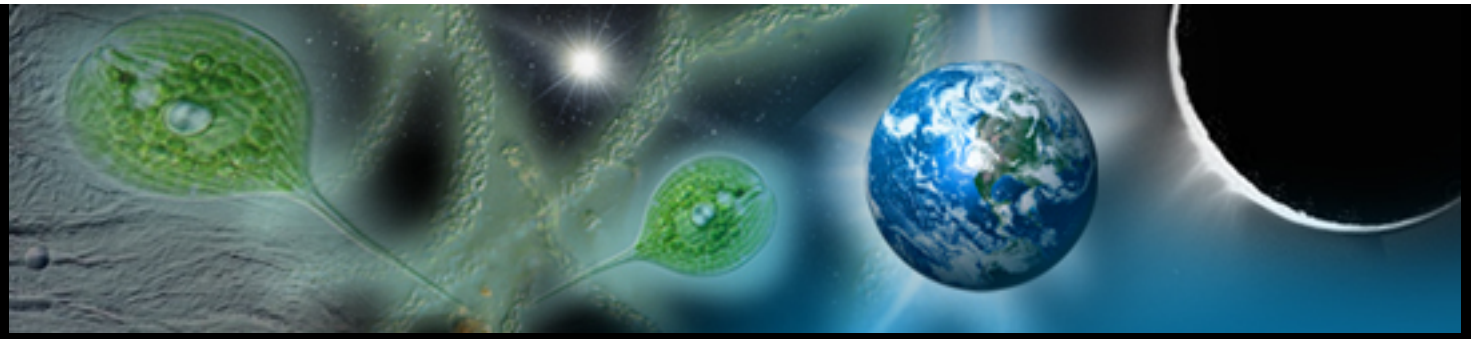
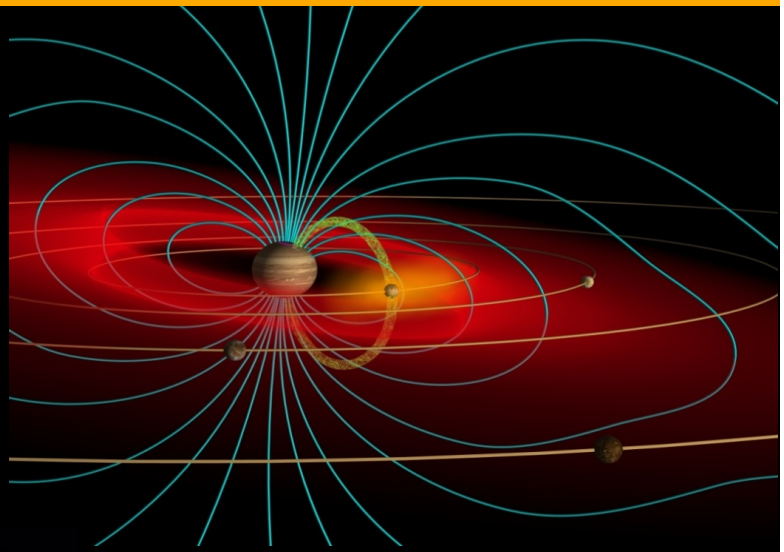


Habitability potential of icy moons around Jupiter and Saturn

Athena Coustenis

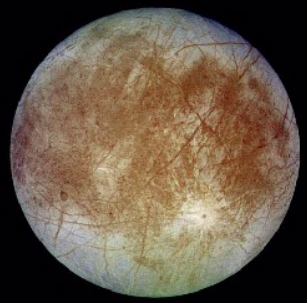
LESIA, Paris-Meudon Observatory, France

Organics, deep oceans within the giant icy moons and more: implications for the habitability of the Outer Solar System



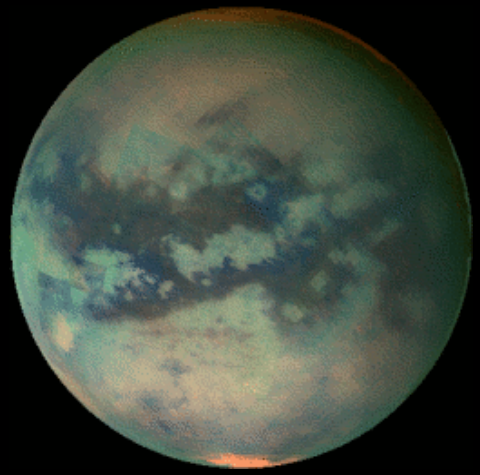
Context

- *What is habitability*
- *Previous missions to the OP*



Jovian system

- *Ganymede and Europa*
- *JUICE*

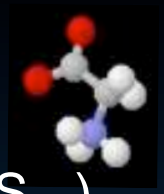


Saturnian system

- *Titan and Enceladus*
- *Cassini and the future*

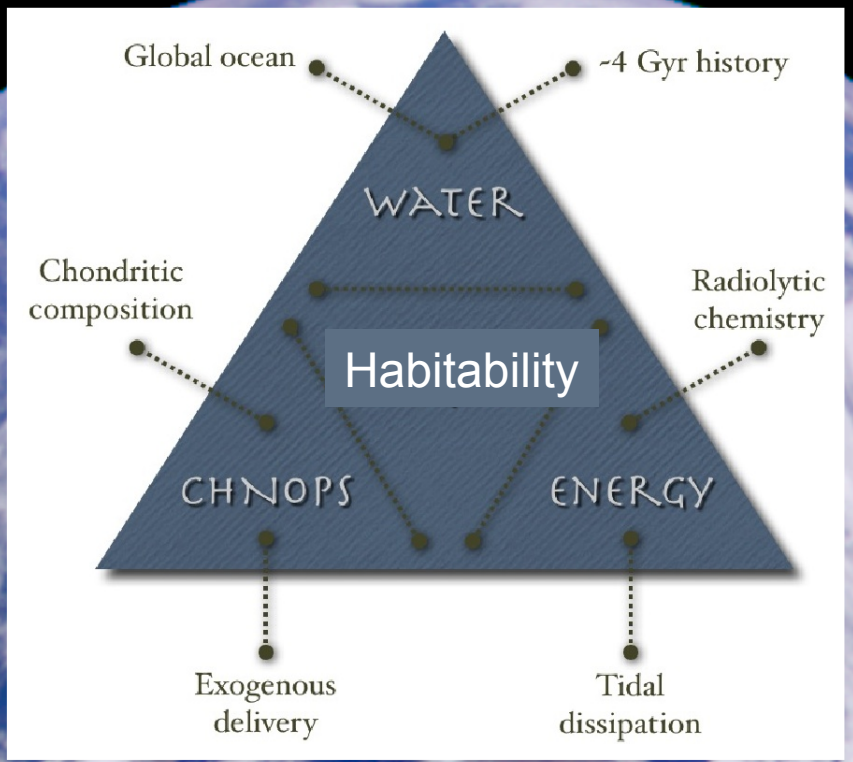
Habitability: four requirements

water 

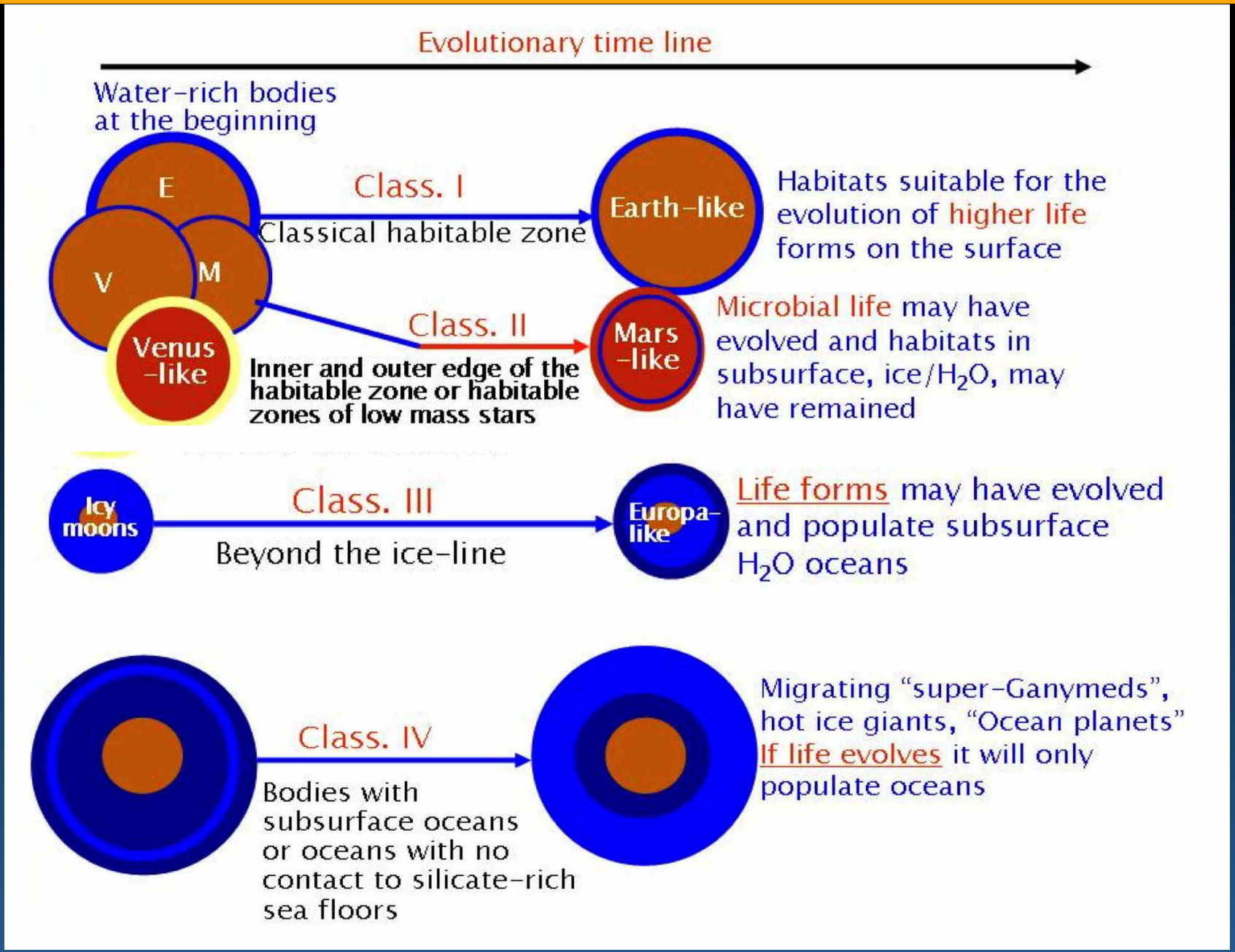
essential elements (CHNOPS...) 

chemical energy 

stable environment 

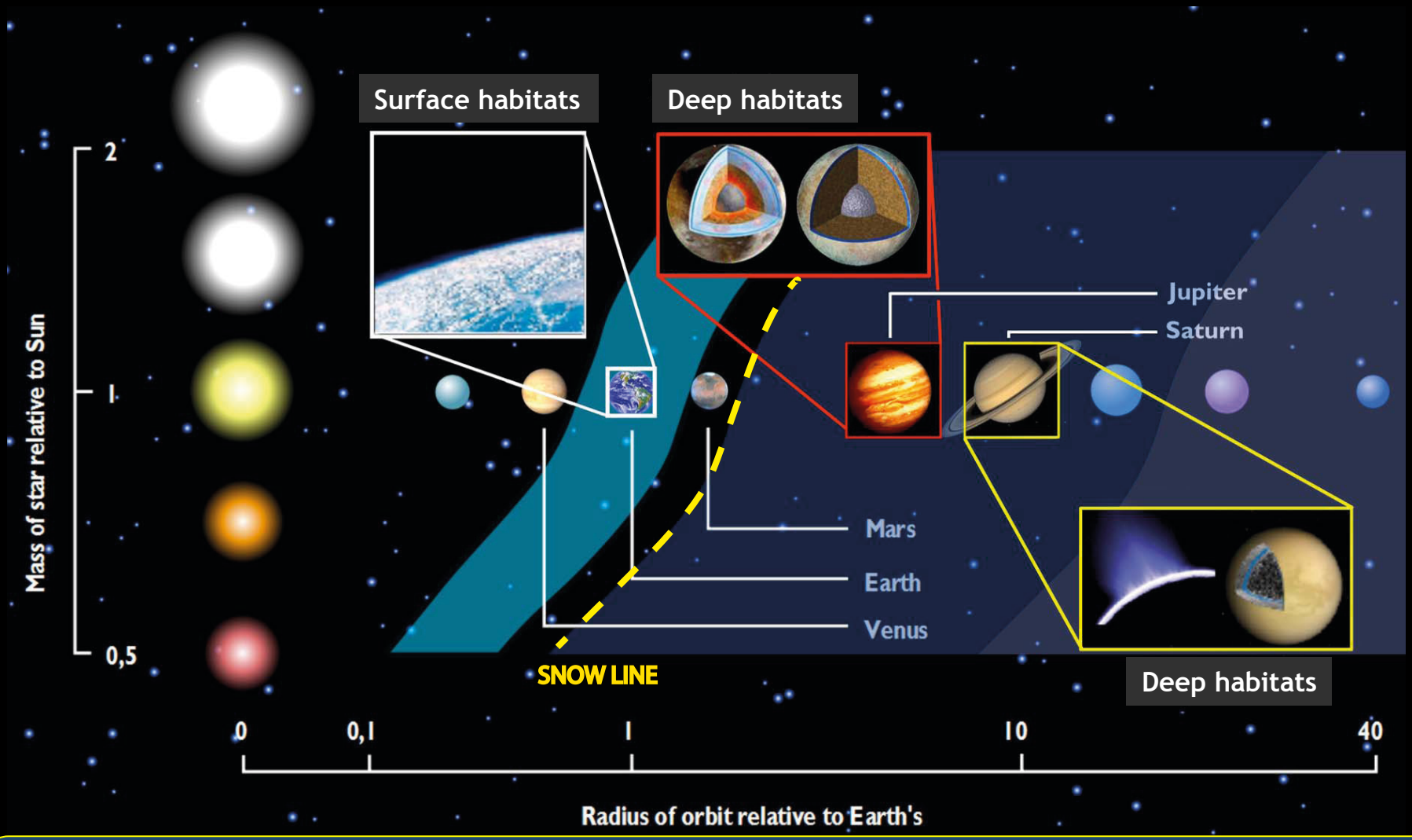


What are the habitable worlds?



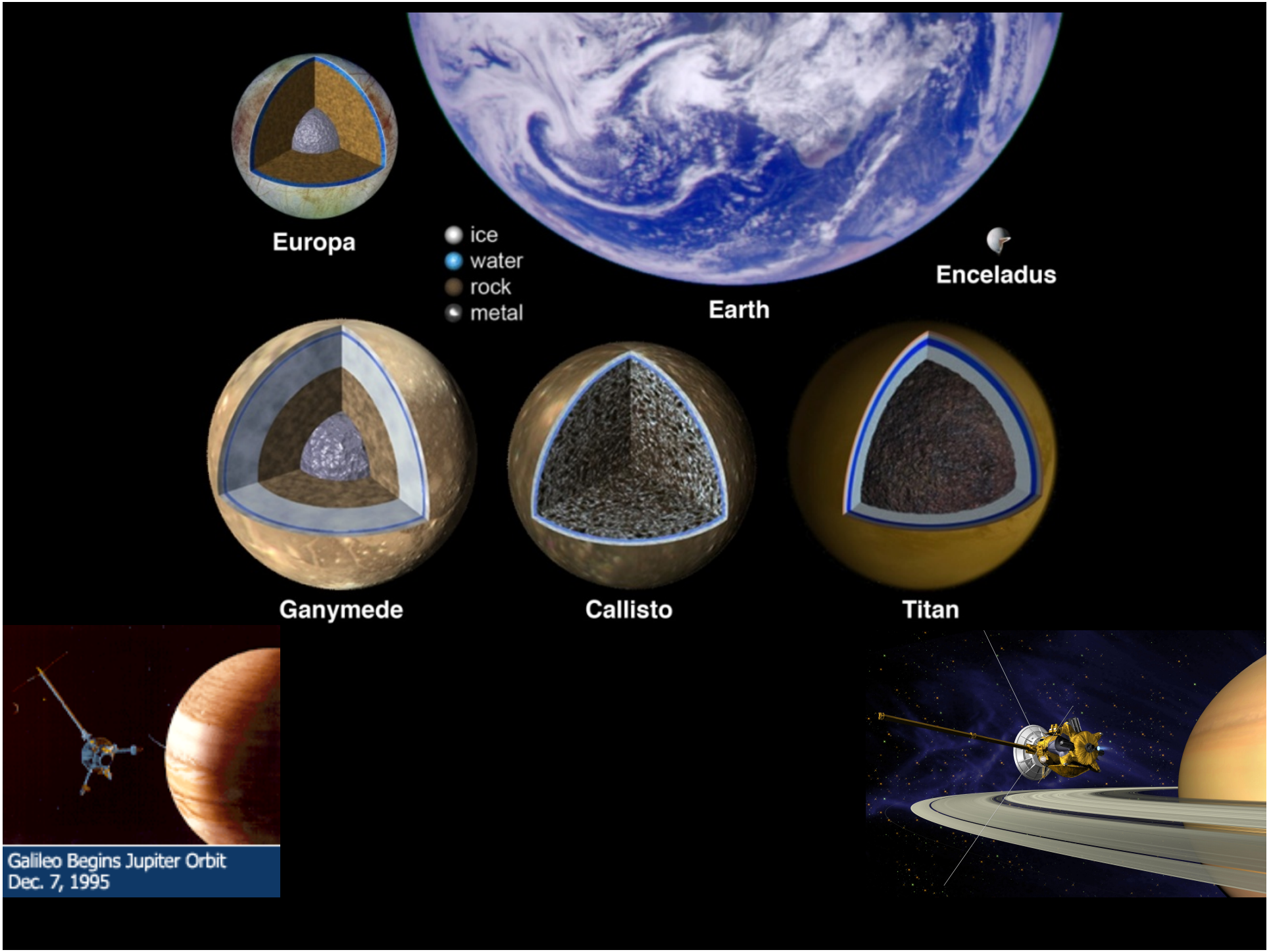
Lammer et al., 2009

Icy moons : deep habitats in the solar system



Classes I-II: habitable zones on the surface, not much water, small domain
Beyond the snow-line: deep habitats within the hydrospheres. Icy moons, Ganymede and Europa and Titan and Enceladus, are the archetypes of classes III-IV of habitable worlds

Characteristic	Ganymede	Titan	Enceladus	Triton	Pluto
R_{planet}	14.99 R_J	20.25 R_S	3.95 R_S	14.33 R_N	[39.53 AU]
M [10^{22} kg]	14.82	13.5	0.011	2.14	1.31
R_e [km]	2631	2575	252	1352	1150
ρ [kg/m^3]	1936	1880	1608	2064	2030
g [m/s^2]	1.43	1.35	0.12	0.78	0.4
T_O [days]	--	--	--	--	[248.5 yr]
T_S [days]	7.16	15.95	1.37	5.877	[6.38]
i [deg]	0.18	0.33	0.02	157	17.14
e	0.001	0.029	0.005	0.000	0.25
A	0.4	0.2	1.4	0.4	0.52
v_e [km/s]	2.75	2.64	0.235 (< v_T !)	1.50	1.1
Surface T [K] P	110 X	94 1.5 bar	114-157	38 16 μb	40 58 μb (var)
Atmosphere	O_3, *(H_2O_2-i)*	N_2, CH_4	H_2O, N_2, CH_4, CO_2, CO	N_2, CH_4	N_2, CH_4, *(H_2O-i)*


Europa
ice
water
rock
metal
Earth
Enceladus
Ganymede
Callisto
Titan
Galileo Begins Jupiter Orbit
Dec. 7, 1995

Some interesting considerations for astrobiology

Astrobiological aspects: **organic chemistry, liquid water (on the surface or in the interior), sources of energy (internal activity), stability**

Icy moons with
- organic chemistry : Titan, Enceladus, Triton
- with subsurface liquid water oceans (TBC): Europa, Ganymede, Callisto, Enceladus, Titan…
- evident (cryovolcanic or tectonic) activity (Enceladus, Triton, Io, Titan?)

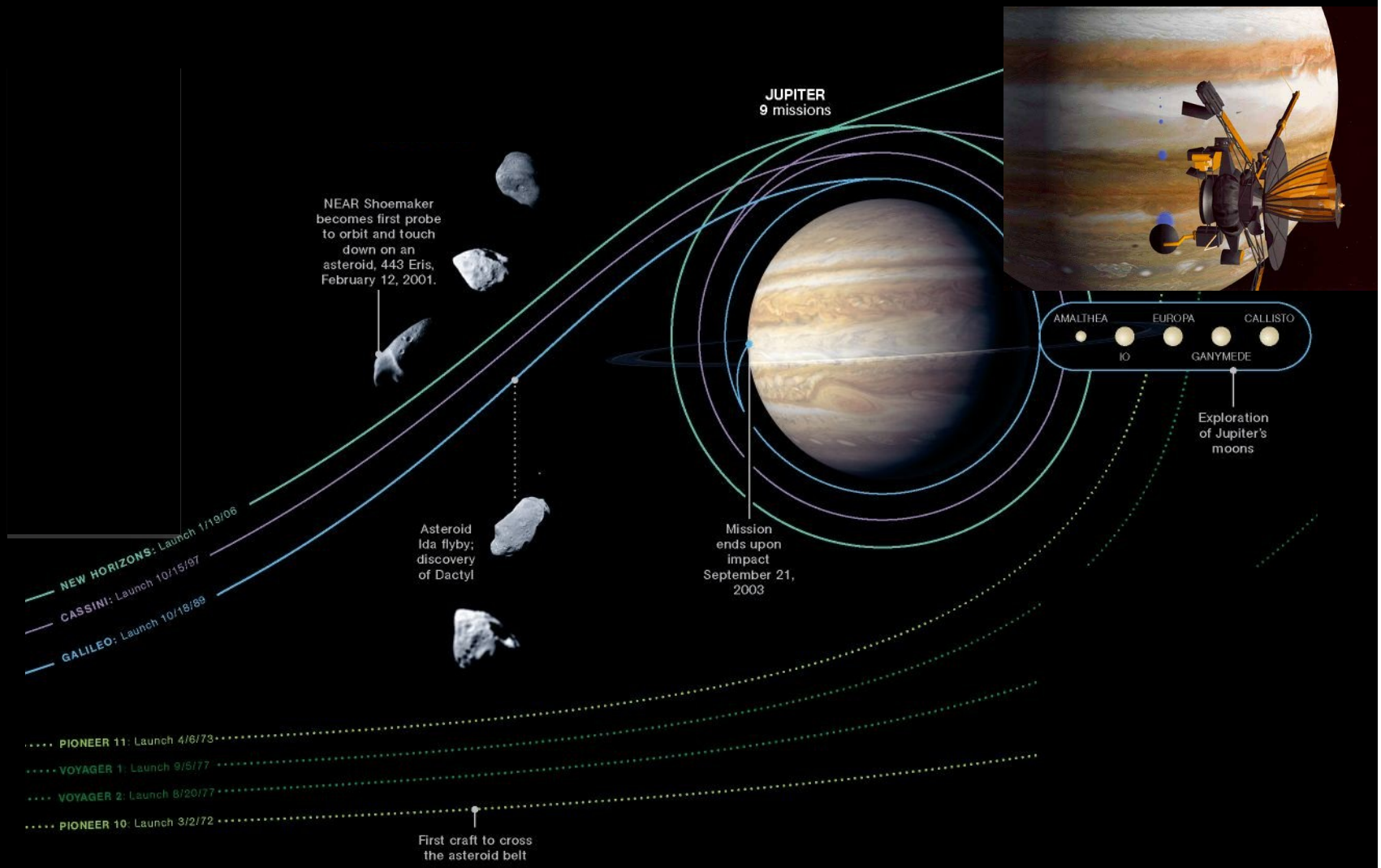
With the exception of Titan the icy moons with possible subsurface oceans and/or activity reside in giant planet magnetospheres, Enceladus and Triton, are ***not*** in the giant planet magnetosphere section with the most extreme surface irradiation harmful to organics.

What is the astrobiological potential of these objects?

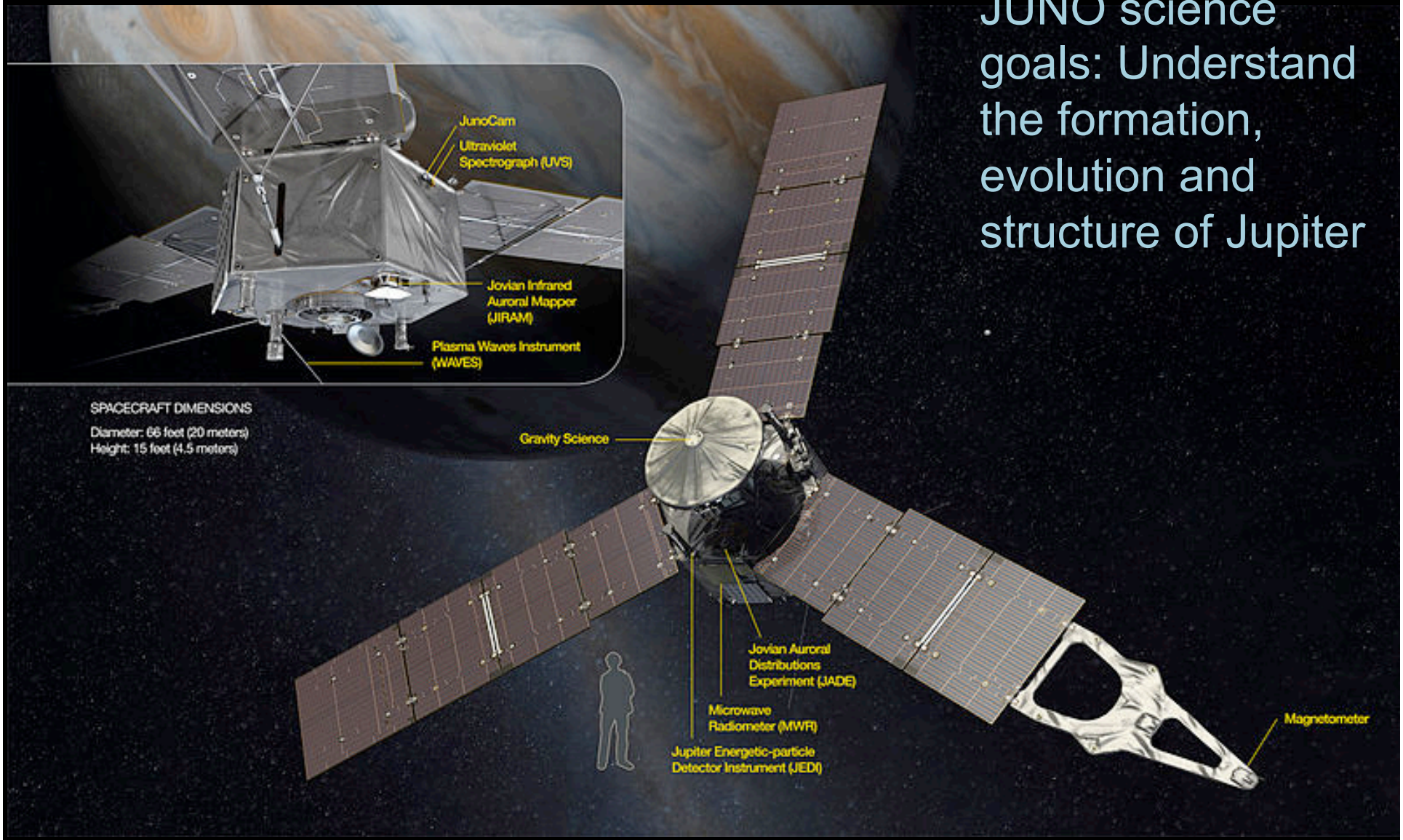
Jupiter’s satellites

Previous missions

A few flybys and an orbiter (Galileo)



Present mission (cruise phase) - JUNO



JUNO science goals: Understand the formation, evolution and structure of Jupiter

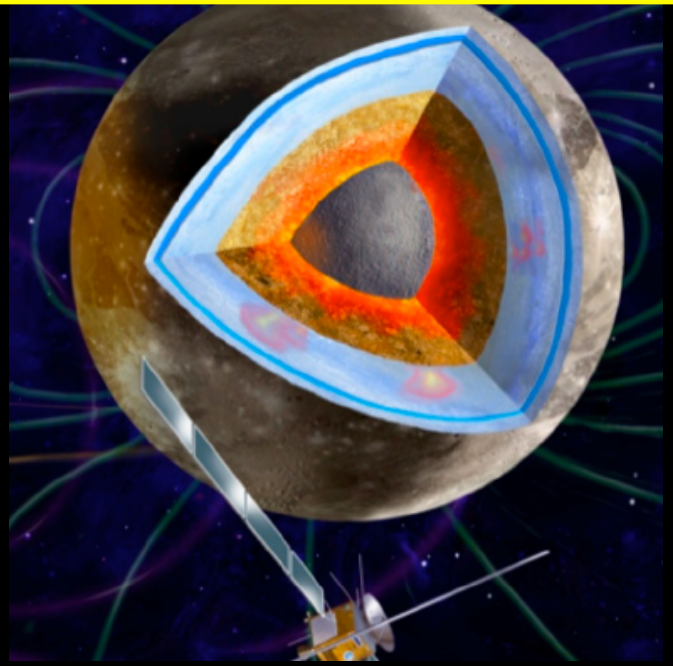
The habitable zone around Jupiter

Three large icy moons

Ganymede – class IV

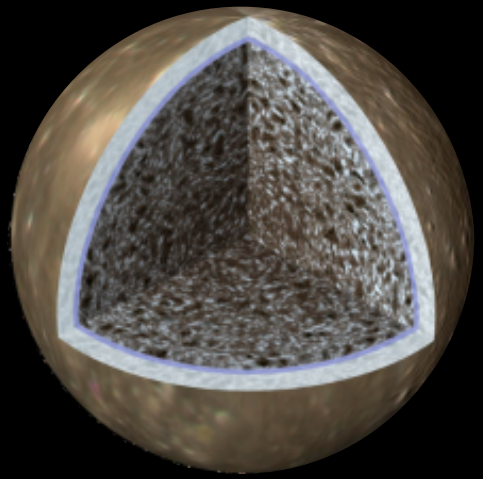
- Largest satellite in the solar system
- A deep ocean
- Internal dynamo and an induced magnetic field – unique
- Richest crater morphologies

- Archetype of waterworlds
- Best example of liquid environment trapped between icy layers



Callisto – class IV

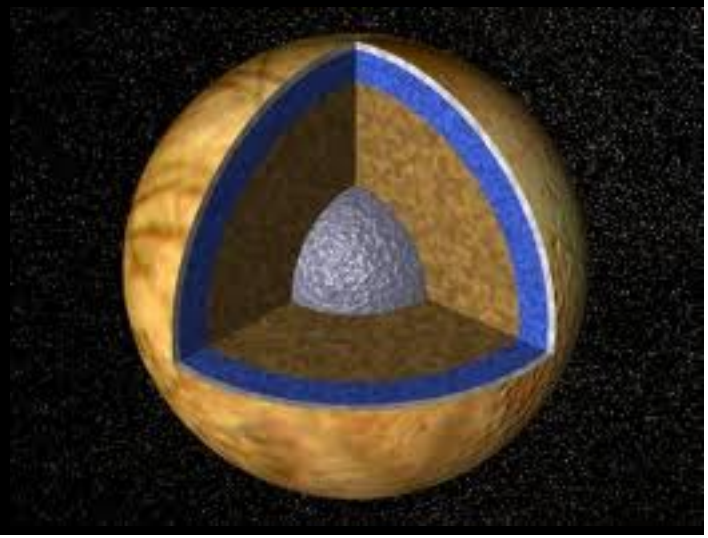
- Best place to study the impactor history
- Differentiation – still an enigma
- Only known example of non active but ocean-bearing world
- The witness of early ages



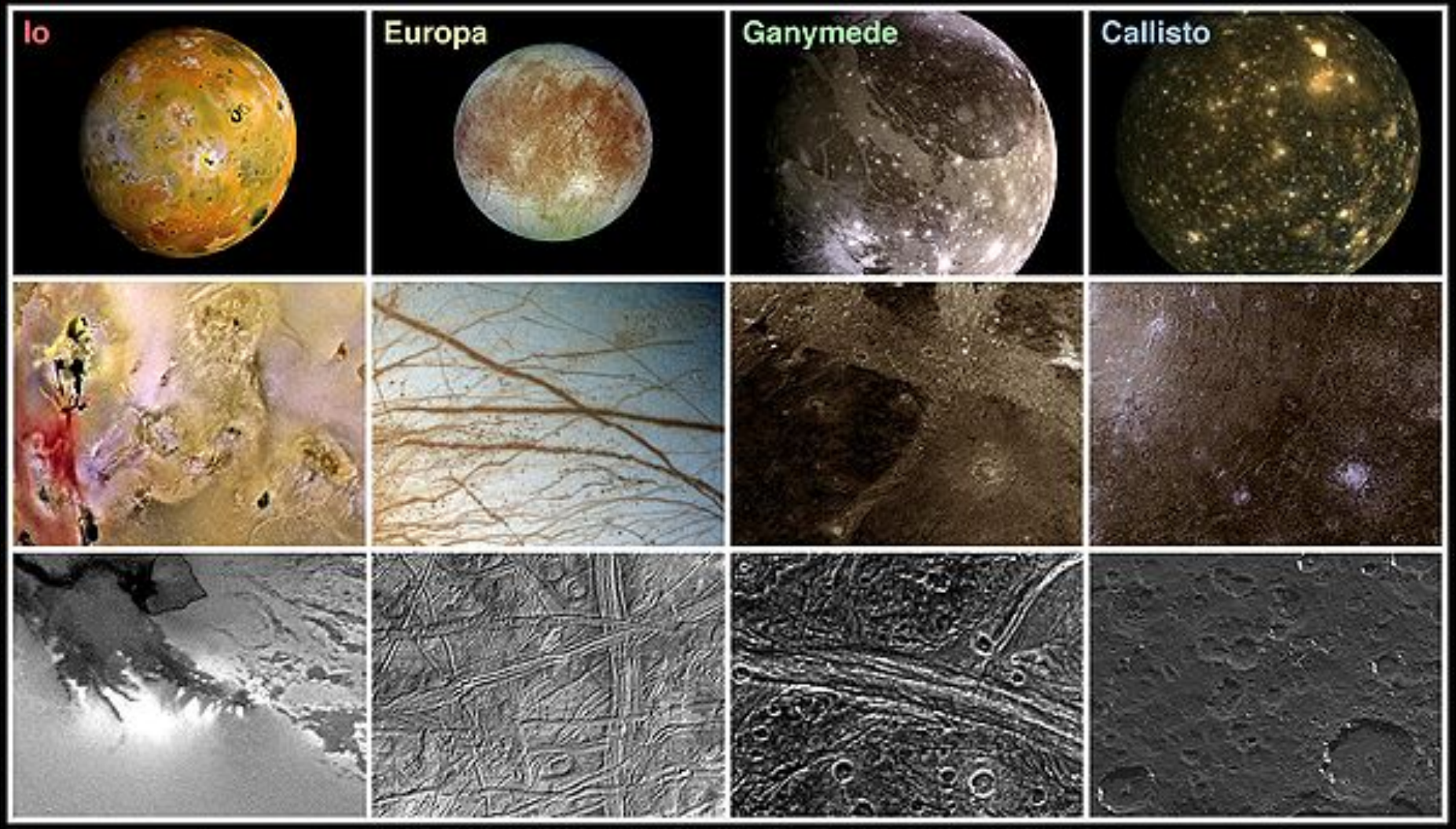
Europa – class III

- A deep ocean
- An active world?

- Best example of liquid environment in contact with silicates



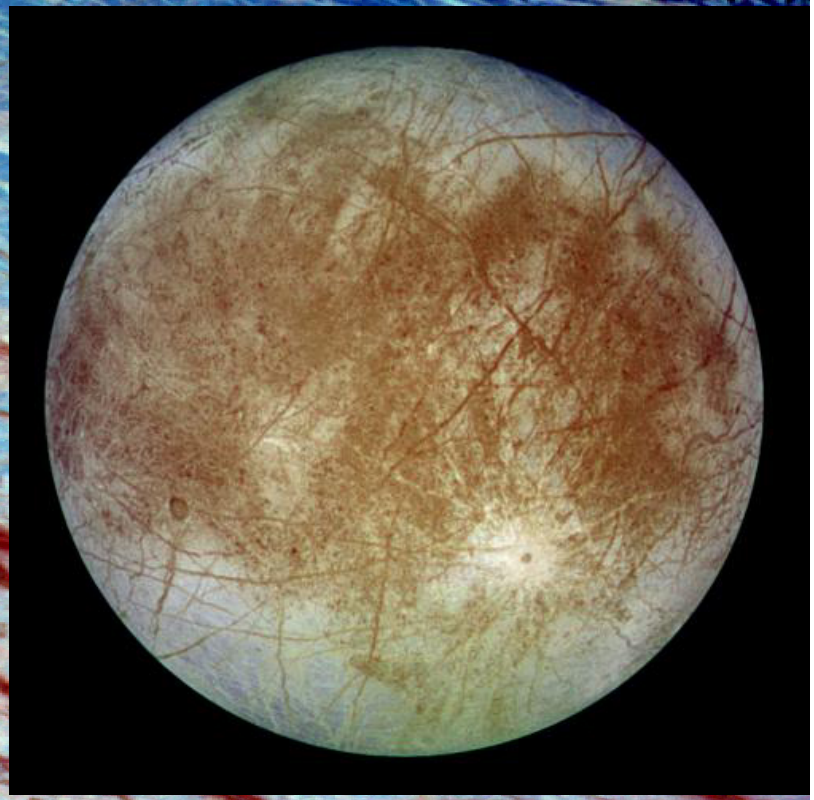
← To Jupiter



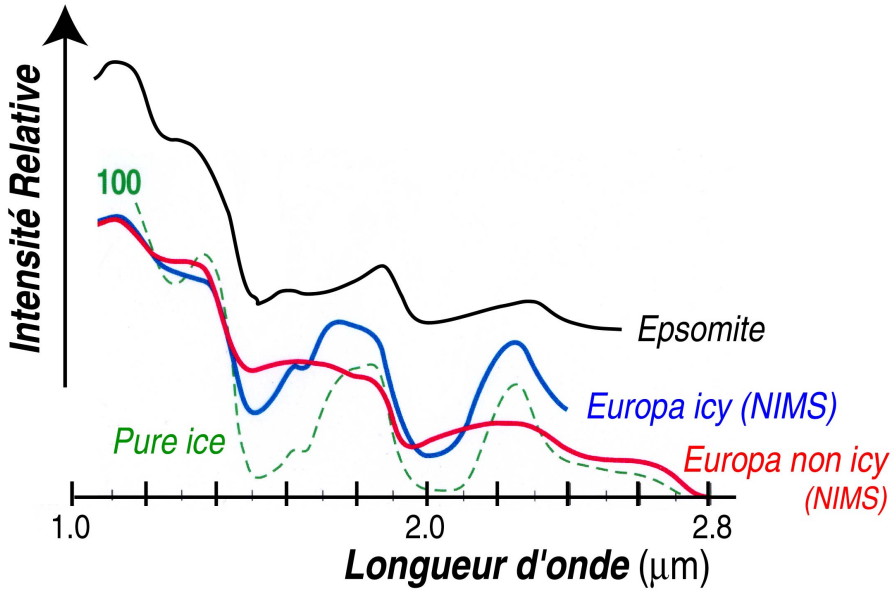
The closer a moon is to Jupiter, the hotter its interior and better chance of differentiation, while the surface is subject to dynamic movements

About the existence of deep liquid layers

Hyperspectral evidences on Europa



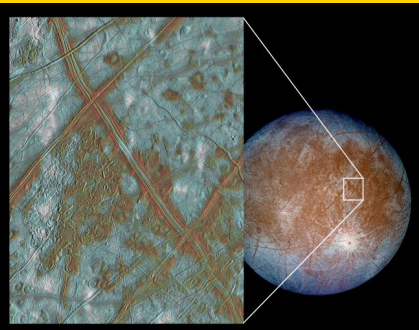
Composition of ices

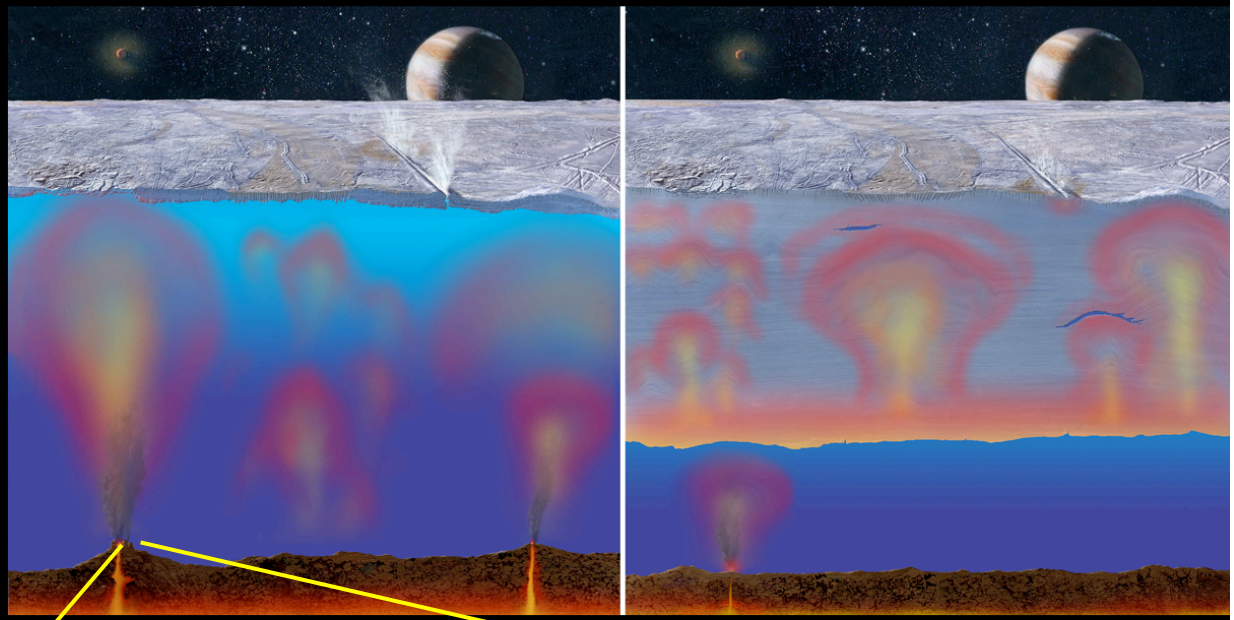


from McCord et al. (1999)

What are the habitable worlds in the outer solar system ?

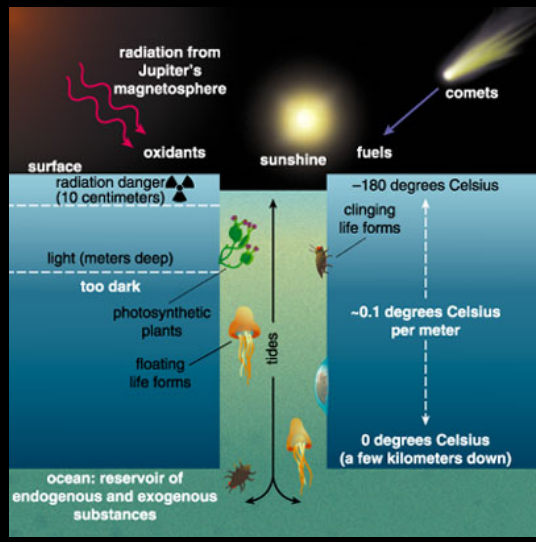
Class III : subsurface oceans in contact with silicates - Europa





Europa-like

- 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 ⇒ oxidants.
  - Mantle contact: serpentinization and possible hydrothermal activity
- Relatively stable environment:
  - Large satellite retains heat.
  - But activity might not be steady-state.

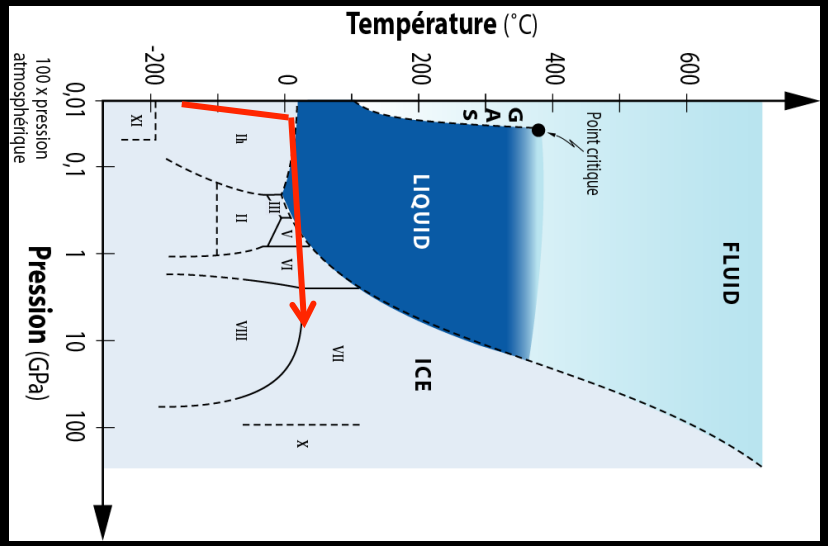


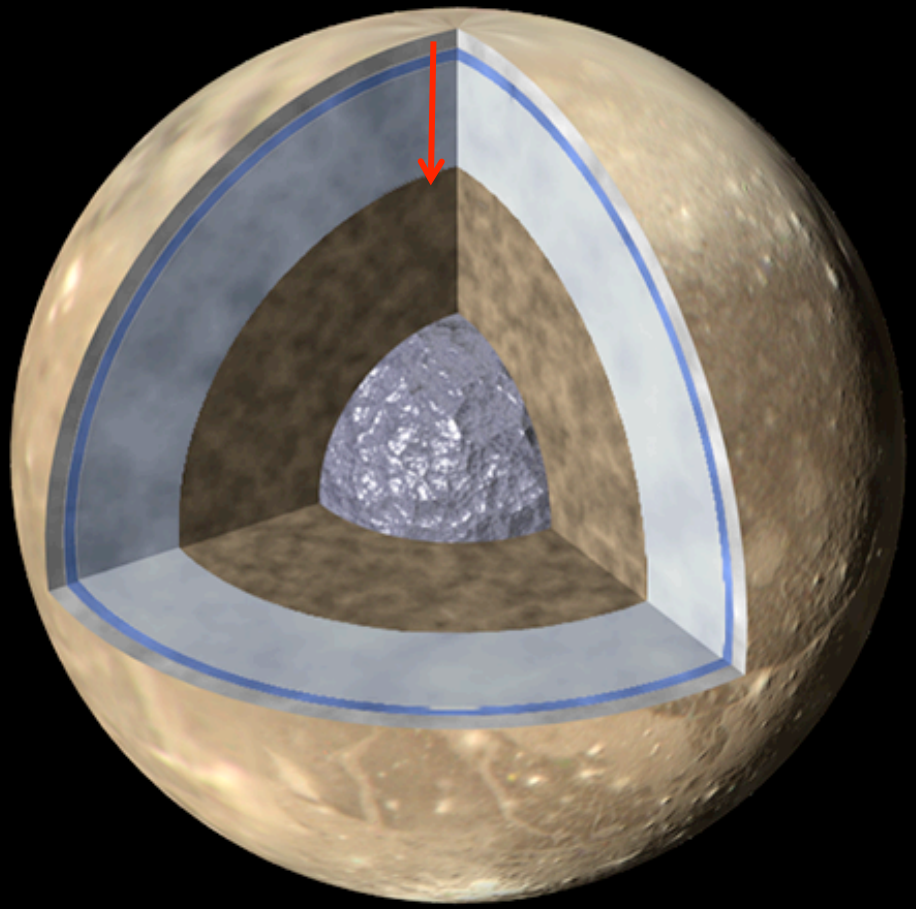
What are the habitable worlds?

Class IV : subsurface oceans without any contact with the silicates

Ganymede-like

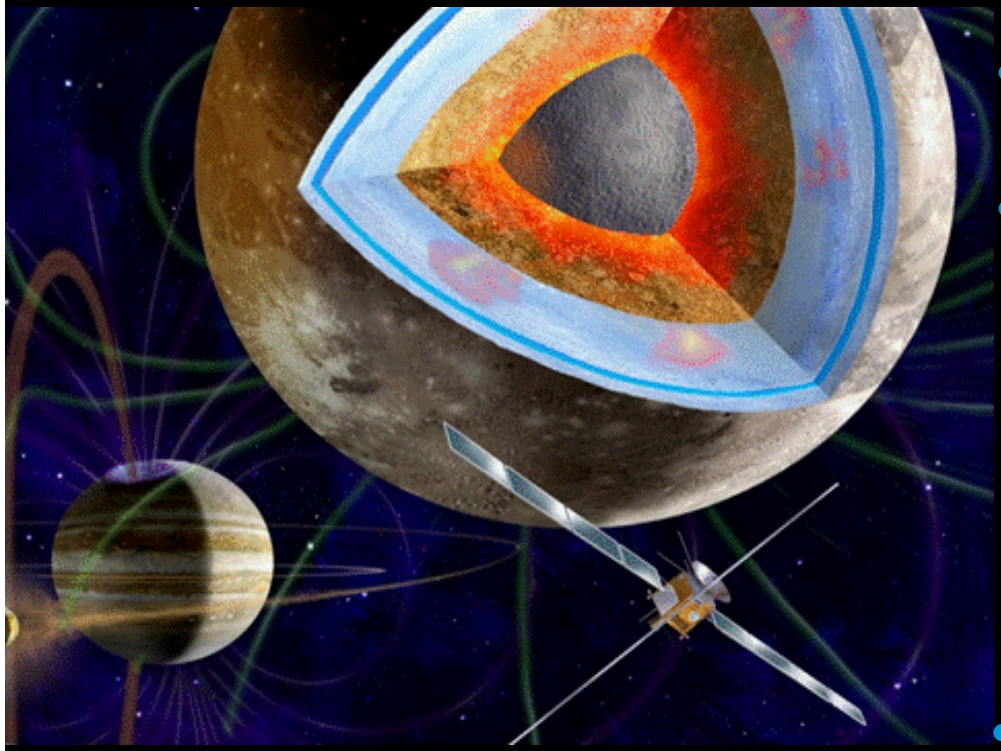
- Liquid water
- Chemistry: silicate needed…?
- Energy: heat transfer ?
- Stable environment





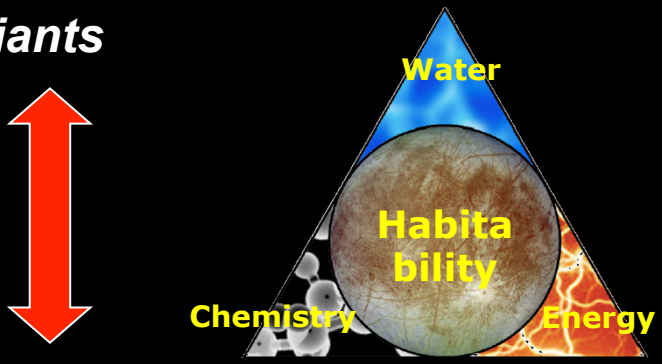
H2O Well-known since 1912 (Bridgman)
Modern experiments (for planetology) devoted to complex mixtures.

JUICE: JUpiter Icy moons Explorer



JUICE Science Goals

- *Emergence of habitable worlds around gas giants*
- *Jupiter system as an archetype for gas giants*



Cosmic Vision Themes

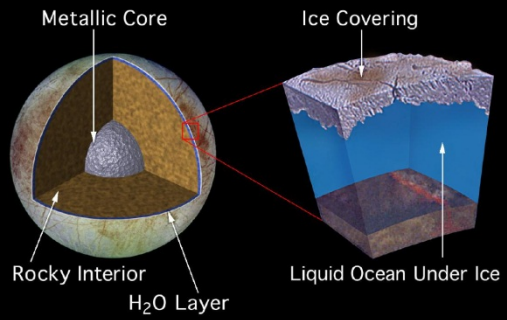
- *What are the conditions for planetary formation and emergence of life?*
- *How does the Solar System work?*

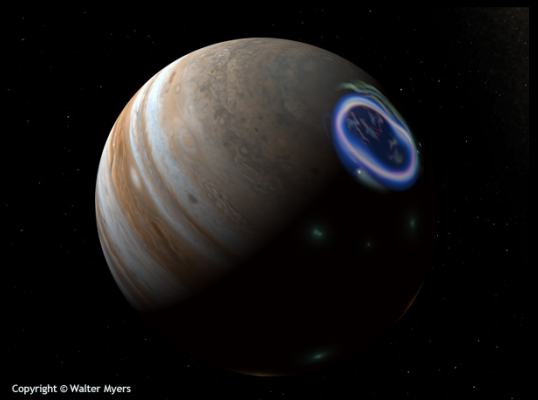
JUICE : the 1st Large CV mission concept

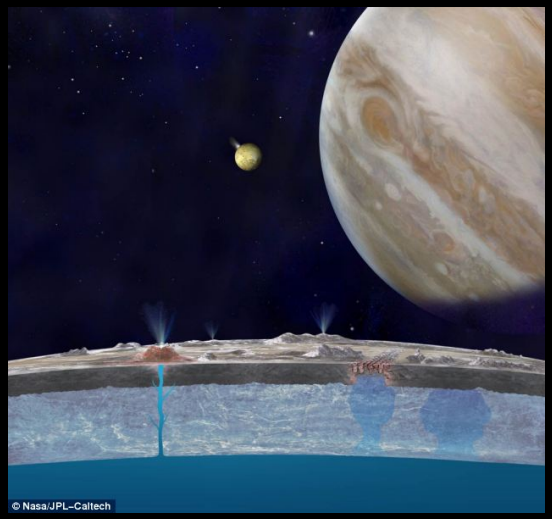
- *Single spacecraft mission to the Jovian system*
- *Investigations from orbit and flyby trajectories*
- *Synergistic and multi-disciplinary payload*
- *European mission with international participation*

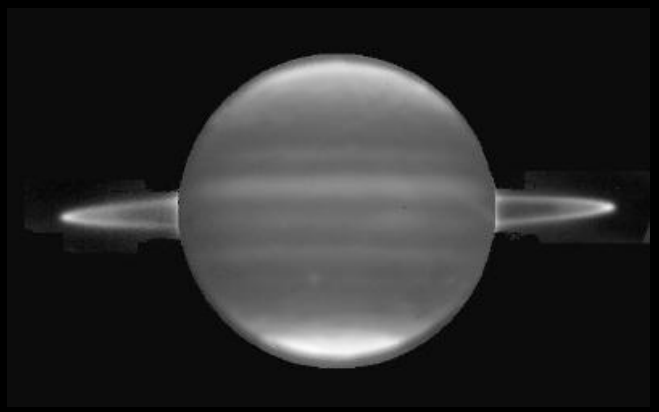
Topics:
Planet, moons, rings, magneto

- Interior
- Subsurface
- Geology
- Atmosphere
- Plasma
- Habitability
- Link to exoplanets





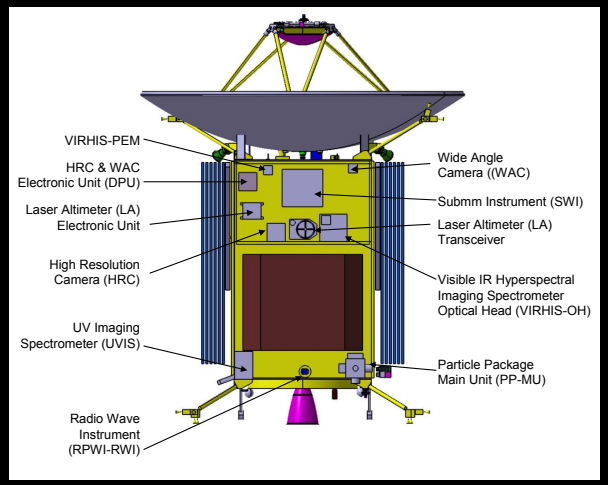


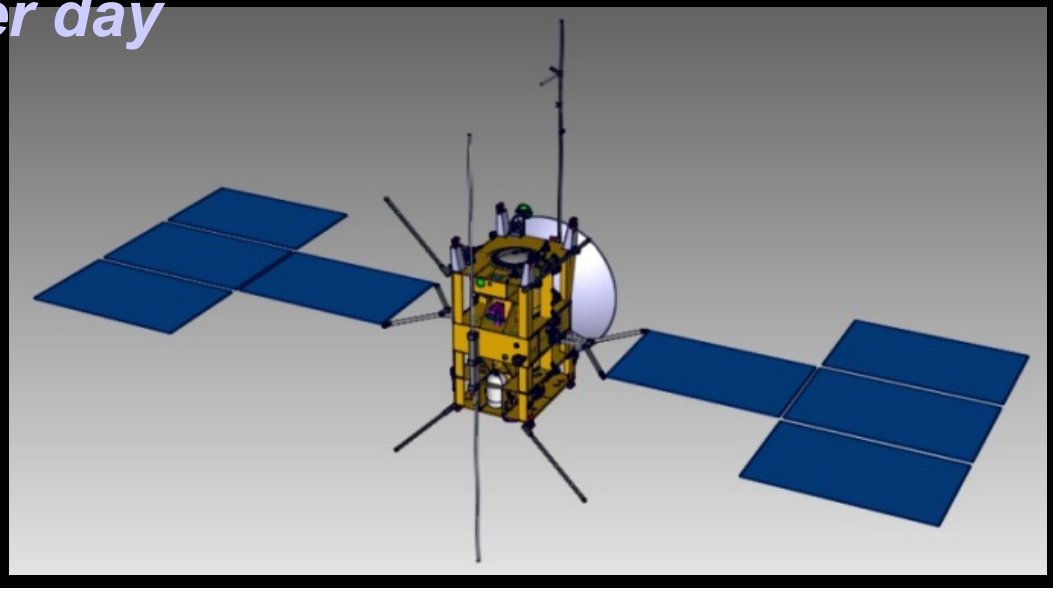


Jupiter system: largest planet, largest storm, fastest rotation, largest magnetic field, largest moon, largest moon system, most active moons

Main features of the spacecraft design

- *Dry mass ~2000 kg, propellant mass ~3000 kg*
- *Launcher - Ariane 5 ECA (mass : 5-5.5 tons), High Δv required: 2600 m/s*
- *Payload ~110 kg, ~ 150 W*
- *3-axis stabilized s/c*
- *Power: solar array ~ 100 m², ~ 800 W*
- *HGA: ~3 m, fixed to body, X & Ka-band*
- *Data return >1.4 Gb per day*





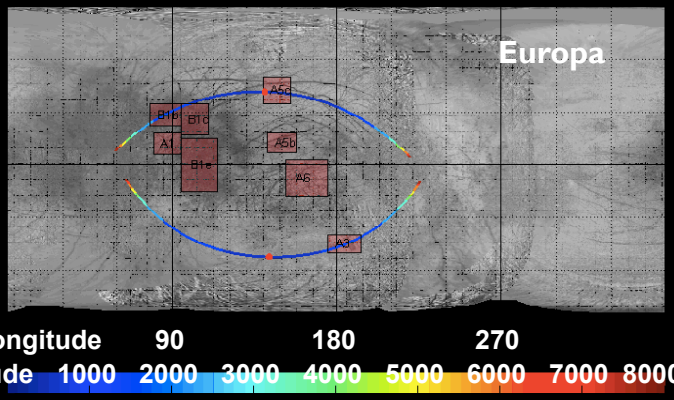
JUICE Payload

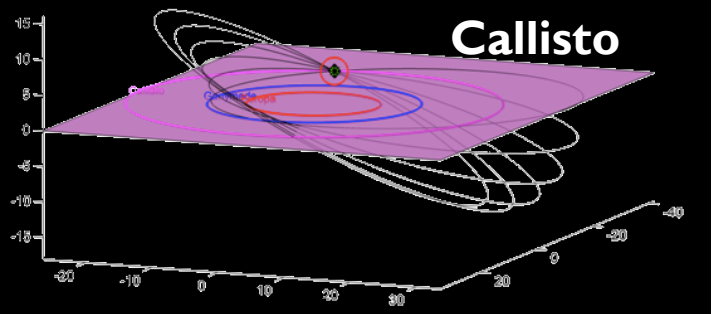
Acronym	PI	LFA	Instrument type
Remote Sensing Suite			
JANUS	P. Palumbo	Italy	Narrow Angle Camera
MAJIS	Y. Langevin G. Piccioni	France Italy	Vis-near-IR imaging spectrometer
UVS	R. Gladstone	USA	UV spectrograph
SWI	P. Hartogh	Germany	Sub-mm wave instrument
Geophysical Experiments			
GALA	H. Hussmann	Germany	Laser Altimeter
RIME	L. Bruzzone	Italy	Ice Penetrating Radar
3GM	L. Iess	Italy	Radio science experiment
PRIDE	L. Gurvits	Netherlands	VLBI experiment
Particles and Fields Investigations			
PEP	S. Barabash	Sweden	Plasma Environmental Package
RPWI	J.-E. Wahlund	Sweden	Radio & plasma Wave Instrument
J-MAG	M. Dougherty	UK	Magnetometer

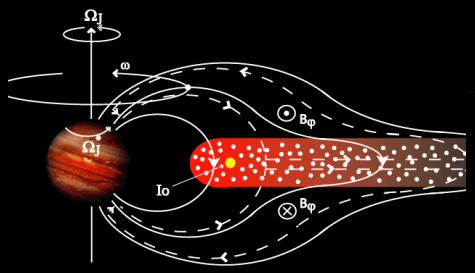
Mission design

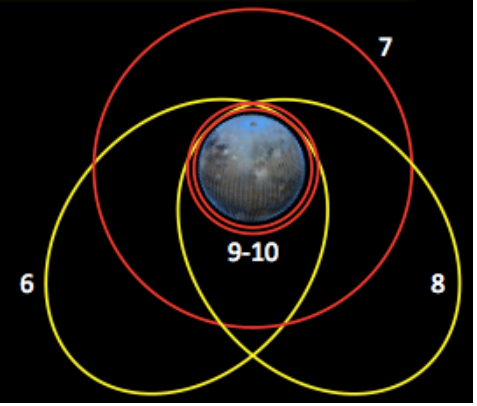
JUICE

Spacecraft Design	Model instruments	Mission phases
Launch	June 2022	
Interplanetary transfer (Earth-Venus-Earth-Earth)	7.6 years (8 years)	
Jupiter orbit insertion and apocentre reduction with Ganymede gravity assists	11 months	
2 Europa flybys	36 days	
Reduction of v_{inf} (Ganymede, Callisto)	60 days	
Increase inclination with 10 Callisto gravity assists	200 days	
Callisto to Ganymede	11 months	
Ganymede (polar) 10,000x200 km & 5000 km 500 km circular 200 km circular	 150 days 102 days 30 days	
Total mission at Jupiter	3 years	



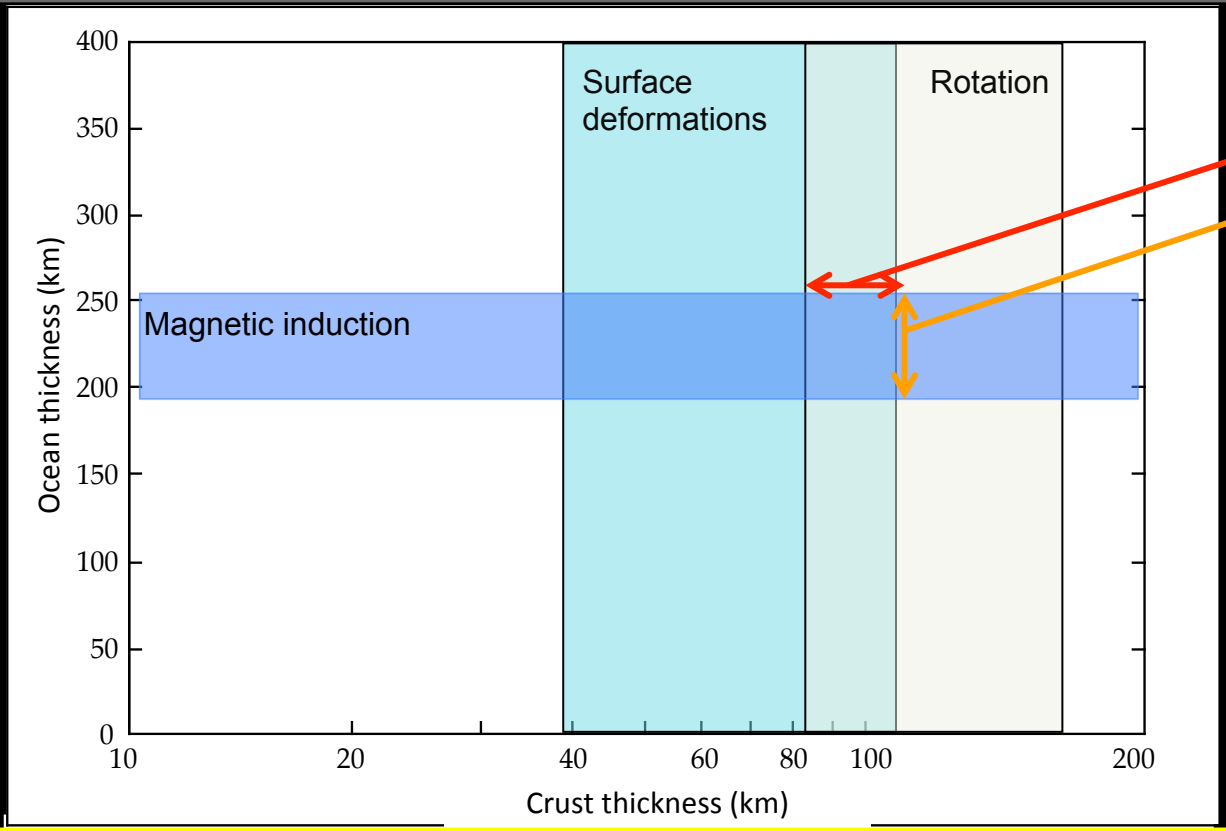




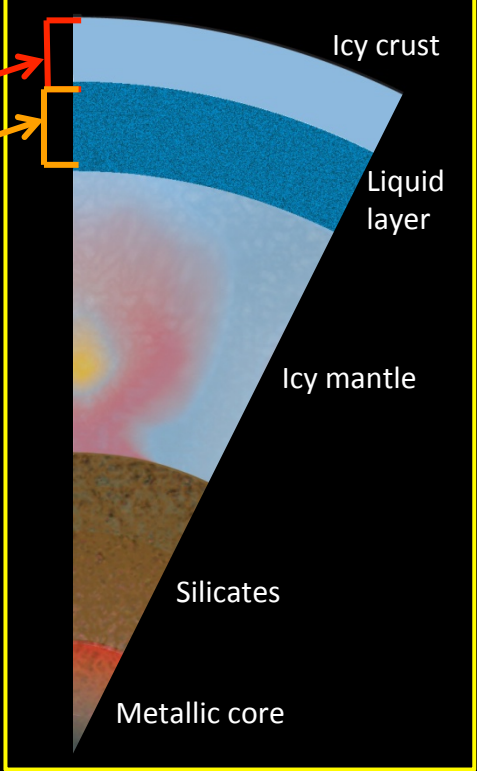


Characterise Ganymede as a planetary object and possible habitat

1. Extent of the ocean and its relation to the deeper interior



Internal structure



JUICE measurements

- Surface deformations
- Periodic variations in the rotation (librations)
- Magnetic induction from the field vector

Instrument Packages

- In situ Fields and Particles
- Imaging
- Sounders and Radio Science

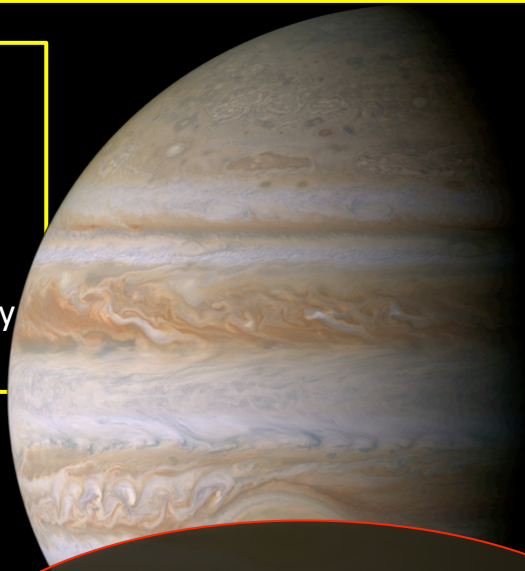
Exploration of the Jupiter system

JUICE

The biggest planet, the biggest magnetosphere, and a mini solar system

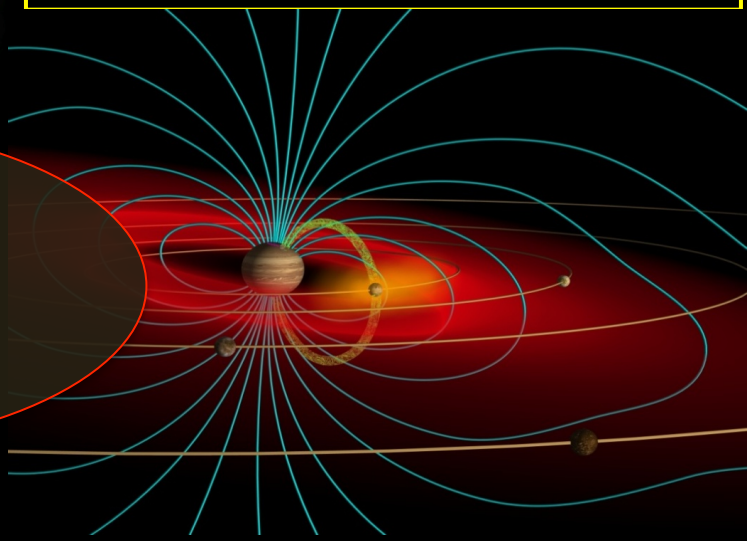
Jupiter

- Archetype for giant planets
- Natural planetary-scale laboratory for fundamental fluid dynamics, chemistry, meteorology,...
- Window into the formational history of our planetary system



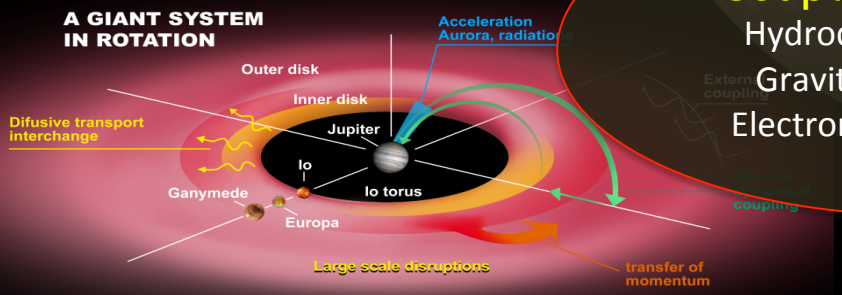
Magnetosphere

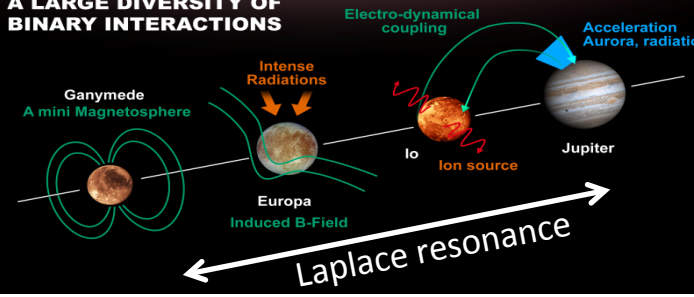
- Largest object in our Solar System
- Biggest particle accelerator in the Solar System
- Unveil global dynamics of an astrophysical object



Coupling processes

Hydrodynamic coupling
Gravitational coupling
Electromagnetic coupling





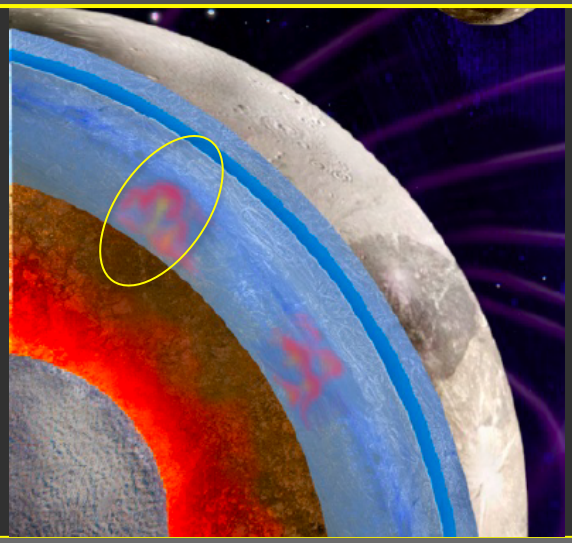
Satellite system

- Tidal forces: Laplace resonance
- Electromagnetic interactions to magnetosphere and upper atmosphere of Jupiter

From the Jupiter system to extrasolar planetary systems

Waterworlds and giant planets | Habitable worlds | Astrophysics Connection

Waterworlds: If habitable, the liquid layers are trapped between two icy layers

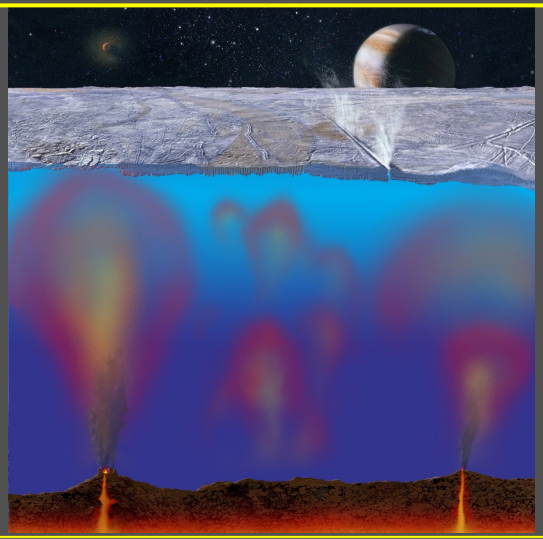


Occurrence:
Largest moons, hot ice giants, ocean-planets…
Most common habitat in the universe ?

Key question:
Are these waterworlds habitable ?

What JUICE will do:
Via characterisation of Ganymede, will constrain the likelihood of habitability in the universe

Europa-like: If habitable, the liquid layers may be in contact with silicates as on Earth



Occurrence:
Europa, Enceladus
Only possible for very small bodies

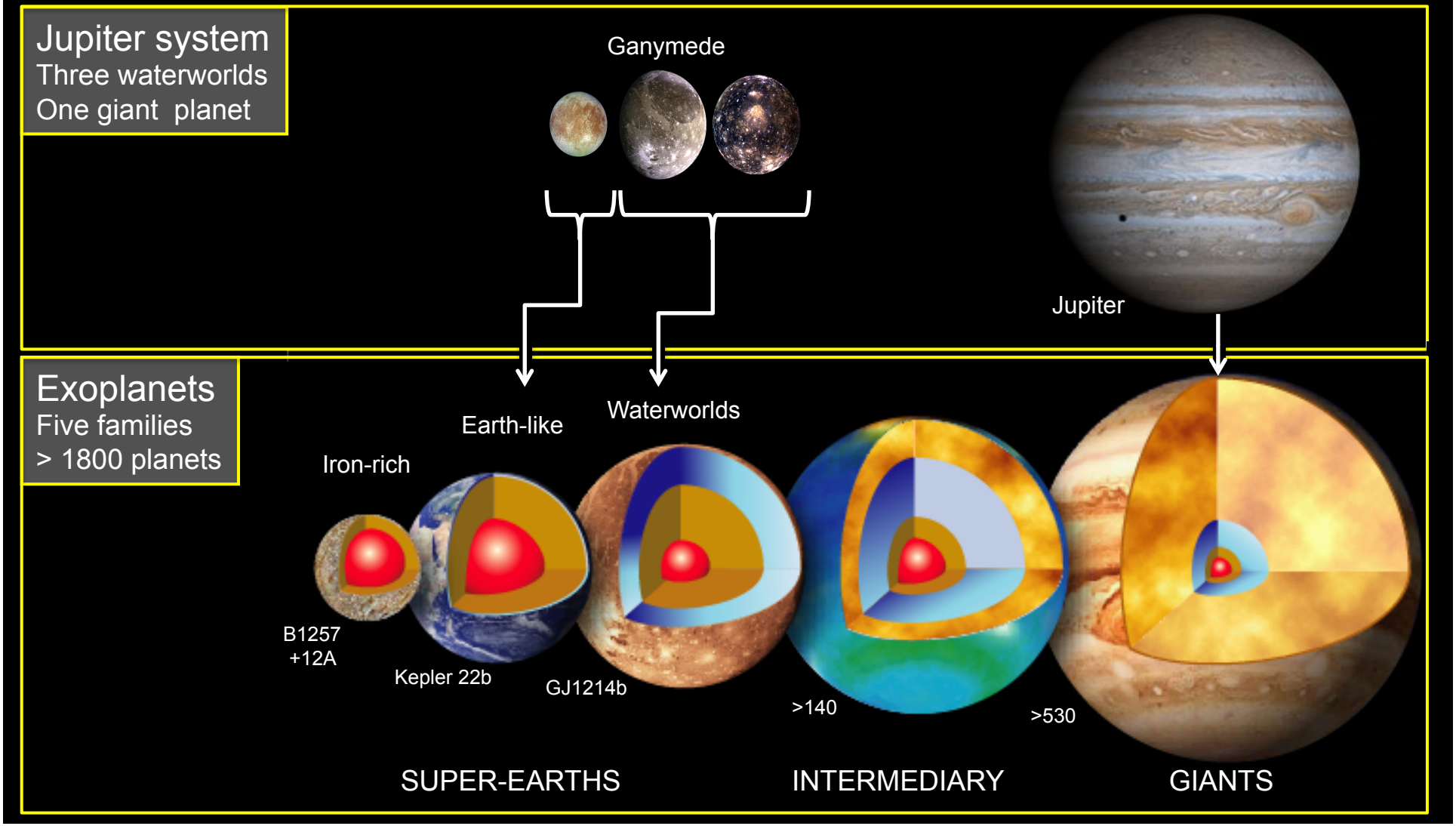
Key question:
How are the surface active areas related to potential deep habitats?

What JUICE will do:
Pave the way for future landing on Europa
Better understand the likelihood of deep local habitats

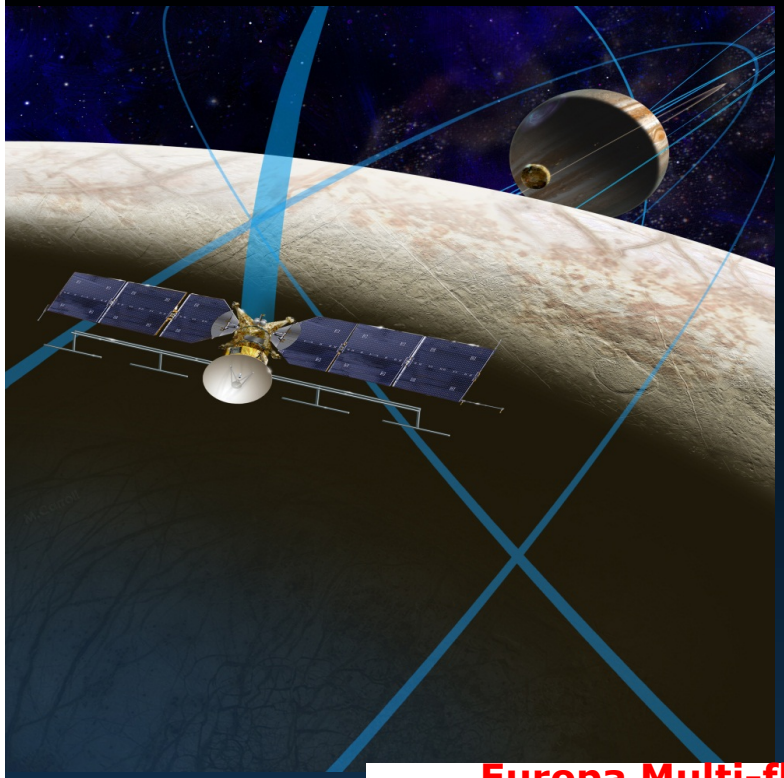
From the Jovian system to extrasolar planetary systems

Waterworlds and giant planets | Habitable worlds | Astrophysics Connection

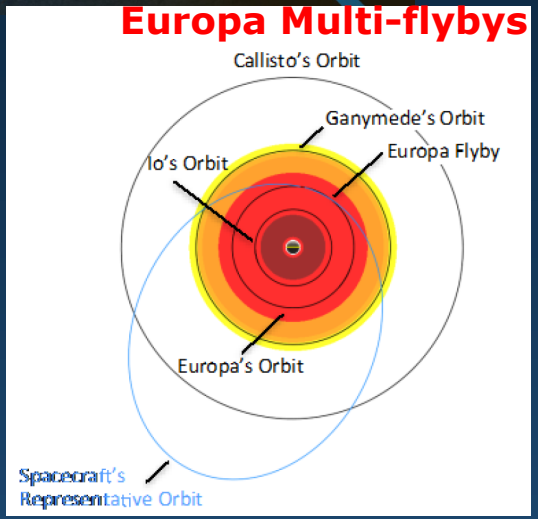
By studying Ganymede, we can characterise an entire family of exoplanets: the waterworlds.



NASA Europa "Clipper" mission



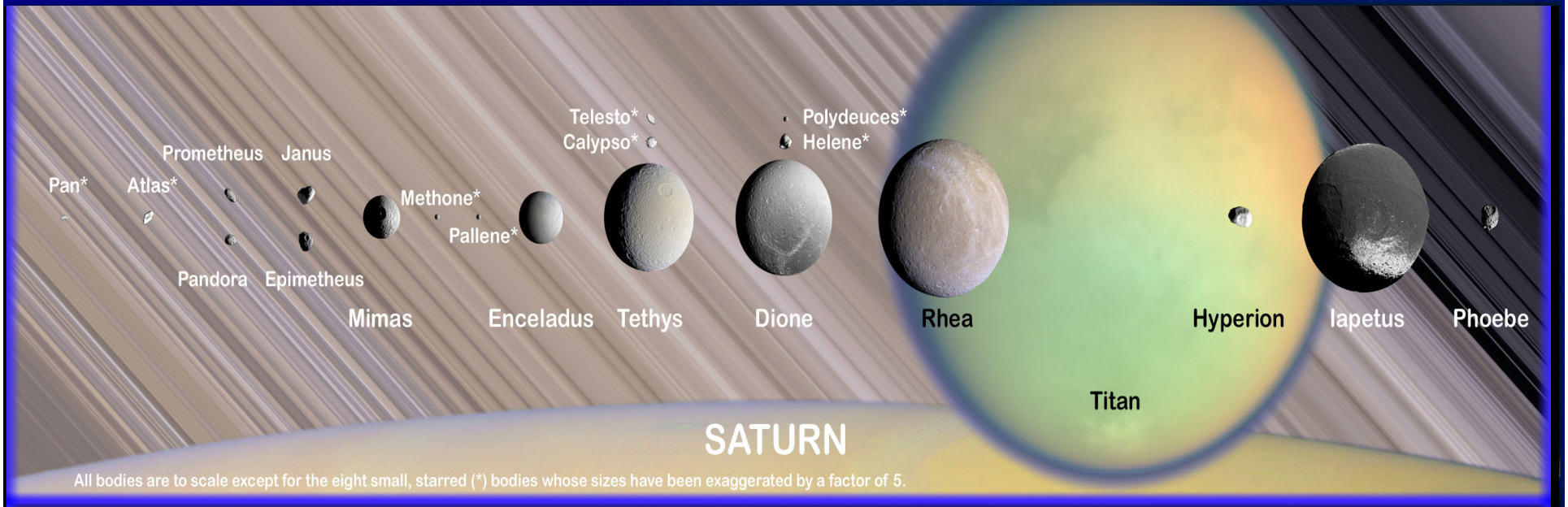
- Spacecraft in orbit around Jupiter
- Science goal: Europa's habitability
- Multiple (45) flybys of Europa
  - Altitudes: 25 – 2700 km
- 9 instruments selected: cameras, magnetometers, radar, dust analyser, spectrometers, plasma + mass spectrometer
- Schedule
  - Start formulation phase in Oct. 2016
  - Launch 2020-2025
  - Cruise: 2 or 7 years
  - Nominal mission: 3-4 years

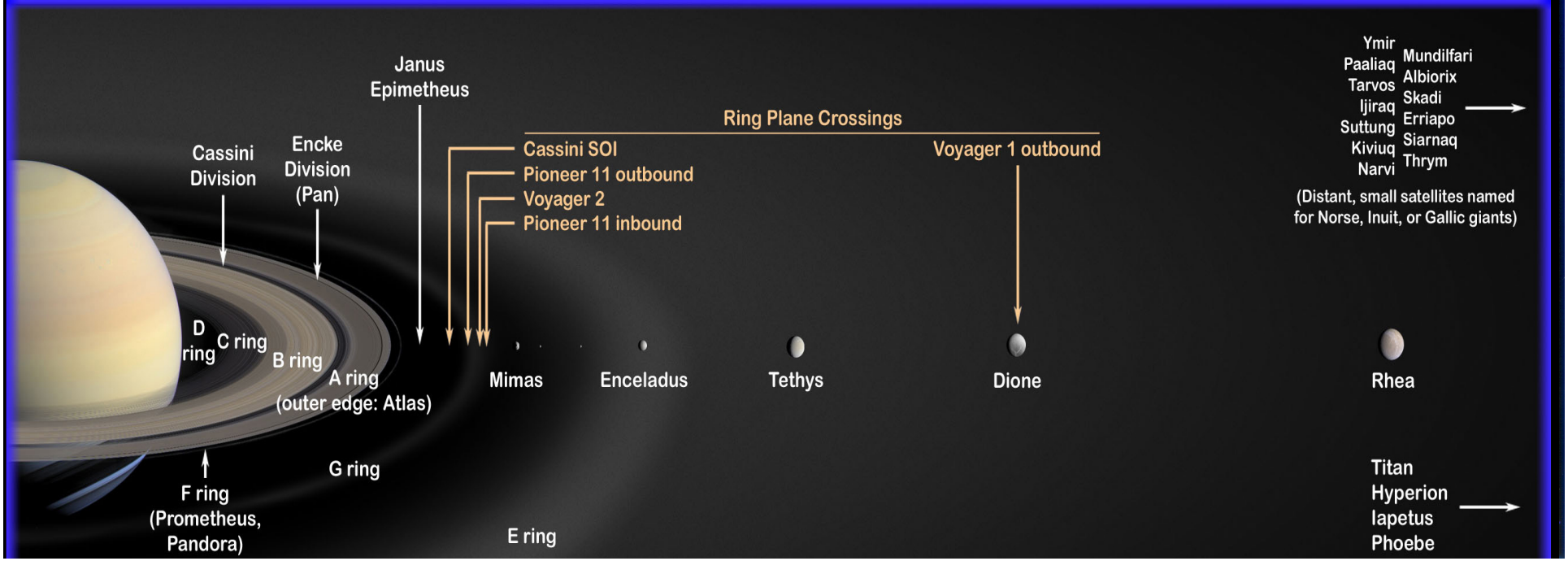


Possible extra probe, penetrator or lander provided by ESA is being considered

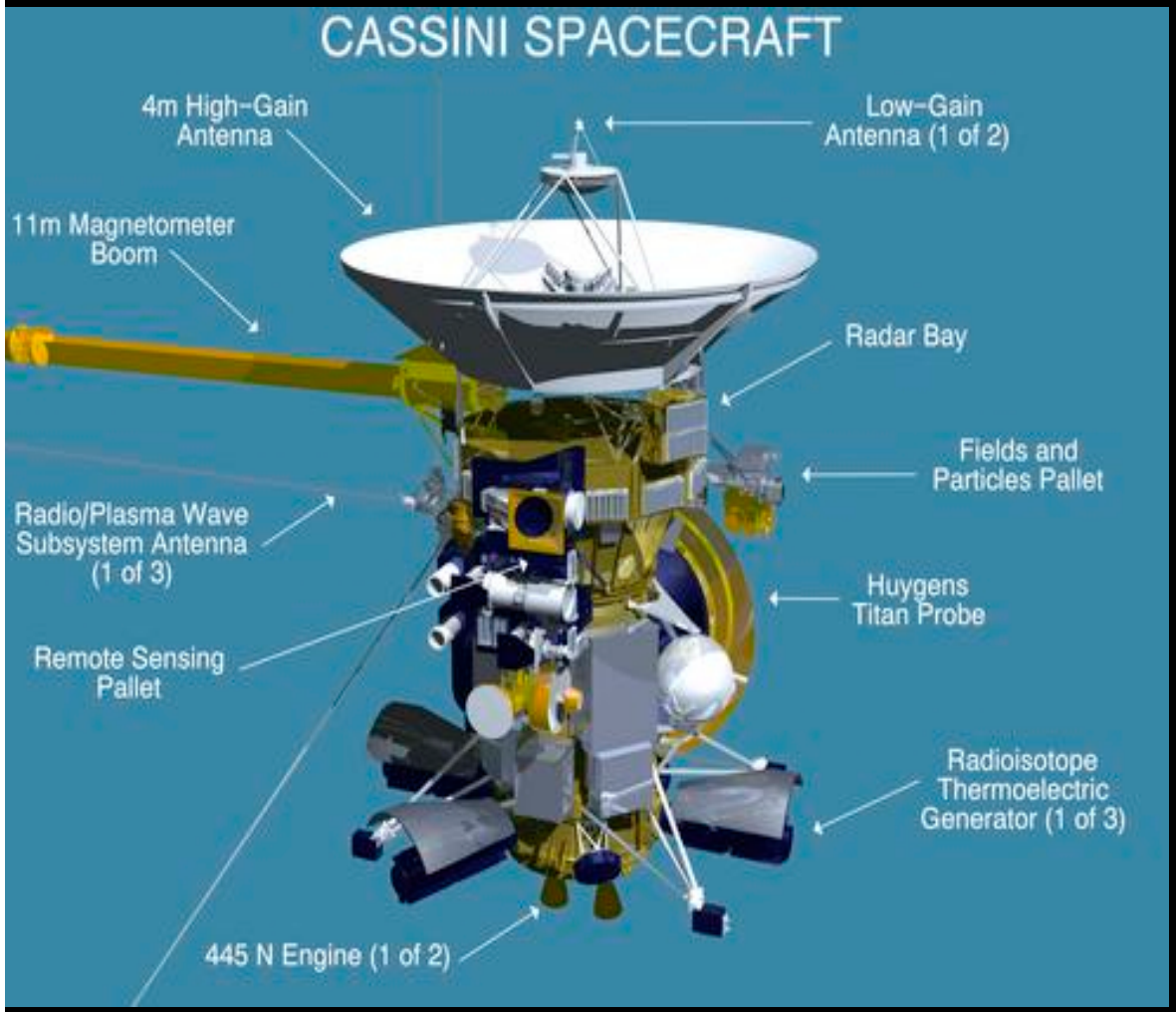
Saturn’s satellites

Saturn's Satellites and Ring Structure

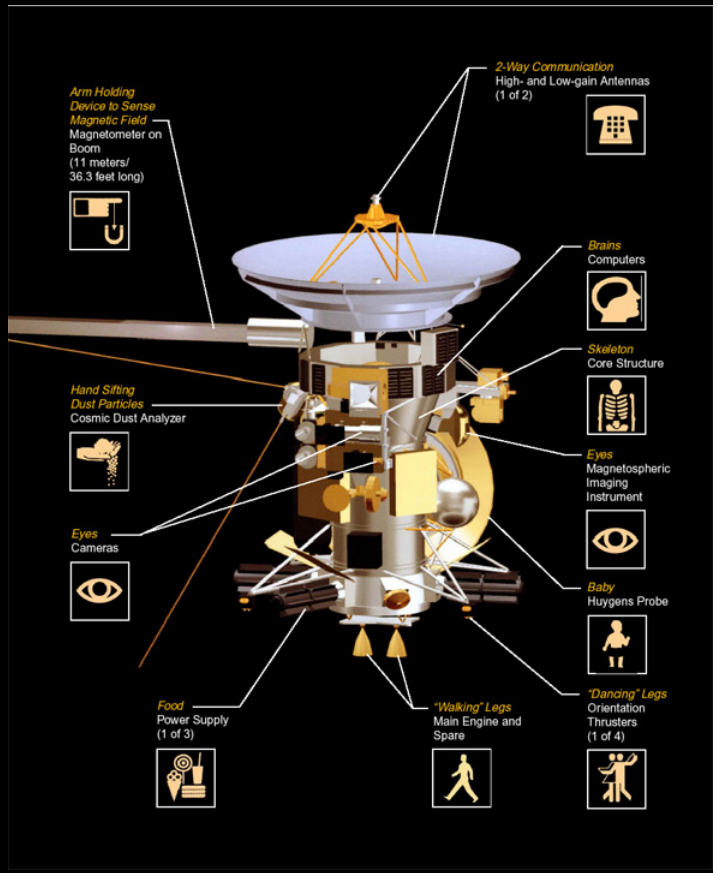




Cassini-Huygens spacecraft



12 instruments on the orbiter
6 instruments on the probe



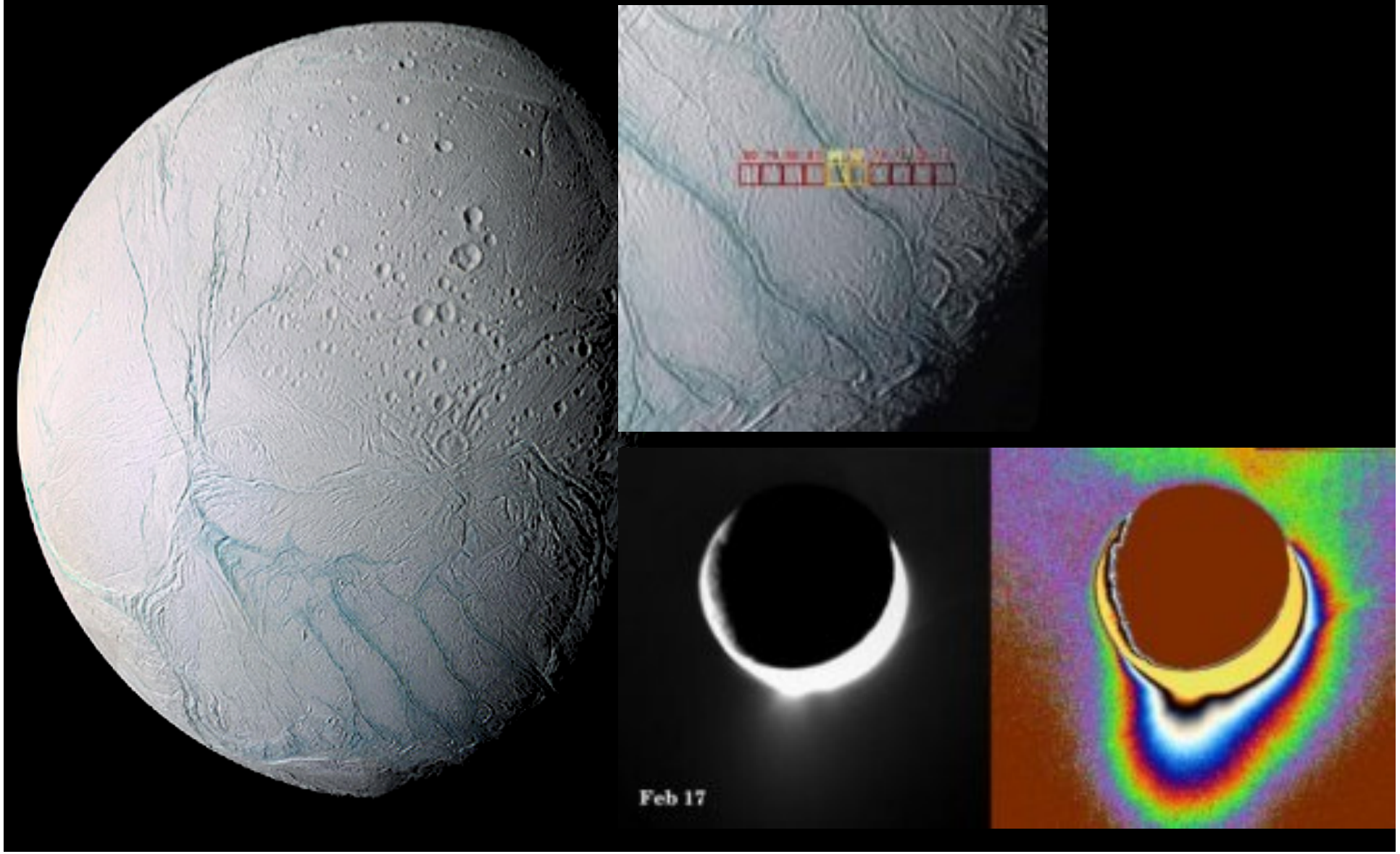
« Human » functions of Cassini-Huygens

Enceladus

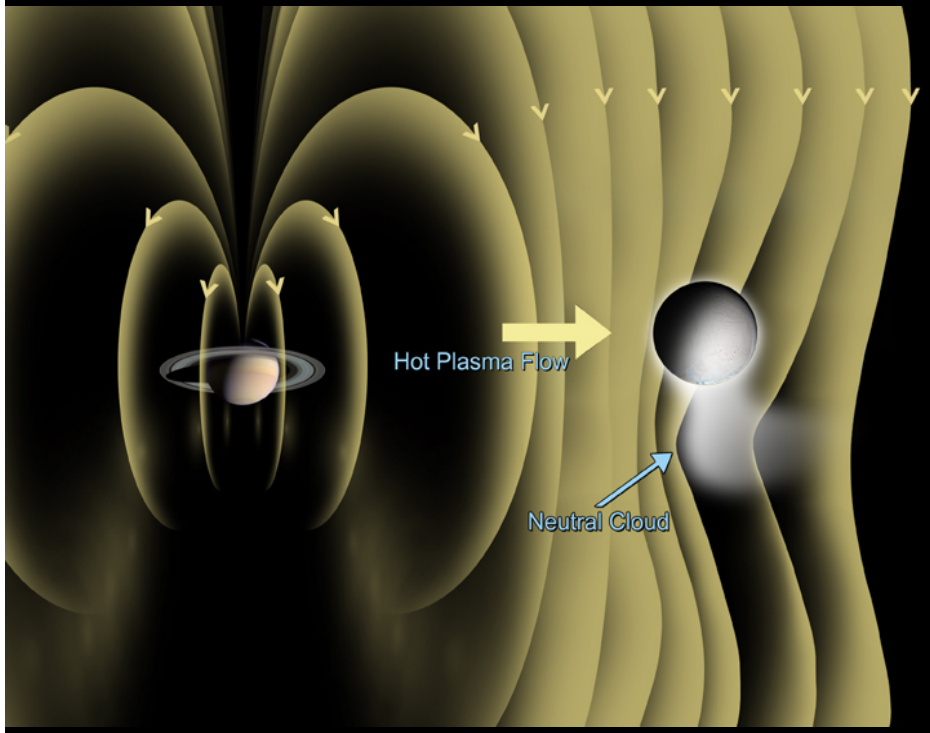
What are the habitable worlds?

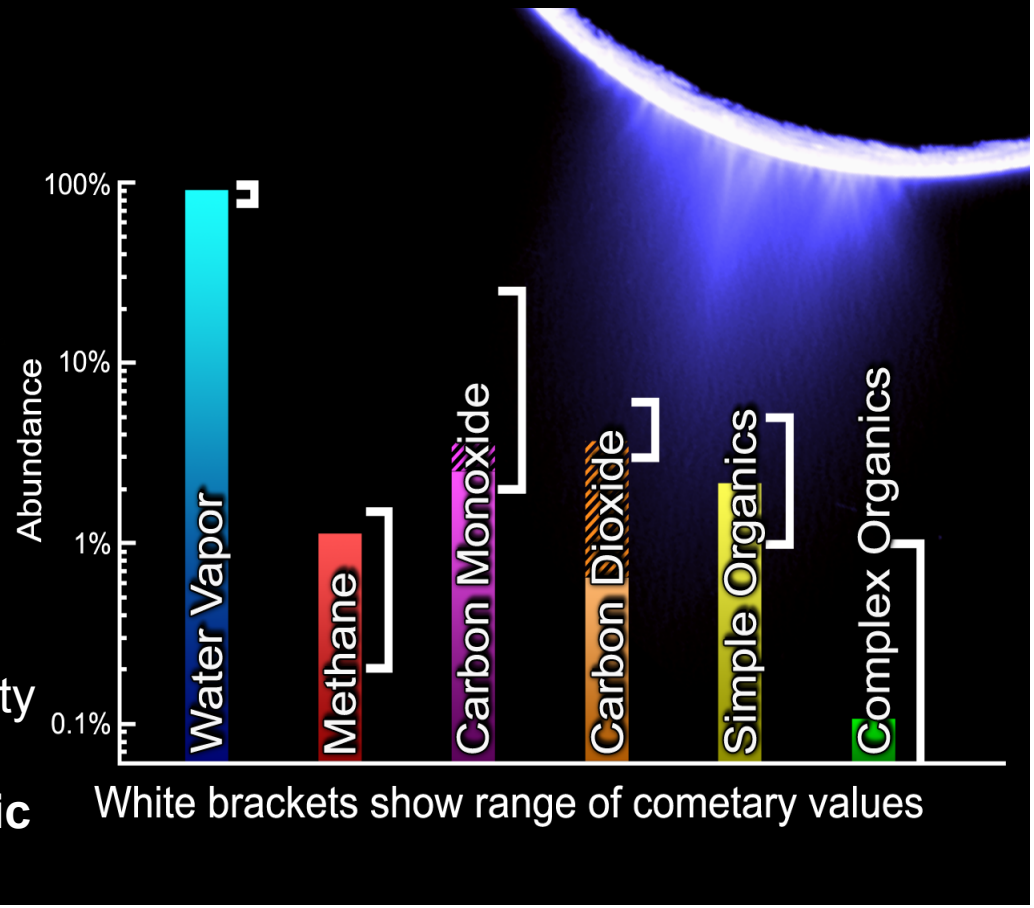
Class III : subsurface oceans in contact with silicates –Enceladus

. “Tiger stripes” and icy geysers …



Enceladus plumes

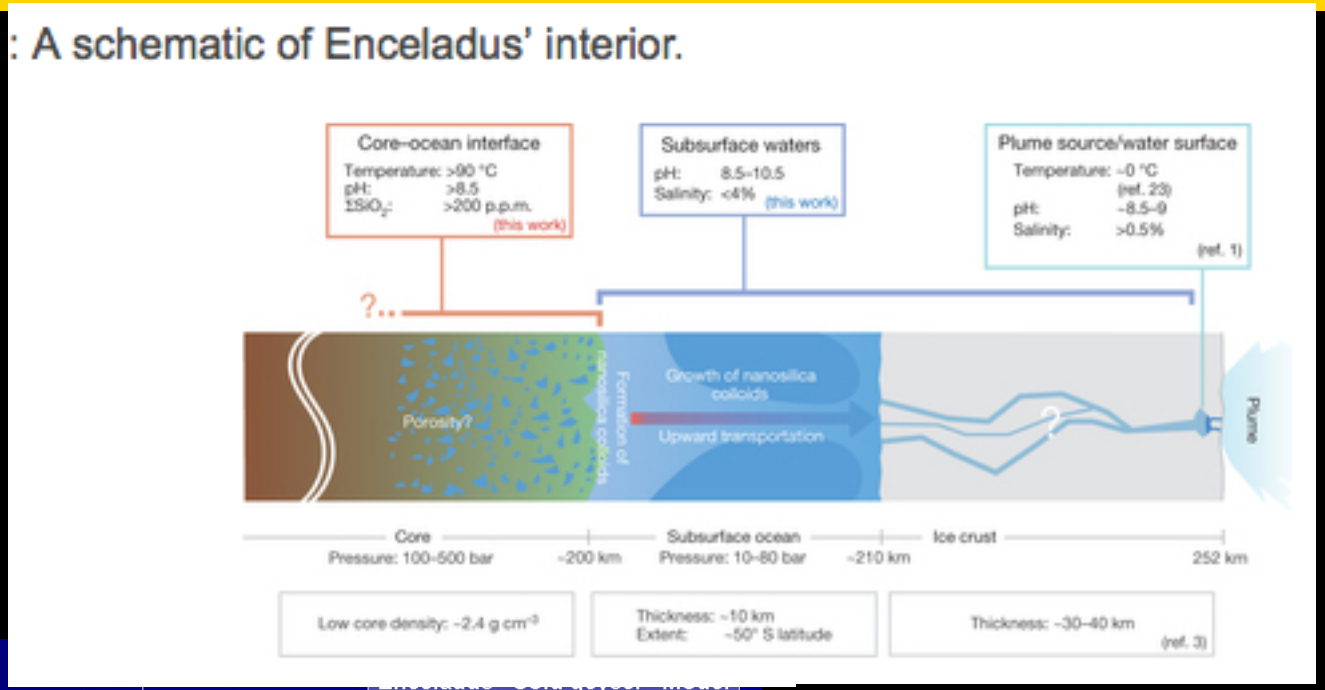




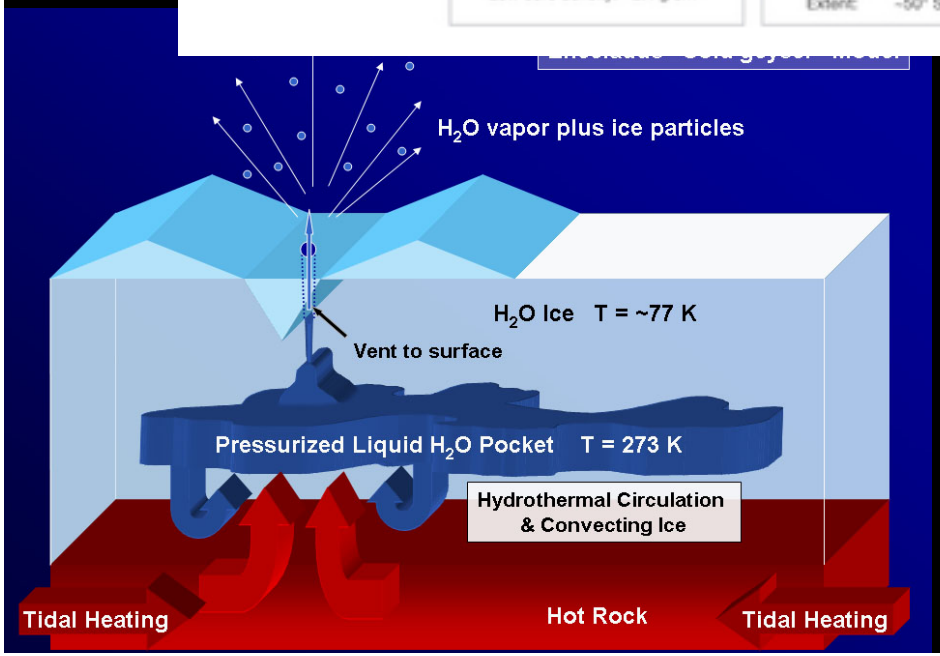
- **What is the origin of the plumes**
- **Replenishment of E-ring?**
- **Water vapor ejecta far away from the Sun** (strong implications for the habitability zones)
- **Indications for the presence of organic chemistry**

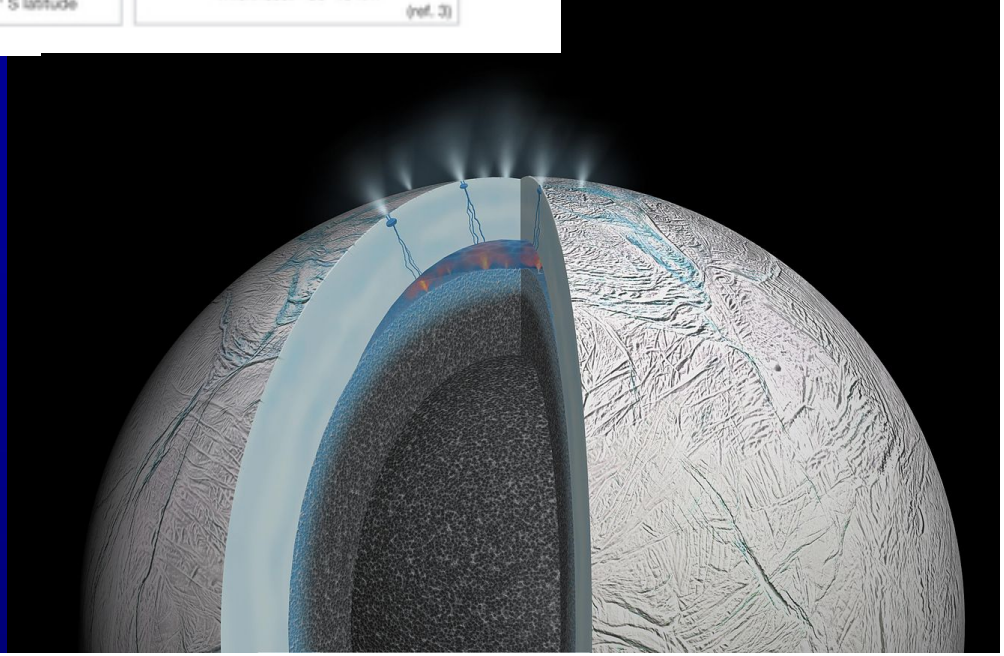
What are the habitable worlds?

Class III : subsurface oceans in contact with silicates –Enceladus



From Hsu et al. 2015

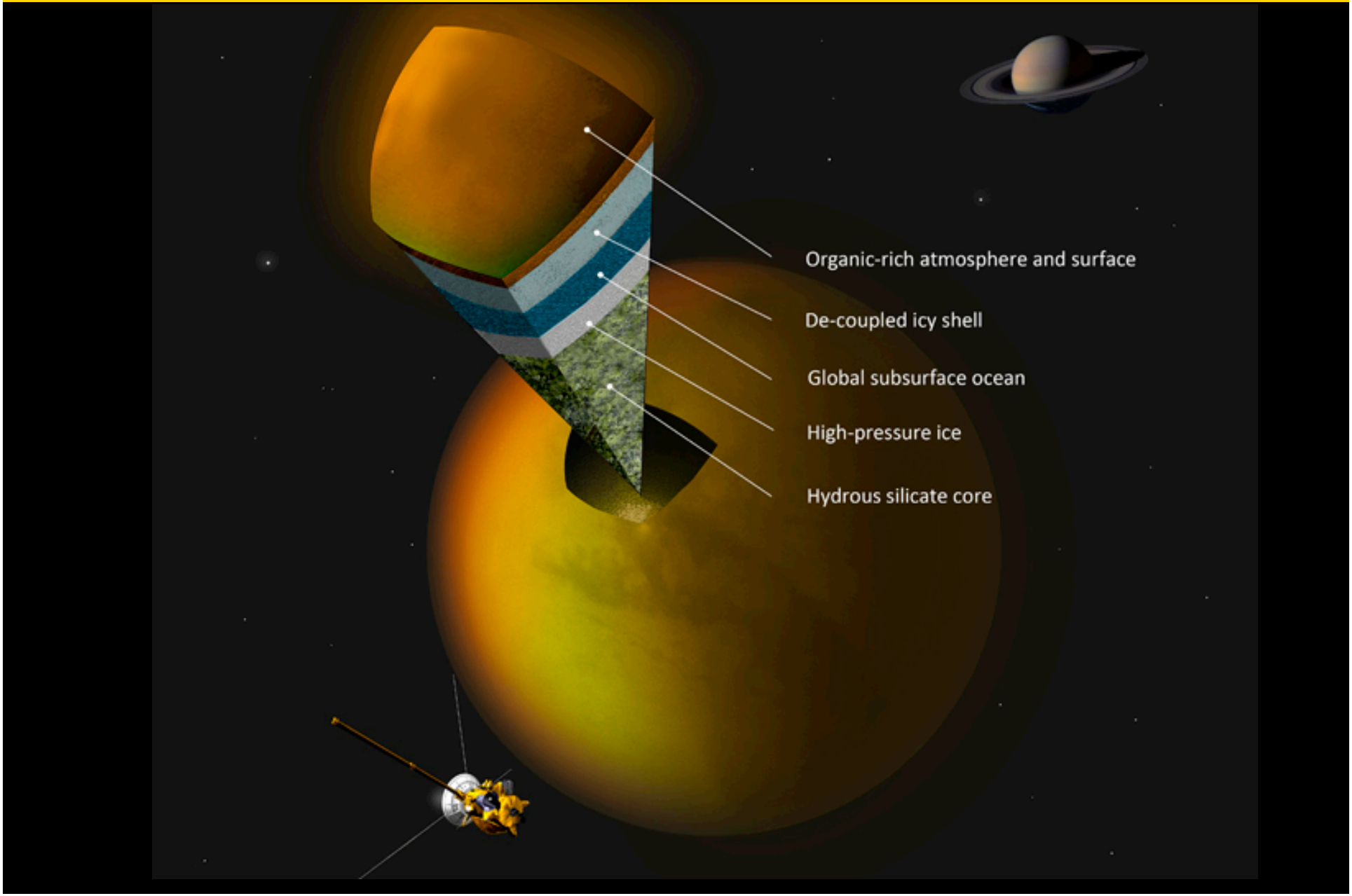




Titan

What are the habitable worlds?

Class IV : subsurface oceans without any contact with the silicates - Titan



Titan Through Time

- Christianus Huygens discovers Titan, 1655
- Ground-based :
  - atmospheric limb darkening (Comas Solas, 1908)
  - CH_4 detected (Kuiper, 1944)
- Voyager (1980)
  - radius = 2575 km (0.98 Ganymede; 1.48 x Moon; 0.76 x Mars)
  - mass = 1.35x 10^{23} kg (0.023 x Earth's)
  - mean density = 1.88 g/cm^3 (50% ice, 50% rock)
  - mean distance from Saturn = 1,211,850 km (~ 3.1 x Earth-Moon distance)
  - Follows Saturn around the Sun (inclined by 26.7°); a season is 7,5 years
  - orbital period= 15.94 days (Earth's moon 27.3 days)
  - atmospheric pressure = 1.5 bars
  - atmospheric density = 4.4 x Earth's atmosphere
  - N_2 detected as main component, CH_4 and other organics (Voyager, 1980)
  - Temperature inversions at tropopause (70° at 40 km altitude) and higher and greenhouse effect
  - mean surface temperature = 93.5 K (-179.5 °C, -291 °F)
- Ground-based and Earth-bound observatories (HST, ISO) – 1990s
  - Heterogeneous surface
  - Interesting atmospheric phenomena
- Cassini arrives at Saturn on 30 June 2004
- Huygens lands on Titan 14 January 2005

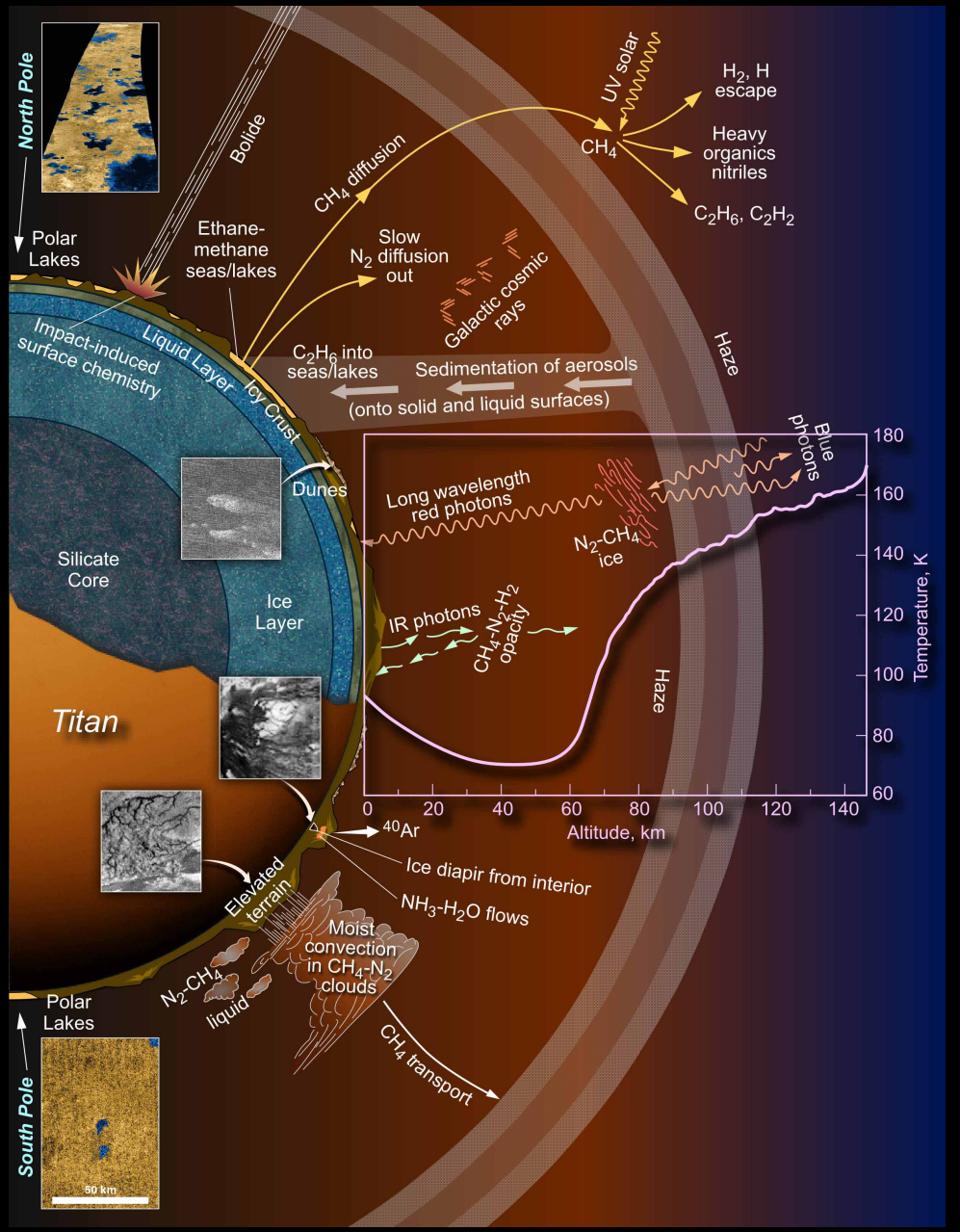
Wow !!!

TITAN: WHY ARE WE INTERESTED?

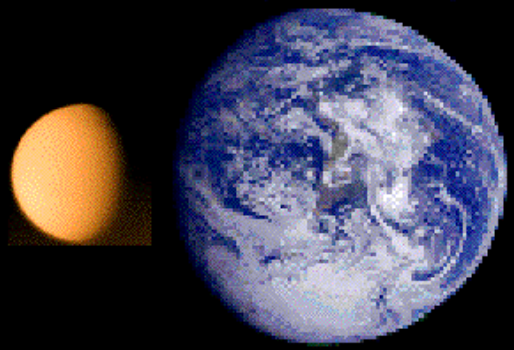
- It is of general interest to the study of chemical evolution:
  - N_2, CH_4 and other abundant organic gases (nitriles and hydrocarbons) are present in the atmosphere
  - An orange-brown cloud deck globally covers the satellite, in which aerosol layers and, methane/ethane clouds are also present.
  - The products of atmospheric chemistry may have been preserved over all of Titan's history.
  - The surface has a pressure of 1.5 bar and hosts several complex features like Earth (dunes, lakes, volcanoes, channels, etc) but with different actors/materials.
  - Atmosphere and surface are and subjected to seasonal effects.
- Conditions on Titan are not identical to those on Early Earth:
  - The temperatures are too low in the atmosphere (70-200 K) and on the surface (T~94 K), where liquid water is absent
  - The composition of the atmosphere is different (CH_4-N_2 vs CO-CO_2-N_2) with very little oxygen
  - Methane cycle vs water cycle
  - The solar UV radiation is only about 1% of that at the Earth
  - The infall of carbonaceous material is smaller today than in the past

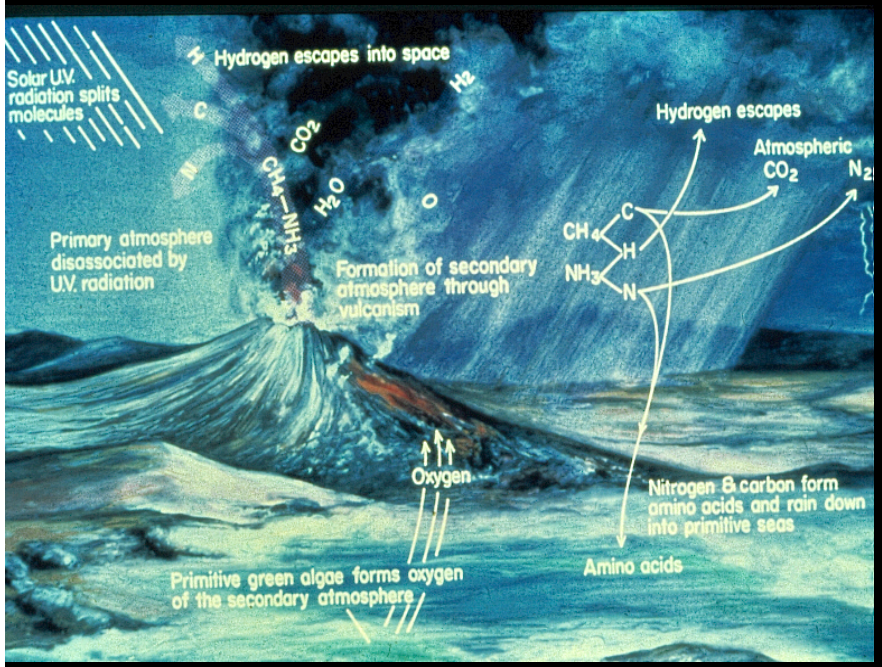
Titan as an astrobiological object

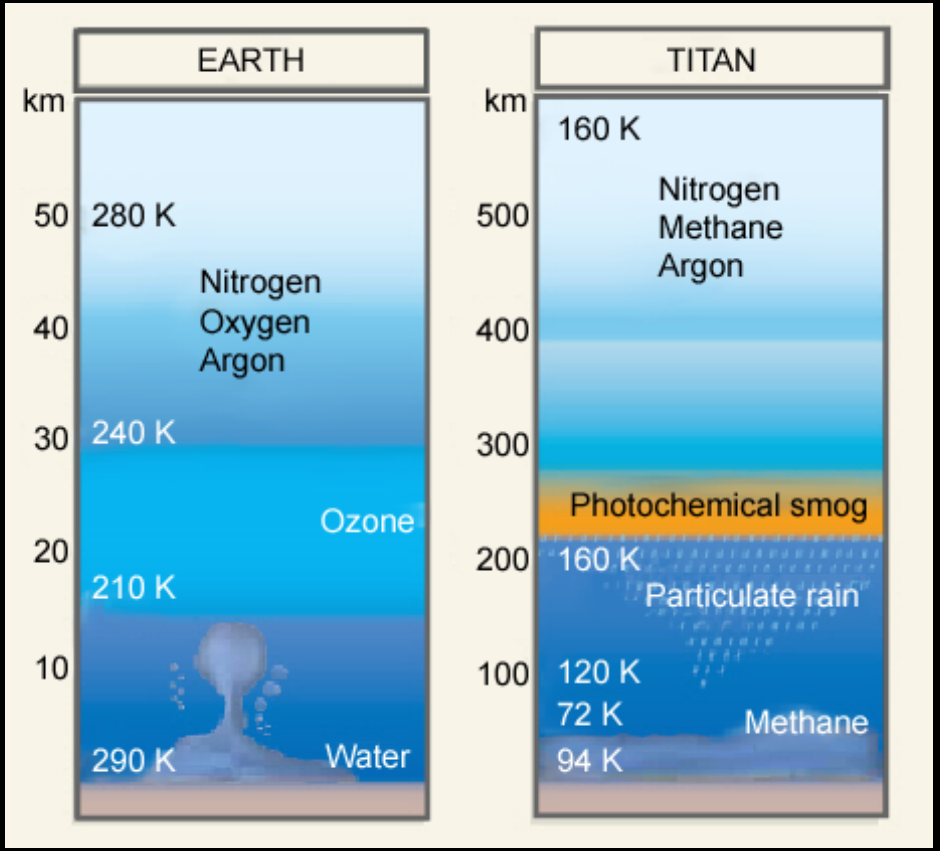
- The physical conditions
- The organic chemistry
- The methane cycle
- The undersurface water ocean
- Climatology/ seasonal effects



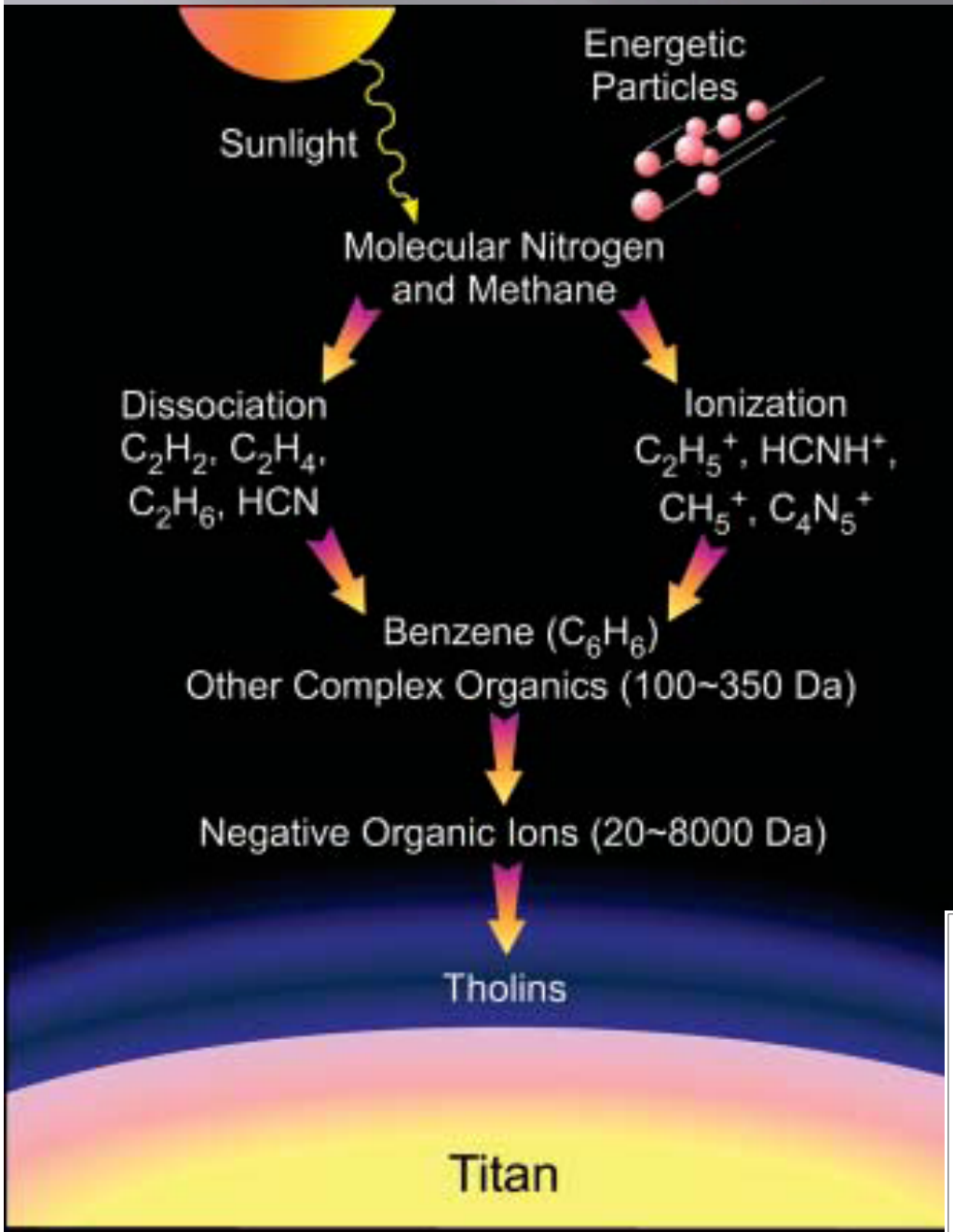
Titan and the Earth





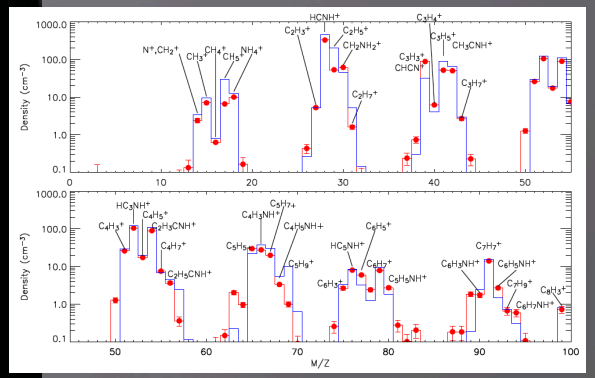


Titan provides a good analogue as a natural laboratory in which chemical and physical processes can be studied on a planetary scale and help us understand early chemical evolution in the primordial atmosphere on Earth

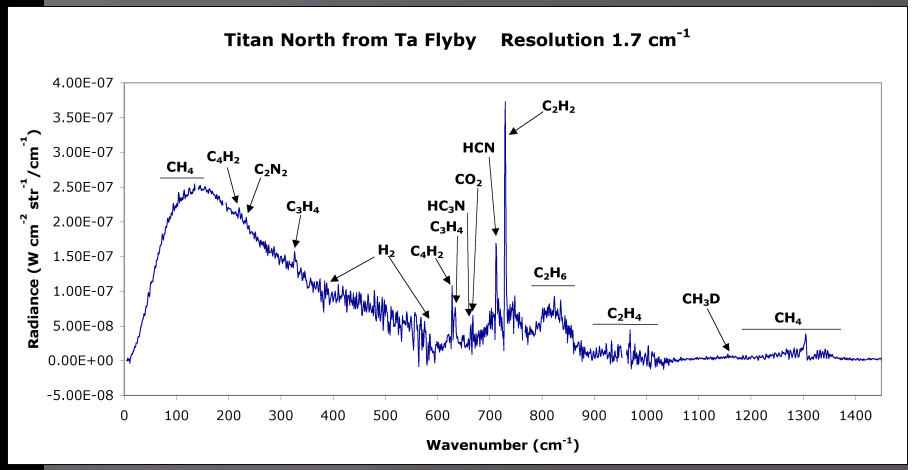


Waite et al., 2005, 2009; Vuitton et al., 2009

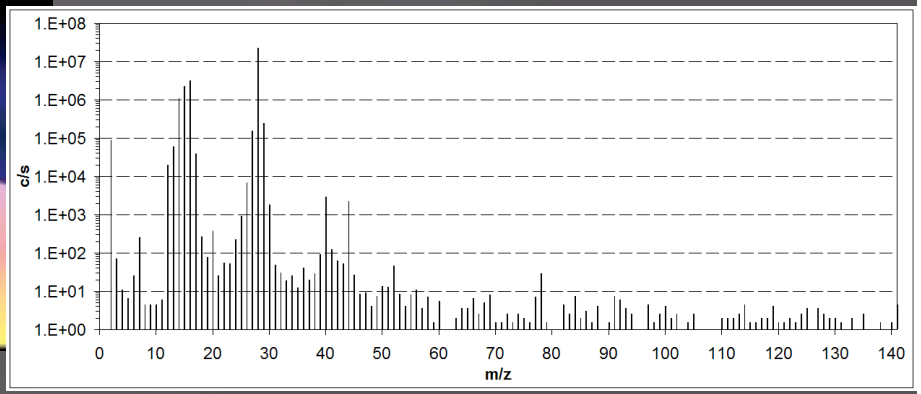
Cassini INMS



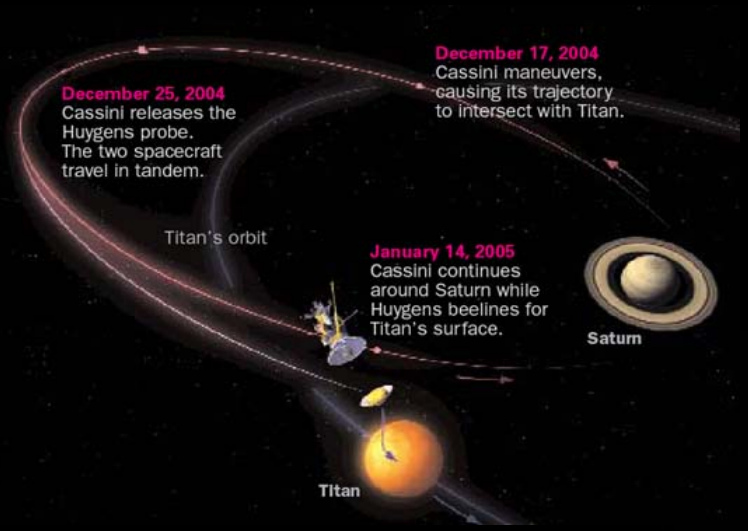
Cassini CIRS

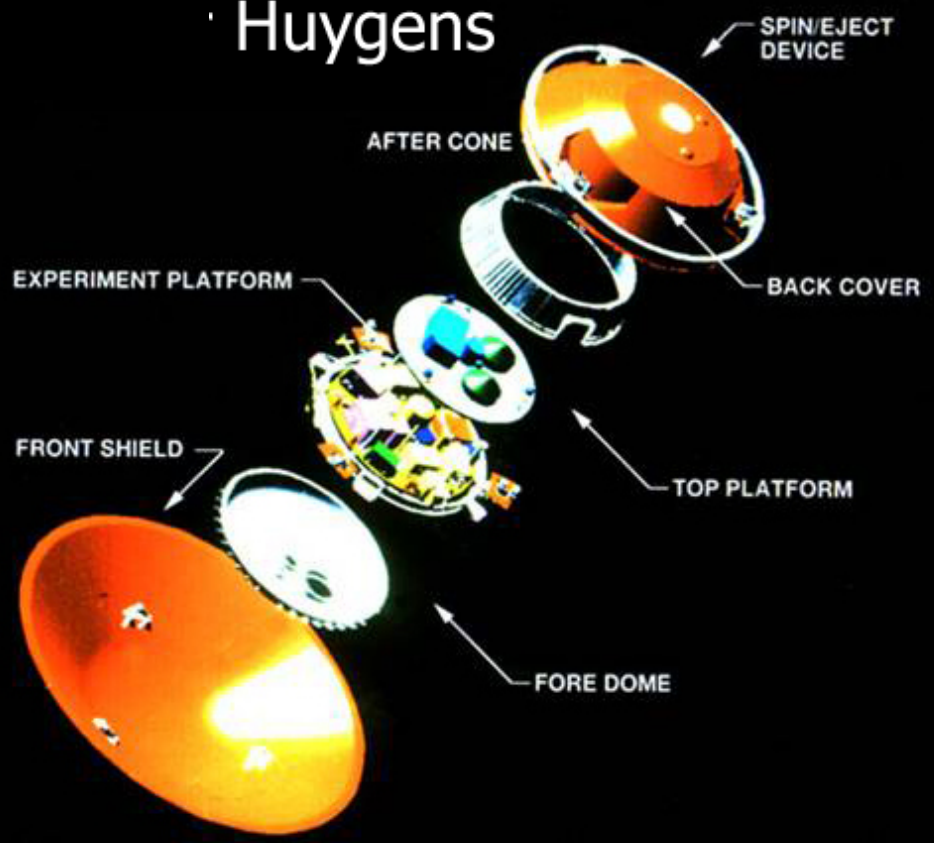


Huygens GCMS

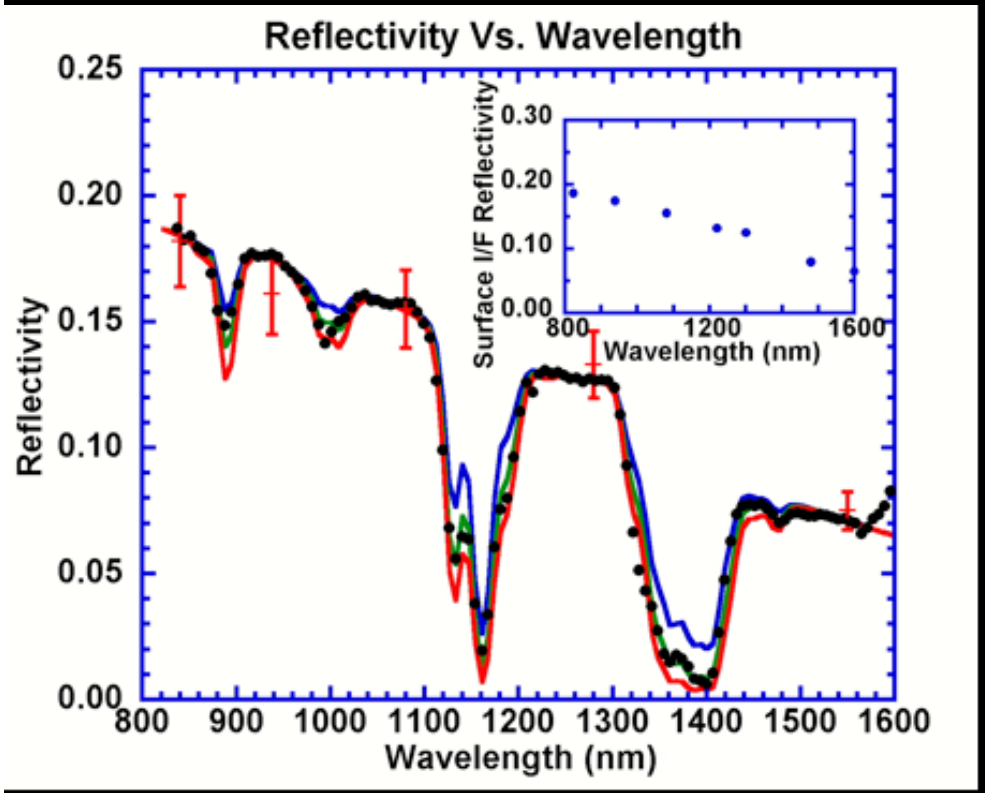


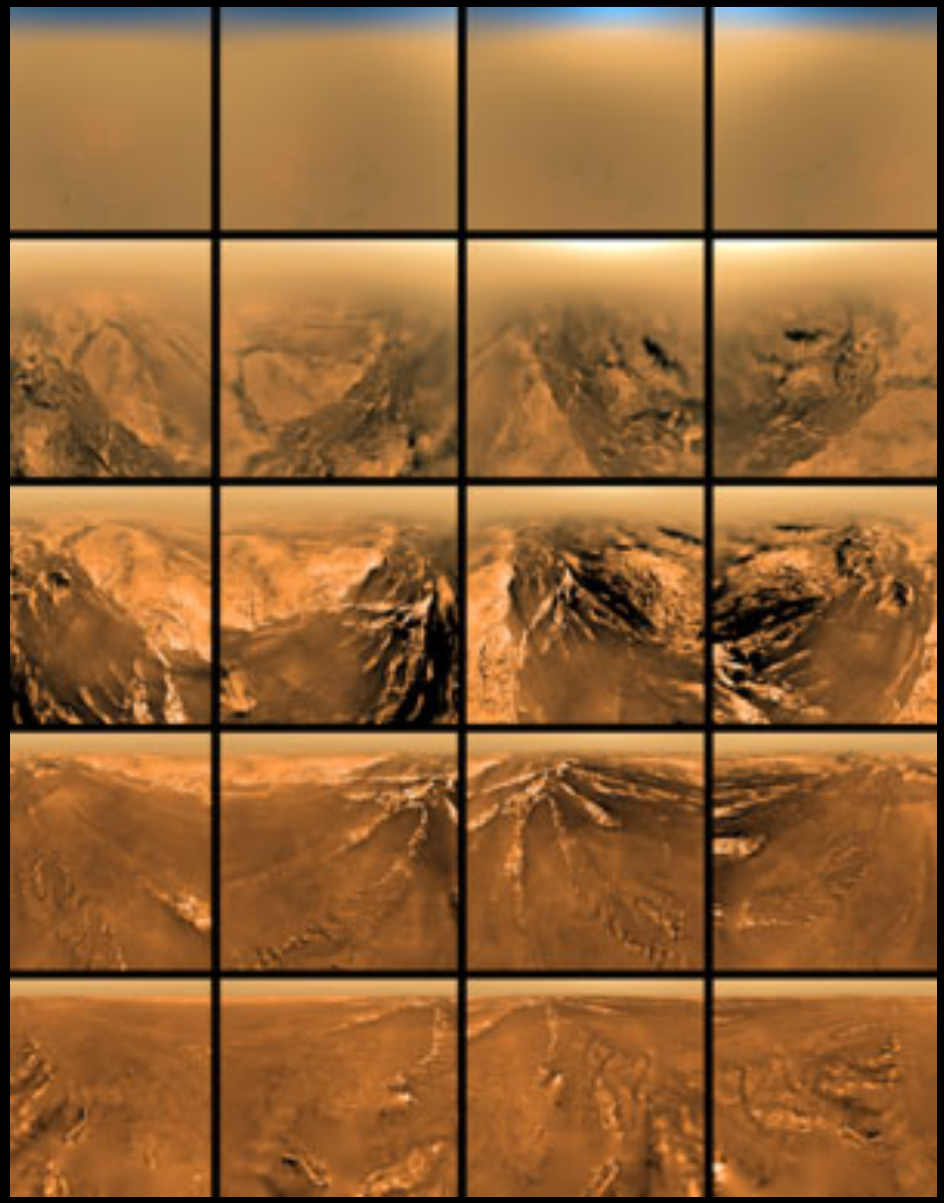
Huygens : the descent module





Titan after Huygens



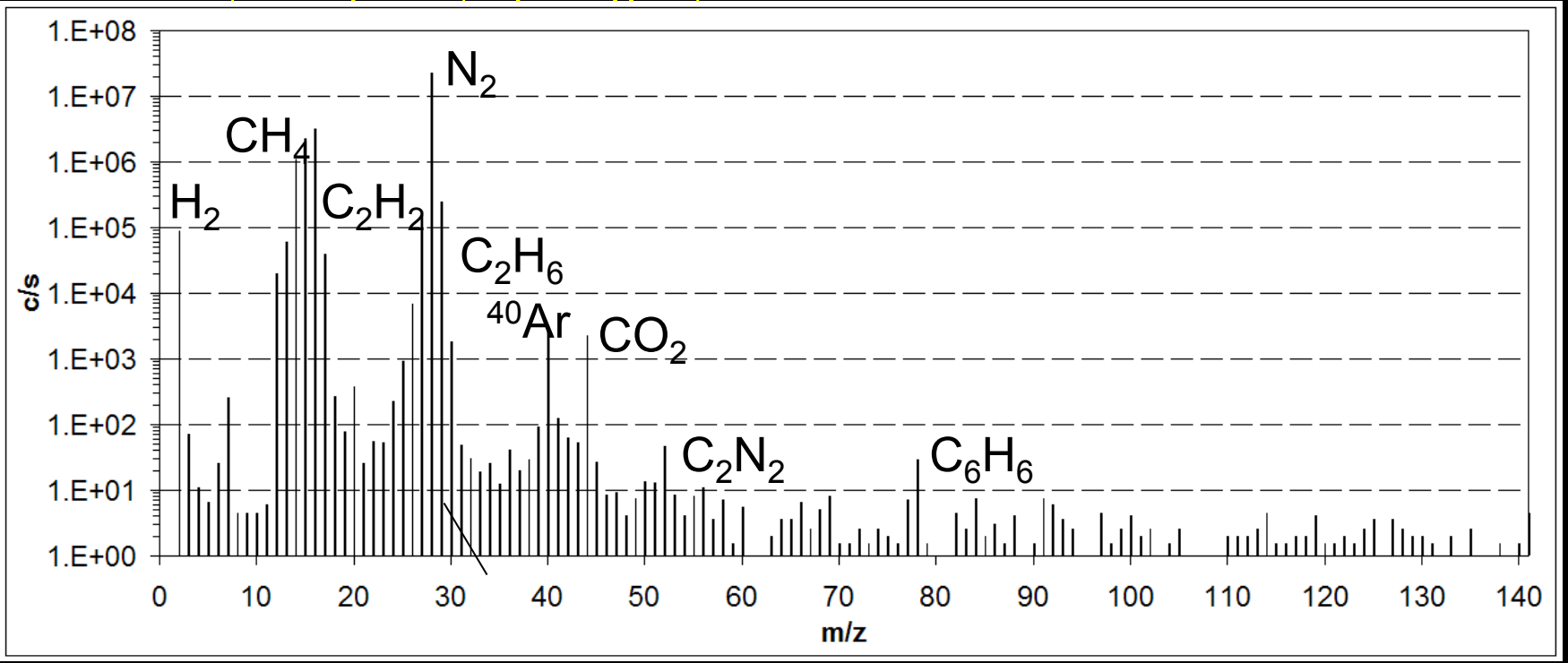


Surface Observations with the GCMS

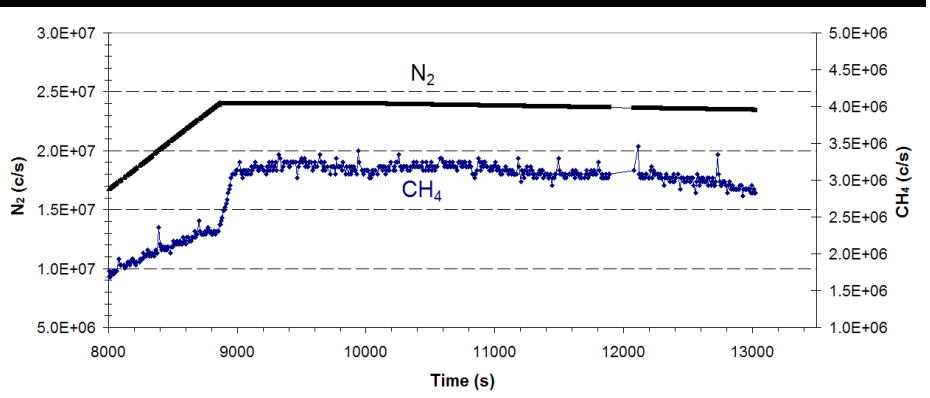
(Niemann et al., Nature, 438, 779-784, 2005)

Detection of various organic compounds on the surface:

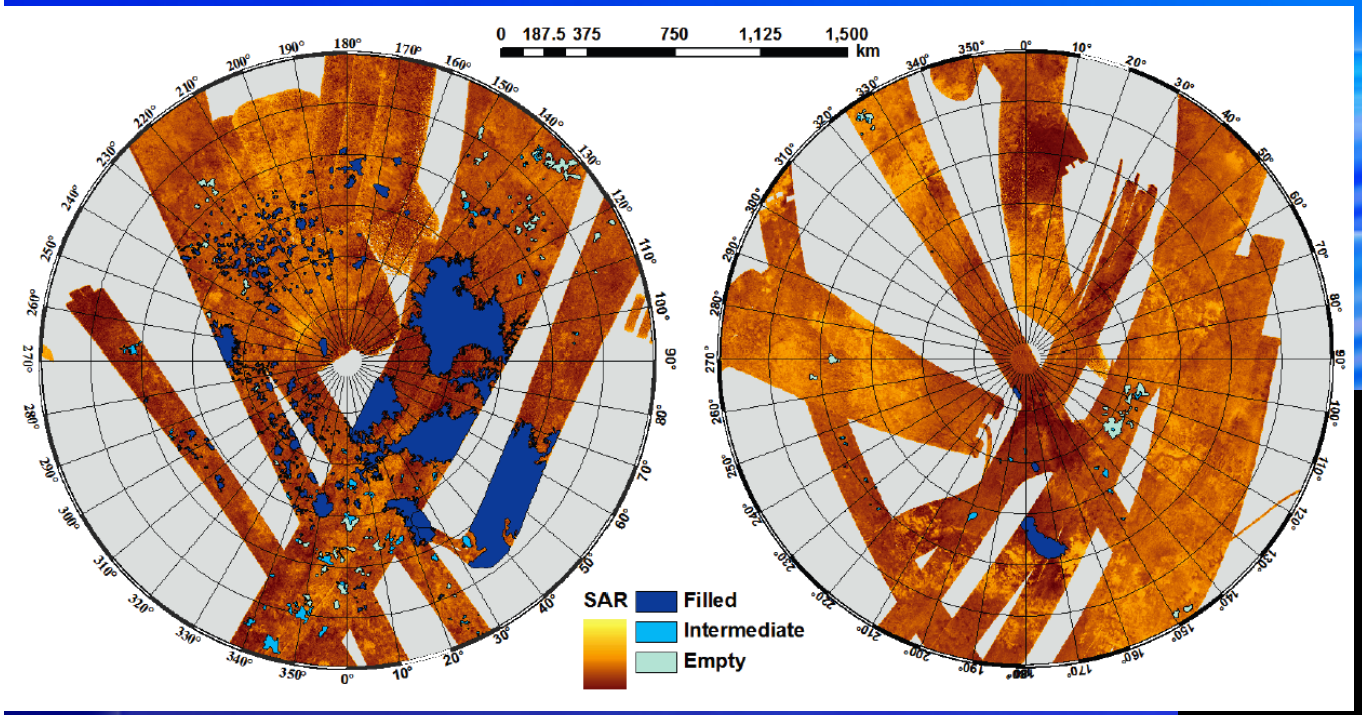
Ethane, acetylene, cyanogen, benzene and in addition carbon dioxide.



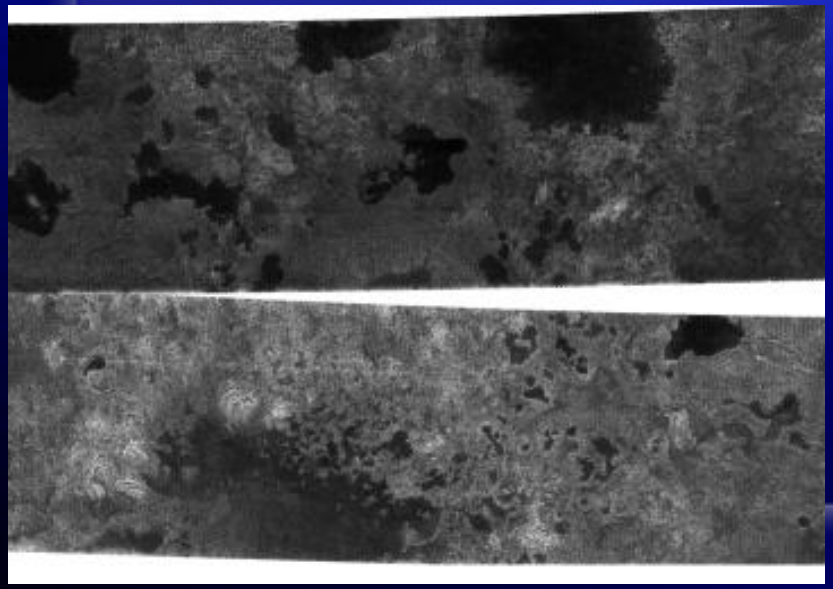
Methane evaporated from the surface after warming from the heated sample inlet as observed by an increase of the methane signal after impact. A moist area with liquid methane in the near sub-surface is indicated.

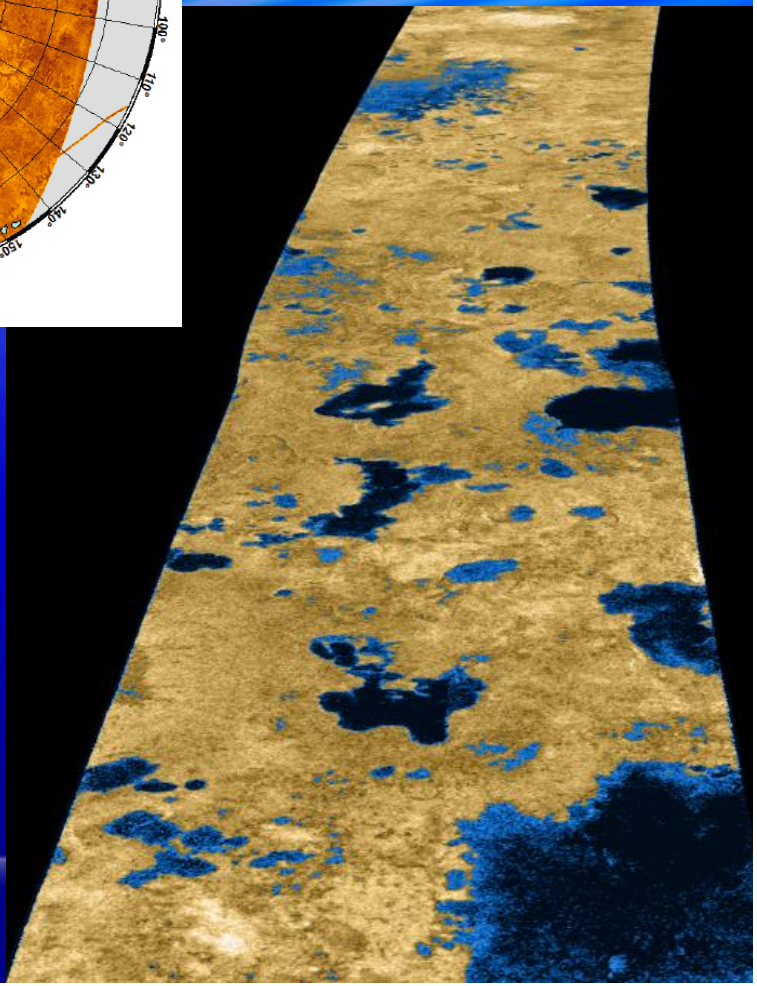


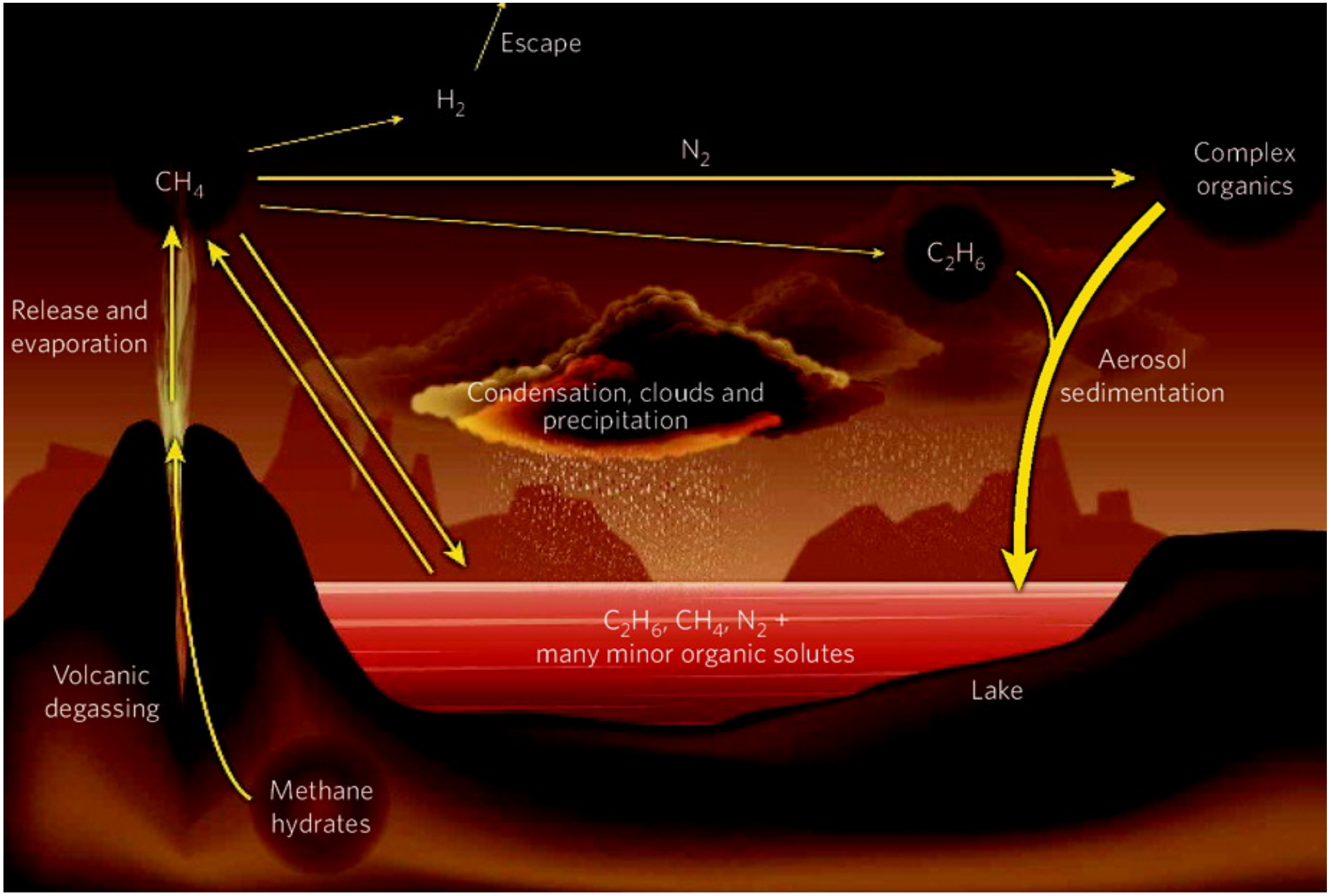
Cassini/RADAR/Titan



Rivers and lakes in the North Pole : the missing CH4 reservoir?







Titan the only place with the Earth having liquid surface bodies

Chemical composition of Titan's lakes

Titan's lakes **made of ~65% ethane and ~30% methane** with many minor species dissolved

-Other hydrocarbons ethylene and propane : several%
C_3-C_7 alkanes, alkenes and benzene : several ‰-1 ppm
Acetylene : 400 ppm diacetylene: ~1 ppm

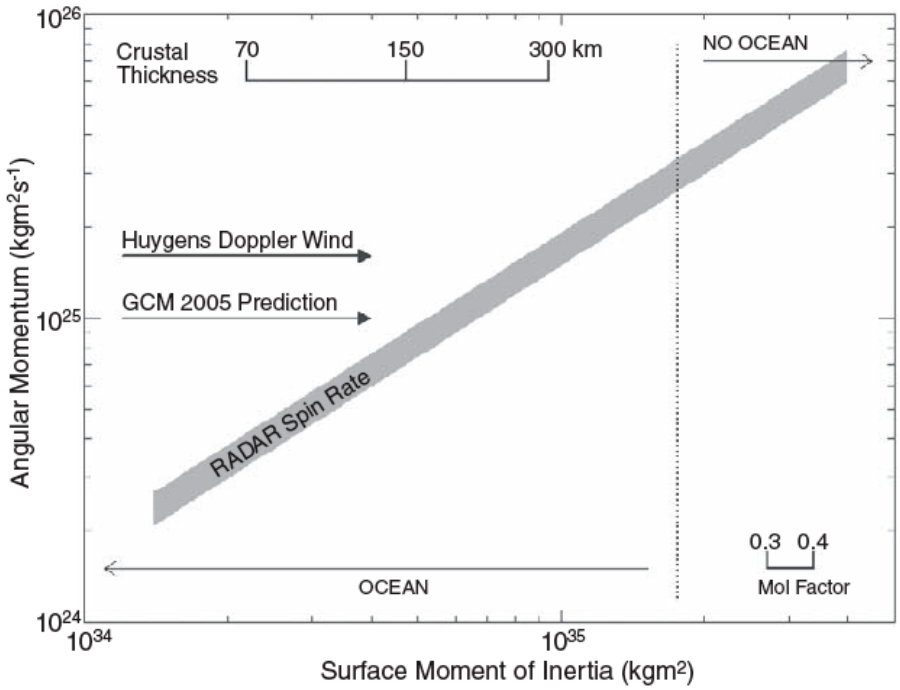
Nitriles 50 – 1 ppm
HCN : 3 ppm - HC_3N : 5 ppm

Heterocyclic bases Pyrimidine 2 ppm - Adenine 10 ppb

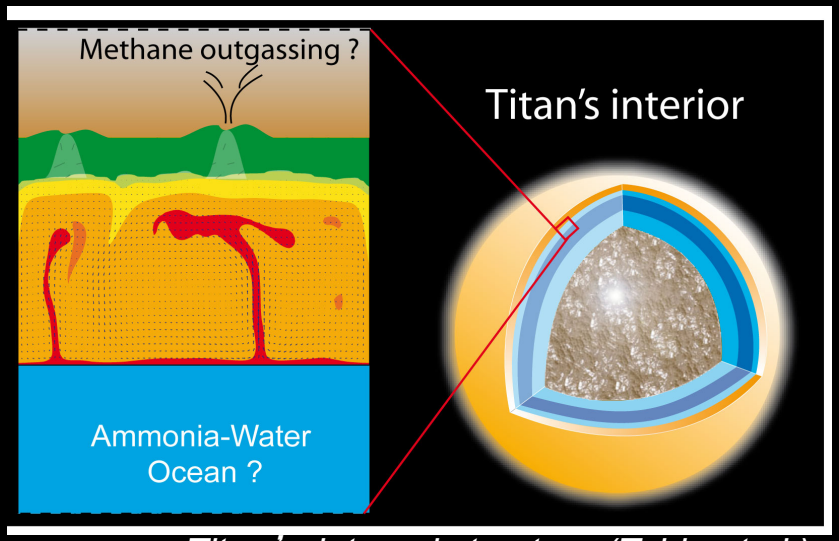
Inorganics CO_2 : 10 ppm
NH_3 : 5 ppm
H_2O : 0.2 ppt !!
CO: ~4 ppm
Ar, other noble gases very soluble:

=> A large variety of organics, with much higher concentration in the lakes than in the atmosphere and easily quantitatively analysable by in situ measurements

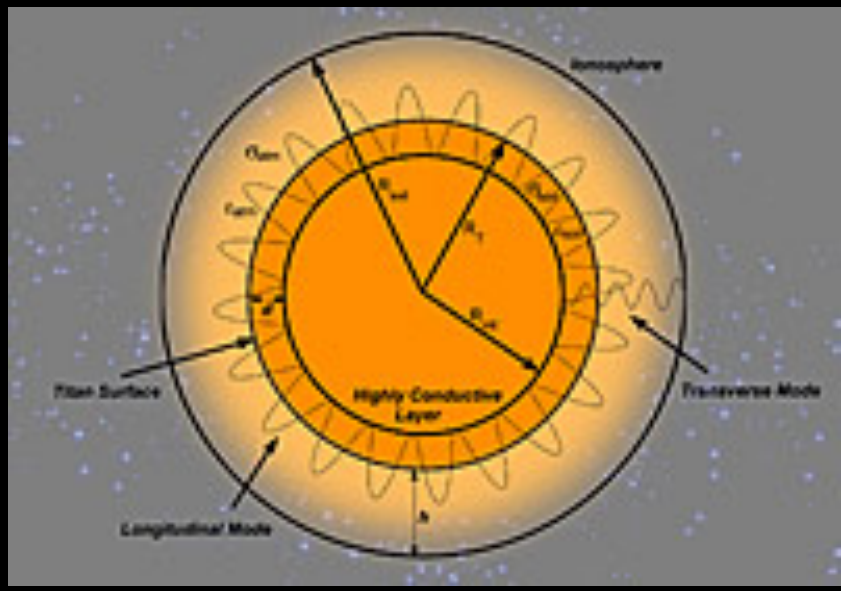
Titan's subsurface ocean



Titan's spin and large tides on the surface indicate the presence of an internal liquid water ocean (less et al., 2012)

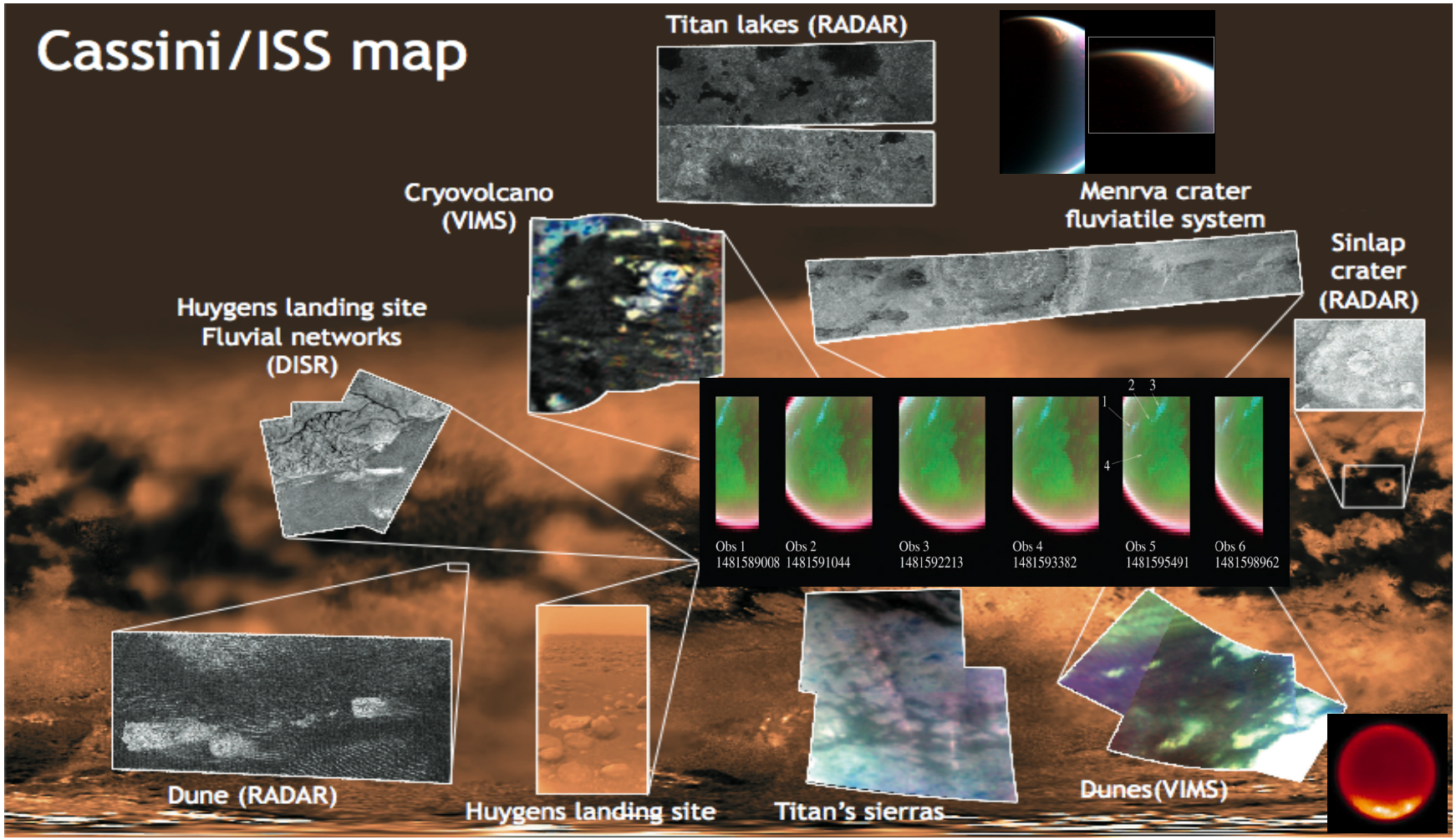


Titan's internal structure (Tobie et al.)

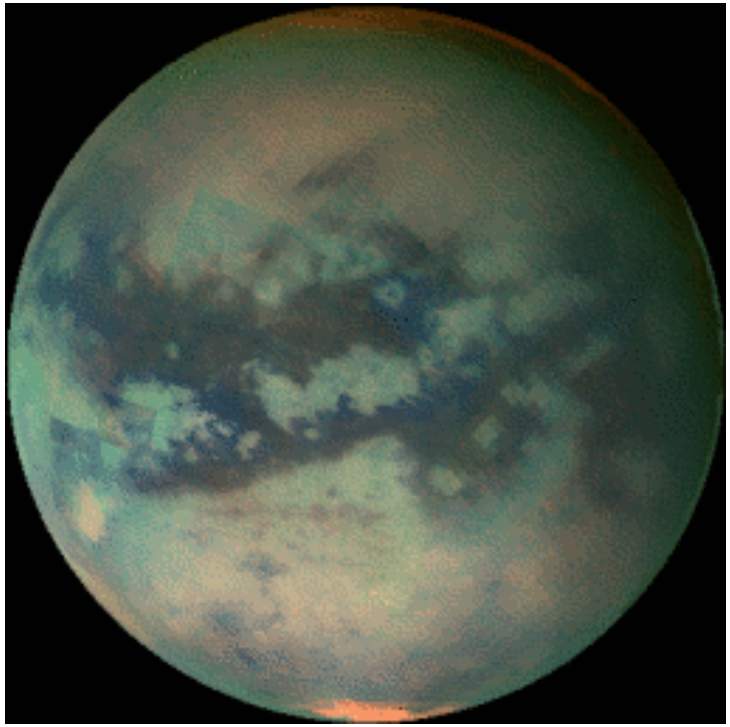


Huygens measures radio wave at extremely low frequency which supports the subsurface ocean theory

Titan's complex surface and atmosphere

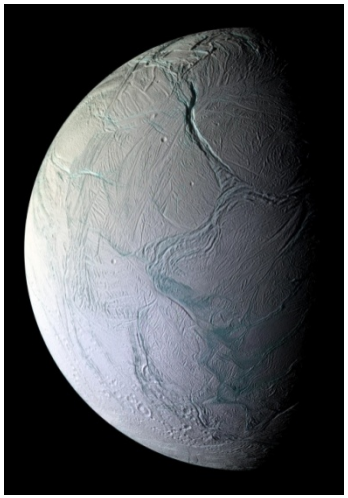


Titan



• Analogies with the Earth in atmosphere and pressure
• Complex organic chemistry
• Potential habitat (undersurface water ocean)
•Energy sources : cryovolcanism

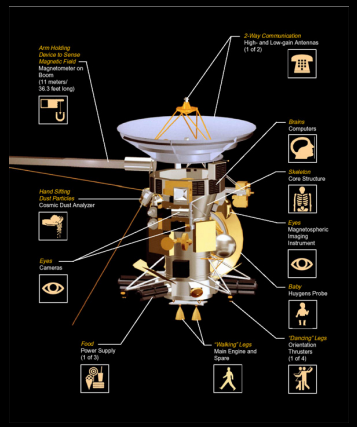
Enceladus

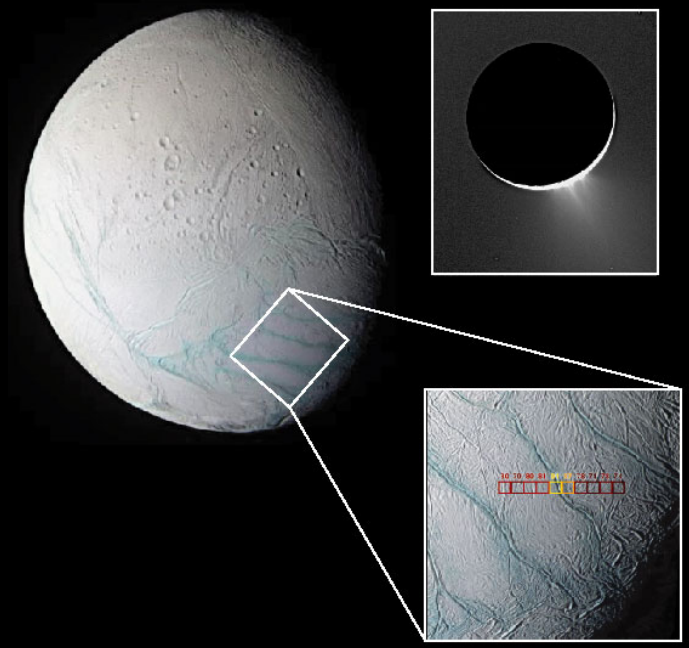


• Complex organic chemistry
• Potential habitat (liquid water under the surface)

(Titan's astrobiology, F. Raulin, C. McKay, J. Lunine and T. Owen, Chap.IX of "Titan from Cassini-Huygens", B. Brown et al. Eds, Springer, 2009
« Life beyond Earth: habitable worlds in the Universe », A. Coustenis and Th. Encrenaz, CUP, in press, 2013.)

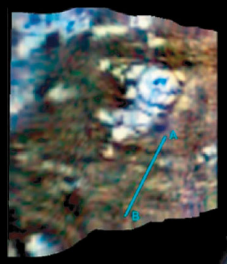
Cassini-Huygens (2004-2017) reveals Titan and Enceladus





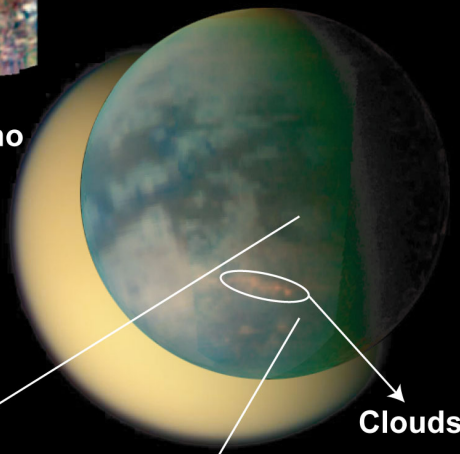
Enceladus

Hydrocarbon lakes



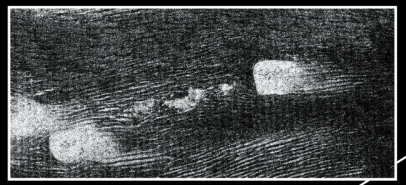
Cryovolcano

Titan: a frozen Earth ?

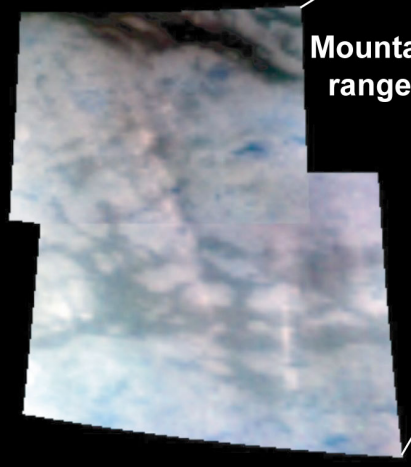


Clouds

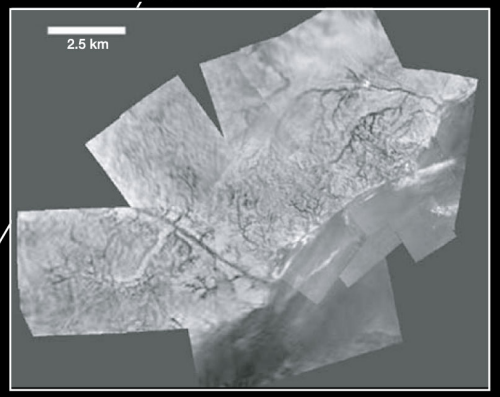
Dune fields



Mountain ranges

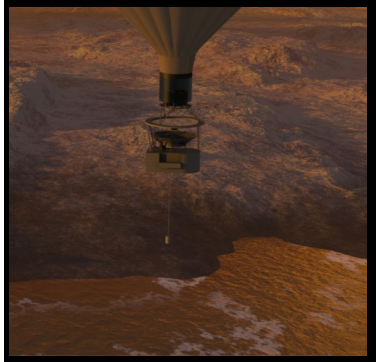


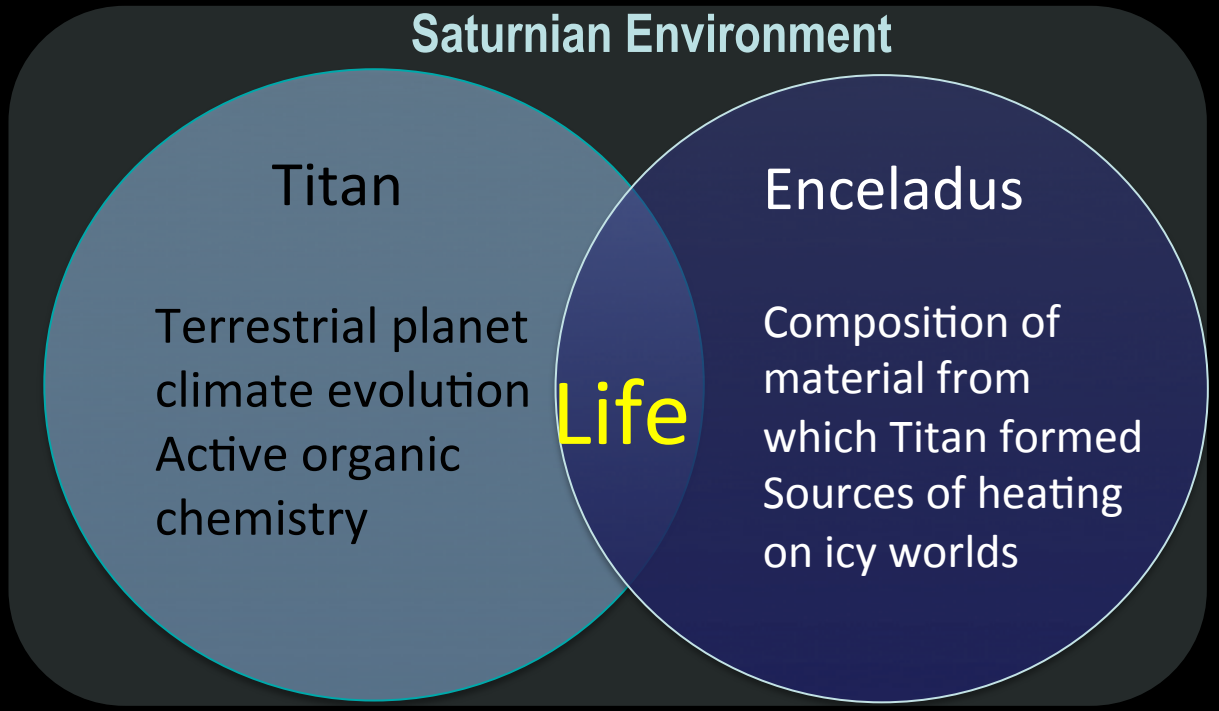
River networks



Titan

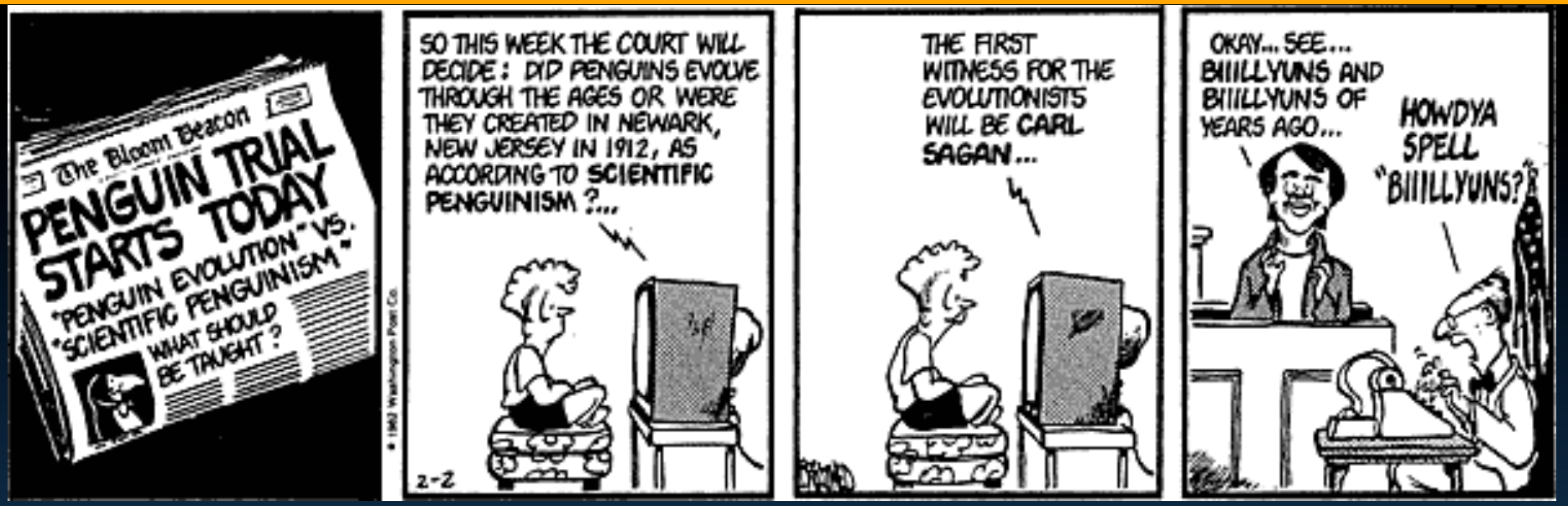
The exploration of the Saturnian system : habitats

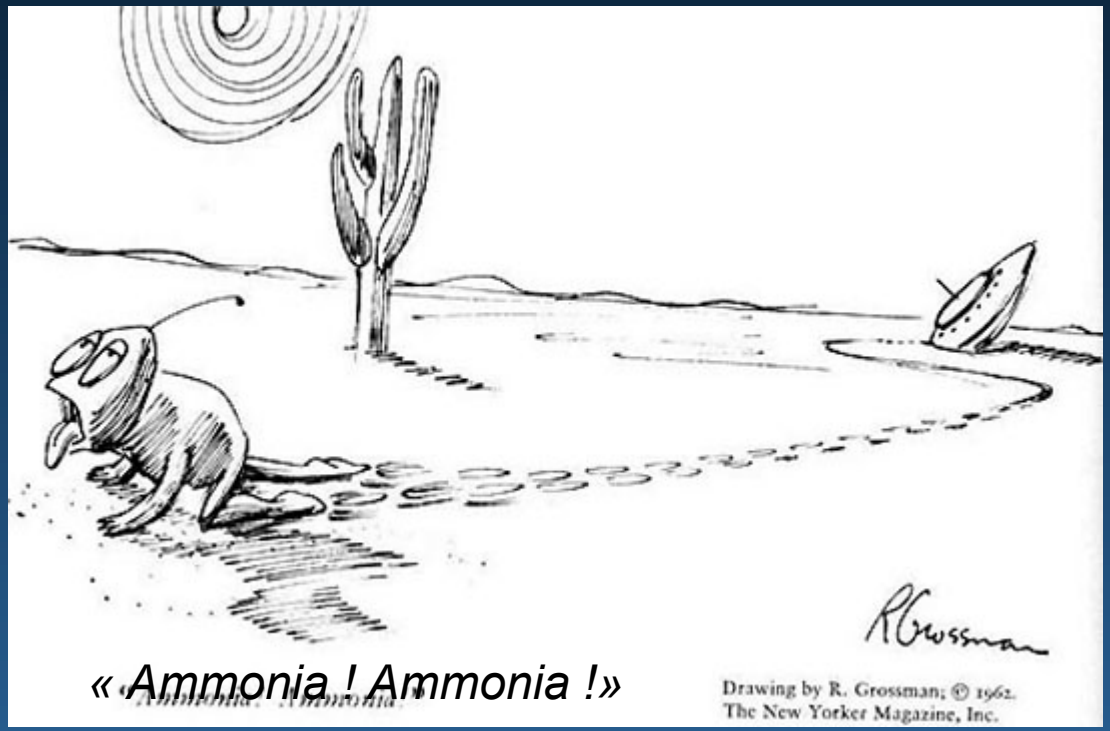




- The Saturnian system is rich in worlds that could bring insights on important aspects of Earth's
  - *climate,*
  - *organic chemistry and*
  - *emergence of life*.

What are habitable worlds?

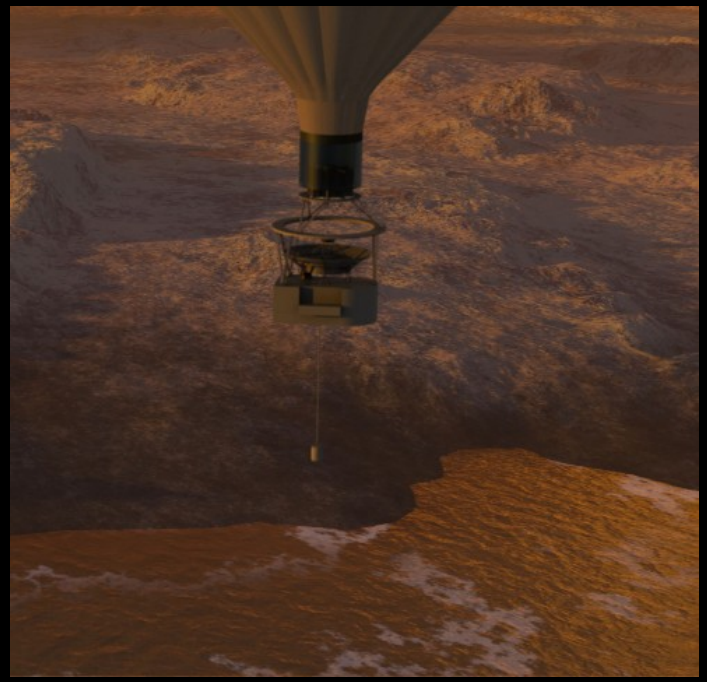




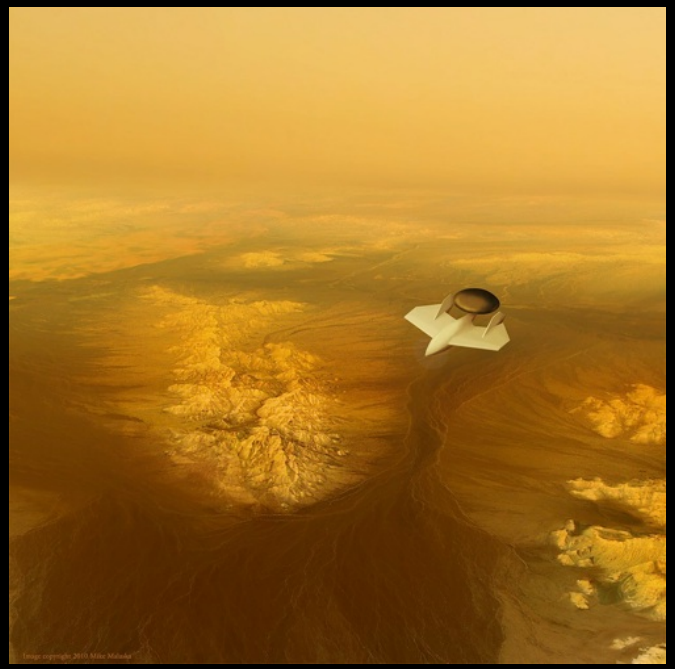
« Ammonia ! Ammonia !»

Drawing by R. Grossman; © 1962. The New Yorker Magazine, Inc.

Ideas/studies for returning to Titan



TSSM: Balloon, lander & orbiter



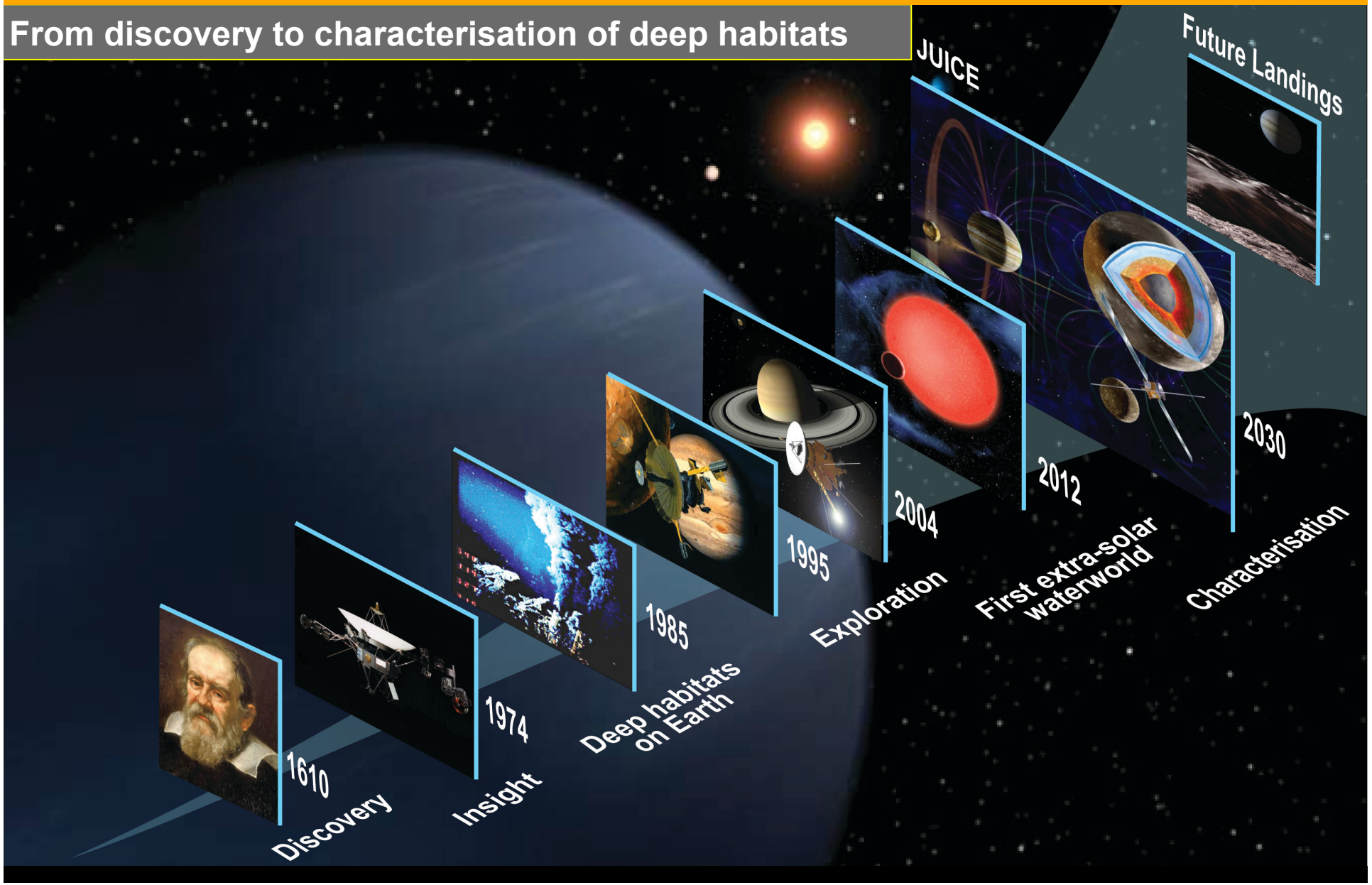
AVIATR /PLANE

TIME: Lake lander

Conclusions

Rich future for exploration of habitable worlds in the outer solar system with JUICE as L1: Studies of Jupiter, the magnetosphere, the icy moons and the interactions

From discovery to characterisation of deep habitats



Thank you
and au revoir !