Neutral gas mass spectrometry on board of ESA's Rosetta and Comet Interceptor missions

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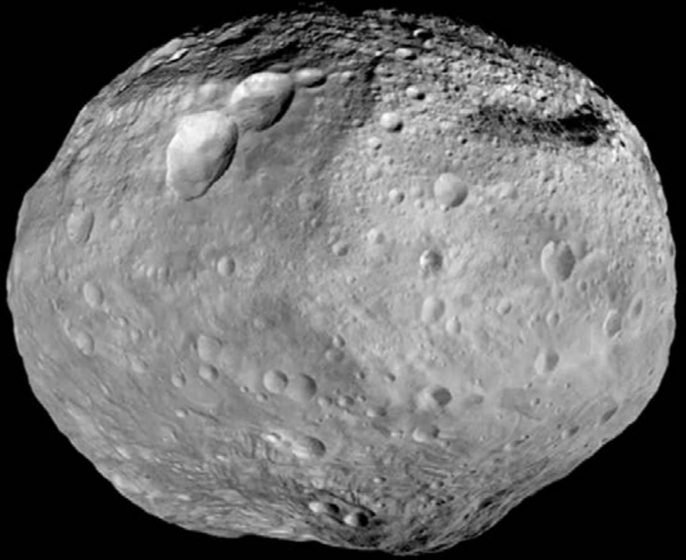
FNRS Astronomy & Astrophysics Contact Group meeting & Astronomy Day of the Royal Observatory

23 May 2024

What is a comet?

- A comet consists of:
  - Solid materials (~50% we don‘t know yet!)
    - Dust & dirt
    - Organic material
  - Ices (~50%) (not asteroids)
    - Water (H_2O)
    - Carbon monoxide (CO)
    - Carbon dioxide (CO_2)
    - And much more ...
- The Sun heats up the outer layers
- At low pressures ice vaporizes directly

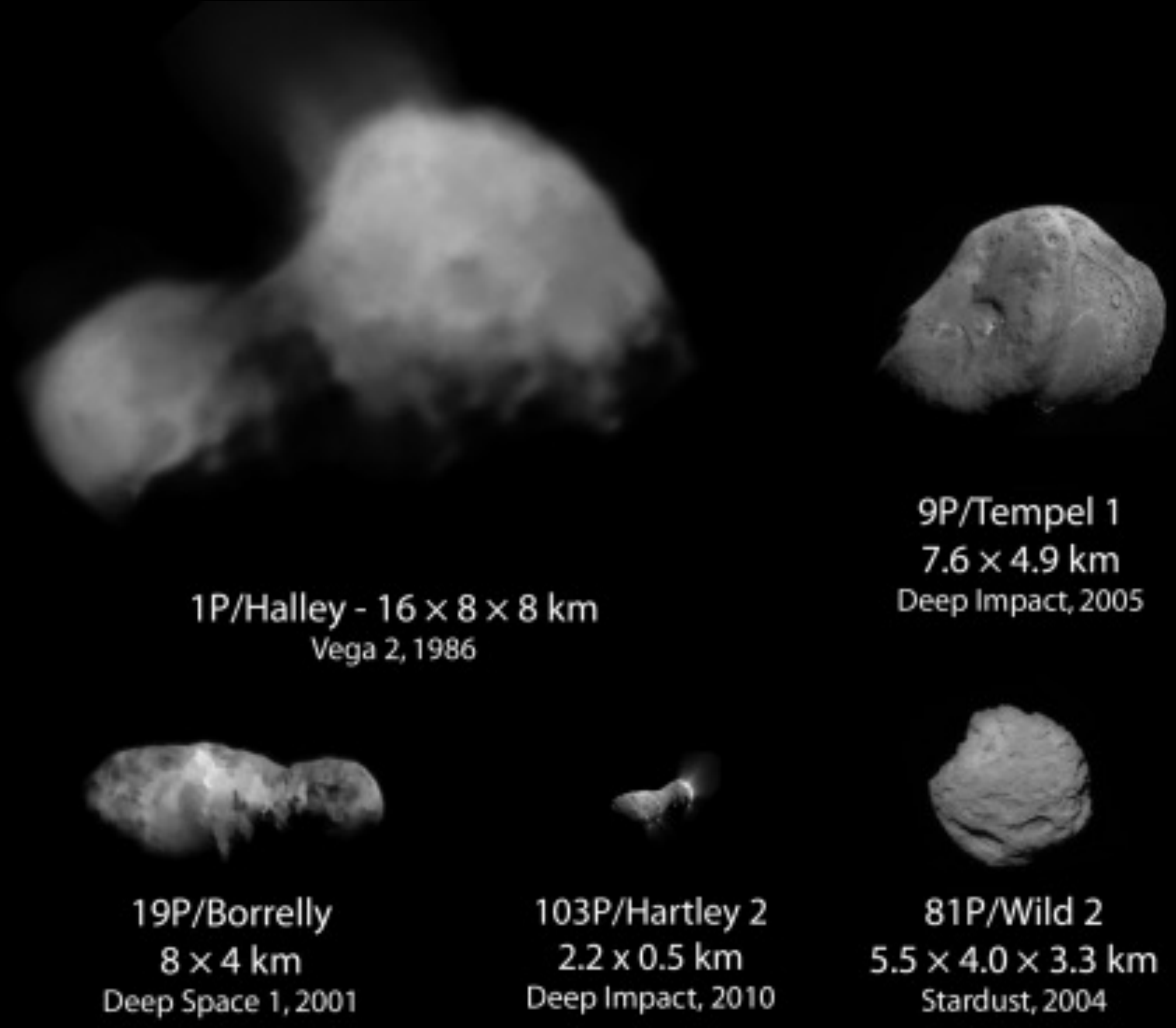
Comet Wild 2

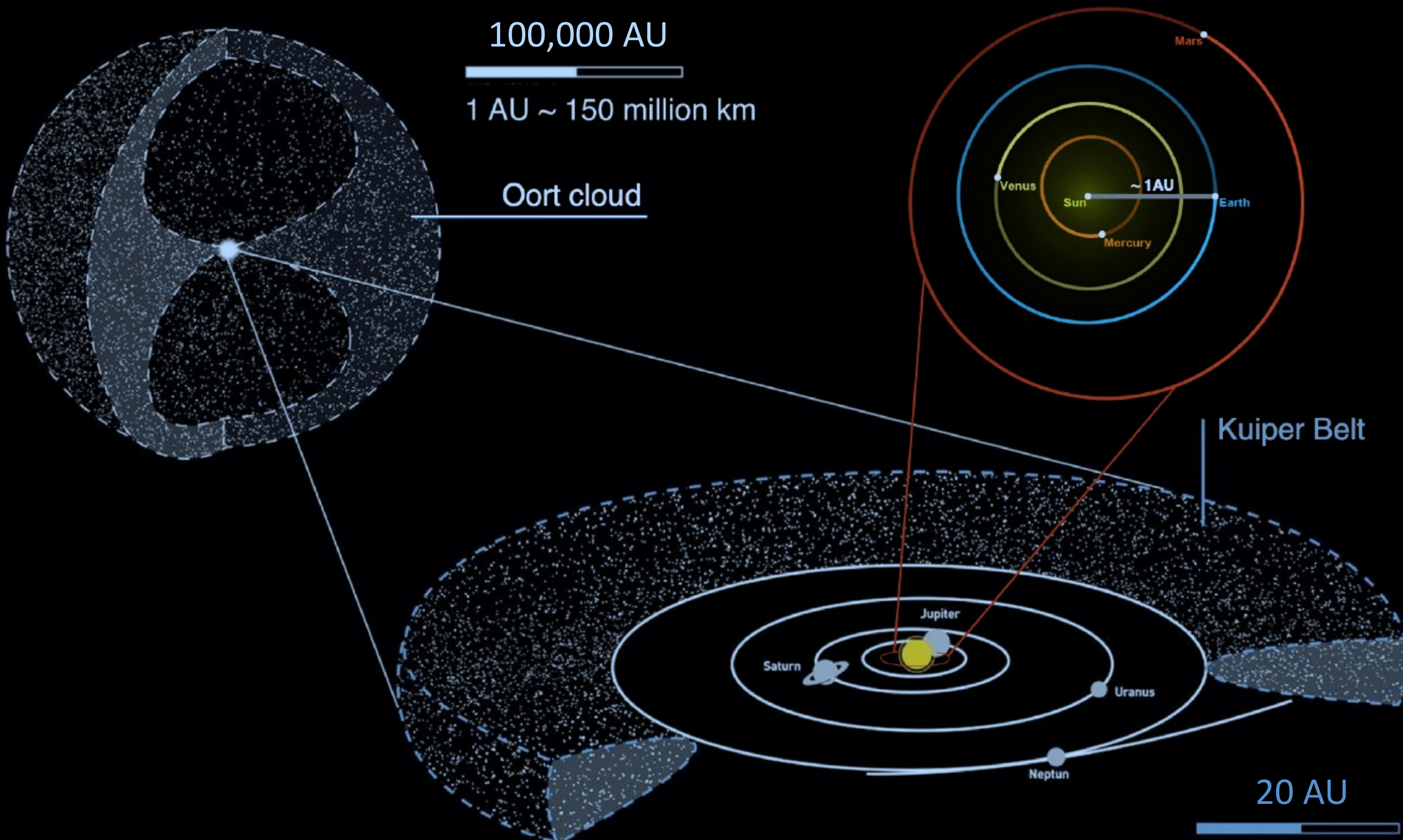


Asteroid Vesta

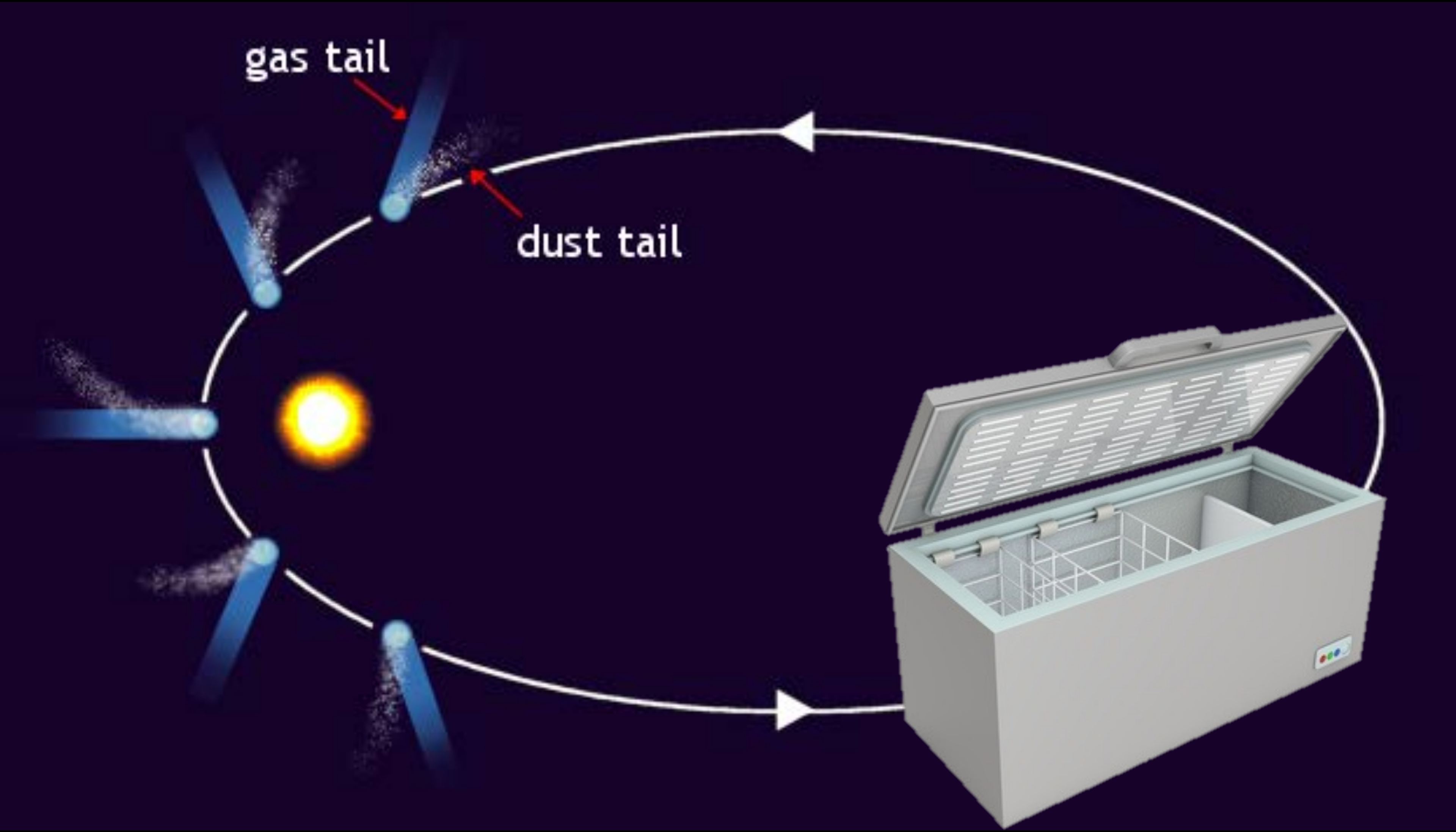
What is a comet?

Comet nucleii




100,000 AU
1 AU ~ 150 million km
Oort cloud
Mars
Venus
~ 1AU
Sun
Earth
Mercury
Kuiper Belt
Jupiter
Saturn
Uranus
Neptun
20 AU

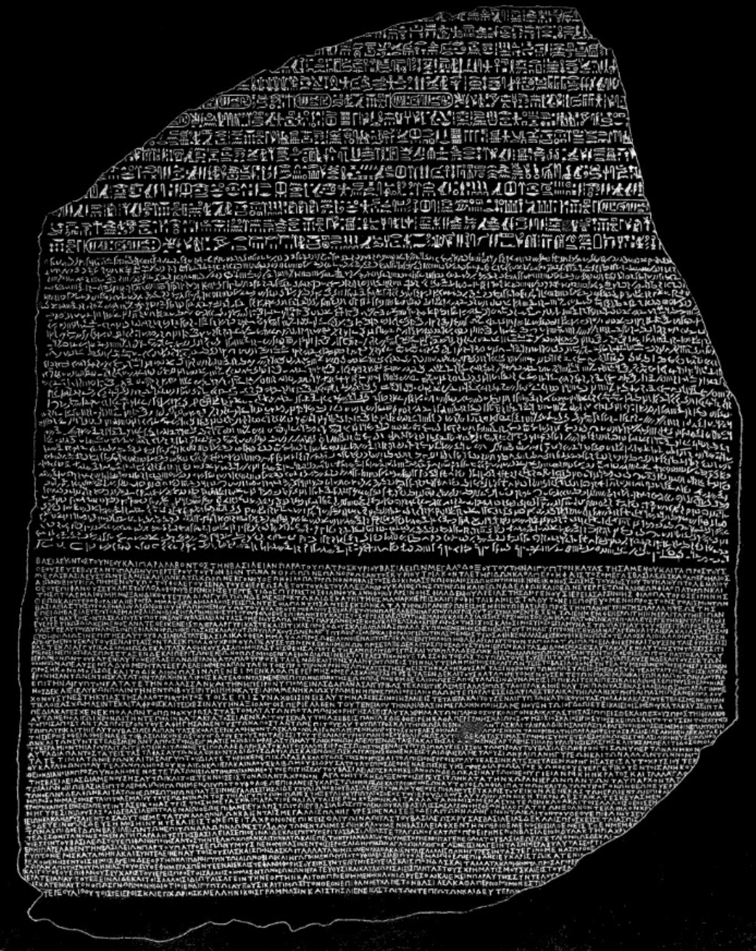
Comet orbits



The Rosetta mission to comet 67P/Churyumov-Gerasimenko

To decipher the **origin** of the **solar system,** the **Earth** and **life** by studying a **comet**

In analogy to the **hieroglyphs** on the **Rosetta stone.**



Mission goals

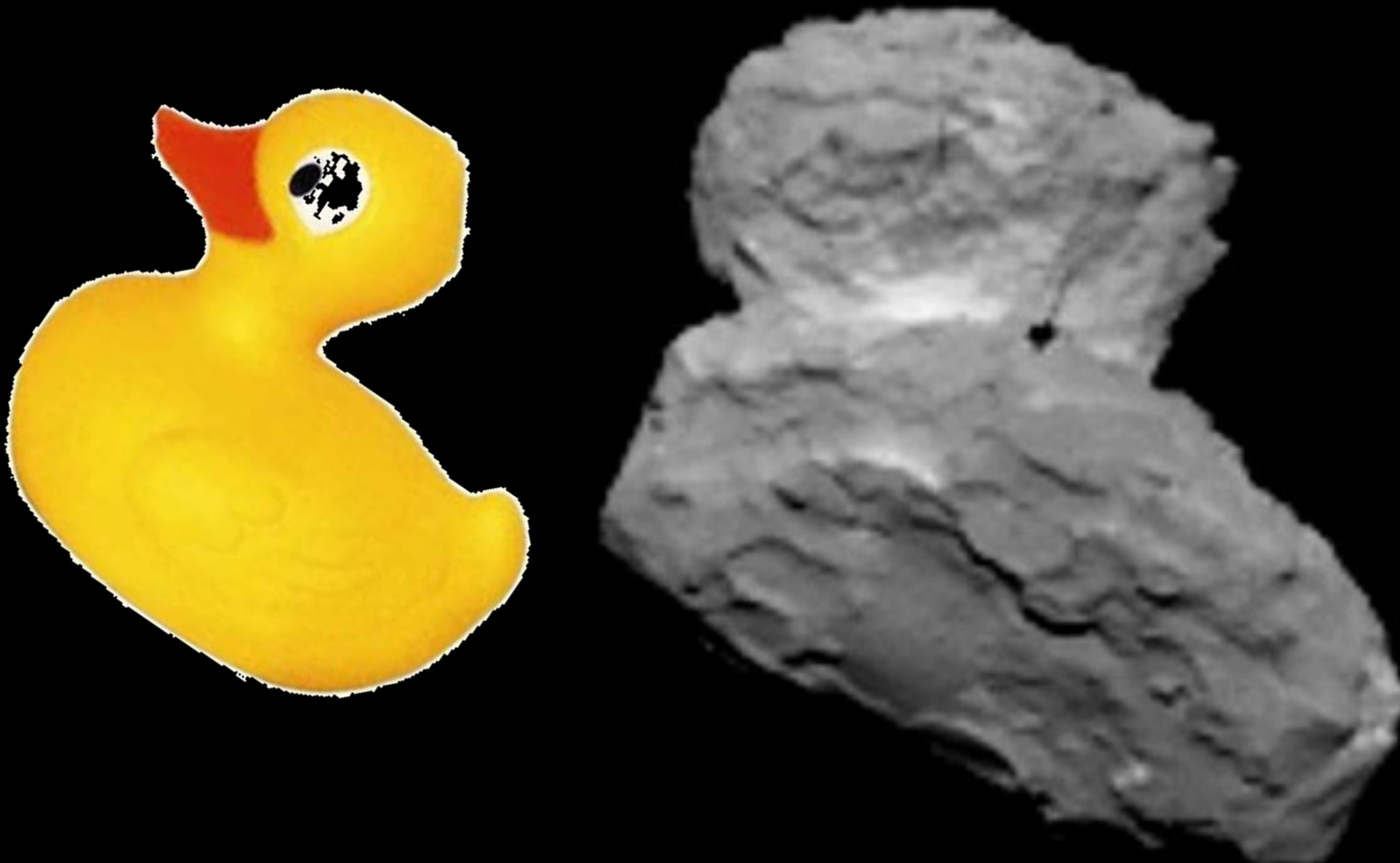
- characterization of the nucleus
- determination of its dynamic properties
- surface morphology and composition
- determination of chemical, mineralogical and isotopic compositions of volatiles and refractories in the cometary nucleus
- determination of the physical properties and interrelation of volatiles and refractories in the cometary nucleus
- studies of the development of cometary activity and the processes in the surface layer of the nucleus and inner coma, that is dust/gas interaction
- studies of the evolution of the interaction region of the solar wind and the outgassing comet during perihelion approach.

Glassmeier et al., 2007

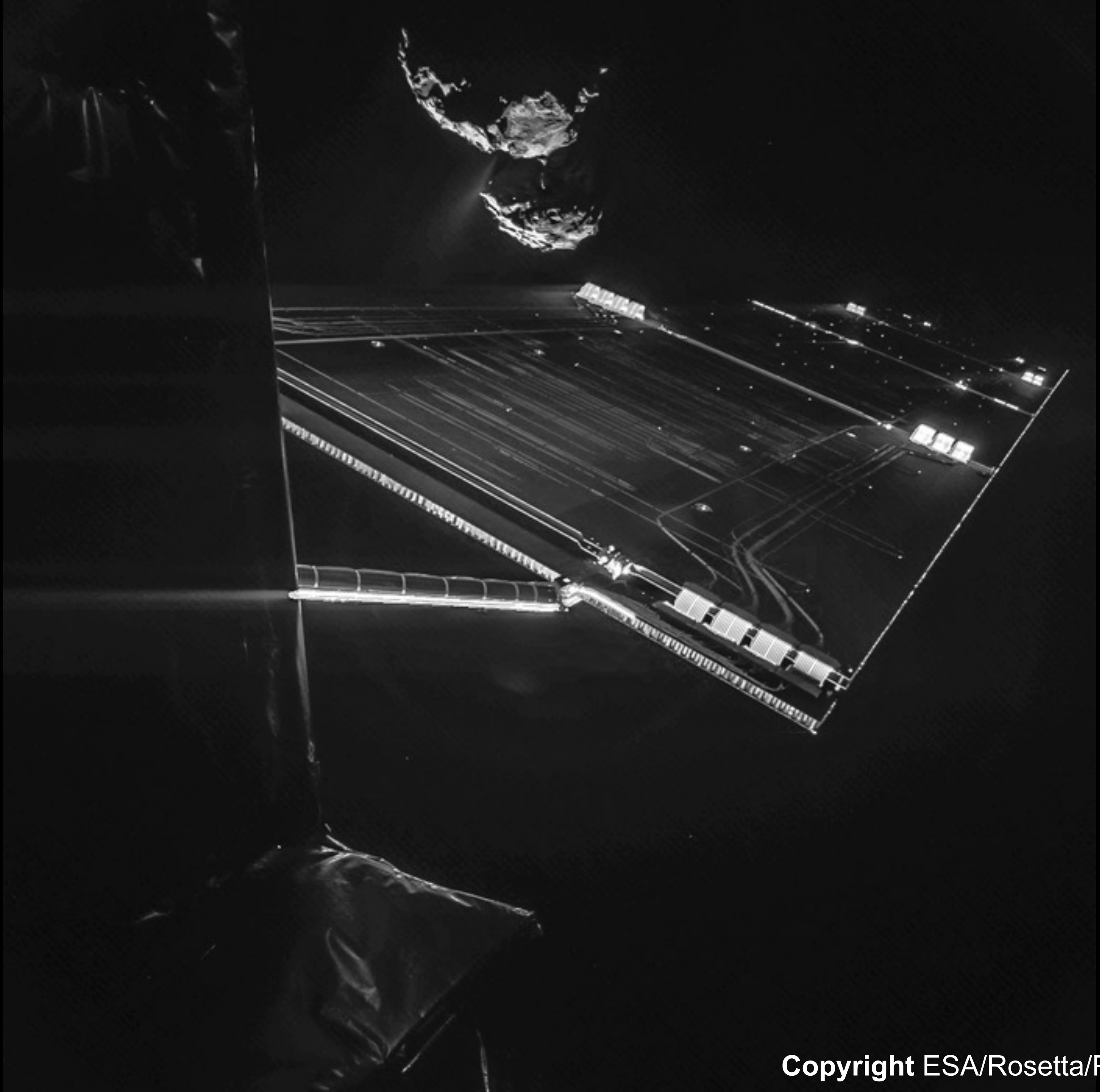
Date: 06 August 2014
Satellite: Rosetta
Depicts: Comet 67P/Churyumov-Gerasimenko

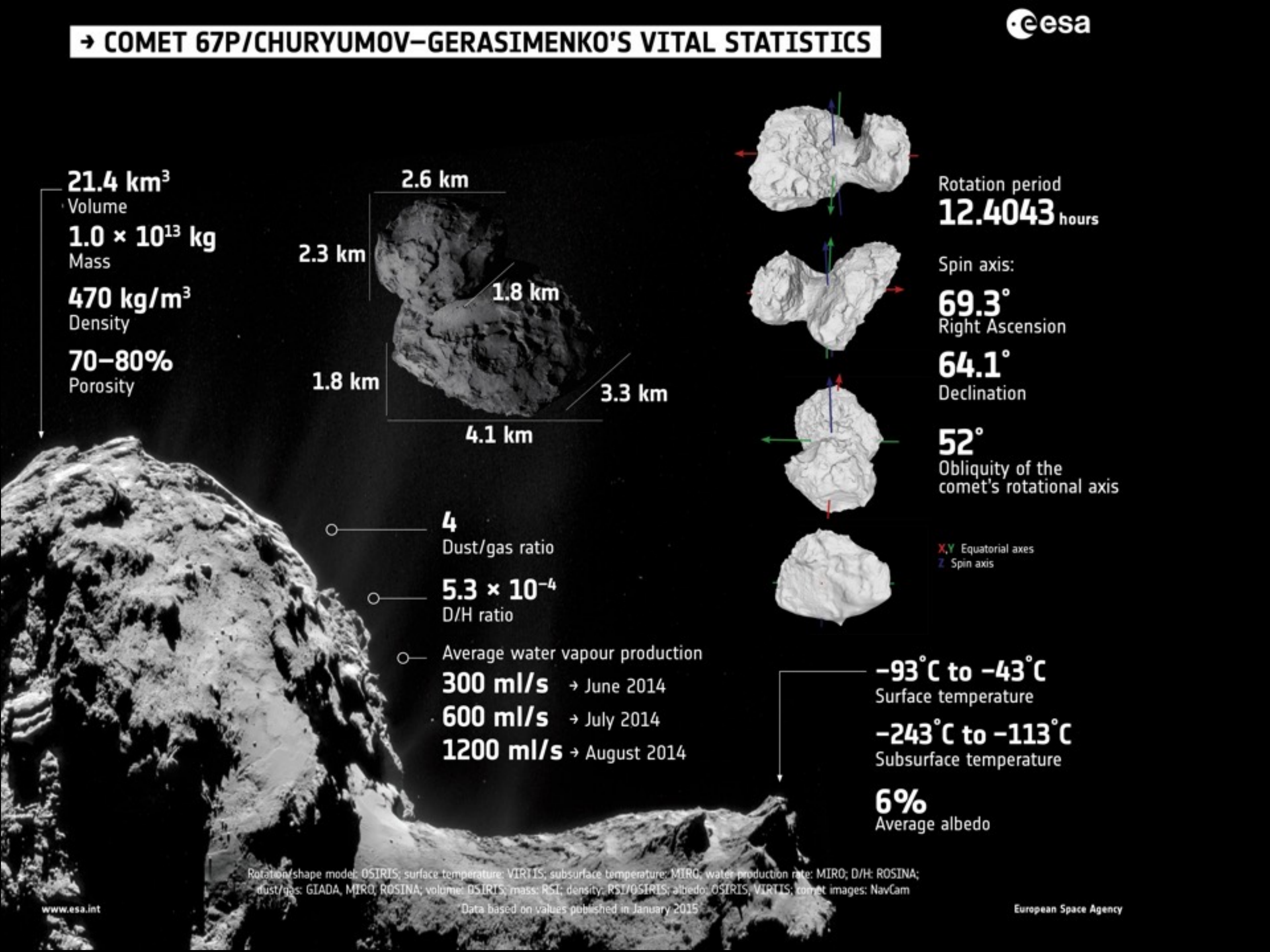
OWLT ~ 45 min

Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO /INTA/UPM/DASP/IDA



Chury – the rubber ducky



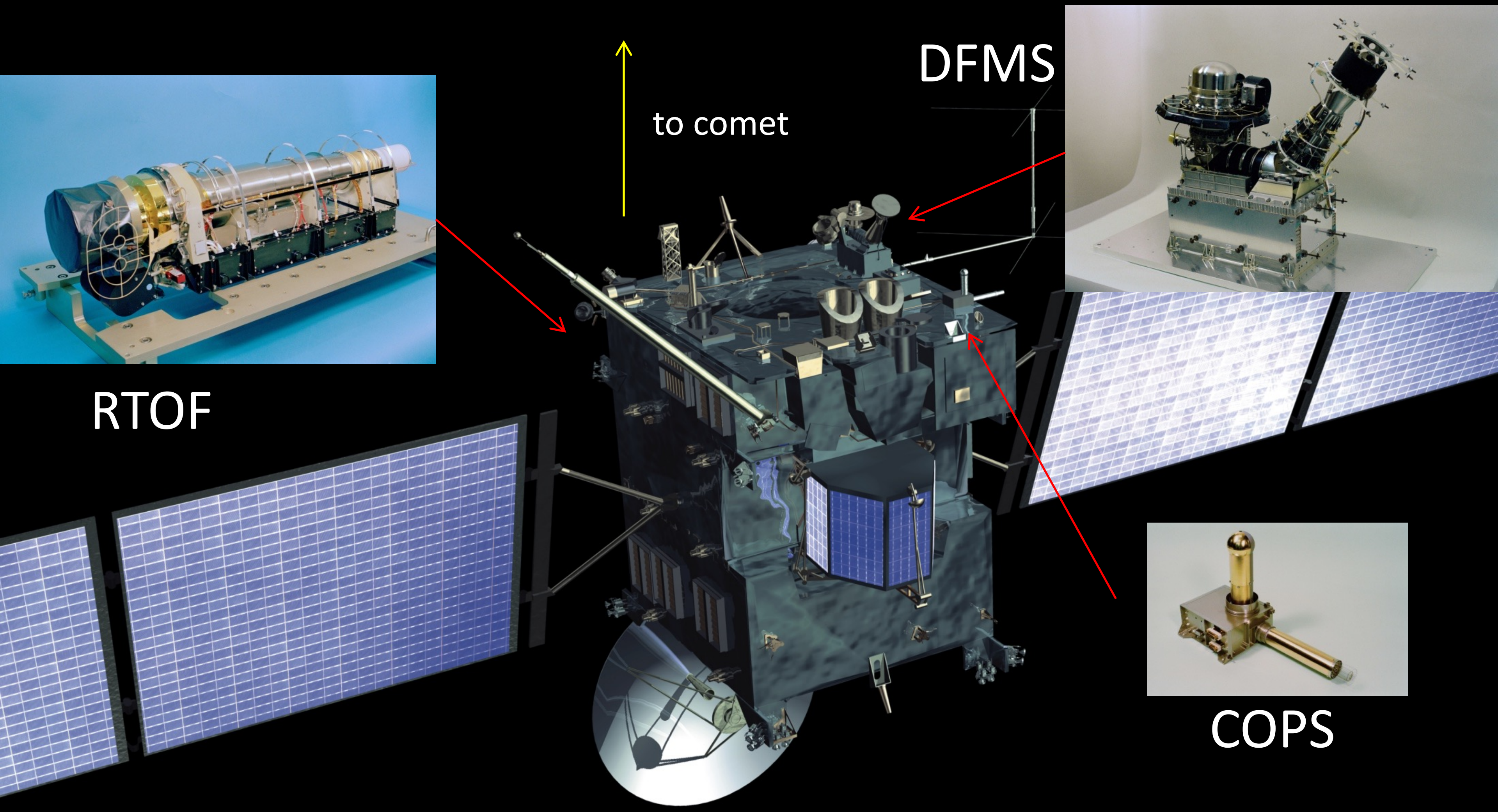


→ COMET 67P/CHURYUMOV–GERASIMENKO'S VITAL STATISTICS
esa
21.4 km³
Volume
1.0 × 10¹³ kg
Mass
470 kg/m³
Density
70–80%
Porosity
2.6 km
2.3 km
1.8 km
1.8 km
3.3 km
4.1 km
Rotation period
12.4043 hours
Spin axis:
69.3°
Right Ascension
64.1°
Declination
52°
Obliquity of the comet's rotational axis
X,Y Equatorial axes
Z Spin axis
4
Dust/gas ratio
5.3 × 10⁻⁴
D/H ratio
Average water vapour production
300 ml/s → June 2014
600 ml/s → July 2014
1200 ml/s → August 2014
–93°C to –43°C
Surface temperature
–243°C to –113°C
Subsurface temperature
6%
Average albedo
Rotation/shape model: OSIRIS; surface temperature: VIRTIS; subsurface temperature: MIRO; water production rate: MIRO; D/H: ROSINA; dust/gas: GIADA, MIRO, ROSINA; volume: OSIRIS; mass: RSI; density: RSI/OSIRIS; albedo: OSIRIS, VIRTIS; comet images: NavCam
Data based on values published in January 2015
www.esa.int
European Space Agency

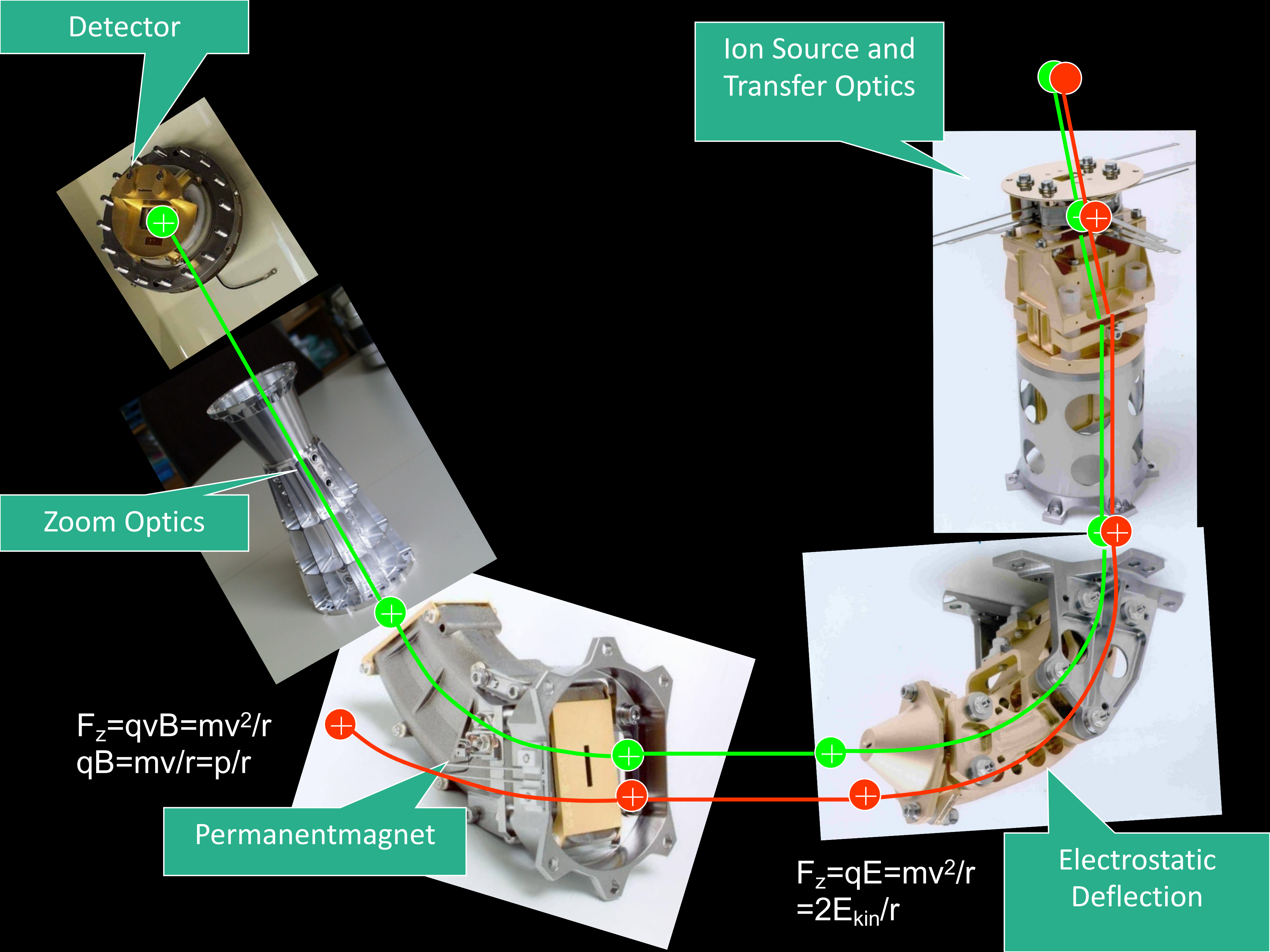
Rosetta Payload

• OSIRIS	Camera	28 kg
• ROSINA	Gas Mass Spectrometer	35 kg
• COSIMA	Dust Mass Spectrometer	20 kg
• GIADA	Dust Flux Analyzer	4.5 kg
• MIDAS	Dust Microscope	5.5 kg
• VIRTIS	Infrared Spectrometer	23 kg
• MIRO	Microwave Experiment	16.2 kg
• ALICE	Ultraviolet Spectrometer	2.2 kg
• RPC	Plasma Instruments: Magnetic Feld, Electrons, (Energetic) Ions	5.7 kg
• RSI	Radio Experiment	0.0 kg
• CONSERT	Comet Nucleus Sounder	2.0 kg
• LANDER PHILAE	With 10 Experiments	100 kg

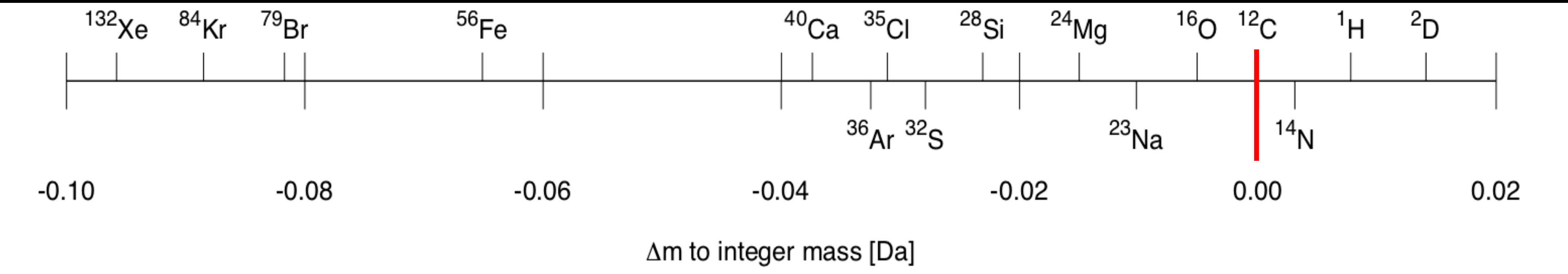
Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA)



… measured gas density and composition in the atmosphere of the comet

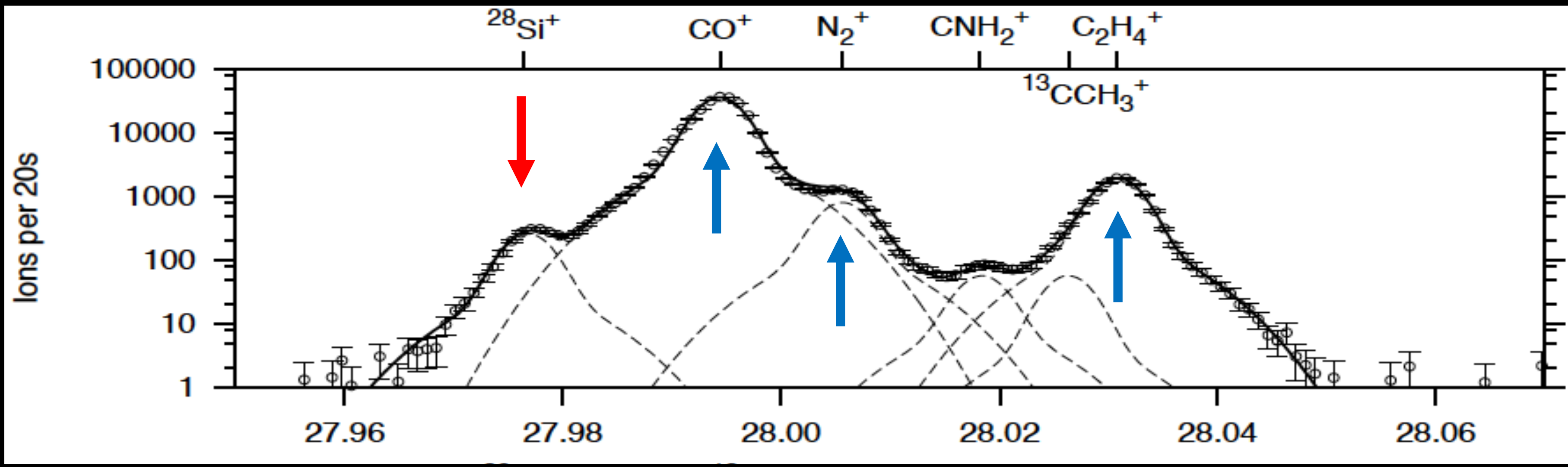

Detector
Ion Source and Transfer Optics
Zoom Optics
$F_z=qvB=mv^2/r$
$qB=mv/r=p/r$
Permanentmagnet
$F_z=qE=mv^2/r$
$=2E_{kin}/r$
Electrostatic Deflection

ROSINA data

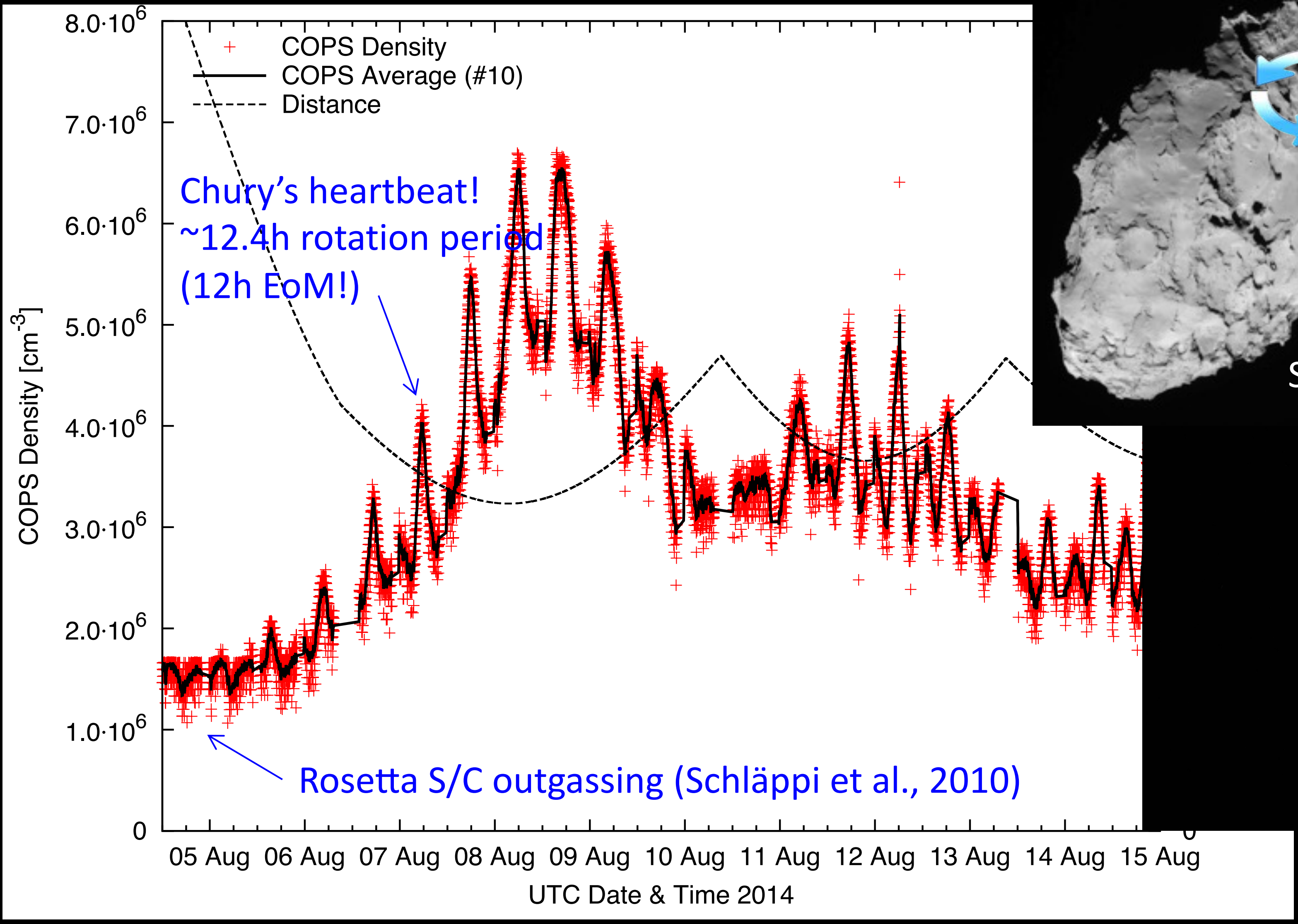


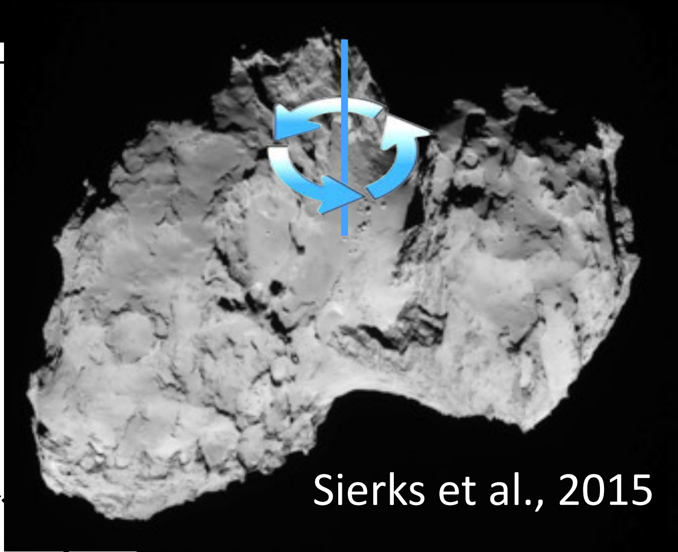
refractory (sputtering?)

Volatiles & fragments



First observations in August 2014

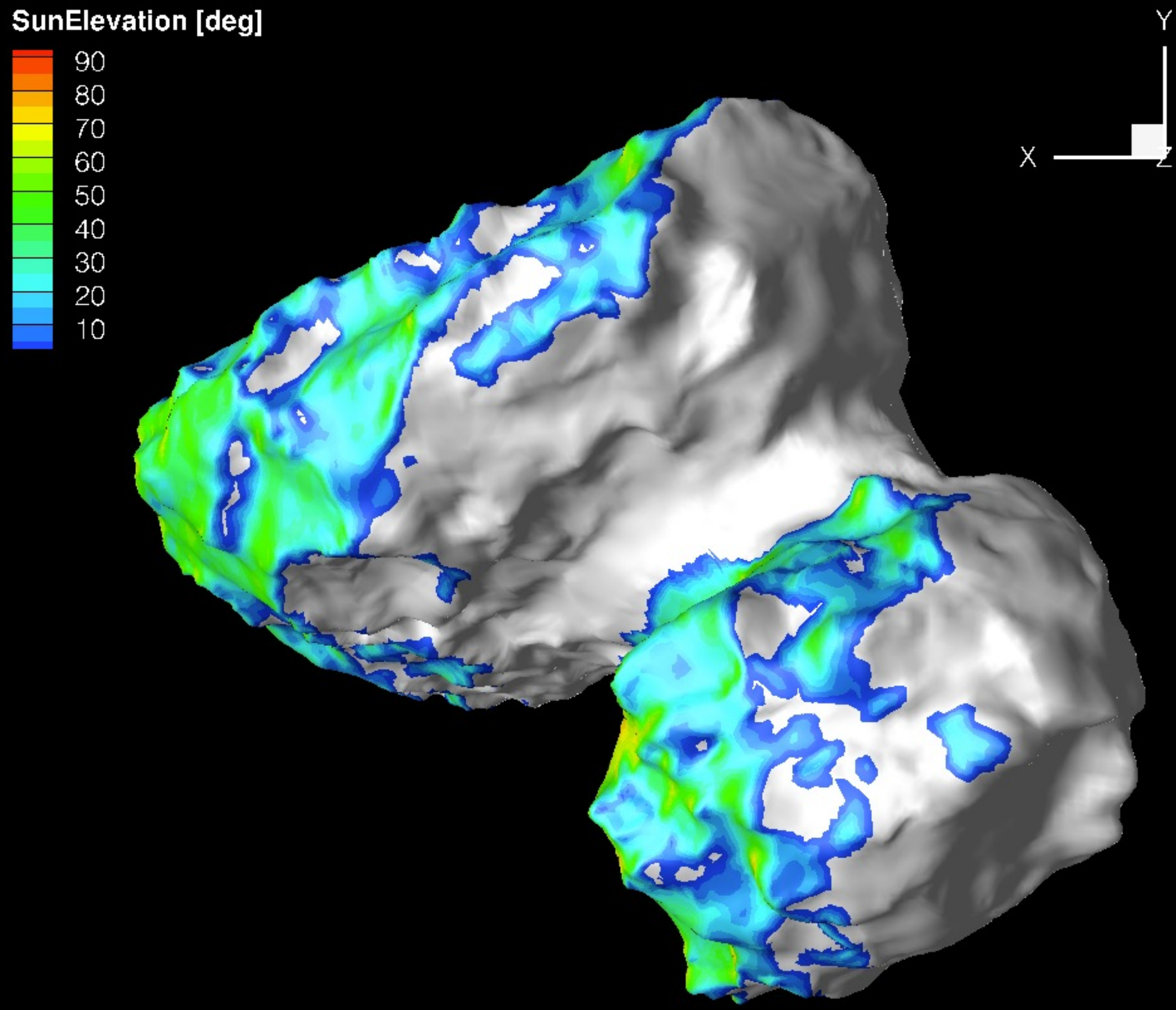




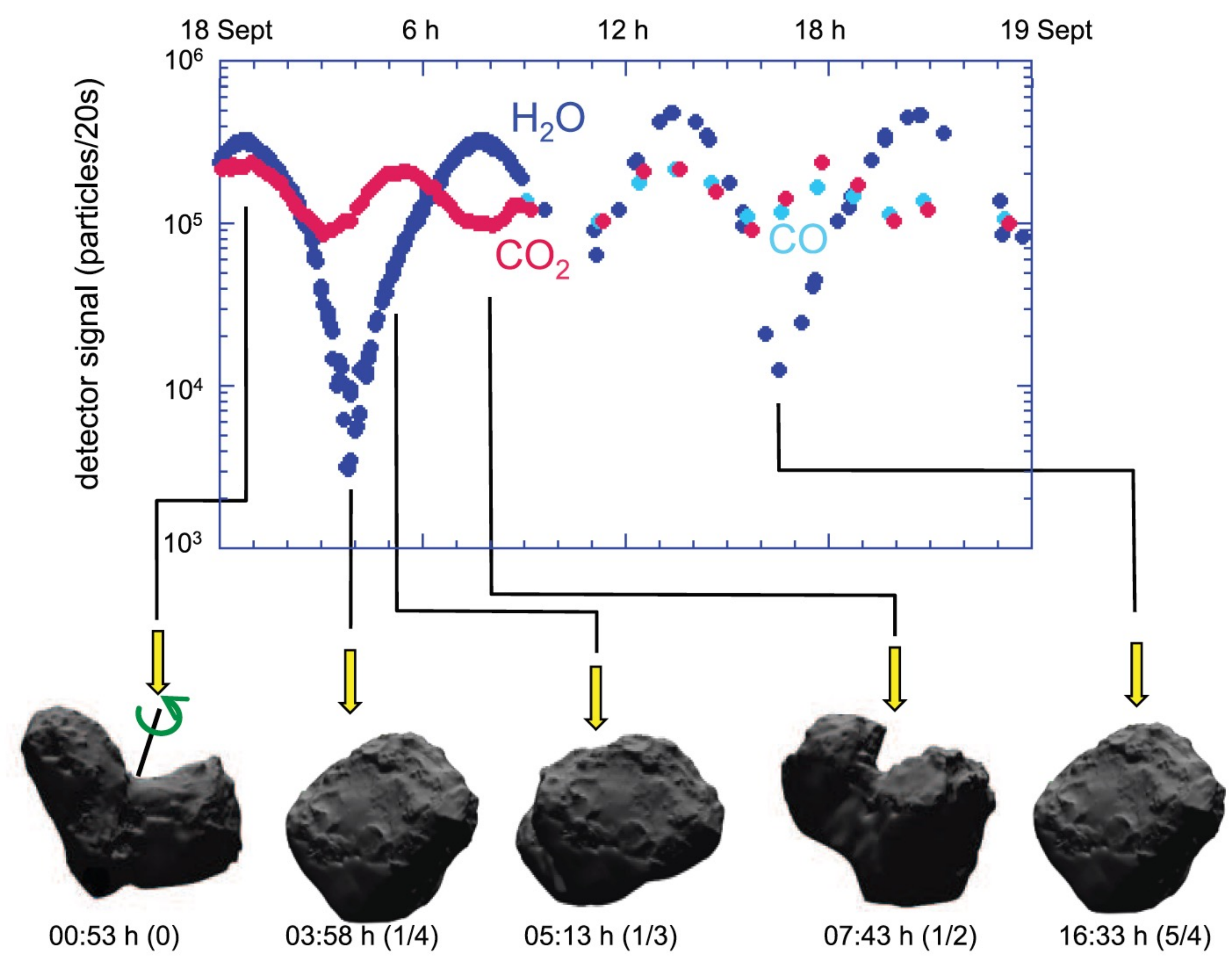
Credits:
ESA/Rosetta/NAVCAM

ESA/Rosetta/ROSINA/UBern, BIRA, LATMOS, LMM, IRAP, MPS, SwRI, TUB, UMich

Illumination as seen from Rosetta

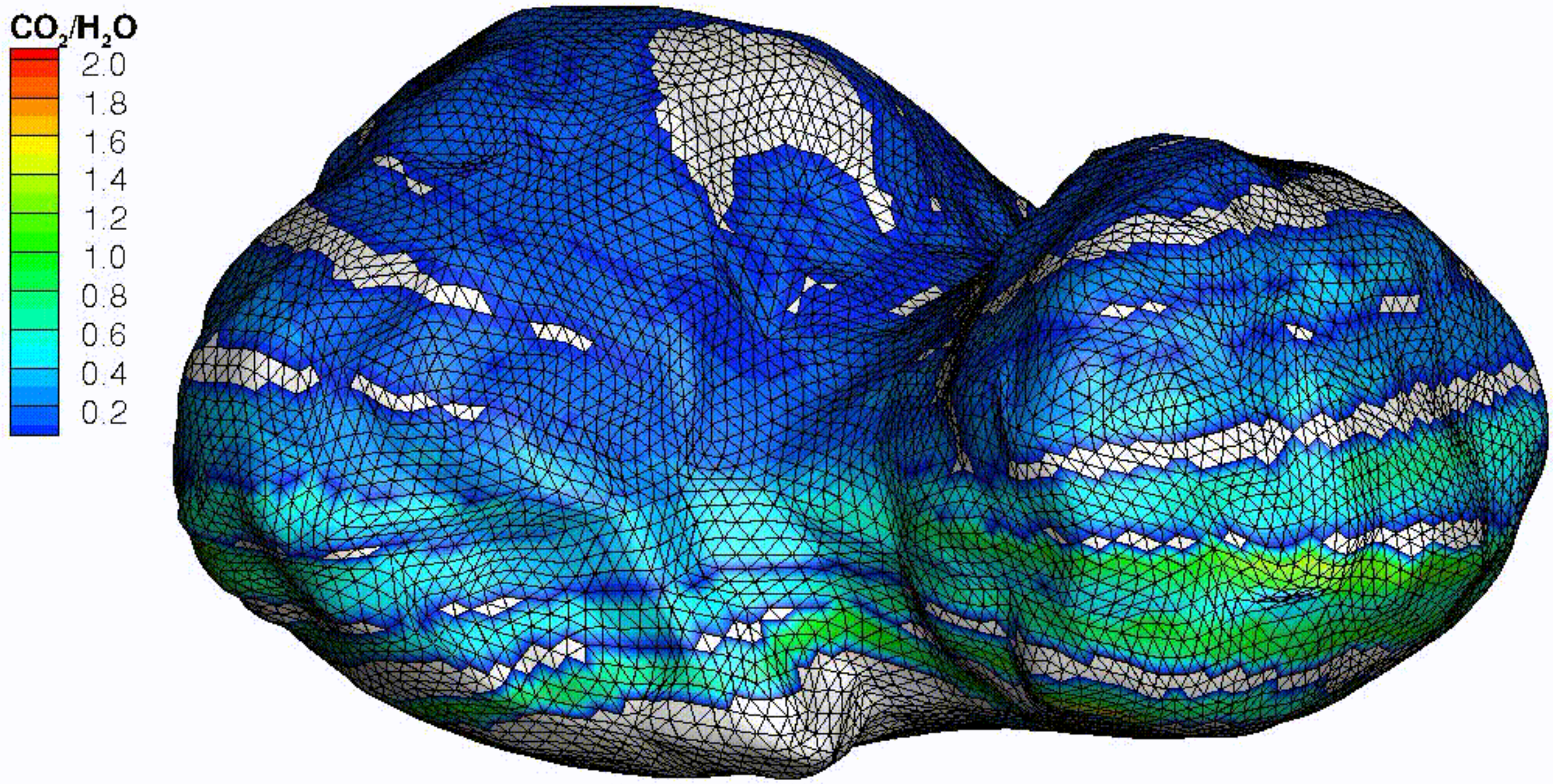


Major species: H_2O, CO_2 & CO



Hässig et al., 2015

CO_2/H_2O

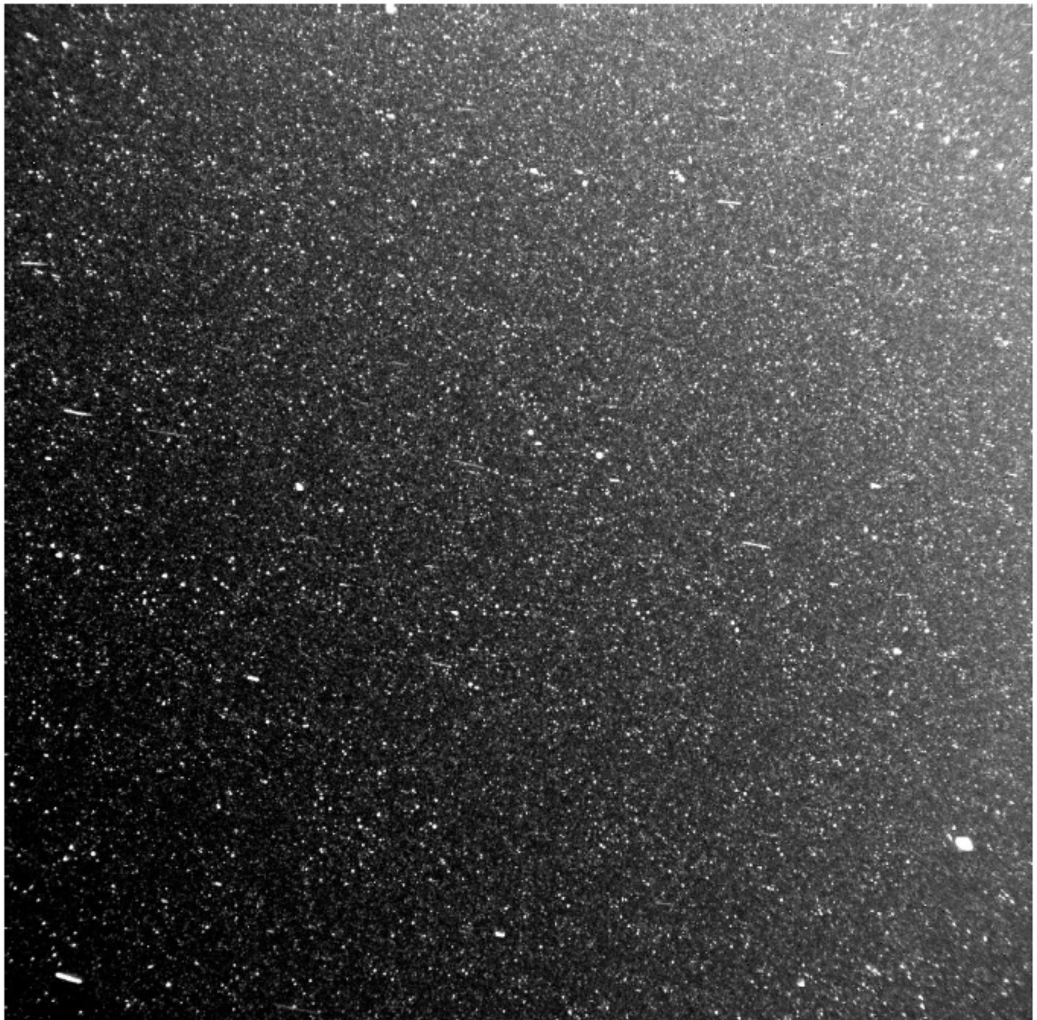


Hässig et al., 2015

Credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

Was ist Restlicht/Streulicht von Staub und was Sterne?

Star Tracker A CCD Read-Out: 2015-07-06



Star Tracker A CCD Read-Out acquired on 6 July 2015 between 06:09 and 09:01 UTC

Distance: 159km
Phase Angle (of CG): 89°

Pointing during that period: *inertial*

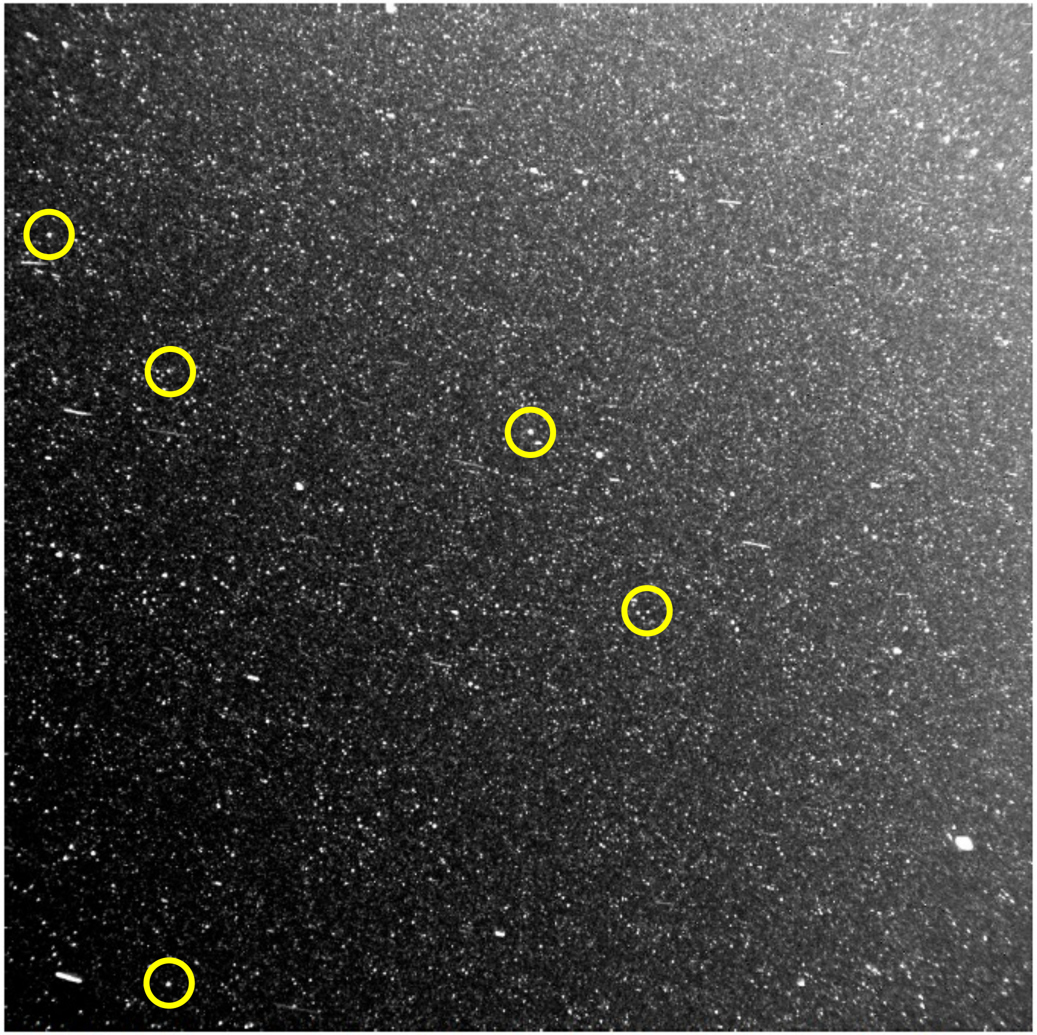
Field of View: 16.5°x16.5°.
Pixel Size: 58″
Integration Time: 1s
(operationally: 0.1s)

Sub-Frame Size: 205x15 Pixel.
Number of Sub-Frames: 345
Integration Time: 1second
Frequency: every 30seconds
(values to be confirmed)

Was ist Restlicht/Streulicht von Staub und was Sterne?

Star Tracker A CCD Read-Out: 2015-07-06

esa



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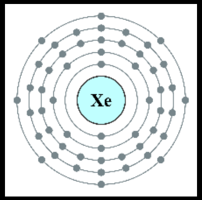
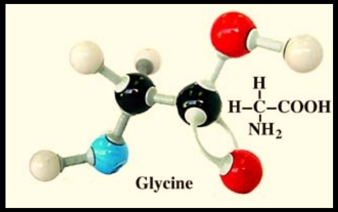
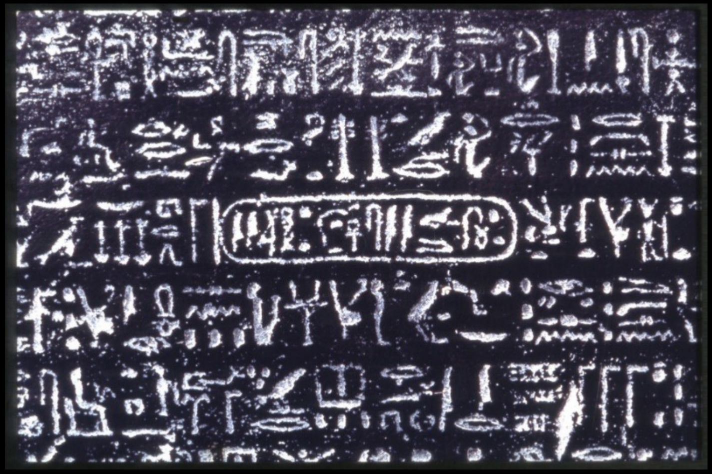
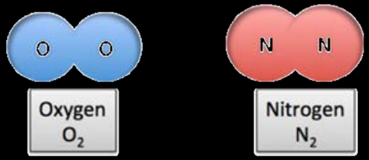
.....starting from the chemical composition

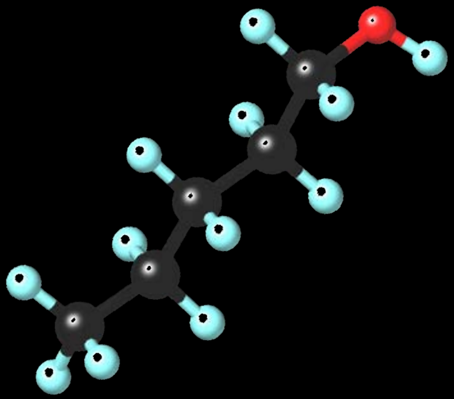




Let each species tell its own tale







Giant Molecular Cloud

Star forming region

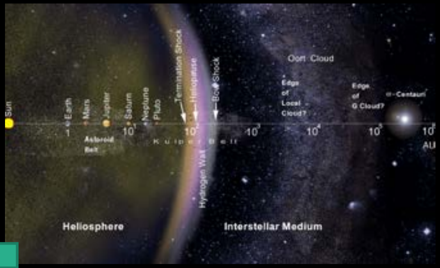
Interstellar medium

Protoplanetary nebula

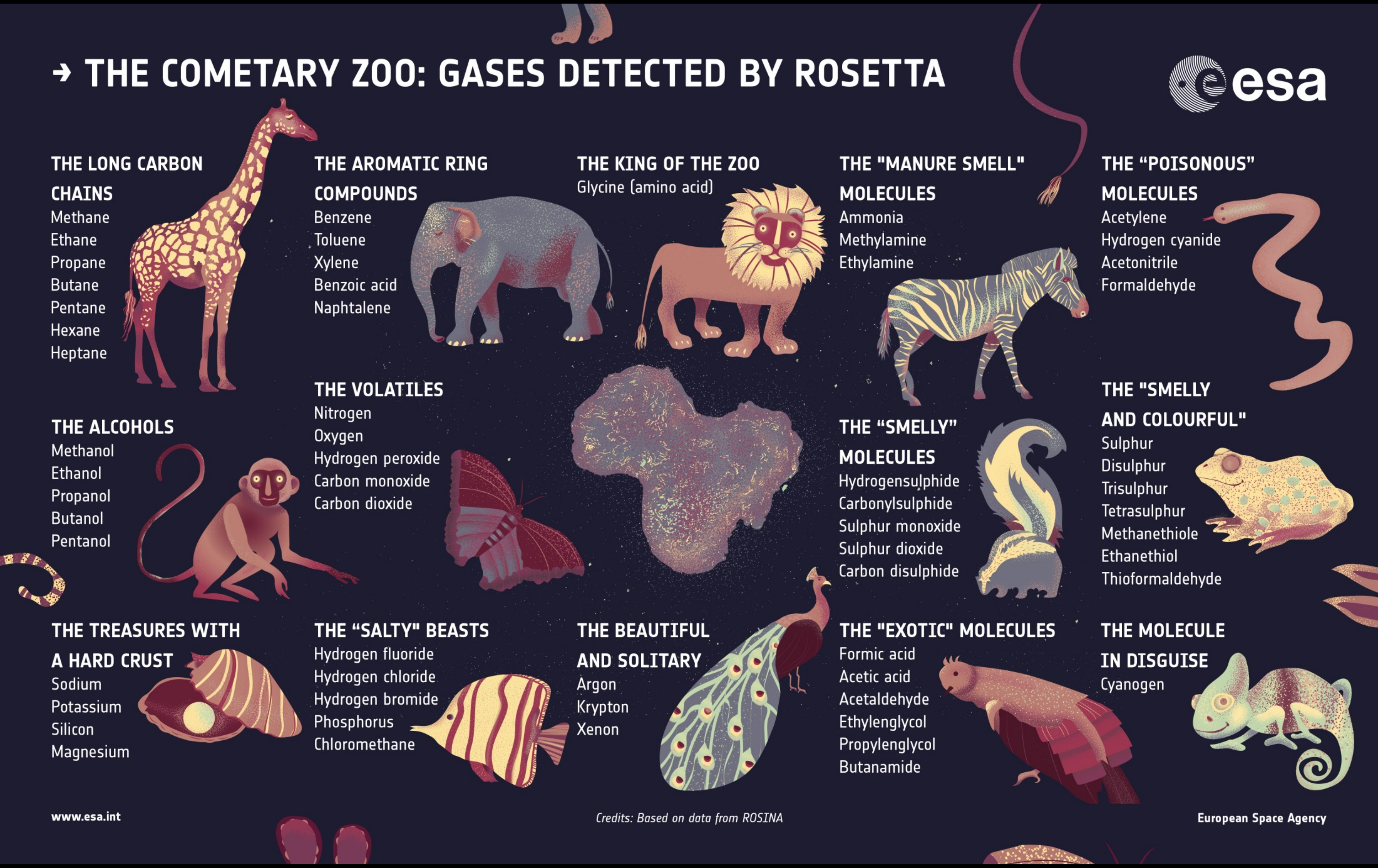
Evolution of the material

Starting conditions
Chemistry
Physical conditions (d, T, t)

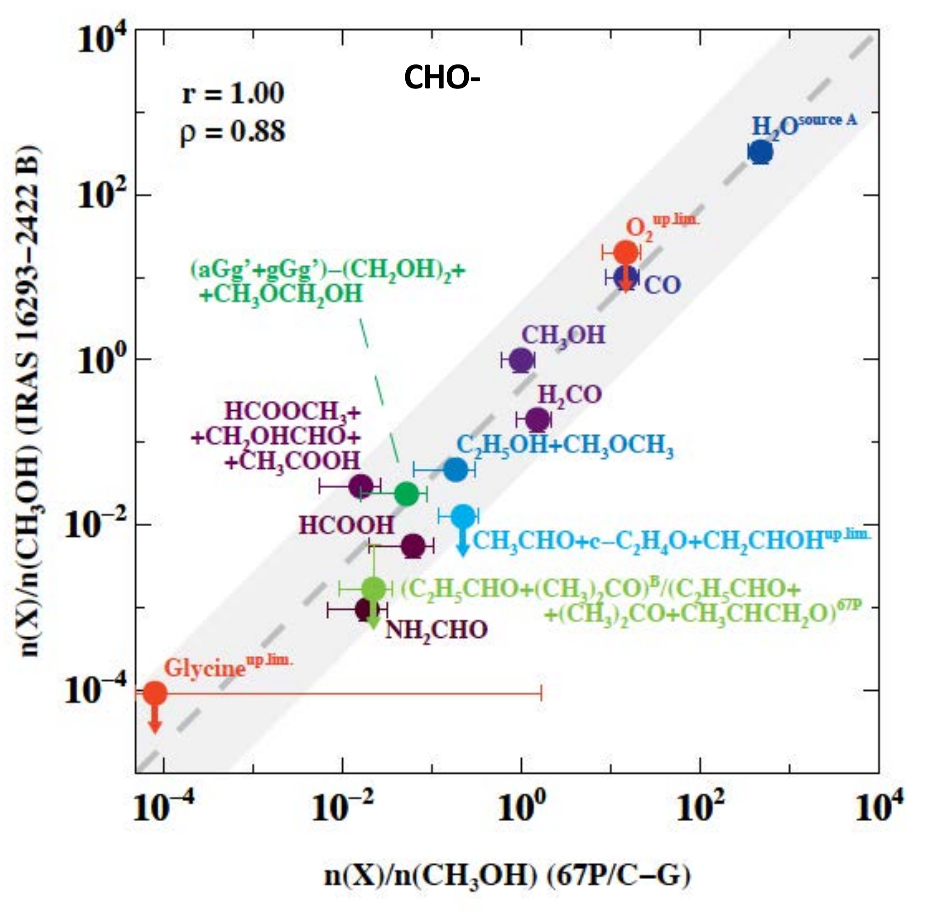
Evolution of life



Solar system


THE COMETARY ZOO: GASES DETECTED BY ROSETTA
esa
THE LONG CARBON CHAINS
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane
THE AROMATIC RING COMPOUNDS
Benzene
Toluene
Xylene
Benzoic acid
Naphtalene
THE KING OF THE ZOO
Glycine (amino acid)
THE "MANURE SMELL" MOLECULES
Ammonia
Methylamine
Ethylamine
THE "POISONOUS" MOLECULES
Acetylene
Hydrogen cyanide
Acetonitrile
Formaldehyde
THE ALCOHOLS
Methanol
Ethanol
Propanol
Butanol
Pentanol
THE VOLATILES
Nitrogen
Oxygen
Hydrogen peroxide
Carbon monoxide
Carbon dioxide
THE "SMELLY" MOLECULES
Hydrogensulphide
Carbonylsulphide
Sulphur monoxide
Sulphur dioxide
Carbon disulphide
THE "SMELLY AND COLOURFUL"
Sulphur
Disulphur
Trisulphur
Tetrasulphur
Methanethiole
Ethanethiol
Thioformaldehyde
THE TREASURES WITH A HARD CRUST
Sodium
Potassium
Silicon
Magnesium
THE "SALTY" BEASTS
Hydrogen fluoride
Hydrogen chloride
Hydrogen bromide
Phosphorus
Chloromethane
THE BEAUTIFUL AND SOLITARY
Argon
Krypton
Xenon
THE "EXOTIC" MOLECULES
Formic acid
Acetic acid
Acetaldehyde
Ethylenglycol
Propylenglycol
Butanamide
THE MOLECULE IN DISGUISE
Cyanogen
www.esa.int
Credits: Based on data from ROSINA
European Space Agency

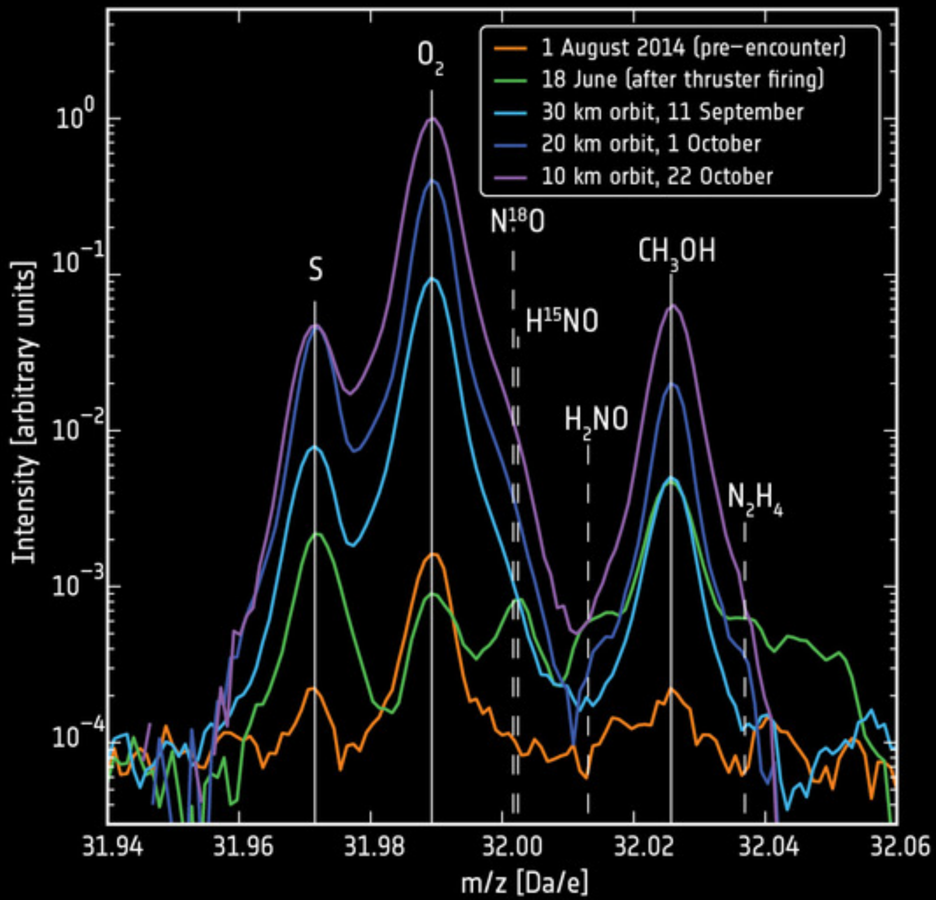
Relative abundances - Connection to the ISM



Drozdovskaya et al., 2019 from PILS survey (see also Bockelée-Morvan et al. 2000)

The O_2 story

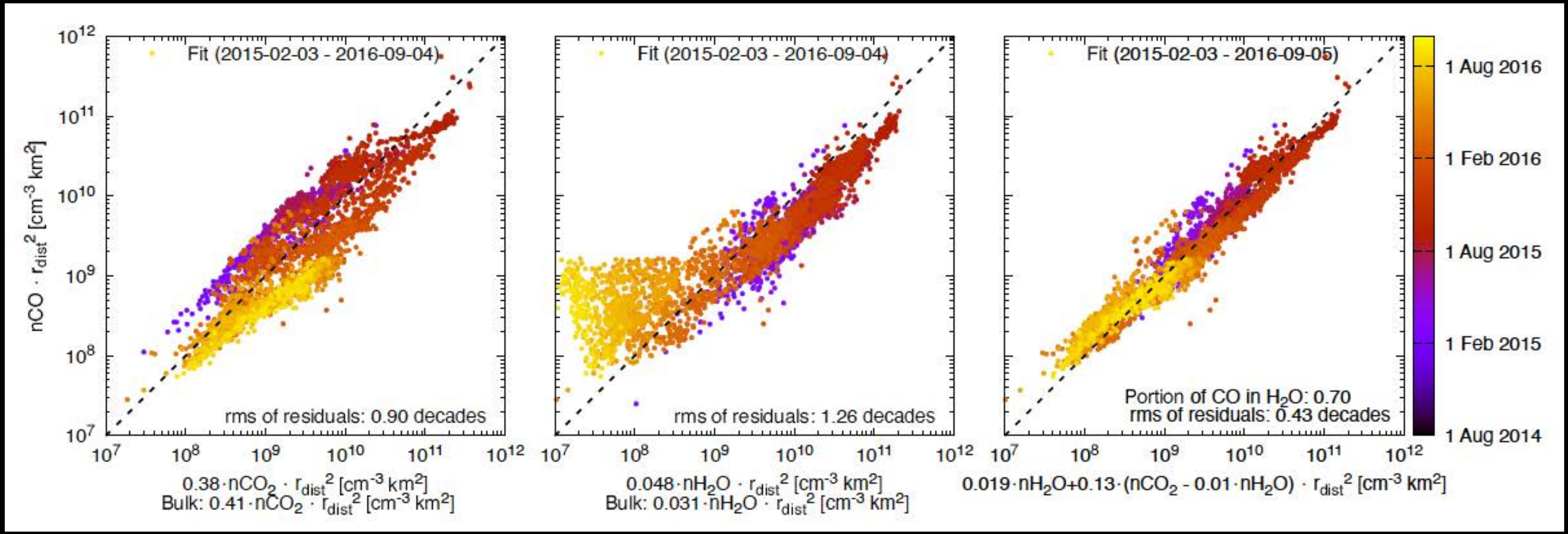
- Significant amounts of O_2 found at 67P, ~3.8% w.r.t. H_2O, lack of H_2O_2 and HO_2 (Bieler et al., 2015)
- O_2 proportional to H_2O → O_2 is very well embedded in the water ice matrix
- O_2 cannot be formed in the protosolar nebula by radiolysis
- O_2 was formed in the star forming regions / molecular clouds either by radiolysis (Mousis et al., 2016), gas phase chemistry (Taquet et al., 2016), dismutation of H_2O during sublimation (Dulieu et al., 2017)
- However, difference in O-isotopes favors an origin of O_2 not from H_2O.



Presence of highly volatiles

The presence of N_2, CO, CH_4, … suggests

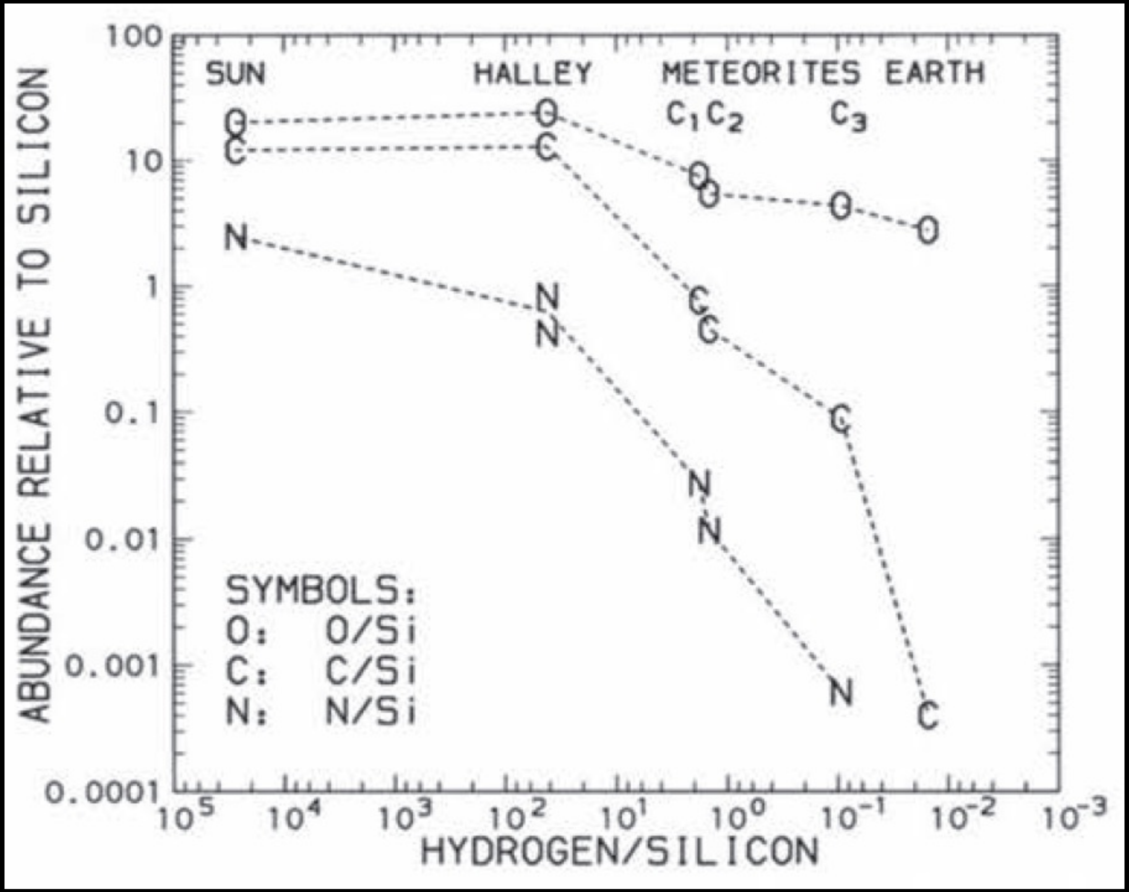
- that comets such as 67P were never warm
- that comets cannot have been part of a big object (heating by radioactivity)
- that comets formed around 25 K (no Ne detected).



- Caveat: to what extent are these (minor) species trapped in CO_2 and H_2O?

Where is the nitrogen?

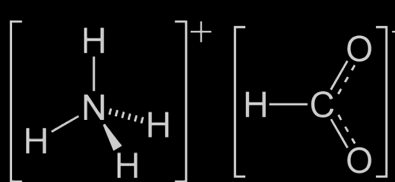
- Lack of N in comets known since the Giotto flyby at 1P/Halley



(Geiss, 1987)

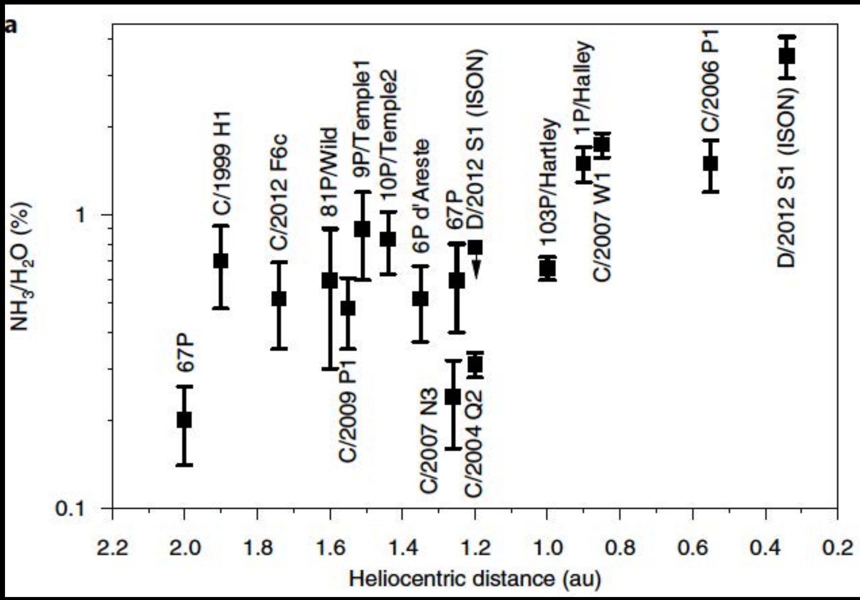
Where is the nitrogen? – Ammonium salts

- Ammonium salts (Altwegg et al. 2020, 2022; Quirico et al. 2016, Poch et al. 2021)
- All sublimation products of a number of different ammonium salts found in ROSINA data
  - Ammonium hydrosulphide: $NH_4^+SH^-$ (T_{sub} = 168 K)
  - Ammonium chloride: $NH_4^+Cl^-$ (T_{sub} = 473 K)
  - Ammonium cyanide: $NH_4^+CN^-$ (T_{sub} = 140 K)
  - Ammonium cyanate: $NH_4^+OCN^-$ (T_{sub} = 200 K)
  - Ammonium formate: $NH_4^+HCOO^-$ (T_{sub} = 200 K)



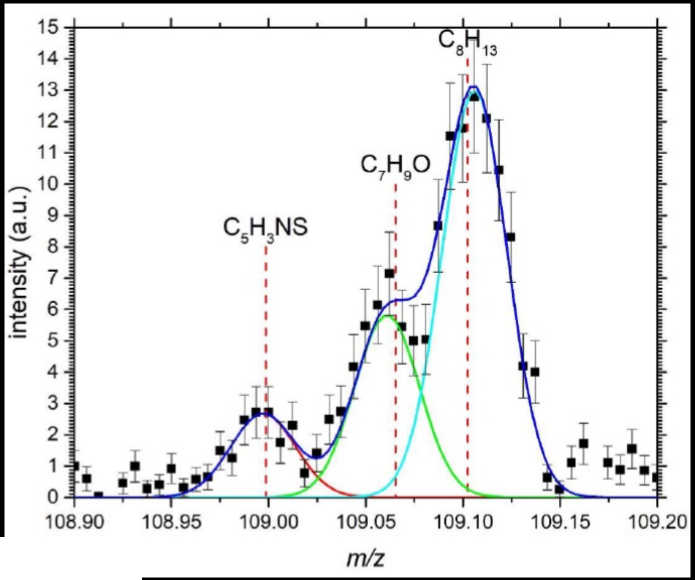
$\longrightarrow$ **$NH_3 + CH_2O_2$**

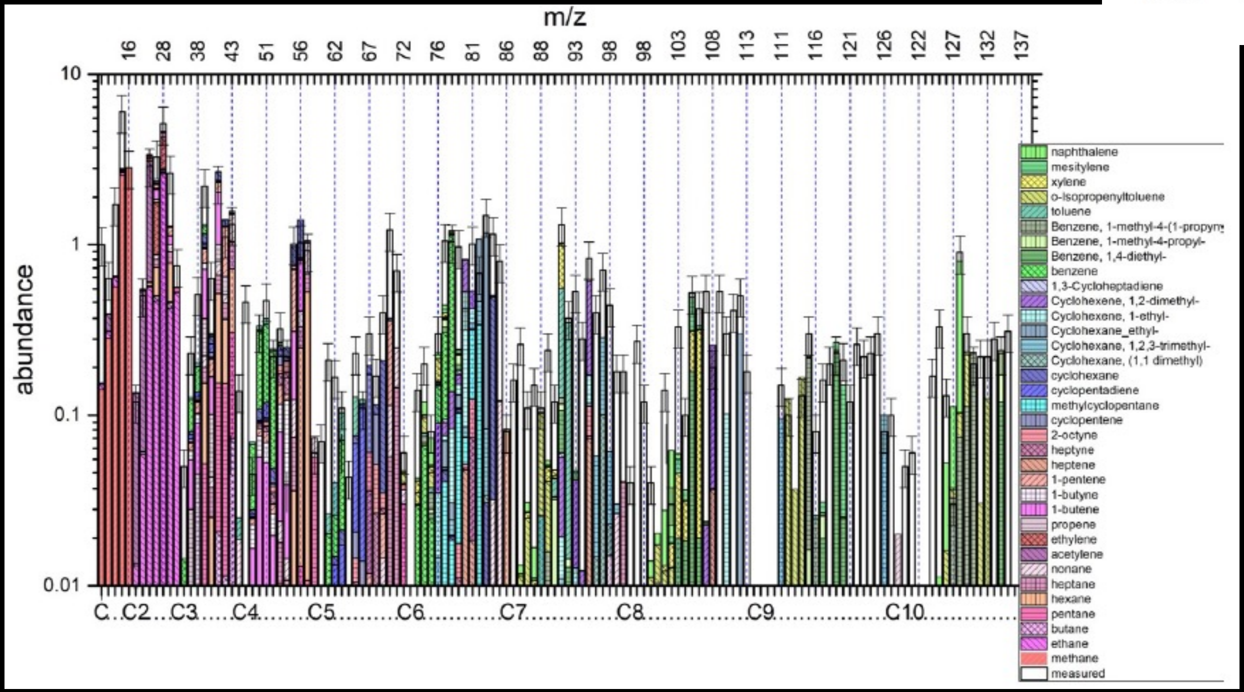
  - Ammonium acetate: $NH_4^+CH_3COO^-$ (T_{sub} = 326 K)



Organics m>100 Da

Evidence for a continuum of cometary organics between volatile and refractory



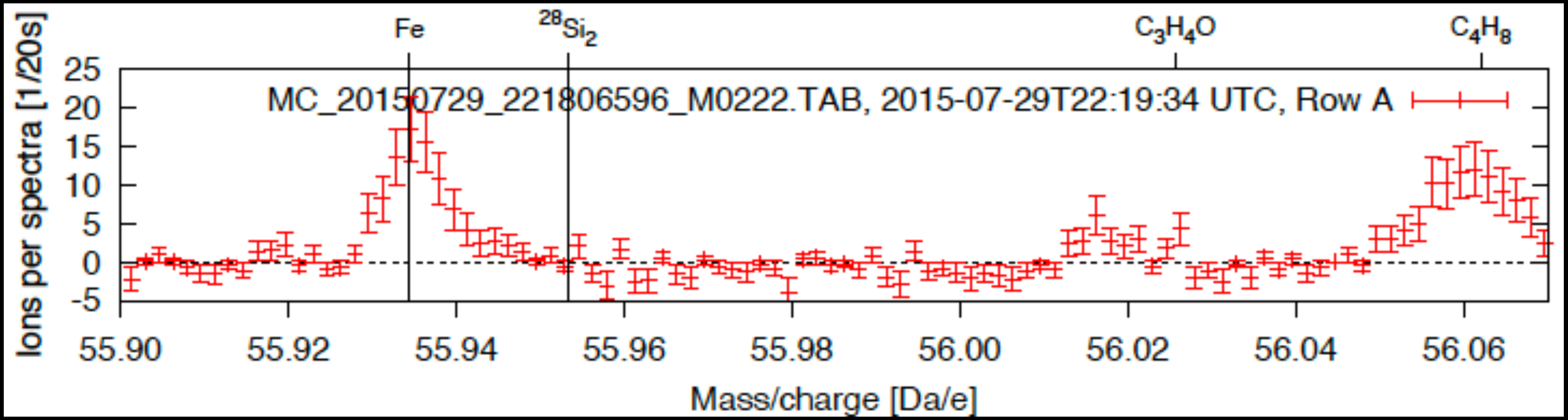


Occam's razor approach:

Chain-based, cyclic, and aromatic species (6:3:1), no polymers (Hänni et al., 2022)

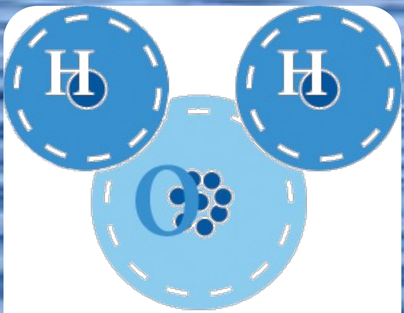
Refractory elements in the gas phase

- Na, Si, Ca, K detected in the gas phase early in the mission, most likely associated to sputtering by solar wind (Wurz et al. 2015)
- Same elements plus Fe detected close to perihelion while solar wind absent/deflected (Behar et al., 2017) ≠ sputtering! cf. Manfroid et al. 2021, Guzik & Drahus 2022



(Rubin et al. 2022)

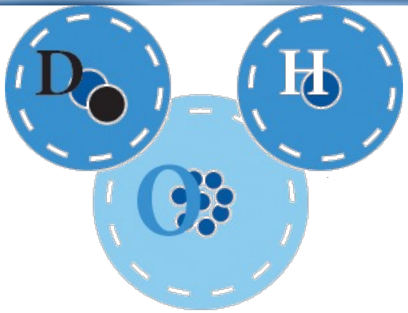
Isotopes in H_2O



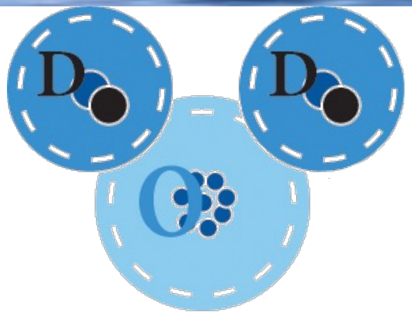
H_2O
(water)

67P: 3.5 x Earth

Earth: ~3/10’000



HDO
(semi-heavy water)



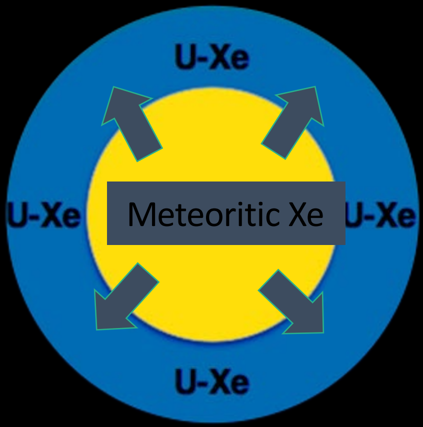
D_2O
(heavy water)

Earth: ~2/100’000’000

67P: 240 x Earth

O: Oxygen
H: Hydrogen
D: Deuterium

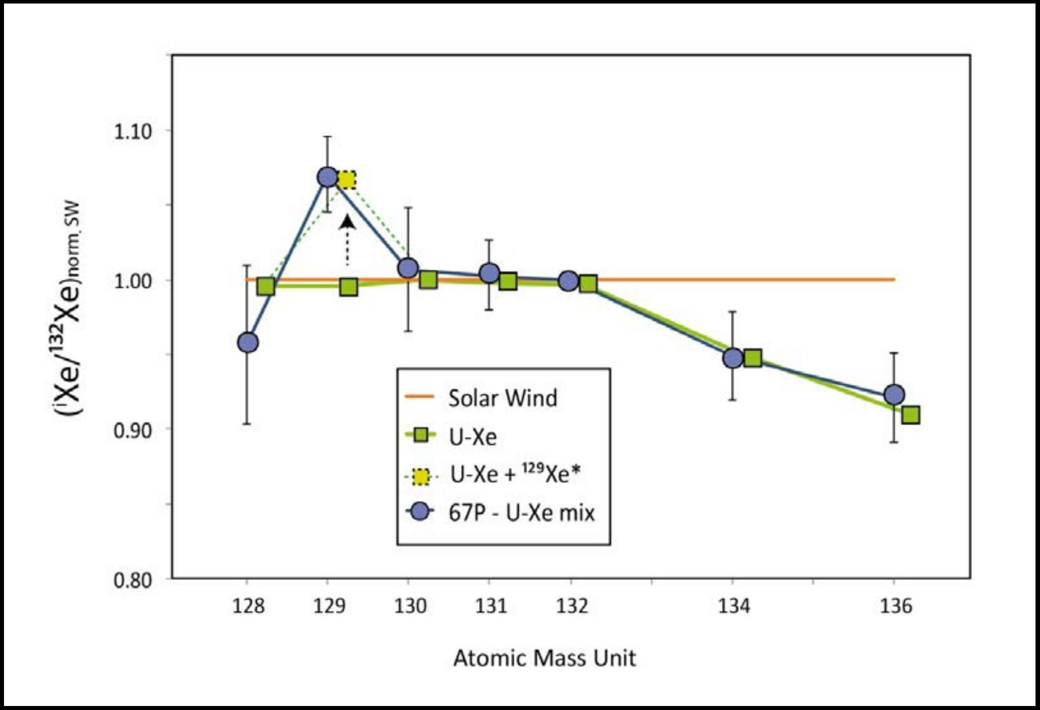
Xenon isotopes / delivery to Earth



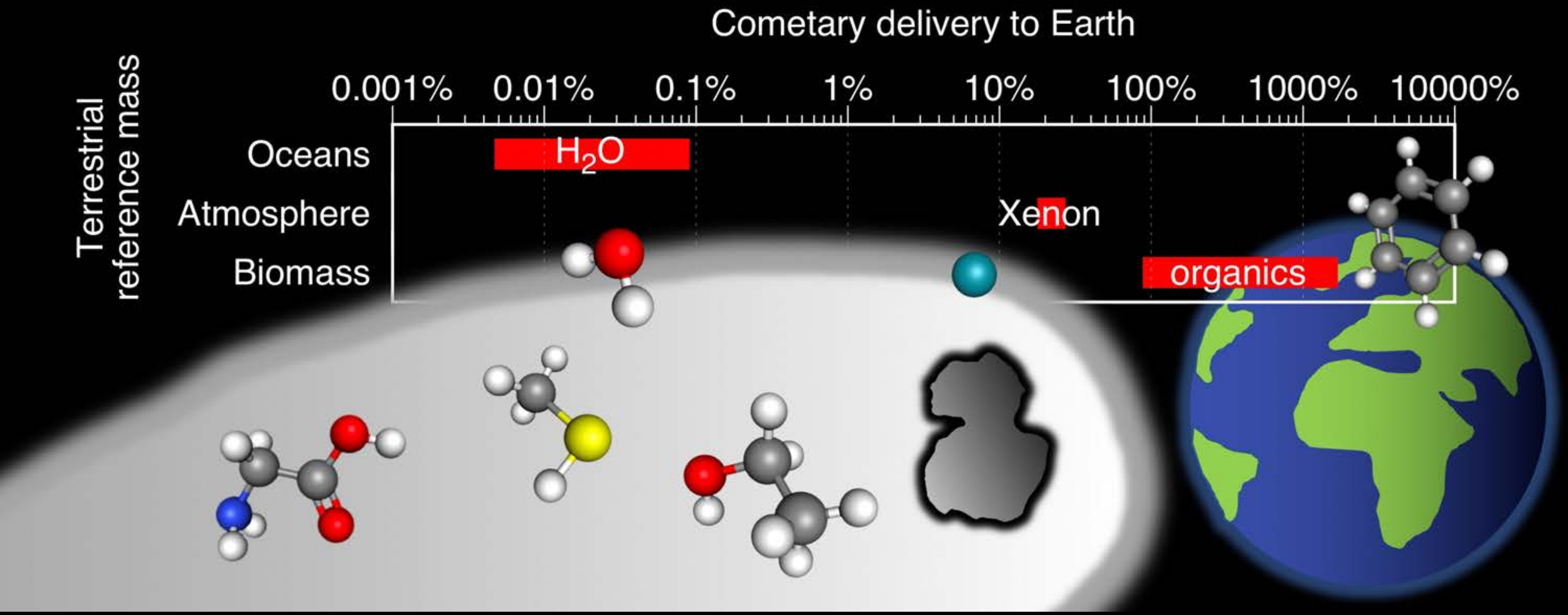
Reproduce Xe isotope ratio of terrestrial atmosphere by mixing

- 22±5% cometary Xe with meteoritic Xe
- and accounting for atmospheric escape/ fractionation

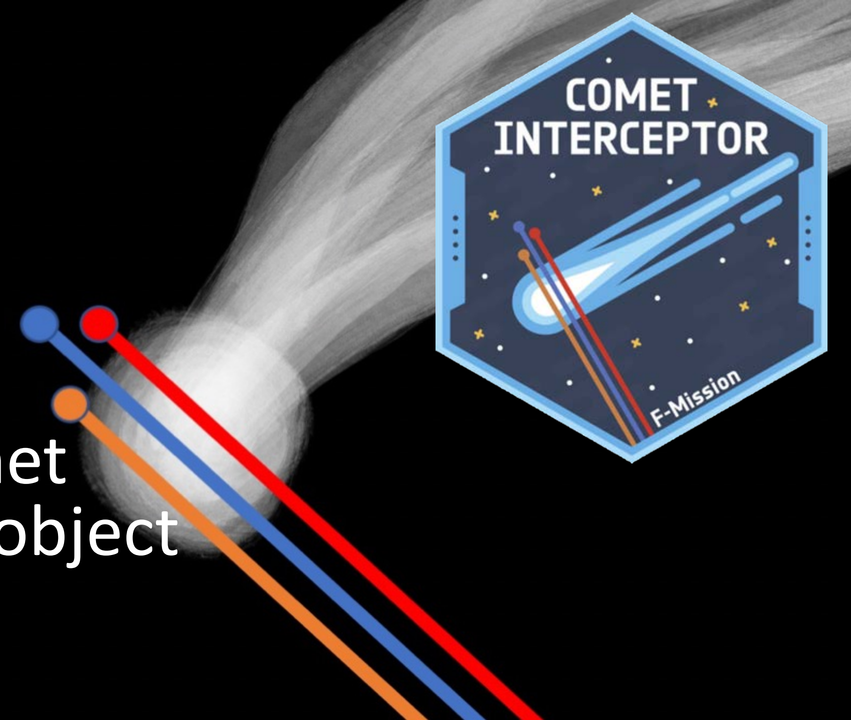
(Marty et al. 2017)



Xenon isotopes / delivery to Earth



Comet Interceptor



- ESA’s new F-class mission
- Launch in 2029 to a yet to be identified dynamically new comet or possibly even an interstellar object

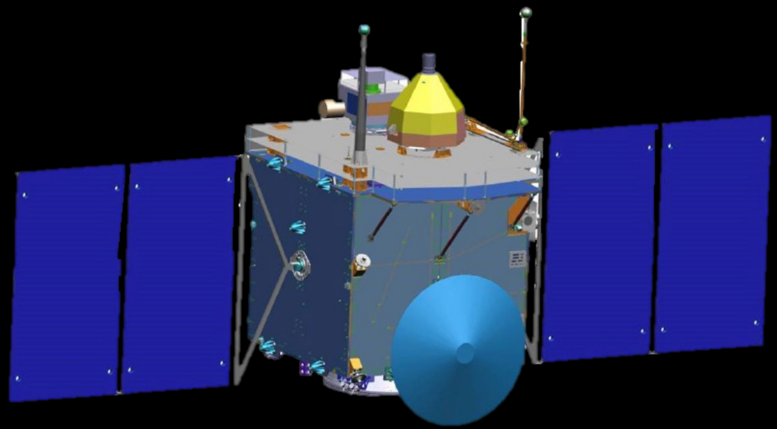
- A: main spacecraft
  - Passes sunward of comet at ~1000 km ('safe' distance)
  - Data relay for other spacecraft
  - Propulsion + communication
  - Main payload to ensure results even if other spacecraft fail

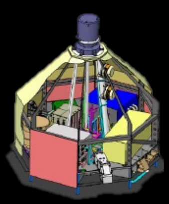
- B1: inner coma
  - Targeted to pass through inner coma
  - In-situ sampling, coma imaging

- B2: nucleus + coma
  - Targeted close to the nucleus (but unlikely to actually hit it)
  - In-situ sampling, nucleus + coma imaging

Comet Interceptor

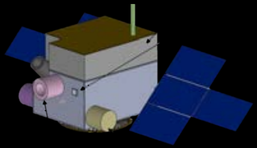
S/C A (ESA)
CoCa, MIRMIS, DFP-A, MANiaC



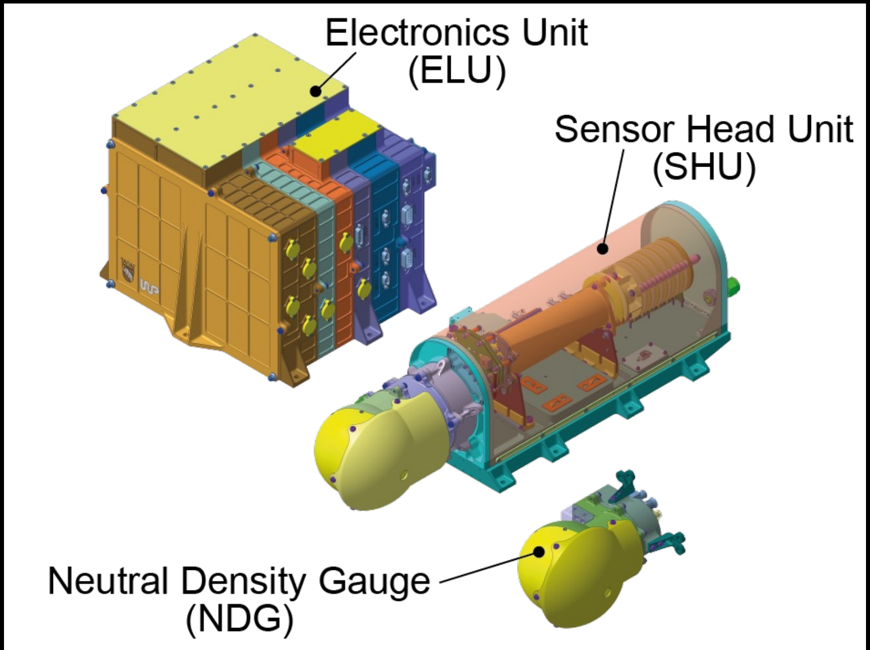


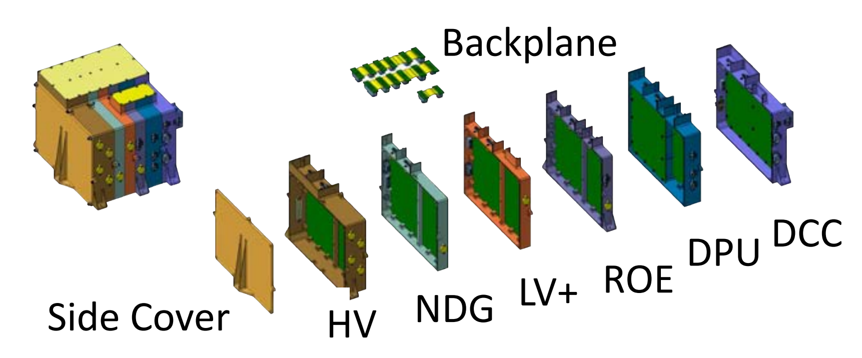
S/C B2 (ESA)
OPIC, EnVisS, DFP-B2

S/C B1 (JAXA)
HI, PS, WAC/NAC



Mass Analyzer for Neutrals in a Coma (MANiaC)





- Consortium: Univ. of Bern (lead), IAA Granada, IWF Graz, IRAP Toulouse, CTI Piaseczno, DLR Berlin
- Time-Of-Flight mass spectrometer (SHU) measures relative abundances coma molecules
- Neutral Density Gauge (NDG) measures absolute densities along trajectory
- Mass:~ 6.8 kg (CBE)
- Power: 35 W at encounter
- Data volume:~ 7 Gbit for post-encounter compression/download and, if available, real-time transmission in low resolution.

Advances with Comet Interceptor

- Visit for the first time a dynamically new comet, if possible even an interstellar object
- Perform multi-point measurements

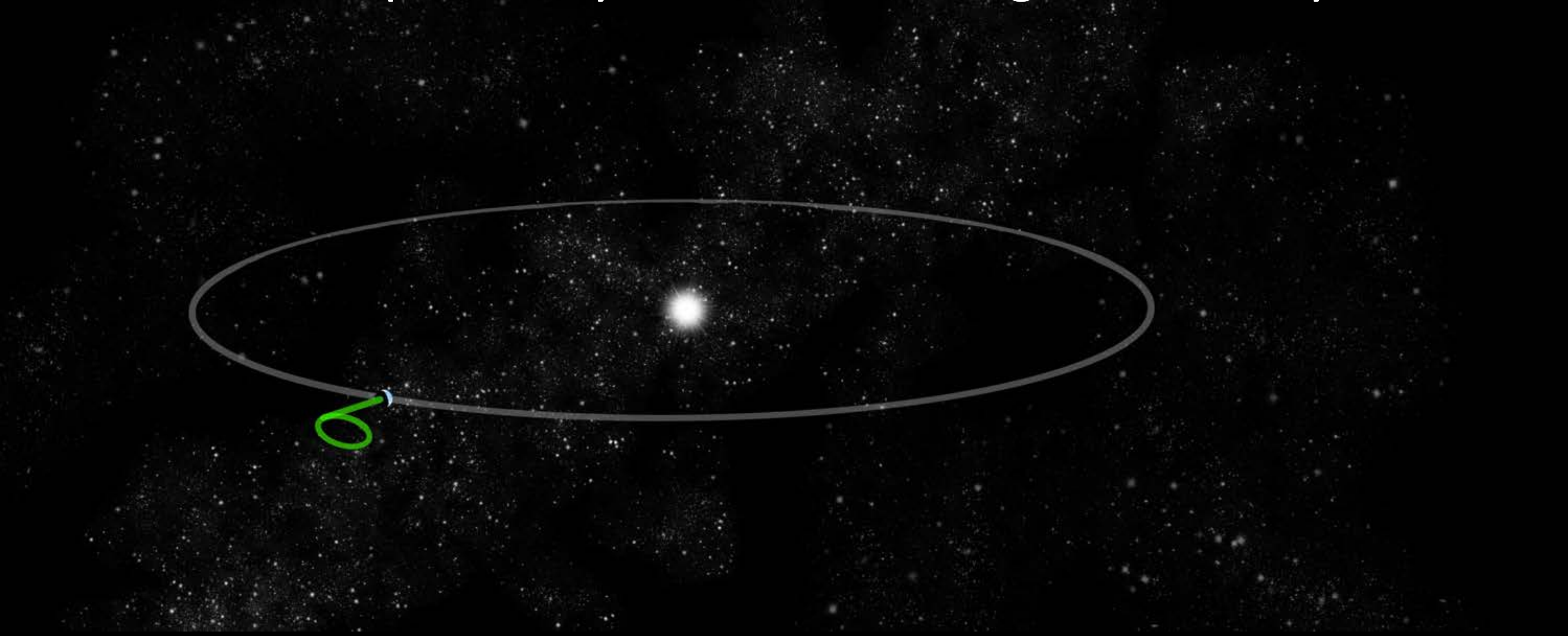
Image credit: www.ohb-italia.it/satellites-missions/

MANiaC science goals

- Monitoring the major volatiles H_2O, CO, and CO_2 in the coma to study the target's activity and associated gas mass loss rate, extended sources, etc.
- Deriving the D/H ratio in H_2O to study the provenience of the water ice in the comet.
- Assess the amount of key volatiles such as O_2 and highly volatile species in a DNC. Relative abundances of highly volatiles.
- Obtain an inventory of (complex) organic molecules and other species important in pre-biotic chemistry
- Measurement of icy grains' composition should some be collected in the ion source

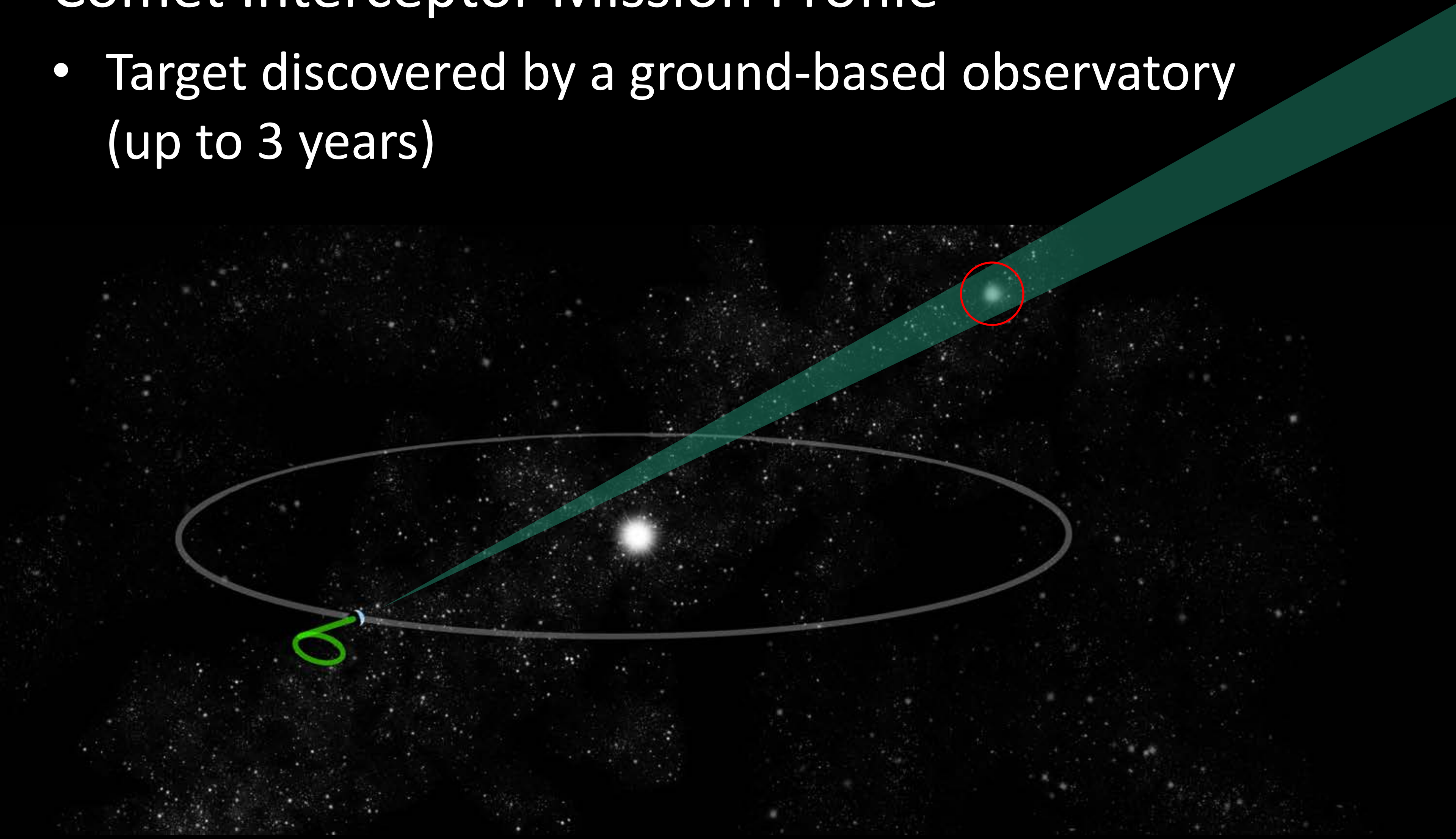
Comet Interceptor Mission Profile

- Mission 'parked' at stable Lagrange point L2 after launch with Ariel
- Waits for up to 2-3 years for new target discovery



Comet Interceptor Mission Profile

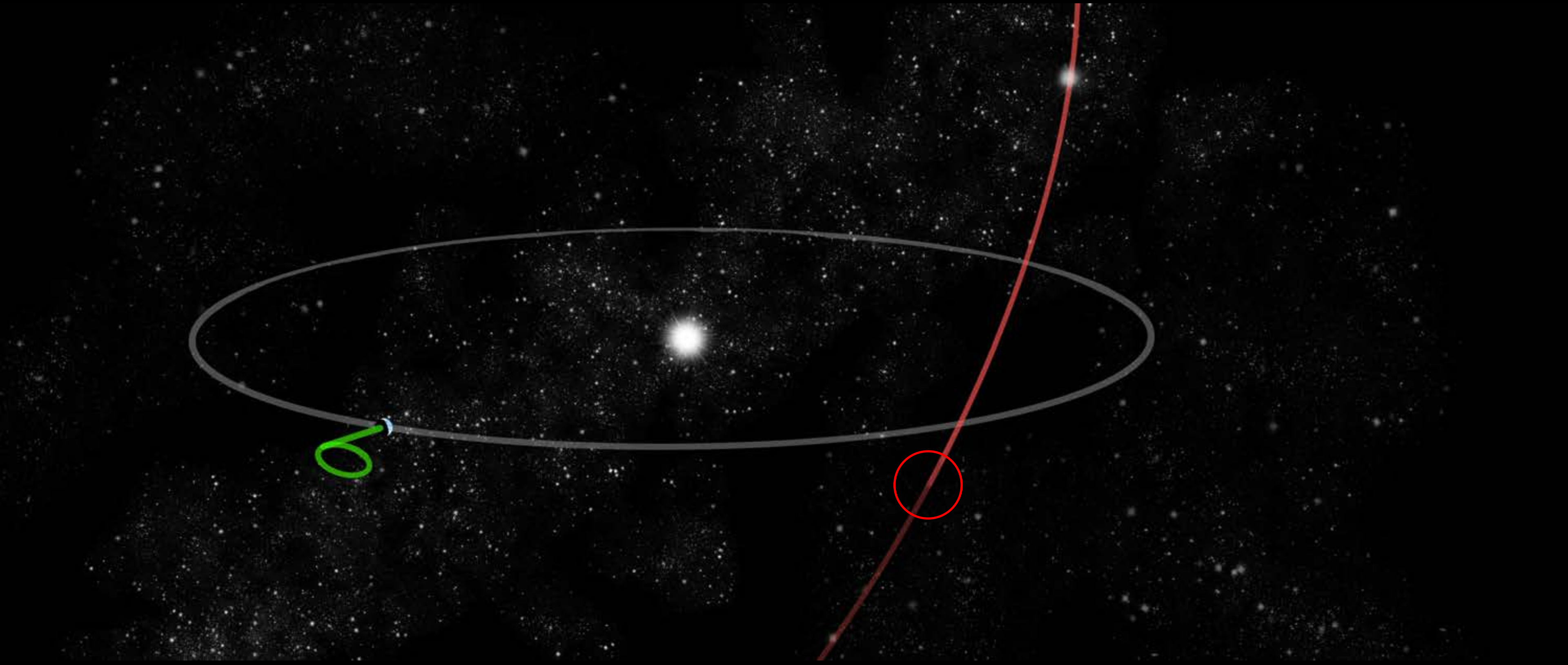
- Target discovered by a ground-based observatory (up to 3 years)



e.g., a dynamically new comet or an interstellar comet

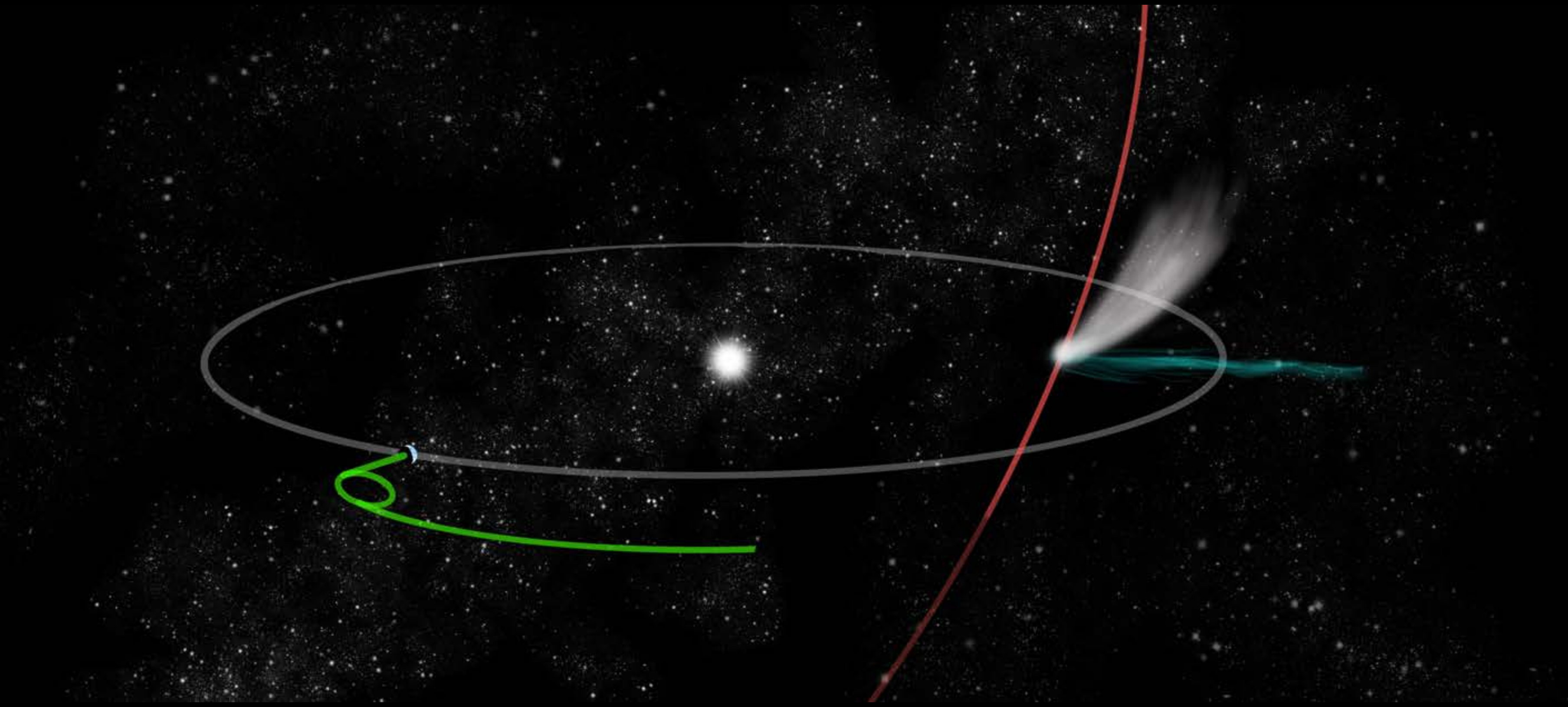
Comet Interceptor Mission Profile

- Orbit computed and ecliptic crossing point predicted



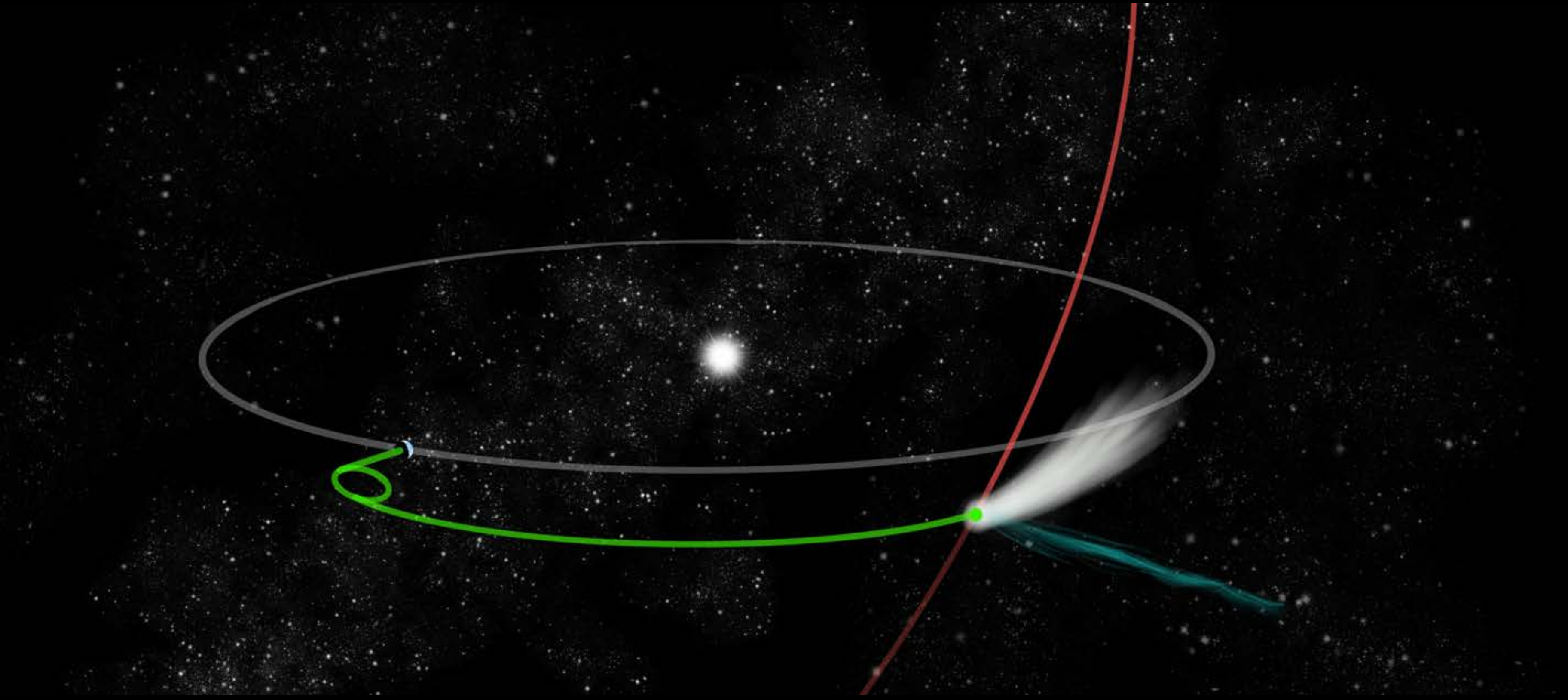
Comet Interceptor Mission Profile

- Comet Interceptor leaves L2 to intercept comet's path



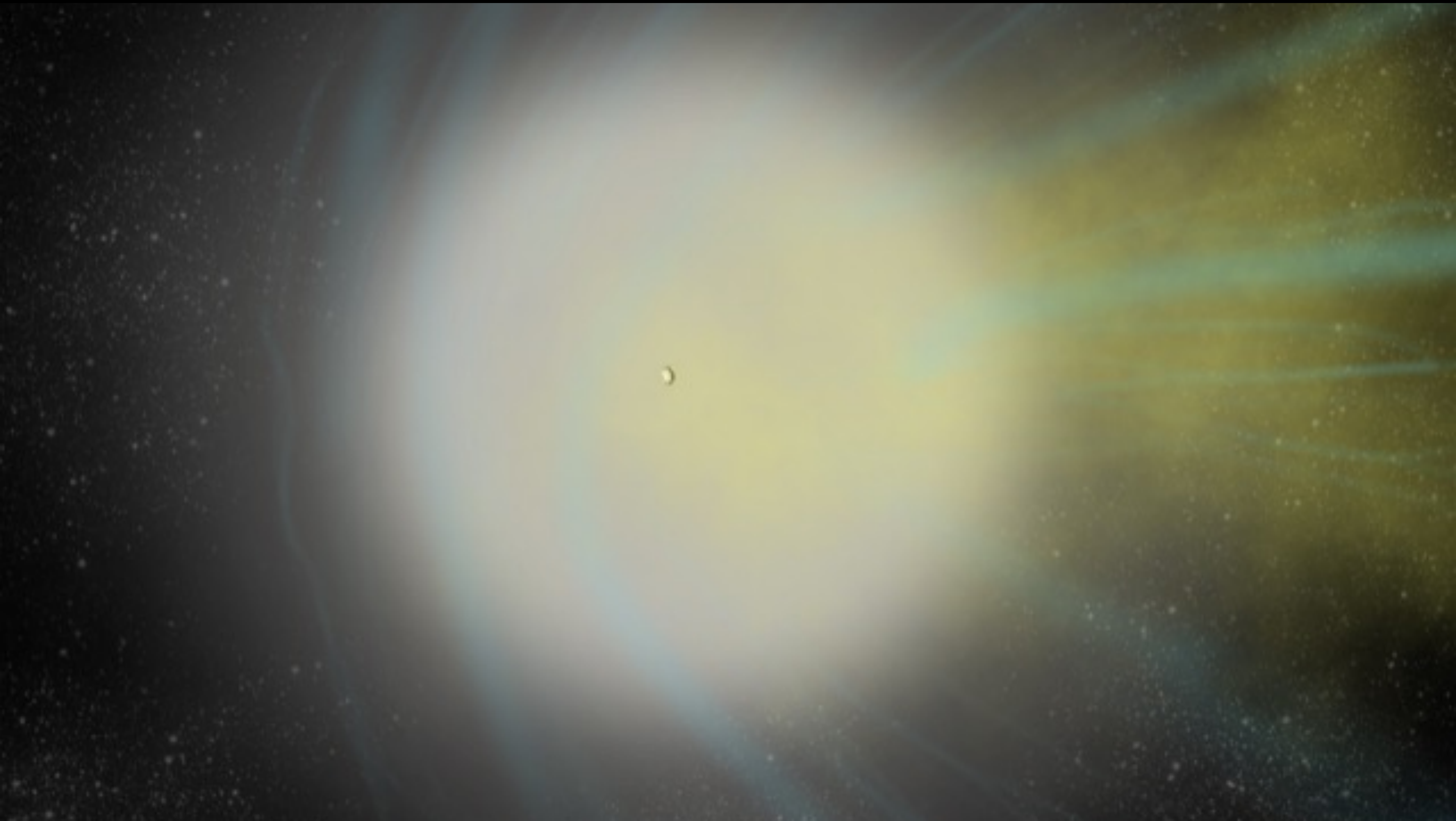
Comet Interceptor Mission Profile

- Encounter with comet close to the ecliptic plane



Comet Interceptor Mission Profile

- Encounter



Thanks for your attention!