

Exploring Ocean Worlds

Prebiotic and Astrobiology Implications

Morgan L. Cable, Ph.D.

9 June 2017

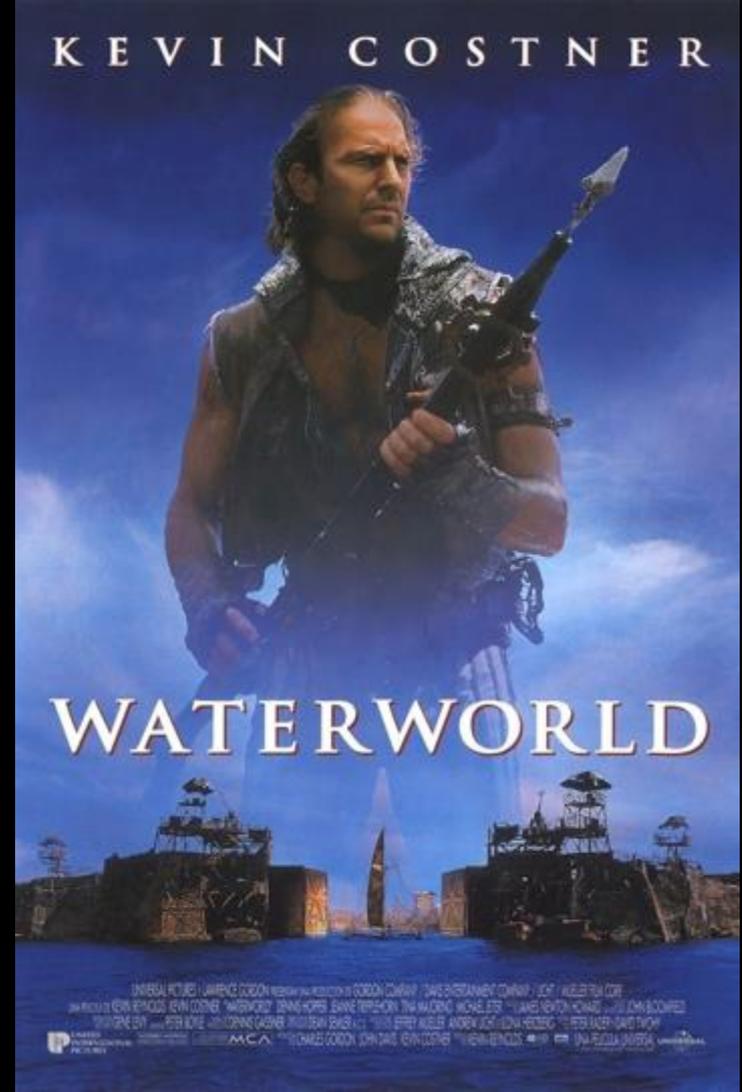
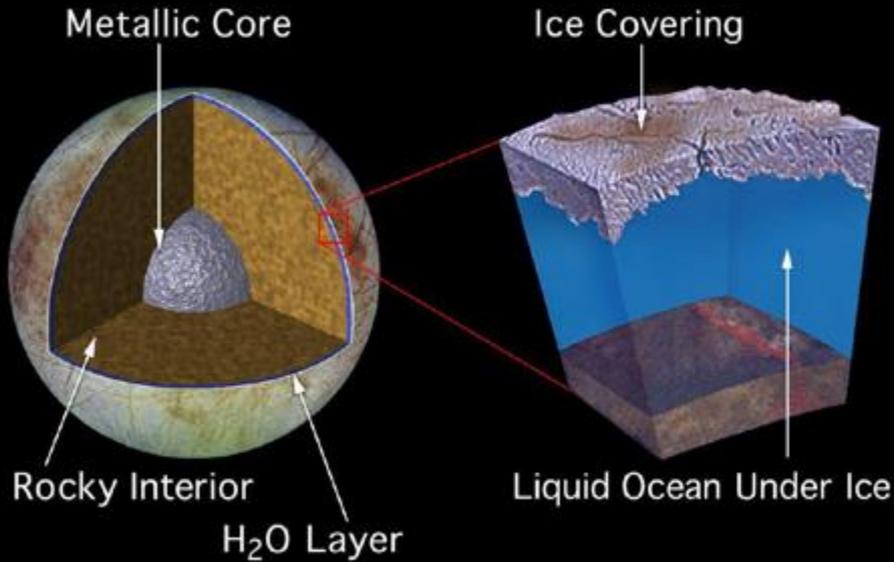


Jet Propulsion Laboratory
California Institute of Technology

Image: NASA/JPL-Caltech/SSI

What is an Ocean World?

There are more than you think!



What is an Ocean World?

There are more than you think!



Europa



Ganymede



Callisto

What is an Ocean World?

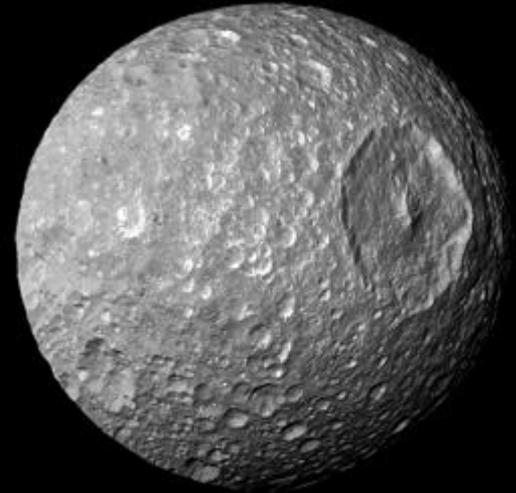
There are more than you think!



Titan



Enceladus



Mimas

What is an Ocean World?

There are more than you think!



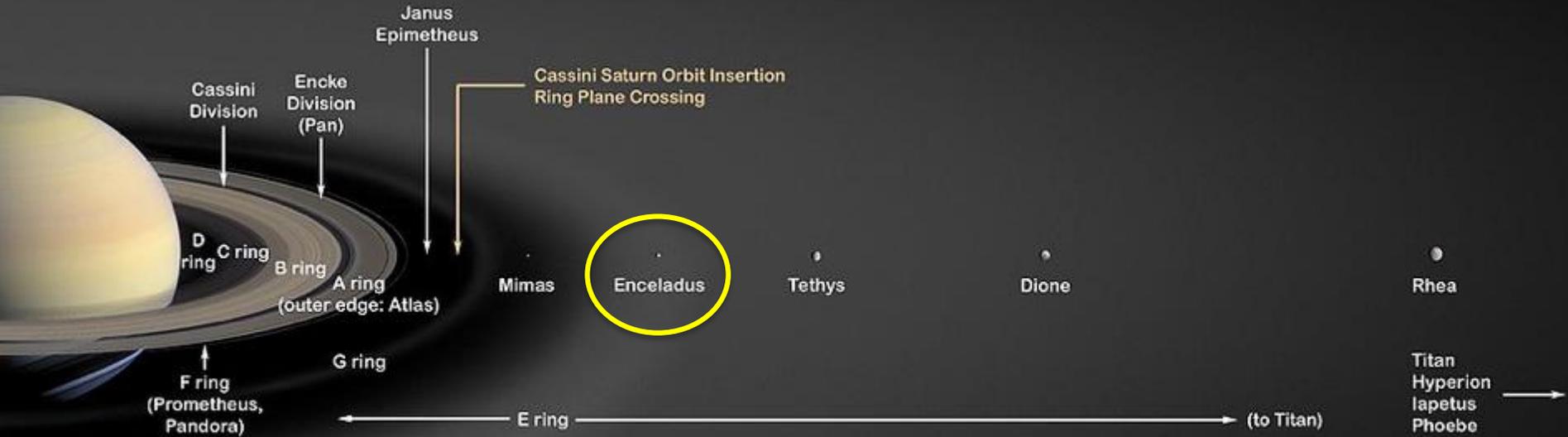
Triton



Pluto

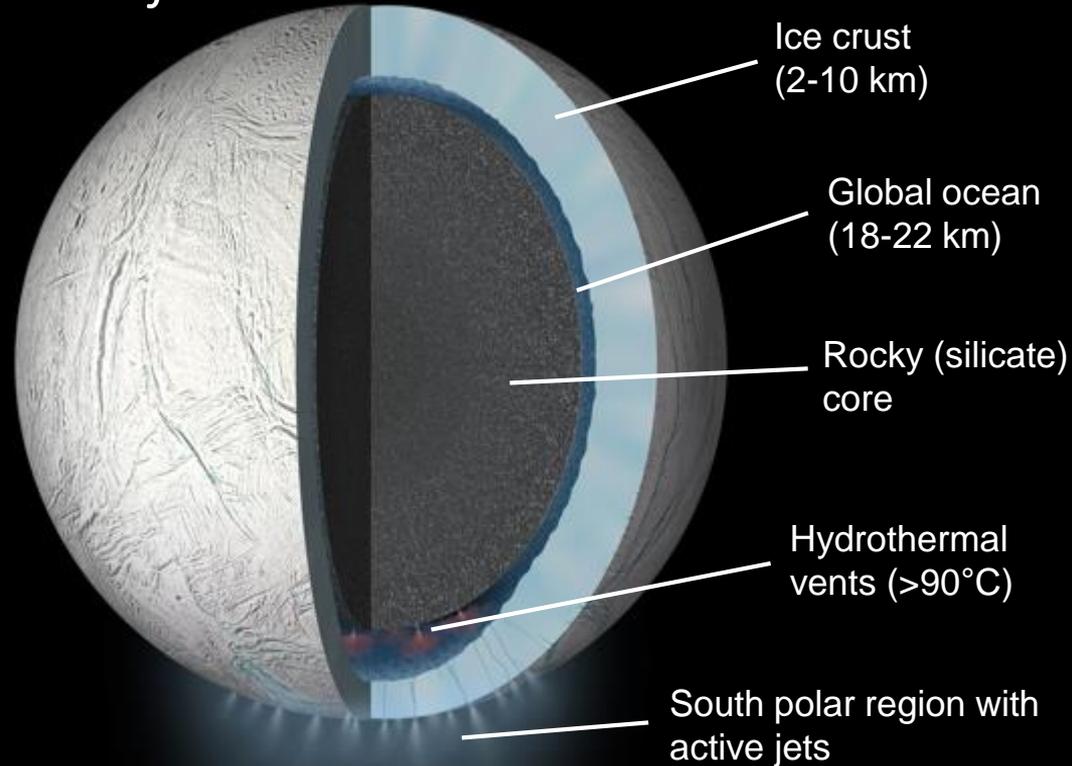
What is an Ocean World?

There are more than you think!



Enceladus: Active, Astrobiologically Relevant, Accessible

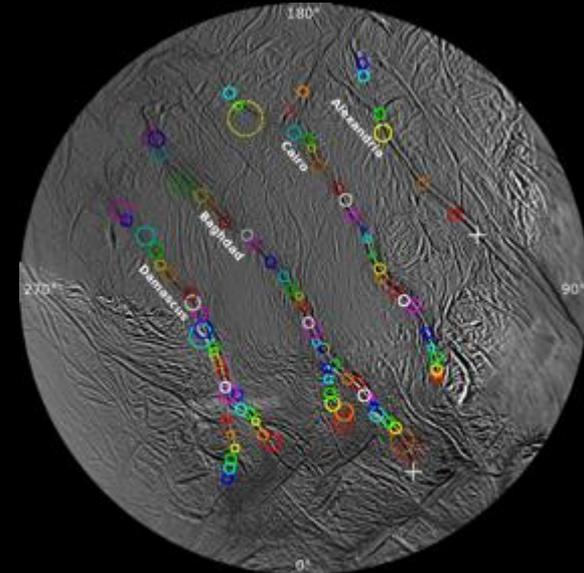
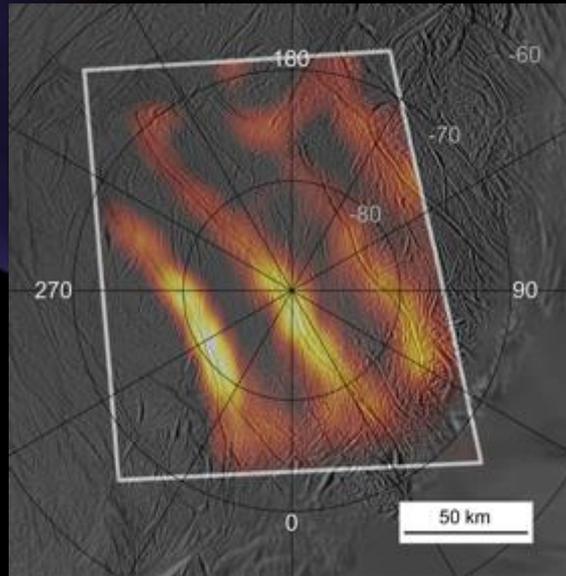
An ideal place to search for aqueous-based life



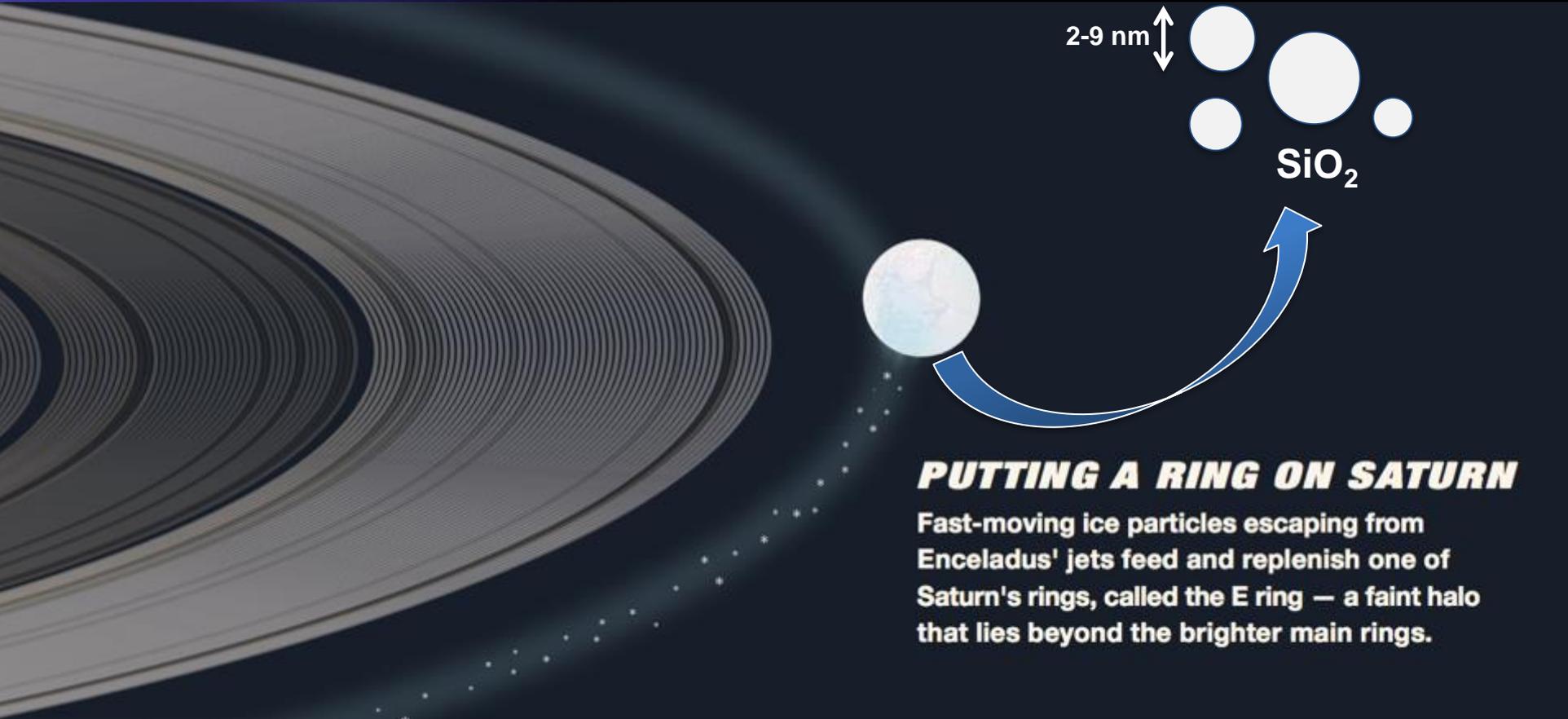
Enceladus: Active, Astrobiologically Relevant, Accessible

Free sample, no need to dig or drill

- ~100 distinct, collimated jets emanating from Tiger Stripes that form a single plume
 - Modulated by diurnal tidal flexing



Enceladus: Active, Astrobiologically Relevant, Accessible

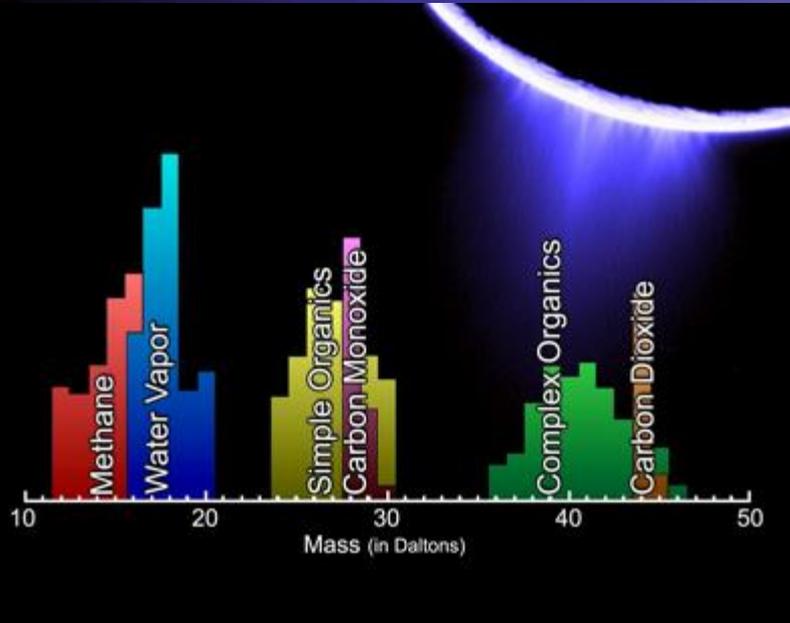
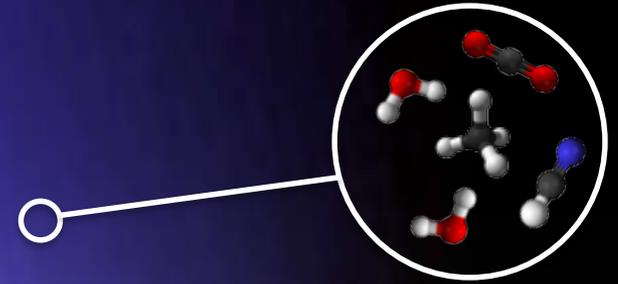


PUTTING A RING ON SATURN

Fast-moving ice particles escaping from Enceladus' jets feed and replenish one of Saturn's rings, called the E ring — a faint halo that lies beyond the brighter main rings.

Plume Composition

Organic-rich, sourced from the subsurface ocean



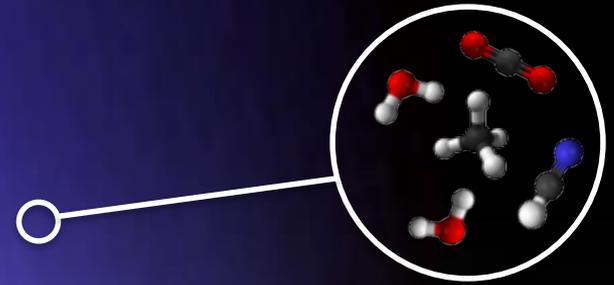
Plume gas

- H_2O , CO_2 , CH_4 , NH_3 , H_2 (yay!), heavier hydrocarbons, **simple and complex organics**
- Mass flux: 200 kg/s

Constituent	Mixing ratio (%)
H_2O	96 to 99
CO_2	0.3 to 0.8
CH_4	0.1 to 0.3
NH_3	0.4 to 1.3
H_2	0.4 to 1.4

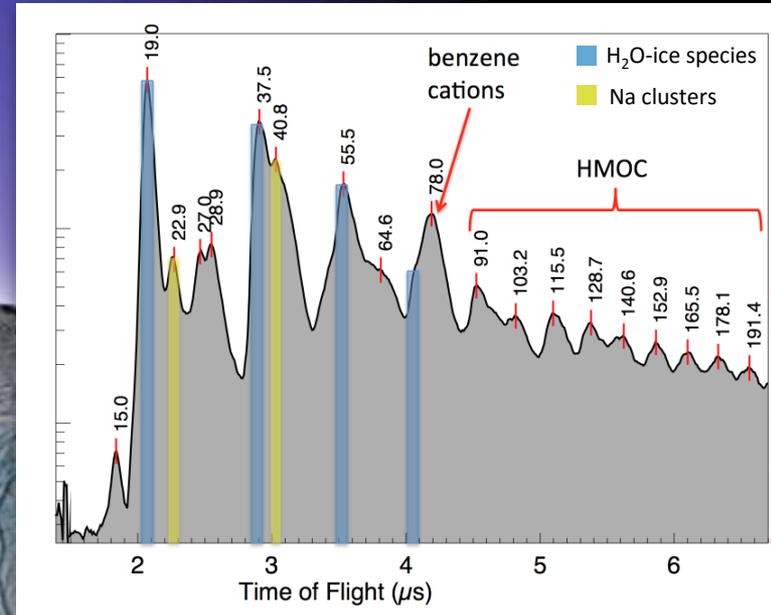
Plume Composition

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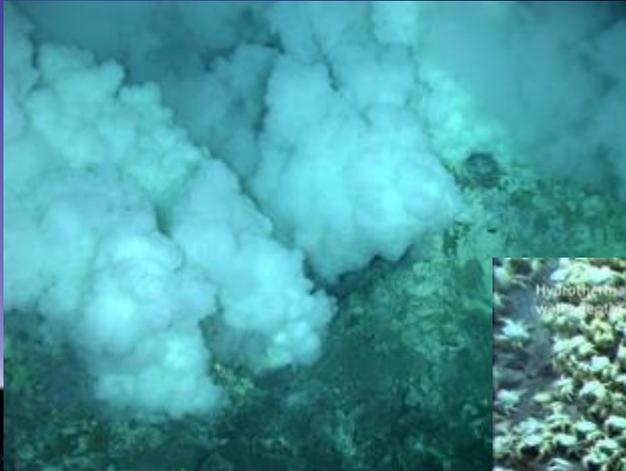
Plume grains

- Water-ice, salts (mostly NaCl), SiO₂, **high mass organic cations (HMOC)**
- Mass flux: 50 kg/s (~10% of particles reach escape velocity)



Hydrothermal Vents?

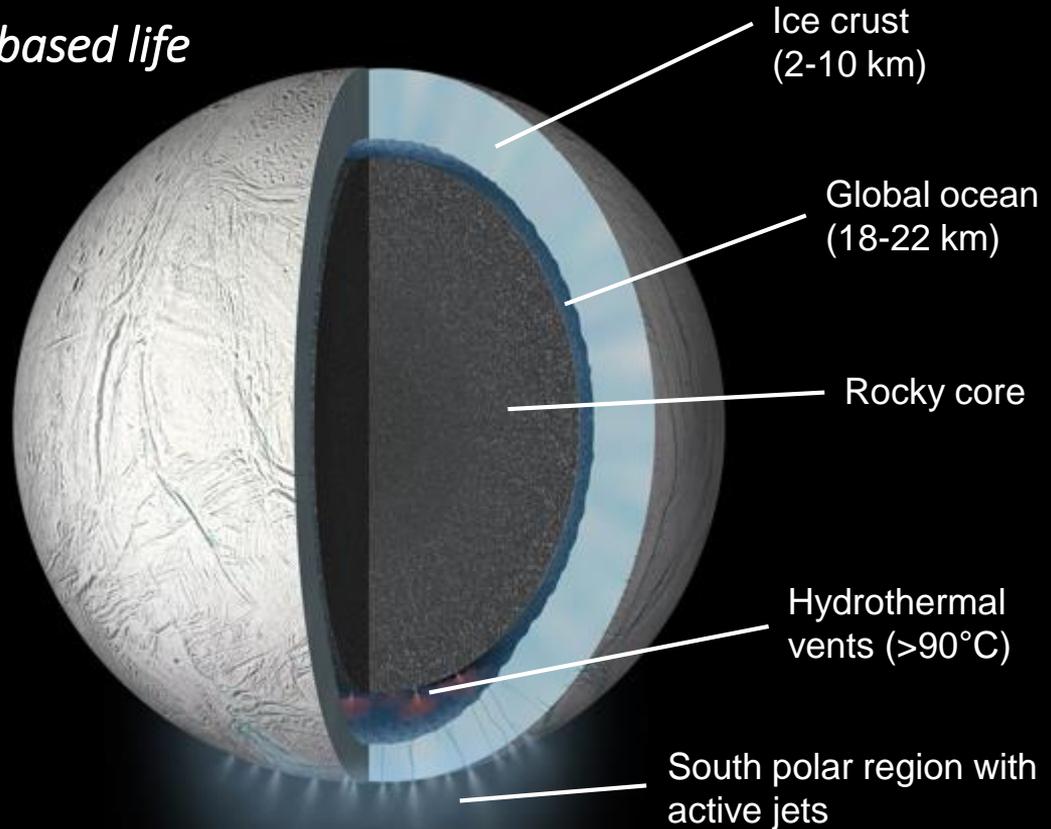
May have been how life originated on Earth

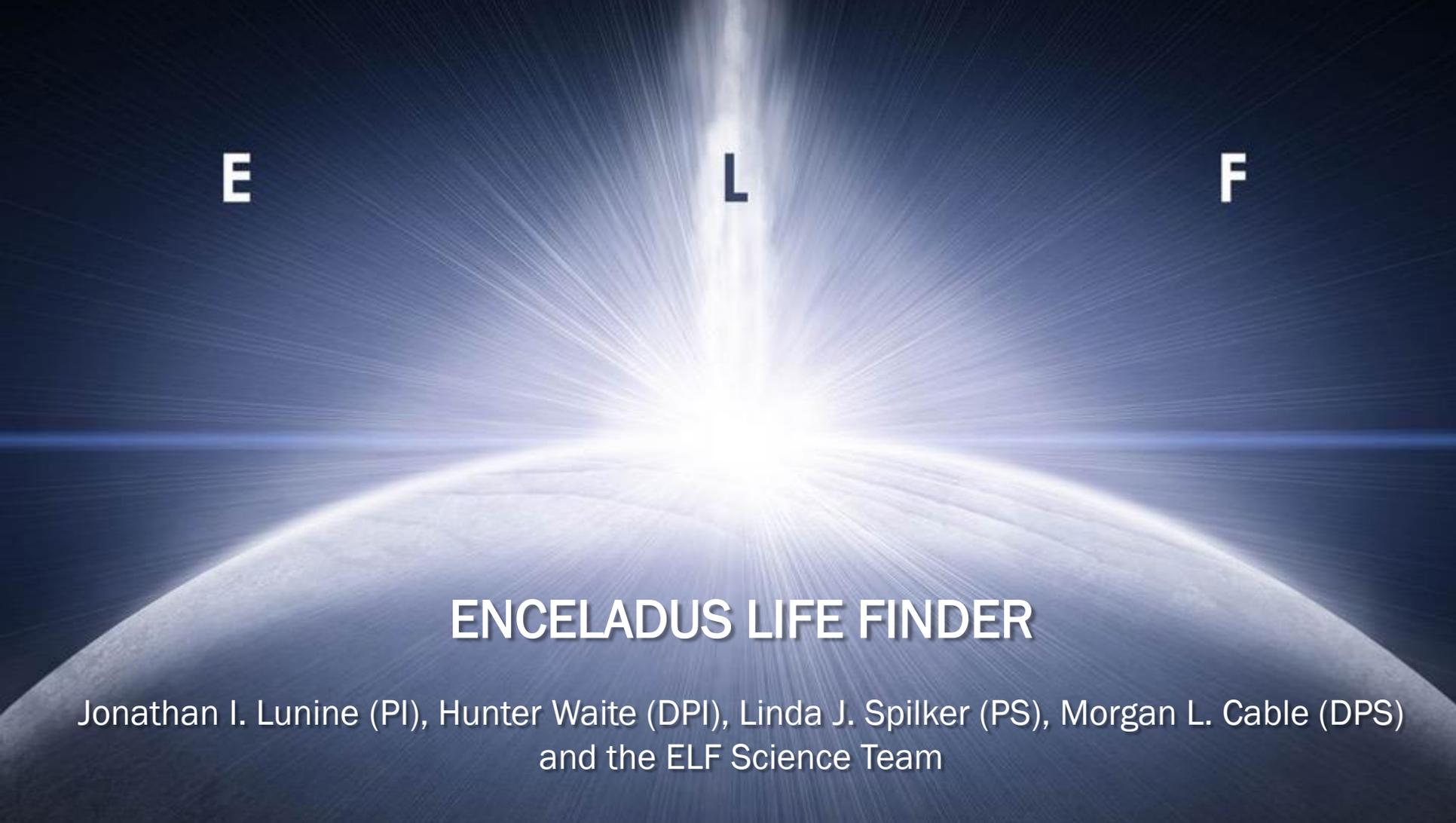


Enceladus Awaits

An ideal place to search for aqueous-based life

WE NEED TO GO BACK



The background features a view of the planet Enceladus from space, showing its curved horizon and a bright, glowing plume of water vapor or ice particles rising from the south pole. The plume is centered and radiates outwards, creating a starburst effect. The letters 'E', 'L', and 'F' are positioned at the top of the image, spaced out horizontally.

E

L

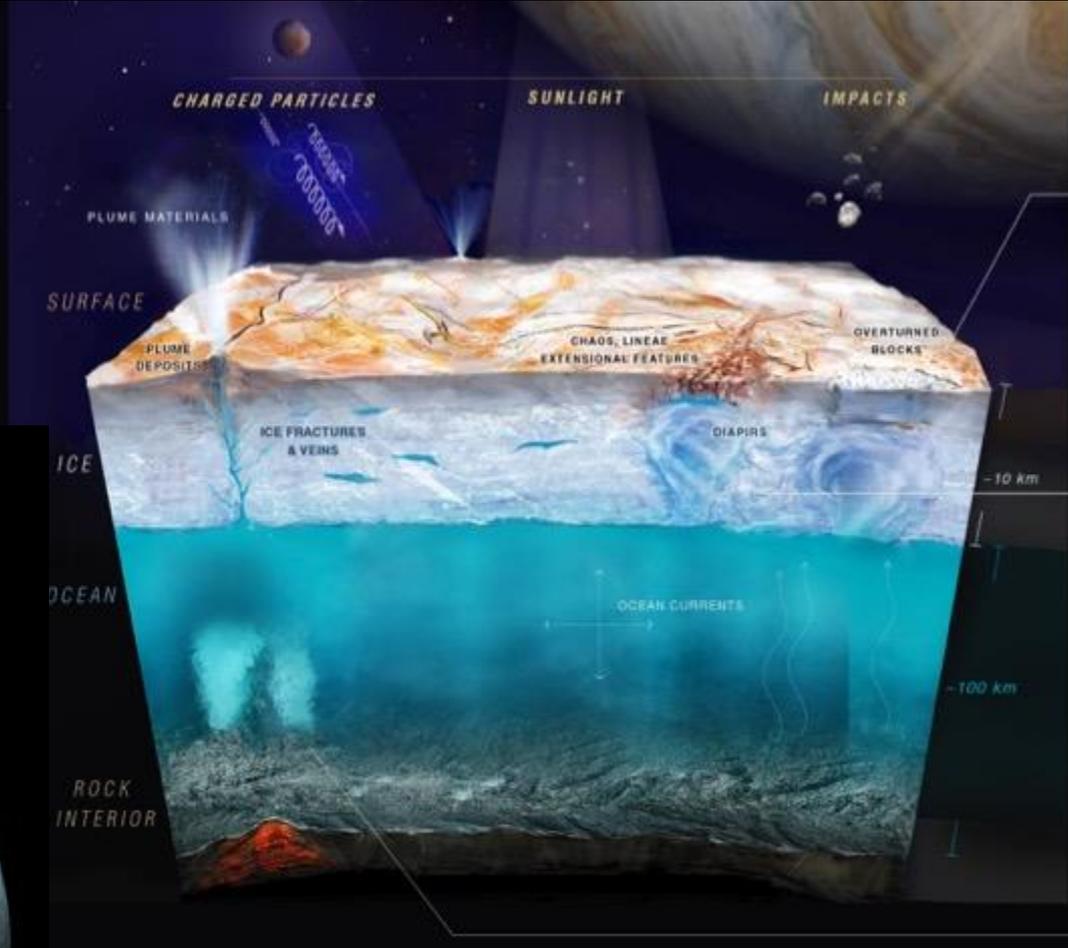
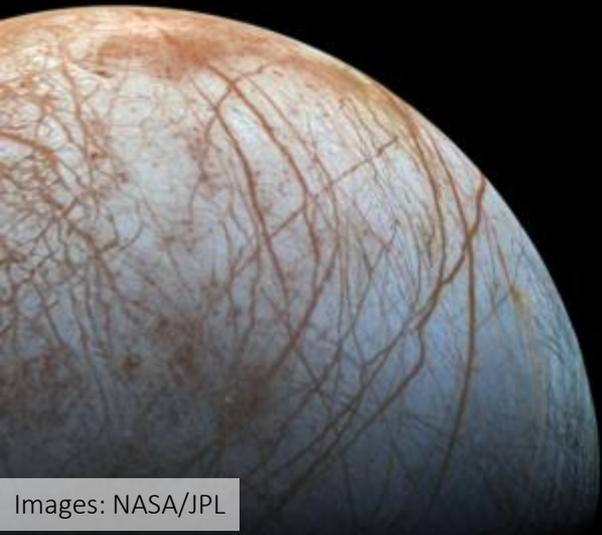
F

ENCELADUS LIFE FINDER

Jonathan I. Lunine (PI), Hunter Waite (DPI), Linda J. Spilker (PS), Morgan L. Cable (DPS)
and the ELF Science Team

Europa Beckons

Jem of the Jovian system



ICE BLOCKS



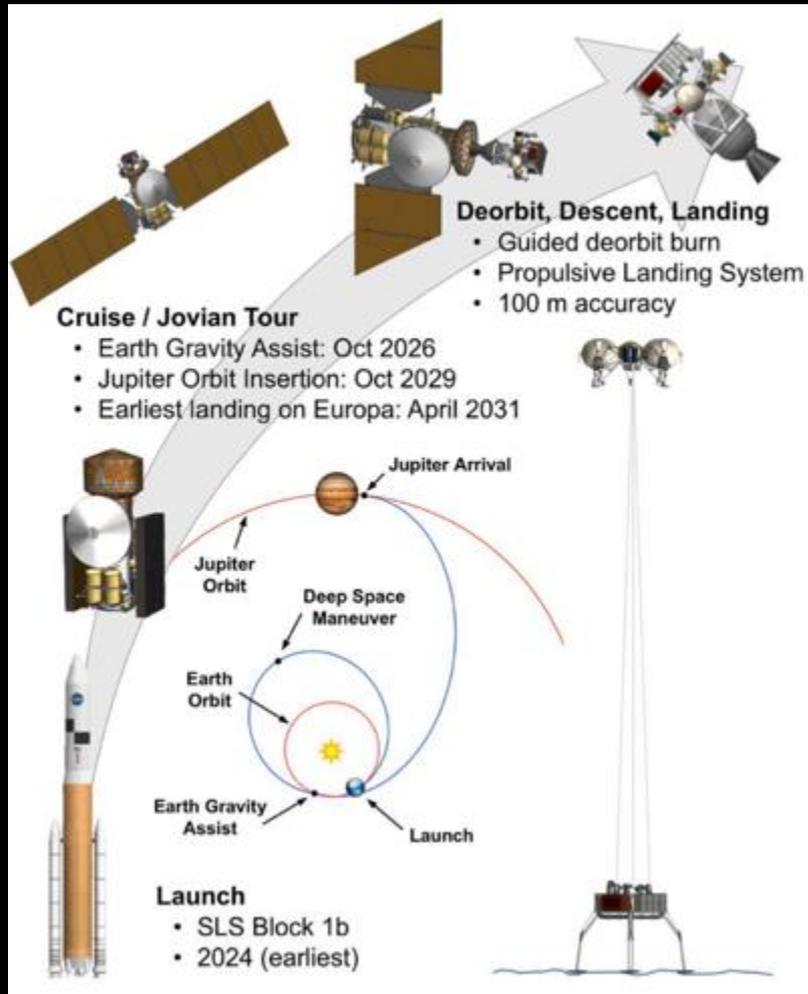
ICE FRACTURES



HYDROTHERMAL VENTS

Europa Beckons

Jem of the Jovian system



Carrier Relay Orbit

- 24-hour period
- >10 hours Lander visibility per orbit

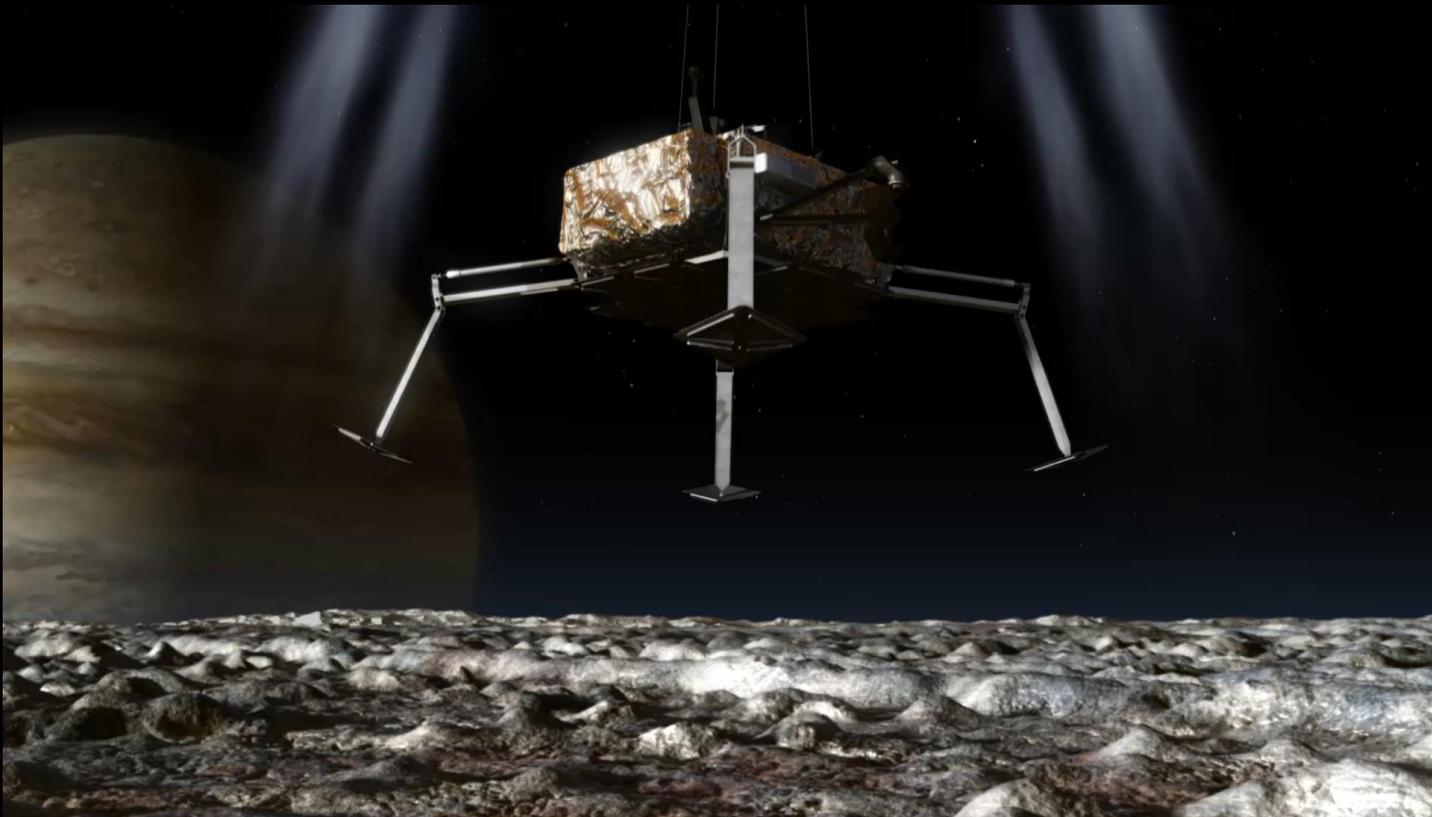


Surface Mission

- 20+ day surface mission
- 5 samples
- Relay communications through Carrier or Europa MFM (backup)
- 3-4 Gbit data return
- 45 kWh battery

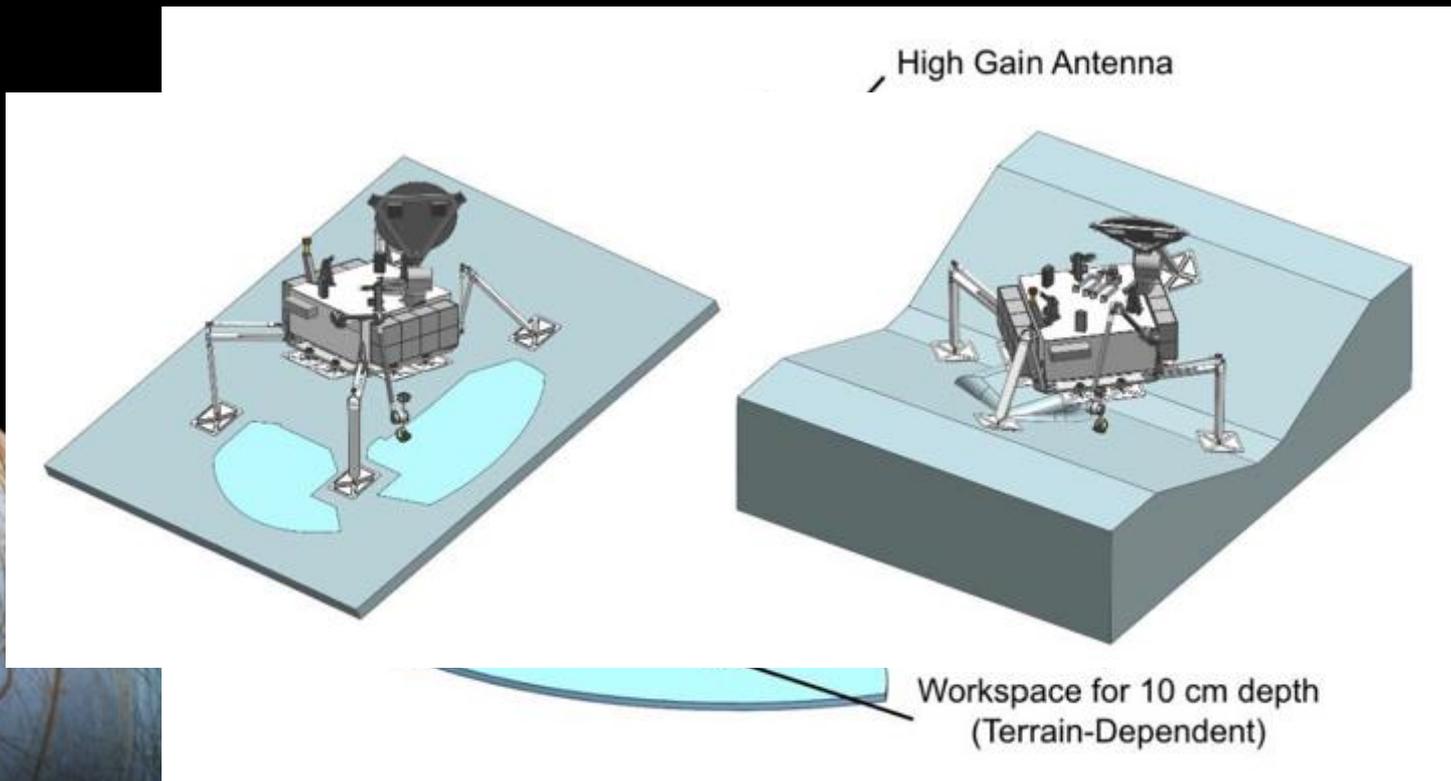
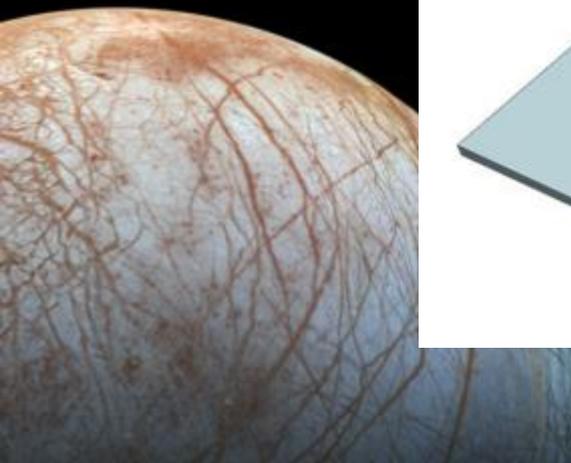
Europa Beckons

Jem of the Jovian system



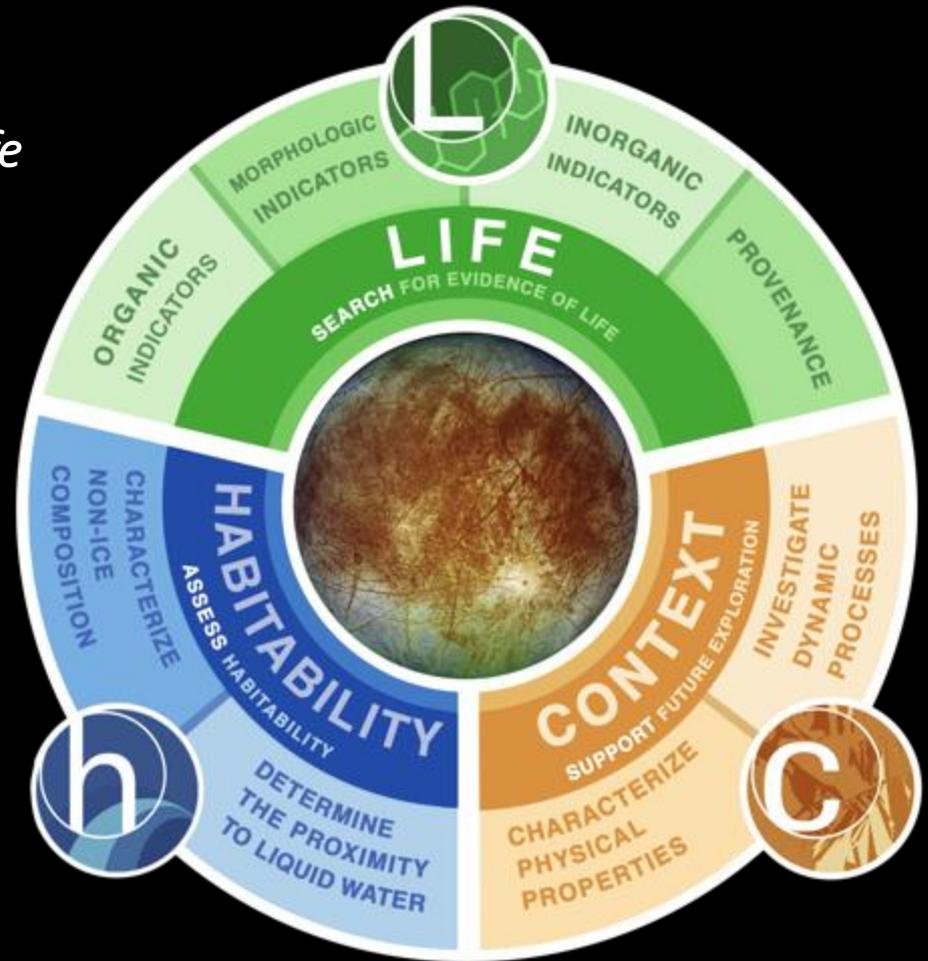
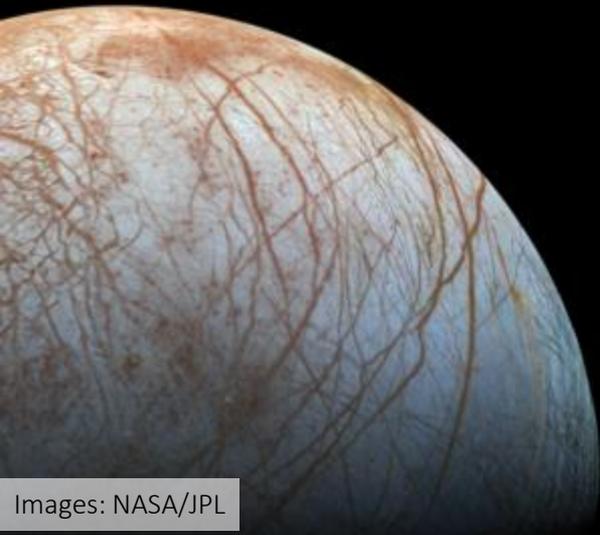
Europa Beckons

Jem of the Jovian system



Europa Beckons

A robust approach to search for signs of life



Europa Beckons

Keeping it all in context

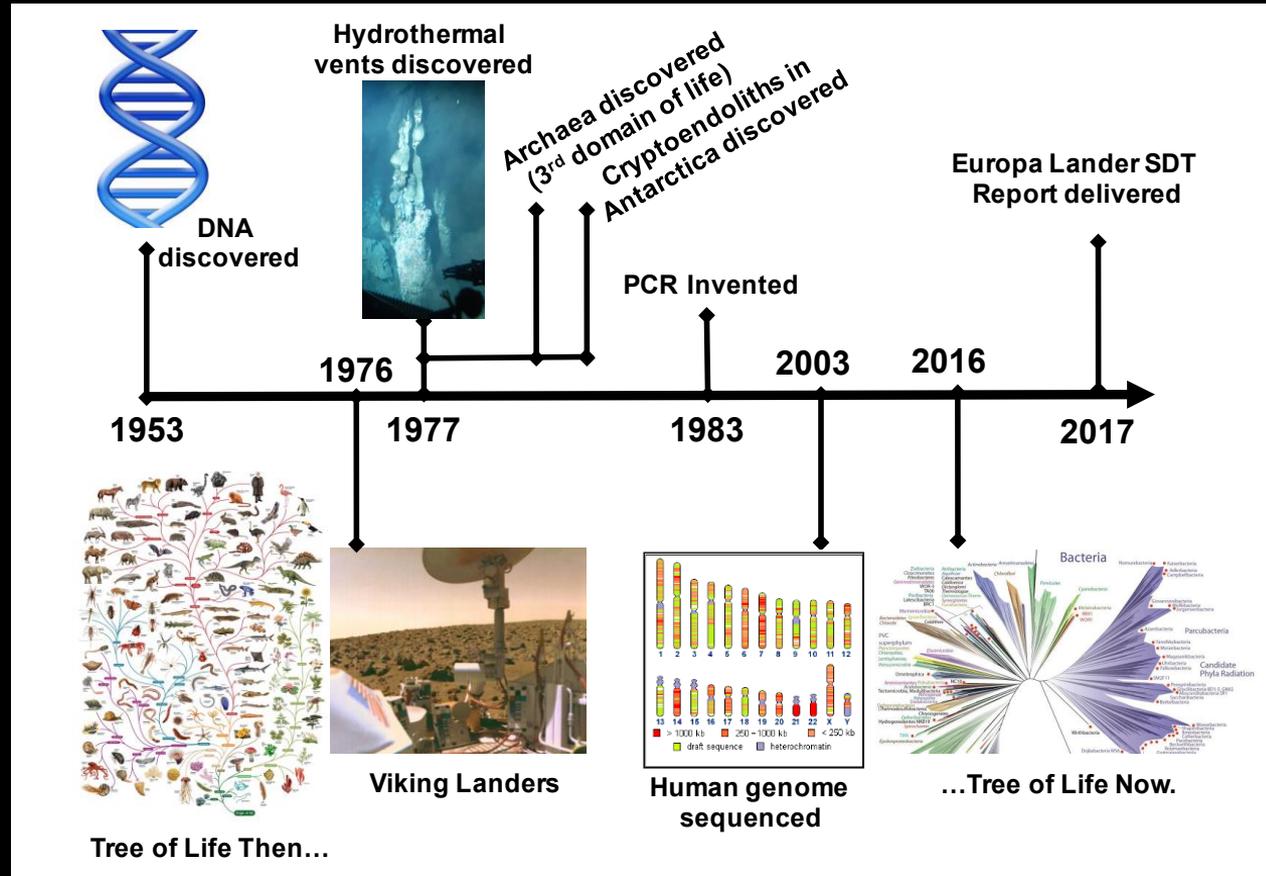
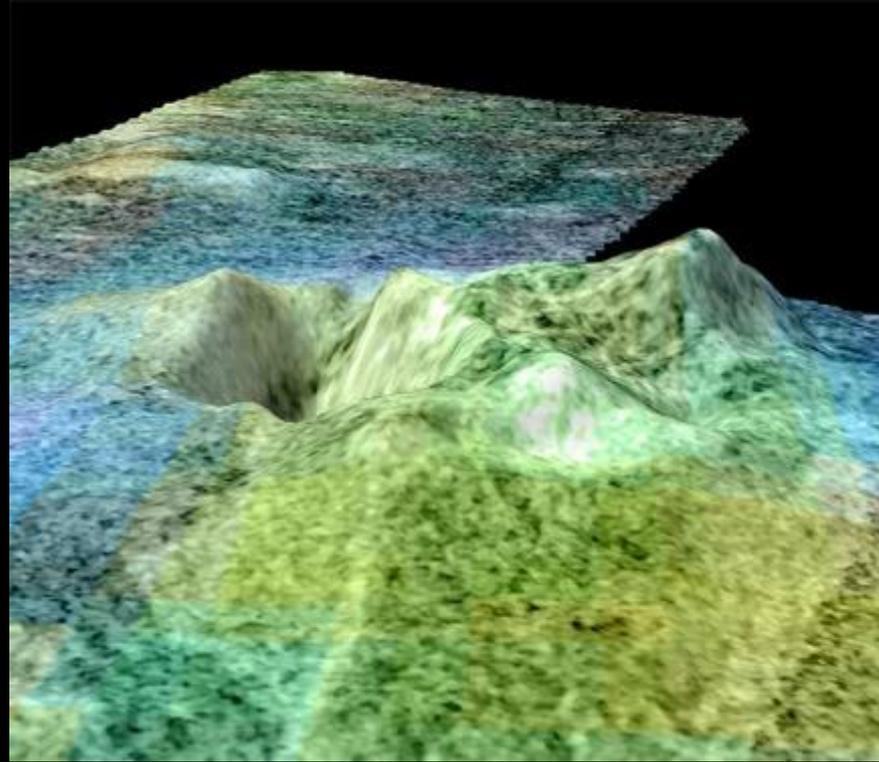


Figure: K. Hand

Titan Tantalizes

Familiar, yet alien

- **Atmosphere**
 - 96% N₂, 4% CH₄
 - 1.5 bar (thicker than Earth)
- **Surface**
 - Water-ice coated in organics
 - Dunes in the equatorial region
- **Hydrologic Cycle**
 - Liquid methane, ethane lakes
 - Methane clouds, drizzle
- **Putative Cryovolcanoes**
 - Slurry of ammonia and water ice, possibly methanol



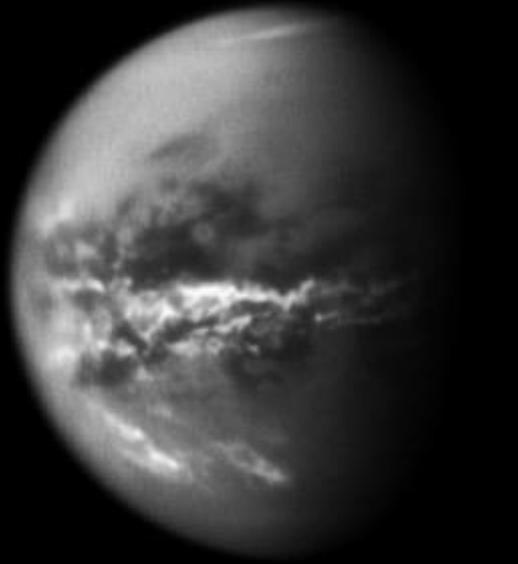
A possible cryovolcano in the Sotra Facula region of Titan
(NASA/JPL/Univ. of Arizona/USGS)

Titan Tantalizes

Familiar, yet alien

TITAN
Clouds

EARTH
Clouds



Titan Tantalizes

Familiar, yet alien

TITAN
River channels



EARTH
River channels

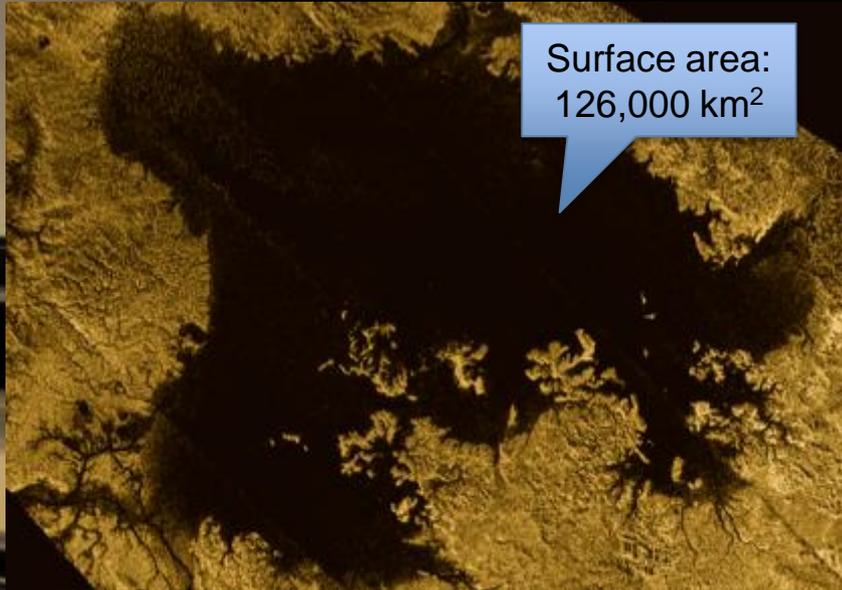


Titan Tantalizes

Familiar, yet alien

TITAN Lakes and Seas

Surface area:
126,000 km²



EARTH Lakes and Seas

Surface area:
58,000 km²

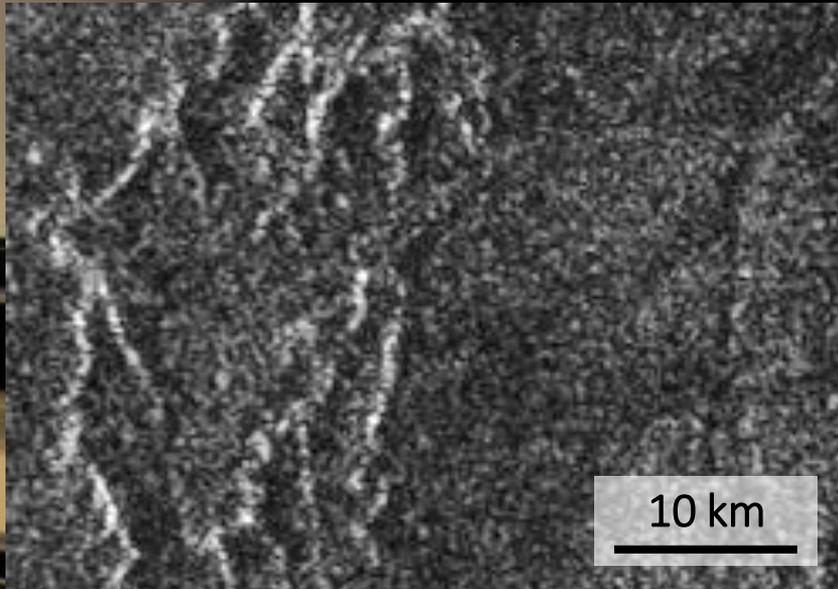


Titan Tantalizes

Familiar, yet alien

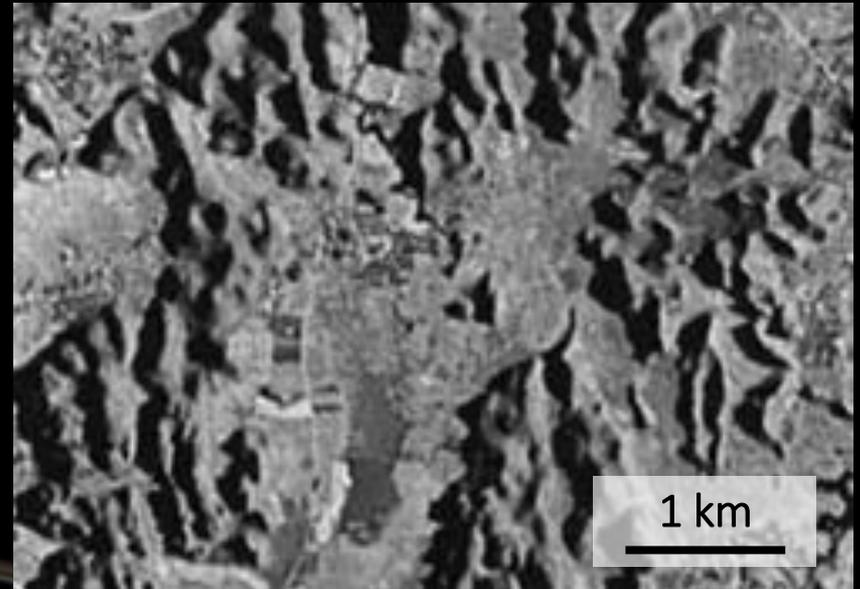
TITAN

Remnants of Ridges (Karst)



EARTH

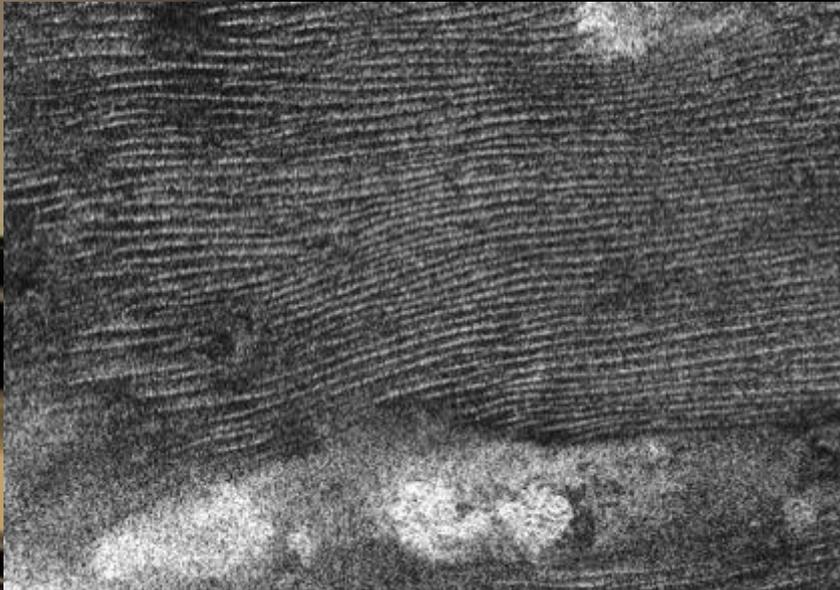
Remnants of Ridges (Karst)



Titan Tantalizes

Familiar, yet alien

TITAN
Dune Fields

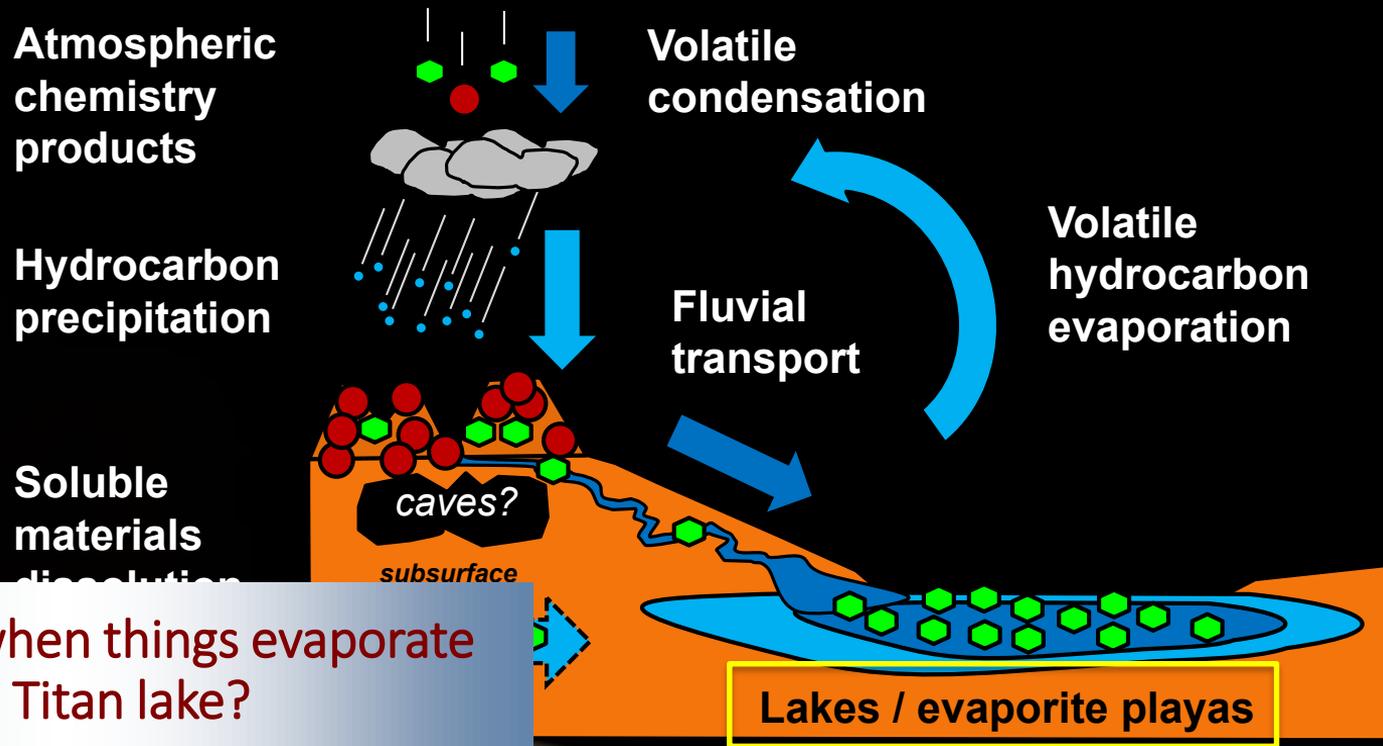


EARTH
Dune Fields



Titan Laboratory Experiments

Tackling Titan's surface chemistry, one experiment at a time

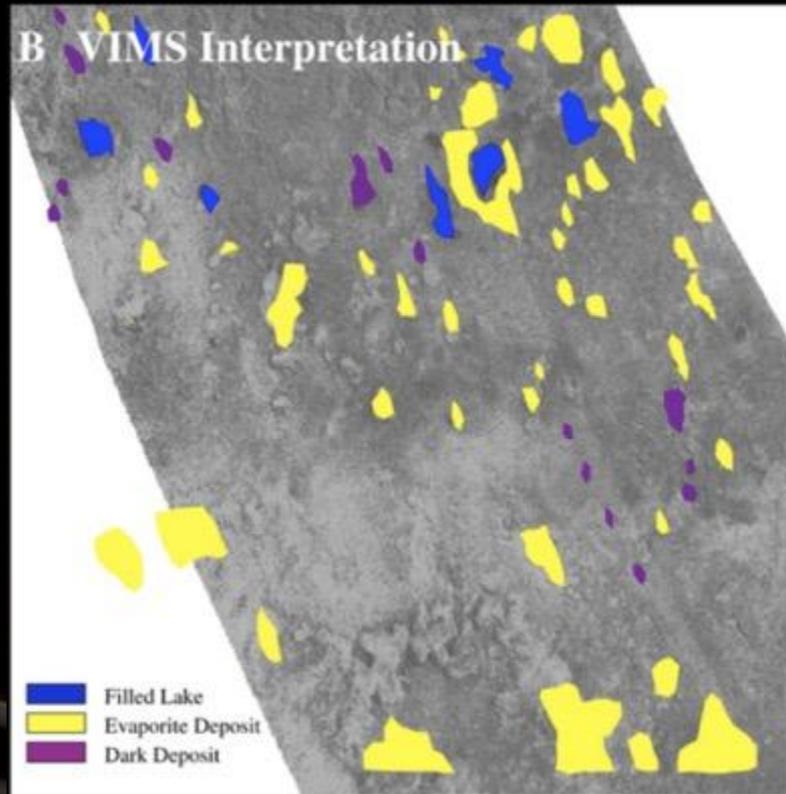


What happens when things evaporate from a Titan lake?

Lakes / evaporite playas

Titan Laboratory Experiments: Surface Deposits

Probing the bathtub rings around Titan's lakes



- Solubility of benzene in liquid ethane is low
- Benzene could be an abundant evaporite around the lakes on Titan

Titan Laboratory Experiments

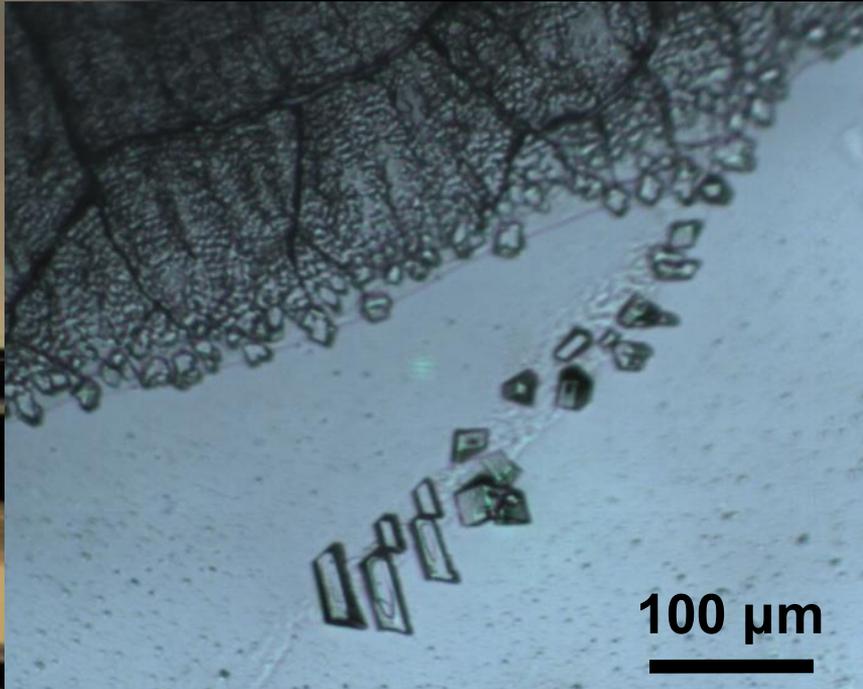
Tackling Titan's surface chemistry, one experiment at a time



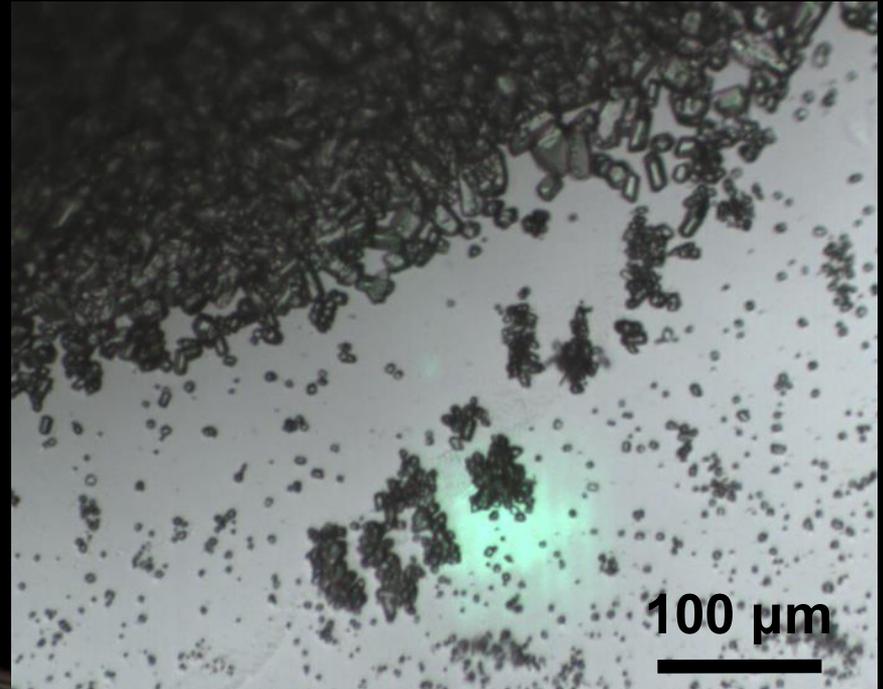
Titan Laboratory Experiments: Surface Deposits

Recrystallization occurs when benzene and ethane are mixed

Before

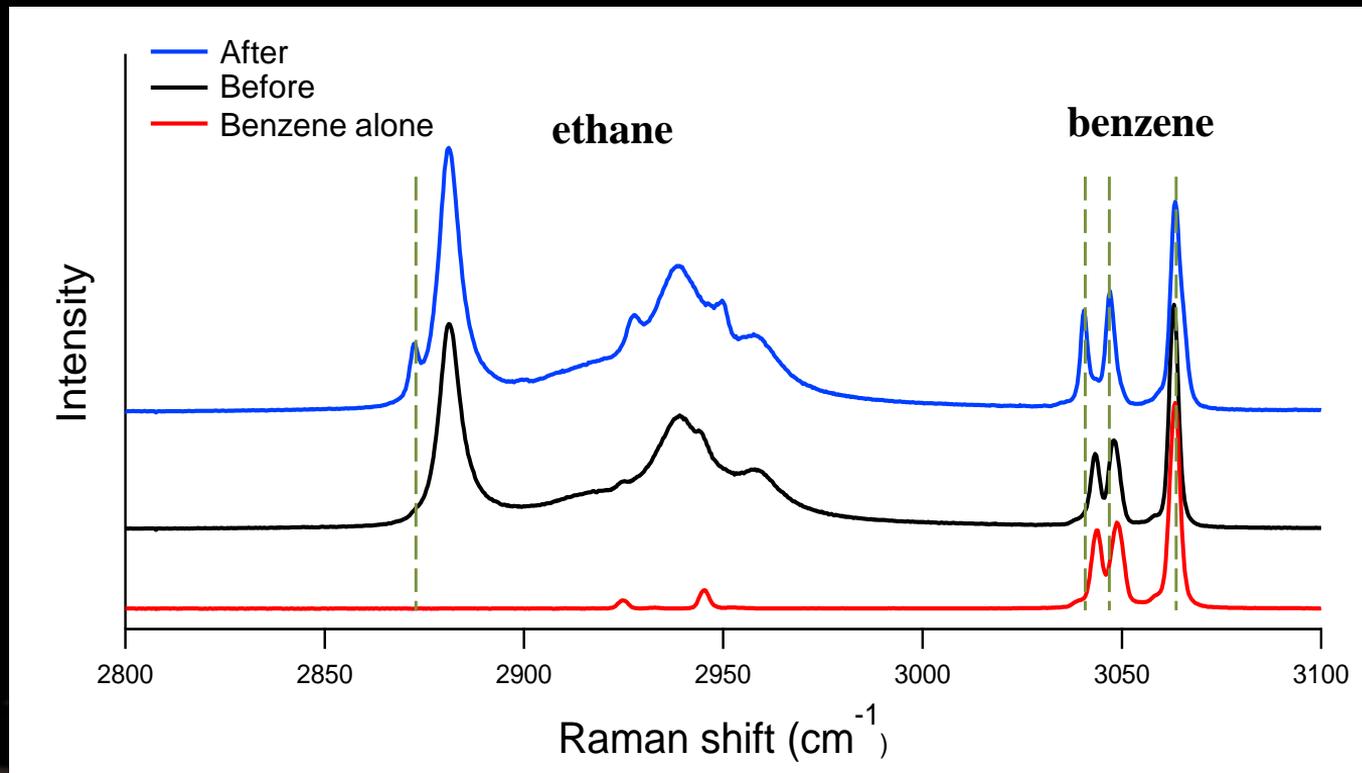


After 15 minutes



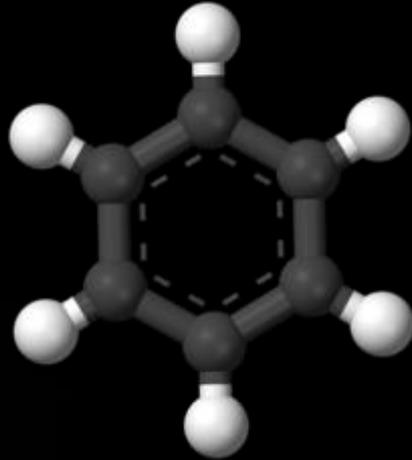
Titan Laboratory Experiments: Surface Deposits

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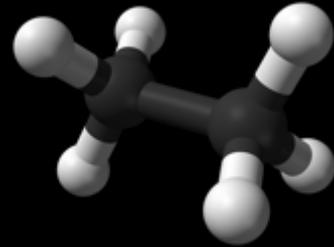


Titan Laboratory Experiments: Surface Deposits

What does it look like?



Benzene (C₆H₆)

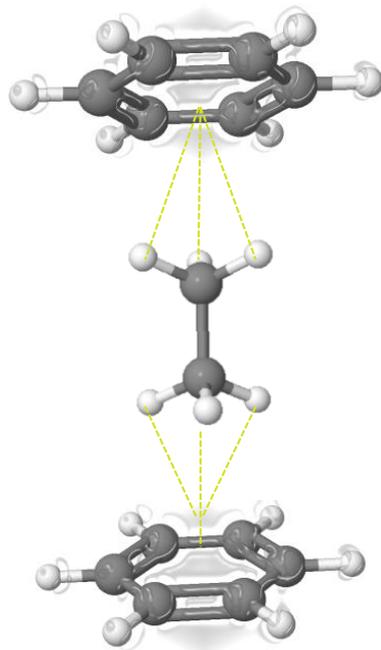


Ethane (C₂H₆)

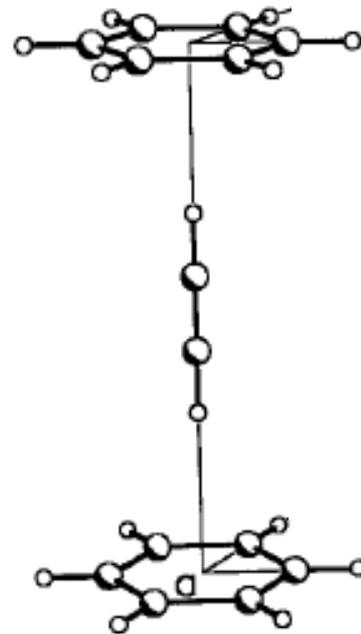
Titan Laboratory Experiments: Surface Deposits

Our best guess . . .

Proposed co-crystal configuration:

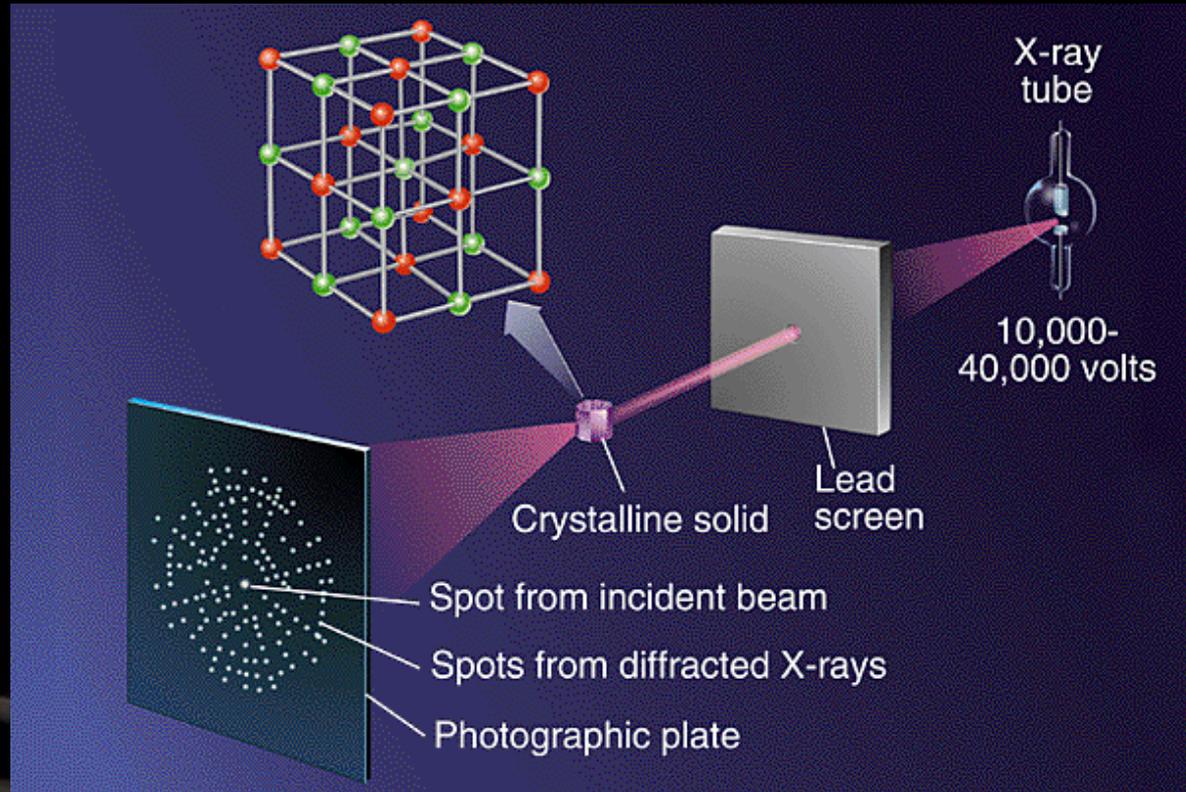


Acetylene/benzene co-crystal structure:



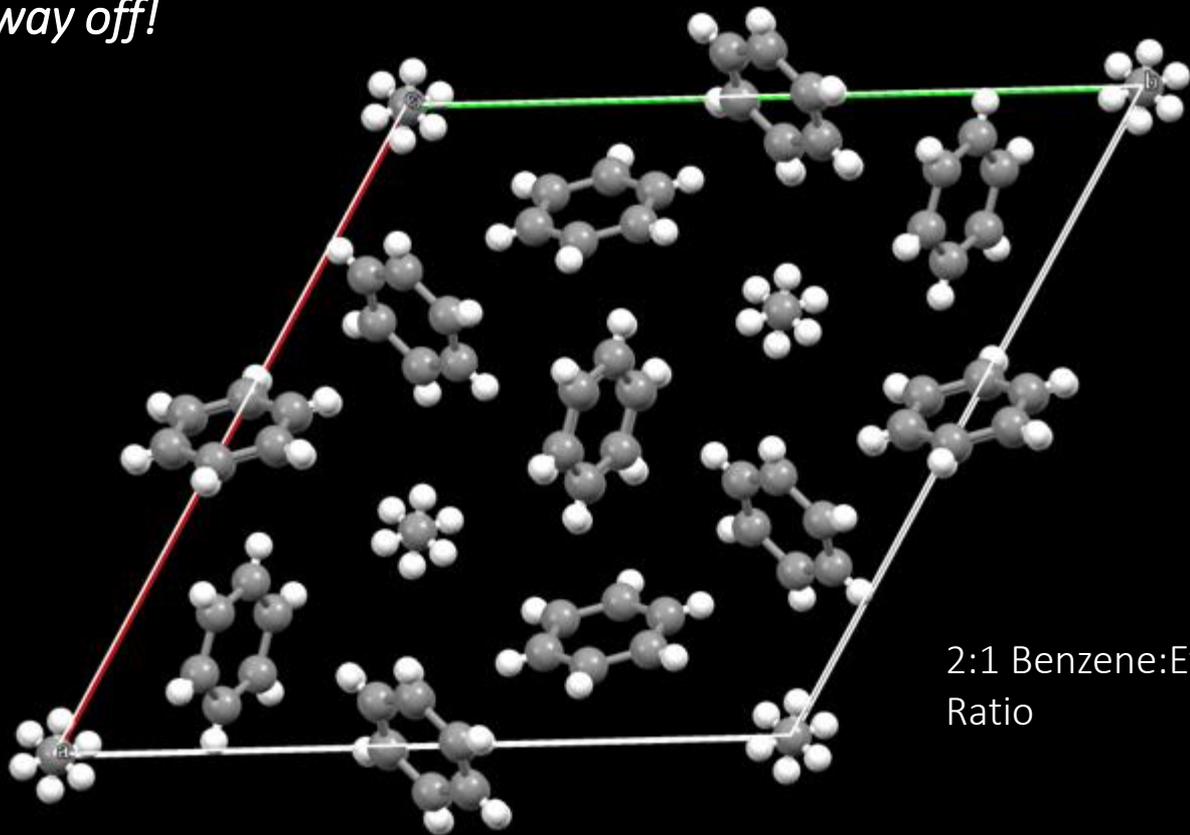
Titan Laboratory Experiments: Surface Deposits

X-rays, figuring out what stuff is made of since 1912



Titan Laboratory Experiments: Surface Deposits

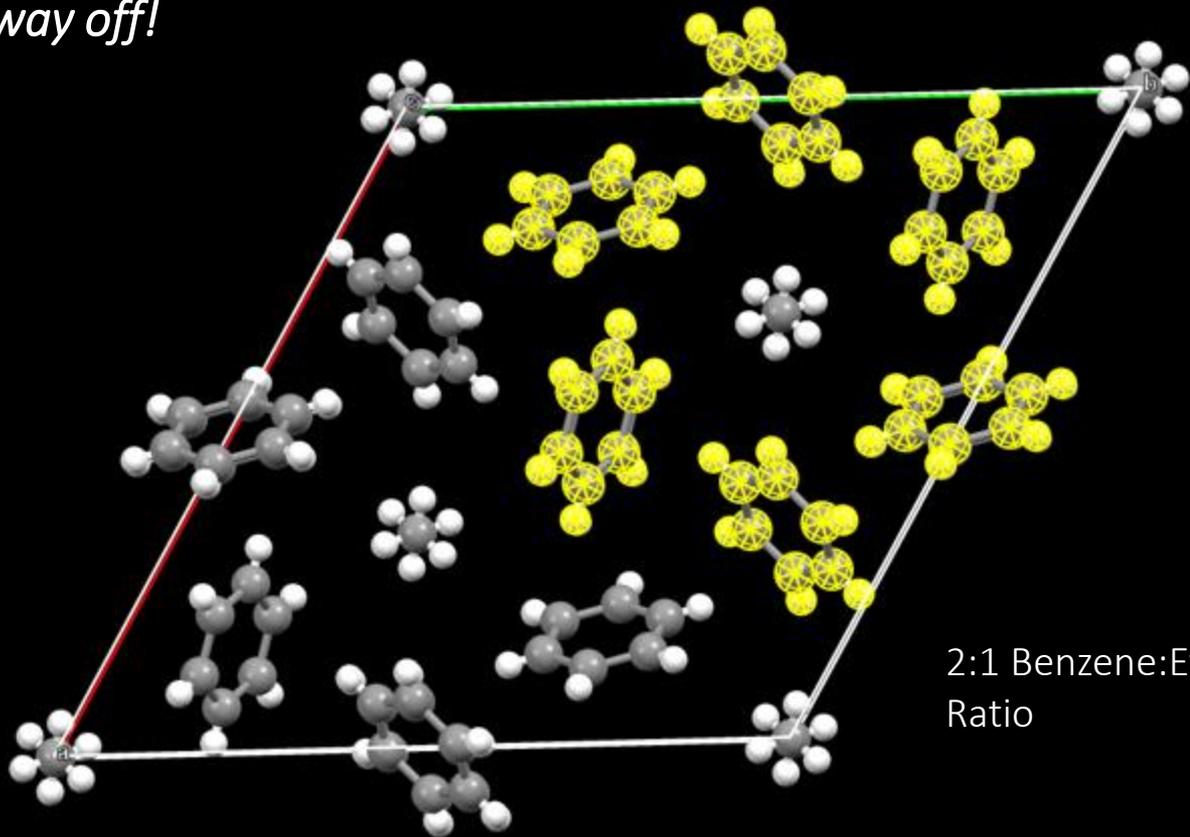
Our best guess . . . was way off!



2:1 Benzene:Ethane
Ratio

Titan Laboratory Experiments: Surface Deposits

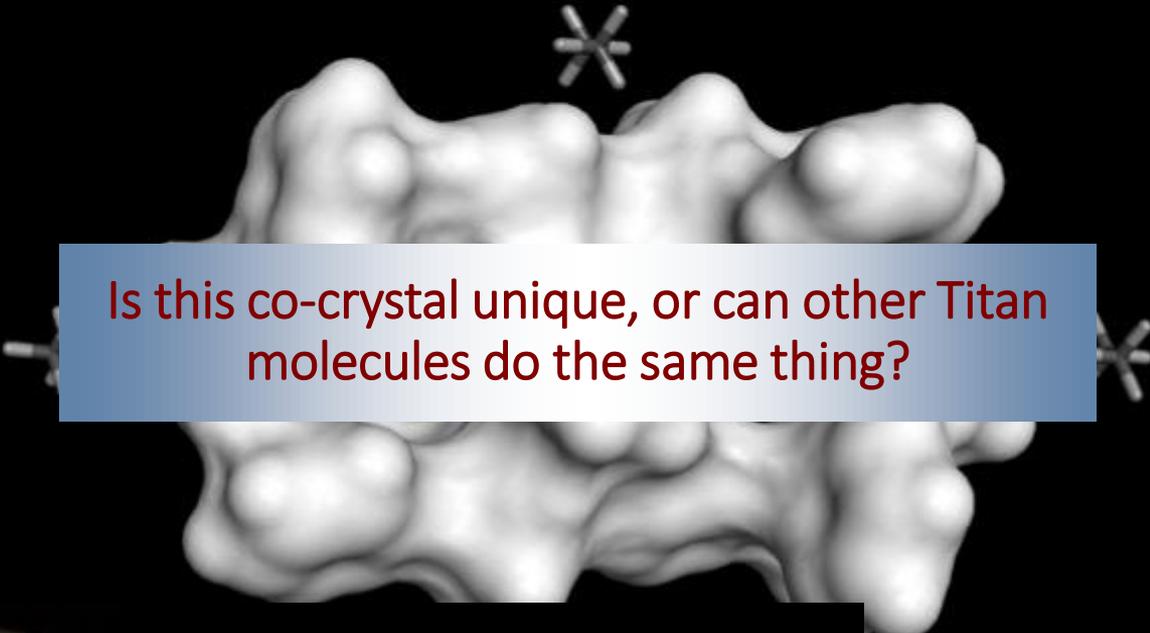
Our best guess . . . was way off!



2:1 Benzene:Ethane
Ratio

Titan Laboratory Experiments: Surface Deposits

Titan's version of a hydrated mineral

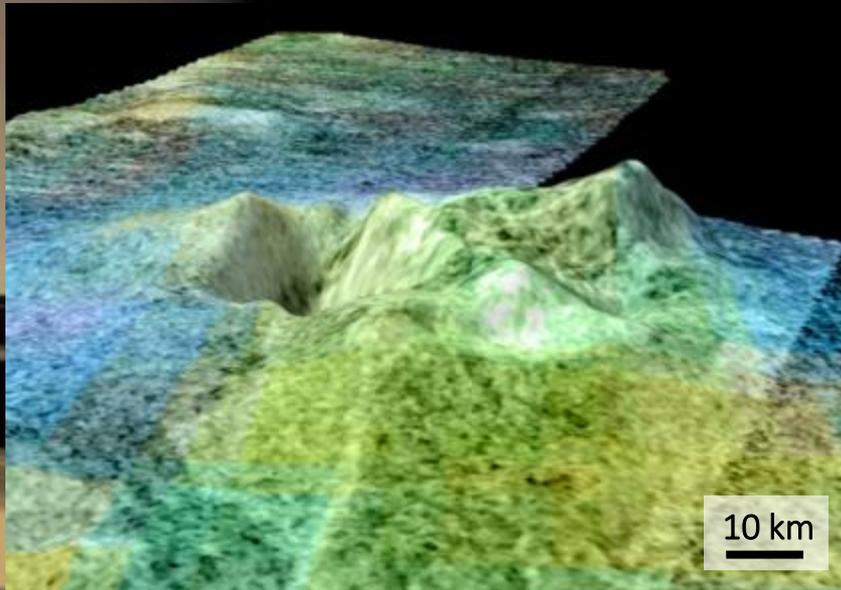


Is this co-crystal unique, or can other Titan molecules do the same thing?

Titan Laboratory Experiments: Acetylene and Ammonia

Another co-crystal?

Evidence of Cryovolcanism



- Acetylene is present on Titan
 - Detected in the atmosphere by INMS¹ and on the surface by Huygens GC-MS²
- Ammonia may also exist on Titan's surface today
 - The origin of Titan's nitrogen-rich atmosphere is most likely ammonia ice^{1,3}
 - Mixing could occur via cryovolcanism or other surface processes⁴

1) Waite, J. H. et al., 2005, *Science*, 308, 982-986.

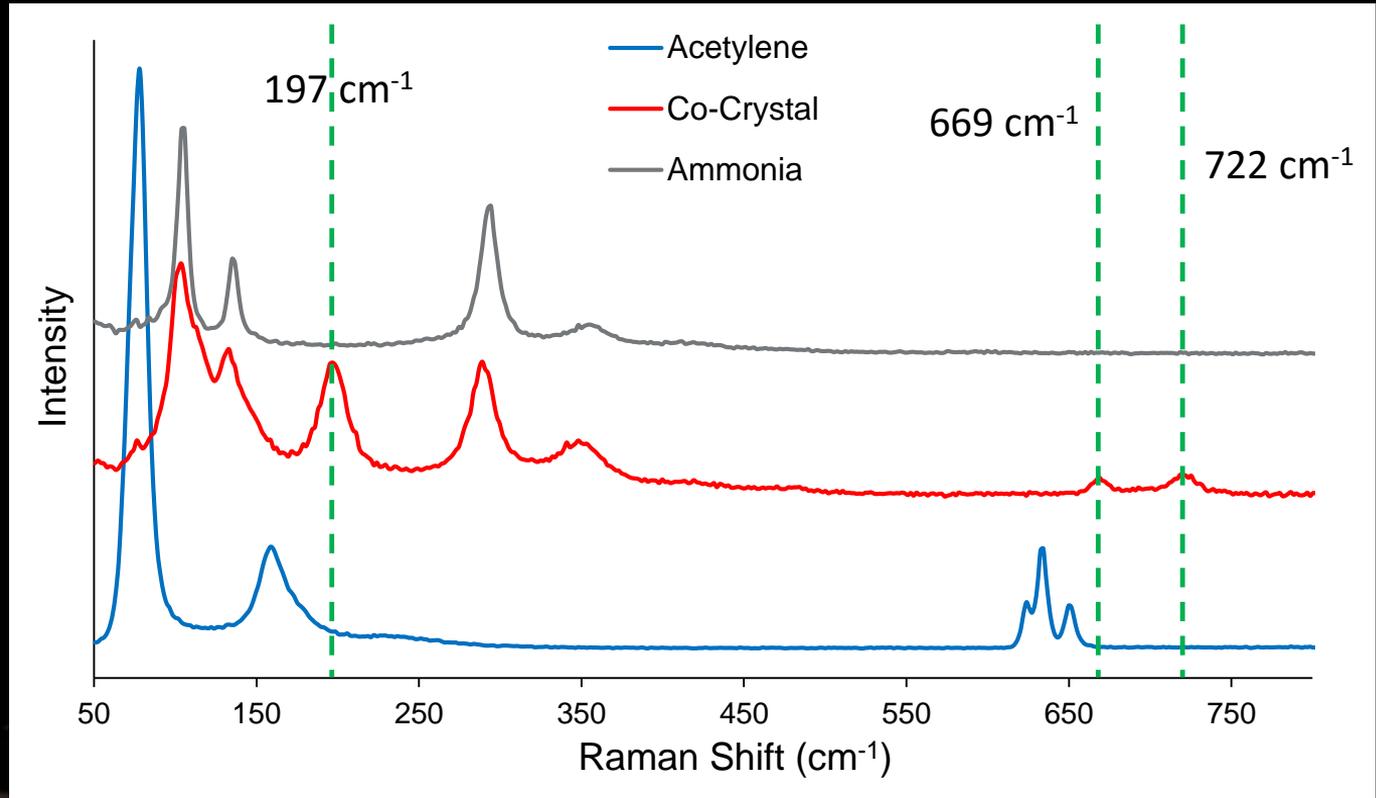
2) Niemann, H. B. et al., 2010, *JGR*, 115, E12006.

3) Mandt, K. E. et al., 2014, *Astrophys. J. Lett.*, 788, L24, 1-5.

4) Lopes R. M. C. et al., 2013, *JGR*, 118, 416-435.

Titan Laboratory Experiments: Acetylene and Ammonia

New features in Raman



Astrobiological Implications

Rethinking our requirements for life

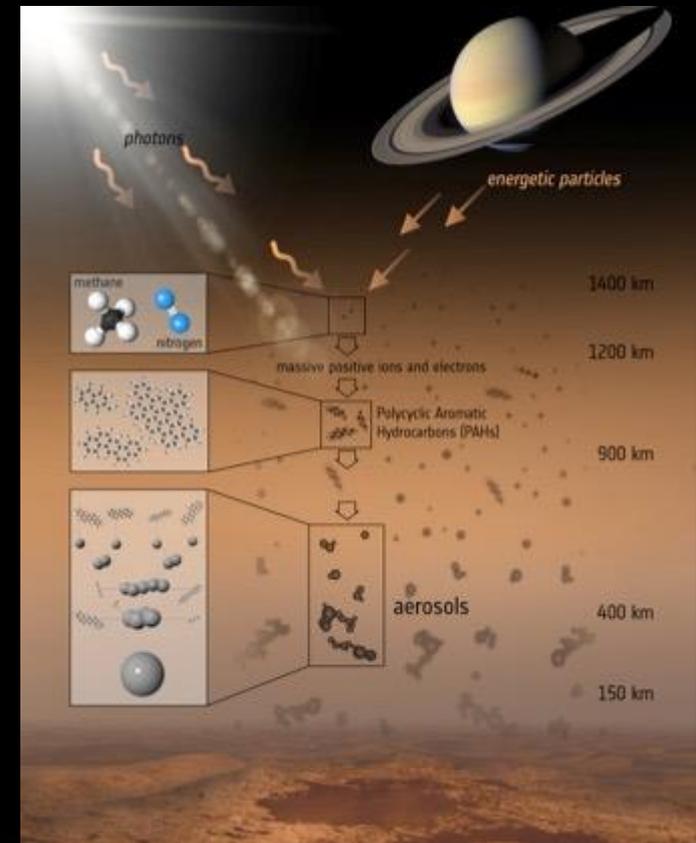
Earth	Titan	Interaction/Bond Strength
Ionic Bond	Covalent Bond	Permanent or semi-permanent
Covalent Bond	Hydrogen bonds, π -bonds	Can be made/broken on timescales relevant for life (ATP, proteins, etc.)
Hydrogen bonds, π -bonds	van der Waals forces	Loose associations that help hold together secondary structures

At cryogenic temperatures, weaker forces become more important in molecular interactions

Titan Laboratory Experiments: Conclusions

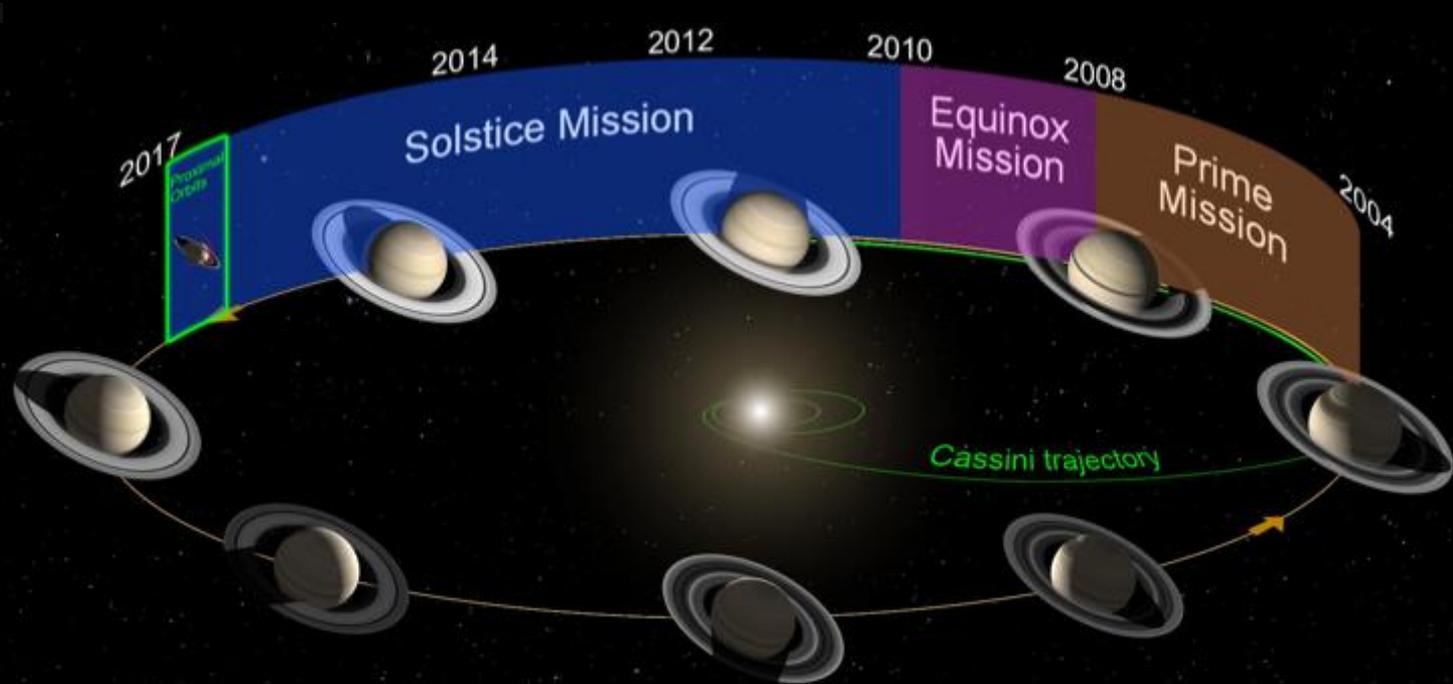
Learning what makes Titan tick

- Titan's surface landscape is strongly influenced by a complex organic cycle.
- Molecules dissolve, precipitate and reorganize readily, leading to novel solid geological materials.
- What's needed?
More lab work! Future missions!



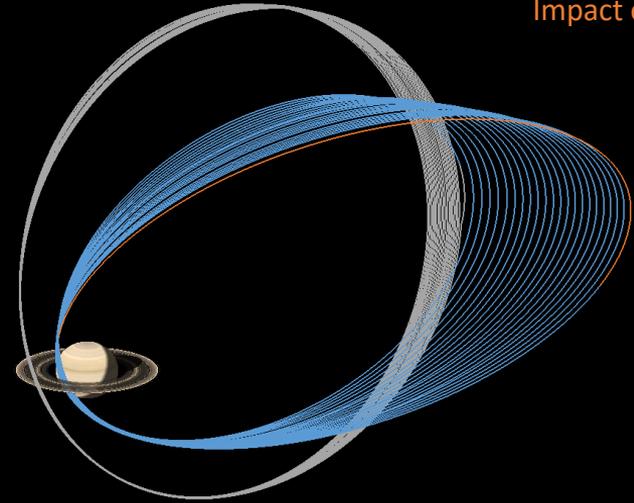
Cassini Mission to Saturn: Latest Discoveries

The makings of a truly Grand Finale



Cassini Mission to Saturn: Latest Discoveries

The makings of a truly Grand Finale



Ring-Grazing orbits
Grand Finale orbits
Impact orbit

Cassini Mission to Saturn: Latest Discoveries

The makings of a truly Grand Finale



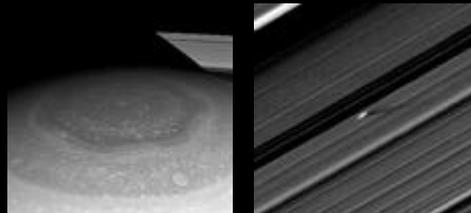
- Saturn internal structure

- Magnetic & gravity high-order moment measurements



- In-situ measurements

- Ionosphere, inner radiation belts, auroral region, and D ring particles

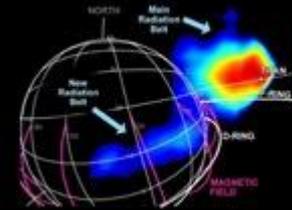


- Ring mass

- Address age of main rings

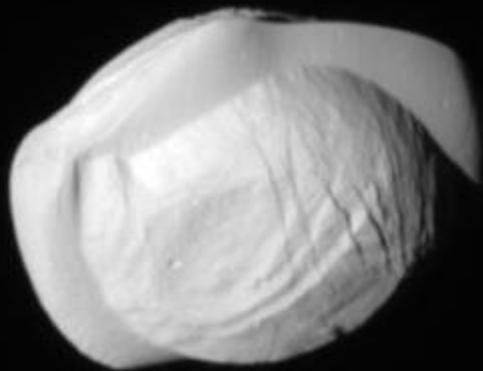
- High resolution observations

- Rings, poles/aurora, atmosphere



Cassini Mission to Saturn: Latest Discoveries

Pan in all its glory

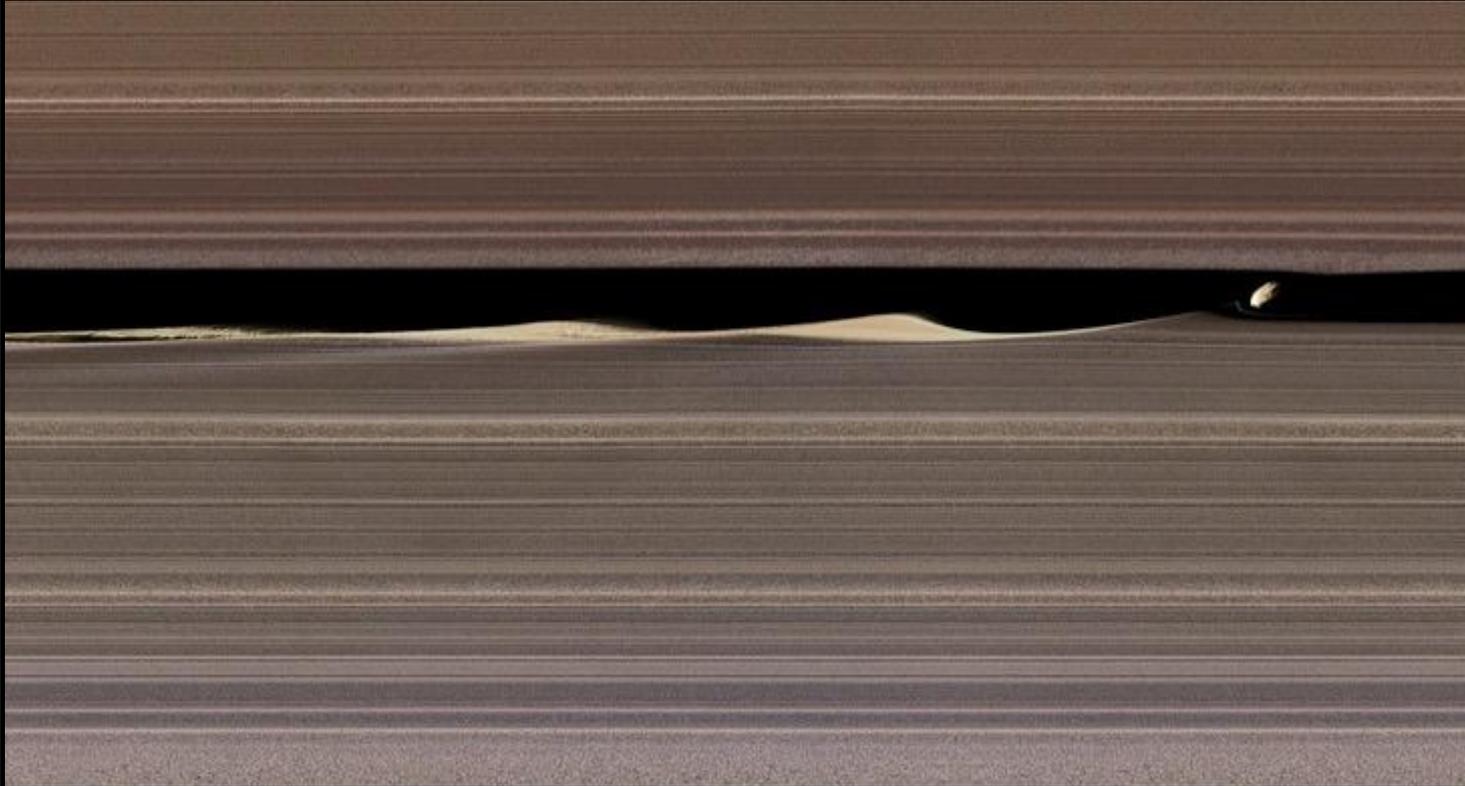


150 m/pixel (500 feet/pixel)



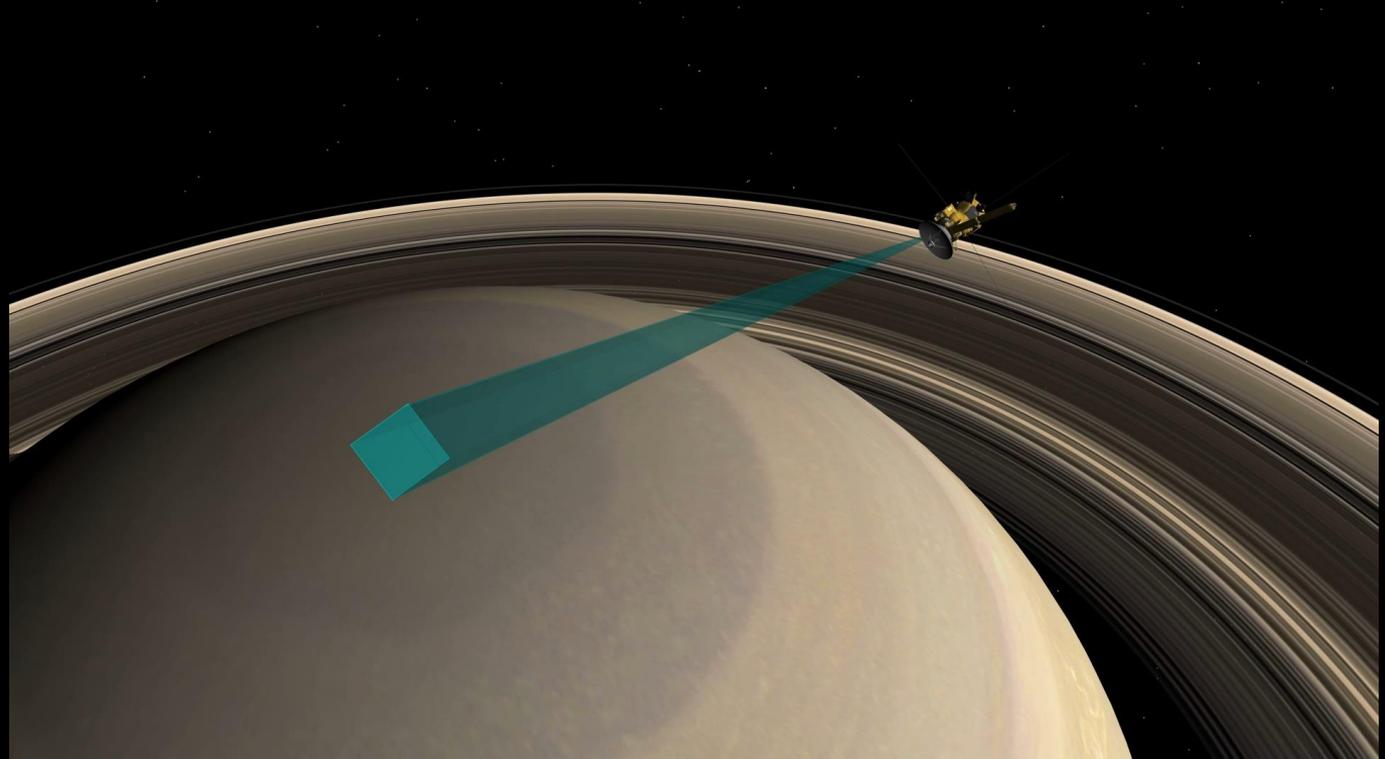
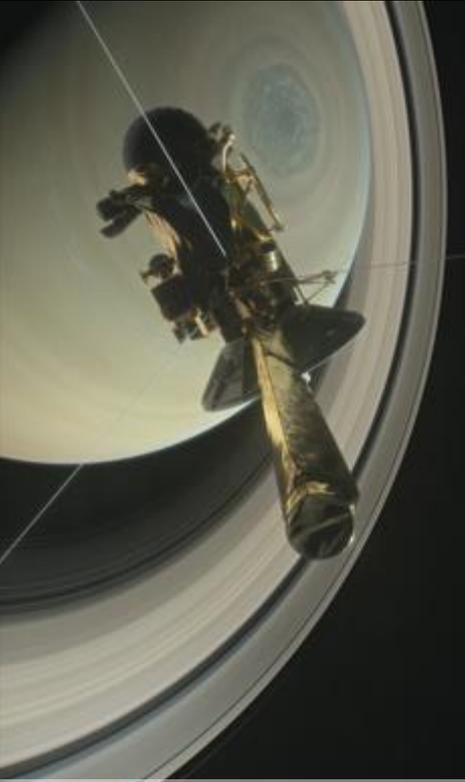
Cassini Mission to Saturn: Latest Discoveries

Daphnis making waves



Cassini Mission to Saturn: Latest Discoveries

Plunging through the gap

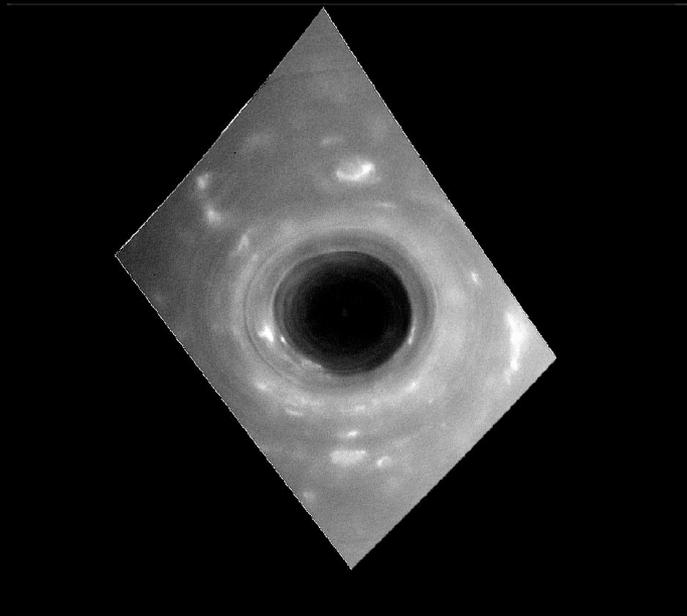


Cassini Mission to Saturn: Latest Discoveries

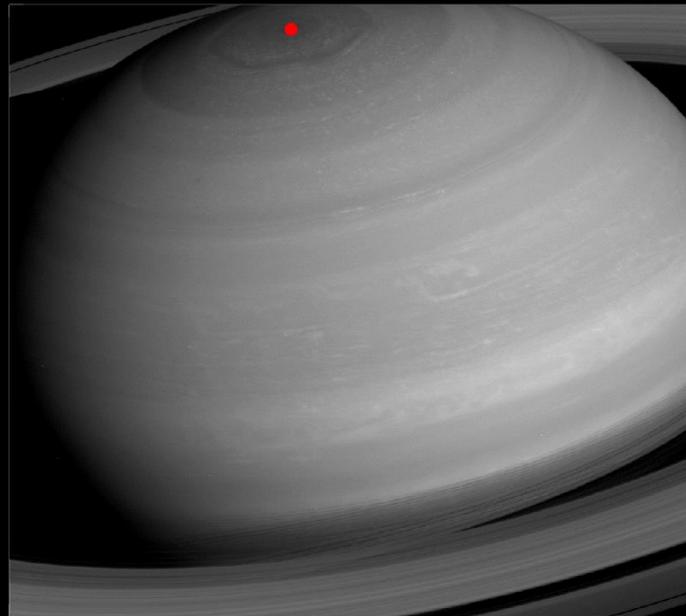
Plunging through the gap



Camera View



Reference View



Acknowledgements

So long, and thanks for all the fish



Jet Propulsion Laboratory
California Institute of Technology

Titan Lab Work

- Rob Hodyss
- Tuan Vu
- Mike Malaska
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- Patricia Beauchamp
- NASA Astrobiology Institute
- NASA Solar System Workings Program
- Australian Nuclear Science and Technology Organization (ANSTO)

Europa Lander

- Kevin Hand, Study Co-Lead
- Alison Murray, Study Co-Lead
- James Garvin, Study Co-Lead
- Cynthia Phillips
- Amy Hofmann
- The Europa Lander Science Definition Team
- The entire Europa Lander Team

Cassini Mission

- Earl Maize, Project Manager
- Linda Spilker, Project Scientist
- Trina Ray, Science Sys Eng
- Erick Sturm, Mission Planning
- The entire Cassini Team



Jet Propulsion Laboratory
California Institute of Technology

E

L

F

ENCELADUS LIFE FINDER

Morgan L. Cable, Jonathan I. Lunine, Linda J. Spilker and the ELF Science Team

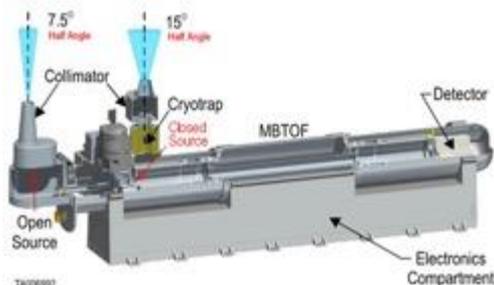
ELF as the Next Logical Step

A robust instrument suite that targets plume gas and grains to search for life

MASPEX

Mass Spectrometer for Planetary Exploration

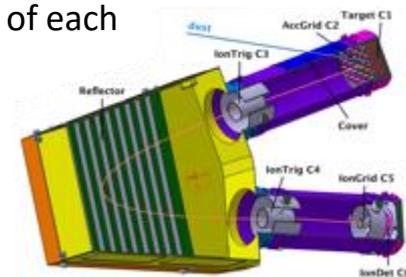
- Target: Plume **gas**
- Extended mass range for heavy organic molecules
- Enhanced mass resolution for critical isotopes
- Enhanced dynamic range for high S/N
- Improved sensitivity (better than 1 ppt with cryotrap) for rare noble gases



ENIJA

Enceladus Icy Jet Analyzer

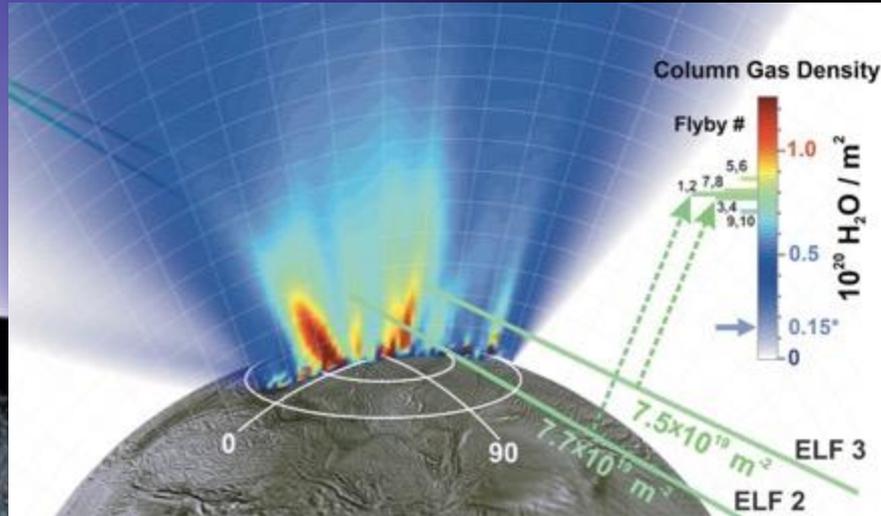
- Target: Plume **grains**
- Heritage: Giotto, Stardust CIDA but improved ion optics, ion detector, spectra processing
- Segmented target for low and high-rate spectra mode (compositional profile with 100 m spatial resolution)
- Complete composition of each ice grain, over a wide mass range



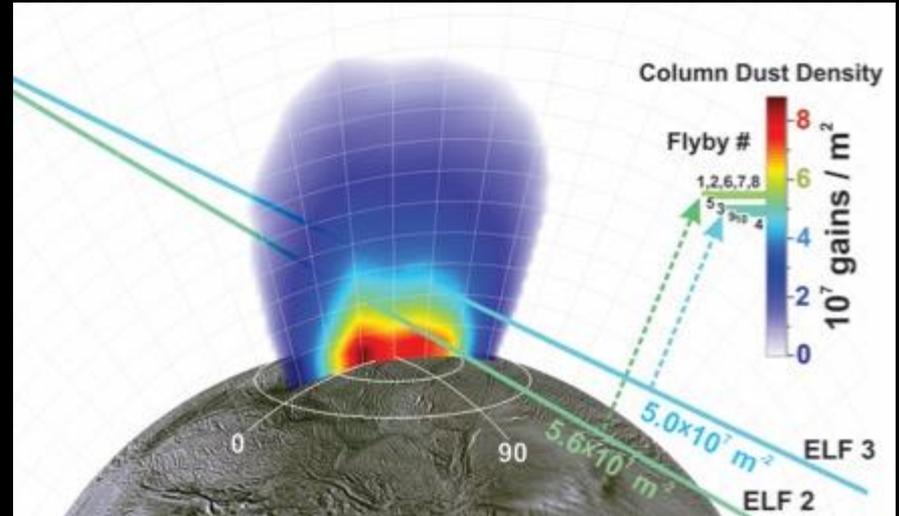
Plume Modeling

Know before you go

Plume Gas Model



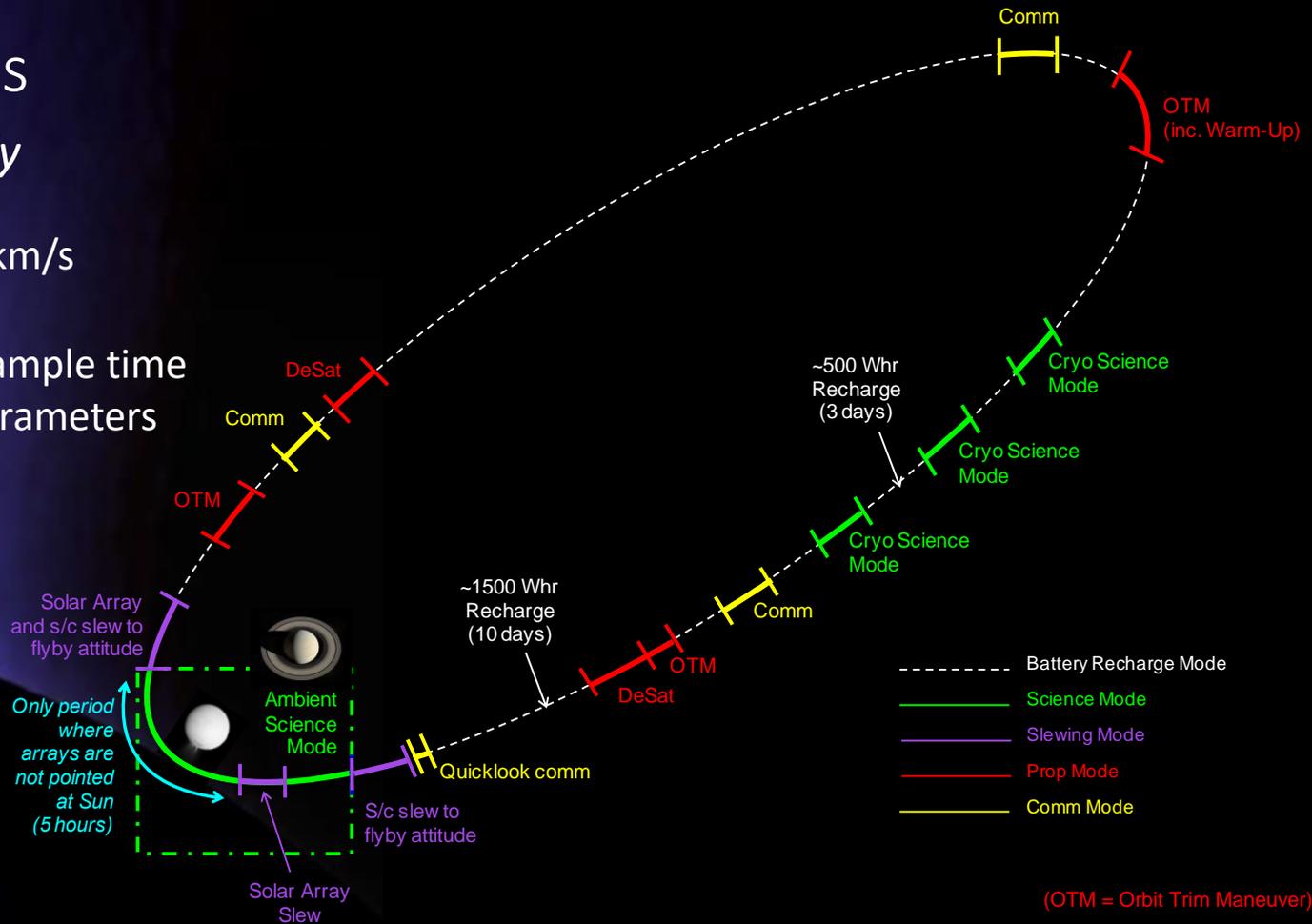
Plume Grain Model



ELF Mission Ops

Life detection on the fly

- 10 flybys, each at 5 km/s
- 62-day orbit allows ample time to set instrument parameters for the next flyby



ELF Science Investigation

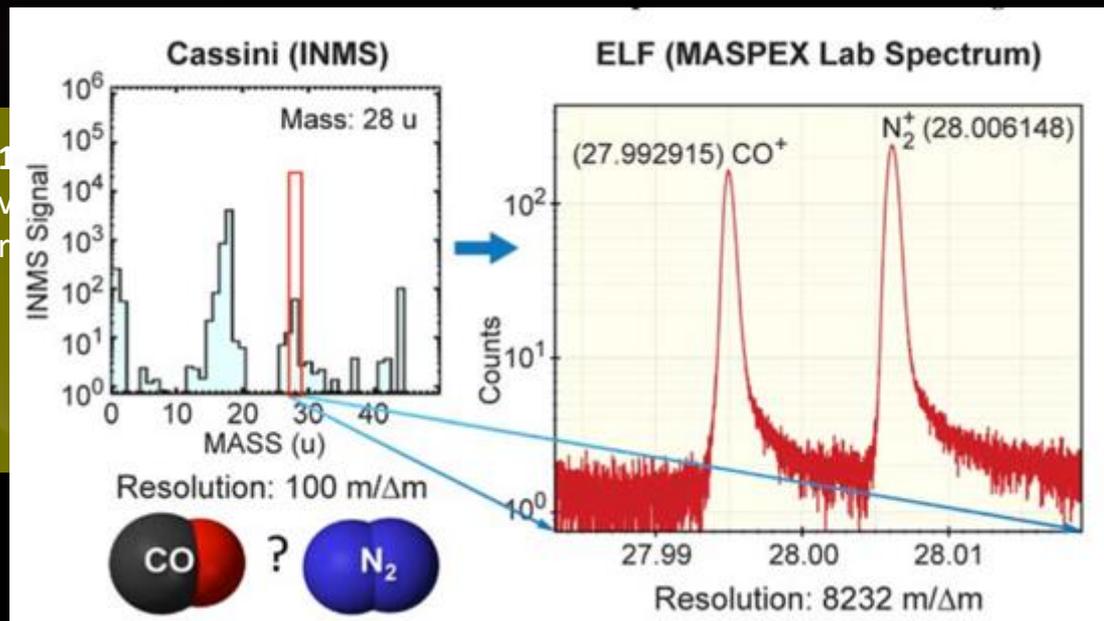
Three objectives, one profound question: Is there life beyond Earth?

Science Objective 1: Evolution

Determine if Enceladus' volatiles, including organics, have evolved over time.

Nitrogen as an Indicator

1a. Determine the original molecular carrier for nitrogen as an indicator of the degree of volatile evolution on Enceladus.



ELF Science Investigation

Three objectives, one profound question: Is there life beyond Earth?

Science Objective 2: Habitability

Determine if the ocean of Enceladus satisfies the basic requirements of habitability.

Temperature

2a. Determine the temperature of the ocean and possible hydrothermal systems to within 100 K.

Redox Energy

2b. Quantify the amount of redox energy available.

Oxidation State

2c. Determine the oxidation state of the ocean.

pH

2d. Determine the pH of the ocean to within an accuracy of 1 unit.

ELF Science Investigation

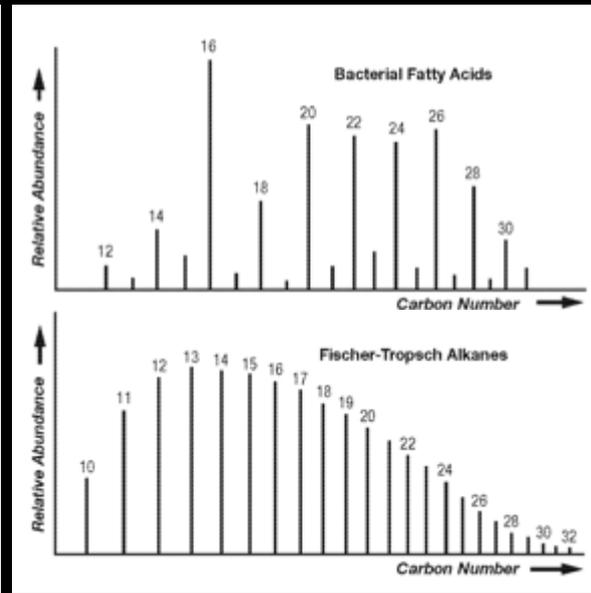
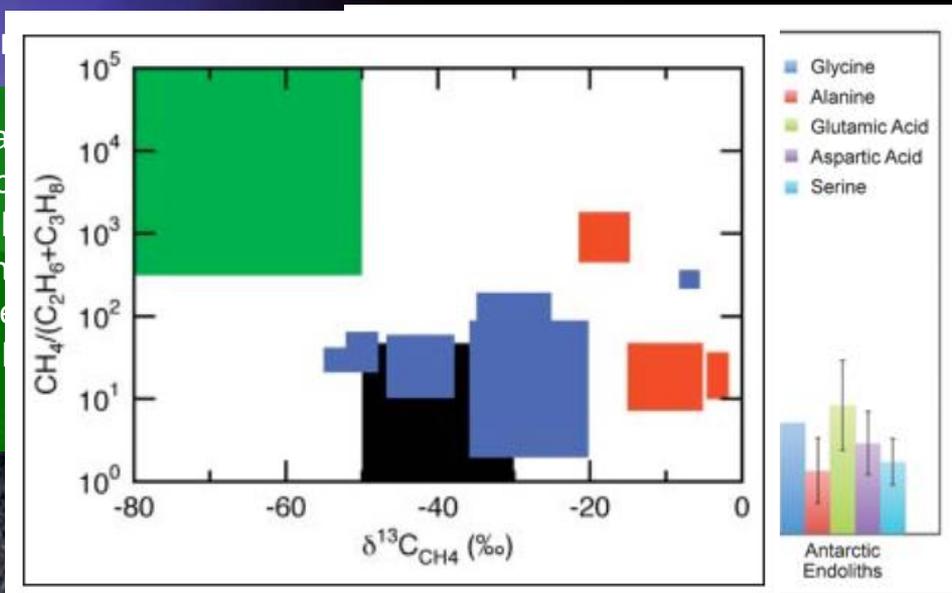
Three objectives, one profound question: Is there life beyond Earth?

Science Objective 3: Life

Determine if the plume of Enceladus contains chemical signatures of biology.

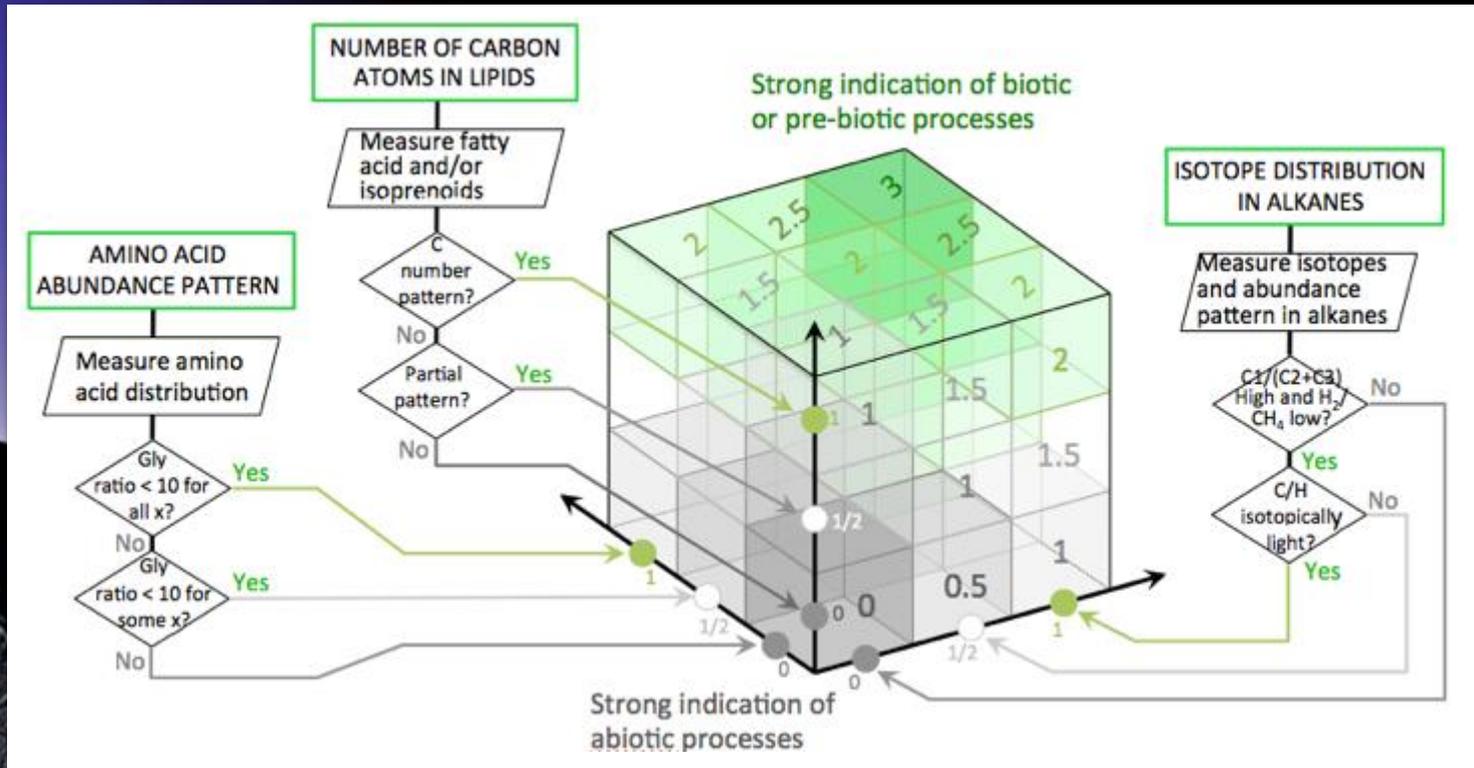
Amino

3a. Look for particular amino acid distribution patterns that are characteristic of biological synthesis. Underrepresented amino acids are energetically disfavored in abiotic form.



A Life Investigation Within Reach

Multiple, independent tests for life shrink the ambiguity box



Enceladus Awaits

An ideal place to search for aqueous-based life

- There is definitive evidence of a subsurface ocean with organics, salts, and free energy.
- The plume of Enceladus includes ocean material and is readily analyzed for evidence of life—a goal of the **Enceladus Life Finder**.

INGREDIENTS FOR LIFE

With its global ocean, unique chemistry and internal heat, Enceladus has become a promising lead in our search for worlds where life could exist.

