Determination of Sizes and Other Physical Properties of Near-Earth Objects by means of Thermophysical Modelling

A Review

By Marco Delbo

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&

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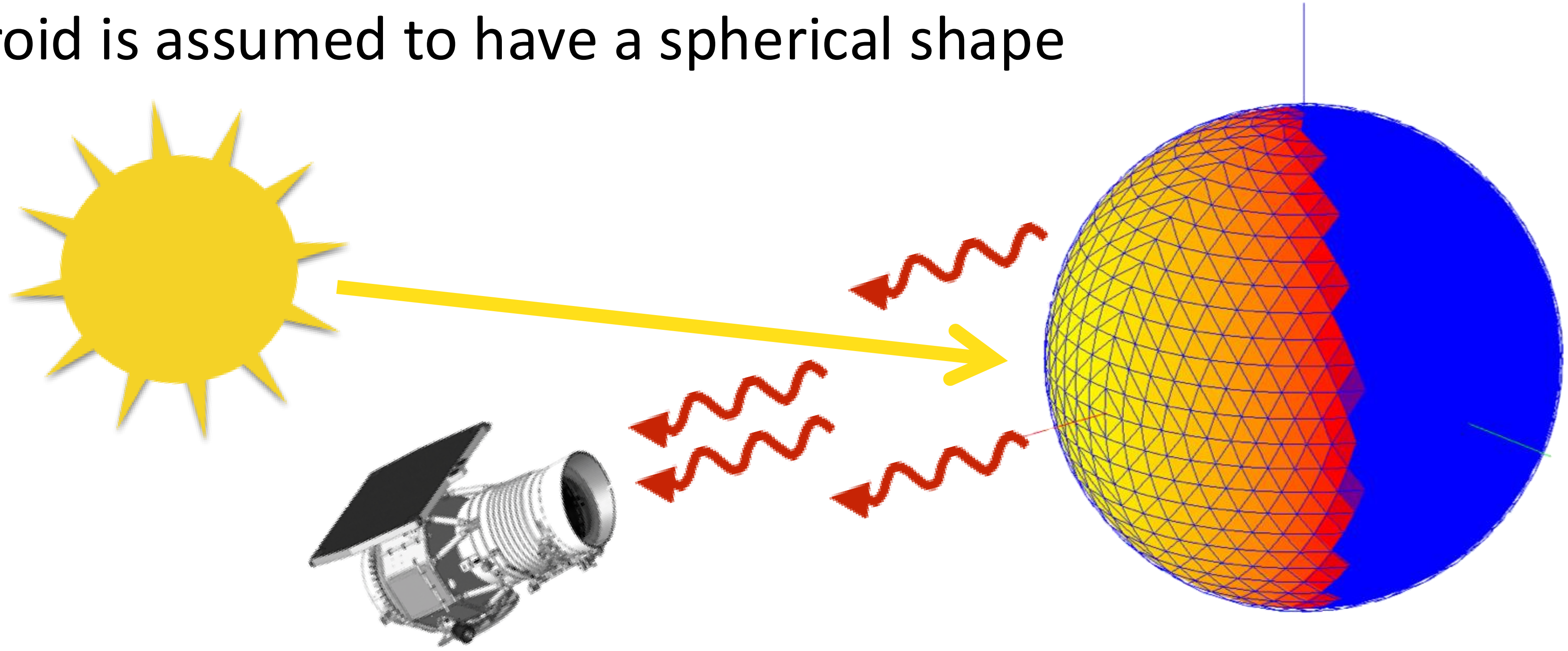
Simple thermal models

- Asteroid is assumed to have a spherical shape



- Temperature distribution is a function of sub-solar latitude θ

$$\frac{(1-A)S_{\odot}}{r^2} = \eta \epsilon \sigma T_{SS}^4$$

$$T(\theta) = T_{SS} \cos^{1/4}(\theta)$$ *For ϑ>0*

A = Bond Albedo

S =Solar constant = 1.37 kW/m2

r = heliocentric distance in au

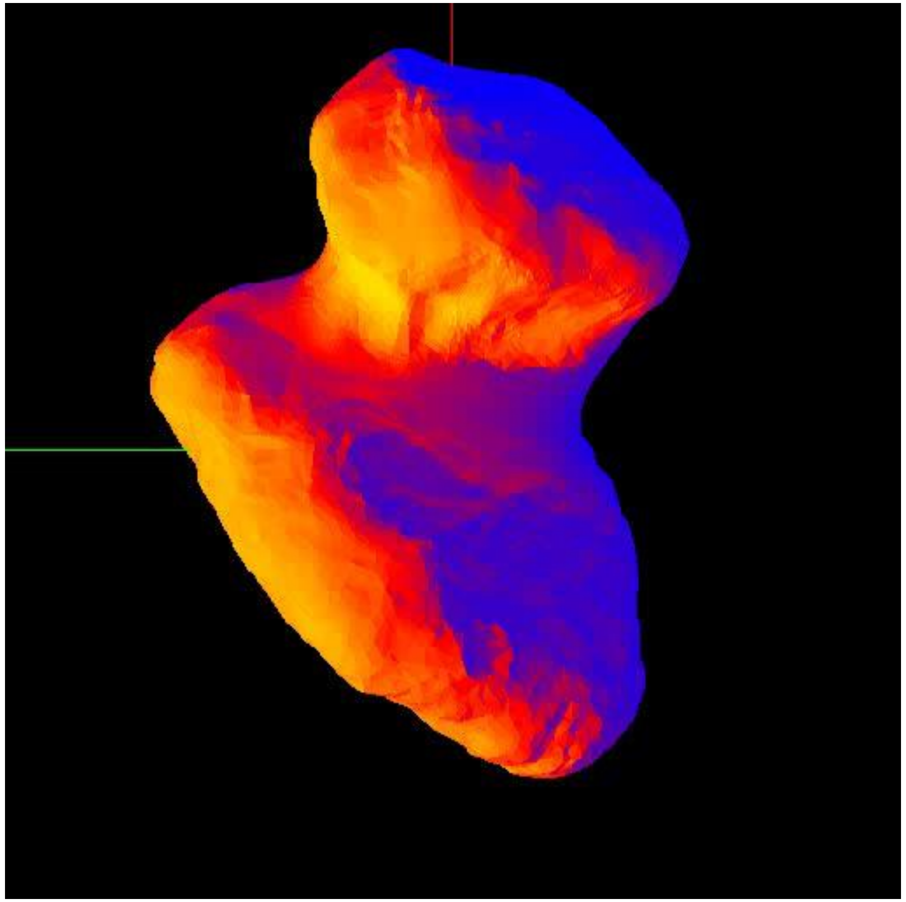
ε = emissivity; η beaming parameter

σ = Stefan Boltzmann Constant

T = temperature (K)

Thermophysical models

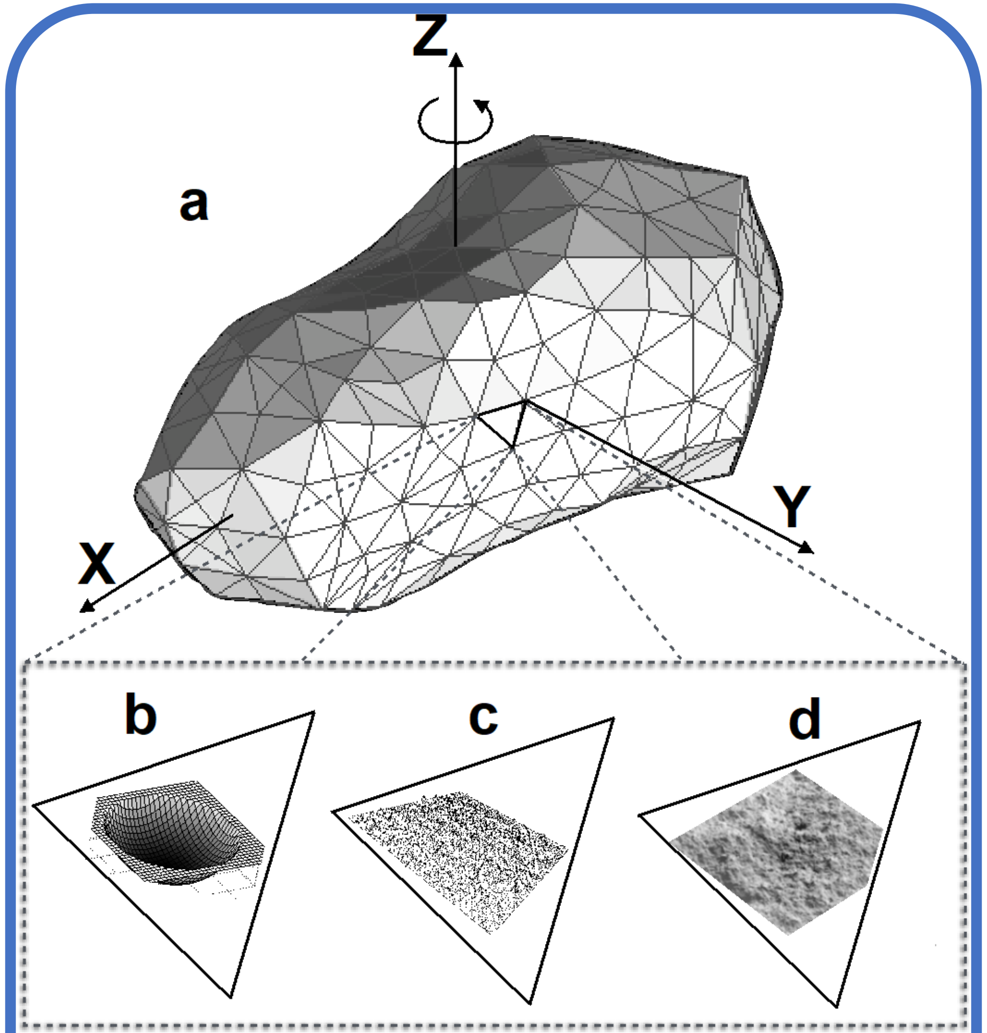
- F(λ) is function of model parameters such as
  - ❖Size (D),
  - ❖Albedo (A),
  - ❖Thermal inertia (Γ)
  - ❖Surface roughness (γ_C,f_C)
  - ❖Spin state
  - ❖Shape
- ❖Temperatures are calculated at the surface and in the subsurface.



Day/Night temperature variations on the nucleus of the the comet 67P/GC.
Ali-lagoa, Delbo, et al. ApJ 2015

Lagerros (1996, 1997, 1998), *Delbo* (2004), *Mueller* (2007), Rozitis (2011), *Rozitis and Green* (2011), *Spencer et al.* (1989) and *Spencer* (1990). *See Delbo et al. 2015 for a review*

Thermophysical model (TPM)



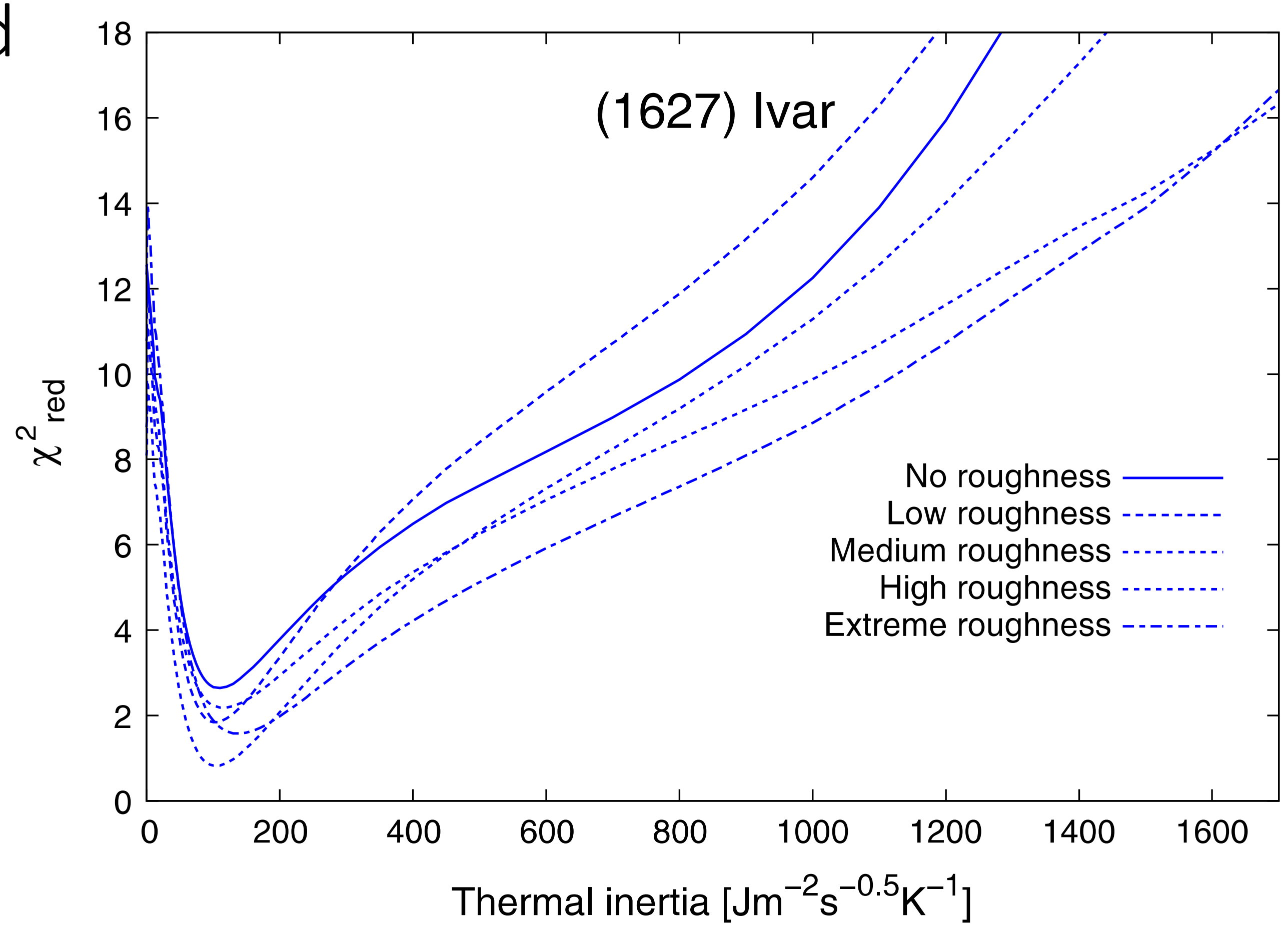
White corresponds to the maximum and dark gray corresponds to minimum temperature.

Delbo et al. 2015 in Asteroids IV for a review

- ❖Body's shape **(a)** is taken into account (Delbo 2004, Mueller 2007, Lagerros 1996,97,98, Rozitis 2011, Capria et al. 2014)
- ❖Heat transfer is calculated.
- ❖Surface roughness is modelled by **(b)** hemispherical section craters (Davidsson et al., 2015), **(c)** Gaussian surface (Rozitis and Green, 2011), and **(d)** fractal surface (Davidsson et al., 2015).

TPM parameters adjusted until $f(\lambda)_{TPM}$ fits $f(\lambda)_{observed}$

- Example of TPM fit to thermal infrared observations of the NEA Ivar (from Hanus, Delbo et al. 2015).

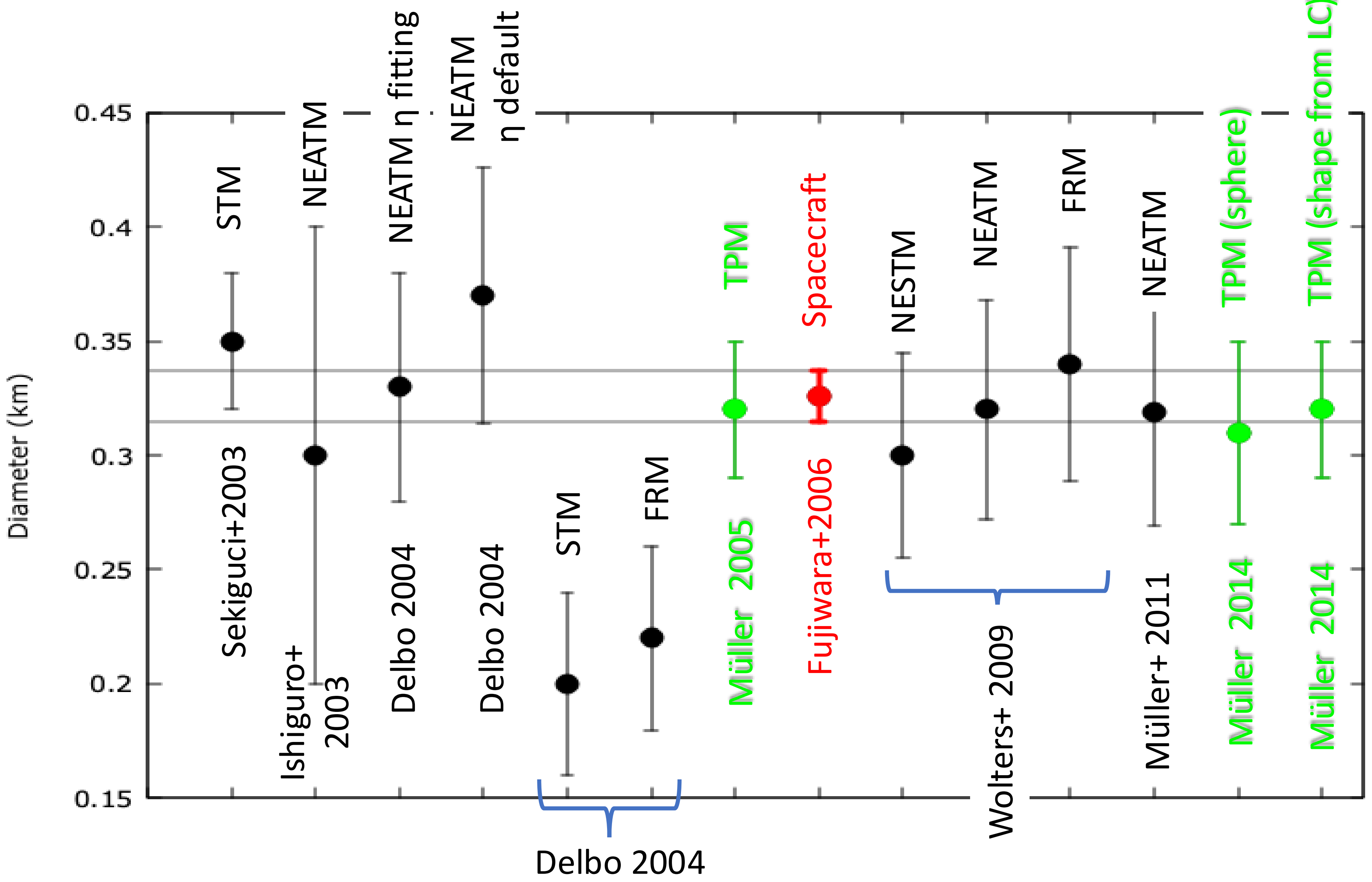


Dependence of the χ^2 values of the TPM fits on the thermal inertia Γ and five different surface roughness values θ for the shape model of Asteroid (1627) Ivar.

Itokawa thermal models and Hayabusa

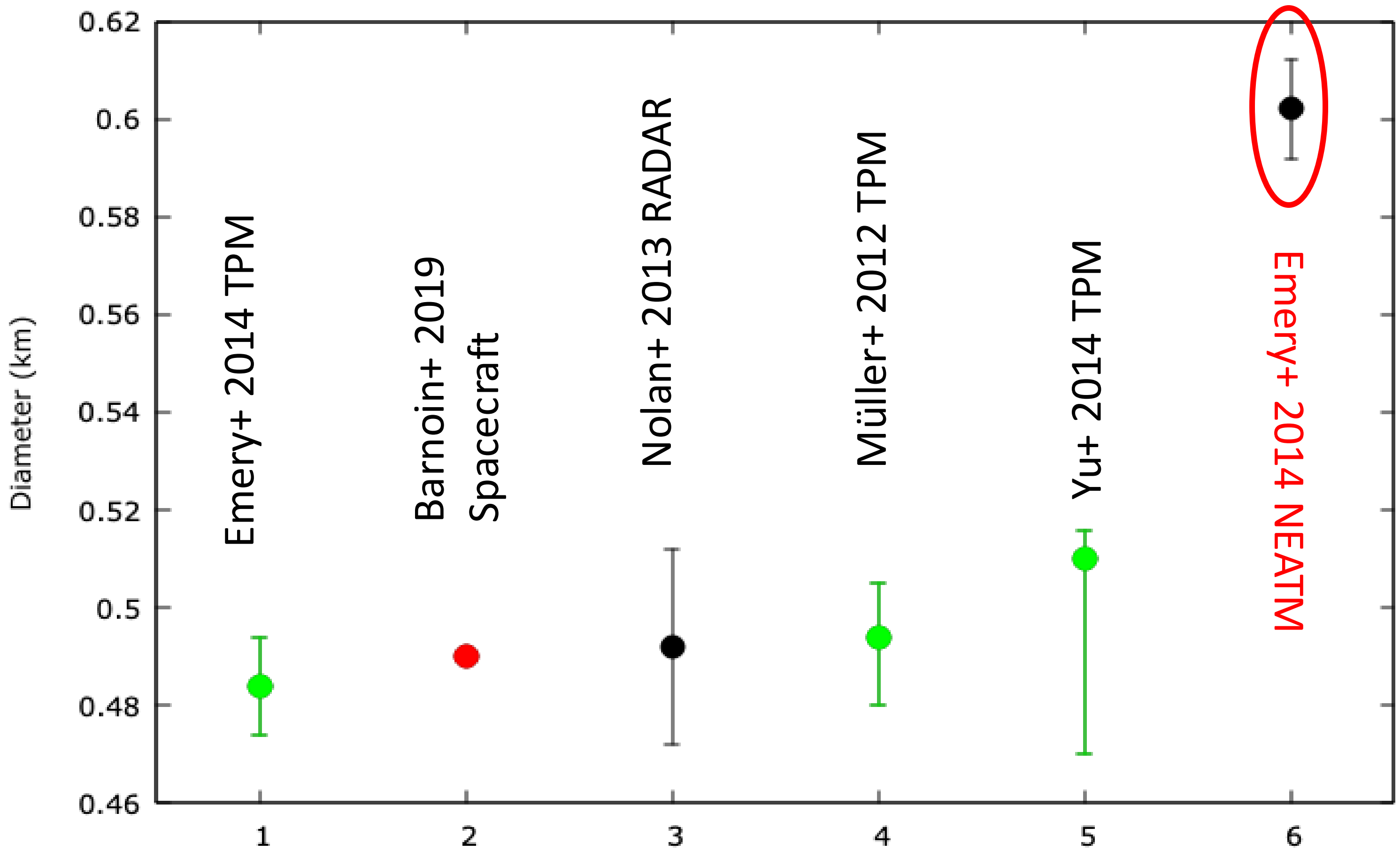
The Delbo 2004 data were taken at phase angle >100° ! They may have been affected by low quality (see Müller+ 2014).

Excellent agreement TPM vs Spacecraft size determination.



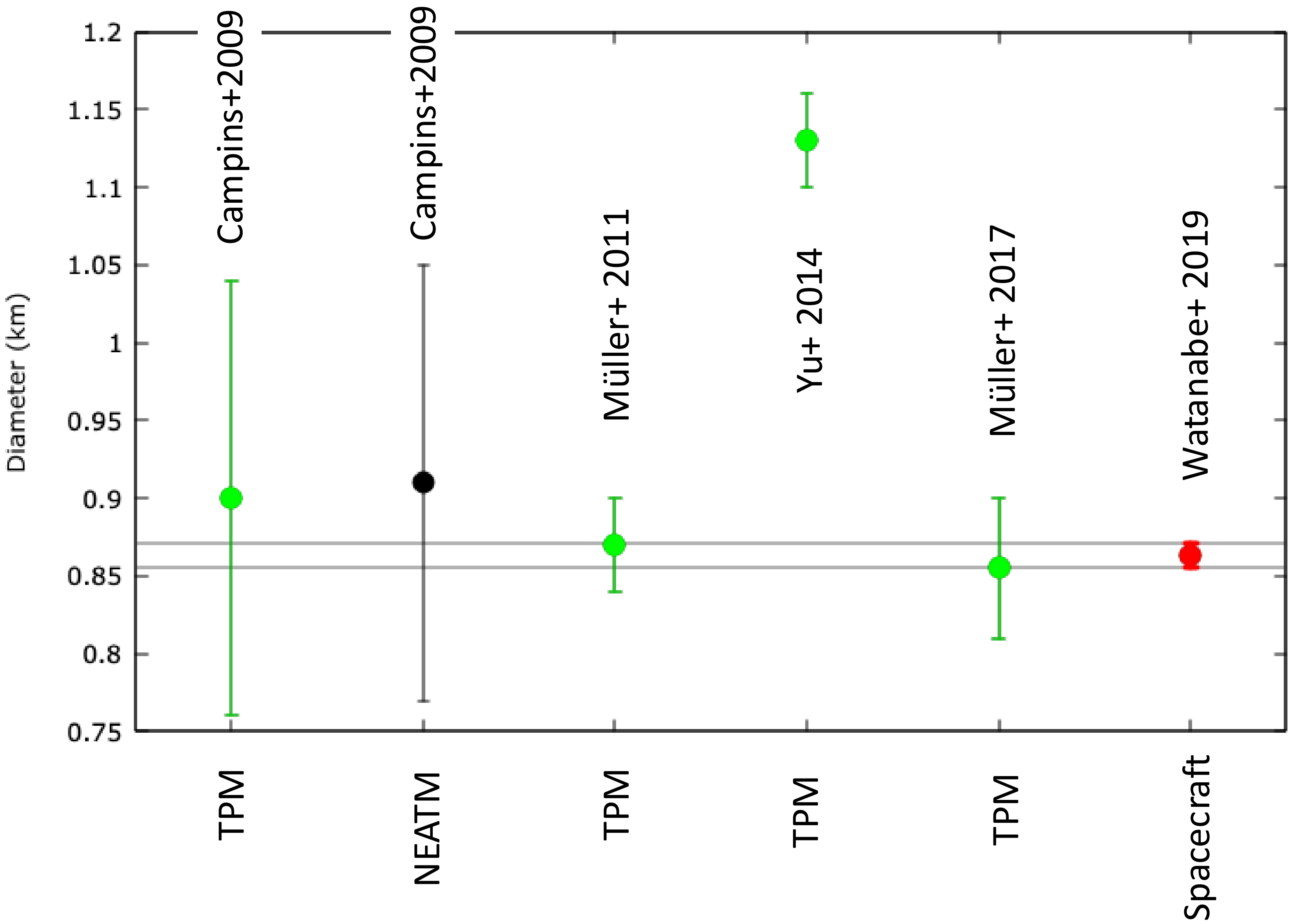
Bennu thermal models, radar, and OSIRIS-REx

- Excellent agreement TPM vs Spacecraft size determination.
- The size determination by means of the NEATM (Emery+ 2014) might have been affected by the large phase angle of the observations (see Emery+ 2014).



Ryugu thermal models and Hayabusa2

- A part from the Yu et al. (2014), the TPM diameters are in good agreement with the one from the spacecraft.



Publ. Astron. Soc. Japan (2014) 66 (3), 52 (1–17)
doi: 10.1093/pasj/psu034
Advance Access Publication Date: 2014 June 19

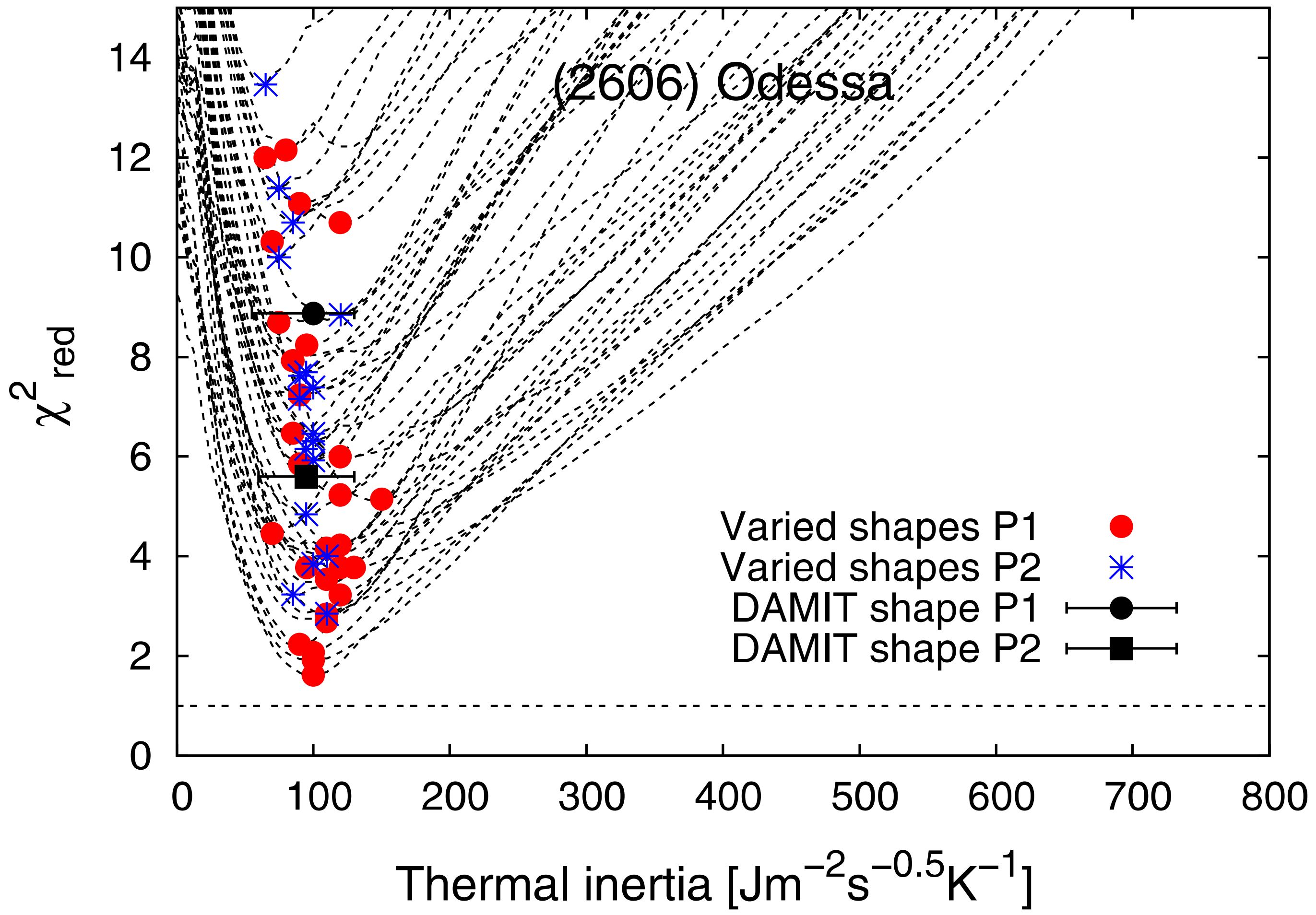
(25143) Itokawa: The power of radiometric techniques for the interpretation of remote thermal observations in the light of the Hayabusa rendezvous results*

Thomas G. MÜLLER,[1,*] Sunao HASEGAWA,[2,*] and FUMIHIKO USUI[3,*]

The varied shape TPM (VS-TPM)

Even though the size is correct, the fit of the thermal data can be not good due to shape effects (Hanus et al. (2015, Icarus)

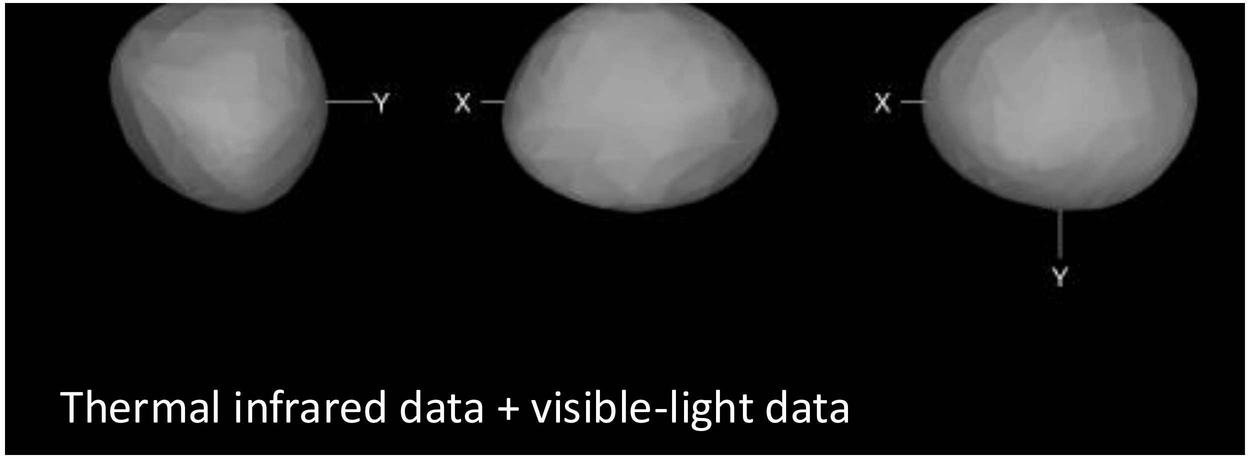
- The idea of J. Hanus was to produce different shape models still compatible with the optical LCs and study how tier TPM fits the data.
- However, the typical variation in the resulting diameter between solutions <10% relative values (J. Hanus, private comm.)



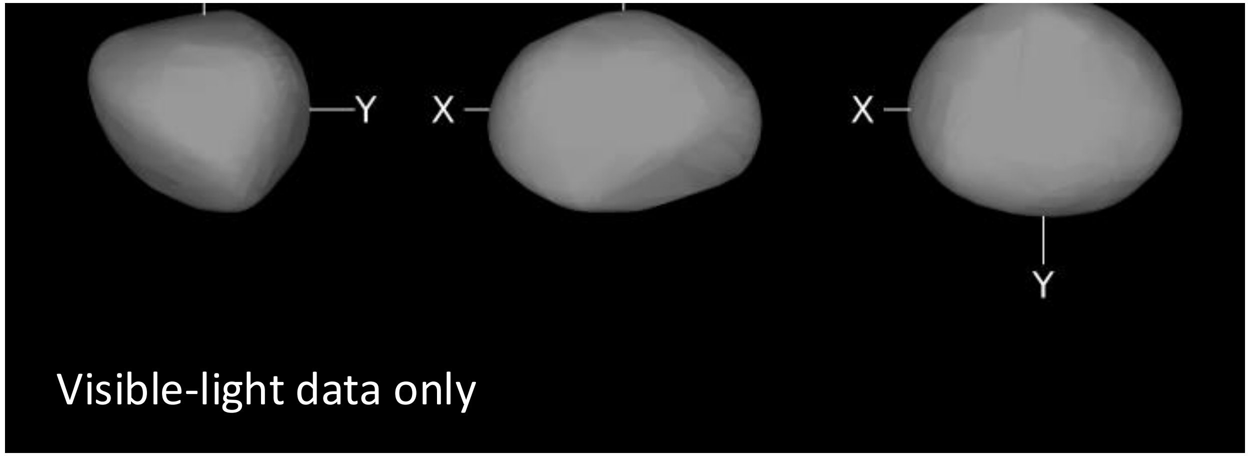
The convex inversion TPM (CI-TPM

by Durech et al. (2017)

Shape, spin state, size, and thermal properties of the asteroid are determined simulatenesouly from thermal infrared & visible data



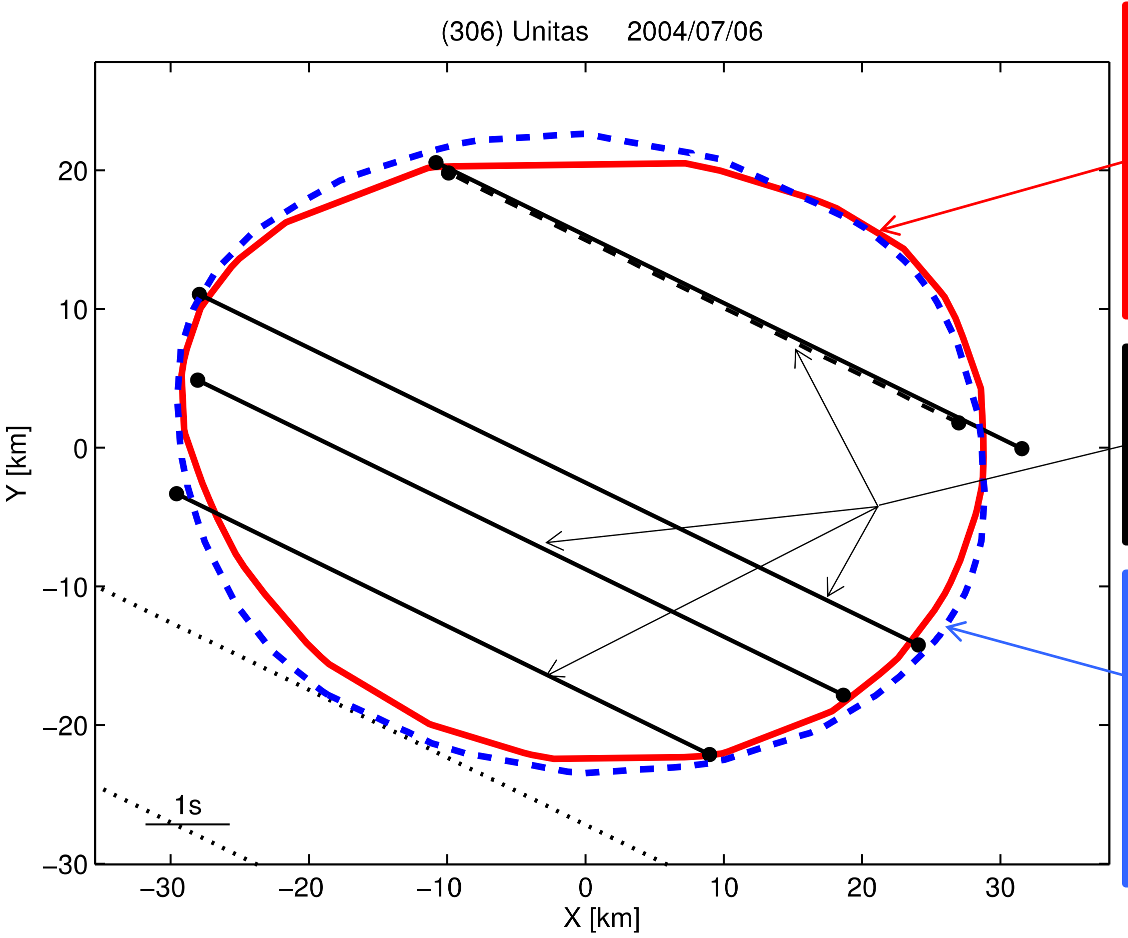
Thermal infrared data + visible-light data



Visible-light data only

Convex-Inversion Thermophysical Model (CI-TPM)

Very good agreement between the CI-TPM model and the shape parameters dereived from indepentent techniques (occultations)



Red: countour of the shape model derived by the CITPM projected on the plane of the sky at the epoch of the occultation measurments

Black: occultation chords reconstructed from timings and positions of individual observers

Blue: contour of the shape model derived INDEPENTENTLY of CITPM from lightcureves and occultations (from Durech et al. 2007)

Durech et al. 2017

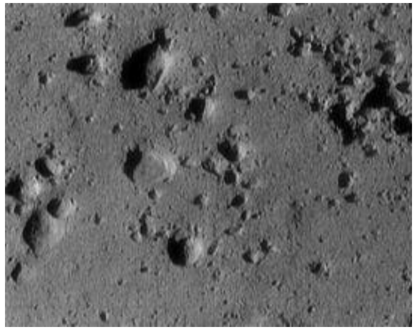
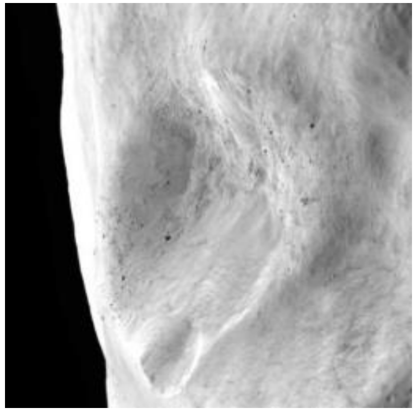
Thermal Inertia (Γ)

$$\Gamma = \sqrt{\kappa \rho C}$$

Measure the resitence of a material to temperature change

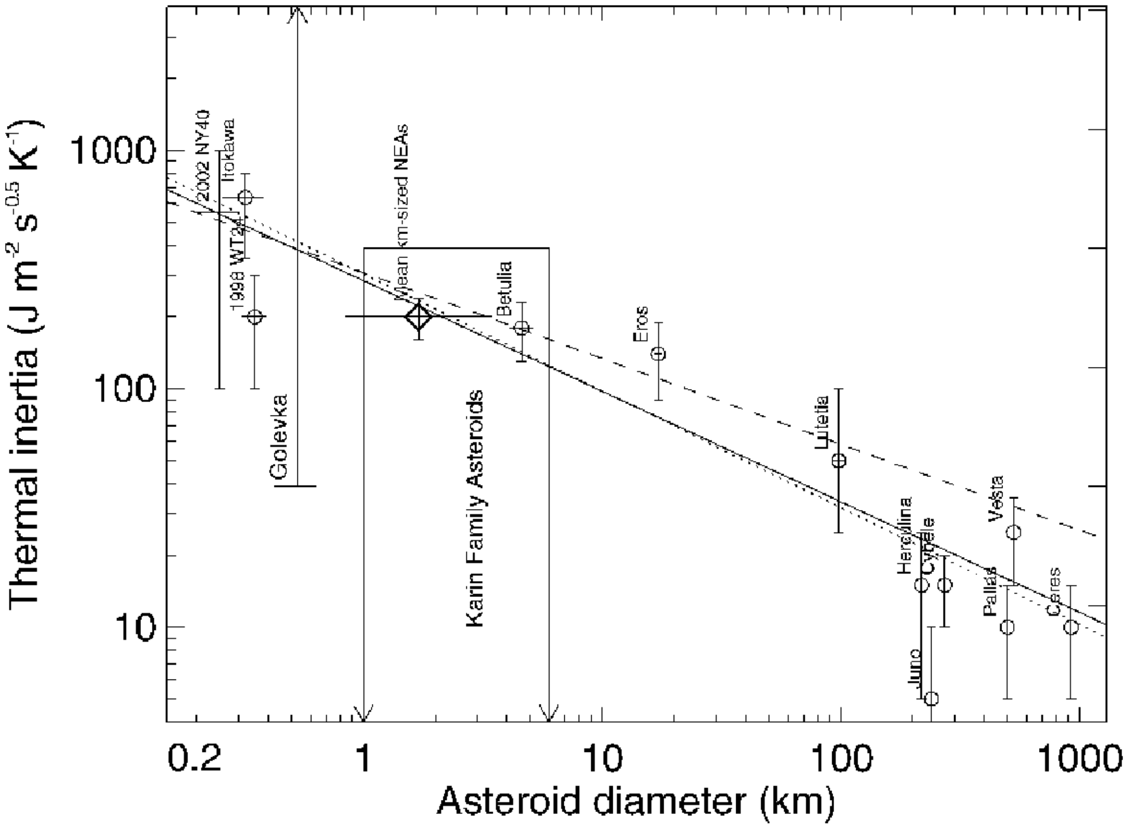
- It gives information about the presence (or absence), depth and thickness of regolith, and the presence of exposed rocks on the surface.
- The higher the value of Γ the coarser is the regolith.
- Its value is temperature dependent !

Hot | Cold

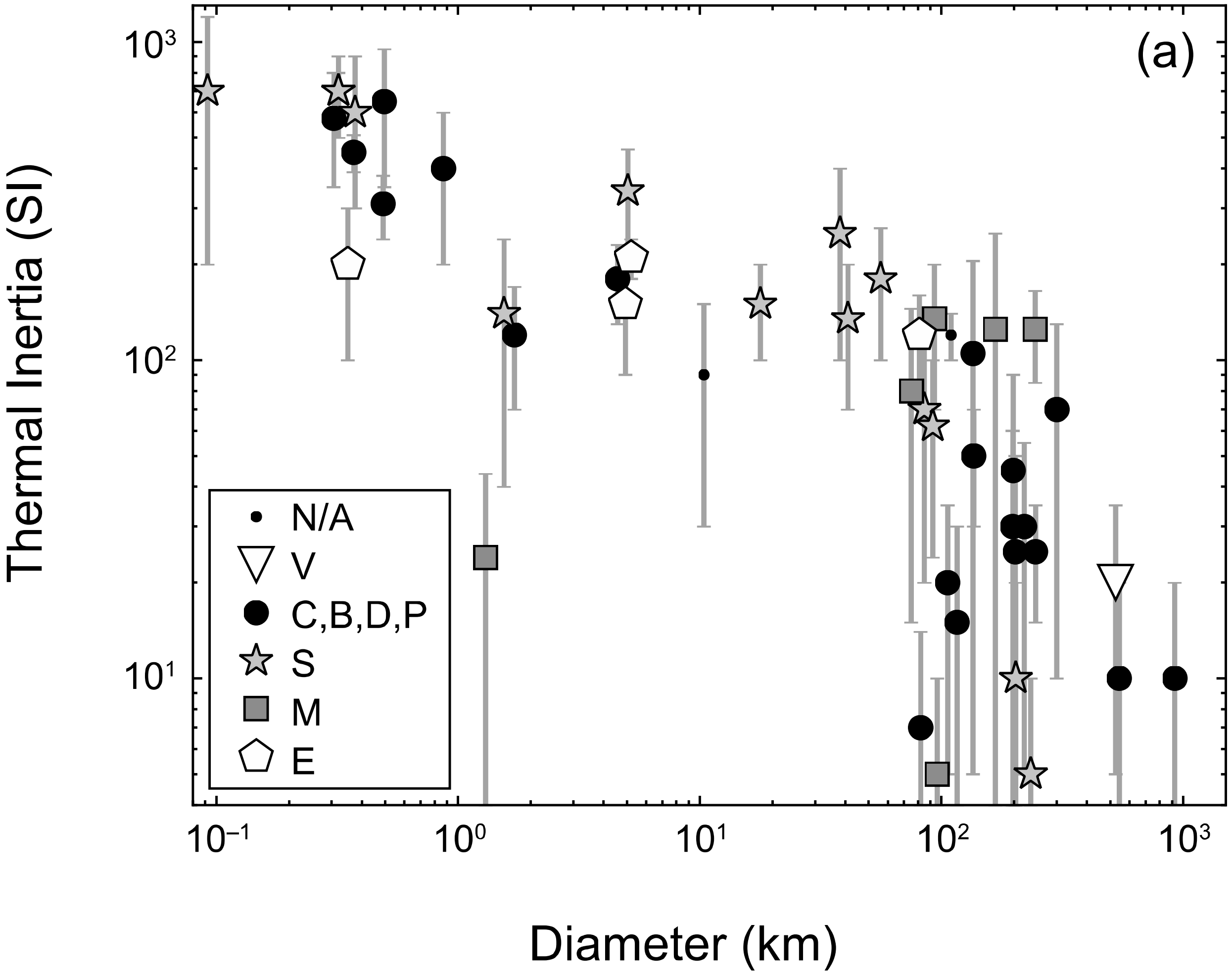
25143 Itokawa	433 Eros	The moon	21 Lutetia
$\Gamma = 750$	$\Gamma = 150$	$\Gamma = 40 - 50$	$\Gamma = 20$
			
Coarse regolith and boulders	Finer and thicker regolith	Mature and fine regolith	Very fine regolith

See, e.g., Delbo et al. (2015) in asteroids IV for a review

Thermal inertia and size correlation



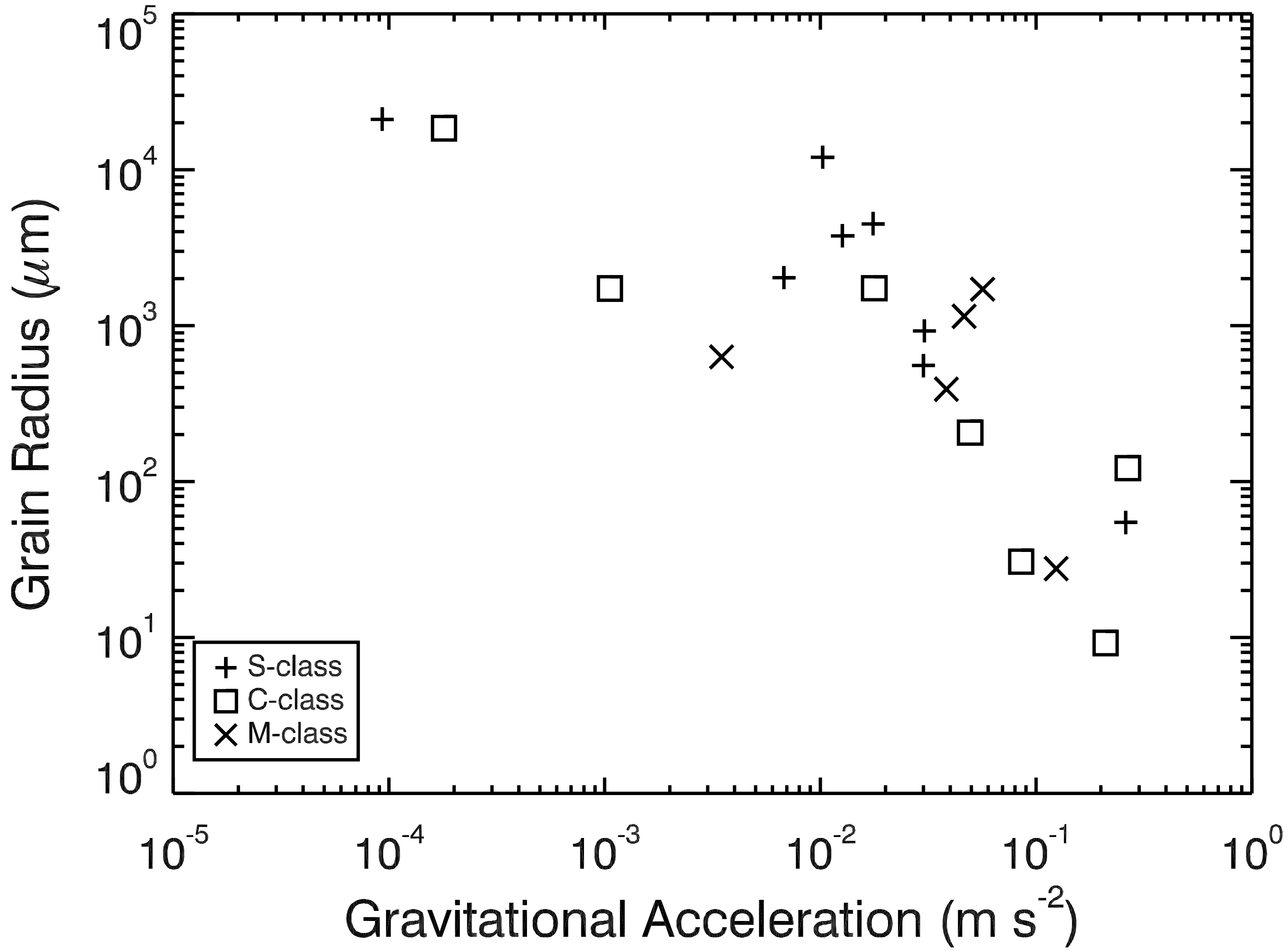
Delbo et al. 2007



Delbo et al. 2015 (review in Asteroids IV)

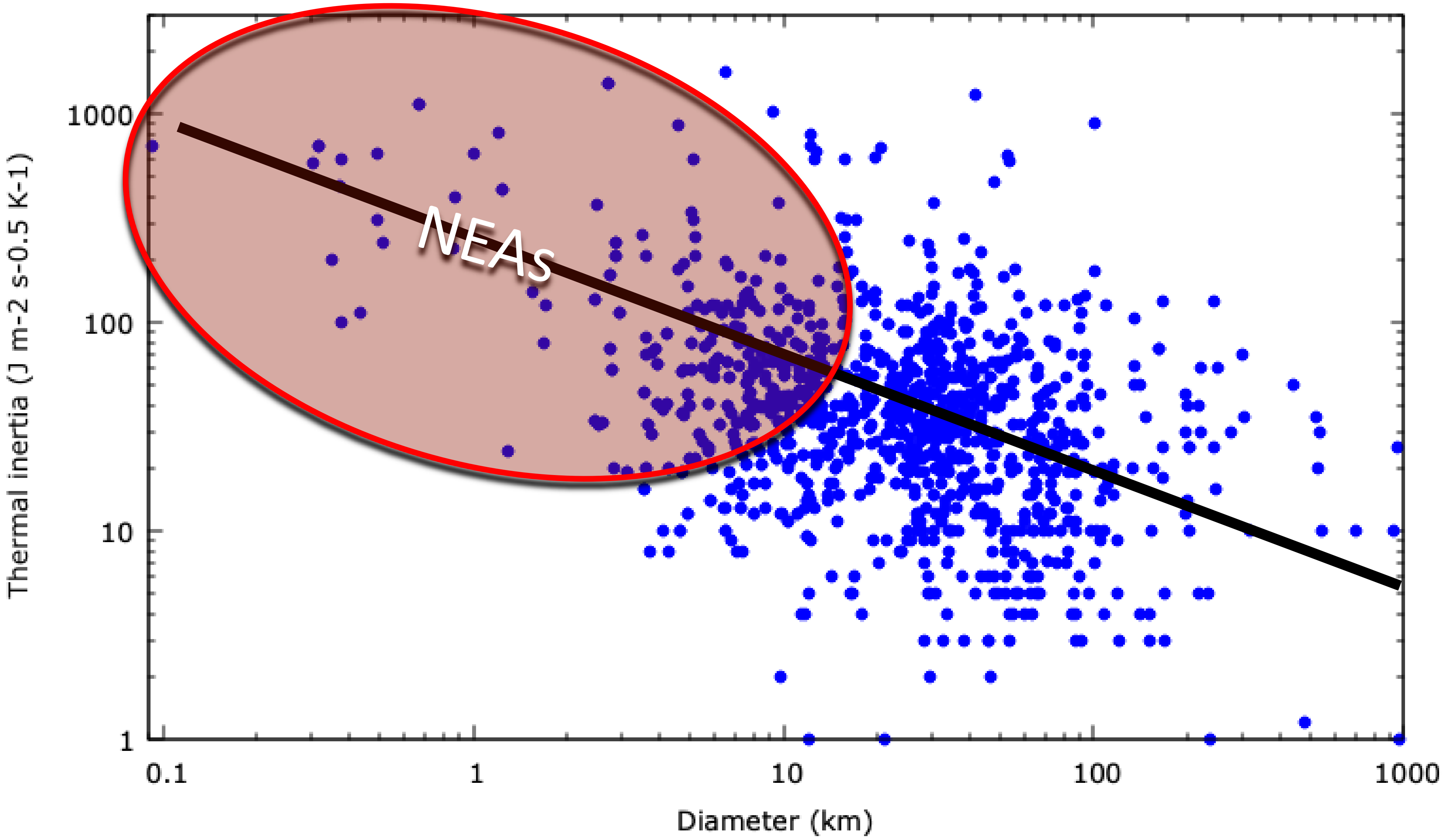
Regolith grain size vs. thermal conductivity

Gundlach & Blum (2013) developed a model to estimate the regolith grain size given the thermal conductivity; The value of the latter derived from remote sensing thermal infrared observations →



By applying this model to asteroids with different size (i.e. different mass, i.e. different gravitation acceleration) they showed that larger asteroids retain smaller grains than smaller asteroids.

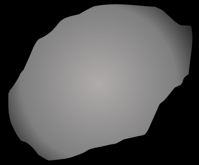
Thermal inertia and size correlation



After MacLennan & Emery 2021 and Hung et al. 2022

The nature of asteroids' surfaces

>100 km sized asteroids
covered by regolith



km sized asteroids: rocky
(e.g., Lebofsky+ 1979)

'70-80s

time

The nature of asteroids' surfaces

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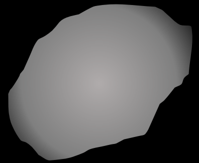

km sized asteroids: rocky
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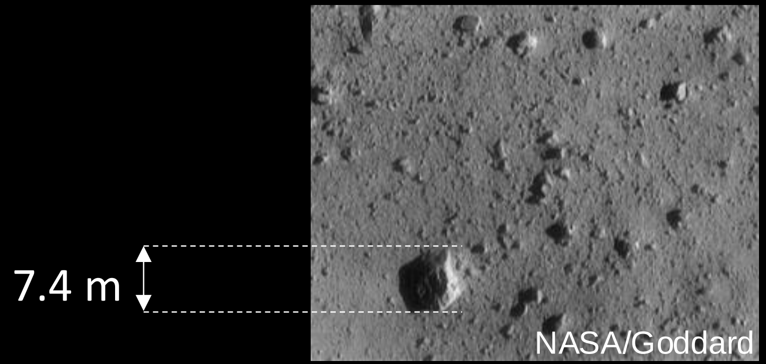
'70-80s

2000s

time

NASA NEAR @ Eros



The nature of asteroids' surfaces

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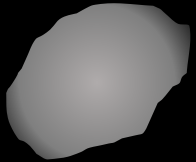
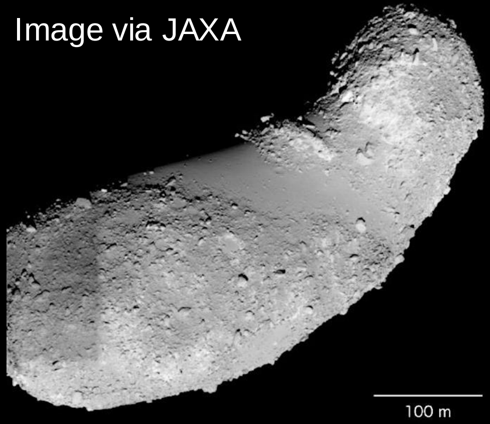


km sized asteroids: rocky
(e.g., Lebofsky+ 1979)

Image via JAXA



JAXA Hayabusa @ Itokawa

'70-80s

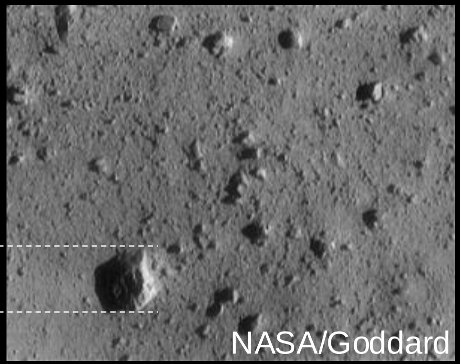
2000s

2005

time

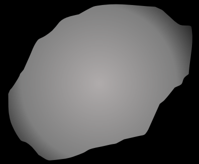
NASA NEAR @ Eros

7.4 m



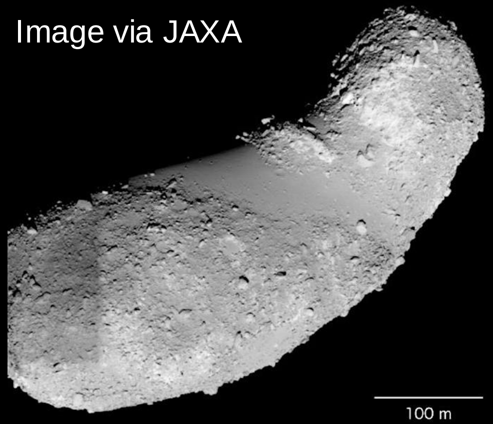
The nature of asteroids' surfaces

>100 km sized asteroids covered by regolith



km sized asteroids: rocky (e.g., Lebofsky+ 1979)

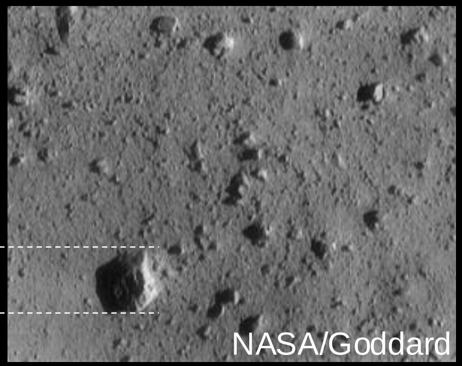
Image via JAXA



JAXA Hayabusa @ Itokawa

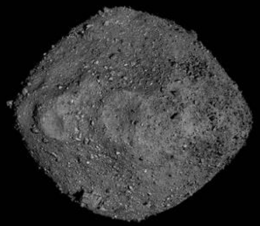
'70-80s — 2000s — 2005 — 2019 — time

NASA NEAR @ Eros

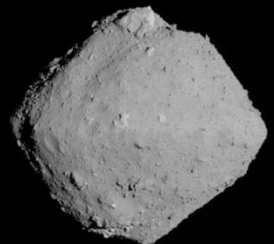


7.4 m

NASA OSIRIS-REx @ Bennu
JAXA Hayabusa 2 @ Ryugu



NASA/Goddard/UA



Credits: JAXA

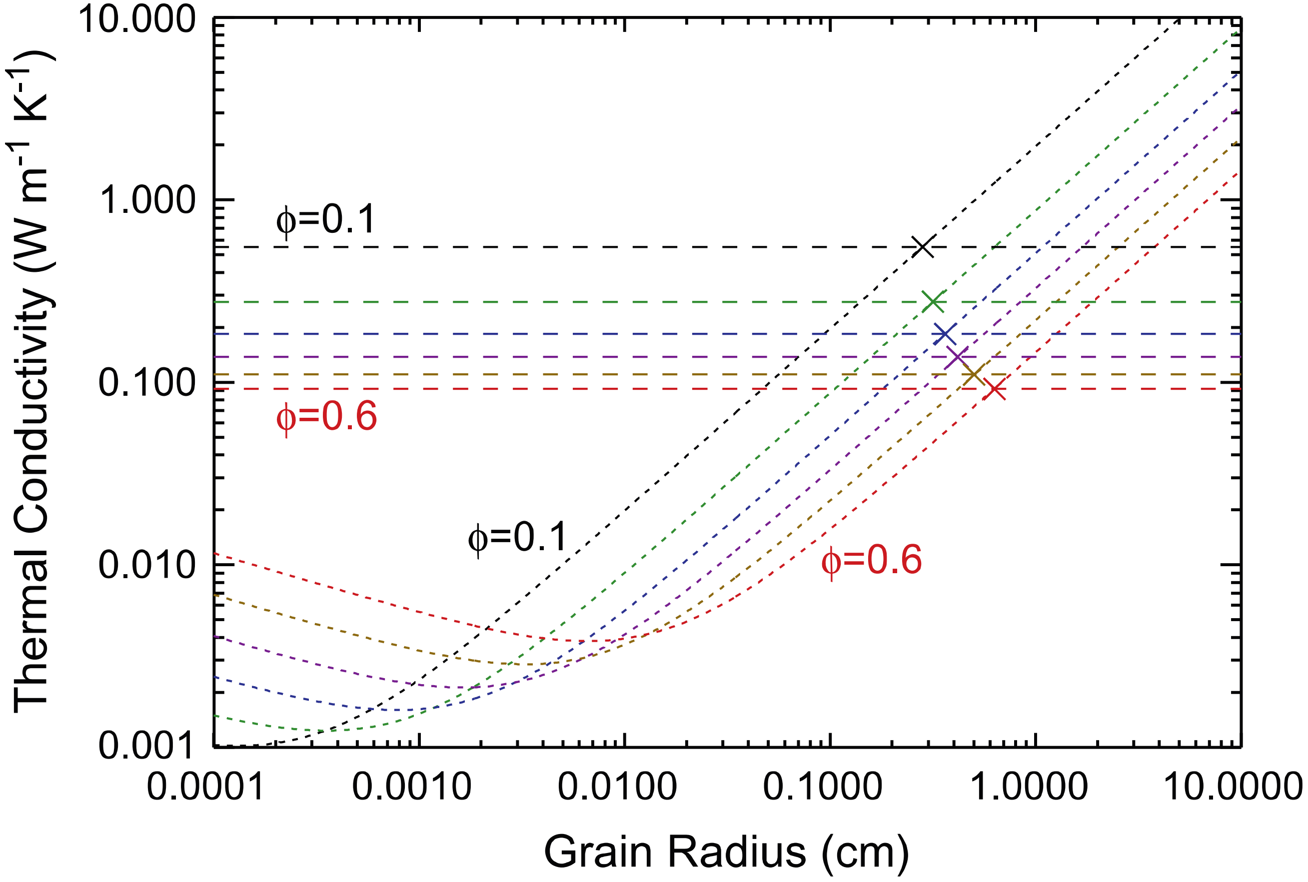
Regolith grain size & sample-return space missions: the case of NASA's OSIRIS-REx

Information about the regolith grain size is crucial for sampling site selection.

Some *dangerous* predictions …

Emery et al. (2014) in Icarus derived a thermal inertia of 310+/-70 J m^{-2} $s^{-0.5}$ K^{-1} applied this model to the thermal inertia of (101955) Bennu
"Qualitative and quantitative arguments indicate that the most likely average grain size is between a 1 and 10 mm, consistent with inferences from radar polarization (Nolan et al., 2013)" &
"We predict that the OSIRIS-REx spacecraft will find a surface with abundant sub-cm sized grains"

Similarly, T.G. Müller et al. (2017) predicted regolith to be present on the asteroid (162173) Ryugu, target of JAXA's Habysabusa2: *"Based on estimated thermal conductivities of the top-layer surface in the range 0.1 to 0.6 W K^{-1} m^{-1}, we calculated that the grain sizes are approximately equal to between 1 and 10 mm. "*



Emery et al. (2014)

The nature of asteroids' surfaces

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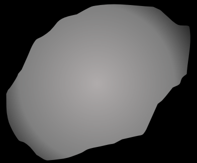

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(e.g., Lebofsky+ 1979)

Image via JAXA

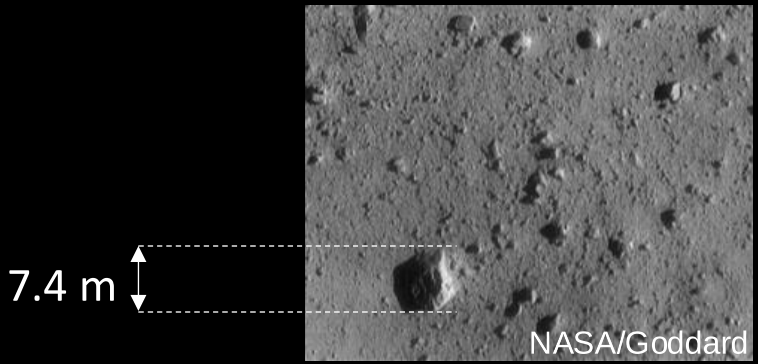
JAXA Hayabusa @

'70-80s

2000s

200

NASA NEAR @ Eros



NASA OSIRIS-REx @ Bennu
JAXA Hayabusa 2 @ Ryugu

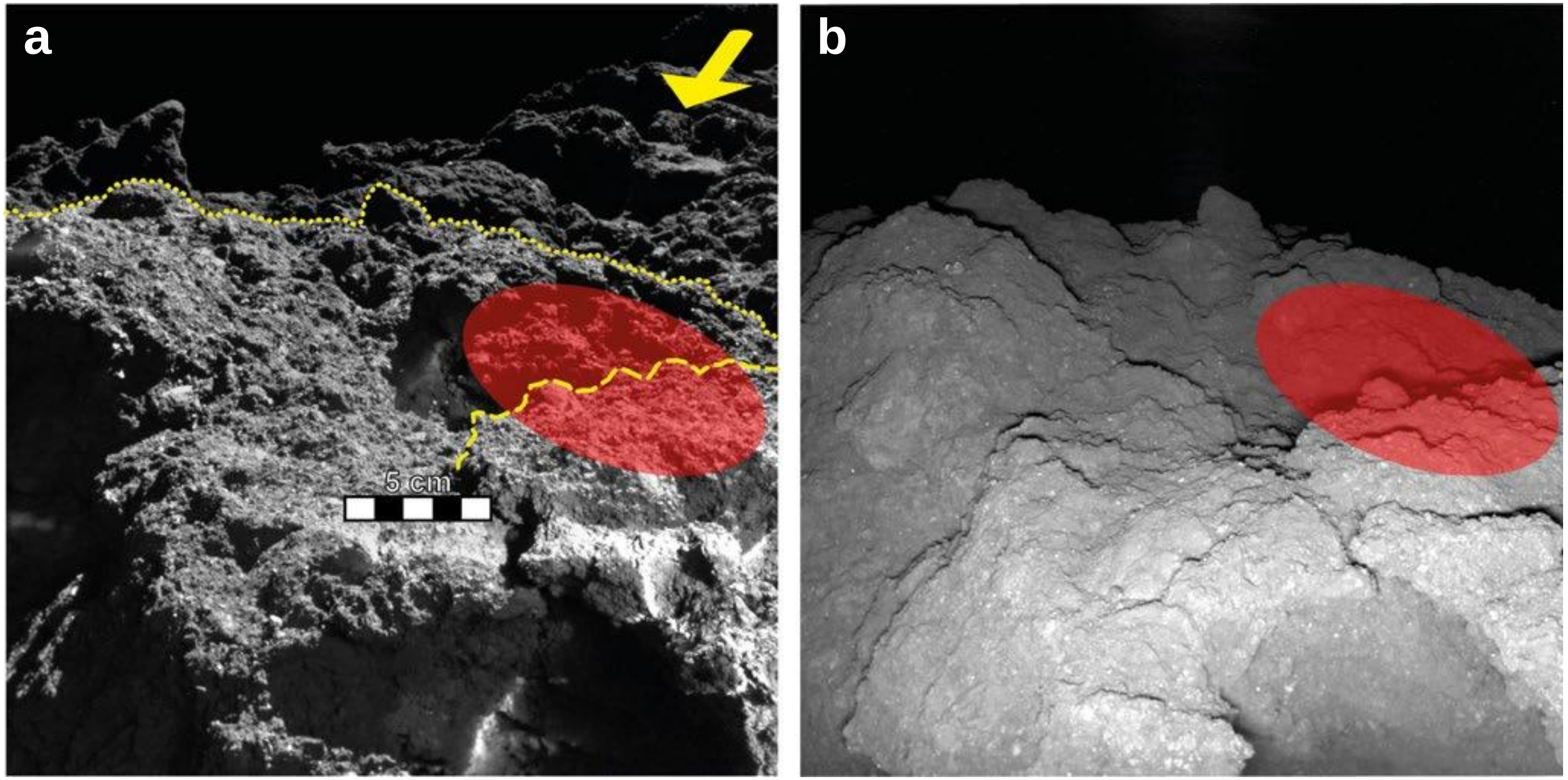
NASA/Goddard/UA

Credits: JAXA

Low thermal inertia rocks !

Interpretation : high porosity

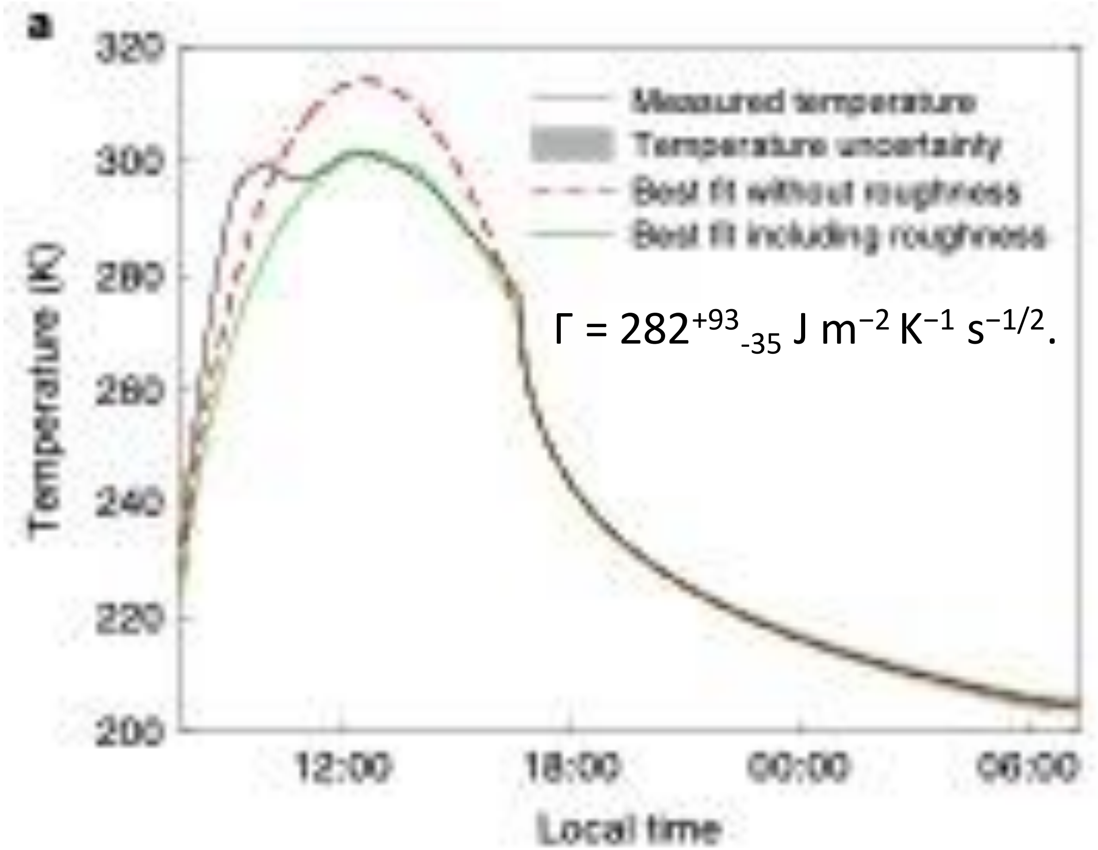
MasCam image of the boulder observed by MASCOT indicating the MARA field of view (red shaded area). a, The location in daylight (local time 09:20)
b, The same location at night (local time 23:18) illuminated by the camera’s red light-emitting diode.



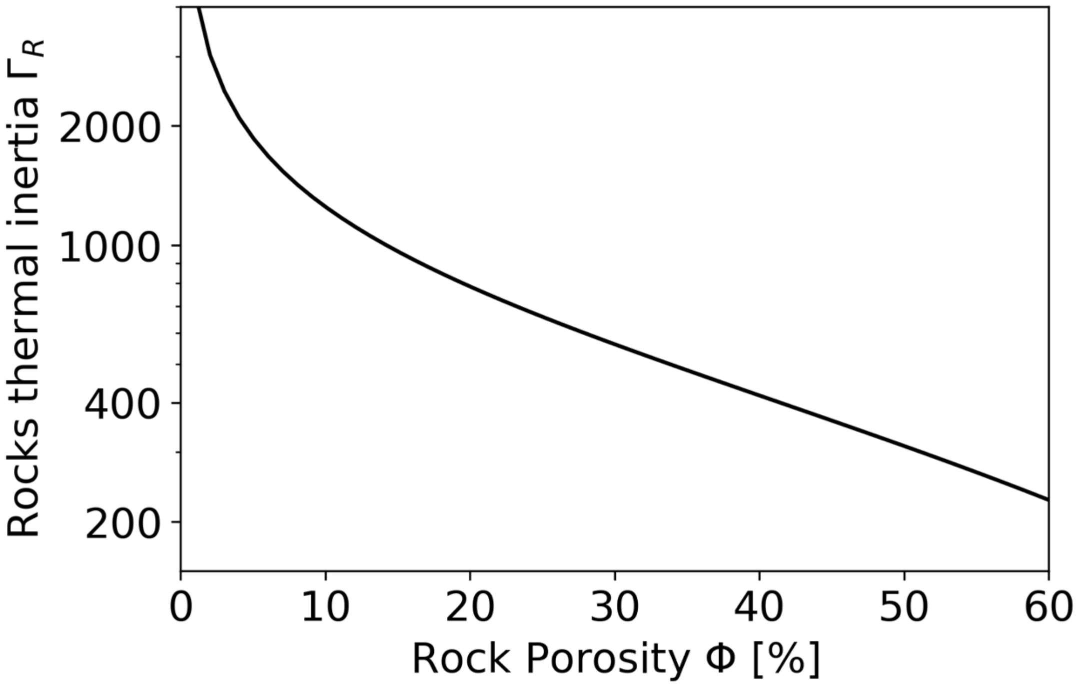
Grott, Knollemberg, Hamm et al. 2019 Nat. Astronomy

Low thermal inertia rocks !

Interpretation : high porosity



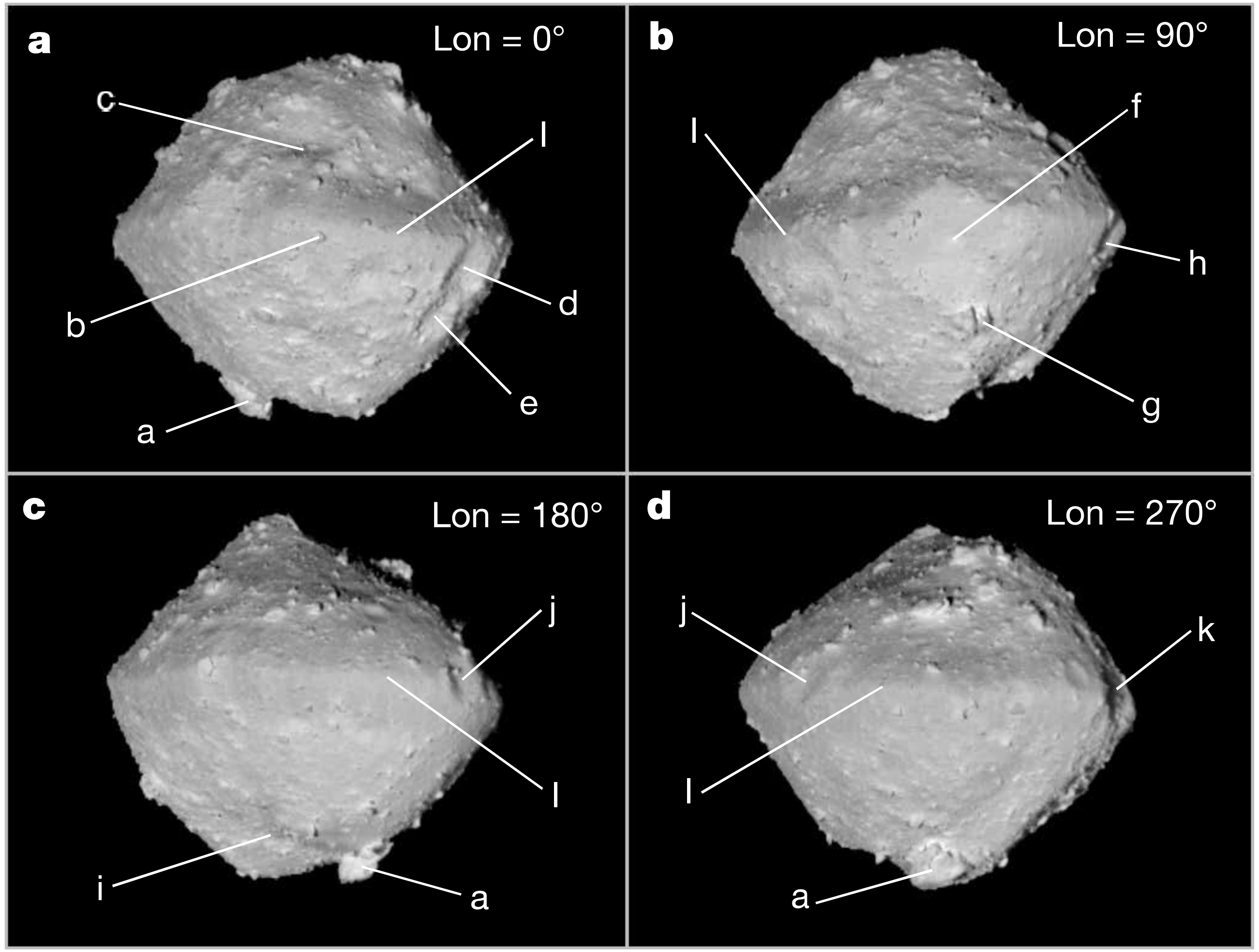
$\Gamma = 282^{+93}_{-35}$ J m^{-2} K^{-1} s$^{-1/2}$.



Grott, Knollemberg, Hamm et al. 2019 Nat. Astronomy

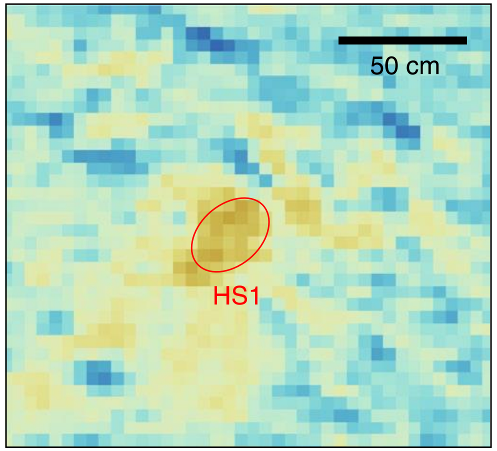
Porous and very porous rocks on Ryugu

Confirmation from TIR global thermal images of Ryugu



Okada et al. 2020 in Nature

Anomalously porous boulders on (162173) Ryugu as primordial materials from its parent body



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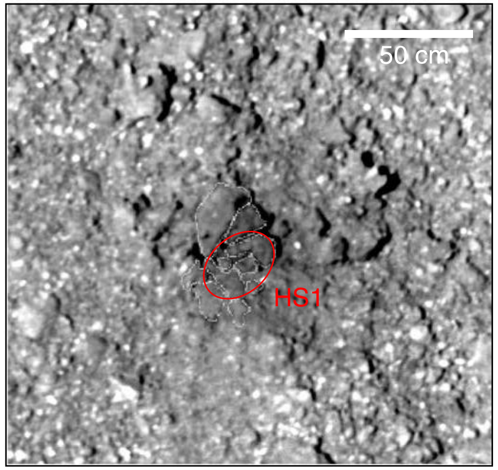
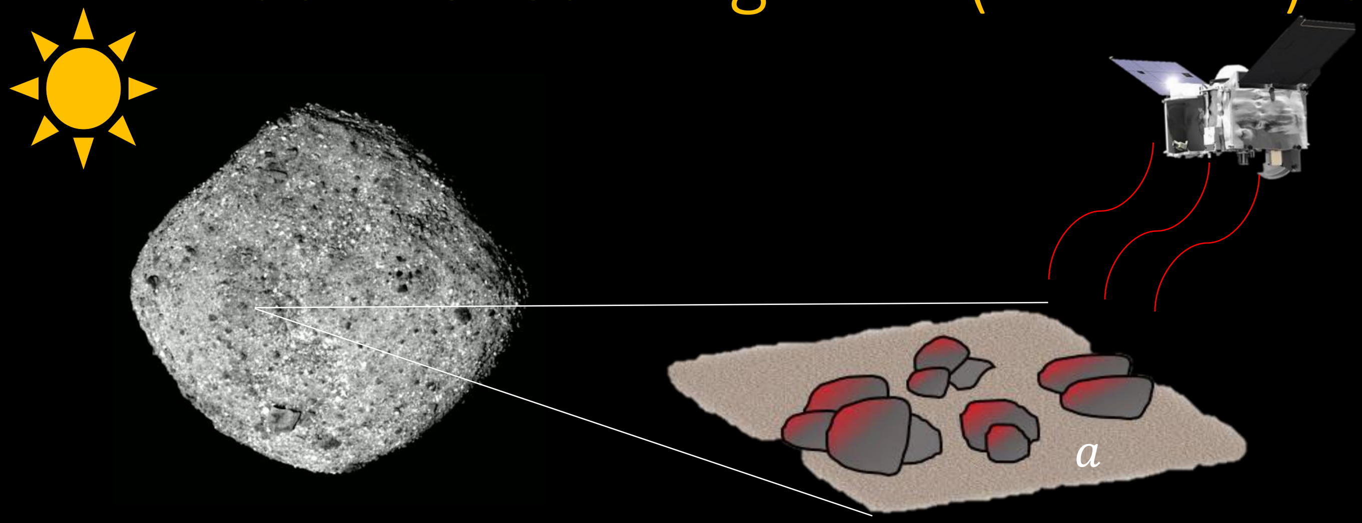


Sakatani et al. 2021 in Nat. Astr.

Thermophysical models w. advanced features

Machine learning TPM (ML-TPM) by Cambioni et al. (2019, 2021)



Physical parameters

$\Gamma_R = \sqrt{\kappa \rho c_p}$ Rock thermal inertia

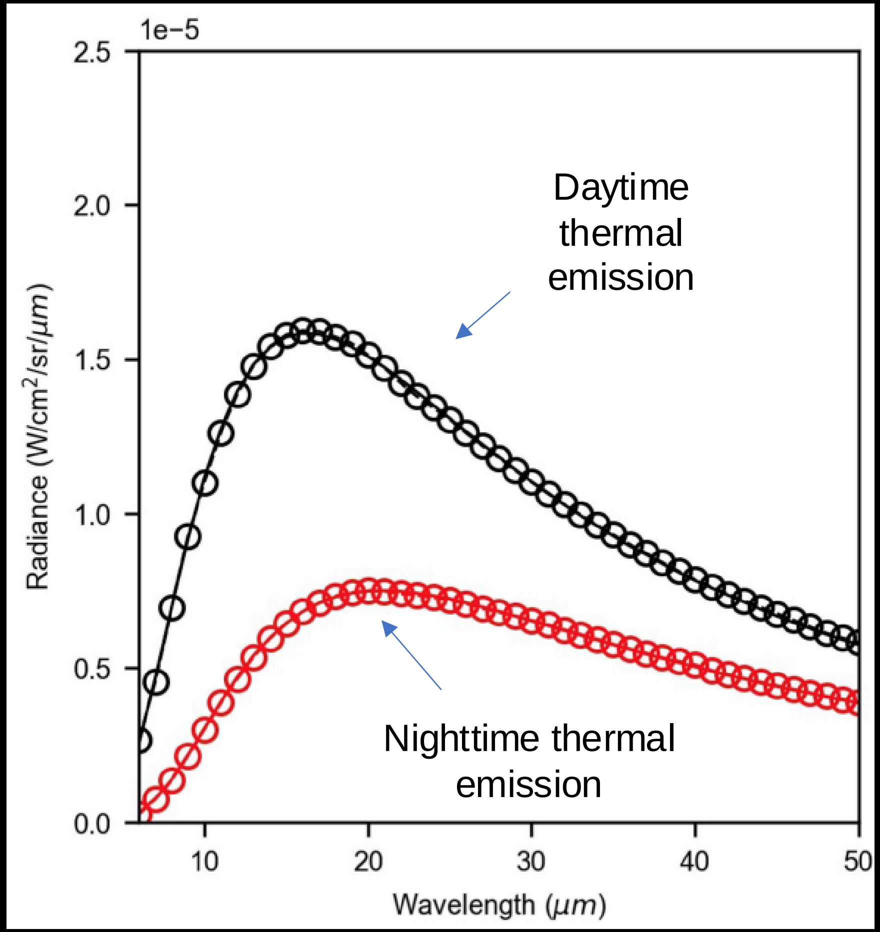
Γ_P Particle (regolith) thermal inertia

- κ thermal conductivity [W/m K]
- ρ bulk density [kg/m^3]
- c_p heat capacity [J/Kg K]

θ roughness of the surface

a abundance of regolith/abundance of rocks

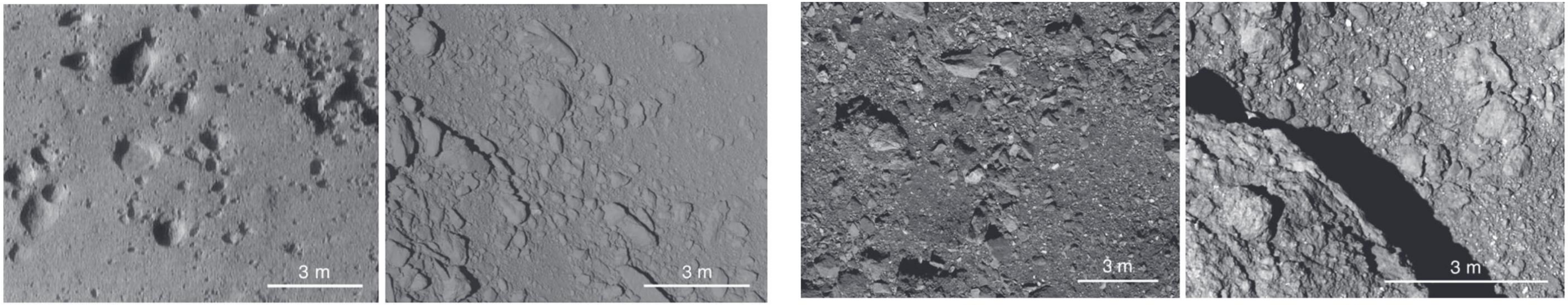
Observable



$$L_{\text{model}}(f_{\text{s}}, \theta, \Gamma_{\text{P}}, \Gamma_{\text{R}}, \alpha) = f_{\text{s}}\left[\alpha L_{\text{regolith}}(\Gamma_{\text{P}}, \theta) + (1-\alpha) L_{\text{rock}}(\Gamma_{\text{R}}, \theta)\right],$$

L is the radiance

Asteroid surfaces observed so far are composed by rocks and by a unit which is below the resolution of the cameras constituted by unconsolidated material, i.e., regolith.



(a) Eros (b) Itokawa (c) Bennu (d) Ryugu

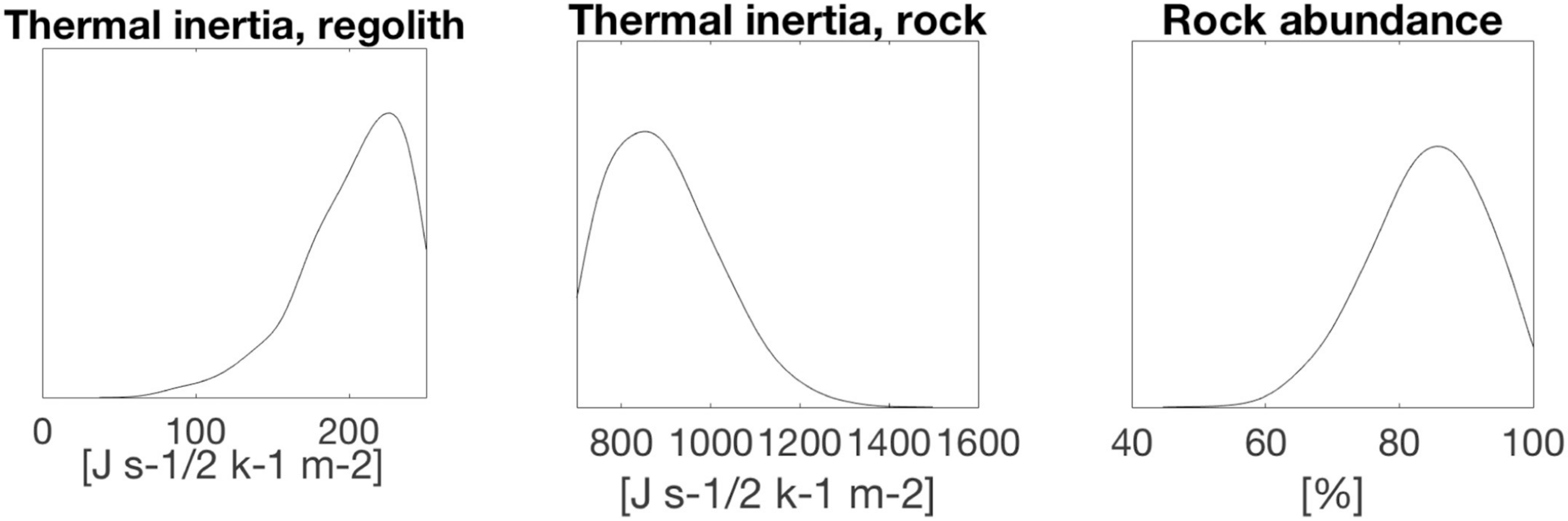
Spacecraft images of the regolith on Eros, Itokawa, Bennu, and Ryugu acquired by the NEAR, Hayabusa, OSIRIS-REx, and Hayabusa 2 missions, respectively. [Adapted from MacLennan and Emery 2022].

Hence it is natural to study the thermal emission of the two units (rocks and regolith) constituting the surface.

Thermophysical models w. advanced features

Machine learning TPM (ML-TPM) by Cambioni et al. (2019, 2021)

Asteroid: Itokawa

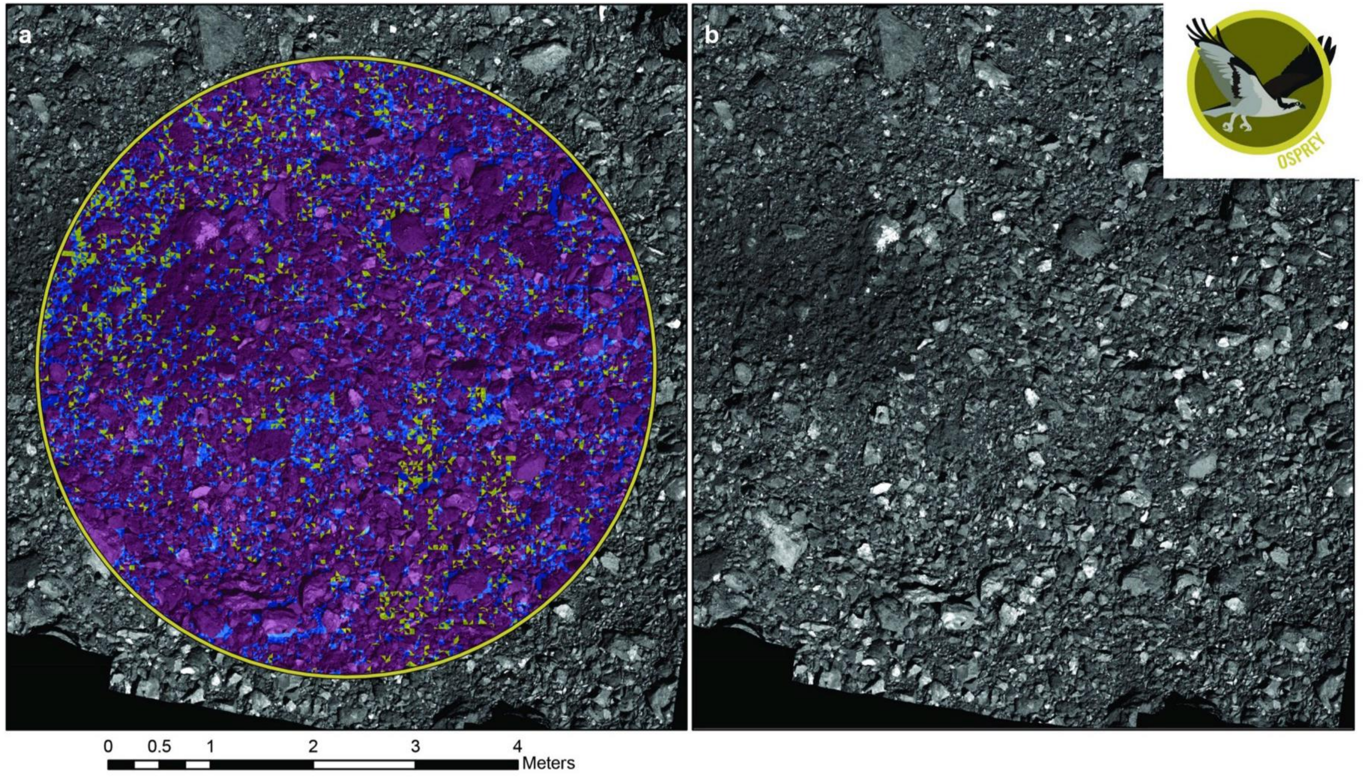


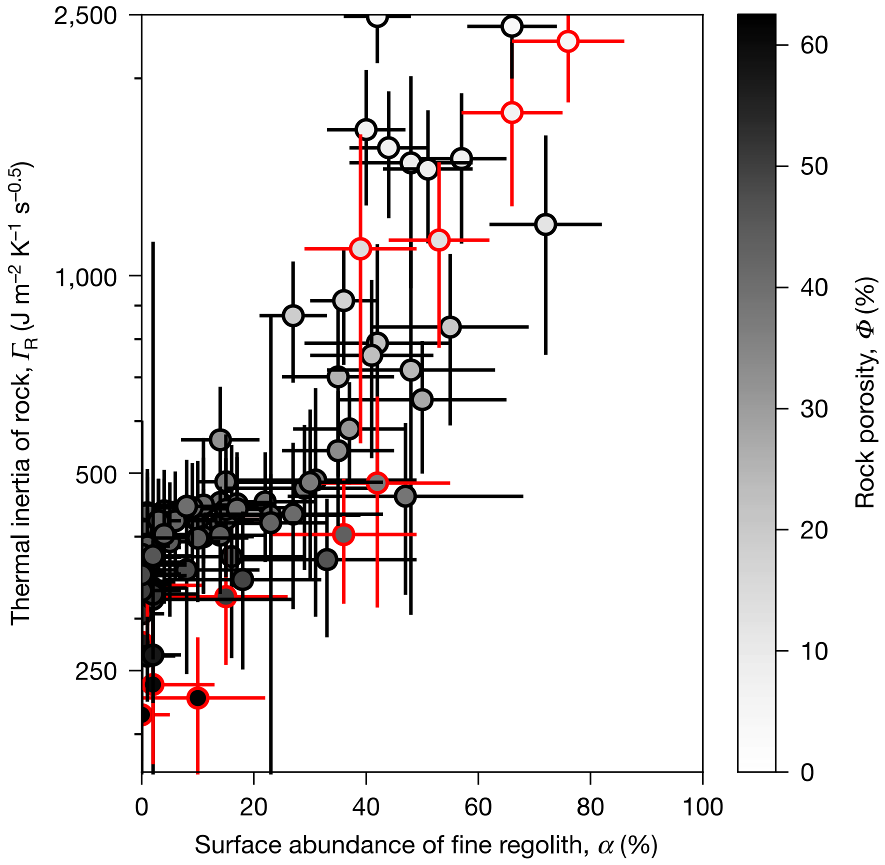
Posterior distribution of the parameters in the Bayesian inversion of the 4-D problem. The inversion is informed by the detailed r 2 survey. The retrieved surface properties are: $\theta=4\pm1^{o}$, $\Gamma_{regolith} = 203 \pm 36$ J $s^{-1/2}$ K^{-1} m^{-2}, $\Gamma_{rock} = 894 \pm 122$ J $s^{-1/2}$ K^{-1} m^{-2}, Rock Aundance = 84 ± 9%.

Thermophysical models w. advanced features

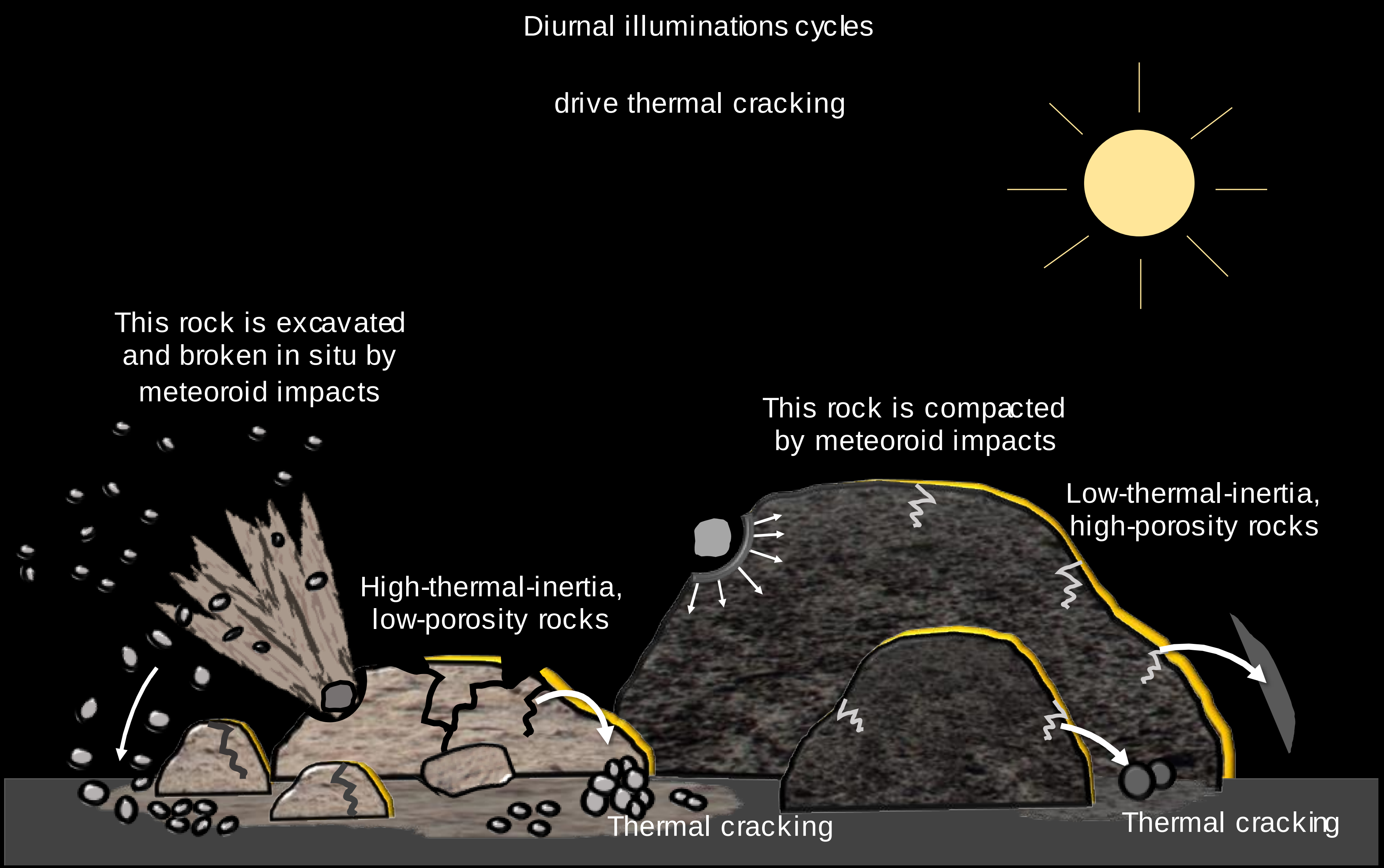
ML-TPM application by Cambioni, Delbo et al. 2021 in Nature

Asteroid: Bennu





Interpretation of the correlation

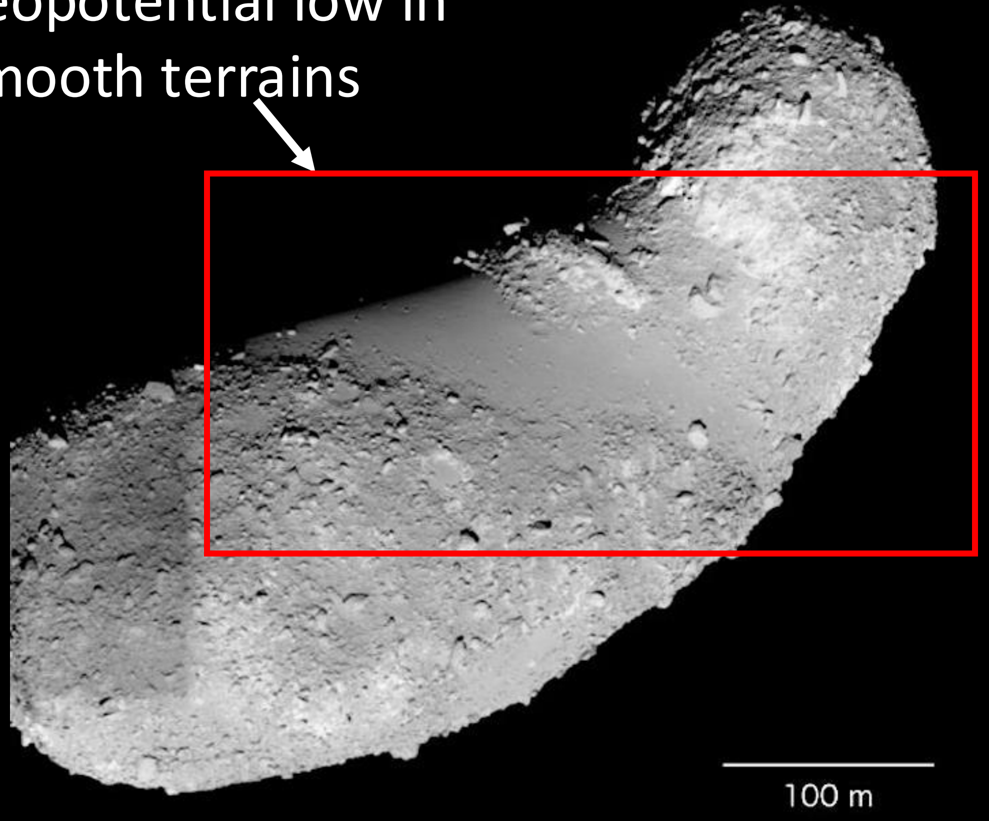


Cambioni Delbo et al. 2021, *Nature*

Diversity of asteroids' surfaces

cm-sized particles accumulate at the geopotential low in smooth terrains

Credit: ISAS, JAXA



Asteroid Itokawa

Class: Stony, low-porosity rocks

No smooth terrains at geopotential low

Credits: NASA Goddard/OSIRIS-REx

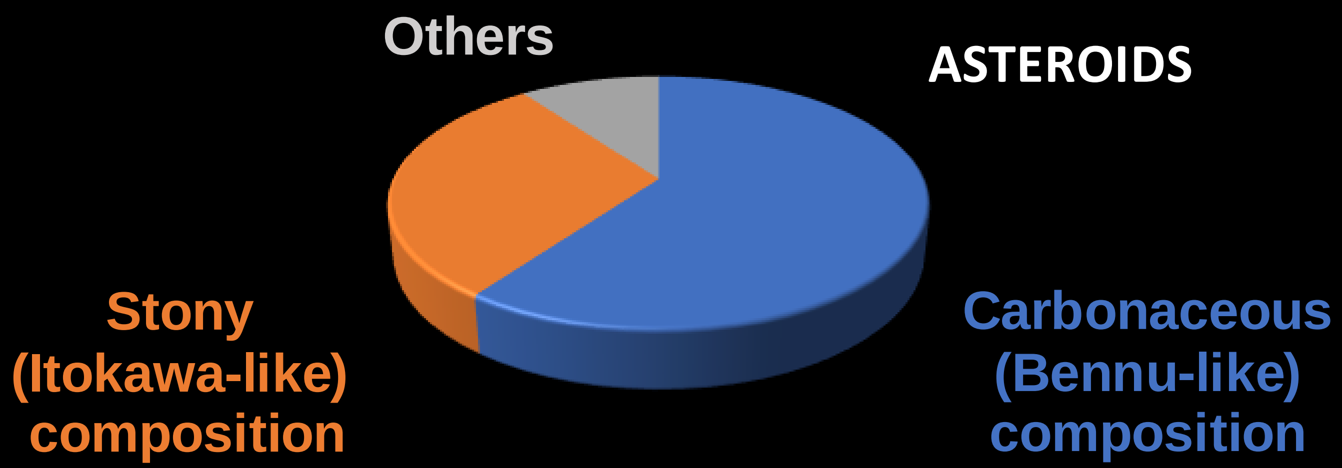
Asteroid Bennu

Class: Carbonaceous, high-porosity rocks

Significance of rock porosity of asteroids

Rock porosity plays a central role in shaping the diversity of asteroid surfaces

Smooth terrains with regolith should be common on stony asteroids but not on carbonaceous asteroids



Porosity links dust aggregates in protoplanetary disks to solid rocks

TPM in presence of reflected light contribution

- SpeX LXD mode:
  - Pre-upgrade (1.95–4.2 μm), and post-upgrade LXD long (1.98–5.3 μm).
  - Very interesting for NEOs (Magri+17, Howell+ 18; Myers+ 22, 24)
- Warm Spitzer
- WISE (W1–W4 bands; with effective wavelengths of 3.4, 4.6, 12, and 22 μm)
  - Post Cryo and NEOWISE regular had only W1 and W2 working (W3 and W4 blinded by high temperature)
- TAO (see J. Benyiama talk) ?

- In this cases directional emissivity has to be related to the directional reflectance (Kirchoff law) and the thermal modelling is intertwined with the scattering model (Muinonen, Carry, Mahlke, etc. talks)

Conclusions

- Thermophysical models are very powerful tools for the interpretation of infrared observations.
- They may provide:
  - Size, albedo, thermal inertia, roughness
  - Shape optimisation
  - Temperature history of the body
  - Internal temperatures
- Can be coupled with light scattering models.

Thermophysical models codes

	Thermophysical model (code)									
Advanced Feature	**Laggeros TPM**	**Delbo TPM**	**Emery TPM**	**Mueller TPM**	**Rozitis ATPM**	**Magri SHERMAN**	**Statler TACO(1)**	**Yu TPM**	**MacLennan shapeTPM**	**Wright TPM (WISE)**
Ephemeris	Not sure	yes	no	no	may	may	no	no	not sure	not sure
Heat diffusion in craters	no	yes	no	no	yes	no	no	yes	yes	no
Topographic shadows	no	yes	no	no	yes	yes	yes	not sure	yes	no
Topographic mutual heating	no	yes	no	no	yes	yes	no	not sure	yes	no
Depth dependent k	no	no	no	no	no	yes	no	no	no	no
Temperature dependent κ	no	no	no	no	no	yes	no	no	no	no
Phase change	no	no	no	no	no	no	no	no	no	no
Internal heating	no	possible(2)	no	no	no	possible	no	no	no	no
Gas heat transfer	no	no	no	no	no	no	no	no	no	no
Beaming parameter (mode)	no	yes	no	no	no	yes	no	no	no	no
Open source	no	yes	no	no	no	no	no	no	no	no
References	*Laggeros 1996, 1997,1998 Müller+ 2011*	*Delbo 2004, Delbo+2007, Ali-Lagoa+2015*	*Emery+ 2006 Emery+1998*	*Mueller, 2007 PhD thesis*	*Rozitis & Green 2011*	*Magri+ 2017, Howell+ 2018*	*Statler 2009*	Yu+ 2014	*MacLennan & Emery 2019; MacLennan+2022*	
Derivation from		*Spencer 1990 & Spencer+ 1989 & Emery+ 1998*					Lagerros 1996	Rozitis & Green 2011	Rozitis & Green 2011	

κ is the thermal conductivity

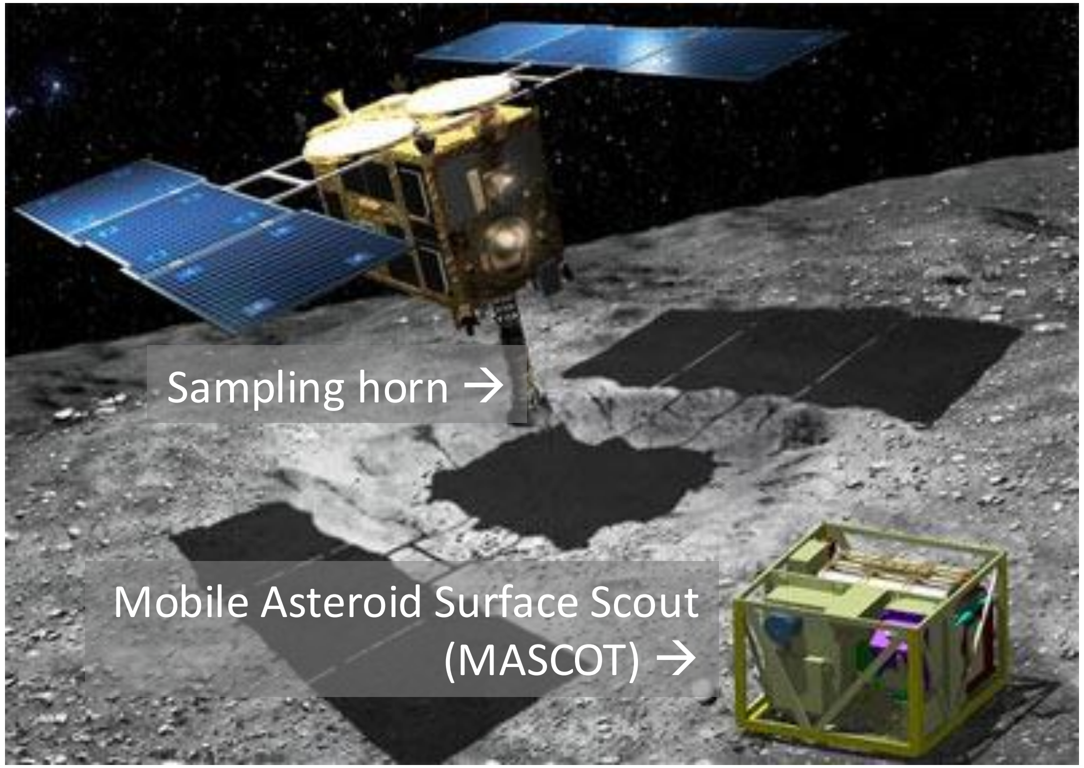
(1) it does not take heat diffusion into account

(2) implemented by Avdellidou, Delbo et al. (2024) in Science

Back up slides

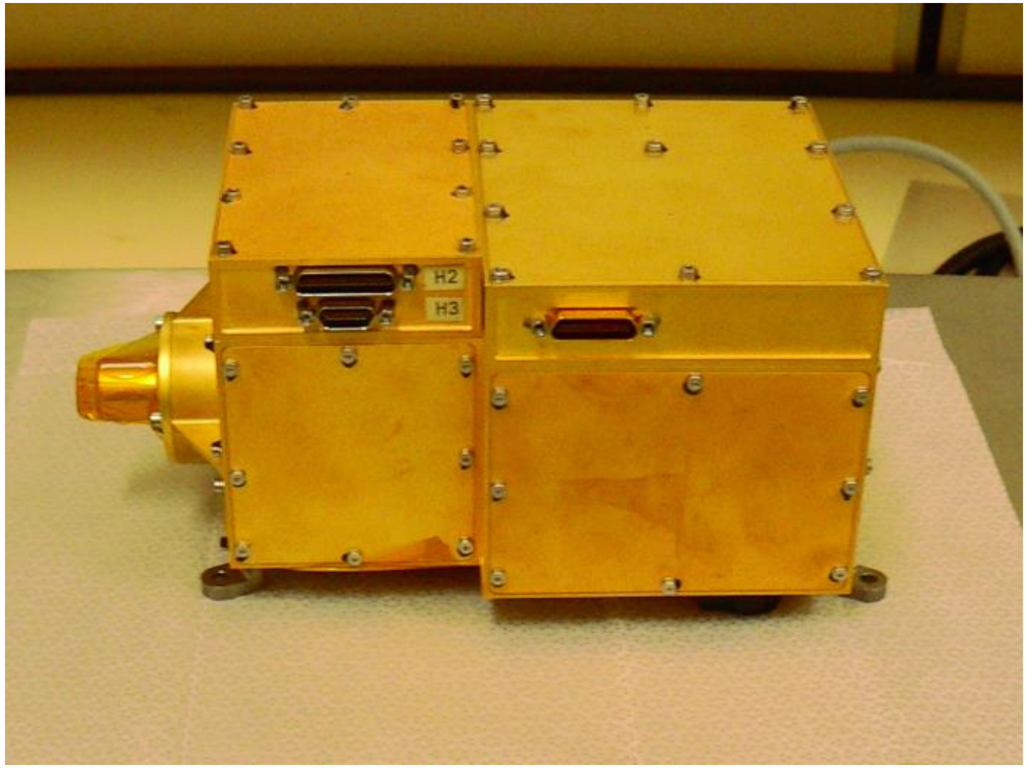
… leading to some failures

Hayabusa2 (Mothership)



MASCOT (Ho et al 2017. Space Sci. Rev.) has a size of a shoebox and included several instruments (e.g. Grott et al. 2019; Jaumann et al. 2019 , including MicrOmega →

MicrOmega is a NIR microscope to study the composition of the terrain.



This instrument was designed to work in contact with the terrain!

… leading to some failures (2)

The MicrOmega instrument could not get in contact with the terrain of Ryugu due to the extreme rugosity of the latter.

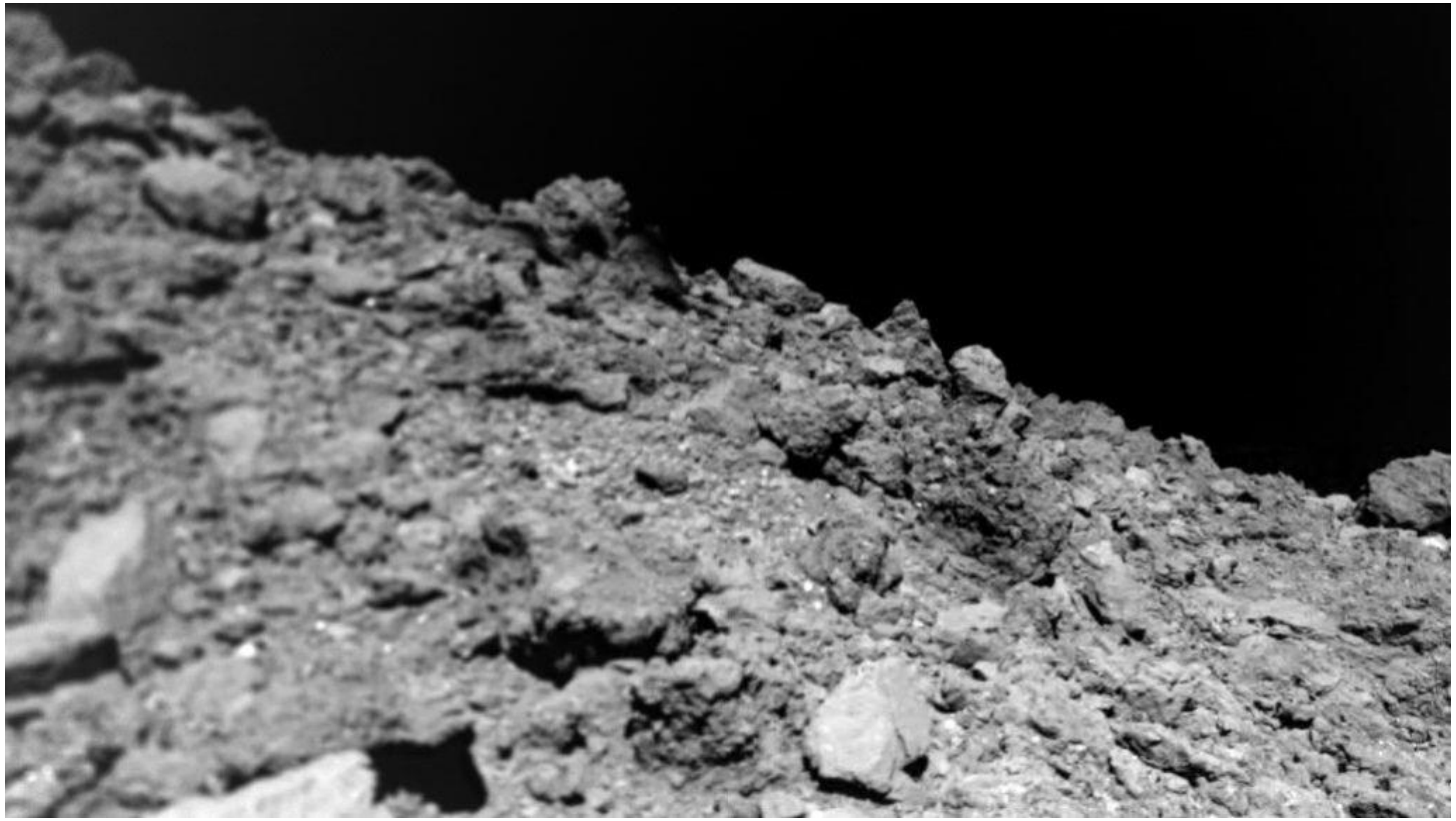
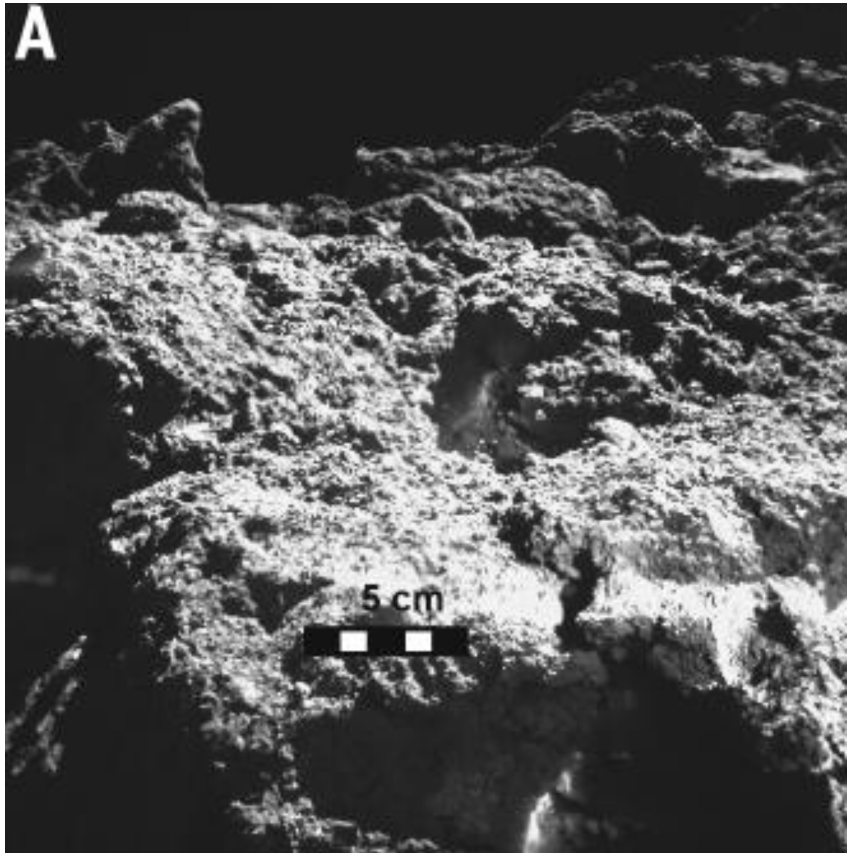


Image from MASCOT camera (Jaumann et al. 2019 in Science)



Bennu

Phaethon