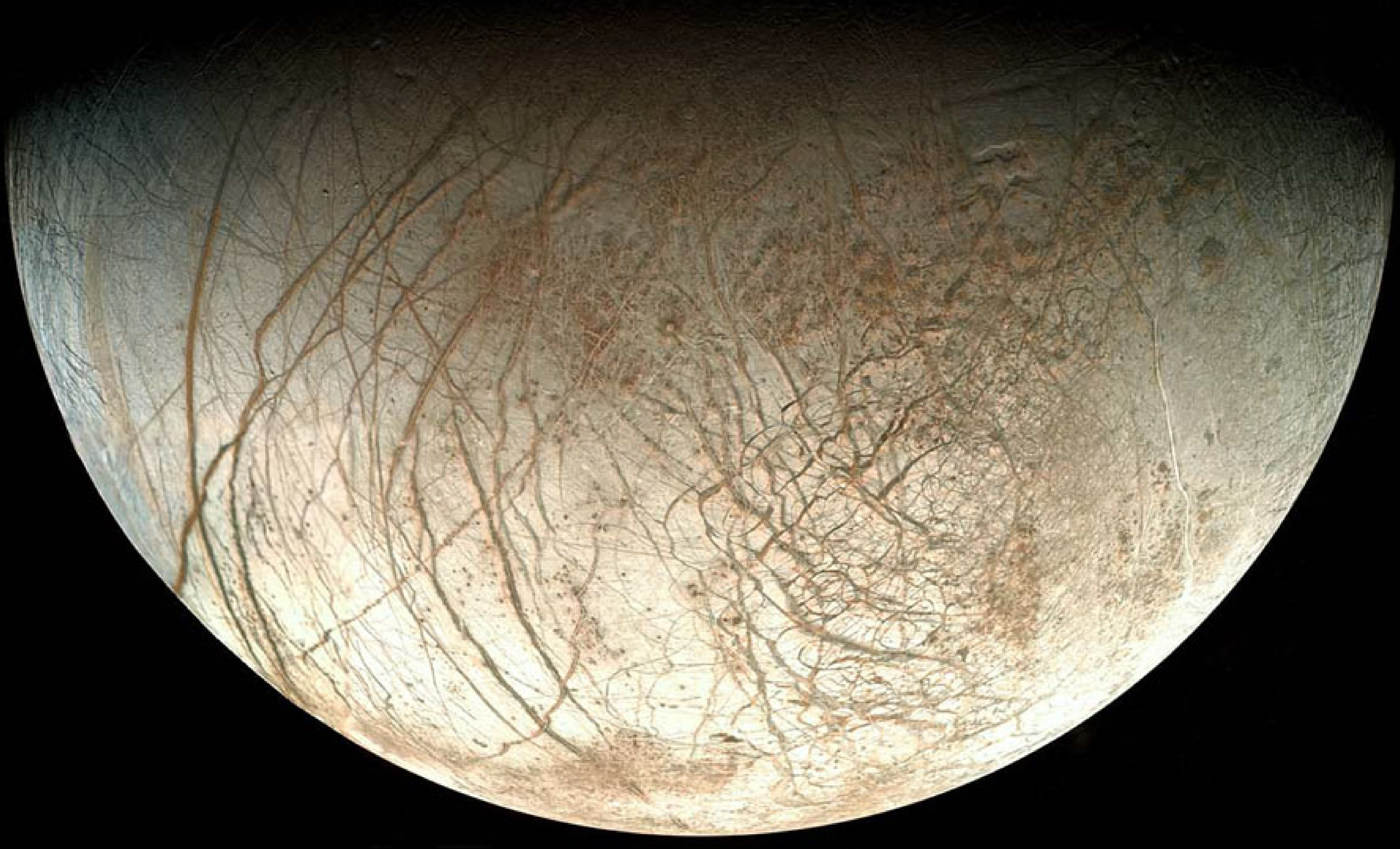
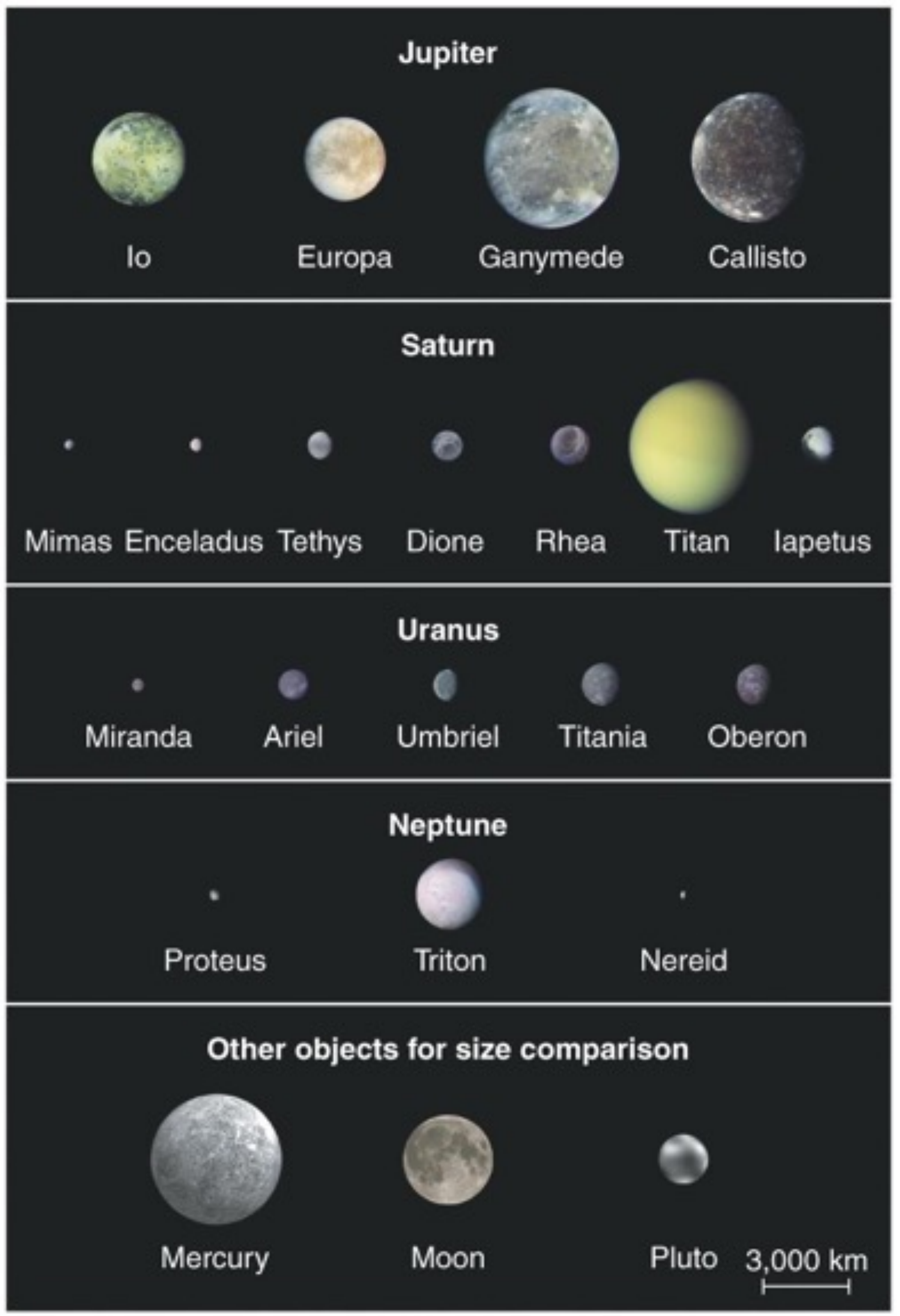
Life on Jovian Moons




30. mane
3. mane
3. Ho. 5.
4. mane.
6. mane
8. mane H. 13.
10. mane.
11.
12. H. 4 vesp:
13. mane'

Which Jovian Moons Could Be Habitable?

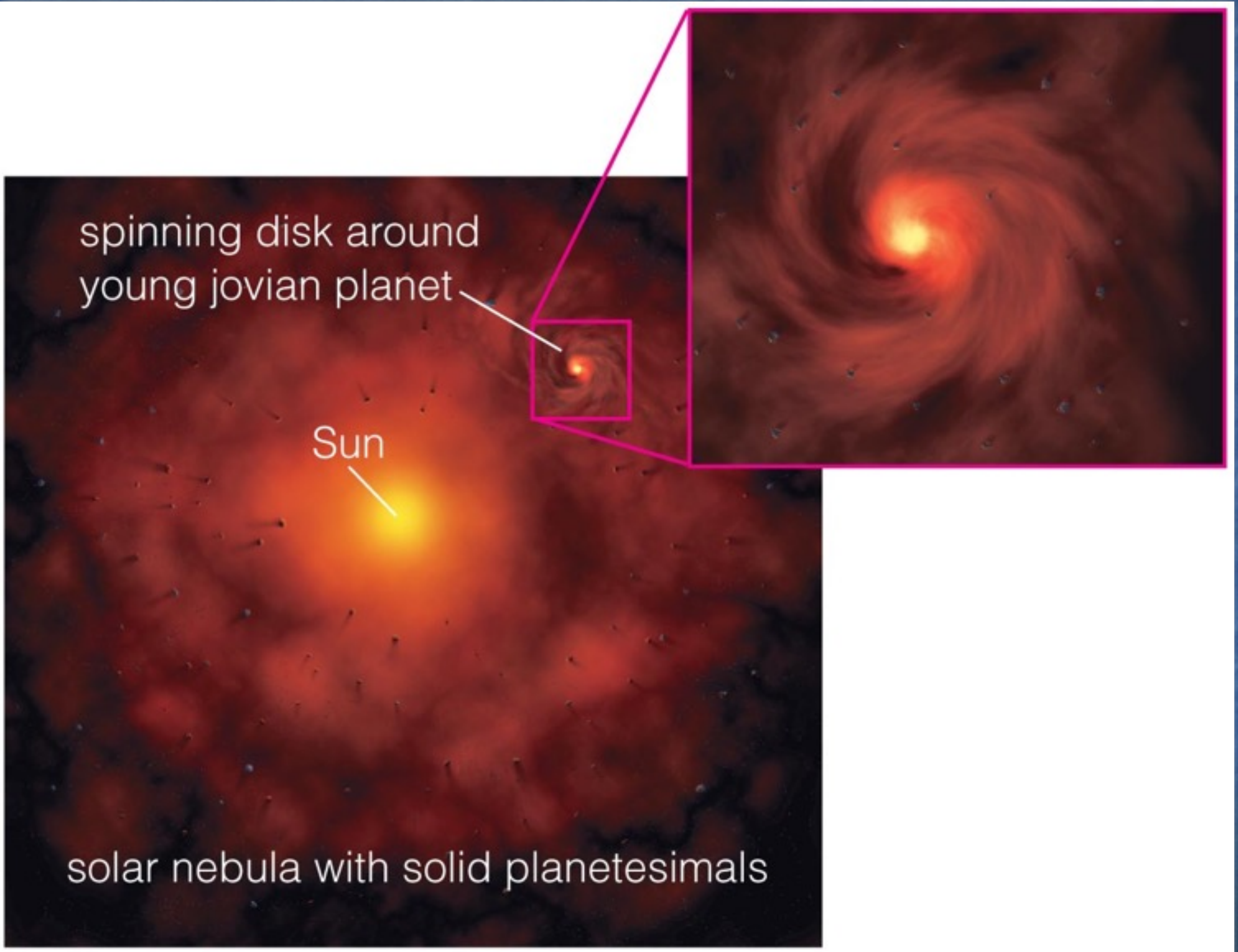
- There are 169 known moons in the solar system
  - 3 orbit terrestrial planets
  - 162 orbit Jovian planets
  - 4 orbit dwarf planets
- Almost all of the Jovian moons are too small to be habitable
  - they are unlikely to have liquid water



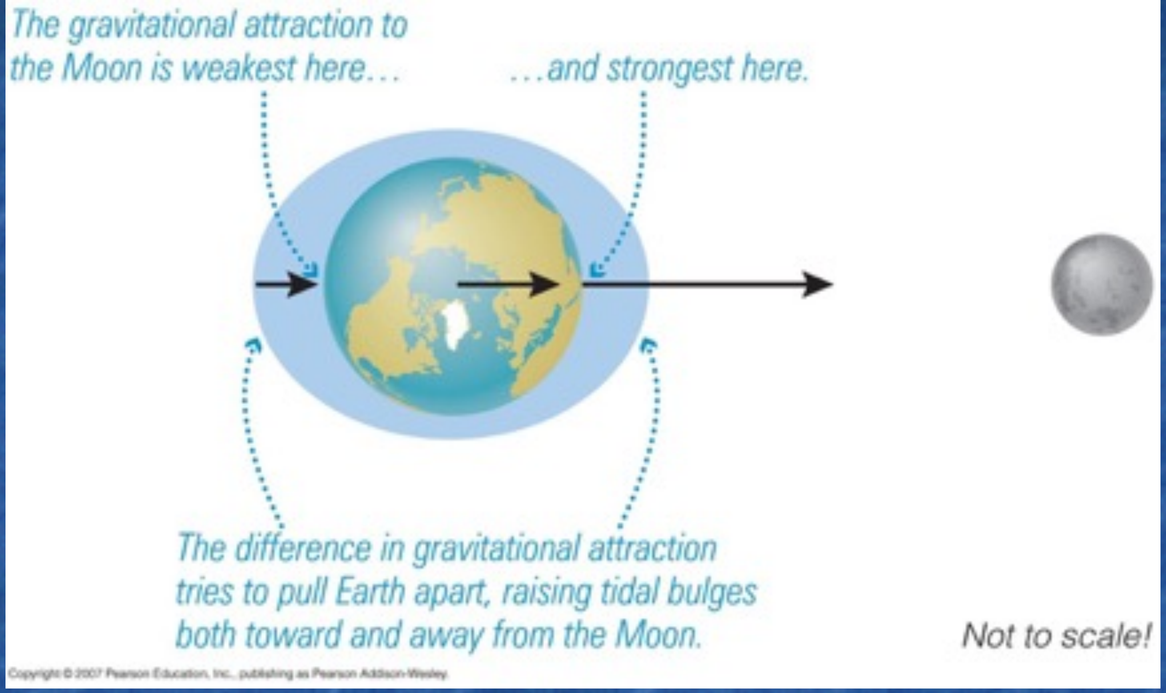
Spacecraft visits to Jovian moons

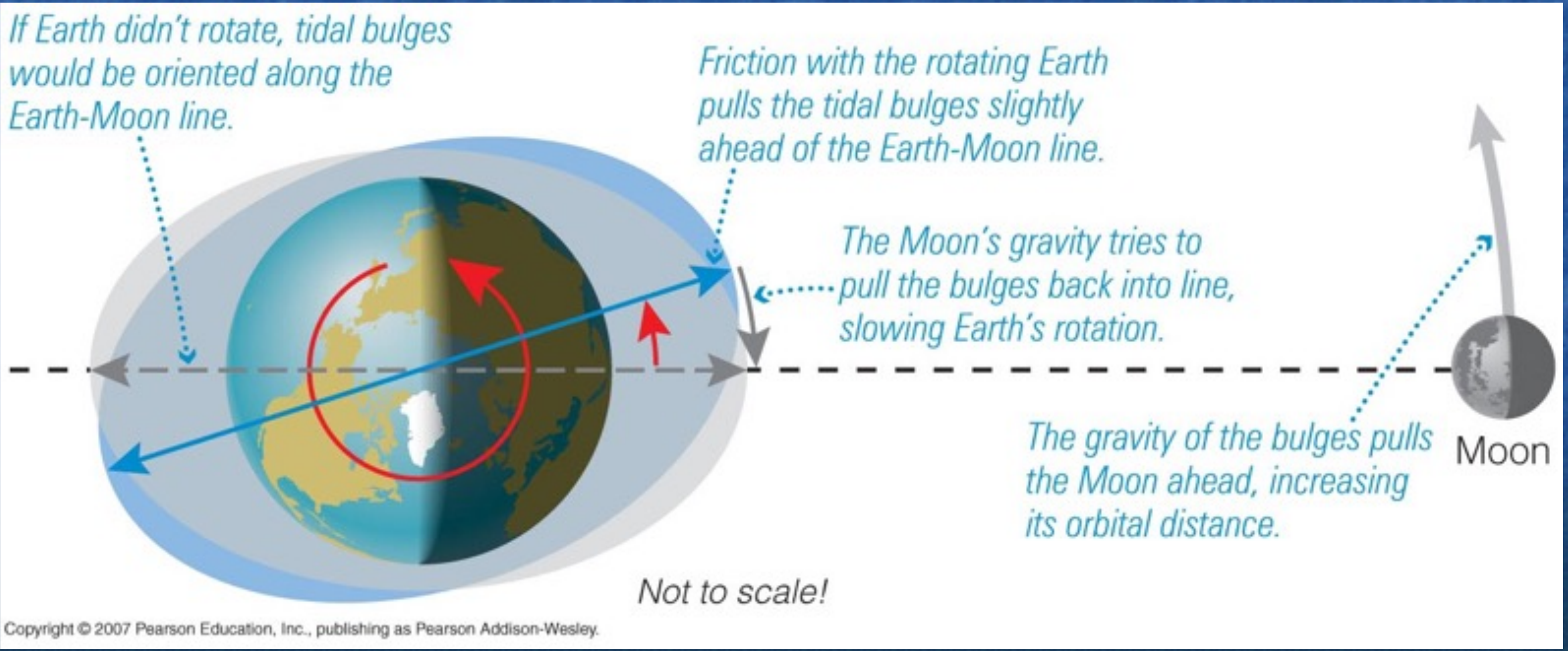
- Pioneer 10, 11 and Voyager 1, 2 were flyby missions.
- Galileo was a Jupiter orbiter mission. In 1995 it launched the Galileo probe into Jupiter's atmosphere. In 2003 Galileo was deliberately sent into Jupiter's atmosphere for "sterile" disposal.
- Cassini is a current Saturn orbiter mission. In 2005 it launched the Huygens lander to the surface of Titan.

Formation of the Galilean Moons

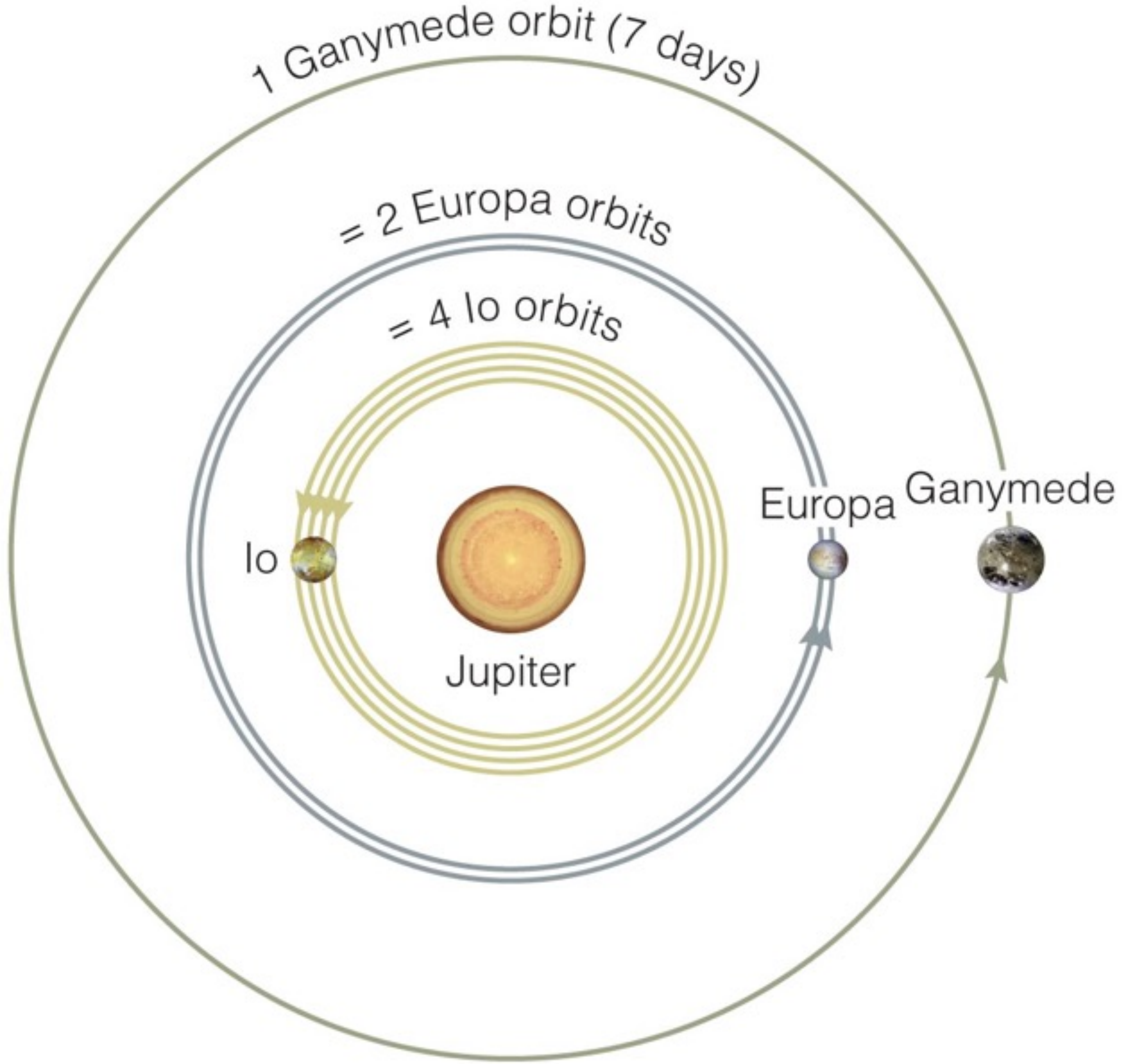


Tidal locking

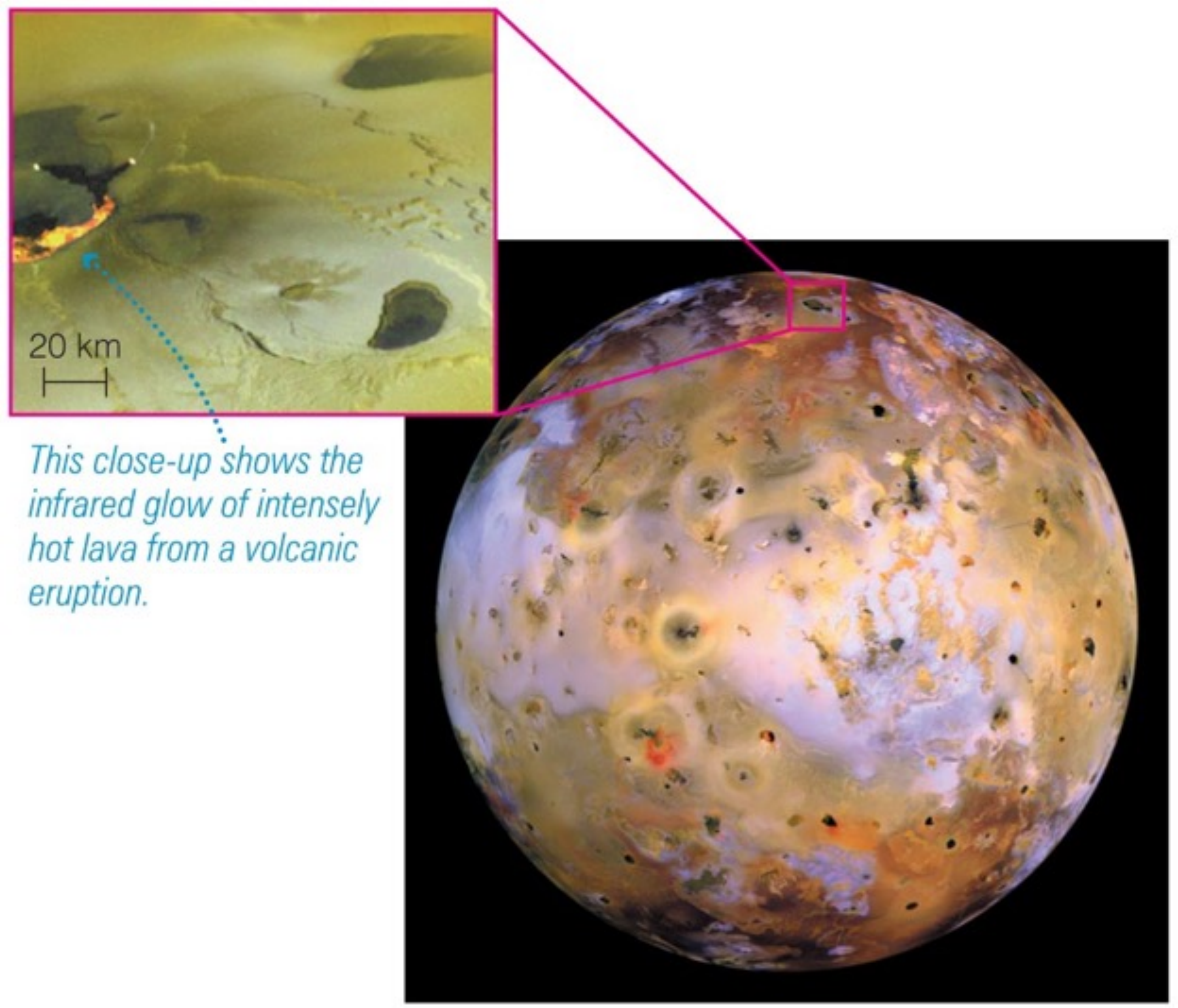


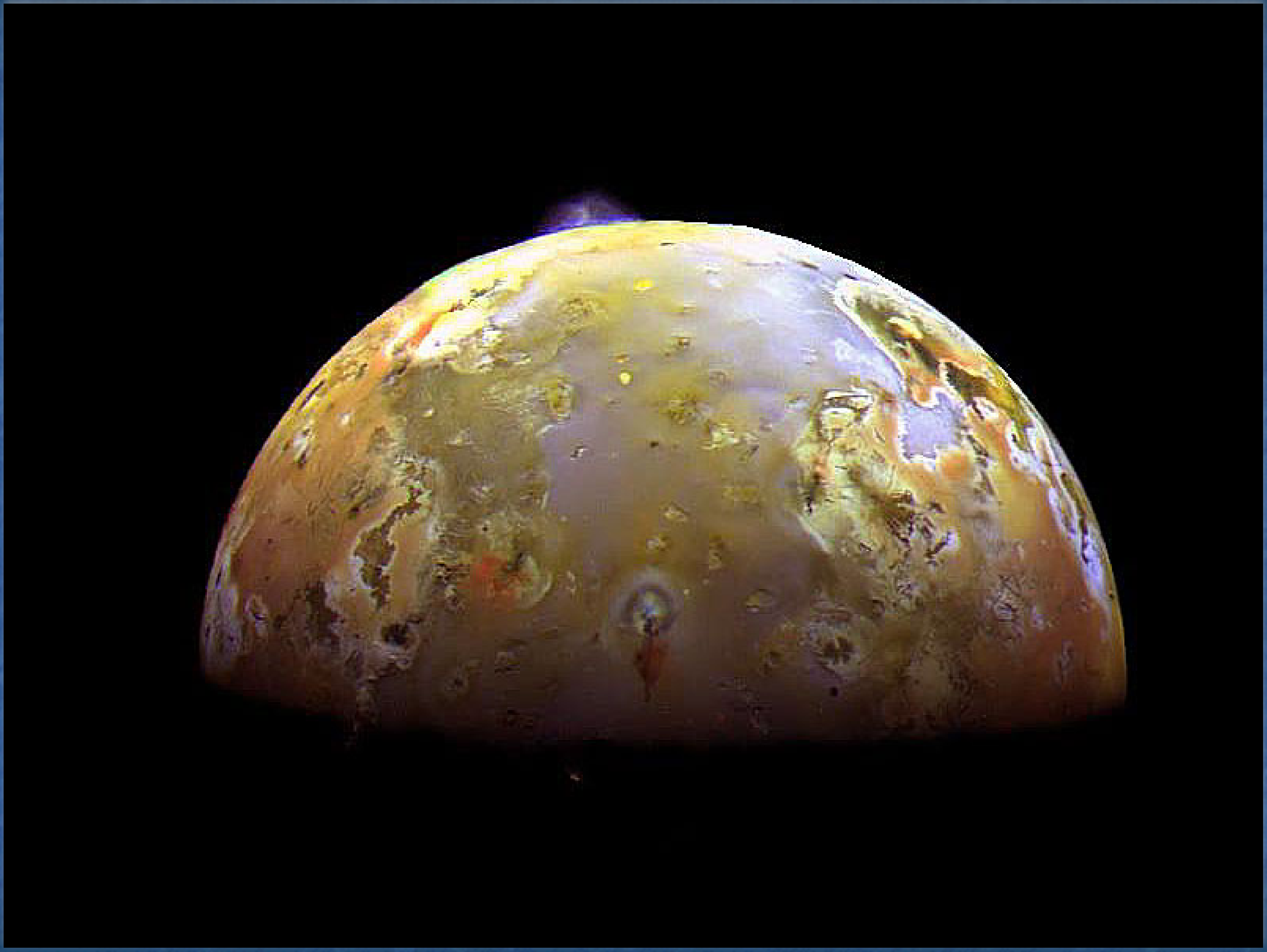


Resonances of Io, Europa and Ganymede

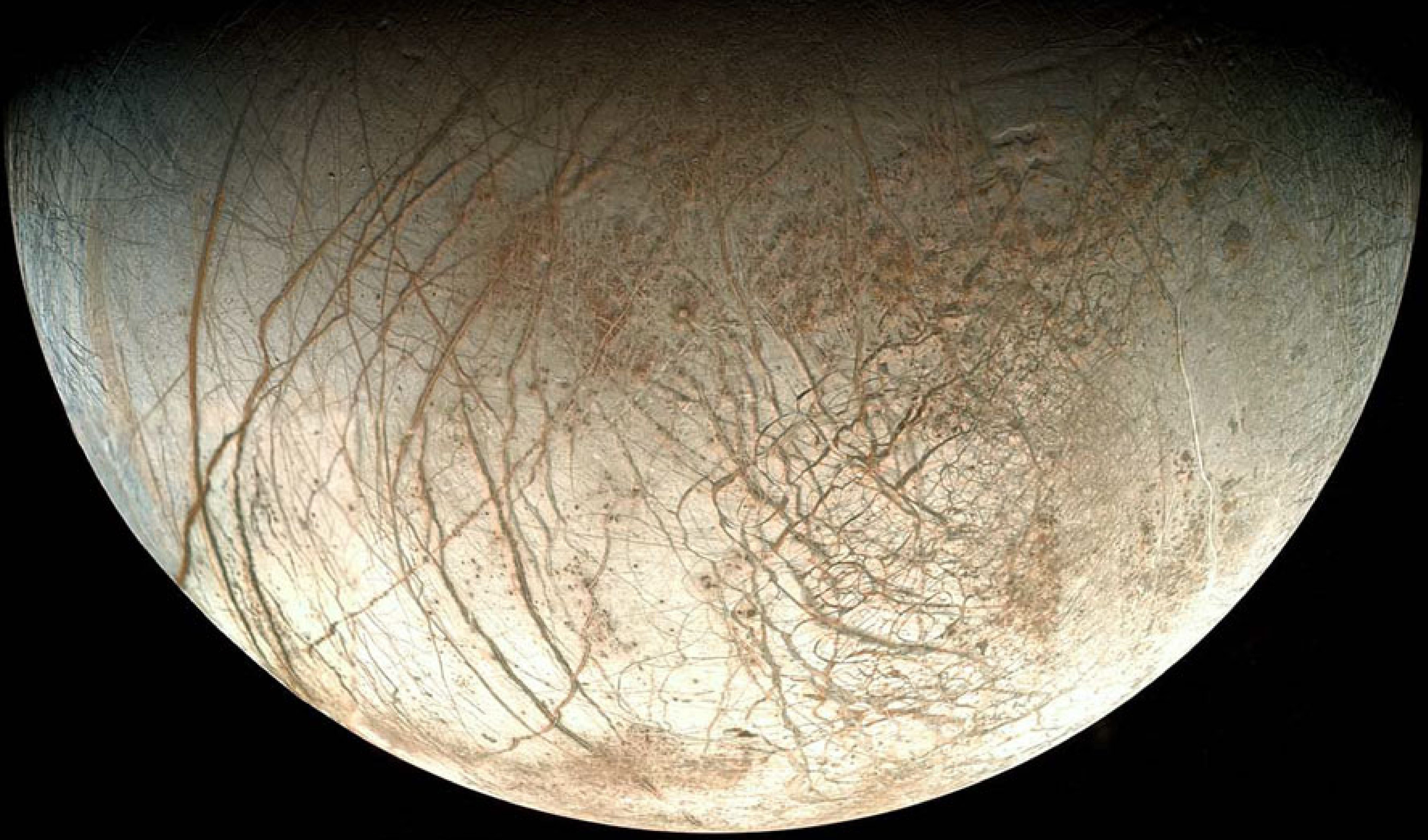


Io

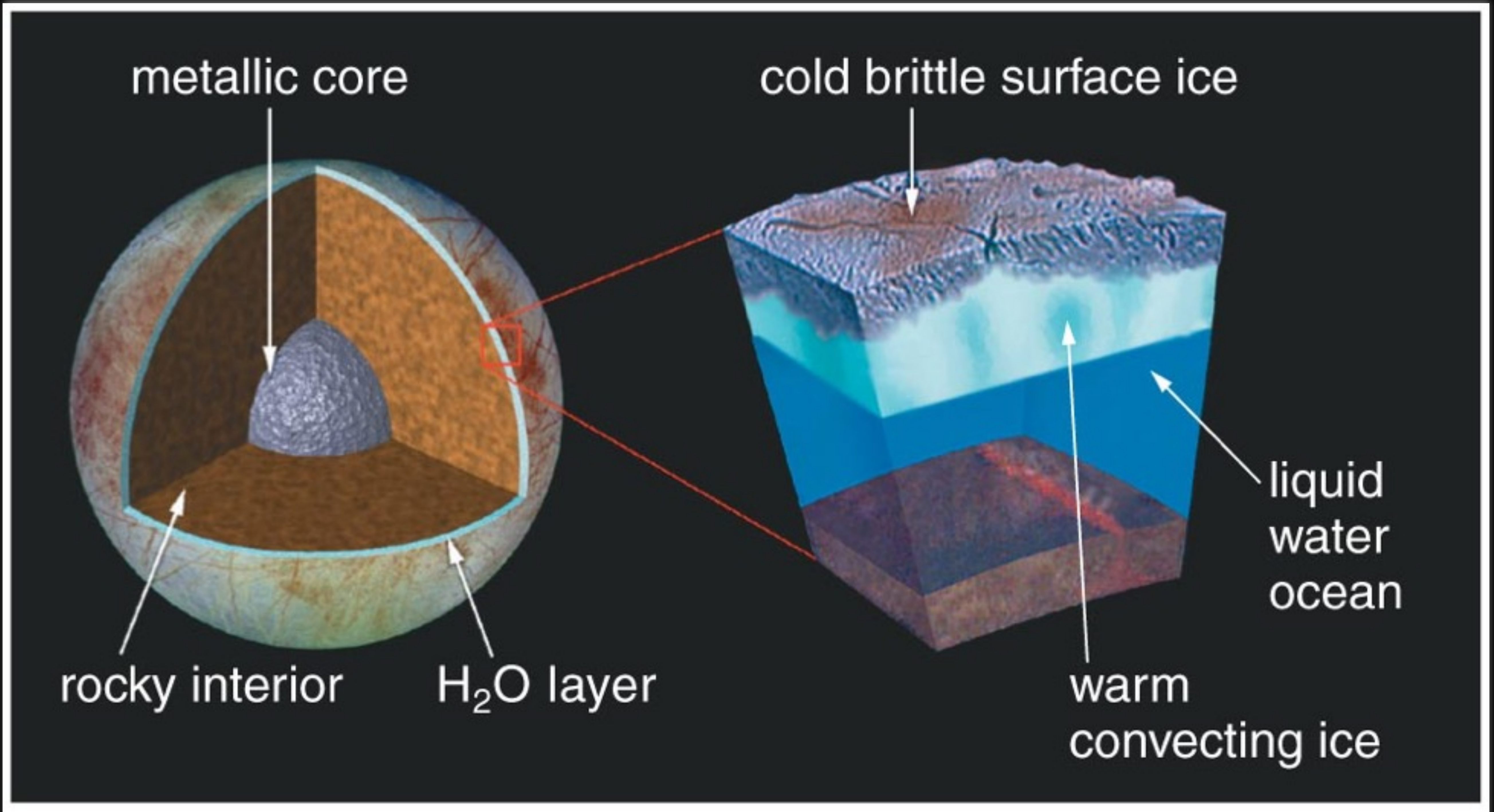

20 km
This close-up shows the infrared glow of intensely hot lava from a volcanic eruption.



Europa

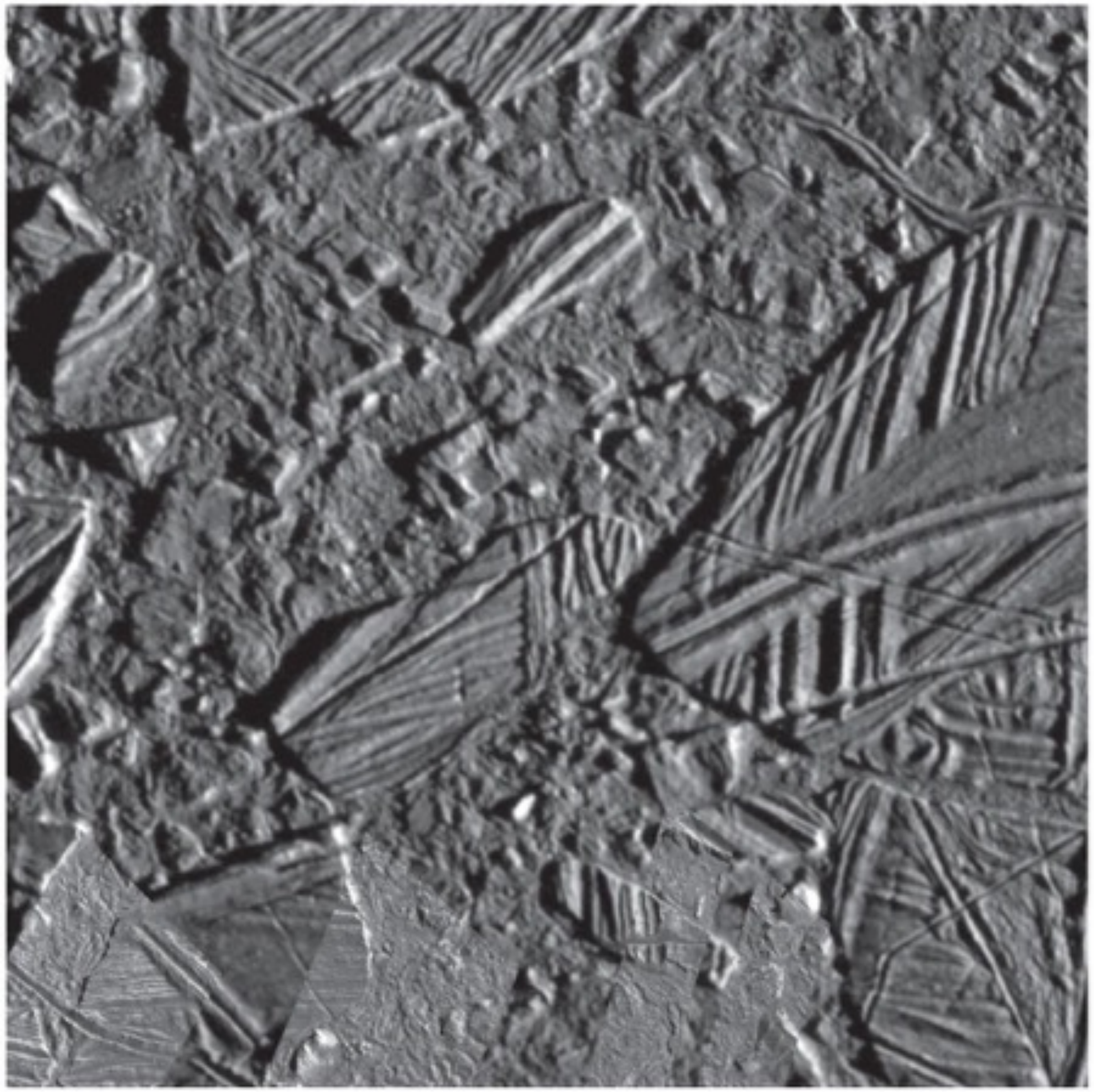


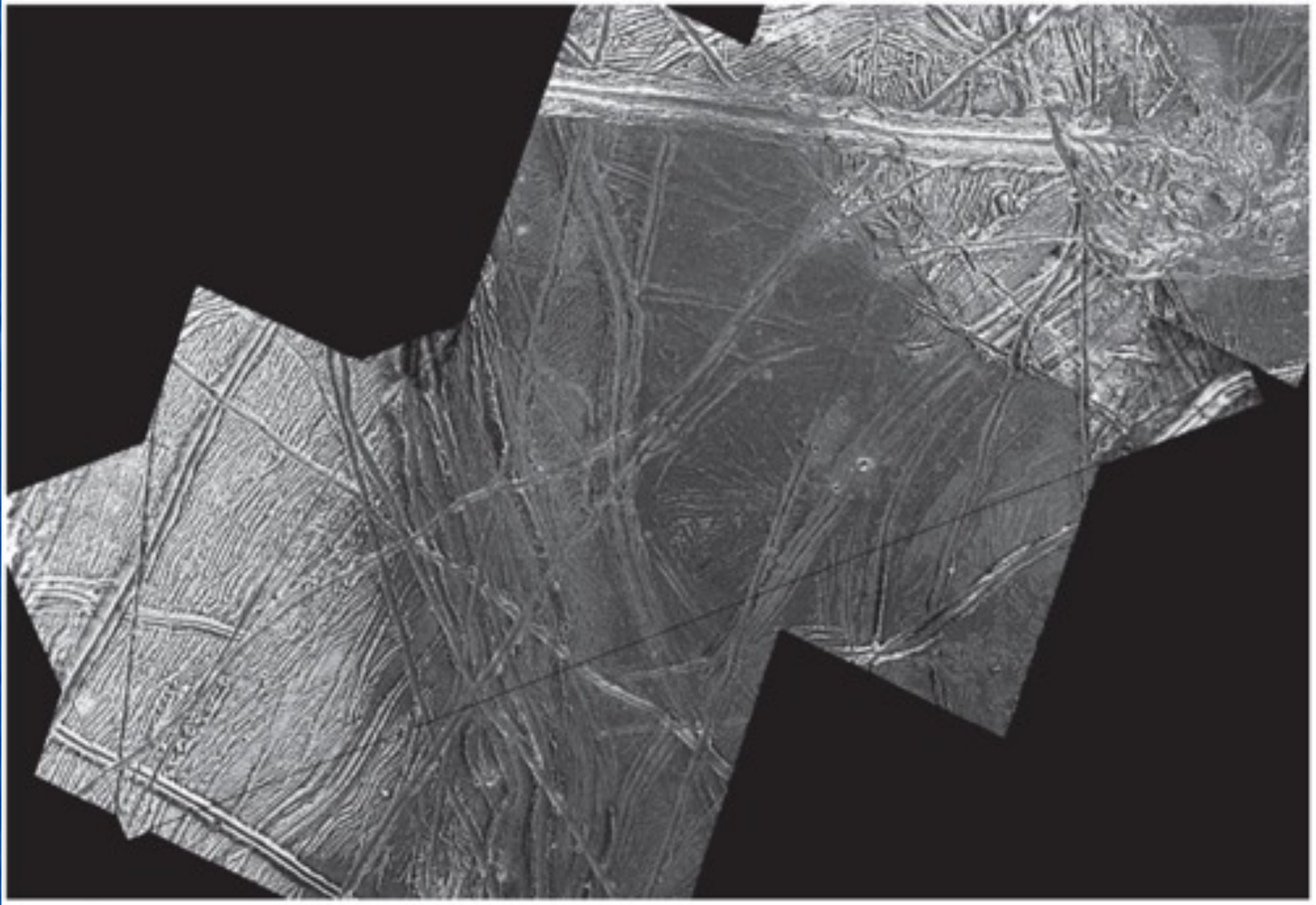
The Interior of Europa



Liquid water on Europa?

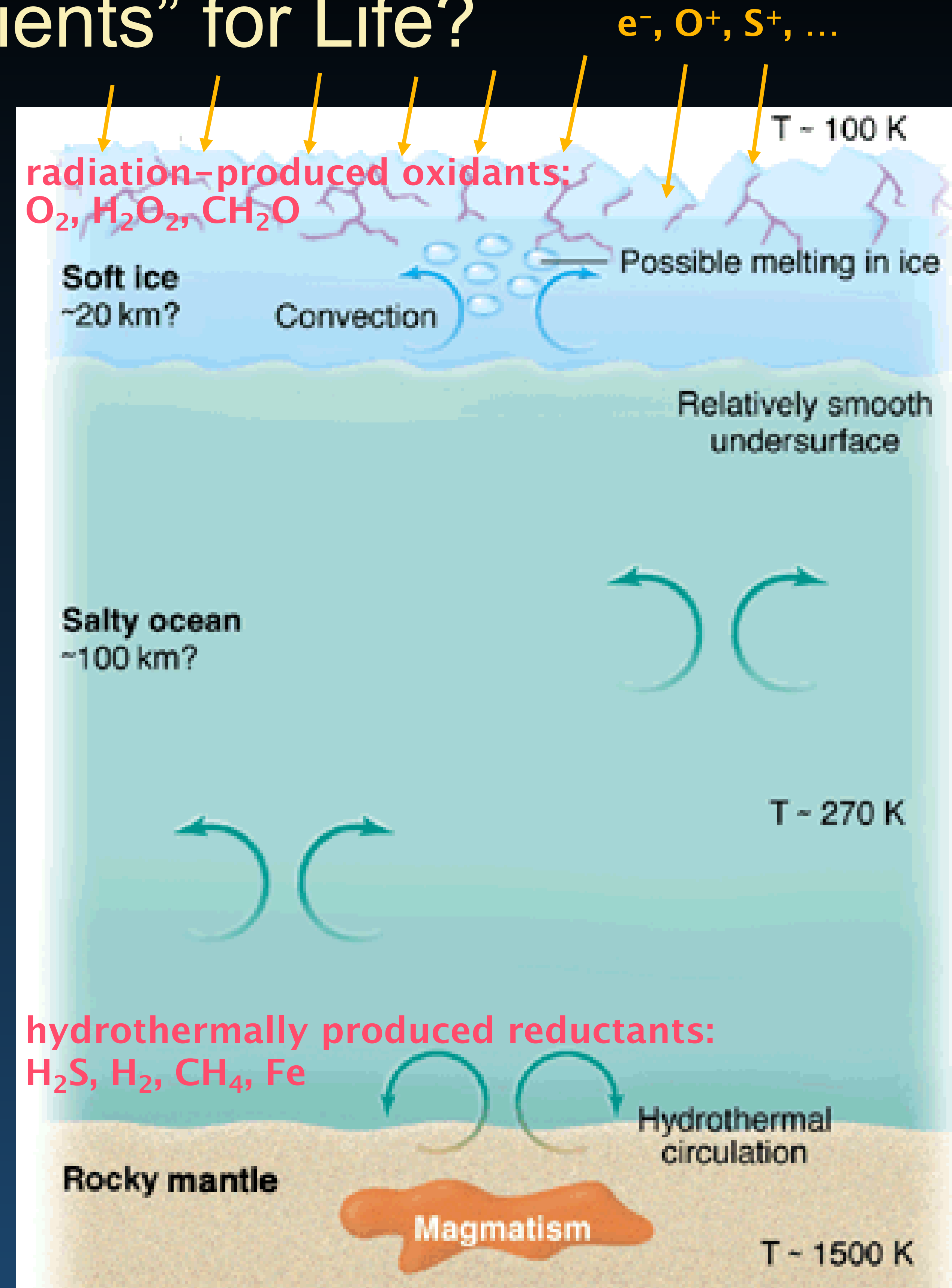
- Re-surfacing: crater counts are low and suggest the surface is tens of millions of years old. Surface features suggest ice floes and upwelling liquid water.
- Gravity Doppler data suggest a water surface over a rocky core.
- Calculations of tidal heating suggest enough energy to maintain liquid water.
- The Europan magnetic field is not fixed. It fluctuates as Jupiter rotates. This suggests the Europan field is induced by Jupiter's. To achieve this Europa must have a salty, liquid water ocean some 100km deep.



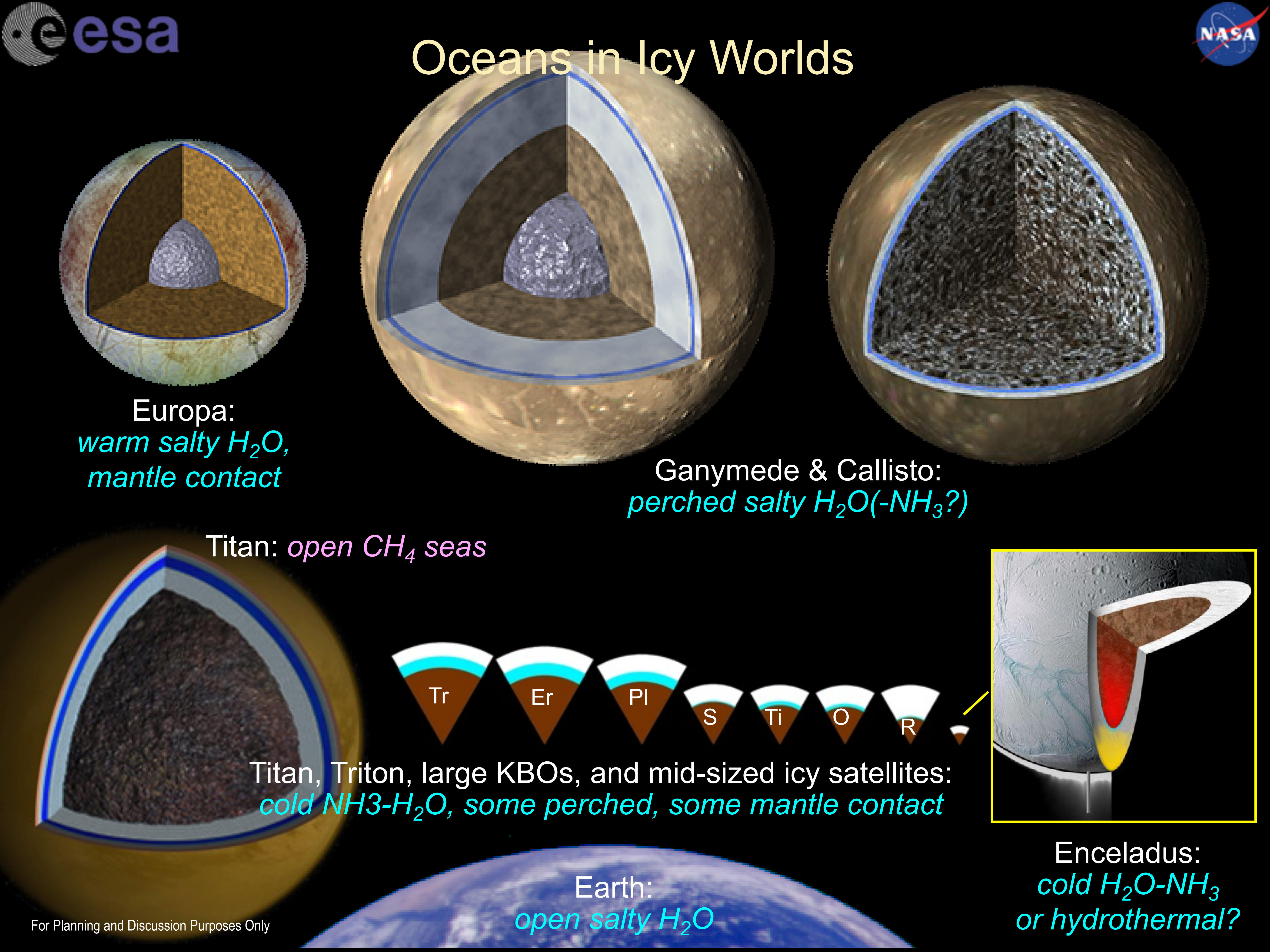


Europa: "Ingredients" for Life?

- Water:
  - Warm salty H_2O ocean.
- Essential elements:
  - Accretion of CO_2?
  - Impactors.
  - But radiation destroys organics in upper ~10s cm of ice.
- Chemical energy:
  - Radiation of $H_2O \Rightarrow$ oxidants.
  - Mantle contact: serpentinization and possible hydrothermal activity.
- Relatively stable environment:
  - Large satellite retains heat.
  - But activity might not be steady-state.

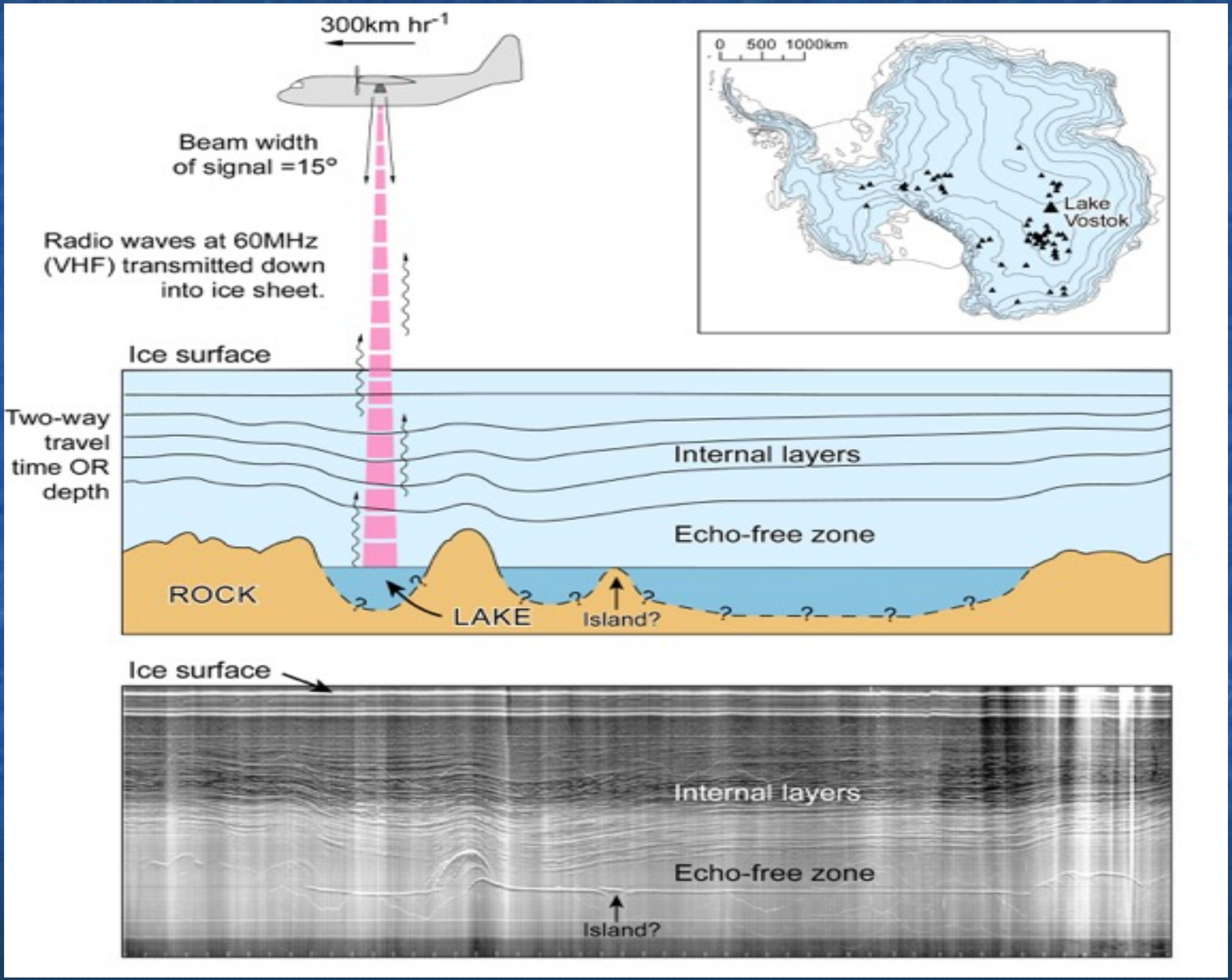


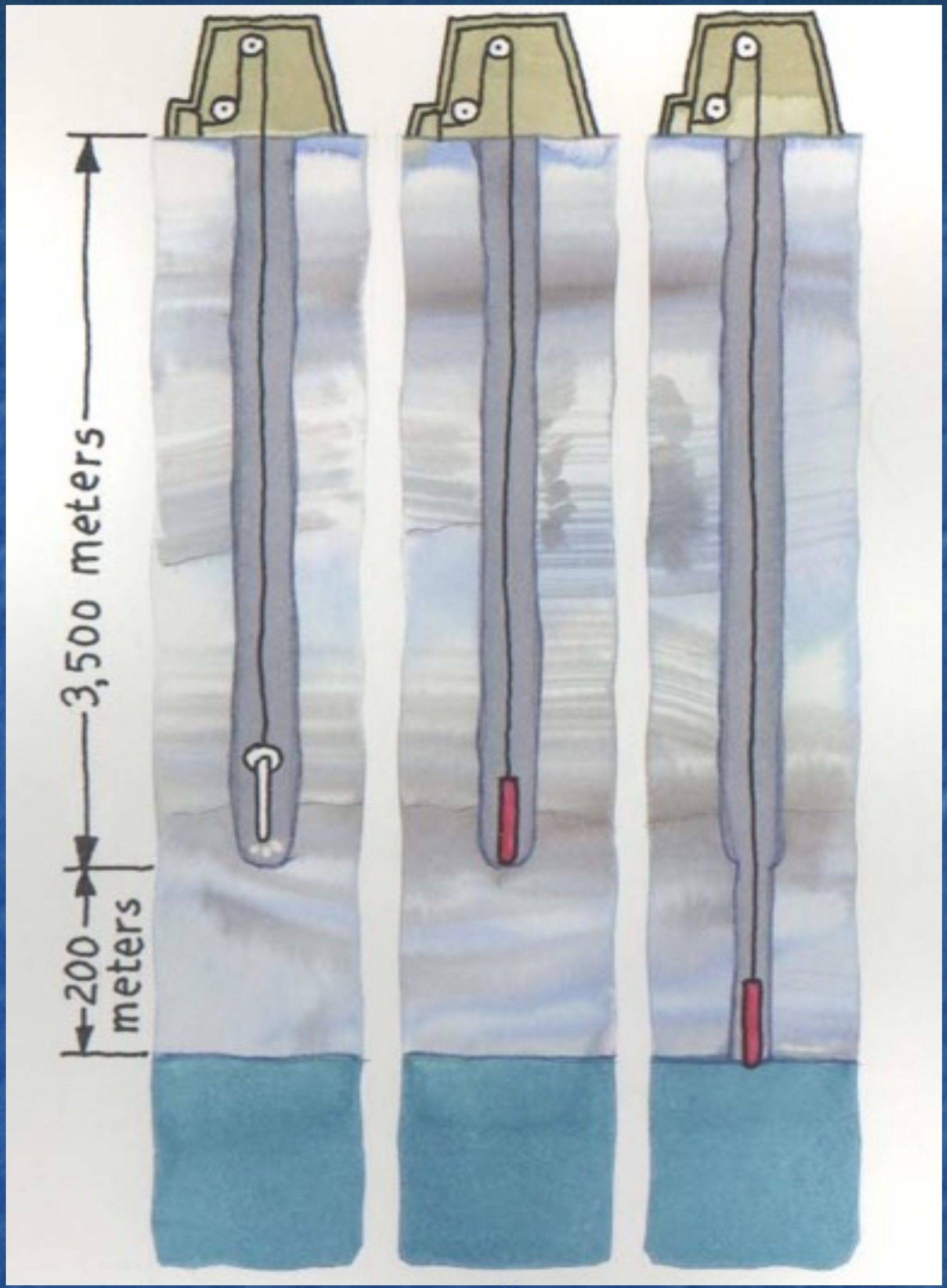
[after *Stevenson, 2000*]

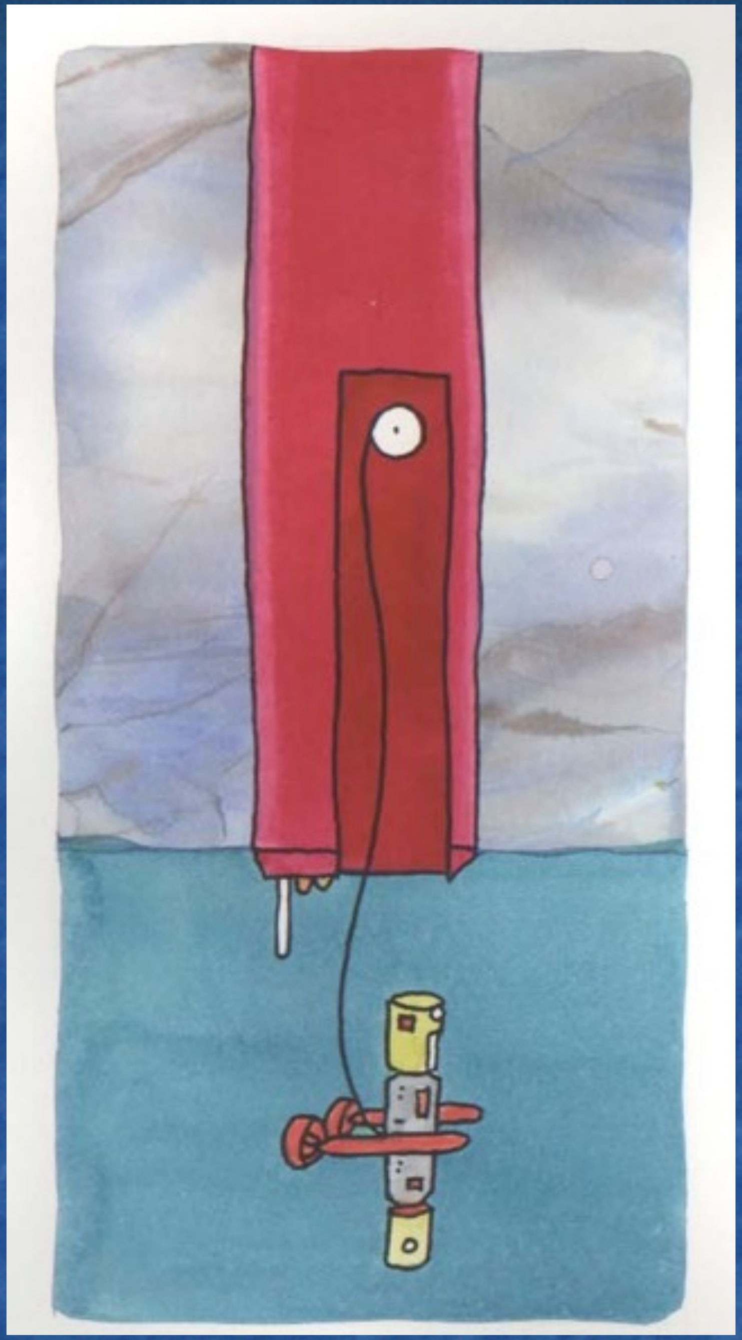


Oceans in Icy Worlds
Europa:
warm salty H_2O, mantle contact
Ganymede & Callisto:
perched salty H_2O(-NH_3?)
Titan: *open CH_4 seas*
Tr
Er
Pl
S
Ti
O
R
Titan, Triton, large KBOs, and mid-sized icy satellites:
cold NH3-H_2O, some perched, some mantle contact
Enceladus:
cold H_2O-NH_3 or hydrothermal?
Earth:
open salty H_2O
For Planning and Discussion Purposes Only

Sub-glacial lakes in Antactica



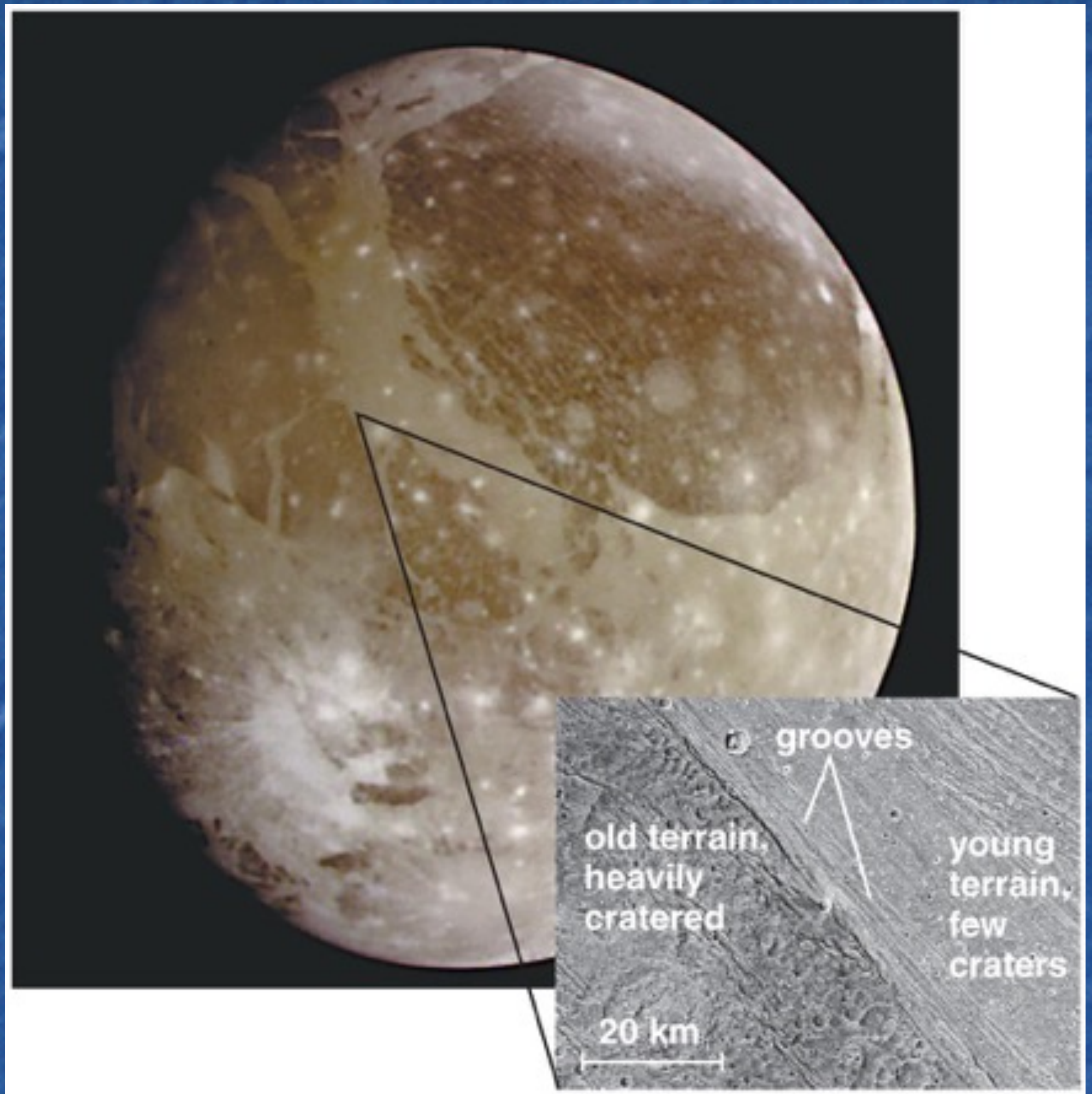

3,500 meters
200 meters

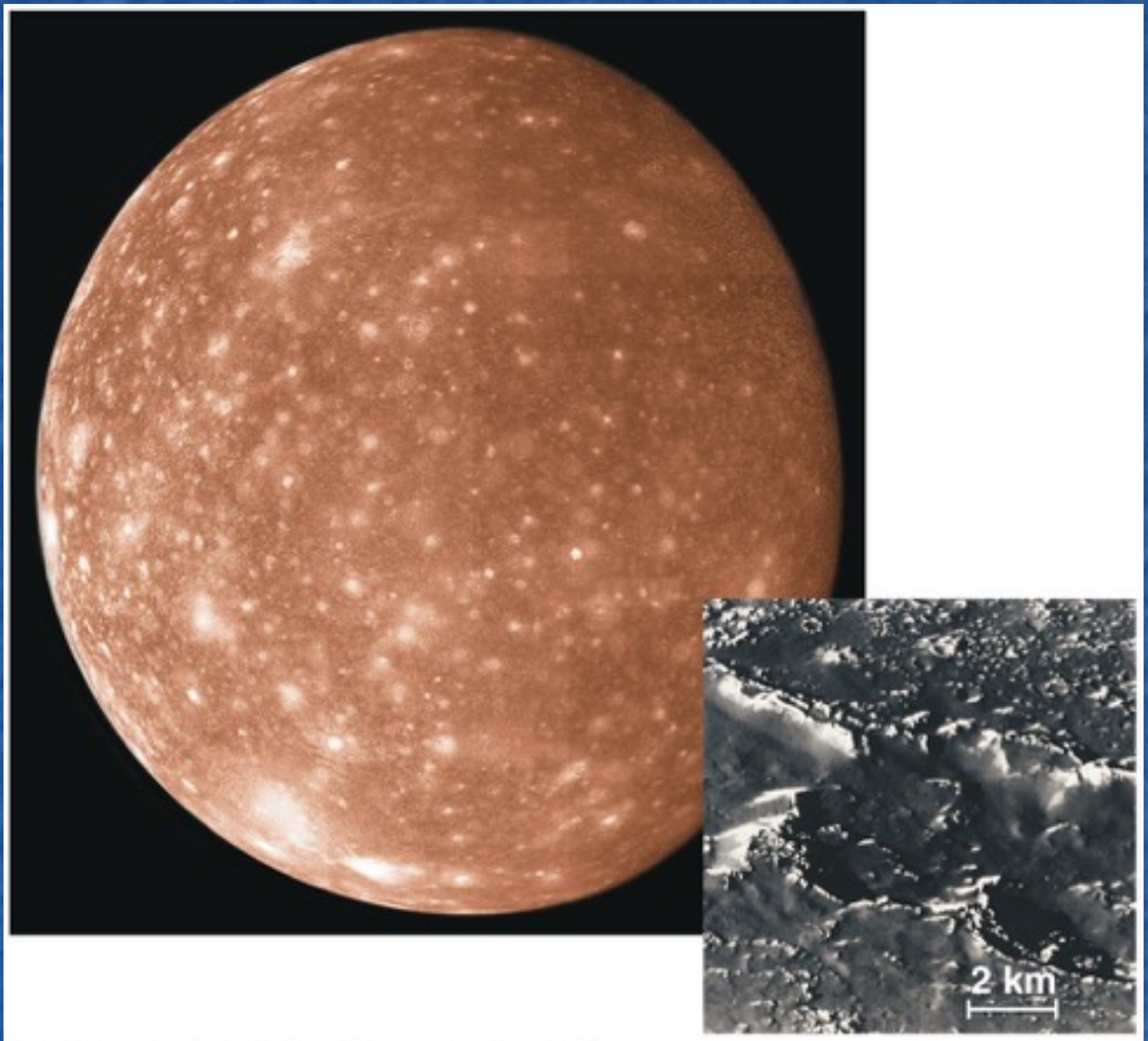


Europa via Lake Joyce

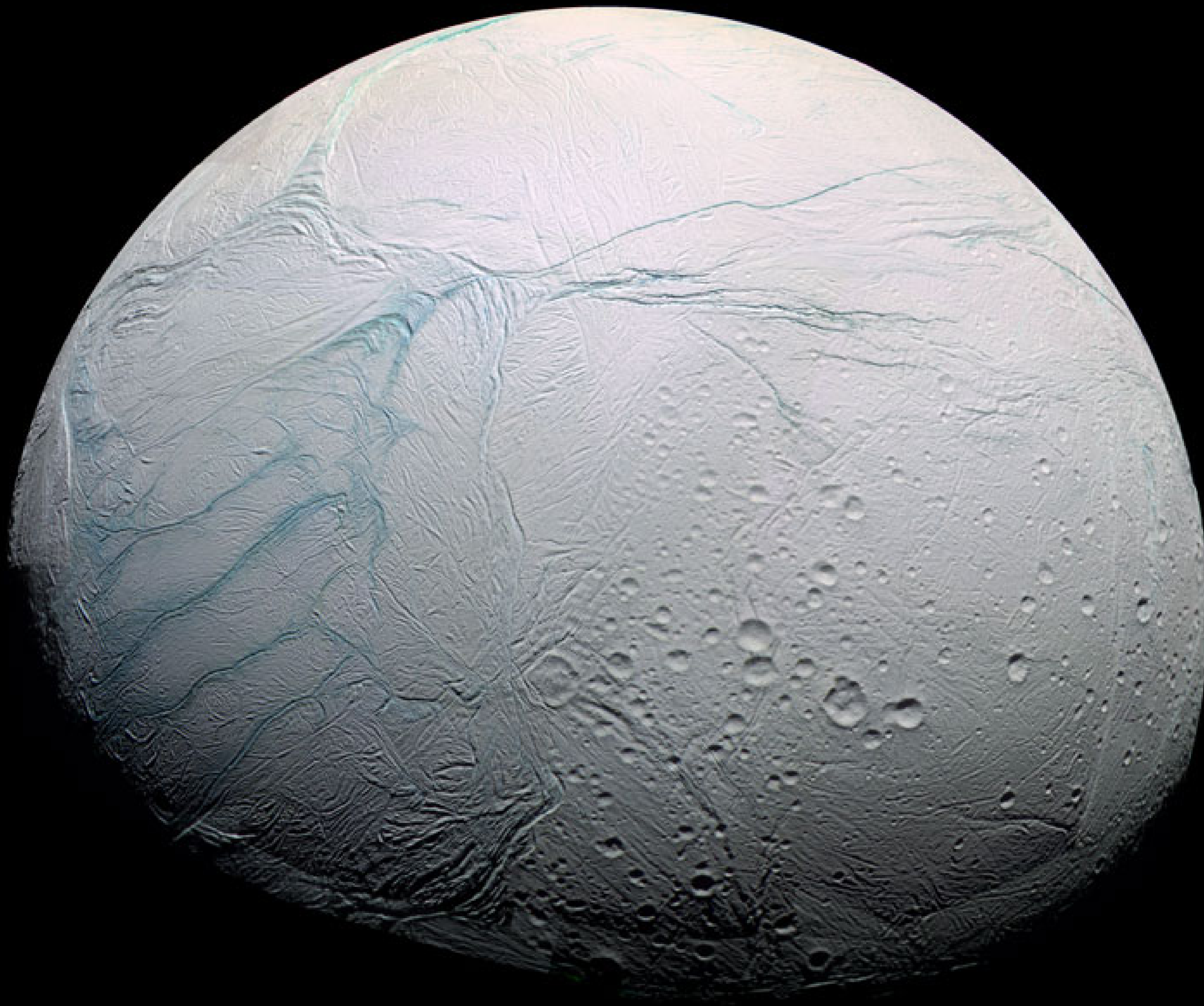
Ganymede and Callisto

- Ganymede is the largest moon in the solar system, and appears to have a recently-resurfaced crust
- Callisto has an old cratered surface
- Both moons may harbour cold salty sub-surface oceans

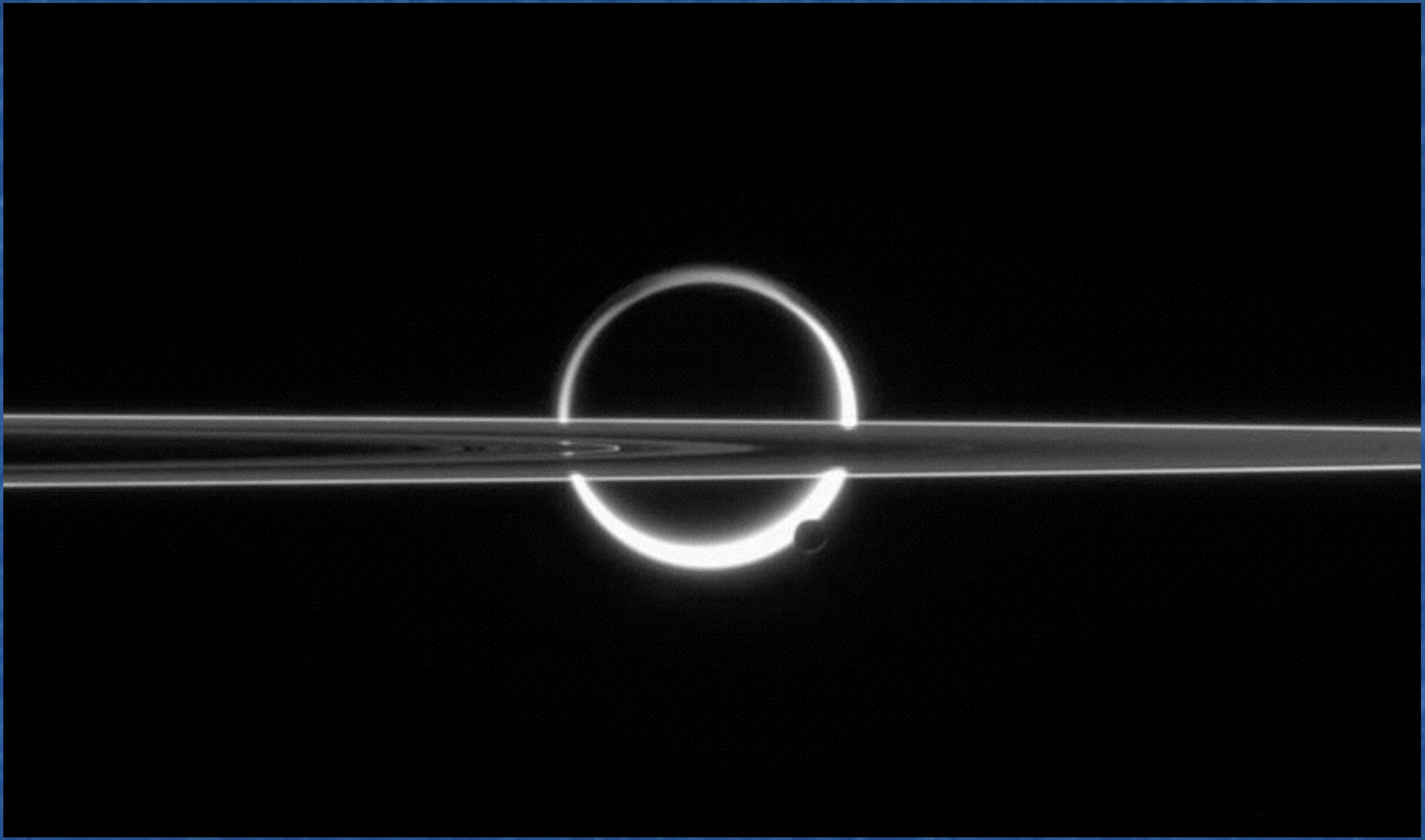

grooves
old terrain, heavily cratered
young terrain, few craters
20 km

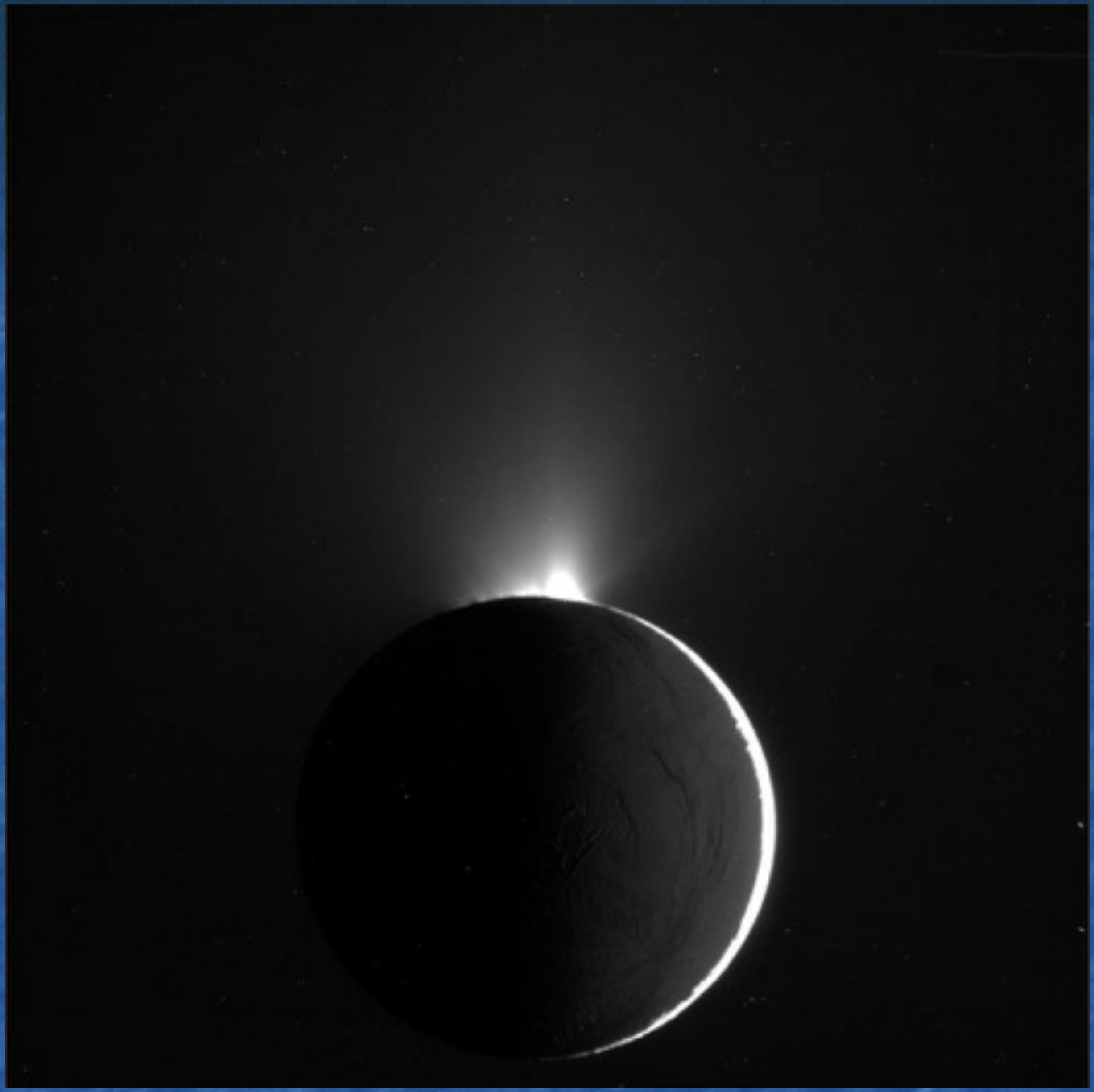
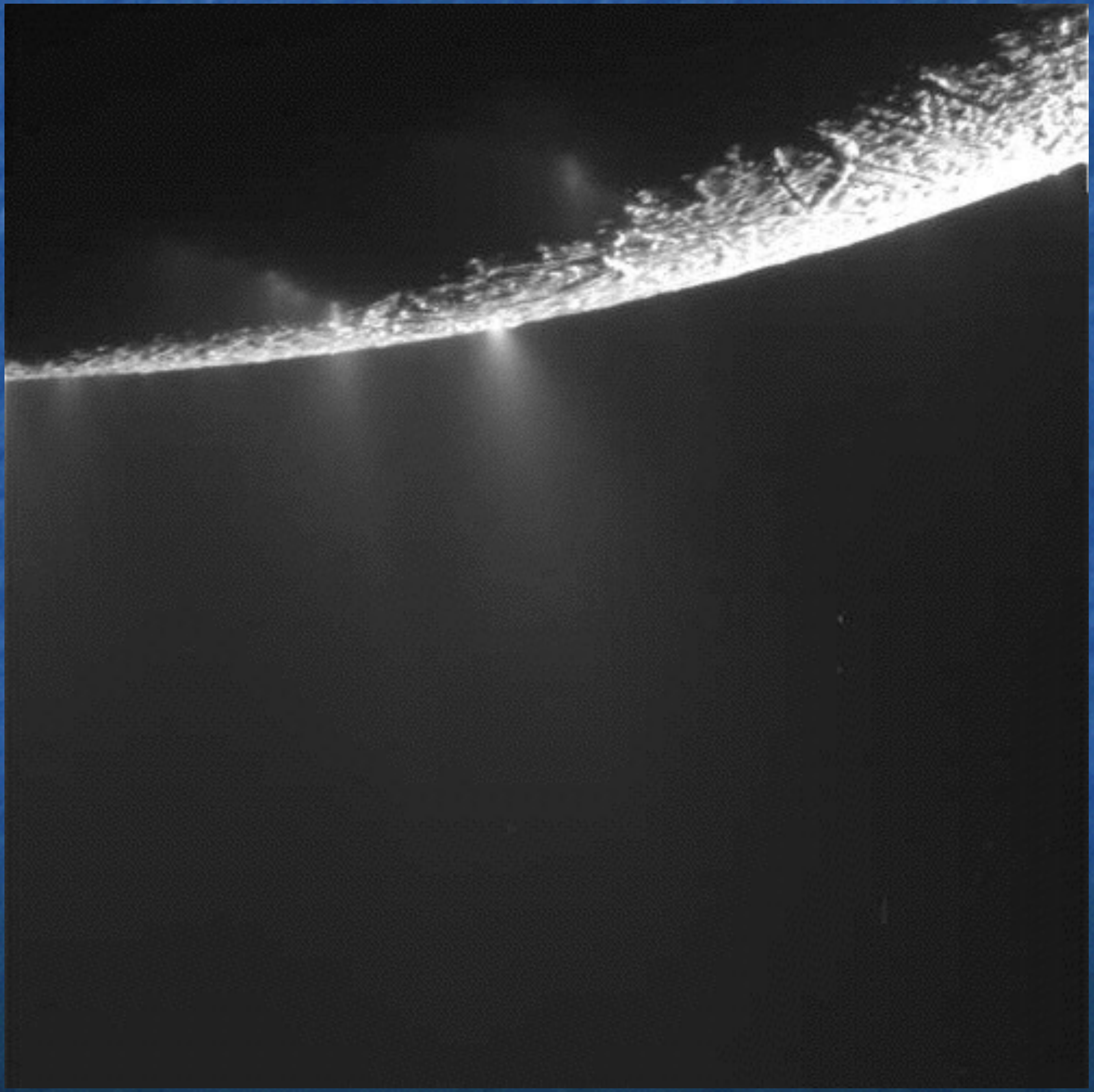

2 km

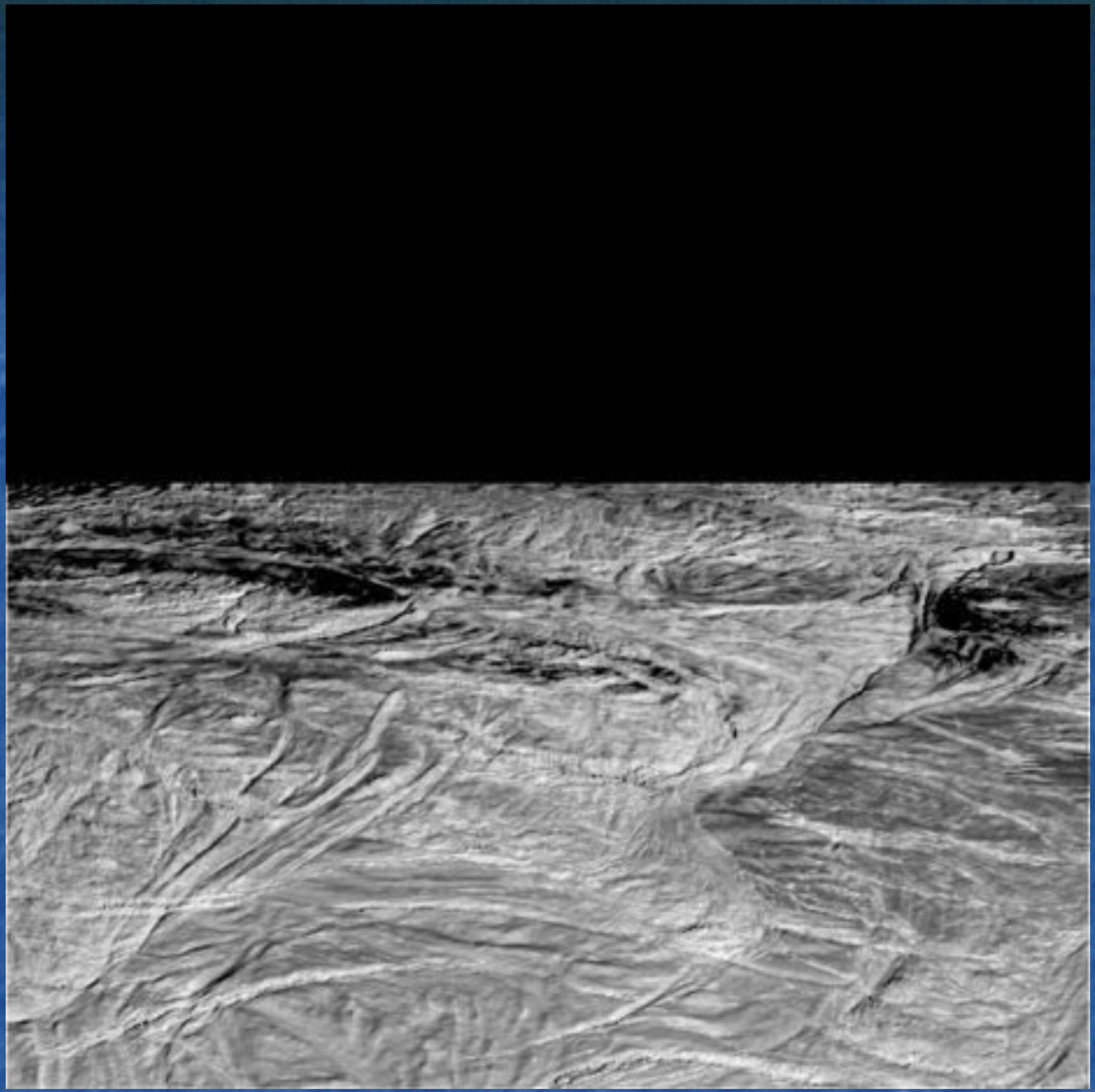
Enceladus

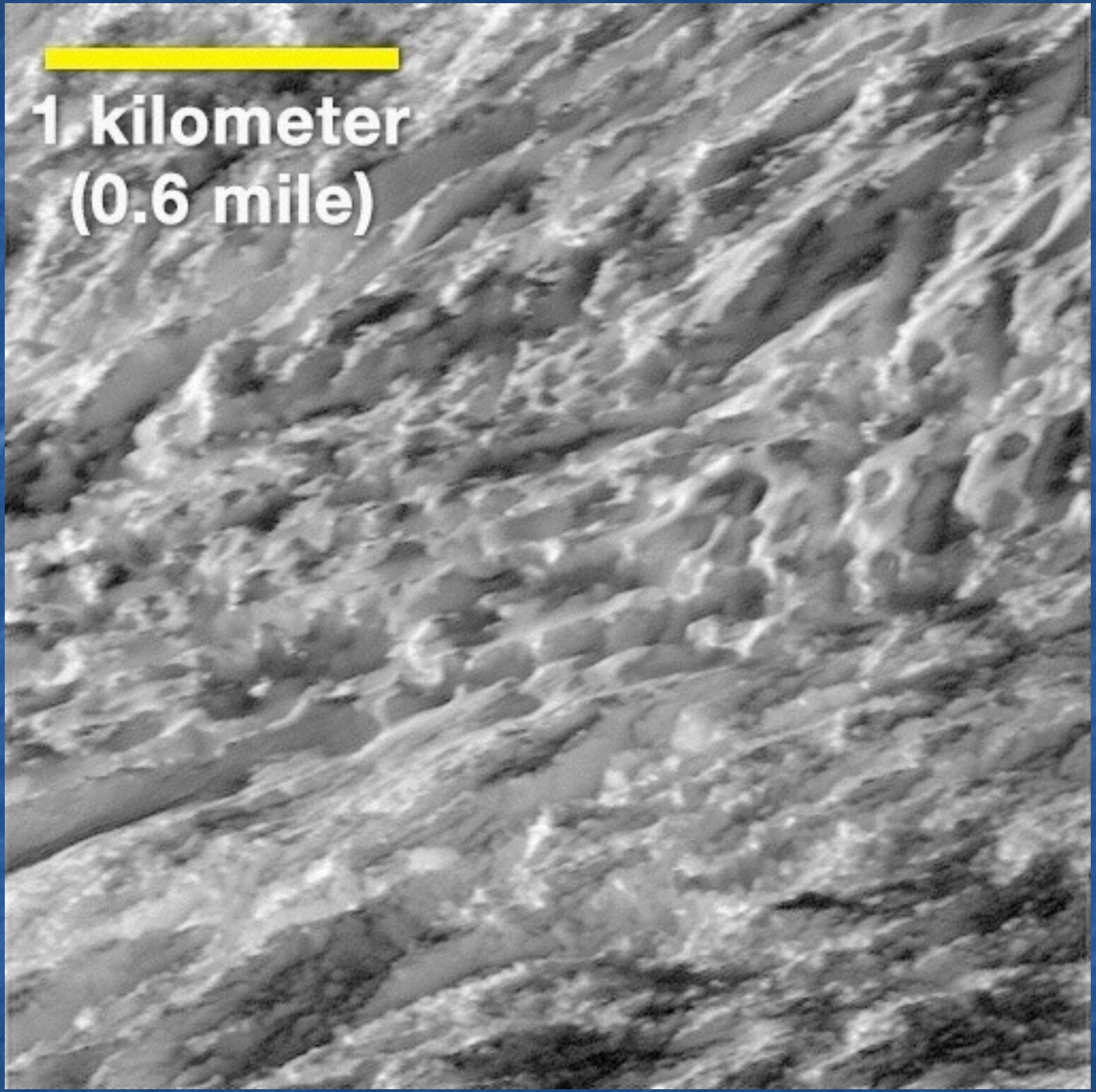


Cassini flyby images

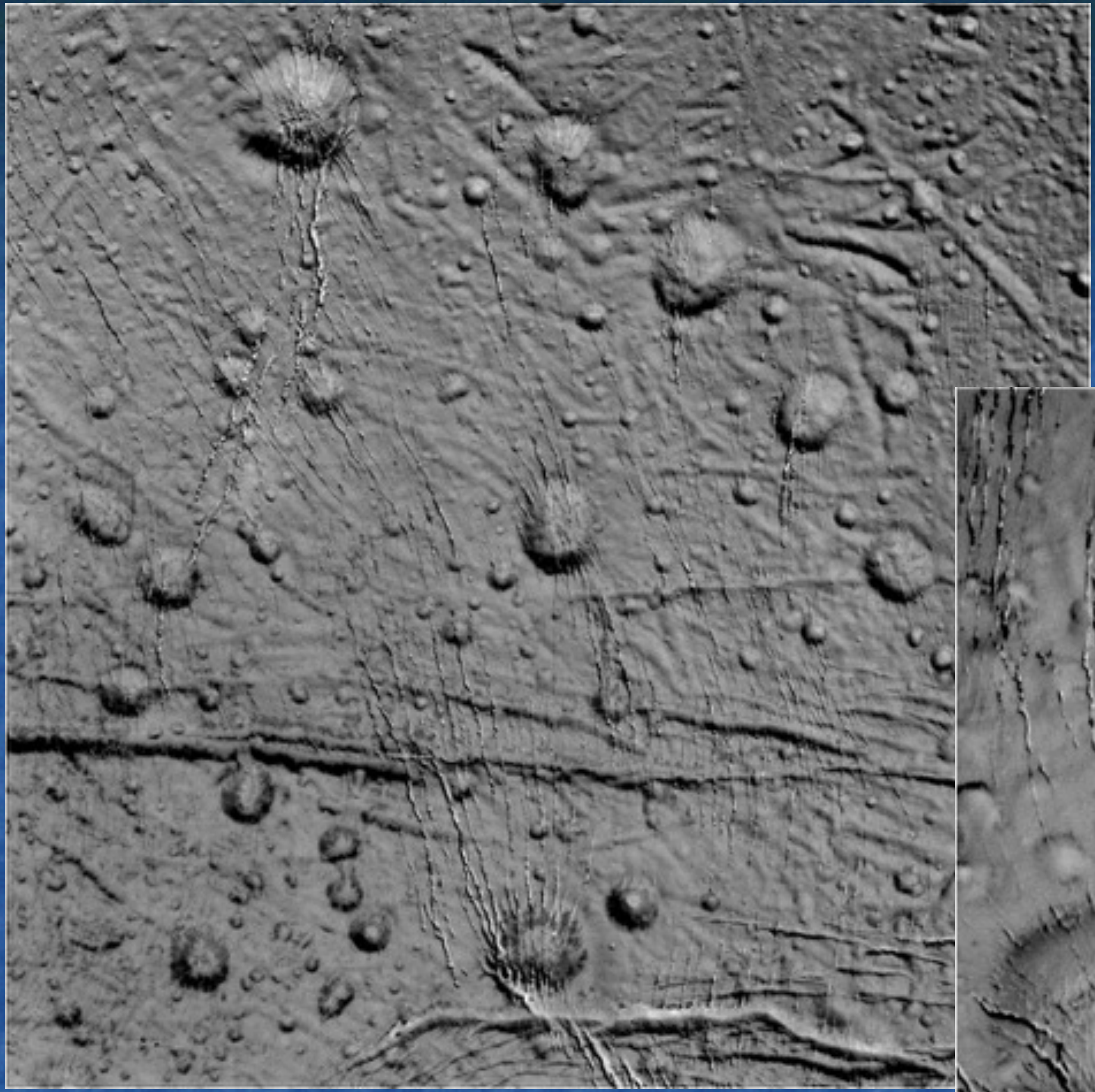
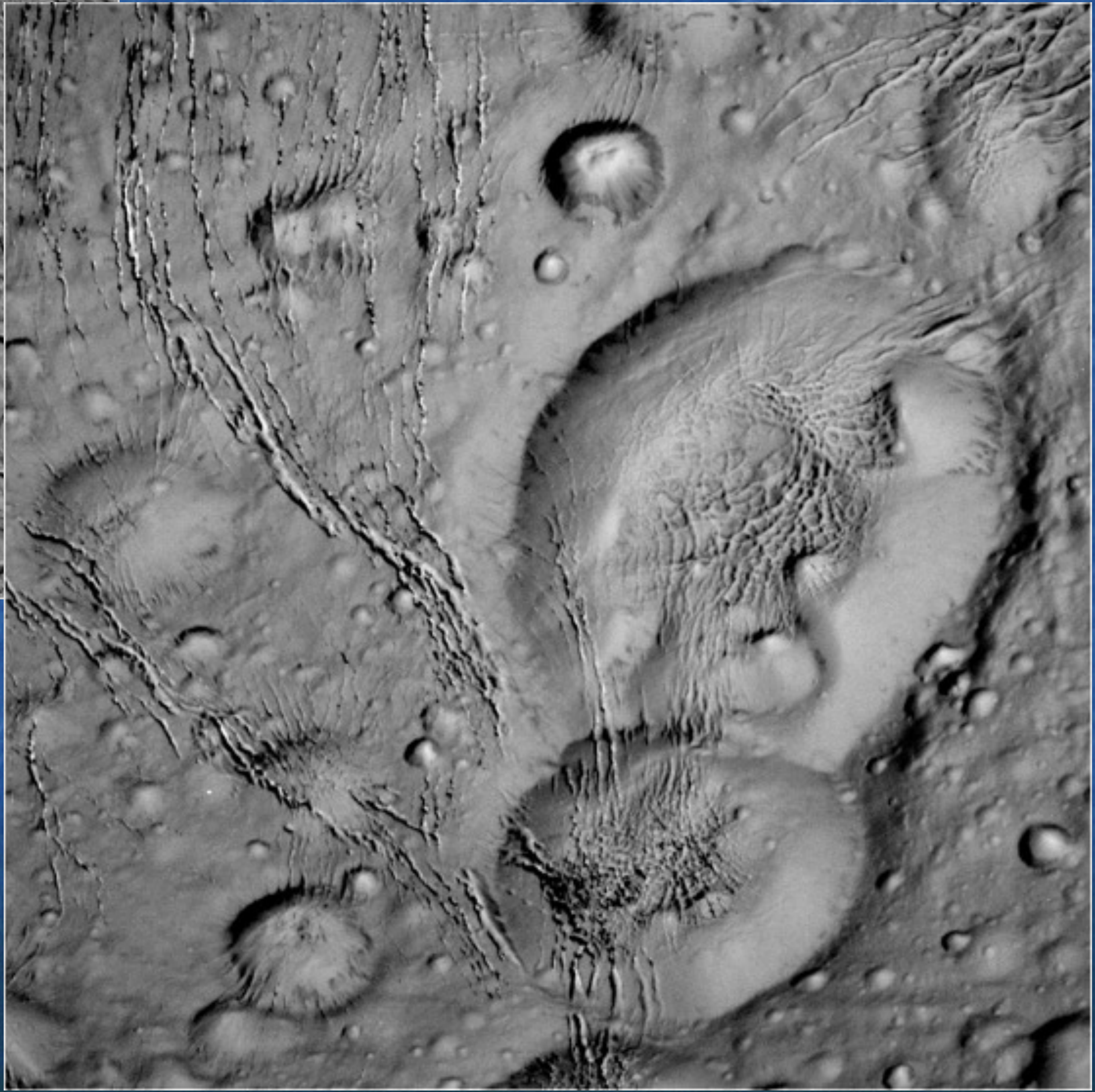




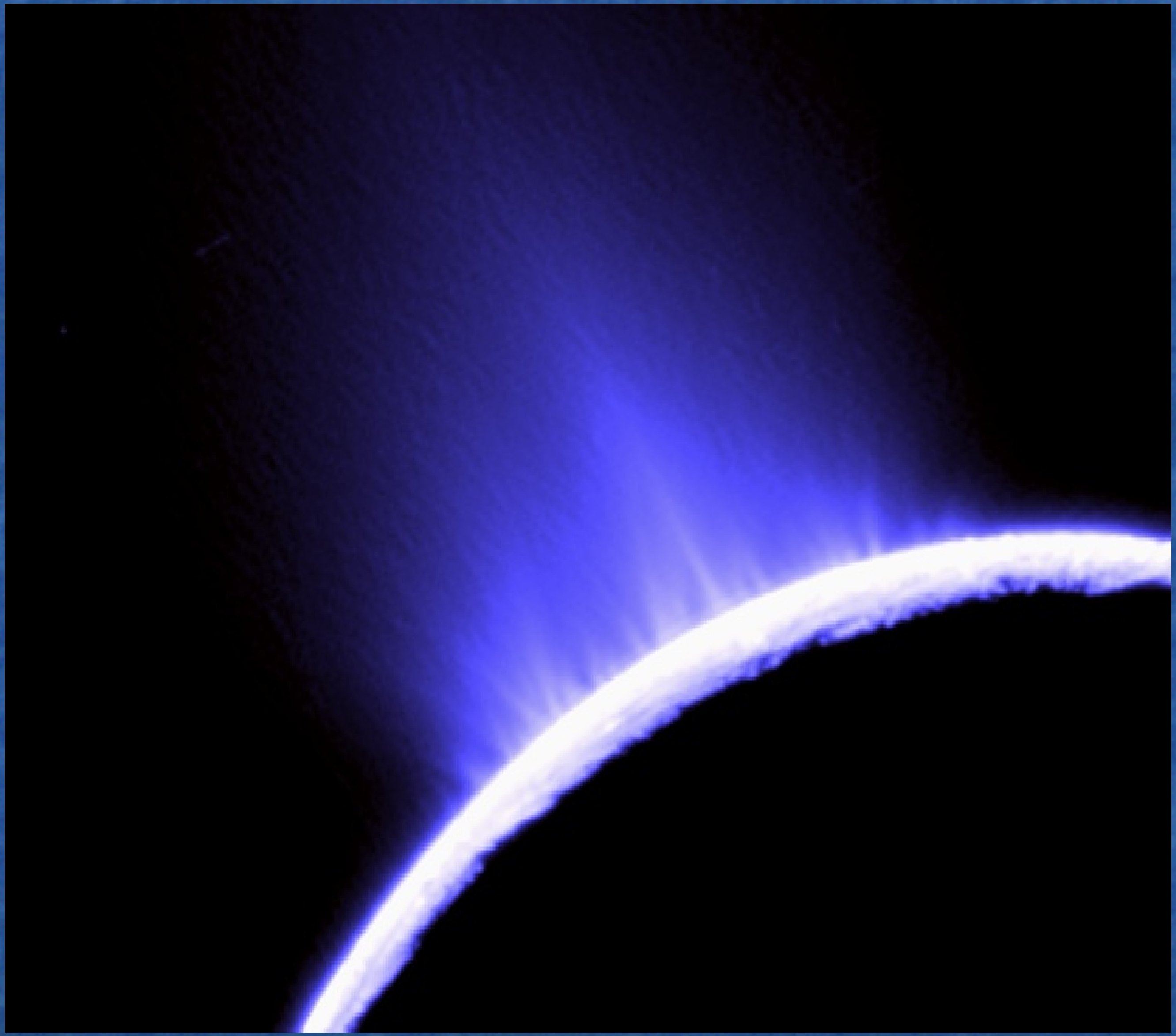


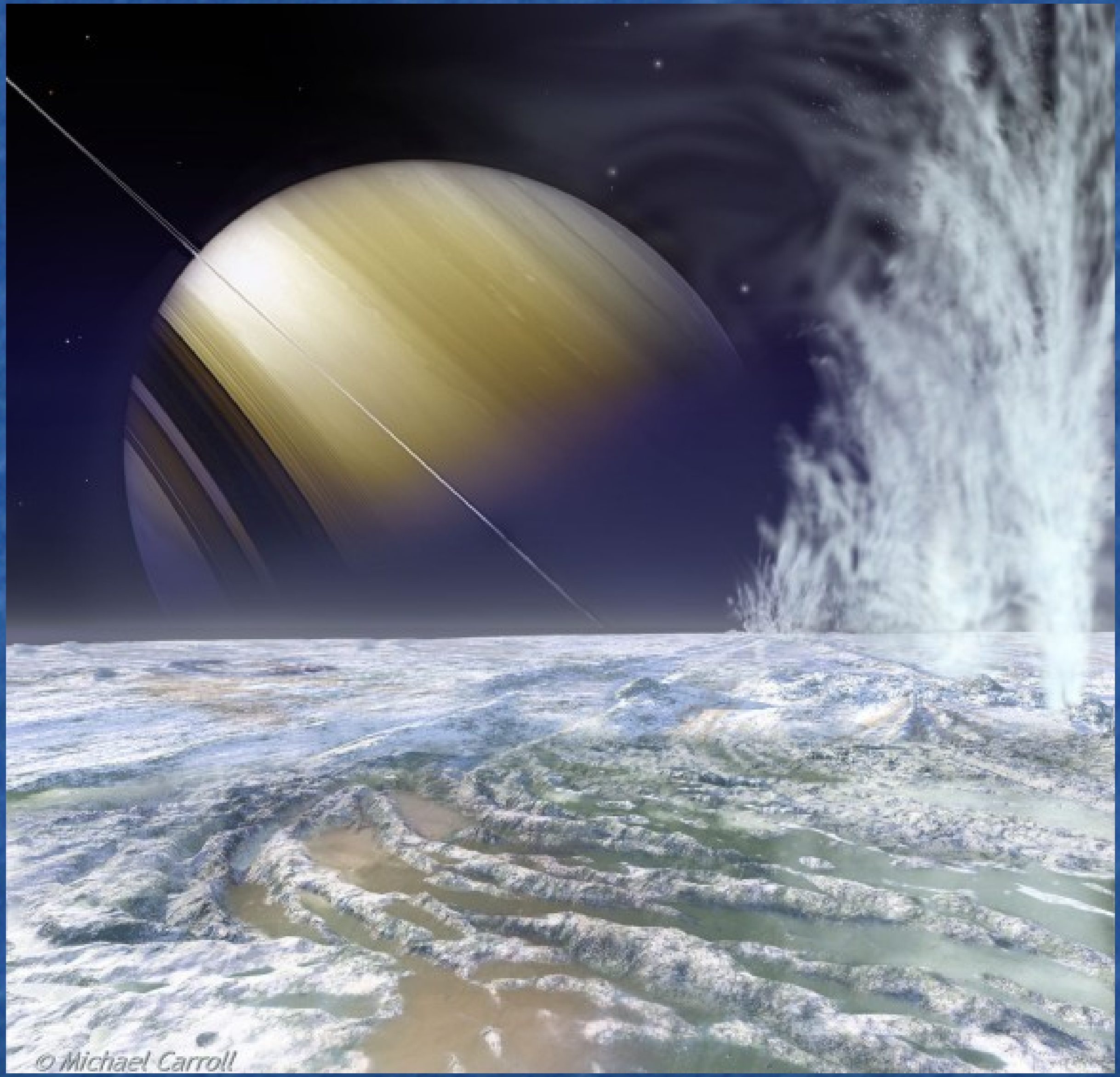
1 kilometer
(0.6 mile)


Janus
Epimetheus
Cassini Saturn Orbit Insertion
Ring Plane Crossing
Cassini
Division
Encke
Division
(Pan)
D
ring
C ring
B ring
A ring
(outer edge: Atlas)
Mimas
Enceladus
Tethys
Dione
Rhea
G ring
F ring
(Prometheus,
Pandora)
E ring
(to Titan)
Titan
Hyperion
Iapetus
Phoebe

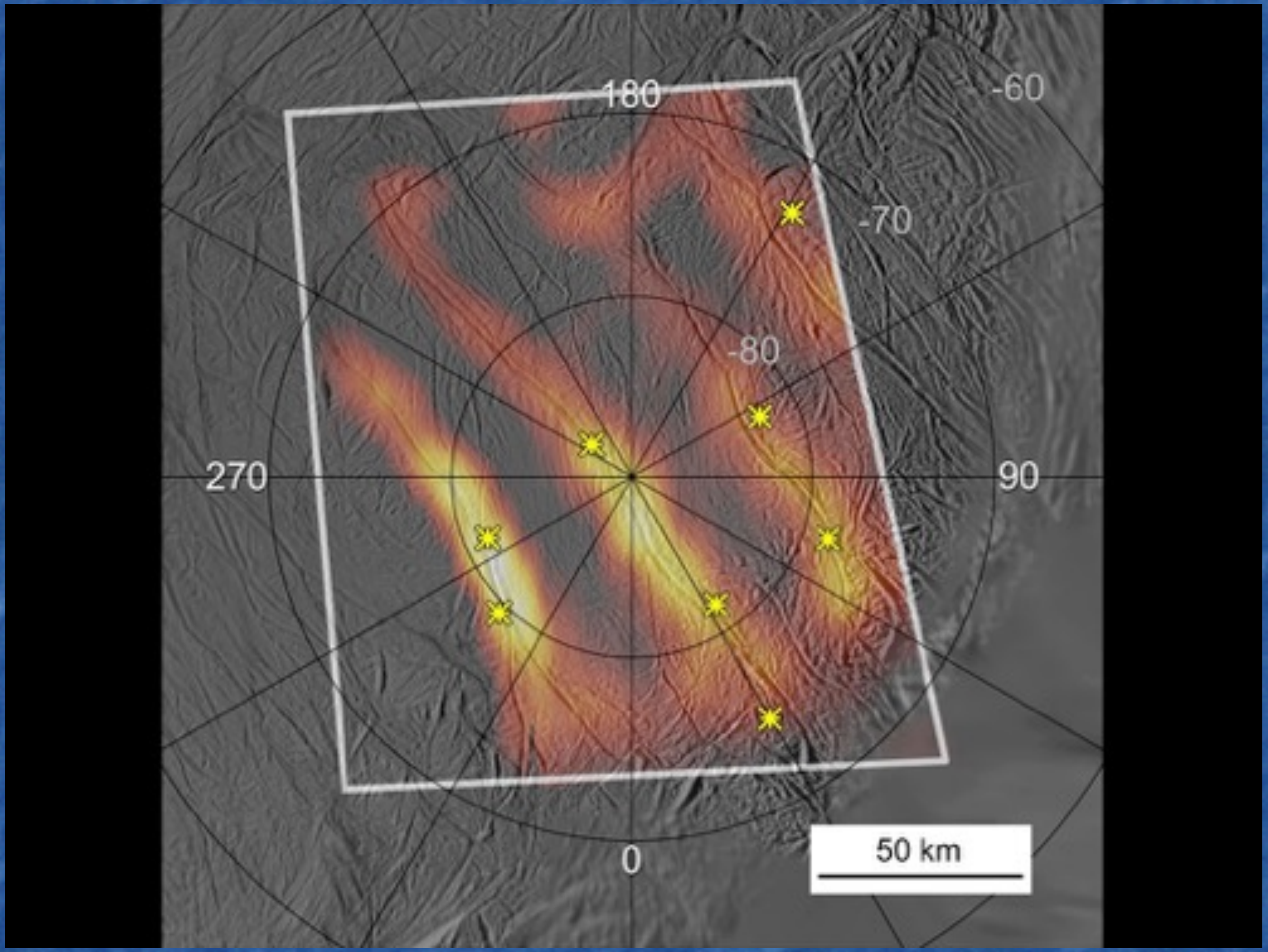
Geysers on Enceladus

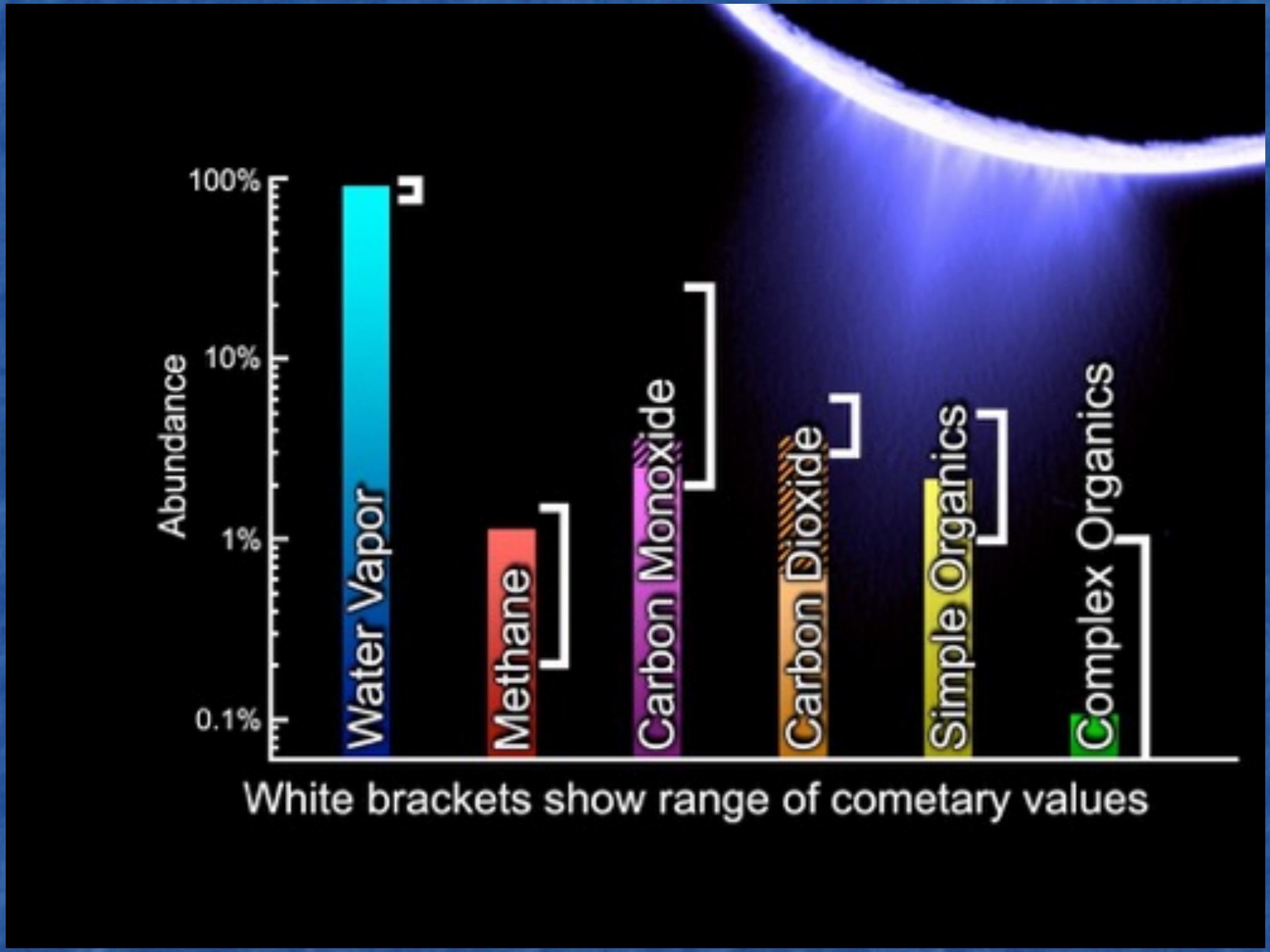




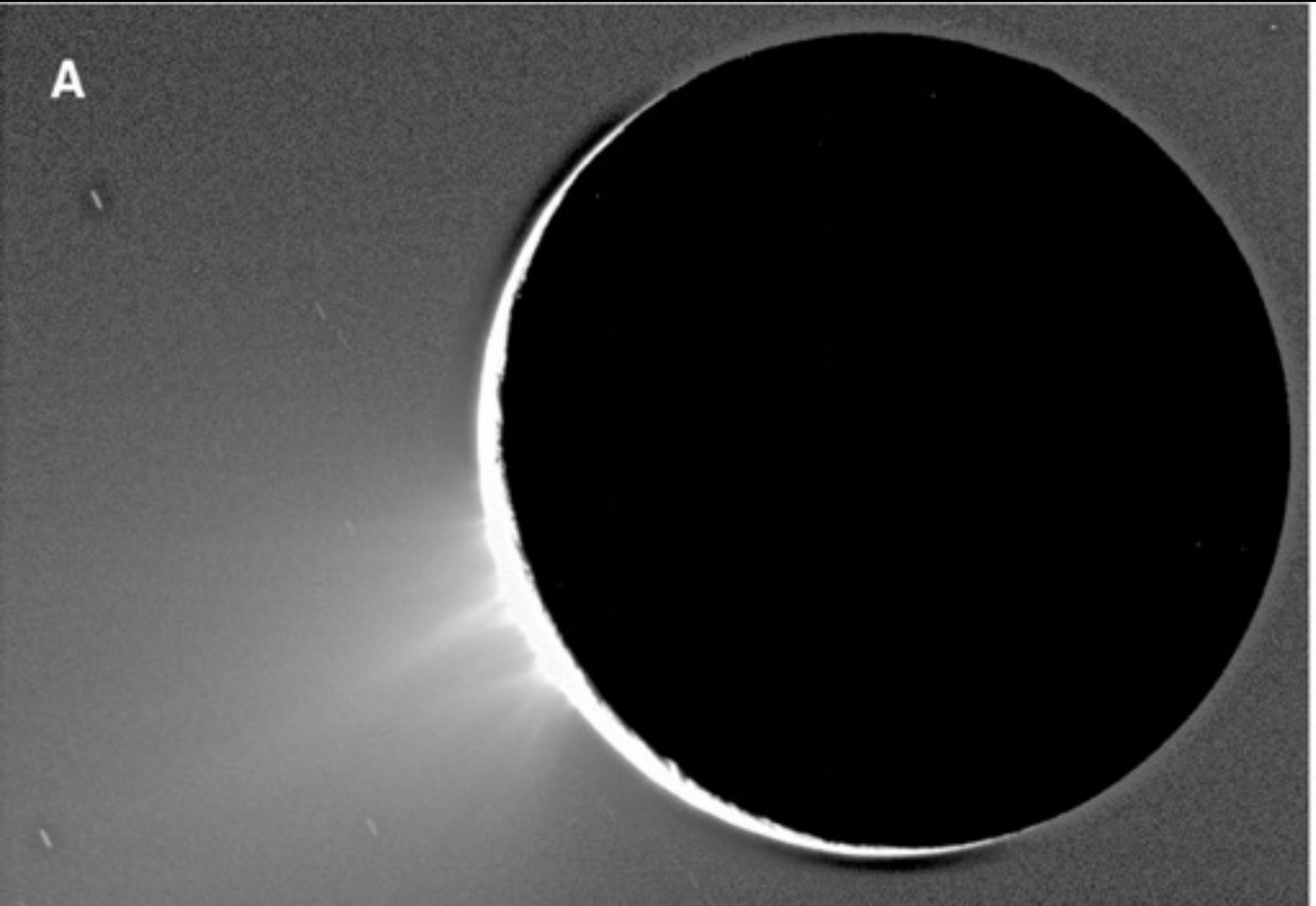
Tidal heating on Enceladus versus Europa

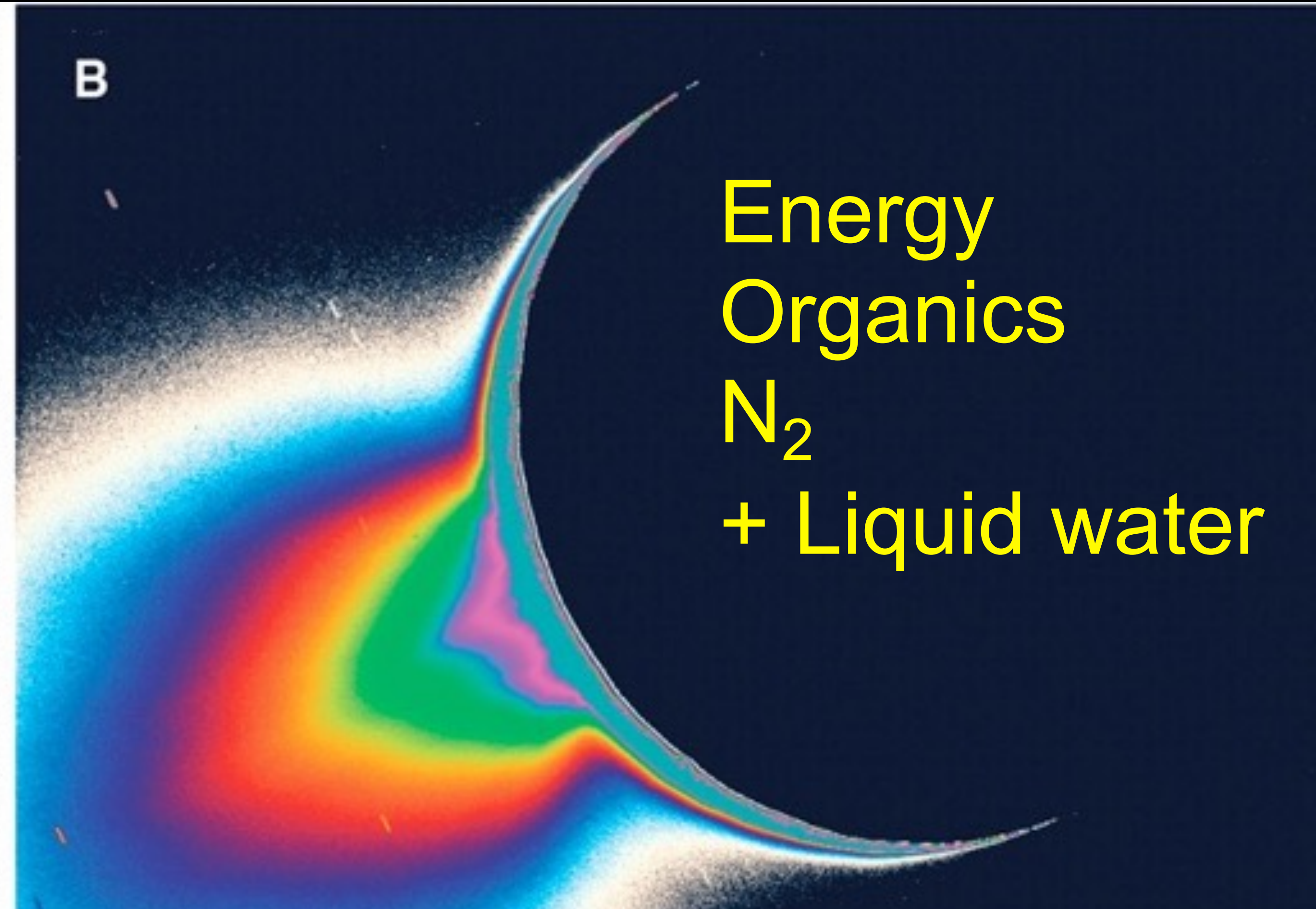
- $M_{Jupiter} = 3\ M_{Saturn}$
- $r_{Europa} = 3\ r_{Enceladus}$
- $e_{Europa} = 2\ e_{Enceladus}$
- Note that tidal heating is proportional to mass and eccentricity yet depends upon the inverse cube of orbital radius.
- Therefore, it is reasonable to expect that the amount of tidal heating per unit mass of material on Enceladus and Europa will be comparable.

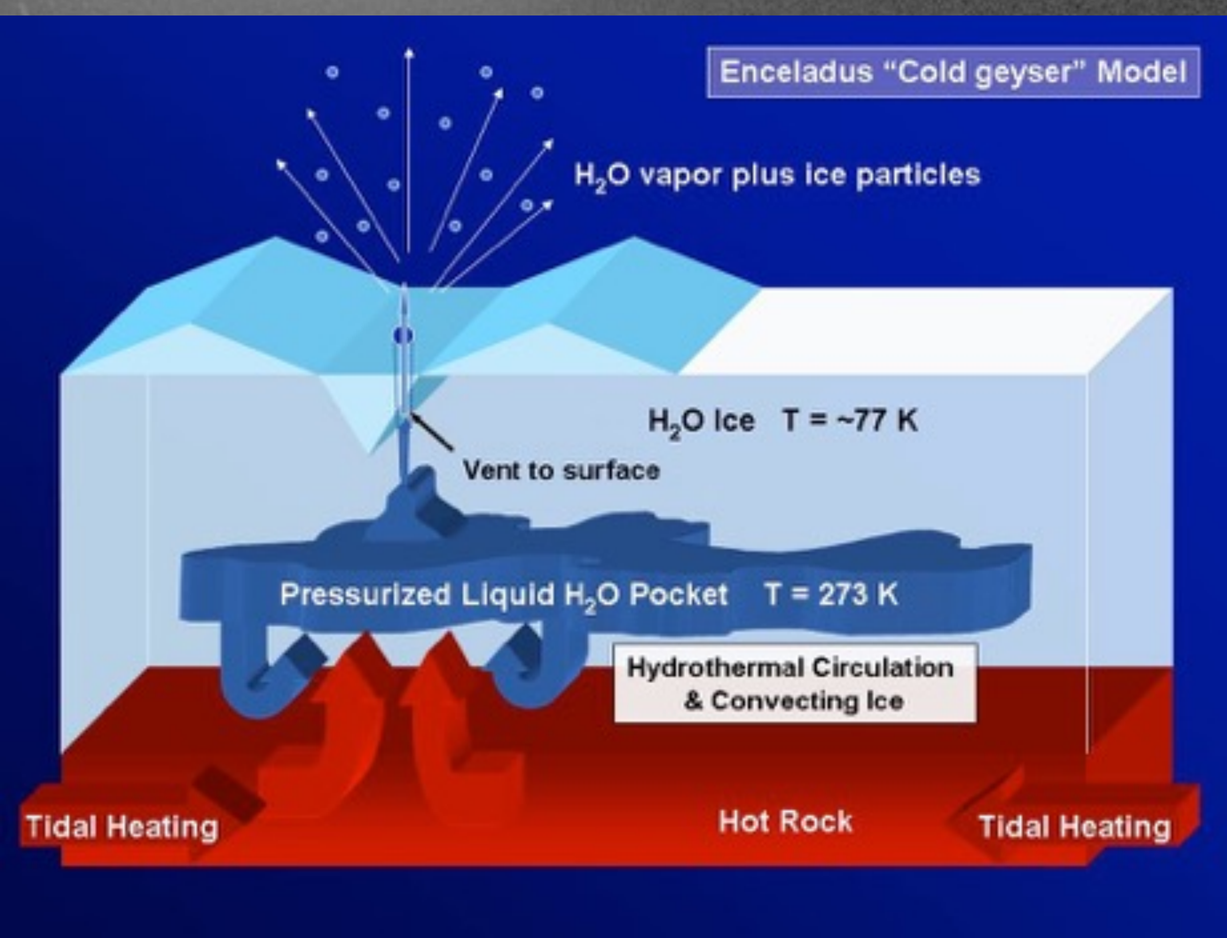

180
-60
-70
-80
270
90
0
50 km

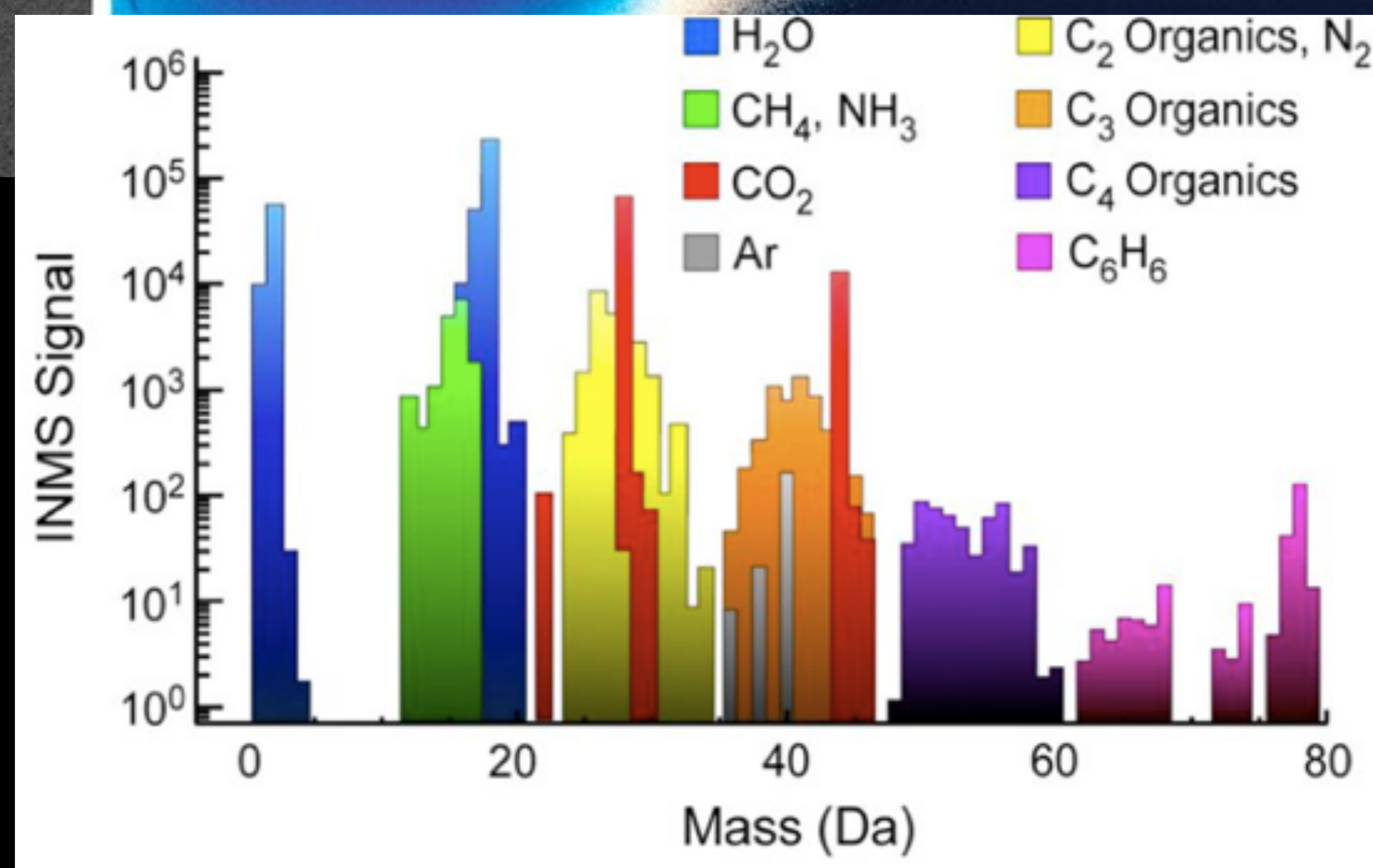

100%
10%
1%
0.1%
Abundance
Water Vapor
Methane
Carbon Monoxide
Carbon Dioxide
Simple Organics
Complex Organics
White brackets show range of cometary values

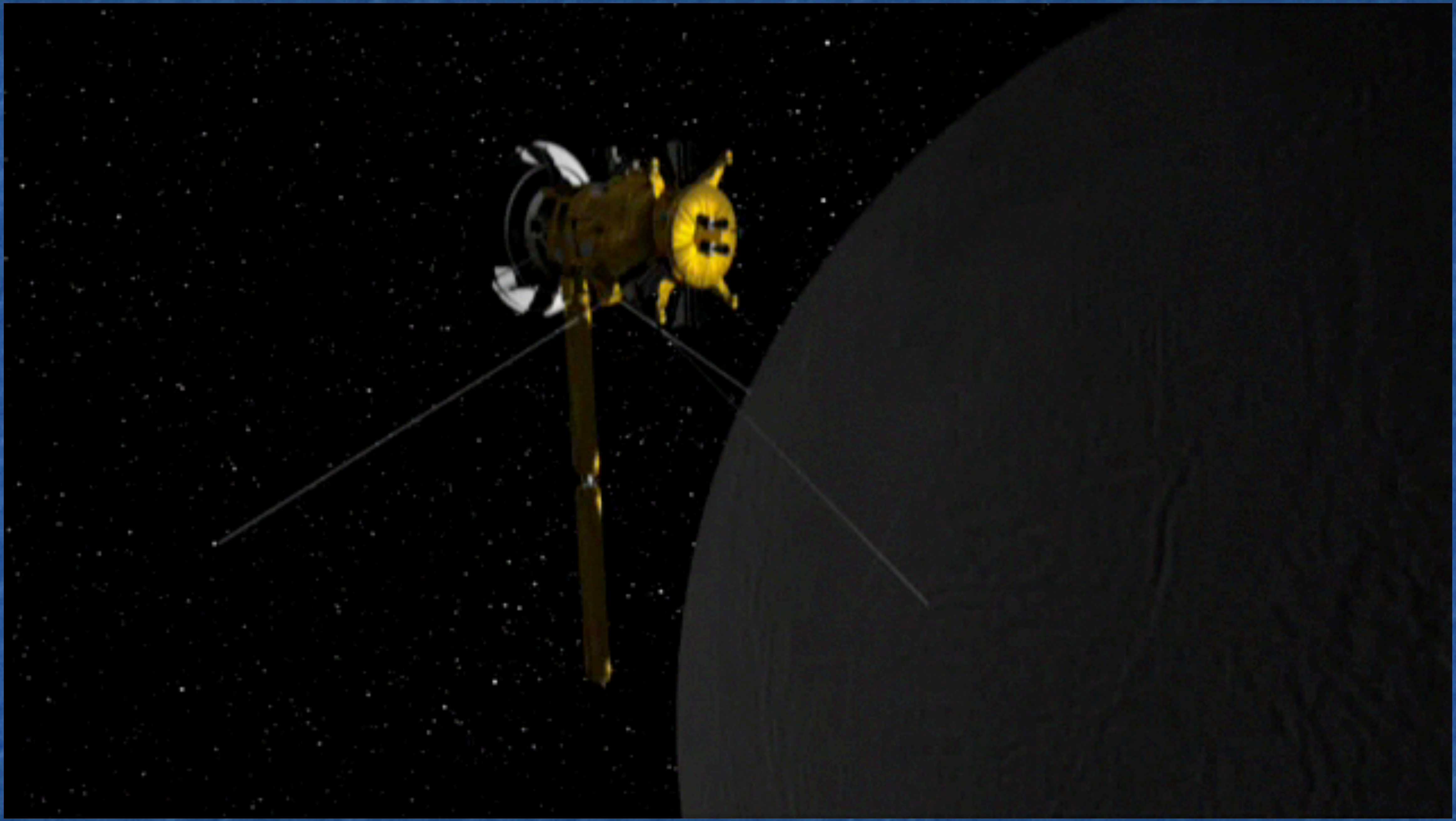
Jets of H_2O on Enceladus

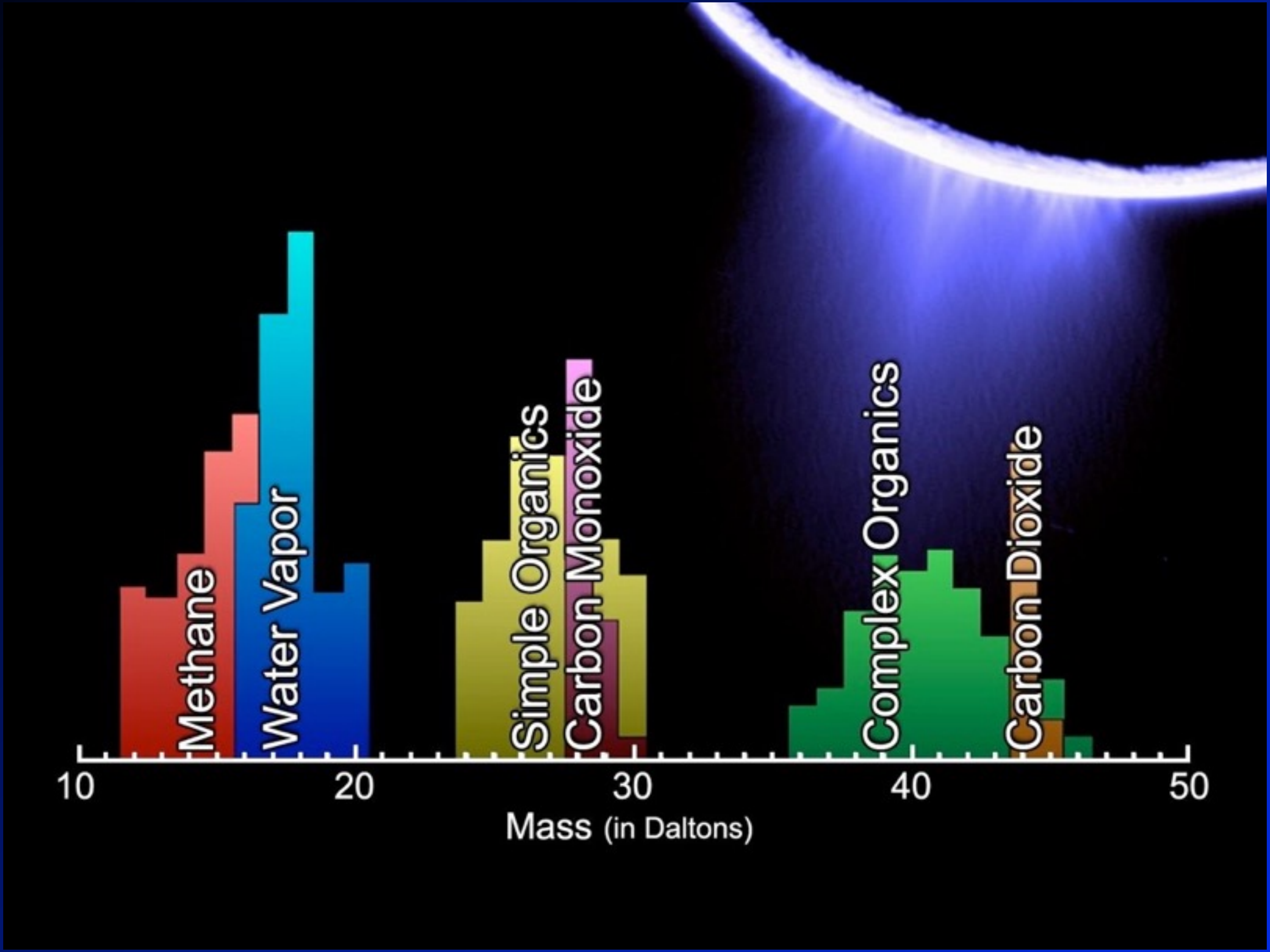










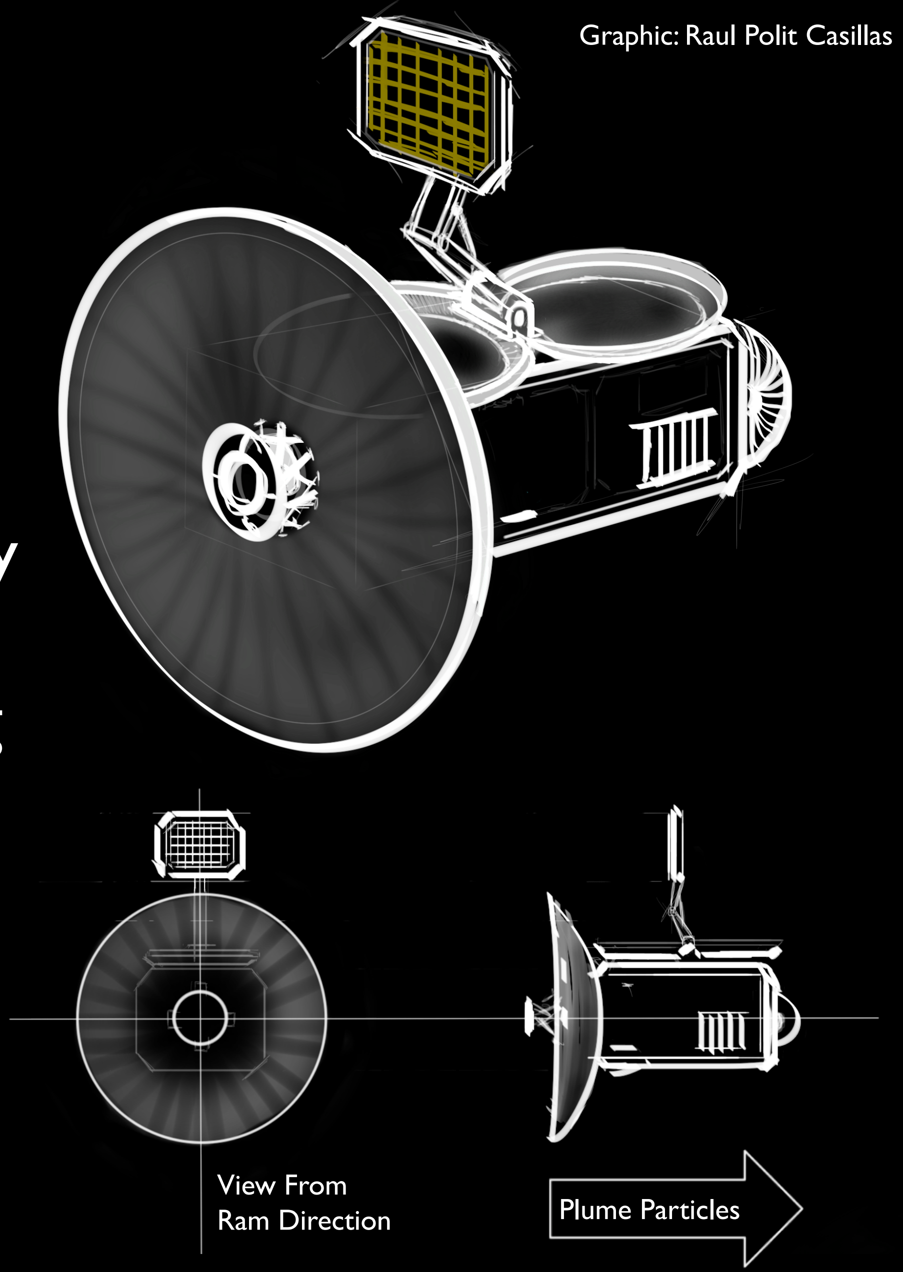


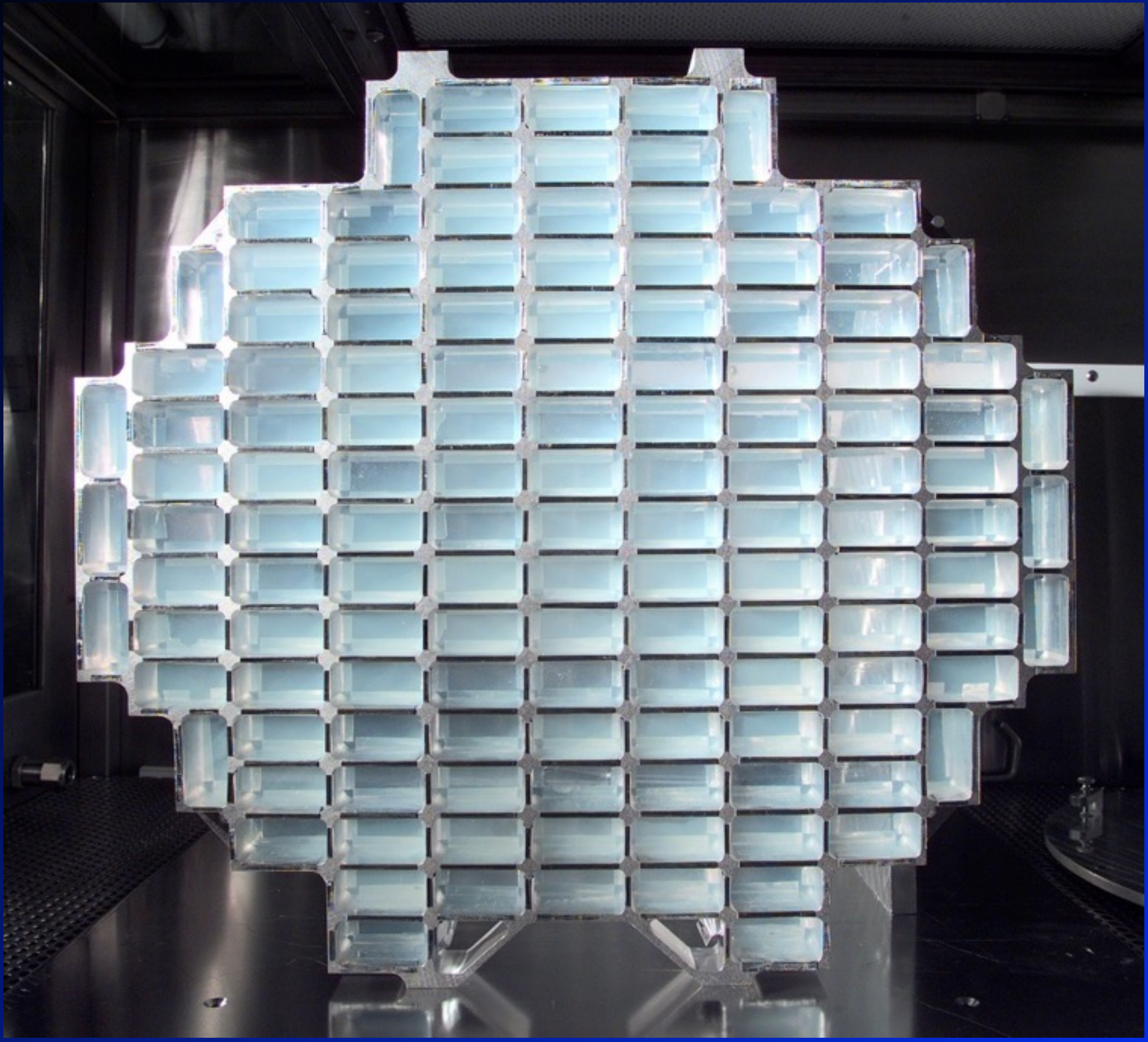
Methane
Water Vapor
Simple Organics
Carbon Monoxide
Complex Organics
Carbon Dioxide
10
20
30
40
50
Mass (in Daltons)

The low-cost Enceladus sample return mission

Spacecraft Concept

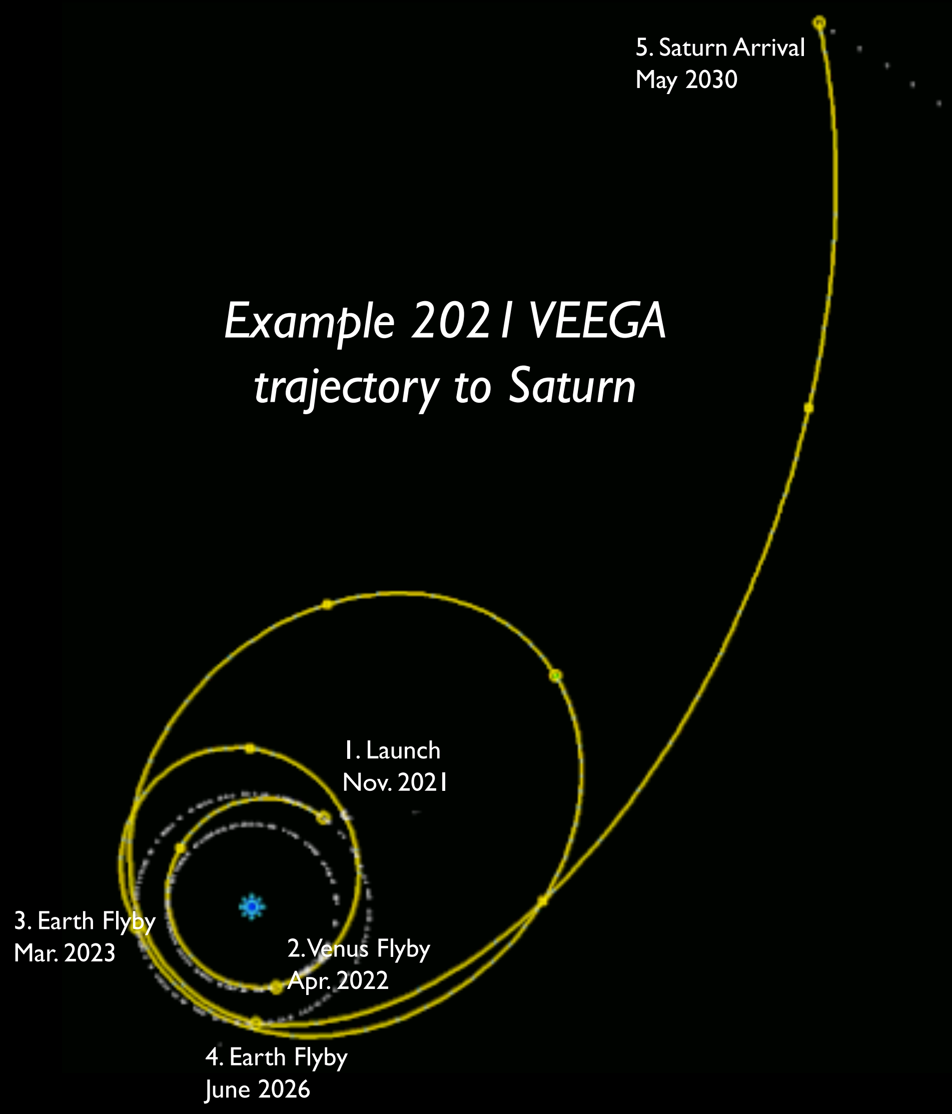
- Spacecraft 3 m HGA used to shield main body of spacecraft from plume particles
- ASRG power source
- 800 kg dry mass, 3 km/s ΔV
- Hibernation during interplanetary cruise
- Dual-use science and engineering instruments such as a navigation camera and radiometric tracking
- Design also compatible with in situ instruments such as dust counter and mass spectrometer

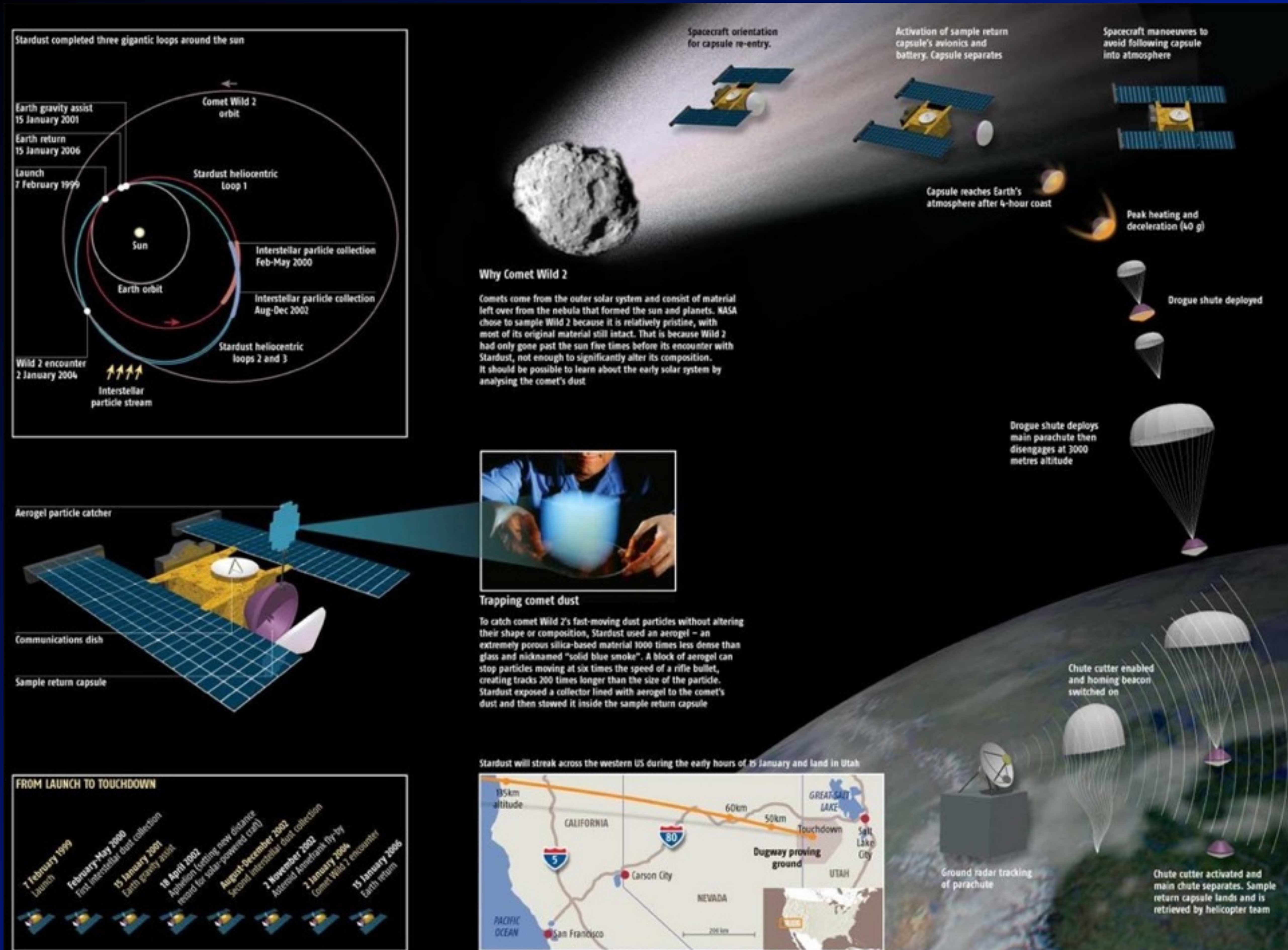




Mission Description

- 15 year mission, launching in early 2020s
- 8.5 years to Saturn (Venus & Earth flybys)
  - multiple trajectory options exist
- 2 years in Saturn orbit
  - multiple Enceladus flybys
  - sample collection from multiple jets possible
- 4.5 year Earth return trajectory
- Earth entry capsule for sample return
- Sample curation and analysis





Stardust completed three gigantic loops around the sun
Comet Wild 2 orbit
Earth gravity assist 15 January 2001
Earth return 15 January 2006
Launch 7 February 1999
Stardust heliocentric Loop 1
Sun
Interstellar particle collection Feb-May 2000
Earth orbit
Interstellar particle collection Aug-Dec 2002
Stardust heliocentric loops 2 and 3
Wild 2 encounter 2 January 2004
Interstellar particle stream
Spacecraft orientation for capsule re-entry.
Activation of sample return capsule's avionics and battery. Capsule separates
Spacecraft manoeuvres to avoid following capsule into atmosphere
Capsule reaches Earth's atmosphere after 4-hour coast
Peak heating and deceleration (40 g)
Why Comet Wild 2
Comets come from the outer solar system and consist of material left over from the nebula that formed the sun and planets. NASA chose to sample Wild 2 because it is relatively pristine, with most of its original material still intact. That is because Wild 2 had only gone past the sun five times before its encounter with Stardust, not enough to significantly alter its composition. It should be possible to learn about the early solar system by analysing the comet's dust
Drogue shute deployed
Drogue shute deploys main parachute then disengages at 3000 metres altitude
Aerogel particle catcher
Communications dish
Sample return capsule
Trapping comet dust
To catch comet Wild 2's fast-moving dust particles without altering their shape or composition, Stardust used an aerogel – an extremely porous silica-based material 1000 times less dense than glass and nicknamed "solid blue smoke". A block of aerogel can stop particles moving at six times the speed of a rifle bullet, creating tracks 200 times longer than the size of the particle. Stardust exposed a collector lined with aerogel to the comet's dust and then stowed it inside the sample return capsule
Chute cutter enabled and homing beacon switched on
FROM LAUNCH TO TOUCHDOWN
7 February 1999 Launch
February-May 2000 First interstellar dust collection
15 January 2001 Earth gravity assist
18 April 2002 Aphelion (setting new distance record for solar-powered craft)
August-December 2002 Second interstellar dust collection
2 November 2002 Asteroid Annefrank fly-by
2 January 2004 Comet Wild 2 encounter
15 January 2006 Earth return
Stardust will streak across the western US during the early hours of 15 January and land in Utah
135km altitude
60km
50km
Touchdown
CALIFORNIA
80
5
GREAT SALT LAKE
Salt Lake City
Dugway proving ground
Carson City
UTAH
NEVADA
PACIFIC OCEAN
San Francisco
Ground radar tracking of parachute
Chute cutter activated and main chute separates. Sample return capsule lands and is retrieved by helicopter team

Published in *Astrobiology*. August 2012, 12(8): 730-742.
DOI: 10.1089/ast.2011.0813

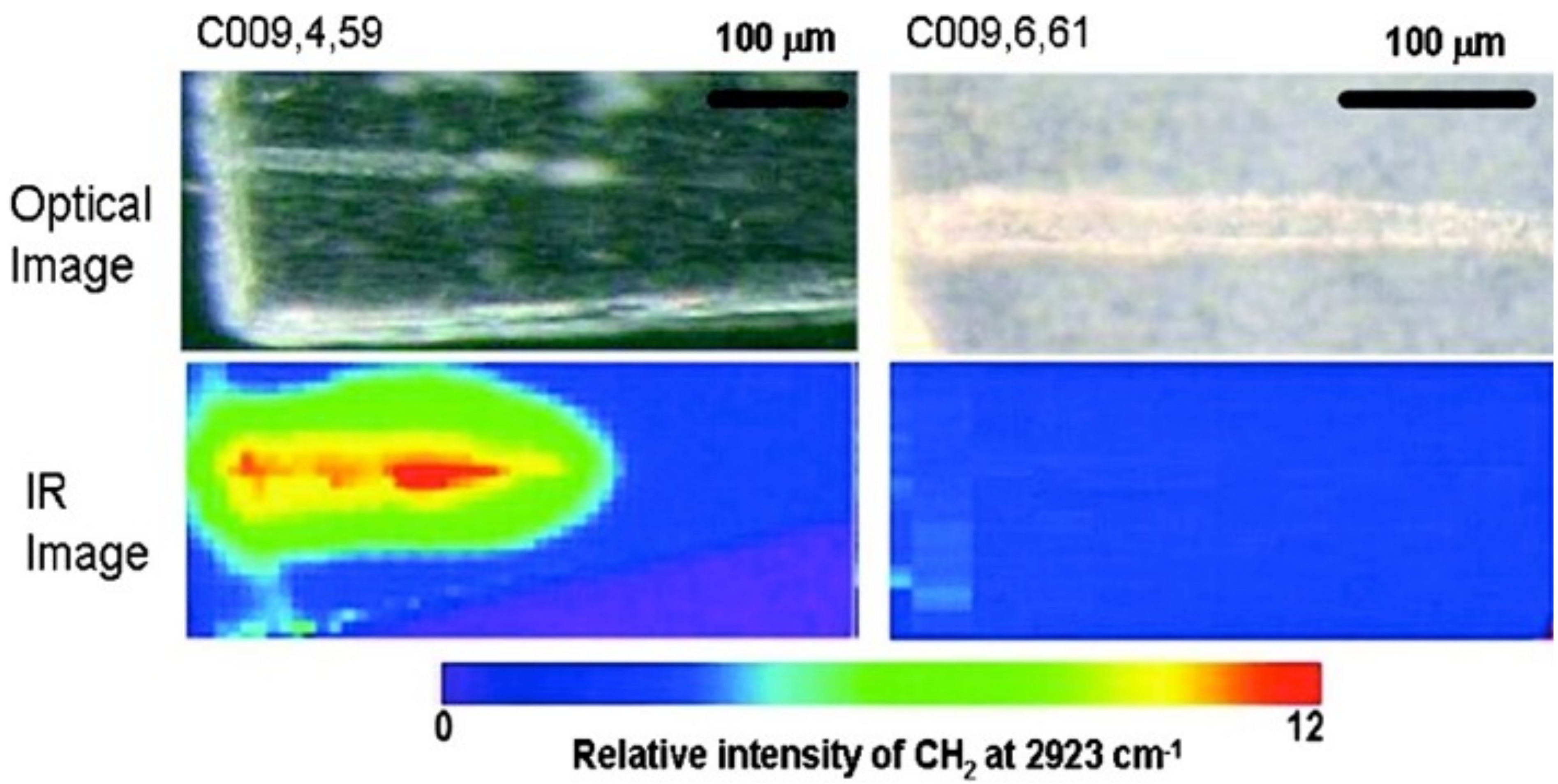


FIG. 3. Retention of CH3 in aerogel. Optical images of track 59 from Stardust Wild 2 cell C009 showing strong IR CH3 image below while no signal for track 61 from the same cell.

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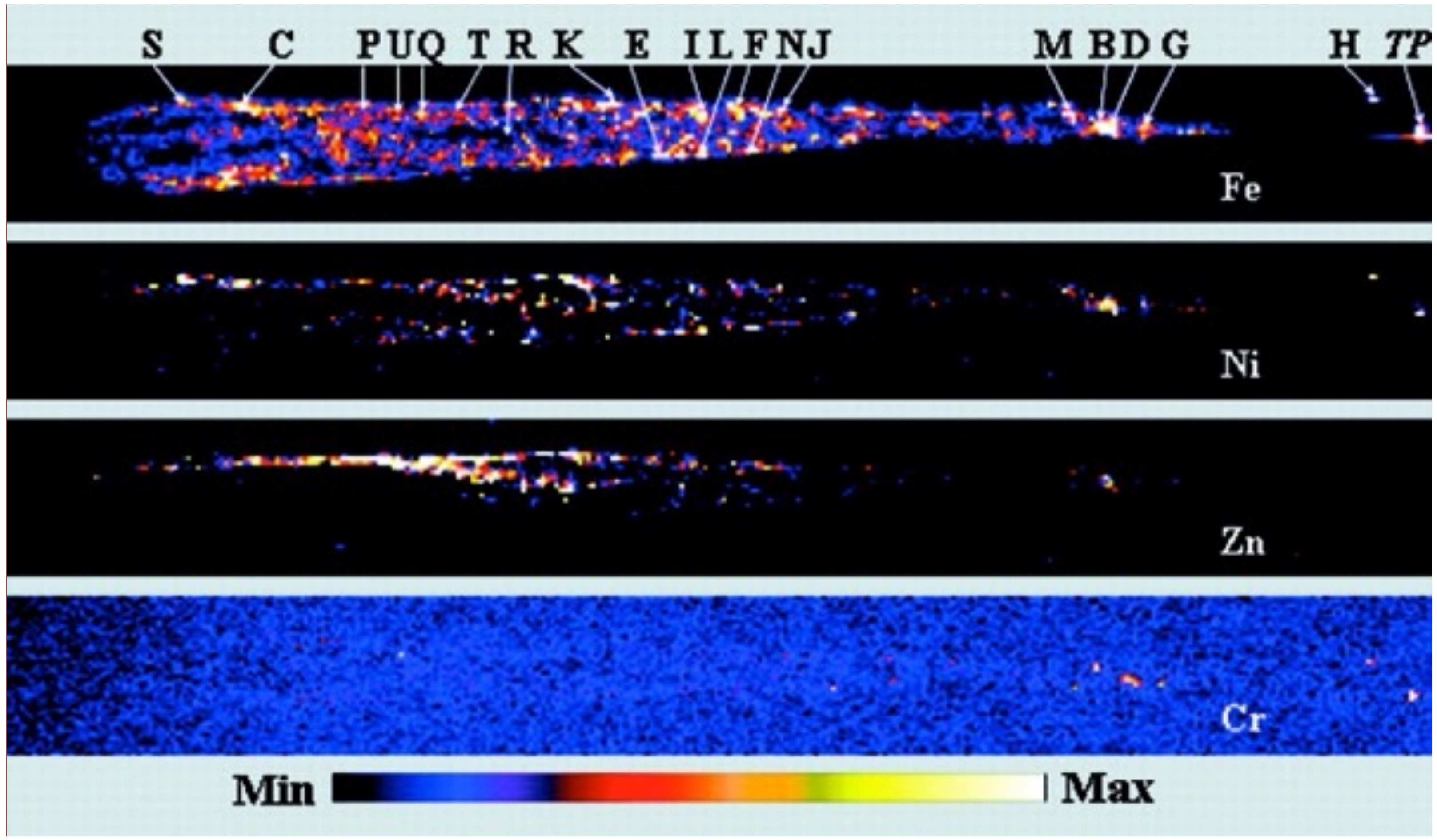
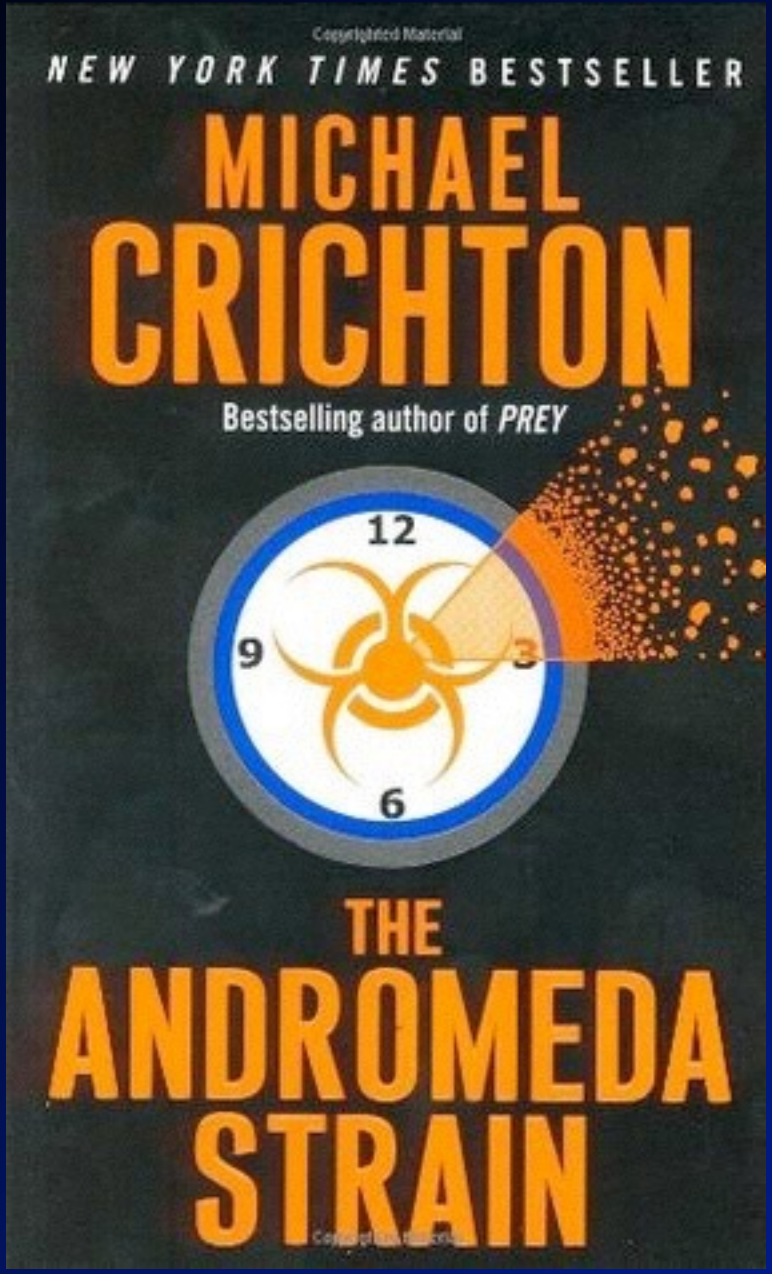


FIG. 2. X-ray fluorescence analysis of a Stardust Wild 2 particle made this 860 long track in the silica aerogel cell. Maps of Fe, Ni, Zn, and Cr fluorescence intensities were obtained with a step size of 3 pixels and a dwell time of 0.5 s/pixel. The 19 hot spots with the most intense concentration of elements (letters B, C to N, P to U) are indicated on the Fe map.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MICHAEL CRICHTON
Bestselling author of PREY
12
9
3
6
THE ANDROMEDA STRAIN

Biggest Budgets

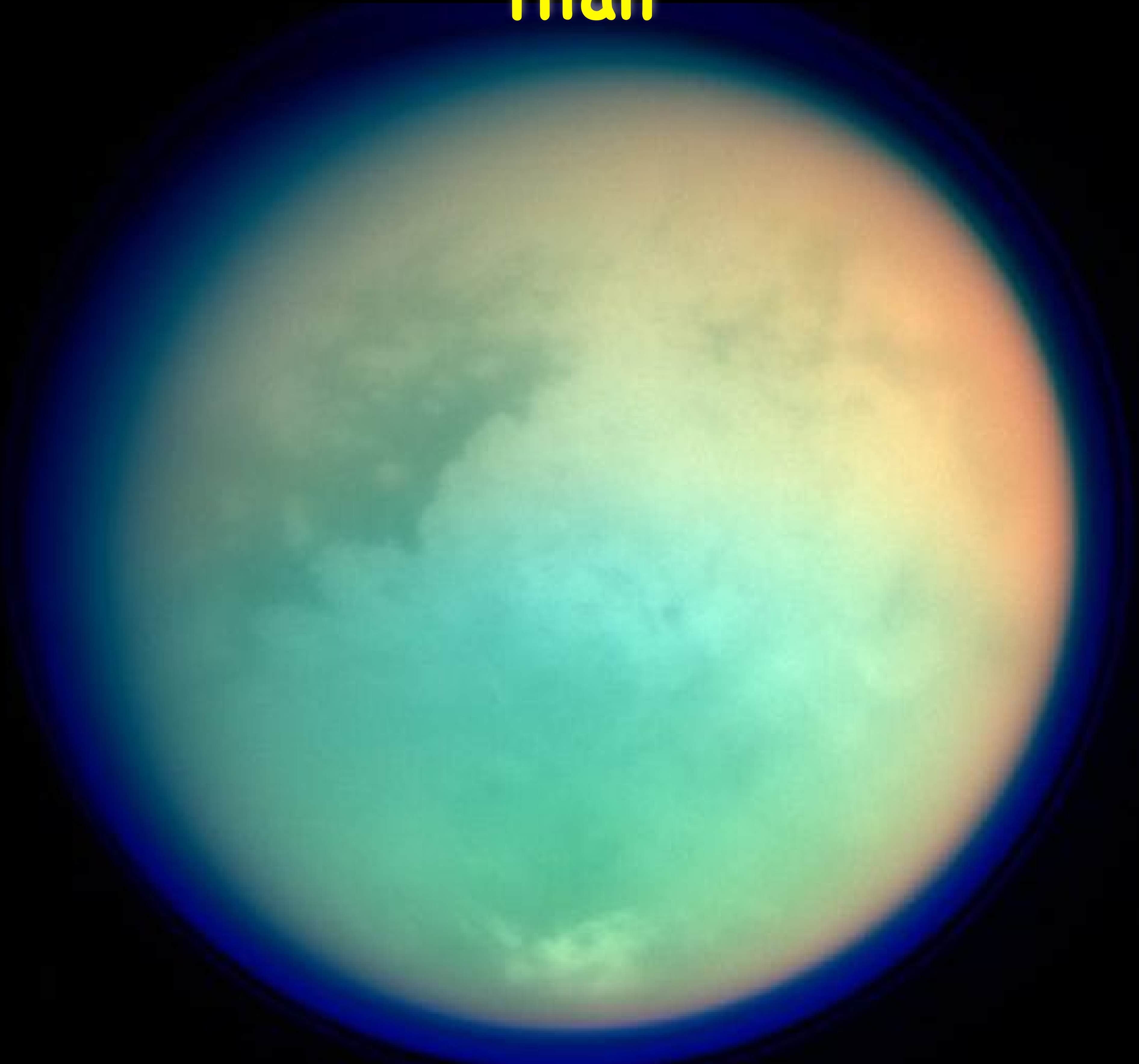
	Release Date	Movie	Production Budget	Domestic Gross	Worldwide Gross
1	12/18/2009	**Avatar**	$425,000,000	$760,507,625	$2,783,918,982
2	5/24/2007	**Pirates of the Caribbean: At World's End**	$300,000,000	$309,420,425	$963,420,425
3	11/6/2015	**Spectre**	$300,000,000	$0	$80,400,000
4	7/2/2013	**The Lone Ranger**	$275,000,000	$89,289,910	$259,989,910
5	3/9/2012	**John Carter**	$275,000,000	$73,058,679	$282,778,100
6	7/20/2012	**The Dark Knight Rises**	$275,000,000	$448,139,099	$1,084,439,099
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					

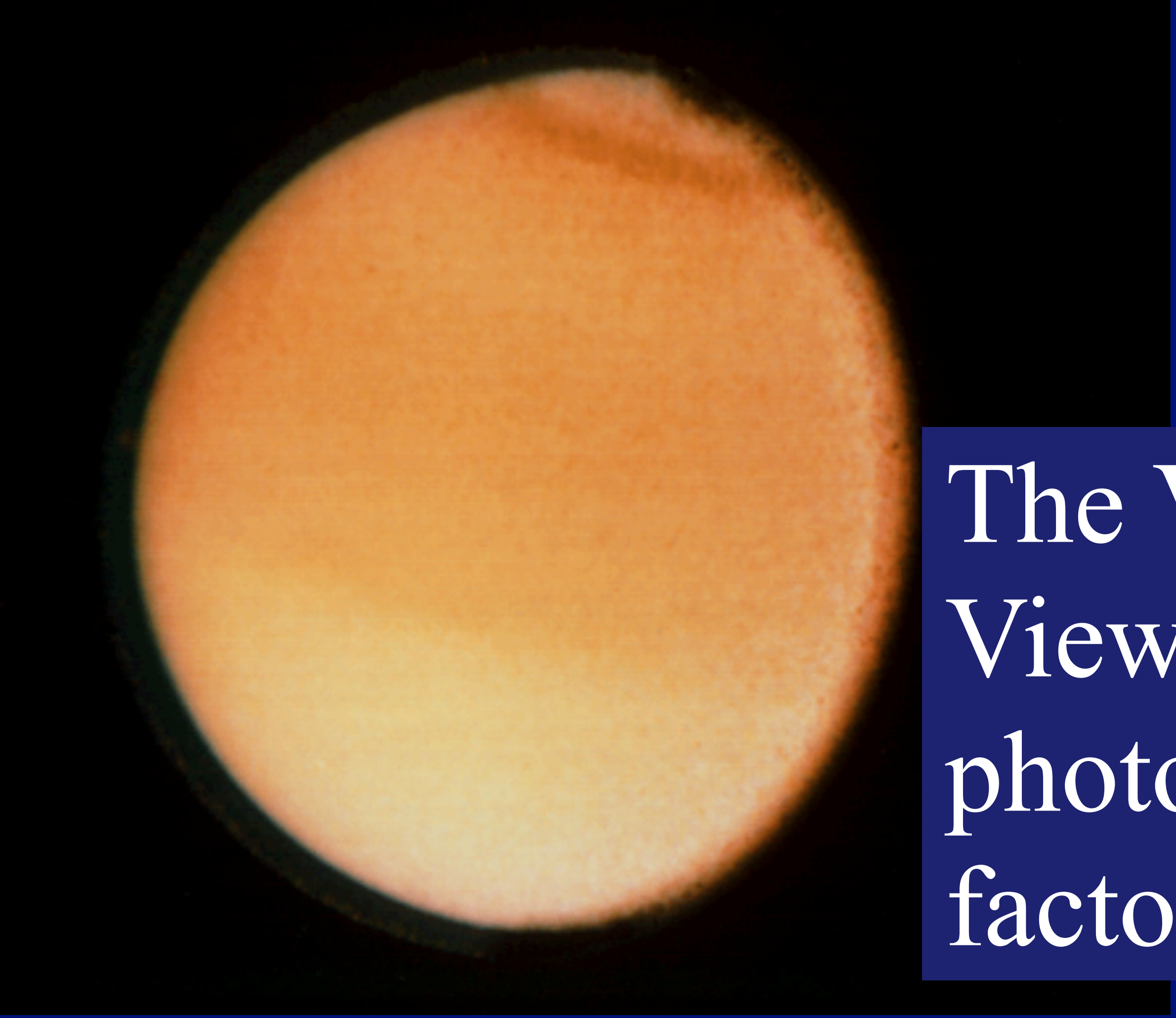
National Aeronautics and Space Administration

FY 2016 PRESIDENT'S BUDGET REQUEST SUMMARY

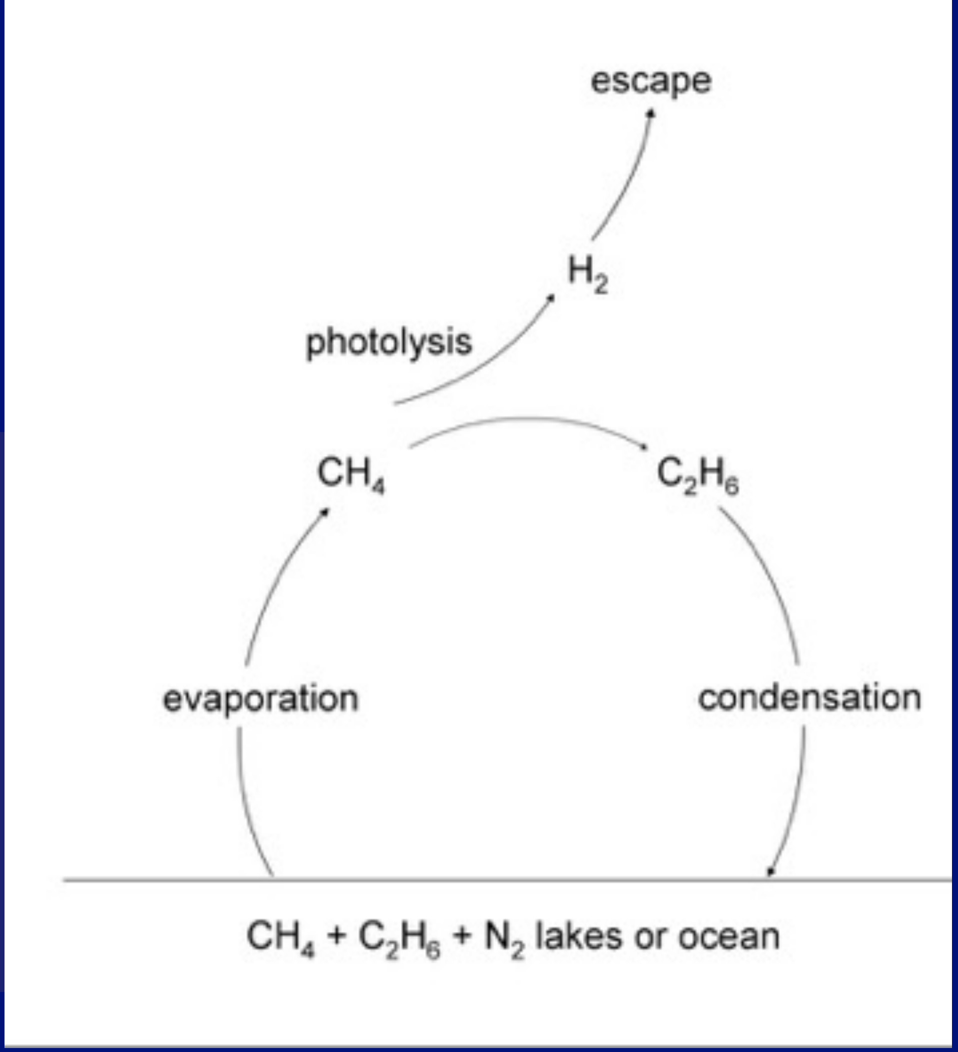
	Fiscal Year						
	Actual	Enacted	Request	Notional			
Budget Authority ($ in millions)	2014	2015	2016	2017	2018	2019	2020
NASA Total	17,646.5	18,010.2	18,529.1	18,807.0	19,089.2	19,375.5	19,666.1
Science	5,148.2	5,244.7	5,288.6	5,367.9	5,488.4	5,530.2	5,613.1
Earth Science	1,824.9	--	1,947.3	1,966.7	1,988.0	2,009.3	2,027.4
Planetary Science	1,345.7	--	1,361.2	1,420.2	1,458.1	1,502.4	1,527.8
Astrophysics	678.3	--	709.1	726.5	769.5	1,005.5	1,138.3
James Webb Space Telescope	658.2	645.4	620.0	569.4	534.9	305.0	197.5
Heliophysics	641.0	--	651.0	685.2	697.9	708.1	722.1
Aeronautics	566.0	651.0	571.4	580.0	588.7	597.5	606.4
Space Technology	576.0	596.0	724.8	735.7	746.7	757.9	769.3
Exploration	4,113.2	4,356.7	4,505.9	4,482.2	4,298.7	4,264.7	4,205.4
Exploration Systems Development	3,115.2	3,245.3	2,862.9	2,895.7	2,971.7	3,096.2	3,127.1
Commercial Spaceflight	696.0	805.0	1,243.8	1,184.8	731.9	173.1	1.1
Exploration Research and Development	302.0	306.4	399.2	401.7	595.1	995.4	1,077.2
Space Operations	3,774.0	3,827.8	4,003.7	4,191.2	4,504.9	4,670.8	4,864.3
International Space Station	2,964.1	--	3,105.6	3,273.9	3,641.0	3,826.0	4,038.3
Space and Flight Support	809.9	--	898.1	917.3	863.8	844.8	826.1

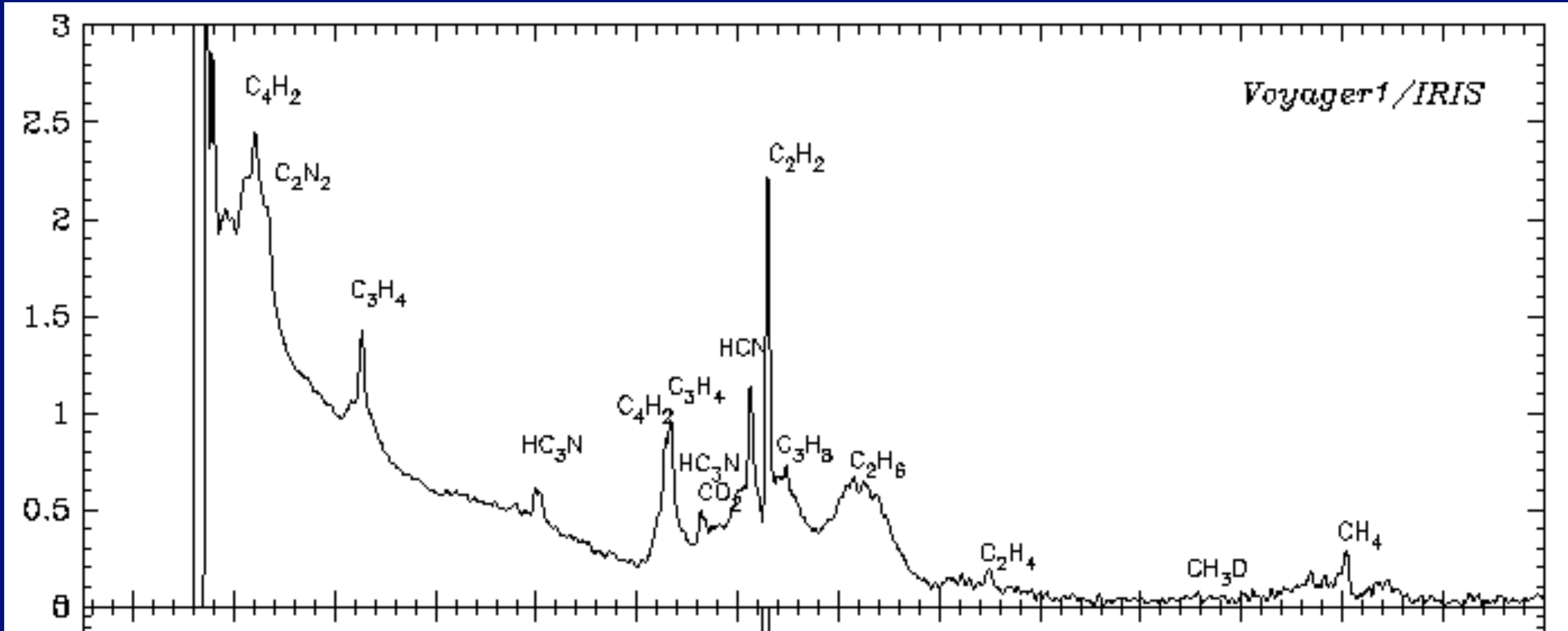
Titan

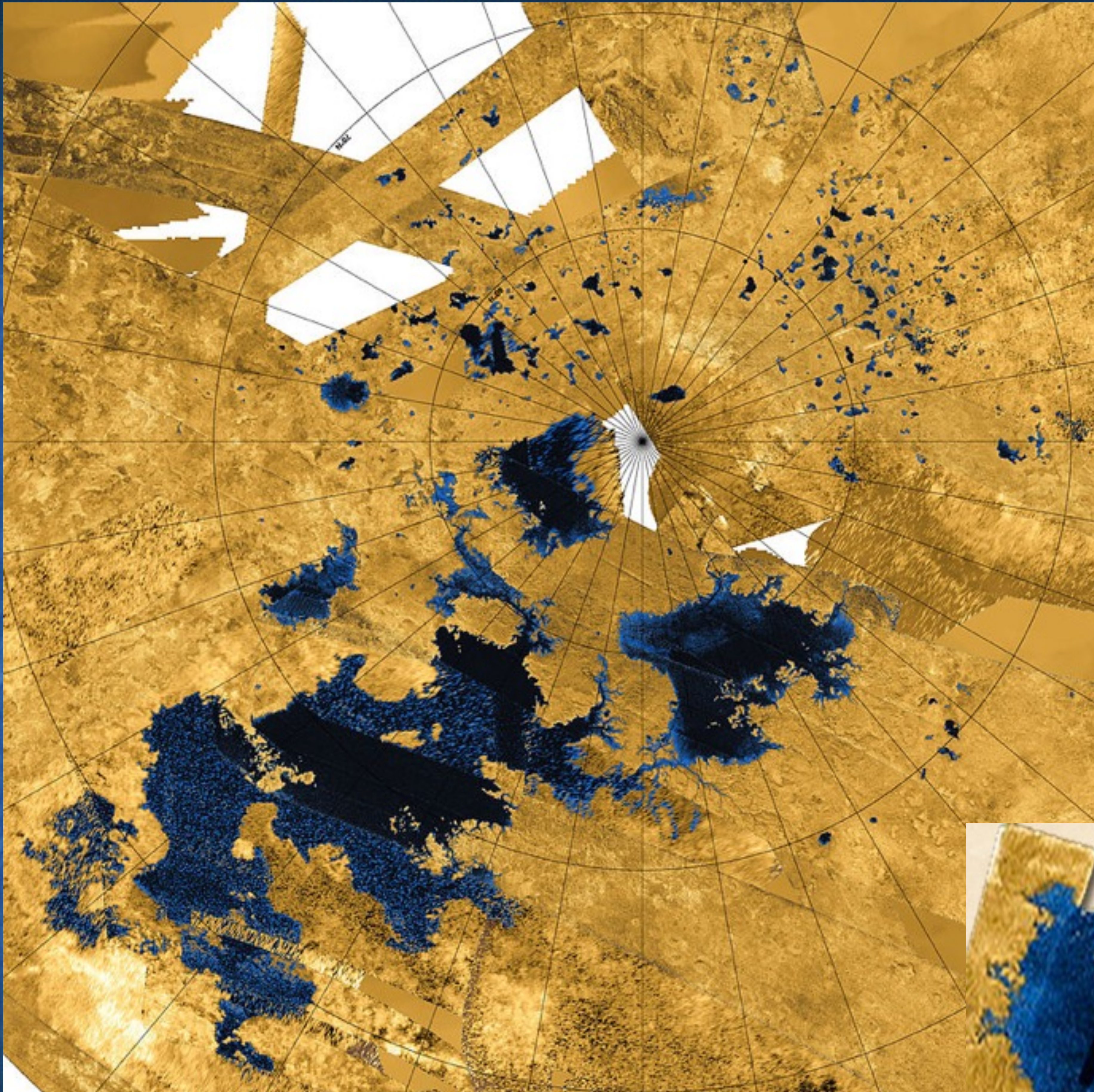


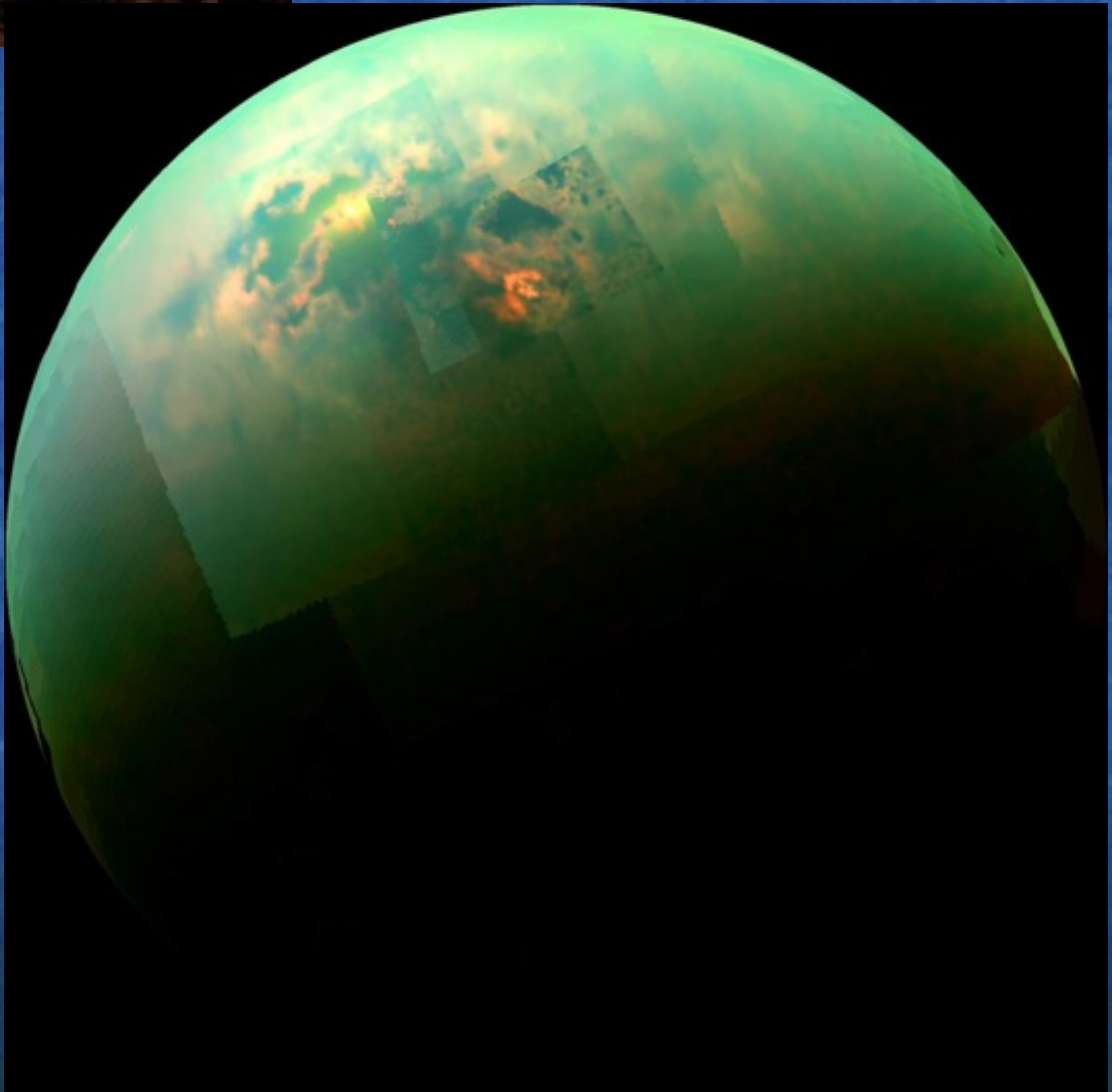


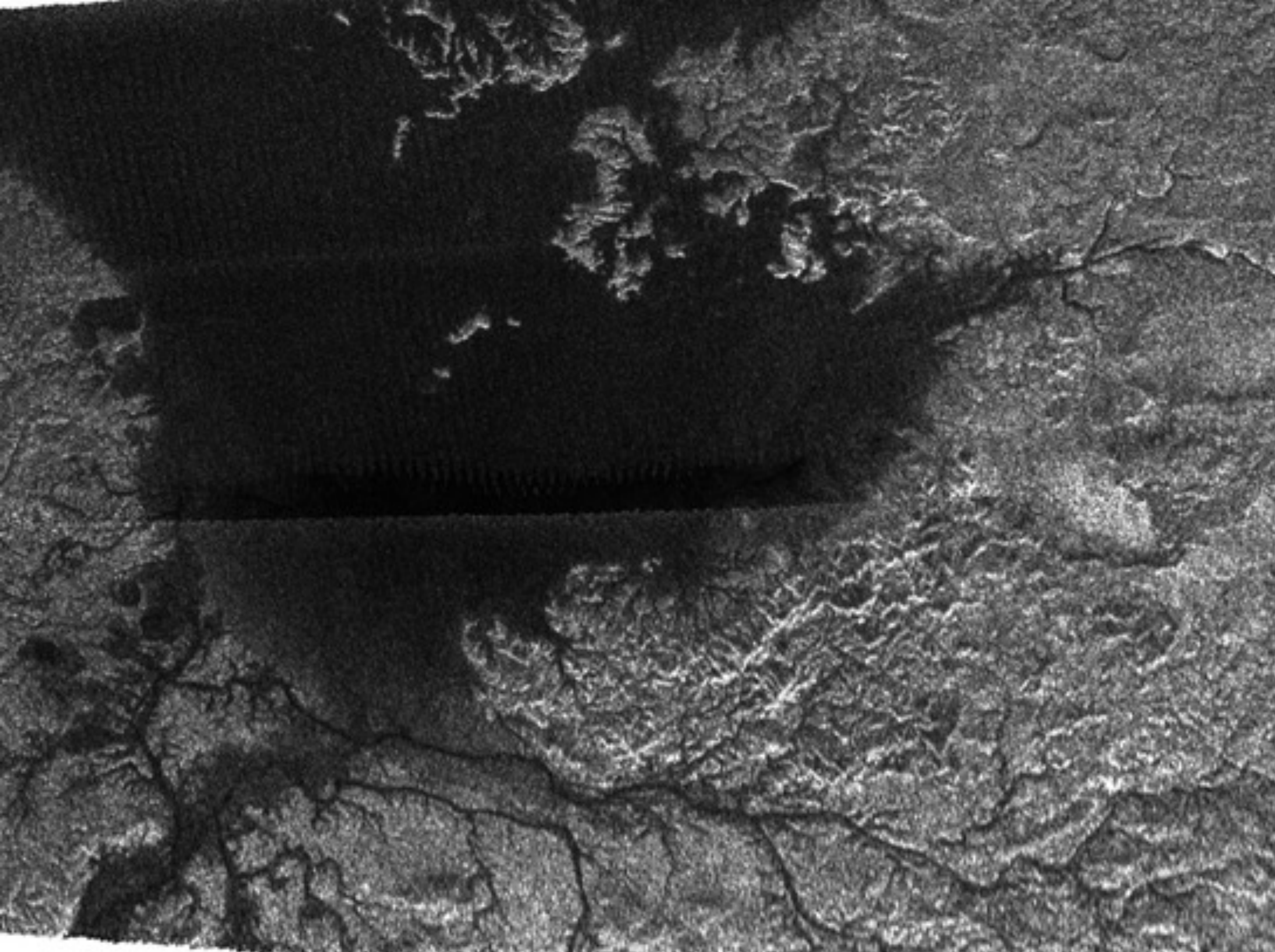
The Voyager View - Titan as a photochemical factory







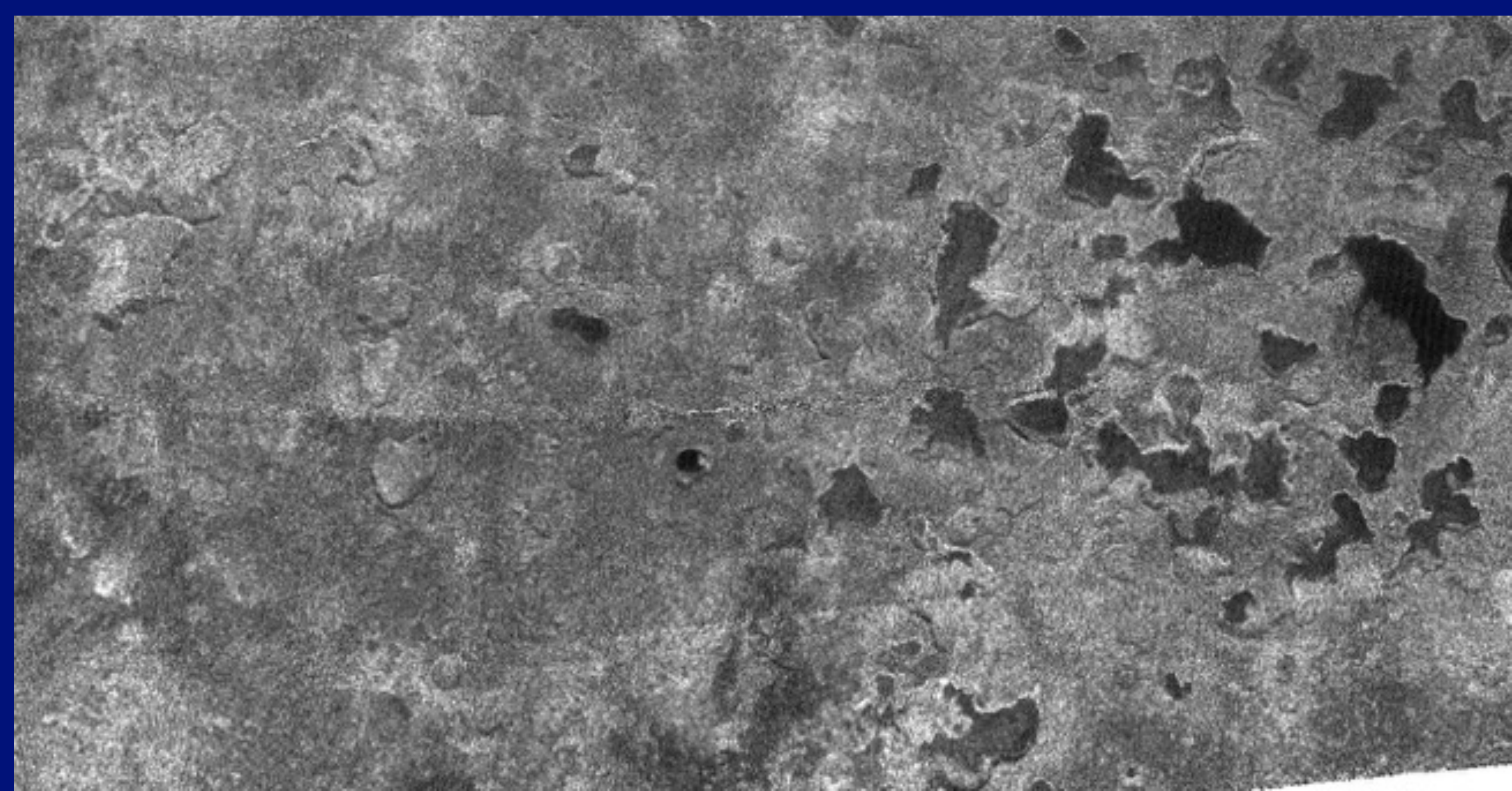




Lakes on Titan discovered in polar regions.

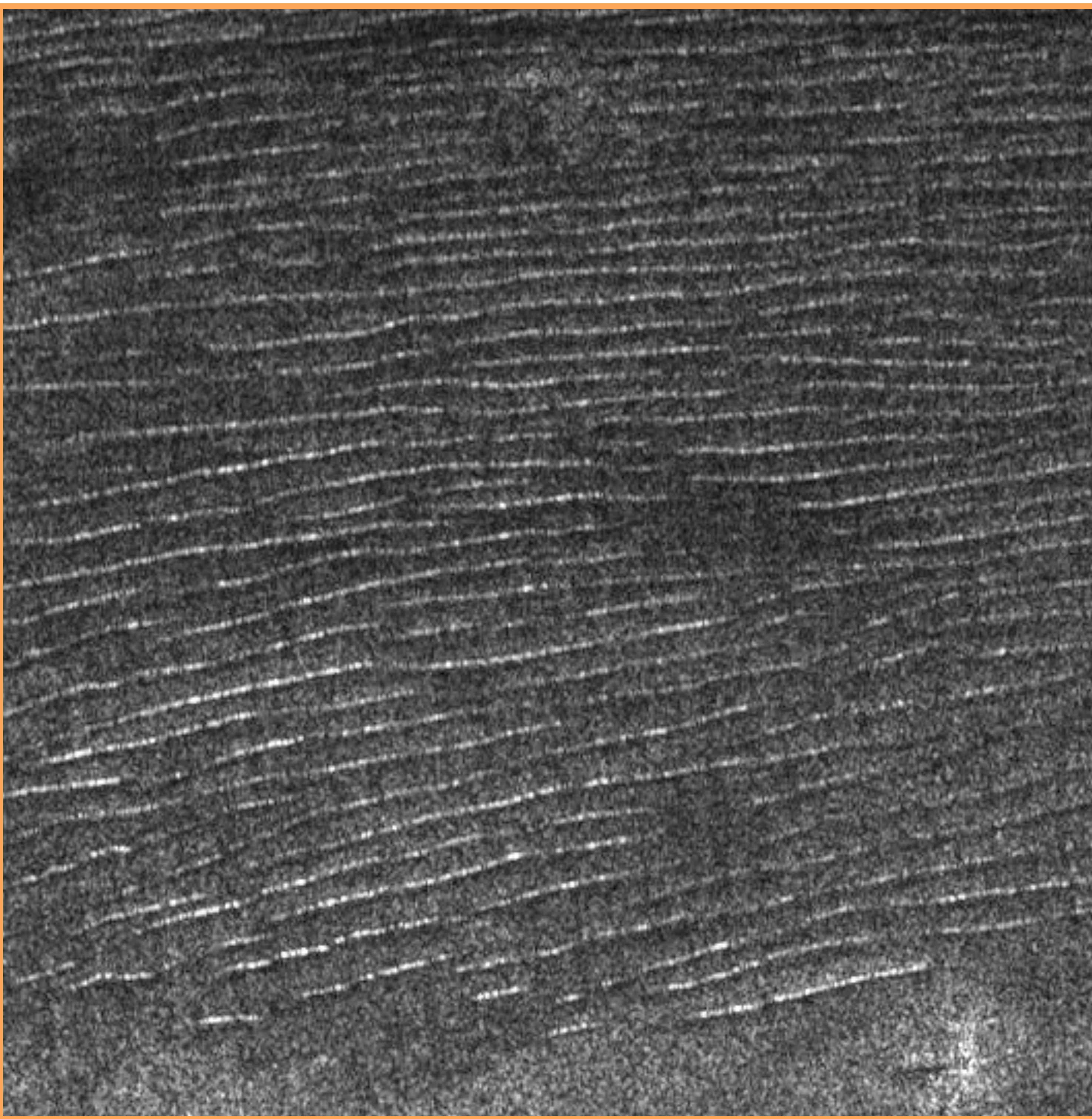
Larger lakes and seas have irregular margins, islands - suggestive of flooding of the landscape .

Some lakes full to their edges, some partially-filled, some dry altogether. Do they dry out seasonally ? Steep-walled karst-like lakes (cf Florida?) Dissolution of crustal material ?



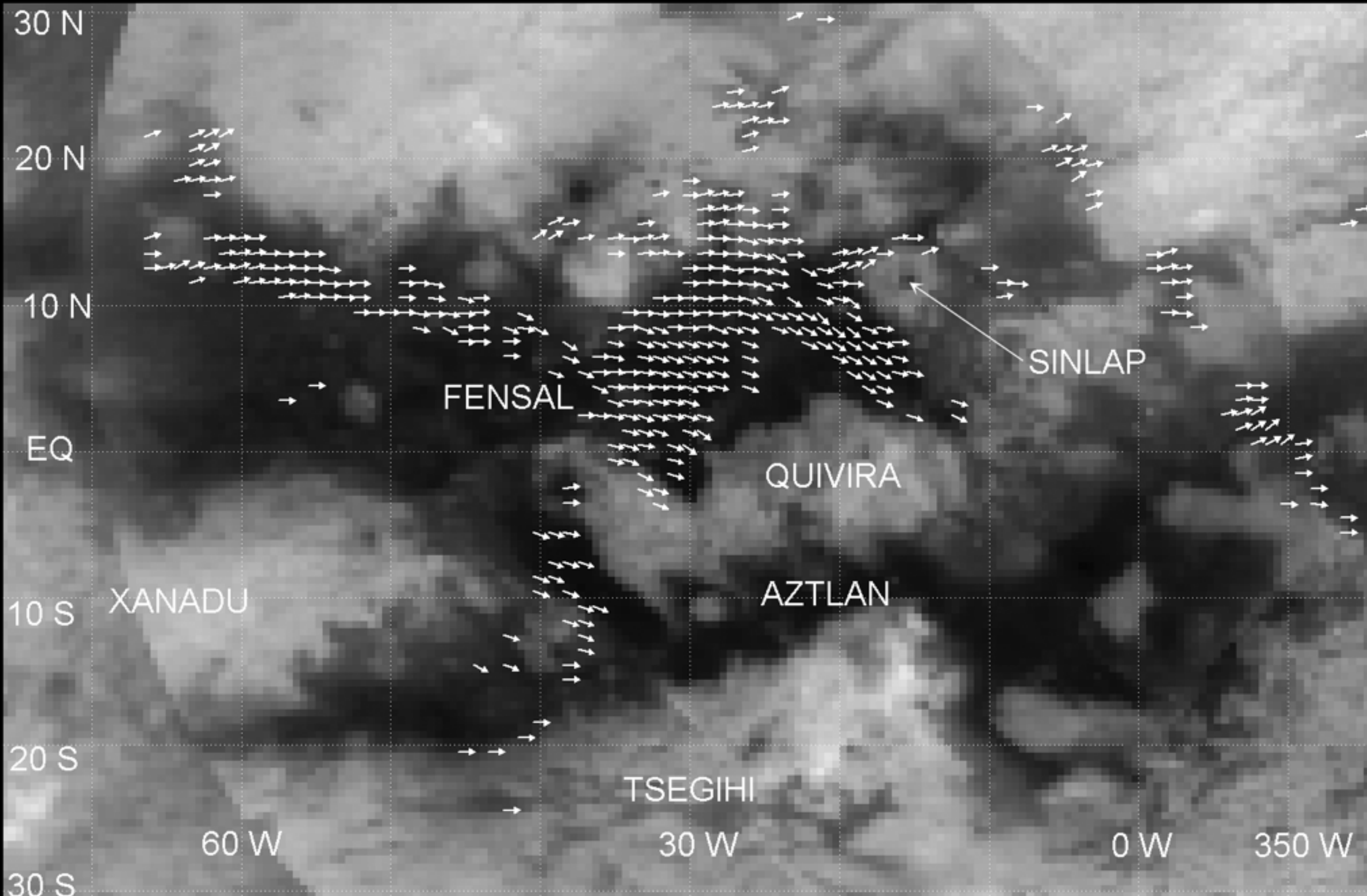
A surprise on Titan - (organic) Dunes !

Sometimes seen as positive ridges ~1-2km wide, 150m high. Sometimes only visible as dark streaks against brighter substrate



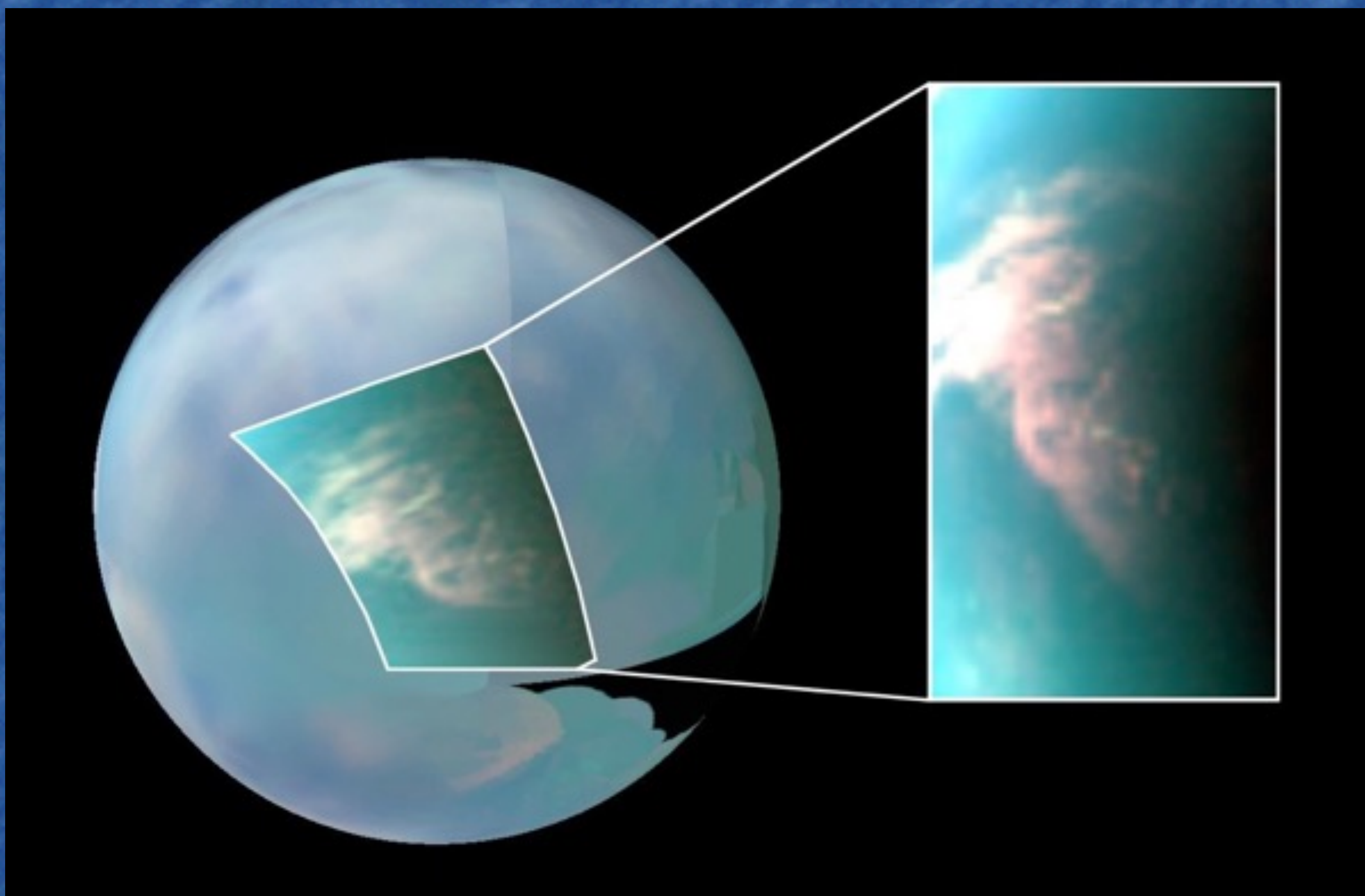
Linear dunes in the Namib Desert

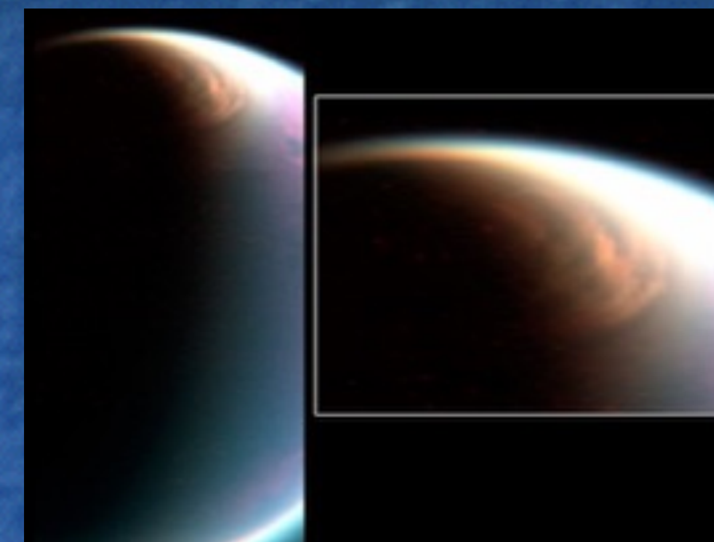
Longitudinal dunes form in alternating wind regime (due to

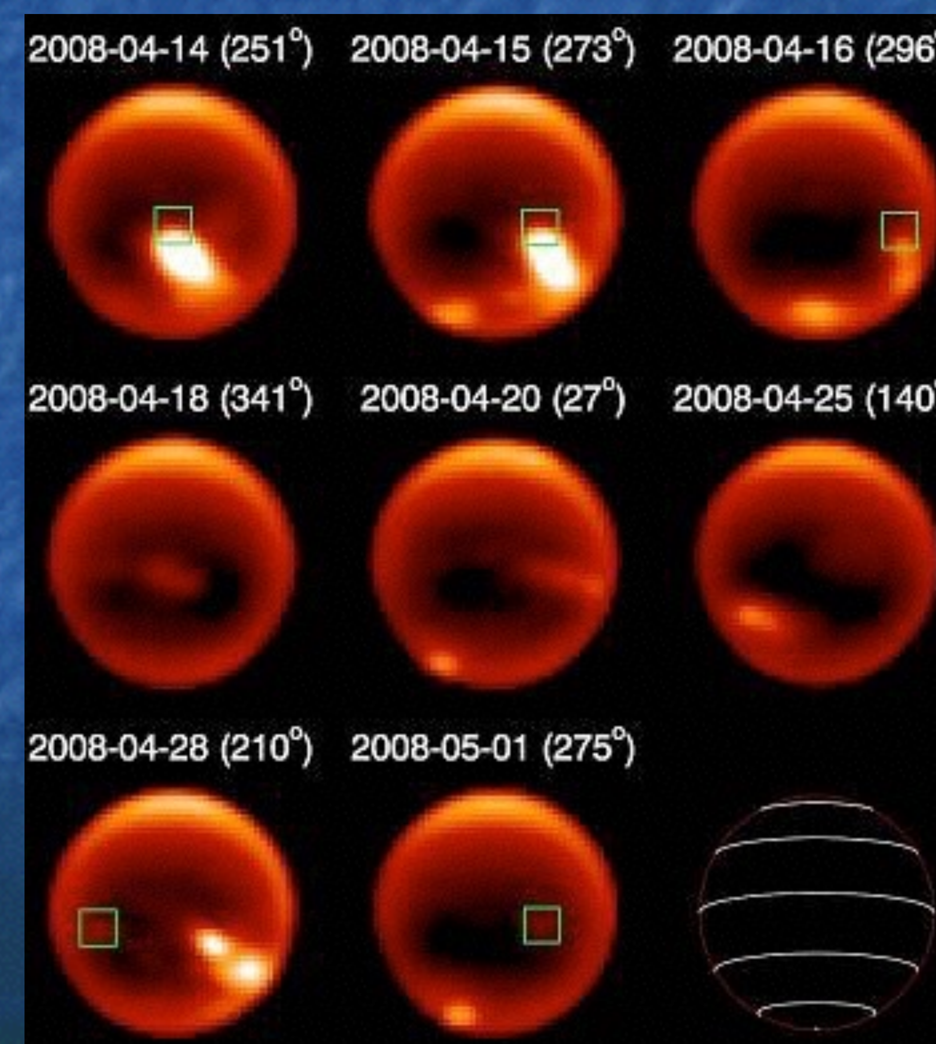


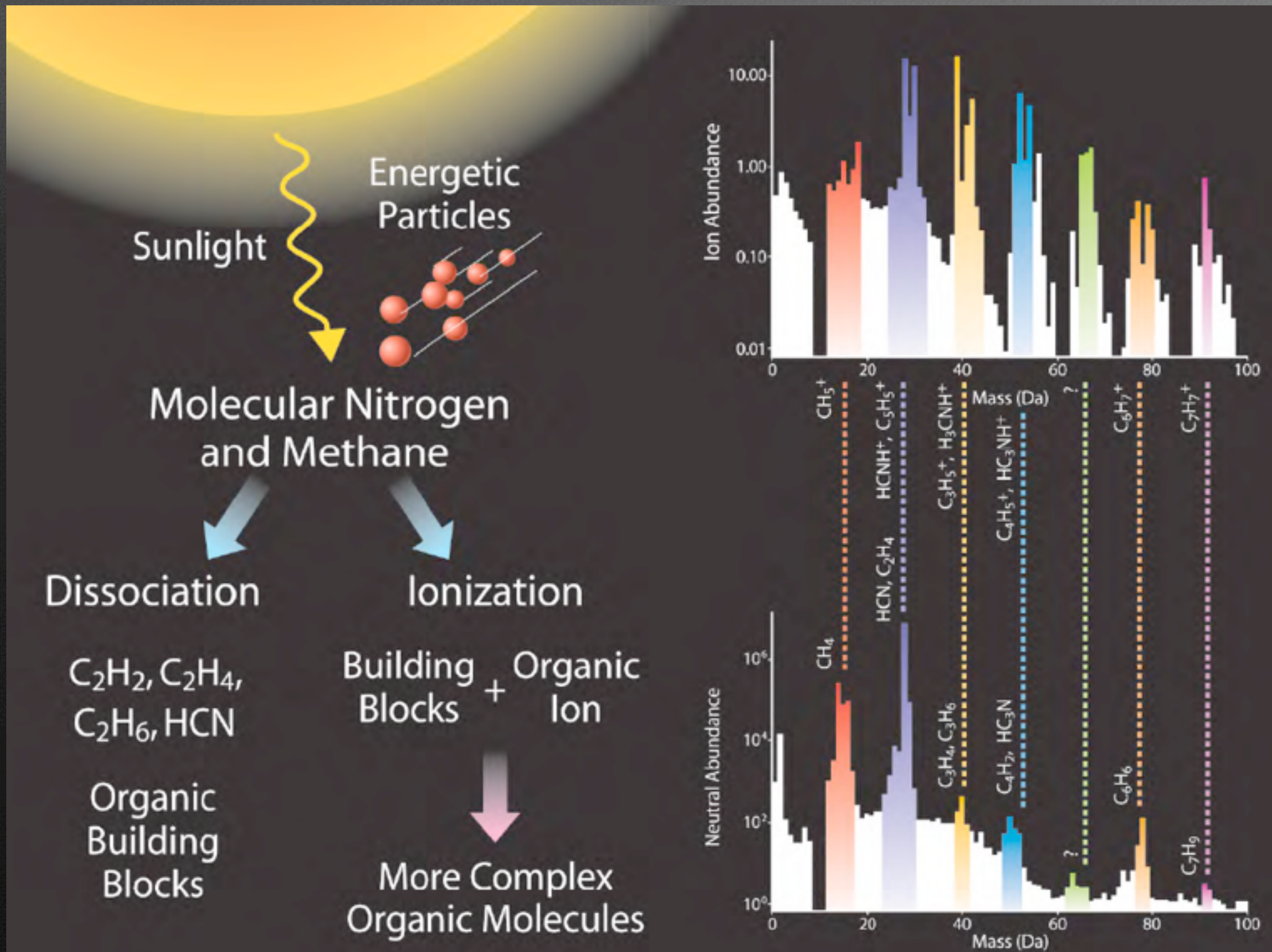
Lorenz and Radebaugh, Geophysical Research Letters, 2009

Clouds on Titan

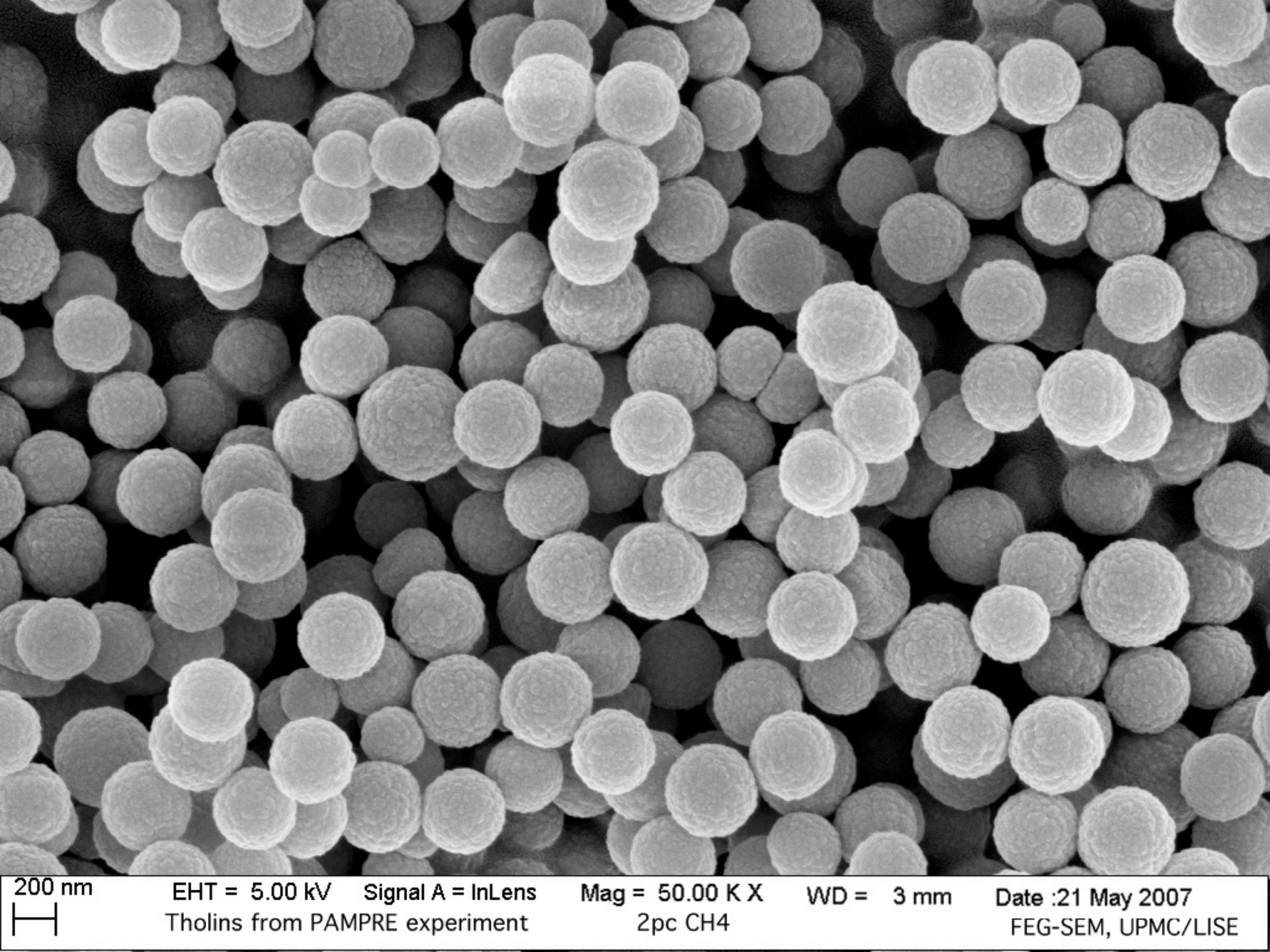




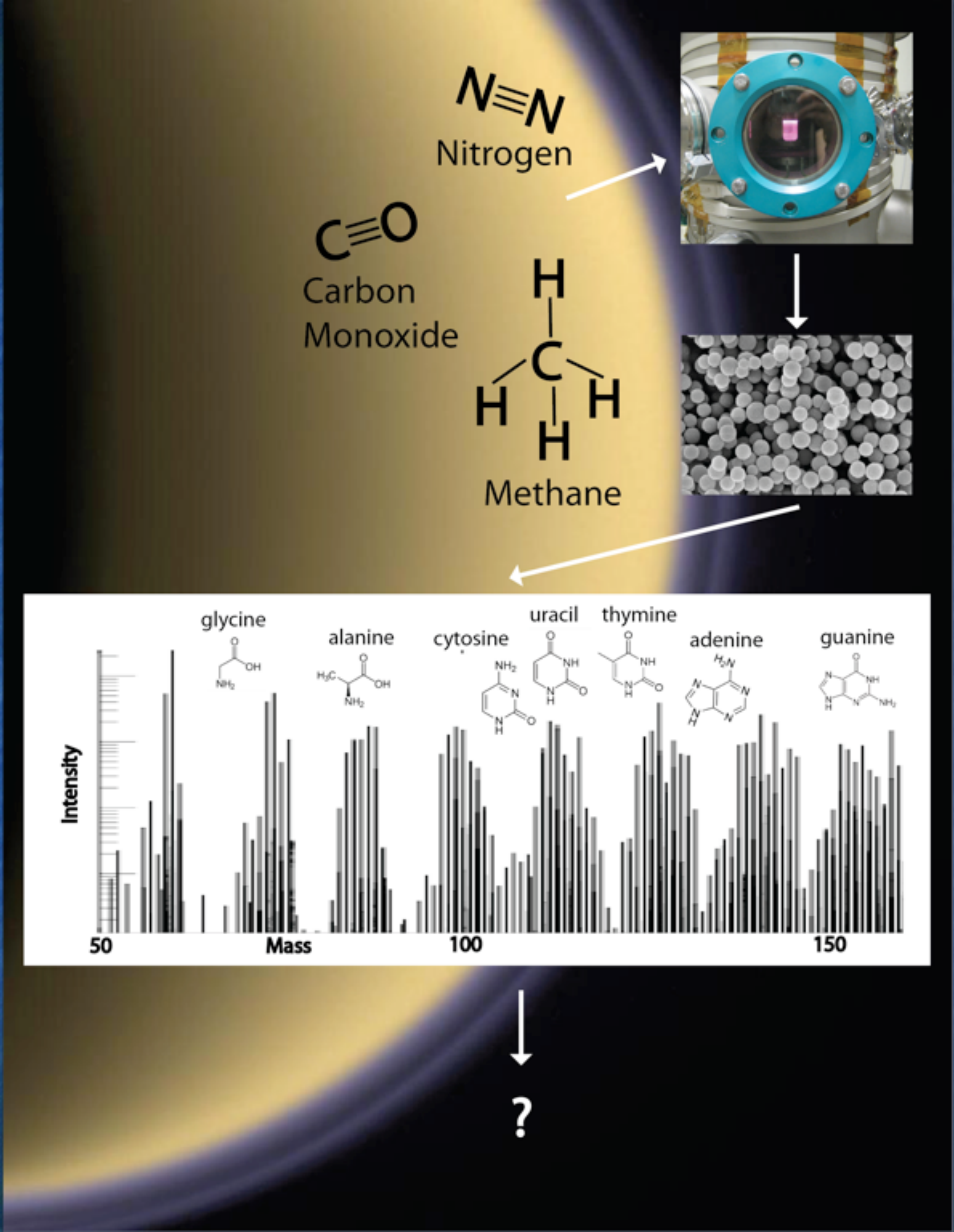


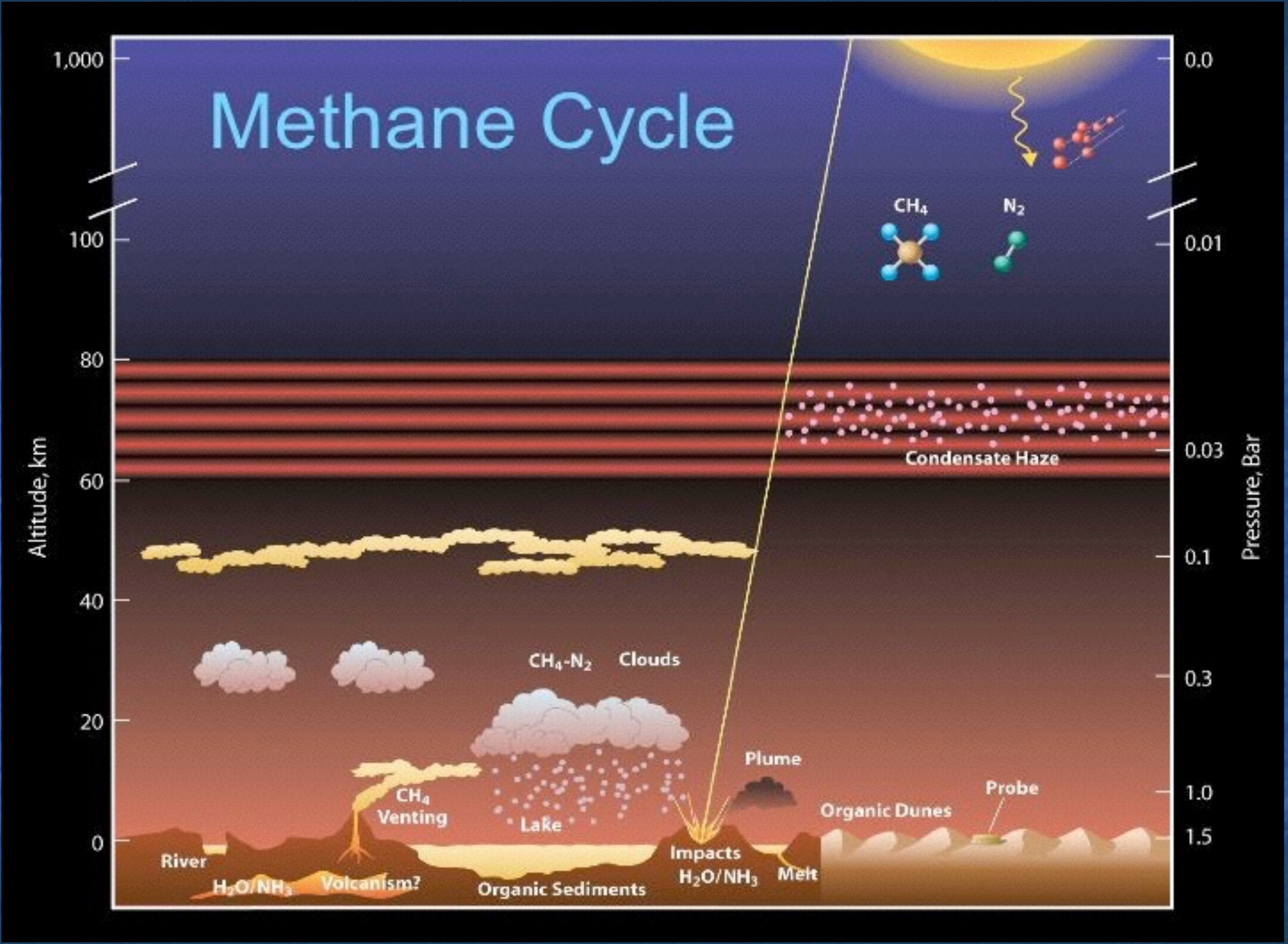


Sunlight
Energetic Particles
Molecular Nitrogen and Methane
Dissociation
Ionization
C_2H_2, C_2H_4, C_2H_6, HCN
Organic Building Blocks
Building Blocks + Organic Ion
More Complex Organic Molecules
Ion Abundance
Mass (Da)
Neutral Abundance
CH_5^+
HCN, C_2H_4 HCNH$^+$, $C_5H_5^+$
$C_3H_5^+$, H_3CNH^+
$C_4H_5^+$, HC_3NH^+
$C_6H_7^+$
$C_7H_7^+$
CH_4
C_3H_4, C_3H_6
C_4H_2, HC_3N
C_6H_6
C_7H_8
?


200 nm
EHT = 5.00 kV
Signal A = InLens
Mag = 50.00 K X
WD = 3 mm
Date :21 May 2007
Tholins from PAMPRE experiment
2pc CH4
FEG-SEM, UPMC/LISE

Miller-Urey on Titan




Methane Cycle
1,000
100
80
60
40
20
0
Altitude, km
0.0
0.01
0.03
0.1
0.3
1.0
1.5
Pressure, Bar
CH_4
N_2
Condensate Haze
CH_4-N_2 Clouds
Plume
Probe
Organic Dunes
CH_4 Venting
Lake
River
H_2O/NH_3
Volcanism?
Organic Sediments
Impacts
H_2O/NH_3
Melt

Methane/Ethane Rain on Titan

Rare Titan

Scientists have discovered liquid (H_2O) on another planet!

however;

- it is extremely corrosive to organics & inorganics

- solution concentrations will be so high as to be toxic

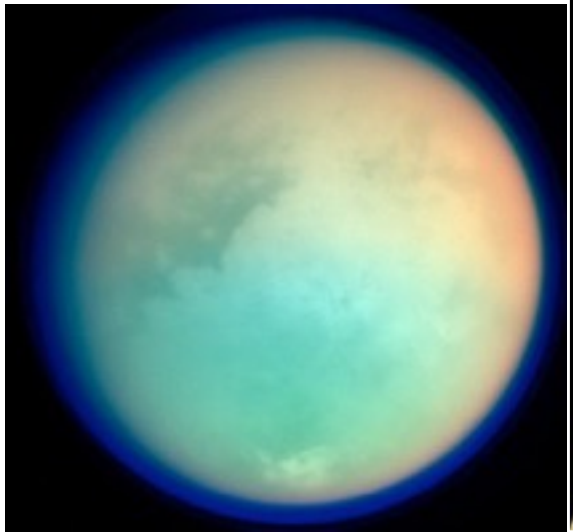
- high temperatures imply life Rx on timescale of days

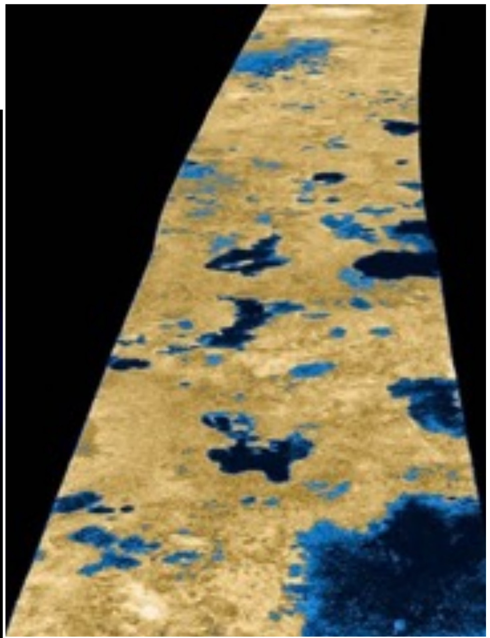
- solid phase floats; rendering the polar & winter regions uninhabitable and creating a climate feedback instability

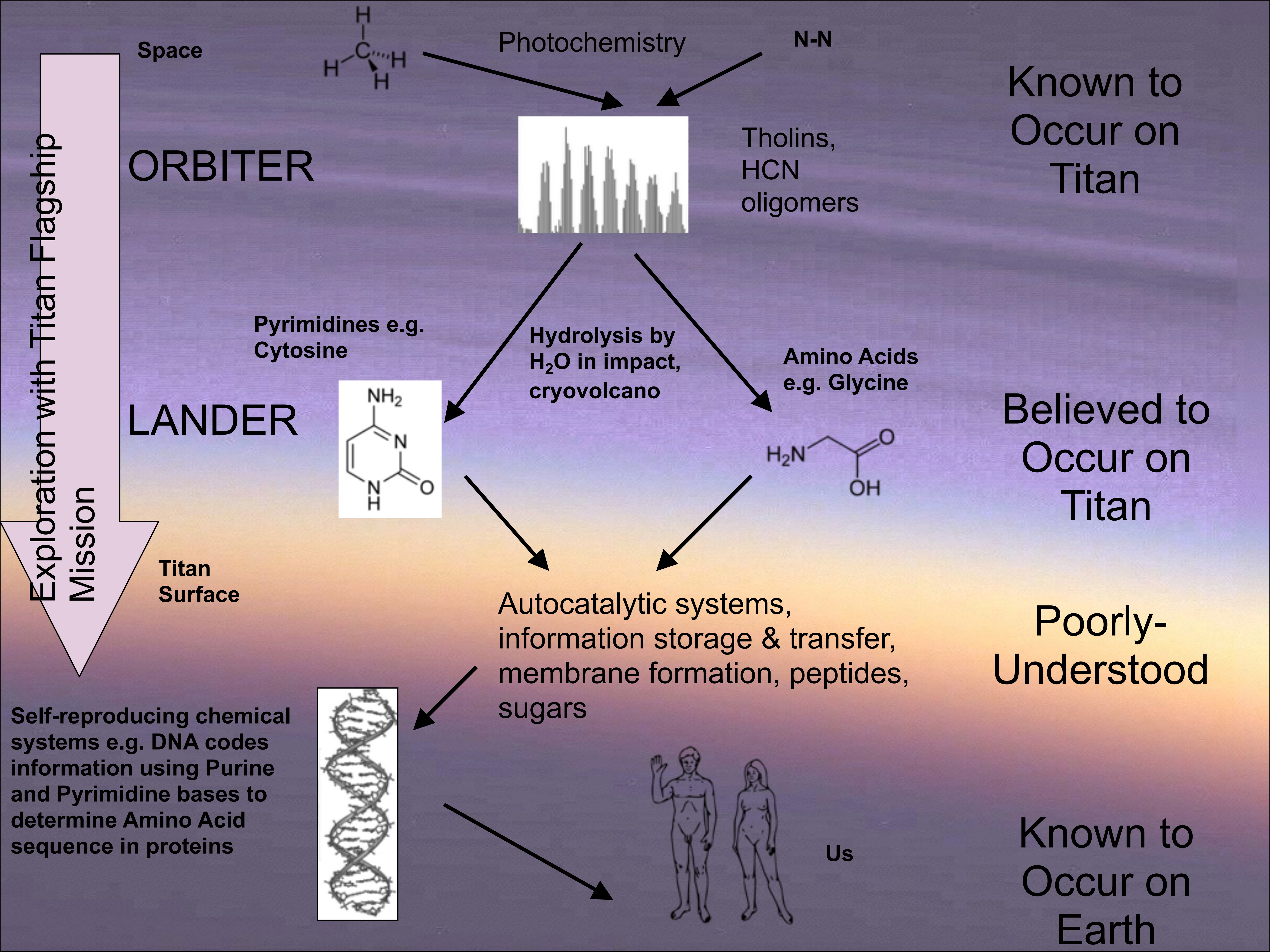
- its photolysis product, O_2, poisons the atmosphere.

…

proving the suitability of our environment of liquid CH_4 at normal temperatures and the intelligence of its design.






Space
Photochemistry
N-N
Known to Occur on Titan
ORBITER
Tholins, HCN oligomers
Exploration with Titan Flagship Mission
Pyrimidines e.g. Cytosine
Hydrolysis by H_2O in impact, cryovolcano
Amino Acids e.g. Glycine
LANDER
NH2
N
N
H
O
H_2N
O
OH
Believed to Occur on Titan
Titan Surface
Autocatalytic systems, information storage & transfer, membrane formation, peptides, sugars
Poorly-Understood
Self-reproducing chemical systems e.g. DNA codes information using Purine and Pyrimidine bases to determine Amino Acid sequence in proteins
Us
Known to Occur on Earth

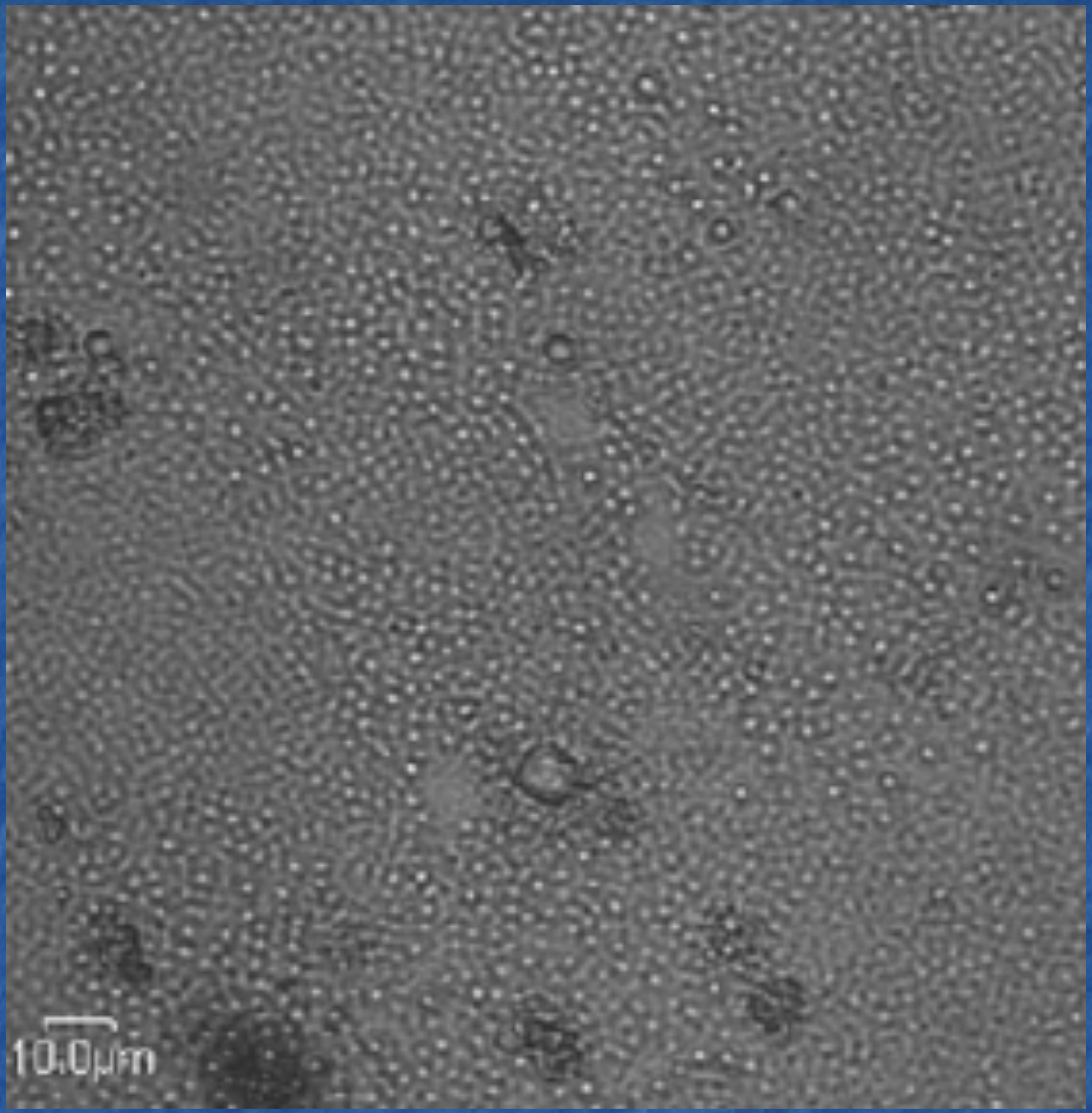
Inspiration from Titan

Cells as water drops emulsified in hydrocarbon

ESA-NASA Cassini-Huygens mission

Put a synthetic genetic system into synthetic cells like those that might be found subsurface on Titan.

A Titan life experiment?



- Water mixed with a hydrocarbon solvent generates micron scale water droplets or "cells".
- Add "synthetic" DNA in the form of nucleotide chains.
- Allow the nucleotide chains to reproduce and evolve using an external help.

Could there be methane life on Titan? ☺

Table 1. Free Energies of Hydrogenation on Titan

Reaction	**ΔG (kcal/mole)**
$C_2H_2 + 3H_2 = 2CH_4$	80
$C_2H_6 + H_2 = 2CH_4$	15
$R\text{-}CH_2 + H_2 = R + CH_4$	13
Earth	
$CO_2 + H_2 = CH_4 + H_2O$	>10

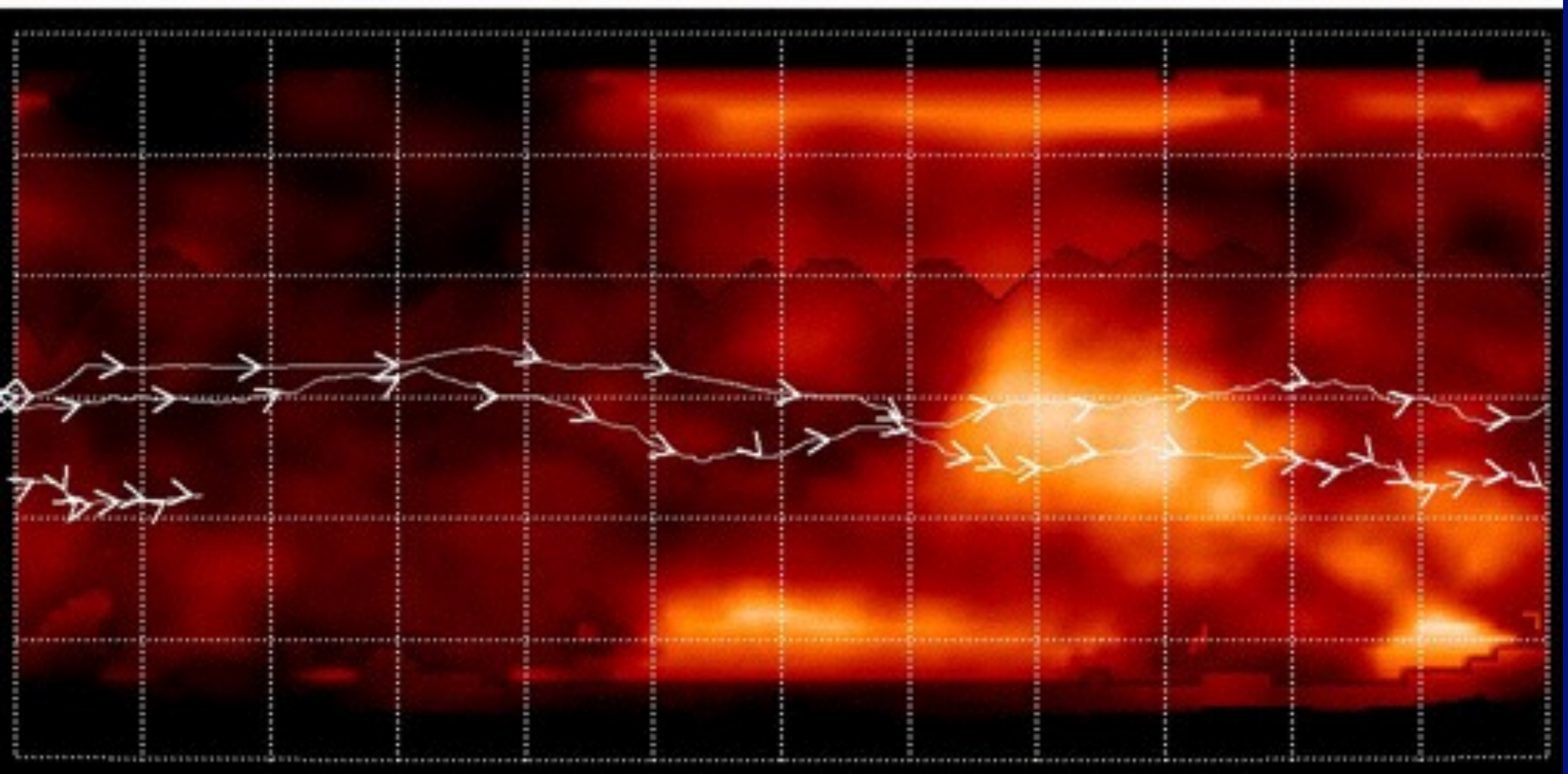
McKay and Smith, Icarus, 2005

Things to be learned about Titan at all scales.

Mars program is a good template

A Titan orbiter will spend more time close to Titan in its first 5 days than Cassini will have.

Titan is easier to land on than Mars (in many ways). A Titan Lander could conduct seismic, magnetic, meteorological monitoring, and detailed analysis of surface materials.



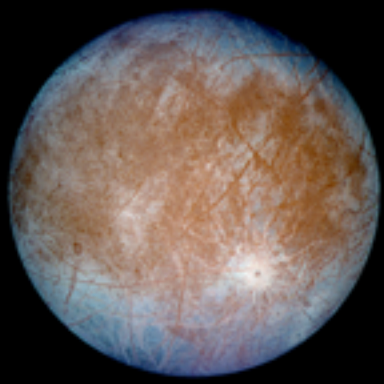
Balloons on Titan

- Titan's thick, cold atmosphere is easy to fly in (planes, balloons) - hot air balloon is particularly attractive.
- Balloon surveys diverse terrains at very high resolution, obtains spectra through less of atmospheric column, and higher resolution subsurface radar sounding than orbiter.
- Expected zonal tropospheric winds ~1 m/s allow two circumnavigations in one year at ~10km altitude (low enough to image surface)
- Altitude control capability makes mission robust to wind field and may allow tidal wind field to be exploited for latitude change.

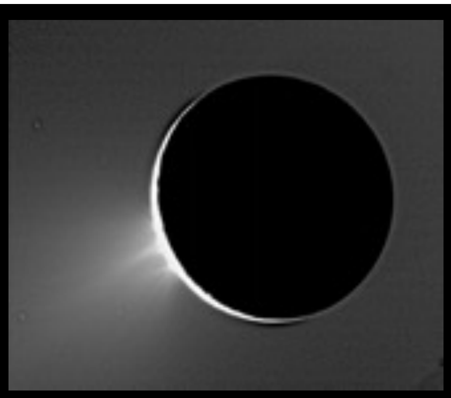
Other worlds with liquids

Mars

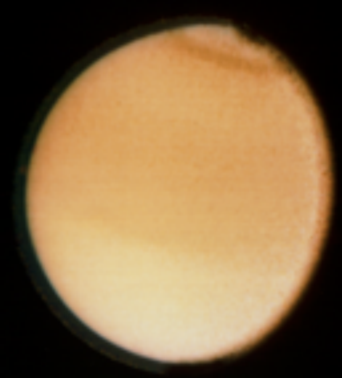
Europa



Enceladus



Titan



Increasing chance of life not related to Earth life