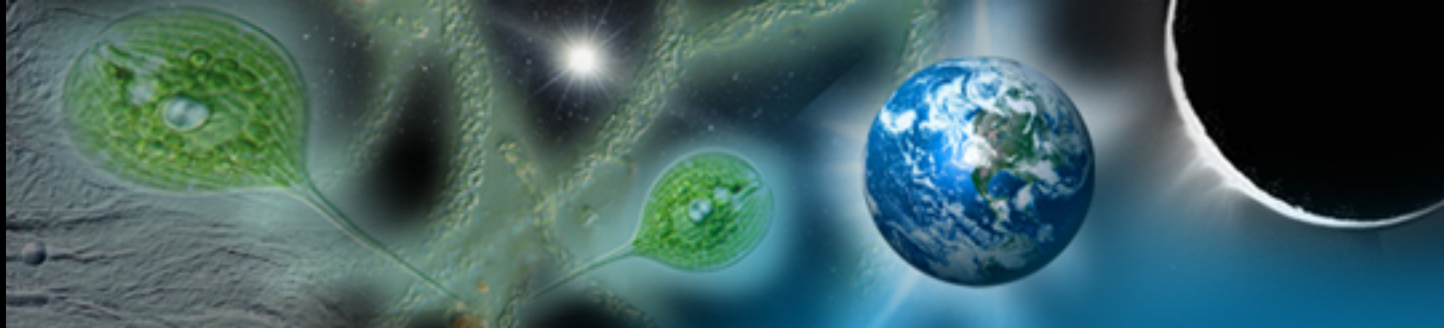


Space exploration of icy moons with undersurface oceans

Athena Coustenis

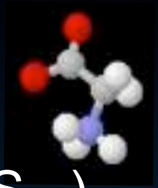
Director of Research, CNRS

President of the ESF-ESSC

LESIA, Paris-Meudon Observatory, France

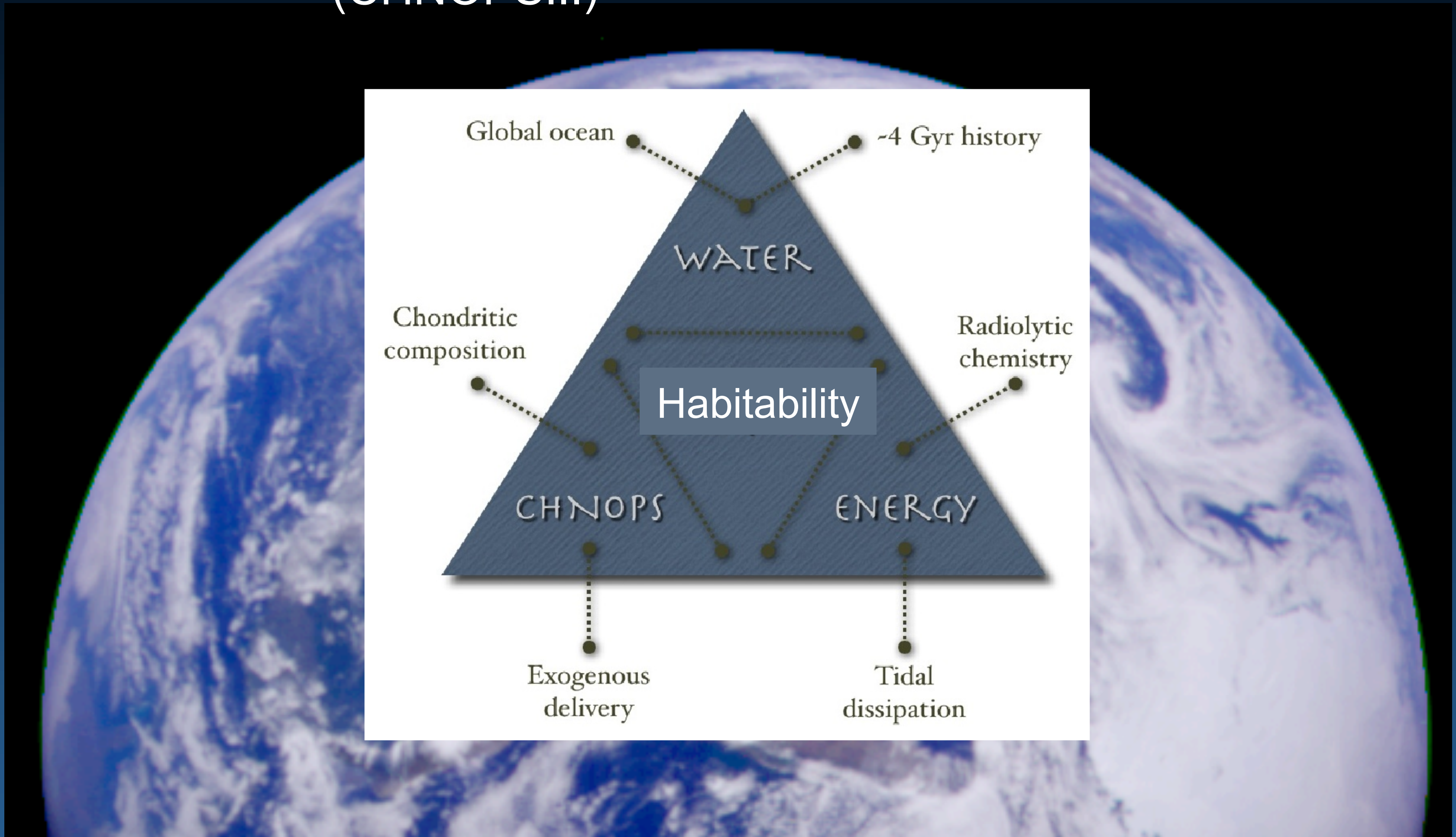
Habitability: four requirements

water 

essential elements (CHNOPS...) 

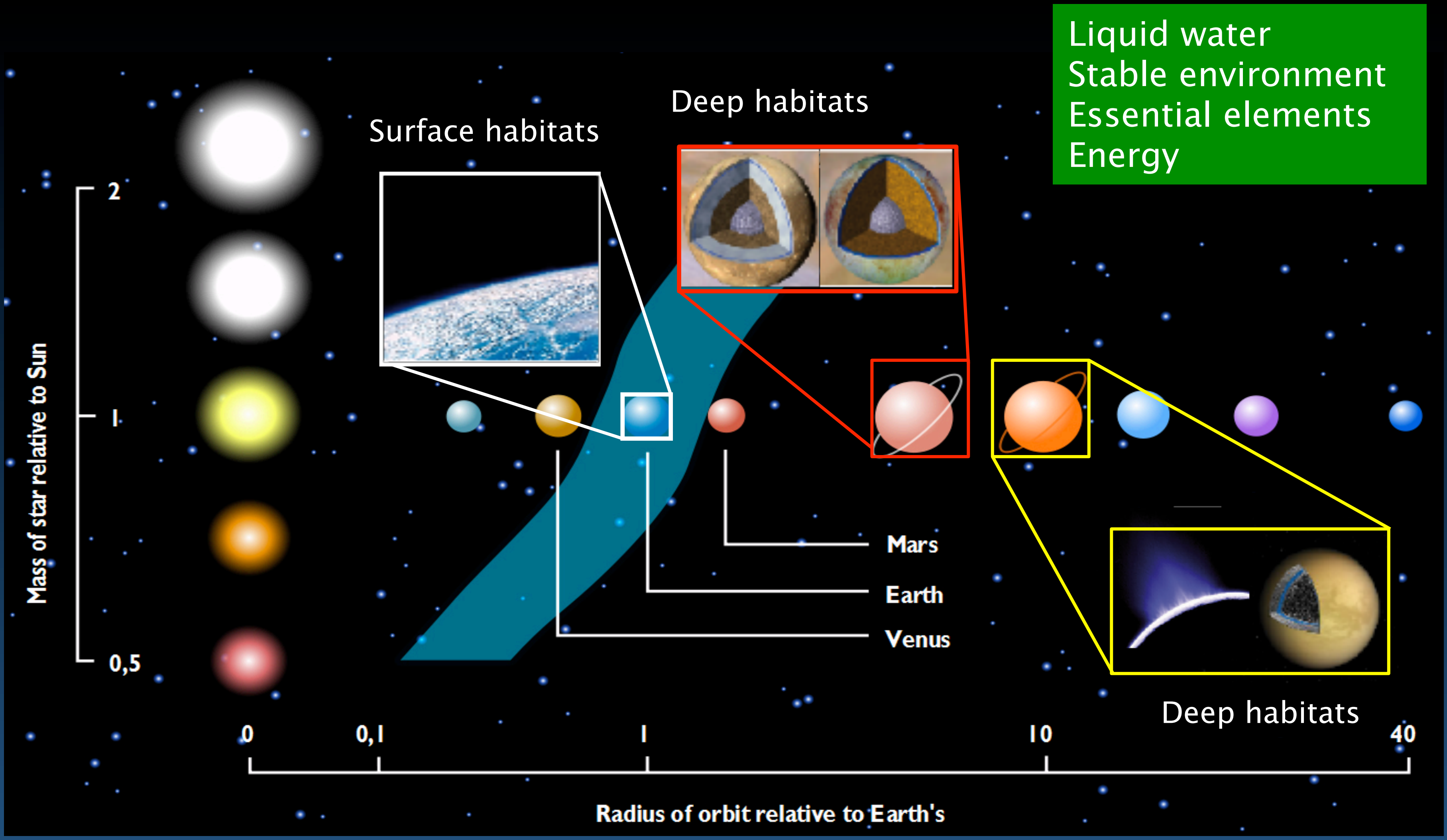
chemical energy 

stable environment 



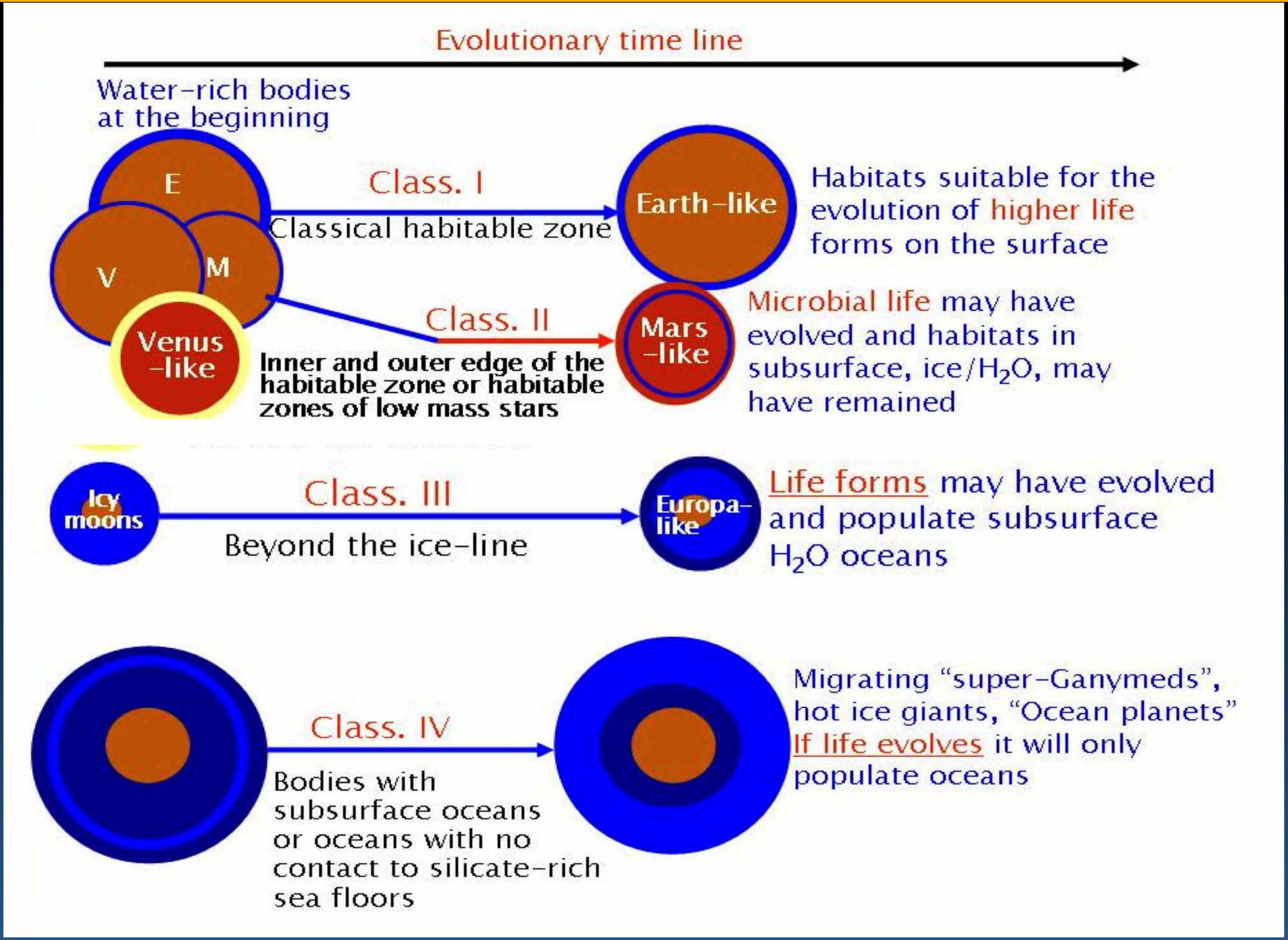
Habitability in the Solar System: extended HZ

Are icy satellites like Ganymede, Europa, Titan or Enceladus habitable worlds ?



The habitable zone is not restricted to the Earth's orbit…

What are the habitable worlds?

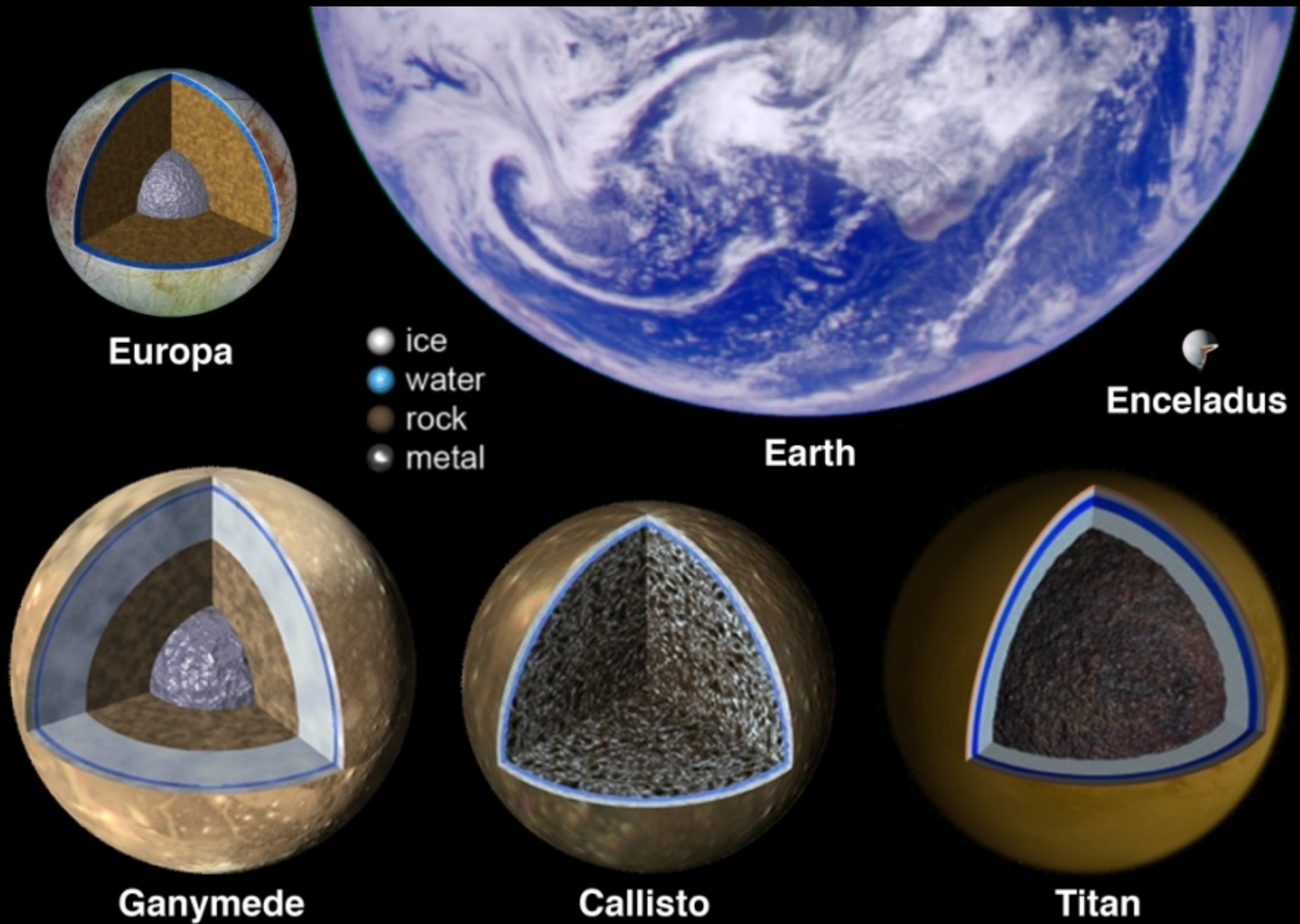


Lammer et al., 2009

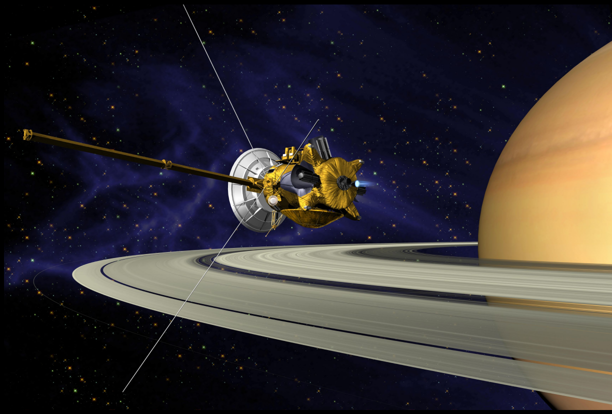
Oceans in the Solar System

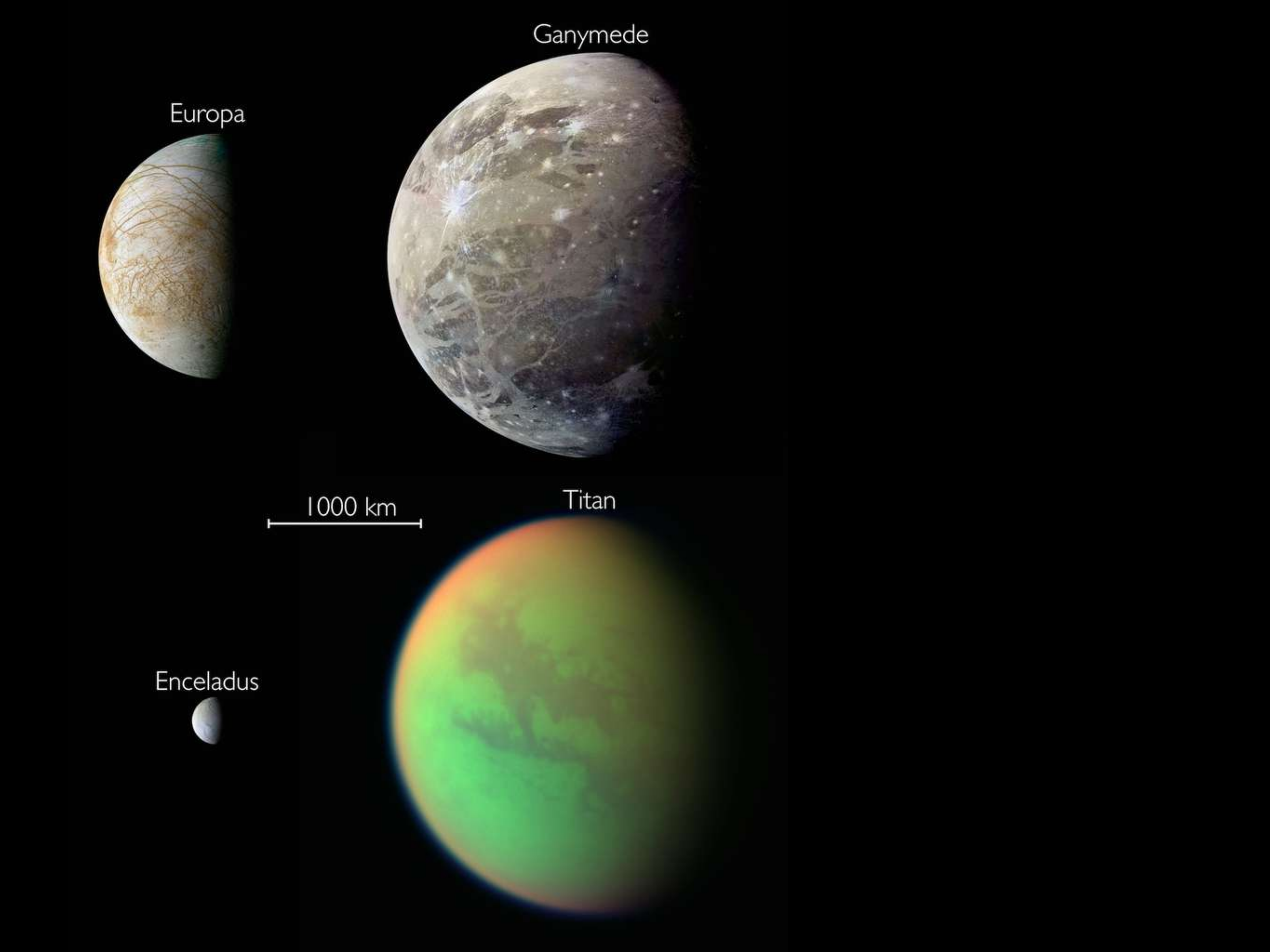
(mass percent of liquid water between parenthesis, excluding water ice)

Credit: PHL @ UPR Arecibo, NASA


Europa
ice
water
rock
metal
Earth
Enceladus
Ganymede
Callisto
Titan


Galileo Begins Jupiter Orbit
Dec. 7, 1995





Ganymede
Europa
1000 km
Titan
Enceladus

What are the habitable worlds in the outer solar system ?
Around JUPITER

Habitats in the Jupiter system

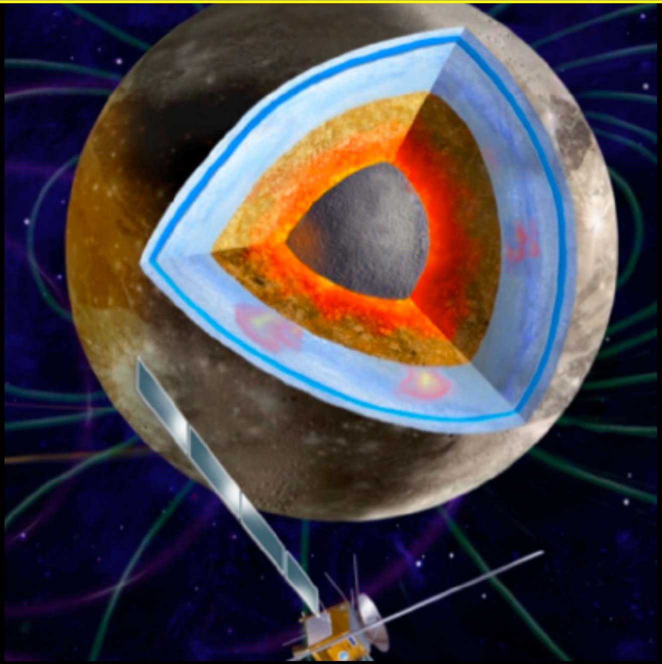
Emergence of the habitable zone around Jupiter

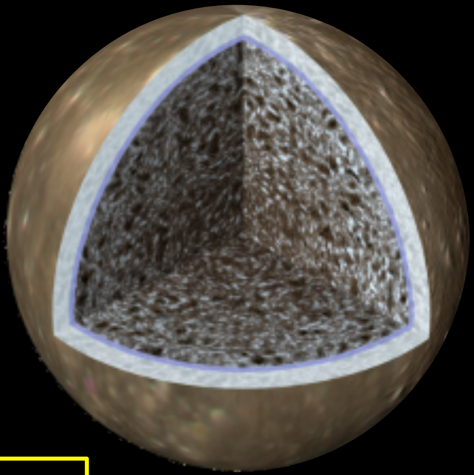
Three large icy moons to explore

Ganymede - class IV

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

- Best example of liquid environment trapped between icy layers





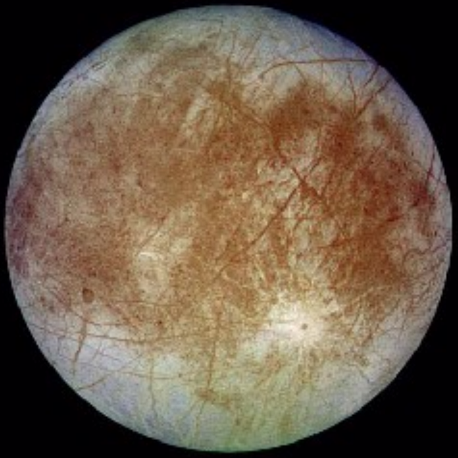
Callisto - class IV

- 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?

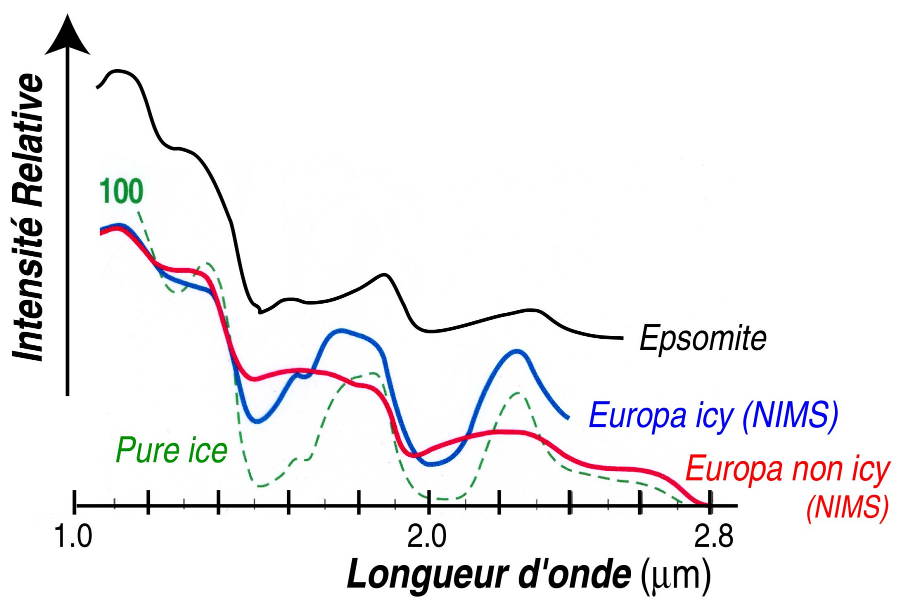
- Best example of liquid environment in contact with silicates



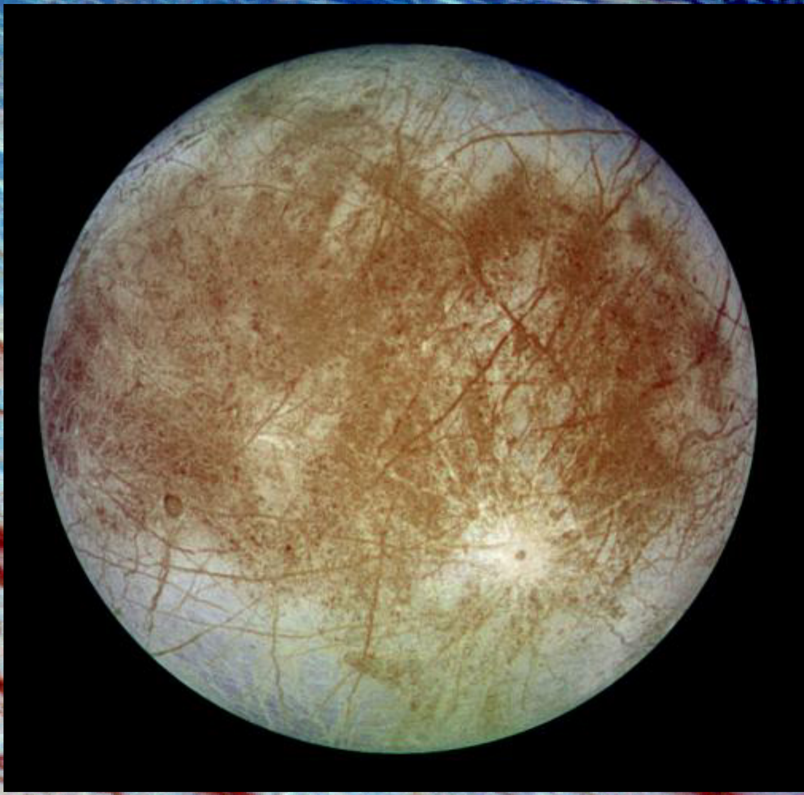
About the existence of deep liquid layers : EUROPA

Hyperspectral evidences

Composition of ices

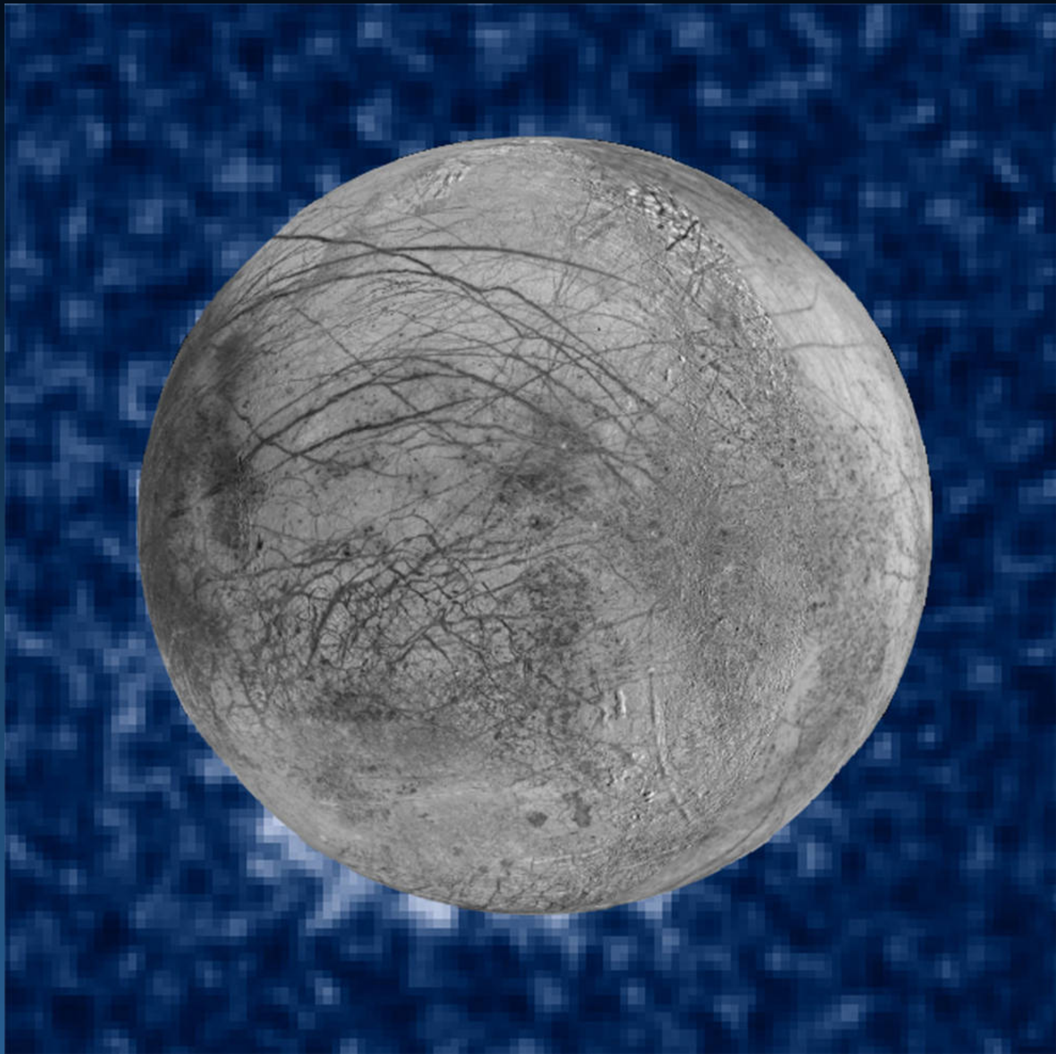


from McCord et al. (1999)



About the existence of deep liquid layers : EUROPA

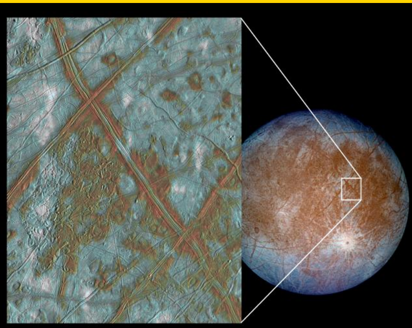
Water plumes on Europa

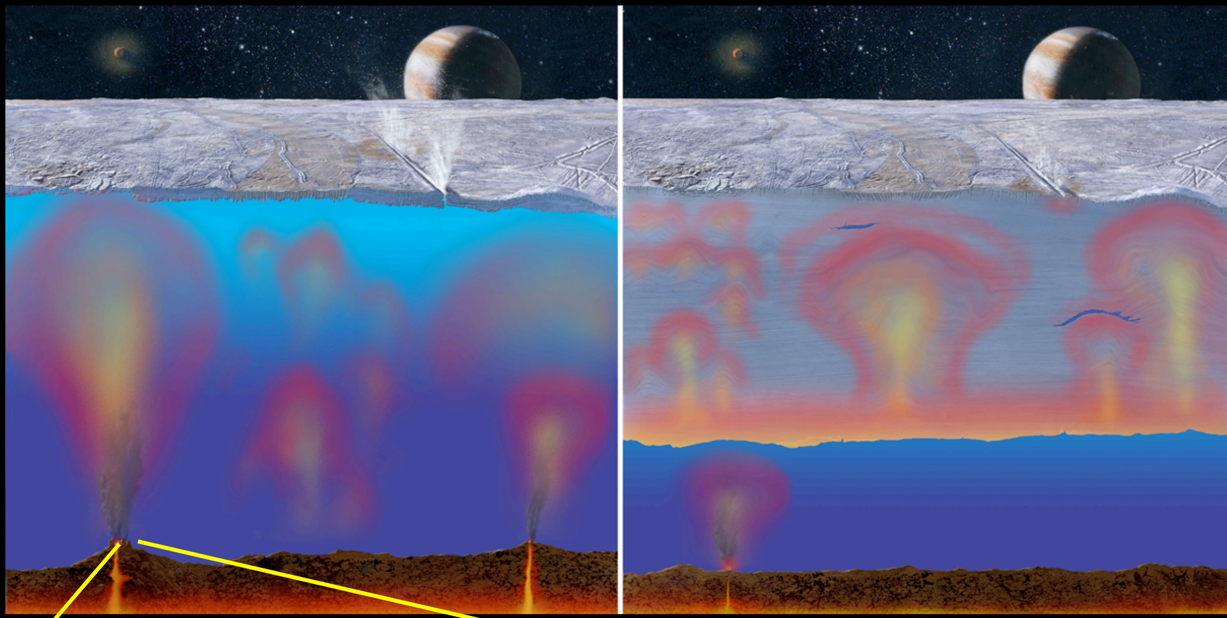


Credits: NASA/ESA/W. Sparks (STScI)/USGS Astrogeology Science Center

What are the habitable worlds?

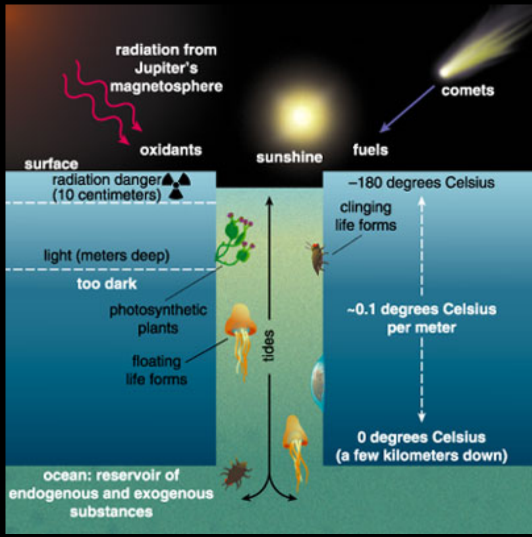
Class III : subsurface oceans in contact with silicates - Europa





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 $H_2O \Rightarrow$ oxidants.
  - Mantle contact: serpentinization and possible hydrothermal activity
- Relatively stable environment:
  - Large satellite retains heat.
  - But activity might not be steady-state.

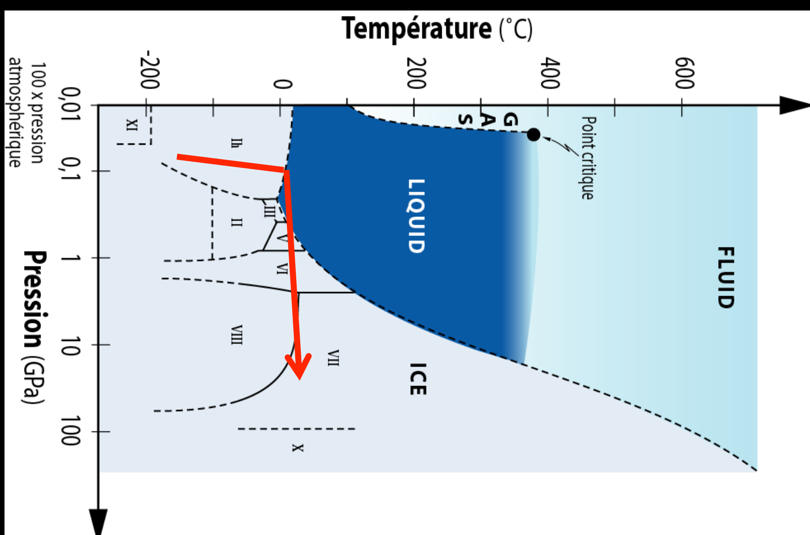


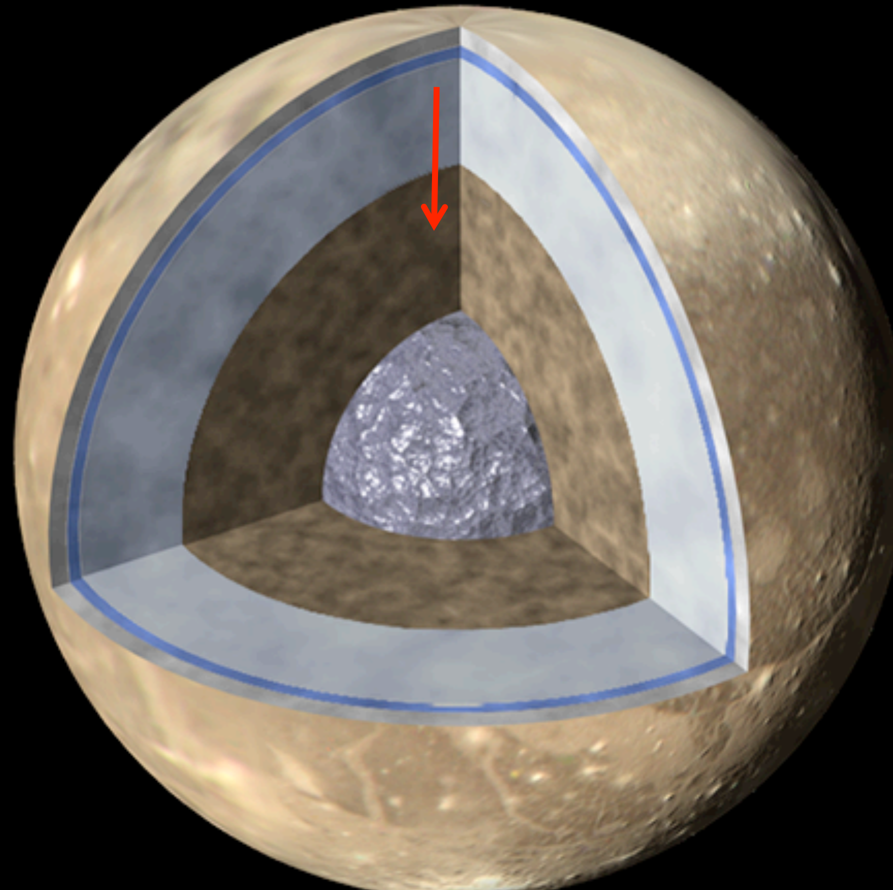
What are the habitable worlds?

Class IV : subsurface oceans without any contact with the silicates

Ganymede-like

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





H2O ice and liquid diagram studied since 1912 (Bridgman)

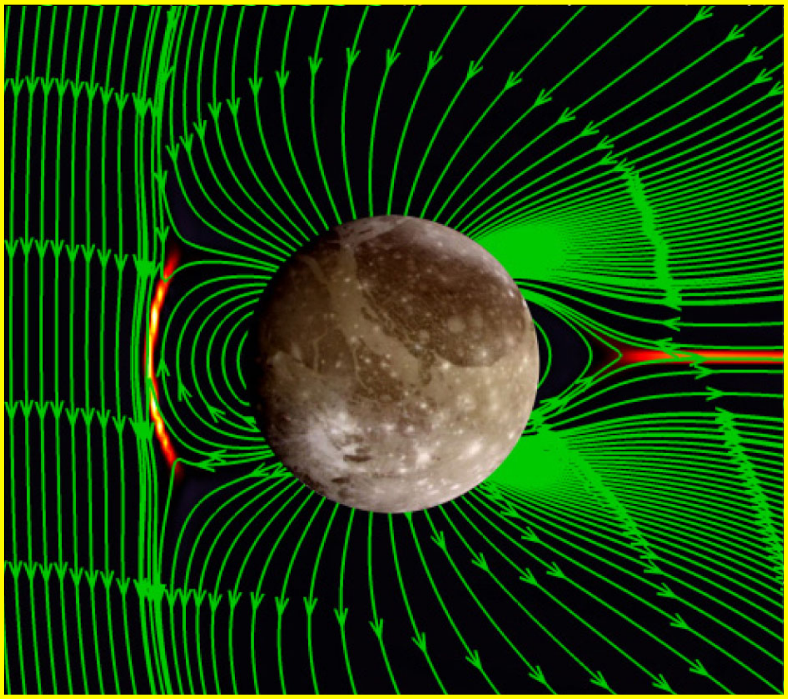
Modern experiments are devoted to complex mixtures and indicate you can have liquid between ice layers.

About the existence of deep oceans : GANYMEDE

Galileo evidences

- **Induced magnetic field from interaction of jovian magneto with conducting layer (ocean?)**

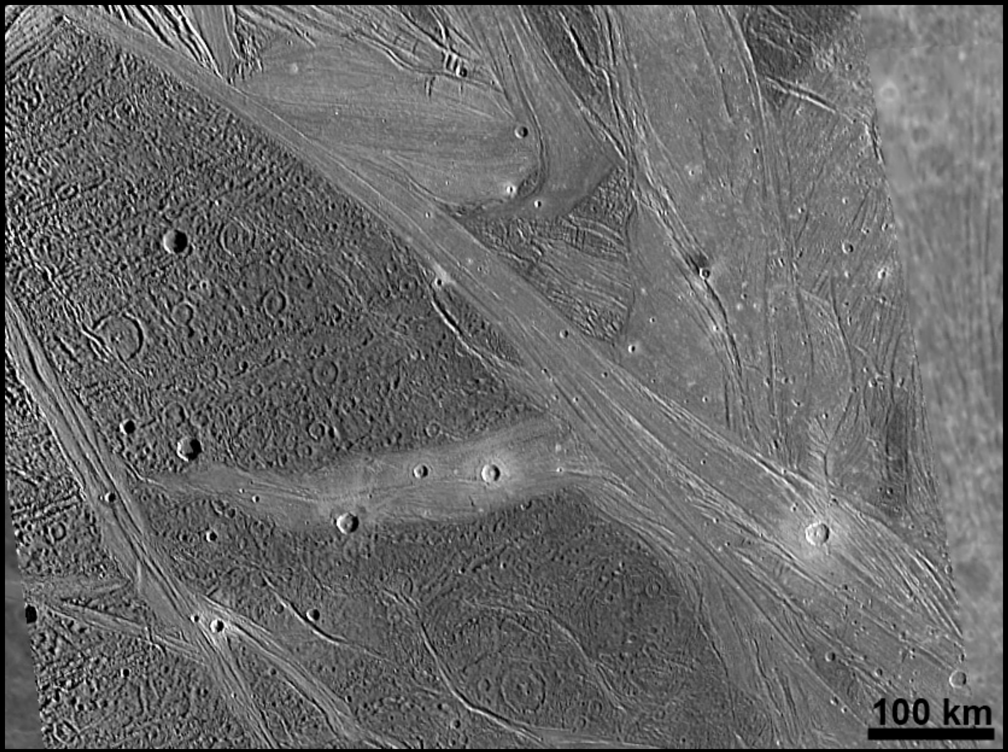
Observed but not characterised



- Own internally-driven dipole magnetic field
- Interaction of Ganymede's mini-magnetosphere with Jupiter's

Geologic activity

Indications for young surface from water flooding



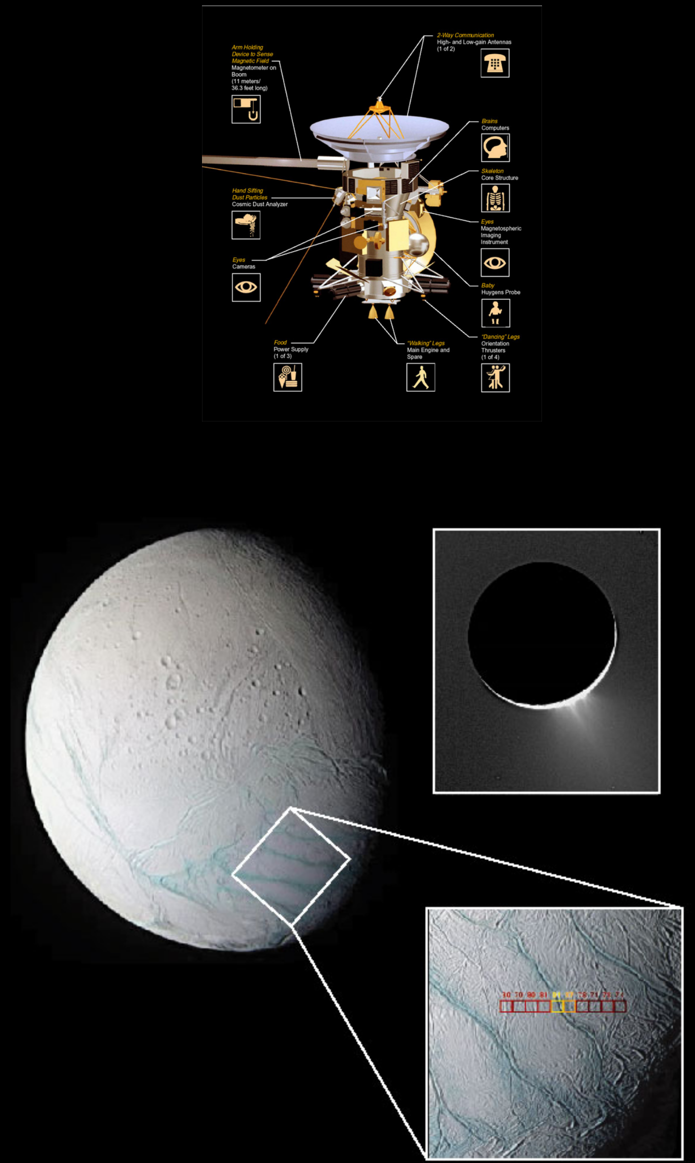
Questions

- ✧ **Which depth?**
- ✧ **Which size?**
- ✧ **What is its composition?**

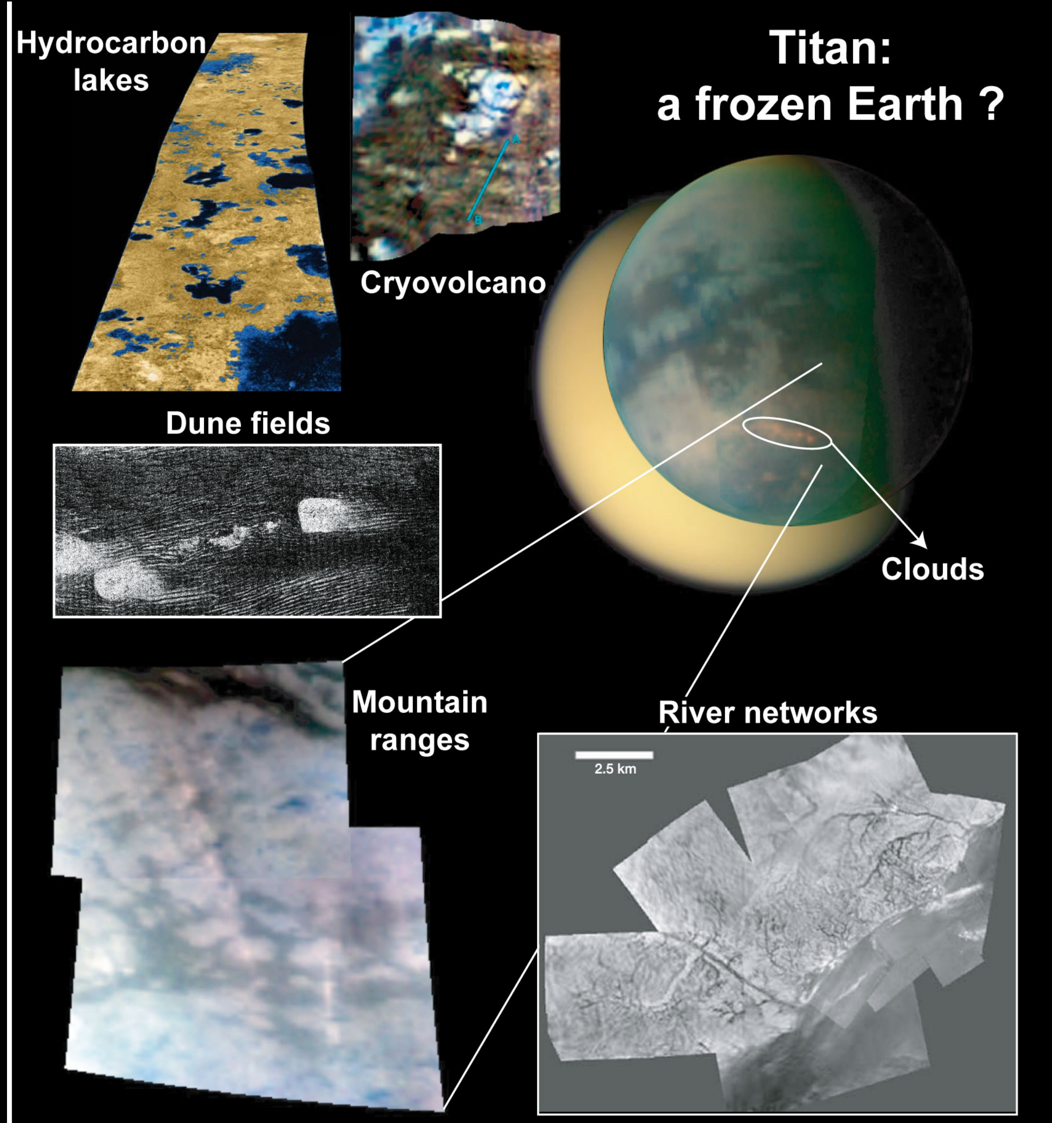
What are the habitable worlds in the outer solar system ? Around SATURN

Habitats in the Saturnian system

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

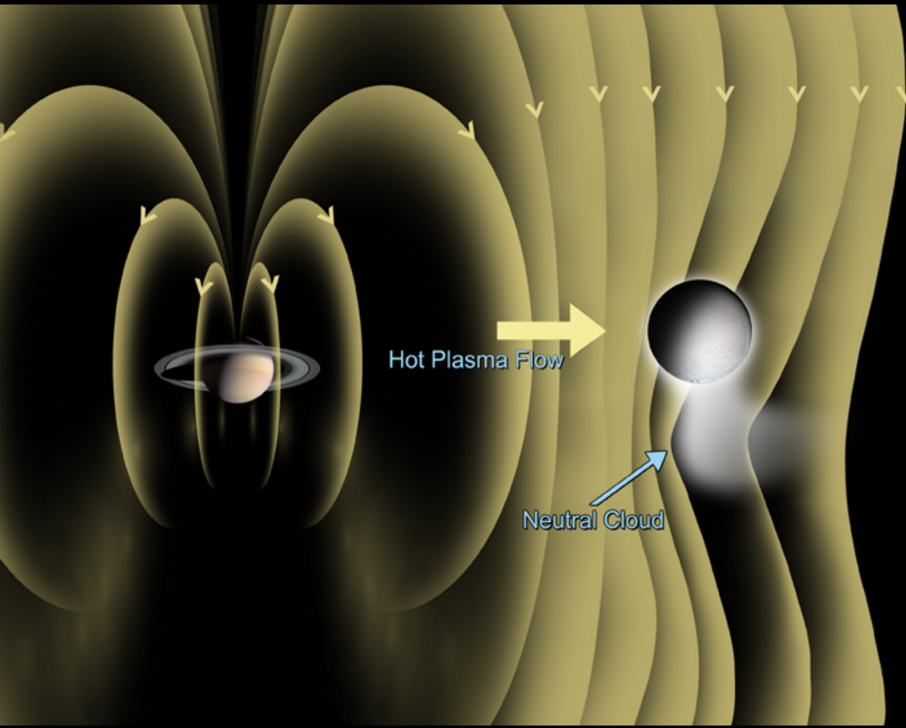


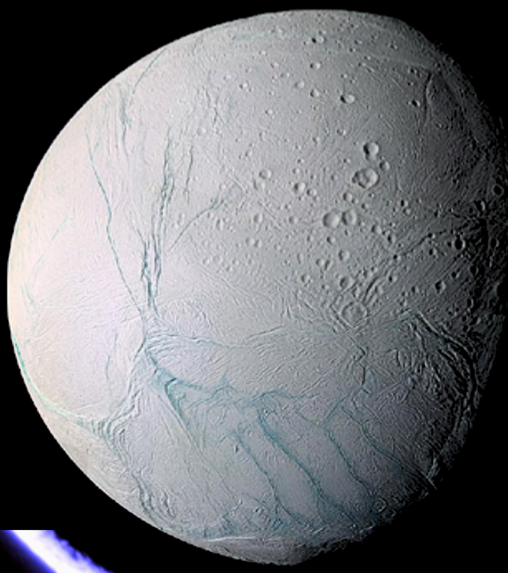
Enceladus

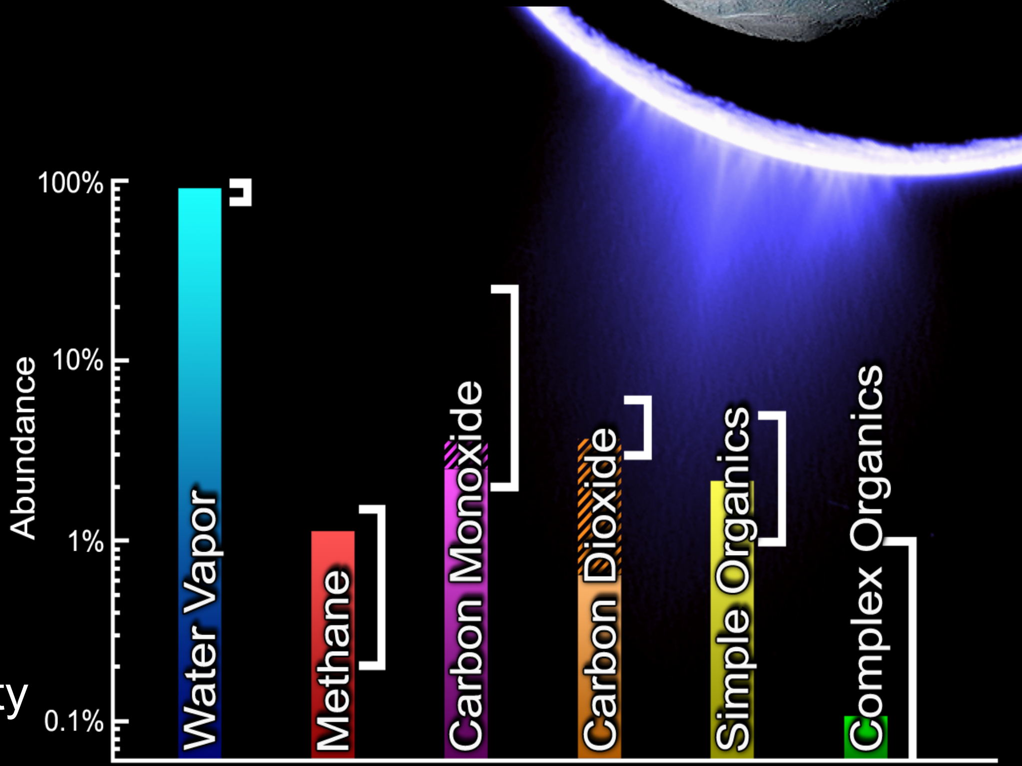


Titan

Enceladus plumes





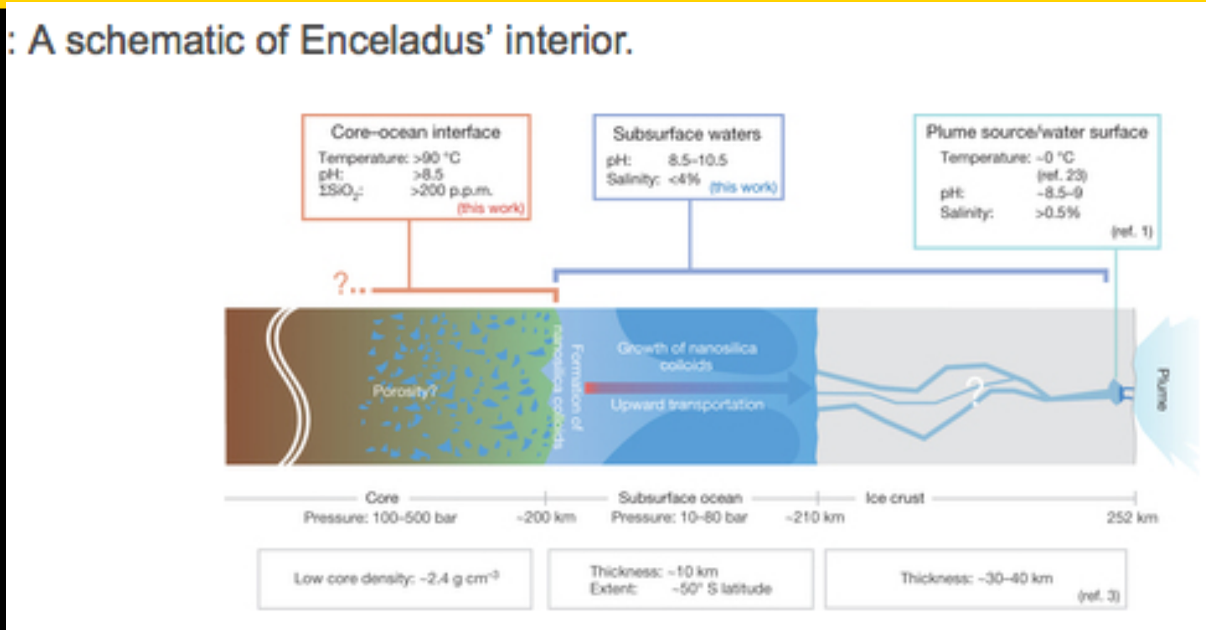


White brackets show range of cometary values

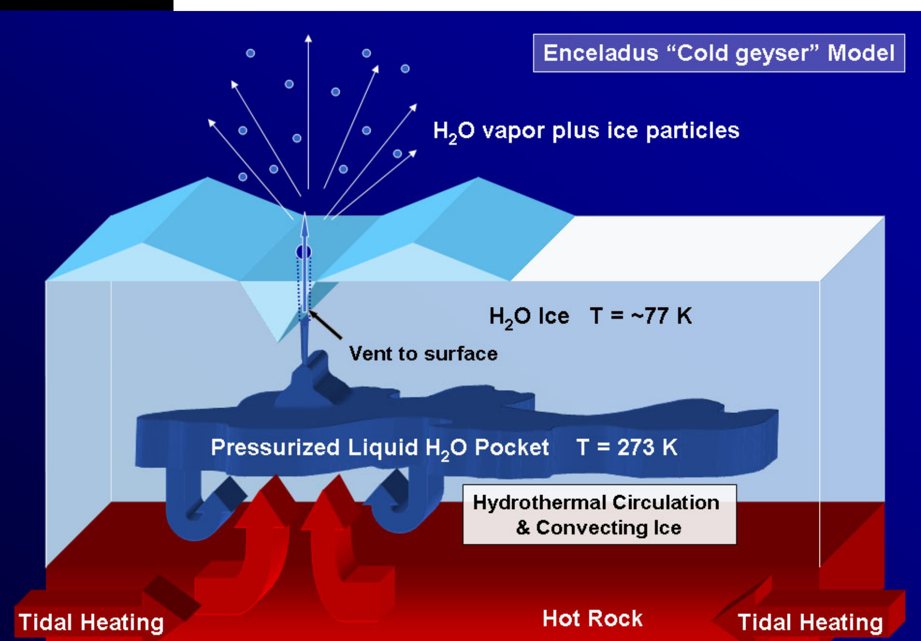
- **What is the origin of the plumes**
- **Replenishment of E-ring?**
- **Water vapor ejecta far away from the Sun** (strong implications for the habitability zones)
- **Indications for the presence of organic chemistry**

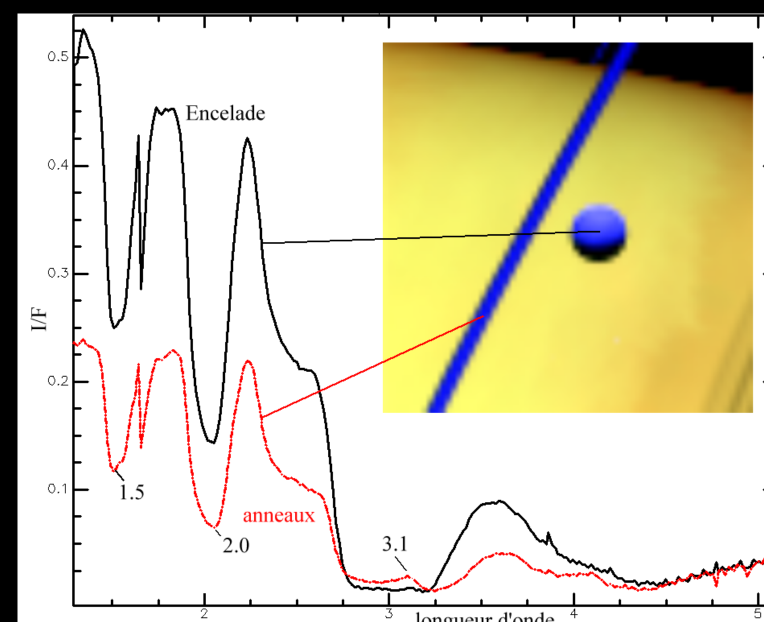
What are the habitable worlds in the outer solar system ? Around SATURN

Class III : subsurface oceans in contact with silicates –Enceladus

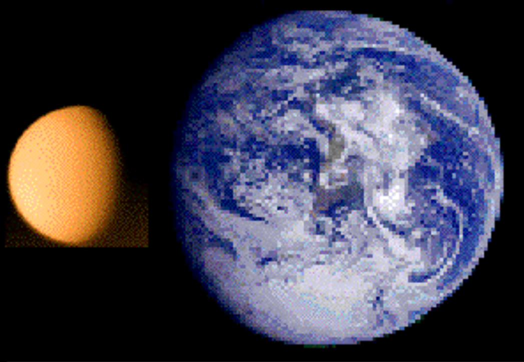


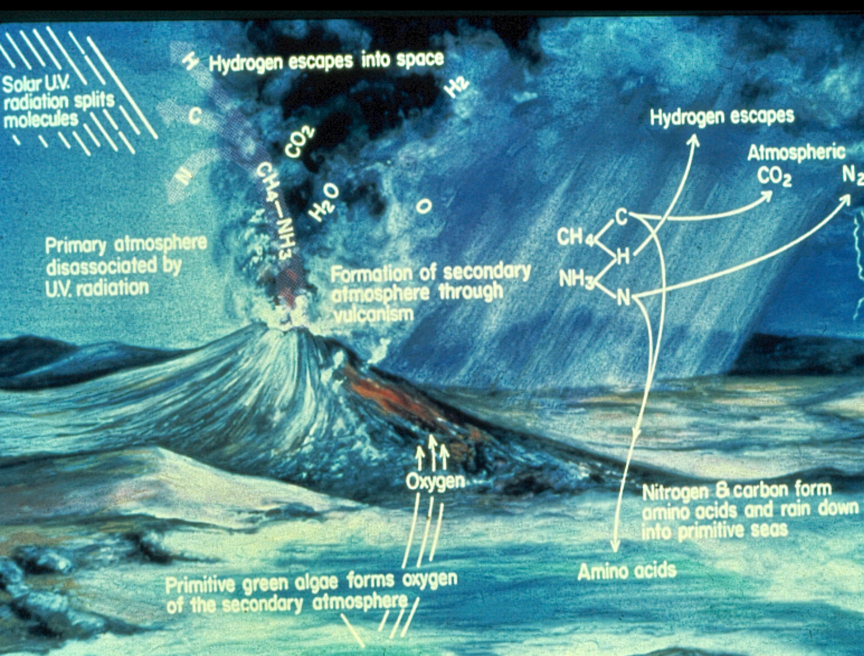
From Hsu et al. 2015

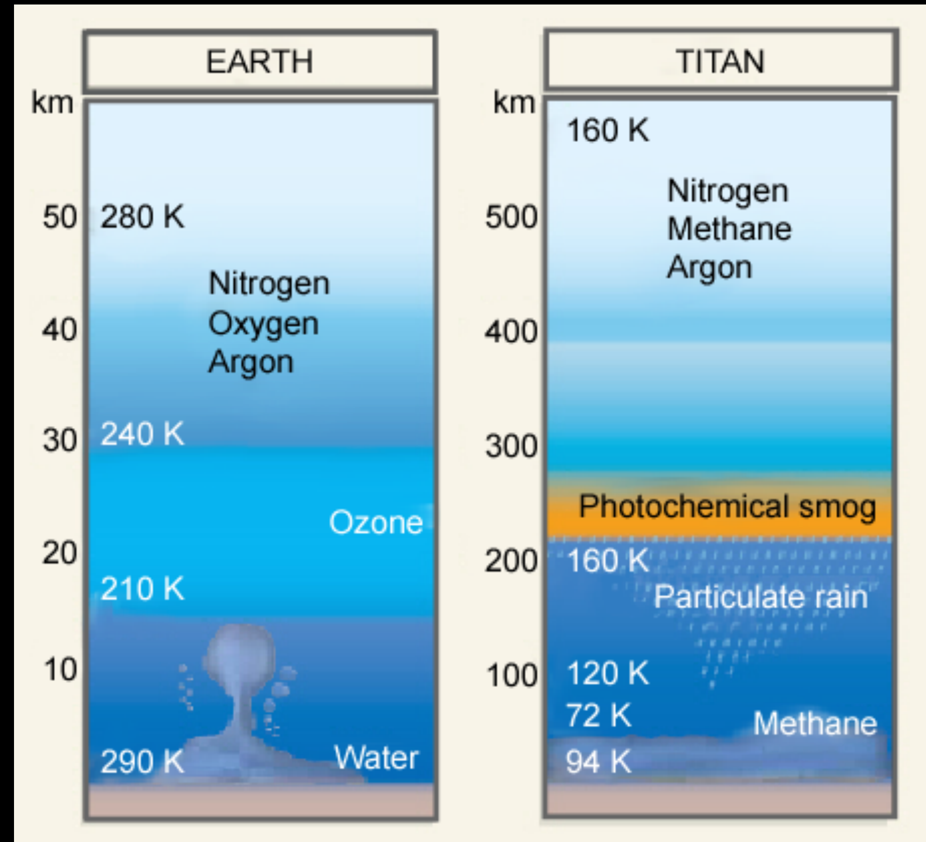




Titan and the Earth

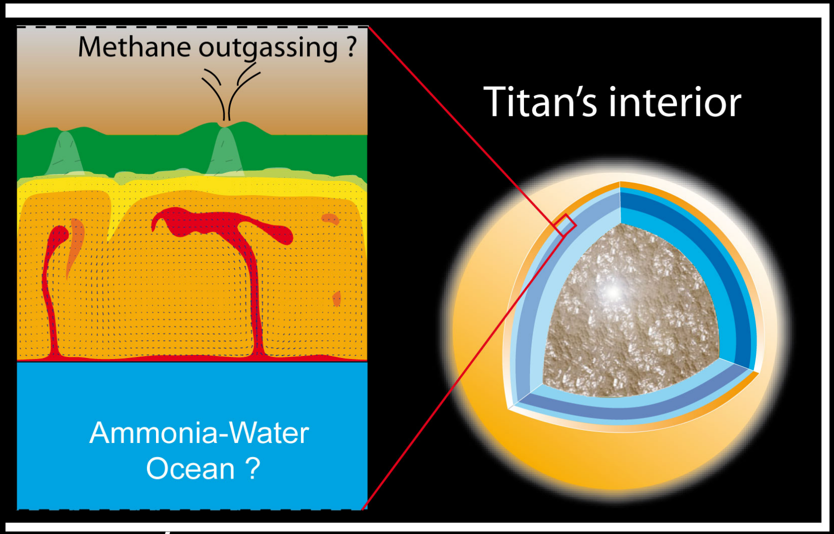




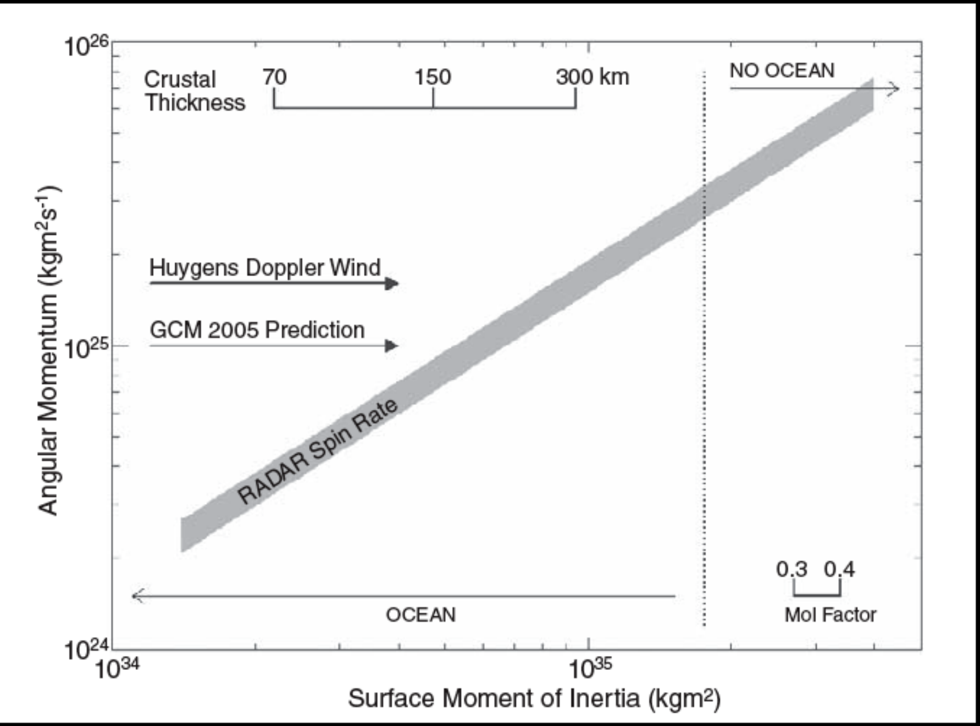


Titan provides a good analogue as a natural laboratory in which chemical and physical processes can be studied on a planetary scale and help us understand early chemical evolution in the primordial atmosphere on Earth

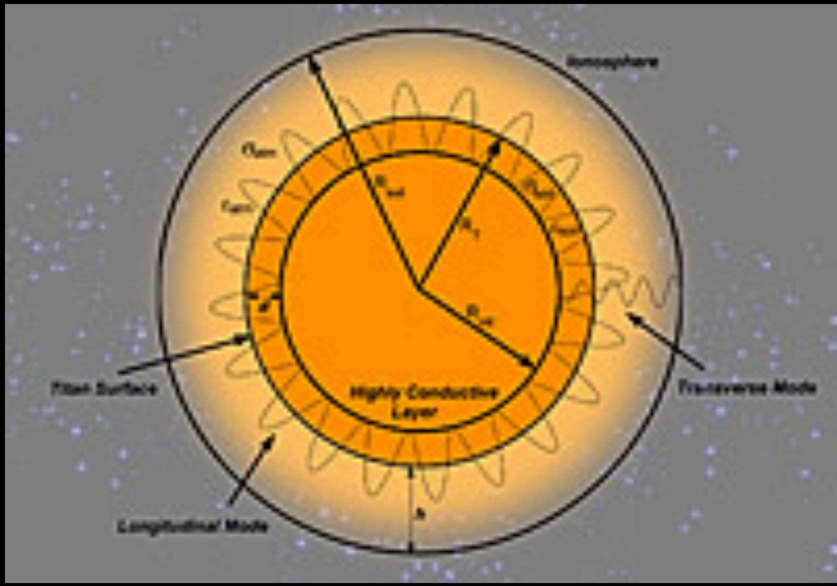
Titan's subsurface ocean



Titan's internal structure (Tobie et al. 2006)



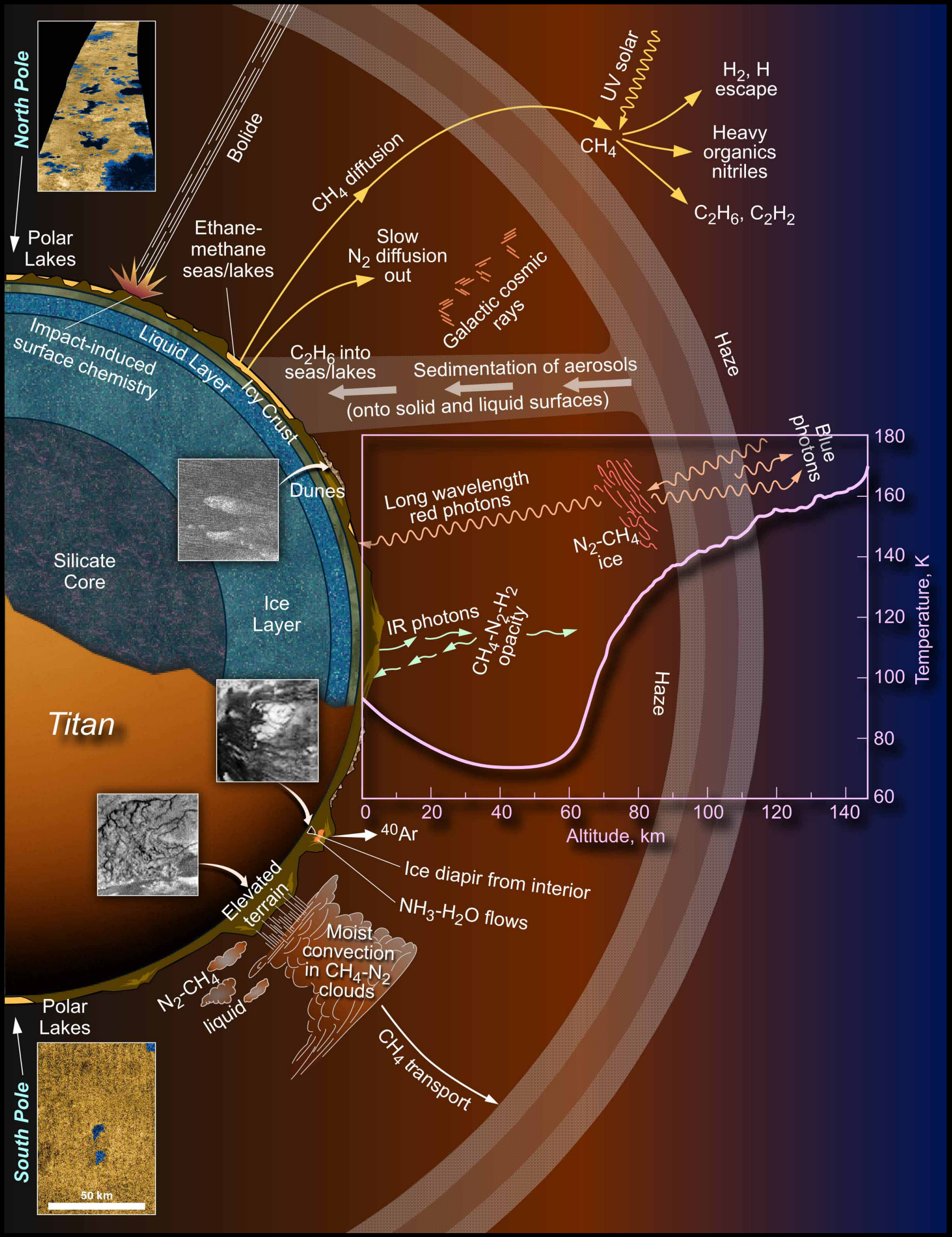
Titan's spin and large tides on the surface indicate the presence of an internal liquid water ocean between ice layers (less et al., 2012)



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

Titan as an astrobiological object

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



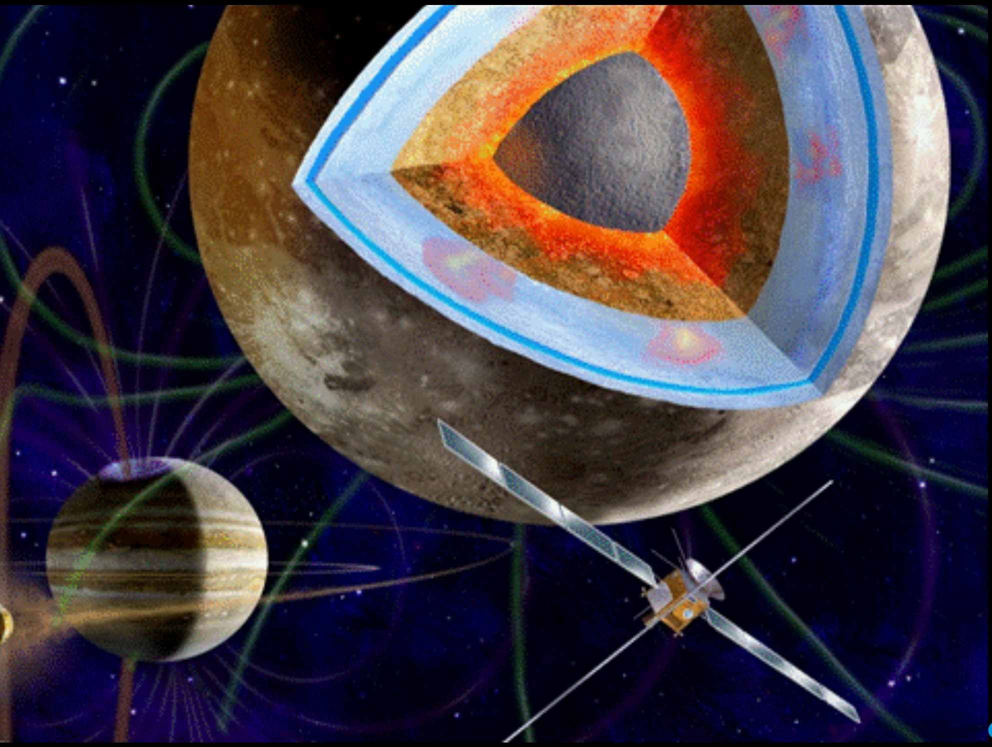
Habitable worlds in the outer solar system ?

Future exploration

Need for further in-depth and in situ exploration of the deep habitats and the extended habitable zone around gas giants

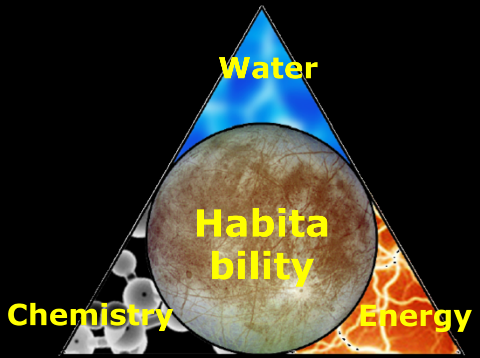
JUICE : Spacecraft, Payload & scenario

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

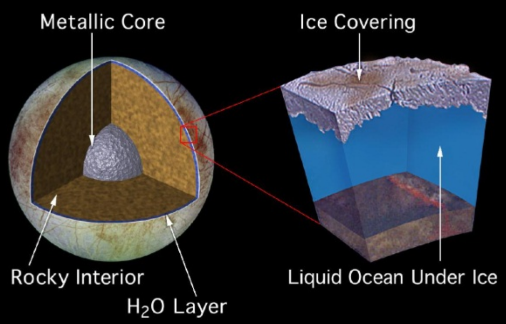
- *What are the conditions for planetary formation and emergence of life?*
- *How does the Solar System work?*

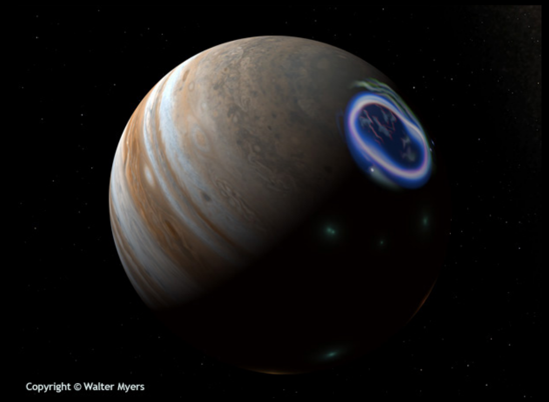
JUICE : the 1st Large CV mission concept

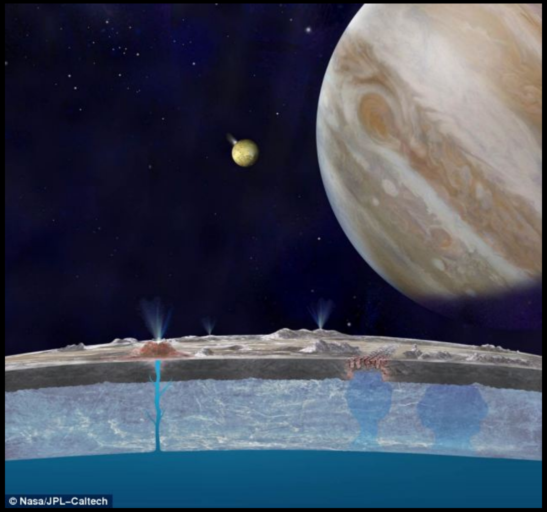
- *Single spacecraft mission to the Jovian system*
- *Investigations from orbit and flyby trajectories*
- *Synergistic and multi-disciplinary payload*
- *European mission with international participation*

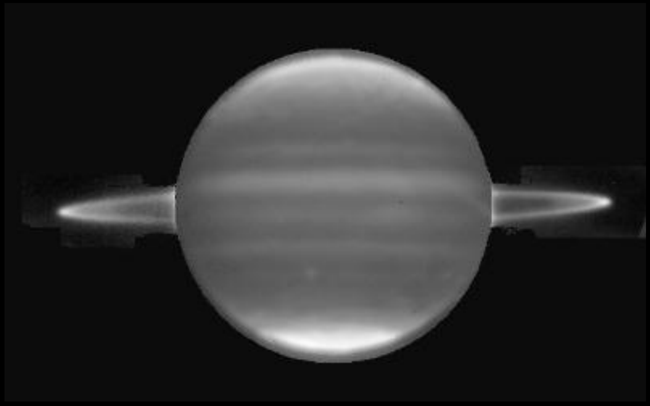
Topics:
Planet, moons, rings, magneto

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





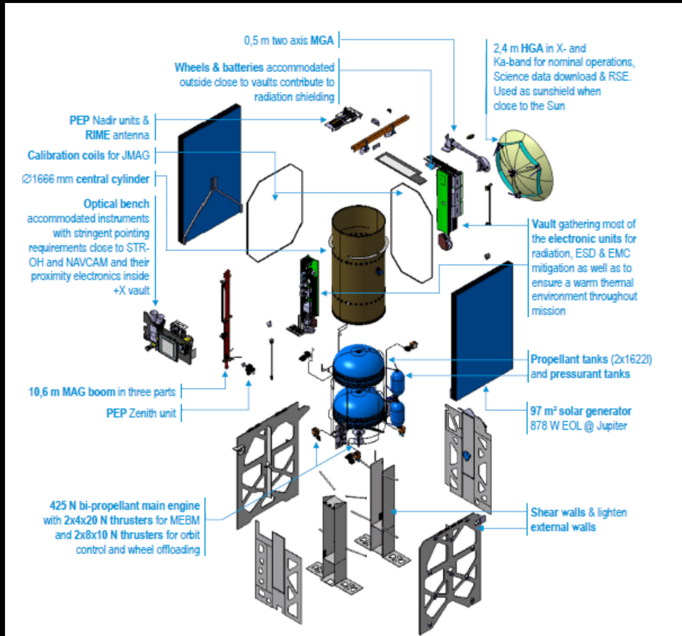


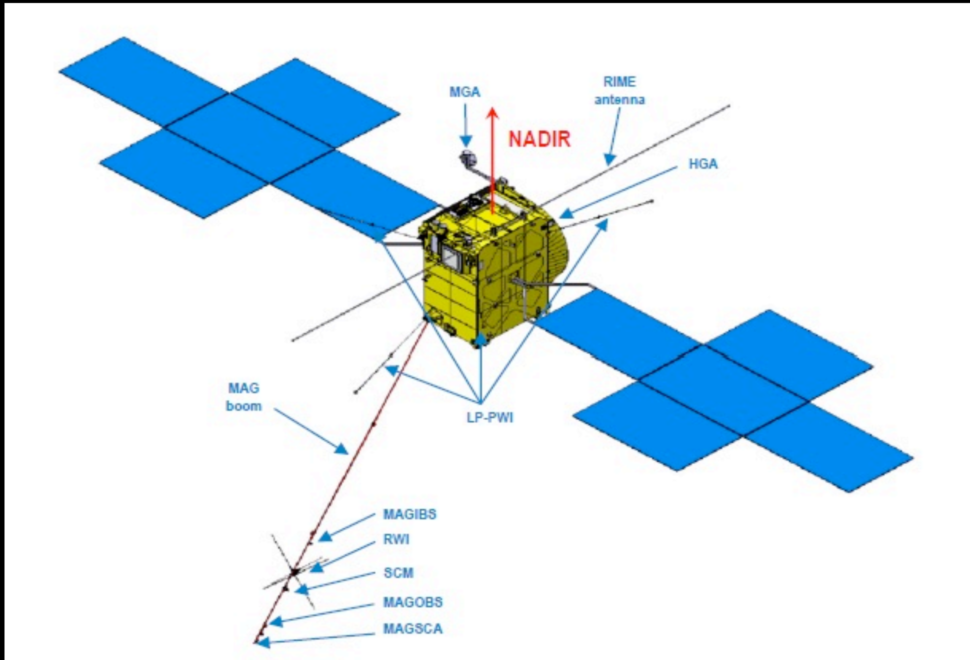


Jupiter system: largest planet, largest storm, fastest rotation, largest magnetic field, largest moon, largest moon system, most active moons

Main features of the spacecraft design

- *Dry mass ~2200 kg, propellant mass ~2900 kg*
- *Launcher - Ariane 5 ECA (mass : ~5.1 tons), High Δv required: 2700 m/s*
- *Payload ~219 kg, ~ 180 -230 W*
- *3-axis stabilized s/c*
- *Power: solar array ~ 70 m², ~ 800 W*
- *HGA: ~3 m, fixed to body, X & Ka-band*
- *Data return >1.4 Gb per day*





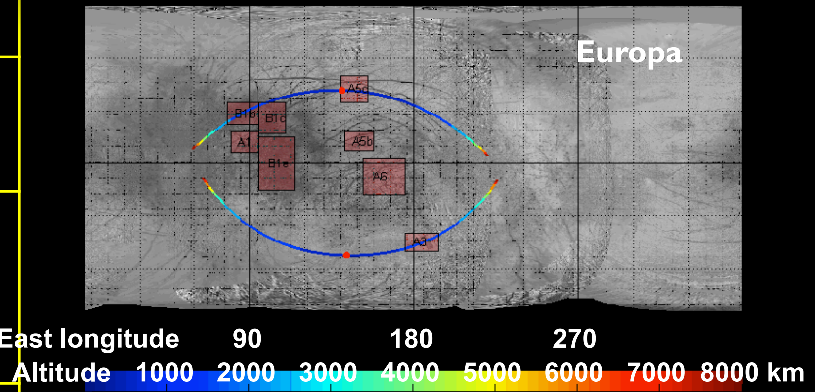
JUICE Payload

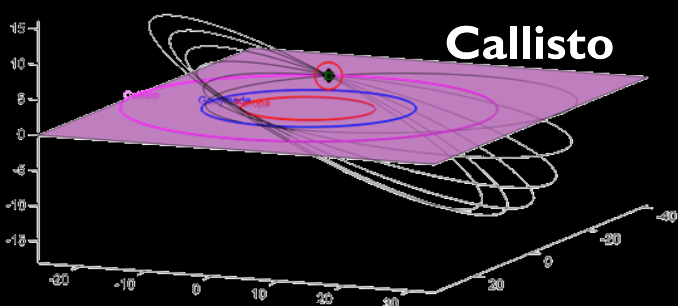
Acronym	PI	LFA	Instrument type
Remote Sensing Suite			
JANUS	P. Palumbo	Italy	Narrow Angle Camera
MAJIS	Y. Langevin G. Piccioni	France Italy	Vis-near-IR imaging spectrometer
UVS	R. Gladstone	USA	UV spectrograph
SWI	P. Hartogh	Germany	Sub-mm wave instrument
Geophysical Experiments			
GALA	H. Hussmann	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

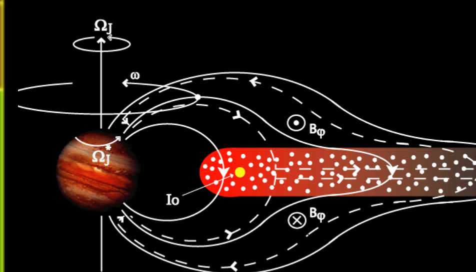
Mission design

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 (TBC)	 150 days 102 days 30 days
Total mission at Jupiter	3 years

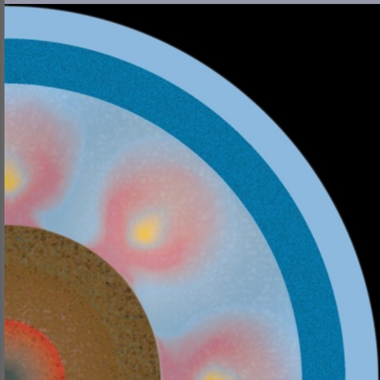






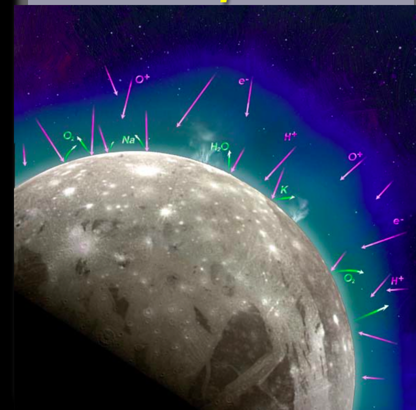
Ganymede: planetary object and potential habitat

Ice shell, ocean, deeper interiors

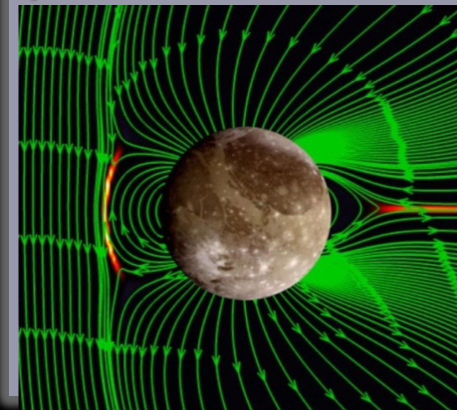


Geology, surface composition

Atmosphere, ionosphere

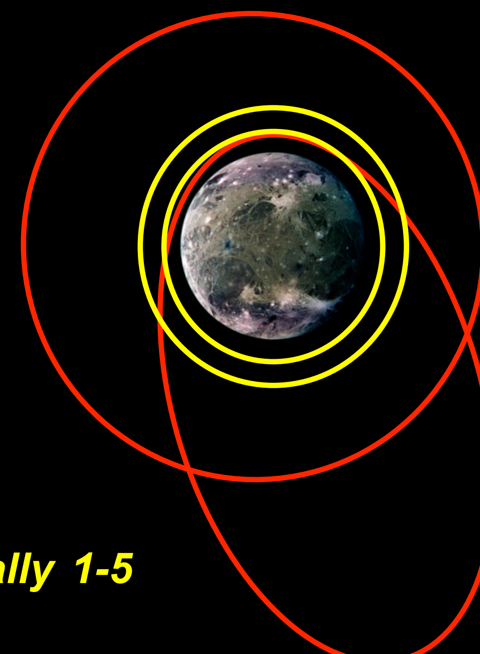


Magnetosphere, plasma environment



Main investigations

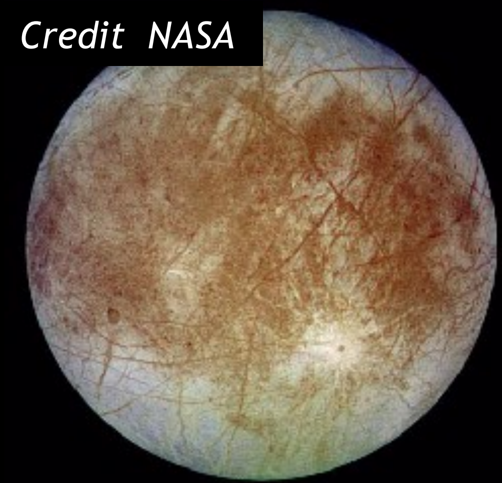
- *Elliptical (1000x10000 km) & high (~5000 km) circular orbit*
- *Medium (500 km) circular orbits*
- *Favorable illumination conditions (β-angle 30°-70°)*
- *Dedicated pointing modes*
- *Sub-surface sounding down to ~9 km depth*
- *Imaging: global ~400 m/px, selected targets ~3 m/px*
- *Mineralogical mapping (especially of non-ice materials): globally 1-5 km/px , selected targets ~25 m/px*

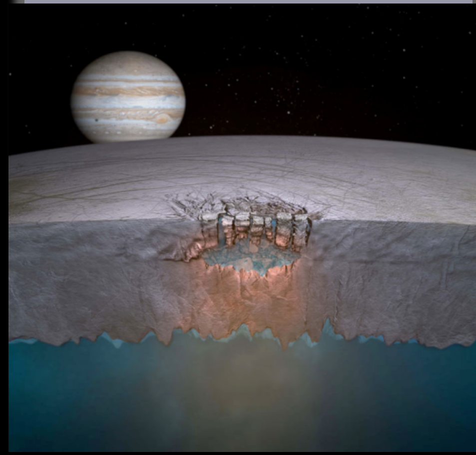


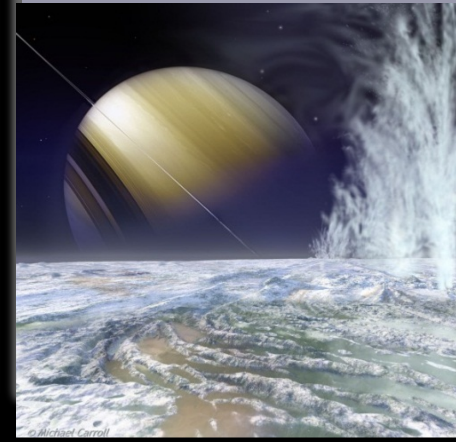
Credit NASA

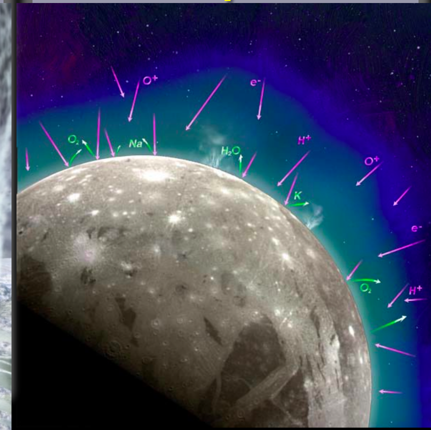
Europa: study of recently active regions

Composition of non-ice material	Liquid sub-surface water	Active processes	Atmosphere, ionosphere





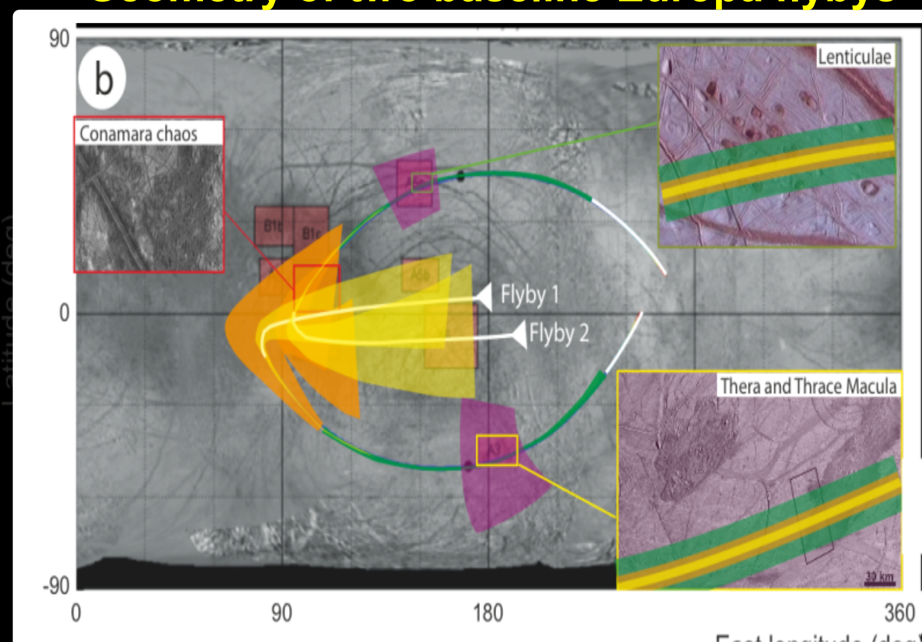




Main investigations

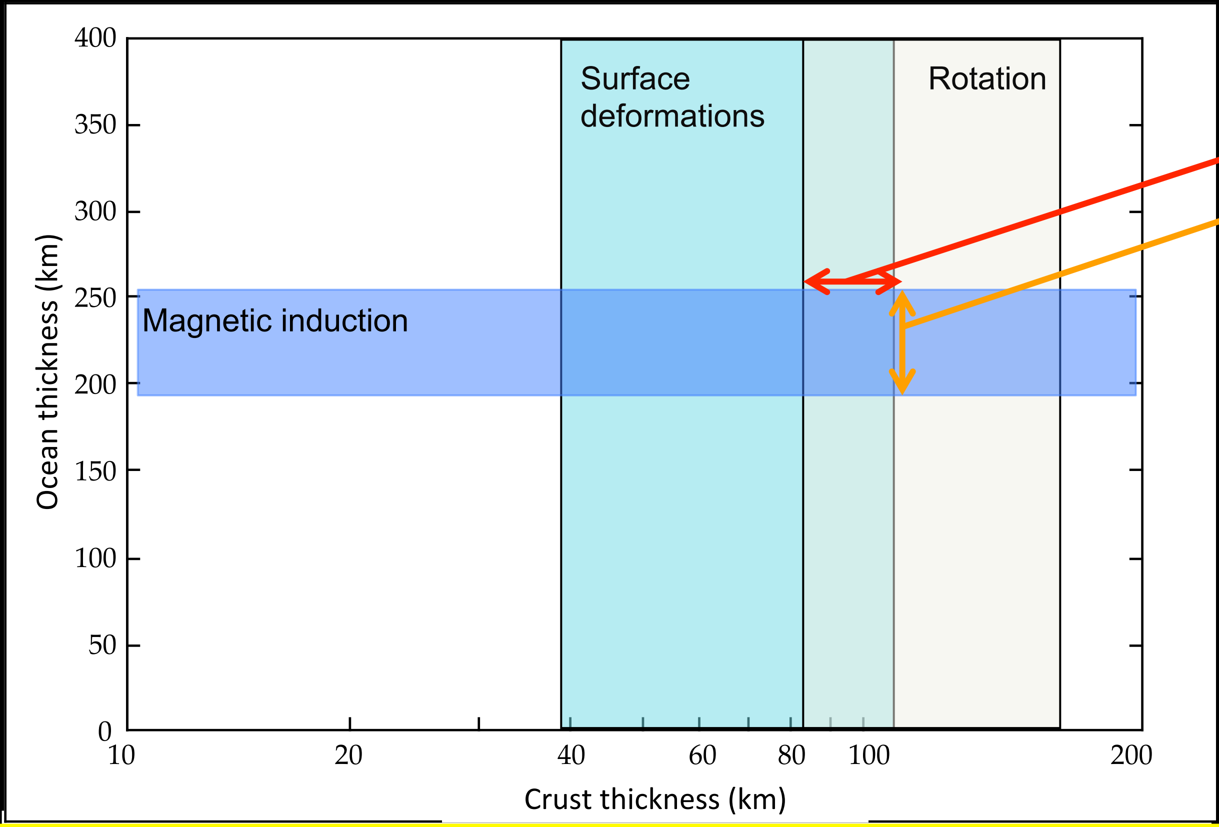
- At least 1 Europa flyby with CA ~400 km over the most active regions
- Favorable illumination conditions at CA
- Anti-Jovian side at CA
- Simultaneous operations of all experiments (including 3GM as a goal)
- Non-ice materials in selected sites mapped at regional (>5 km/px) and local (<500 m/px) scales & processes in active sites

Geometry of two baseline Europa flybys

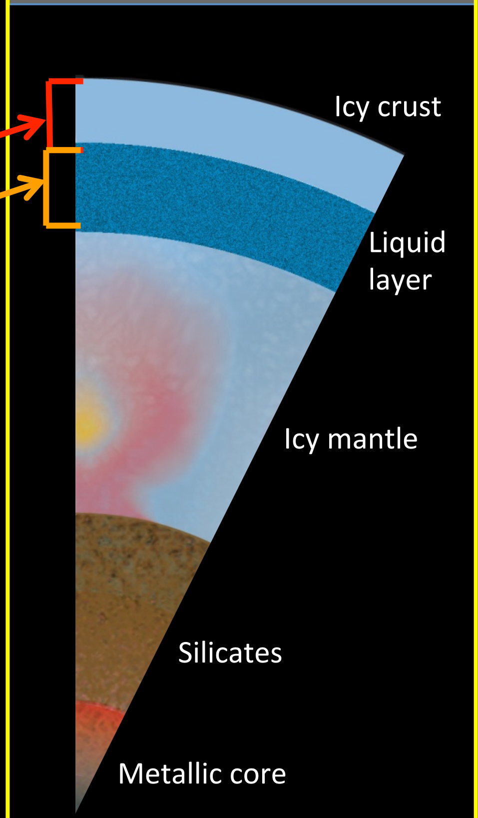


Characterise Ganymede as a planetary object and possible habitat

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



Internal structure



JUICE measurements

- Eccentric orbit ->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

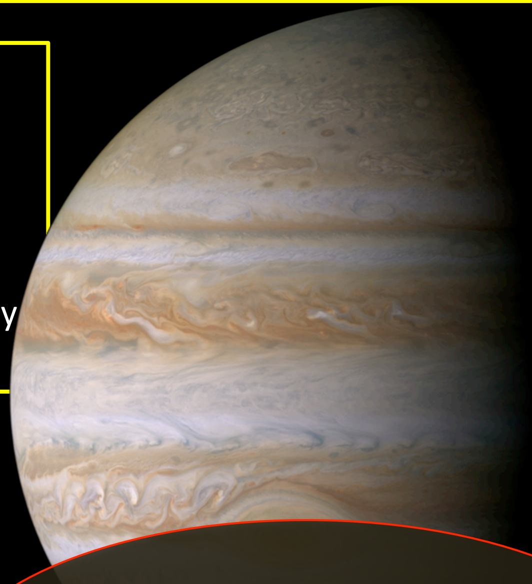
Exploration of the Jupiter system

JUICE

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

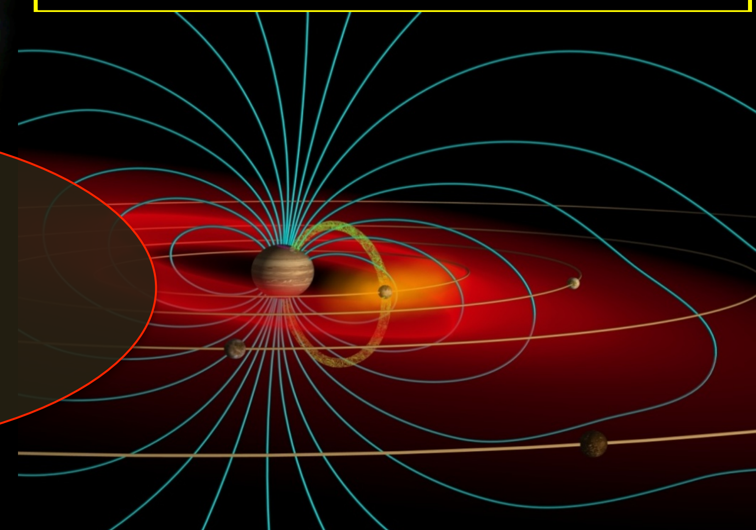
Jupiter

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



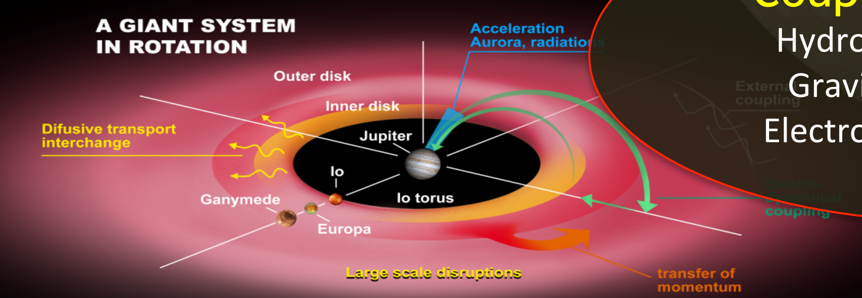
Magnetosphere

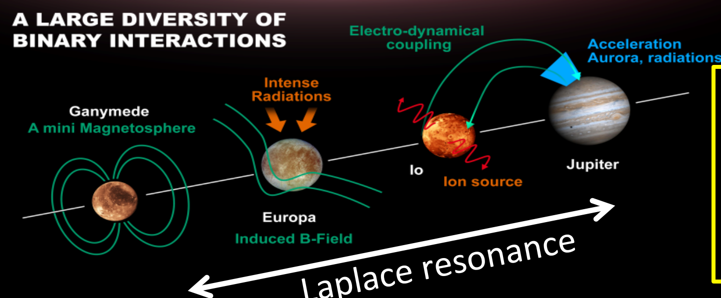
- Largest object in our Solar System
- Biggest particle accelerator in the Solar System
- Unveil global dynamics of an astrophysical object



Coupling processes

Hydrodynamic coupling
Gravitational coupling
Electromagnetic coupling

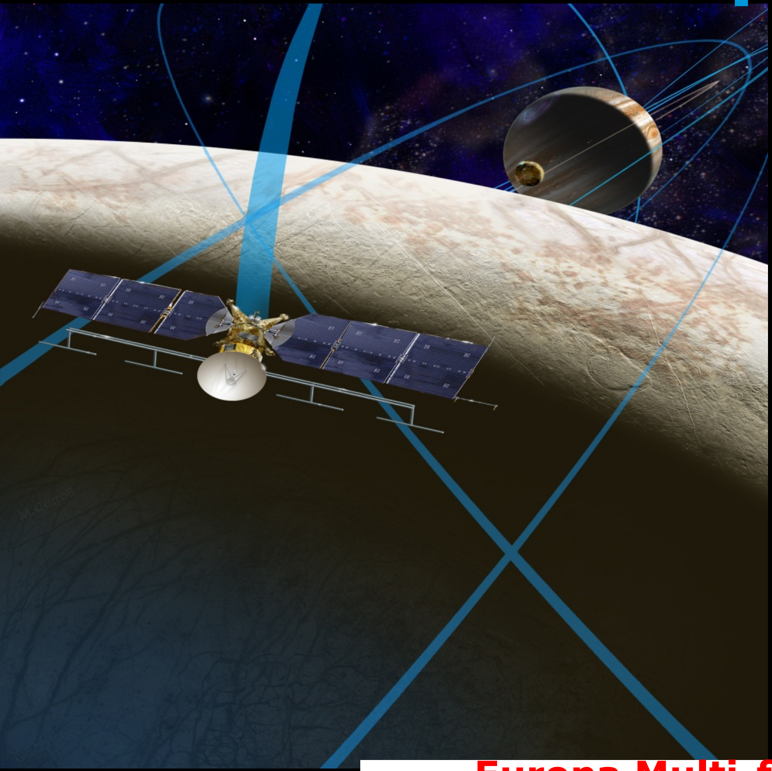




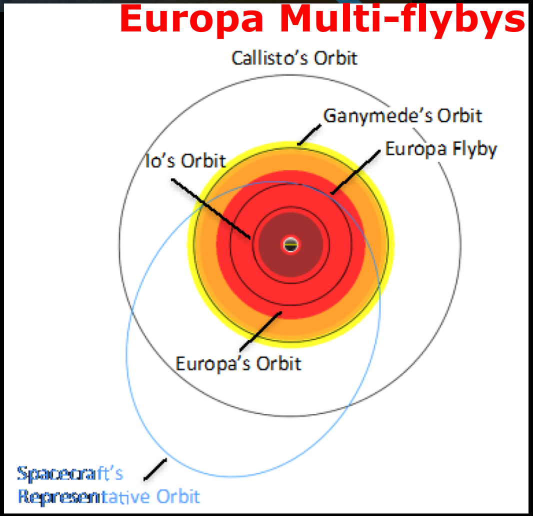
Satellite system

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

NASA Europa "Clipper" mission



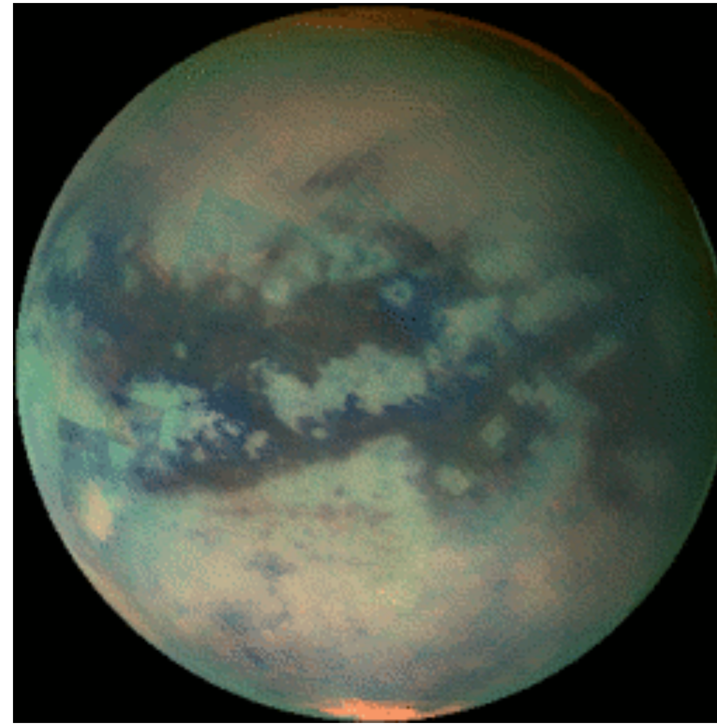
- Spacecraft in orbit around Jupiter
- Science goal: Europa's habitability
- Multiple (45) flybys of Europa
  - Altitudes: 25 – 2700 km
- 9 instruments selected: cameras, magnetometers, radar, dust analyser, spectrometers, plasma + mass spectrometer
- Schedule
  - Start formulation phase in Oct. 2016
  - Launch 2022-2025
  - Cruise: 2 or 7 years
  - Nominal mission: 3-4 years



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

The Saturnian system:
a Post-Cassini mission…

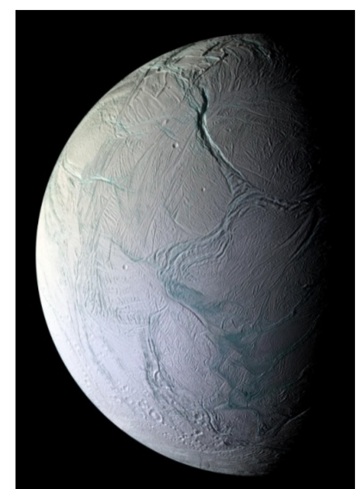
Titan



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

Enceladus

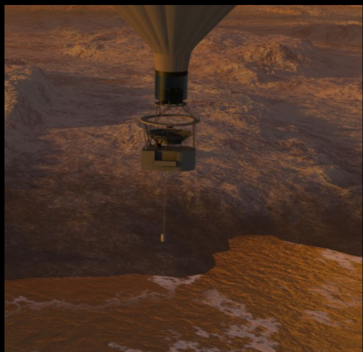
- Complex organic chemistry
- Potential habitat (liquid water under the surface)

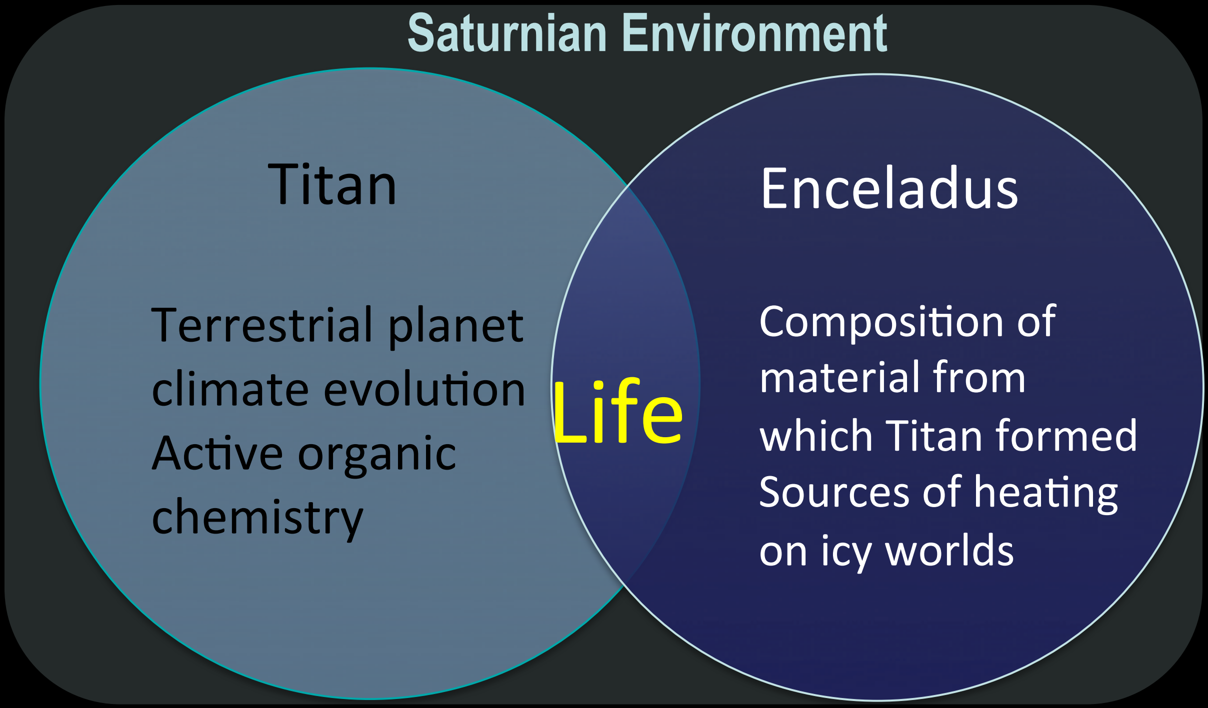


(Titan's astrobiology, F. Raulin, C. McKay, J. Lunine and T. Owen, Chap.IX of "Titan from Cassini-Huygens", B. Brown et al. Eds, Springer, 2009

« Life beyond Earth: habitable worlds in the Universe », A. Coustenis and Th. Encrenaz, CUP, 2013.)

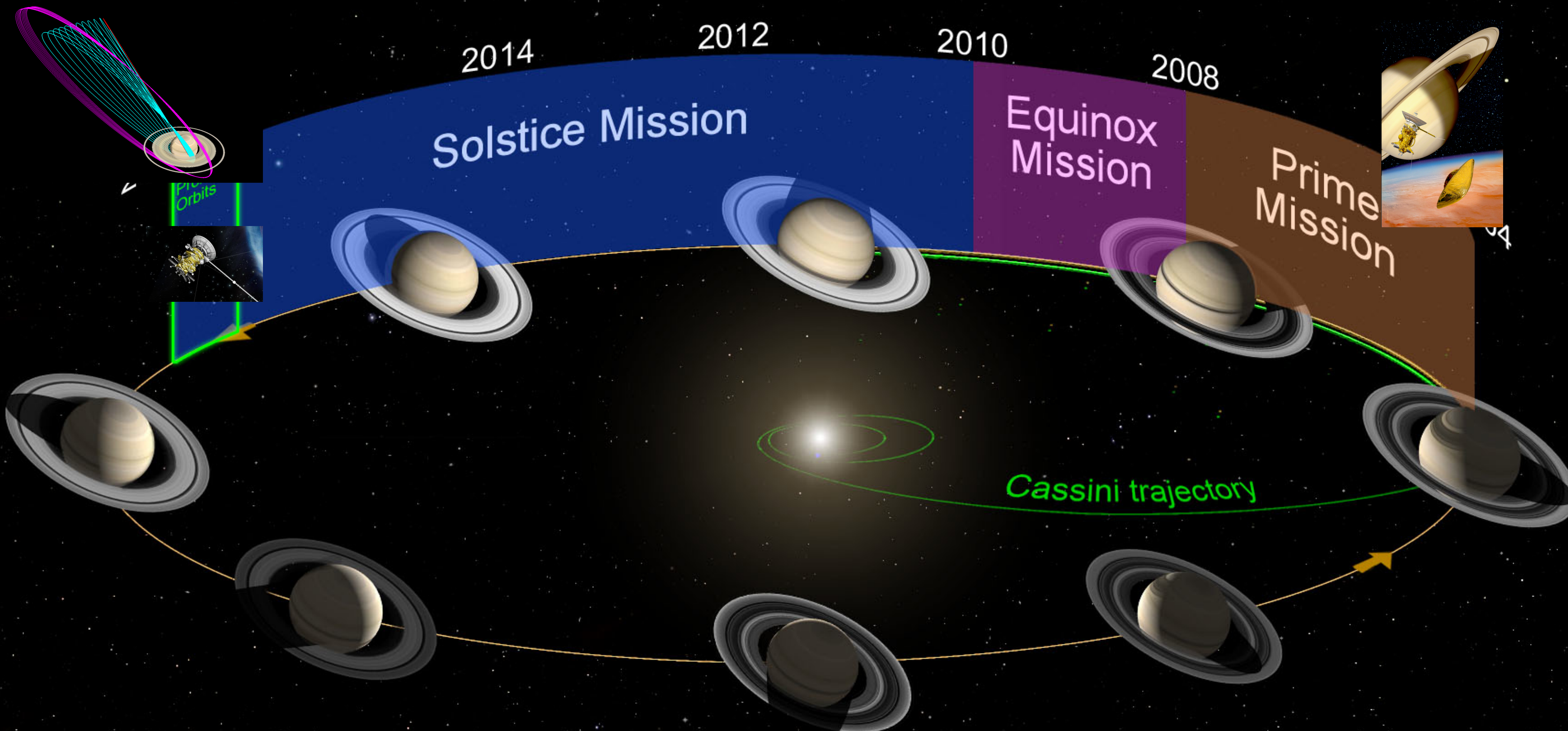
The exploration of the Saturnian system : habitats





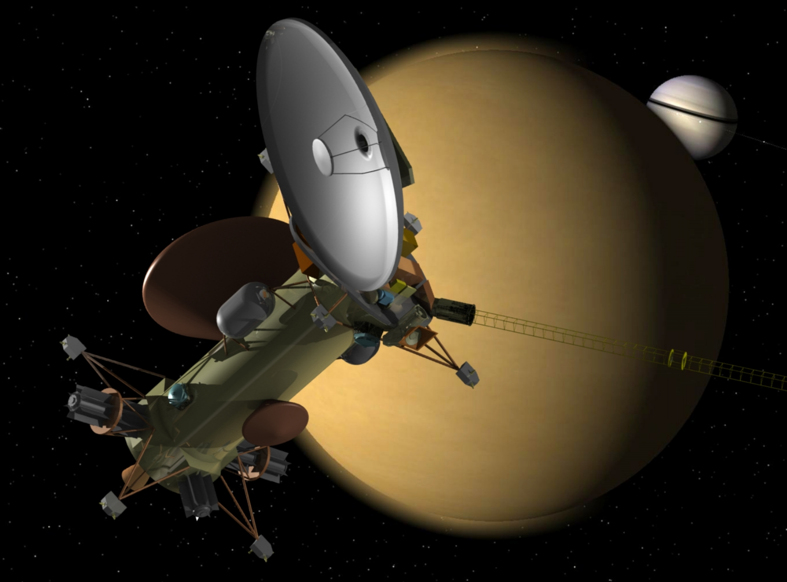
- The Saturnian system is rich in worlds that could bring insights on important aspects of Earth's
  - *climate,*
  - *organic chemistry and*
  - *emergence of life*.

Cassini-Huygens Mission Timeline

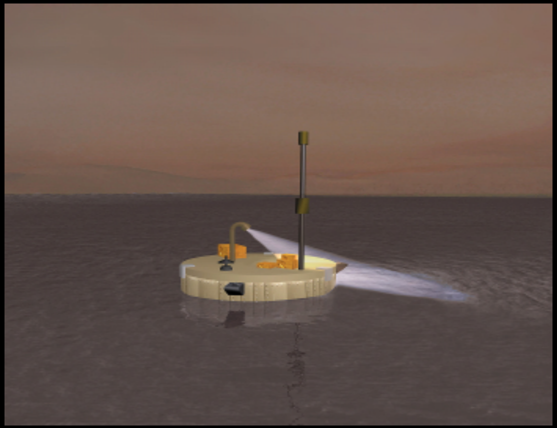


The Cassini spacecraft just performed its first successful dive through the rings on its way to destruction in Saturn by 15/9/17

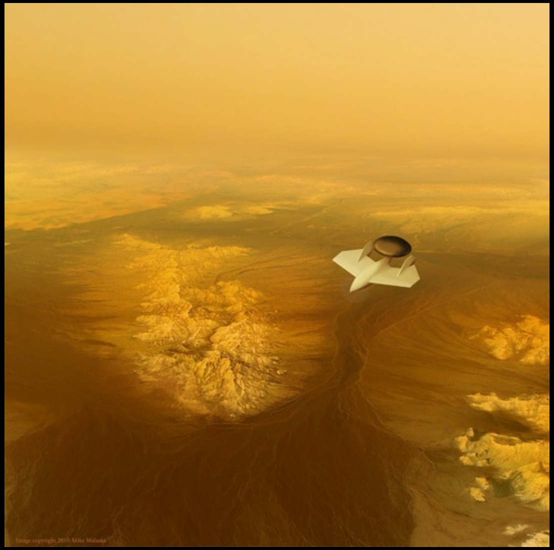
Future Saturnian system exploration



TSSM: Balloon, lander & orbiter
(Coustenis et al. 2009)



TIME: Lake lander
(Stofan et al. 2013)

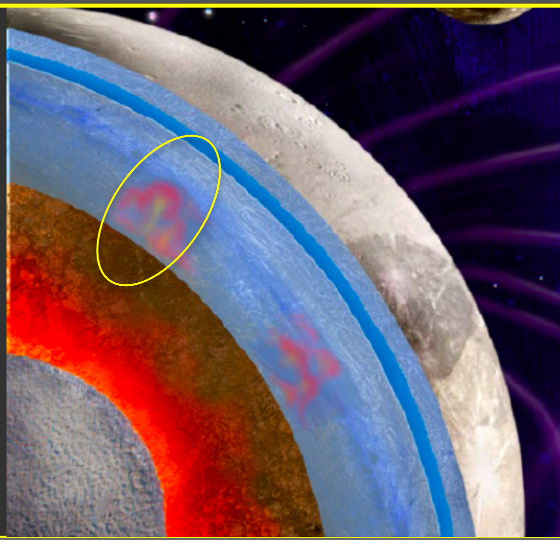


AVIATR /plane
(Barnes et al. 2010)

From the icy moons to extrasolar planetary systems

Waterworlds and giant planets | **Habitable worlds** | Astrophysics Connection

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

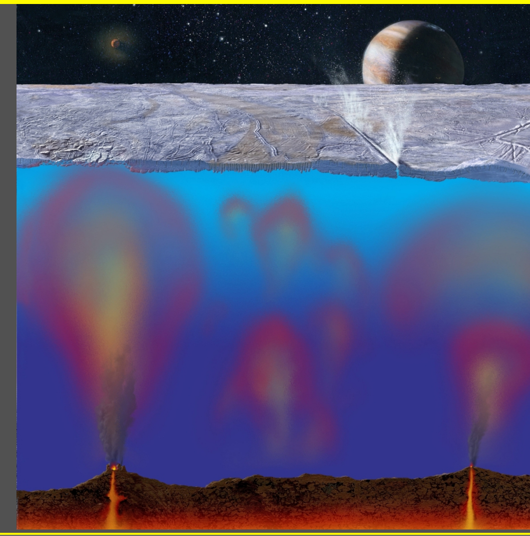


Occurrence:
Largest moons, hot ice giants, ocean-planets…
Most common habitat in the universe ?

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

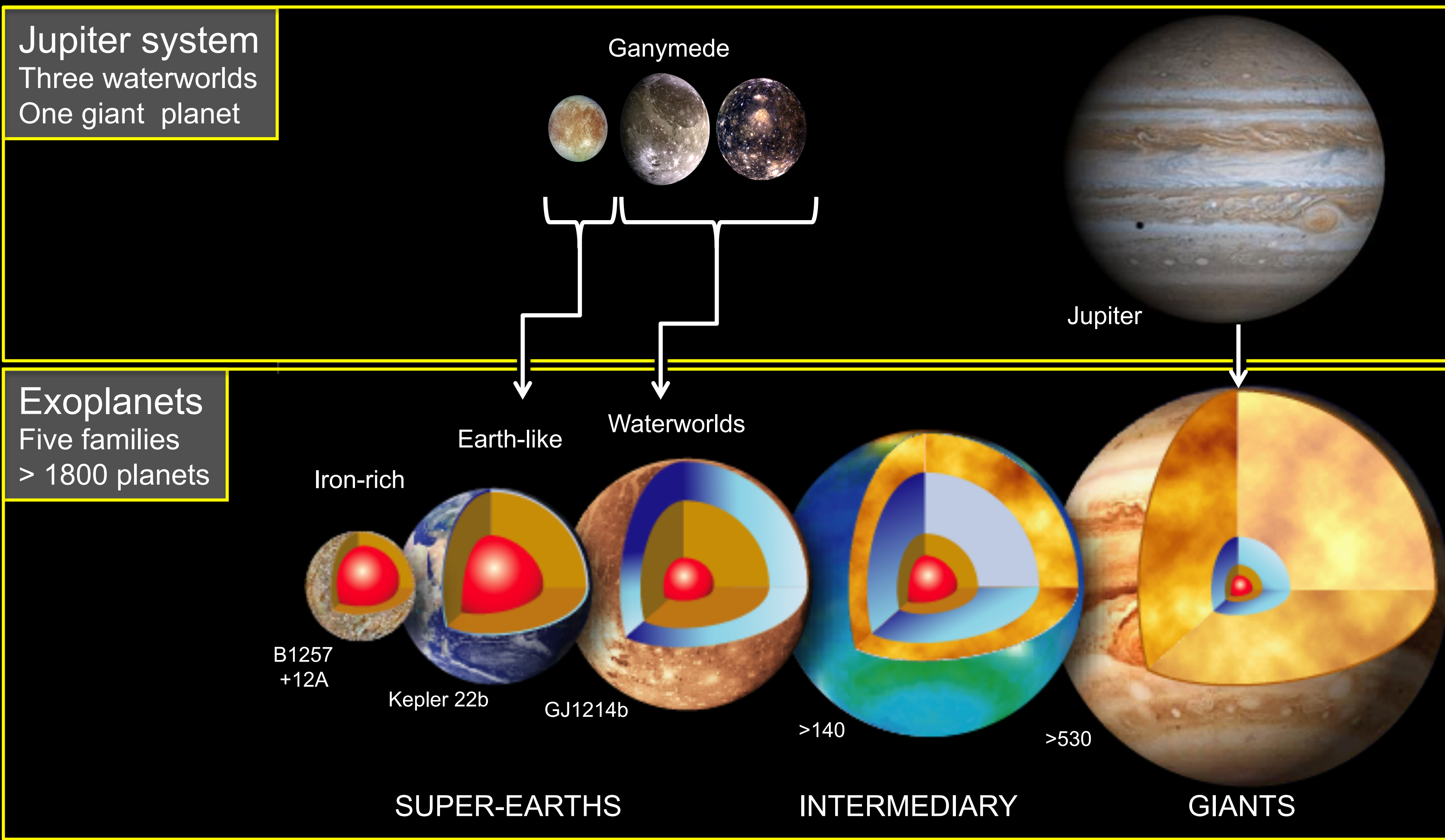
Key question:
How are the surface active areas related to potential deep habitats?

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

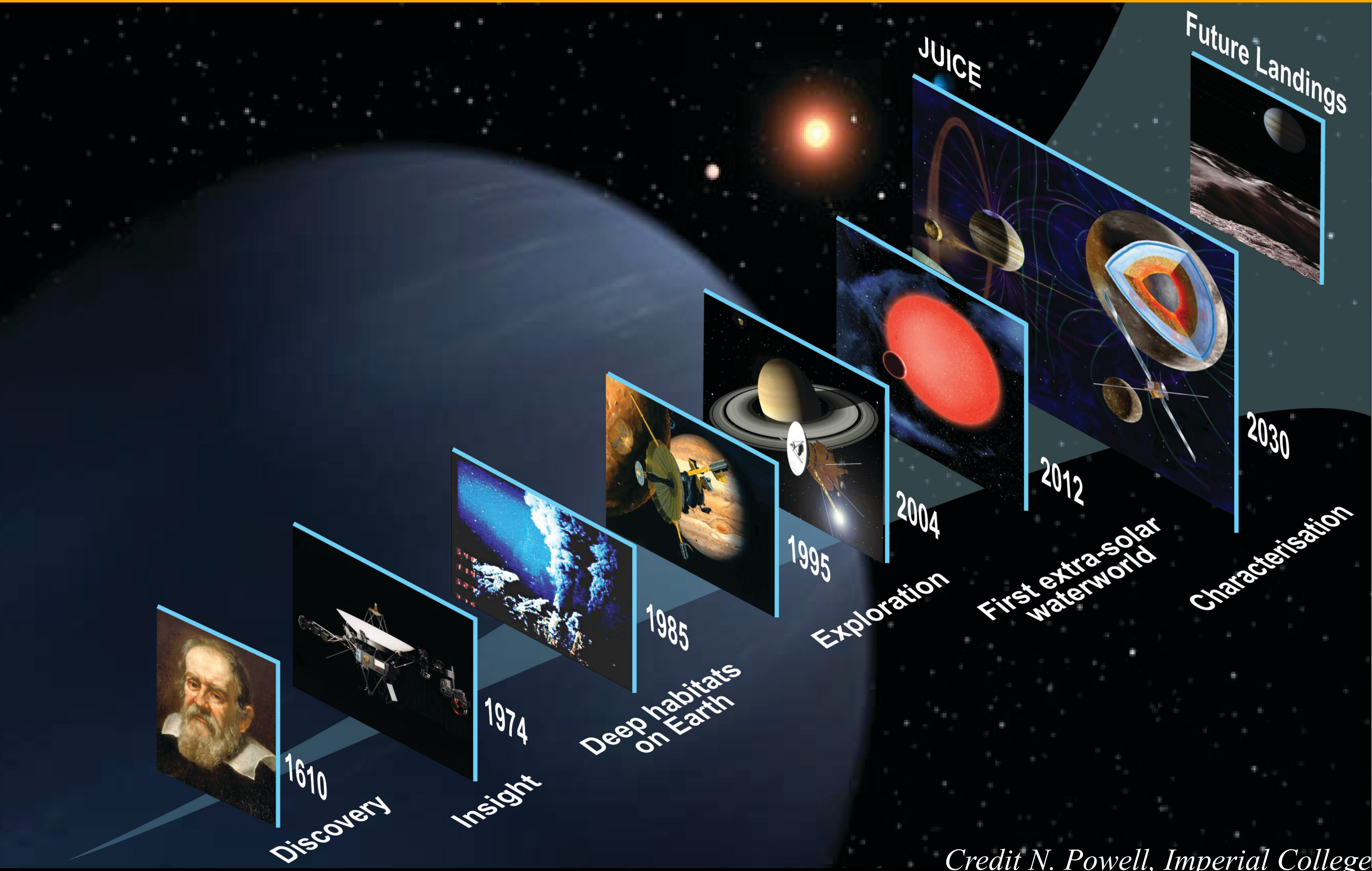
Waterworlds and giant planets | Habitable worlds | Astrophysics Connection

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



THE FUTURE OF EXPLORATION

Rich future for exploration of habitable worlds in the outer solar system with JUICE as L1 and more : missions to Europa, Titan, Enceladus, and exoplanets



Exo-oceans study

SCIENCE CONNECT
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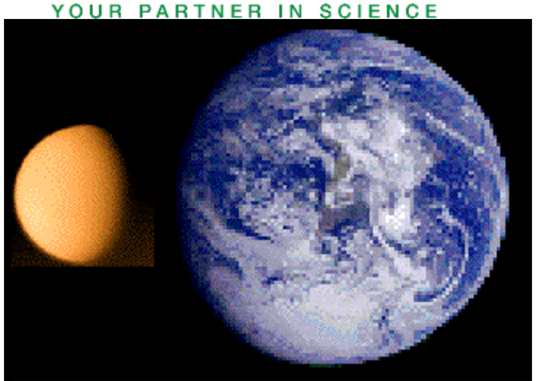
ESSC



Initiated from discussions between the European Space Sciences Committee and the European Marine Board

Study objectives:

- Review and synthesize the current status of astrobiological knowledge about the worlds in the outer solar system with possible subsurface liquid water oceans.
- Bring together our understanding from planetary exploration and Earth observations
- Bring forward future investigations needed to improve our knowledge of waterworlds from space, ground and laboratory work
- Lead to a better understanding of the emergence of life on Earth and initial conditions in the oceans
- Identify and prioritize mission concepts or payload that can make the most appropriate and useful measurements, and an analysis of our ability to interpret mission data and support further exploration.

Exo-oceans

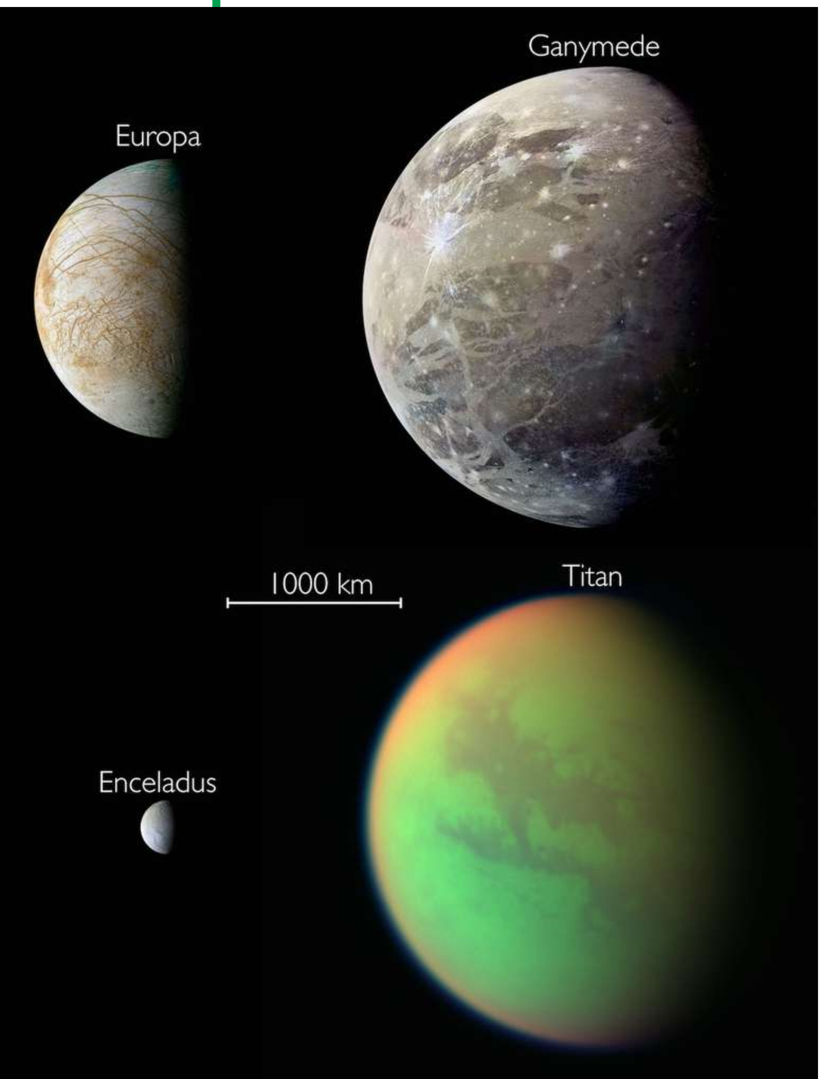
Approach

- Setting up a joint Working Group between ESSC and the European Marine Board, with support from ESSC and EMB (also coordination), ISSI, PSL IRIS-OCAV. Interest declared by ESA. Looking for interest from NAS CAPS….

ESSC Secretariat to provide coordination

→ 10-12 marine scientists, planetary scientists and astrobiologists.

→Three workshops – 8 months study



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Exo-oceans

ESSC

Outcome

- a book within the Space Science Series of ISSI
- a report detailing a science strategy for space exploration of the outer solar system icy moons oceans