Search for habitable worlds in the outer solar system

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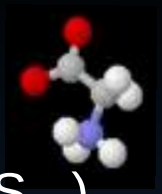
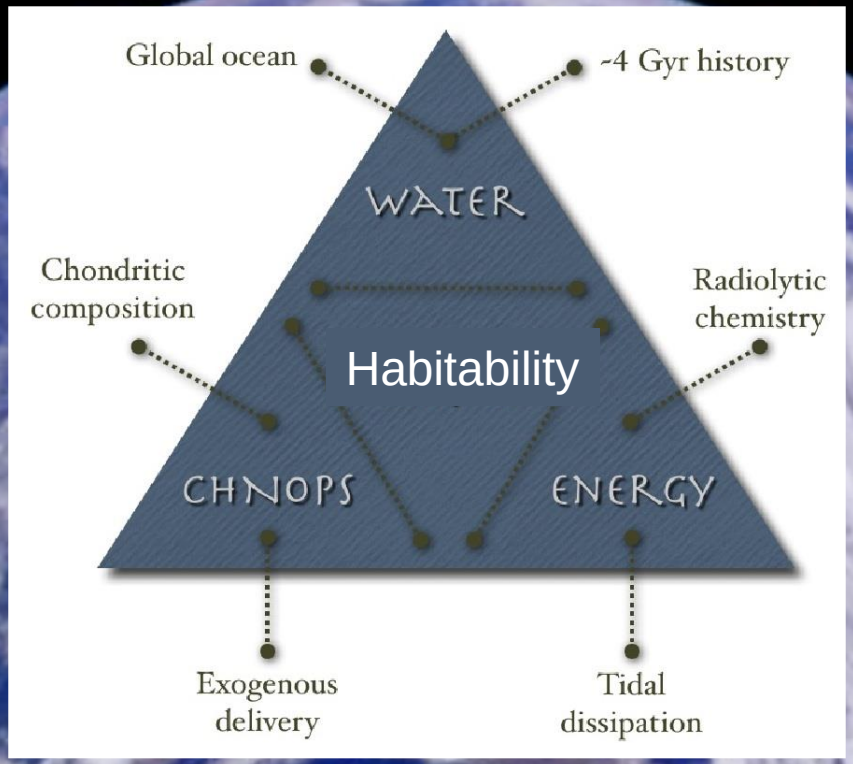
Habitability: four requirements

water 

essential elements (CHNOPS...) 

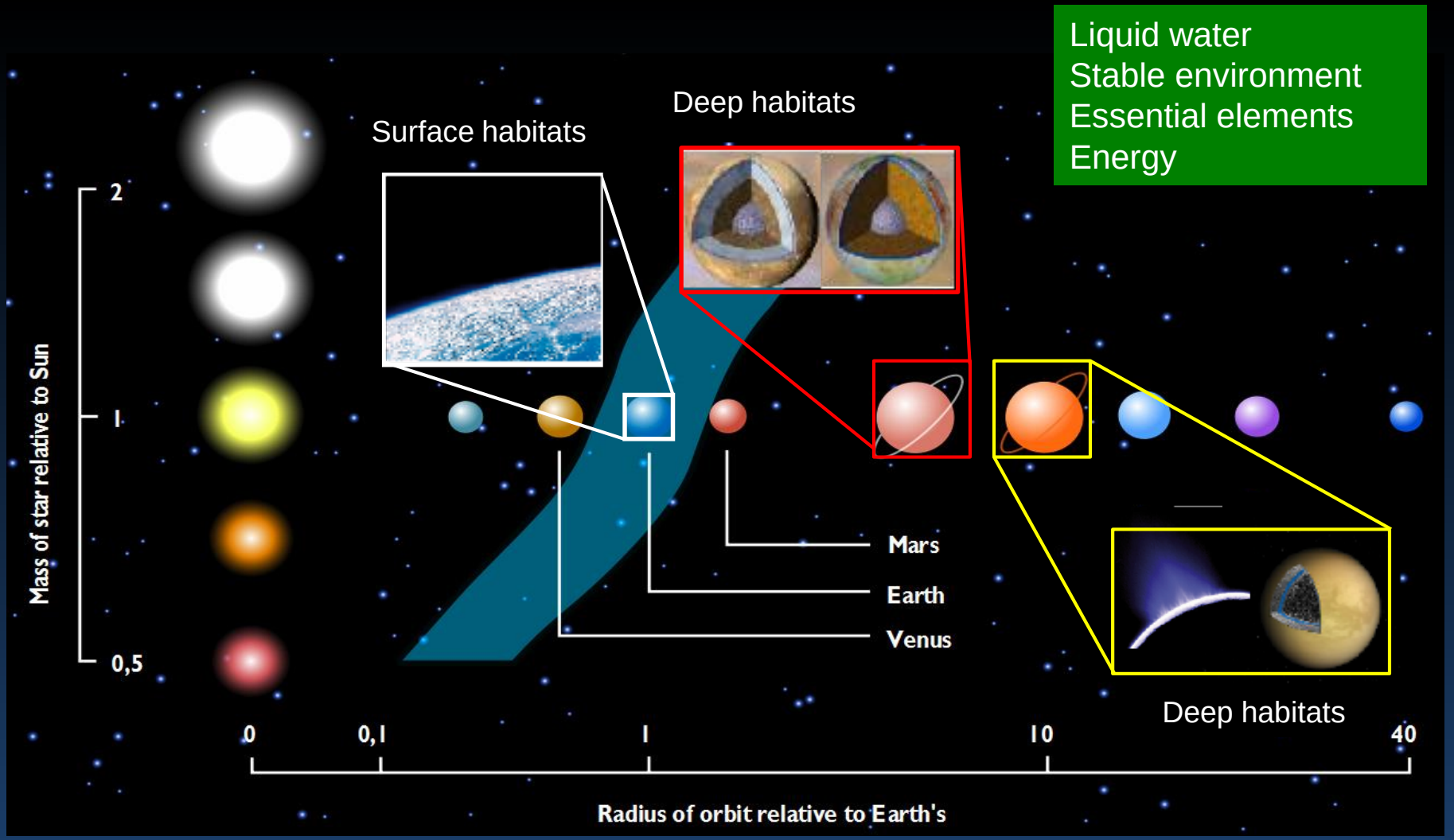
chemical energy 

stable environment 



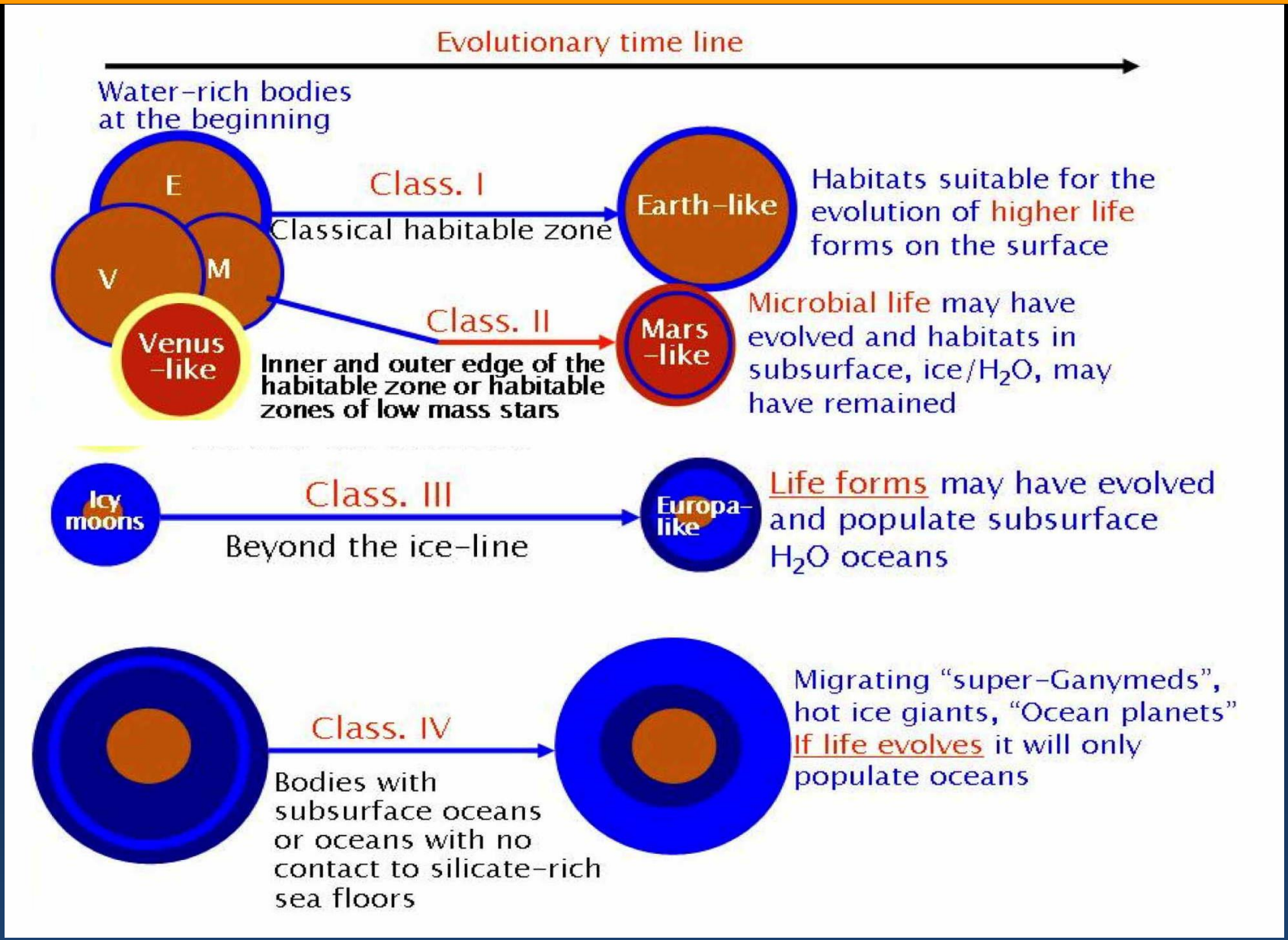
Habitability in the Solar System: extended HZ

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

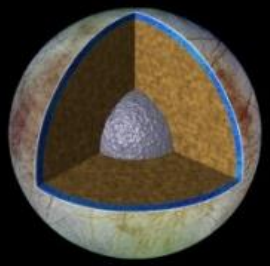


The habitable zone is not restricted to the Earth's orbit…

What are the habitable worlds?



Lammer et al., 2009

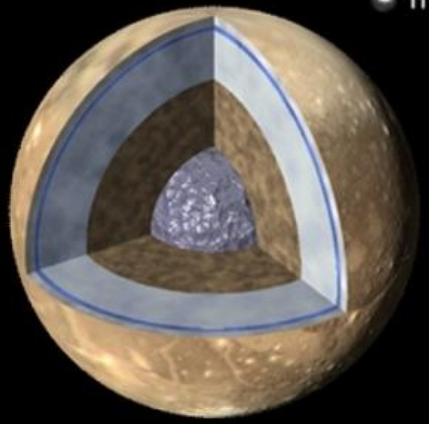


Europa

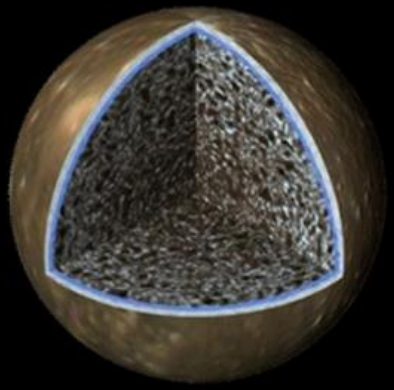
ice
water
rock
metal

Earth

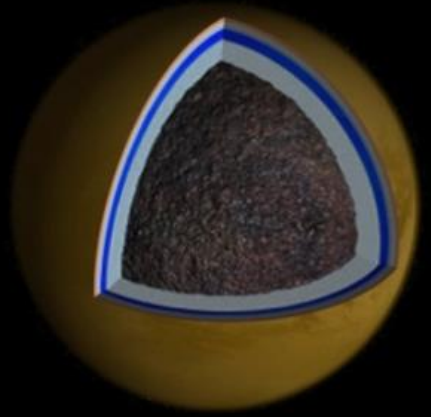
Enceladus



Ganymede

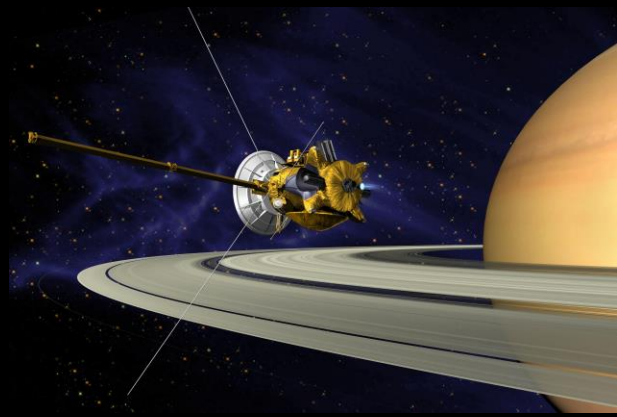


Callisto



Titan

Galileo Begins Jupiter Orbit
Dec. 7, 1995



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

Habitats in the Jupiter system

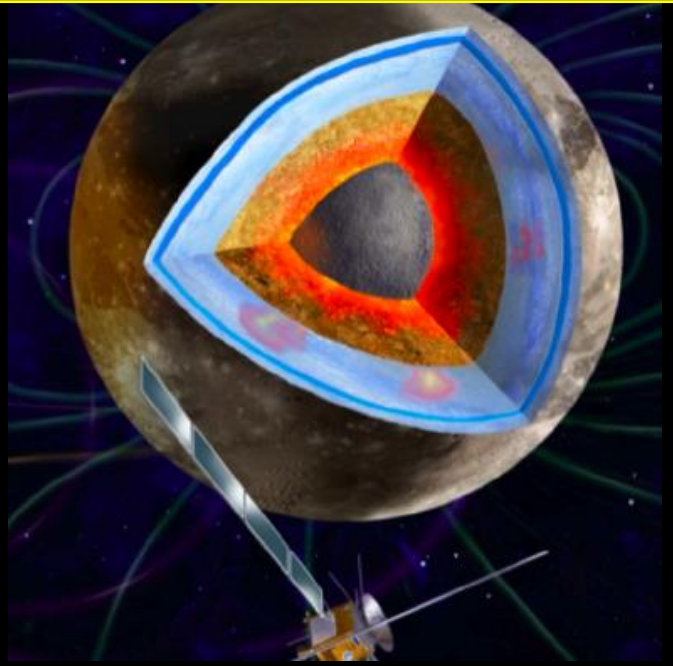
Emergence of the habitable zone around Jupiter

Three large icy moons to explore in search for undersurface water

Ganymede - class IV

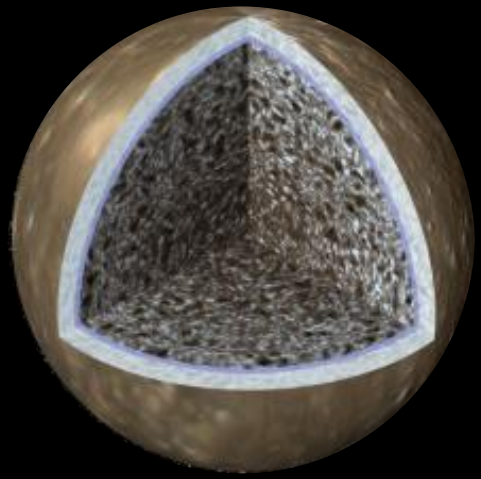
- Largest satellite in the solar system
- A deep ocean
- Internal dynamo and an induced magnetic field – unique
- Richest crater morphologies

- Best example of liquid environment trapped between icy layers



Callisto - class IV

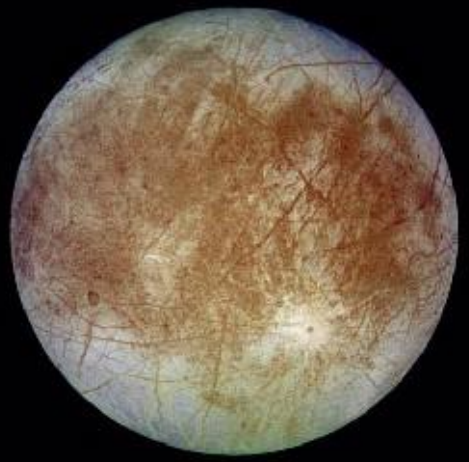
- Best place to study the impactor history
- Differentiation – still an enigma
- Only known example of non active but ocean-bearing world
- The witness of early ages

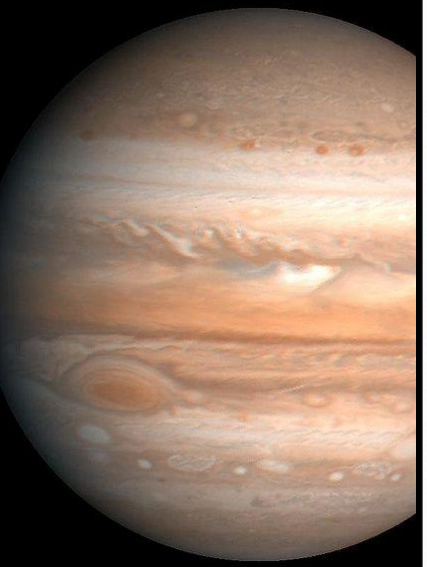


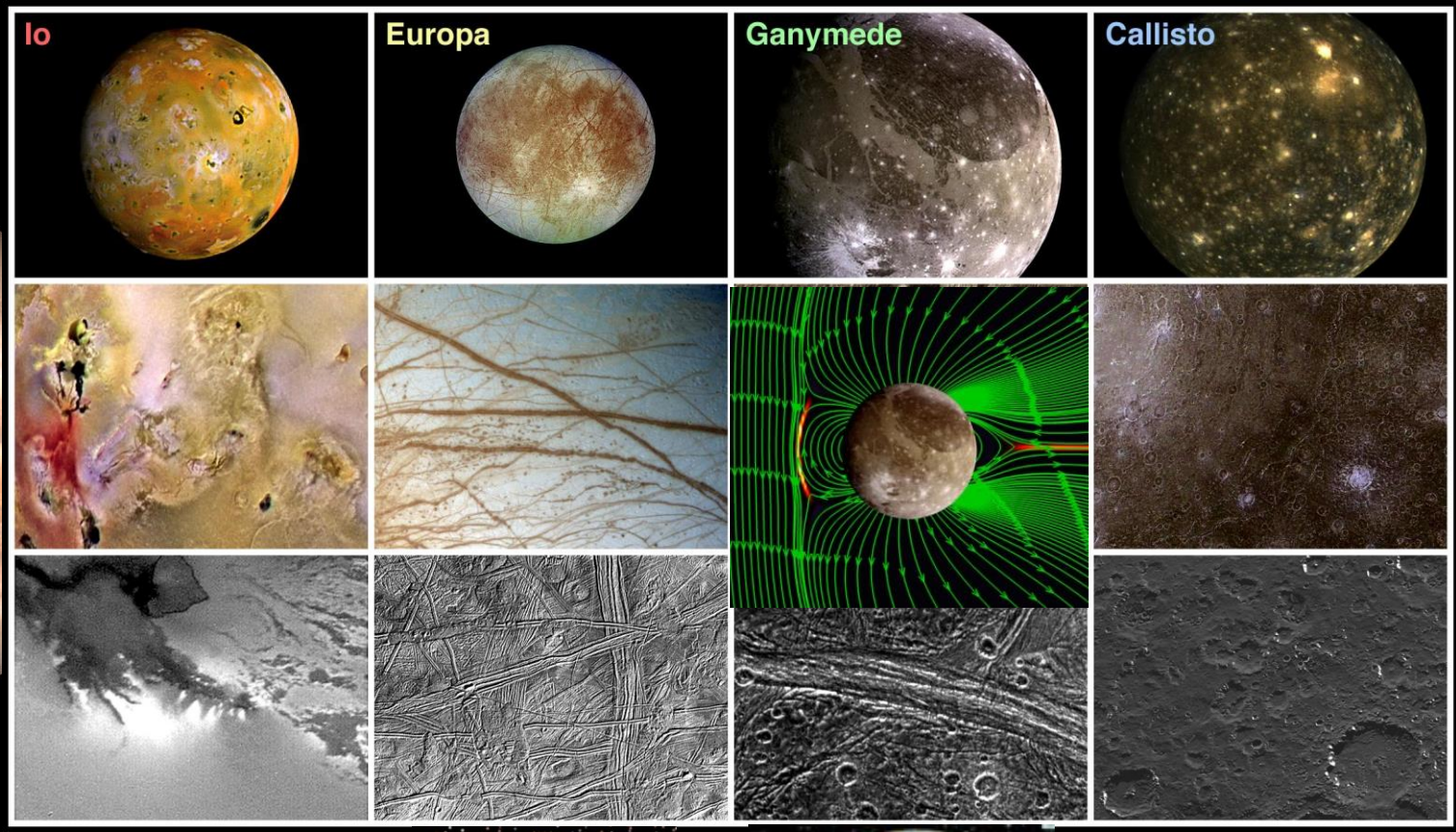
Europa - class III

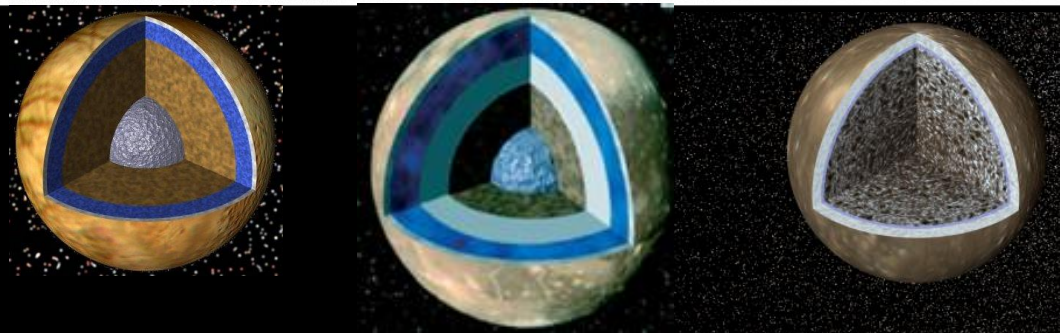
- A deep ocean
- An active world?

- Best example of liquid environment in contact with silicates





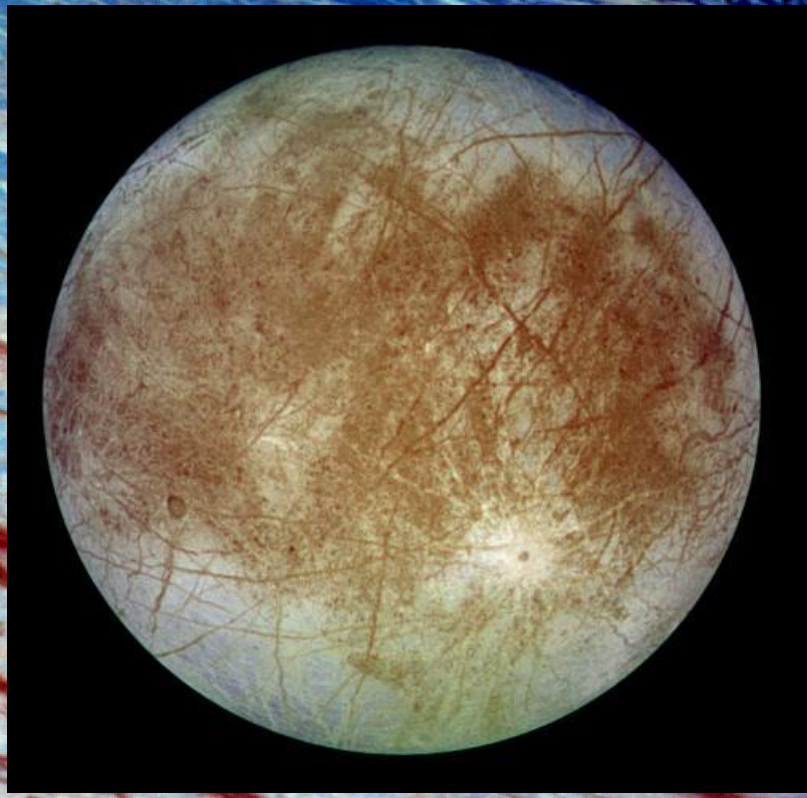




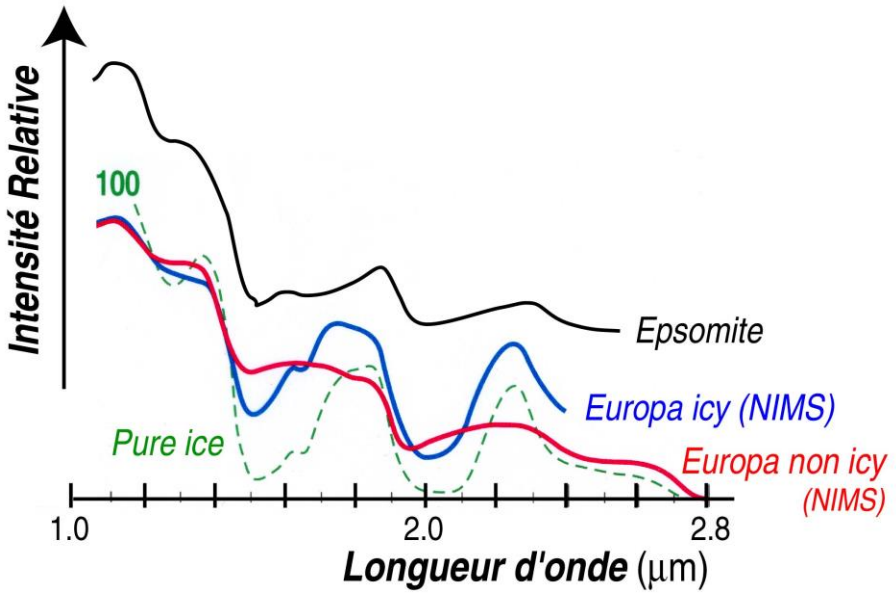
Credit NASA

About the existence of deep liquid layers : EUROPA

Hyperspectral evidences



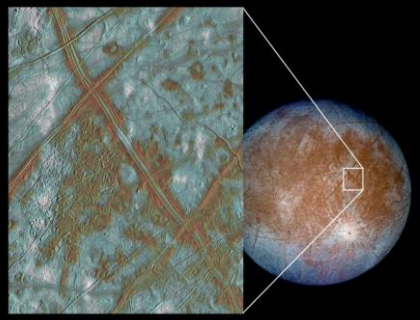
Composition of ices

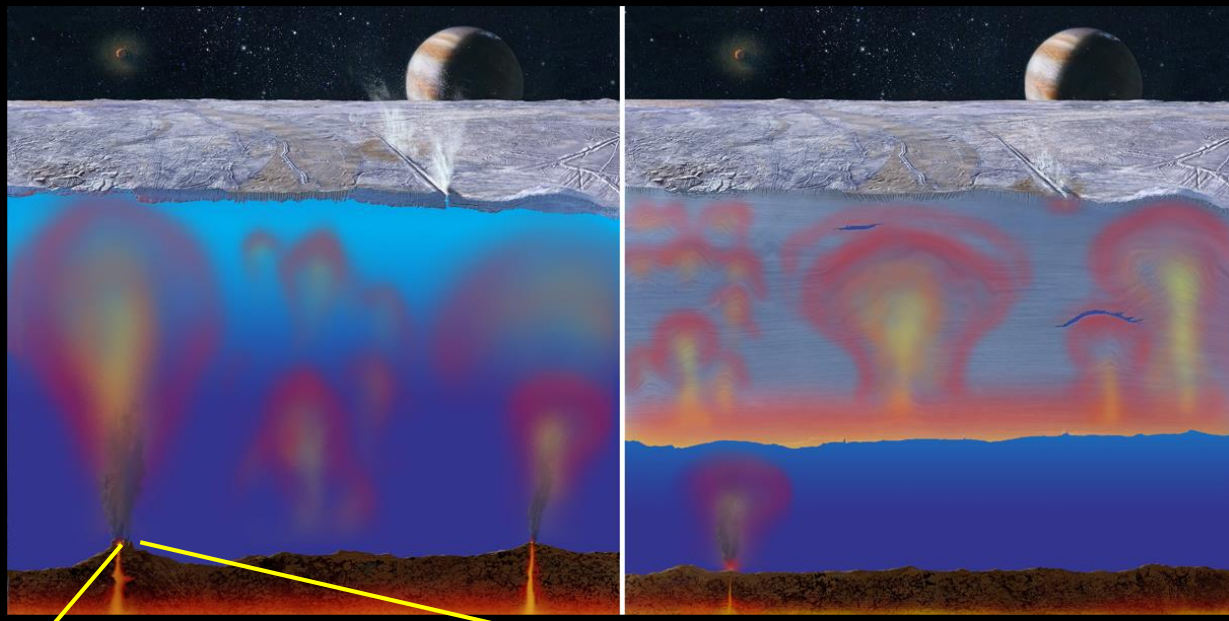


from McCord et al. (1999)

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

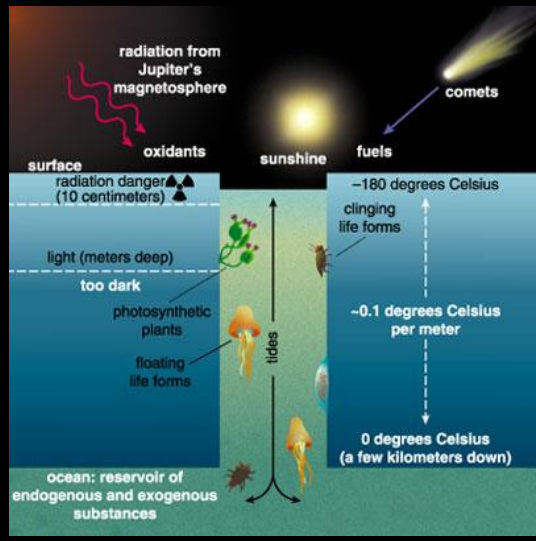
Class III : subsurface oceans in contact with silicates - Europa





Europa-like worlds:

- Water:
  - Warm salty H_2O ocean.
- Essential elements:
  - Impactors.
  - Photolysis -> O, O2
  - 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.

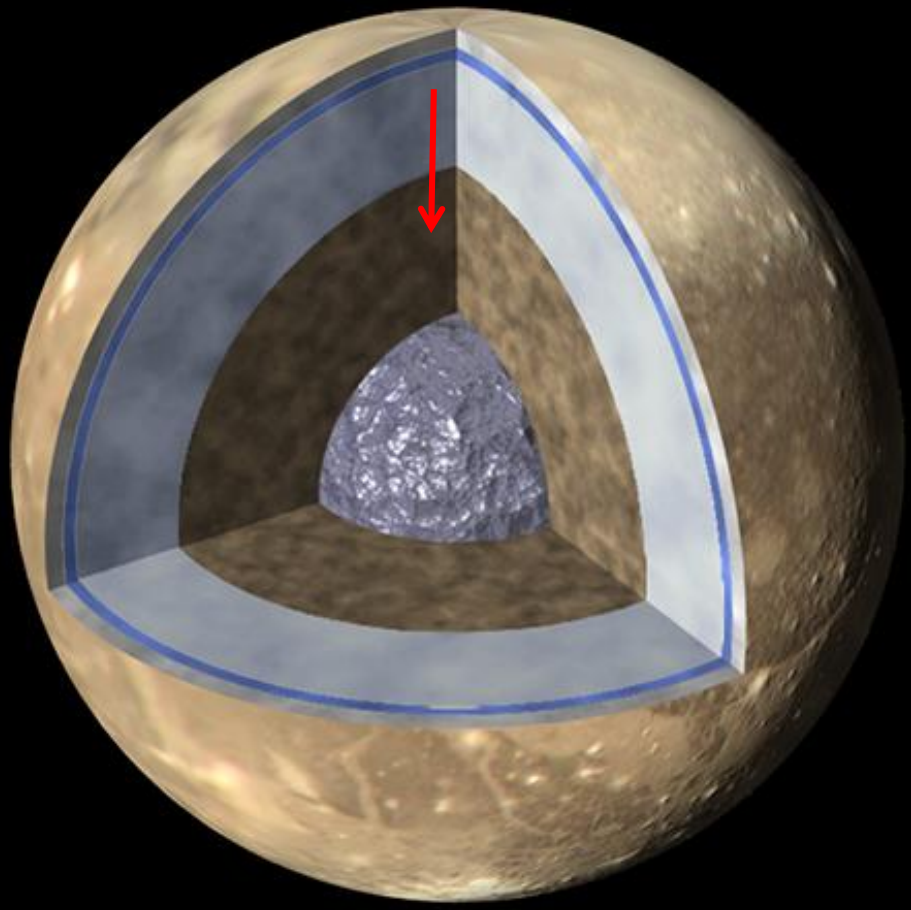


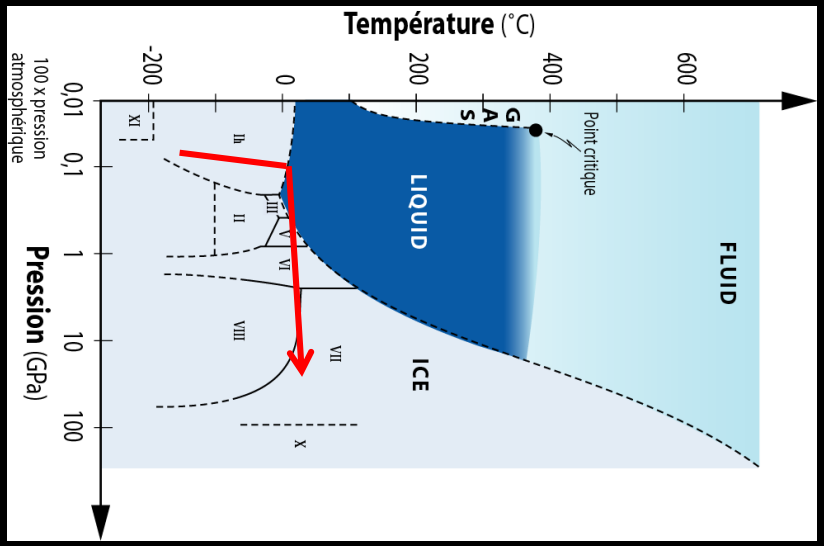
What are the habitable worlds?

Class IV : subsurface oceans without any contact with the silicates

Ganymede-like

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





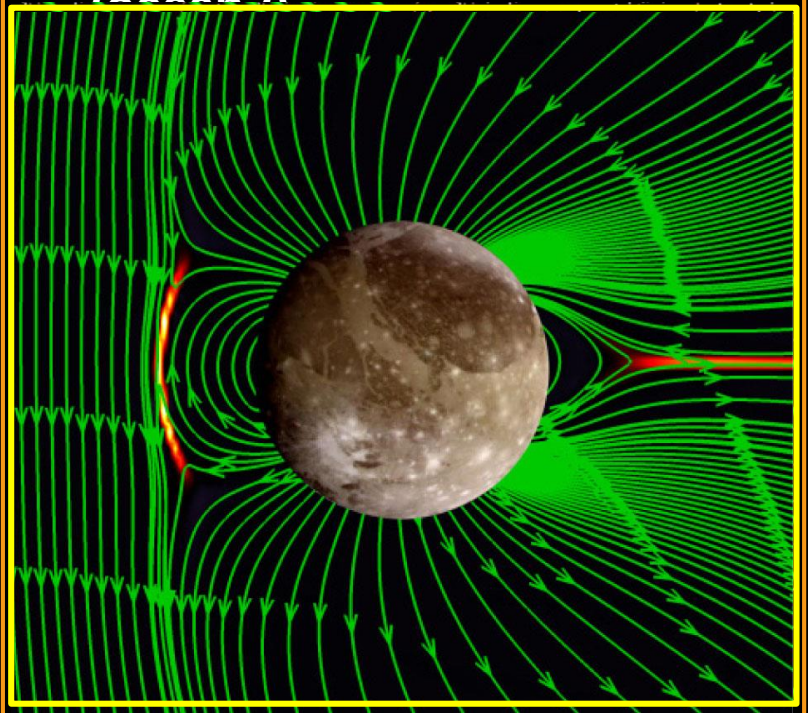
H2O ice and liquid diagram studied since 1912 (Bridgman)
Modern experiments are devoted to complex mixtures and indicate you can have liquid between ice layers.

About the existence of deep oceans : GANYMEDE

Galileo evidences

- **Induced magnetic field from interaction of jovian magneto with conducting layer**

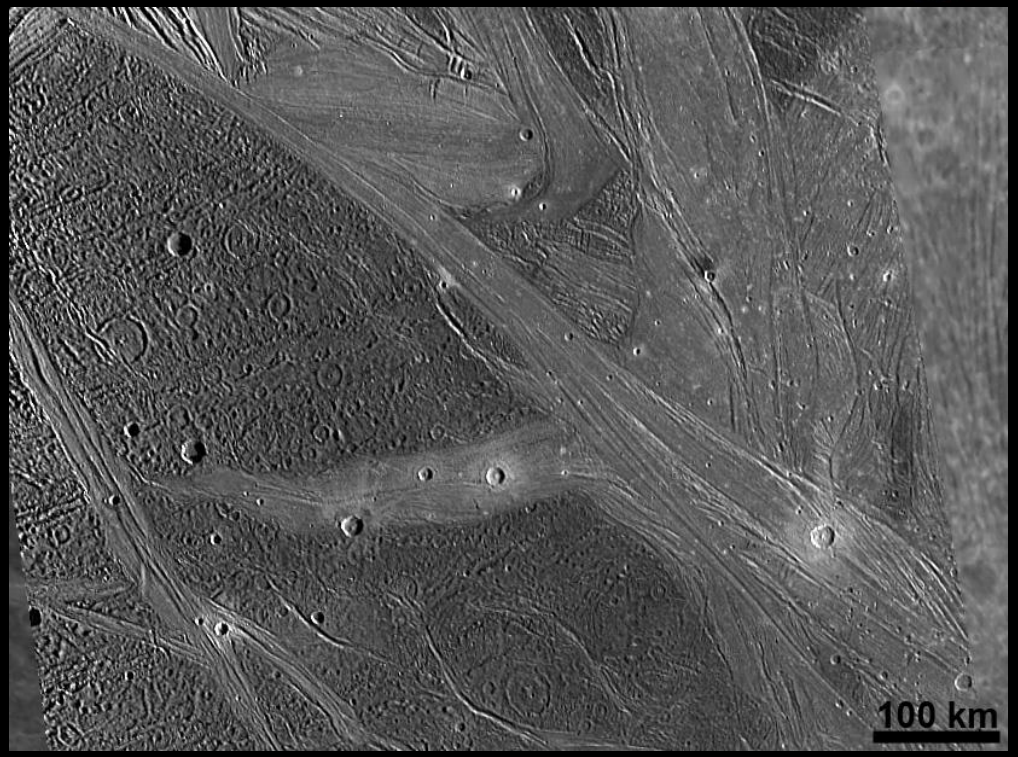
Observed but not characterised



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

Geologic activity

Indications for young surface from water flooding



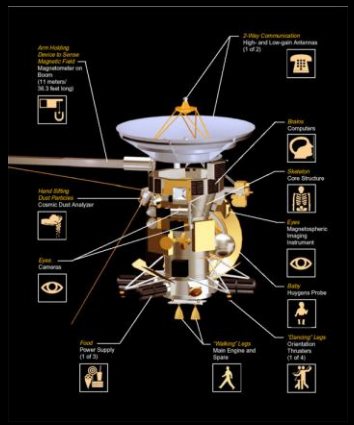
Questions

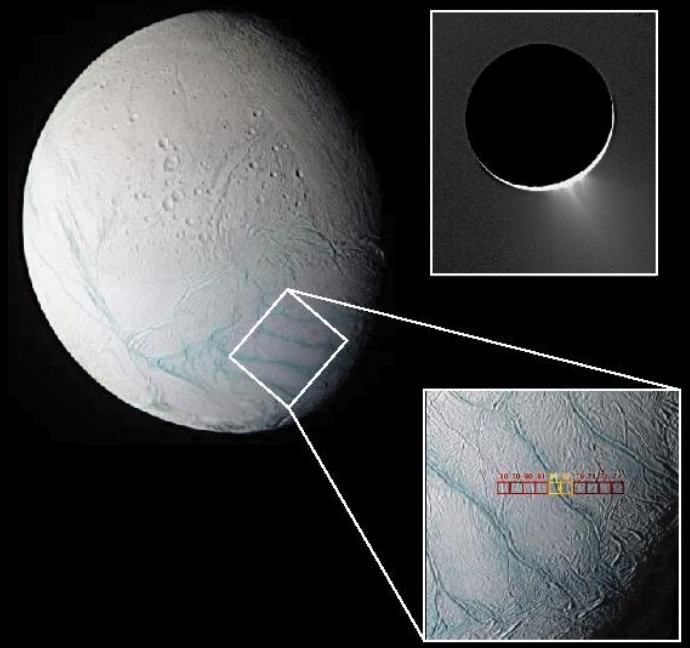
- Which depth?
- Which size?
- What is its composition?

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

Habitats in the Saturnian system

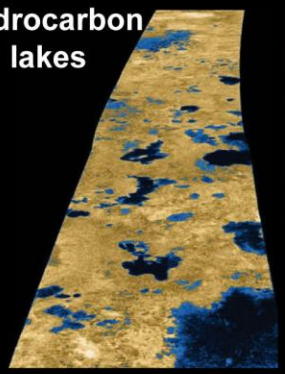
Cassini-Huygens (2004-2017) reveals Titan and Enceladus

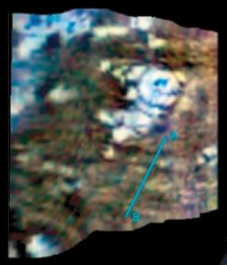




Enceladus

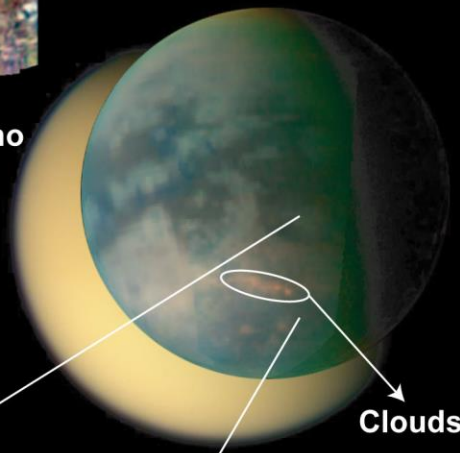
Hydrocarbon lakes





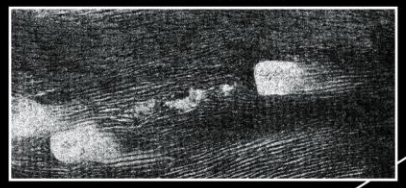
Cryovolcano

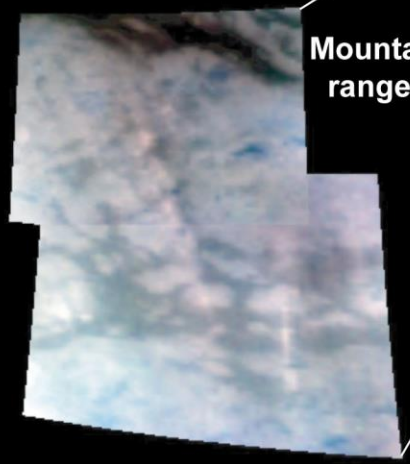
Titan: a frozen Earth ?



Clouds

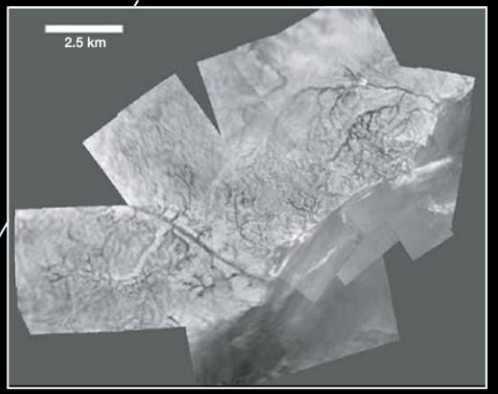
Dune fields





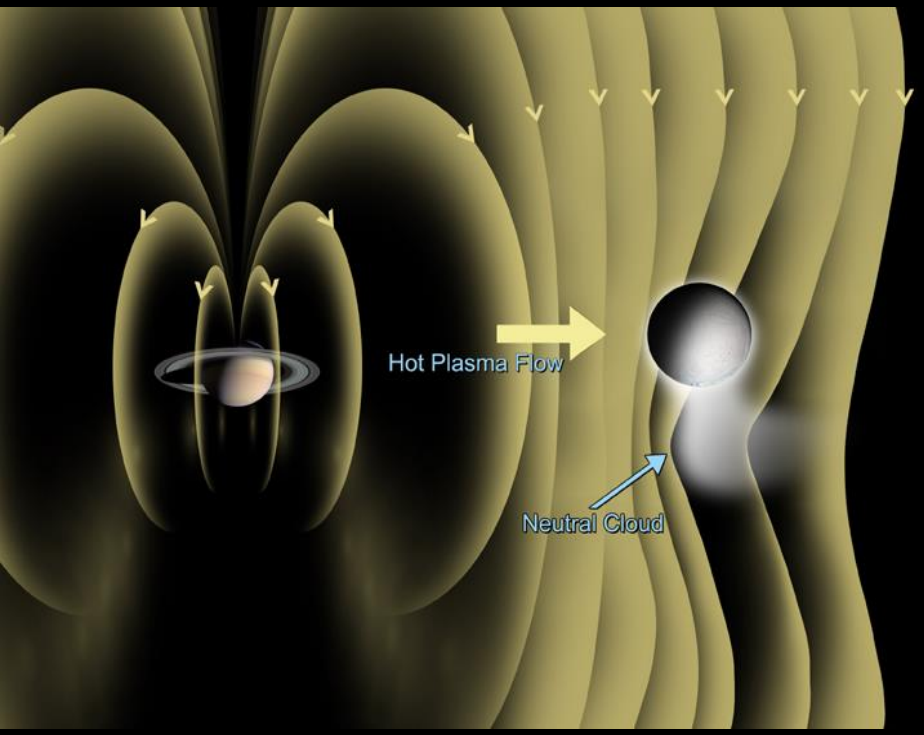
Mountain ranges

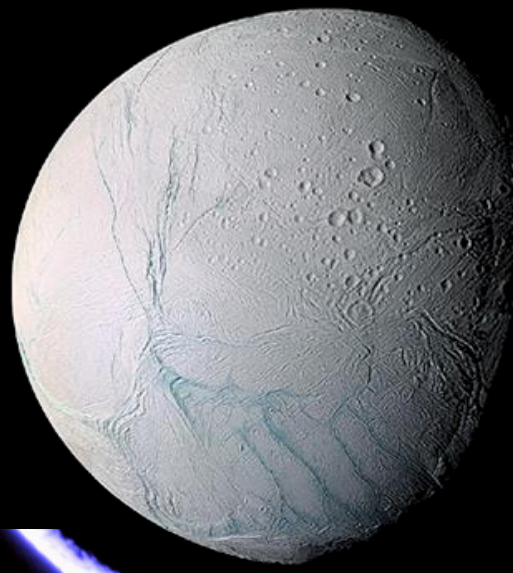
River networks

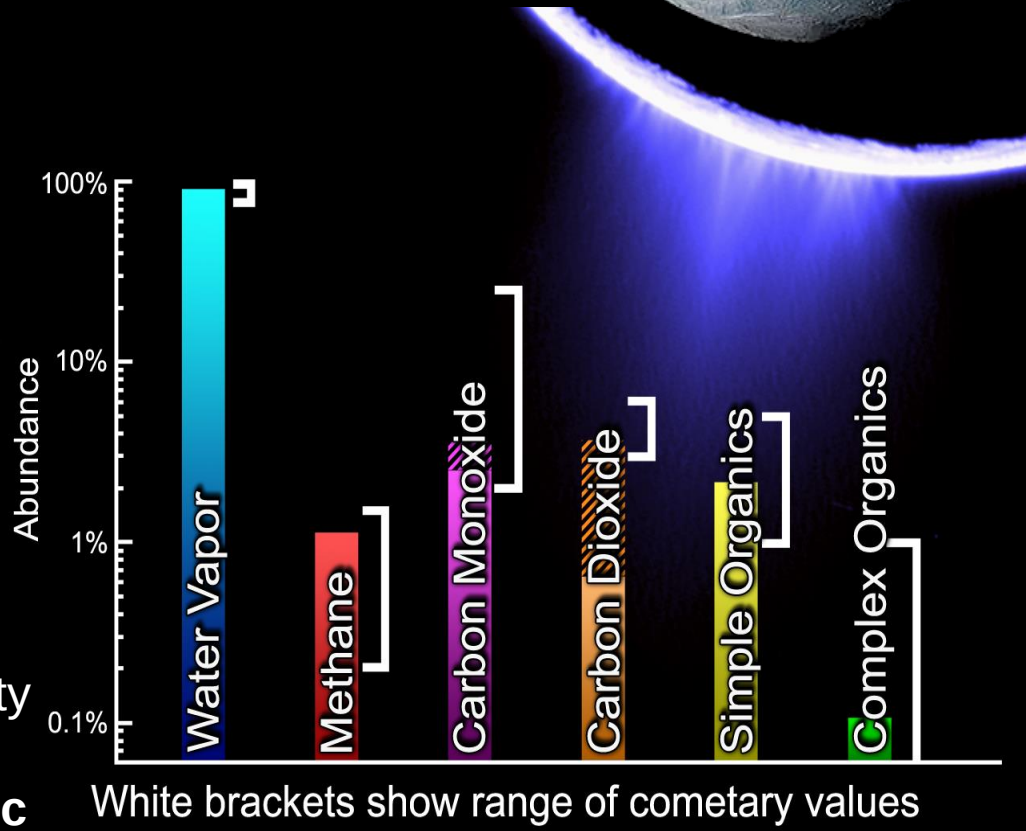


Titan

Enceladus plumes



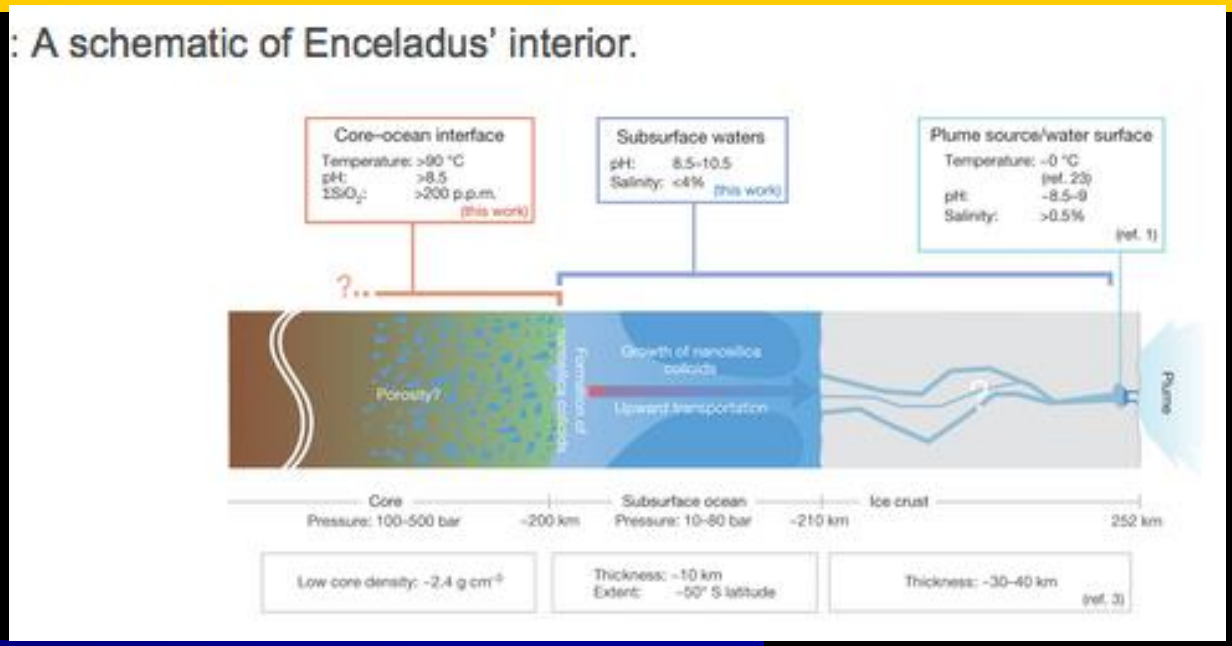




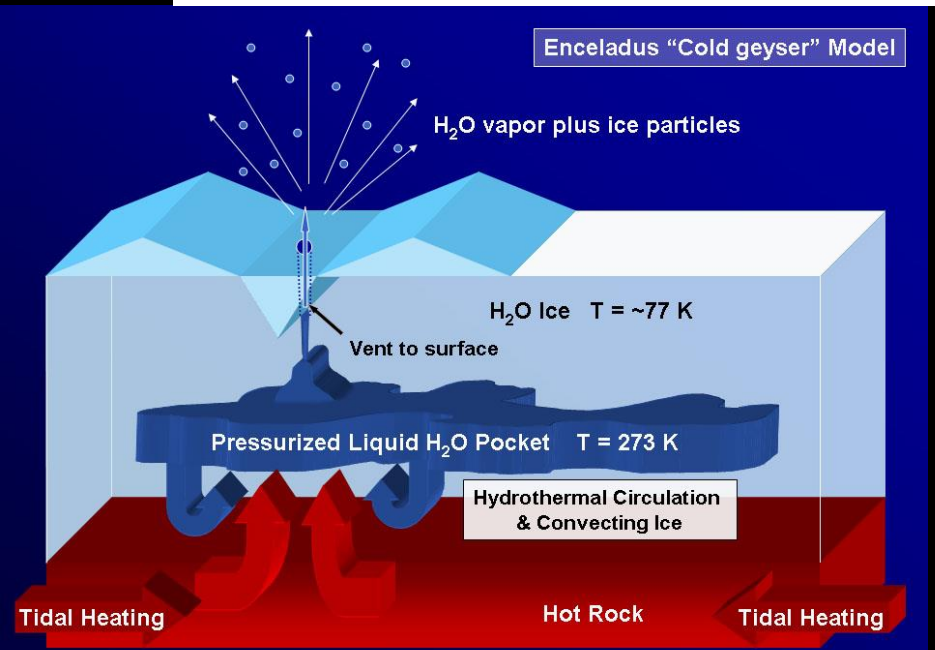
- **What is the origin of the plumes**
- **Replenishment of E-ring?**
- **Water vapor ejecta far away from the Sun** (strong implications for the habitability zones)
- **Indications for the presence of organic chemistry**

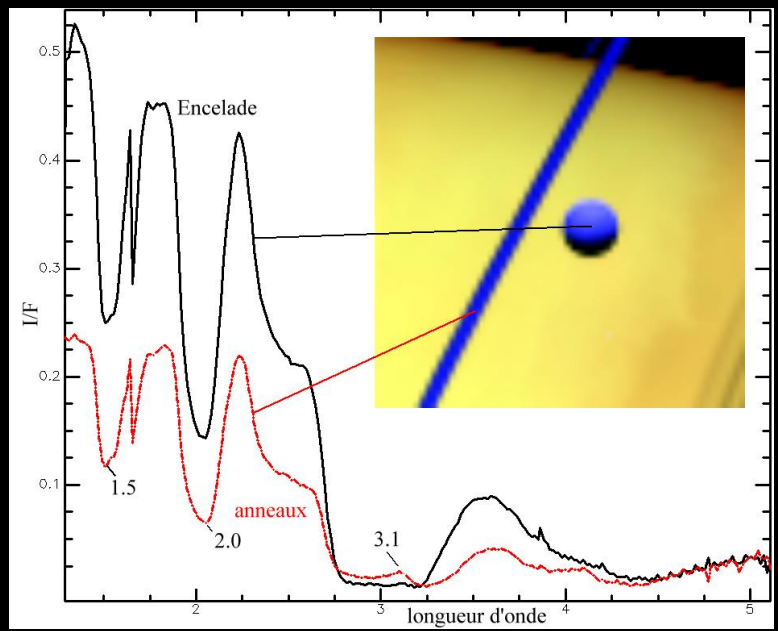
What are the habitable worlds in the outer solar system ? Around SATURN

Class III : subsurface oceans in contact with silicates –Enceladus



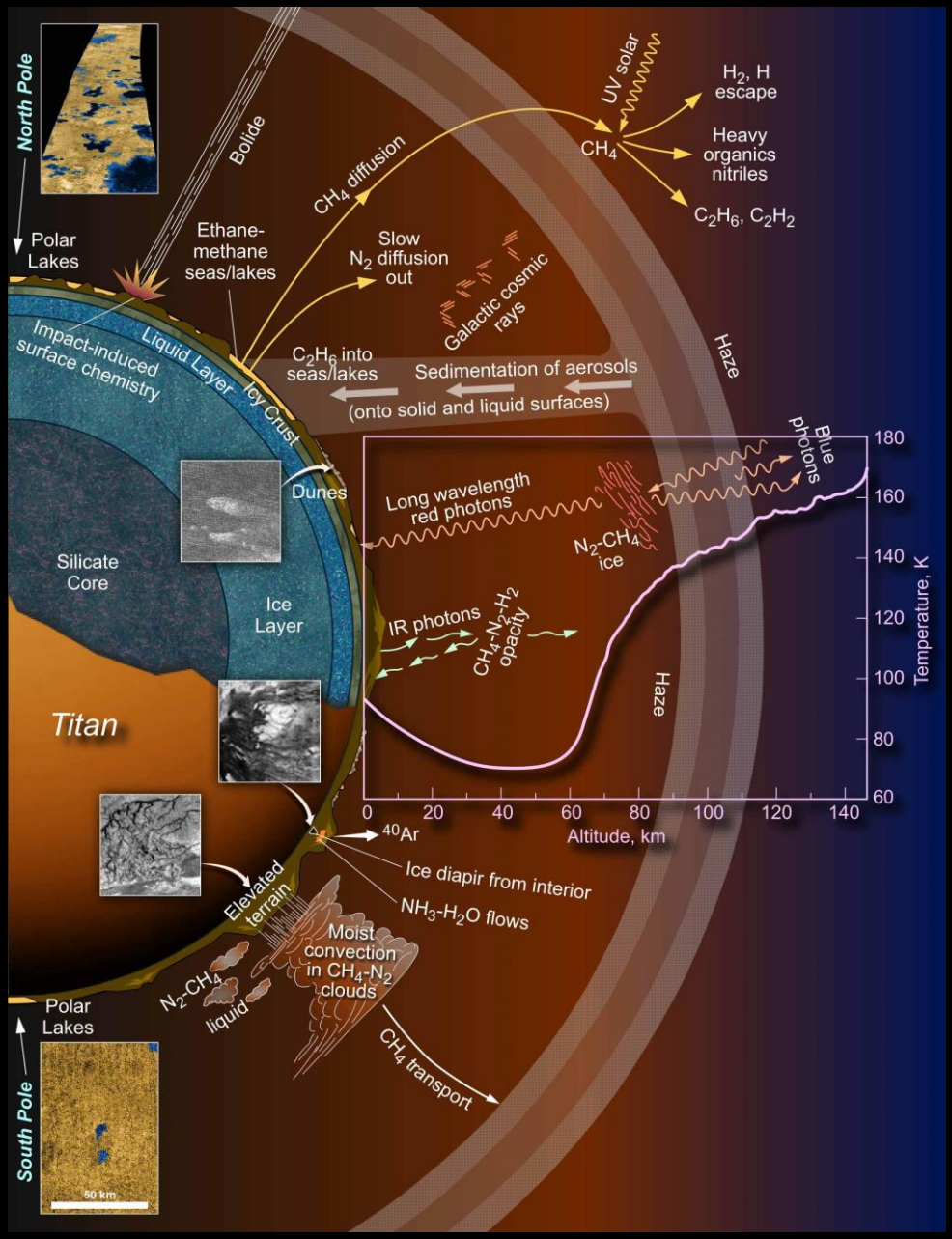
From Hsu et al. 2015





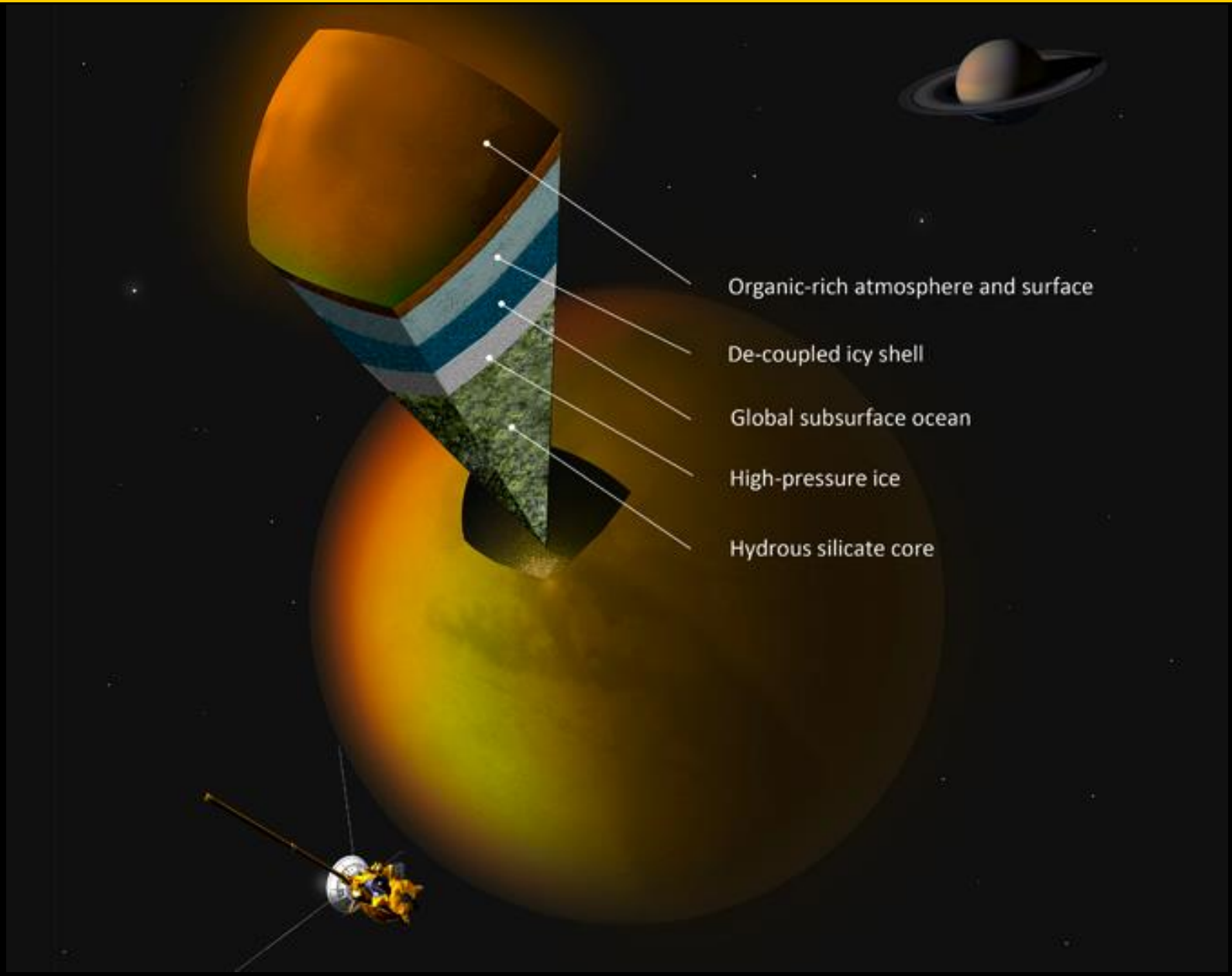
Titan as an astrobiological object

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

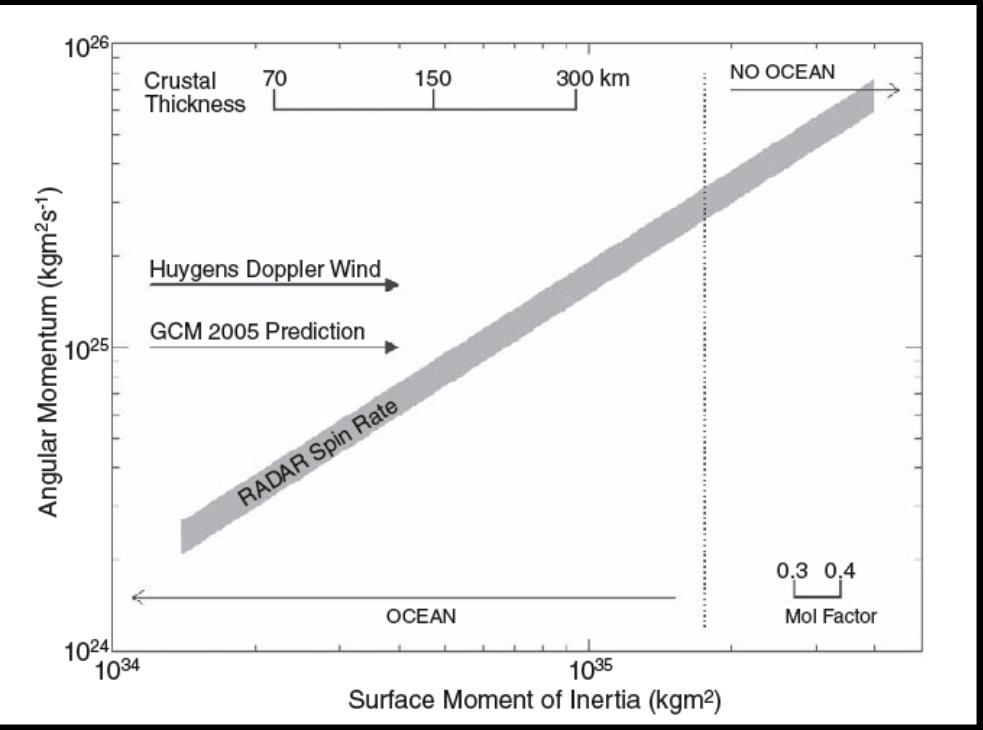


What are the habitable worlds in the outer solar system ? Around SATURN

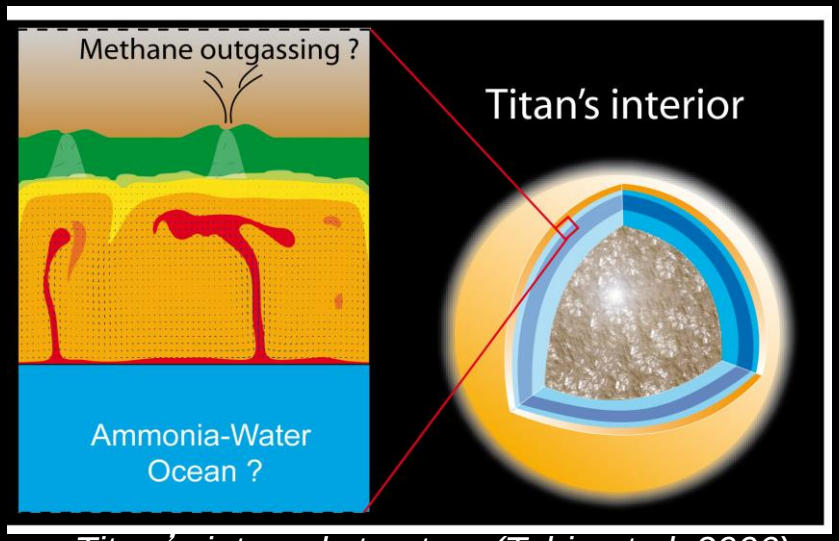
Class IV : subsurface oceans without any contact with the silicates - Titan



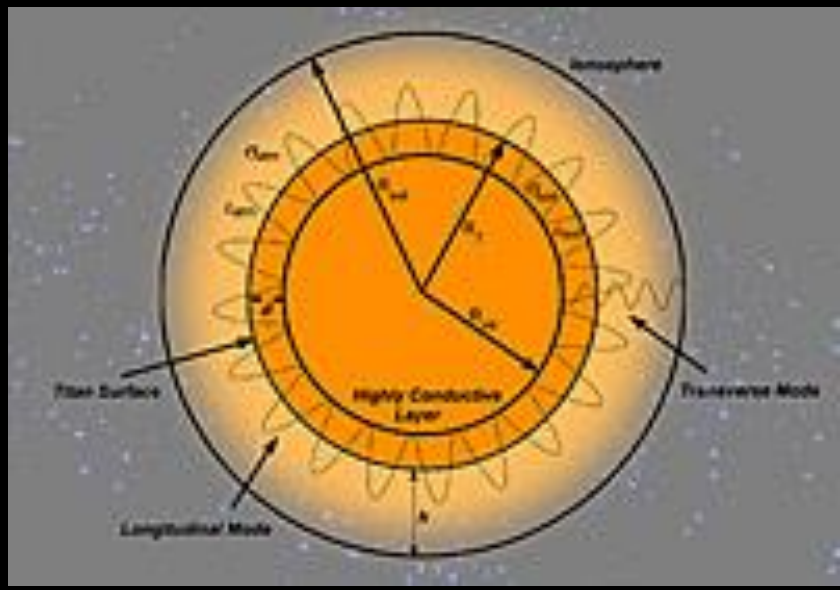
Titan's subsurface ocean



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. 2006)



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

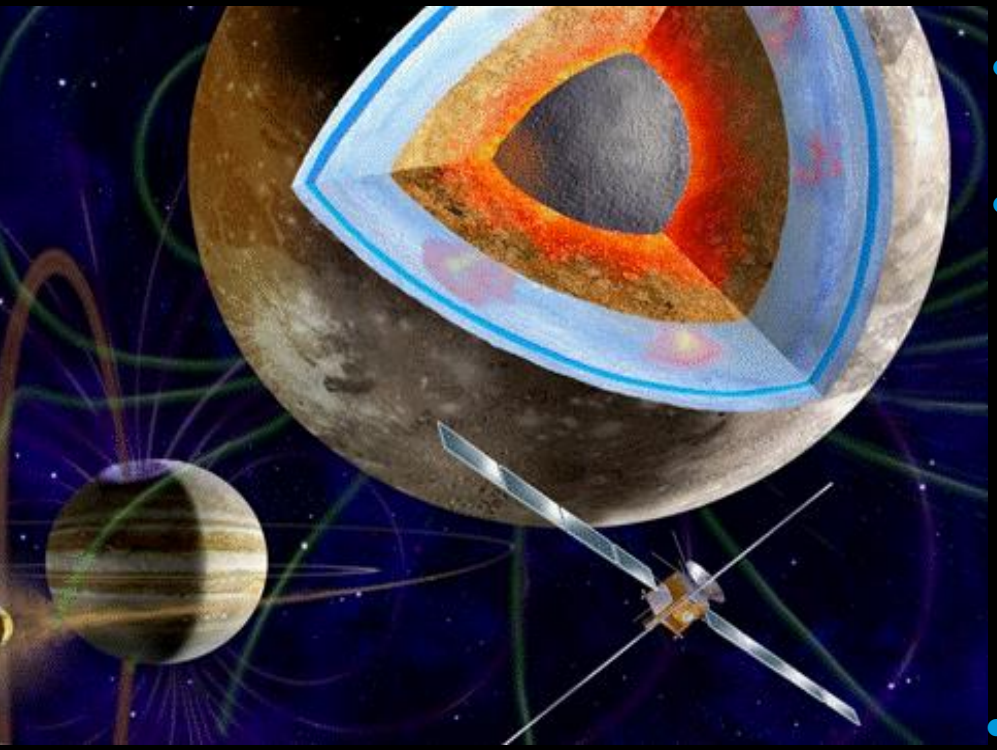
Habitable worlds in the outer solar system ?

Future exploration

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

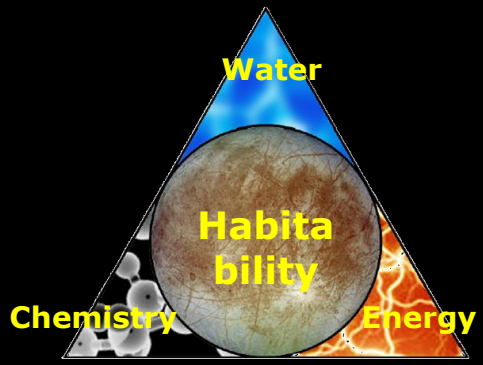
JUICE : Spacecraft, Payload & scenario

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

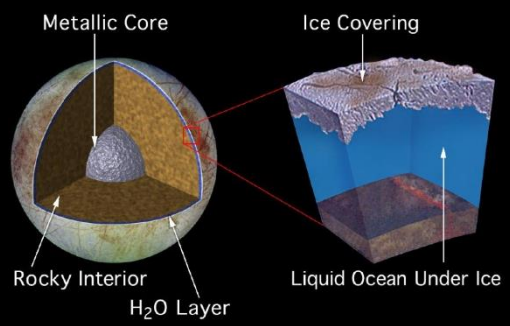
- *What are the conditions for planetary formation and emergence of life?*
- *How does the Solar System work?*

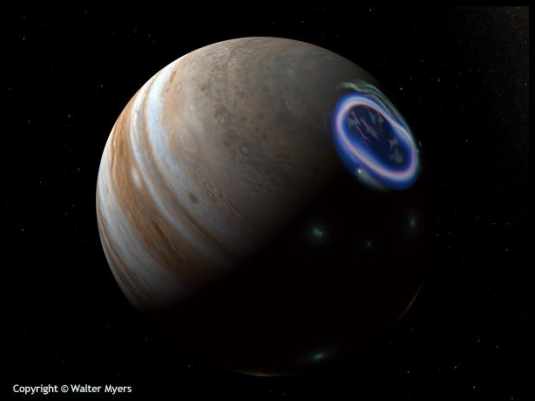
JUICE : the 1st Large CV mission concept

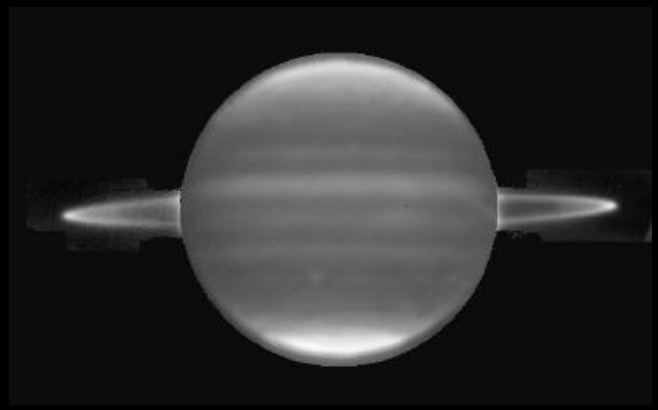
- *Single spacecraft mission to the Jovian system*
- *Investigations from orbit and flyby trajectories*
- *Synergistic and multi-disciplinary payload*
- *European mission with international participation*

Topics:
Planet, moons, rings, magneto

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



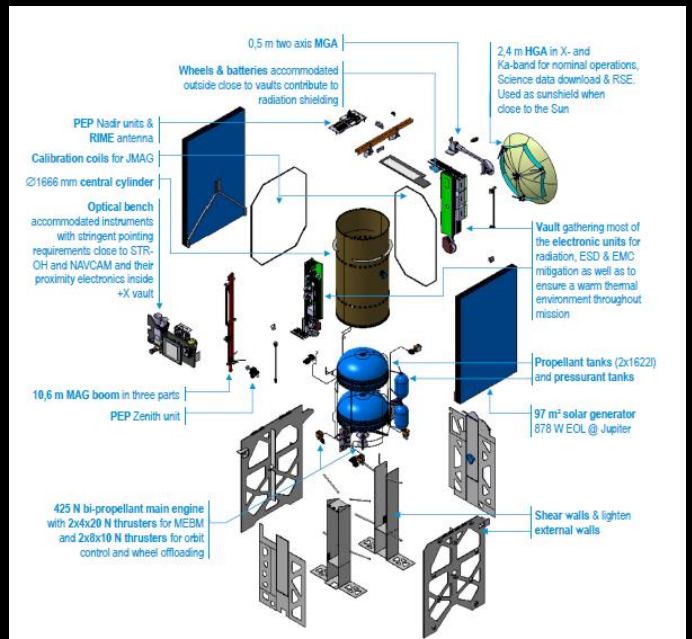


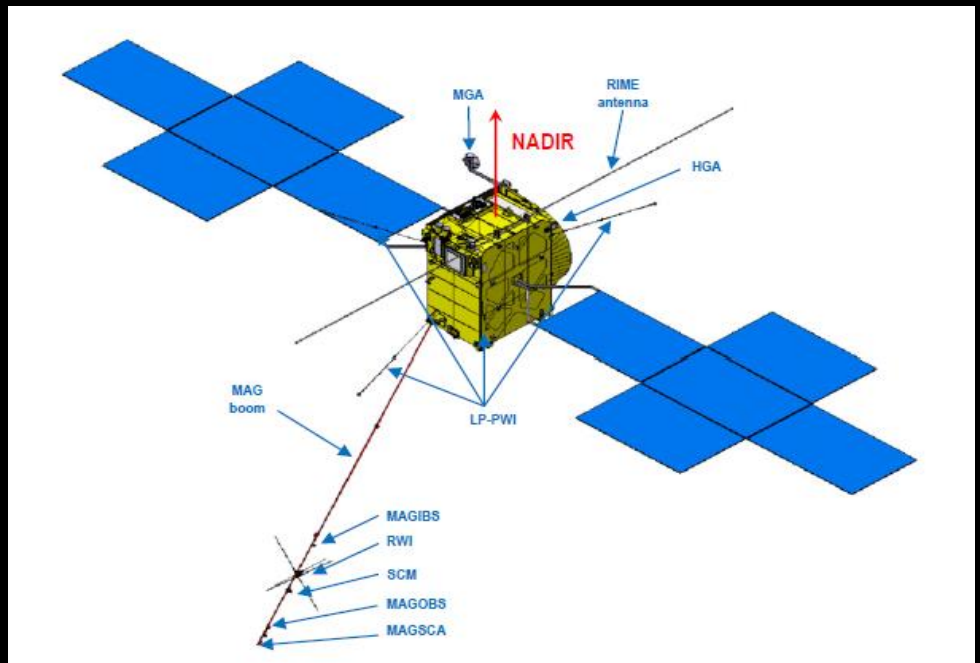


Jupiter system: largest planet, largest storm, fastest rotation, largest magnetic field, largest moon, largest moon system, most active moons

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

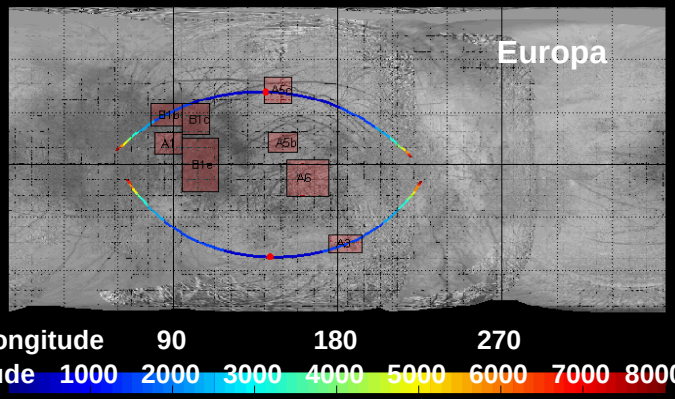
Acronym	PI	LFA	Instrument type
Remote Sensing Suite			
JANUS	P. Palumbo	Italy	Narrow Angle Camera
MAJIS	Y. Langevin G. Piccioni	France Italy	Vis-near-IR imaging spectrometer
UVS	R. Gladstone	USA	UV spectrograph
SWI	P. Hartogh	Germany	Sub-mm wave instrument
Geophysical Experiments			
GALA	H. Hussmann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

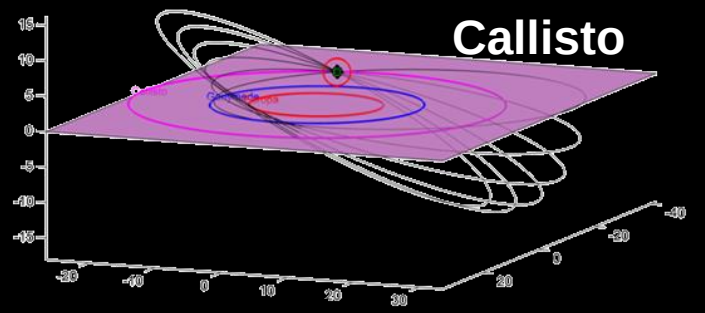
Mission design

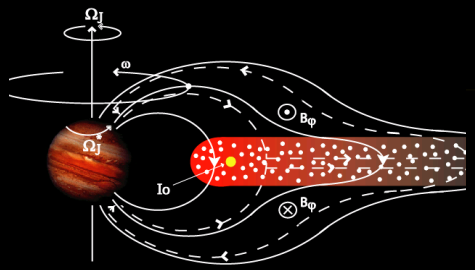
JUICE

Spacecraft Design	Model instruments
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	**150 days**
500 km circular	**102 days**
200 km circular (TBC)	**30 days**
Total mission at Jupiter	**3 years**

Mission phases



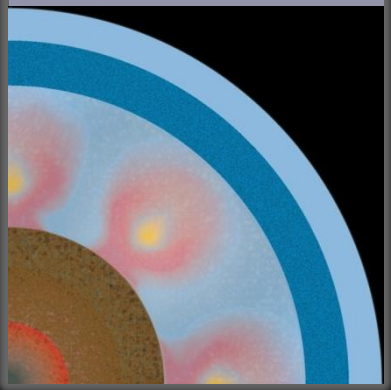




JUICE : Science investigations

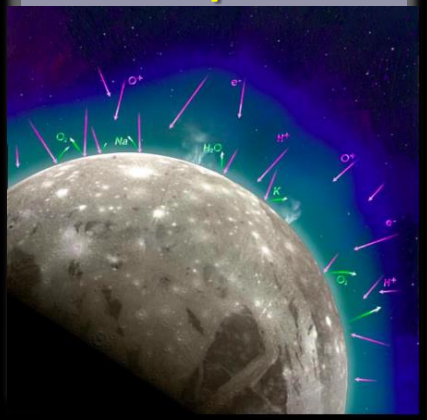
Ganymede: planetary object and potential habitat

Ice shell, ocean, deeper interiors

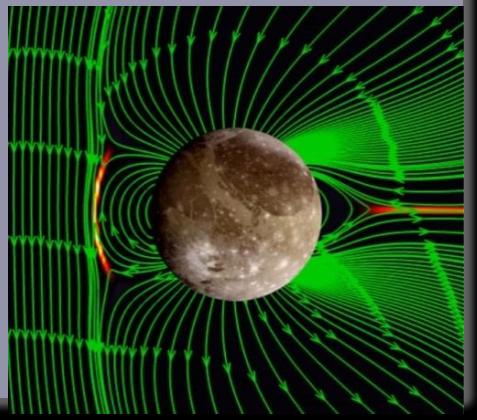


Geology, surface composition

Atmosphere, ionosphere

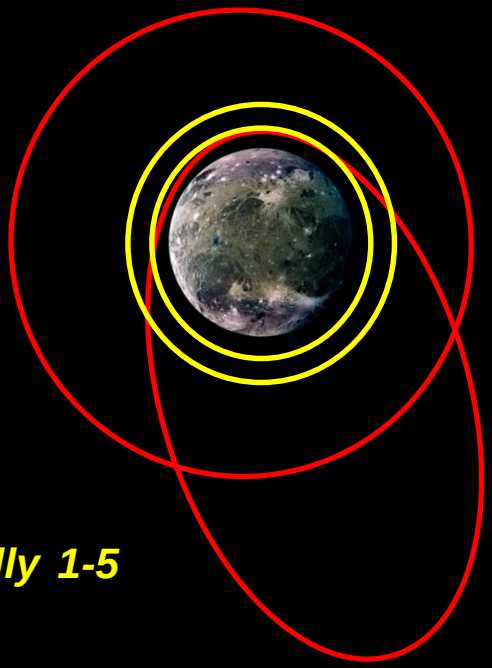


Magnetosphere, plasma environment



Main investigations

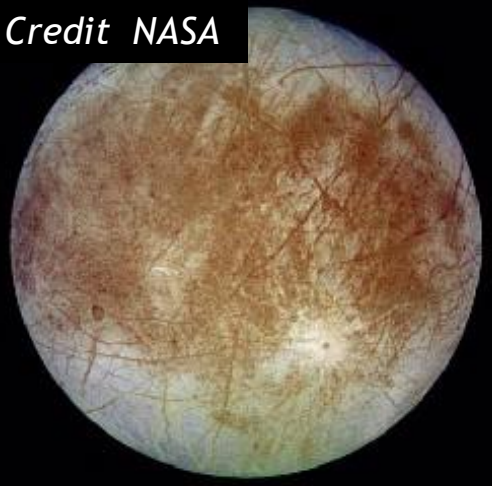
- ***Elliptical (1000x10000 km) & high (~5000 km) circular orbit***
- ***Medium (500 km) circular orbits***
- ***Favorable illumination conditions (β-angle 30°-70°)***
- ***Dedicated pointing modes***
- ***Sub-surface sounding down to ~9 km depth***
- ***Imaging: global ~400 m/px, selected targets ~3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

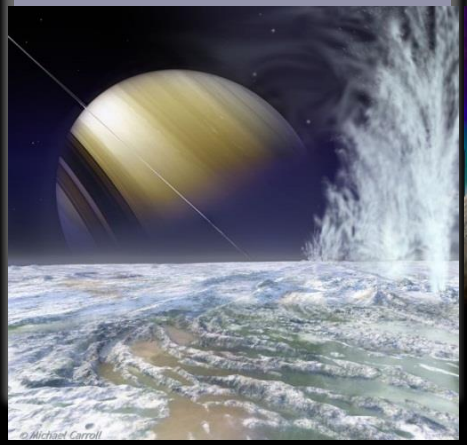


Credit NASA

Europa: study of recently active regions

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

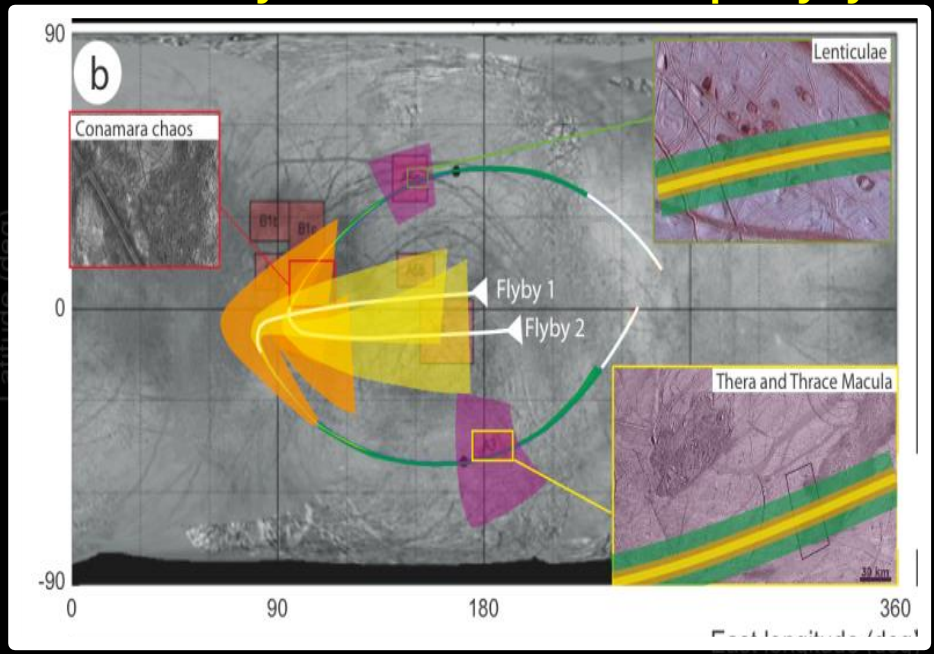




Main investigations

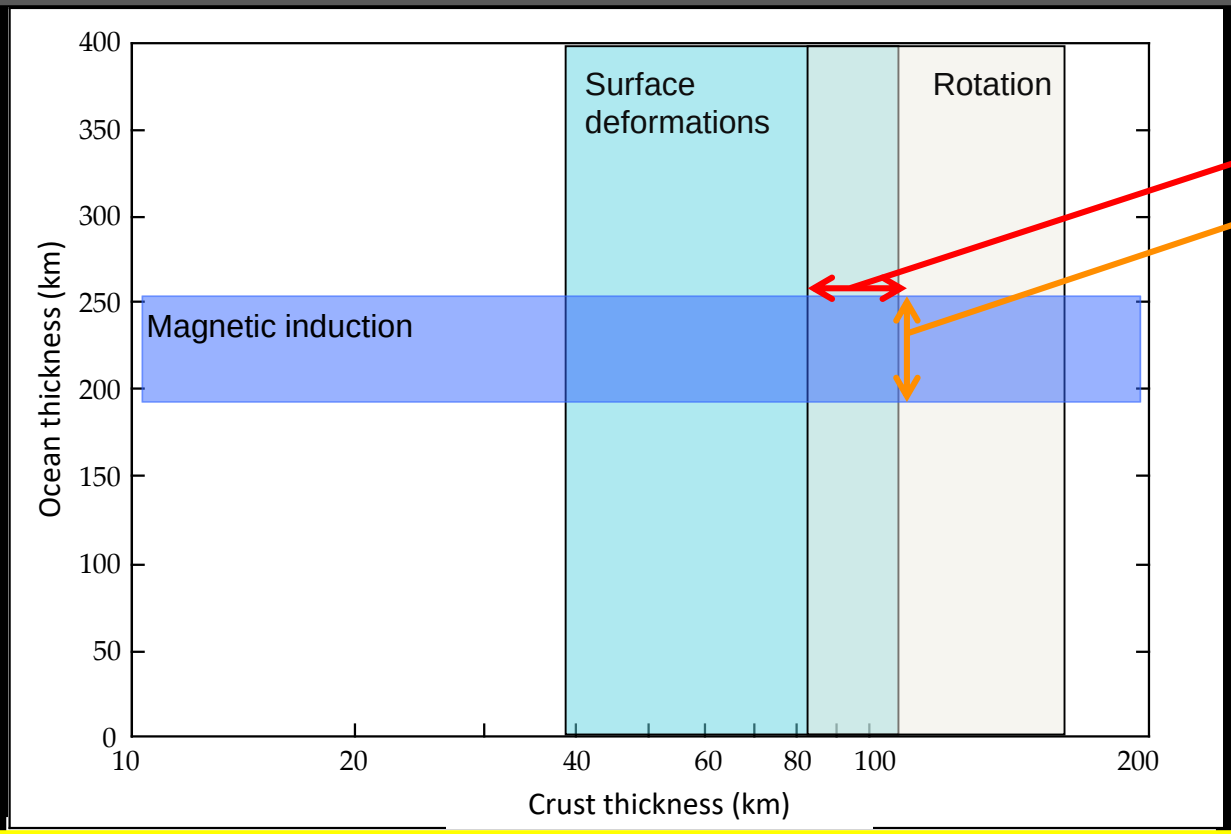
- At least 1 Europa flyby with CA ~400 km over the most active regions
- Favorable illumination conditions at CA
- Anti-Jovian side at CA
- Simultaneous operations of all experiments (including 3GM as a goal)
- Non-ice materials in selected sites mapped at regional (>5 km/px) and local (<500 m/px) scales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

Geometry of two baseline Europa flybys

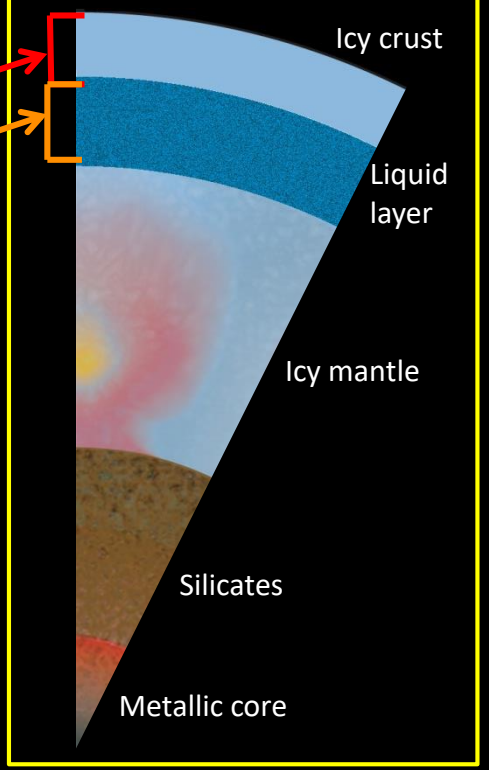


Characterise Ganymede as a planetary object and possible habitat

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



Internal structure



JUICE measurements

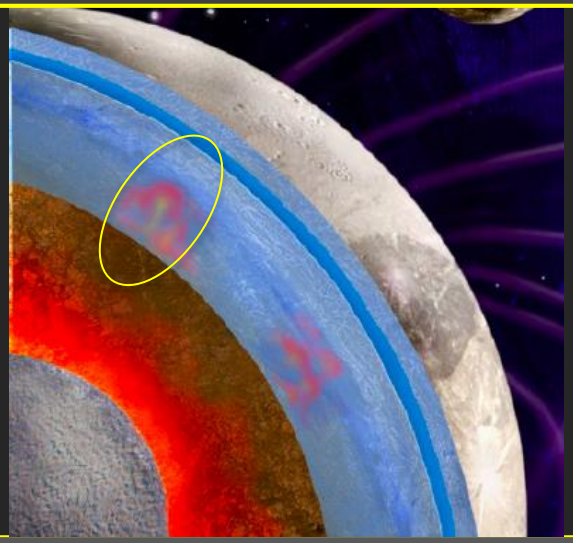
- Eccentric orbit ->Surface deformations
- Periodic variations in the rotation (librations)
- Magnetic induction from the field vector

Instrument Packages

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

From the Jupiter system to extrasolar planetary systems

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

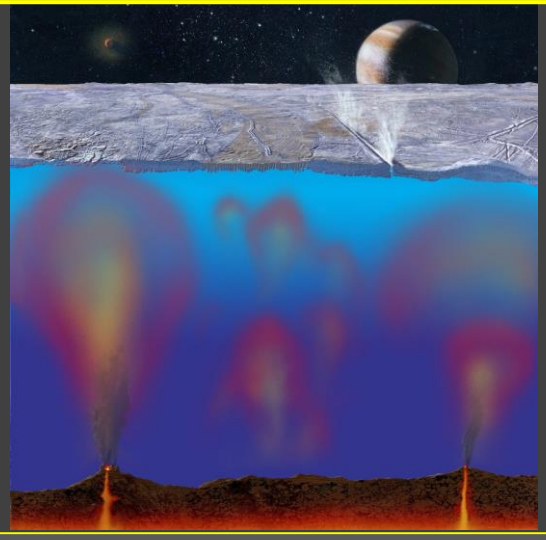


Occurrence:
Largest moons, hot ice giants, ocean-planets…
Most common habitat in the universe ?

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

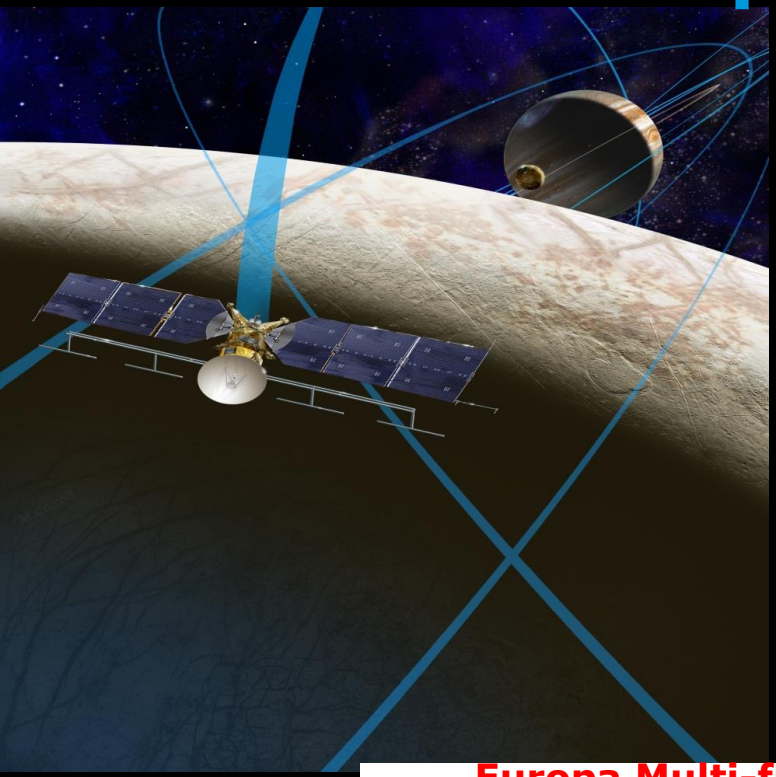


Occurrence:
Europa, Enceladus
Only possible for very small bodies

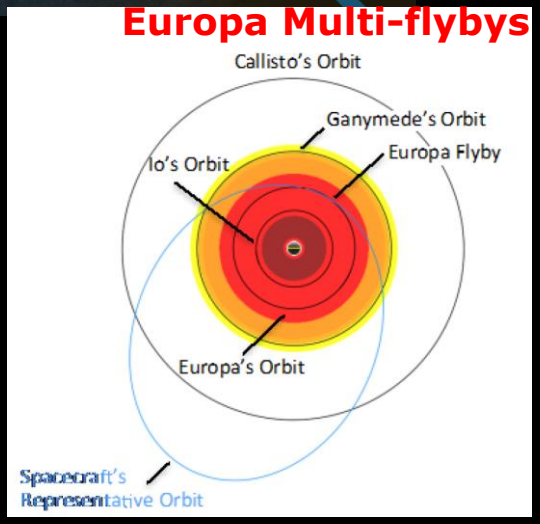
Key question:
How are the surface active areas related to potential deep habitats?

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

NASA Europa "Clipper" mission



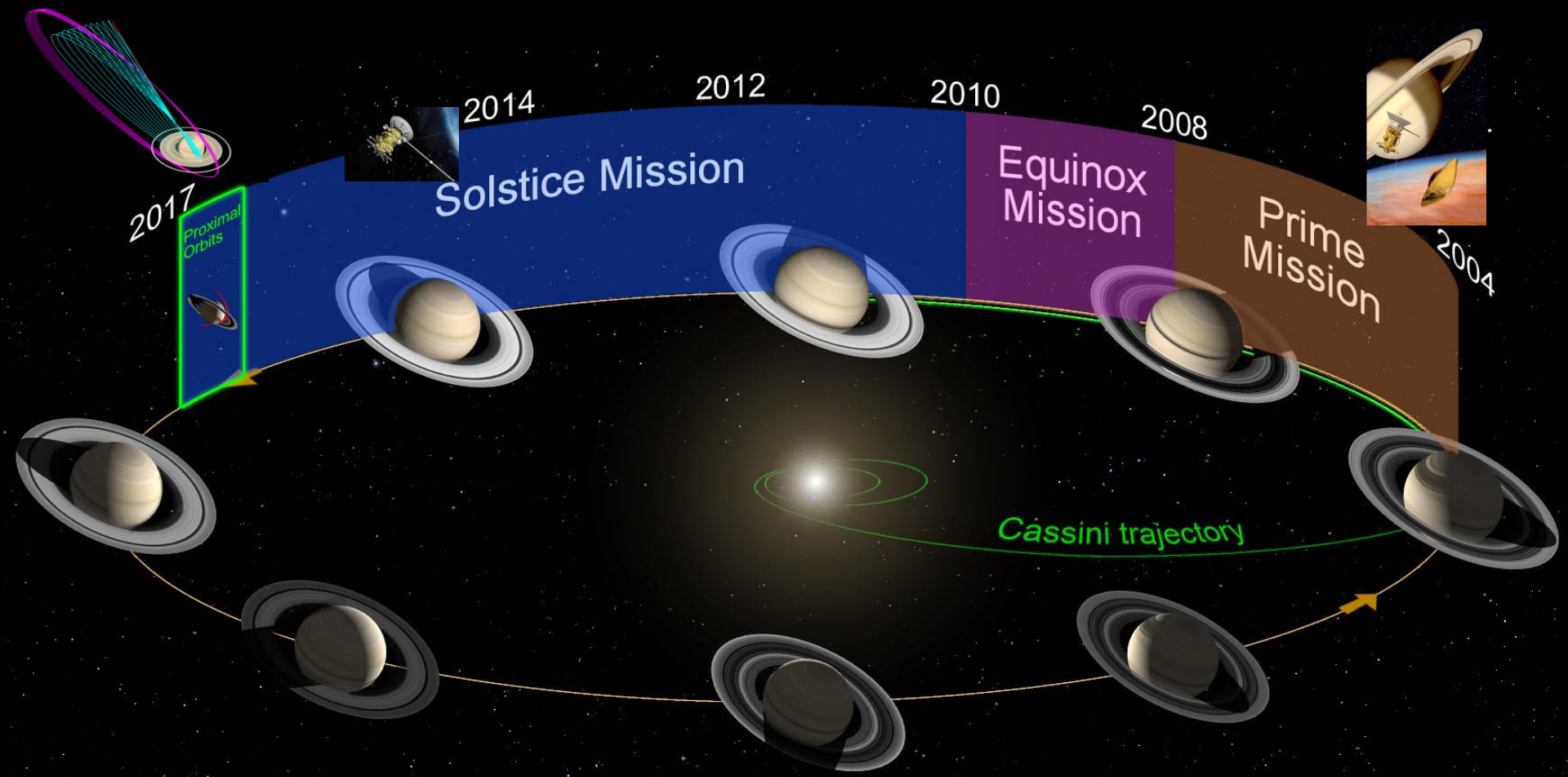
- Spacecraft in orbit around Jupiter
- Science goal: Europa's habitability
- Multiple (45) flybys of Europa
  - Altitudes: 25 – 2700 km
- 9 instruments selected: cameras, magnetometers, radar, dust analyser, spectrometers, plasma + mass spectrometer
- Schedule
  - Start formulation phase in Oct. 2016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



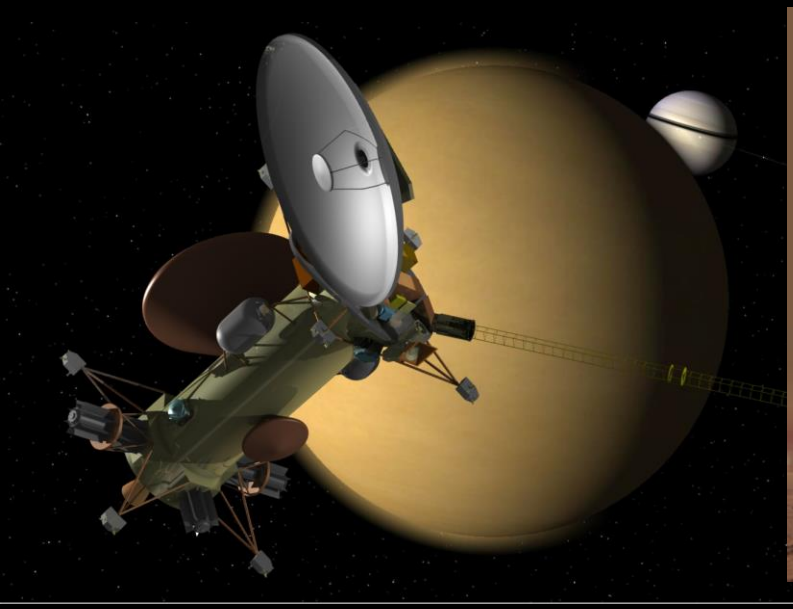
Possible extra probe, penetrator or lander provided by ESA is being discussed

The Saturnian system: a Post-Cassini mission…

Cassini-Huygens Mission Timeline



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)

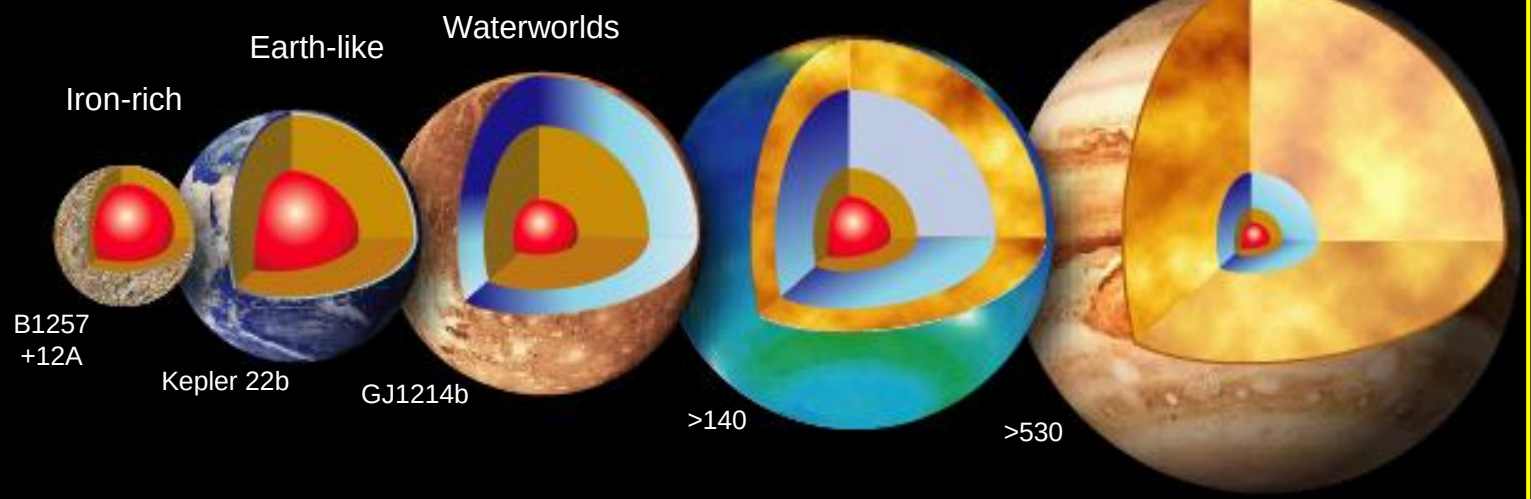
From the Jovian system to extrasolar planetary systems

Waterworlds and giant planets | Habitable worlds | Astrophysics Connection

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

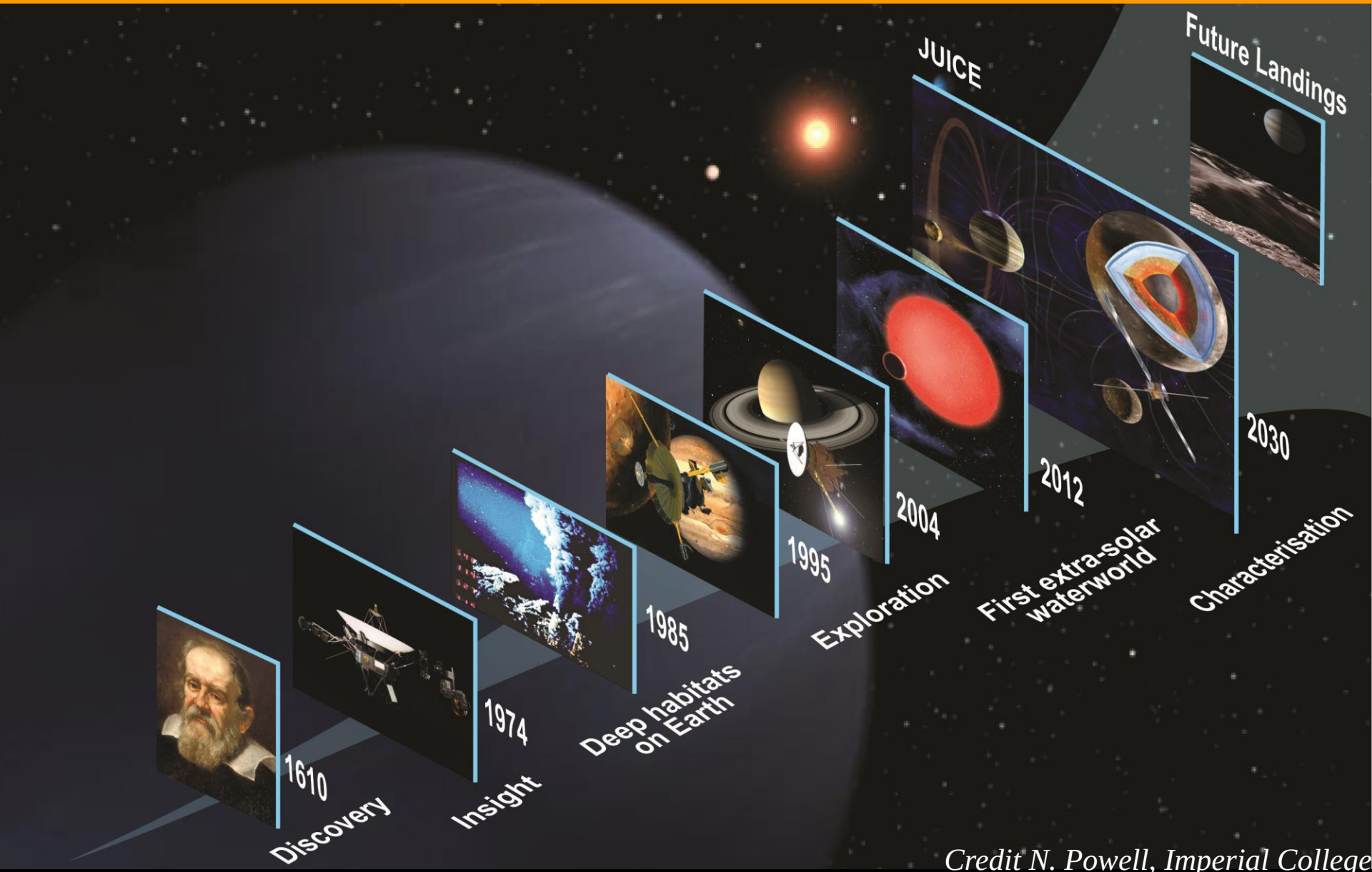
Jupiter system
Three waterworlds
One giant planet

Exoplanets
Five families
> 1800 planets



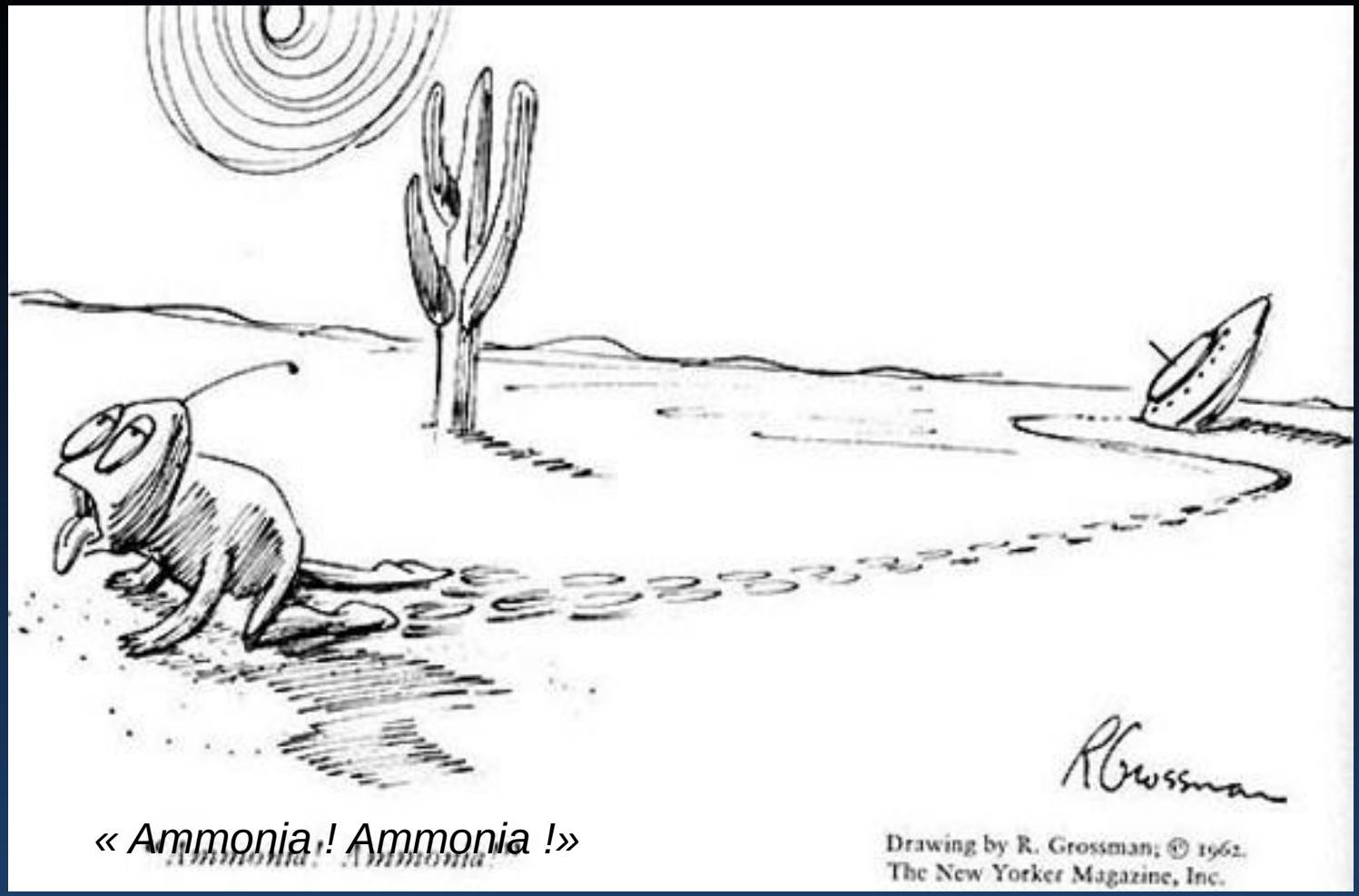
THE FUTURE OF EXPLORATION

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



Credit N. Powell, Imperial College

OTHER LIFE FORMS AND THE LOOK FOR HABITATS



« Ammonia ! Ammonia !»

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

Thank you
and au revoir !