



Developing autonomous technologies for biological missions to deep space

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ARC Space Biosciences

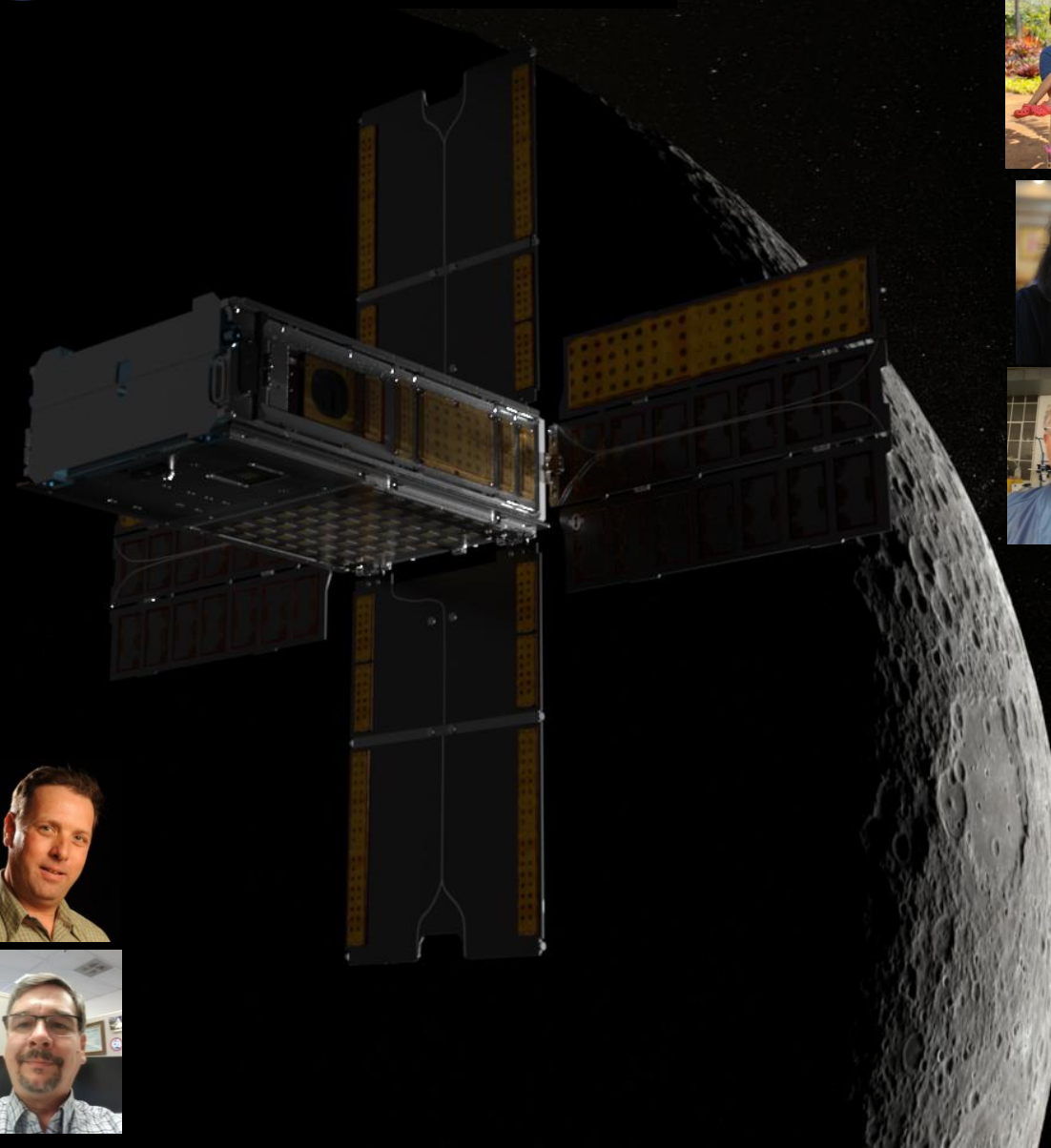
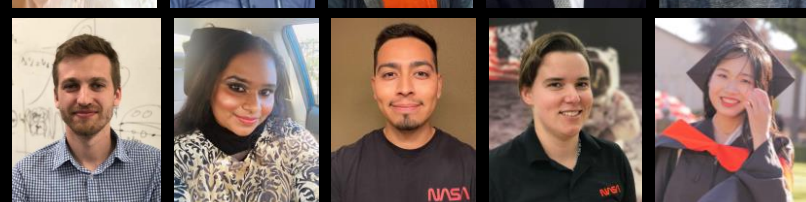
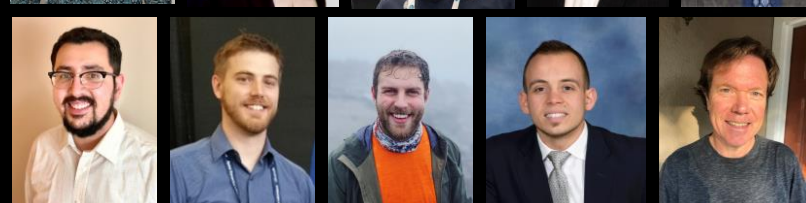
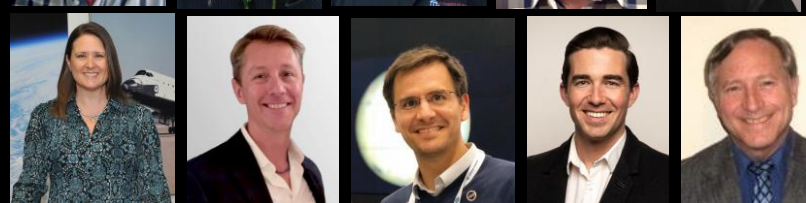
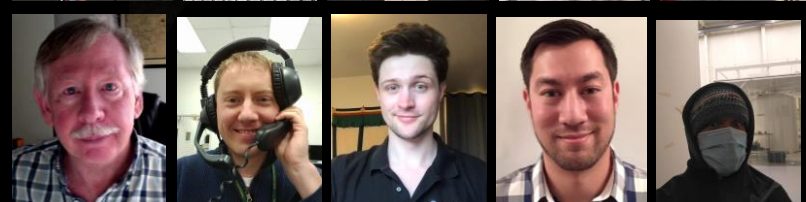
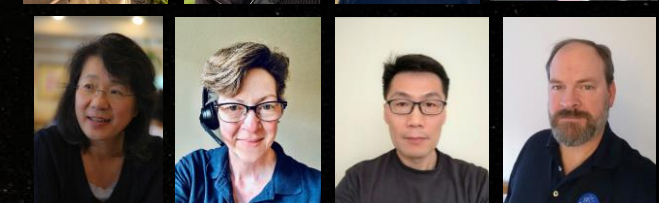
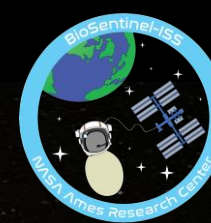
sergio.r.santamaria@nasa.gov







BioSentinel team (part of it)



What are we going to encounter beyond LEO?

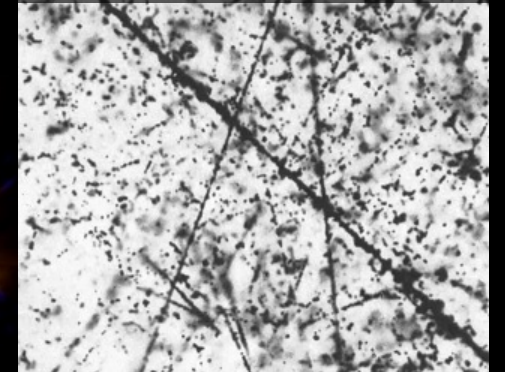
Reduced gravity



Space radiation (CGRs & SPEs)

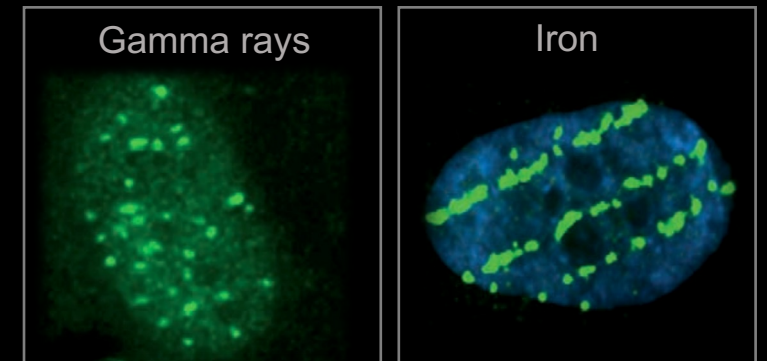


Apollo XI particle tracks



Schaefer *et al.* 1972

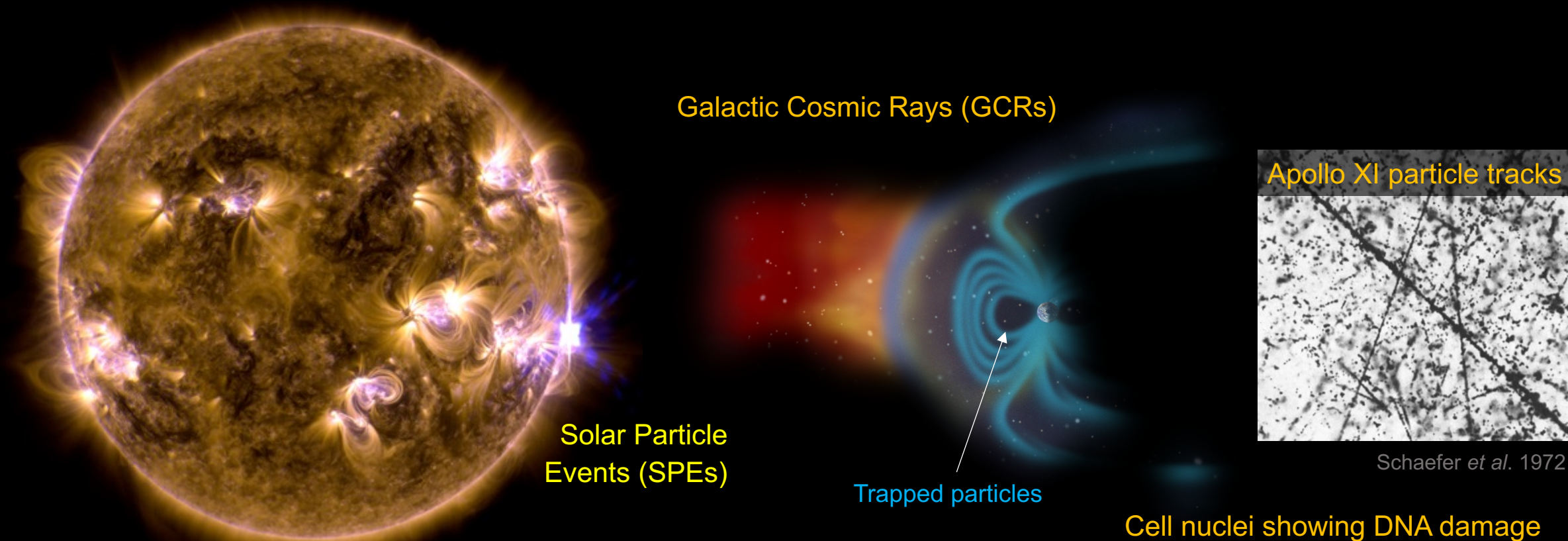
Cell nuclei showing DNA damage



Cucinotta & Durante, 2006



What are we going to encounter beyond LEO?

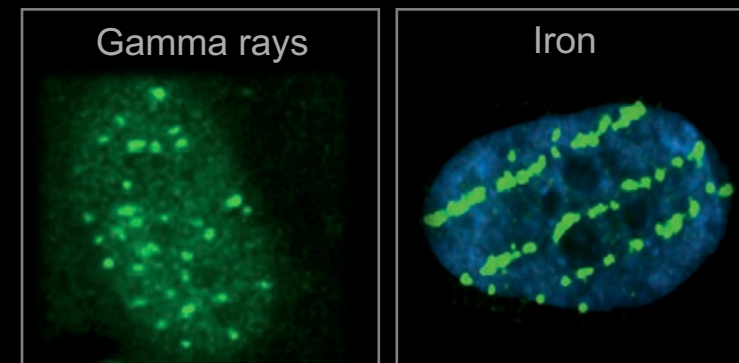


Schaefer *et al.* 1972

- Both interplanetary & modulated by the solar cycle
- GCRs: high-energy protons and highly charged, energetic heavy particles
- GCRs not effectively shielded & can fragment

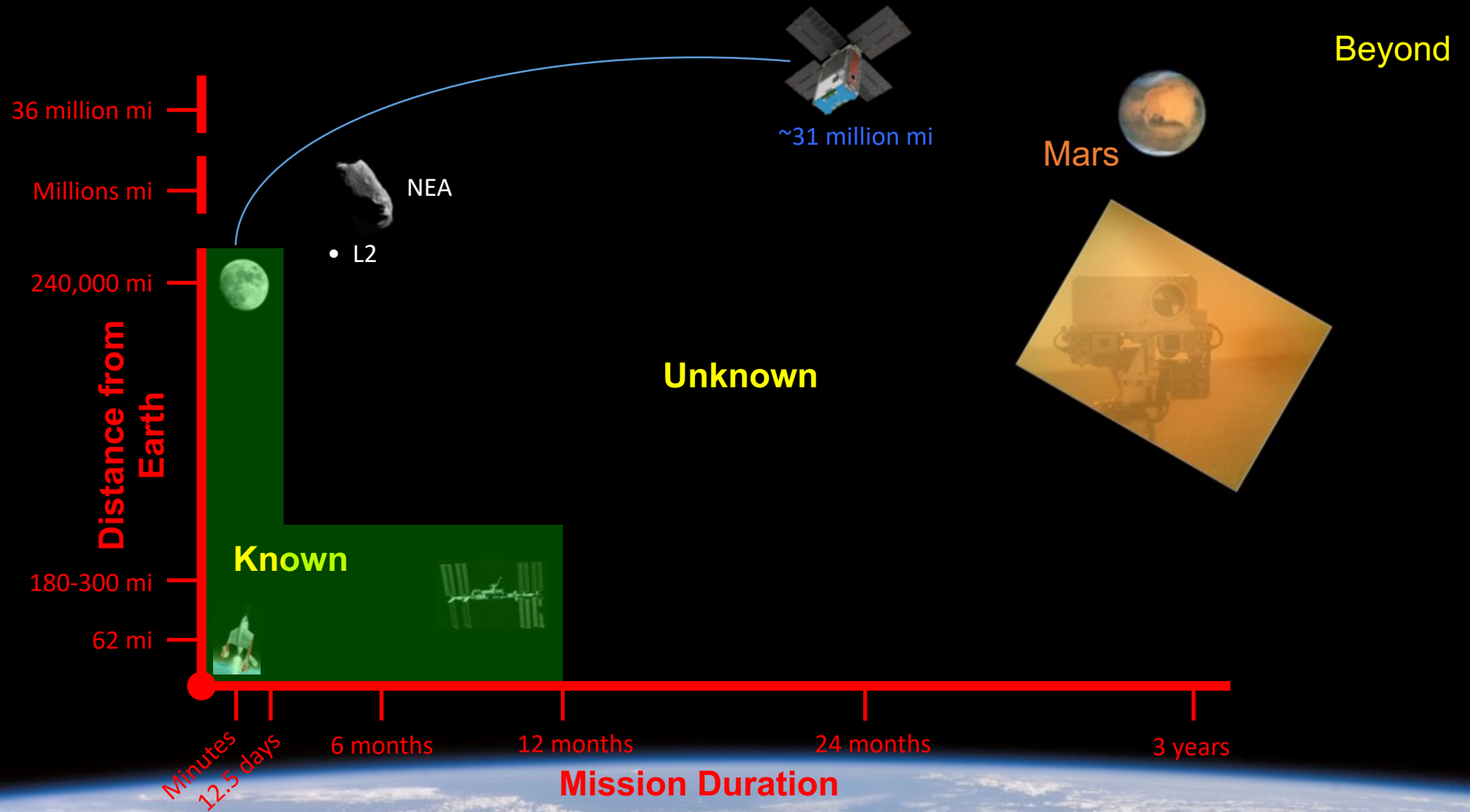
Challenges: SPEs – unpredictable; large doses in short time
GCRs – biology effects poorly understood (but most hazardous)

Cell nuclei showing DNA damage



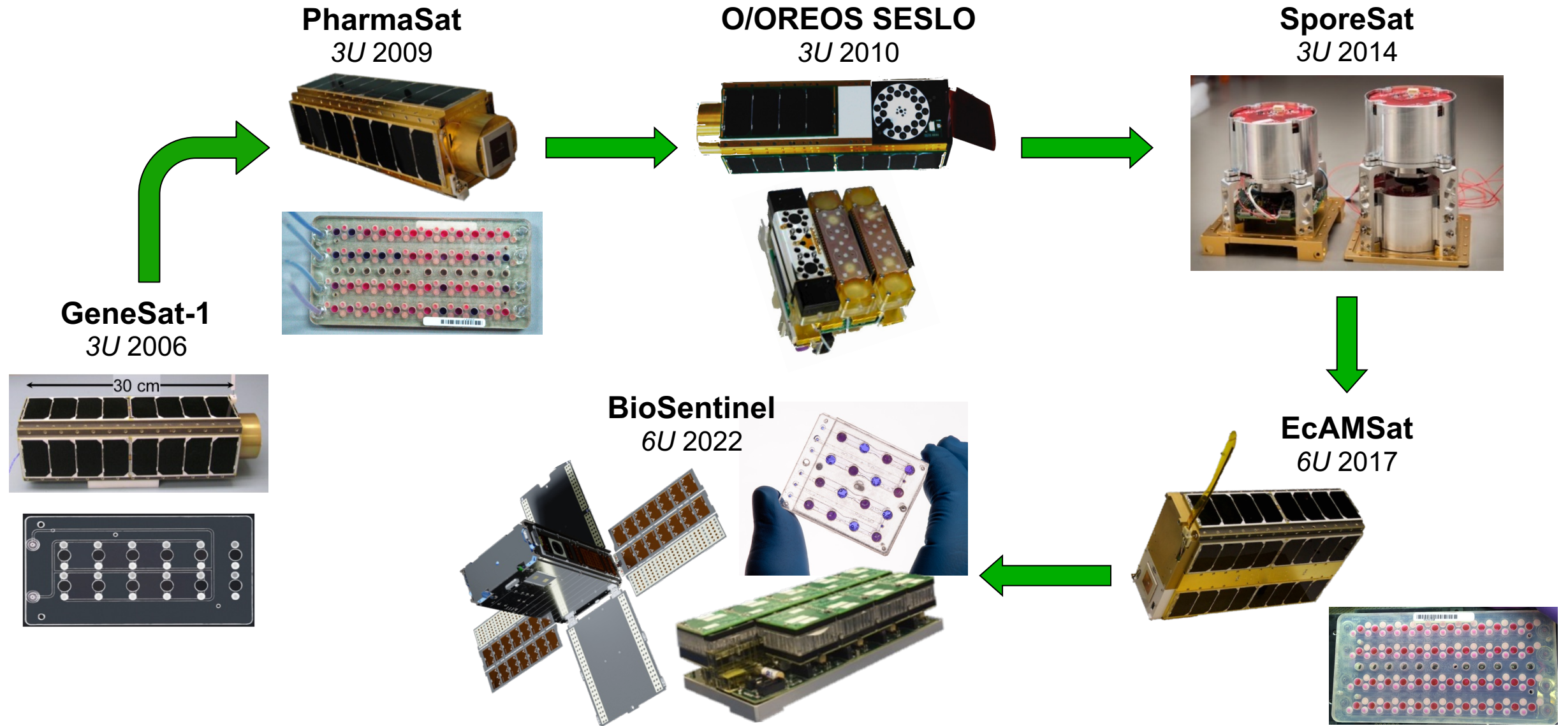
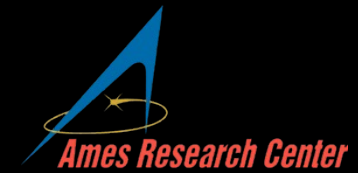
Cucinotta & Durante, 2006

The limits of life in space – as we know it – is 12.5 days on a lunar round trip or 1.2 years in LEO. As we send people further into space, we need to understand the biological risks and how they can be addressed





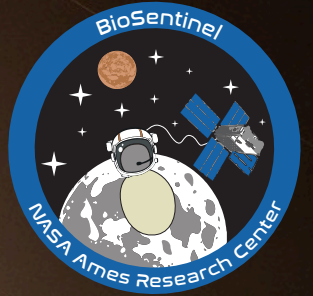
NASA Ames biological CubeSat missions



BioSentinel missions

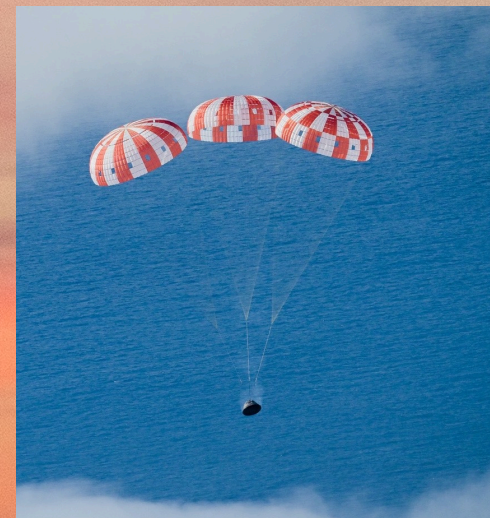


SpaceX-24



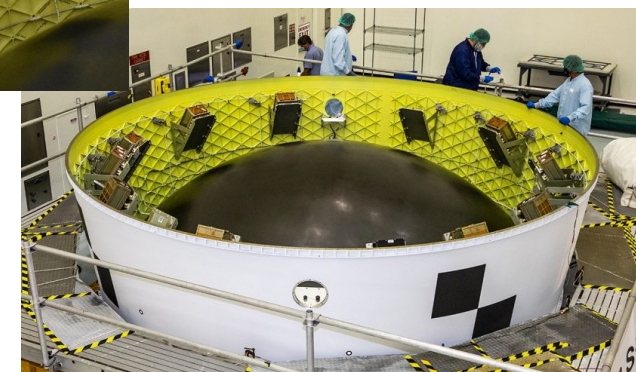
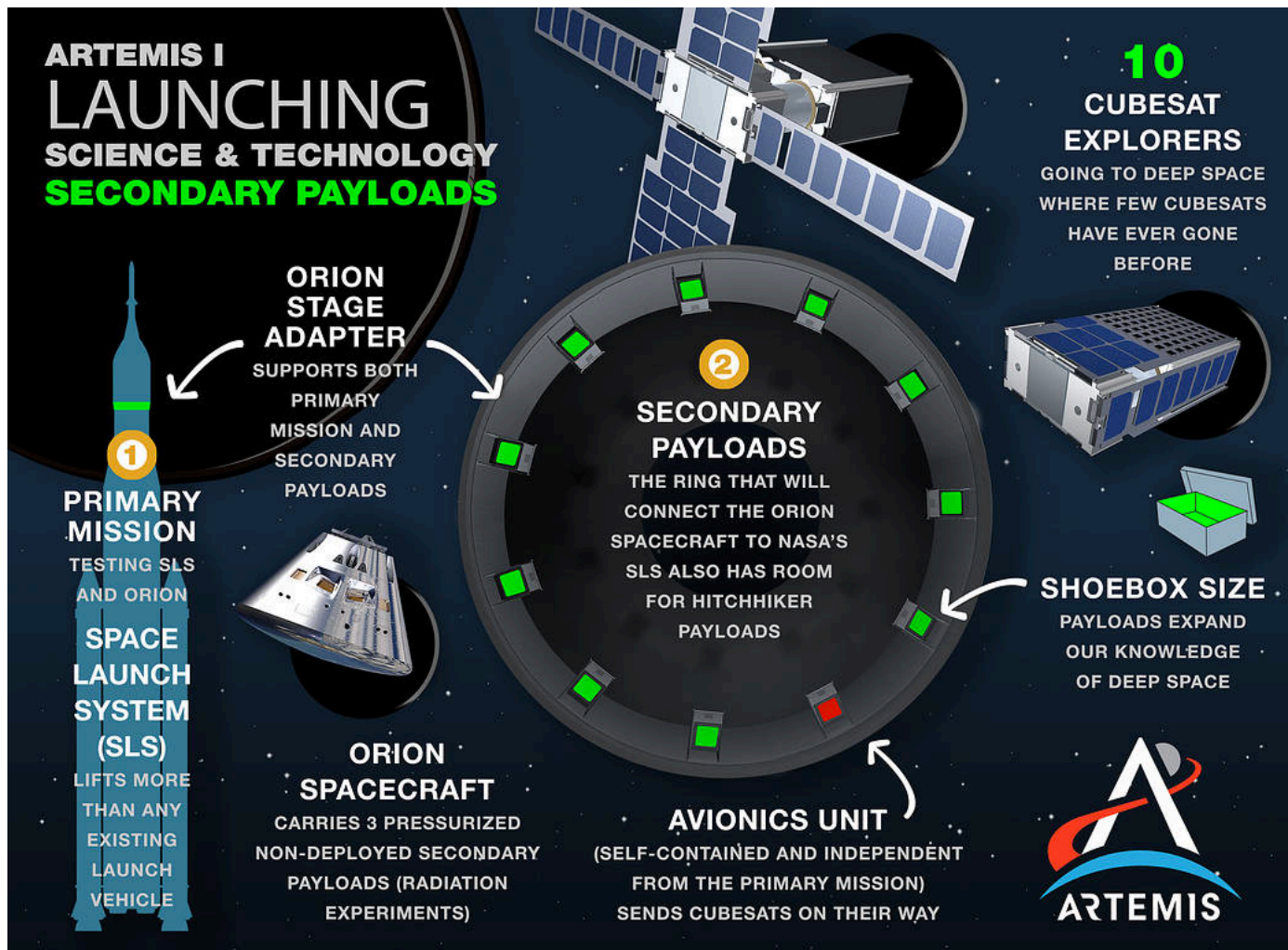


NASA Artemis I mission





Artemis I: secondary payloads (6U CubeSats)

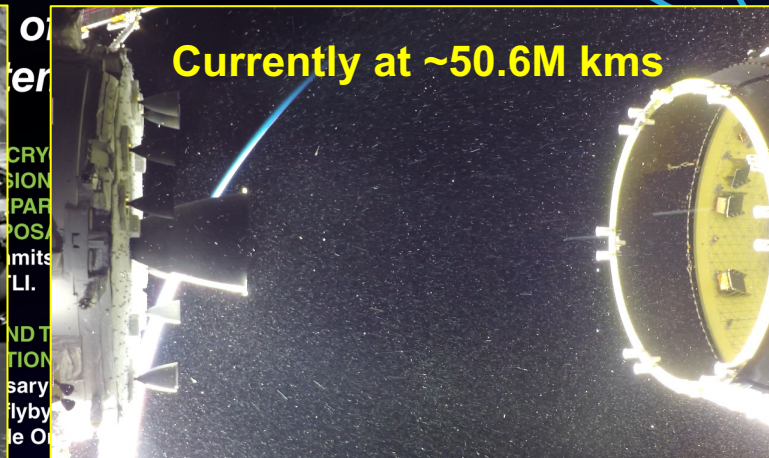




A B C
CUBESATS DEPLOY
ICPS deploys 10
CubeSats total

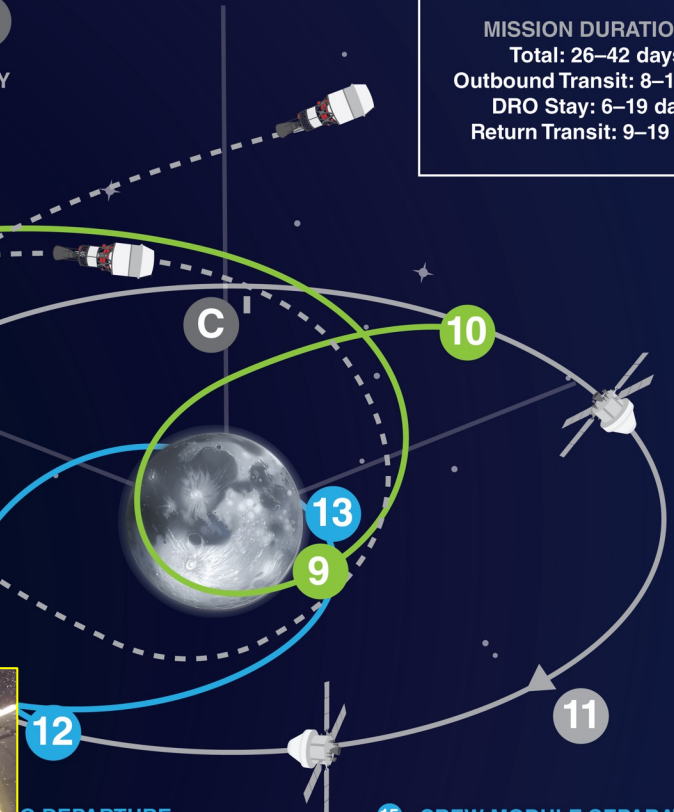
MISSION DURATIONS:
Total: 26–42 days
Outbound Transit: 8–14 days
DRO Stay: 6–19 days
Return Transit: 9–19 days

ARTEMIS I



Currently at ~50.6M kms

56,000 nmi from the surface of the moon.



10 DEPARTURE
Leave DRO and start
turn to Earth.

11 TURN POWERED FLYBY (RPF)
RF burn prep and return
fast to Earth initiated.

12 TURN TRANSIT
Return Trajectory Correction
(TC) burns as necessary to
align for Earth's atmosphere.

**15 CREW MODULE SEPARATION
FROM SERVICE MODULE**

16 ENTRY INTERFACE (EI)
Enter Earth's atmosphere.

17 SPLASHDOWN
Pacific Ocean landing within view
of the U.S. Navy recovery ship.



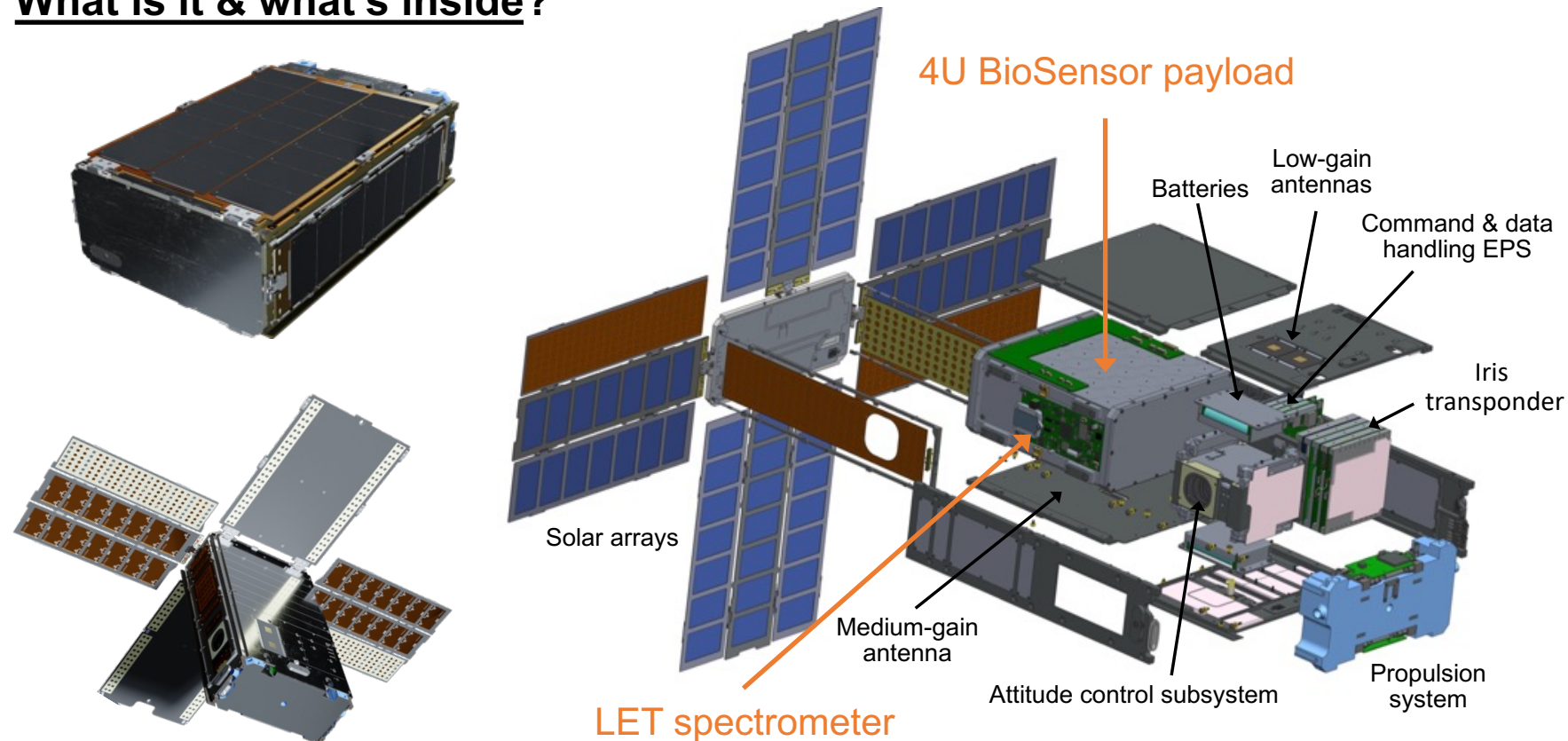
BioSentinel mission



Objectives:

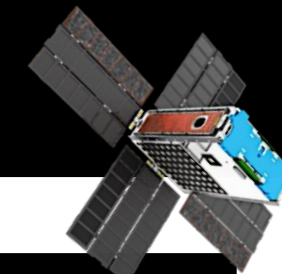
- Develop a deep space tool with autonomous life support technologies
- Study the space radiation environment beyond LEO and its effect on biology

What is it & what's inside?





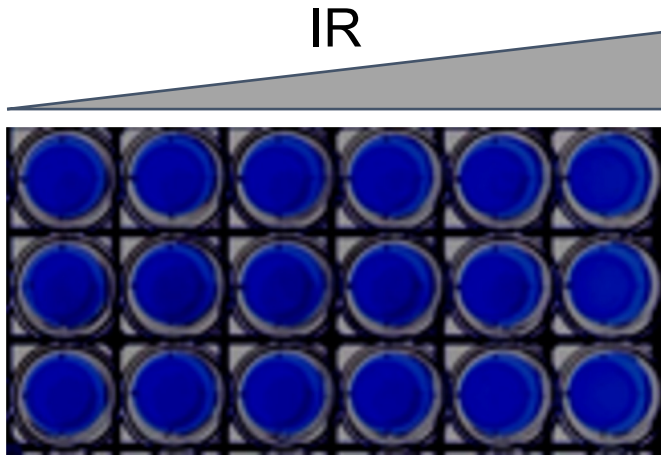
BioSentinel: key components



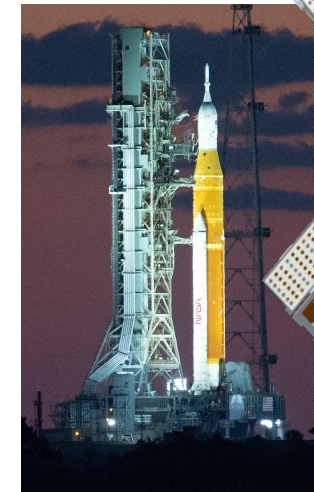
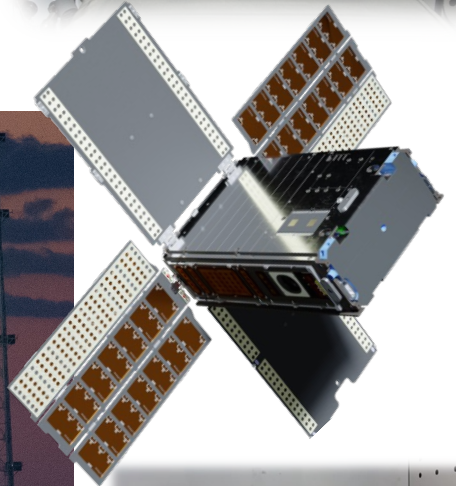
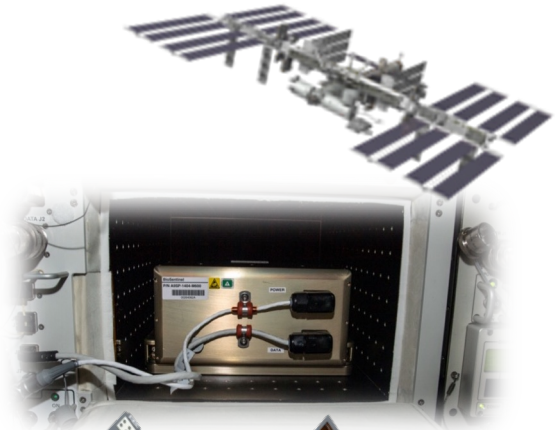
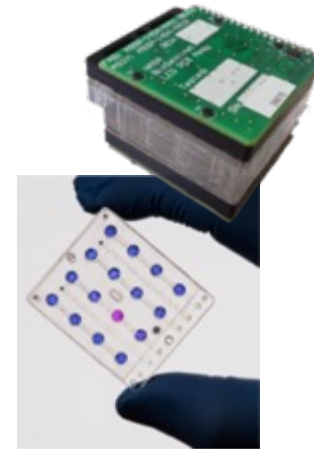
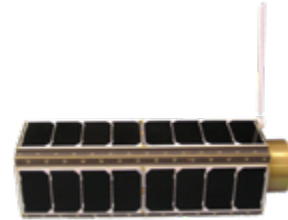
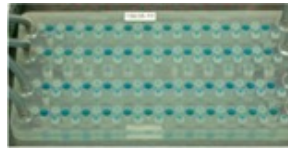
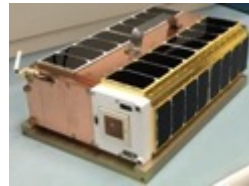
Subsystem	Description	Vendor	Subsystem	Description	Vendor
4U BioSensor			LET spectrometer		
Fluidics	18 PC cards & manifolds with integrated valves, pumps, bubble traps & desiccant chambers	NASA ARC	Radiation sensor	Timepix-based sensor (TID and LET particle characterization)	NASA JSC
Optics	3 LED lights & TAOS sensor per fluidic well (16 wells per card)		Bus ADCS		
Thermal	Dedicated thermal control per fluidic card		Reaction Wheels / Star Tracker / IMU	XACT 3-axis Attitude-Control System & Star Tracker	Blue Canyon Technologies
Sensors	Temperature, RH, pressure		Sun Sensors	5 sun sensors	SolarMEMS
Bus C&DH			Bus Power		
Processor	UT700 LEON 3	Space Dynamics	EPS	TI-MSP430 FRAM	NASA ARC
Data Storage	MRAM & Flash		Batteries	18650B Li-ion	Panasonic
Bus Comm			Solar Array	4 HaWK solar arrays	MMA Design
Radio	Iris v2 transponder	JPL	Propulsion		
Antenna	Medium & low gain		Thruster	7-nozzle 3D printed system	Lightsey Space Research



BioSentinel: how did we get here?



Instrument &
flight heritage



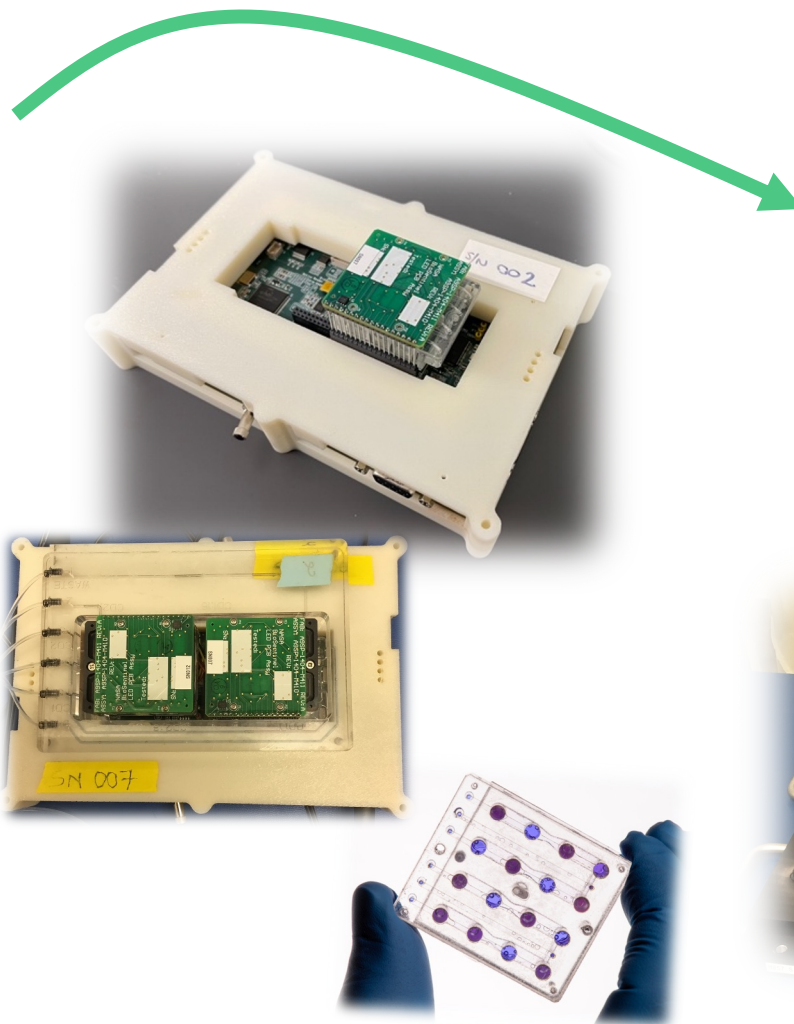
- Model organism & strain selection
- How to fly the biology? Dry/wet?
- Long-term viability & biocompatibility
- Materials, sterilization method, reagents, fluidic components...
- Multiple fluidic cards; 288 wells
- LEO control (and ground)
- Data telemetry & processing



Flight mission design constraints

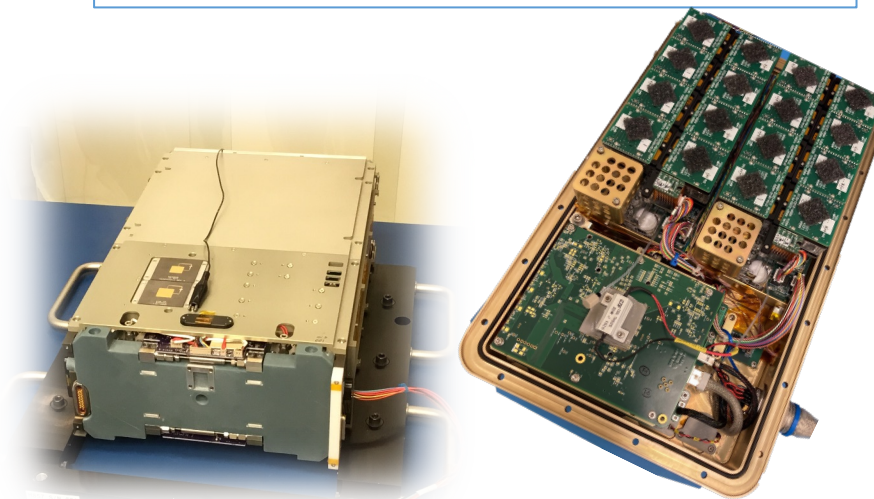
Minimize:

- Mass
- Volume
- Energy
- Bandwidth
- Crew time
- Mass transport artifacts
- Cost
- Development time
- Sensitivity to extraneous environmental variables



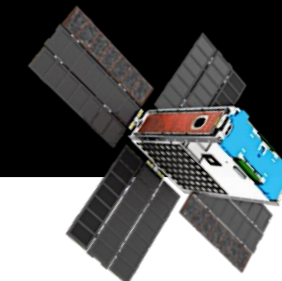
Maximize:

- Experiment autonomy
- Robustness of response
- Signal to noise ratio
- Tolerance to launch site static condition & delays
- Sample statistics
- Hardware material biocompatibility

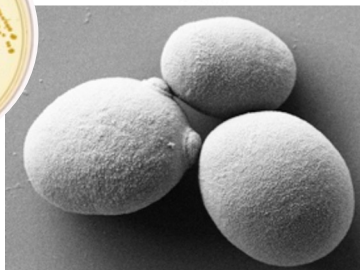




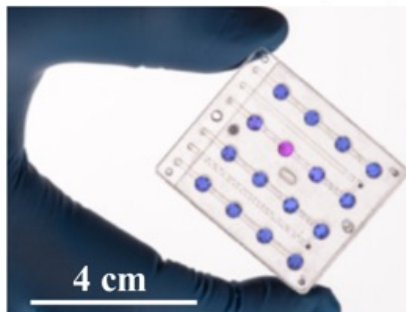
BioSentinel: science instrumentation



Budding yeast



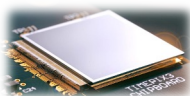
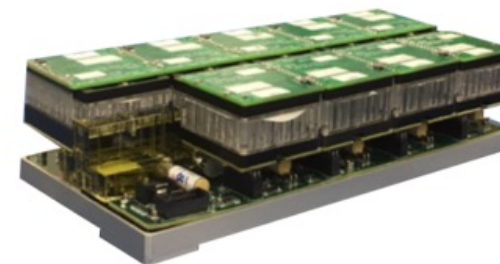
16-well fluidic card (x18)



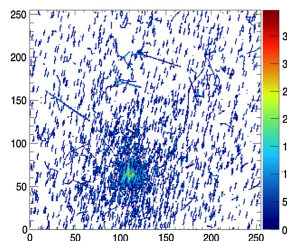
Card stack



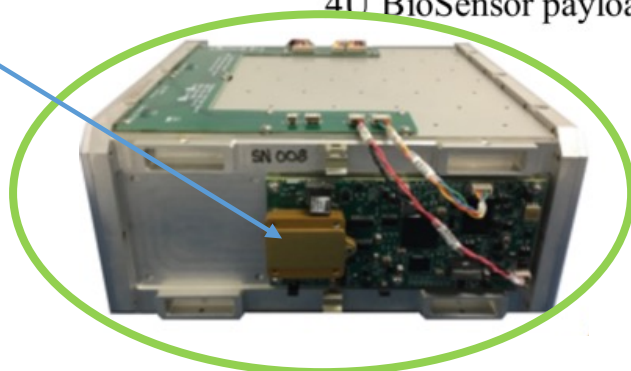
9-card fluidic manifold (x2)



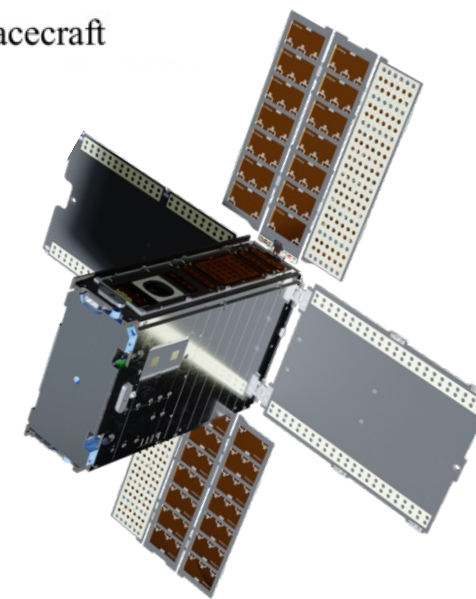
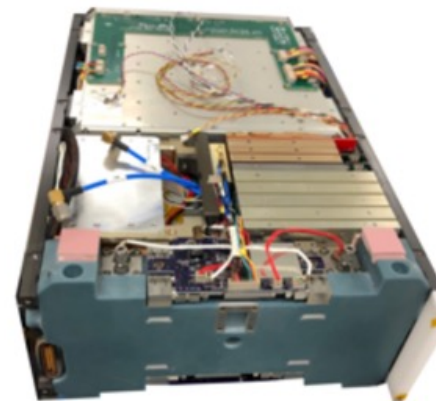
LET spectrometer



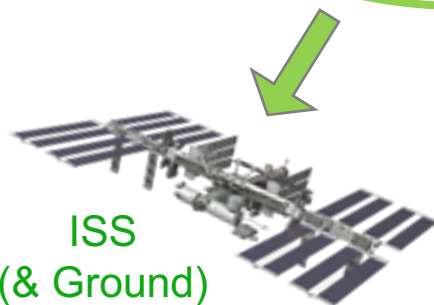
4U BioSensor payload



6U BioSentinel spacecraft

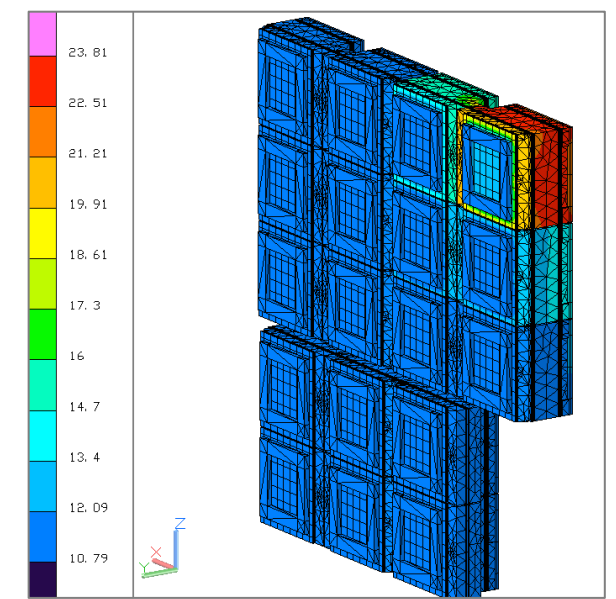
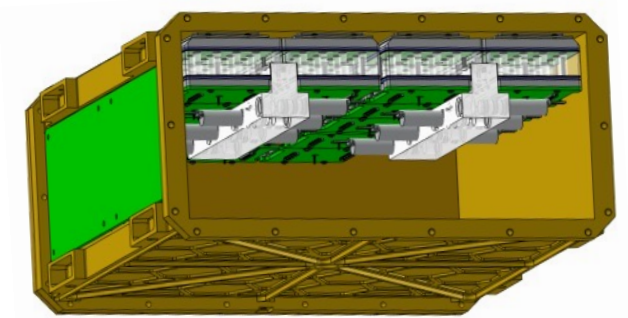
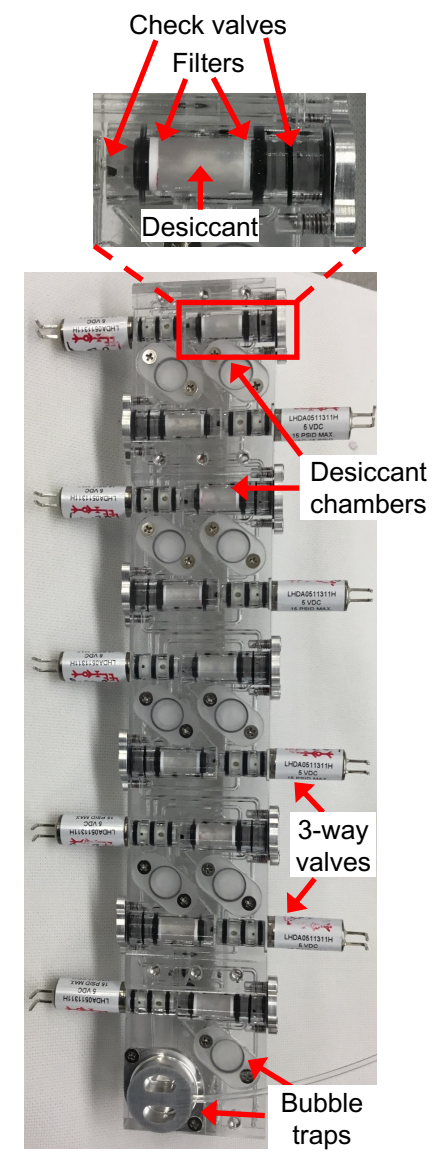
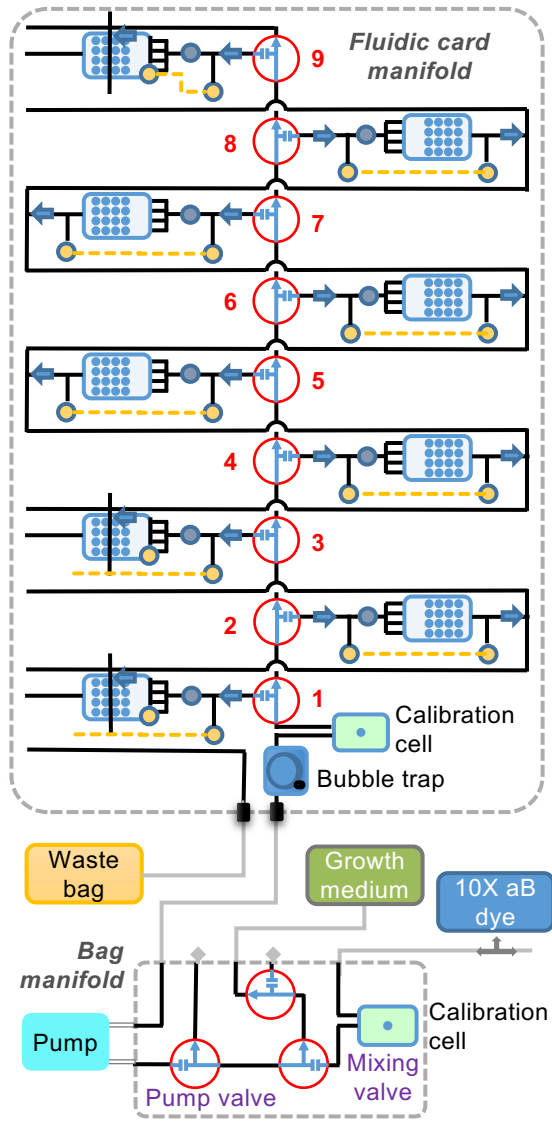
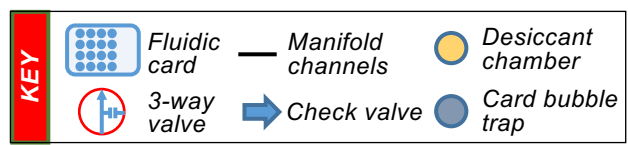
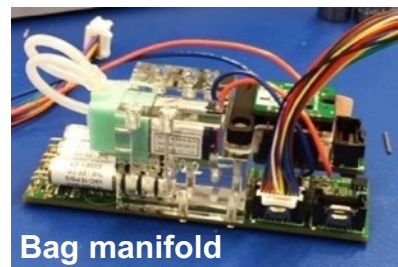
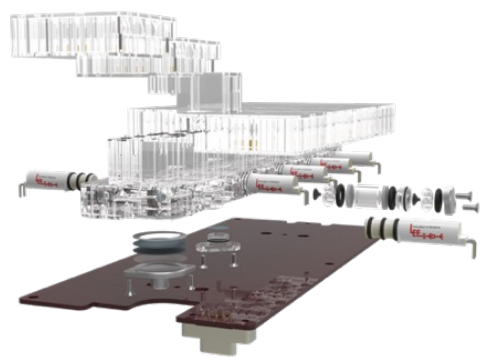
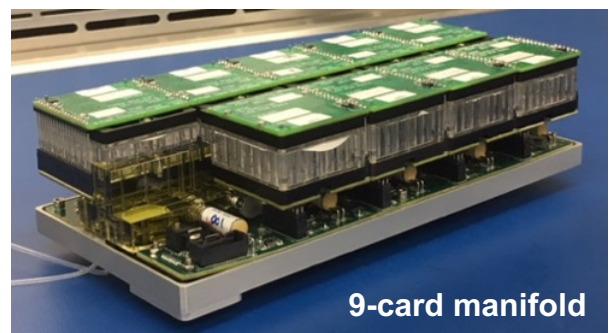
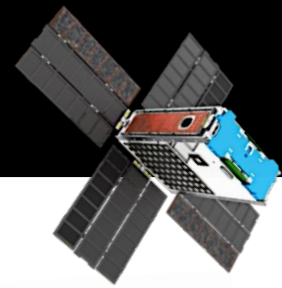


ISS
(& Ground)



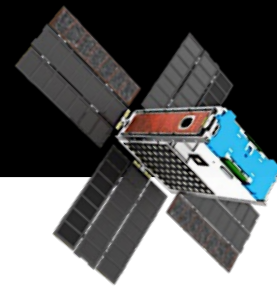


BioSentinel: microfluidics

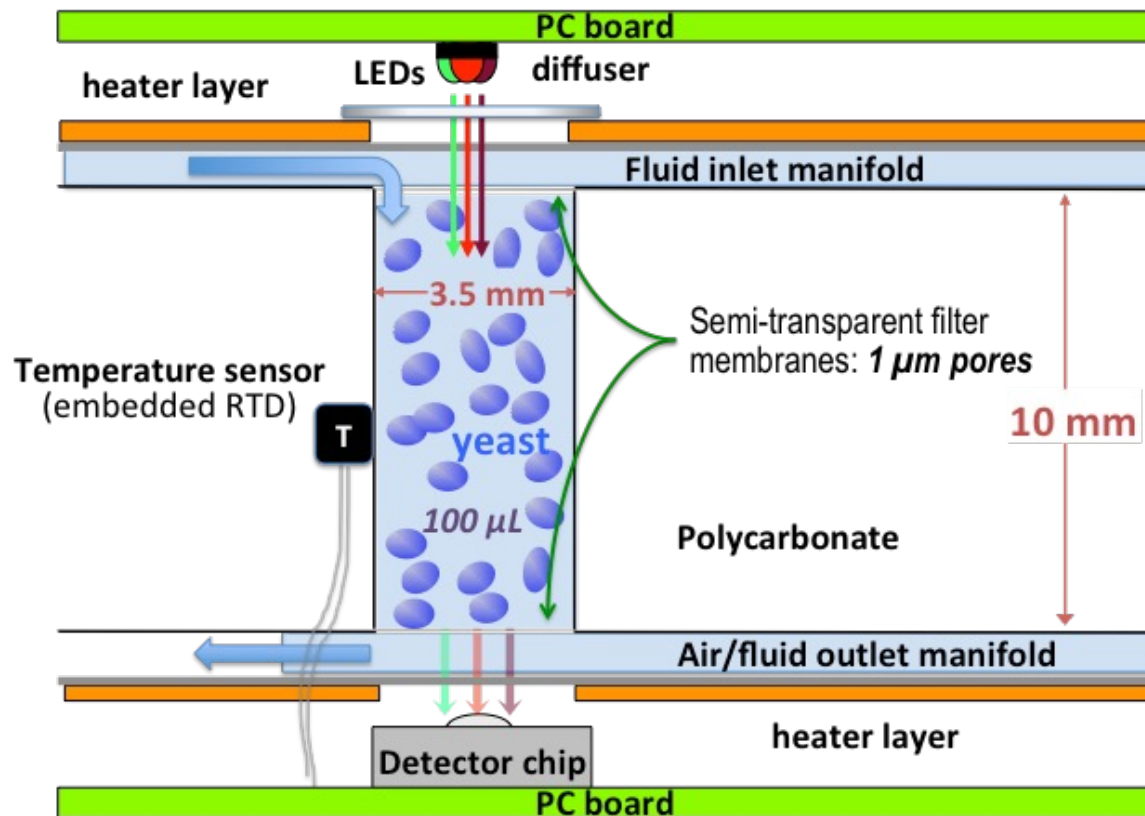
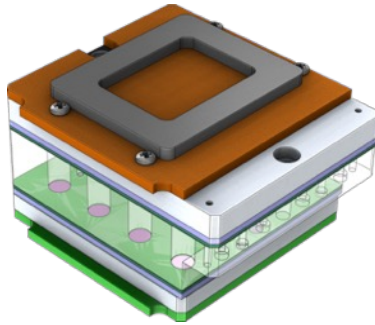




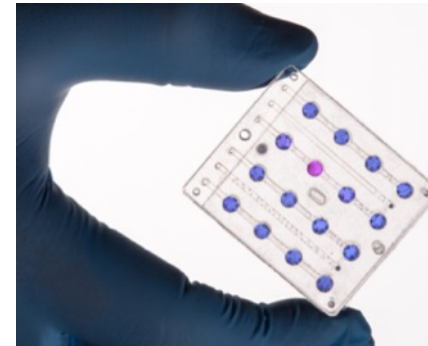
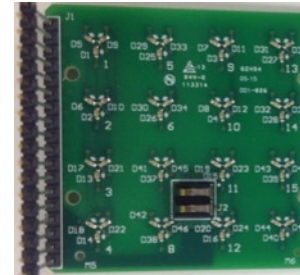
BioSentinel: microfluidics



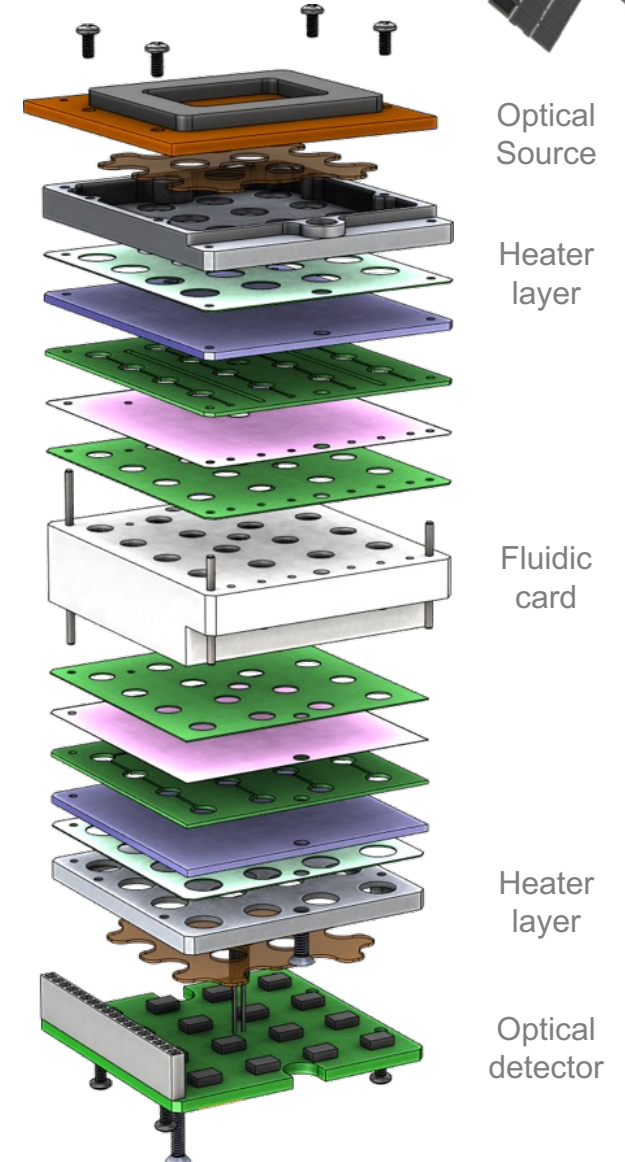
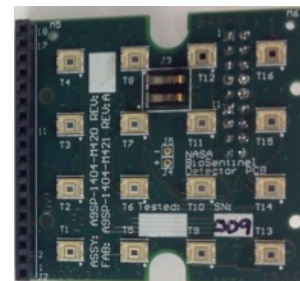
Microfluidic card (x18)



3-LED emitter

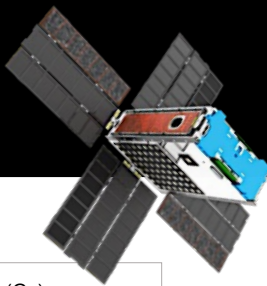


Photodiode detector array





BioSentinel: optical detection system



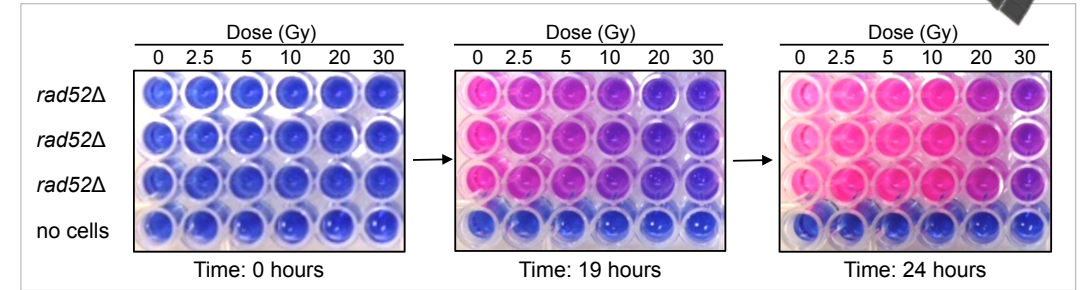
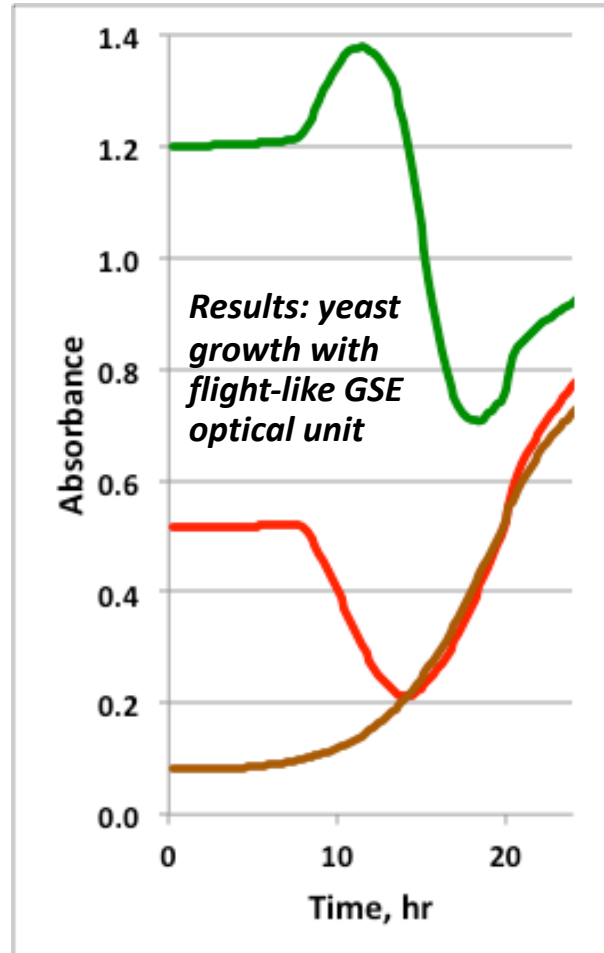
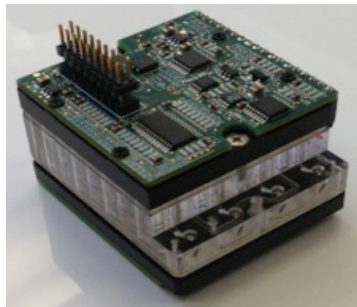
Dedicated 3-color optical system at each well to track growth *via* optical density and cell metabolic activity *via* dye color changes

LEDs:

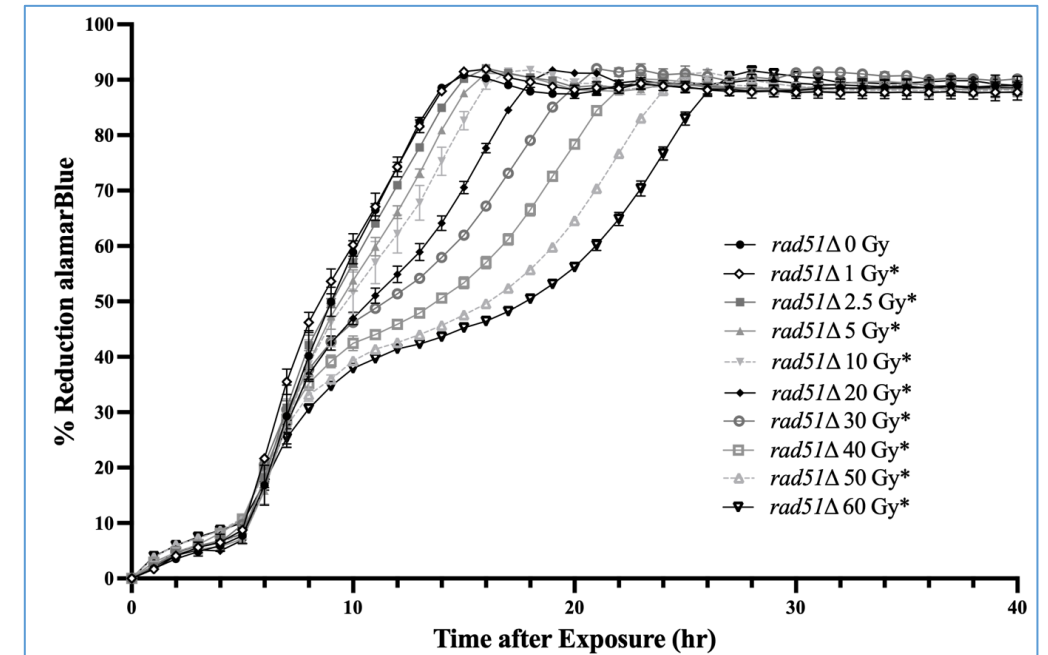
570 nm (green, measures pink)

630 nm (red, measures blue)

850 nm (infrared, measures growth)



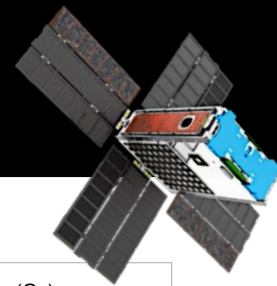
alamarBlue turns pink when cells are metabolically active



HR repair defective cells show sensitivity to ionizing radiation



BioSentinel: optical detection system



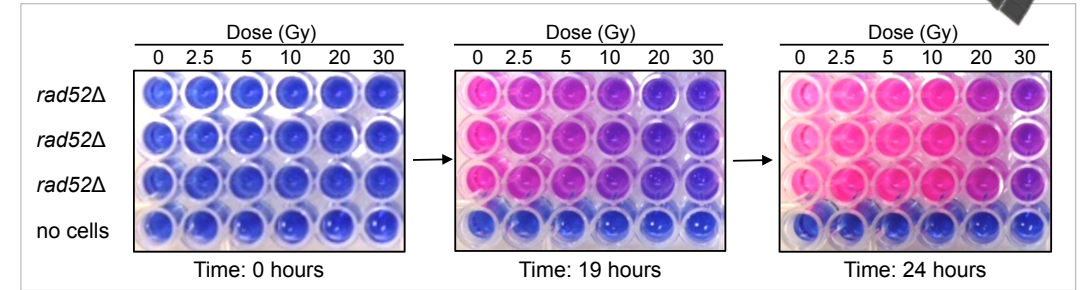
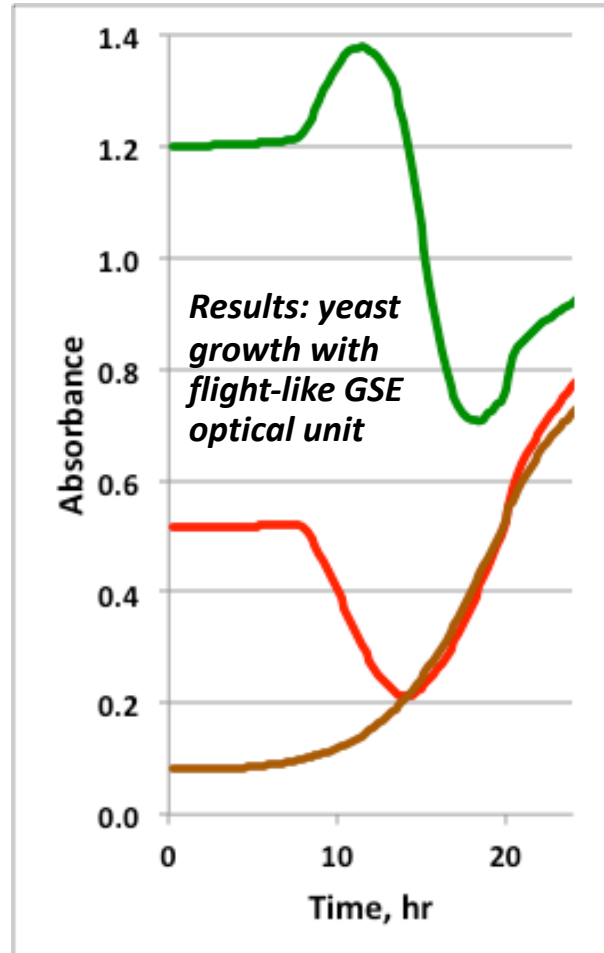
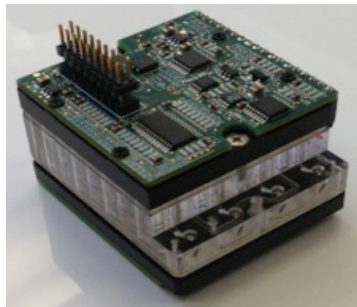
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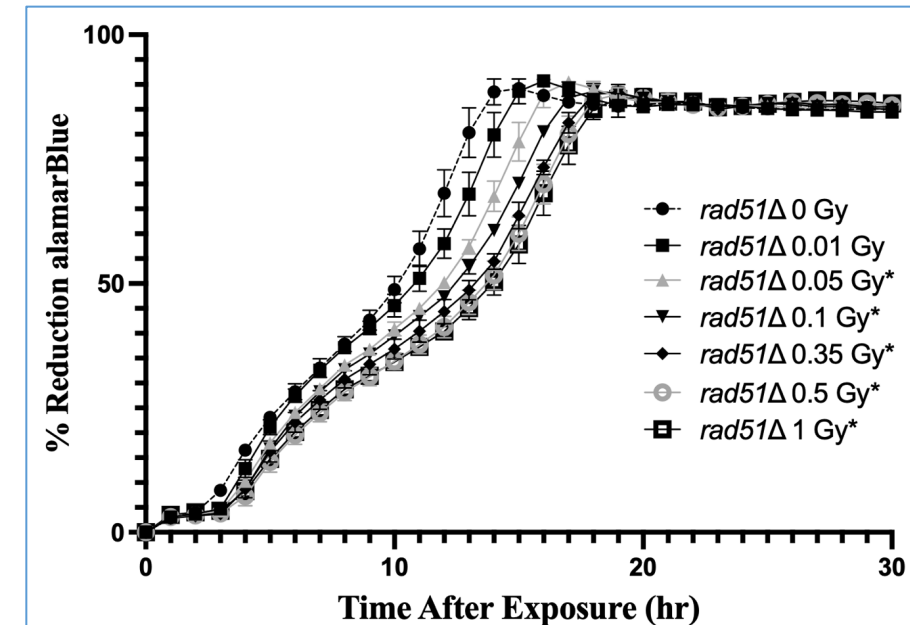
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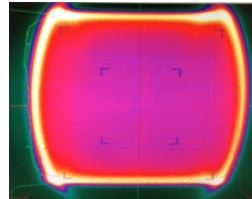
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alamarBlue turns pink when cells are metabolically active

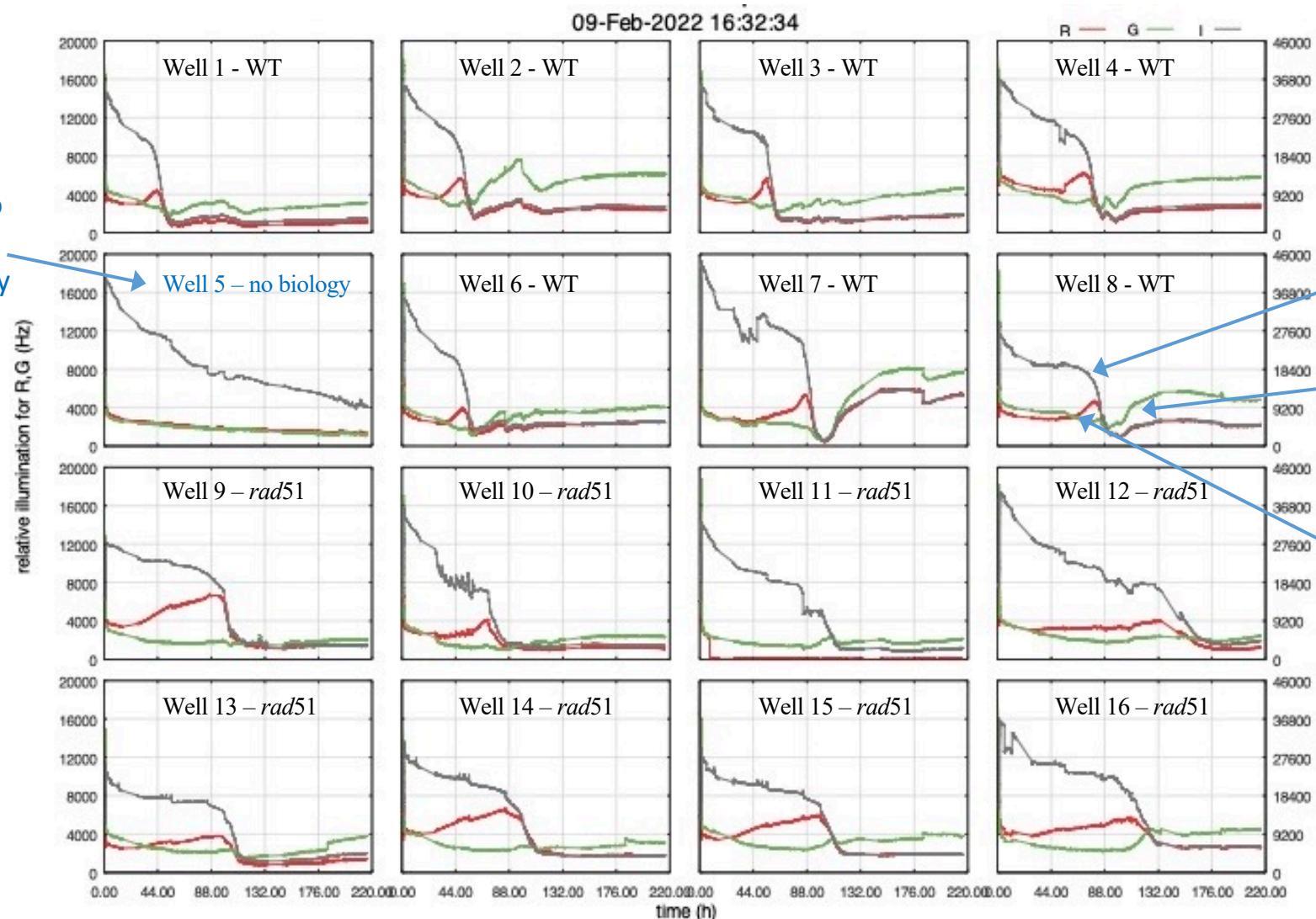
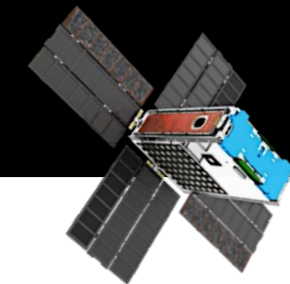


HR repair defective cells show sensitivity to GCRsim ionizing radiation





BioSentinel: ISS experiment



Well #5 in all cards has no biology, thus no optical changes due to cell activity are expected

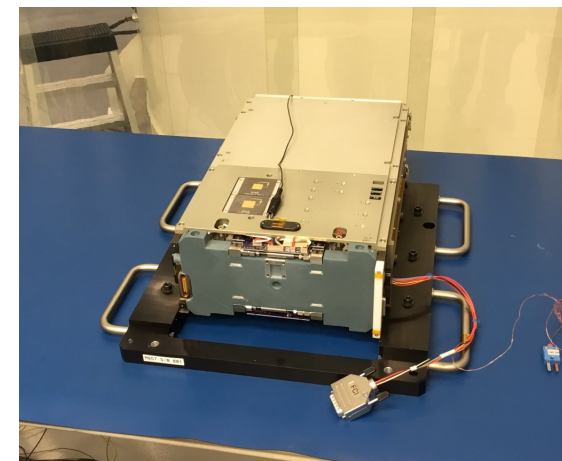
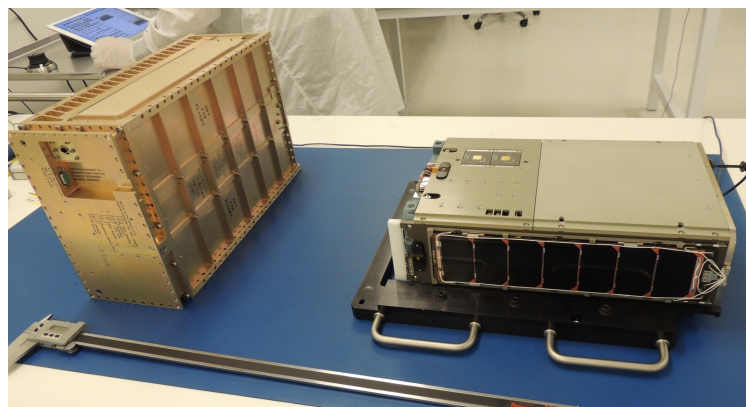
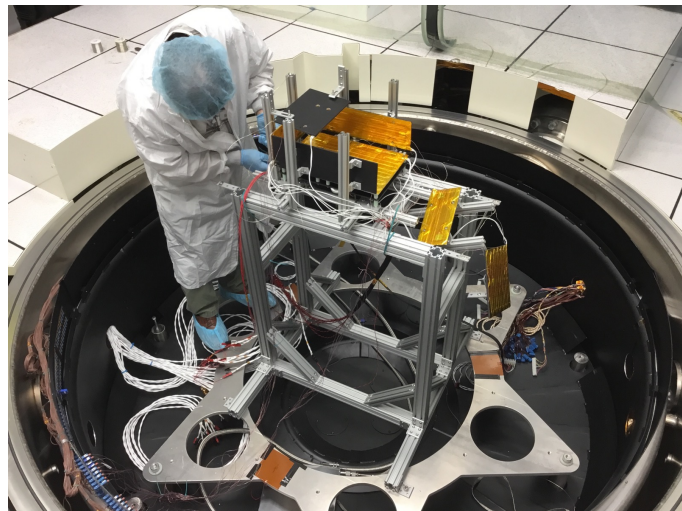
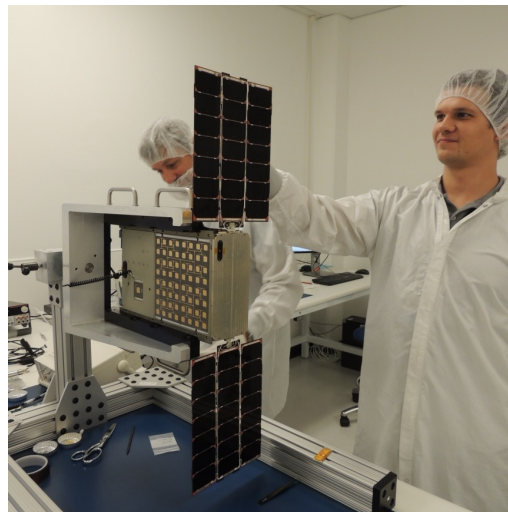
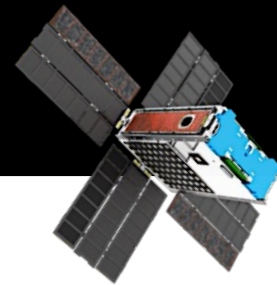
850nm readings show cell growth

570nm readings (green, going down then up) show transition to pink color, then clear

630nm readings (red, going up) show disappearance of the blue color



BioSentinel tests: vibe, TVPM, fit checks, etc.





BioSentinel: trajectory uncertainty & lunar impact risk



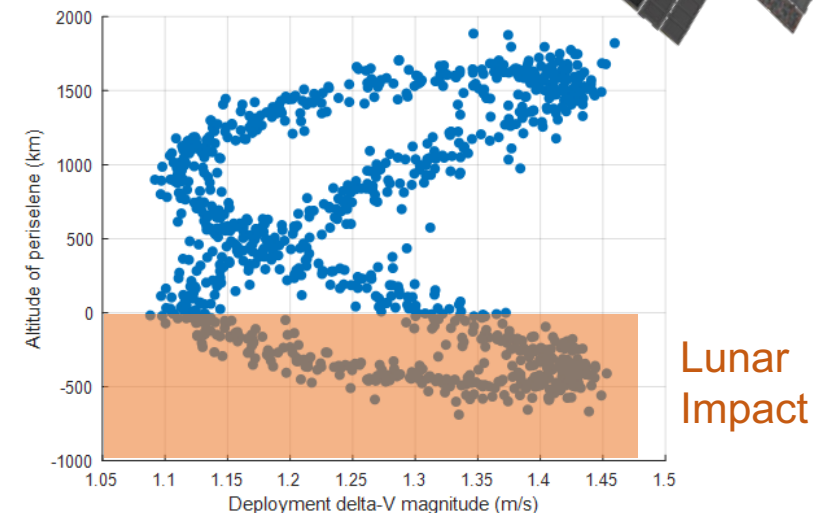
Baseline ConOps did not have a ΔV (delta velocity) maneuver planned. Initial lunar impact risks of $< 10\%$ was deemed an acceptable risk

However, high probability of lunar impact for new launch dates:

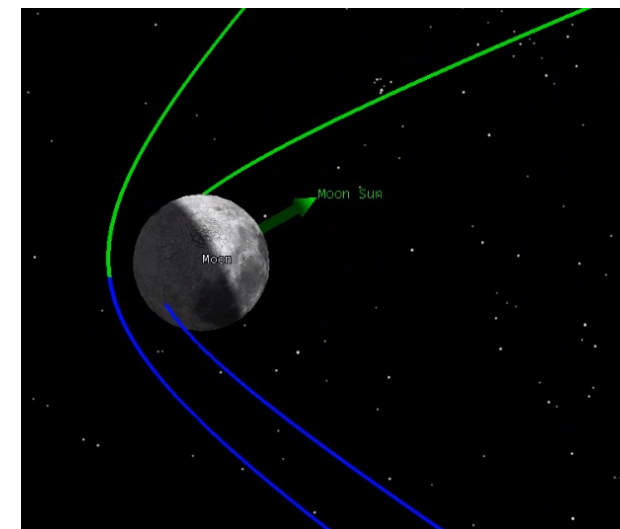
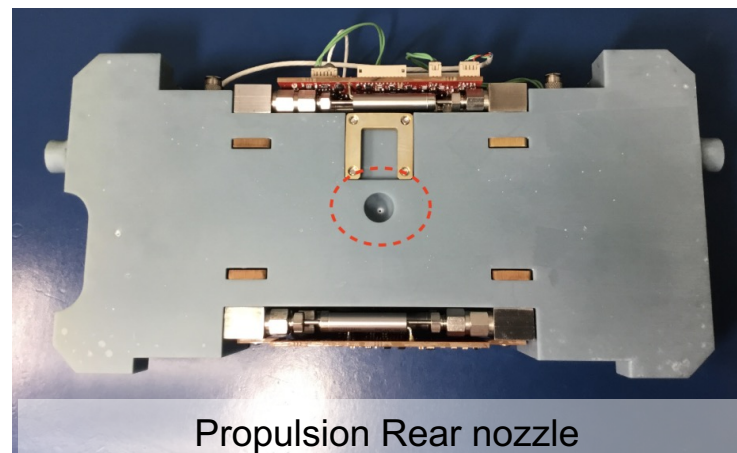
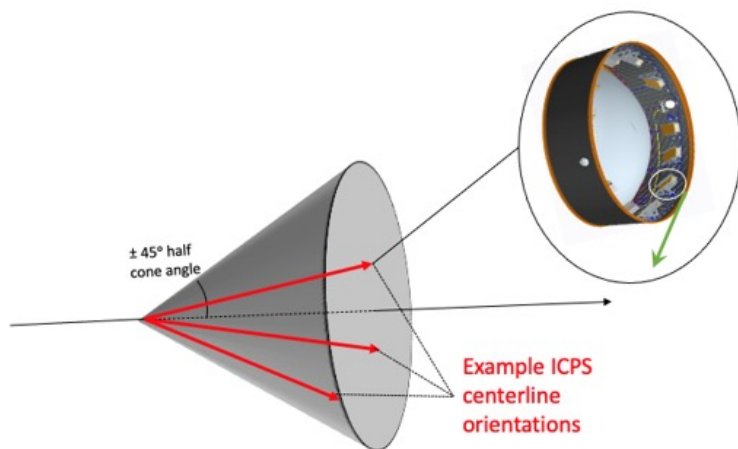
Aug 29: **30 %** / Sep 2: **54 %** / Sep 5: **56 %** / Nov 16: **14 %**

Avoiding lunar impact requires a ΔV maneuver shortly after deployment

ΔV capability was possible because the propulsion system fortuitously included extra fuel and an extra rear nozzle that had not been planned for the nominal mission

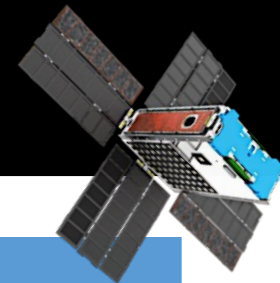


Aug 29 launch deployment variability





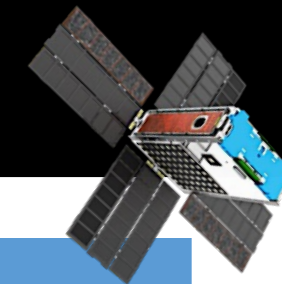
BioSentinel: flight tracker



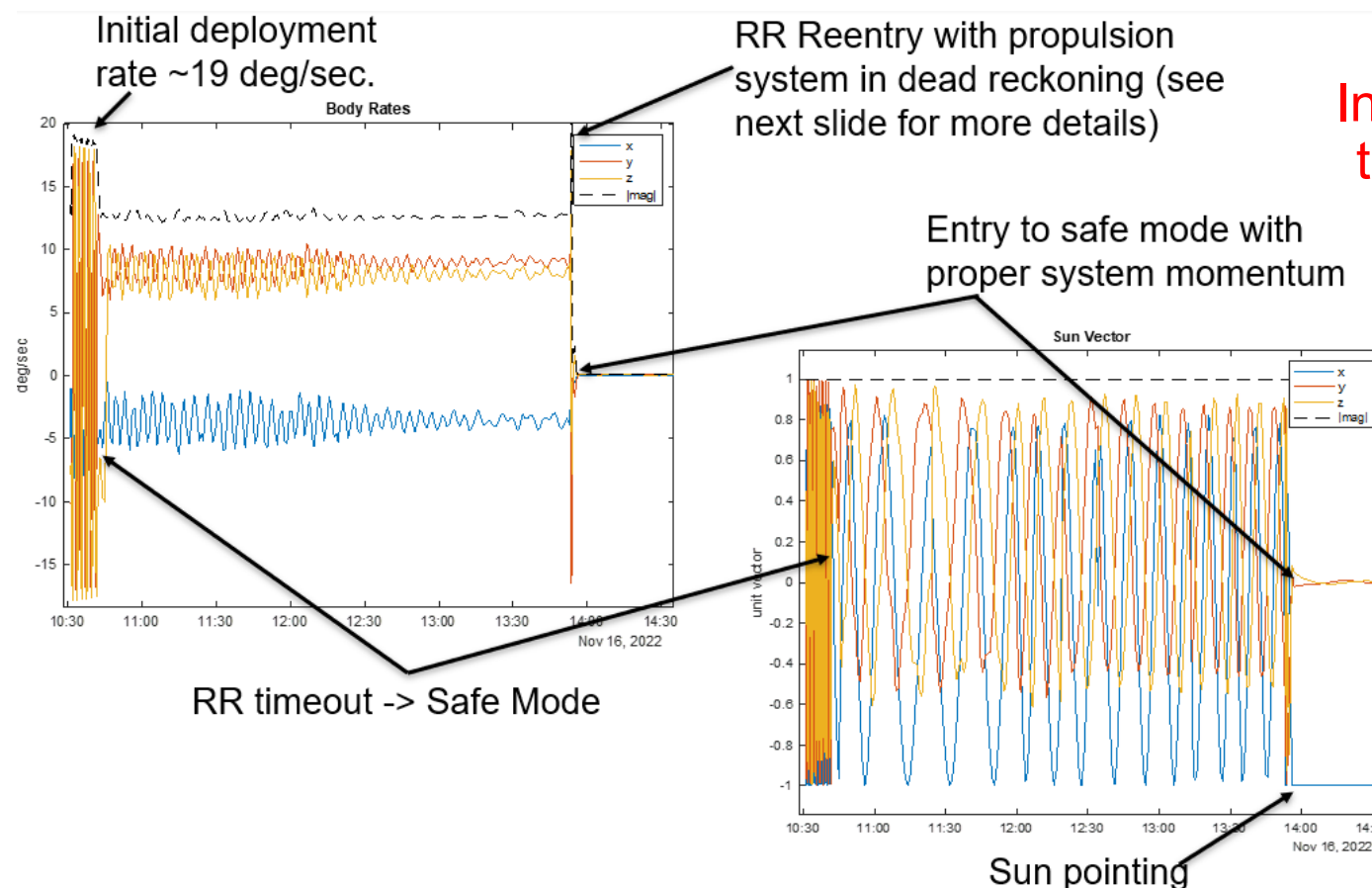
Pass	Date/Time (UTC)	Station	Notes
1	16 Nov 202320/11:41	DSS-25	Initial Acquisition. Rate reduction not complete, spacecraft tumbling



BioSentinel: flight tracker

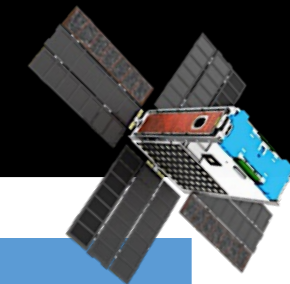


Pass	Date/Time (UTC)	Station	Notes
1	16 Nov 2022 320/11:41	DSS-25	Initial Acquisition. Rate reduction not complete, spacecraft tumbling





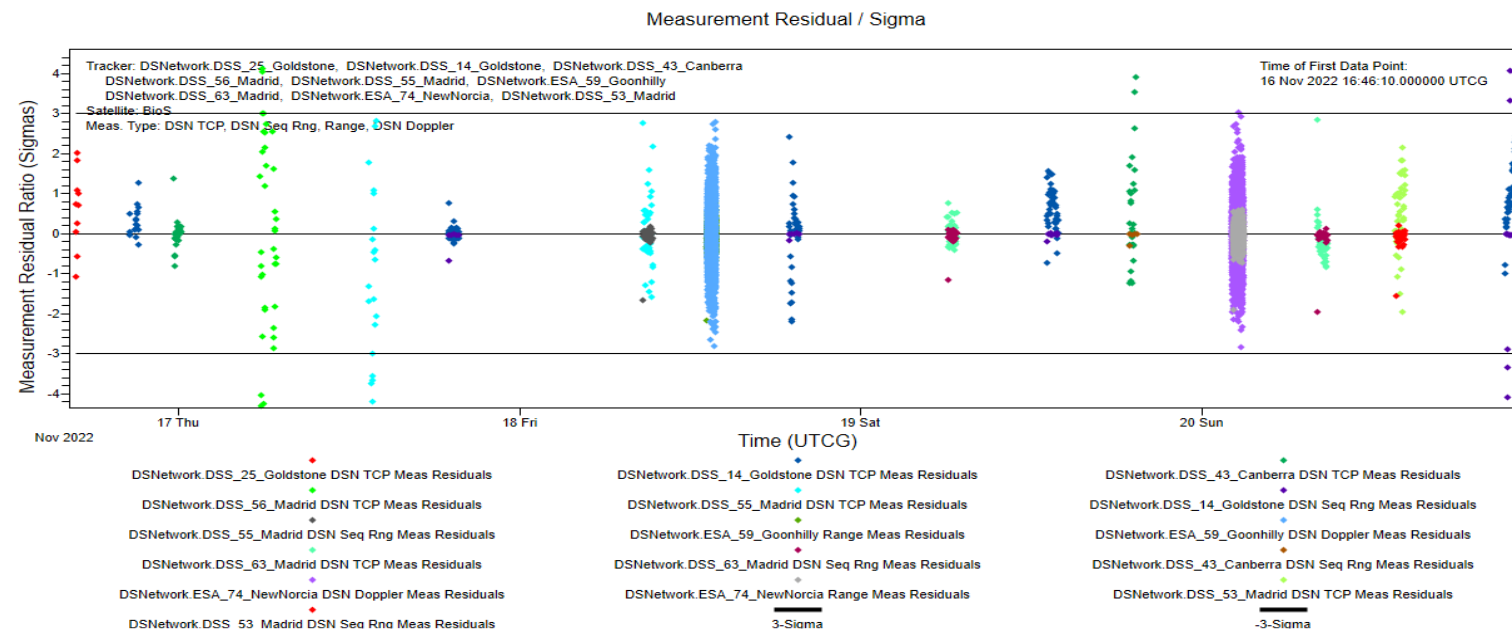
BioSentinel: flight tracker



Pass	Date/Time (UTC)	Station	Notes
1	16 Nov 2022 320/11:41	DSS-25	Initial Acquisition. Rate reduction not complete, spacecraft tumbling
1-extra	16 Nov 2022 320/13:52	DSS-14	Blind command to re-enabled rate reduction
2	16-Nov-22 320/16:25	DSS-25	Confirmed rate reduction complete
3	16-Nov-22 320/20:20	DSS-14	Deployed Solar Arrays
4	16 Nov 2022 320/23:20	DSS-43	Orbital Determination from first 4 passes. Lunar avoidance maneuver called-off

Final pre-flyby OD indicated:

- Flyby Altitude: 406 km
- Eclipse Duration: 36.5 min

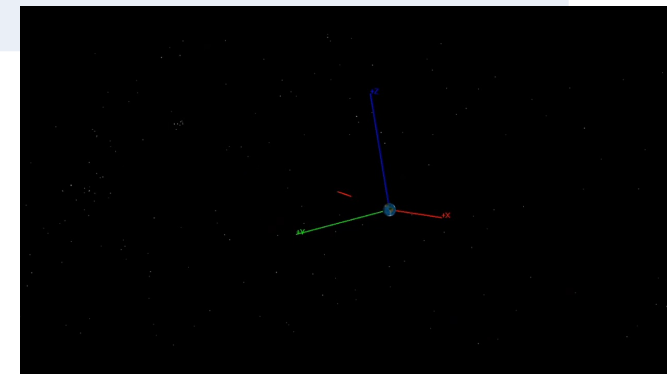




BioSentinel: flight tracker



Pass	Date/Time (UTC)	Station	Notes
1	16 Nov 2022 320/11:41	DSS-25	Initial Acquisition. Rate reduction not complete, spacecraft tumbling
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2	16-Nov-22 320/16:25	DSS-25	Confirmed rate reduction complete
3	16-Nov-22 320/20:20	DSS-14	Deployed Solar Arrays
4	16 Nov 2022 320/23:20	DSS-43	Orbital Determination from first 4 passes. Lunar avoidance maneuver called-off
5	17 Nov 2022 321/06:05	DSS-56	(would have been the pass for the dV maneuver) Transitioned to nominal pointing
...			
	21 Nov 2022 325/15:41		Lunar Flyby @ 406 km periselene altitude

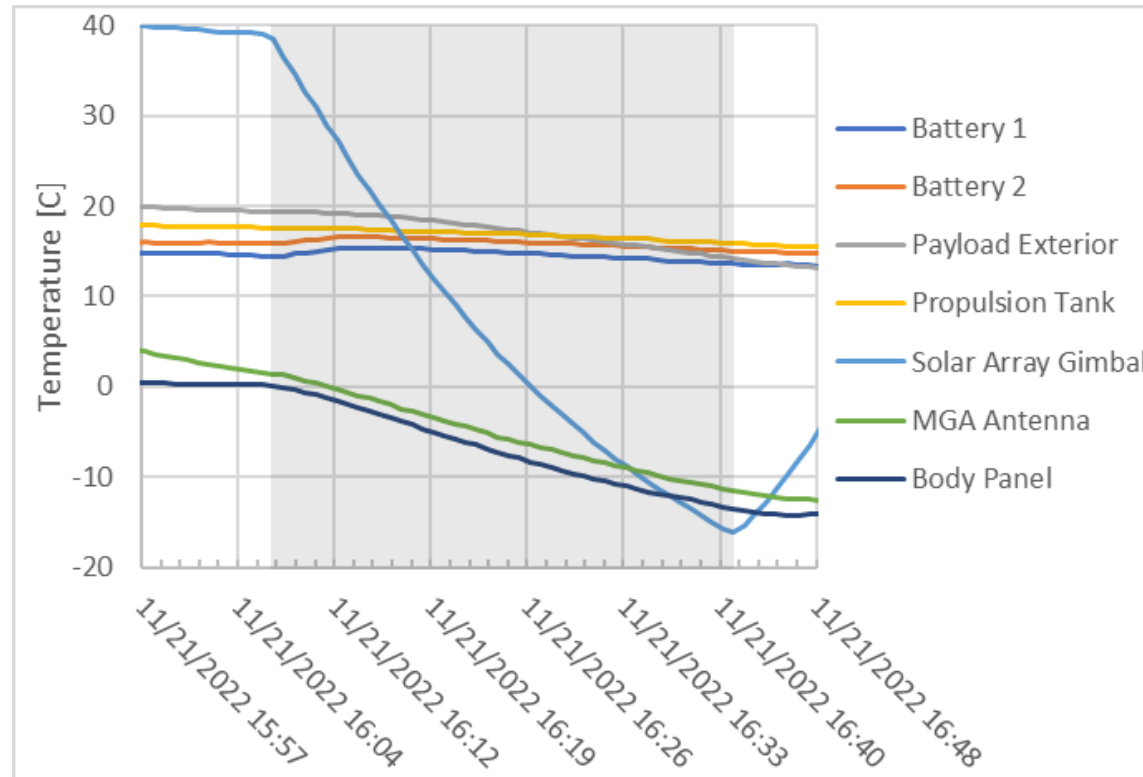




BioSentinel: flight tracker



During the 36.5-min eclipse, the payload could not drop below freezing or risk bursting fluidics





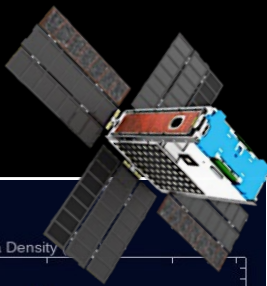
BioSentinel: flight tracker



Pass	Date/Time (UTC)	Station	Notes
1	16 Nov 2022 320/11:41	DSS-25	Initial Acquisition. Rate reduction not complete, spacecraft tumbling
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5	17 Nov 2022 321/06:05	DSS-56	(would have been the pass for the dV maneuver) Transitioned to nominal pointing
...			
	21 Nov 2022 325/15:41		Lunar Flyby @ 406 km periselene altitude
21	21 Nov 2022 17:15	DSS-14	Post Eclipse H&S nominal
...			
54	05 Dec 2022 16:00	DSS-65	Science Phase - Experiment #1 Start
...	288 successful DSN comm passes to date... ~ 100% success rate		



BioSentinel: science payloads



BioSensor payload:

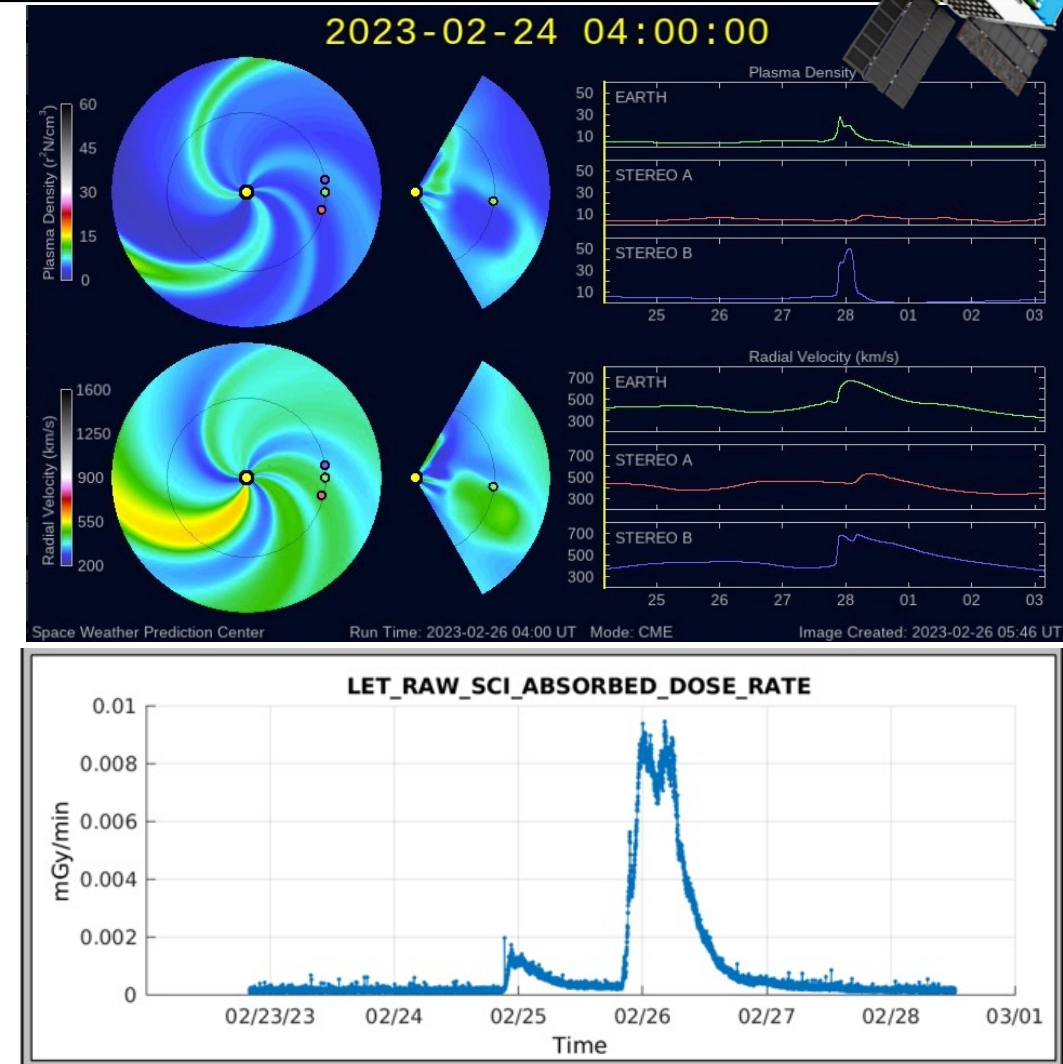
- Successfully filled and monitored 4 fluidic cards. However, no biology growth observed in fluidic wells; similar results observed on the ground control unit.

Top potential reason: cell viability and electronics were affected by long exposure to increased humidity inside the BioSensor enclosure (*i.e.*, sealed early in 2020 + delays)

- BioSensor payload technologies were demonstrated in deep space and learnings will be implemented in future mission including a new CLPS mission, LEIA.

Linear Energy Transfer (LET) spectrometer payload:

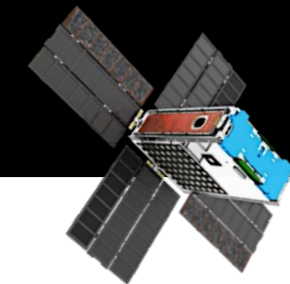
- Continues to gather radiation dosimetry.
- LET spectrometer has captured multiple solar events including coronal mass ejections.



Flux measurements from the GOES satellite (top) and BioSentinel LET spectrometer (bottom) recorded for a pair of Coronal Mass Ejection events on Feb. 24 and 25, 2023



BioSentinel: current status & extensions



First extension: ESDMD Mars Campaign Office (MCO) extended the BioSentinel after nominal mission

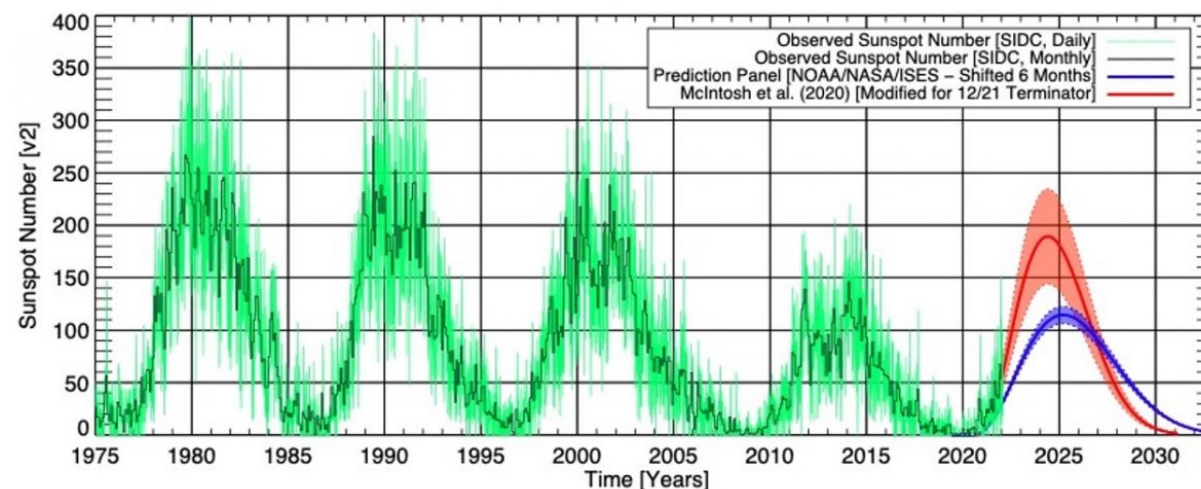
Second extension (current): SMD Heliophysics will continue supporting mission ops into 2025

Science Objectives (in partnership with JSC RadWorks & SMD Heliophysics):

1. Characterize solar particle events (SPEs), especially as continue through solar maximum
2. Provide space radiation characterization in multiple environments using the same radiation detector, including heliocentric orbit, low Earth orbit, cis-lunar space, and on the lunar surface
3. Monitor galactic cosmic radiation (GCR) flux rates in a unique location while transitioning into solar max

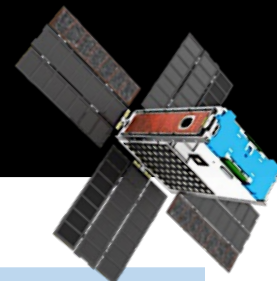
Hardware Heritage for long durations in deep space:

1. LET Timepix detectors ahead of future operations on Lunar Gateway and Artemis missions
2. NASA Engineering and Safety Center (NESC) EEE COTS parts validation for CubeSat components





BioSentinel: radiation environment characterization

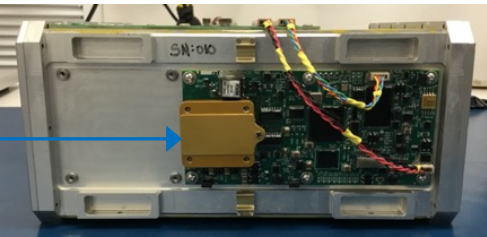


- LET spectrometer mounted outside the BioSensor enclosure
- Reports cumulative dose, dose rate & particle distribution based on LET
- Performing nominally; unaffected by BioSensor issues

Science objectives:

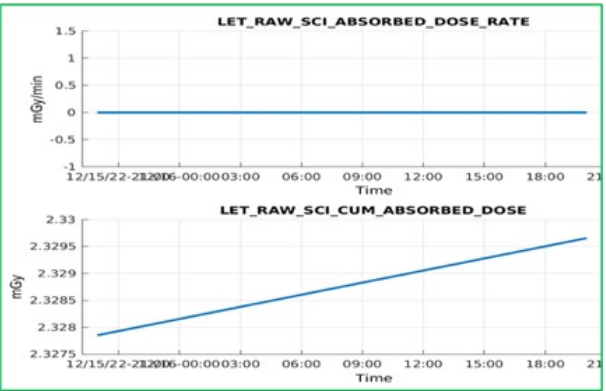
- Characterize radiation environment
- Compare ISS, deep space, and ground data
- Characterize contribution from solar and GCR particles
- Characterize solar particle events (SPEs)

LET spectrometer

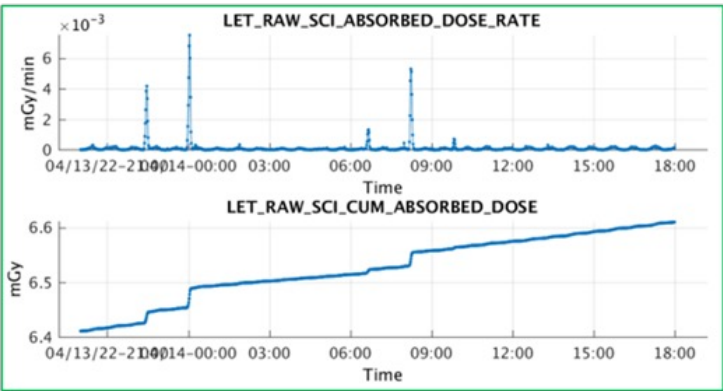


	Absorbed dose rate (mGy/day)	Total absorbed dose (6-mo mission)
Ground	~ 0.0003	0.055 mGy
ISS (Jan 31 – Jun 17, 2022)	0.217	-
Free-flyer	0.306	55.78 mGy
Free-flyer (transport modeling)	0.25 ± 0.04	-

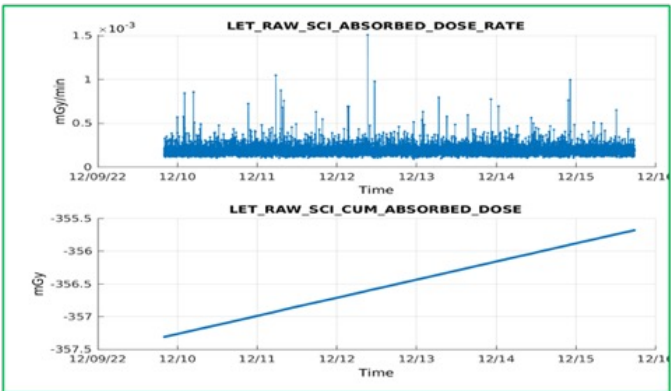
Ground LET spectrometer – Dec 16



ISS LET spectrometer – April 14

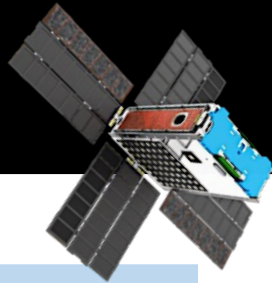


Free-flyer LET spectrometer – Dec 16





BioSentinel: radiation environment characterization

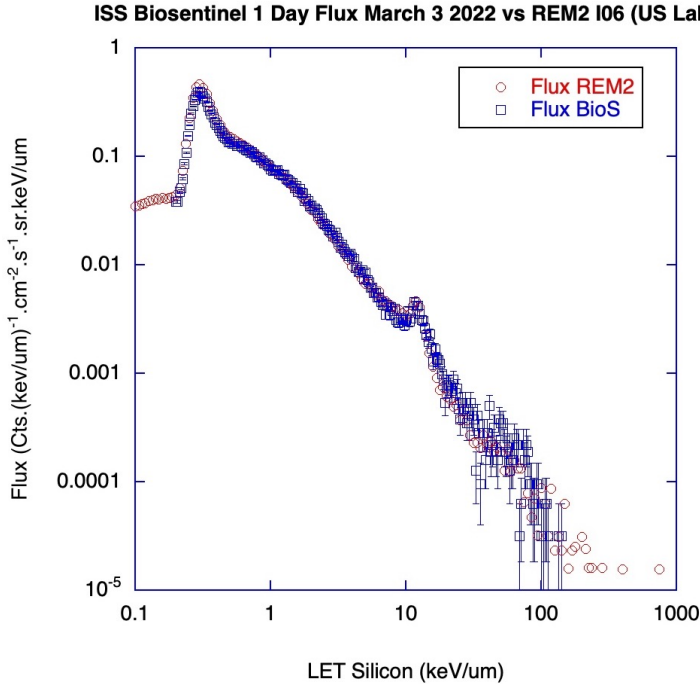


- LET spectrometer mounted outside the BioSensor enclosure
- Reports cumulative dose, dose rate & particle distribution based on LET
- Performing nominally; unaffected by BioSensor issues

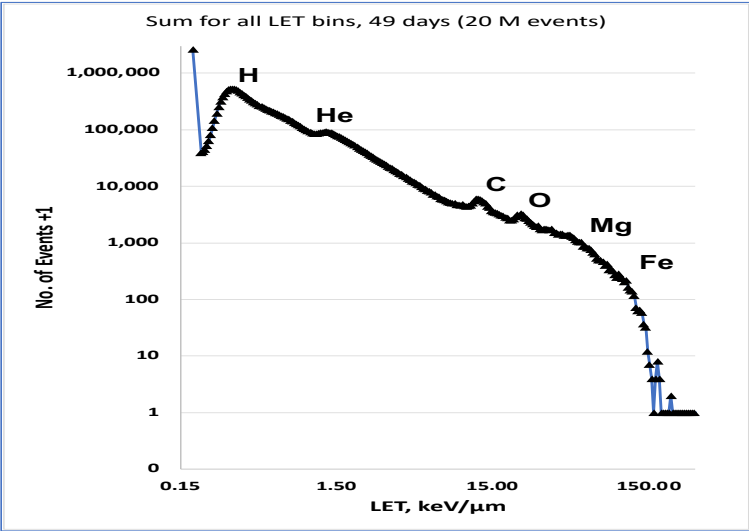
Science objectives:

- Characterize radiation environment
- Compare ISS, deep space, and ground data
- Characterize contribution from solar and GCR particles
- Characterize solar particle events (SPEs)

	Absorbed dose rate (mGy/day)	Total absorbed dose (6-mo mission)
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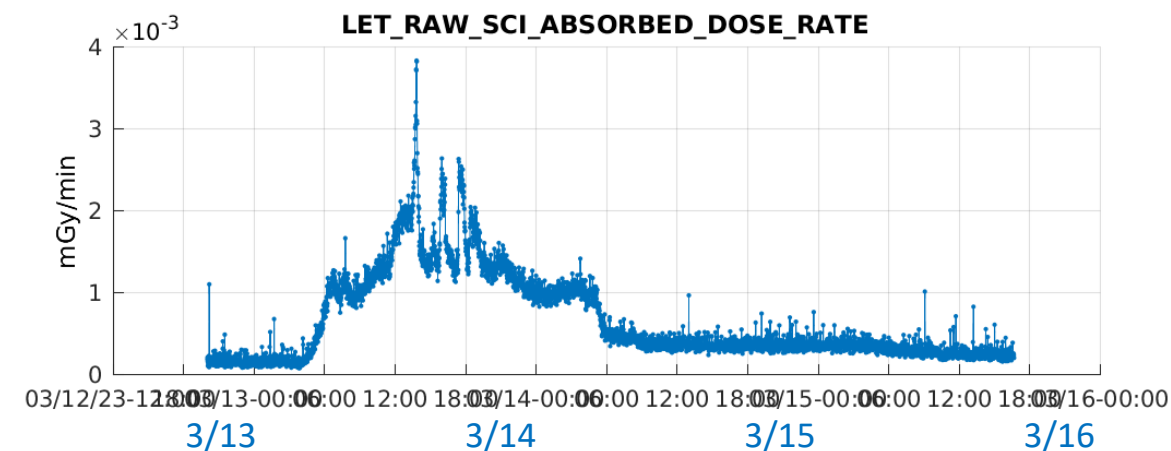
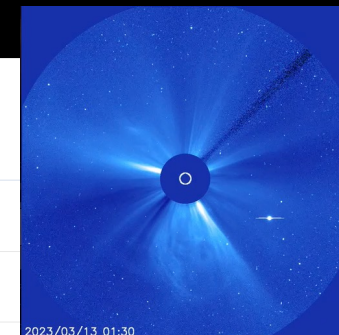
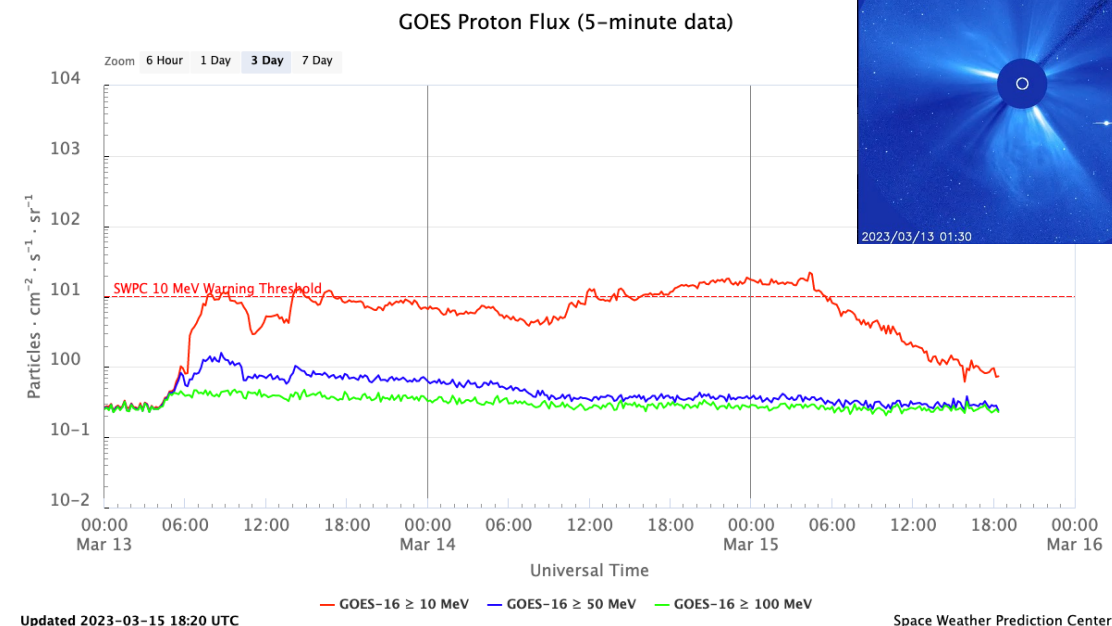
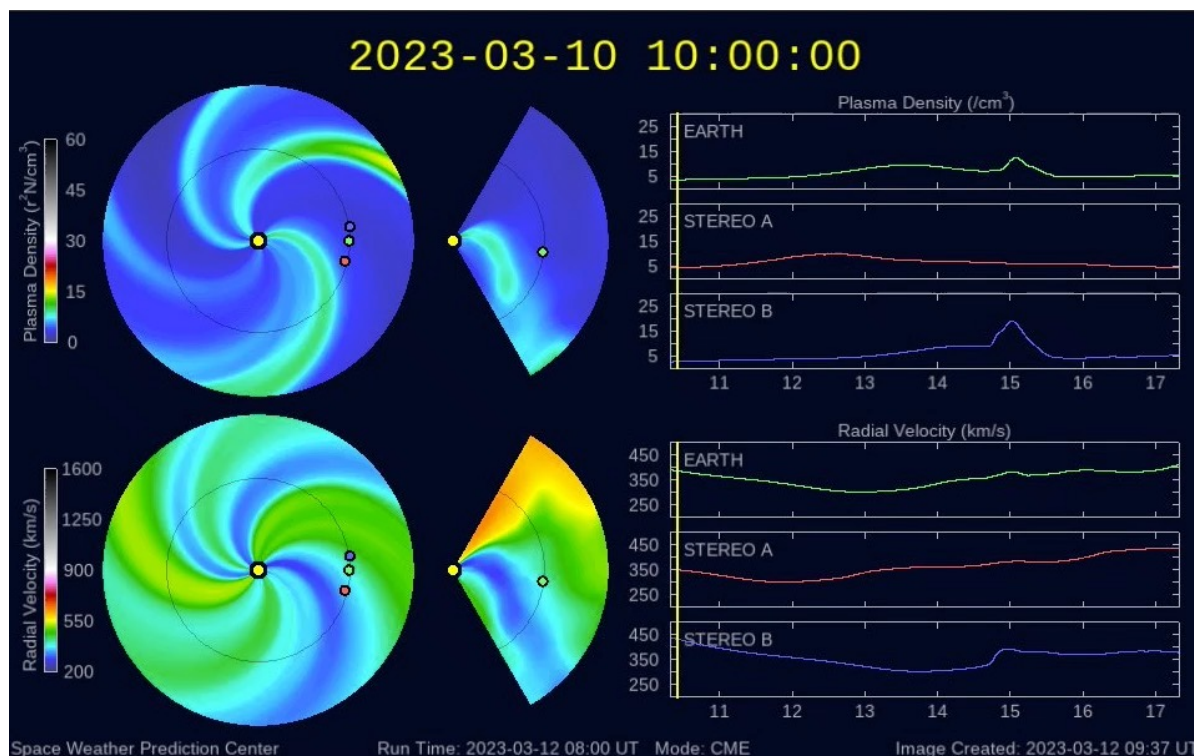
LET spectrum (in Si; 20M events); first 49 days





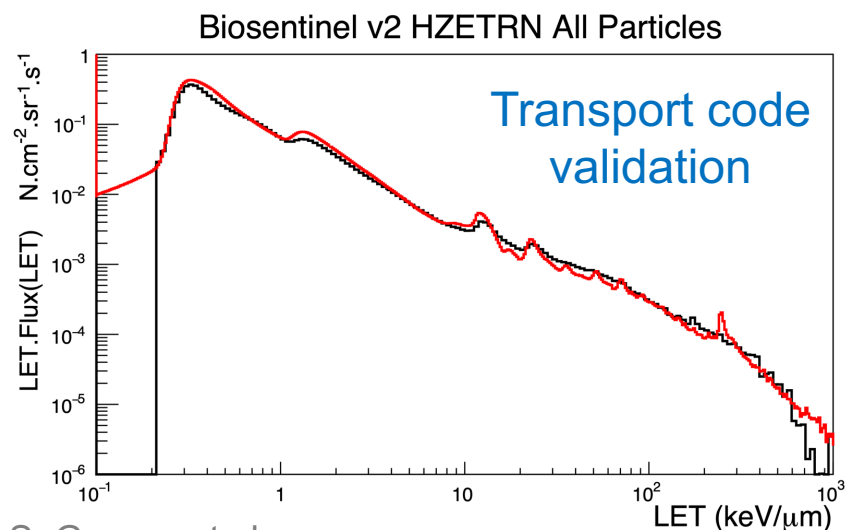
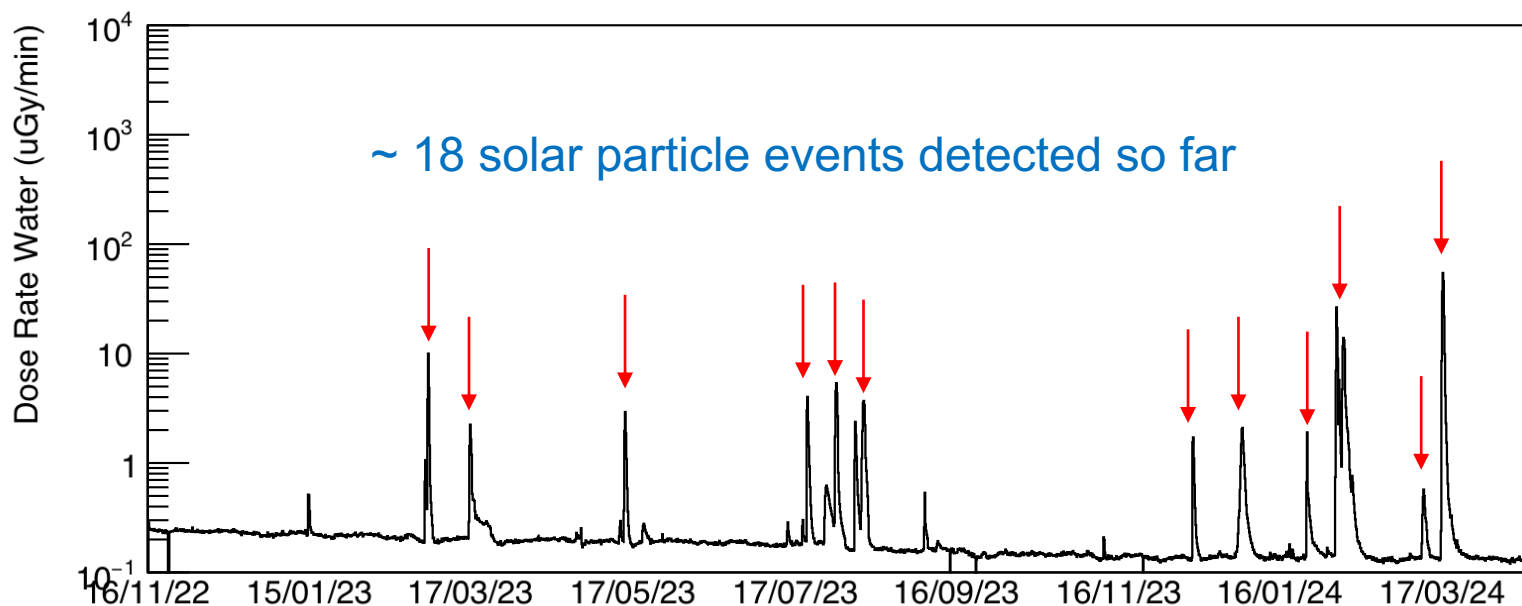
BioSentinel: radiation environment characterization

- CME event on March 13, 2023
- >100 MeV proton intensity enhancement
- Steady return to background levels
- BioS LET spectrometer detected event



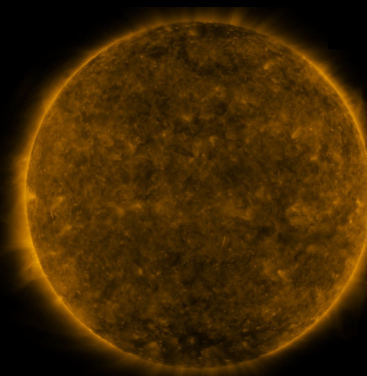


BioSentinel: radiation environment characterization

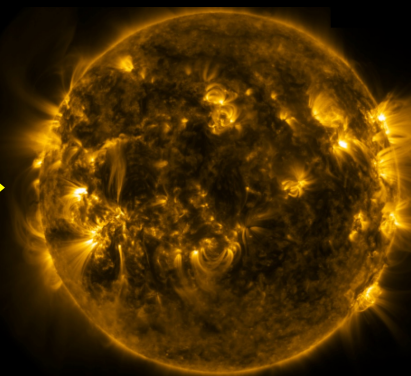


S. George et al.

Magnetically quiet and active sun



Feb 2019



Feb 2024
(~ solar max)



MODERATE Solar Radiation Storm Event

S2

WHAT: A Solar Energetic Particle Event is in Progress

EVENT:

The greater than 10 MeV proton flux became enhanced following an X1.1 flare at 23/0133 UTC. Solar radiation storms at S1-S2 (Minor-Moderate) levels have been observed.

TIMING:

S1 (Minor) levels were observed beginning at 23/0815 UTC, and S2 (Moderate) levels began at 23/1405 UTC.

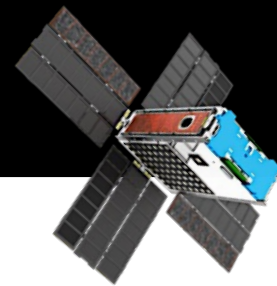
EFFECTS:

Degradation to HF communications in the polar regions; possible risk to space launch and satellites; high flying interests along polar routes should monitor the situation for updates. The general public need not be concerned.

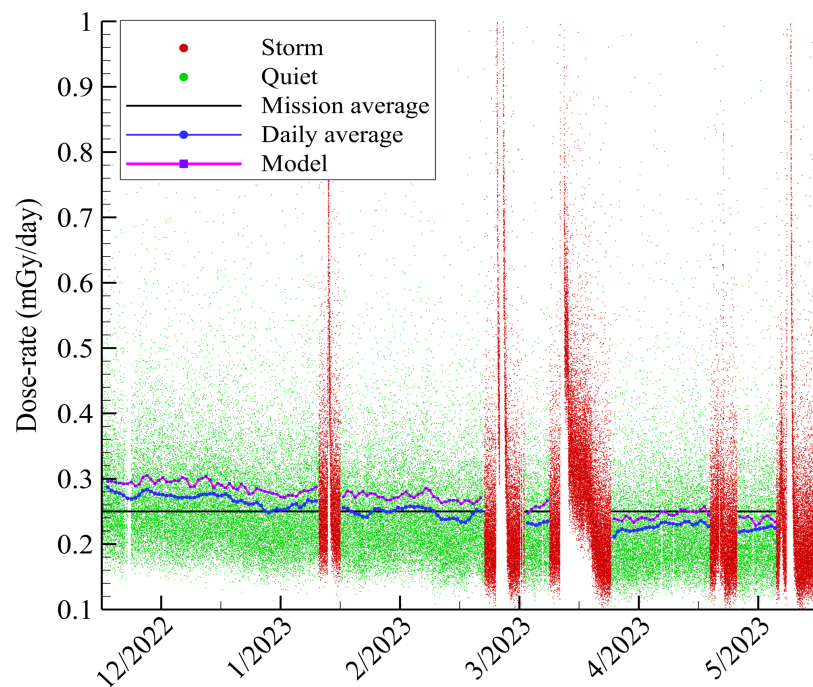




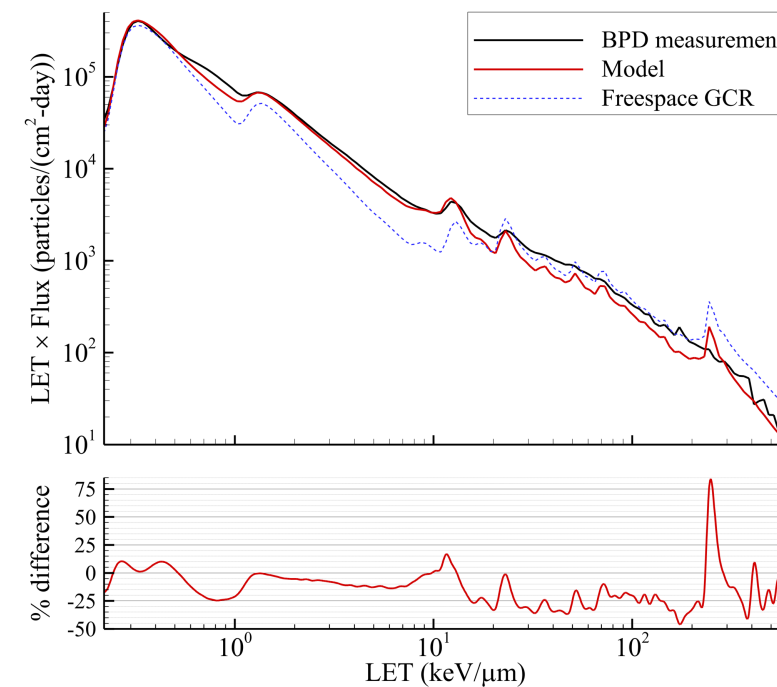
BioSentinel: radiation model prediction vs. flight



Good agreement between GCR model predictions and measurements for both average dose rate and LET spectrum (particularly below 10 KeV/ μ m)



	Absorbed dose rate (mGy/day)
Flight measurement	0.25
Model post mission calculation	0.264 (6%)
Model pre-mission prediction	0.27 ± 0.04 (8% $\pm$ 16%)



How are we improving LEIA based on lessons learned from BioSentinel?

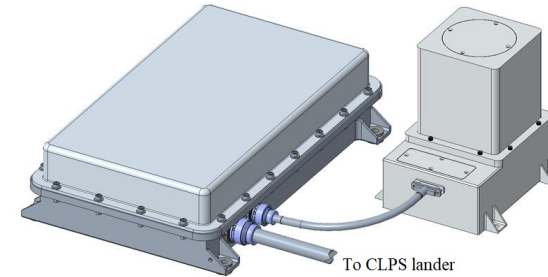
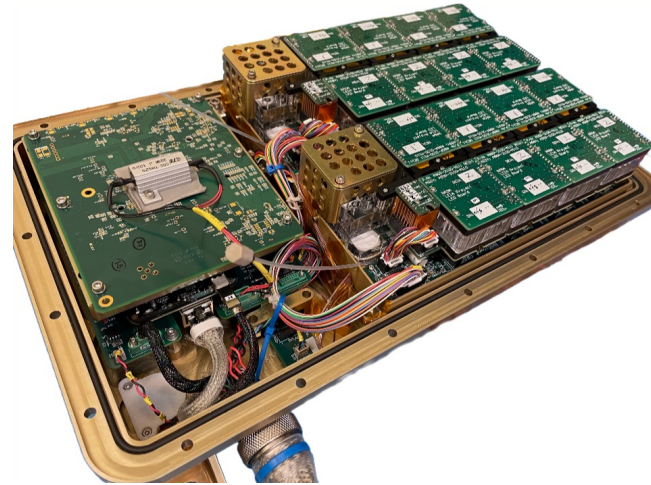
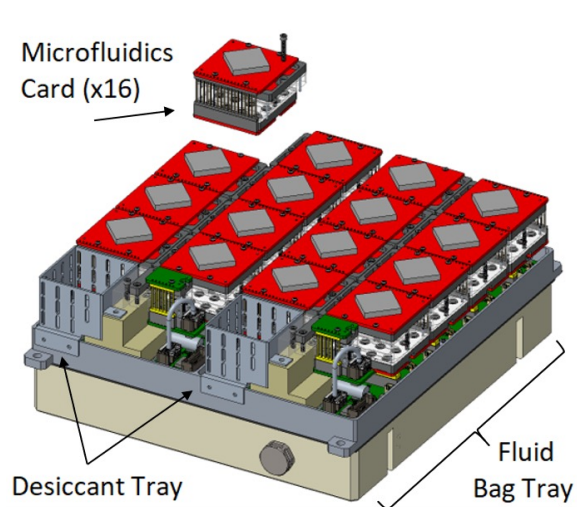




LEIA lunar surface mission

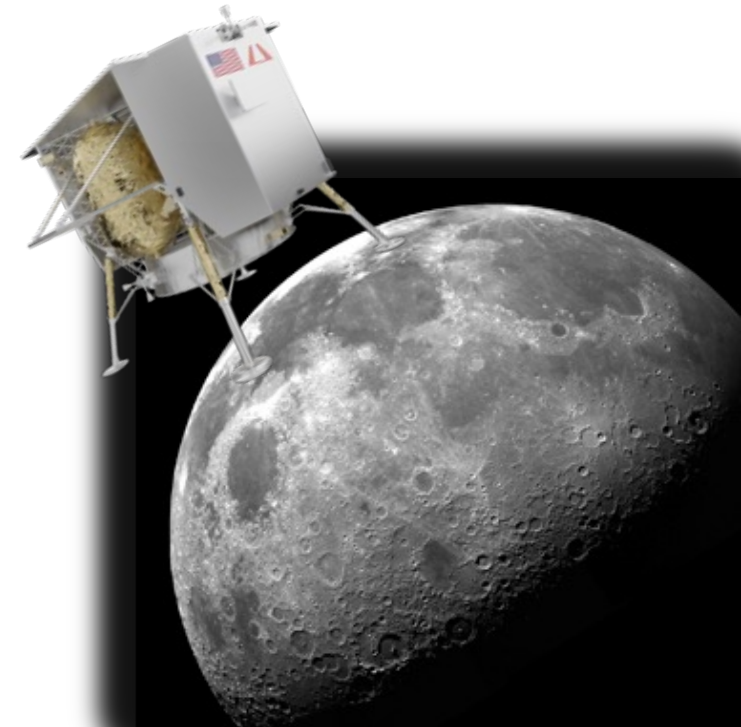


LEIA: Lunar Explorer Instrument for space biology Applications



Science Aims:

1. Determine cellular sensitivity to the lunar surface environment
2. Test production of antioxidant carotenoids for use in crew diet
3. Engineer genetic countermeasures to test for enhanced tolerance to the lunar surface
4. Measure biologically relevant radiation at the south pole landing site



Genetically engineer microbes to produce essential nutrients

Why?

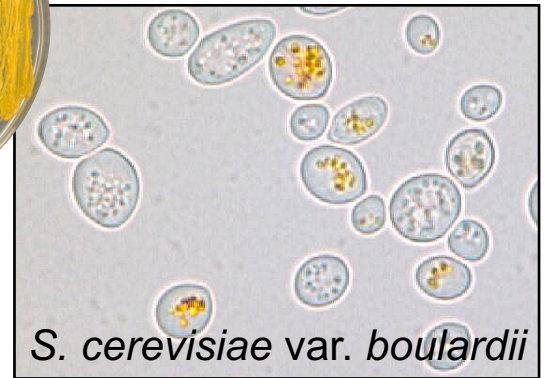
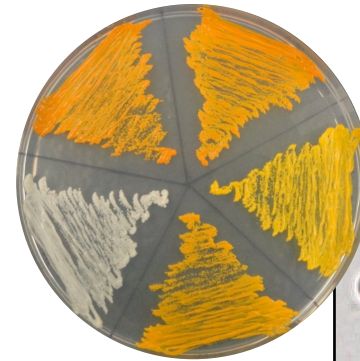
- Pre-packaged foods in the NASA Food System have a limited shelf life; need a 5-year shelf-life to go to Mars
- Current pre-packaged foods lose palatability and essential nutrients during long-term storage

What?

- Rapid, on-demand production
- Room temperature storage of organisms
- Enriches pre-packaged foods with labile nutrients



BioNutrients: on-orbit operations



S. cerevisiae var. *boulardii*

Carotenoids selected as initial demo nutrient:

- Light sensitive; degrades in packaged foods
- Important to protect from macular degeneration
- Antioxidant activity to protect against DNA damage



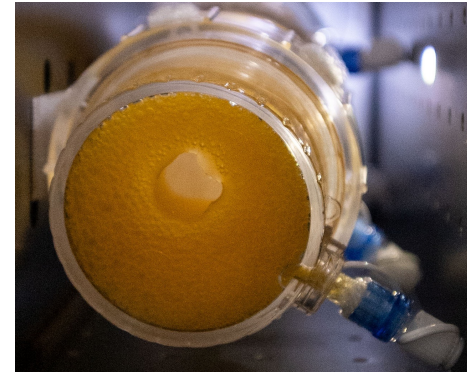
Biomanufacturing: transitioning from the ISS to the Moon



- Radiation dose on the lunar surface is higher than in low Earth orbit (LEO)
- Higher radiation doses are expected to increase DNA and ROS damage to cells
- Cells may shift energy from growth and production to repairing damage
- Will antioxidant production in yeast be reduced?



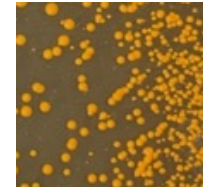
Jan 2023: NASA astronaut Nicole Mann works on the BioNutrients-2 investigation



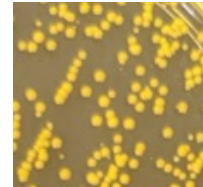
β -carotene strain



23°C



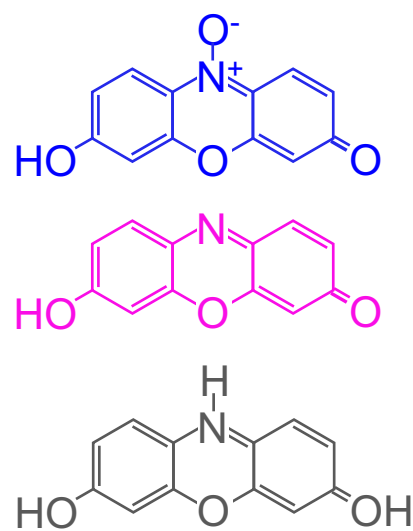
25°C



30°C



35°C



Resazurin
(blue)



Resorufin
(pink)



Dihydroresorufin
(colorless)

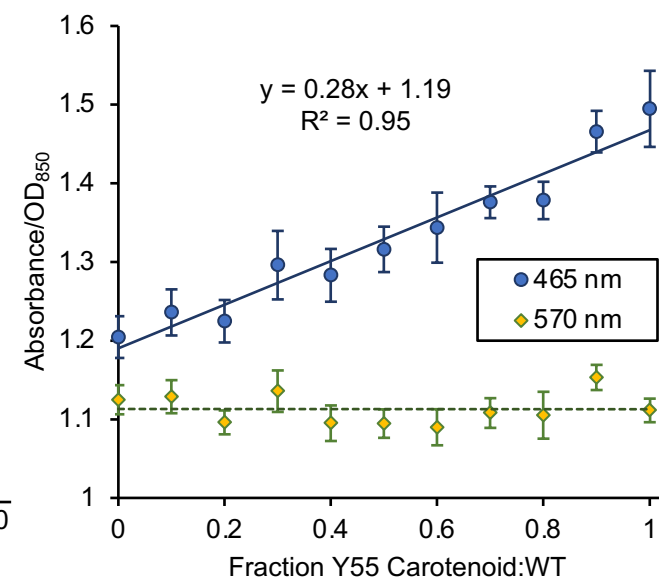
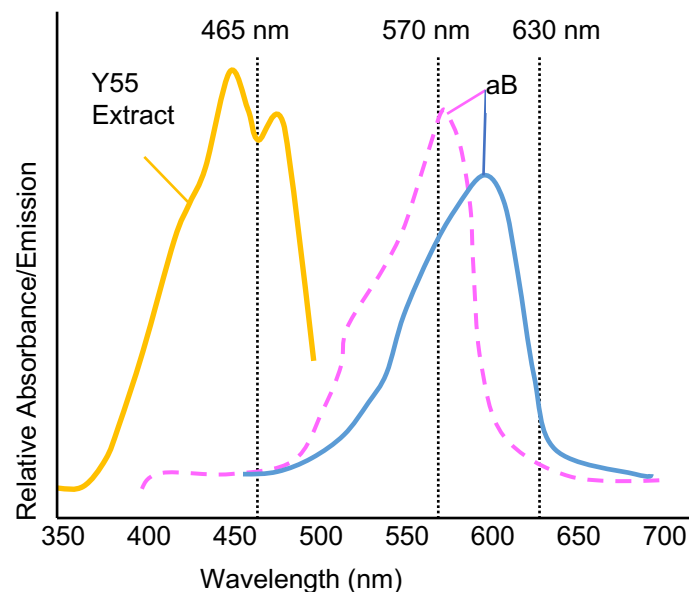
Reduction of aB changes dye color:

570 nm LED – measures pink aB

630 nm LED – measures blue aB

850 nm LED – measures cell growth

How are we tracking carotenoid production?



Carotenoids absorb in blue wavelengths:

- Replace 570 nm with a 465 nm LED light
- Spectroscopy approach allows a direct read-out of nutrient production levels



CP-22 planned landing site is at Mons Mouton

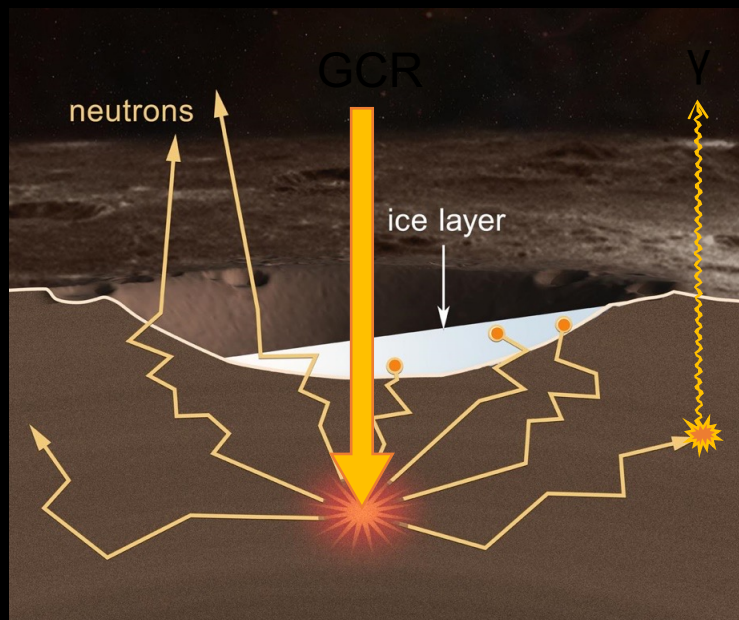


Mons Mouton is a mesa-like lunar mountain near the Nobile Crater

Mons Mouton is visible from Earth and roughly the size of the state of Delaware



Lunar surface radiation is a distinct environment from deep space

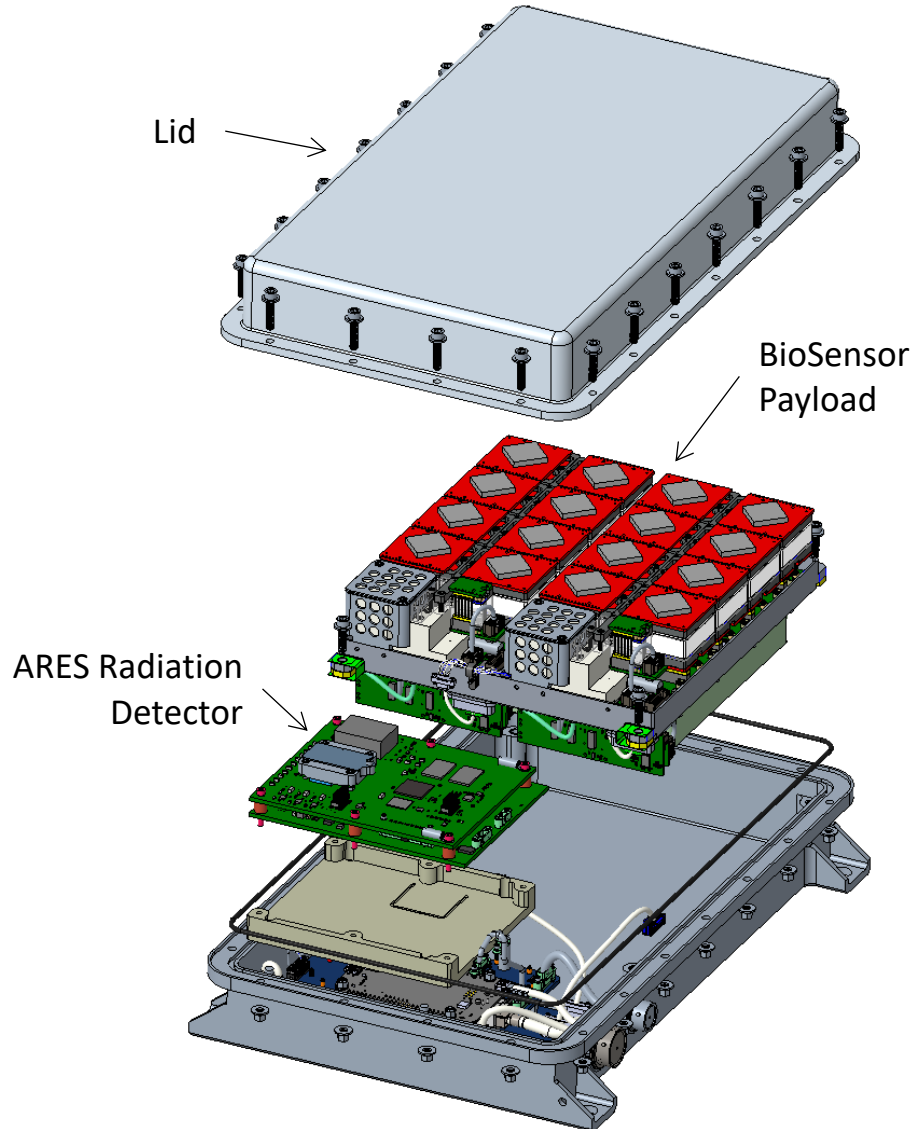


Estimates of fast neutrons in lunar surface radiation

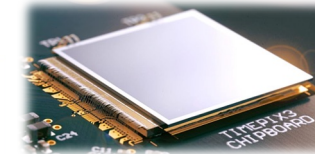
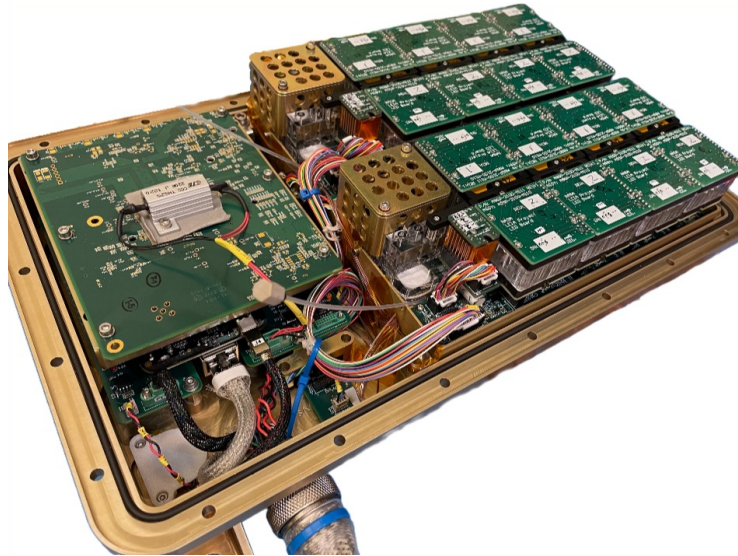
Mission	Project	Dose Type	% Fast Neutron
Lunar Prospector	LP	Effective	16-18%
Chandrayaan-1	RADOM	Effective	2-20%
LRO	CRaTER	Absorbed	0.7%
Chang'E 4	LND	Absorbed	23%

Lunar regolith absorbs GCR to produce secondary albedo neutrons:

- High-energy fast neutrons cause direct cellular damage
- Fast neutrons also produce ionizing radiation
- Neutrons pass through common shielding materials
- Estimates of surface neutron doses vary widely



BioSensor



Linear Energy Transfer (LET) spectrometer



Mini-Fast Neutron Detector (mini-FND)

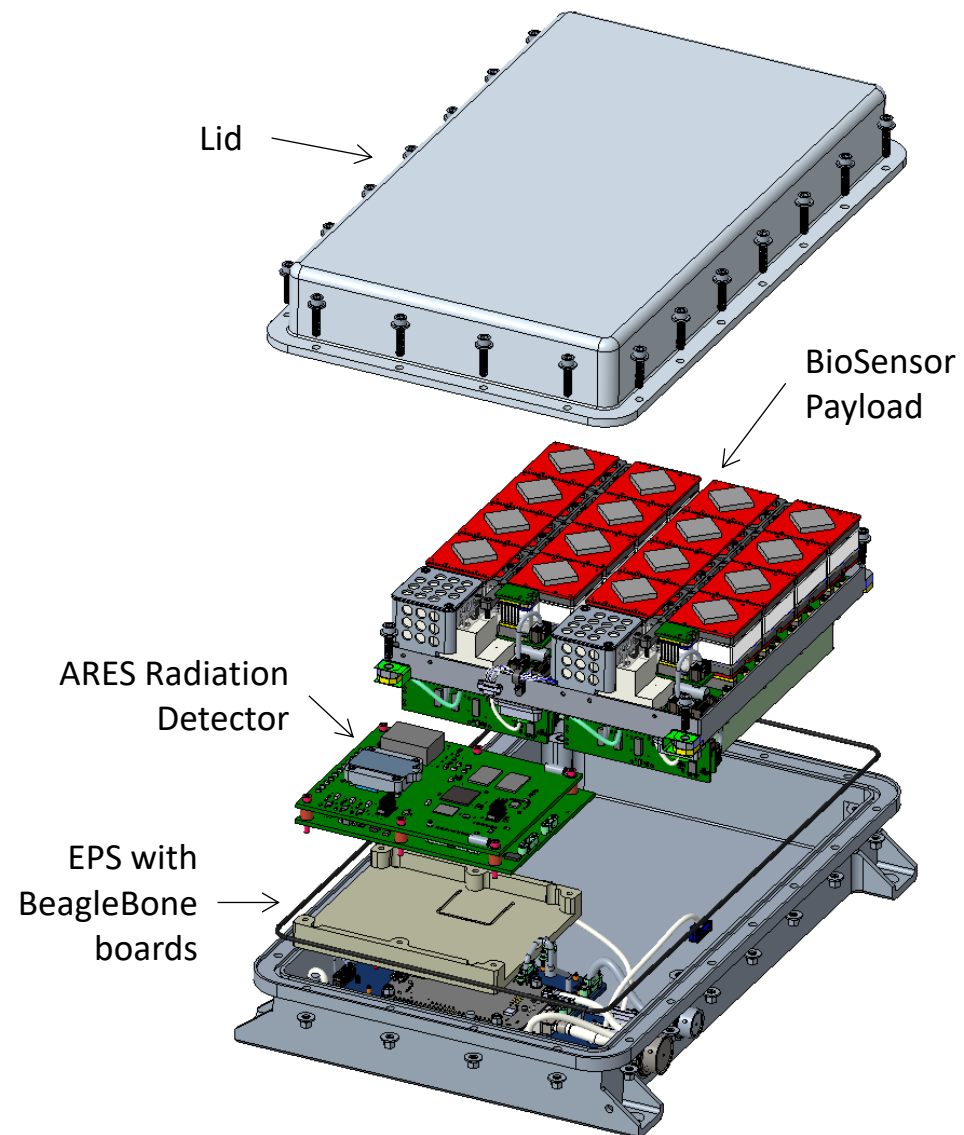
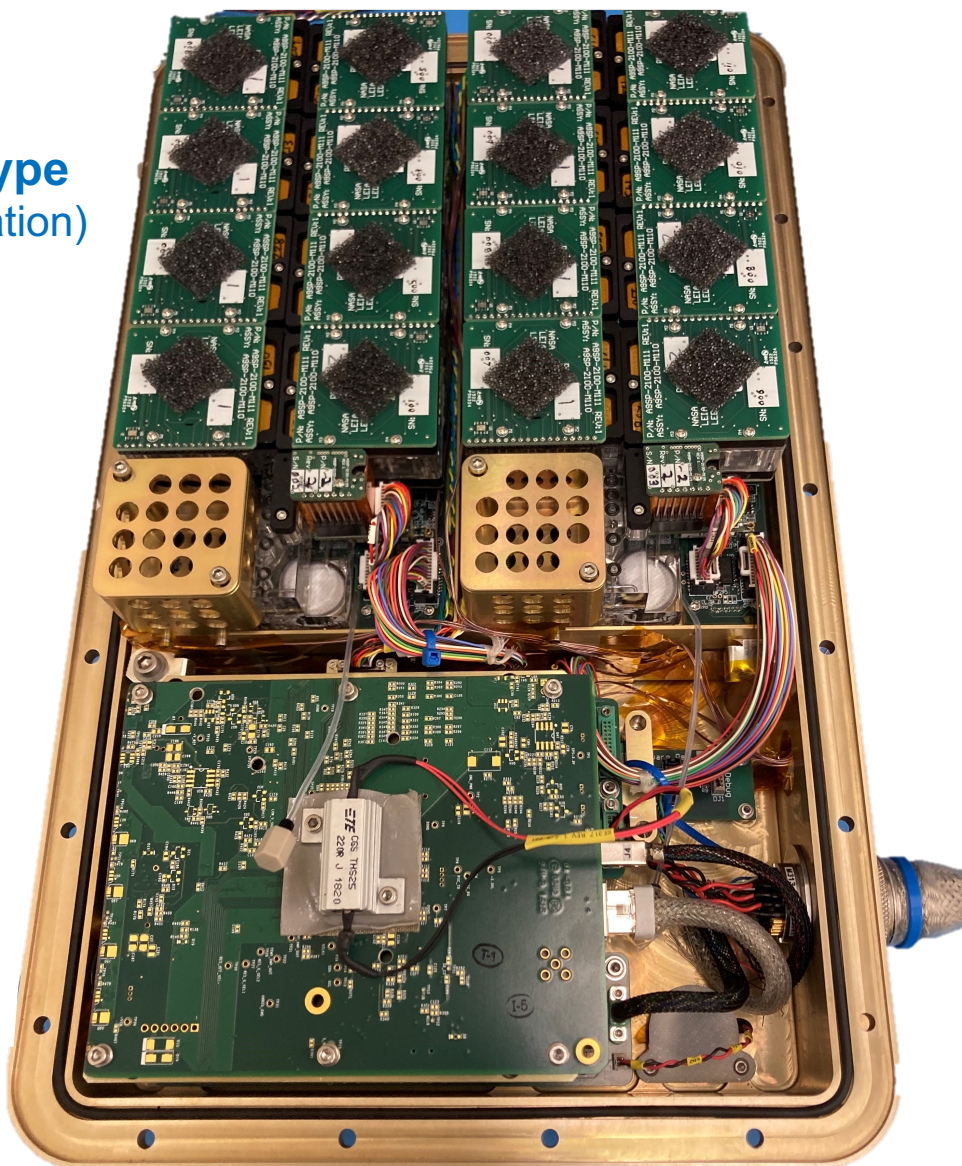
- BioSensor is a microfluidic culturing system to measure yeast growth and metabolism.
- ARES Timepix3 LET spectrometer measures charged particle radiation
- Mini-FND is a fast neutron detector



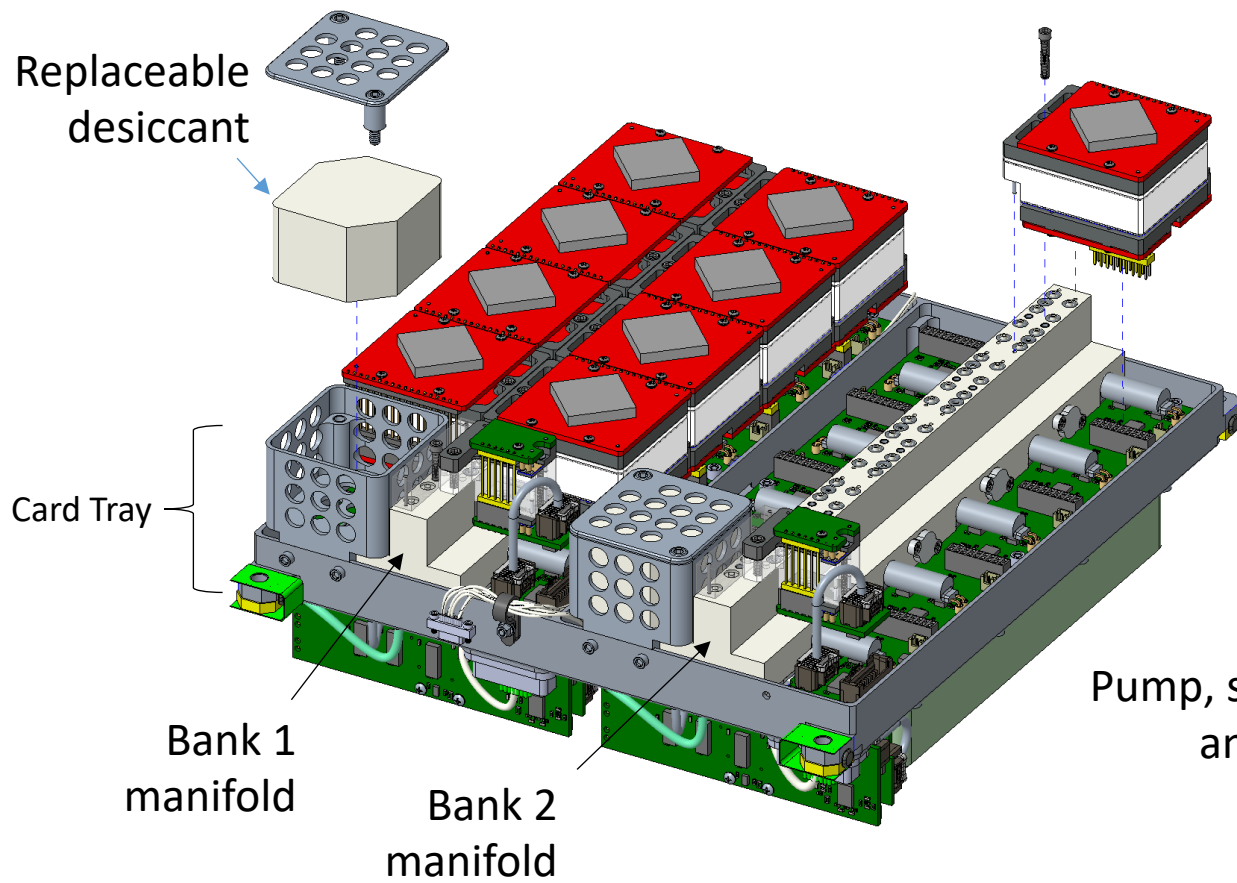
LEIA improvements



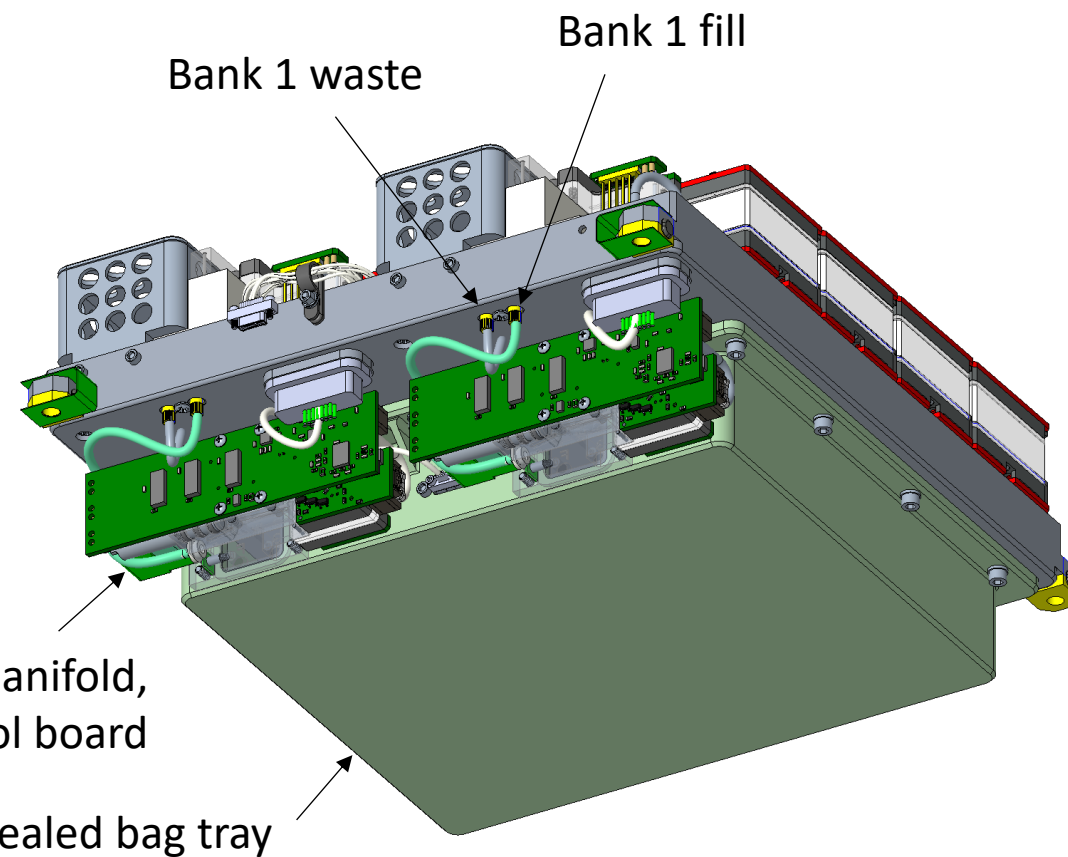
LEIA prototype
(open configuration)



How are we preventing high humidity inside the BioSensor enclosure?



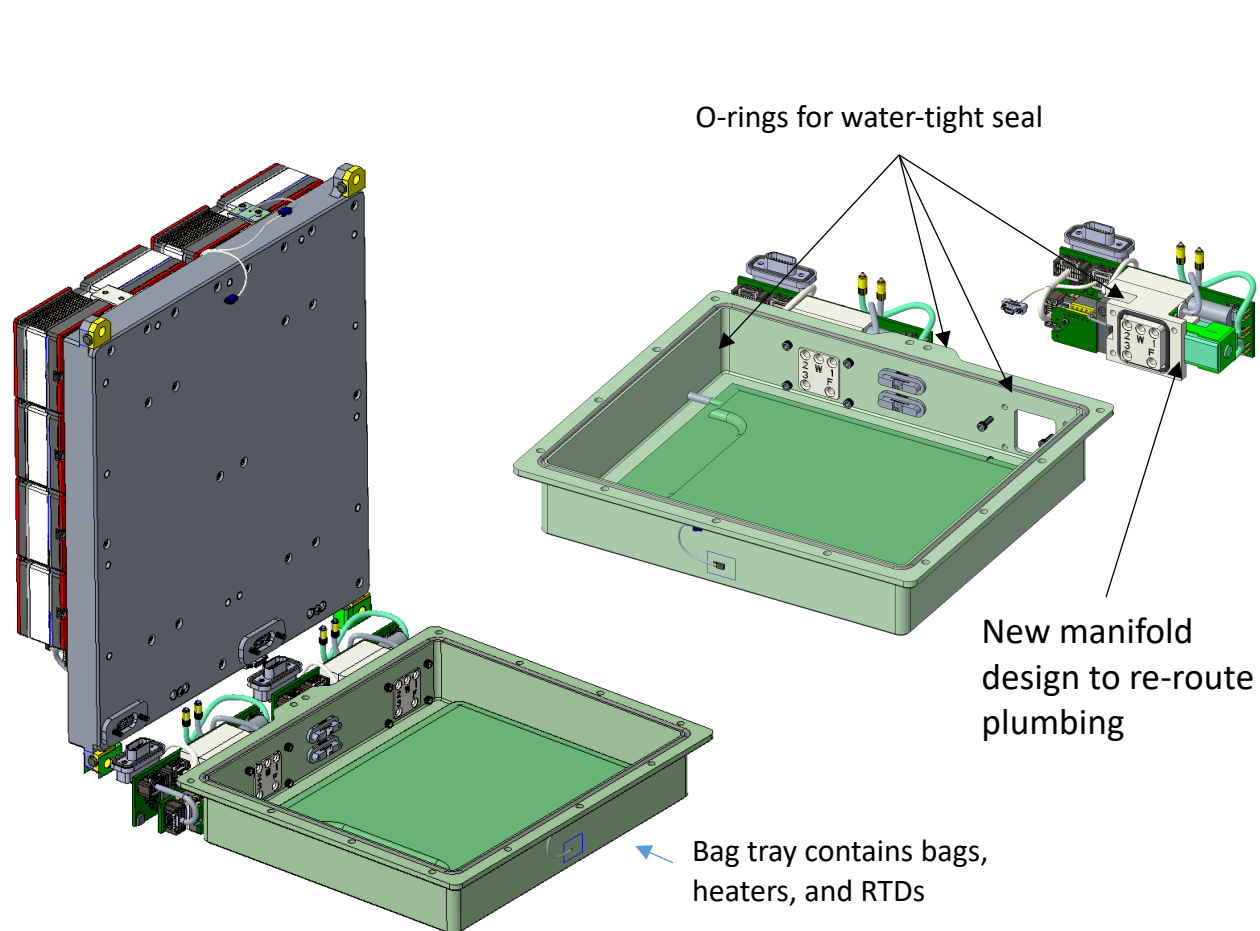
Increased desiccant



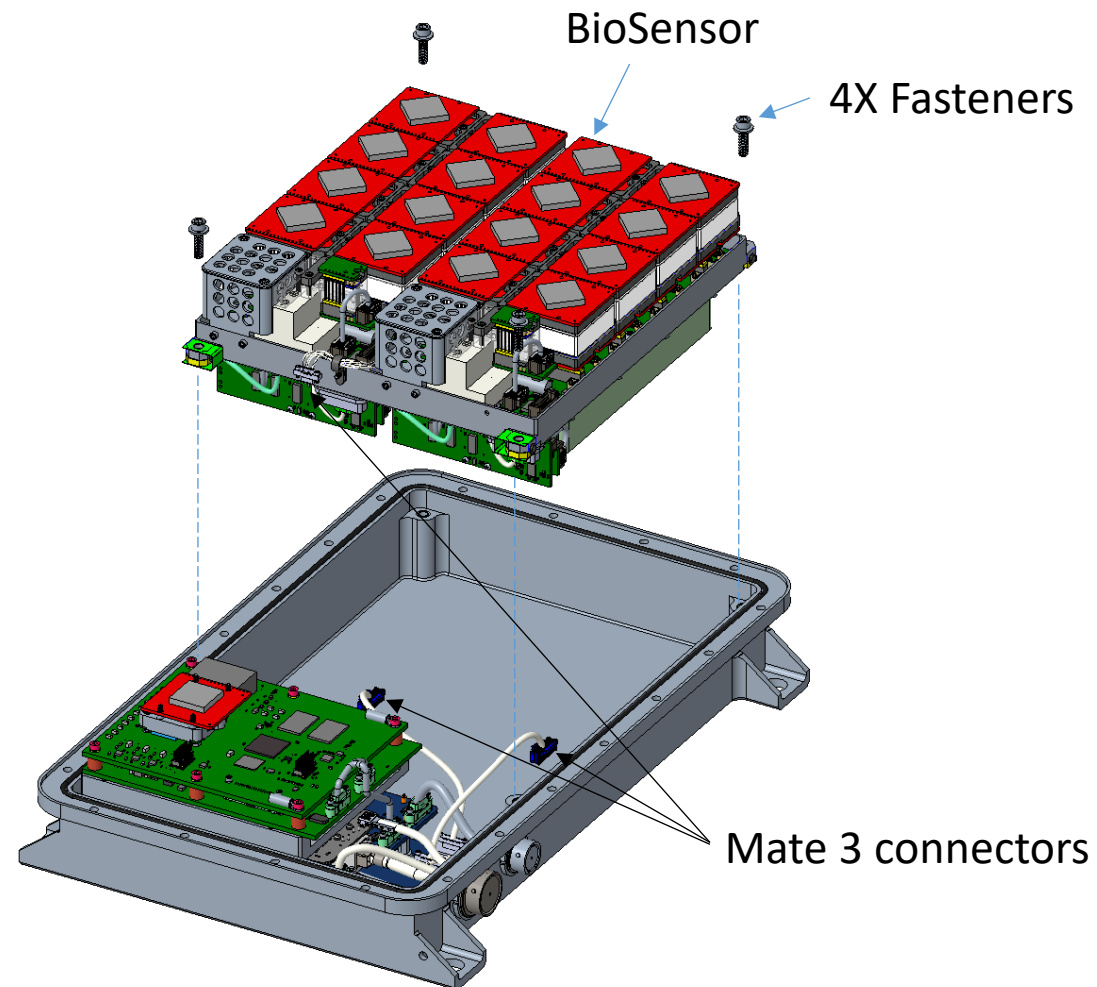
Improved seals & protected connectors



LEIA improvements



Redesigned bag tray & re-routed plumbing

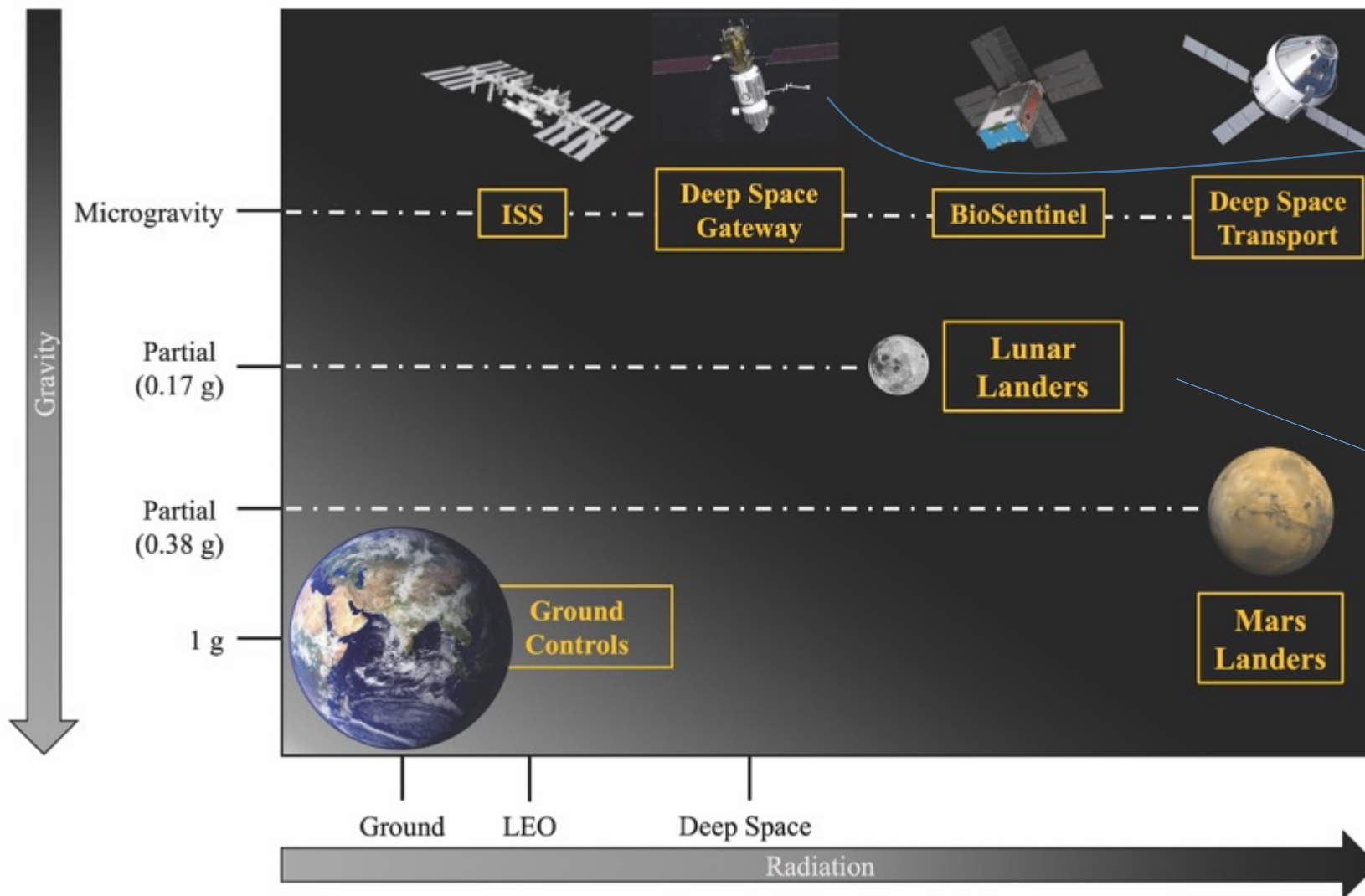


Late load installation



Beyond LEO instrumentation: future & ongoing

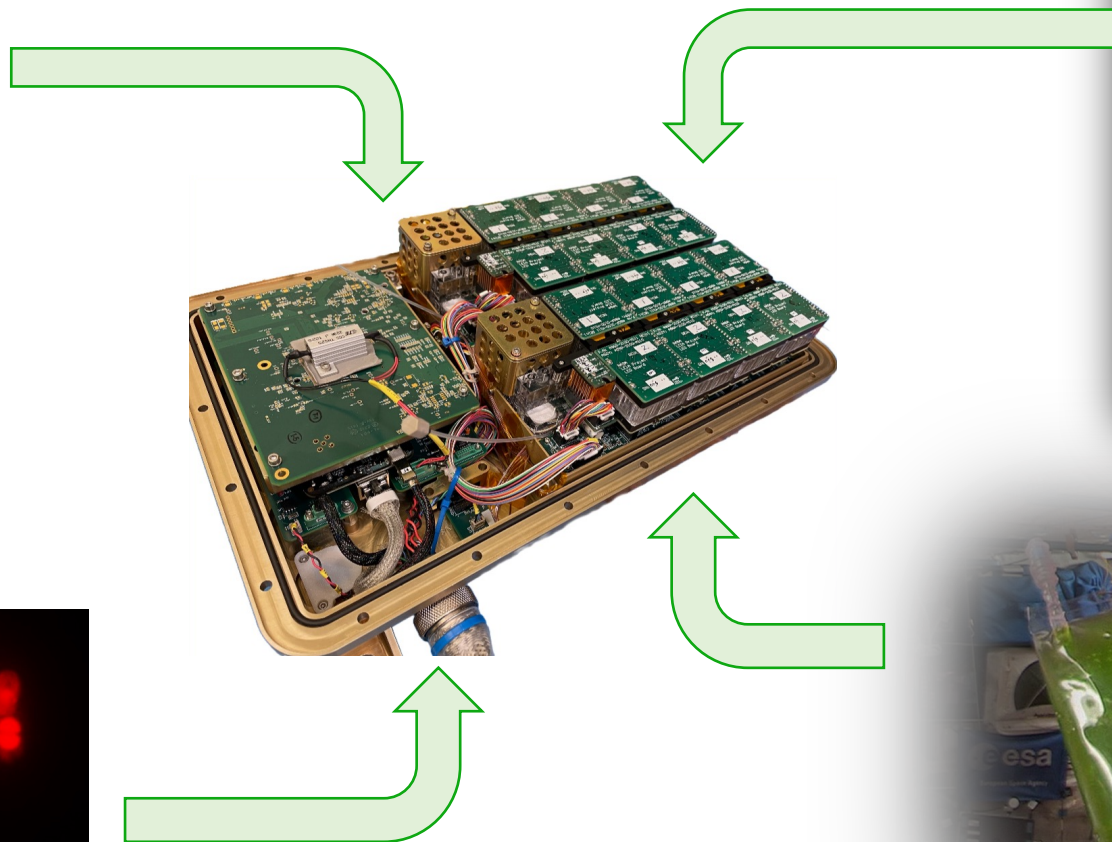
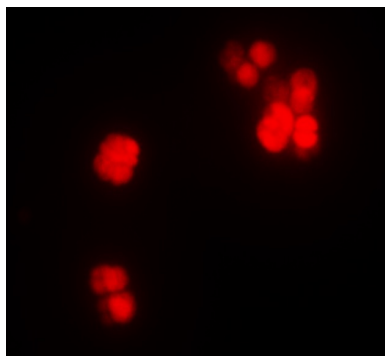
A flexible design that will be used in different space environments.... and with new technologies





Beyond LEO instrumentation: future & ongoing

A flexible design that will be used in different space environments.... and with new technologies





LEIA Project team

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Funding: NASA Exploration Science Strategy and Integration Office





Thank you!

