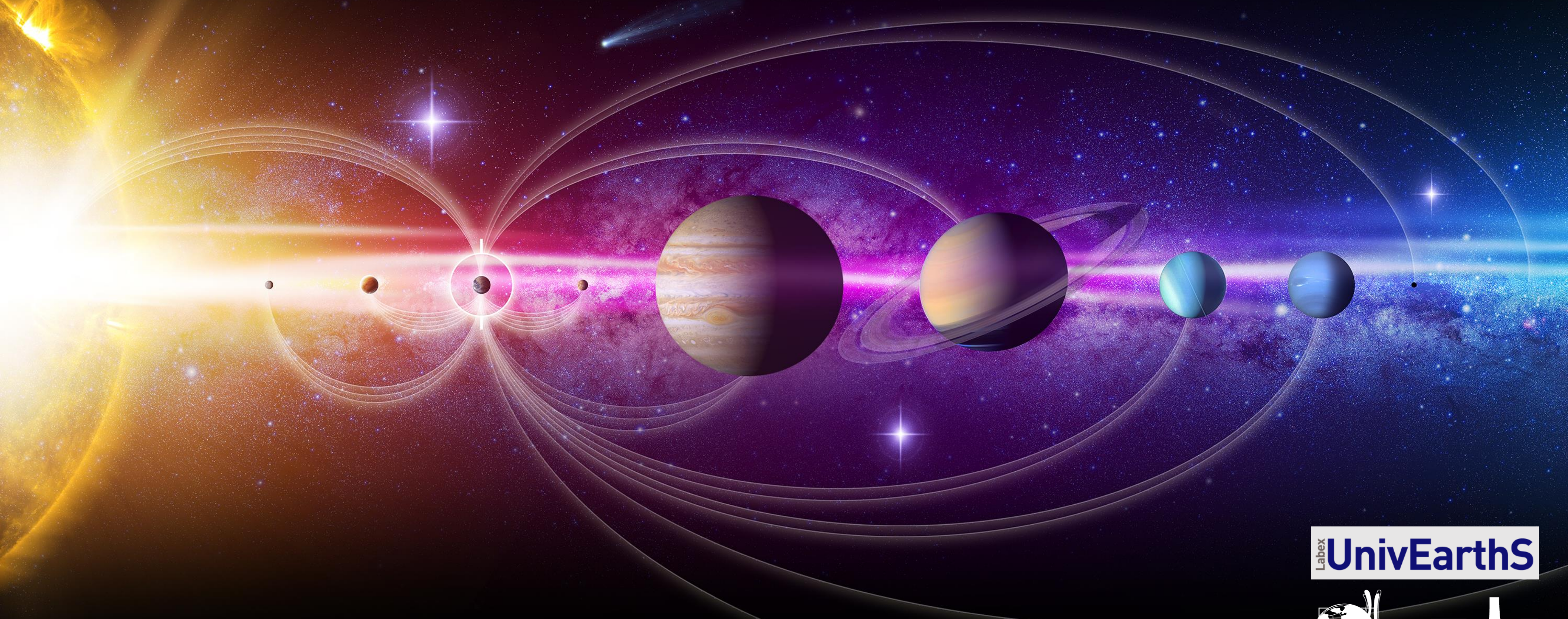
Space & Planetology: past, ongoing and future exploration of the inner and outer Solar System



Labex UnivEarthS

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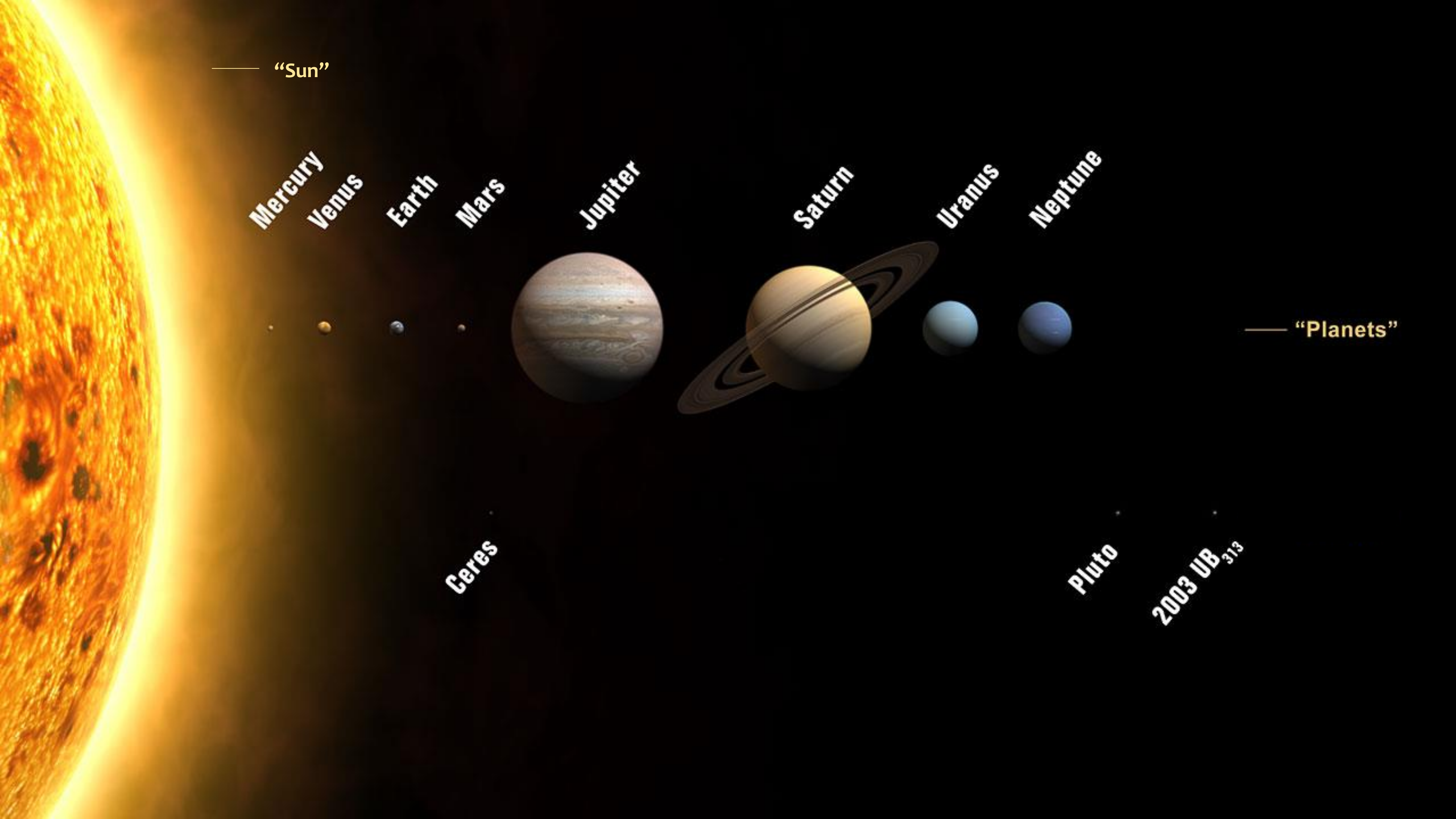
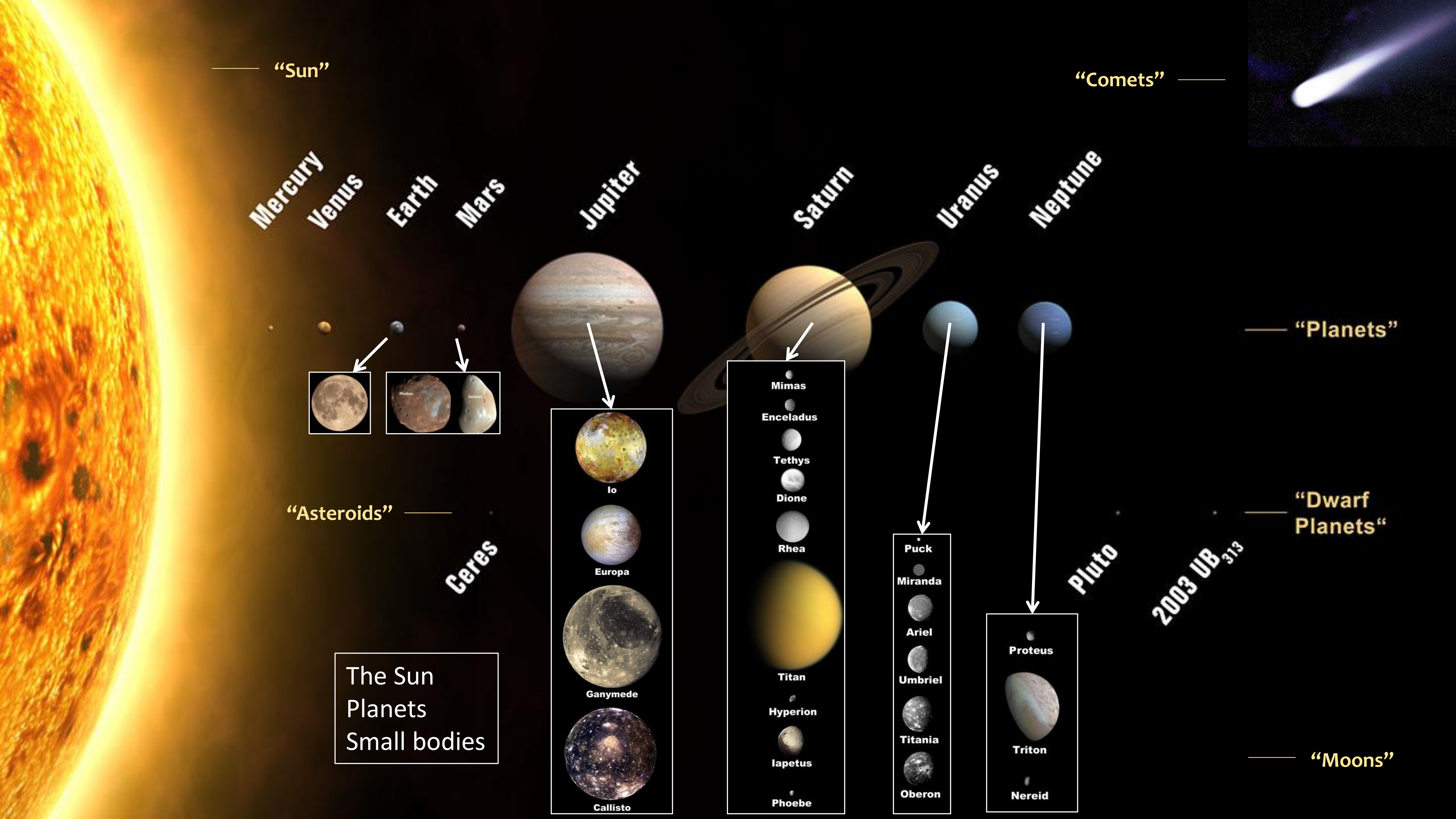
Institut de Physique du Globe de Paris
Planetology and Space Science

IPGP INSTITUT DE PHYSIQUE DU GLOBE DE PARIS

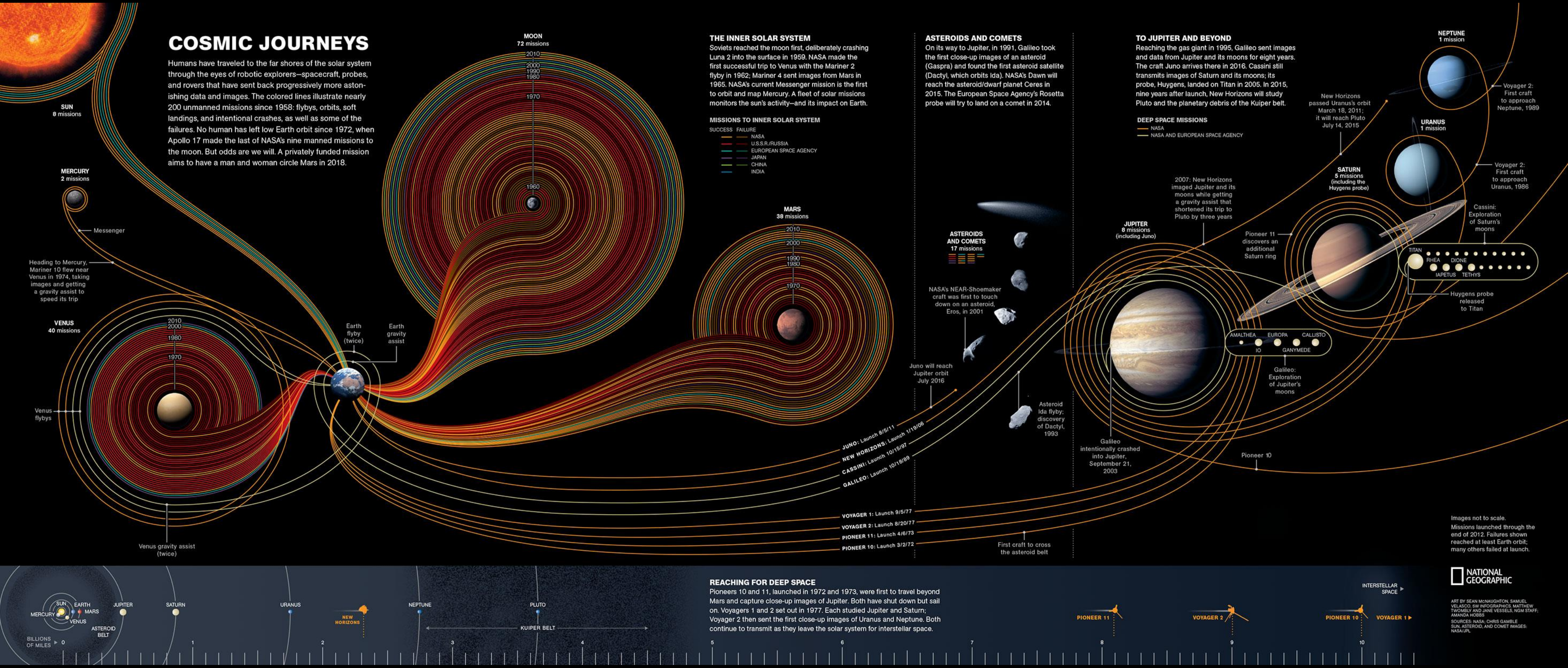
Université de Paris


"Sun"
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
"Planets"
Ceres
Pluto
2003 UB_{313}

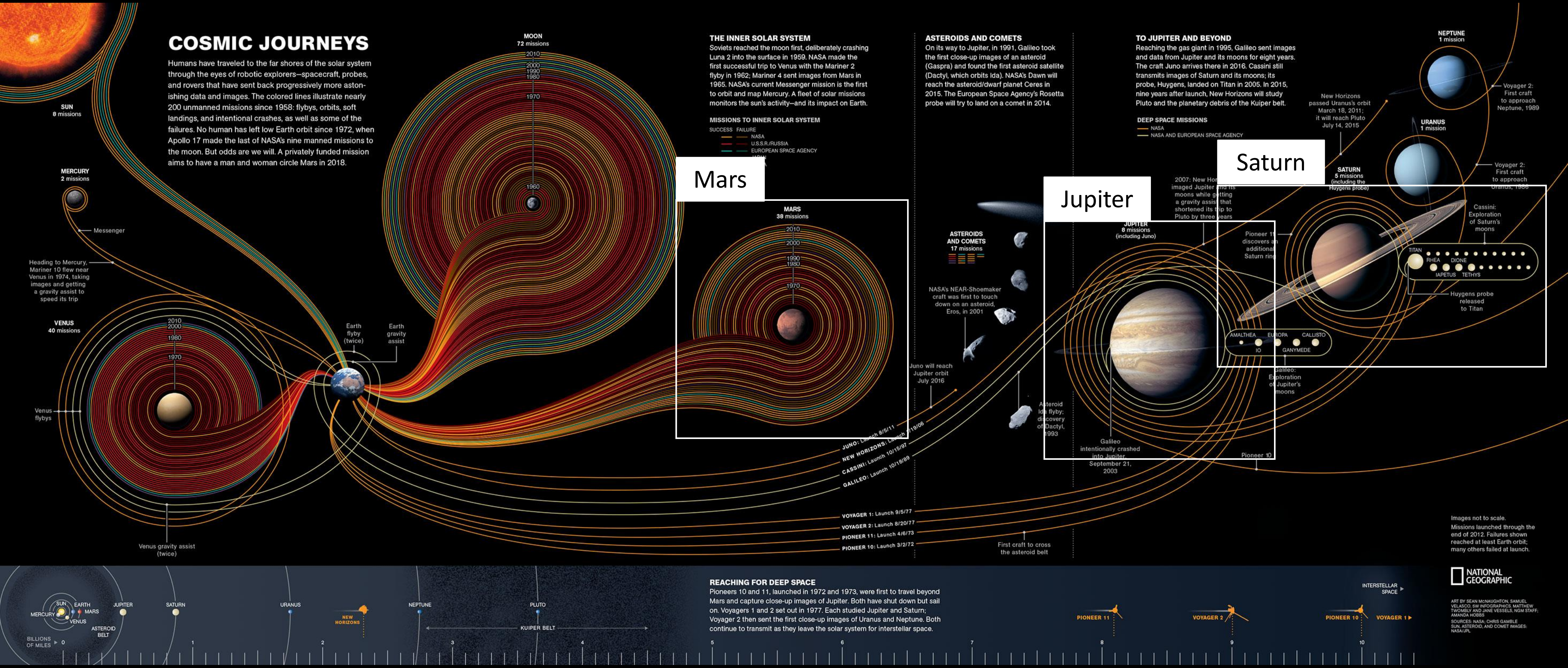


"Sun"
"Comets"
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
"Planets"
Io
Europa
Ganymede
Callisto
Mimas
Enceladus
Tethys
Dione
Rhea
Titan
Hyperion
Iapetus
Phoebe
Puck
Miranda
Ariel
Umbriel
Titania
Oberon
Proteus
Triton
Nereid
"Asteroids"
Ceres
Pluto
2003 UB313
"Dwarf Planets"
"Moons"
The Sun
Planets
Small bodies

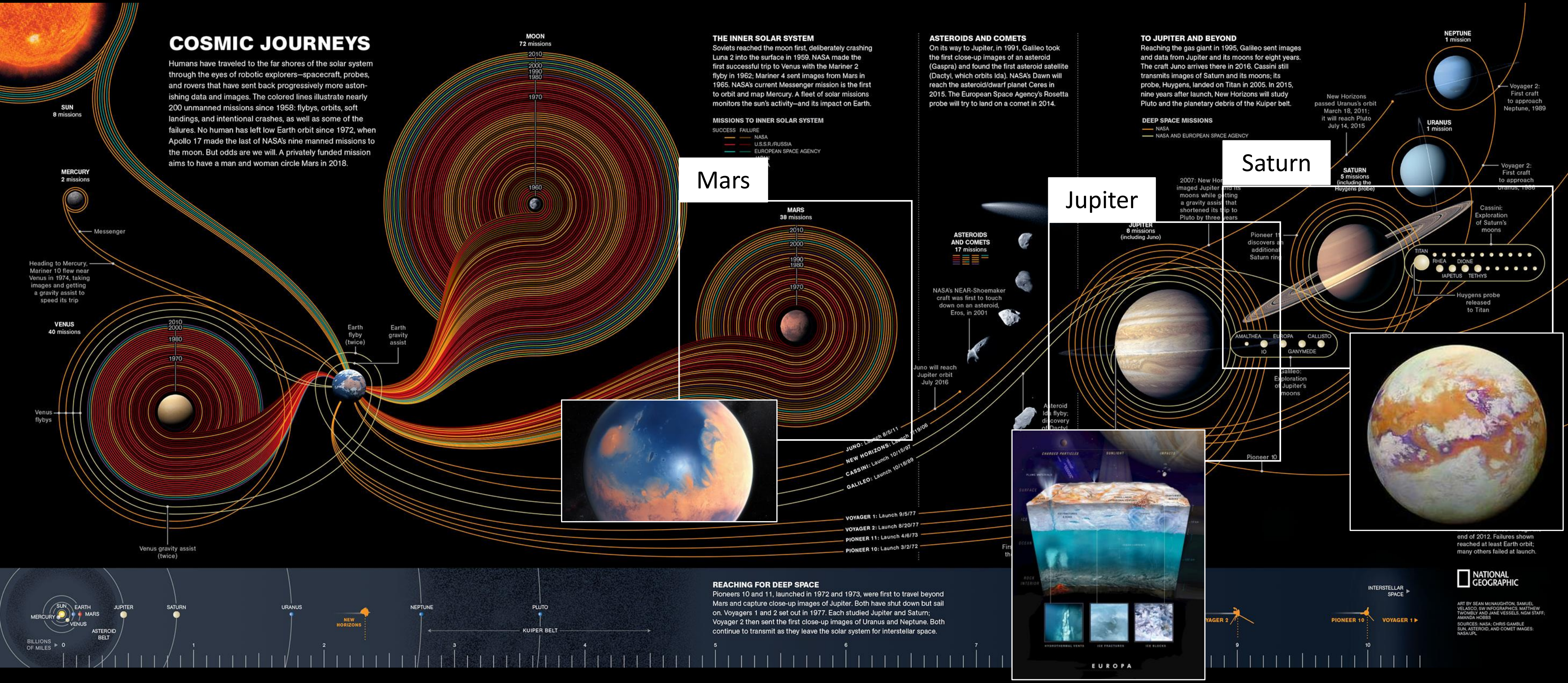
54 years of space exploration. Et voilà !



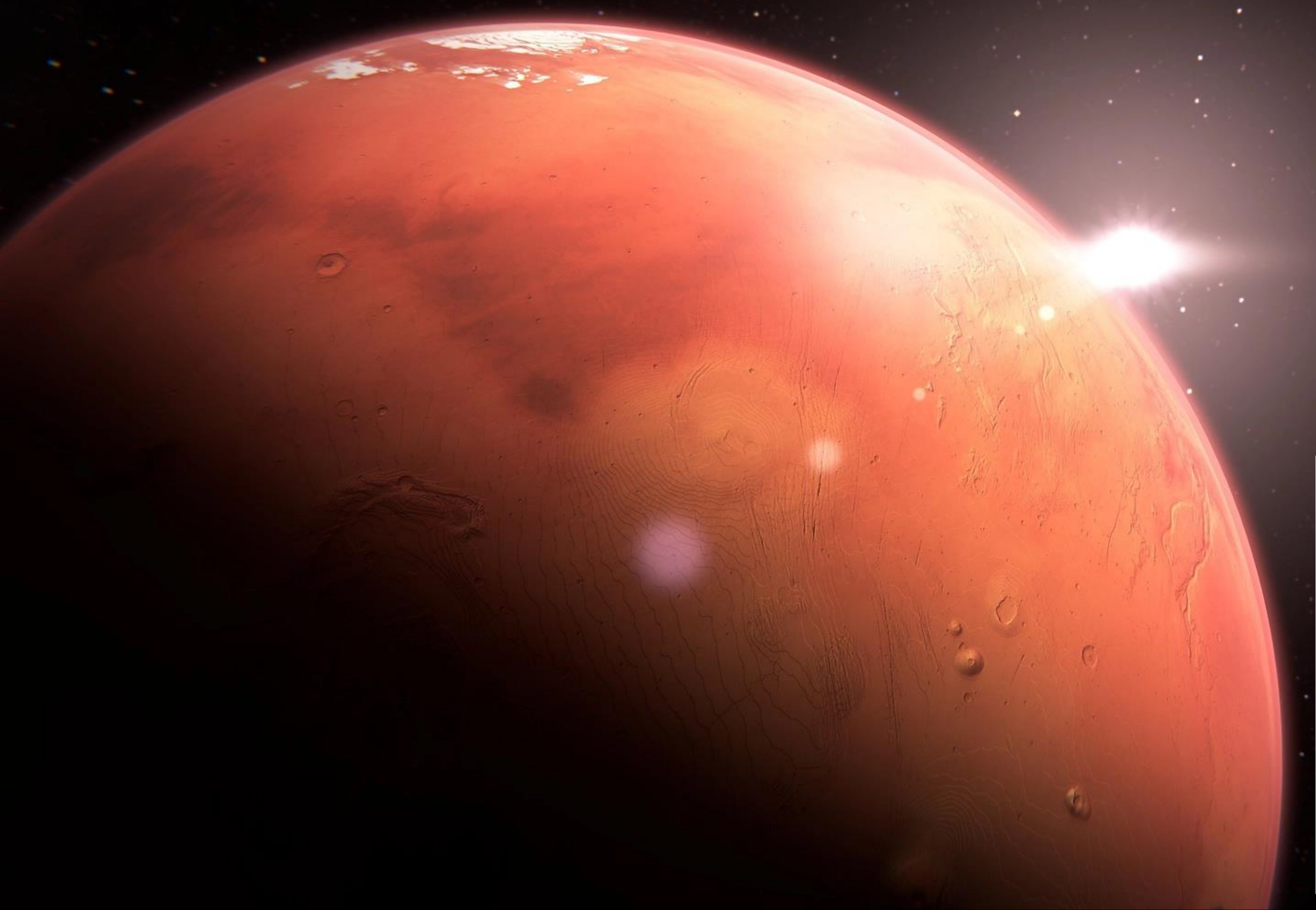
Focus on Mars, Saturn, and a bit on Jupiter

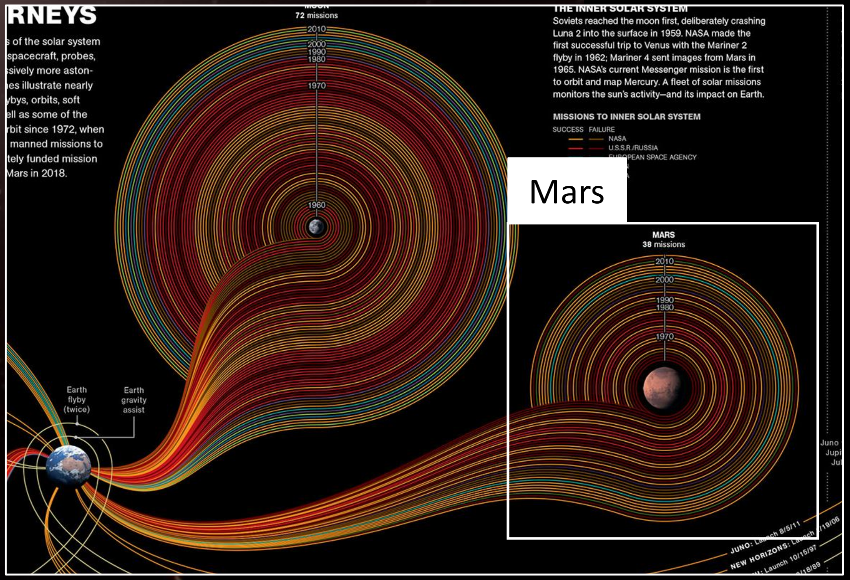


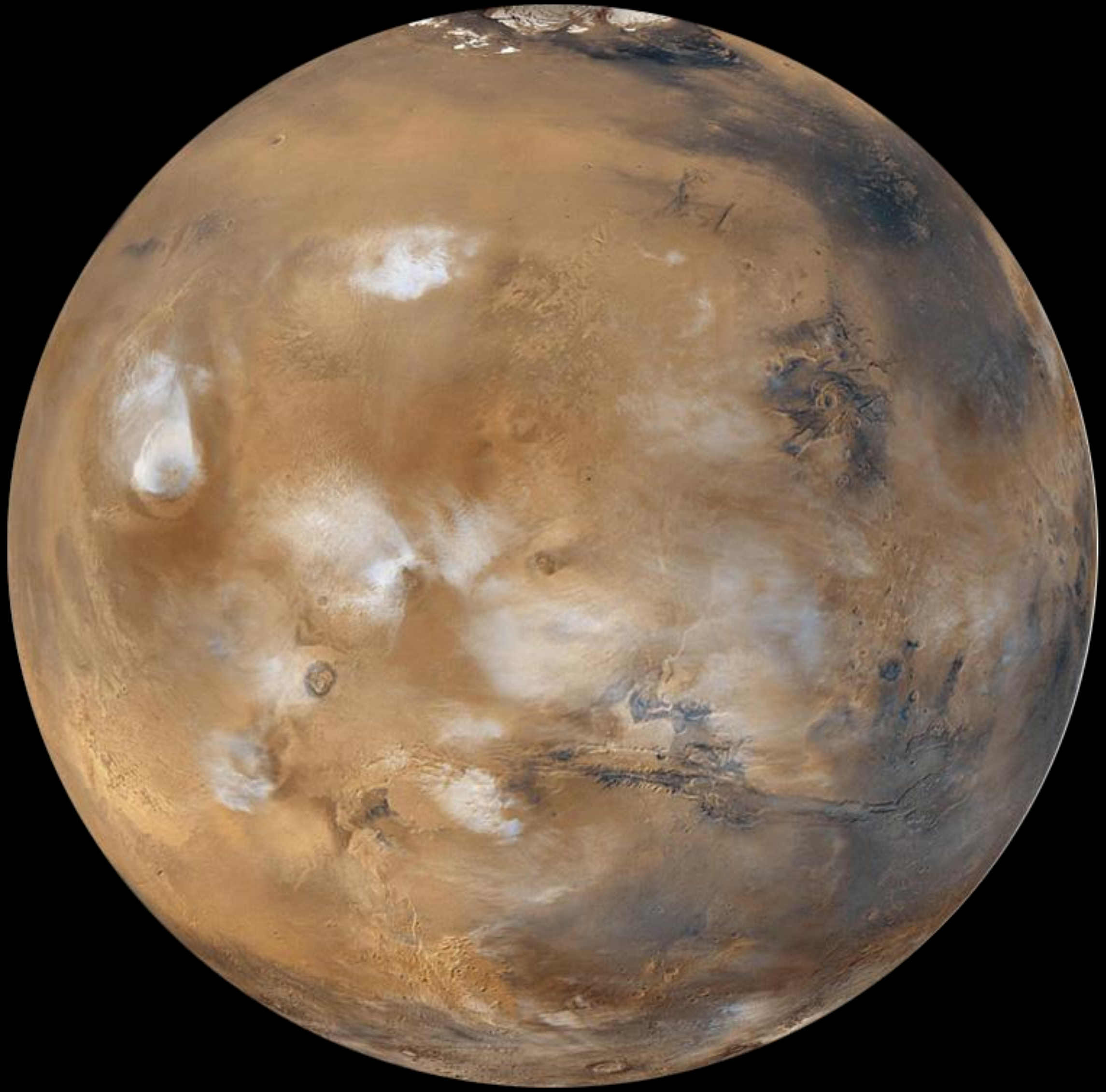
Focus on Mars, Saturn, and a bit on Jupiter & discuss the science done!



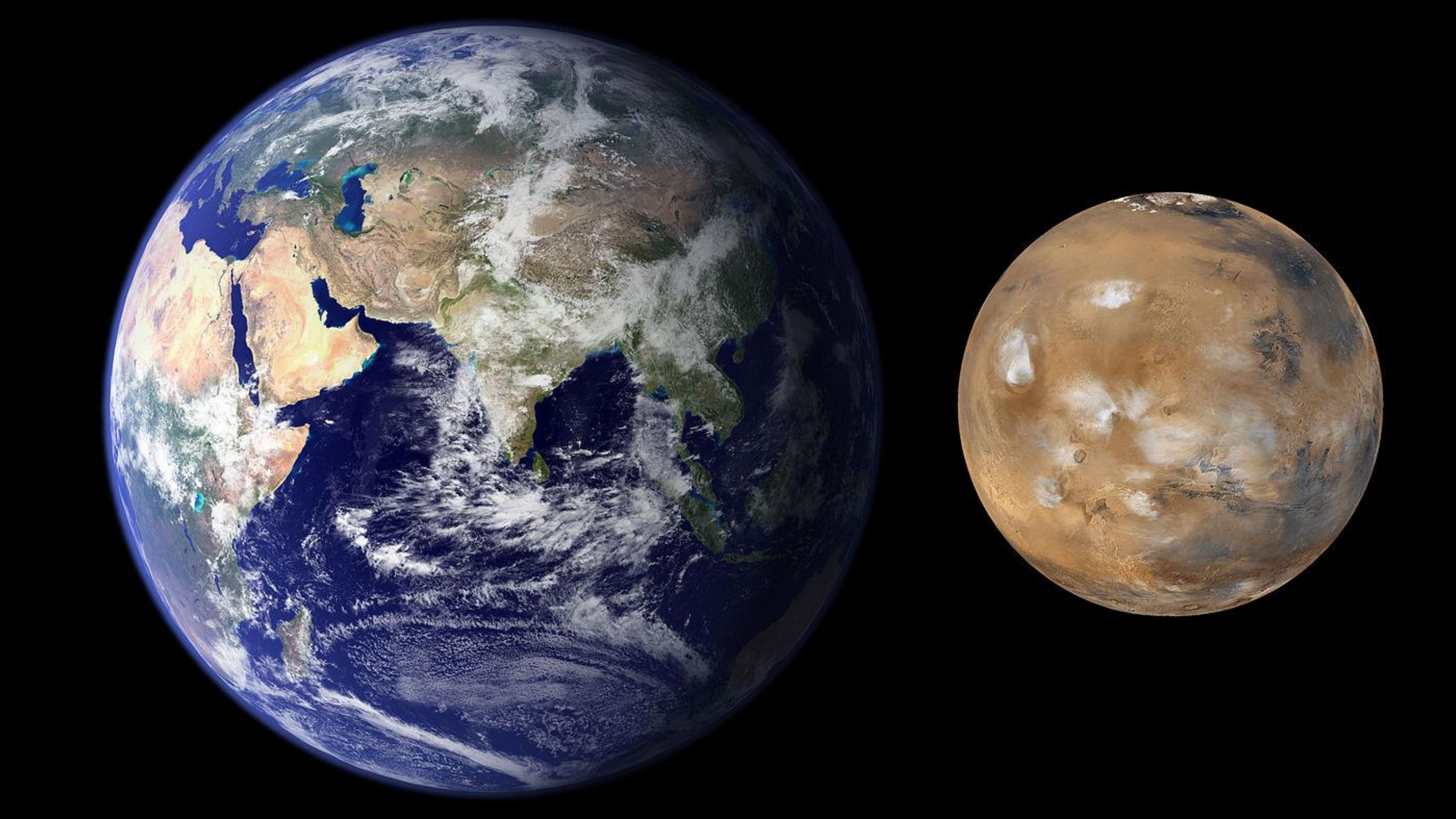
Space exploration of Mars





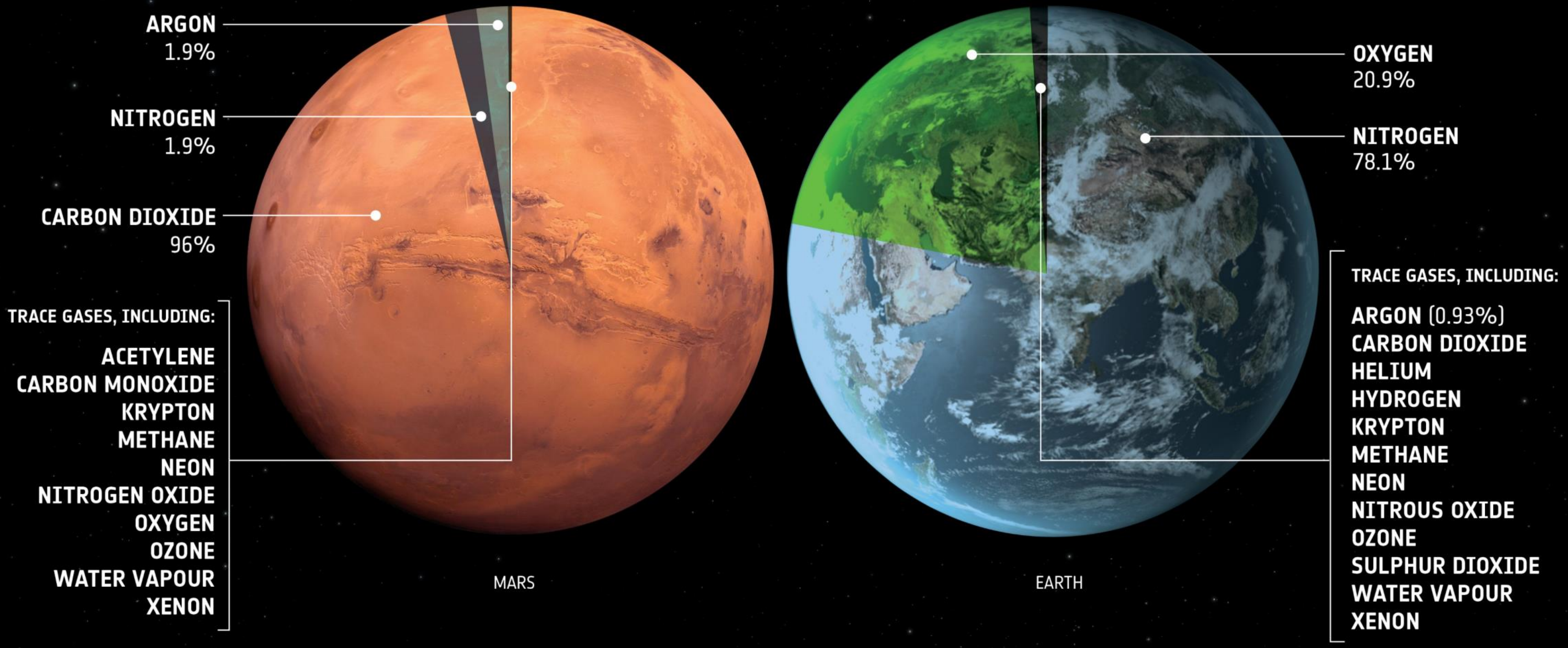


	Earth	Mars
Distance from Sun	149,597,870 km	228,000,000 km **(1.5x)**
Year duration	365,25 days	687 days **(1.9x)**
Diameter	12 755 km **(1.9x)**	6 791 km
Volume	1,08321×10^{12} km^3 **(6.6x)**	1,6318×10^{11} km^3
Mass	5,97237×10^{24} kg **(9.3x)**	6,4171×10^{23} kg
Surface gravity	9,80665 m/s^2 **(2.6x)**	3,72076 m/s^2
Escape velocity	11,186 km/s	5,027 km/s
Axial tilt	23,4392811°	25,19°
Max. temp.	56.9°C	35°C
Min. temp.	-89.7°C	-143°C
Avg. temp.	14°C	-63°C
Surface pressure	1013 hPa	6-10 hPa **(≈1%)**

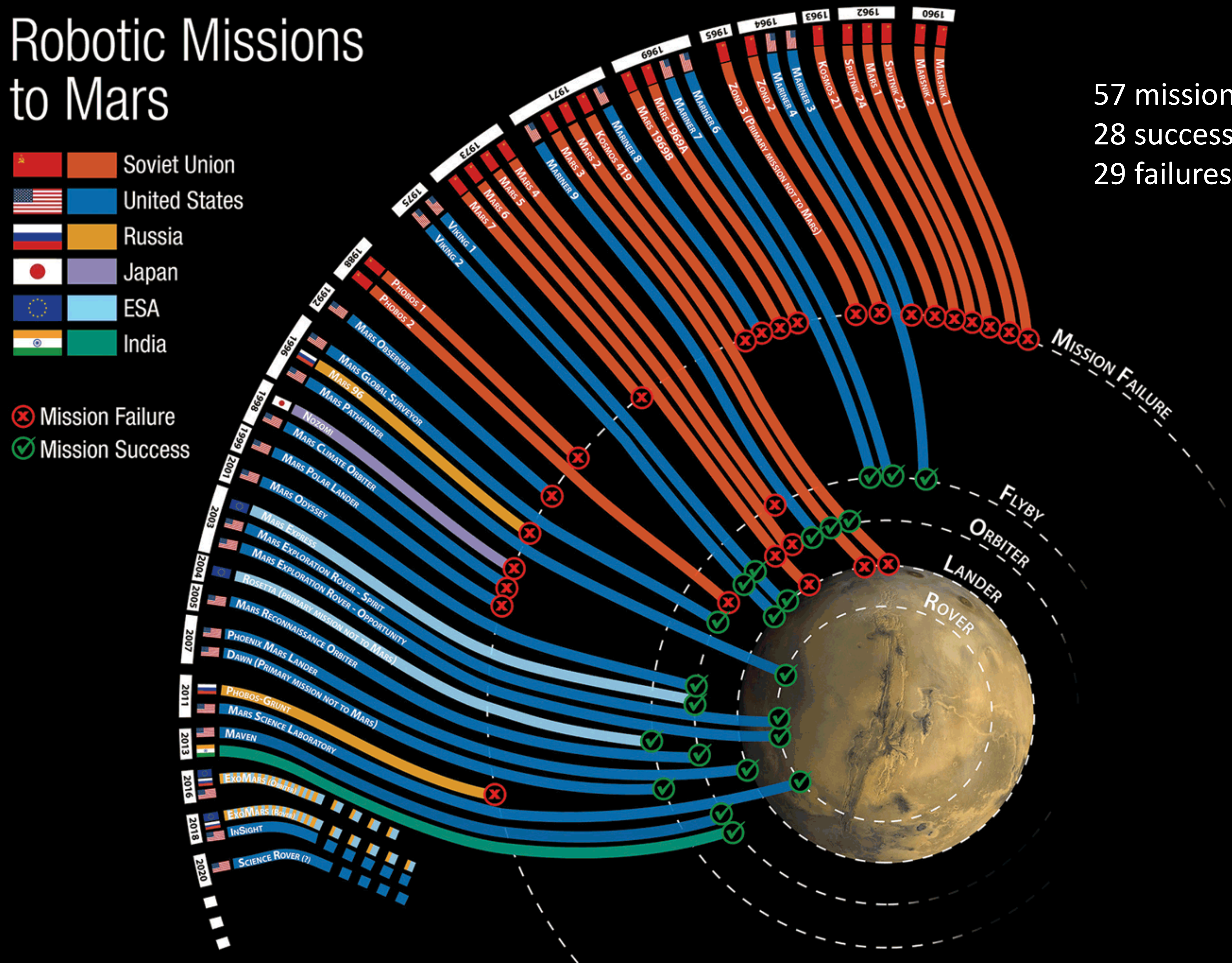


esa

→ COMPARING THE ATMOSPHERES OF MARS AND EARTH



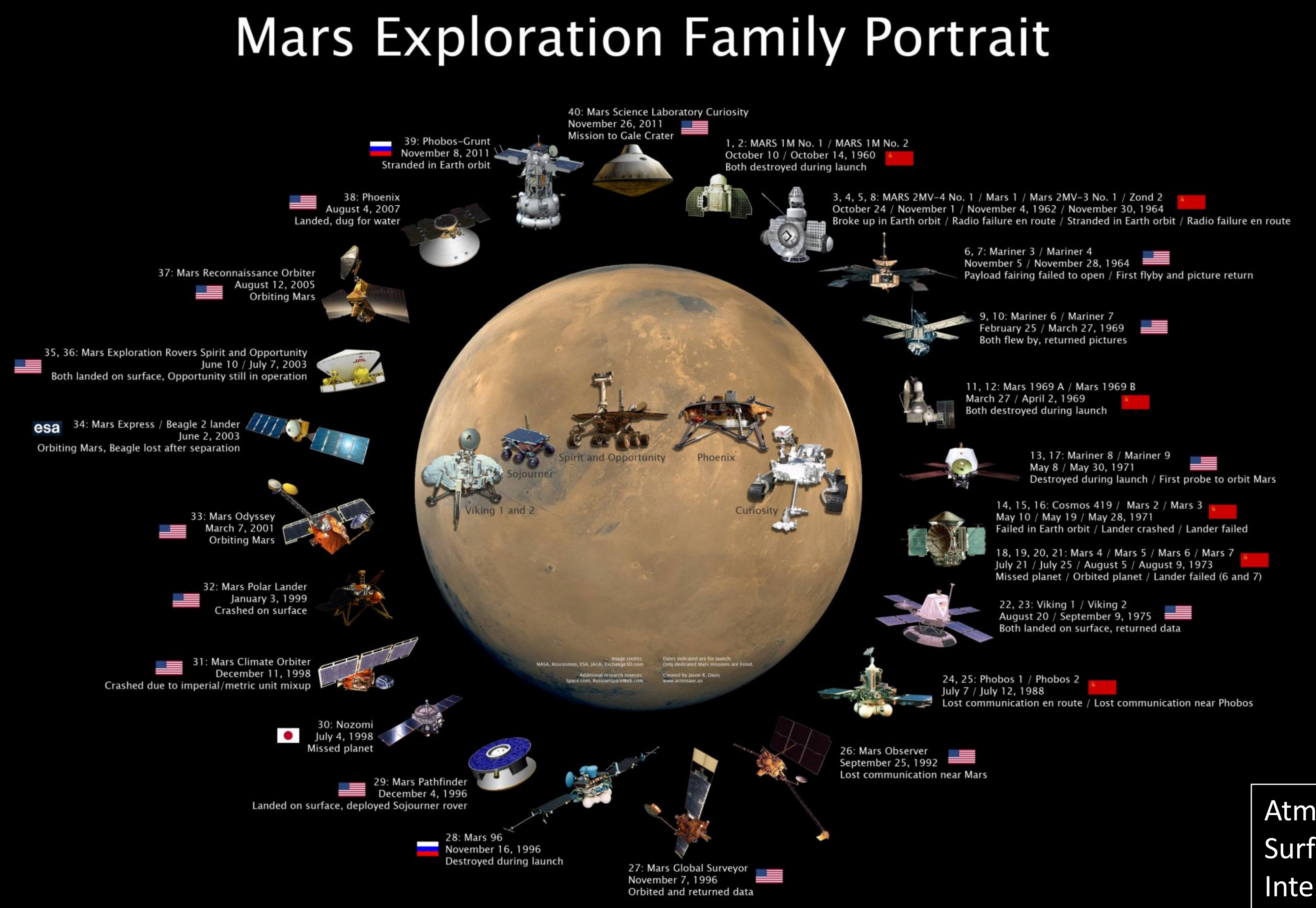
Atmospheric composition by volume | Planets not to scale | Atmosphere of Mars is less than 1% of Earth's | Trace gases listed alphabetically



57 missions in total (starting back in 1960!)

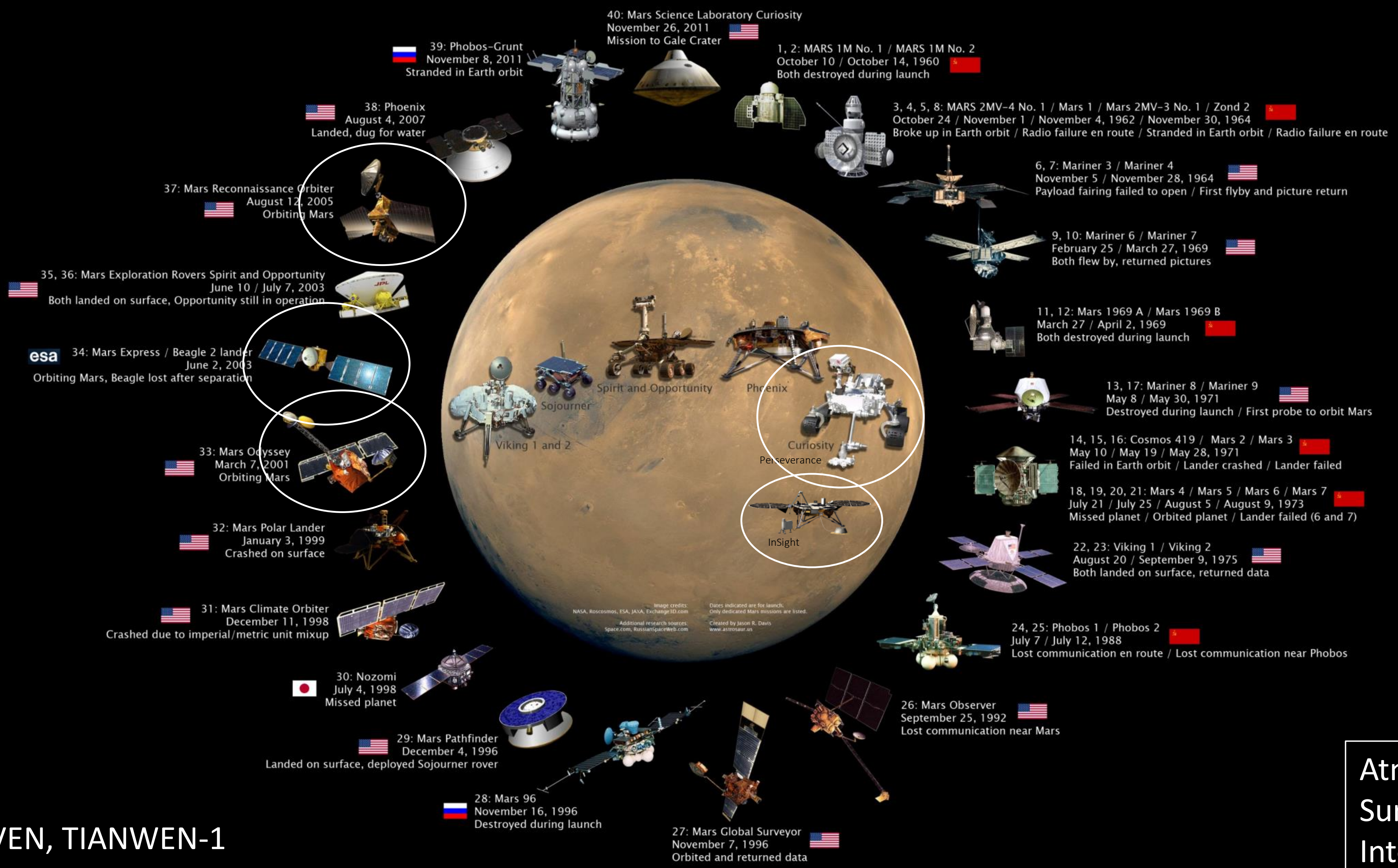
28 successes

29 failures



Atmosphere
Surface
Interior

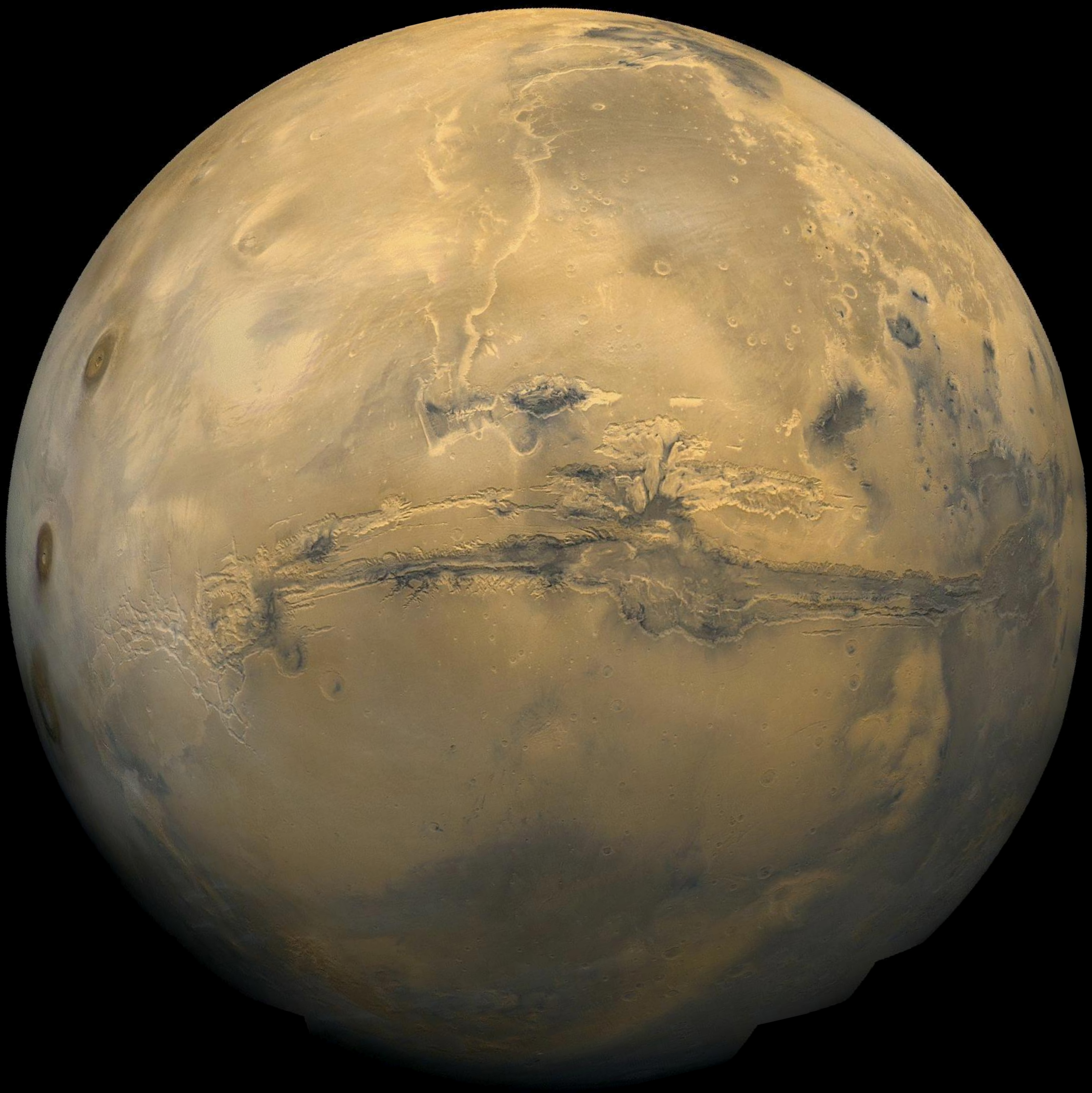
Mars Exploration Family Portrait



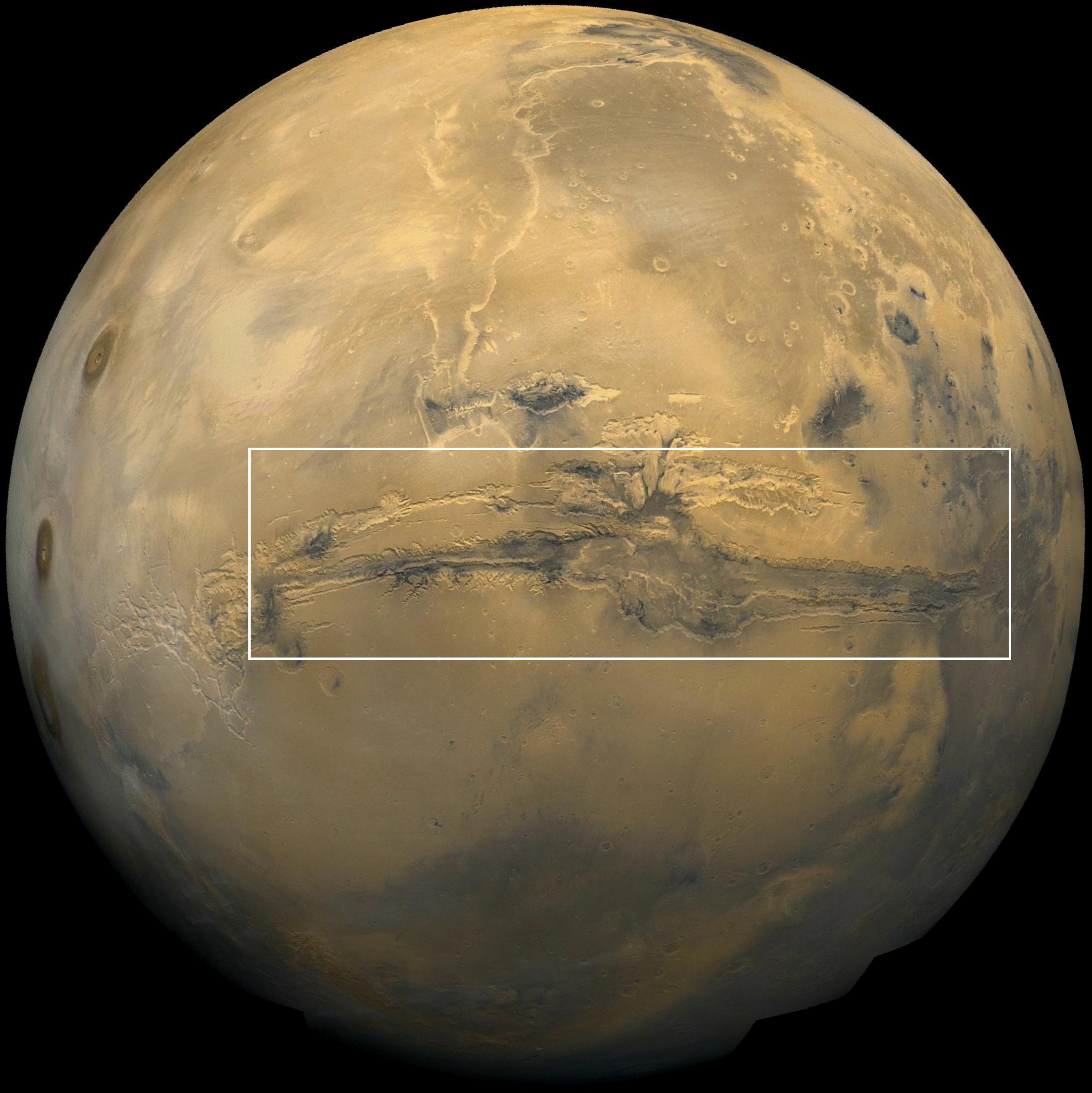
+ TGO, MAVEN, TIANWEN-1

Atmosphere
Surface
Interior

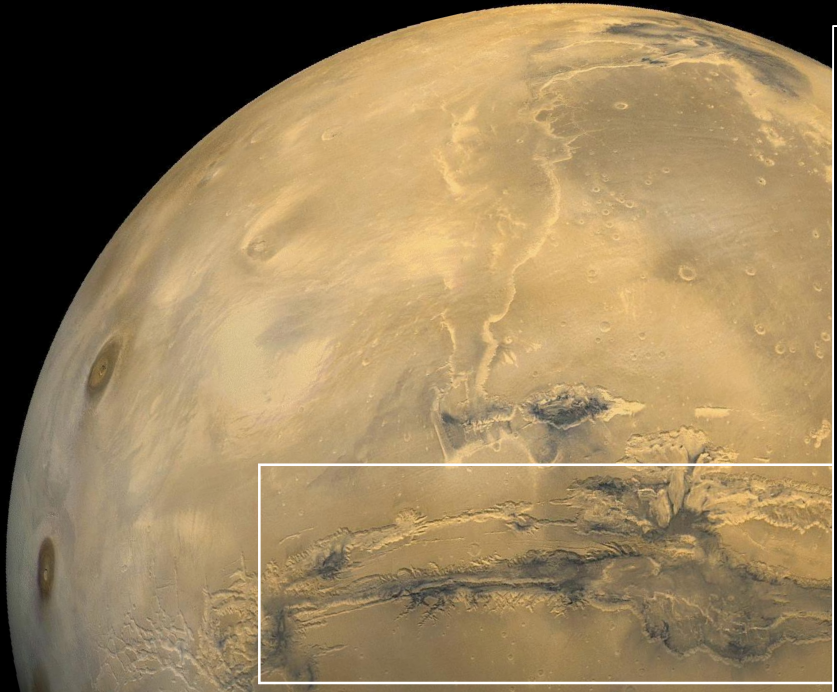
Gigantic geological structures



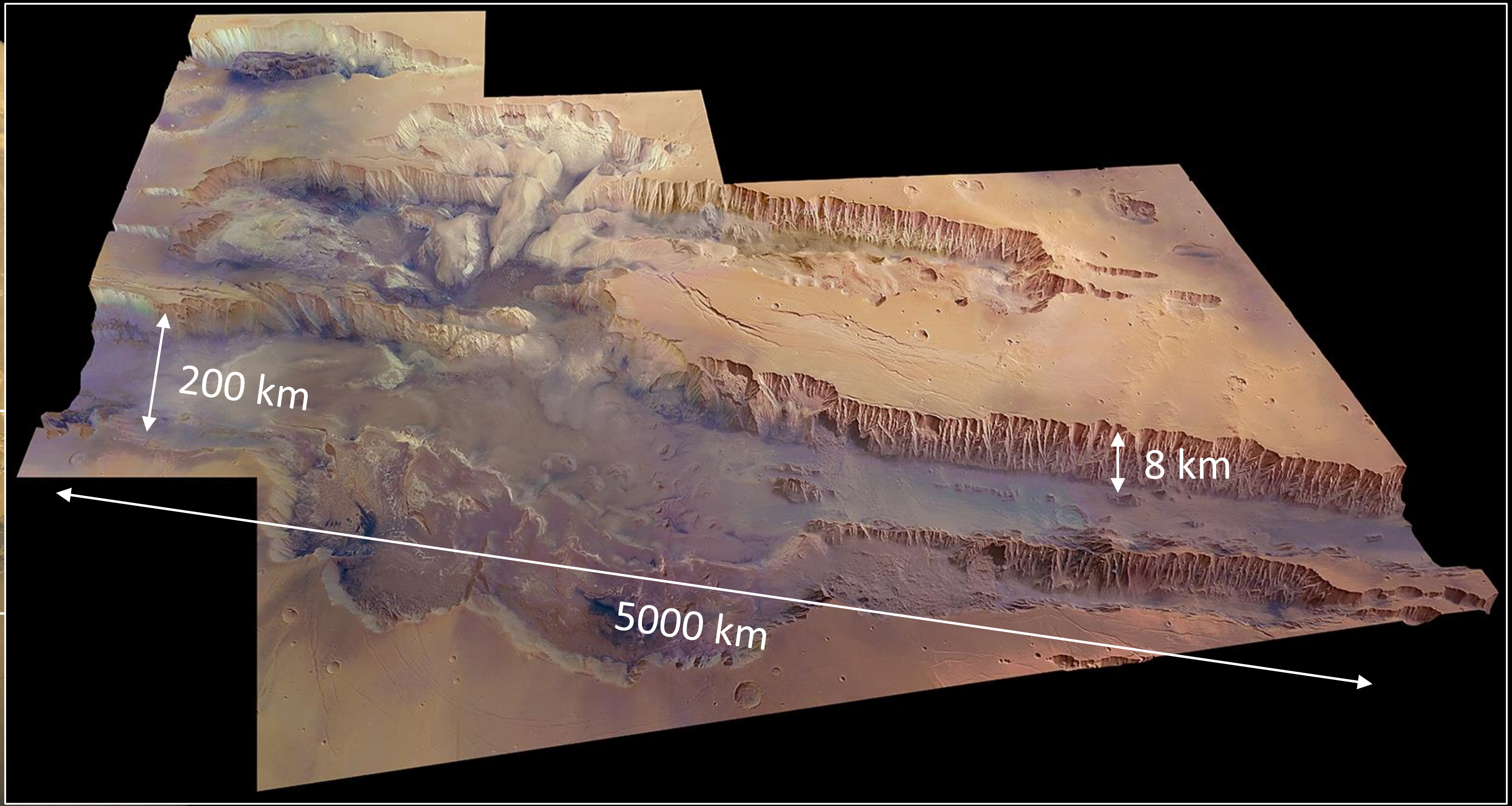
Gigantic geological structures



Gigantic geological structures

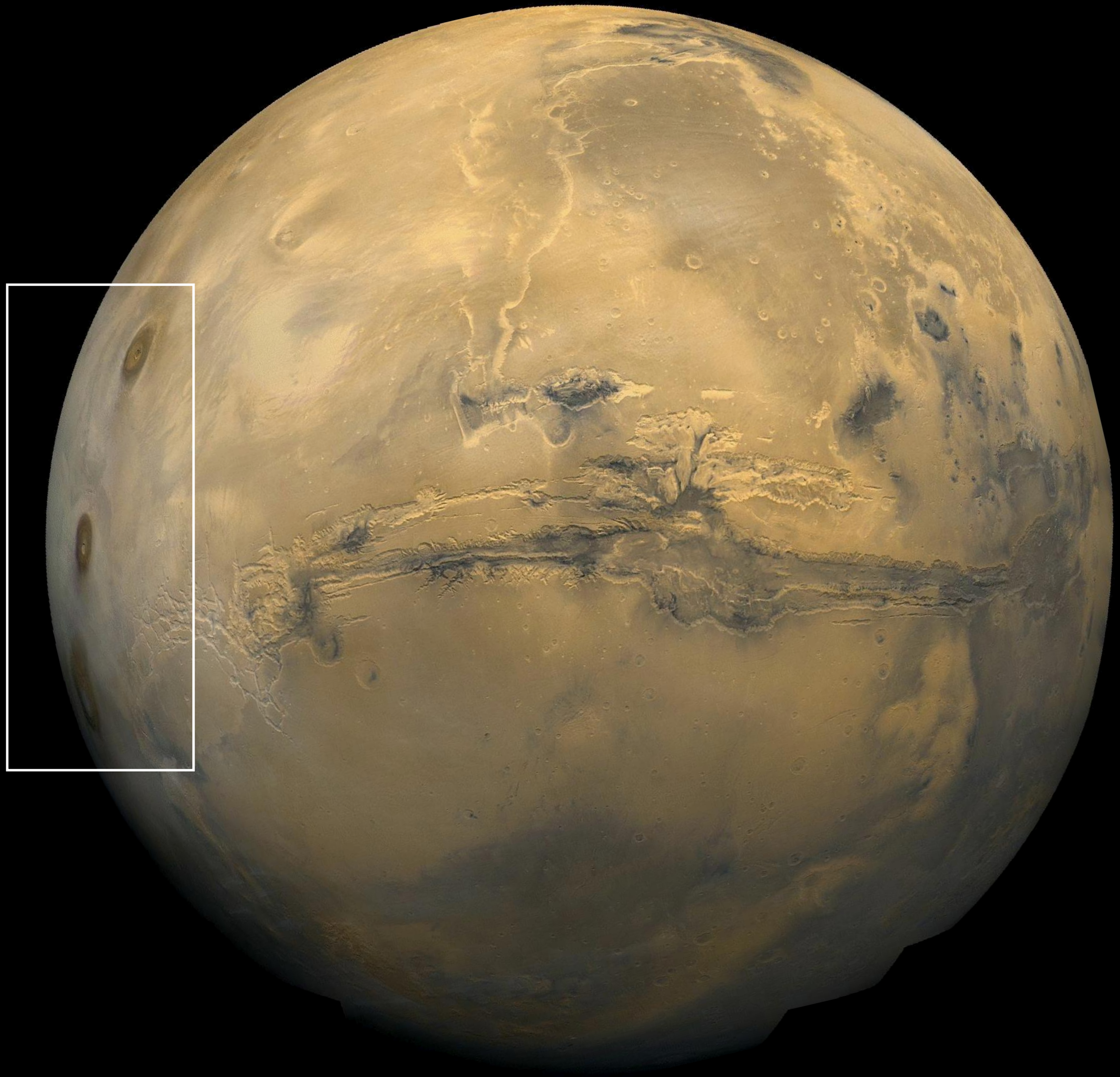


Valles Marineris, Mars – tectonic, 3.5 Gy old

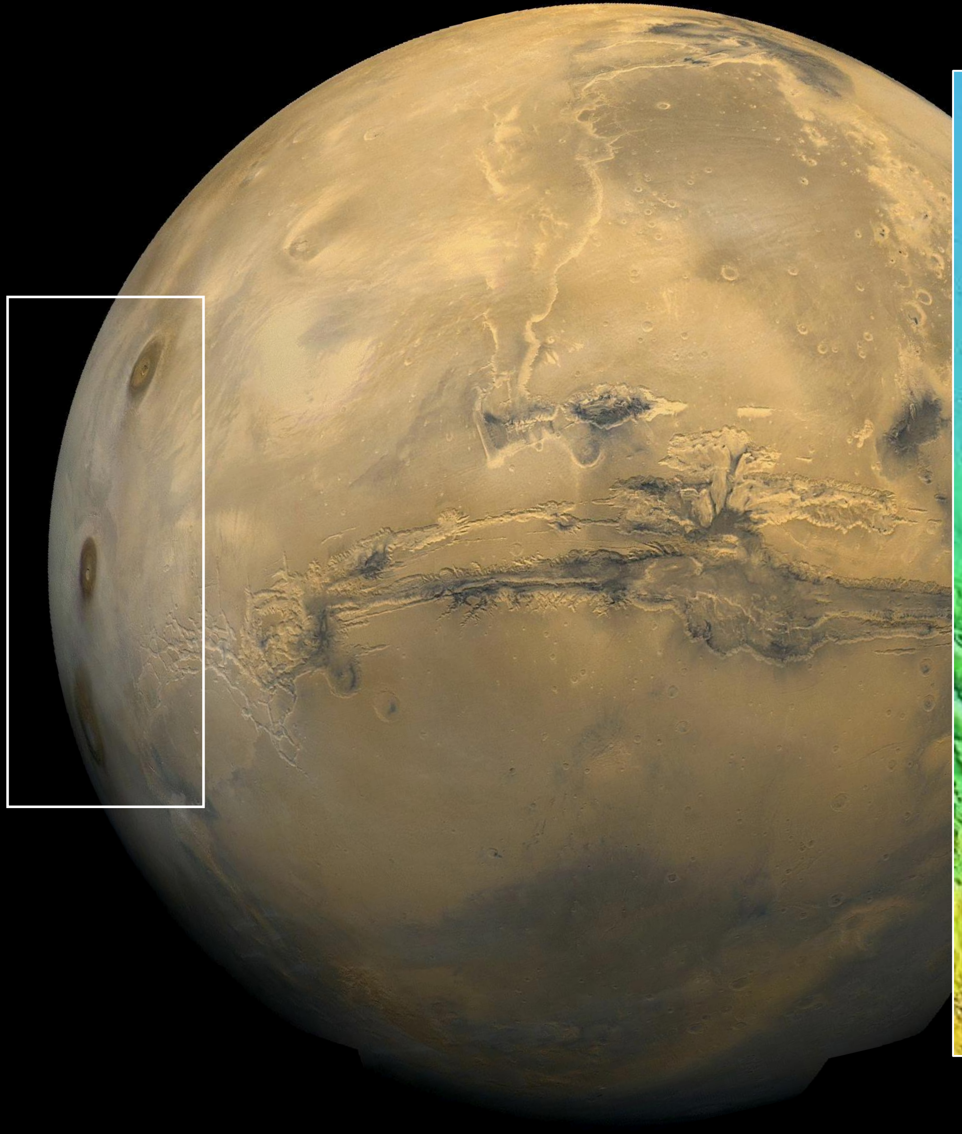


Grand Canyon, USA (450 km long, 1.6 km deep)

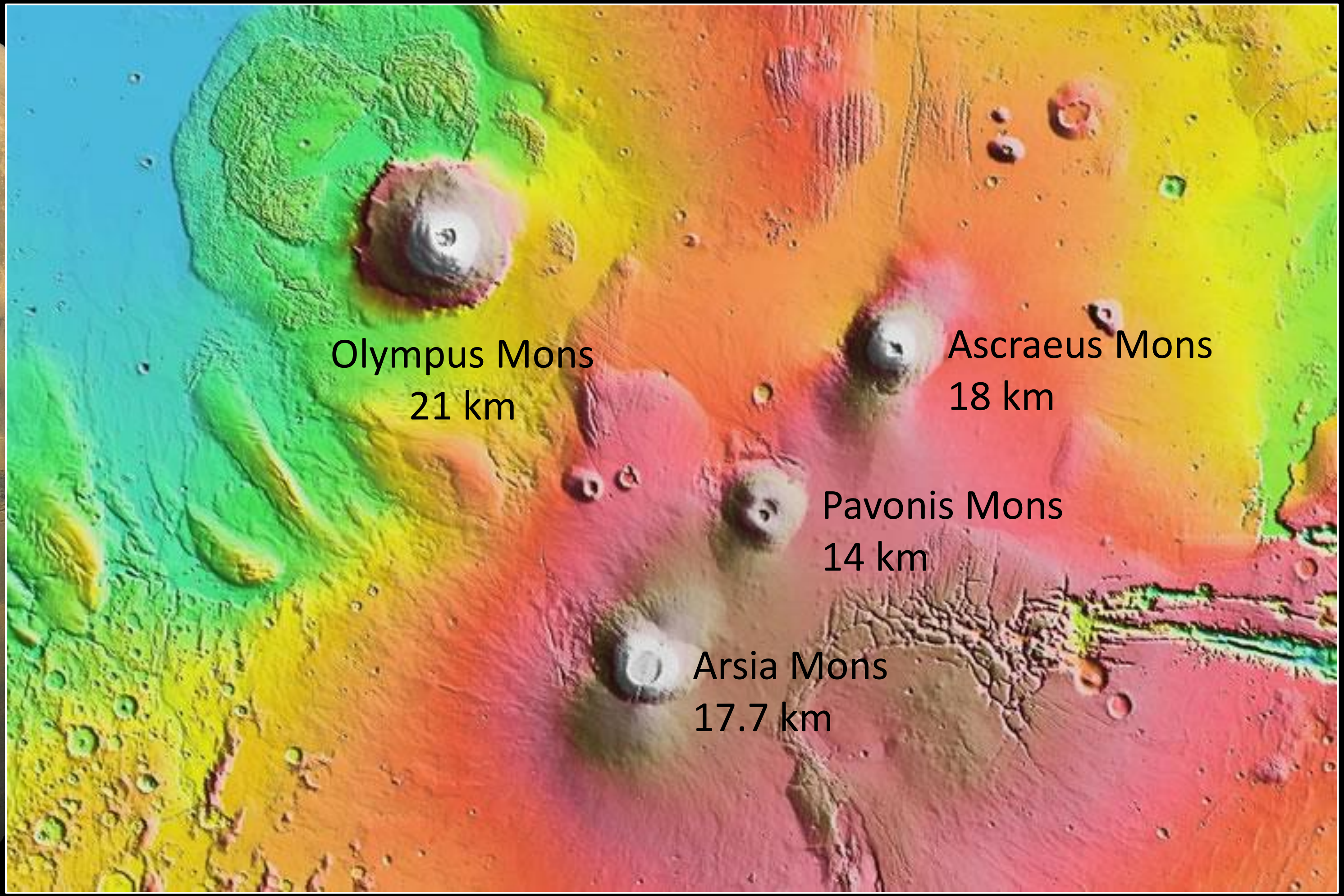
Gigantic geological structures



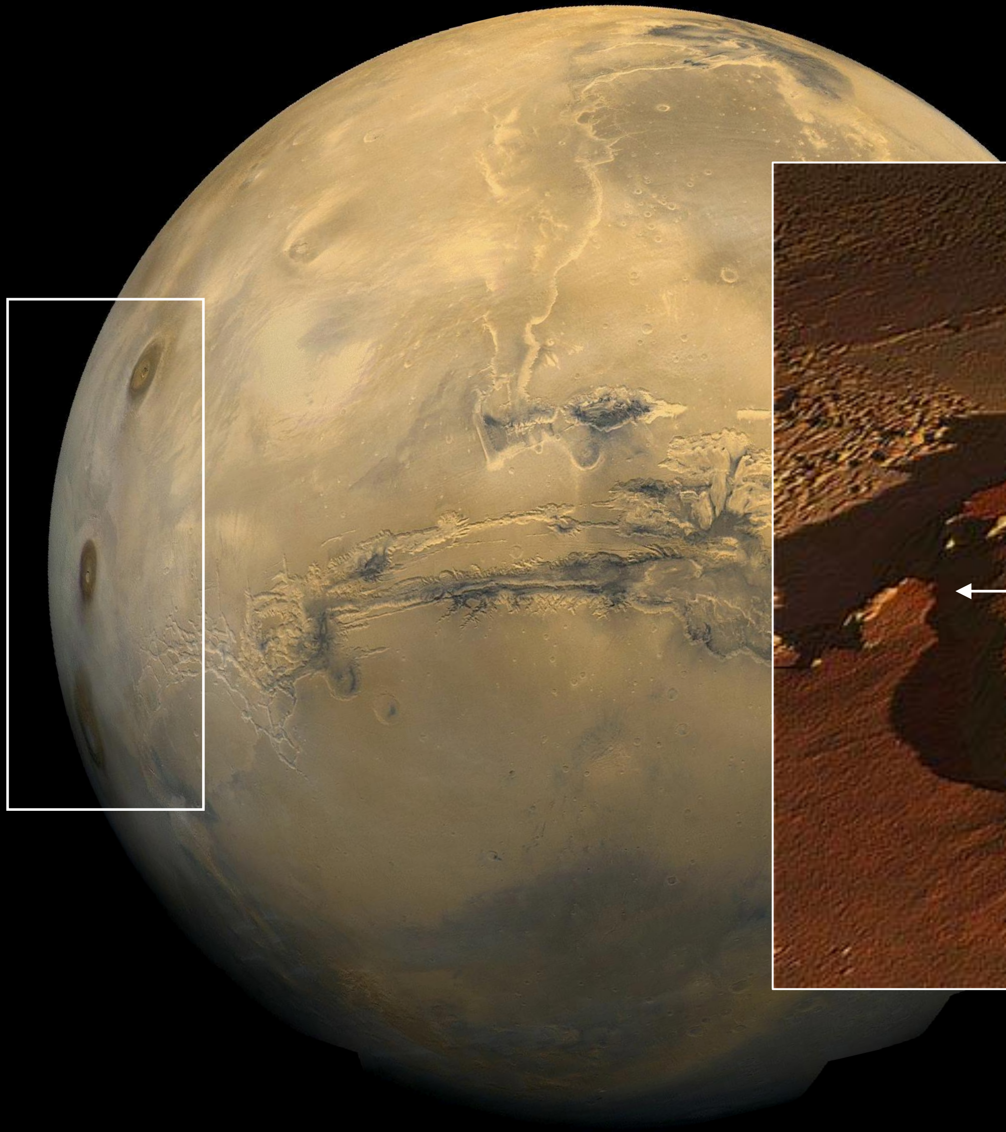
Gigantic geological structures



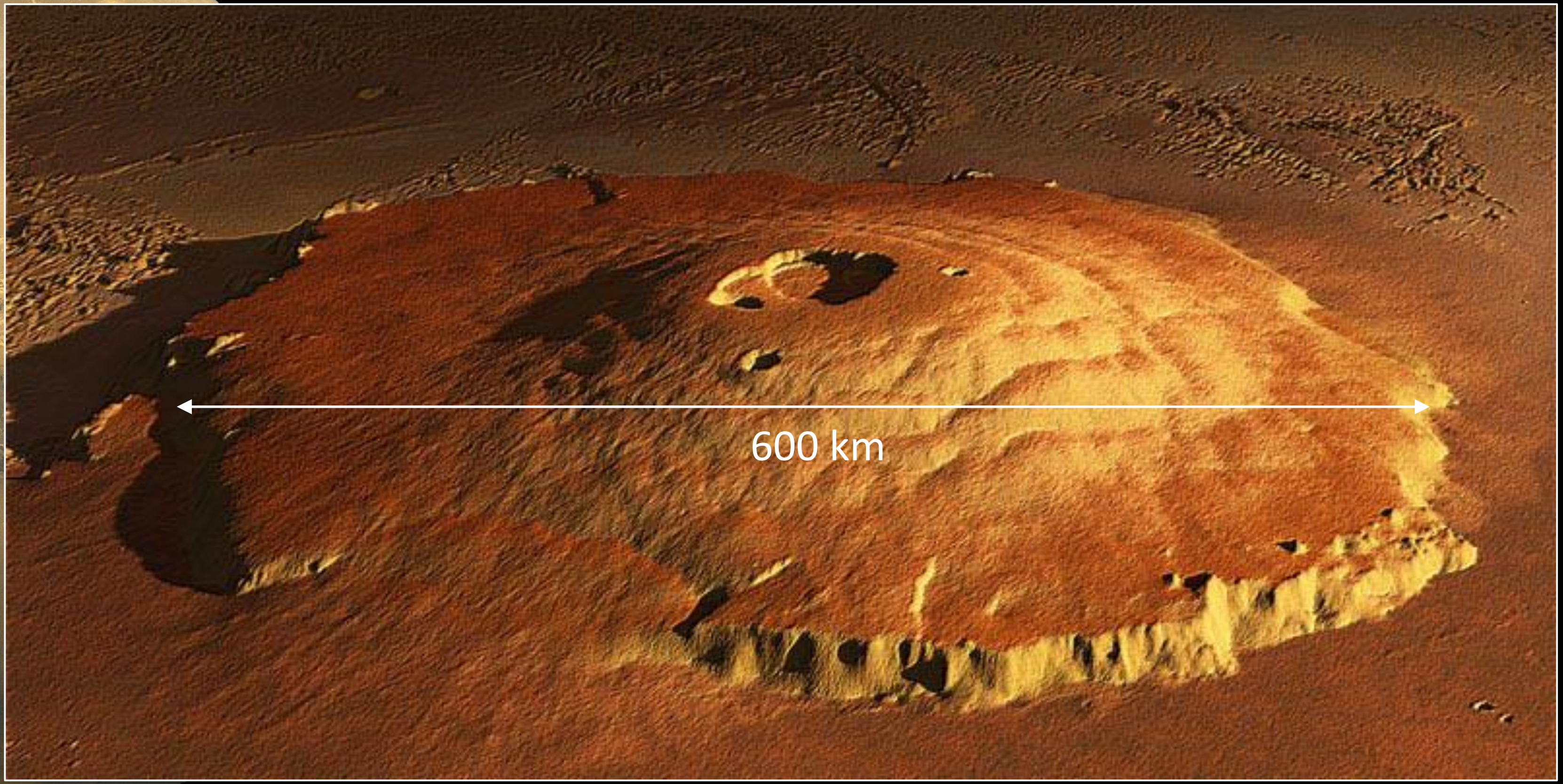
Tharsis volcanic system – 3.5-3.8 Gy old



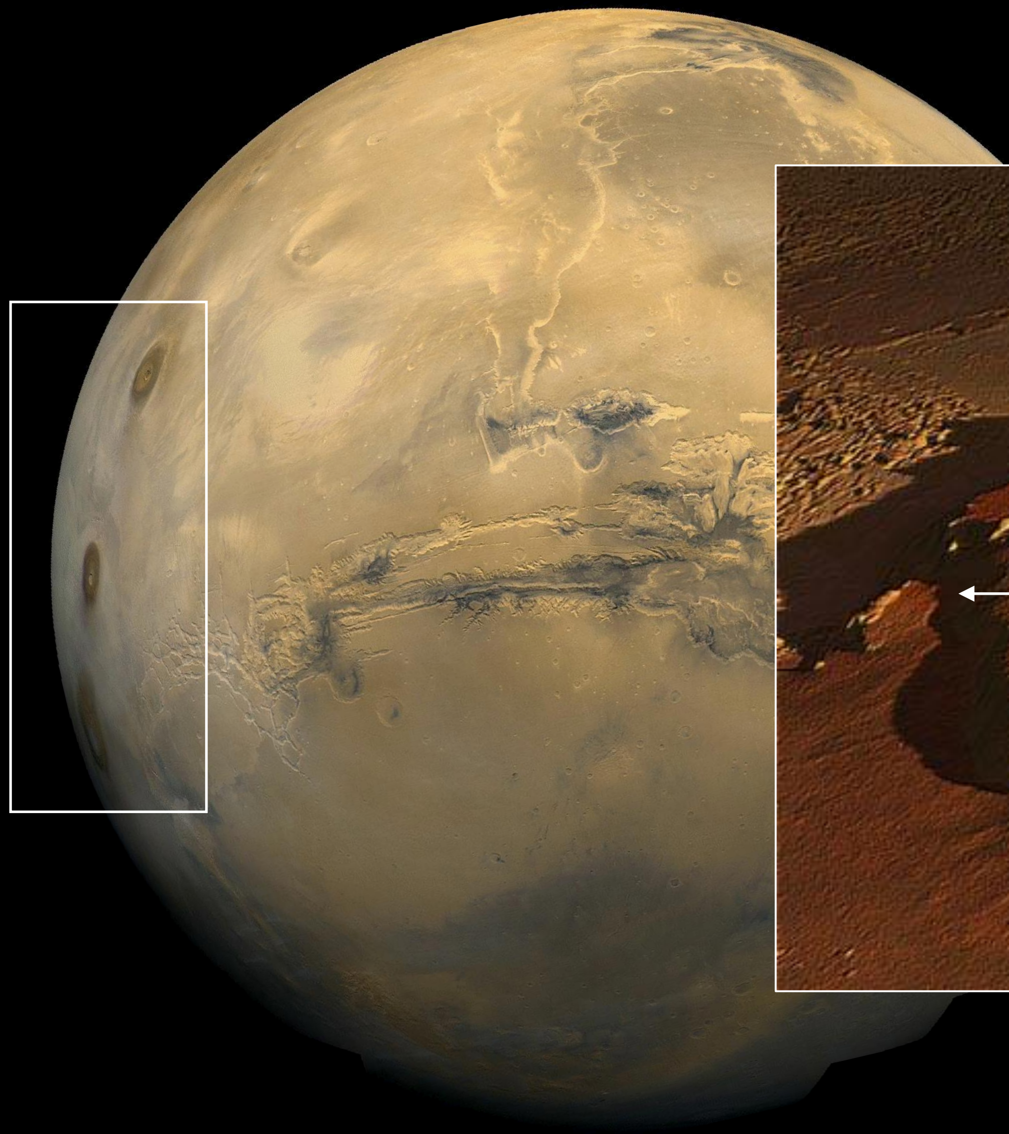
Gigantic geological structures



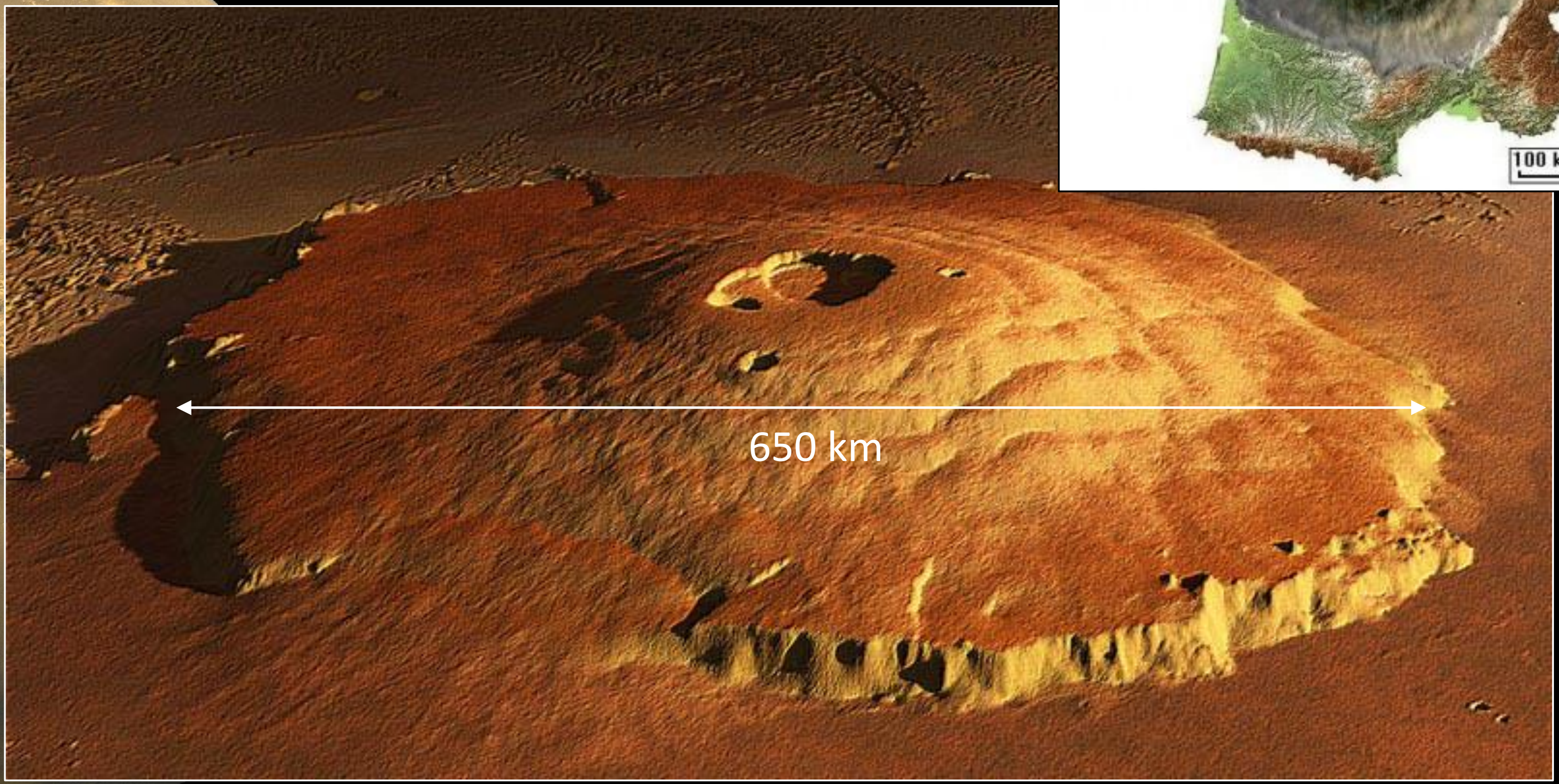
Olympus Mons – still active 2 My ago



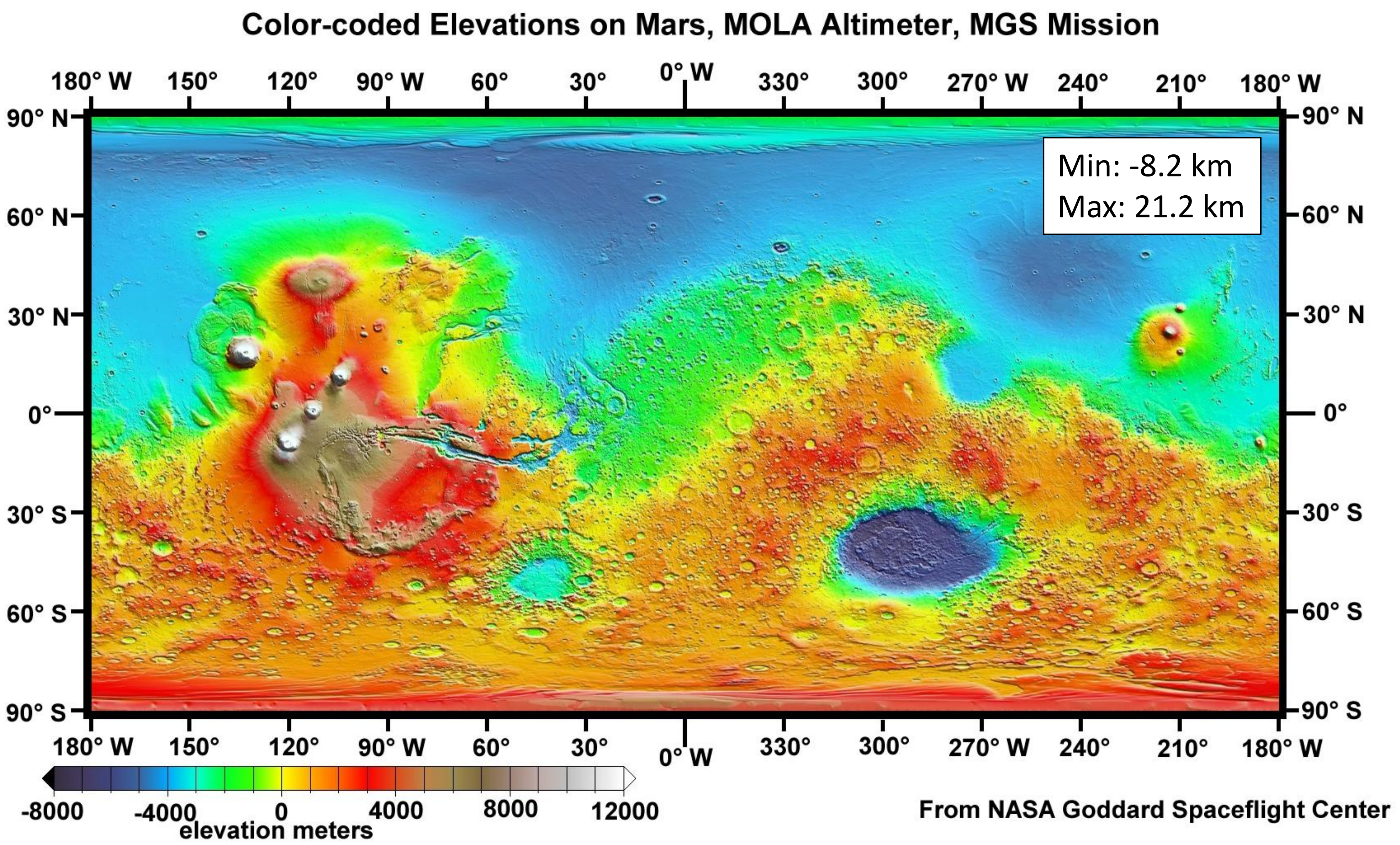
Gigantic geological structures



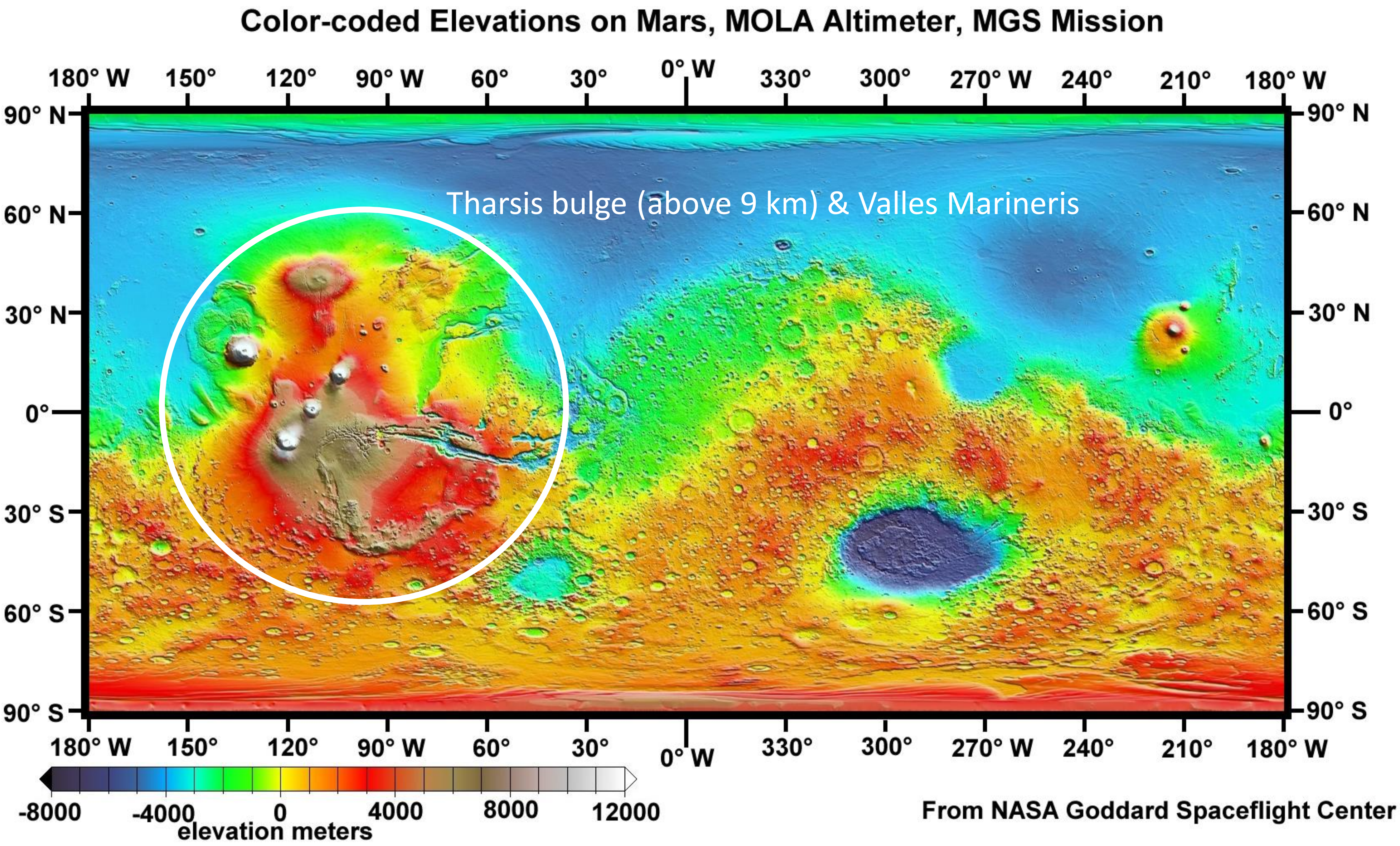
Olympus Mons



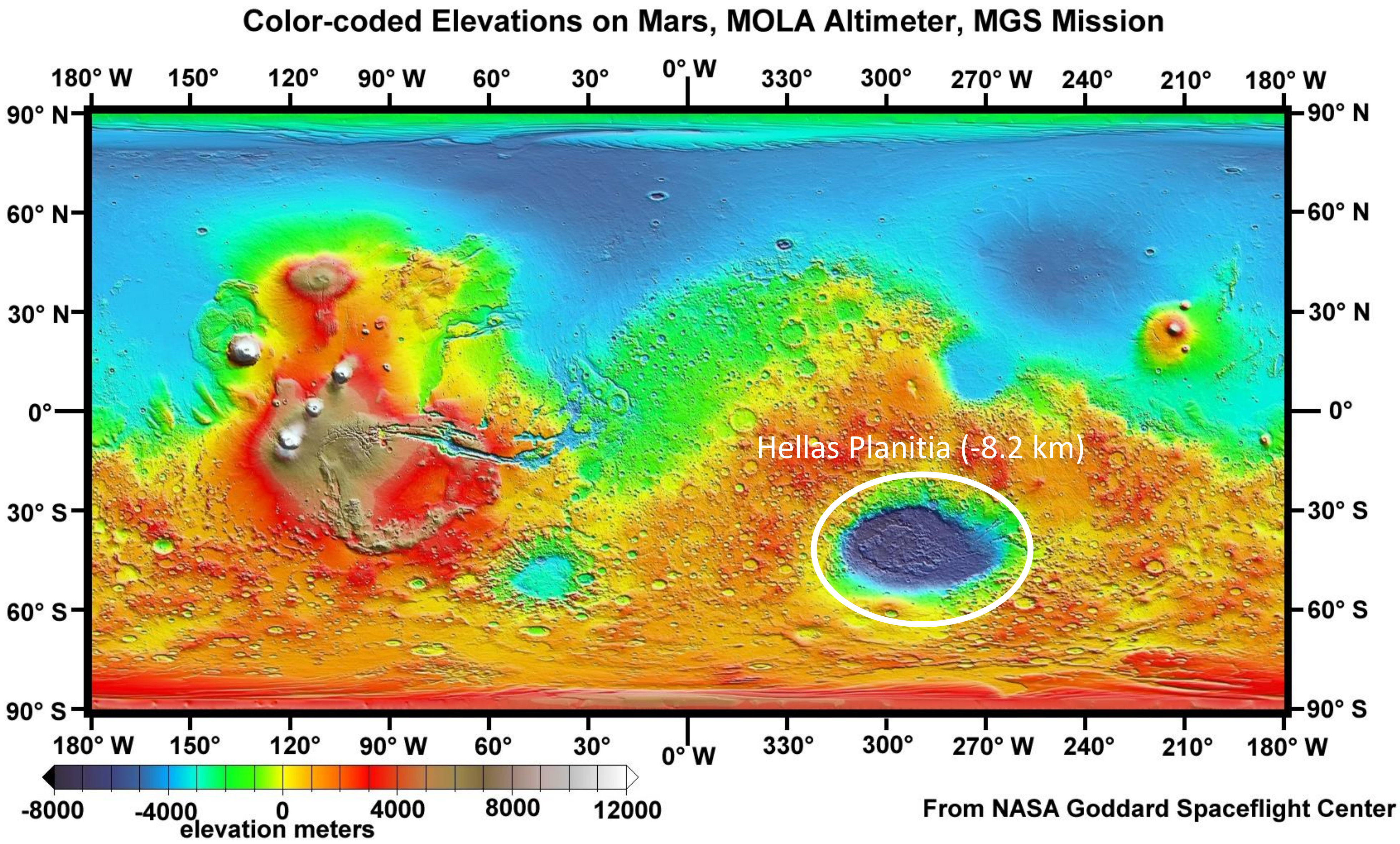
Hemispheric dichotomy



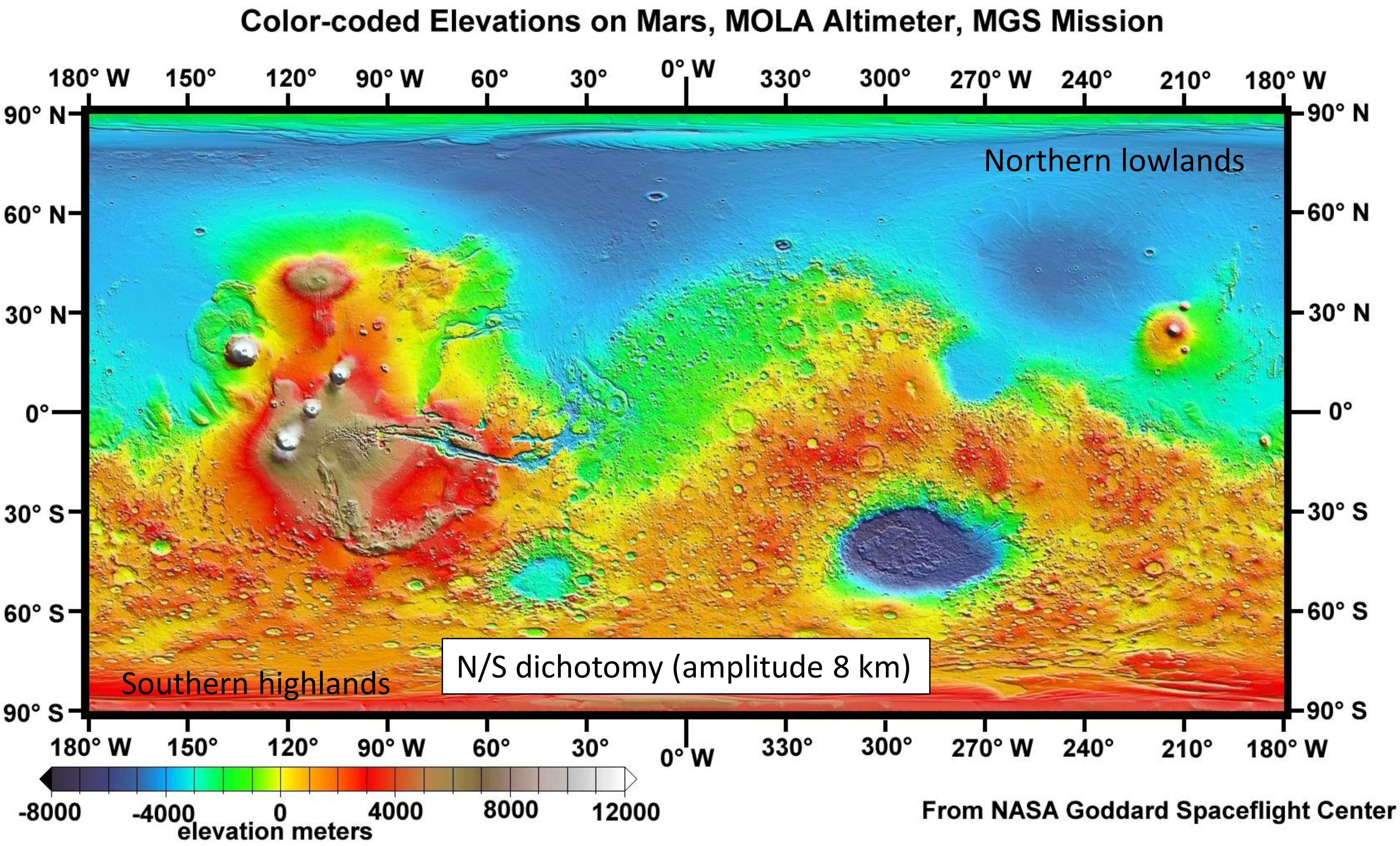
Hemispheric dichotomy



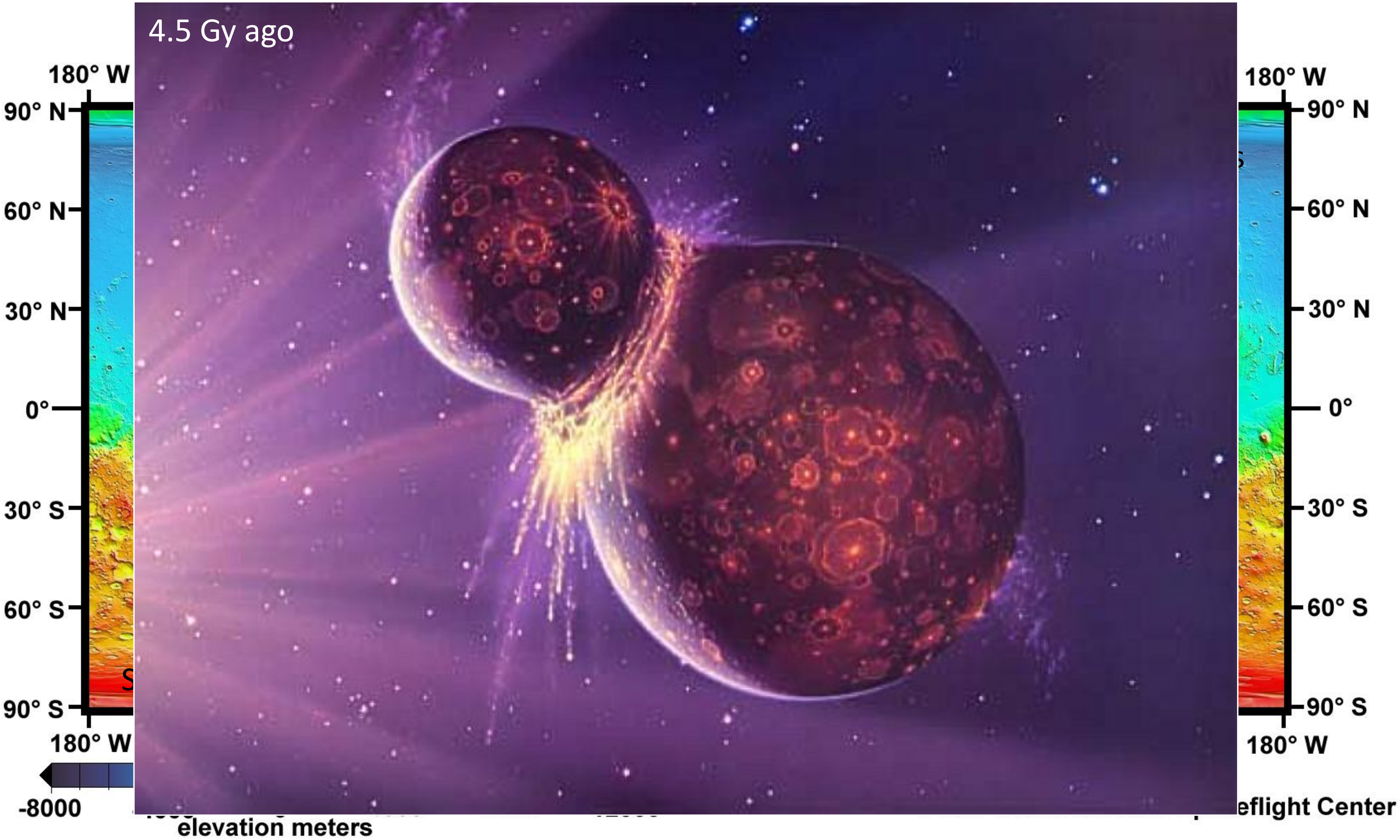
Hemispheric dichotomy

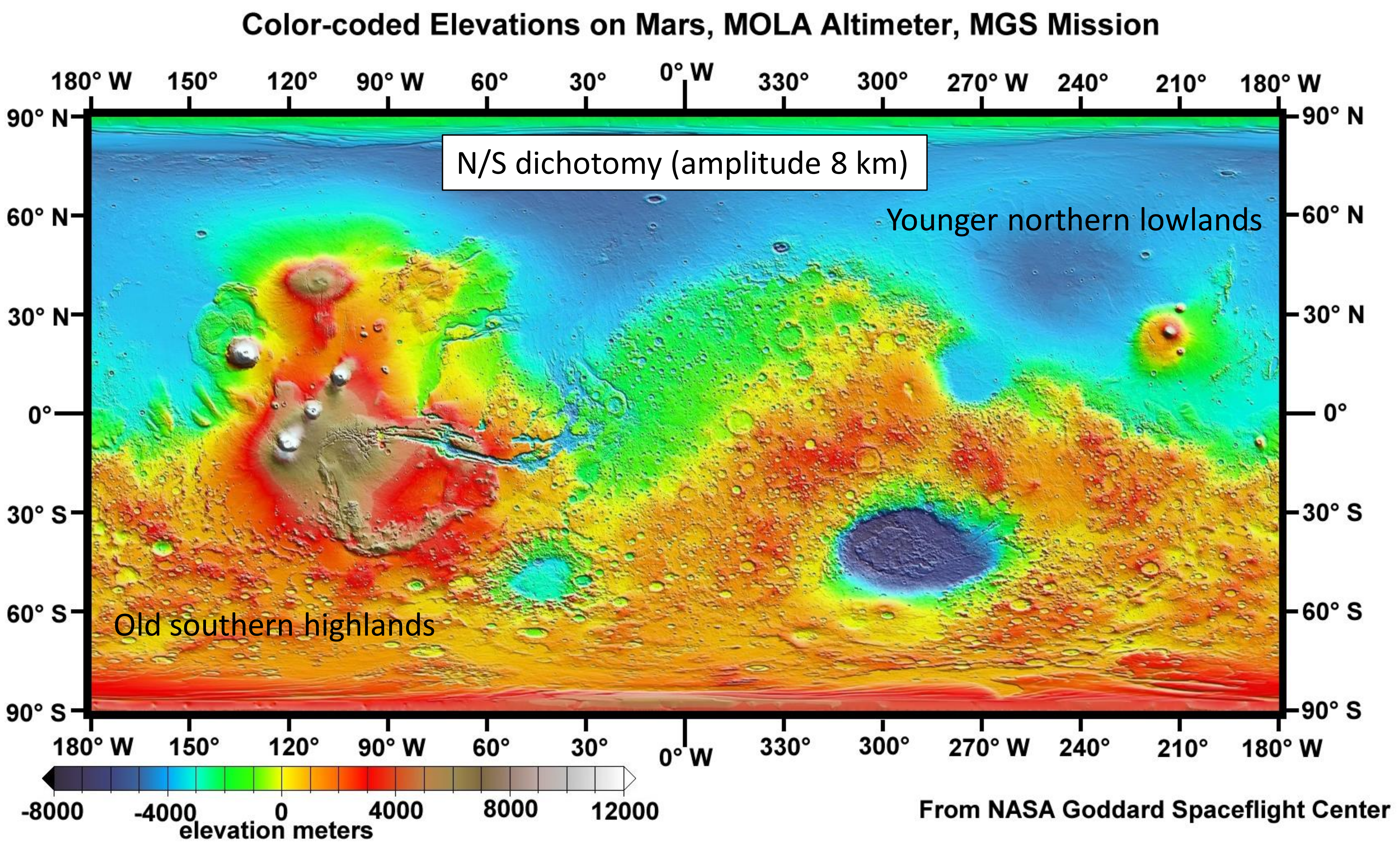


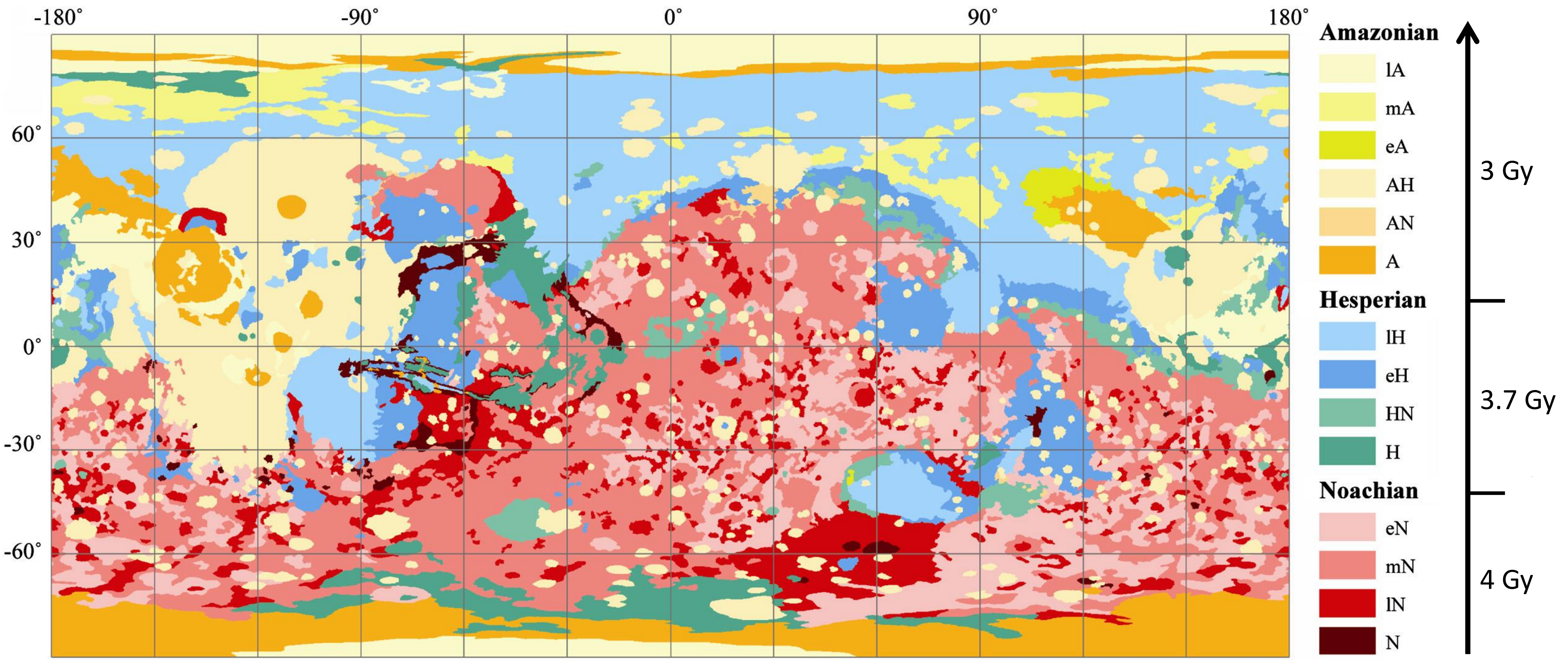
Hemispheric dichotomy



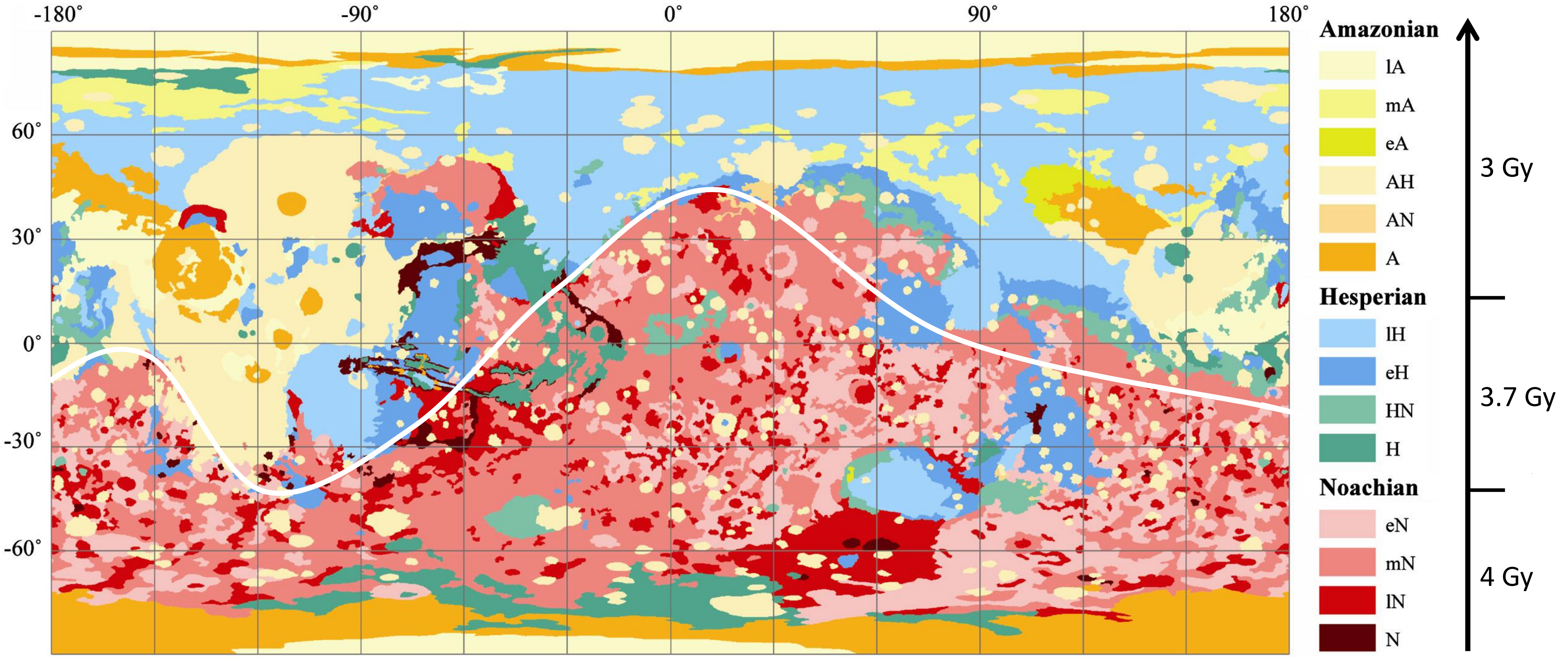
Hemispheric dichotomy



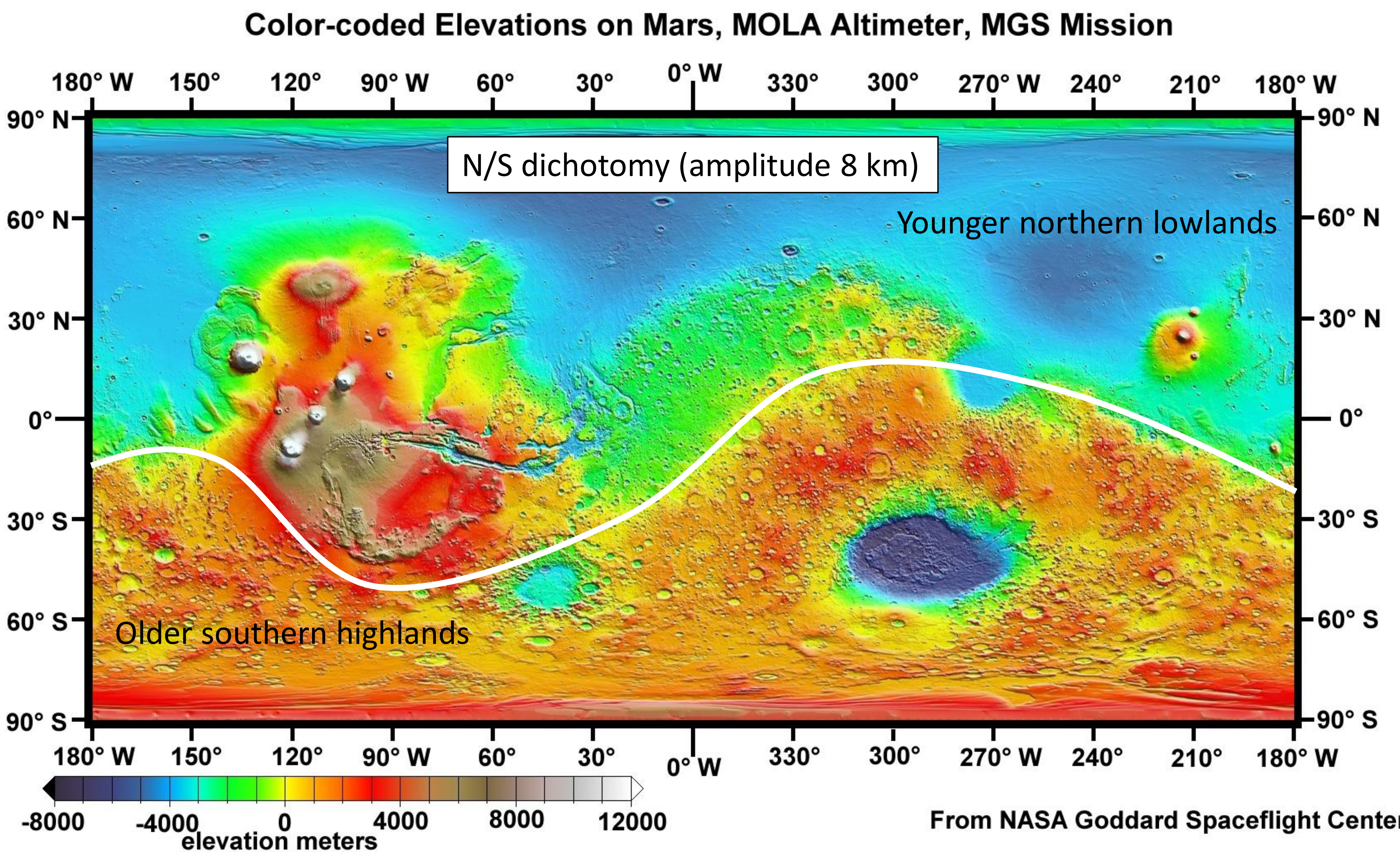

Color-coded Elevations on Mars, MOLA Altimeter, MGS Mission
180° W
150°
120°
90° W
60°
30°
0° W
330°
300°
270° W
240°
210°
180° W
90° N
60° N
30° N
0°
30° S
60° S
90° S
N/S dichotomy (amplitude 8 km)
Younger northern lowlands
Old southern highlands
-8000
-4000
0
4000
8000
12000
elevation meters
From NASA Goddard Spaceflight Center



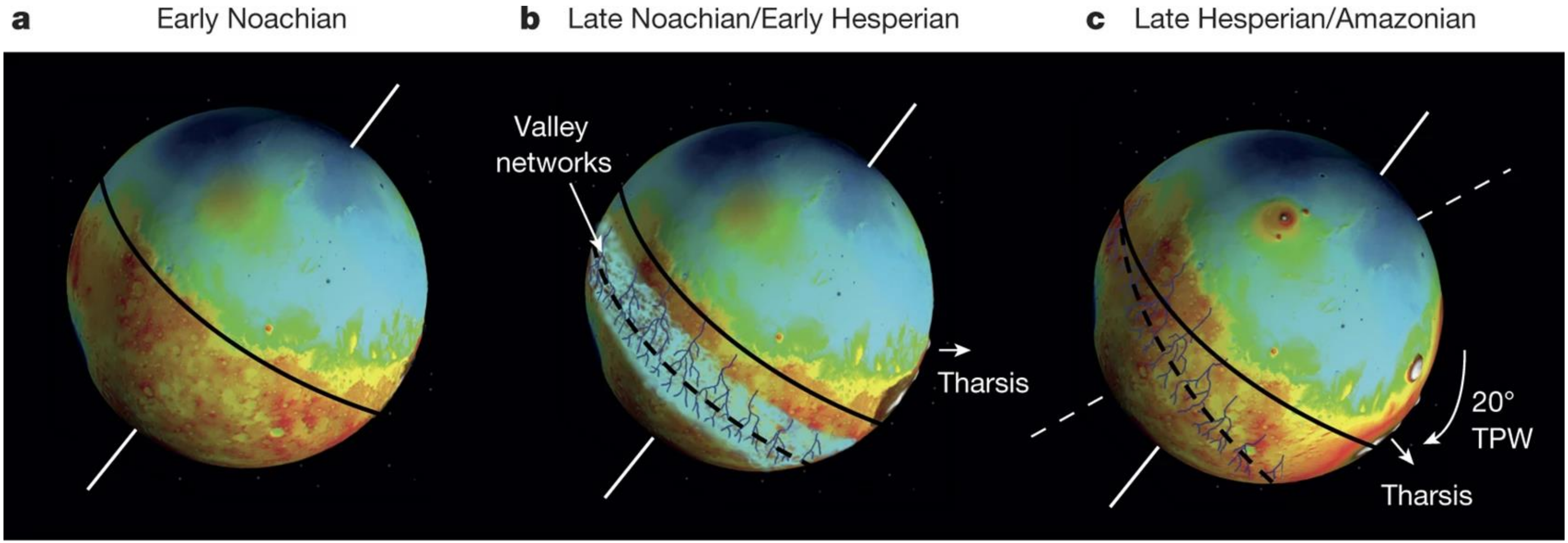
No plate tectonics, long period of weak erosion ⇨ widespread VERY old rocks, giving access to ancient Mars


-180°
-90°
0°
90°
180°
60°
30°
0°
-30°
-60°
Amazonian
lA
mA
eA
AH
AN
A
Hesperian
lH
eH
HN
H
Noachian
eN
mN
lN
N
3 Gy
3.7 Gy
4 Gy

Hemispheric dichotomy



From NASA Goddard Spaceflight Center



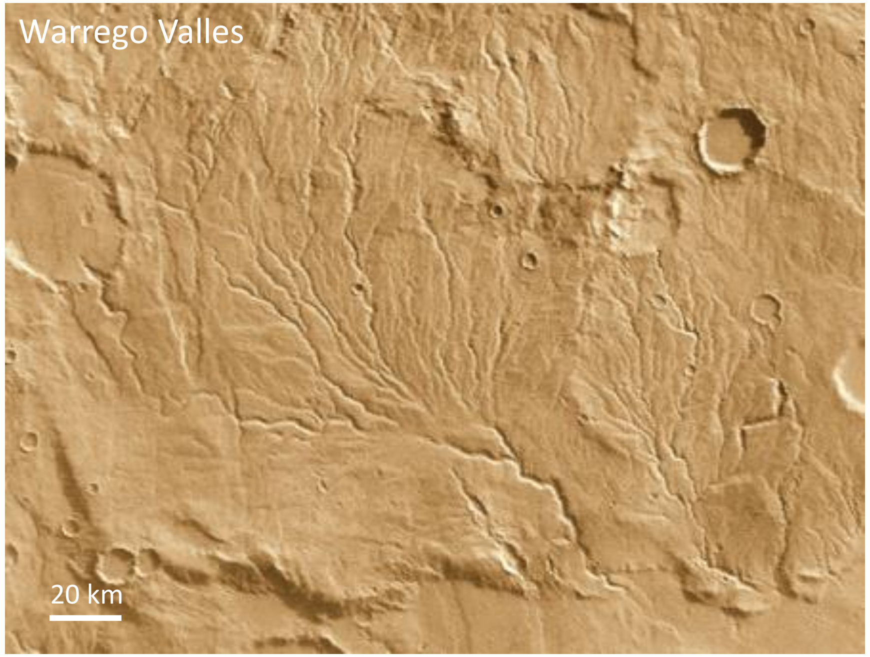
Formation of the dichotomy, heavy bombardment, dichotomy boundary in equatorial position

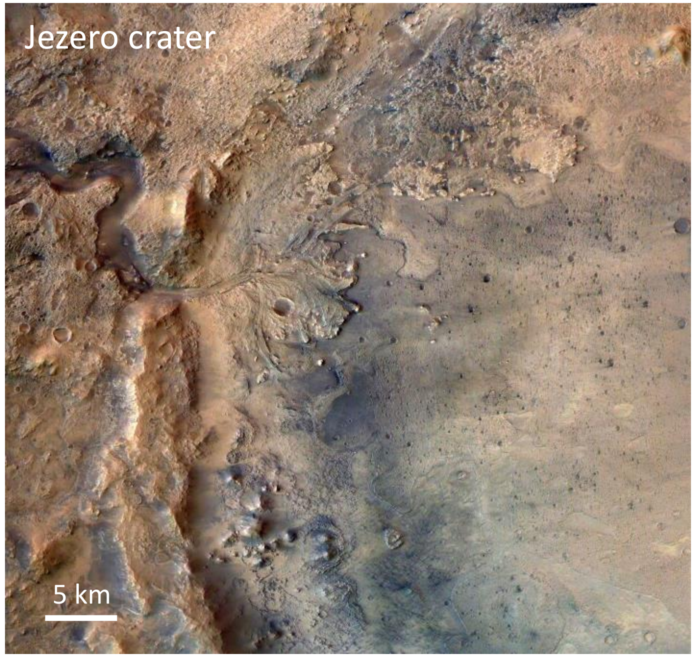
Tharsis dome formation, tropical precipitation with valley networks formation

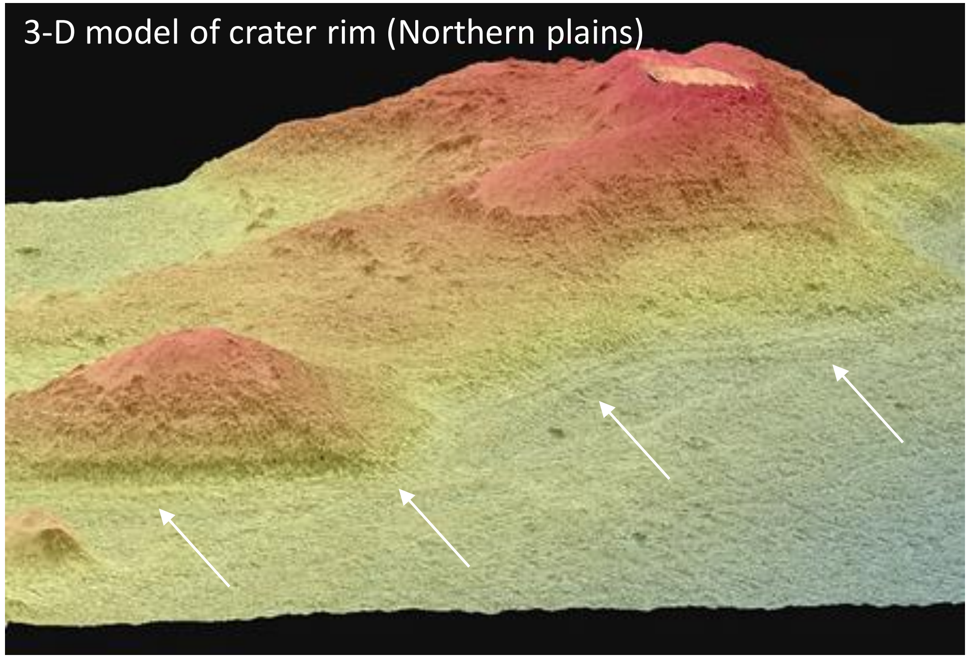
Tharsis formation causes a TPW, valley networks on a small circle, Tharsis bulge on the equator

From an aqueous past… Geological markers

- Global cartography from Mariner 9 in 1972
- Since, numerous hi-res observations from multiple instruments (e.g. MOLA altimeter, HRSC/Mex, HiRISE/MRO, Cassis/TGO):
  - Fluvial valleys with alluvial fans (tropical to equatorial southern regions), indicative of a "liquid" cycle in additive to "ground-liquids"
  - Lakes' markers in impact craters and topographic depressions: layered sediment deposits, liquid erosion, deltas and "flush" valleys outgoing the craters
  - Putative ancient semi-global ocean in the northern lowlands: possible shorelines, tsunami markers?

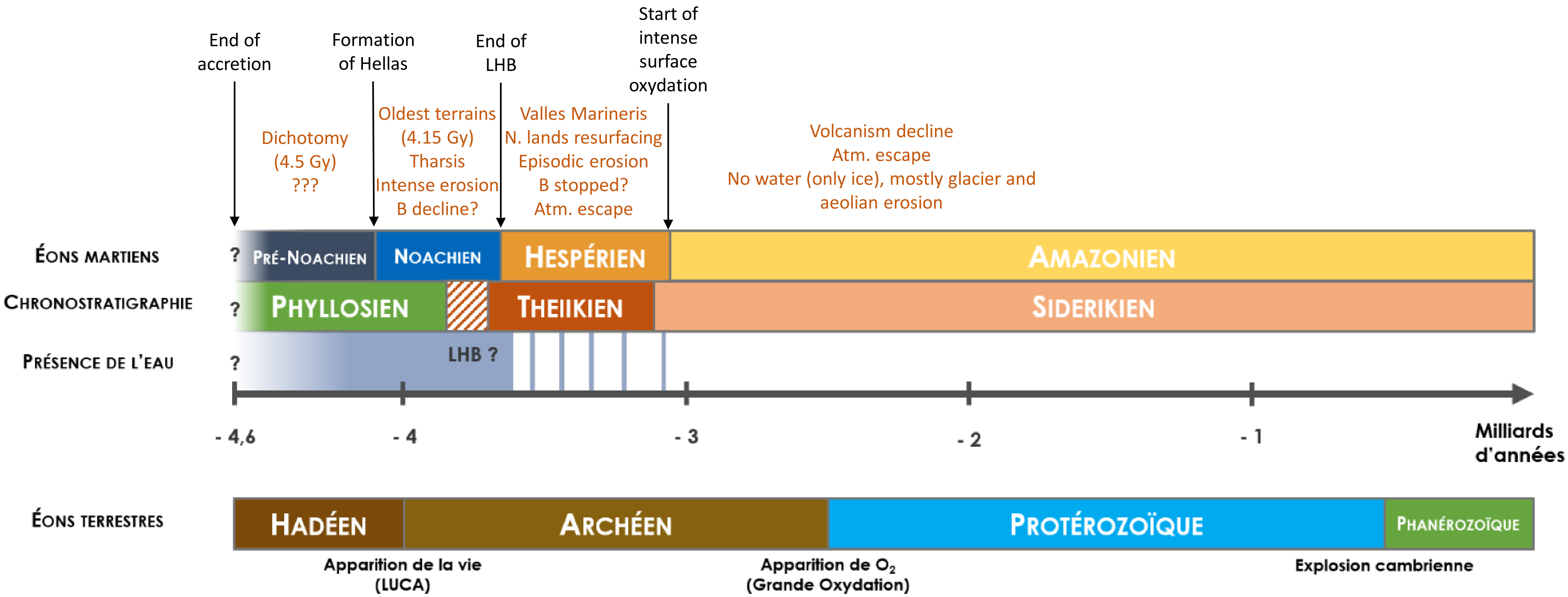






A wealth of geomorphological evidences for liquid(s), in NOACHIAN (oldest) terrains, but still open questions about nature of the liquid, long-term stability and chemical environment (more related to habitability)

Geological chronostratigraphy
Towards a Martian global history



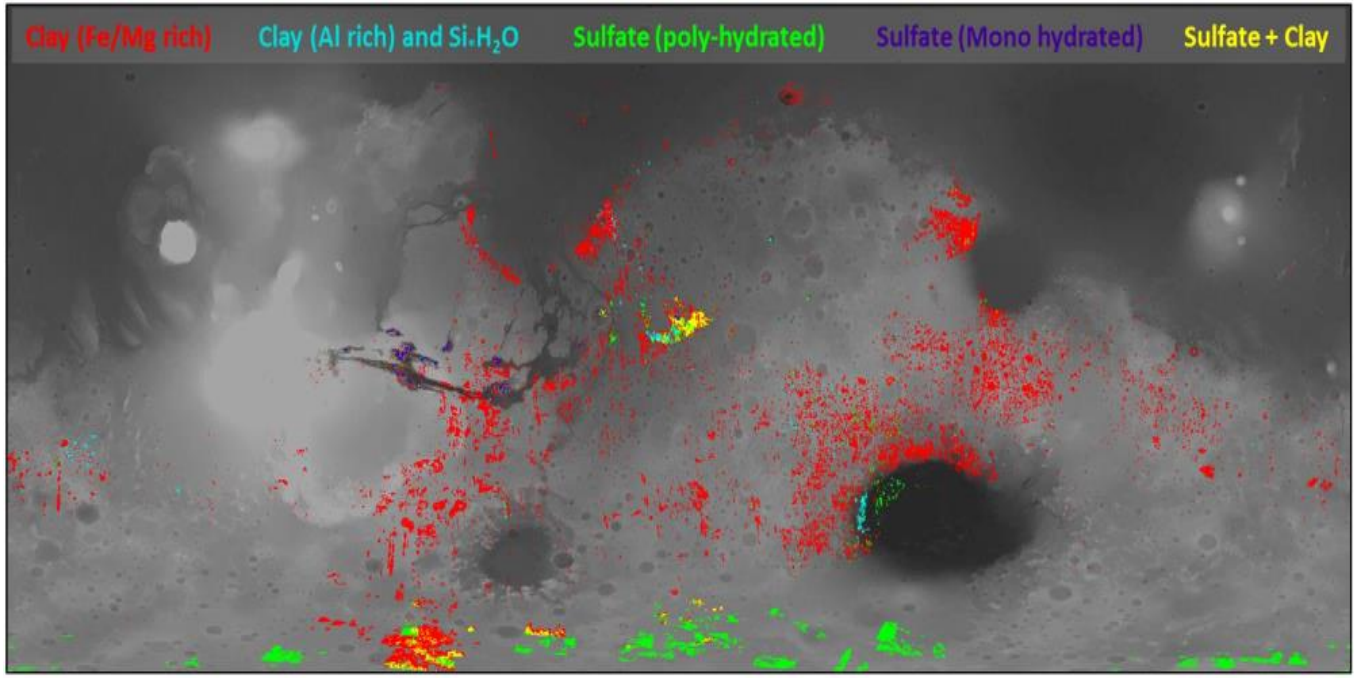
From an aqueous past… Chemical markers

- Starts in early XXI^e century
- The revolution of Martian near-infrared spectroscopy and spectral-imagery (e.g. OMEGA/Mex, CRISM/MRO), starting in 2004 – complemented by local *in situ* analyses by landers and rovers (MERs, Phoenix, Curiosity, Perseverance):
  - Reveal the nature of soil minerals (primary or products of alteration): detection of hydrated minerals
  - Bring strong constraints on formation conditions (temperature, pression, contact with liquid water or water ice, pH, composition of the atmosphere and surface water, duration of contact with water…)
  - Main families of hydrated minerals found on Mars:

    - Phyllosilicates: clays, need long contact with liquid water to form (≈100 My), temperate water temperature.

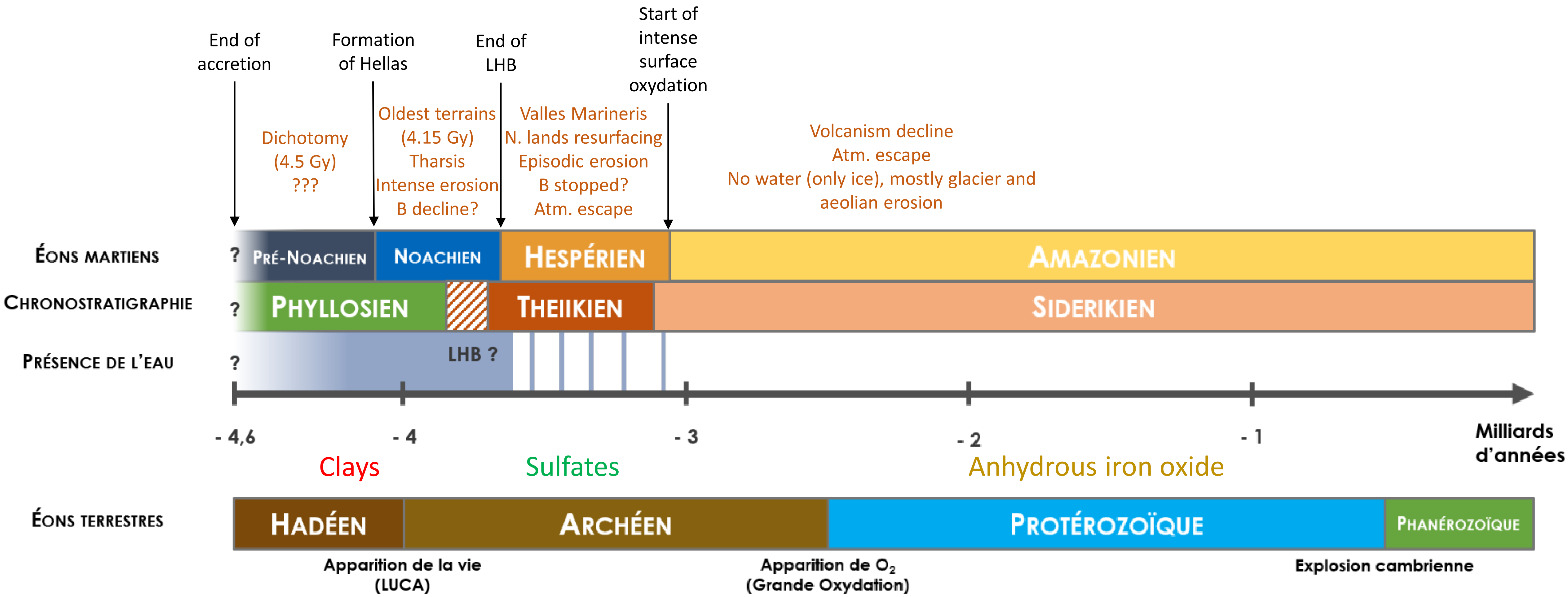
    - Sulfates: hydrated salts with sulfur, formed by precipitation in evaporating liquid water (shorter time of formation, but need for surface water, low pH). ✋ Icy alteration!

    - Carbonates: interaction of atmospheric CO_2 with liquid water or adsorbed water in minerals.

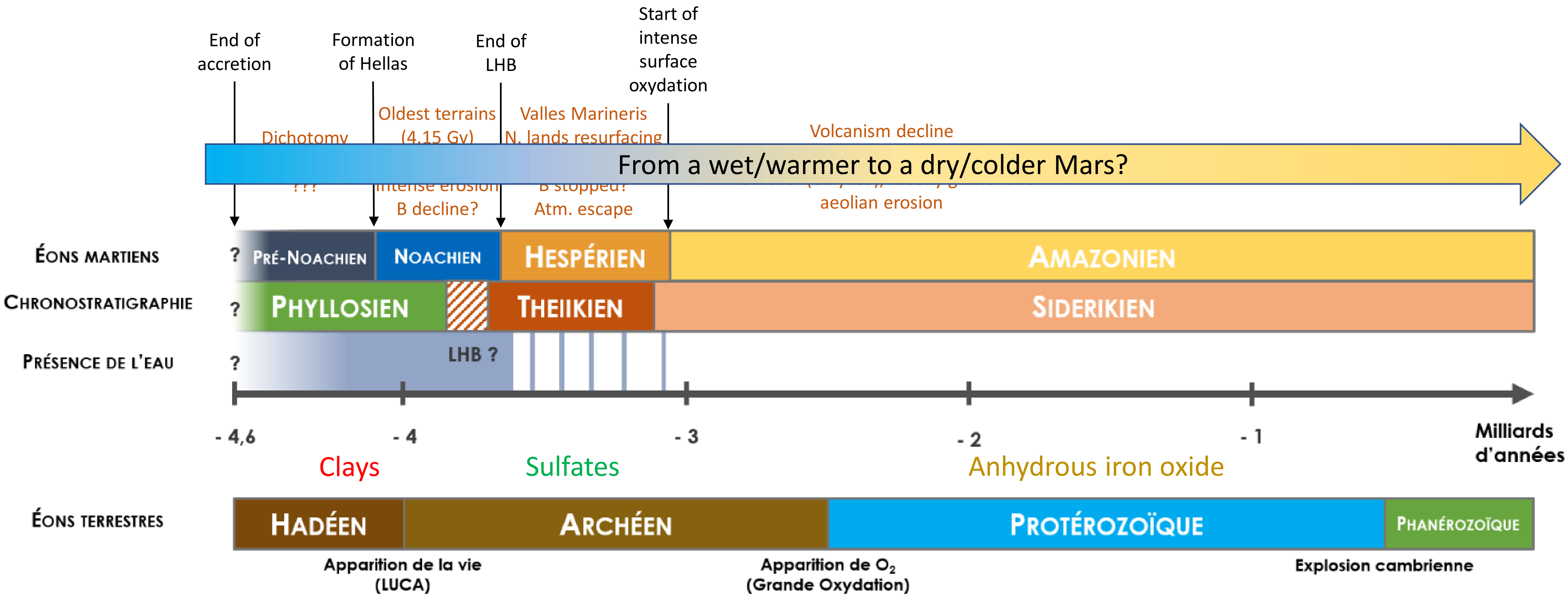


A wealth of mineralogical evidences for surface liquid water, in NOACHIAN (oldest) terrains

Geological and mineralogical chronostratigraphy
Towards a Martian global history



Geological and mineralogical chronostratigraphy
Towards a Martian global history



From an aqueous past... to a dry/arid present

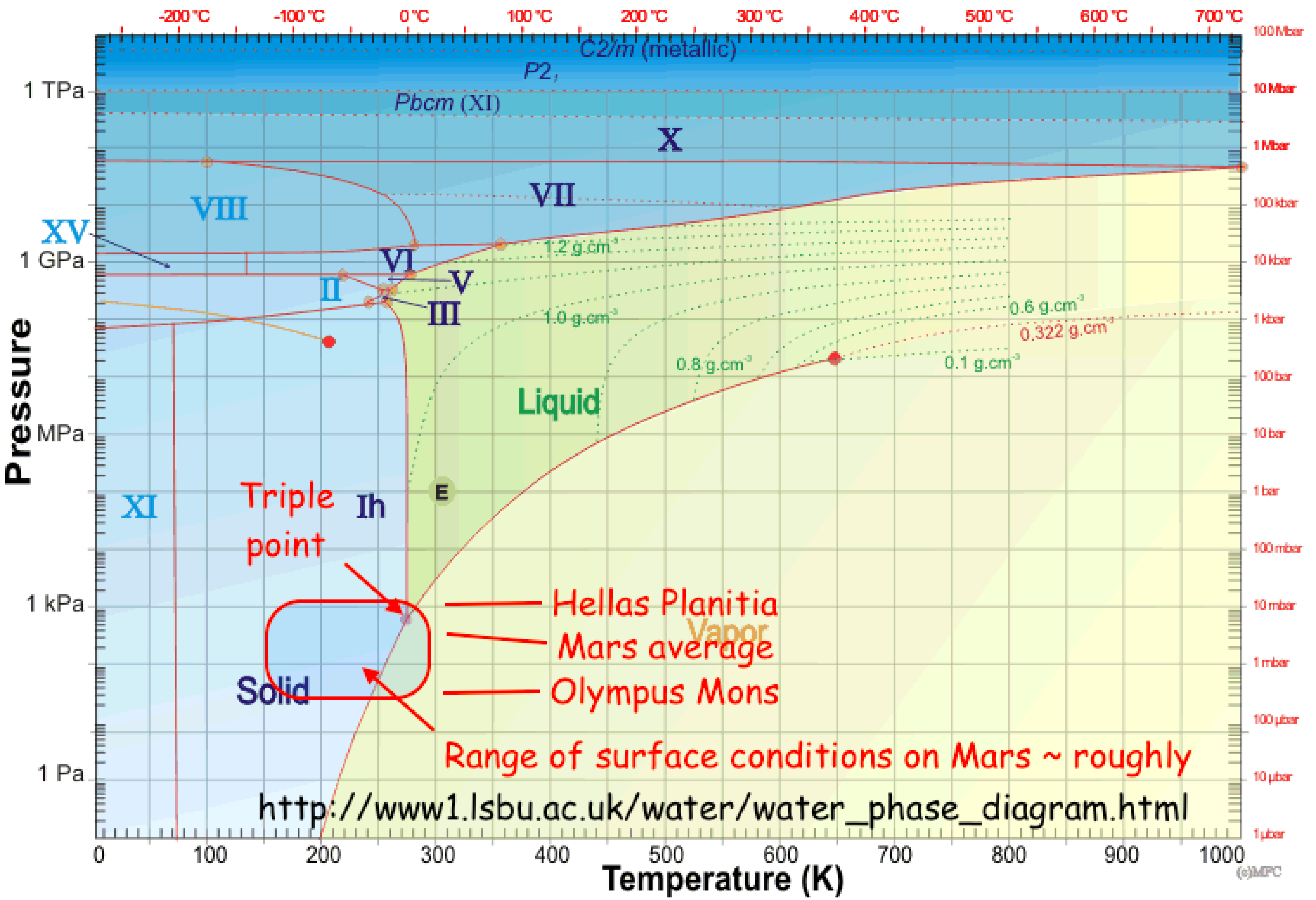
Mastcam-Z/Perseverance

Nowadays: dramatic desertic landscape, covered by dust, cold and windy

No more surface liquid water? Other reservoirs? Abundances? Where did the missing water go?

From an aqueous past… to a dry/arid present

Stability of liquid water under Mars surface conditions



Only vapor and ice are stable

When exposed to higher T° ⇨ sublimation

Fusion is possible, but short-lived

If mixed with salt (brines), possible lower fusion T° and higher surface stability

Recurring slope lineae

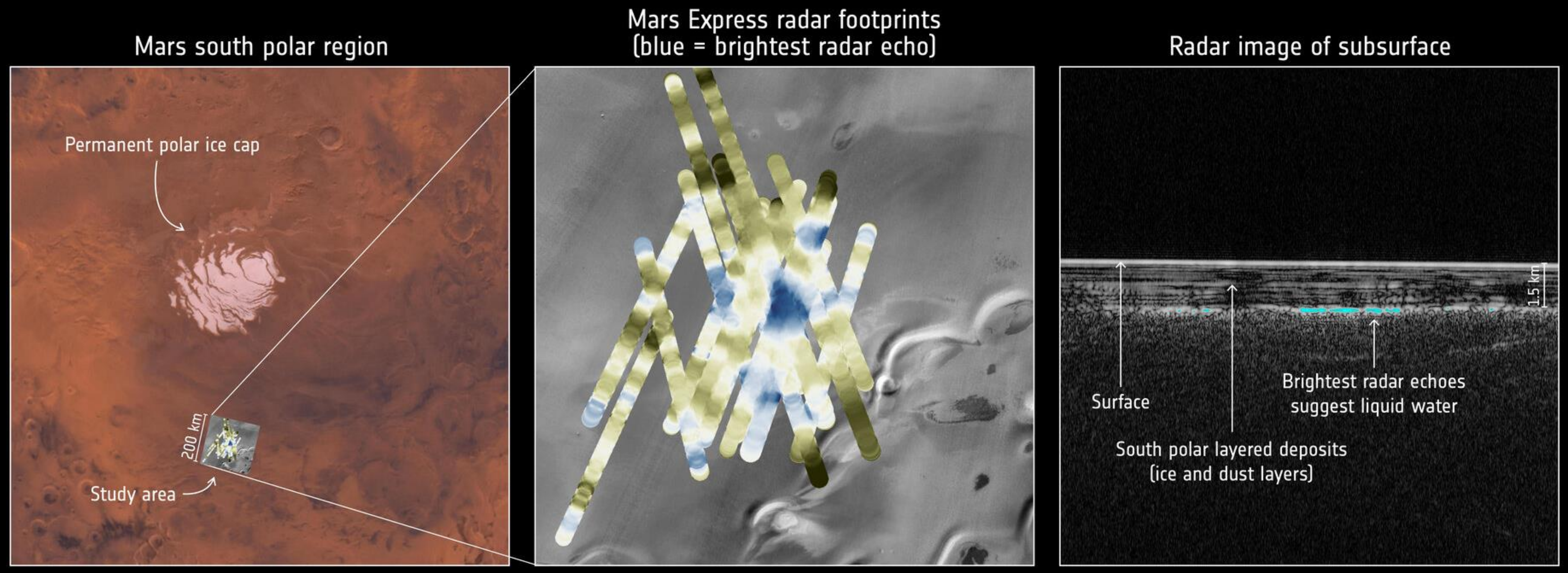
Possible present-day water runoff

Also dry landslides destabilized by gound-ice sublimation or wind

From an aqueous past… to a dry/arid present

Stability of liquid water under Mars surface/ground conditions

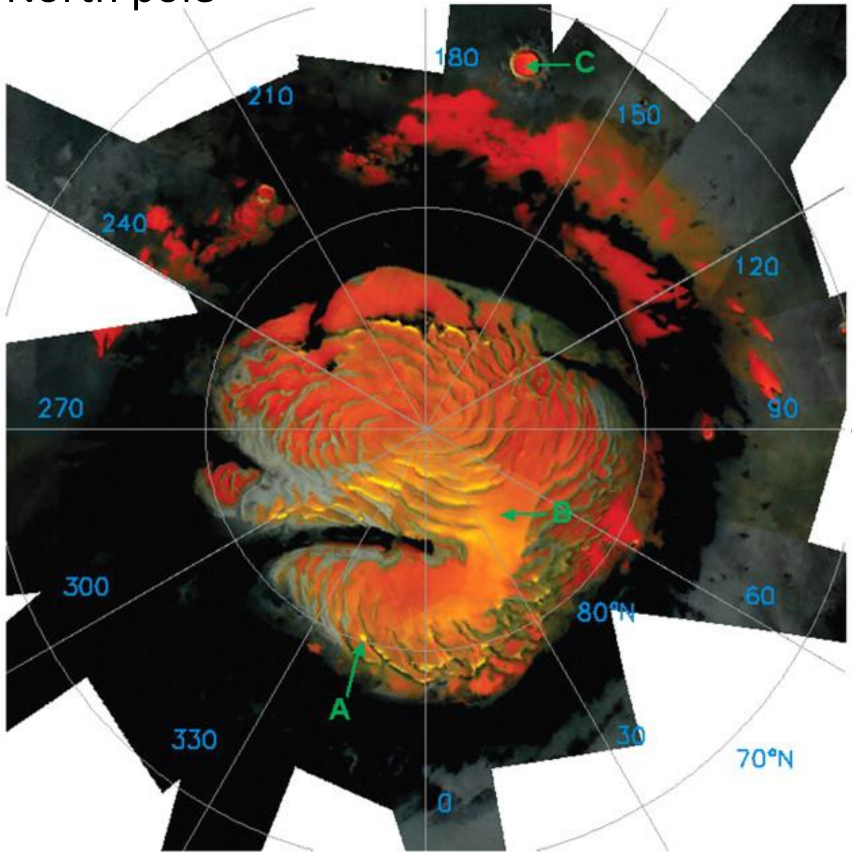
To date, only dubious detections…



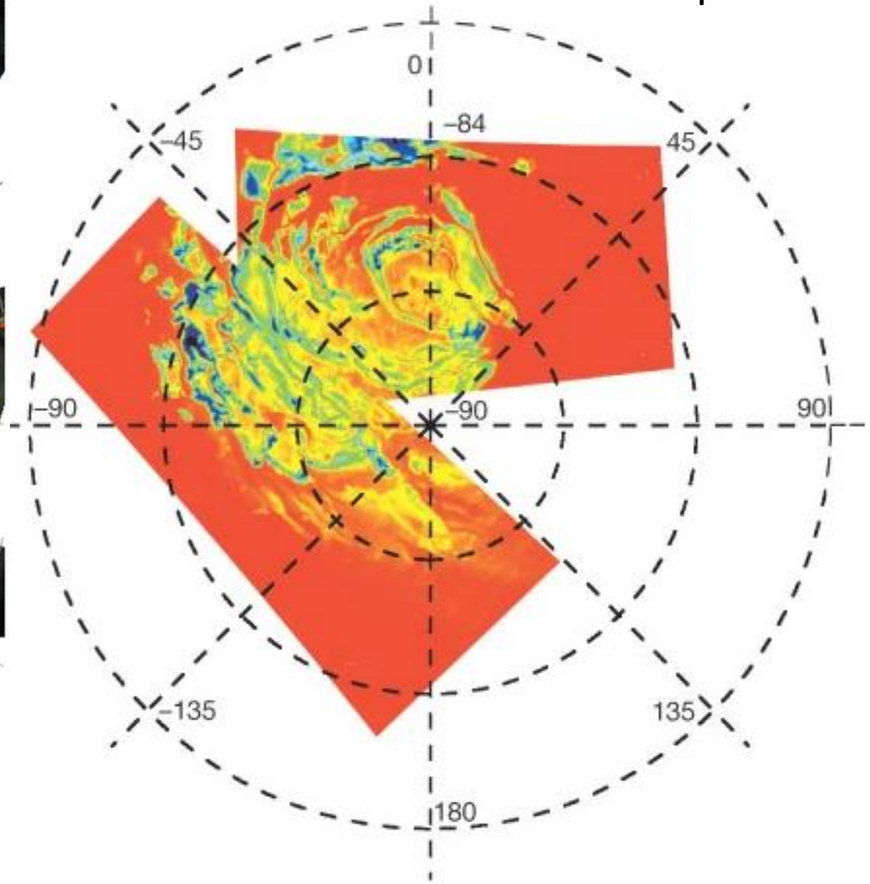
From an aqueous past… to a dry/arid present

Water on today Mars is mostly ice and vapor!

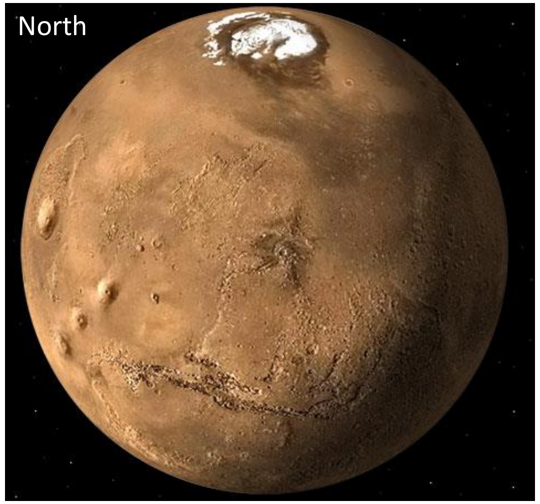
North pole

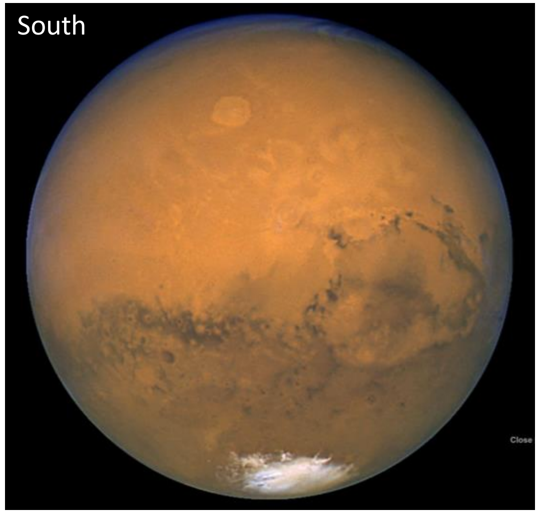


South pole



Water ice infrared signature (Water ice cap is perennial, CO_2 ice cap is seasonal)





3-km thick, 1500-km wide
≈20 cm deep global ocean

From an aqueous past... to a dry/arid present

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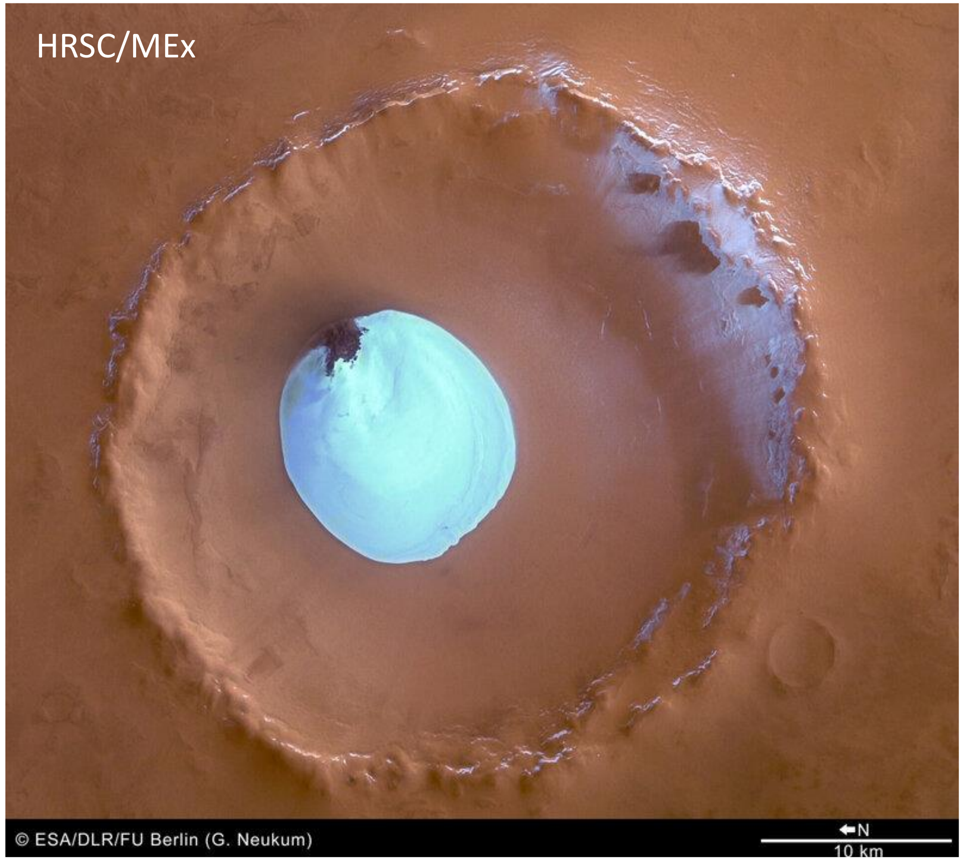
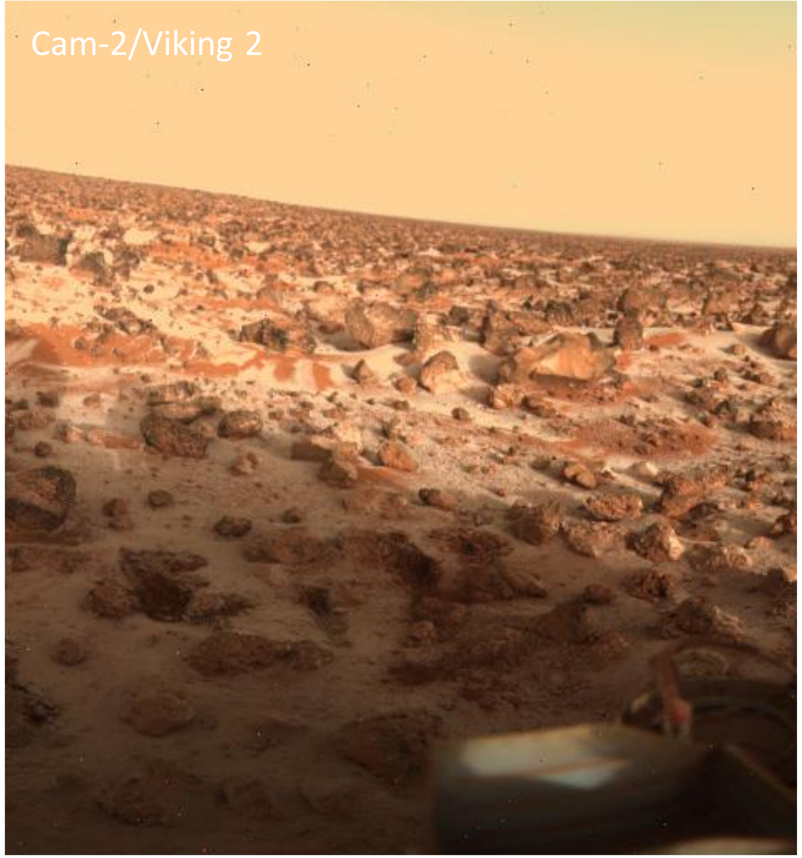
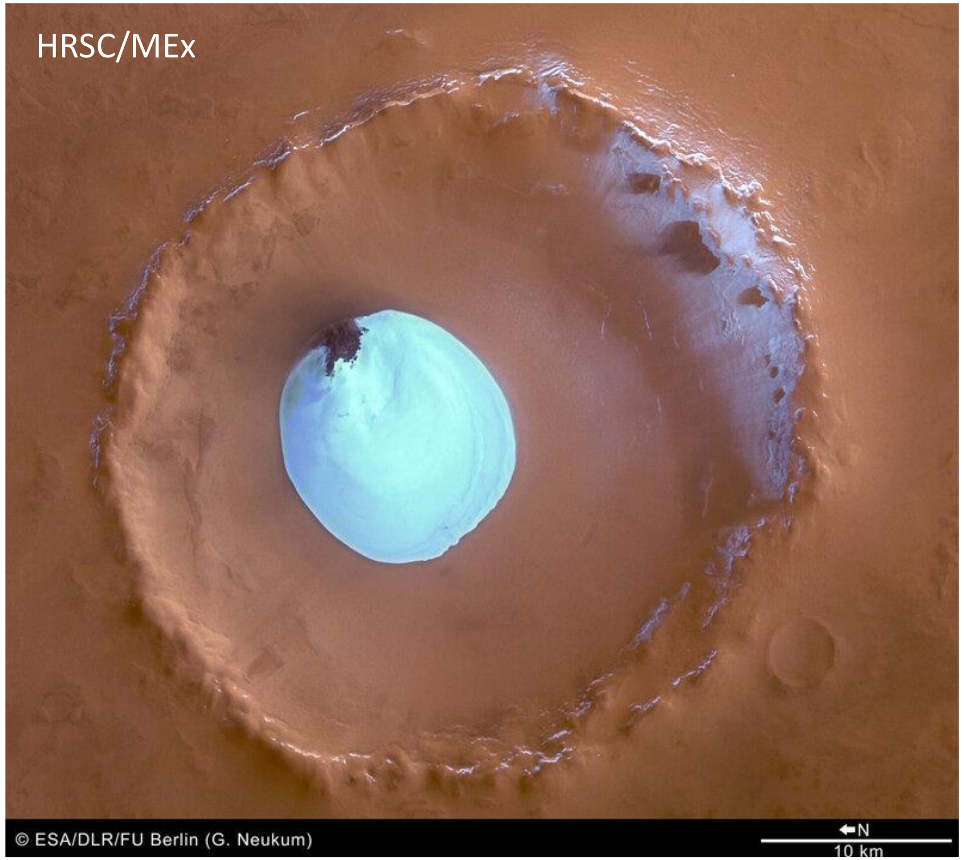


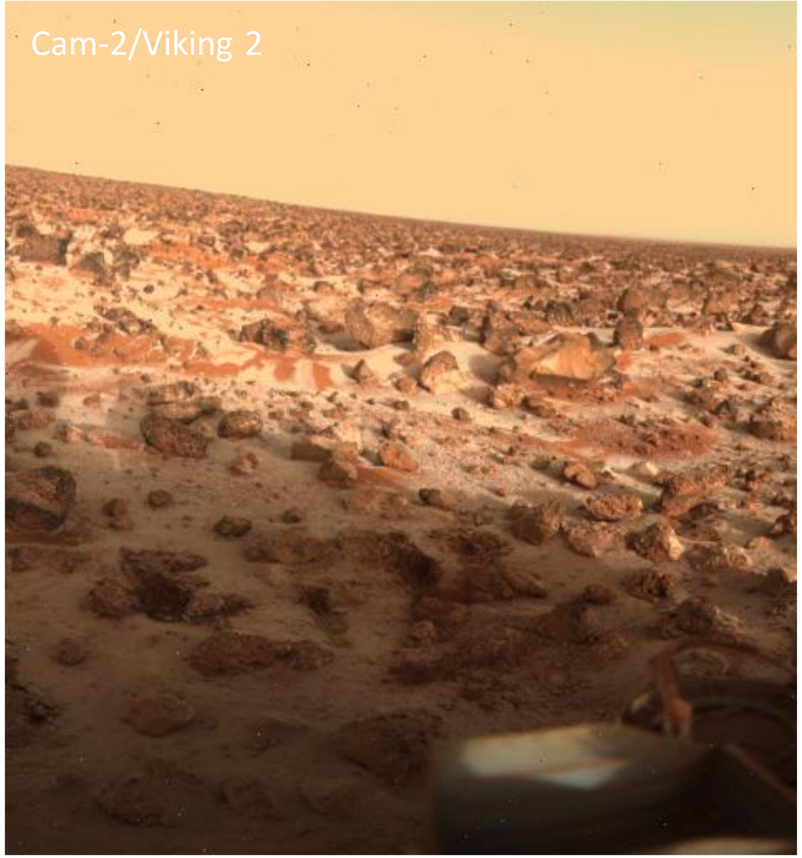


Ice patches and frost deposits in craters and pole facing slopes (in shadows)
Even more frequent that we get closer to the poles

From an aqueous past... to a dry/arid present

Water on today Mars is mostly ice and vapor!



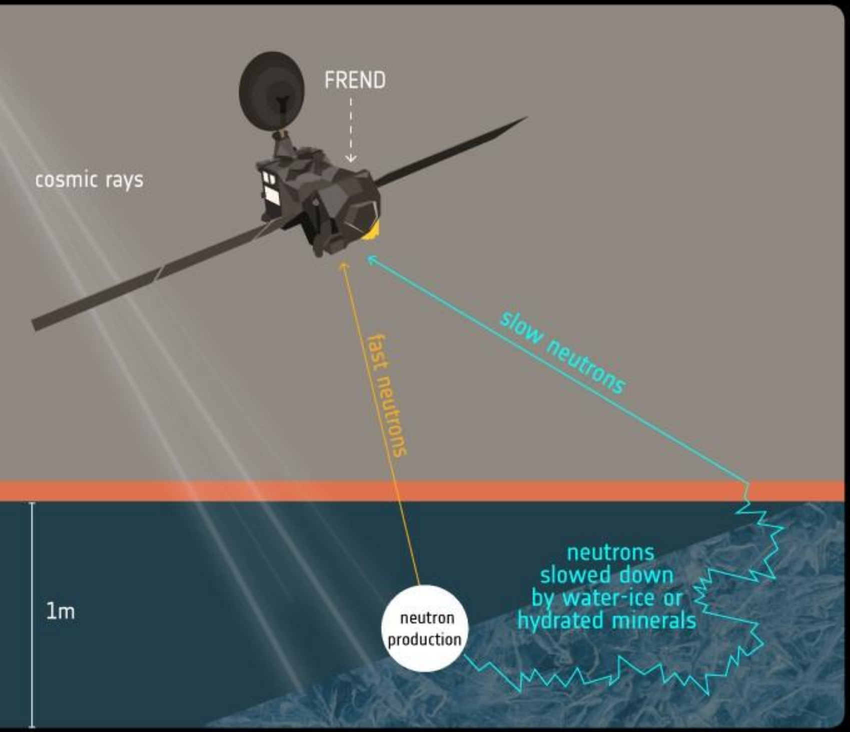


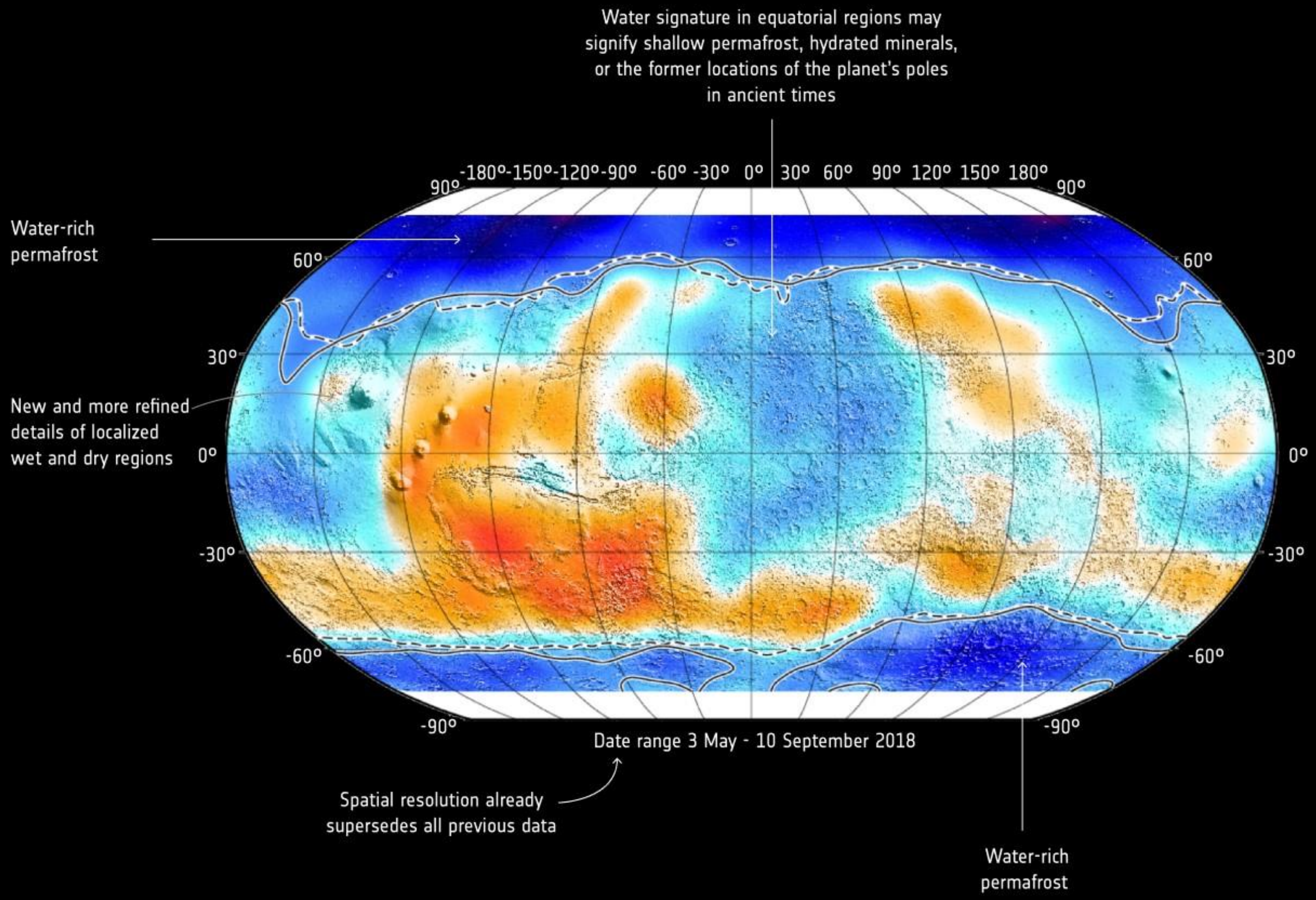
Ice patches and frost deposits in craters and pole facing slopes (in shadows)
Even more frequent that we get closer to the poles

Permafrost
only ≈cm deep at high latitudes,
deeper at lower latitudes

→ FIRST RESULTS FROM THE EXOMARS TRACE GAS ORBITER

First map of subsurface water distribution



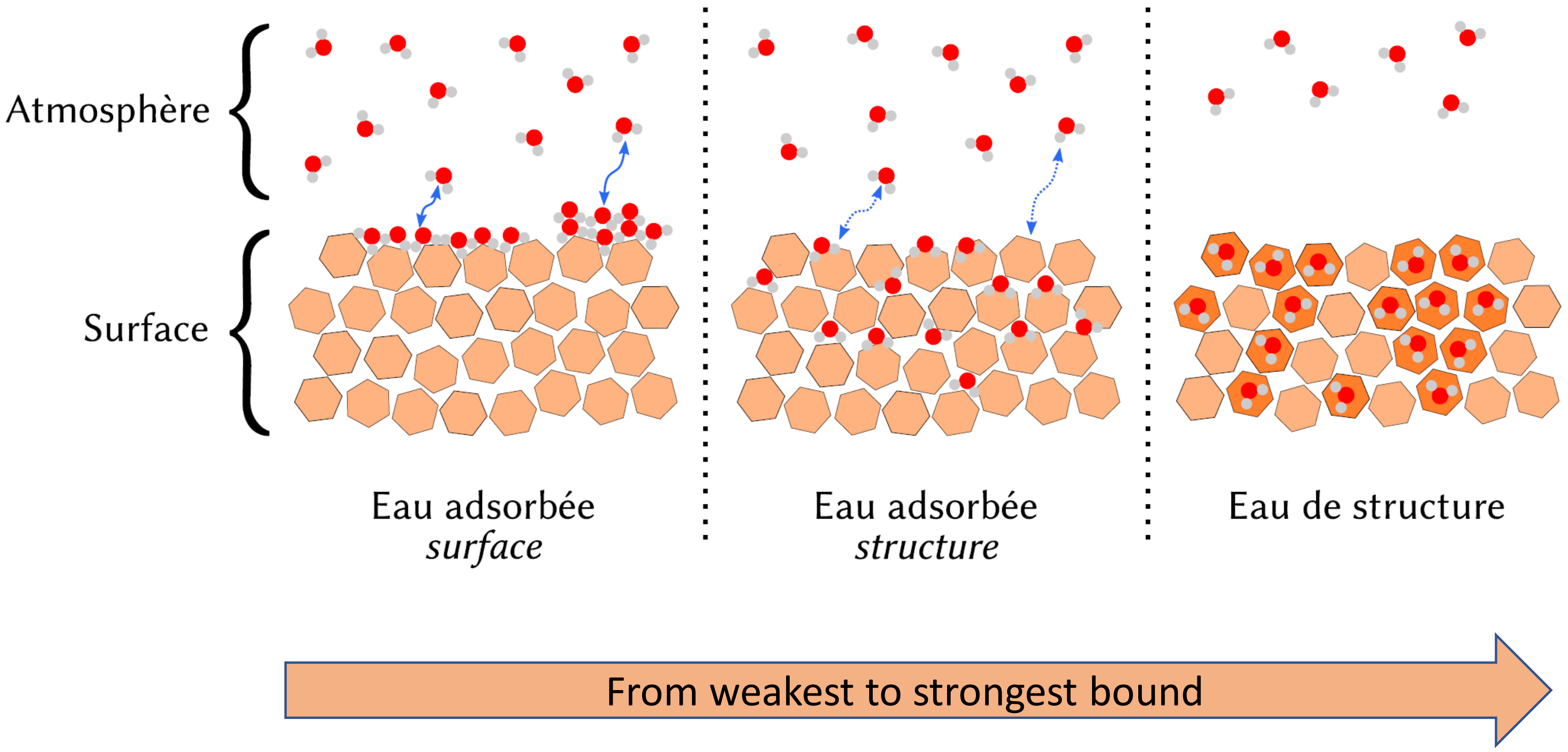


#Exomars

From an aqueous past… to a dry/arid present

Water on today Mars is mostly ice and vapor, and hydrated minerals!

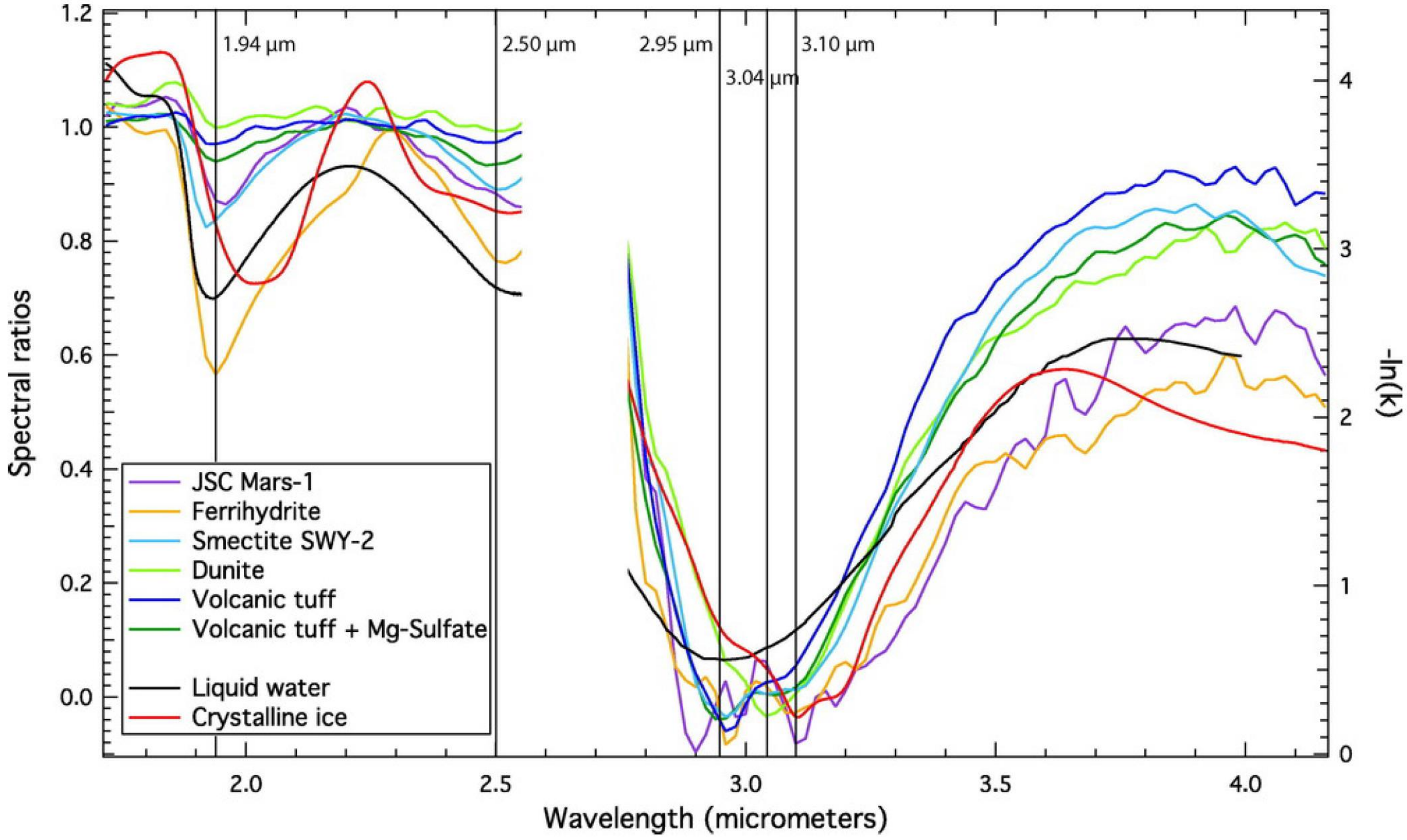
Water can chemically (at the mineral structural level) or physically (adsorption) interacts and bounds with soils.



From an aqueous past… to a dry/arid present

Water on today Mars is mostly ice and vapor, and hydrated minerals!

Discrete surface signature, possibly detectable in soil infrared spectra.



Position, shape and depth of the IR bands vary depending on:

- Water state: pure, ice, included in mineral structure
- Type of "host" mineral

⇨ Diagnostic of the presence, state, and abundance of water

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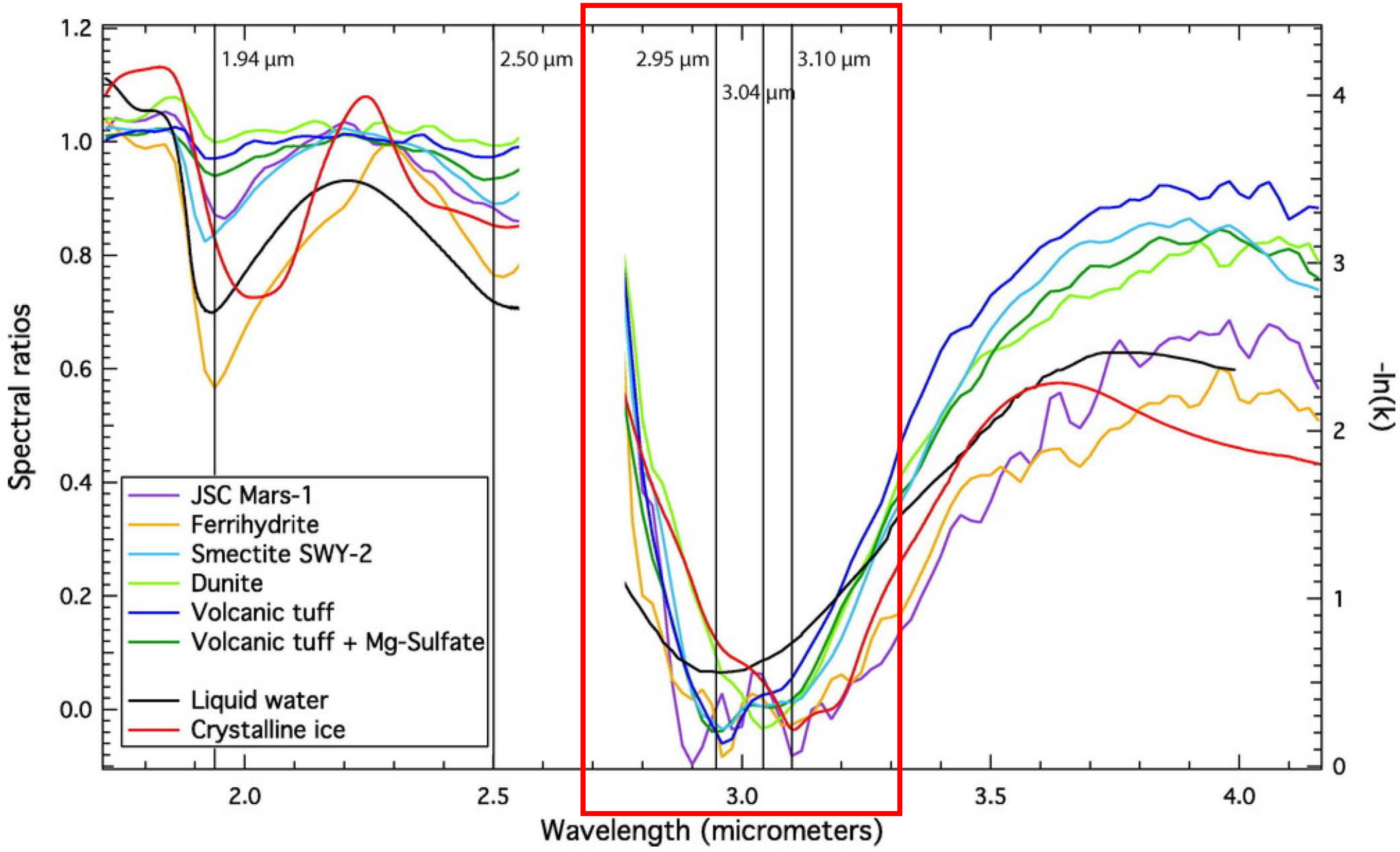

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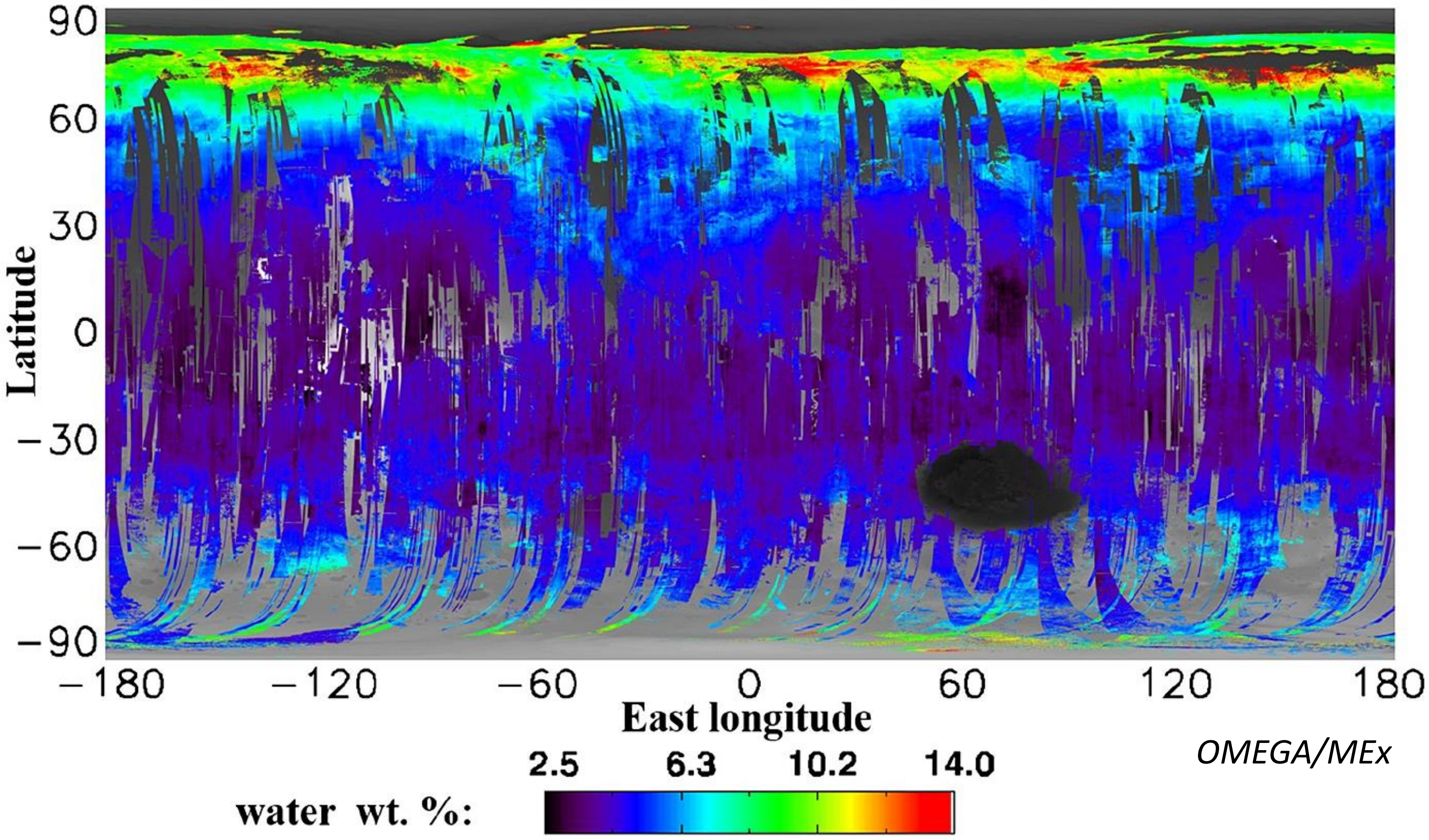
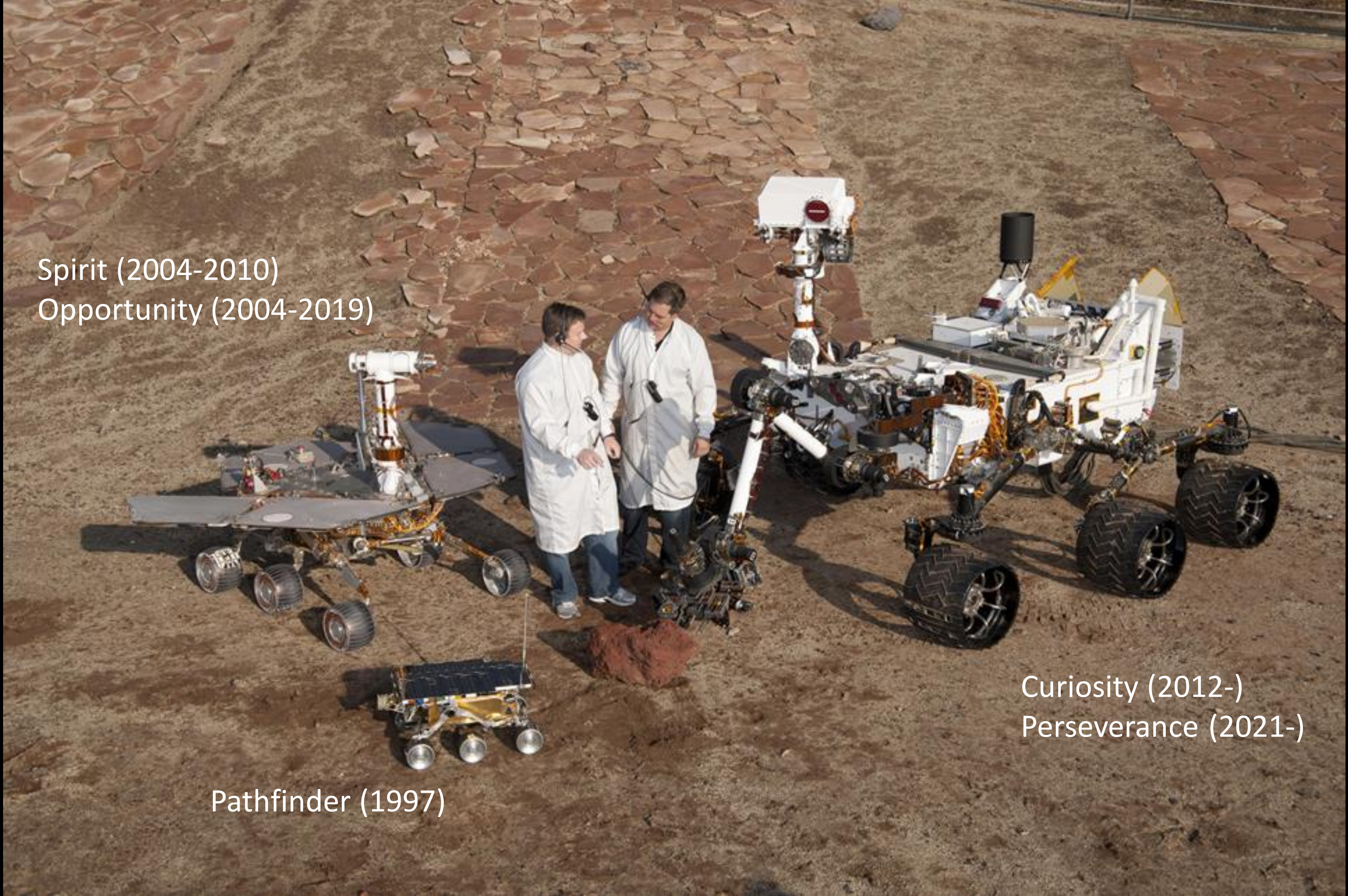
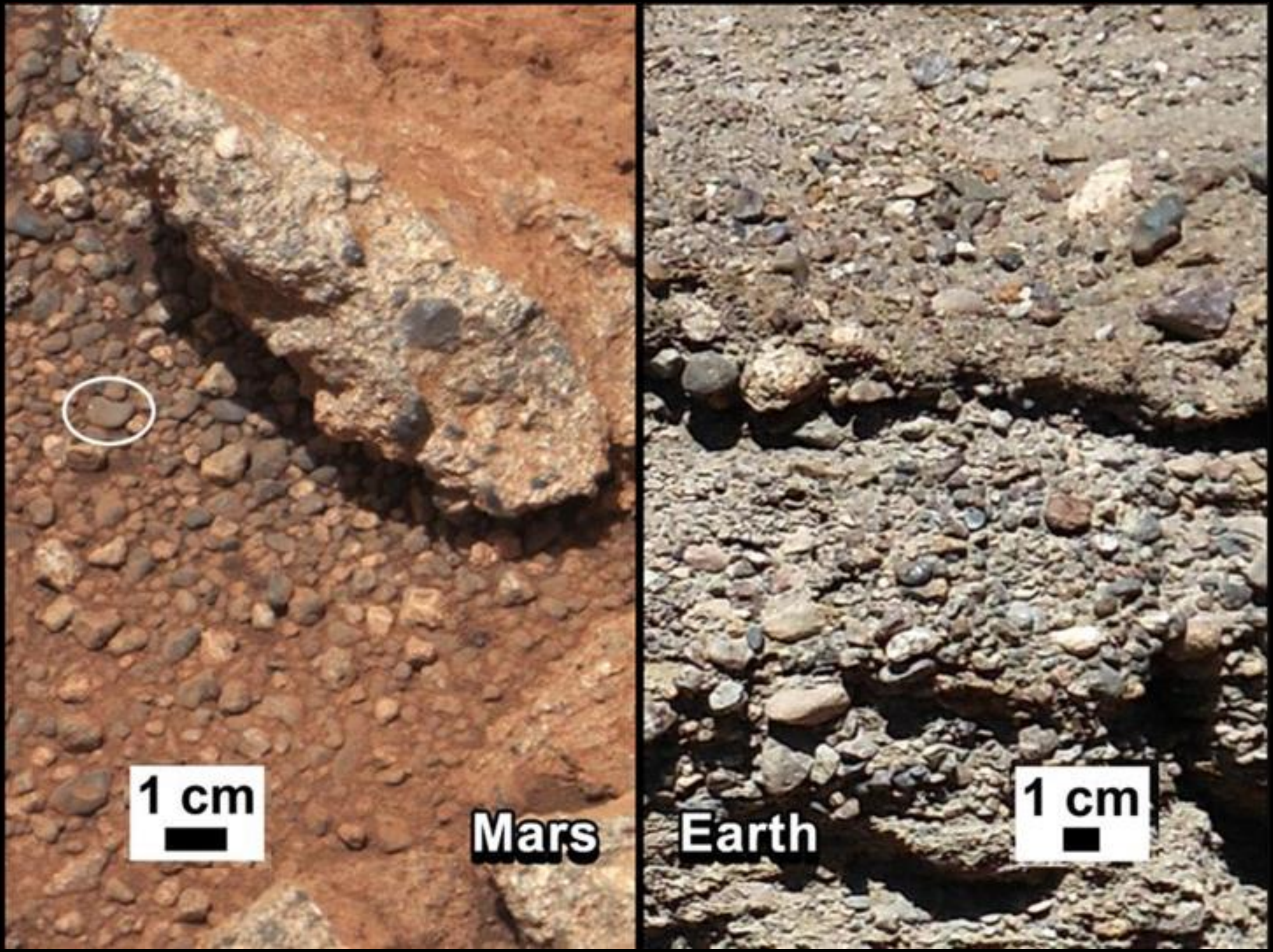


OMEGA/MEx


Spirit (2004-2010)
Opportunity (2004-2019)
Curiosity (2012-)
Perseverance (2021-)
Pathfinder (1997)

2 September 2012



Rounded and cimented boulders: active and long-lived transport and sedimentary deposit sby water **(quiet rivers, ≈1 m/s, with ≈1m depth)**

13 February 2013

Hesperian

« Wopmay » rock (Opportunity)

Sulfates + concretions :

precipitation in liquid water

Non-habitable environment : highly acid water, weak chemical gradient (low available energy), very high saltiness (slow down microbial metabolism)

Noachian

«Sheepbed » unit (Curiosity)

Concretions + Ca-sulfates veins:

precipitation in liquid water

Habitable environment: neutral pH, sulfates + sulfurs (energy), low saltiness

From an aqueous past… to a dry/arid present

Water on today Mars is mostly ice and vapor!

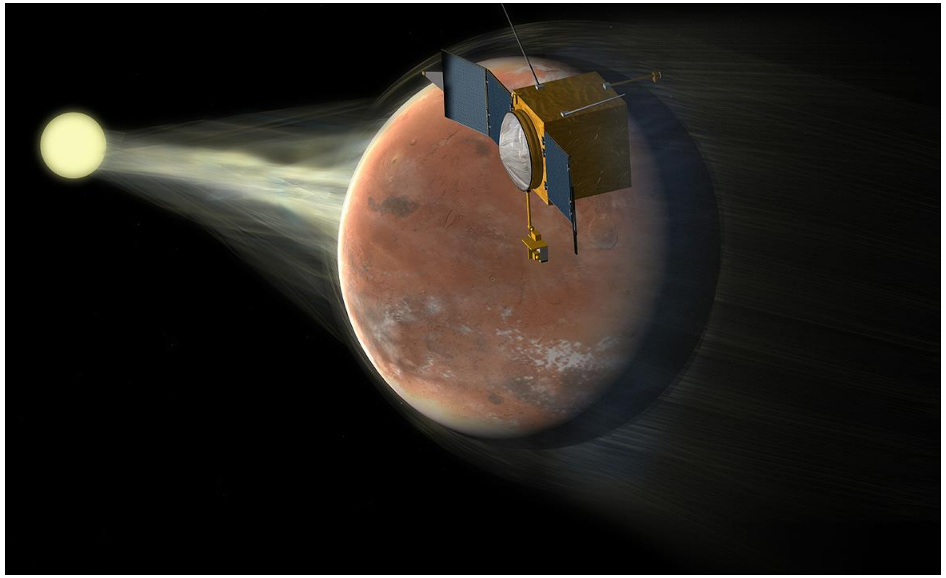
- Water was supposed to be abundant on early Mars.
- Today, no more liquid water.
- Today, water trapped in atmospheric (vapor), cold surface (ice caps) and sub-surface (permafrost) reservoirs, in only small volumes.
- A certain amount in hydrated minerals?
- The missing water?
    - D/H 5x greater on Mars than on Earth: missing H

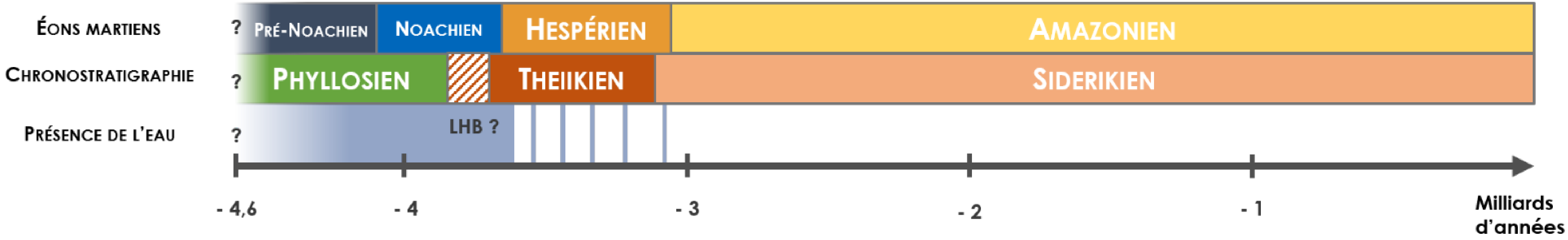
      ⇨ H_2O escape toward space

      MAIN ORIGIN OF WATER LOSS

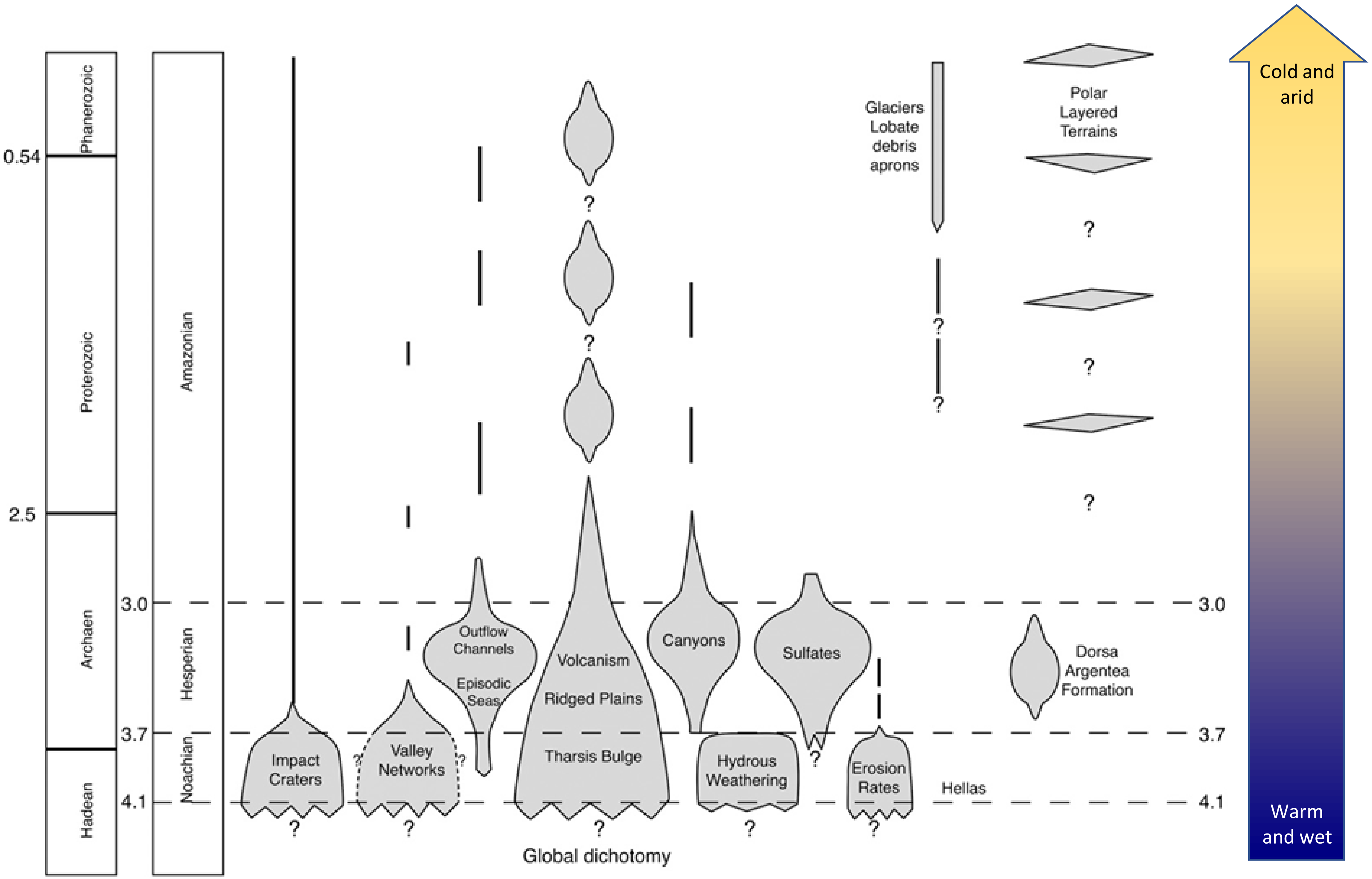
      Largely accelerated when Mars lost its B (3.7-3.8 Gy), due to Mars size!

      Greenhouse dramatically decreased, along with T° and pressure

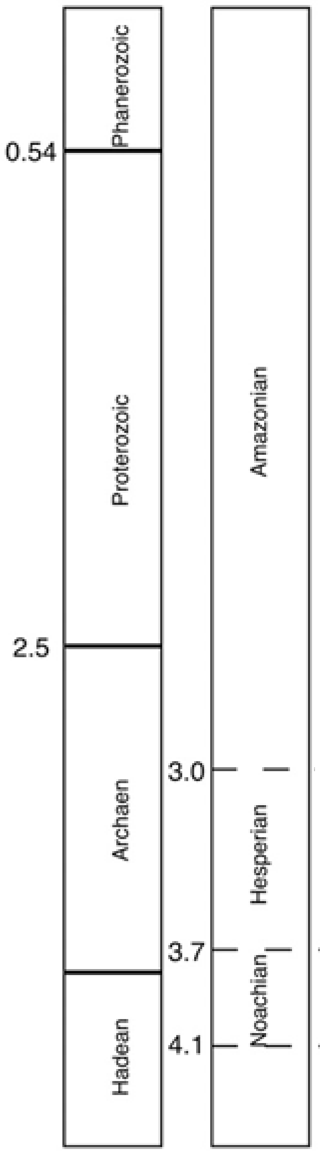


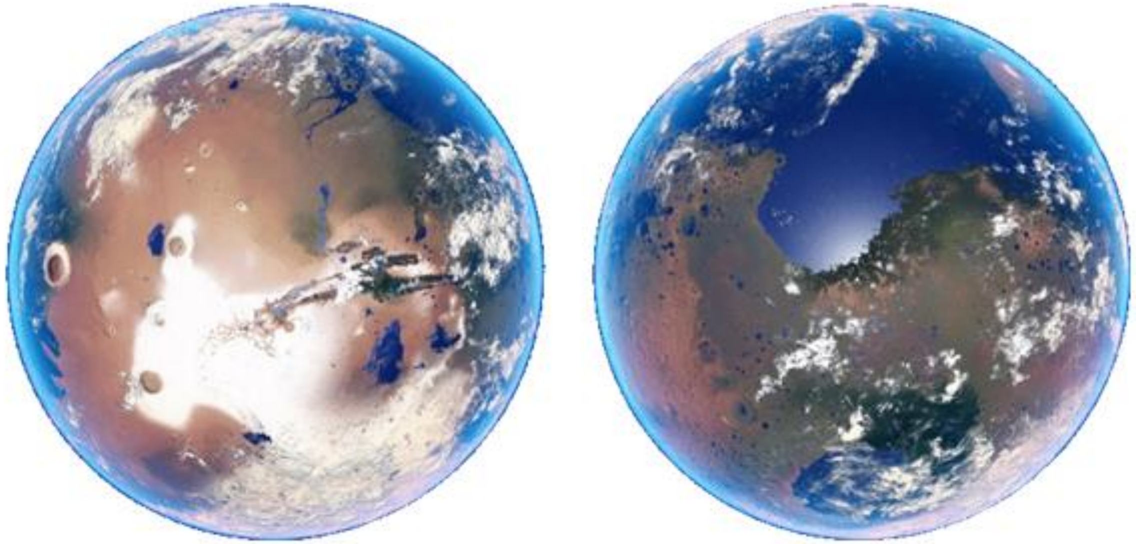


From an aqueous past... to a dry/arid present

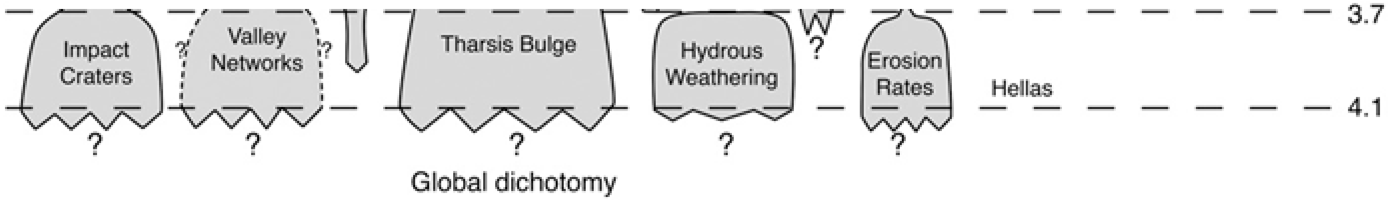


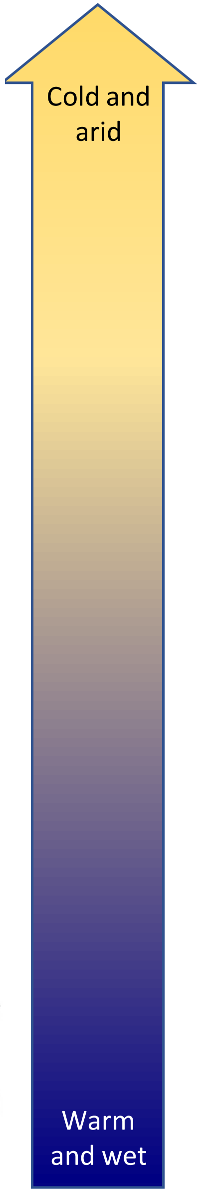
From an aqueous past… to a dry/arid present



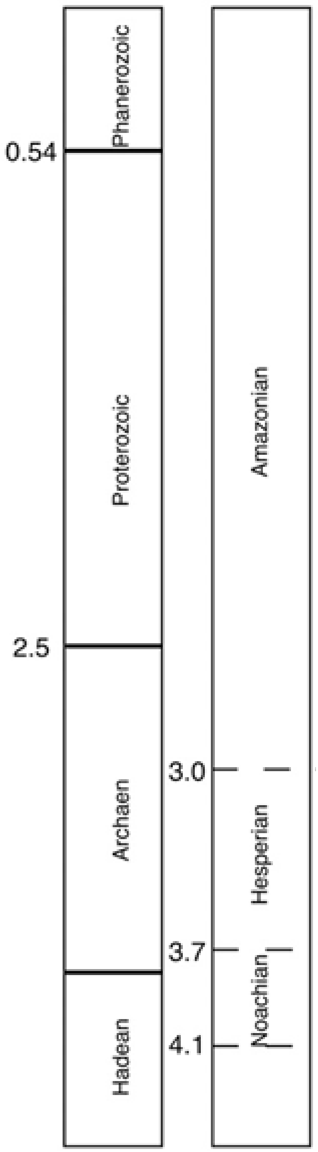


During ≈800 My: STABLE LIQUID WATER. Habitable?
Favorable conditions to the apparition of life ?

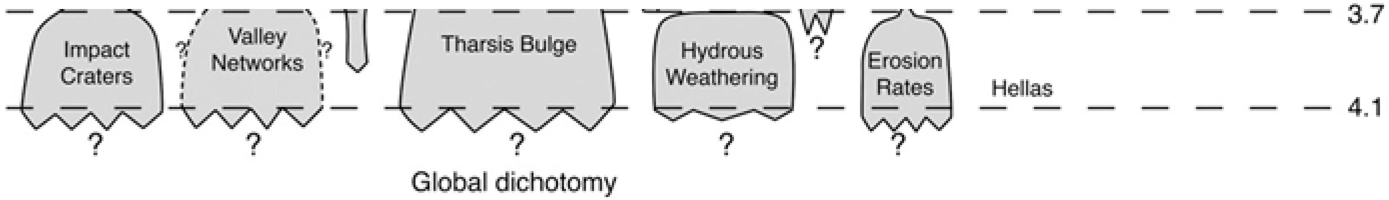


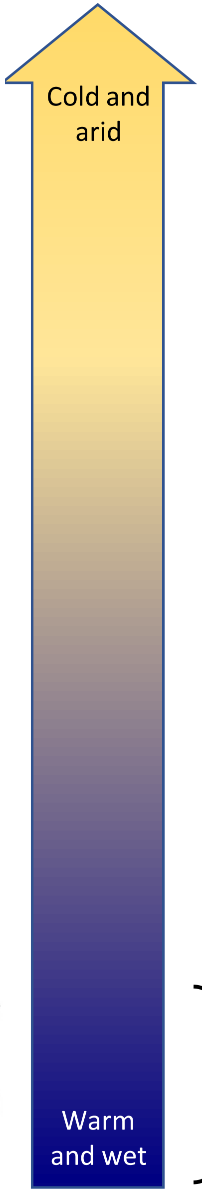


From an aqueous past... to a dry/arid present



During ≈800 My: STABLE LIQUID WATER. Habitable?
Favorable conditions to the apparition of life ?
Then : runaway desertification and glaciation.

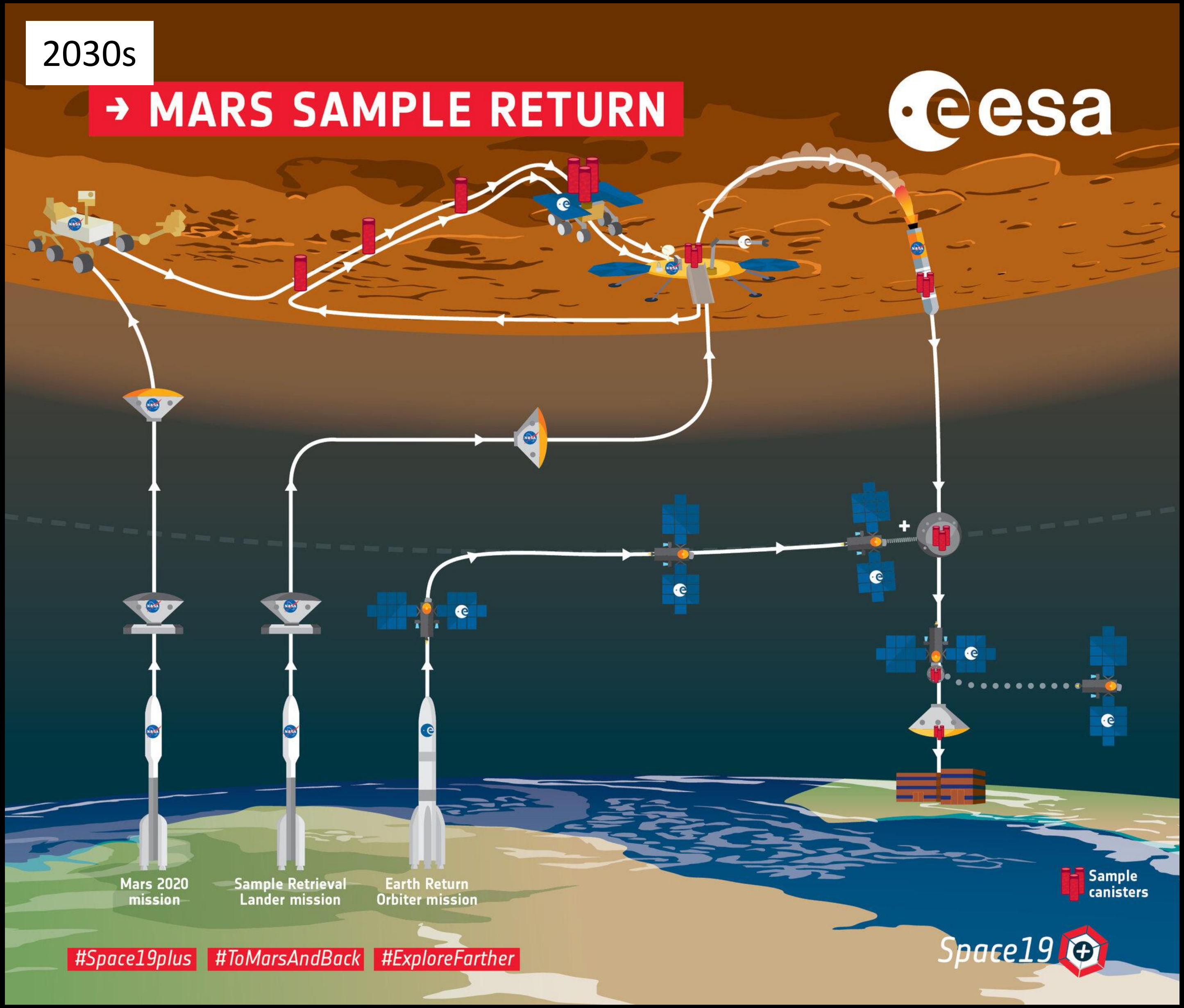




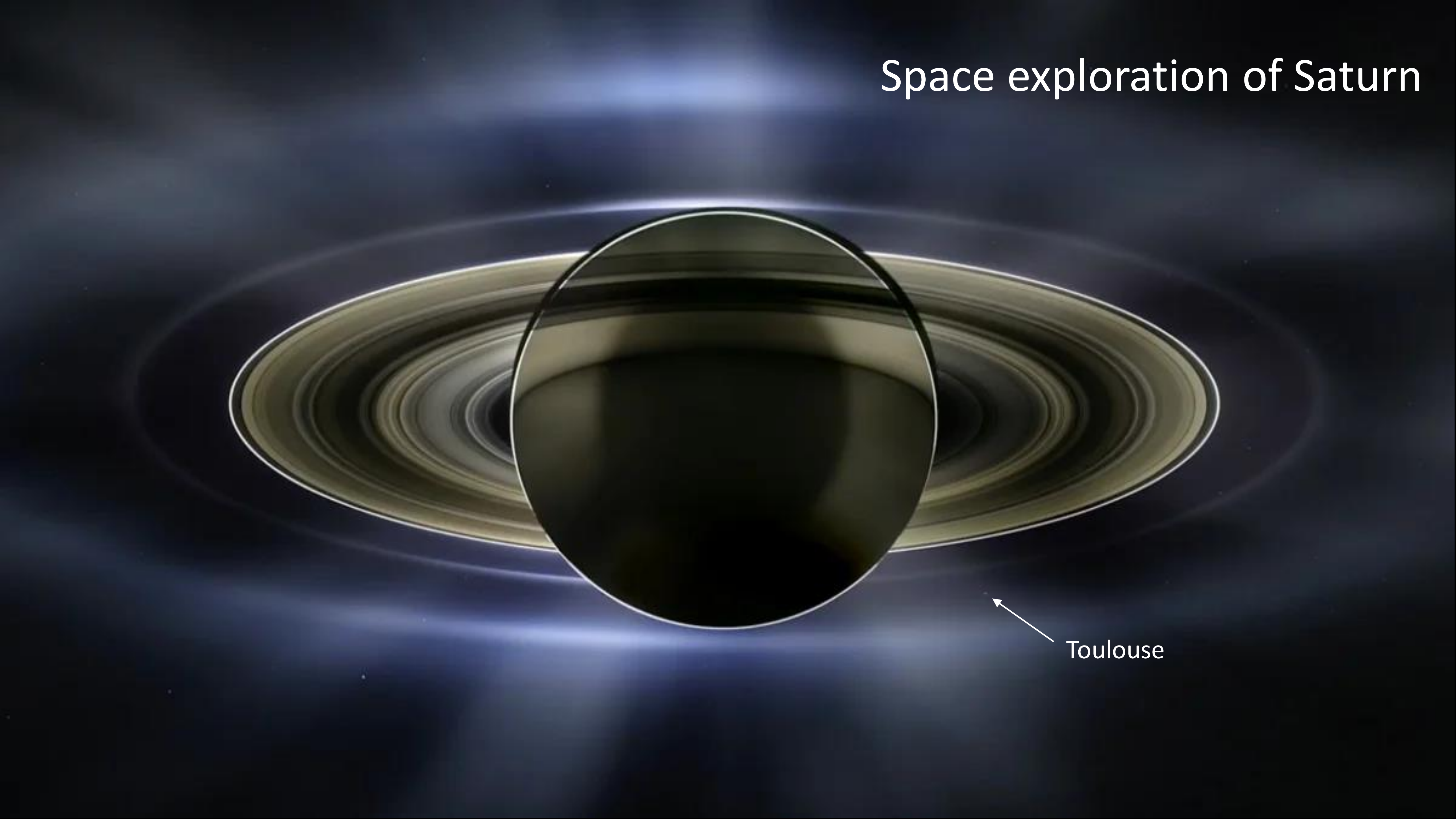
What happened then?

The near-future of Mars space exploration

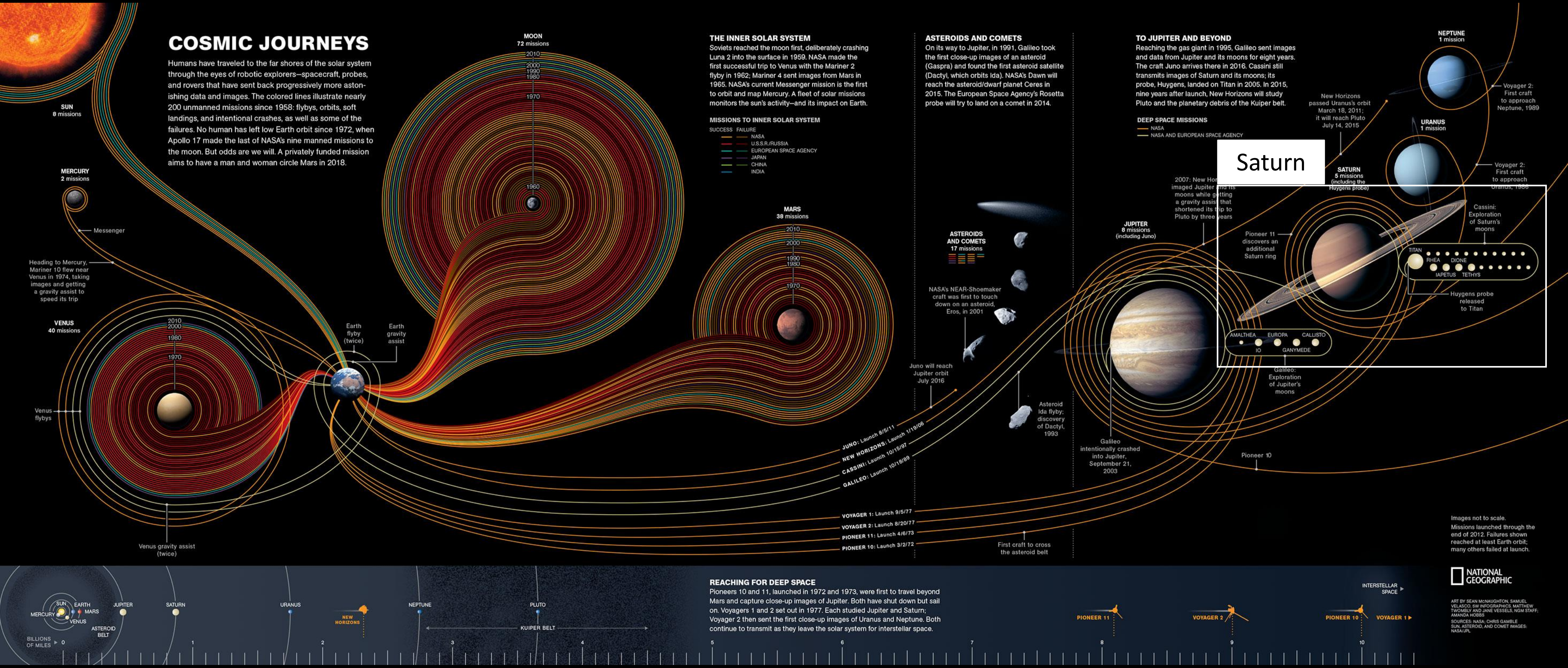
The near-future of Mars space exploration



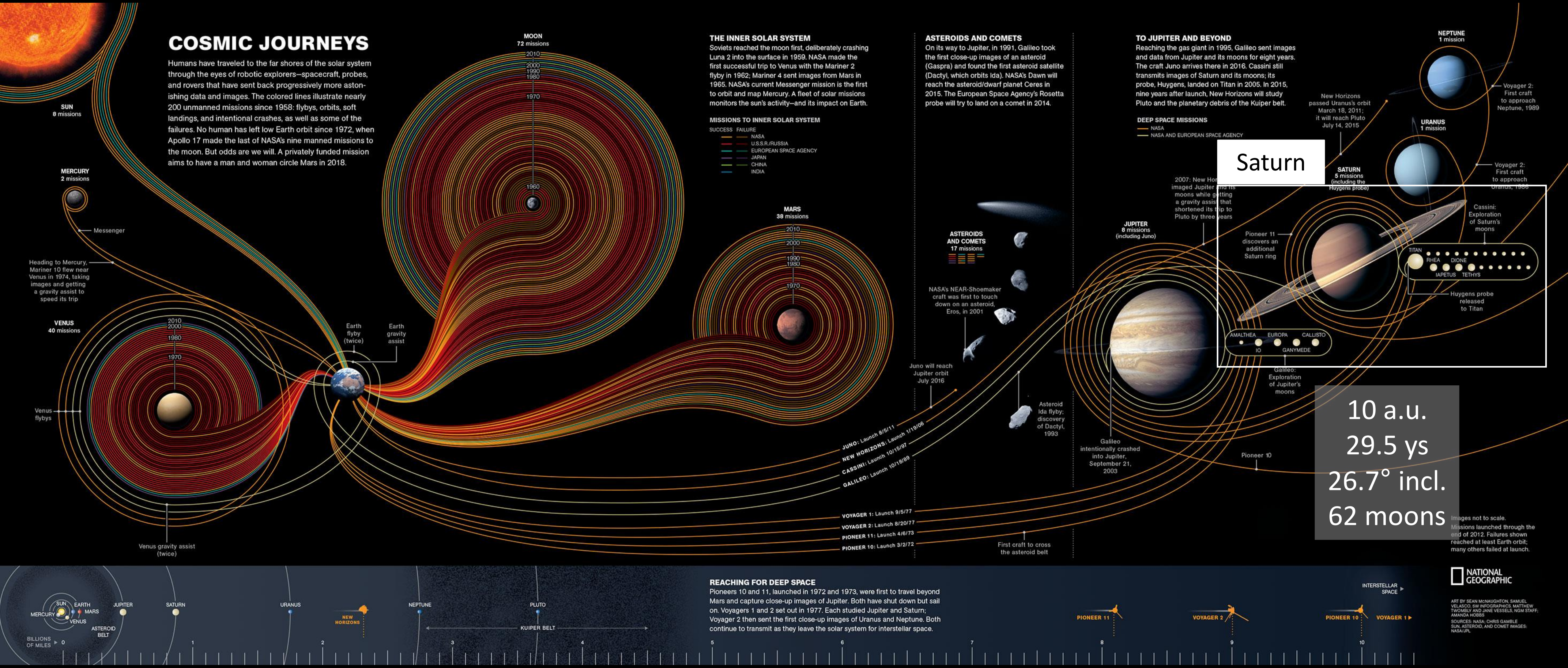
Space exploration of Saturn



Focus on Saturn

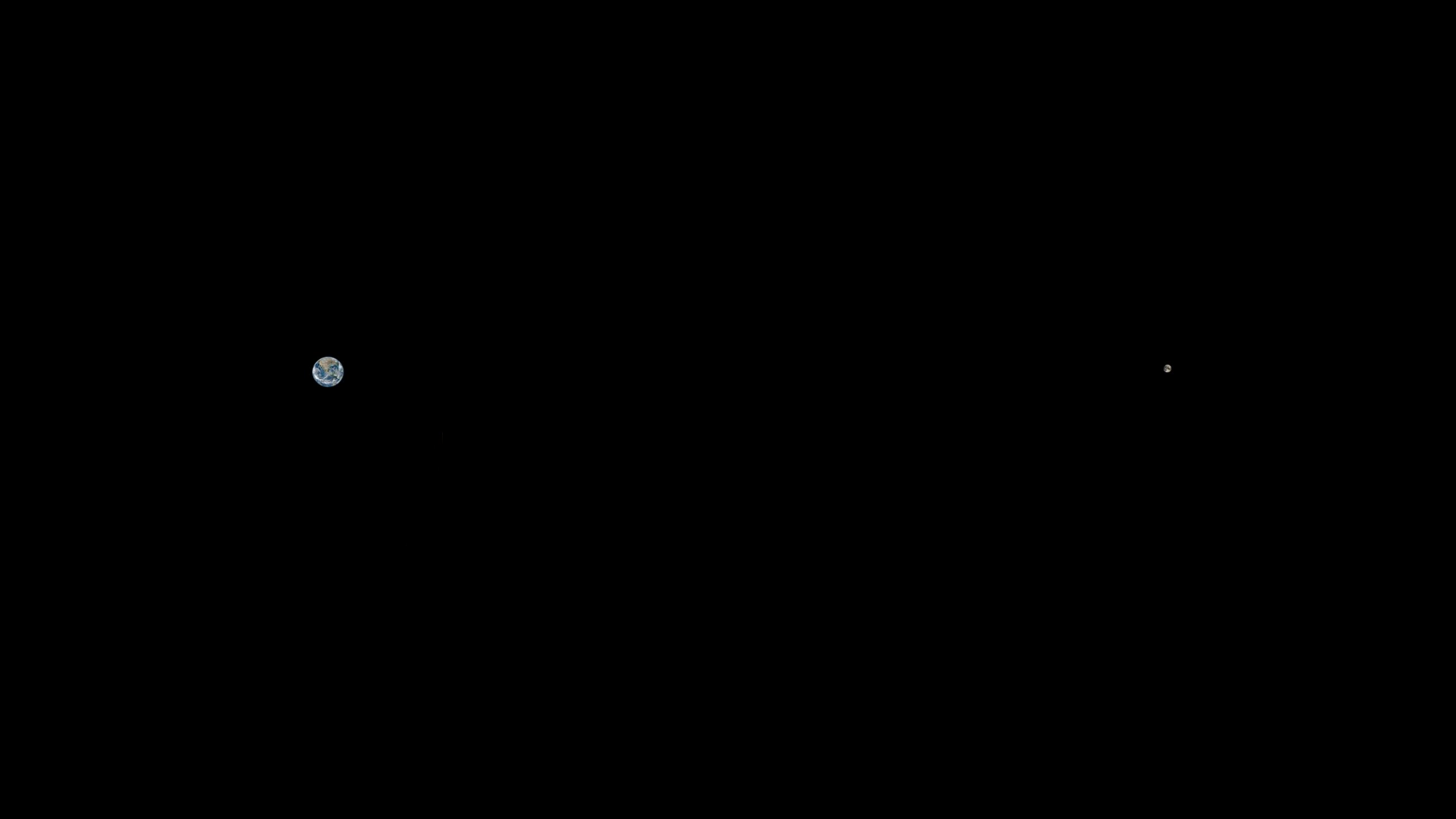


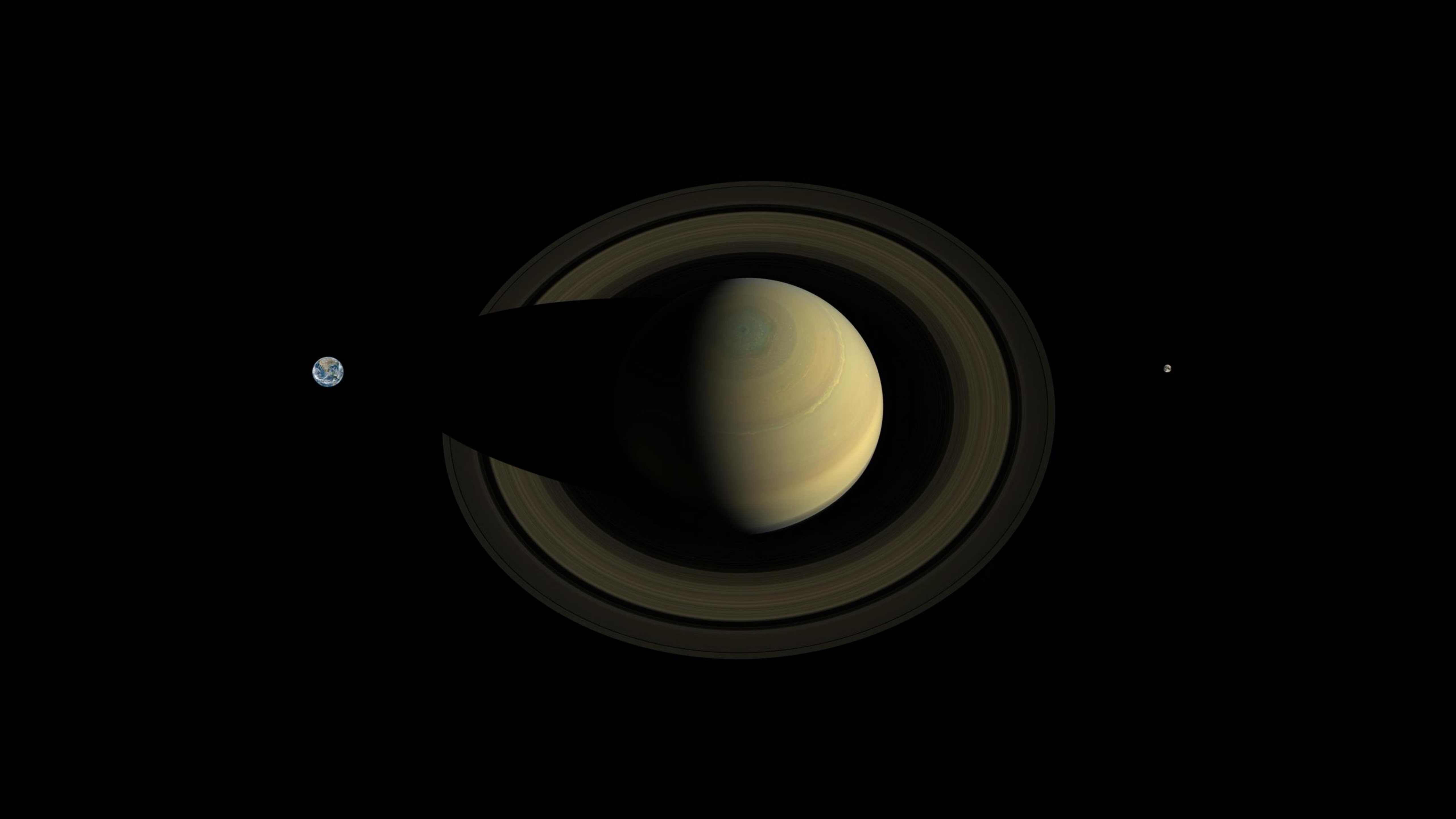
Focus on Saturn

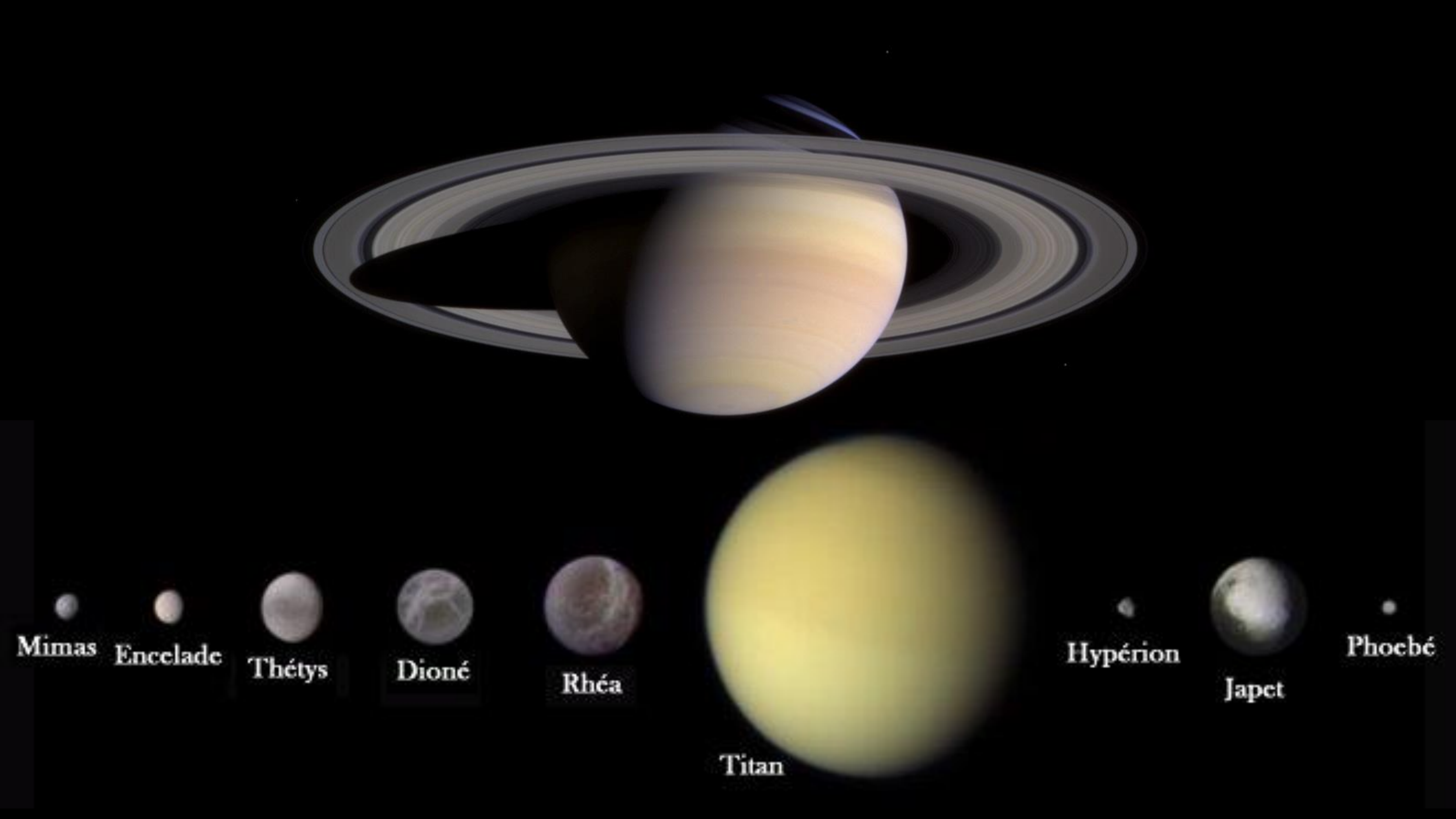


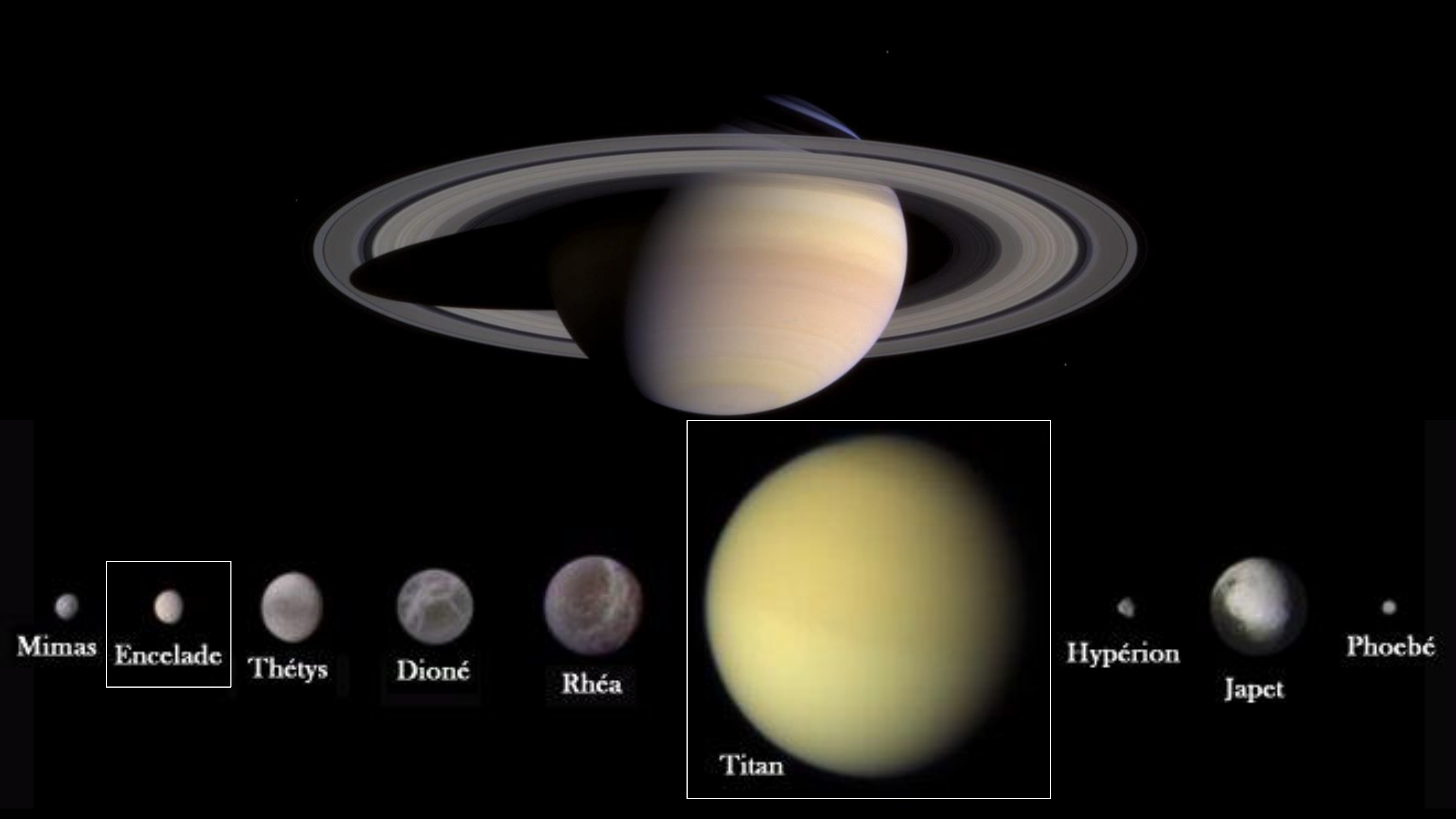
Saturn

10 a.u.
29.5 ys
26.7° incl.
62 moons






Mimas
Encelade
Thétys
Dioné
Rhéa
Titan
Hypérion
Japet
Phoebé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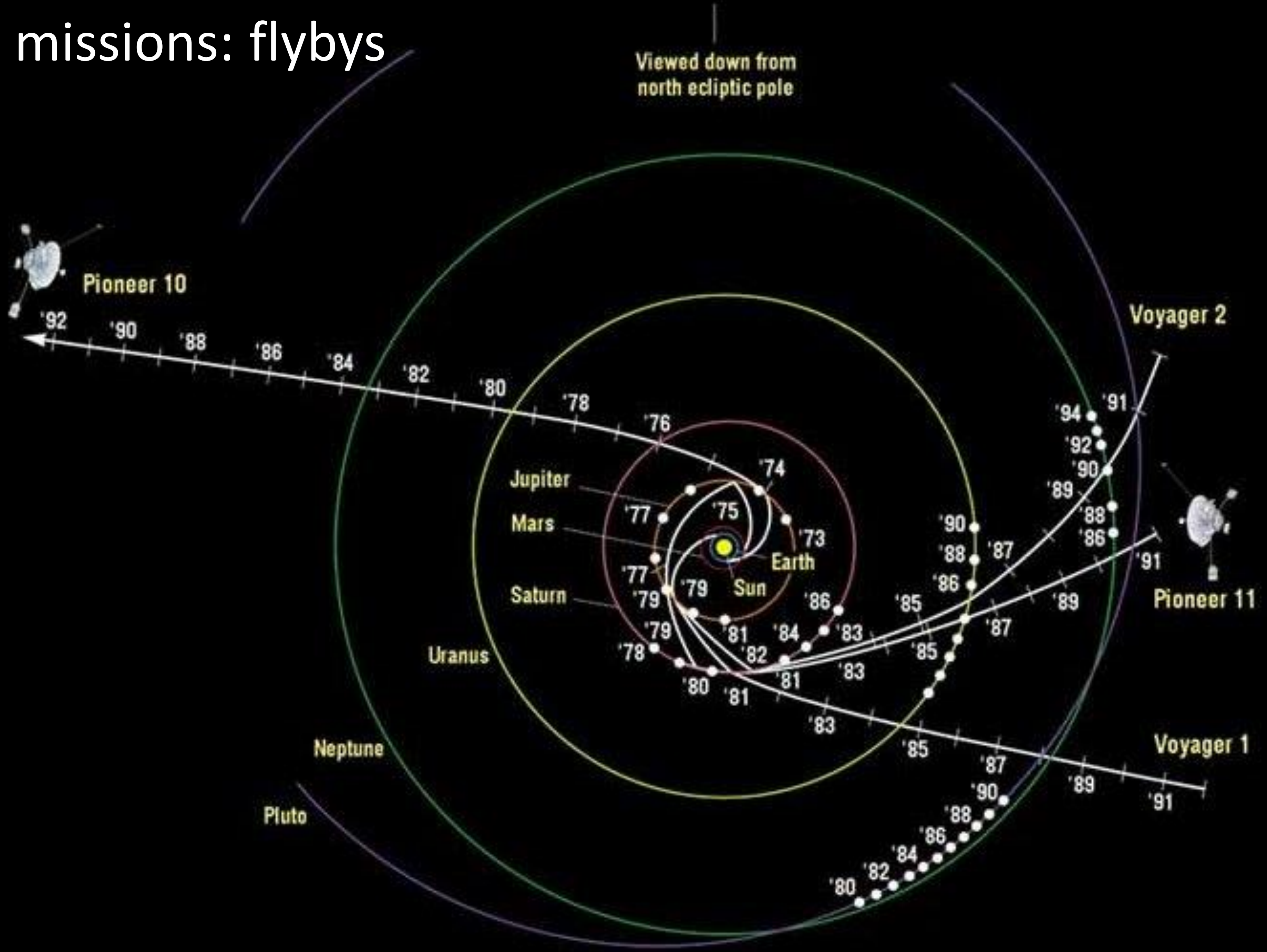
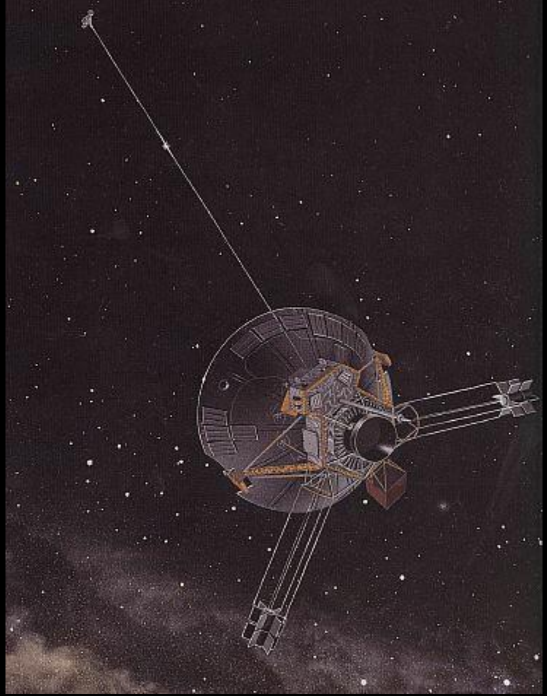
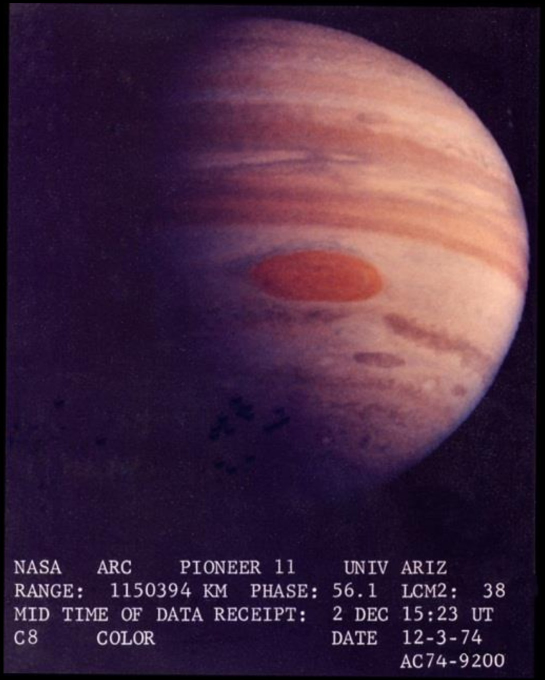
Very first missions: flybys

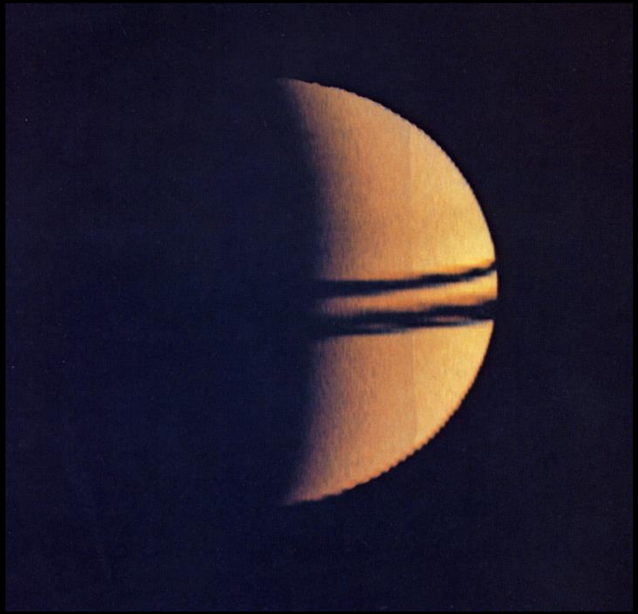


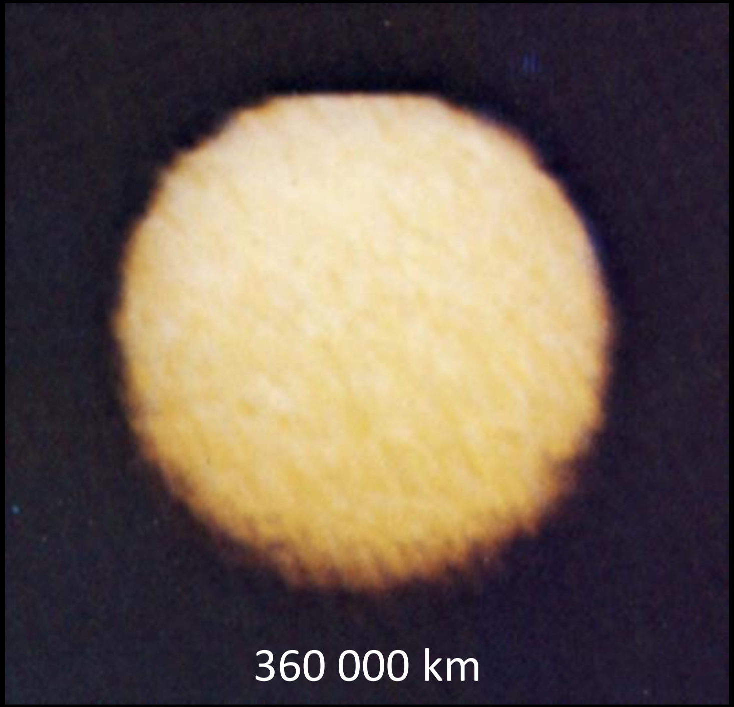
Pioneer 11 (1973)

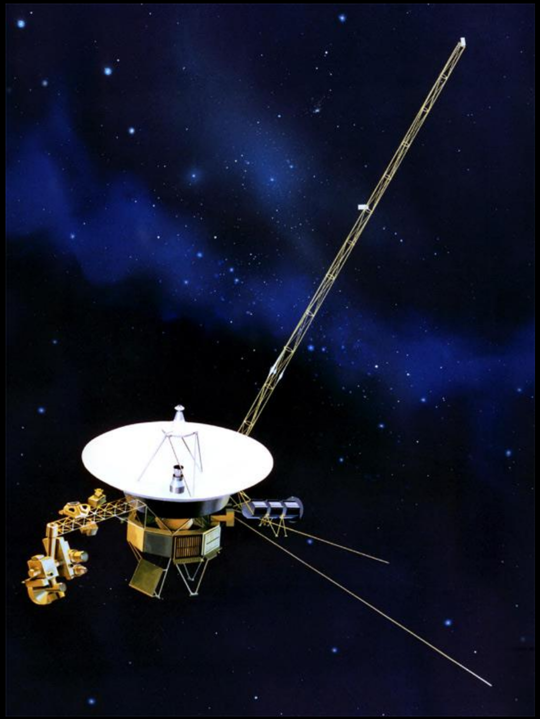
Saturn’s flyby : 1st September 1979 (21 000 km)

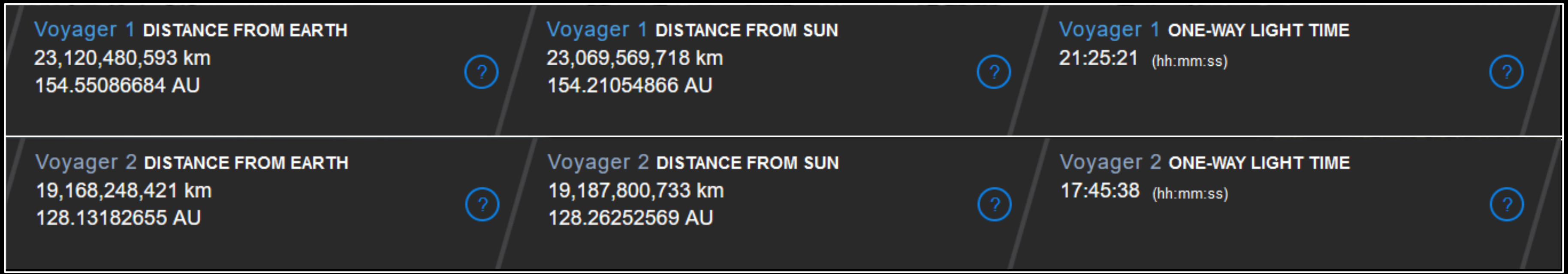






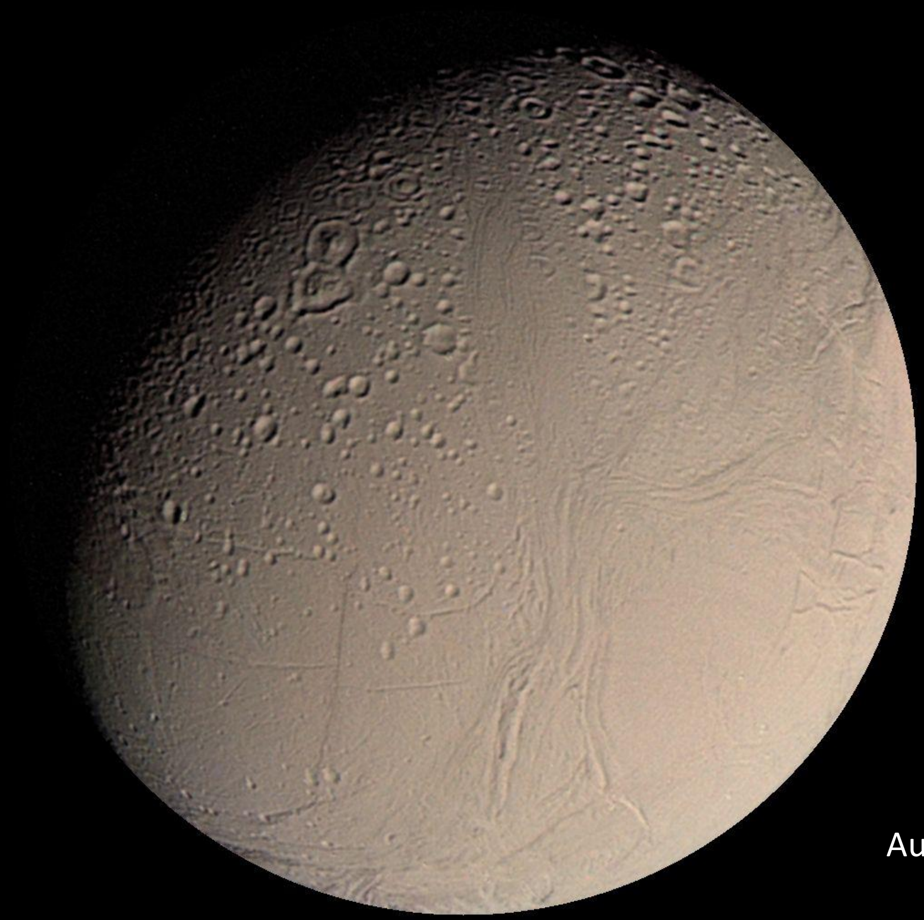






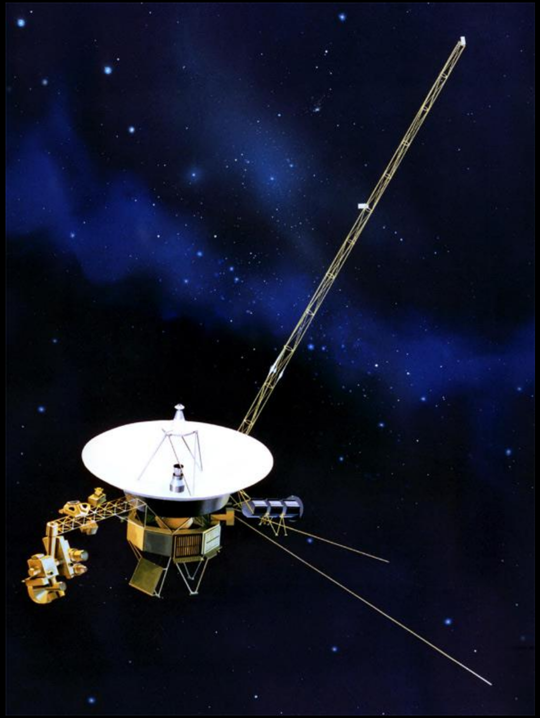
Voyager 1 & 2 (1977)

Saturn’s flybys:
12 Nov. 1980 (124 000 km)
25 Aug. 1981 (101 000 km)



Enceladus
Aug. 1981 (87 000 km) [V2]

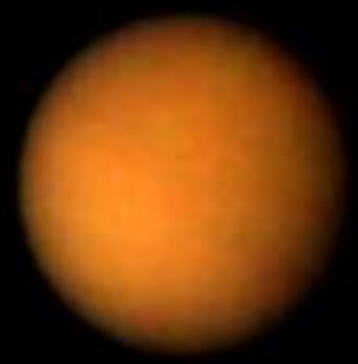
Very old & very young terrains?



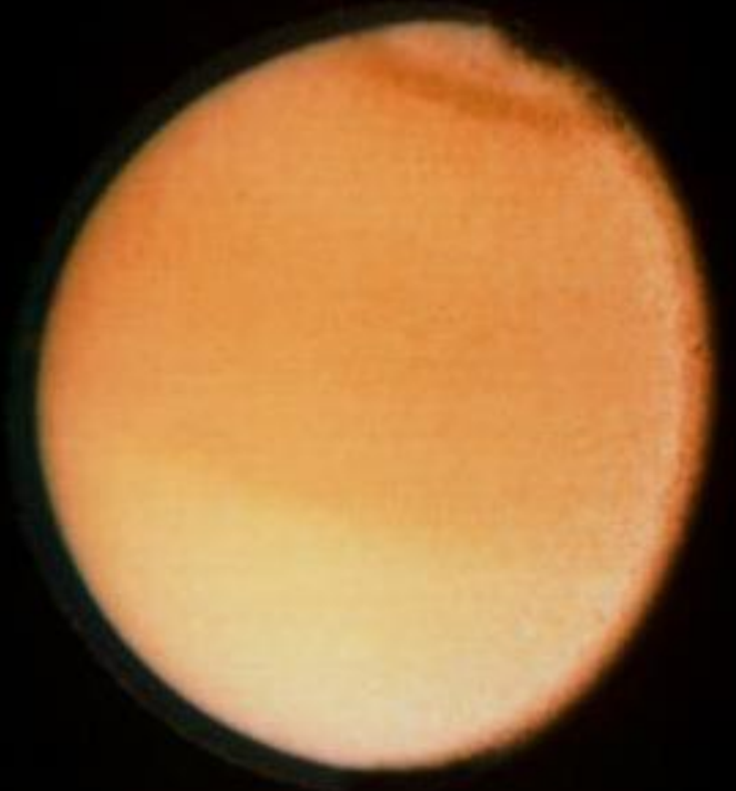
Voyager 1 DISTANCE FROM EARTH	Voyager 1 DISTANCE FROM SUN	Voyager 1 ONE-WAY LIGHT TIME
23,120,480,593 km 154.55086684 AU	23,069,569,718 km 154.21054866 AU	21:25:21 (hh:mm:ss)
Voyager 2 DISTANCE FROM EARTH	**Voyager 2 DISTANCE FROM SUN**	**Voyager 2 ONE-WAY LIGHT TIME**
19,168,248,421 km 128.13182655 AU	19,187,800,733 km 128.26252569 AU	17:45:38 (hh:mm:ss)

Voyager 1 & 2 (1977)

Saturn – Titan's flybys:
12 Nov. 1980 (124 000 km – 6 490 km)
25 Aug. 1981 (101 000 km – 665 960 km)

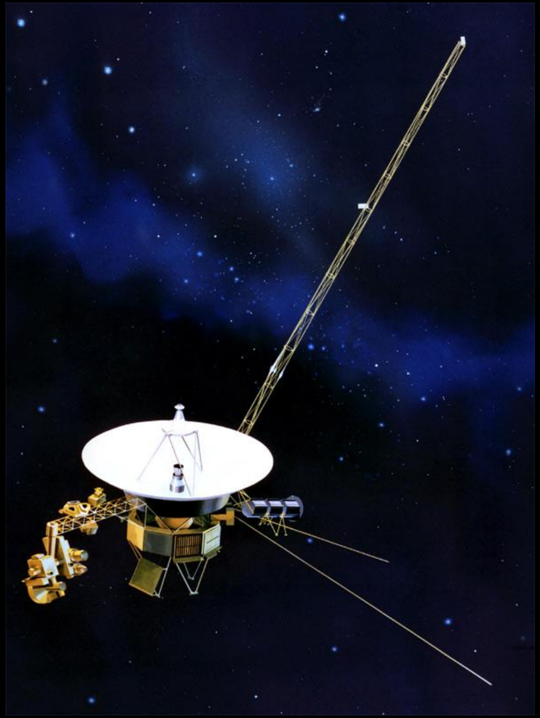


Titan
4 Nov. 1980 (12 millions km) [V1]



Titan
23 August 1981 (2.3 millions km) [V2]

Dense and hazy atmosphere



Voyager 1 DISTANCE FROM EARTH 23,120,480,593 km 154.55086684 AU	Voyager 1 DISTANCE FROM SUN 23,069,569,718 km 154.21054866 AU	Voyager 1 ONE-WAY LIGHT TIME 21:25:21 (hh:mm:ss)
Voyager 2 DISTANCE FROM EARTH 19,168,248,421 km 128.13182655 AU	Voyager 2 DISTANCE FROM SUN 19,187,800,733 km 128.26252569 AU	Voyager 2 ONE-WAY LIGHT TIME 17:45:38 (hh:mm:ss)

Voyager 1 & 2 (1977)

Saturn – Titan’s flybys:

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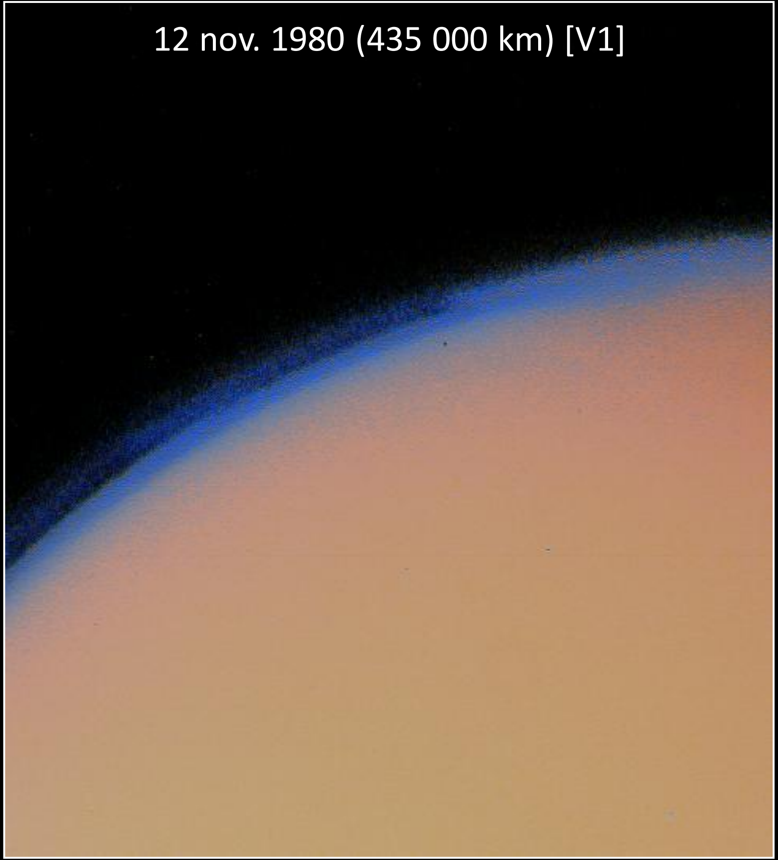
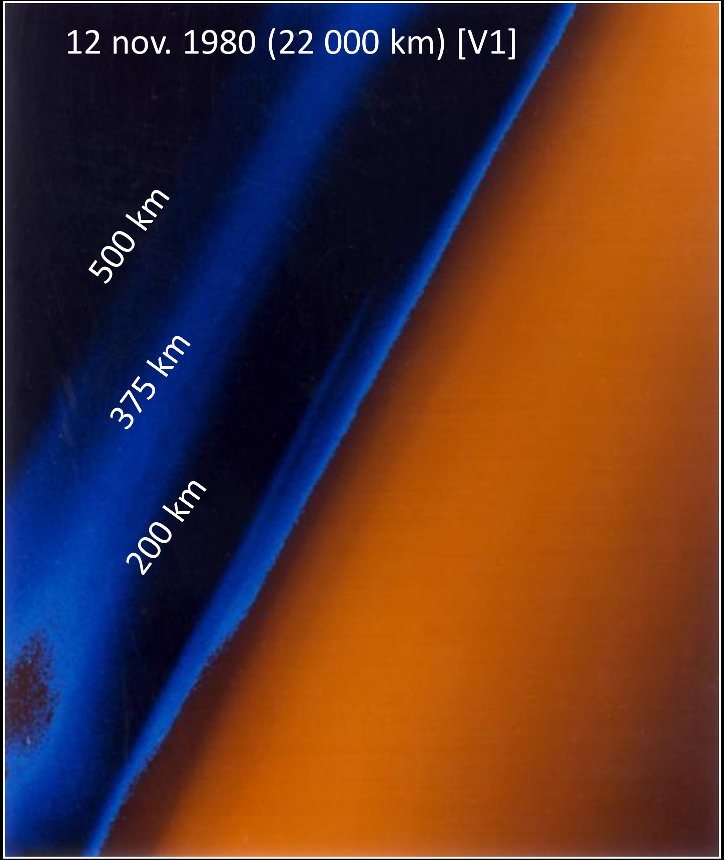


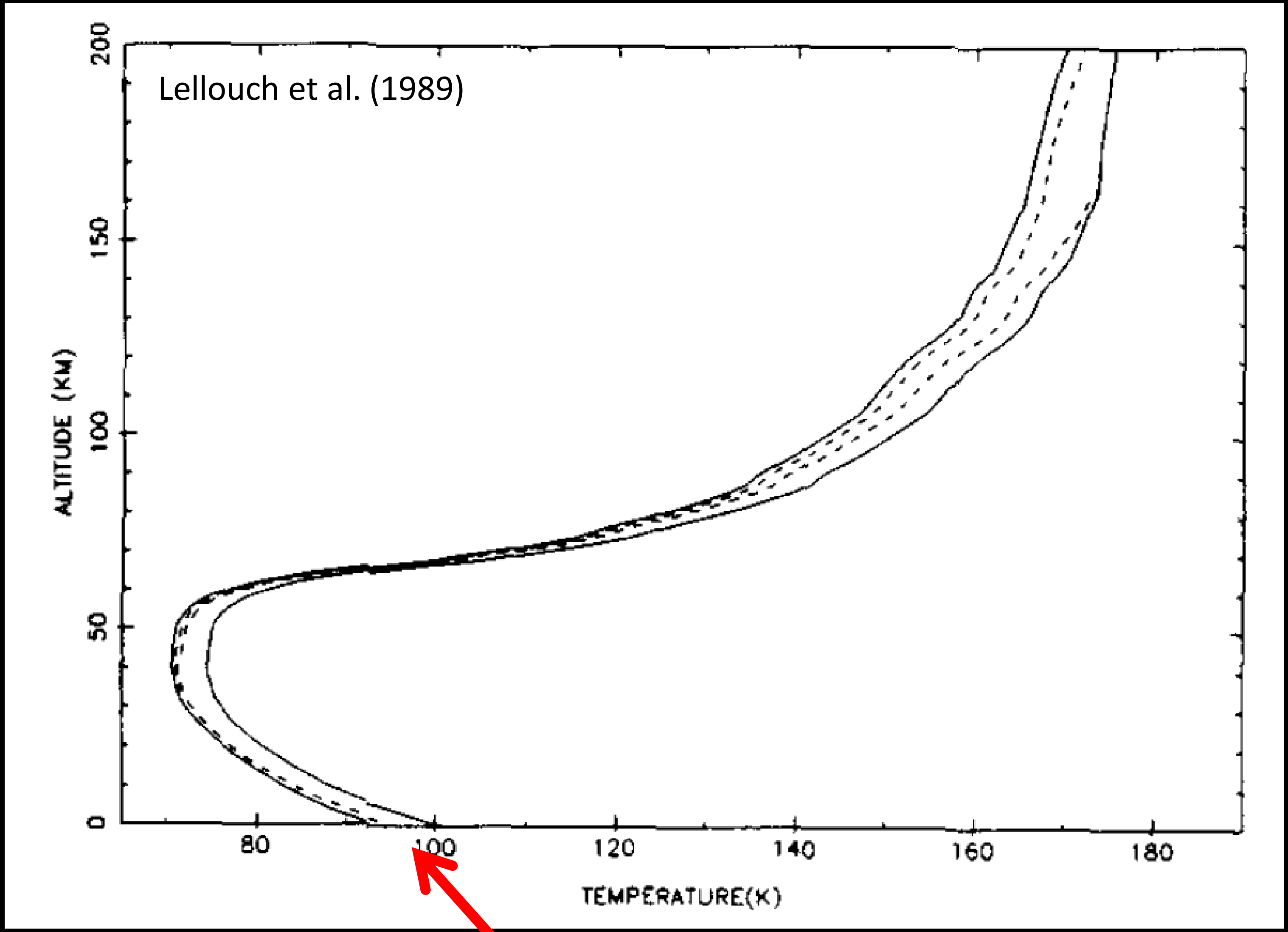
12 nov. 1980 (435 000 km) [V1]



12 nov. 1980 (22 000 km) [V1]

Dense and hazy atmosphere

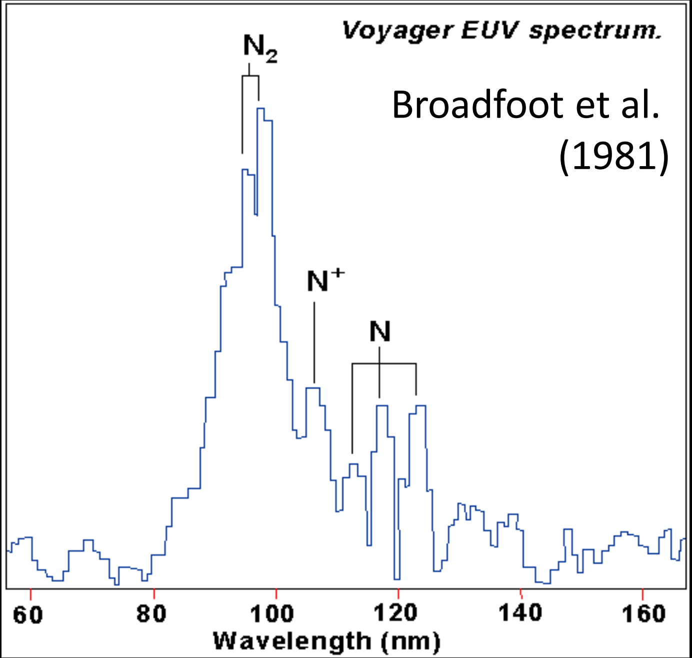
An atmosphère very close to Earth's ones, but colder!

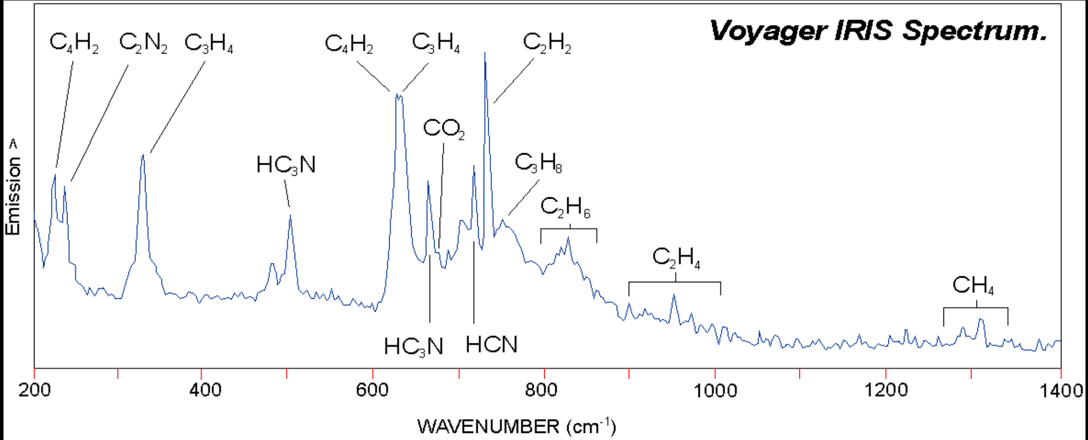


94 K (-179°C) and 1,44 bar

A very active gaseous organic chemistry! To high atomic numbers and solid particles!

Prebiotic chemistry? Possible condensation of hydrocarbons: hydrocarbon cycle(s)? Surface?

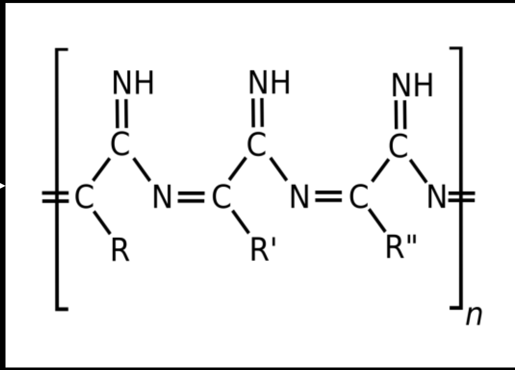


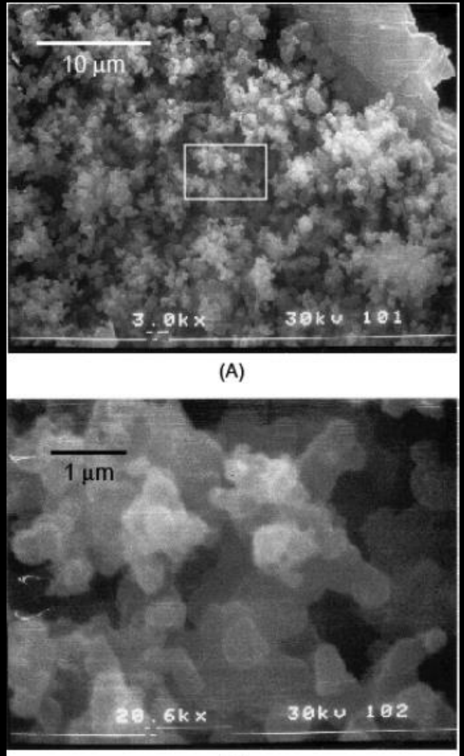


Courtin (1982)

N_2	Nitrogen	77-85%
^{36}Ar	Argon	≈ 12-17%
CH_4	Methane	≈ 3-6%
H_2	Hydrogen	0.1-0.4%
C_2H_6	Ethane	20ppm
C_3H_8	Propane	5-20ppm
C_2H_2	Ethyne	2ppm
C_2H_4	Ethene	0.4ppm
HCN	Methanenitrile (Hydrogen Cyanide)	0.2ppm
C_4H_2	Butadiyne (Diacetylene)	0.03ppm
C_3H_4	Propyne (Methylacetylene)	0.03ppm
HC_3N	Propynenitrile (Cyanoacetylene)	0.01-0.1ppm
C_2N_2	Ethanedinitrile (Cyanogen)	0.01-0.1ppm
CO_2	Carbon Dioxide	0.01ppm
CO	Carbon Monoxide	10ppm*

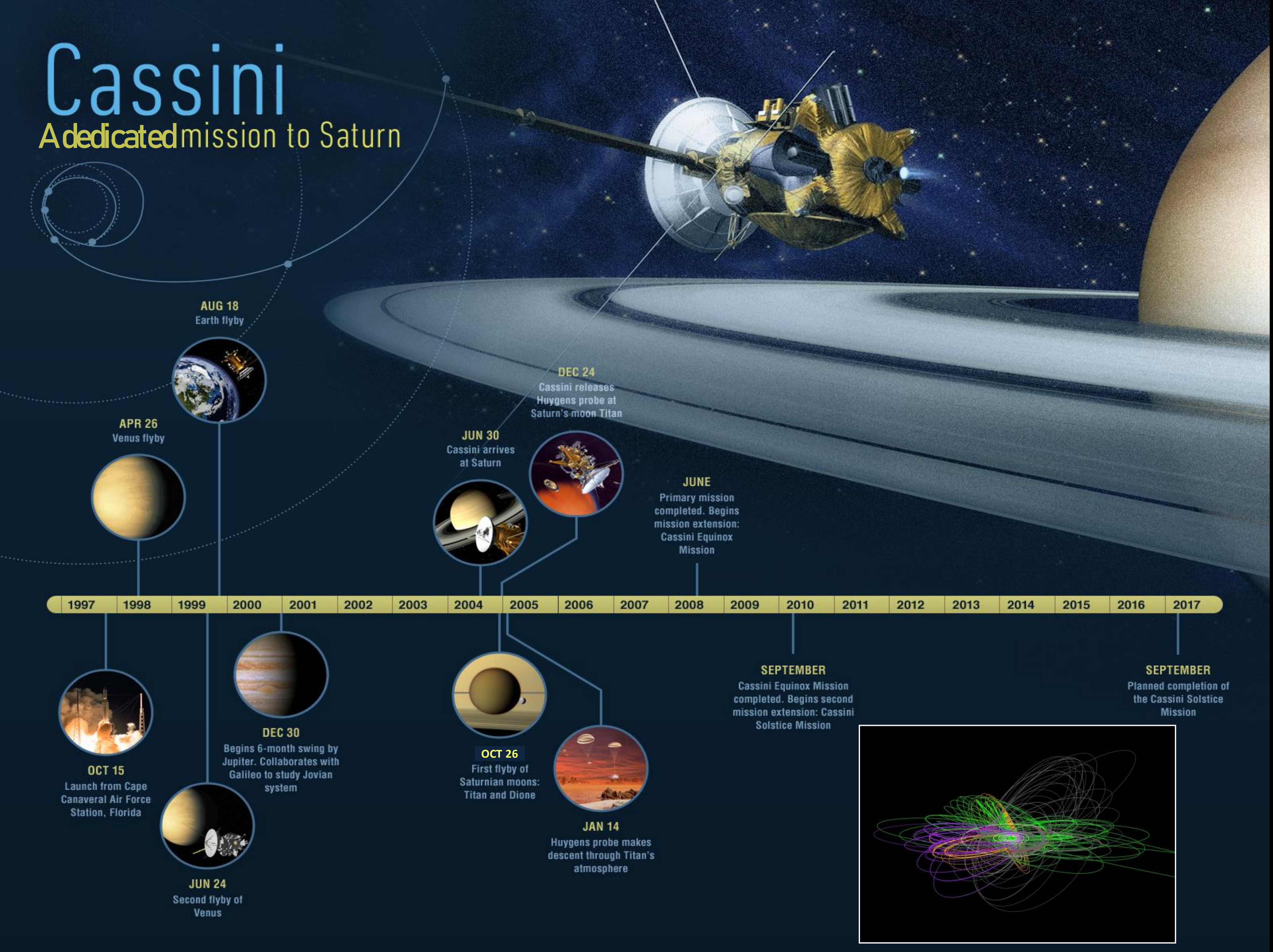
From Thompson et Sagan (1984)





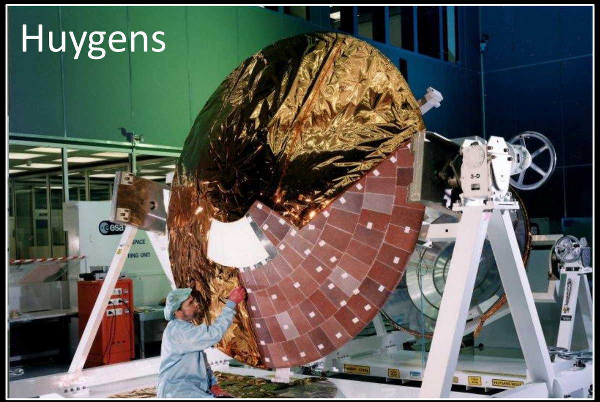
(A)

(B)



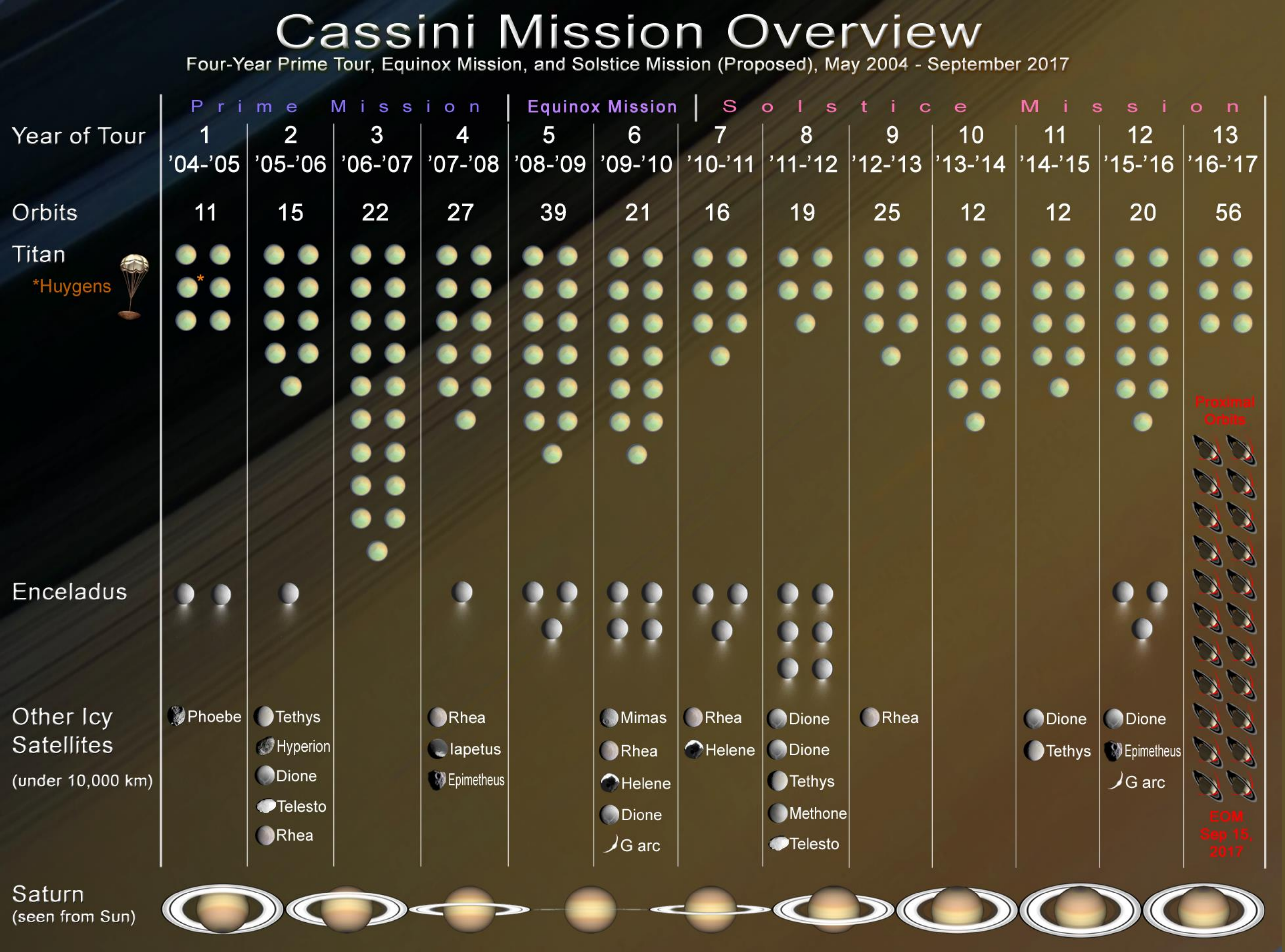
Cassini
A dedicated mission to Saturn
AUG 18
Earth flyby
APR 26
Venus flyby
DEC 24
Cassini releases Huygens probe at Saturn's moon Titan
JUN 30
Cassini arrives at Saturn
JUNE
Primary mission completed. Begins mission extension: Cassini Equinox Mission
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
OCT 15
Launch from Cape Canaveral Air Force Station, Florida
JUN 24
Second flyby of Venus
DEC 30
Begins 6-month swing by Jupiter. Collaborates with Galileo to study Jovian system
OCT 26
First flyby of Saturnian moons: Titan and Dione
JAN 14
Huygens probe makes descent through Titan's atmosphere
SEPTEMBER
Cassini Equinox Mission completed. Begins second mission extension: Cassini Solstice Mission
SEPTEMBER
Planned completion of the Cassini Solstice Mission

Cassini

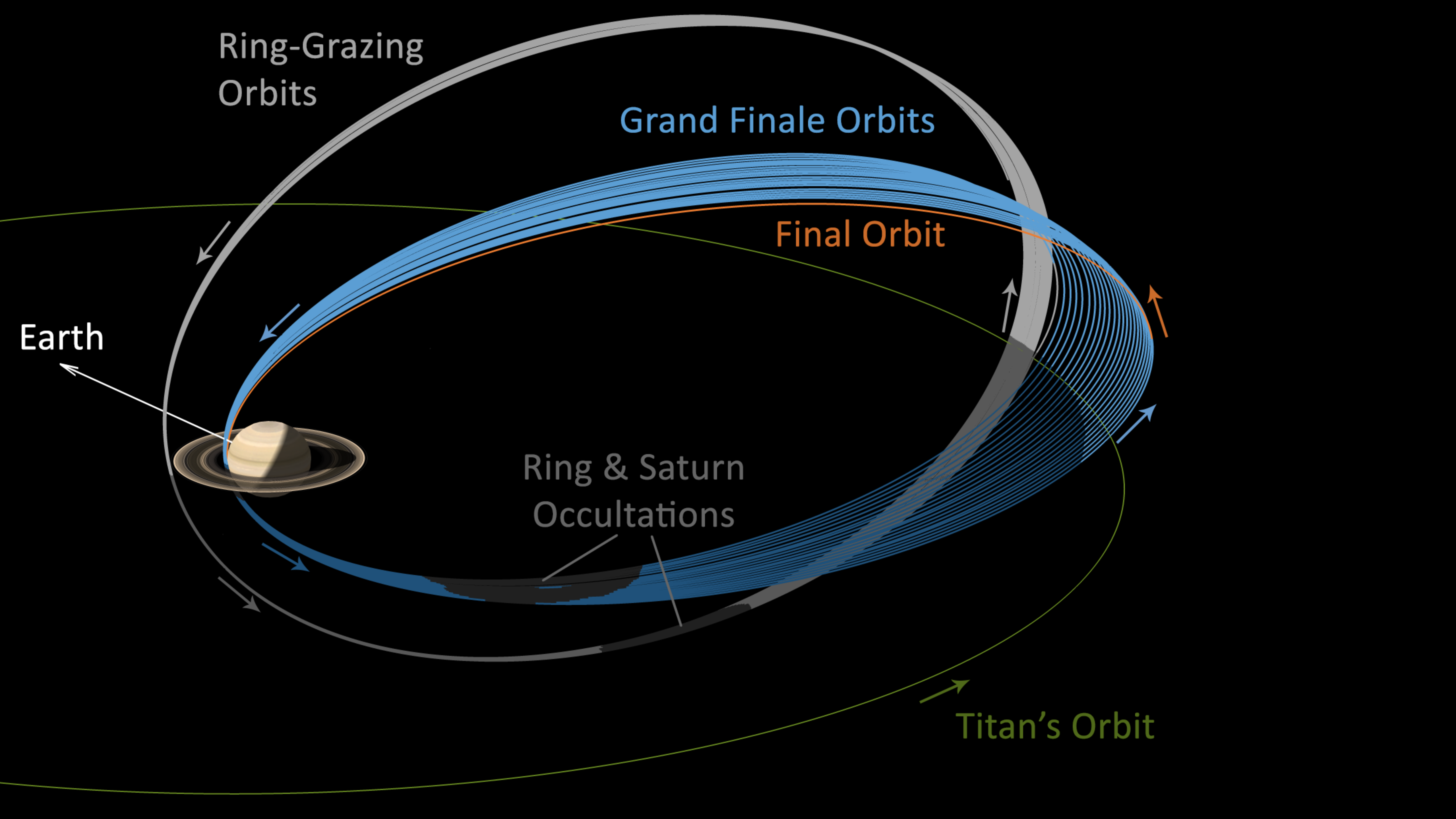


Huygens

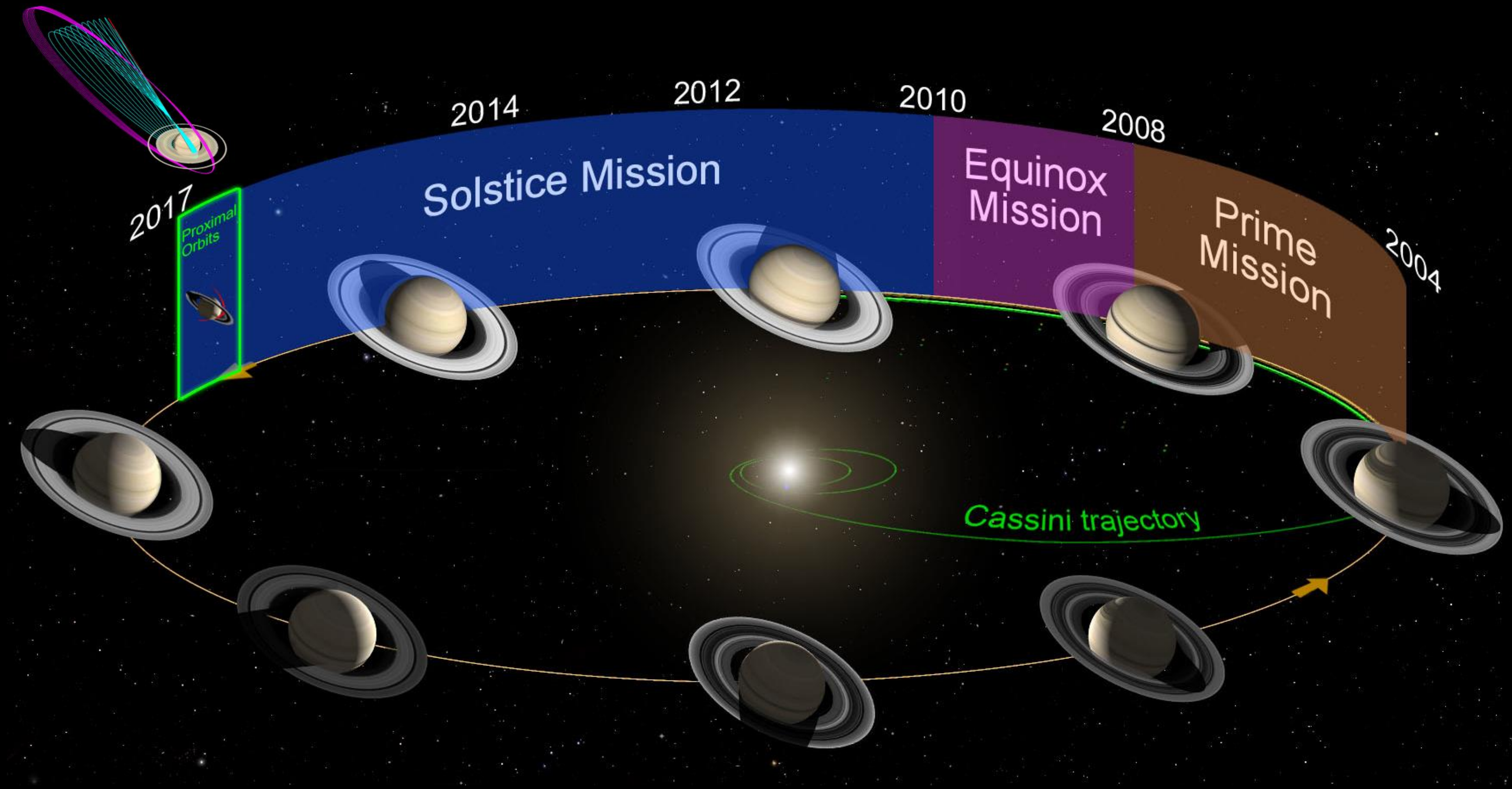
Denmark
Belgium
France
United States
Germany
Italy
Israel
United Kingdom
Poland
Netherlands
Czech Republic
Austria
Spain
Finland
Switzerland
Ireland
Hungary
Sweden
Norway
International Participation in
CASSINI
Saturn Orbiter and Huygens Titan Probe



- 13-year mission
- ≈300 Saturn's revolutions
- 127 Titan's flybys
- 1 probe release in Titan's atmosphere
- 23 Enceladus' flybys
- Grand Finale:
    - 22 rings fly-through
    - Dive in Saturn's atm.

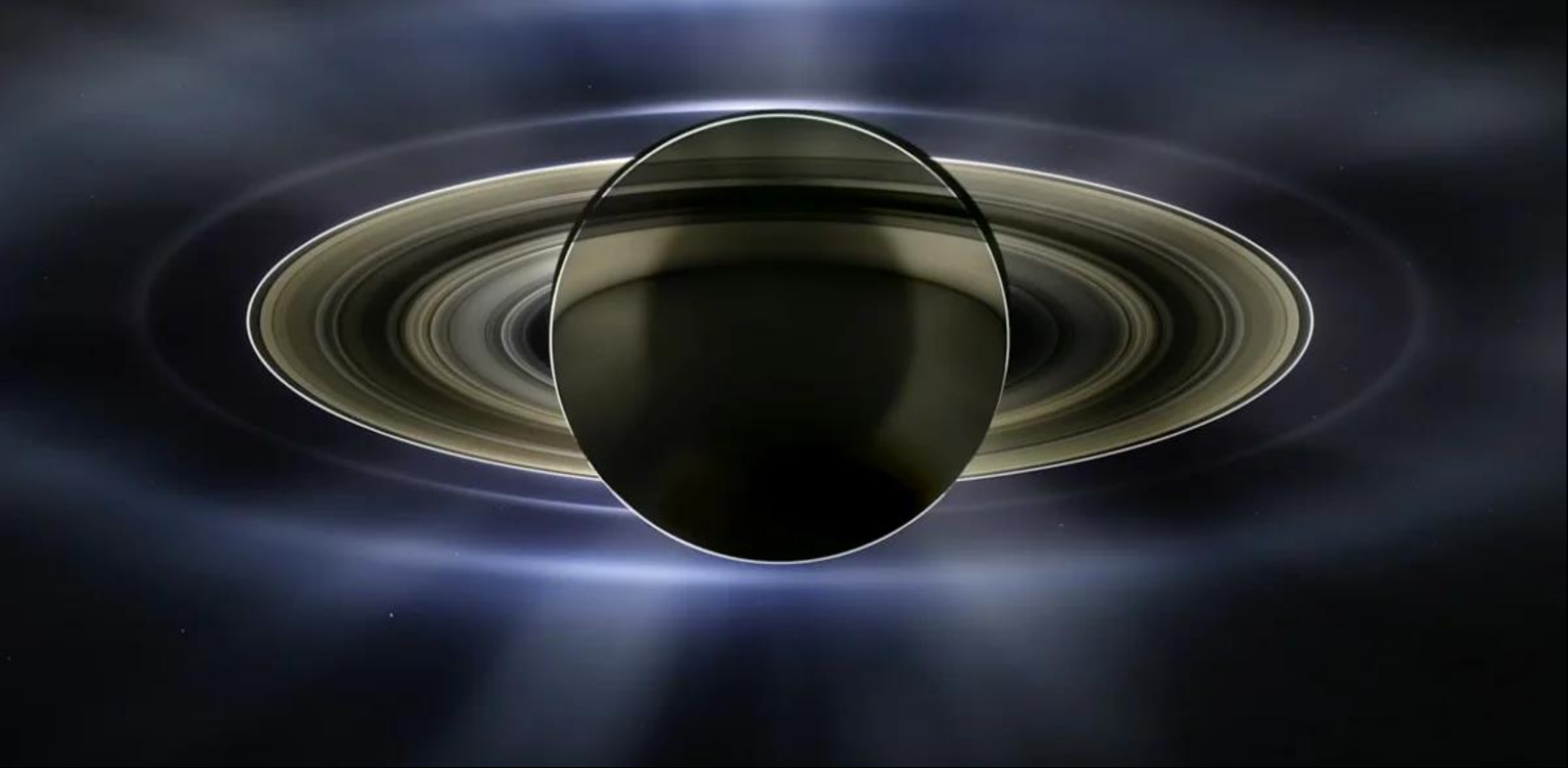

Ring-Grazing Orbits
Grand Finale Orbits
Final Orbit
Earth
Ring & Saturn Occultations
Titan's Orbit

≈ Half a Saturn year

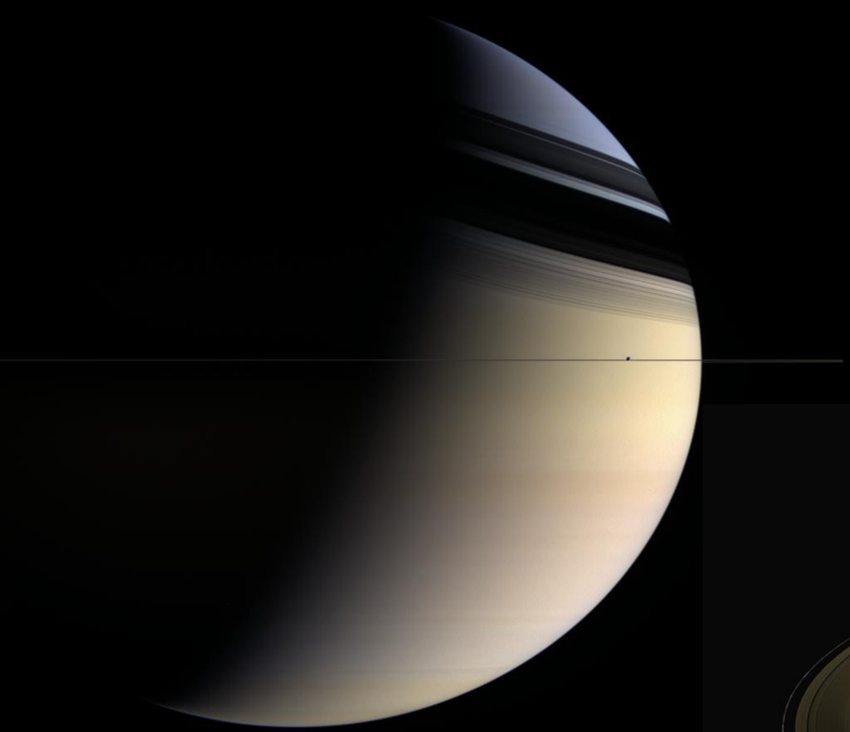


15 September (≈1:00 p.m. GMT+2)

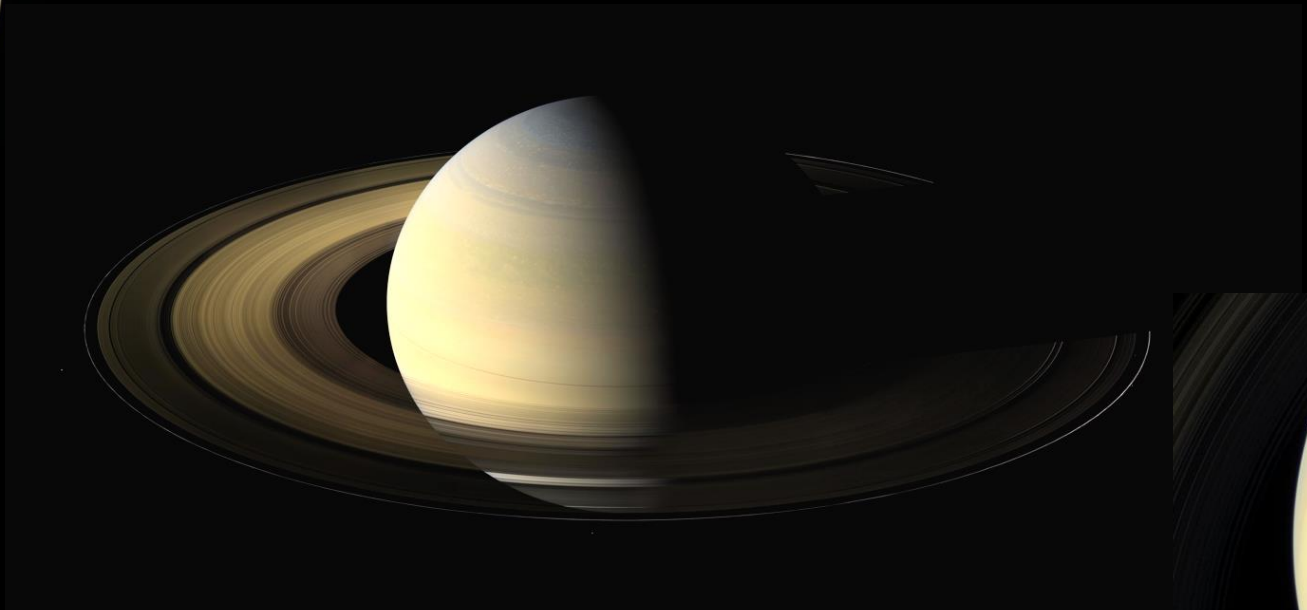
A few Cassini's beautiful images of Saturn



Watching Saturn seasons change

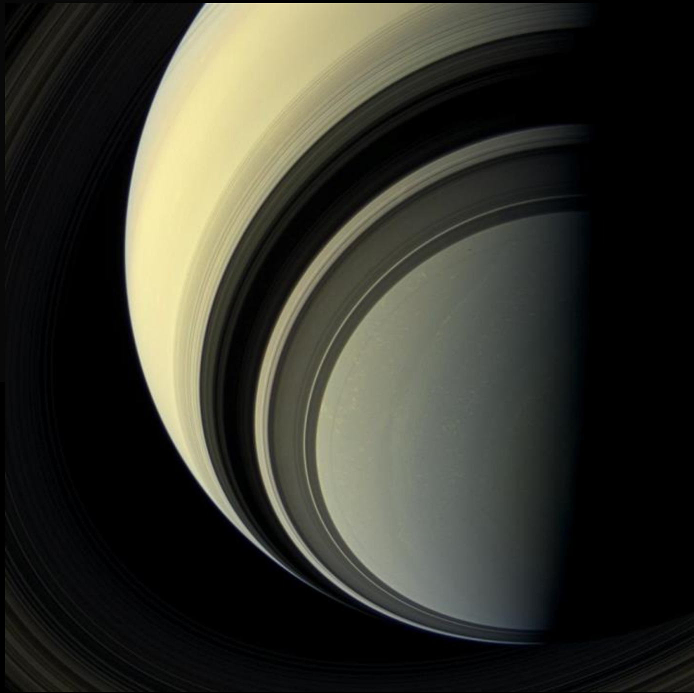


Southern summer
(2004)

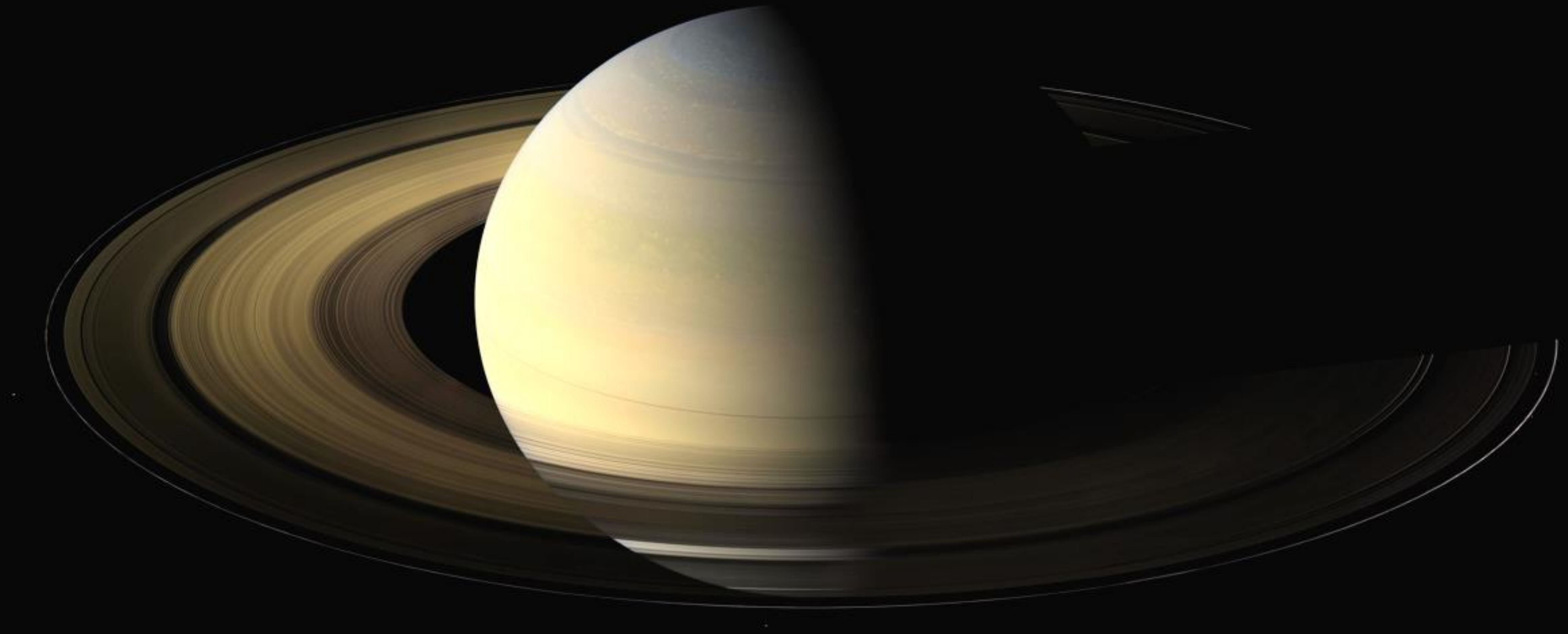


Spring equinox
(2009)

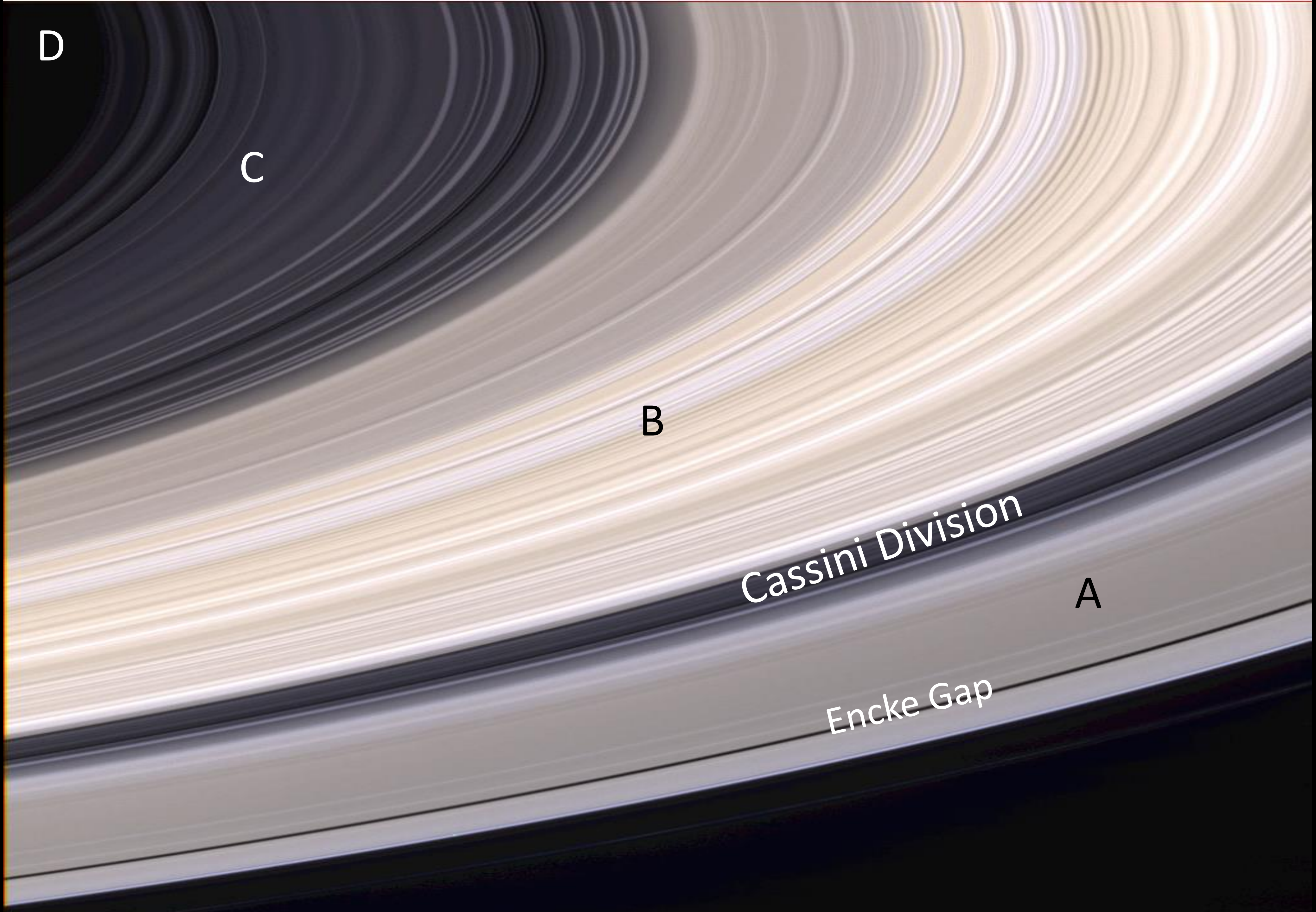
Northern summer
(2016)

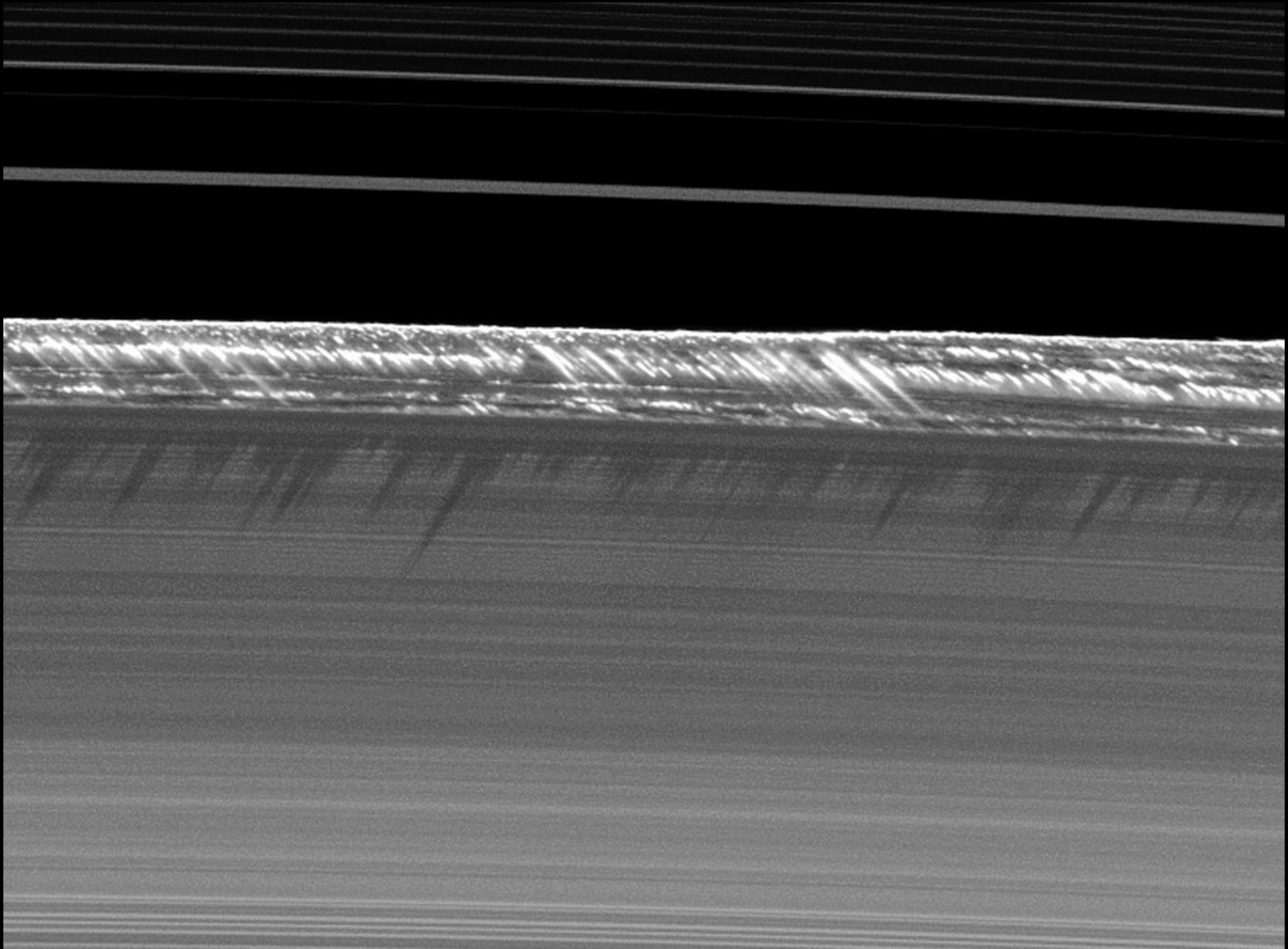


Saturn's rings at equinox

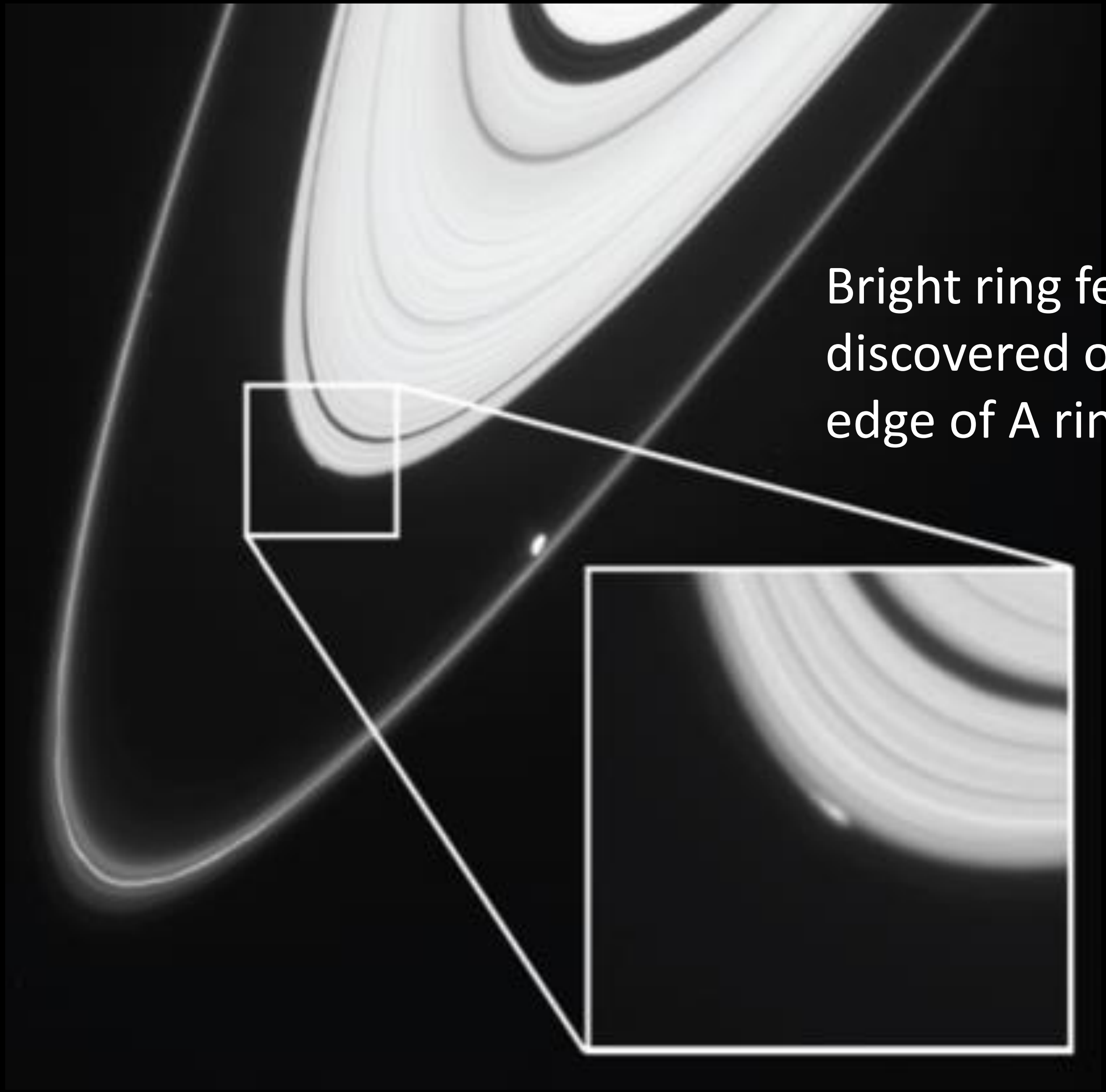


No ring shadow on the planet which occurs only ≈15 years


D
C
B
Cassini Division
A
Encke Gap



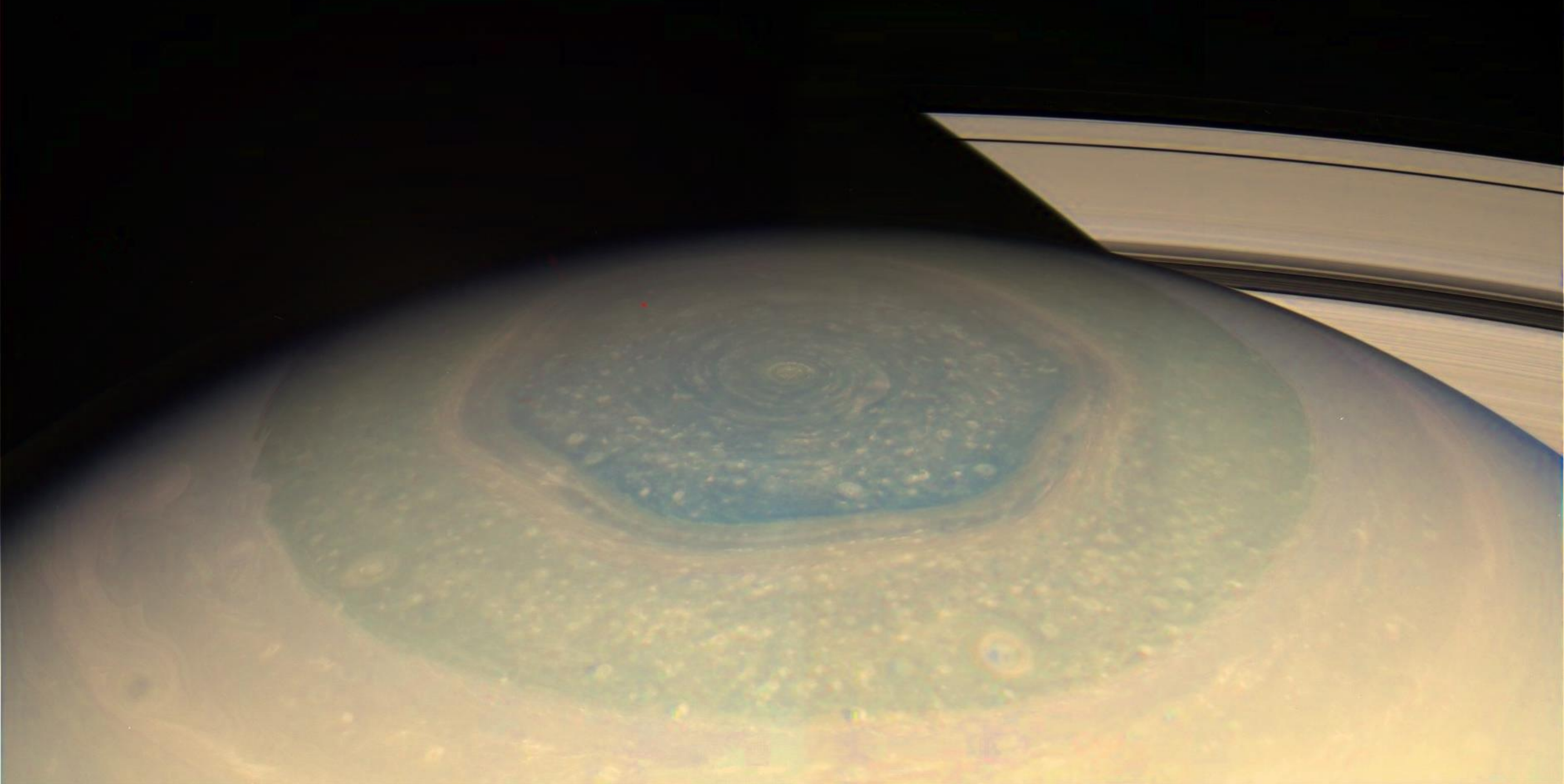
A New Moon is Born?

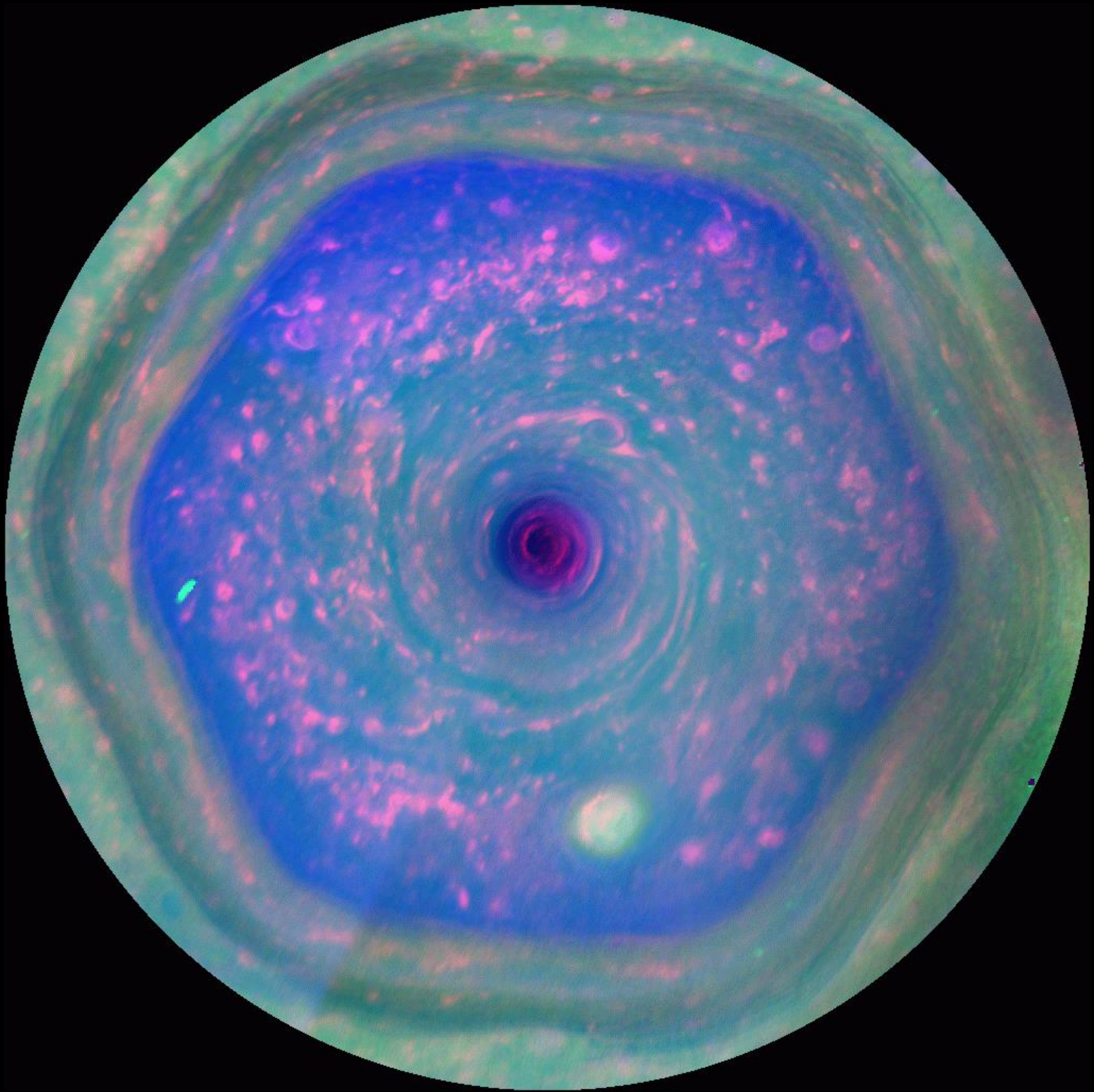


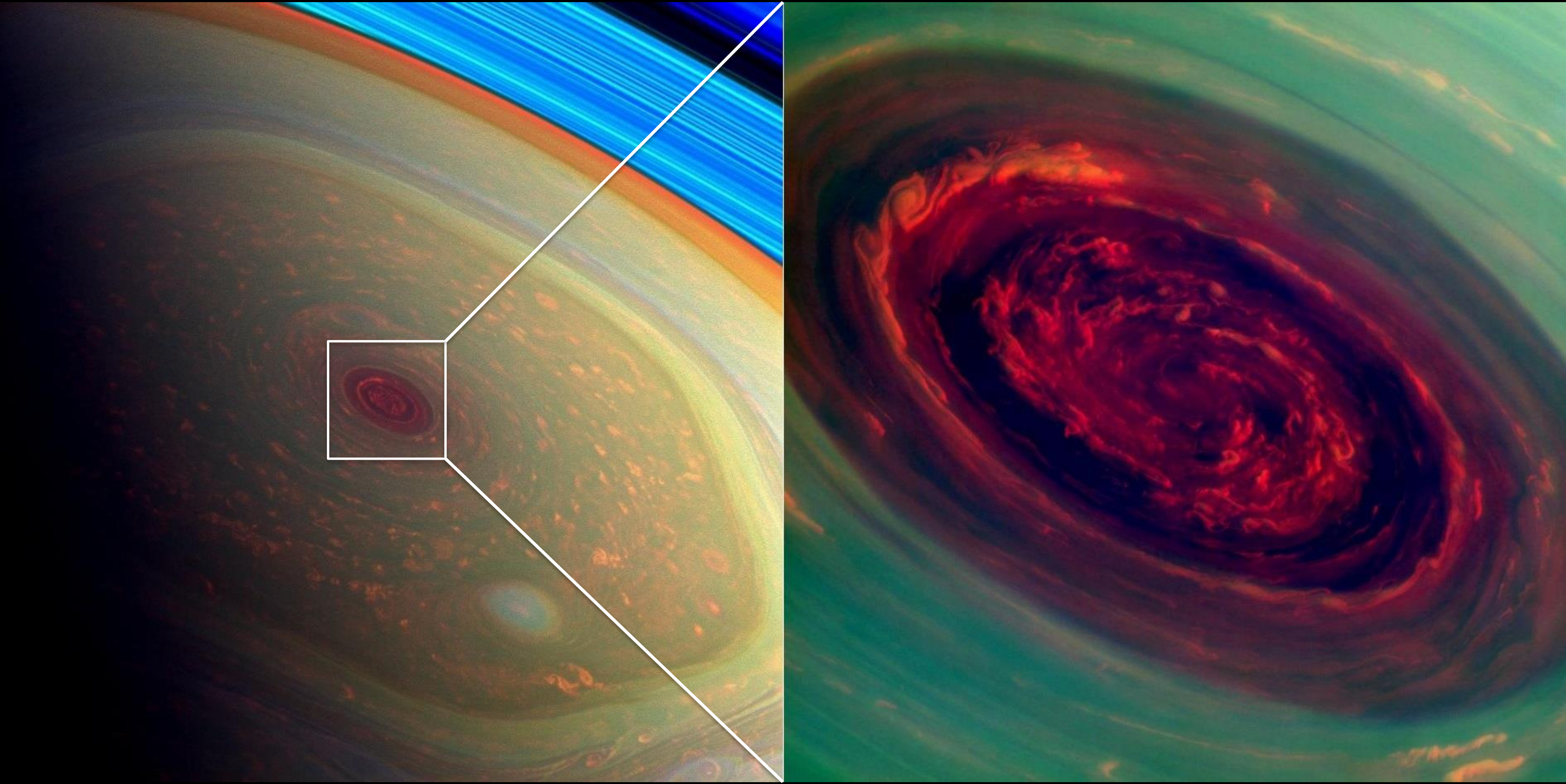
Bright ring feature discovered on outer edge of A ring

Appears to be associated with birth of small, icy infant moon nicknamed Peggy

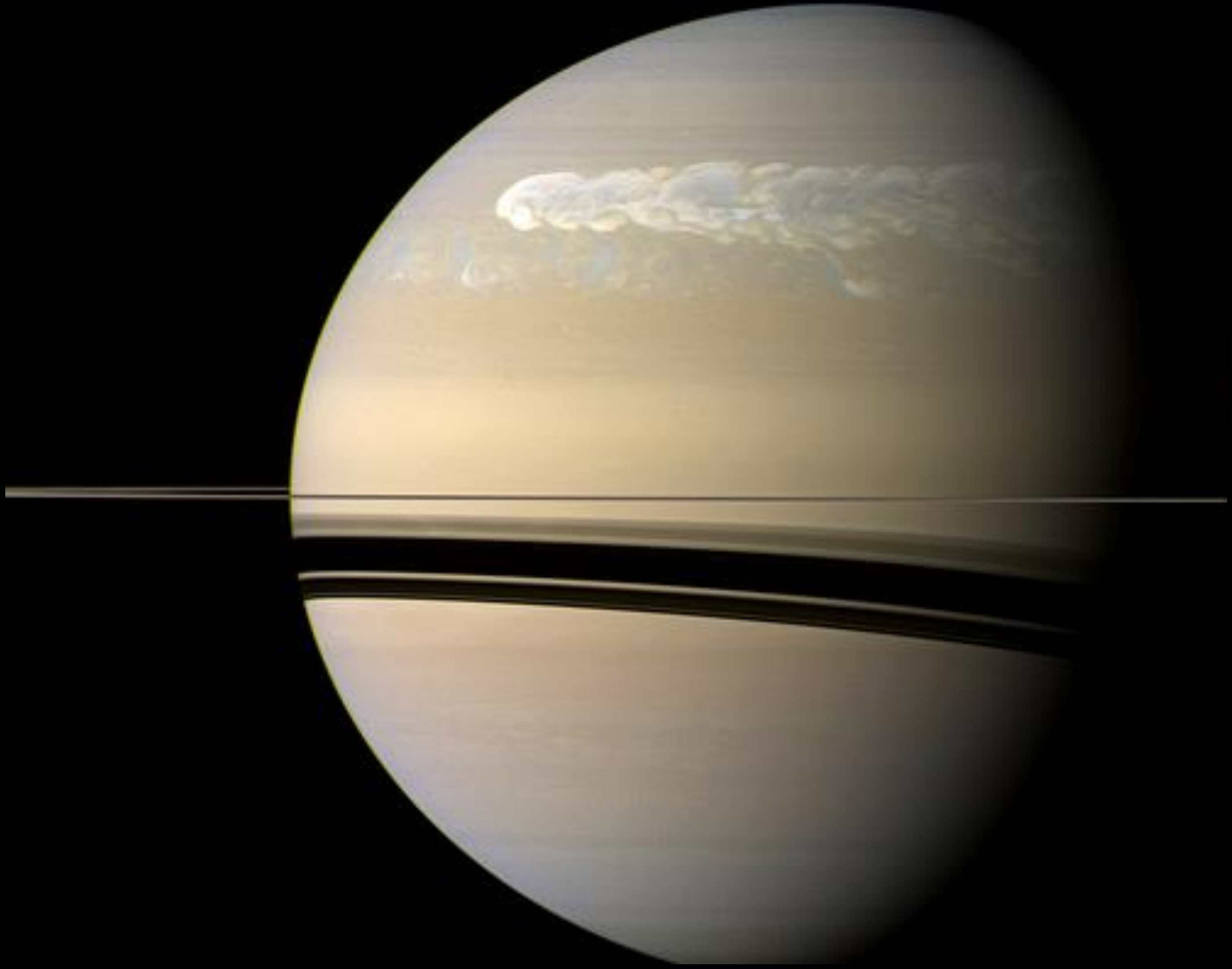
North Pole hexagon



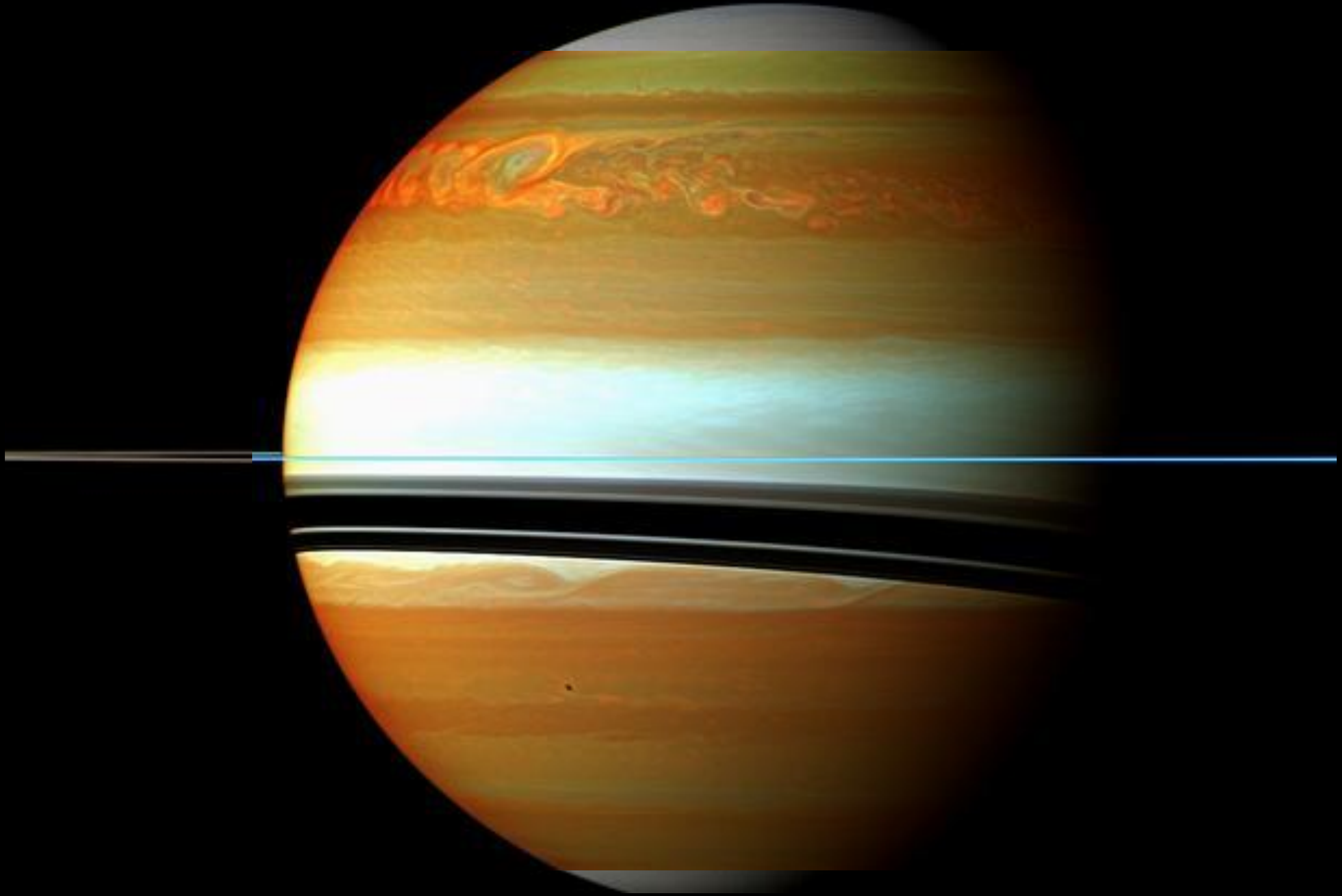




Giant Storm: Head eats tail



Giant Storm: Head eats tail

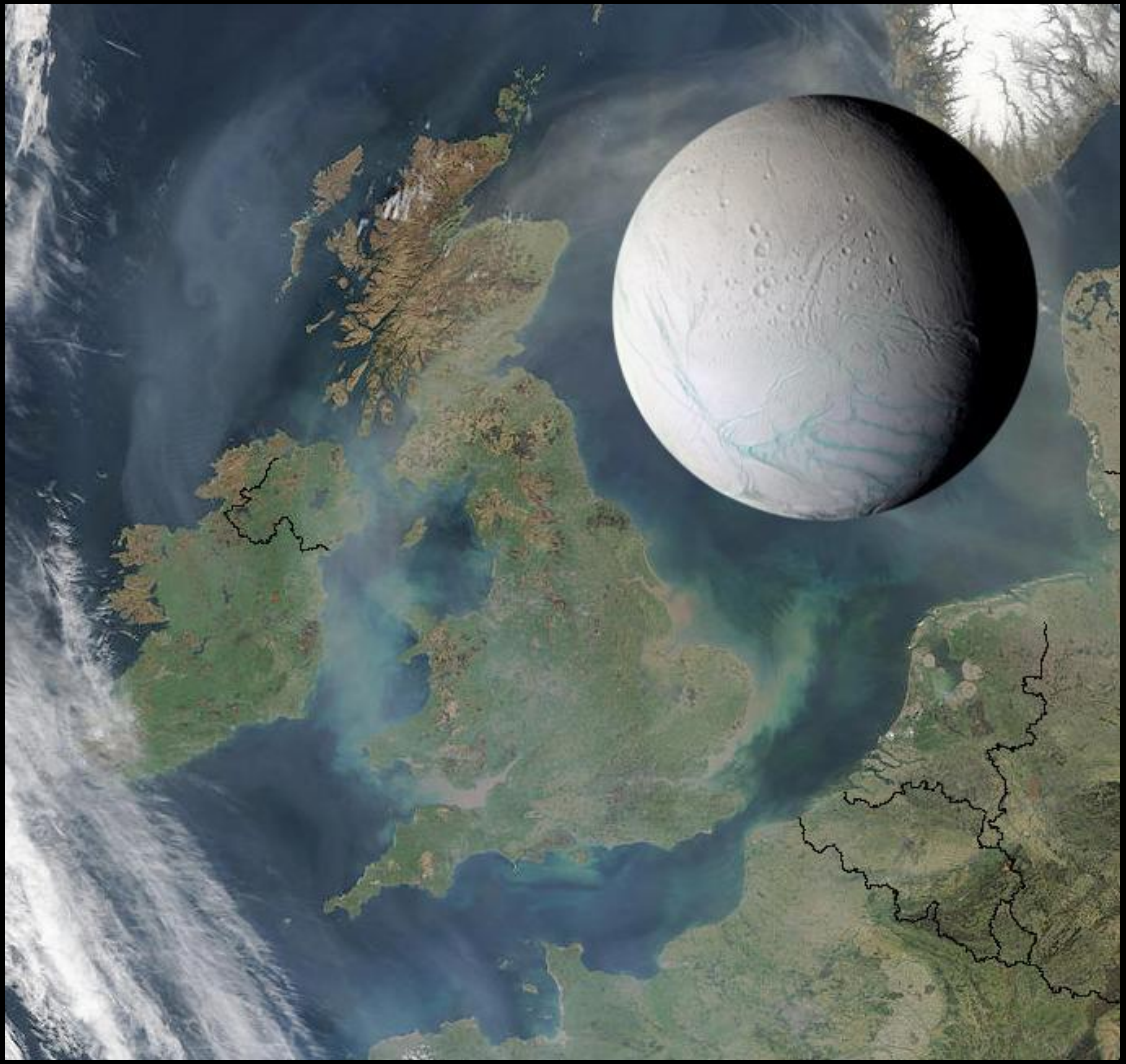


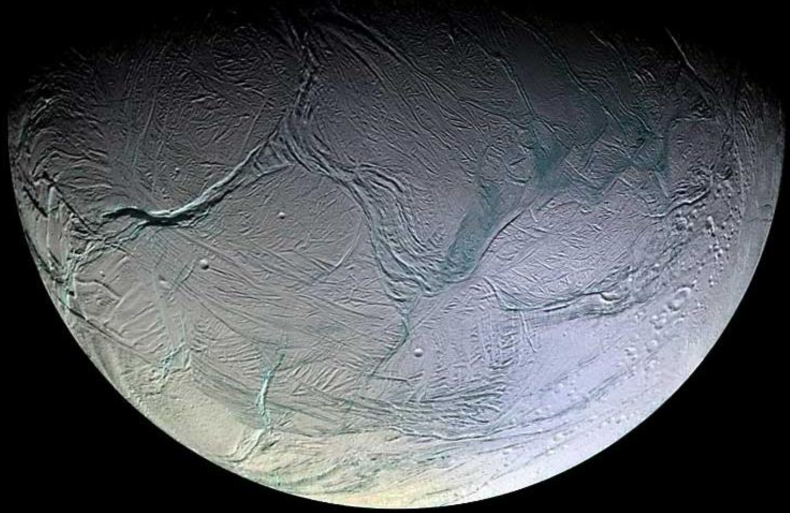
Enceladus science with Cassini

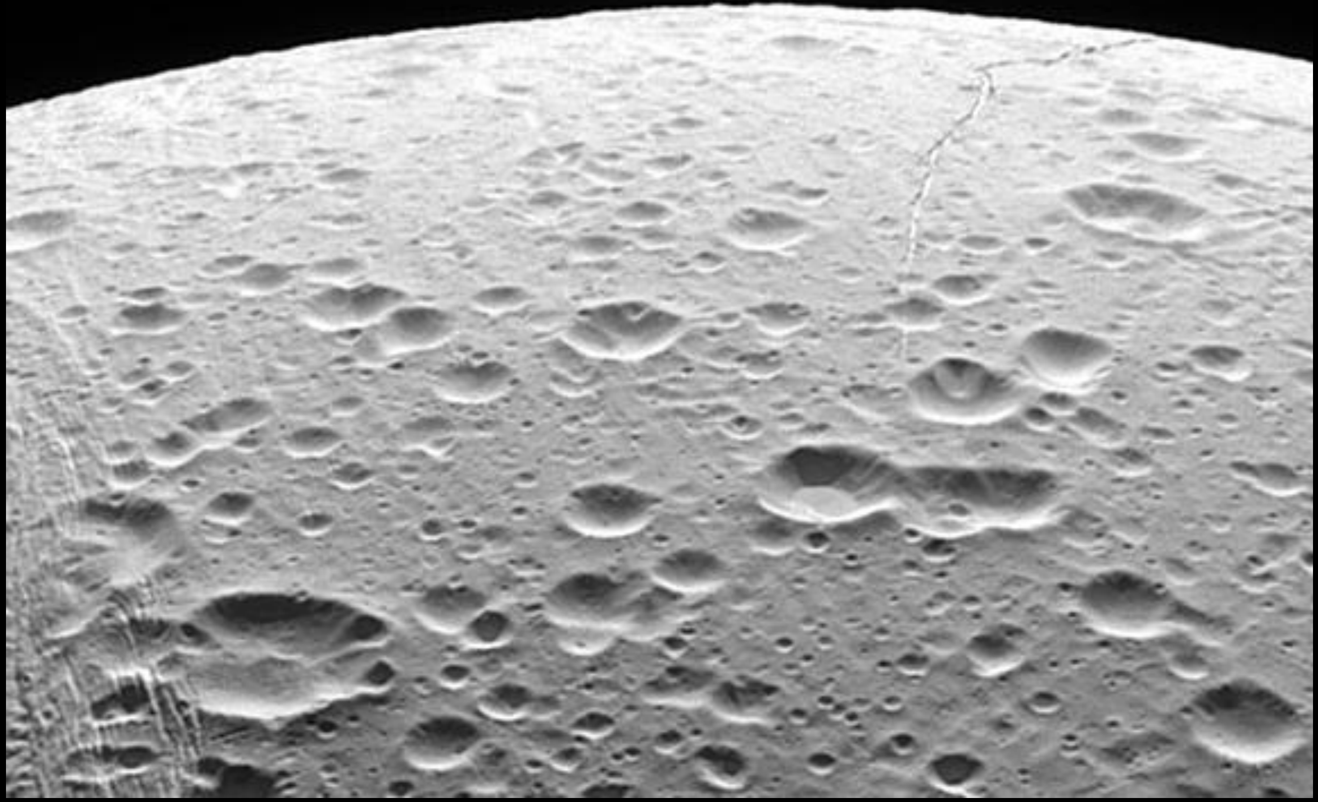
Small icy moon (500 km in diameter), almost pure ice

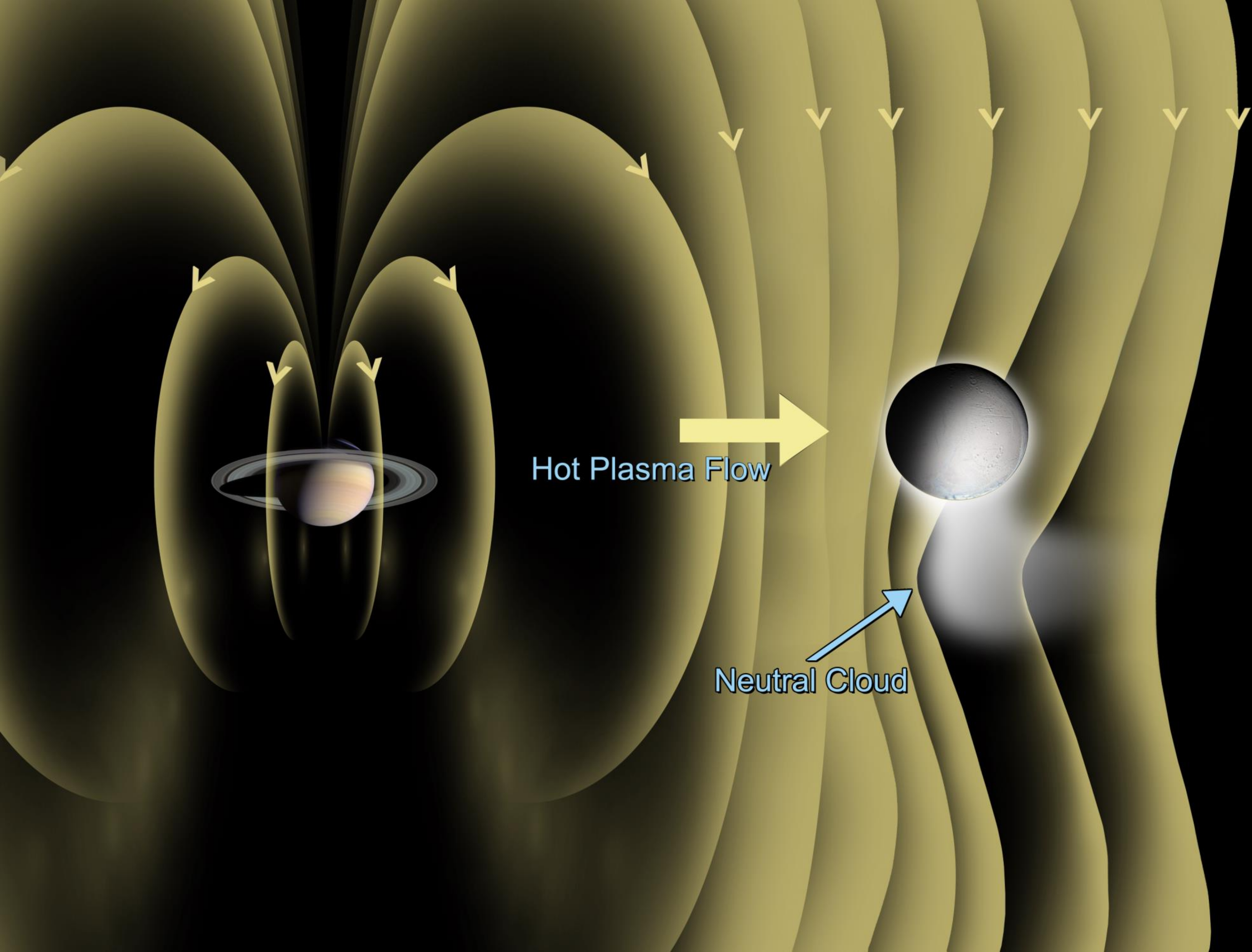
Very old and very young terrains?

⇨ Active tectonics for such a small moon?





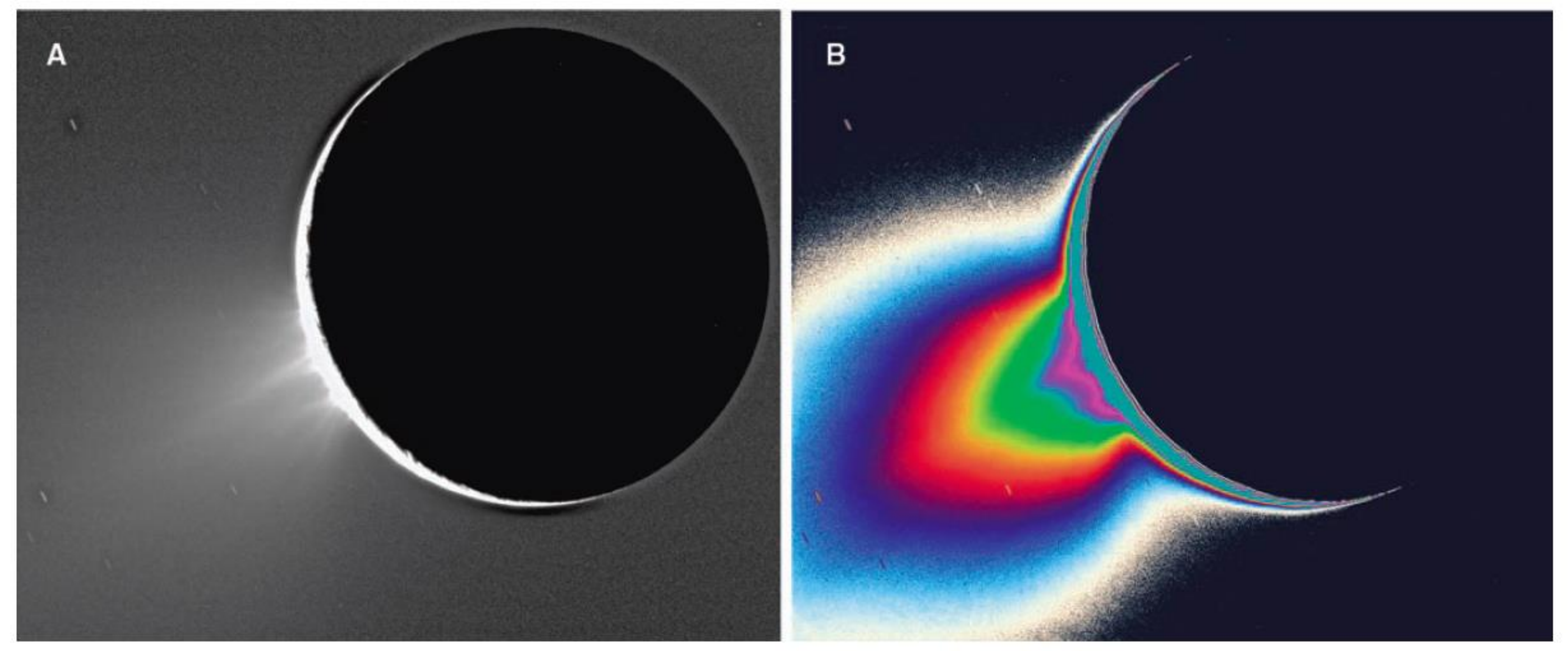




2005: First flyby close to Enceladus is 1000 km, unusual comet-like magnetic field signature detected

Third flyby altitude decreased to 175 km

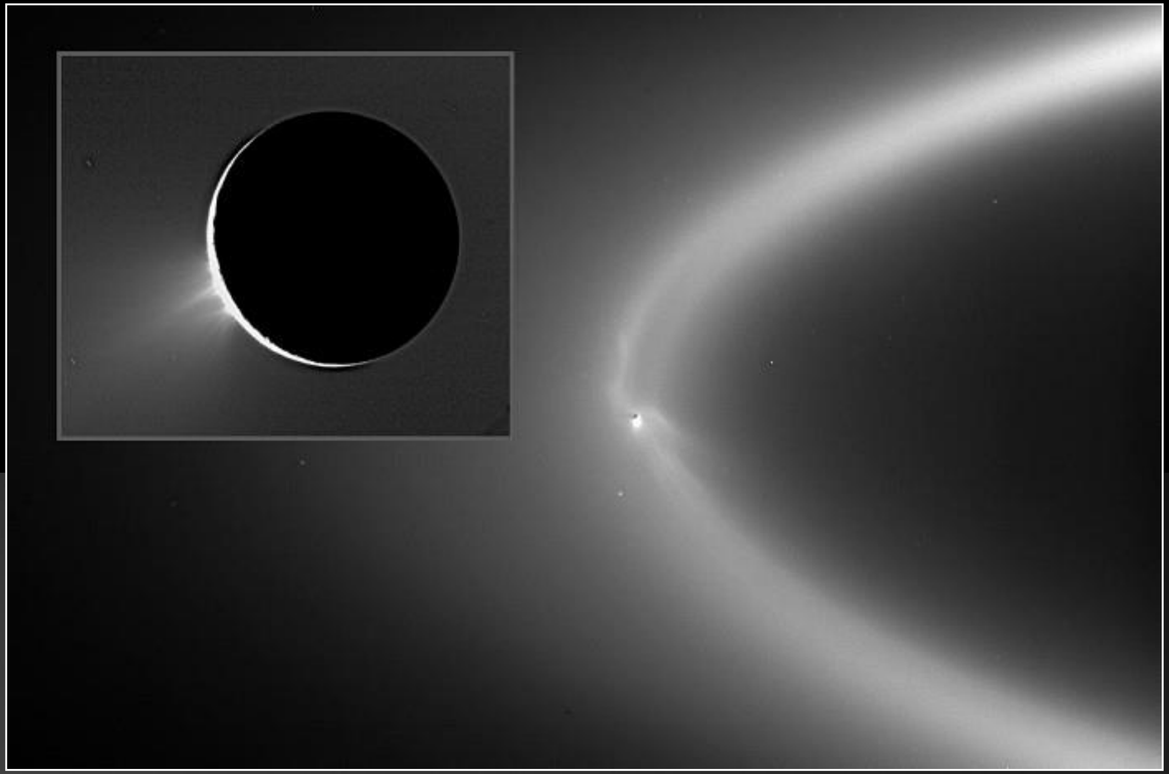
Outstanding discovery (2005):
Geysers at Enceladus's south pole



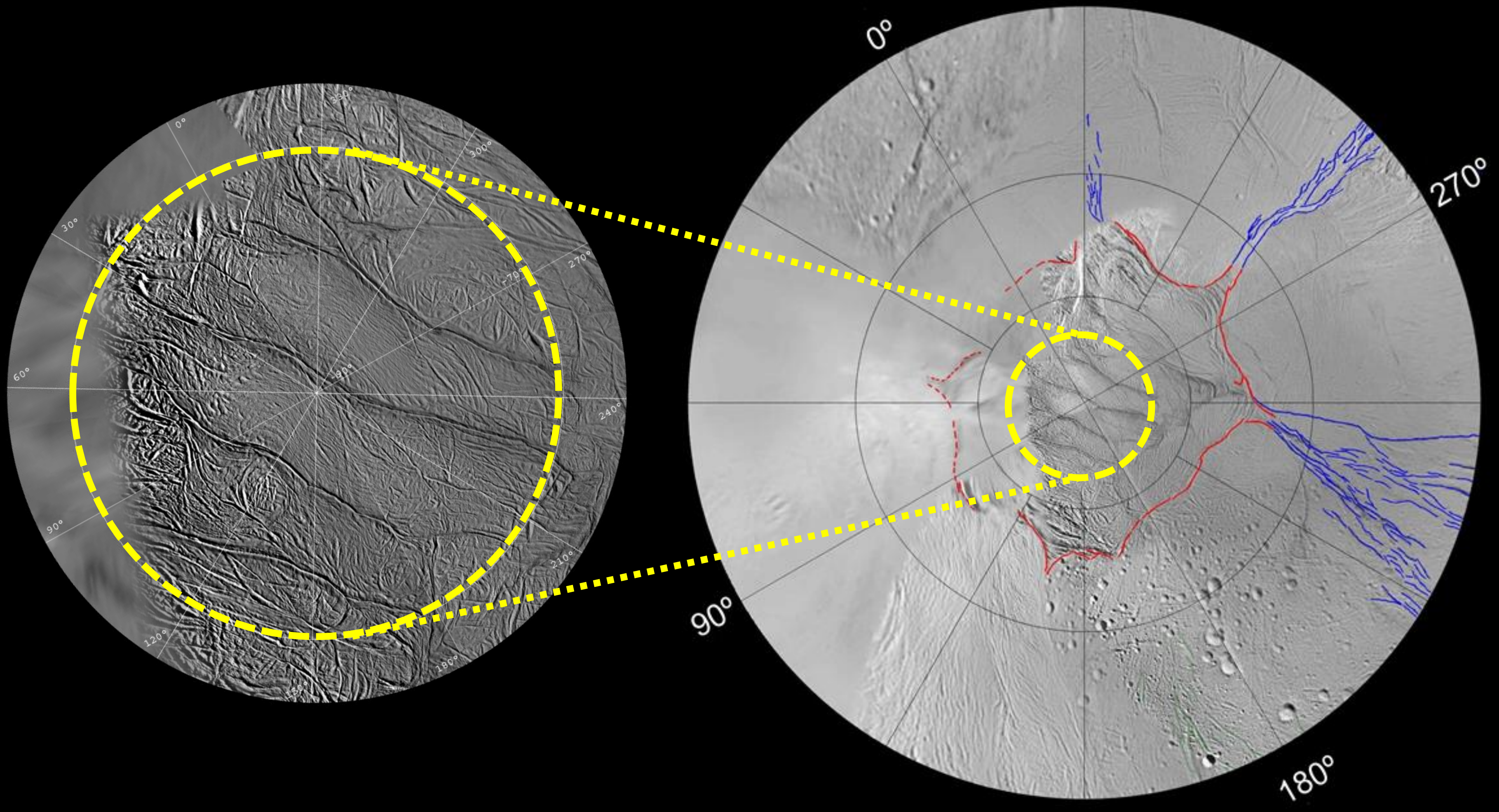
Detection of a tenuous atmosphere, but Enceladus is too small to retain it .

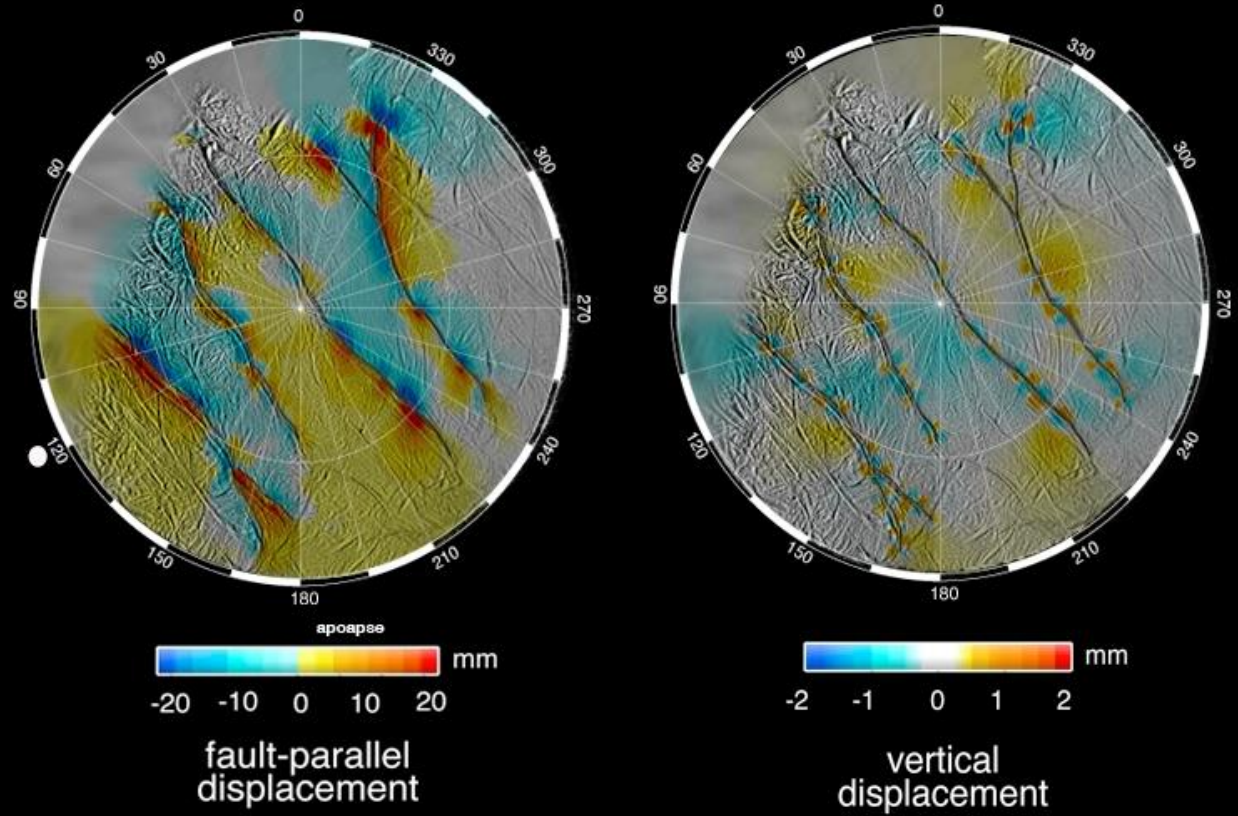
Feeds E-ring with icy particles.

⇨ Internal source? Icy volcanism?



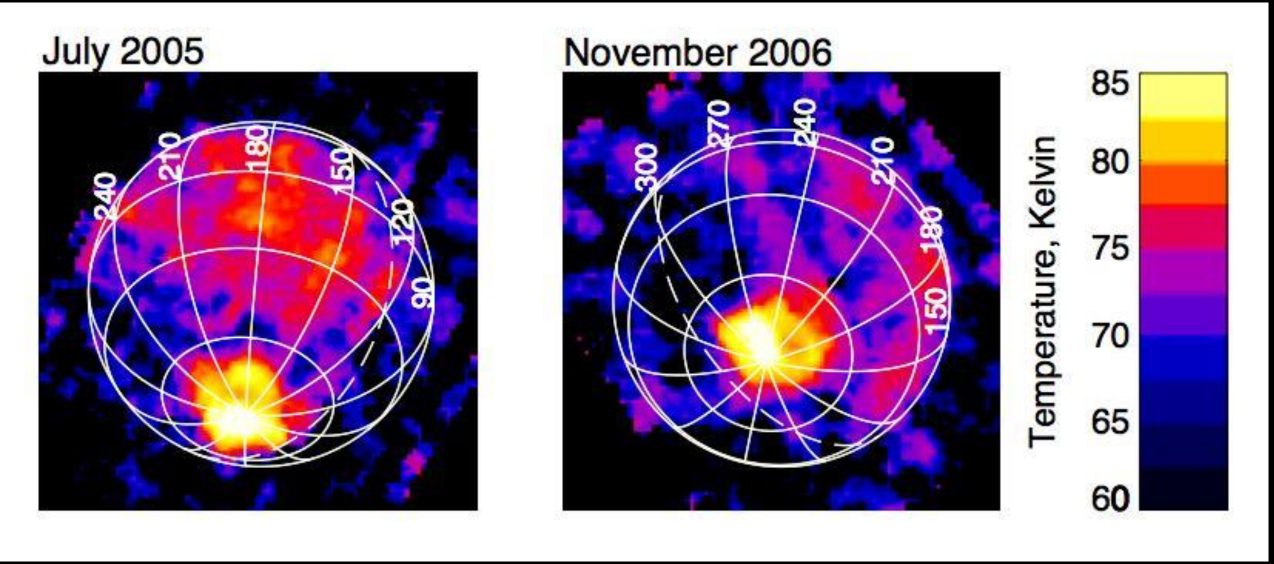
Geologic unit and location	*N*-ratio	Age (10^6 years) (lunar-like)	Age (10^6 years) (constant flux)
I. Heavily cratered plains (15° to 45°N, 340° to 360°W; 20°N to 30°S, 160° to 210°W)	1/4.7	4200	1700
II. Striated and folded plains in Sarandib Planitia (15°N to 5°S, 305° to 320°W)	1/70	3750	170
III. Ridged and grooved plains in Samarkand Sulcus (55° to 65°S, 170° to 240°W)	1/1170	980	10
IV. South Polar Terrain (>55°S, 160° to 320°W)	1/10,770	100	1
V. Single WAC frame within SPT 37 m/pixel (350°W, 75°S)	<1/311,000	<4	<0.5

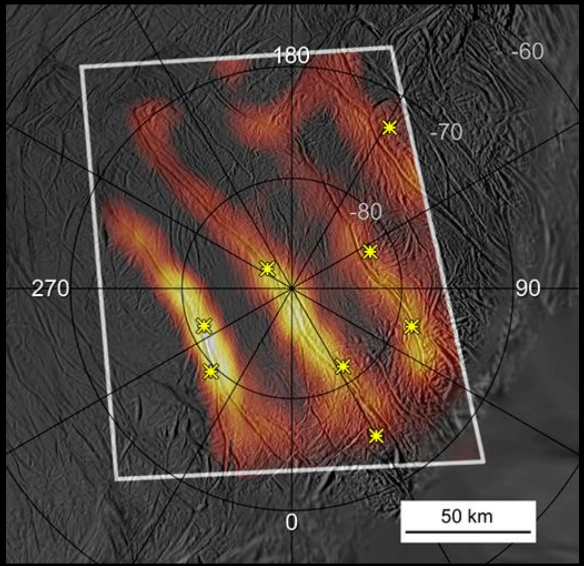




Area of very strong tectonic constraints

South pole hotspots

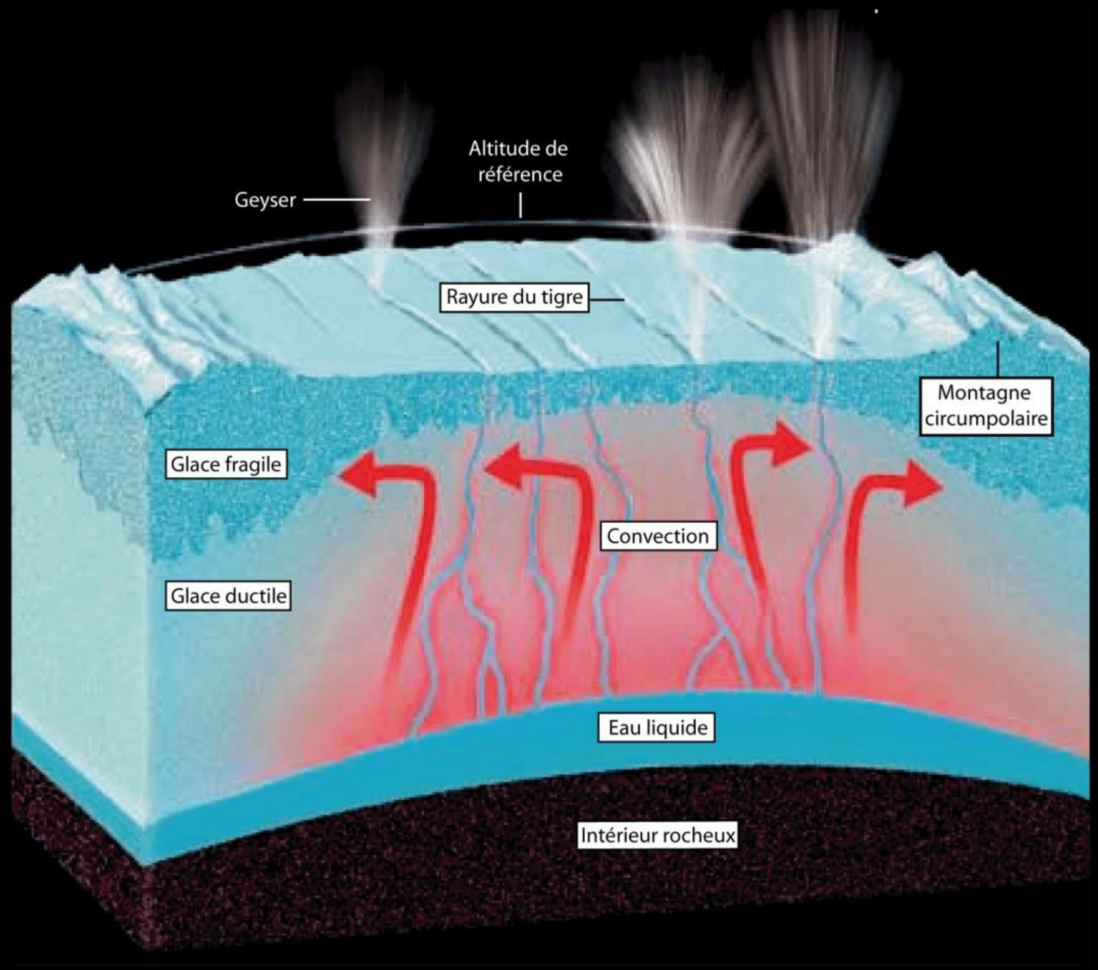




Internal heating by Saturn’s tides, localized at Enceladus’ south pole.

Formation of undergroung liquid water pockets, or more global layer, under pressure.

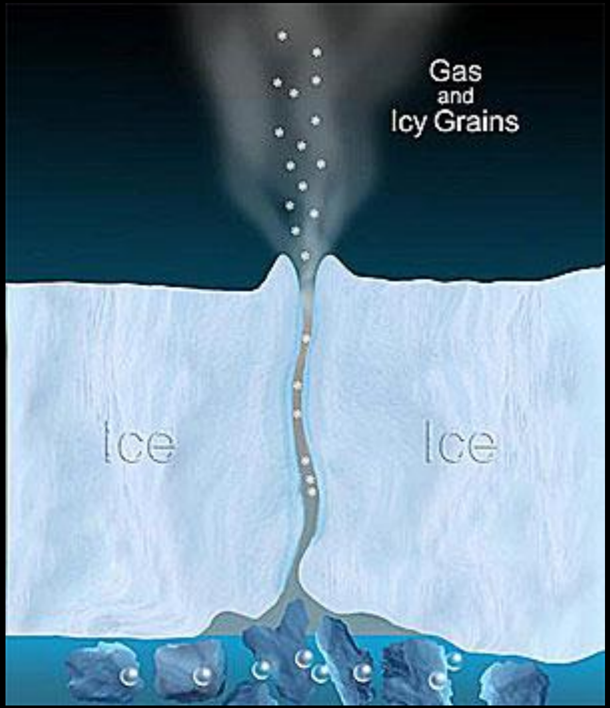
Ascent of underground material through cracks of icy crust.

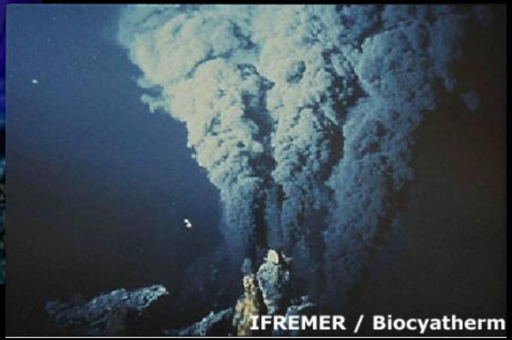


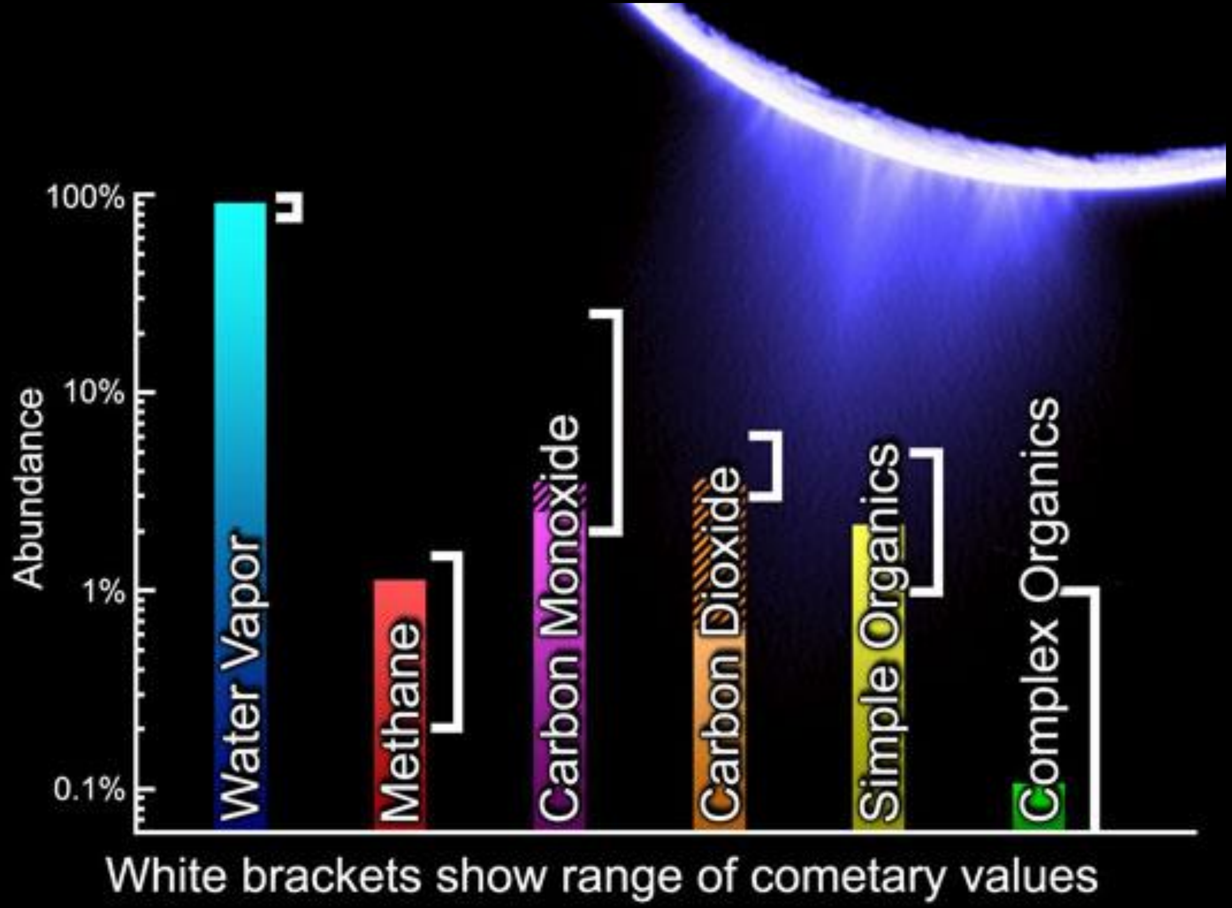
Internal ocean or sea(s) of liquid water, in contact with rocky core.

Detection of organic matter and H in geysers' plumes!

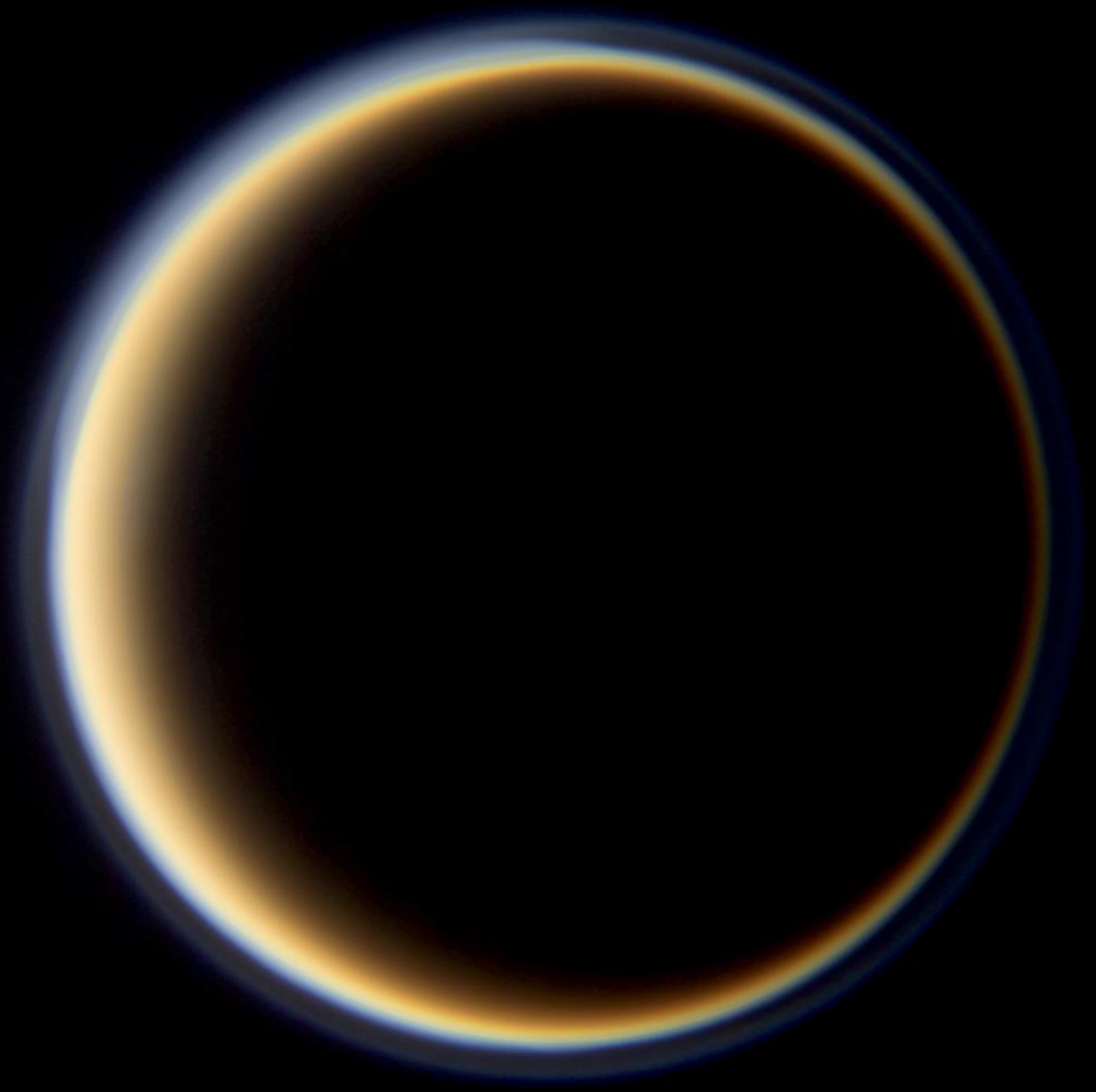
Sign for hydrathermal activy! and live?

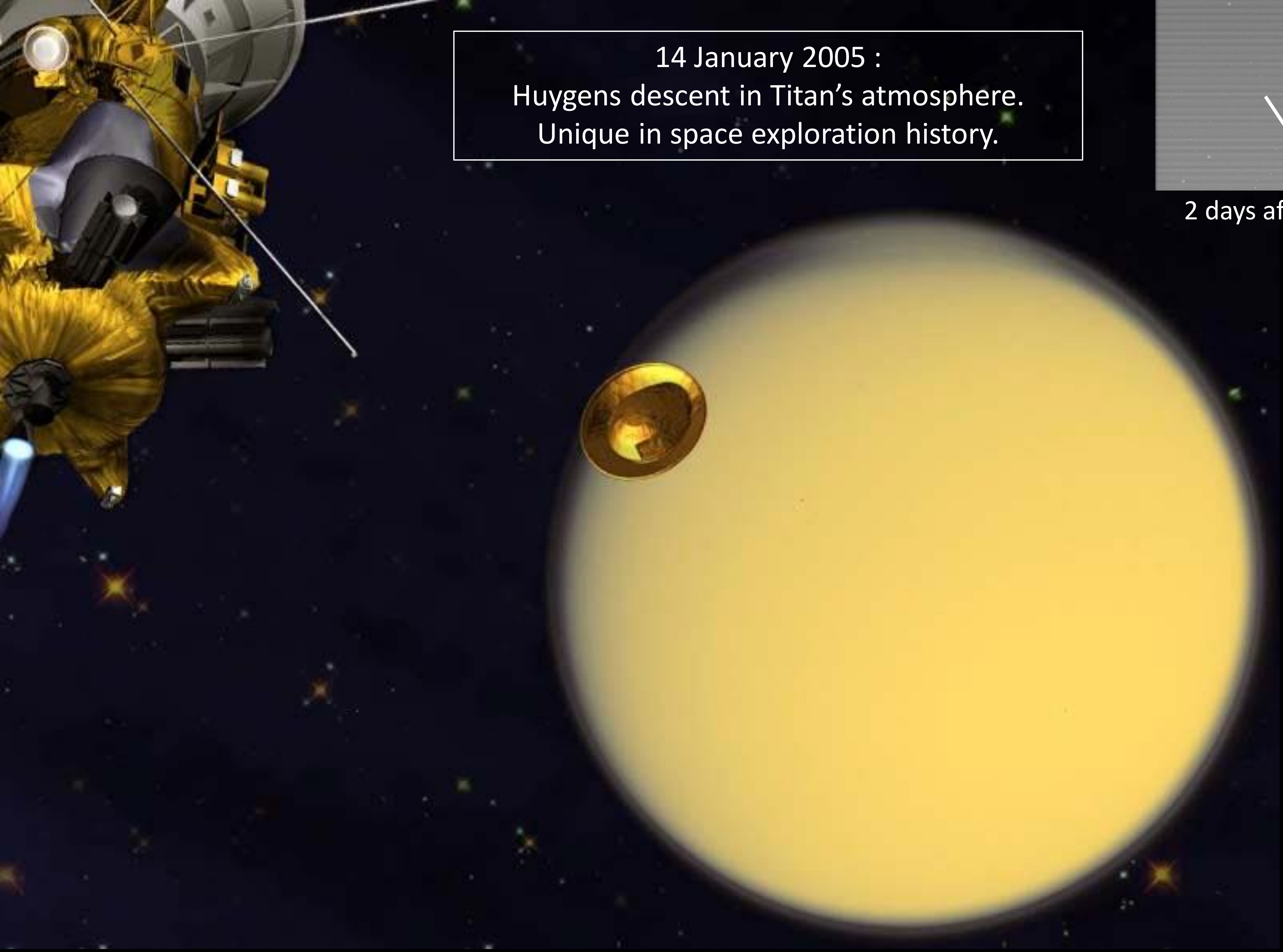






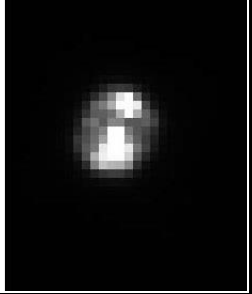
Titan science with Cassini & Huygens



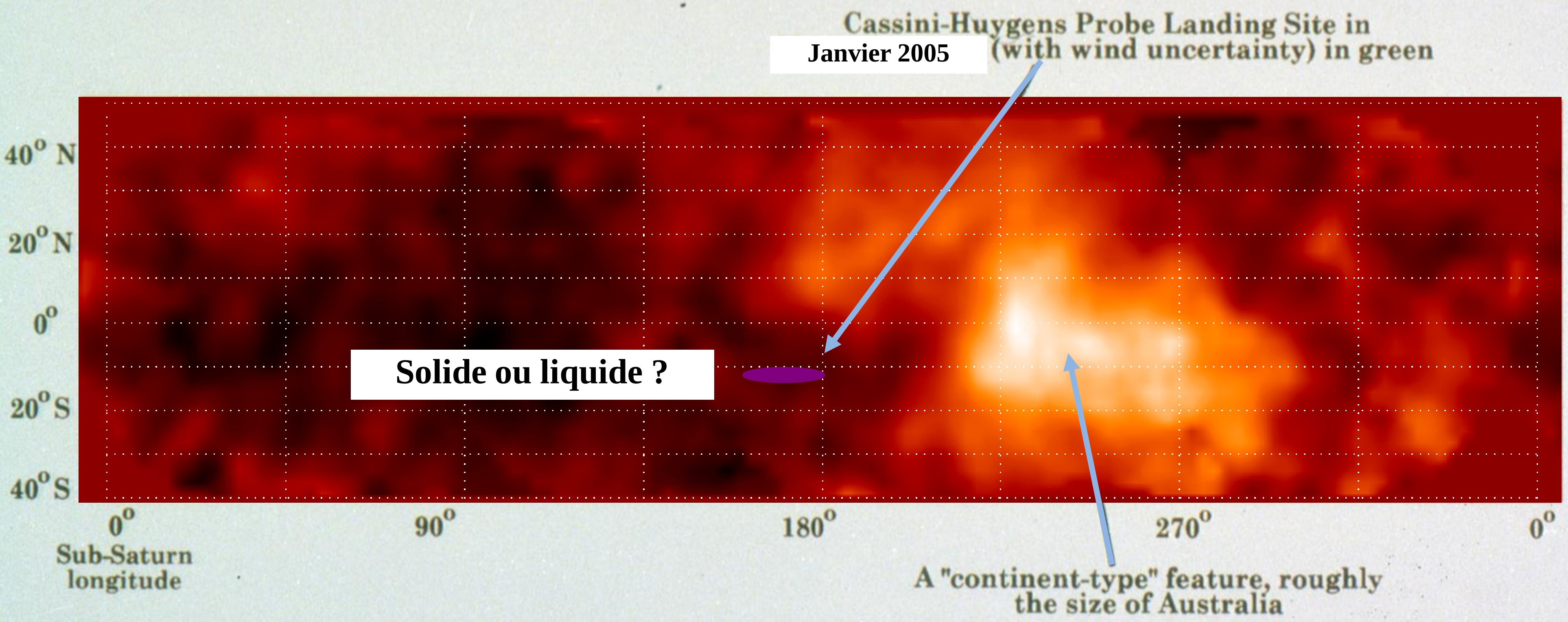


14 January 2005 :
Huygens descent in Titan's atmosphere.
Unique in space exploration history.

2 days after

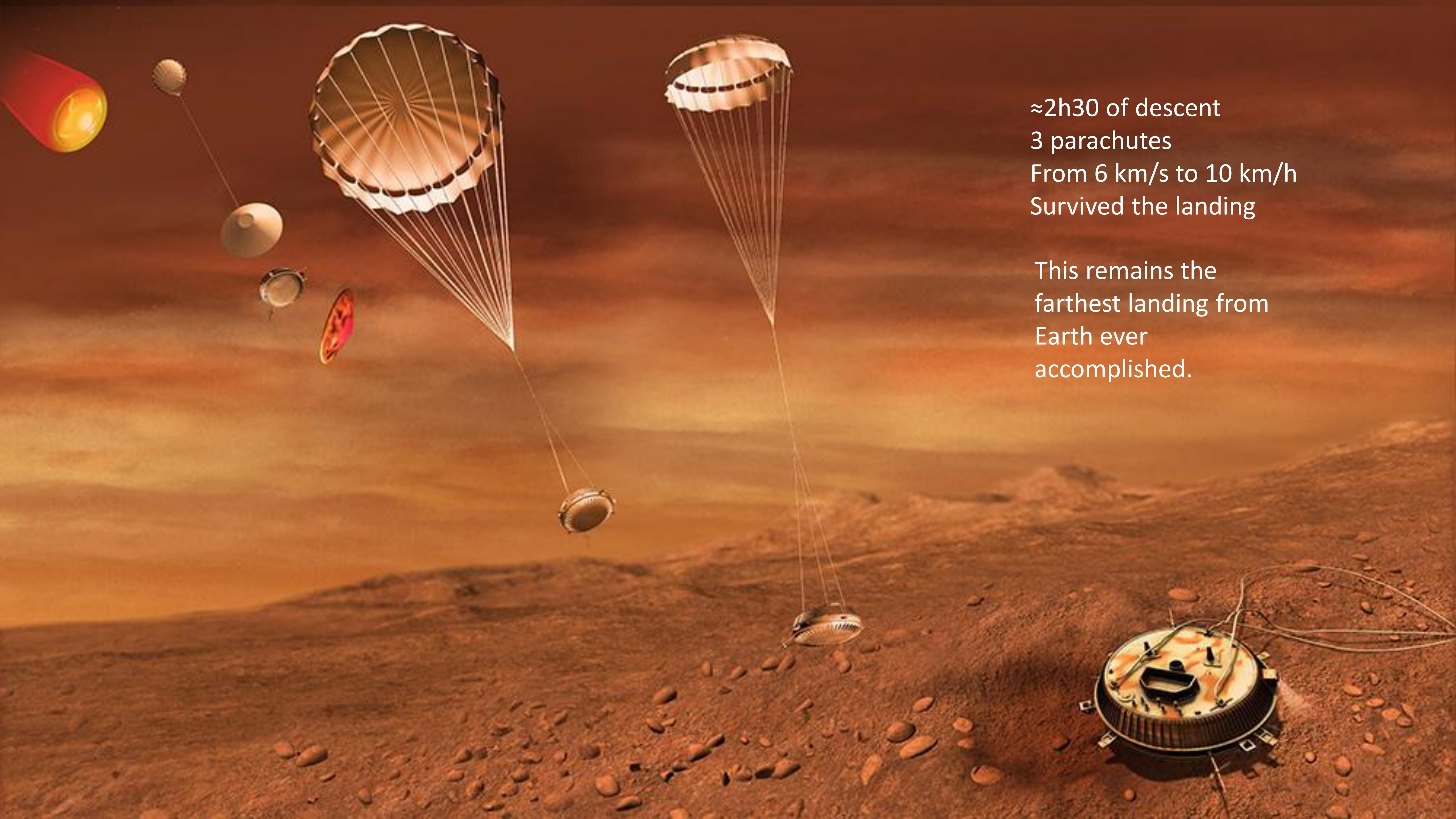


Titan Mercator Projection



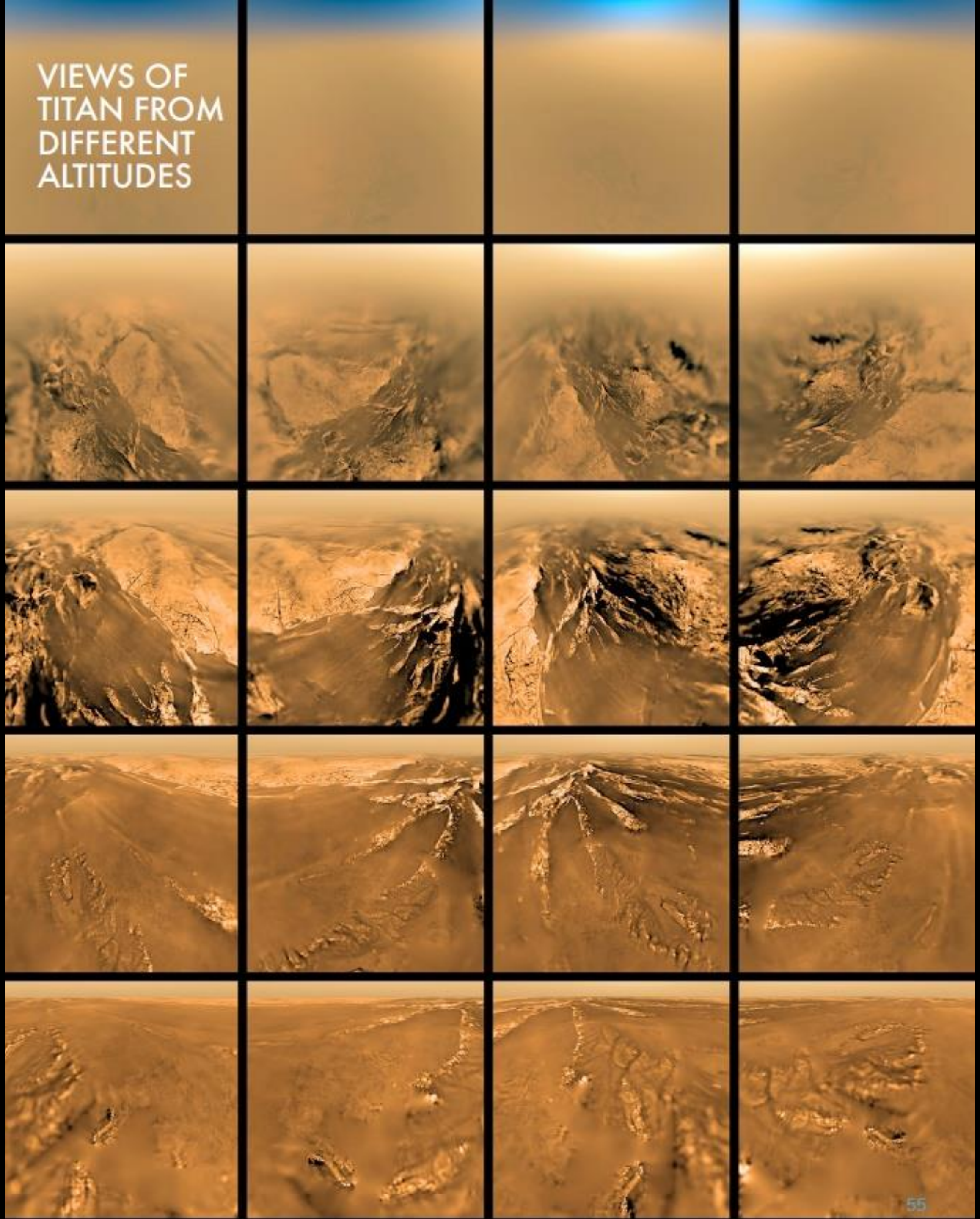
Data taken by the Hubble Space Telescope Wide Field
Planetary Camera-2 in October 1994

P. Smith, et.al., LPL, Univ. of
Arizona, M. Adler, JPL



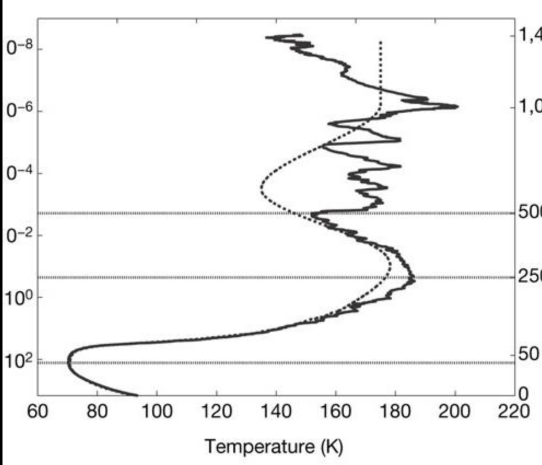
≈2h30 of descent
3 parachutes
From 6 km/s to 10 km/h
Survived the landing

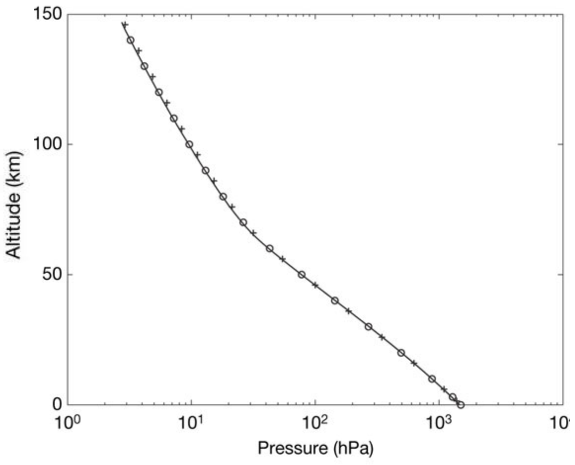
This remains the farthest landing from Earth ever accomplished.

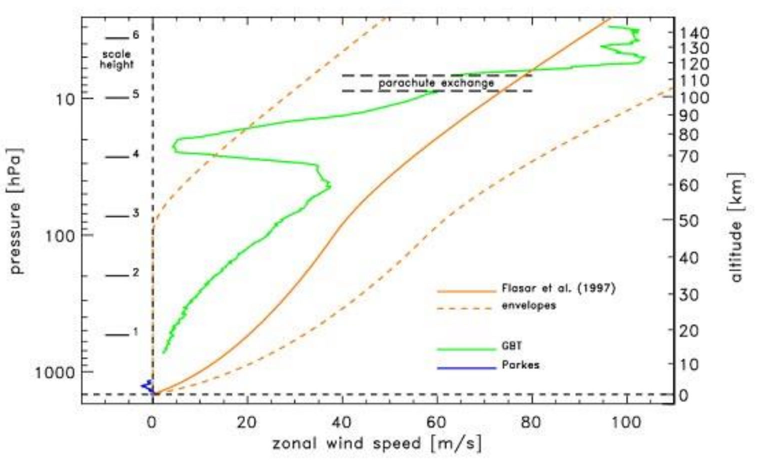


Complete atmospheric characterization

First glints of Titan's surface at high spatial resolution (10m)

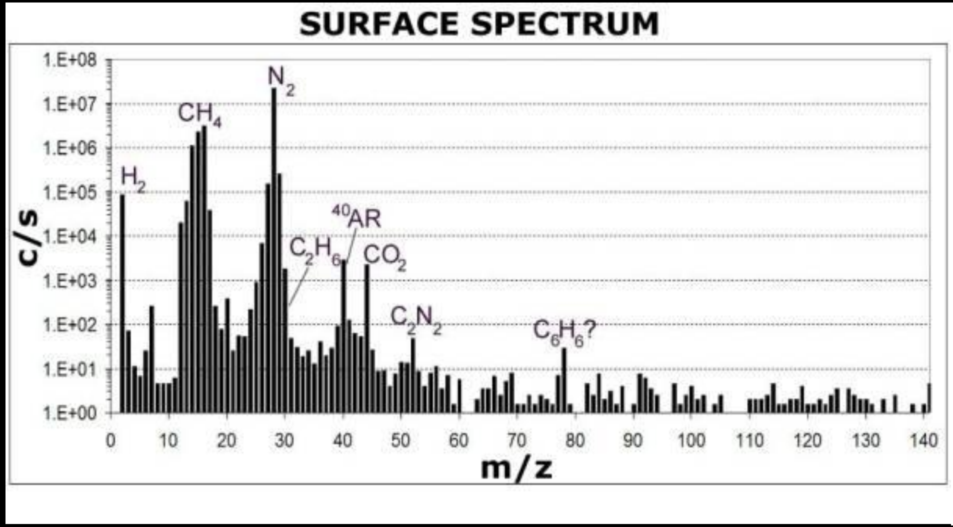


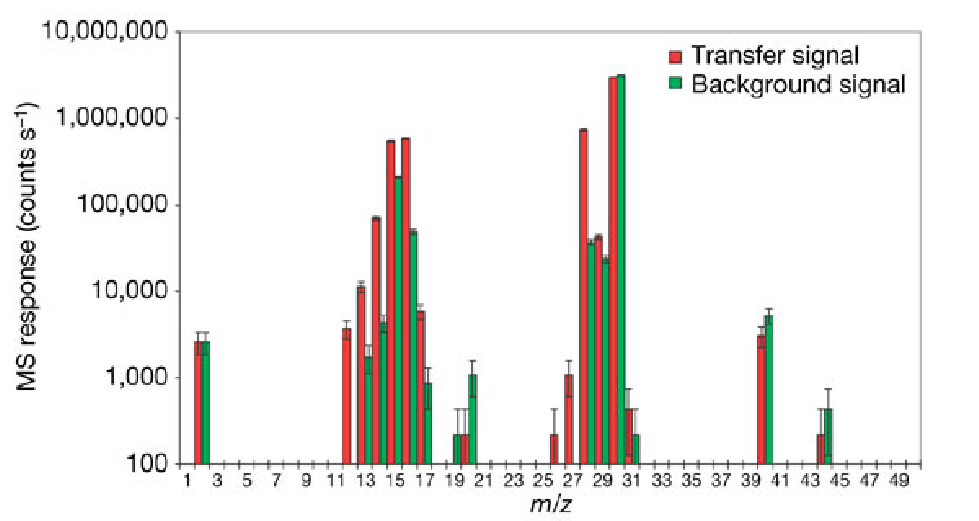




T_{surf} = 93.65 ± 0.25 K and P_{surf} = 1.467 ± 0.001 bar

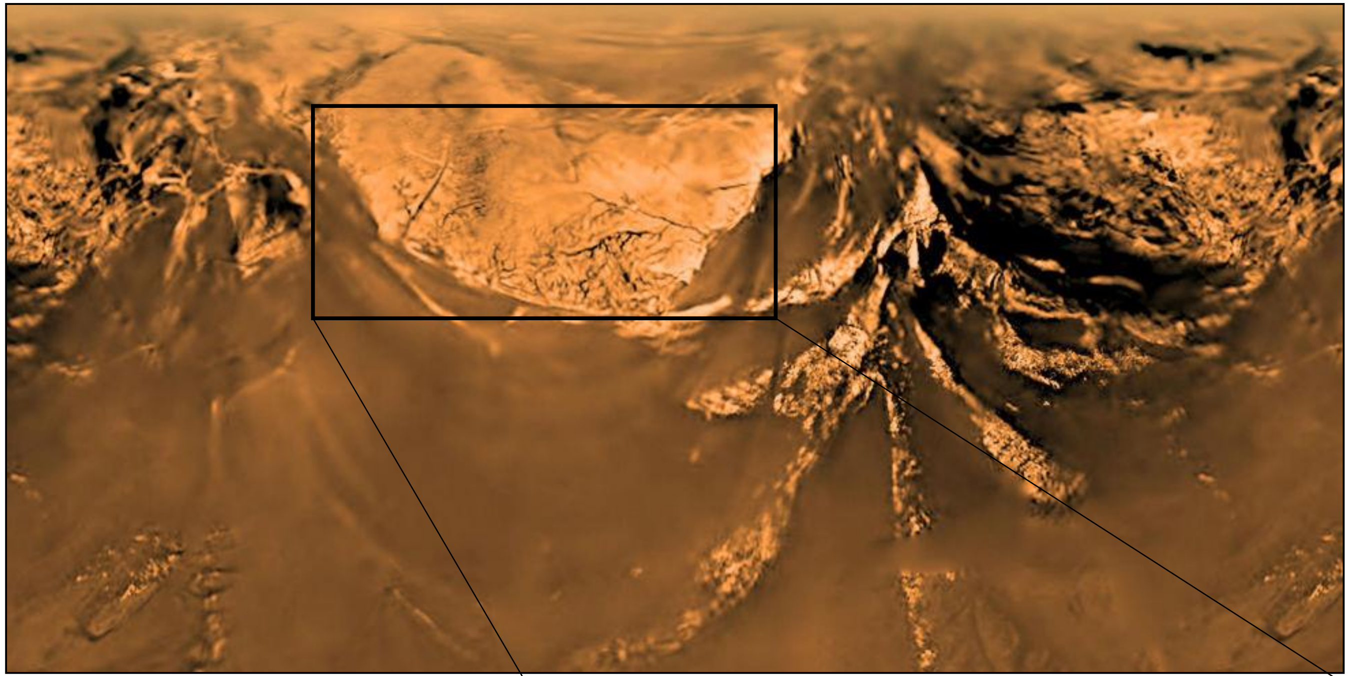
98 % N_2 and 1.6 % CH_4 (5% close to surface)



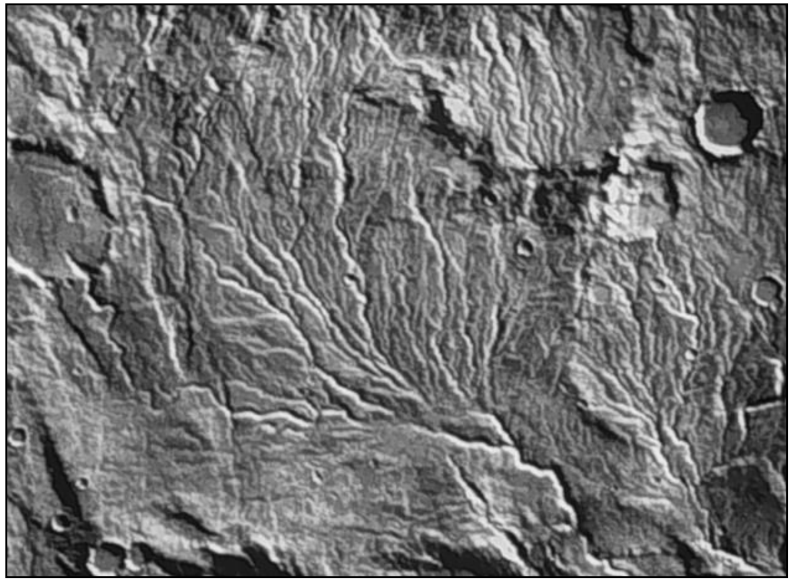


Aerosols’ pyrolysis

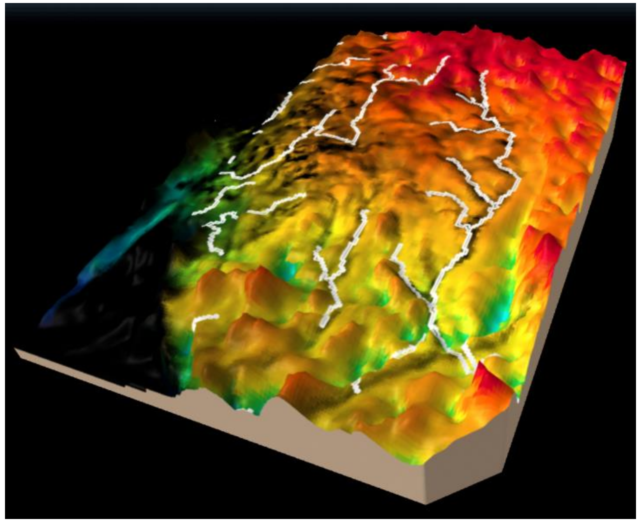
Altitude: 15 km

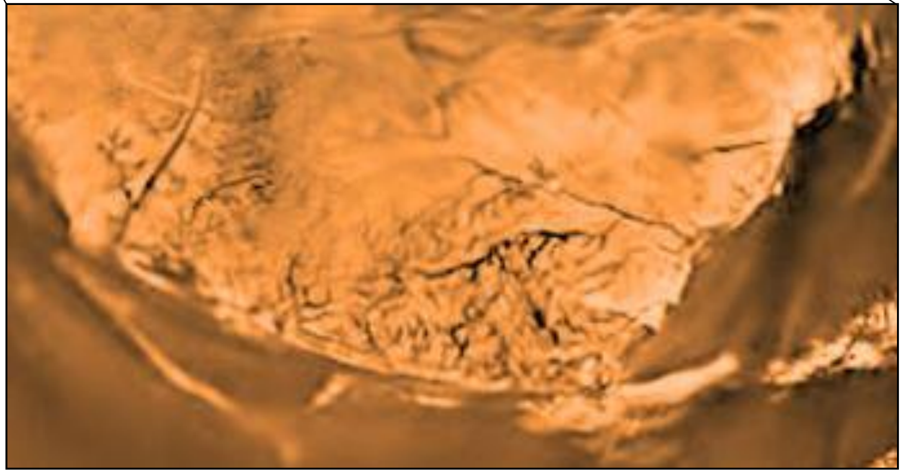


Credits : ESA/NASA/JPL/University of Arizona

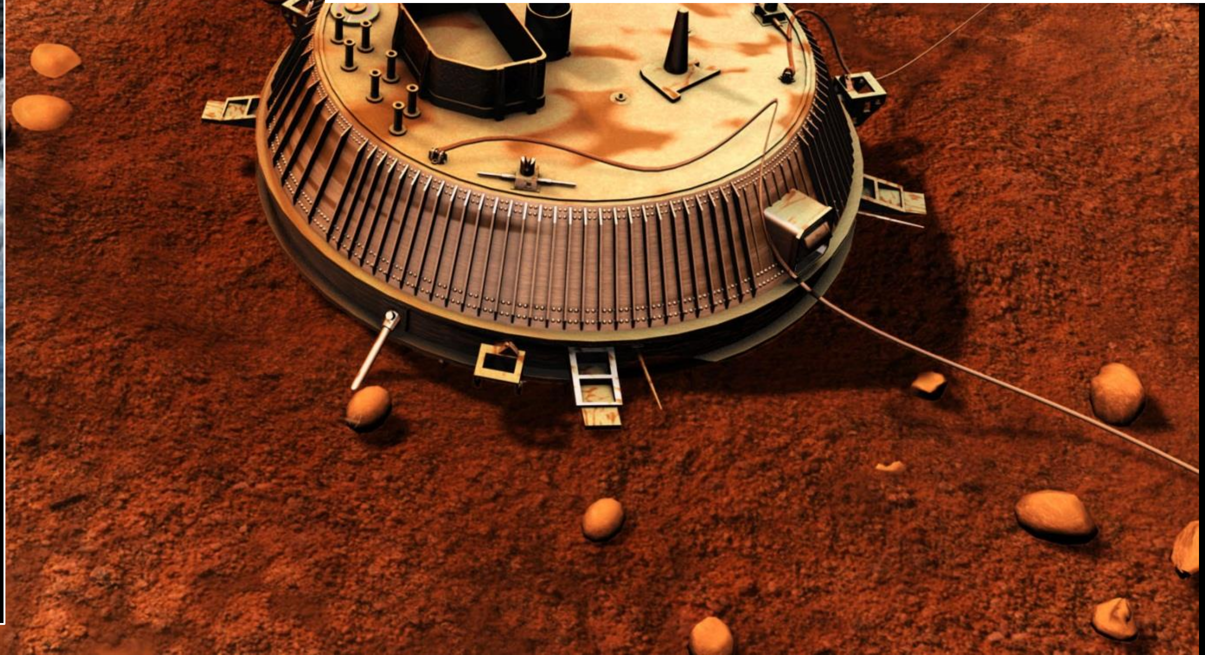


Dry river network on Mars

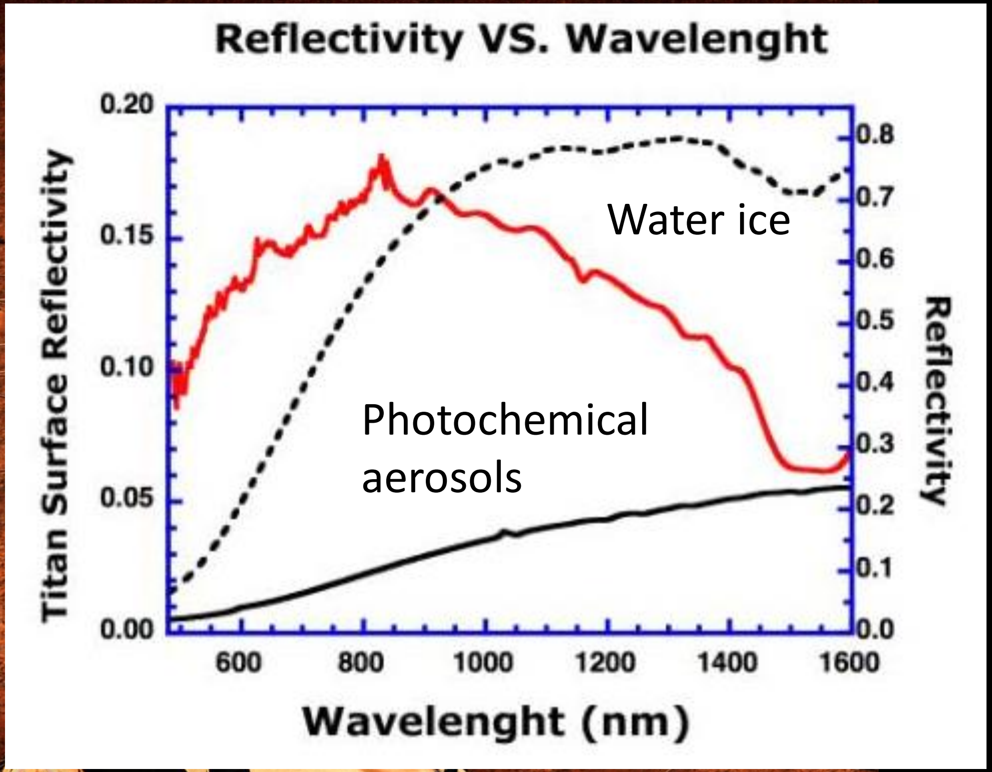




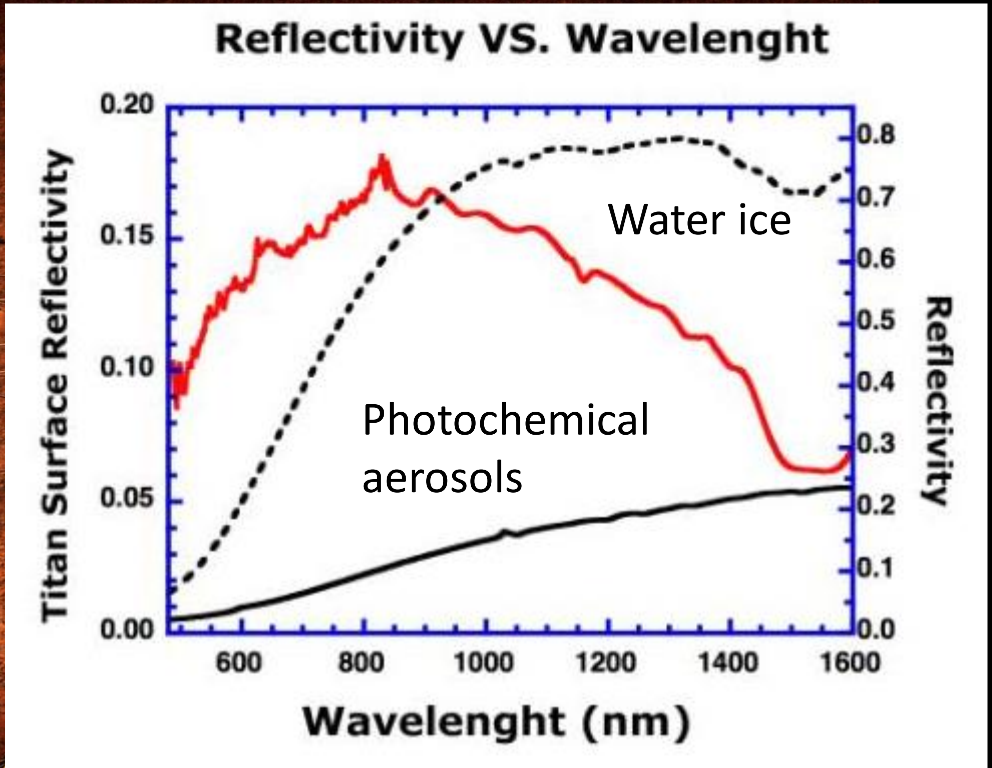
River network, Yemen, Earth

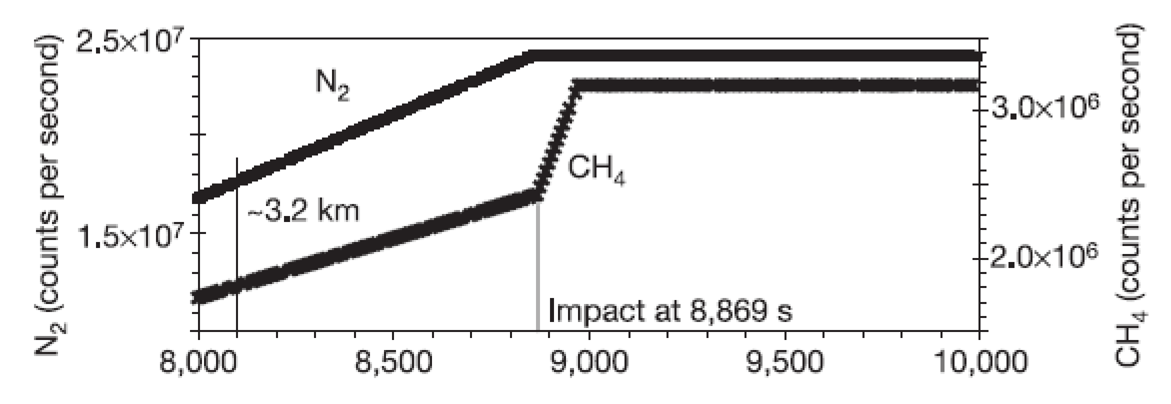


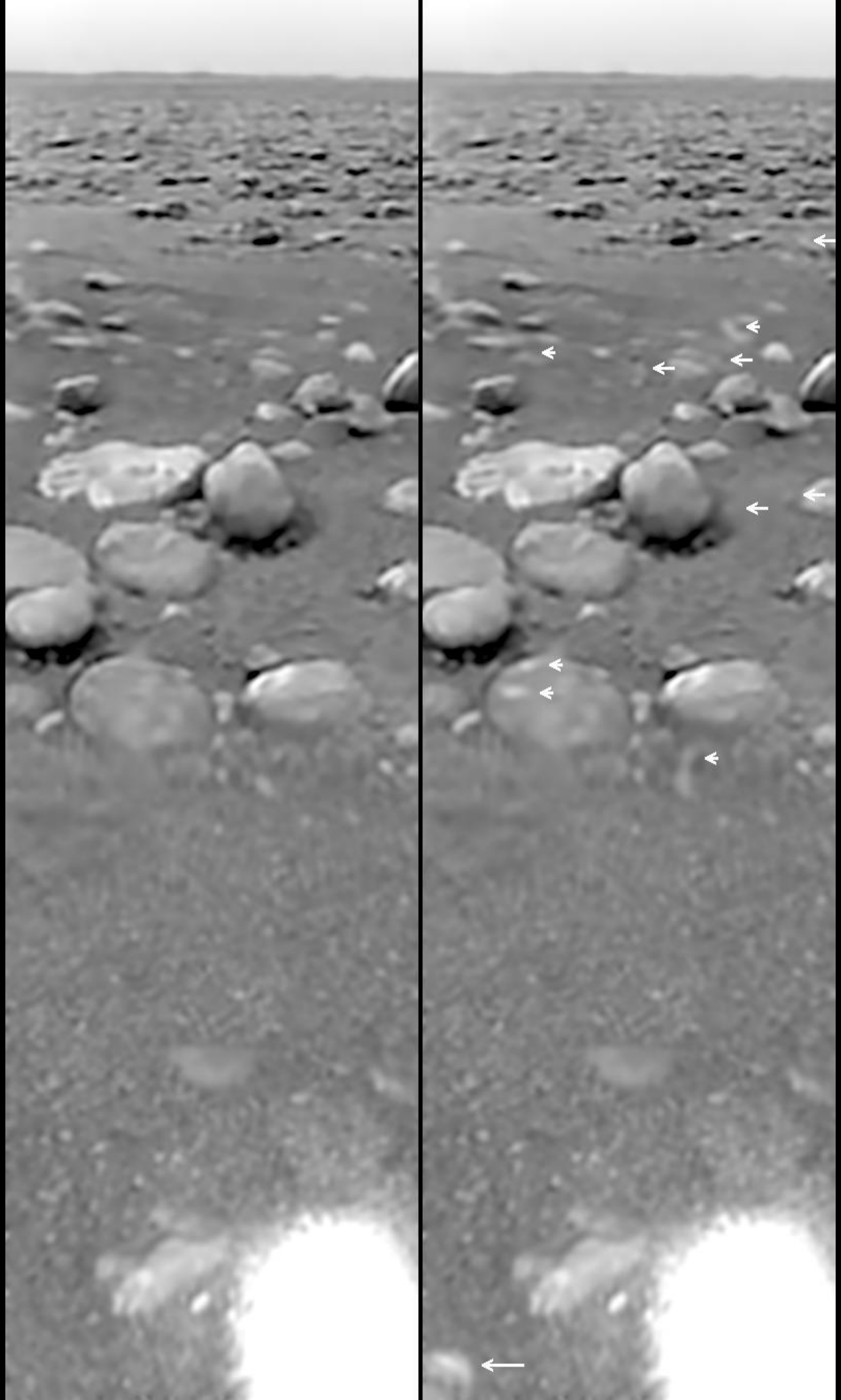

Titan
Moon at Similar Scale
Earth’s river bed


Reflectivity VS. Wavelenght
Titan Surface Reflectivity
0.20
0.15
0.10
0.05
0.00
Reflectivity
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
600
800
1000
1200
1400
1600
Wavelenght (nm)
Water ice
Photochemical aerosols

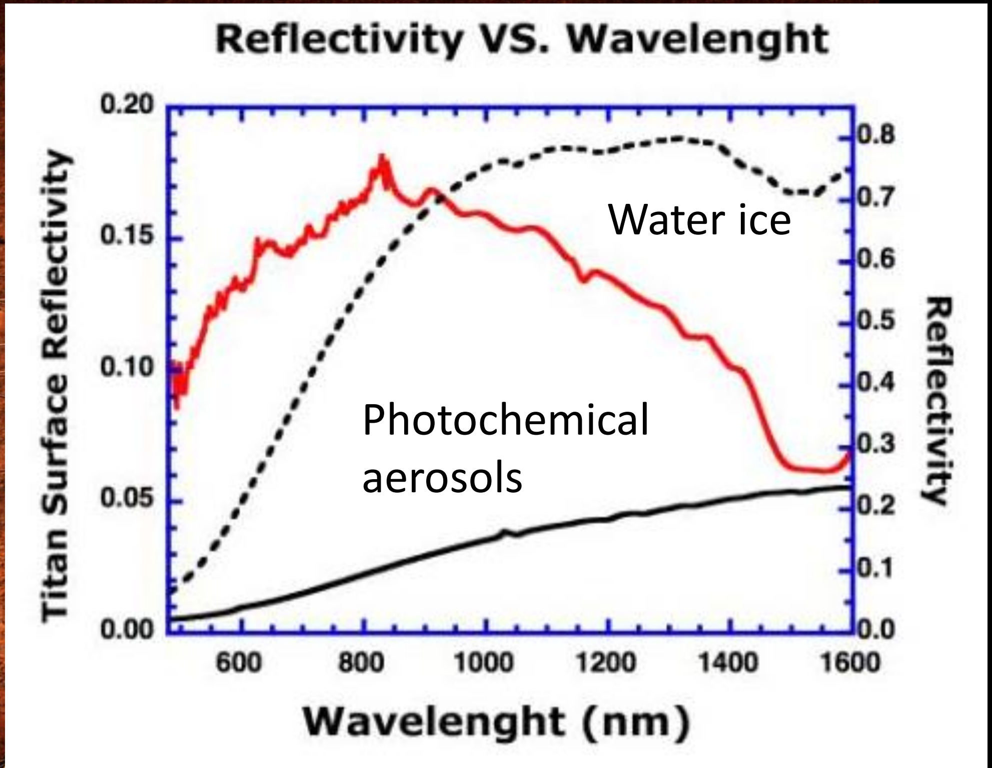

Titan
Moon at Similar Scale
Earth's river bed

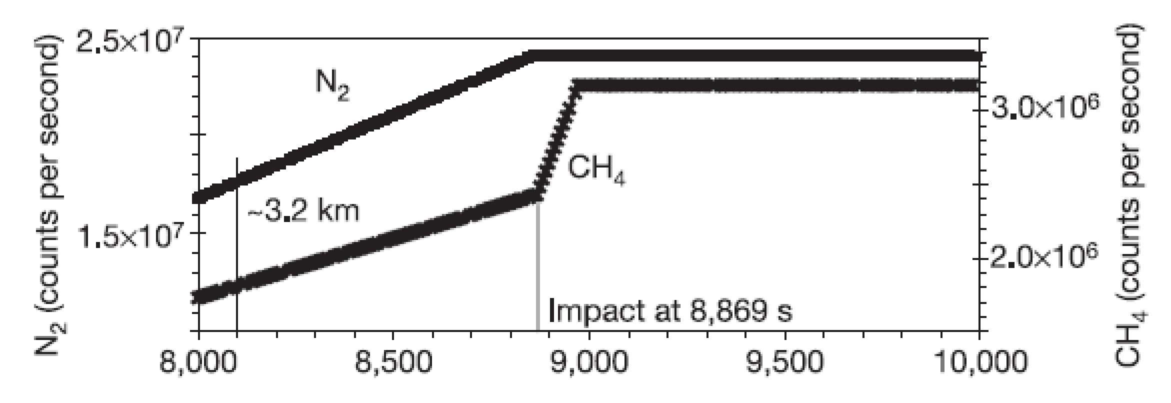

Reflectivity VS. Wavelenght
Titan Surface Reflectivity
0.20
0.15
0.10
0.05
0.00
600
800
1000
1200
1400
1600
Wavelenght (nm)
Reflectivity
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Water ice
Photochemical aerosols


N2 (counts per second)
2.5×10^7
1.5×10^7
N2
CH4
~3.2 km
Impact at 8,869 s
8,000
8,500
9,000
9,500
10,000
3.0×10^6
2.0×10^6
CH4 (counts per second)



The first ever evidences for extraterrestrial (methane) dew on Titan

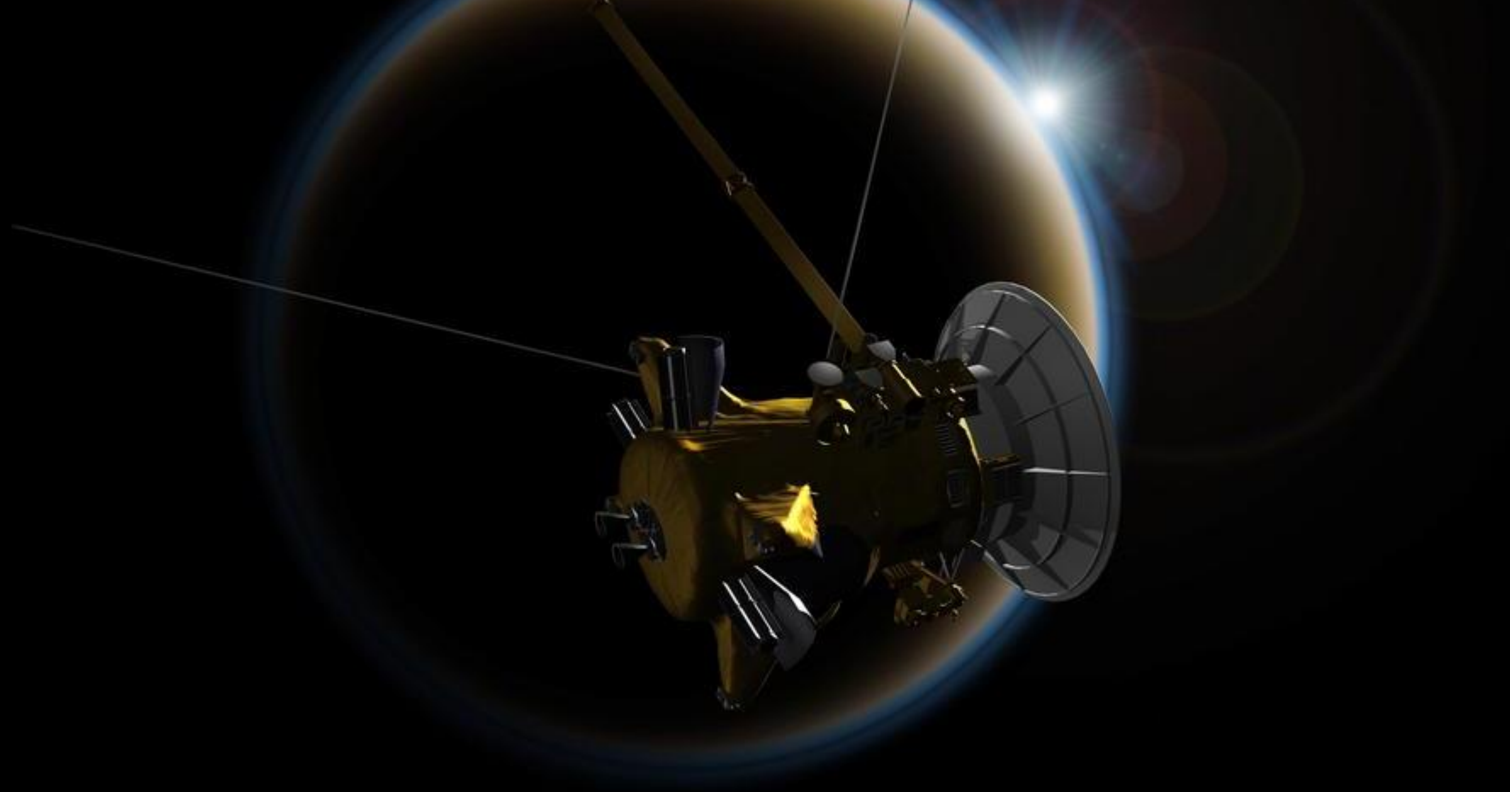




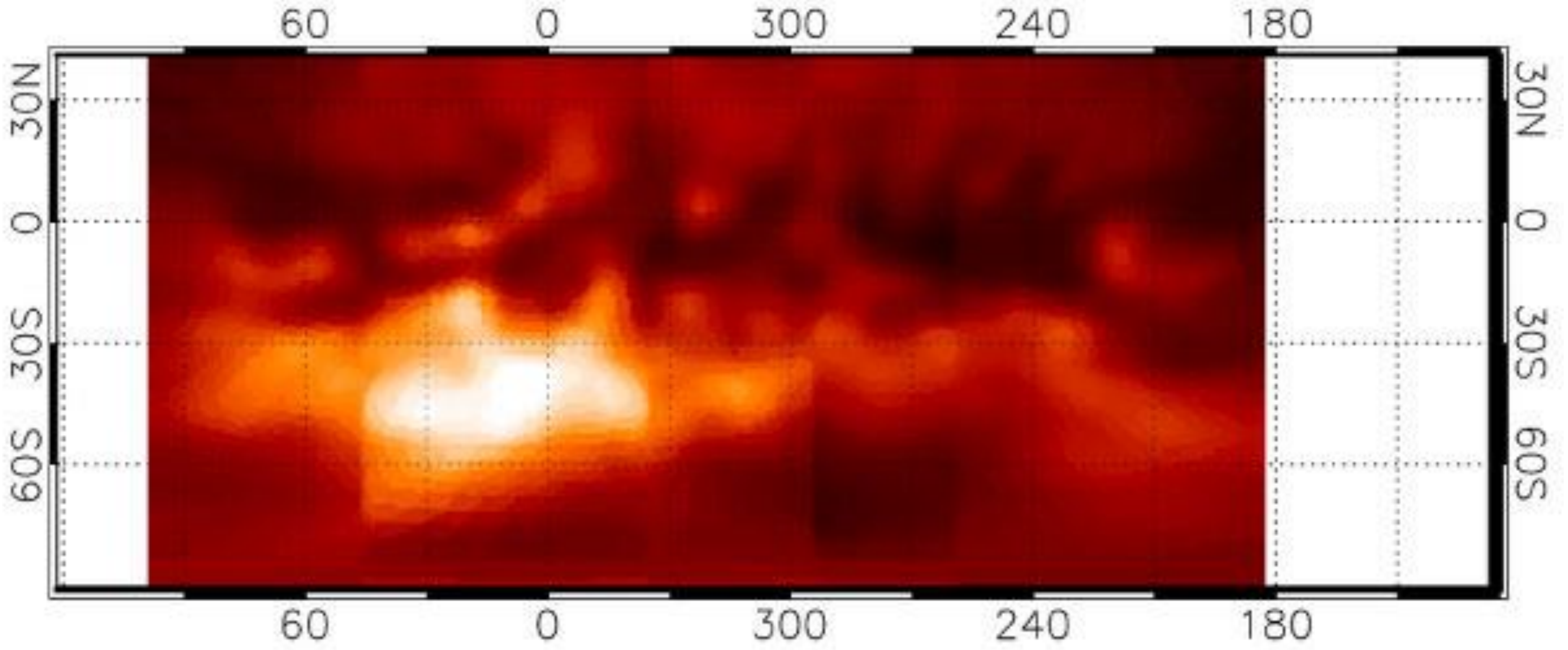
Great diversity of landscapes, atmospheric and climatic processes

But at 1 date and 1 location, only!

13 years of Cassini : a comprehensive mapping of Titan’s surface and atmosphere



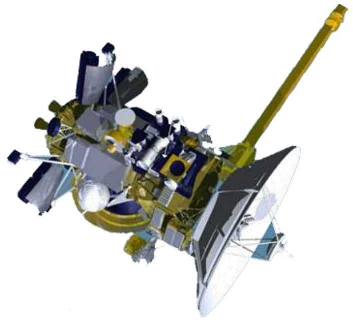
In 2004, from Earth…



Map of Titan's Surface Features at 1.575µm
(VLT YEPUN + NACO/SDI)

ESO PR Photo 11a/04 (14 April 2004)

Piercing Titan’s hazy veil with Cassini

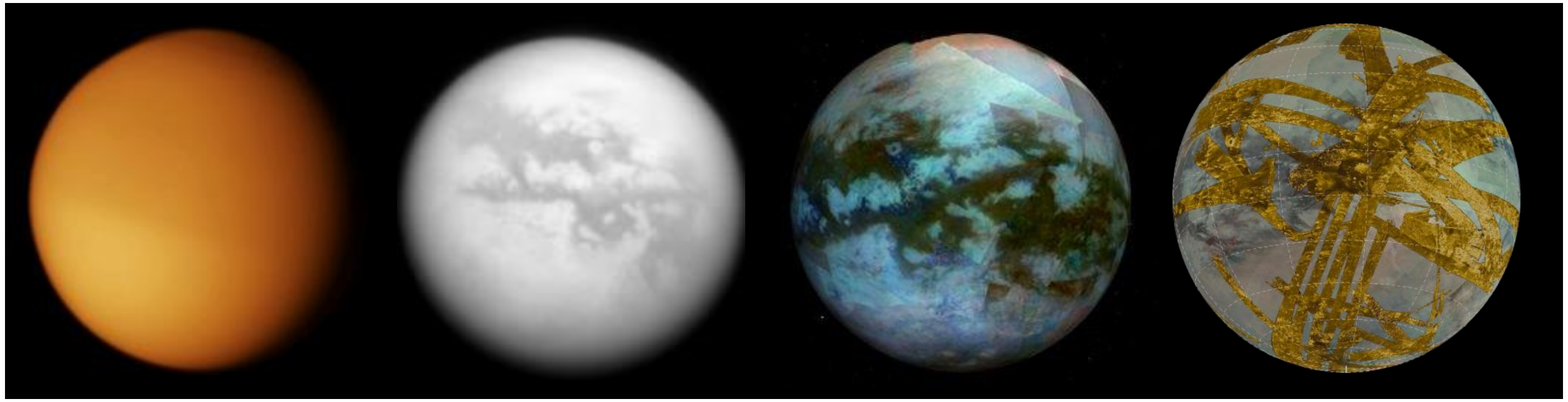


On board Cassini, 3 instruments allow to observe Titan’s surface:

- **ISS** and **VIMS**, through 7 « atmospheric windows » in the near-infrared (NIR)
- **RADAR** in the micro-waves

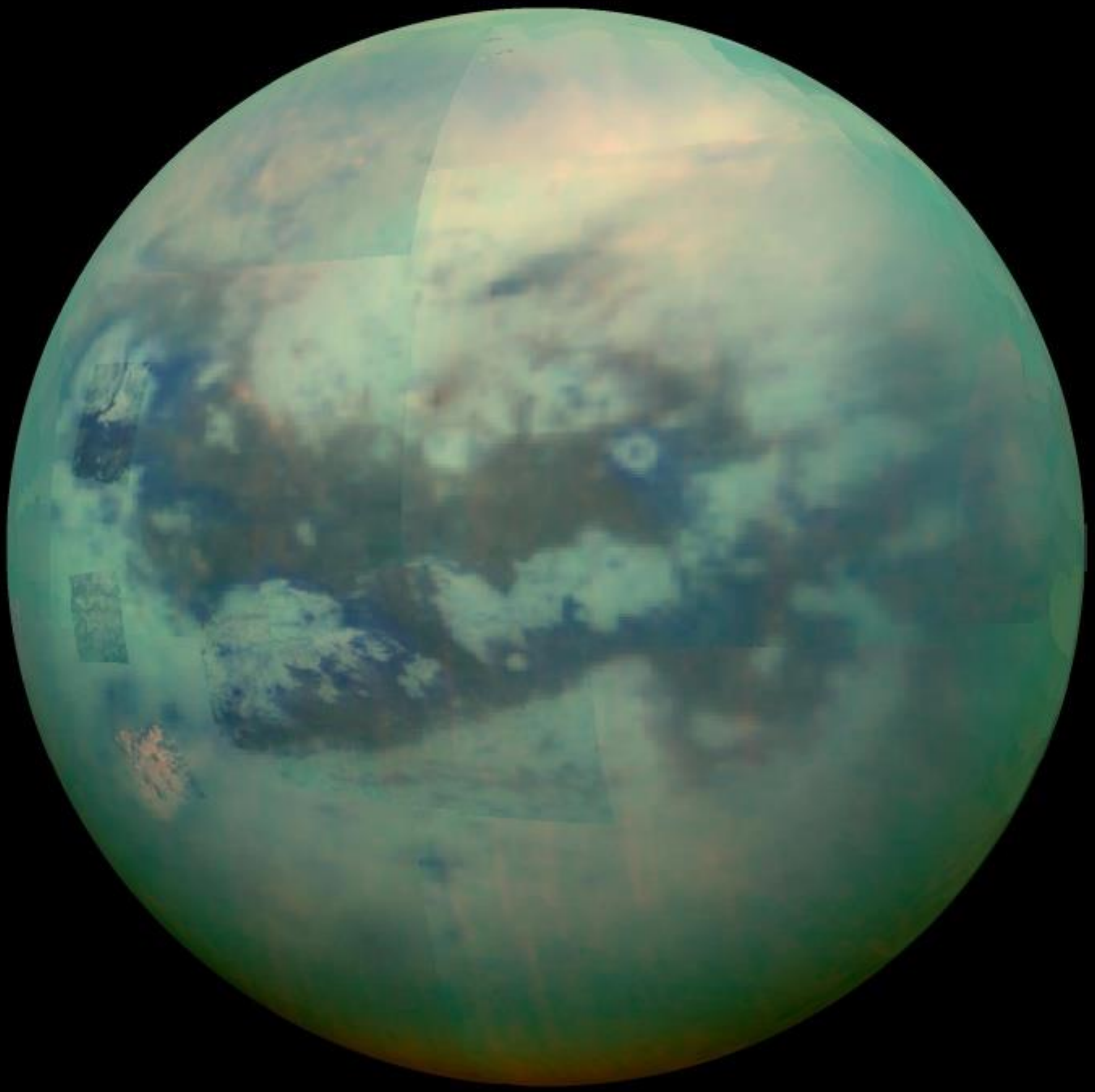
VOYAGER 1

CASSINI

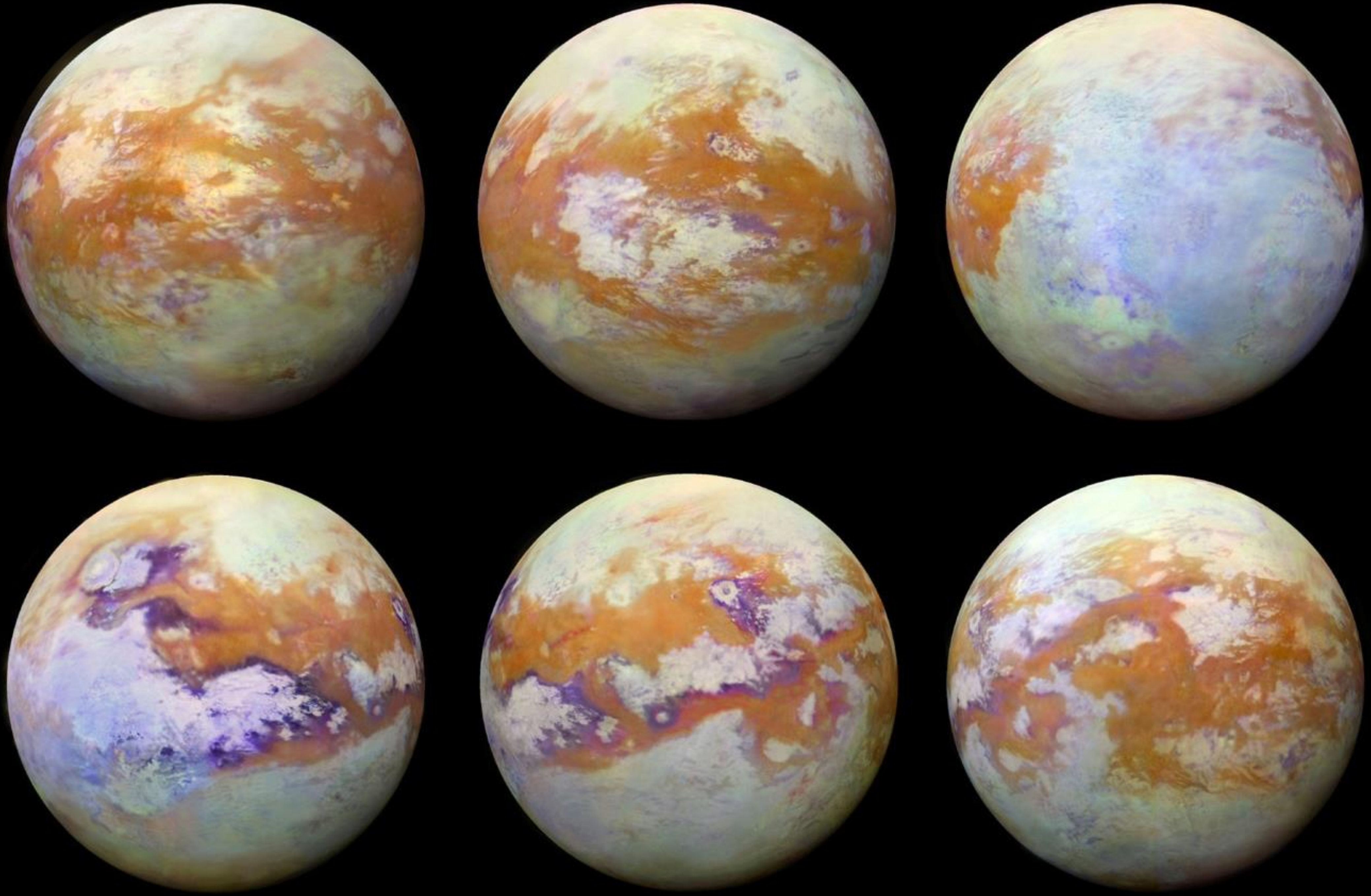


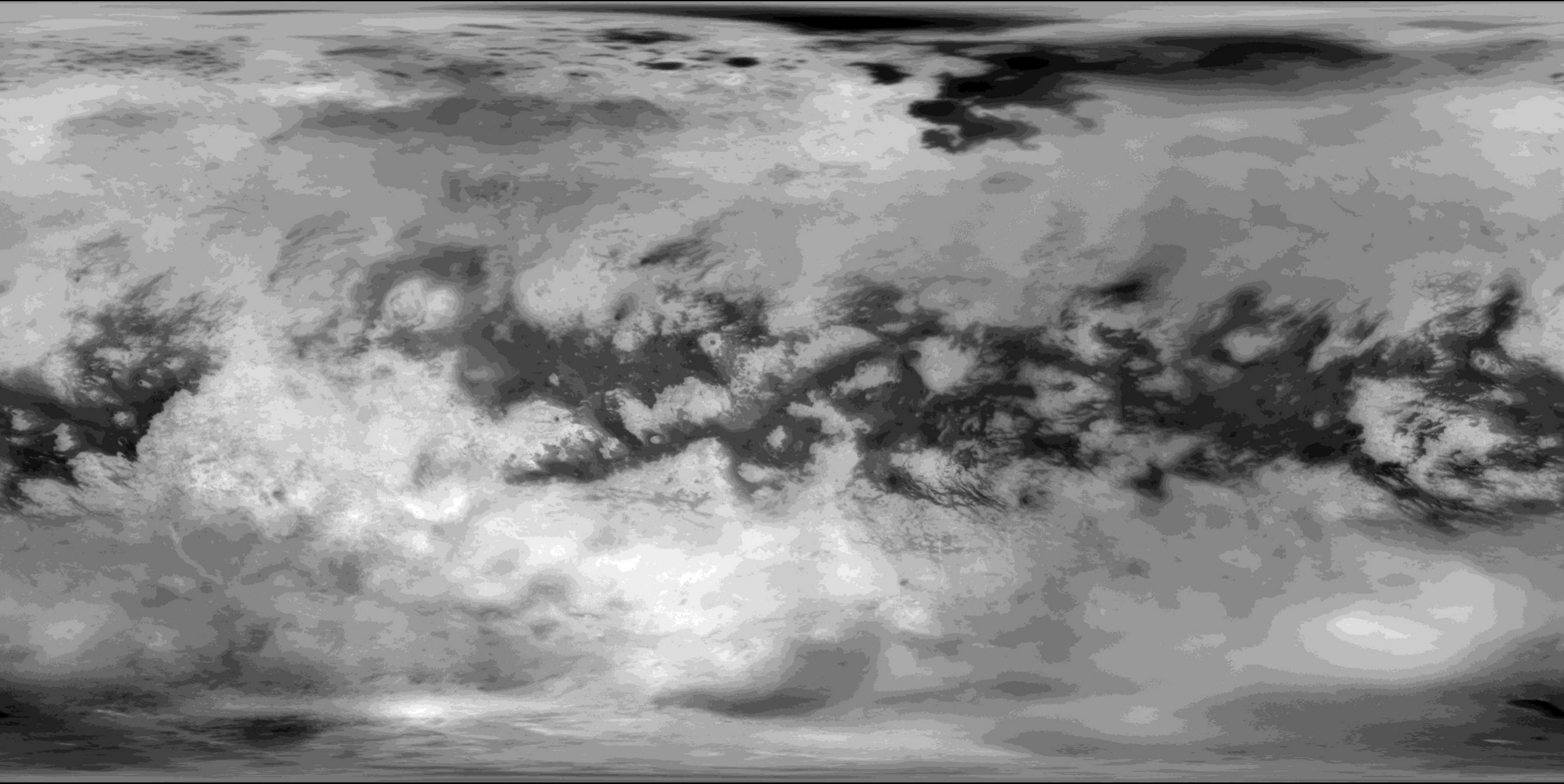
Optical domain	**ISS** NIR (0.939 µm)	**VIMS** NIR (0.939,1.08,1.59,2.03,2.7-2.8,5.0 µm)	**RADAR** Micro-waves (2 cm)

Increasing wavelength

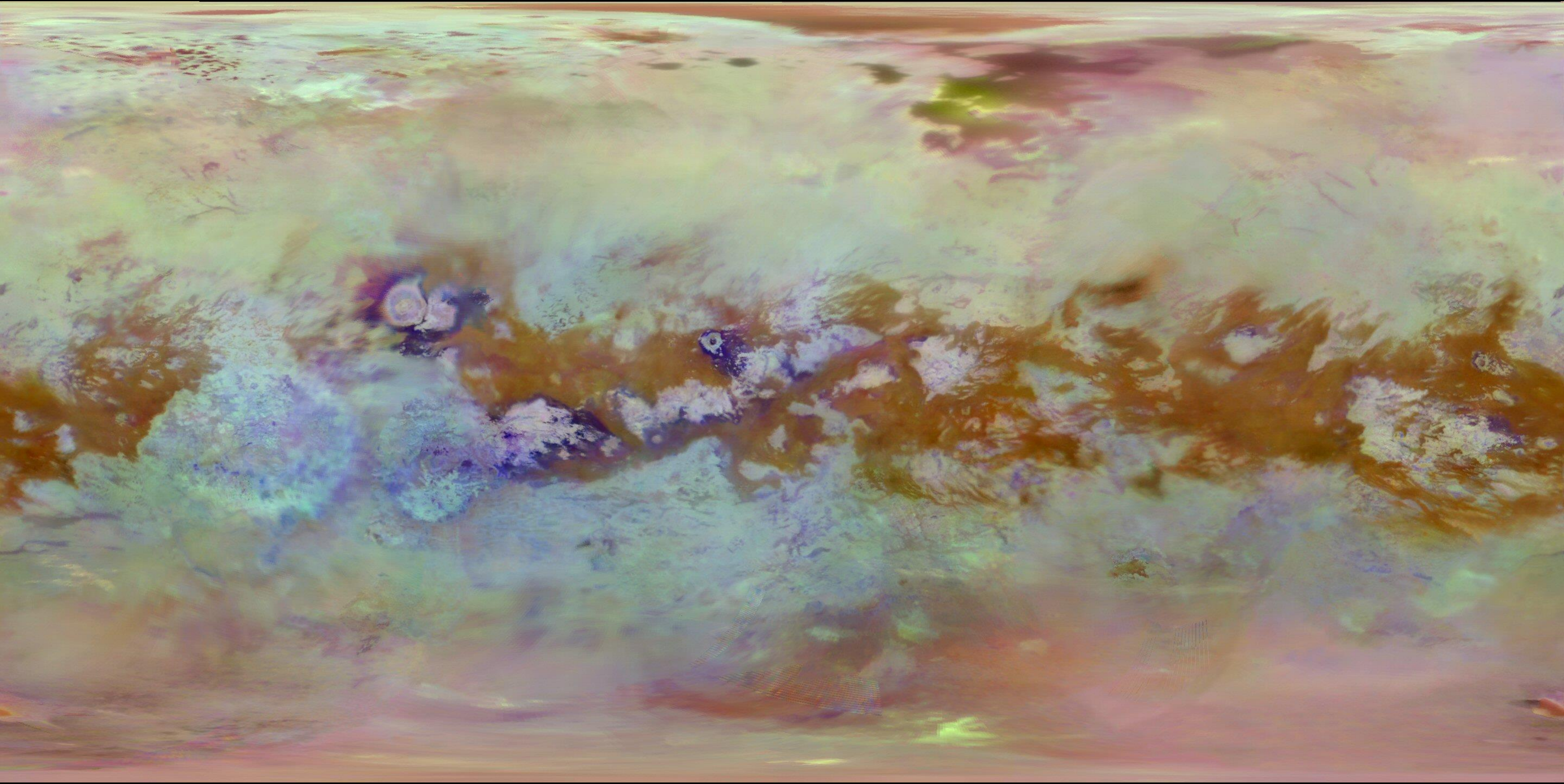


VIMS spectral-imager: Global mapping at ≈15 km resolution

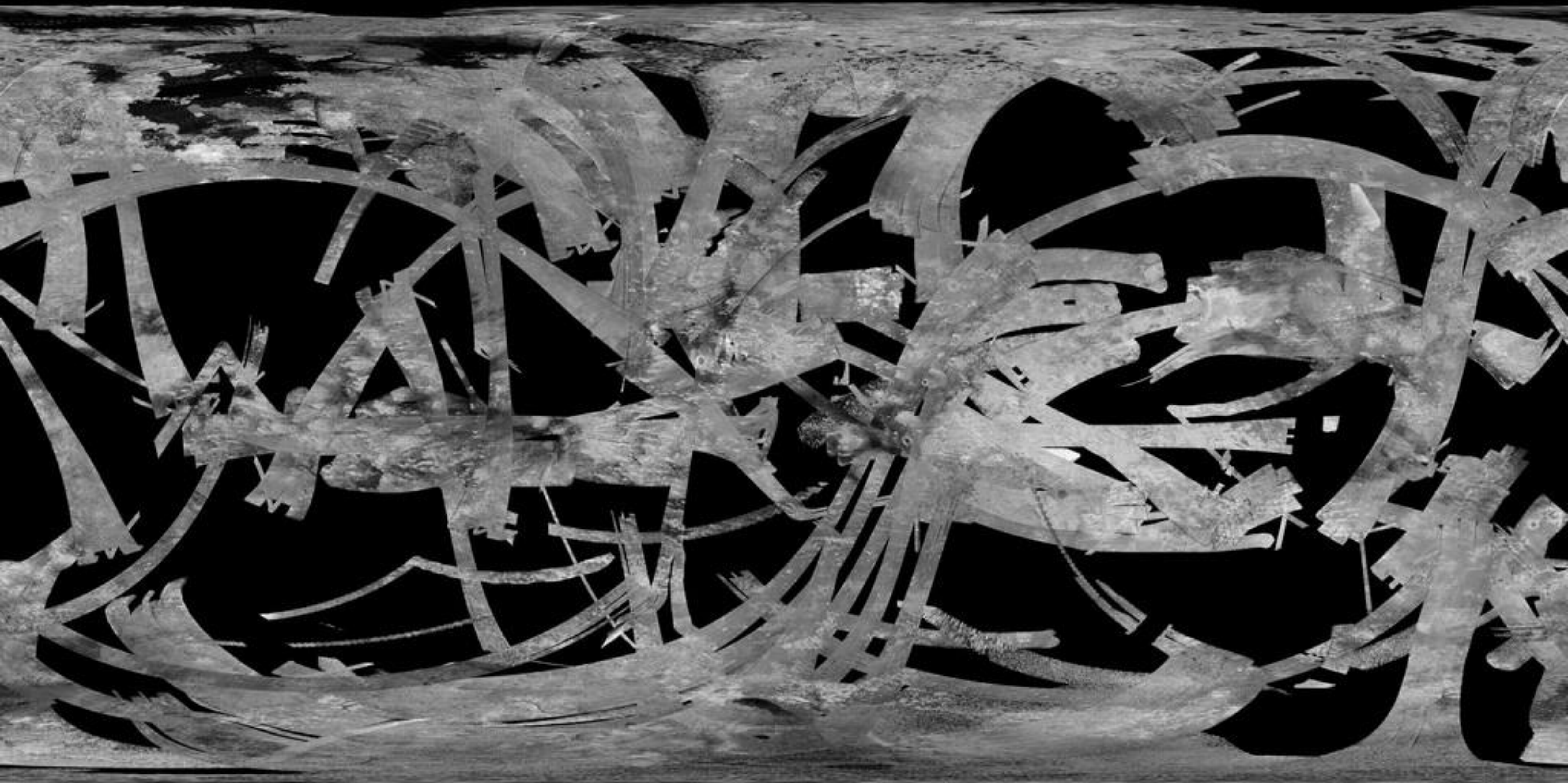




ISS cameras: Global mapping at 4-5 km resolution

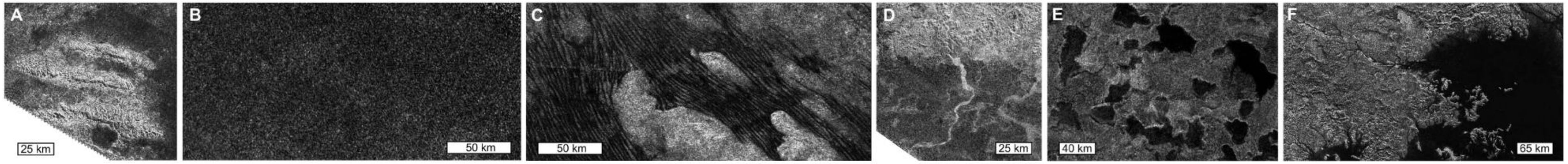


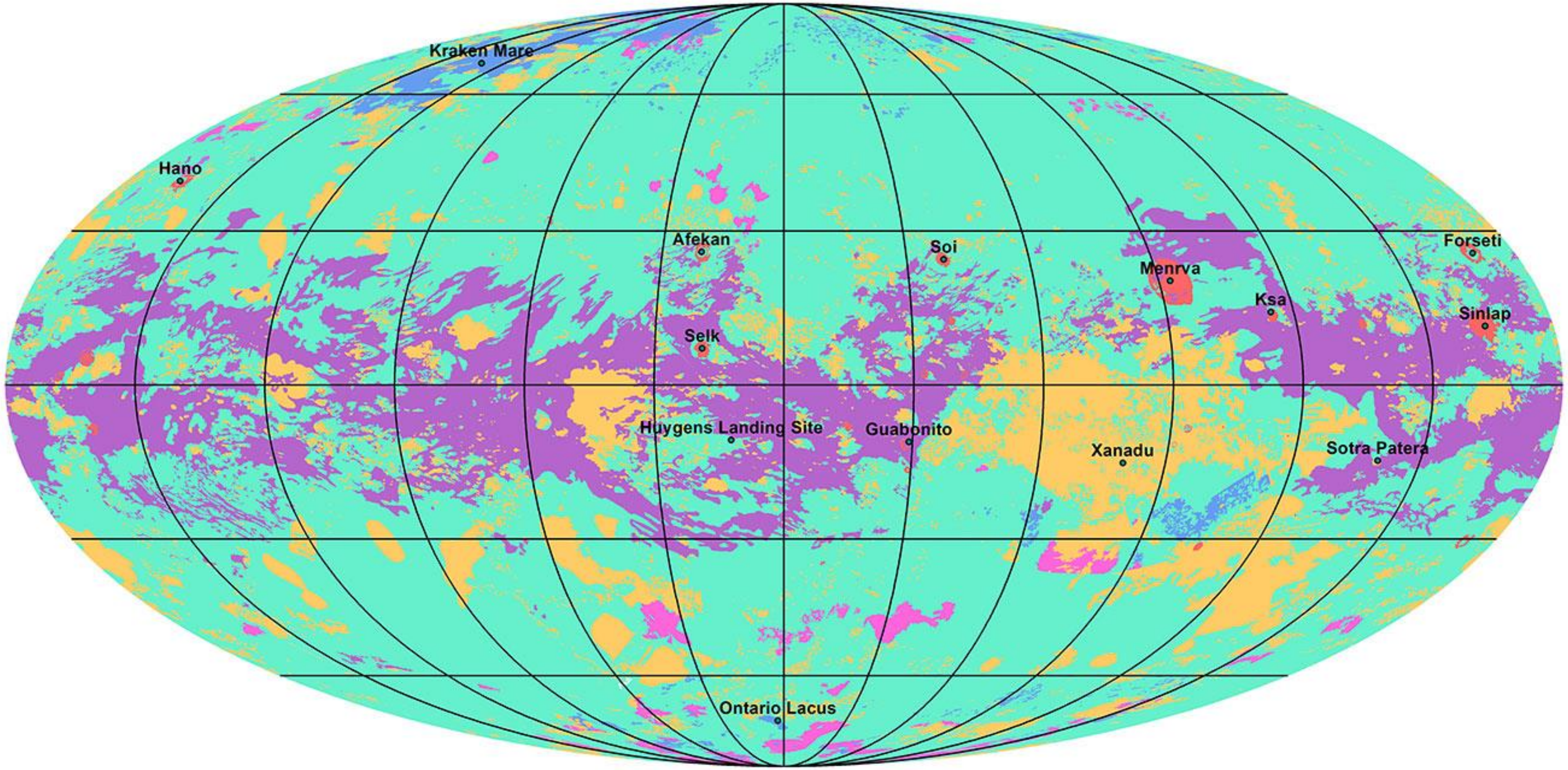
Combining VIMS and ISS best maps



RADAR SAR (imager mode) : Partial mapping (65%) at ≈300 m resolution

From geography to geomorphological map

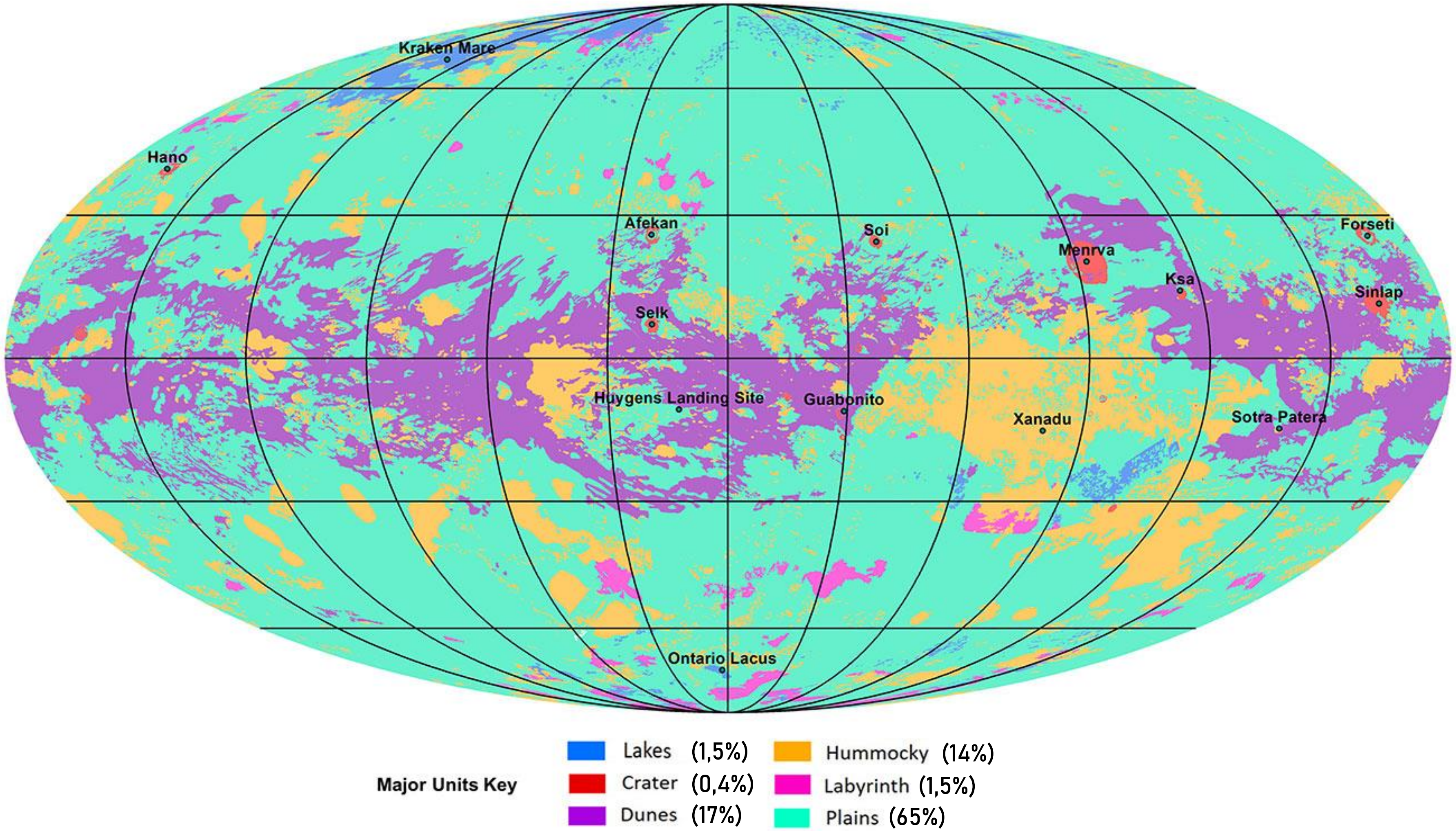


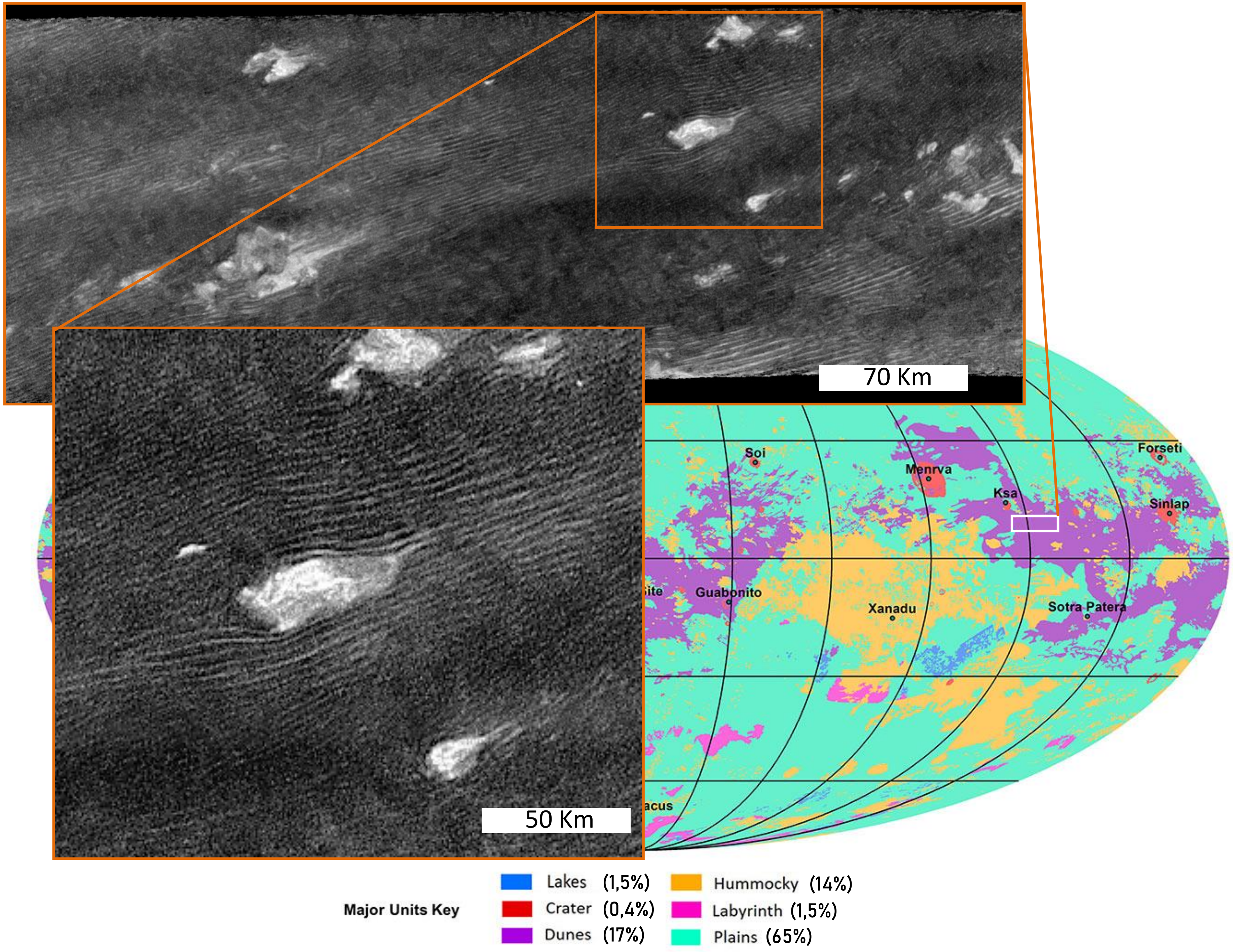


Major Units Key

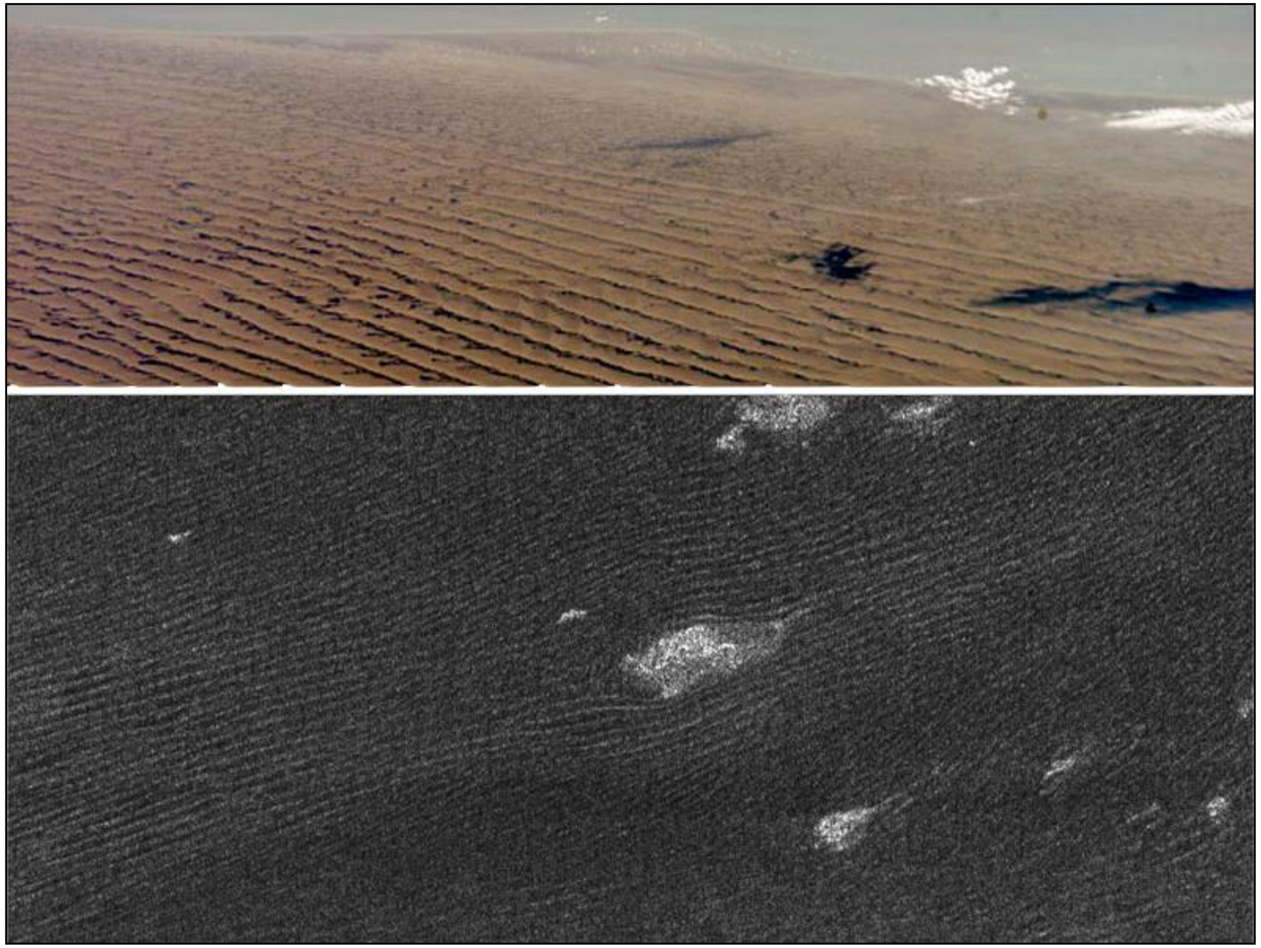
Lakes (1,5%)	Hummocky (14%)
Crater (0,4%)	Labyrinth (1,5%)
Dunes (17%)	Plains (65%)

Equatorial terrains




70 Km
50 Km
Soi
Menrva
Ksa
Forseti
Sinlap
Guabonito
Xanadu
Sotra Patera
Major Units Key
Lakes (1,5%)
Crater (0,4%)
Dunes (17%)
Hummocky (14%)
Labyrinth (1,5%)
Plains (65%)

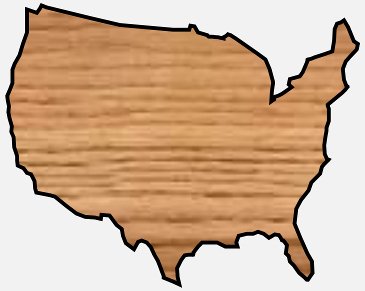
Wind distributing surface materials and shaping the landscape



Linear dunes in Namibia (Earth) and on Titan.

Credits: NASA/JPL-Caltech

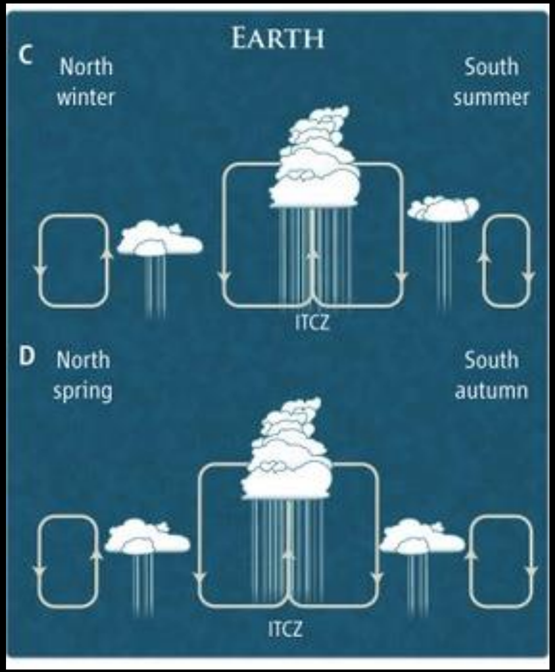
≈ 15% of Titan's surface is covered with linear dunes

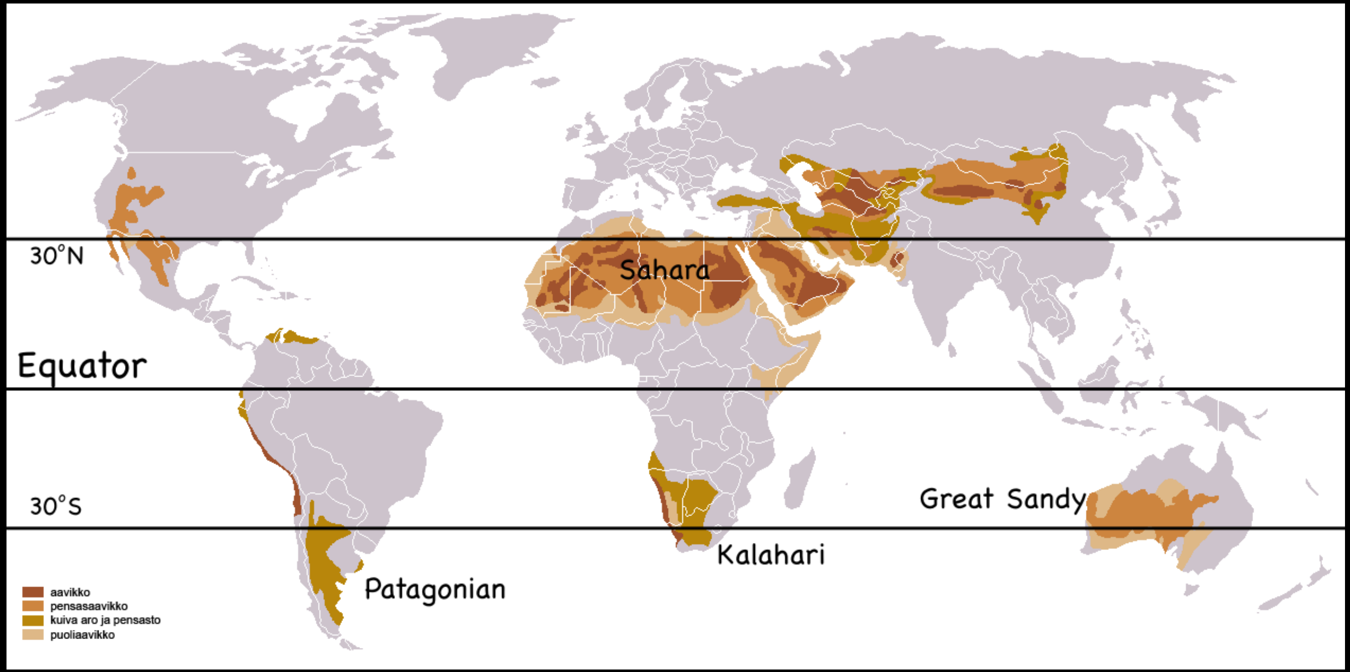


Giant dunes: ≈50-200 m high, ≈1-3 km wide, and 100s of km long.

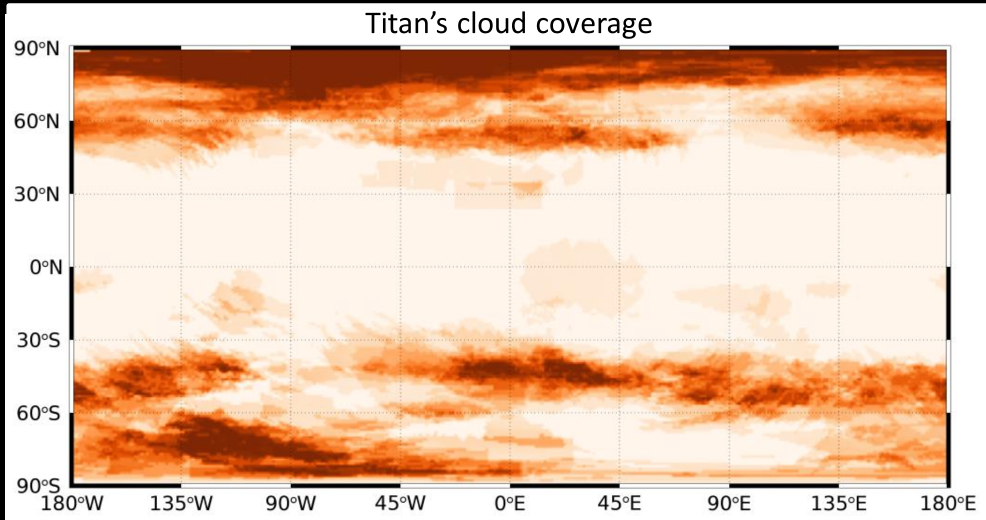
Sand grains are organics (100-200 µm in diameter)

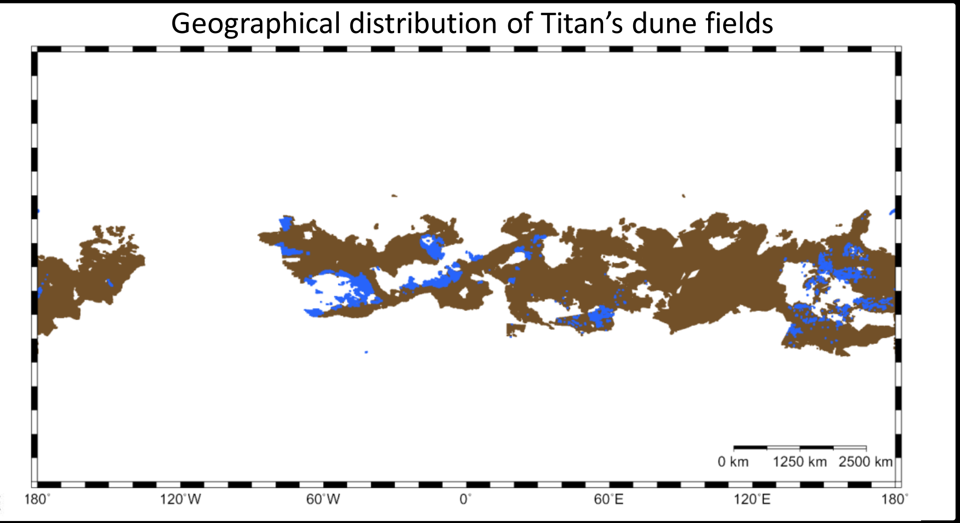
On Earth



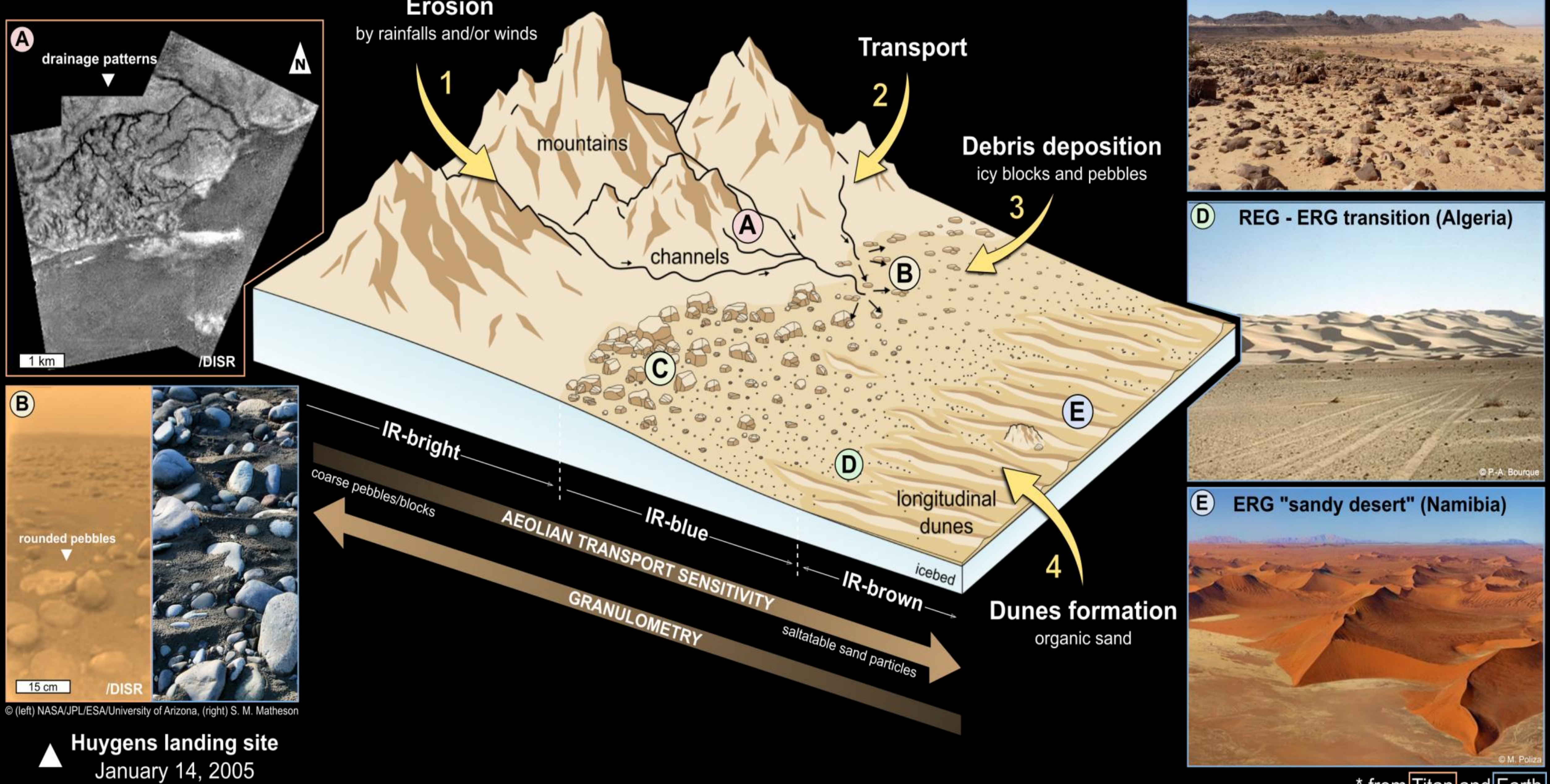


Titan's climate?



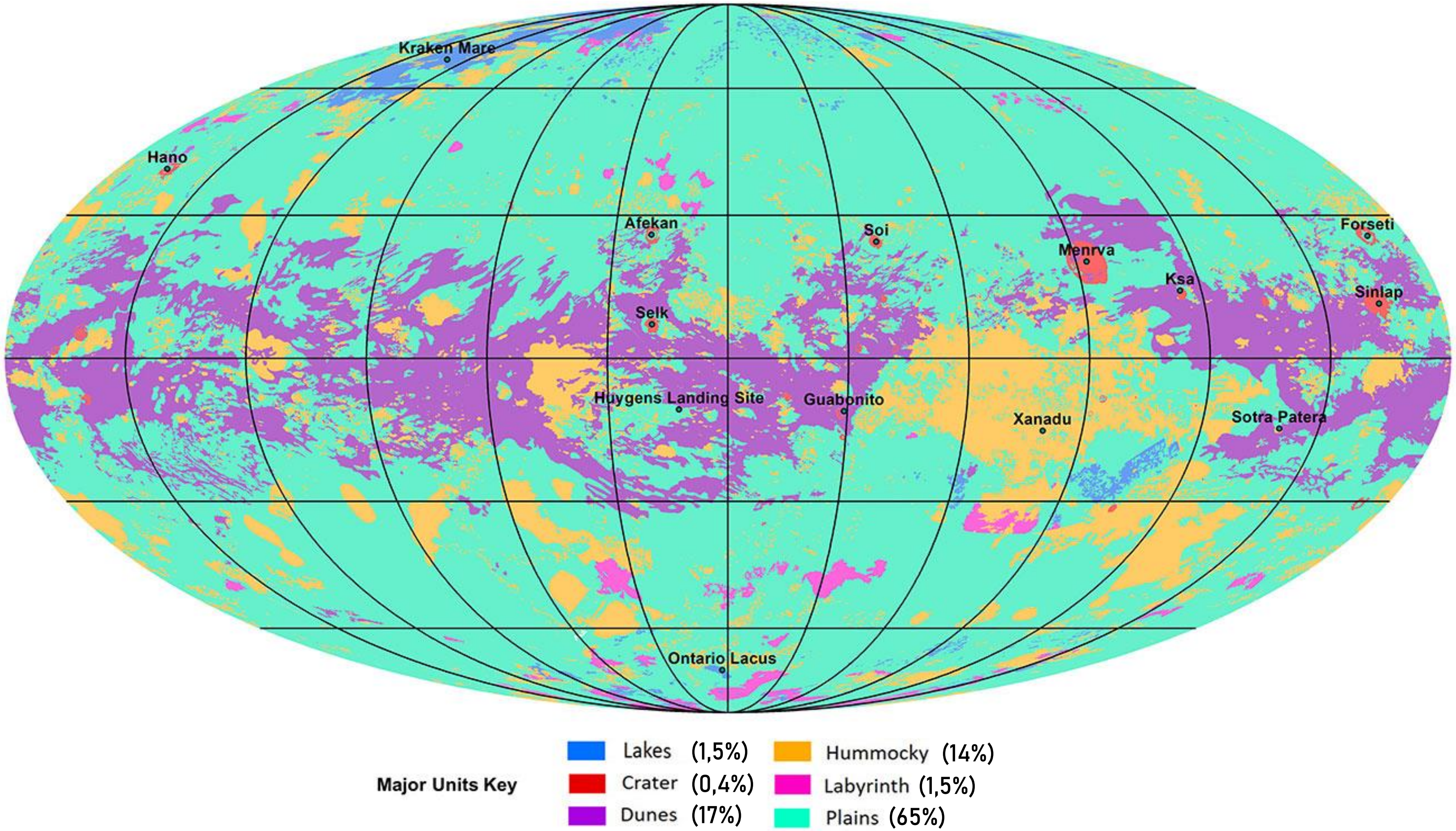


Strong analogy with terrestrial desert?

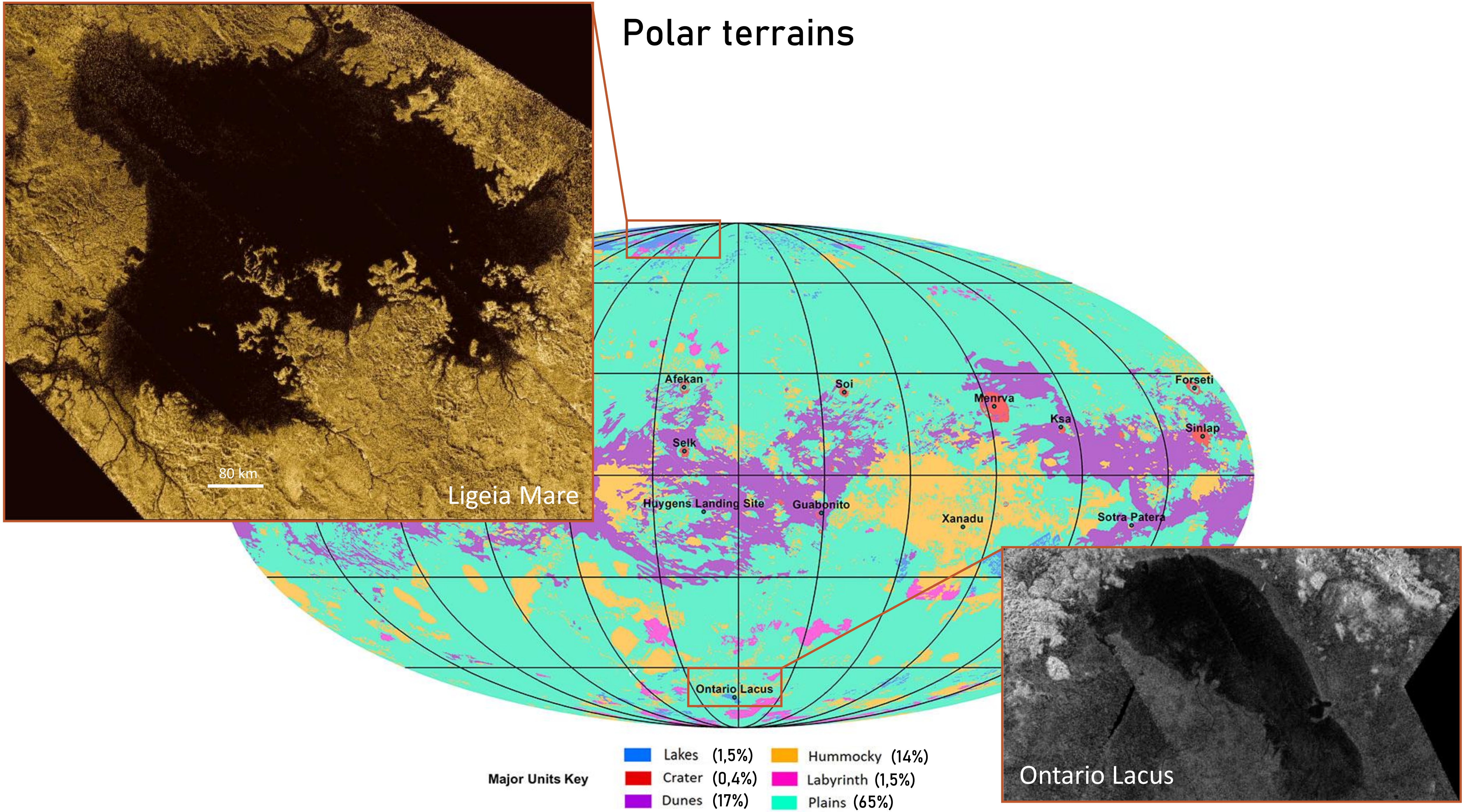


* from Titan and Earth

Polar terrains

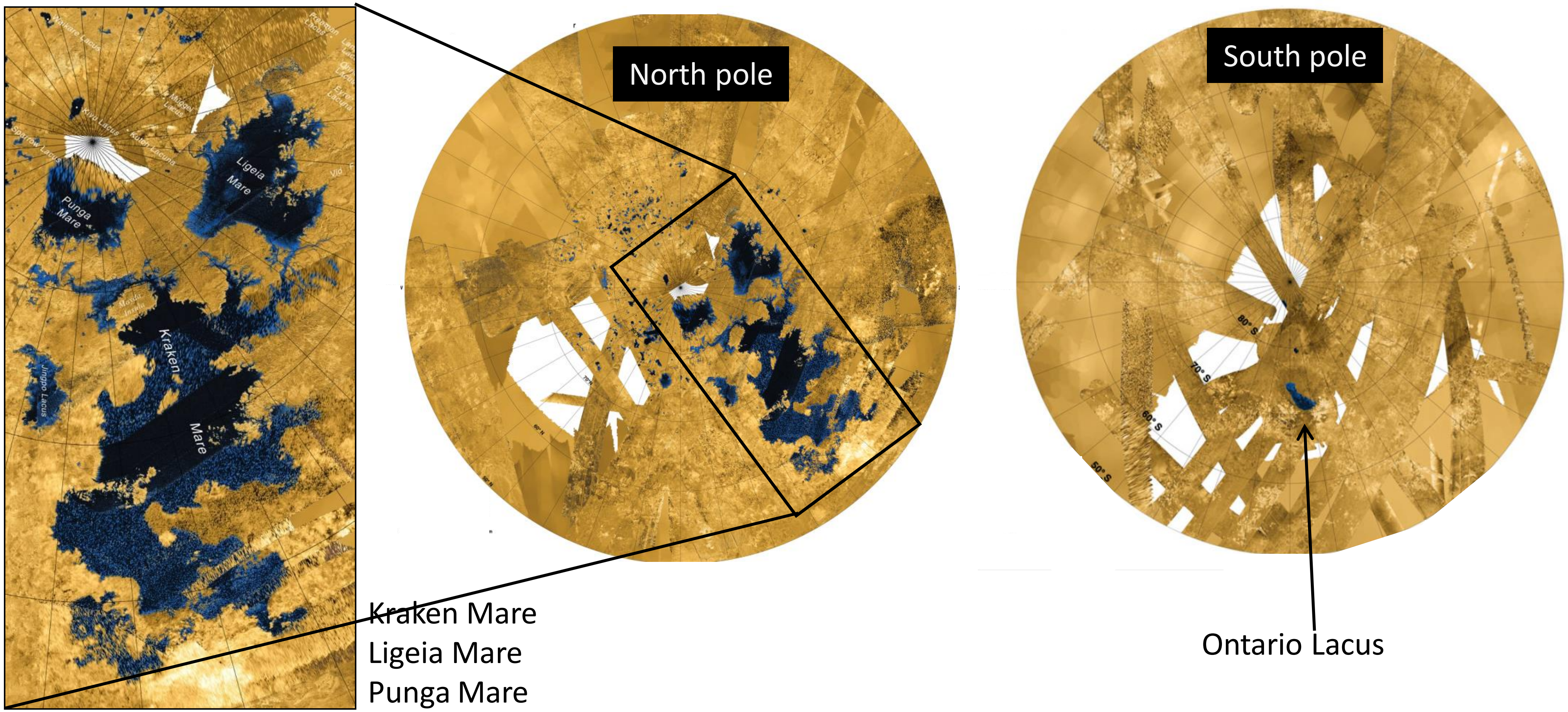


Polar terrains



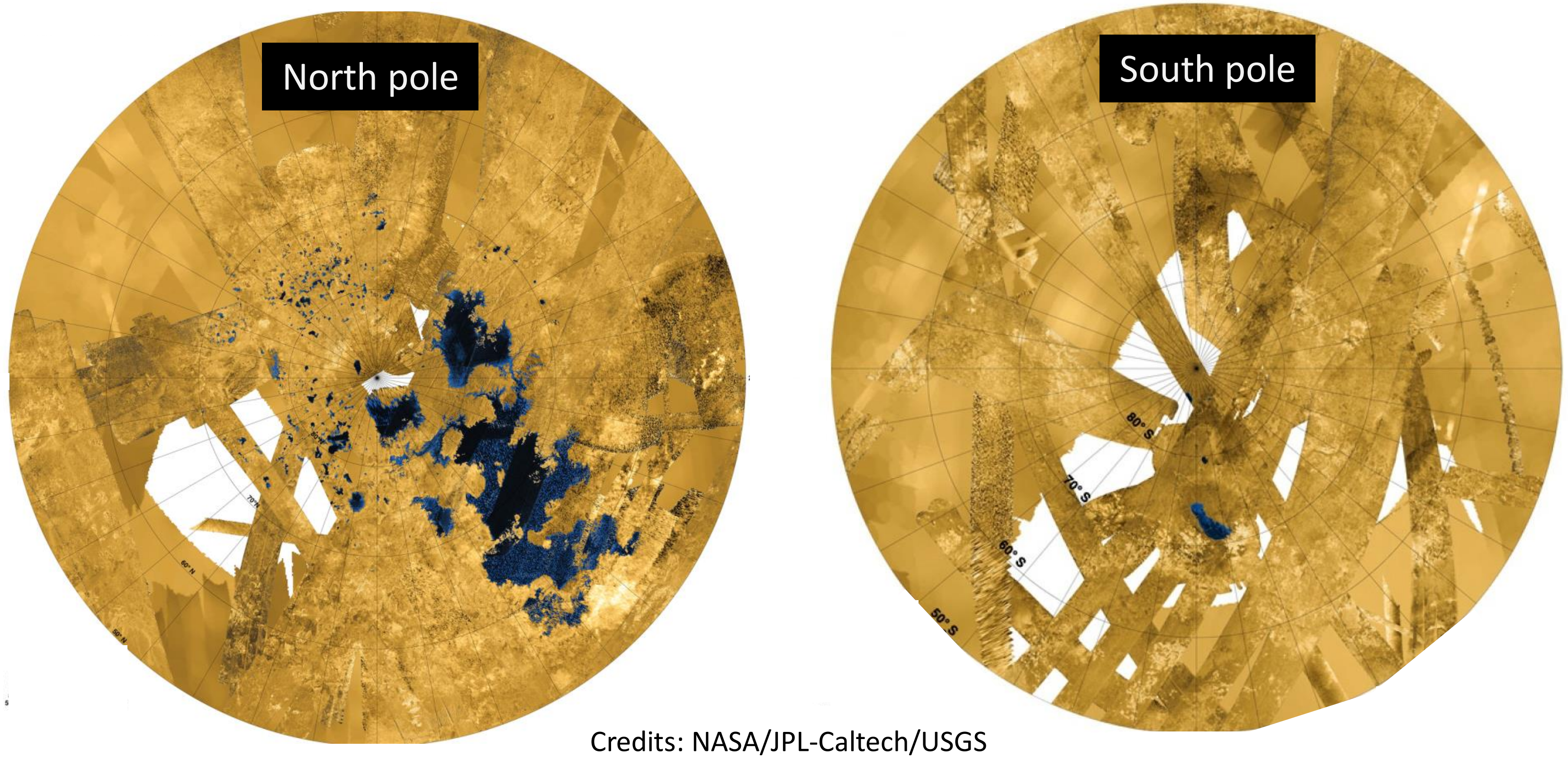
Hydrocarbon lakes and seas!

Titan is the only extraterrestrial body having stable liquids at surface.



Credits: NASA/JPL-Caltech/USGS

North/South dichotomy?

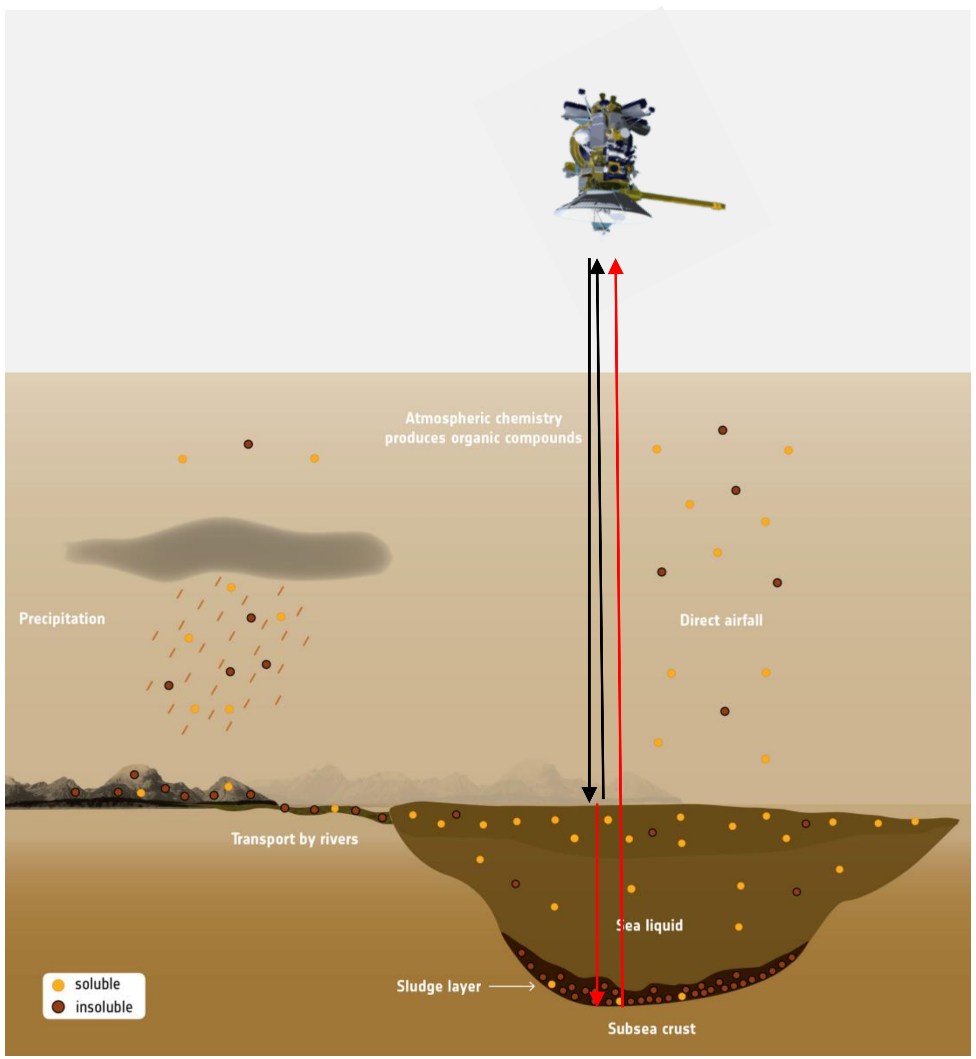


Credits: NASA/JPL-Caltech/USGS

The North/South dichomoty can be explained by shorther, but more intense, southern summer than northern summer.

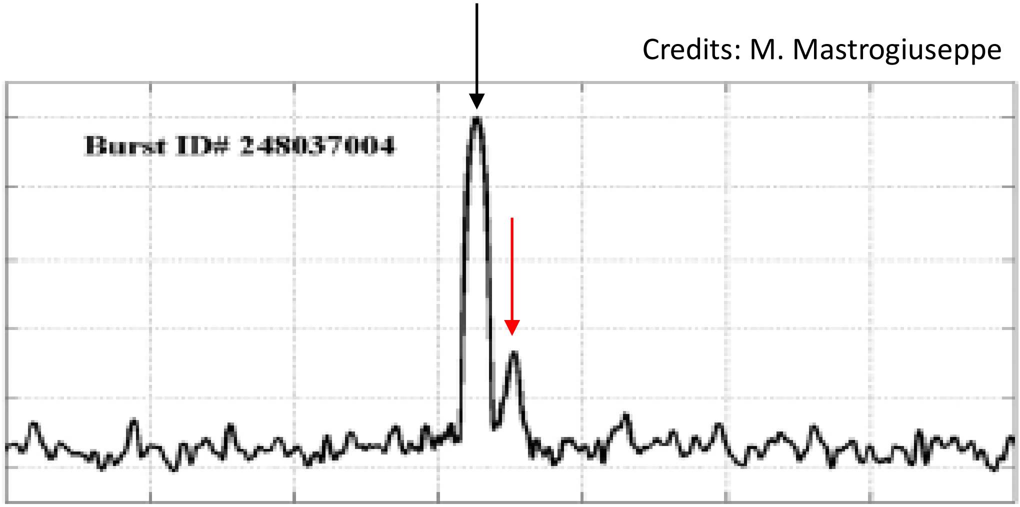
This situation overturns every ≈50 000 years (analoguous to Croll-Milankovitch cycle on Earth).

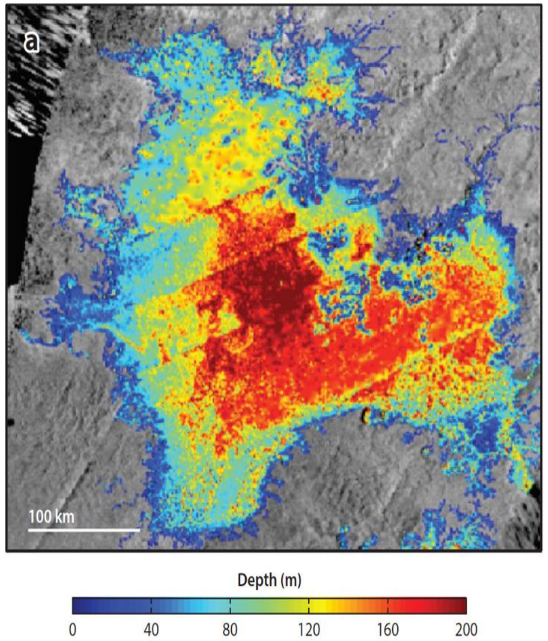

First detection of an extraterrestrial lake's bottom!



Credits: ESA

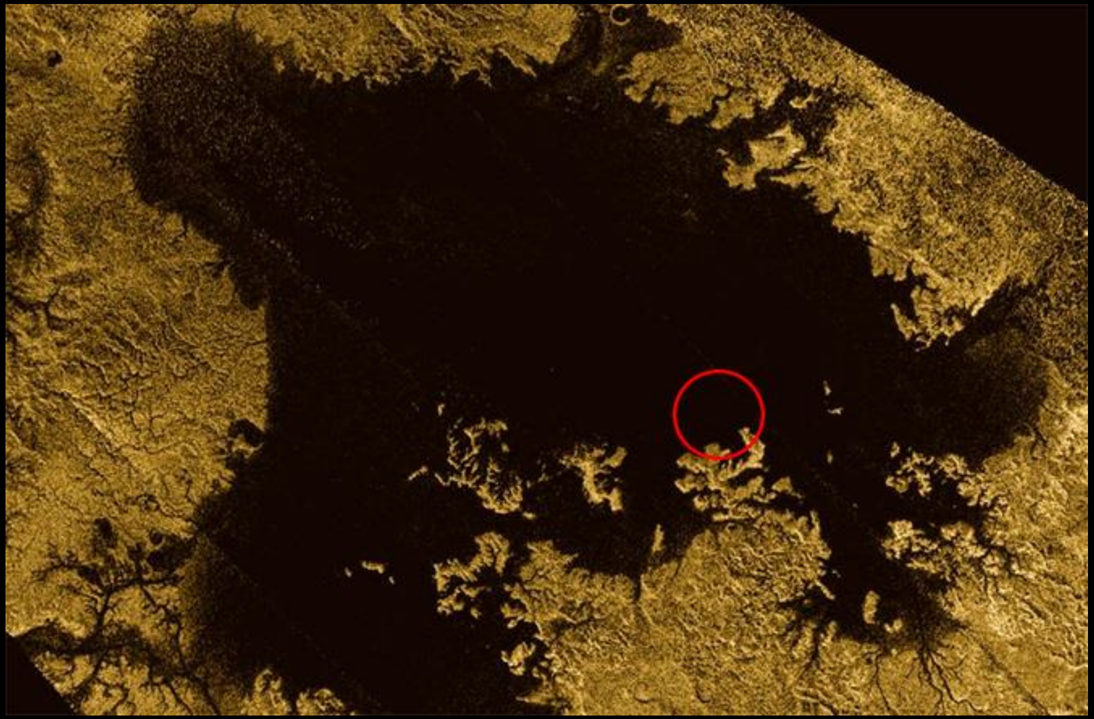
Credits: M. Mastrogiuseppe





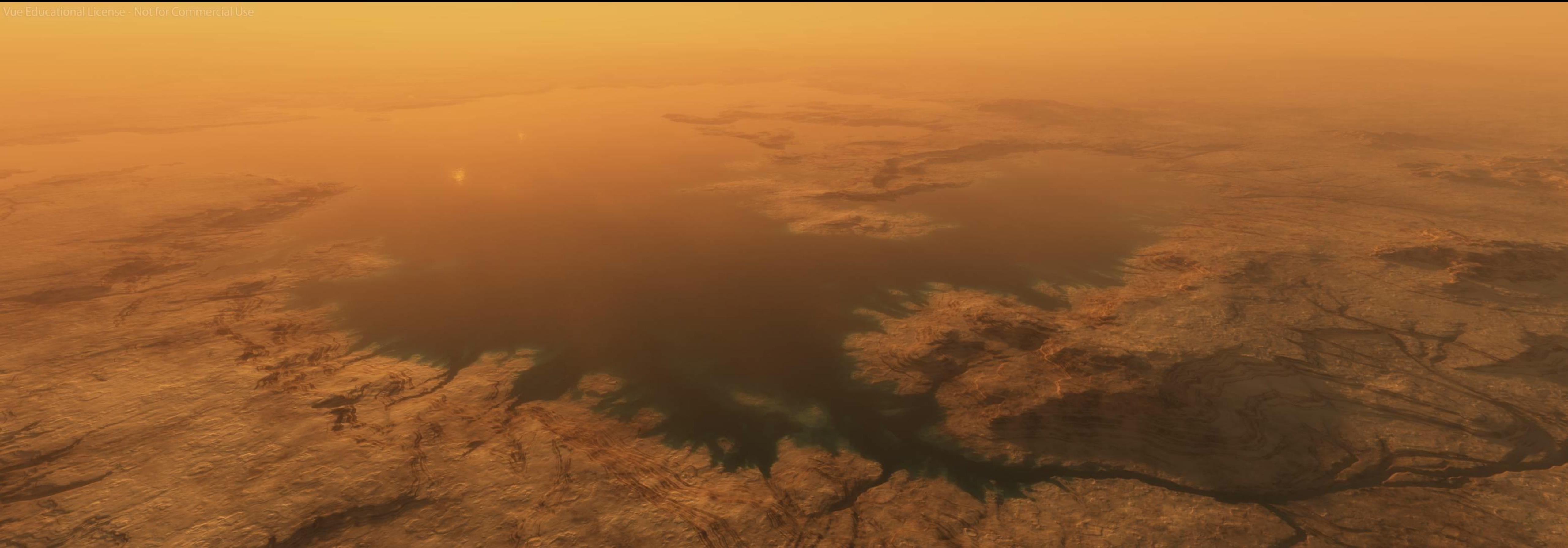
First bathymetric map of an extraterrestrial lake

Credits: A. Hayes

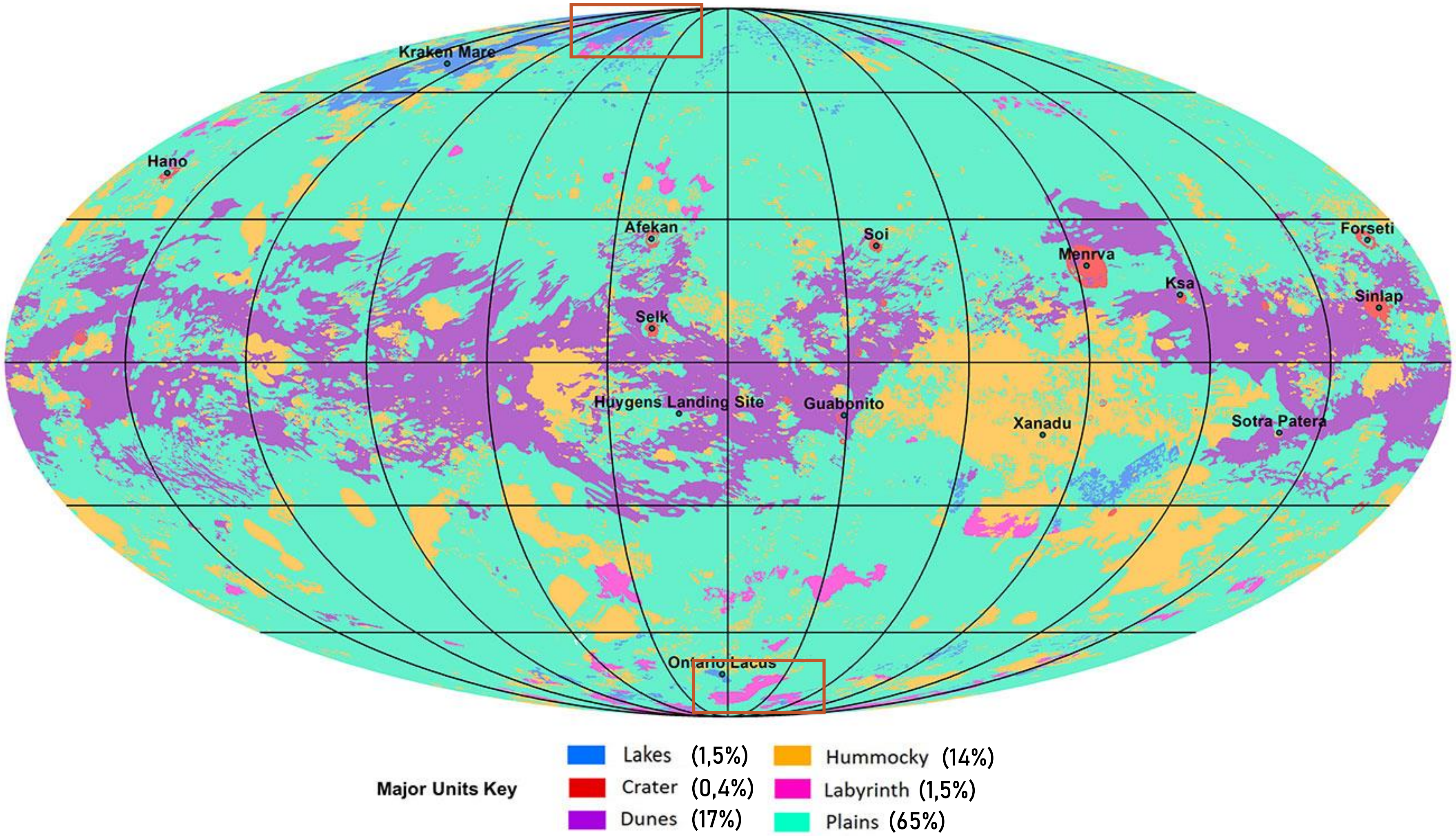


Magic island!

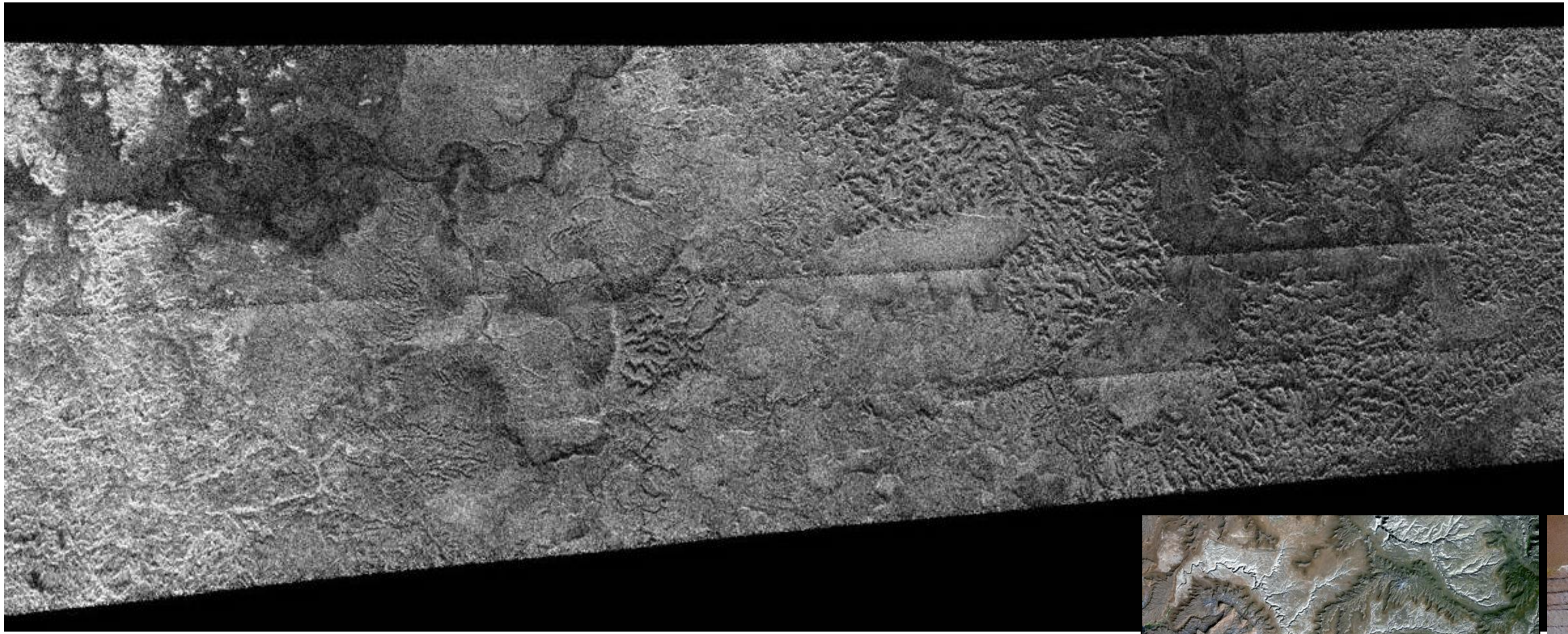

You are here.


Vue Educational License - Not for Commercial Use

Polar terrains



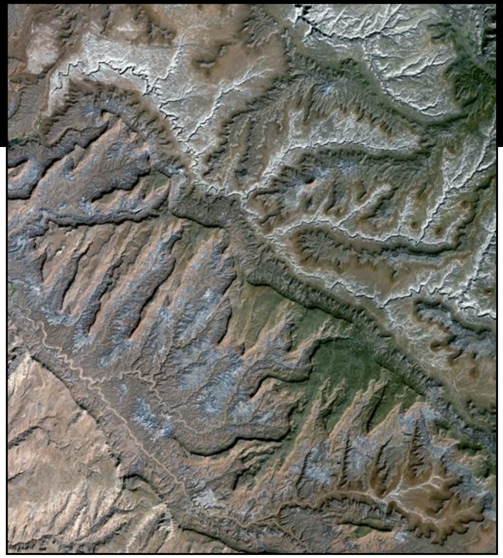
Labyrinth: karstic terrains?

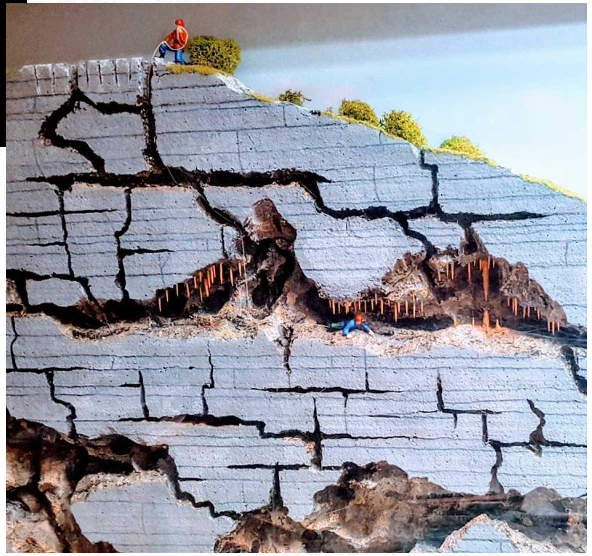


Crédits: NASA/JPL-Caltech

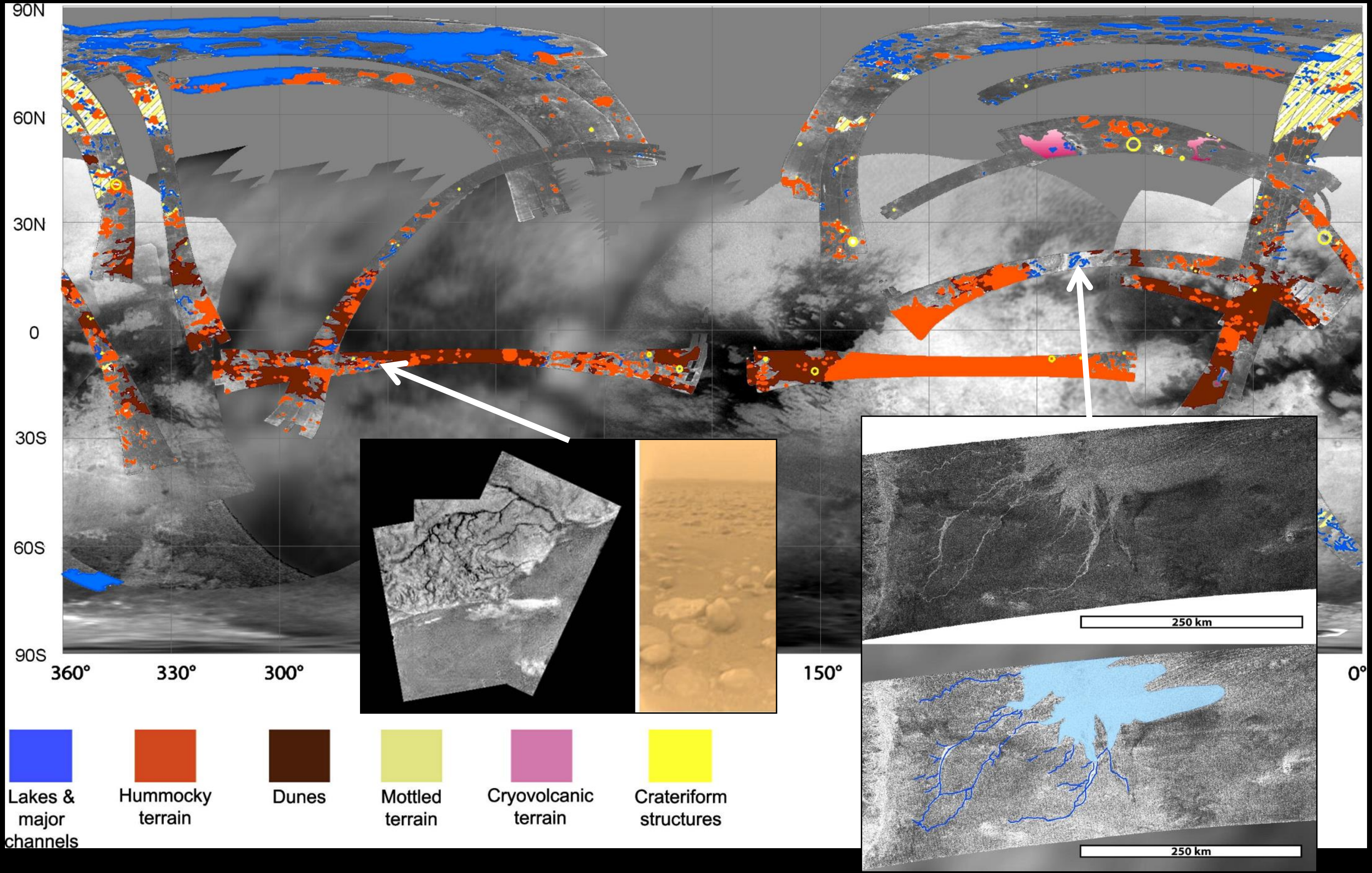
Liquid methane can be an erosion agent, either mechanical and/or chemical, of a icy and/or organic-rich crust. As efficient as water with silicate rocks and limestone on Earth.

White Canyon, Utah
Credits:
NASA/GSFC/METI/ERSDAC/
JAROS, and U.S./Japan
ASTER Science Team





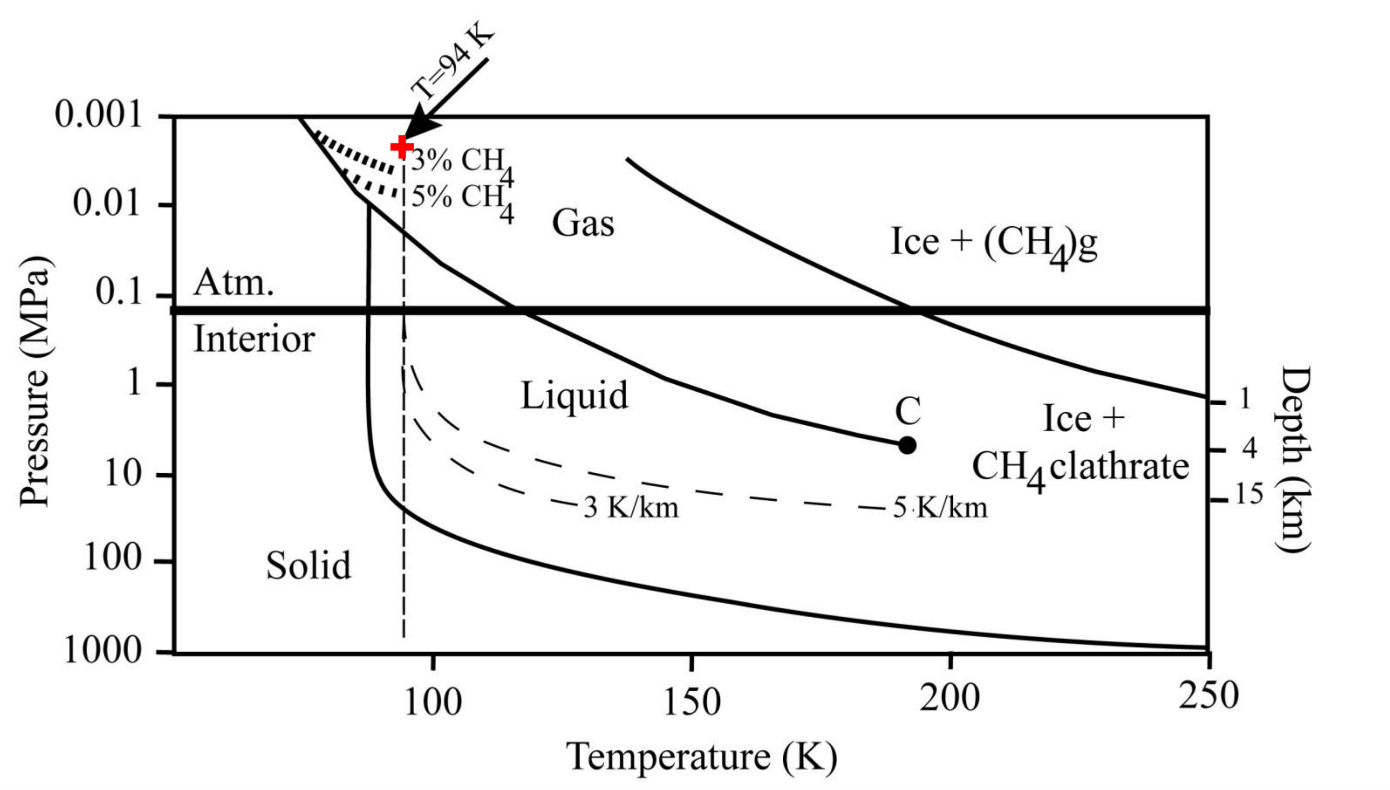
At mid-latitudes:

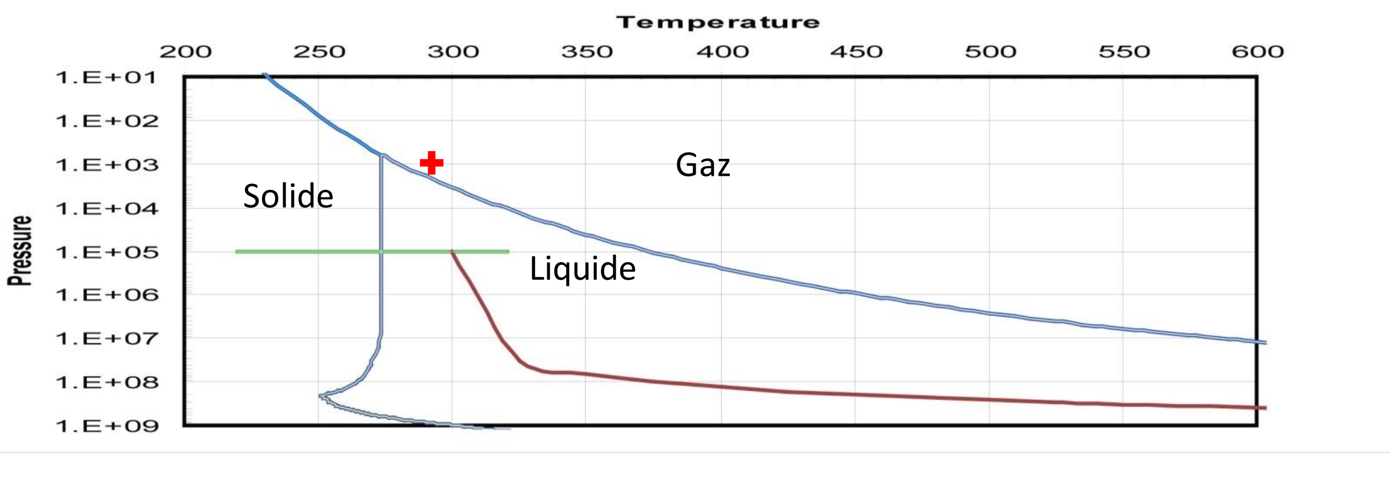


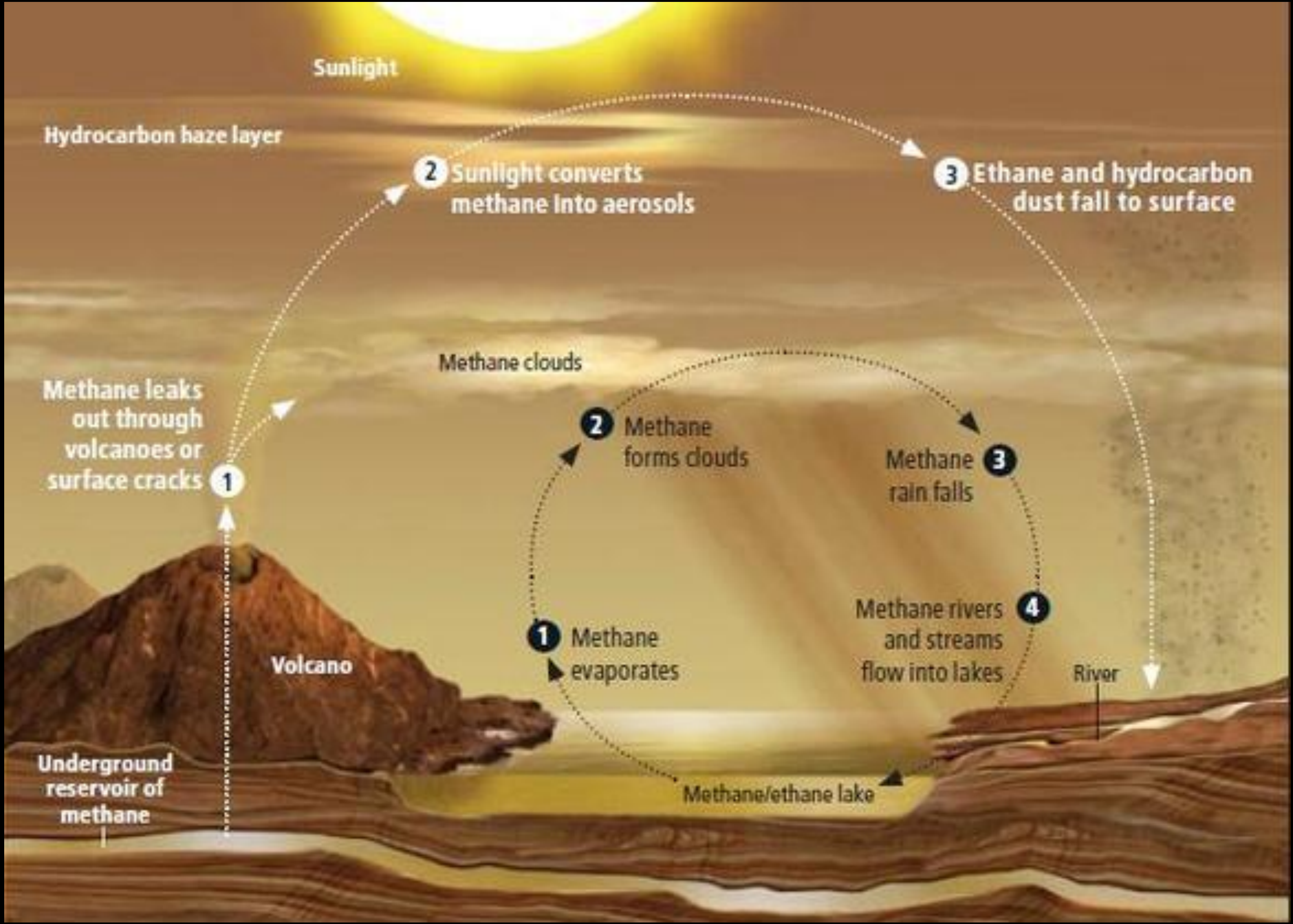
Methane balance in Titan's low atmosphere:

CH_4 on Titan

H_2O on Earth



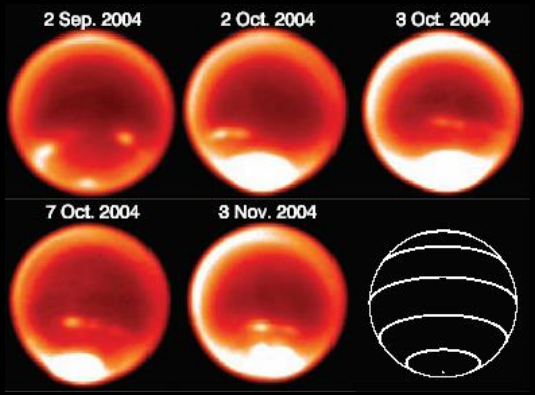




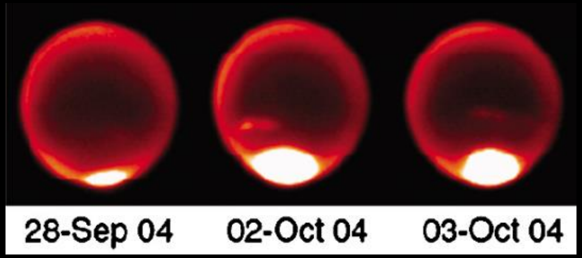
Sunlight
Hydrocarbon haze layer
2 Sunlight converts methane into aerosols
3 Ethane and hydrocarbon dust fall to surface
Methane clouds
Methane leaks out through volcanoes or surface cracks 1
2 Methane forms clouds
Methane 3 rain falls
Methane rivers and streams flow into lakes 4
1 Methane evaporates
Volcano
River
Underground reservoir of methane
Methane/ethane lake

Hydrocarbon clouds in Titan's atmosphere

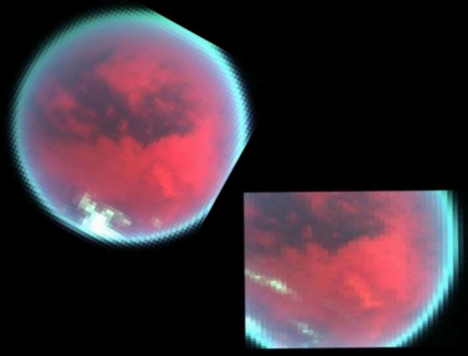
Since 1995, observed at south pole, southern mid-latitudes, and more recently near north pole



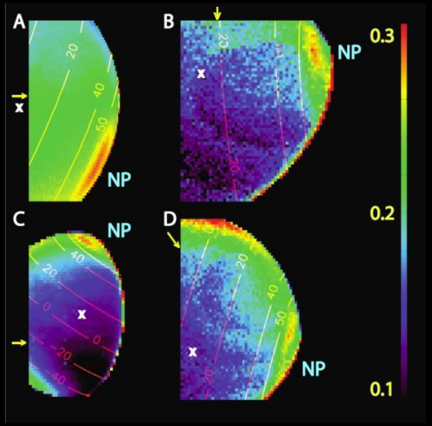
(Roe *et al.*, Science, 2005)



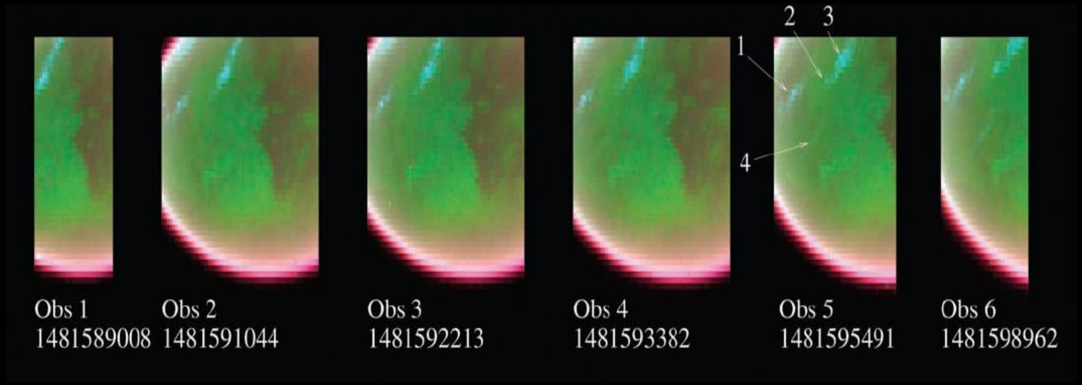
(Shaller *et al.*, Icarus, 2006)



(Baines *et al.*, EM&P, 2005)



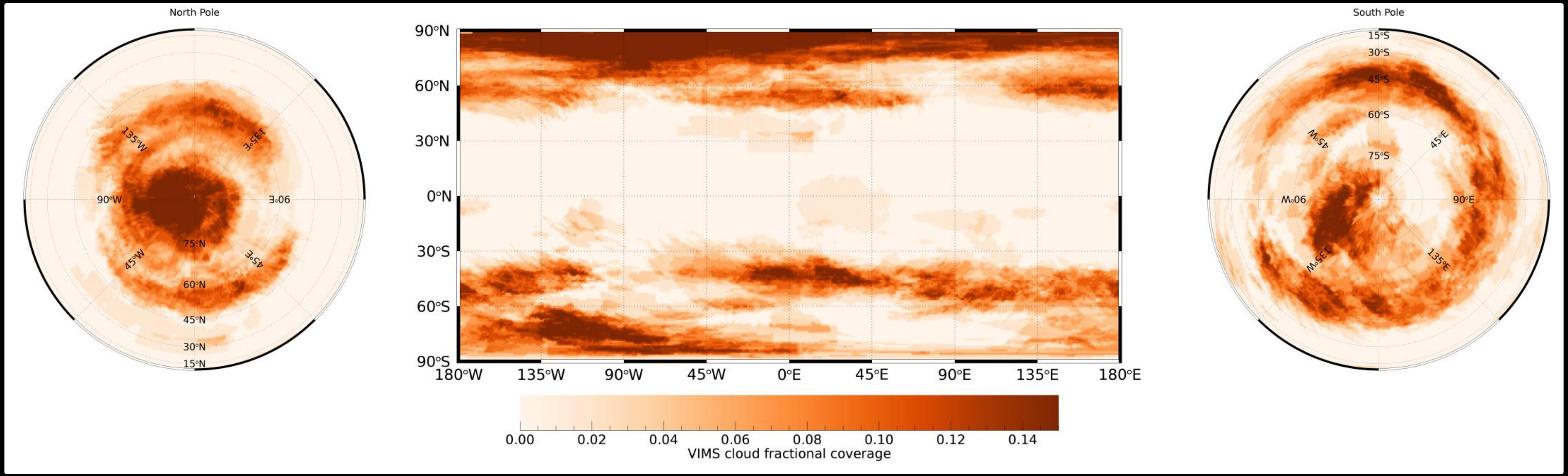
(Griffith *et al.*, Science, 2006)

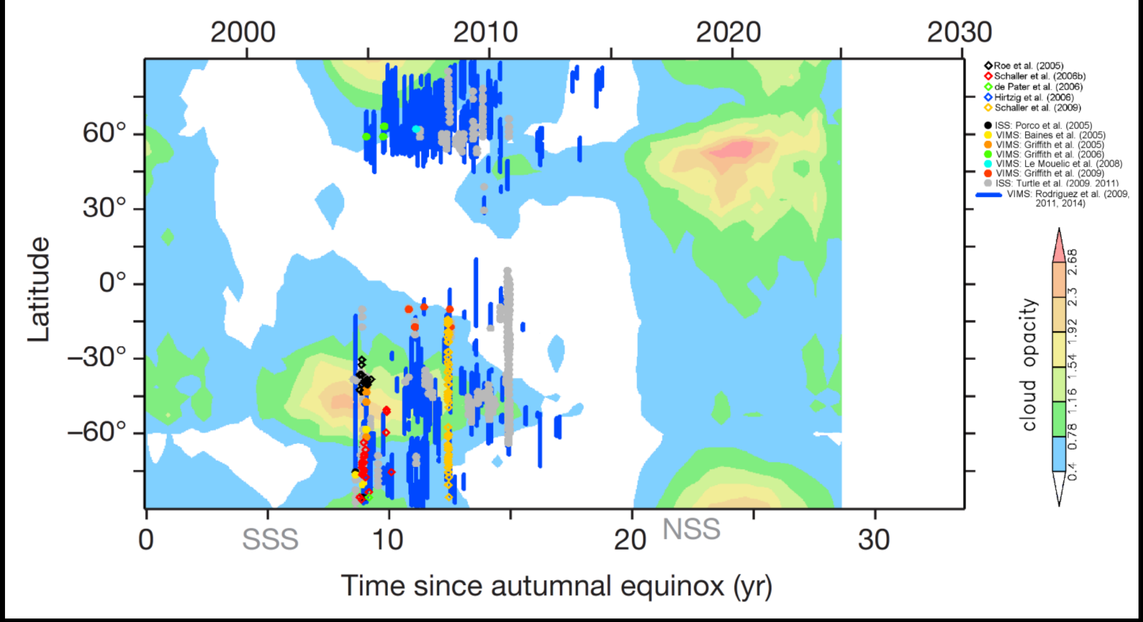


(Griffith *et al.*, Science, 2005)

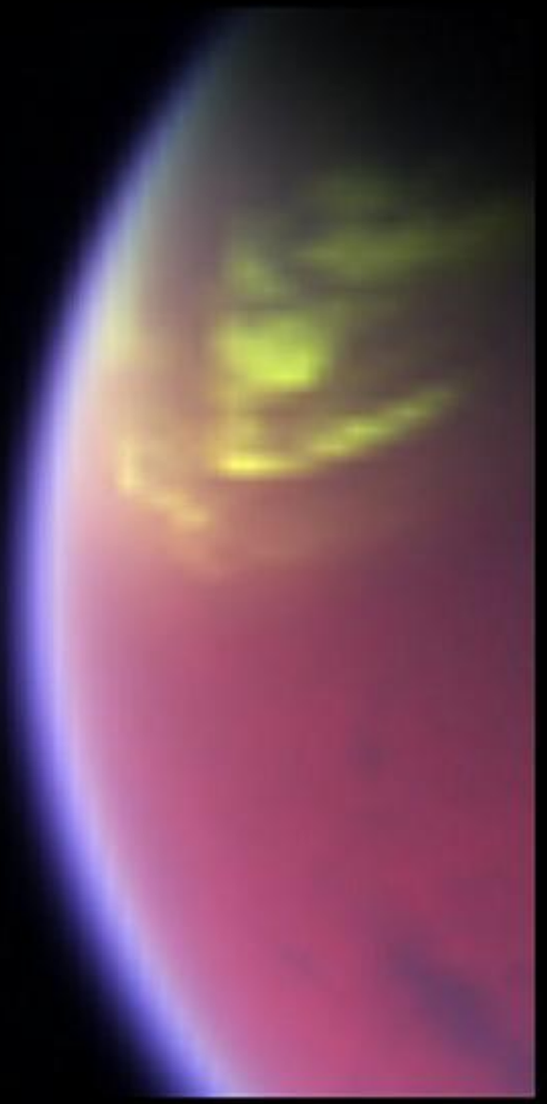
(Le Mouélic *et al.*, 2012)

13 years of Cassini Titan's cloud detection, mapping and characterization

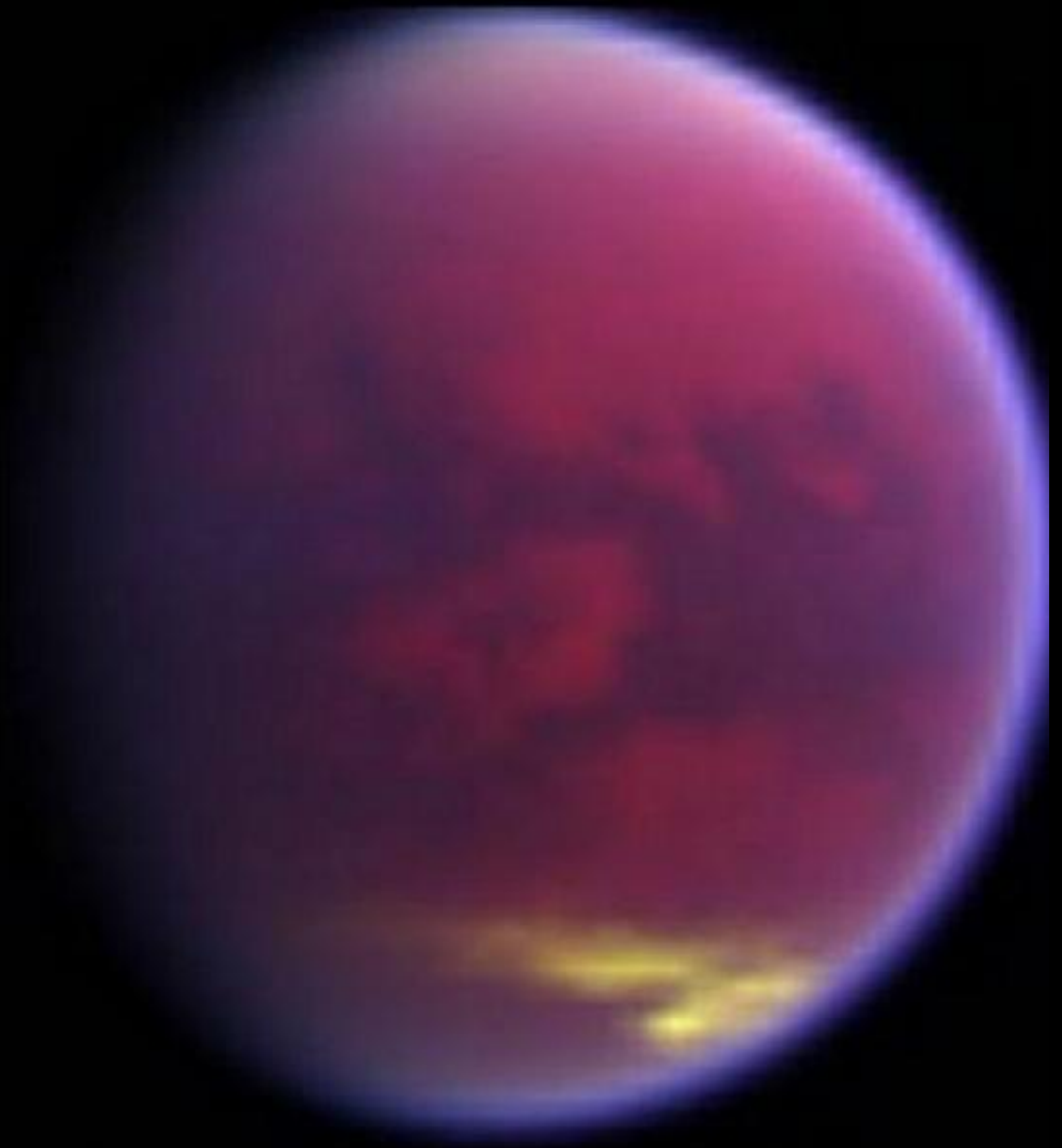




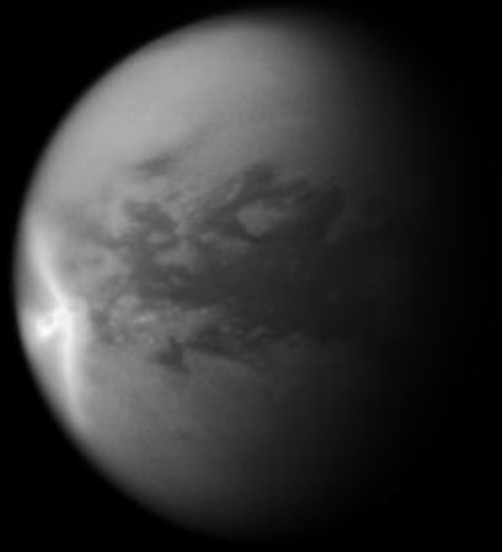
- Moderate cloud activity (≈10 % of instantaneous coverage).
- Arid to semi-arid climate.
- Latitudinal distribution mainly controlled by global atmospheric circulation.
- Change with seasons.



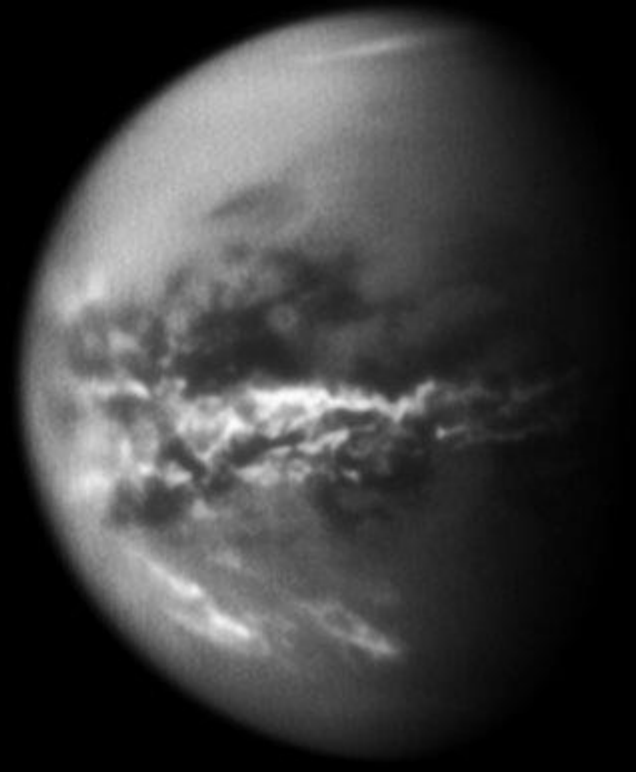
Northern summer



Spring equinox

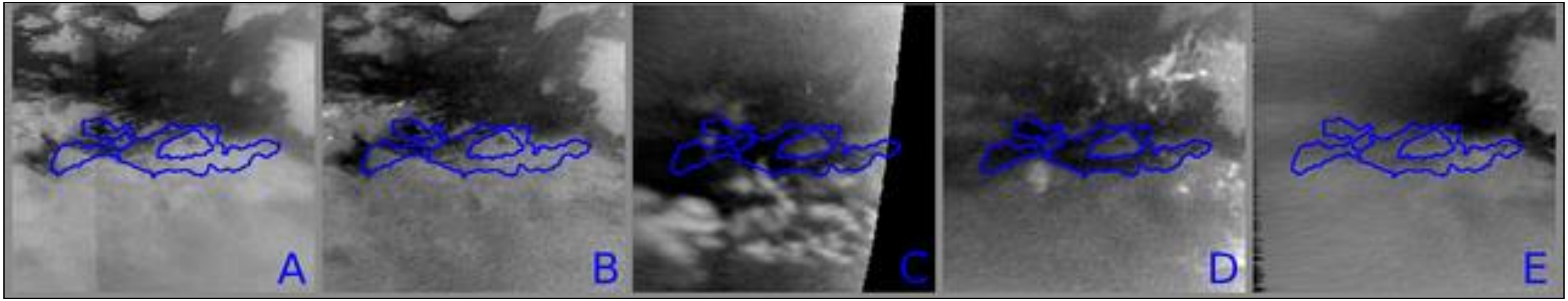


27 September 2010



18 October 2010

Rare, but intense rainfalls…

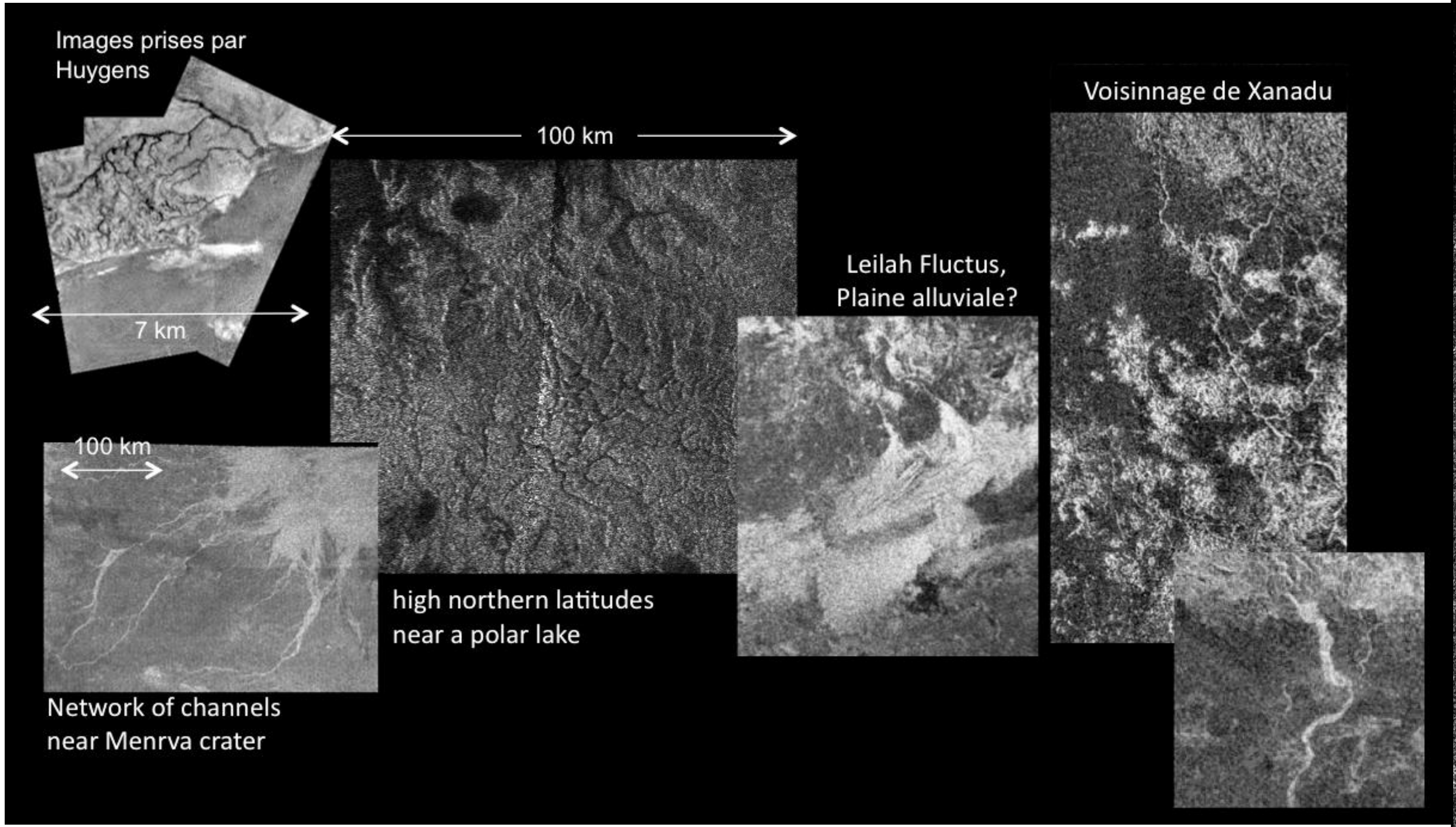


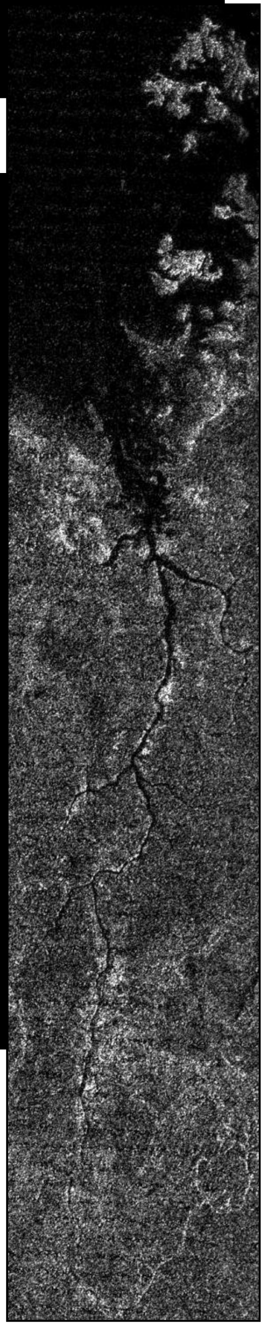
Credits: NASA/Space Science Institute

A few rainfalls have been observed.

Less abundant precipitations on Titan than on Earth, but probably intense.

…which shape the surface

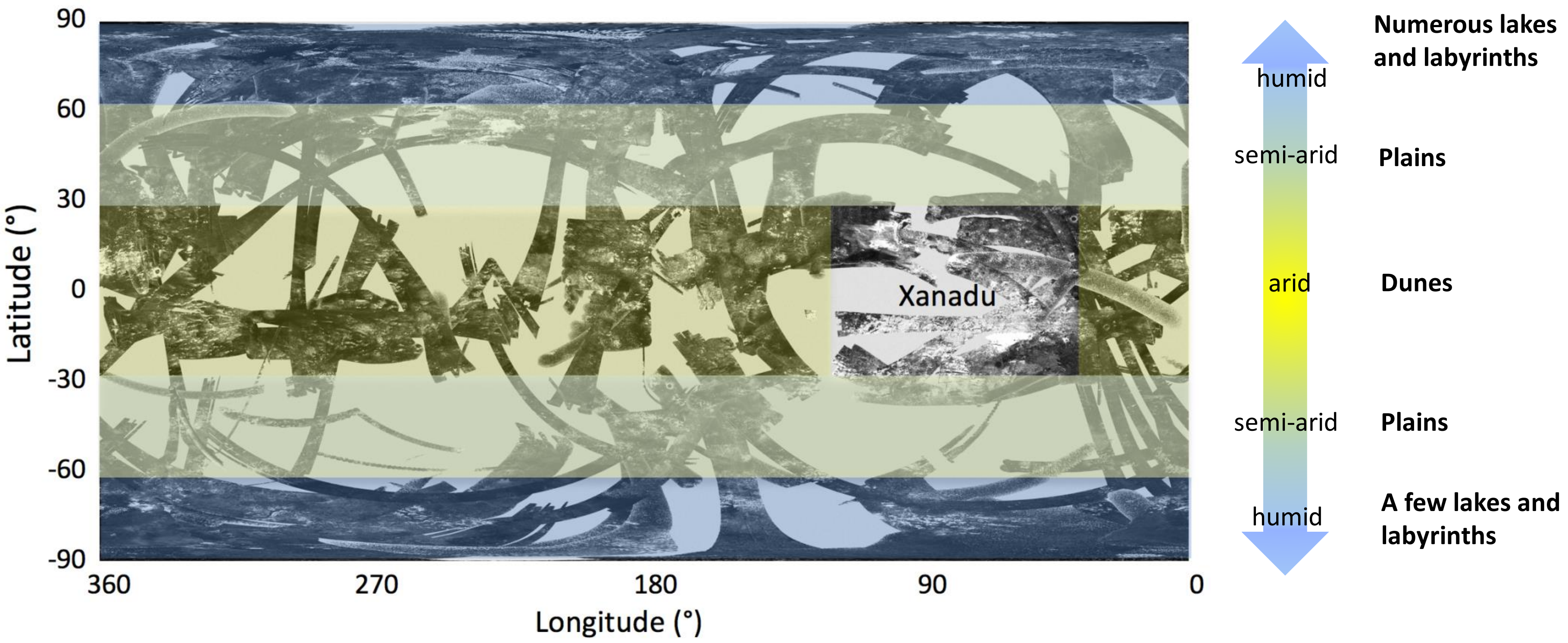




Credits: NASA/JPL-Caltech

Canyons, valleys have been scultped by rainfall and fluvial erosion.

To sum up



Landscape distribution is strongly linked with methane "weather" (past and present).
An organic world, more than icy.
A world shaped by aeolian and fluvial erosion.
A freezing cold world, but highly active.

And life? (organics + water?)

Titan has one of the highest habitability potential in the Solar System. But, it is still an outstanding open question.

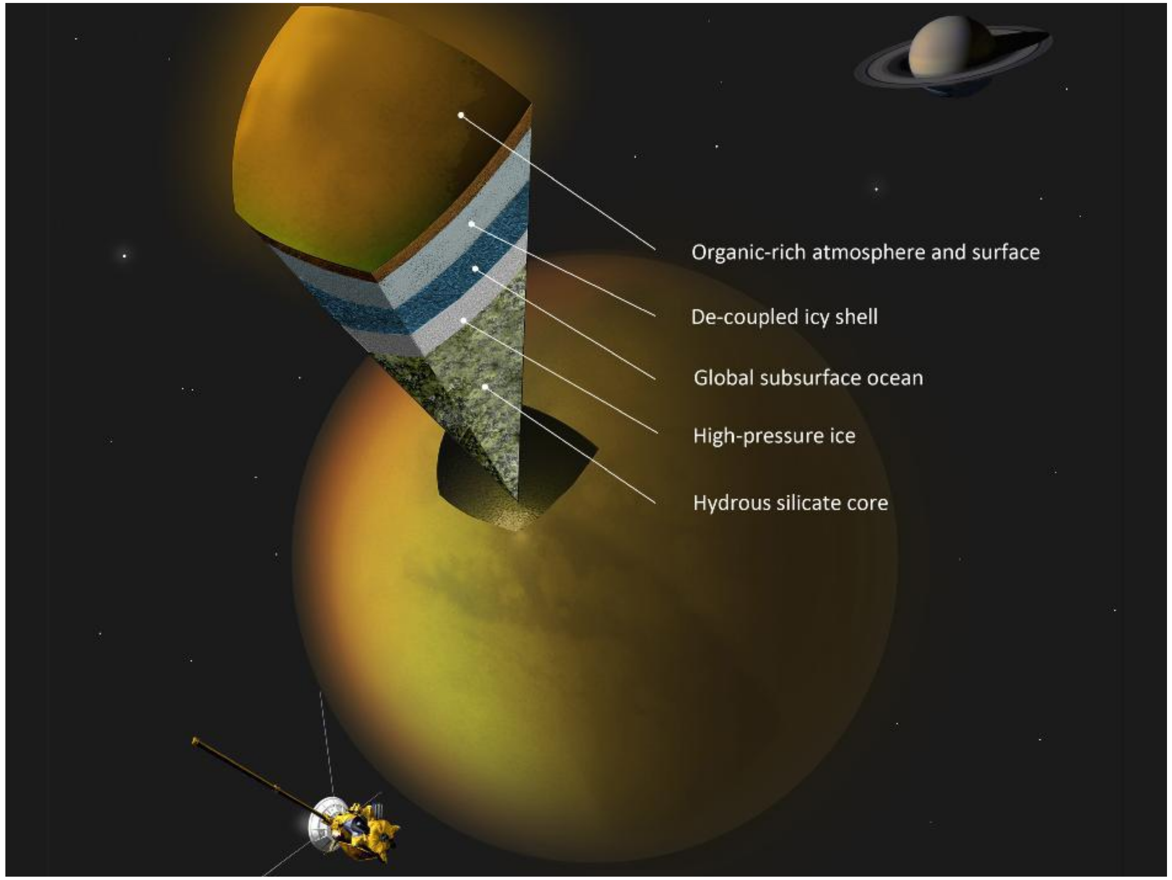
Life (as we know it on Earth): organics + liquid water + energy.

At surface:

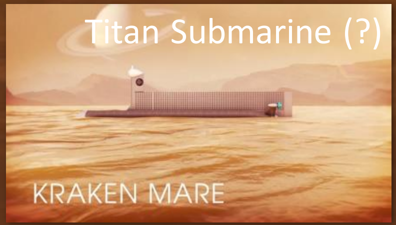
- Detection of extremely complex organic molecules: precursors for prebiotic molecules?
- Transient liquid water? (after impact cratering or cryo-lava spreading)
- But also liquid methane: possible cradle for a different form of life? Titan's azotosomes (membrane stable in methane)?

In the interior:

- A global salty internal ocean.
- In contact (past or present) with the surface (through fractures) and/or the rocky core?
- Higher temperatures.

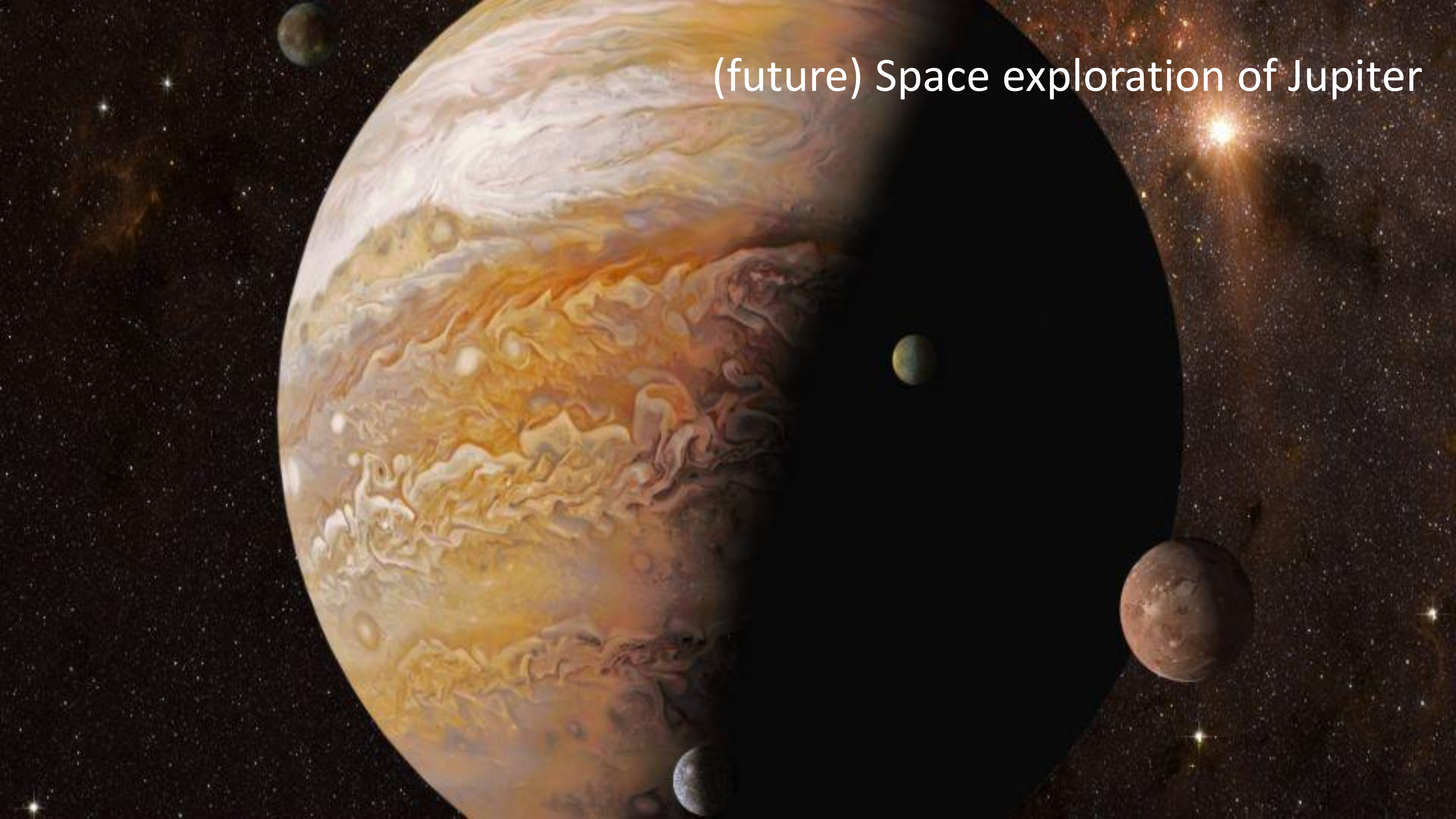


After Cassini?

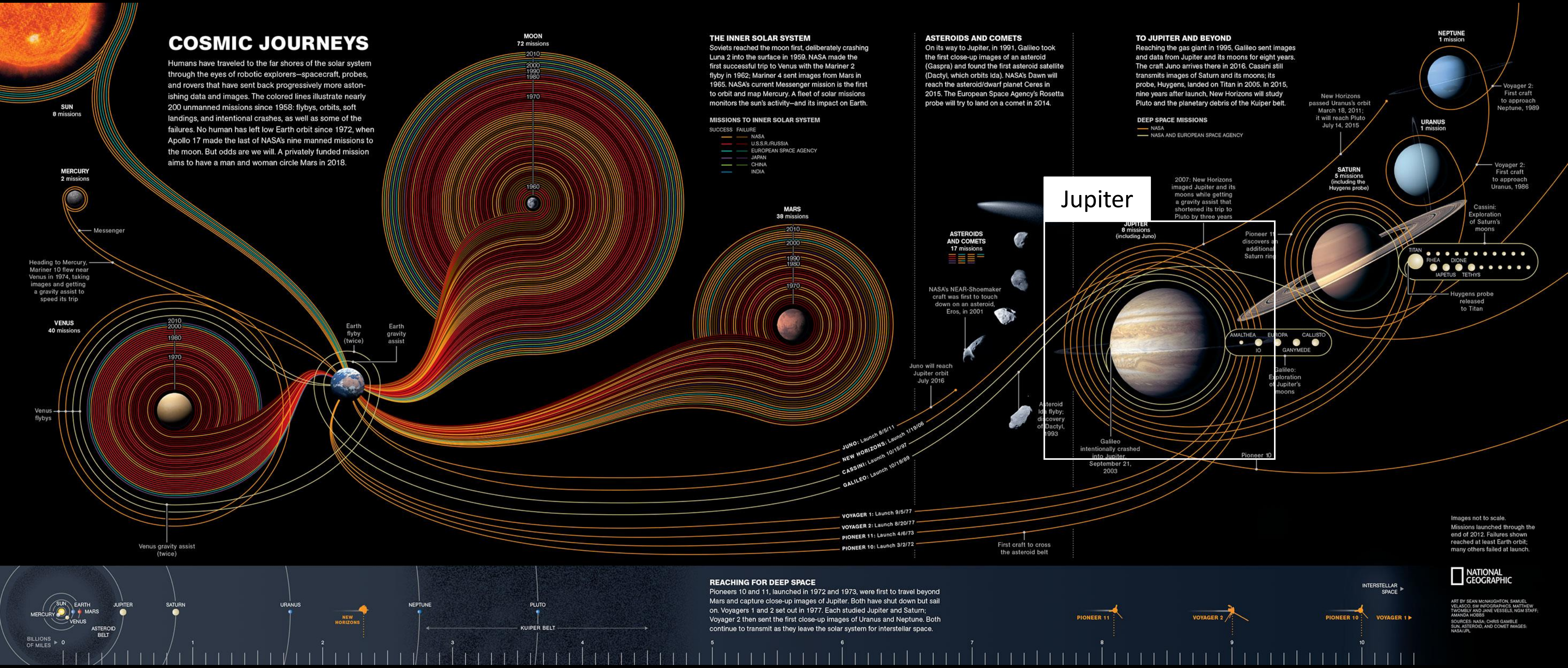


- Cassini (ended in Sept. 2017) ⇨ 10+ years of data anlyses
- Terrestrial ground-based observations (Keck, Gemini, VLT, IRTF)
- JWST (to be launched on 12/18/2021)
- Dragonfly (selected by NASA in 2019, arrival in mid-2030s)
- Titan: one of ESA Voyage 2050 priorities (we proposed an orbiter + mobile in situ element(s))

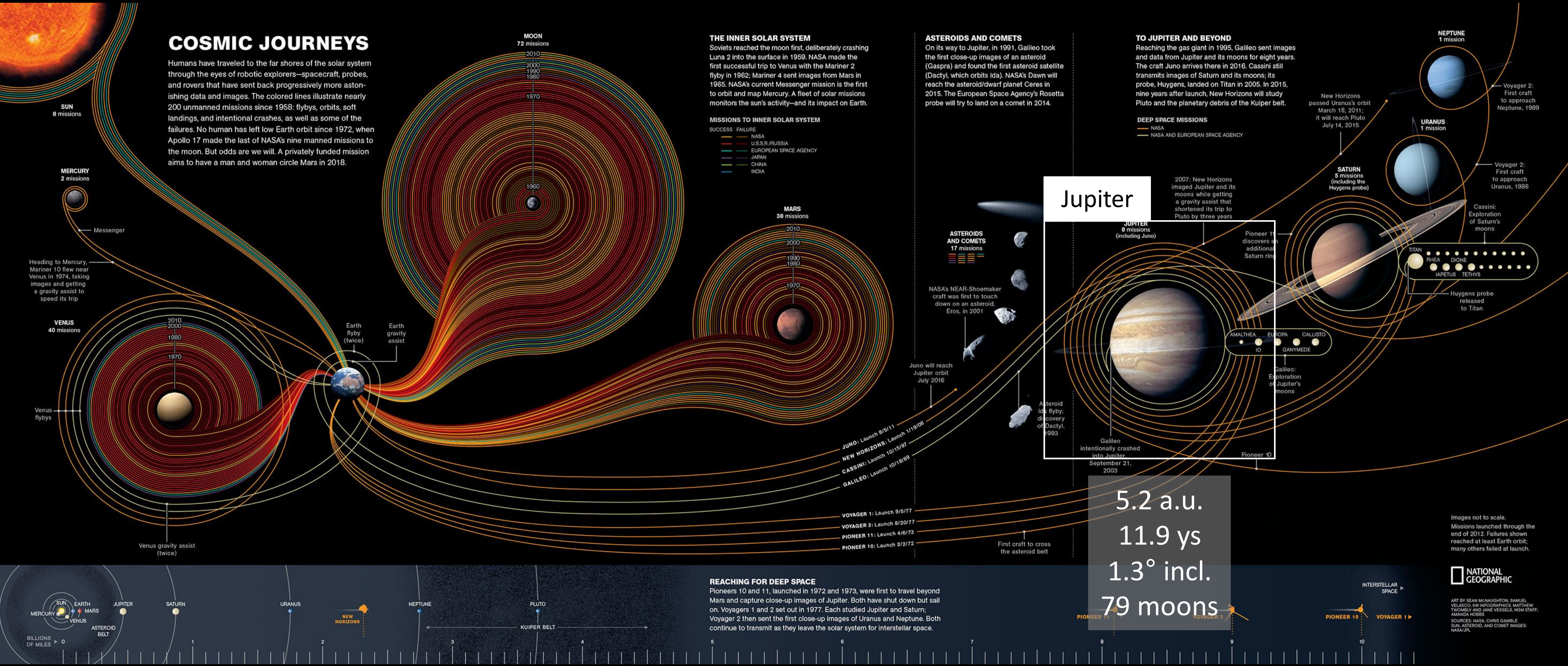
(future) Space exploration of Jupiter



Focus on Jupiter

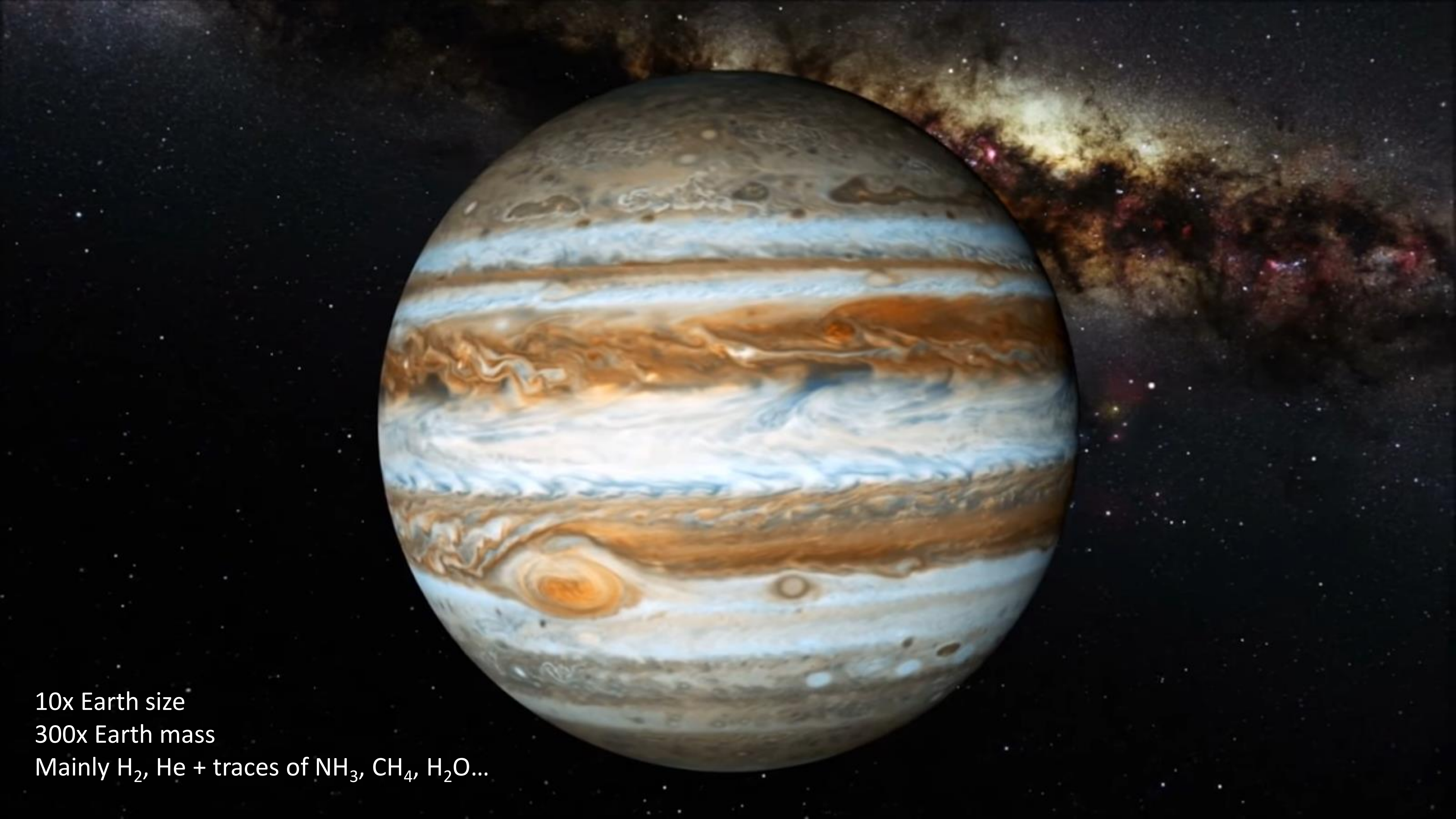


Focus on Jupiter



Jupiter

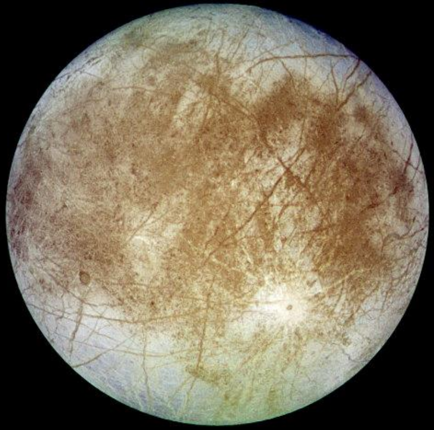
5.2 a.u.
11.9 ys
1.3° incl.
79 moons


10x Earth size
300x Earth mass
Mainly H_2, He + traces of NH_3, CH_4, H_2O…

Galilean moons of Jupiter

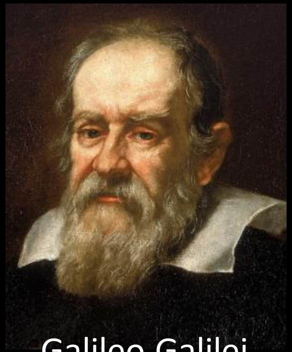
Io

Europa

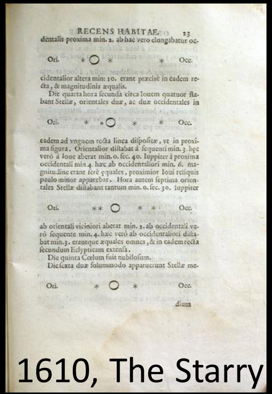


Ganymede

Callisto



Galileo Galilei



RECENS HABITAE. 23

dentalis proxima min. 2. ab hac vero elongabatur oc-

Ori. * ○ * * Occ.

cidentalior altera min: 10. erant præcisè in eadem re-
cta, & magnitudinis æqualis.
Die quarta hora secunda circa Iouem quatuor sta-
bant Stellæ, orientales duæ, ac duæ occidentales in

Ori. * * ○ * * Occ.

eadem ad vnguem recta linea dispositæ, vt in proxi-
ma figura. Orientalior distabat à sequenti min. 3. hęc
verò à Ioue aberat min. o. sec. 40. Iuppiter à proxima
occidentali min. 4. hæc ab occidentaliori min. 6. ma-
gnitudine erant ferè ęquales, proximior Ioui reliquis
paulo minor apparebat. Hora autem septima orien-
tales Stellæ distabant tantum min. o. sec. 30. Iuppiter

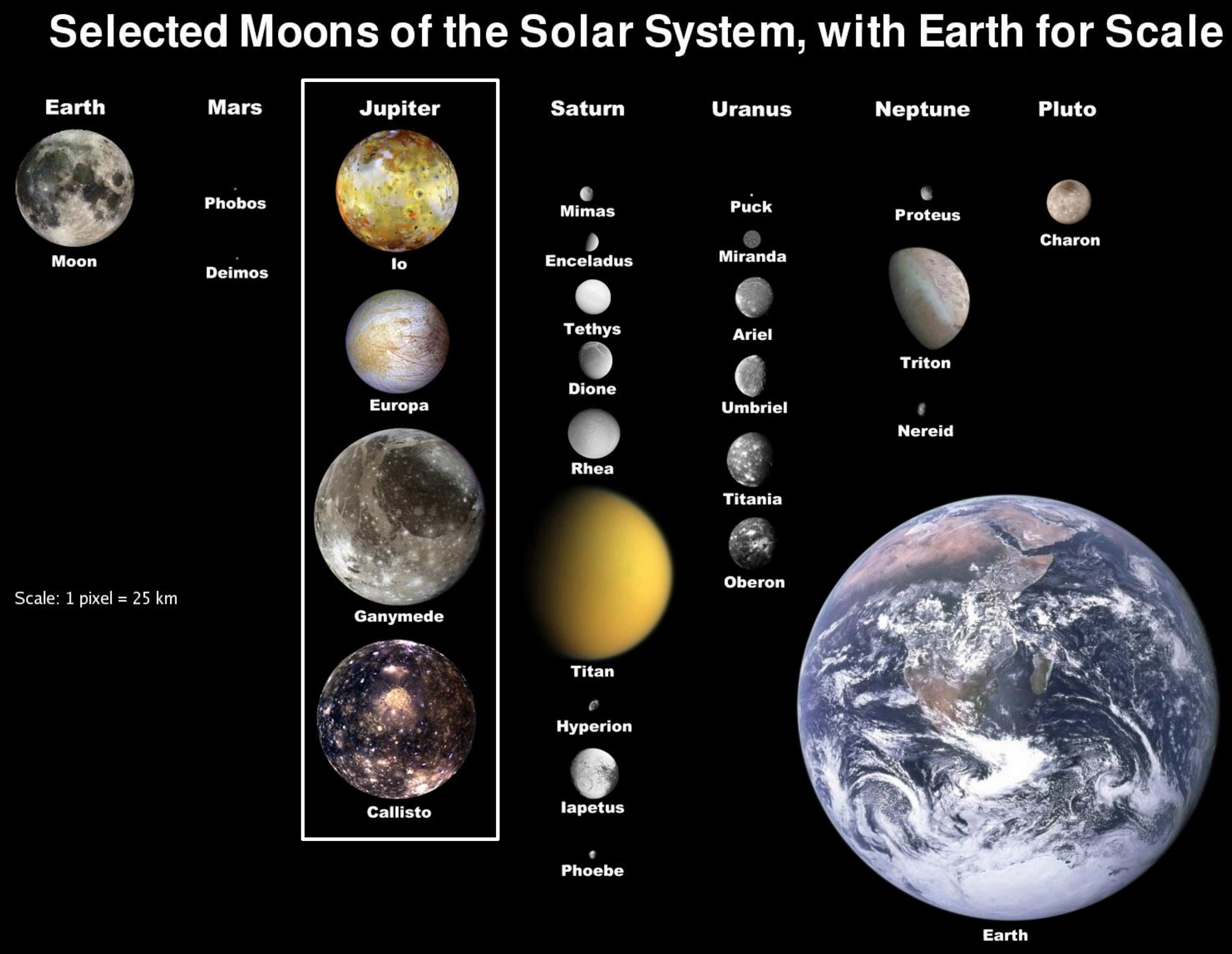
Ori. ** ○ * * Occ.

ab orientali viciniori aberat min. 2. ab occidentali ve-
rò sequente min. 4. hæc verò ab occidentaliori dista-
bat min. 3. erantque æquales omnes, & in eadem recta
secundum Eclypticam extensa.
Die quinta Cœlum fuit nubilosum.
Die sexta duæ solummodo apparuerunt Stellæ me-

Ori. * ○ * Occ.

dium

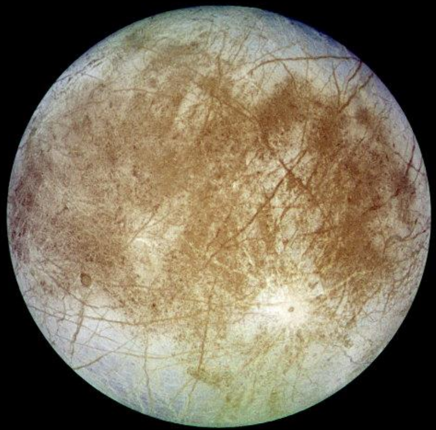
1610, The Starry Messenger


Selected Moons of the Solar System, with Earth for Scale
Earth
Moon
Mars
Phobos
Deimos
Jupiter
Io
Europa
Ganymede
Callisto
Saturn
Mimas
Enceladus
Tethys
Dione
Rhea
Titan
Hyperion
Iapetus
Phoebe
Uranus
Puck
Miranda
Ariel
Umbriel
Titania
Oberon
Neptune
Proteus
Triton
Nereid
Pluto
Charon
Earth
Scale: 1 pixel = 25 km

Galilean moons of Jupiter

Io

Europa



Ganymede

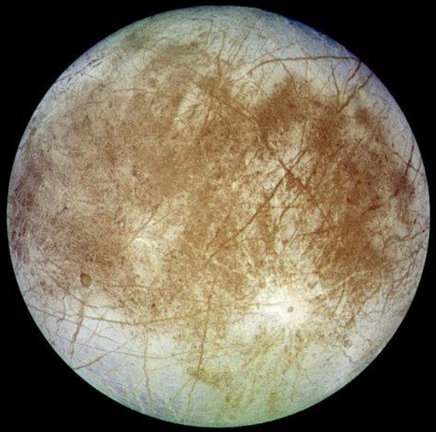
Callisto

∅: 3660 km
420 000 km
density: 3.53
400 volcanoes
Sulfur ice(s)

Galilean moons of Jupiter

Io

Europa



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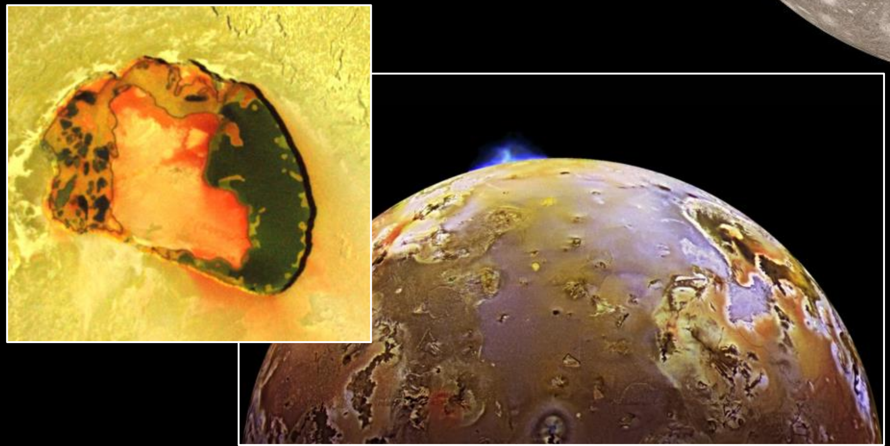

Galilean moons of Jupiter

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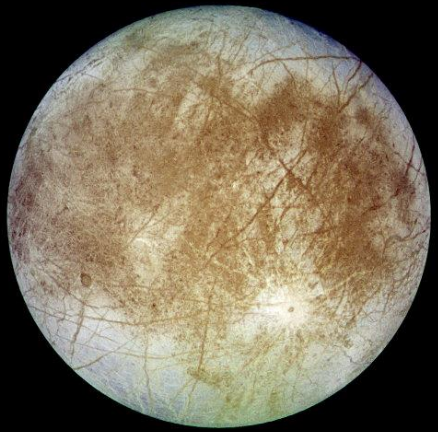
Europa



∅: 3120 km
670 000 km
density: 3
Young surface
Pure water ice

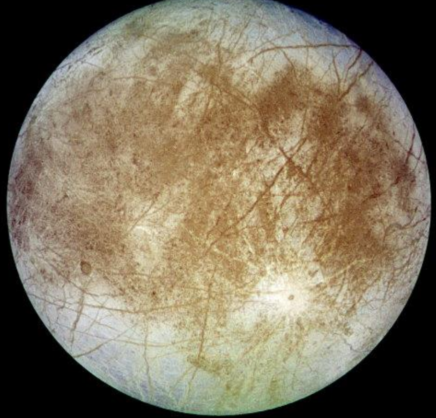
Ganymede

Callisto

Galilean moons of Jupiter

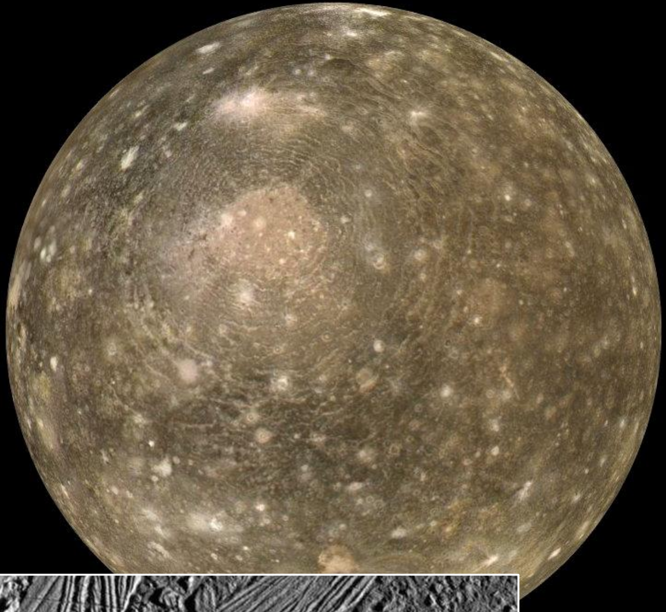
Io

Europa



Ganymede

Callisto



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density: 3.53
400 volcanoes
Sulfur ice(s)

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density: 3
Young surface
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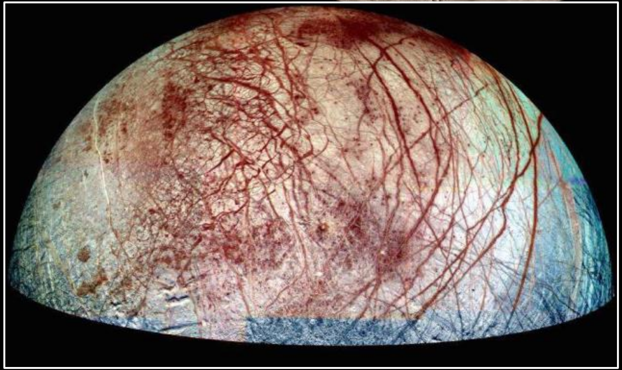

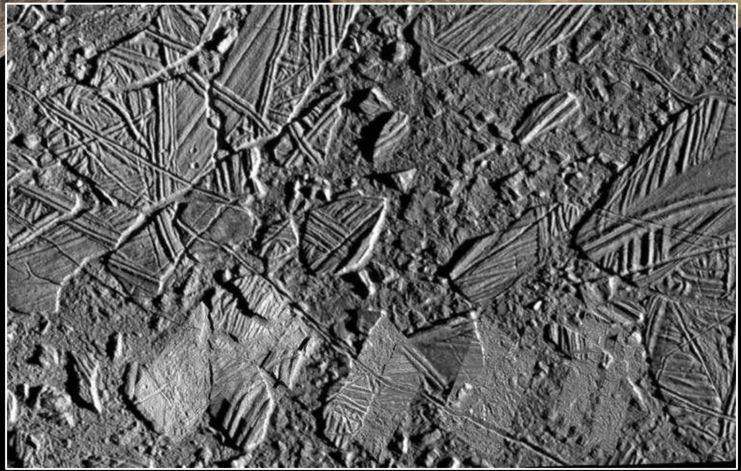

Galilean moons of Jupiter

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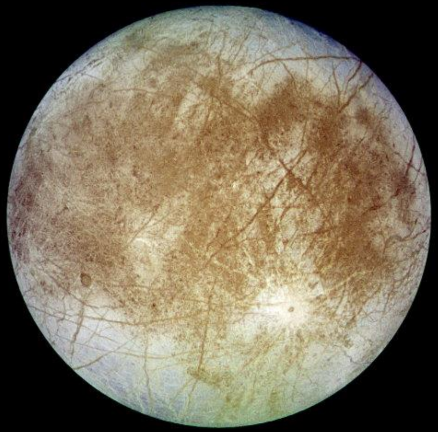


∅: 3120 km
670 000 km
density: 3
Young surface
Pure water ice

Ganymede

∅: 5270 km
1 000 000 km
density: 1.9
≈old icy surface
Own B

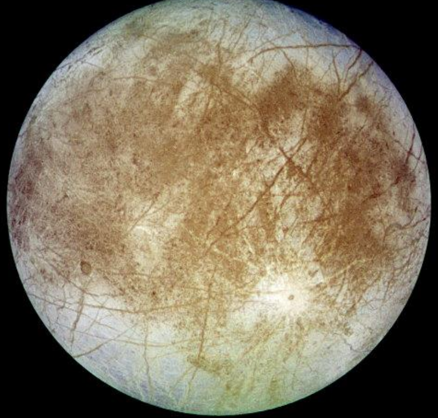
Callisto

Galilean moons of Jupiter

Io

∅: 3660 km
420 000 km
density: 3.53
400 volcanoes
Sulfur ice(s)

Europa



∅: 3120 km
670 000 km
density: 3
Young surface
Pure water ice

Ganymede

∅: 5270 km
1 000 000 km
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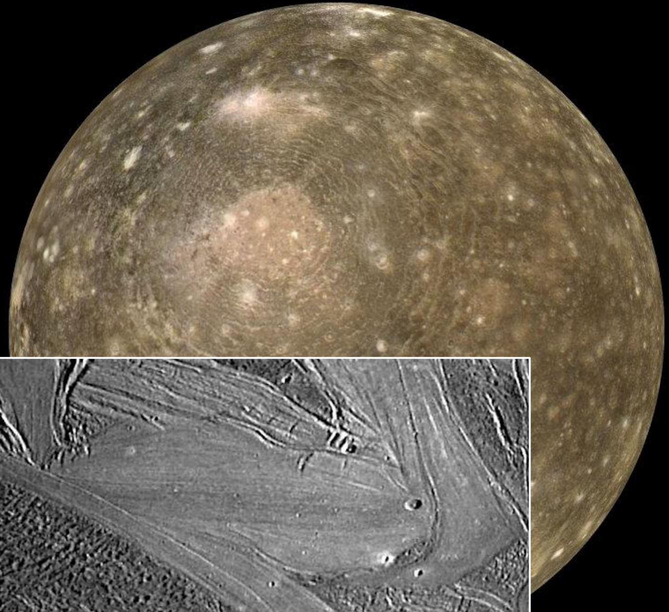
≈old icy surface
Own B

Callisto

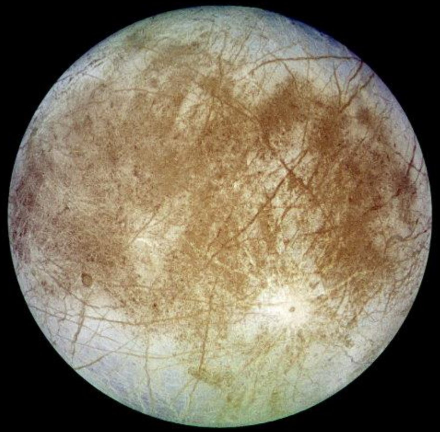


Galilean moons of Jupiter

Io

∅: 3660 km
420 000 km
density: 3.53
400 volcanoes
Sulfur ice(s)

Europa



∅: 3120 km
670 000 km
density: 3
Young surface
Pure water ice

Ganymede

∅: 5270 km
1 000 000 km
density: 1.9
≈old icy surface
Own B

Callisto

∅: 4820 km
1 900 000 km
density: 1.8
Very old icy surface
Perfectly conductive sphere

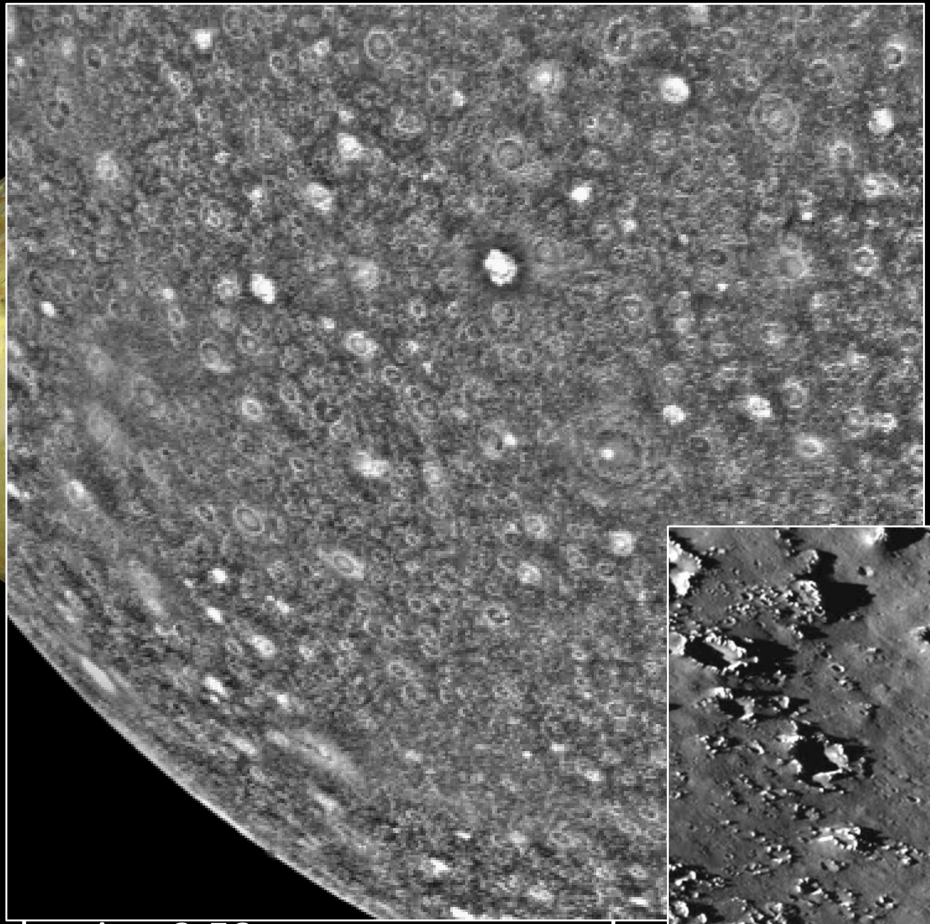
Galilean moons of Jupiter

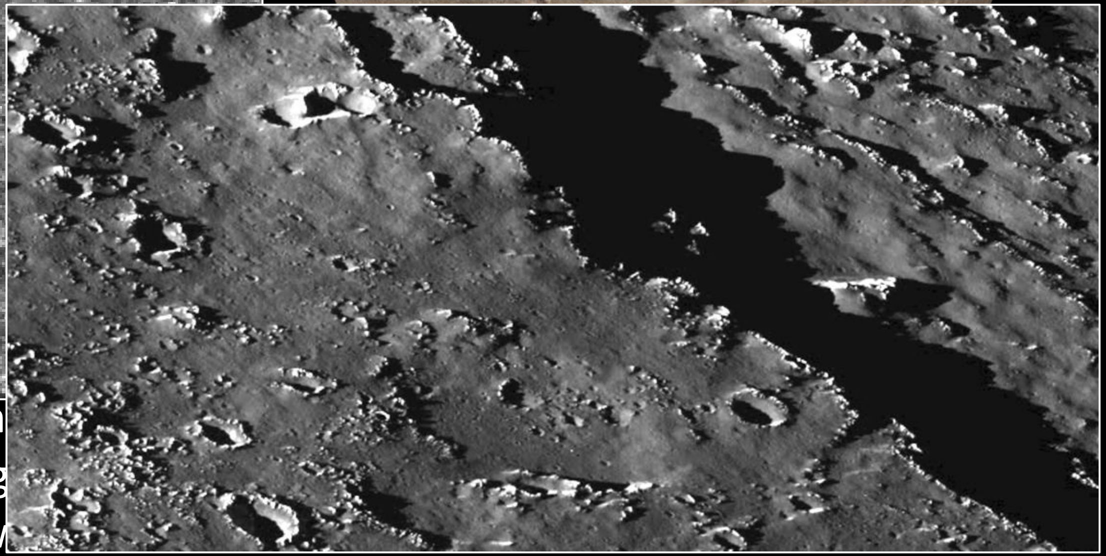
Io

Europa

Ganymede

Callisto





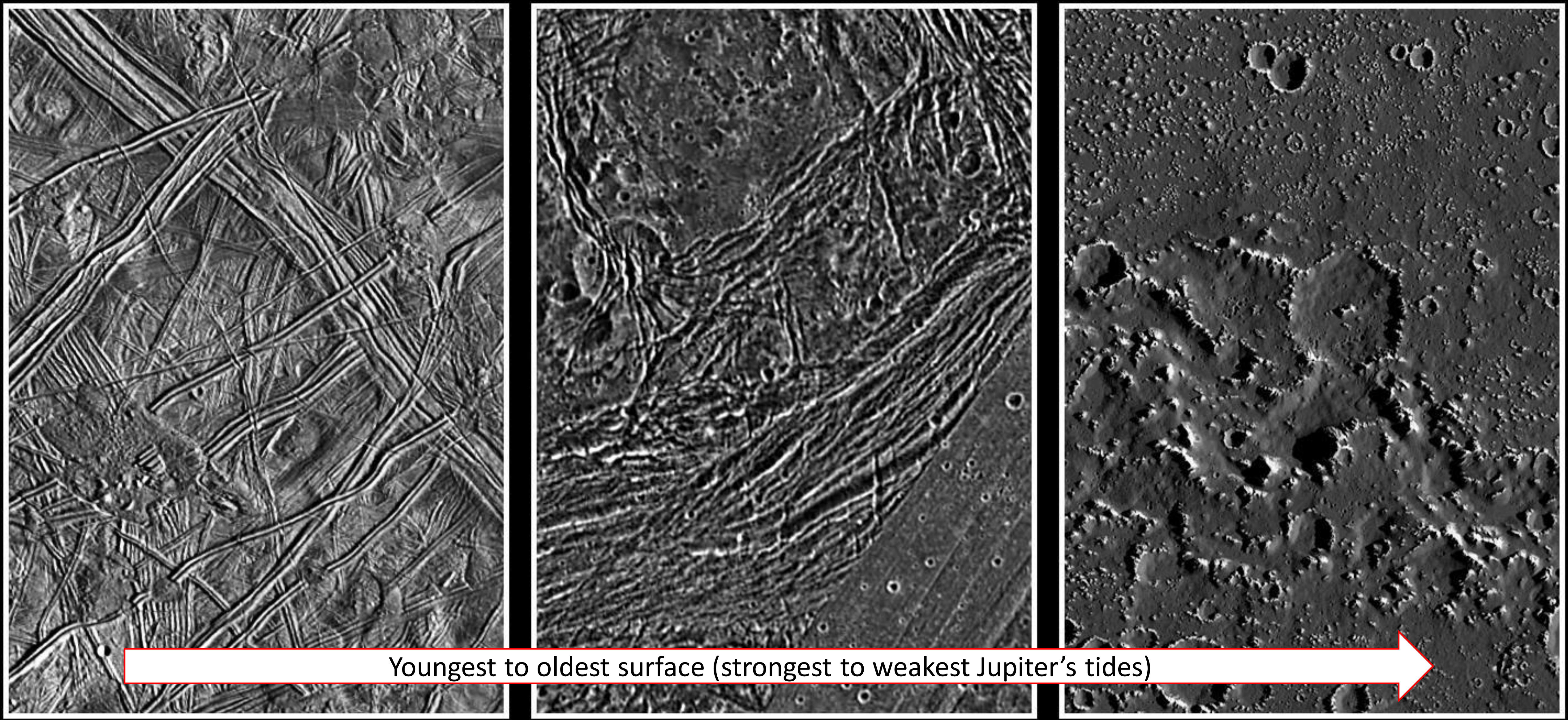
density: 3.53
400 volcanoes
Sulfur ice(s)

den
Young
Pure v

∅: 4820 km
1 900 000 km
density: 1.8
Very old icy surface
Perfectly conductive sphere

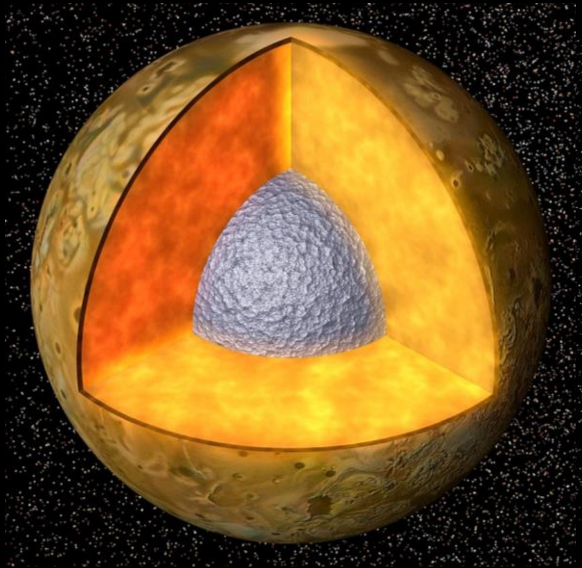
Galilean moons of Jupiter

Europa | Ganymede | Callisto

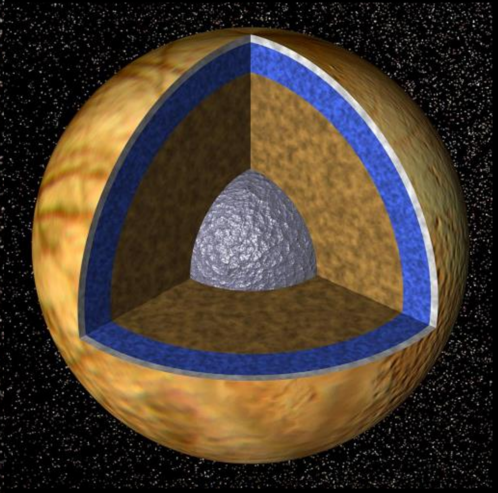


Galilean moons of Jupiter

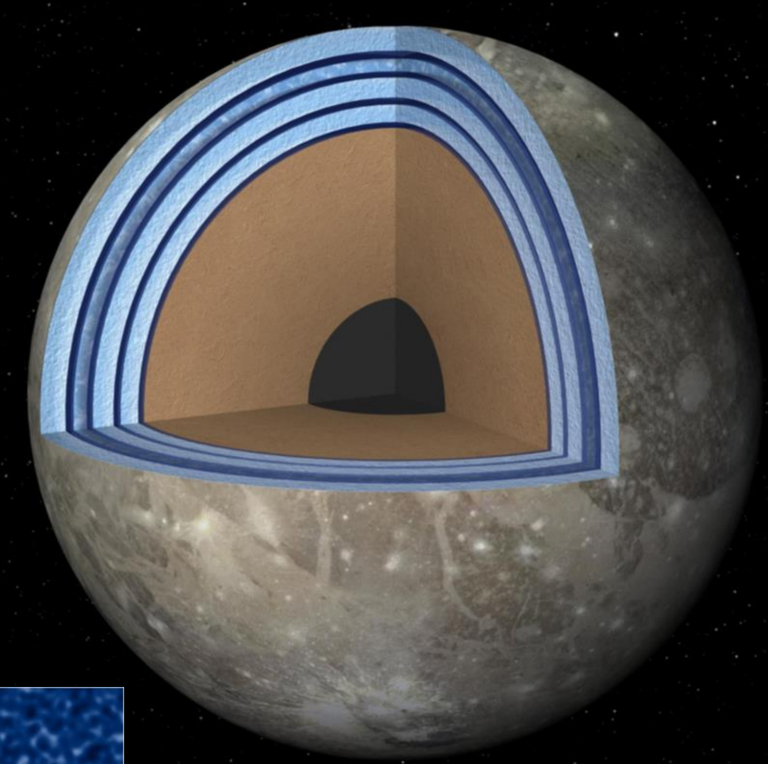
Io



Europa

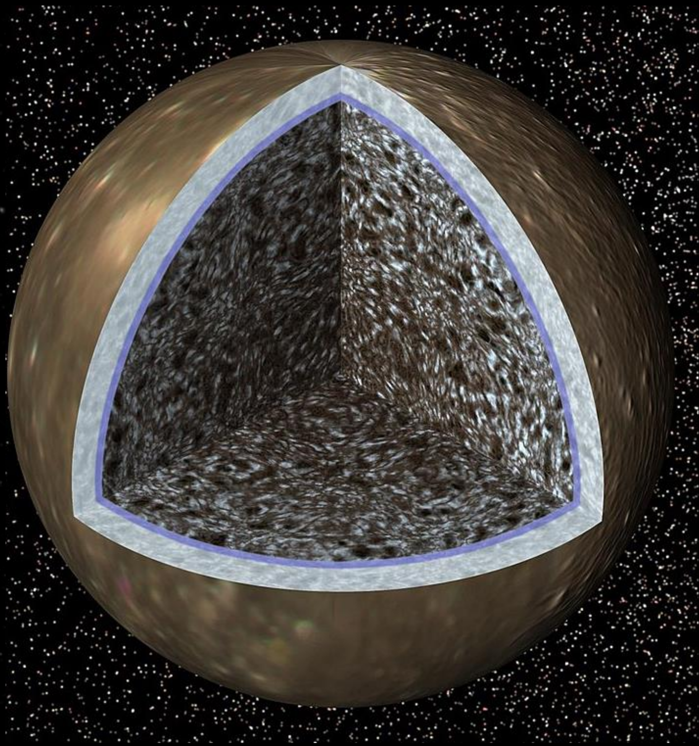


Ganymede



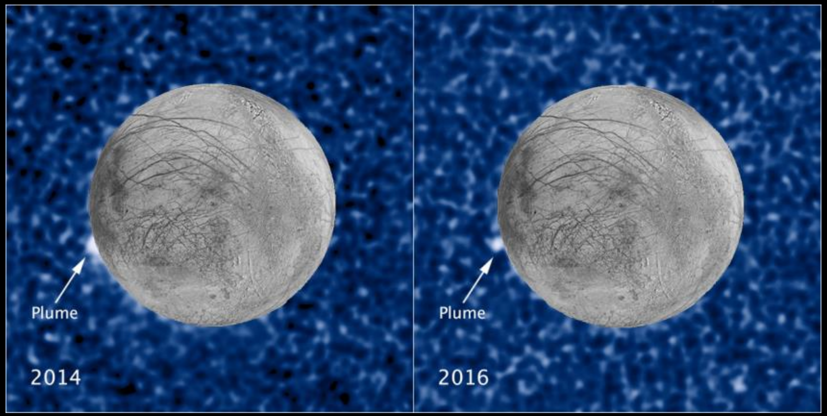
B

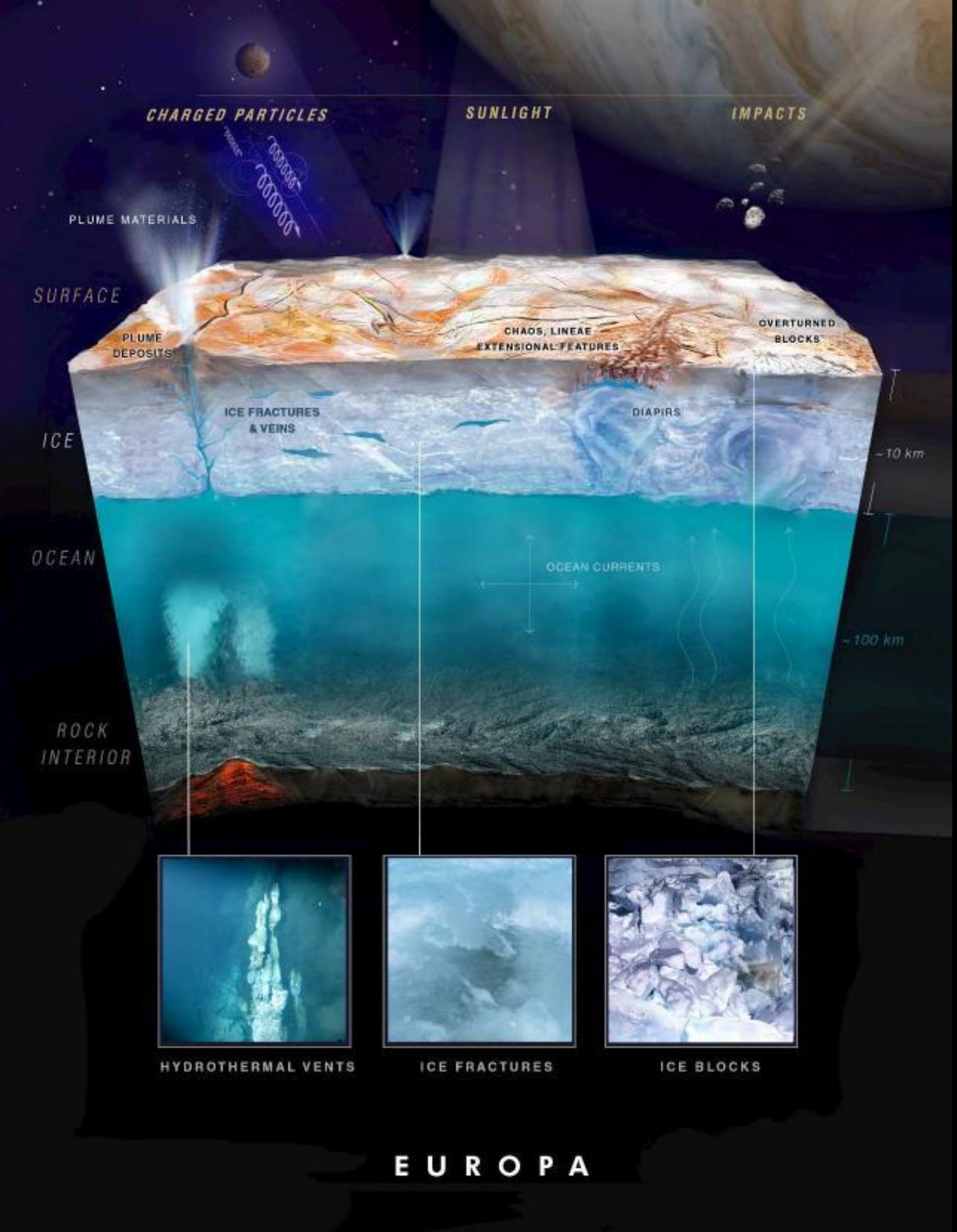
Callisto

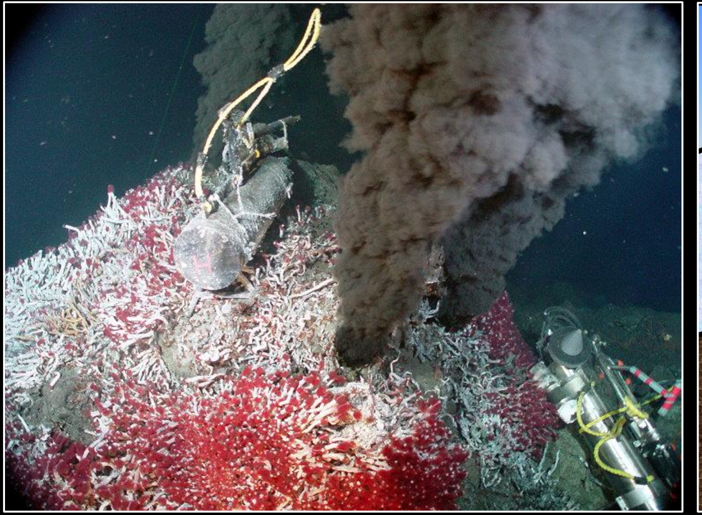


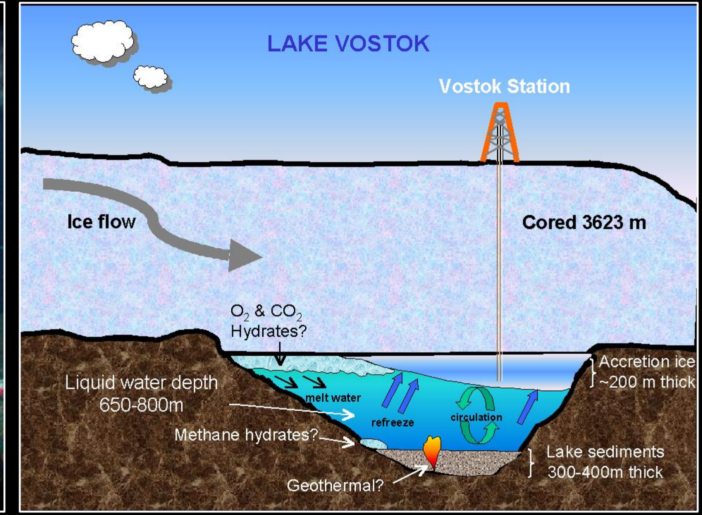
Conductive internal fluid

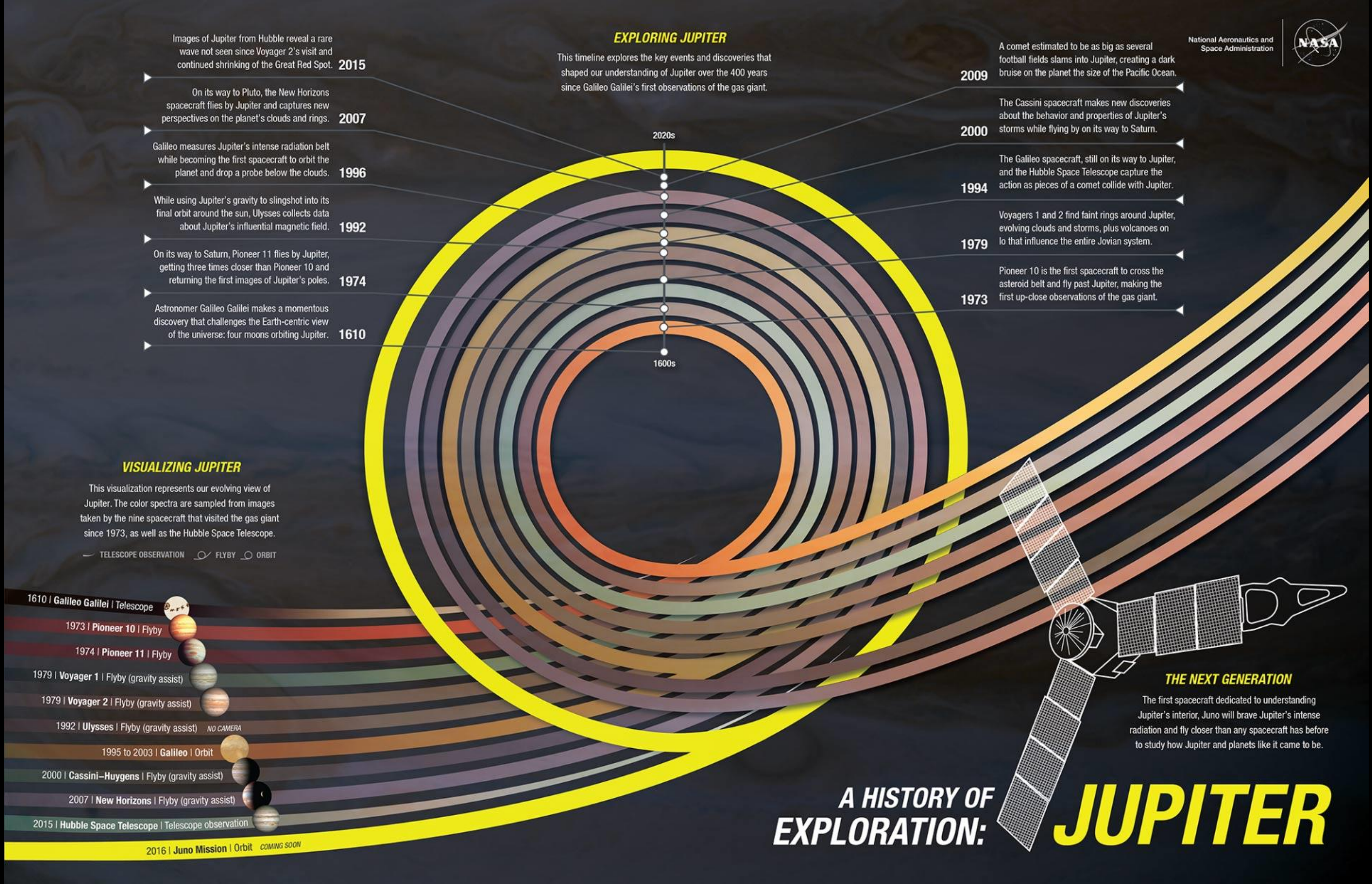
Plumes



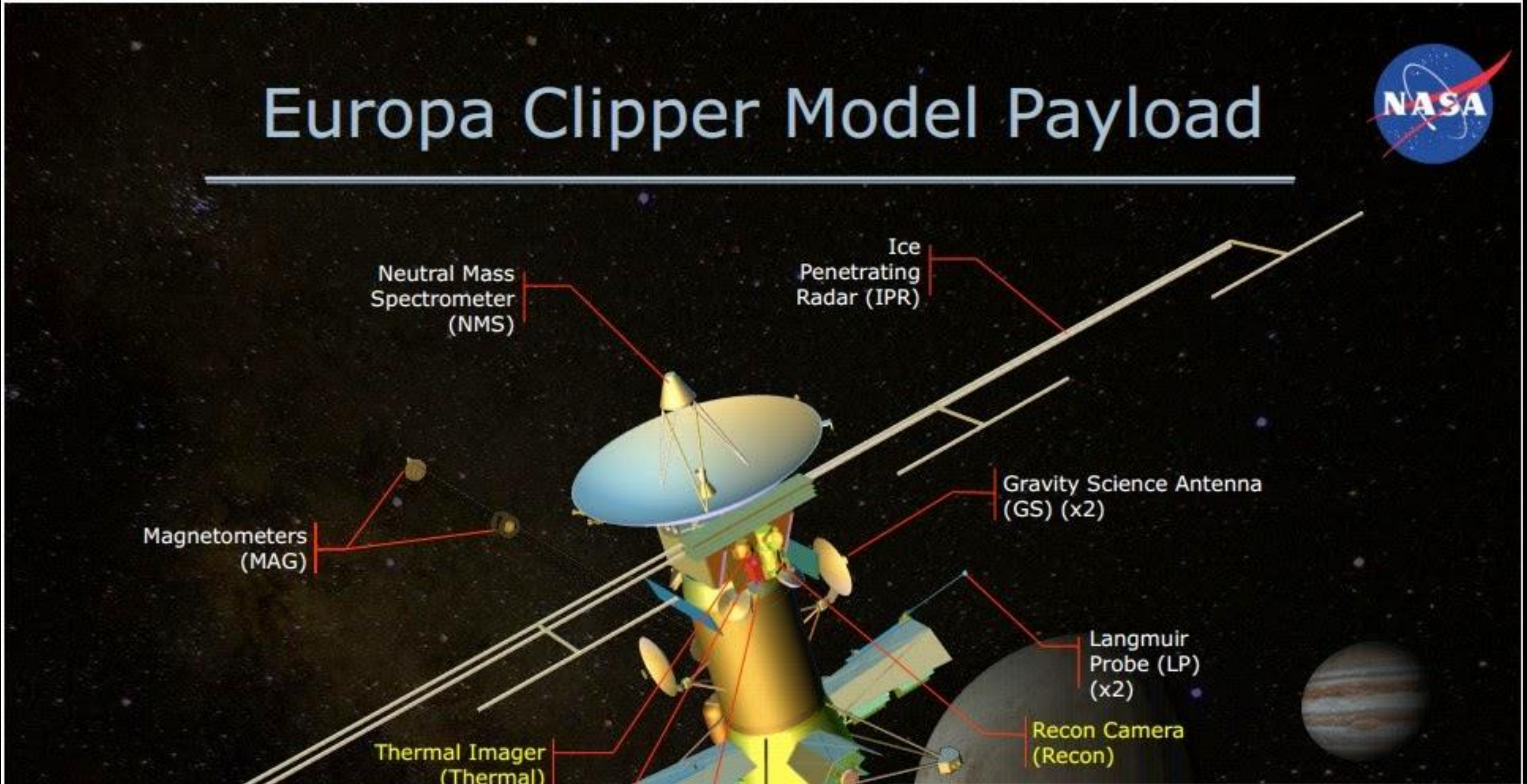

CHARGED PARTICLES
SUNLIGHT
IMPACTS
PLUME MATERIALS
SURFACE
PLUME DEPOSITS
CHAOS, LINEAE
EXTENSIONAL FEATURES
OVERTURNED BLOCKS
ICE
ICE FRACTURES & VEINS
DIAPIRS
~10 km
OCEAN
OCEAN CURRENTS
~100 km
ROCK INTERIOR
HYDROTHERMAL VENTS
ICE FRACTURES
ICE BLOCKS
EUROPA



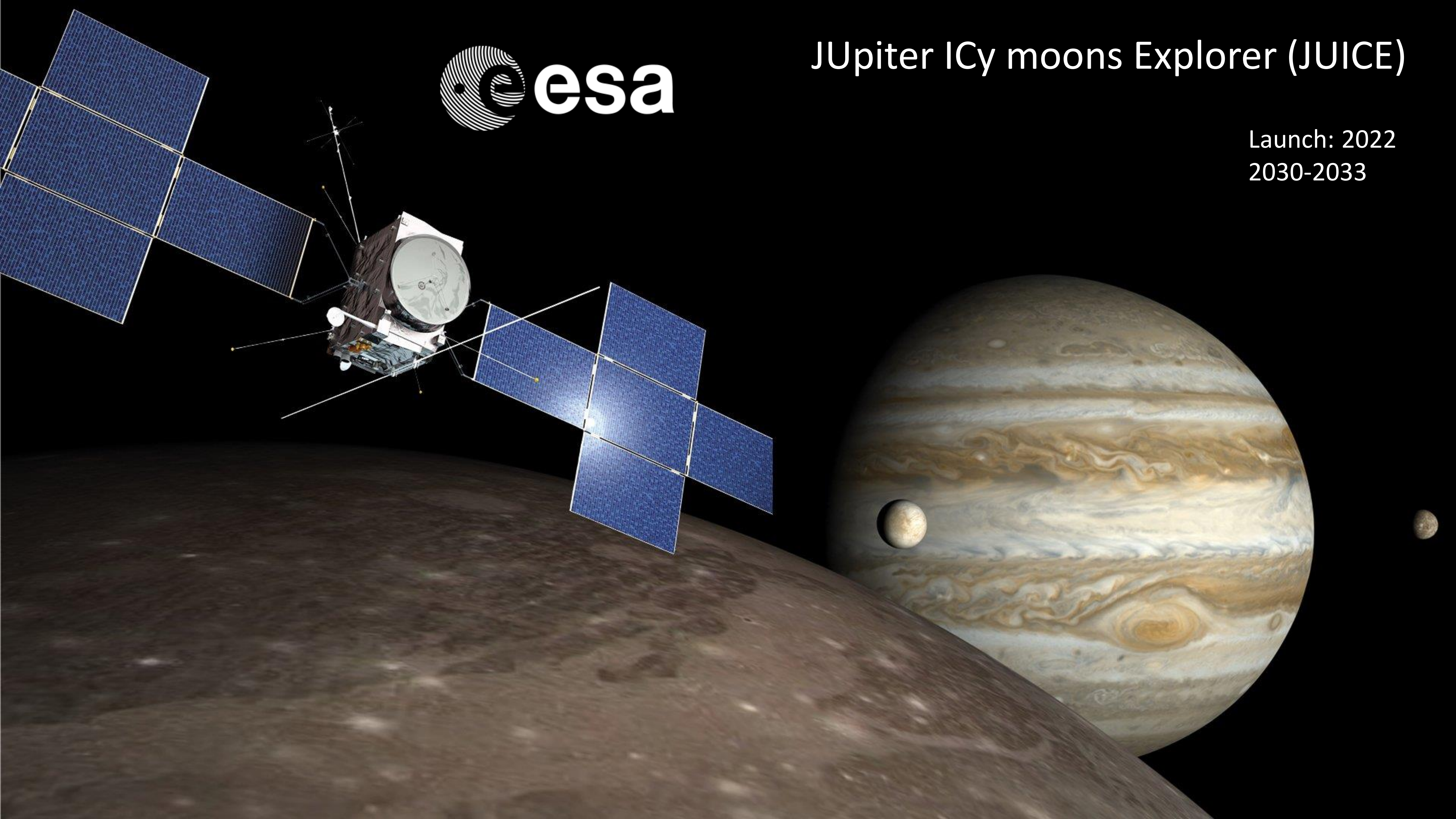

LAKE VOSTOK
Vostok Station
Ice flow
Cored 3623 m
O_2 & CO_2 Hydrates?
Accretion ice ~200 m thick
Liquid water depth 650-800m
melt water
refreeze
circulation
Methane hydrates?
Lake sediments 300-400m thick
Geothermal?

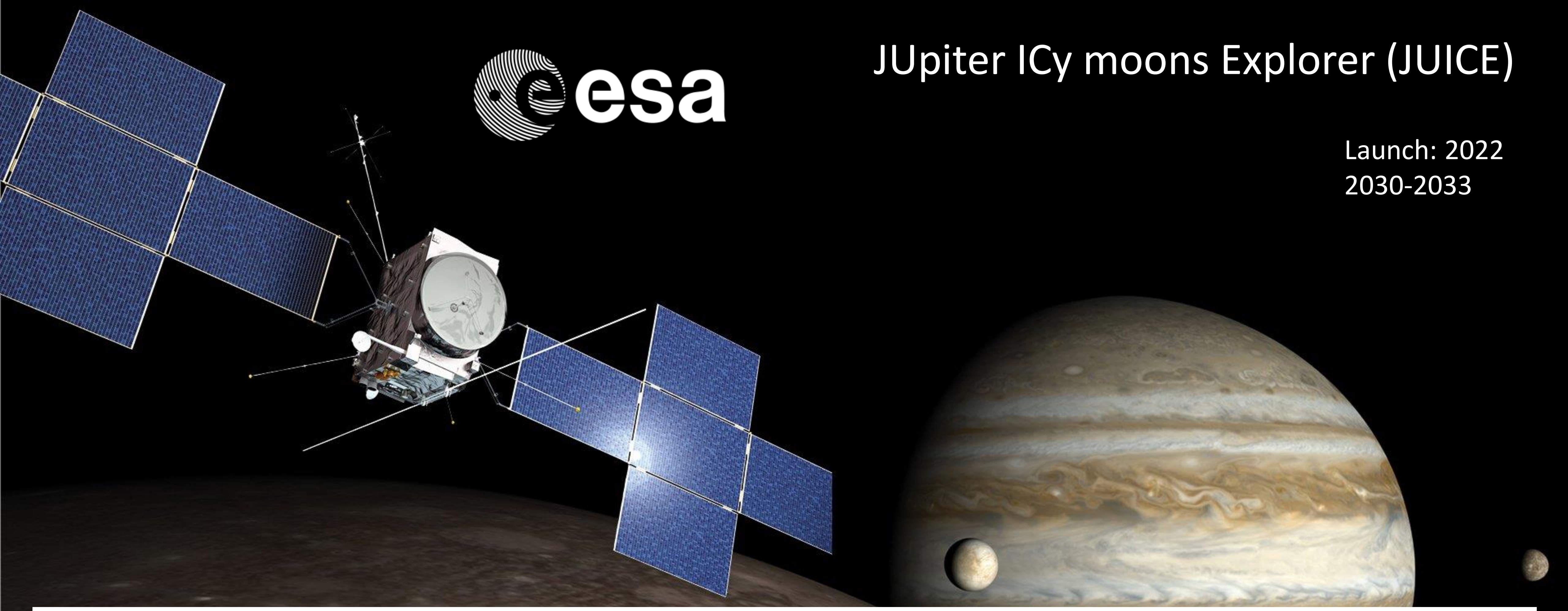

National Aeronautics and Space Administration
NASA
EXPLORING JUPITER
This timeline explores the key events and discoveries that shaped our understanding of Jupiter over the 400 years since Galileo Galilei's first observations of the gas giant.
2020s
1600s
Images of Jupiter from Hubble reveal a rare wave not seen since Voyager 2's visit and continued shrinking of the Great Red Spot. 2015
On its way to Pluto, the New Horizons spacecraft flies by Jupiter and captures new perspectives on the planet's clouds and rings. 2007
Galileo measures Jupiter's intense radiation belt while becoming the first spacecraft to orbit the planet and drop a probe below the clouds. 1996
While using Jupiter's gravity to slingshot into its final orbit around the sun, Ulysses collects data about Jupiter's influential magnetic field. 1992
On its way to Saturn, Pioneer 11 flies by Jupiter, getting three times closer than Pioneer 10 and returning the first images of Jupiter's poles. 1974
Astronomer Galileo Galilei makes a momentous discovery that challenges the Earth-centric view of the universe: four moons orbiting Jupiter. 1610
2009 A comet estimated to be as big as several football fields slams into Jupiter, creating a dark bruise on the planet the size of the Pacific Ocean.
2000 The Cassini spacecraft makes new discoveries about the behavior and properties of Jupiter's storms while flying by on its way to Saturn.
1994 The Galileo spacecraft, still on its way to Jupiter, and the Hubble Space Telescope capture the action as pieces of a comet collide with Jupiter.
1979 Voyagers 1 and 2 find faint rings around Jupiter, evolving clouds and storms, plus volcanoes on Io that influence the entire Jovian system.
1973 Pioneer 10 is the first spacecraft to cross the asteroid belt and fly past Jupiter, making the first up-close observations of the gas giant.
VISUALIZING JUPITER
This visualization represents our evolving view of Jupiter. The color spectra are sampled from images taken by the nine spacecraft that visited the gas giant since 1973, as well as the Hubble Space Telescope.
TELESCOPE OBSERVATION
FLYBY
ORBIT
1610 | Galileo Galilei | Telescope
1973 | Pioneer 10 | Flyby
1974 | Pioneer 11 | Flyby
1979 | Voyager 1 | Flyby (gravity assist)
1979 | Voyager 2 | Flyby (gravity assist)
1992 | Ulysses | Flyby (gravity assist) NO CAMERA
1995 to 2003 | Galileo | Orbit
2000 | Cassini–Huygens | Flyby (gravity assist)
2007 | New Horizons | Flyby (gravity assist)
2015 | Hubble Space Telescope | Telescope observation
2016 | Juno Mission | Orbit COMING SOON
THE NEXT GENERATION
The first spacecraft dedicated to understanding Jupiter's interior, Juno will brave Jupiter's intense radiation and fly closer than any spacecraft has before to study how Jupiter and planets like it came to be.
A HISTORY OF EXPLORATION: JUPITER

Launch: 2024
2030-2034



Launch: 2025?


JUpiter ICy moons Explorer (JUICE)
Launch: 2022
2030-2033



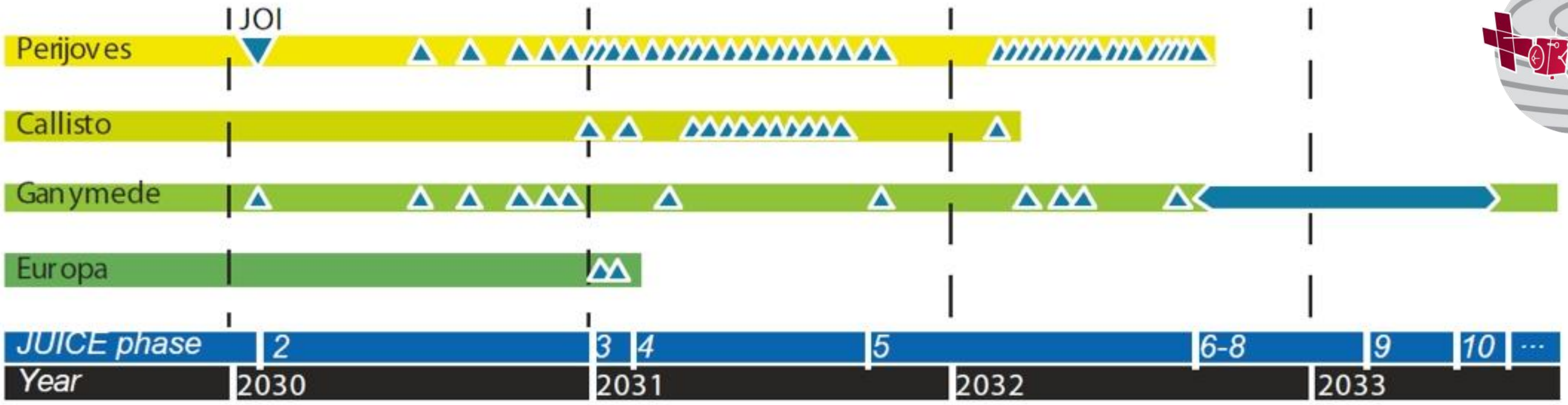
JUpiter ICy moons Explorer (JUICE)

esa

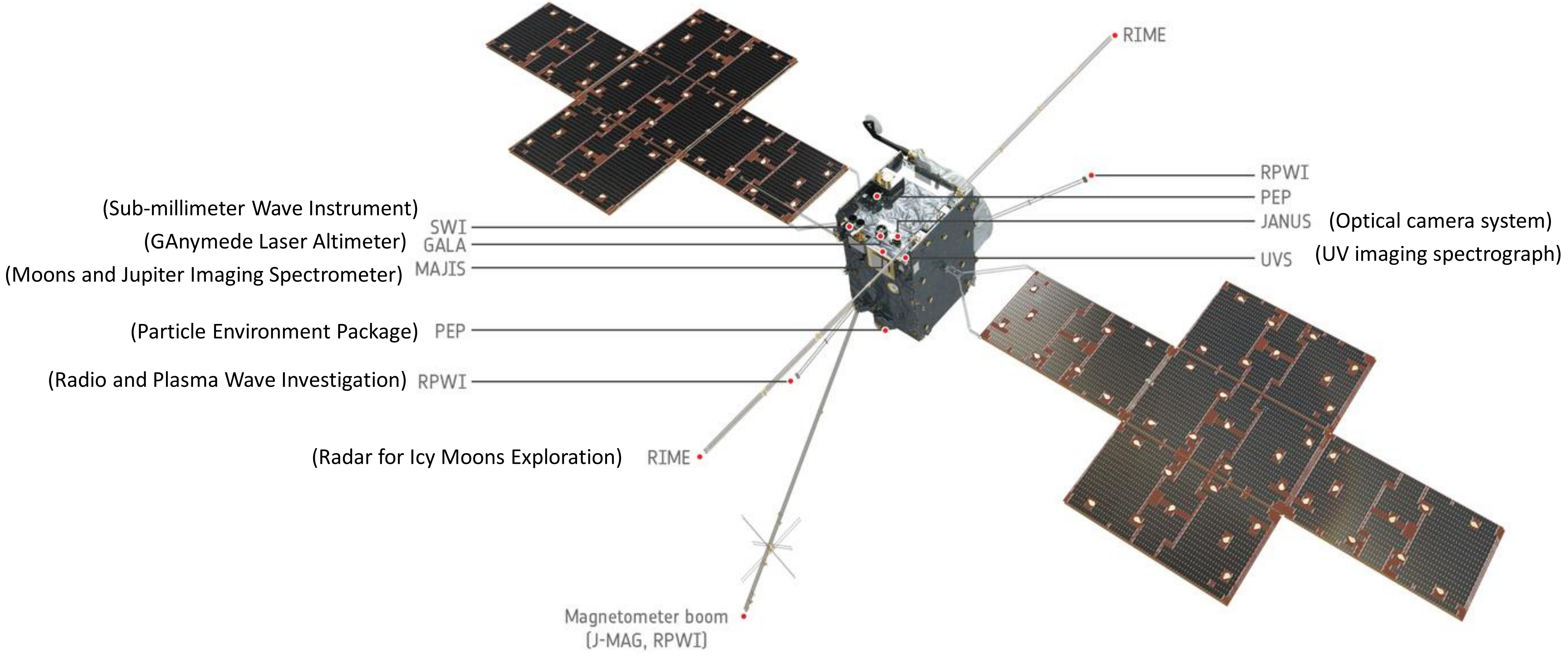
Launch: 2022
2030-2033

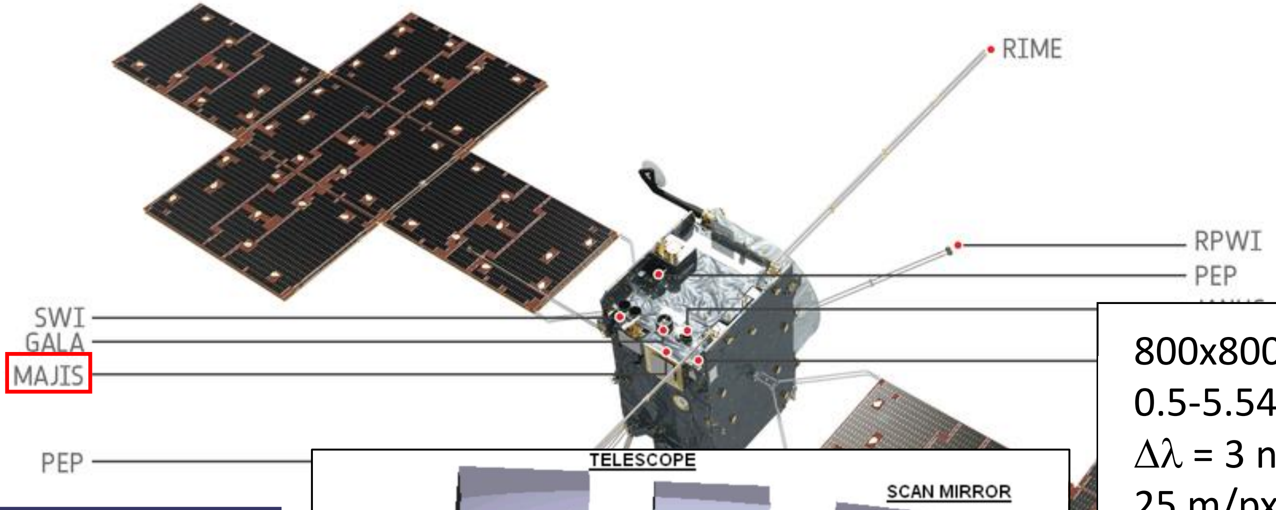
Main objectives:

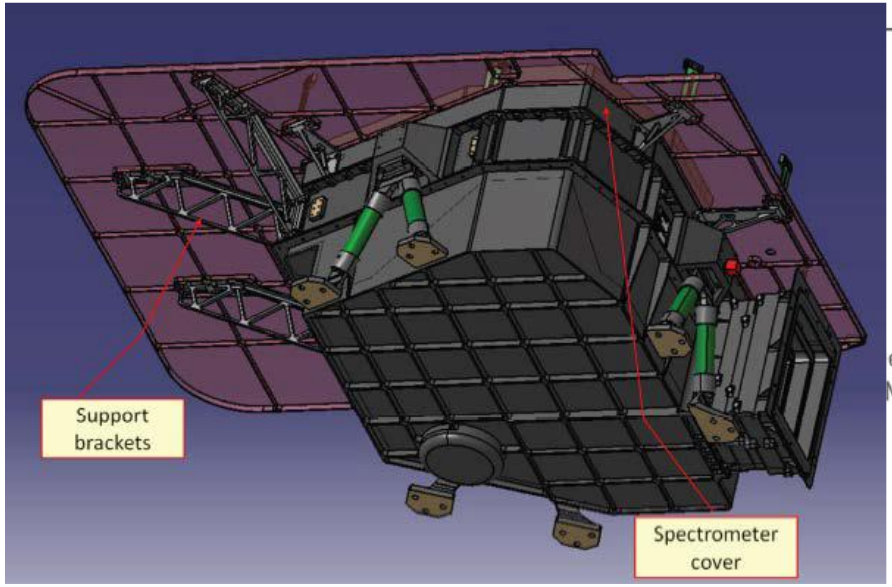
1) Conduct a comparative study of Ganymede, Callisto and Europa, with an emphasis on the characterization of Ganymede as a planetary object and possible habitat,
2) Provide a complete spatio-temporal characterization of the giant, rotating magnetosphere, and of the meteorology, chemistry and structure of Jupiter's gaseous atmosphere,
3) Study coupling processes inside the Jupiter system, with an emphasis on the two key coupling processes within that system: the tidal effects that couple Jupiter with its satellites, and the electrodynamic interactions that couple Jupiter and its satellites with their atmospheres, subsurface oceans, magnetospheres and magnetodisc.

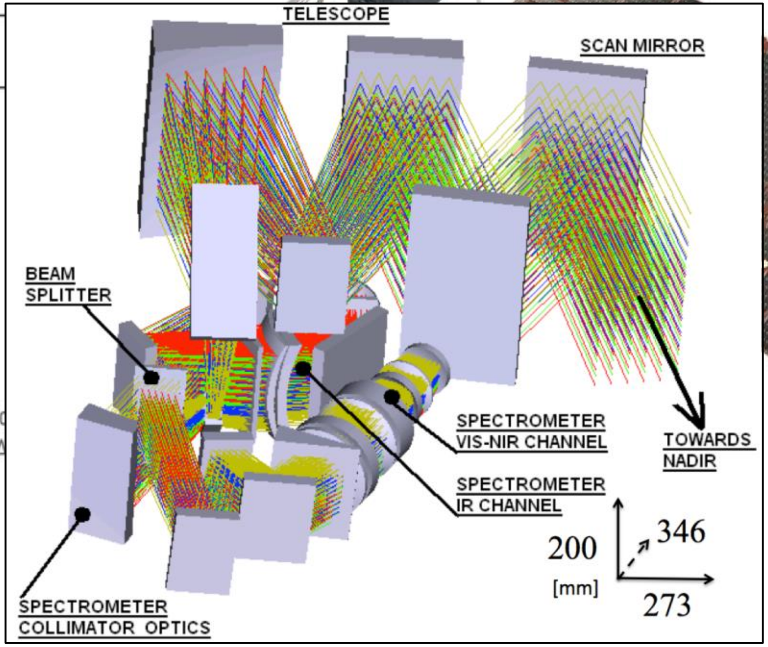


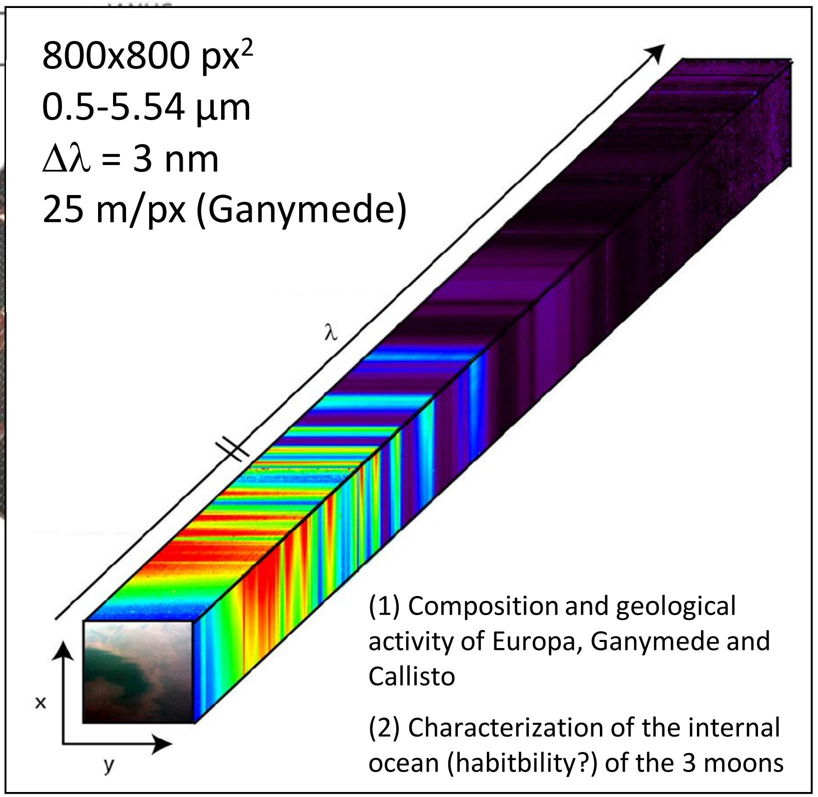
- June-August 2022: launch from Kourou, French Guyana
- January 2030: Jupiter orbit insertion
- 2030-2032: Icy moons flybys (13x Ganymede & Callisto)
- 2031: two flybys of Europa
- September 2032: Ganymede orbit insertion (never accomplished so far!)
- February 2033: Circular orbits around Ganymede (500 km altitude)
- February 2034: End of the nominal mission

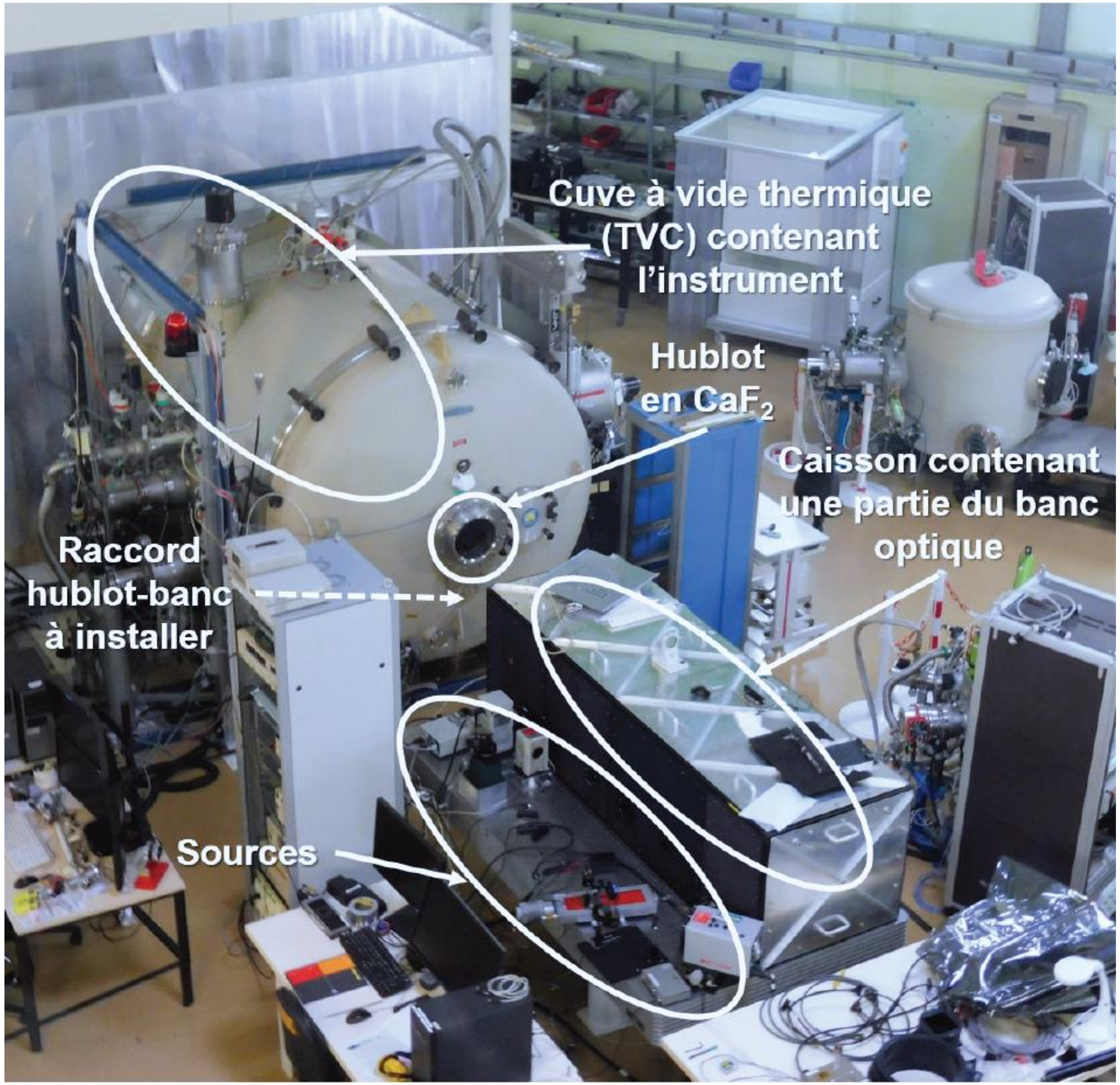

RIME
RPWI
PEP
JANUS (Optical camera system)
UVS (UV imaging spectrograph)
(Sub-millimeter Wave Instrument) SWI
(GAnymede Laser Altimeter) GALA
(Moons and Jupiter Imaging Spectrometer) MAJIS
(Particle Environment Package) PEP
(Radio and Plasma Wave Investigation) RPWI
(Radar for Icy Moons Exploration) RIME
Magnetometer boom
(J-MAG, RPWI)


RIME
RPWI
PEP
SWI
GALA
MAJIS
(Moons and Jupiter Imaging Spectrometer)
PEP


Support brackets
Spectrometer cover


TELESCOPE
SCAN MIRROR
BEAM SPLITTER
SPECTROMETER VIS-NIR CHANNEL
SPECTROMETER IR CHANNEL
TOWARDS NADIR
SPECTROMETER COLLIMATOR OPTICS
200
[mm]
346
273


800x800 px²
0.5-5.54 µm
Δλ = 3 nm
25 m/px (Ganymede)
λ
x
y
(1) Composition and geological activity of Europa, Ganymede and Callisto
(2) Characterization of the internal ocean (habitbility?) of the 3 moons



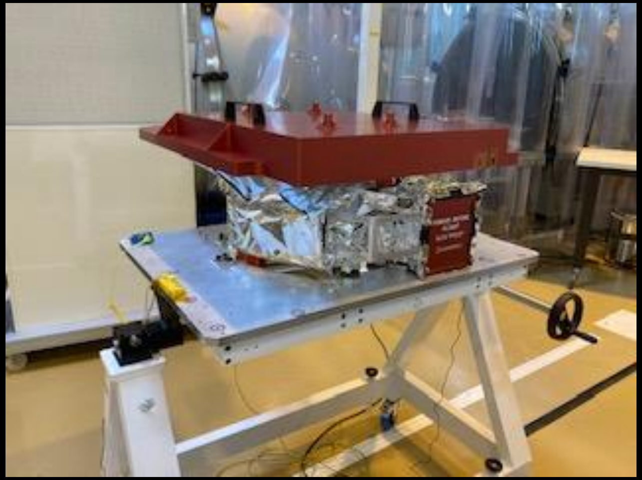
Calibration campaign (IAS – UPS):

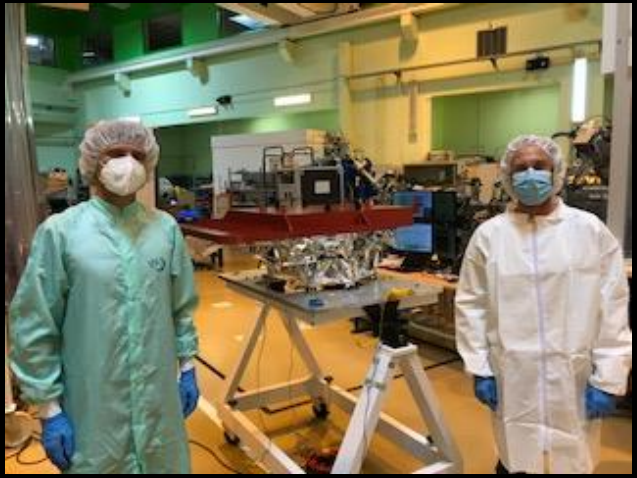
- 1.5 year of preparation (optical bench, simulations, sequences)
- 4 intense weeks (end-August to mid-September 2021) before shipping MAJIS to Airbus in Toulouse and before its final integration on JUICE platform

Full characterization of the instrument performances and calibration functions in a few “spatial” configurations (controlling temperature and pressure): radiometric, spatial, and spectral, and Transfer Function estimation.

During calibration activities

Leaving to Toulouse





Go MAJIS! For beautiful images and spectra!