

# Enceladus and Ocean Worlds: Recent Scientific and Technological Advancements for New Frontiers

Amanda R. Hendrix

with inputs from

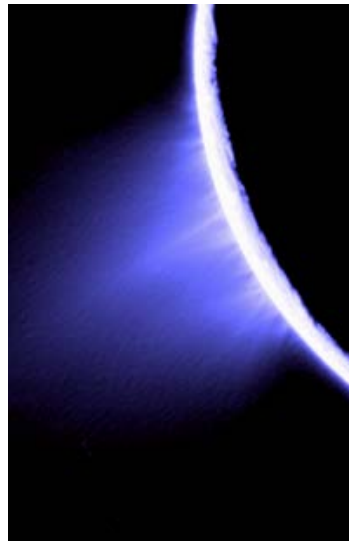
Morgan Cable

Shannon Mackenzie

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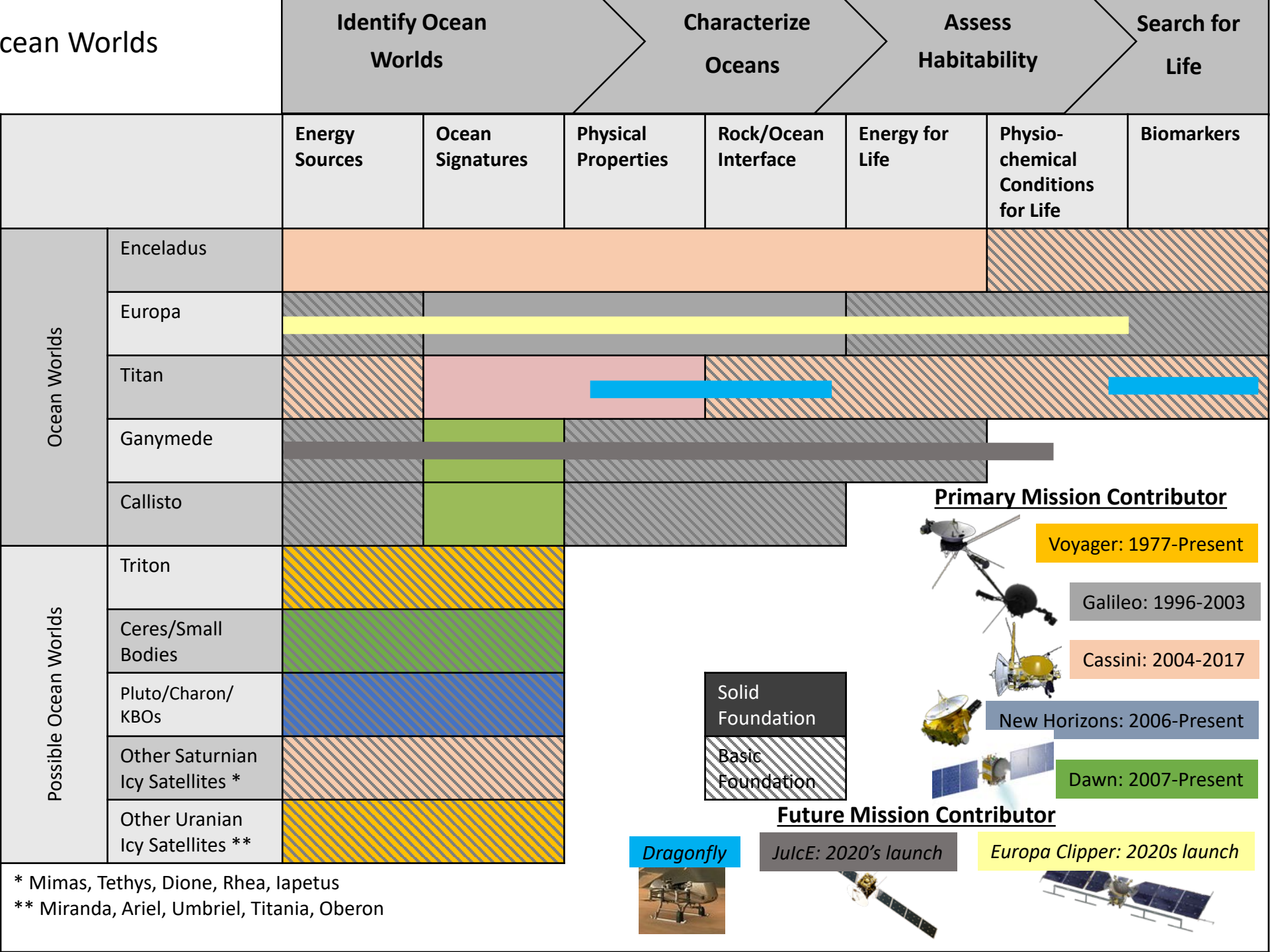
and other investigators listed herein



# Introduction/Summary

- For the first time, NASA is posed with the opportunity to search for signs of recent and extant life in a habitable environment beyond Earth. This is a key objective of the 2018 NASA Strategic Plan tackling an overarching question of the Vision & Voyages Decadal Survey (“Beyond Earth, are there contemporary habitats [...] and do organisms live there now?”)
- The subsurface ocean of Enceladus is the only confirmed modern habitable environment beyond Earth, meeting the canonical requirements for habitability: liquid water, chemical building blocks, and energy sources (e.g. McKay et al. 2008, 2014; Cockell et al. 2016; Hendrix et al. 2019)
- The next strategic step is to search for signatures of life in the ocean materials
- The Enceladus plume provides direct access to recently ejected ocean-derived materials
- Current mature instrumentation and measurement strategies can enable the detection of trace quantities of key features expected to be universal to life, while also measuring possible abiotic or prebiotic compositions.
  - The search for recent and extant life in the Enceladus ocean materials is possible with today’s technology
- This can be done under the New Frontiers Program!
- Finally, given that the “Ocean Worlds” theme in NF4 is quite broad, and only partially addressed by Dragonfly, “Ocean Worlds” should remain as a theme in NF5

Roadmaps to Ocean Worlds



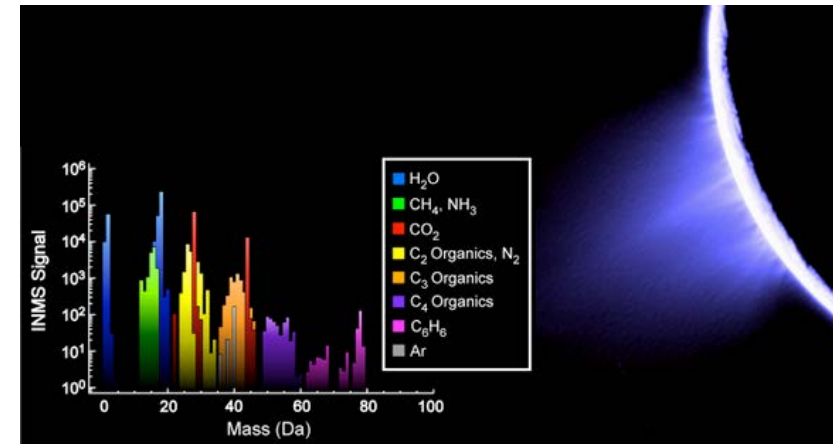
# Why should Enceladus be a NF5 target? (1)

- As an ocean world, Enceladus is distinct from Titan and Europa
  - The potentially habitable environments *Dragonfly* will interrogate (transient liquid water environments created by impacts or cryovolcanic activity) are inherently distinct from the subsurface ocean environment that an Enceladus mission would investigate by sampling ejected ocean materials in the plume or deposited at the surface.
  - *Cassini* revealed that the Enceladus subsurface ocean and crust appear to be sufficiently different from that of Europa in terms of dynamics, composition, activity rates, and scale such that the two bodies beg for different investigative strategies. The *Europa Clipper* mission and the Europa Lander concept provide grounds for the European strategy, but Enceladus requires an independent line of investigation.
- In strategizing about search-for-life missions, an Enceladus NF-class mission will be more affordable – and perhaps more successful – than some other (flagship) options under discussion



# Why should Enceladus be a NF5 target? (2)

- Including Enceladus in the current Ocean World mission suite would support **comparative planetology** investigations focused on Ocean Worlds, an investigative strategy that is unprecedented in the history of solar system exploration.
- The Roadmap to Ocean Worlds Committee, commissioned by the Outer Planets Assessment Group, proposed that the strategy for accomplishing the goal to search for life on ocean worlds should “identify ocean worlds, characterize their oceans, evaluate their habitability, search for life, and ultimately understand any life we find” (Hendrix et al. 2019). *Cassini* checked off the first three steps of the Roadmap to Ocean Worlds for Enceladus—***the only world to reach this level of characterization.***



Waite et al., 2009

# Ocean Worlds: Recent Scientific and Technological Advancements

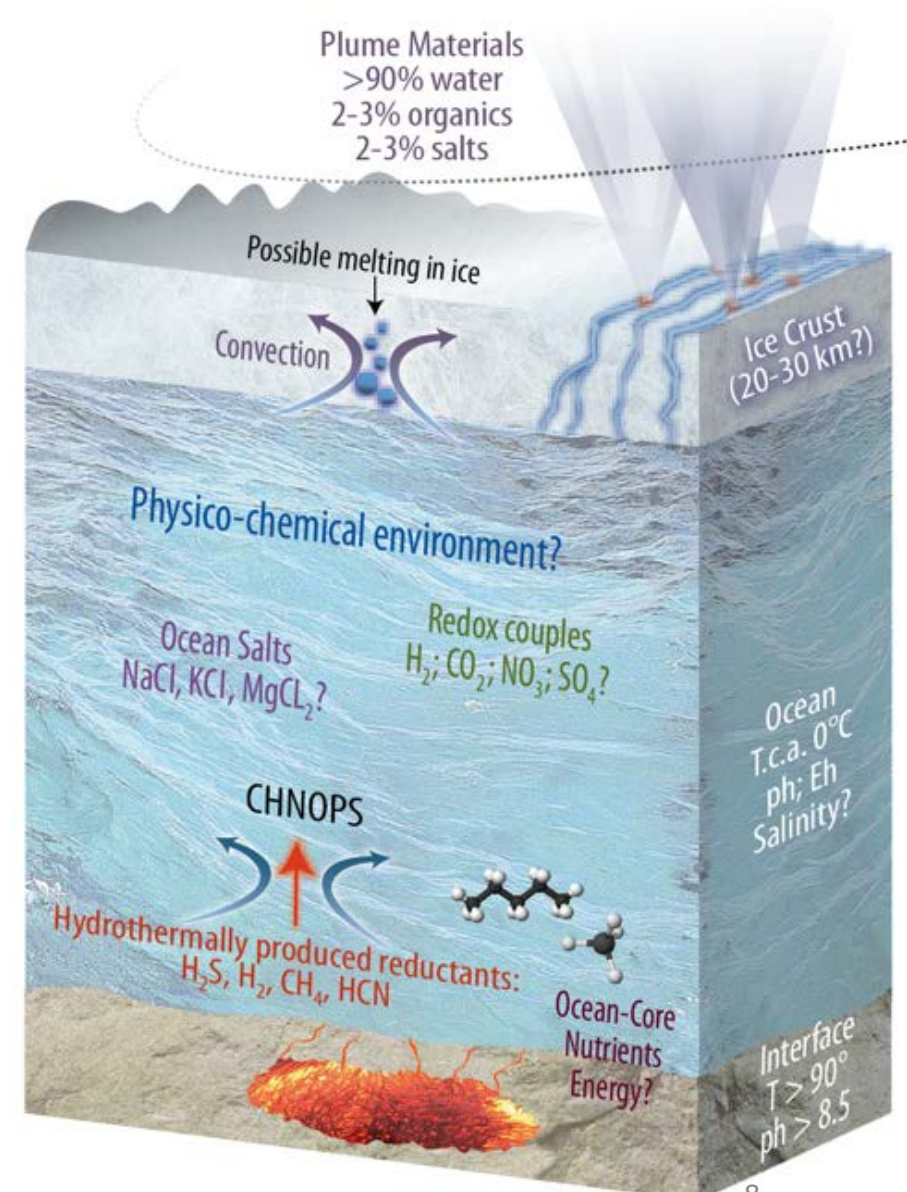
- Cassini data analysis
- ICEE-2 programs
- COLDTech programs
- NF4 technology study
- Astrobiology RCNs

# Recent advancements in our scientific understanding of Enceladus

- Following the release of the NF4 AO, additional discoveries
  - strengthen the case for habitability of the ocean
  - provide new insights into both in-flight and on-surface sample collection

# Detection of molecular hydrogen (a signature of water-rock interactions) (*Waite et al. 2017*)

- INMS reported detection  $H_2$  in the plume after careful elimination of all possible sources of contamination.
- The most plausible source of this hydrogen is ongoing hydrothermal reactions of rock containing reduced minerals and organic materials.
- The relatively high abundance of  $H_2$  in the plume signals thermodynamic disequilibrium that favors the formation of methane from  $CO_2$  in Enceladus' ocean.

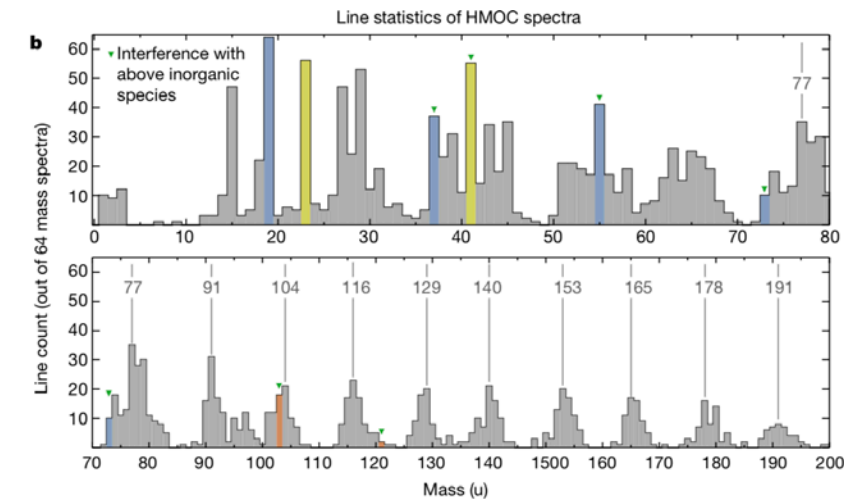
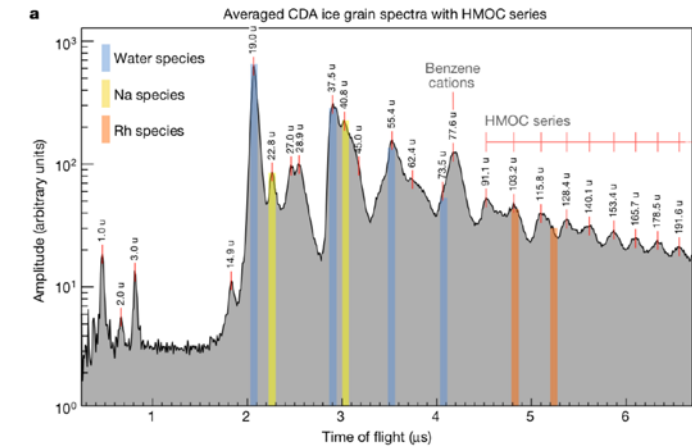
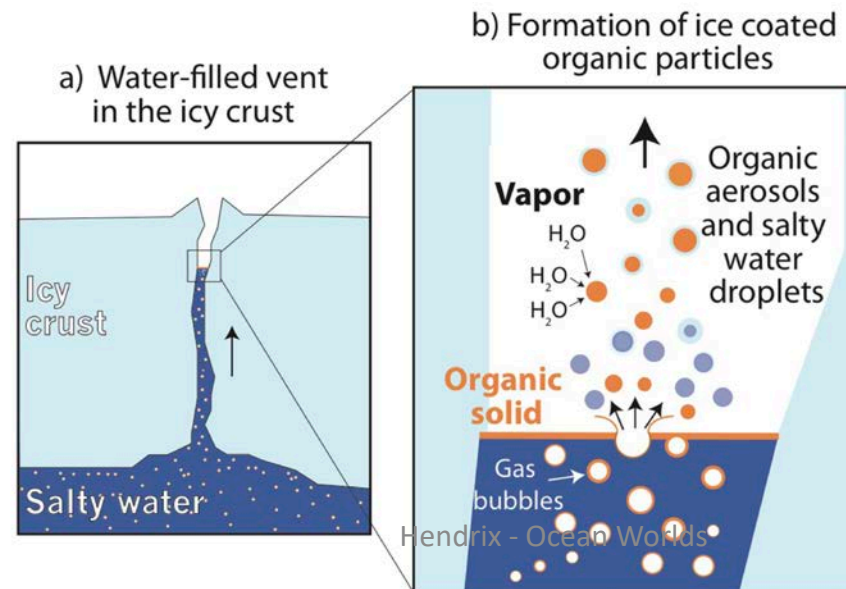


# Better understanding of CO<sub>2</sub> concentration, sources in Enceladus ocean (*Glein & Waite, 2020*)

- Deep dive into Enceladus carbonate geochemistry via the plume
- Derived new estimates of the thermodynamic activity of CO<sub>2</sub> in Enceladus' ocean using two different datasets:
  - INMS: estimate of the CO<sub>2</sub> molality in the ocean from the molar ratio of CO<sub>2</sub>/H<sub>2</sub>O in the plume gas
  - CDA: constrain the activity of CO<sub>2</sub> in the ocean from the carbonate chemistry expressed in salt-rich particles from the plume
- Evidence indicates one mineral source for CO<sub>2</sub> (quartz/talc/carbonate) and another for H<sub>2</sub> (serpentinite), implying a mineralogically and thermally diverse environment in the rocky core.
- These results, together with previous findings of silica and H<sub>2</sub> at Enceladus, support the hypothesis of a heterogeneous structure for the rocky core (carbonated upper layer, serpentinized interior), which provides a geochemical gradient for habitability.

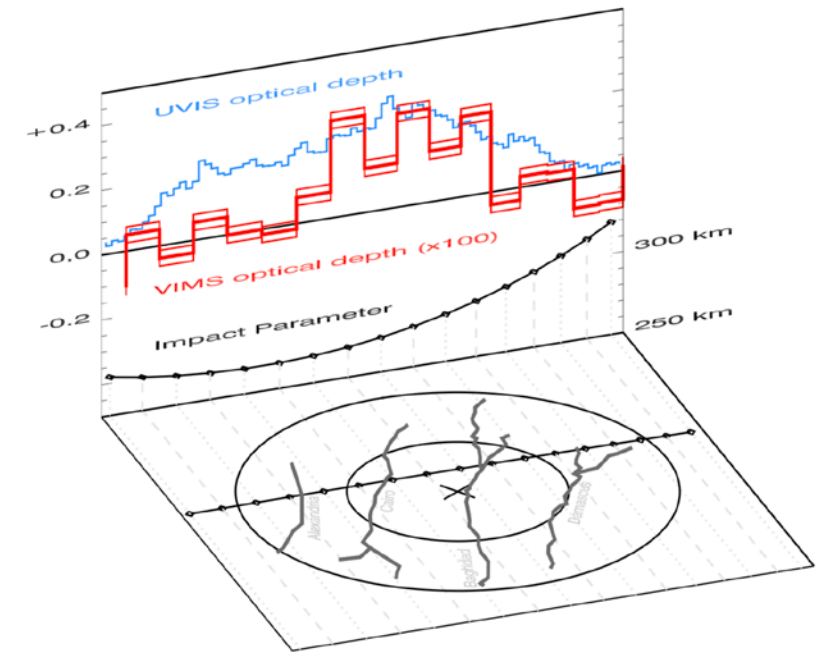
# Detection of complex organic compounds in the Enceladus plume (*Postberg et al. 2018*)

- Cassini CDA records TOF mass spectra (1-~200 u)
- CDA observes complex macromolecular organic species in the Enceladus plume
- Data suggest that organics are not dissolved in ocean water but exist in a layer on top of water table



# Spatial variations in plume properties

- Hedman et al. (2018) used a solar occultation to study simultaneous measurements of plume dust (VIMS) and gas (UVIS) at high spatial resolution
- Portions of the plume – above the Baghdad and Damascus fractures – show 10x higher dust/gas ratio than above Alexandria and Cairo sulci
  - Consistent with *in situ* data from RPWS and INMS
- Suggests variations in subsurface source material/plumbing trends
  - Useful consideration for *in situ* plume sample collection
- Southworth et al. (2019) have made new maps of the fallout of Enceladus' plume material
  - Comparisons of deposition models with observed reflectance data provides understanding of plume particle dynamics
  - Implications for dynamics, structure in subsurface vents



# Recent advancements in technology for searching for life signatures in Ocean Worlds

- Technology developed for Ocean Worlds via programs like NASA ROSES *MATISSE*, *COLDTech*, and *ICEE-2* can be leveraged at Enceladus.

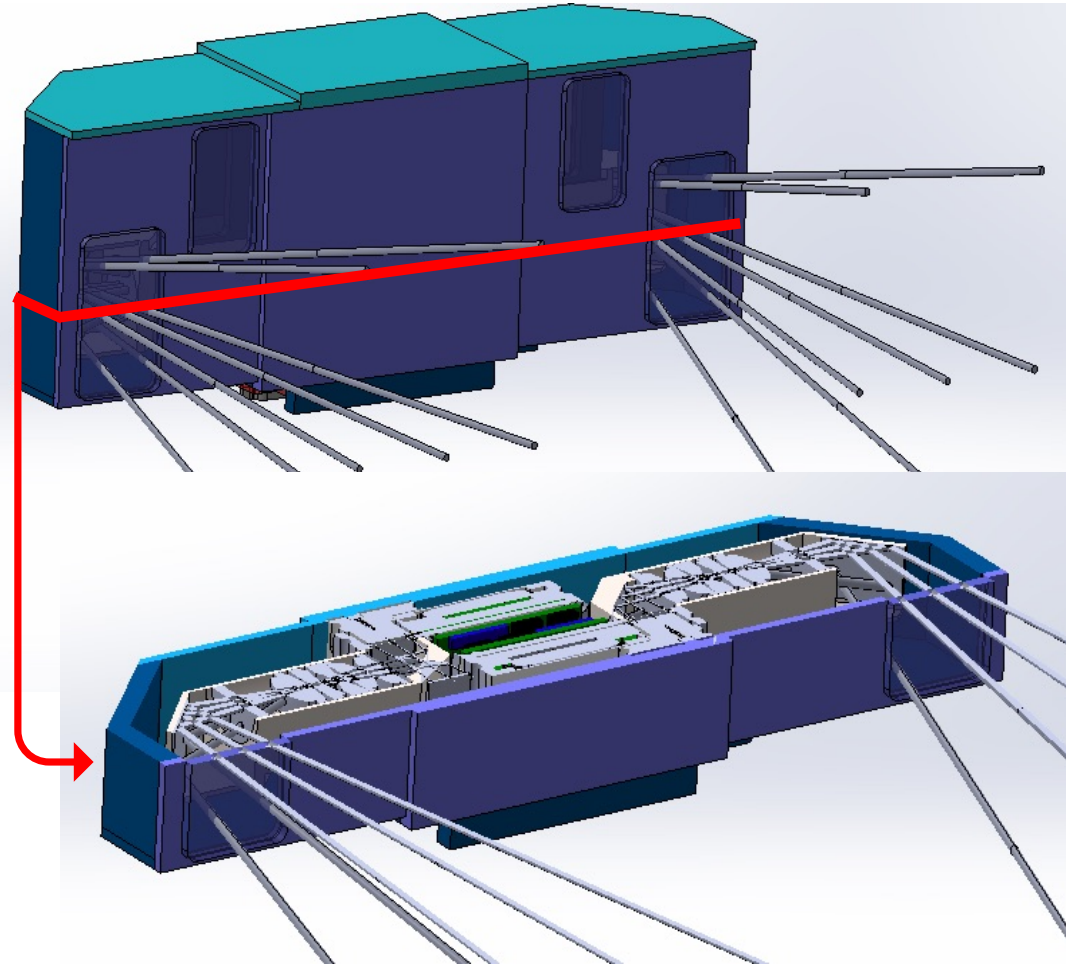


## **COLD LIGHTWEIGHT IMAGERS FOR EUROPA (C-LIFE)**

**Developed under COLDTech and ICEE-2 at the Lunar and Planetary Laboratory, University of Arizona**

PI: Shane Byrne, DPI: Christian d'Aubigny, PM: Catherine Merrill

Industry Partners at Space Dynamics Lab, SRI International and Ball Aerospace



### **Developed for the (highly constrained) Europa Lander mission**

- Stereo color imaging with dual-periscope design
- LEDs for imaging within shadows
- LEDs to excite fluorescence in organic material
- No moving parts with progressive focus & strip filters
- Highly radiation tolerant
- Minimal or no survival heating
- Accommodates the most stringent Planetary Protection protocols
- Advanced data filtering and compression to accommodate low data rates

**C-LIFE is suitable for the surface of other airless Ocean Worlds with little modification**

# Europa Lander Stereo Spectral Imaging Experiment (ELSSIE)

Scott L. Murchie<sup>1</sup> (scott.murchie@jhuapl.edu), John D. Bold<sup>1</sup>, Karl Hibbitts<sup>1</sup>, Russell S. Layman<sup>1</sup>, Joseph J. Linden<sup>1</sup>, Jorge I. Núñez<sup>1</sup>, Frank P. Seelos<sup>1</sup>, Kimberly D. Seelos<sup>1</sup>, and Calley L. Tinsman<sup>1</sup>.  
<sup>1</sup>Johns Hopkins University Applied Physics Laboratory, 11101 Johns Hopkins Rd., MS 200-W230, Laurel MD 20723. <sup>2</sup>California Institute of Technology, 1200 E. California Blvd., MC 150-21, Pasadena, CA 91125.  
<sup>3</sup>Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109.

**ELSSIE is a visible/short-wave infrared (VSWIR) stereo imager and point spectrometer that would provide for Europa Lander (EL):**  
**1) panoramic and workspace views to support sampling and geological analyses;**  
**2) VSWIR images and point spectra to identify and characterize enrichments in organics and non-ice phases and determine which ice is least radiation-damaged, thus supporting selection of the best samples for detailed in situ analysis;**  
**3) surveys of the landscape for morphological and spectral evidence of active surface processes.**

REFERENCES:  
 [1] Murchie S. et al. (2007) JGR Planets, 112, E05S03.  
 [2] Blaney D.L. et al. (2017) Lunar Planet. Sci. 48, #2244.  
 [3] Smith P.H. et al. (1997) JGR Planets, 102, 4003-4025.  
 [4] Hand, K. et al (2017) https://europa.nasa.gov/resources/58/europa-lander-study-2016-report/  
 [5] Turtle, E.P et al. (2016) Lunar Planet. Sci. 47, #1626.

## Technical Inspirations

MRO/CRISM imaging spectrometer [1]

- SWIR reveals phases invisible at 0.4-1.0  $\mu\text{m}$  (VIS)
- Most information can be captured by a few colors
- "Summary images" show mineral indices

Europa Clipper/MISE imaging spectrometer [2]

- Sorting and averaging of many short exposures mitigates radiation-induced noise
- Onboard image math in the DPU

Imager for Mars Pathfinder stereo multispectral imager [3]

- Images from multiple sensors on a single focal plane; on Europa Lander cameras, enables just 1 radiation shield



## How SWIR Informs EL Sample Selection

The signatures of an interesting sample are:

- Hydrated salts indicating concentrated ocean water
- Organics indicating possible biosignatures
- Fresh ice without grains (and organics) disordered by radiation

How to find hydrated salts

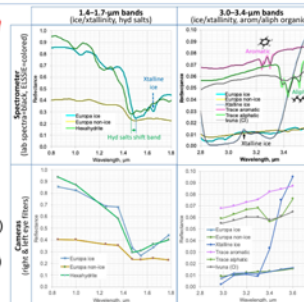
- 1.5- $\mu\text{m}$  band offset to shorter wavelengths

How to find & distinguish organics

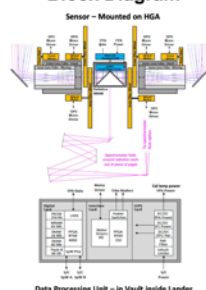
- 3.3- to 3.4- $\mu\text{m}$  band
- Longer-wavelength band for aliphatic, shorter for aromatic

How to find fresh ice (using depths different wavelengths penetrate)

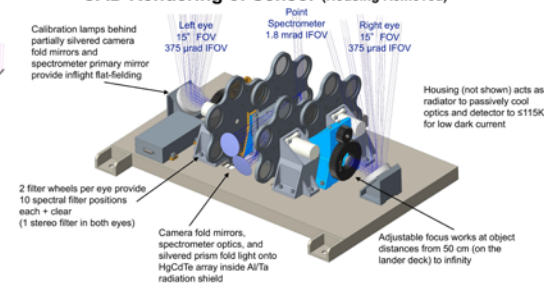
- Freshest – amorphous (no 1.65- $\mu\text{m}$  band, no 3.1- $\mu\text{m}$  peak)
- Fresh – has crystallized (has 1.65- $\mu\text{m}$  band, has 3.1- $\mu\text{m}$  peak)
- Radiation damaged crystalline ice – grain rims have become amorphous (has 1.65- $\mu\text{m}$  band, no 3.1- $\mu\text{m}$  peak)



## Block Diagram



## CAD Rendering of Sensor (Housing Removed)



Housing (not shown) acts as radiator to passively cool optics and detector to  $\sim 115\text{K}$  for low dark current

2 filter wheels per eye provide 10 spectral filter positions each + clear (1 stereo filter in both eyes)

Camera fold mirrors, spectrometer optics, and silvered prism fold light onto HgCdTe array inside Al/Ta radiation shield

Adjustable focus works at object distances from 50 cm (on the lander deck) to infinity

## ELSSIE Concept

## Science Traceability

ELSSIE science in gray boxes is enabled by SWIR wavelength coverage

| ELSSIE Science                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | ELSSIE Science                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | ELSSIE Science                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | ELSSIE Science                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>ELSSIE Science</b><br>(A) Detect any organic indicators of past or present life<br>(B) Identify & characterize morphological, textural, or other indicators of past or present life<br>(C) Detect inorganic minerals<br>(D) Detect potential biomarkers<br>(E) Determine presence of sampled material<br>(F) Assess the non-sterility of Europa ice<br>(G) Characterize the surface composition of Europa ice<br>(H) Determine physical properties of surface materials<br>(I) Characterize physical properties of surface materials<br>(J) Characterize chemical composition of surface materials | <b>ELSSIE Science</b><br>(A1) Detect organic compounds in the sampled material, w/ emphasis on biological characteristics<br>(B1) Resolve & characterize morphological structures < 1.5 mm in size, in color, @ 0.5 m<br>(C1) Detect inorganic minerals<br>(D1) Detect potential biomarkers<br>(E1) Determine presence of sampled material<br>(F1) Assess the non-sterility of Europa ice<br>(G1) Characterize the surface composition of Europa ice<br>(H1) Determine physical properties of surface materials<br>(I1) Characterize physical properties of surface materials<br>(J1) Characterize chemical composition of surface materials | <b>ELSSIE Science</b><br>(A2) Search for organic-rich material in a 15 mm object @ 2.5 m<br>(B2) Resolve structures < 1.5 mm in size, in color, @ 0.5 m<br>(C2) Detect inorganic minerals<br>(D2) Detect potential biomarkers<br>(E2) Determine presence of sampled material<br>(F2) Assess the non-sterility of Europa ice<br>(G2) Characterize the surface composition of Europa ice<br>(H2) Determine physical properties of surface materials<br>(I2) Characterize physical properties of surface materials<br>(J2) Characterize chemical composition of surface materials | <b>ELSSIE Science</b><br>(A3) Search for organic-rich material in a 15 mm object @ 2.5 m<br>(B3) Resolve structures < 1.5 mm in size, in color, @ 0.5 m<br>(C3) Detect inorganic minerals<br>(D3) Detect potential biomarkers<br>(E3) Determine presence of sampled material<br>(F3) Assess the non-sterility of Europa ice<br>(G3) Characterize the surface composition of Europa ice<br>(H3) Determine physical properties of surface materials<br>(I3) Characterize physical properties of surface materials<br>(J3) Characterize chemical composition of surface materials |

## Design & Testing in ICEE-2

### ICEE-2 Development Tasks

- 1) Iterate sensor & DPU designs to shrink volume, mass, resource utilization, then proceed to mechanical design
- 2) Demonstrate compatibility of suitable detector with heat microbial reduction
- 3) Model radiation at FPA to verify noise within tolerance of onboard processing; iterate shielding design as needed
- 4) Build prototype lens cell and demonstrate performance at cryogenic temperature (leverage EIS development [5])
- 5) Build prototype adjustable focus and demonstrate performance at cryogenic temperature
- 6) Build prototype spectrometer
- 7) Prototype & demonstrate onboard processing algorithms

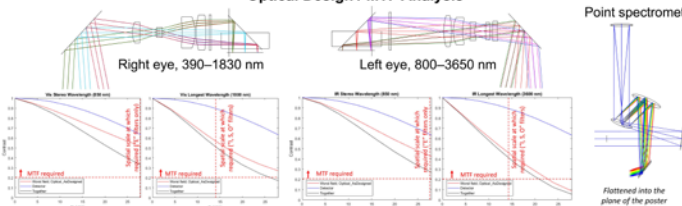
\*2019 priorities

### Filters / # Exposures for Radiation Mitigation, SNR

| Filter Pos | Name | Center Wl | FWHM | Typical Bitting | Single Exposed (100% SNR) | Single Exposed (100% SNR) |
|------------|------|-----------|------|-----------------|---------------------------|---------------------------|
| R1         | E1   | 428       | 80   | None            | 8                         | 3                         |
| R2         | E2   | 545       | 70   | None            | 7                         | 3                         |
| R3         | E3   | 670       | 60   | None            | 7                         | 3                         |
| R4         | E4   | 850       | 100  | None            | 6                         | 3                         |
| R5         | E5   | 1000      | 100  | 2x2             | 7                         | 3                         |
| R6         | S1   | 1355      | 50   | 2x2             | 9                         | 3                         |
| R7         | S2   | 1475      | 60   | 2x2             | 10                        | 3                         |
| R8         | S3   | 1545      | 70   | 2x2             | 10                        | 3                         |
| R9         | S4   | 1650      | 70   | 2x2             | 10                        | 3                         |
| R10        | S5   | 1750      | 100  | 2x2             | 10                        | 3                         |
| L1         | E4L  | 850       | 100  | None            | 7                         | 3                         |
| L2         | E1L  | 428       | 80   | None            | 8                         | 3                         |
| L3         | E2L  | 545       | 70   | None            | 7                         | 3                         |
| L4         | E3L  | 670       | 60   | None            | 7                         | 3                         |
| L5         | E4L  | 850       | 100  | None            | 6                         | 3                         |
| L6         | S1L  | 1355      | 50   | 2x2             | 9                         | 3                         |
| L7         | S2L  | 1475      | 60   | 2x2             | 10                        | 3                         |
| L8         | S3L  | 1545      | 70   | 2x2             | 10                        | 3                         |
| L9         | S4L  | 1650      | 70   | 2x2             | 10                        | 3                         |
| L10        | S5L  | 1750      | 100  | 2x2             | 10                        | 3                         |

\* 1/4 of images taken per filter, before onboard processing (1/4 of images)  
 \* 1/4 of images classified to improve SNR, after rejecting high values in radiation flux. The resulting image frame is compressed and downsampled to 1/4 of original resolution for a 1/4 of original image composition for detection.

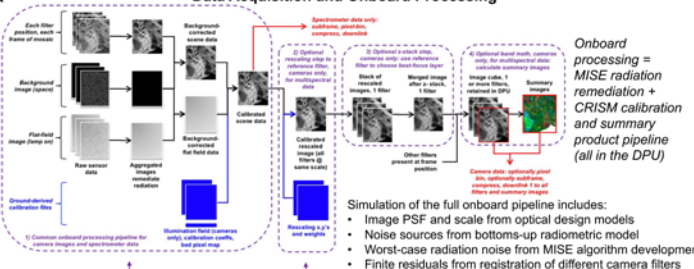
### Optical Design / MTF Analysis



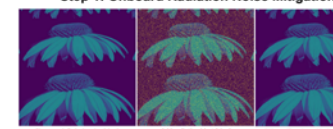
Point spectrometer

Flattened into the plane of the poster

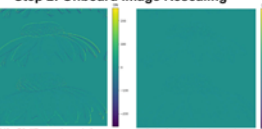
### Data Acquisition and Onboard Processing



### Step 1: Onboard Radiation Noise Mitigation



### Step 2: Onboard Image Rescaling



- Statistical approach – acquire N frames, rank pixel values, throw out X highest, coadd remaining frames
- Based on MISE radiation statistics – 15% event probability for 0.05-s exposure
- Due to scale differences, must co-register filters
- Image math shown before / after onboard rescaling
- Scaling matrix function f (filter, focus, T) solved onboard using telemetry; coefficients calibrated onground

# Seismometer for the Investigation of Ice and Ocean Worlds (SIIOS)

PI: S.H. (Hop) Bailey University of Arizona (UA)

**Platform:** Lander or Rover

## **Mission Goals:**

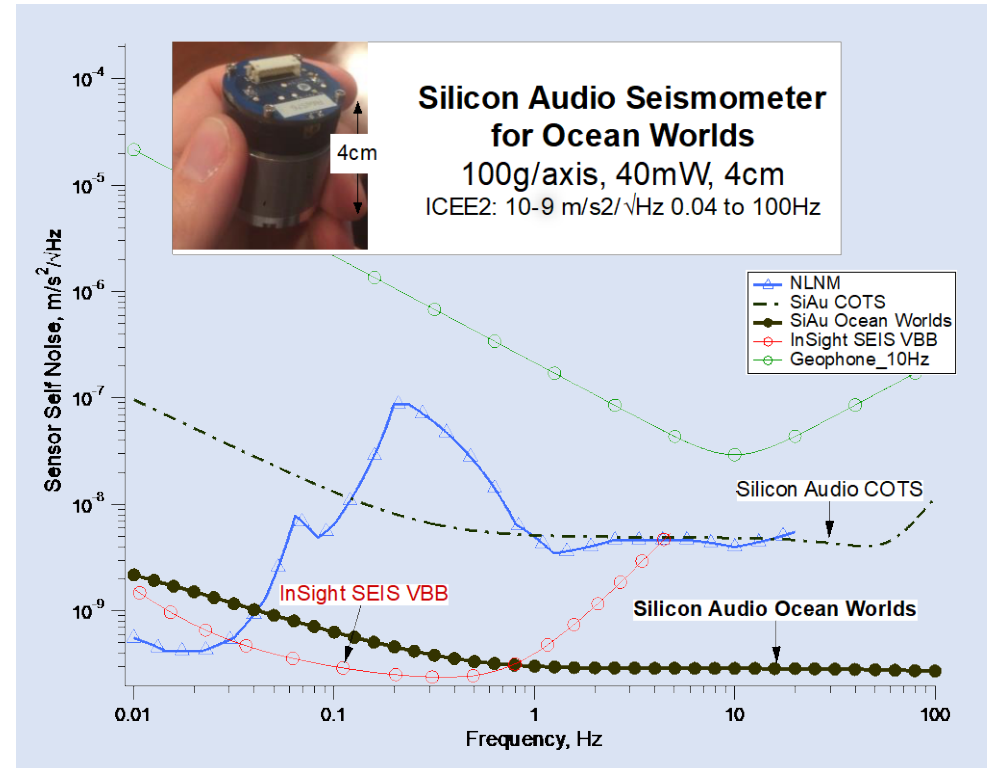
- Land a single-station seismic experiment on an Ocean World.
- Collect seismic events and background signals and transmit those to Earth.
- Analyze seismic signals to infer inner structure.

## **Methodology:**

- Develop flight prototype comprised of the Silicon Audio COTS detector and Space Dynamics Lab control electronics
- Conduct environmental testing to achieve TRL 6
- Work with mission planning team on interfaces and accommodations
- Conduct analysis to determine placement of seismometer on the lander to optimize seismic transmission
- Develop methods of autonomous analysis of continuously collected seismic data to fit within downlink capabilities

**CoIs:** Renee Weber/MSFC, Science PI; Daniella DellaGiustina/UA, Co-I; Brad Avenson/Silicon Audio, Co-I; Robert Burt/SDL, Co-I; Nick Schmerr/UMD, Co-I; Matthew Siegler/PSI, Co-I; Veronica Bray, Co-I/UA

**Collaborators:** Naomi Murdock/ISAE-SUPAERO

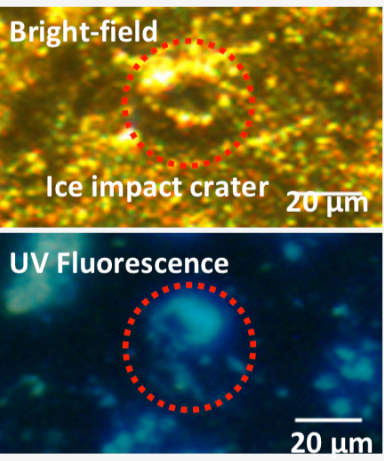


## **Schedule:**

- TRL 6 by February 2021
- Interfaces to JPL Europa lander defined (complete)
- Europa CONOPS and SIIOS operation defined by June 2020
- Autonomous analysis methods by February 2021



Micron-sized ice particles are **efficiently captured with excellent organic survival** at transit velocities below 3 km/s



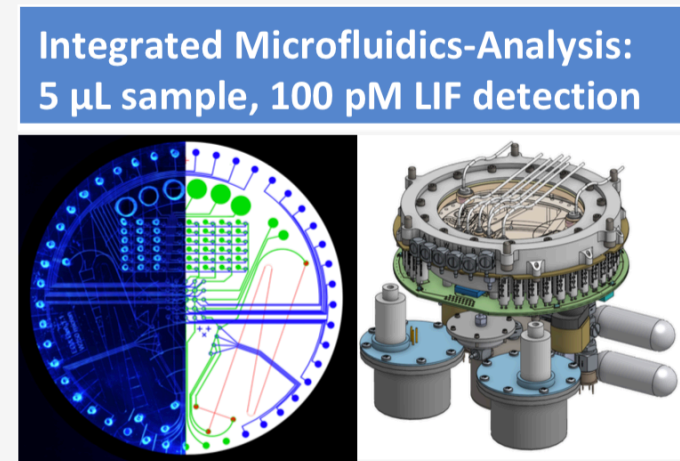
- Ice shots at Kent UK light gas gun facility
- Soft metallic capture surface
- Ice doped with fluorescent dye
- Captured organic dye quantitated by fluorescence
- >50% capture efficiency for micron particles @ ~1 km/s

**100 cm<sup>2</sup> Capture Plate** dissolves captured ice in a small microliter volume and transfers conc. organics for analysis



- Capture on surface and lid providing 100 cm<sup>2</sup> area
- Close and seal lid to enable extraction of captured ice in small 25 μL volume providing high concentration for analysis

**Enceladus Organic Analyzer (EOA)** provides microfluidic processing and high performance 100 pM detection of biosignatures and chirality



- High performance analysis
- Low volume microfluidic processing
- LOD 0.01 ppb amino acids
- High resolution microfabricated capillary electrophoresis CE separations for individual species quantitation and identification

**Multipass gathering of plume ice** by an orbiter provides sufficient ice sample to enables ppb detection of biosignatures at Enceladus

| Accumulation Increases Sensitivity |                                 |                    |
|------------------------------------|---------------------------------|--------------------|
| Ice Sample<br>μL                   | Transits<br>100 cm <sup>2</sup> | Sensitivity<br>ppb |
| 0.02                               | 1                               | 100                |
| 0.2                                | 10                              | 10                 |
| 2                                  | 100                             | 1                  |

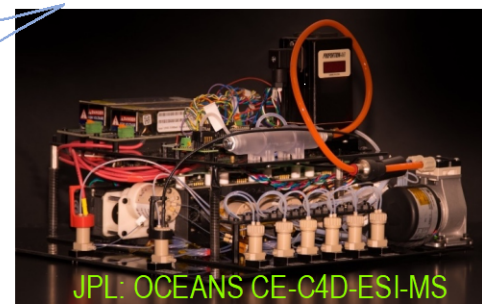
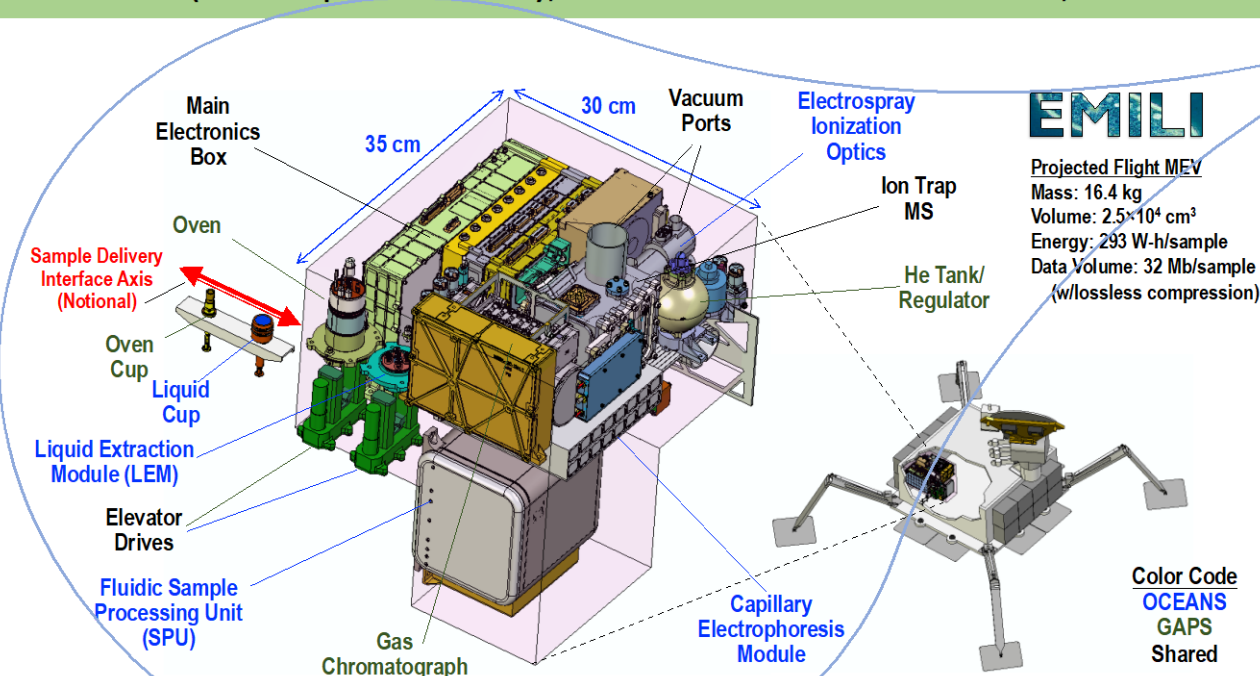
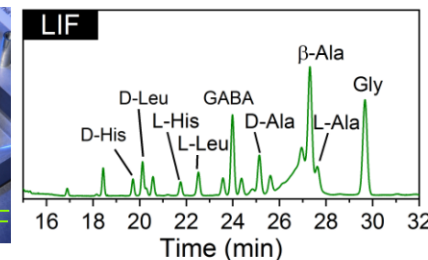
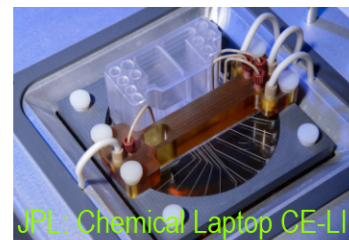
- Multi-pass orbital gathering powerfully increases sample size
- Efficient capture, dissolution and transport of integrated sample to high performance analyzer enables valuable habitability and biosignature measurements.

# High-Precision In Situ Molecular Biosignature Analysis on Enceladus, Europa, and Beyond

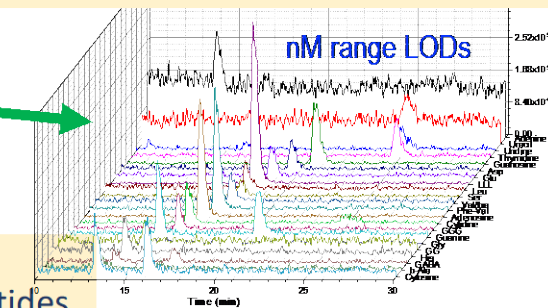
*A Life Detection Technology Partnership between Goddard, JPL, Ames, Honeybee Robotics, and Others [POC: W. Brinckerhoff, GSFC]*

Newly-developed and demonstrated (COLDTech, ICEE-2) technology combines complementary liquid and gas sample processing with exquisitely sensitive, precise, and broad molecular characterization methods (mass spectrometry, laser-induced fluorescence, conductivity)

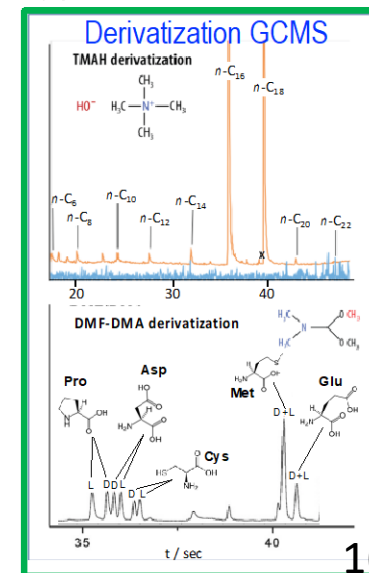
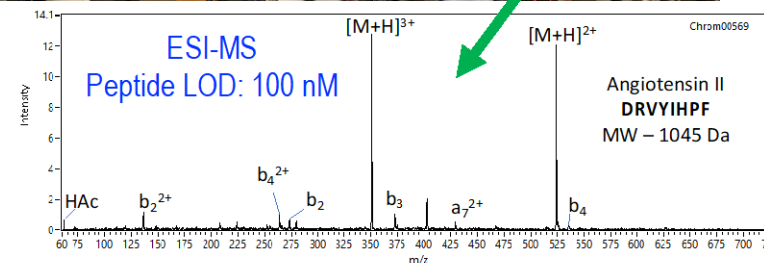
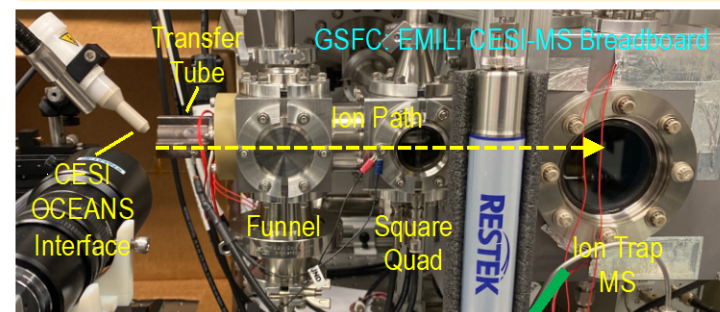
**Demonstrated**  
1-5 nM amino acid  
limit of detection  
(LOD) with CE-LIF



**Demonstrated**  
Integrated & automated CE-C4D-ESI-MS



**Demonstrated**  
Wide mass range ESI-MS analysis of peptides



## European Molecular Indicators of Life Investigation (EMILI)

Complete analysis of organic compounds (amino acids, peptides, carboxylic acids, aromatics, ...), light volatiles, and salts in ocean world samples. Merges Capillary Electrophoresis (CE), Laser Induced Fluorescence (LIF), Gas Chromatography (GC), and Ion Trap Mass Spectrometry (ITMS) on track to TRL 5/6 meeting all Europa SDT objectives and **fully adaptable to Enceladus**.



# SPLIce: Sample Processor for Life on Icy Worlds

*Microfluidic technology development for Enceladus & Europa life search*

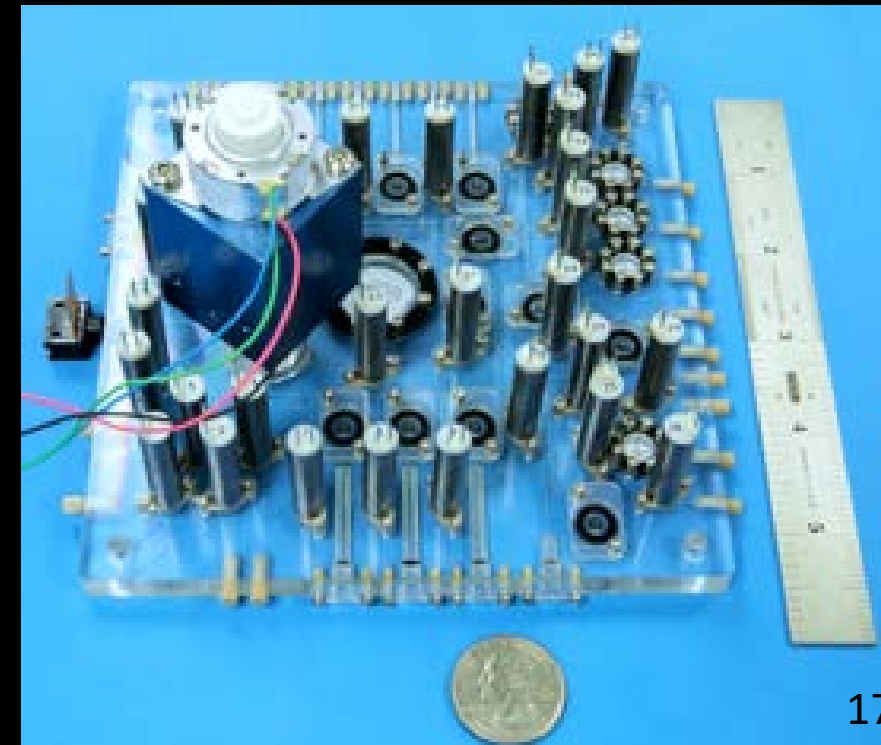
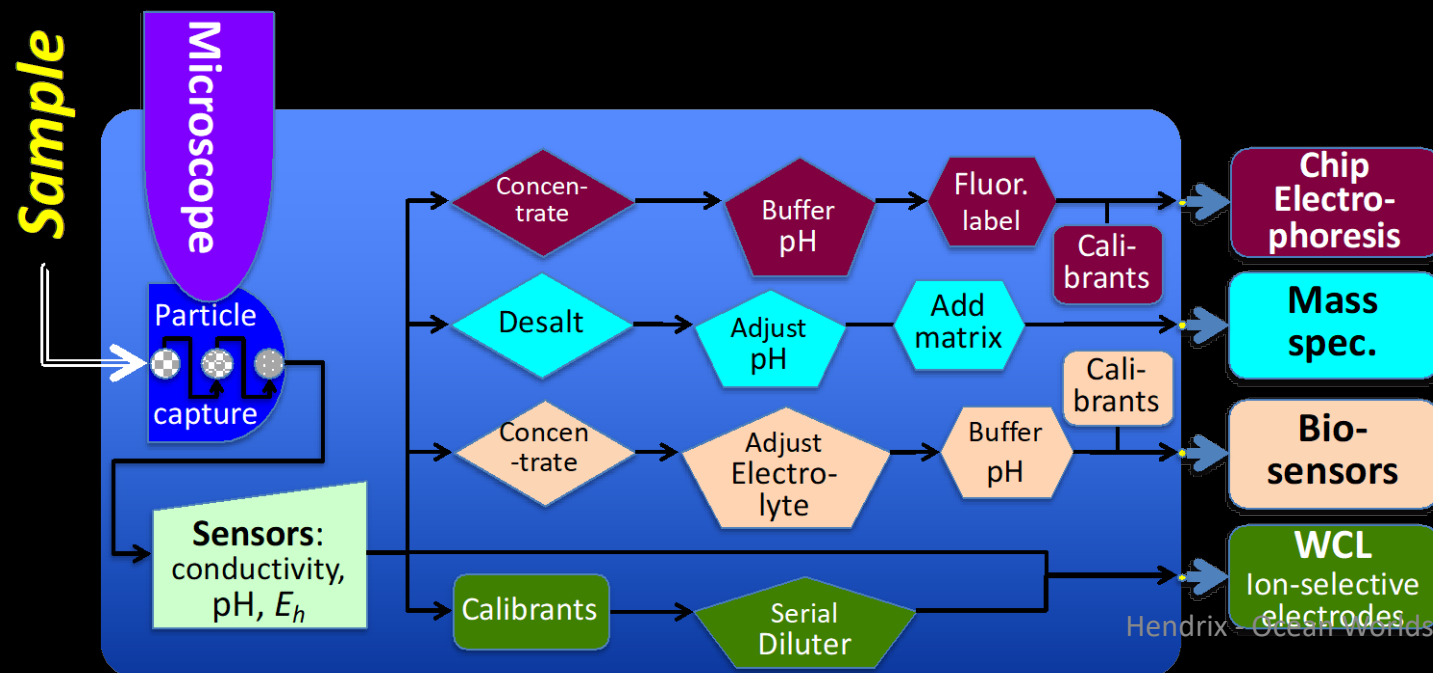
*Multifunctional sample processing hub for science payload integration*

Lead: **ARC** Partners: **APL, GSFC, JPL, MIT, Tufts, MIT** Funding: **COLDTech**

PI/Co-I's: A. Ricco, R. Quinn; S. Getty, W. Brinckerhoff; P. Willis, A. Noell; E. Adams, R. Gold; S. Kounaves; M. Hecht

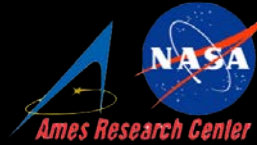
Infusion: **Three ICEE-2's → Europa Lander, Enceladus fly-by mission concepts**

**Highlights:** > 95% sample recovery; Long-term on-board reagent storage / radiation stability / reconstitution; bubble trapping; 128x sample concentration; autonomous sequenced processing; integrated sensors; metered delivery; particle trapping; dye addition



# MICA: Microfluidic Icy-world Chemical Analyzer

## Fluidically Integrated Habitability Assessment for Icy Worlds

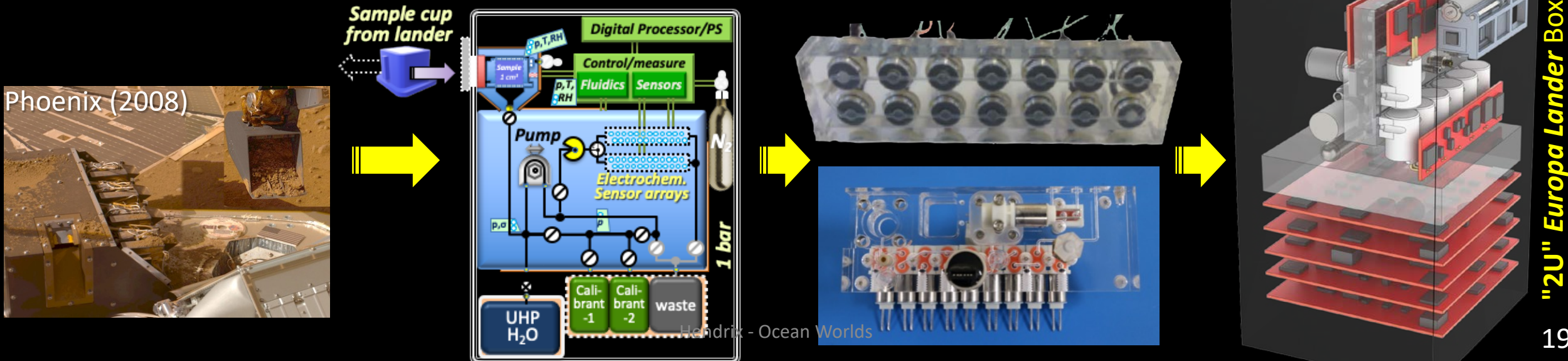


**Heritage:** Phoenix Wet Chemistry (WCL) Lab advanced *via* COLDTech projects: microfluidic WCL (mWCL) and SPLIce (Sample Processor for Life on Icy worlds)

**Lead:** ARC    **Partners:** JPL, Tufts, MIT, U. of Alberta, Honeybee Robotics    **Funding:** ICEE-2  
**PI/Co-I's:** A. Ricco, R. Quinn, J. Koehne, J. Forgione; A. Noell, P. Willis; S. Kounaves; M. Hecht; J. Harrison; K. Zacny

**Key Measurements:** pH, ionic conductivity, specific ions:  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Li}^+$ ,  $\text{NH}_4^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-/\text{ClO}_4^-$ ,  $\text{PO}_4^{3-}$ ,  $\text{SO}_4^{2-}$ ,  $\text{CO}_3^{2-}$ ; solution energetics: discrete & weighted average of redox-active species ( $E_h$ )

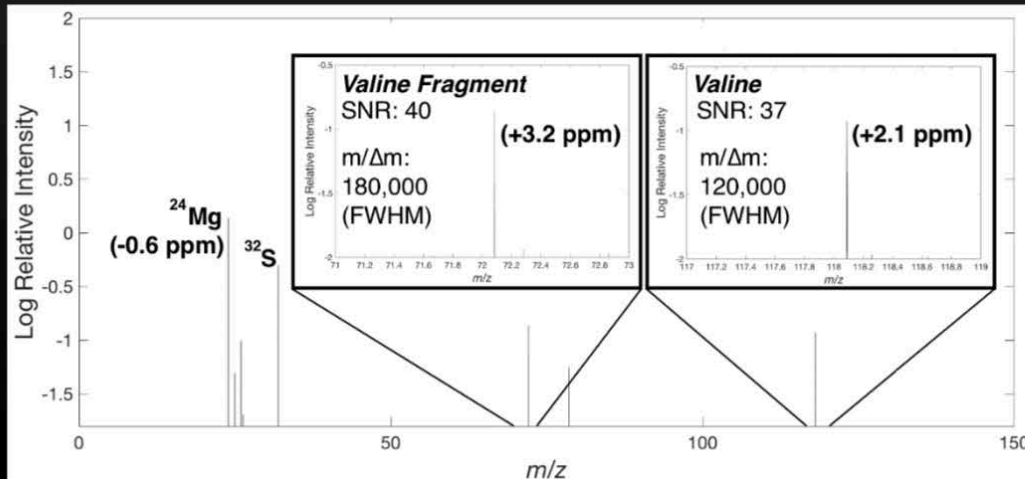
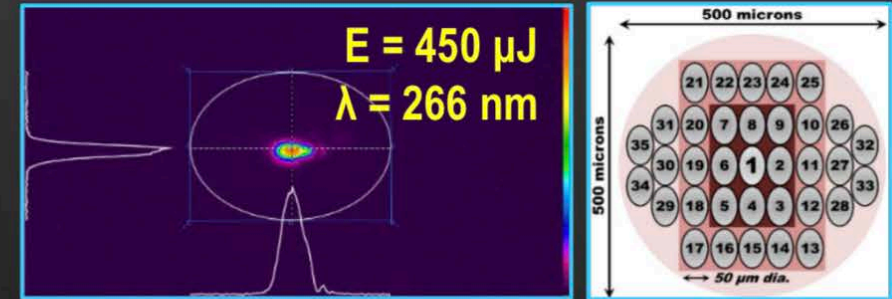
**Fluidic Functions :** Receive & melt icy samples; prepare/deliver conditioning, blank, & calibrant solutions at multiple concentrations; control temperature & pressure; execute & buffer all measurements





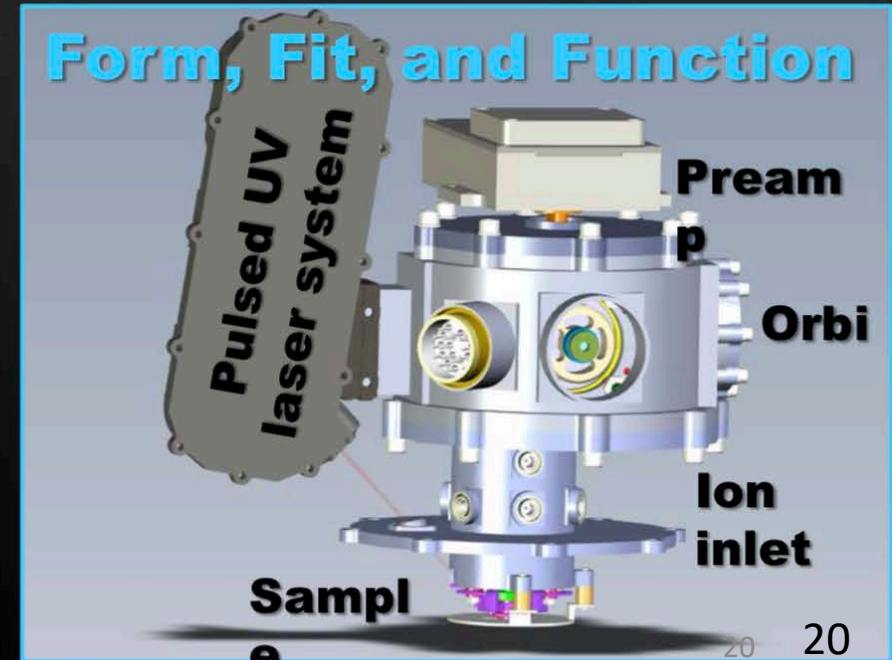
# ICEE 2 /CORALS: A Laser-Enabled Orbitrap Analyzer

- **CORALS:** Characterization of Ocean Residues and Life Signatures
- **NOVEL IONIZATION SOURCE:** High-power UV laser (266 nm)
  - Output energies exceeding 450  $\mu\text{J}$  (3x MOMA)
  - Chemical mapping (2D) via beam rastering
- **MOLECULAR DISAMBIGUATION:** Ultrahigh mass resolution ( $m/\Delta m \geq 10^5$ ) and dual polarity operations (vs. SAM and MOMA)
- **SCIENCE GOALS:** Analyze organic/inorganic populations
  - < pmol/mm<sup>2</sup> LOD, plus precise < 1% (2 $\sigma$ ) isotopic abundances
- **ADAPTABILITY:** 8 kg, peak 47 W, low-pressure ops



*Identification of molecular ions and diagnostic fragments with ppm-level mass accuracy*

Arevalo et al. (2018)



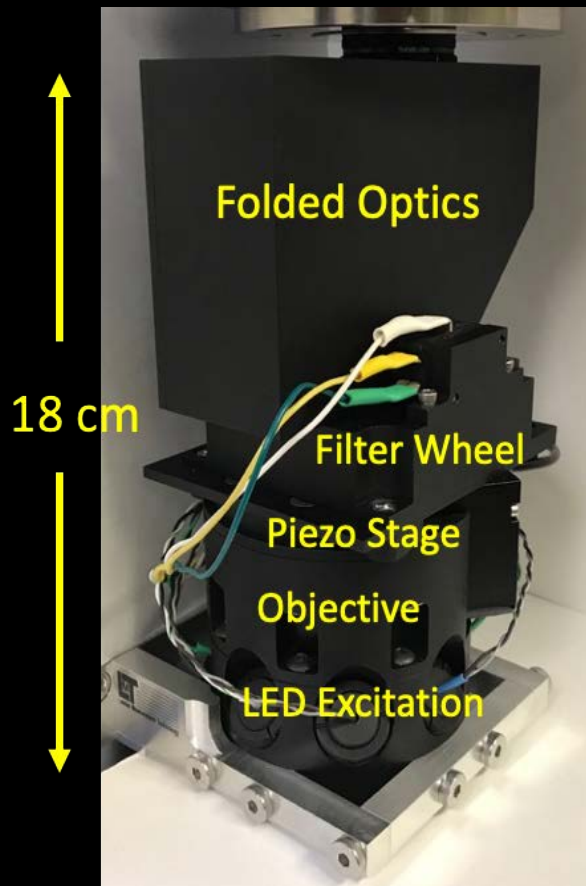


# Ames Research Center Microscopes for Life Detection

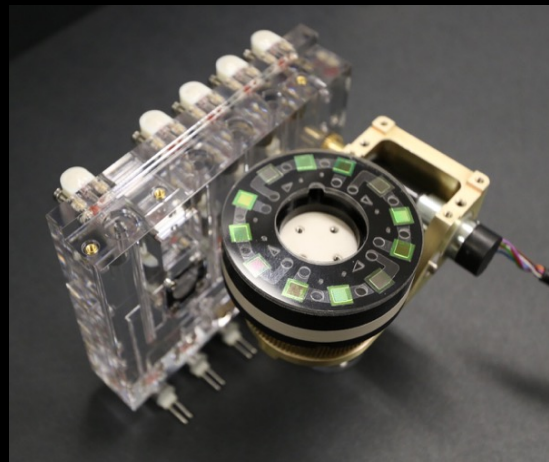
**LfE: Luminescence Imager for Exploration (NASA COLDTech Program)**

**ELM: Europa Luminescence Microscope (NASA ICEE2 Program)**

**PI/Co-I's: R.C. Quinn<sup>1</sup>; A.J. Ricco<sup>1</sup>, N. Bramall<sup>2</sup>, J. Forgione<sup>1</sup>, L. Timucin<sup>1</sup>, K. Zacny<sup>3</sup>**

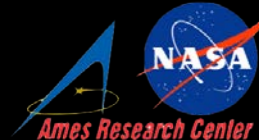


- **Visible light imaging of organic and inorganic structures with submicron resolution.**
- **Sample is autonomously manipulated to chemically stain key molecular and structural indicators of microbial life (proteins, lipids, nucleic acids) for fluorescence microscopic detection.**



- **Uses DUV and visible excitation of native luminescence; mineralogical and biological.**
- **In-line filter sets capture successively smaller particle sizes on 10, 1.0, and 0.1  $\mu\text{m}$  pore-size filters for sample imaging.**

# Enabling Life Detection with Fluidic Integration



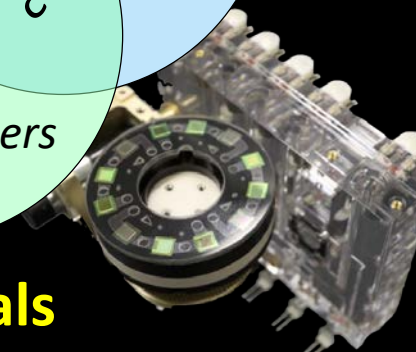
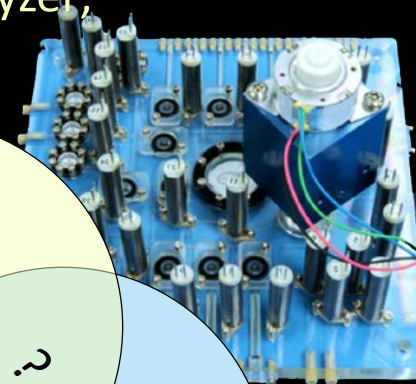
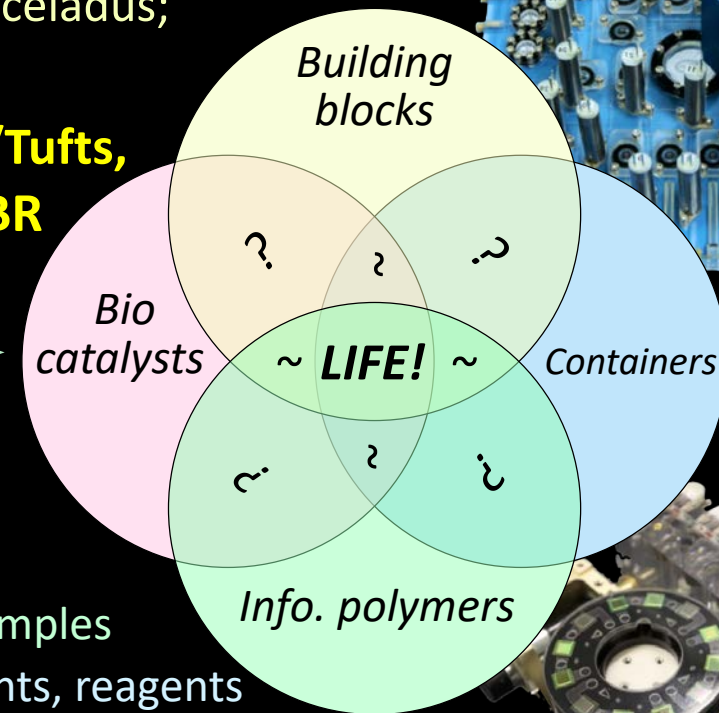
**ARC / GSFC / JPL / APL Collaborative activity spans multiple COLDTech & ICEE-2 Projects:**

**EMILI:** European Molecular Indicators of Life Investigation; **MICA:** Microfluidic Icy-world Chemical Analyzer;  
**ELM:** Europa Luminescence Microscope; **mWCL:** Microfluidic Wet Chemistry Laboratory;  
**LifeE:** Luminescence Imager for Exobiology; **EFun:** Plume Sampling System for Enceladus;  
**SPLIce:** Sample Processor for Life on Icy worlds

**NASA PIs: Brinckerhoff, Quinn, Ricco, Willis; also Adams/APL, Kounaves/Tufts, Zacny/HBR**

## Guiding Principles to Search for Indicators of Life

1. Follow the water: *Enceladus, Europa*
2. Seek multiple, **diverse indicators**: *dispel ambiguity*
3. Employ a **suite of complementary instruments**: *extraordinary proof*



## A Fluidically Integrated Analytical Suite will:

- Maintain **molecular and structural integrity** of life indicators
- Extract, process, filter, concentrate, de-bubble, label, aliquot, and deliver samples
- **Optimize instrument performance:** meter samples, blanks, controls, calibrants, reagents

## NOT a matter of "if" but "what's required": systems at TRL 5-6 for NF 5 proposals

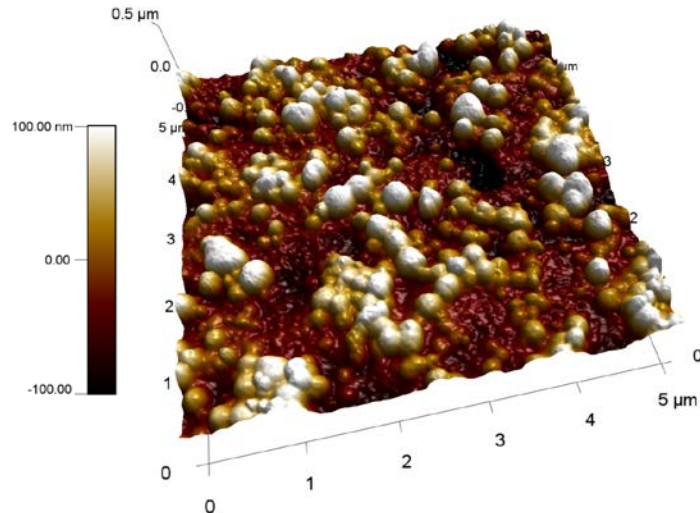
- Enabling fluidics technology has **matured dramatically** thru repetitive design, development, integration, spaceflight
- Achieving this **powerful combination of measurements** on a planetary mission is **NO LONGER** a **HIGH-RISK** proposition

# Atomic Force Microscopy has Distinct Advantages to Detecting Biosignatures in Ocean Worlds Applications

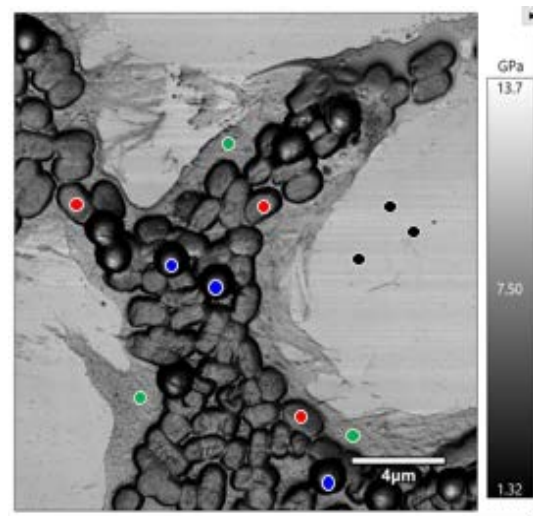
COLDTech NNX17AF49G PI Alison Murray/Earth & Ecosystem Sciences, Desert Research Institute, Reno, NV, USA; Sandor Kasas and Giovanni Dietler, EPFL, Lausanne Switzerland, Farooq Azam, Scripps Institute of Oceanography, La Jolla, CA, USA; Roger Proksch, Asylum Research Inc., Santa Barbara, CA, USA.

**For landed missions to ocean worlds and fly-by missions collecting ocean plumes to outer solar system targets – atomic force microscopy provides critical advantages to detecting physical signs of life.**

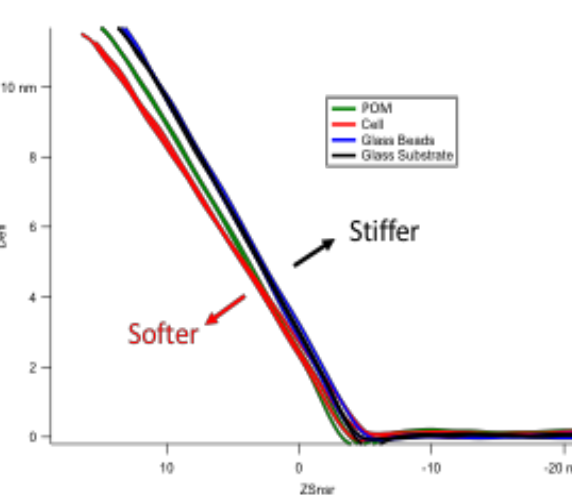
- **AFM has sub-micron resolution down to 10's of nanometers and can work with a lower resolution optical microscope to focus on regions of interest in collected sample**
- **AFM offers the ability to provide high resolution topographical data in 3D for ALL potentially biogenic and abiotic particles in a sample**
- **AFM also offers the ability to provide nanomechanical forces about all particles including stiffness, adhesion, and energy dissipation**



**AFM micrograph provides 3D topographic maps of > 0.2 micron cells in subzero Antarctic brine samples**



**AFM micrograph with both biological and abiotic meteorite particles**



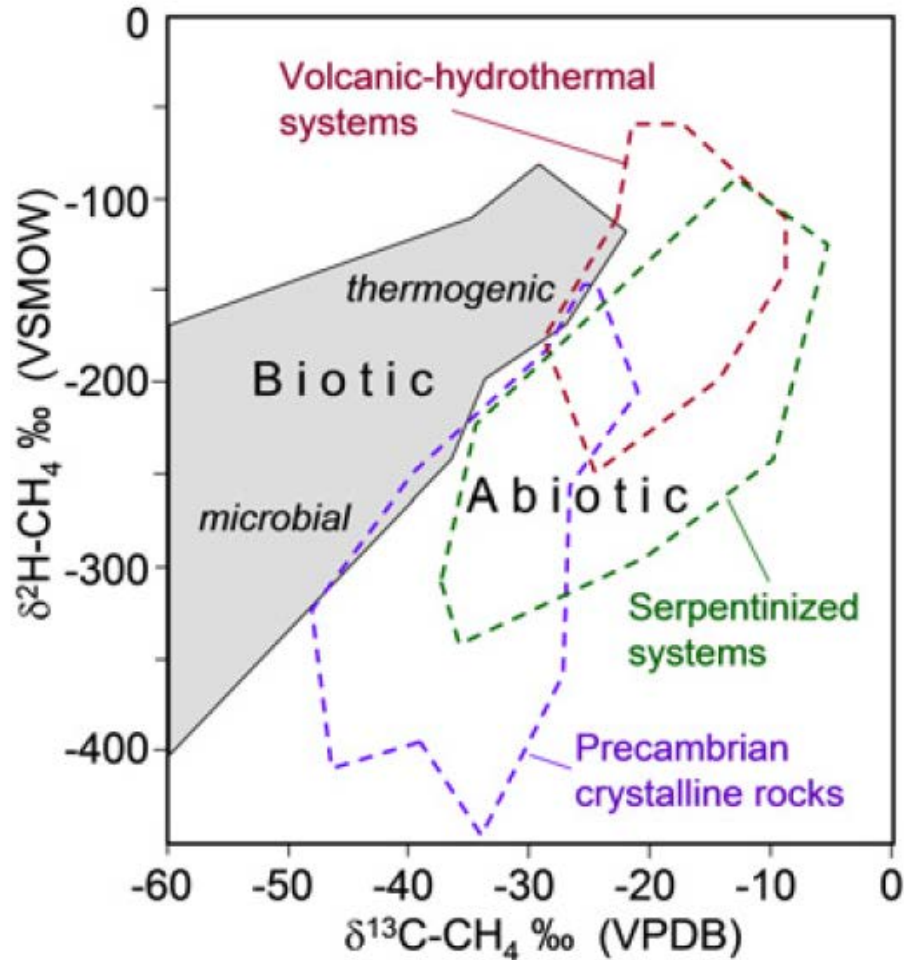
Cypher S, FFM mode

**Force-distance curve shows nanomechanical properties – stiffness - of abiotic and biological particles**



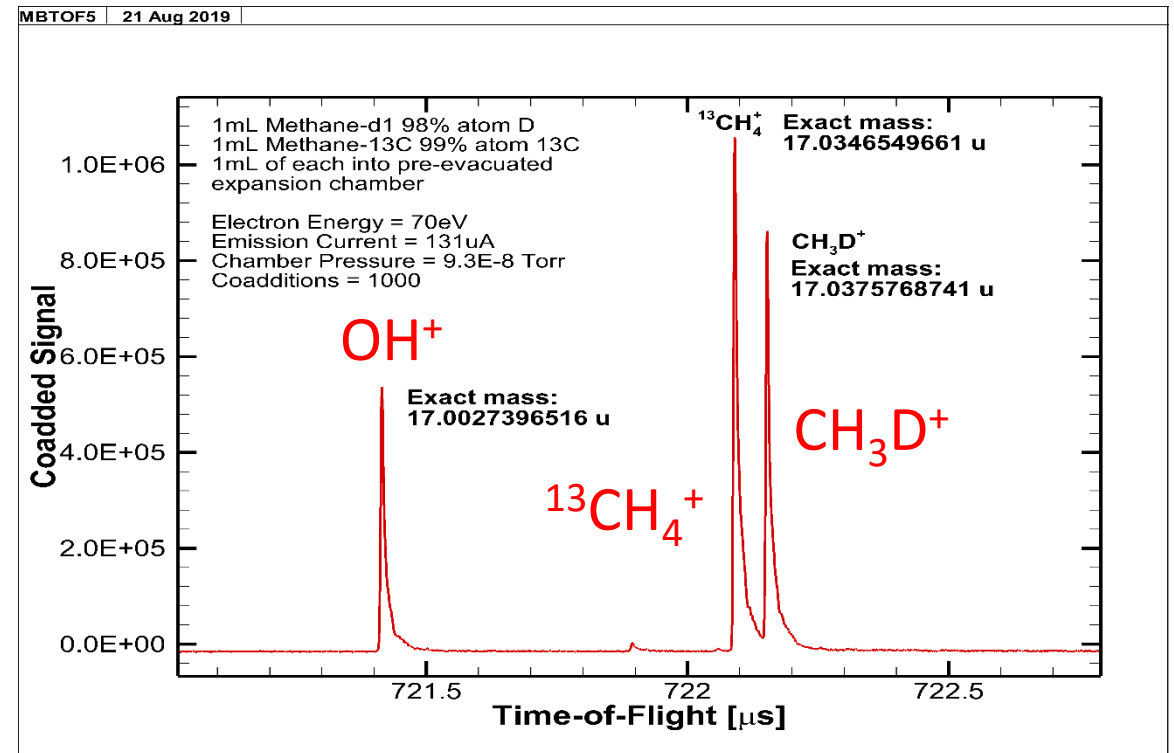
## ICEE-2 MASPEX-ORCA (Glein et al.)

- Isotopes as part of the biosignatures toolbox
- The importance of methane



Etiope & Schoell (2014)

- Methane is in the Enceladus plume (Waite et al., 2017) → low risk
- Its origin is unknown
- Spaceflight mass spectrometers in this decade can resolve similar mass peaks to quantify these isotope ratios

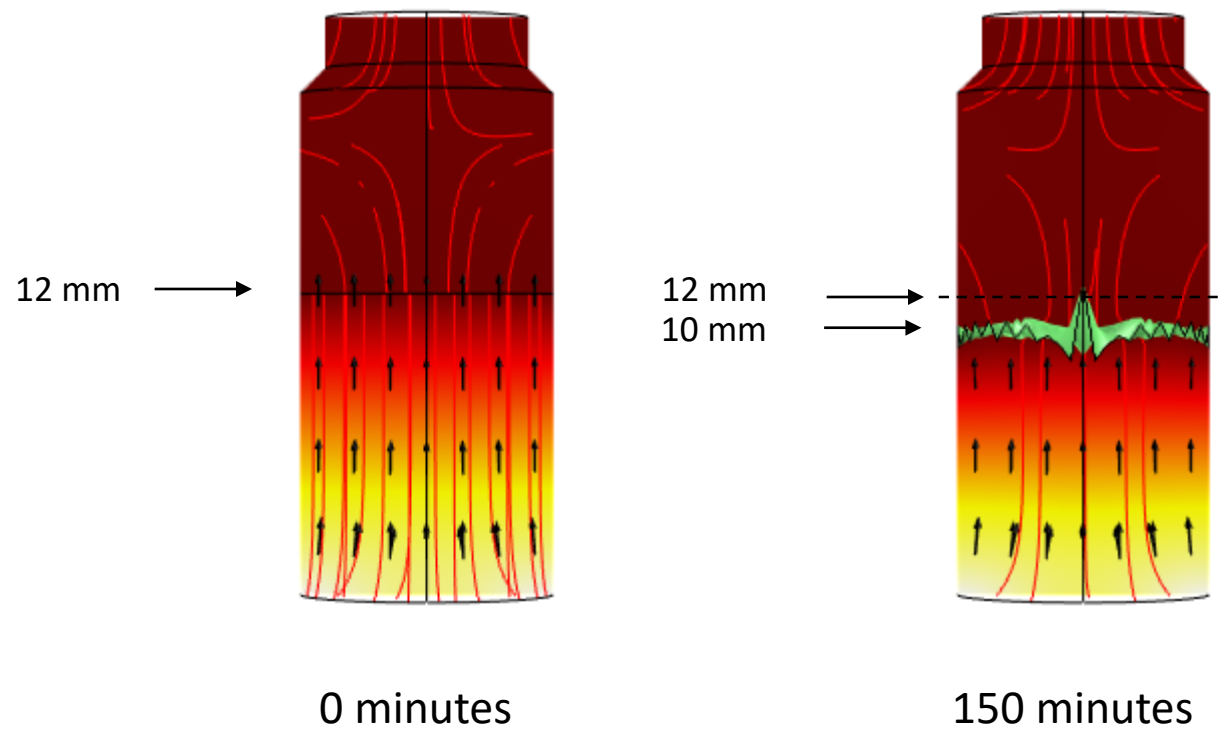


Hendrix - Ocean Worlds

Credit: C. Glein, K. Miller, H. Waite



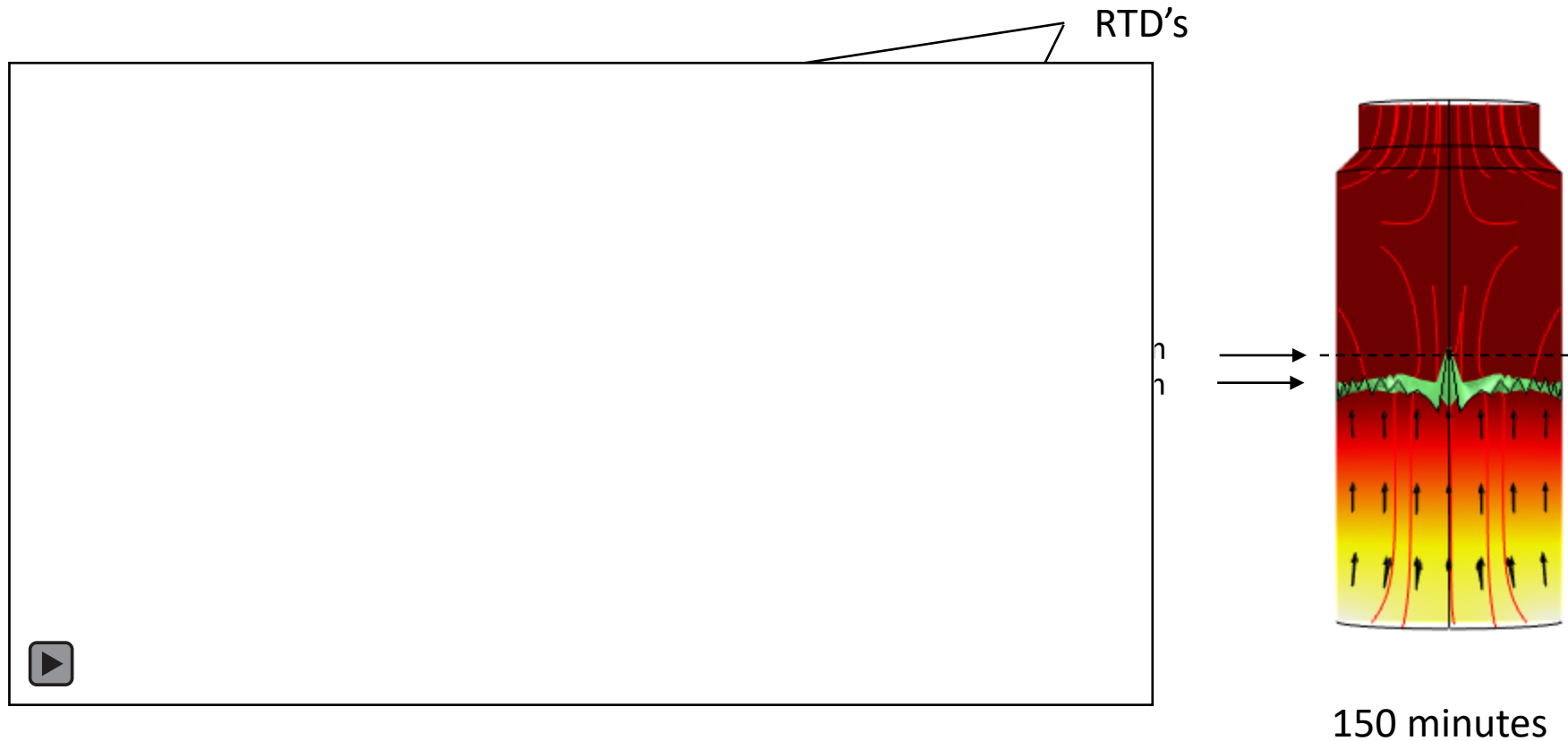
# Simulation of Sublimation



~ 14% decrease in volume; estimate ~17 hours to completion

Bruce Hammer, Univ. Minnesota

# Actual H<sub>2</sub>O Lyophilization Compared to Comsol Simulation

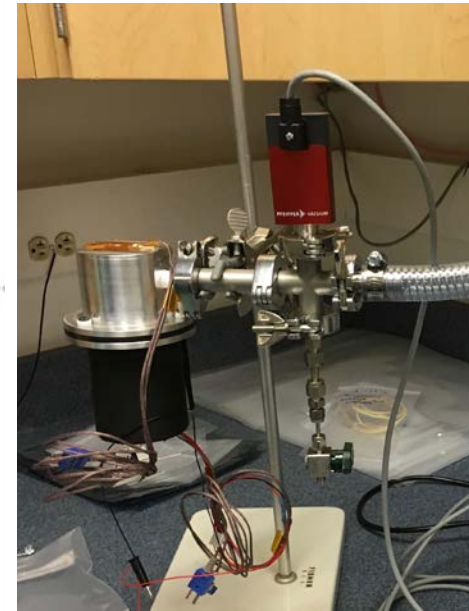
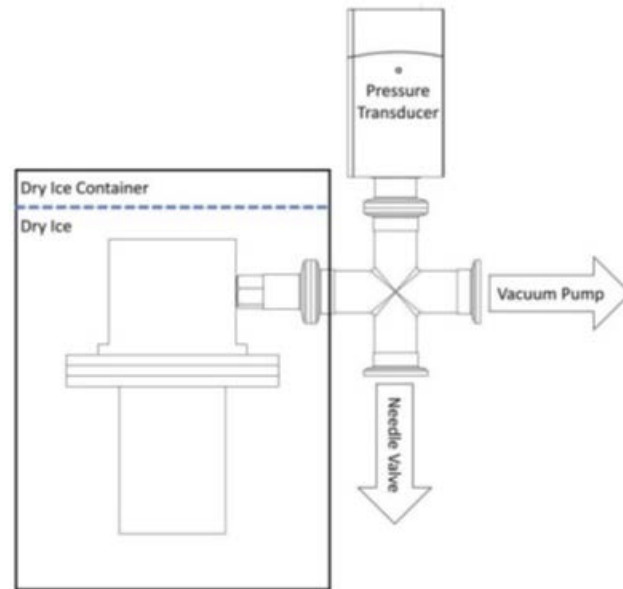


$P_{\text{ext}} = 0.1 \text{ Pa}$ ;  $P_{\text{vapor}} = 10 \text{ Pa}$ ;  $T_{\text{ice}} = -39 \text{ C}$

Bruce Hammer, Univ. Minnesota

# Miniature Lyophilizer Prototype for Spaceflight

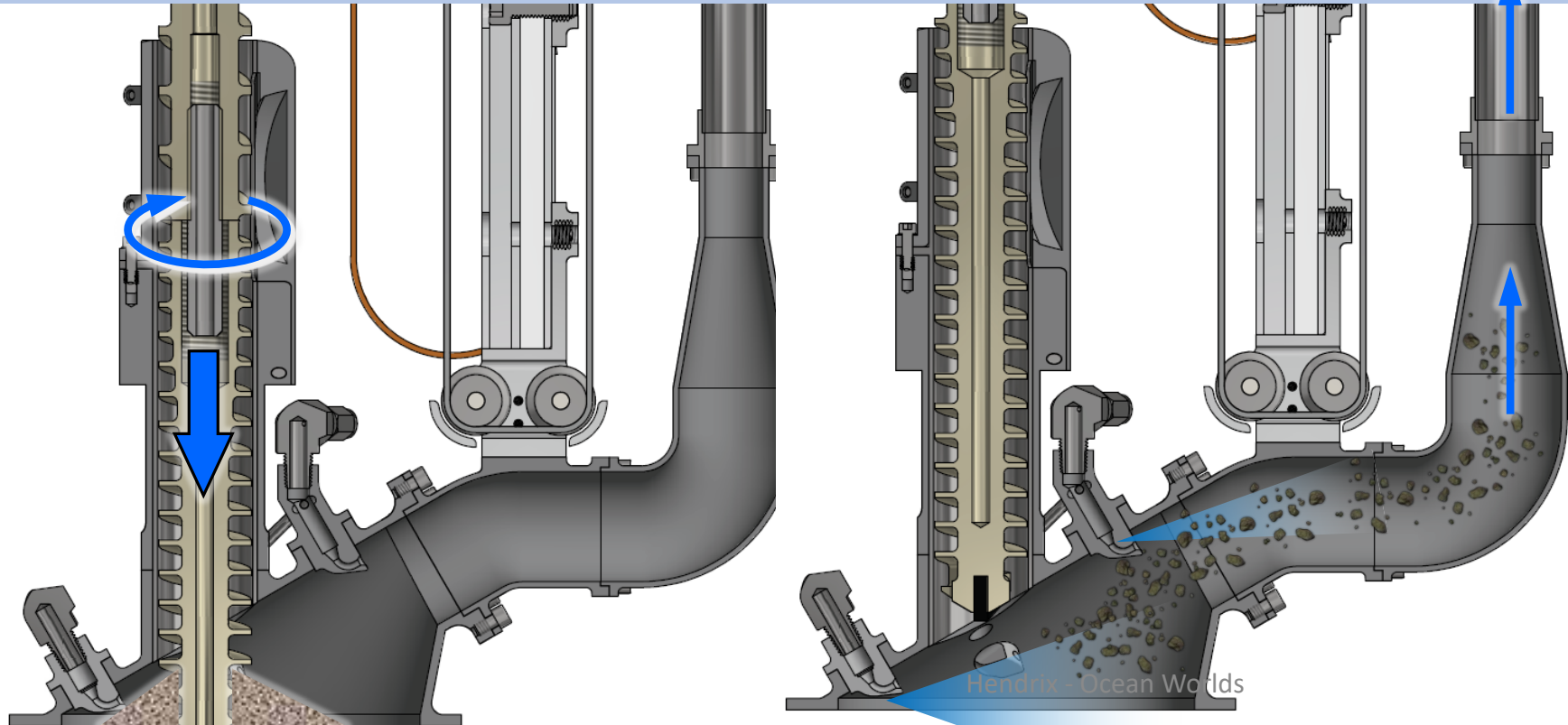
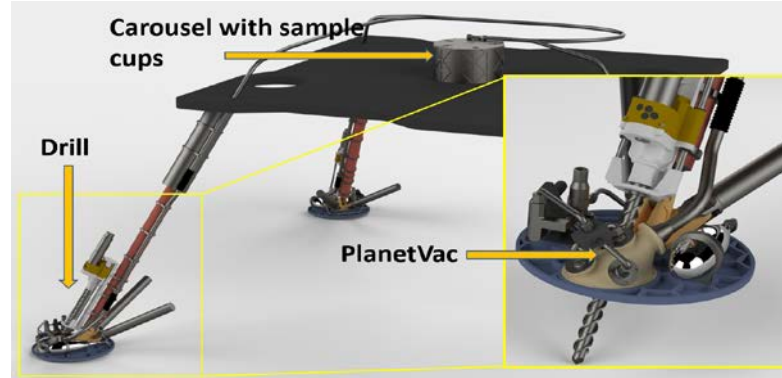
- ✓ Space has a vacuum
- ✓ Space is cold
  - Freeze sample
  - Keep condenser 20 C less than sample temp
- Need heat source
- Sample conveyance



Bruce Hammer, Univ. Minnesota

# Integrated Sampling System for Ocean Worlds (COLDTech – Zacny)

- Drill brings sample to a surface
- PlanetVac delivers sample to a carousel/instrument/sample return container
- Parts of the technology infused into flight:
  - Dragonfly – Titan (2026 launch)
  - CLPS – the Moon (2023 launch)
  - MMX – Phobos (2024 launch)







# ExCALiBR: Extractor for Chemical Analysis of Lipid Biomarkers in Regolith

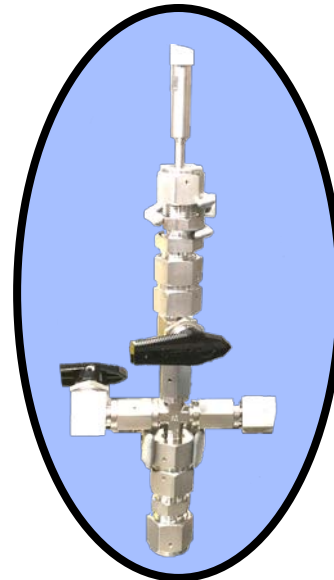


Mary Beth Wilhelm (PI), Tony Ricco, Matt Chin, Jen Eigenbrode, Linda Jahnke, Michael Furlong, Denise Buckner, Tori Chinn, Kanch Sridhar, Tom McClure, Travis Boone, Leslie Radosevich, Abe Rademacher, Trinh Hoac, Morgan Anderson, Stephanie Getty, Adrian Southard, Ross Williams, Xiang Li, Trey Smith

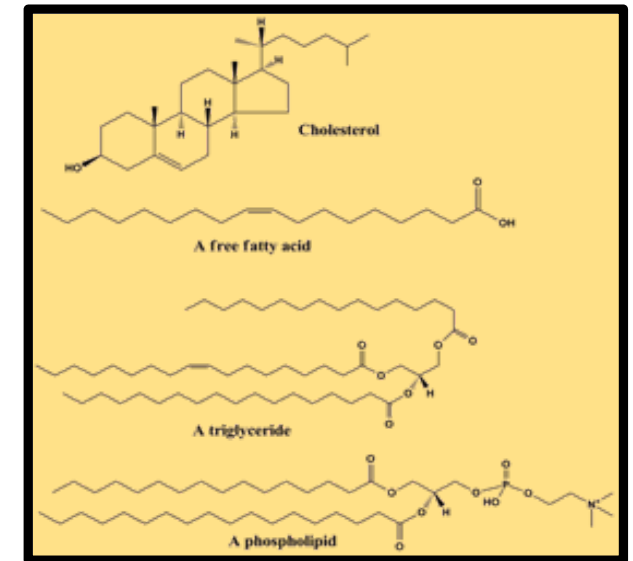
We are developing a non-aqueous fluidic system capable (*TRL 5 by 2021*) of integrating and automating laboratory **sample preparation processes** that enables optimal instrumental analysis of organics contained in regolith or icy regolith.



ExCALiBR breadboard



origin-diagnostic lipid structures



NASA ARC has a proven track record in developing fluidic systems for spaceflight.

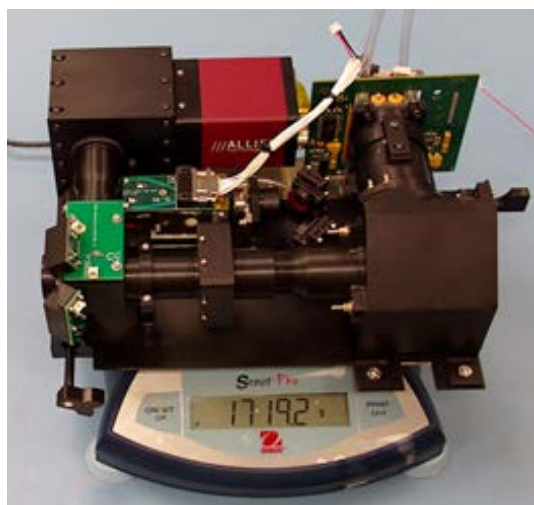
Hendrix - Ocean Worlds



# CIRS SPECS VS EUROPA Baseline and Threshold VIBRATIONAL SPECTROMETER INSTRUMENTS

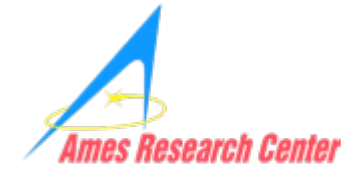


**CIRS Instrument**



**CIRS Instrument (1.7kg)  
w/o case/control electronics**

| Parameter                   | Threshold/<br>(SHERLOC)               | Baseline/<br>(ExoMars)    | CIRS                                                                           |
|-----------------------------|---------------------------------------|---------------------------|--------------------------------------------------------------------------------|
| Wavelength                  | 248.6 nm                              | 532 nm                    | 532 nm                                                                         |
| Laser Spot Size             | 50 $\mu\text{m}$ (100 $\mu\text{m}$ ) | 50 $\mu\text{m}$          | 15 $\mu\text{m}$                                                               |
| Raman Coverage              | 1000 – 3500 $\text{cm}^{-1}$          | 150–2000 $\text{cm}^{-1}$ | 186–4000 $\text{cm}^{-1}$                                                      |
| Resolution                  | 77 $\text{cm}^{-1}$                   | 6 $\text{cm}^{-1}$        | 8 $\text{cm}^{-1}$                                                             |
| Fluorescence Spectral Range | Ex: 248.6nm<br>Em:270-360 nm          | N/A                       | Ex: 266nm or 467nm<br>Em: 535-670 nm                                           |
| Field of View               | 7 x 7 mm                              | point                     | 5.5 x 4 mm (imager)<br>10mm linear (Raman)                                     |
| Raman DOF                   | $\pm 12.5$ mm ( $\pm 0.5$ mm)         | $\pm 1$ mm                | $\pm 10$ mm with SNR >7.9@100s                                                 |
| Imaging/ Resolution         | Color (Watson)/ 30 $\mu\text{m}$      | None                      | Mono / 3.4 $\mu\text{m}$ w/o Lightfield<br>With Lightfield: 13.5 $\mu\text{m}$ |
| Speed                       | 50 spots/hr                           | 100-300 spots/hr          | 51 spots/hr (SNR>47; pyroxene)                                                 |
| Data Volume (uncompressed)  | 320 Mbits/ sample                     | 80 Mbits/sample           | 33 Kbits/ spot; 23Mbits/image                                                  |
| Fluorescence Mitigation     | Inherent (Spectral Partitioning)      | Photobleaching            | SSE, Photobleaching                                                            |
| Calibration                 | External                              | External                  | Neon & Diamond                                                                 |
| Mass                        | <5.4Kg                                | <5.4Kg                    | 4.7Kg                                                                          |
| Volume                      | Not Specified                         | Not Specified             | Head: 3524 $\text{cm}^3$ Ctr: 1621 $\text{cm}^3$                               |
| Power                       | CBE: 54W                              | Not Specified             | 18W @ -20°C                                                                    |



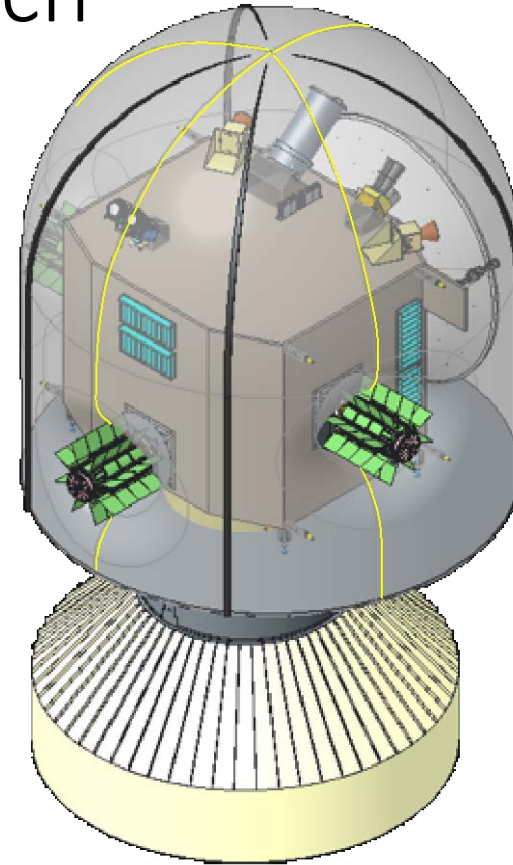
PI: Chris McKay, NASA Ames

- ELSAH was evaluated as Cat II for NF4
  - Instrumentation and mission implementation concepts exist to achieve life detection objectives
  - Demonstrated that a life detection mission can fit in the NF cost cap
- ELSAH was selected for technology development
  - Receiving funds to develop cost-effective techniques that limit spacecraft contamination and thereby better enable life detection measurements on cost-capped missions.

# Technology Development for Contamination Control at Launch

- Launch Vehicle Contamination
- Bio/Molecular Barrier Design
- Barrier Deployment

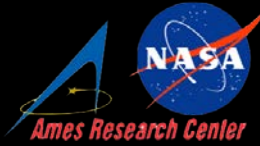
Extremely clean spacecraft are required for sensitive targets such as Europa and Enceladus. Barrier is applied around fully tested and cleaned spacecraft before delivery to launch vehicle. Barrier accommodates all processing steps such as RTG mounting.



Final report scheduled for Summer 2020 (pre-COVID-19)



# $\mu$ CAFE: microChemical Analyzer of Fluids for Exobiology



Microfluidic system of *ELSAH*: Enceladus Life Signatures and Habitability

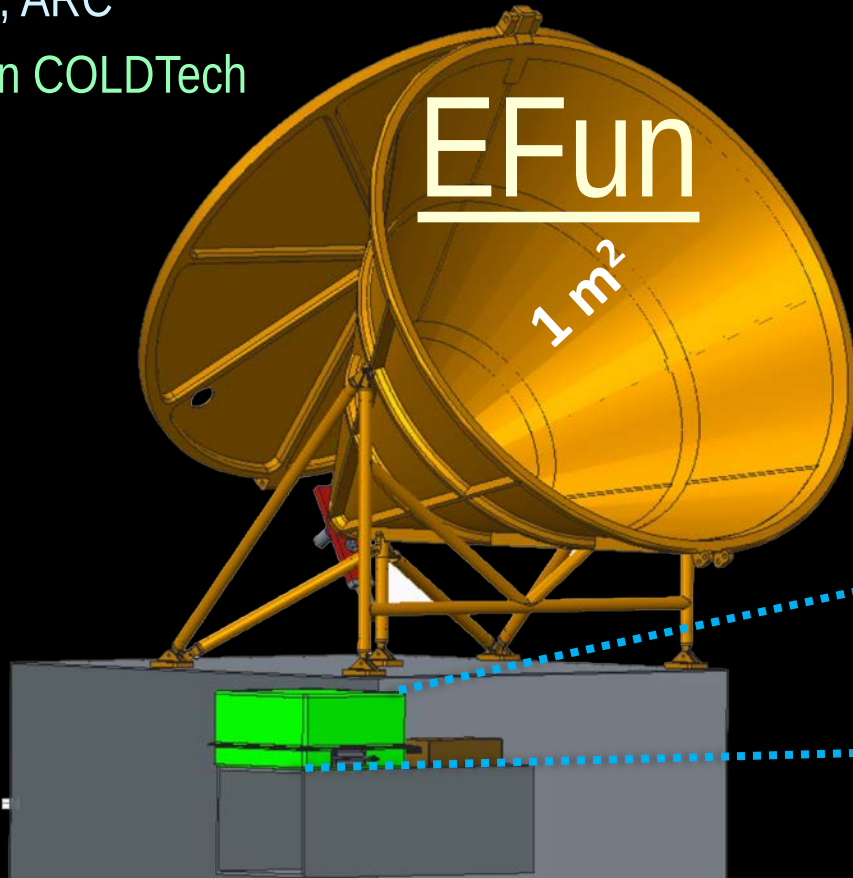
NF4 submission; C.P. McKay, PI (selected for tech. dev.)

**Partners:** ARC, APL, GSFC, JPL, Tufts, MIT [POC: A. Ricco, ARC]

Plume Ice Collector

APL, ARC

EFun COLDTech



## $\mu$ CAFE

Tufts, ARC, JPL

COLDTech/ICEE2

micro-Wet Chemistry  
Laboratory

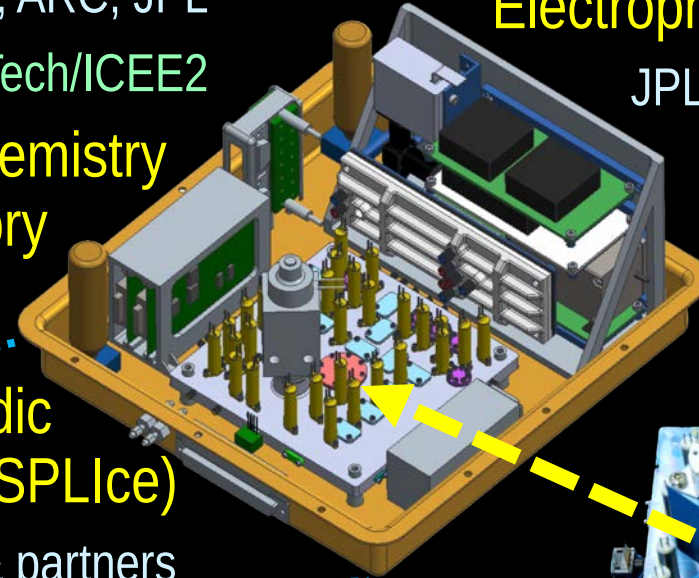
Microfluidic  
Processor (SPLIce)

ARC & partners

COLDTech

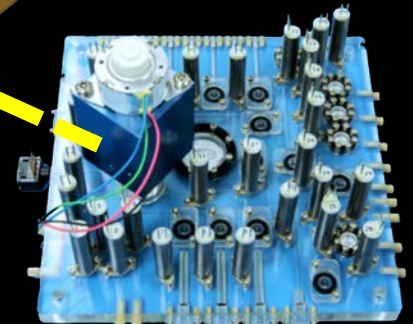
Microchip Capillary  
Electrophoresis

JPL



to GCMS

GSFC

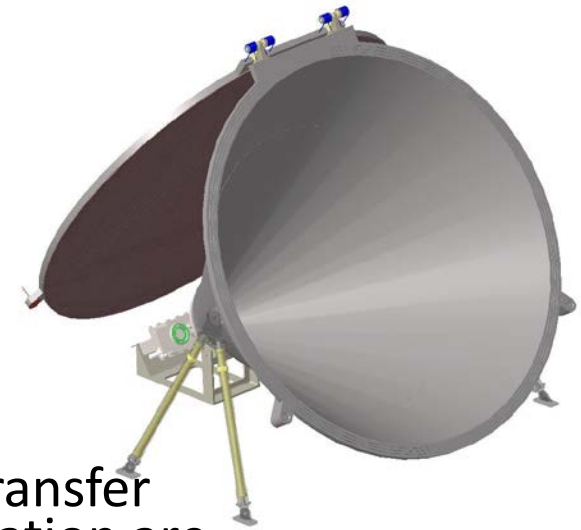


# The EFun System (Elena Adams)

- EFun is the front half of a complete ice plume collection and processing system
- The full system collects, concentrates, melts, transfers, prepares the sample for analysis by follow-on instrumentation
- EFun and the SPLICE back half of the system were developed under ColdTech grant
- EFun has a large aperture designed for Enceladus or similar diffuse ice plumes
- The EFun system consists of a large collector cone with a one-time opening cover, sample melt and transfer station, and thermal isolation
- Thermal design keeps the sample cryogenic until it is processed

## STATUS:

- Designs of collector, cover, transfer mechanism and thermal isolation are complete
- Tests of ice collection at the Ames vertical gun show >90% collection efficiency
- An engineering model of the transfer mechanism, the most complex subsystem, has been built and operated
- Quotes for construction of the large collector and remaining subsystems have been received. They were not built to devote funds to the more challenging components
- TRL = 5 for the new technologies, the remaining components just require standard engineering development

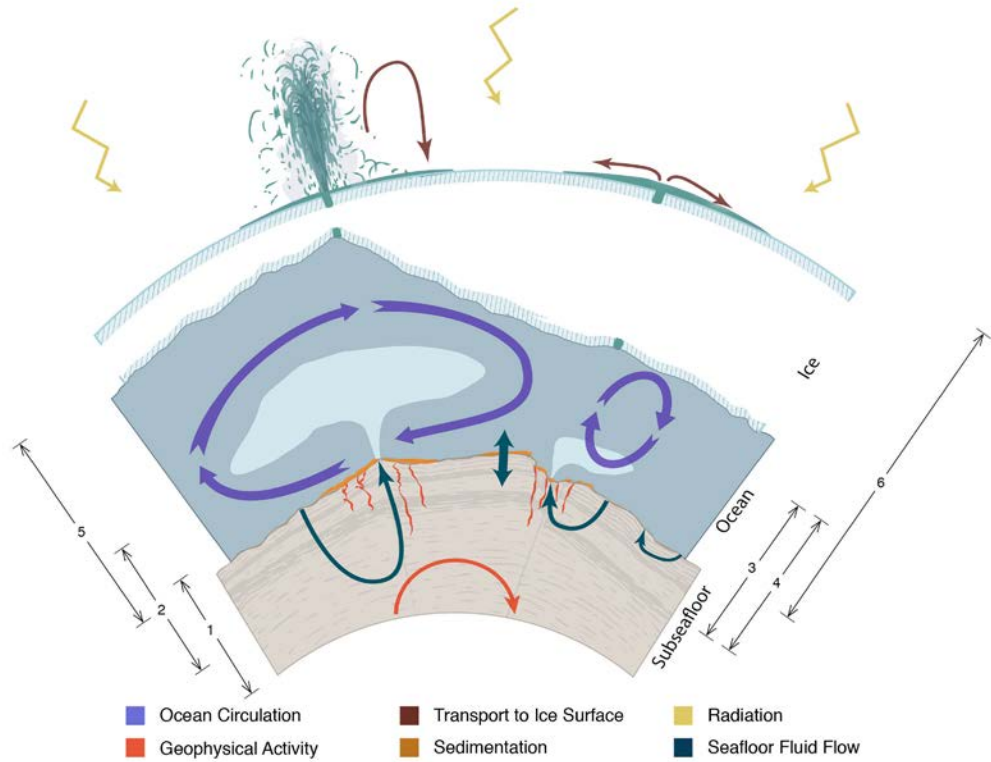


NASA has invested in building expertise through R&A specifically targeting ocean worlds and/or the detection of life.

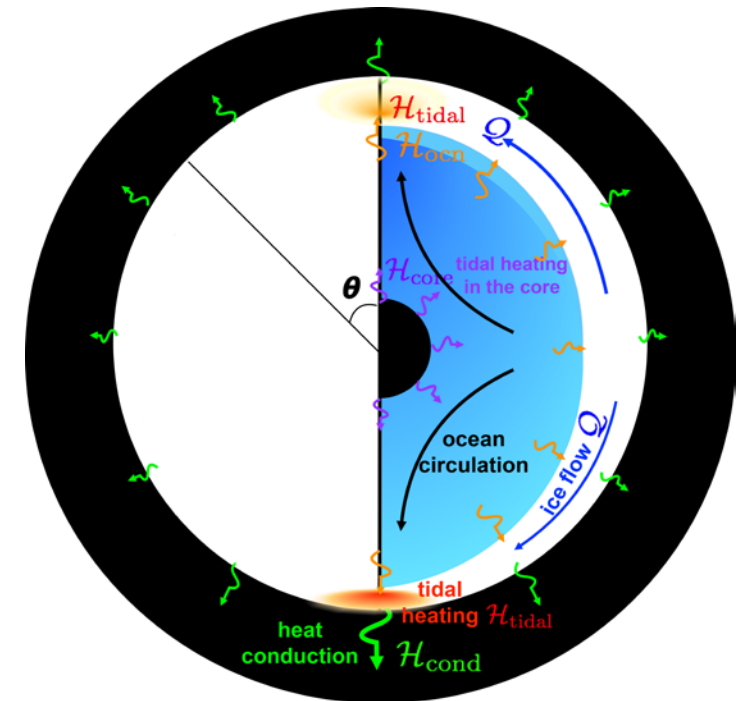
- These community efforts include establishment of **research coordination networks** focused on developing life detection technologies, understanding the pathways of prebiotic chemistry, exploring ocean worlds, and investigating the evolution of cellular life.
- Coordination between projects under these themes is well poised to inform the planning and interpretations of key measurements for life detection.



## Exploring Ocean Worlds: Concept



## Enceladus Circulation: Schematic



John Marshall, Wanying Kang, Suyash Bire (MIT)  
Andreas Thurnherr (LDEO), Christophe Sotin (JPL)





# Conclusion: Ocean Worlds/Enceladus should be included in the NF5 target list

- Doing so not only maximizes the science return for the entire suite of Ocean World missions being implemented, it also is a timely response to the discoveries of *Cassini*.
- It would also be responsive to the direction from the US House Appropriations Committee to create an Ocean World Exploration Program including the use of NASA's New Frontiers Program.
- Scientific momentum to explore Ocean Worlds is growing:
  - the NF4 final selection of *Dragonfly* to Titan,
    - and the two completely independent **Enceladus plume fly-through NF4 mission proposals**, representing 17% of the submittals.
  - the ongoing *Europa Clipper* flagship mission design and build, and
  - post-mission *Cassini* science reports
  - the significant NASA resources funneled to ICEE-2, COLDTech, other programs

# Finally...

- We have confirmed the existence of a habitable ocean beyond Earth.
  - Enceladus' ocean could be host to a separate genesis of life
  - It could be uninhabited or in a prebiotic state
  - Groundbreaking discoveries from any Enceladus mission exploring these possibilities are inevitable
  - Thus, a focused investigation into Enceladus' ocean materials for biological potential is a high priority
- Allowing teams to propose Enceladus missions in the NF5 competition allows **bold but achievable steps forward** for NASA in addressing the search for life in our solar system.



# Ocean Worlds are important destinations

- In May 2015, the US House Appropriations Committee directed NASA to create an Ocean World Exploration Program with the goal “to discover extant life on another world” using a mix of Discovery, New Frontiers and flagship class missions.
- Consistent with this directive and in response to the scientific achievements of *Cassini*, NASA added an Ocean Worlds Mission Theme with Titan and/or Enceladus targets to the New Frontiers 4 (NF4) Announcement of Opportunity (NNH16ZDA011O) released in 2017.
  - The planetary science and astrobiology communities responded with two completely independent **Enceladus plume fly-through mission proposals**, representing 17% of the submittals.
    - This response demonstrates **community interest as well as investment** from several centers and industry partners.
    - One team (ELSAH) received funds to develop techniques to limit spacecraft contamination and thereby enable life detection measurements on cost-capped missions
- Scientific momentum to explore Ocean Worlds is growing:
  - the NF4 final selection of *Dragonfly* to Titan,
  - the ongoing *Europa Clipper* flagship mission design and build, and
  - post-mission *Cassini* science reports



## Distinct Differences between Titan and Enceladus

| Typical Ocean World                                                    | Enceladus | Titan                                                                         |
|------------------------------------------------------------------------|-----------|-------------------------------------------------------------------------------|
| No atmosphere (or tenuous exosphere)                                   | Yes       | No – thick atmosphere of N <sub>2</sub> and CH <sub>4</sub>                   |
| Water-ice shell over global, subsurface liquid water ocean             | Yes       | Yes, but also veneer of organic material (and liquid hydrocarbons) on surface |
| Ocean in contact with rocky core (with possible hydrothermal activity) | Yes       | No – high-pressure ice layer between ocean and rocky interior                 |

Enceladus is much more representative of a typical Ocean World, while Titan represents a particular endmember case. Sending a mission to Titan, while critical to understand this moon, will not address all questions of typical Ocean Worlds.