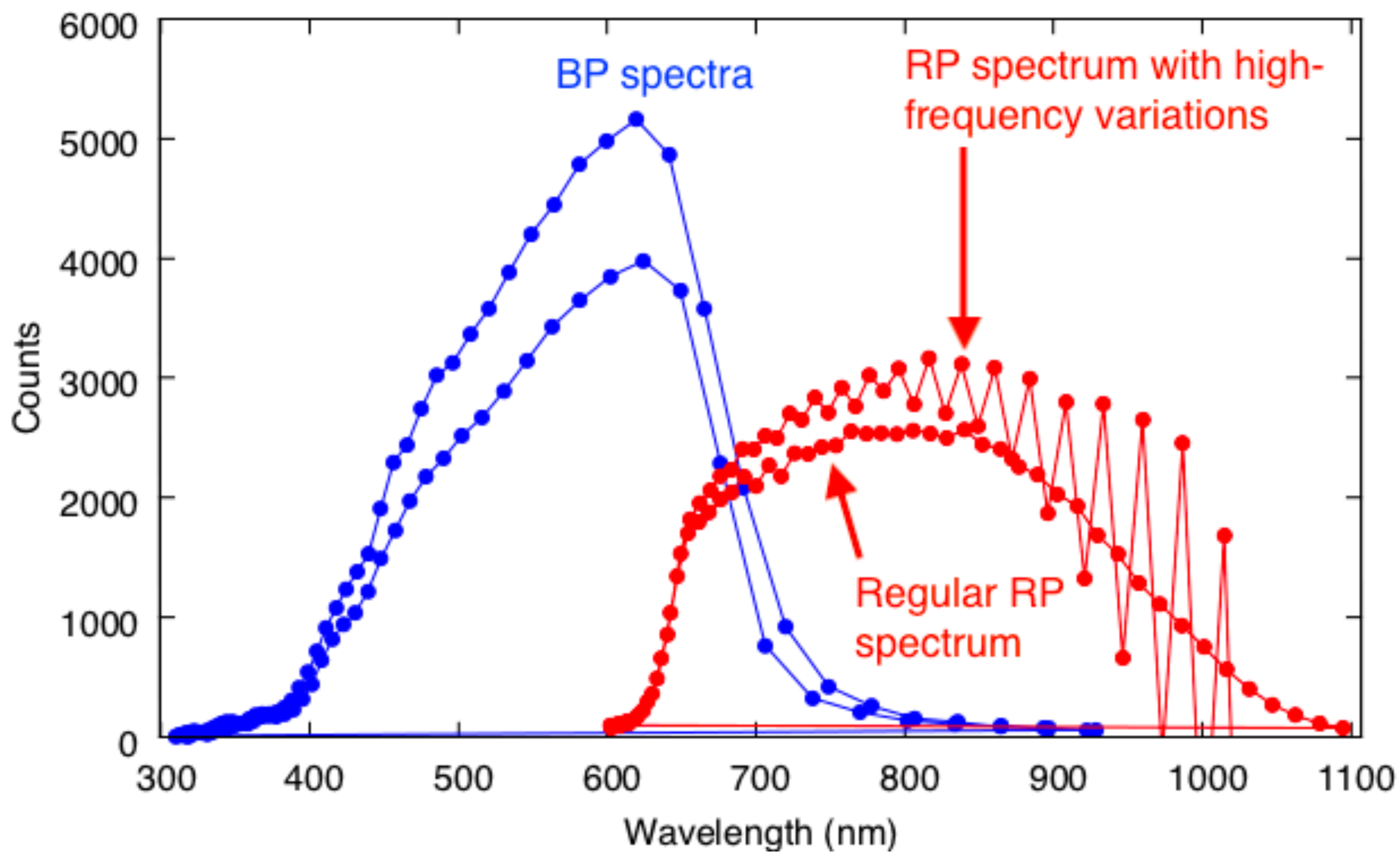
- **Blue and Red photometers**



optimised for the blue part: [330 - 680] nm

optimised for the red part: [640 - 1050] nm

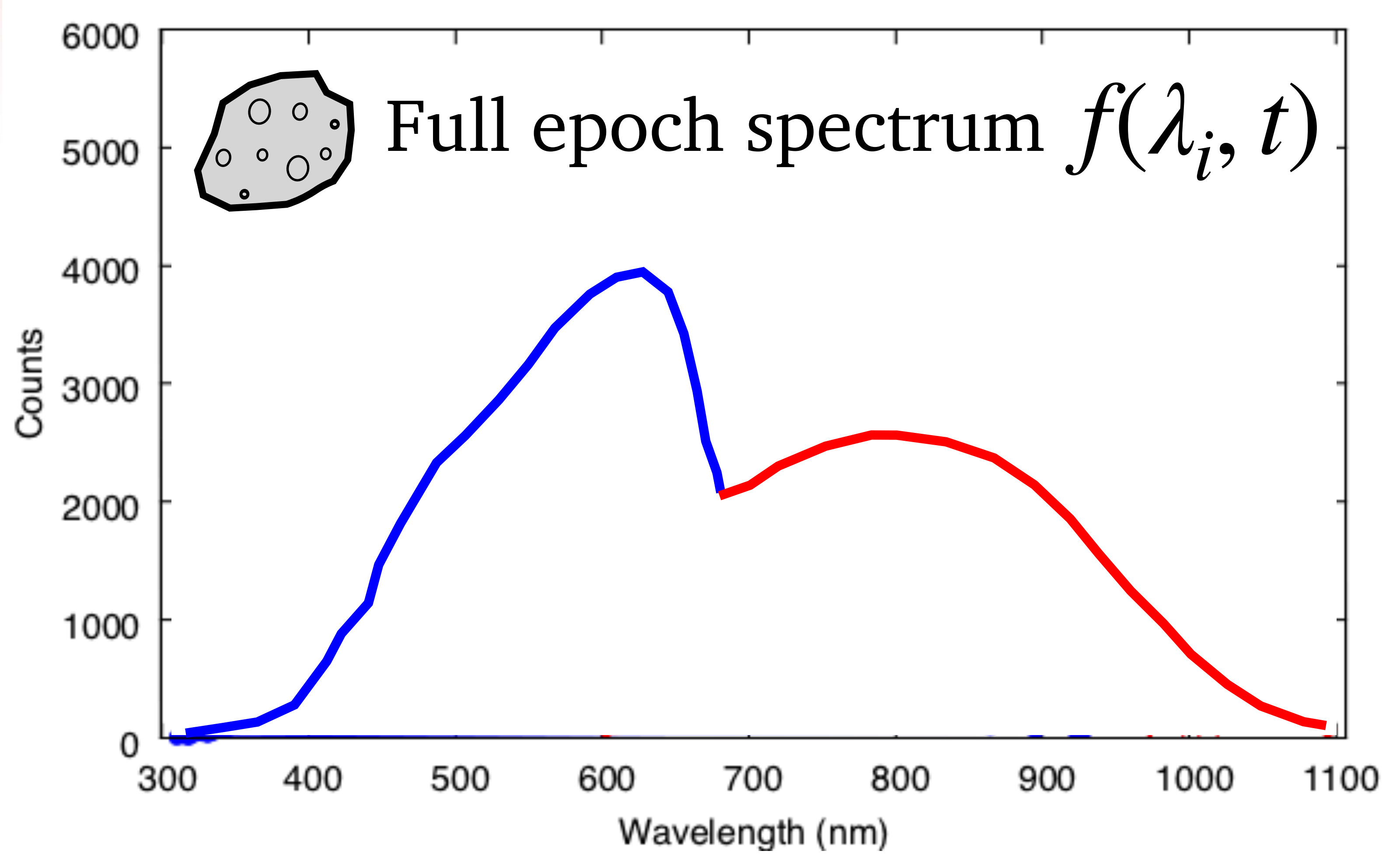
Epoch spectra

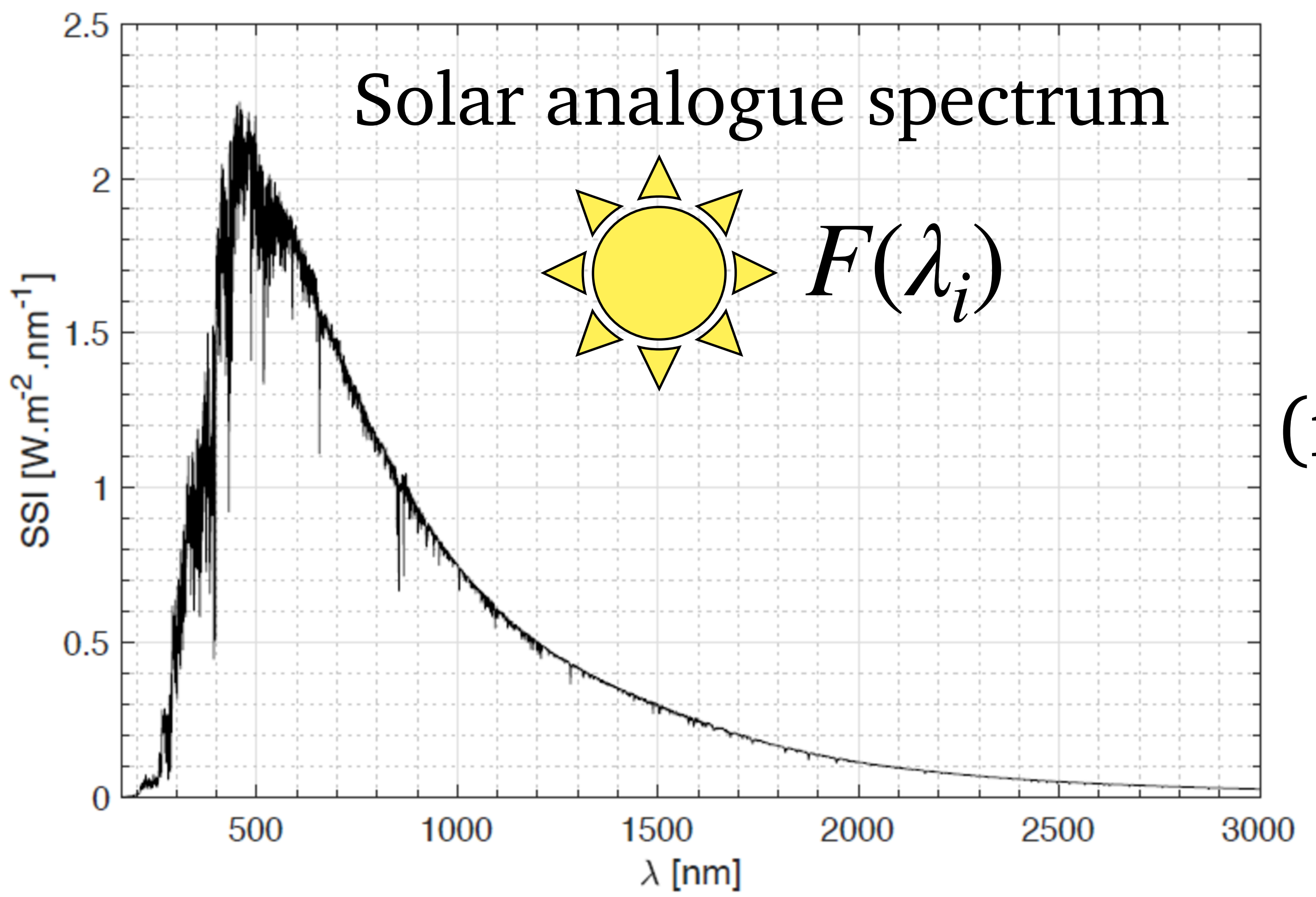


➡ overlap [640 - 680] nm: production of a full epoch spectrum

Credit figure : Gallucio et al., Gaia collaboration 2022

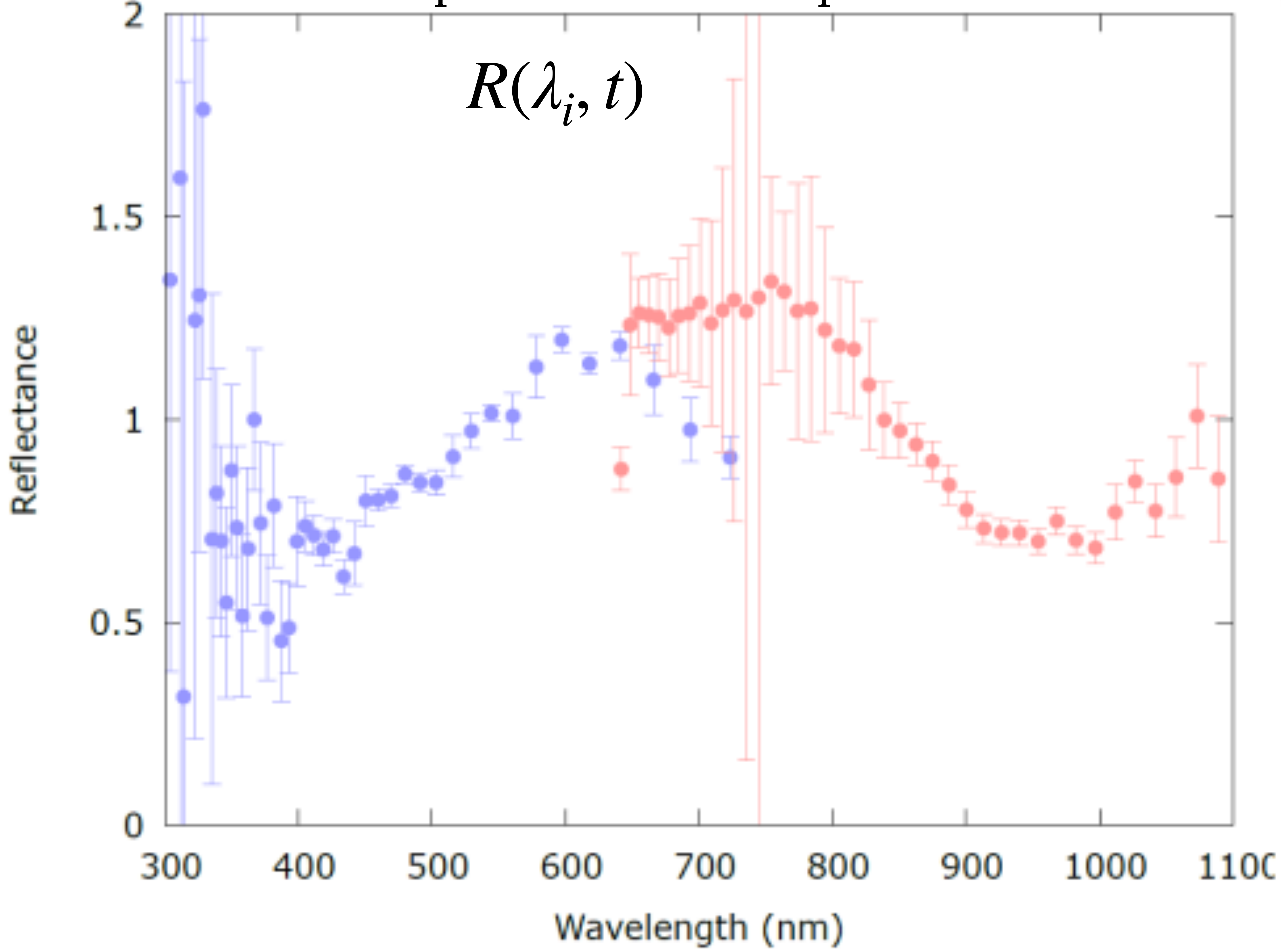
Production of mean reflectance spectra





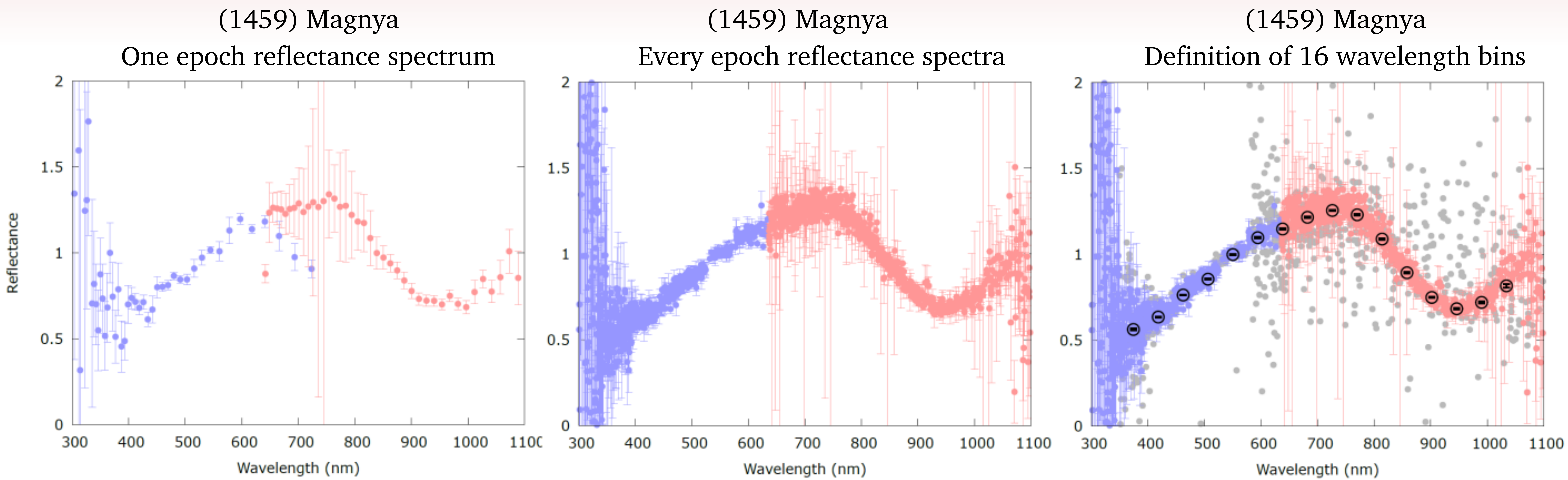
$$R(\lambda_i, t) = \frac{1}{\xi(t)} \frac{f(\lambda_i, t)}{F(\lambda_i)}$$

normalisation factor
(reflectance = 1 at 550 nm)



Credit figure : Gallucio et al., Gaia collaboration 2022

Production of mean reflectance spectra



➡ 16 wavelength bands: [374 - 1034] nm

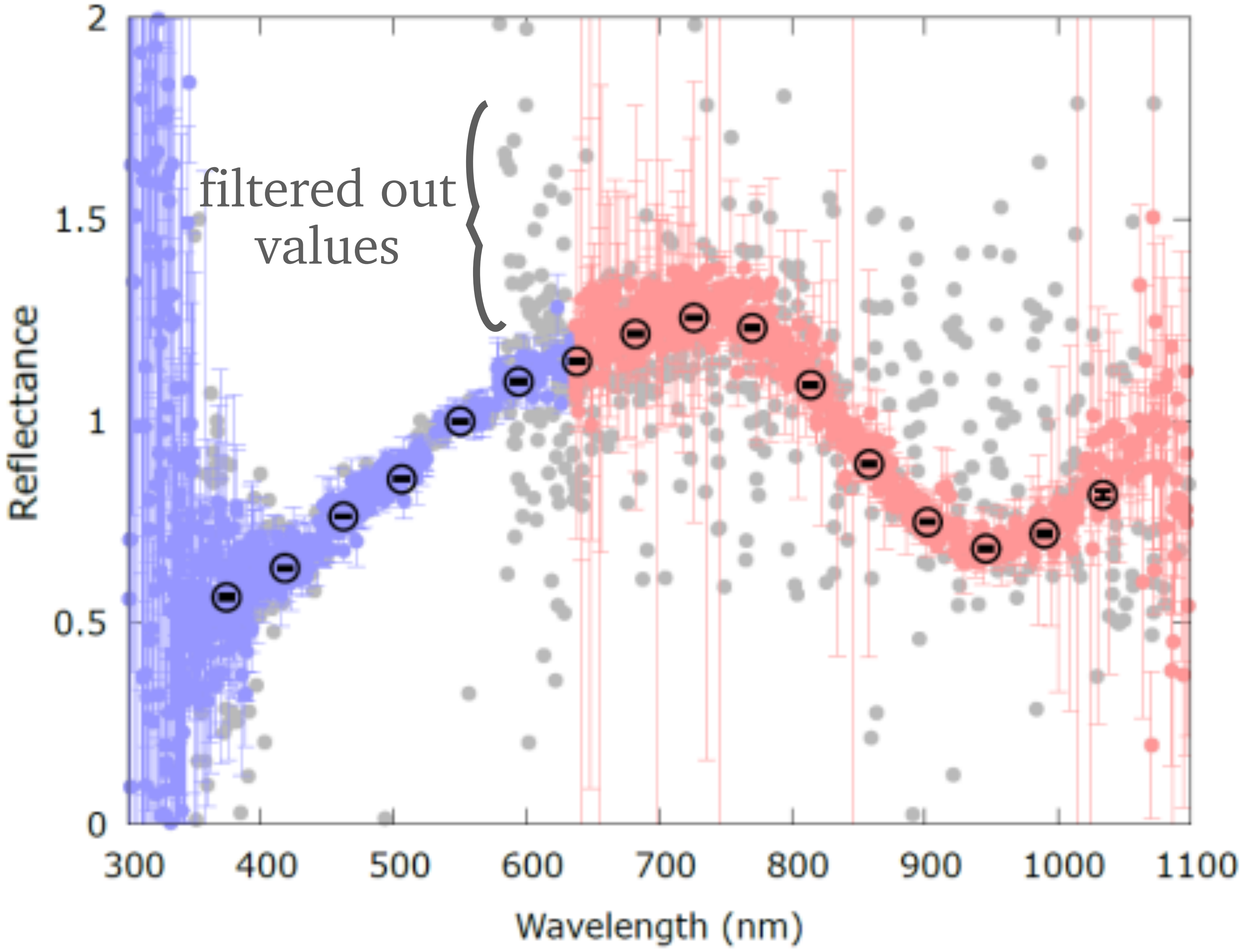
➡ Band every 44 nm, bin large of 44 nm.

Credit figure : Gallucio et al., Gaia collaboration 2022

Production of mean reflectance spectra

(1459) Magnya

Definition of 16 wavelength bins



- **Sigma-clipping**

➡ In each bin, the median reflectance and median absolute deviation MAD were calculated.

➡ **Values outside of [median-2.5MAD, median+2.5MAD] filtered out**

➡ Repeated twice

➡ Minimum number of epoch spectra required to produce a mean spectrum: **3**

➡ **Most objects have around 15 epoch spectra**

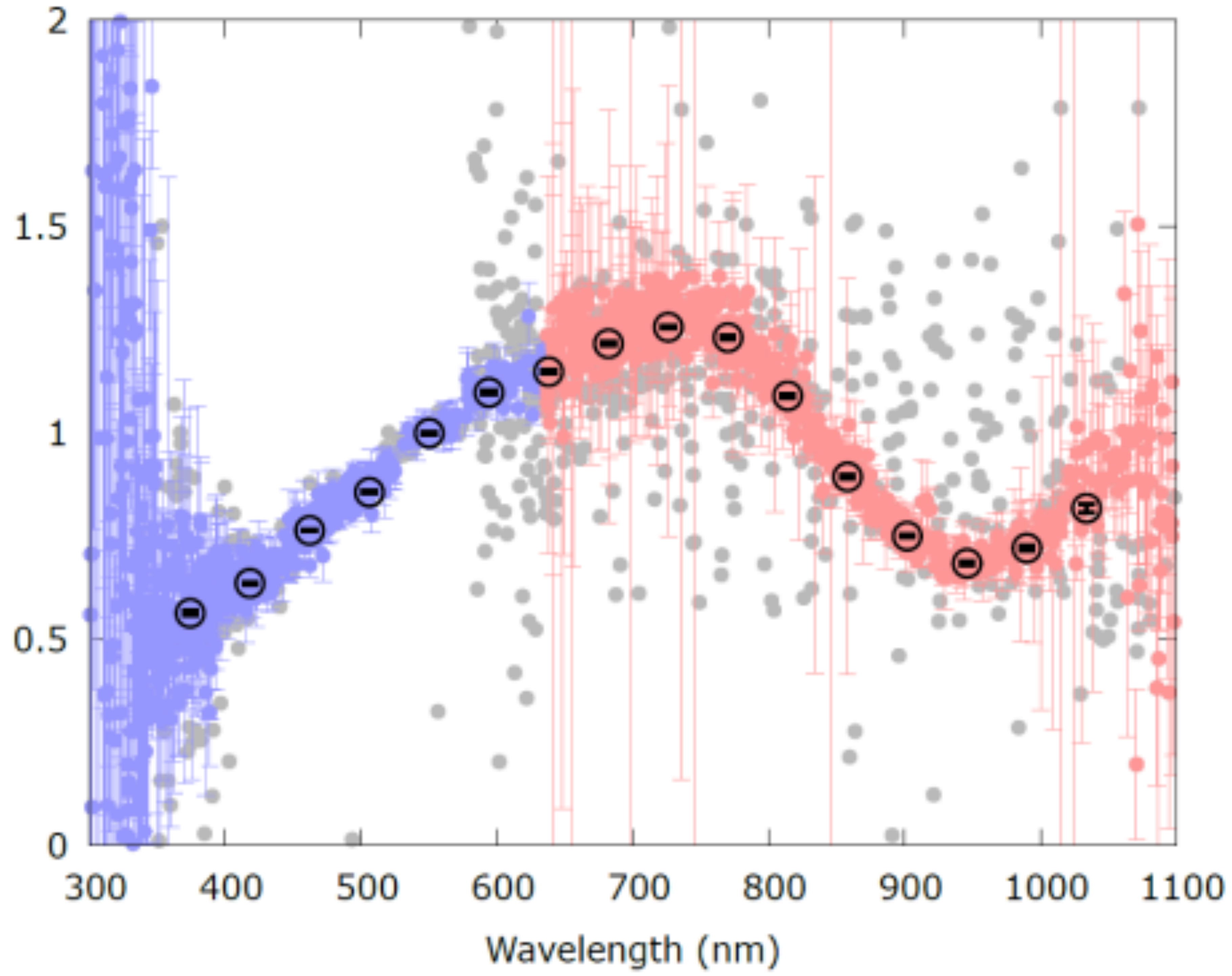
Credit figure : Gallucio et al., Gaia collaboration 2022

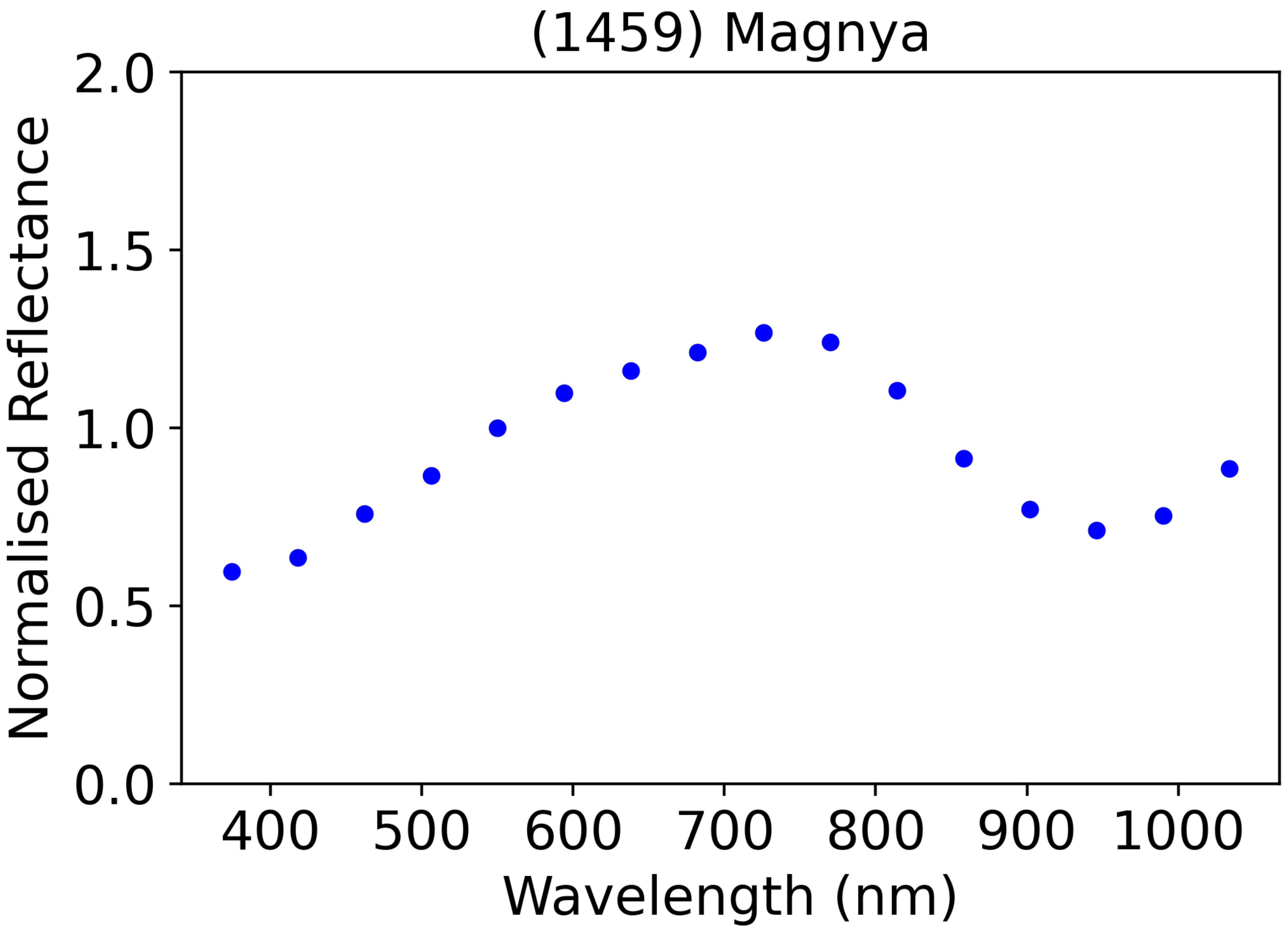
Production of mean reflectance spectra

- <u>**Mean reflectance spectrum**</u>

➡ In each bin, **weighted mean** of the filtered $R(\lambda_i, t)$

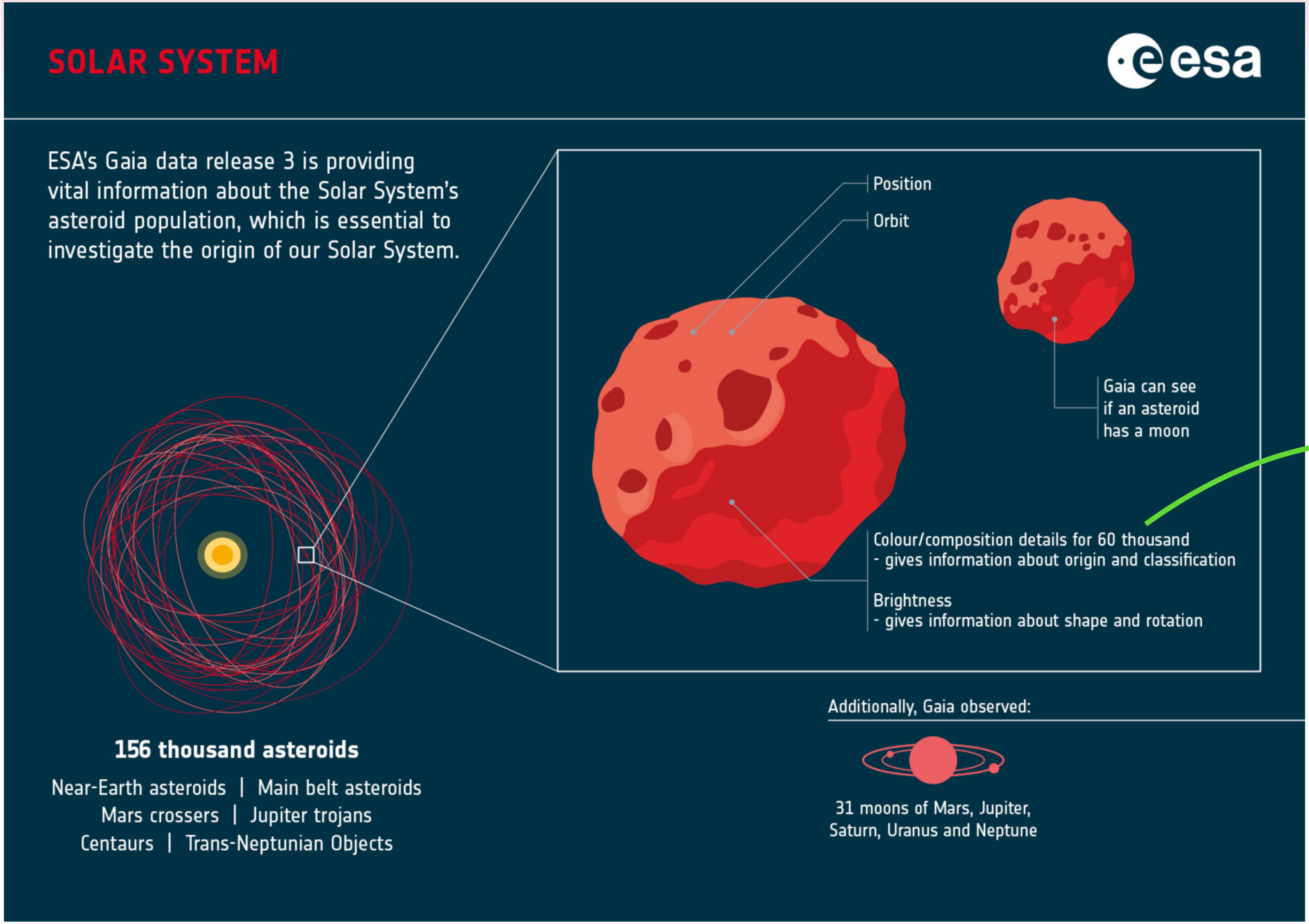
➡ **Normalisation** at 550 nm





Credit figure : Gallucio et al., Gaia collaboration 2022

Gaia Data Release 3

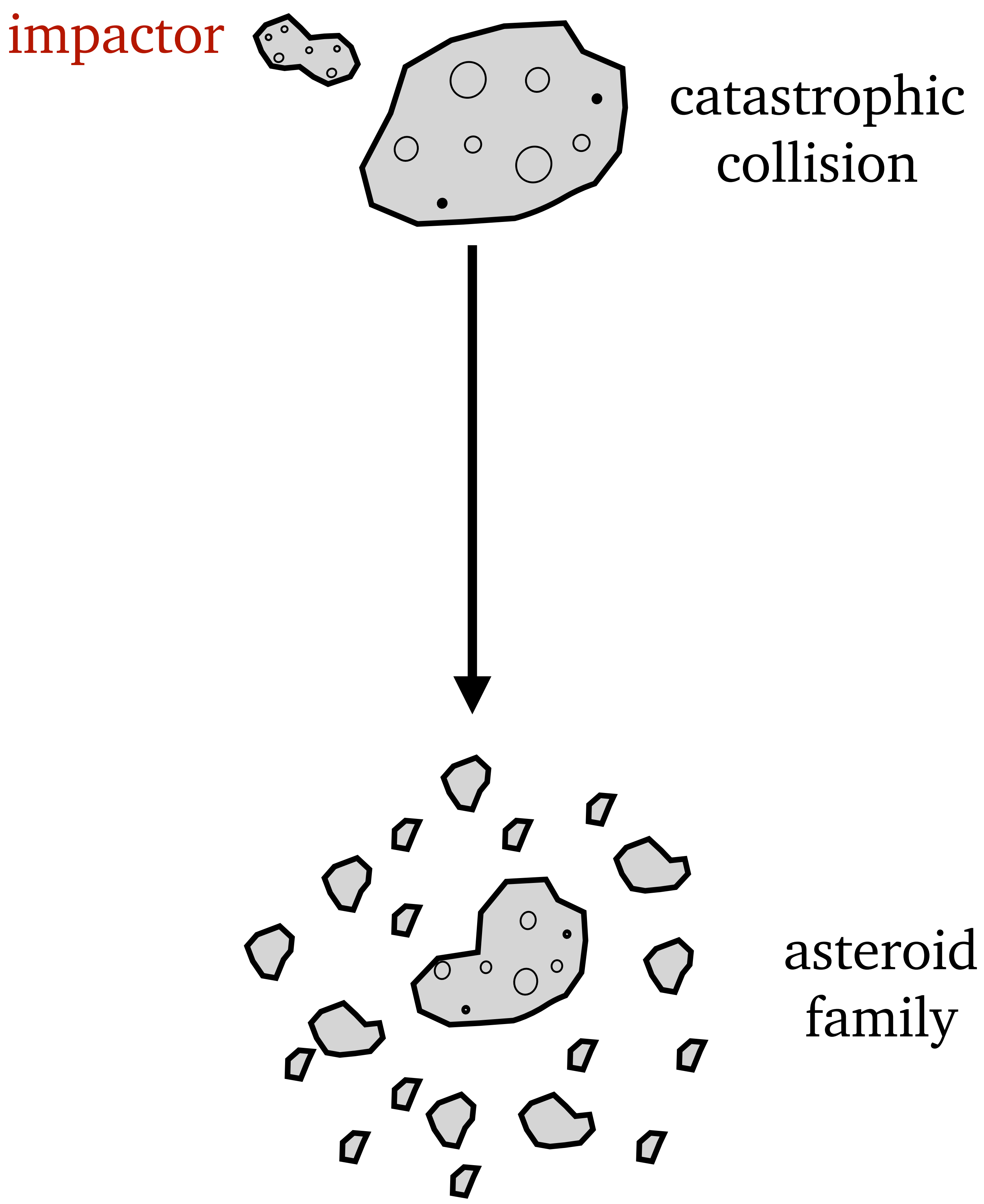


- Released June, 13 2022
- Almost 3 years of data (2014-2017)

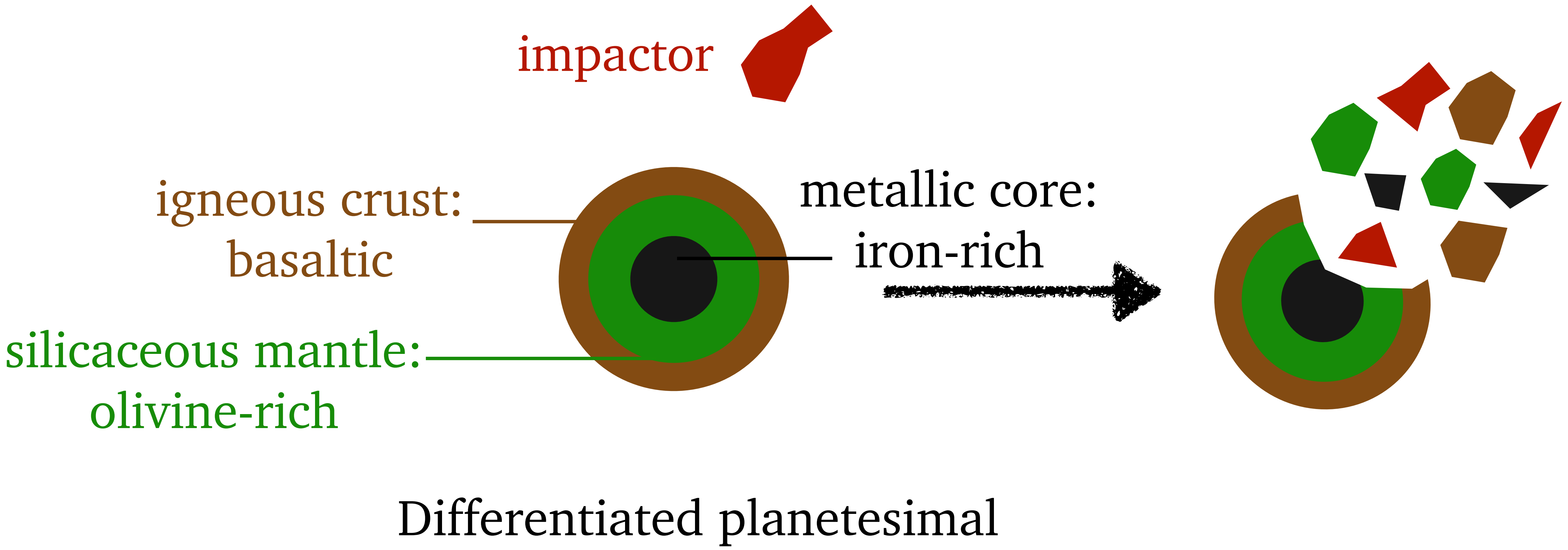
60 518 mean reflectance spectra of Solar System small bodies

Study of asteroid family (36256) 1999 XT17 with the Gaia DR3 spectral data

Asteroid families



^{26}Al radioactive decay ➡ heat



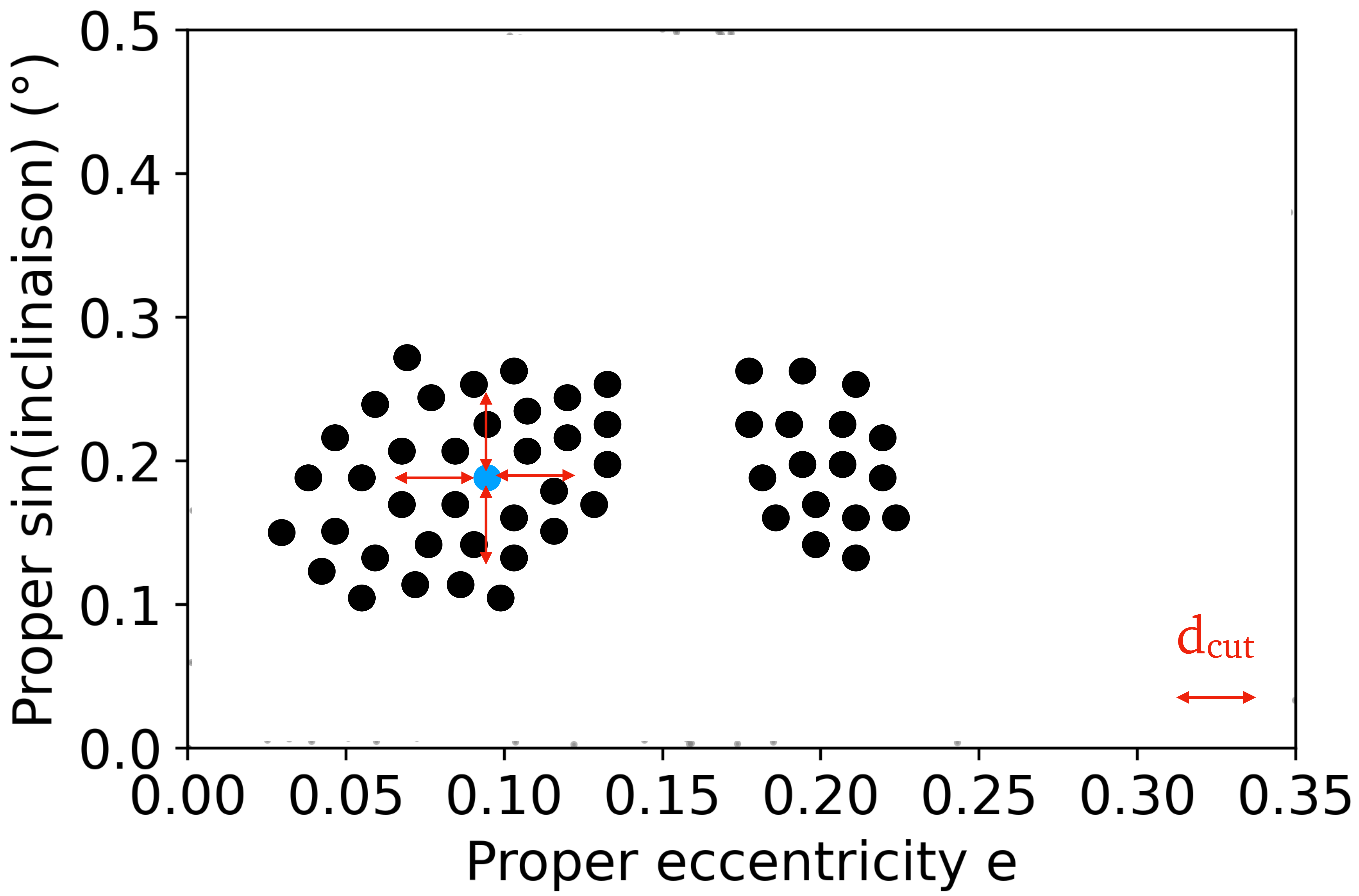
➡ Should see traces of layers of differentiated planesetimals in asteroid families

Asteroid families

- Defined with a dynamical point of view: **hierarchical clustering method** (HCM) (Nesvorny+2015)

- Applied to the distribution of asteroids in proper orbital elements space (a_p,e_p,i_p)

➡ defines a cutoff distance d_{cut}, and requires that the distance $d(a_p,e_p,i_p)$ between 2 neighboring orbits clustered by the algorithm is $d(a_p,e_p,i_p) < d_{cut}$

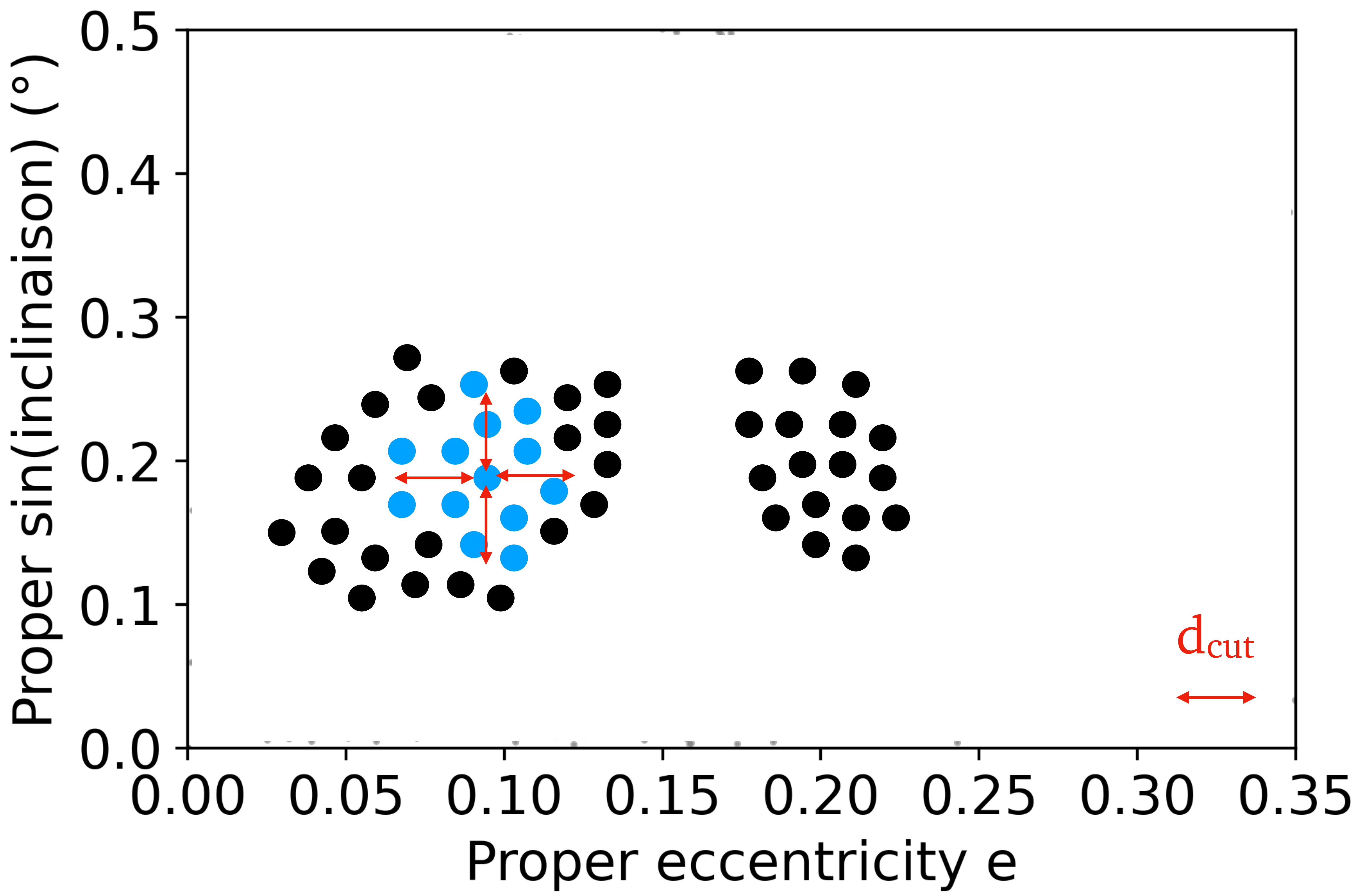


Asteroid families

- Defined with a dynamical point of view: **hierarchical clustering method** (HCM) (Nesvorny+2015)

- Applied to the distribution of asteroids in proper orbital elements space (a_p,e_p,i_p)

➡ defines a cutoff distance d_{cut}, and requires that the distance $d(a_p,e_p,i_p)$ between 2 neighboring orbits clustered by the algorithm is $d(a_p,e_p,i_p) < d_{cut}$

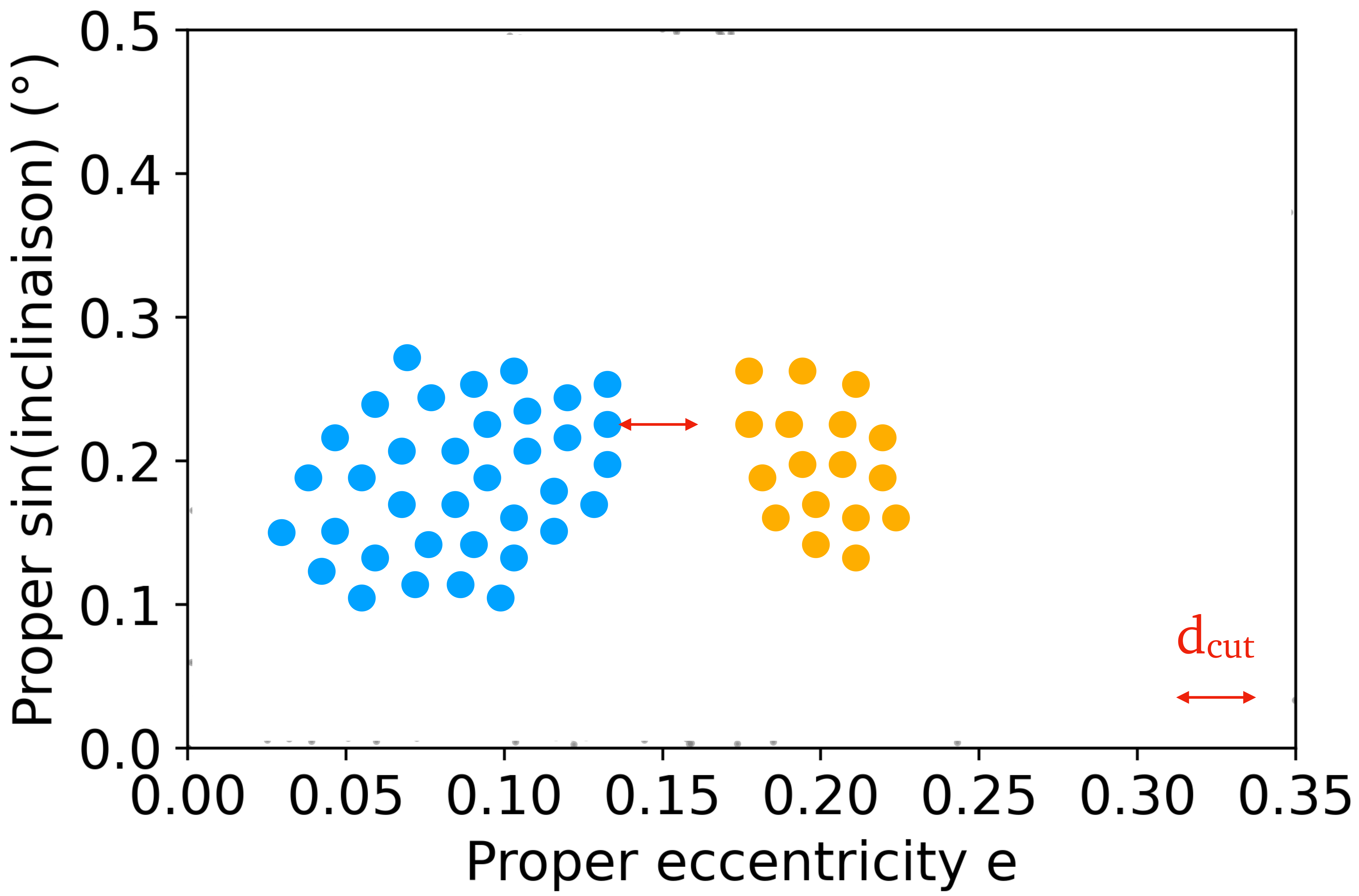


Asteroid families

- Defined with a dynamical point of view: **hierarchical clustering method** (HCM) (Nesvorny+2015)

- Applied to the distribution of asteroids in proper orbital elements space (a_p,e_p,i_p)

➡ defines a cutoff distance d_{cut}, and requires that the distance $d(a_p,e_p,i_p)$ between 2 neighboring orbits clustered by the algorithm is $d(a_p,e_p,i_p) < d_{cut}$

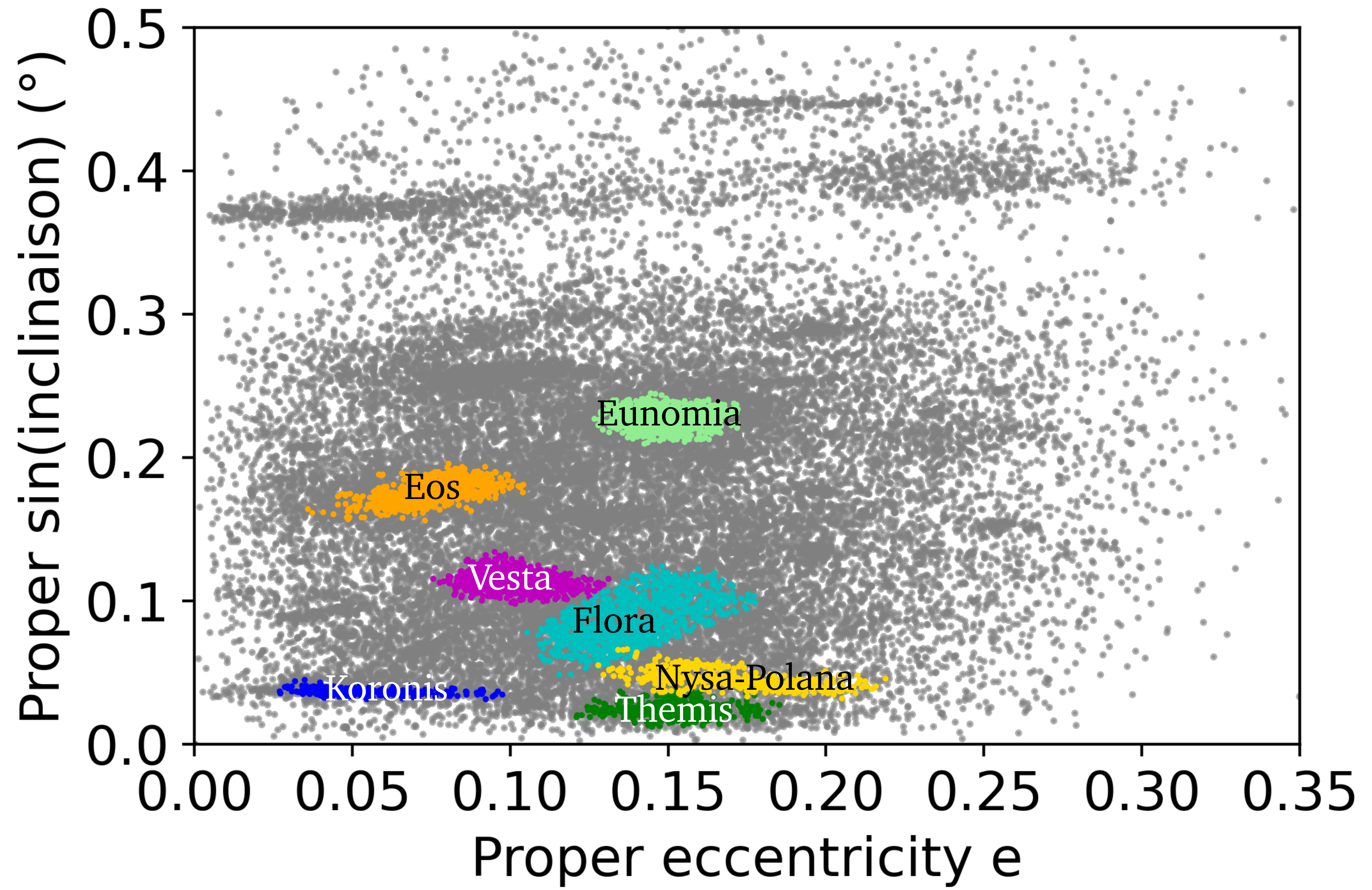


Asteroid families

- Defined with a dynamical point of view: **hierarchical clustering method** (HCM) (Nesvorny+2015)
- Applied to the distribution of asteroids in proper orbital elements space (a_p,e_p,i_p)

➡ defines a cutoff distance d_{cut}, and requires that the distance $d(a_p,e_p,i_p)$ between 2 neighboring orbits clustered by the algorithm is $d(a_p,e_p,i_p) < d_{cut}$

➡ Nesvory+2015: **122 identified families**

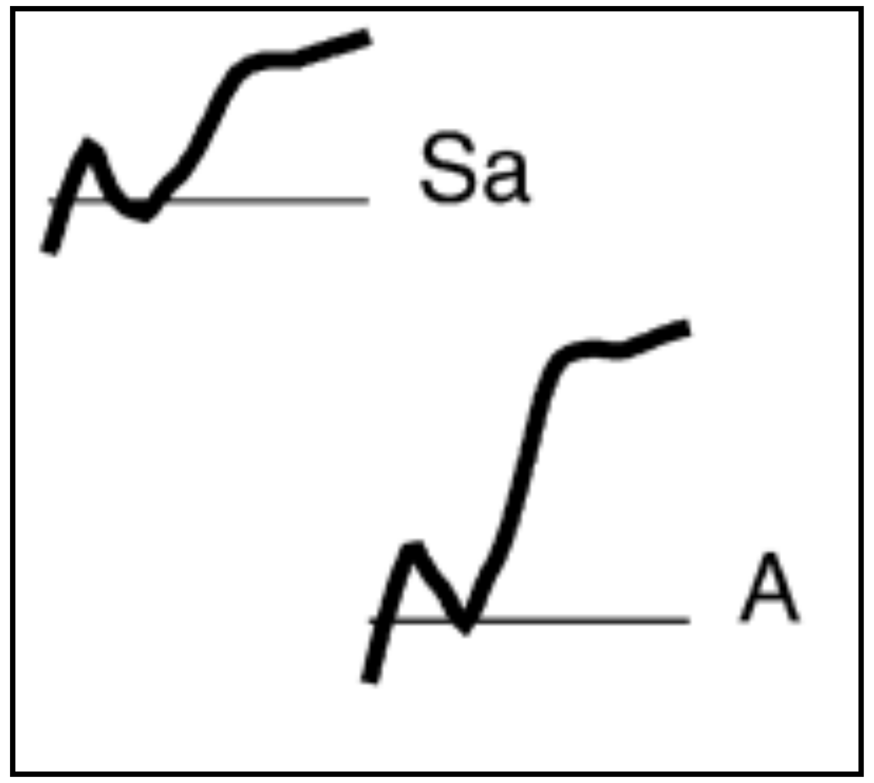


The ‘missing mantle’ problem

- Basaltic crust-like asteroids ✓
- Iron-rich core-like asteroids ✓
- Olivine-rich mantle-like asteroids… ? ➡ A-type asteroids

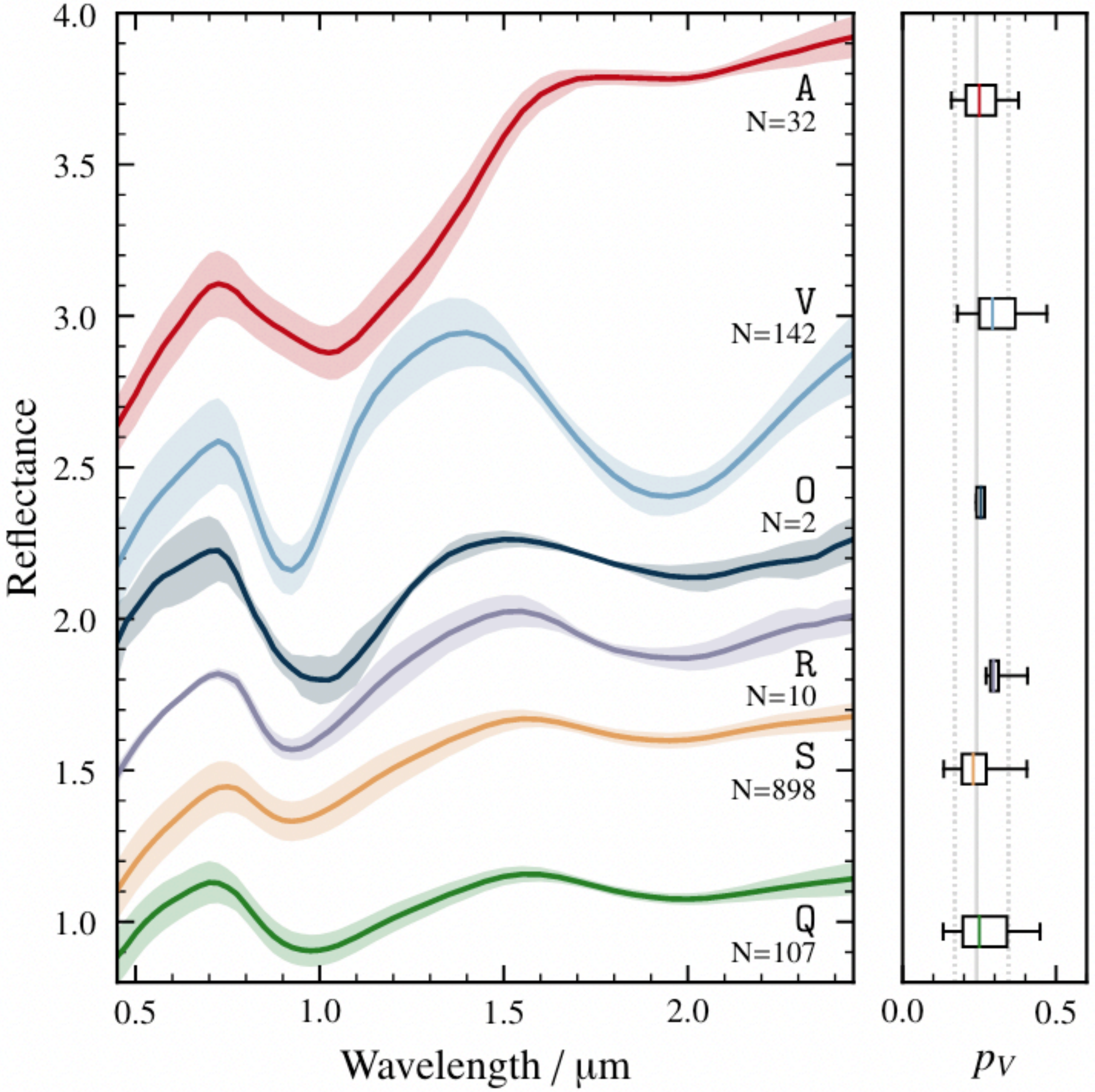
Class	Spectrum	Albedo
A	Broad and deep absorption feature at 1 μm, strong red slope in the near-infrared.	$0.25^{0.09}_{0.07}$

Mahlke+2022



Bus-DeMeo 2009 taxonomy

Mahlke 2022 taxonomy

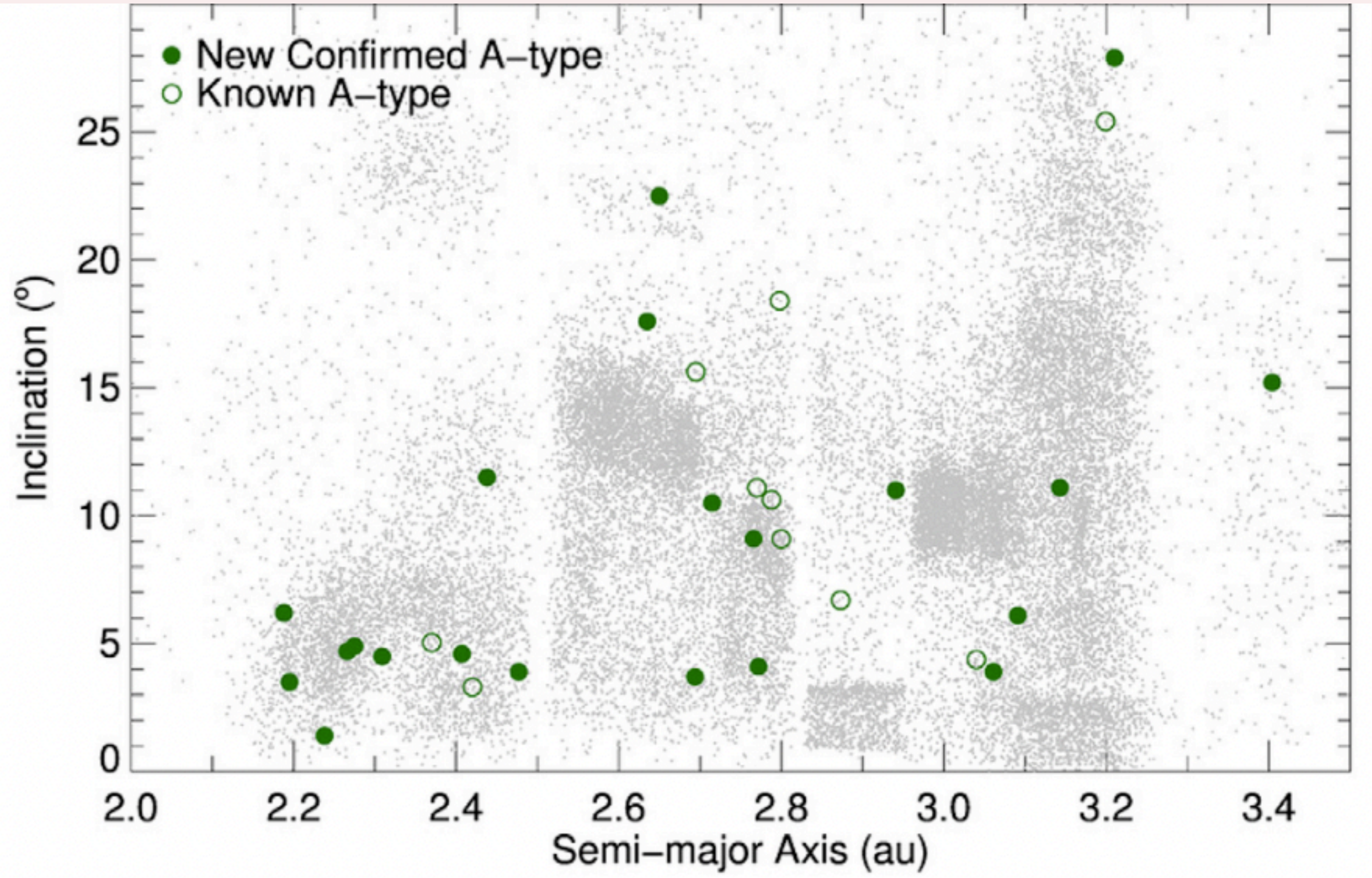


The ‘missing mantle’ problem

- DeMeo+2019:

Olivine-dominated A-type asteroids in the main belt: Distribution, abundance and relation to families

Francesca E. DeMeo[*,a], David Polishook[b], Benoît Carry[c], Brian J. Burt[d], Henry H. Hsieh[e,f], Richard P. Binzel[a], Nicholas A. Moskovitz[d], Thomas H. Burbine[g]



➡ ‘A-type asteroids account for less than 0.16% of all main-belt objects larger than 2 km’

➡ ‘rather evenly distributed throughout the main belt’

➡ ‘have no statistically significant concentration in any asteroid family.’

Family selection

- Literature: families with a high number of A-types (potential and/or confirmed)
  - Families and family memberships of Nesvorny+2015
  - asteroid classification from ~50 articles (mp3c.oca.eu)

➡ proportion of asteroids classified as A-type / asteroids classified otherwise in each family

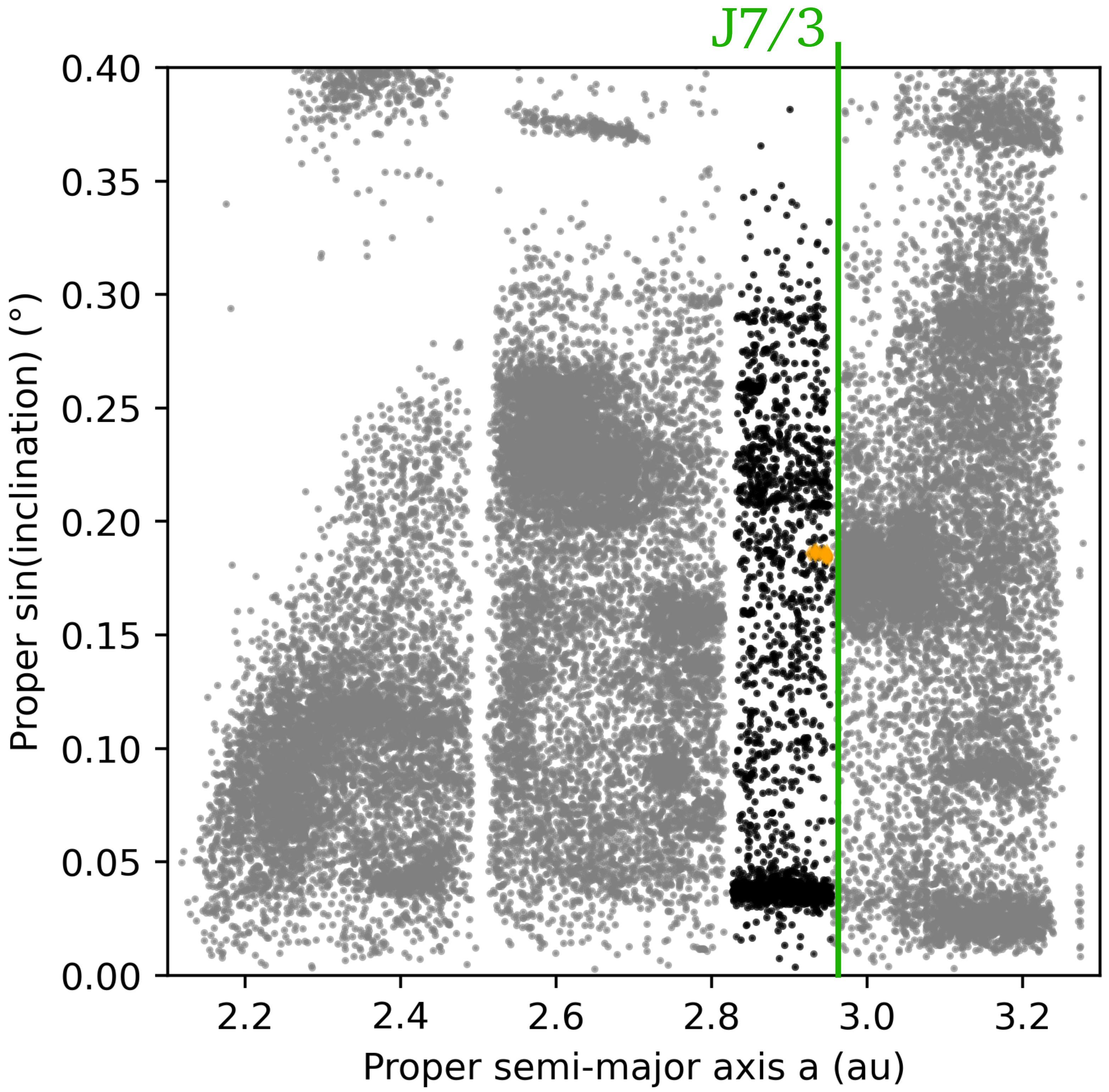
➡ Consider only the families with a proportion of potential A-types above 10% (arbitrary choice)

Family selection

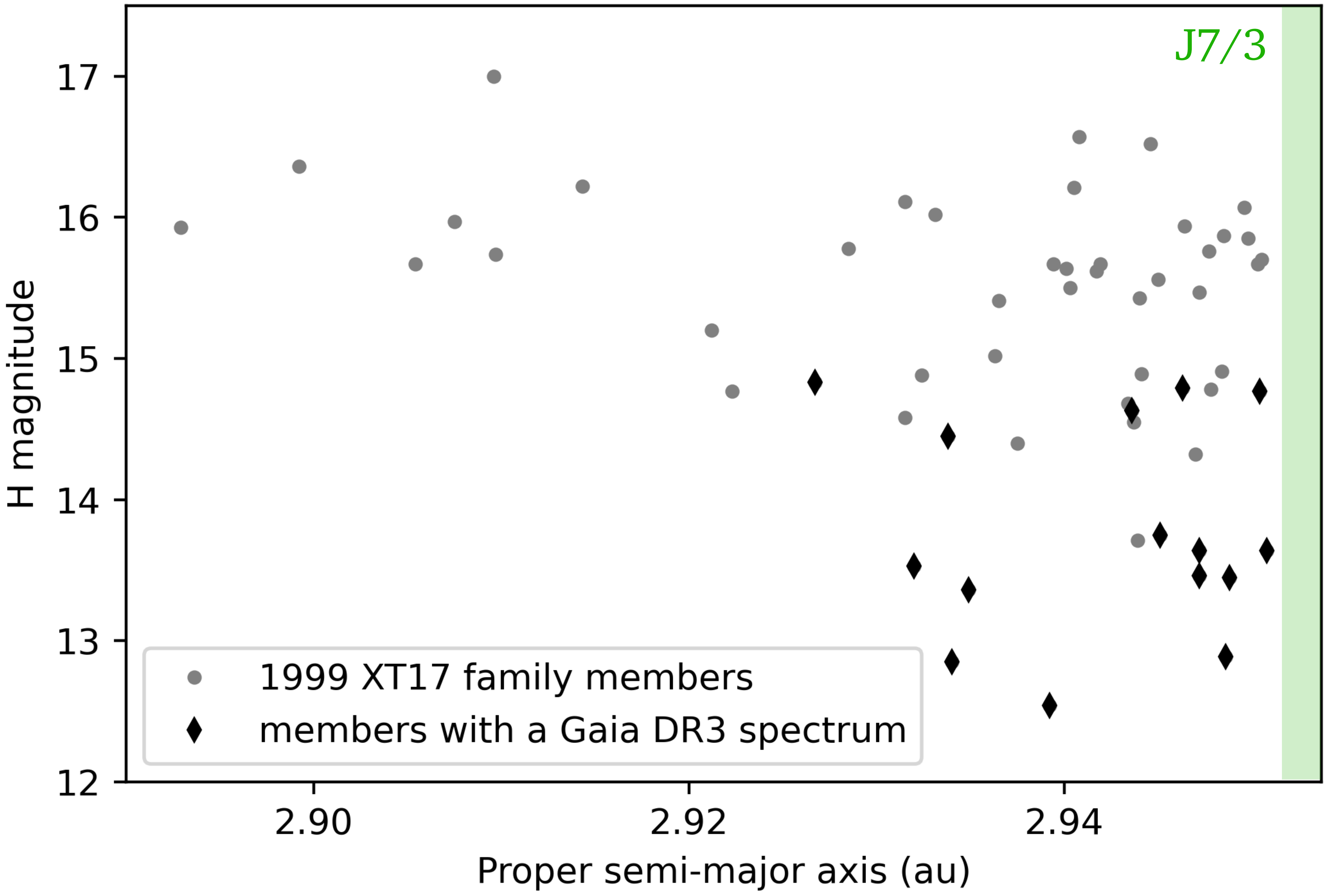
- Results:
  - 3 families with a **potential A-types proportion >10%**:
    (10811) Lau : 13%
    (36256) 1999 XT17 : 23 %
    (7468) Anfimov : 28 %
  - In the **Gaia DR3** spectral dataset:
    (10811) Lau : 1 spectrum, asteroid Lau itself ✗
    (36256) 1999 XT17 : 15 spectra
    (7468) Anfimov : 7 spectra
  - **Average SNR**:
    (36256) 1999 XT17 : mean average SNR of 40
    (7468) Anfimov : asteroids (7468) and (18853): SNR of 47.41 and 32.21. ✗
    Others: SNR~25,19,15,13 ➔ low SNR
    ➔ Classified before? Yes, A-types VISNIR spectroscopy (DeMeo+2019, Mahlke+2022)

Family (36256) 1999 XT17

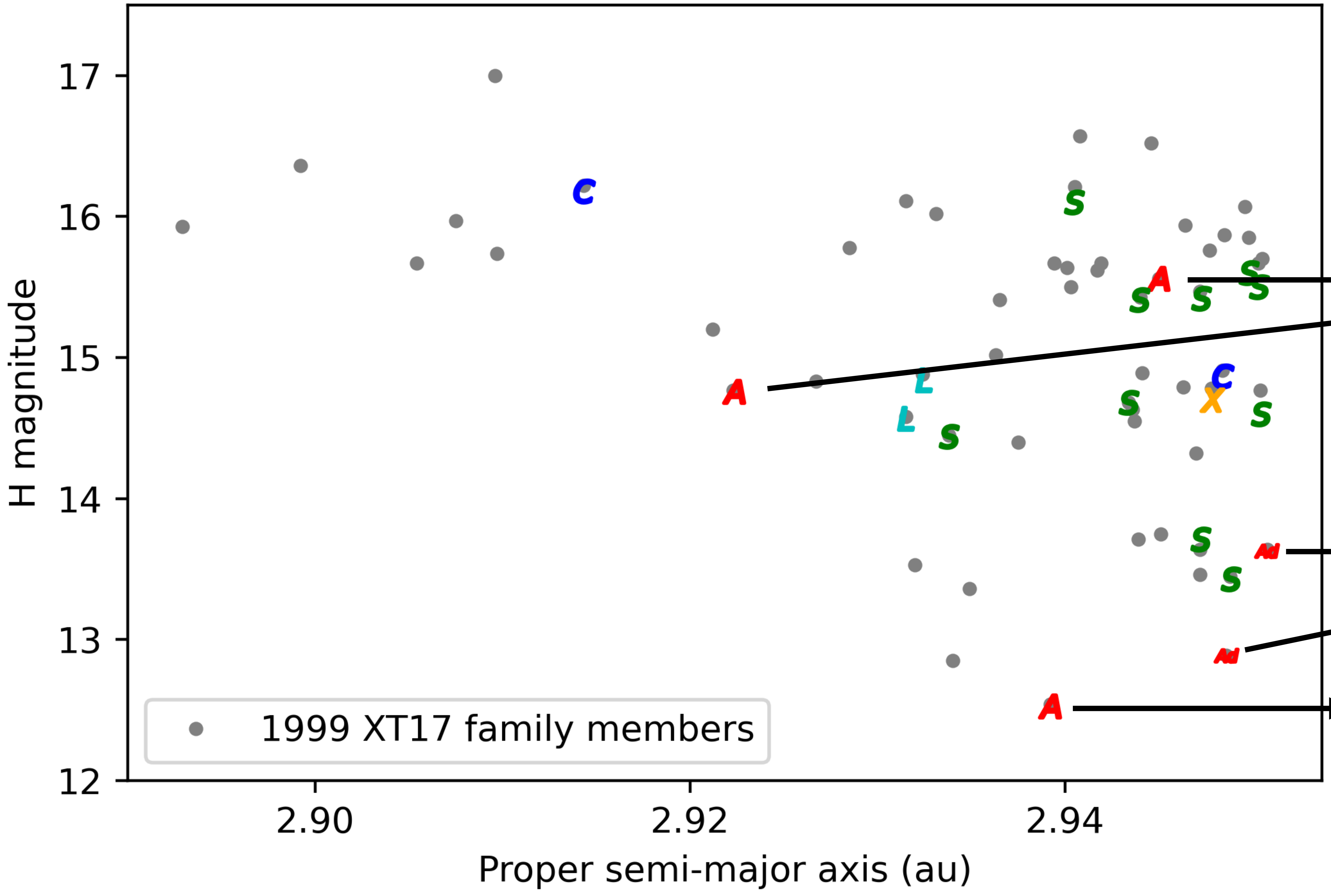
- **58 members,** $p_V = 0.21$
  Nesvorny+2015
- Located in the 'pristine zone'



- Gaia DR3: 15 spectra
  - 7 classified in the literature
  - 8 never classified before
  - 9 with SNR>28



Family (36256) 1999 XT17



- Literature

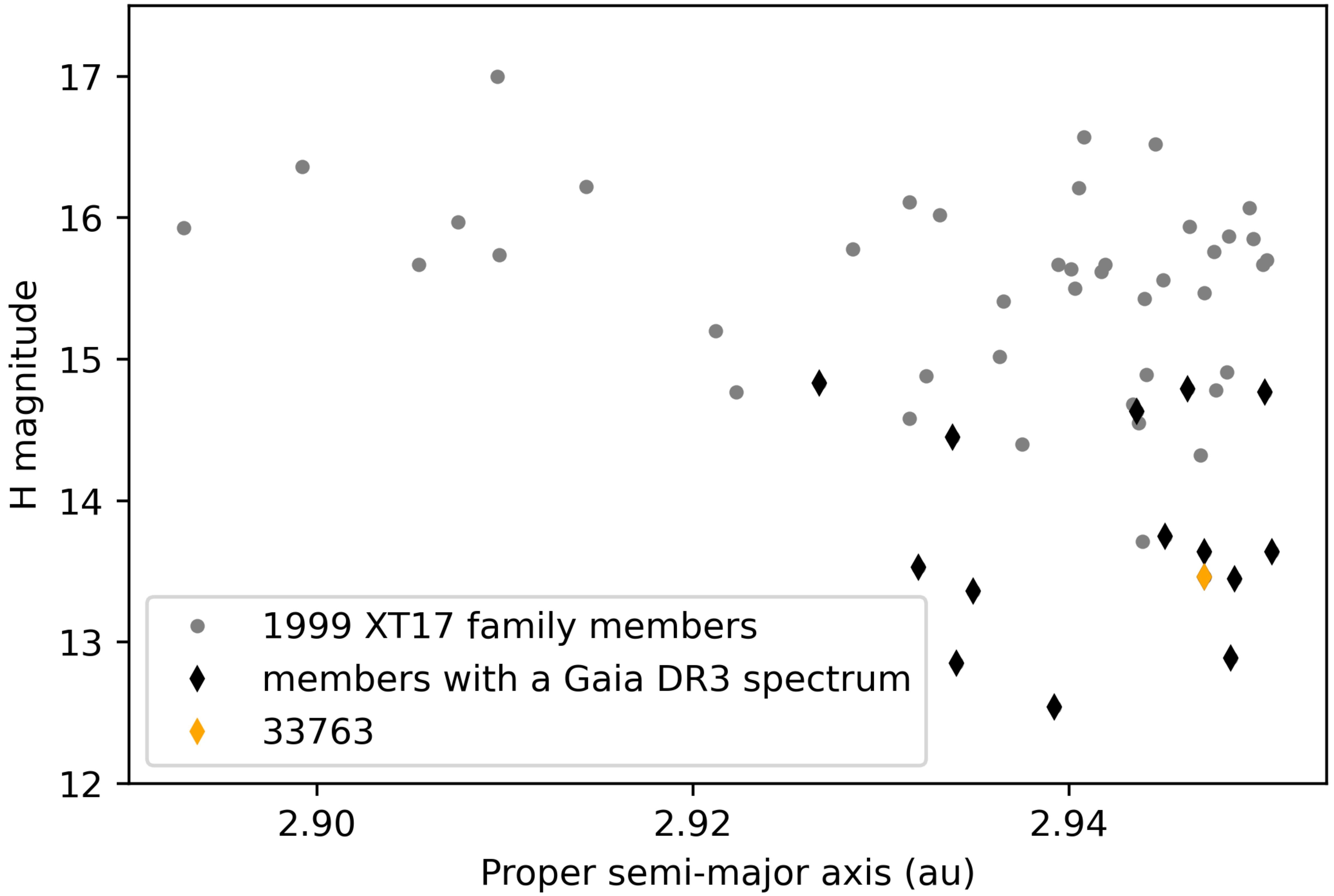
201232, 112560
photometry
Carvano+2010, Sergeyev+2022

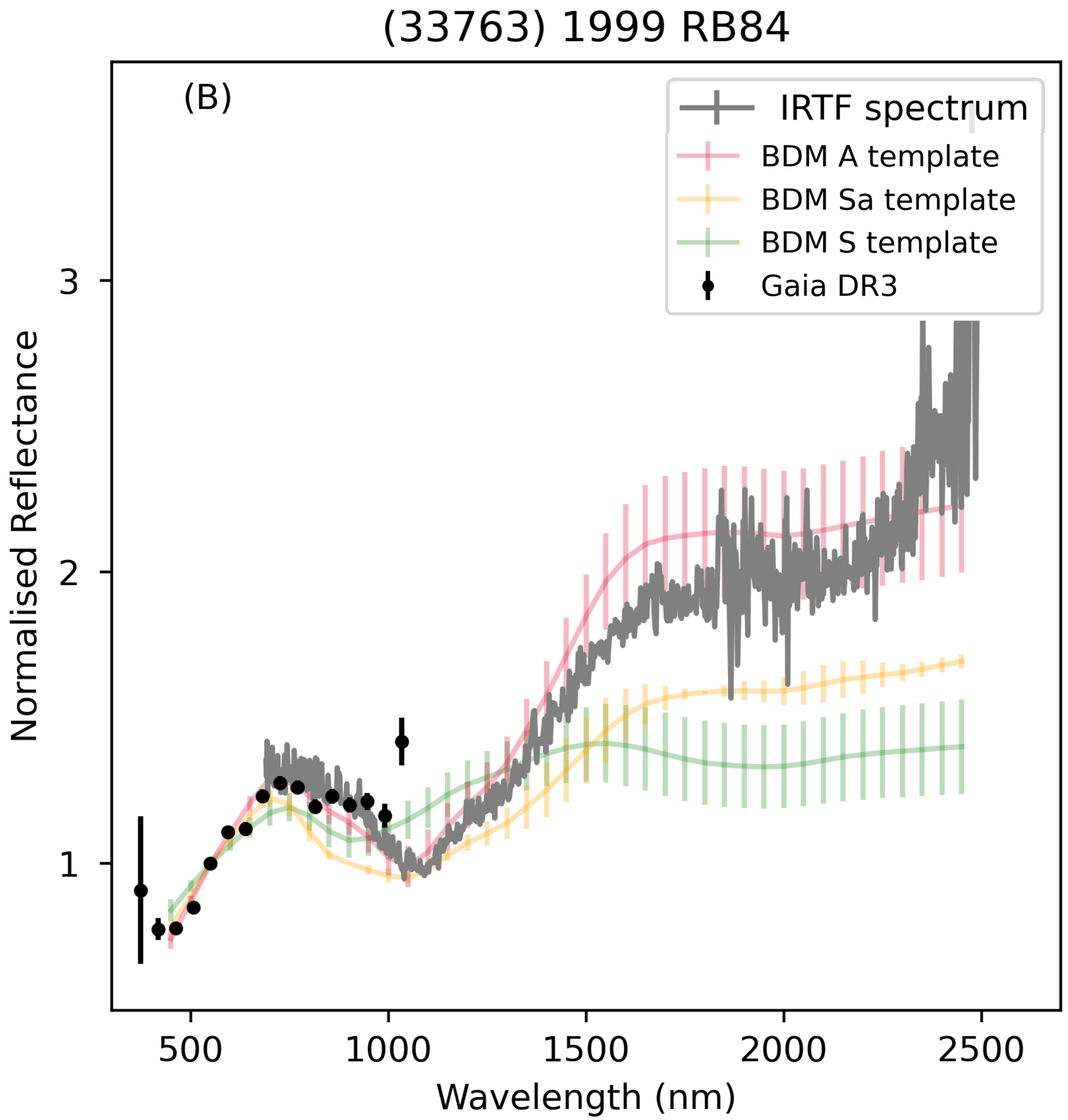
25356, 40671
MOVIS
Popescu+2018

36256
NIR spectroscopy
DeMeo+2019

Observation of (33763) 1999 RB84

- IRTF (near-infrared)





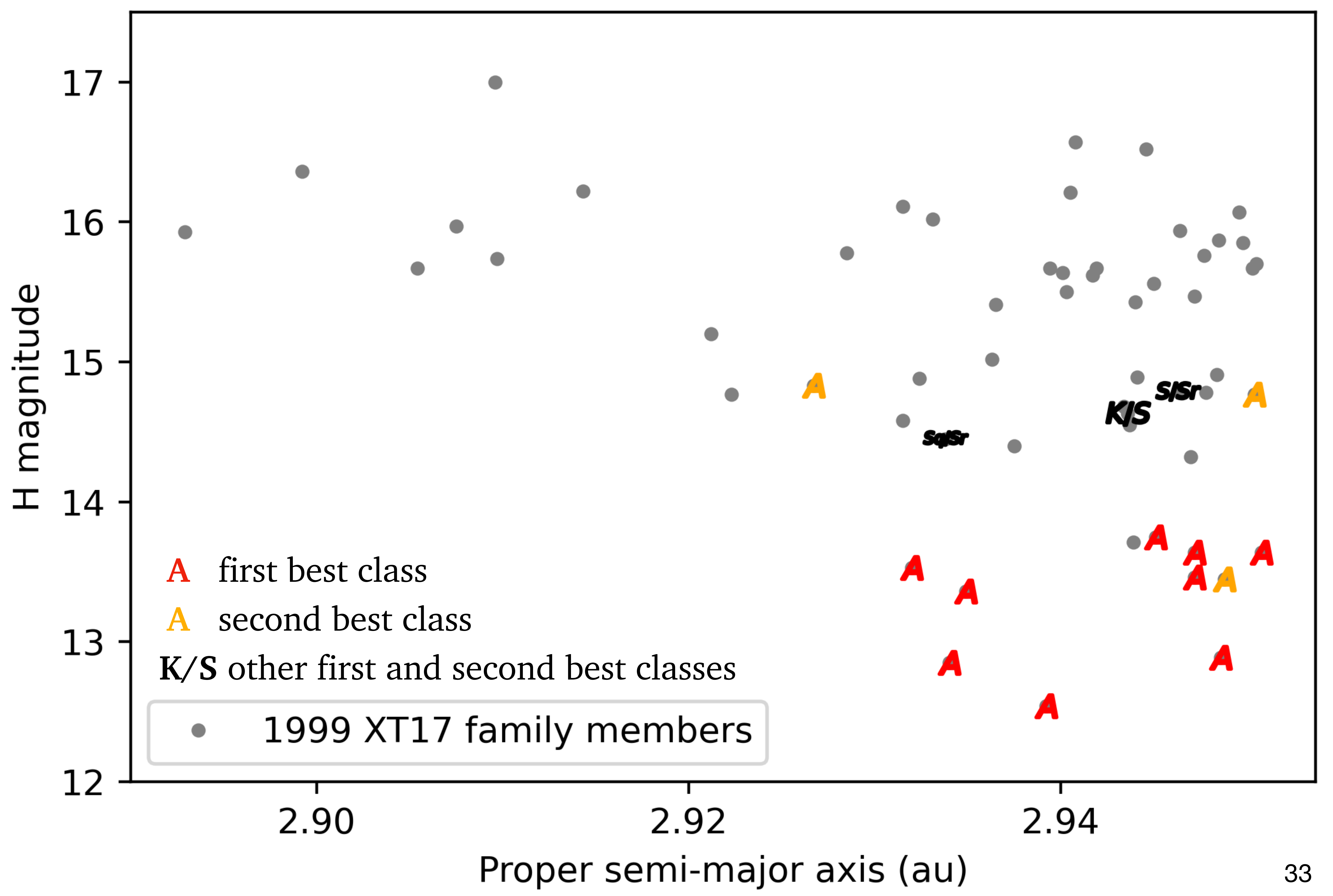
Classification of Gaia DR3 spectra

- Algorithm: developed in Avdellidou+2022
- Curve matching: calculate a reduced χ^2 between asteroids spectra and Bus-DeMeo templates
- Gaia DR3 spectra: from 450 to 900 nm (cut off first 2 and last 4 data points)
- $\chi^2_{tot} = \chi^2_{DR3} + \chi^2_{NIRspec} + \chi^2_{NIRcolor} + \chi^2_{SDSS}$
  - **36256:** $\chi^2_{tot} = \chi^2_{DR3} + \chi^2_{NIRspec} + \chi^2_{SDSS}$
  - **33763:** $\chi^2_{tot} = \chi^2_{DR3} + \chi^2_{NIRspec}$
  - **25356, 40671:** $\chi^2_{tot} = \chi^2_{DR3} + \chi^2_{NIRcolor}$
  - **99004:** $\chi^2_{tot} = \chi^2_{DR3} + \chi^2_{SDSS}$
  - **Others:** $\chi^2_{tot} = \chi^2_{DR3}$
- Gives best 2 classes

Classification of Gaia DR3 spectra

- Results:
  12 asteroids classified A-type as first or second best class

Asteroid	Average SNR	H	Class
15610	35.32	13.3	A,L
16789	38.25	13.5	A,Sv
20975	36.01	13.6	A,Sv
25356	66.49	12.8	A,Sa
27565	20.74	13.6	A,L
33763	48.07	13.4	A,Sa
34902	14.7	14.4	Sq,Sr
36256	66.56	12.4	A,Sa
40671	28.09	13.6	A,Sa
57276	128.74	12.9	A,Sv
66676	52.28	13.3	L,A
83124	14.88	14.7	S,Sr
88057	20.75	14.5	K, S
99004	13.93	14.6	L,A
140349	13.86	14.7	Sv, A

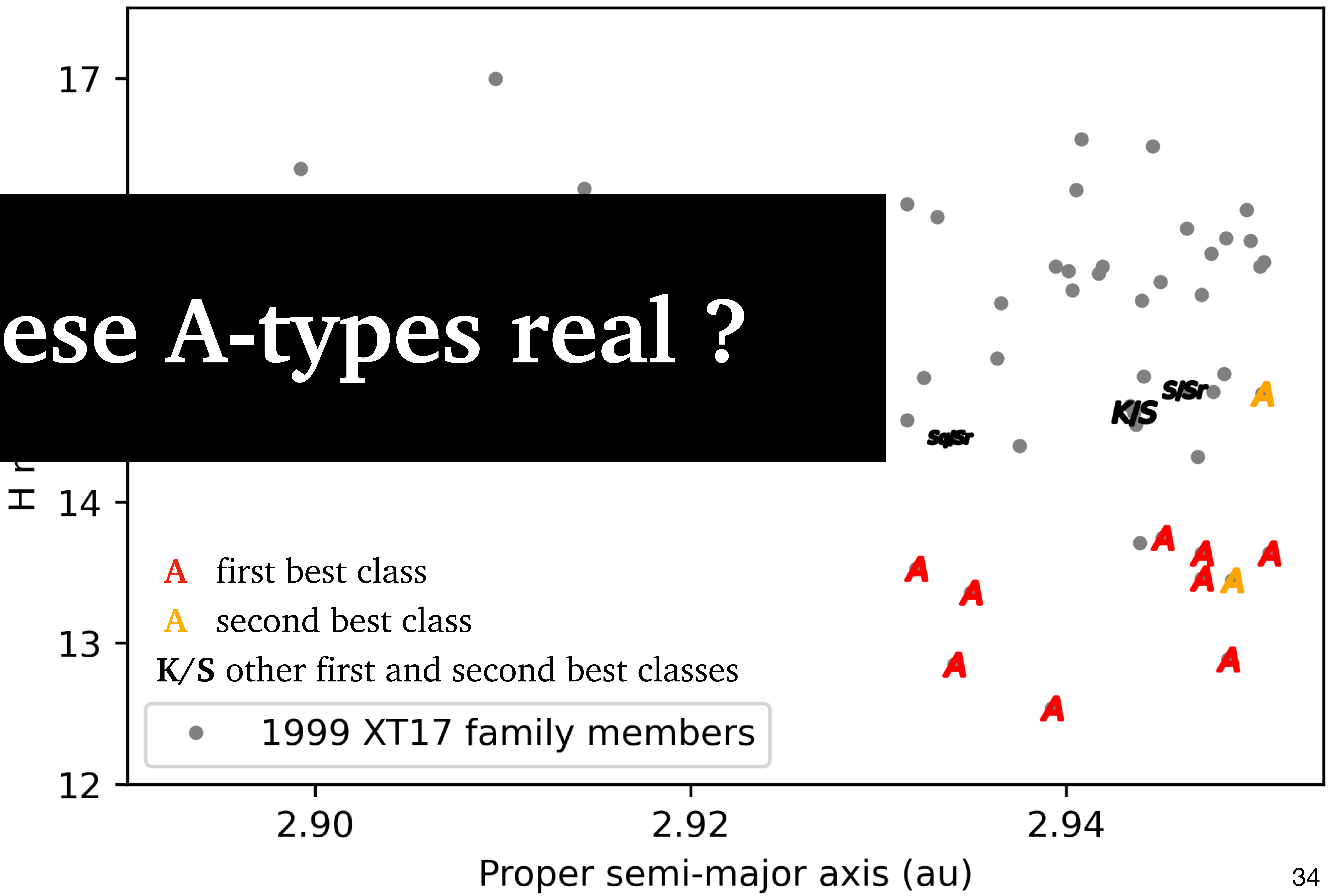


Classification of Gaia DR3 spectra

- Results:
  12 asteroids classified A-type as first or second best class

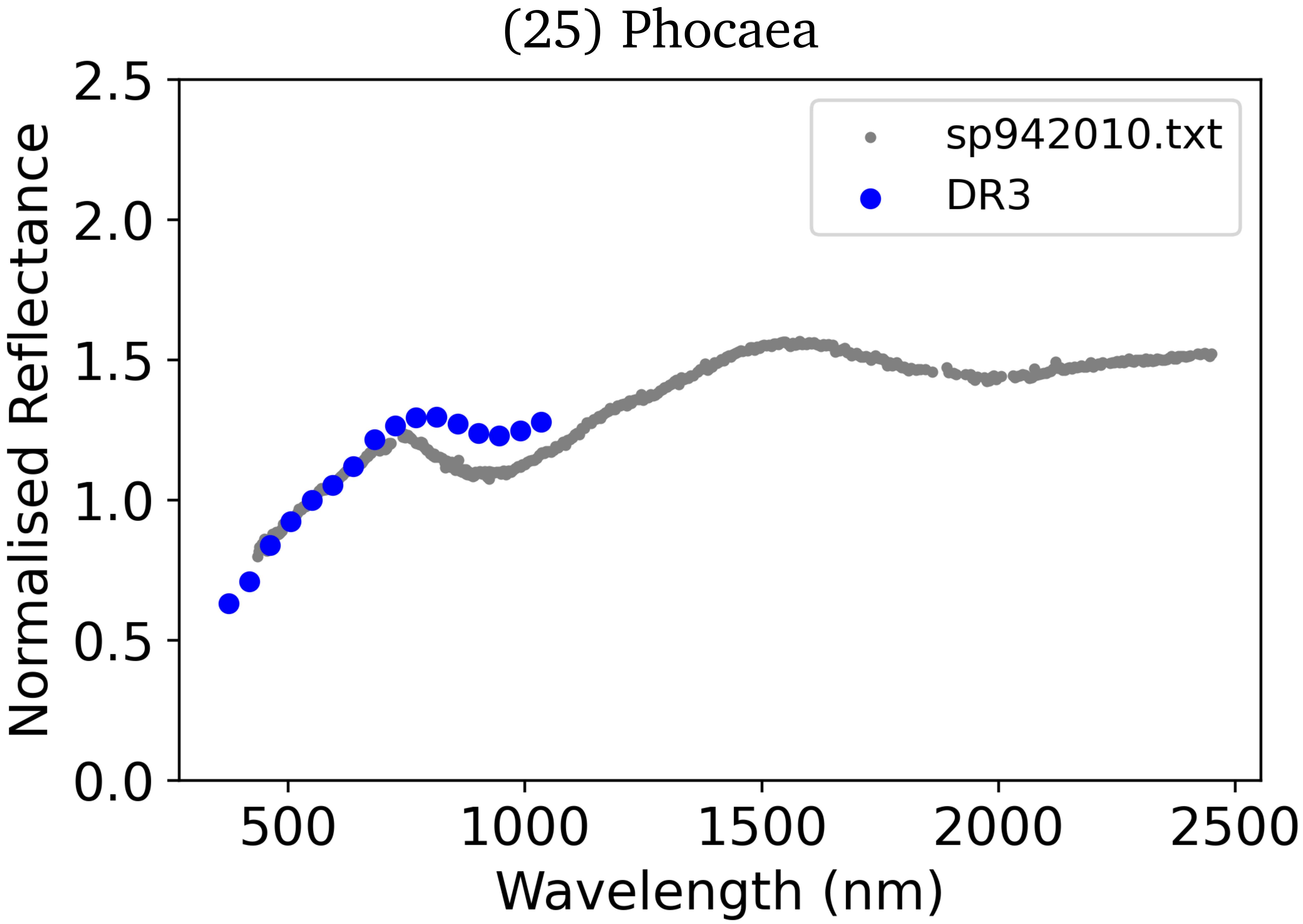
Asteroid	Average SNR	H	Class
15610	35.3[illegible]	[illegible]	[illegible]
16789	38.25	[illegible]	[illegible]
20975	36.01	[illegible]	[illegible]
25356	66.49	[illegible]	[illegible]
27565	20.74	[illegible]	[illegible]
33763	48.07	13.4	A,Sa
34902	14.7	14.4	Sq,Sr
36256	66.56	12.4	A,Sa
40671	28.09	13.6	A,Sa
57276	128.74	12.9	A,Sv
66676	52.28	13.3	L,A
83124	14.88	14.7	S,Sr
88057	20.75	14.5	K, S
99004	13.93	14.6	L,A
140349	13.86	14.7	Sv, A

Are these A-types real ?



Classification of Gaia DR3 spectra

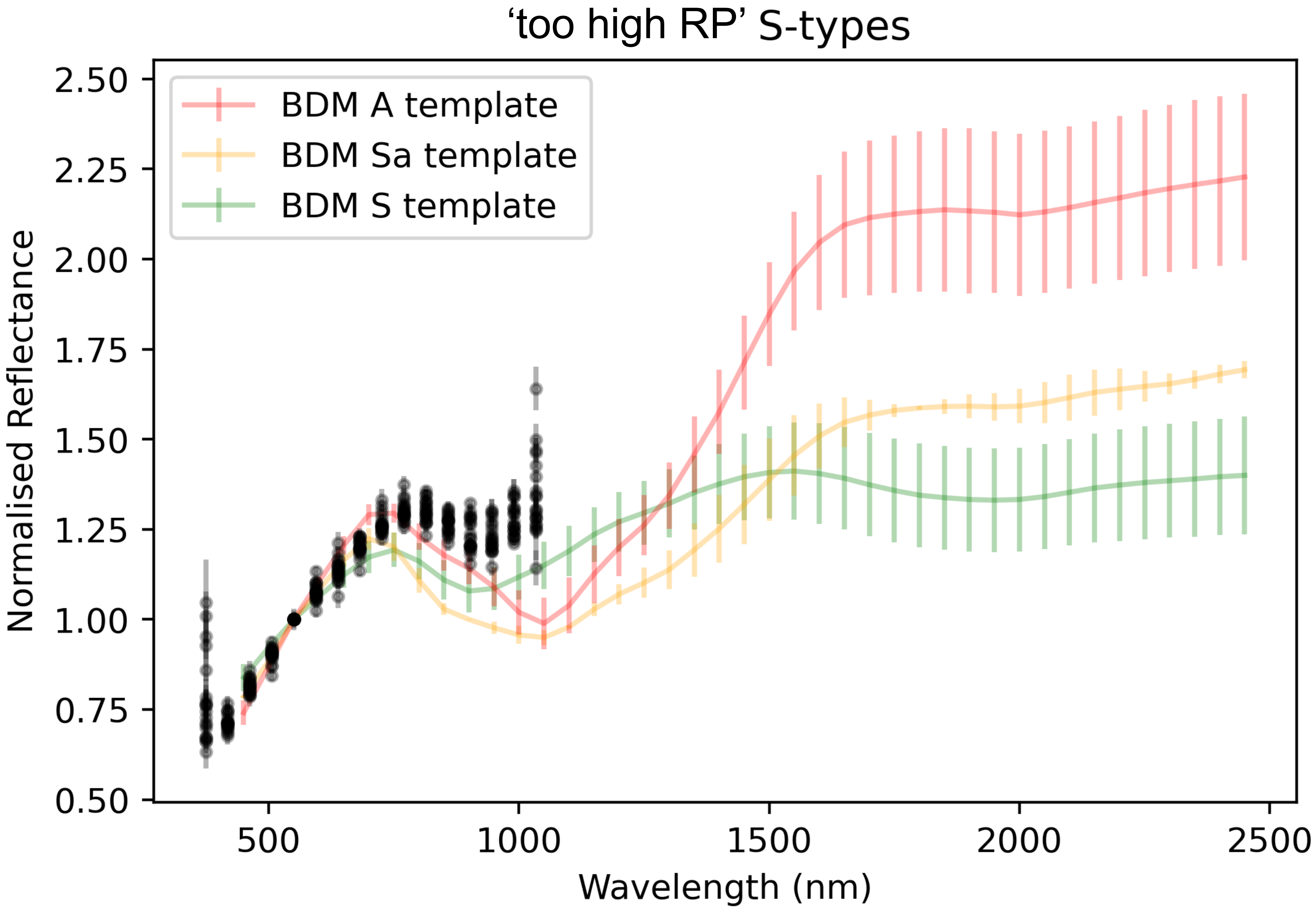
- The Gaia RP problem



- **S-type** (Carvano+2001, Bus&Binzel+2002, Lazzaro+2004, DeMeo+2009, Mahlke+2022)
- Affected by a reflectance increase of its RP part

Classification of Gaia DR3 spectra

- The Gaia RP problem



- S-types literature
- Affected by a reflectance increase of its RP part

➡ Does this issue affect our classification ?

Classification of Gaia DR3 spectra

- Test of the algorithm: list of asteroids having a Gaia DR3 spectrum + classified in the NIR with the Bus-DeMeo scheme ➔ **389 asteroids, 21 A-types**

- **Classify only the Gaia DR3 spectra**

- Some identified 'too high RP' S-types

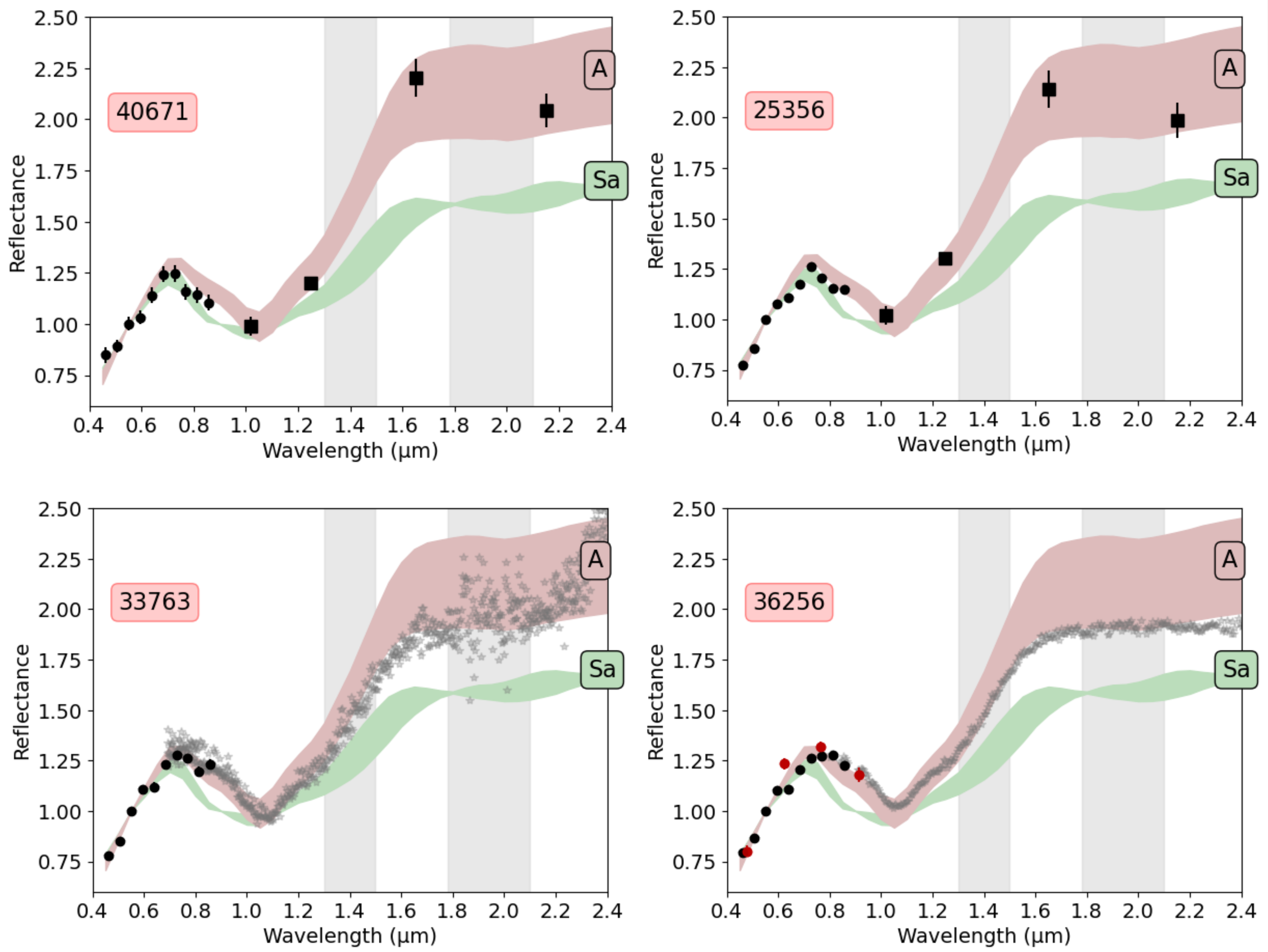
number	literature	type1	type2
25	S	L	Sv
512	Sqw	L	Sv
913	Sw	L	Sv
1147	Sw	L	Sv
2074	Sw	A	L
3858	Srw	L	Sv
6067	S	L	Sv
7057	S	L	Sv

➡ Classification of A-types not affected by the RP problem

Classification: recap

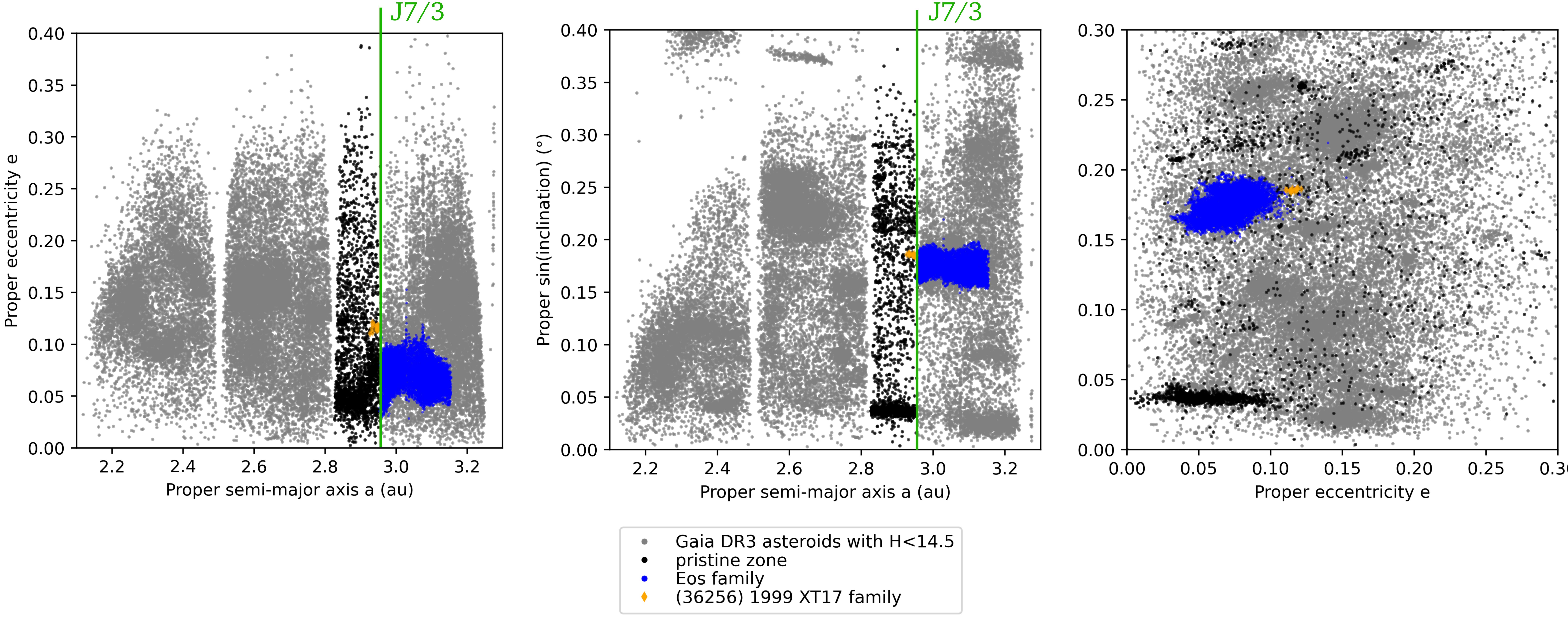
<u>**(36256) 1999 XT17 family with Gaia DR3**</u>

- 12 asteroids found A-type
  - 9 with a SNR>21: probable A-types. Among these, 4 confirmed by NIR
  - 3 with a SNR<21
- 6 asteroids in total have a SNR<21: members of the **S-complex**



Dynamical study

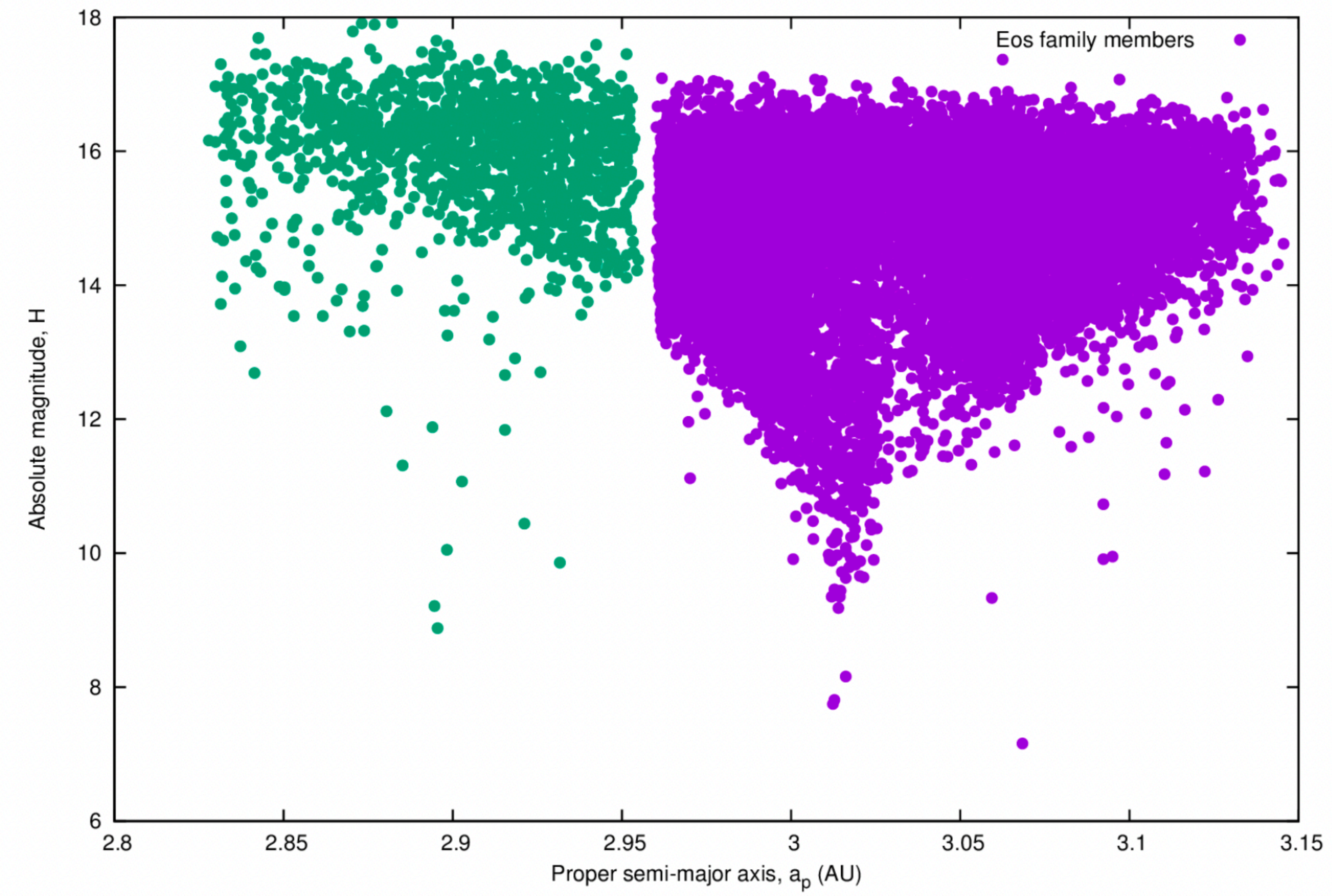
- Located in the ‘pristine zone’



Dynamical study

Tsirvoulis+2018:

- found **Eos fugitives**: selected zone in the proper orbital elements space with
  $2.82 < ap < 2.96$
  $0.03 < ep < 0.1$
  $0.12 < \sin ip < 0.2$
- Eos family members cross the J7/3 MMR and orbit in the 'pristine zone'

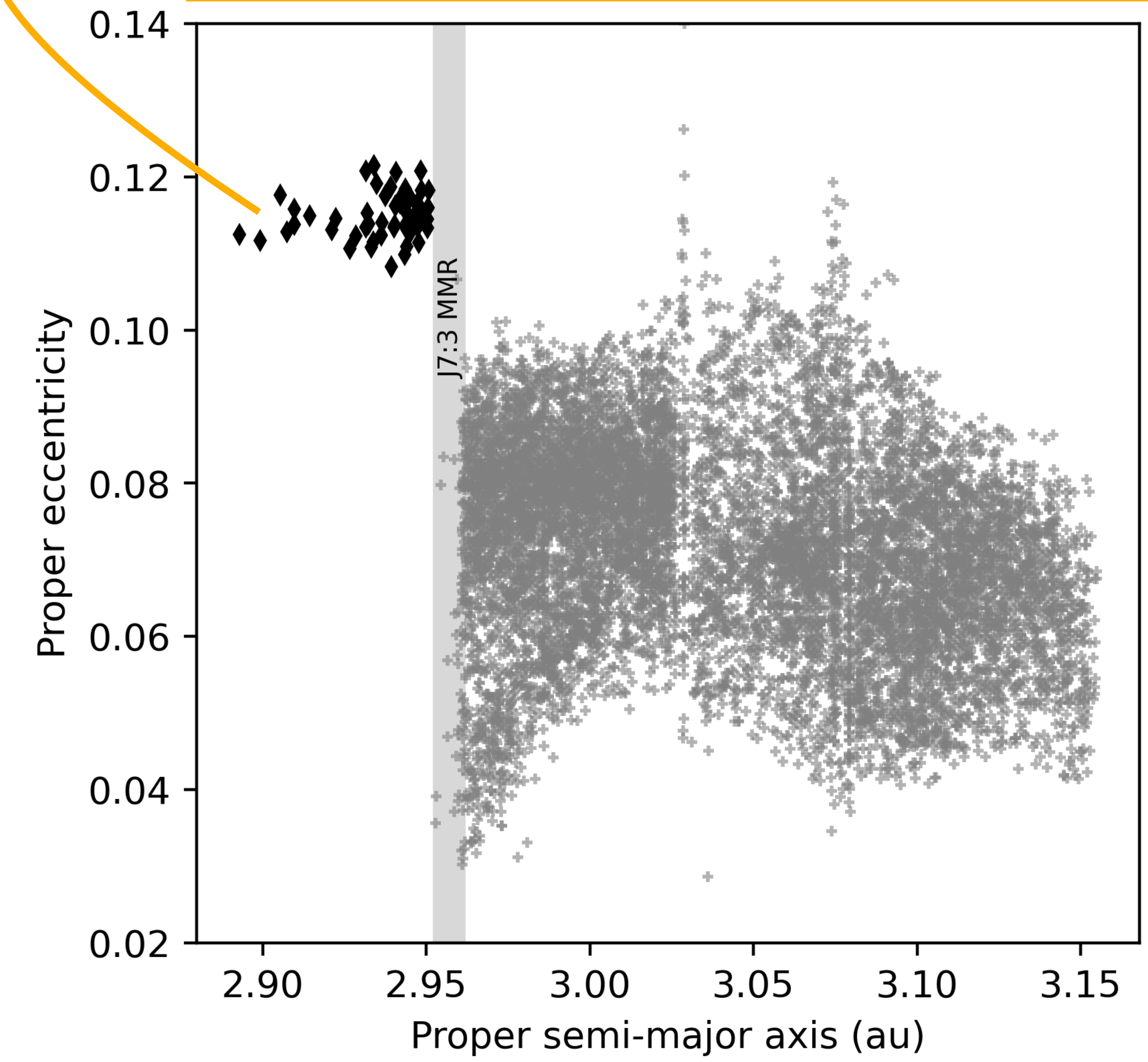


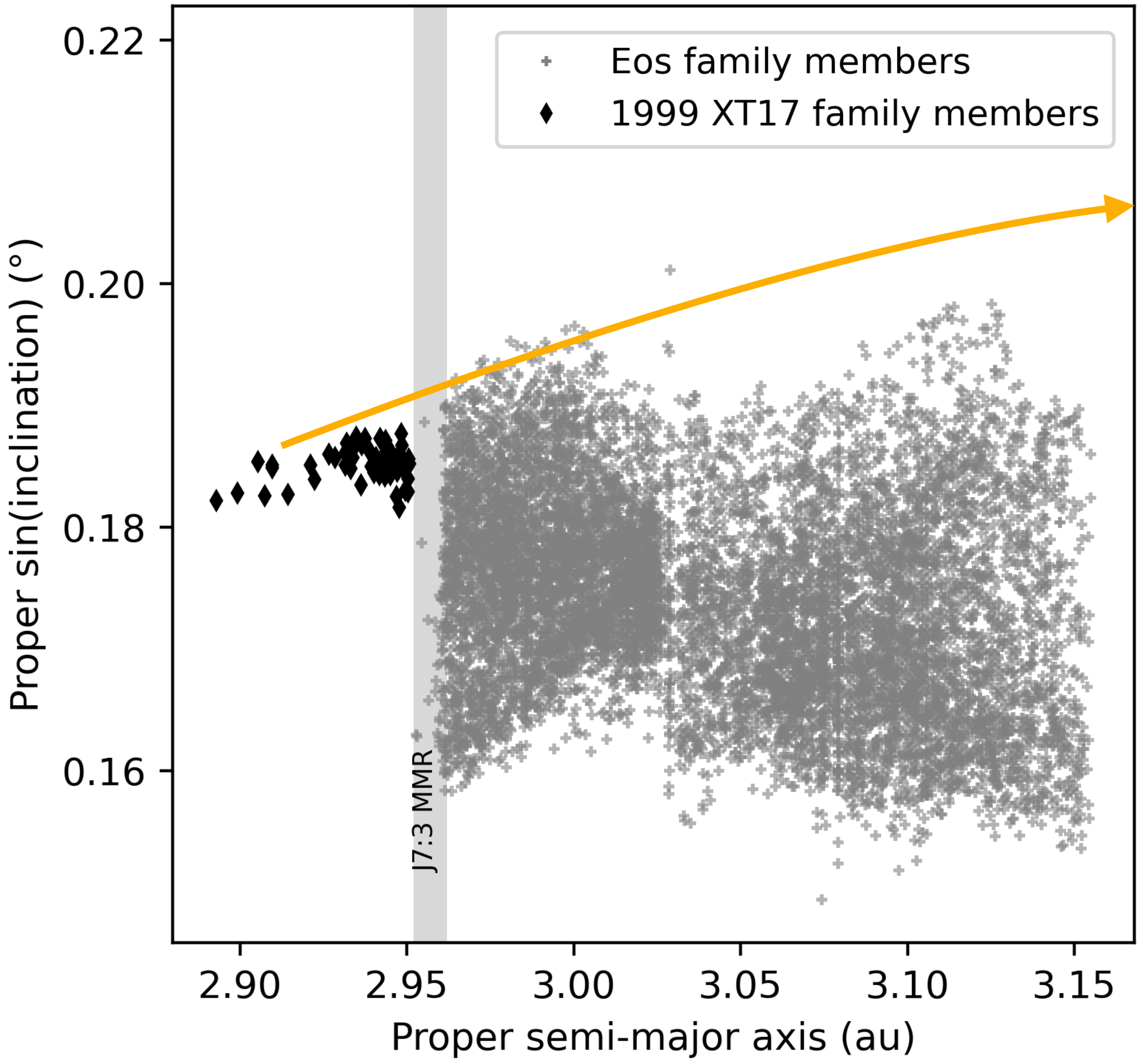
Dynamical study

Broz&Morbidelli+2019, Nesvorny+2015:

➡ family (36256) may contribute to the contamination of the 'pristine zone'

resonance weak/asteroid small and drifts fast in a_P: orbit can cross the resonance, « perhaps suffering a discontinuity in e_P during the crossing »



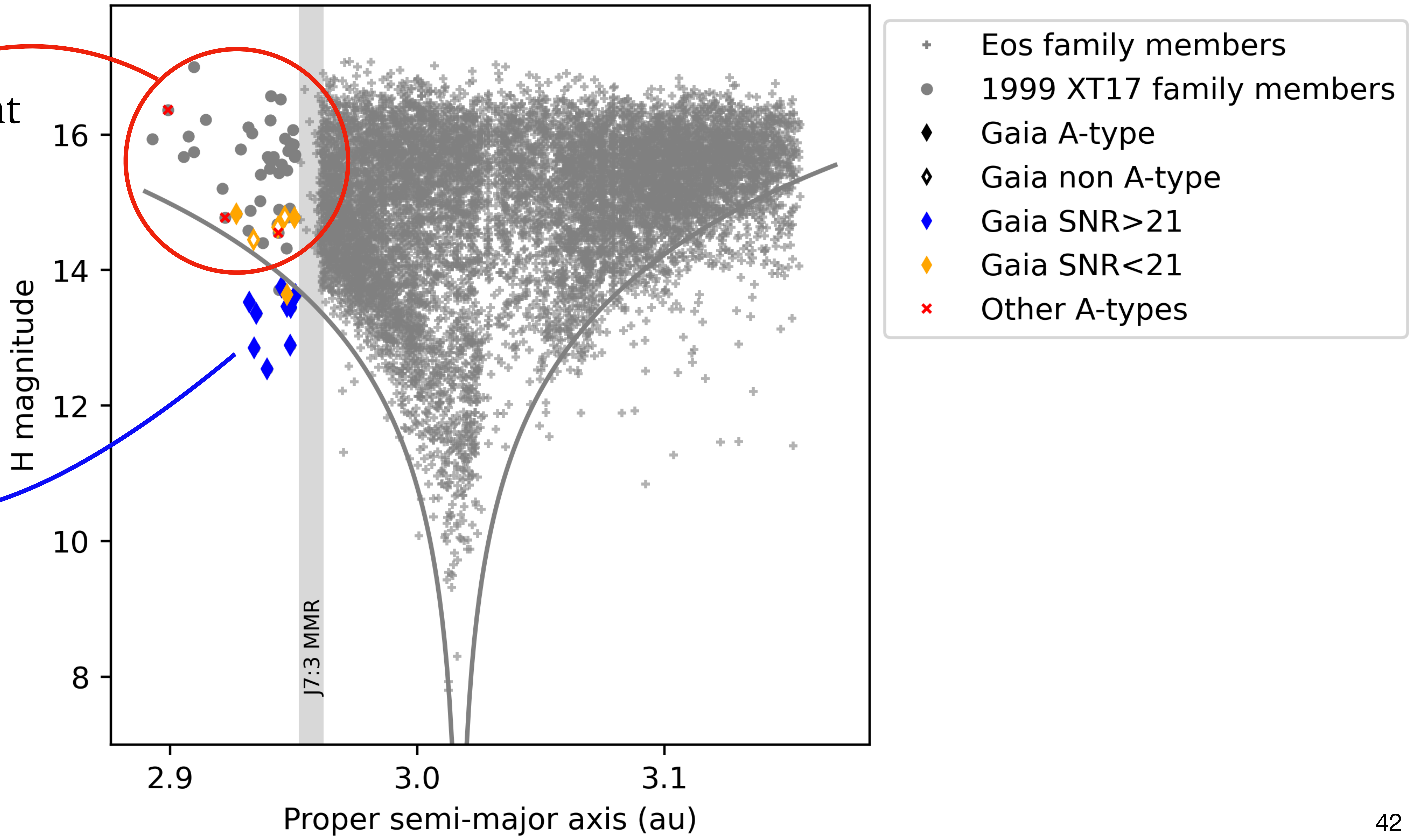


Effects of MMR on i_P generally smaller

Dynamical study

Some members might be Eos fugitives?

olivine-rich parent body that got disrupted?



Recap

- 15 Gaia DR3 spectra: **12 potential A-types**, 4 confirmed by NIR data.
  5 more found A-type asteroids with SNR>21, 6 asteroids with SNR<21 members of the S-complex.

- In total: 36 family members with a classification, 16 potential A-type asteroids ➔ **44.4% of A-types in the classified asteroids.**
  Secondary class: S-complex ➔ 30.5%

- family in the pristine zone, but probably got dynamically implanted there.

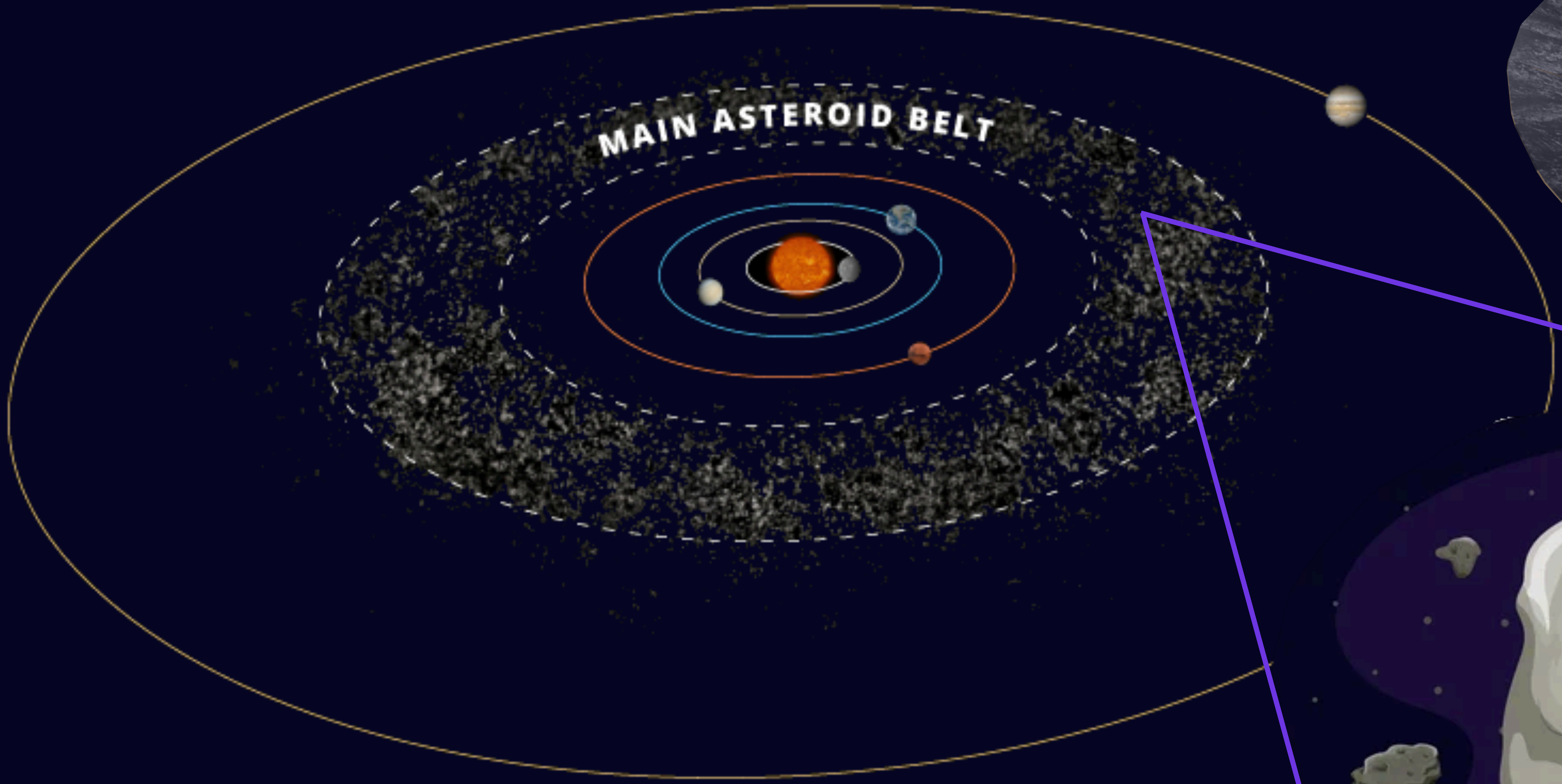
- grouping of potential A-types outside the V-shape of Eos, probable mix with Eos fugitives

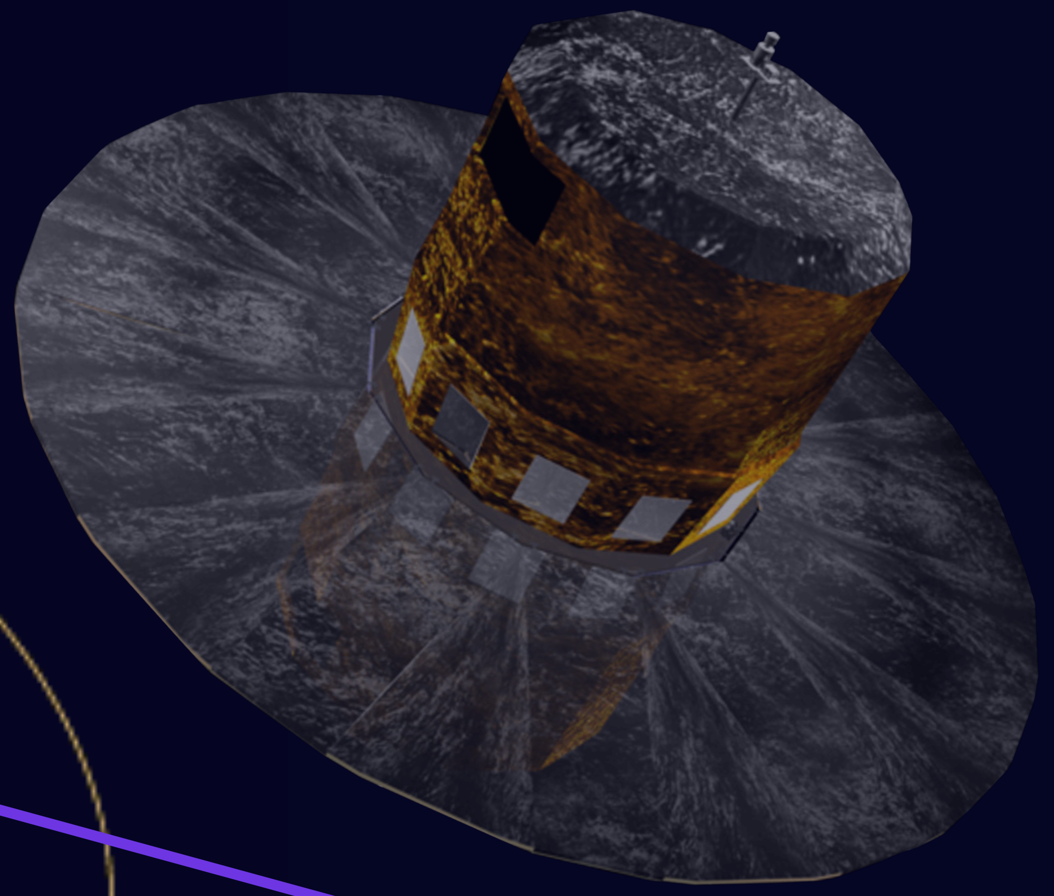
- *IF* **A-types are real, and are the only real members of family (36256) 1999 XT17:**
  dynamical family (36256) mix of A-types from a **common olivine-rich parent body** + interlopers.

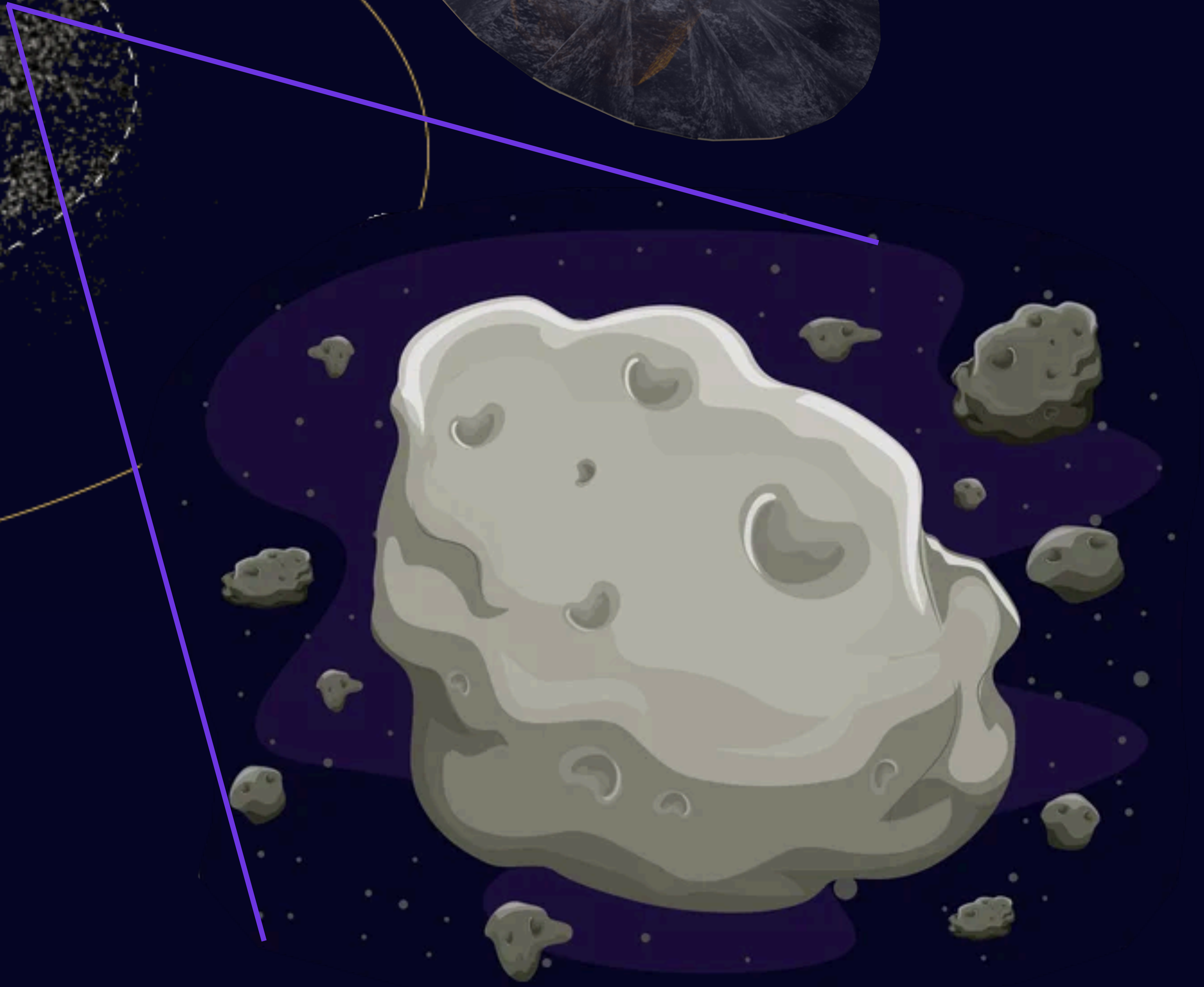
  Olivine-rich parent body once part of the mantle of a differentiated planetesimal? Planetesimal catastrophically disrupted in another region, and a fragment of it implanted in pristine zone?

Conclusion and perspectives

- **Spectroscopy** is a powerful tool to probe the surface composition of asteroids.
- The ***Gaia* DR3** increased drastically the amount of available small bodies spectra.
- **Large homogeneous dataset**: allows to study asteroid families, for example.
- Family (36256) 1999 XT17: potential small **A-type family**.
- Need **NIR observations** to confirm the spectral type of the asteroids, and to confirm any scenario
- If A-types are confirmed, there is a concentration of A-type asteroids in an asteroid family.







Thank you !