Extraterrestrial Mass Spectrometry: Searching for Habitable Environments in the Solar System

NASA/JPL-Caltech/Lizbeth B. De La Torre

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Are we alone?

What processes led to the development of life?

Has life developed elsewhere in our solar system?

What makes a planet or moon habitable for life?

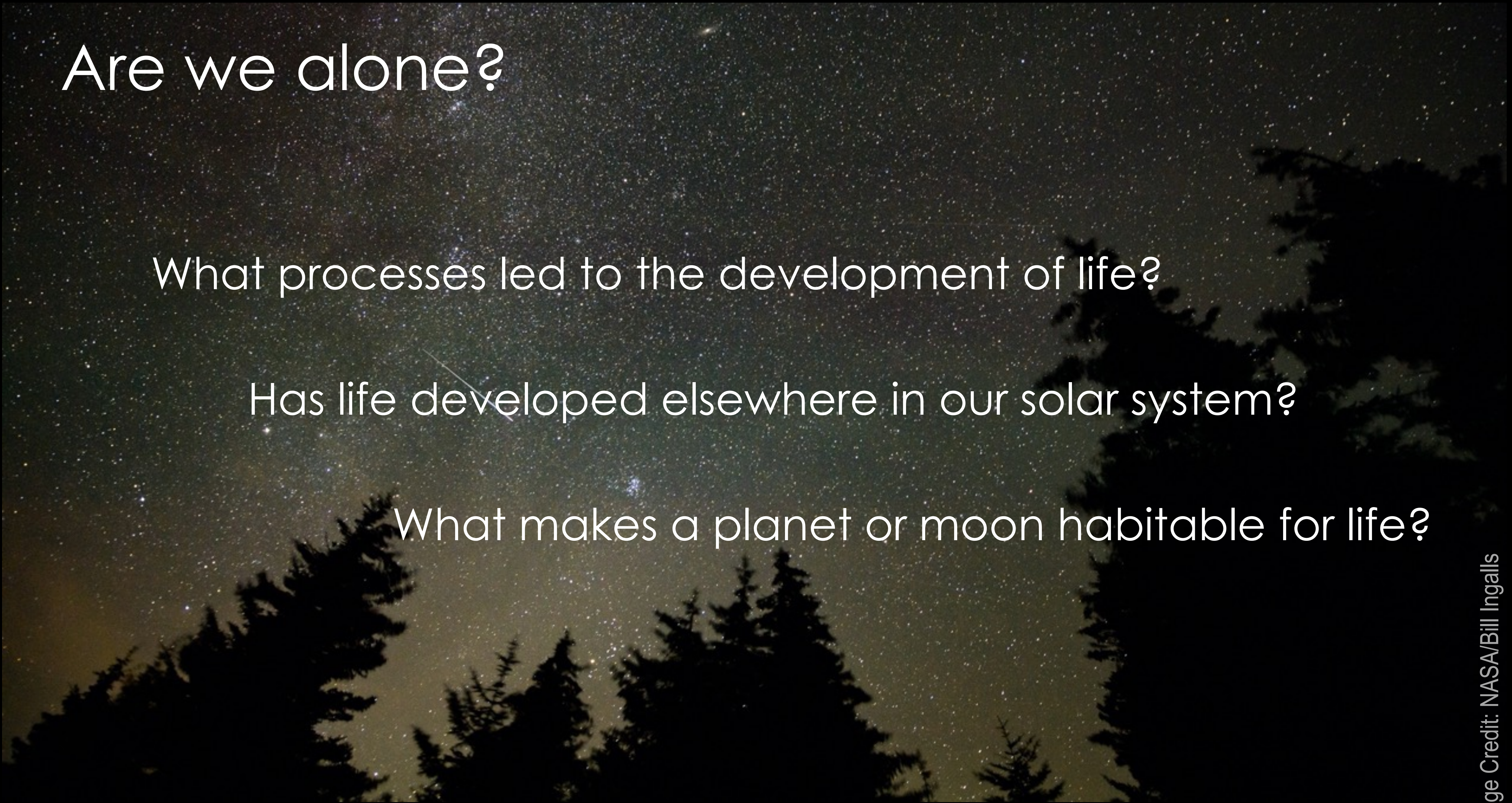
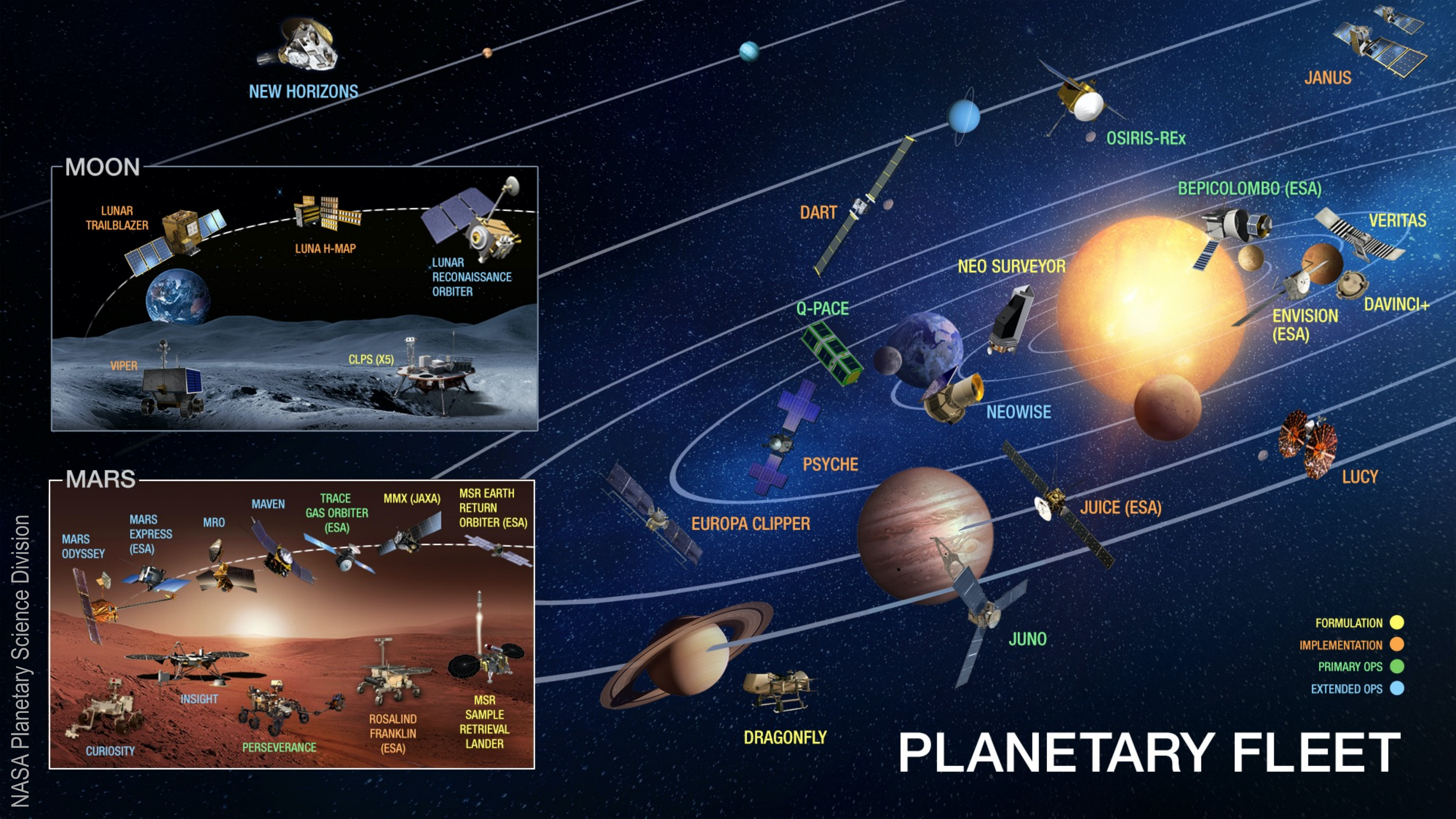


Image Credit: NASA/Bill Ingalls


PLANETARY FLEET
NEW HORIZONS
JANUS
OSIRIS-REx
DART
BEPICOLOMBO (ESA)
VERITAS
NEO SURVEYOR
Q-PACE
ENVISION (ESA)
DAVINCI+
NEOWISE
PSYCHE
LUCY
EUROPA CLIPPER
JUICE (ESA)
JUNO
DRAGONFLY
MOON
LUNAR TRAILBLAZER
LUNA H-MAP
LUNAR RECONAISSANCE ORBITER
VIPER
CLPS (X5)
MARS
MARS ODYSSEY
MARS EXPRESS (ESA)
MRO
MAVEN
TRACE GAS ORBITER (ESA)
MMX (JAXA)
MSR EARTH RETURN ORBITER (ESA)
INSIGHT
CURIOSITY
PERSEVERANCE
ROSALIND FRANKLIN (ESA)
MSR SAMPLE RETRIEVAL LANDER
FORMULATION
IMPLEMENTATION
PRIMARY OPS
EXTENDED OPS
NASA Planetary Science Division

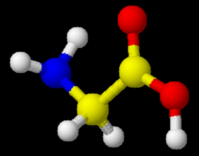
"Ingredients" for Life

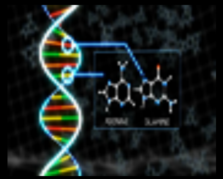
Life as We Know It

Major Biogenic Elements + Energy + Liquid (chemical medium) = Habitable environment

Major Biogenic Elements

Carbon C
Hydrogen H
Nitrogen N
Oxygen O
Phosphorus P
Sulfur S





Energy

Sunlight
(photosynthesis)

Chemical
(redox)

Thermal

Liquid
(chemical medium)

Water

Habitable environment

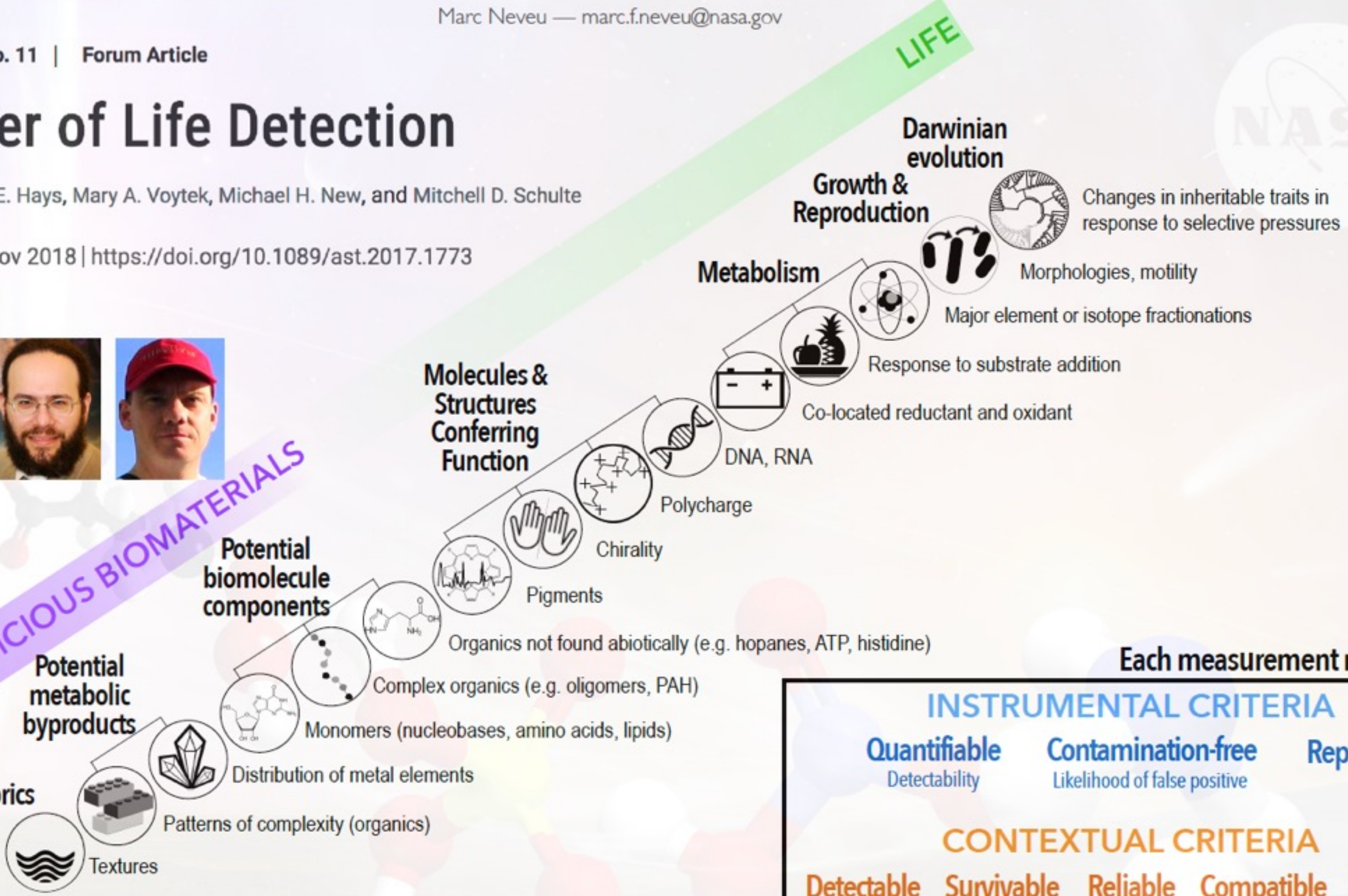
Marc Neveu — marc.f.neveu@nasa.gov

Astrobiology, Vol. 18, No. 11 | **Forum Article**

The Ladder of Life Detection

Marc Neveu, Lindsay E. Hays, Mary A. Voytek, Michael H. New, and Mitchell D. Schulte

Published Online: 13 Nov 2018 | https://doi.org/10.1089/ast.2017.1773



Habitability: Liquid water, building blocks, energy source, gradients

Each measurement must meet:

INSTRUMENTAL CRITERIA

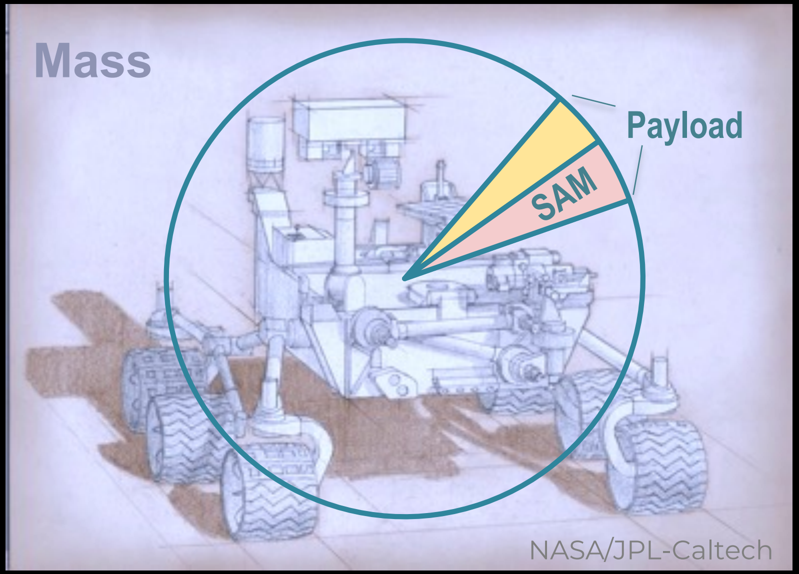
Quantifiable	Contamination-free	Repeatable
Detectability	Likelihood of false positive	

CONTEXTUAL CRITERIA

Detectable	Survivable	Reliable	Compatible	Last-resort
Environment allows measurement	Likelihood of false negative	Ambiguity of feature	Specificity to Earth life	Ambiguity of interpretation

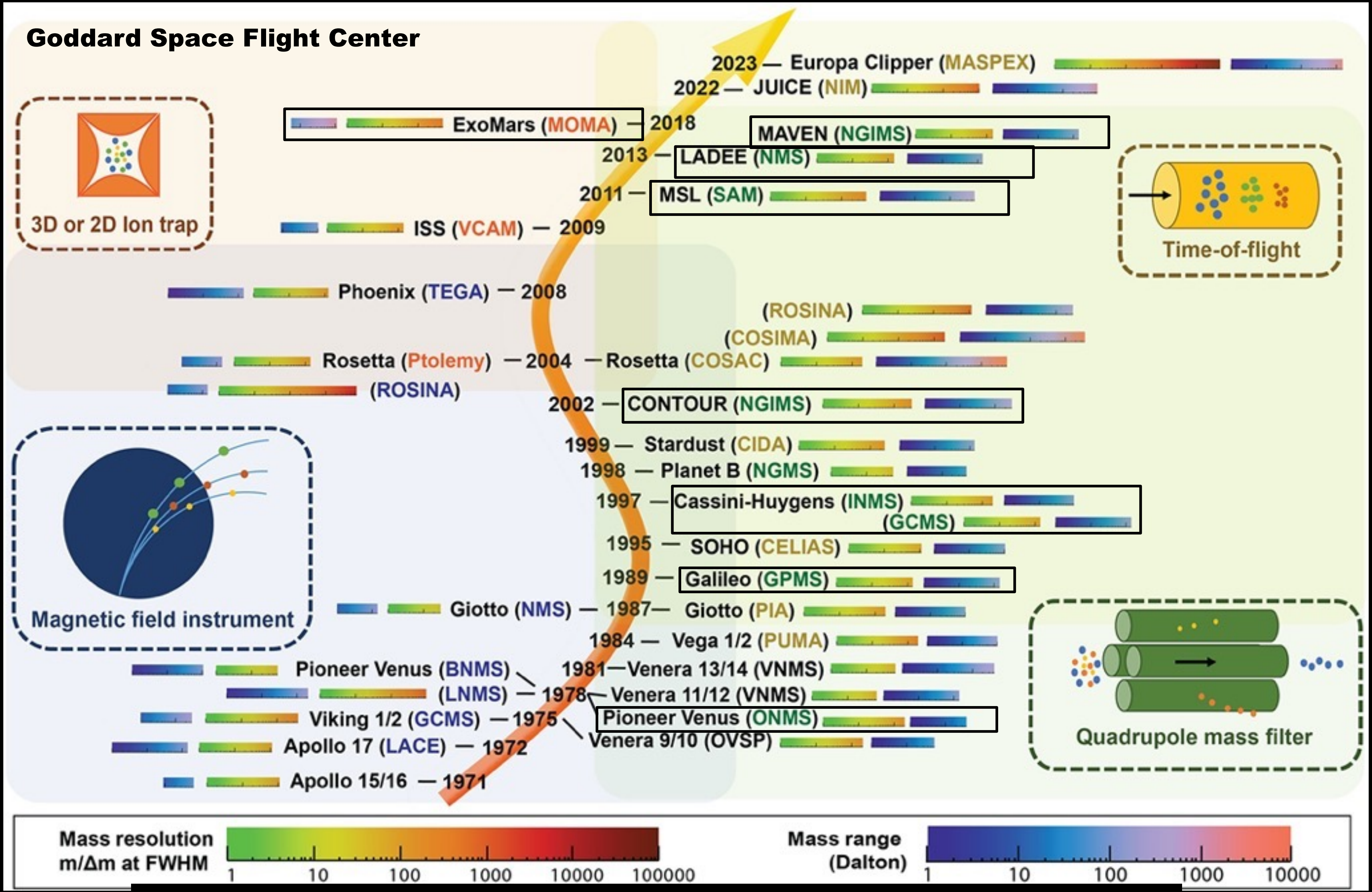
In situ planetary mass spectrometry

- Punishing launch and landing environment
- Extreme temperatures and temperature variations
- Limited power and energy consumption
- Restricted mass
- Autonomous control
- Limited communication bandwidth
- High radiation environments

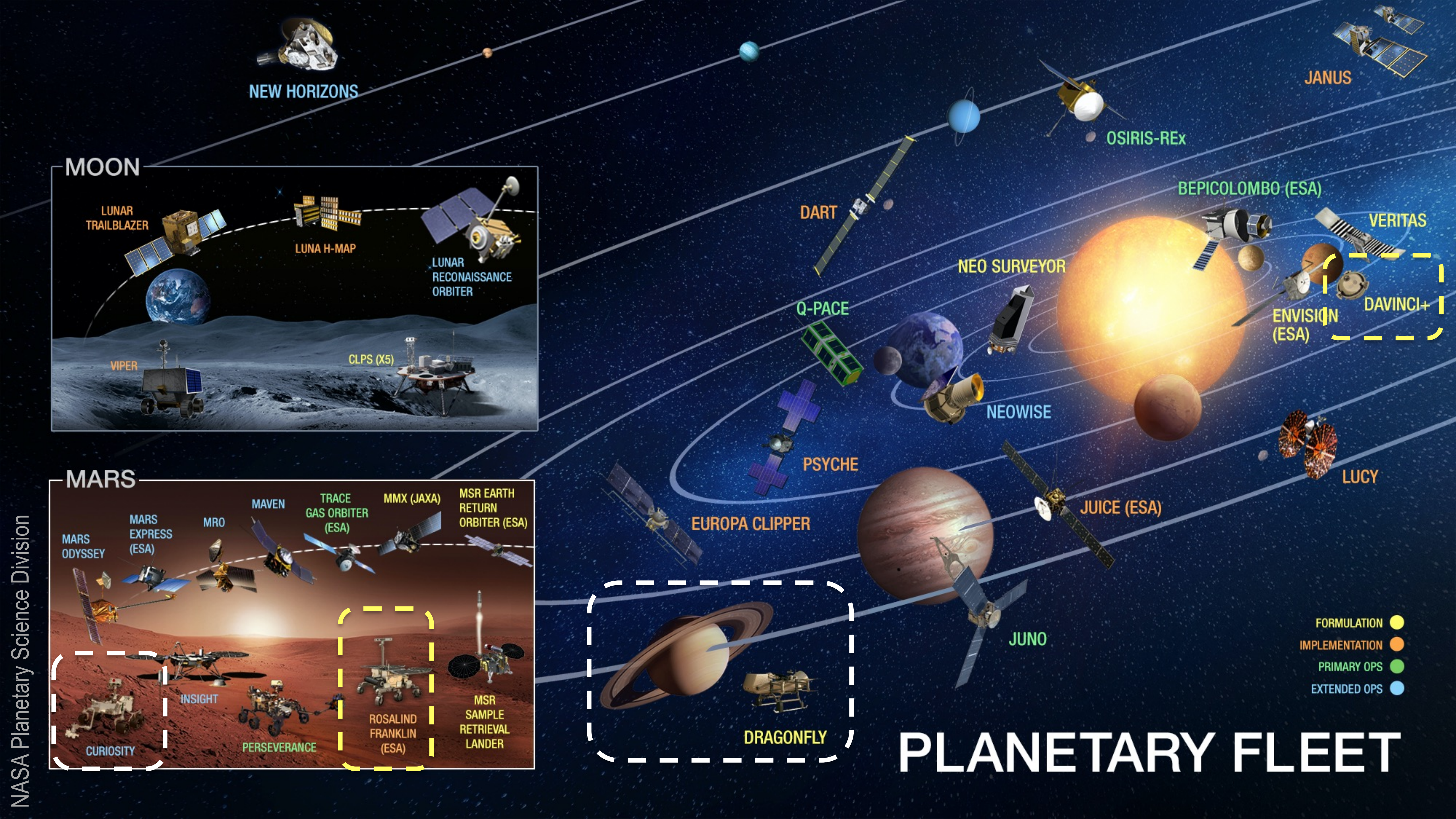


Graphics credit: Slidesgo and Flaticon

MASS SPECTROMETERS IN SPACE



Arevalo et al., Journal of Mass Spectrometry, Vol 55, Iss 1, 29 Oct 2019, DOI: (10.1002/jms.4454)



NEW HORIZONS
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OSIRIS-REx
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CLPS (X5)
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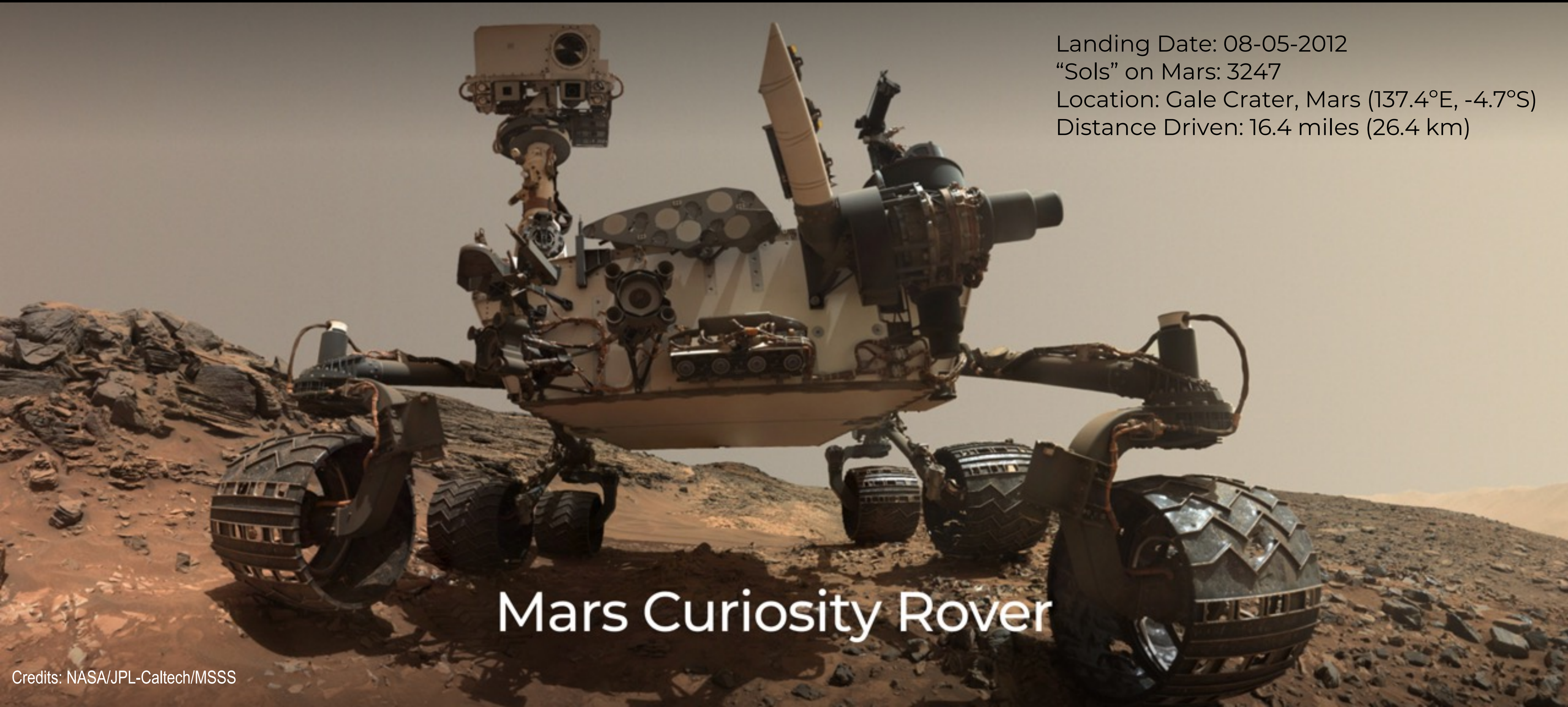
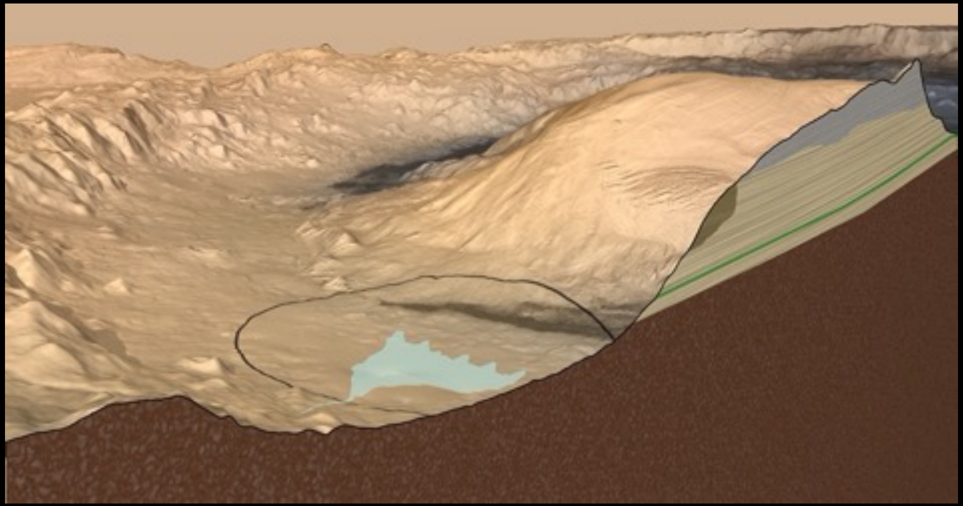
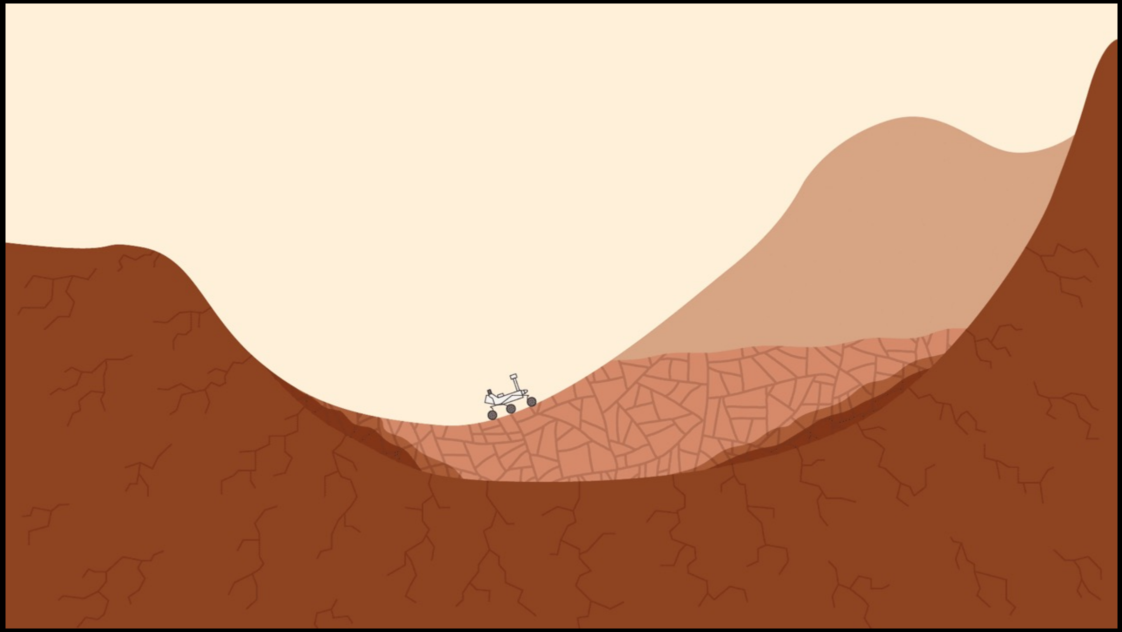
Sample Analysis at Mars (SAM)







Gale Crater, Mars

NASA/JPL-Caltech

Sample Analysis at Mars (SAM) instrument suite

SAM suite instruments:

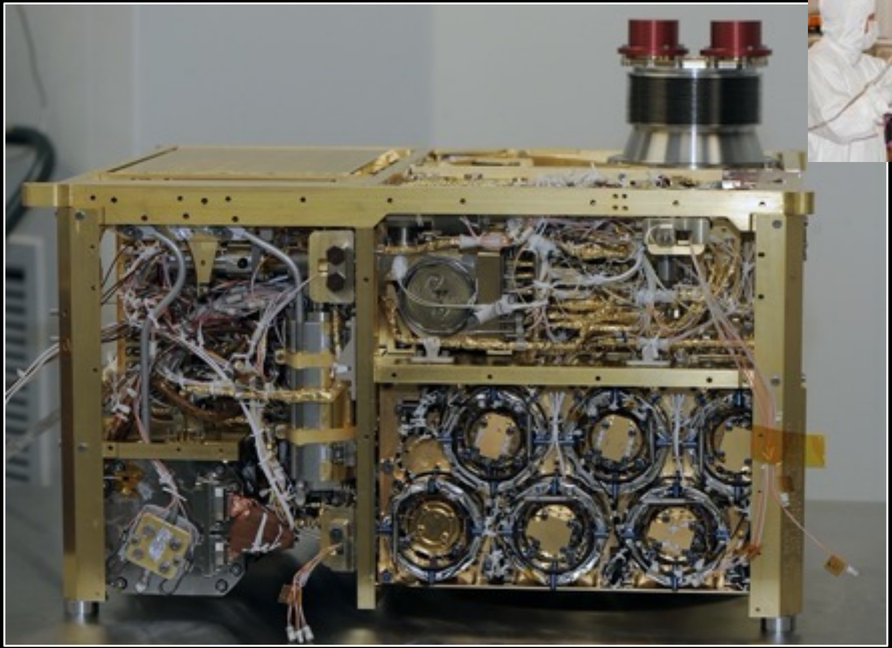
Quadrupole Mass Spectrometer-GSFC

Gas Chromatograph-University of Paris, France

Tunable Laser Spectrometer (JPL)

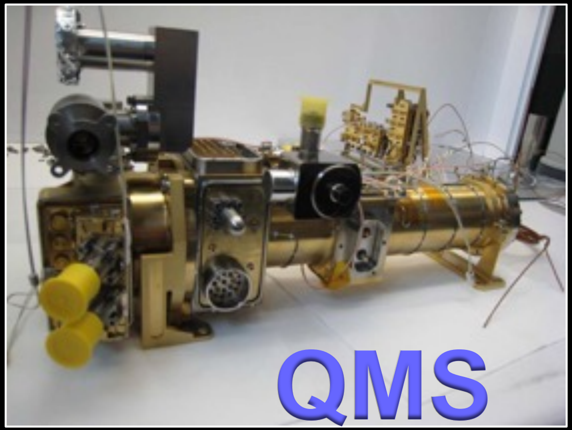
Gas Processing System-GSFC

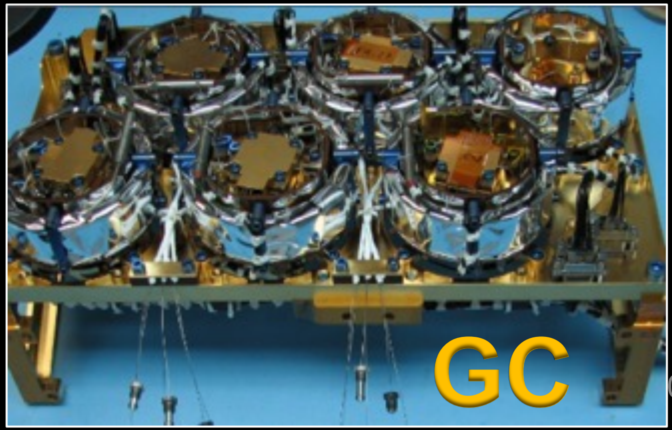
Sample Manipulation System-Honeybee Robotics

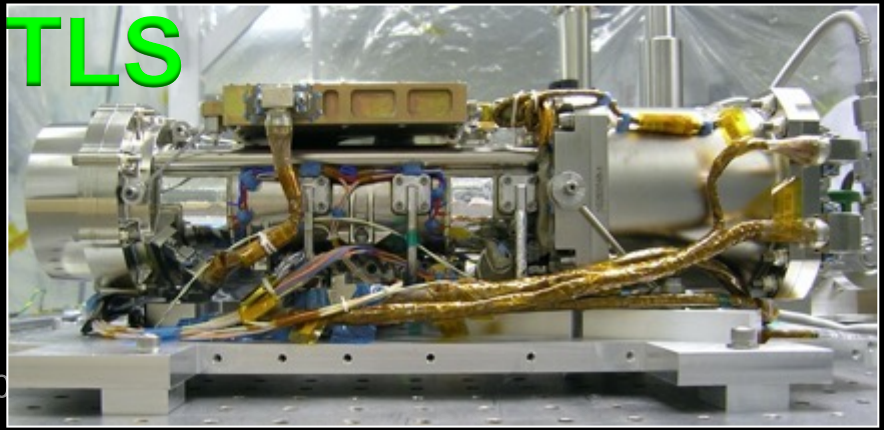


Wide Range Pump
Creare, Inc.

Microvalves
Mindrum

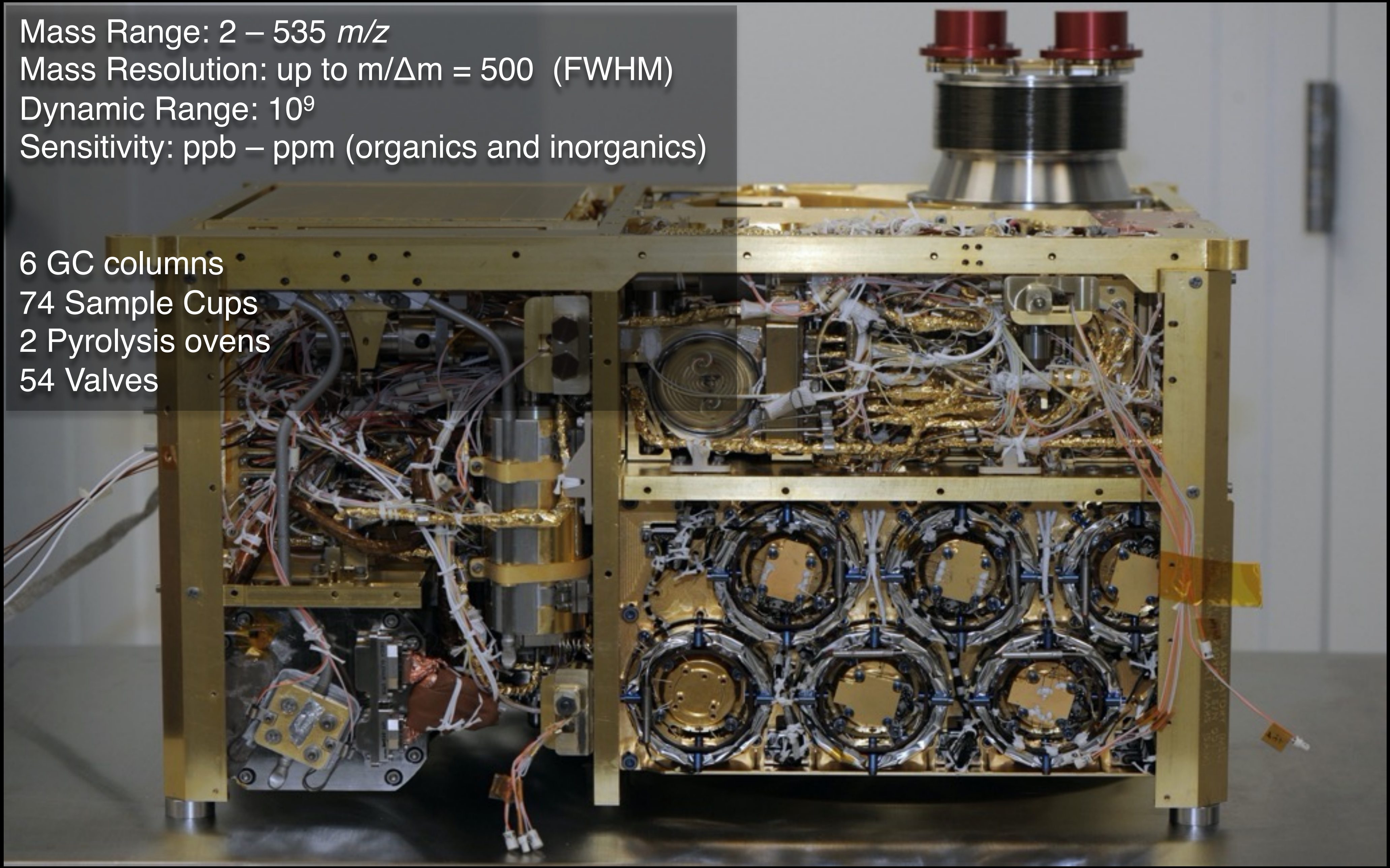


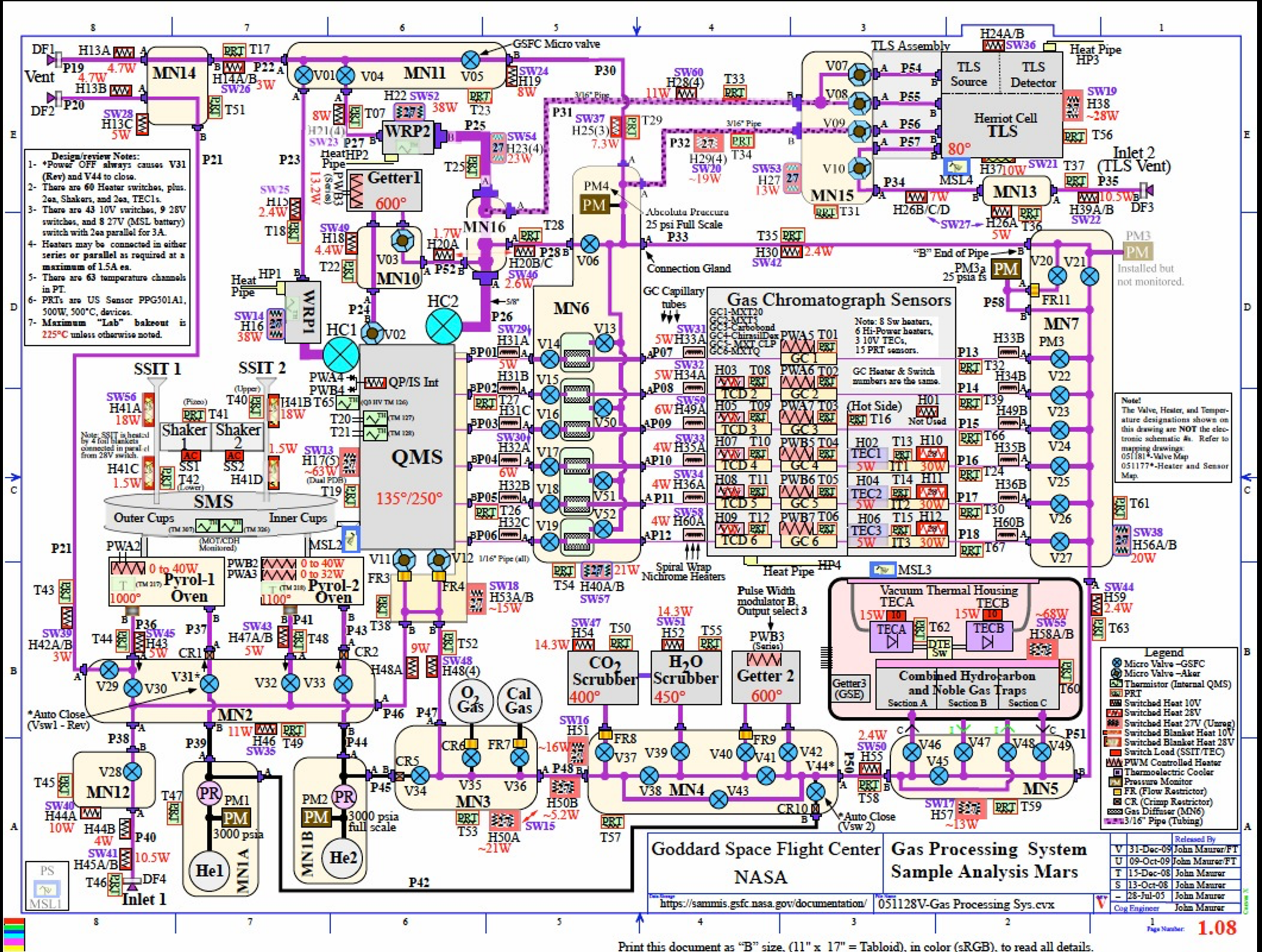


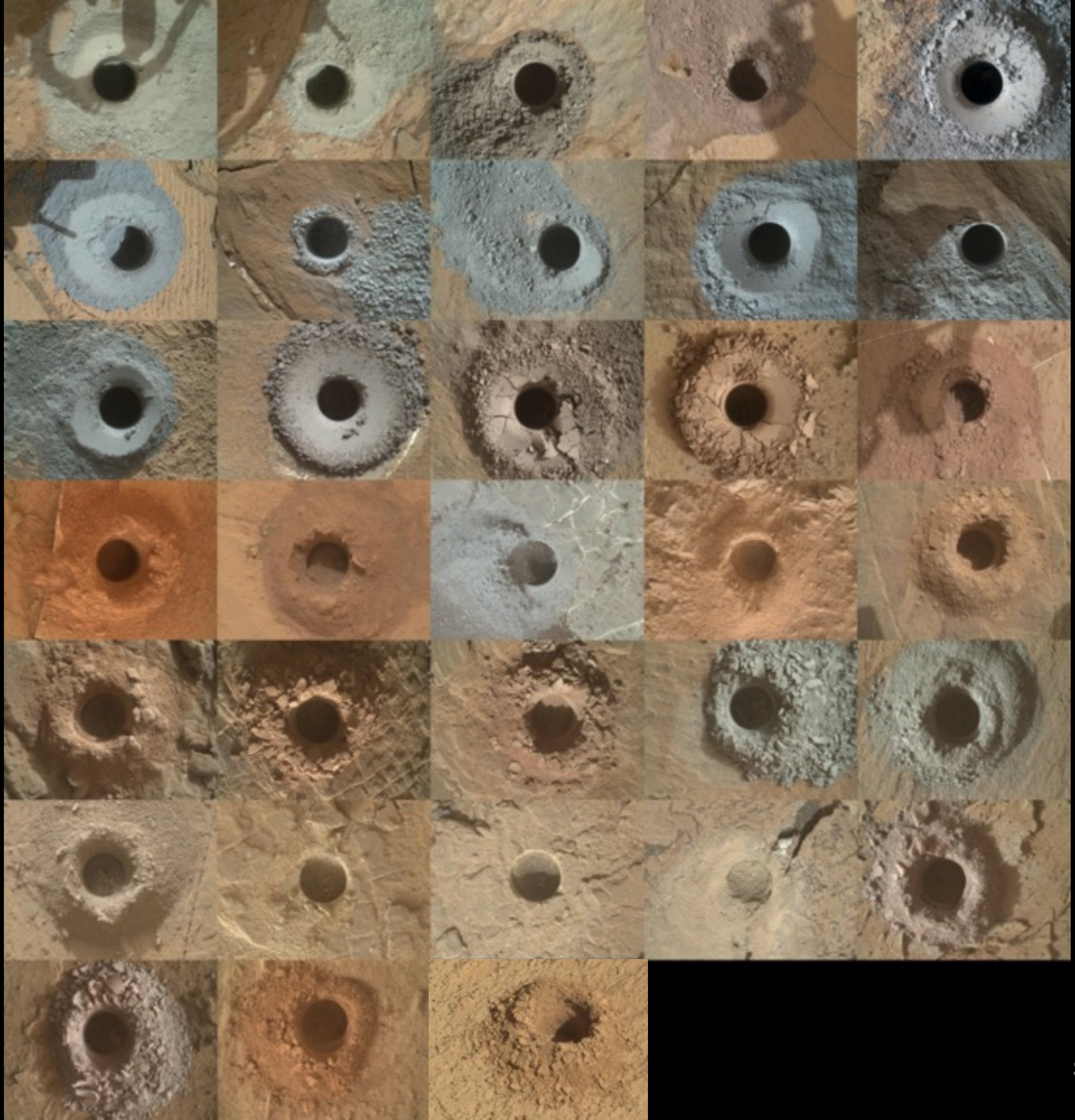


Mass Range: 2 – 535 *m/z*
Mass Resolution: up to $m/\Delta m = 500$ (FWHM)
Dynamic Range: 10^9
Sensitivity: ppb – ppm (organics and inorganics)

6 GC columns
74 Sample Cups
2 Pyrolysis ovens
54 Valves



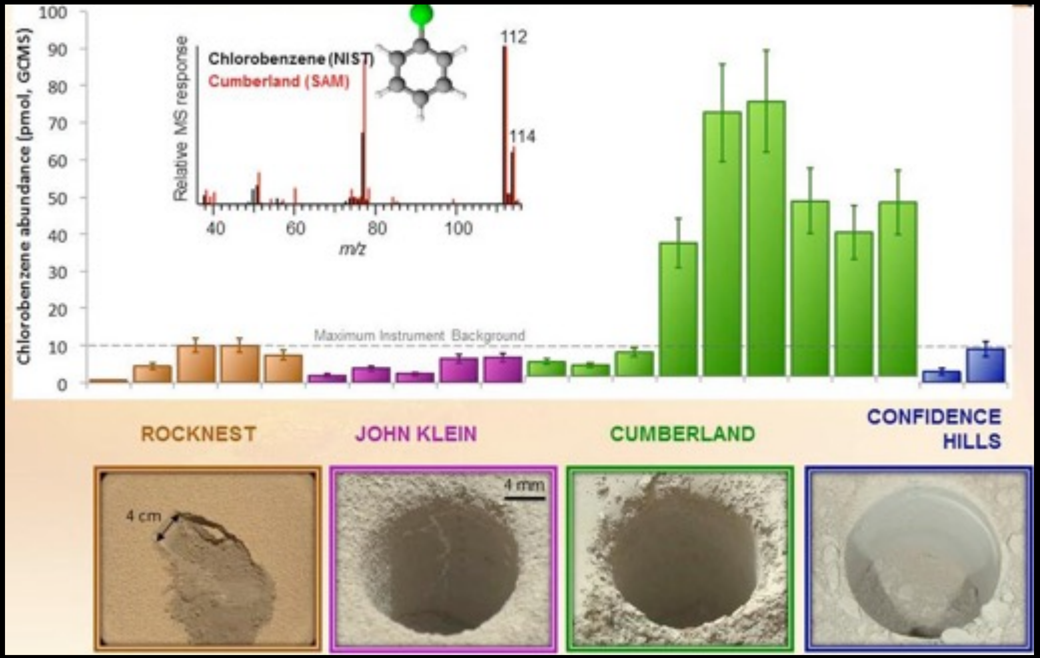

Design/review Notes:
1- *Power OFF always causes V31 (Rev) and V44 to close.
2- There are 60 Heater switches, plus. 2ea, Shakers, and 2ea, TEC1s.
3- There are 43 10V switches, 9 28V switches, and 8 27V (MSL battery) switch with 2ea parallel for 3A.
4- Heaters may be connected in either series or parallel as required at a maximum of 1.5A ea.
5- There are 63 temperature channels in PT.
6- PRTs are US Sensor PPG501A1, 500W, 500°C, devices.
7- Maximum "Lab" bakeout is 225°C unless otherwise noted.
Gas Chromatograph Sensors
Note: 8 Sw heaters, 6 Hi-Power heaters, 3 10V TECs, 15 PRT sensors.
GC Heater & Switch numbers are the same.
Note!
The Valve, Heater, and Temperature designations shown on this drawing are NOT the electronic schematic #s. Refer to mapping drawings:
051181*-Valve Map
051177*-Heater and Sensor Map.
QMS
135°/250°
SSIT 1
SSIT 2
SMS
Outer Cups
Inner Cups
Pyrol-1 Oven
Pyrol-2 Oven
TLS Assembly
TLS Source
TLS Detector
Herriot Cell
TLS
Inlet 2 (TLS Vent)
Inlet 1
Vent
Getter1
600°
CO_2 Scrubber
400°
H_2O Scrubber
450°
Getter 2
600°
Vacuum Thermal Housing
Combined Hydrocarbon and Noble Gas Traps
Section A
Section B
Section C
O_2 Gas
Cal Gas
He1
He2
3000 psia
3000 psia full scale
Absolute Pressure 25 psi Full Scale
Connection Gland
Spiral Wrap Nichrome Heaters
Pulse Width modulator B, Output select 3
Installed but not monitored.
*Auto Close (Vsw1 - Rev)
*Auto Close (Vsw 2)
GSFC Micro valve
Legend
Micro Valve –GSFC
Micro Valve –Aker
Thermistor (Internal QMS)
PRT
Switched Heat 10V
Switched Heat 28V
Switched Heat 27V (Unreg)
Switched Blanket Heat 10V
Switched Blanket Heat 28V
Switch Load (SSIT/TEC)
PWM Controlled Heater
Thermoelectric Cooler
Pressure Monitor
FR (Flow Restrictor)
CR (Crimp Restrictor)
Gas Diffuser (MN6)
3/16" Pipe (Tubing)
Goddard Space Flight Center
NASA
Gas Processing System
Sample Analysis Mars
https://sammis.gsfc.nasa.gov/documentation/
051128V-Gas Processing Sys.cvx
Released By
V 31-Dec-09 John Maurer/FT
U 09-Oct-09 John Maurer/FT
T 15-Dec-08 John Maurer
S 13-Oct-08 John Maurer
– 28-Jul-05 John Maurer
Cog Engineer John Maurer
1.08
Print this document as "B" size, (11" x 17" = Tabloid), in color (sRGB), to read all details.



NASA/JPL-Caltech/MSSS.

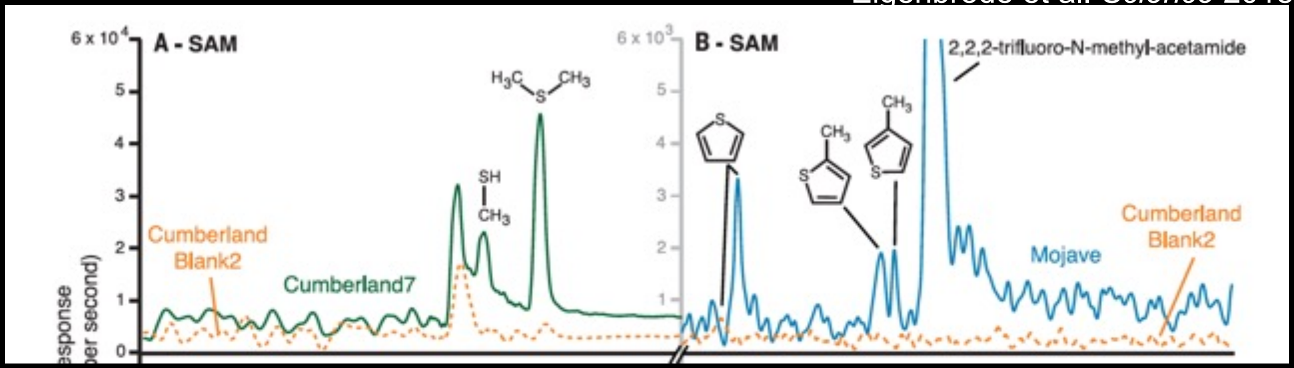
33 Drill holes on Mars

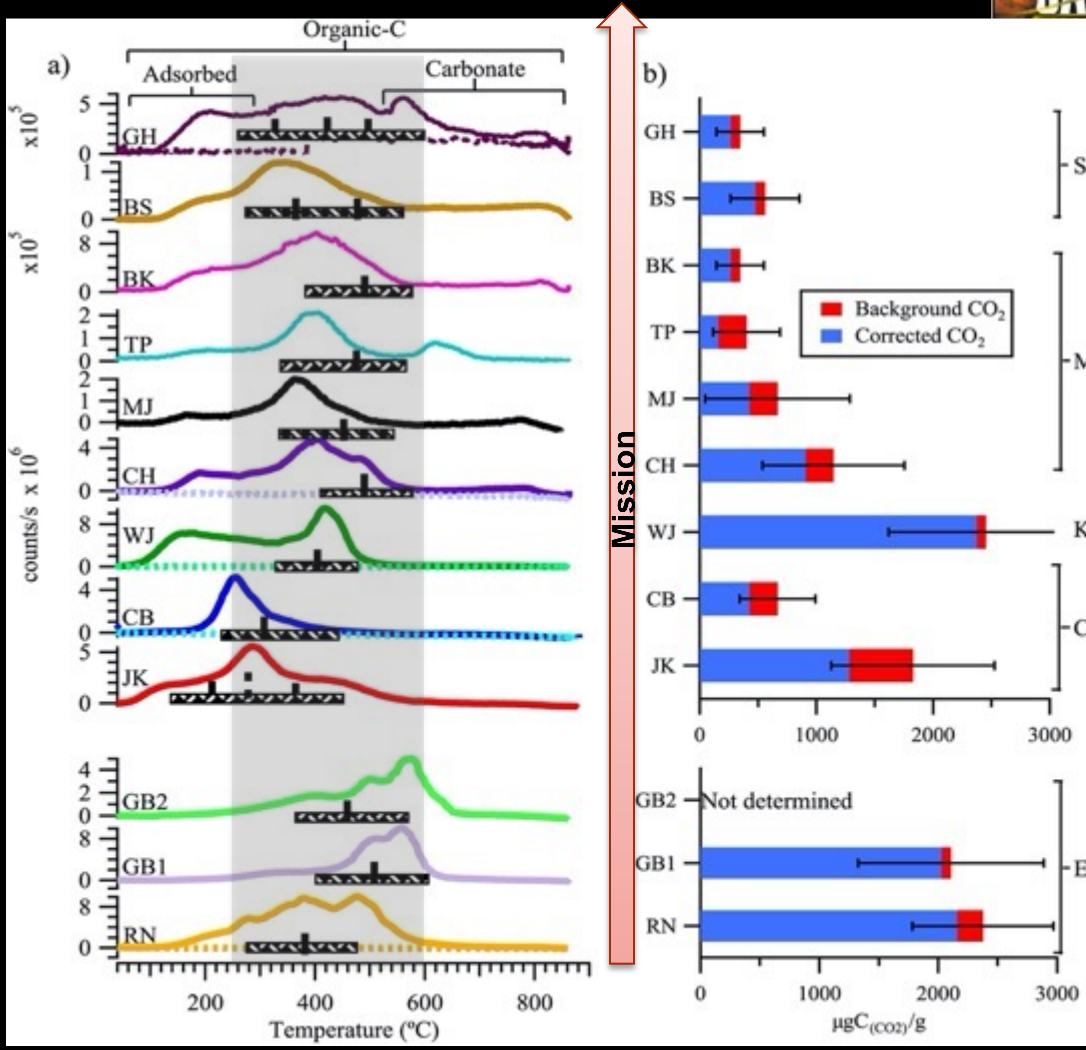
Major Discoveries – Organic Carbon



Freissinet et al. *JGR* 2015

Eigenbrode et al. *Science* 2018

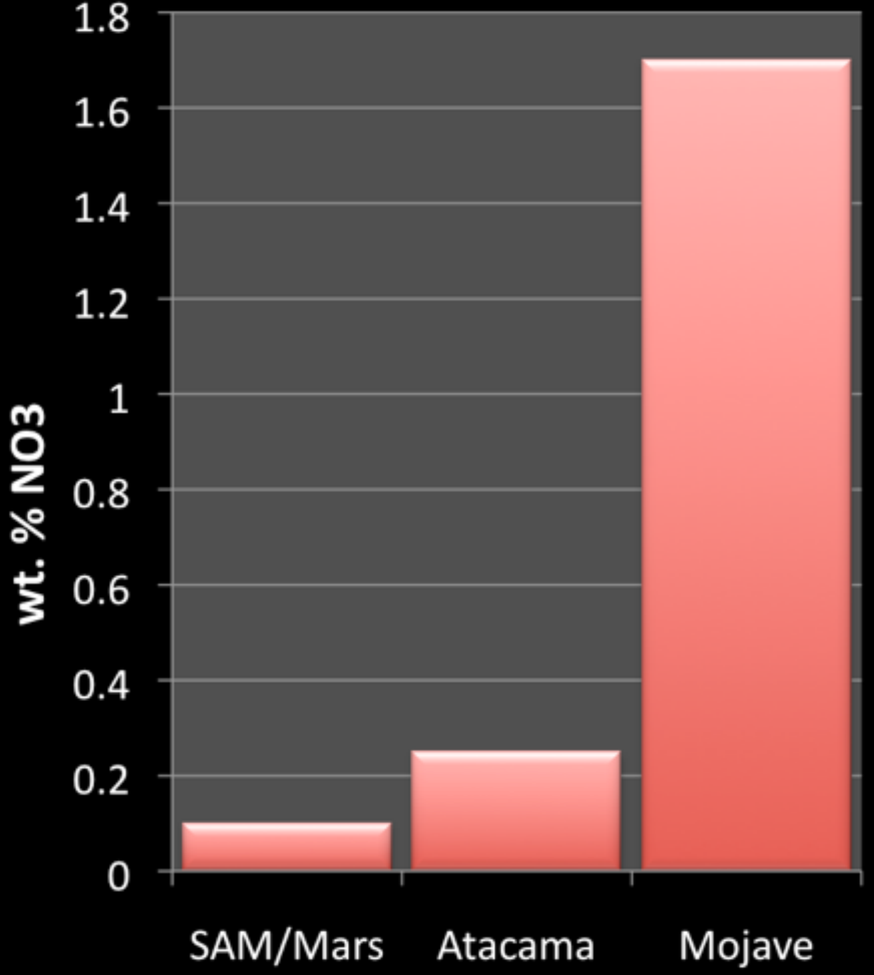




Sutter et al. JGR 2017

Major Discoveries – Nitrate

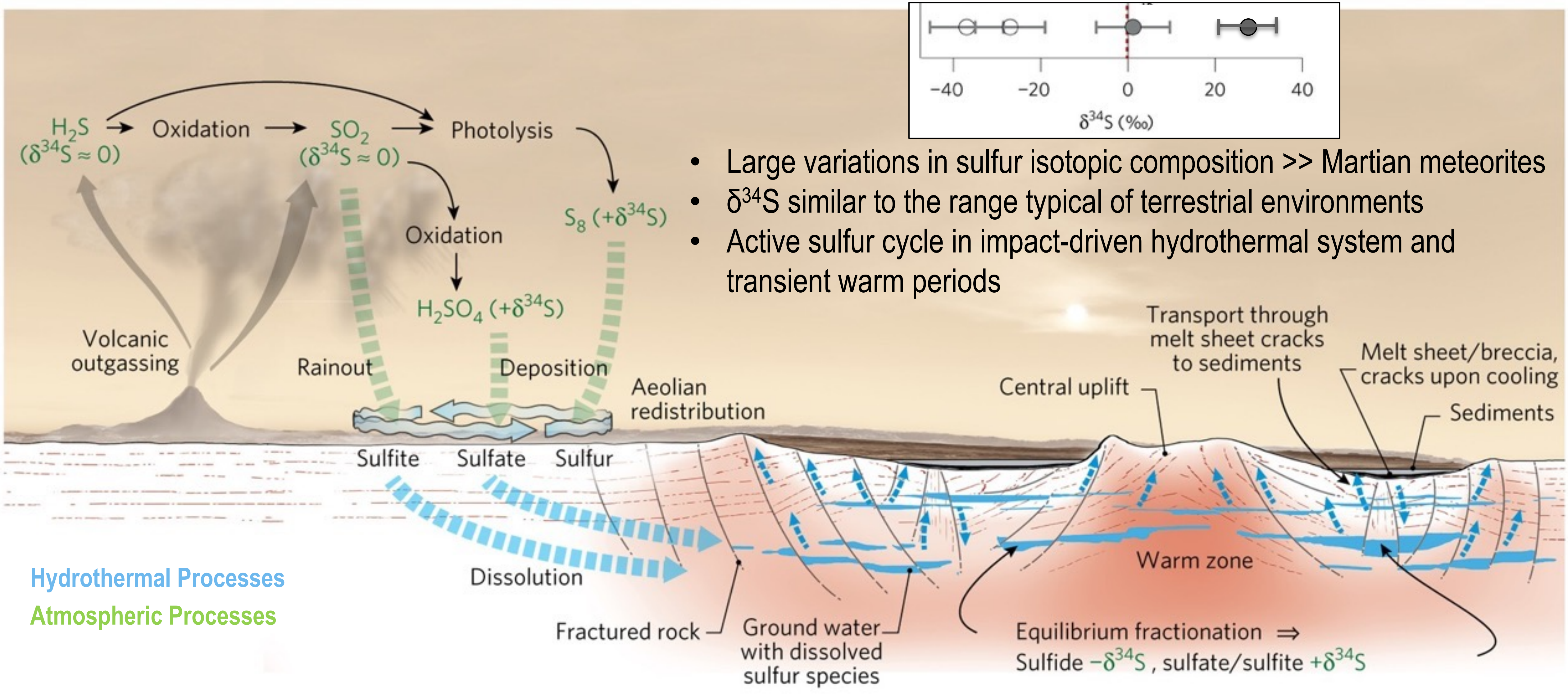
Stern et al. 2015, PNAS



- Nitrogen is key nutrient for life on Earth
- Nitrate is a form of "fixed" nitrogen that is chemically and biologically available.
- Life on Earth evolved metabolic pathways to break the N_2 bond so N could be used a nutrient
- Evidence of a nitrogen cycle on Mars

"Organic C and nitrate detections in Gale indicate **that two very important constituents for microbiology were present in Gale Crater**. Although nitrogen may have been limiting, the presence of organic C **suggests that heterotrophic microbiology could have been possible on ancient Mars**."
-- Sutter et al. *JGR* 2017

Major Discoveries – Sulfur Isotope Fractionation

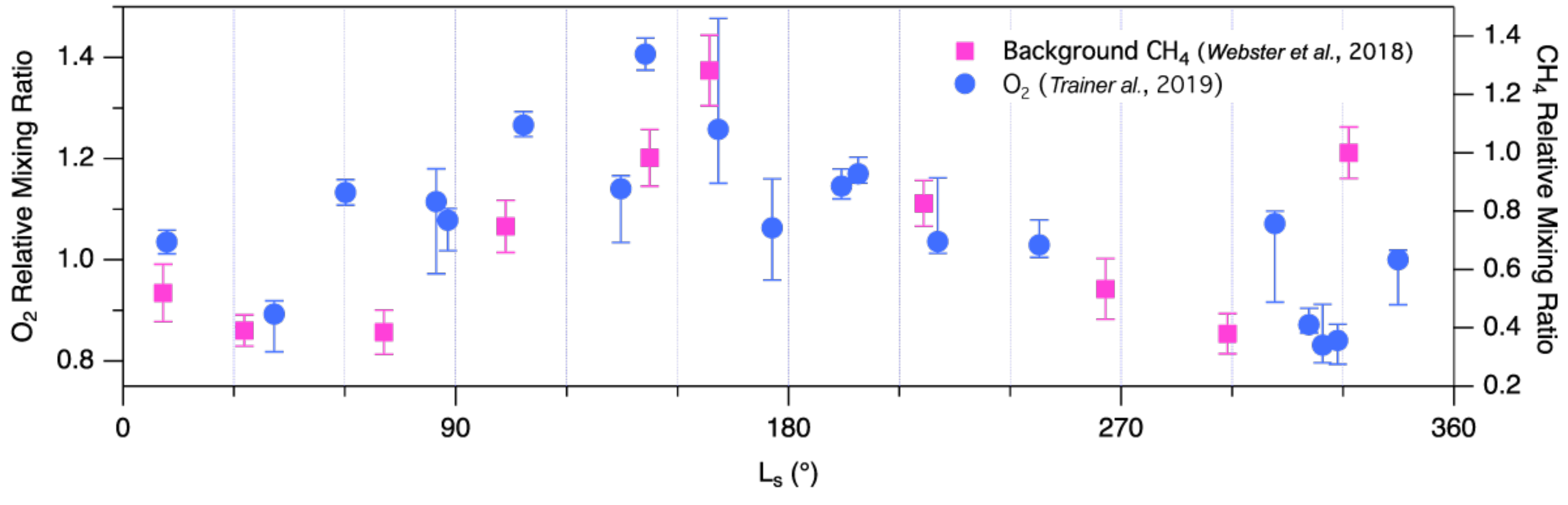


- Large variations in sulfur isotopic composition >> Martian meteorites
- $\delta^{34}S$ similar to the range typical of terrestrial environments
- Active sulfur cycle in impact-driven hydrothermal system and transient warm periods

Franz et al. *Nature Geoscience* 2017

Major Discoveries – Methane and Oxygen

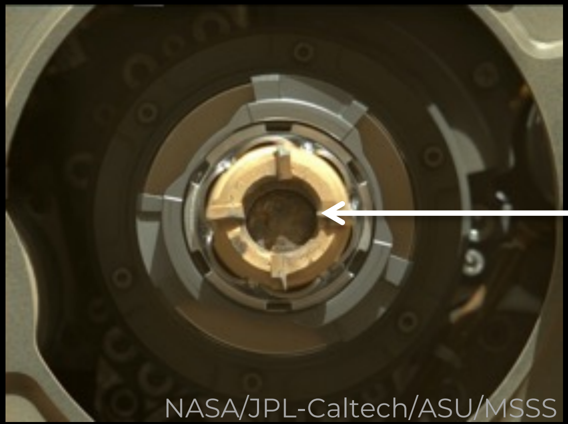
Trainer et al. JGR 2019



- Over 3 Mars years periodic sampling of atmosphere revealed surprising seasonal cycles in O_2 and CH_4
- Oxygen shows interannual variability with increase in N. Spring, unknown source
- Possible correlation between CH_4 and O_2 seasonal trends is both counterintuitive and puzzling, and requires additional work, considering especially their significance for the habitability of Mars

Stay tuned for more news from the Red Planet…

Mission: Mars 2020
Rover: Perseverance
Landing: Feb. 18, 2021,
Jezero Crater, Mars



Main Job: Seek signs of ancient life and collect samples of rock and regolith (broken rock and soil) for possible return to Earth.

EXOMARS

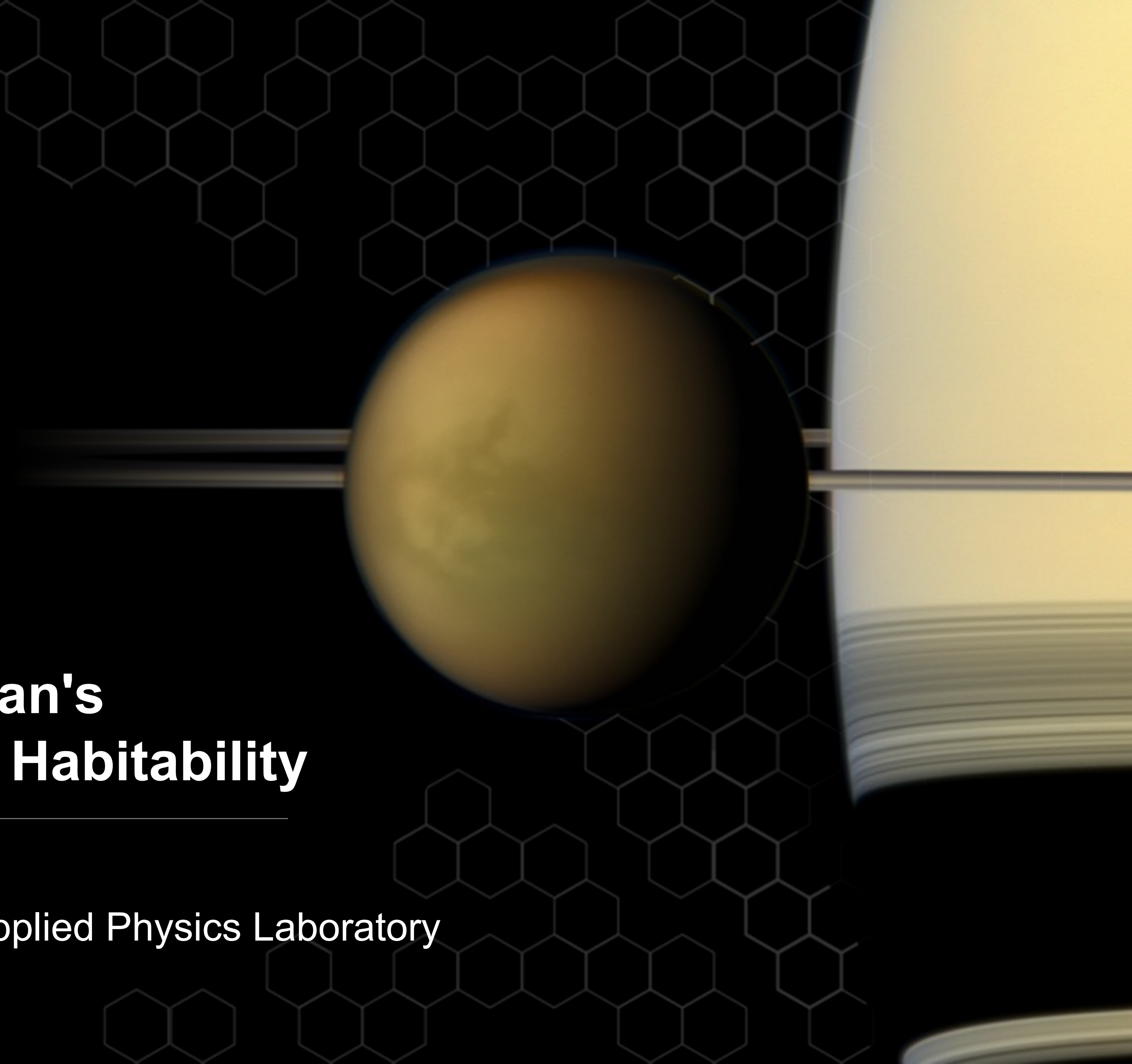
Mission: ExoMars
Rover: Rosalind Franklin
Launch: Sept. 2022

NASA's Goddard Space Flight Center Conceptual Image Lab

Main Job: Seek signs of life in subsurface with Mars Organic Molecule Analyzer (LIT-MS)

DRAGONFLY

A relocatable lander to explore Titan's
prebiotic chemistry and habitability

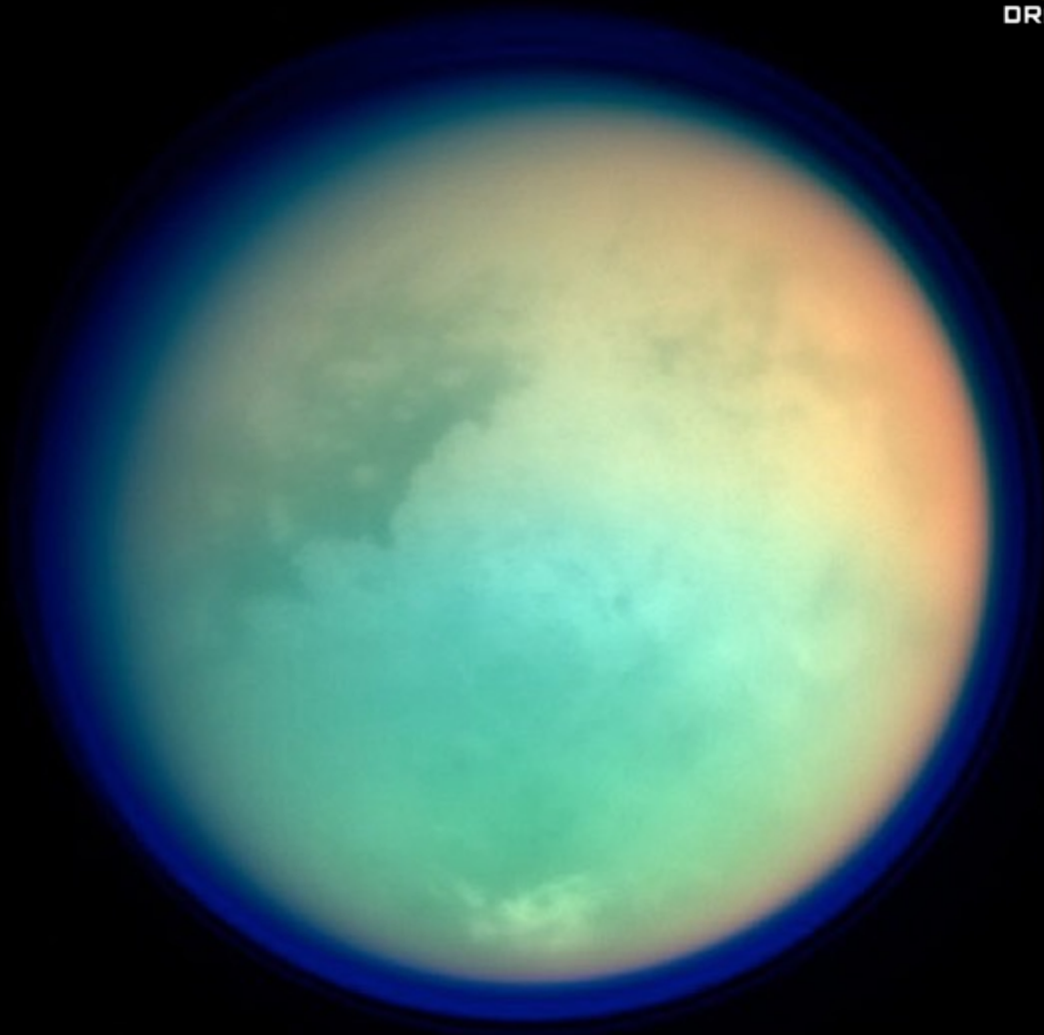


Dragonfly
In Situ Exploration of Titan's Prebiotic Chemistry and Habitability

NASA New Frontiers Mission
led by Johns Hopkins University Applied Physics Laboratory

Titan

- Diameter = 5,150 km (3,193 miles)
- Surface gravity = 1.35 m/s2 = 0.14 g
  - 14% of gravity at Earth's surface
  - 83% of gravity at Moon's surface
- Surface pressure = 1.5 bar
  - 1.5× pressure at Earth's surface
- Surface temperature = 94 K = –290°F
  - Bedrock composition = water ice
  - Atmospheric composition = N_2, few % methane



NASA/JPL/ESA/Space Science Institute/ University of Arizona

26 October 2004

Titan

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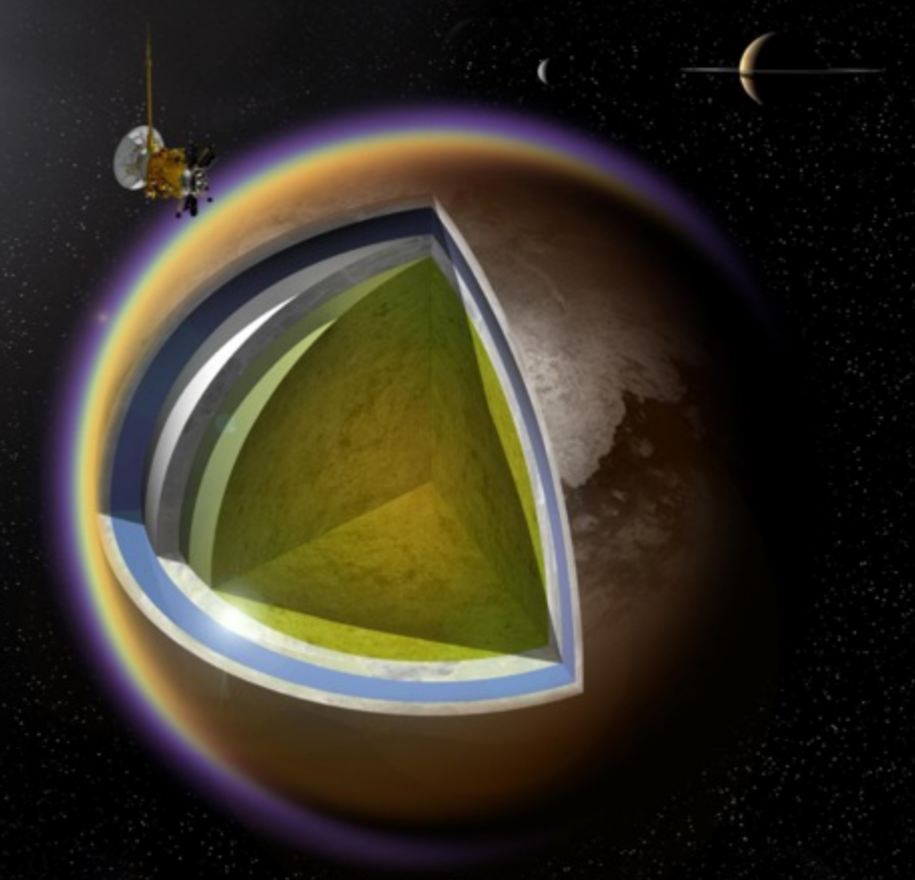
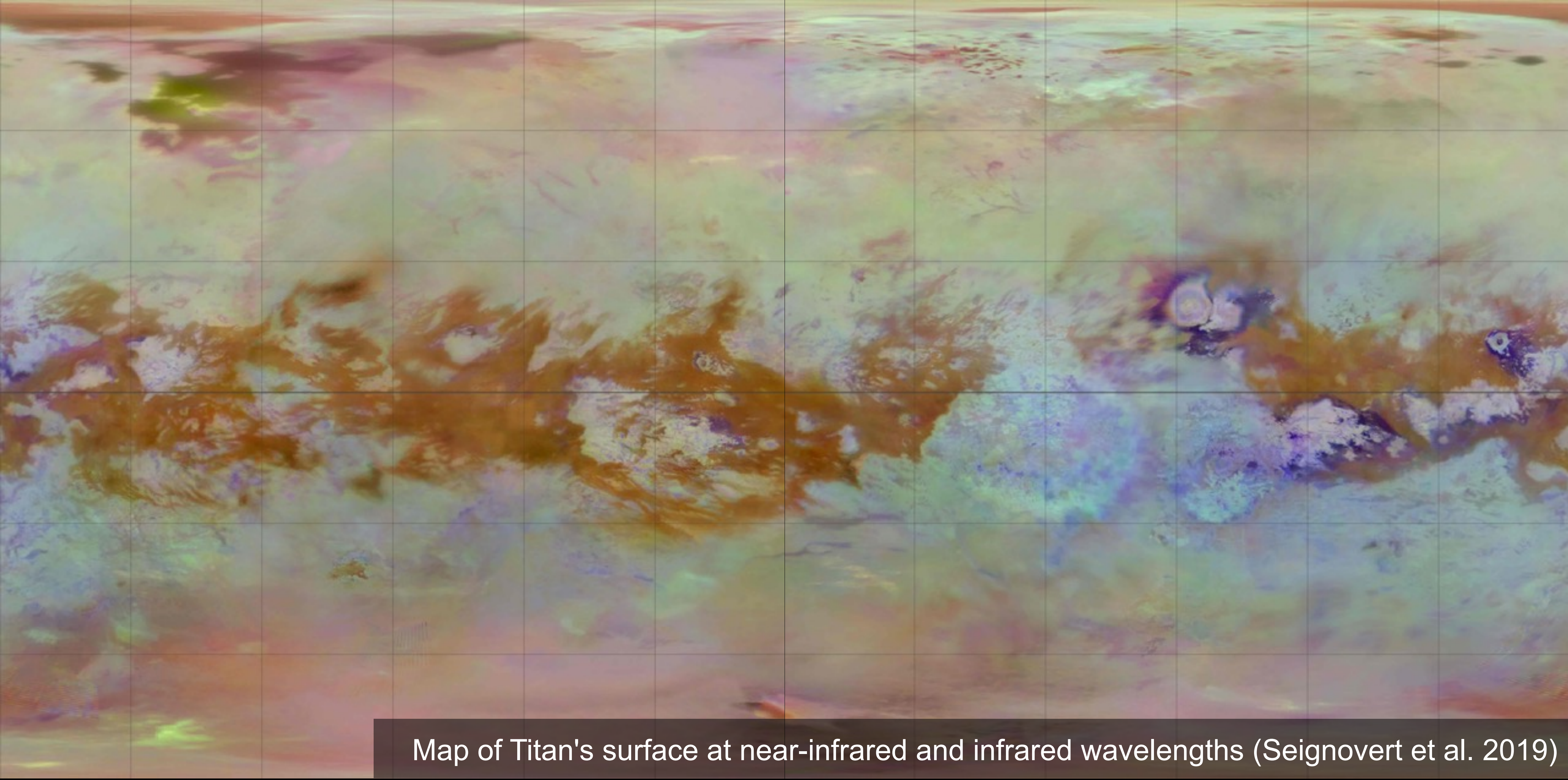
  - 1.5× pressure at Earth's surface
- Surface temperature = 94 K = –290°F
  - Bedrock composition = water ice
  - Atmospheric composition = N_2, few % methane
- Deep interior ocean of liquid water



Credit: A. D. Fortes/UCL/STFC

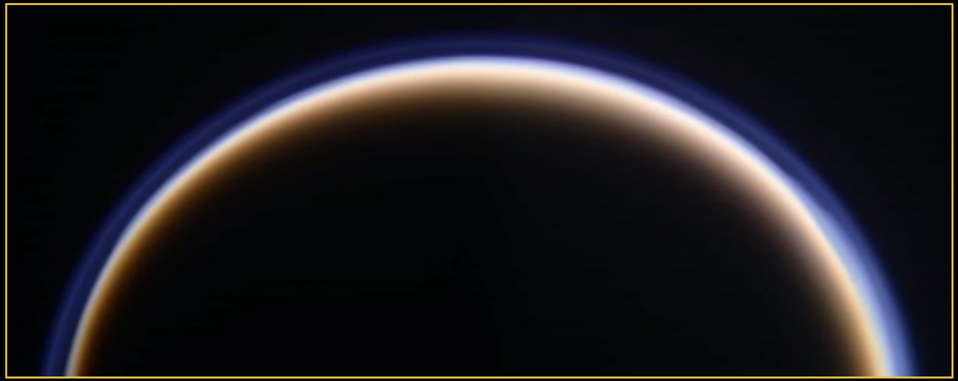
26 October 2004



Map of Titan's surface at near-infrared and infrared wavelengths (Seignovert et al. 2019)

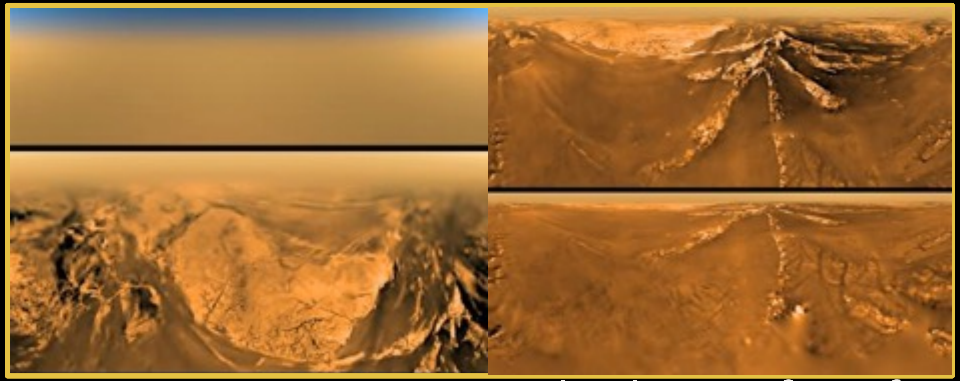
Titan has key ingredients known to be necessary for life

Energy



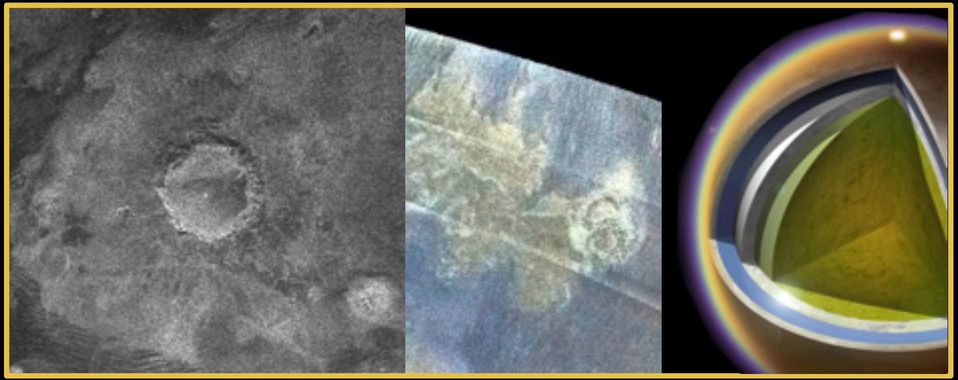
sunlight, photochemistry

Organic chemistry



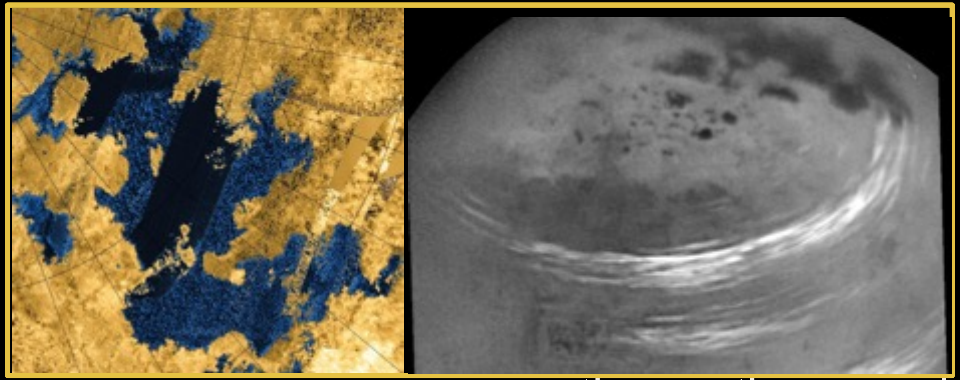
organics in atm & surface

Solvent: water



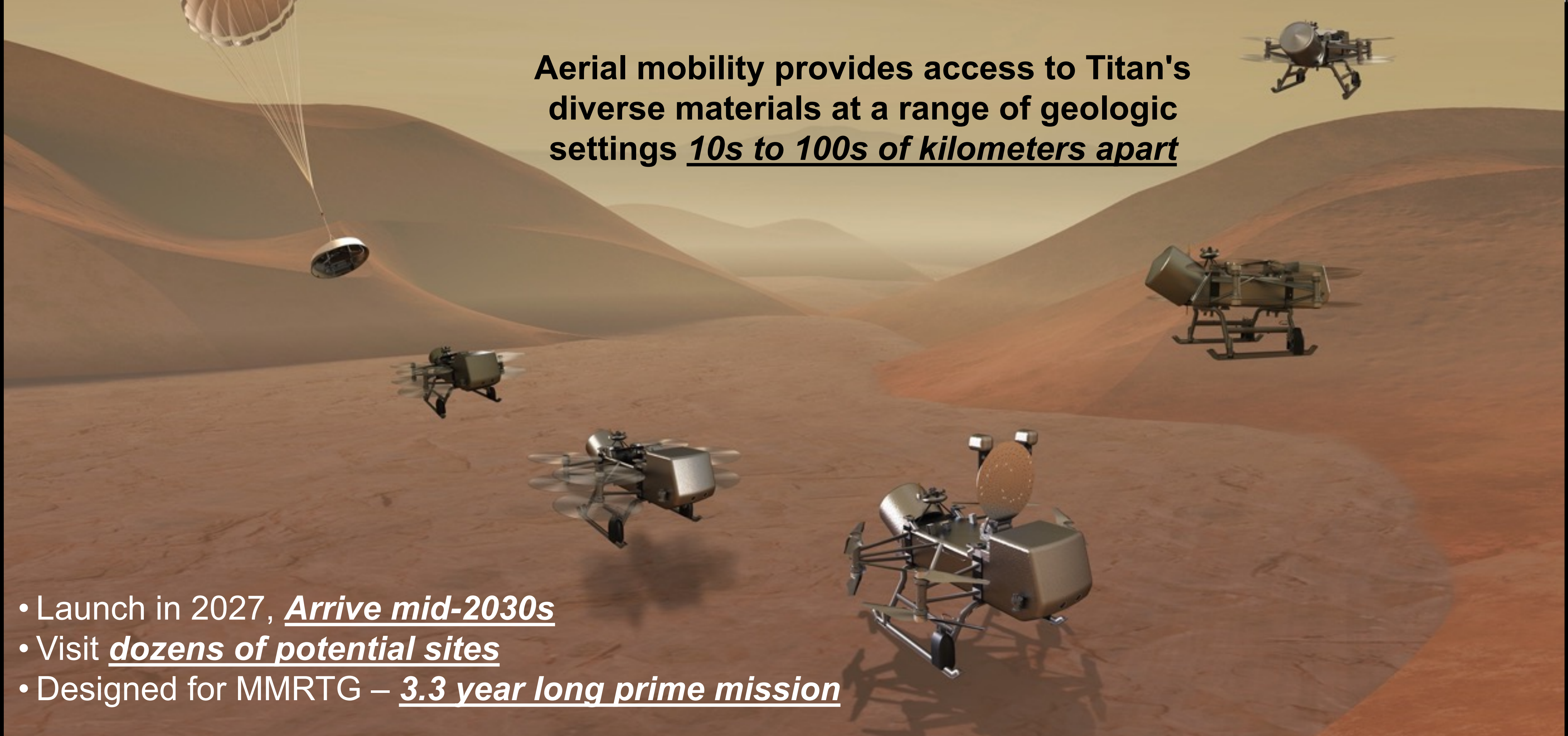
available on the surface in past

Solvent: methane



active methane cycle

Dragonfly: A relocatable lander to explore Titan's habitability and prebiotic chemistry



Aerial mobility provides access to Titan's diverse materials at a range of geologic settings *<u>10s to 100s of kilometers apart</u>*

- Launch in 2027, ***<u>Arrive mid-2030s</u>***
- Visit ***<u>dozens of potential sites</u>***
- Designed for MMRTG – ***<u>3.3 year long prime mission</u>***

IMAGE CREDIT: JOHNS HOPKINS APL

Lander with aerial mobility enables wide-ranging in situ exploration

NASA

DRAGONFLY

- Heavier-than-air mobility highly efficient at Titan
  (Lorenz 2000; Langelaan et al. 2017)
  - Titan's atmosphere 4x denser than Earth's
  - Titan's gravity 1/7th Earth's
- Powered by Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)
  - Charge battery used for flight & science
  - Waste heat maintains nominal thermal environment in lander
  - Enables highly capable scientific payload and operations
- Direct-to-Earth communication

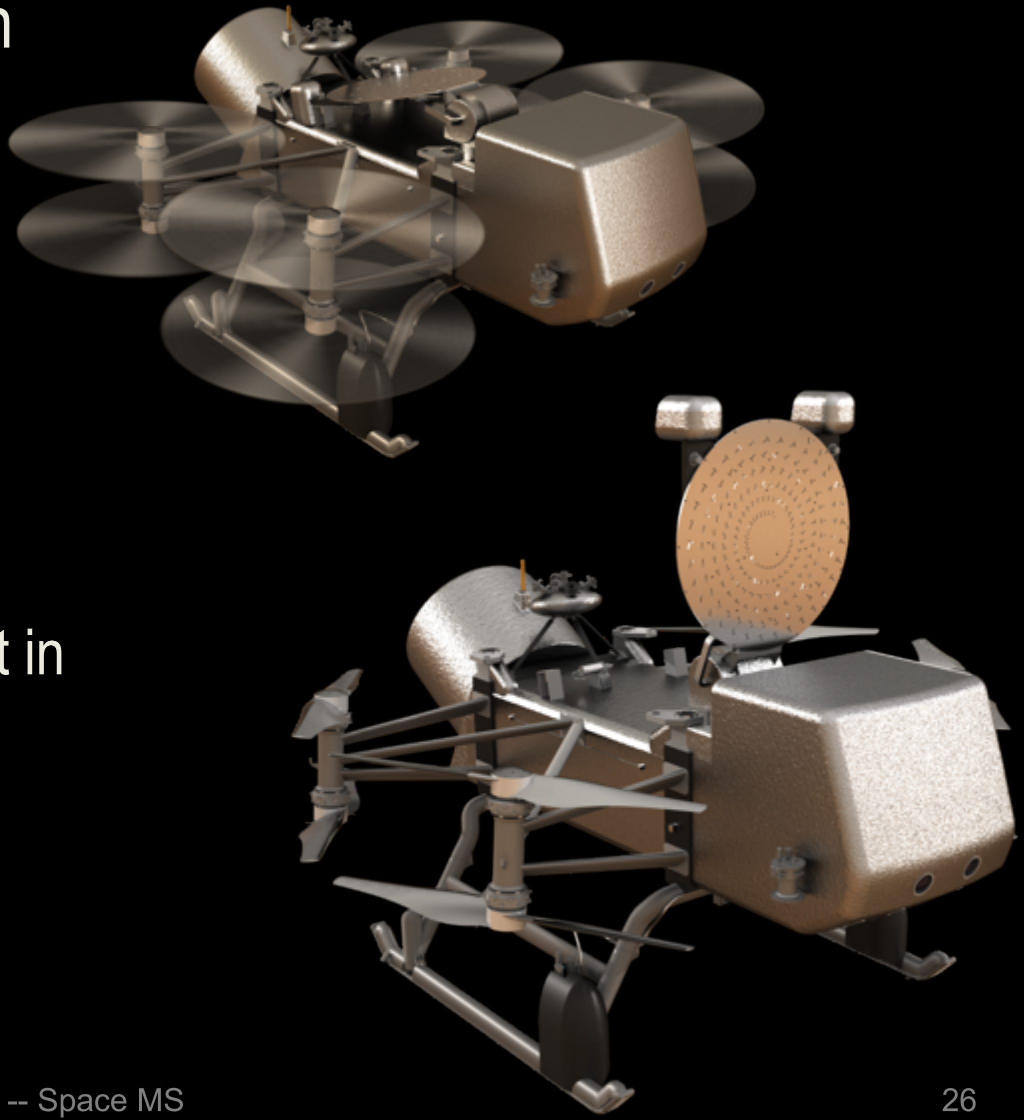


IMAGE CREDIT: JOHNS HOPKINS APL

Landing site and region of exploration

- Initial landing site provides access to a variety of materials
  - Sand dunes: organic sediments
  - Interdune areas: materials with a water-ice component
  - **Selk impact crater**: materials where organics may have mixed with liquid water impact melt

Organic Sand
Interdune Materials
Ejecta Blanket
Impact Melt

IMAGE CREDIT: JOHNS HOPKINS APL

Science goals and payload focus on chemical inventory and opportunities for materials to interact

- **DraMS: Mass Spectrometer (GSFC, CNES)**
- DrACO: Drill for Acquisition of Complex Organics (Honeybee Robotics)
- DraGNS: Gamma-ray Neutron Spectrometer (APL, LLNL, GSFC, Schlumberger PNG)
- DraGMet: Geophysics & Meteorology Package (APL, JAXA Lunar-A seismometer)
- DragonCam: Camera Suite (MSSS)

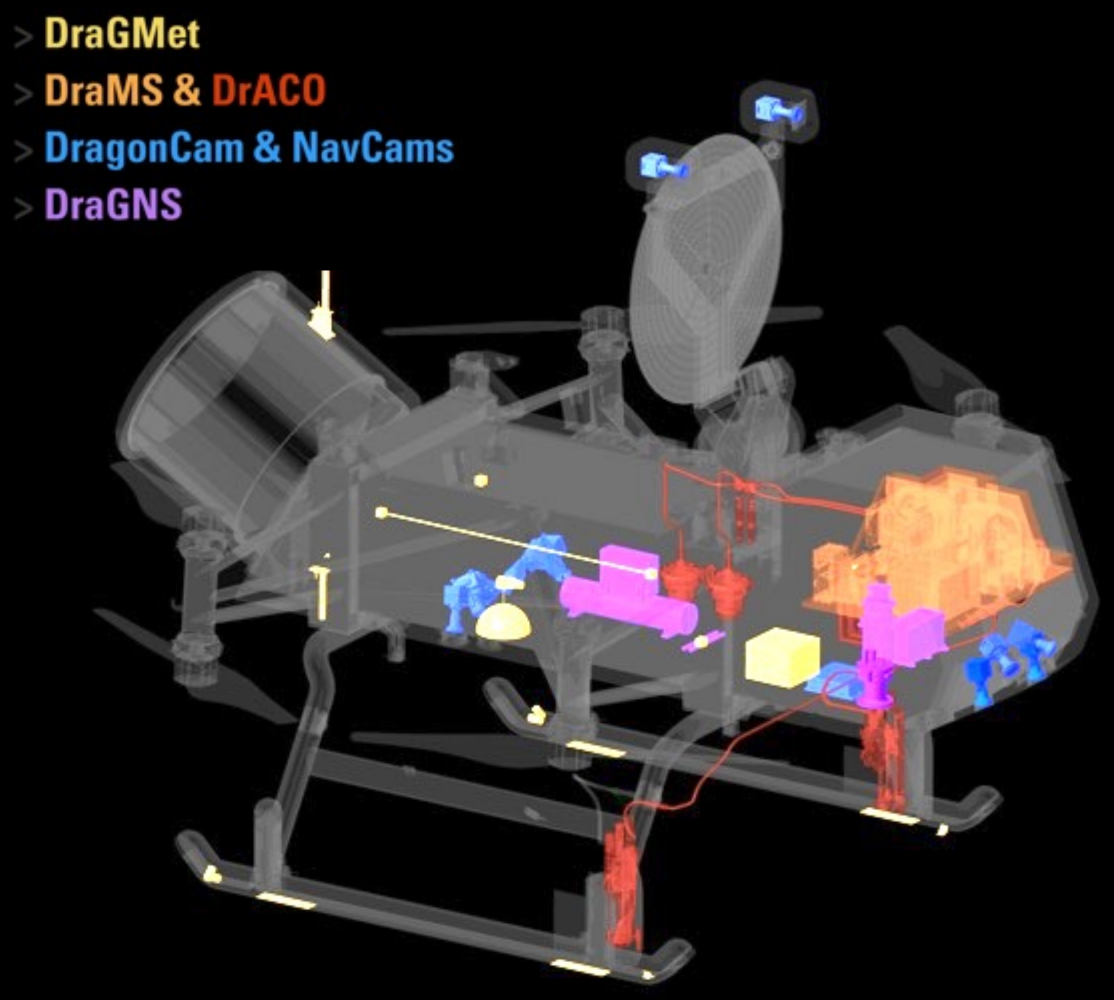


IMAGE CREDIT: JOHNS HOPKINS APL

Dragonfly Mass Spectrometer (DraMS)

- Inherits from SAM and MOMA - Mars Instruments
- Dual-Inlet Ion Trap Mass Spectrometer
  - Arevalo Jr. et al. *IEEE* 2015
- Uses two modes to assess chemical composition of surface materials:
  - Laser Desorption MS for high molecular-weight organics
    - Grubisic et al. *IJMS* 2021
  - Gas Chromatography MS with derivatization for biologically-relevant molecules
  - Sample carousel (60 cups total) delivers samples to each 'inlet'

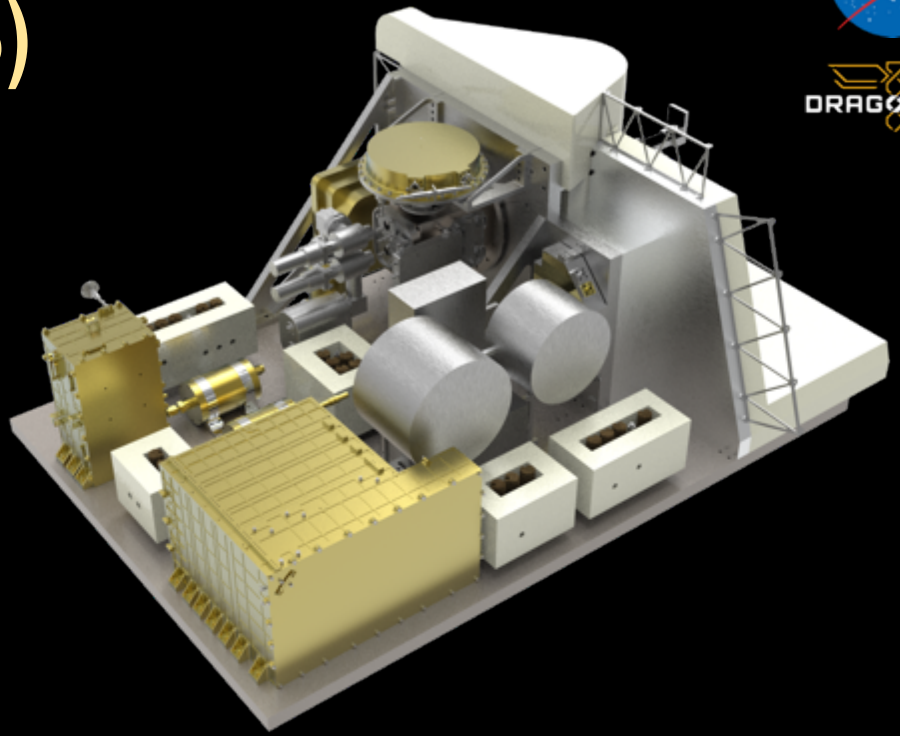
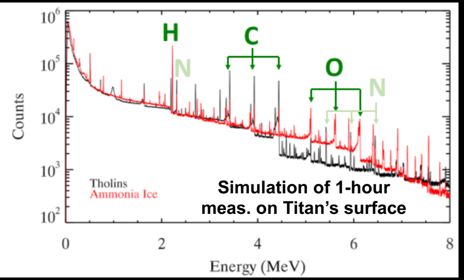


IMAGE CREDIT: NASA/GSFC

Characteristic	Predicted Performance
Mass Range	15 – 1950 Da
Mass Resolution	0.4 – 3 Da (FWHM)
Mass Accuracy	± 0.4 Da
Ion polarity	Positive and Negative ion detection
Limit of detection	100 ppbw organics in surface sample
GC Columns	Two; General and Chiral separation

Dragonfly will provide a detailed investigation of carbon compounds on Titan's surface

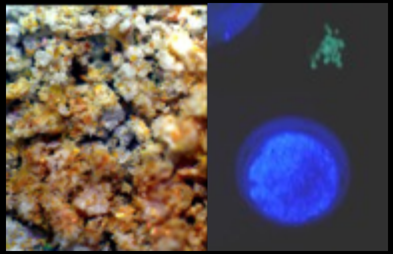
Site characterization and distribution of carbon



Gamma-Ray & Neutron Spectroscopy

Elemental abundances identify C-containing materials & layering

CH_4 cycle & subsurface reservoirs



Microscopic Imaging

Compositional variety at grain scale with fluorescence

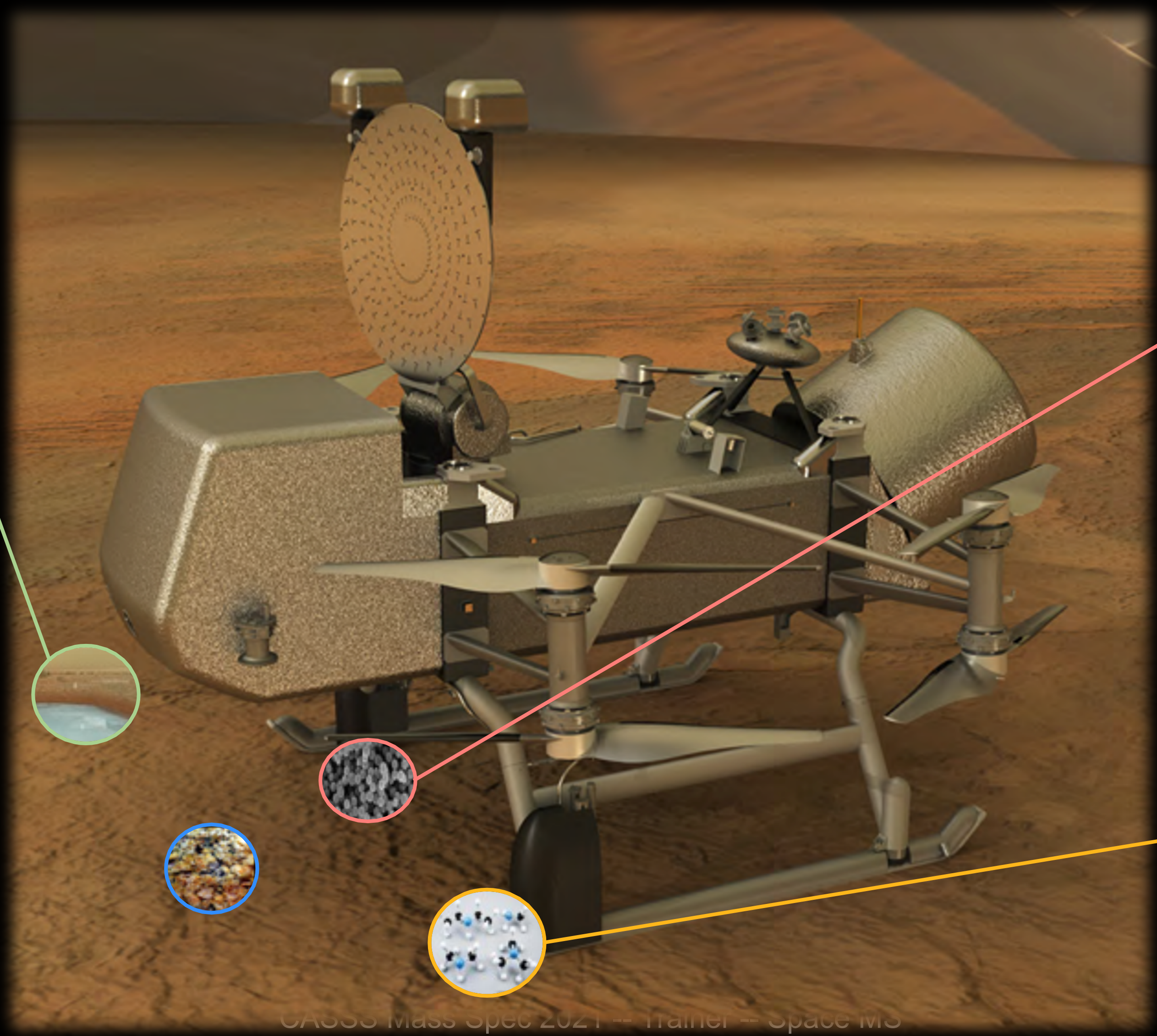
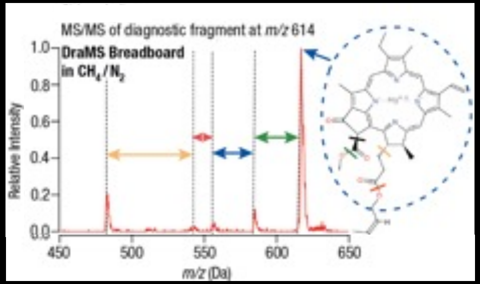


IMAGE CREDIT: JOHNS HOPKINS APL

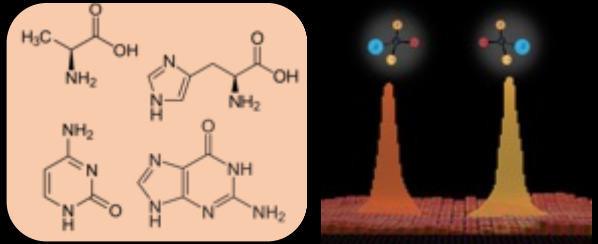
Molecular composition of surface materials



Broad Survey Mass Spectrometry

Organic inventory of high molecular weight organics

Preferential patterns and structural elucidation

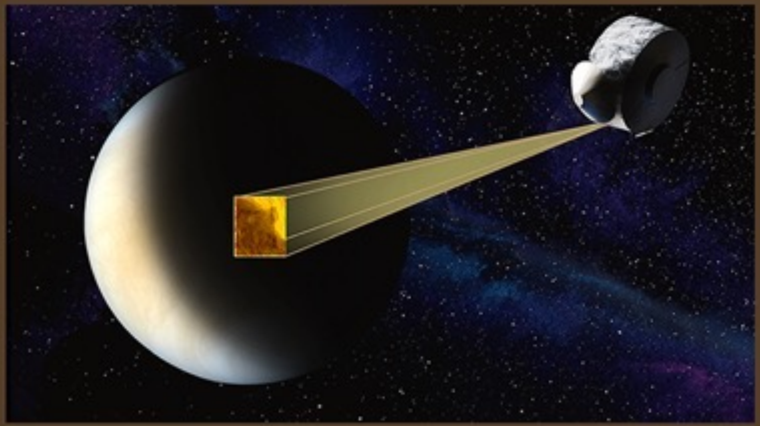


Sensitive and Selective MS

Gas chromatography targeting potential biomolecules

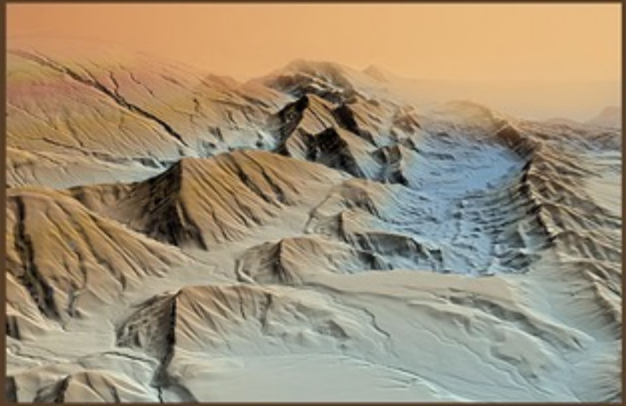
Search for enantiomeric excess

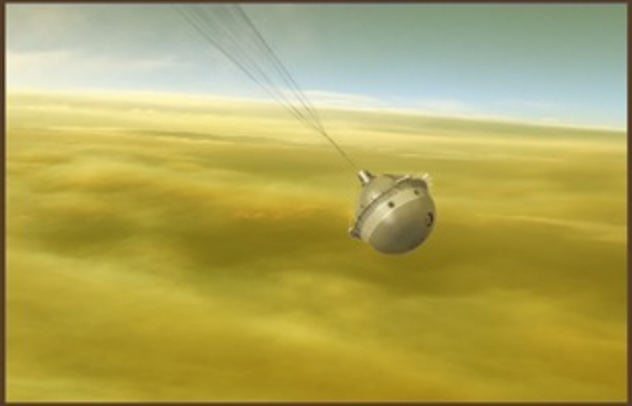
Principal Investigator
Dr. James B. Garvin, NASA's GSFC
Deputy Principal Investigators
Dr. Stephanie A. Getty, NASA's GSFC
Dr. Giada N. Arney, NASA's GSFC



DAVINCI

Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging





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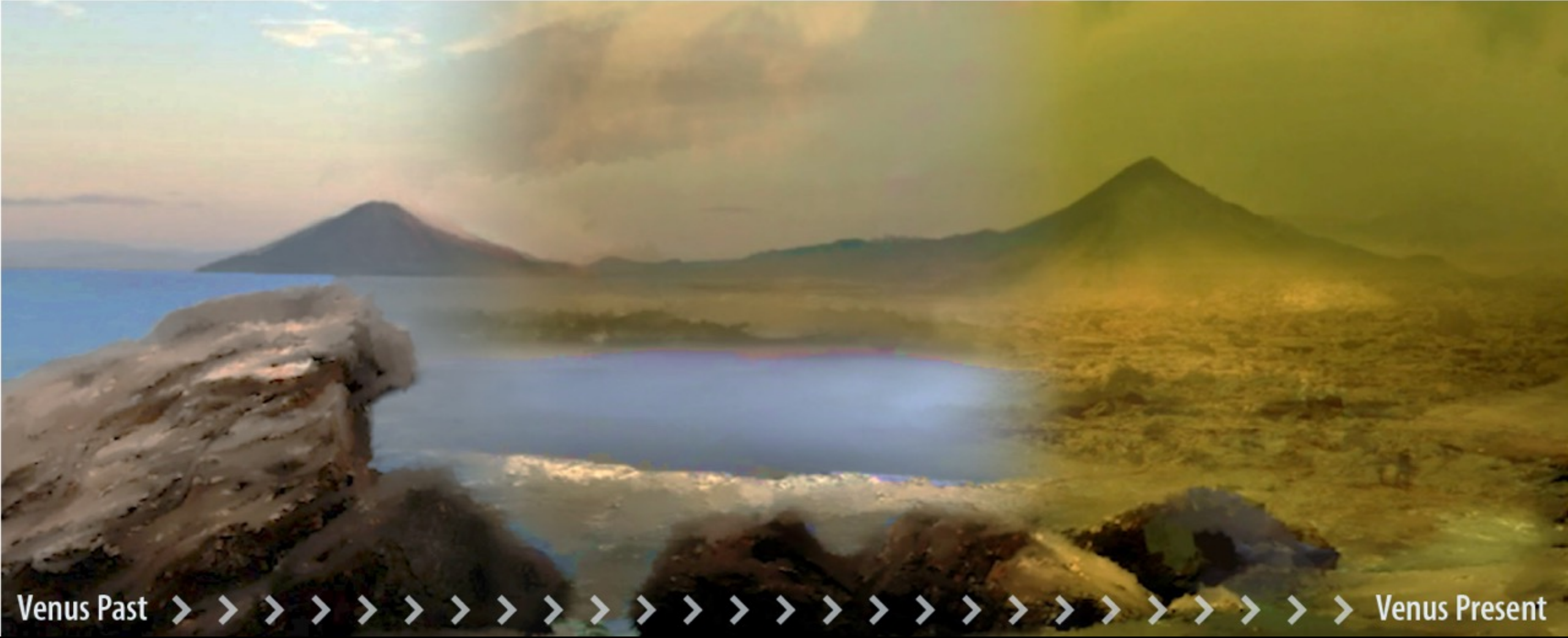
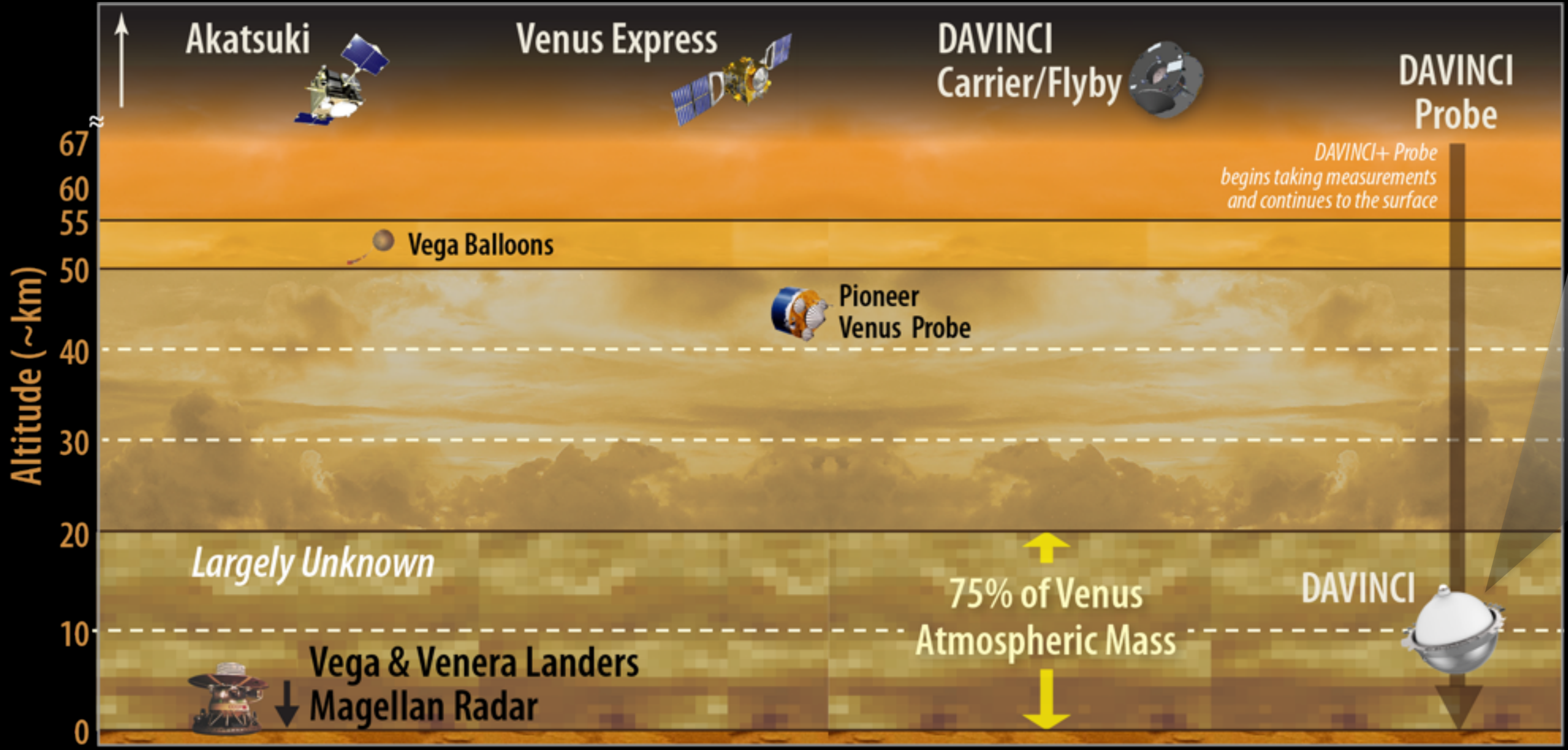


"Ultimately, the assessment of whether or not a planet is habitable will need to be embedded in the context of the outcomes of terrestrial exoplanet evolution."

- 2018 *Exoplanet Science Strategy* report

Venus deep atmosphere is essentially unknown



Venus Mass Spectrometer
QMS + enrichment

- Major chemical species
- Noble gases & isotopes

Acknowledgments

MSL Science & Engineering Teams
Dragonfly Team
DAVINCI Team
NASA Science Exploration

Image credit: NASA/JPL-Caltech/Space Science Institute