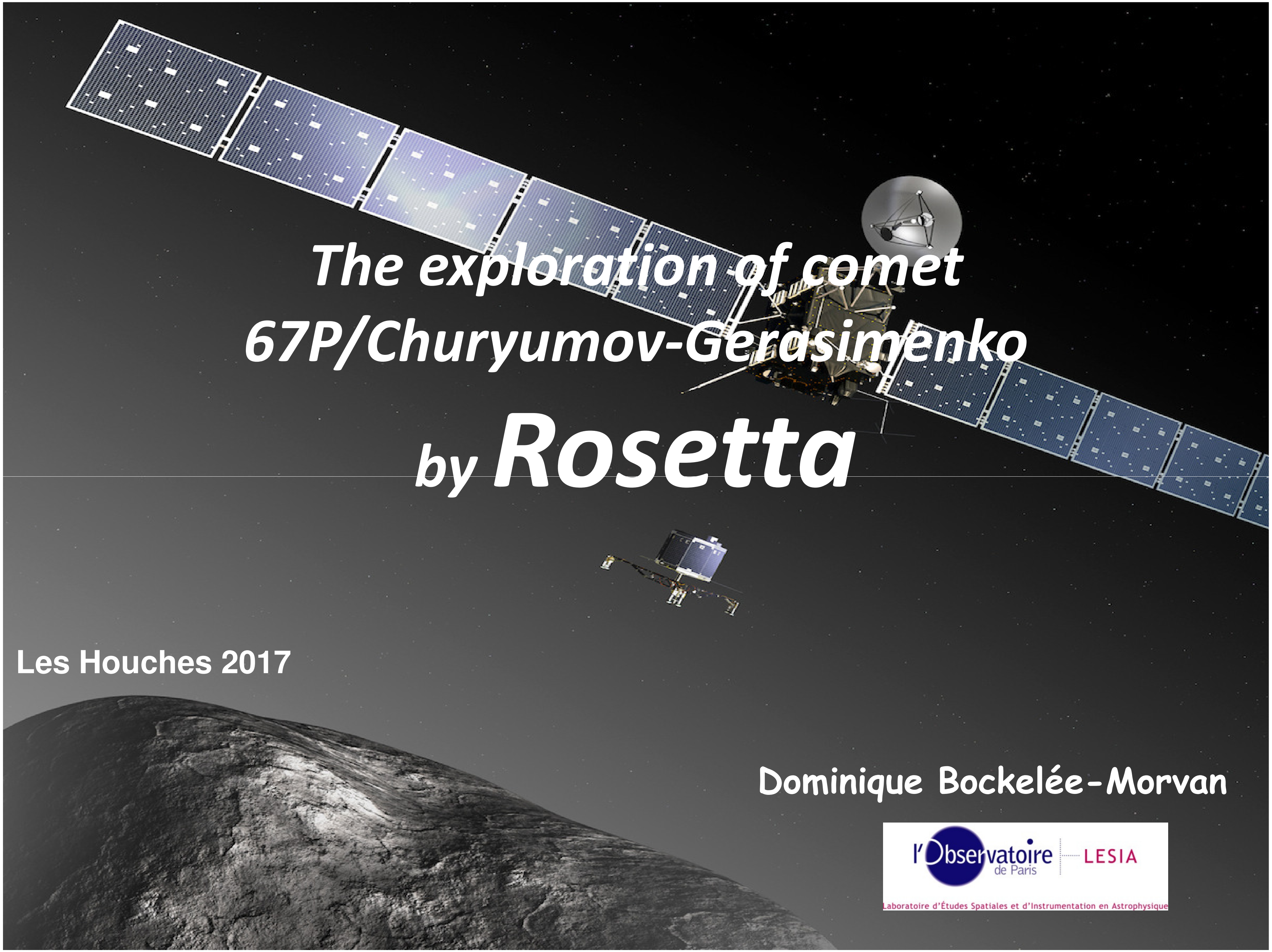


The exploration of comet 67P/Churyumov-Gerasimenko by Rosetta

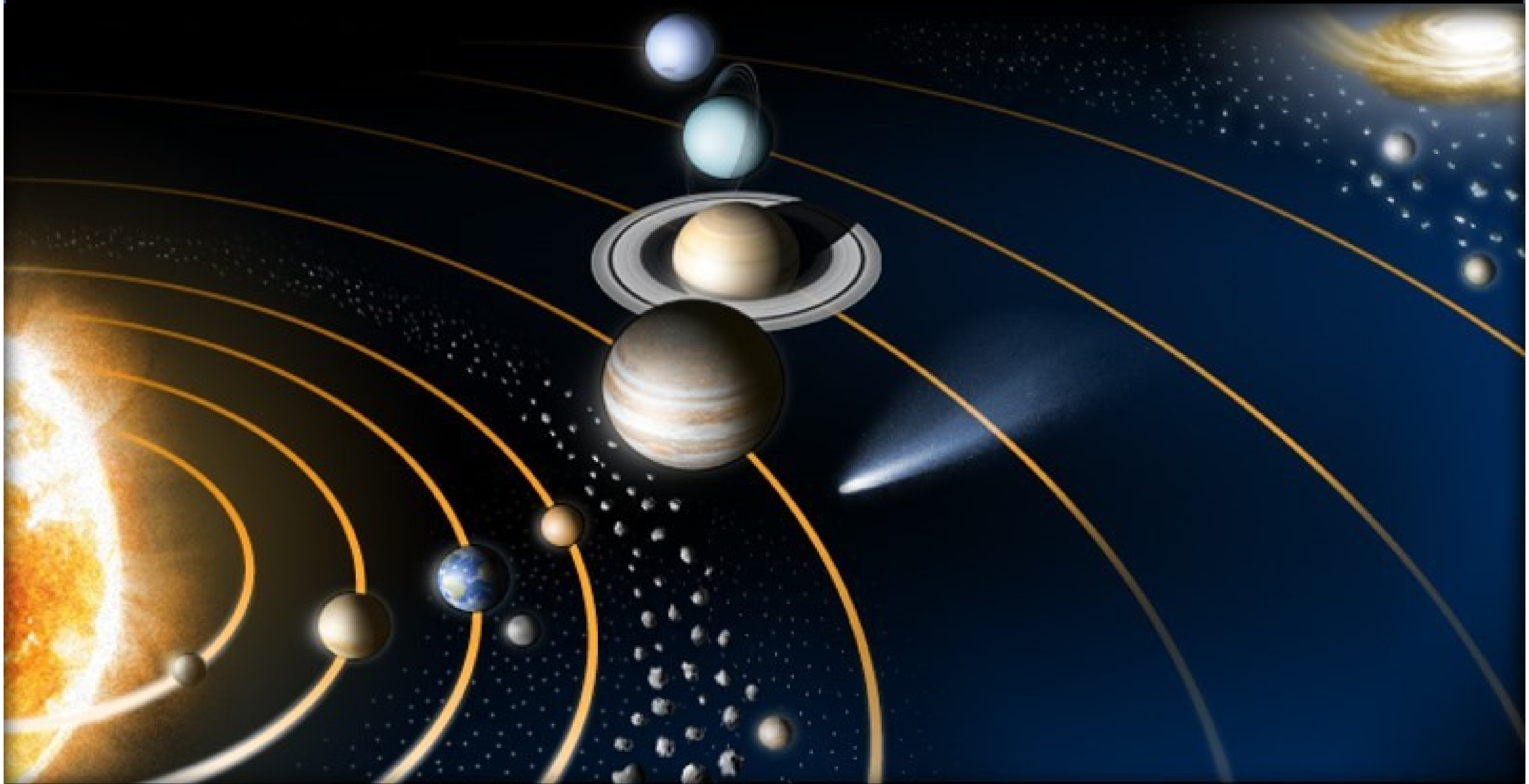
Les Houches 2017

Dominique Bockelée-Morvan

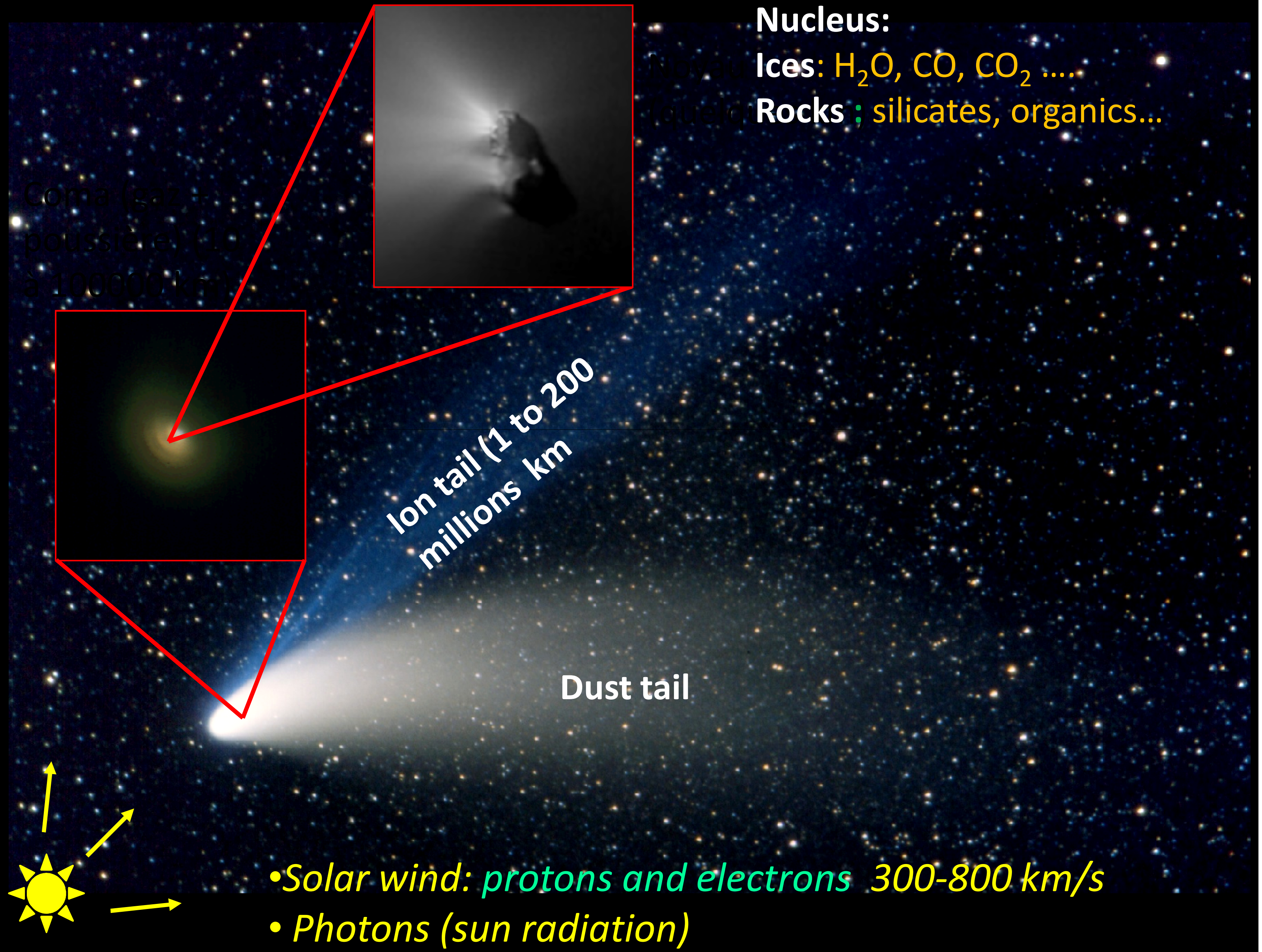
l'Observatoire de Paris — LESIA

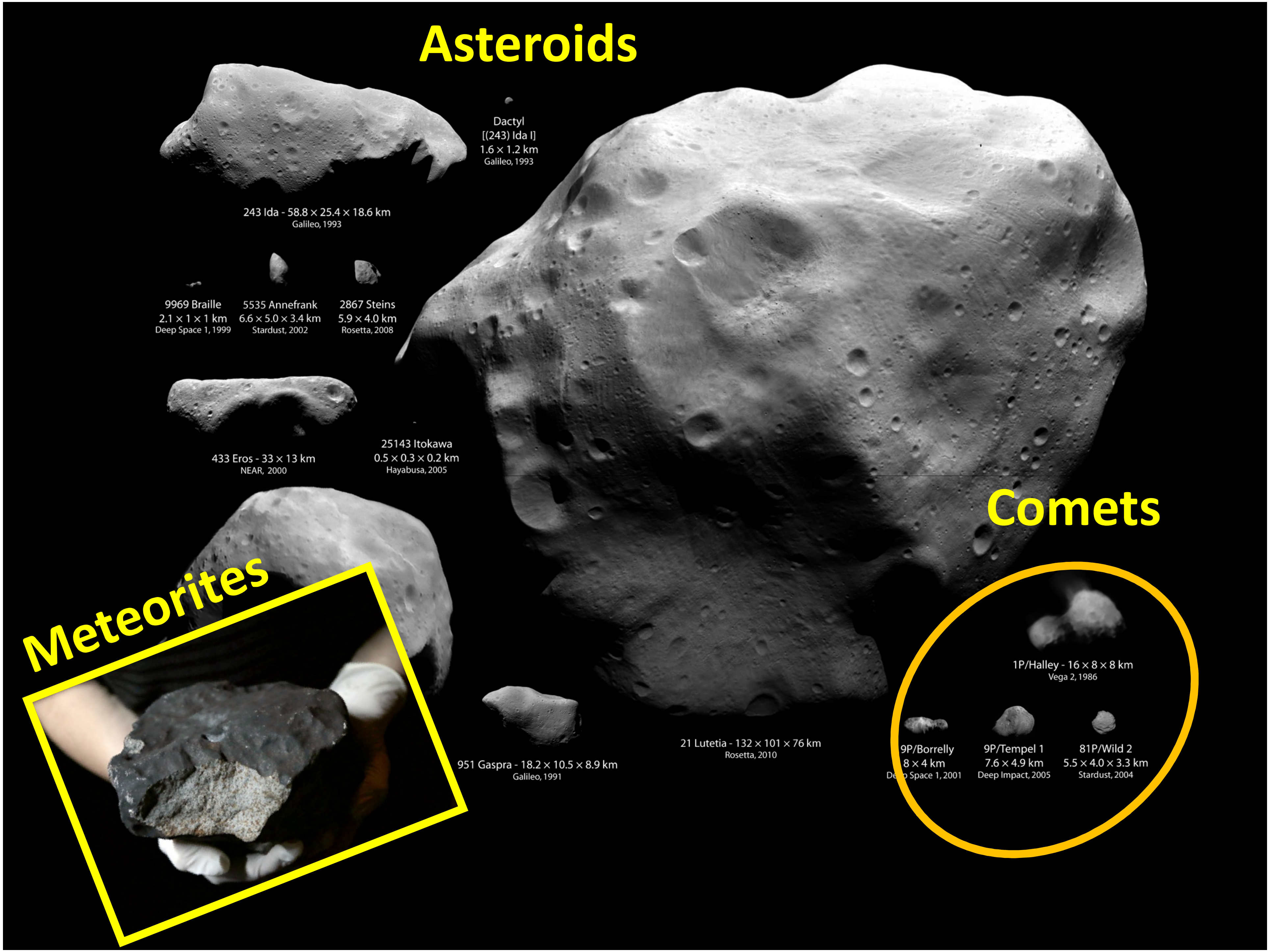
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

The Solar System



Comets


Nucleus:
Ices: H_2O, CO, CO_2 ….
Rocks : silicates, organics…
Ion tail (1 to 200 millions km
Dust tail
•Solar wind: protons and electrons 300-800 km/s
• Photons (sun radiation)



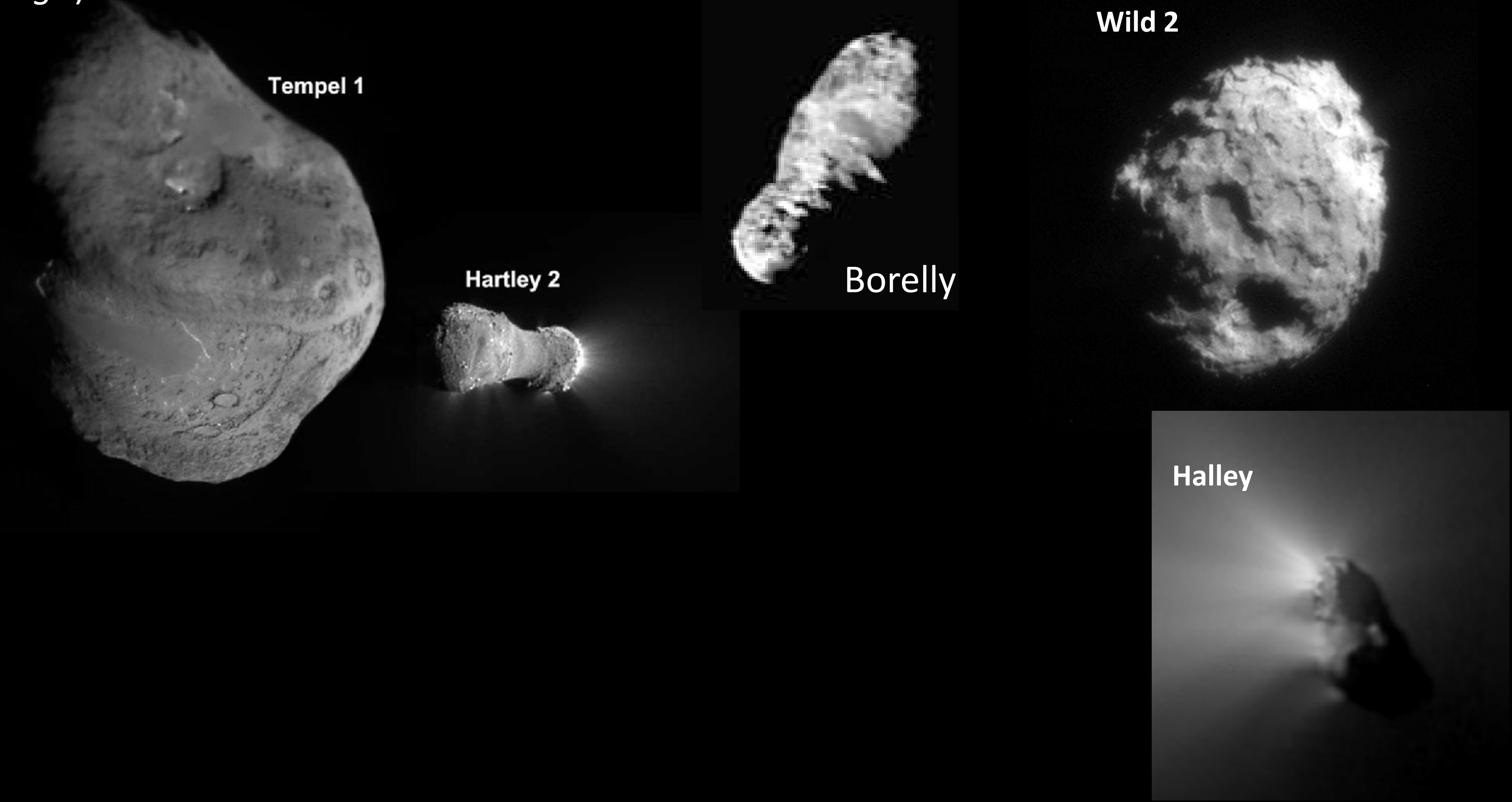
Asteroids
Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993
9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
433 Eros - 33 × 13 km
NEAR, 2000
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
Comets
1P/Halley - 16 × 8 × 8 km
Vega 2, 1986
9P/Borrelly
8 × 4 km
Deep Space 1, 2001
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004
21 Lutetia - 132 × 101 × 76 km
Rosetta, 2010
951 Gaspra - 18.2 × 10.5 × 8.9 km
Galileo, 1991
Meteorites

Comets, asteroids: source of Earth oceans, prebiotic molecules

In 2010, water similar to Earth oceans found in a comet!

Space missions to comets

1986	1992	2001	2005	2006	2010	2011	2014-2015
Halley (*Giotto, Vega*)	**Grigg-Skjellerup** (*Giotto*)	***Borelly*** *(DS 1)*	**Tempel 1** *(Deep impact)*	**Wild 2** (*Stardust*)	**Hartley 2** (*EPOXI*)	**Tempel 1** **(*NEXT*)**	**67P/CG** **(*ROSETTA*)**



Rosetta

Ambitious mission of l'European Space Agency (ESA)

1. Meet a comet at 4 AU*
2. Put a lander on the surface
3. Accompany the comete along its orbit

Scientific objectives

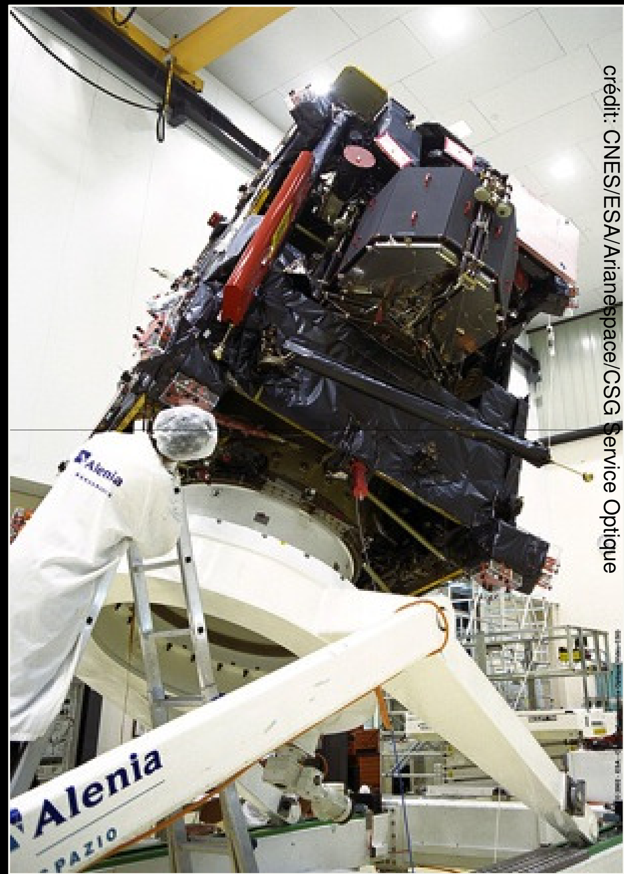
1. Better understand the origin of the Solar System
2. Understand the development of cometary activity
3. Better understand the origin of life

* AU = astronomic unit = distance Earth-Sun= 150 millions kilometers

ROSETTA

- Launched on 2 March 2004 from Kourou (french Guyana)
- Launcher Ariane 5G+
- Orbiter + Lander (Philæ)

Target: 67P/churymov-Gerasimenko
Discovery **:** 1969
Périod: 6.6 year , *perihelion:*1.29 AU
Event : change trajectory in 1959
Origin*:* Kuiper Belt
Size: ~4×3 km (rotation period 12.3h)
Activity: ~0.3 tonnes/s au périhélie



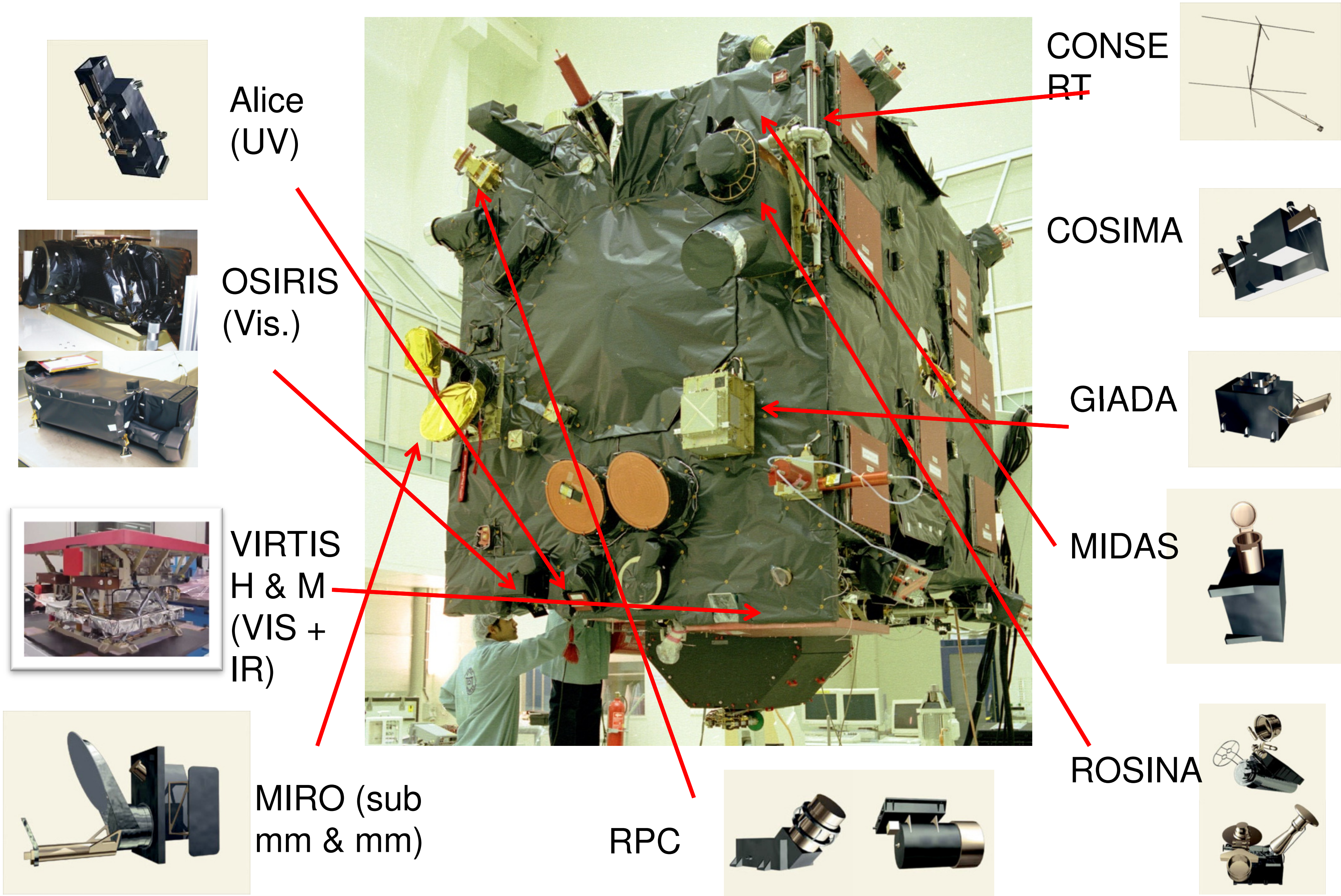
Construction de la sonde Rosetta par Airbus Defence & Space (anciennement Astrium)

Rosetta orbiter

- Mass : 3 050 kg (ergol : 1 750 kg)
- Size : 32 m
- The largest solar panels (65 m^2)
- 11 instruments

Rosetta

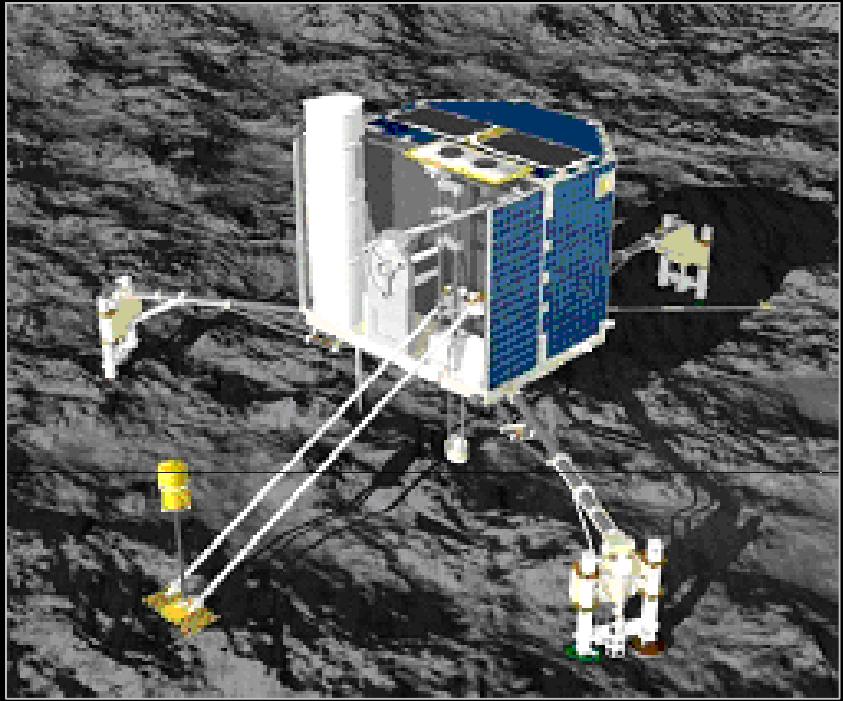
Instruments on Rosetta orbiter



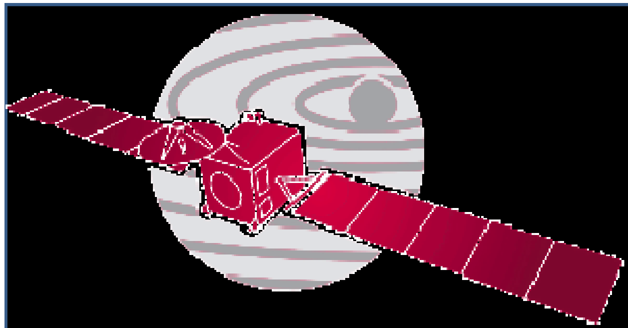
Philæ lander

- Mass : 98 kg
- First *lander* on a comet
- 10 instruments

APXS	***Spectromètre X***
CIVA	***Caméras panoramiques***
CONSERT	***Sondage radio***
COSAC MODULUS	***Analyseurs de gaz***
MUPUS	***Propriétés de la surface***
ROLIS	***Système d'imagerie***
ROMAP	***Magnétomètre***
SESAME	***Instrument acoustique***



SD2 : drill system

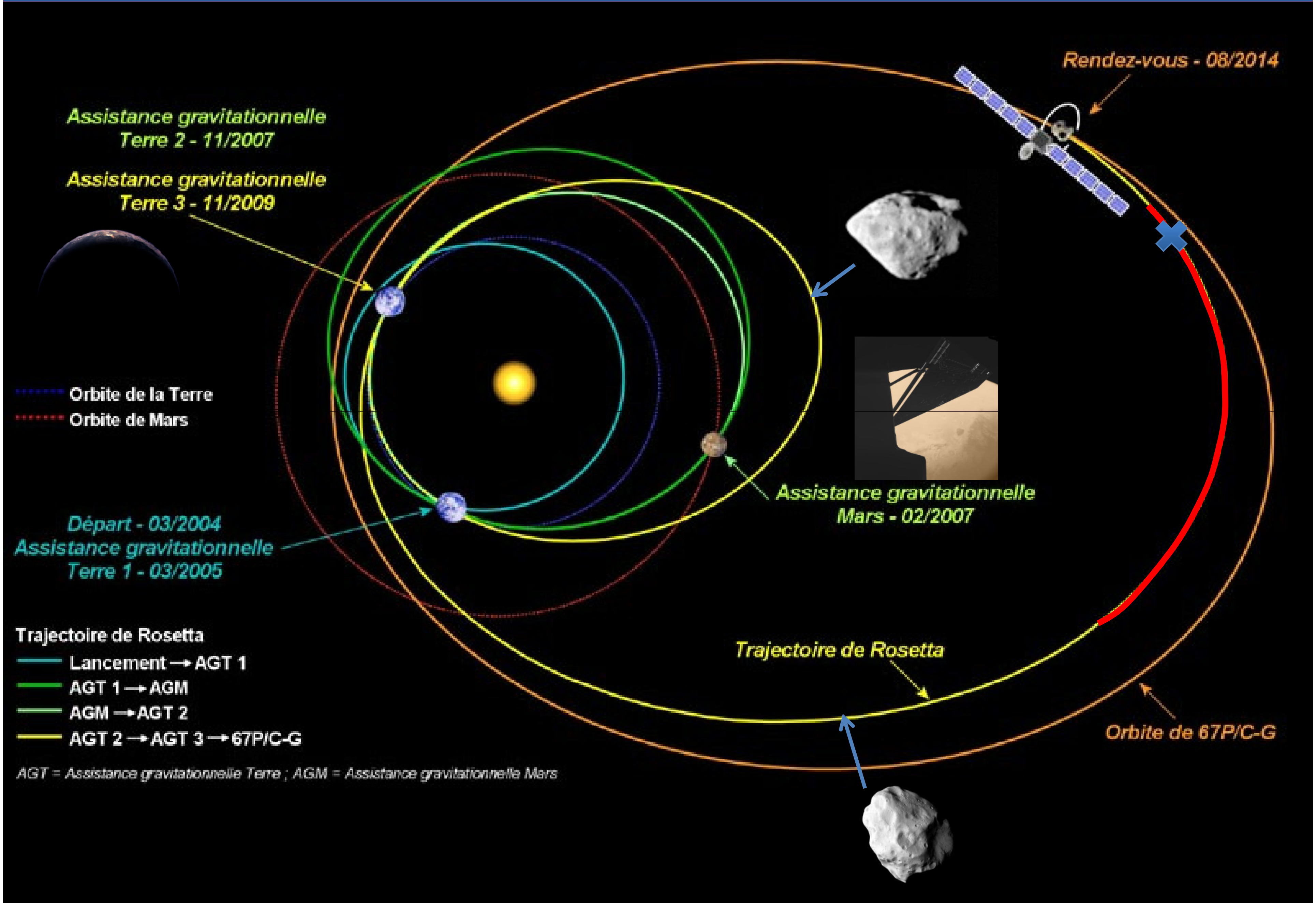


Rosetta trip

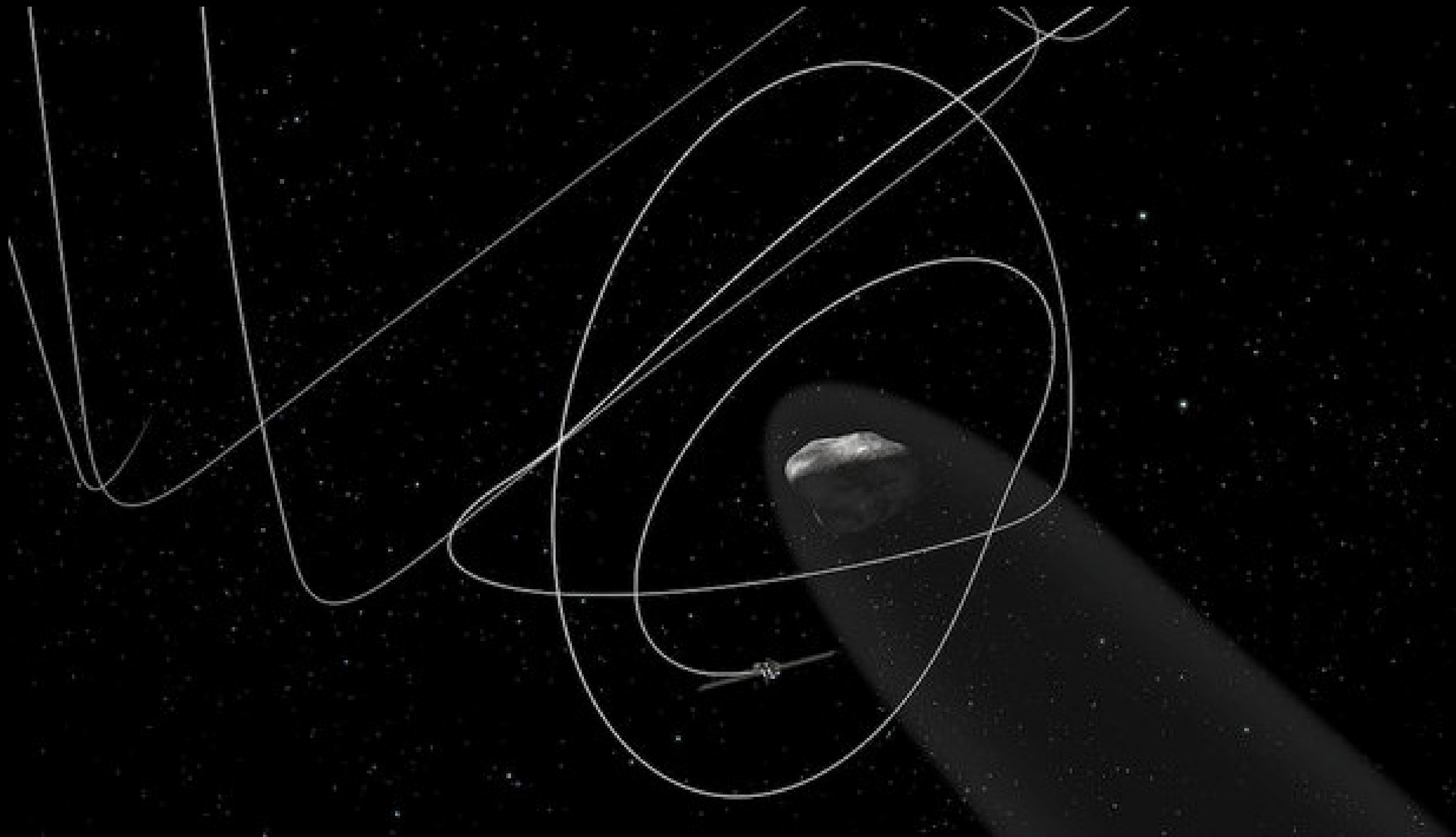
- ✓ 2 March 2004 : launch by Ariane 5 G+
- ✓ 2008, 2010 flyby of asteroids Steins & Lutetia
- ✓ 2005, 2007, 2009 Earth flyby
- ✓ 2007 Mars flyby
- ✓ 20 January 2014 : out of hibernation
- ✓ Summer 2014 : arrival to the comet at 4 AU
- ✓ and put in orbit around the comet
- ✓ 12 November 2014 : PHILAE released on the surface
- ✓ 2015-2016 : Scientific operations of Rosetta
- ✓ 30 September 2016 End of mission
  ROSETTA: controlled impact on the comet

Complex mission : unknown target with varying activity

Rosetta journey

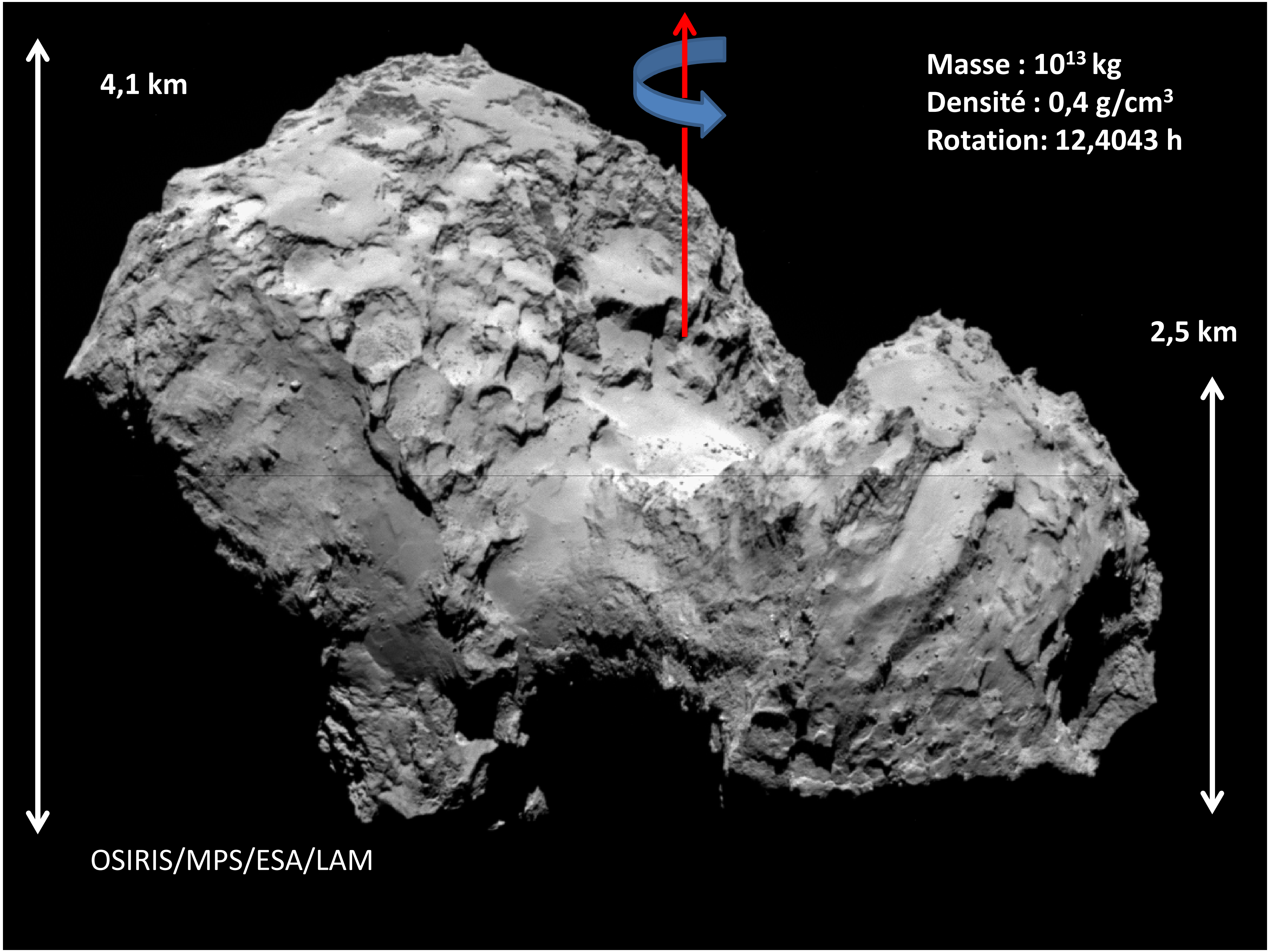


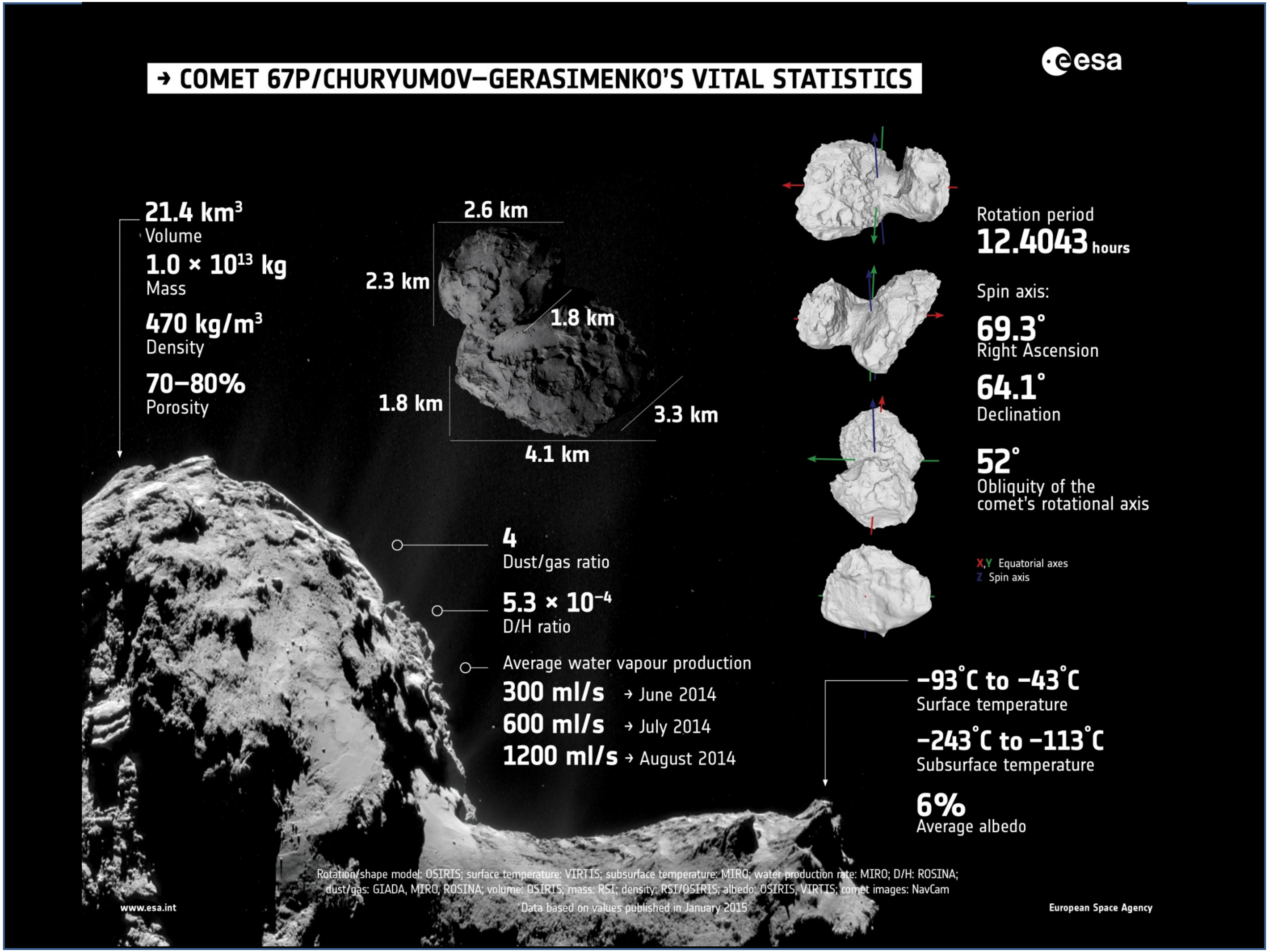
Exemple of navigation : August 2014 to November 2014 approach from 100 to 30 km and orbital insertion



14 July 2014 – 12000 km

Crédits : MPS/LAM/ESA


4,1 km
Masse : 10^{13} kg
Densité : 0,4 g/cm^3
Rotation: 12,4043 h
2,5 km
OSIRIS/MPS/ESA/LAM

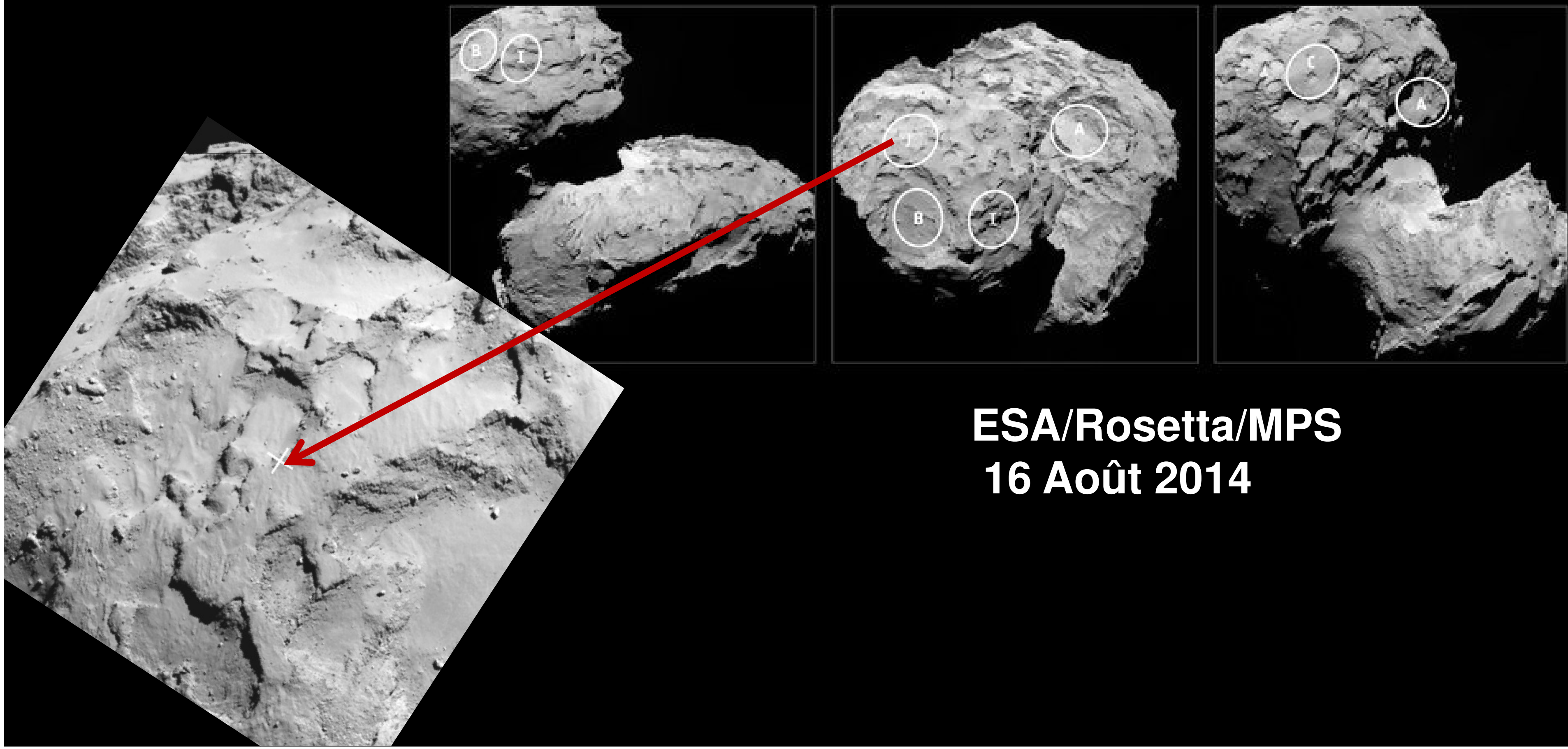

→ COMET 67P/CHURYUMOV–GERASIMENKO'S VITAL STATISTICS
esa
21.4 km^3
Volume
1.0 × 10^{13} kg
Mass
470 kg/m^3
Density
70–80%
Porosity
2.6 km
2.3 km
1.8 km
1.8 km
3.3 km
4.1 km
Rotation period
12.4043 hours
Spin axis:
69.3°
Right Ascension
64.1°
Declination
52°
Obliquity of the comet's rotational axis
X,Y 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

Philae stories

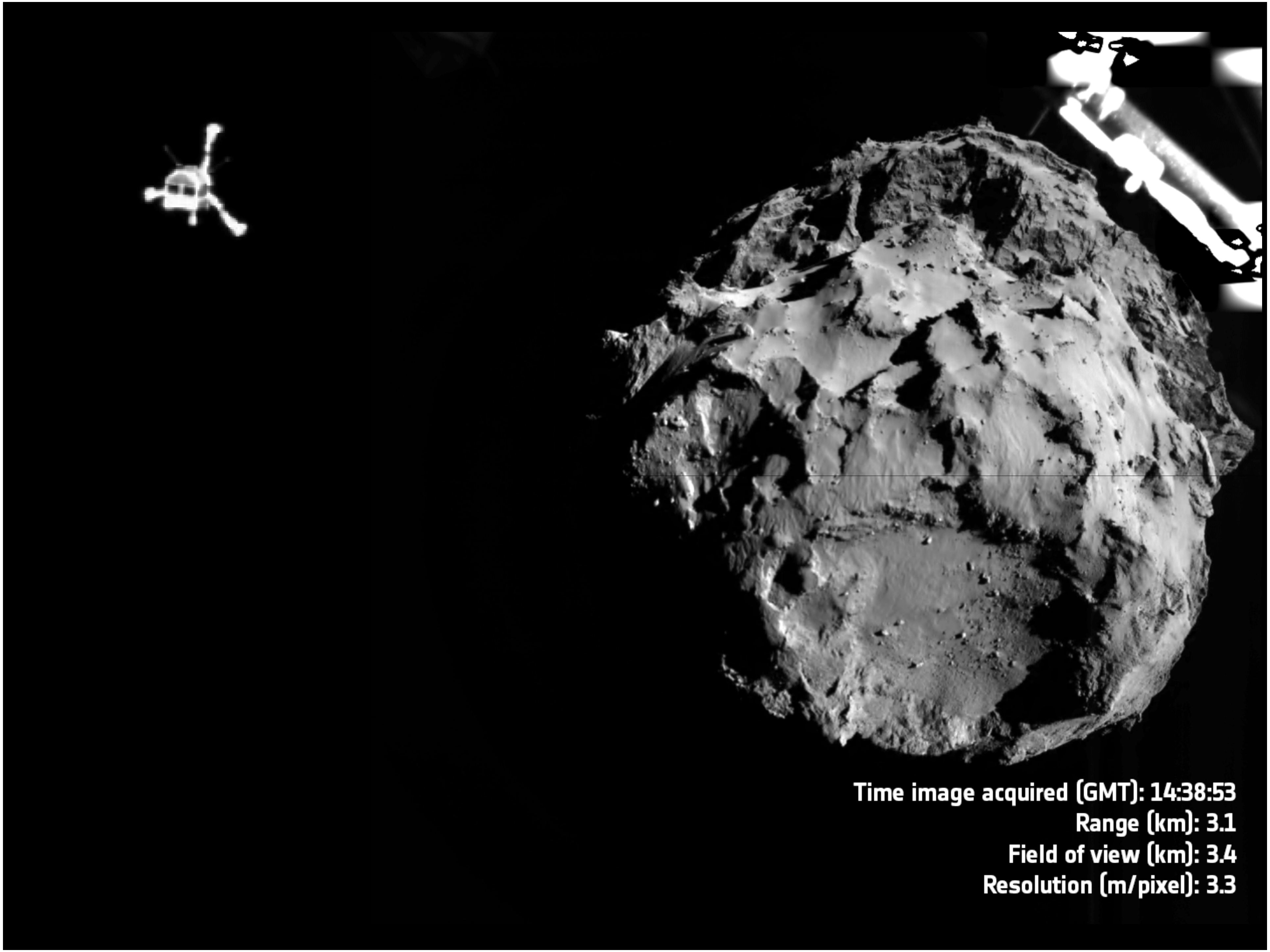
August-October 2014 : nucleus characterization

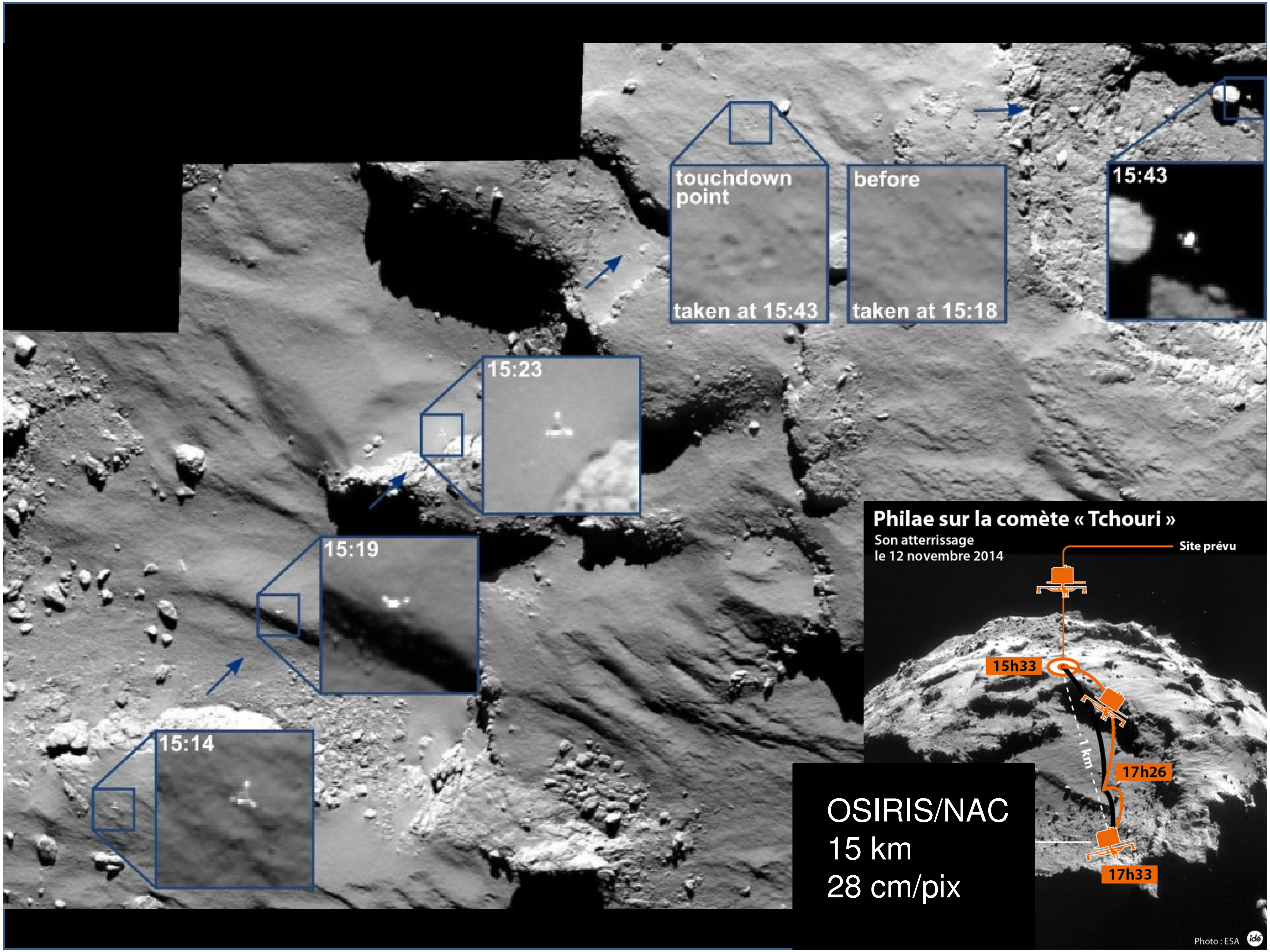
24 August : 5 sites selected
14 September : site J selected, site C backup

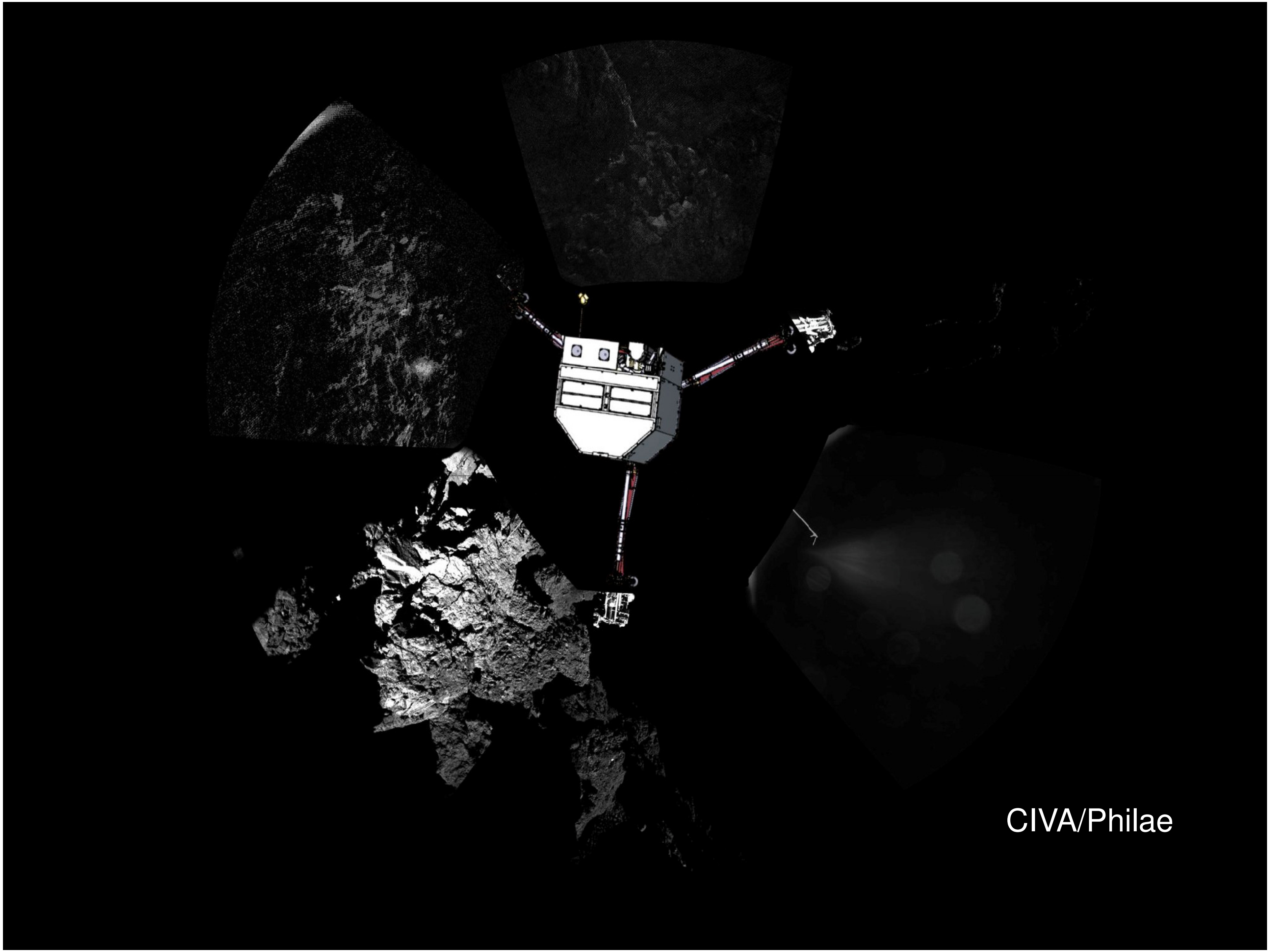
Criteria : land safely

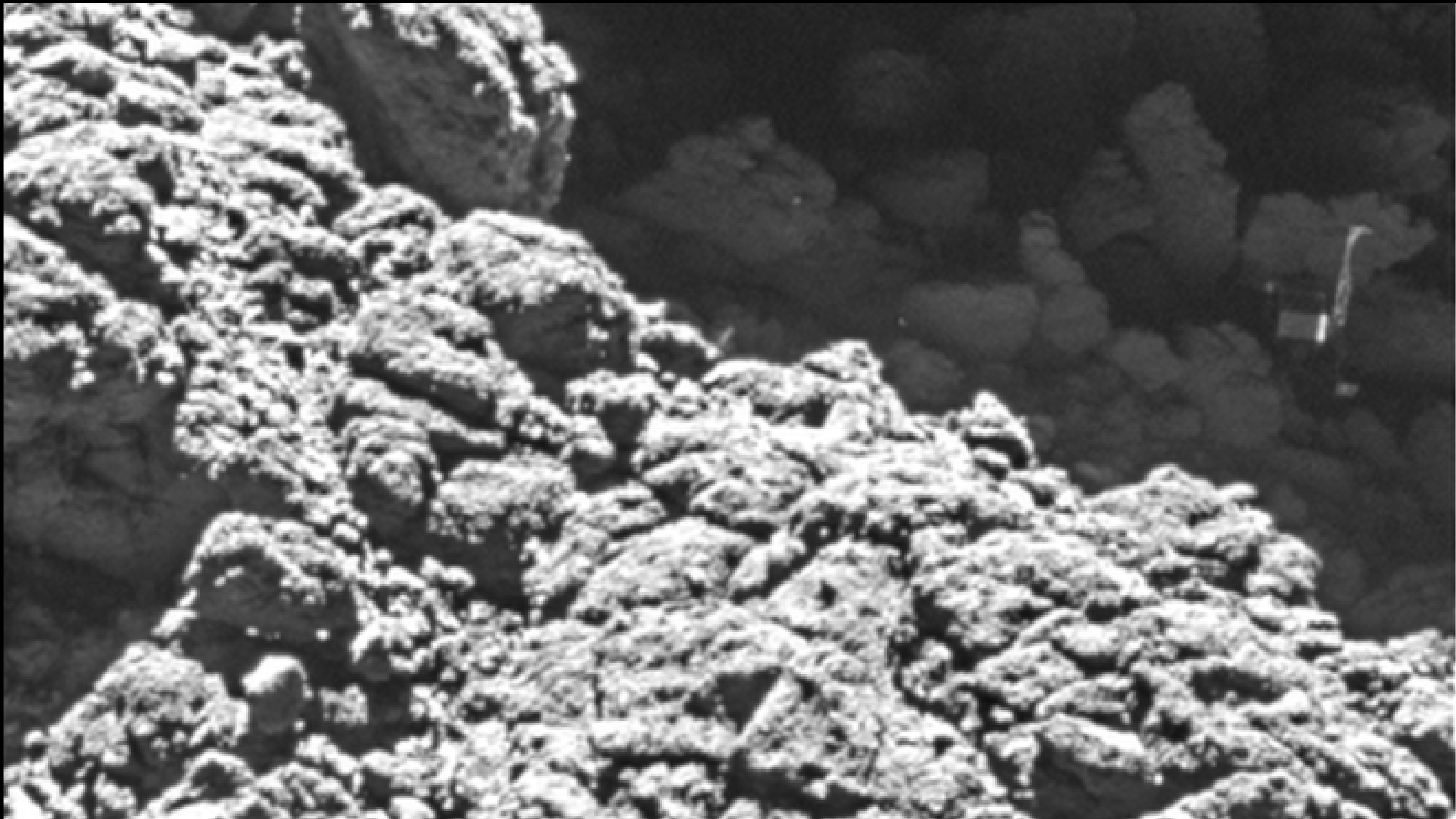


ESA/Rosetta/MPS
16 Août 2014


Time image acquired (GMT): 14:38:53
Range (km): 3.1
Field of view (km): 3.4
Resolution (m/pixel): 3.3


touchdown point
taken at 15:43
before
taken at 15:18
15:43
15:23
15:19
15:14
Philae sur la comète « Tchouri »
Son atterrissage
le 12 novembre 2014
Site prévu
15h33
17h26
17h33
1 km
Photo : ESA
OSIRIS/NAC
15 km
28 cm/pix


CIVA/Philae



Philae found on 25September 2016 !

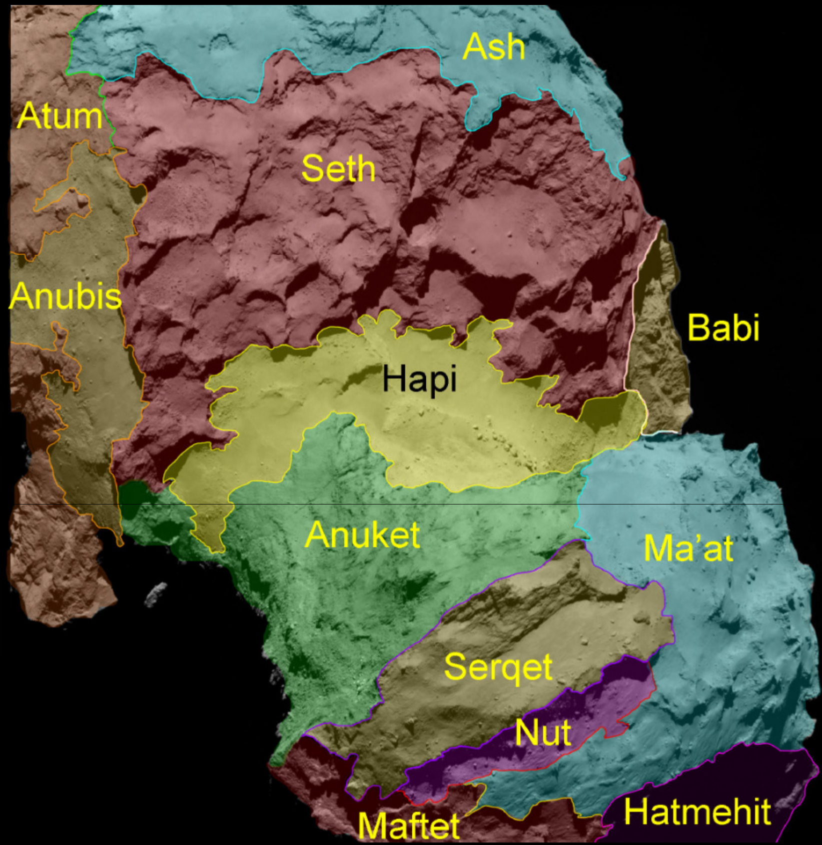
ESA/Osiris

Philae Flight

The nucleus of 67P/Churyumov-Gerasimenko

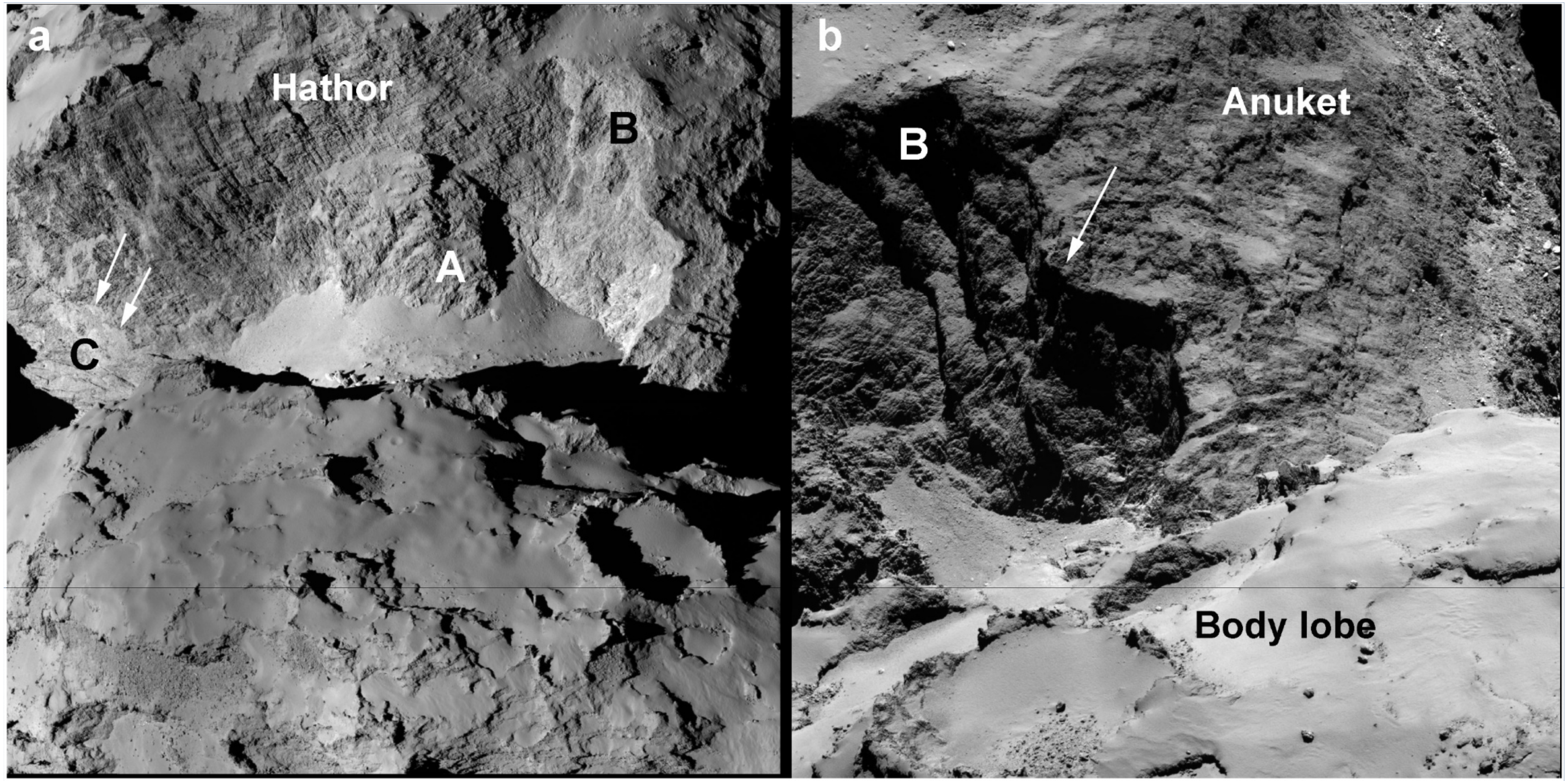
A complex body & surface

A variety of lands



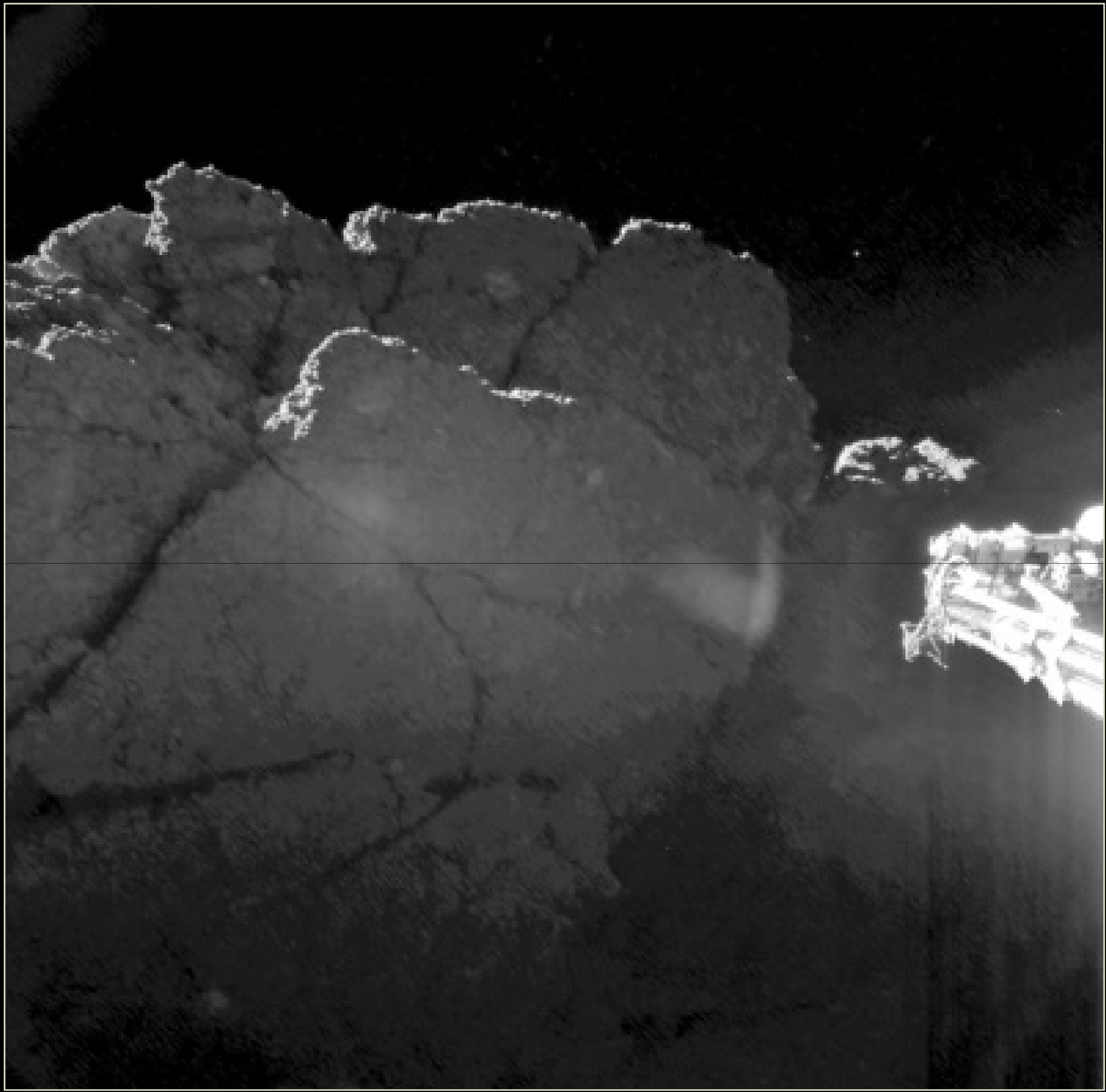
<u>**3 types of lands :**</u>

- **consolidated terrains, with fractures and terrasses**
- **smooth areas covered by dust**
- **depressions**

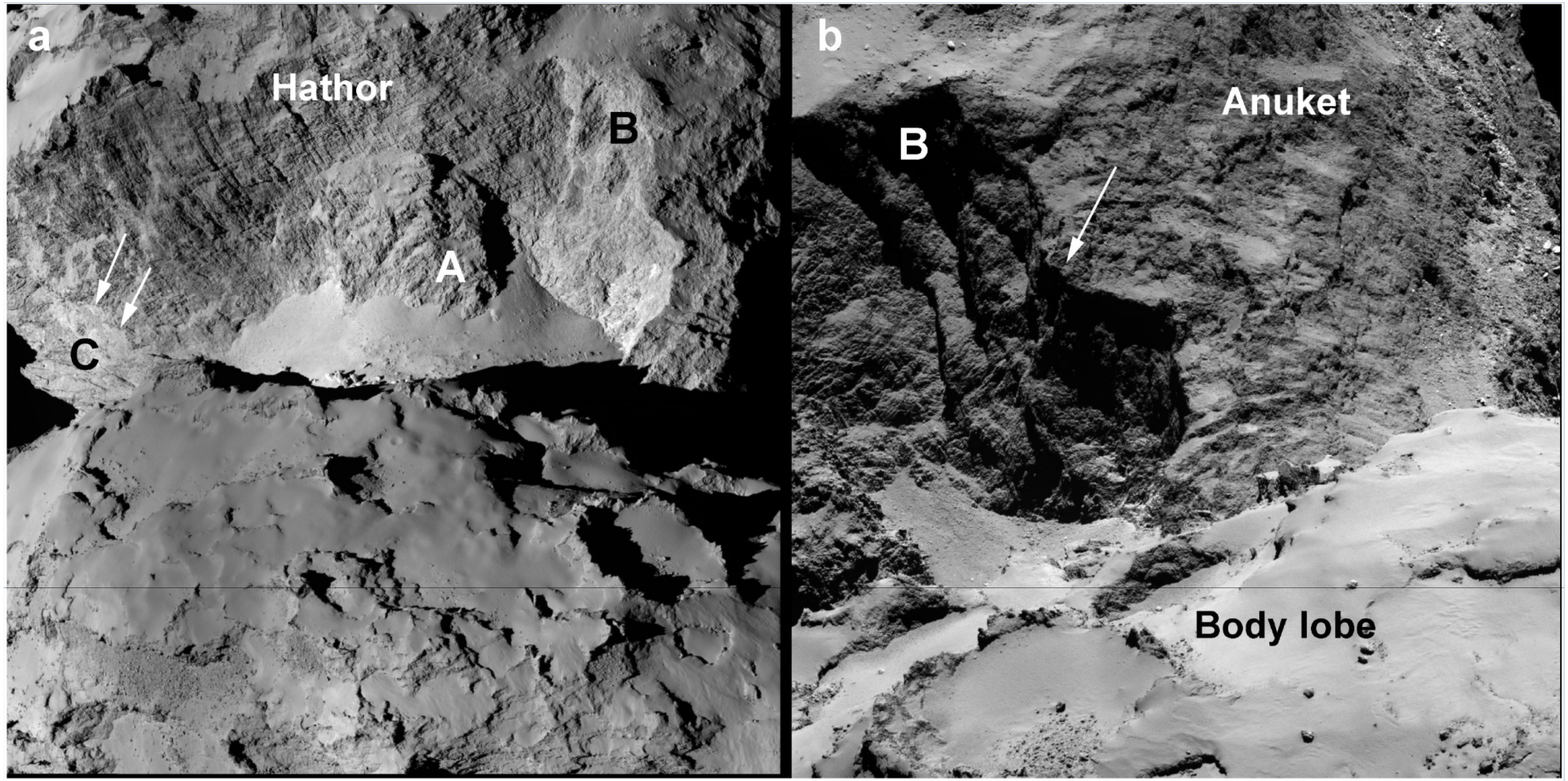


Hathor et Anuket
- **terrains consolidés**
- **présence de fractures : forts contrastes de température jour/nuit (fatigue thermique)**

Fractures at all scales



CIVA/Philae

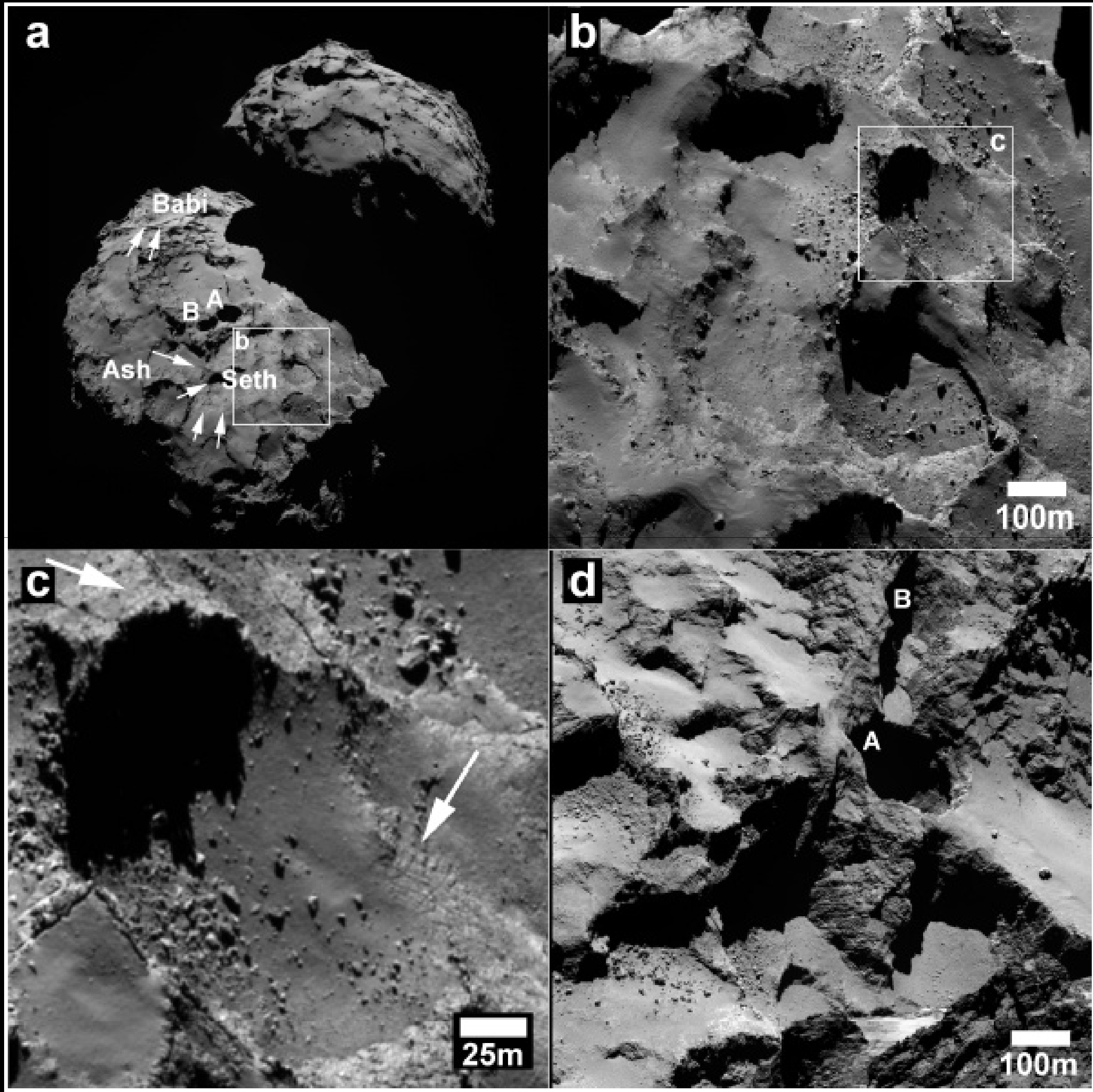


Hathor & Anuket

- **consolidated terrains**
- **fractures : due to large temperature contrasts between day and night**

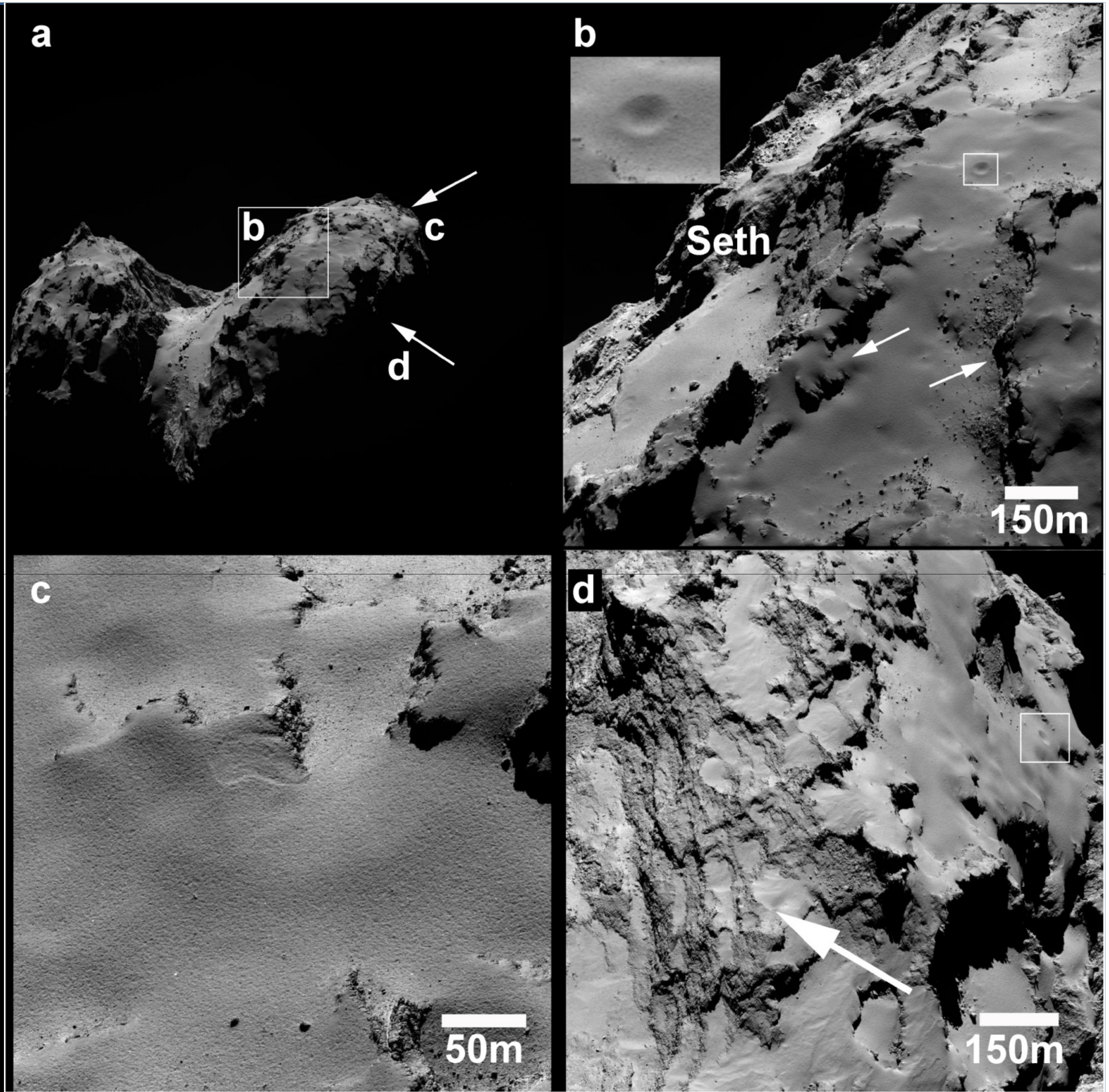
Seth
a lot of pits

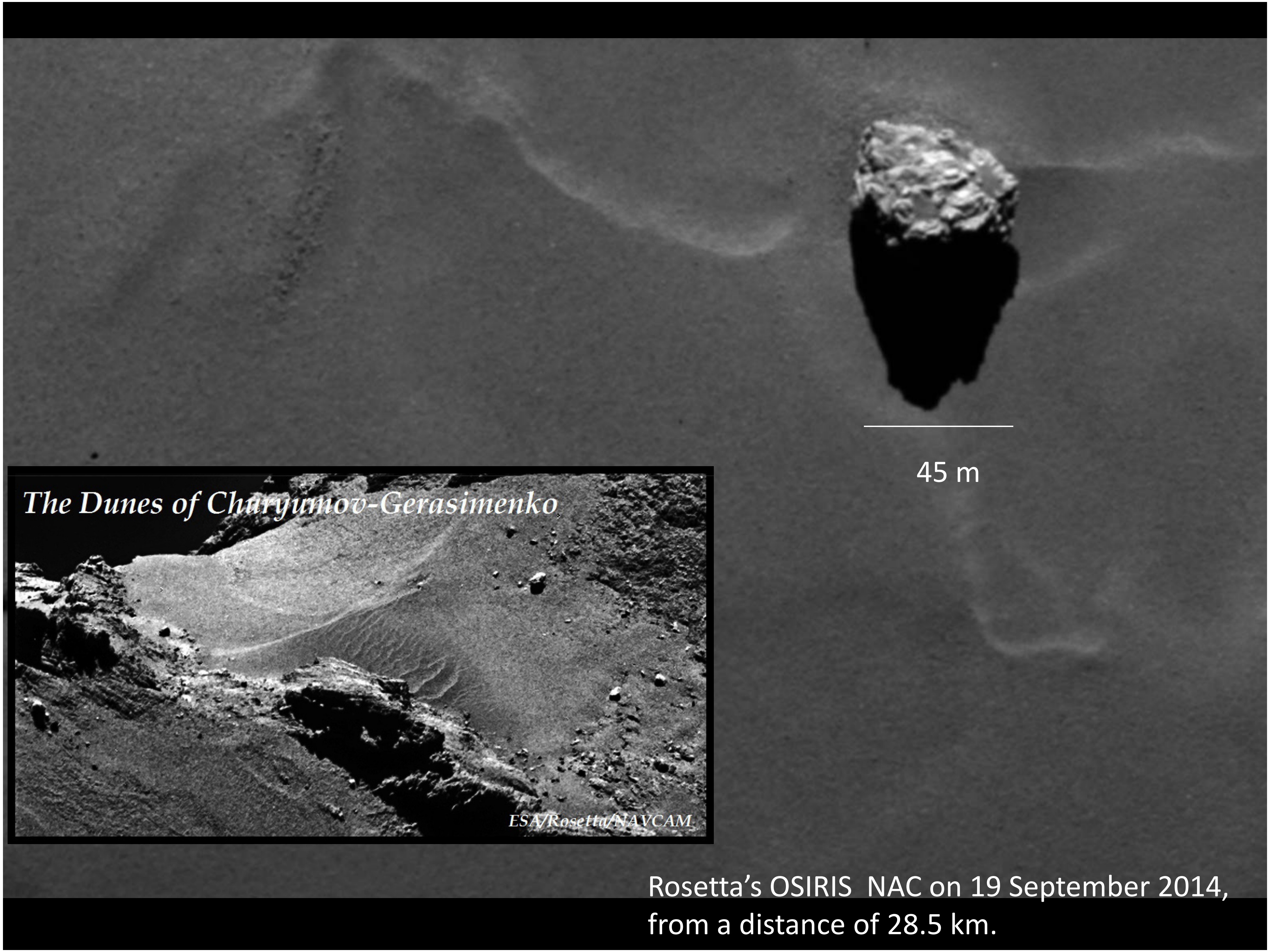
pits:
- analog to sinkholes found on Earth



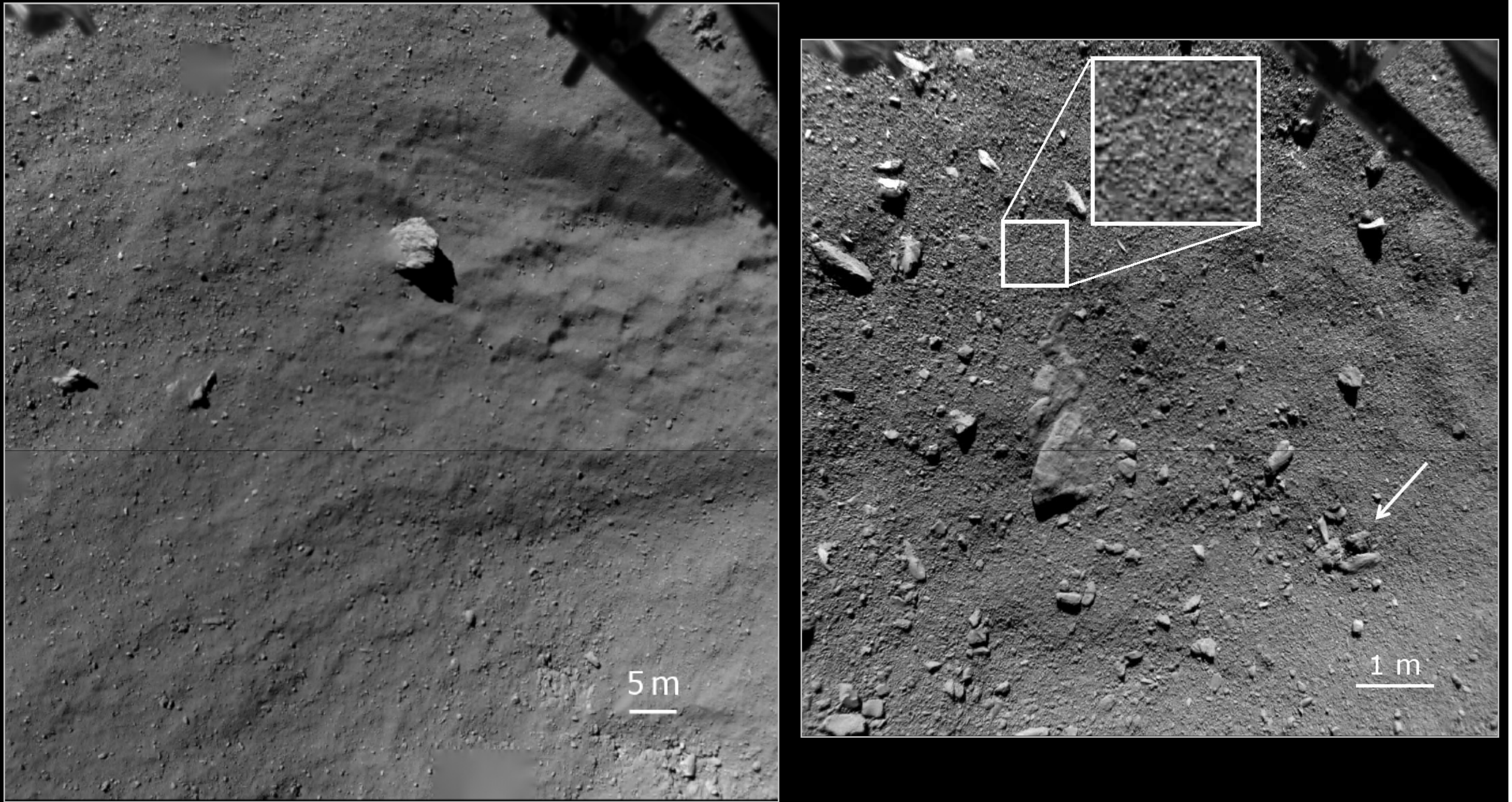
Ash
smooth region

Dust cover:
1 m thickness



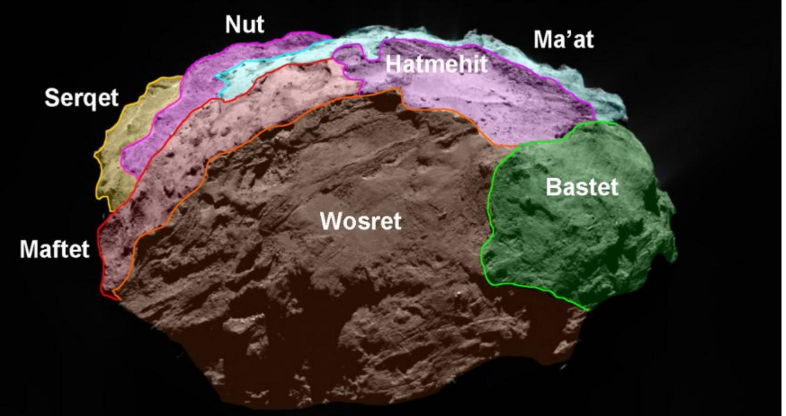


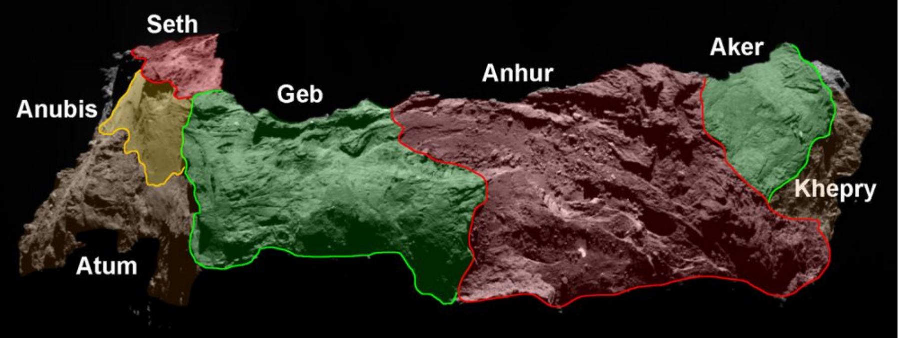
Rosetta's OSIRIS NAC on 19 September 2014, from a distance of 28.5 km.



ESA/Rosetta/Philae/Rolis

The southern hemisphere





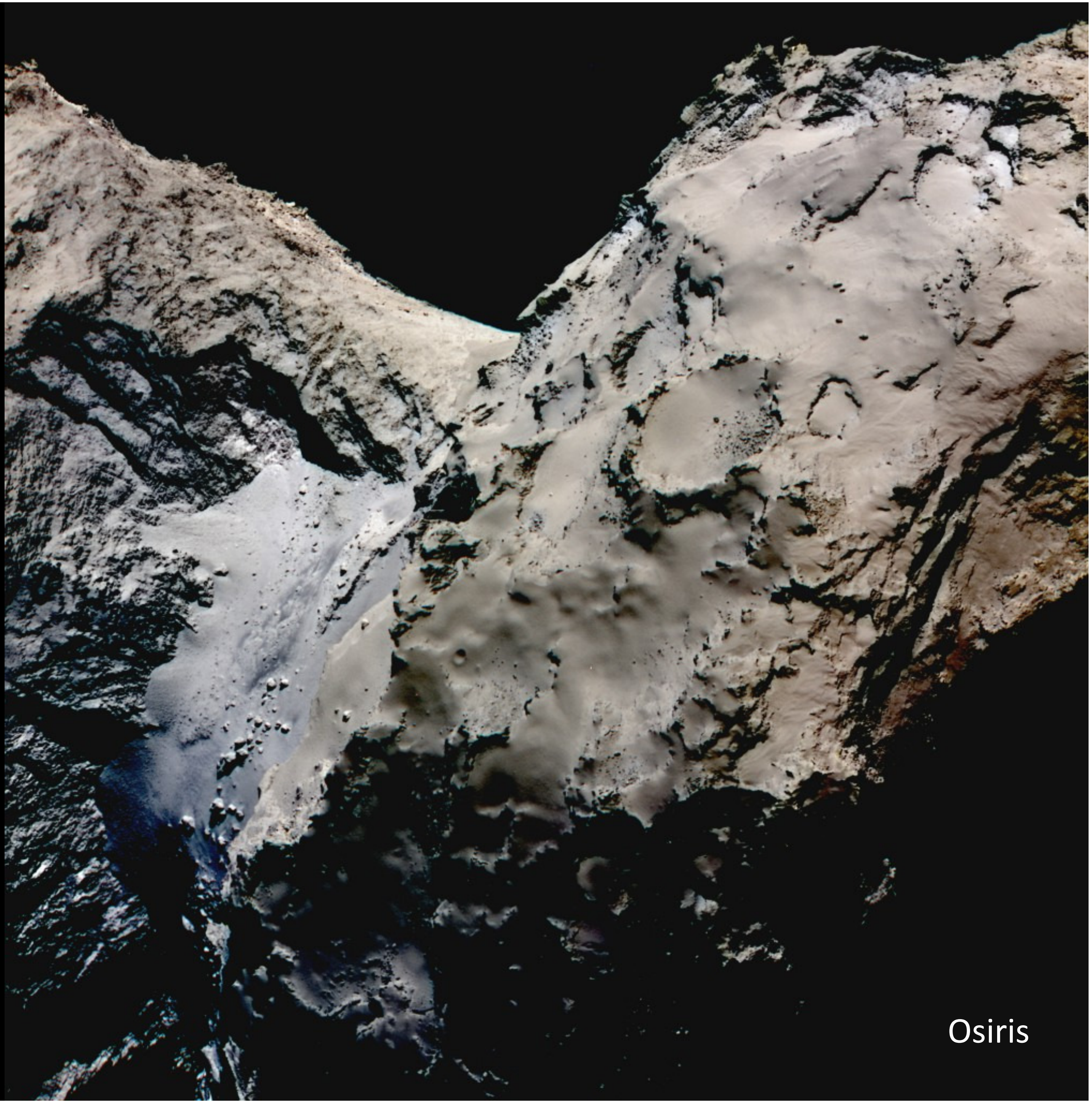
No smooth dust-covered regions

The nucleus of 67P/Churyumov-Gerasimenko

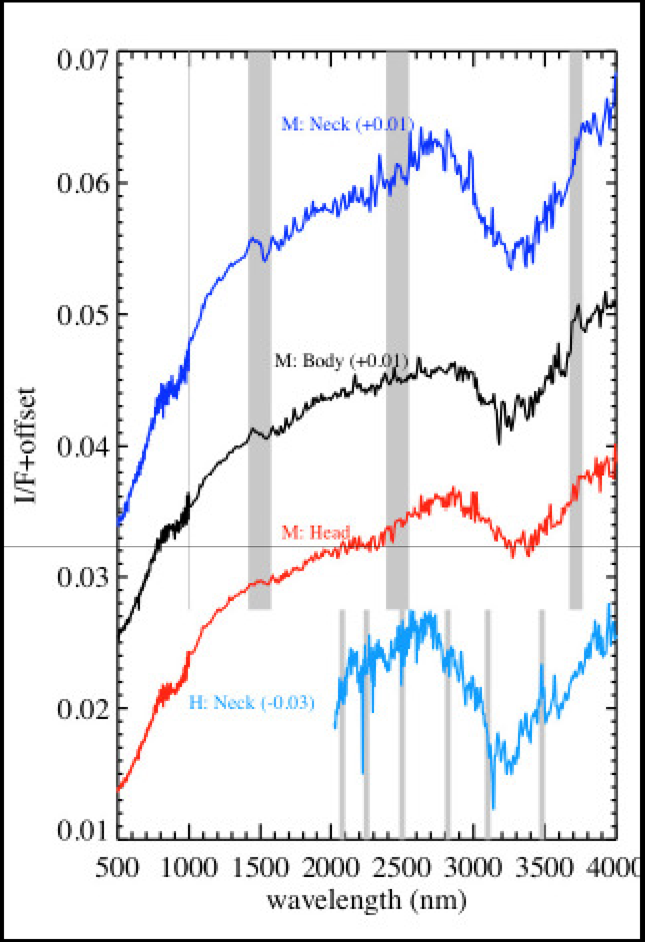
Black as coal

Very dark:
Albedo: 5 %

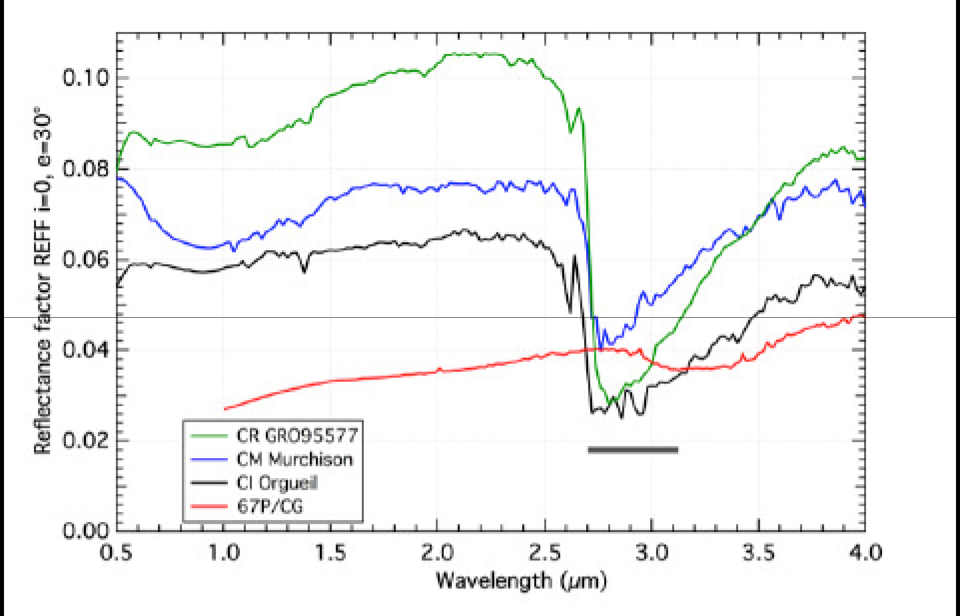
Color:
Red



Composition of the Surface by VIRTIS spectroscopy



Capaccioni et al. 2015



Quirico et al. 2016

- **small albedo & red color :** poly-aromatics <u>& opaque minerals</u> (sulfides – FeS & Fe-Ni alloys)
- **3.2 μm bands**: carboxyles groups RCCOH or NH_4^+
- no phyllosilicates : no liquid water

Activity means that ice is outgassing

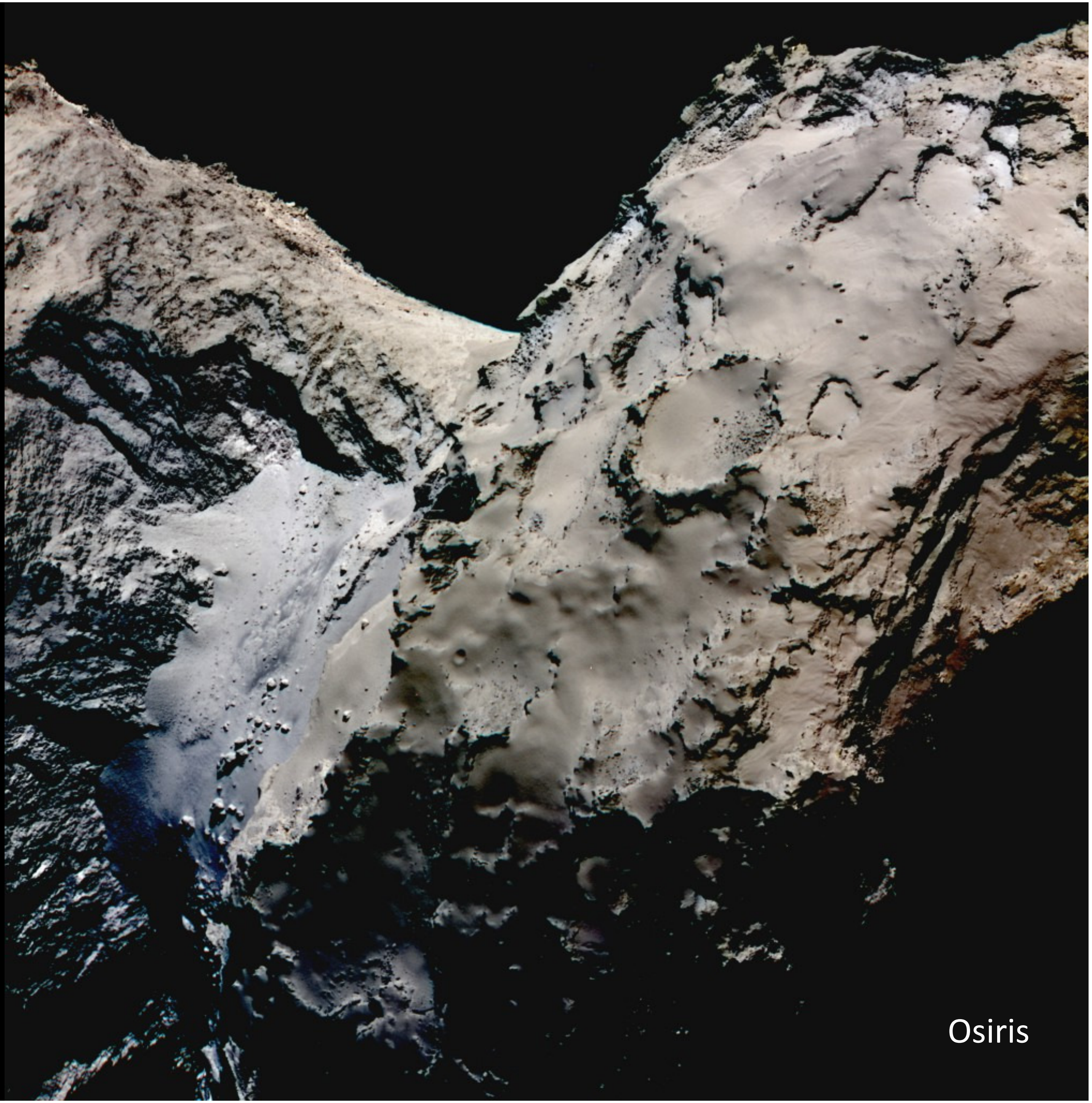
OSIRIS/MPS/ESA/LAM

The nucleus of 67P/Churyumov-Gerasimenko

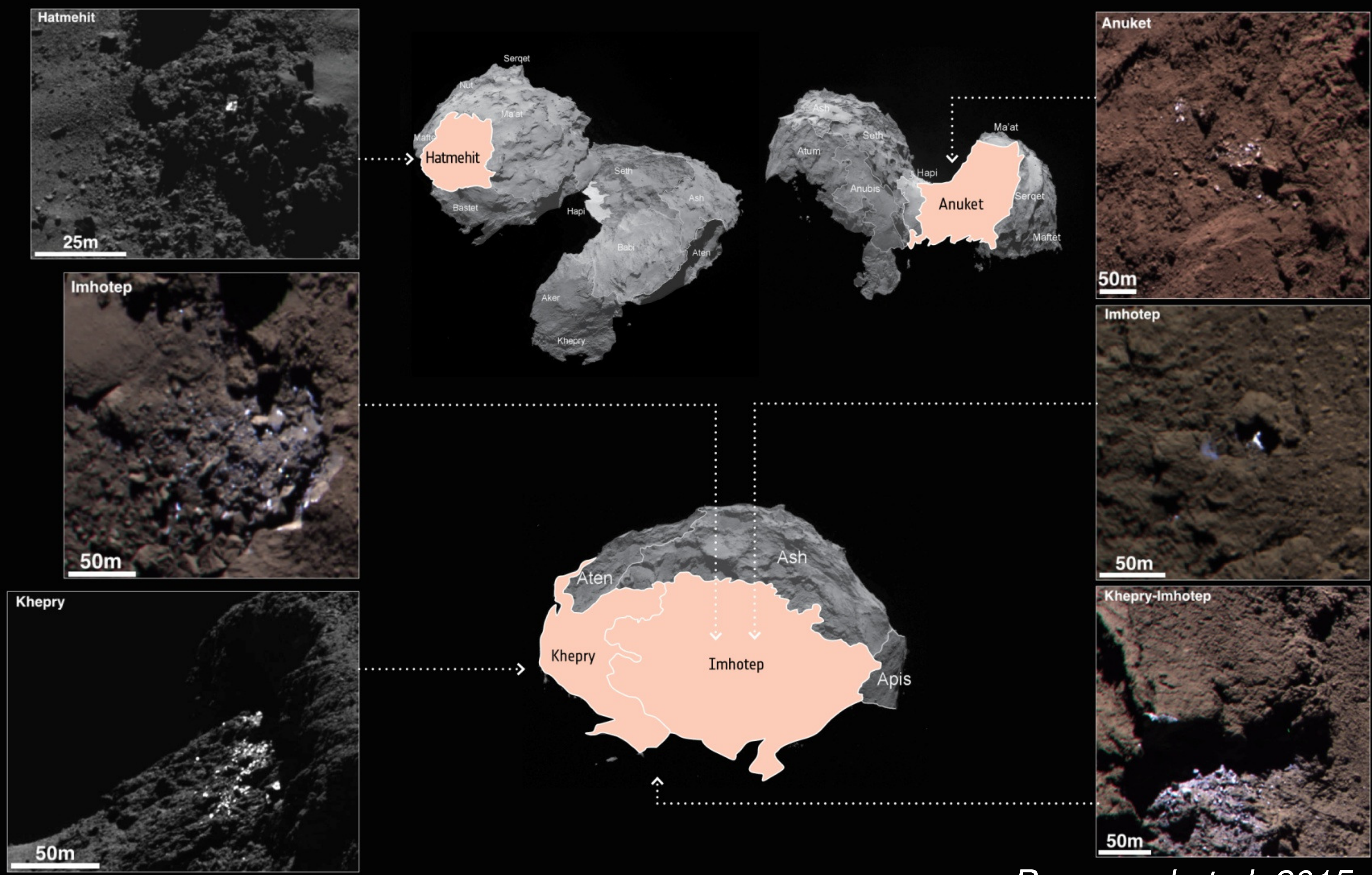
Where is the ice ?

The color is bluer on the neck

Ice !

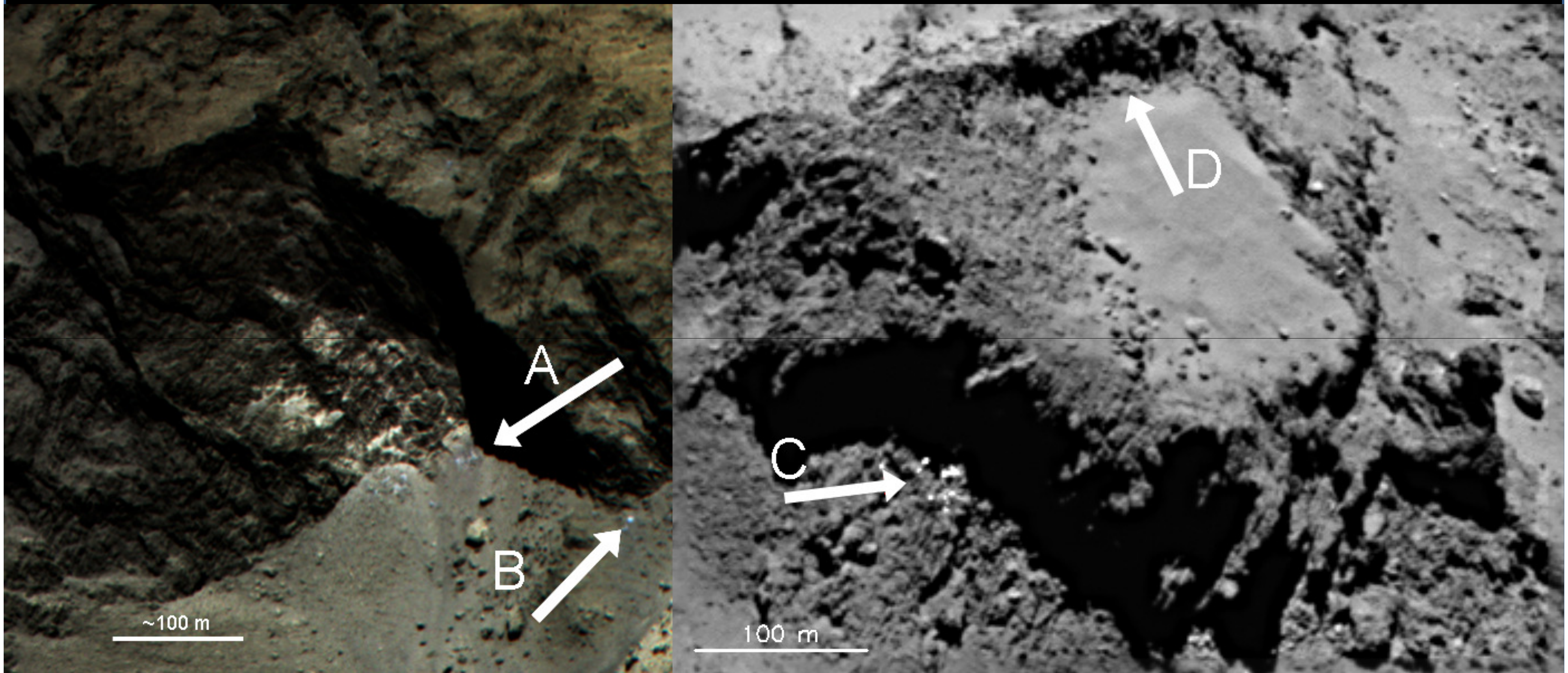


Bright patches of ice are found near collapsing walls



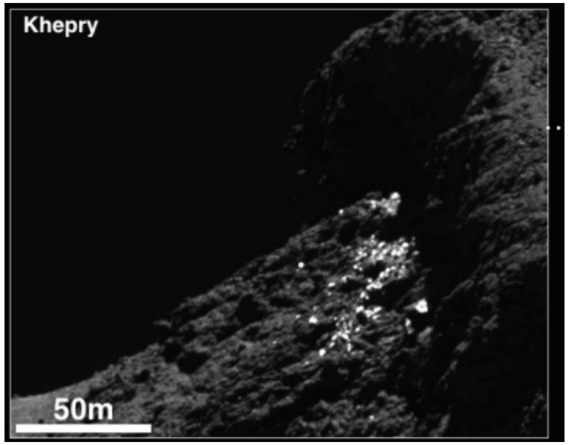
Pommerol et al. 2015

Icy blocks

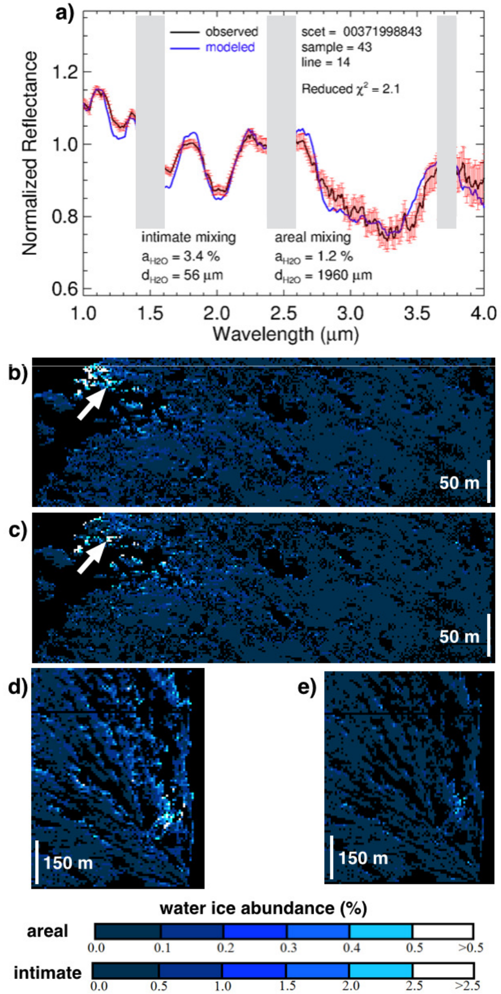


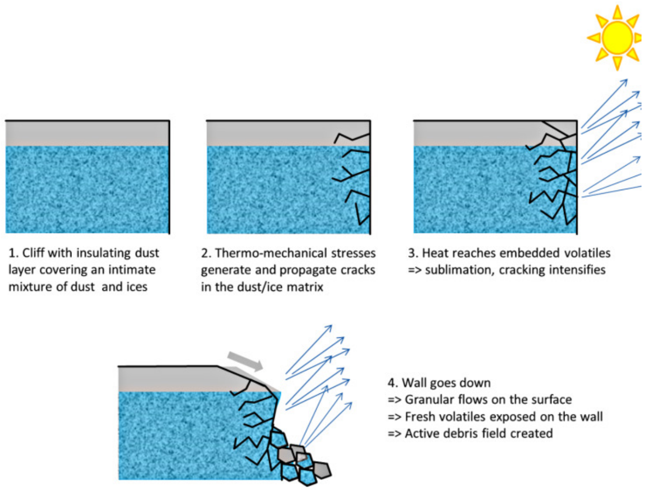
Water ice-rich spots

- Ice spots associated to debris falls related to erosion and mass wasting – short or long-lived
- Dust jets associated to fractured walls and mass wasted debris
- VIRTIS-M spectra show ice signatures on bright /blue spots

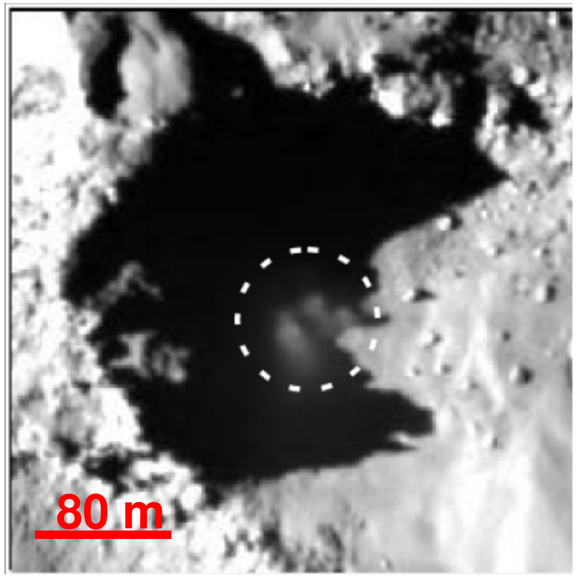


OSIRIS/Pommerol et al. (2016)



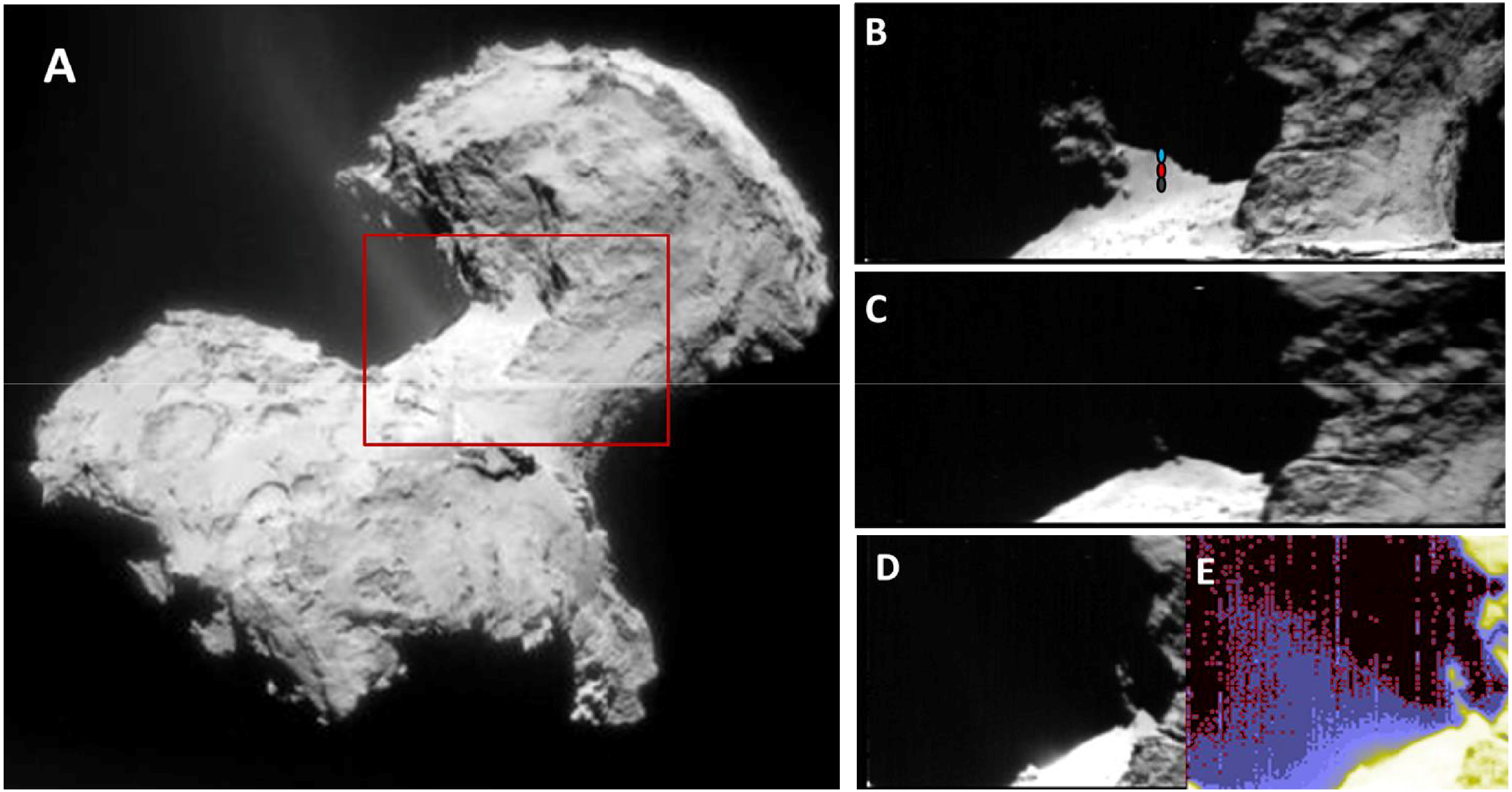


OSIRIS/Vincent et al. (2016)



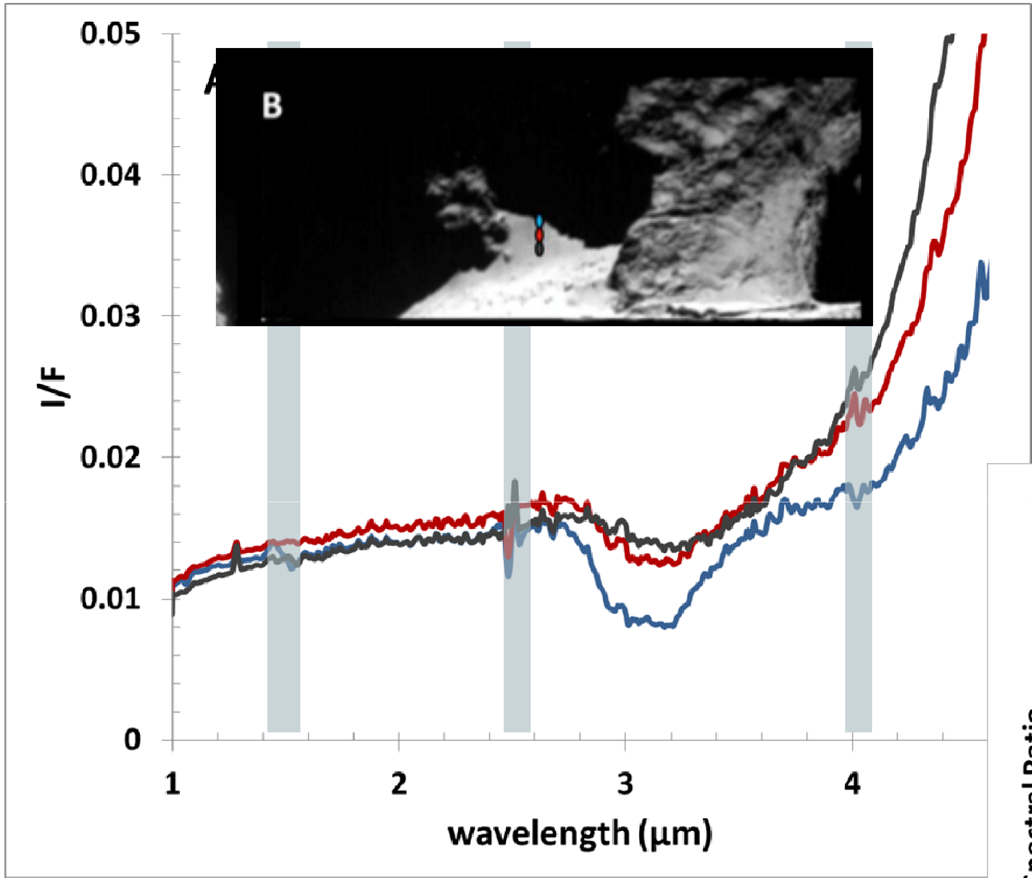
VIRTIS/Filacchione et al. 2016

The diurnal water cycle on 67P/CG



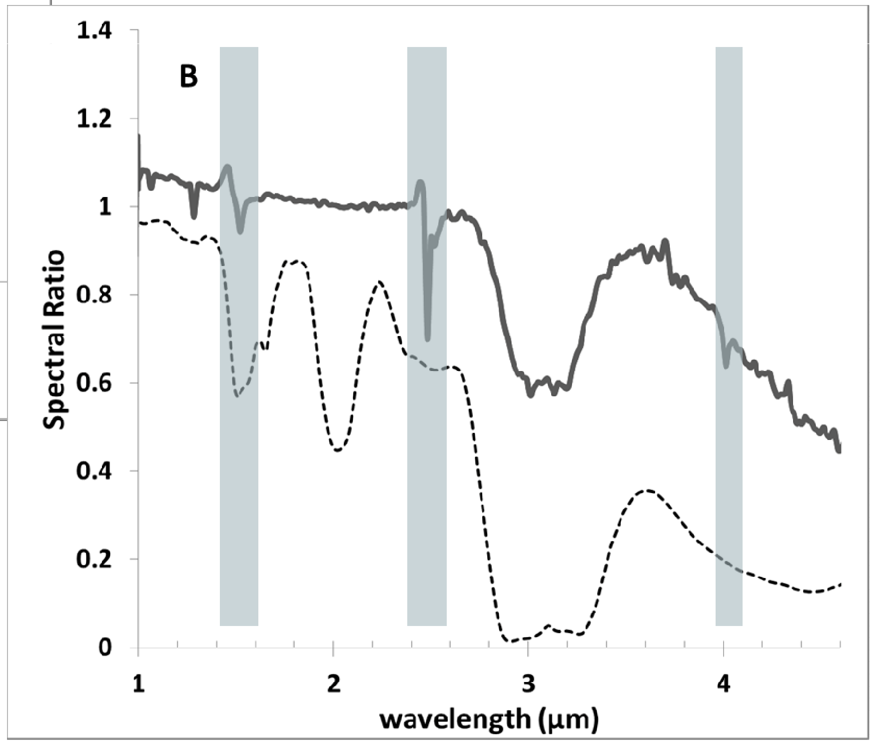
De Sanctis et al, Nature, 2015

The diurnal water cycle on 67P



Solid spectrum: ratio blue/black

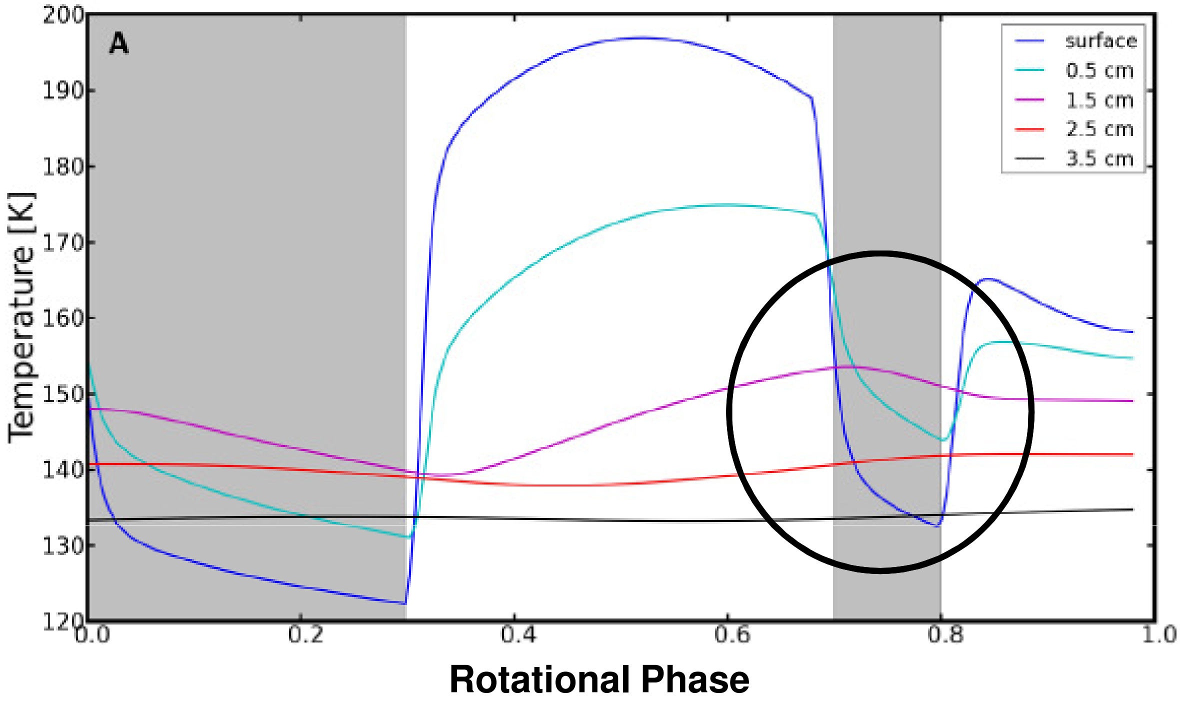
Dotted spectrum: pure water ice, 10µm grain size

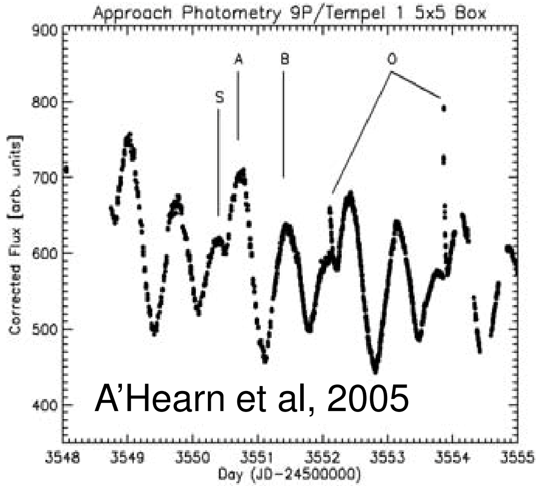


De Sanctis et al, Nature, 2015

Water vapour transport to the surface

- Transport of water from deeper layer to the dehydrated surface
- At night or in shadows the surface layer is colder than deeper layer
- Low thermal inertia (<50SI) drives the effect.

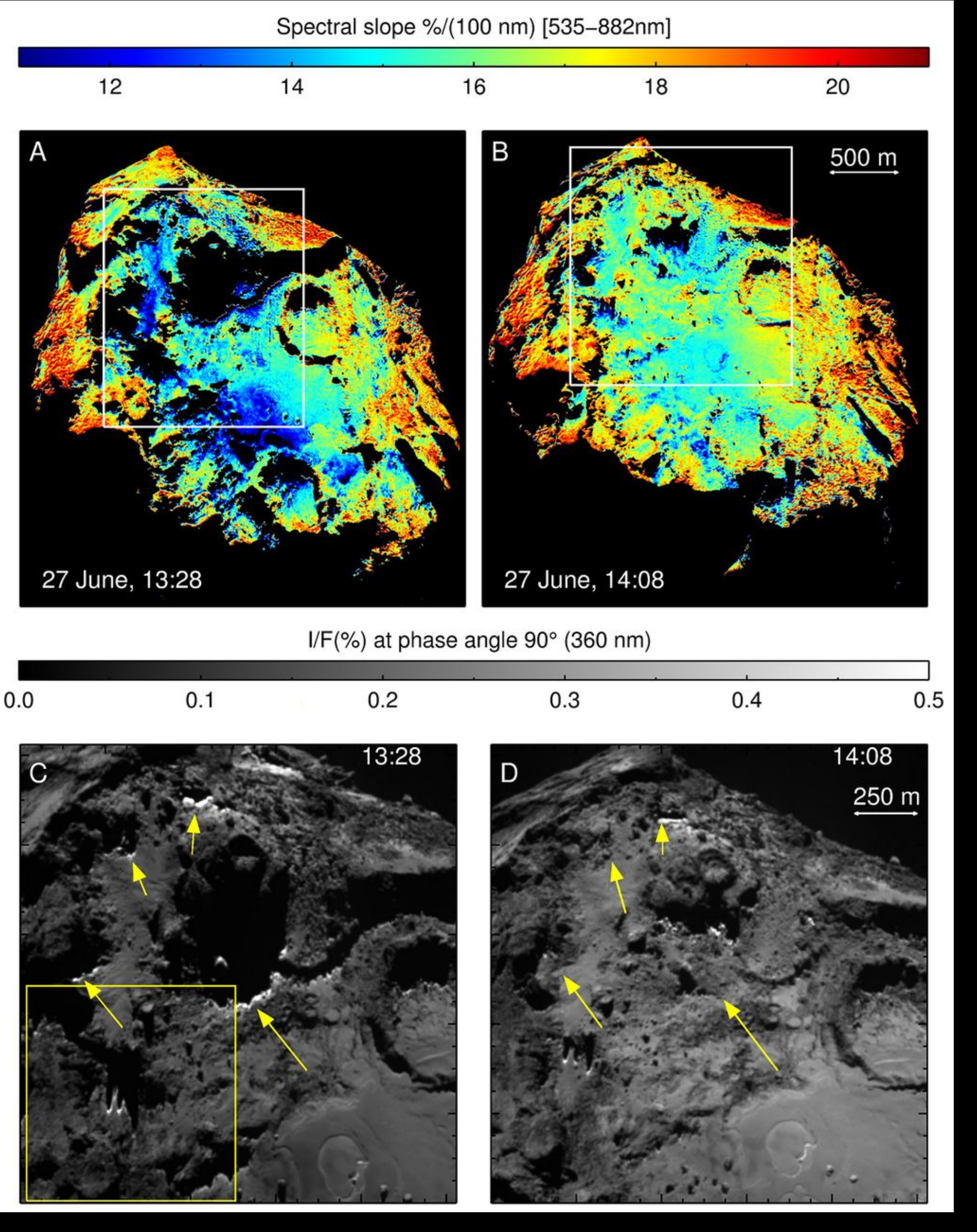




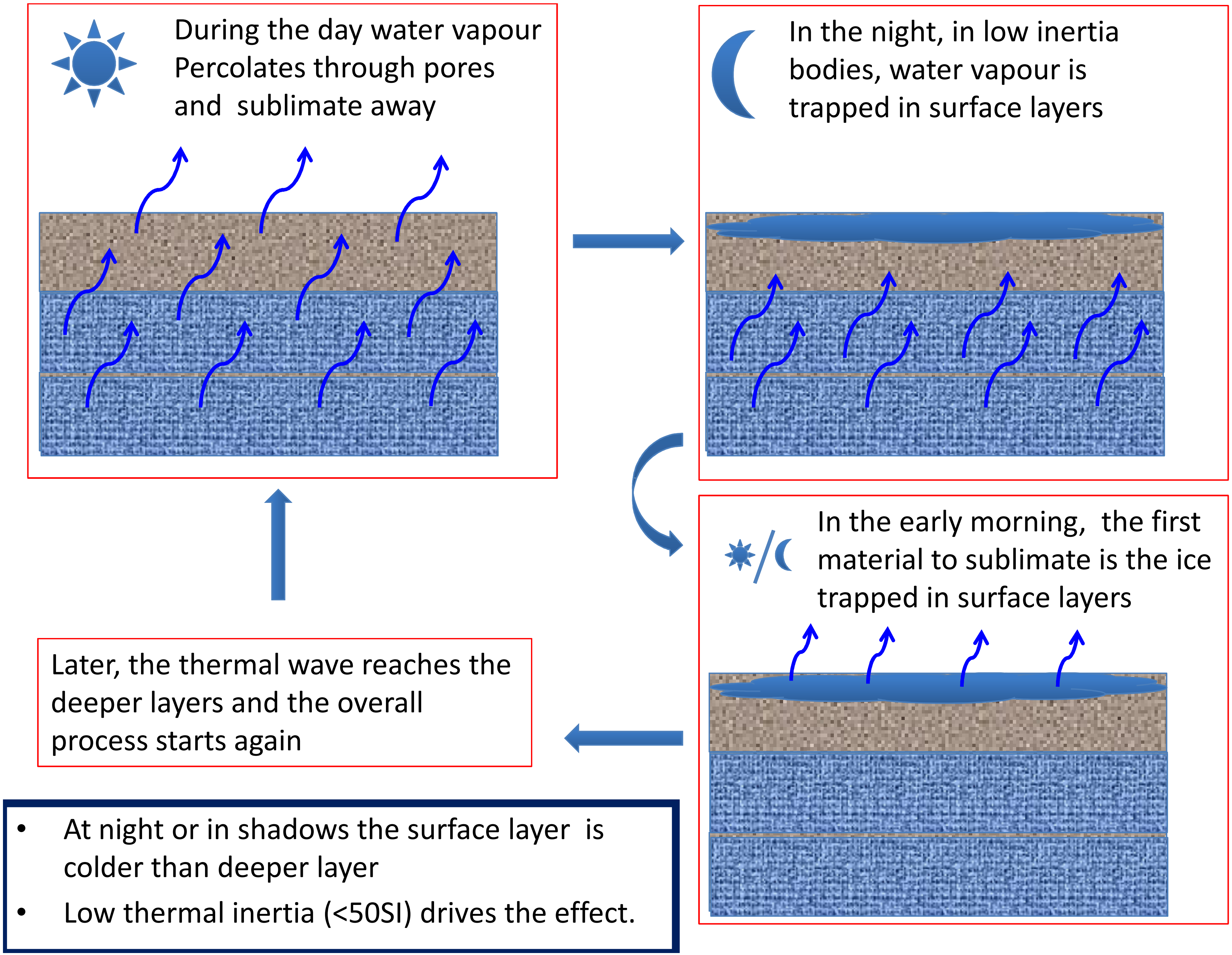
Short lived outbursts observed on Tempel 1, located on morning side

Possibly acting a similar effect of sublimation from subsurface warmer layers and recondensation close to the cold surface during shadowing periods.

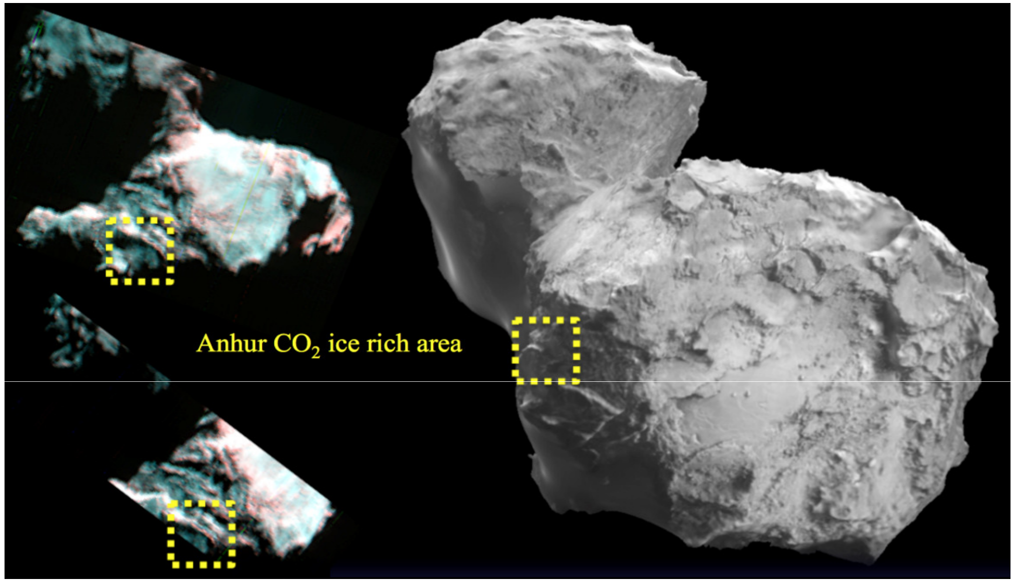
Morning ice observed by OSIRIS

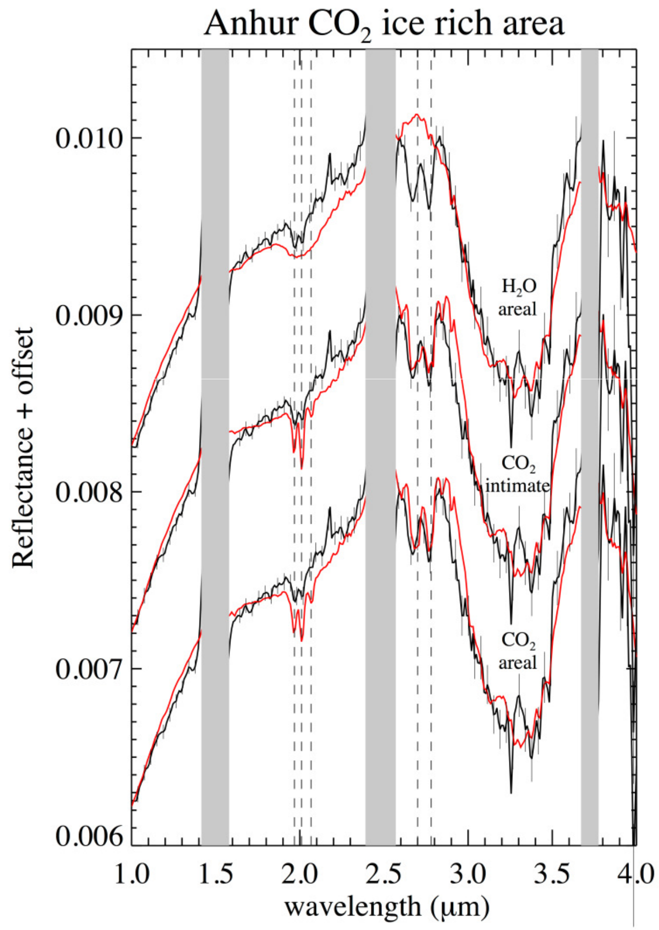


Fornasier et al. 2016


During the day water vapour
Percolates through pores
and sublimate away
In the night, in low inertia
bodies, water vapour is
trapped in surface layers
In the early morning, the first
material to sublimate is the ice
trapped in surface layers
Later, the thermal wave reaches the
deeper layers and the overall
process starts again
• At night or in shadows the surface layer is
colder than deeper layer
• Low thermal inertia (<50SI) drives the effect.

Detection of CO_2 ice on 67P ground





- Detection on Anhur region (south hemisphere) at 2 AU when leaving from winter.
- No longer seen one month later
- Low amount of CO_2 ice
- Presence related to hotter temperature below the surface

Filacchione et al. 2016 Science

The nucleus of
67P/Churyumov-Gerasimenko

What do we know about underground ?

Proposed models in the past …

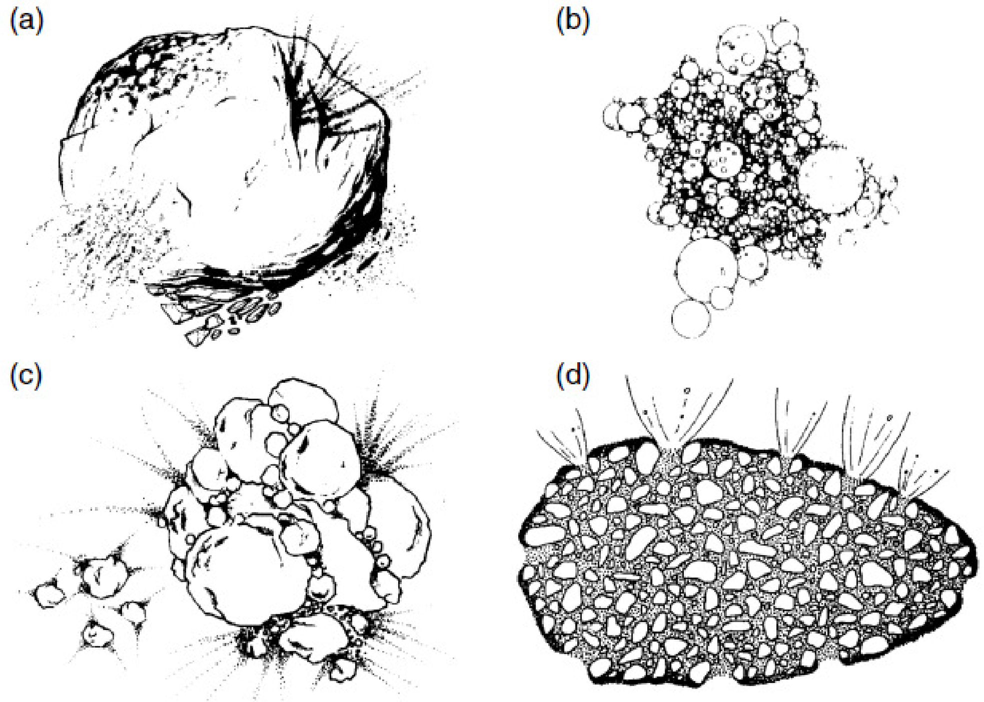
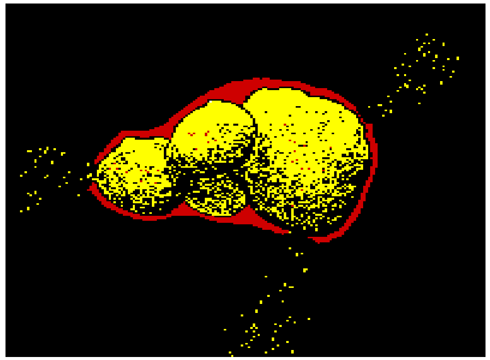
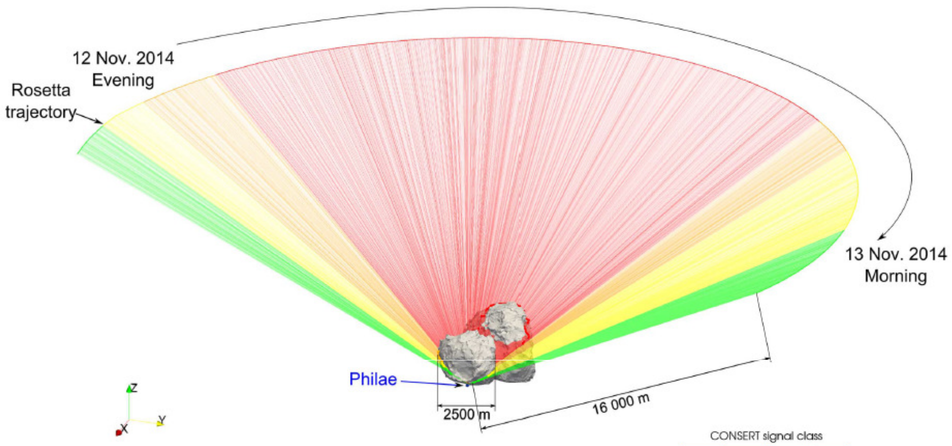


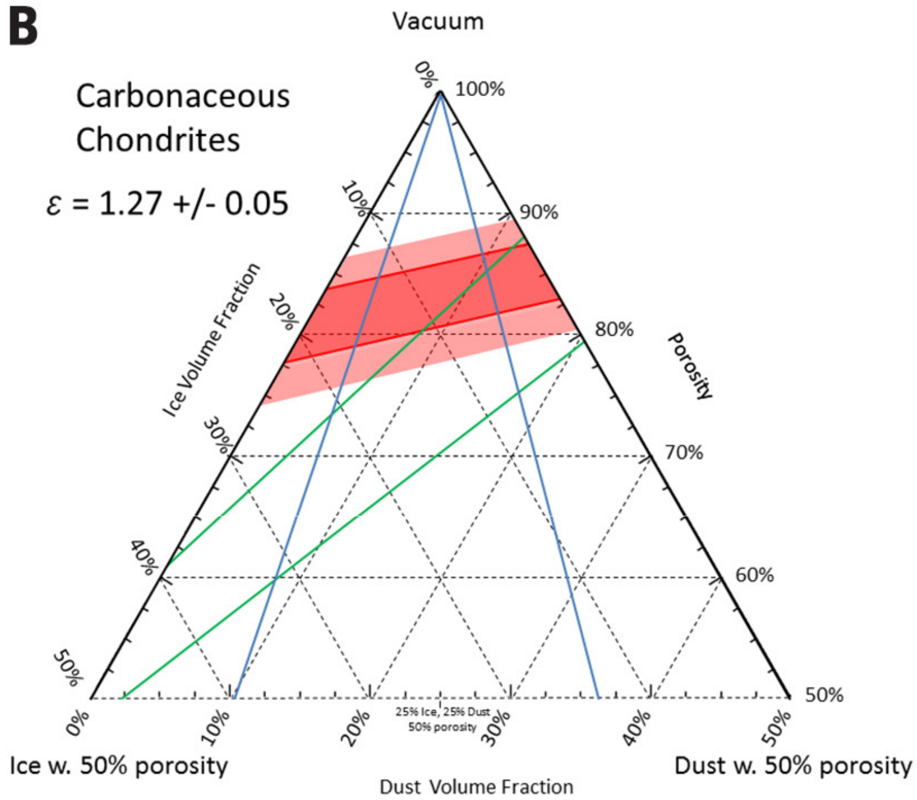
Fig. 2. Artists' concepts of various models for cometary nuclei: (**a**) Whipple's icy conglomerate model as envisioned by *Weissman and Kieffer* (1981); (**b**) the fractal aggregate model of *Donn et al.* (1985); (**c**) the primordial rubble pile model of *Weissman* (1986); and (**d**) the icy-glue model of *Gombosi and Houpis* (1986). All but (**d**) were proposed prior to the spacecraft flybys of comet 1P/Halley in 1986.



Constraints from CONSERT

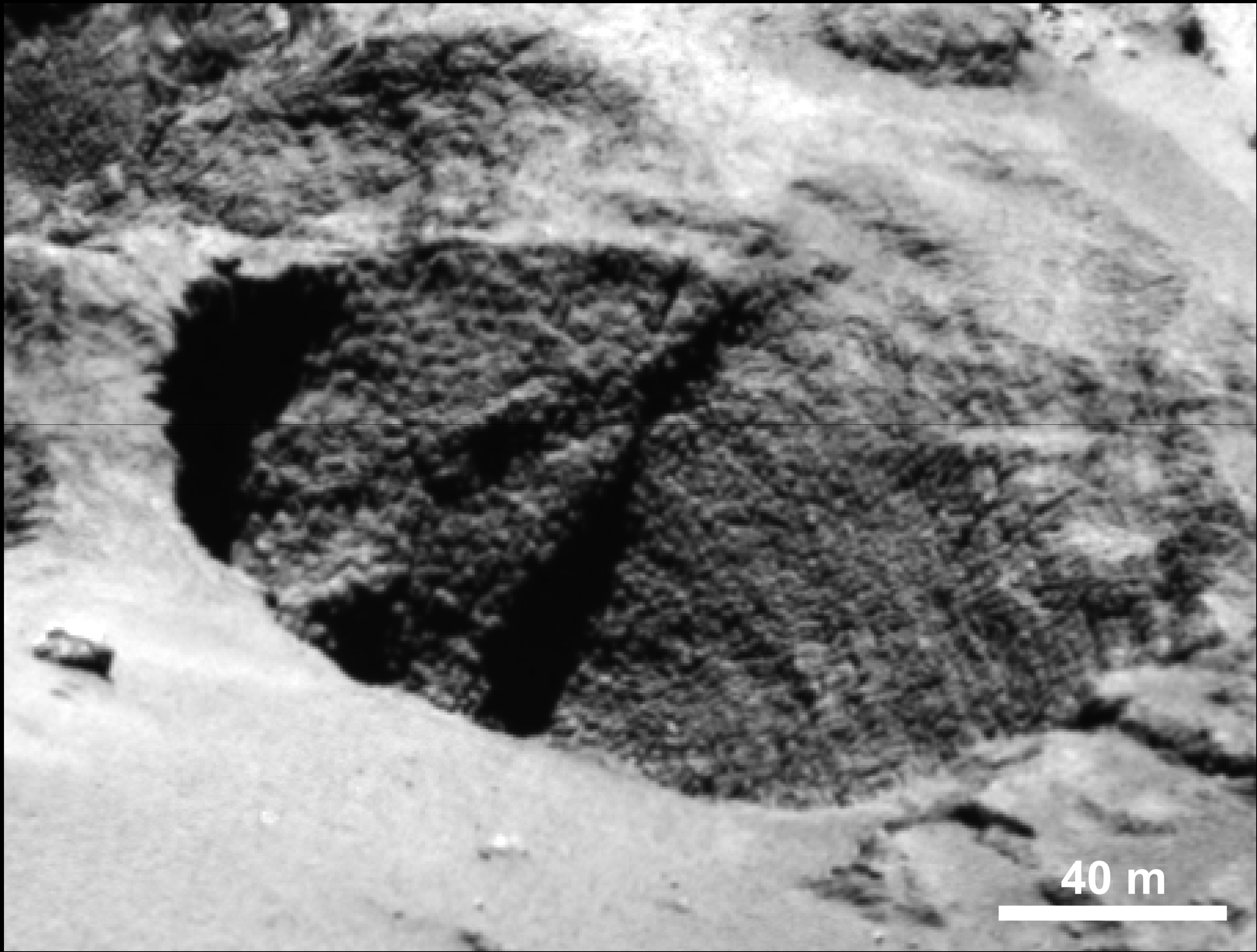


Kaufmann et al. 2015



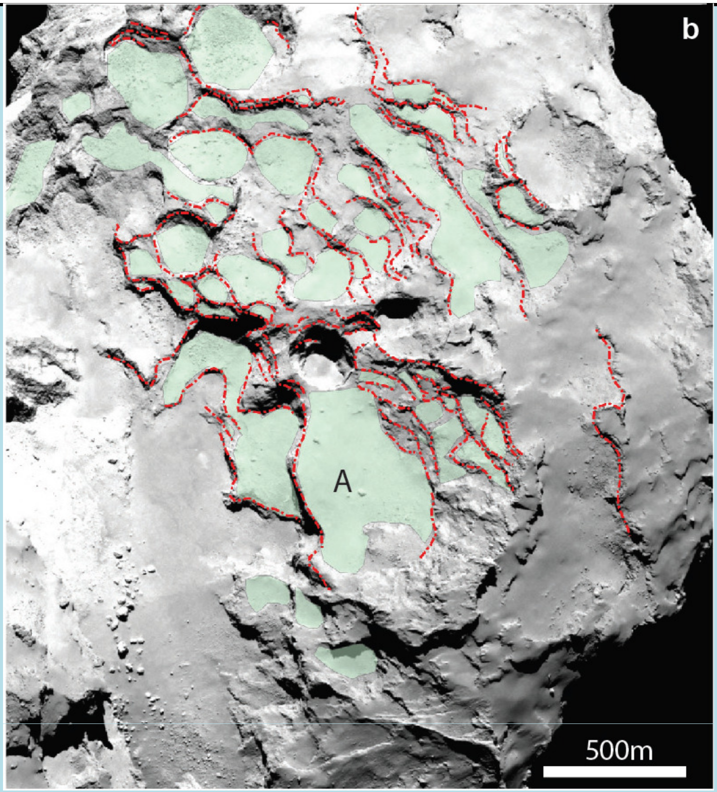
- Measurement of the permitivity at 90 MHz: 1.27 +/-0.05
- decrease of permitivity with depth (Ciarletti et al. 2015)
- porosity : 75-85 % in agreement with nucleus density of ~ 0.5 g/cm^3
- Dust/ice ratio = 0.4-2.6 in volume
- No reflections : homogeneity on a scale of ten meter

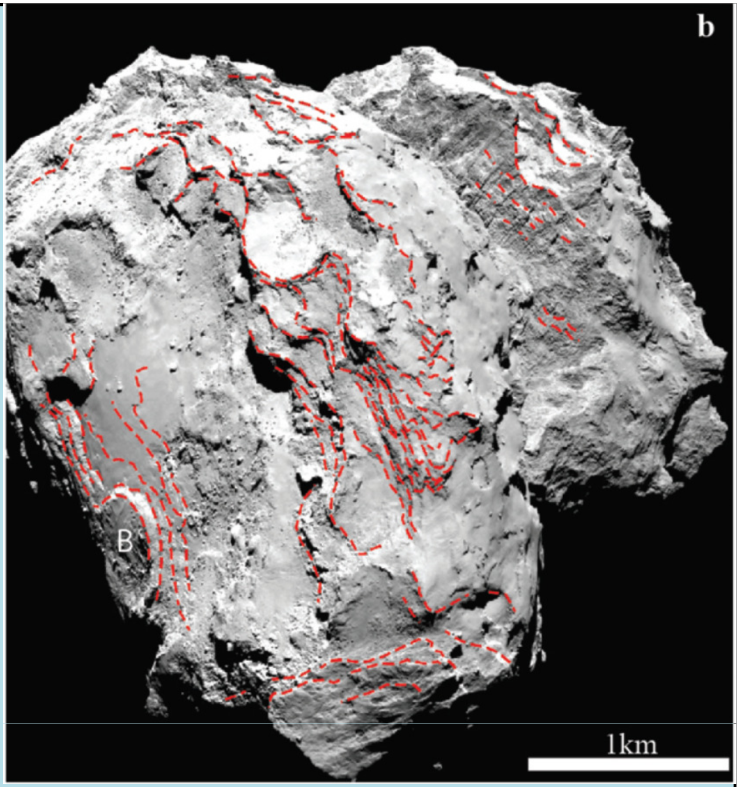
Building blocks of the comet ?
goose gumps



Strates, cuestas, terraces

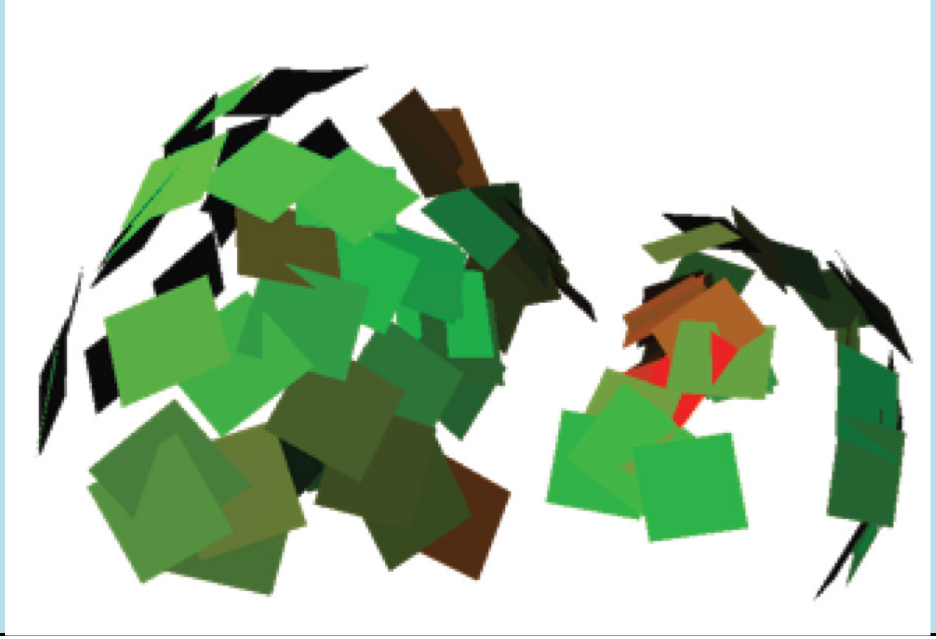
Ognon structure of the 2 lobes



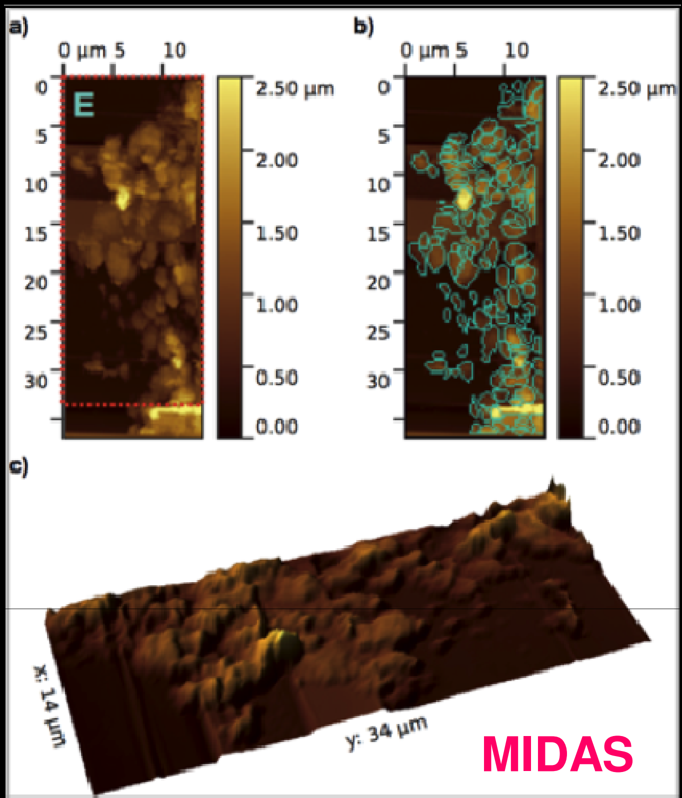


Formation of 67P

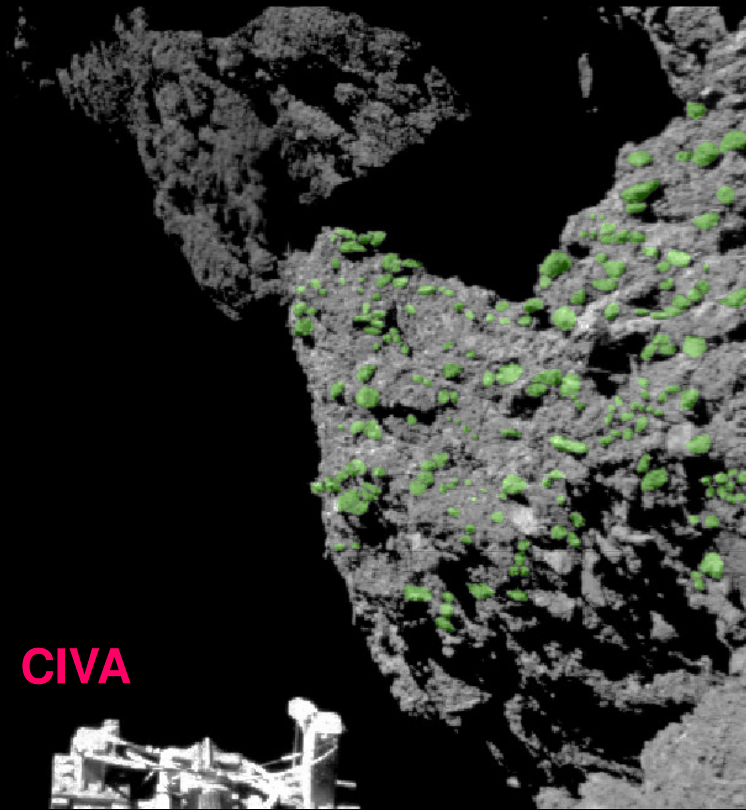
agglomération at low velocity of 2 bodies

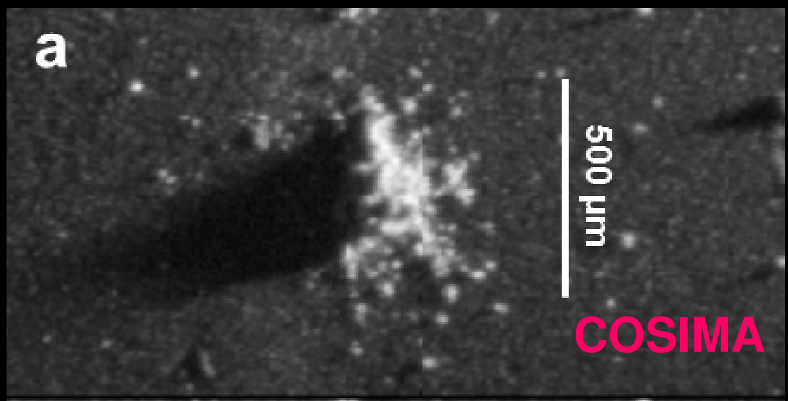


Fractal grains



Peebles ~ 1 cm



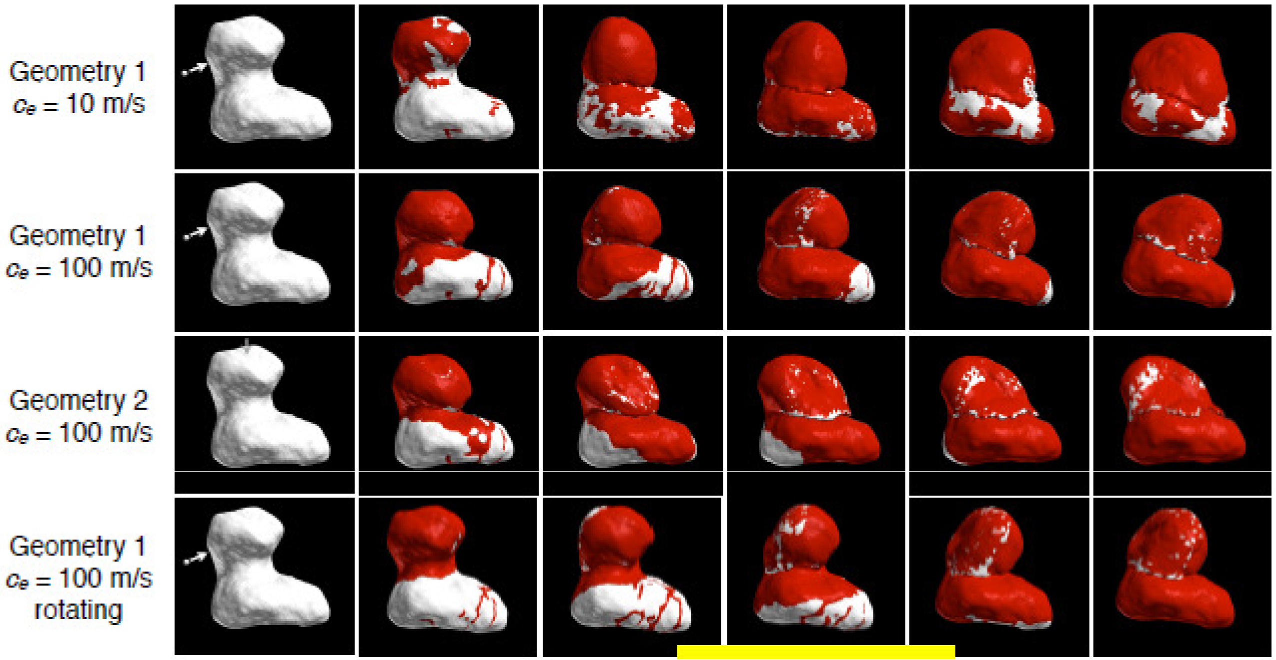


Peebles : In agreement with formation of planetesimals by gas streaming instabilities.

Fractal grains : relics of pristine fractals that survived compaction ?

How primordial
is the structure of 67P nucleus ?

The primordial nature of 67P shape is debated



v (m/s)	10	30	50	80	100
Q (J/Kg)	0.01	0.08	0.23	0.59	0.92

Jutzi et al. 2017

- 67P should have experienced several shape-changing collisions
  - ✓simulations done during the dispersion of trans-Neptunian disk caused by giant planet migration (Jutzi et al. 2017)
- Modelling shows that this should not have affected 67P porosity and ice content
- The bi-lobed structure might have originated from a recent event (1 Gyr).
- 67P may have formed by reaccumulation of collisional debris (Michel et al. 2016)

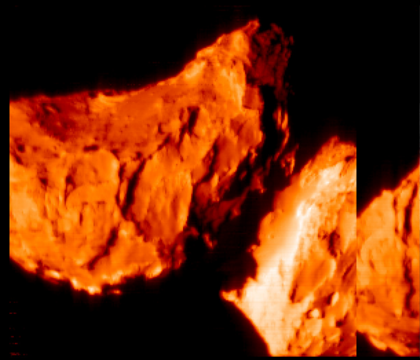
The nucleus of 67P/Churyumov-Gerasimenko

Thermophysical properties

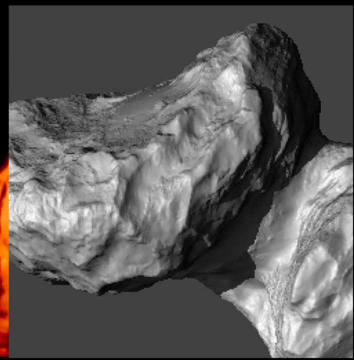
Thermal properties of 67P nucleus

Temperature

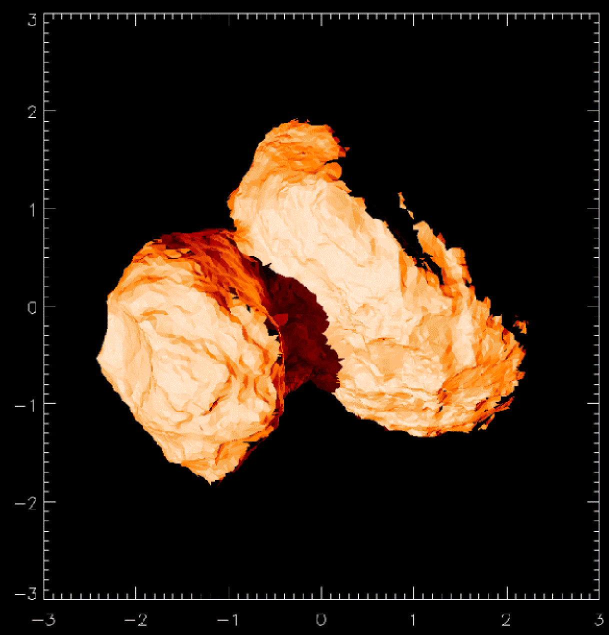
- Local hour
- Seasons
- T max : ~310 K
- Small thermal inertia $<60\ Jm^{-2}K^{-1}s^{-1/2}$

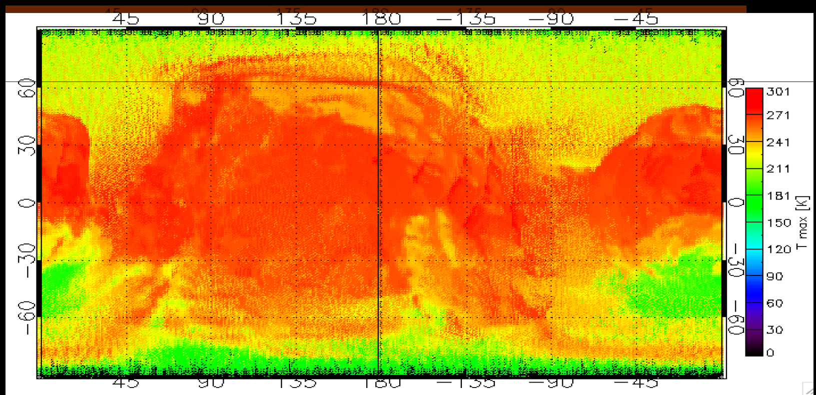


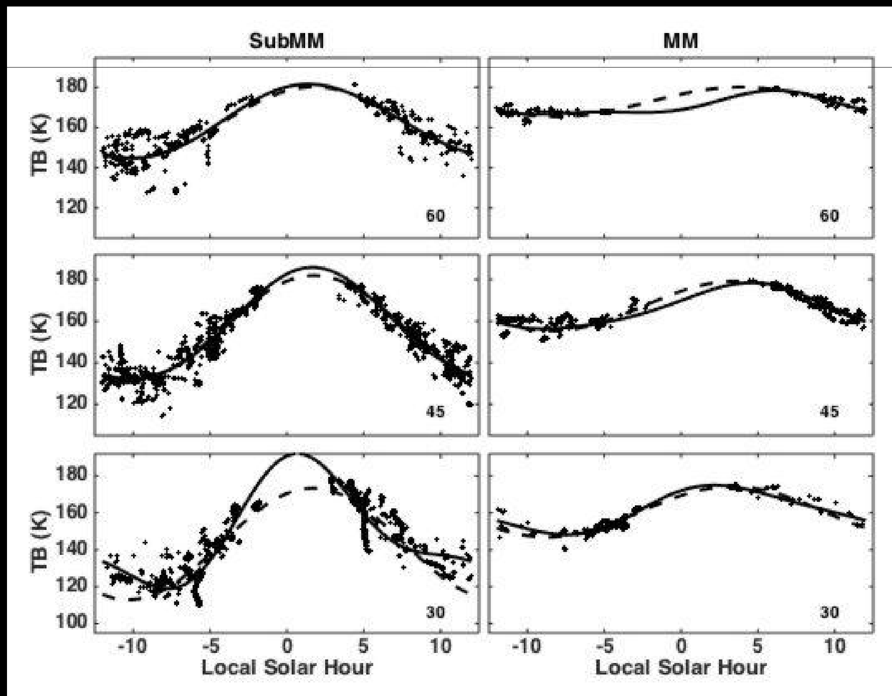
VIRTIS-Temperature



Predicted illuminations



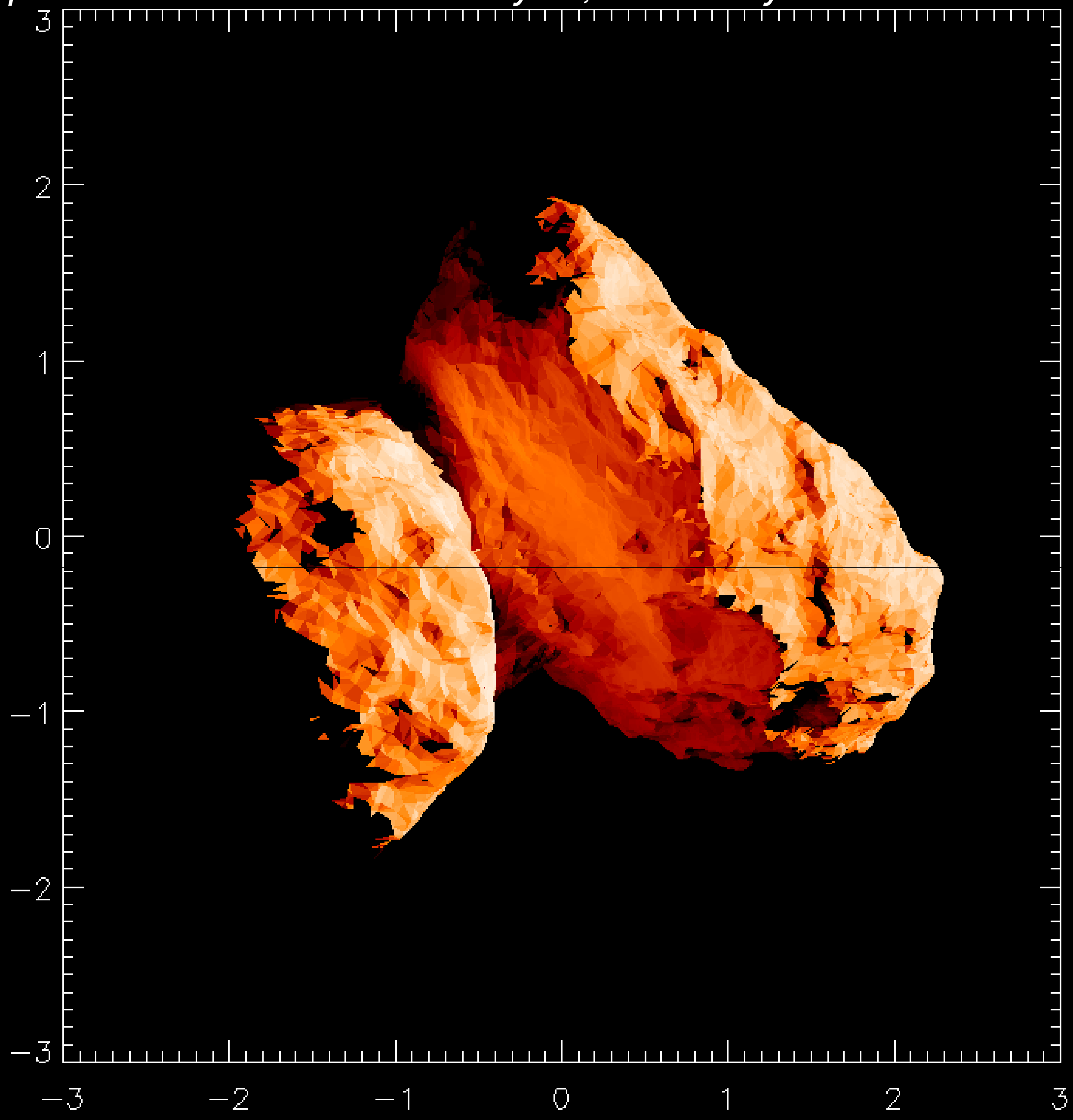




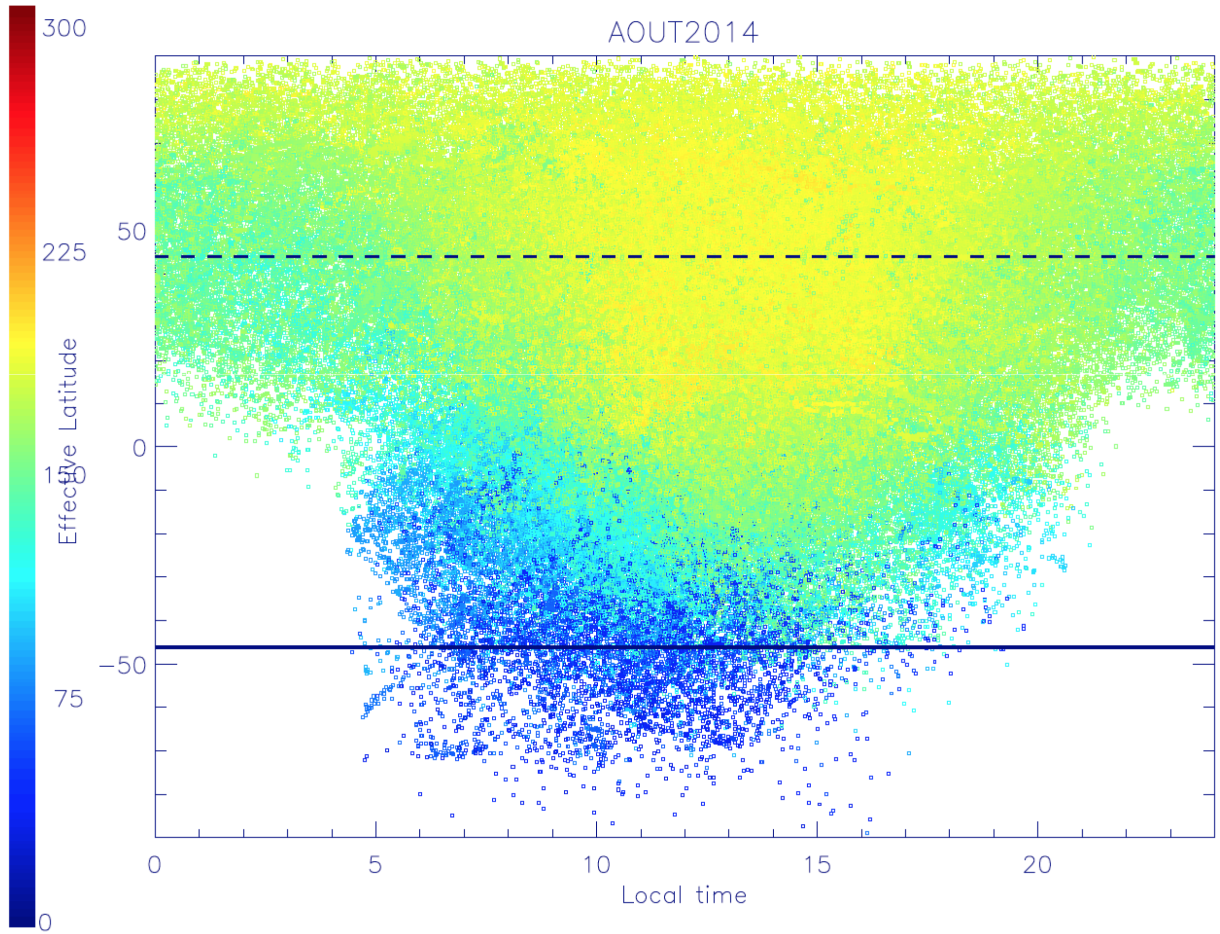
- <u>**MIRO : sub-surface T at 2 depths**</u>
  - 20 millions of data
  - Seasonal & diurnal variations
  - T min =40 K (polar night)
  - Very small thermal inertia

C. Leyrat, E. Lellouch courtesy

Modélisation Température de surface - C. Leyrat,   courtesy

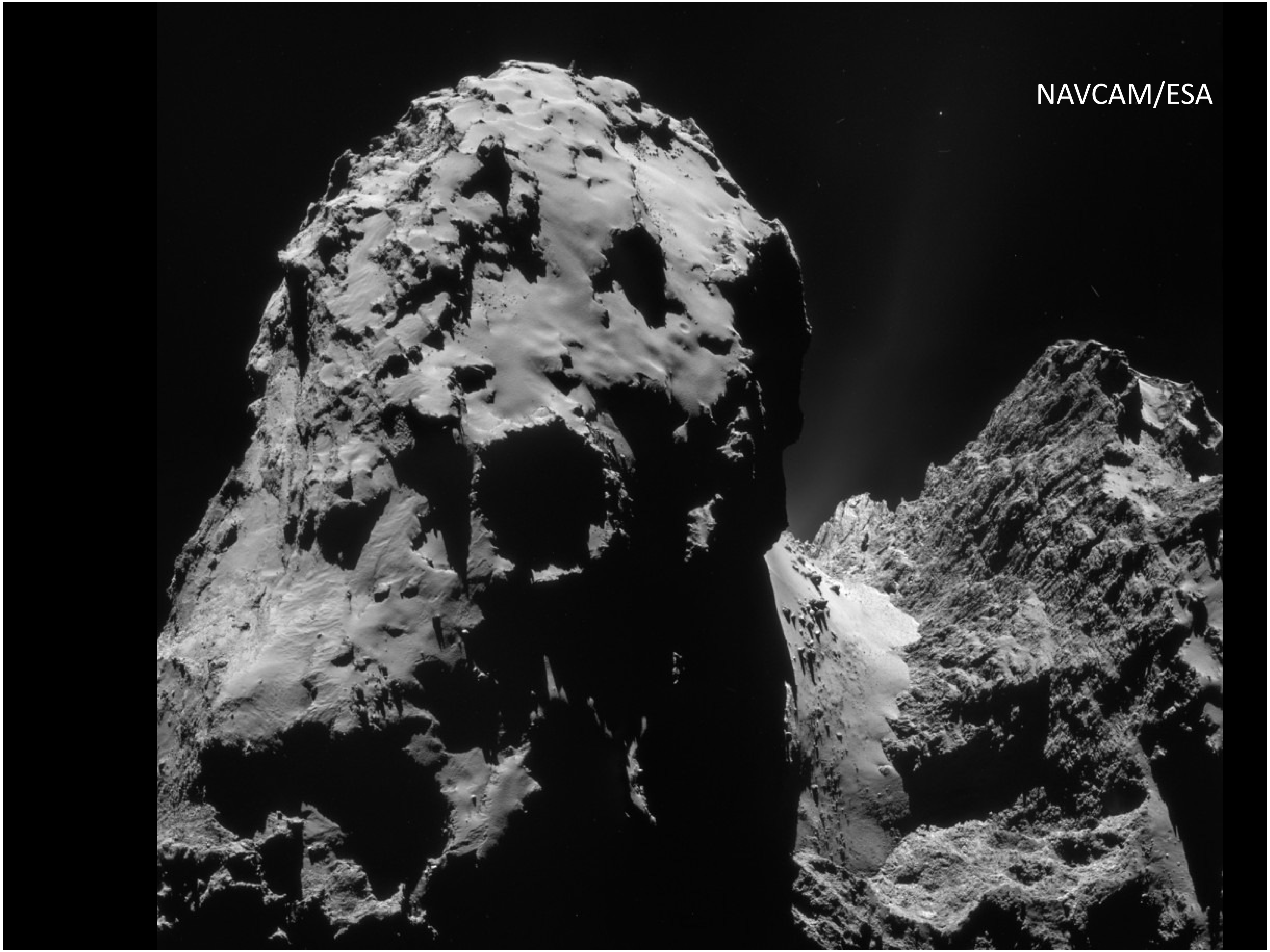


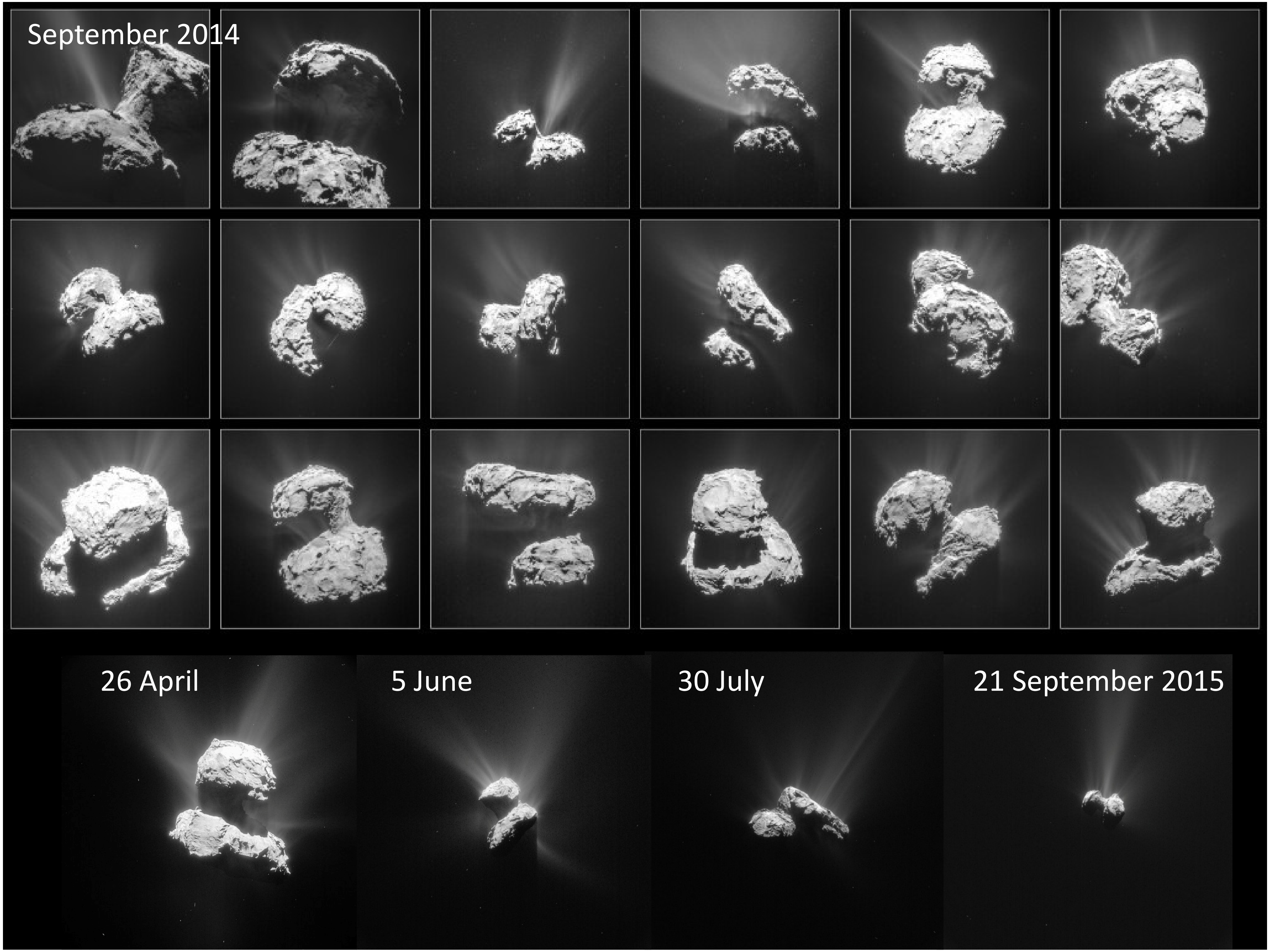
Antenna température MIRO – 0.5 mm



Activity of the nucleus

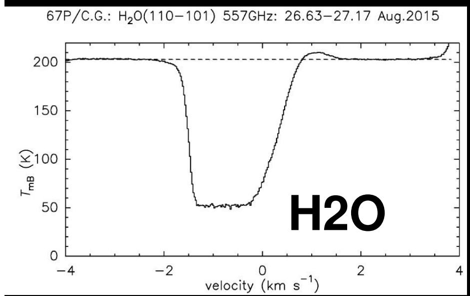
The role of seasons

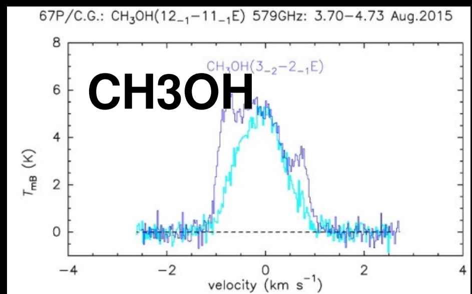

NAVCAM/ESA

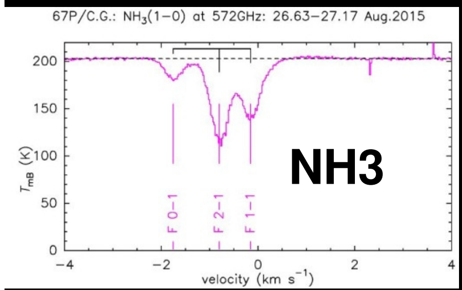

September 2014
26 April
5 June
30 July
21 September 2015

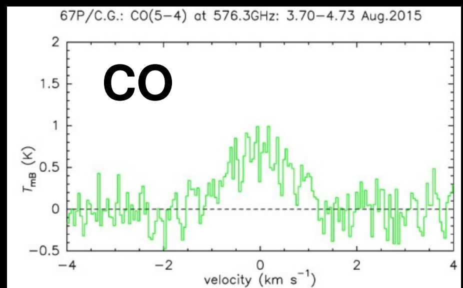
Evolution of gaseous activity

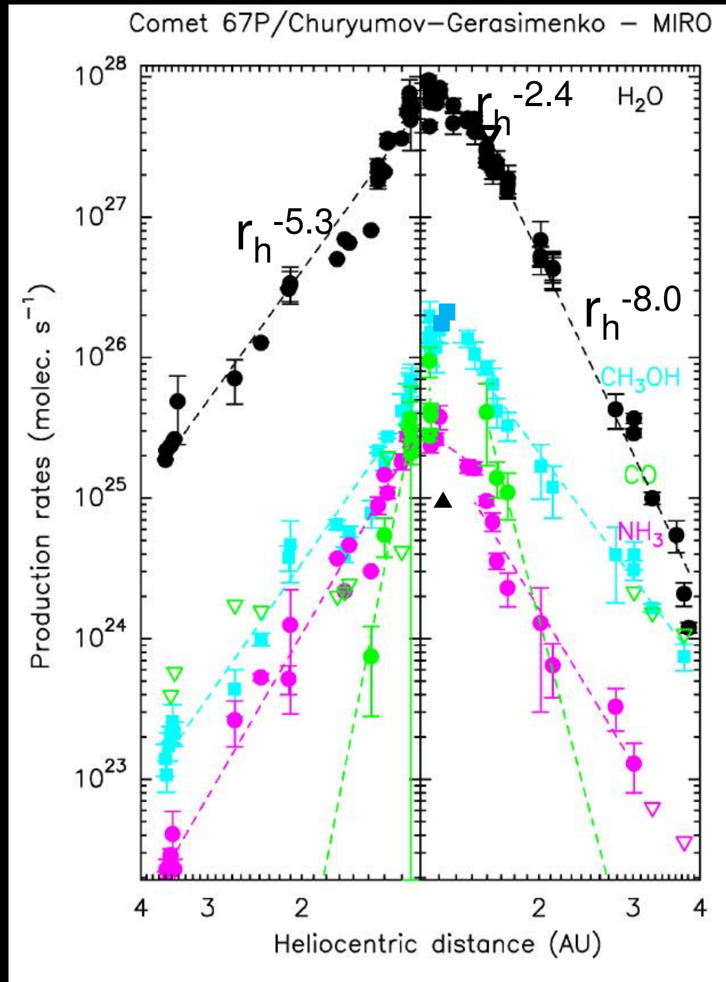
MIRO results





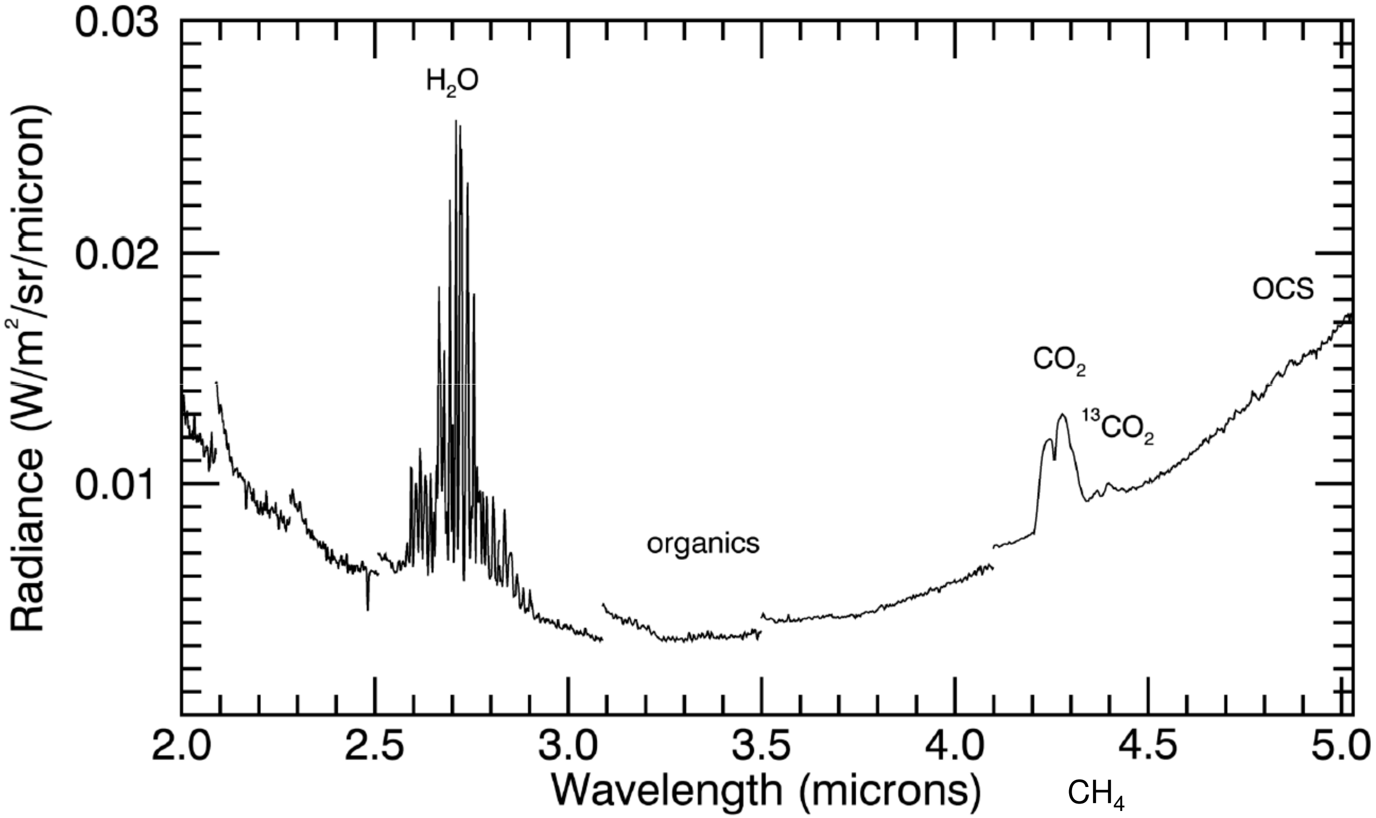






Biver et al. courtesy

67P coma observations with VIRTIS-H

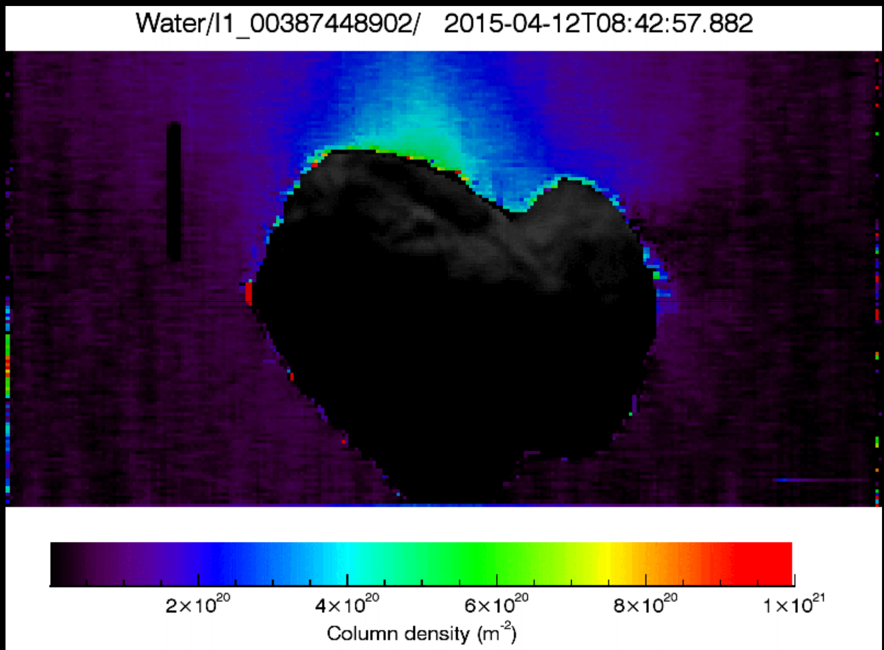


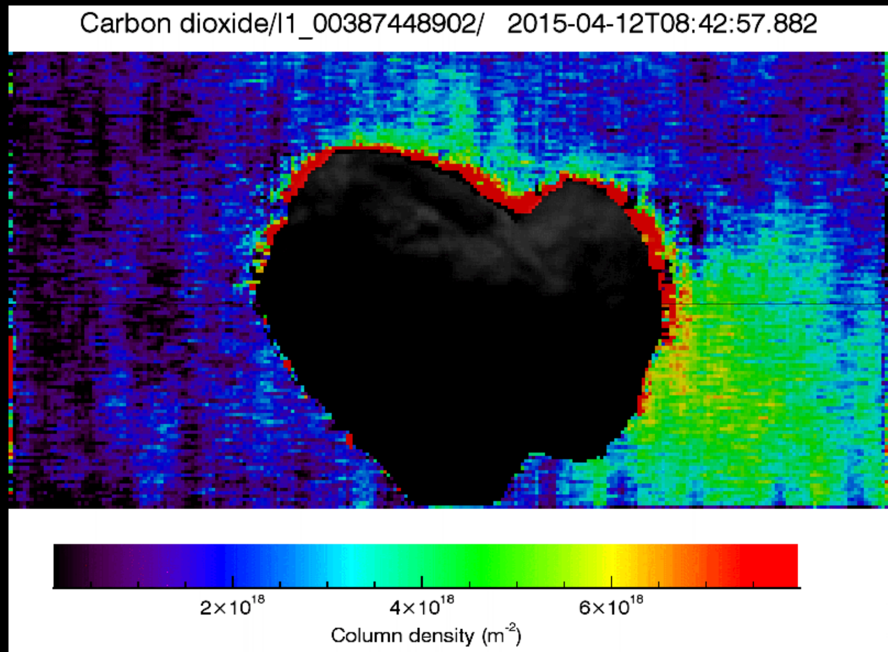
Bockelée-Morvan et al. 2016

Gaseous coma from VIRTIS-M – April 2015

H_2O 2.67 µm

$CO2$ 4.27 µm

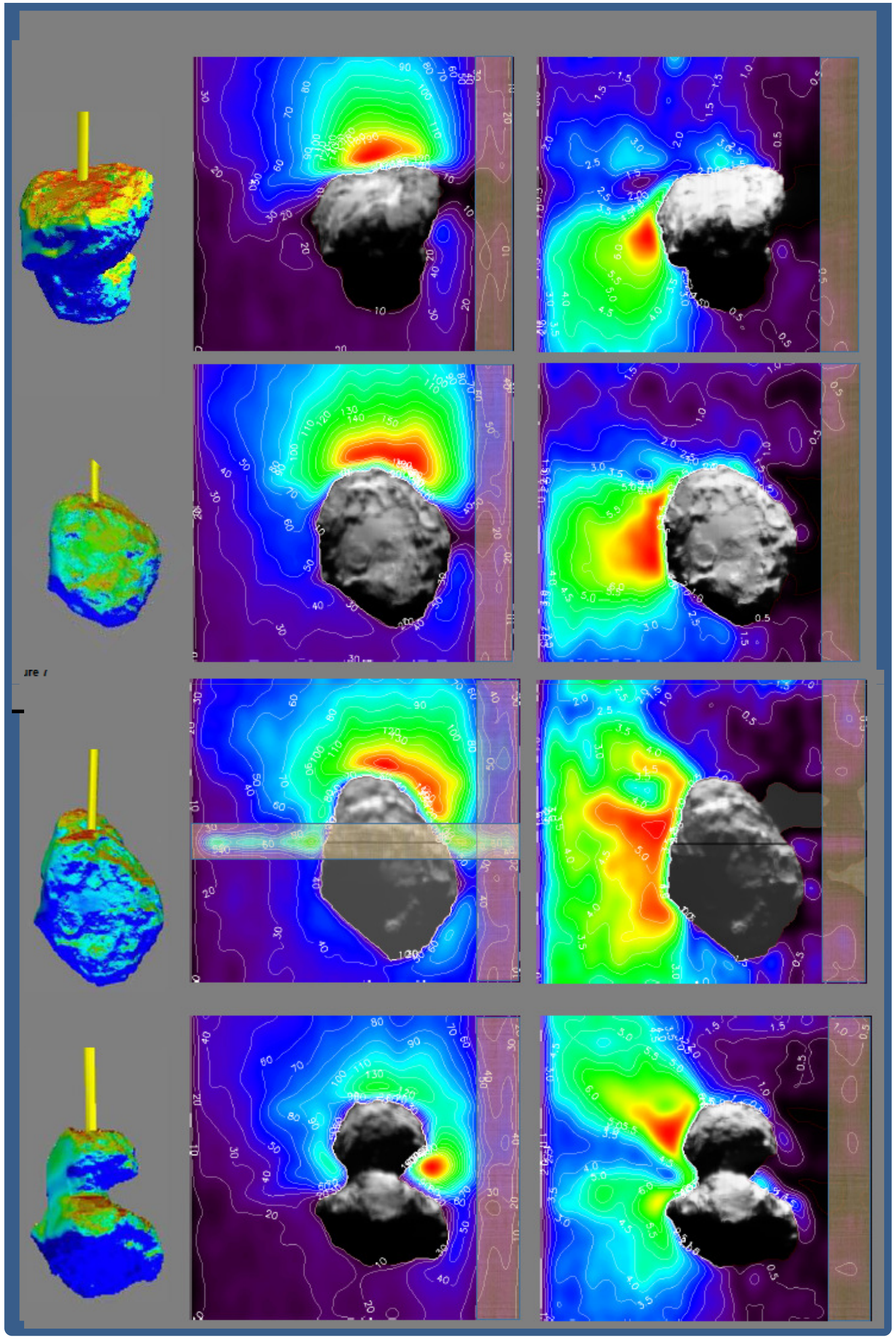




Eau

Dioxyde de carbone

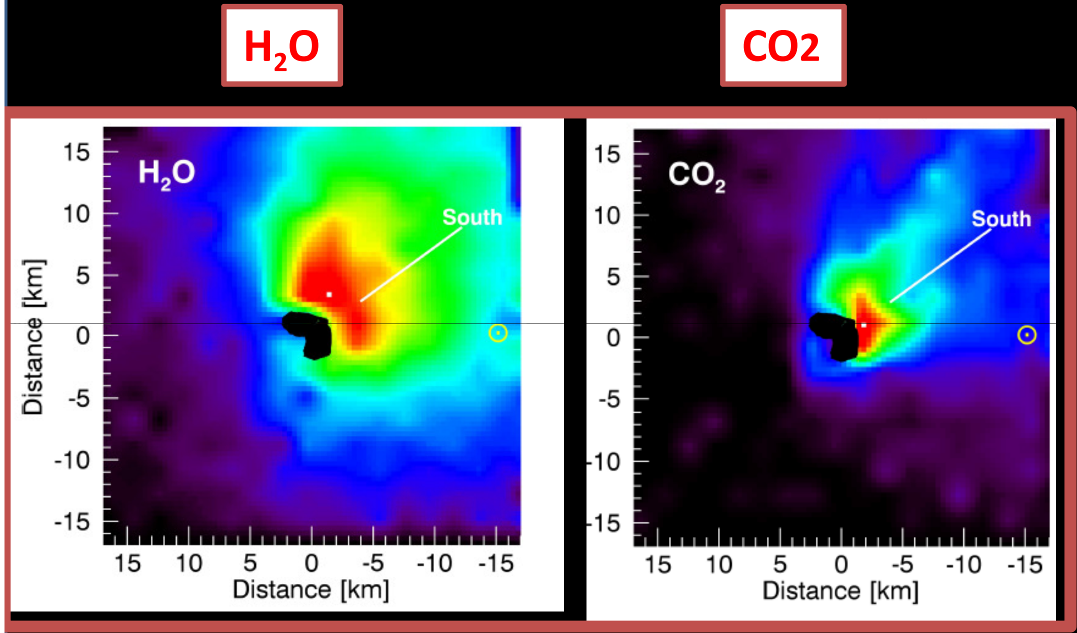
VIRTIS-M
27 April. 2015

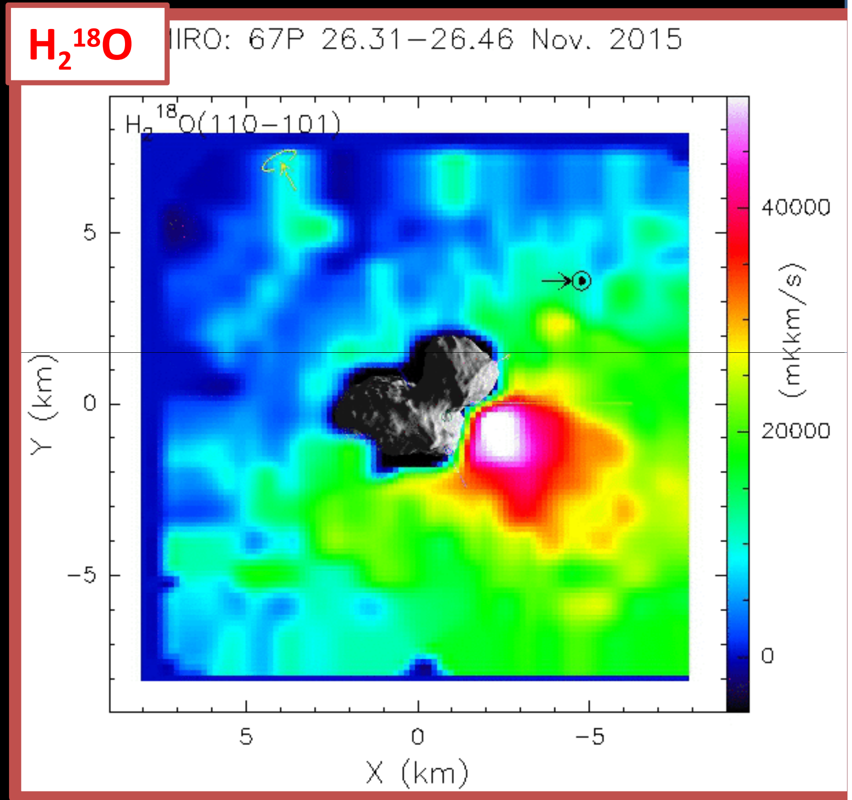


→ N

Fink et al. 2016

Activity from the southern hemisphere





August 2016 (1.3 AU)

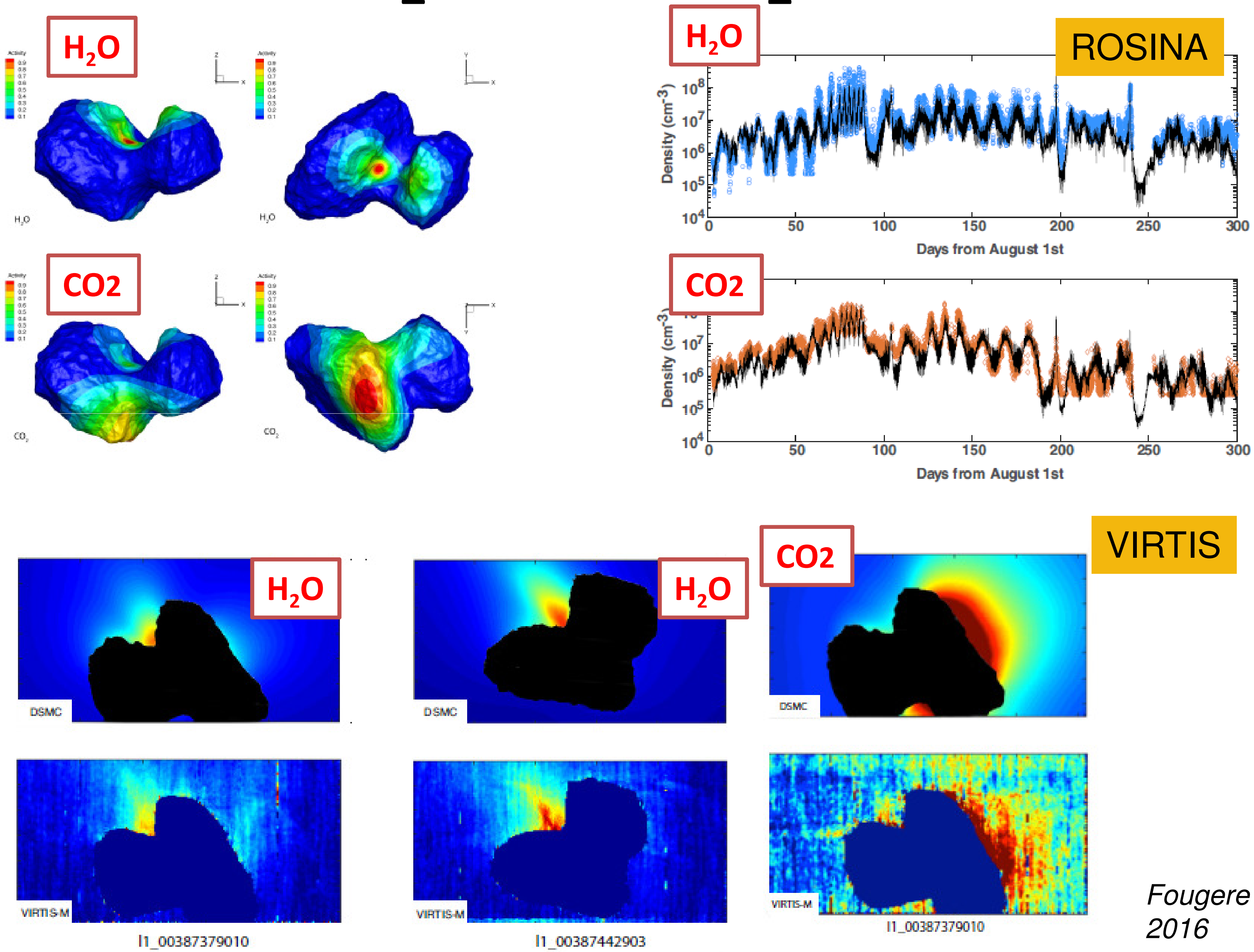
VIRTIS

Nov. 2016 (1.7 AU)

MIRO

Bockelée-Morvan et al. 2016

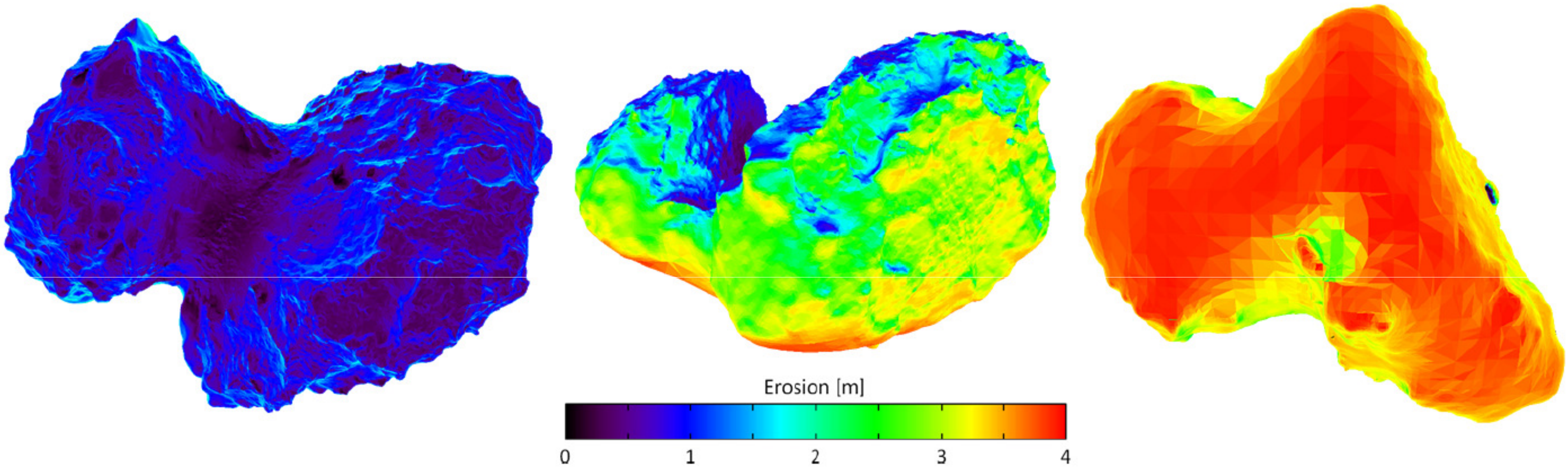
Modelling H_2O and CO_2 distributions



Fougere et al. 2016

The importance of seasons

Large obliquity of the rotation axis: 45 deg

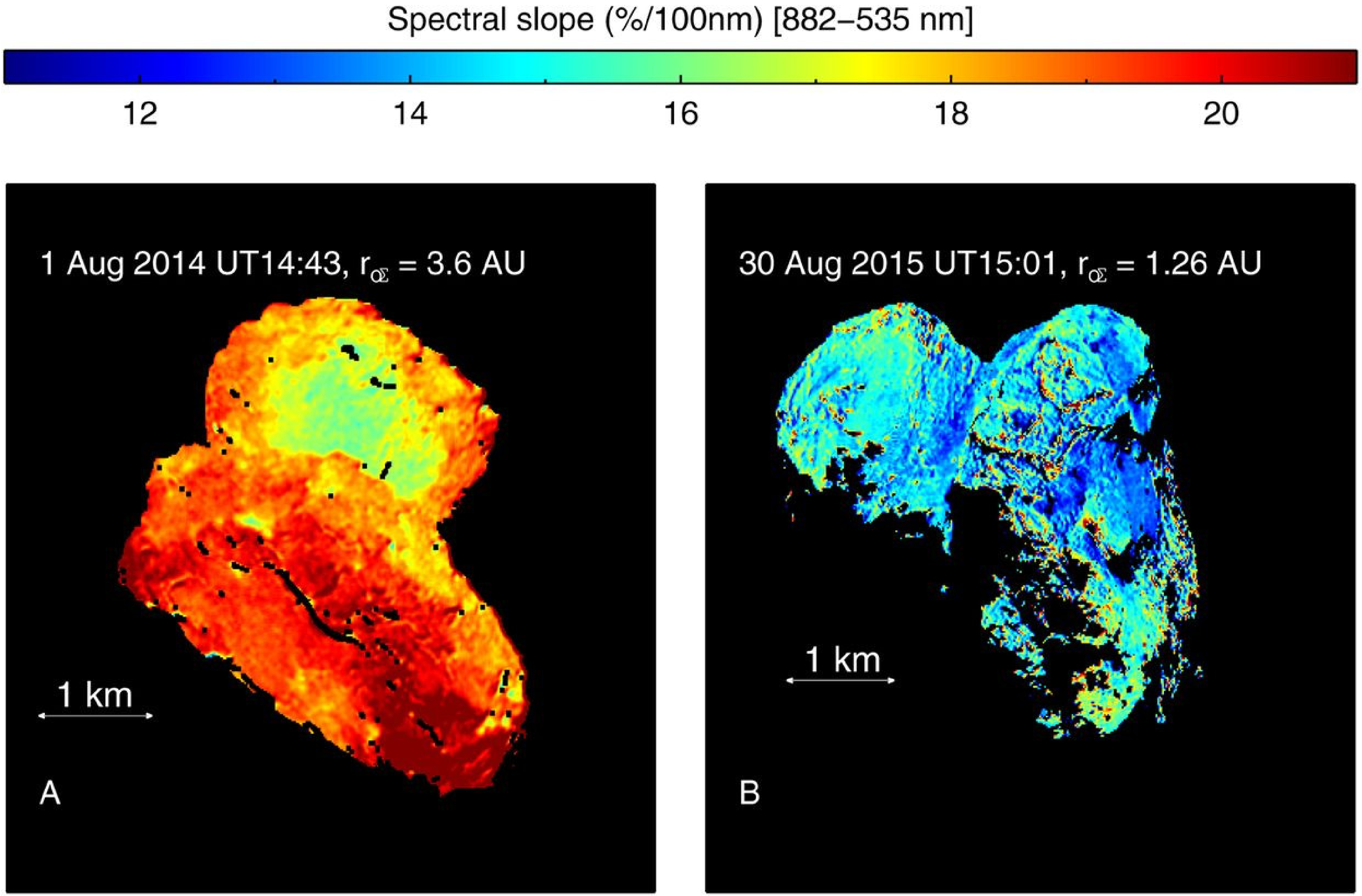


North Hemisphere
Long summer, weak solar illumination
Weak erosion

South Hemisphere
Short summer , strong illumination
Strong erosion

<u>Activity</u>: from one glass/s to 300 kg/s
<u>Erosion</u> : up to a few meters
<u>Dynamic transport of dust from the south to the north</u> : explains smooth areas

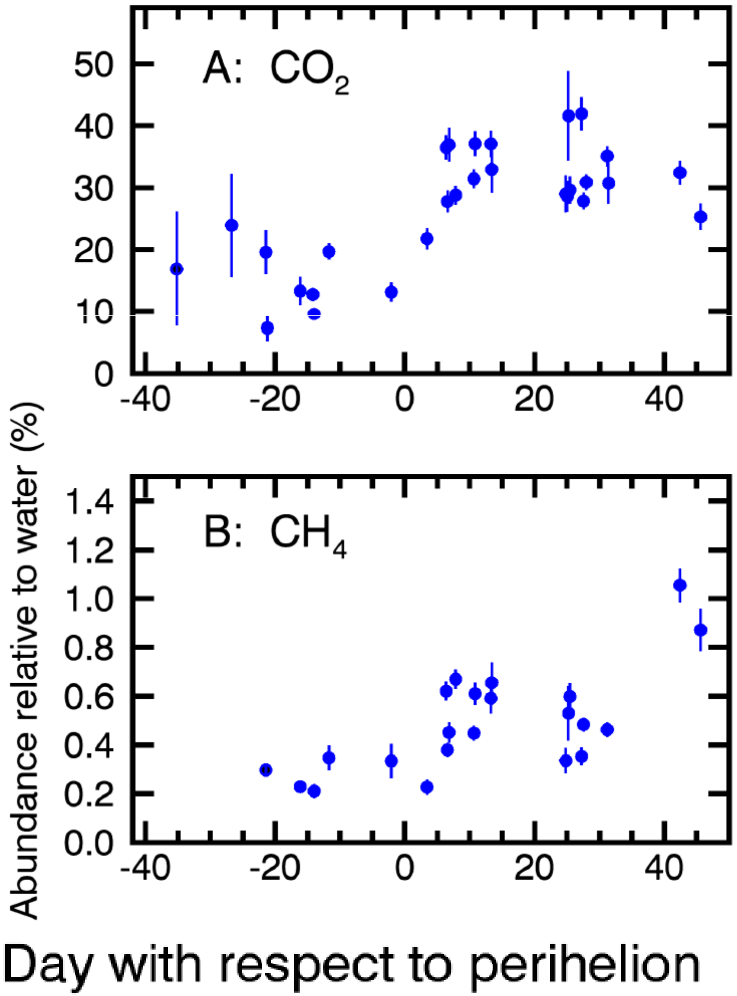
The changing color of comet 67P



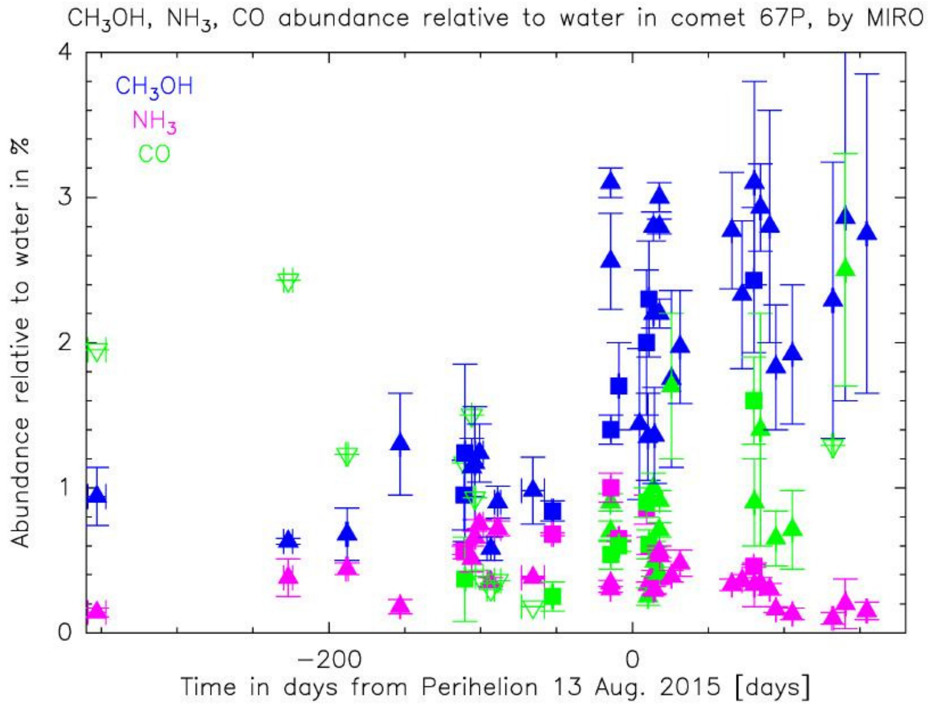
Fornasier et al. 2016 Science

Change in coma chemical properties after perihelion

VIRTIS results



MIRO results



Bockelée-Morvan et al. 2016

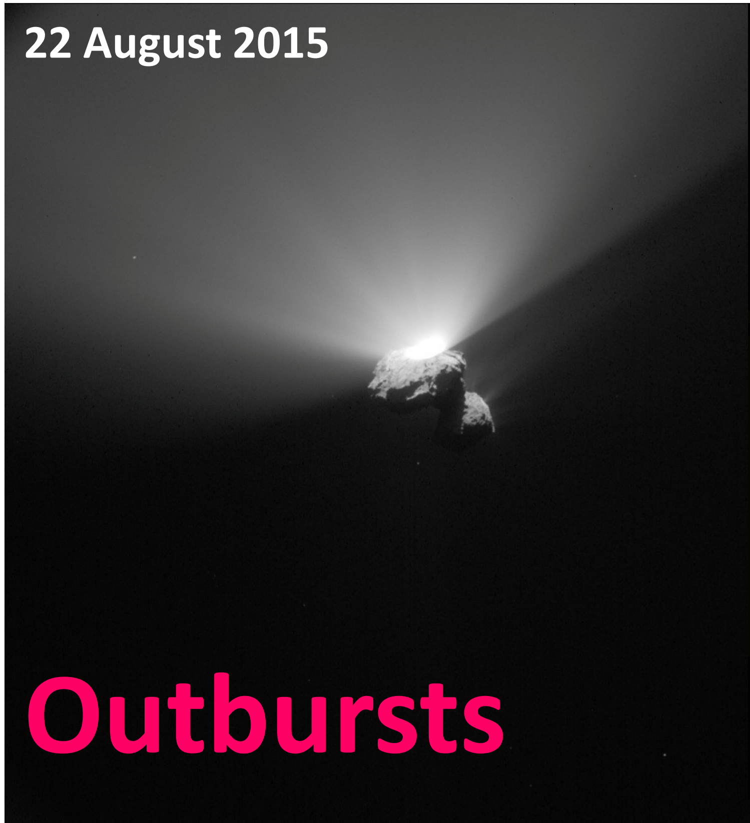
Biver et al, 2016

Seasonal variations of abundances relative to water

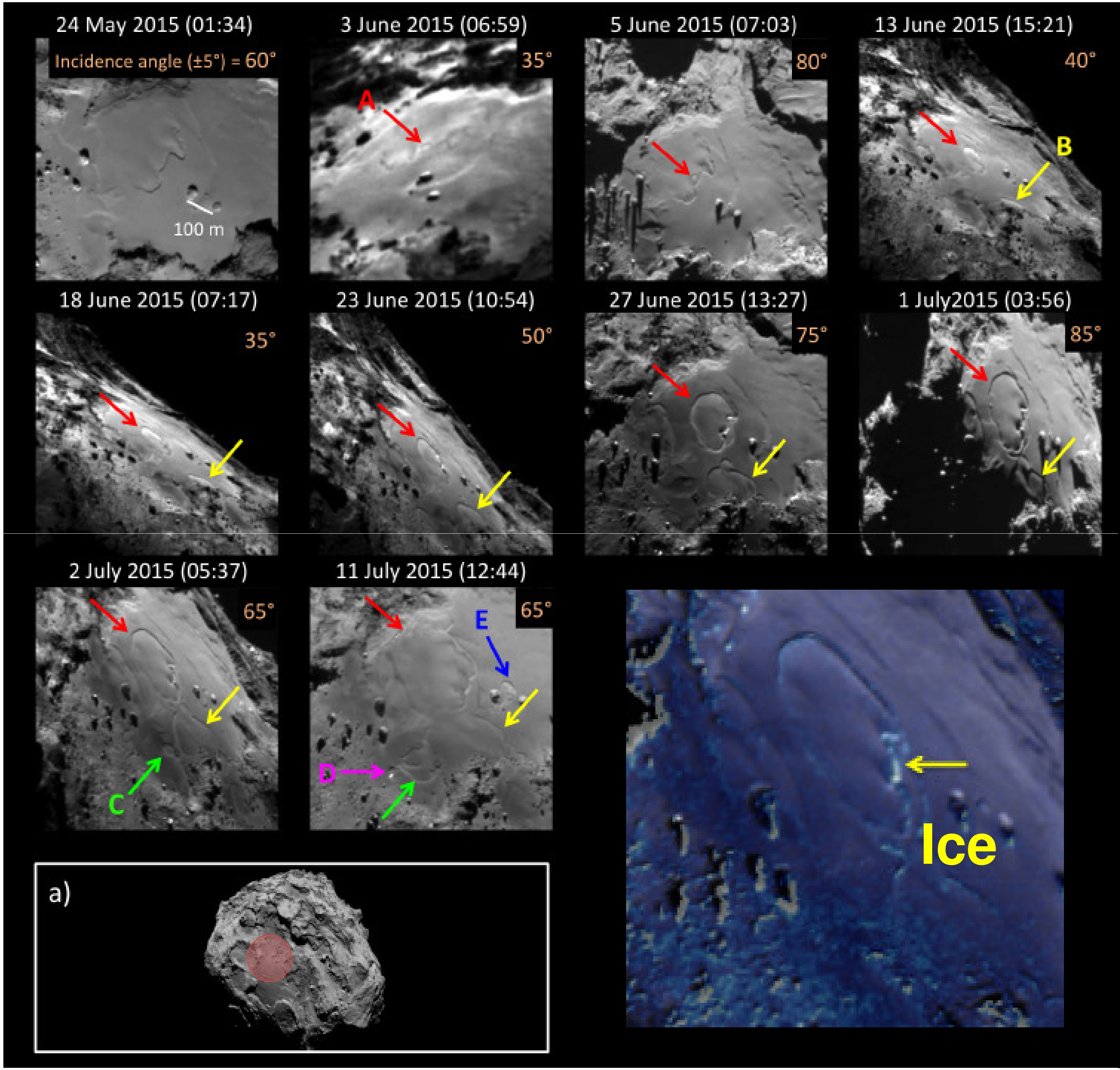
		Summer time		
		Northern hemisphere	Southern hemisphere	Southern hemisphere
Molecule	**Tsublimation (K)**	**2-3 AU pre-peri**	**1.24-1.3 AU pre-peri**	**1.24-1.4 AU Post-peri**
CO_2	72	1-3 %	14 %	32 %
CO	24	< 1%, 2.7 %	0.5 %	1 %
CH_4	31	0.1%	0.2 %	0.5 %
OCS	57	0.02%	0.1 %	0.2 %
CH_3OH	99	1%	1%	2.5 %
NH_3	78	0.2-0.4%	0.5 %	0.3%

Outbursts

22 August 2015



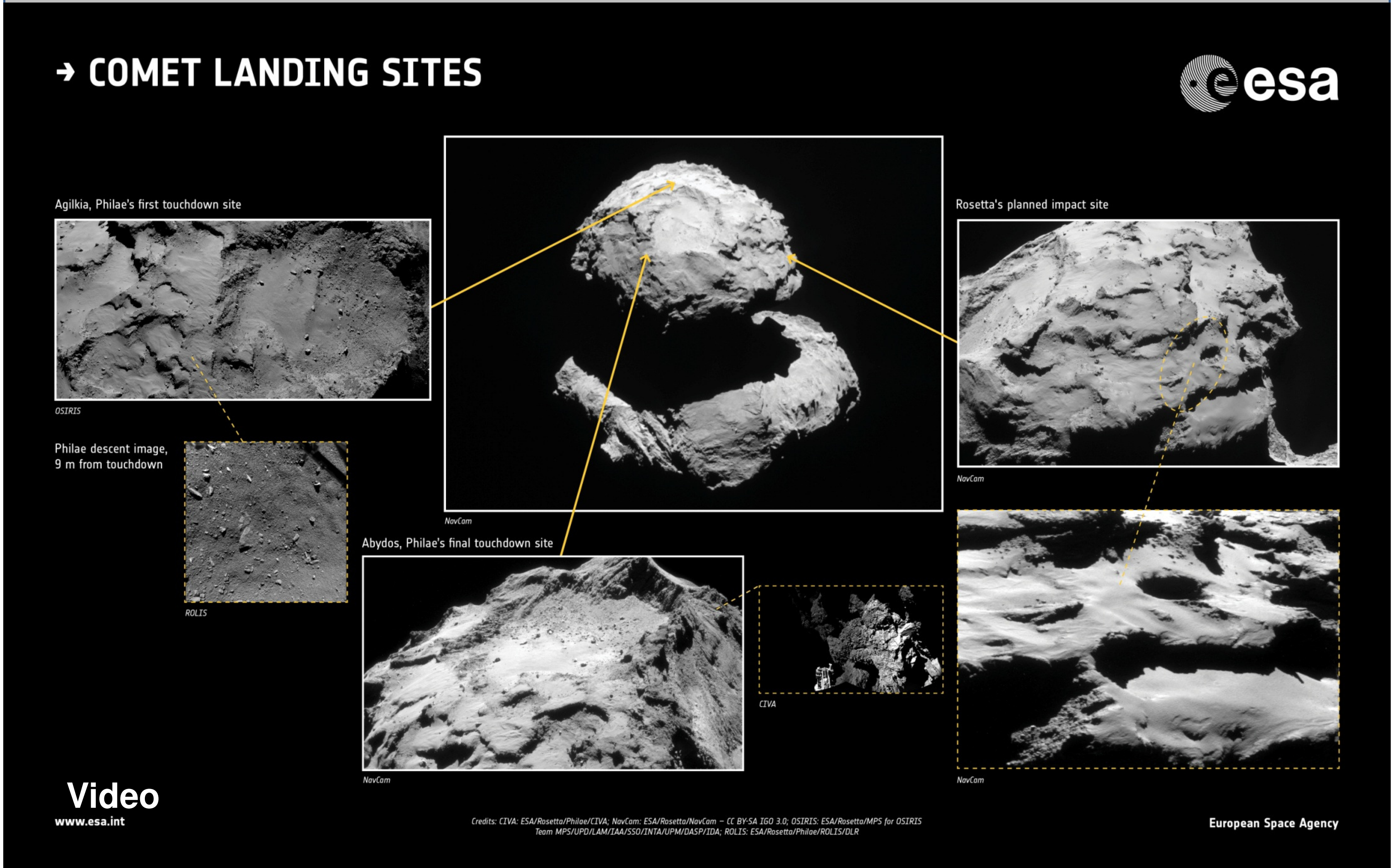
11 August 2015



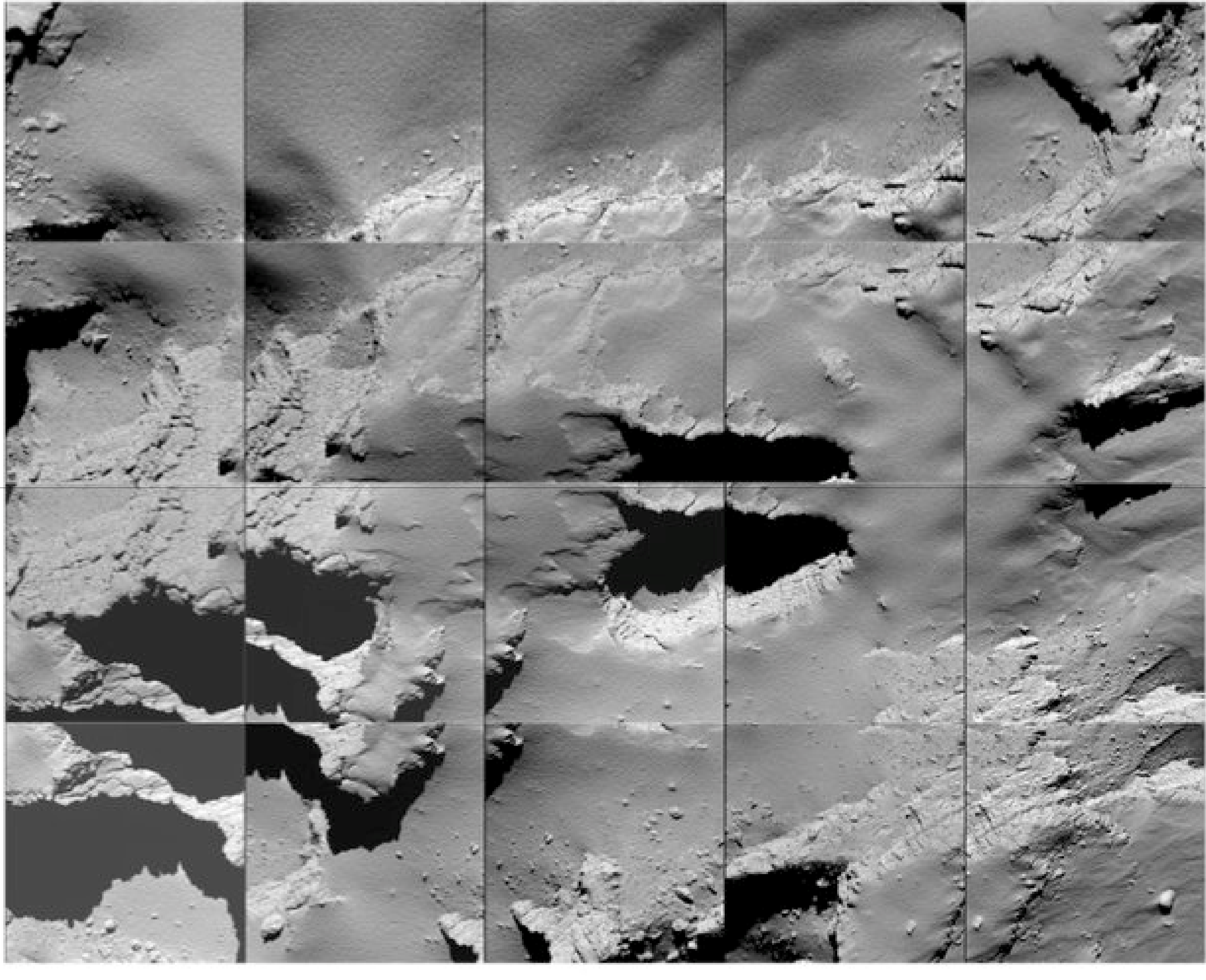
Circular structure

- Depth: 5 m
- Extension : -> 200 m
- Velocity: 5 m/day

The end of the Rosetta mission and the last images taken by Rosetta

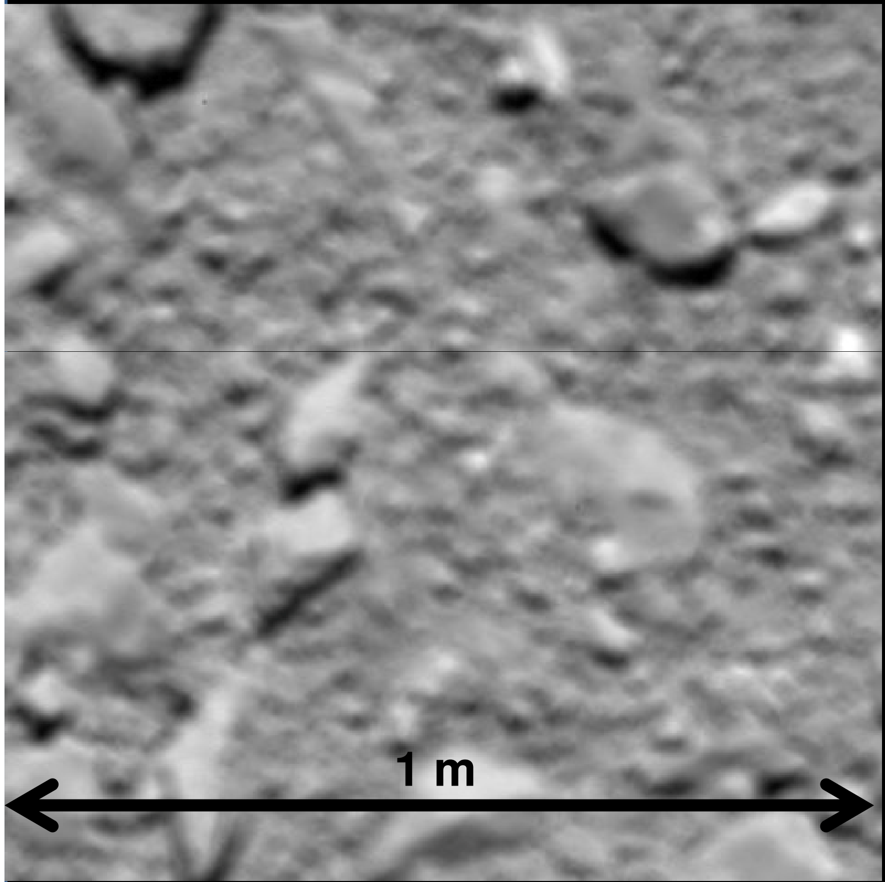


Video



Rosetta last

Last image: 20 m from the surface
2 mm/pixel



Last contact: 13:19 CEST, 30 September 2016

End