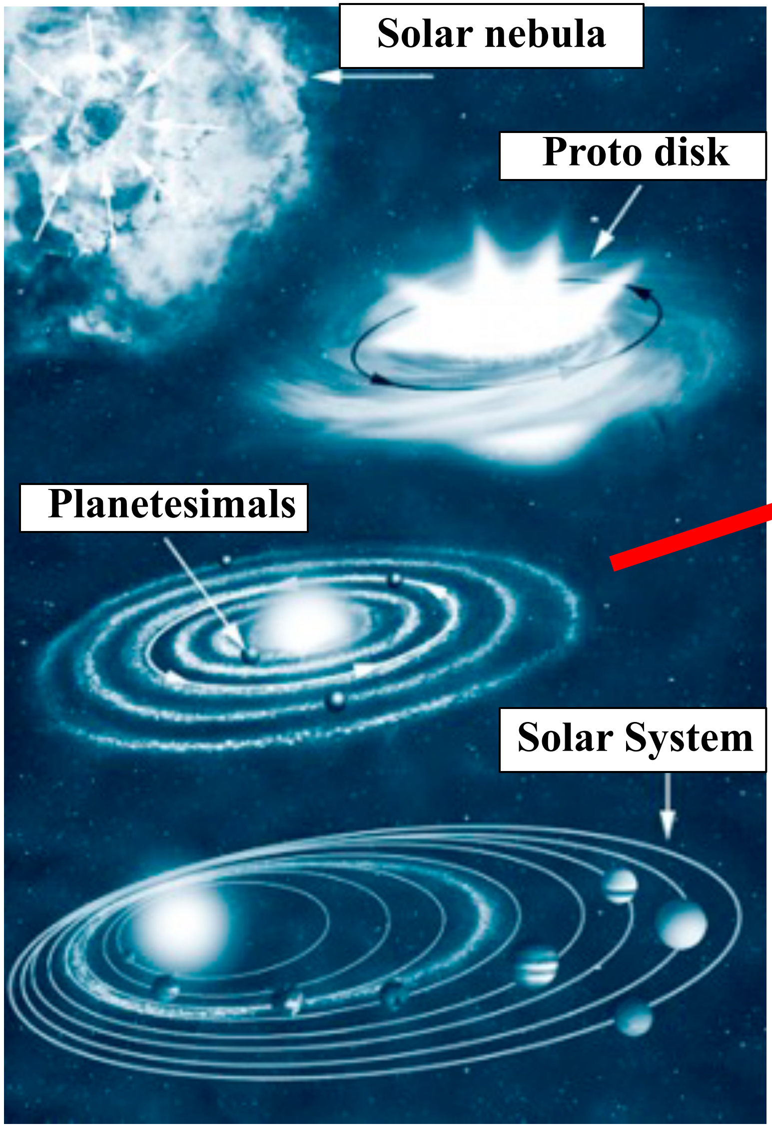
Constraints on the formation and evolution of primordial main belt asteroids

P. Vernazza (LAM), L. Jorda, B. Carry, F. Marchis, M. Marsset, J. Hanus, M. Viikinkoski, T. Santana-Ros, T. Fusco, C. Dumas, B. Yang, M. Birlan, E. Jehin, J. Durech, M. Kaasalainen, and the HARISSA team

Deciphering the History of the Solar System



Planetesimals:
asteroids
comets
TNOs

provide detailed constraints on:

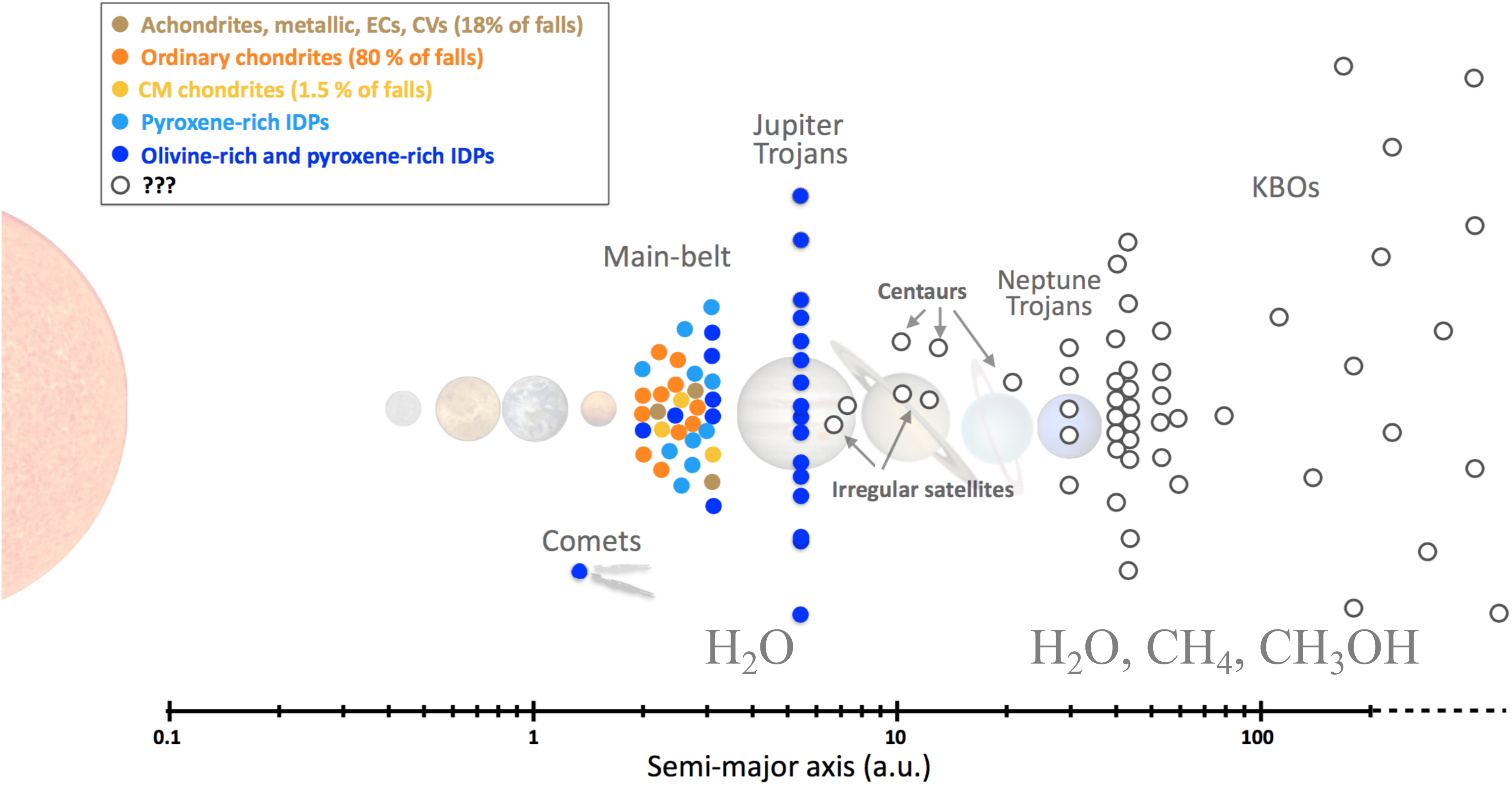
- The chronology of the early solar system (first 5-10 Myrs)

- The primordial chemical composition from which planets once accreted

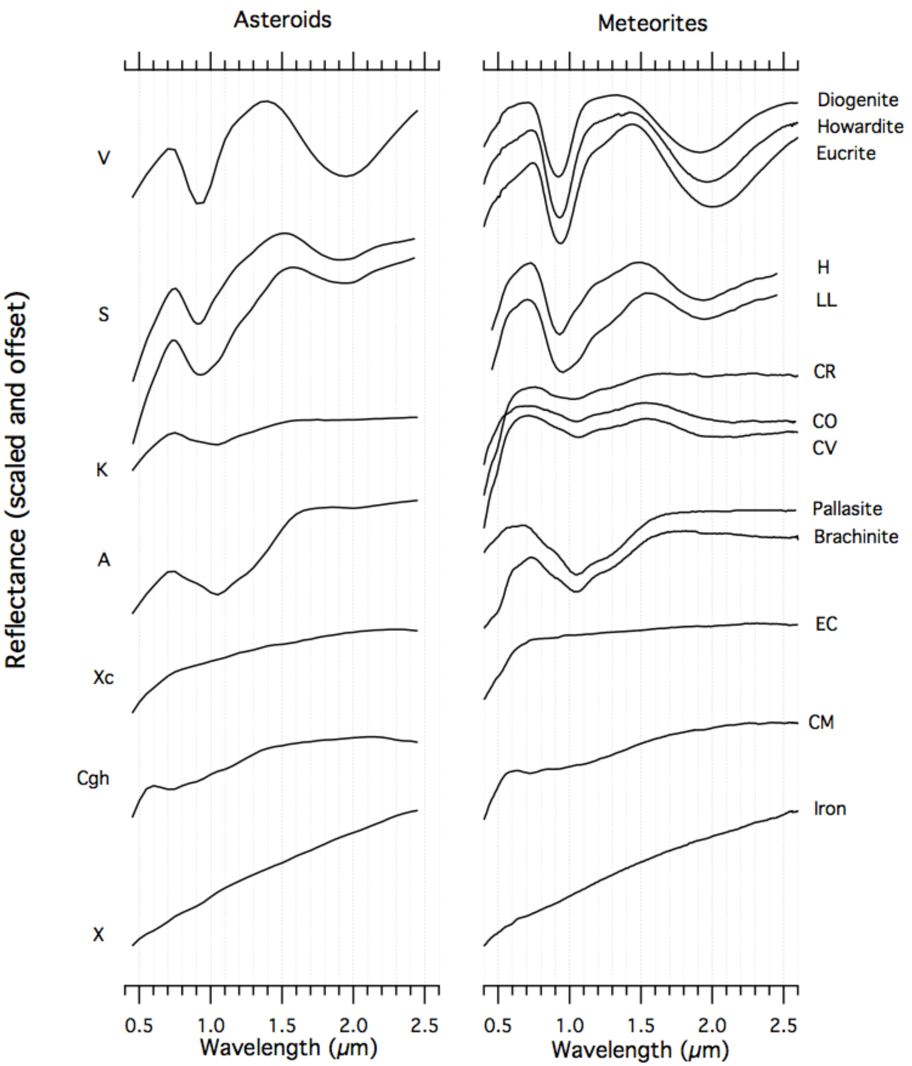
- The dynamical evolution of the solar system

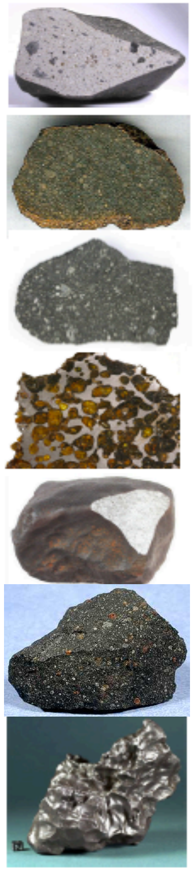
Compositional distribution across the solar system: State of the art before the start of the large programme

From Vernazza & Beck (2017)



Examples of asteroids with meteoritic analogues

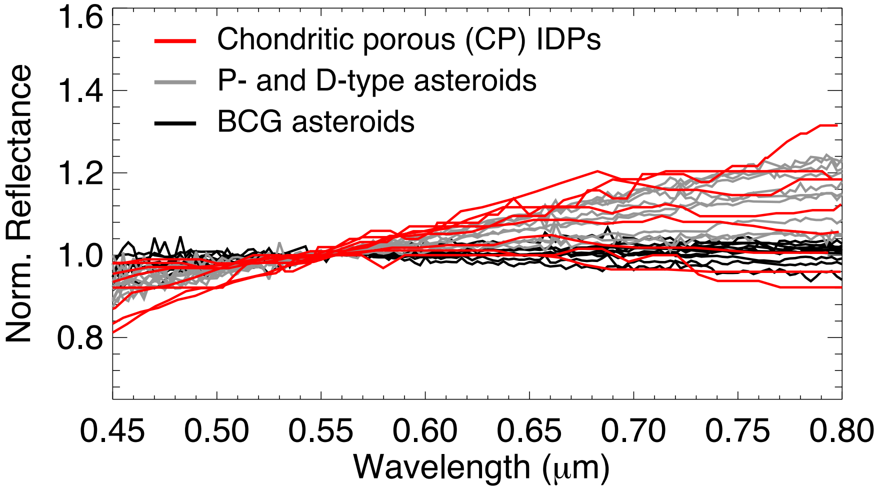


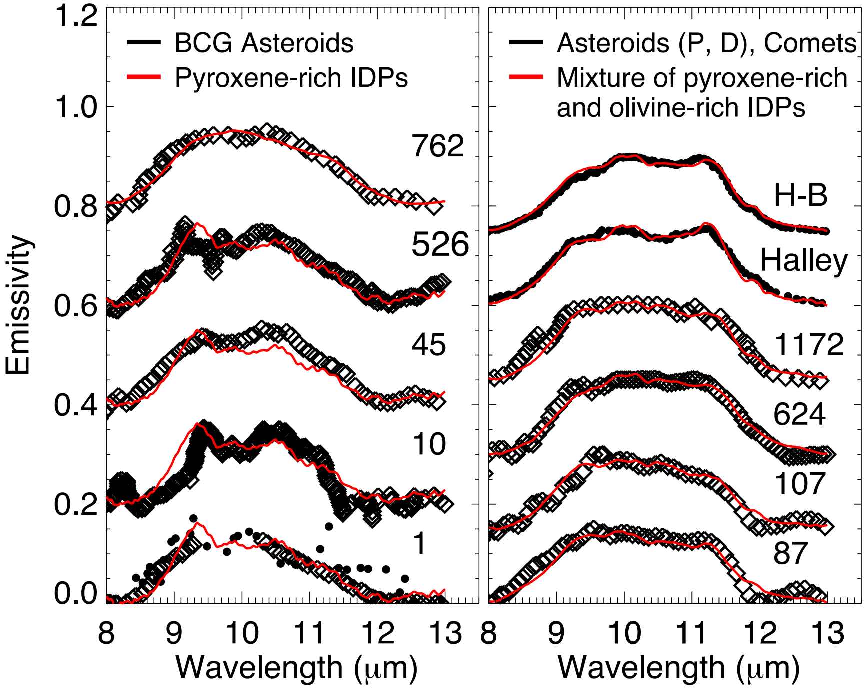


Vernazza & Beck 2016

Falls	Mass in the asteroid belt
6.2%	9.6%
80.0%	8.4%
1.9%	1.0%
1.1%	0.4%
2.5%	0.1%
1.5%	7.0%
4.6%	3.3%
Total	Total
~98%	~30%

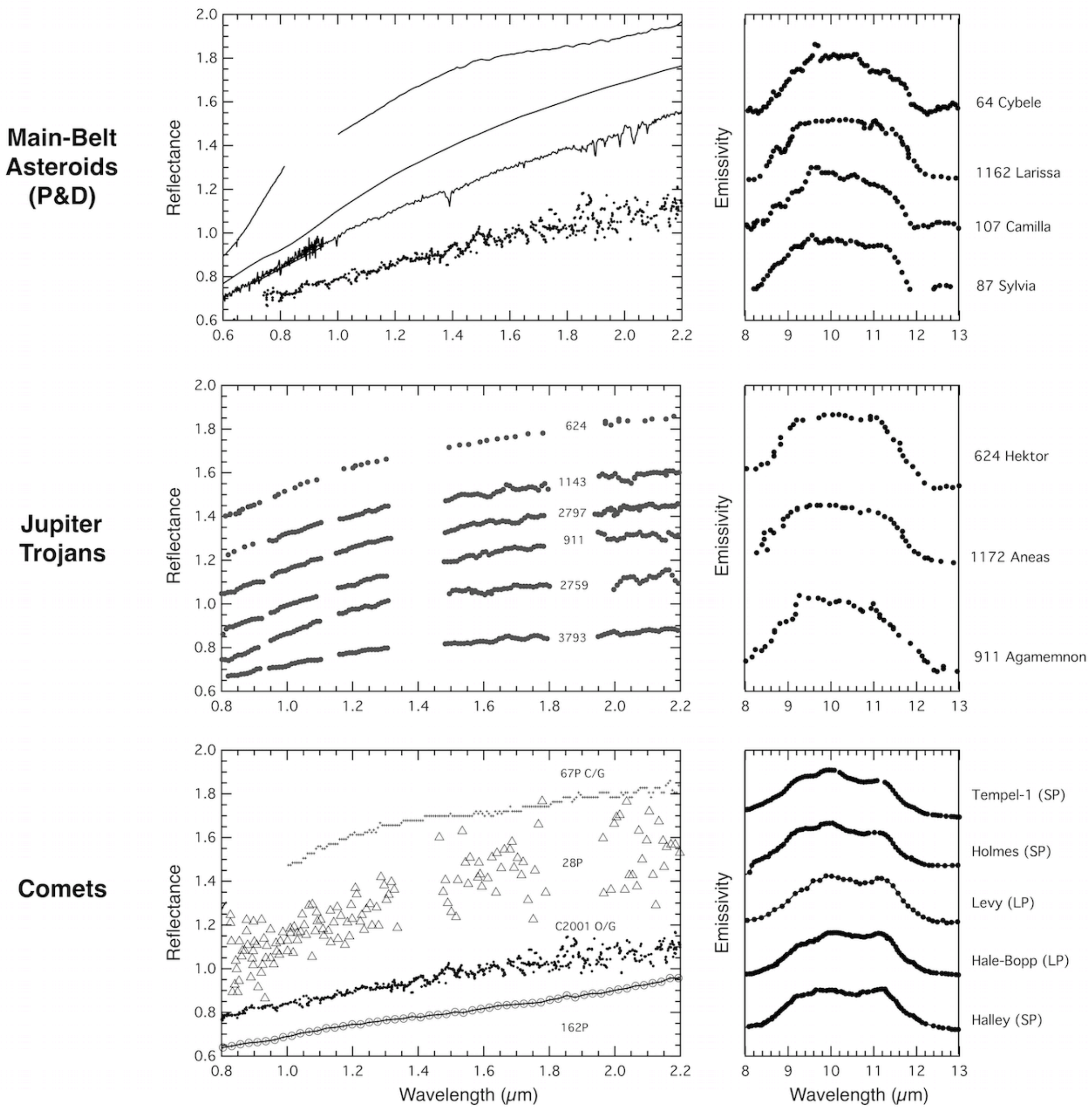
IDPs as plausible analogues of the surfaces of C, P and D types



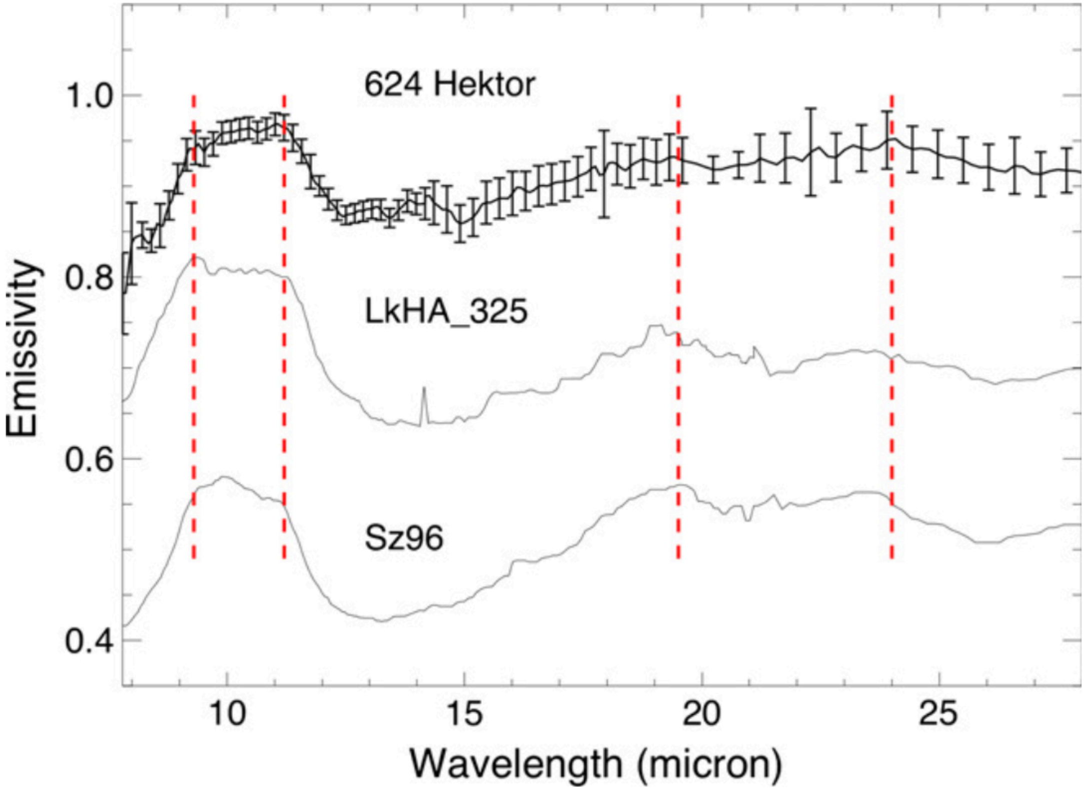


Vernazza et al. 2015

Connection between P/D-type asteroids and the outer Solar System



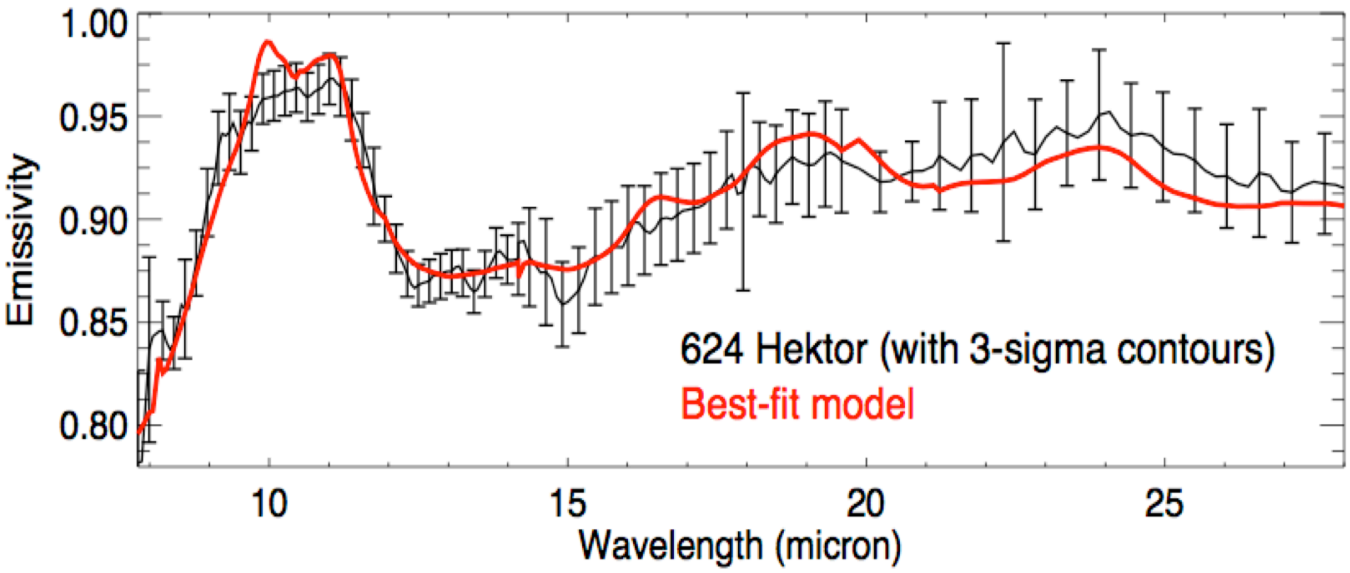
IDP-like asteroids versus Protoplanetary disks



Vernazza et al. 2012

Composition of IDP-like asteroids

Surface composition dominated by fine-grained crystalline olivine and amorphous silicates
=> Important heritage from the ISM

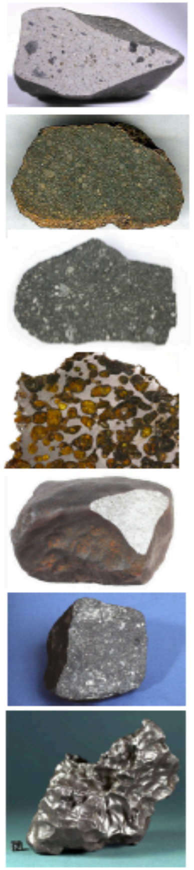


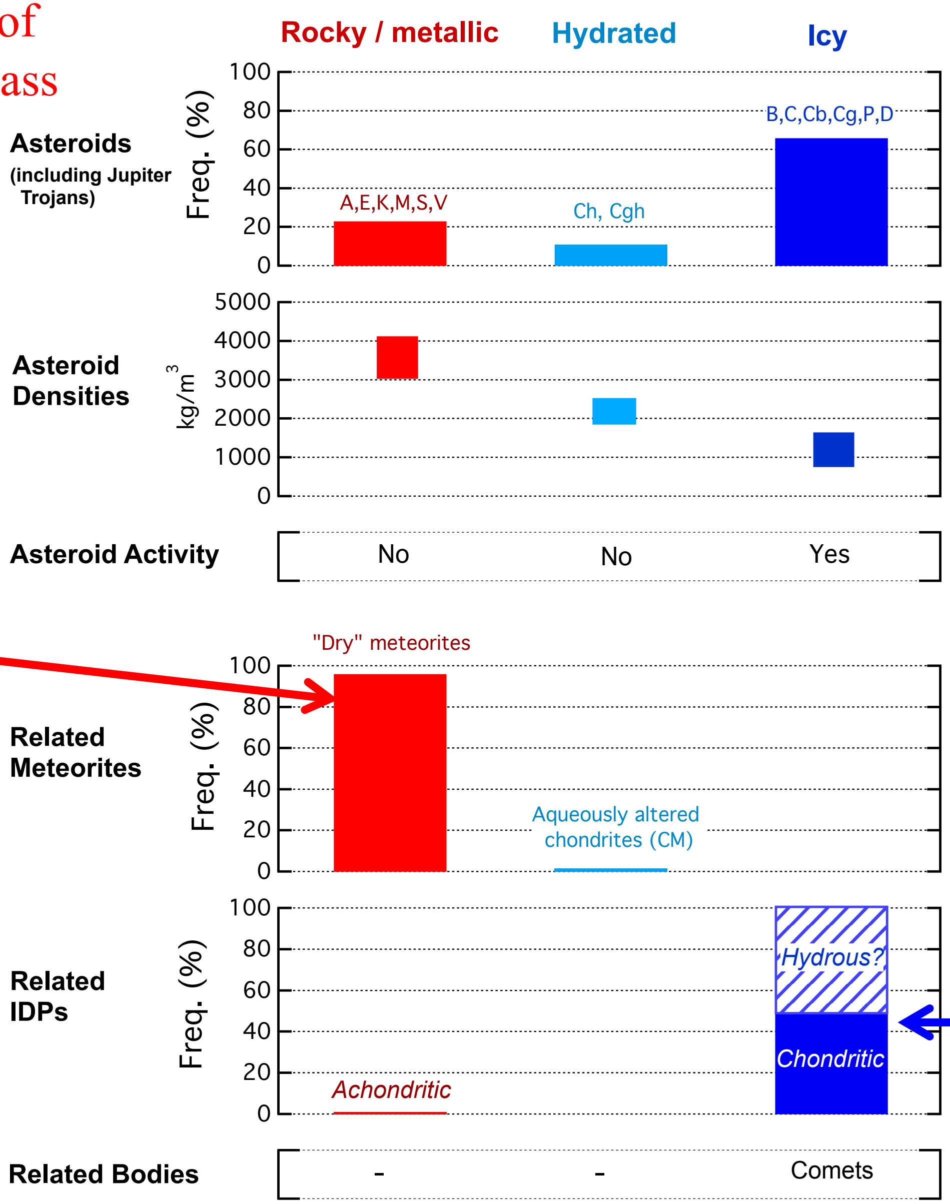
Vernazza et al. 2012

Mineral species	Abundance (in mass)	Abundance of the silicates (in mass)
Silica (SiO_2)	0.00	-
Crystalline olivine	0.68	22.74
Crystalline pyroxene	0.05	1.67
Amorphous olivine [(MgFe)SiO_4, Mg_2SiO_4]	2.19	73.25
Amorphous pyroxene [$MgSiO_3$, (MgFe)Si_2O_6]	0.07	2.34
Amorphous carbon	97.01	-

Asteroid Belt: Meteorites vs IDPs

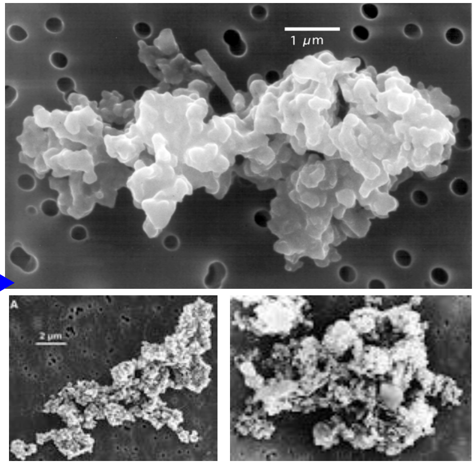
On Earth: <2% of extraterrestrial mass



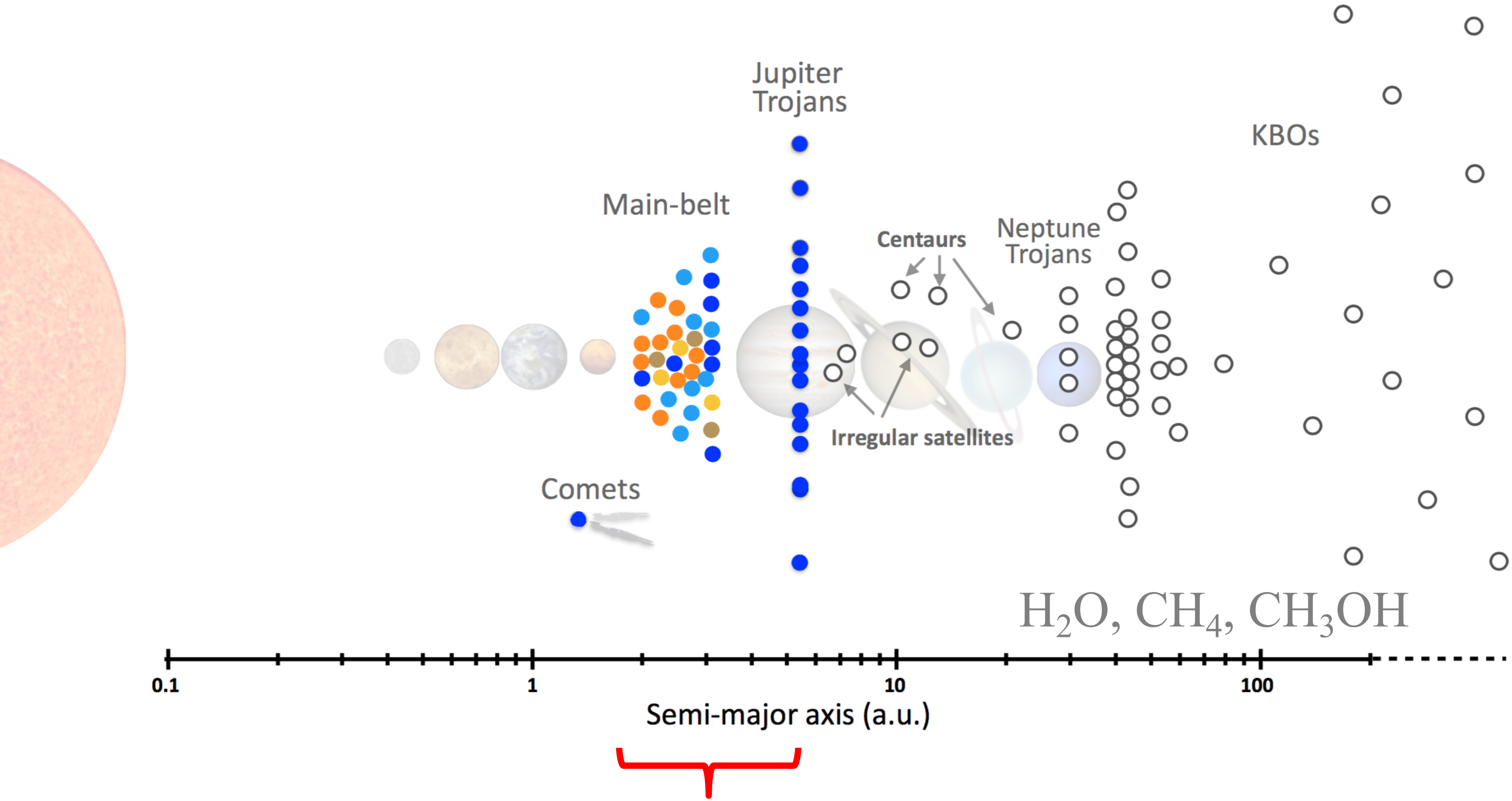


Vernazza et al. 2015

On Earth: >98% of extraterrestrial mass



Compositional distribution across the solar system: The next step



H_2O, CH_4, CH_3OH

Bulk composition (Density) / Geology

ESO Large program on VLT/SPHERE
(PI: P. Vernazza)

Purpose of the LP

- High angular-resolution imaging survey of a representative sample of all D≥100 km main-belt asteroids with VLT/SPHERE (**~35 objects**; **covering the main compositional types**) throughout their rotation

Output of the LP

- Precise 3D shapes and thus volumes for all targets (<10% error on the volume)
  => Density estimate for all targets (error comes mostly from mass determinations)
- The deconvolved images allow characterizing the distribution, size and profile of craters with D>30km.
- Potential discovery of new satellites

Outstanding questions linked to the LP

A) What is the diversity in shapes among large asteroids and are the shapes close to equilibrium ?

B) How do large impacts affect asteroid shapes ?

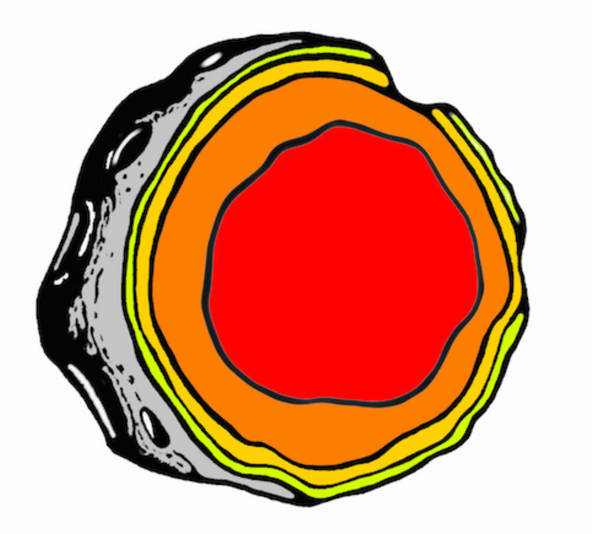
C) What is the bulk density of large asteroids and is there a relationship with their surface composition? Is there any evidence of differentiation among those bodies?

D) Is the density of those bodies that are predicted to be implanted bodies from the outer solar system compatible with that of TNOs ?

E) What physical properties drive the formation of companions around large asteroids?

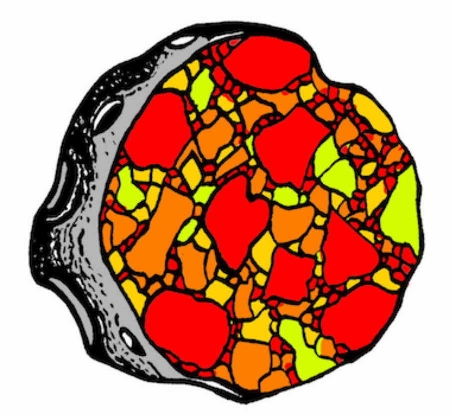
Primordial main belt asteroids: Definition

Primordial (Morbidelli et al. 2009):
D>~100km



Low macroporosity
Density: Powerfull constraint of the bulk composition

Rubble piles:
D<100km



High macroporosity
Density: Weak constraint of the bulk composition

Primordial D>100km main belt asteroids: Current knowledge

- There are ~230 MBAs with D>100km (23 MBAs with D>200km)
- For these bodies, the following properties are well characterized:
  - Orbit
  - Albedo
  - Visible and near-infrared spectrum
- For most of these bodies, mass and 3D shape/volume - hence density - are not well constrained
- For most of these bodies, a surface map of the craters does not exist

=> Few geologic constraints available for these bodies

(FB) Ida (56 km)

Dactyl (1 km)

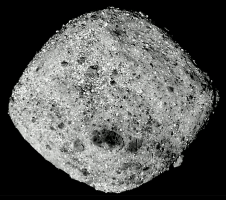
(FB) Gaspra (12 km)

(RV) Eros (33 km)

(RV) Itokawa (330 m)

(FB) Mathilde (66 km)

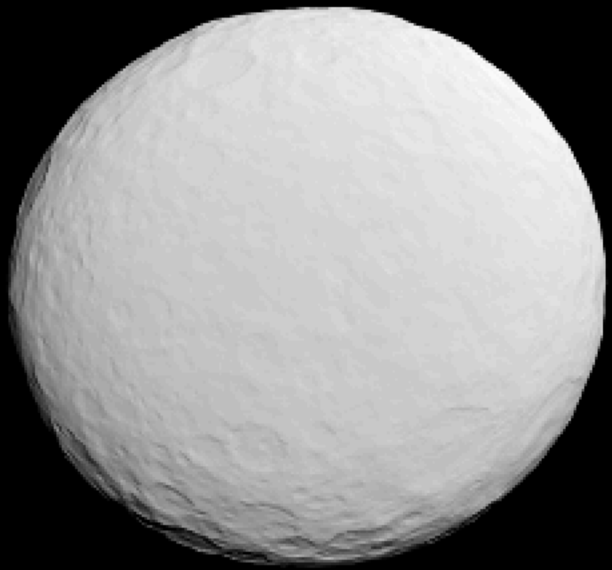
(RV) Bennu (490 m)



(RV) Ryugu (980 m)

(FB) Steins (5 km)

(RV) Ceres (950 km)



(RV) Vesta (525 km)

(FB) Lutetia (98 km)

Current status

- No time loss: all the allocated time (152) has been executed.

- ZIMPOL data for 42 objects. Good rotational coverage (≥ 4 epochs) for **39 objects** (1 Ceres, 2 Pallas, 3 Juno, 4 Vesta, 6 Hebe, 7 Iris, 8 Flora, 9 Metis, 10 Hygiea, 11 Parthenope, 12 Victoria, 13 Egeria, 15 Eunomia, 16 Psyche, 18 Melpomene, 19 Fortuna, 21 Lutetia, 22 Kalliope, 24 Themis, 29 Amphitrite, 30 Urania, 31 Euphrosyne, 41 Daphne, 45 Eugenia, 51 Nemausa, 52 Europa, 63 Ausonia, 87 Sylvia, 88 Thisbe, 89 Julia, 128 Nemesis, 130 Elektra, 173 Ino, 187 Lamberta, 216 Kleopatra, 324 Bamberga, 354 Eleonora, 511 Davida, and 704 Interamnia)+ data for 48 Doris, 145 Adeona, 230 Athamantis

- Publications: - 16 papers published among which 2 in Nature Astronomy

  (Broz et al. 2021, 2022; Carry et al. 2019; 2021, Dudzinski et al. 2020; Ferrais et al. 2020; Fetick et al. 2019; Hanus et al. 2019, 2020; Marchis et al. 2021; Marsset et al. 2020; Vernazza et al. 2018, 2020, 2021, Viikinkoski et al. 2018; Yang et al. 2020).

  - 1 paper submitted, 1 paper in preparation

VLT/SPHERE/ZIMPOL versus VLT/NACO

2 Pallas

Angular diameter: 0.42”

Angular diameter: ~0.5”

Rosetta versus VLT/SPHERE/ZIMPOL

D~100km

21 Lutetia (seen at a distance of $\sim 7x10^4$ km)

D~200km

7 Iris (seen at a distance of $\sim 1.35x10^8$ km)

Deconvolution:
Observed vs synthetic (moffat) PSF

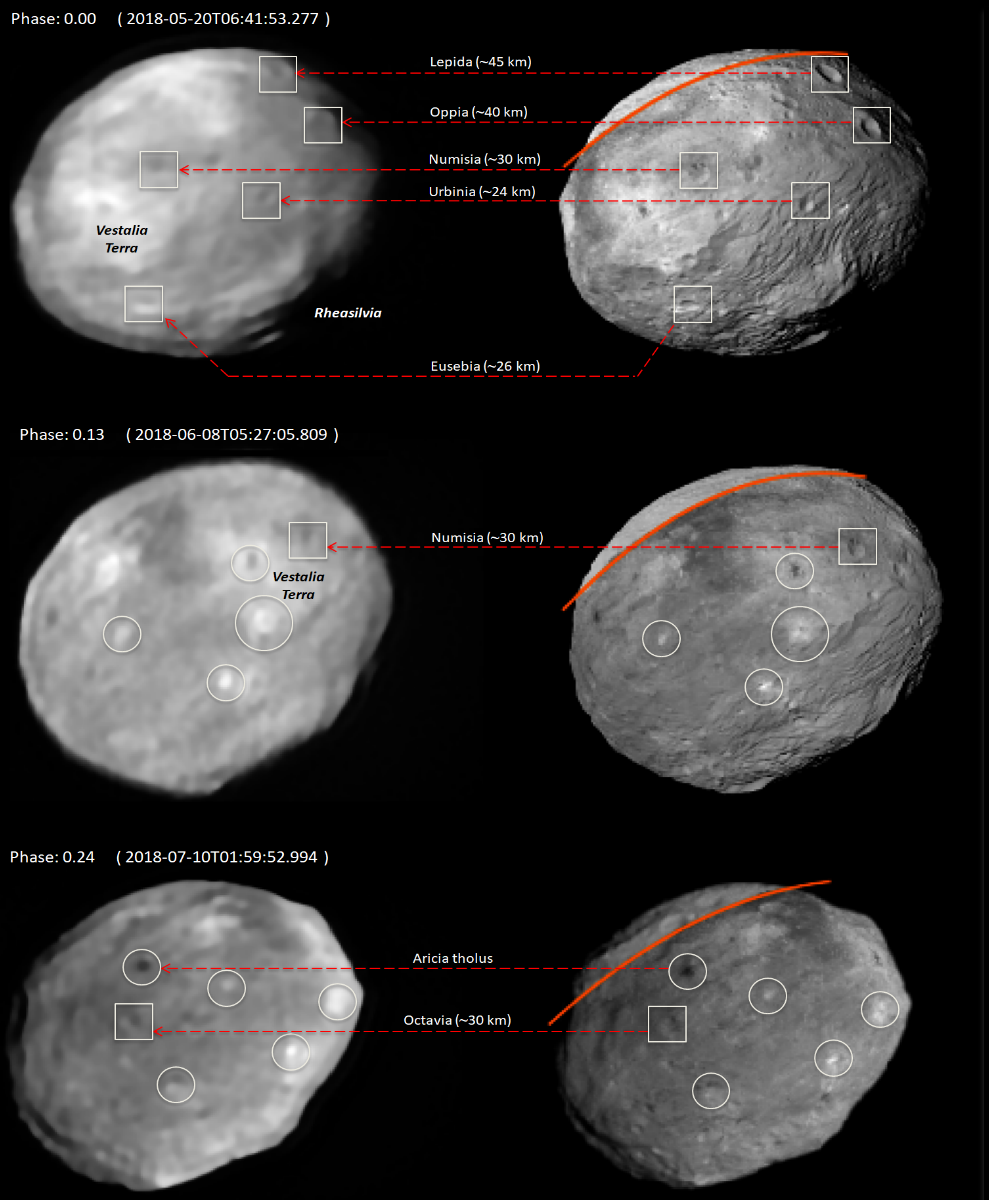
Deconvolution
with observed PSF

Deconvolution
with synthetic PSF

=> Systematic use of synthetic PSF.

VLT/SPHERE

DAWN/OASIS



Phase: 0.00 (2018-05-20T06:41:53.277)

Phase: 0.13 (2018-06-08T05:27:05.809)

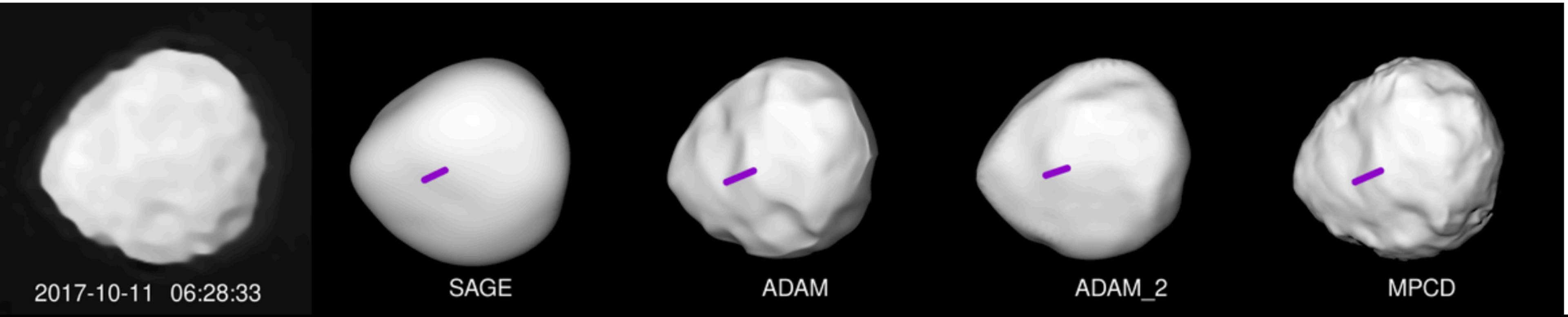
Phase: 0.24 (2018-07-10T01:59:52.994)

Fetick et al. 2019

Reconstruction of the 3D shape

We started the observing program with one 3D shape reconstruction model (ADAM). Three yers later, we have 3 models to play with.

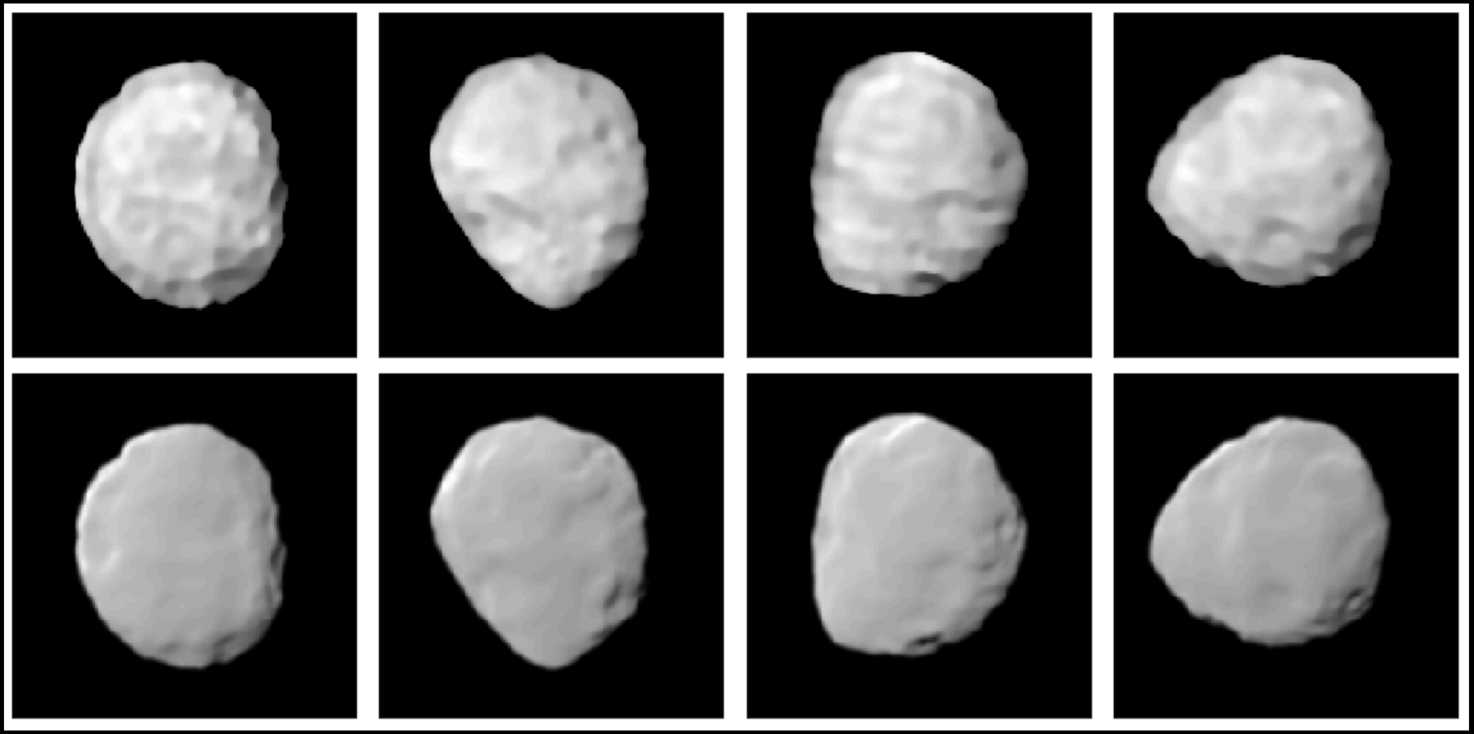
Dudzinski et al. 2020



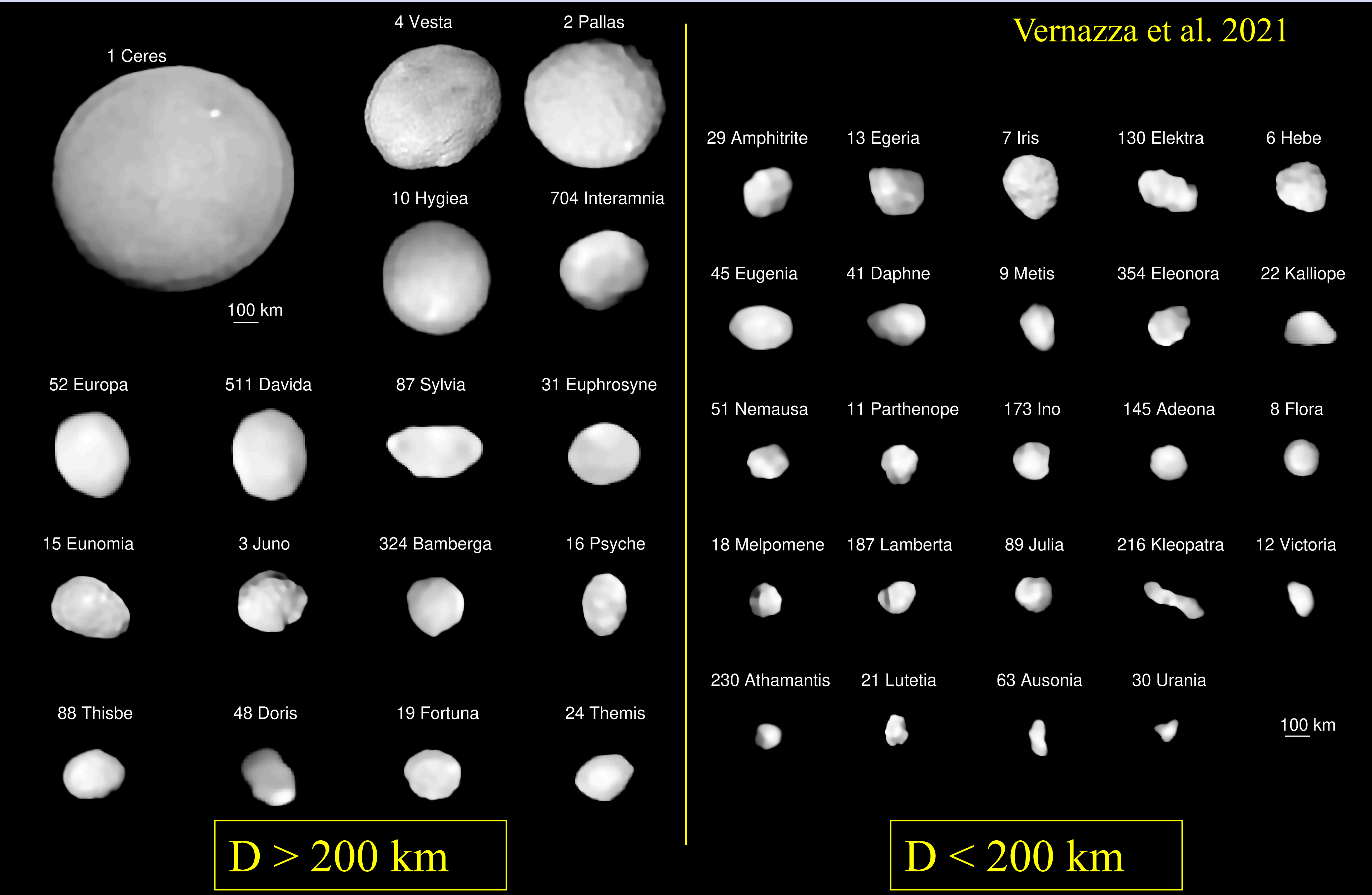
AO + LCs	AO + LCs+ Occ+ Radar	AO + LCs+ Occ+ Radar	AO

Reconstruction of the 3D shape

7 Iris

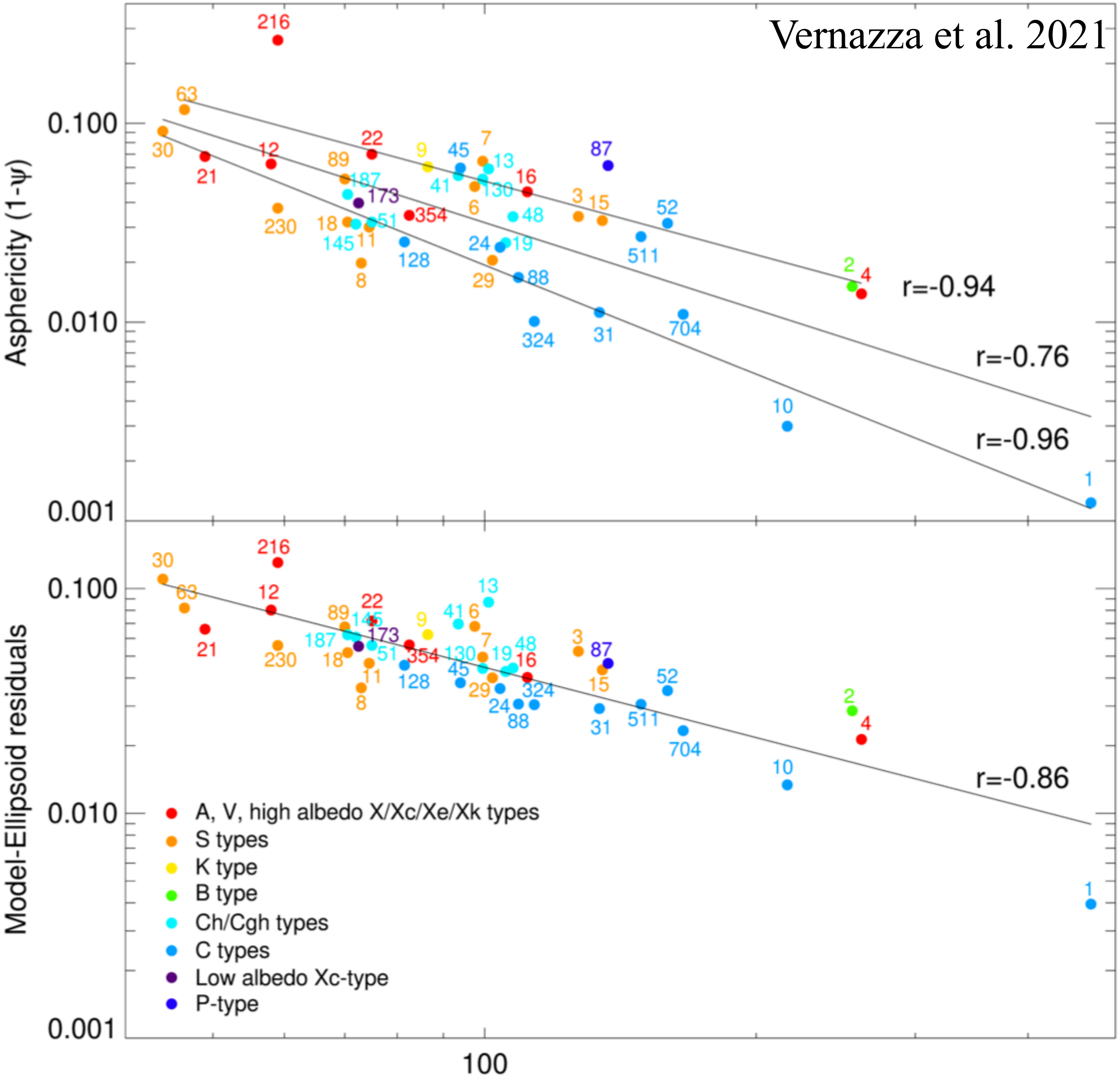


Organization chart with photographs of the largest asteroids



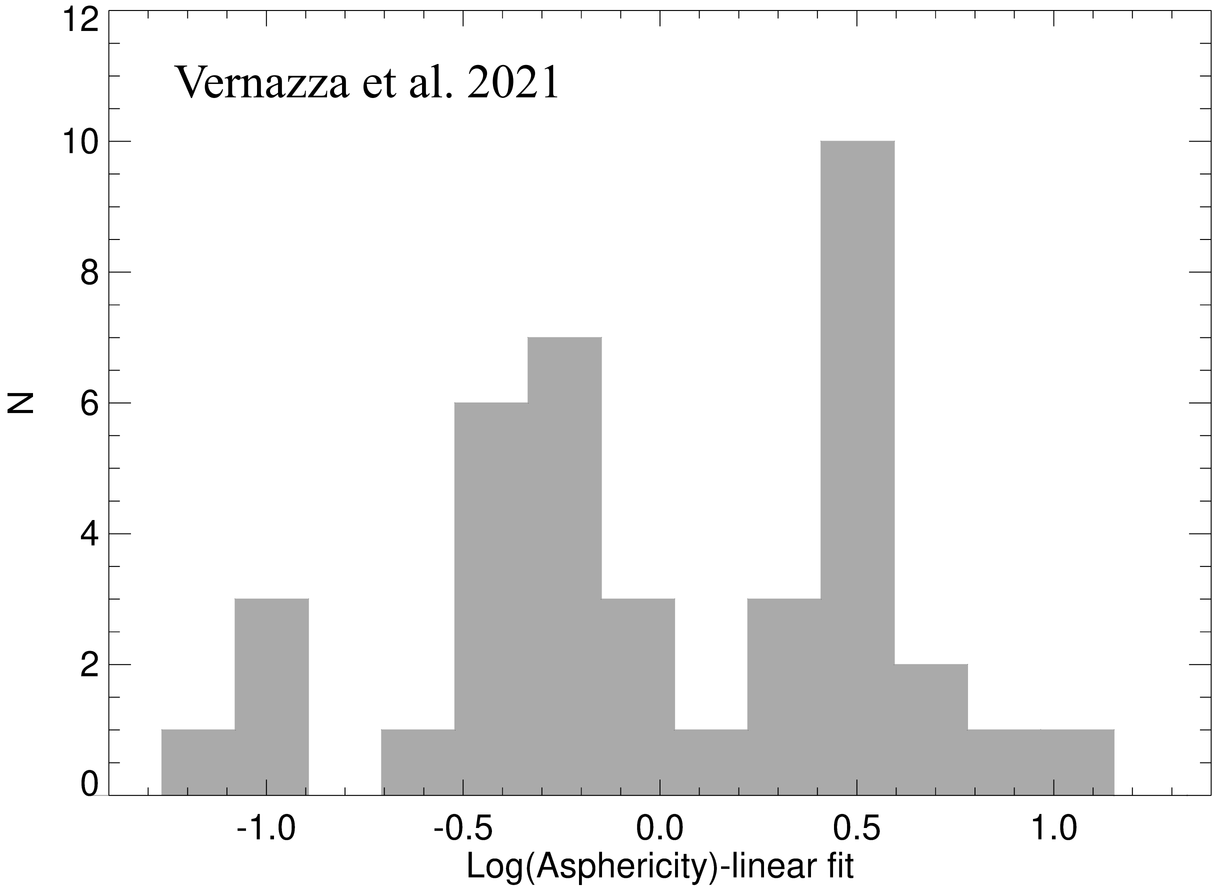
Vernazza et al. 2021

Strong correlation between size and shape



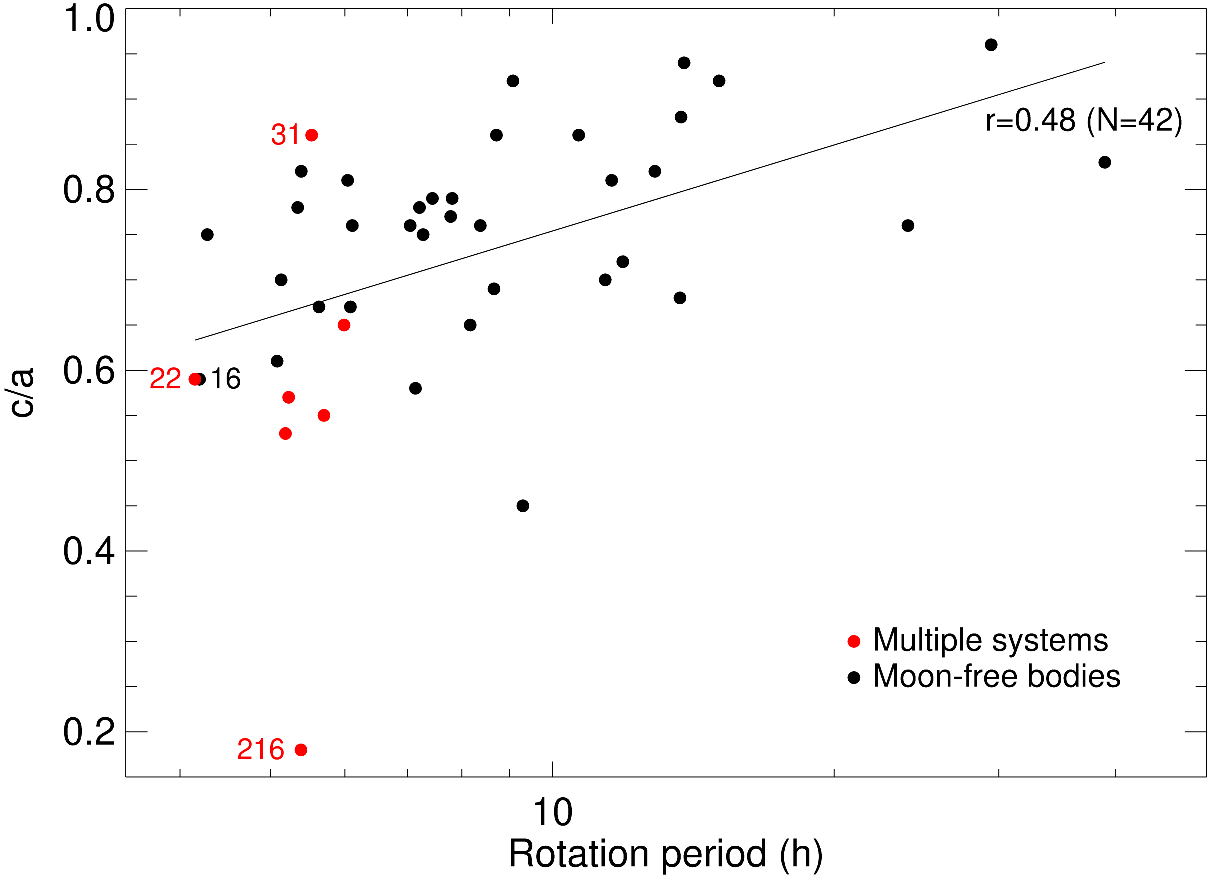
Vernazza et al. 2021

Bimodal distribution of the shapes



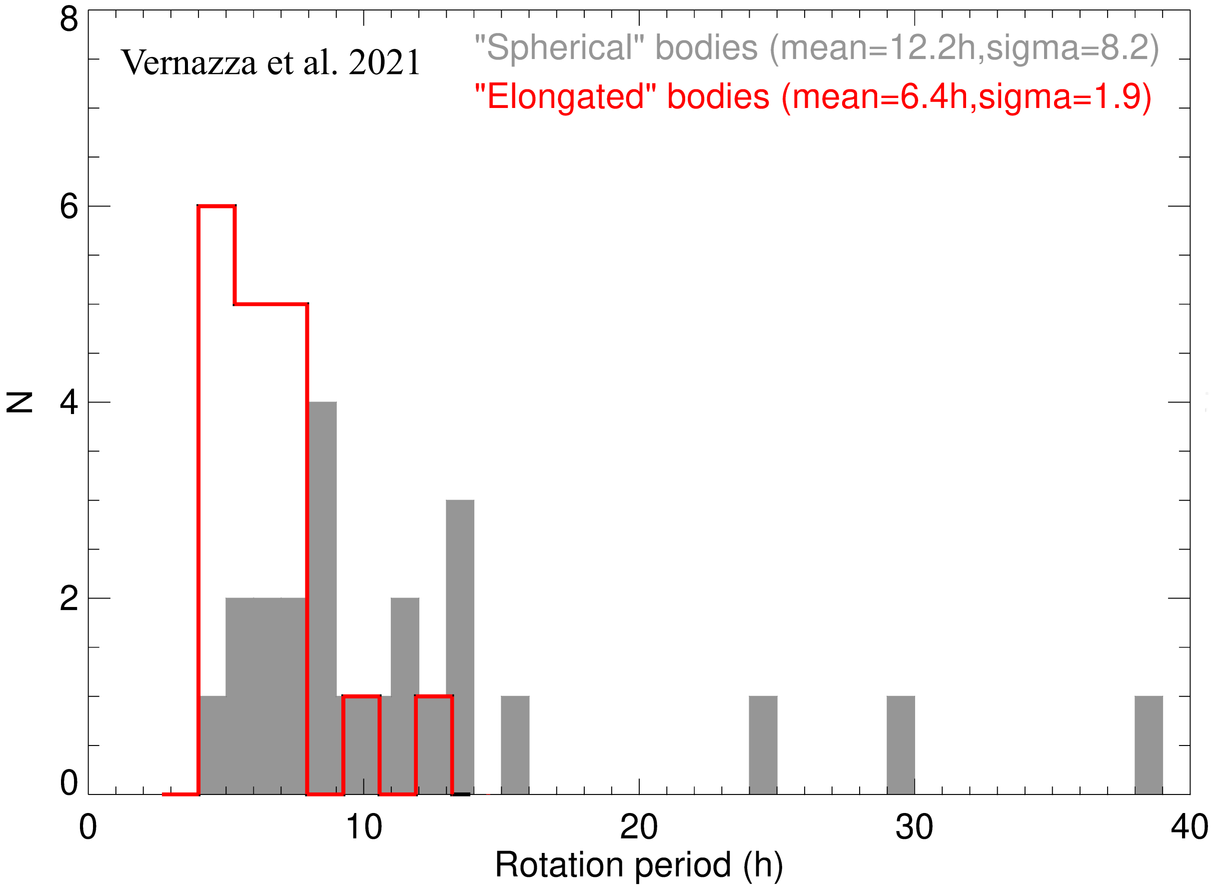
Rotation period as the main origin of the elongation/sphericity of bodies

All large multiple systems rotate in less then 6h and
5\6 have c/a < 0.65; 31 Euphrosyne is an exception !



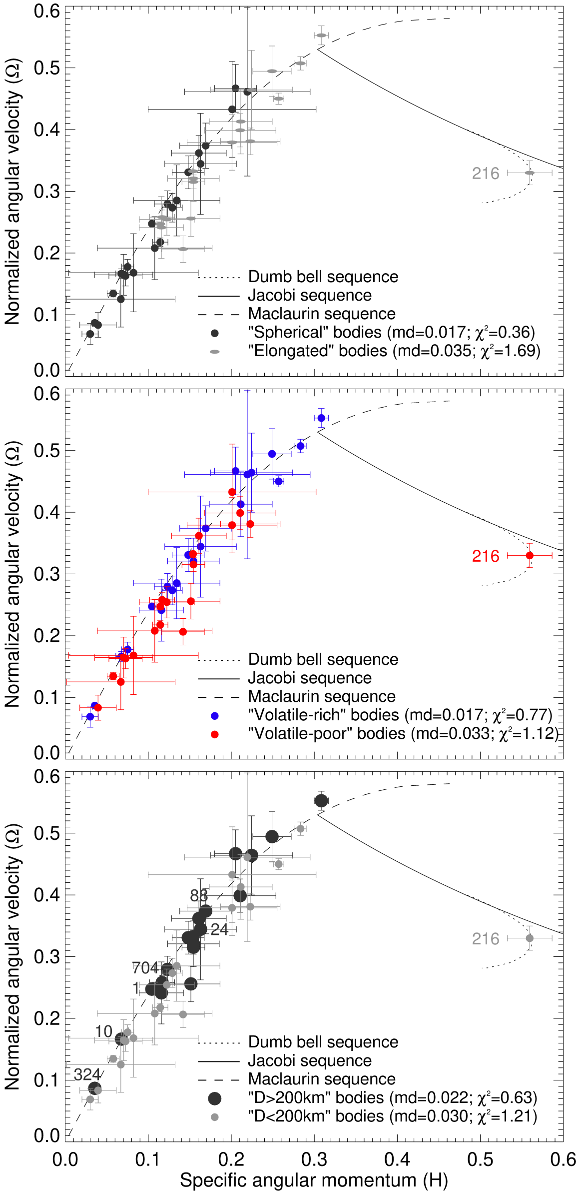
Vernazza et al. 2021

Rotation period as the main origin of the bimodal distribution of the shapes

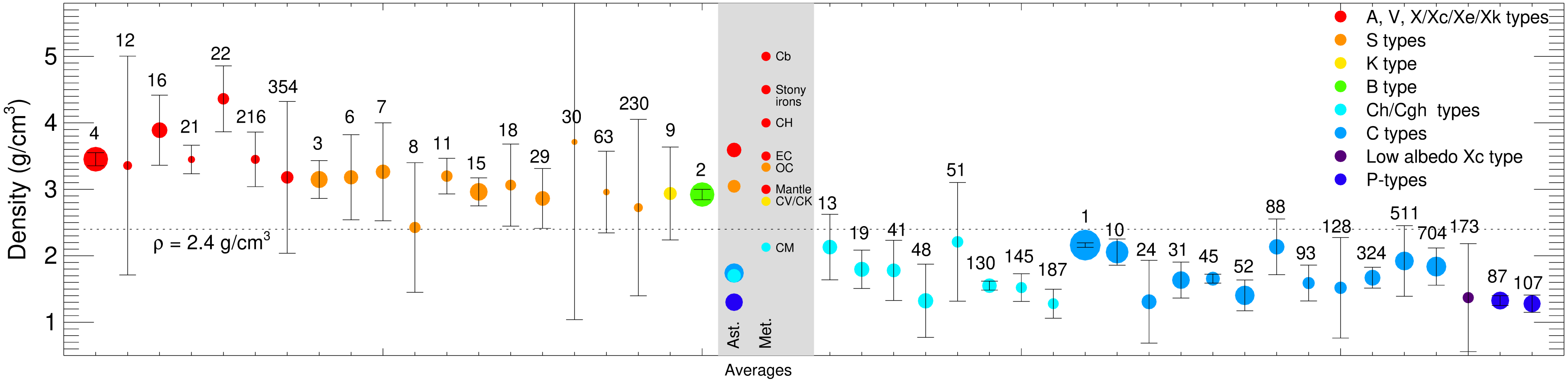


Size, shape and bulk composition define how close a body falls along the MacLaurin sequence

Vernazza et al. 2021

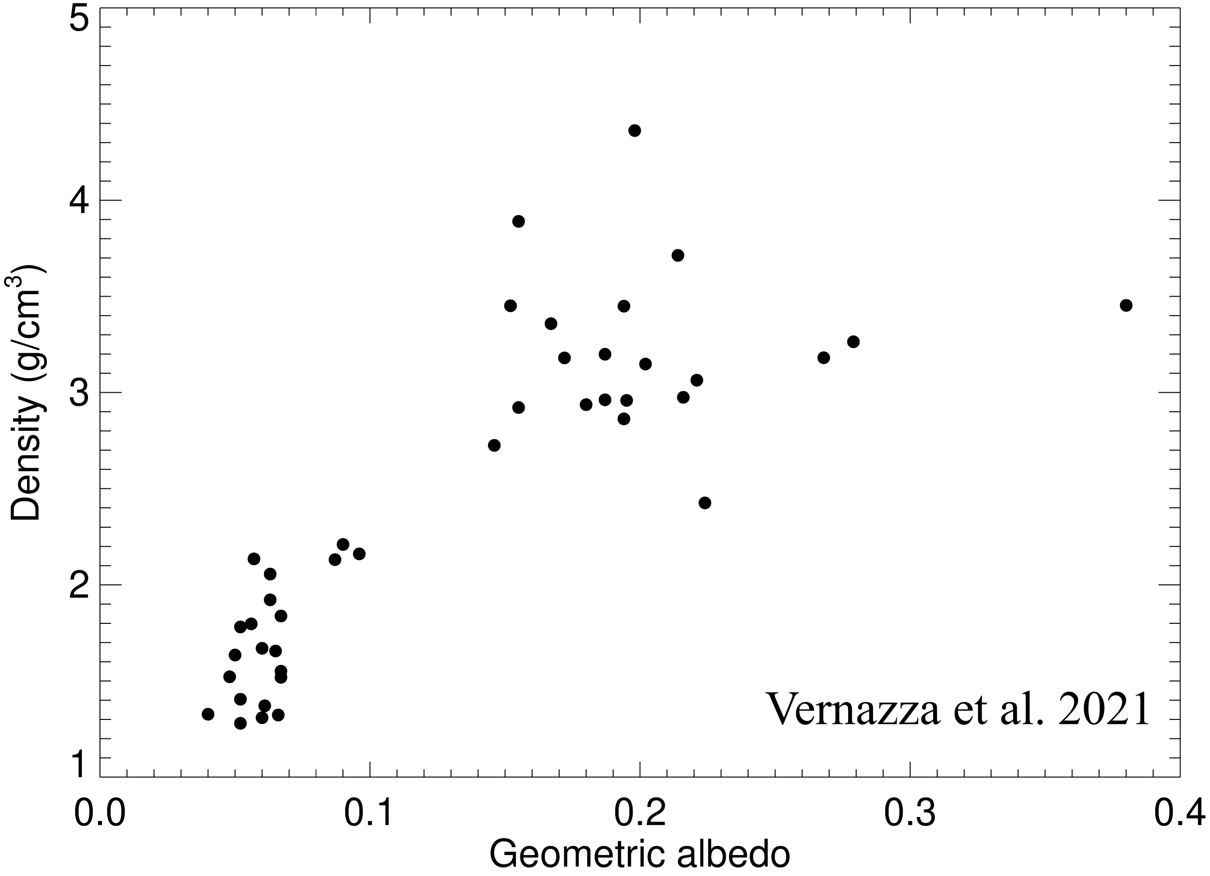


Densities of the largest asteroids

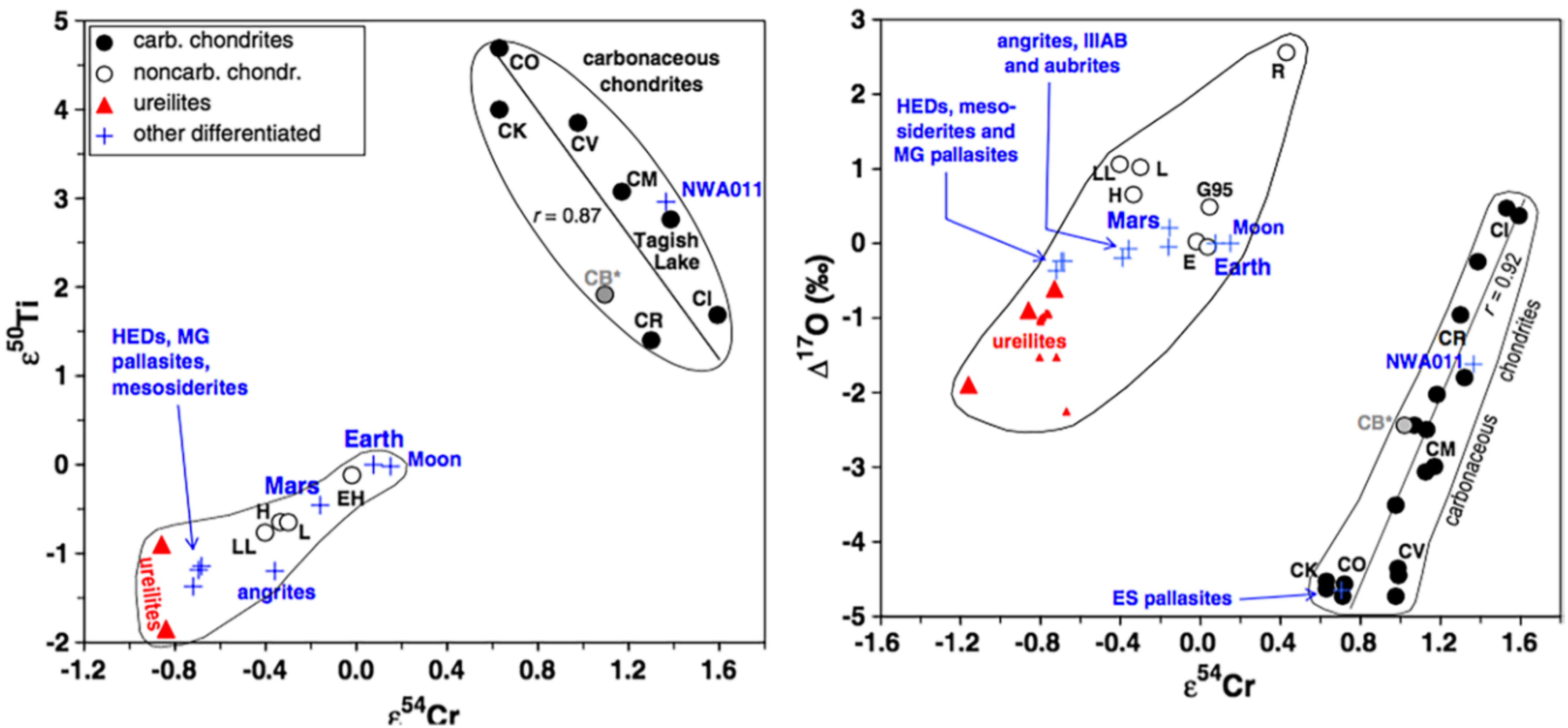


Vernazza et al. 2021

Relationship between the geometric albedo and density of large asteroids



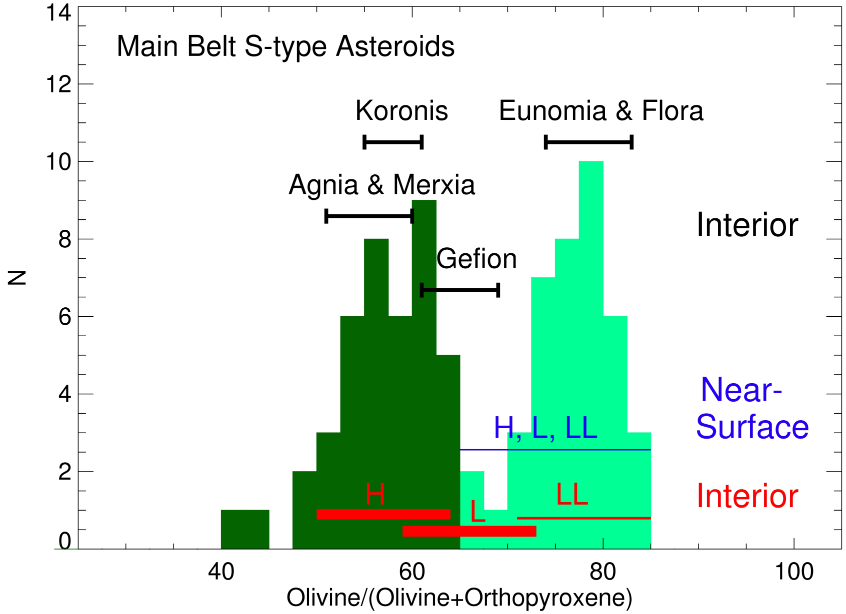
This dichotomy remains that (isotopic) between inner and outer solar system materials

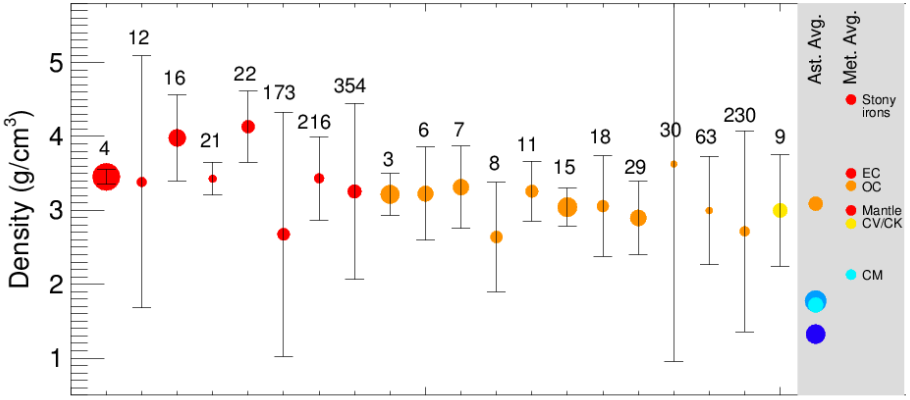


Warren 2011

Constraints on the formation and evolution of S-types (OC-like surfaces)

Vernazza et al., 2014



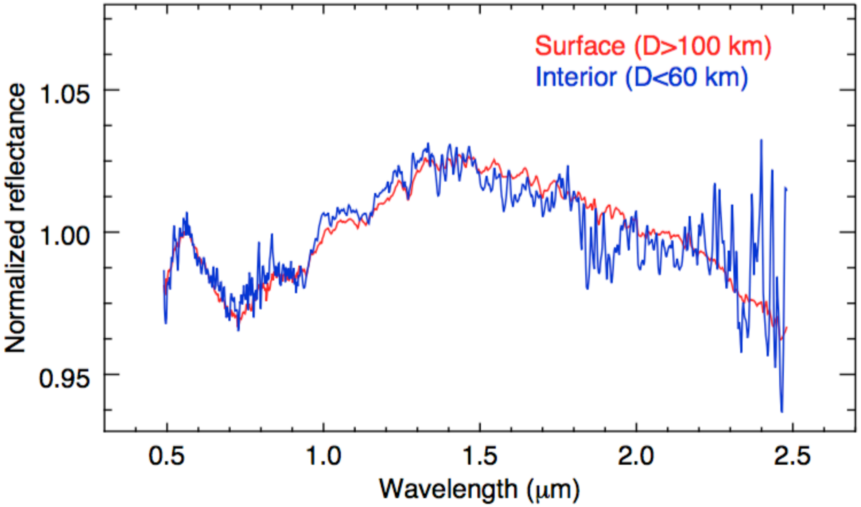


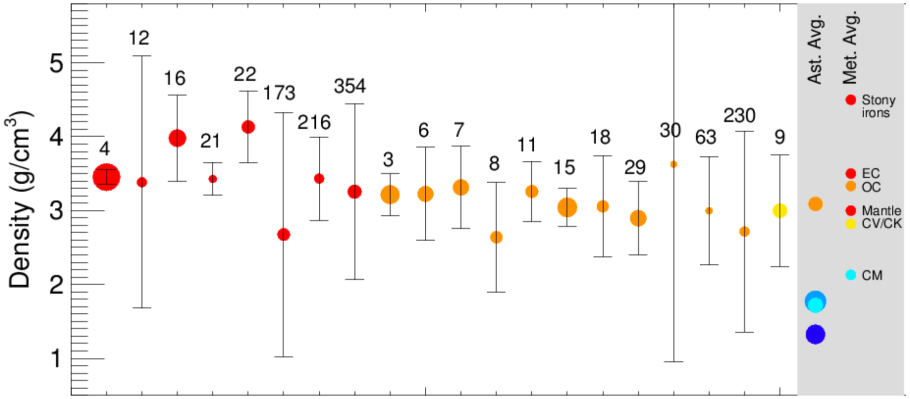
Vernazza et al. 2021

Implication: Absence of differentiation

Constraints on the formation and evolution of Ch/Cgh-types (CM-like surfaces)

Vernazza et al., 2016

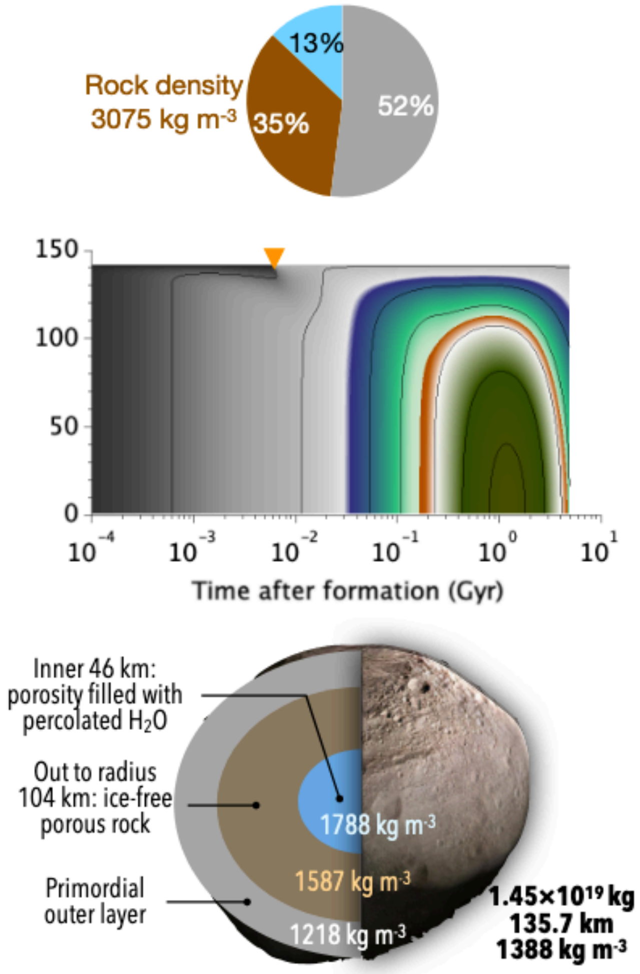




Vernazza et al. 2021

Implication: Absence of differentiation

Constraints on the formation and evolution of P/D-types (comet-like surfaces)



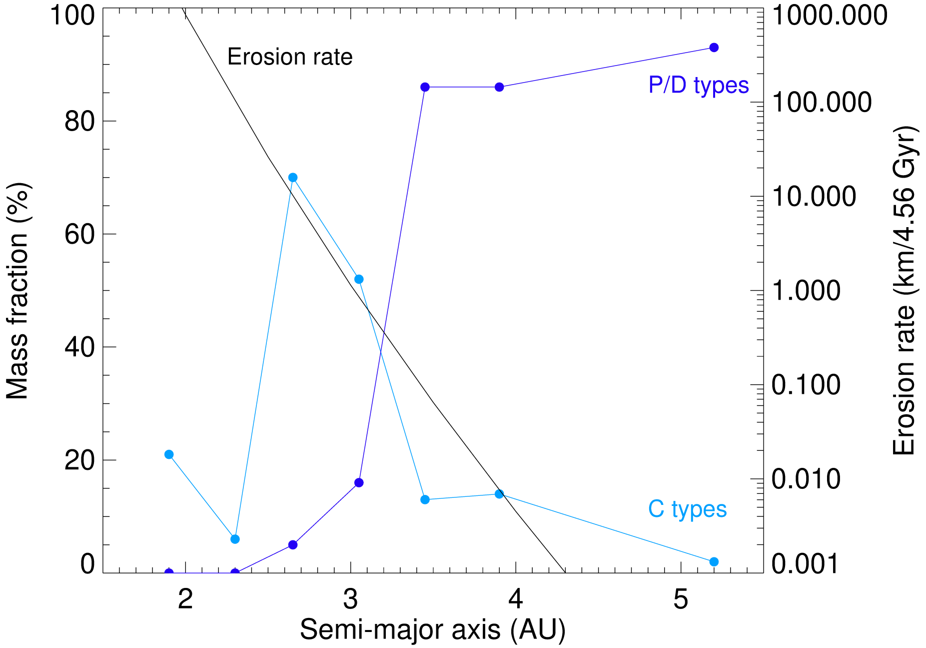
Carry et al., 2021

- The internal structure of 87 Sylvia implies a differentiated interior. A similar conclusion has been reached in the case of 107 Camilla (2nd largest P-type).
- Simulations shows that D>130 km P-types (TNOs) should have followed a similar thermal evolution.
- In the case of Sylvia, the density of the D~200 km large core amounts to ~1.7 g cm^{-3}, a value that is consistent with that of C-type asteroids.
- Eurybates collisional family among Jupiter Trojans shows mix of C- and P- types !

Implication: Evidence of differentiation

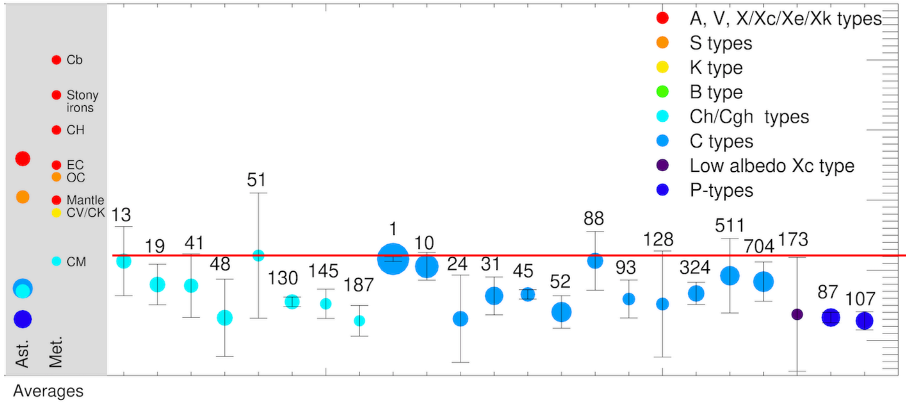
Constraints on the formation and evolution of C-types

- Similarity in density with Ch/Cgh types and the cores of large P-types
- In most cases, aqueous alteration did occur up to the surface, implying that the action of liquid water has litified the whole body as in the case of CM-like bodies (which may explain the similarity in density)
- Rather brutal transition in the asteroid belt from P- to C-types : similar origin but different evolution once implanted in the asteroid belt due to sublimation?

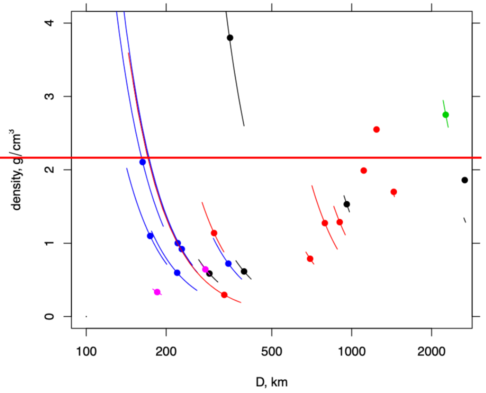


Vernazza et al. 2021

Density of C/P/D-types versus TNOs



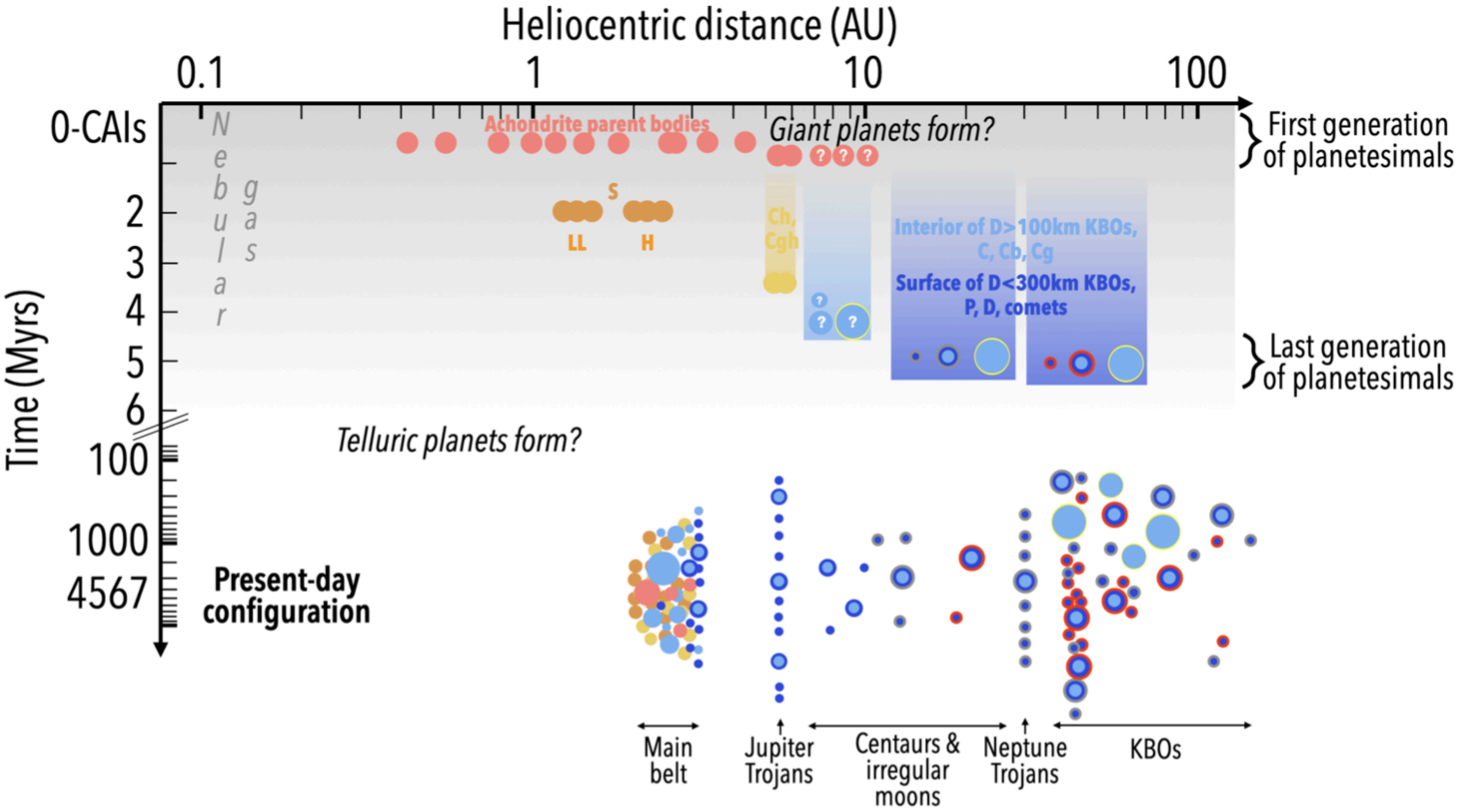
Vernazza et al. 2021



ρ=2.2 g/cm^3

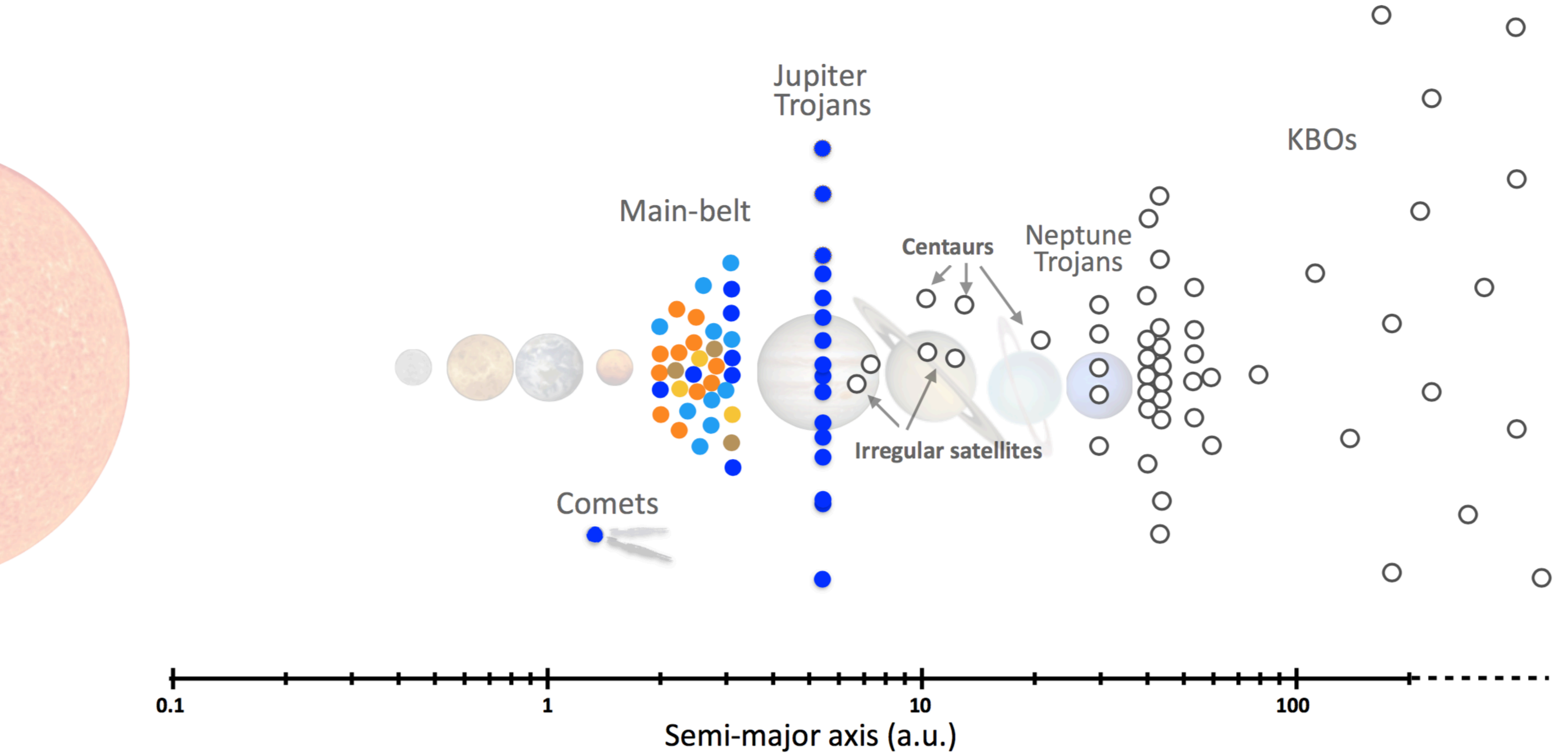
Kovalenko et al., 2017

Summary



Vernazza et al. 2021

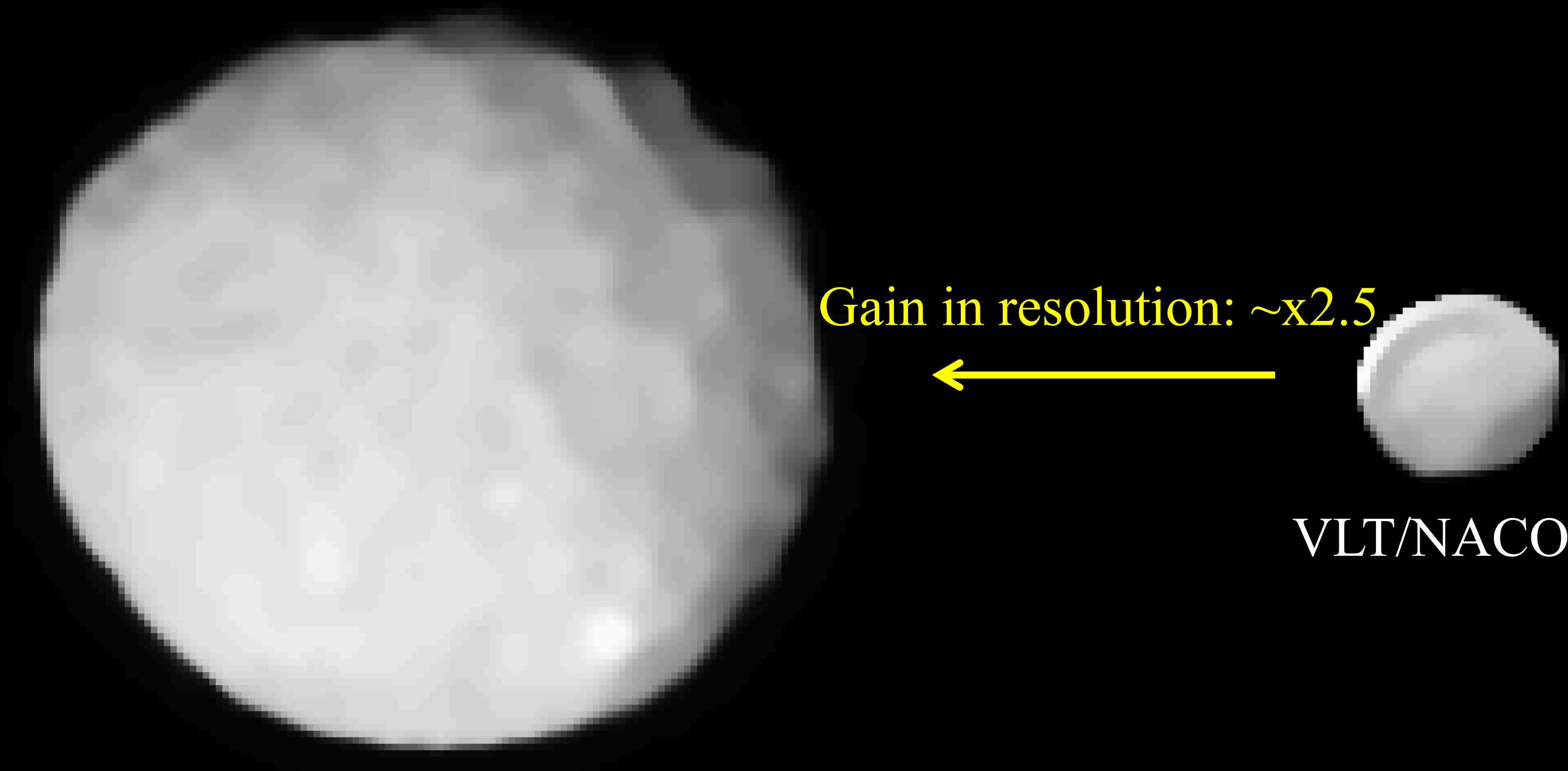
Compositional distribution across the solar system: The ELT era



Geology/Geophysics : Shape, Density

First light ELT observations: visualizing the gain in resolution w.r.t VLT/SPHERE/ZIMPOL

2 Pallas

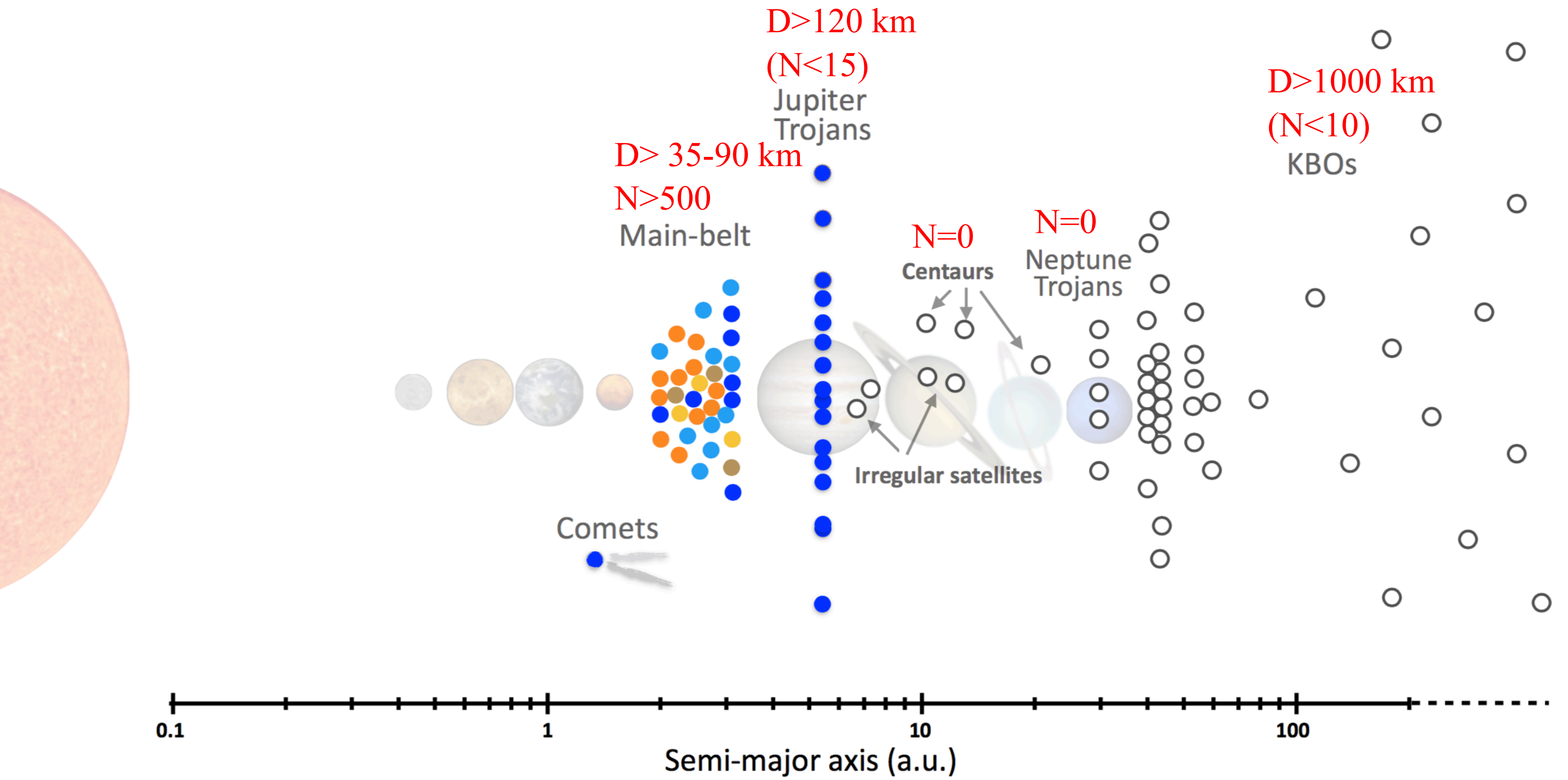


Gain in resolution: ~x2.5

VLT/NACO

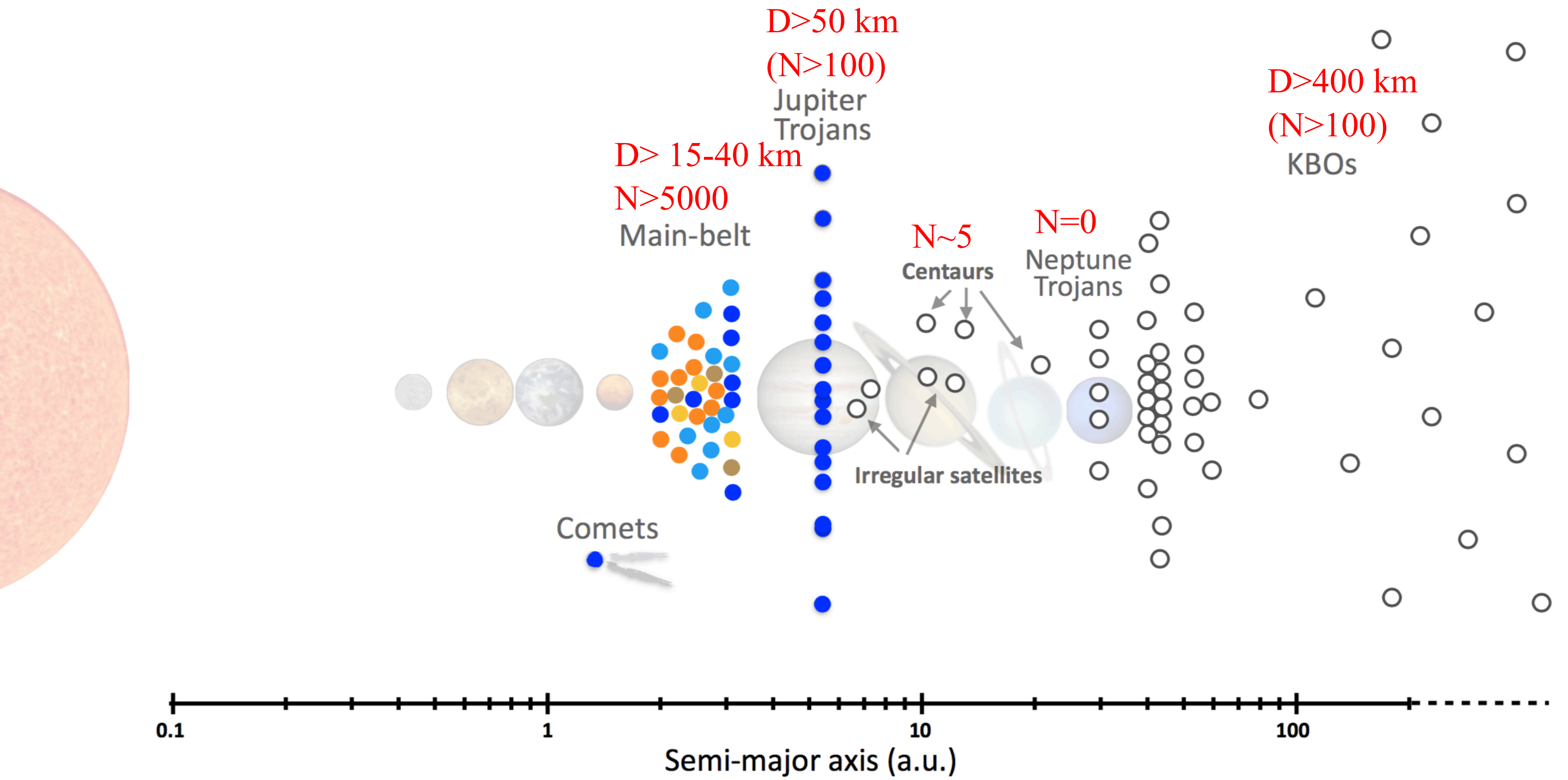
VLT/SPHERE/ZIMPOL

What to expect from the first generation AO cameras on the ELT (MICADO+MAORY)



Geology/Geophysics : Shape, Density

What to expect from a second generation AO camera (ZIMPOL equivalent) on the ELT



D>50 km
(N>100)

D> 15-40 km
N>5000

N~5

N=0

D>400 km
(N>100)

Geology/Geophysics : Shape, Density

Characterize binary systems

- So far, ~350 binary small bodies identified (they are found among all dynamical populations) and only a handful (~10) that are well characterized via AO observations

- With ELT, we expect to charactize >100 binary systems

- Binary systems are our best chance to get precise density estimates

- ELT will enable the characterization of the shape of the largest moons !

Conclusion

ZIMPOL has been a revolution in the field of asteroid studies.

In the field of high angular resolution AO imaging observations of Solar System small bodies, a giant step forward will only be achieved via the combination of the ELT and a ZIMPOL-like instrument operating at the diffraction limit in the optical.

Thank you