HERA, there, and everywhere

Tom Campbell-Ricketts

(Leidos Inc.)

NASA Space Radiation Analysis Group

29th WRMISS, Prague,

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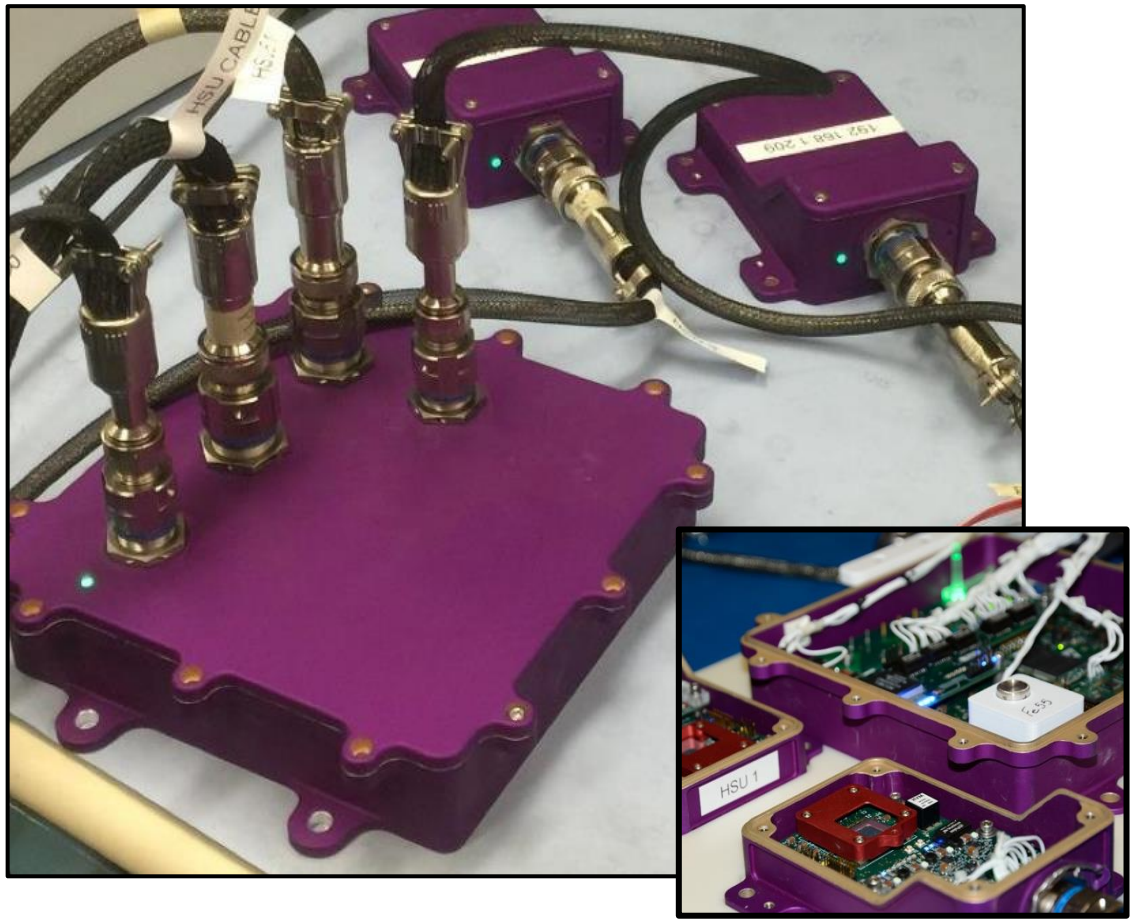
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Overview

- HERA measurements from Artemis II – preliminary results
- HERA measurements on Fram2
- More HERA-like instruments coming soon to a Moon near you

Introduction, HERA

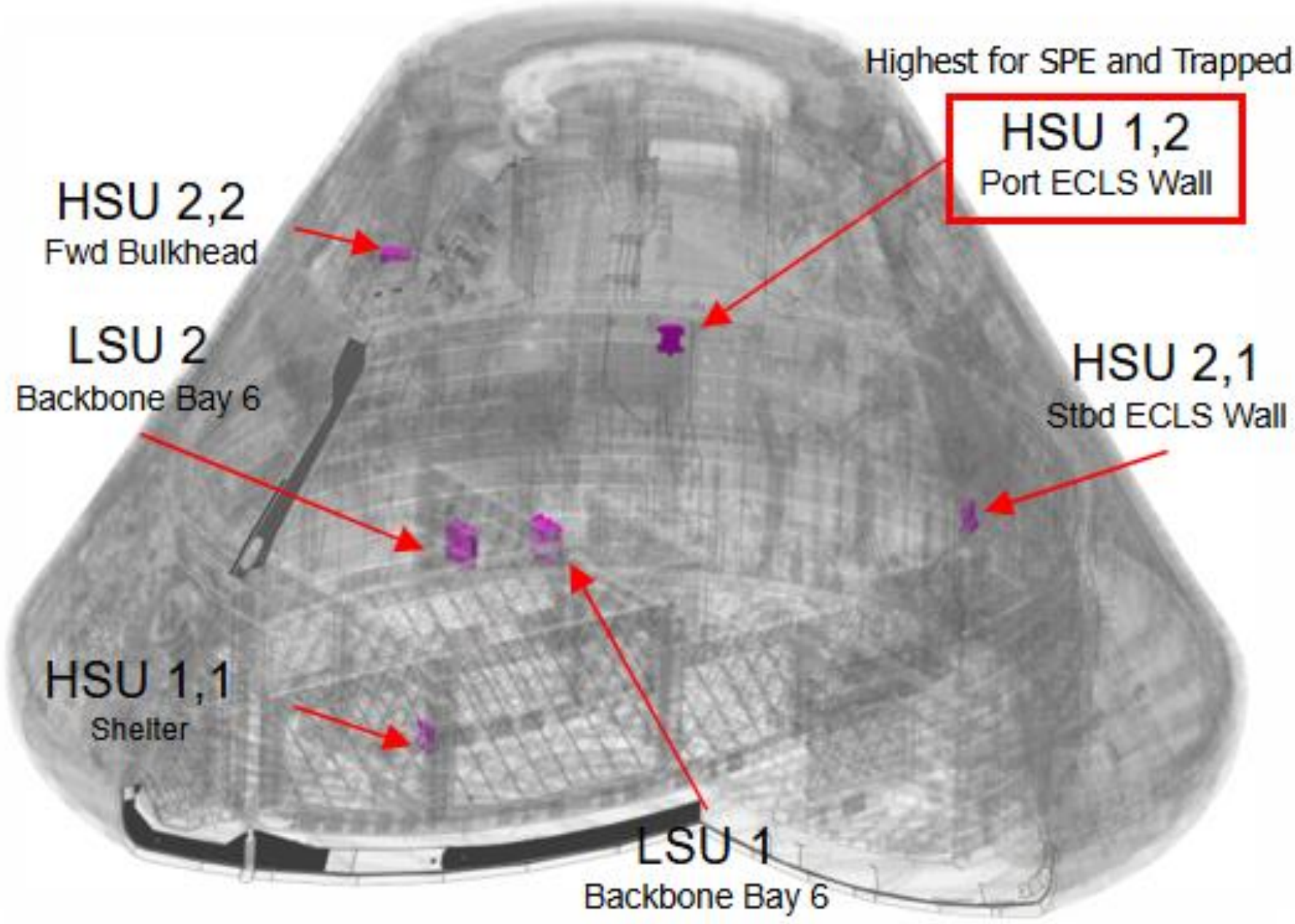
- HERA based on Timepix hybrid pixel technology, with 500 µm silicon sensor, pixels: 256x256, 55 µm
- Pixels record individual particle tracks → ‘digital nuclear emulsion’
  - Deposited energy
  - Track length
  - LET
  - Track orientation
  - Per-minute dose, flux, dose equivalent
- HERA system usually consists of 3 detectors, 2 of which are connected by cables to the central unit
- Broader HERA-family includes ARES, LETS, CEPS

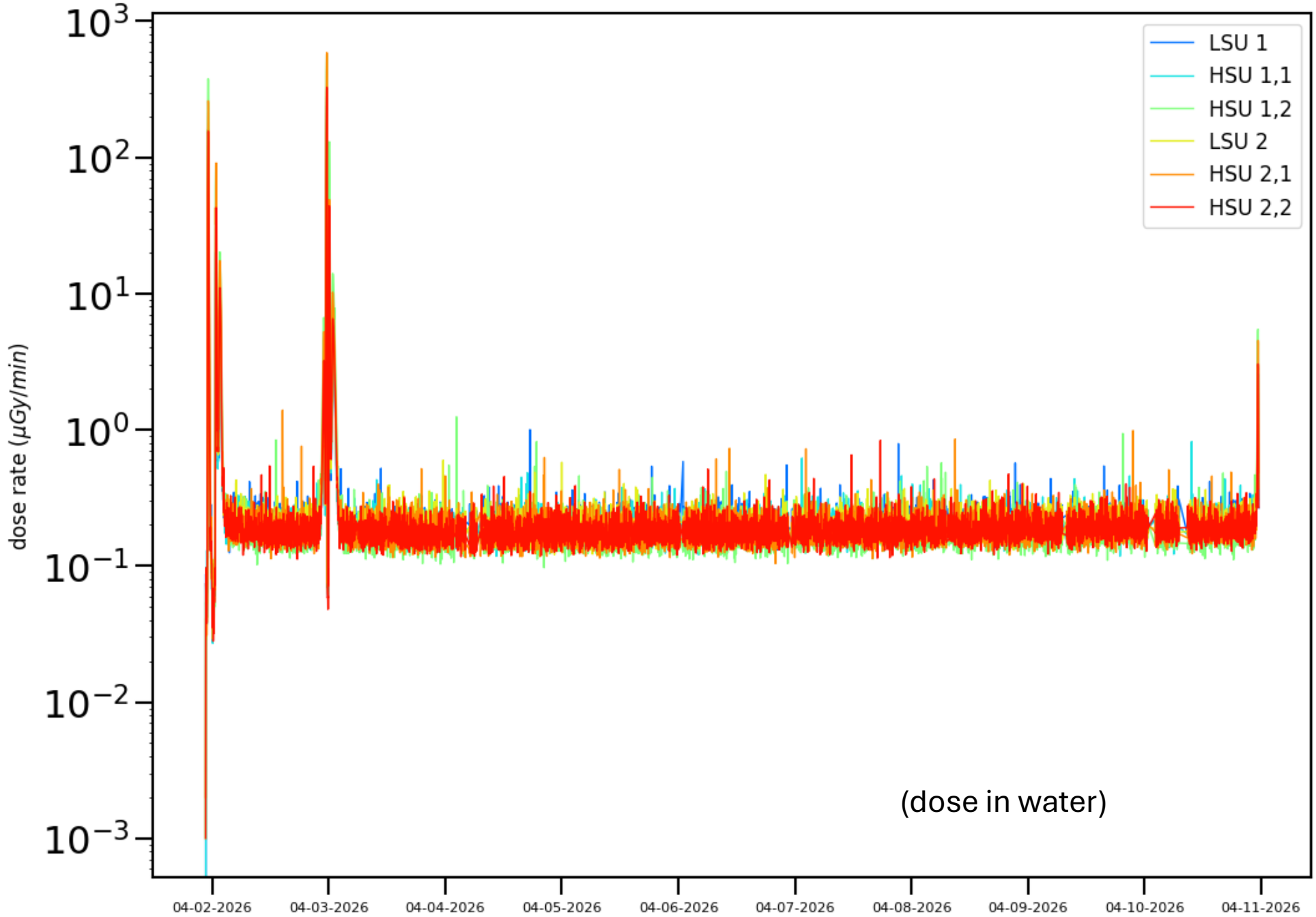


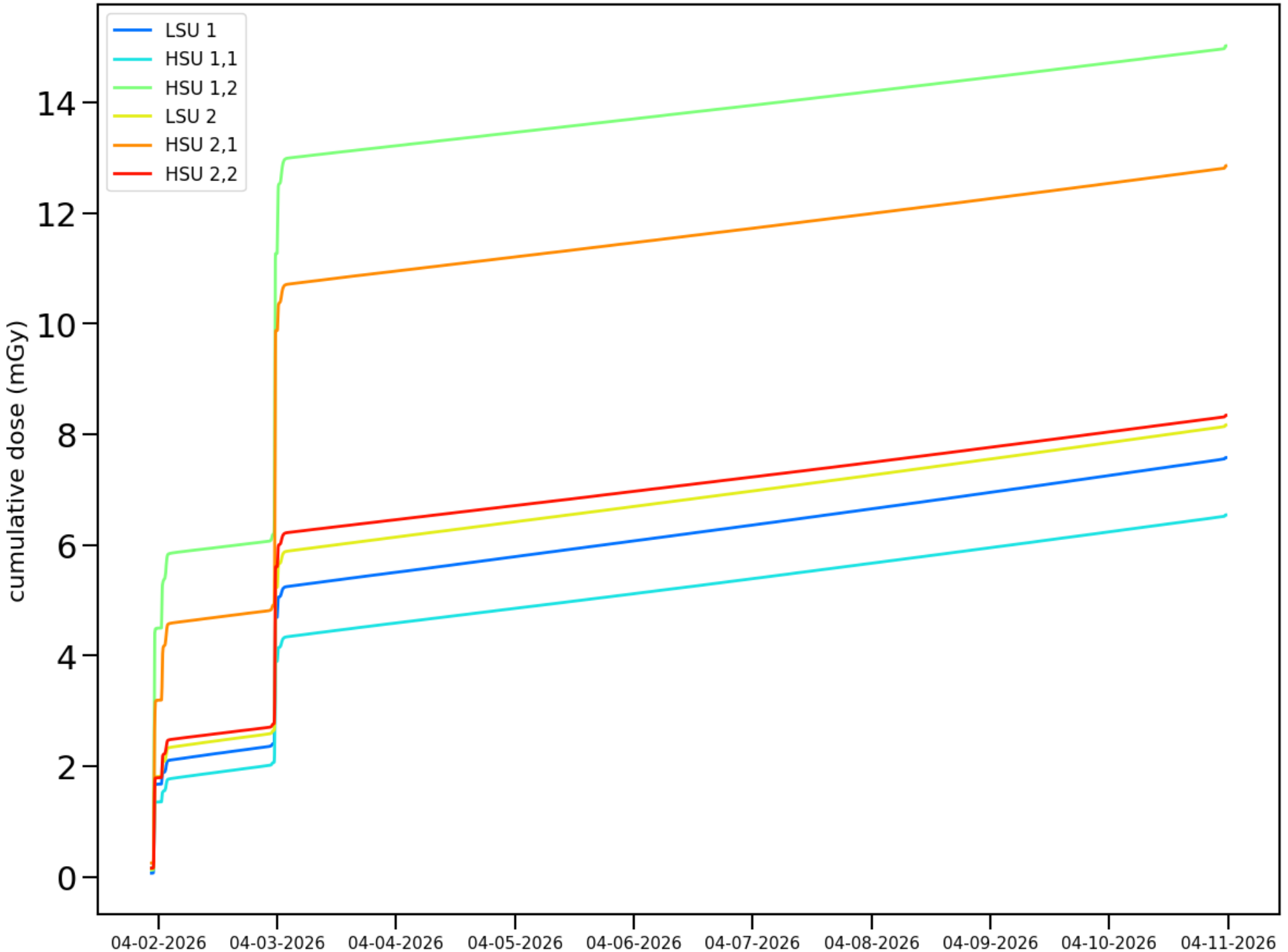
Artemis II

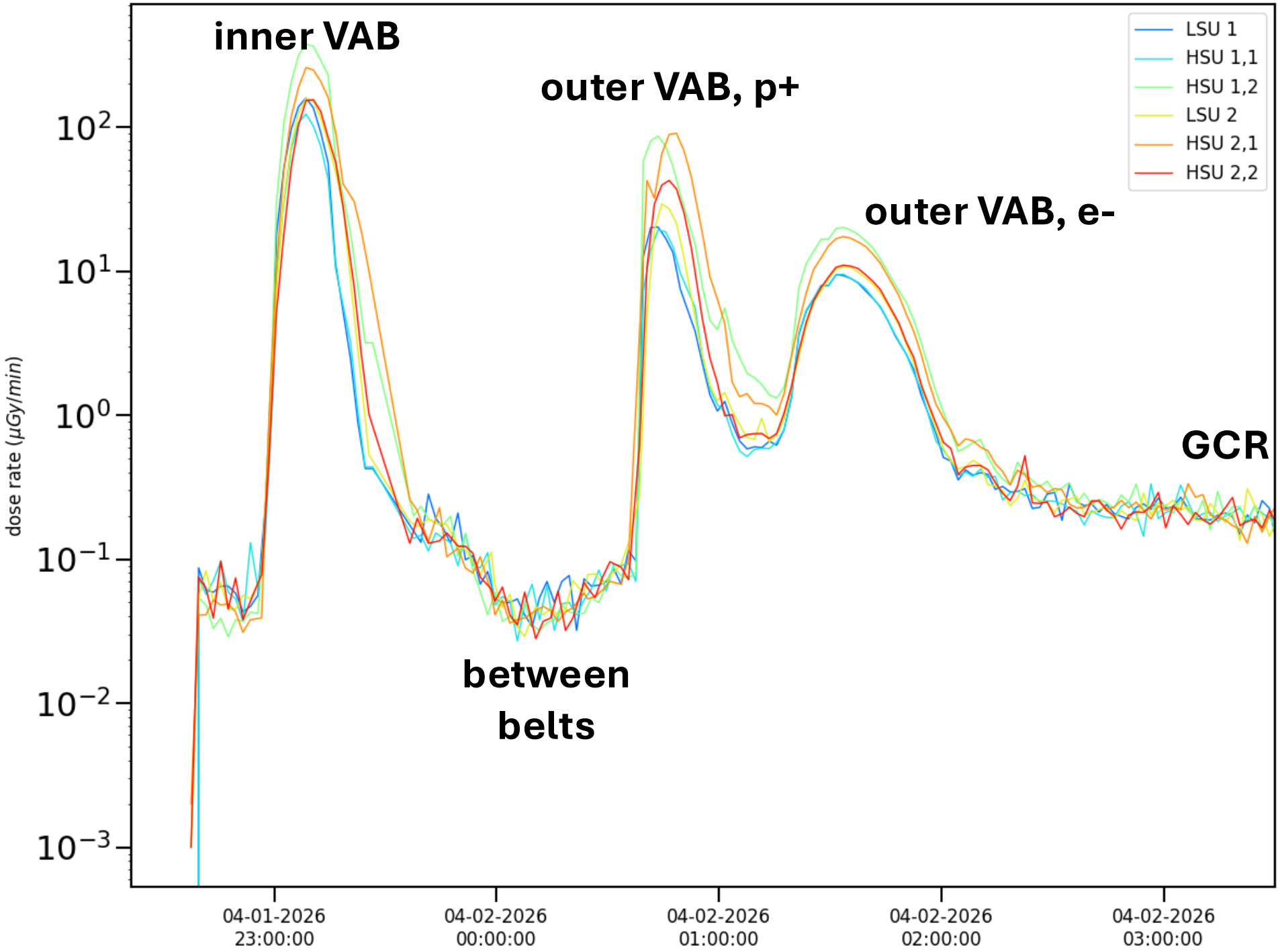


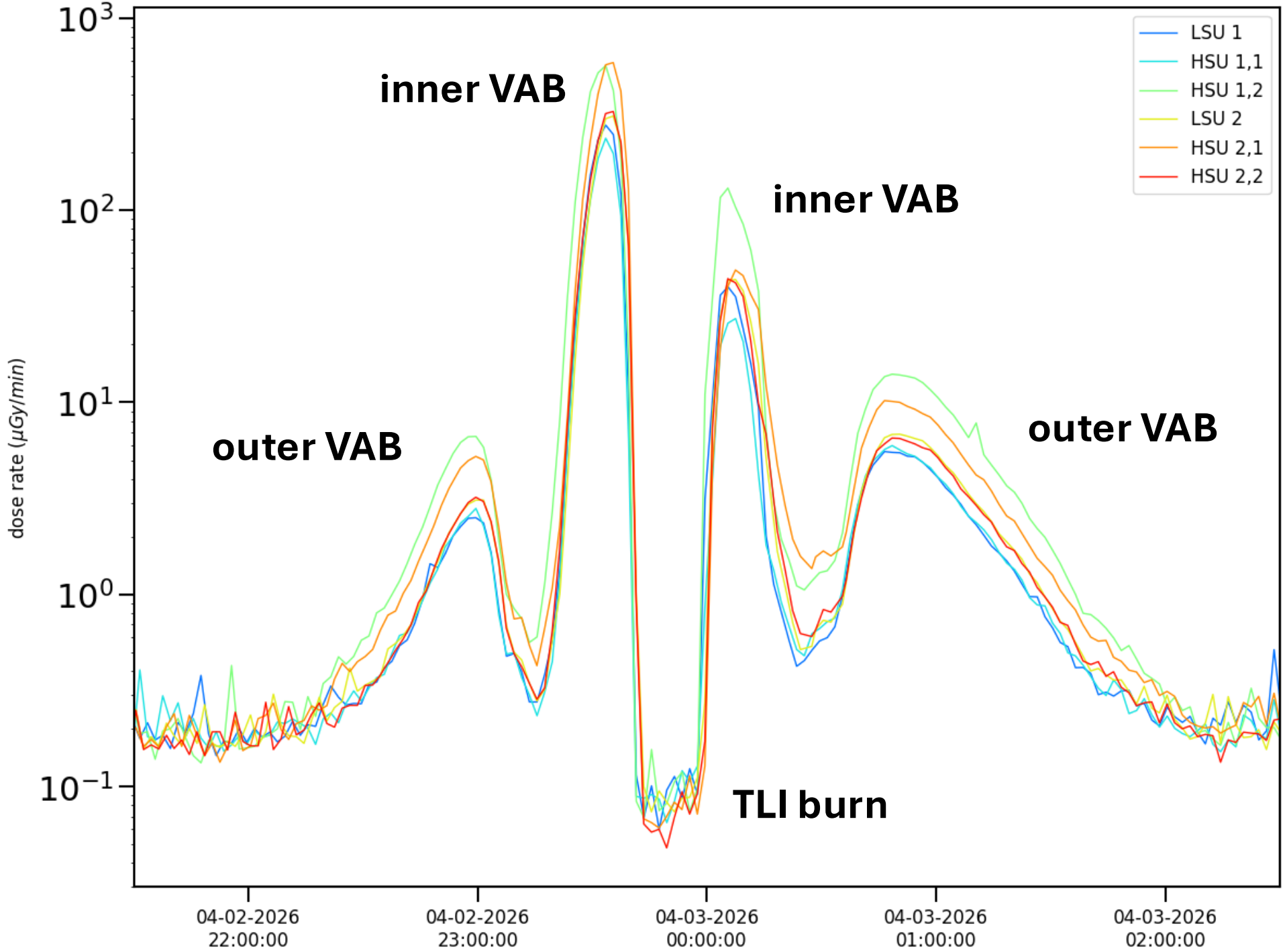
- HERA powered by vehicle, provides caution and warning, provides real-time readout to crew & ground
- Real-time dose-rate data was received on the ground during flight
  - 2-minute cadence
  - Some short outages, e.g. passing behind the Moon
- Full dataset, including raw frames, LET spectra, and ‘outages’, will be available after HERAs removed from Orion capsule
- Removal of HERAs scheduled for ~~July~~ ~~August~~ October (?)
- HERAs were turned off about 30 minutes prior to splashdown


Highest for SPE and Trapped
HSU 1,2
Port ECLS Wall
HSU 2,2
Fwd Bulkhead
LSU 2
Backbone Bay 6
HSU 2,1
Stbd ECLS Wall
HSU 1,1
Shelter
LSU 1
Backbone Bay 6


LSU 1
HSU 1,1
HSU 1,2
LSU 2
HSU 2,1
HSU 2,2
dose rate (μGy/min)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
04-02-2026
04-03-2026
04-04-2026
04-05-2026
04-06-2026
04-07-2026
04-08-2026
04-09-2026
04-10-2026
04-11-2026
(dose in water)

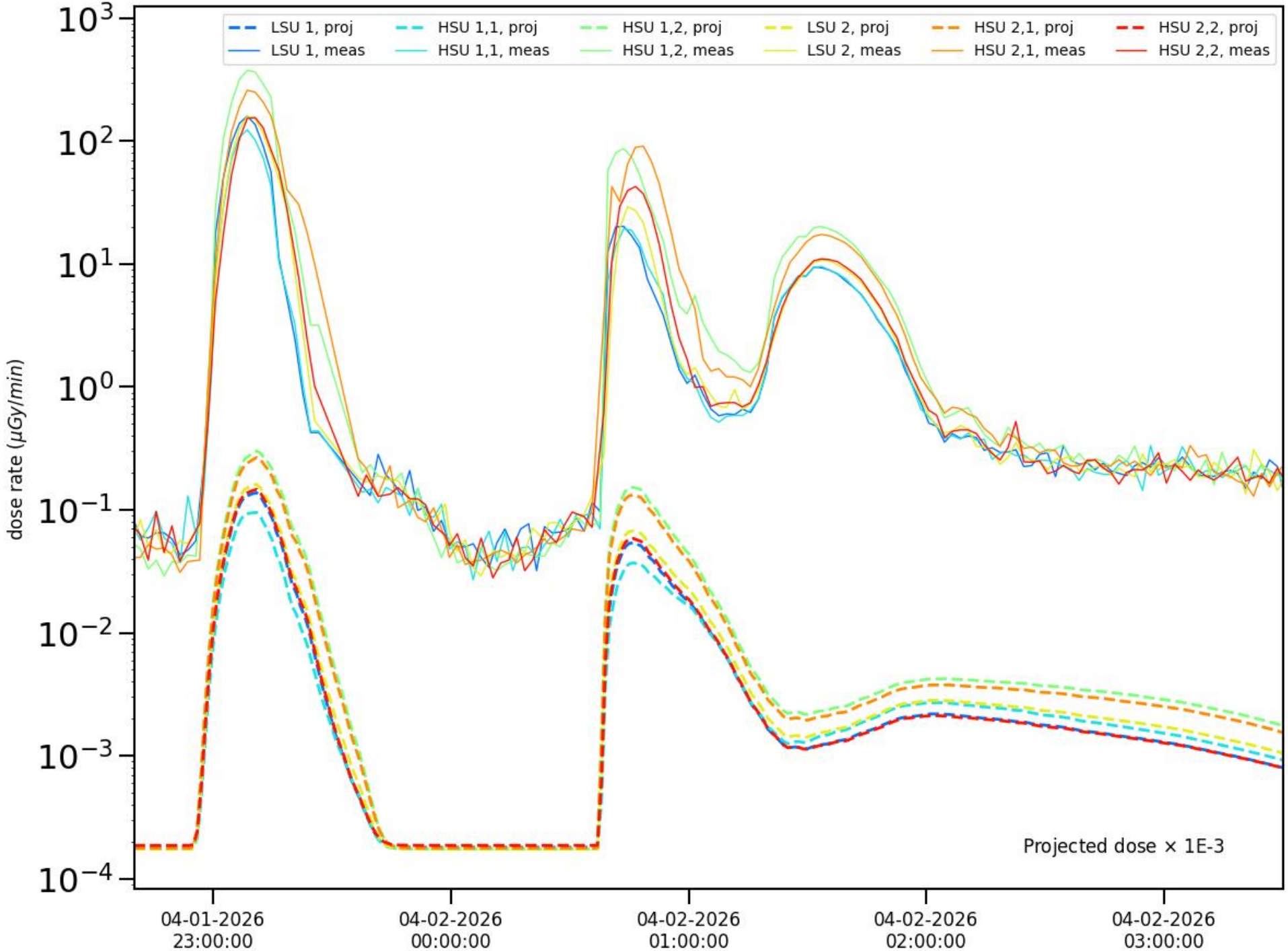

LSU 1
HSU 1,1
HSU 1,2
LSU 2
HSU 2,1
HSU 2,2
cumulative dose (mGy)
0
2
4
6
8
10
12
14
04-02-2026
04-03-2026
04-04-2026
04-05-2026
04-06-2026
04-07-2026
04-08-2026
04-09-2026
04-10-2026
04-11-2026


inner VAB
outer VAB, p+
outer VAB, e-
GCR
between belts
LSU 1
HSU 1,1
HSU 1,2
LSU 2
HSU 2,1
HSU 2,2
dose rate (μGy/min)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
04-01-2026 23:00:00
04-02-2026 00:00:00
04-02-2026 01:00:00
04-02-2026 02:00:00
04-02-2026 03:00:00


inner VAB
inner VAB
outer VAB
outer VAB
TLI burn
LSU 1
HSU 1,1
HSU 1,2
LSU 2
HSU 2,1
HSU 2,2
dose rate (μGy/min)
10^3
10^2
10^1
10^0
10^−1
04-02-2026 22:00:00
04-02-2026 23:00:00
04-03-2026 00:00:00
04-03-2026 01:00:00
04-03-2026 02:00:00

Projected doses

- Trapped fields:
  - AP9
  - AE9
- GCR from BON2020
- Geomagnetic model -> IGRF13
- Uniform flux transported through a high-fidelity vehicle model


LSU 1, proj
LSU 1, meas
HSU 1,1, proj
HSU 1,1, meas
HSU 1,2, proj
HSU 1,2, meas
LSU 2, proj
LSU 2, meas
HSU 2,1, proj
HSU 2,1, meas
HSU 2,2, proj
HSU 2,2, meas
dose rate (μGy/min)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Projected dose × 1E-3
04-01-2026 23:00:00
04-02-2026 00:00:00
04-02-2026 01:00:00
04-02-2026 02:00:00
04-02-2026 03:00:00

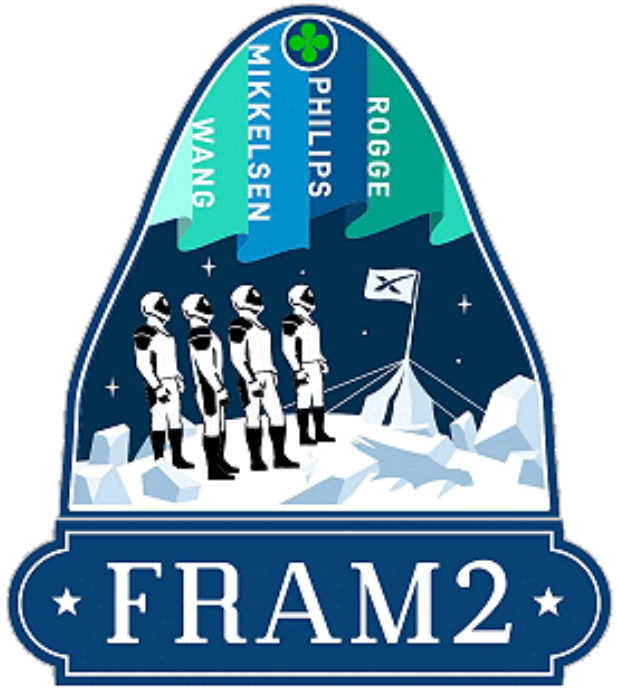
Projected doses

Detector	Measured total, Si (mGy)	Projected total (mGy)*	Projected, last 30 minutes (mGy)
HSU1, 1	5.23	7.37	0.34
LSU1	6.28	9.06	0.49
LSU2	6.54	10.40	0.57
HSU2, 2	6.67	9.55	0.53
HSU2, 1	10.28	16.23	1.02
HSU1, 2	12.02	18.11	1.16

	mean (mGy)	standard deviation (mGy)
Measured	7.84	2.44
Projected*	12.48	4.24

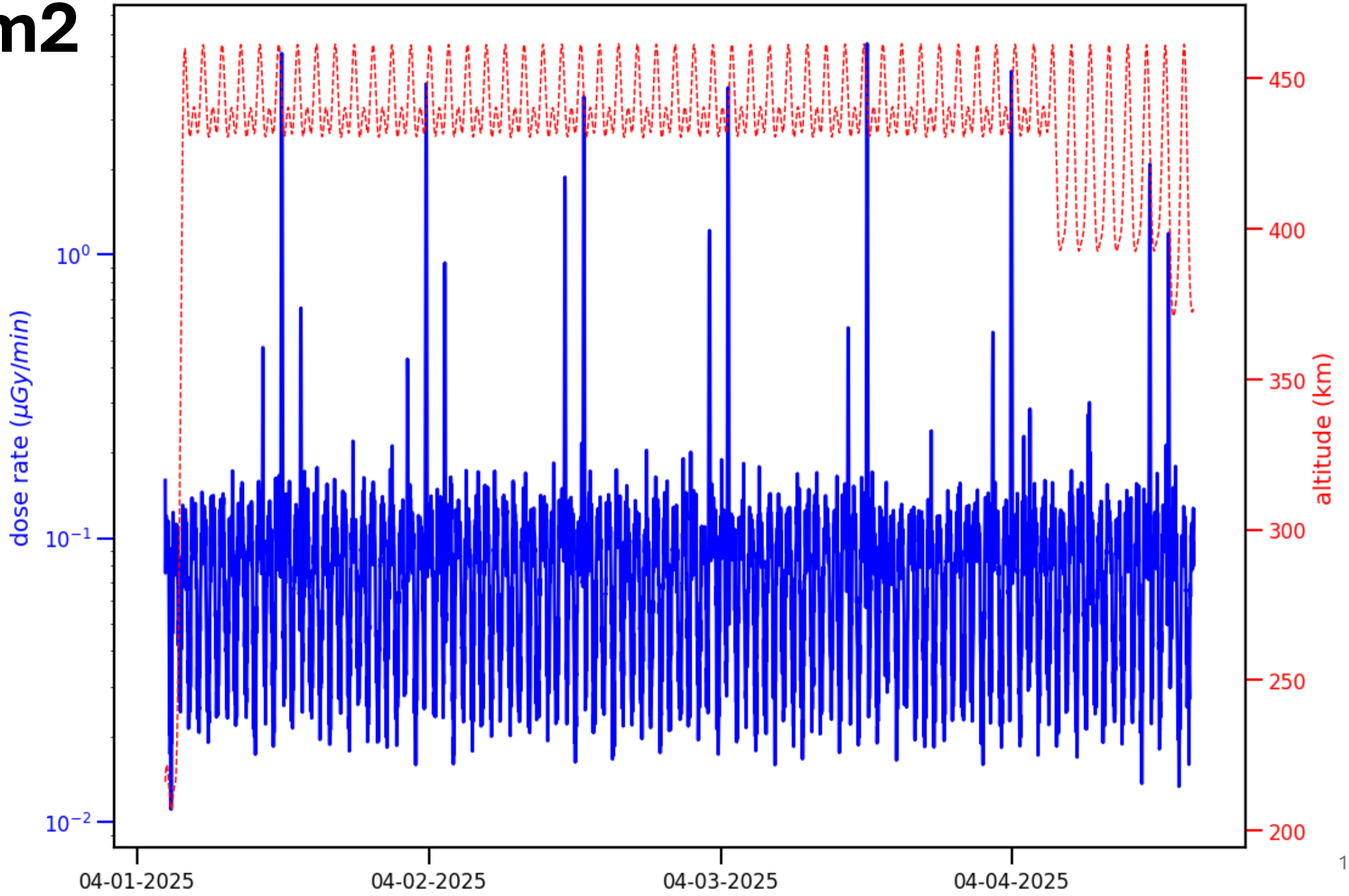
*Up to time when HERAs turned off

Fram2

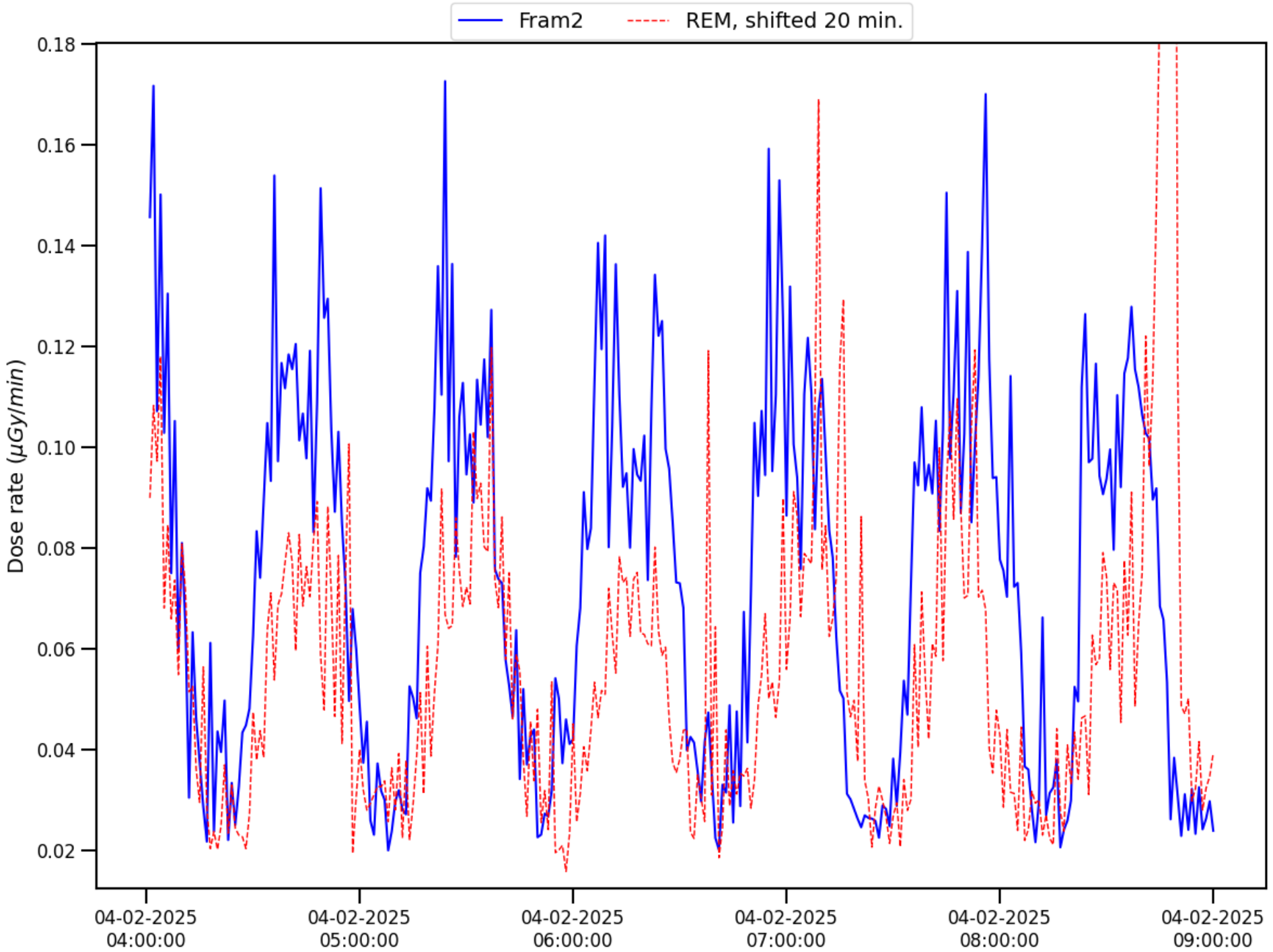


- Privately-funded SpaceX Crew Dragon flight
- 4 crew
- Polar orbit, first for a crewed vehicle
- 4/1/2025 to 4/4/2025 (3 days, 14.5 hours)
- Single HERA HPU/LSU on board
- LEO, around 400-450 km, inclination 90.01°
- Radiation measurement work supported by TRISH
- (Original Fram was a ship used in polar exploration by Fridtjof Nansen, Roald Amundsen, & others)

Fram2


dose rate (μGy/min)
10^{0}
10^{-1}
10^{-2}
altitude (km)
450
400
350
300
250
200
04-01-2025
04-02-2025
04-03-2025
04-04-2025

Fram2


Fram2
REM, shifted 20 min.
Dose rate (μGy/min)
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
04-02-2025 04:00:00
04-02-2025 05:00:00
04-02-2025 06:00:00
04-02-2025 07:00:00
04-02-2025 08:00:00
04-02-2025 09:00:00

Fram2

Total Dose (µGy)	**527.0**	
Total Dose Equivalent (µSv)	**986.2**	**<Q>=1.87**

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Mean REM dose, same period (4 REMs, averaging 10 fewer acq. minutes):

Mean REM Dose (μGy)	**676.5**	**(σ = 26.1)**	
Mean REM Dose Equivalent (μSv)	**1135.9**	**(σ = 56.3)**	**<Q>=1.68**

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Mean REM Dose (μGy)	676.5	(σ = 26.1)	
Mean REM Dose Equivalent (μSv)	1135.9	(σ = 56.3)	<Q>=1.68

SAA transits (B < 23 μT, L <= 3):

Fram2 D_{SAA} (μGy)	169.5		<Q>=1.51
Mean REM D_{SAA} (μGy)	412.5	(σ = 47.1)	<Q>=1.45
Fram2 transits	N=39	Minutes=394	<minutes>=10.1
ISS transits	N=41	Minutes=639	<minutes>=15.6

Future missions to the Moon

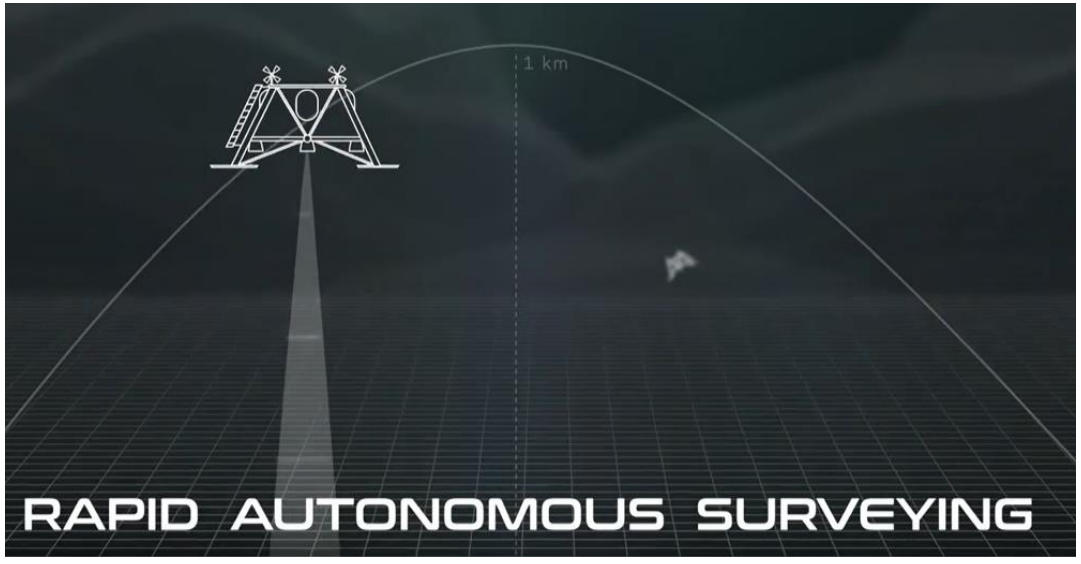
- MoonFall: 3x LETS2 instruments (HERA family)
- Astrobotic landers: 2x LETS2
- Intuitive Machines lander: 1x LETS2
- Firefly Blue Ghost: 1xLETS2
- CAPSTONE2 lunar orbiters: 2x CEPS

MoonFall

https://www.jpl.nasa.gov/missions/moonfall/

- NASA JPL project targeting 2028 launch
- 3 drones, each will carry a LETS2 and other instruments
- Deployment at the South pole
- Drones will each execute a series of ~5 hops over the surface of the Moon, covering ~5 km with each hop, conducting a variety of measurements at each location, over the course of a lunar day





MoonFall

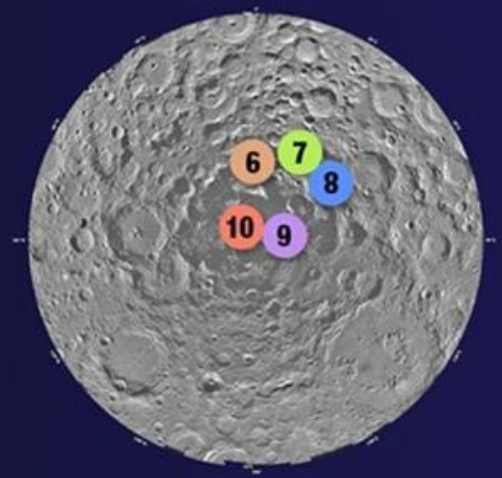
- LET spectra will be collected in 9 equally spaced polar-angle bins
- This is hoped to shed light on some hypothesized processes concerning lunar albedo
- Part of the goal of MoonFall is to demonstrate ability to survive lunar night
  - Depending on TBD details, LETS2 may get turned back on after the night
  - Instrument already survived multiple cooling cycles to 50 K, suffering only minor spectral shift
  - We have devised a means to correct this shift, which we are itching to test

Commercial Lunar Payload Services | **Landing Sites**

National Aeronautics and Space Administration







NEAR SIDE

1 **ASTROBOTIC PEREGRINE MISSION-1**
Landing Site: Did not land on the Moon
Lander Name: Peregrine
CLPS Contract Award: TO 2-AB

2 **INTUITIVE MACHINES IM-3**
Landing Site: Reiner Gamma
Lander Name: NOVA-C
CLPS Contract Award: TO CP-11

3 **FIREFLY BLUE GHOST MISSION 1**
Landing Site: Mare Crisium
Lander Name: Blue Ghost
CLPS Contract Award: TO 19D

FAR SIDE

4 **FIREFLY BLUE GHOST MISSION 2**
Landing Site: Lunar Far side and Orbit
Lander Name: Blue Ghost
CLPS Contract Award: TO CS-3 and CS-4

5 **TEAM DRAPER**
Landing Site: Schrodinger Basin
Lander Name: ispace-U.S. APEX 1.0 Lunar Lander
CLPS Contract Award: TO CP-12

SOUTH POLE

6 **INTUITIVE MACHINES IM-1**
Landing Site: Malapert A
Lander Name: NOVA-C
CLPS Contract Award: TO 2-IM
Status: Completed

7 **ASTROBOTIC GRIFFIN MISSION-1**
Landing Site: Mons Mouton
Lander Name: Griffin
CLPS Contract Award: TO 20A

8 **INTUITIVE MACHINES IM-4**
Landing Site: Mons Mouton
Lander Name: NOVA-C
CLPS Contract Award: CP-22

9 **BLUE ORIGIN BLUE MOON / MK1 PATHFINDER**
Landing Site: South Polar Region
Lander Name: Blue Moon Mark 1 Lander
CLPS Contract Award: CP-22

10 **INTUITIVE MACHINES IM-2**
Landing Site: South Polar Region
Lander Name: NOVA-C
CLPS Contract Award: TO PRIME-1

https://science.nasa.gov/lunar-science/clps-deliveries/

CAPSTONE 2 / CEPS

https://www.nasa.gov/mission/capstone02/



CAPSTONE 2 / CEPS

- 2 lunar orbiters, testing autonomous maneuvering capabilities
- Each will carry a CEPS instrument
- CEPS: Compact Electron Proton Spectrometer
- Space weather instrument designed to help assess solar particle events
- Timepix2 with a CdTe sensor
  - CdTe gives better electron/proton discrimination
  - Timepix2 gives uninterrupted recording during the highest conceivable fluxes
- CEPS is designed to be an extravehicular instrument, but will sit inside the CAPSTONE flyers

