UNVEILING MERCURY: A SPECIAL FOCUS ON THE NORTH POLAR CRATERS WITH PERMANENT SHADOWED REGIONS

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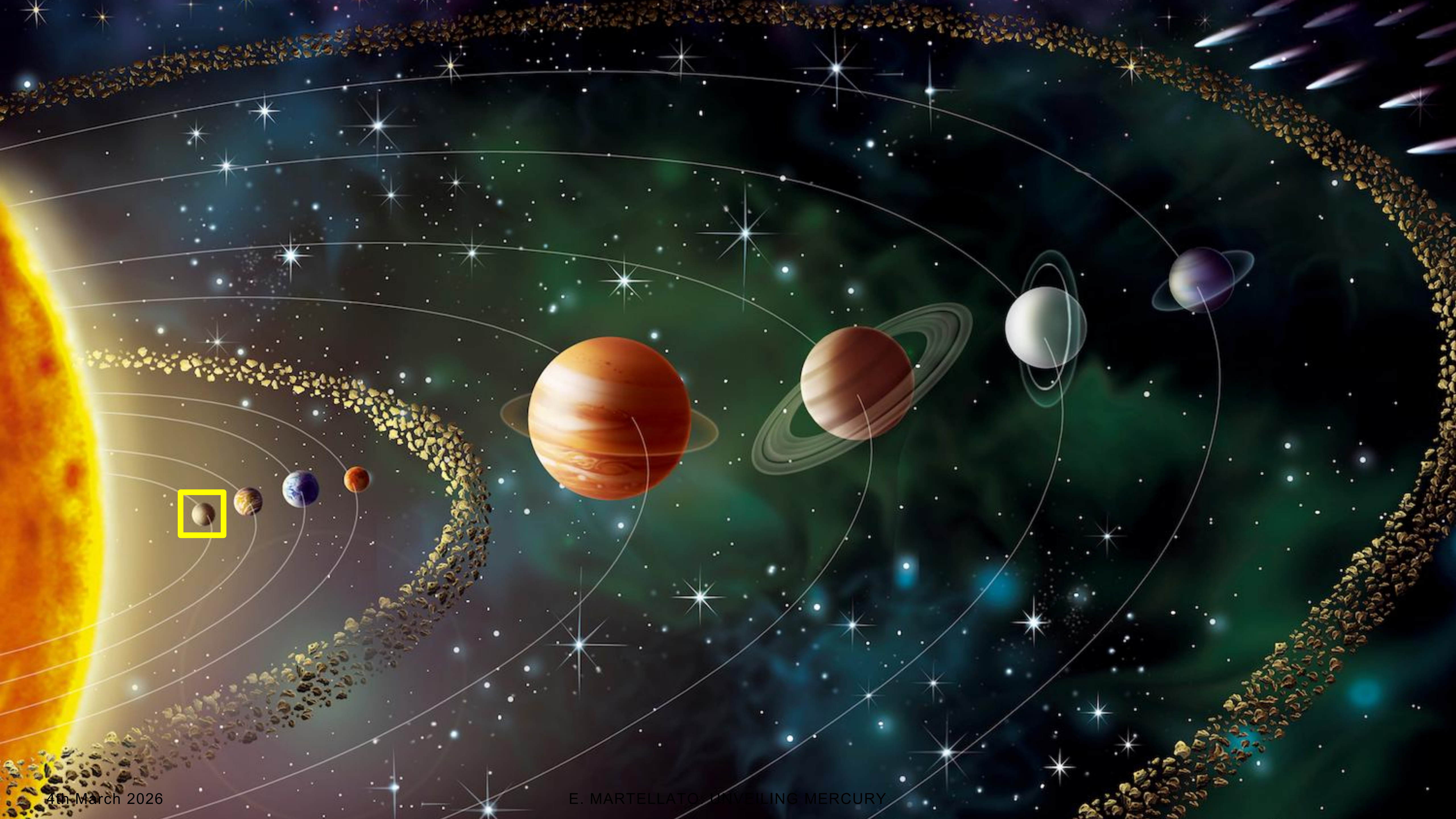
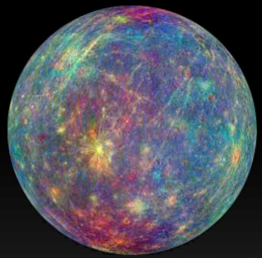
di Padova

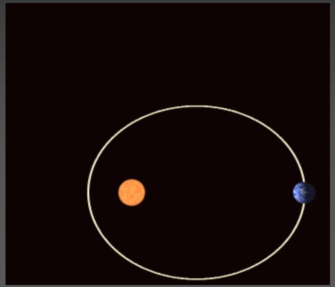




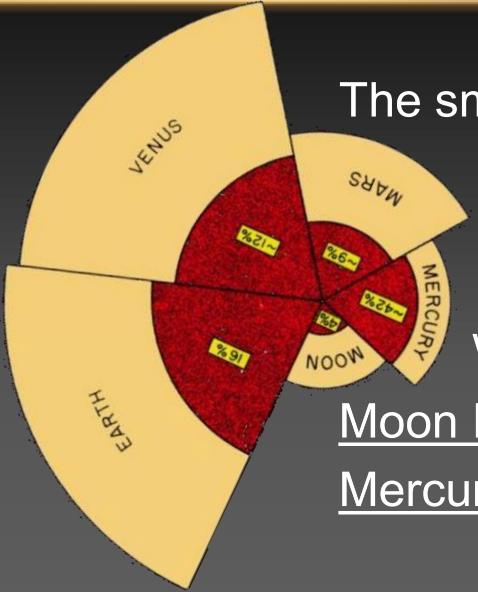
MERCURY:
THE PLANET OF THE EXTREMES

The closest to the Sun: semimajor axis = 59 M km = 0.4 AU

The most elliptical orbit: 0.205
Perihelion: 0.31 AU
Aphelion: 0.47 AU



ORBIT PRECESSION: 43 arcsec due to the Sun Mass warping the nearby space

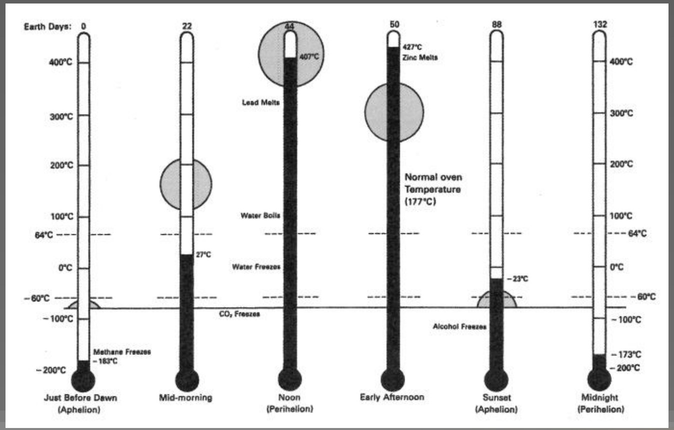


The smallest planet: R = 2439 km $\approx 0.4\ R_{Earth}$

with the largest aspect ratio:

Moon Nucleus Radius = 20% R_{MOON}

Mercury Nucleus Radius = 75% $R_{MERCURY}$

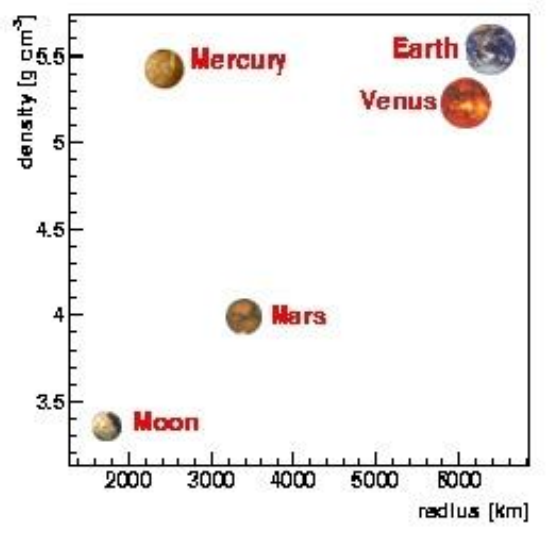


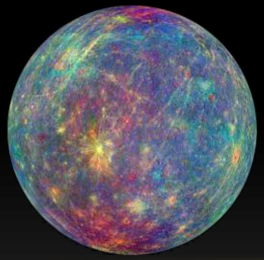
The one with the highest temperature gradient:
450°C @day
-180°C @night

The one with the hardest radiation environment

high density: large iron (Fe)-fraction of 60–80 wt%, mostly stored in the core

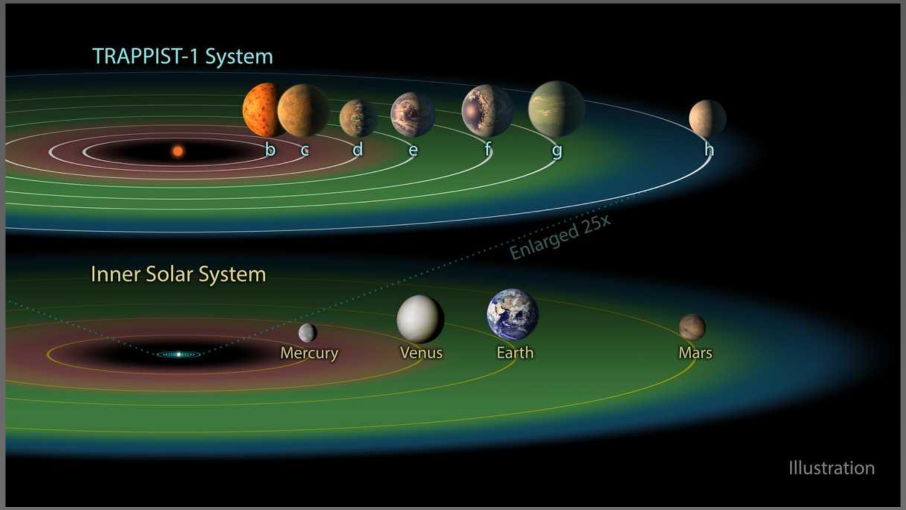
UNCOMPRESSED DENSITY:
5.3 g/cm^3 vs 4.0 g/cm^3



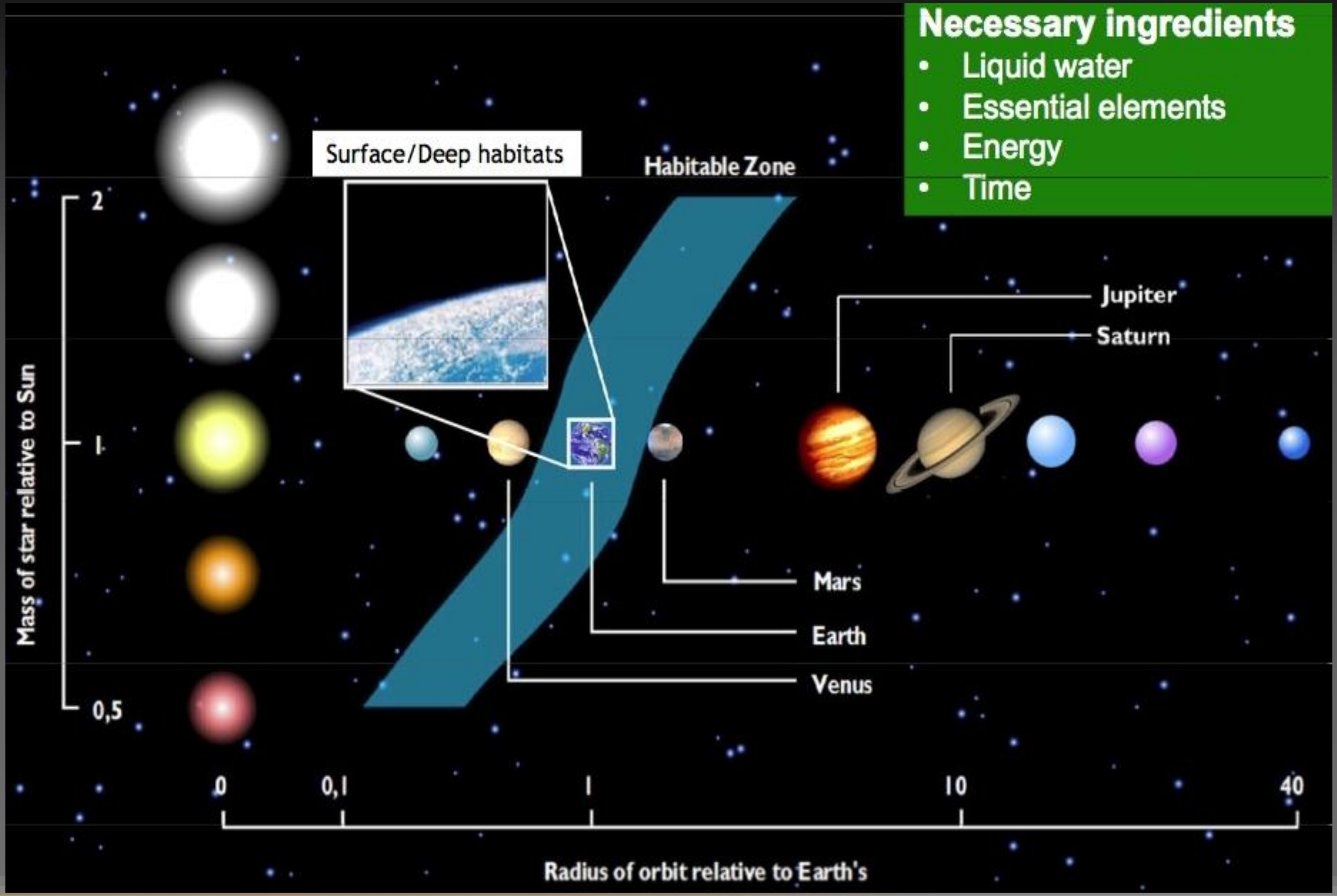


MERCURY:
HINTS TO OTHER PLANETARY SYSTEMS

- it’s important to understand the evolution of our Solar System and provide the nearest laboratory to study exoplanet formation



Credits: NASA/JPL-Caltech



Necessary ingredients
- Liquid water
- Essential elements
- Energy
- Time

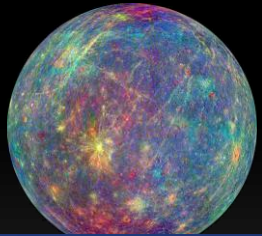
HAS MERCUY KNOWN AND STUDIED IN THE PAST?

Pigalle, Louvre

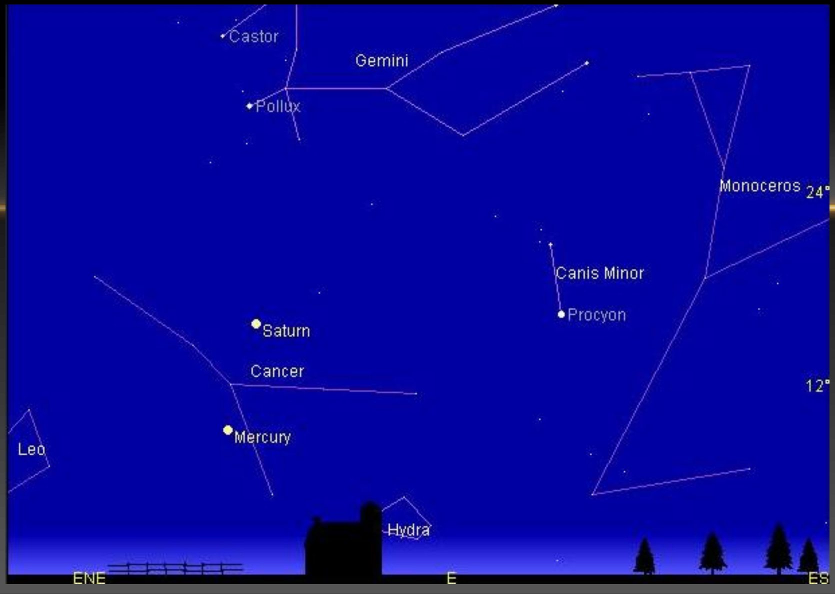
- a tireless god, a rapid traveler, with an elusive nature

- Mercury is the most rapid planet to move in respect to the fixed stars: it remains only 7.33 days in each zodiac constellation

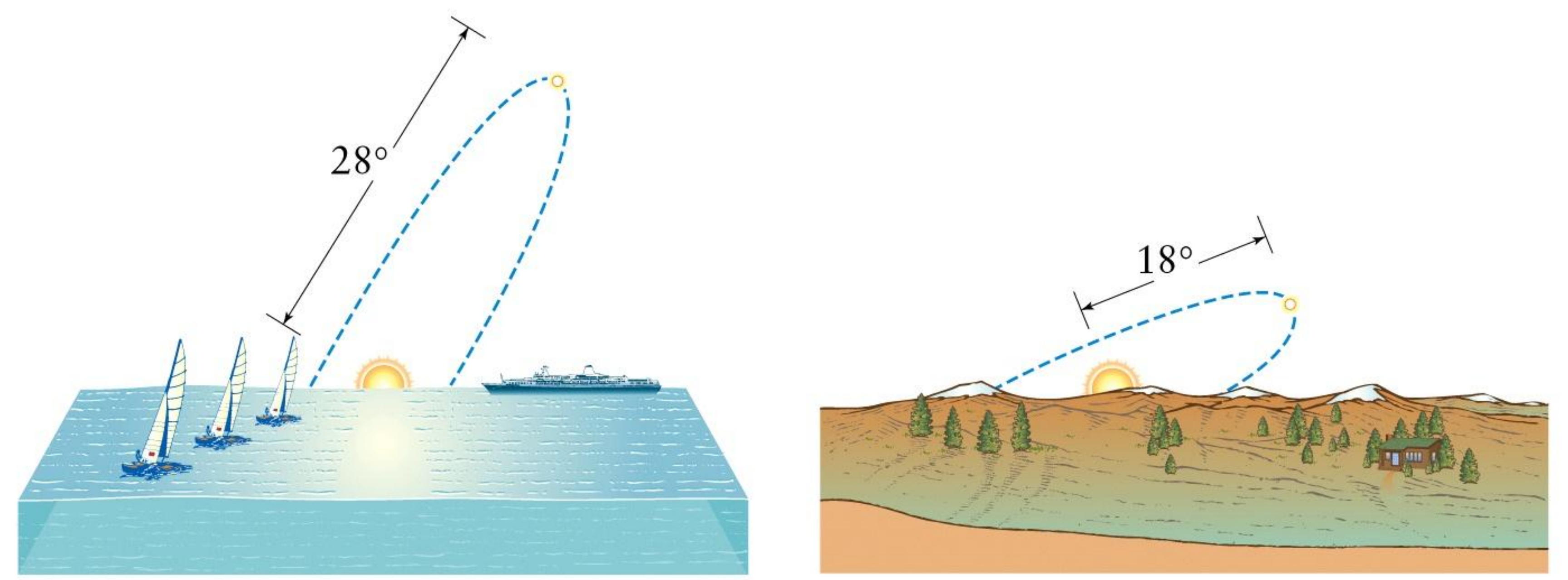
AND TODAY?



THEMIS, Tenerife, Canarias 0.90-m Solar telescope



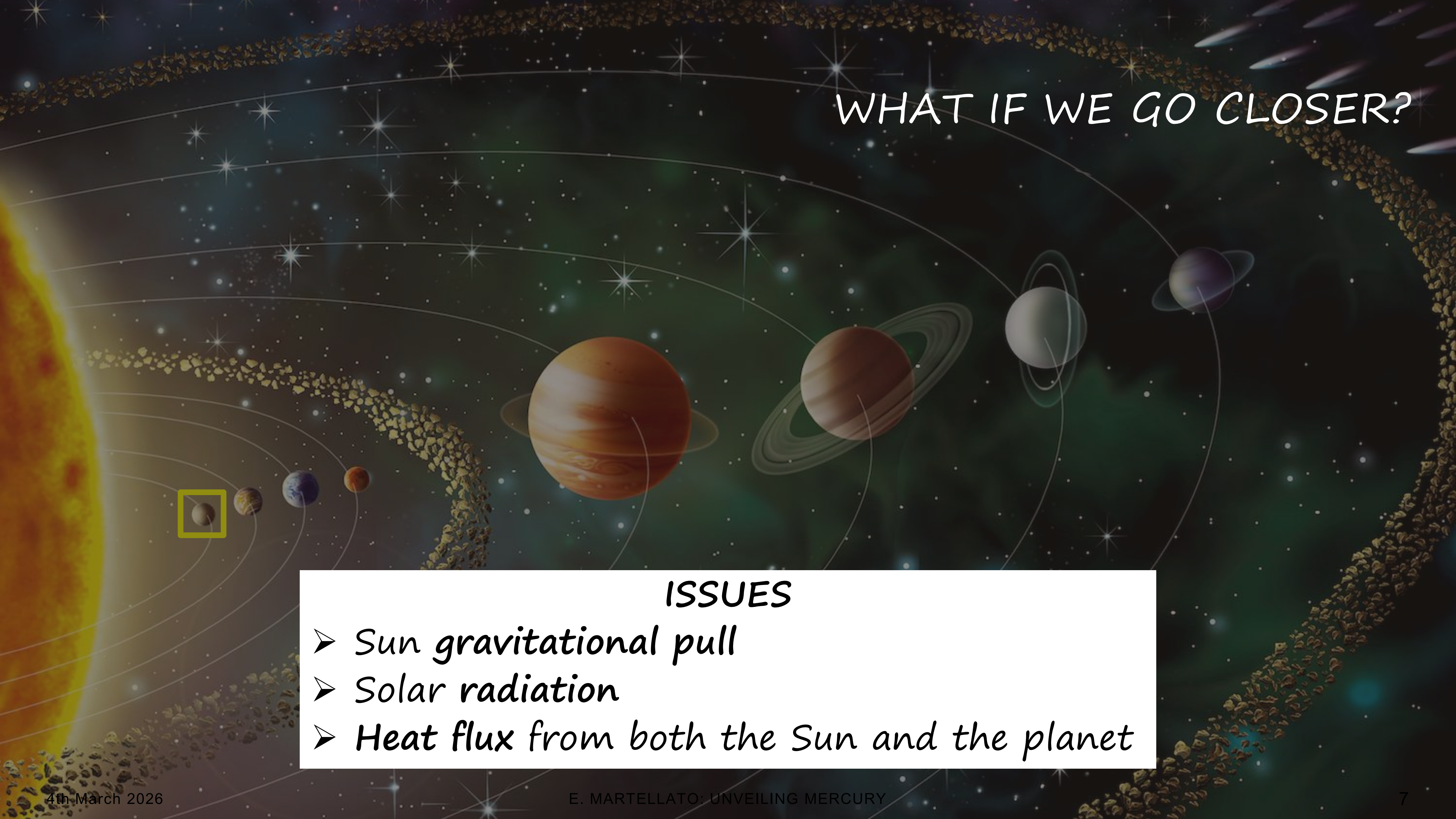
Keck, Mauna Kea, Hawaii 10-m telescope



Favorable elongation

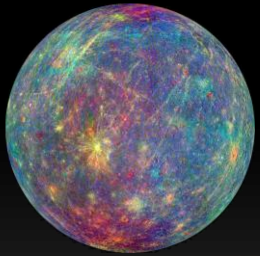
Unfavorable elongation

WHAT IF WE GO CLOSER?



ISSUES

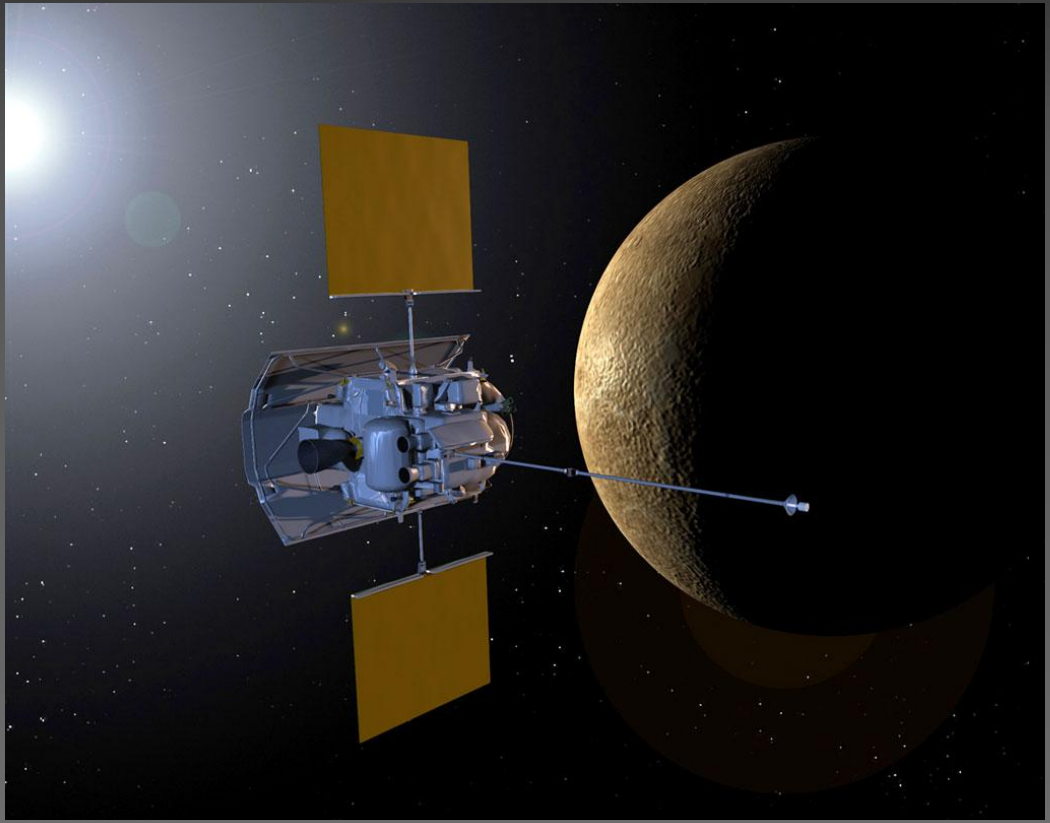
- Sun **gravitational pull**
- Solar **radiation**
- **Heat flux** from both the Sun and the planet



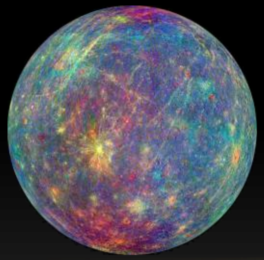
SPACE EXOPLORATION TO MERCURY 1/2

Mariner 10

MESSENGER

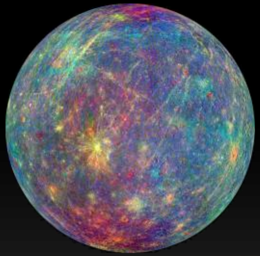


Credits: NASA



SPACE EXOPLORATION TO MERCURY 2/2

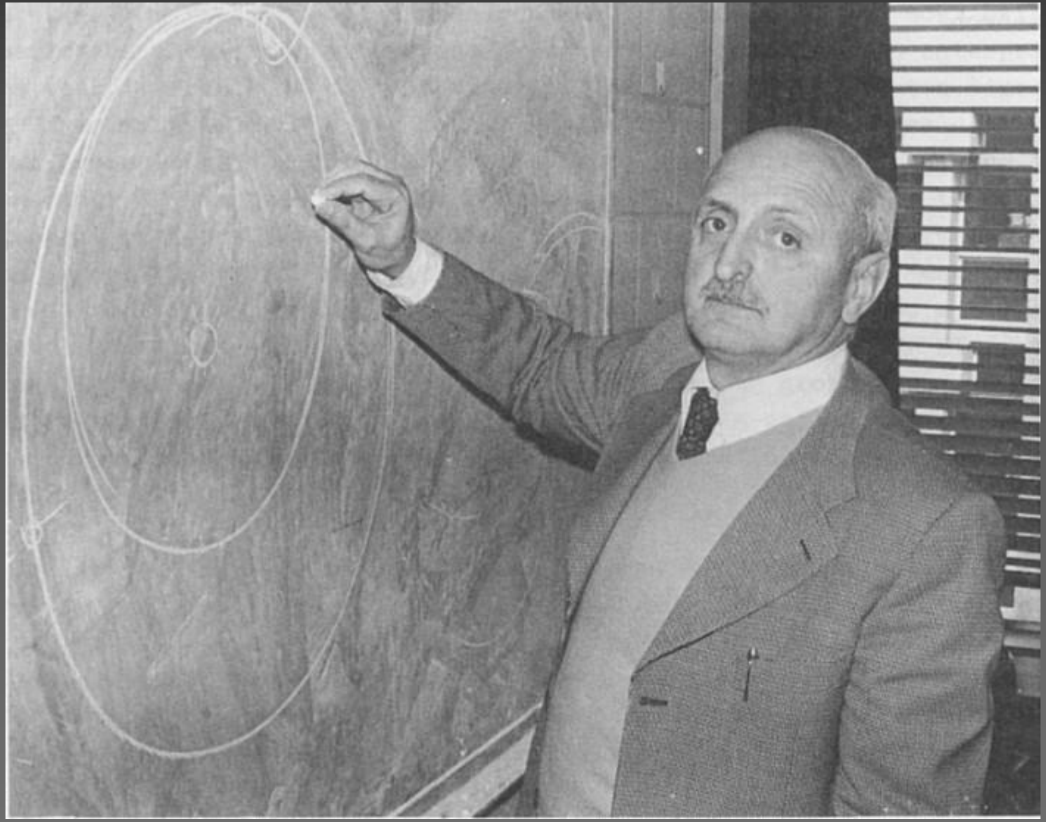
Mariner 10		*MESSENGER*
1973-11-03	*Lunch date*	2004-08-03
473.9 kg	*Mass*	485.2 kg
gravity assist: first probe that uses this technique	*Cruise*	gravity assist
3 flybys (1974-1975)	*Operational Phase*	3 flybys (2008-2009) + orbit (2011-2015)
Mercury environment atmosphere characeristics of the planet and the surface	*Goals*	surface chemical composition geological evolution nature of the magnetic field magnetosphere and exosphere size and physical state of the nucleus volatile components at poles



BEPICOLOMBO

The Scientist

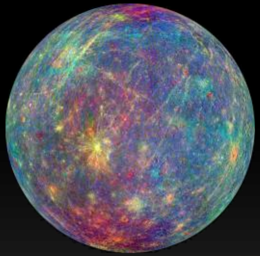
Padova, 1920 – 1984



The Mission

ESA – JAXA joint mission, launched in 2018

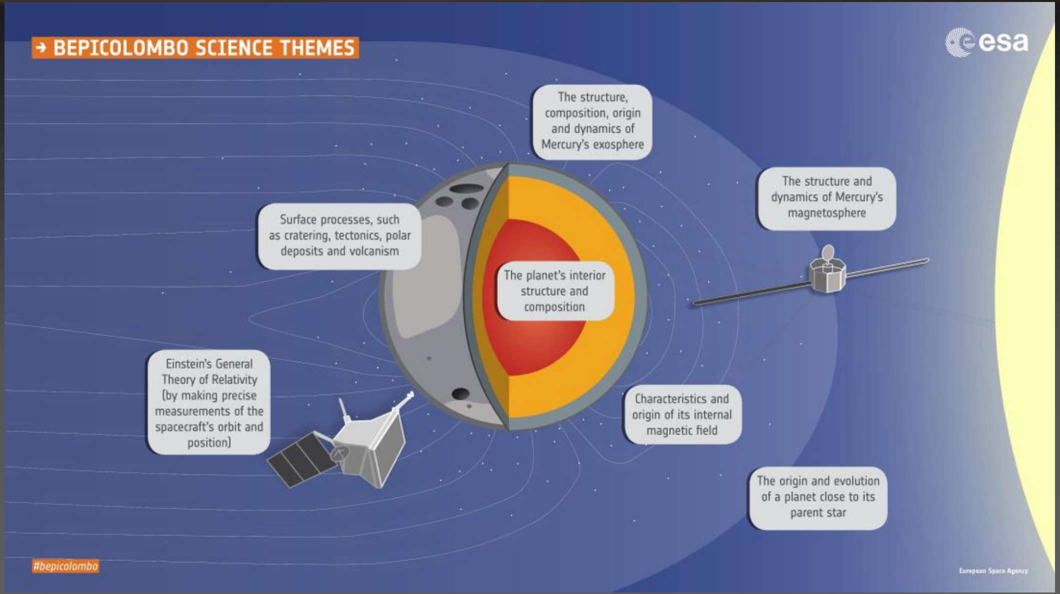
Credits: ESA



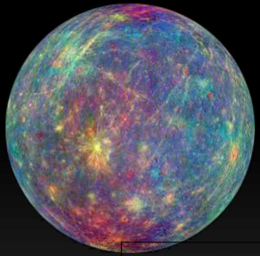
BEPICOLOMBO : TRAVELLING TOWARDS MERCURY

Goals: study Mercury’s composition, geophysics, exosphere, magnetosphere, and evolution:

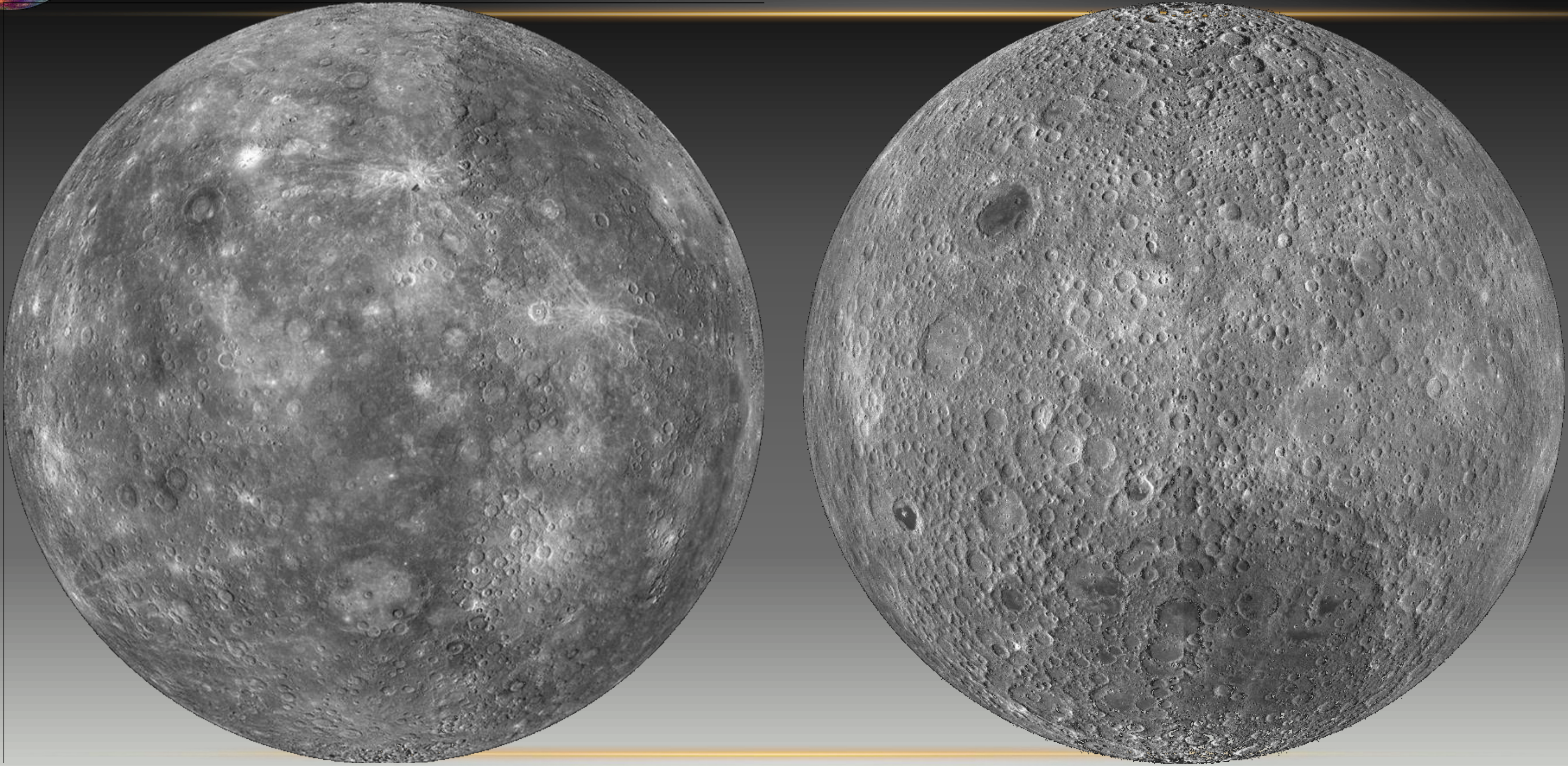
- origin and evolution of a planet close to its star;
- global mapping and 3D reconstruction of the entire surface;
- geology, surface composition, and impact craters;
- polar deposits, their composition and origin;
- inner structure of the planet, and determine the origin of the magnetic field;
- magnetosphere’s structure, and dynamics;
- exosphere’s structure, composition, and dynamics;
- test of the Enstein’s general relativity.

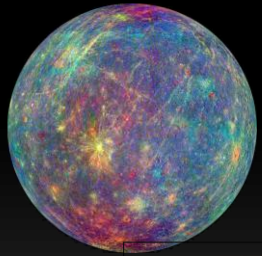


- *Launch date*: 2018-10-20
- *Mass*: 4100 kg
- *Cruise*: gravity assist
  - 1 Earth flyby, 2 Venus flybys, 6 Mercury flybys (last one on 8 Jan 2025)
- *Arrival*: Nov 2026 → *Operations beginning*: early 2027

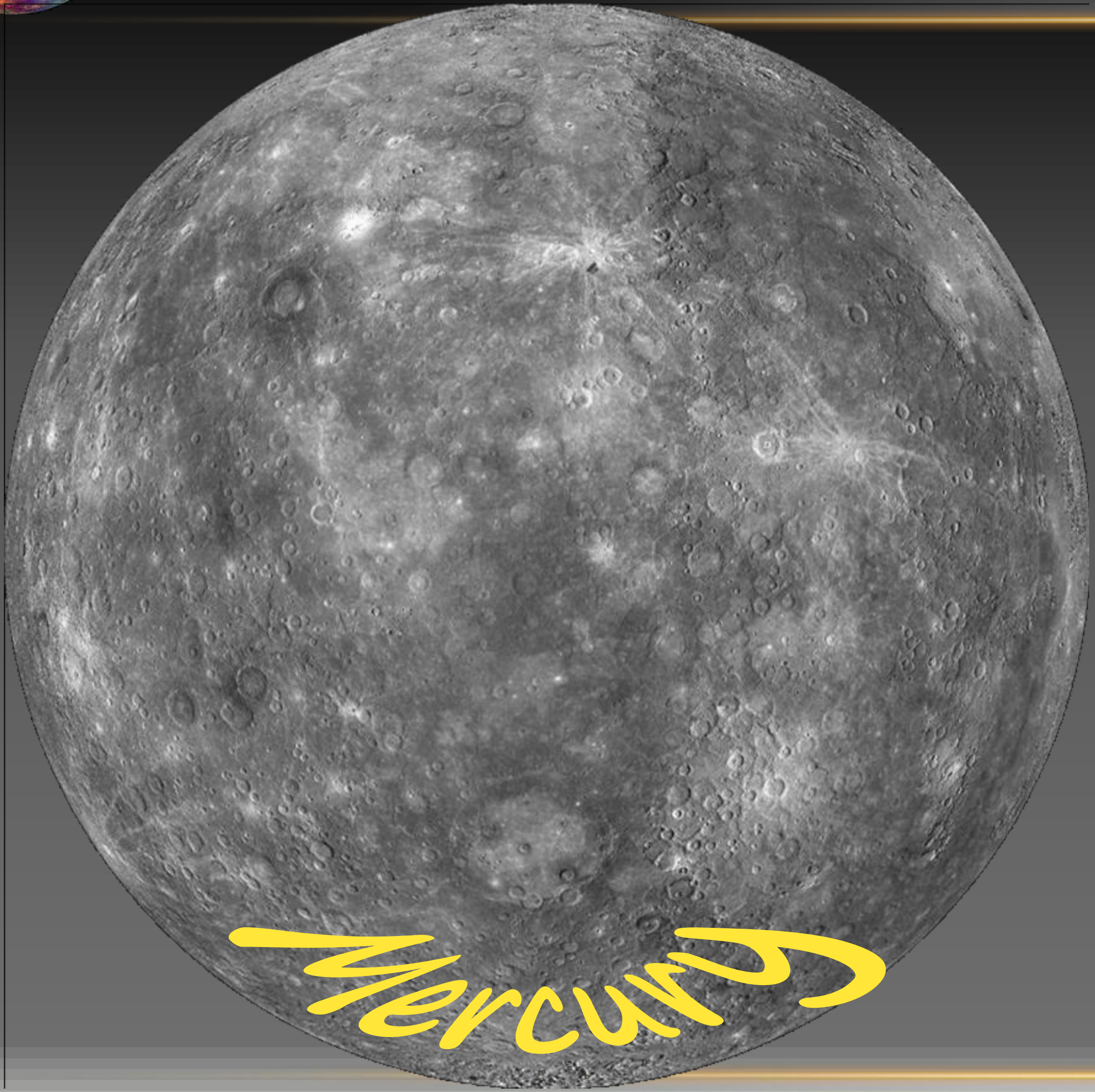


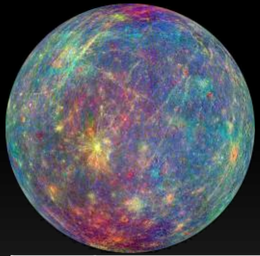
MERCURY = MOON ?



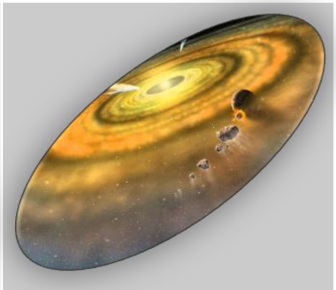
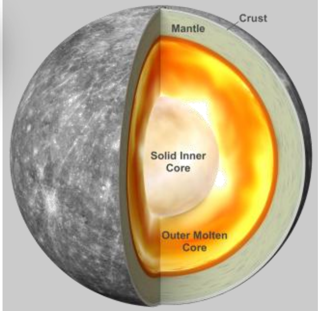
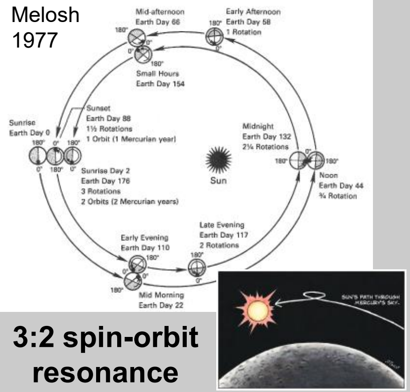
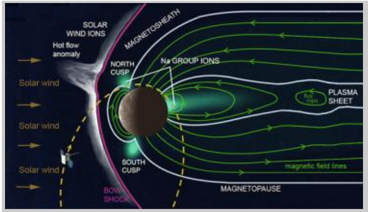
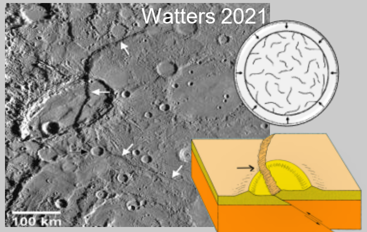
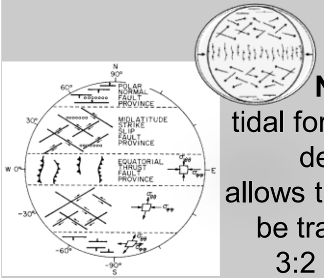
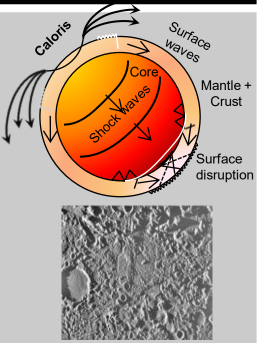
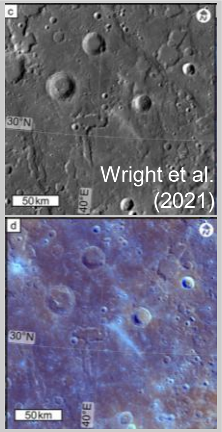
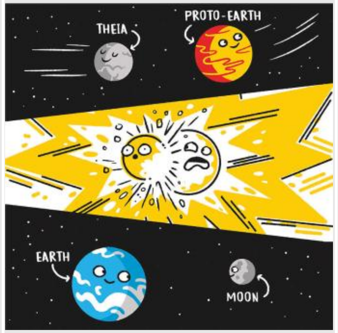
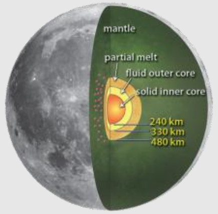
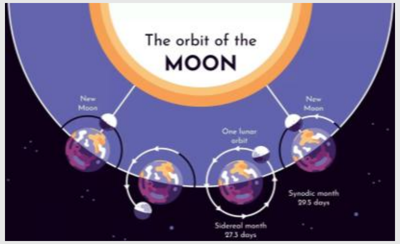
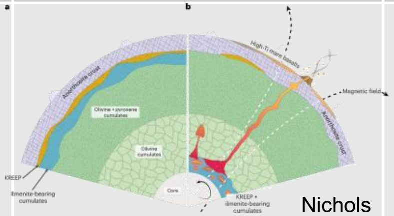
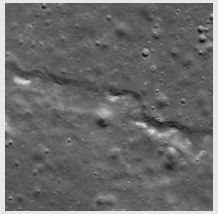


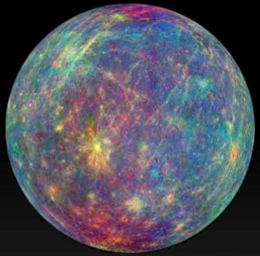
LET'S HAVE A LOOK



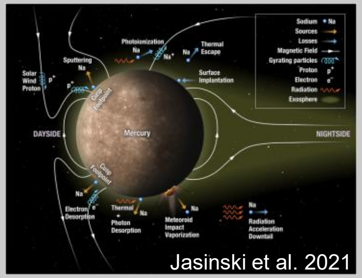
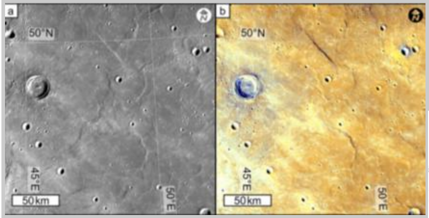
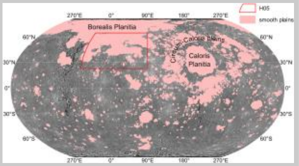
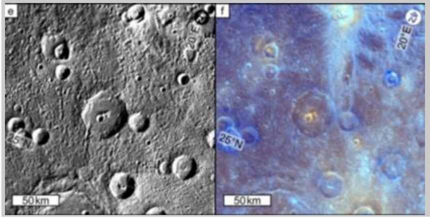
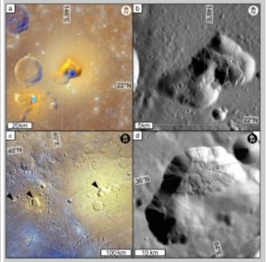
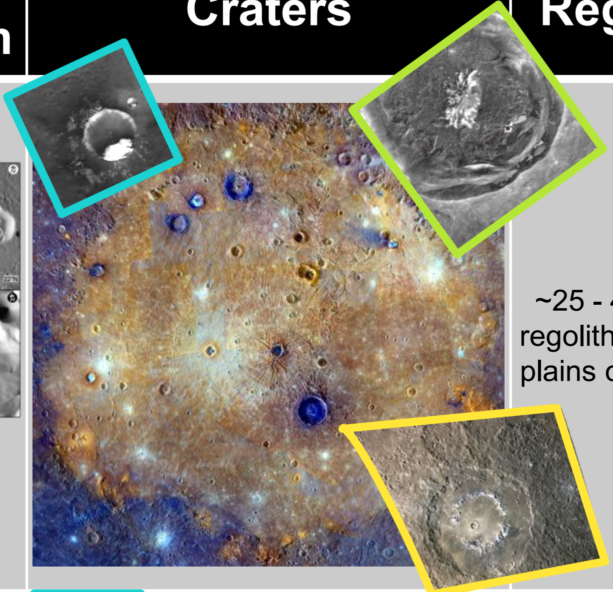
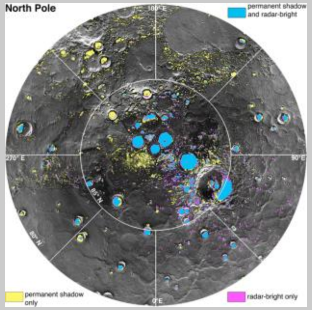
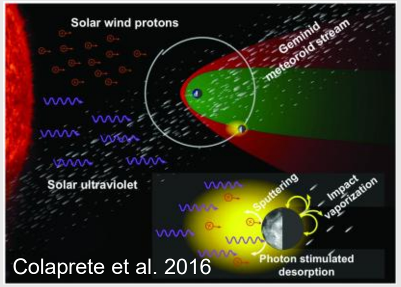
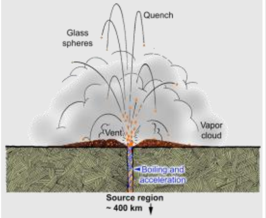
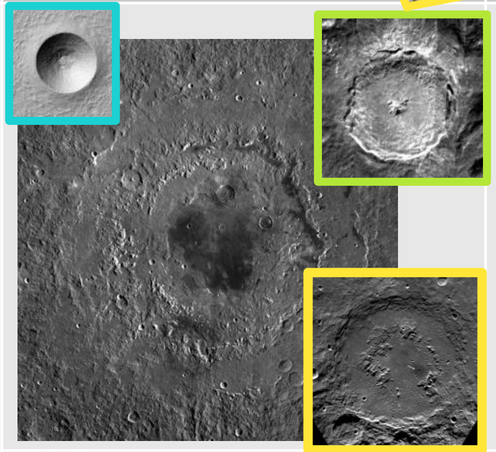
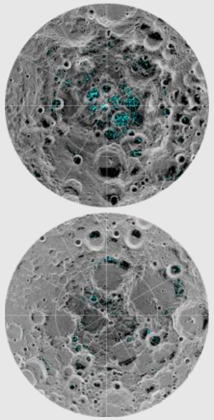


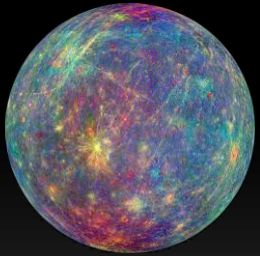
MERCURY VS MOON: DIFFERENCES

	Origin	Inner structure	Orbit	Magnetic field	Tectonics	Surface units
Mercury	 1) originally much bigger, perhaps twice its current bulk and nearly Mars' size; 2) orbiting farther away from the Sun	 $R_{core} \sim 75\% R_M$	 Melosh 1977 **3:2 spin-orbit resonance** - 1 solar day = 2 years - an emisphere faces the Sun each 2 periherms	 Rothery 2014 dipolar magnetic field ~1% the Earth's one at the surface	**LOBATE SCARPS:** global contraction after cooling   **GLOBAL NETWORK:** tidal forces caused despinng that allows the planet to be trapped in the 3:2 resonances  **CHAOTIC TERRAINS:** hilly and lineated terrains opposite to Caloris Basin	 Wright et al. (2021) **INTERMEDIATE PLAINS**
Moon	 CREDITS: IOP	 - dense metallic core: Fe, Ni, S - mantle and crust formed when this magma ocean began to cool	 CREDITS: American Scientist	 Nichols et al. (2026) a high-intensity lunar dynamo at times between 3.3 and 3.9 Ga	 local deformation after cooling of the basaltic lava	✗

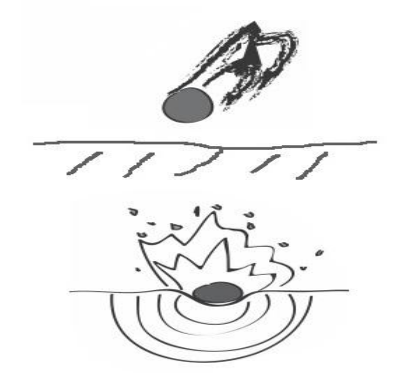


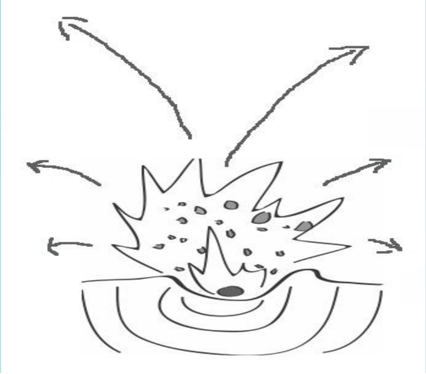
MERCURY VS MOON: SIMILARITIES

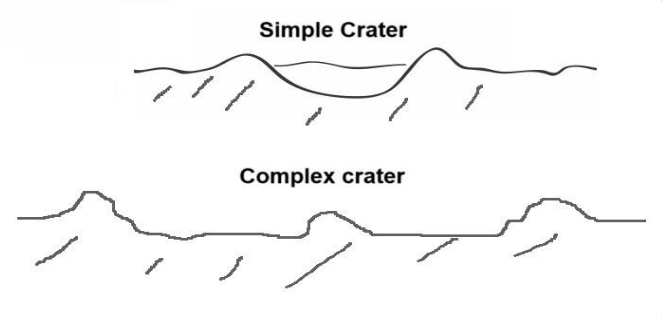
	Exosphere	Surface units	Explosive Volcanism	Craters	Regolith	Ice
Mercury	 Jasinski et al. 2021 **Components**: Na, O, H, He, K, Ca, Mg, Al, Mn **Sources:** photon-stimulated desorption; ion loss; meteoroid impact vaporization	 Wright et al. (2021) **SMOOTH PLAINS:** ▪ 27% surface ▪ age > 3.5 Ga   **INTERCRATER PLAINS:** ▪ >70% surface ▪ age: 3.8 – 4.1 Ga	 Wright et al. (2021)		~25 - 40 m thick regolith in smooth plains on Mercury	
Moon	 Colaprete et al. 2016 • variation of a 2÷3 factor over a month, as different parts are exposed to sunlight • increases shortly after the Moon passes through streams of meteoroids	**HIGHLANDS** **MARIA** 	 CREDITS: LPI		5 – 10 m thick in maria and highlands  CREDITS: NASA	



IMPACT CRATERS: THE PHYSICS

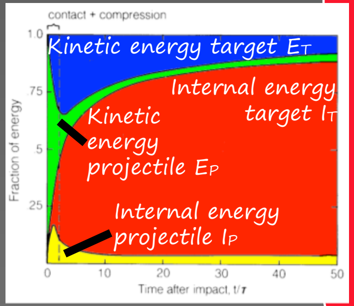






1) Contact & compression

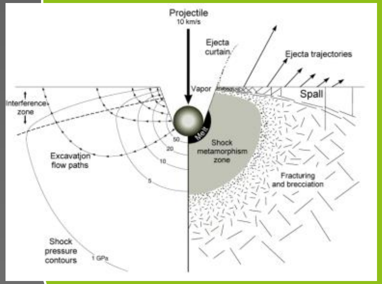
- **Collisions between two planetary bodies**: the projectile kinetic energy is transfered into the target by means of shock waves, travelling faster than the sound, and it is converted into:
  - **internal energy** causing vaporization and melting of material
  - **kinetical energy** causing material movements



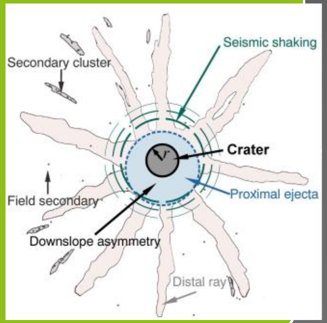
O'Keefe & Ahrens (1982)

2) Excavation

- Excavation flow: the wave sets target material into motion, opening the cavity
- ballistic ejection of target rock debris



French (1998)

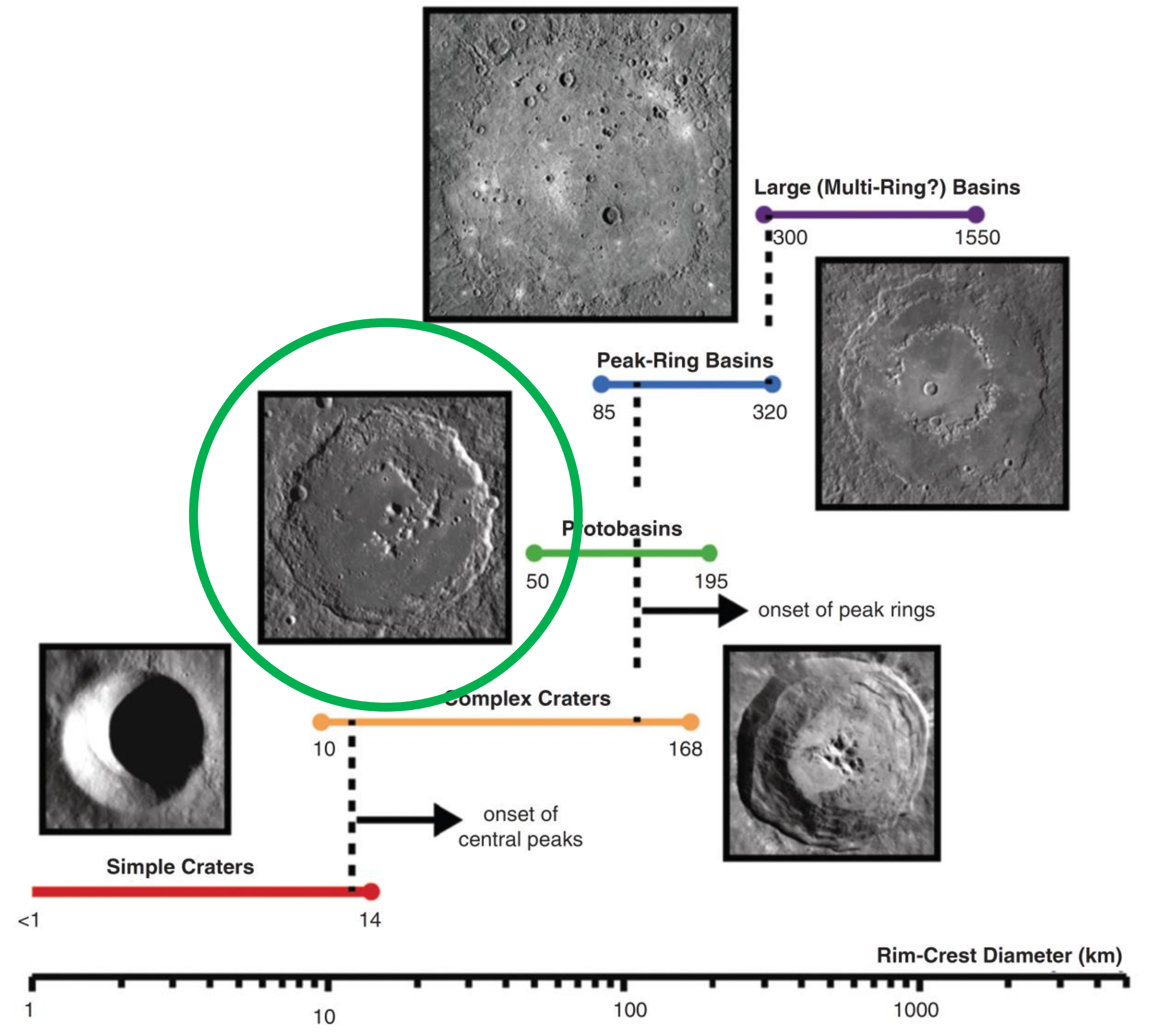


Minton et al. (2019)

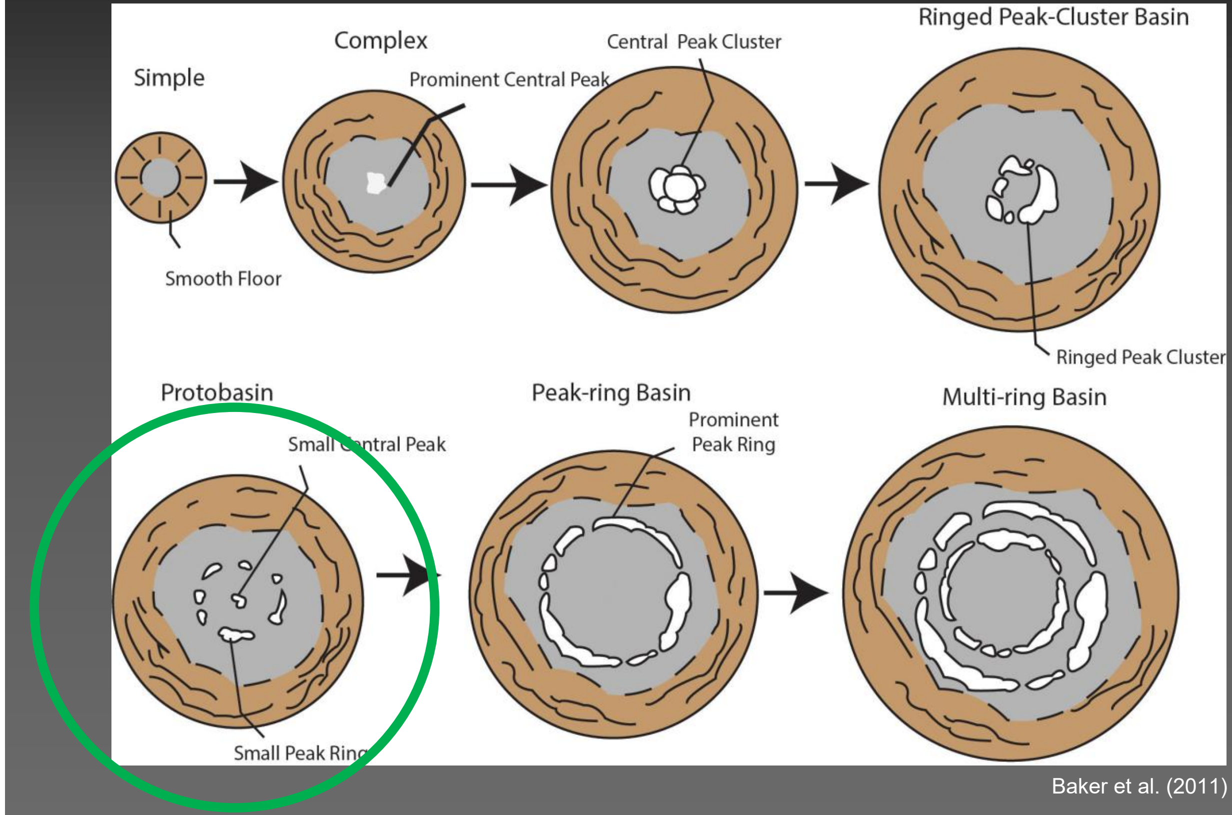
3) Modification

- **SMALLER** craters (*simple craters*): materian on the upper wall slips down the crater center, creating a breaccia lens
- **LARGER** craters (*complex craters with central peak or peak ring*): the crater floor rises, while the wall collapses to form terraces

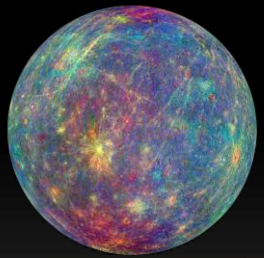
IMPACT CRATERS: MORPHOLOGY



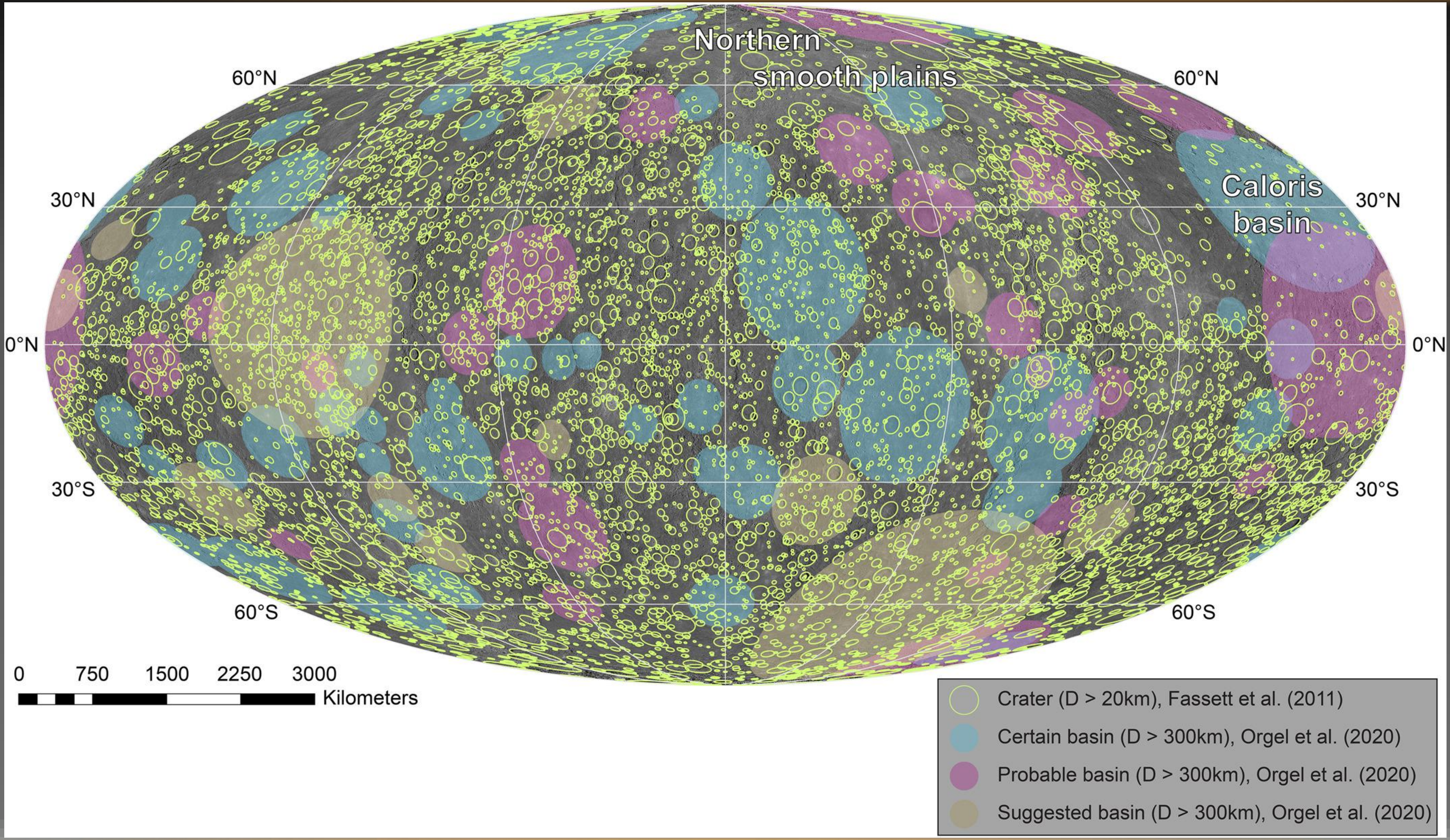
Chapman et al. (2018)



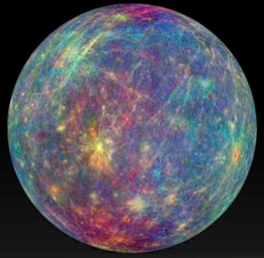
Baker et al. (2011)



IMPACT CRATERS: GLOBAL MAP



Riedel et al. (2021)



IMPACT CRATER: EJECTA

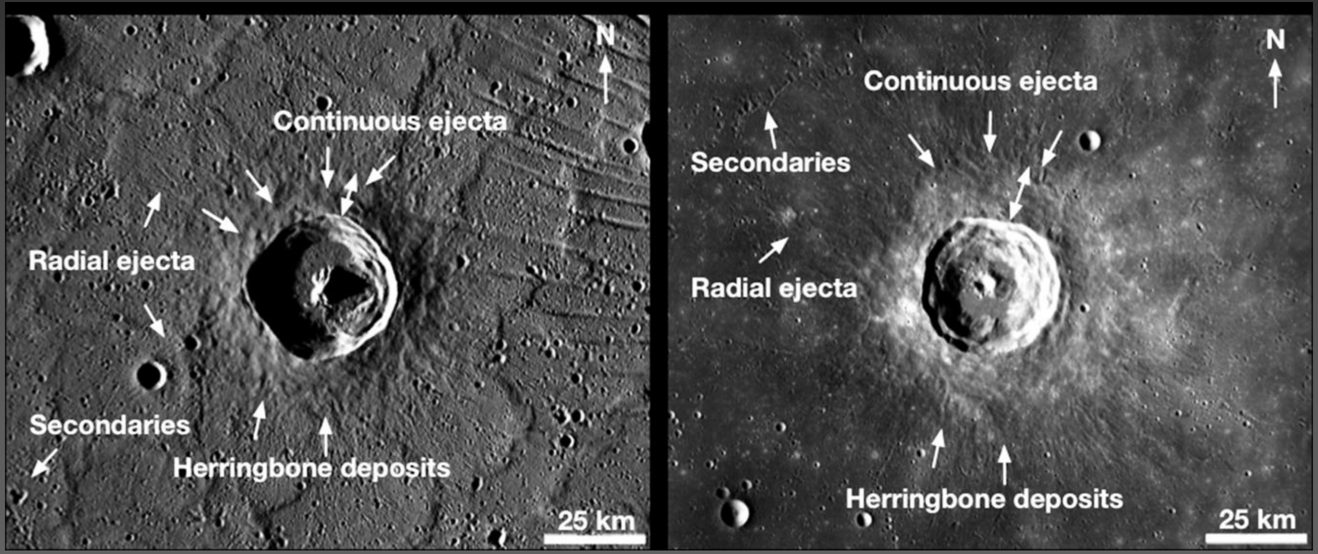
Mercury

Cunningham

D=36 km, 30.4°N, 202.9°E

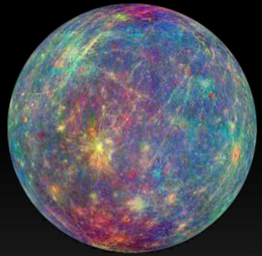
Timocharis

D=34 km, 26.7°N, 246.9°E

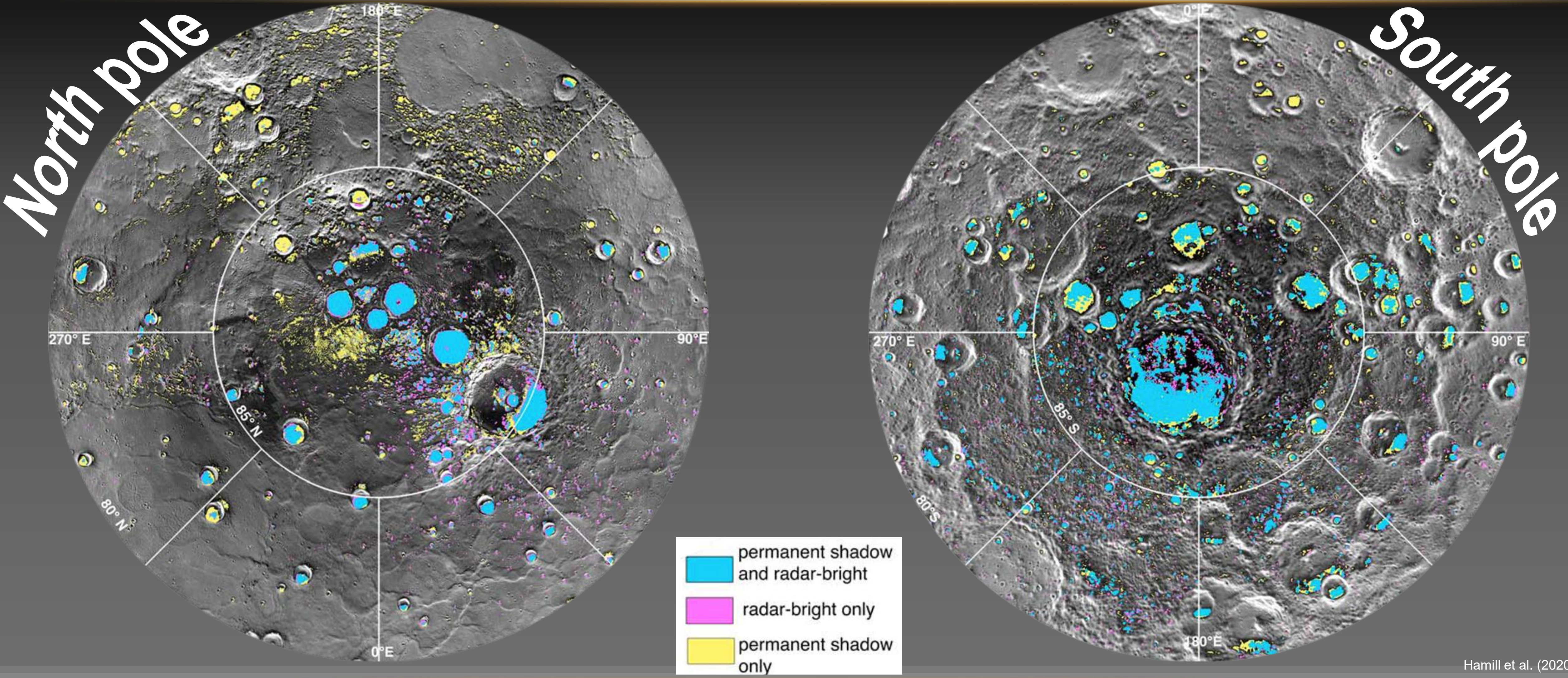


Moon

Chapman et al. (2018)



IMPACT CRATERS: POLAR REGIONS



🟦 permanent shadow and radar-bright

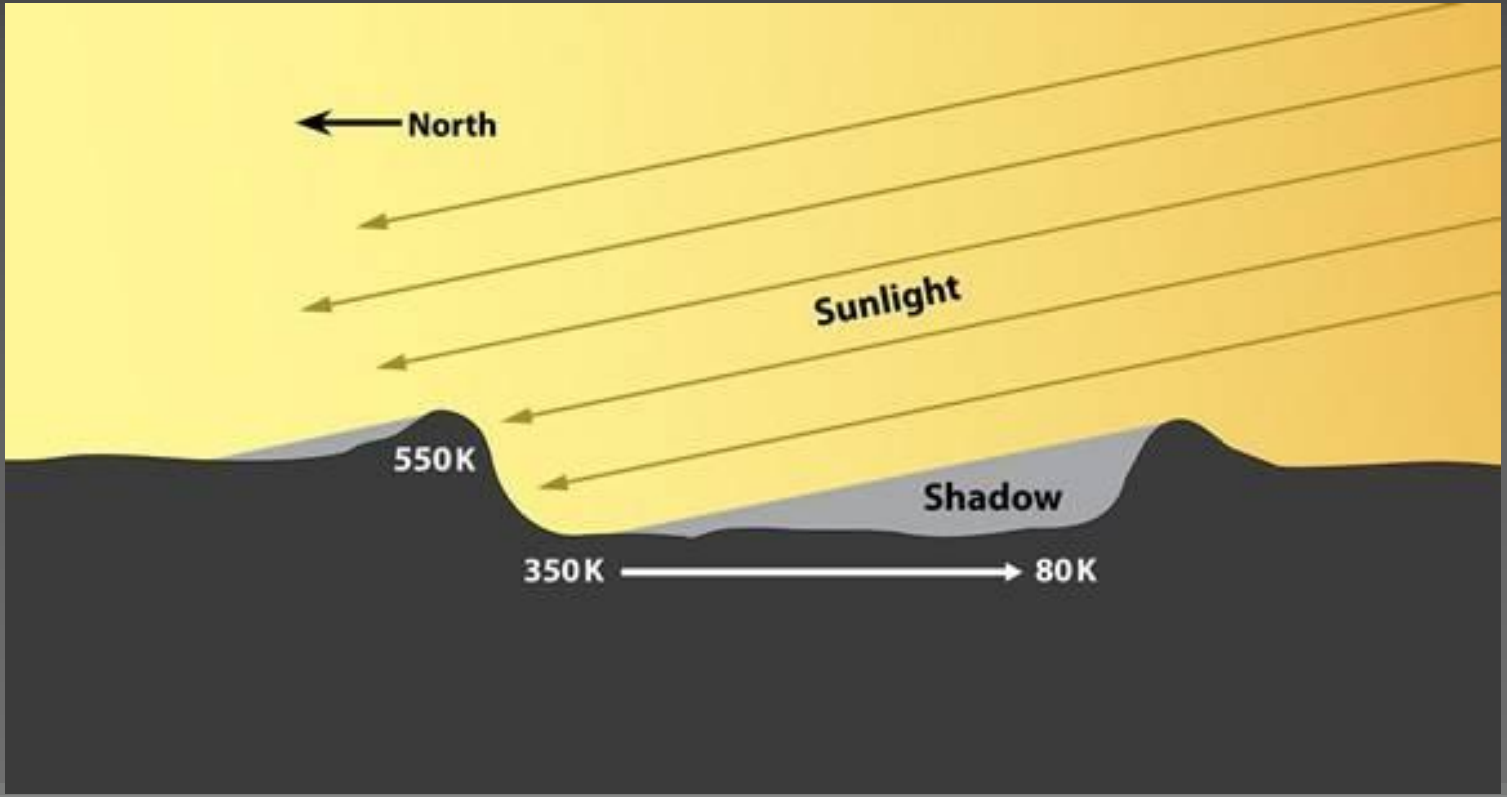
🟪 radar-bright only

🟨 permanent shadow only

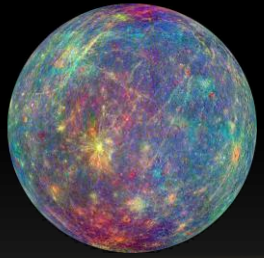
Hamill et al. (2020)

PSRs = PERMANENTLY SHADOWED REGIONs

Areas associated with craters, depressions, and fault scarps located on airless bodies surfaces that are never directly reached by solar flux, due to local rough topography, high latitude, and a small rotation axis obliquity (0.01° ~ 2 arcmin for Mercury)



Credits: NASA /oddard Space Flight Center / John Hopkins Univ.



MOON – MERCURY COMPARISON

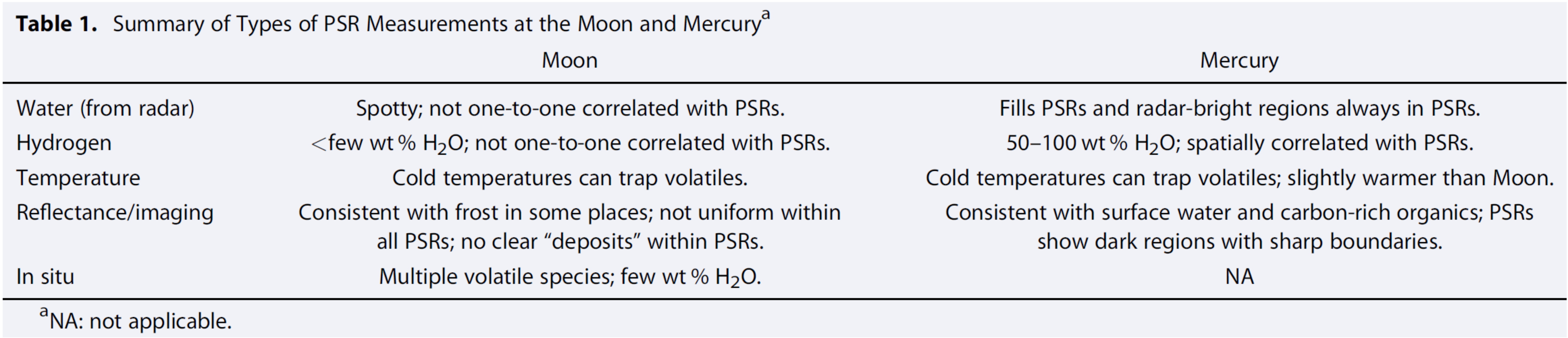


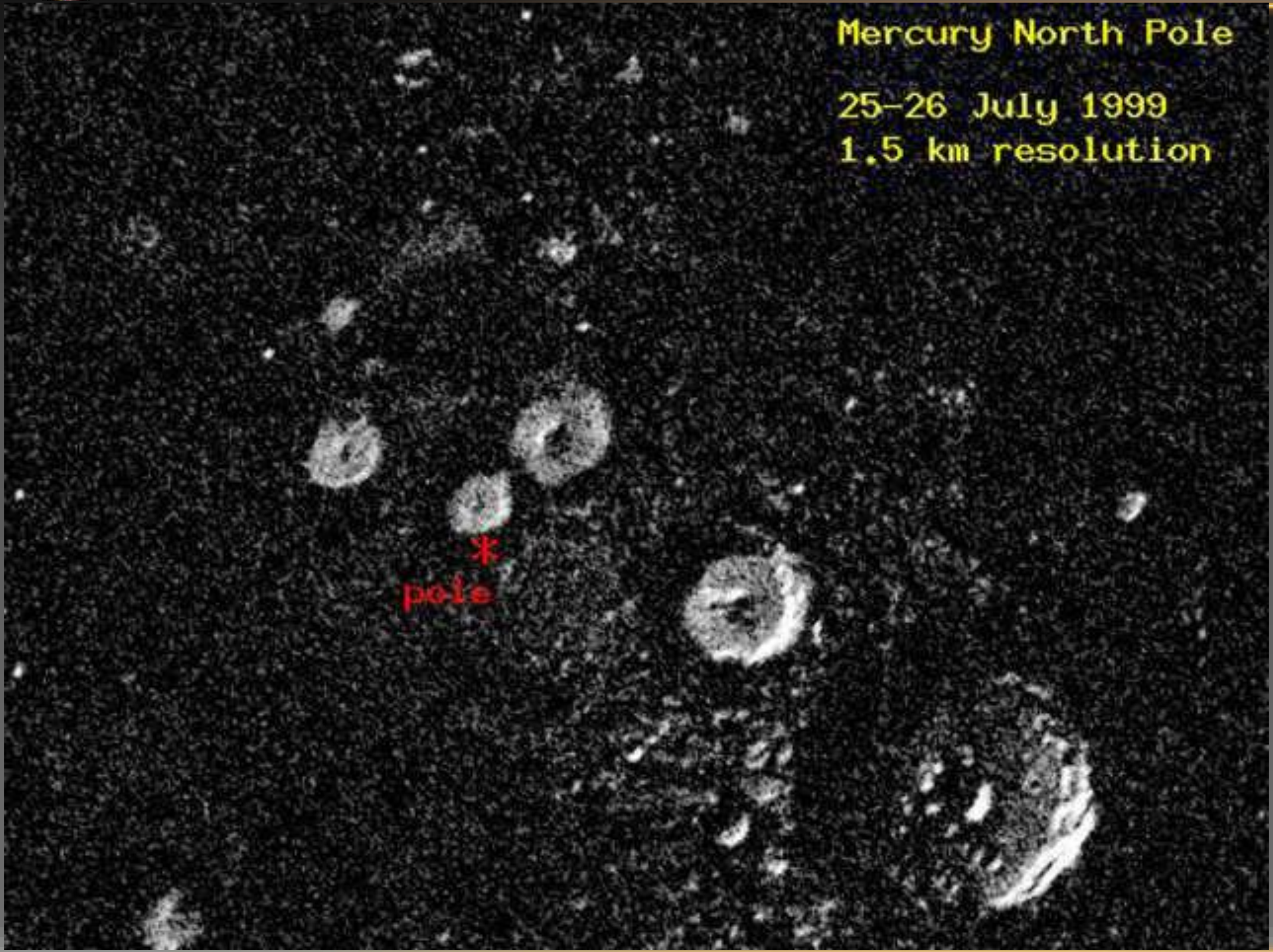
Table 1. Summary of Types of PSR Measurements at the Moon and Mercury[a]

	Moon	Mercury
Water (from radar)	Spotty; not one-to-one correlated with PSRs.	Fills PSRs and radar-bright regions always in PSRs.
Hydrogen	$<$few wt % H_2O; not one-to-one correlated with PSRs.	50–100 wt % H_2O; spatially correlated with PSRs.
Temperature	Cold temperatures can trap volatiles.	Cold temperatures can trap volatiles; slightly warmer than Moon.
Reflectance/imaging	Consistent with frost in some places; not uniform within all PSRs; no clear “deposits” within PSRs.	Consistent with surface water and carbon-rich organics; PSRs show dark regions with sharp boundaries.
In situ	Multiple volatile species; few wt % H_2O.	NA

[a] NA: not applicable.

Lawrence et al. (2016)

OBSERVATIONS 1: RADAR REFLECTIVITY

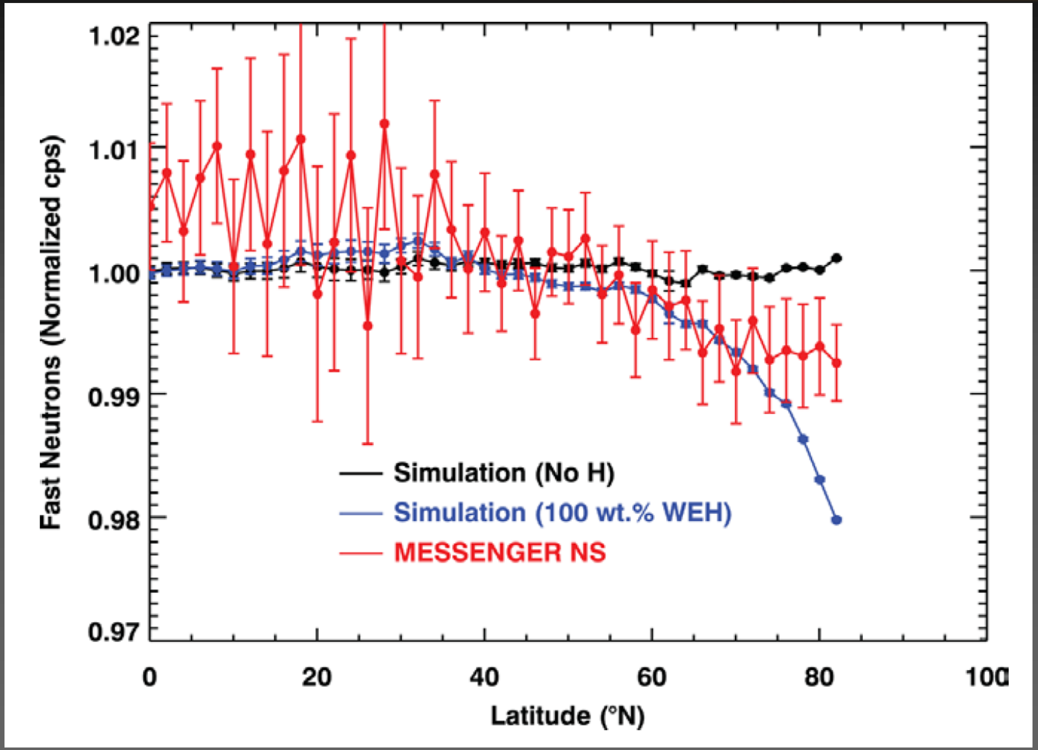


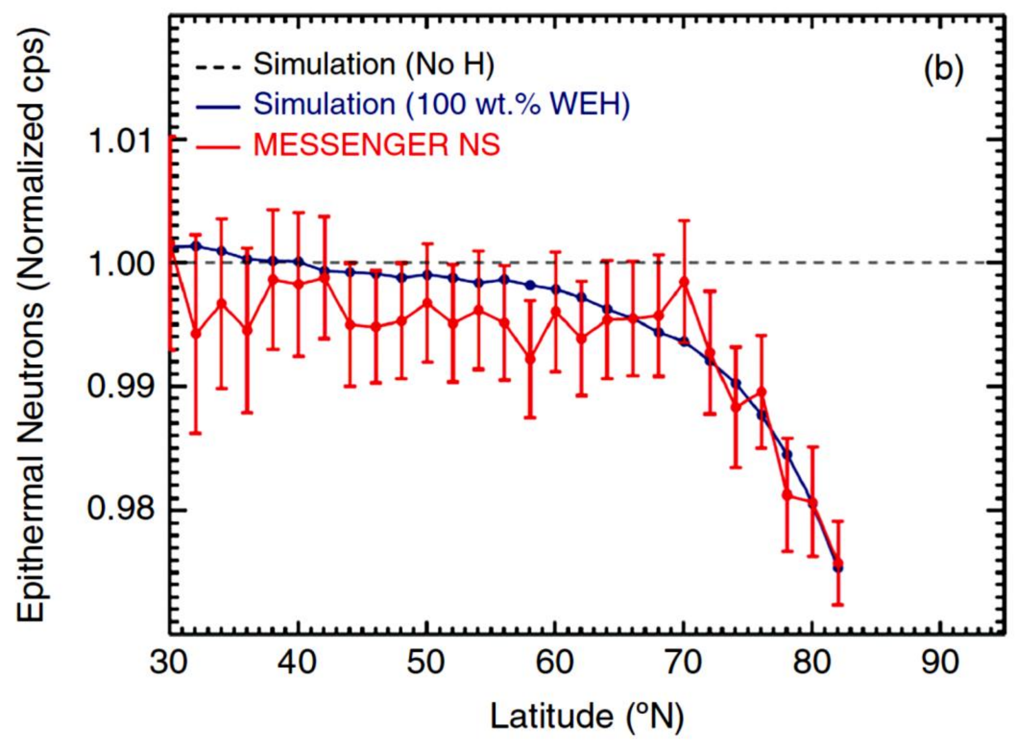
1991 Goldston-m radio antenna and subsequently Arecibo radar observations:

high radar backscattered and circular polarization ratios

Harmony et al. (2011)

OBSERVATIONS 2: MESSENGER NEUTRON SPECTROMETER

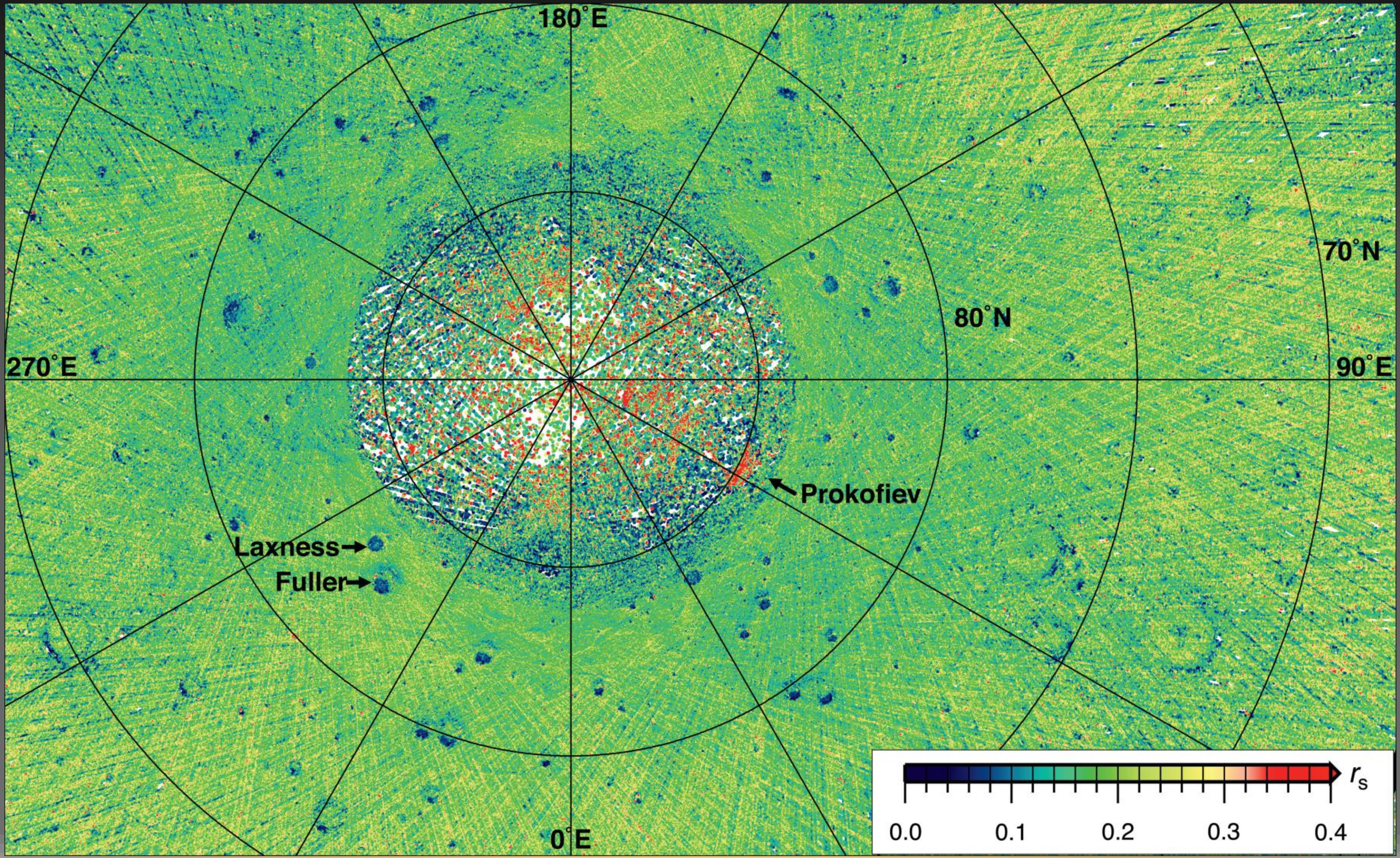




Lawrence et al. (2013)

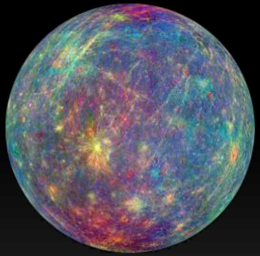
- ☐ Neutrons are created by nuclear spallation reactions when high-energy cosmic rays strike the surface of an airless planetary body.
- ☐ Momentum transfer between hydrogen and neutron causes the number of epithermal neutrons to be strongly depressed so that they are highly sensitive to the presence of hydrogen in planetary materials

OBSERVATIONS 3:
MERCURY LASER ALTIMETER REFLECTANCE



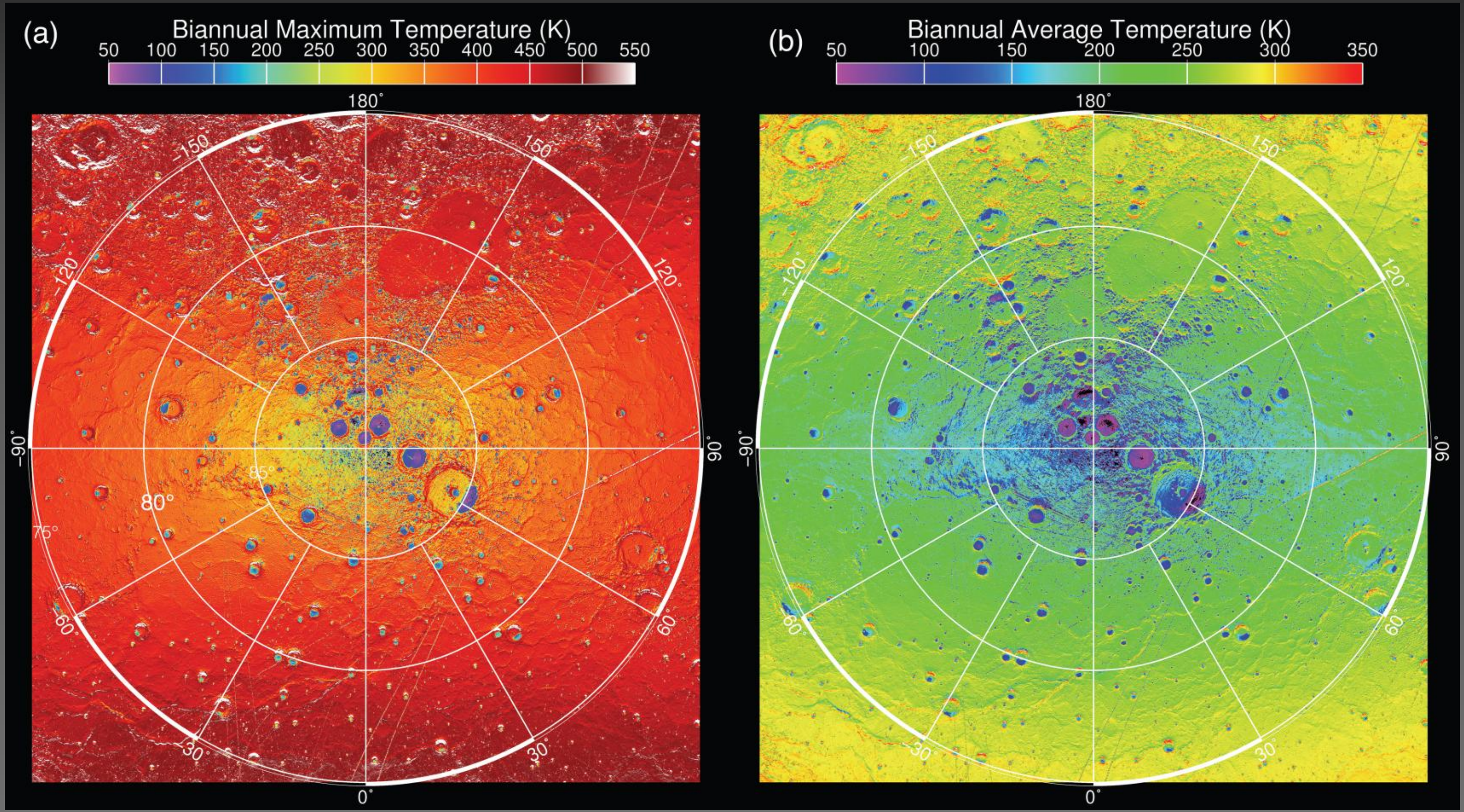
Neumann et al. (2013)

Surface reflectance

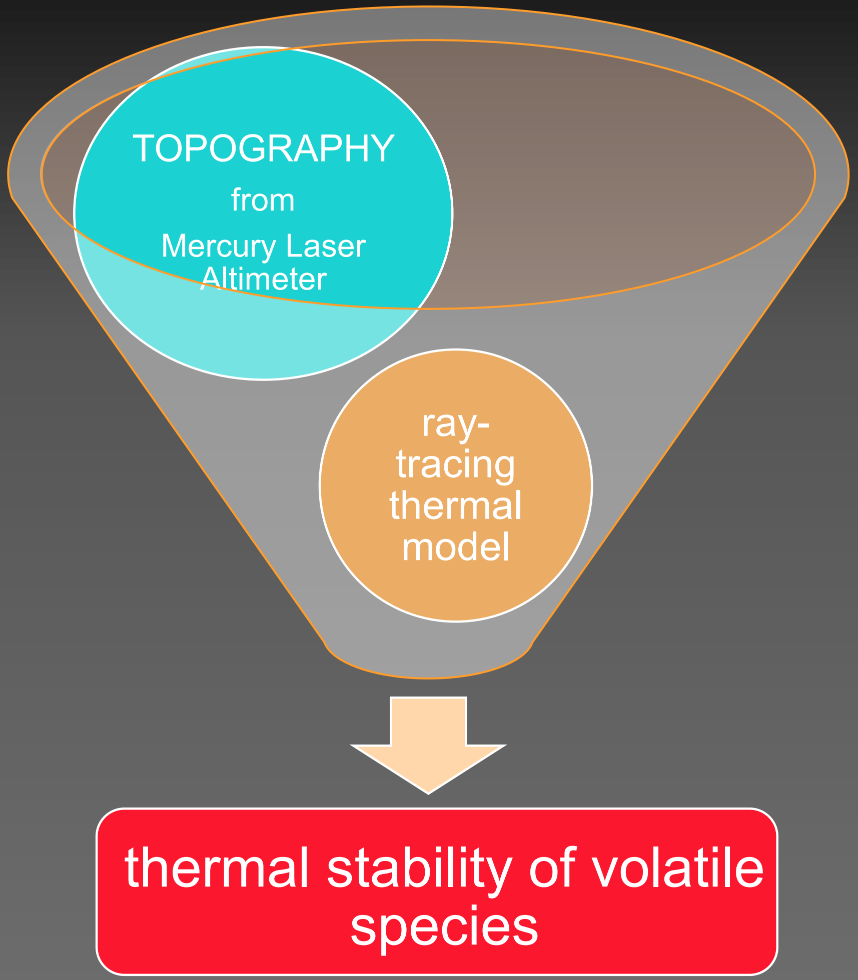


OBSERVATIONS 4: TEMPERATURES

maximum surface temperatures in large craters at high latitudes are sufficiently low to permit water ice deposits to be stable at the surface for geologically long intervals



Paige et al. (2013)



TOPOGRAPHY
from
Mercury Laser Altimeter

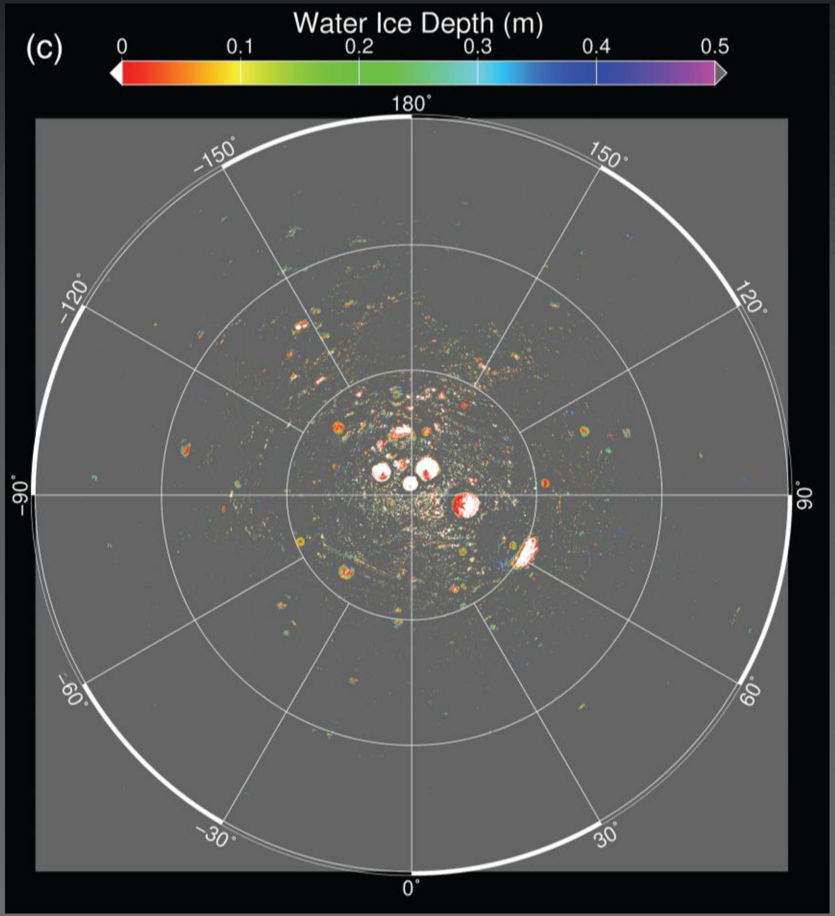
ray-tracing thermal model

thermal stability of volatile species

OBSERVATIONS 5: ICE STABILITY

COLD TRAPS

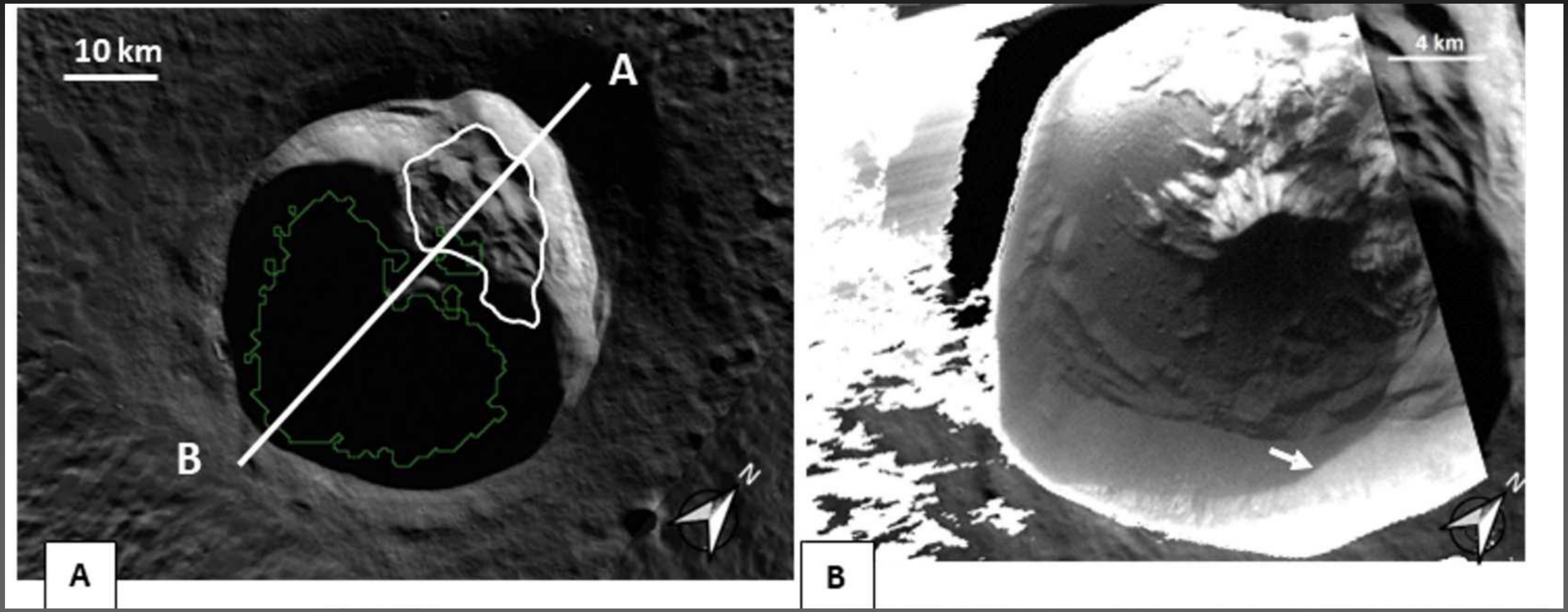
preserve volatile substances, such as water ice, for geologic time periods



Paige et al. (2013)

water ice deposits equatorward of 83°N would be thermally stable only if buried beneath a ~10-cm thick layer of low-reflectance, low-conductivity, ice-free, soil-like material

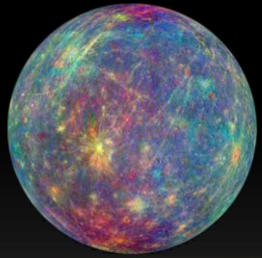
OBSERVATIONS 6: POLAR CRATER MORPHOLOGY



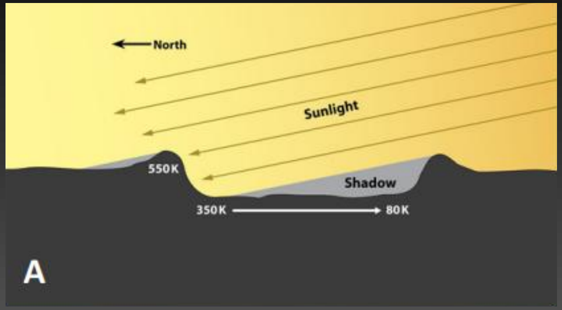
Bertoli et al. (2024)

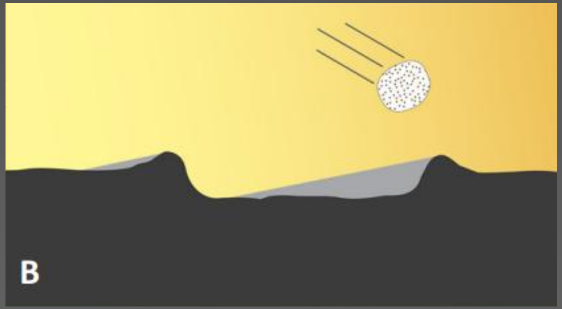
presence of bright and low-reflectance zones with sharp boundaries

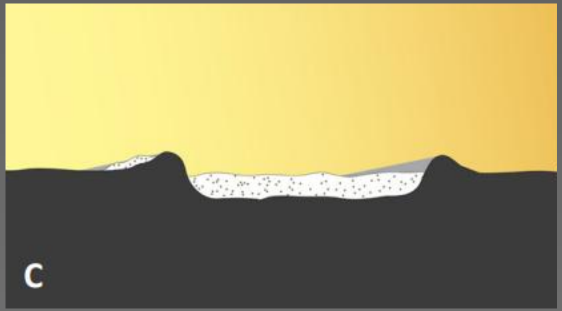
thermal modelling suggests that ice deposits can be both exposed at the surface and insulated by 10−30 cm of a carbon-rich material sublimation lag

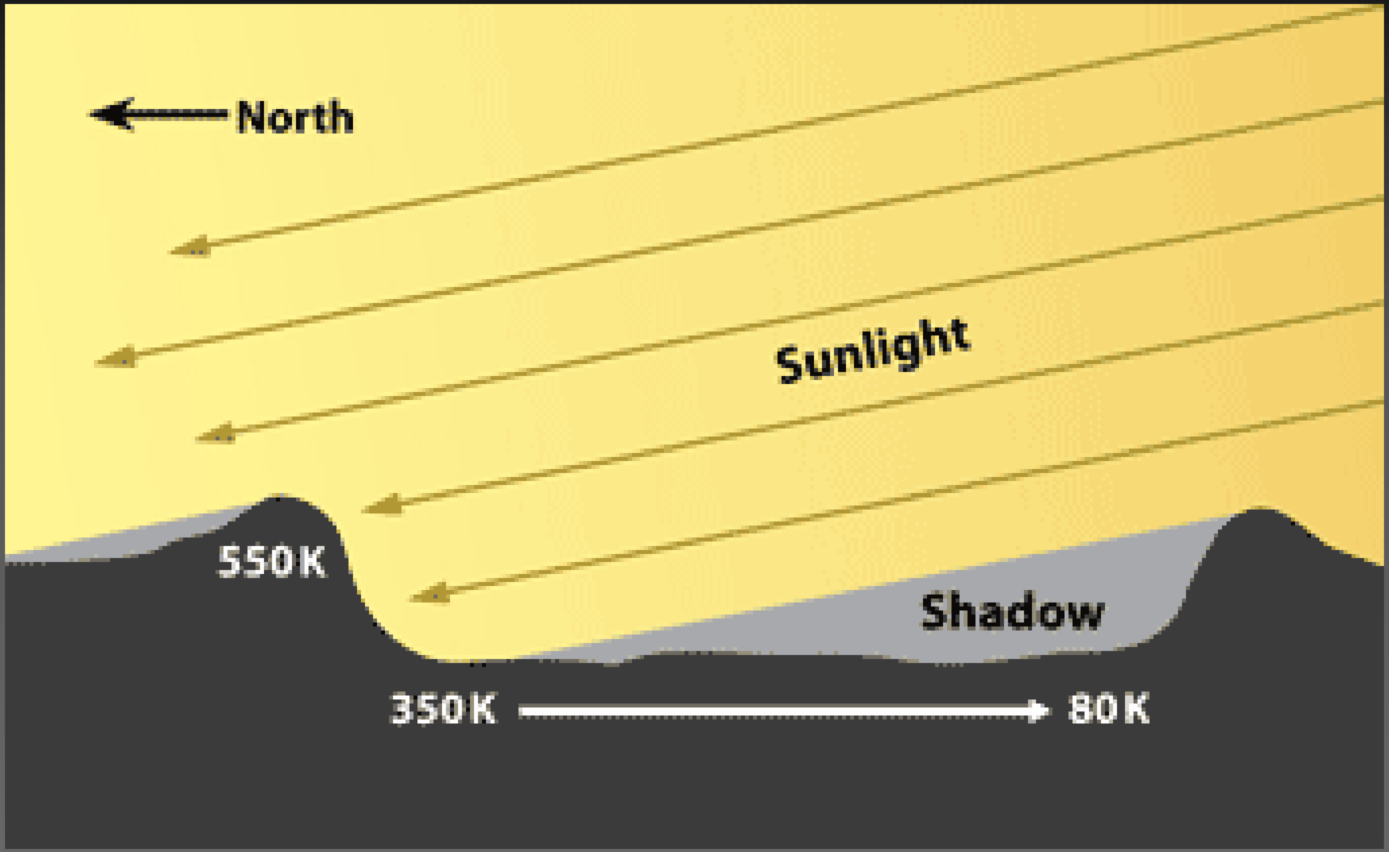


ICE DEPOSITS FORMATION

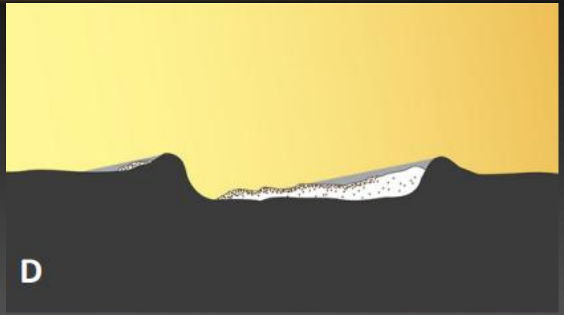


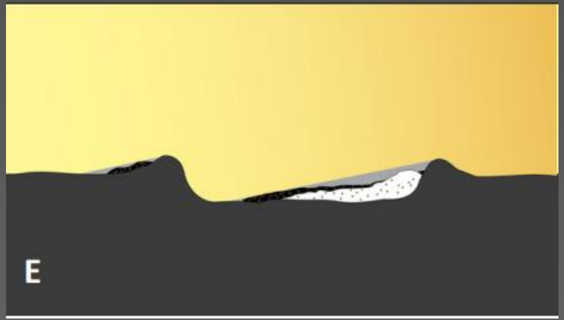


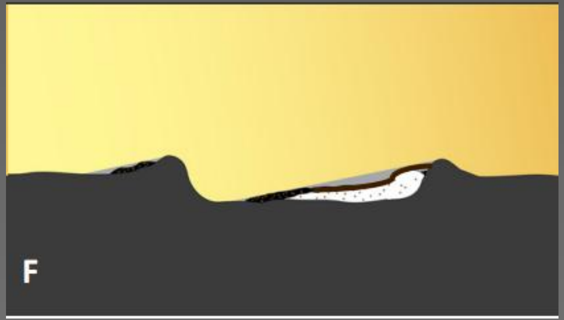


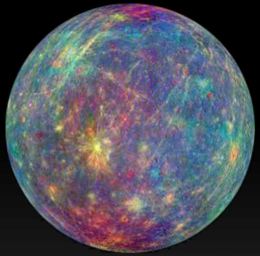


Credits:
NASA / UCLA / JHU-APL /
Carnegie Inst. of Washington

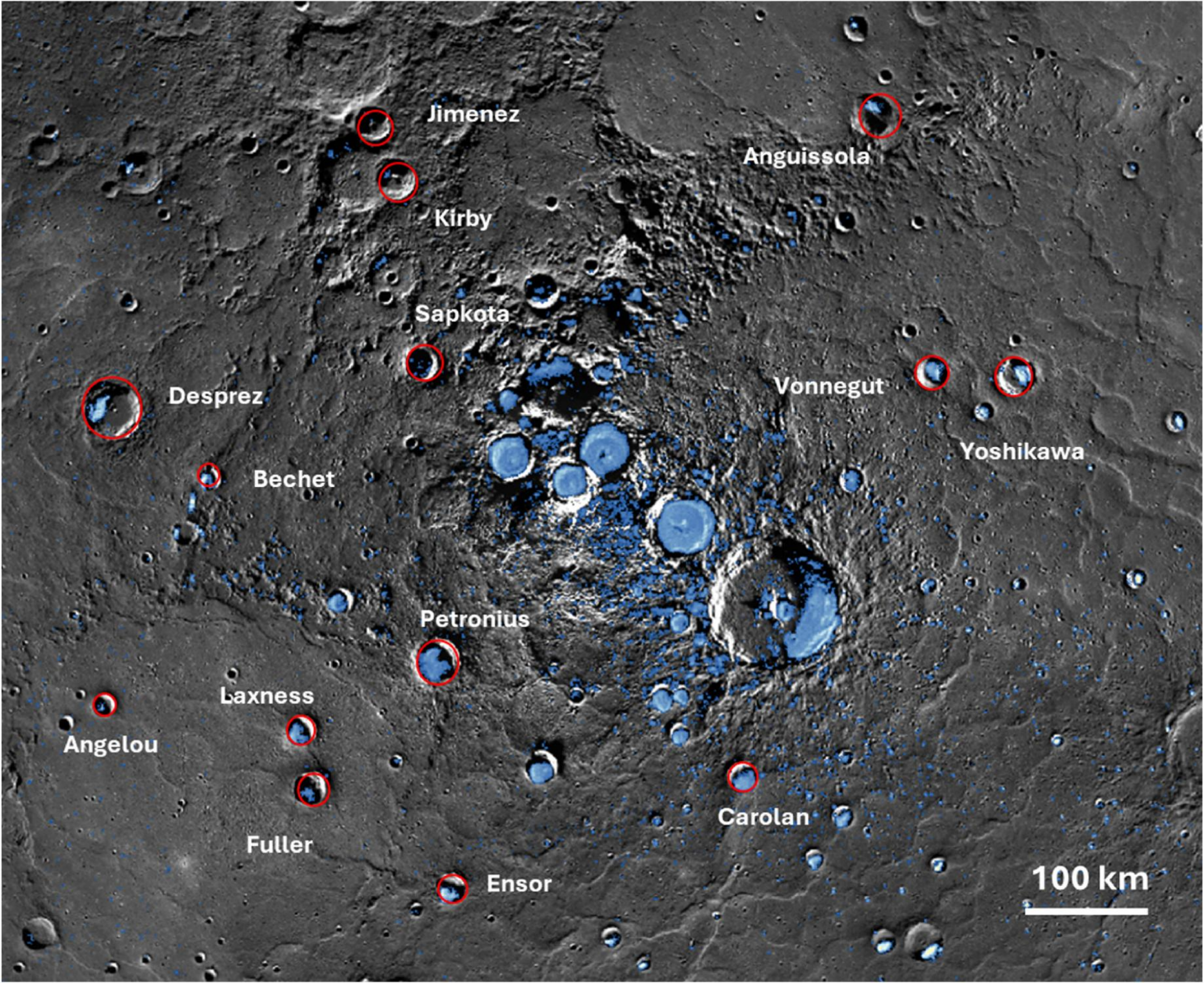




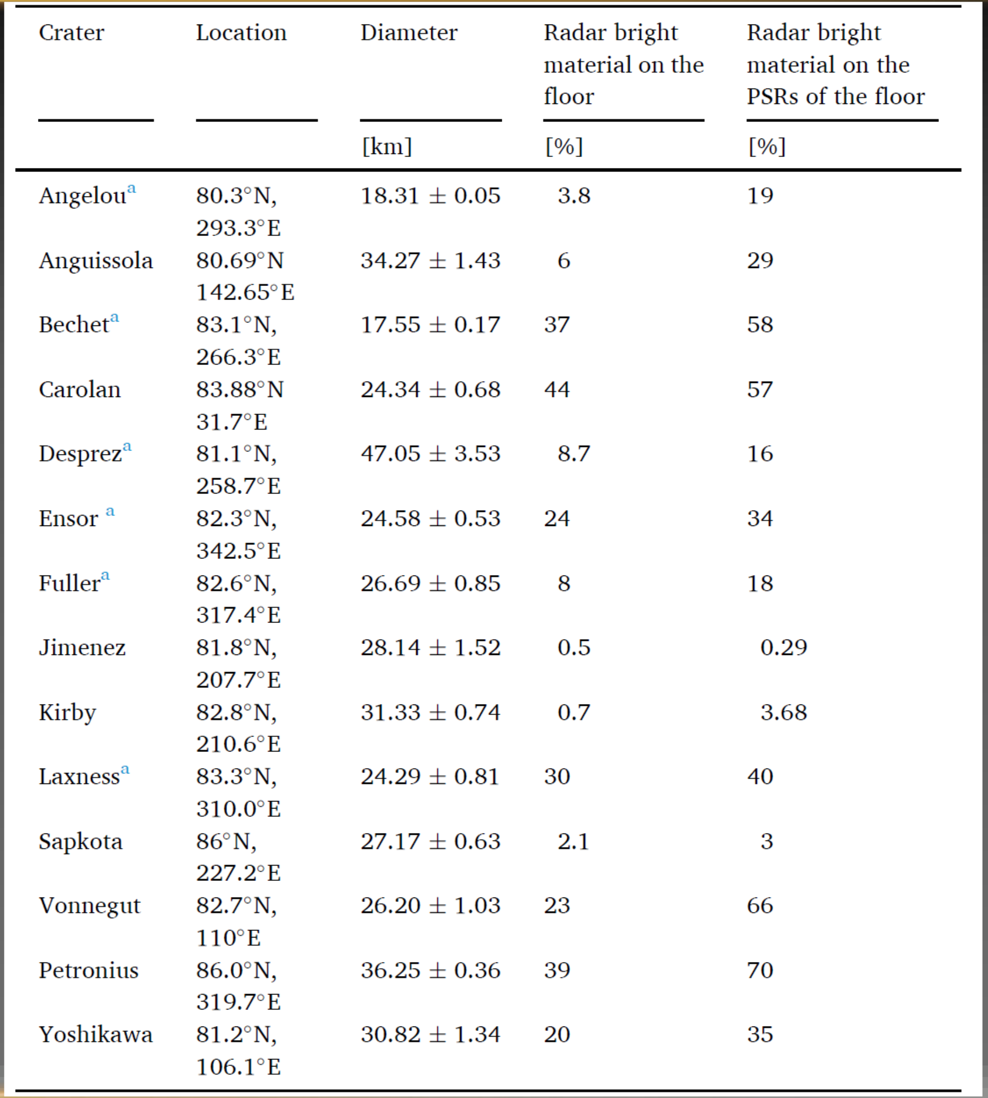




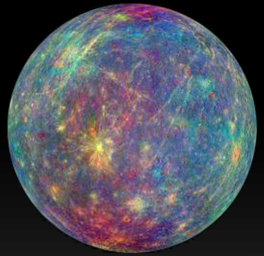
A CLOSER LOOK ON THE POLAR CRATERS



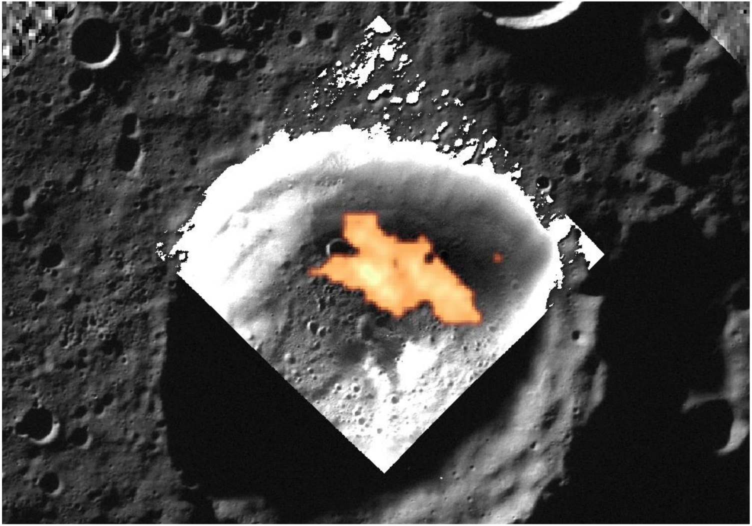
Bertoli et al.
(2024, 2025)



Crater	Location	Diameter	Radar bright material on the floor	Radar bright material on the PSRs of the floor
		[km]	[%]	[%]
Angelou[a]	80.3°N, 293.3°E	18.31 ± 0.05	3.8	19
Anguissola	80.69°N 142.65°E	34.27 ± 1.43	6	29
Bechet[a]	83.1°N, 266.3°E	17.55 ± 0.17	37	58
Carolan	83.88°N 31.7°E	24.34 ± 0.68	44	57
Desprez[a]	81.1°N, 258.7°E	47.05 ± 3.53	8.7	16
Ensor [a]	82.3°N, 342.5°E	24.58 ± 0.53	24	34
Fuller[a]	82.6°N, 317.4°E	26.69 ± 0.85	8	18
Jimenez	81.8°N, 207.7°E	28.14 ± 1.52	0.5	0.29
Kirby	82.8°N, 210.6°E	31.33 ± 0.74	0.7	3.68
Laxness[a]	83.3°N, 310.0°E	24.29 ± 0.81	30	40
Sapkota	86°N, 227.2°E	27.17 ± 0.63	2.1	3
Vonnegut	82.7°N, 110°E	26.20 ± 1.03	23	66
Petronius	86.0°N, 319.7°E	36.25 ± 0.36	39	70
Yoshikawa	81.2°N, 106.1°E	30.82 ± 1.34	20	35

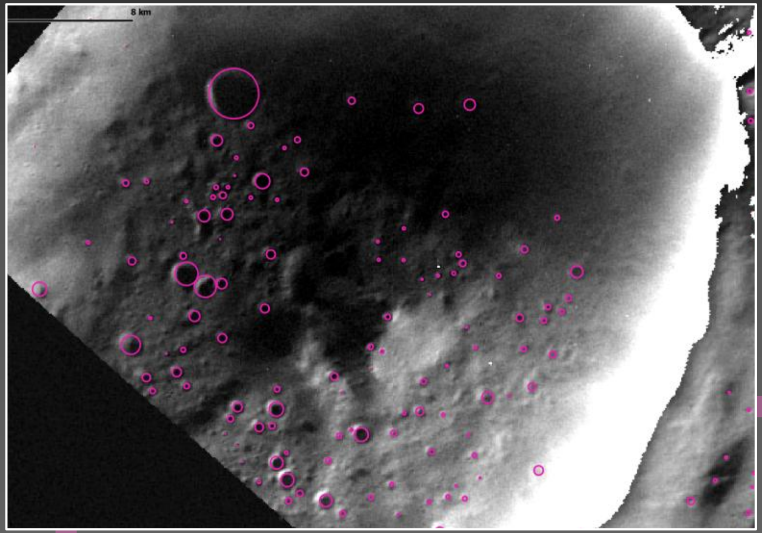


PROJECT METHODLOGIES



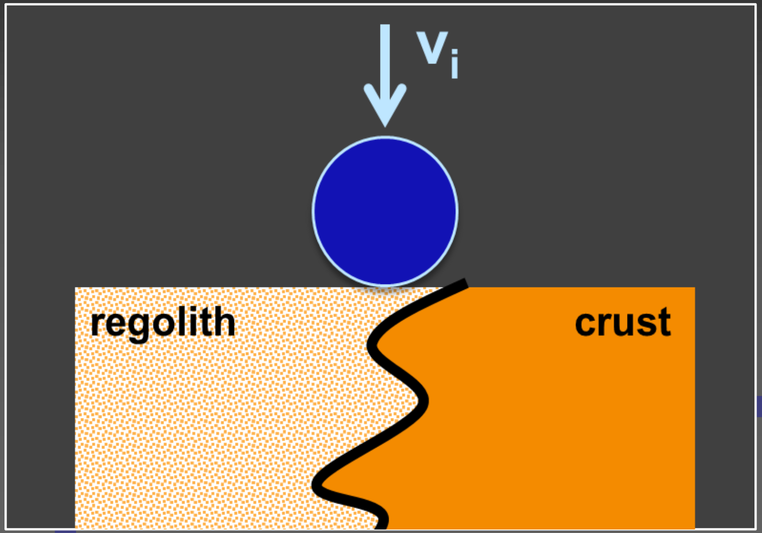
QGIS:

geological mapping and photointerpretation



CRATERSTAT + Le Feuvre & Wieczorek (2011):

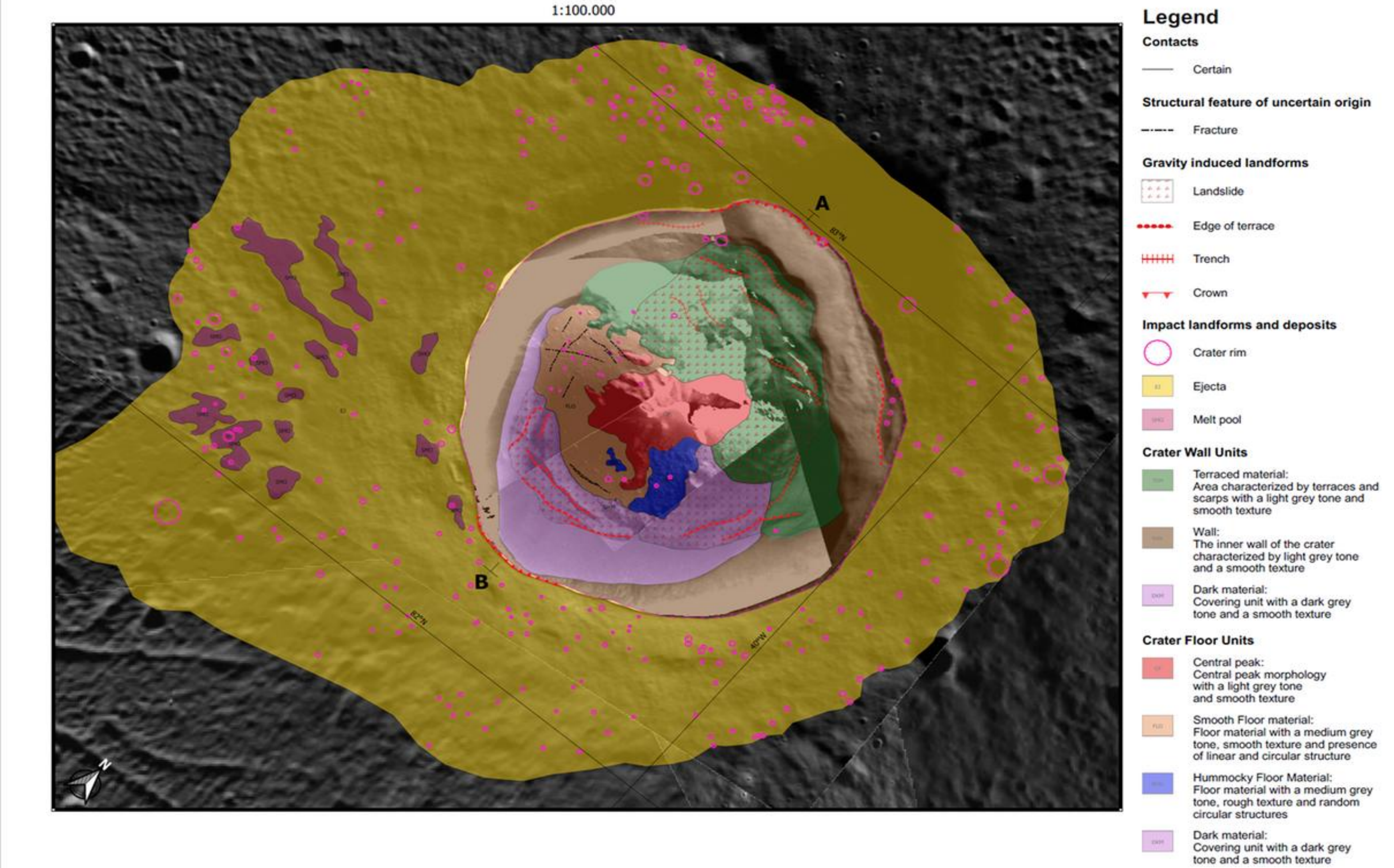
crater counting for datation

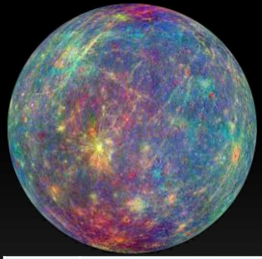


iSALE shock physics code:

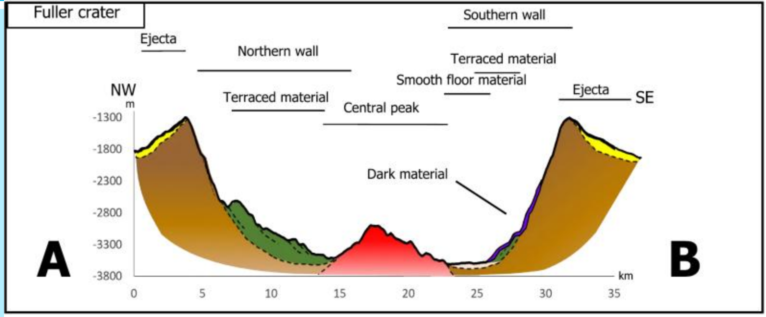
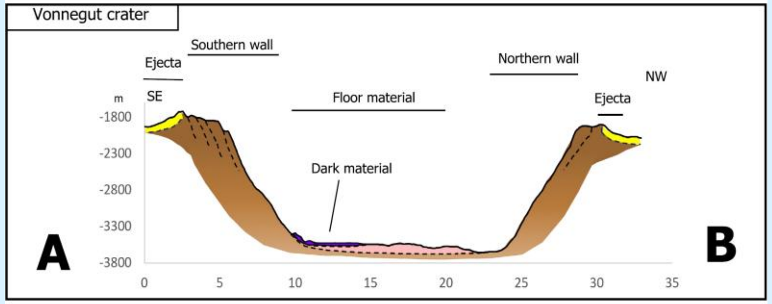
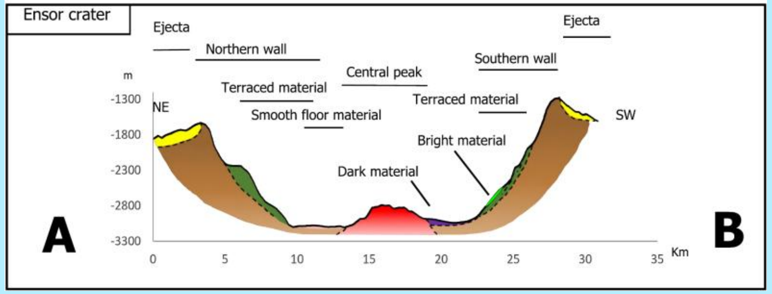
https://isale-code.github.io

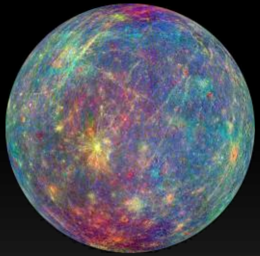
numerical modeling


1:100.000
A
B
Legend
Contacts
Certain
Structural feature of uncertain origin
Fracture
Gravity induced landforms
Landslide
Edge of terrace
Trench
Crown
Impact landforms and deposits
Crater rim
Ejecta
Melt pool
Crater Wall Units
Terraced material: Area characterized by terraces and scarps with a light grey tone and smooth texture
Wall: The inner wall of the crater characterized by light grey tone and a smooth texture
Dark material: Covering unit with a dark grey tone and a smooth texture
Crater Floor Units
Central peak: Central peak morphology with a light grey tone and smooth texture
Smooth Floor material: Floor material with a medium grey tone, smooth texture and presence of linear and circular structure
Hummocky Floor Material: Floor material with a medium grey tone, rough texture and random circular structures
Dark material: Covering unit with a dark grey tone and a smooth texture

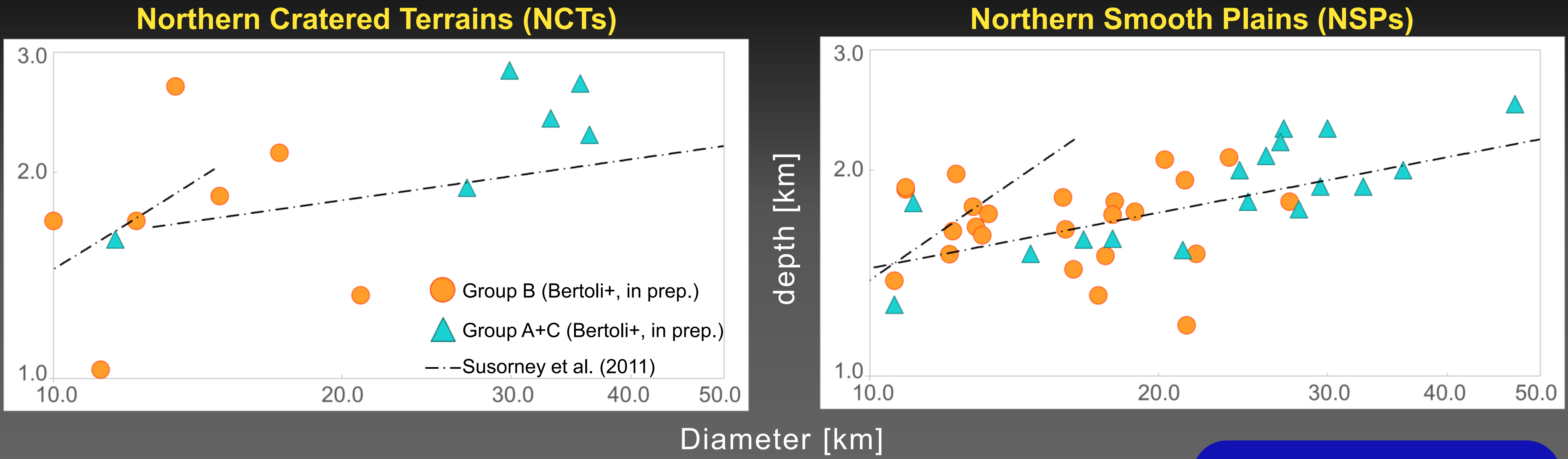


MAP AGE MODEL

	Morphological Group	Crater Examples	Crater Characteristics	Topographic Profile Bertoli et al. (2024)
A	Complex morphology	Fuller, Laxness, Kirby, Jimenez, Yoshikawa	• well defined central peak (height > 500 m) • localized landslide and terraces • flat floor covered in part by slumped material	
B	No-complex morphology	Bechet, Angelou, Vonnegut	• no central peak • few terraces • flat floor covered in part by slumped material, rarely terraced	
C	Uncomplete complex morphology	Desprez, Petronius, Anguissola, Sapkota, Carolan, Ensor	• poorly defined central peak (height < 500 m) • terraced walls • flat floor covered by impact and/or slumped material	

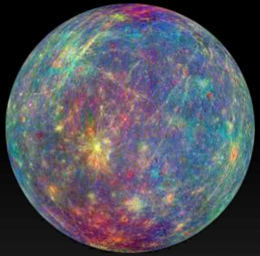


MAP AGE MODEL

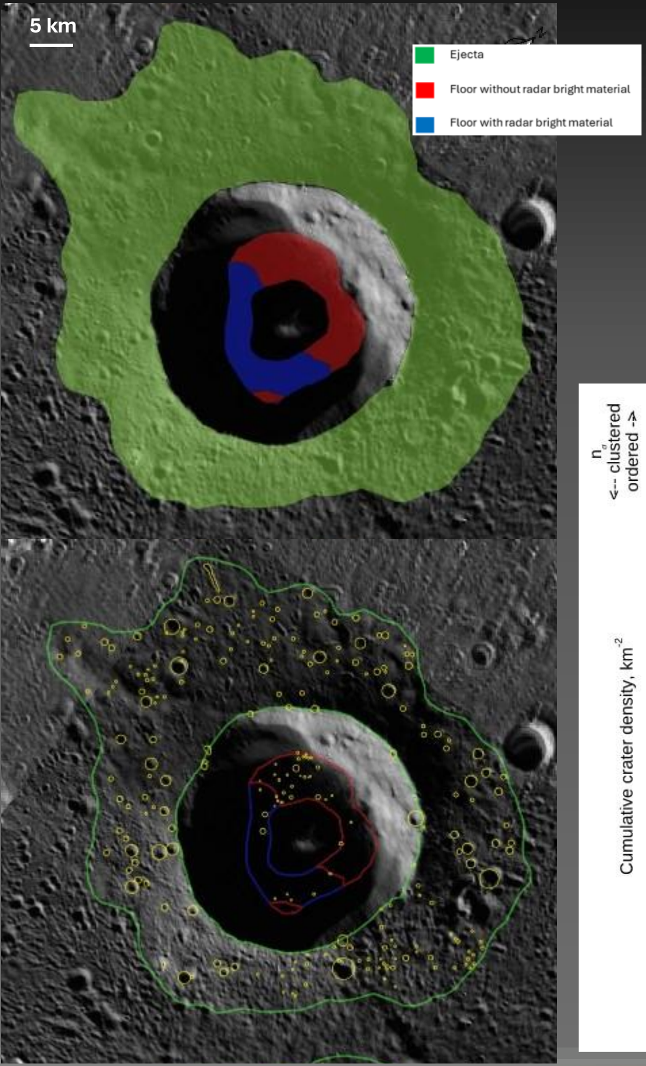


- ❑ in the NCTs, the complex morphology seems to onset at crater diameter of ~30 km;
- ❑ in the NSPs, the complex and transitional morphologies coexist in the diameter range between 10 km (the theoretical onset value) and 25 km, value at which the complex morphology seems to take the lead.

➡ more plastic and weaker surface in the northern regions, which could be given by the presence of ice mixed with regolith



MAP AGE MODEL

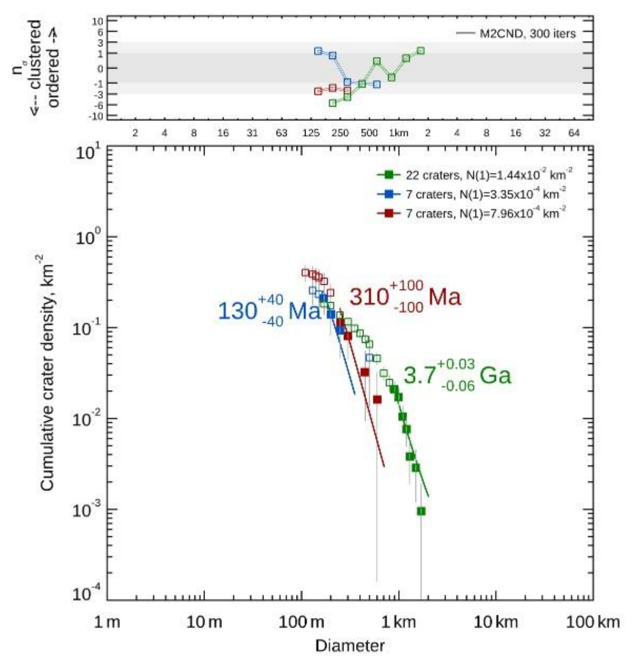


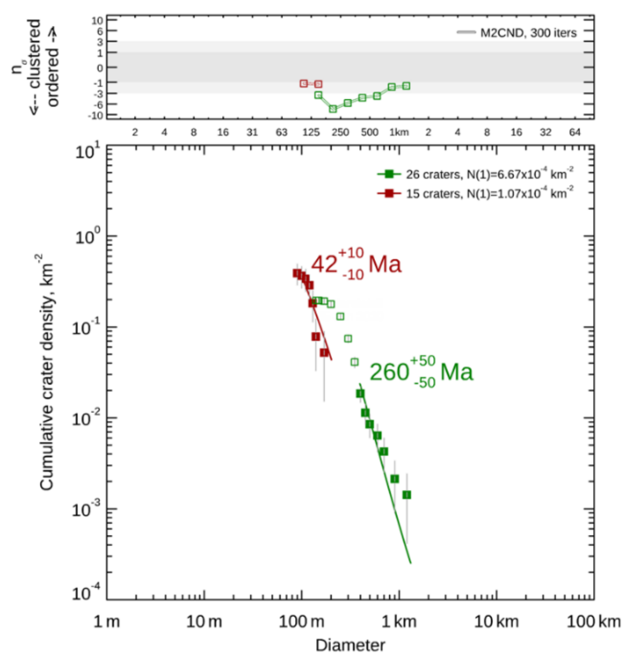
Laxness

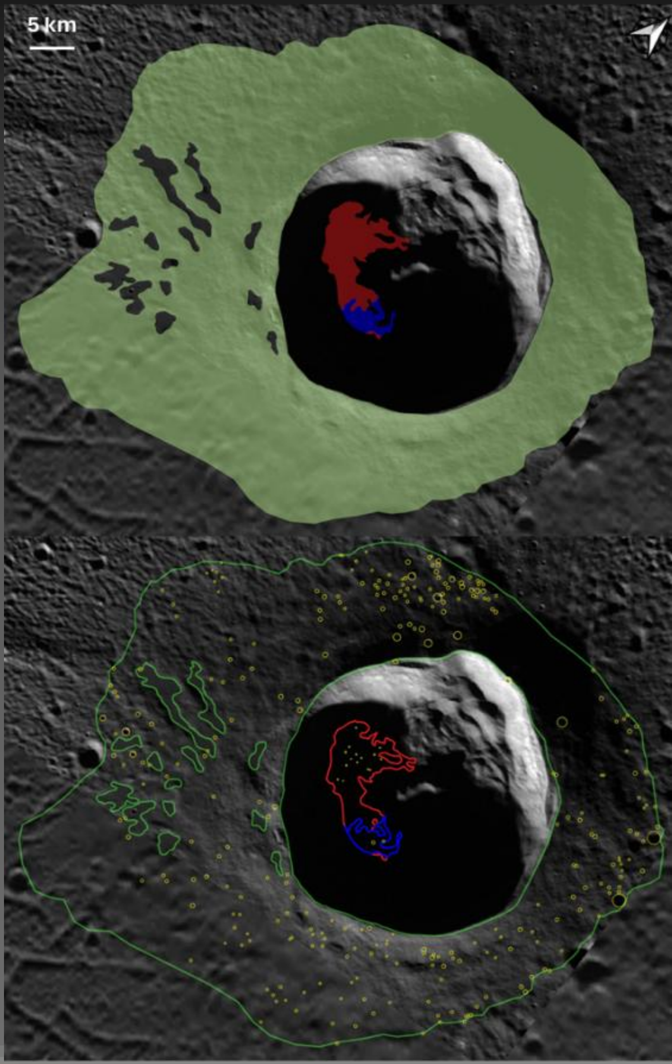
D = 26 km

Fuller

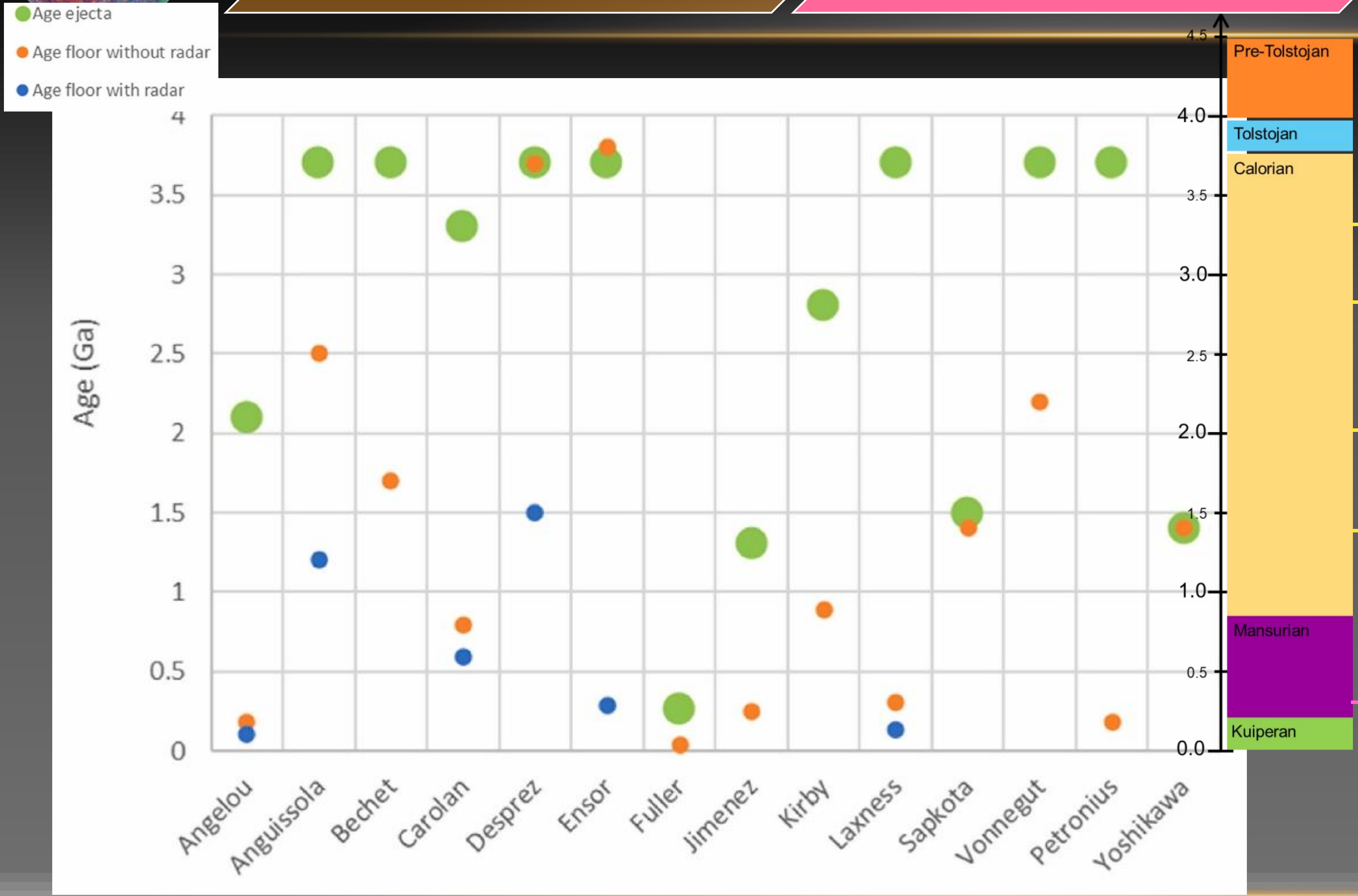
D = 27 km







MAP AGE MODEL



Desprez, Petronius, Bechet, Vonnegut, Enson, Laxness, Anguissola

Carolan

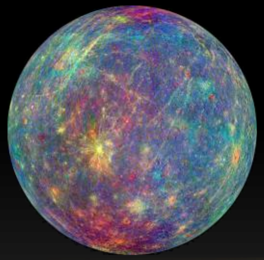
Kirby

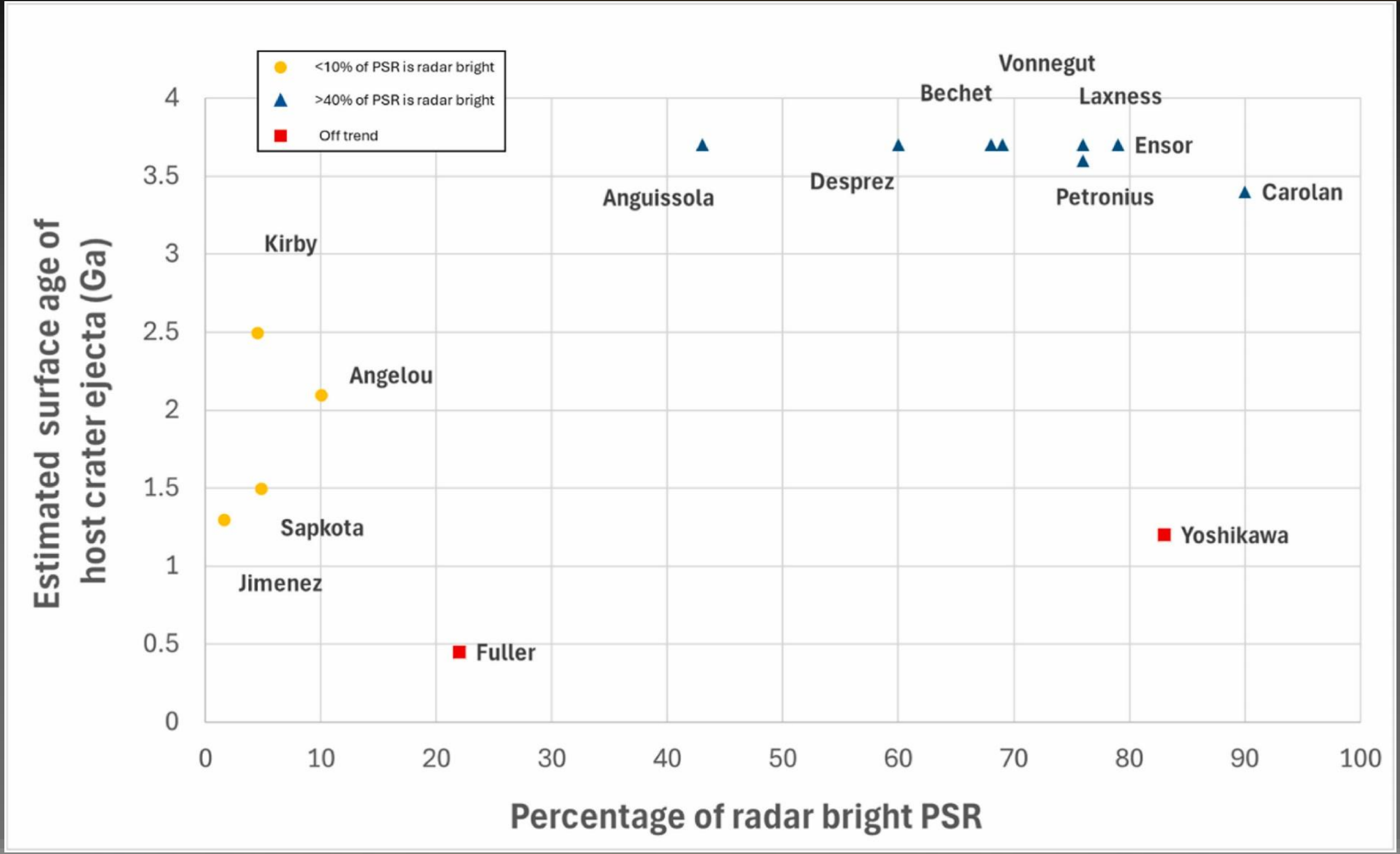
Sapkota, Angelou

Jimenez, Yoshikawa

Fuller

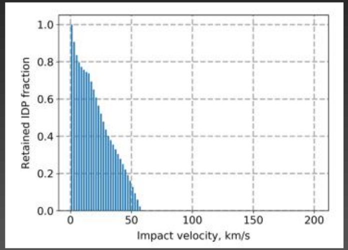
general rejuvenation of the floors containing radar-bright material



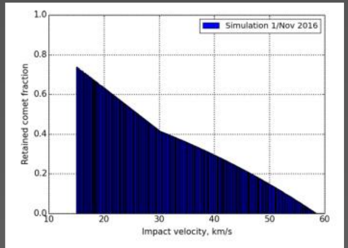

● <10% of PSR is radar bright
▲ >40% of PSR is radar bright
■ Off trend
Estimated surface age of host crater ejecta (Ga)
0
0.5
1
1.5
2
2.5
3
3.5
4
Percentage of radar bright PSR
0
10
20
30
40
50
60
70
80
90
100
Kirby
Angelou
Sapkota
Jimenez
Fuller
Anguissola
Desprez
Bechet
Vonnegut
Laxness
Ensor
Petronius
Carolan
Yoshikawa

ICE SOURCES

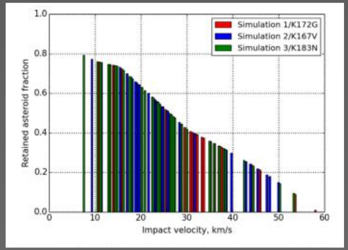
continuous flux of water-bearing micrometeoroids



IDPs: 16×10^3 kg/yr



comets: 1×10^3 kg/yr



hydrated asteroids: 1×10^3 kg/yr

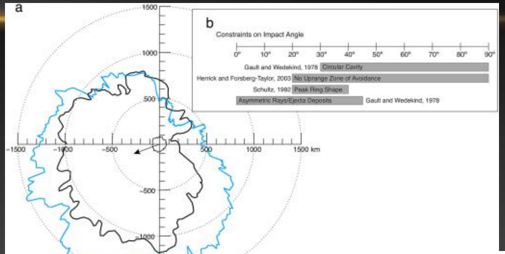
Frantseva et al. (2022)

Total deposition over 3.7 Ga ≈6×10^{13} kg

few individual and large impacts of comets and/or hydrated asteroids

HOUKUSAI crater

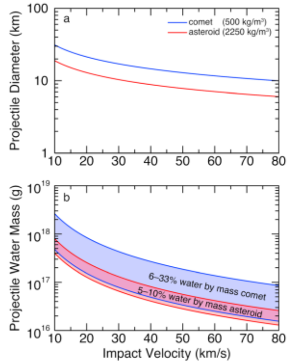
D = 97 km



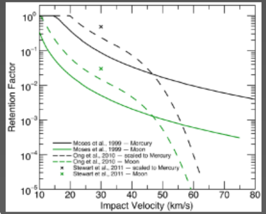
Projectile:

D = 6÷30 km

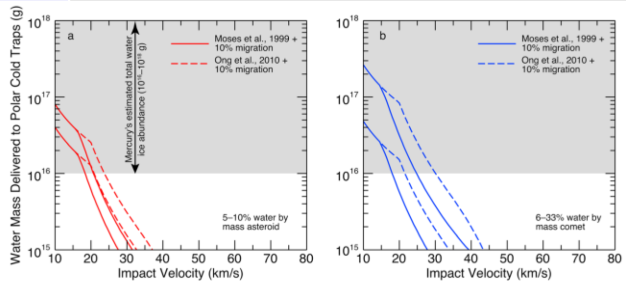
v = 42 km/s & α=35°



Water retention: ~3% Mass for a 2-km comet at 30 km/s



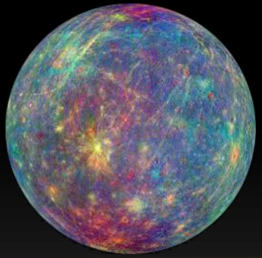
Water migration survival rate: 5—15%



Ernst et al. (2018)

Total deposition ≈1×10^{13} kg of ice to the north pole

total ice inventory on Mercury around 10^{13}–10^{15}



MAP AGE MODEL

Impactor 1

continuous flux of water-bearing micrometeoroids

ice delivery

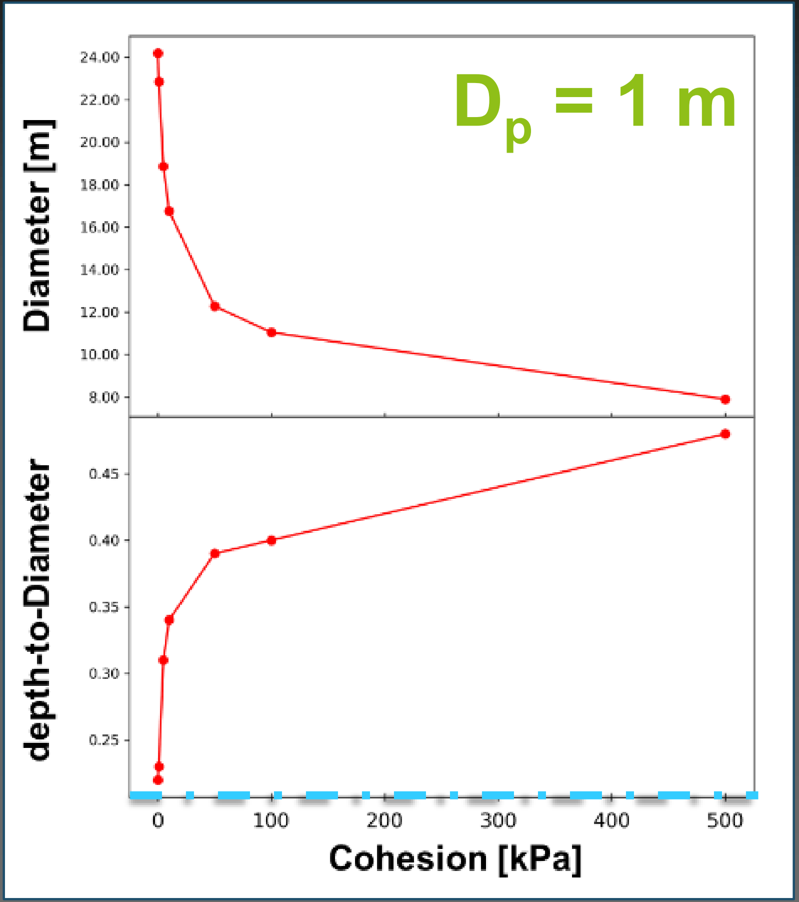
Impactor 2

few individual and large impacts of comets and/or hydrated asteroids

- ice projectile
    - size: 1 mm to 1 m
    - ice Ih EoS by Tillotson
    - Pressure and damage-dependent strength model by Collins et al. (2004)
- impact velocity v = 20 km/s (Borin et al. 2016)

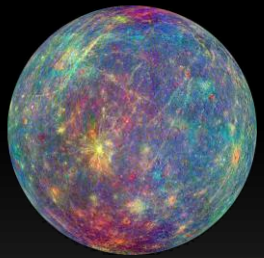
- ice projectile
    - size: 1 m to 1 km
    - ice Ih EoS by Tillotson
    - Pressure and damage-dependent strength model by Collins et al. (2004)
- impact velocity v = 40 km/s (Marchi et al. 2009)

PROJECTILE 1:
PROJECTILE SIZE COMPARISON



D_p	D	d/D
1 µm	17.35 µm	0.38
1 mm	17.58 mm	0.38
1 m	16.76 m	0.34

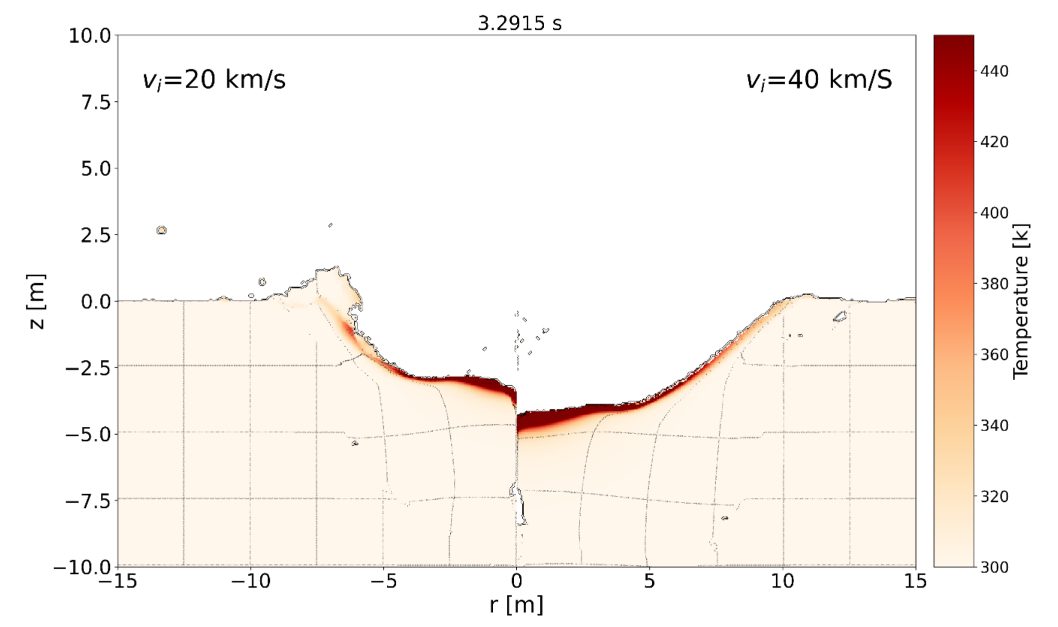
>1km simple craters:
d/D = 0.2 (Susorney et al., 2011)

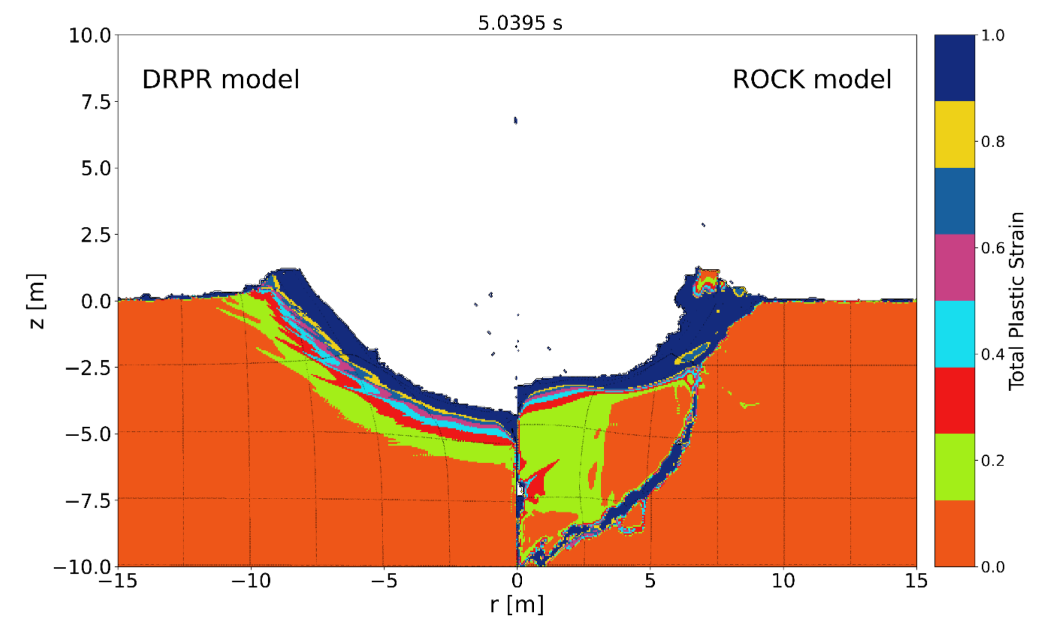


PROJECTILE 1:
VELOCITY AND STRENGHT MODEL COMPARISON

- cone-truncated morphology
- 25% diameter increase with the higher velocity
- d/D decrease from 0.2 to 0.18
- temperature maps show a thin >400 K layer on the crater floor

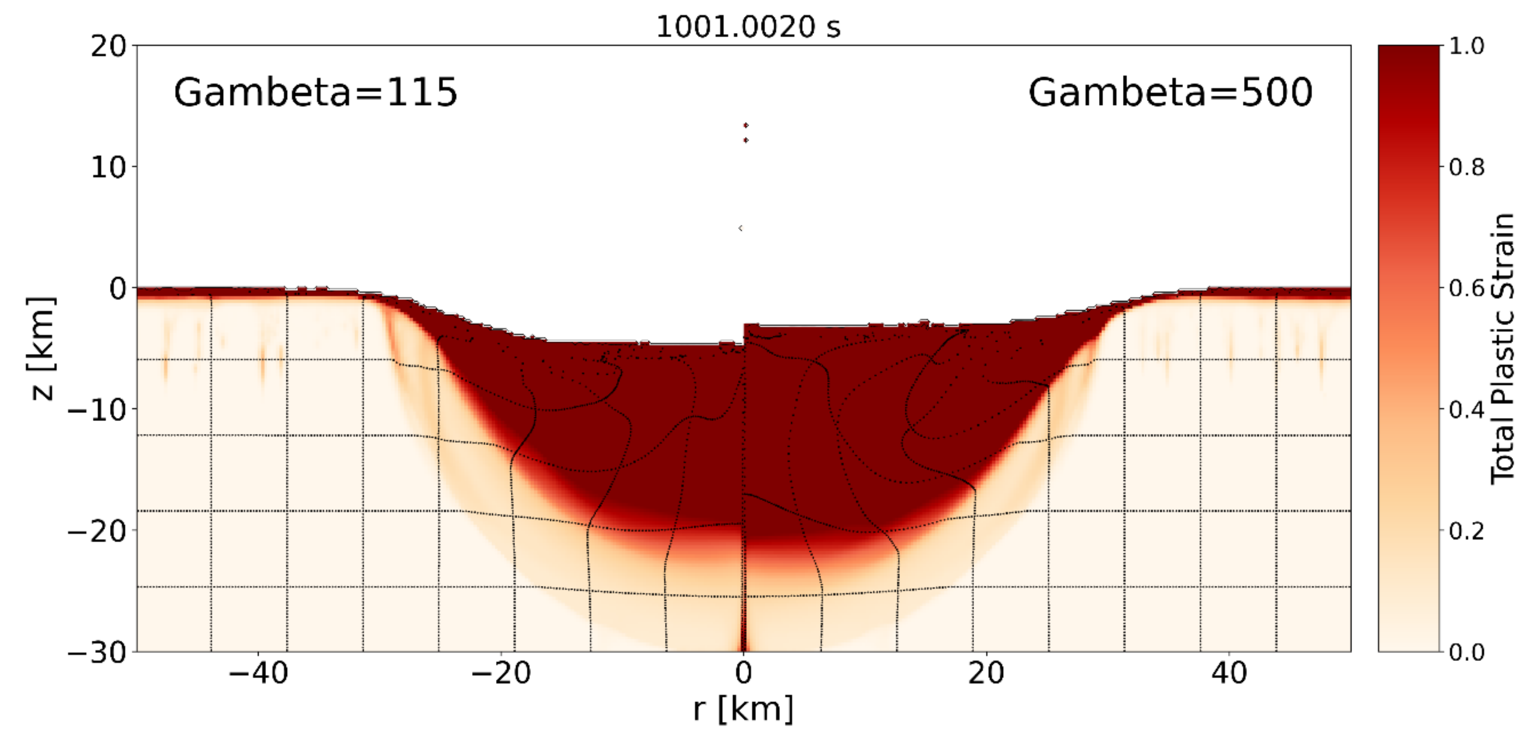
- difference in the faults development:
  - DRPR model: hemispherical
  - ROCK mode: radial with respect to the impact site





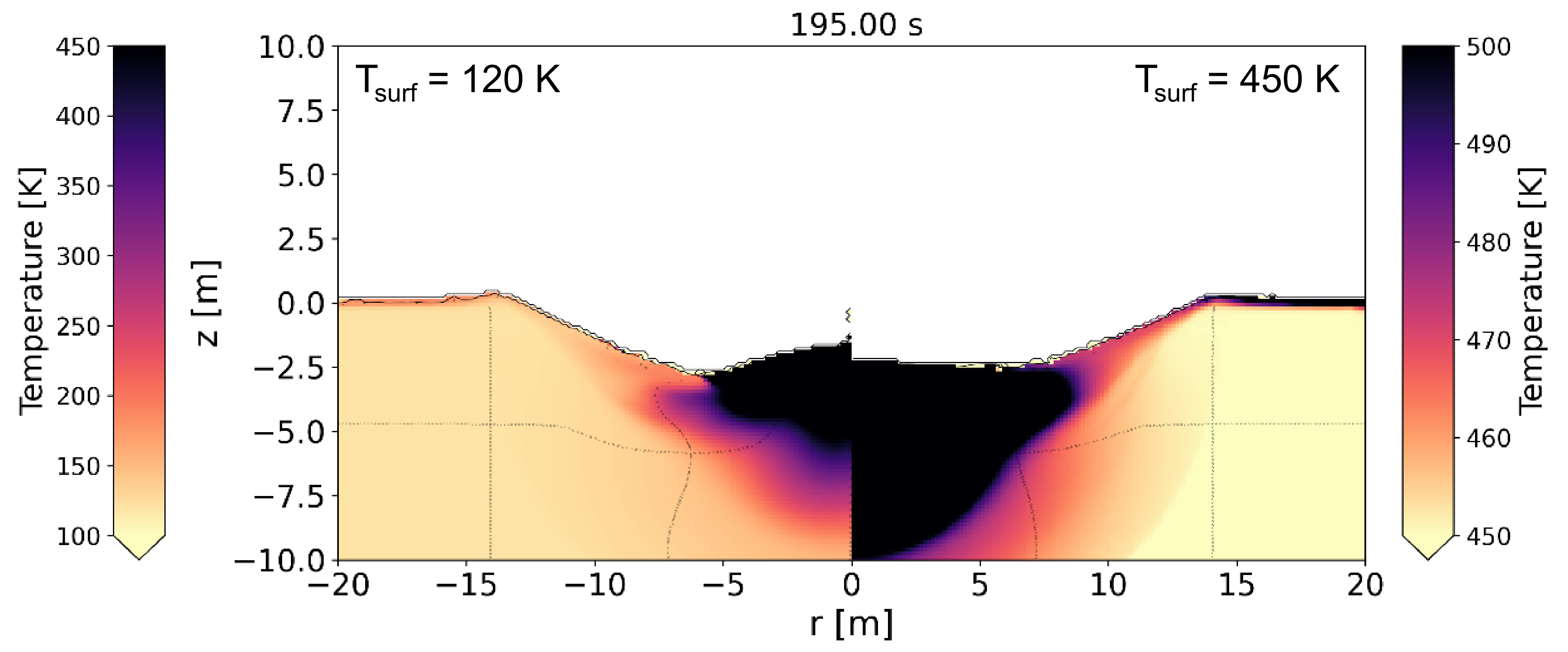
PROJECTILE 2:
5 KM @ 40 KM/S

the peak formation is sensitive to the higher decay time *τ*



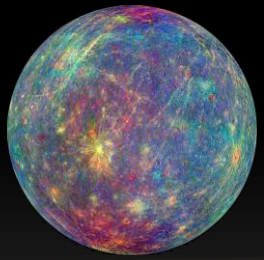
The left and right panels show the BM decay time related parameter, for the same value of BM viscosity parameter (1×10^{-3})

PROJECTILE 2: THE CASE OF FULLER CRATER



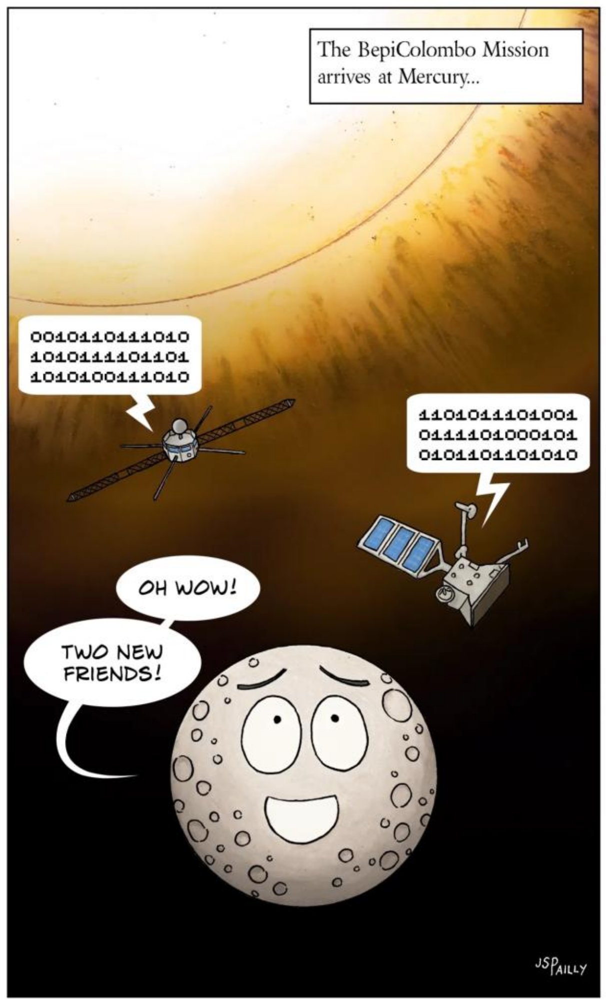
MODEL: projectile of 1.4 km in size striking the surface at 20 km/s

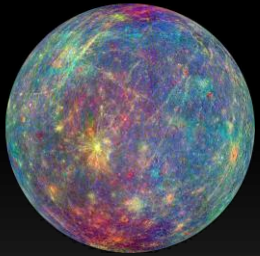
In the case the impact occurred in the night-side (left panel), the post-impact temperatures are lower than 300 K on the floor of the modelled crater. This is area within the Fuller crater where ice deposit is expected.

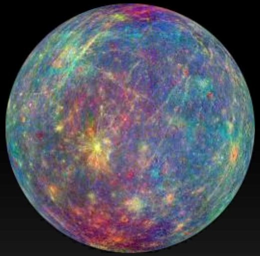


TAKE HOME MESSAGE

- Mercury: a planet eager to be discovered
  - BepiColombo is going to start its operative orbit around Mercury in 1 year from now
- Water ice: more detailed measurements are needed to constrain sources and evolution
  - SIMBIO-SYS/VIHI: hyperspectral imager in the visible and near-infrared range that will map the ice composition, abundance, and grain size in the 0.4–2.0 μm range. It is particularly optimized to detect ice in the "penumbra" (partially illuminated) zones, exploiting light scattered from the crater rims.
  - MERTIS: a thermal infrared (IR) imaging instrument that will contribute to studying the thermal environment of the PSRs.
  - BELA: laser altimeter that will provide high-resolution, 3D mapping of the north pole craters to better understand the morphology and thermal stability of the ice.
- Modelling: more models and ice delivery quantification analysis







MERCURY:
MODELS OF THE ORIGIN OF THE INNER STRUCTURE

- ✓ **Giant Impact** (Wetherill 1988, Benz et al. 1988, 2007):
  - 50 Ma after its formation, the planet was 2.5 times the current mass: it was then hit by a planetary body with mass = 0.03 M_{Earth}. The two metalling nuclei mixed together and only 50% of the rock fragments re-accumulated around.
    - If true, the surface should be poor in Ca, Al, alkali metals, while the mantle in volatile material, e.g FeO and Ti
- ✓ **Aerodynamic sorting** (Weidenschilling 1978):
  - Dynamic separation of large, dense particles from low-density mantle silicates by gas drag from the sun
    - this model implies a nearly chondritc composition of the mantle
    - problem: Why not seen on Venus or Earth
- ✗ **Mantle evaporation** (Fegley & Cameron 1987):
  - Light materials e.g. Na and K were vaporized and removed by the strong solar wind
    - this model il modello implies a very hot primordial Sun, and a crust poor in volatile elements and rich in metallic components
    - strong depletion of volatile elements
- ✗ **Incomplete condensation of silicates** (Lewis 1973; Hubbard 2014):
  - High pressure and high temperature environment where Fe can condense
    - strong depletion of volatile elements
    - refractory element enrichment