The Solar System and its small bodies with PRIMA

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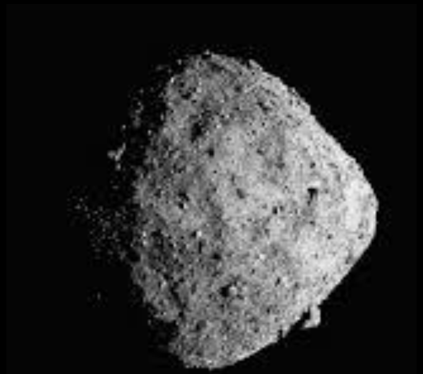
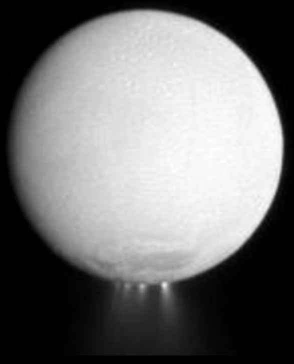
PRIMA conference 31 March – 2 April 2025, Marseille, France



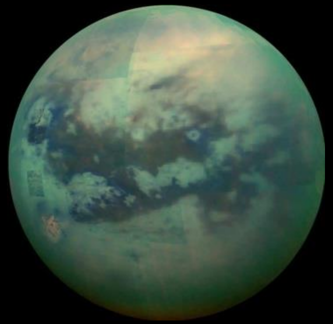
Asteroid Bennu

Comet 67P

Hyperion



Enceladus



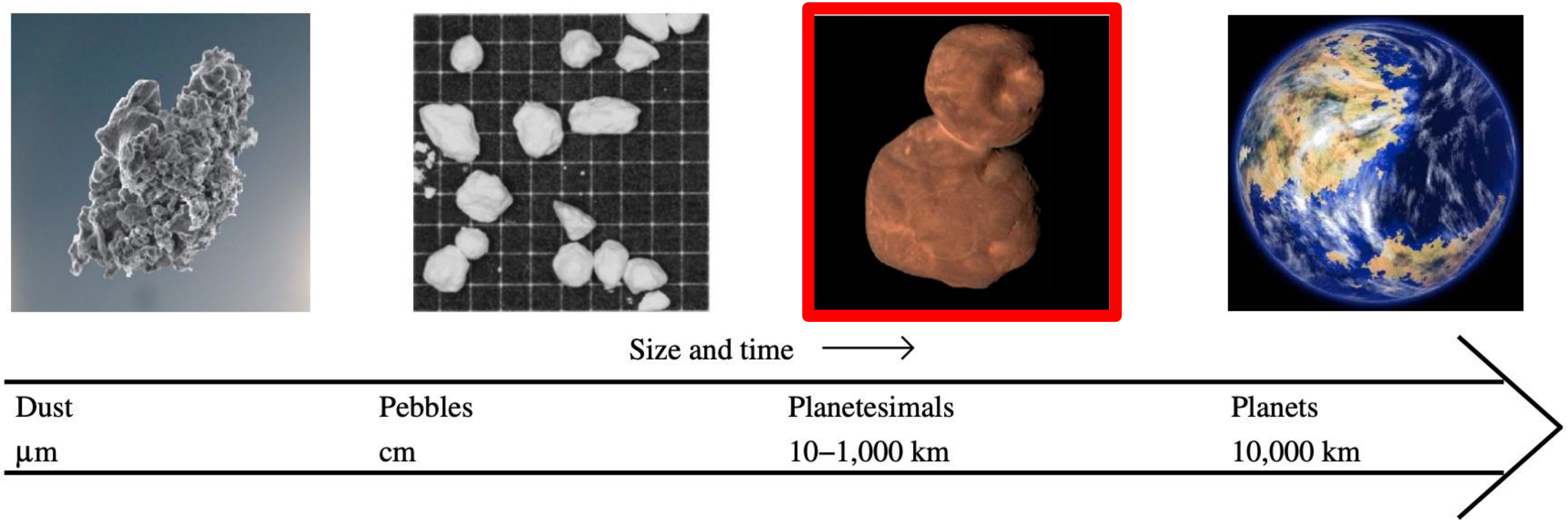
Titan

TNO Arrokoth

Outline

- Key scientific questions for the solar system for PRIMA
- Examples of science cases for PRIMAger
- Examples of science cases for FIRESS
- Synergy with space missions

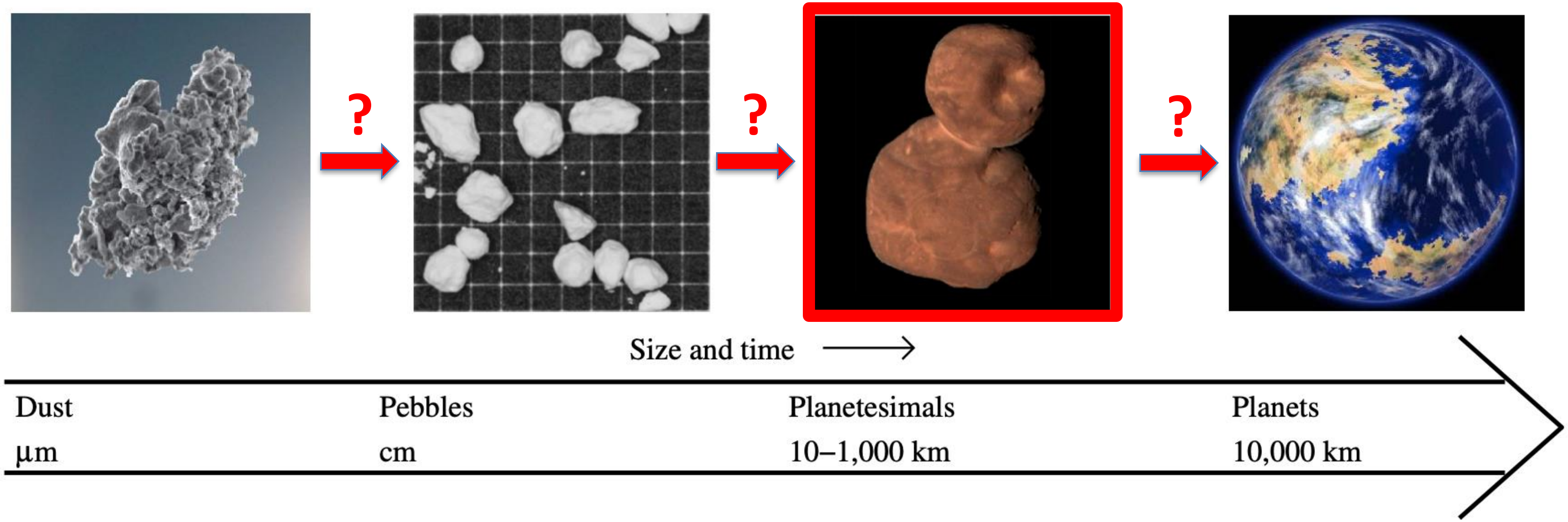
Planet formation : small bodies as leftovers



- Planets form in protoplanetary discs consisting of gas and dust orbiting young stars
- Dust and ice grains stick to form pebbles of millimeter sizes
- Pebbles come together to form kilometer-sized planetesimals
- Planets grow by accreting pebbles, planetesimals and gas

Adapted from Johansen (2024)

Planet formation : small bodies as leftovers



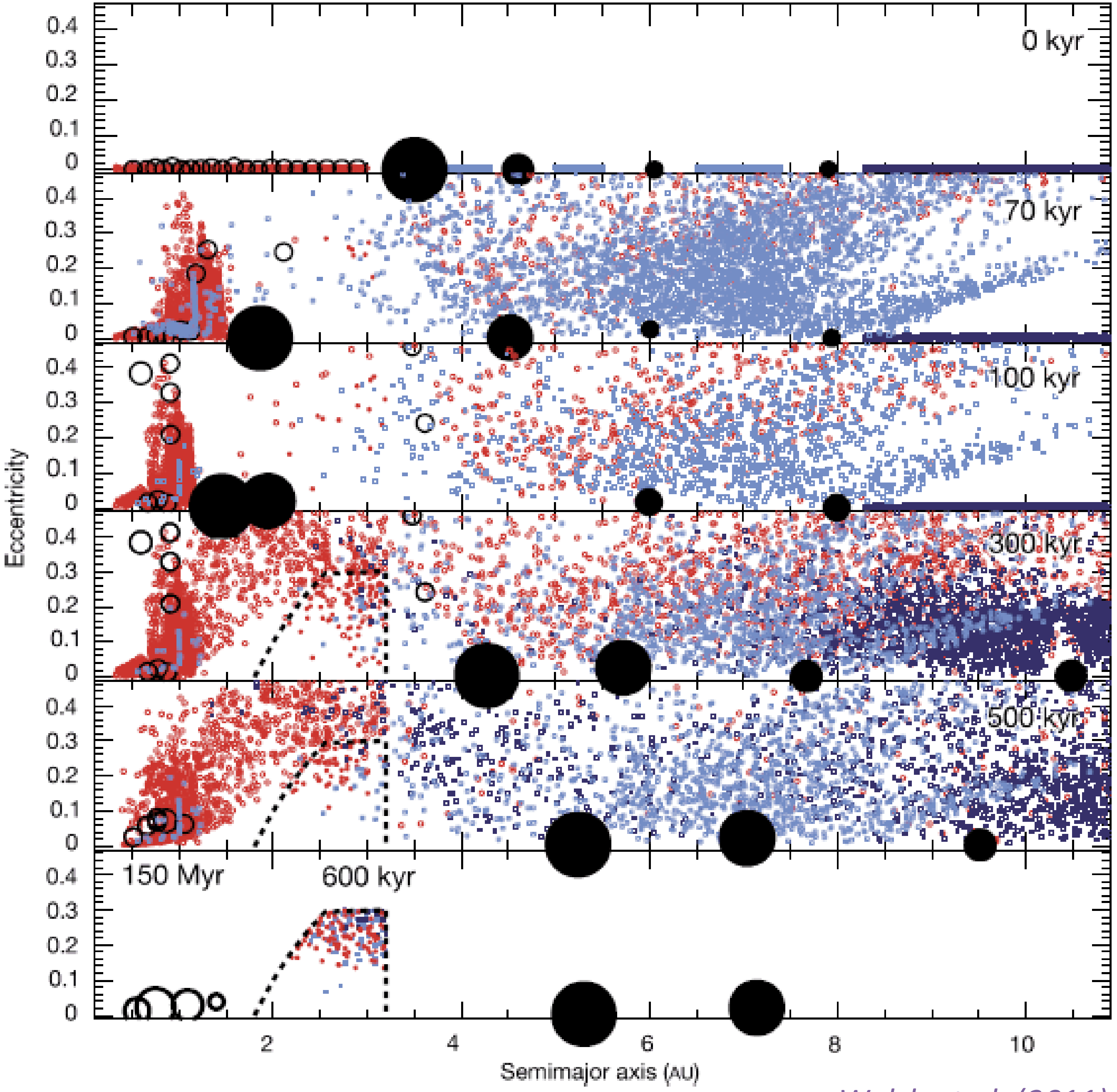
What are the processes involved in this planet formation scenario ?

Adapted from Johansen (2024)

Planet formation : migration and radial mixing

- The migration of giant planets, inwards and outwards, with Jupiter at 1.5 a.u. from the Sun !

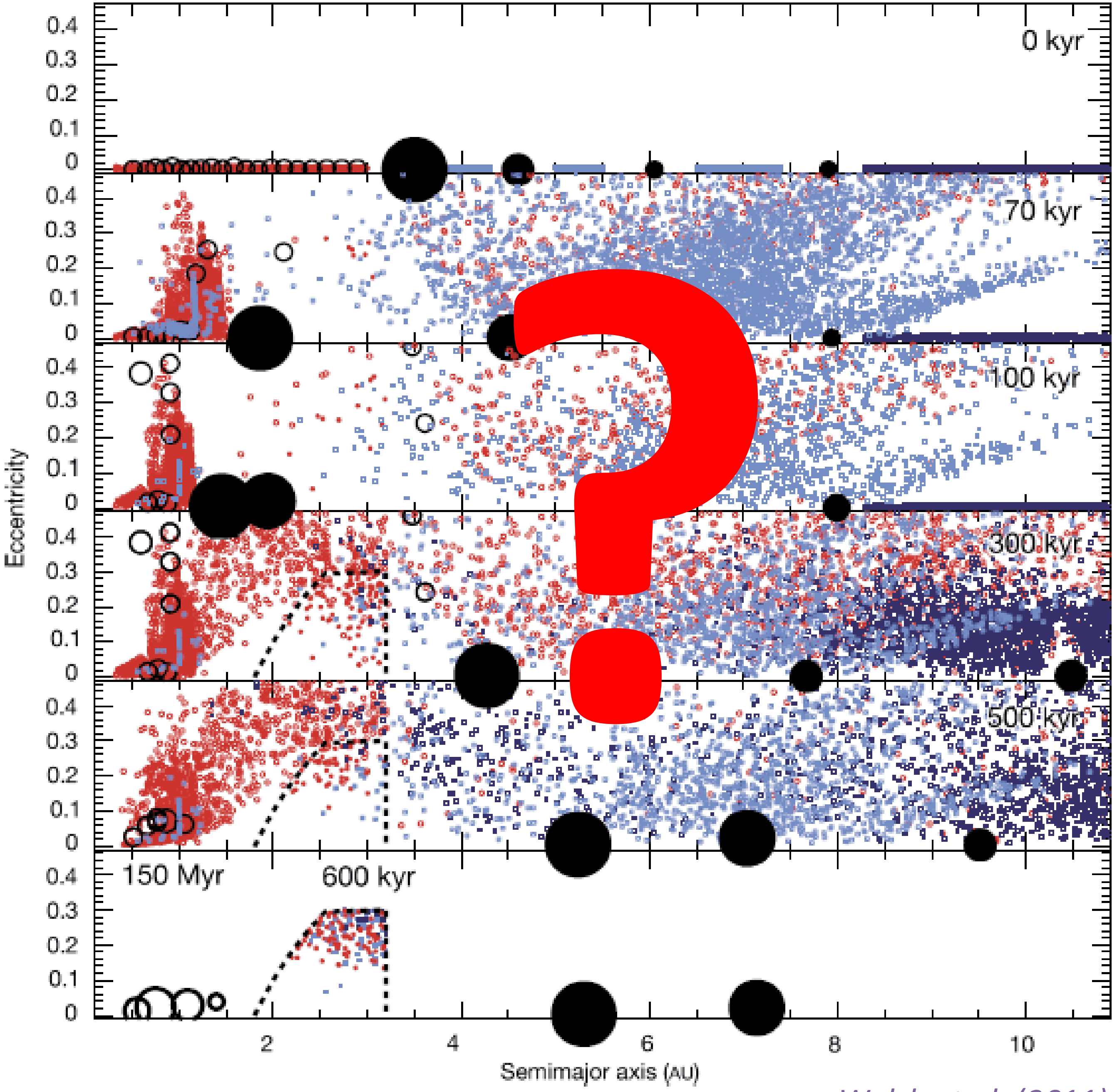
- Induces a radial mixing of planetesimals across the entire solar system (asteroids, comets, TNOs, …)



Walsh et al. (2011)

Planet formation : migration and radial mixing

Are the current physical properties and composition of small bodies compatible with dynamical models ?



Walsh et al. (2011)

Priority science questions

Origins, Worlds, and Life

A Decadal Strategy for Planetary Science and Astrobiology 2023 – 2032

- Accretion in the outer solar system
- Origin of Earth and inner solar system bodies
- Impacts and dynamics
- Solid body interiors and surfaces
- Solid body atmospheres and exospheres
- Giant planet structure and evolution
- Insights from Terrestrial life
- Dynamic Habitability
- Search for life elsewhere

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PRIMA main science

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Examples of science cases for PRIMA

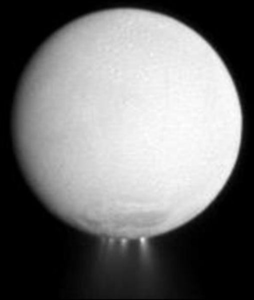
PRIMAger (low spectral resolution) :

- Physical properties of small TNOs and Centaurs :
  - Size
  - Thermal properties (surface temperature, thermal inertia)
  - Shape and rotation

FIRESS (high spectral resolution):

- Comets composition (H_2O, HCN, CO, OH, CH_4)
- Comets isotopic composition (D/H)
- Enceladus plumes (H_2O, HCN)
- Titan atmosphere (CH_4)
- Surface composition of Centaurs, Trojans, and TNOs (water ice)

TNO Arrokoth



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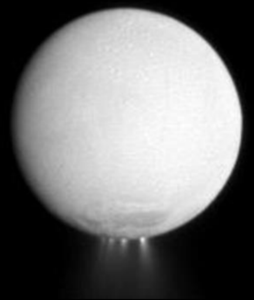


Enceladus

Titan

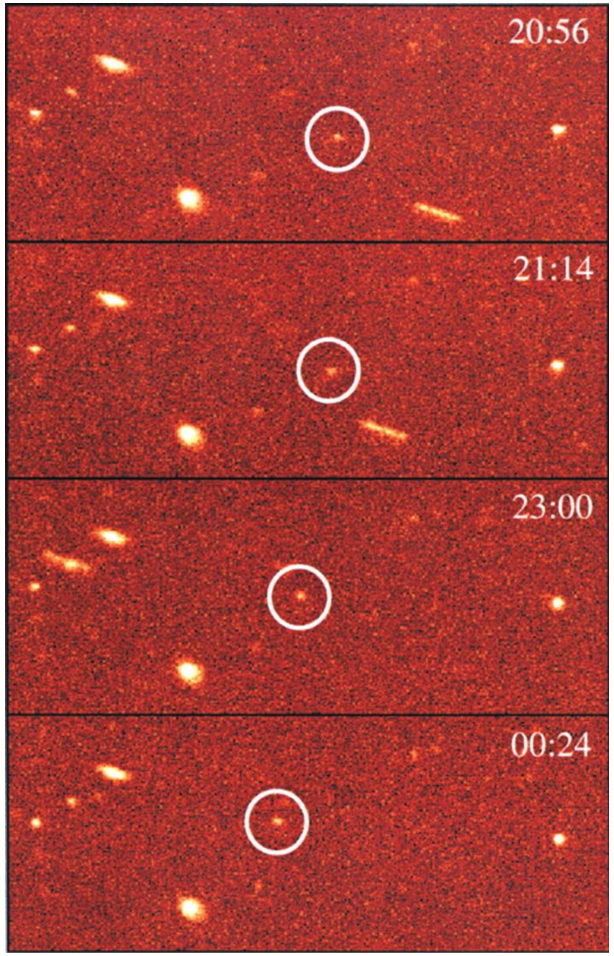
Comet 67P

Trans-Neptunian objects and Centaurs

Introduction

- ~3,500 minor bodies discovered since the 90's
  - 30 km to 2 500 km in diameter
  - distances from 10 AU to several hundreds of AU
- Prediction: 70 000 small bodies > 100 km
- Among the least altered material of the Solar System
- A complex orbital structure (not a thin disk with circular orbits…)
- Combining the surface/composition properties and the dynamical history…

➡ Constraints on the formation scenario of the early Solar System



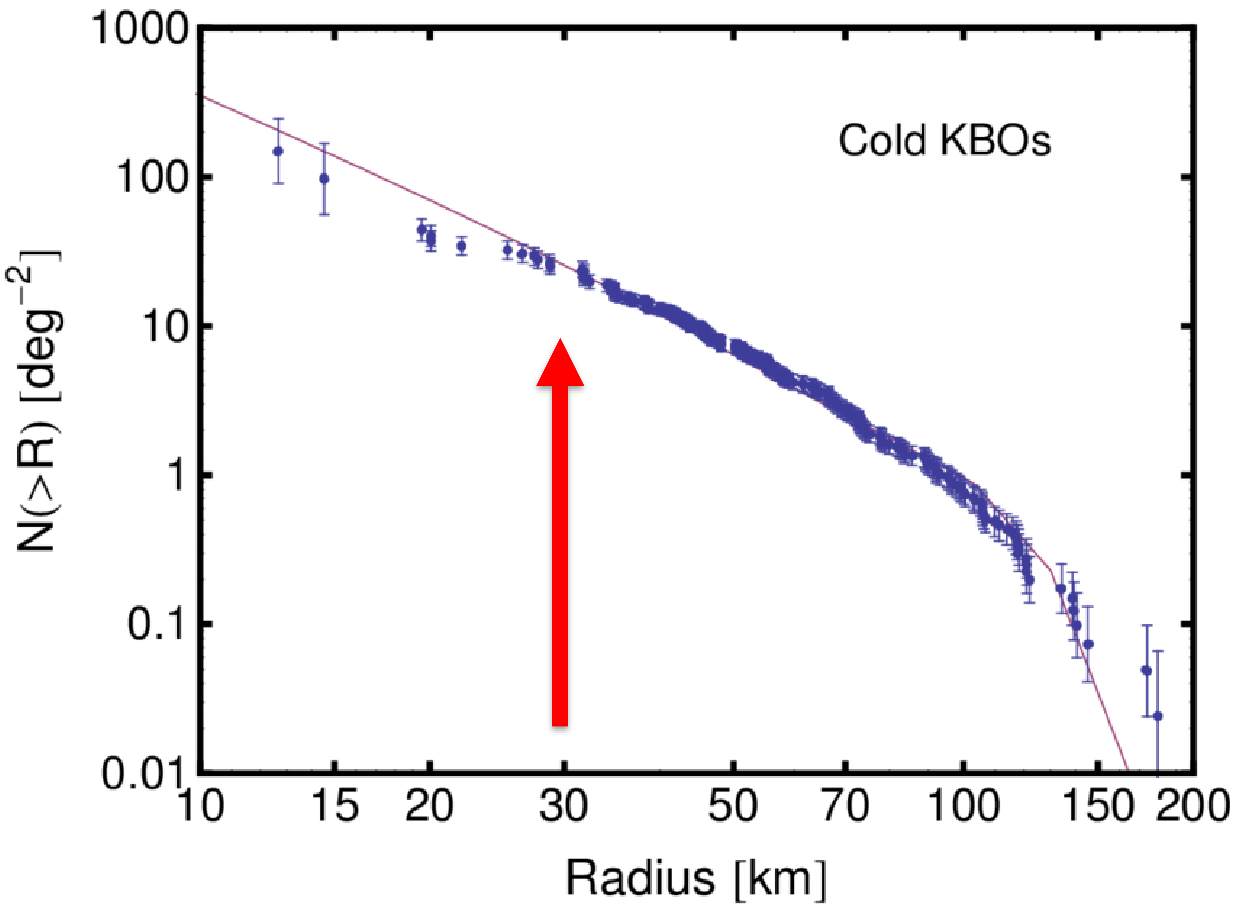
David Jewitt and Jane Luu *discovered 1992 QB1 on August 30th, 1992*

Adapted from Delsanti (2024)

Size of small TNOs and Centaurs

Scientific rationale

- Determine the mass in the trans-Neptunian region, to constraint the solar system formation/evolution models
- Understand the competition between accretion and collisional erosion.
- The size distribution of the largest bodies is controlled by the accretion process, while that of smaller bodies (radius <30 km) is believed to result from collisional evolution.
- >10 000 small ones to discover with LSST (Vera C. Rubin Observatory)



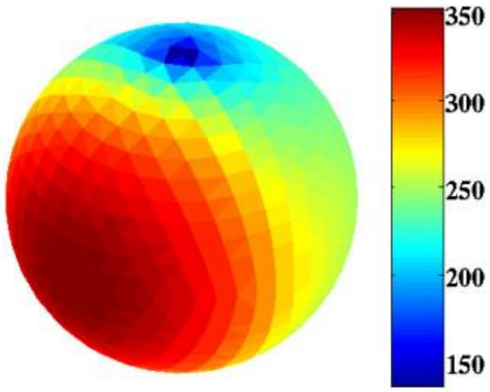
Schlichting et al. (2013)

Size of small TNOs and Centaurs

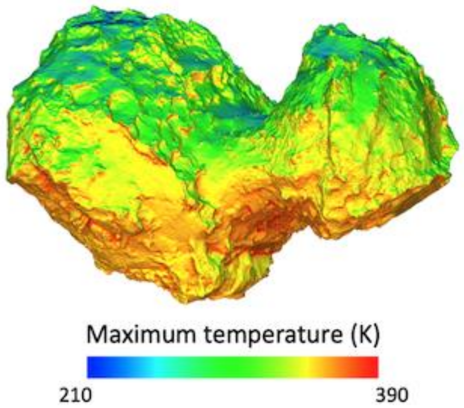
Method to determine the size (and the albedo)

- Radiometric method, from the 70's
- Thermal model : estimate the surface temperature
- Observations : combine IR (thermal emission) and VIS (scattered light)
    - IR provides constraints on size and thermal model
    - VIS provides constraints on size and albedo

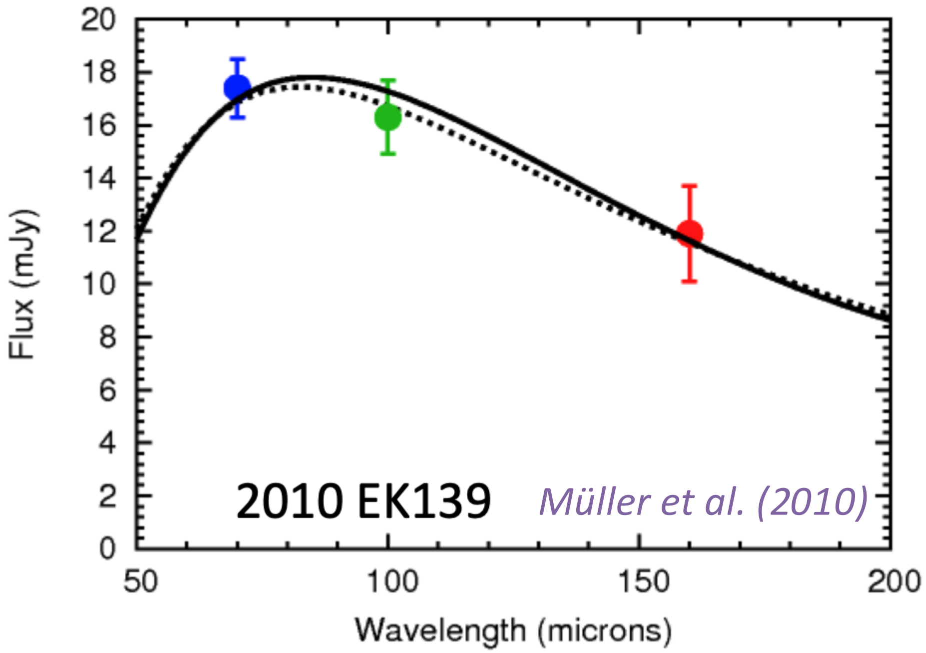
➡ The combination IR + VIS provides a unique (size, albedo) solution



Groussin et al. (2025)



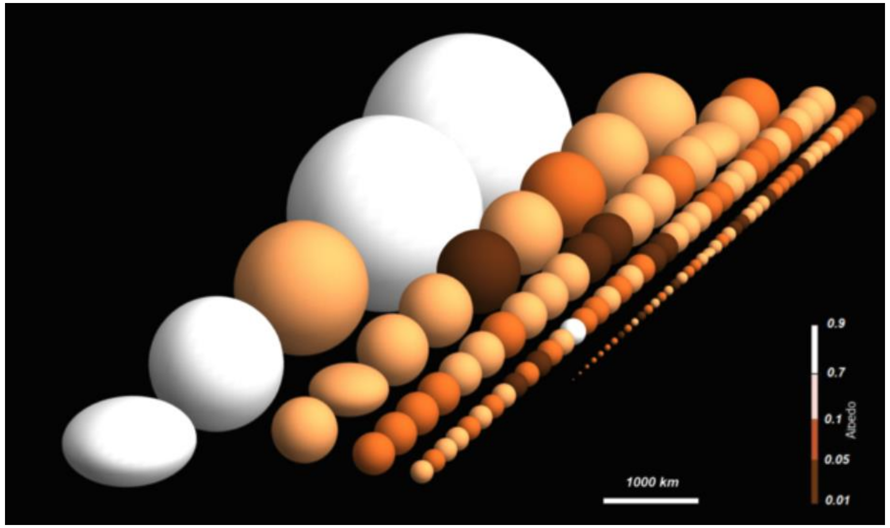
From simple to complex thermal models



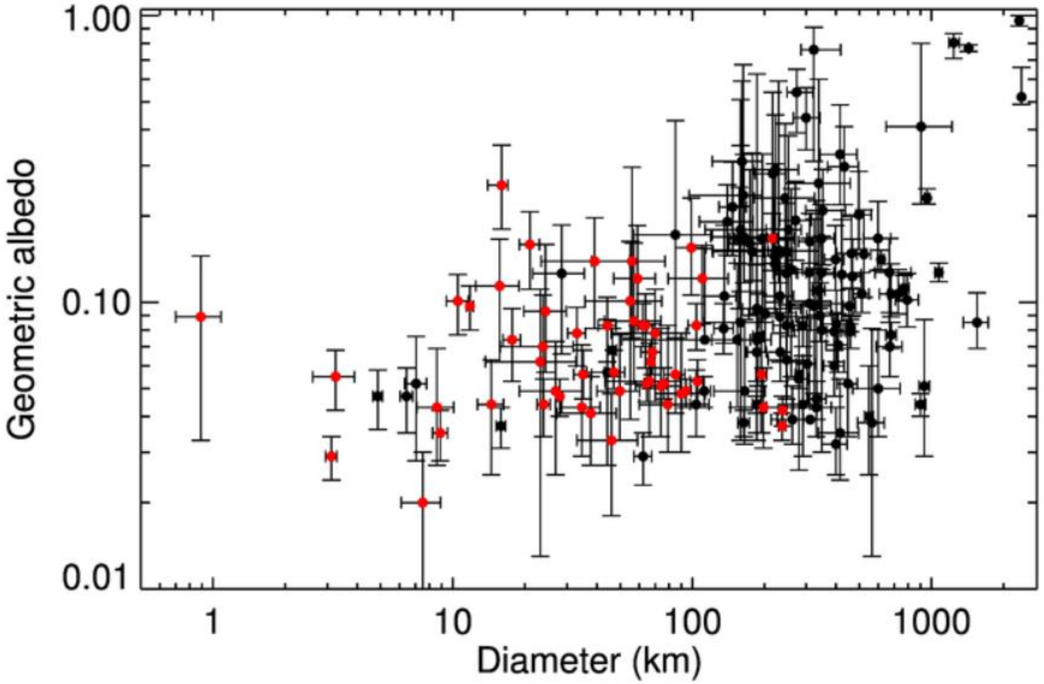
Size of small TNOs and Centaurs

Results from Spitzer and Herschel:

- 178 objects studied, including 25 multiple systems
- Bulk size for TNOs > 200 km diameter
- Lacking small TNOs to compare with Centaurs
- No clear correlation between size and albedo



Copyright: ESA/Herschel/PACS/SPIRE; acknowledgements: M. Rengel, P. Lacerda, T. Müller, and the Herschel



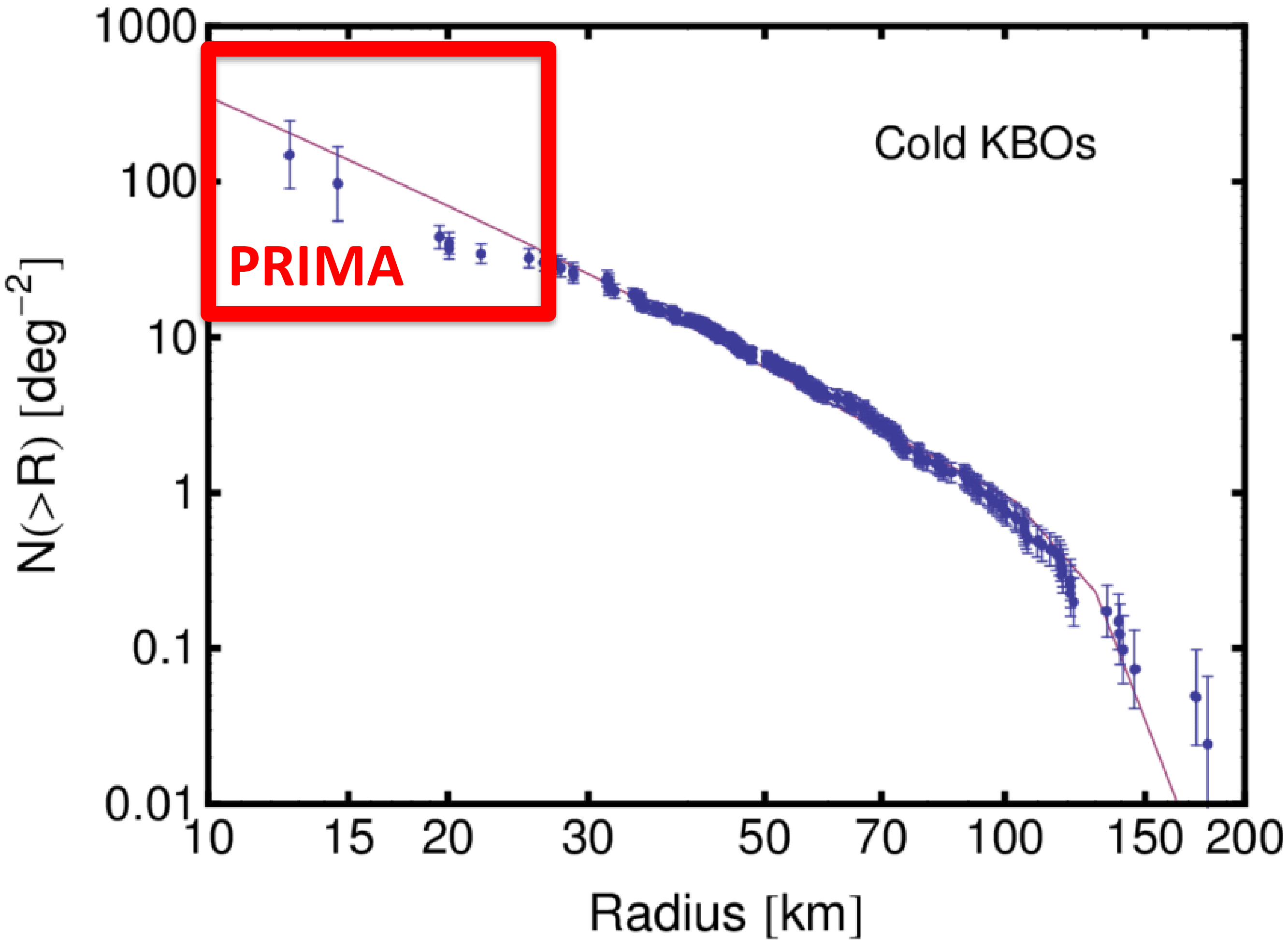
Müller et al. (2019)

Size of small TNOs and Centaurs

What to expect with PRIMA ?

- Measure size down to 10 – 20 km radius
- Fill the gap at small size
- Hundreds of potential objects to study
- Look for families and trends in size, albedo, colour

➡ Complementarity with stellar occultation, which is now easier to predict (e.g. GAIA) and more accurate than IR observations.

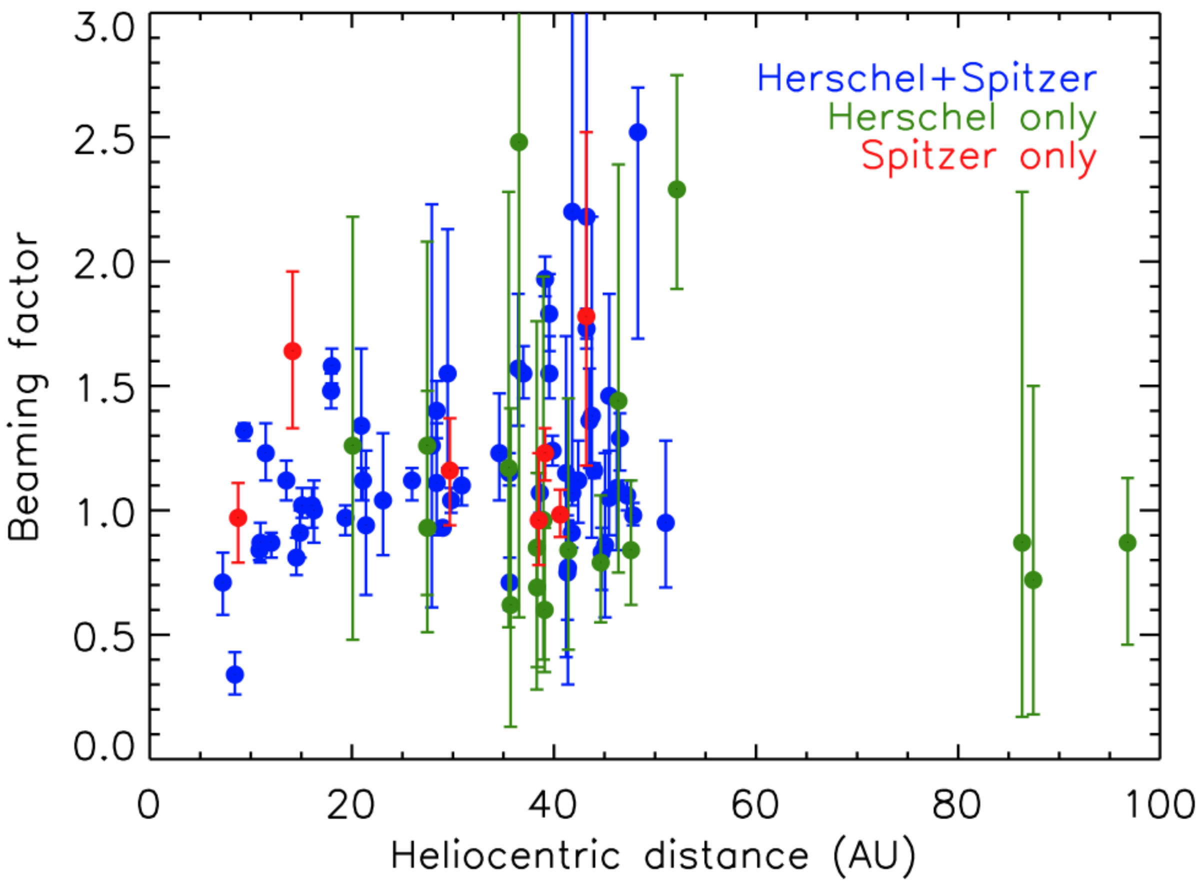


Schlichting et al. (2013)

Thermal properties of small TNOs and Centaurs

Scientific interest :

- Surface energy balance at large heliocentric distances
- Link with composition
- Degree of surface / interior evolution
- Trends with size, families ?



Lellouch et al. (2013)

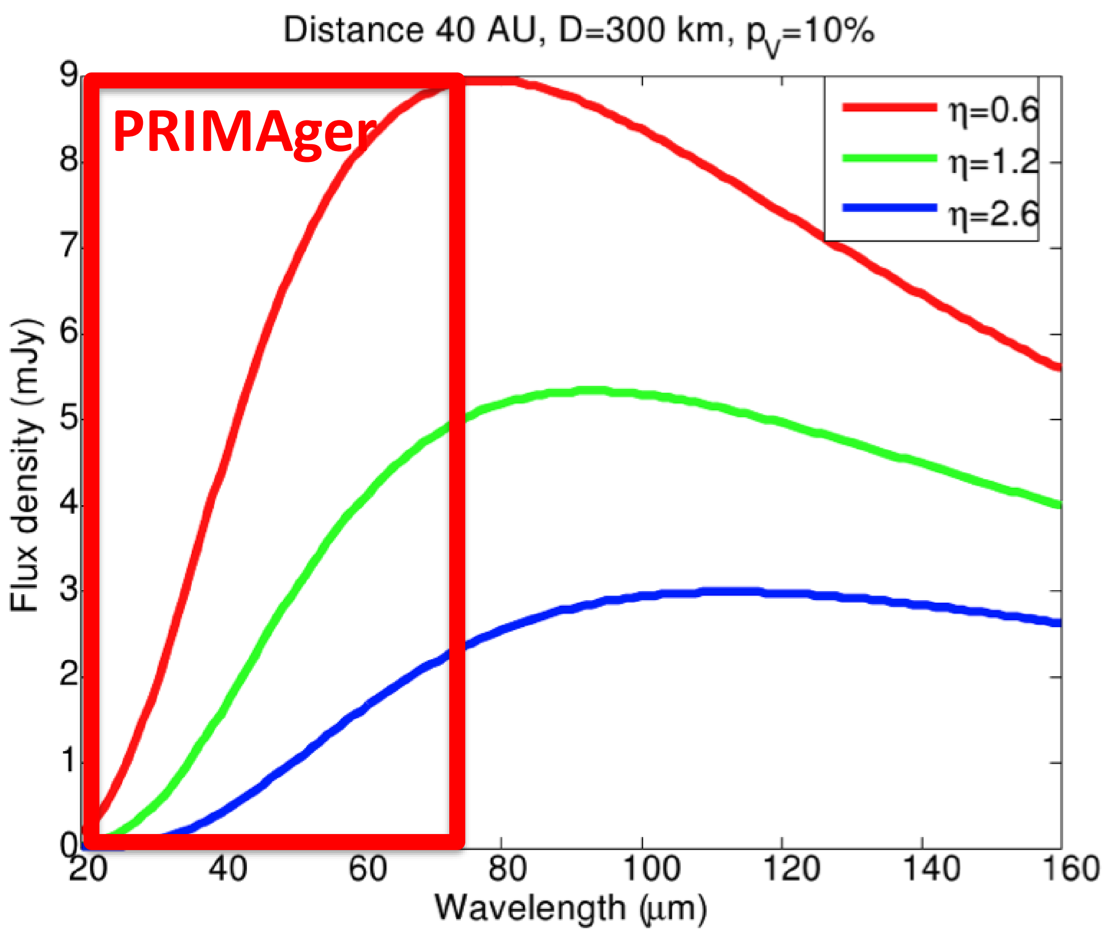
Thermal properties of small TNOs and Centaurs

Method :

- Constrain the thermal properties (thermal inertia) from the shape of the SED

What to expect from PRIMA ?

- Larger statistics : observer smaller and/or more distant, objects
- More robust determination thanks to the SED (instead of photometry from Herschel)

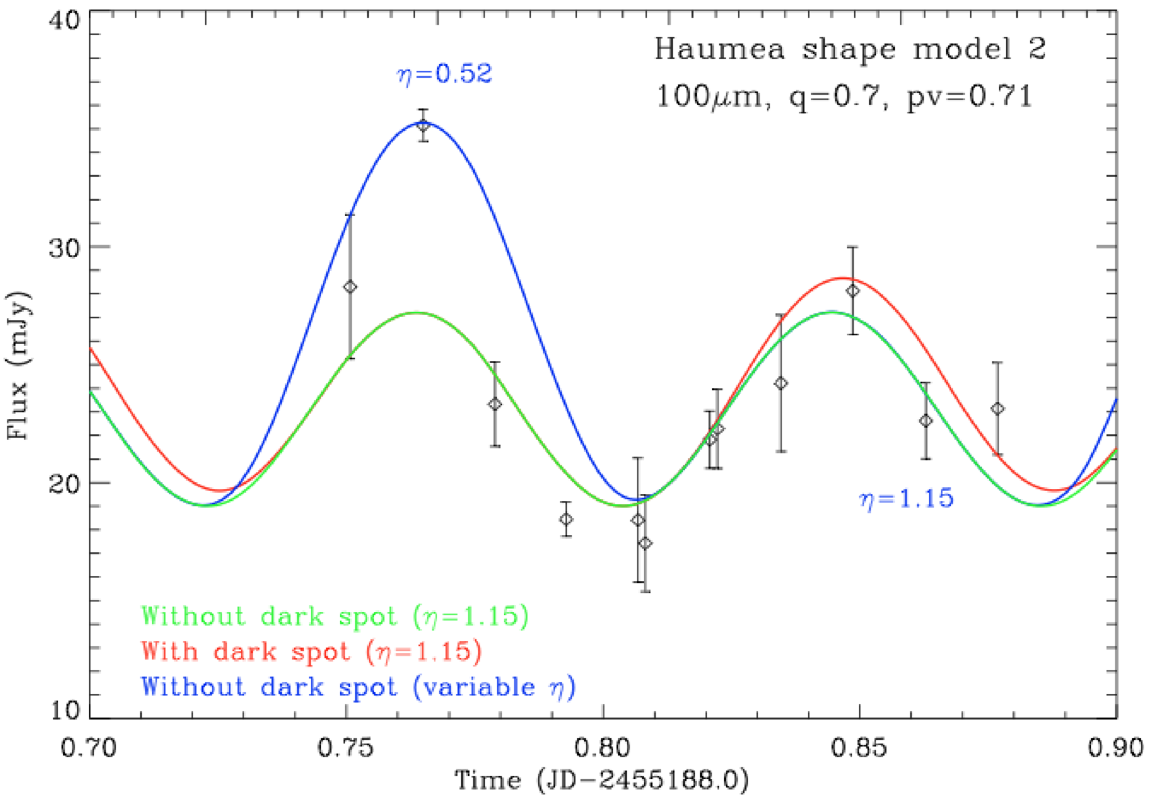


Müller et al. (2010)

Shape and rotation of small TNOs and Centaurs

Scientific rationale :

- Shape help to constrain formation and evolution scenario
- Study surface variegations of physical properties and/or composition
- Minimum density derived from rotation period
- About 100 objects known today



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Lellouch et al. (2010)

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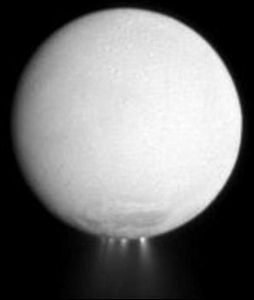
TNO Arrokoth


Enceladus


Titan


Comet 67P

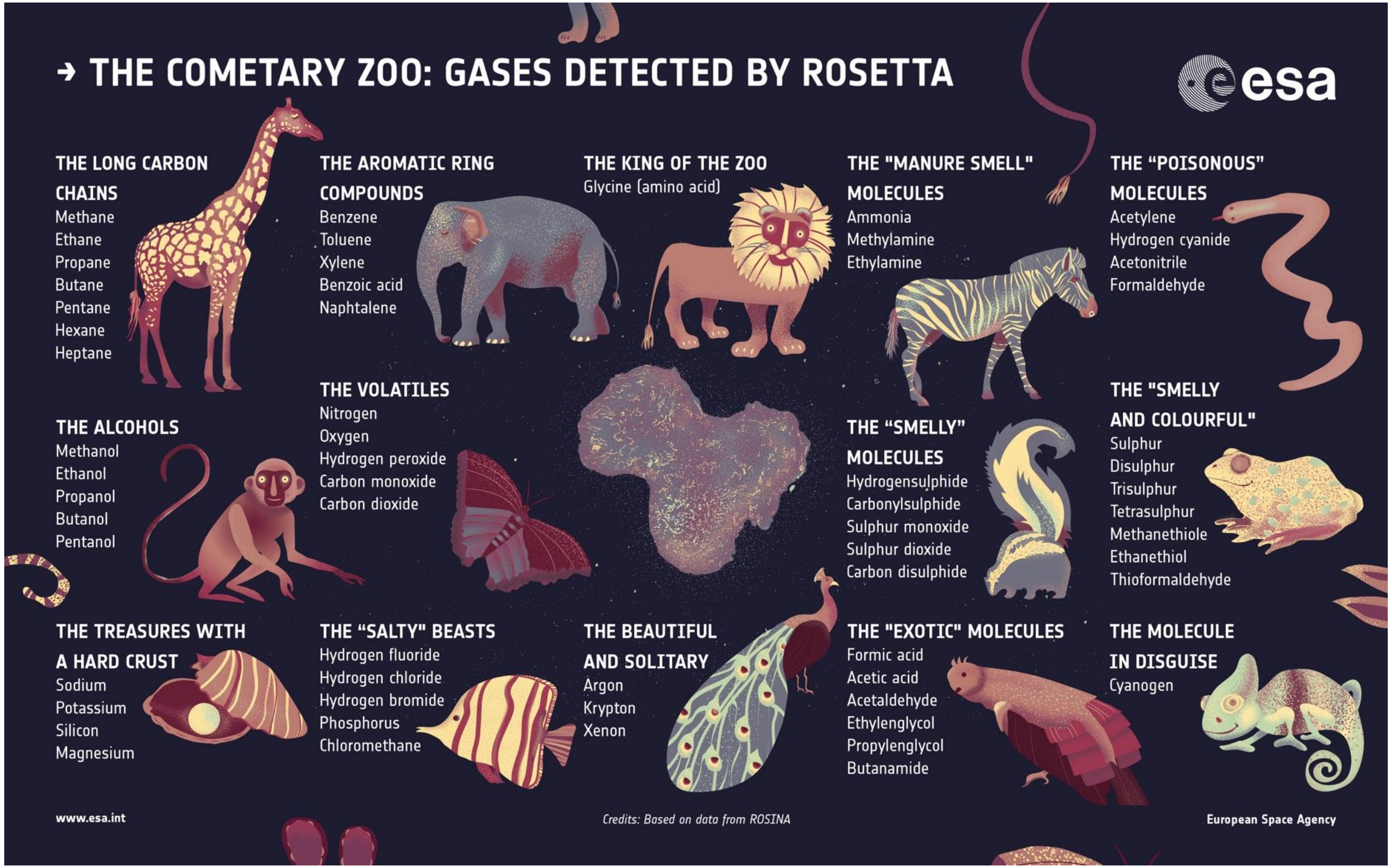
Comets composition

Scientific rationale :

- Understanding their origin
- The interstellar heritage
- The link with life on Earth ?

PRIMA / FIRESS :

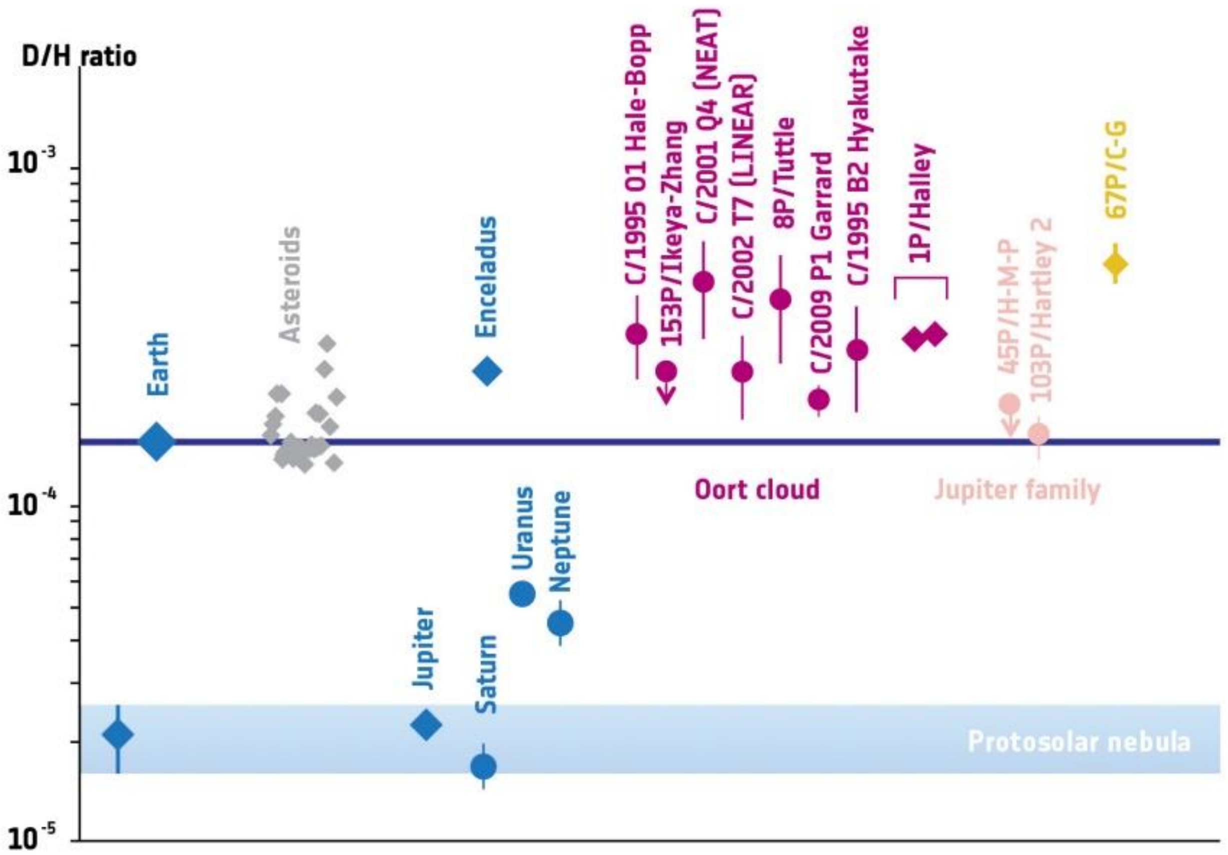
- Mainly gaseous H_2O, HCN, CO, OH, and CH_4
- Greatly enlarge the statistics with a gain of about 2 orders of magnitude in sensitivity compared to Herschel (i.e. fainter, smaller, comets)
- Activity at large heliocentric distances



Comets isotopic composition (D/H)

Scientific rationale :

- The origin of comets : different populations ?
- The origin of water in Earth (<10%)



Credits: Data from Altwegg et al. (2014) and references therein

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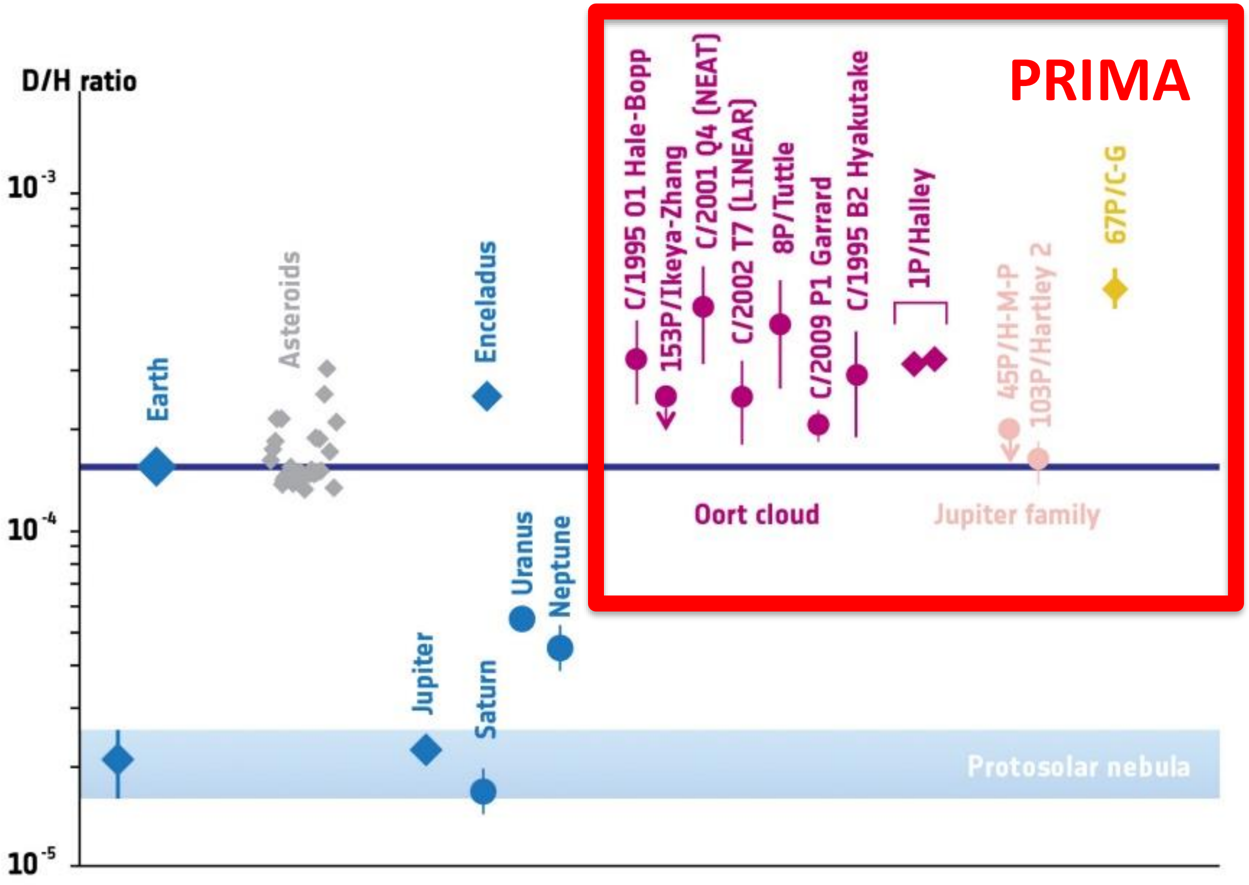
PRIMA / FIRESS :

- 2 orders of magnitude more sensitive than Herschel
- D/H measurable in 10 to 100 new comets
- A paradigm shift in statistics !



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Enceladus plumes

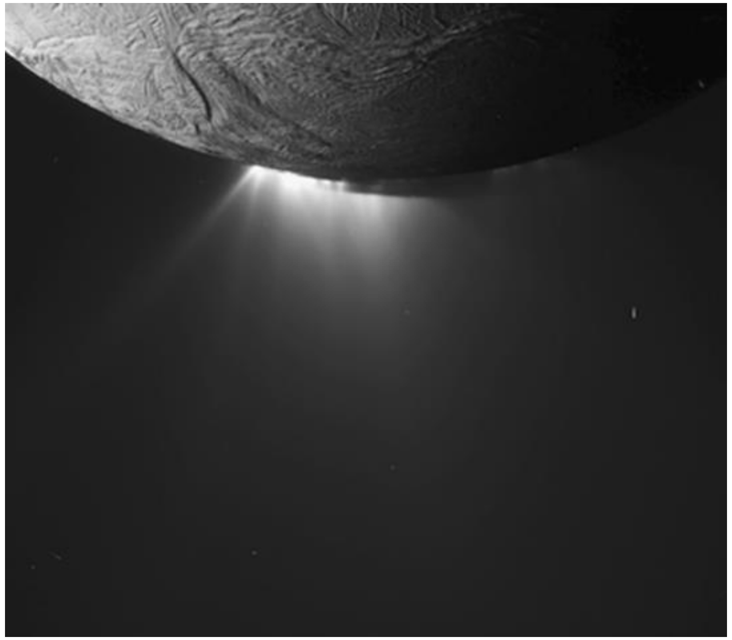
Scientific rationale :

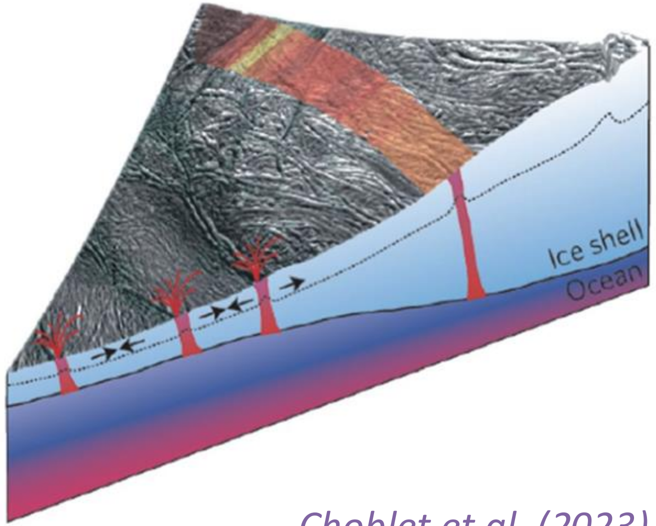
- An ocean world !
- Habitability in the solar system (and beyond)
- Tidal heating
- First direct sampling of subsurface water reservoir

PRIMA / FIRESS :

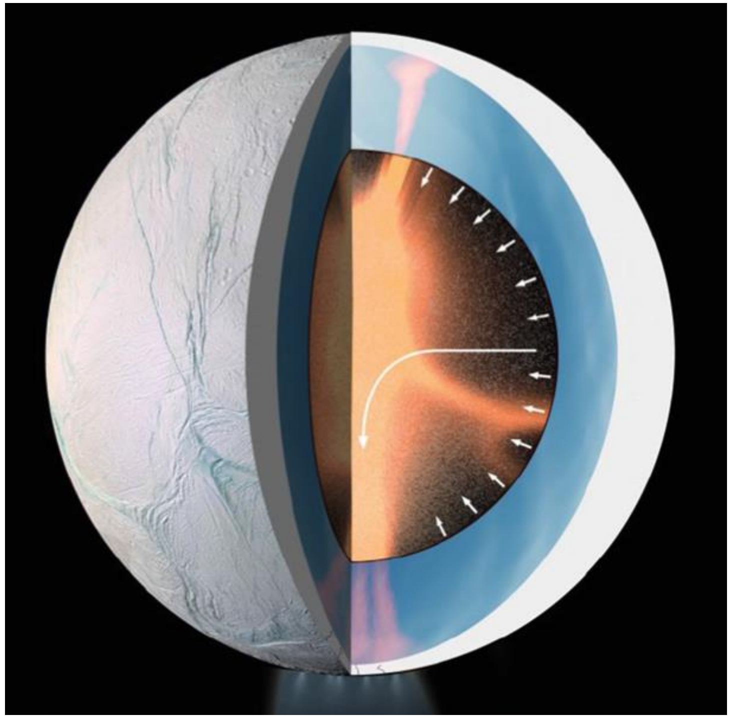
- Water content in the plumes
- D/H measurements
- Temporal variations

Feasibility to be demonstrated !





Choblet et al. (2023)



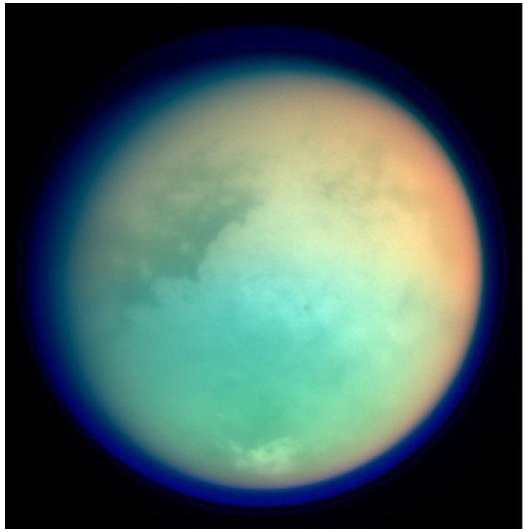
Titan atmosphere

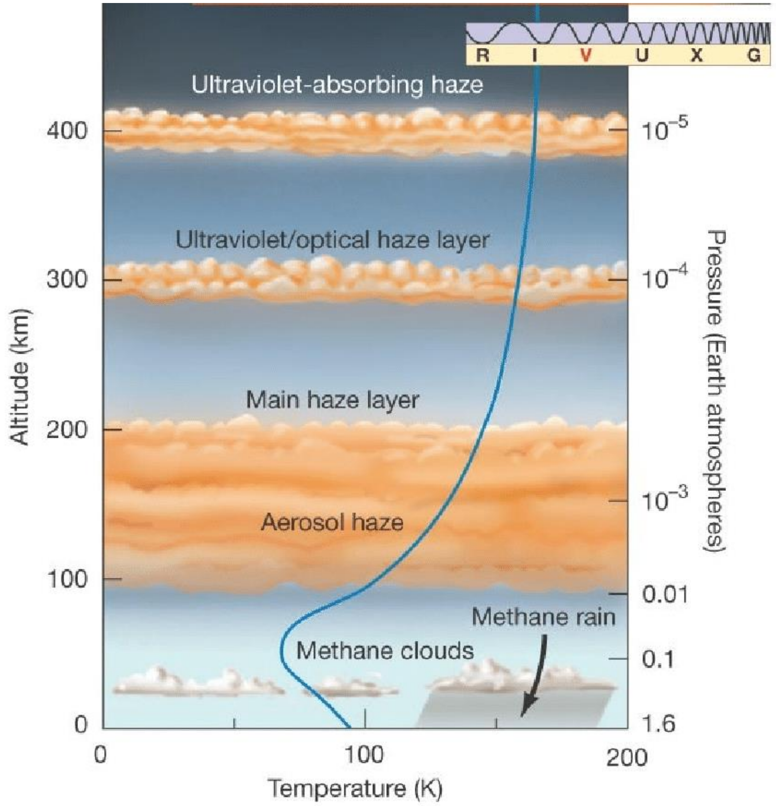
Scientific rationale :

- The only solar system satellite with an atmosphere
- Close to the Earth's primitive atmosphere, but much colder
- Mainly nitrogen (N_2), but also methane (CH_4)
- Sub-surface ocean ?

PRIMA / FIRESS :

- Methane only
- Long term monitoring of the stratospheric composition



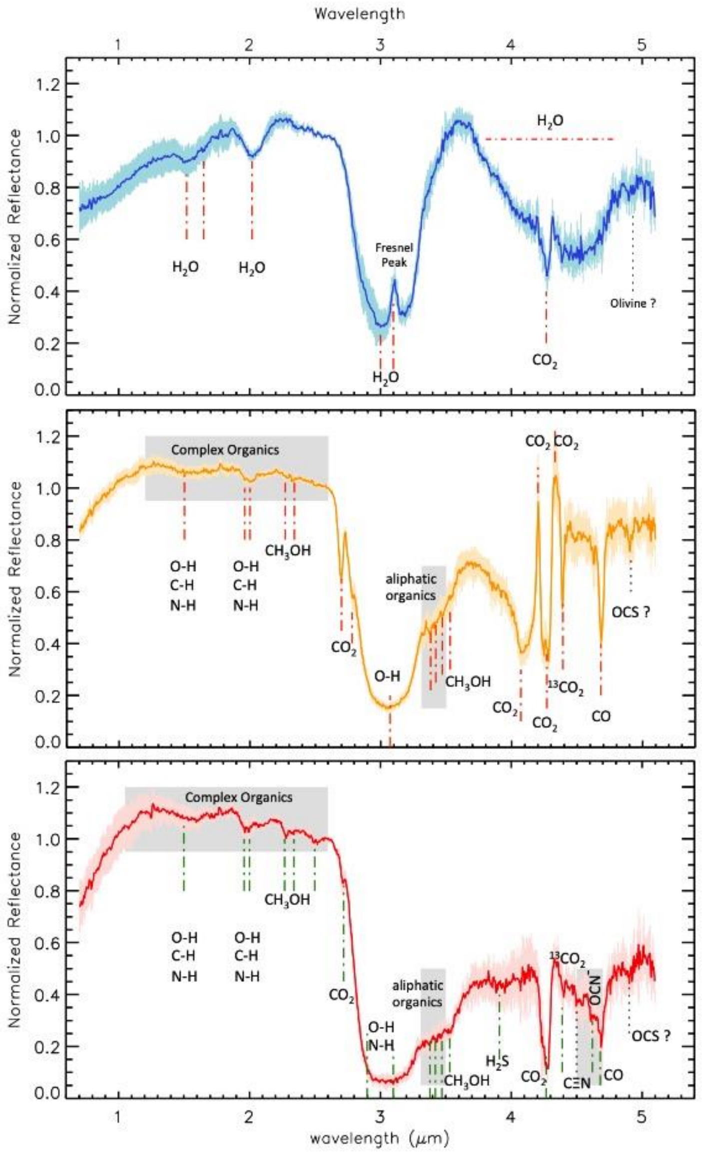


Surface composition of icy bodies

Comets, Centaurs, Trojans, TNOs

Scientific rationale:

- Water ice is ubiquitous in the Solar System
- In depth study of TNOs compositional families (from JWST) :
    - 1st group (25%) : water dominated + CO_2
      → Dynamically excited
    - 2nd group (43%) : CO/CO_2 dominated + aliphatic & complex organics (O-H, C-H, N-H bands), water poor
      → Dynamically excited
    - 3rd group (32%) : CO_2 + aliphatic & complex organics dominated (additionnal O-H & N-H absorptions)
      → Cold classical



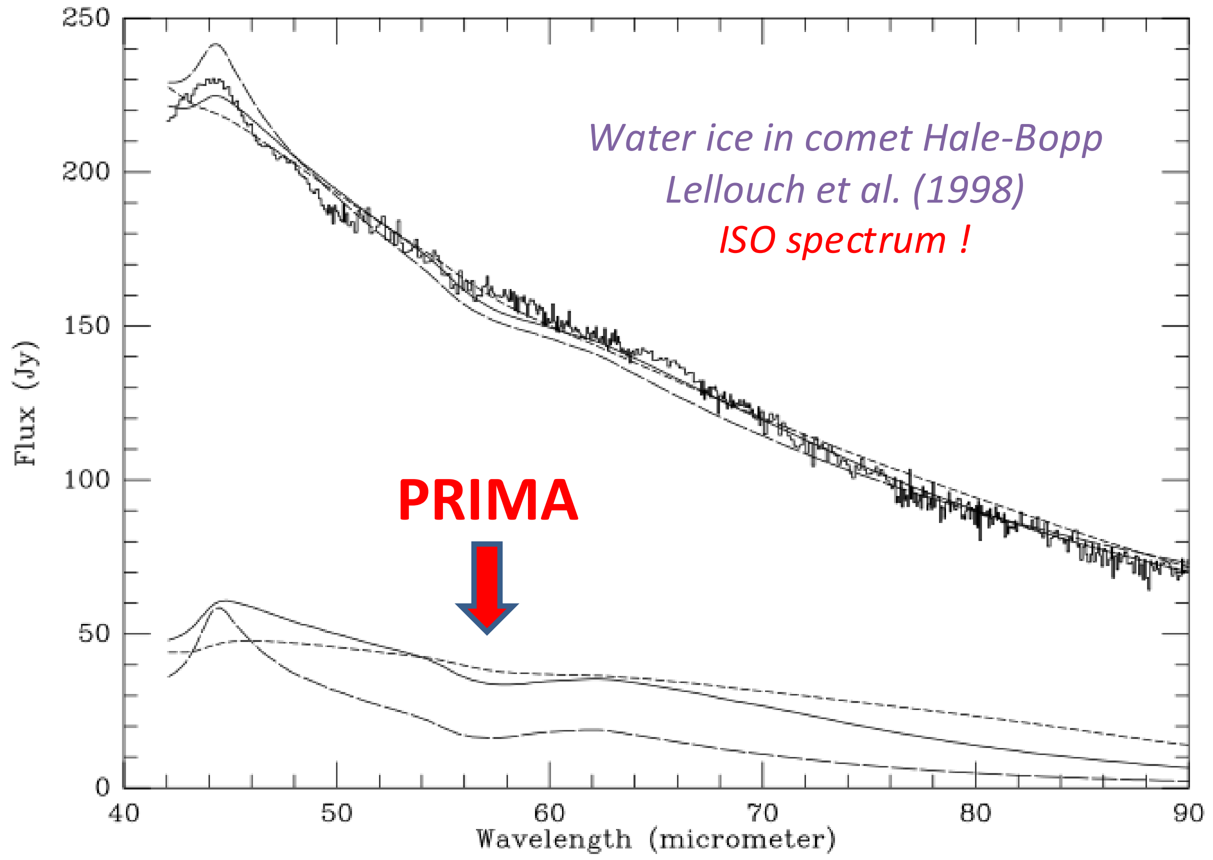
Pinilla-Alonso et al. (2024)

Surface composition of icy bodies

Comets, Centaurs, Trojans, TNOs

PRIMA / FIRESS :

- Water ice
- Study a larger number of objects, in the different families, to link composition with origin
- Study a larger range of sizes, in particular the smaller ones (<50 km):
    - Retain primordial organics, not buried under $H_2O/CO/CO_2$ ices ?
    - Different composition resulting from their evolution (collisions) ?



⚠ A (mostly) unexplored wavelength range for surface composition studies…

Synergy with space missions

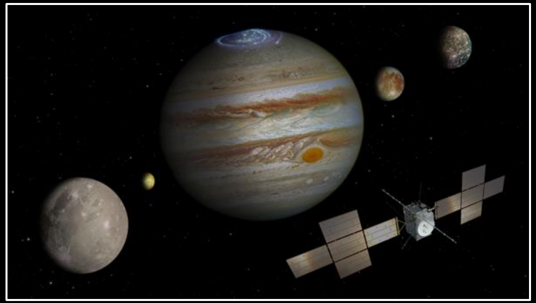
Comet Interceptor (>2030)

- Target characterization
  - Size, albedo, rotation, shape, composition, activity

Europa Clipper (>2030) and Juice (>2031) and Dragon fly (>2034)

- Complementary observations during the mission
  - Different field of view (context)
  - Additional wavelength
- Ground proof
  - Strengthen the analysis of distant observations vs. in situ
  - Allow a long-term monitoring, after the end of the mission






Take-home messages

1) PRIMA is a promising space telescope to study the Solar System

2) Two major potential scientific breakthroughs :

- **Determining the size of small Trans-Neptunian Objects**

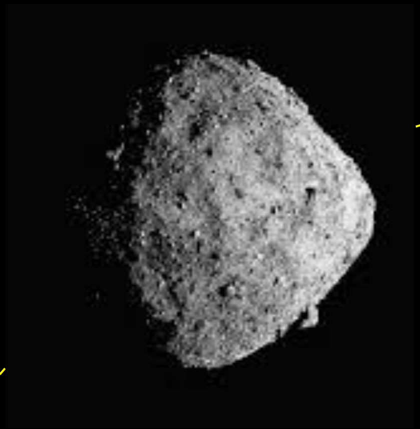
  To understand the erosion and collisional history of the outer Solar System

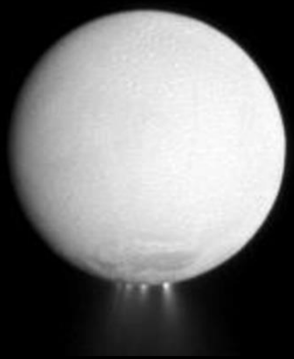
  → *PRIMAger*

- **Inventory of D/H in comets**

  To understand the interstellar heritage and the origin of water on Earth

  → *FIRESS*






Thank you !