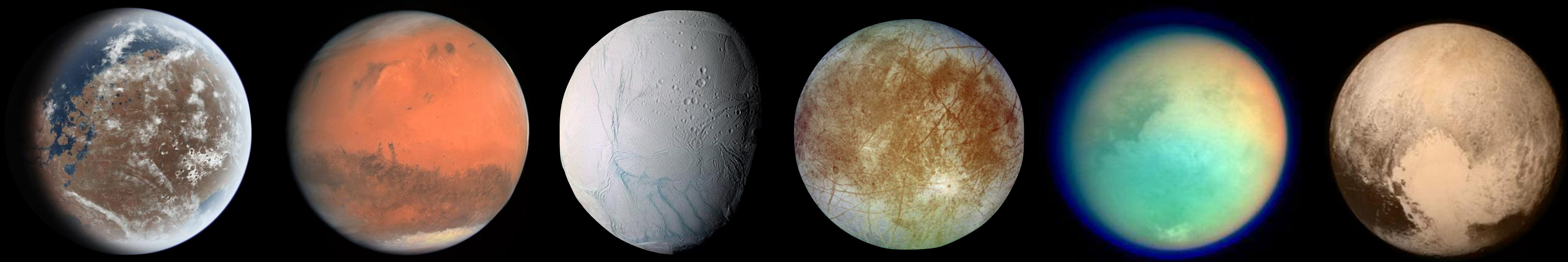
JENNIFER EIGENBRODE
NASA GODDARD SPACE FLIGHT CENTER

LIFE DETECTION



VISION and VOYAGES

Life detection is mention twice

MARS: EVOLUTION OF AN EARTH-LIKE WORLD

With regards to instrument development for the Max-C rover concept, “Examples include isotopic characterization of a variety of biomarkers, identification of organic materials indicative of current or past biological systems, sensitive life-detection experiments, analysis of metastable minerals and organic compounds, and in situ geochronology experiments.” p163 V&V

PLANETARY SCIENCE AND RESEARCH INFRASTRUCTURE

With regards to Restricted Earth Return Samples: “Biohazard assessment (following established protocols for life detection)” p296 V&V

VISION and VOYAGES

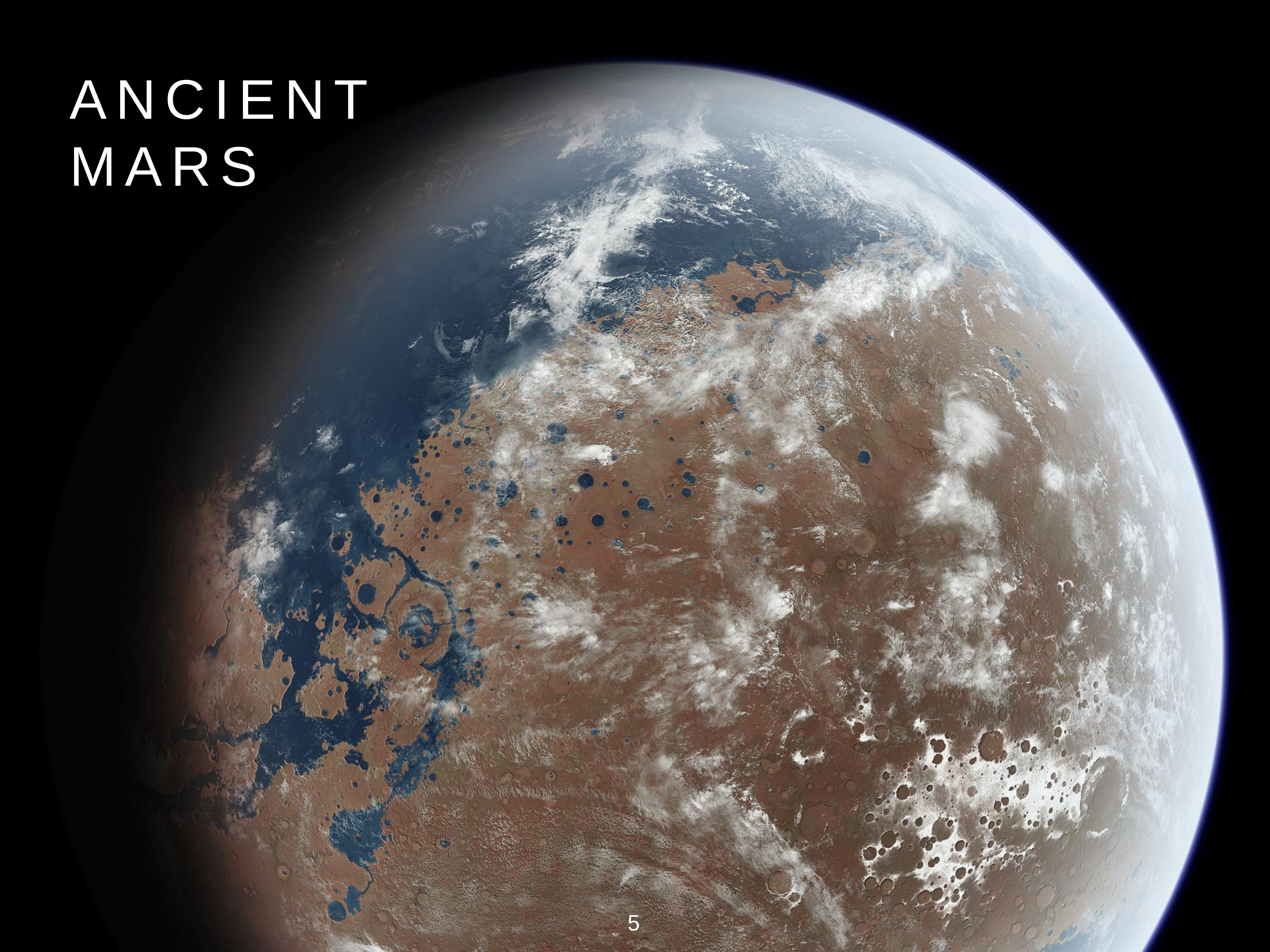
Life is mentioned ~340 times.

"Was the origin of life a unique event
or was it repeated elsewhere in the solar system …?
What conditions are required?
The fundamental question is broader than whether or not life exists or existed on one particular planetary body like Mars, Europa, or elsewhere. Rather, the question is how life came to exist at all."
p70 V&V

Are we prepared to conduct a life detection mission?

YES, BUT…

ANCIENT MARS



ANCIENT MARS

- 2012-2018 MSL Curiosity rover:
  - ancient habitability: Water, CHNOPS, organics, chemical energy sources, sustained aqueous environments at the surface ✓
  - atmospheric methane confirmation ✓
- 2020-2023 Mars2020 rover: Collect, document, and package samples for future collection and return to Earth ✓
- Learn from ESA's 2016 and 2020 ExoMars missions ✓

ANCIENT MARS

- CHALLENGES FOR ANCIENT LIFE DETECTION
  - Preservation of biosignatures, especially in surface radiation environment laden with water and perchlorate
  - What is preserved? How do we access the record? - We might not know until we get samples. Sample return adds flexibility.
  - Mixed sources? meteoritic and igneous additions may complicate interpretations of ancient biologically derived molecules
  - Contamination

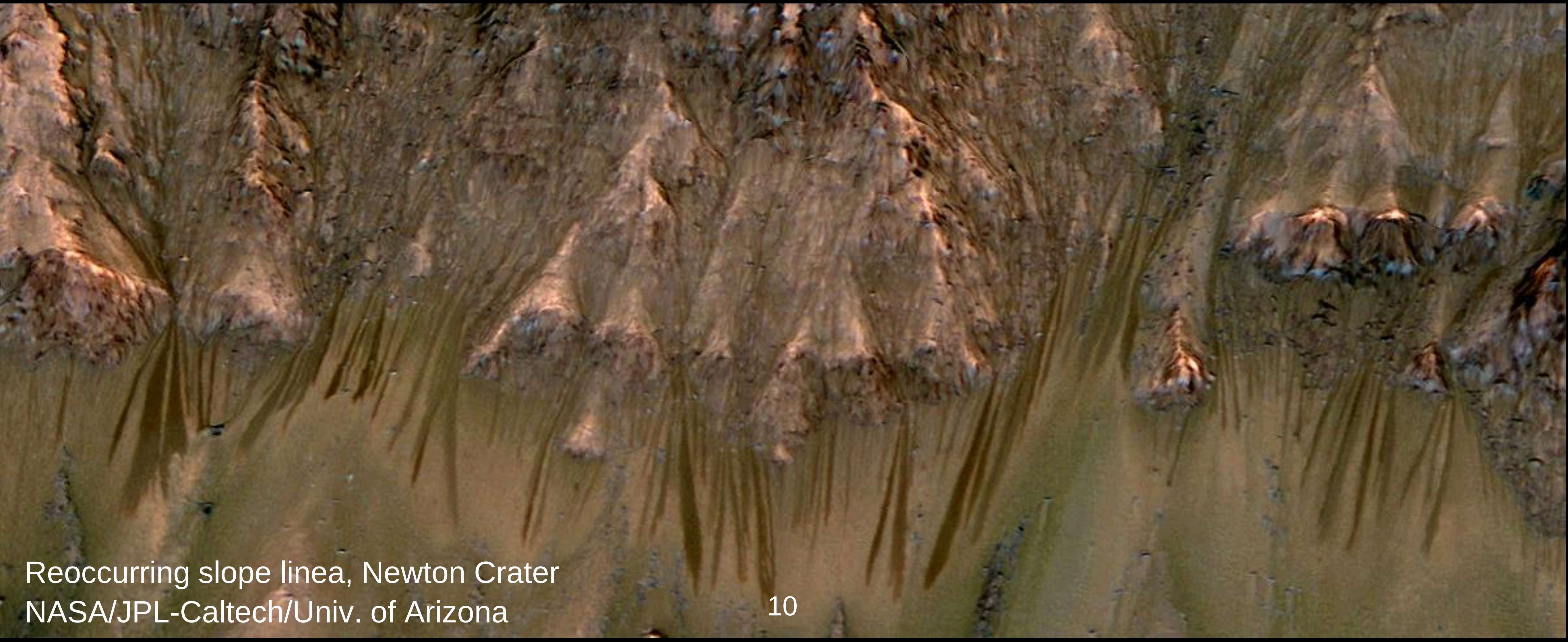
ANCIENT MARS

- NEXT STEP
    - Prepare for possible sample return

MODERN MARS

MODERN MARS

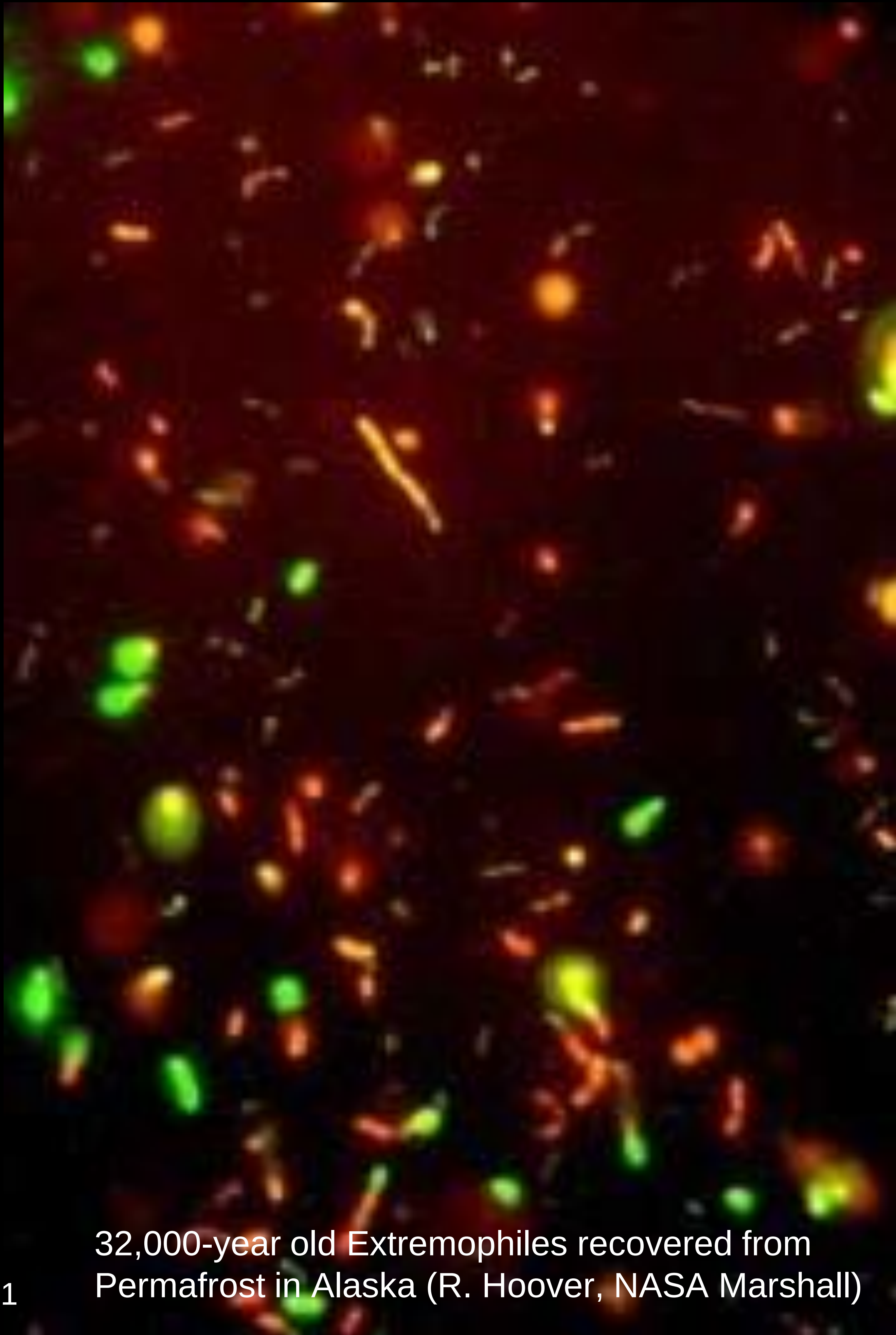
- Mars is an active place. Seasonal groundwater seeping at surface.
- Refugia in the subsurface? During high obliquity, ground water activity more prevalent
- Abode for life in caves?



Reoccurring slope linea, Newton Crater
NASA/JPL-Caltech/Univ. of Arizona

MODERN MARS

- Productivity of life in the wet subsurface may be limited to times of warmer climate
- Freezing may actually preserve viable life as it does in the Earth's permafrost



32,000-year old Extremophiles recovered from Permafrost in Alaska (R. Hoover, NASA Marshall)

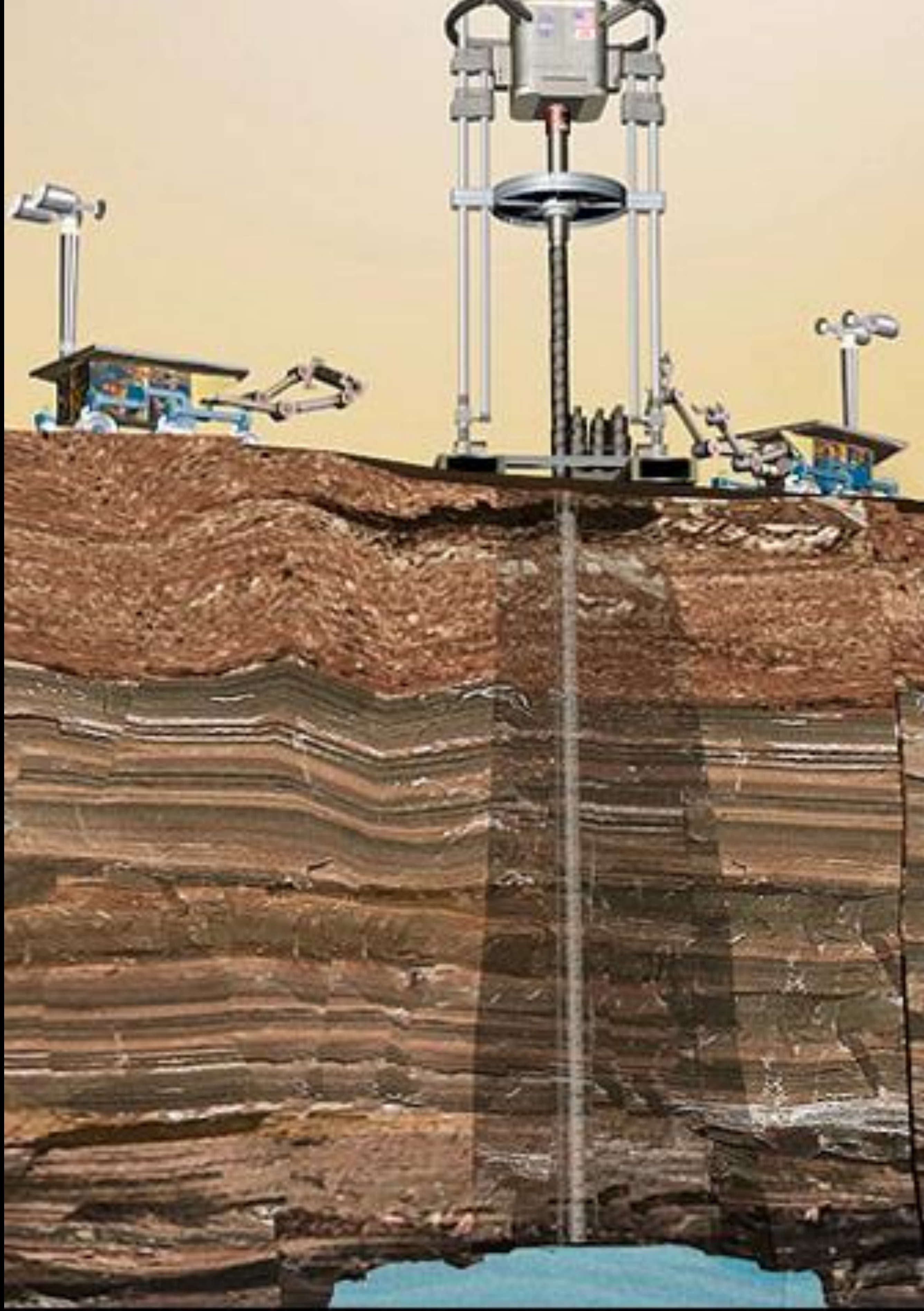
MODERN MARS

CHALLENGES FOR MODERN LIFE DETECTION

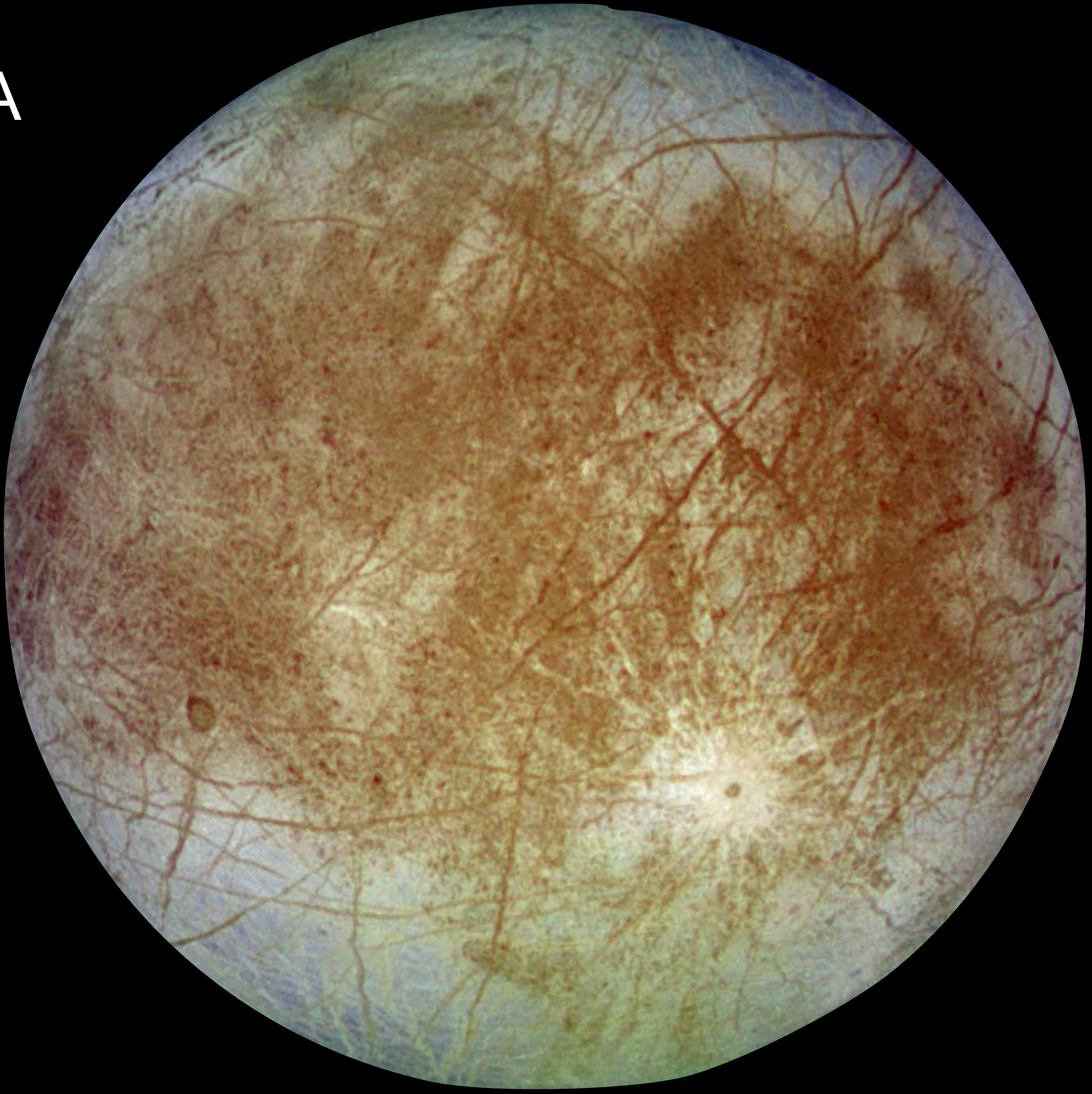
- Finding and accessing water or ice below the most intense radiation zone (2-3 m or deeper)
- Expect low signal concentrations in fluids and particles
- Mixed sources
- Low signals, heterogeneity
- Contamination

NEXT STEP

- Map accessible water to locate mission targets
- Plan and conduct life detection investigation



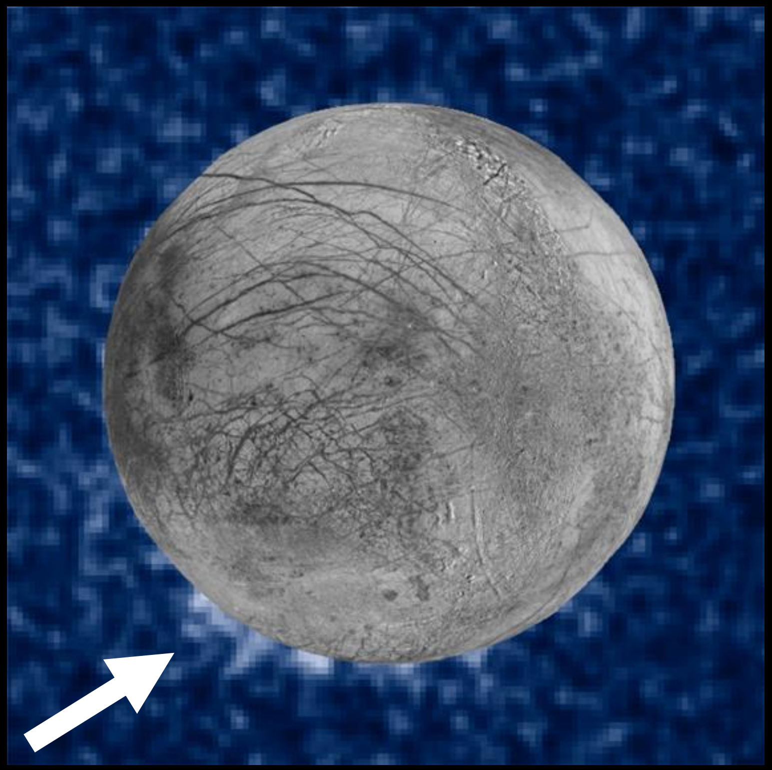
EUROPA

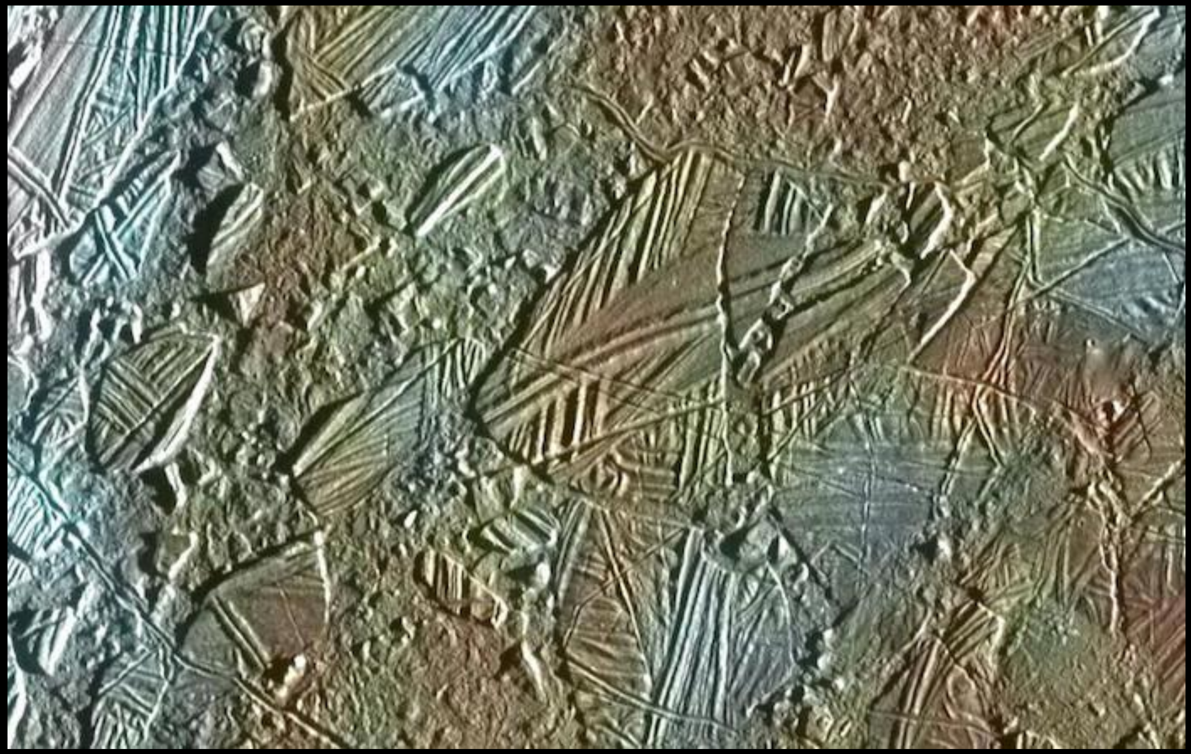


EUROPA

- DISCOVERY: Hubble UV observations of Europa suggest possible plumes - corroborating presence of a subsurface ocean
- Surface terrain varies widely. Suggests active processing and communication with ocean.

“Candidate plumes” of Europa (as of 2017)





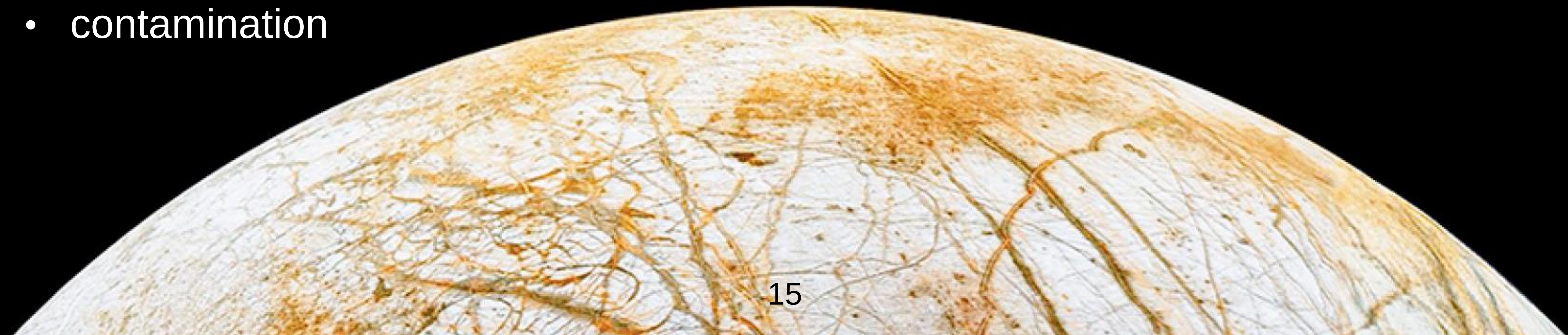
EUROPA

CHALLENGES FOR LIFE DETECTION

- Ocean is not directly accessible (plumes not confirmed yet)
- Timing and nature of ice-ocean processing unclear (ice source? age? reprocessing?)
- Surface gardening by Io dust - complicates interpretations of ocean record deposited at surface
- Surface weather triggered by jovian magnetic belt electrons/ions and <u>GCR</u> radiation - preservation of an ocean-derived chemical record uncertain. (Organic biosignatures buried within 1 meter of the surface would last only 1 to 2 million years – Teodoro et al., 2016, LPSC Abstract 2601)

—> Will measurements support interpretations of ocean habitability and possible life?

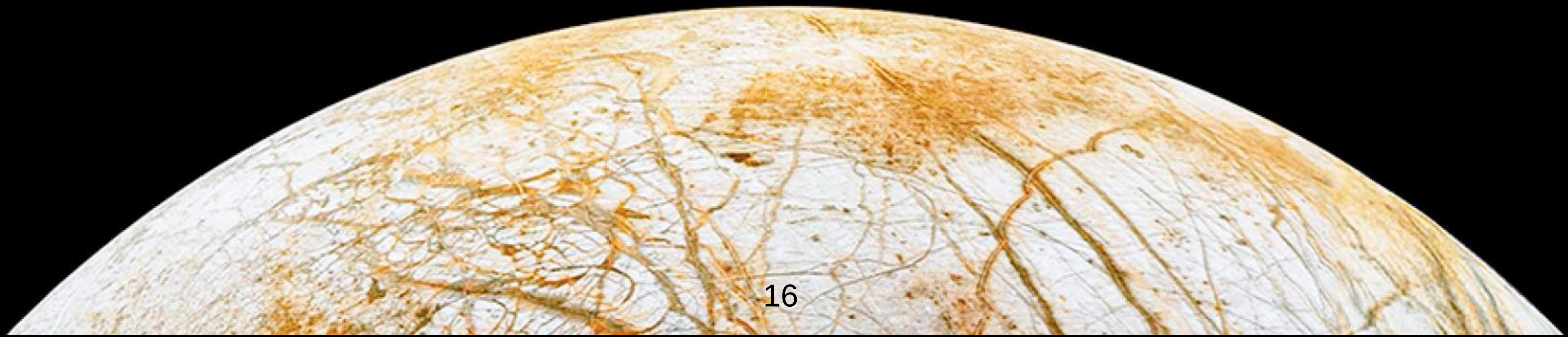
- low signals, heterogeneity
- contamination



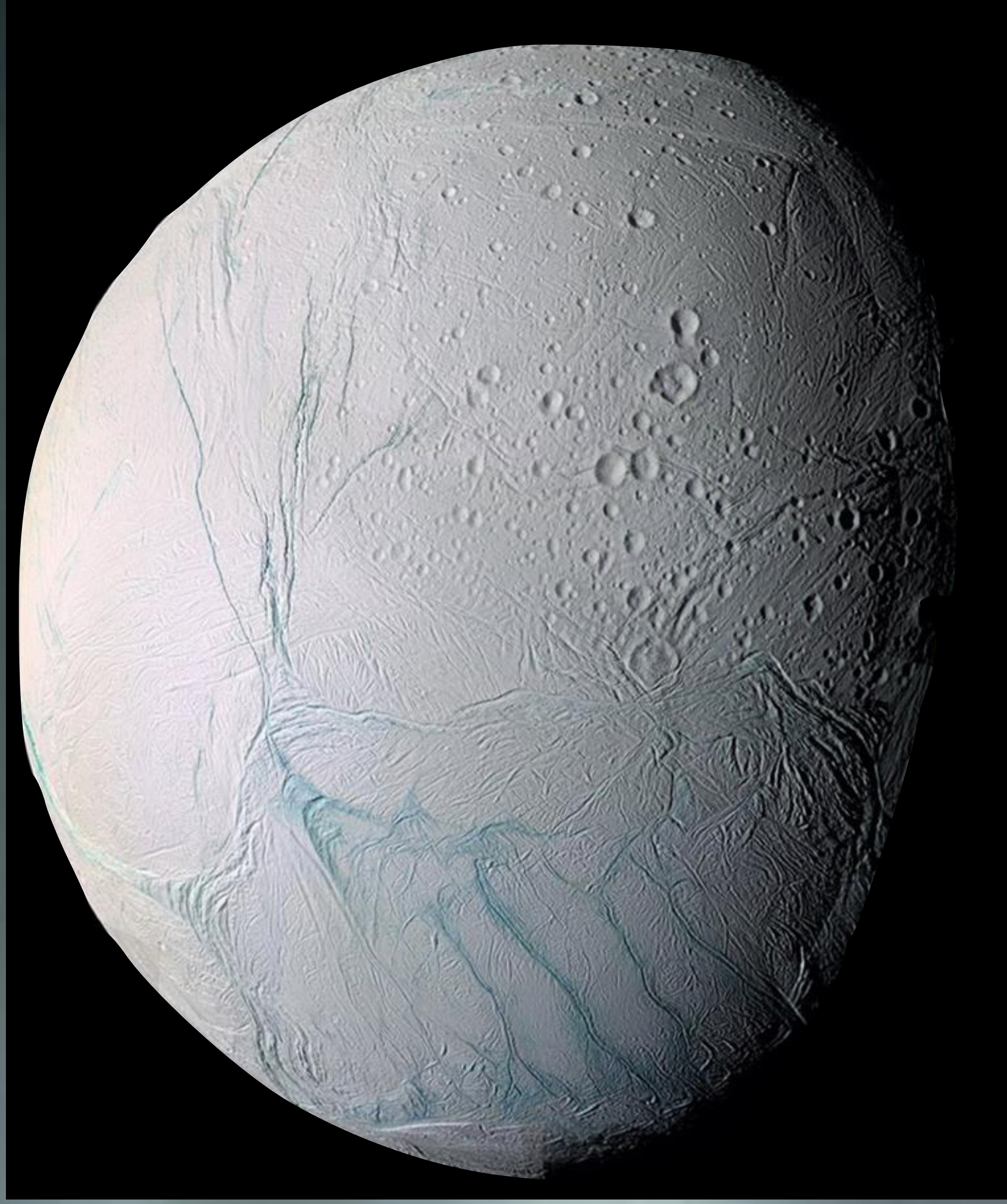
EUROPA

NEXT STEP

- Europa Clipper - establish a better understanding of the ice-ocean processing and general chemistry. Confirm the presence and consistency of plumes!!! ✓
- A lander would provide key chemical and physical context for understanding surface processes, enabling a better understanding of the Europan system (consistent with V&V).



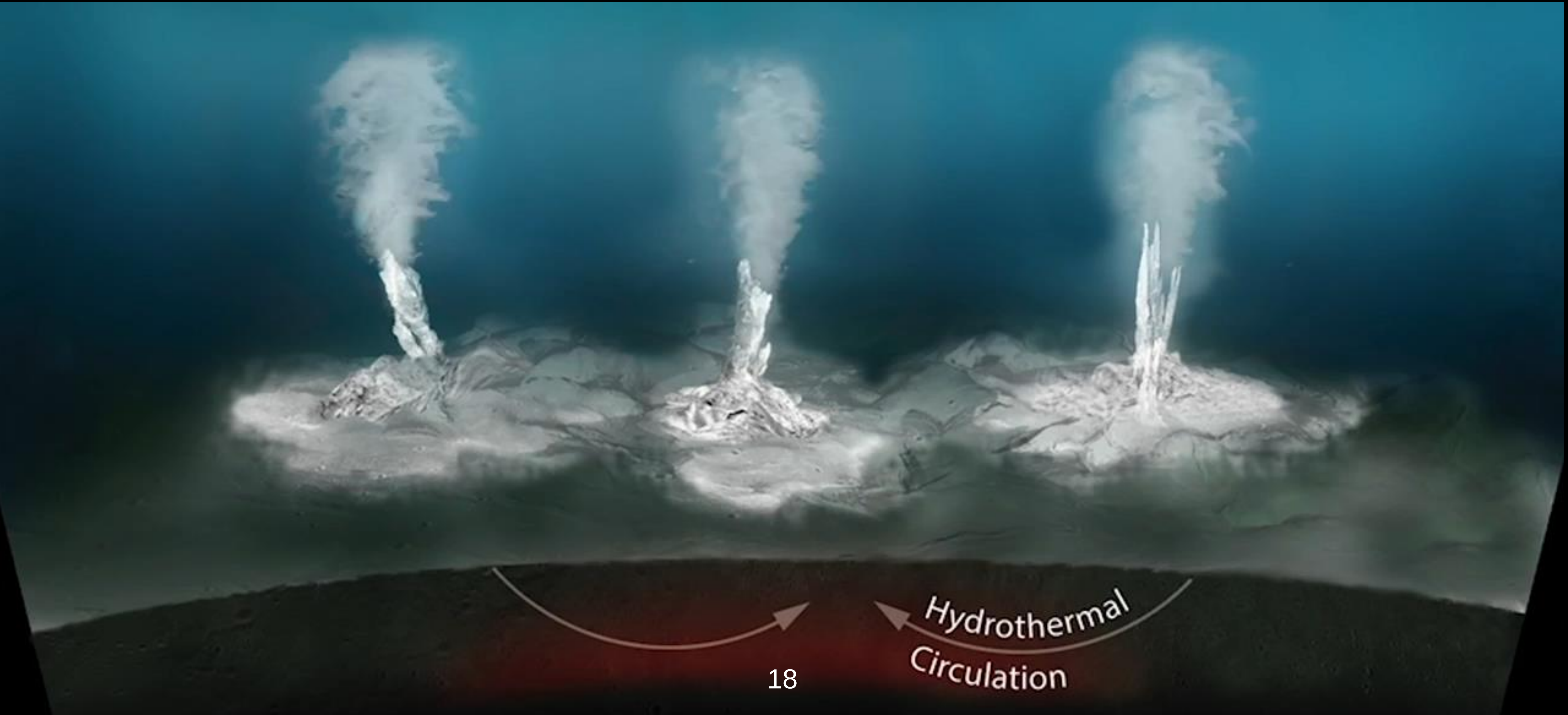
ENCELADUS



- Cassini explored Enceladus from 2005-2015
- DISCOVERIES: Confirmed that the Enceladus ocean has the key ingredients needed for life

ENCELADUS

- Cassini data interpretations (H_2, SiO_2-nanoparticles, pH) support a hydrothermal scenario for the rock-water contact



ENCELADUS

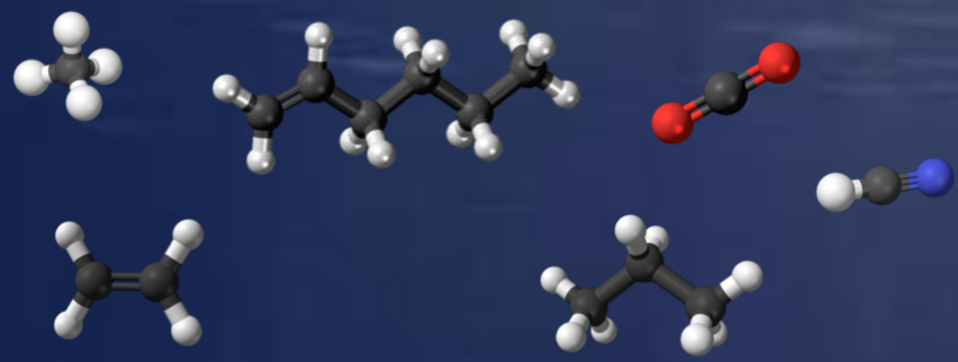
CHALLENGES TO LIFE DETECTION

- sample size
- low signals
- high velocity impact at collection
- heterogeneity within plume
- contamination

ENCELADUS

NEXT STEP

- An Enceladus multiple flyby mission designed to sample the plume and look for signs of life, fill in missing details of the ocean habitability, and explore the ice-ocean connection.



H_2

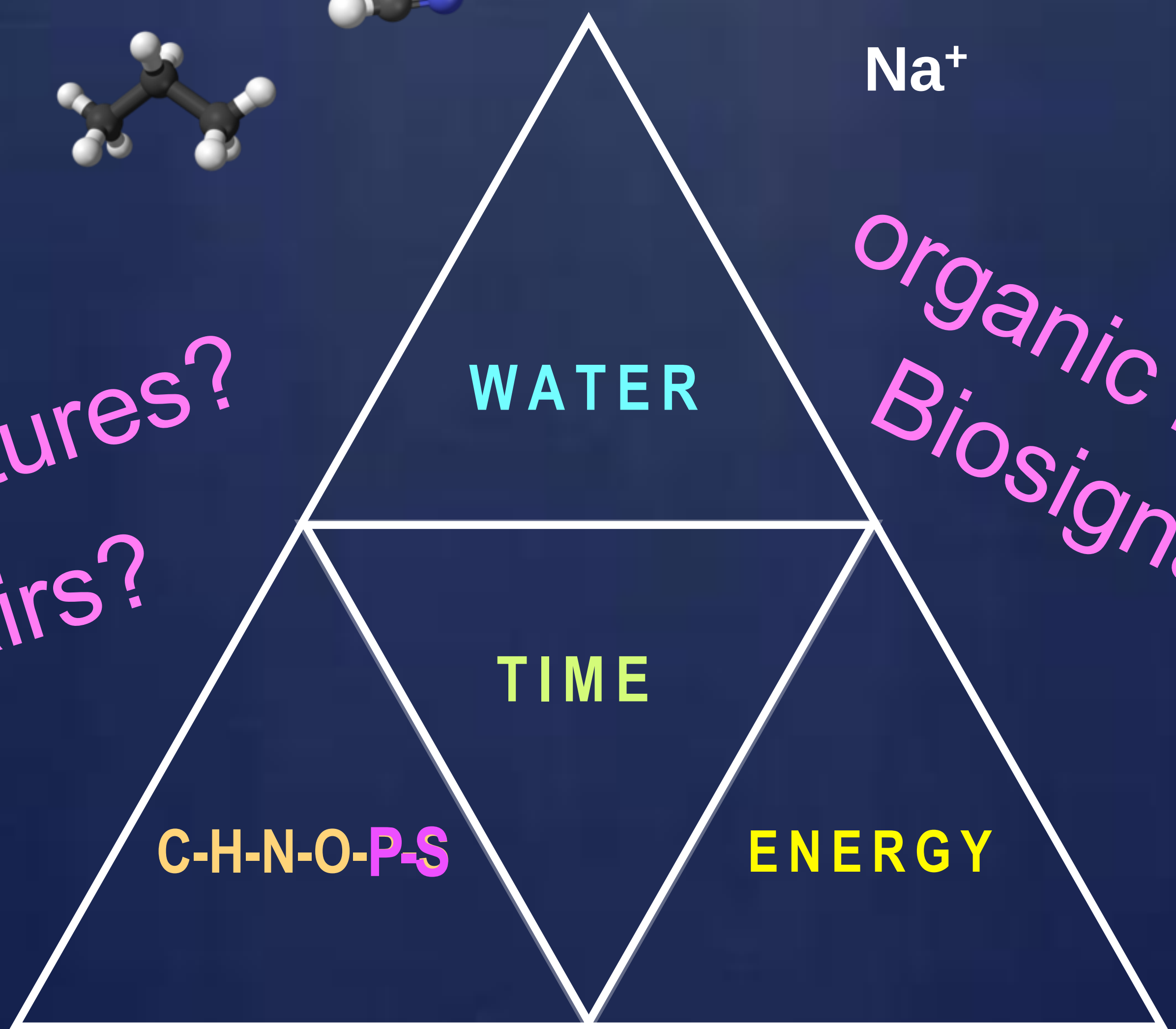
K^+

Na^+

SiO_2

Biosignatures?

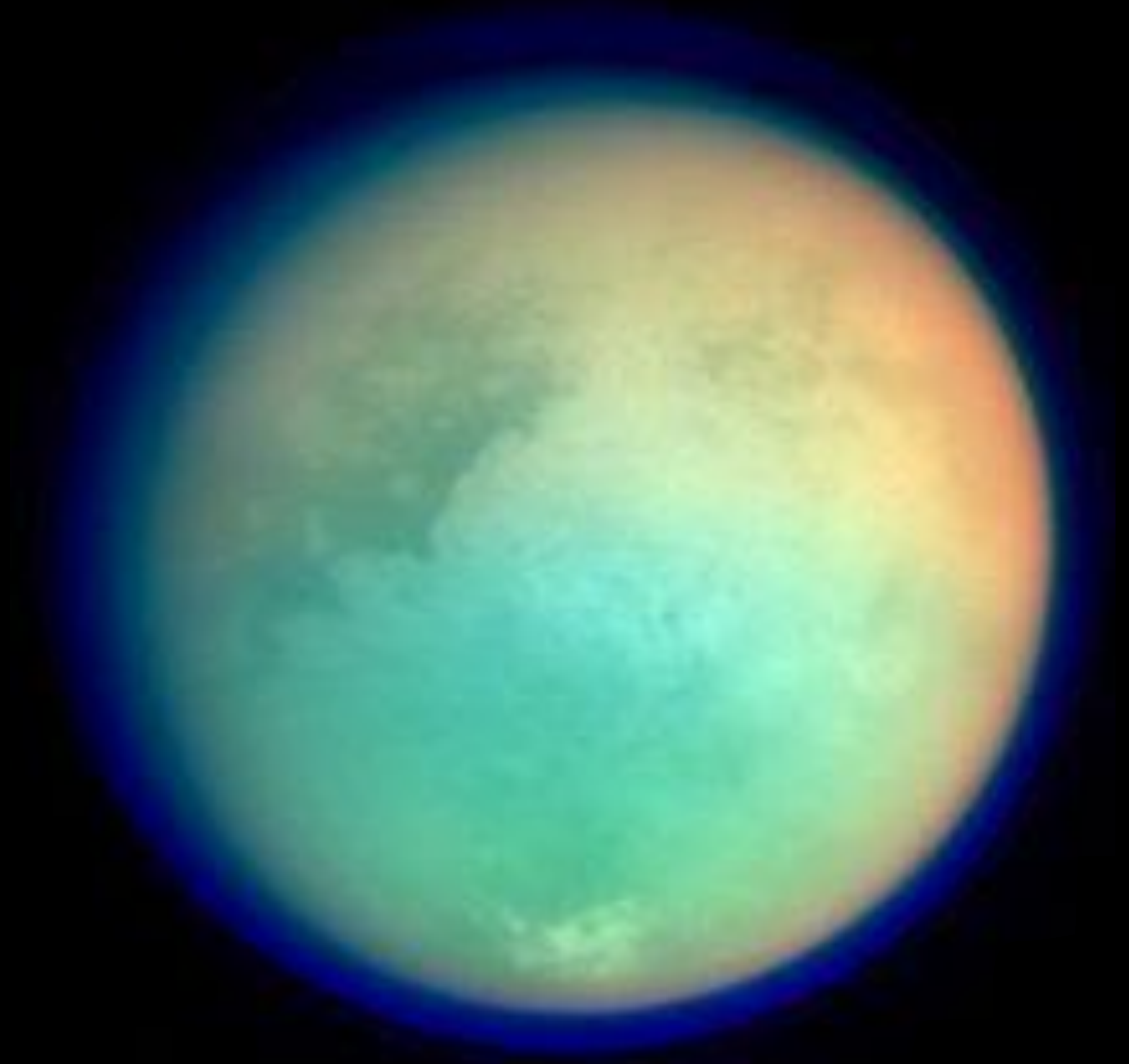
redox pairs?



organic molecules?

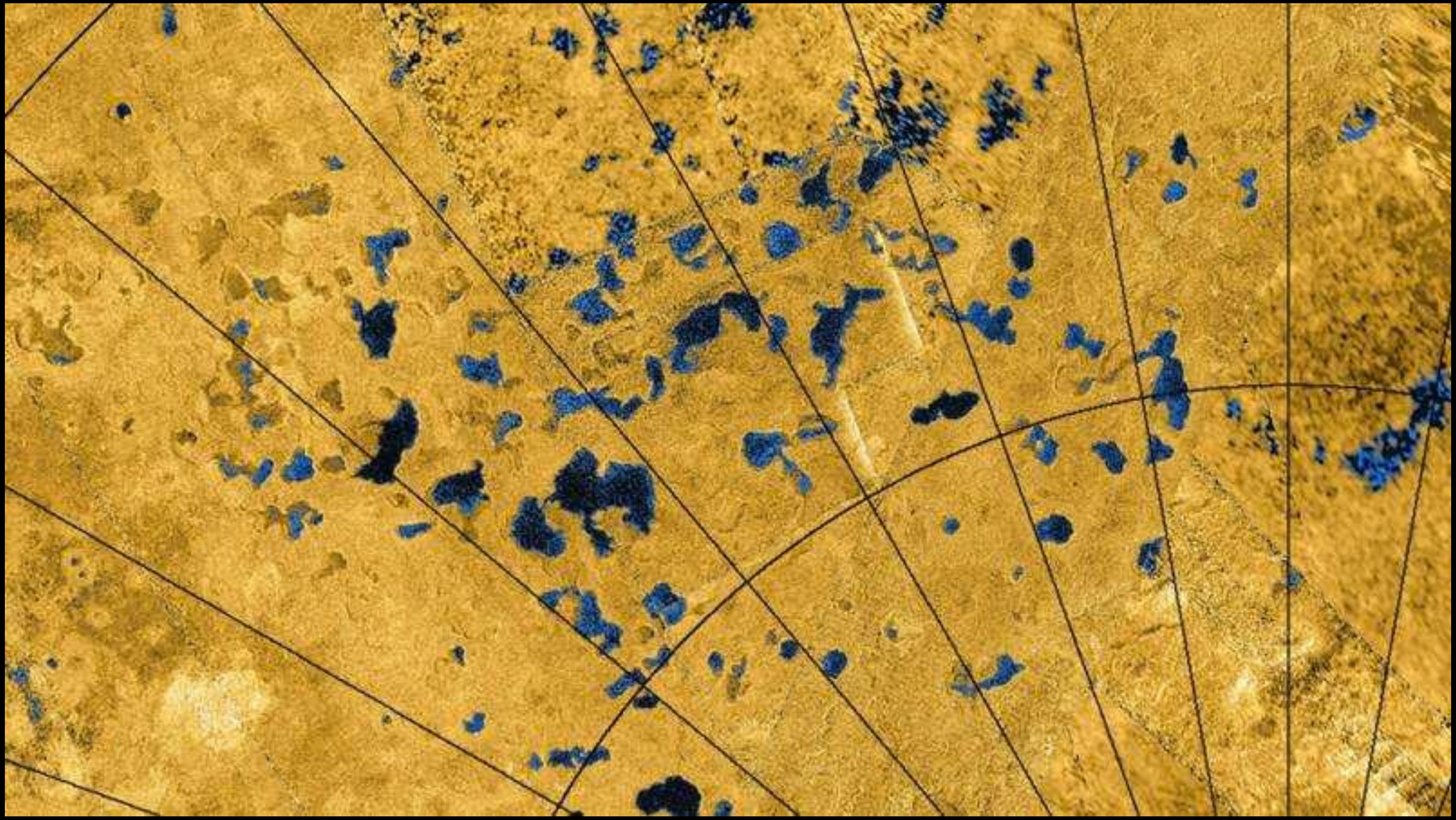
Biosignatures?

TITAN



TITAN

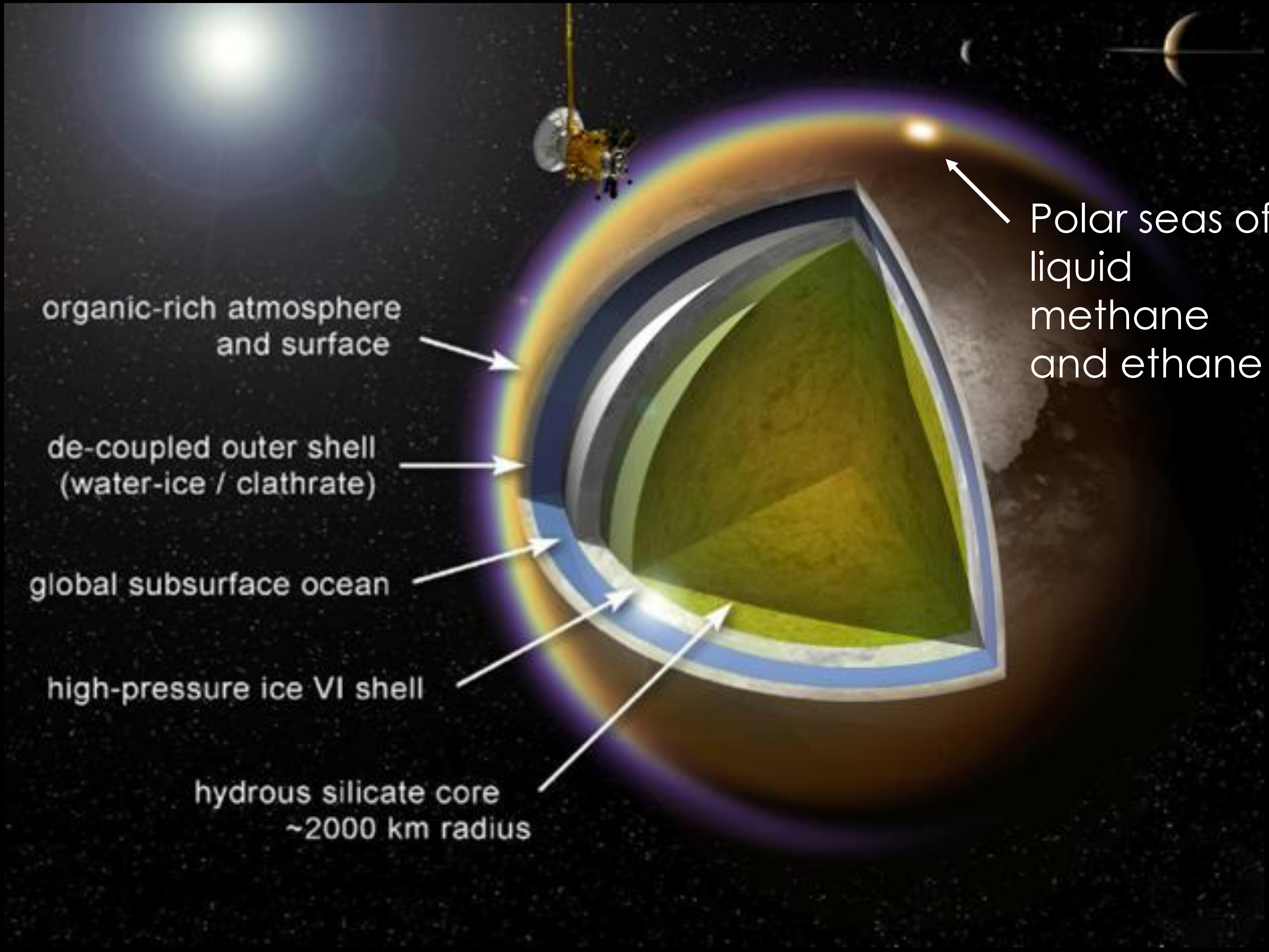
- DISCOVERIES: Cassini observations constrain compositions and their diversity at the surface (e.g. hydrocarbons, water ice)



Radar images from NASA’s Cassini spacecraft reveal many lakes on Titan’s surface, some filled with liquid hydrocarbons, and some appearing as empty depressions. Credit: NASA/JPL-Caltech/ASI/USGS

TITAN

- Hypothesis: A world of two oceans
- What are the habitable environments of Titan? Does life inhabit the ocean? Does weird-life inhabit the hydrocarbon media of the surface?



TITAN

- CHALLENGES TO LIFE DETECTION
  - too cold at surface for Earth-like life
  - thick aerosol atmosphere masks the surface
  - heterogeneity
  - large environmental background signal for organics
  - contamination

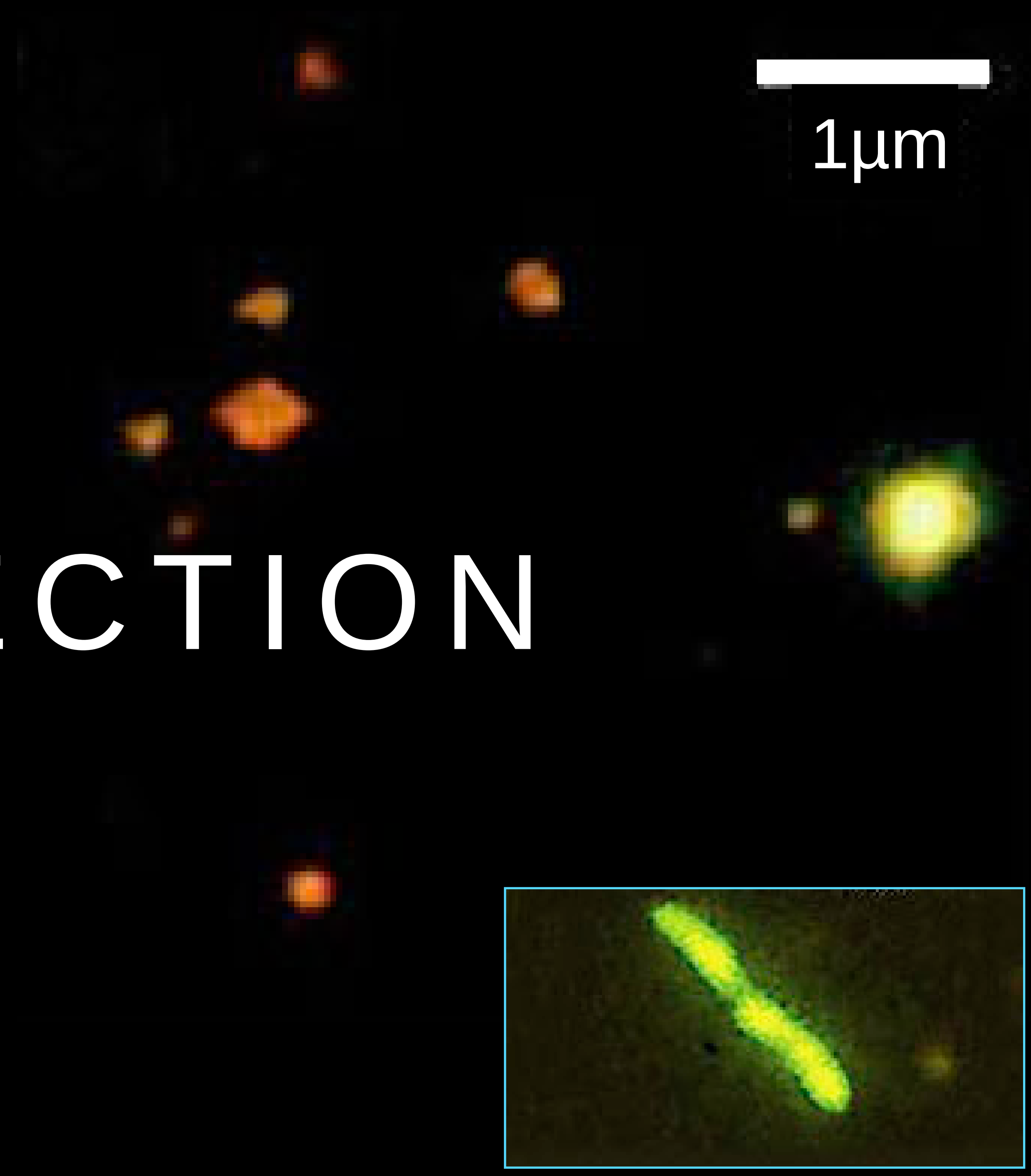
- NEXT STEP
  - Mobile surface mission to explore different environments and sample for prebiotic to early biotic (?) chemistry

PLUTO

- New Horizons observations indicate crater fill with nitrogen ice.
- Debate on whether a water/ammonia ocean is required to explain this feature.
- IF there is an ocean, could life live in it?

NEXT STEP ???

LIFE DETECTION SCIENCE



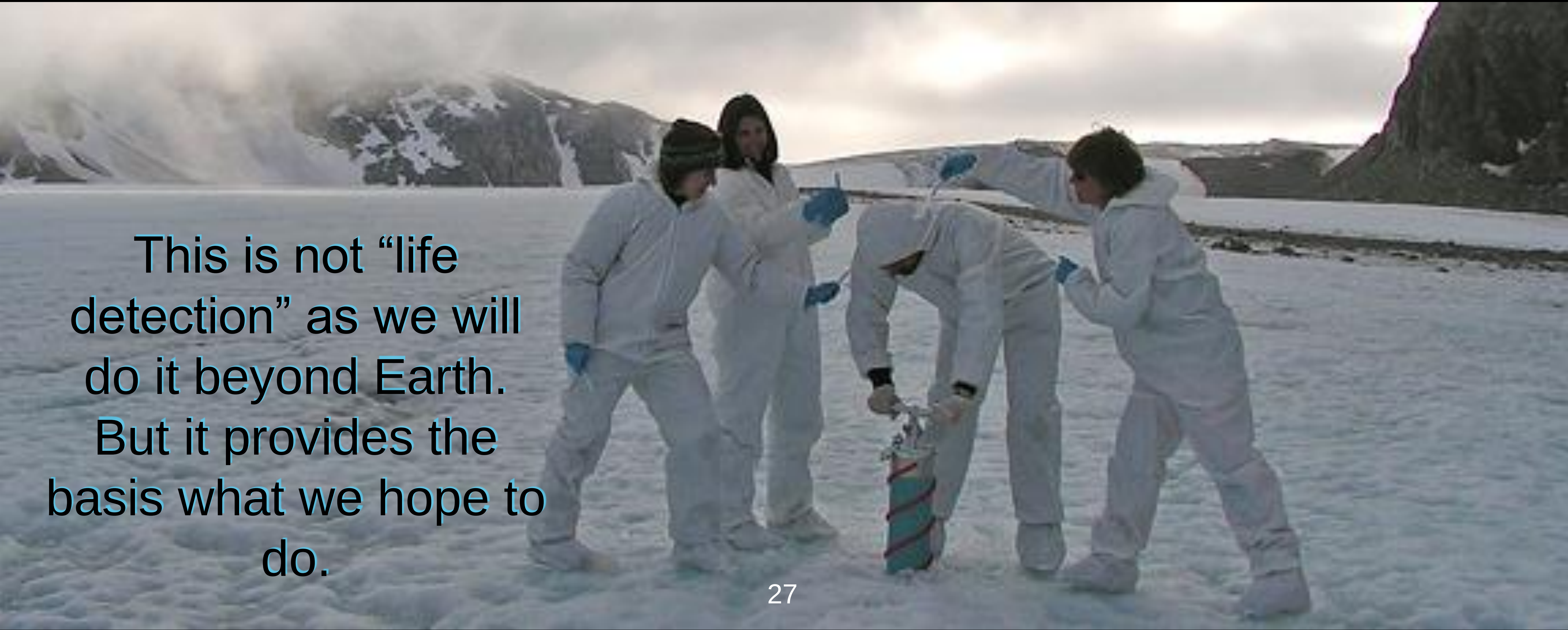
Microscopic images of bacteria found in melt samples of accreted ice, Lake Vostok, Antarctica

https://www.nsf.gov/discoveries/disc_images.jsp?cntn_id=100705&org=NSF

Credit: David M. Karl et al, University of Hawaii

HOW DO WE STUDY EXTREMOPHILES ON EARTH?

- Environmental sampling – physical and chemical context
- Biogeochemical analysis – What is life doing? What is life made of? What is it living in?
- Genomics – Who is there?
- Microscopy – What does life look like? What is it doing? Diversity? Size? Dead or alive?
- Integrative study – What is the system-level ecology?



This is not “life detection” as we will do it beyond Earth. But it provides the basis what we hope to do.

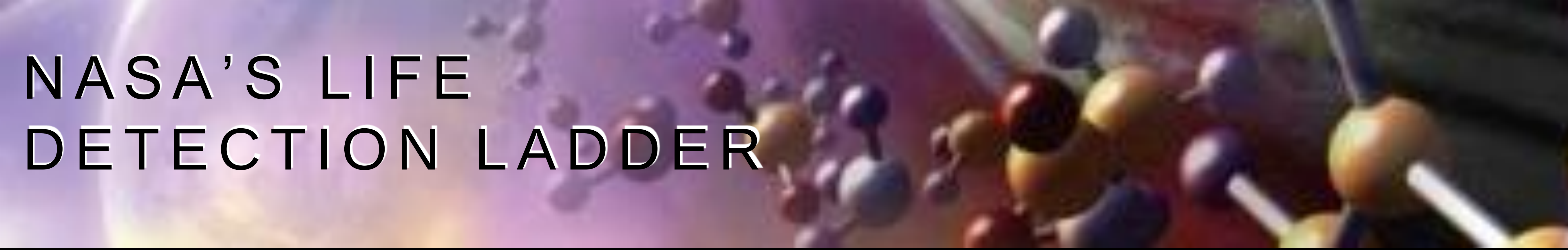
LIFE DETECTION QUESTIONS

1. Is or has life been present? Yes or no.
2. Is it Earth-like?
3. What is it doing?

LIFE DETECTION SCIENCE

- Biosignature = a measurement result interpreted as indicative of the current or past presence of life
- Ambiguity in interpretations —> “possible biosignatures”
- Confidence level in interpretation will vary case by case based on data type, quality, and context
- NASA’s Life Detection Ladder

NASA'S LIFE DETECTION LADDER



Ladder Ru	Feature	Measurement	Instrument	Target	Likelihood	Specific to Earth Lif Potential for Generi	Ambiguity of Featu	Ambiguity of Interpretation (how likely produced abotically?)	False Positive	False Negative	Detectability
Life (metabolism, growth, reproduction)											
Darwinian Evolution	changes in heritable traits in response to selective pressures	not possible			no	~	~		~		~
Growth and Reproduction	concurrent life stages or identifiable reproductive form [growth and reproduction]	cell(like?) structures in multiple stages	microscope	plume sample	low	Earth	What is a cell? What morphological differences exist?	low	high (not really a cell)	high (don't recognize stages, timing off, sample size low)	hard
Metabolism	isotopes	isotopes indicative of active metabolism	irMS	plume sample	low/med	Earth (can you abstract?)	source, sink, context	low	high	low	easy
	co-located reductant and oxidant (e.g. persistant H_2 +/- CH_4 v. O_2, nitrate, Fe^{3+}, CO_2) [Inferred Persistence]	chemical concentrations of substrates and products involved in redox reactions	spectroscopy	remote detection	med/high	Generic	mixed reactions, large inventory of chemistries	low-med	low-med	med-high	hard (linked to specificity of instrument)
Suspicious biomaterials [not necessarily biogenic]											
Functional Molecules	DNA	material produced by extraterrestrial life	spectrographic, immunoassay, PCR, hi-prec MS	plume sample	low	Earth	None	Negligible	high (contamination)	high (technology limited, only terran)	hard (linked to specificity of instrument)
	RNA	material produced by extraterrestrial life	spectrographic, immunoassay, PCR, hi-prec MS	plume sample	low	Earth	None	Negligible	low (RNA reactive, contamination possibility low)	high (technology limited, only terran) highly reactive	hard to measure on earth,
	pigments	material produced by extraterrestrial life	Spectrometer	plume sample	low/med	Earth (can you abstract?)	How to define if it is not the ones we know?	very low	low	high (limitation of what we are looking for)	easy (fluorescence)
	structural preferences in organic molecules (non random and enhancing function)	evidence of non random chemistries (such as specific biochemical pathways)	LCMS	plume sample	low/med	Earth	How much of preference is needed to detect?	medium	low	high	hard, need a lot of material and overprinting must be discernable
Potential Biomolecule Components	complex organics (peptides, PAH, nucleic acids, hopanes)	increasing complexity of potential biomolecules	LCMS	plume sample	med	Generic	abiotic production known	medium	low	low	easy if enough material
	amino acids (e.g. glycine, alanine)	material produced by extraterrestrial life	GCMS	plume sample	high	Generic	abiotic production known (glycine not required)	medium	low	low (if only looking for glycine false negative high)	easy, if enough material
	lipids (fatty acids, esters, carboxylic acids)	material produced by extraterrestrial life	GCMS	plume sample	med/high	Generic	known abiotic pathways to some products	med-high	high (contamination)	low	limit of detection, need a lot of material
General indicators	distribution of metals (e.g. vanadium in oil reserves or others like Fe, Ni, Mo/W, Co, S, Se, P)	deviation from background bulk concentrations (Preferences)	XRF	plume sample	med	Generic	knowledge of background	medium	low	high	easy except background issue
	patterns of complexity (organics)	deviation from random organic complexity distribution	LCMS	plume sample	high	Generic	documentation of differences between abiotic and biotic limited	medium	low	high	background issue, material limited
	chirality	material produced by extraterrestrial life	LC-MS/MS	plume sample	high	Generic	How much of an excess is necessary?	high	low	low	mixed sample both processes present
Habitability											
	water, presence of building blocks for use, energy source, gradients	environments conducive to habitability	Redox/T/pH/energy/disequilibria		high	Generic	None	high	low	med	easy for some measurements, hard for others

S I G N A L S

Biosignatures of Extant Life on Ocean Worlds Workshop
Sept 2016, NASA GSFC

- **Evidence or organism**
  - "Cells" (alive, dead, fossil, containment structures, partial membranes, aggregates)
      - High-resolution morphology
      - Cell activity: biochemical activity, mobility, reproduction, response to stimuli under microscope (i.e. with stains)
      - Chemical information directly associated with cell morphology
      - (e.g., labeling with a biomolecule-specific stain, or native fluorescence in a specific wavelength range)

- Potential Biomolecules (informational, functional, structural)
  - Cellular biomolecules (lipids, proteins, etc.)
    - Unstable molecules that might not exist without life
    - (e.g., biomolecules involved in electron transfer or other energy function)
    - DNA/RNA, informational polymers
    - Pigments/anti-oxidants
    - Extracellular polysaccharides ("Europa snot")
  - Molecular selectivity: distributions, patterns, and anomalous abundances (aka "over-represented")
    - Limited fatty acid (or other lipid) molecular weight distribution
      - Patterning within fatty acid (or other lipid) distribution
      - (e.g. terrestrial odd over even predominance)
    - Limited pool of amino acids (out of 70 expected possibilities)
      - Enantiomer excess (aka chirality)
    - Functional group distribution
    - Compound specific isotopic signatures
  - Complex organic molecules (e.g. peptides, proteins) – identification of complexity,
  - not the actual structure

- **Chemical disequilibrium at local scale environment – context signal, not a biosignature**
  - Possible metabolic signatures (e.g., co-located redox couples)

- Macroscale Biofabrics (particularly biofilms)
  - cell aggregates

Other
- Enrichments/depletions of transition metals
- Isotopic abundances
- Biominerals
- Gradients in the distribution of all of the above
- Chemoluminescence

Context/Habitability measurements:
- Chemical disequilibrium
- Trace gases
- Organic matter

LIFE DETECTION SCIENCE

- 1-3 positive detections for possible biosignatures does not necessarily indicate presence of life
- Integrative measurement sets are more powerful in terms of interpretation strength and establishing confidence (e.g., amino acid ratios + chirality; lipid distributions + patterns; cell structures + activity)
- Podium test

LIFE DETECTION SCIENCE

Life detection measurements require science consideration of:

1. signal
2. noise
3. factors that impede specific approaches

NOISE

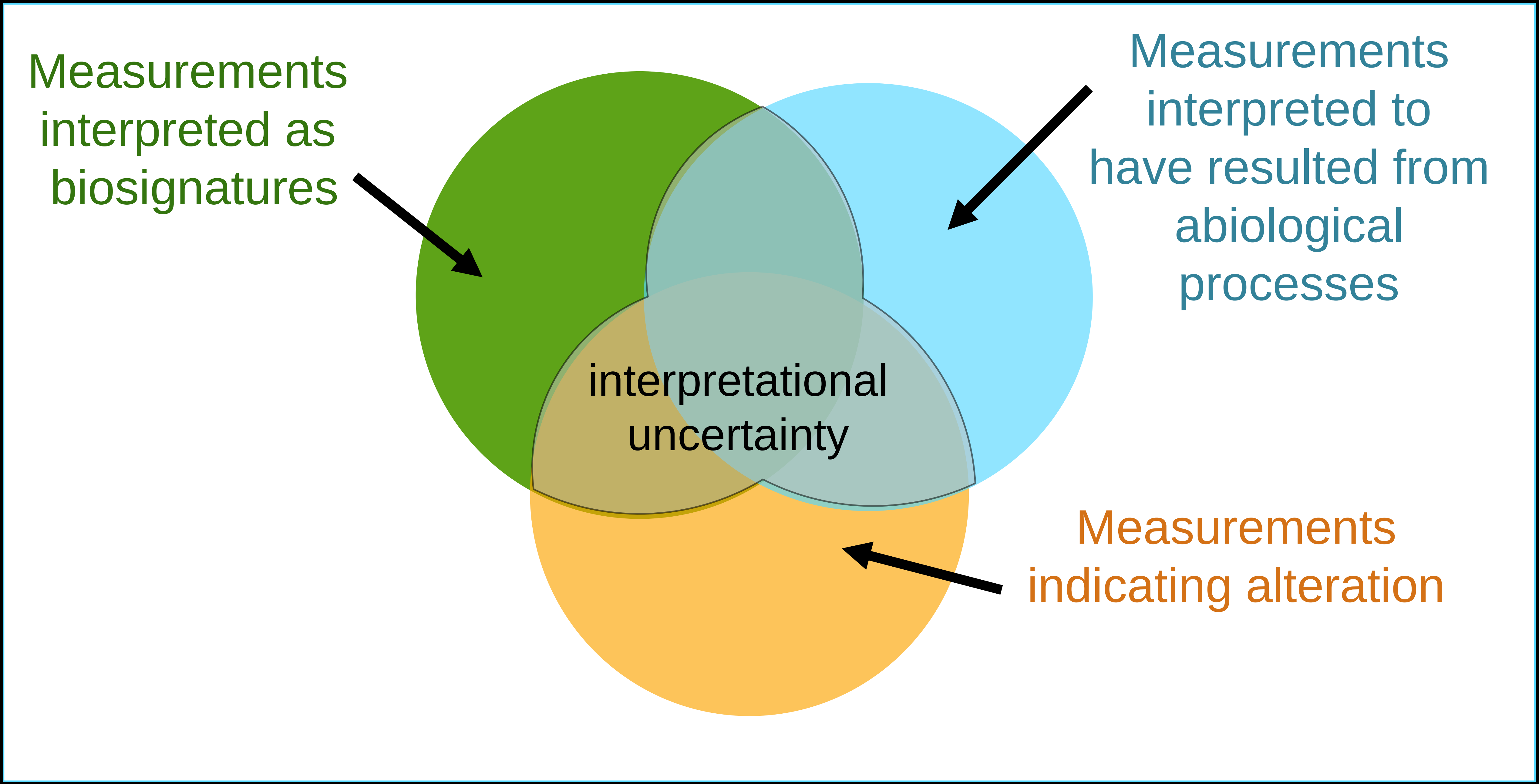
Biosignatures of Extant Life on Ocean Worlds Workshop
Sept 2016, NASA GSFC

Types of noise:

1. What you bring with you
2. How what you bring with you reacts
3. Analytical artifacts
4. Abiotic and alteration processes that can fool us or challenge interpretations

Abiotic lipid micelle or lipospheres.
Optical microscopic images of solid lipid microspheres.
Sareen et al. 2015

GOOD DATA - SIGNAL VS NOISE



OVERCOMING NOISE

- Need multiple lines of evidence/techniques (different signal and different noise levels, independence). Signals should be additive or multiplicative. The noise should not be.
- Statistical Power
- Look for populations within distributions
- Need environmental background measurements and context
- Wide analytical dynamic range and sample volume adjustment/ condensing processing
- Establish instrument background after preconditioning and before first sample analysis
- The list goes on….

FACTORS THAT IMPEDE SPECIFIC APPROACHES

- Biosignatures out of their context could be interpreted as noise
- Background from planetary body—e.g., unexpected chemistry
- Instrument Level Noise – inherent to the instrument or induced by flight or environment
- In situ concentration of target feature may not match optimal analytical range
- Sample preparation and handling
- Spacecraft contamination transfer
- The list goes on….

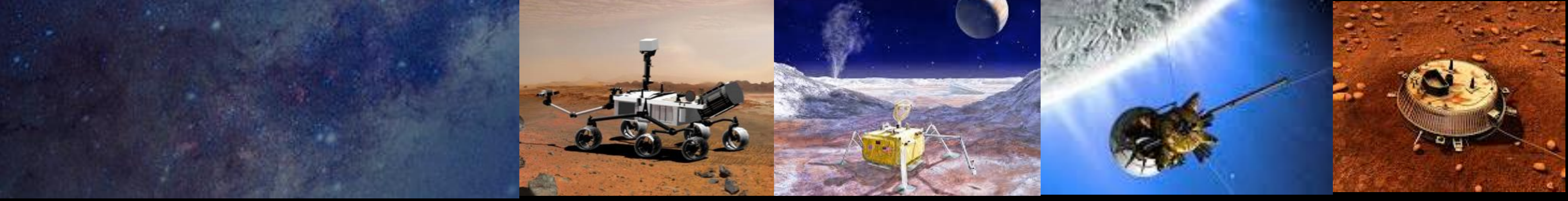
LIFE DETECTION SCIENCE

Life detection missions demand a strategy.

It must be optimized to each destination, each environment, in order to reduce risks and increase our chances of successfully answering the question:

Is there evidence of life?

- Science measurements of signal and noise
- Interpretational strategy for life detection and confidence level
- Technologies
- Operations

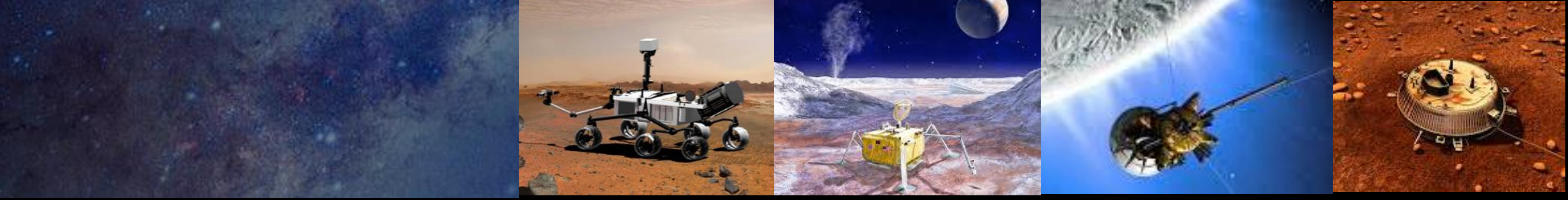


TECHNOLOGIES FOR LIFE DETECTION

Instruments that measure for possible biosignatures

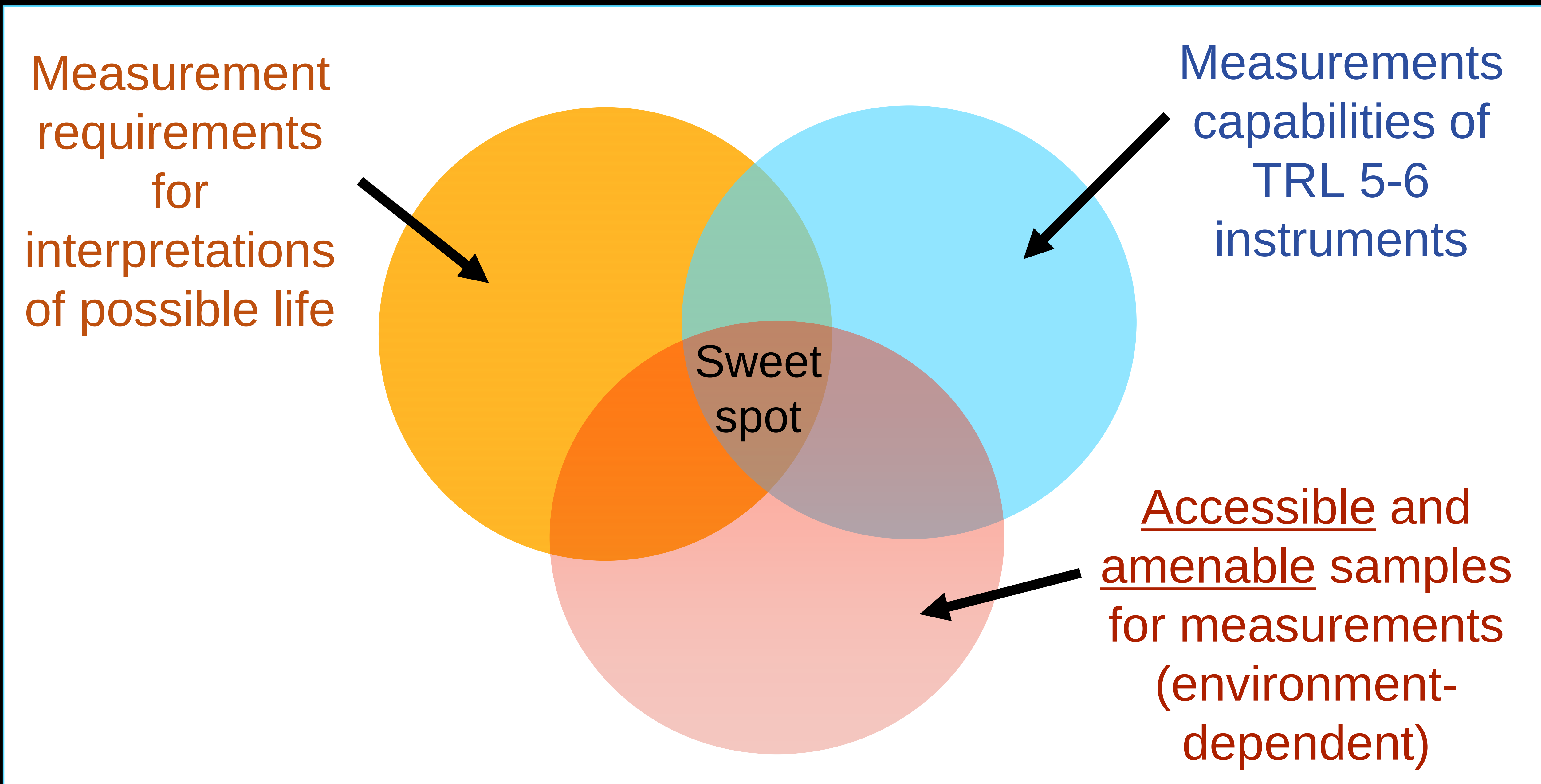
- Molecular measurements - separation and detection/identification
    - examples of separation:
        - gas and liquid chromatography
        - capillary electrophoresis
        - mass and shape filters
    - examples of detection/identification:
        - mass spectrometry
        - fluorescences with molecular tags



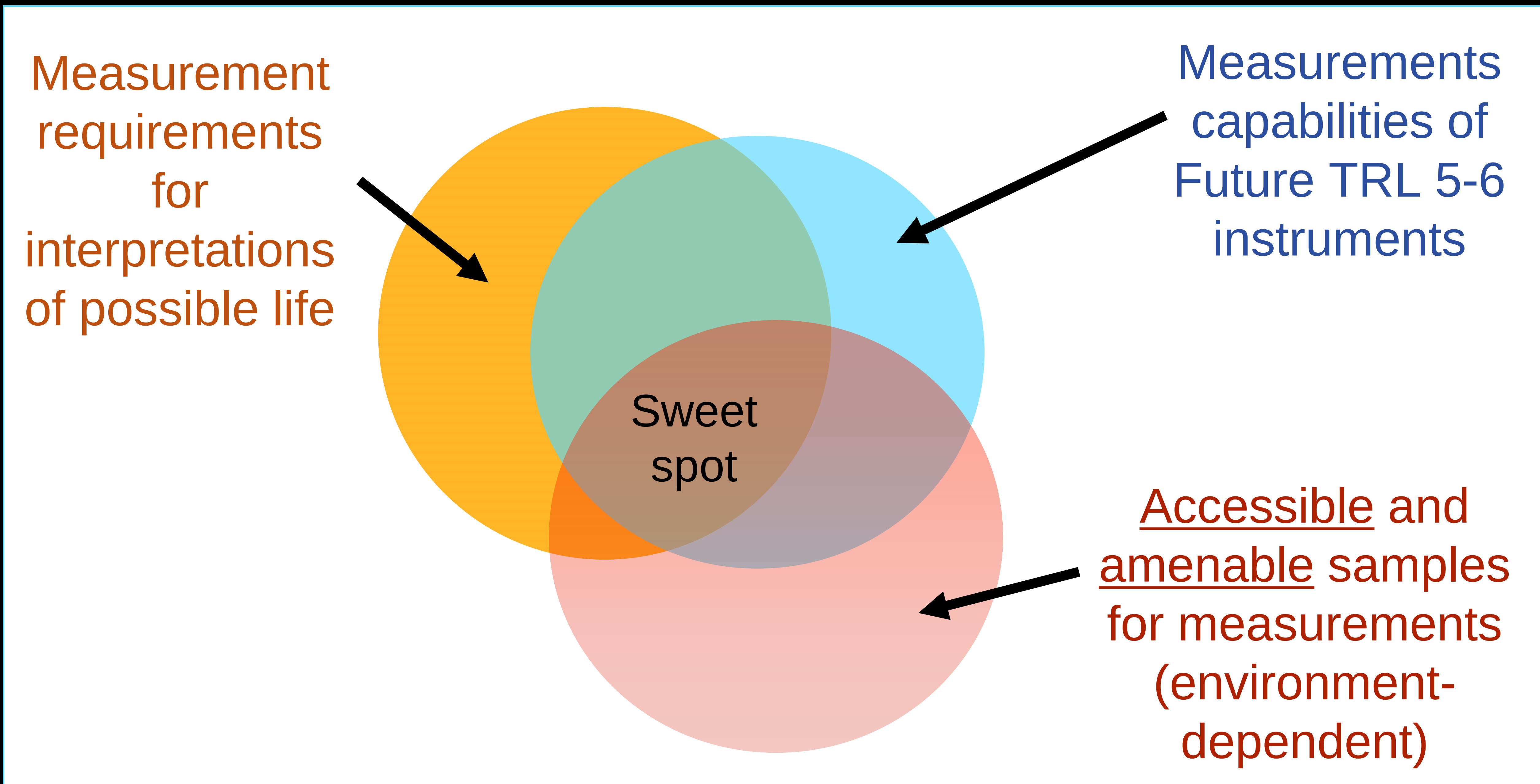
Instruments that measure for possible biosignatures

- Morphological imaging and augmentations examples:
    - optical or fluorescence microscopy
    - Raman, IR, UV microscopy
    - epifluorecent microscopy
    - scanning electron microscopy
    - atomic force microscopy

SAMPLES, MEASUREMENTS, & CAPABILITIES



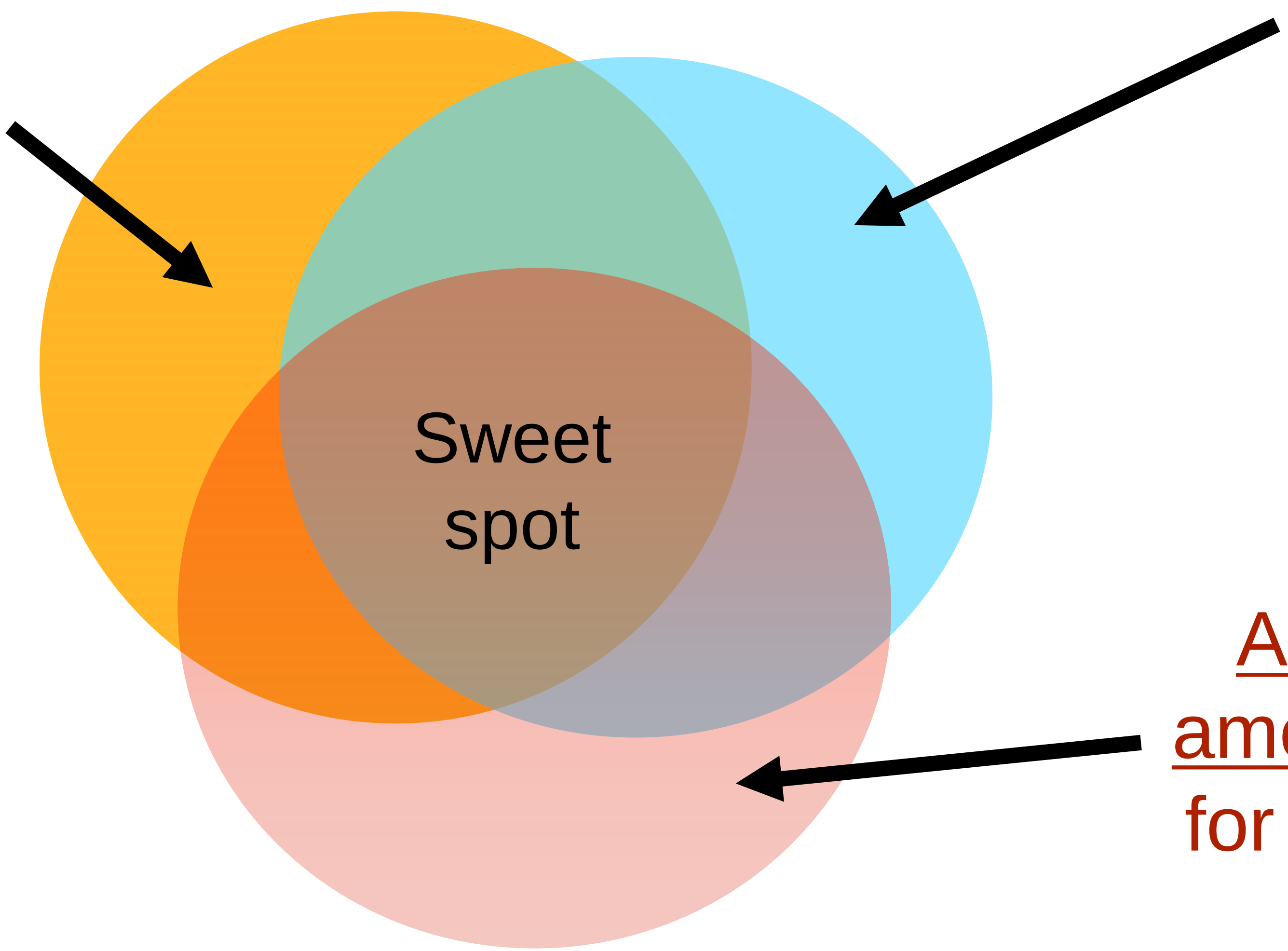
SAMPLES, MEASUREMENTS, & CAPABILITIES



SAMPLES, MEASUREMENTS, & CAPABILITIES

Measurement requirements for interpretations of possible life

Measurements capabilities of Future TRL 5-6 instruments



<u>Accessible</u> and <u>amenable</u> samples for measurements with future optimization

SAMPLES, MEASUREMENTS, & CAPABILITIES




We have instruments at TRL 4-7 that can support measurements for biosignatures. More are in the works.

The missing technology tends to be sample acquisition and processing. This is not just an engineering issue. It is a technology development.

Arguably, biosignature contamination control is a limiting issue as well…

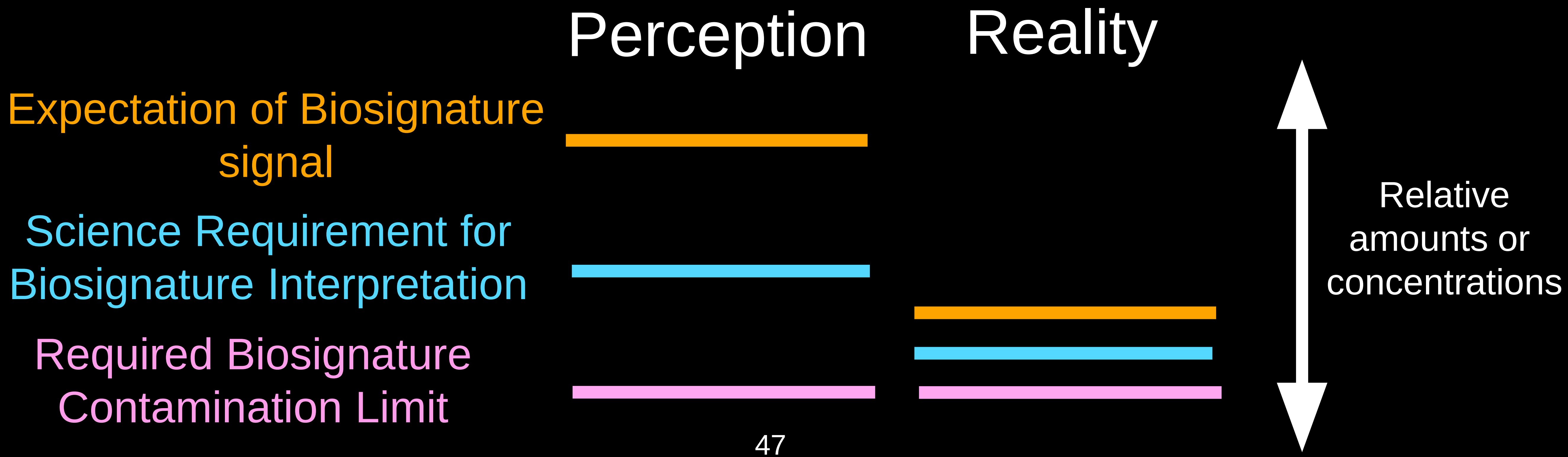
CONTAMINATON

- Contamination = any material that compromises the integrity of biosignature interpretations. Includes: dead cells, organic molecules, reaction products, materials transferred from spacecraft and rocket.

- We need to improve our understanding of the chemistry and transfer of biosignature contaminants in order to remove, prevent and test for their presence.

CONTAMINATON

- Instruments are getting more sensitive in order to meet detection requirements… this means we have to get better at controlling contamination.

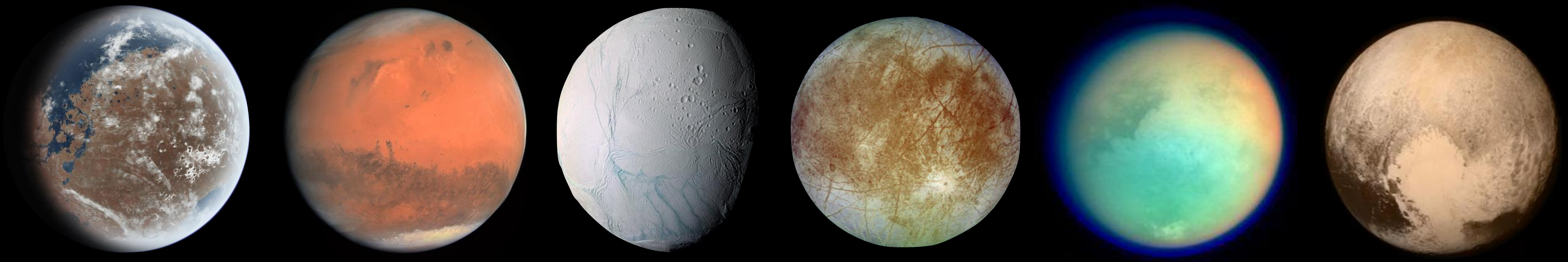


Life is ubiquitous on Earth. Despite our best efforts to clean pre-launch. We will take some Earth-life with us. Is this a problem for science?

To succeed in *in situ* life detection beyond Earth, we will probably need to de-contaminate both instruments and spacecraft after launch and before landing. A second decontamination operation requires consideration in payload and spacecraft designs.

The alternative for subsystems is to use hermetical seals.

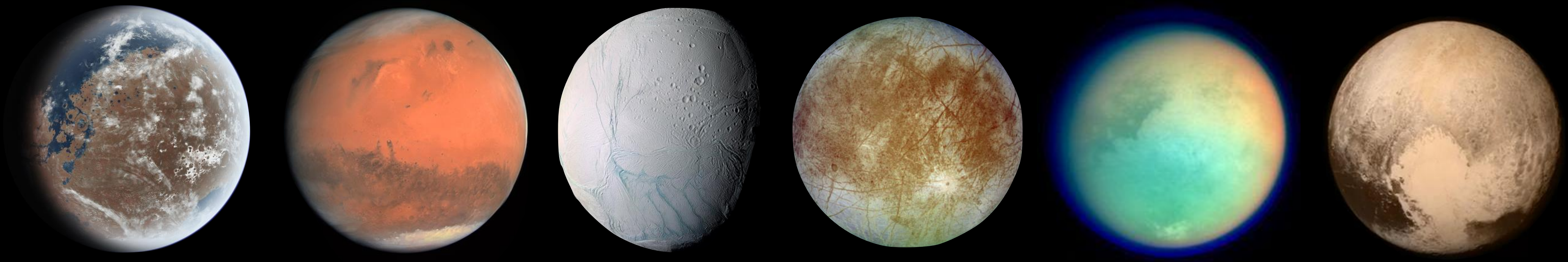
LIFE DETECTION



Extraordinary claims require extraordinary evidence.

There is no better case for this than life detection.

LIFE DETECTION



We can attempt life detection now. We will make discoveries. And we will learn from our successes and mistakes.

In the next 5 years, development of science strategy, technologies for samples acquisition, processing and testing, and operational schemes that aim to overcome noise — all of these — are needed to pave the way to robust exploration of extraterrestrial life in the Solar System.