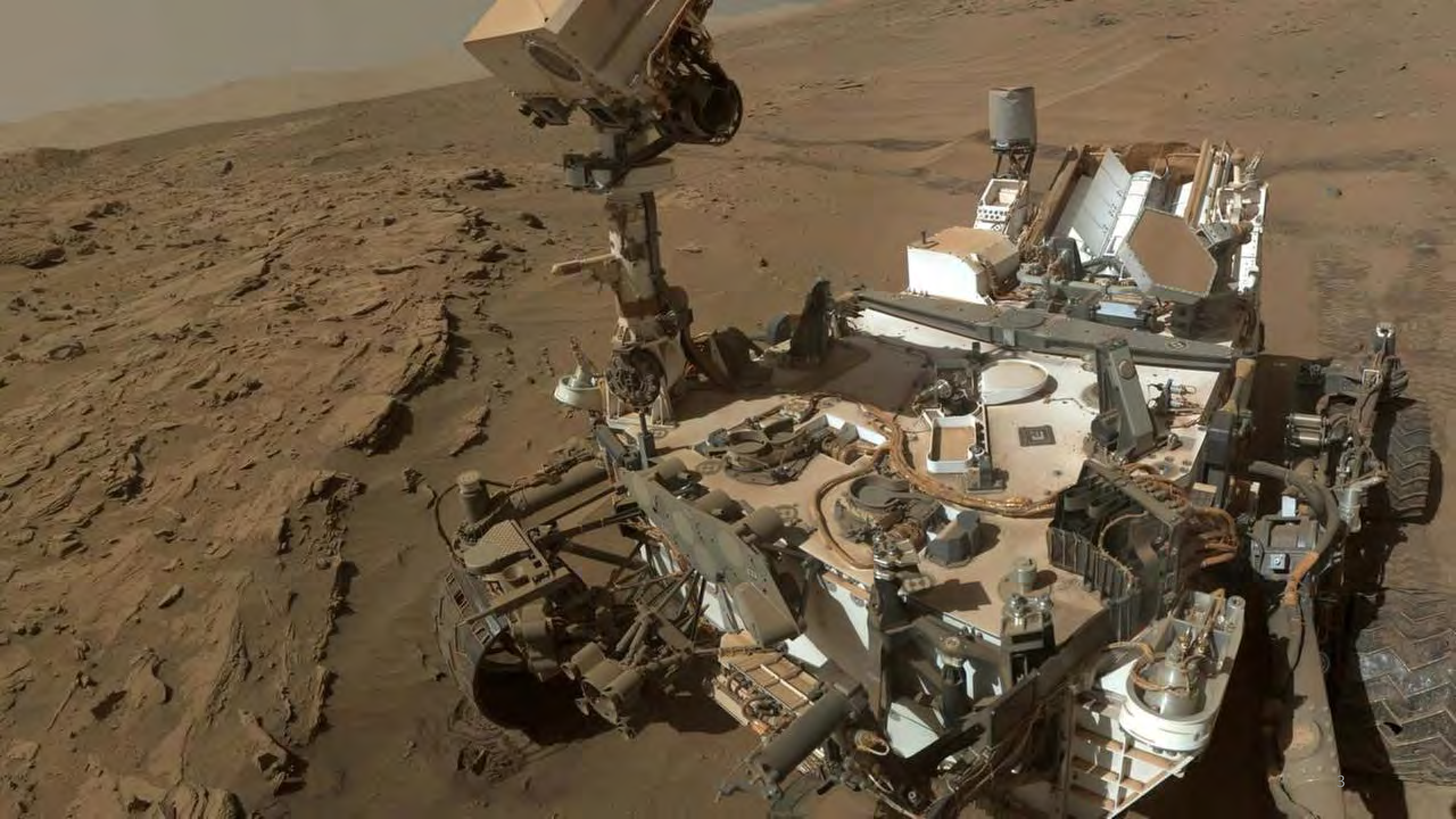
Jet Propulsion Laboratory
California Institute of Technology

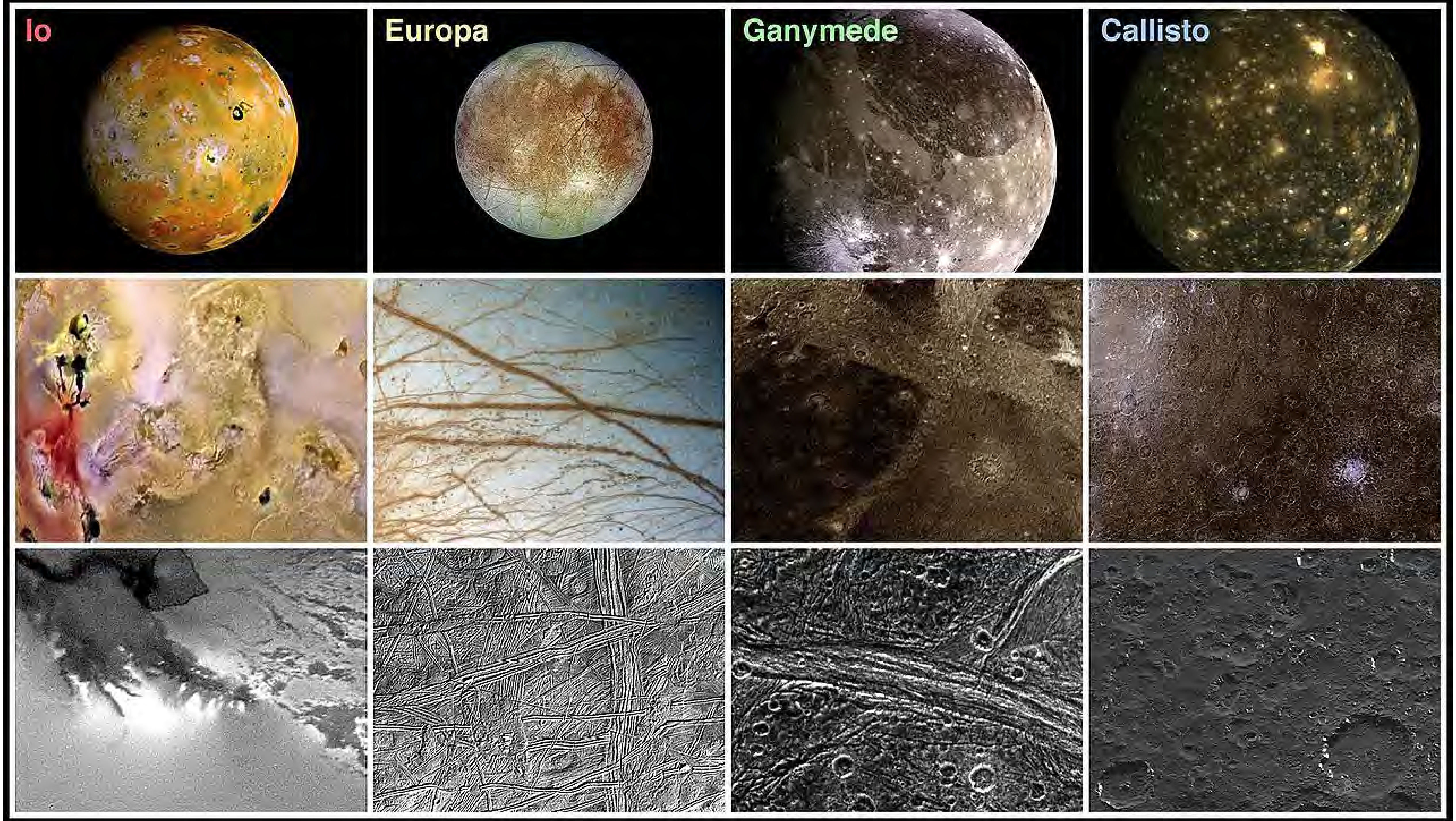
Spacecraft & 3D Packaging Technologies: Infusion and Opportunity

Dr. Douglas J. Sheldon

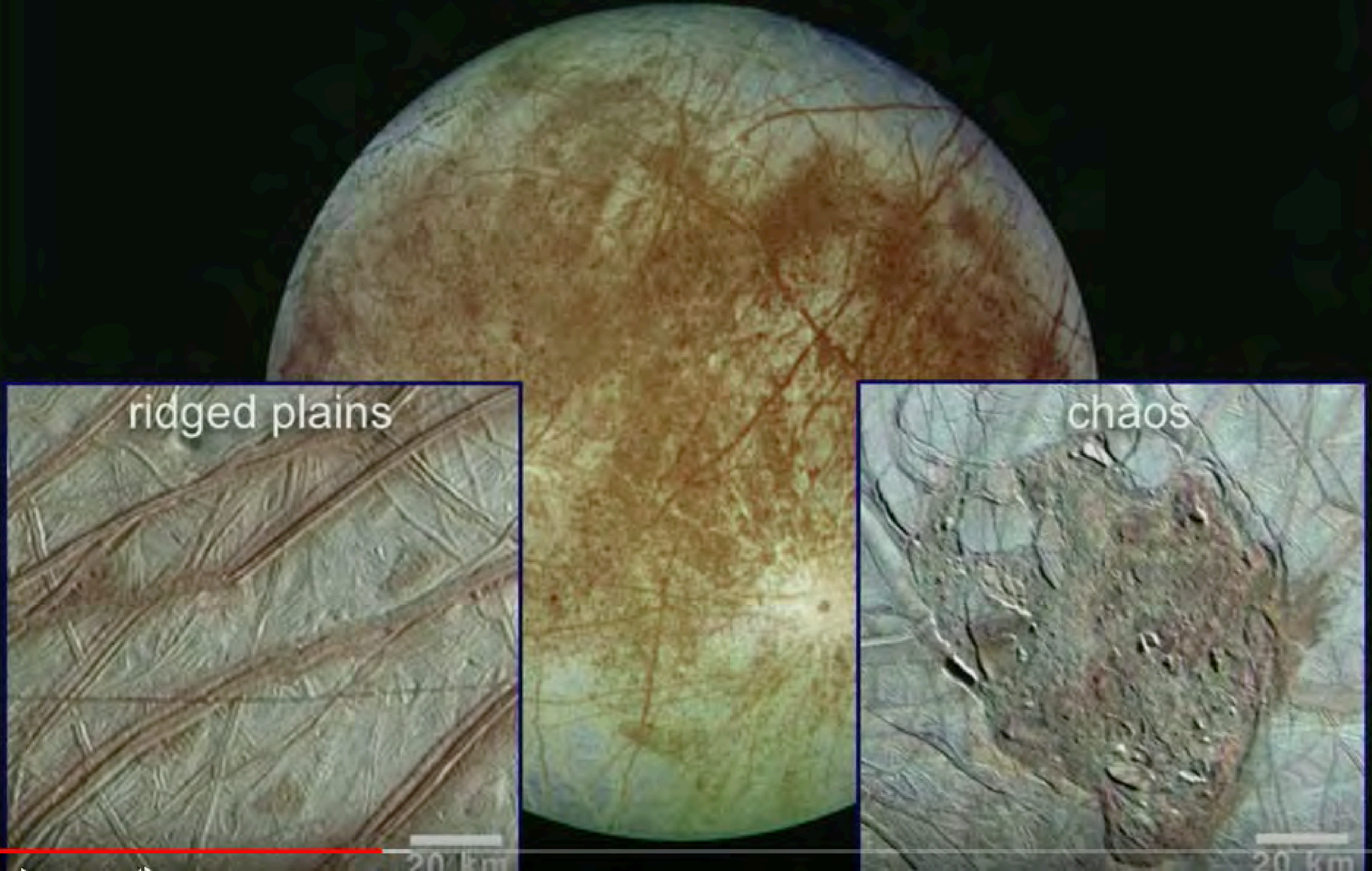
Assurance Technology Program Office (ATPO) Manager
Office of Safety and Mission Success
Jet Propulsion Laboratory, California Institute of Technology

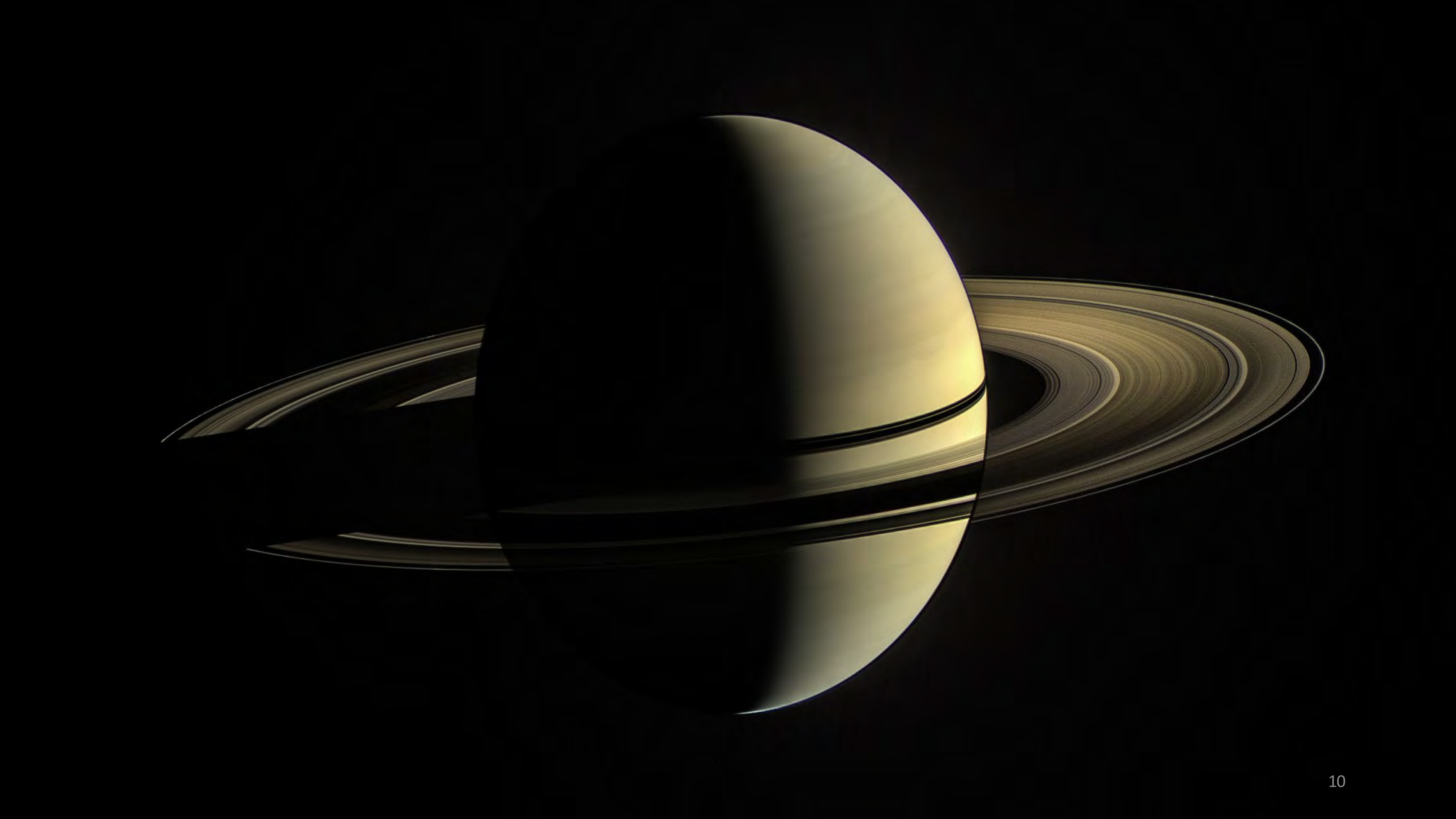


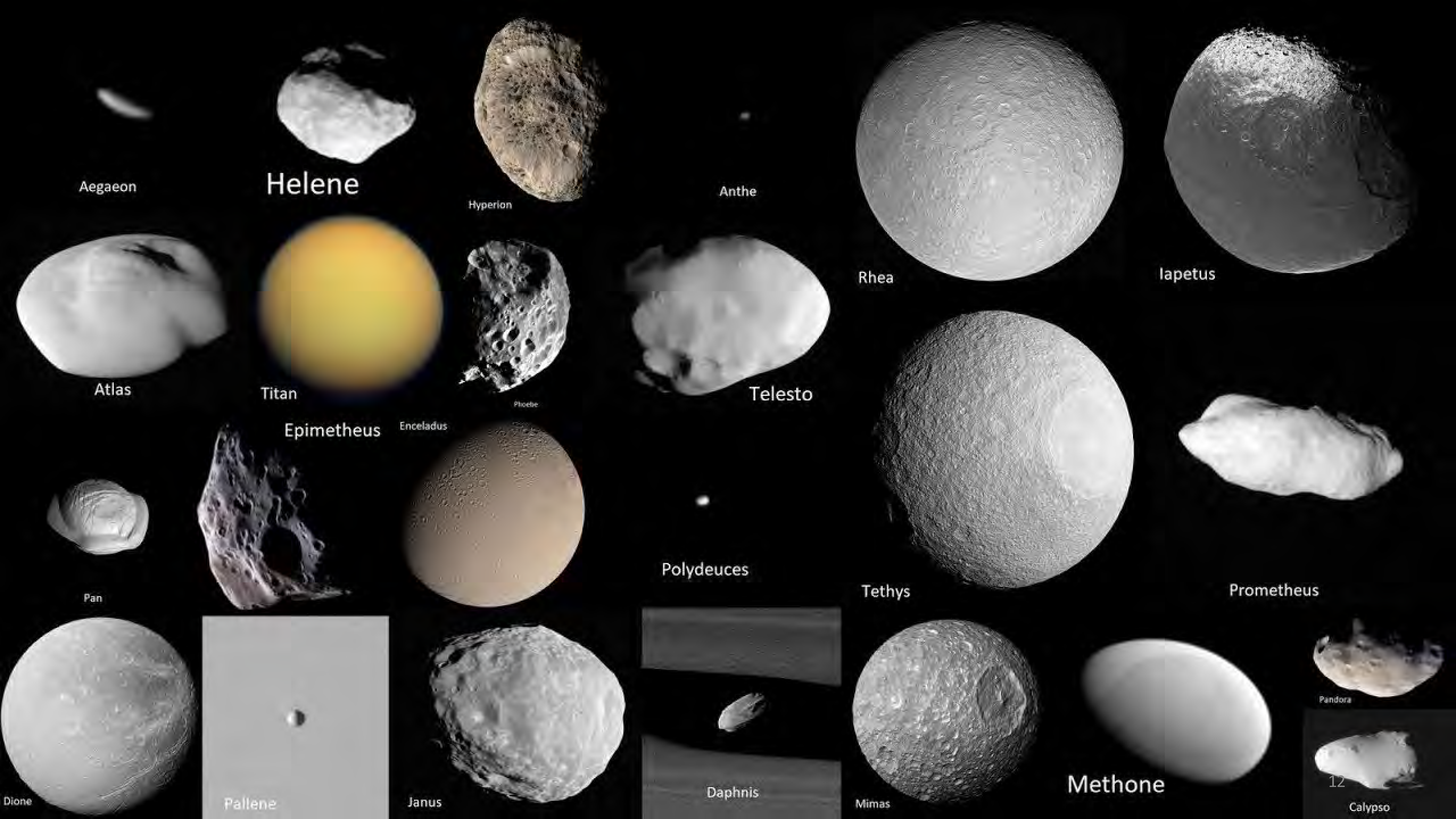

Curiosity

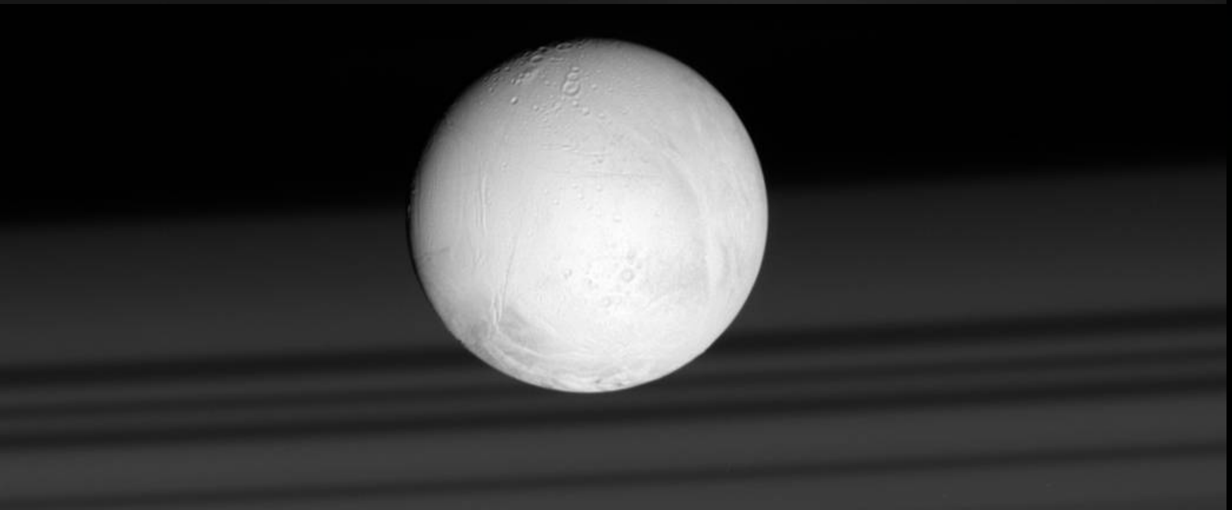

Io
Europa
Ganymede
Callisto

Europa's Surface





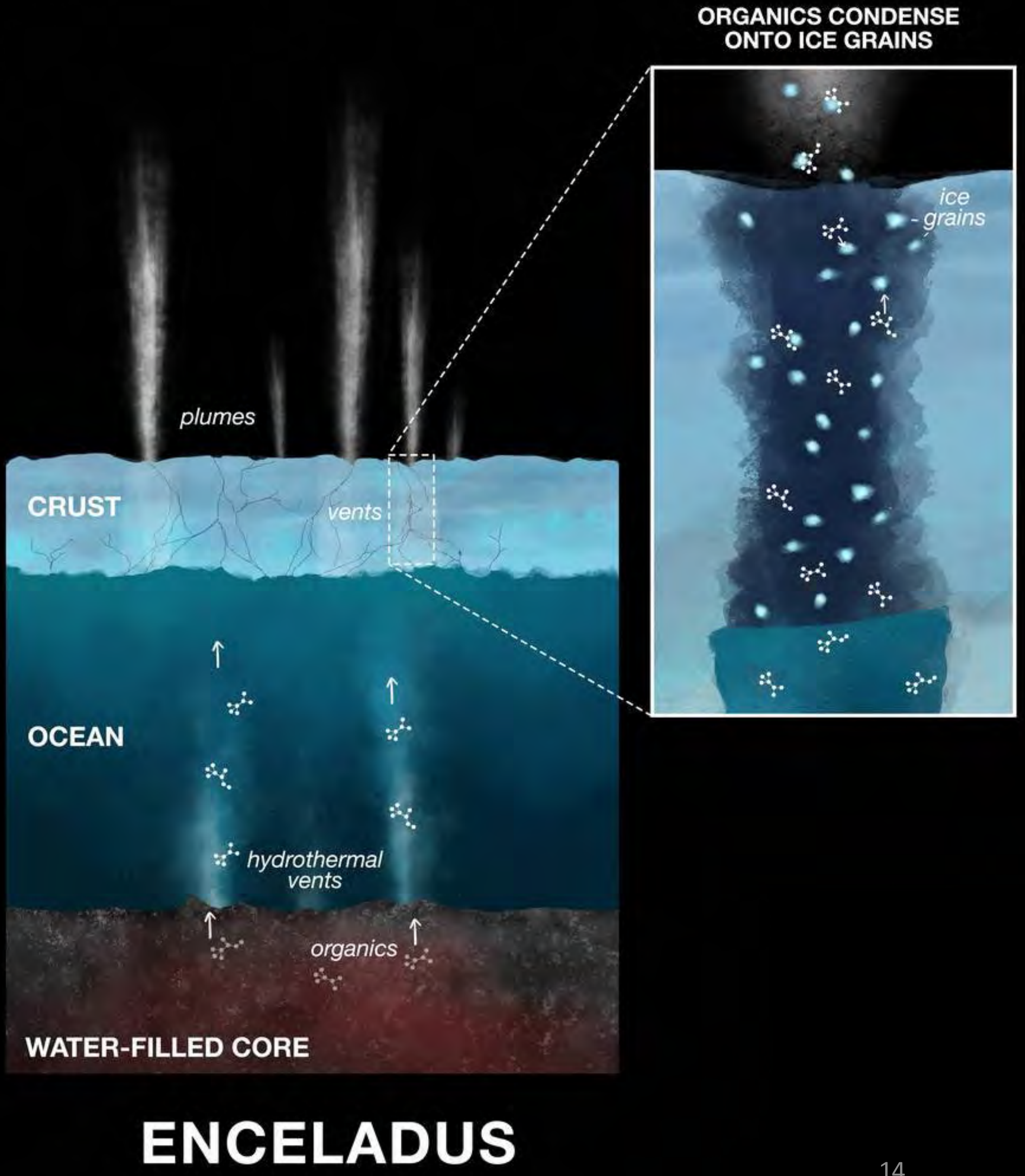

Aegaeon
Helene
Hyperion
Anthe
Rhea
Iapetus
Atlas
Titan
Phoebe
Telesto
Epimetheus
Enceladus
Polydeuces
Tethys
Prometheus
Pan
Dione
Pallene
Janus
Daphnis
Mimas
Methone
Pandora
Calypso



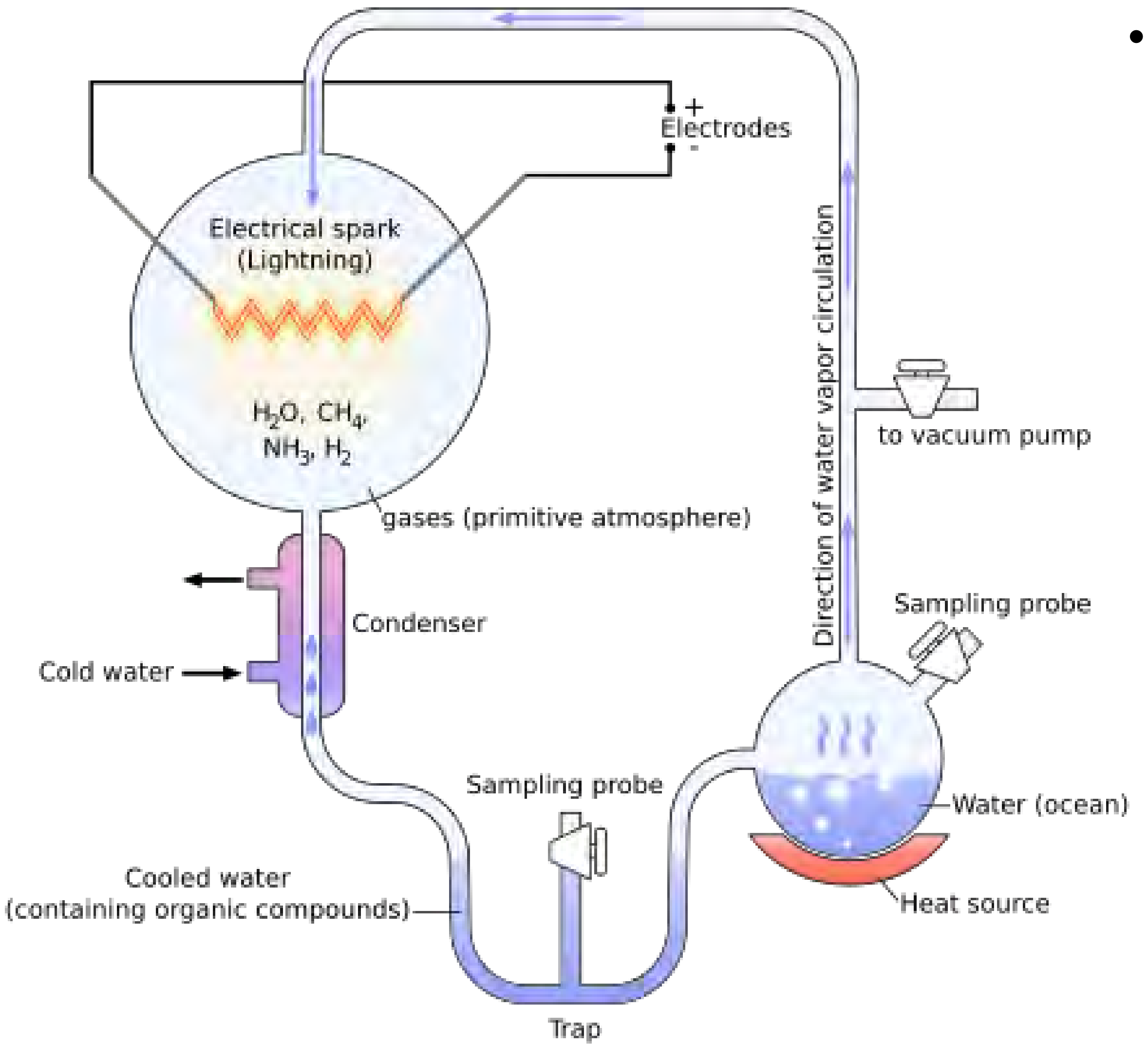
Macromolecular organic compounds from the depths of Enceladus

“We report observations of emitted ice grains containing concentrated and complex macromolecular organic material with molecular masses above 200 atomic mass units.”

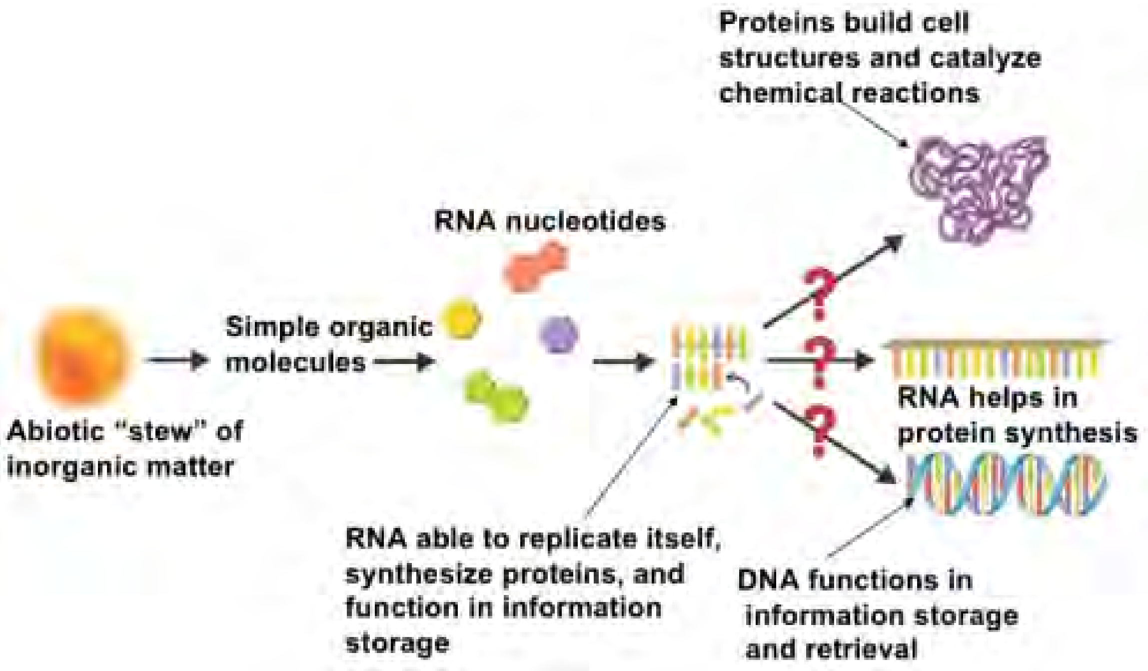
Nature volume 558, pages564–568 (2018)



Miller–Urey experiment (1952) & the origins of life



- The classic Miller-Urey experiment demonstrated that amino acids, important building blocks of biological proteins, can be synthesized using simple starting materials under simulated prebiotic terrestrial conditions



OWLS Project - Looking for life on Ocean Worlds

Molecular analyses

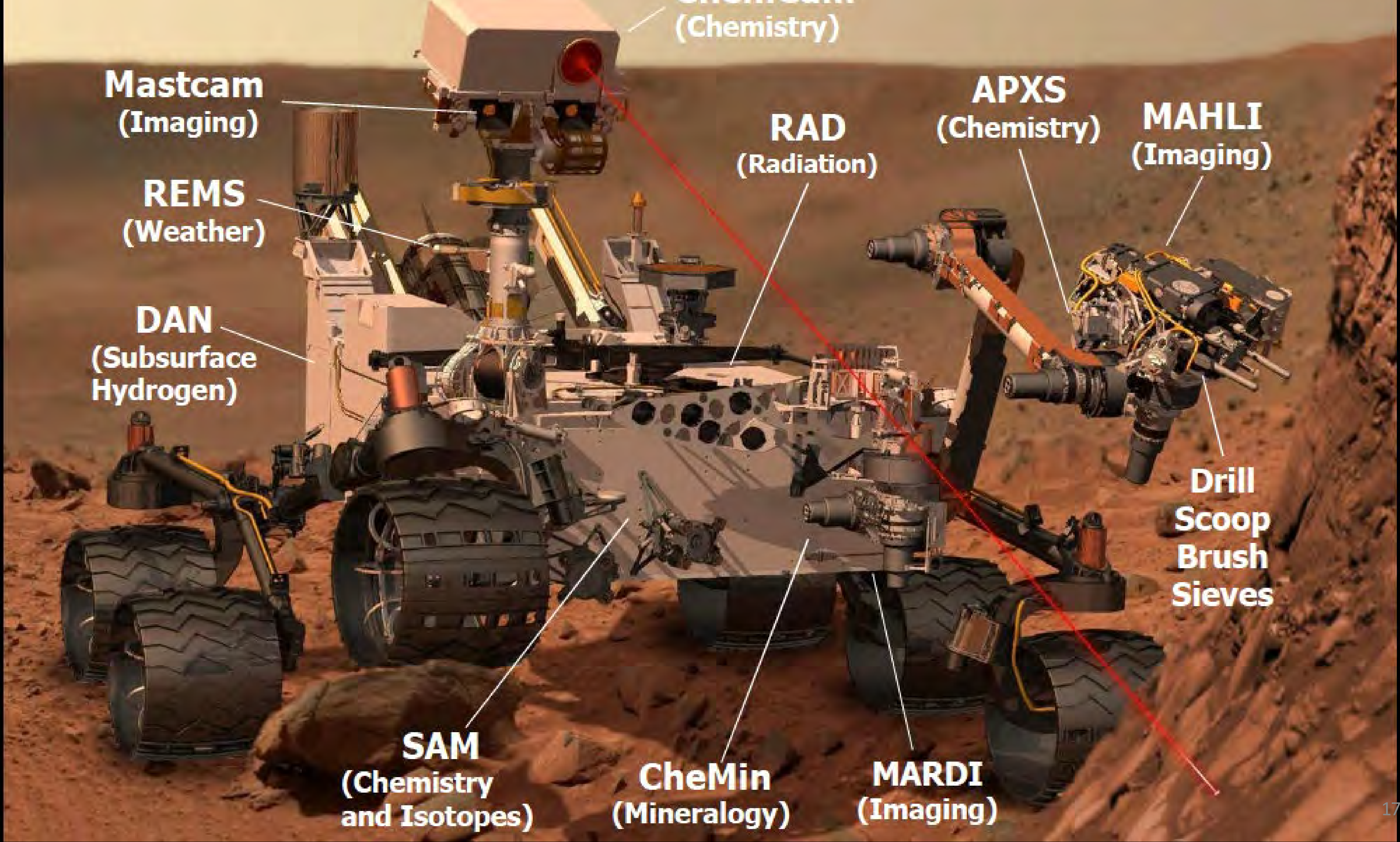
- *Capillary Electrophoresis-Laser Induced Florescence (CE-LIF) detection for amino and carboxylic acids*
- *Capillary Electrophoresis Capacitively-Coupled Contactless Conductivity Detector (CE-C4D) for detecting charged species*
- *Capillary Electrophoresis-Electrospray Ionization coupled to Mass Spectrometry (CESI-MS) for broad-based detection and characterization of collections of organic molecules.*

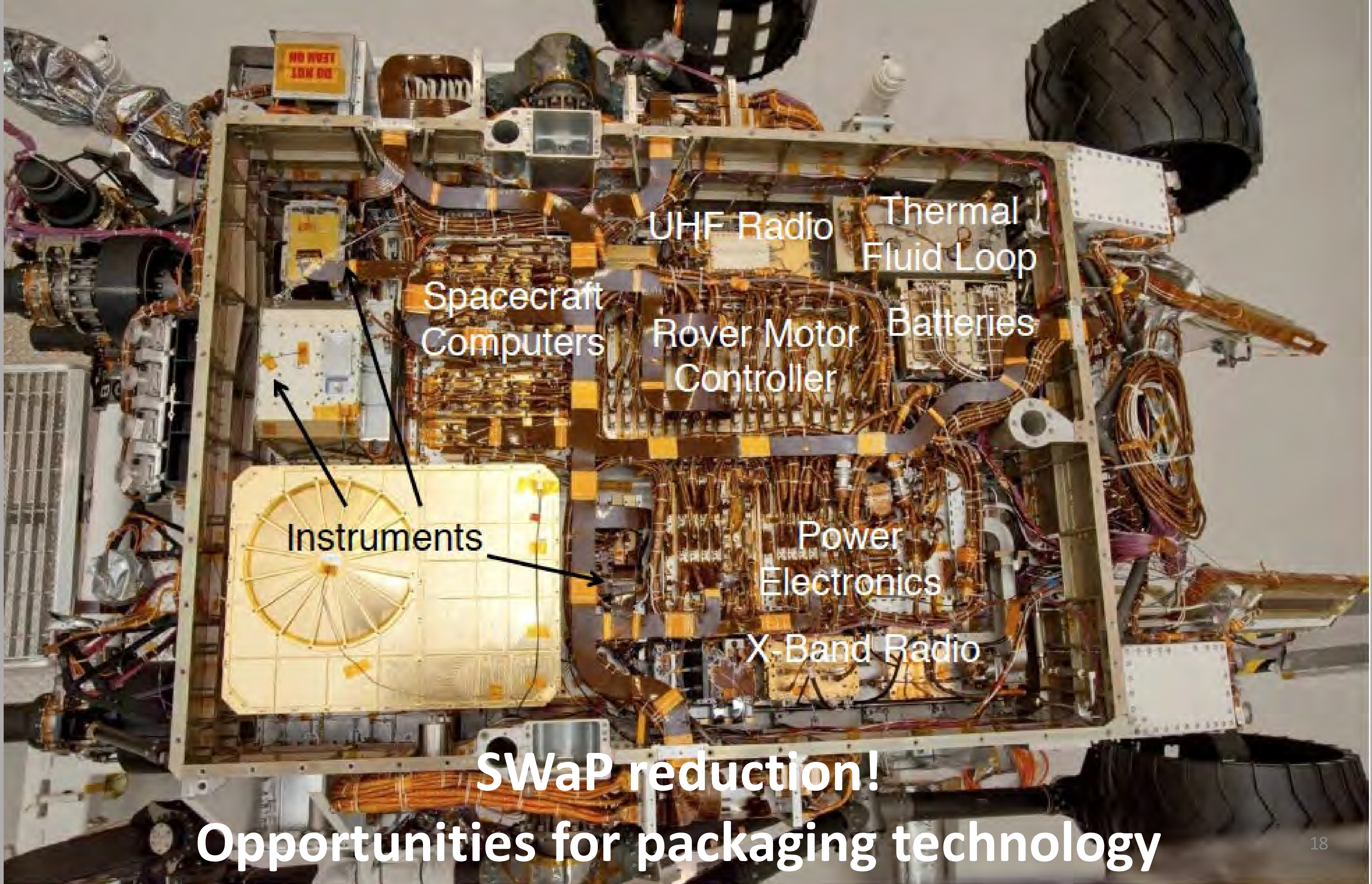
Cellular Analysis

- *Digital Holographic Microscope (DHM) to detect number, composition and motion of particles*
- *Volume Fluorescence Imager (VFI) to identify biomolecules associated with the objects identified in the DHM.*

Integrated lasers and electronics and high voltage required – Heterogenous Packaging Opportunity!

Science instruments on MSL



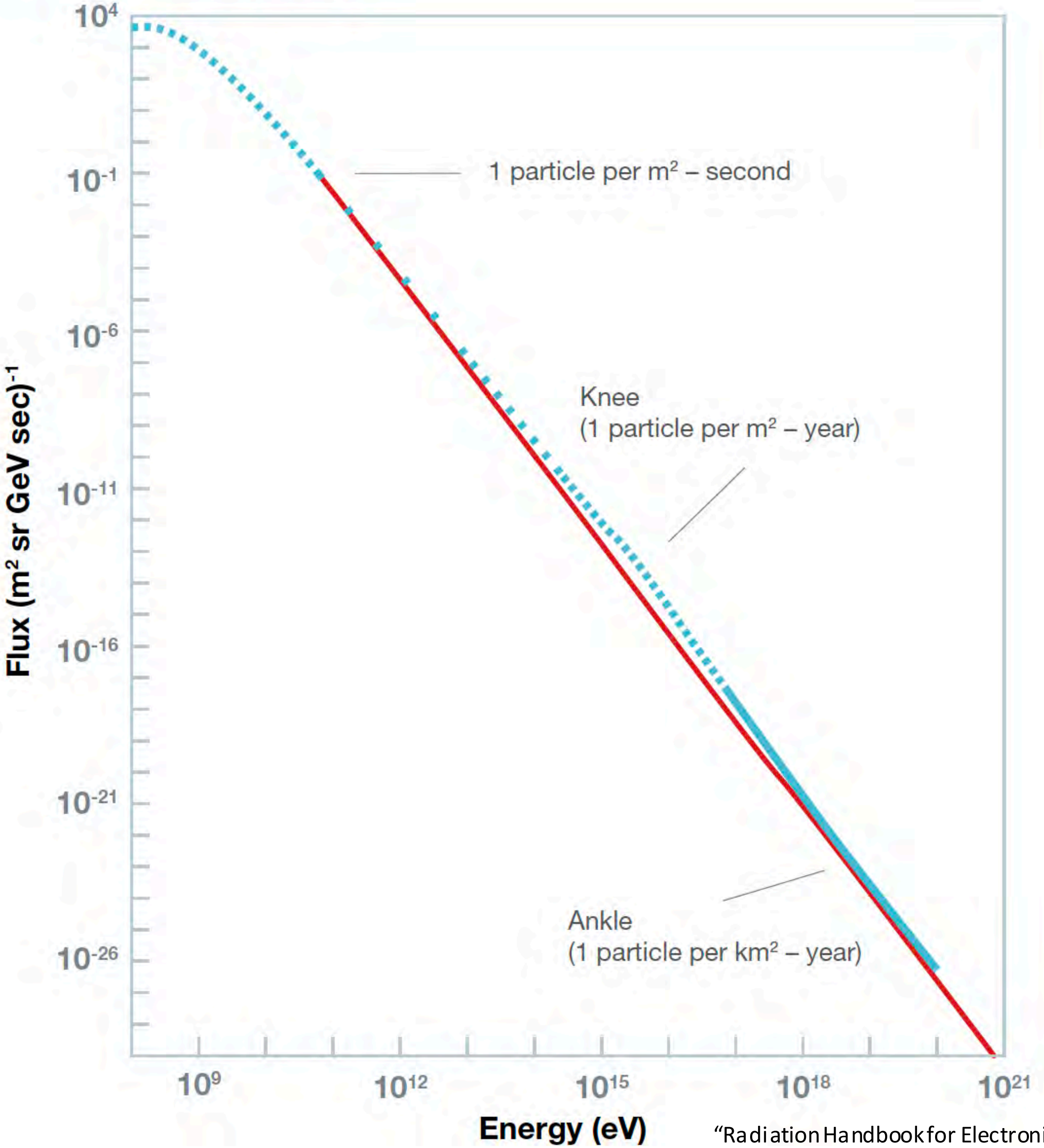


SWaP reduction!

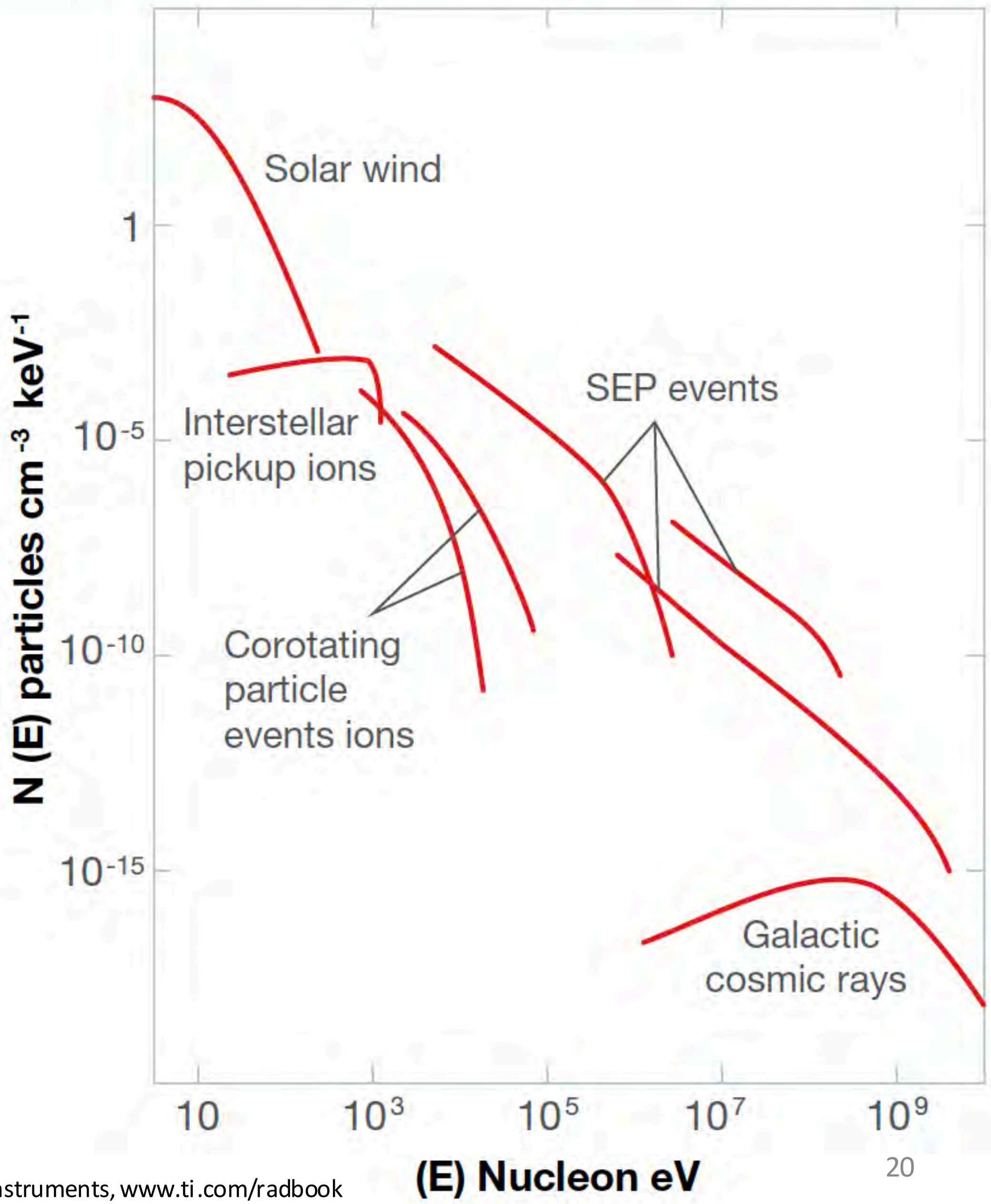
Opportunities for packaging technology

But does it work in space...?

Flux of cosmic rays



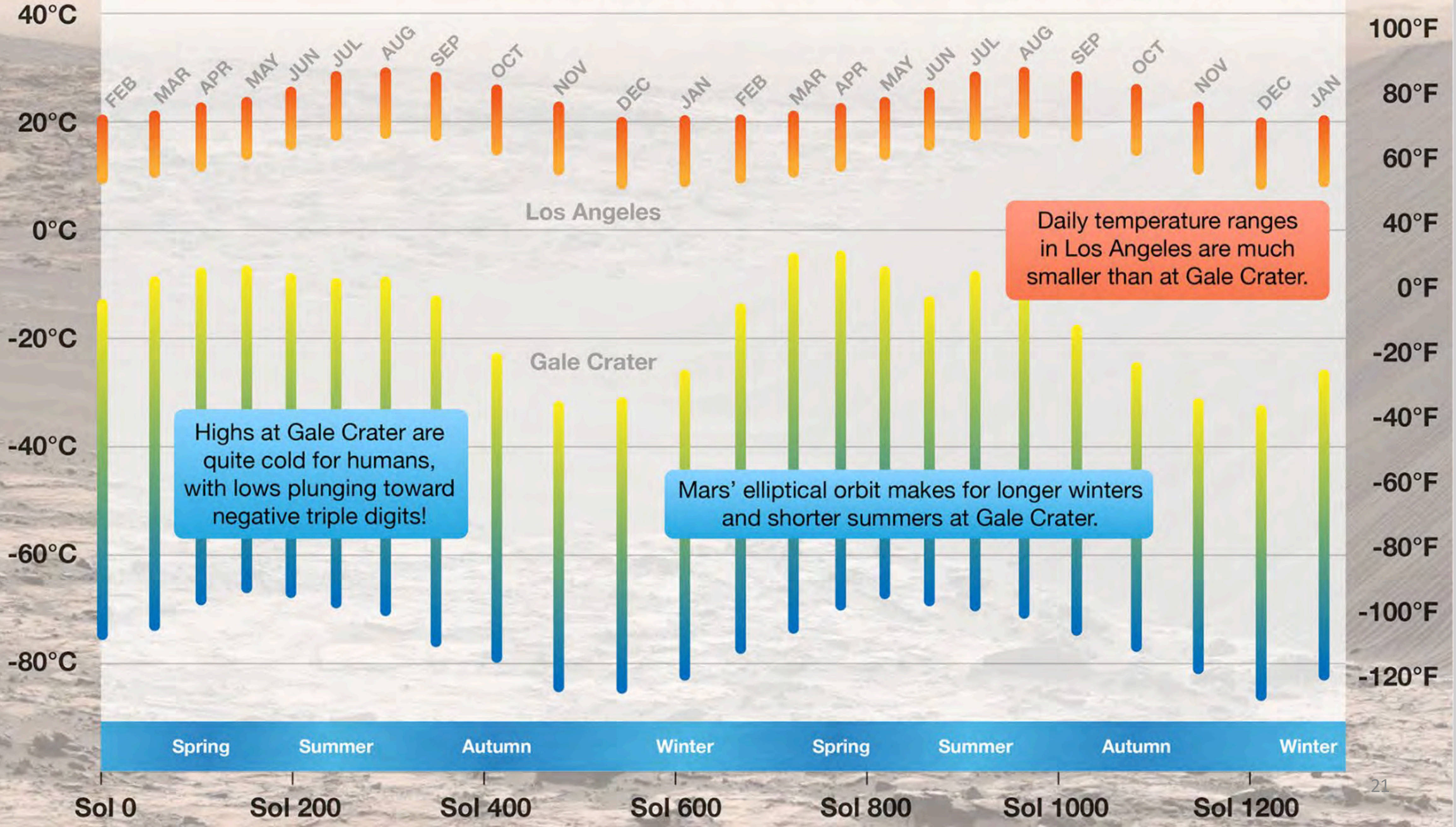
Representative proton energy spectra at 1 AU



"Radiation Handbook for Electronics", Texas Instruments, www.ti.com/radbook

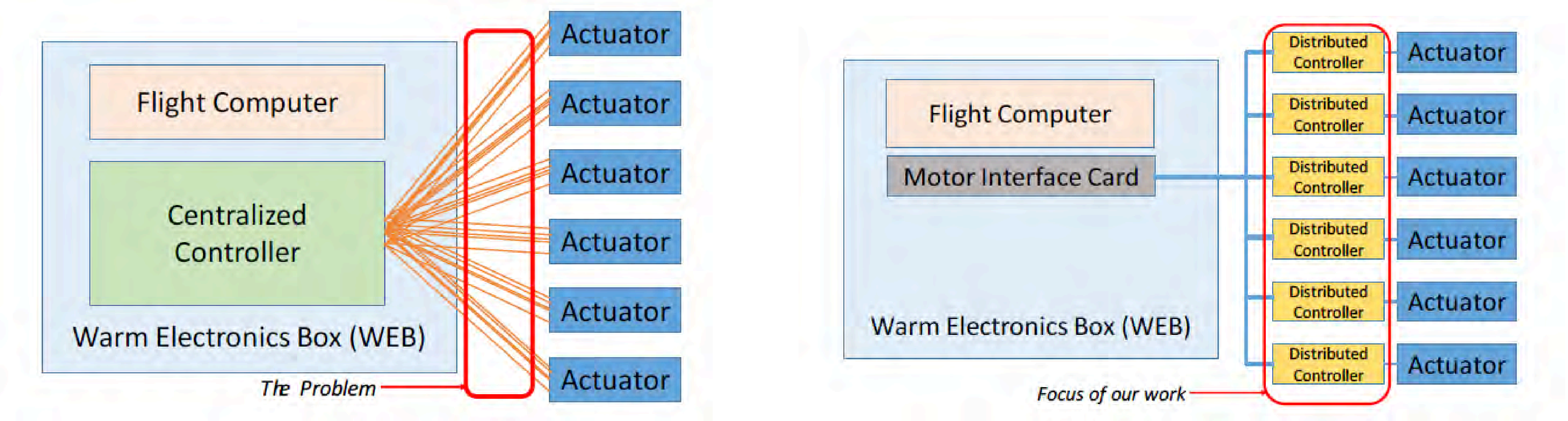
Seasonal Temperature Ranges at Gale Crater

(with temperatures in Los Angeles at equivalent seasonal points)



Cold Survivable Electronic Packaging

Rover System	Pathfinder	MER	MSL	MSL w/DMC	Benefit
Total Wiring Mass	1.4 Kg	10.4 Kg	52.7 Kg	37 Kg	35.2 Kg (90%) reduction in actuator harness mass
Actuator Wiring Mass	0.35 Kg	3.0 Kg	17.4 Kg	1.8 Kg	
Percentage of Actuator Harness Mass	25 %	29 %	33 %	5 %	

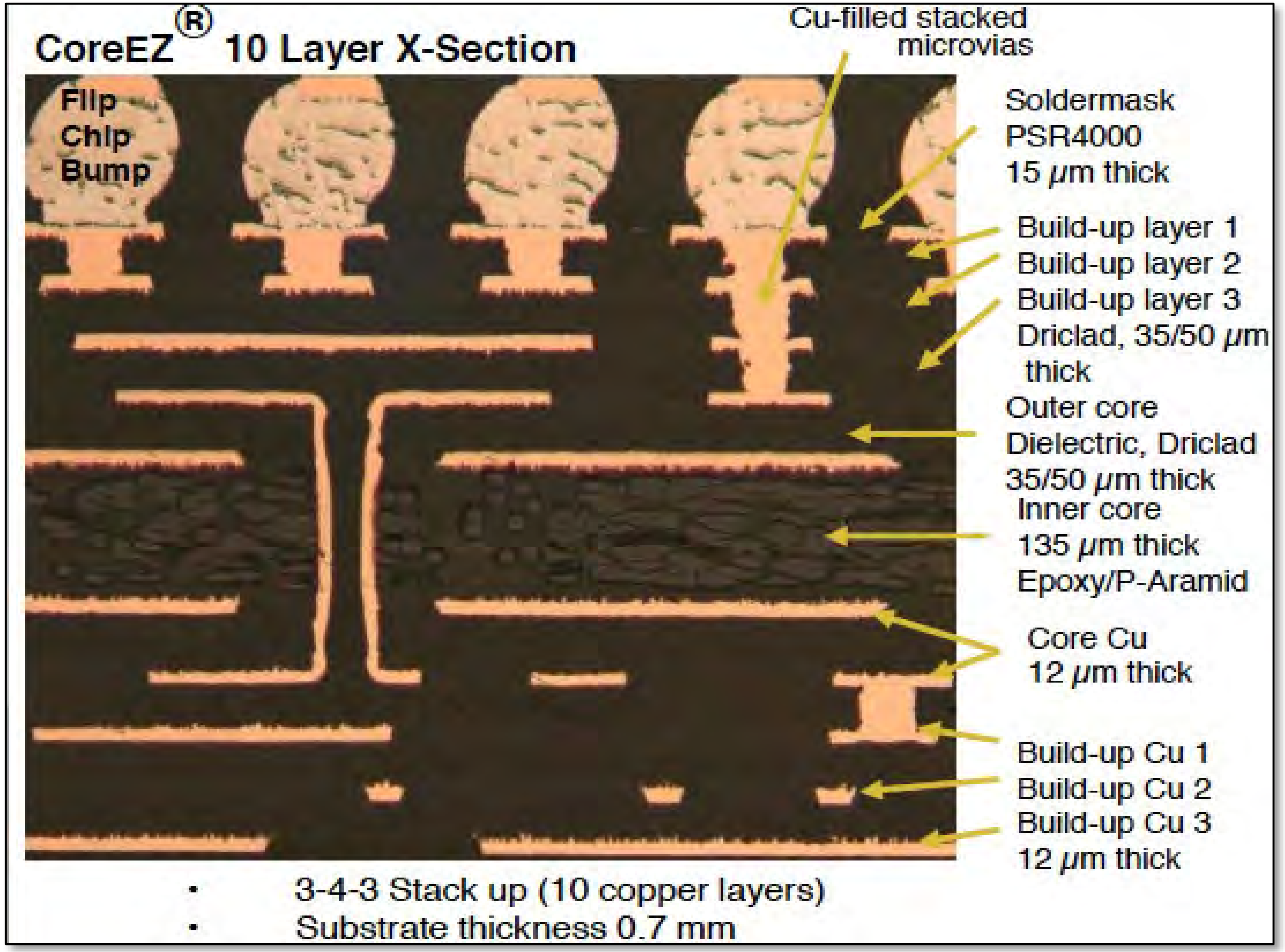


- The goal of our effort is to decrease in the volume (10x), and mass (3x), of electronic assemblies through the use of advanced packaging technology.
- The energy required to keep the electronics warm is reduced by allowing the electronics to be stored at the ambient environment and heated prior to operation.

"Cold Survivable Electronic Packaging", Bolotin, et, al, IEEE Aerospace 2019

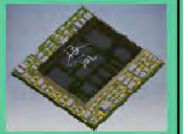
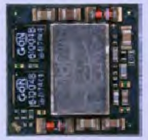
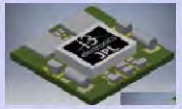
Key Technology Enabler – High Density Substrate

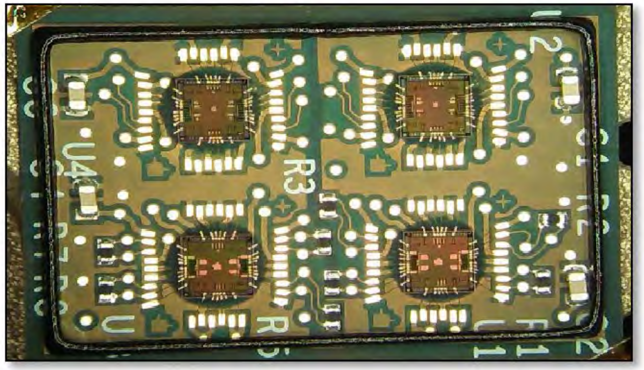
- **CoreEZ® high density substrate from i3 Corporation** *(formerly IBM Endicott)*
- Originally developed by IBM in 1990's
  - Requirement to develop high speed, high reliability flip chip substrate technology for use in enterprise telecom/server applications
- **Combination of low dielectric constant material w/ stress compensation layer**
  - ε_r = 3.7, 25um line/space
- High Reliability
  - **Temperature Cycles:**
    - Board attach - >5,000 cycles @ 0 to 100 °C
    - Individual die - >1,000 cycles @ -55 to 125°C
    - Outgassing - < 1% TML, <0.1% CVCM)
  - **Radiation:**
    - >5MRad

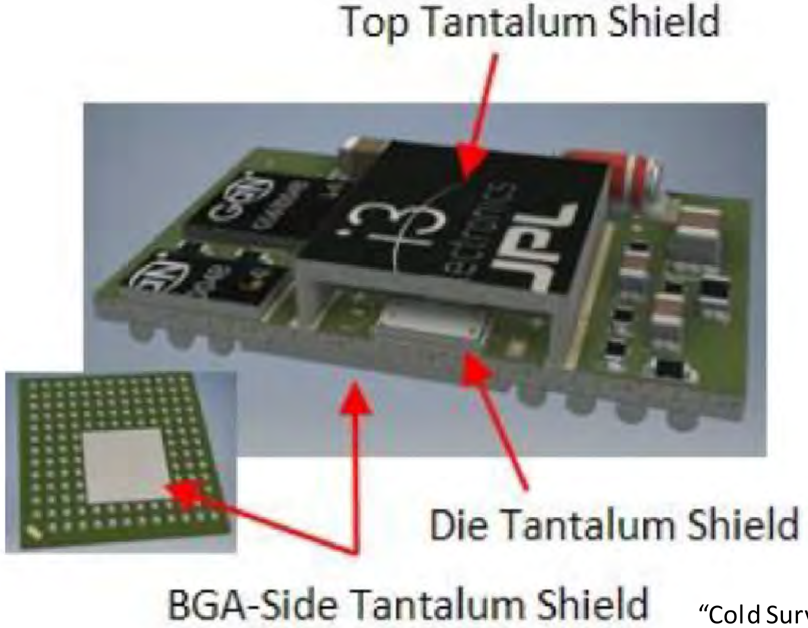


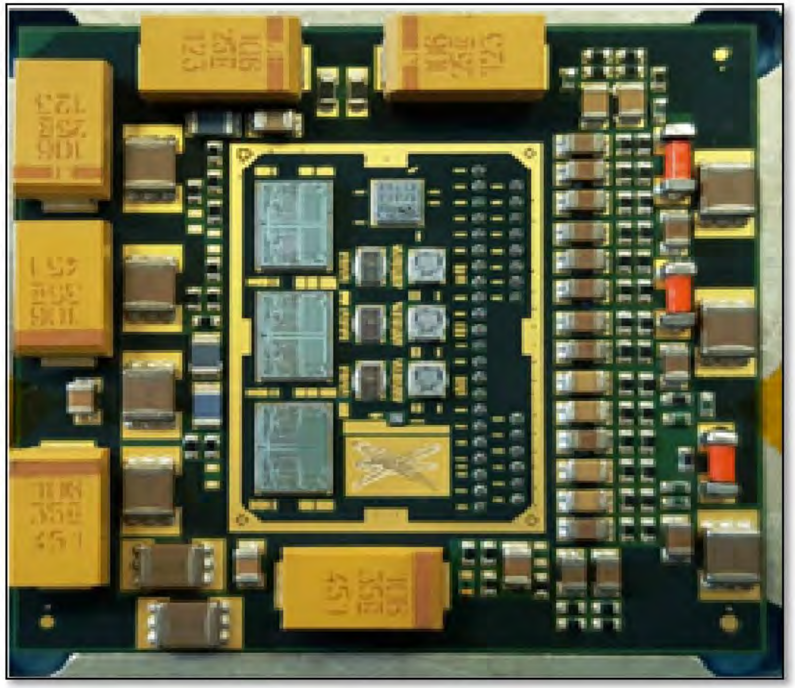
"Cold Survivable Electronic Packaging", Bolotin, et, al, IEEE Aerospace 2019

Cold Survivable Electronic Packaging

Technology	Picture
Motor Driver Module	
Resolver Module	
Low Voltage Differential Switching (LVDS) Module	
Current Sense Module	
Point of Load Regulator Module	
Isolated Converter Module	

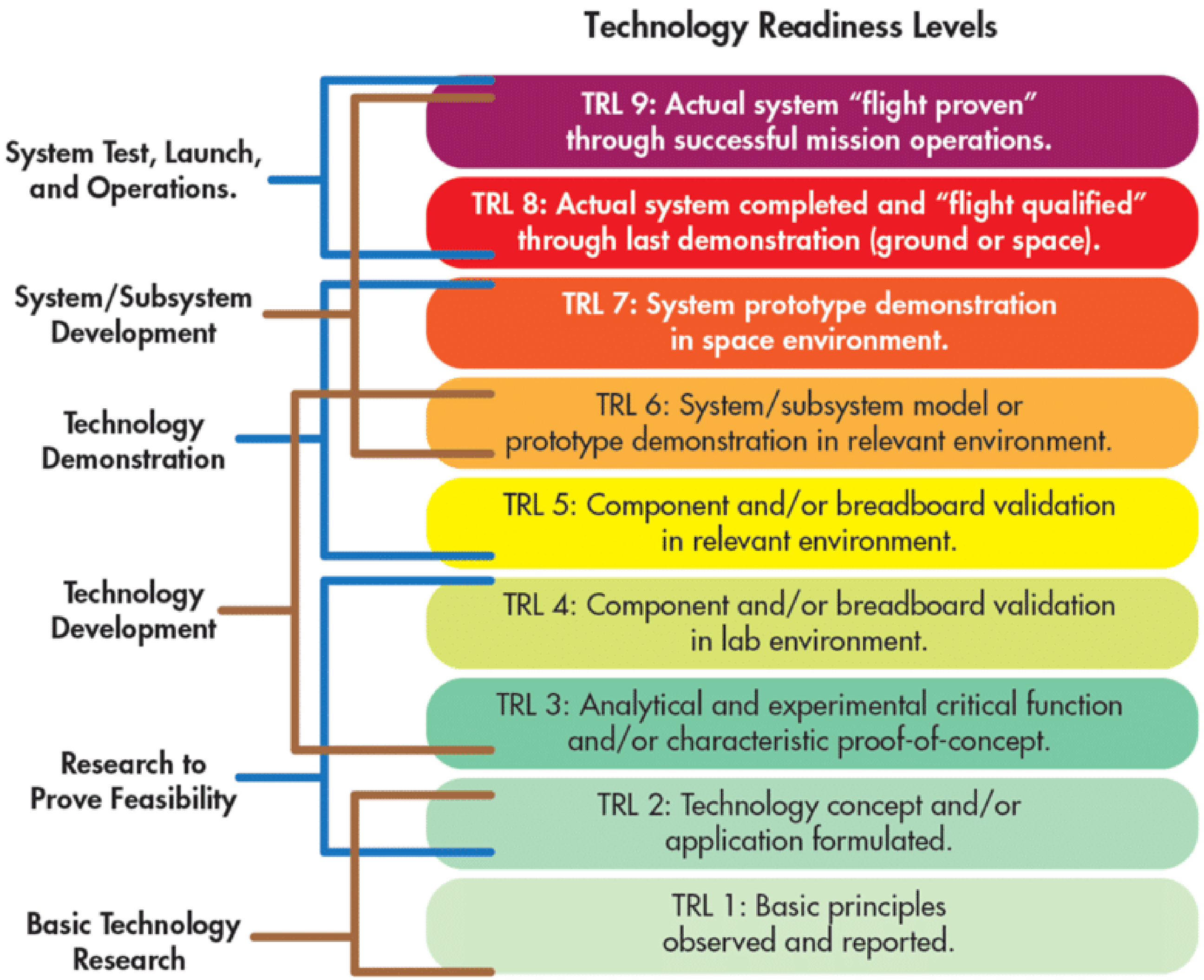


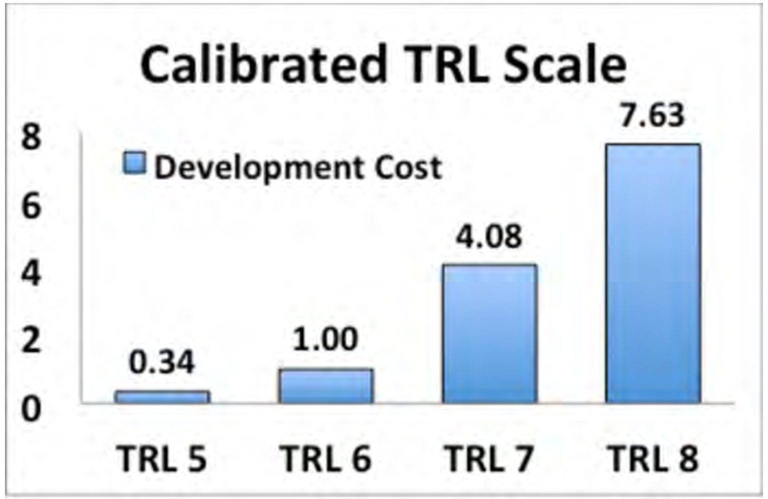




"Cold Survivable Electronic Packaging", Bolotin, et, al, IEEE Aerospace 2019

How to infuse technologies?



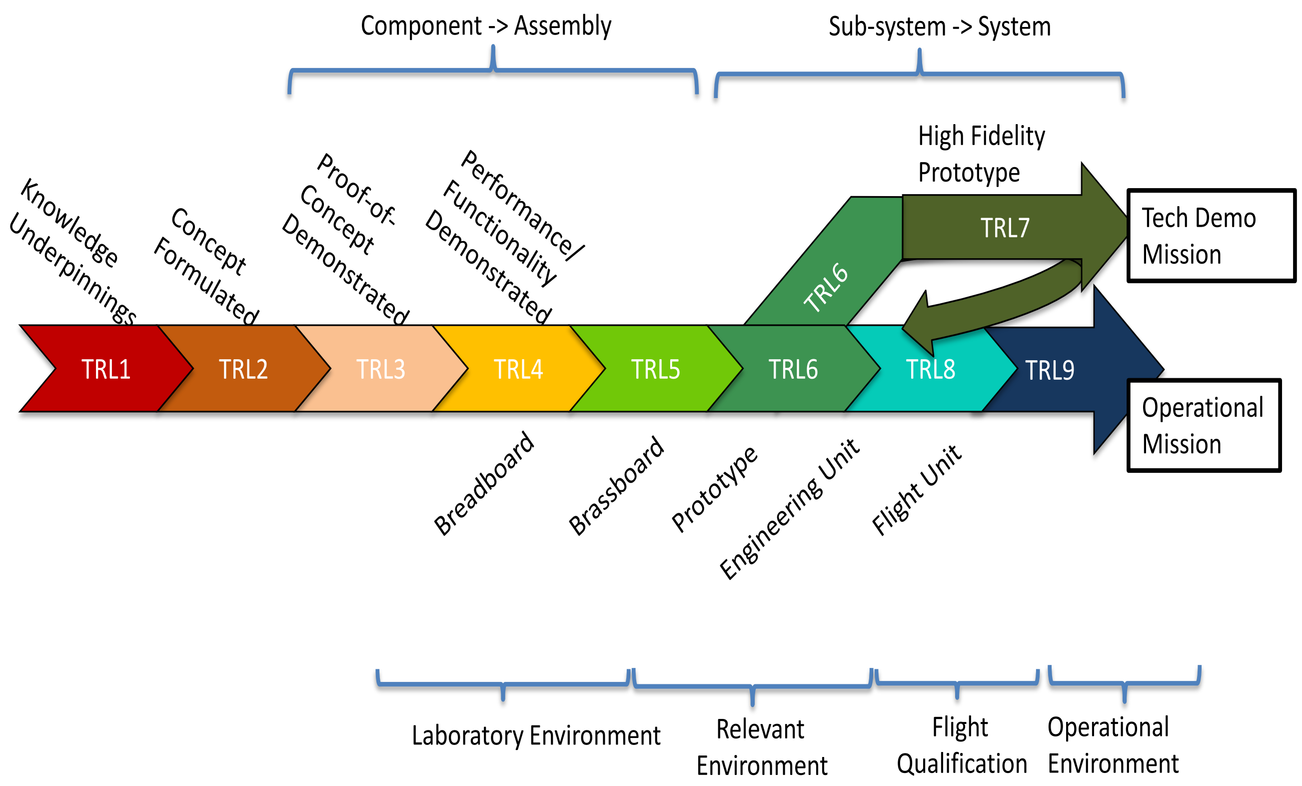


TRL 6 – The key R&D milestone

TRL	Definition	Hardware Description	Software Description	Exit Criteria
6	System/sub-system model or prototype demonstration in a relevant environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale, realistic problems. Partially integrated with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.

- Once TRL 6 is demonstrated, the risk associated with the new technology is roughly equivalent to the risk of a new design that employs standard engineering practice and is bounded by previously implemented ground-based systems
- Following TRL 6 demonstration, the standard engineering development cycle for new designs is followed that includes building and testing an engineering unit, detailed analysis, and detailed drawings prior to the Critical Design Review (CDR

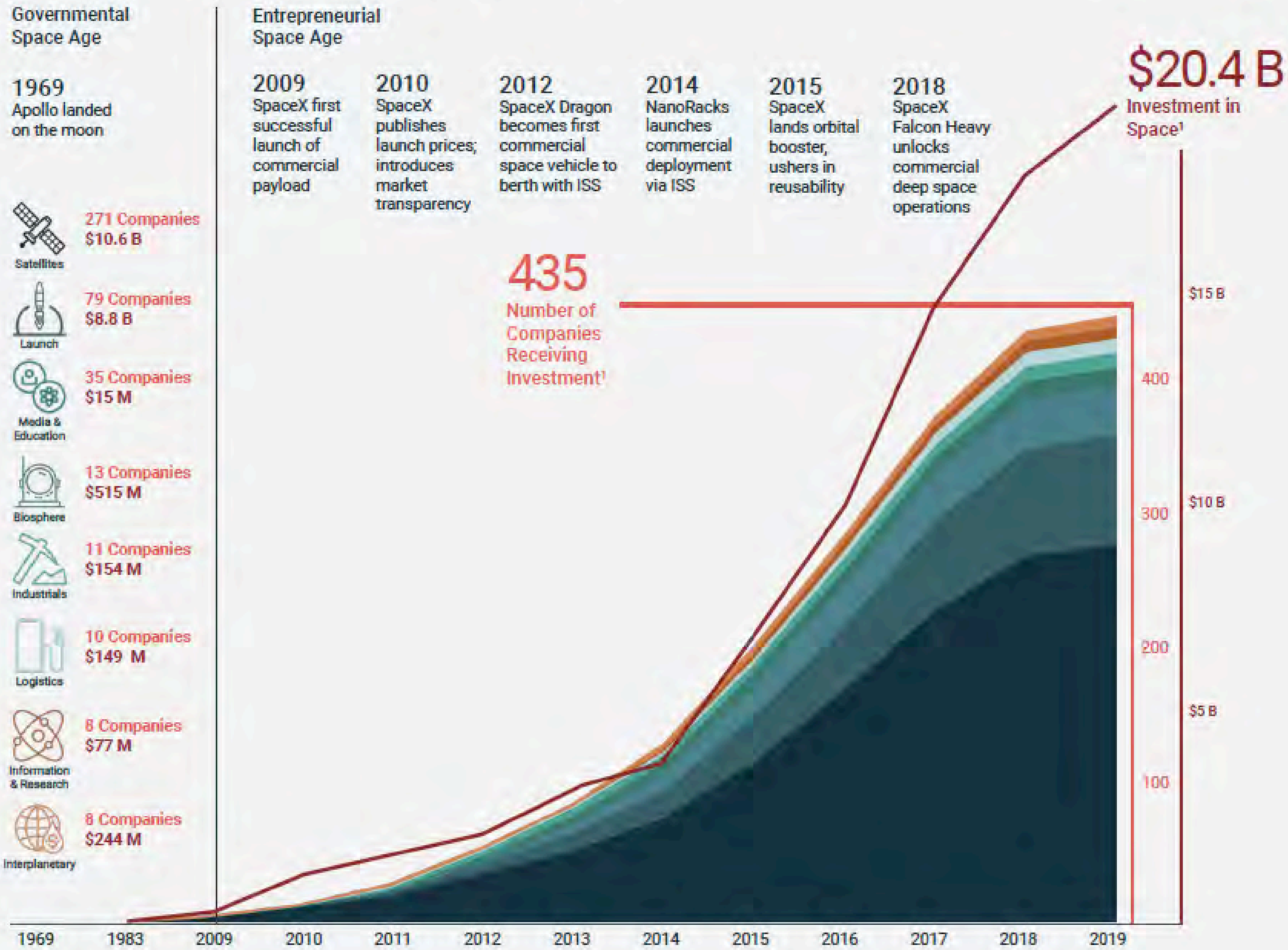
Two paths to flight



- For technologies where lifetime is a major consideration and a key technology issue, it needs to be addressed as part of the technology readiness assessment.
- Technology maturation programs should address life requirements as follows:
  - TRL 4 – Identify life-limiting mechanisms and failure modes.
  - TRL 5 – Characterize, by means of test, the physics of the life-limiting mechanisms and failure modes and develop and validate an analytical model/simulation that predicts life limiting mechanisms and failure modes from which predictions of life duration can be made with some confidence.
  - TRL 6 - Verify by test that the technology is resilient to the effects of life-limiting mechanisms. One method for this is to predict through analytical models the end-of-life conditions and then testing that performance is met under those conditions.
  - TRL 8 - Complete life tests.

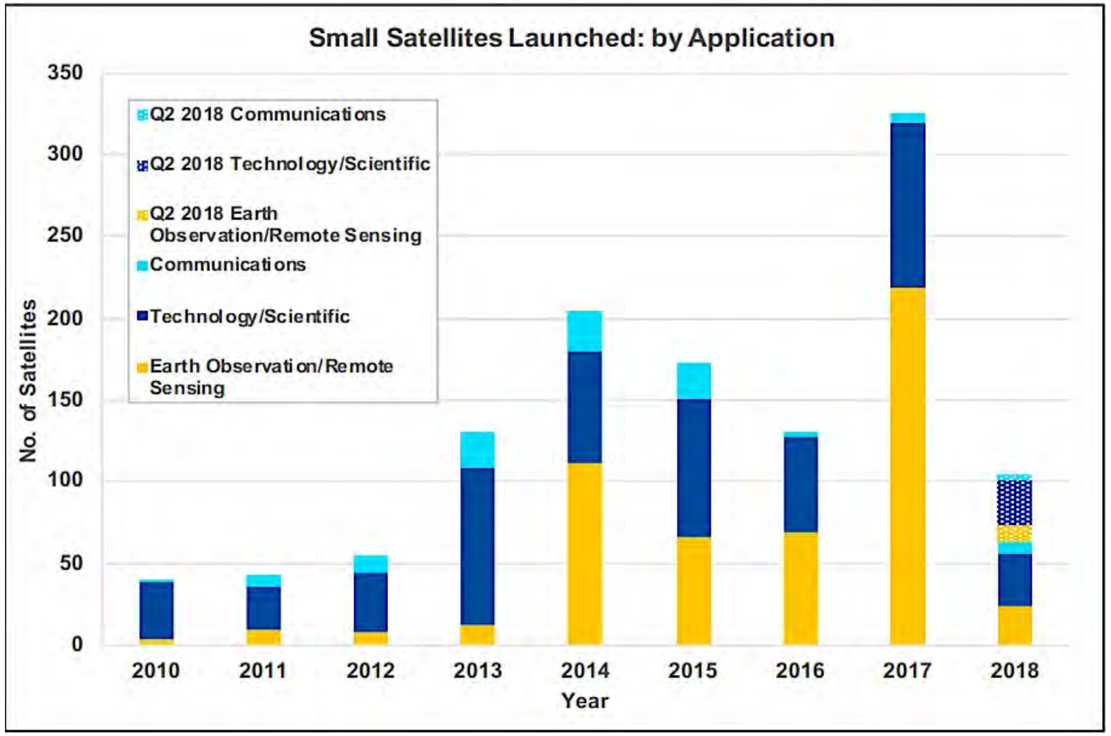
DAWN OF THE ENTREPRENEURIAL SPACE AGE

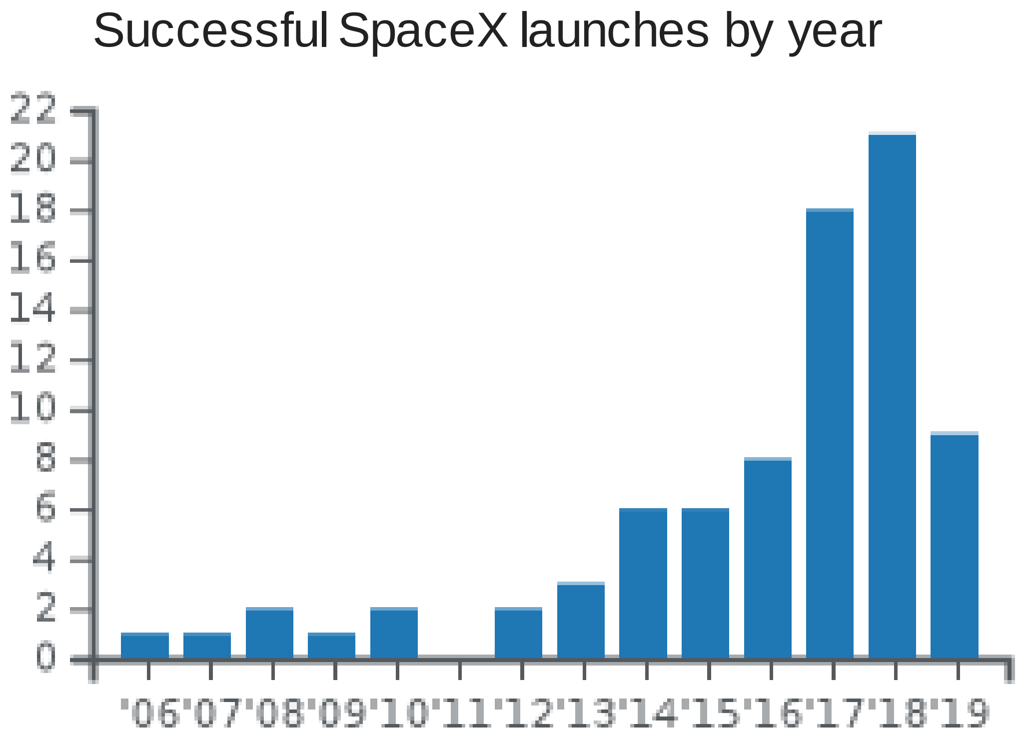
Cumulative Equity Investments From 2009 To Present

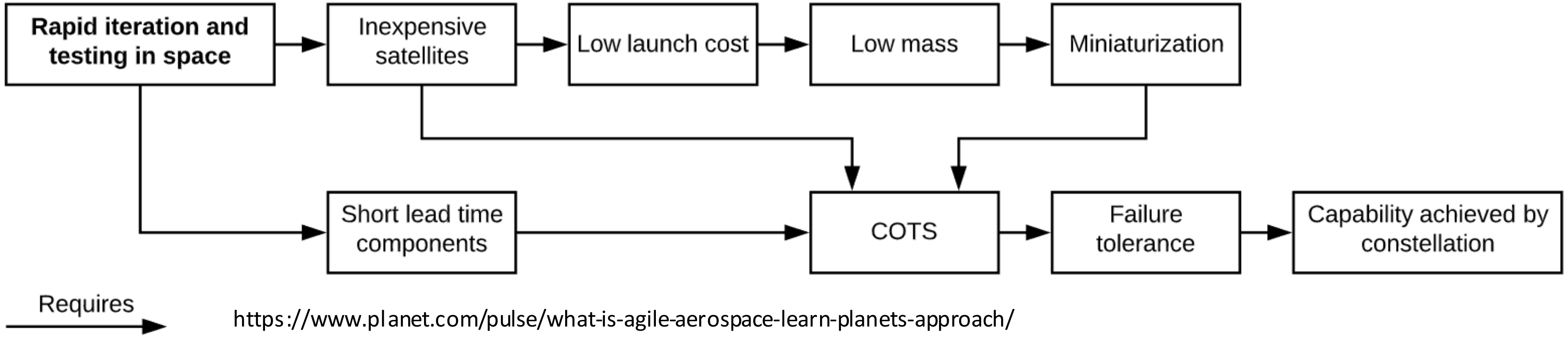


https://www.spaceangels.com/

Small Sats, SpaceX and Learning Cycles







https://www.planet.com/pulse/what-is-agile-aerospace-learn-planets-approach/

- 150+ satellites in orbit, Planet can image anywhere on Earth daily at 3–5 meter and 72 centimeter resolution with four spectral bands (red, green, blue, and near-infrared)
- Upgrading to 50-centimeter-resolution and eight spectral bands

https://www.planet.com/gallery/

Conclusion

- Space exploration is ripe for innovations in packaging technologies that can have profound impacts both in terms of SWaP and the ability to do fundamental science
- Successful infusion of technology into NASA missions should be based on rigorous completion of TRL 6 milestones and formal review processes
- Commercial space companies are aggressively using agile and quick turn development techniques to shorten learning cycles and therefore rapidly increase the the infusion of new technology
- Being able to leverage and share between these two approaches can provide the broadest and most robust technology infusion and adoption path

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov