Astrobiology
An Overview

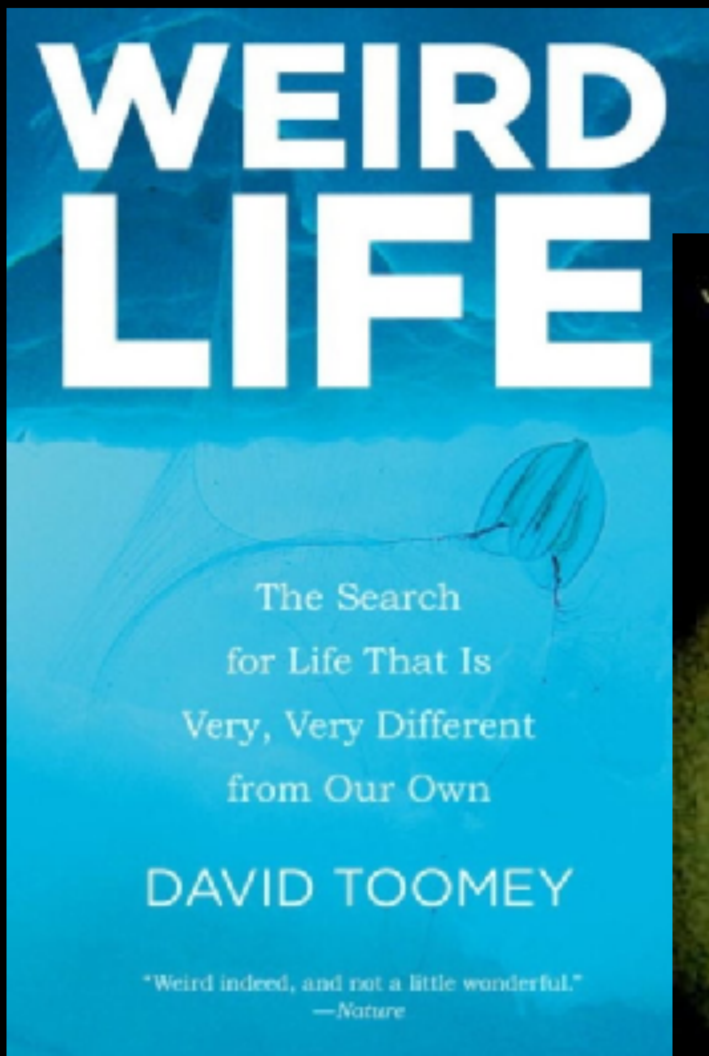
Markus Kissler-Patig

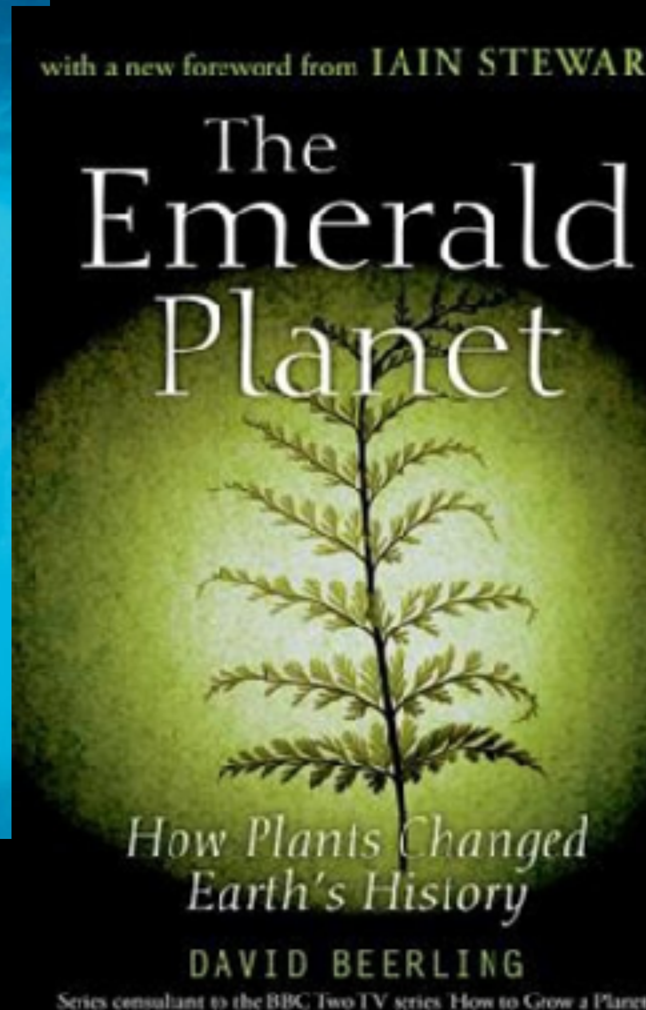
IMPRS Graduate School

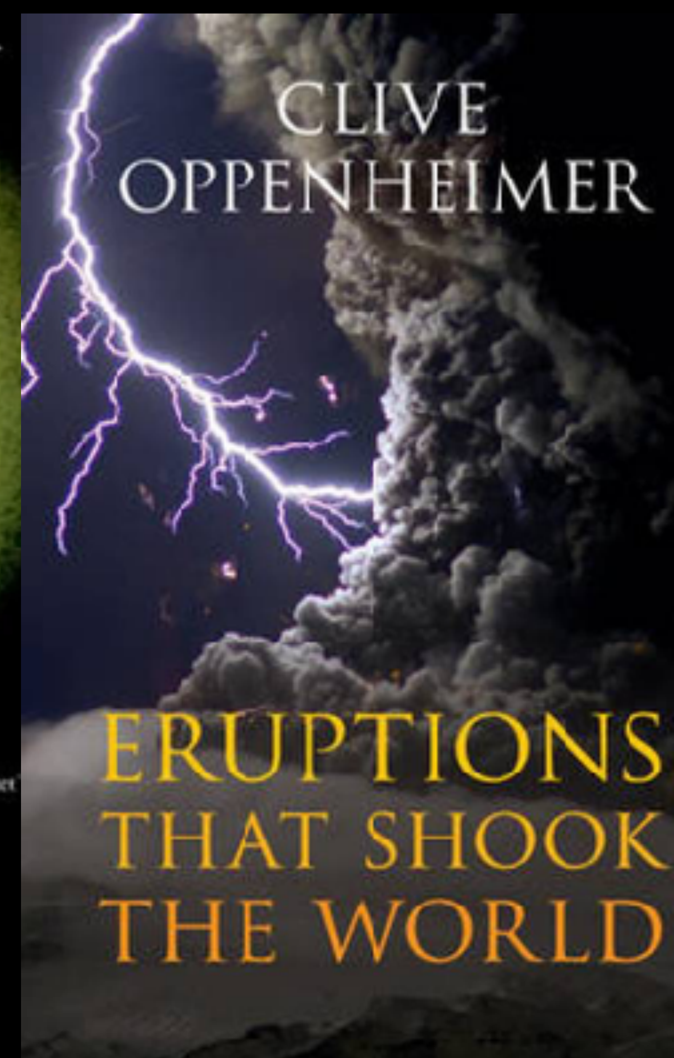
November 20-24, 2023

Daily: 10:00-12:00 & 13:00-14:00

Books mentioned yesterday:







Astrobiology
An Overview

Day 3

Habitable Places in the Solar System; Mars; Moons of Giant Planets

https://www.cosmos.esa.int/web/astrobio/imprs-2023

Monday November 20	Day 1: Definition of Life; Origin of Life; Evolution of Life; Limits of Life 10:00-12:00 & 13:00-14:00
Tuesday November 21	Day 2: Earth Climate History; Mars and Venus Climates 10:00-12:00 & 13:00-14:00 OLD SEMINAR ROOM
Wednesday November 22	Day 3: Habitable Places in the Solar System; Mars; Moons of Giant Planets 10:00-12:00 & 13:00-14:00
Thursday November 23	Day 4: Habitable Places beyond the Solar System; Exoplanets properties; Biosignatures 10:00-12:00 & 13:00-14:00
Friday November 24	Day 5: Search for Extraterrestrial Intelligence; Alien Biochemistry 10:00-12:00 & 13:00-14:00

The Solar System Formation

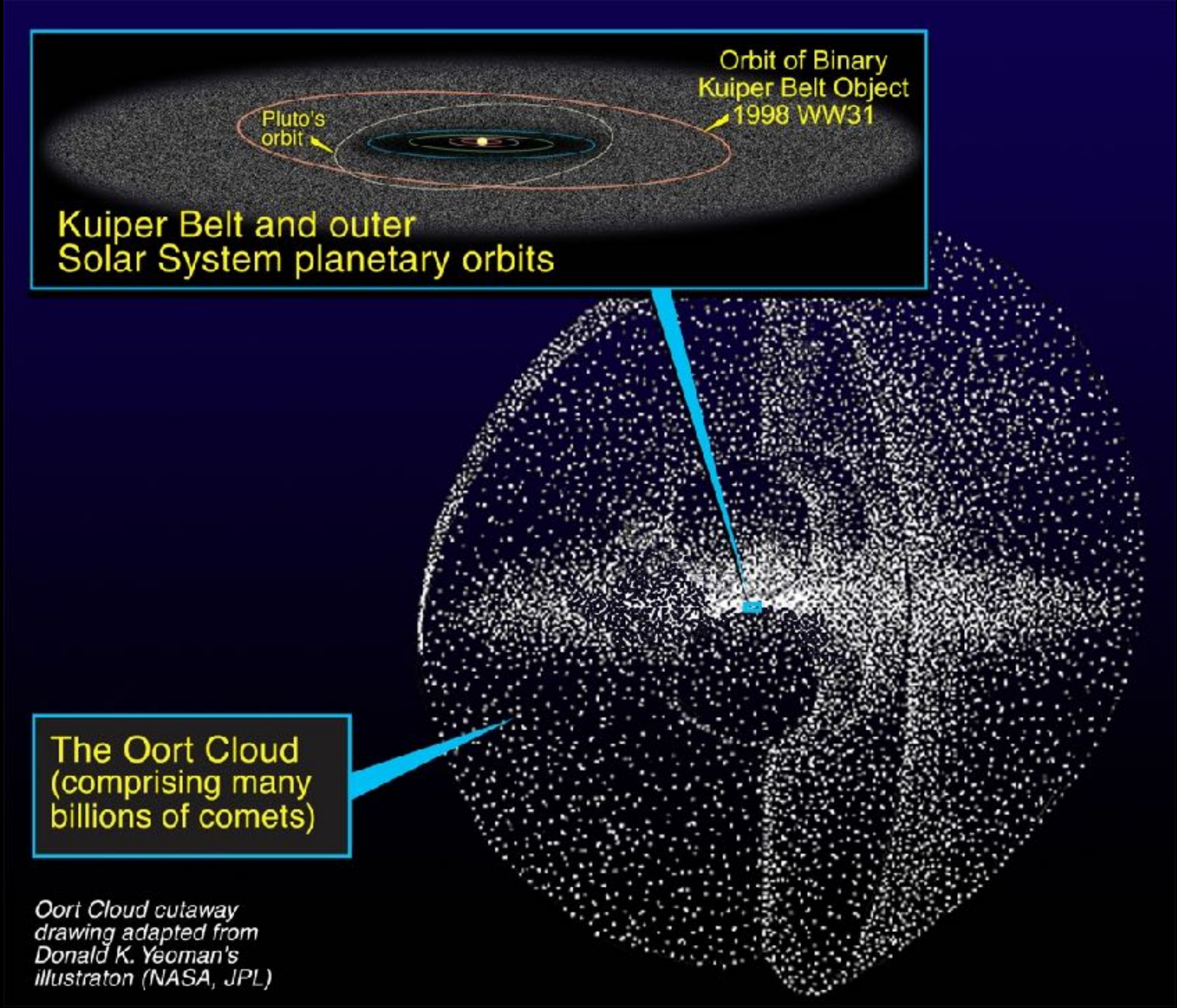
How do we know how the Solar System formed?

We can study the formation of the Solar System

- By observing our Solar System and reconstructing the past (dynamical models, chemical models, ...)

or

- By observing analogs for our Solar System currently forming (proto-planetary disks, debris disks)

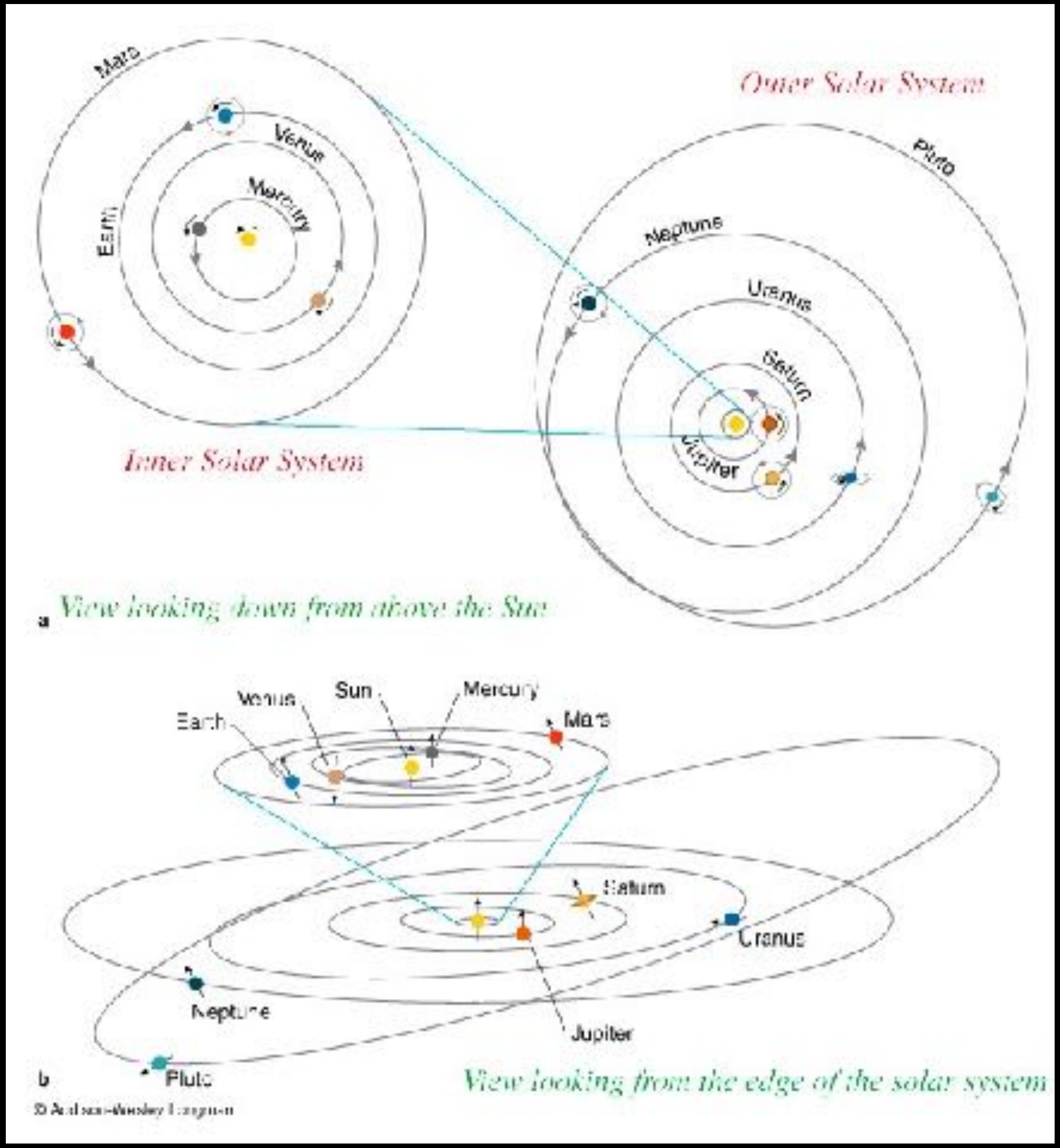


Oort Cloud cutaway drawing adapted from Donald K. Yeoman's illustraton (NASA, JPL)

Observations

What do we know about the Solar System?

★ 99.8% of the mass, but only 2% of the angular momentum is in the Sun

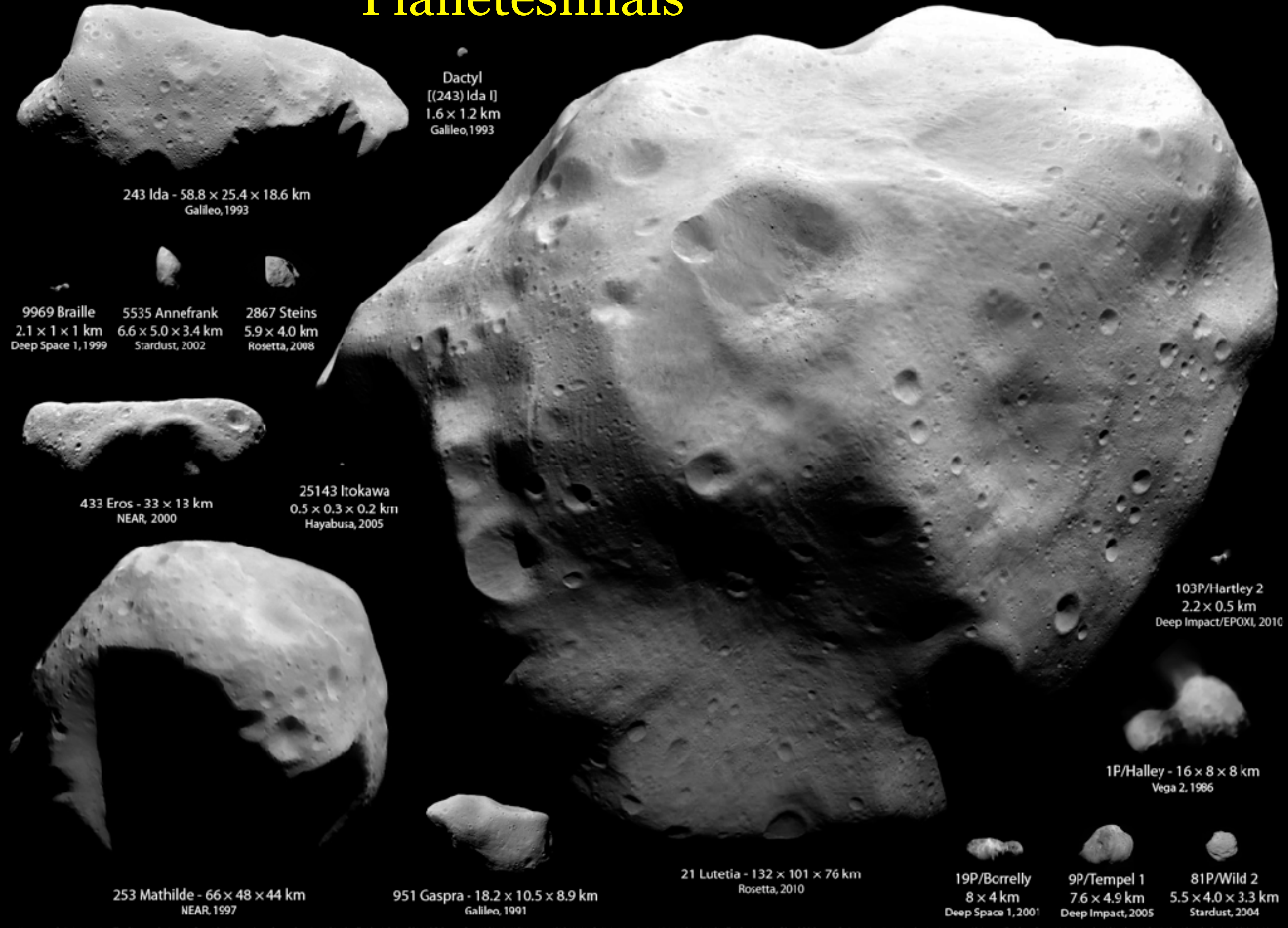


Kant (1724-1804) and Laplace (1749-1827) were the first to propose the formation out of a Nebula

- Orbits of planets are regular, coplanar, near ecliptic.
- Inner planets are rocky. Outer planets are gaseous. Minor bodies are icy.

- Giant planets have similar chemical composition to the Sun (but less H and He).
- Jupiter and Saturn differ from Uranus and Neptune (rocky vs icy core, H/He abundance)
- Asteroids suggest disk of planetesimals

Planetesimals



How do we know the age of the Solar System (4.567 ± 0.002) Gyr?

What does it mean?

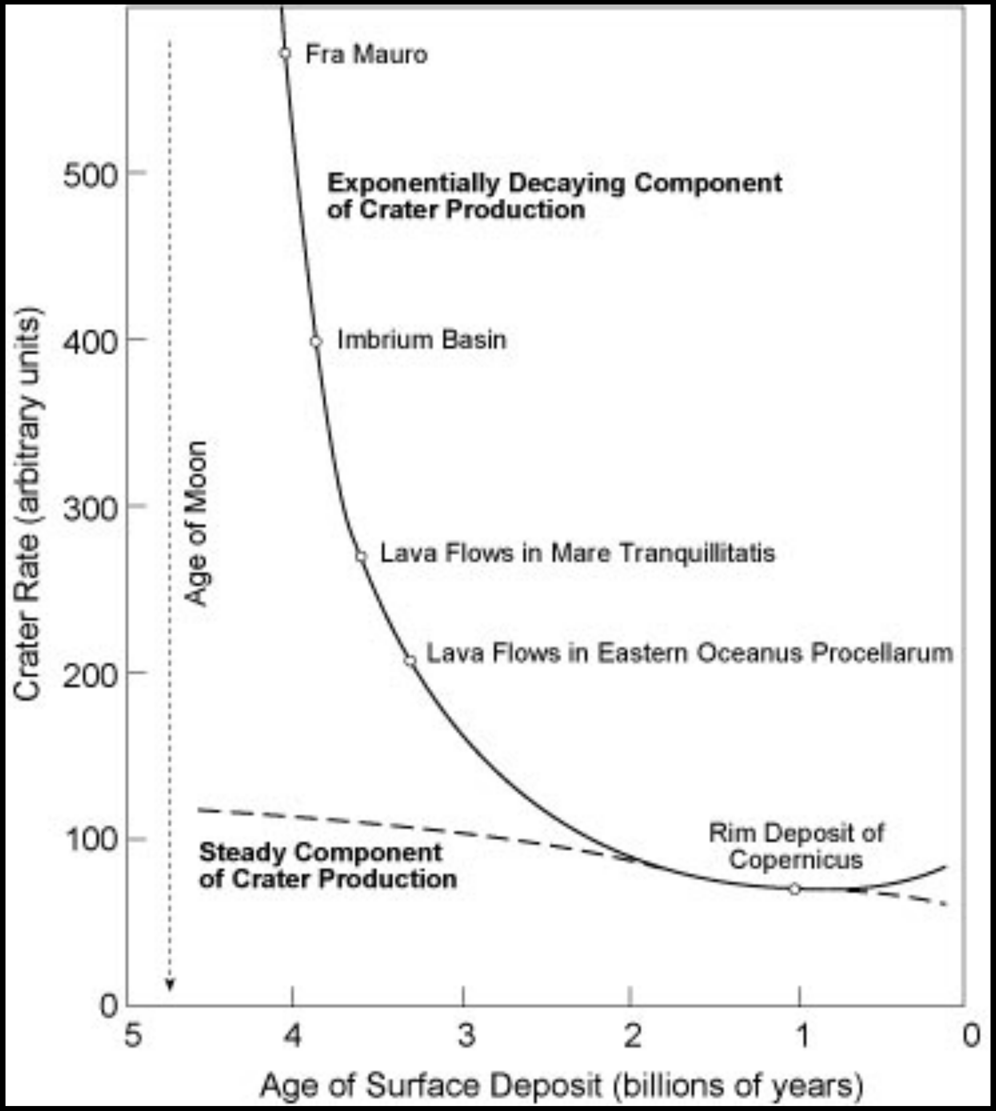
- ★ Age of the Solar system is 4.567 Gyr
- ★ < 100 Myr elapsed between separation from the ISM and planet formation
- ★ Meteorites probe the primordial composition of the Solar system
- ★ Chondrites (80% of the meteorites) contain Chondrules (mm silicate glass spheres), as old as 4.56 Gyr → the Solar system cooled rapidly
- ★ Deuterium: is destroyed in stars (p-p-chain). Jupiter has the primordial D/H abundance

Dwarf planets

- ★ The dynamics of the asteroids, comets and Kuiper belt represent the dynamics of the proto-planetary disc.

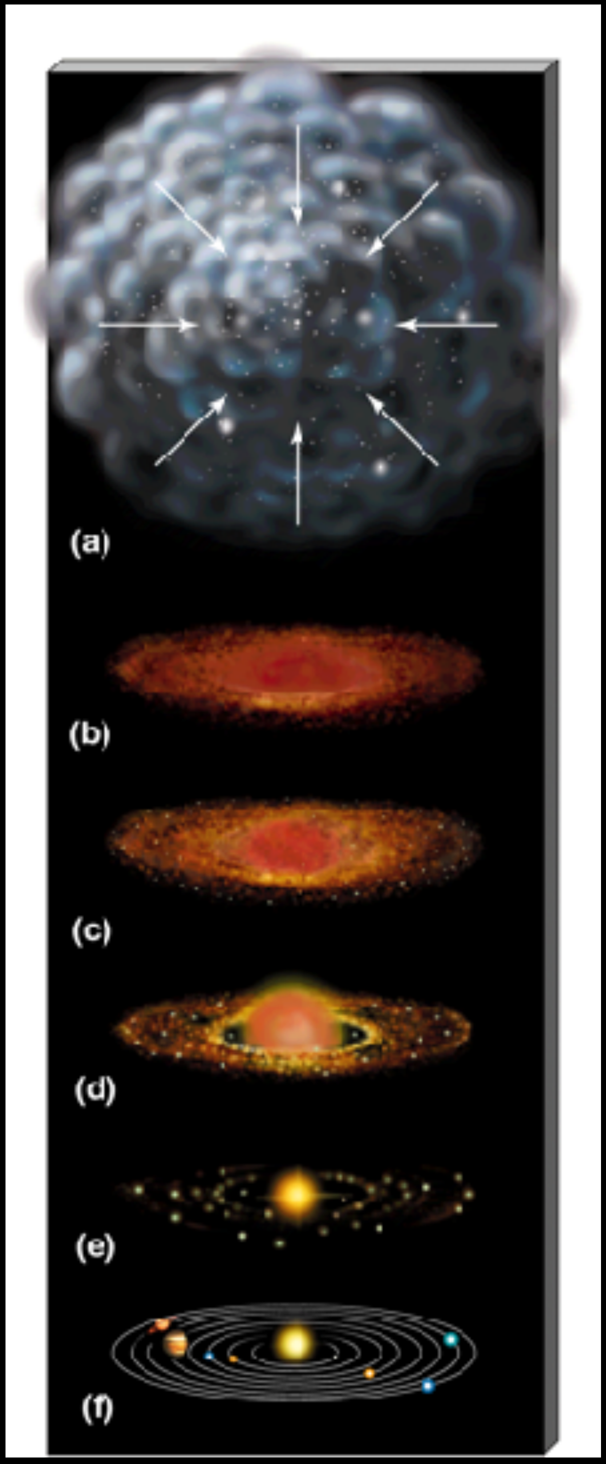
- ★ The number of craters and rate of degradation allow dating of events

- ★ The sun lost its angular momentum through mass loss (slowed down from 1/2 day to ~26 days rotation period)



The ‘Standard Model’

Rapid differentiation between dust disc and low-mass gaseous nebula.



- The Nebula
- Formation of planetesimals
- Runaway accretion
- Formation of Jupiter
- Dispersal of gas
- Terrestrial planets
- Giant planets
- Catastrophic Collisions
- Rings and Satellites
- Small bodies

Check what the melting temperatures are for: Ca, Mg, Fe, Si, CO_2, H_2O

Planetesimals

- A temperature gradient in the disk allows condensation:
  - of metals close to the Sun (Al, Ti, Ca, Mg)
  - of silicate material (‘rocks’) a bit further out (Si, Fe, …)
  - of ice beyond the ‘snow-line’ (H, O, C, N)

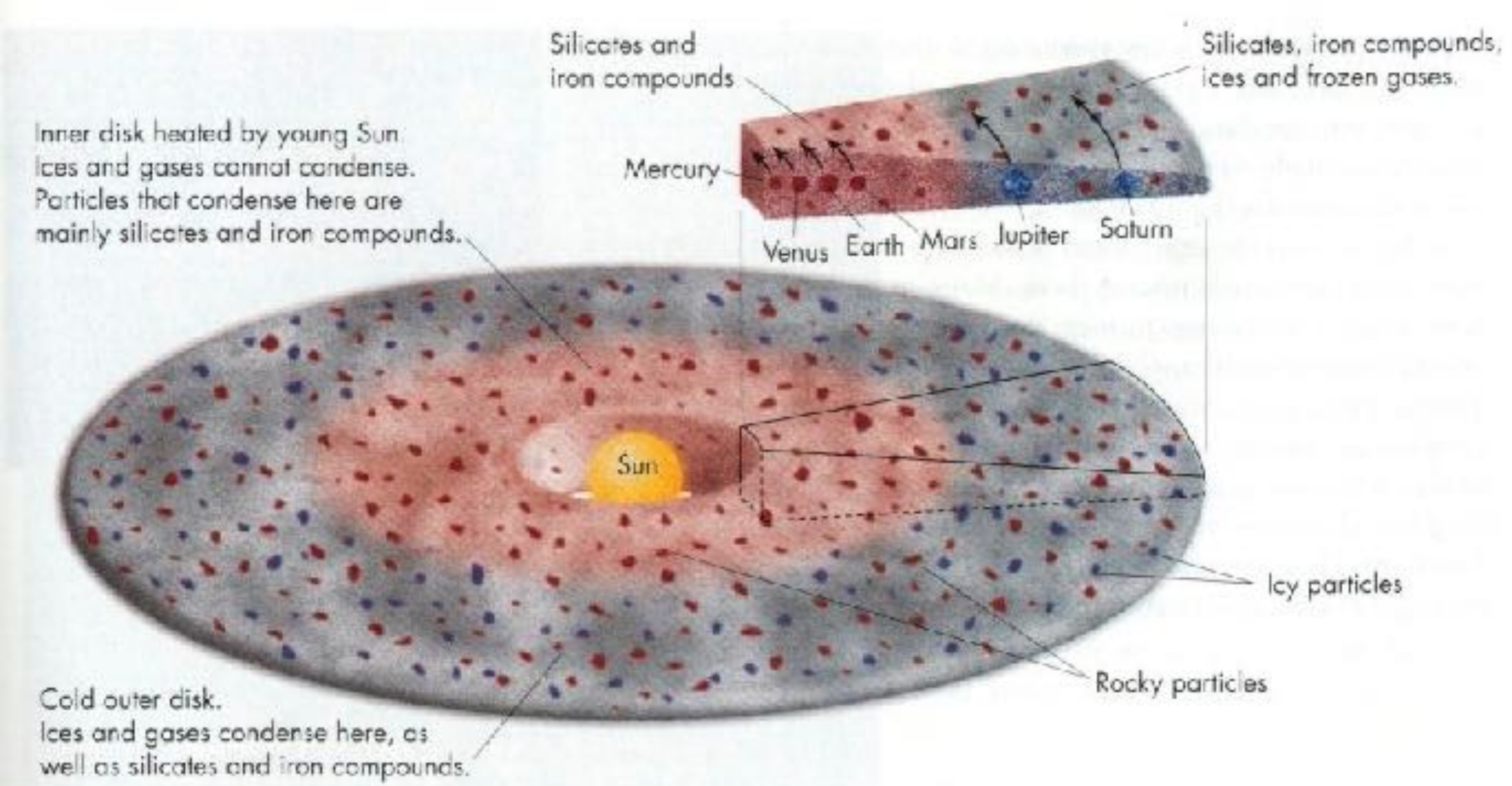


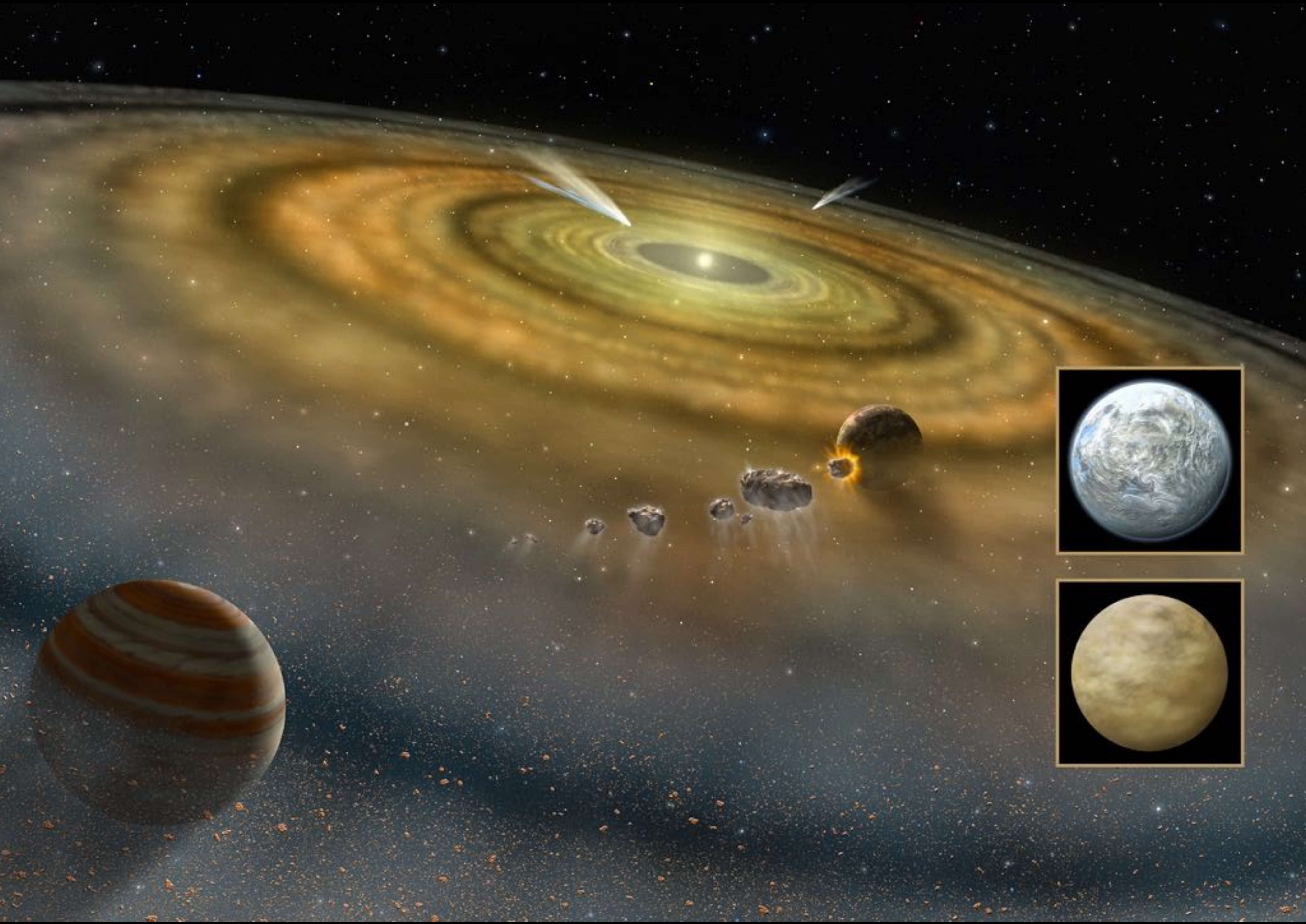
FIGURE OV4.6
Heat from the young Sun prevented ice from condensing in the inner parts of the Solar Nebula. The planetesimals—and ultimately the planets—that formed there are therefore composed mainly of rock and iron.

Planetesimals

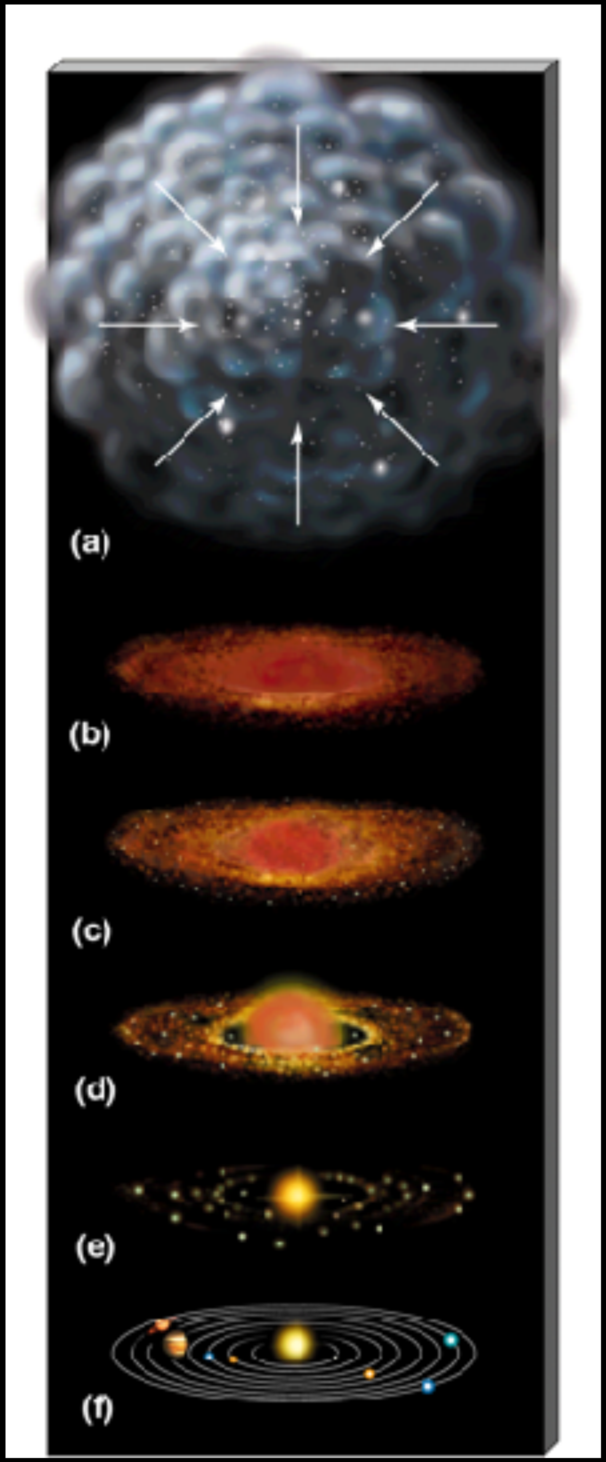
- Condensed grains sink to the equatorial plane (450K limited at ~2.5 AU: carbonaceous vs. ordinary chondrites in asteroid belt)

- Disc becomes thin, slows downs, gravitational instabilities arise:
  - 10 km ∅ at 1 AU (500-1000K)
  - 80 km ∅ at 5 AU (150-200K - the "snow line")

- These are the planetesimals



Rapid differentiation between dust disc and low-mass gaseous nebula.



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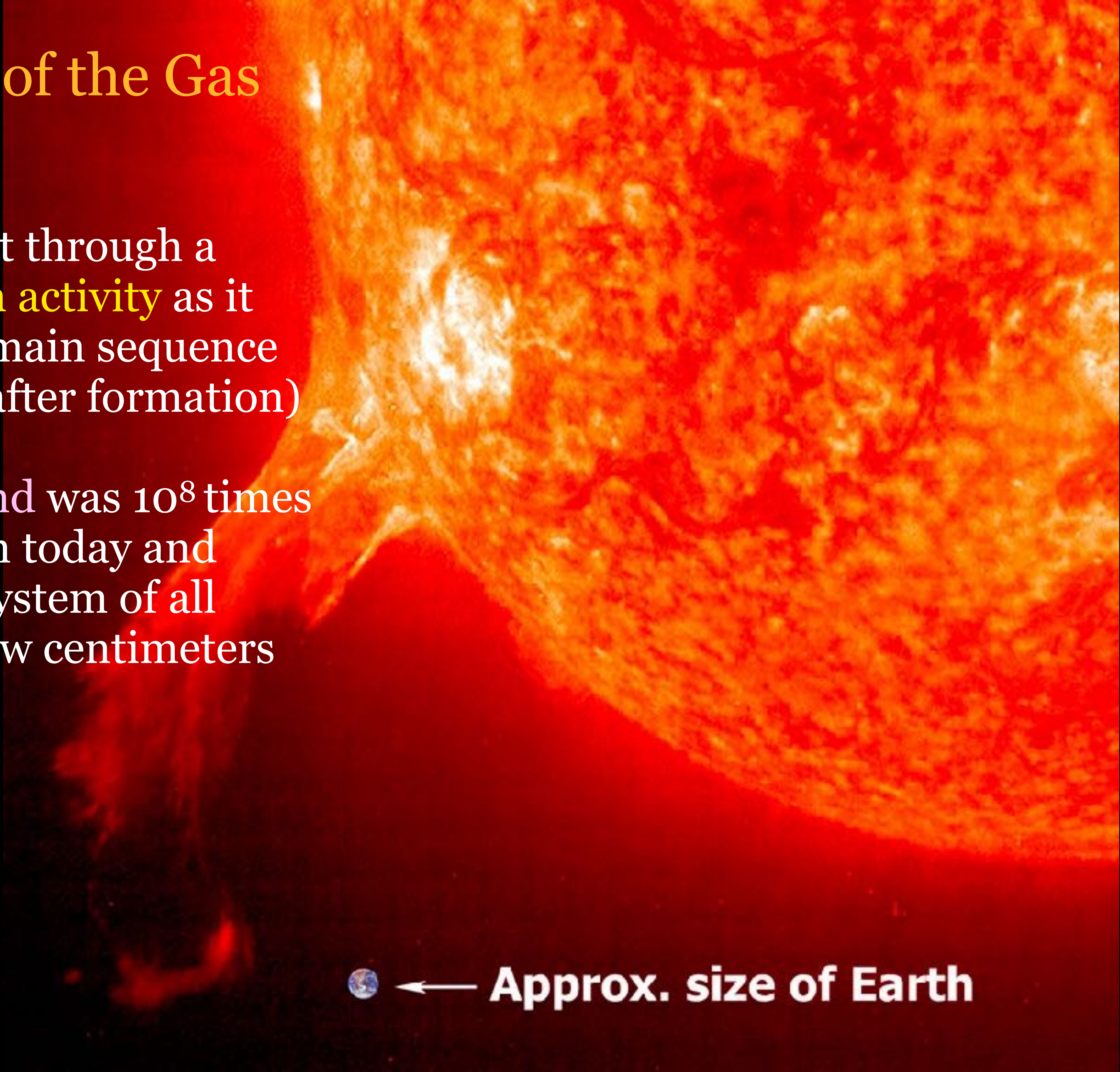
Dispersal of the Gas

The Sun went through a phase of high activity as it reached the main sequence (30-50 Myr after formation)

The solar wind was 10^8 times stronger than today and cleared the system of all particles > few centimeters



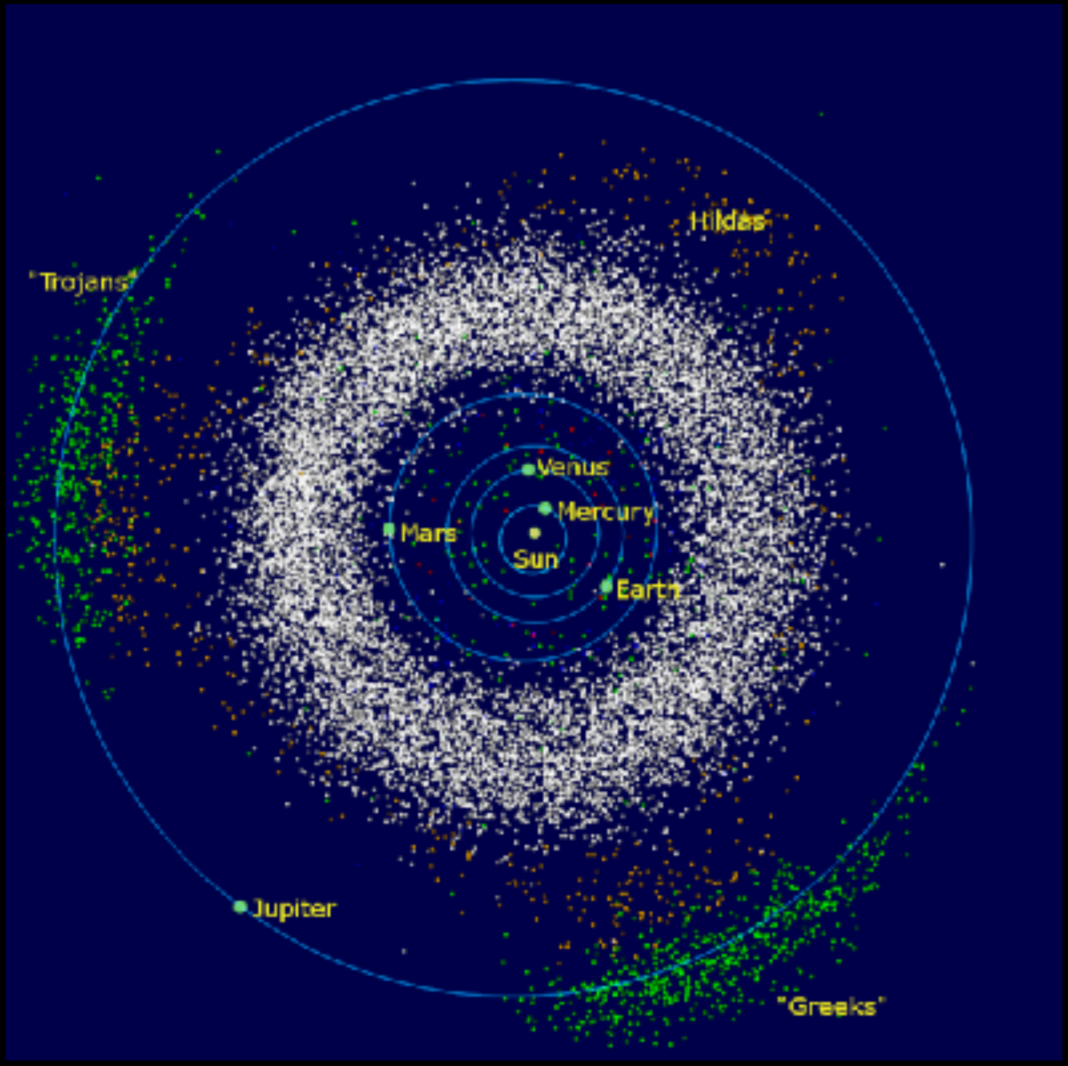
The formation of Jupiter

- Asteroid belt has been stable since its formation
- Jupiter has high H/He content

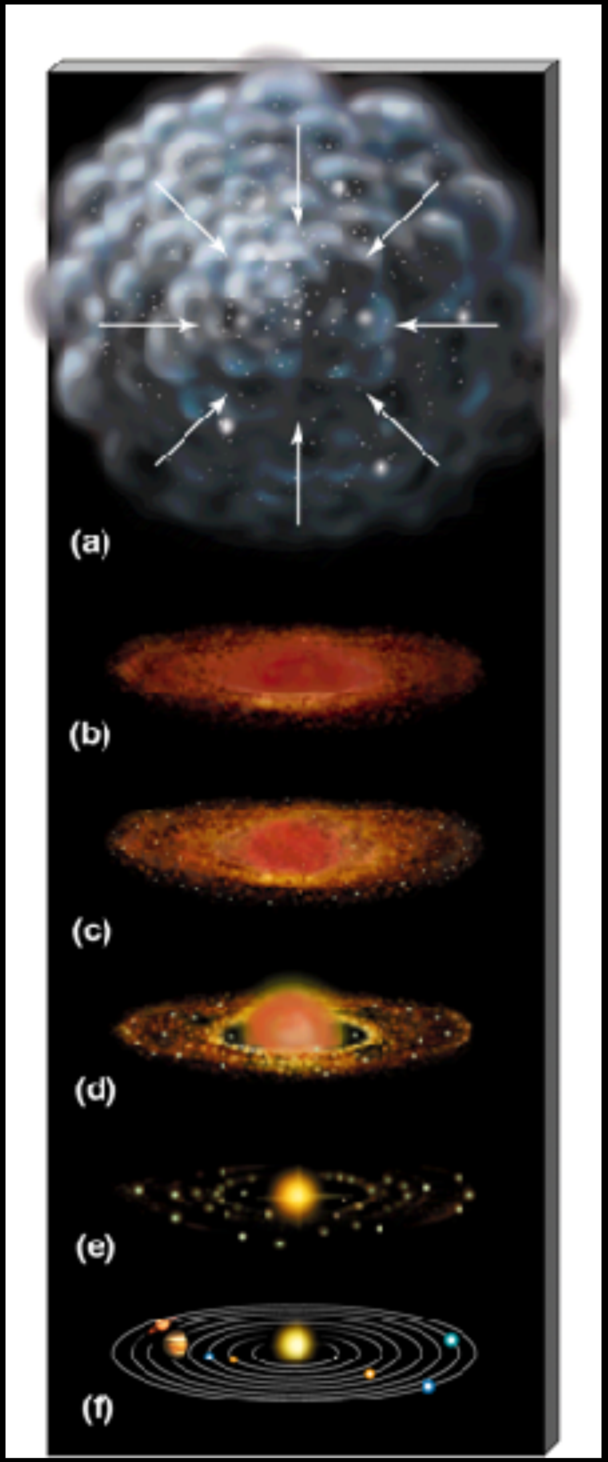
⇒ Jupiter must have formed very early in the Solar system history (before the Solar Wind destroyed the gas Nebula)

To accrete the gas mass, it must have started with a core of ~10 Earth masses

Such a core can only form in 10^6 years at Jupiter's orbit, where the surface density is high due to ice and condensed volatiles



Rapid differentiation between dust disc and low-mass gaseous nebula.



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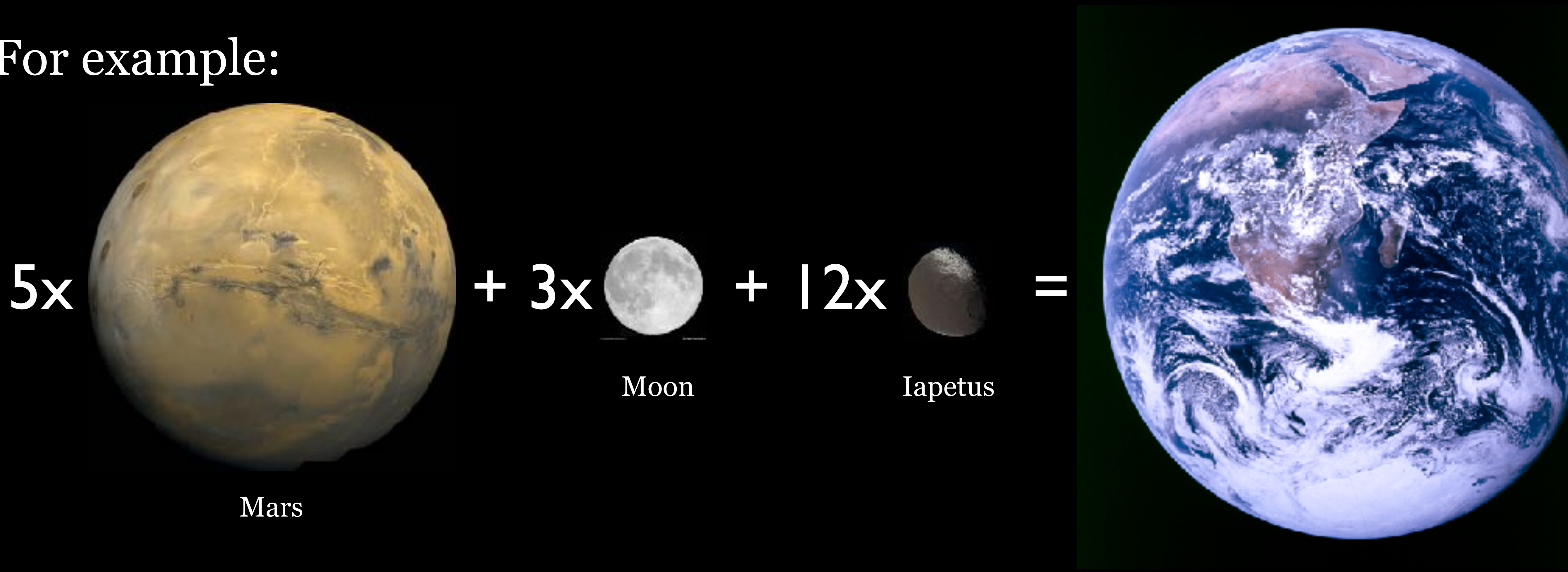
The formation of Terrestrial Planets

- Terrestrial planets formed in 10^7-10^8 years
- Each from differentiated bodies in a narrow zone
- No gas nor volatiles (incl. water) were present (?)

Current Simulations: About 100 ± Mercury-size embryos in the inner 1.5 AU collide to form 3-4 terrestrial planets.

For example:



The formation of Giant Planets

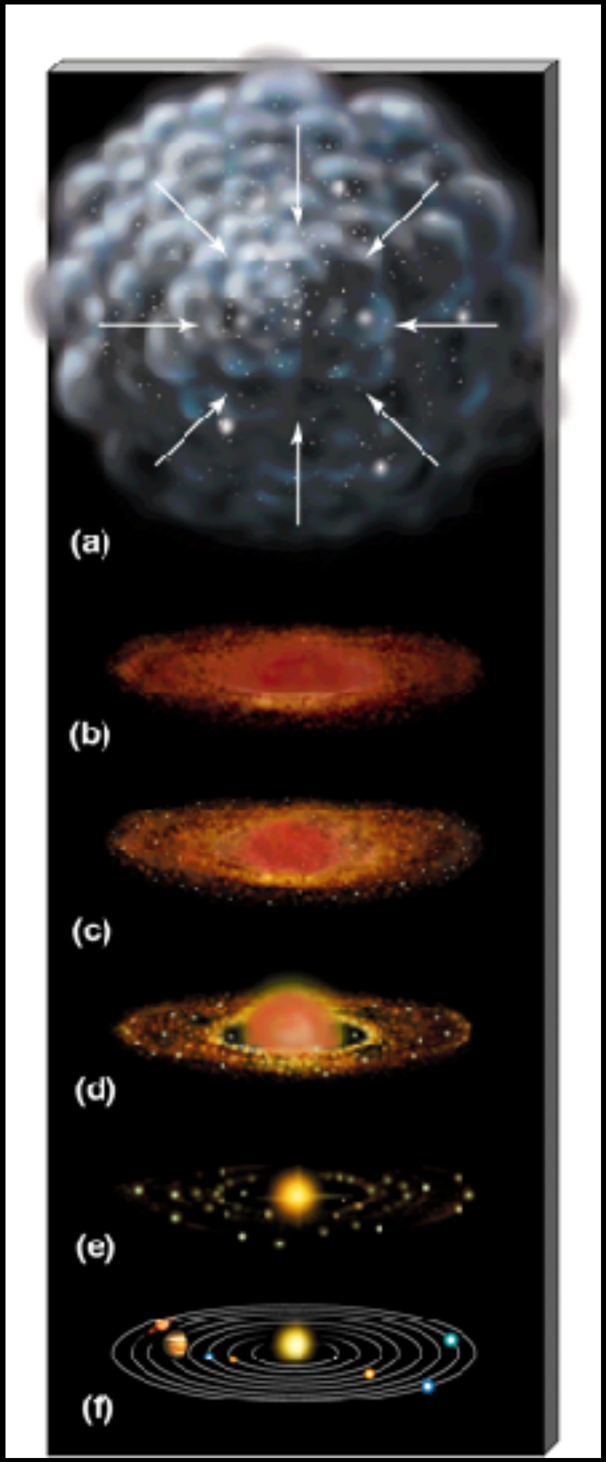
Problem: timescales of the mechanisms…

- Proto-planets must attain sufficient mass to accrete atmospheres before the solar wind swept the disc clear of gas and dust

The differences in H/He content can be explained by the chronology:

1. Jupiter - formed very early (90/10 H/He)
2. Saturn - formed as the nebula was already partly dispersed (97/3 H/He)
3. Uranus and Neptune - formed even later (ices: H_2O, CH_4, NH_3)

Rapid differentiation between dust disc and low-mass gaseous nebula.



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Catastrophic Collisions

In the final phase of planet formation (10- 100 Myr), a few 100 large bodies underwent catastrophic collisions

- Formation of Earth’s moon
- Removal of the silicate mantle of Mercury (ρ= 5.4 g/cm^3)
- Uranus axis of rotation
- Retrograde rotation of Venus

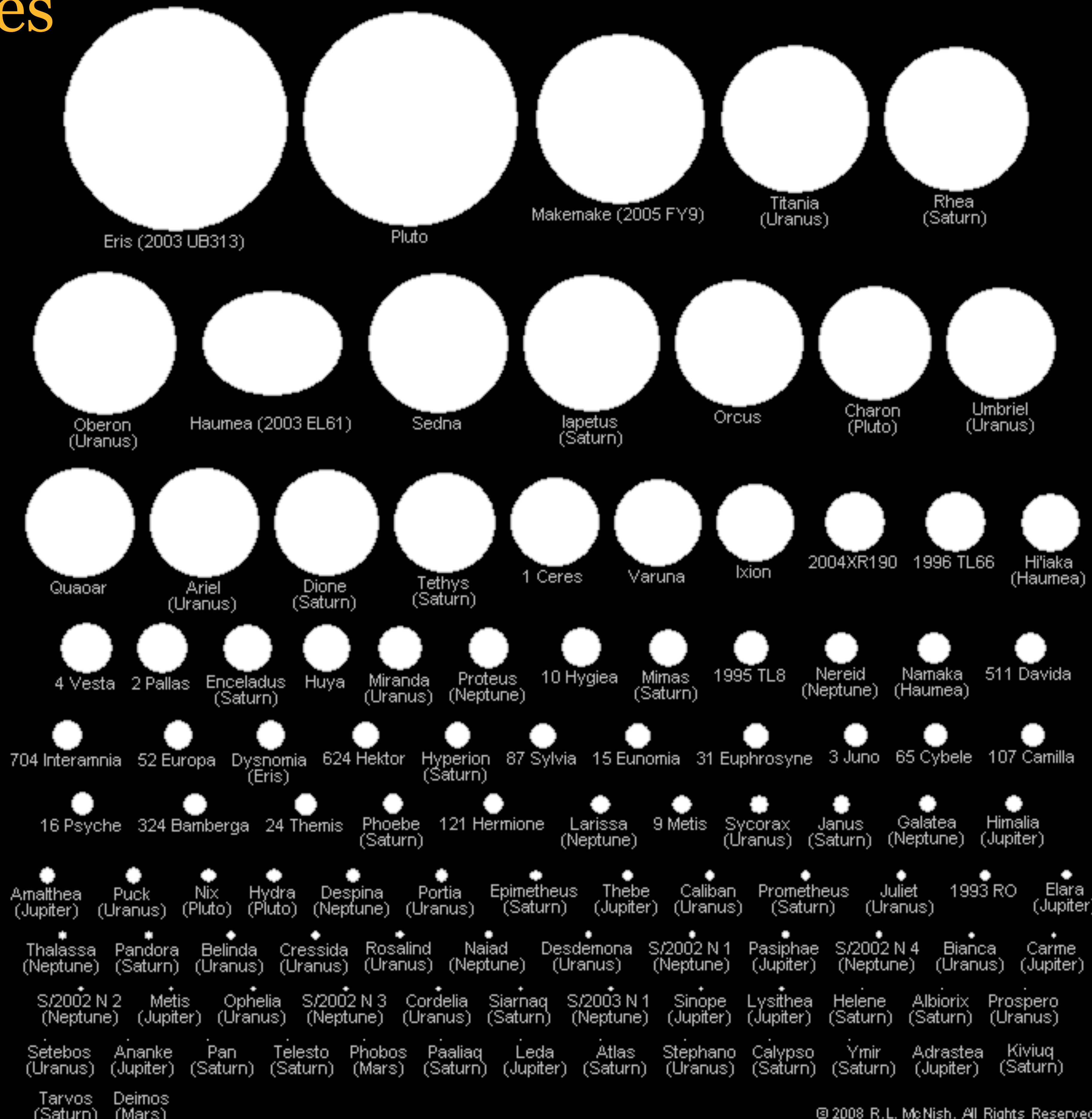
The Small Bodies

Planetesimals between Mars and Jupiter survived but were unable to accrete into one body

All others were dispersed:

inwards → bombarded the terrestrial planets

outwards → formed the Oort cloud



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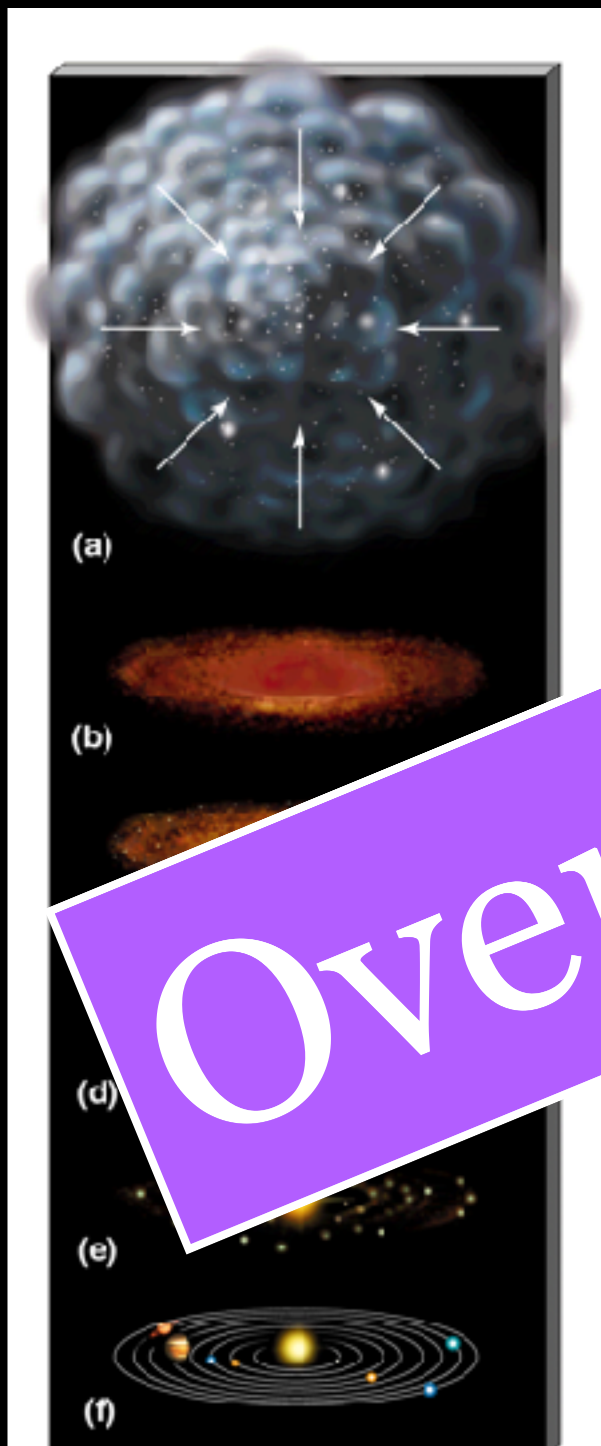

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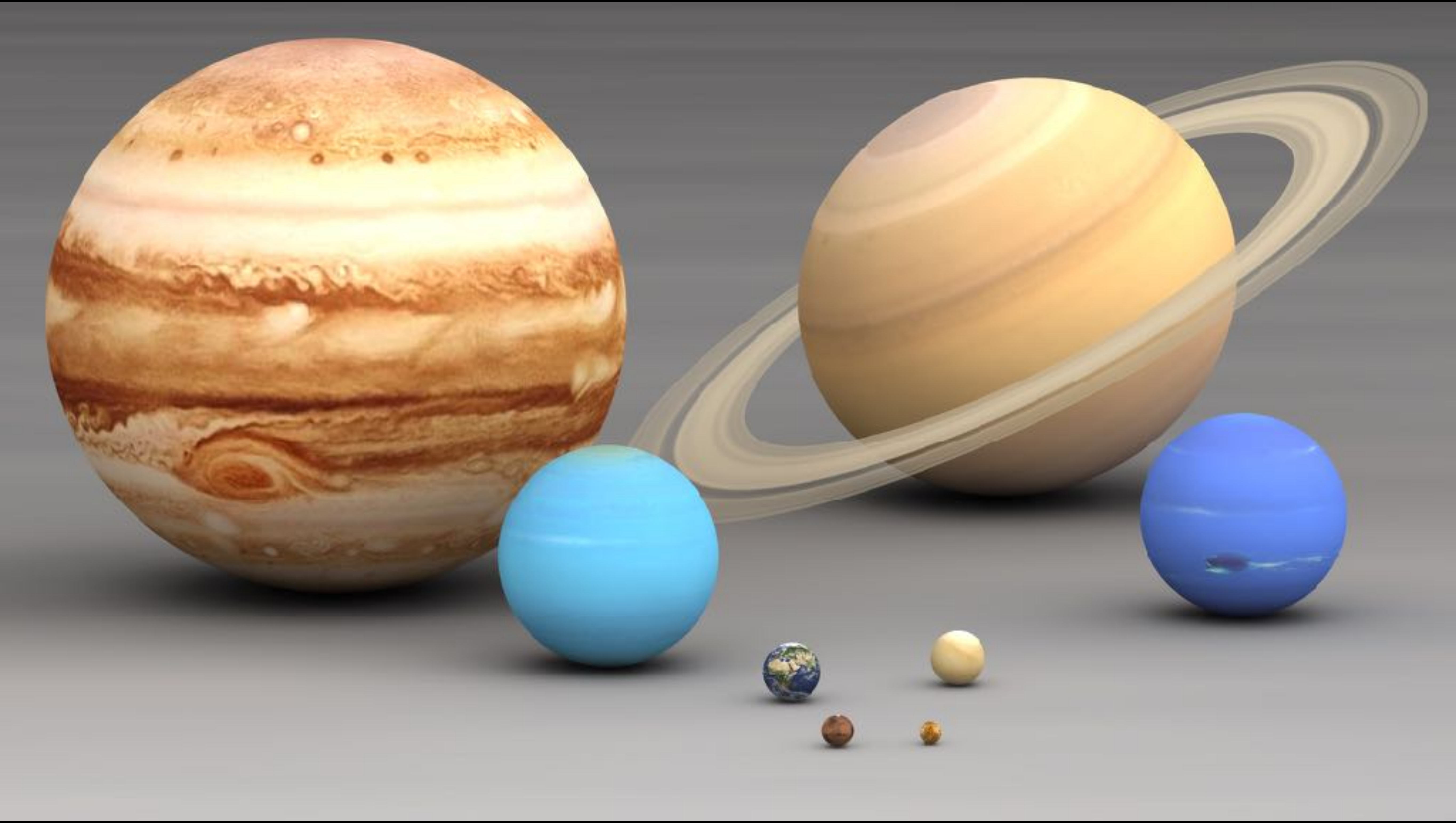
Over after ~200 Myr

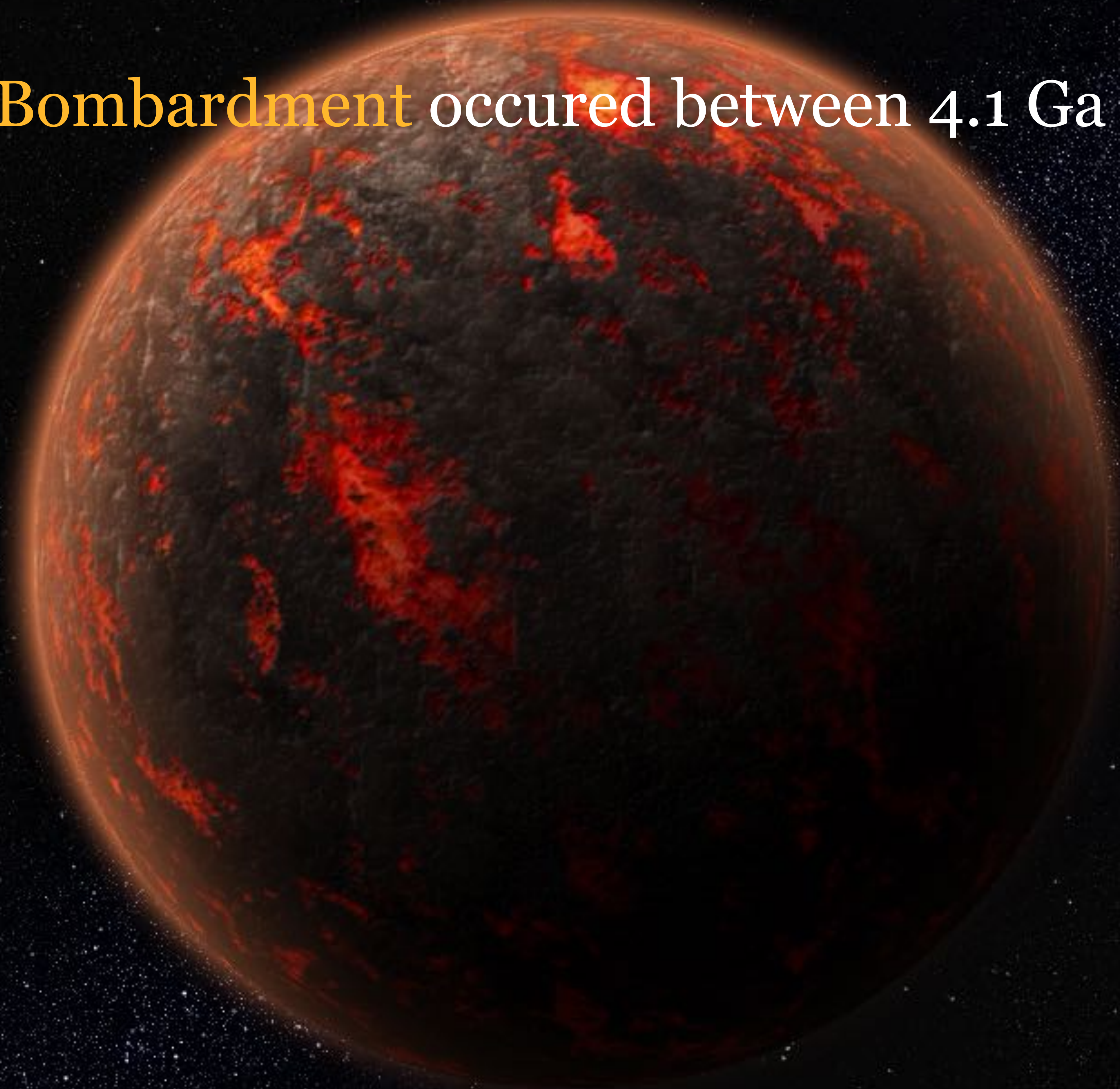
Where/when in the Solar System
could Life have formed,
if not on Earth?



Earth’s Water

Earth's curst remained molten in the Hadean eon

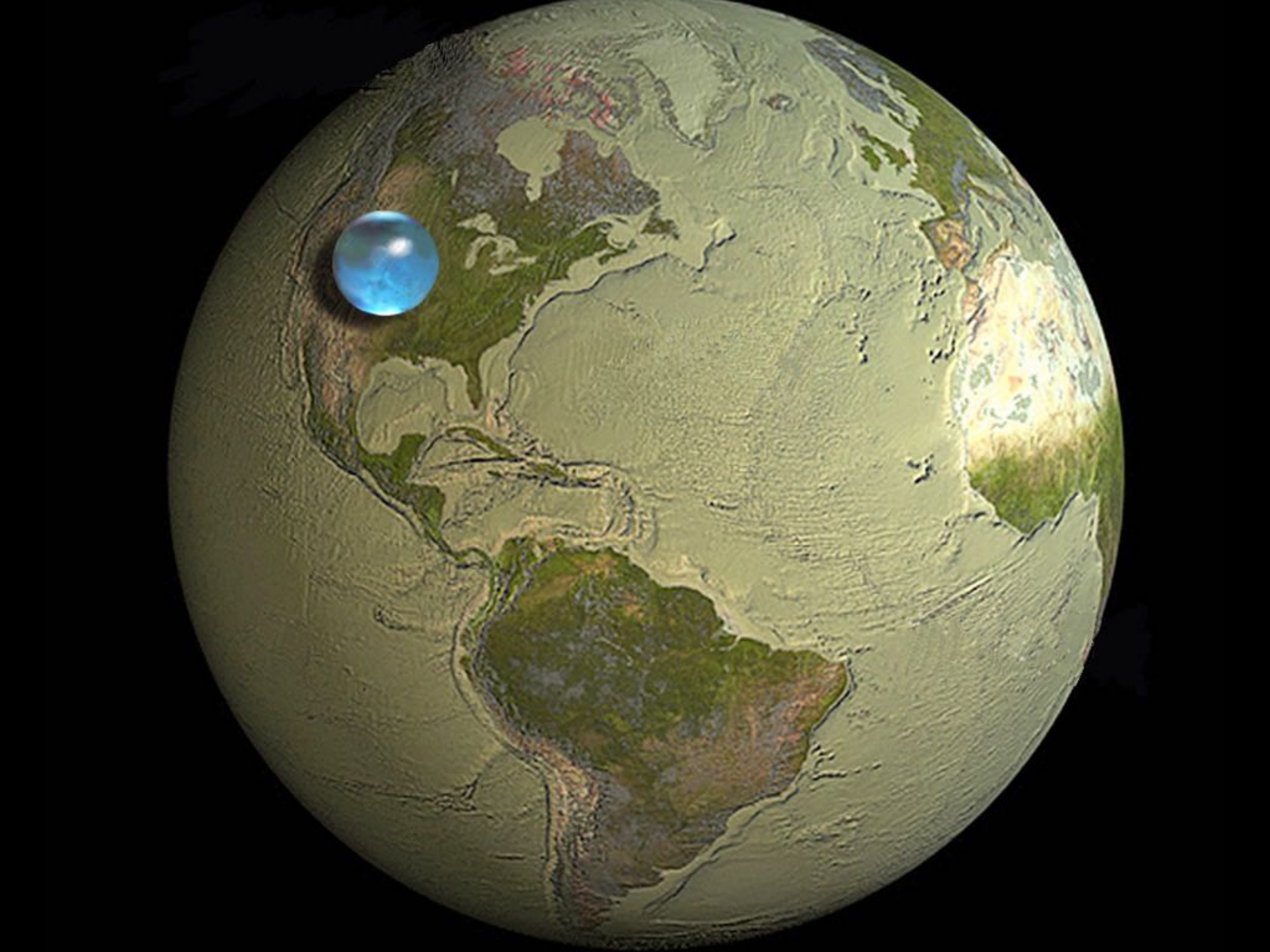
Late Heavy Bombardment occured between 4.1 Ga and 3.8 Ga



Where did Earth's Water come from?

At 1 AU the temperature during the planet formation phase was 500-1000K ...

Too hot to condensate H_2O or to lock it into minerals



Earth ($6x10^{24}$ kg) contains
$1.4x10^{21}$ kg, i.e. 0.02% of water

>98% is on the surface

>97% of surface H_2O is in oceans

BUT recent findings indicate a large reservoir trapped in minerals ~500km deep (between lower and upper mantle); perhaps as much as 3x the surface water...

First Model: (Lewis & Prinn 1984)

Hydrated silicate minerals

e.g. Serpentine $(Mg,Fe)_3Si_2O_5(OH)_4$

Chlorite $(Mg,Fe,Al)_6(Si,Al)_4O_{10}(OH)_8$

contain water and can condense at Earth/Mars orbit

but at 1 AU, hydrated minerals need several Gyr to form

Could they have come from the (outer) asteroid belt?

Other Models:

Earth could have formed out of ordinary Chondrites, but these would have delivered < 10% of today's water.

Earth could have formed out of Carbonaceous Chondrites (~5% of know meteorites), but these would have delivered 300 x today's water

Current Model:

A single planetesimal (~ Moon size) from the outer (water-rich) asteroid belt would be enough to fill Earth's Ocean

[supported by modern N-body simulations]

N.B. Water on terrestrial planets could be a stochastic event

=

How could we determine the origin of ‘our’ water?

Does Earth’s water have a characteristic signature?

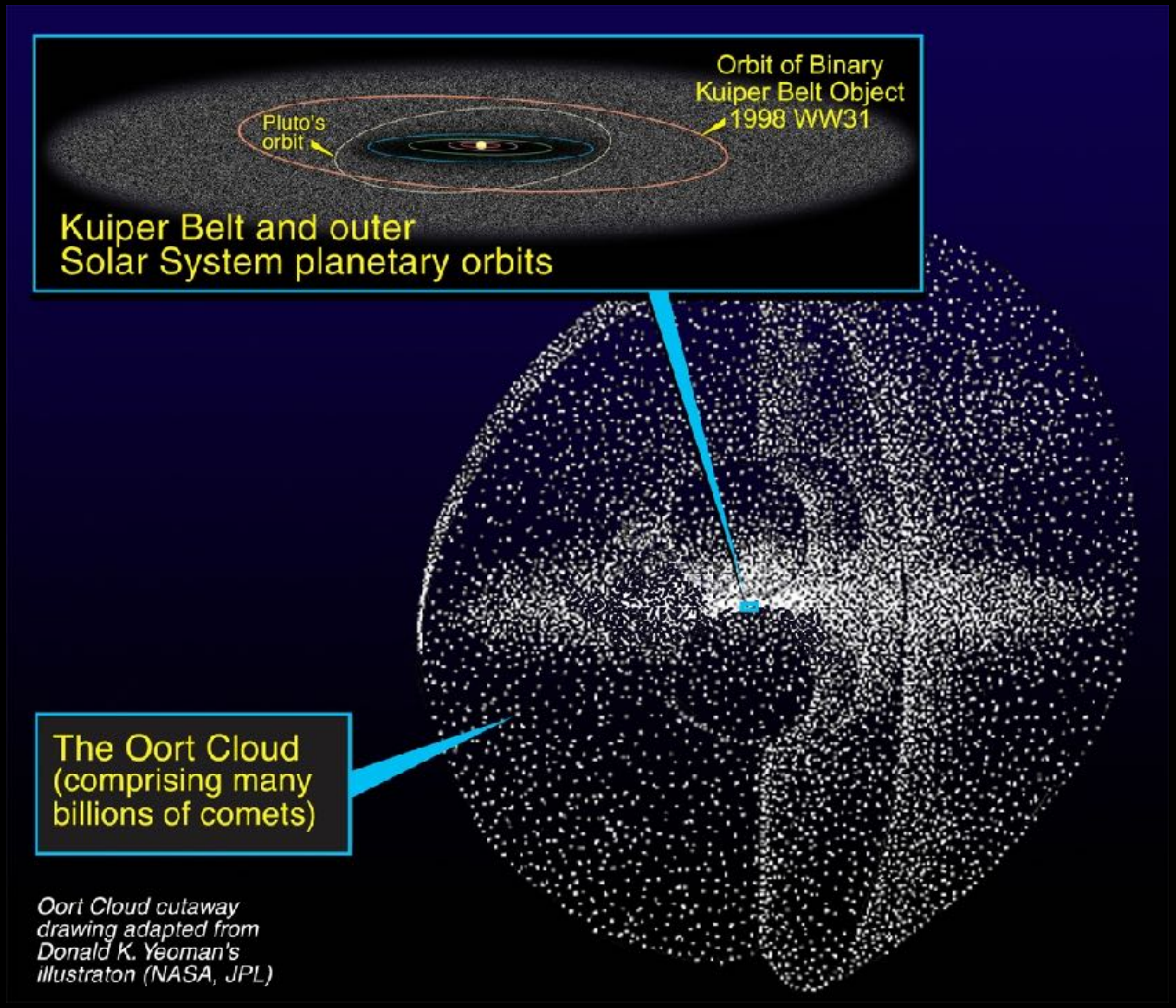
Alternative Model?

Could the planetesimal (~ Moon size) have come from the Kuiper-belt or the Oort cloud?

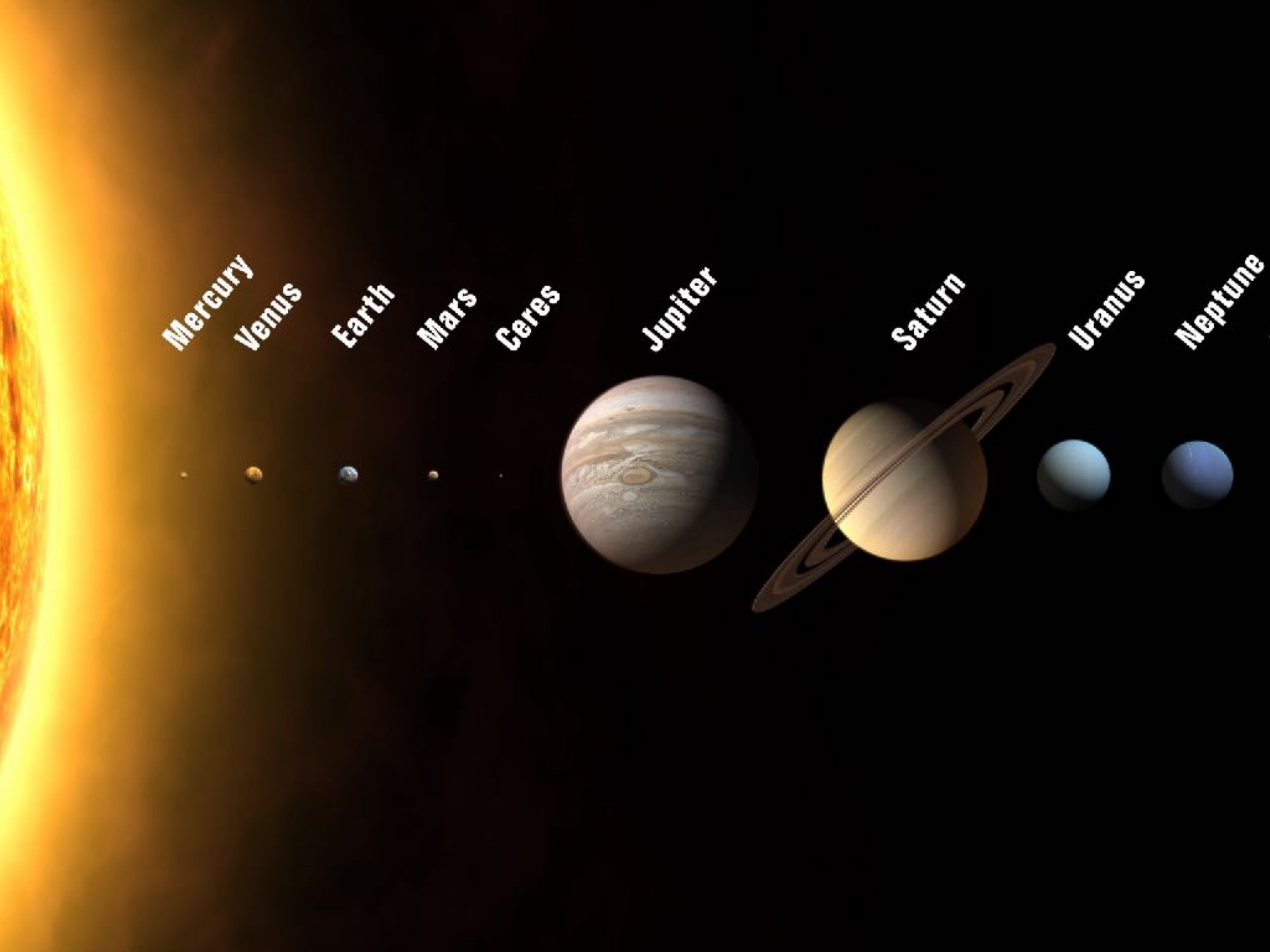
Water content is the right one and would explain noble gas pattern on Earth

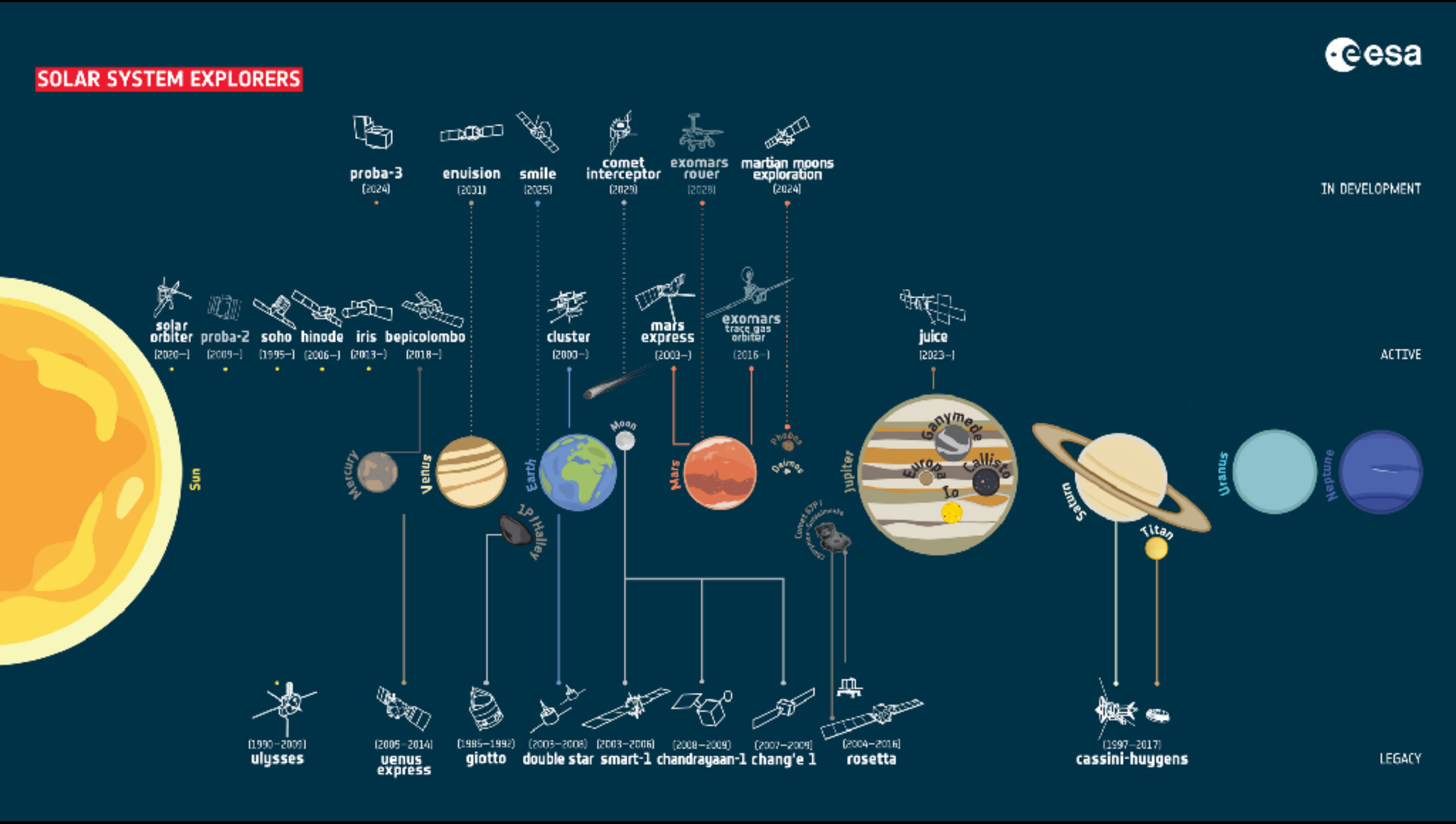
But....

D/H ratio of Halley, Hayakatake and Hale-Bopp is 3x the ratio of the Earth seawater (while on average Carbonaceous chondrites have the ocean ratio)



Potentially habitable worlds in the Solar System


Mercury
Venus
Earth
Mars
Ceres
Jupiter
Saturn
Uranus
Neptune



SOLAR SYSTEM EXPLORERS
esa
IN DEVELOPMENT
proba-3 (2024)
envision (2031)
smile (2025)
comet interceptor (2029)
exomars rover (2028)
martian moons exploration (2024)
ACTIVE
solar orbiter (2020–)
proba-2 (2009–)
soho (1995–)
hinode (2006–)
iris (2013–)
bepicolombo (2018–)
cluster (2000–)
mars express (2003–)
exomars trace gas orbiter (2016–)
juice (2023–)
Sun
Mercury
Venus
Earth
Moon
Mars
Phobos
Deimos
Jupiter
Ganymede
Europa
Callisto
Io
Saturn
Titan
Uranus
Neptune
1P/Halley
LEGACY
(1990–2009) ulysses
(2005–2014) venus express
(1985–1992) giotto
(2003–2008) double star
(2003–2006) smart-1
(2008–2009) chandrayaan-1
(2007–2009) chang'e 1
(2004–2016) rosetta
(1997–2017) cassini-huygens

SCIENCE & EXPLORATION

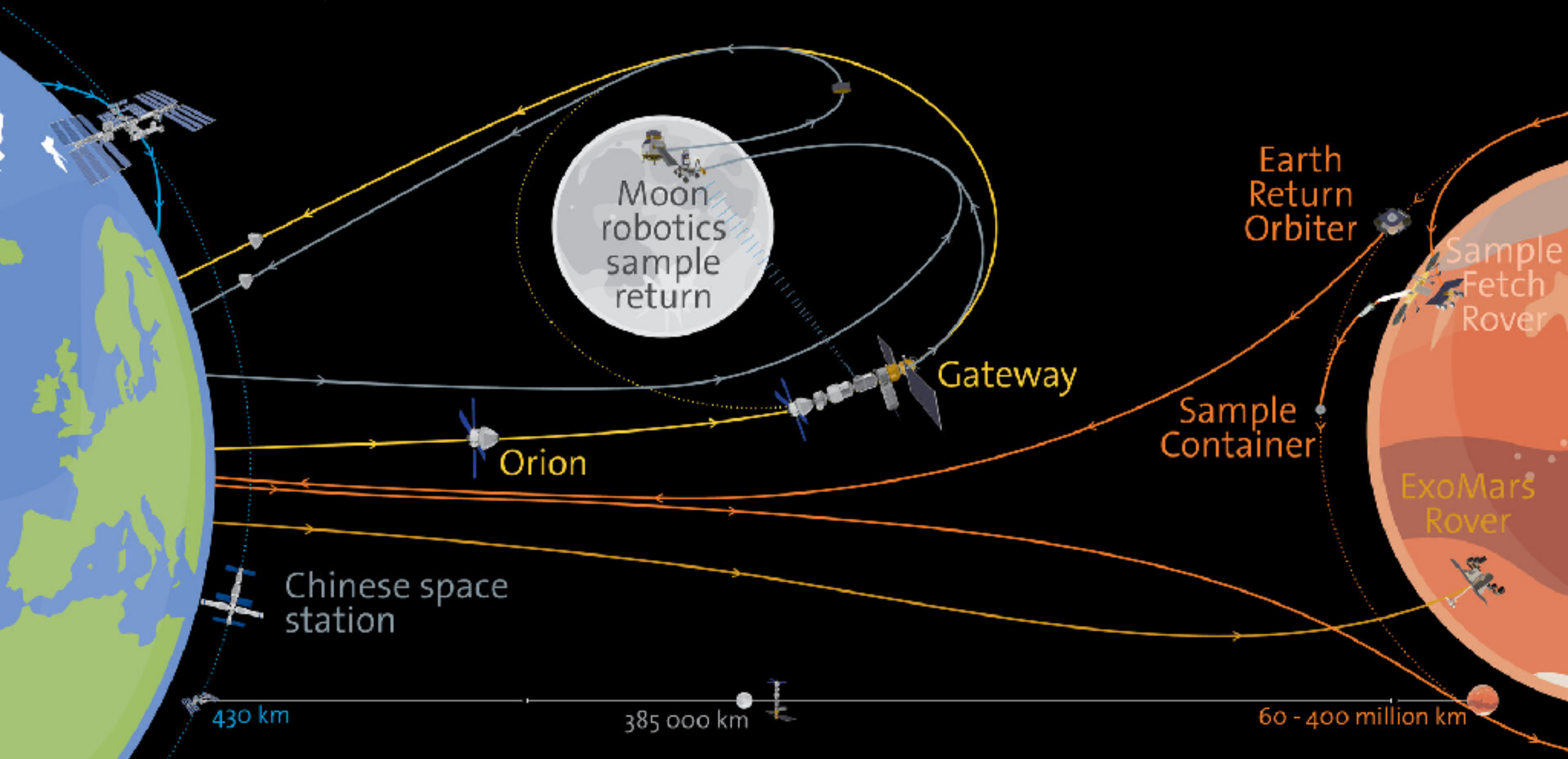
Human and Robotic Exploration

Cornerstone 1
International Space Station

Cornerstone 2
Gateway

Cornerstone 3
Opportunity missions

Cornerstone 4
Mars Sample Return
ExoMars



What is needed for (Earth-like) life?

- Elemental building blocks (C,H,N,O,S,P,...):
  they are common in the Solar System

- Organic molecular building blocks (amino acids, ...):
  They are found in meteorites, asteroids and comets
  H_2O is abundant in the solar system
  Complex chemistry (as in hydrothermal vents) still needs to happen...

- An energy source to drive chemical disequilibrium (reactions back to equilibrium support metabolism):
  sunlight is always available, chemical energy sometimes, geological energy often

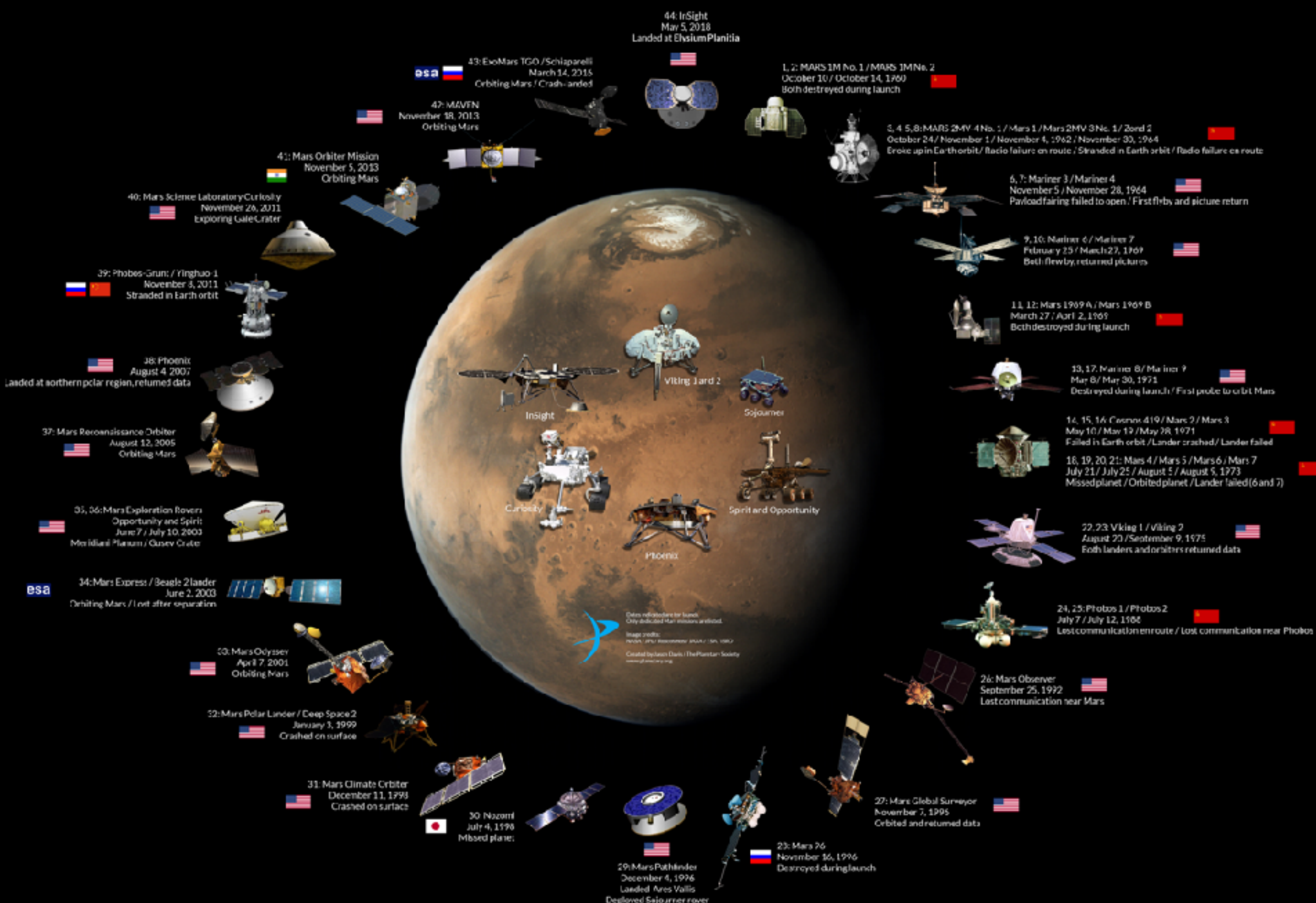
Take a break…

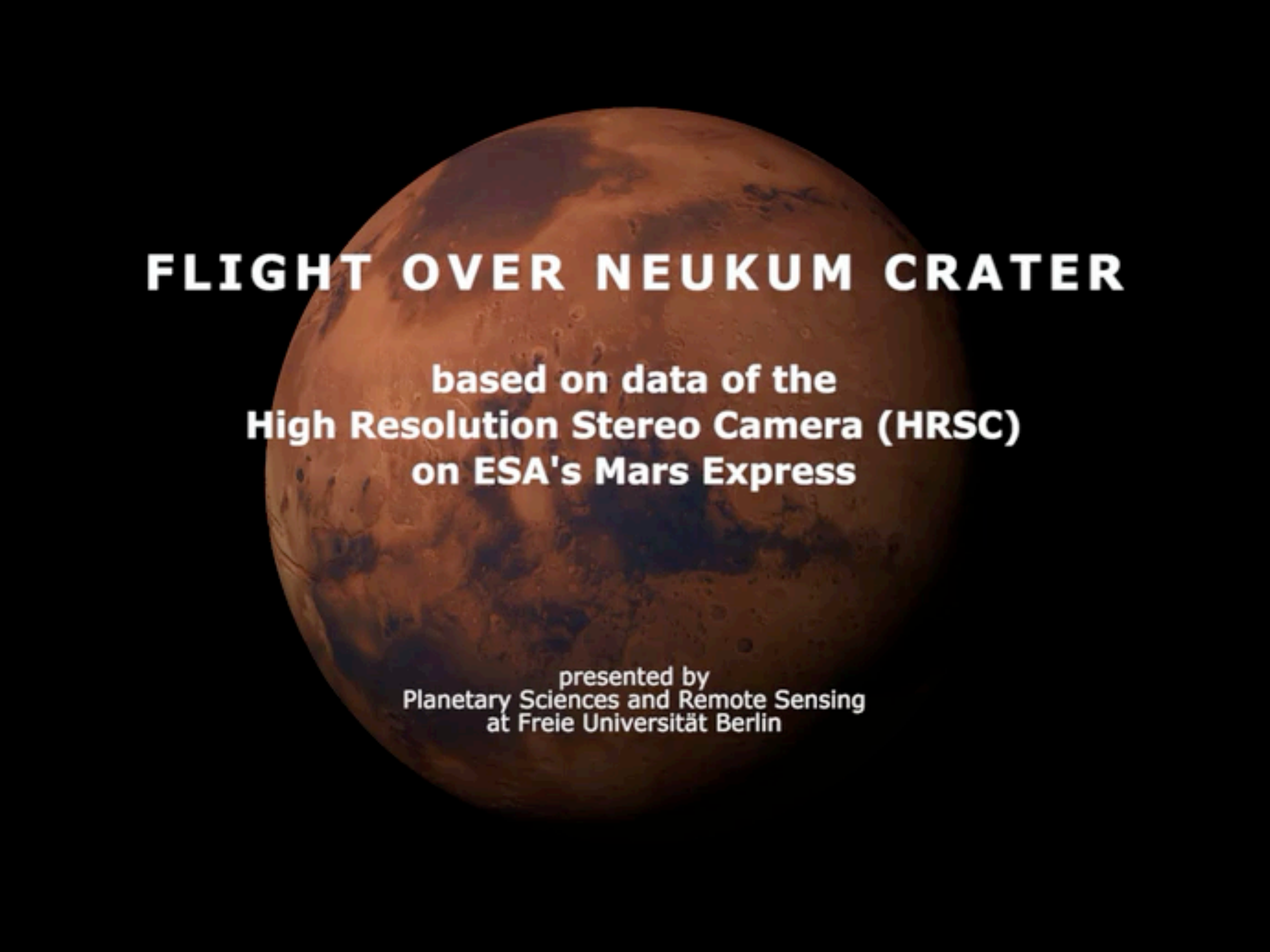
If Life follows water, where should we start looking in the Solar System?

Life on Mars?

Take a look at https://en.wikipedia.org/wiki/List_of_missions_to_Mars

Mars Exploration Family Portrait




FLIGHT OVER NEUKUM CRATER
based on data of the
High Resolution Stereo Camera (HRSC)
on ESA's Mars Express
presented by
Planetary Sciences and Remote Sensing
at Freie Universität Berlin

Mars: the red planet

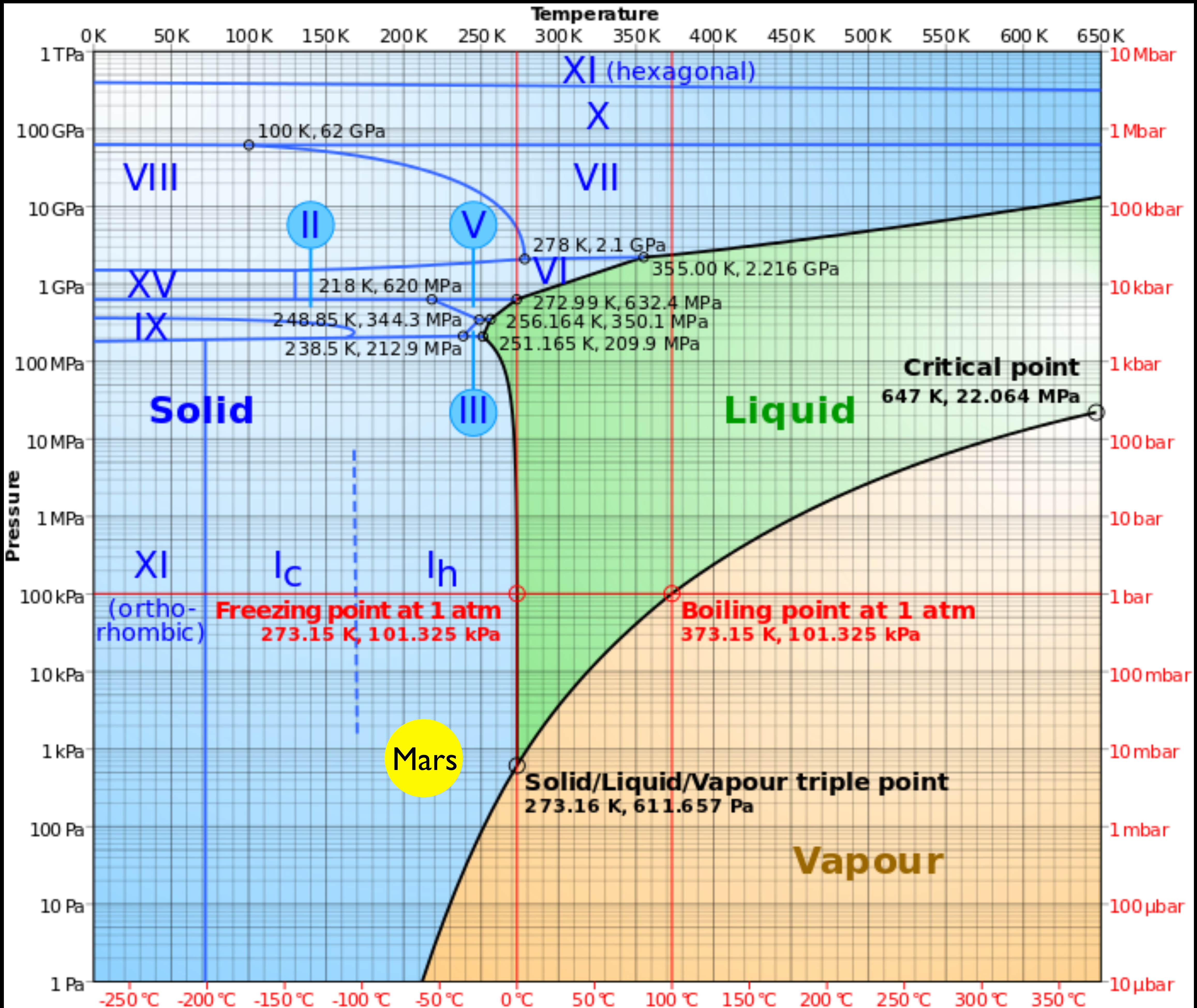
Distance from Sun: 1.52 AU
Mass: 11% of Earth
Density: 70% of Earth's

T_{surf} = -55 °C
P_{surf} ~ 6-8 mbar (water sublimates)

No plate tectonics, but some Volcanism

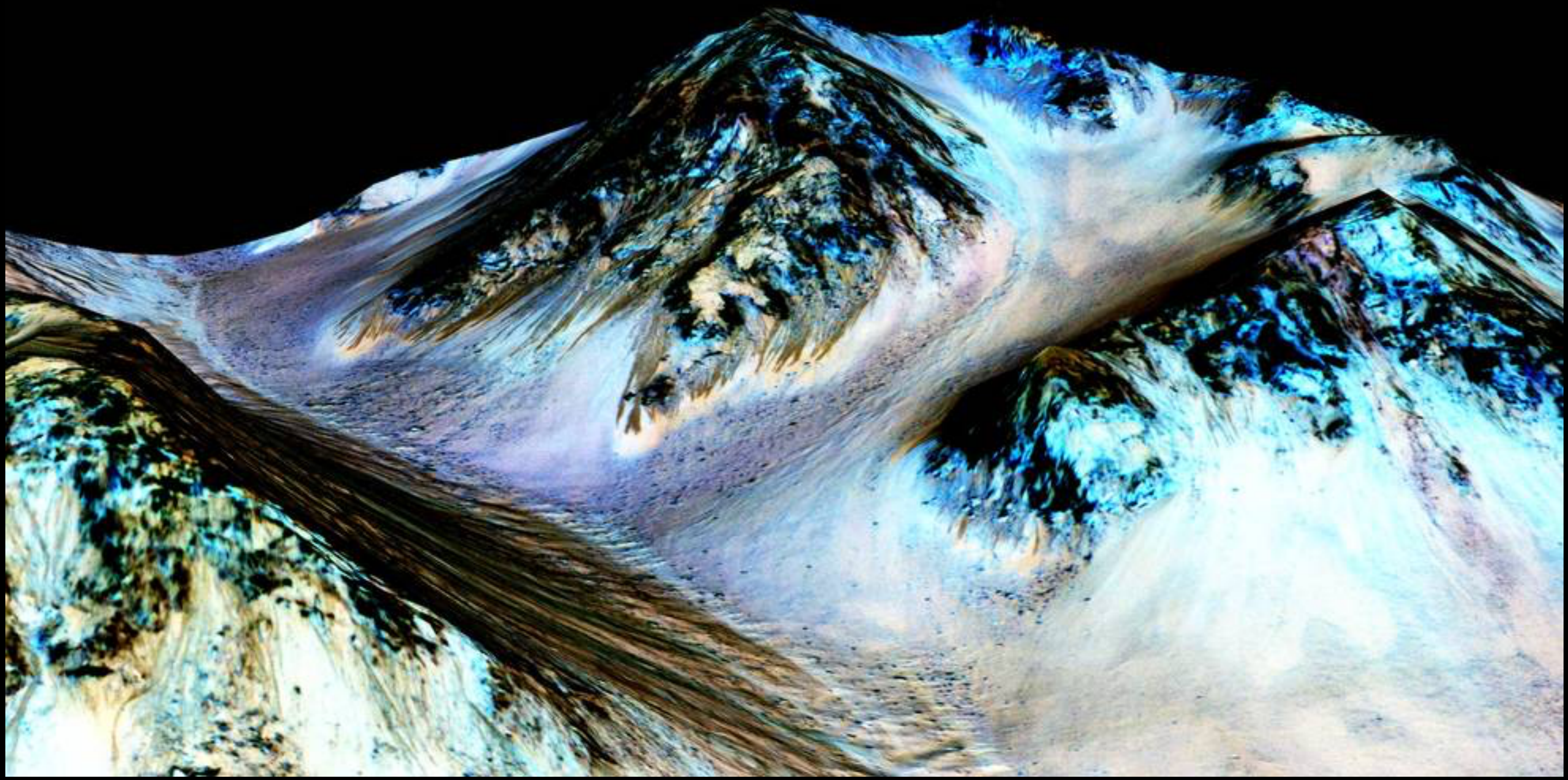
ATM: CO_2 (95.3%), N_2 (2.7%), Ar (1.6%)
traces of O_2, CO, H_2O

Obliquity changes by ± 10° in 10^5 -10^6 yr cycles chaotically


Temperature
0 K
50 K
100 K
150 K
200 K
250 K
300 K
350 K
400 K
450 K
500 K
550 K
600 K
650 K
1 TPa
100 GPa
10 GPa
1 GPa
100 MPa
10 MPa
1 MPa
100 kPa
10 kPa
1 kPa
100 Pa
10 Pa
1 Pa
Pressure
10 Mbar
1 Mbar
100 kbar
10 kbar
1 kbar
100 bar
10 bar
1 bar
100 mbar
10 mbar
1 mbar
100 µbar
10 µbar
-250 °C
-200 °C
-150 °C
-100 °C
-50 °C
0 °C
50 °C
100 °C
150 °C
200 °C
250 °C
300 °C
350 °C
XI (hexagonal)
X
100 K, 62 GPa
VIII
VII
II
V
278 K, 2.1 GPa
VI
355.00 K, 2.216 GPa
XV
218 K, 620 MPa
272.99 K, 632.4 MPa
IX
248.85 K, 344.3 MPa
256.164 K, 350.1 MPa
238.5 K, 212.9 MPa
251.165 K, 209.9 MPa
Critical point
647 K, 22.064 MPa
Solid
III
Liquid
XI
(ortho-
rhombic)
I_c
I_h
Freezing point at 1 atm
273.15 K, 101.325 kPa
Boiling point at 1 atm
373.15 K, 101.325 kPa
Mars
Solid/Liquid/Vapour triple point
273.16 K, 611.657 Pa
Vapour

Liquid Water on Mars?

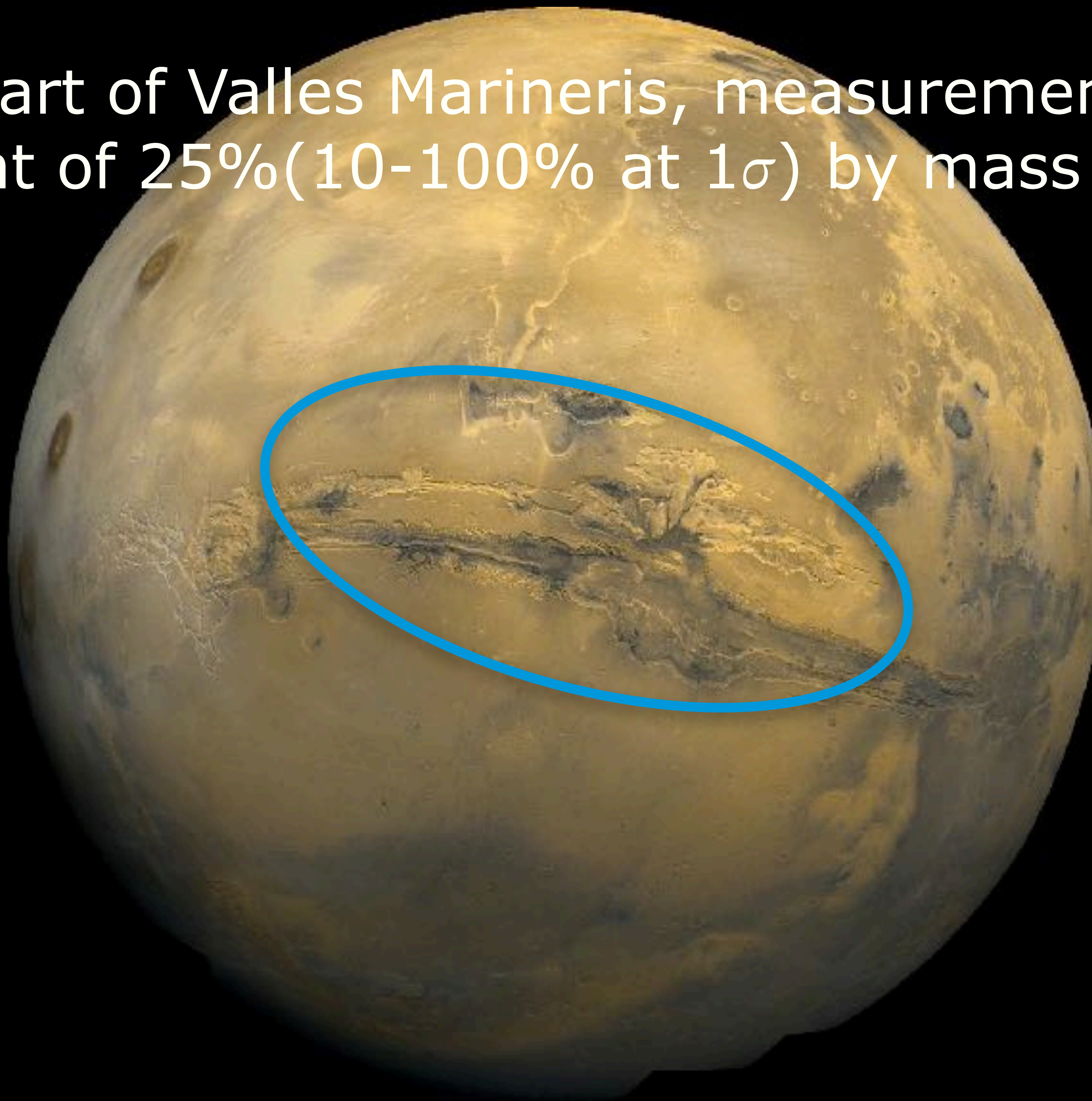
Not abundant on surface today (too low temperature and pressure) but likely in the past and sub-surface: Valleys, weathered craters, surface chemistry…

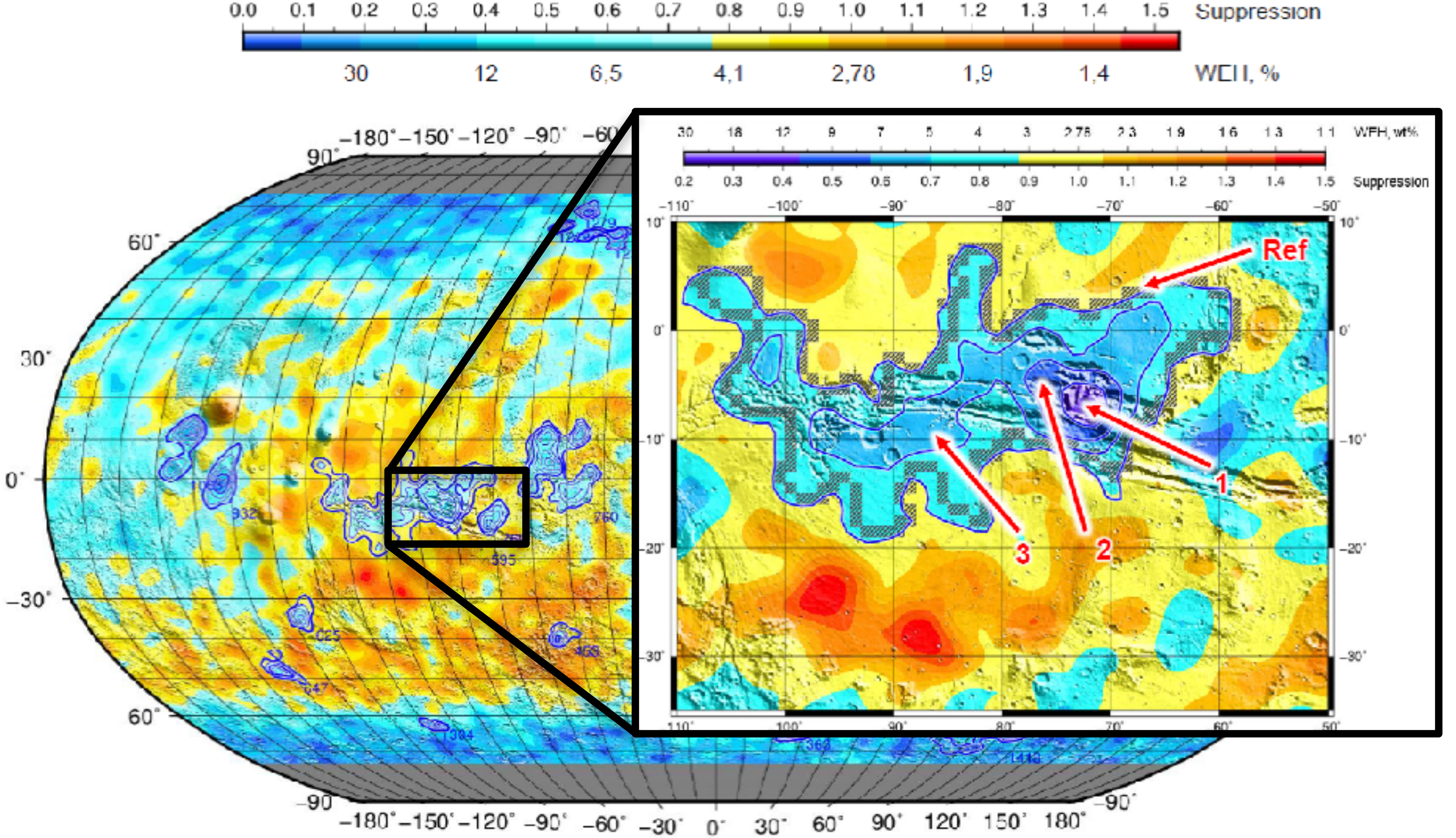


ExoMars TGO Water

FREND neutron spectrometer (ROSCOSMOS) found areas with shallow (1m depth) sub-surface water

At central part of Valles Marineris, measurements imply water (ice) content of 25%(10-100% at 1σ) by mass





Valles Marineris close-up
1x1 degrees bins
Smoothed over 5 degrees
WEH = ‘Water Equivalent Hydrogen’

Stereo Views of Mars
from High Resolution Stereo Camera (HRSC) Images
of the ESA Mars Express Mission

HRSC Principal Investigator:
Gerhard Neukum

Visualisation:
Jörn Levenhagen, Stephan van Gasselt, Alexander Dumke

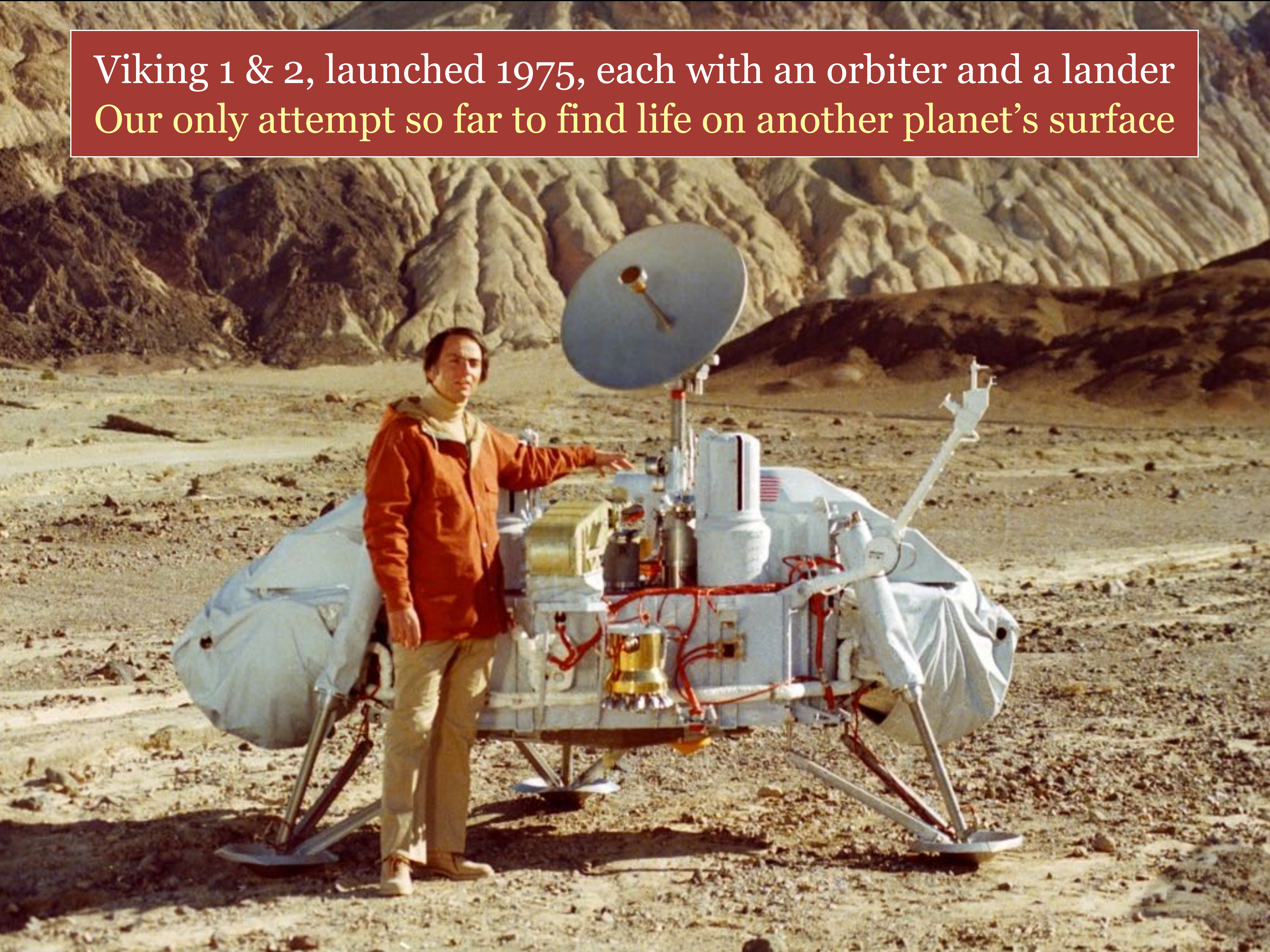
Data Processing:
Sebastian Walter

PLANETARY SCIENCES AND REMOTE SENSING, INSTITUTE OF GEOLOGICAL SCIENCES, FREE UNIVERSITY OF BERLIN

The Viking Missions

Viking 1 & 2, launched 1975, each with an orbiter and a lander

Our only attempt so far to find life on another planet's surface



Viking Lander - 40th Anniversary

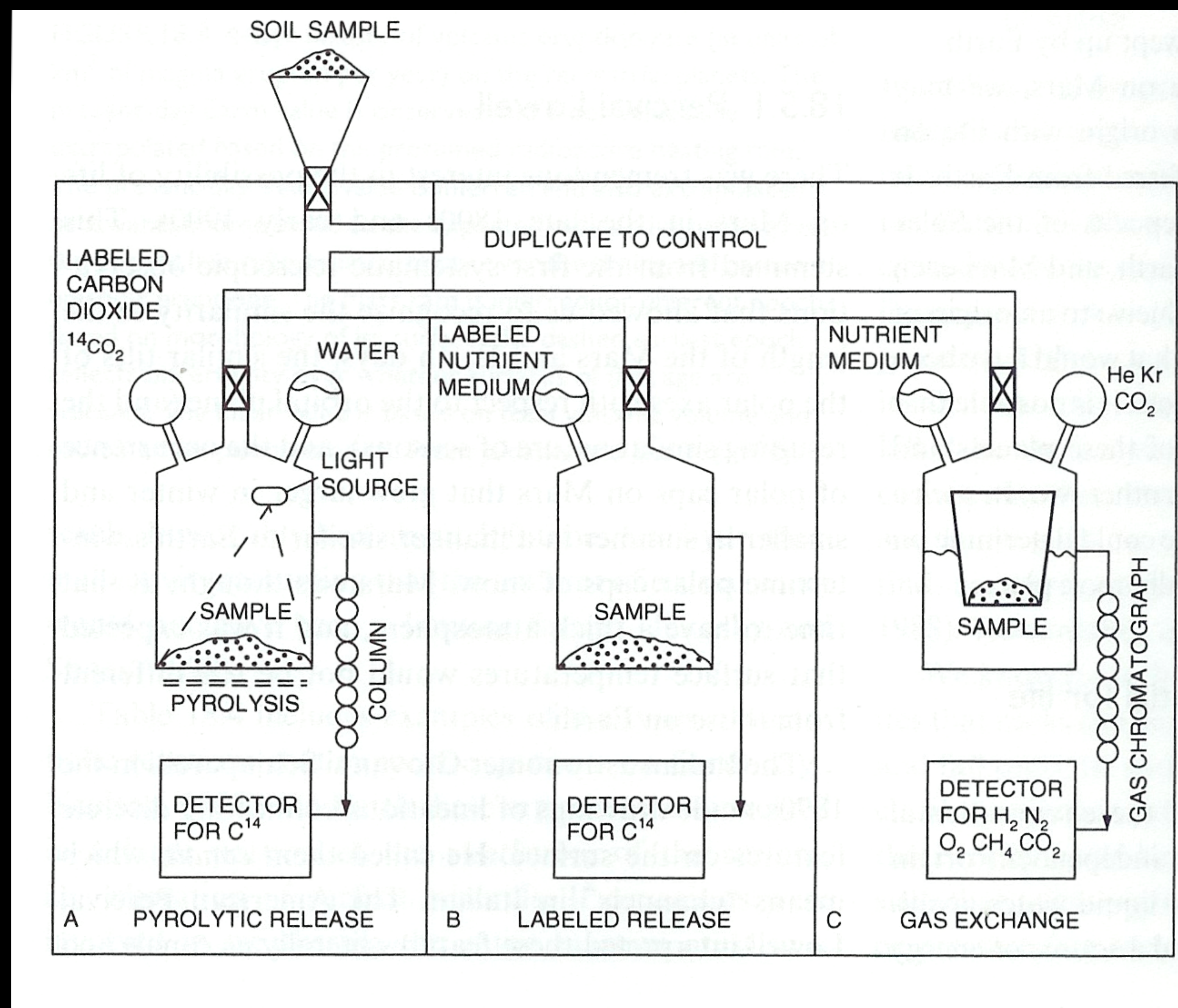
20 July 1976 - Viking I landed on Mars (until 1982)

[4:30 min]

The Viking landers tested chemistry, geology, seismology, magnetic properties etc…

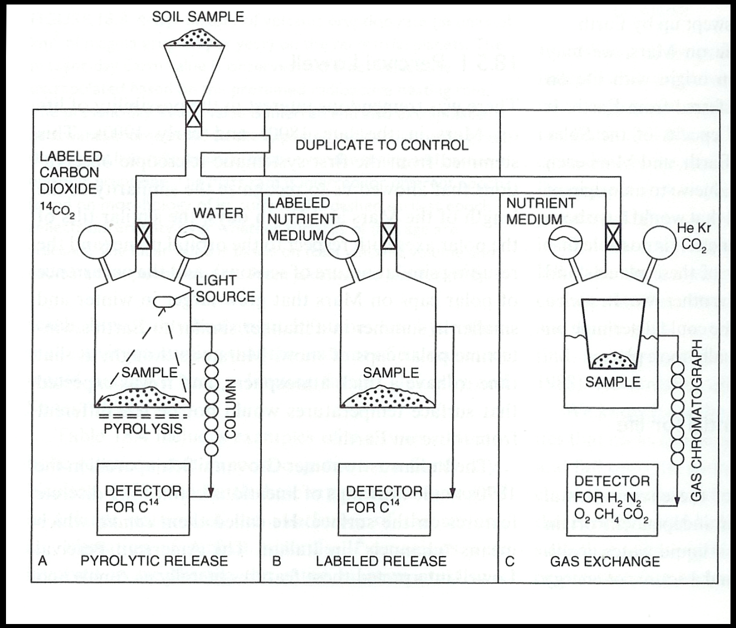
The biology package (15kg) obtained single soil samples and distributed them to three instruments:
All three gave positive (although not unique) responses
but the mass spectrograph failed to detect **any** organic molecules (at ppb!)

Each tested a different metabolic pathway, trying to culture organisms



How would you search for Life on Mars?

The Viking biology package was very limited due to the limits on payload (15kg, 0.03m^3)



It was driven by optimism
(only 1 in 100 to 1000 organisms on Earth can be cultured in a lab)

It assumed life forms very similar to the ones on Earth

It was a severe setback for the NASA exobiology program

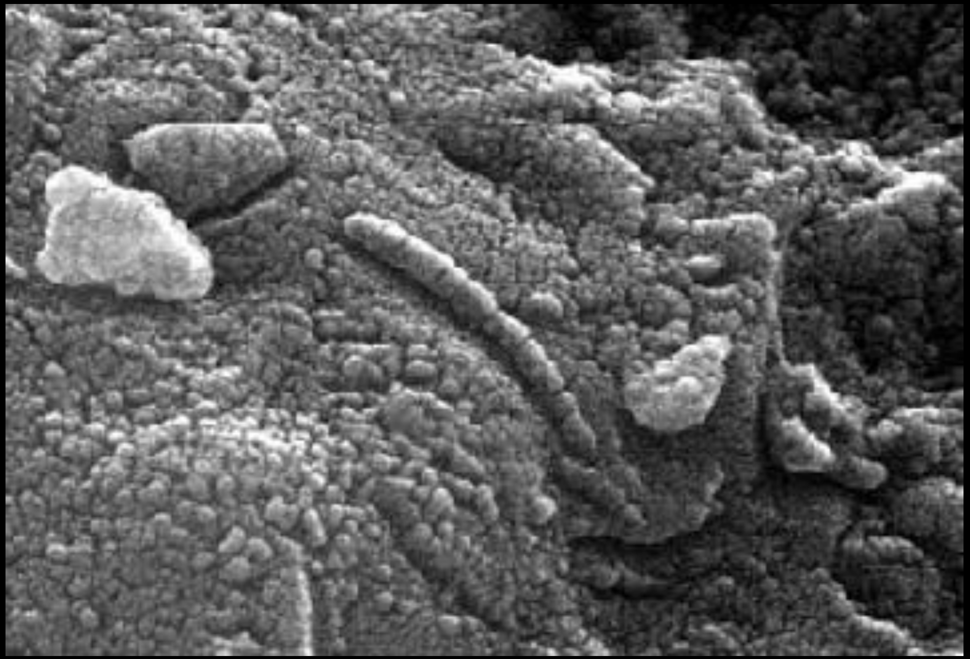
Today, scientist plans to look for sub-surface life on Mars and ultimately to returned samples from Mars

Reliable Biosignature on Mars

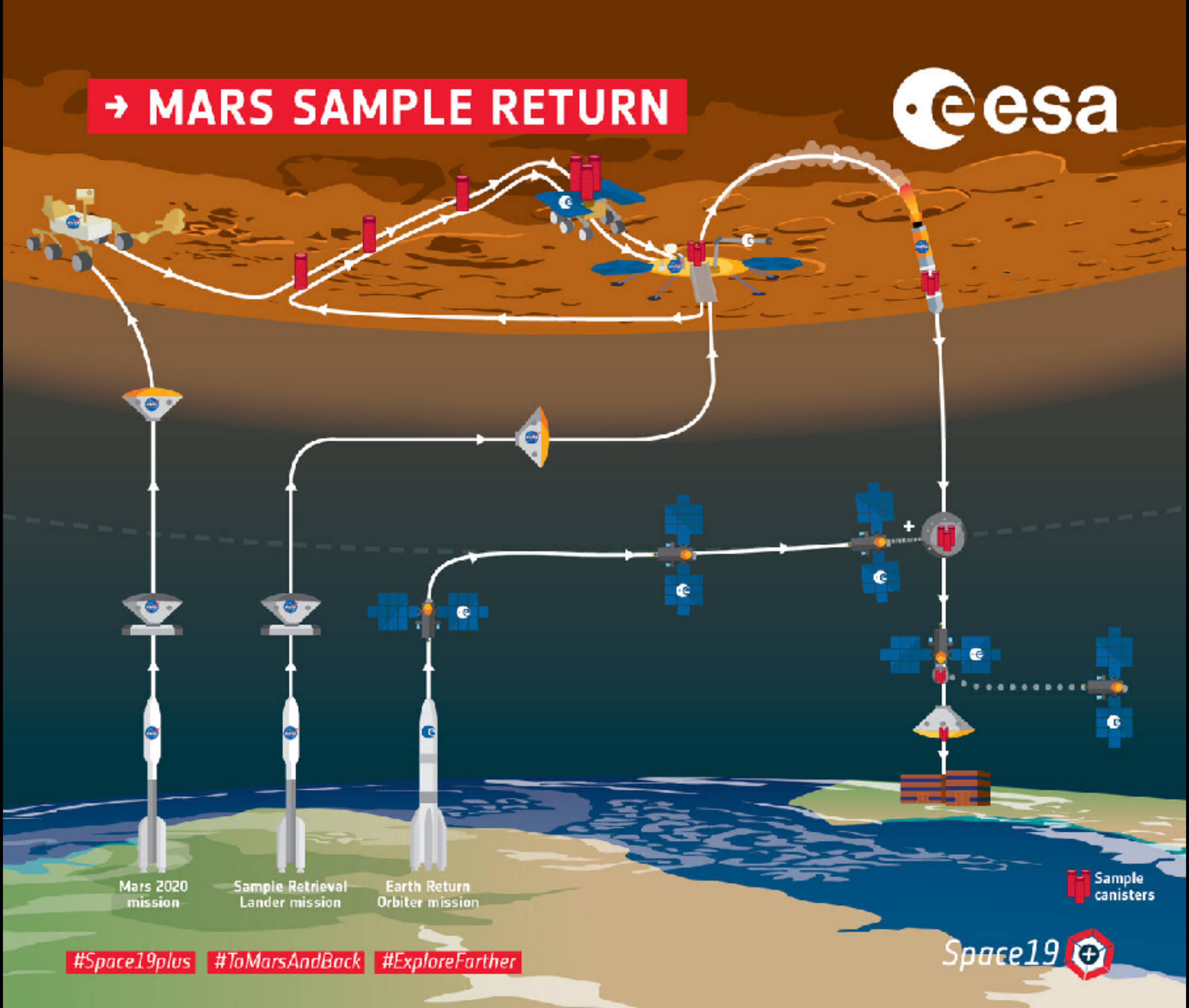
Isotopic ratios:
as on Earth, ^{12}C is preferred to ^{13}C by organisms
but on Mars atoms escape to space and confuse the ratio

Fossil cells:
if not heated or squeezed, fossils can be preserved for Gyrs
but structures are hard to interpret and Martian organism
might not have the same structural features

Organic Molecules:
Homo-chirality could be a reliable biomarker
Also complex molecules in disequilibrium with the
atmosphere




BRINGING MARS
BACK TO EARTH



→ MARS SAMPLE RETURN
esa
Mars 2020 mission
Sample Retrieval Lander mission
Earth Return Orbiter mission
Sample canisters
#Space19plus
#ToMarsAndBack
#ExploreFarther
Space19

Mars had all the ingredients for an origin of life

If life is found:

Could it have the same origin than life on Earth (Panspermia)?

Or would it represent a independent origin of life?


If you look closely,
you can see a fossil
right here!

Should we explore Mars further or should we invest in other astrobiology missions?

Lunch break...

Warning: you are leaving the habitable zone

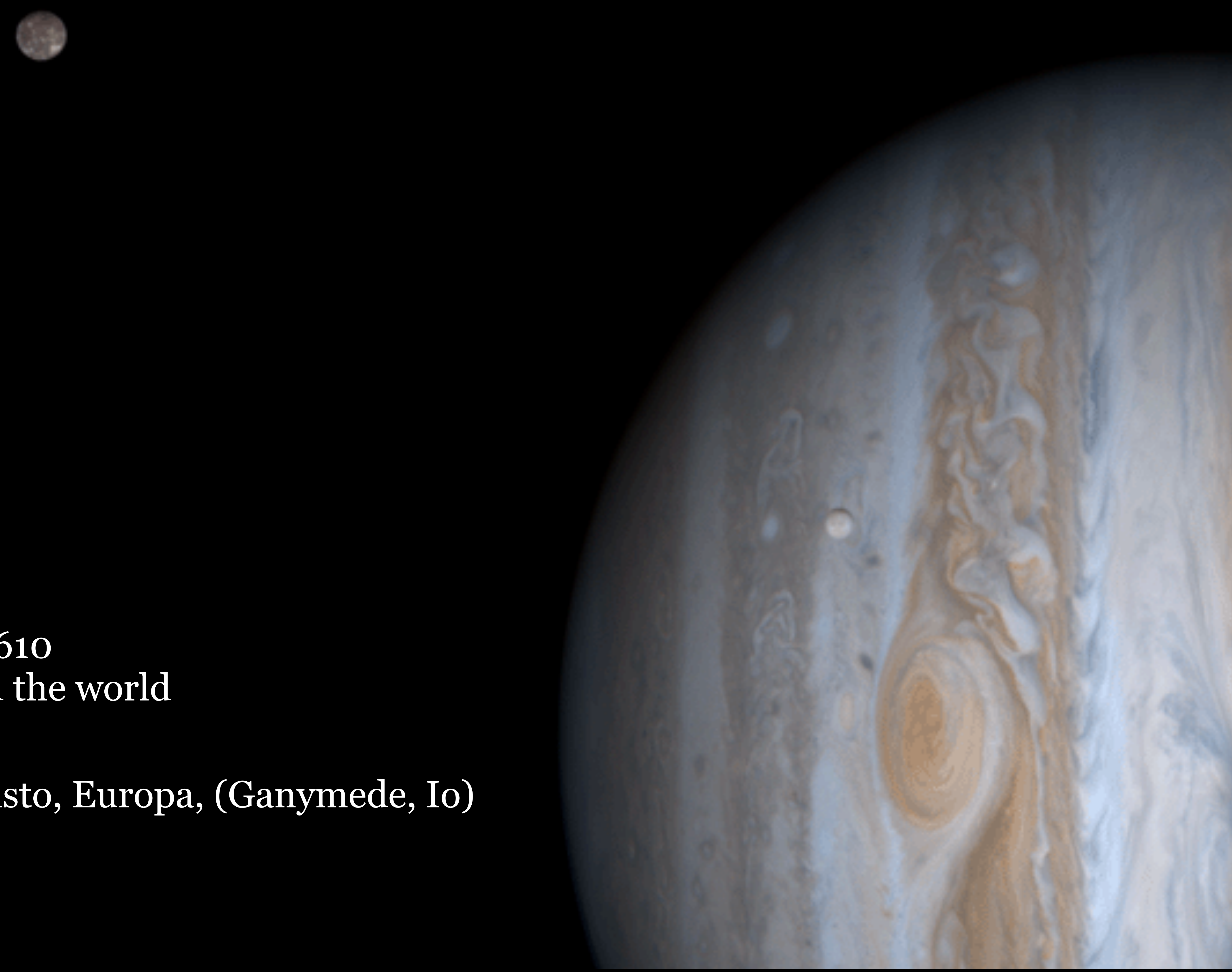
Life on Europa?

Juno (NASA) mission
“Trailer”

[2 min]

What is needed for (Earth-like) life?

- Elemental building blocks (C,H,N,O,S,P,...): they are common in the Solar System
- Organic molecular building blocks (amino acids, ...): They are found in meteorites, asteroids and comets H_2O is abundant in the solar system Complex chemistry (as in hydrothermal vents) still needs to happen...
- An energy source to drive chemical disequilibrium (reactions back to equilibrium support metabolism): sunlight is always available, chemical energy sometimes, geological energy often



1610
Changed the world

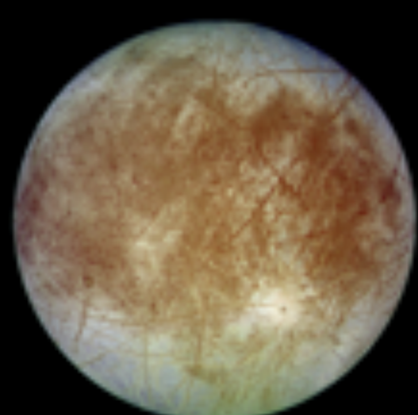
Galilean Moons: Callisto, Europa, (Ganymede, Io)

Jupiter

- Gas giant (318 M_{Earth}), 86% H, 13% He, ~10 M_{Earth} core
- Below the atmosphere: liquid metallic H → strong magnetic field
- Jupiter emits 1.7x as much energy as it absorbs from the Sun
- Jupiter and the Galilean Moons formed near the snow line

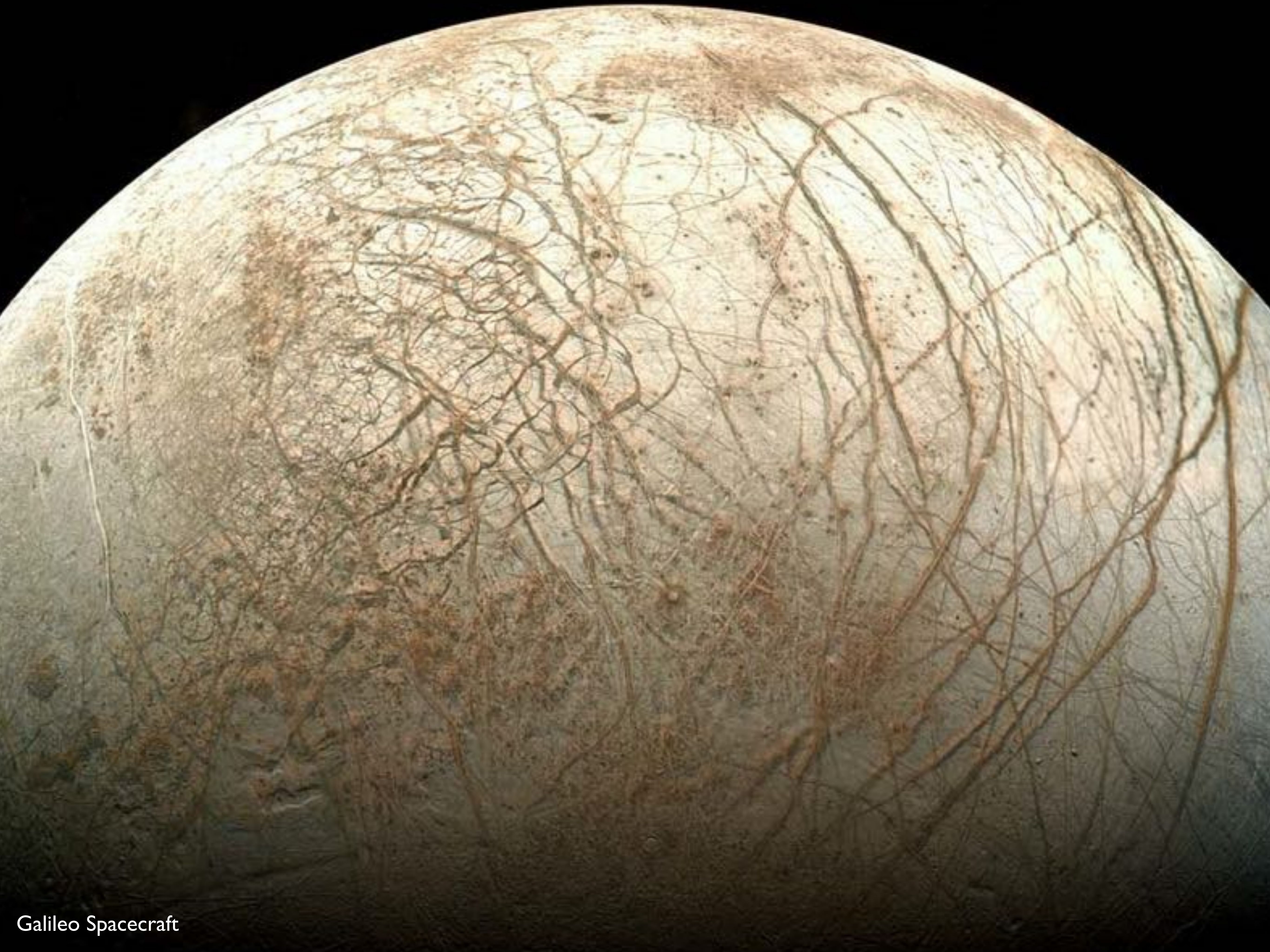
Io	Europa	Ganymede	Callisto
water-free volcanic	ice/water on rock 3.0 g/cm³	ice/water on rock 1.9 g/cm³	not differentiated 1.8 g/cm³

Moon



Europa

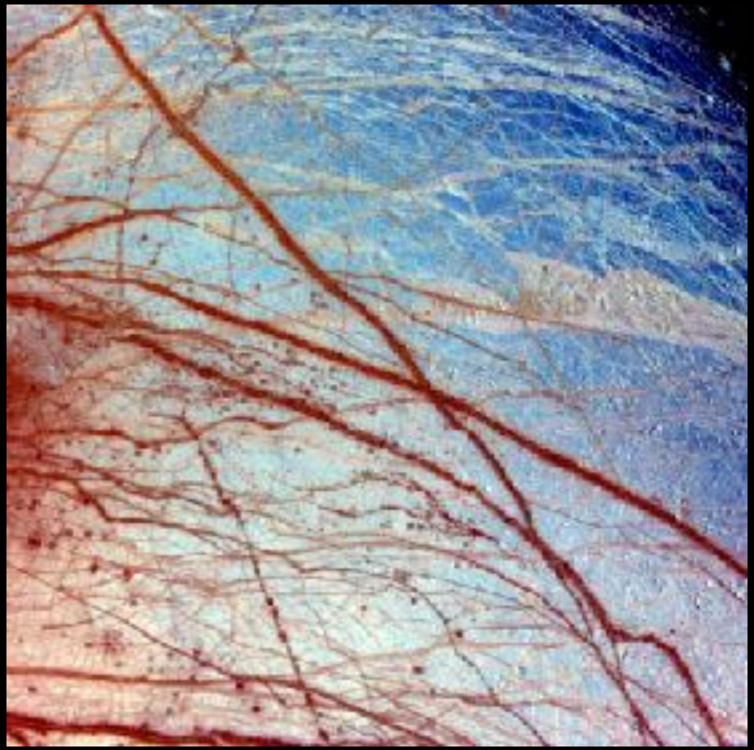
Earth



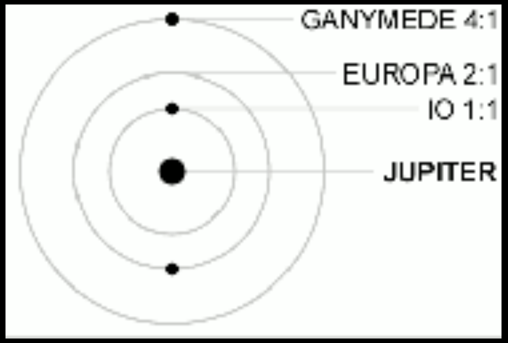
Galileo Spacecraft

Europa

- Most likely, Europa host a sub-surface ocean twice the volume of Earth's ocean
- Tidally locked to Jupiter (period 3.6 Earth days)
- Slight eccentricity (0.01) causes tidal heating in interior
- Albedo 68% !! (Earth's Moon 12%)
- T_{surf} = 50K (poles)-130K ('daytime')
- High radiation on surface, but habitable >1m below ice crust

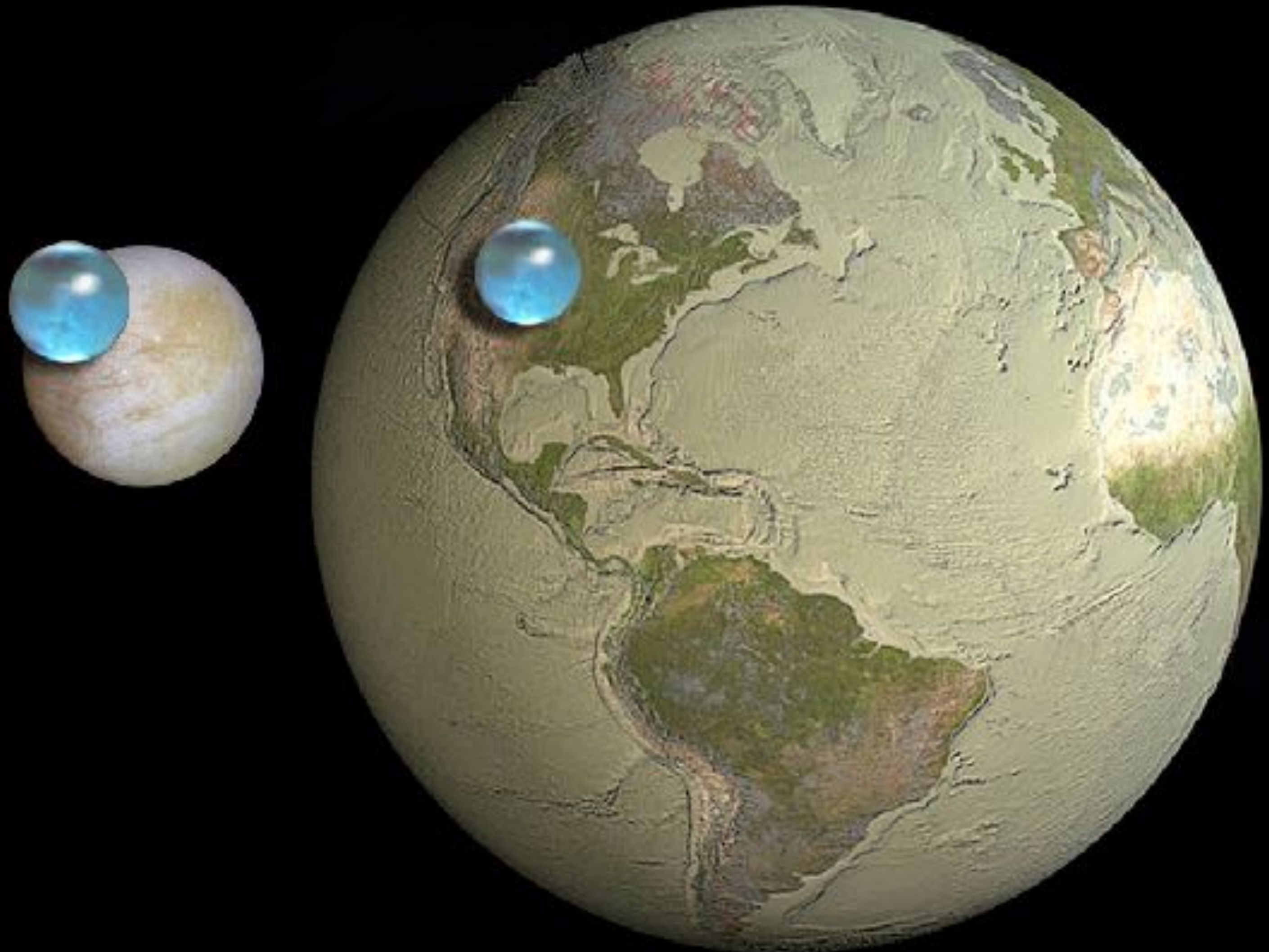


Europa



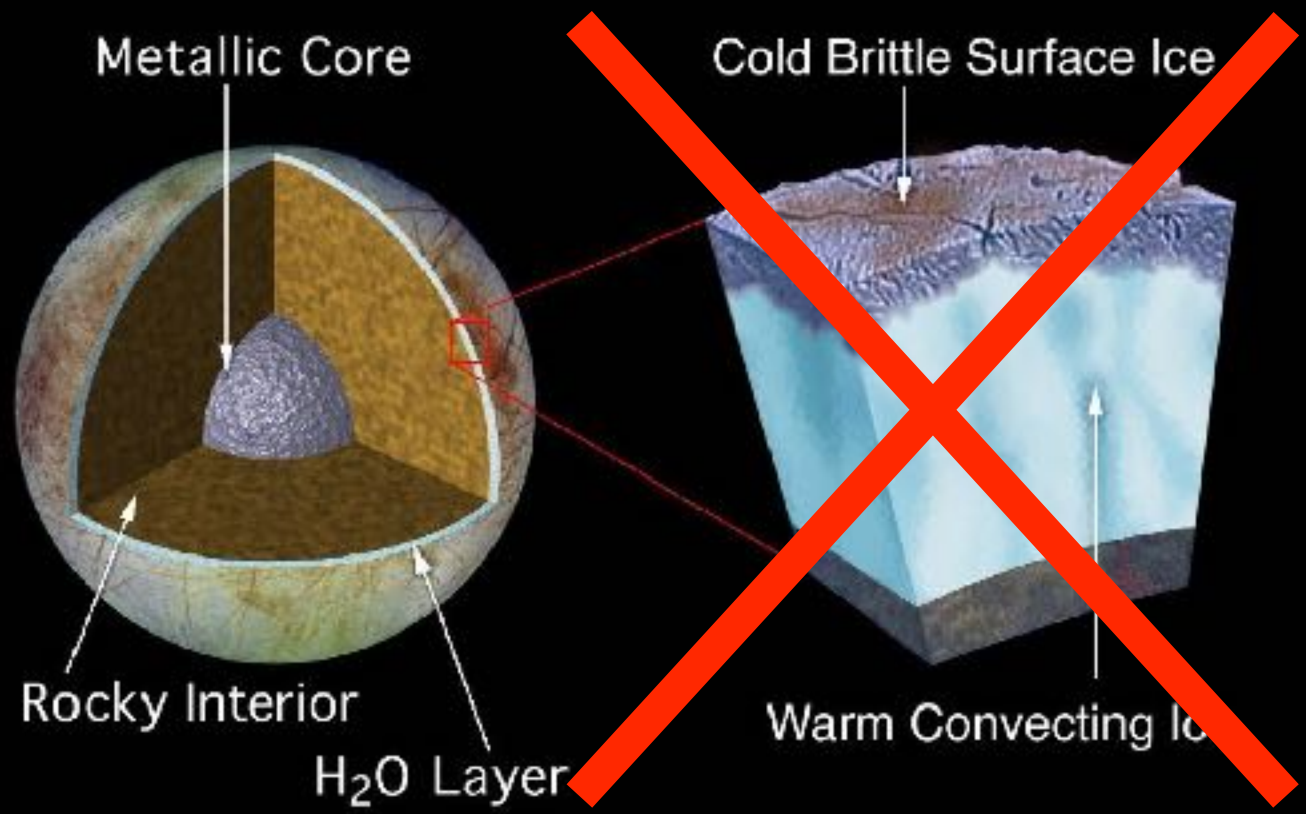
Key evidence for liquid water layer

- Tidal heating model through forced eccentricity
- Density, Gravity Measurements and Magnetometer data (induced magnetic field from Jupiter) require a conducting, sub-surface global spherical shell: salt water



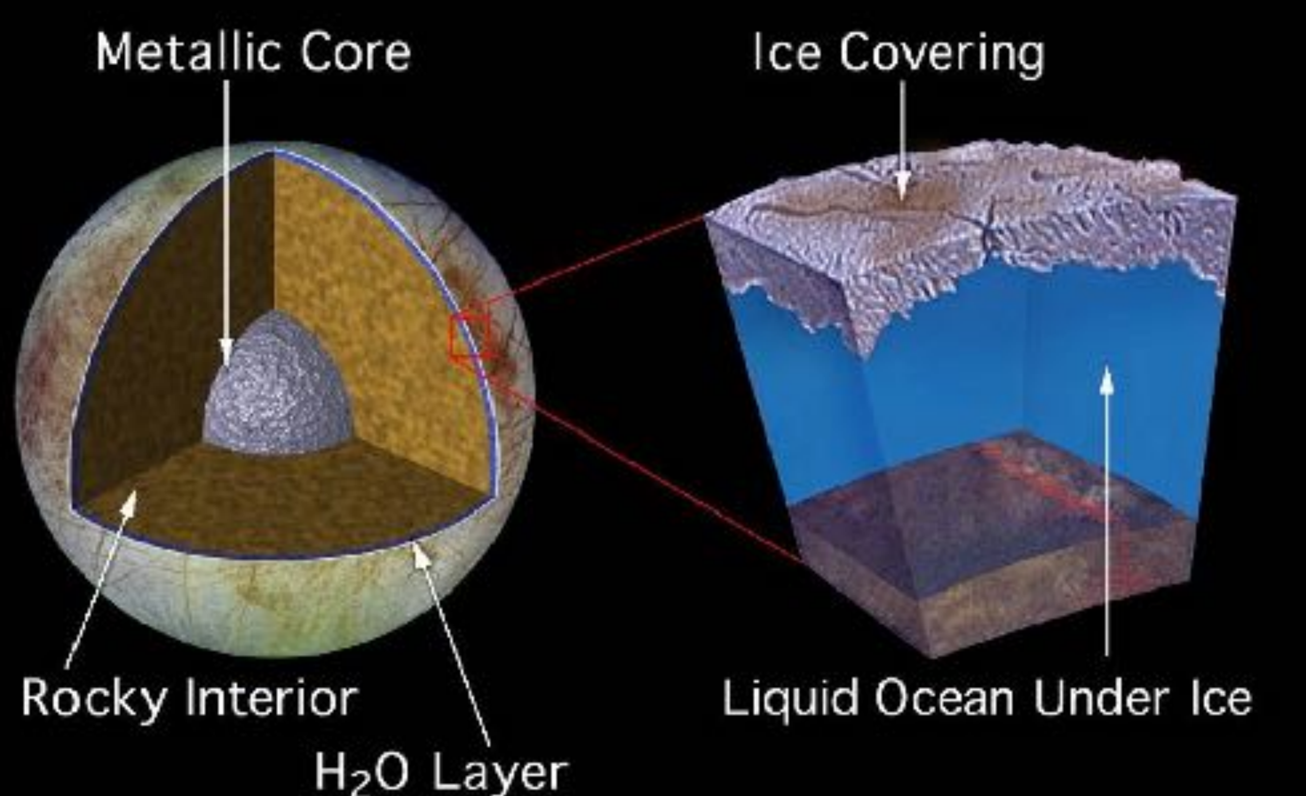
Europa

- Very thin atmosphere of O_2 (and H_2O_2) from sputtered H_2O off surface
  (similar to Earth at 400km altitude)
- Surface age ~50 Myr from impact rate
  (Earth sea floors ~200 Myr)



Thermal models:

- Differentiation: silicate core - ~100 km of liquid H_2O - ~1-10 km ice crust (→ no topography)
- ~6% H_2O total, as chondrites



Europa - Habitability

The source of Energy could be

- ★ thermal: hydrothermal activity
- ★ chemical disequilibria: organics and oxidants from the surface mixed into the ocean

First assumption for Chemistry: similar to carbonaceous chondrites (i.e. few % organic material)

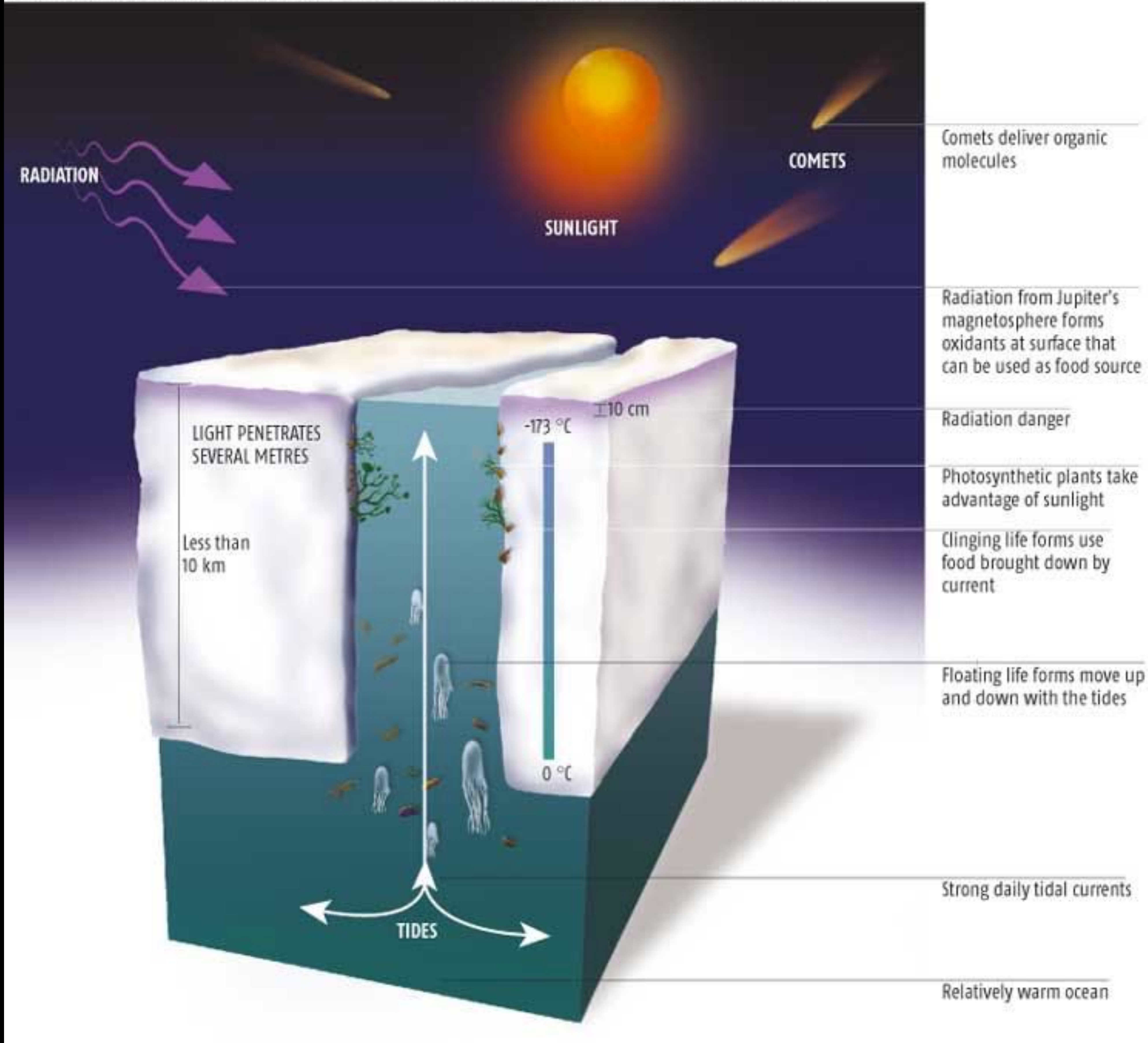
Photosynthesis below the ice crust is not impossible but difficult

Hydrothermal vents (in 100km depth) depend on the tidal heating models and are disputed

If they exist, they could support methanogens

IS THERE LIFE ON EUROPA?

If Europa's icy crust is thin enough, cracks would provide a habitat where life could thrive



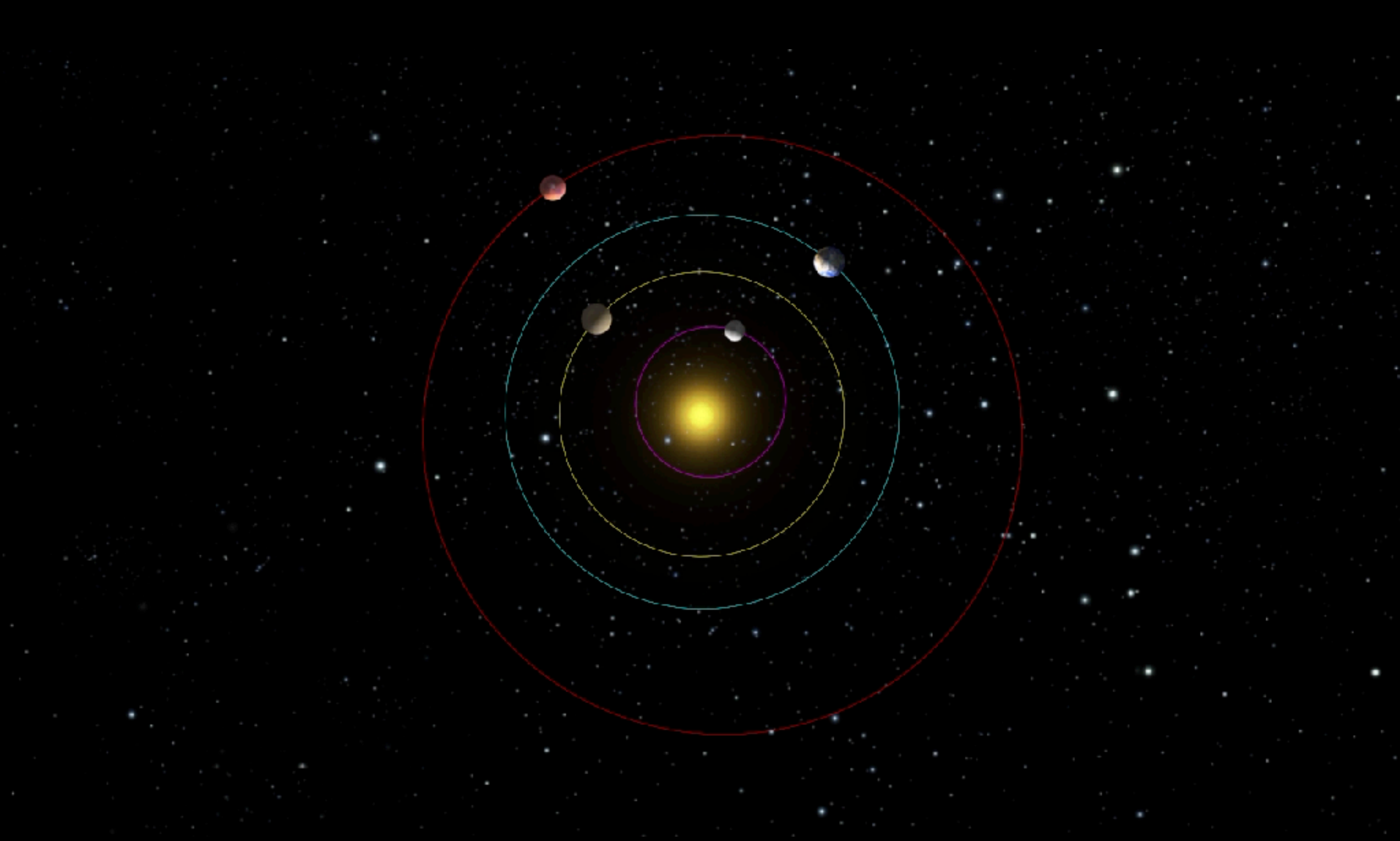
If we found Life on Europa,
what could it mean

for early Earth?

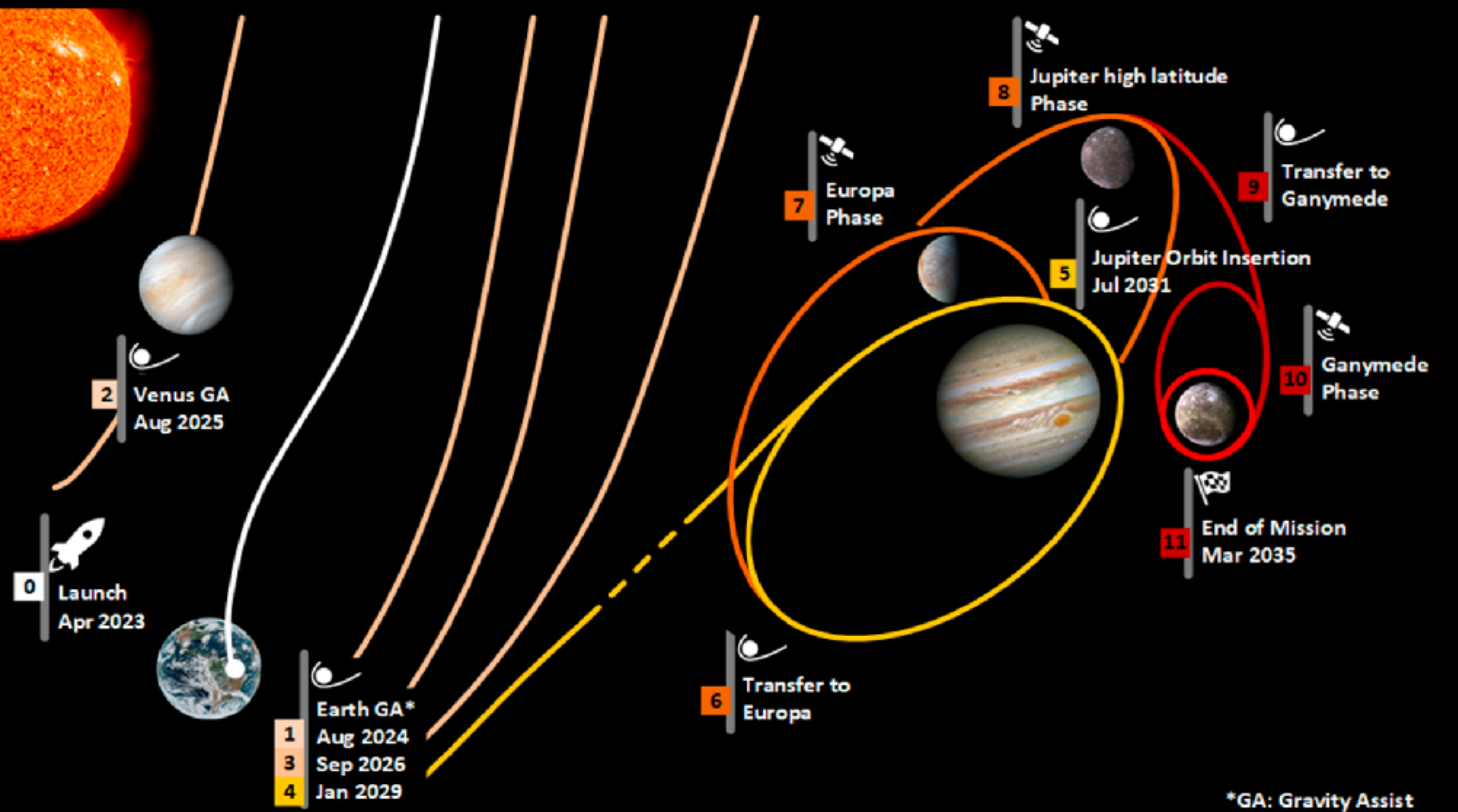
for Snowball Earth?

Europa’s Ocean appears to be habitable by microorganisms

ESA JUICE Mission - launched 2023



ESA JUICE Mission - launched April 2023



ESA JUICE Mission - launched April 2023

Ganymede and Callisto:

- characterisation of the ocean layers and detection of putative subsurface water reservoirs;
- topographical, geological and compositional mapping of the surface;
- study of the physical properties of the icy crusts;
- characterisation of the internal mass distribution, dynamics and evolution of the interiors;
- investigation of the exosphere;

Europa:

- focus on the chemistry essential to life, including organic molecules
- understanding the formation of surface features and the composition of the non water-ice material
- first subsurface sounding of the moon, including the first determination of the minimal thickness of the icy crust over the most recently active regions


Jet Propulsion Laboratory
California Institute of Technology
NASA mission: Europa Clipper to be launched 2025

Wilder...

[3:30 min]

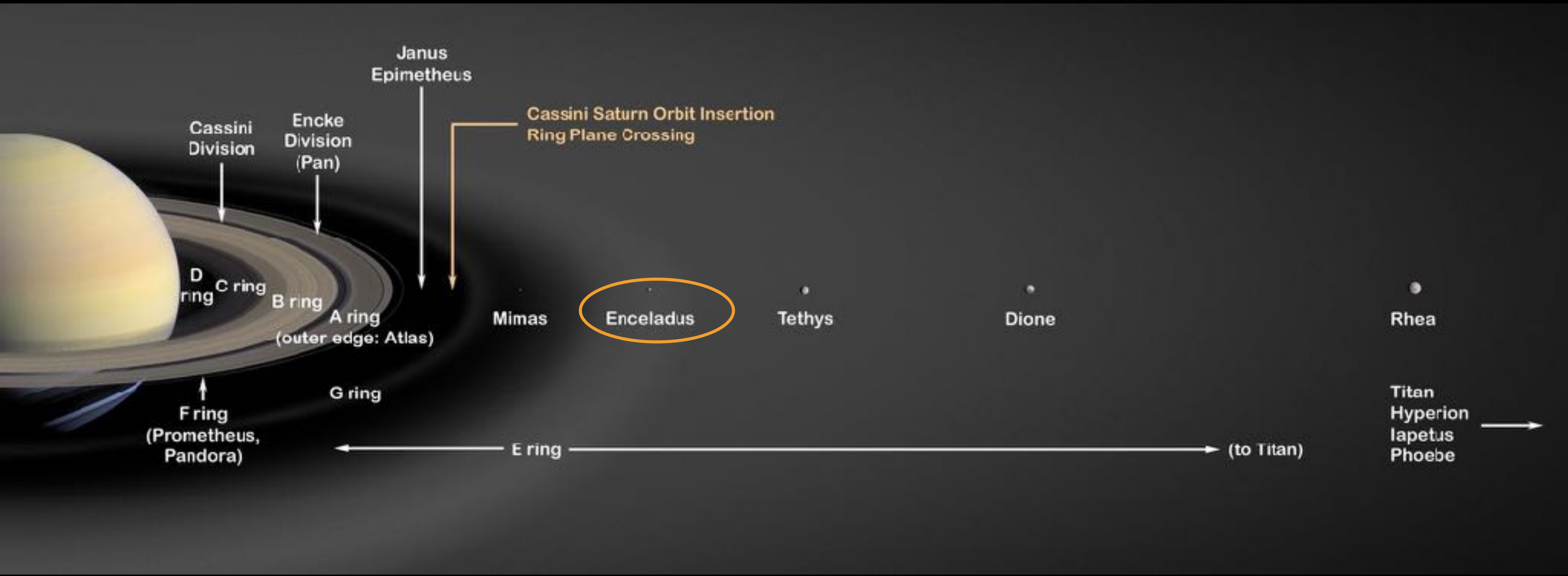
Life on Enceladus?

Enceladus

Major moon of Saturn

Located at 180 000 km

500 km ∅



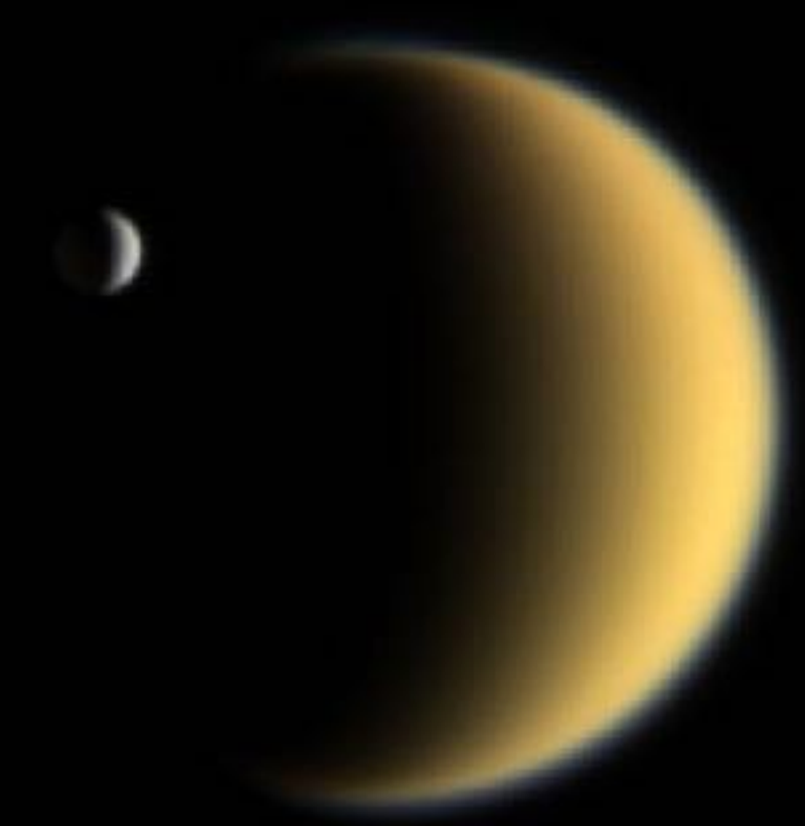
Enceladus

Enceladus is one of three outer solar system objects with known active eruption

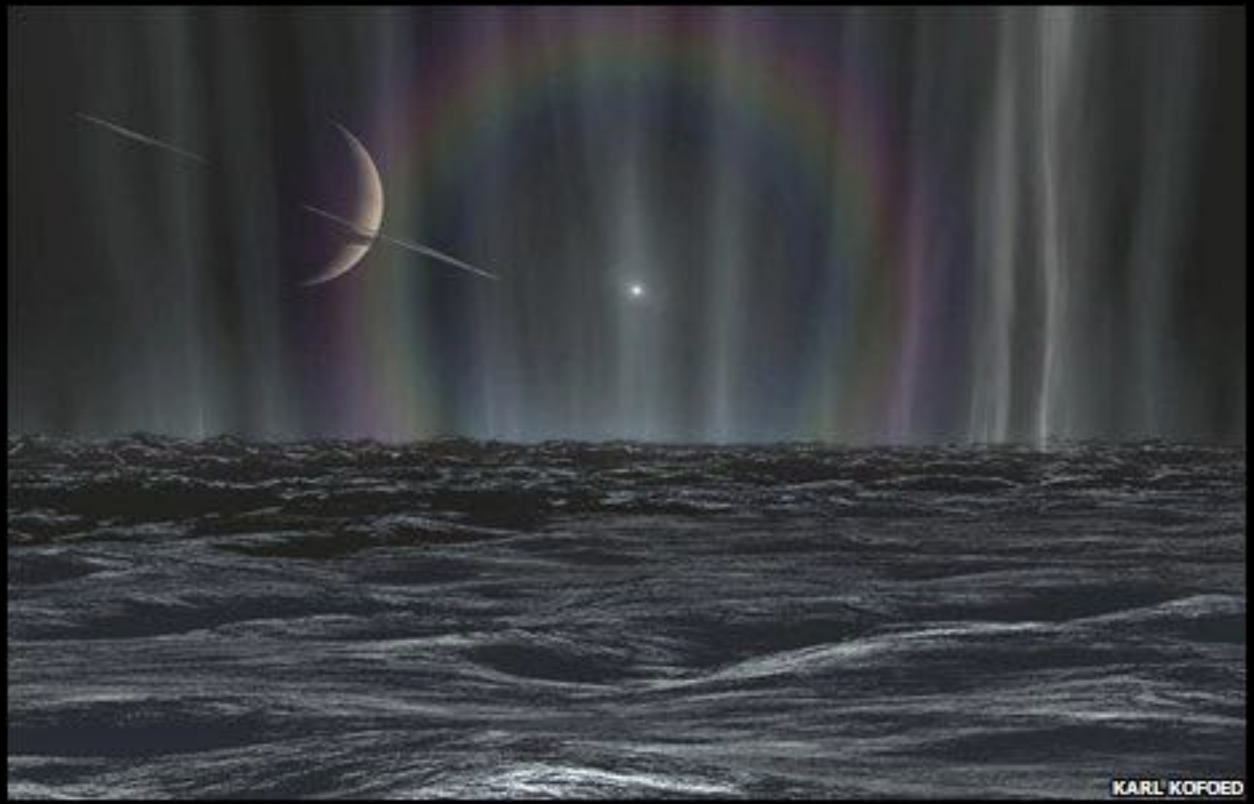
2011: The plume observed from Enceladus is mostly salty H_2O (with organic compounds: CO_2, CH_4, N_2, C_2H_4, ...)

2015: Cassini did fly one last time of Enceladus - data are being analyzed...

Enceladus is now assumed to have a sub-surface ocean, containing organic material, with a heat source (tidal heating or radioactive decay) that makes it possibly habitable



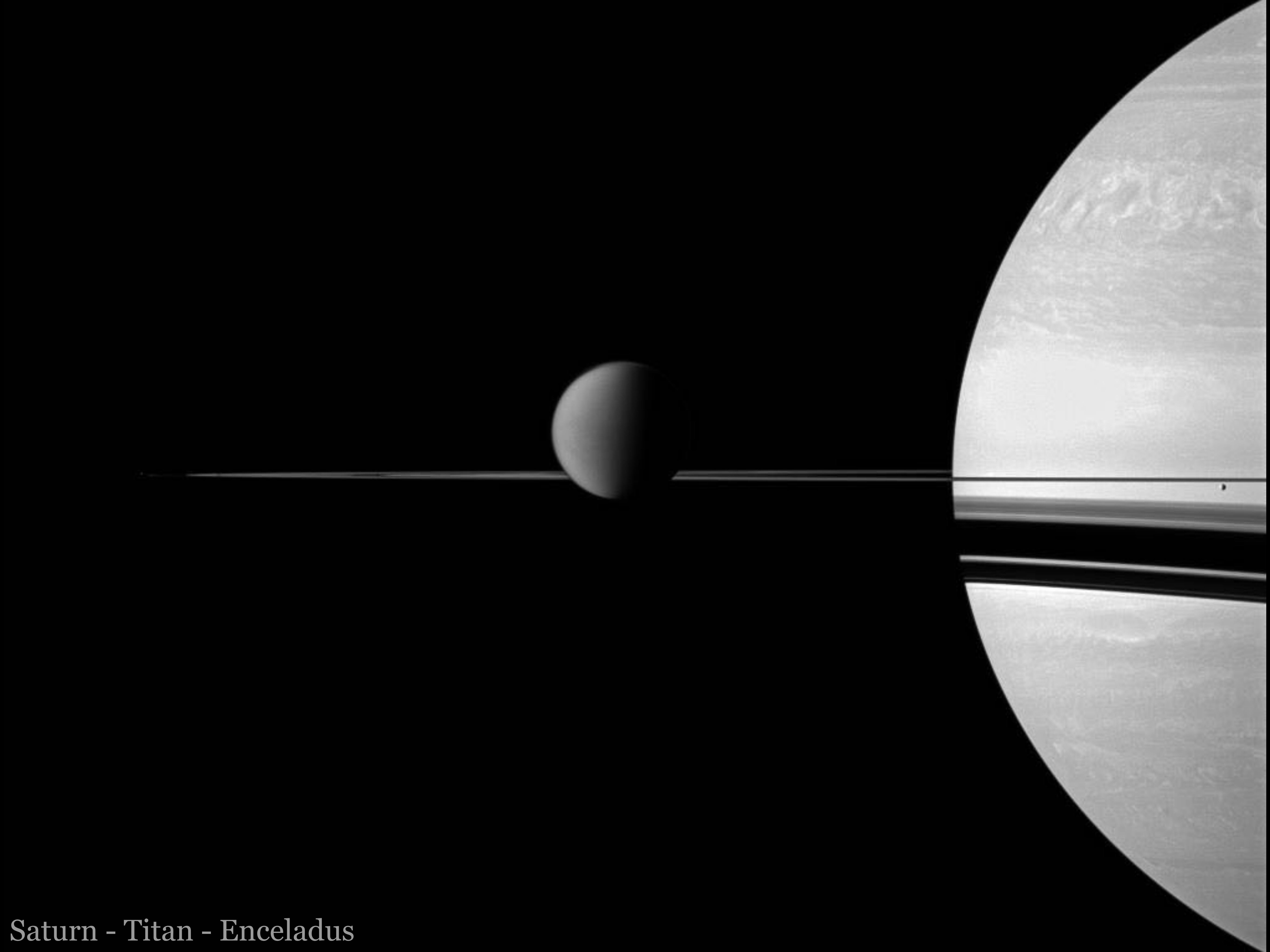
Enceladus transits Titan



Artist impression

Which Solar System bodies are now associated with liquid water?

Life on Titan?



Saturn - Titan - Enceladus

The Largest Moons and Smallest Planets

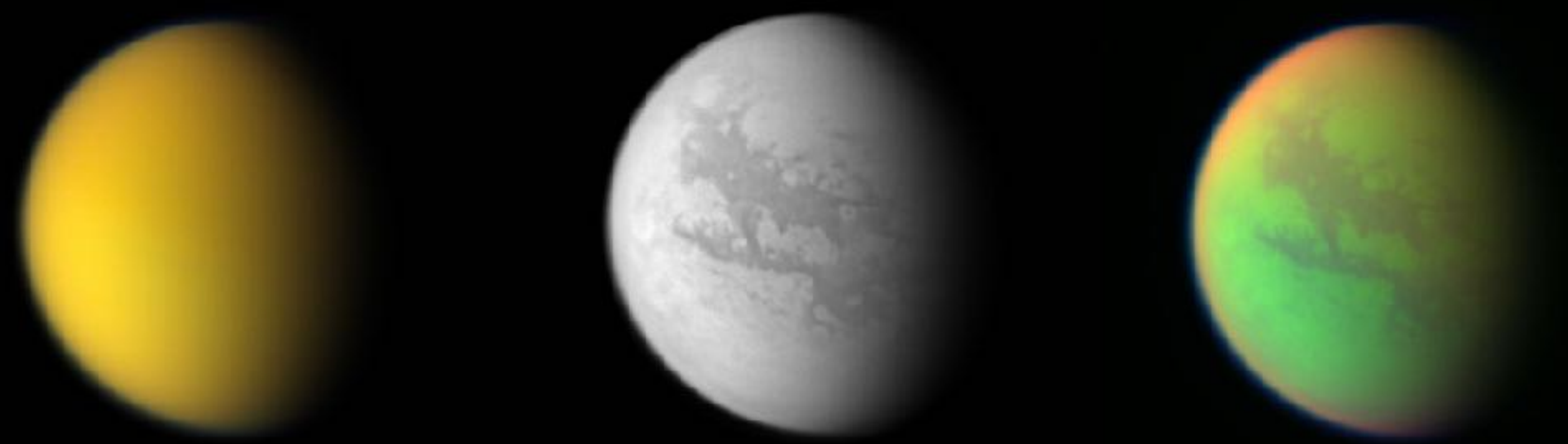
Titan

Dense (1.5 bar) atmosphere of N_2 (90-98%) and CH_4 (0.5-4%)

Methane-driven meteorology

Density 1.9 g/cm^3 → half rock, half water ice

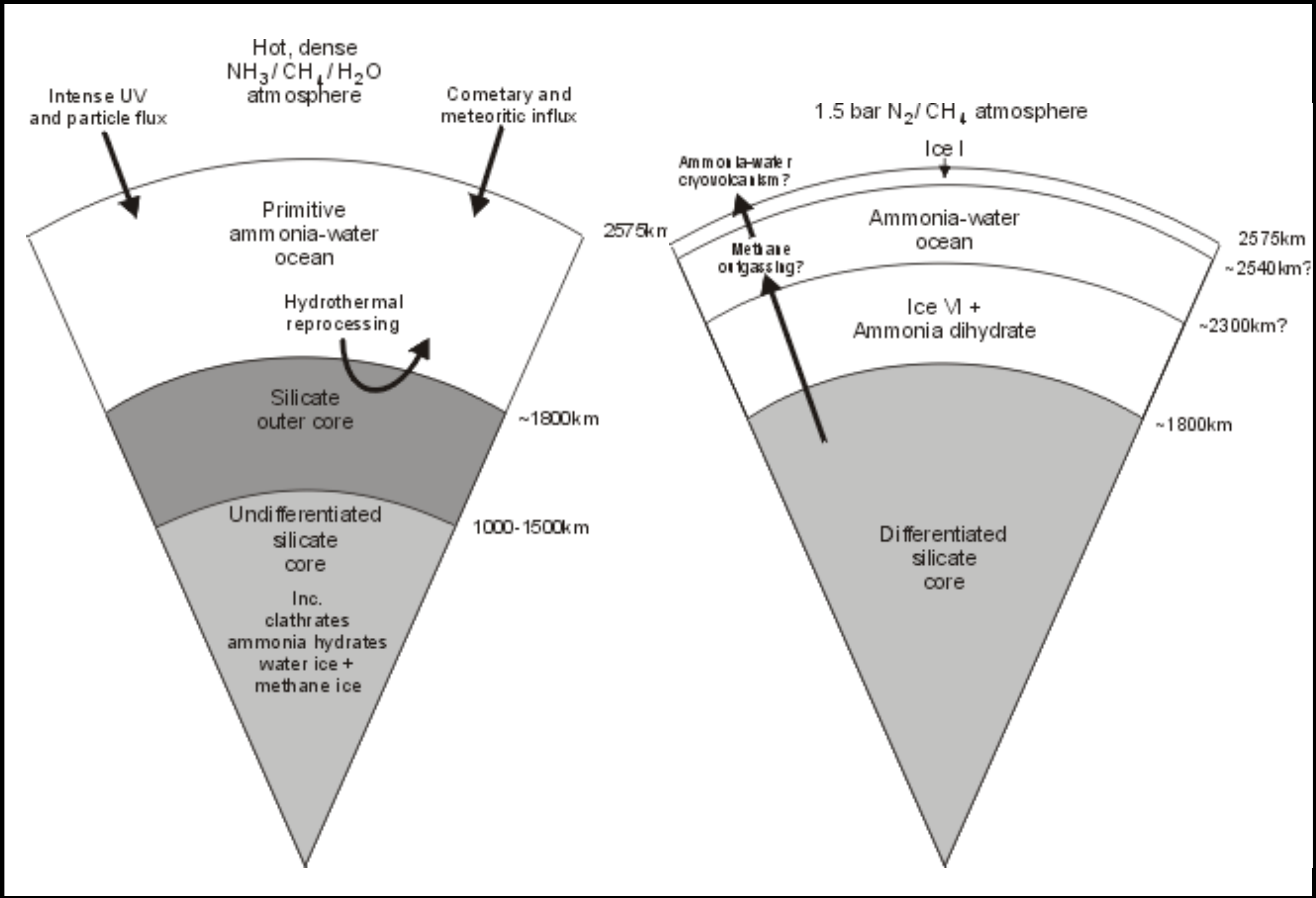
As Ganymede and Callisto, Titan might have formed in situ



optical infrared composite

Titan’s interior

Possible models for Titan’s interior structure:

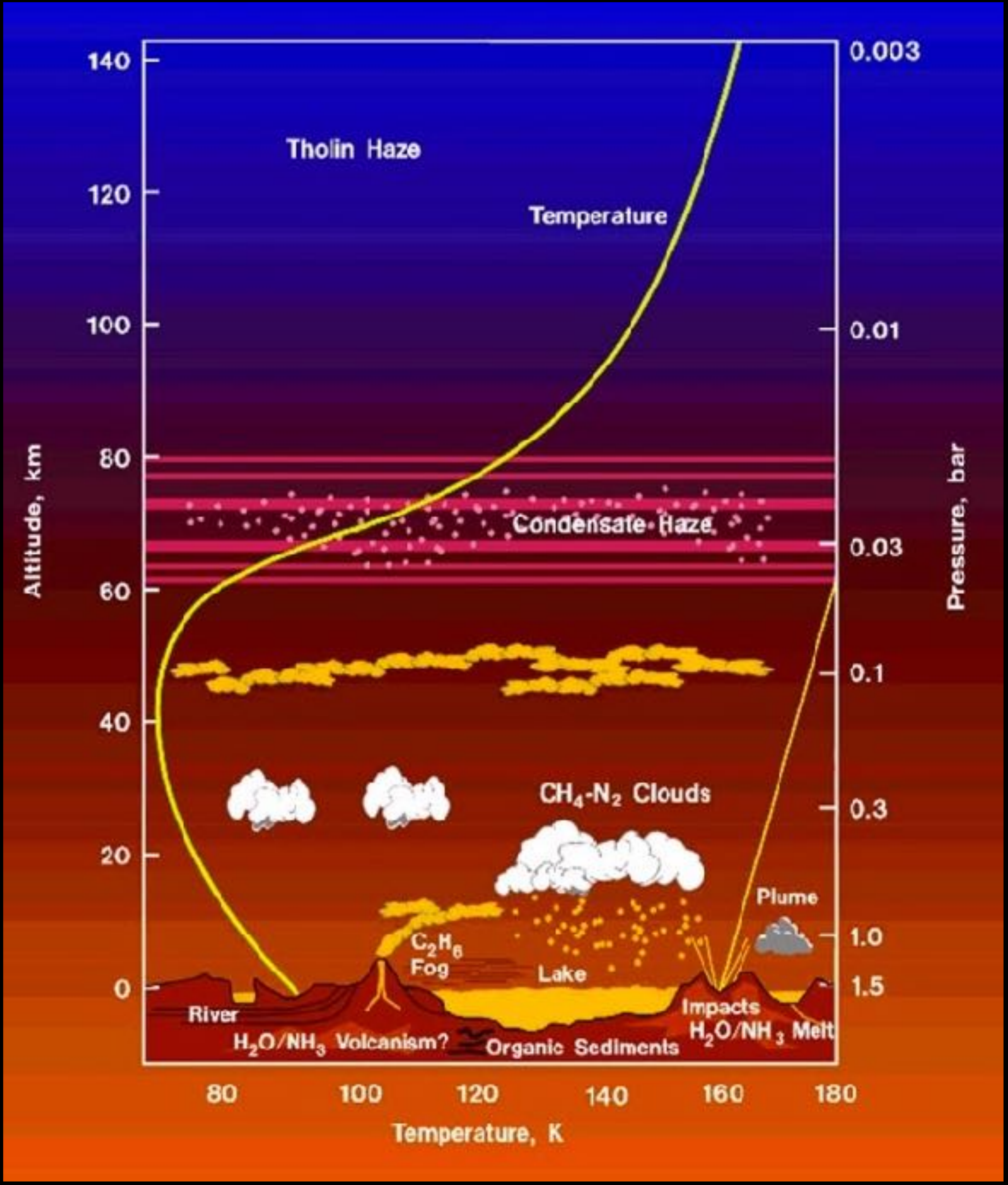


During accretion of planetesimals — After accretion

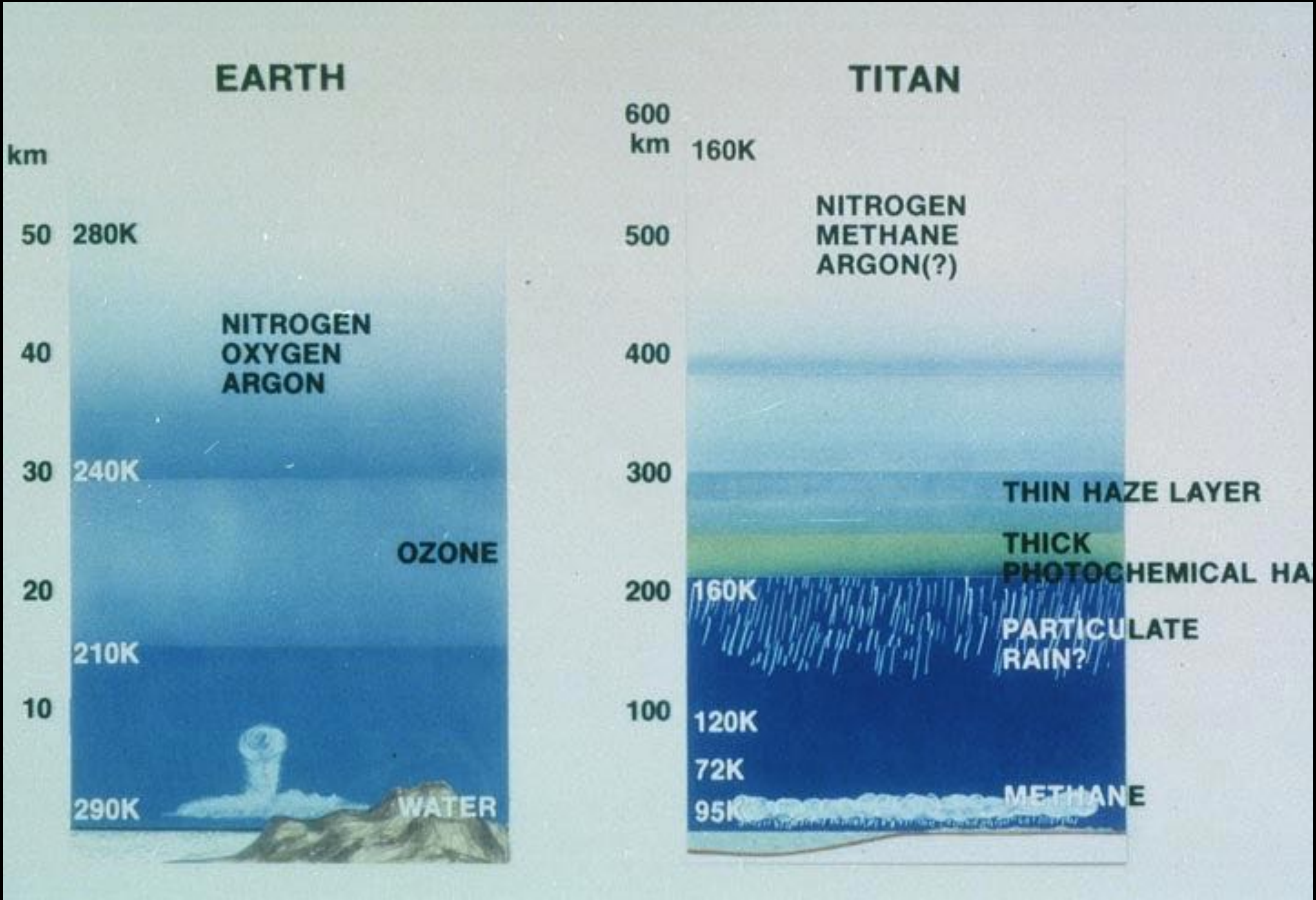
But it is really Titan’s atmosphere that makes it unique…

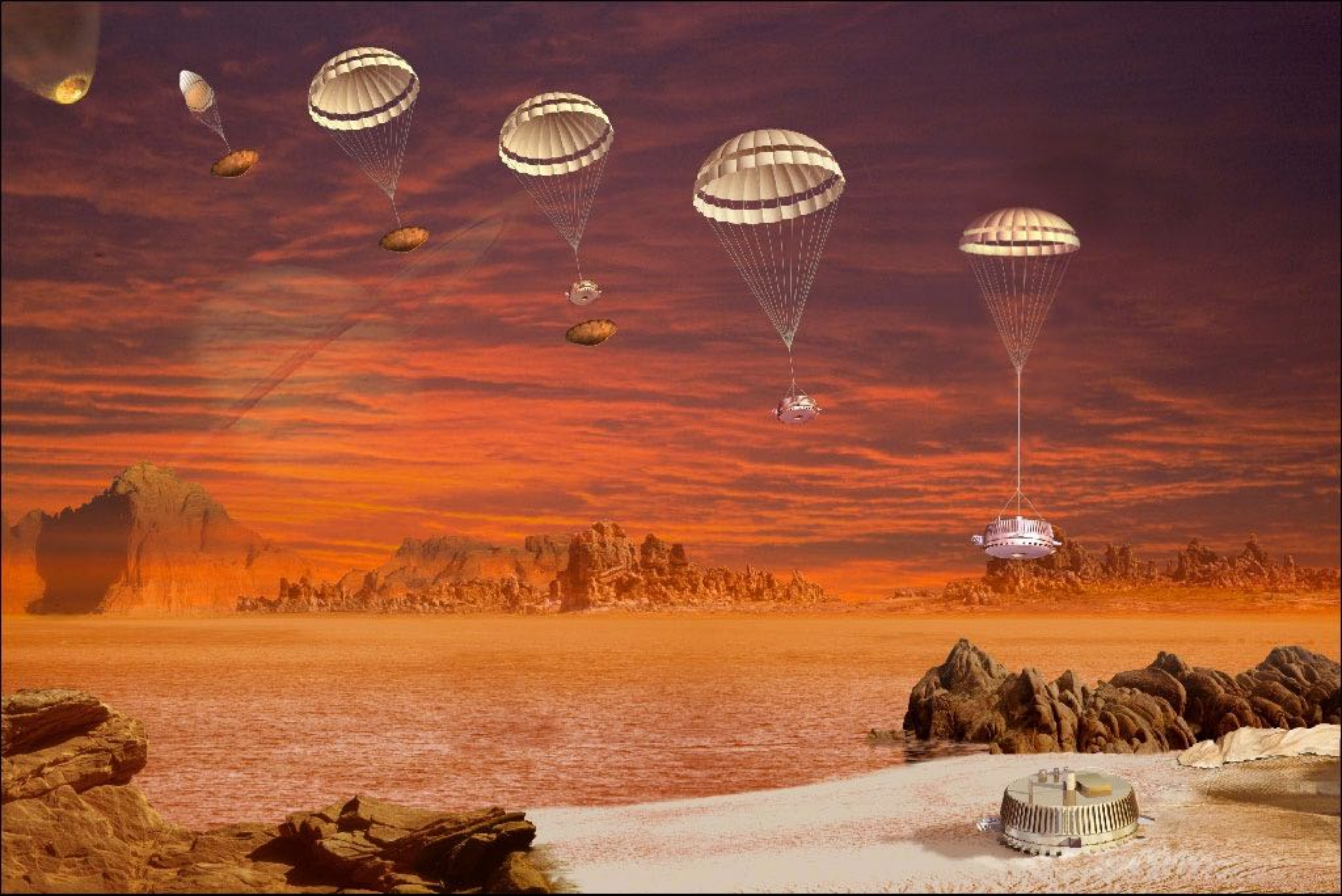
Titan's atmosphere

- Second densest atm after Venus
- N_2 (90-98%) and CH_4 (0.5-4%)
- Lower temperature but similar temperature profile as Earth
- Greenhouse effect adds 10K to the otherwise 85K
- Low H (atomic and molecular) means only weakly reducing atmosphere



Titan atmosphere





Huygens probe landing on Titan
Mission launched 1997, landed 2005

Huygens probe landing on Titan

Mission launched 1997, landed 2005

[5 min]

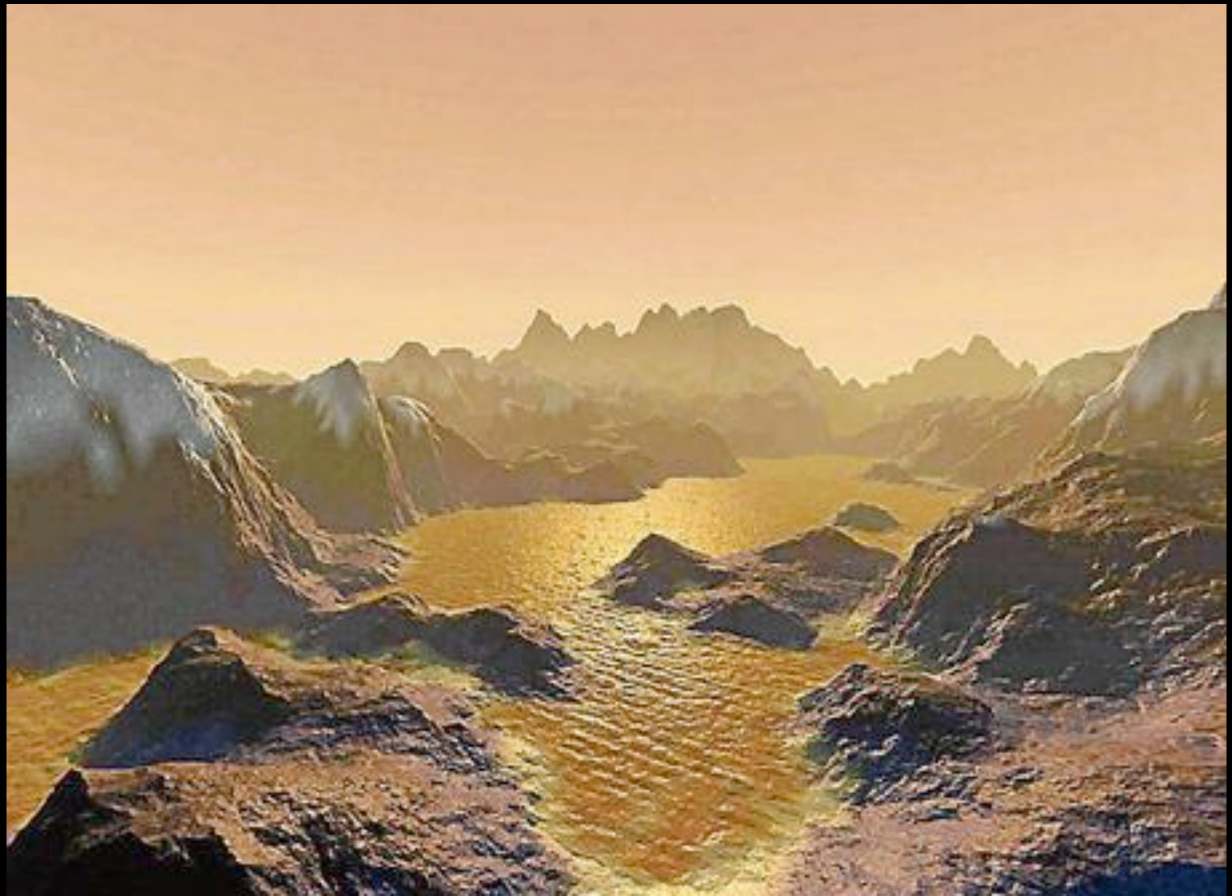
Titan's surface

At 95K: Methane CH_4 - Ethane C_2H_6 lakes exit,
and with volcanism, they replenish the atmosphere in CH_4 (previously thought to be oceans)

No liquid water on the surface
but water/ammonia mix under the ice is possible

Source of Energy: Volcanism

(Sun irradiation is just 1% of Earth's)



Astrobiological speculations

Live on Titan would use an organic solvent (not polar), not H_2O

→ it would necessarily be different from life on Earth (no panspermia)

Below surface (tens of km of ice), Titan host a liquid water/ammonia ocean: Could life have developed in there?

Probes are not feasible (several km deep), it would have to manifest through outgassing...

What is the main challenge of chemistry at low temperature?

What might Life look like on Titan?

Take home ideas

- The temperature gradient in the initial solar nebulae determines which elements condense where
- The origin of Earth's water is still speculative
- Mars remains the primary target to search for life in the Solar System
- Moons of Jupiter and Saturn host sub-surface liquid water
- Titan would host a weird life form

Homework:

- Read the (4 page) article by Nisbet & Sleep (Nature 2001)

- Read the two chapters of ‘Weird Life’: Shadow Biosphere and Extremophiles

Monday November 20	Day 1: Definition of Life; Origin of Life; Evolution of Life; Limits of Life 10:00-12:00 & 13:00-14:00 ✔
Tuesday November 21	Day 2: Earth Climate History; Mars and Venus Climates 10:00-12:00 & 13:00-14:00 OLD SEMINAR ROOM ✔
Wednesday November 22	Day 3: Habitable Places in the Solar System; Mars; Moons of Giant Planets 10:00-12:00 & 13:00-14:00 ✔
Thursday November 23	Day 4: Habitable Places beyond the Solar System; Exoplanets properties; Biosignatures 10:00-12:00 & 13:00-14:00
Friday November 24	Day 5: Search for Extraterrestrial Intelligence; Alien Biochemistry 10:00-12:00 & 13:00-14:00

The End for Today

Thank you!