



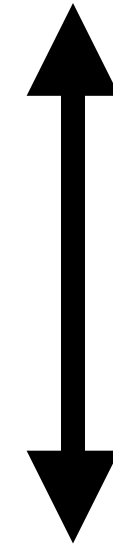
Deep space radiation measurements and crew radiation protection for the NASA Artemis program



Dr. Stuart George on behalf of the wider NASA Space Radiation Group @ JSC and the BioSentinel Team @ AMES

**Space Radiation Analysis Group - an O2R2O Organization at
NASA Johnson Space Center**

**OPERATIONAL - Protect crew, keep crew ALARA, enable longer
and more complicated missions**

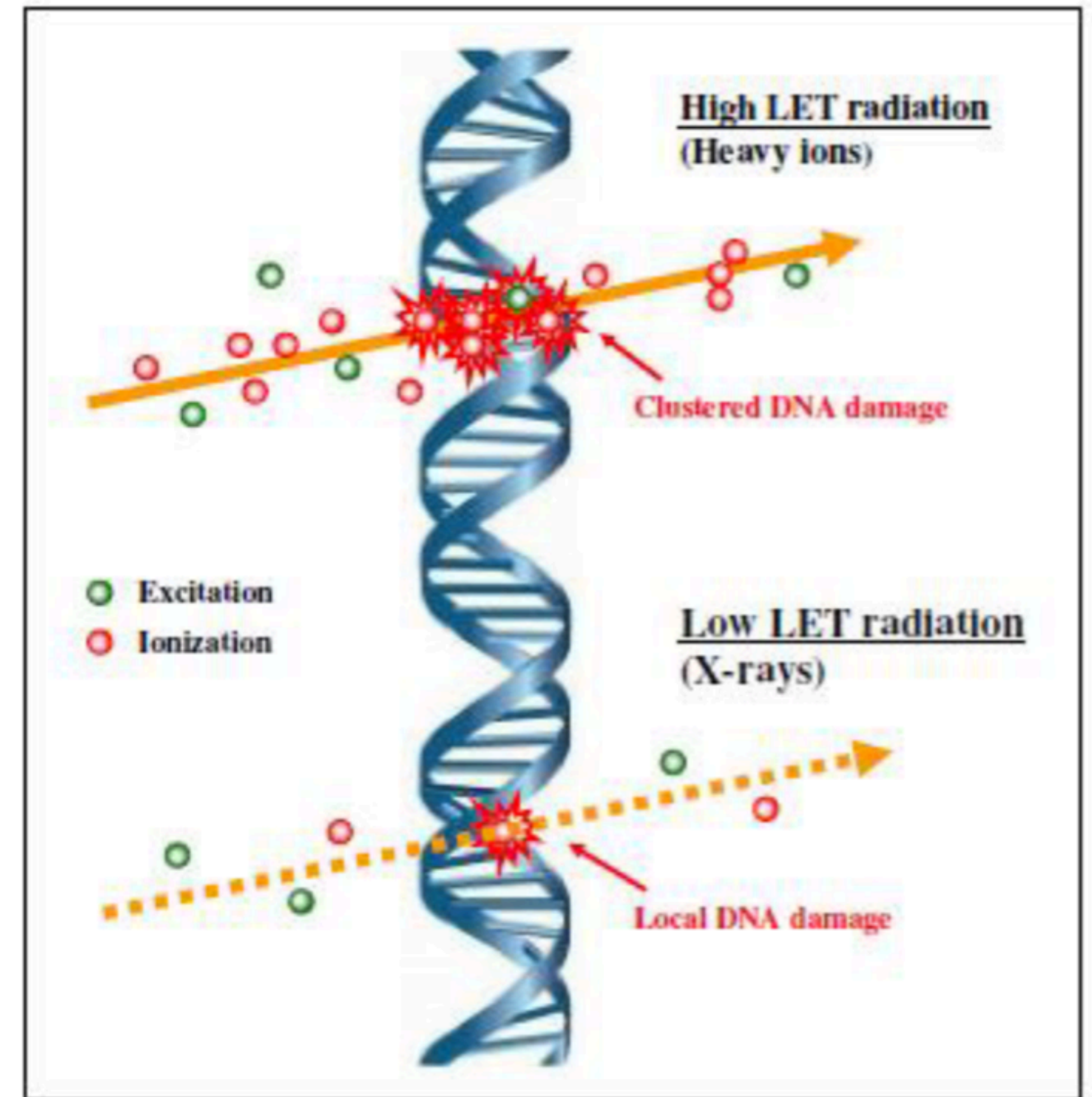


**RESEARCH - Understand risks of radiation, understand
radiation risks in new and different environments, understand
radiation transport through shielding and appropriate shielding
strategies for different environments**

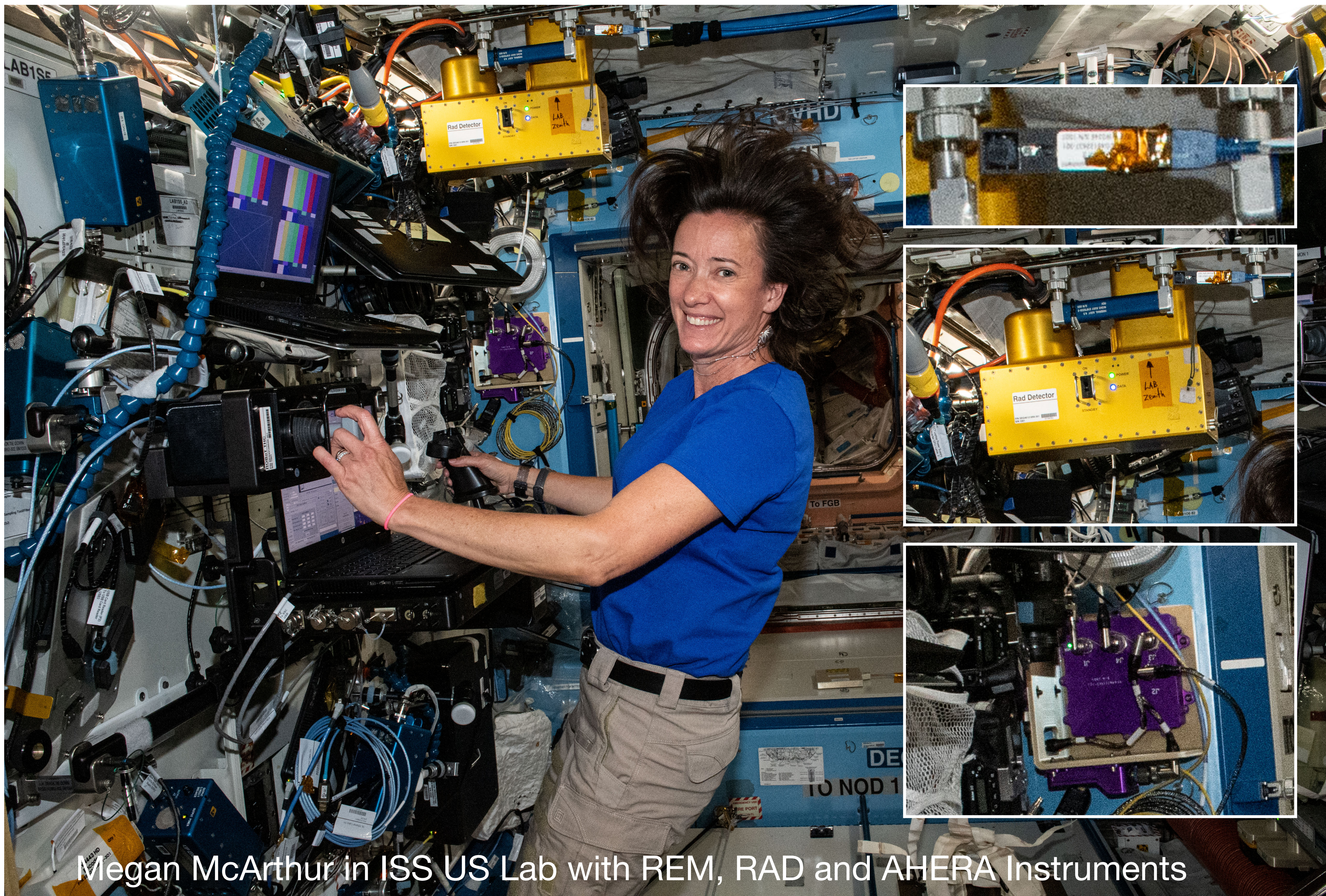
**I will discuss the challenges in space radiation protection for the Artemis program
heading back to the moon via our measurements from the ARTEMIS I mission and
the BIOSENTINEL satellite**

Why do we care about radiation in space at all?

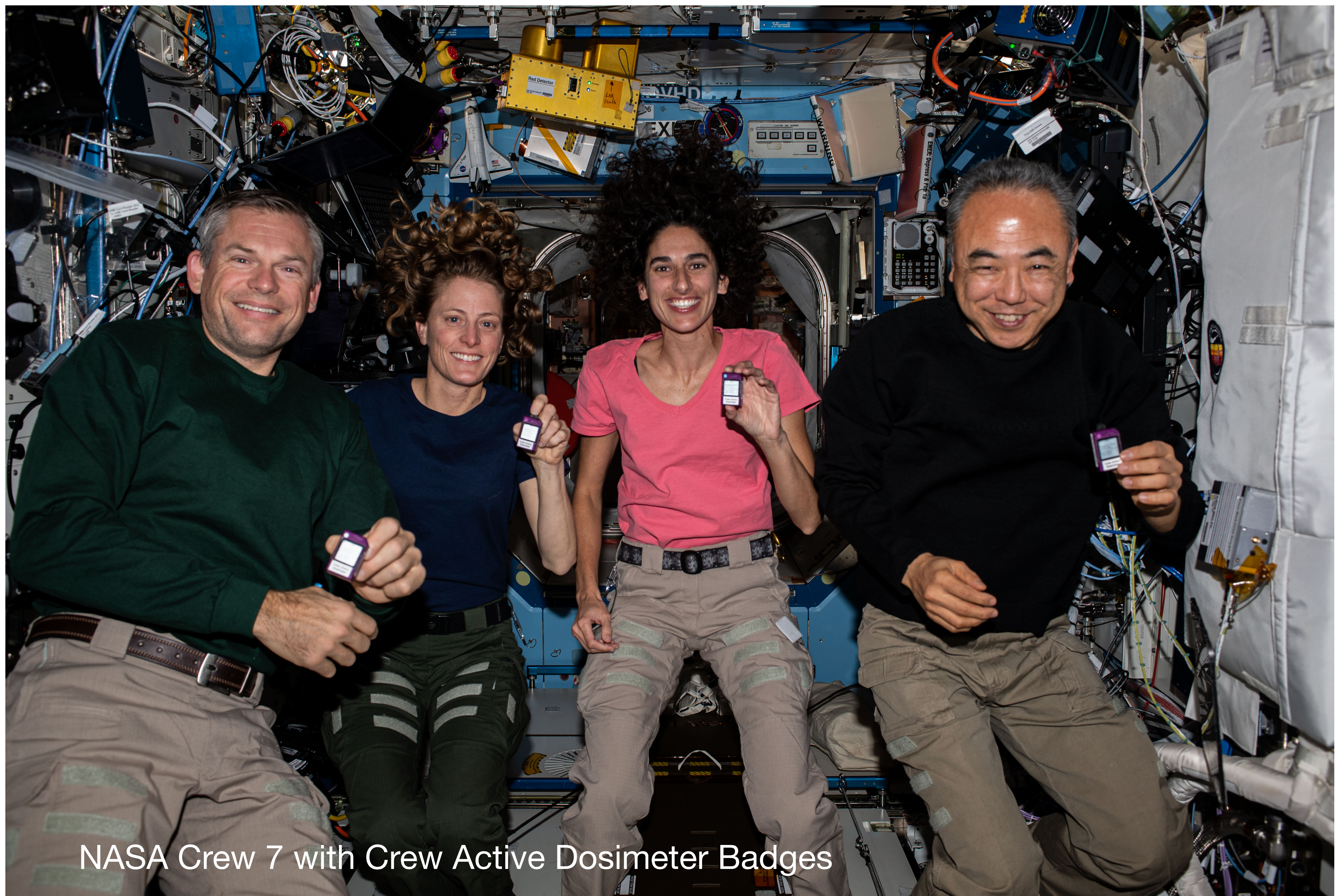
- Astronauts can be exposed to quite a lot of radiation. For example on ISS, 0.5 mGy/day. (Average yearly exposure on the ground is 3 mGy/year).
- Most of the time this radiation is “Galactic Cosmic Rays” containing heavy ions. These can cause cancer and perhaps other effects.
- In addition we also worry about Space Weather
- A large reference space weather event in a lightly shielded vehicle might cause moderate acute radiation syndrome enough to impact crew.
- An exceptionally large space weather event (similar to those observed in the historical record, but not the spaceflight era) could cause mission threatening exposures.



Heavy ions cause clustered damage along their tracks, causing outside biological effect compared to terrestrial radiation sources like x-rays. From Tinganelli and Durante (2020)



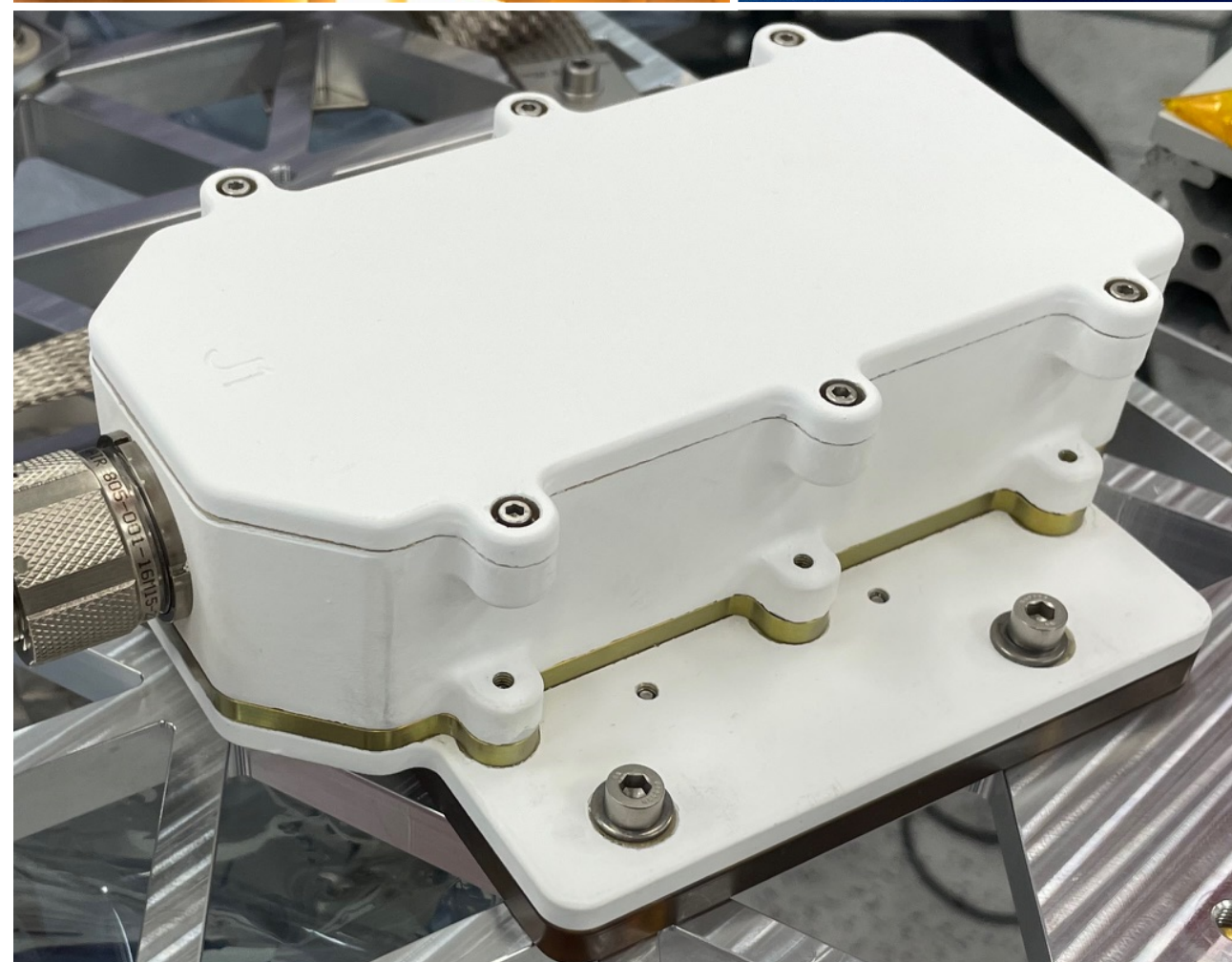
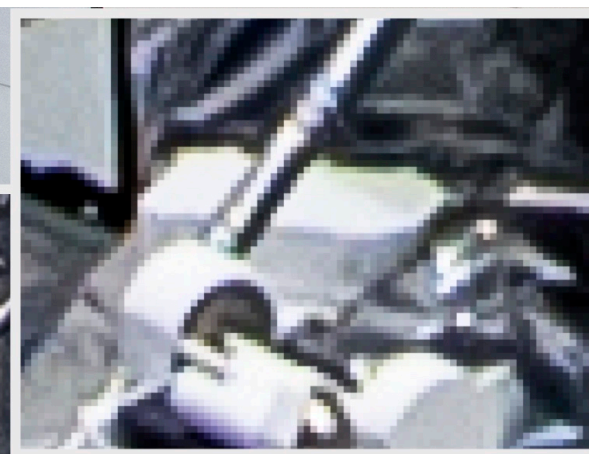
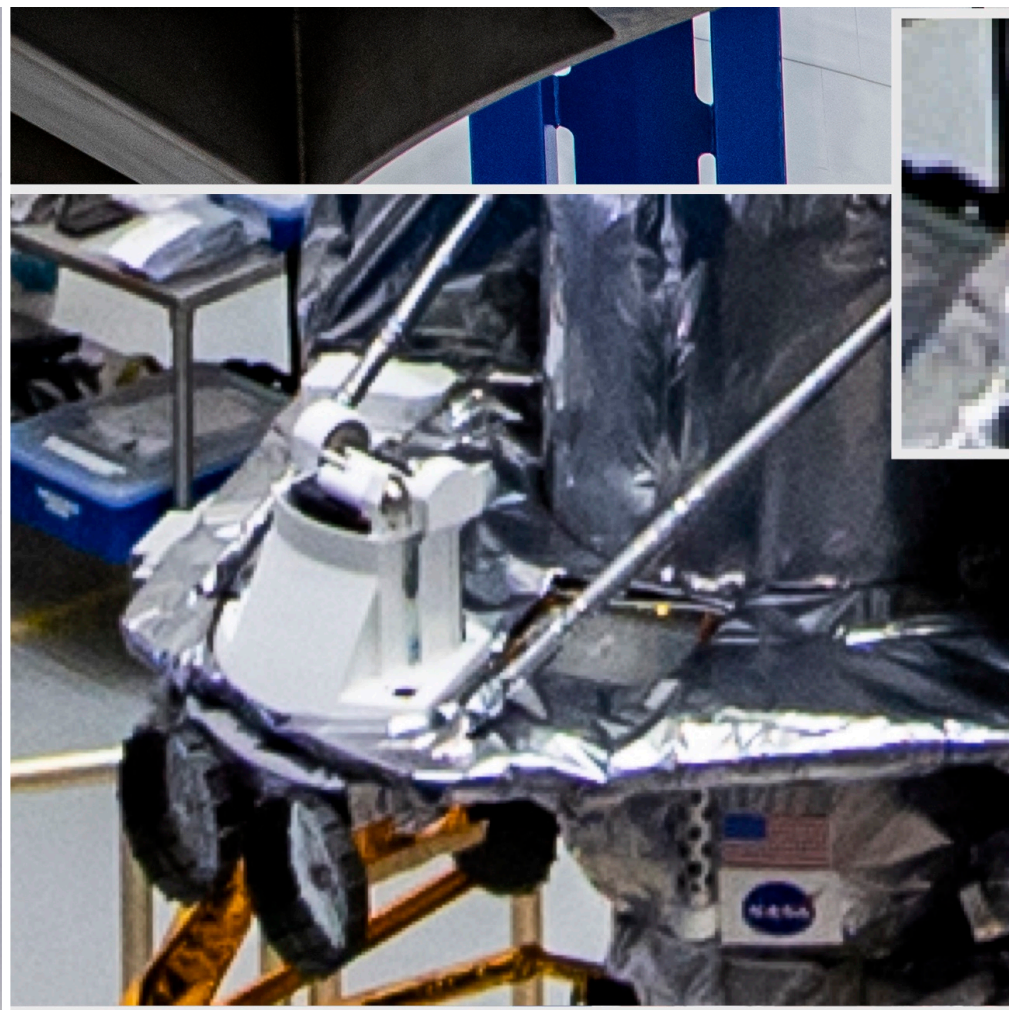
Megan McArthur in ISS US Lab with REM, RAD and AHERA Instruments



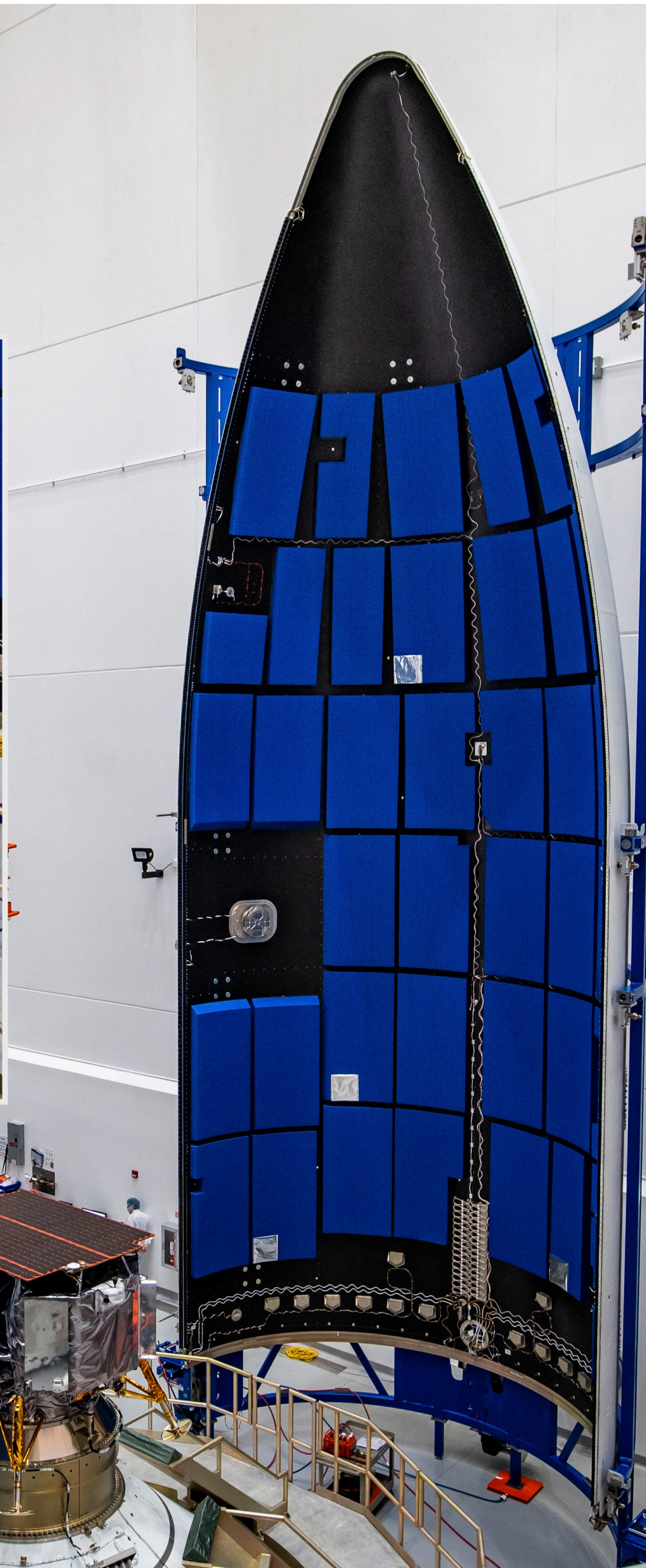
NASA Crew 7 with Crew Active Dosimeter Badges

Polaris Dawn Crew with HERA





LETS Instrument on Peregrine Mission 1

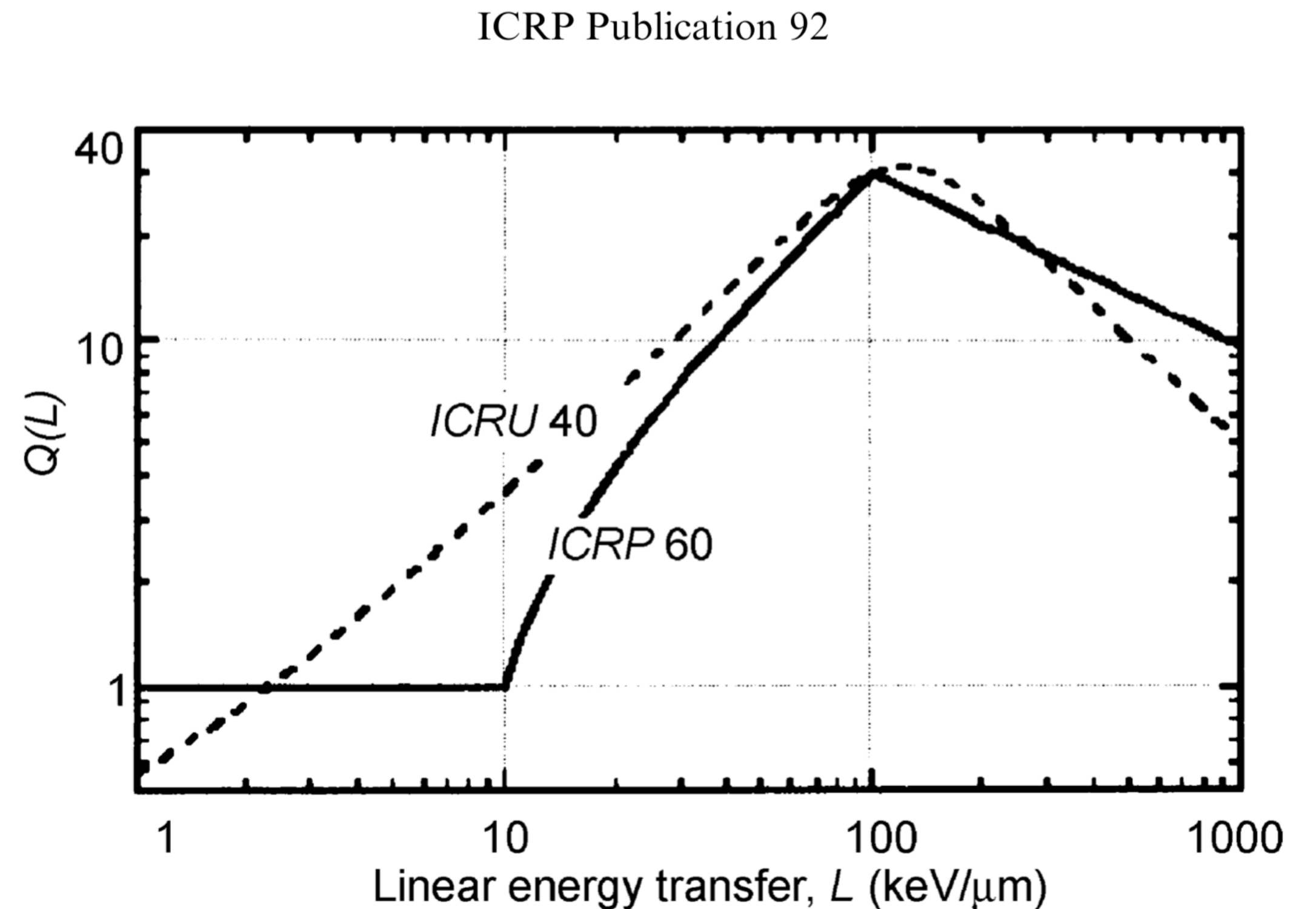


Reminder of Radiation Dosimetry and Space Physics Quantities

- Stopping power/**LET** - energy per track divided by track length
- Dose **D** - energy imparted per unit mass, typical units “Gray”. Normally “converted to dose in water” through multiplication by flat factor, ~ 1.25
- Dose Equivalent **H** - Dose weighted for biological impact, unit “Sievert”
 - Accounts for the fact that pound for pound some radiations more effective at causing negative biological end points than others
 - Results in average quality factor $\langle Q \rangle$ - **$H = \langle Q \rangle \cdot D$**
 - $\langle Q \rangle$ values for free space cosmic rays and **especially inside shielding** of wide scientific interest.
 - For space based galactic cosmic rays $\langle Q \rangle > 1$

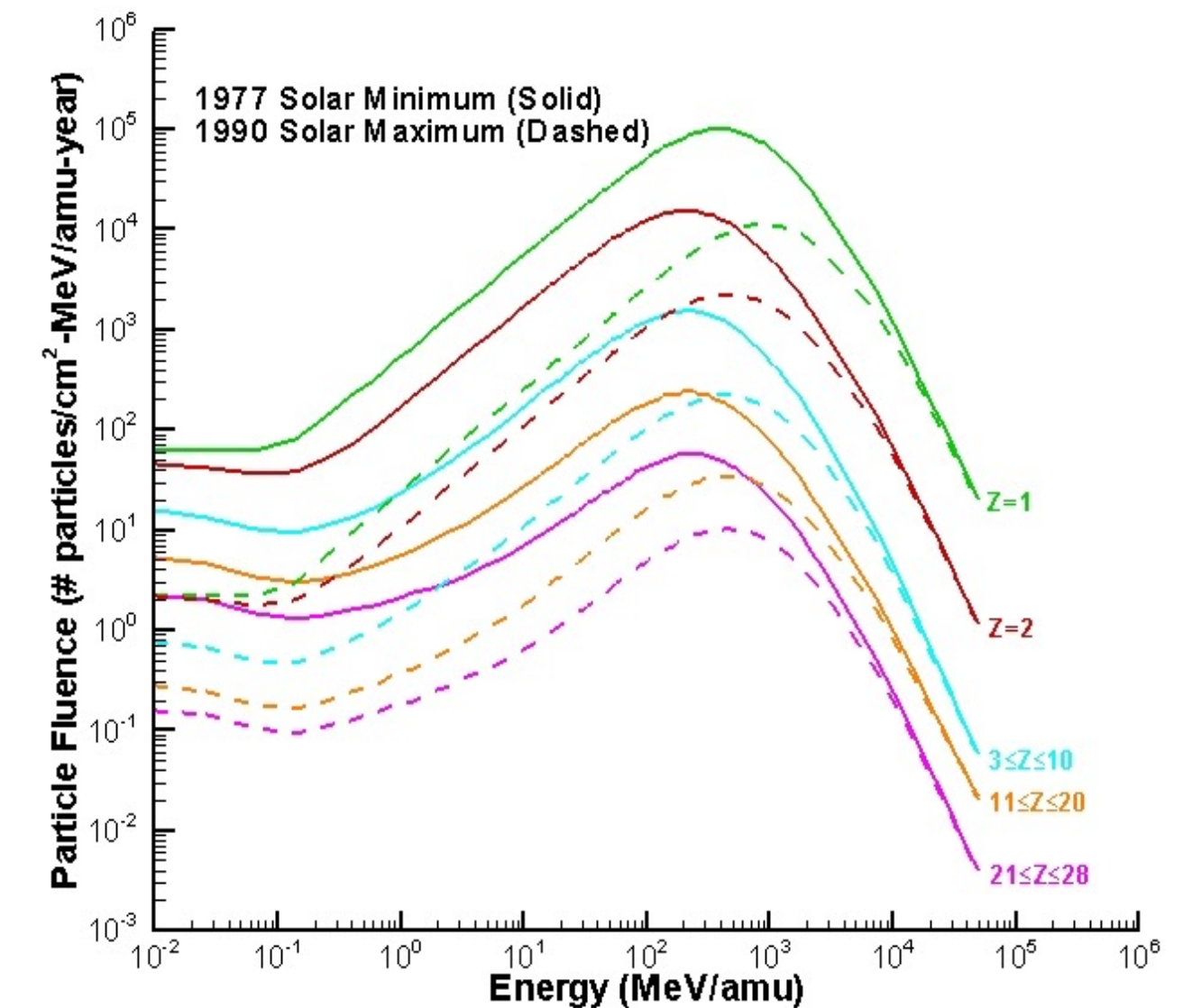
Quality Factors

- Based on observation that high LET radiation does more biological damage than would be expected from absorbed dose only
- Physical basis hypothesized to be largely in prevalence of “double strand breaks” in DNA. DSB’s use a different repair process to SSB’s. DSB’s more likely to induce cancer.
- Very high LET radiation has fall of in Q due to ‘overkilling’ effect.
- For a single particle dose equivalent, $H = QD$
- For a field $\langle Q \rangle = H/D$, $\langle Q \rangle$ is the “average quality factor” - how much more biologically effective the field is than an equivalent dose of gamma rays

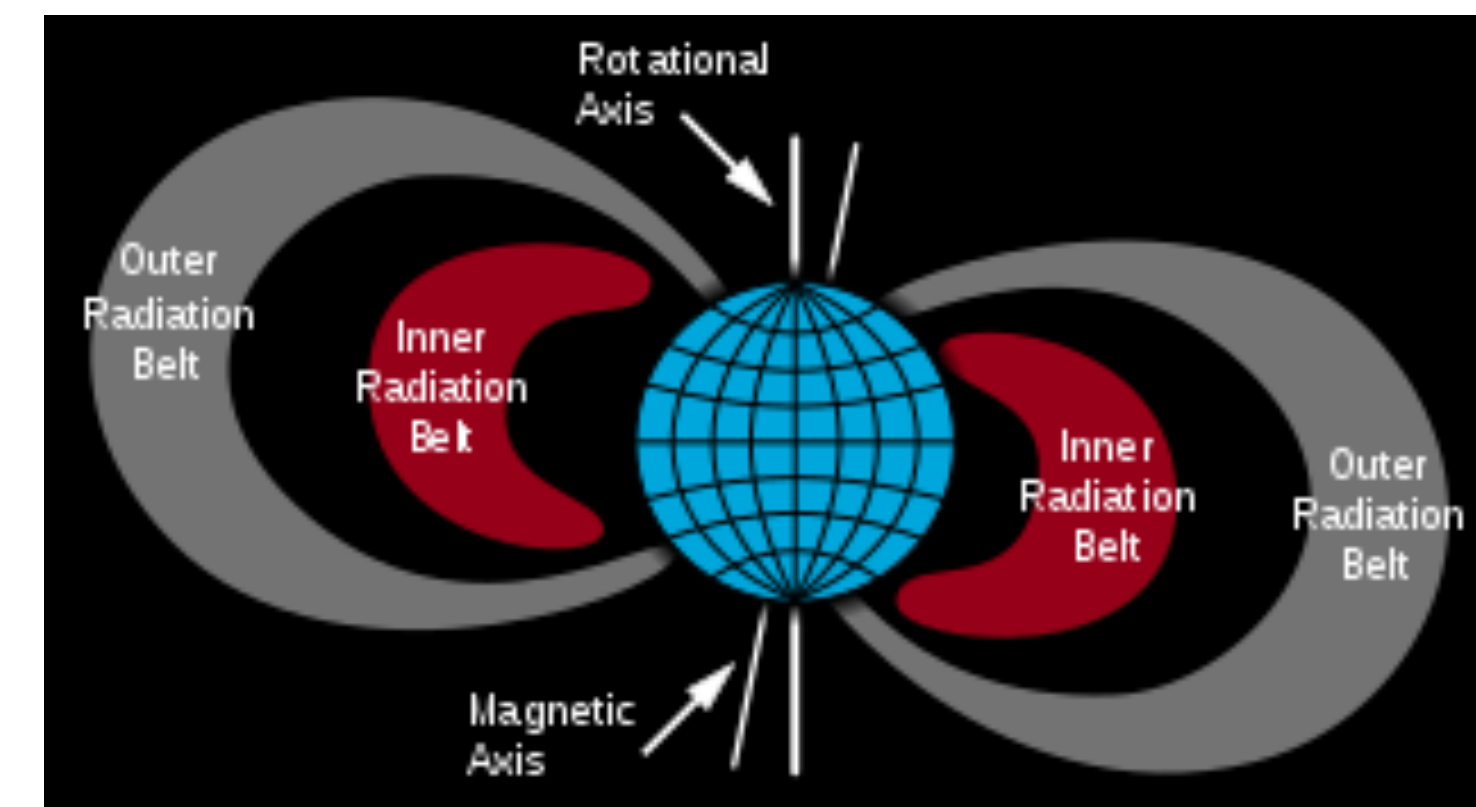


Space Radiation Environments

	Composition	Effectiveness of Shielding*	Predictability	Primary Mitigation	Risks
Galactic Cosmic Rays, Surfaces	Peaked high energy mixed ions	Low	Constant (ish)	Mission length	Chronic
Particle Belts	Decreasing power law protons and electrons	High	Affected by big Geomagnetic Storms	Optimised Trajectory	Generally Chronic (Unless extended stay)
Solar Particles	Decreasing power law protons and electrons	High	Low Think extreme rare weather events	Forecasting/ nowcasting/ Shelter	Potentially acute. Esp if poorly shielded



Galactic Cosmic Rays



Why do Radiation Measurements in Space?

- **OPERATIONS**

- Track crew radiation exposures
- Keep crew ALARA
- Protect crew from large exposures - NASA career limit 600 mSv, short term limit 250 mSv

- **TO RESEARCH**

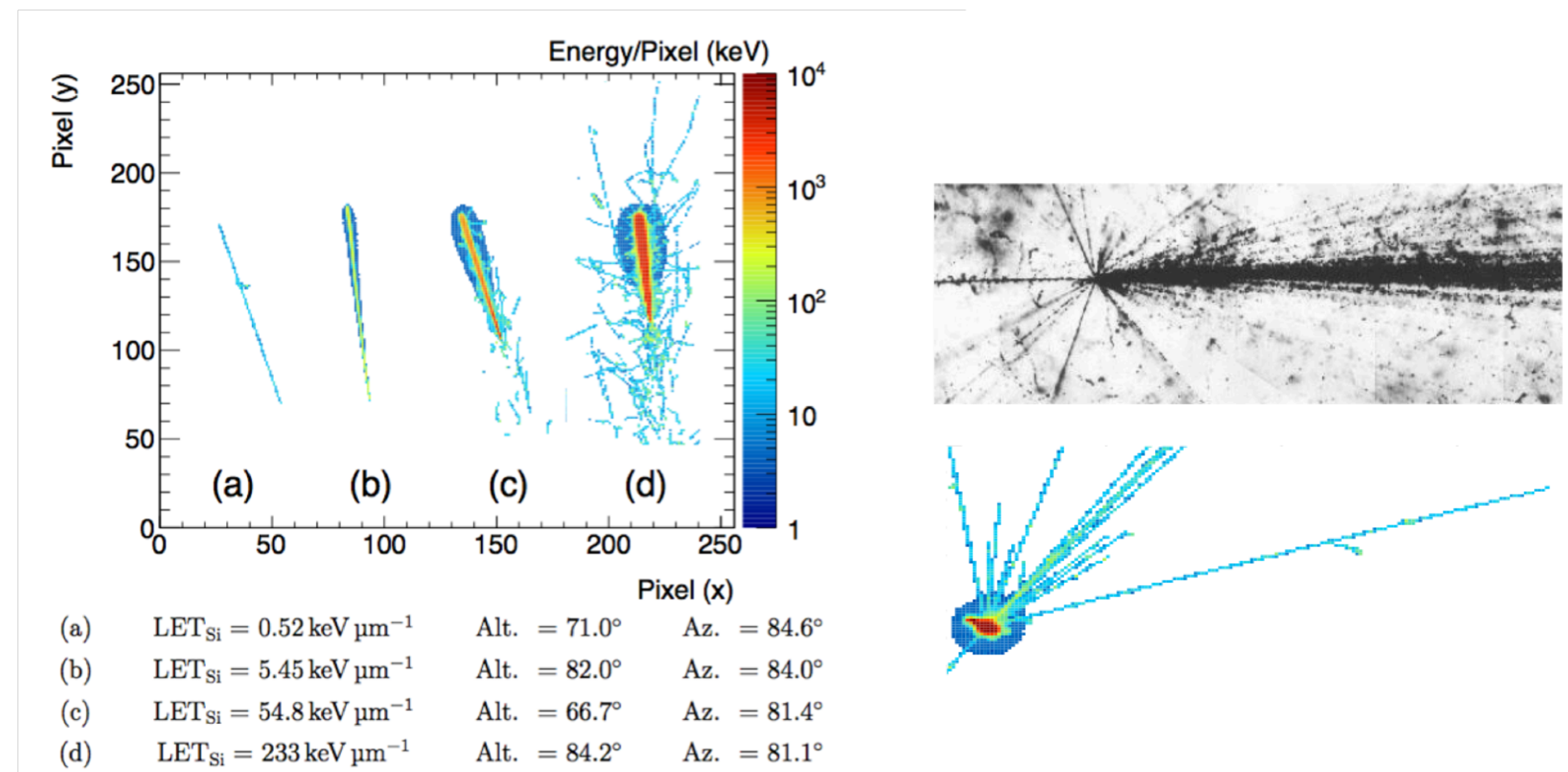
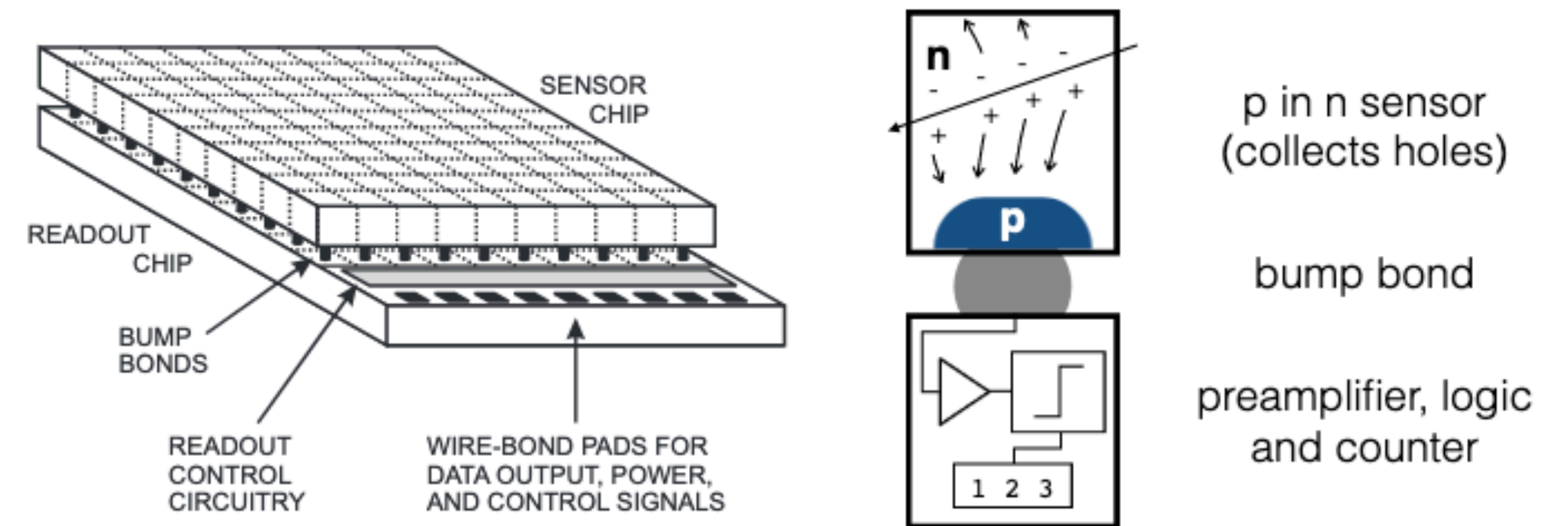
- Crewed vehicle heavily shielded - unlike science mission exposures
- Previous measurements ISS, Mir, Shuttle – Apollo/Gemini/Mercury quite limited
- Baseline environments for research
- Validate and improve spacecraft shielding models

- **TO OPERATIONS**

- Design and improve storm shelters
- Better mission planning for long duration missions into more extreme radiation environments and helps to plan better radiation operations

Why Use Timepix in Space

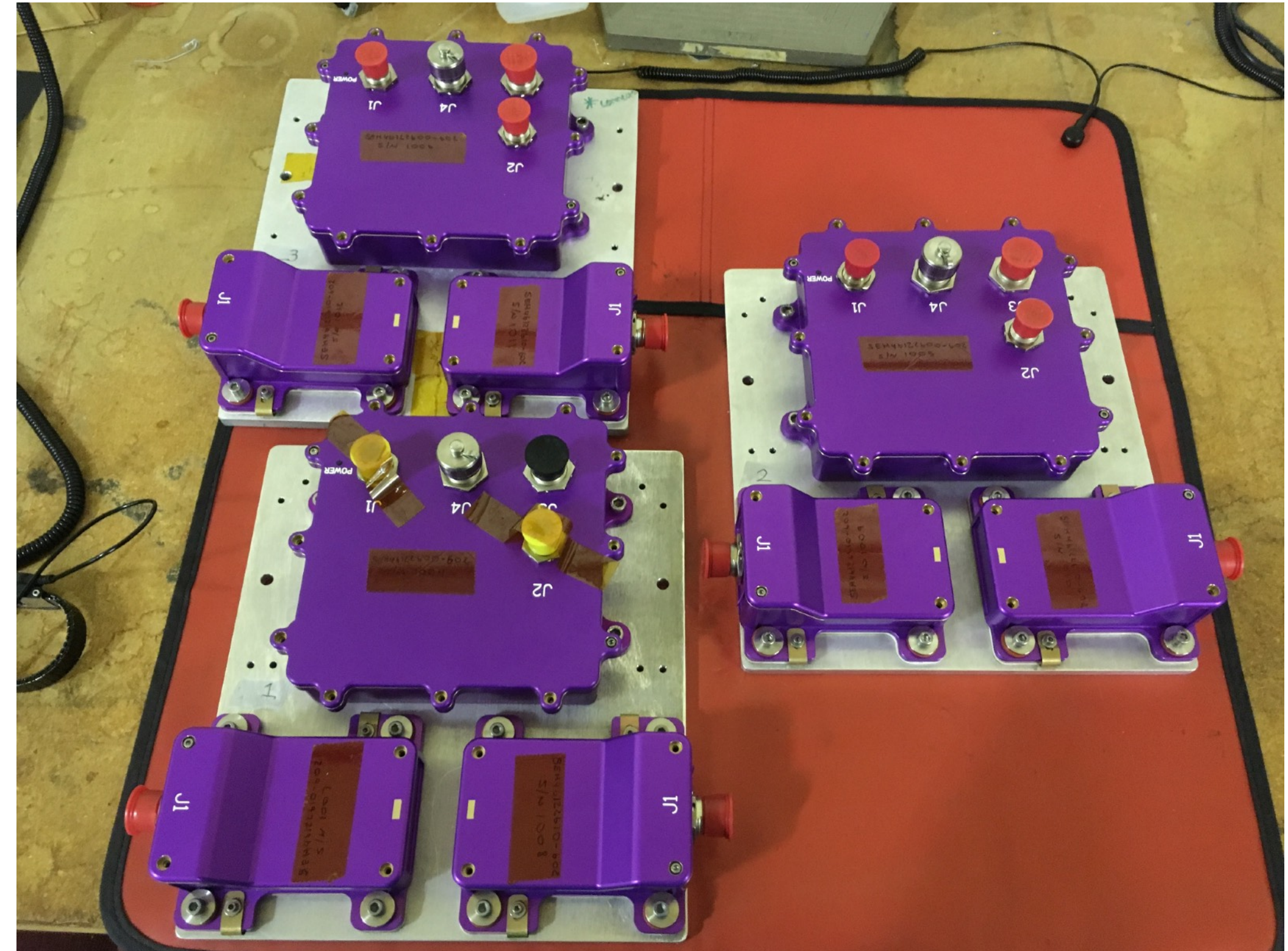
- 256 x 256 hybrid pixel detector array, Wilkinson type ADC where time over threshold can be calibrated to energy deposit. Min threshold 5 keV
- High energy range, with appropriate calibration can measure from 5 keV deposit in sensor to GeV deposits from heavy ions
- Analogue electronics integrated into ASIC, enabling easily miniaturized instruments
- Stable, robust technology with commercial supply chains
- Tracks provide true dE/dX measurement, extra information in tracks - technology acts like 'solid state nuclear emulsion'



(Top) Schematic of Timepix Detector and individual pixel, (bottom left) example tracks in Timepix detector from ions (bottom right) example nuclear fragmentation in nuclear emulsion and Timepix showing analogy with 'solid state nuclear emulsion'

HERA Is Our Instrument

- HERA is a fully autonomous radiation monitoring instrument for NASA exploration programs, specifically the Orion spacecraft
- HERA performs real time onboard calibration and PID/binning
- Each HERA consists of an HPU (HERA processing unit) and two HSU's (HERA Sensor Unit), each containing a timepix for a total of 3
- Many challenges - needed to implement full on board data processing chain due to limited telemetry bandwidth (1.5 kB/min)
- Qualified for shock/vibe/thermal environments
- Data processing provide dosimetry, science data, crew display and caution and warning data
- Mass = ~1.5 kg (not including cabling), power consumption 9W

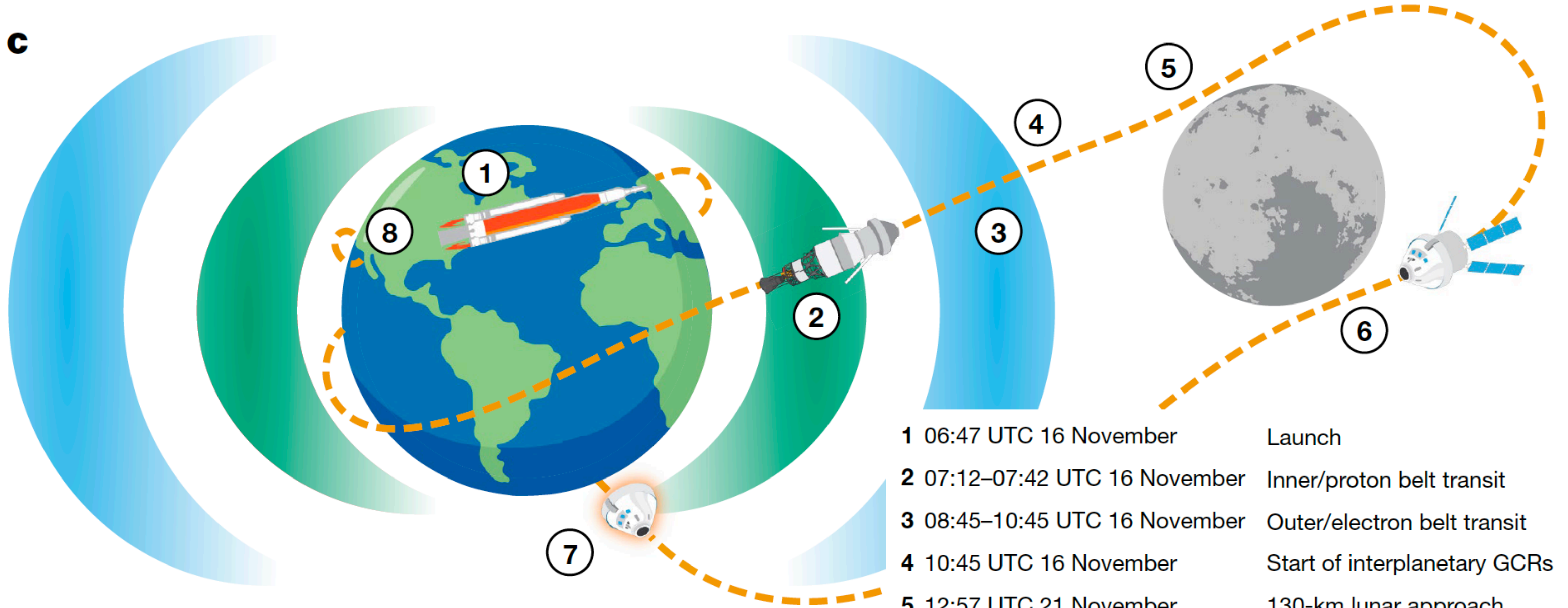


Three HERA Flight Strings for Artemis 2 during calibration at BNL Tandem

Artemis I Launch - November 22nd 2022

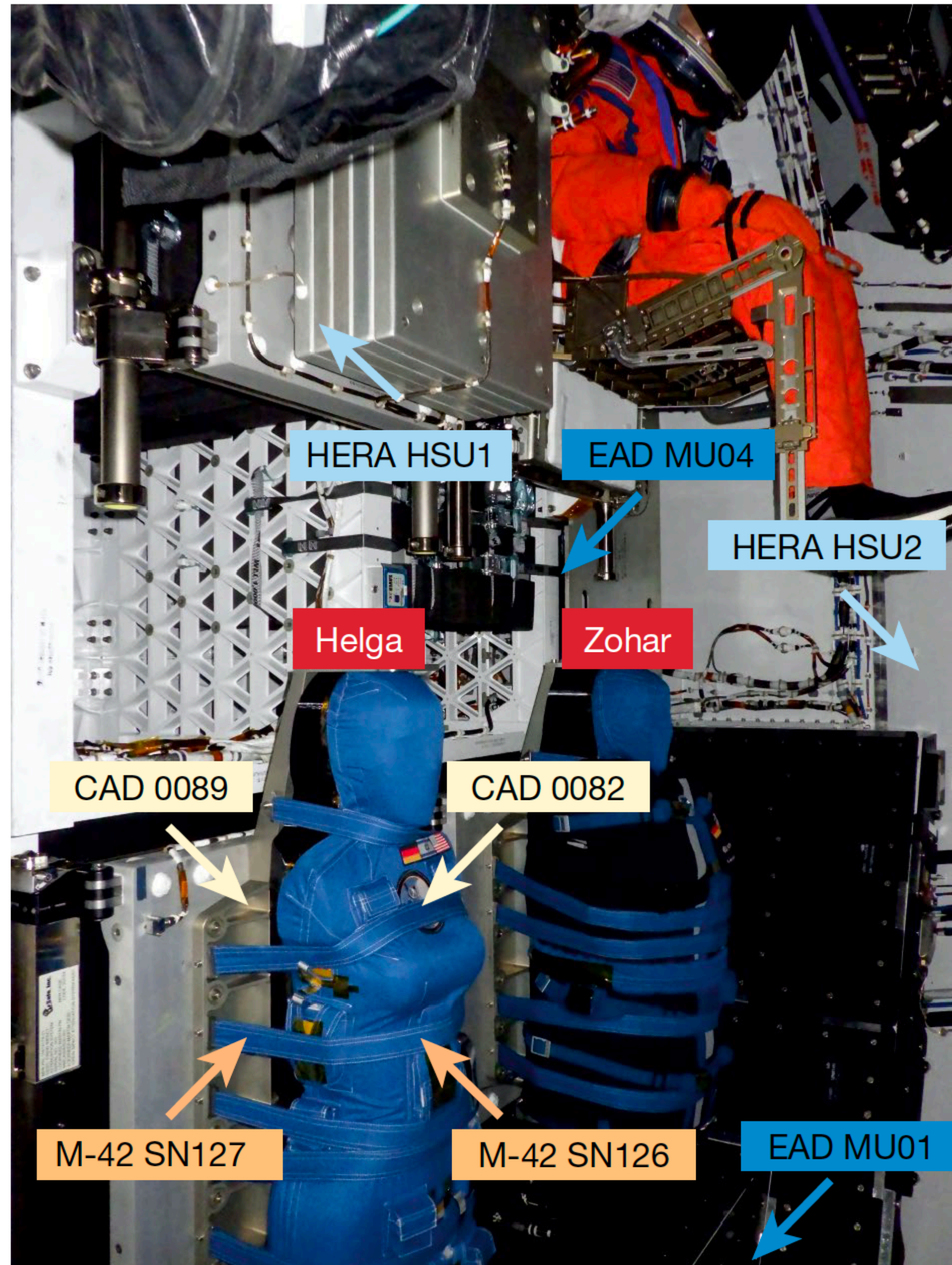


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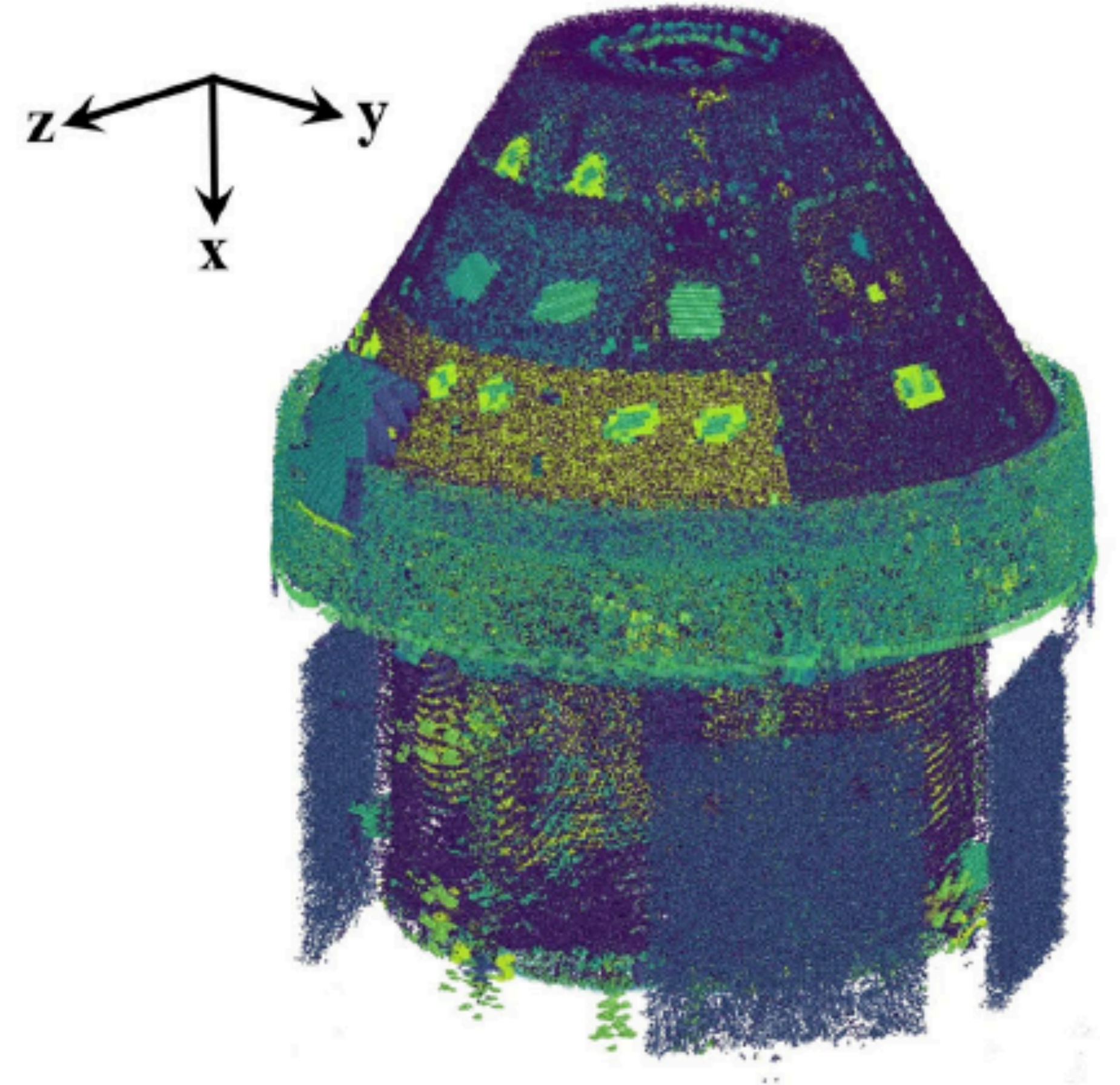
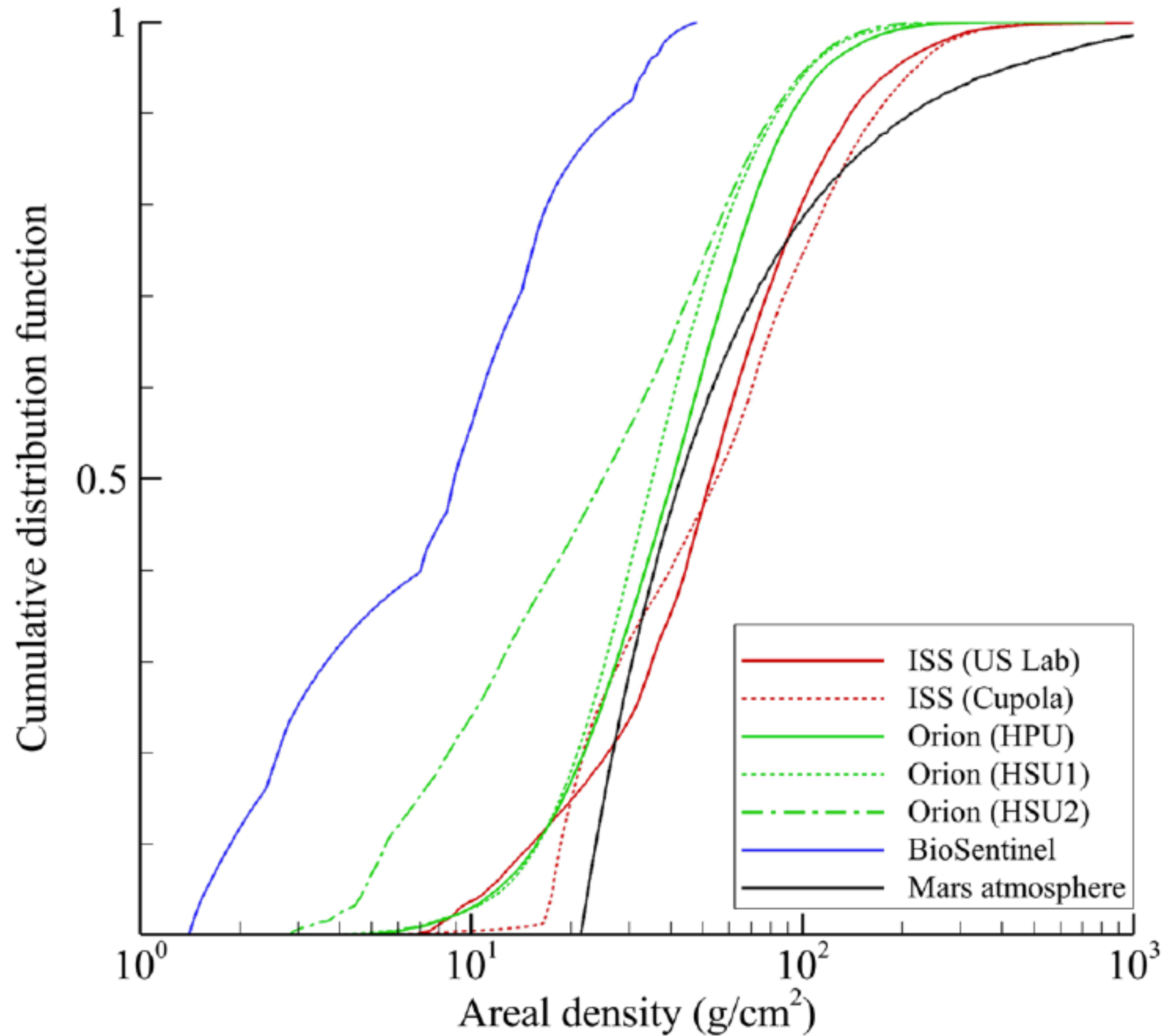


- Inner belt (proton rich)
- Outer belt (electron rich)
- Spacecraft trajectory

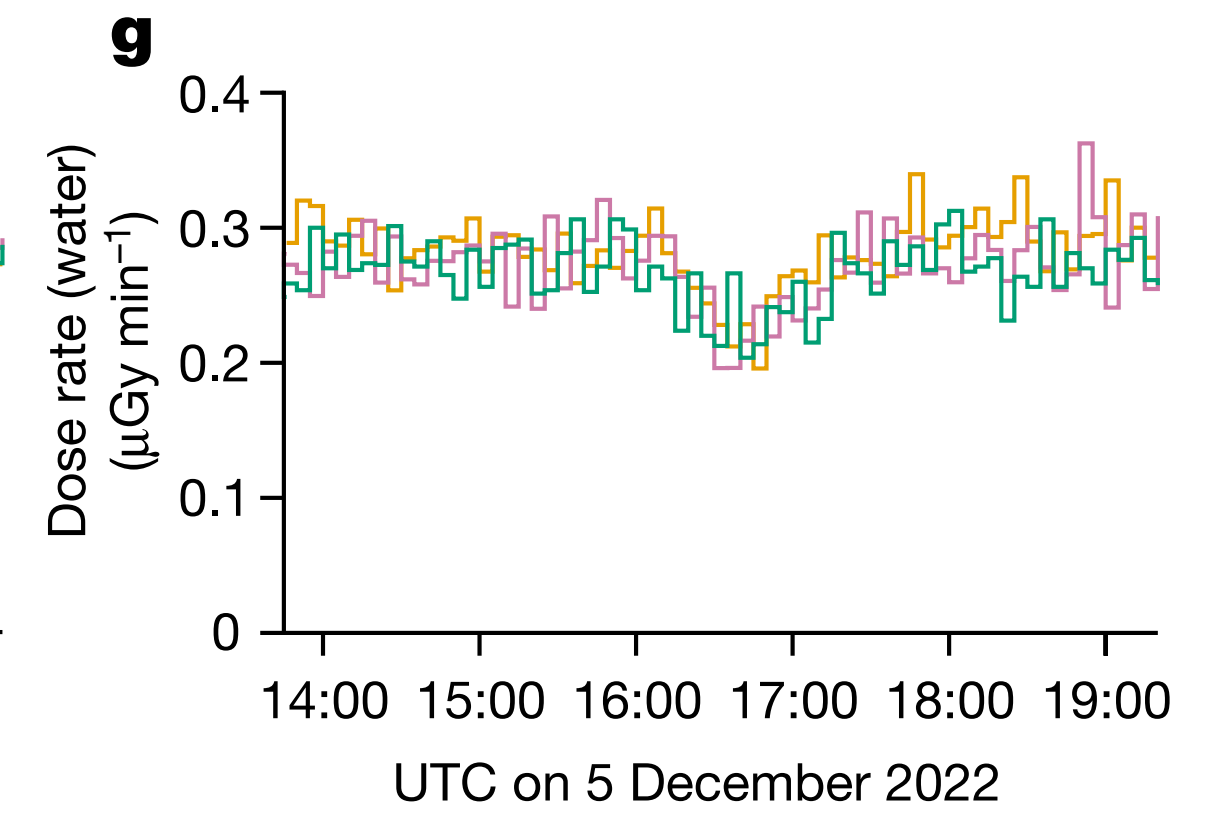
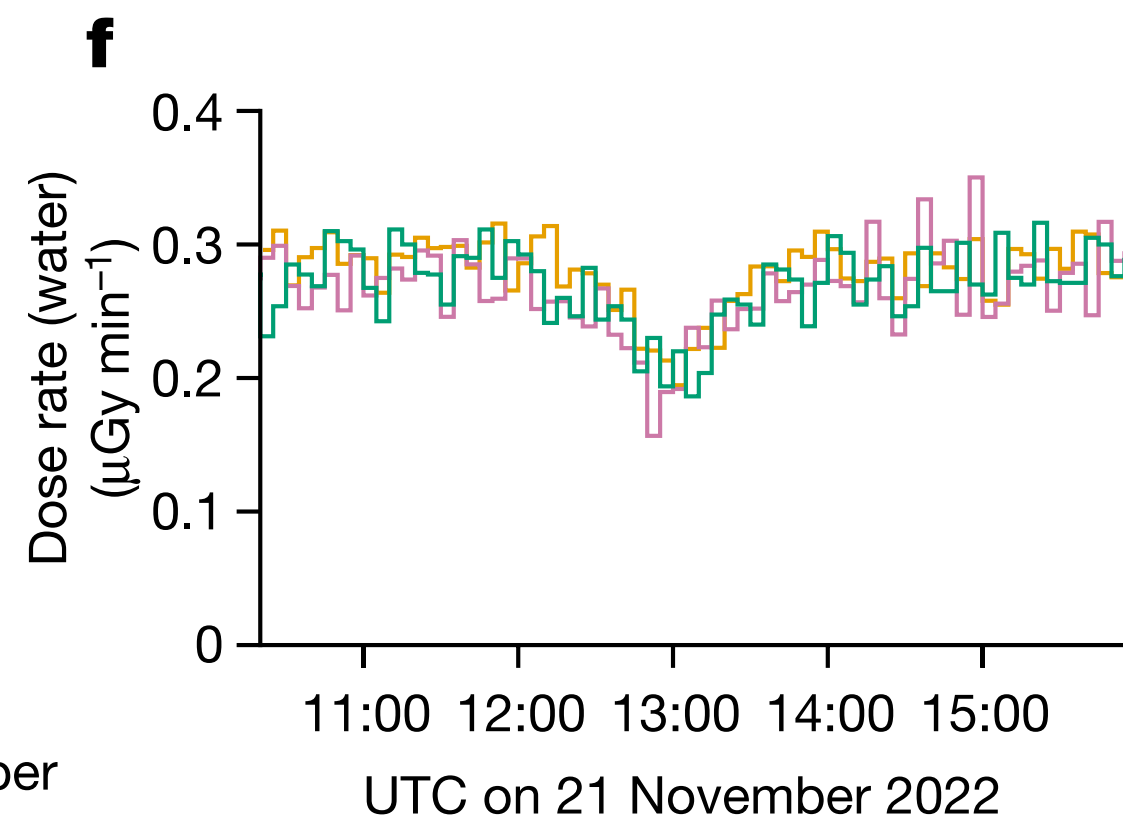
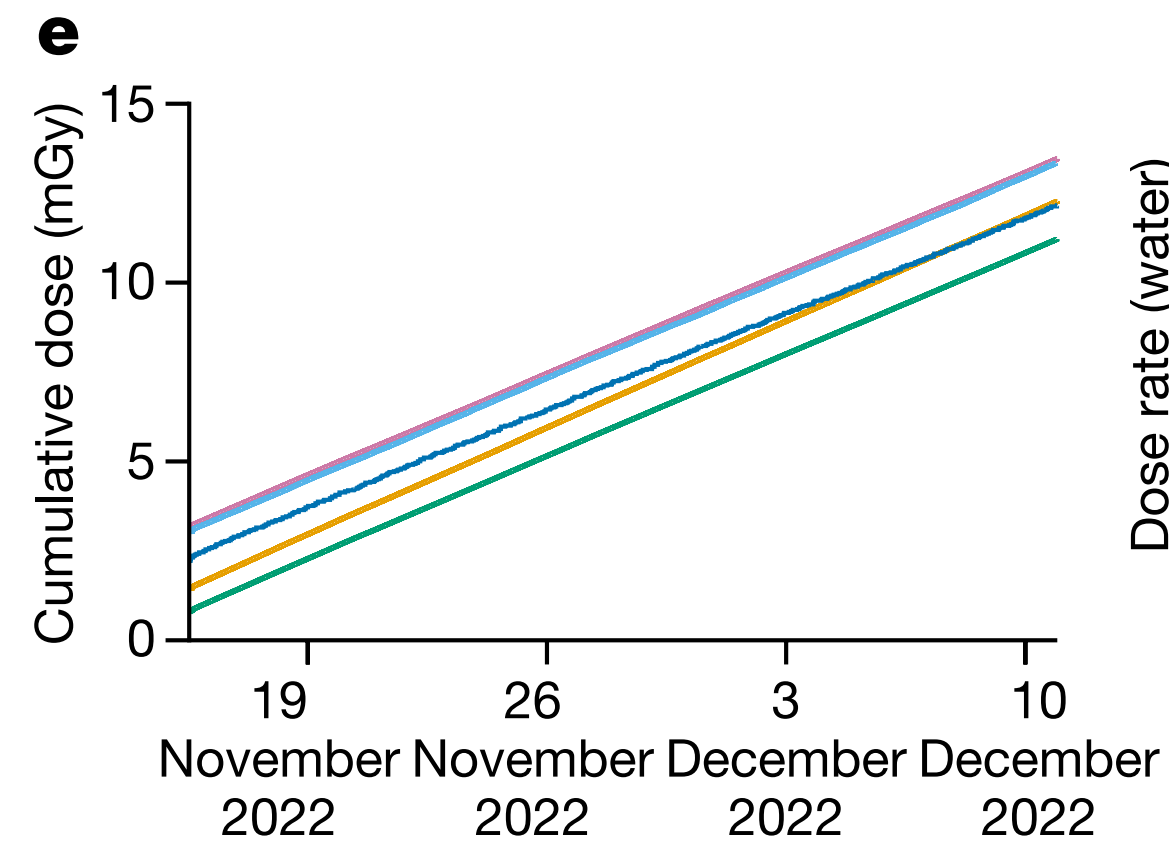
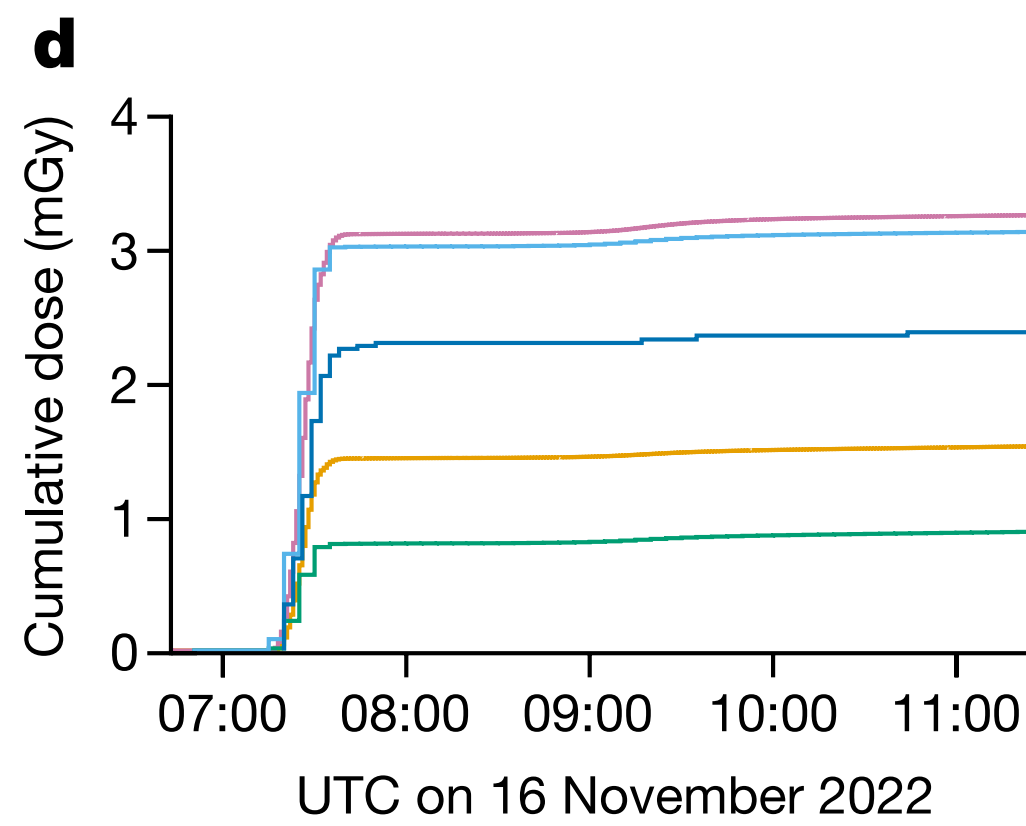
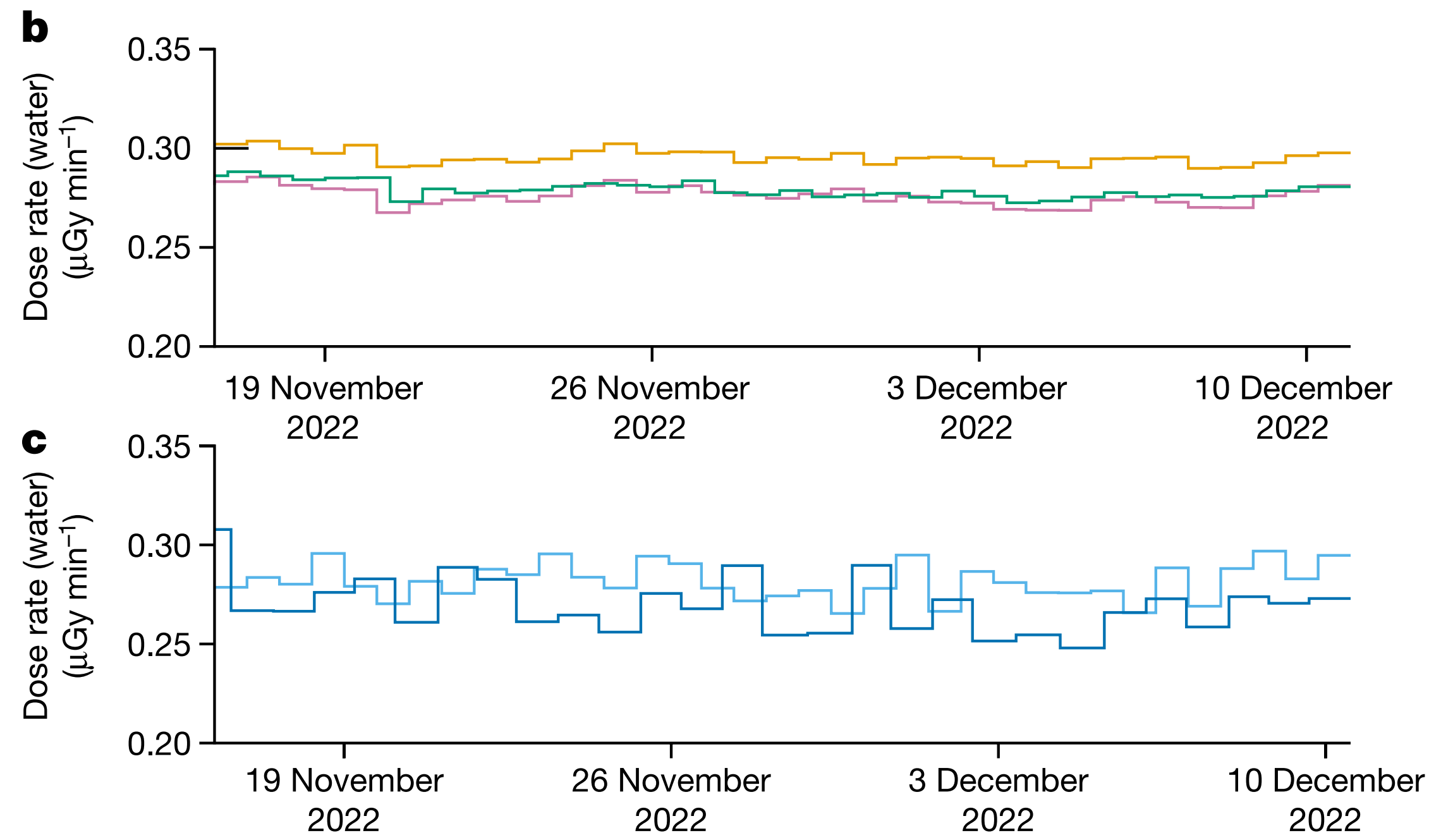
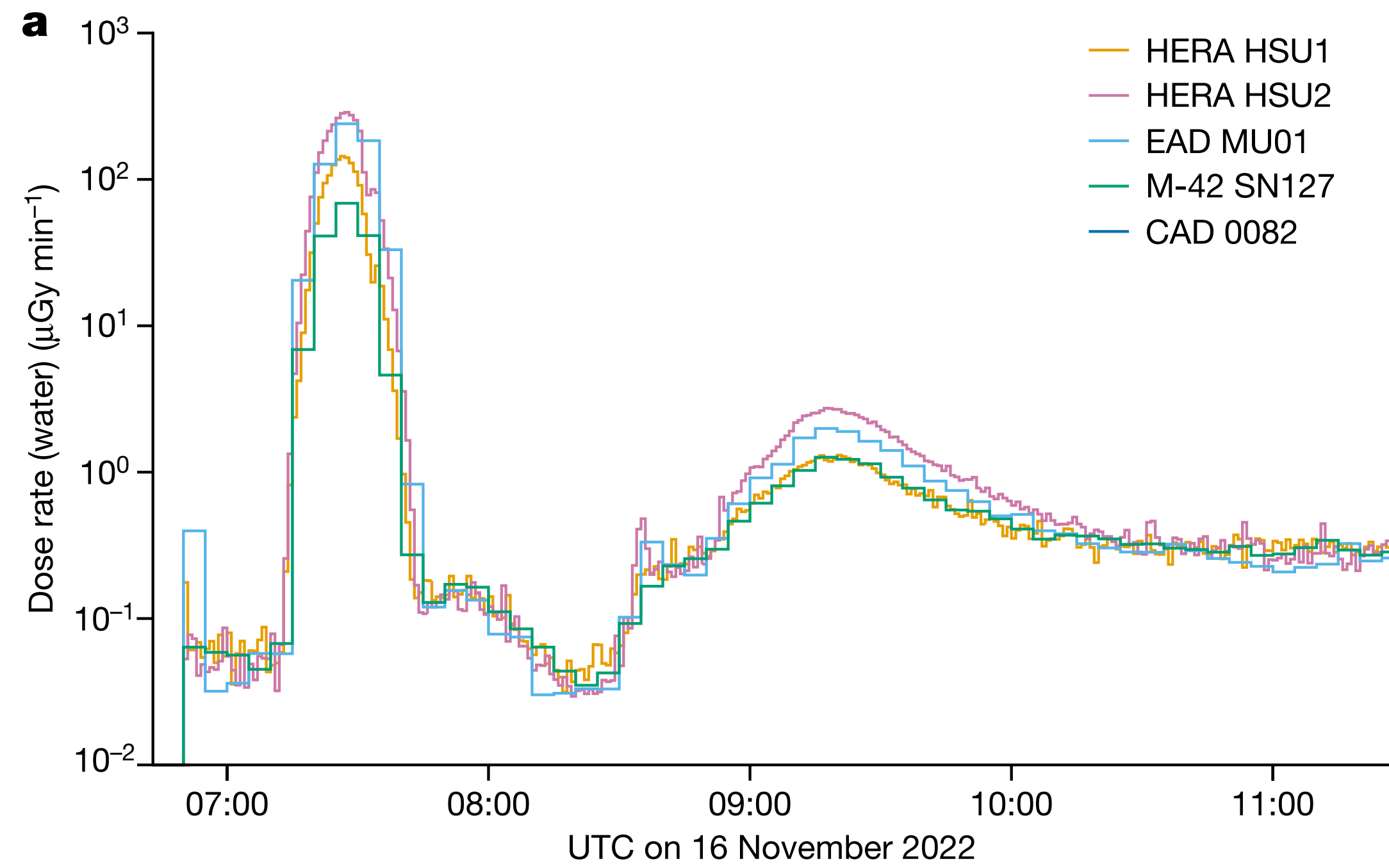
1	06:47 UTC 16 November	Launch
2	07:12–07:42 UTC 16 November	Inner/proton belt transit
3	08:45–10:45 UTC 16 November	Outer/electron belt transit
4	10:45 UTC 16 November	Start of interplanetary GCRs
5	12:57 UTC 21 November	130-km lunar approach
6	16:43 UTC 5 December	128-km lunar approach
7	17:00 UTC 11 December	Polar re-entry
8	17:40 UTC 11 December	Landing

a**b**

Orion is a Heavily Shielded Vehicle



Artemis I - Absorbed Dose Rate Measurements



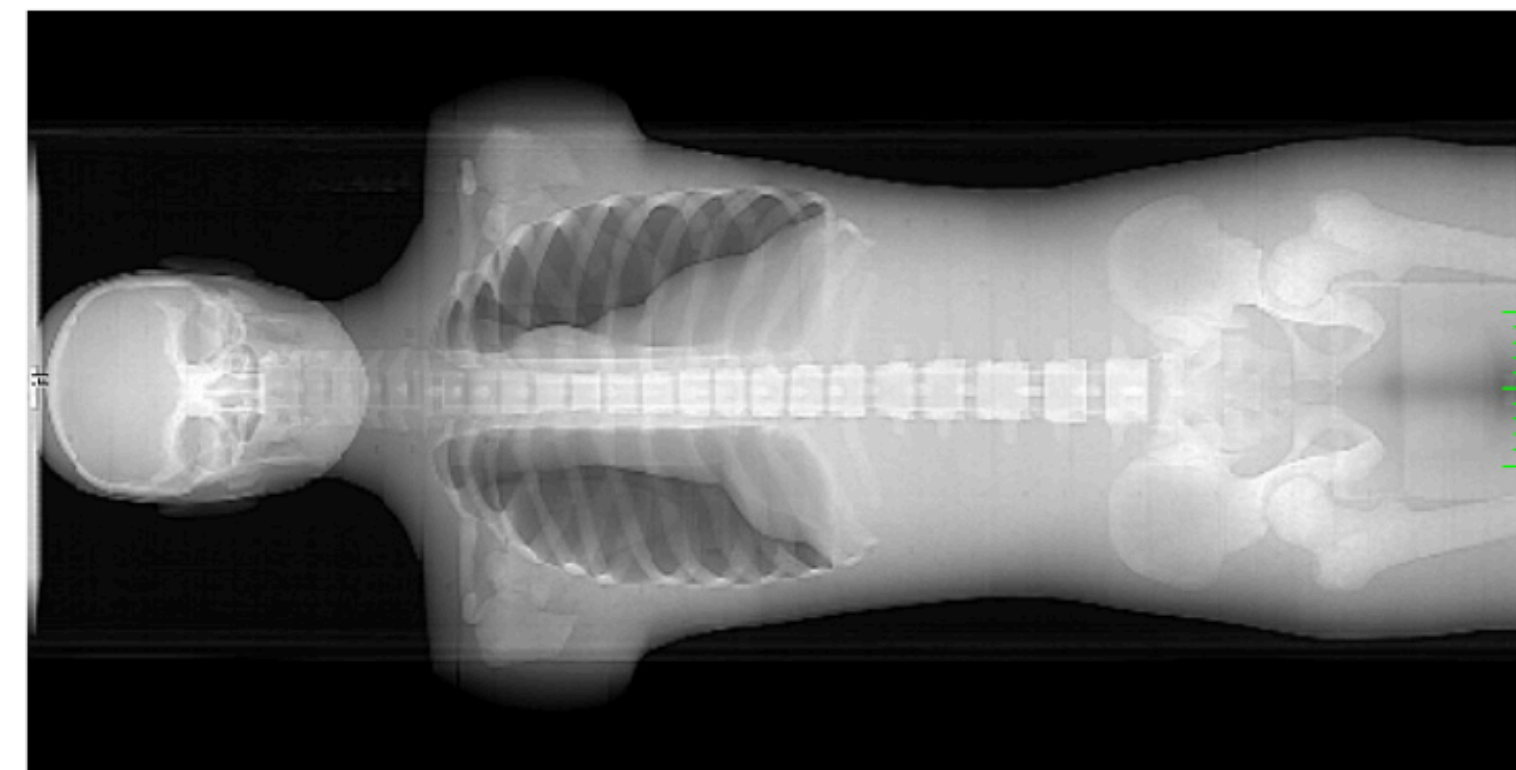
(a) Inner belt pass, (b,c) GCR dose rates, (d,e) cumulative doses, (f,g) dose rate drop on lunar close approach

Artemis I - Radiation Phantom Measurements

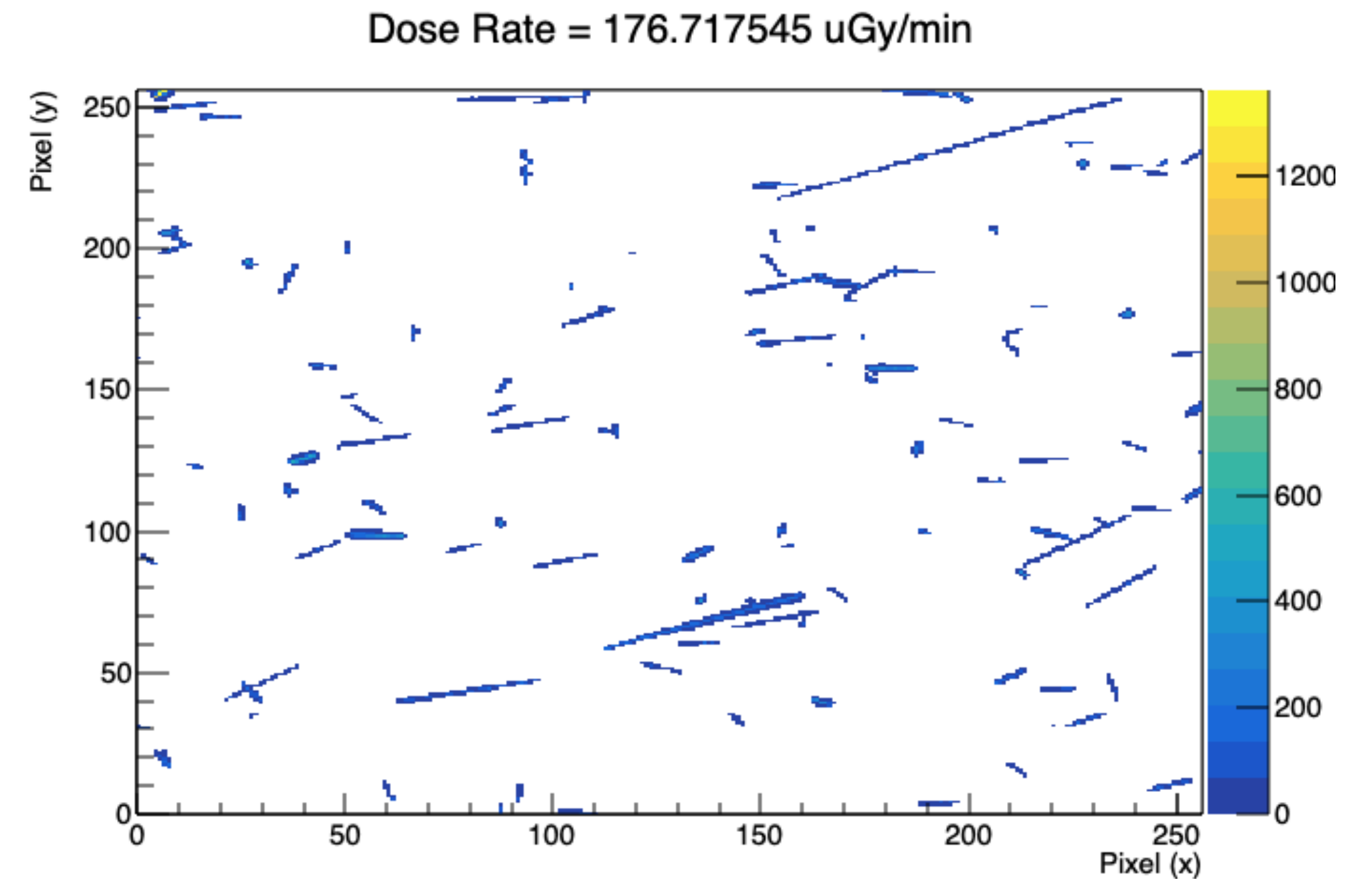
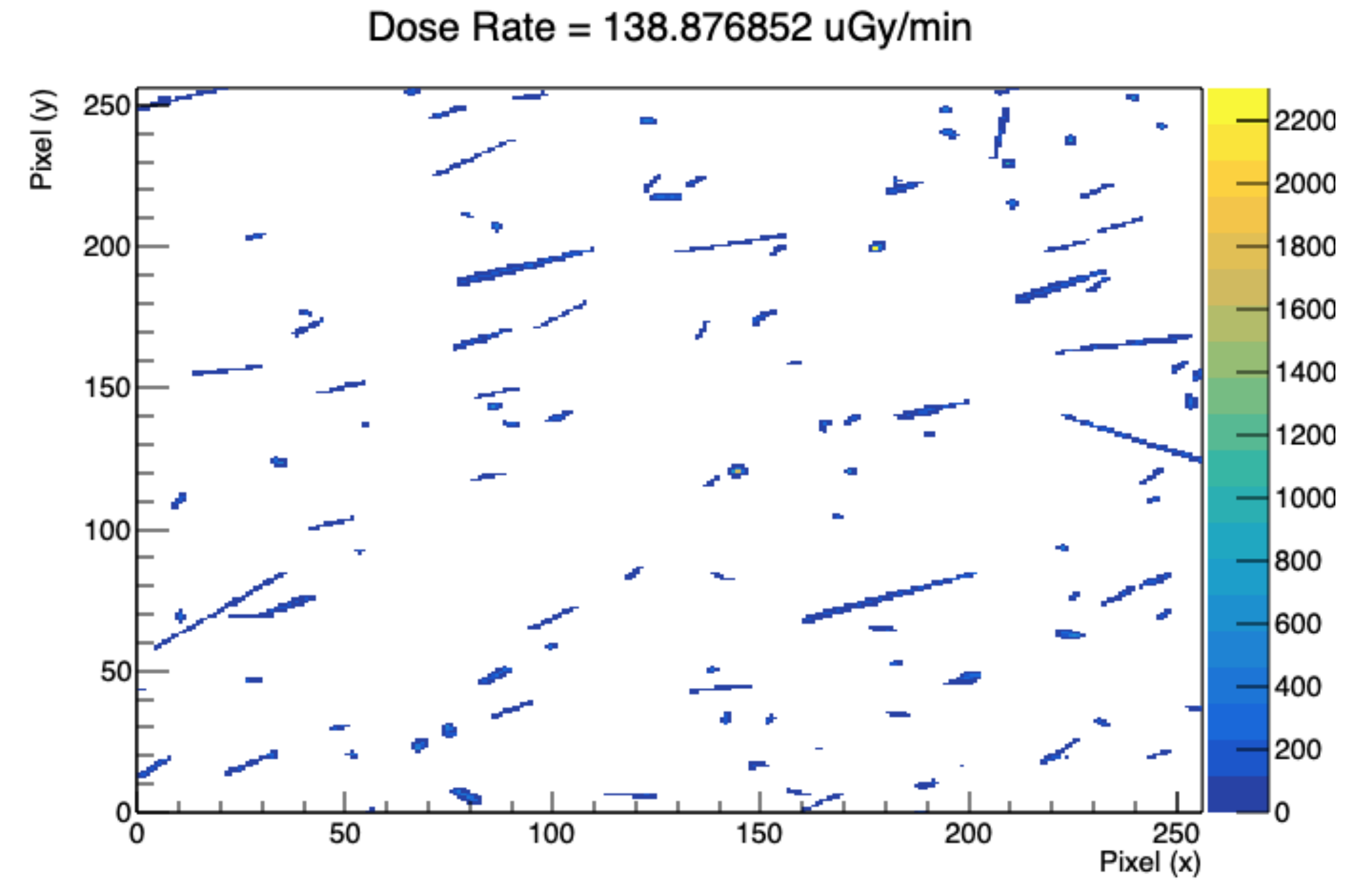
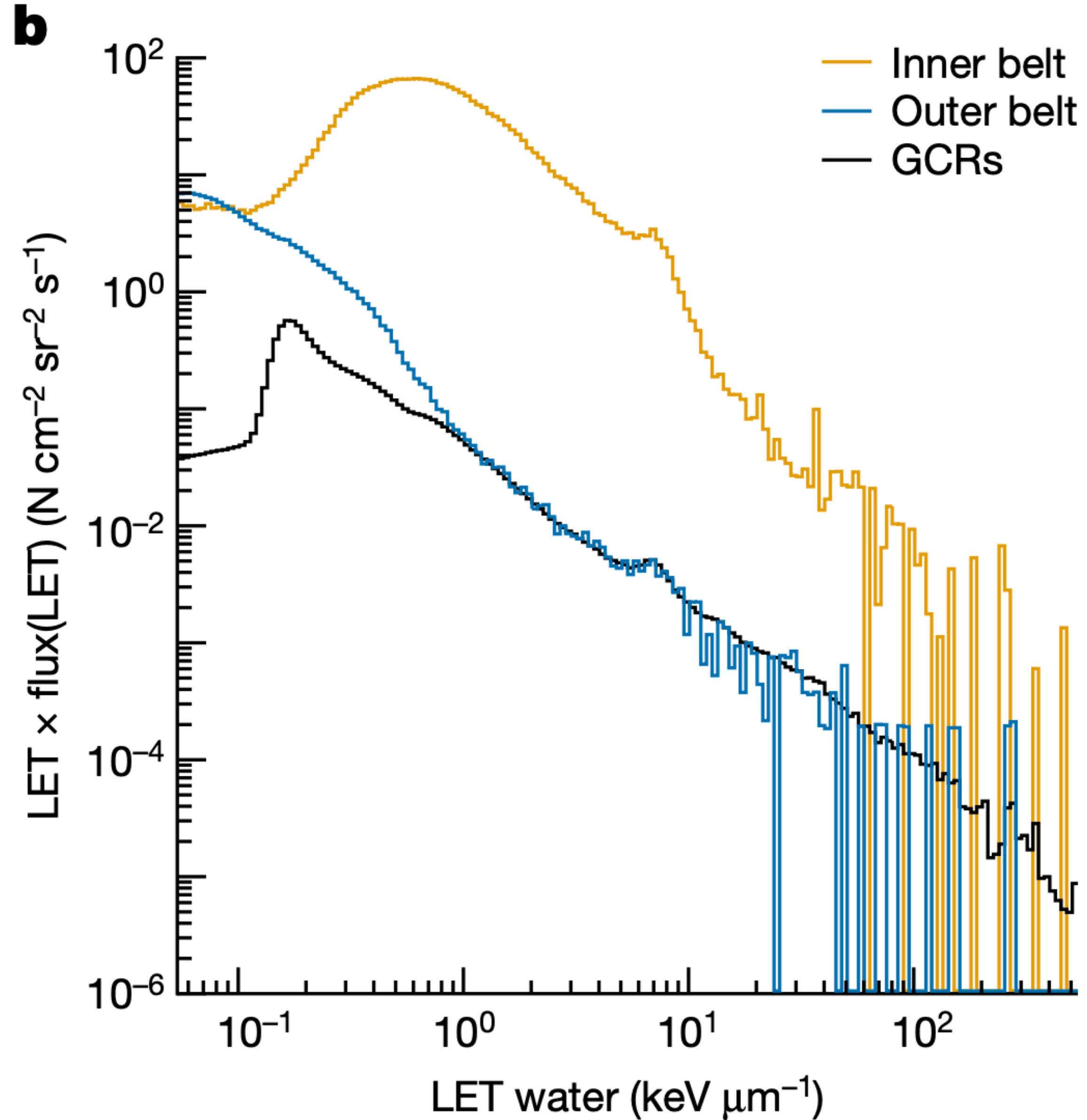


Table 1 | Absorbed dose values inside and outside the MARE Helga phantom

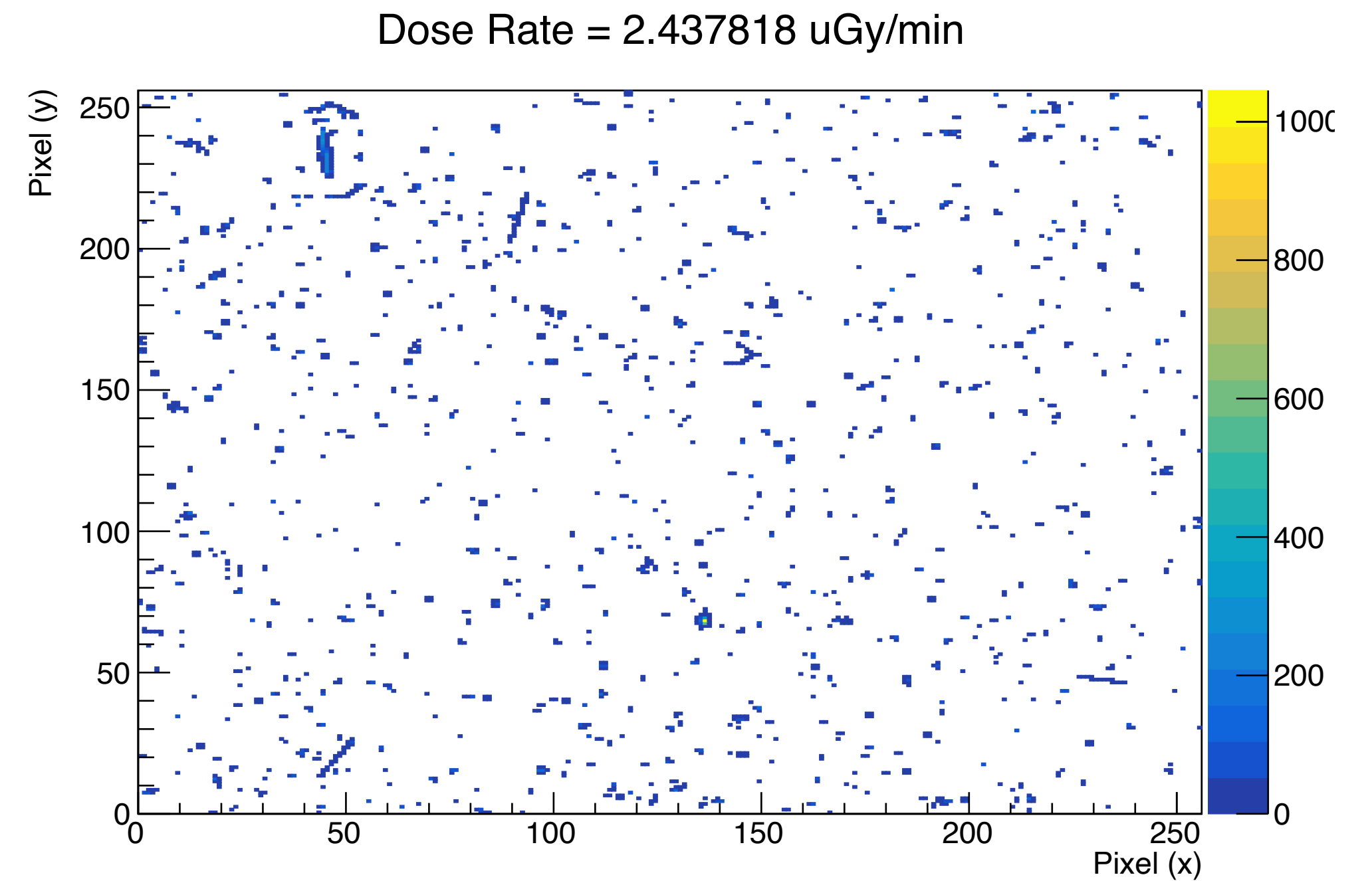
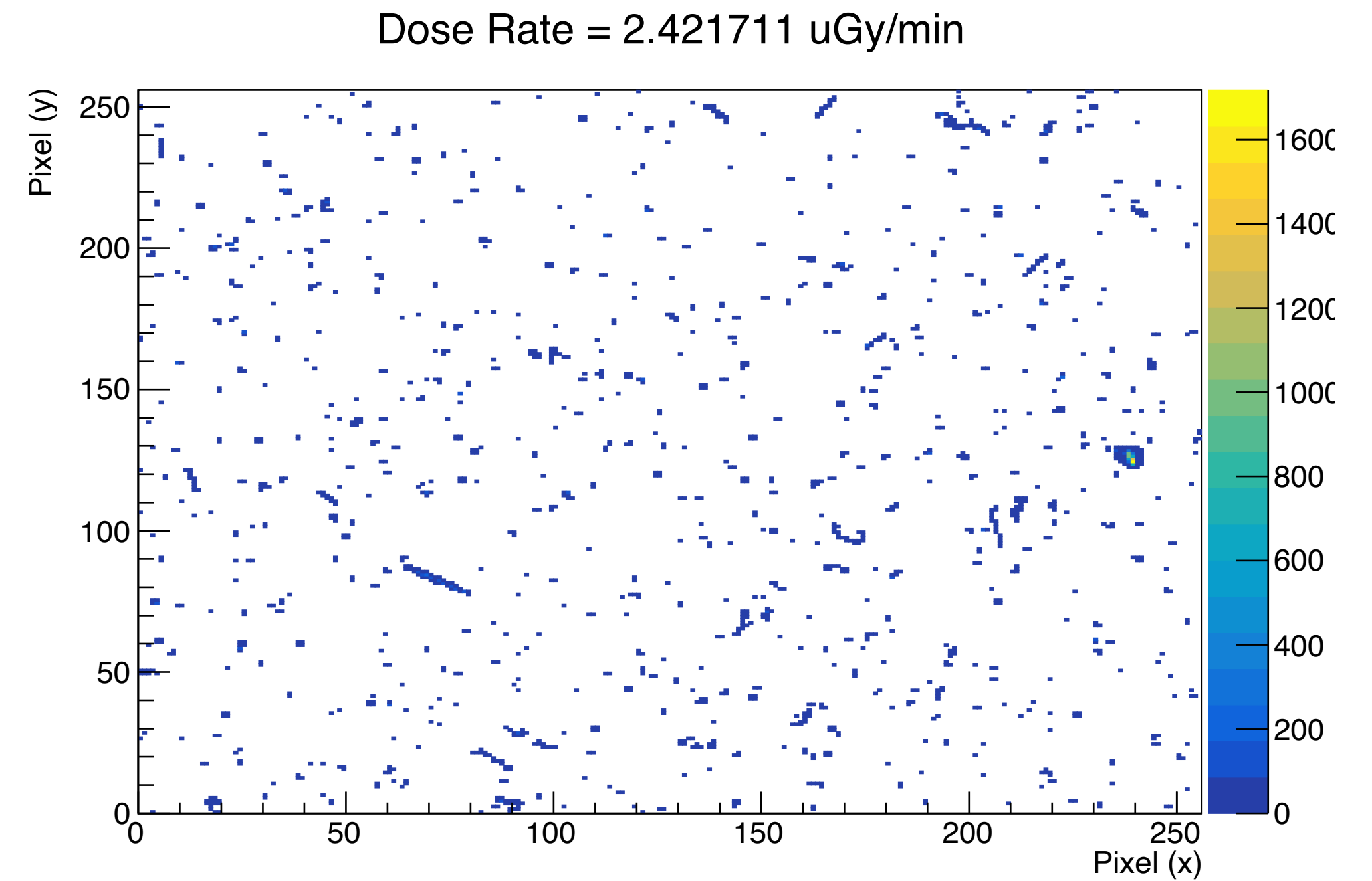
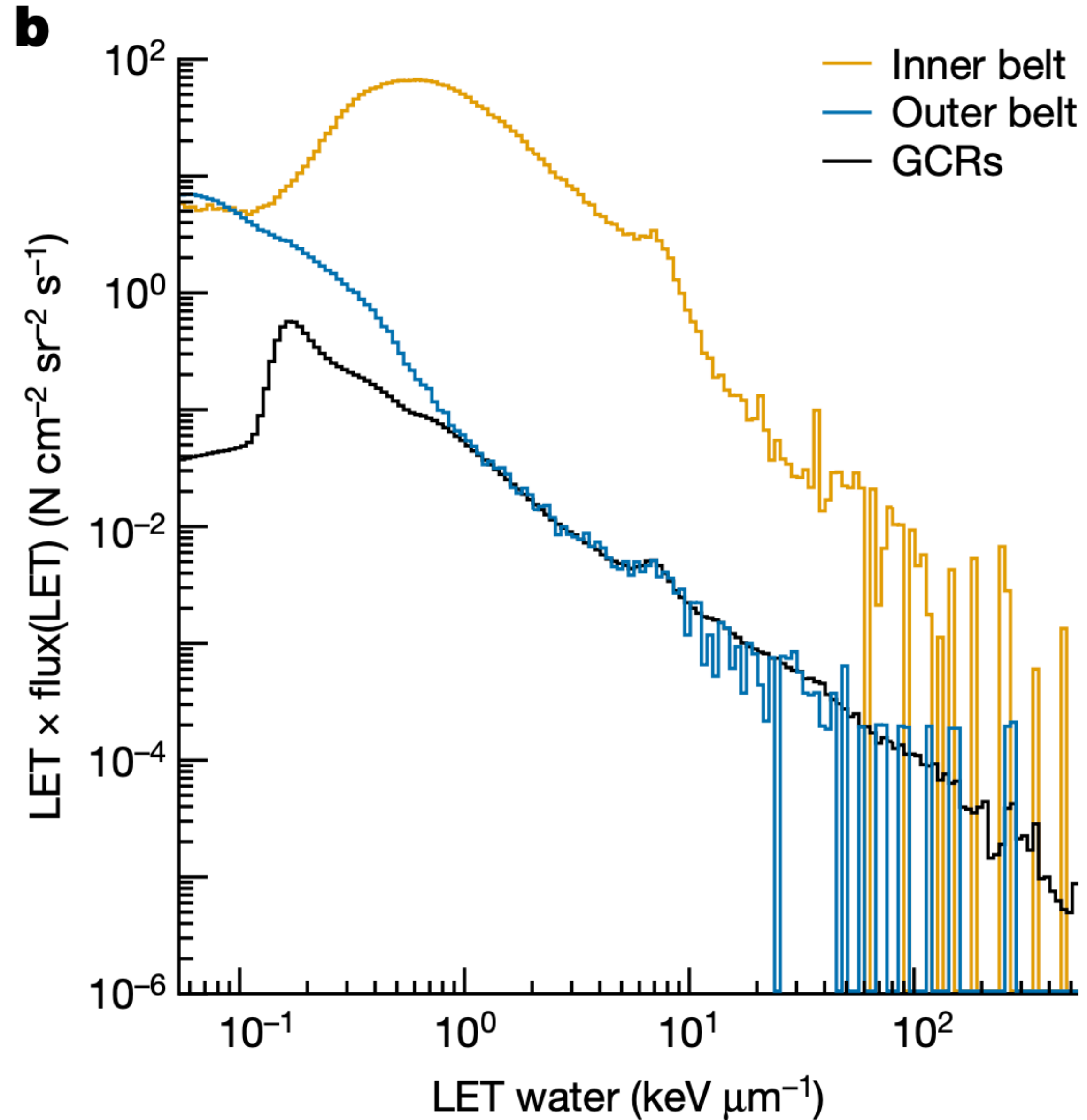
M-42		Cumulative absorbed dose D (mGy)		
No.	Location	Inner belt	Outer belt	GCR
SN126	Skin (front)	1.96 ± 0.22	0.11 ± 0.01	9.38 ± 1.03
SN144	Left lung	1.00 ± 0.11	0.09 ± 0.01	9.44 ± 1.04
SN145	Right lung	1.19 ± 0.13	0.08 ± 0.01	9.44 ± 1.04
SN146	Stomach	0.91 ± 0.10	0.08 ± 0.01	9.42 ± 10.4
SN147	Uterus	0.95 ± 0.10	0.09 ± 0.01	10.07 ± 1.11
SN148	Spine	0.61 ± 0.07	0.06 ± 0.01	9.56 ± 1.05
SN127	Skin (back)	0.80 ± 0.09	0.07 ± 0.01	10.17 ± 1.12



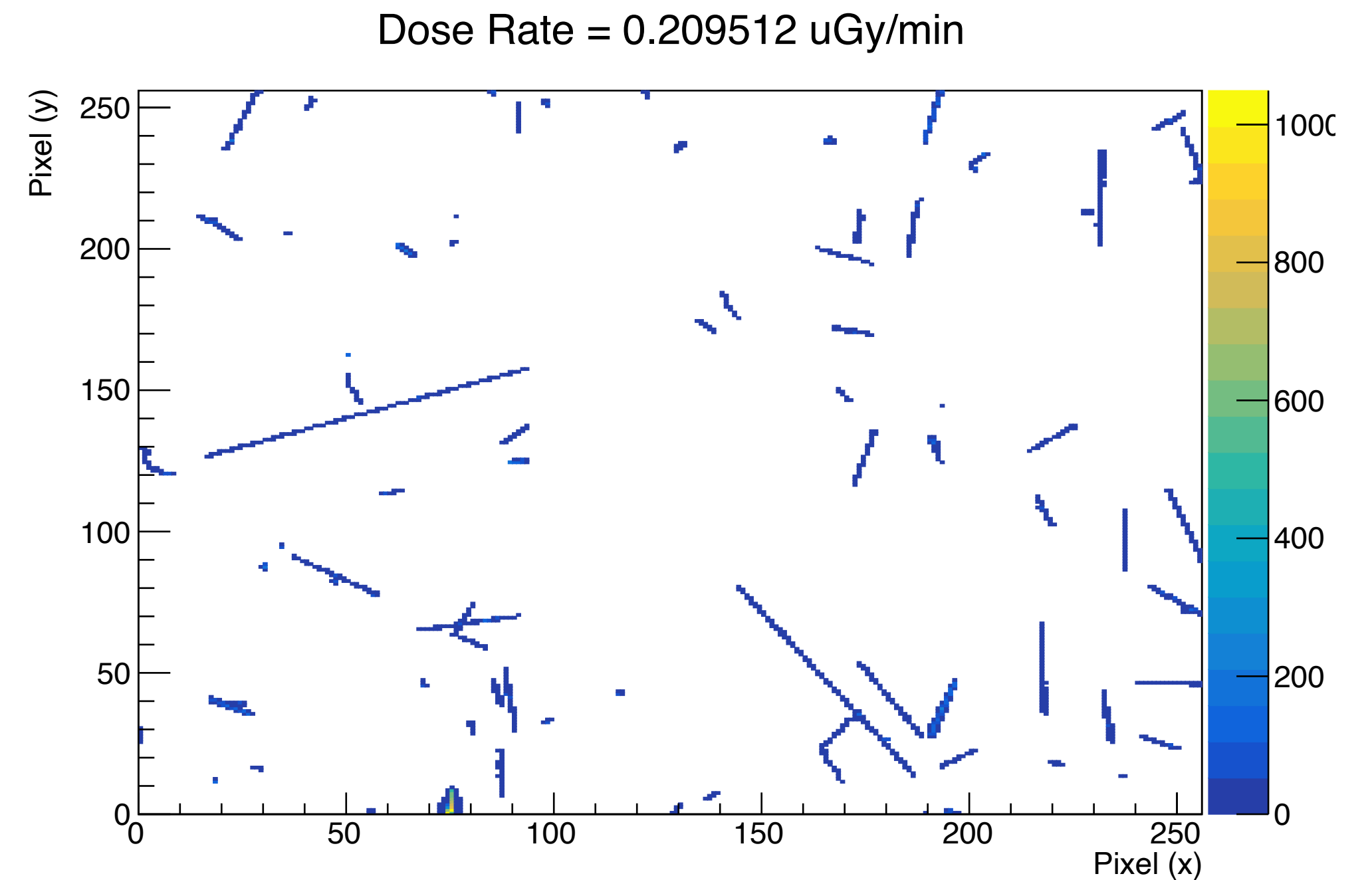
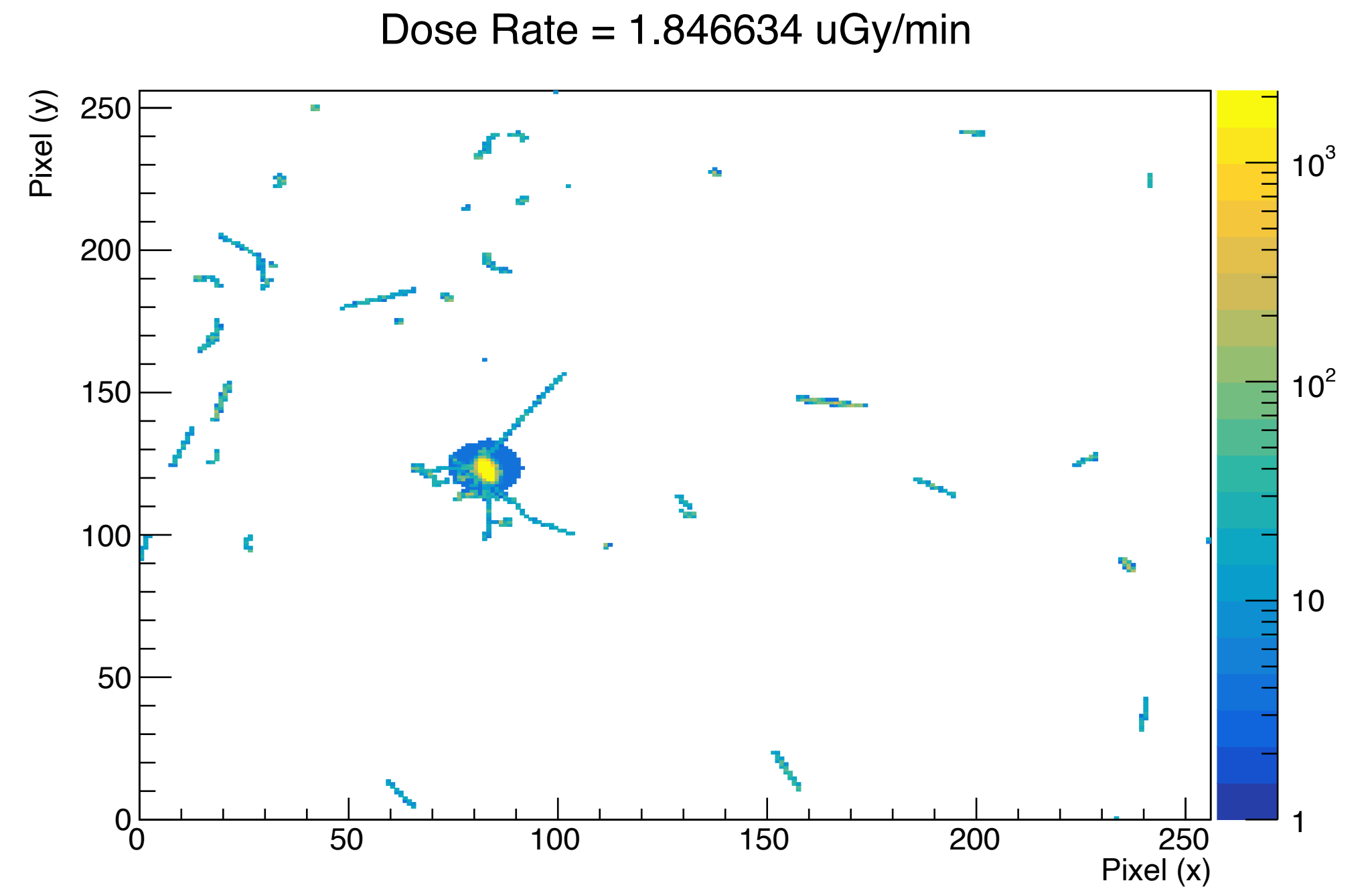
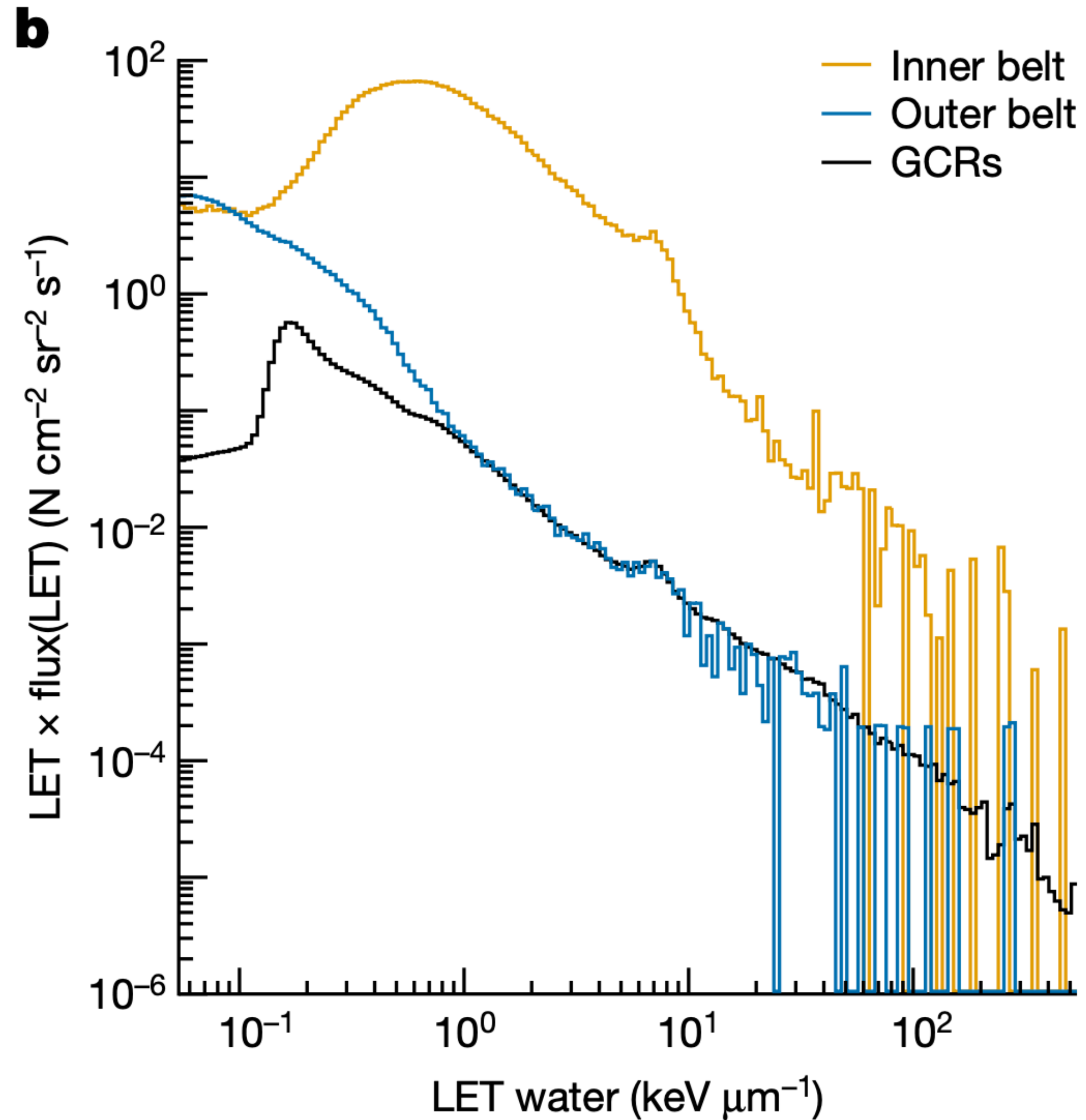
Artemis I - LET Measurements



Artemis I - LET Measurements



Artemis I - LET Measurements



Flight phase	Instrument								
	HPU			HSU1			HSU2		
	D (mGy)	<Q>	H (mSv)	D (mGy)	<Q>	H (mSv)	D (mGy)	<Q>	H (mSv)
Inner belt	1.45 ± 0.16	1.24 ± 0.03	1.80 ± 0.20	1.49 ± 0.17	1.26 ± 0.03	1.88 ± 0.21	3.13 ± 0.35	1.26 ± 0.03	3.94 ± 0.45
Outer belt	0.08 ± 0.01	1.46 ± 0.13	0.12 ± 0.02	0.08 ± 0.01	1.60 ± 0.15	0.13 ± 0.02	0.13 ± 0.01	1.40 ± 0.10	0.18 ± 0.02
GCR	10.75 ± 1.19	2.30 ± 0.05	24.7 ± 2.8	10.32 ± 1.15	2.63 ± 0.05	27.1 ± 3.06	10.21 ± 1.13	3.06 ± 0.06	31.2 ± 3.52
Whole mission	12.28 ± 1.28	-	26.7 ± 2.8	11.90 ± 1.32	-	29.2 ± 3.1	13.47 ± 1.5	-	35.4 ± 3.6

The flight phases relate to the crossing of the inner and outer radiation belts, as well as the GCR environment in free space and the whole mission. Provided is the relevant cumulative absorbed dose (D), the mean quality factors $\langle Q \rangle$ and the cumulative dose equivalents (H) split by phase of flight. Relevant mounting locations are provided in Extended Data Fig. 4. Absolute errors quoted after \pm .

GCR dose rates 0.96 - 1.24 mSv/day (Nov 2022)

Effects of Vehicle Orientation on Directional Radiation

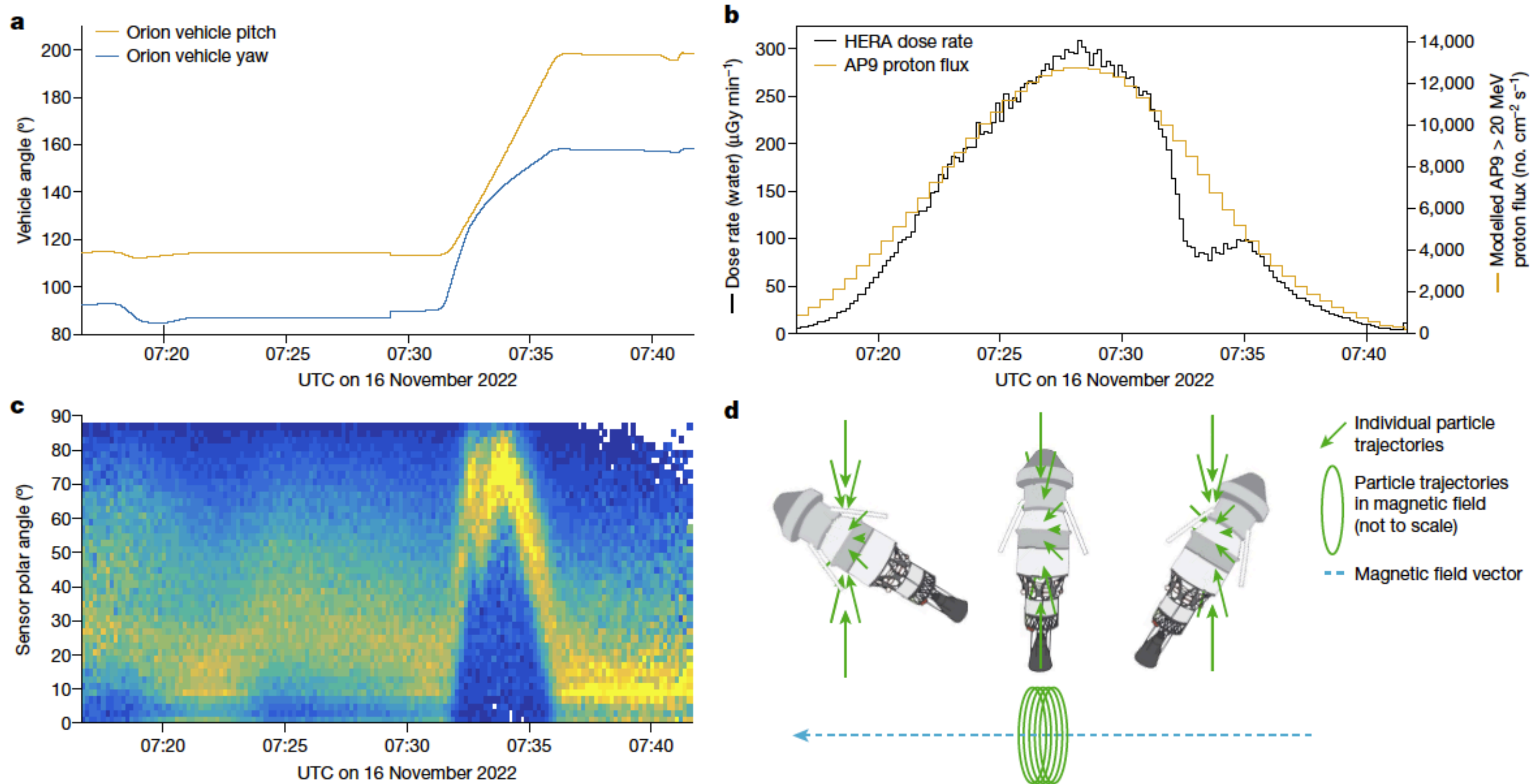


Fig. 3 | Unexpected dose decrease during the inner-belt pass. a, Orion spacecraft pitch (up and down with respect to the nose/docking adapter of the Orion capsule) and yaw (left and right) angle. **b**, Measured absorbed dose rate from HERA HSU2 and modelled AP9-IRENE proton flux. **c**, Measured particle polar angle distribution from HERA HSU2. Ninety degrees corresponds to

the long axis of the spacecraft. **d**, The Orion spacecraft with upper stage attached shown in relation to the magnetic-field vector and the particle trajectories. Individual particles rotate in tight spirals around the magnetic-field line, forming a 'plane' of radiation. The observed dose-rate drop is interpreted as the vehicle rotating its heavily shielded axis through this plane.

What Do These Dose Rates Tell us About Mars Missions

- NASA has a 600 mSv crew exposure limit - 3% risk of exposure induced death for 35y/female at the limit
- We are very unlikely to hit this on an Artemis mission because of mission length (short) and storm shelters for big solar particle events.
- Project Artemis I dose out to to different scenarios from NASA Mars DRM + Curiosity RAD surface rates

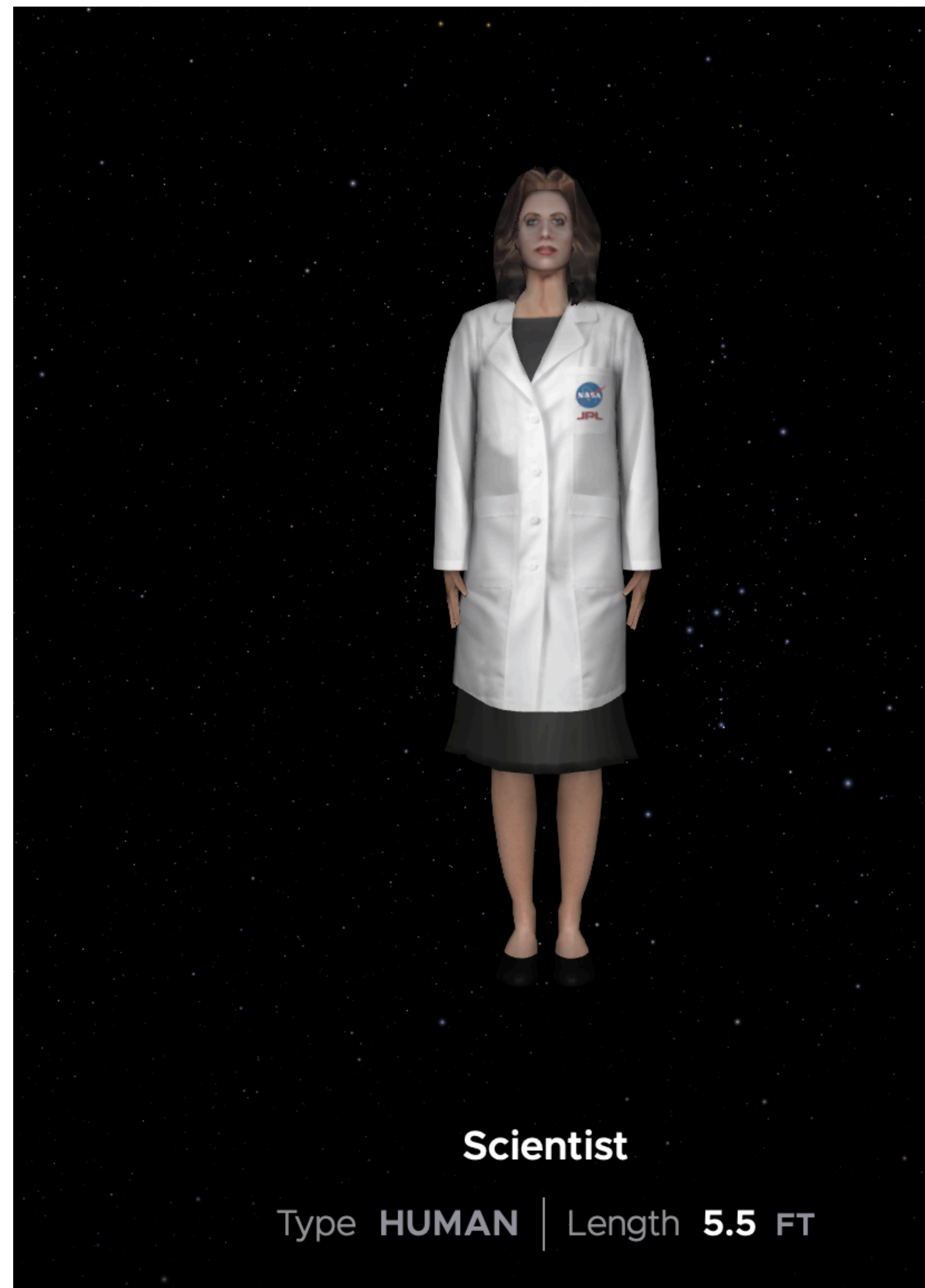
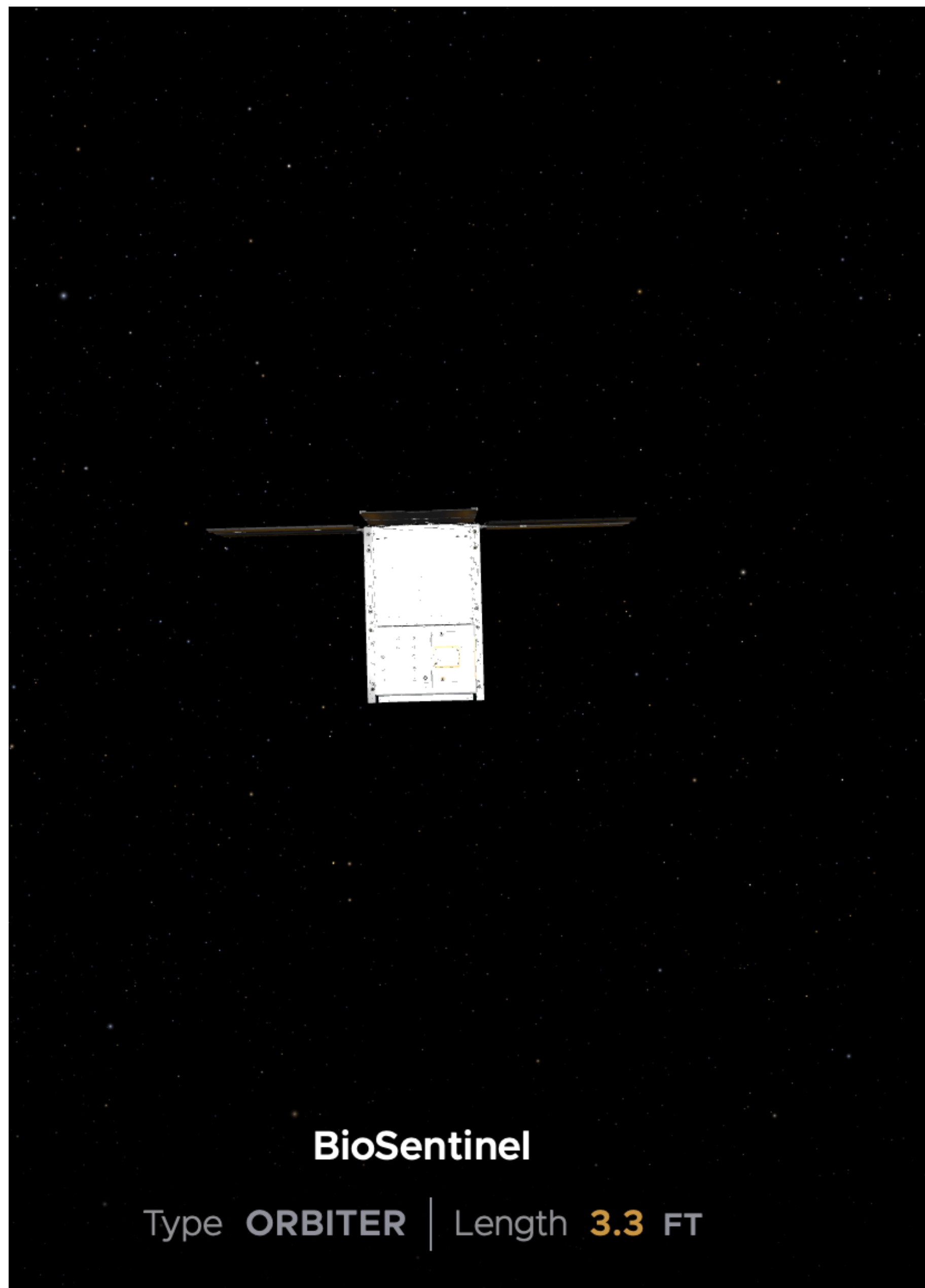
Scenario	HERA HPU	HERA HSU1	HERA HSU2	Mission Duration
1. Long stay, moderate transit	0.66 Sv	0.69 Sv	0.77 Sv	860 days
2. Short stay, long transit	0.53 Sv	0.58 Sv	0.68 Sv	560 days
3. Long stay, short transit	0.64 Sv	0.66 Sv	0.69 Sv	900 days

1. Long surface stay (500 days), moderate transit (360 days)
2. Short surface stay (30 days), (fuel efficient) long transit via Venus slingshot (530 days)
3. Long surface stay (700 days), short transit with nuclear propulsion (200 days)

Lots of caveats - solar cycle, no big solar events, assumes spacecraft is like Orion

Biosentinel Introduction

- Biosentinel is a NASA Ames designed cubesat launched on Artemis I (one of 12) and was lofted into Heliocentric orbit on Artemis I mission (NASA/ESA)
- Now ~55M km away
- Originally intended as a six month radiation biology experiment. Radiation hardware is a LETS board supplied by JSC Radworks
- Mission extended thrice, once by NASA Moon to Mars program and twice by NASA Heliophysics, end date now Sept 2025 (we hope for more extensions)
- Biosentinel is the only energetic particle measurement asset (or space weather asset) in its position in the heliosphere
- Measures dose, LET, now protons
- Biosentinel gathers minute wise dose and stopping power data, downlinked once weekly over DSN
- **Orion is a heavily shielded spacecraft. Biosentinel is lightly shielded, perhaps like a space suit or inflatable**



Biosentinel lightly shielded - crew BFO dose or skin dose in poorly shielded vehicle

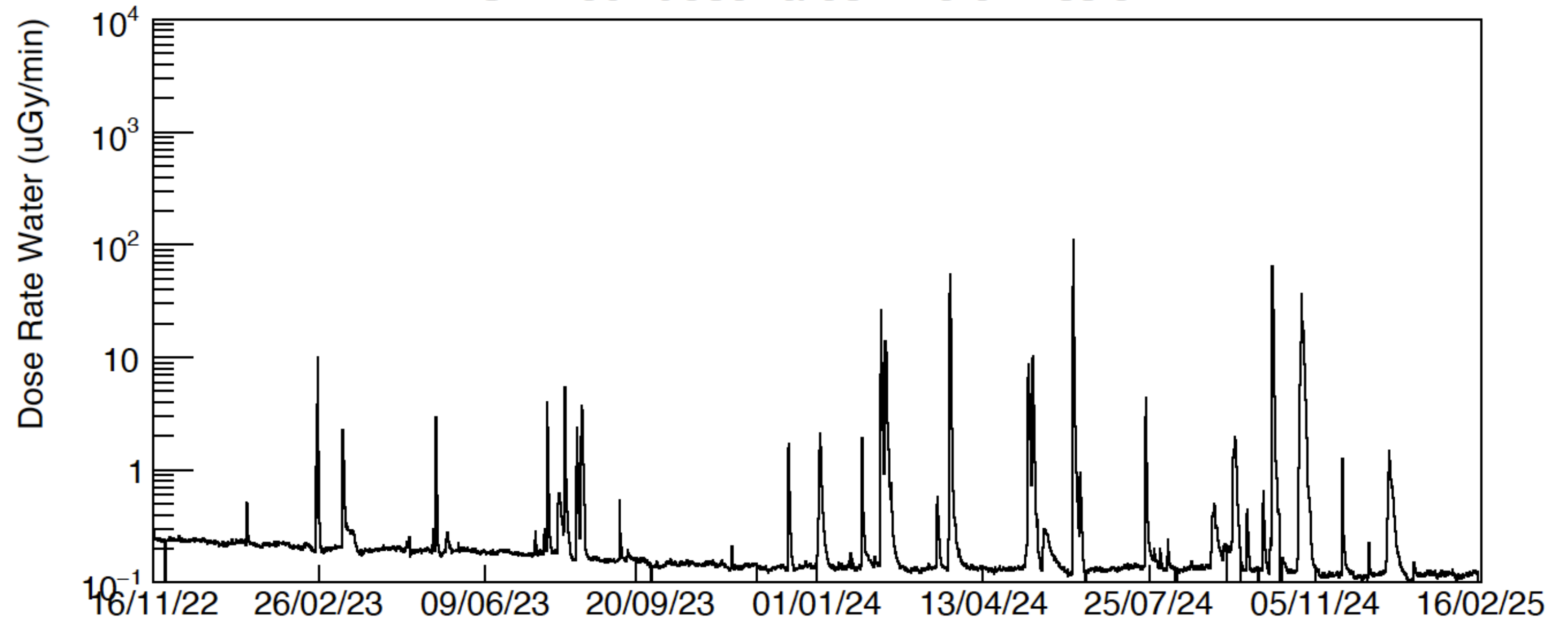


Biosentinel now ~55 Mkm, ~1/3 AU, 183 light seconds away, continuous measurement since November 2022

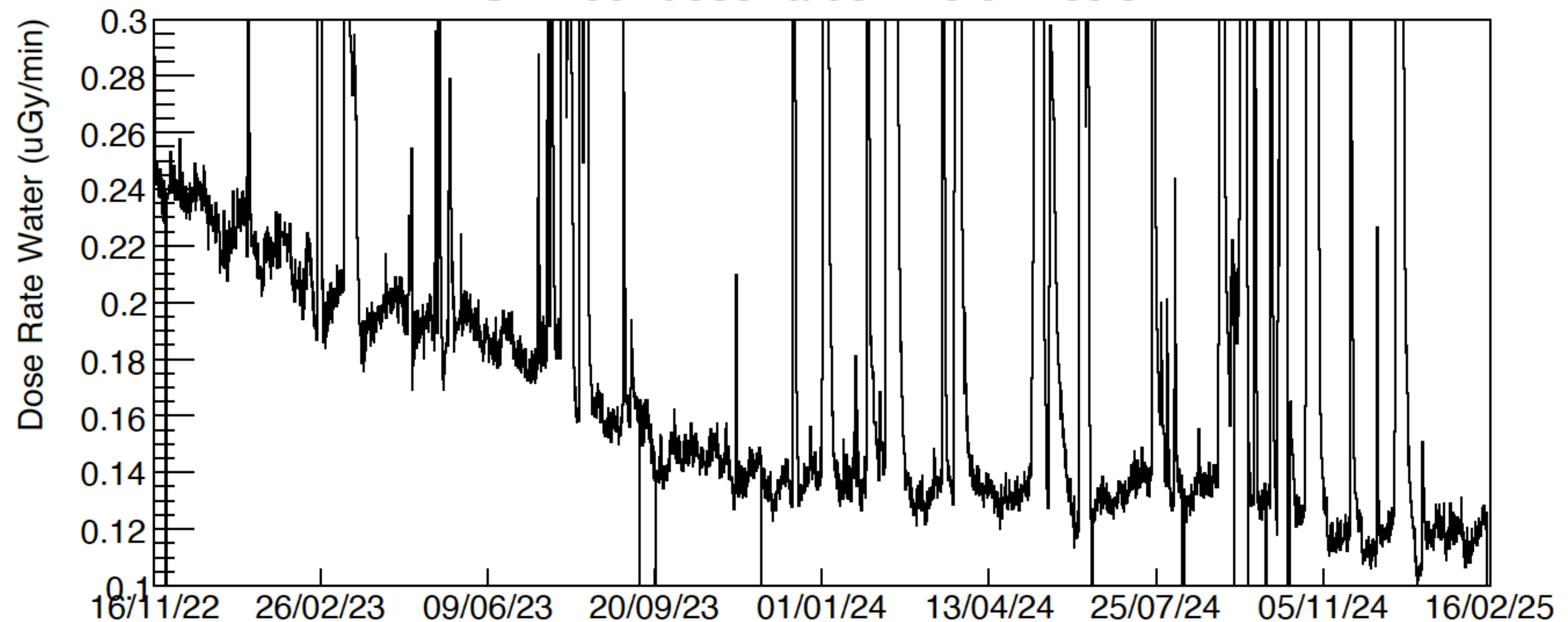
Dose Measurements Heading into Solar Maximum

- Dose rate approximately 60% of what it was in November 2022
- ~30 solar particle events, all 'small' or 'medium small'
- Two days dose rate > 50 mGy/day
- To my knowledge, first long term measurement of this kind in free space (closest is CRaTER in low lunar orbit and MSL-RAD cruise)

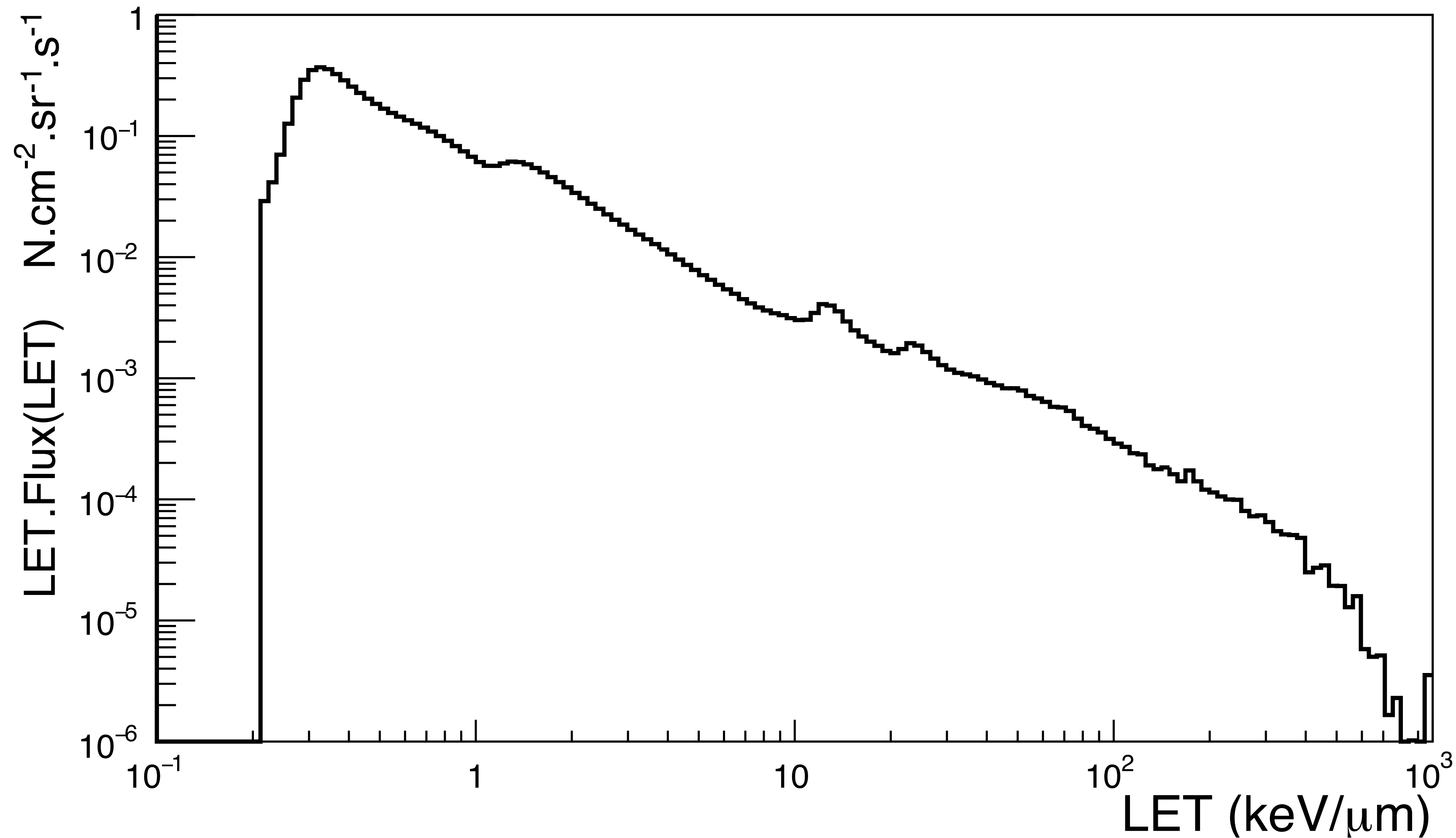
Six hour dose rates whole mission



Six hour dose rates whole mission



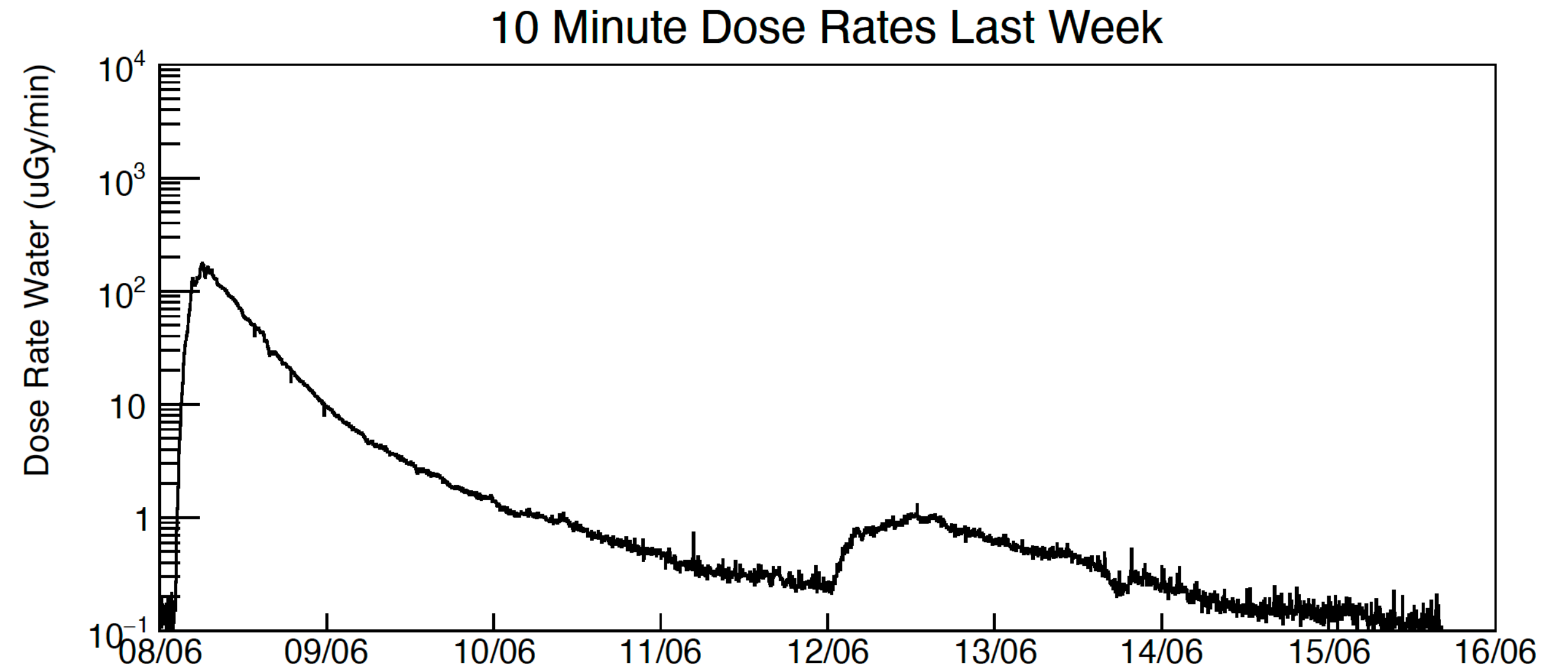
GCR LET Spectra Measurements



GCR LET Spectra $\langle Q \rangle = 4.1$ Biosentinel provides key data for benchmarking free space GCR flux models and transport models through shielding

Example Solar Storms - ISS vs Biosentinel

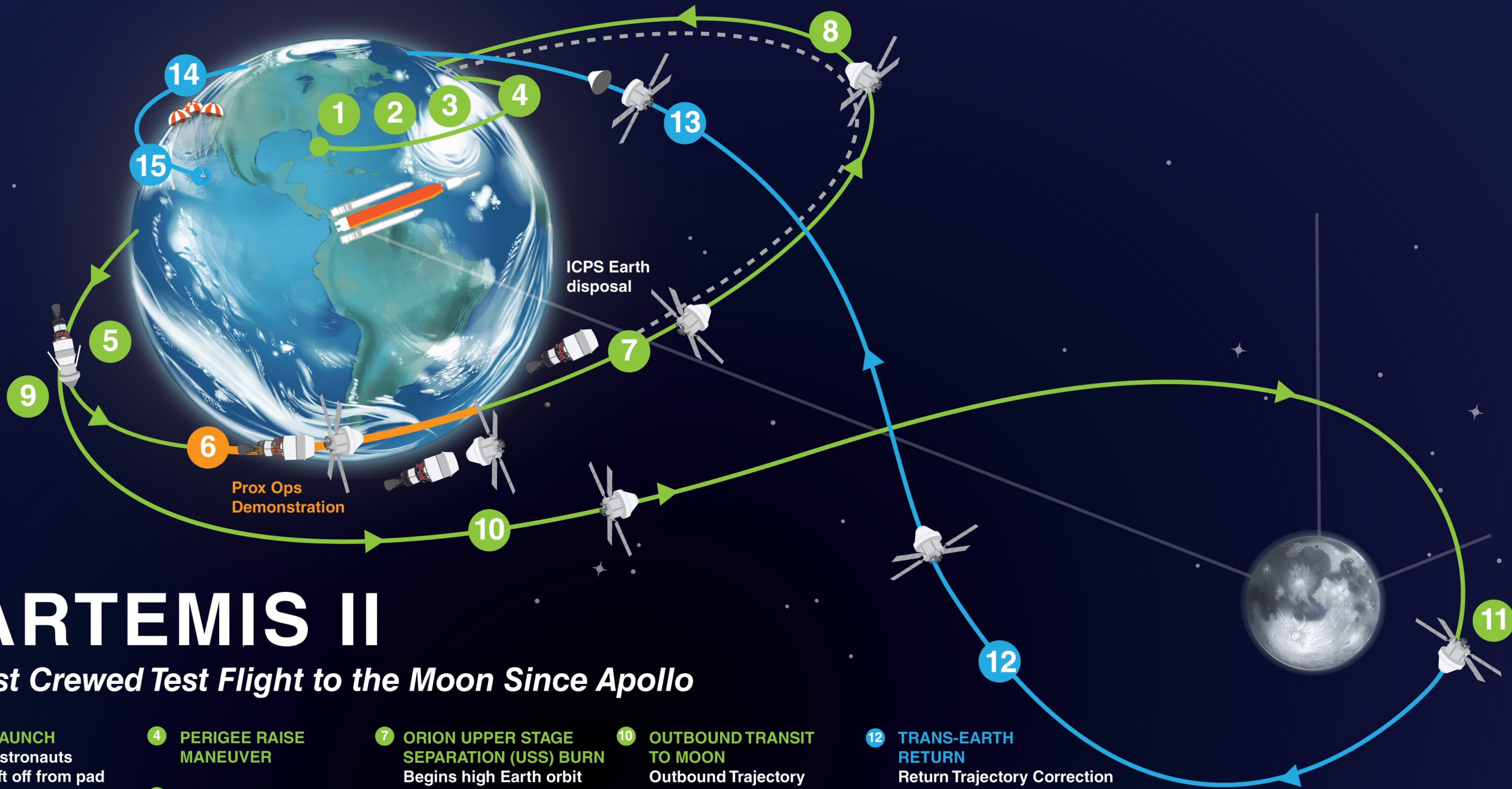
- S2 (hard spectrum) and S3 (soft spectrum) solar storms in May and June of 2024
- Can compare to ISS doses (heavily shielded, like storm shelter)
- ISS dose can be ‘scaled’ to free space if well exposed to SPE
- Shielding environments profoundly affect dose from SPE



Event	ISS	ISS scaled to free space	Biosentinel
May 2024	22.3 uGy	330 uGy	40 mGy
June 2024	Negligible	~	68 mGy

Artemis II





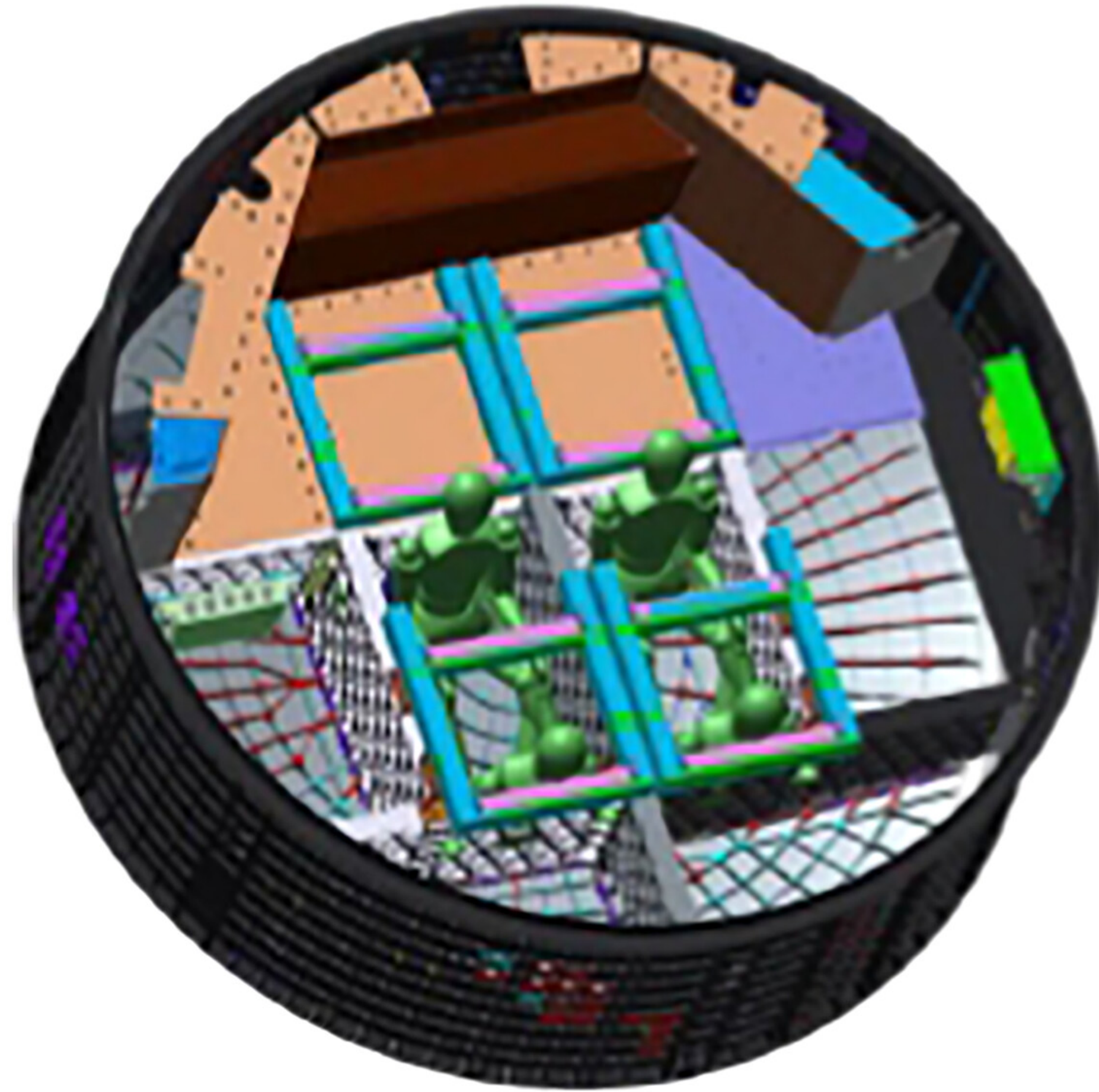
ARTEMIS II

First Crewed Test Flight to the Moon Since Apollo

- 1 LAUNCH**
Astronauts lift off from pad 39B at Kennedy Space Center.
- 2 JETTISON SOLID ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM**
- 3 CORE STAGE MAIN ENGINE CUT OFF**
With separation.
- 4 PERIGEE RAISE MANEUVER**
- 5 APOGEE RAISE BURN TO HIGH EARTH ORBIT**
Begin 23.5 hour checkout of spacecraft.
- 6 ORION SEPARATION FROM INTERIM CRYOGENIC PROPULSION STAGE (ICPS) FOLLOWED BY PROX OPS DEMO**
Plus manual handling qualities assessment for up to 2 hours.
- 7 ORION UPPER STAGE SEPARATION (USS) BURN**
Begins high Earth orbit checkout. Life support, exercise, and habitation equipment evaluations.
- 8 PERIGEE RAISE BURN**
- 9 TRANS-LUNAR INJECTION (TLI) BY ORION'S MAIN ENGINE**
Lunar free return trajectory initiated with European service module.
- 10 OUTBOUND TRANSIT TO MOON**
Outbound Trajectory Correction (OTC) burns as necessary for Lunar free return trajectory; travel time approximately 4 days.
- 11 LUNAR FLYBY**
6,479 miles / 10,427 km (mean) lunar farside altitude.
- 12 TRANS-EARTH RETURN**
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time approximately 4 days.
- 13 CREW MODULE SEPARATION FROM SERVICE MODULE**
- 14 ENTRY INTERFACE (EI)**
Enter Earth's atmosphere.
- 15 SPLASHDOWN**
Ship recovers astronauts and capsule.

PROXIMITY OPERATIONS DEMONSTRATION SEQUENCE	
1	9
2	10
3	11
4	12
5	13
6	14
7	15
8	16
	17

Artemis II - Original Radiation Shelter Concept



- As designed radiation shelter has crew cramming into storage lockers at the bottom of the Orion and barricading themselves in with the contents



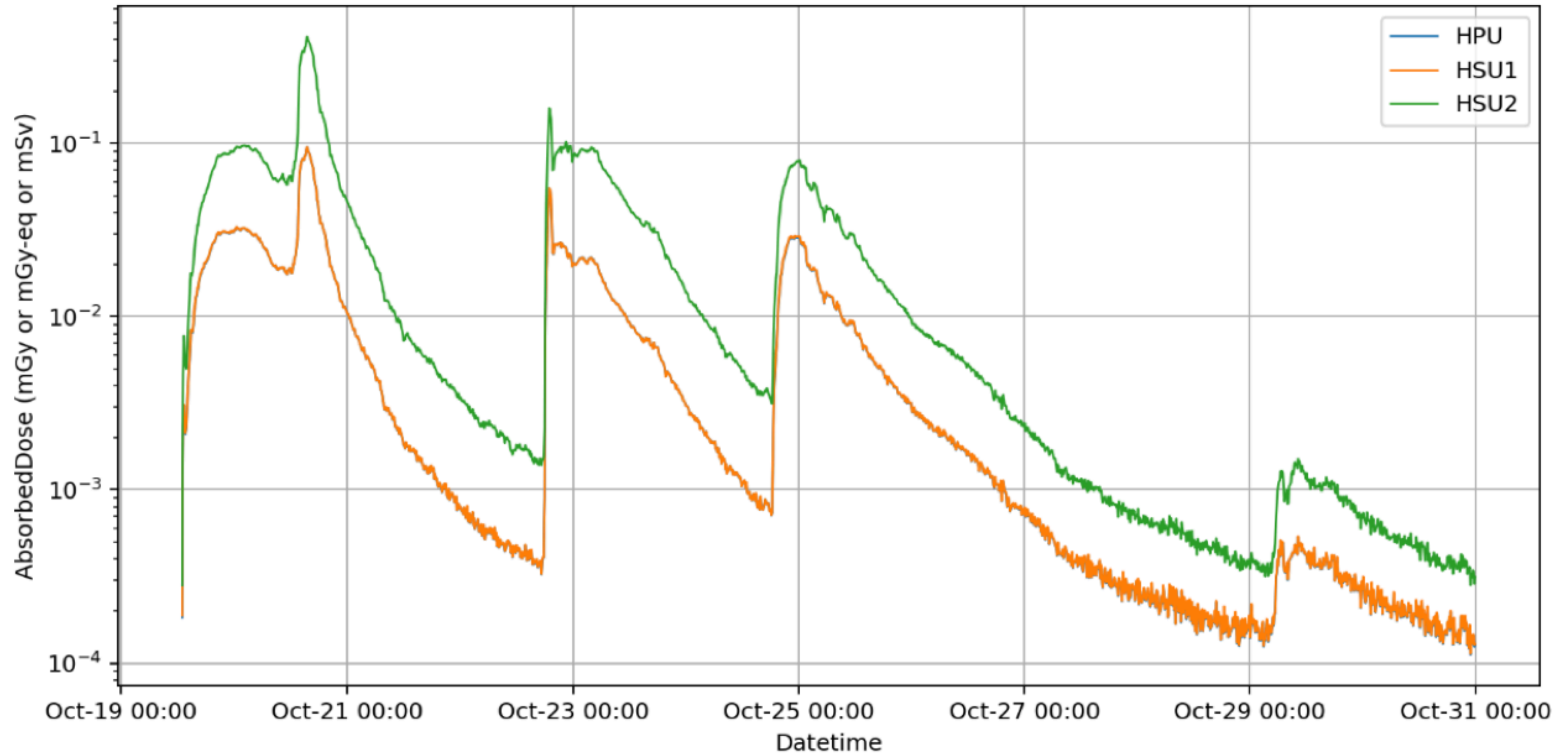
<https://www.youtube.com/watch?v=70GrihLXmSs>

Effectiveness of Shelter - Validated by Artemis I Measurements

Artemis I Belt Pass	HPU ($\mu\text{Gy}/\text{min}$)	HSU1 ($\mu\text{Gy}/\text{min}$)	HSU2 ($\mu\text{Gy}/\text{min}$)
Measured inner belt pass	144.4	133.54	287.5
Simulated inner belt pass	101.4	104.2	228.9
% of max (HSU2) measured	50.2%	46.4%	100%
% of max (HSU2) simulated	45.5%	44.3%	100%
Large Reference SPE	HPU	HSU1	HSU2
Simulated Oct 89 SPE	95.4	95.3	414.6
% of max HSU2 Oct 89 SPE simulated	23.0%	23.0%	100%

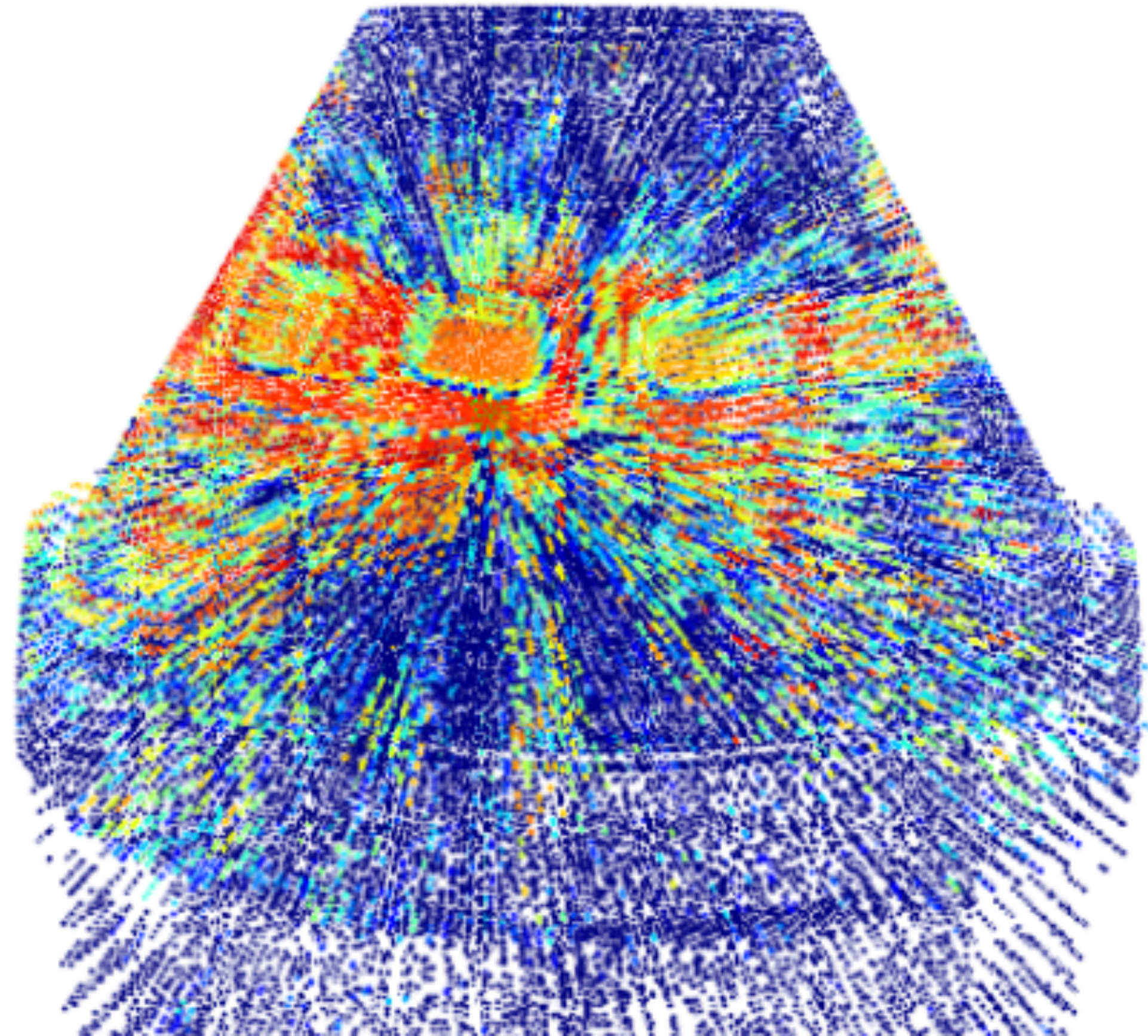
Artemis II Revised Shelter Concept

1989-10-19 13:00



Simulation of the October 1989 event series - this goes on for over a week! Is the proposed shelter really viable for extreme space weather?

Artemis II Revised Shelter Concept

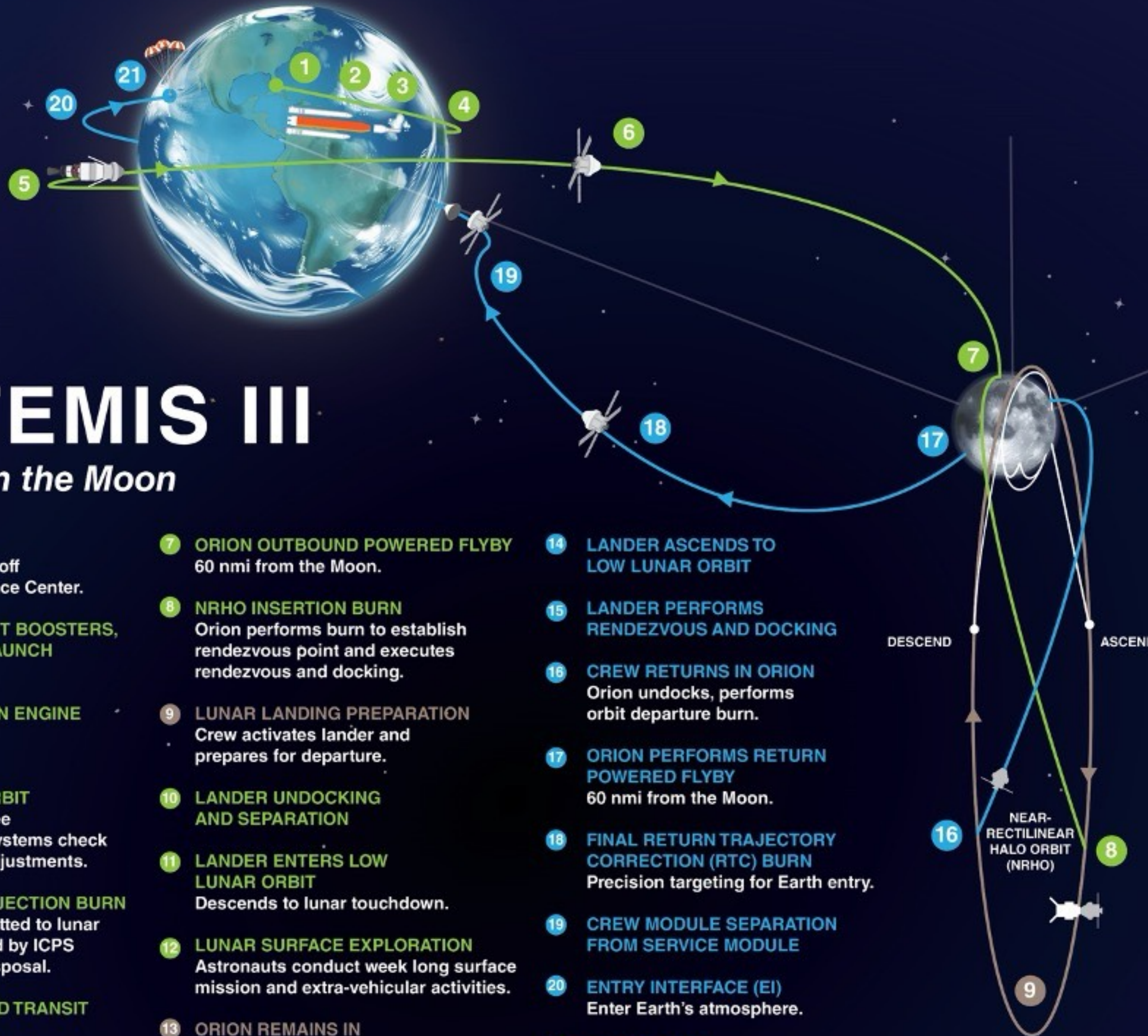


- Ray tracing shows one region of Orion spacecraft wall quite thinly shielded
- Barricade consumable mass and similar against cabin wall
- Shelter is much more practical, ~20-40% dose reduction
- Revised shelter a DTO for Artemis II

Ray trace of Orion spacecraft - (Red = less shielding, Blue = More)

1989 Tylka SPE	Nominal	Shelter Configuration Average	Shelter Configuration Restricted
BFO Dose (mGy-eq)	191	150	115
Dose Savings over Nominal	-	41	76
% Savings over Nominal	-	22%	40%

1972 King SPE	Nominal	Shelter Configuration Average	Shelter Configuration Restricted
BFO Dose (mGy-eq)	181	114	66
Dose Savings over Nominal	-	67	114
% Savings over Nominal	-	37%	63%



ARTEMIS III

Landing on the Moon

- 1 LAUNCH**
SLS and Orion lift off from Kennedy Space Center.
- 2 JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM**
- 3 CORE STAGE MAIN ENGINE CUT OFF**
With separation.
- 4 ENTER EARTH ORBIT**
Perform the perigee raise maneuver. Systems check and solar panel adjustments.
- 5 TRANS LUNAR INJECTION BURN**
Astronauts committed to lunar trajectory, followed by ICPS separation and disposal.
- 6 ORION OUTBOUND TRANSIT TO MOON**
Requires several outbound trajectory burns.
- 7 ORION OUTBOUND POWERED FLYBY**
60 nmi from the Moon.
- 8 NRHO INSERTION BURN**
Orion performs burn to establish rendezvous point and executes rendezvous and docking.
- 9 LUNAR LANDING PREPARATION**
Crew activates lander and prepares for departure.
- 10 LANDER UNDOCKING AND SEPARATION**
- 11 LANDER ENTERS LOW LUNAR ORBIT**
Descends to lunar touchdown.
- 12 LUNAR SURFACE EXPLORATION**
Astronauts conduct week long surface mission and extra-vehicular activities.
- 13 ORION REMAINS IN NRHO ORBIT**
During lunar surface mission.
- 14 LANDER ASCENDS TO LOW LUNAR ORBIT**
- 15 LANDER PERFORMS RENDEZVOUS AND DOCKING**
- 16 CREW RETURNS IN ORION**
Orion undocks, performs orbit departure burn.
- 17 ORION PERFORMS RETURN POWERED FLYBY**
60 nmi from the Moon.
- 18 FINAL RETURN TRAJECTORY CORRECTION (RTC) BURN**
Precision targeting for Earth entry.
- 19 CREW MODULE SEPARATION FROM SERVICE MODULE**
- 20 ENTRY INTERFACE (EI)**
Enter Earth's atmosphere.
- 21 SPLASHDOWN**
Ship recovers astronauts and capsule

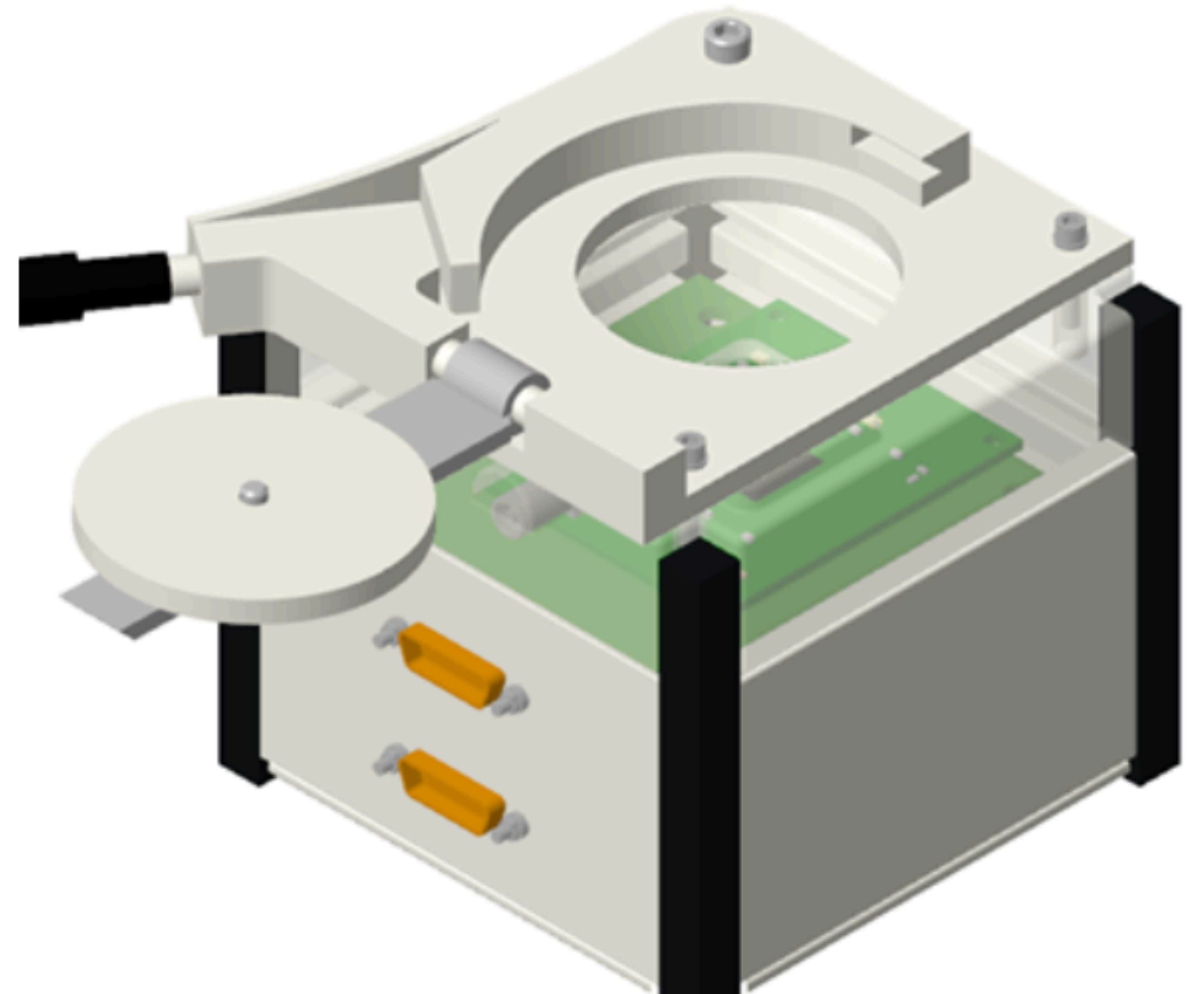
Artemis III Surface Conops

- Spacesuits equipped with portable dosimeter - nominally “ARD” based design w. Teledyne μDOS007 sensor.
- Lunar lander equipped with Timepix based “ARES” detector and storm shelter area
- Provides minute wise dose rate measurement suitable for SPE warning.
- Solar Particles during EVA biggest radiation concern
- Return to shelter after dose rate above threshold + ability to go out during the descending phase of a large SPE
- Target control dose for EVA far below short term threshold - nominally 10 mGy.
- Potential to be exceeded for fast rise, large events especially with extended return to vehicle.



The Future

- Want to predict dose rises from space weather events before they arrive
- Nowcasting, SEP Scoreboard and SEP Validation effort
- <https://ccmc.gsfc.nasa.gov/scoreboards/sep/>
- Instruments to support nowcasting - Compact Electron Proton Spectrometer
- Ultimately - Earth independent capability for Mars missions

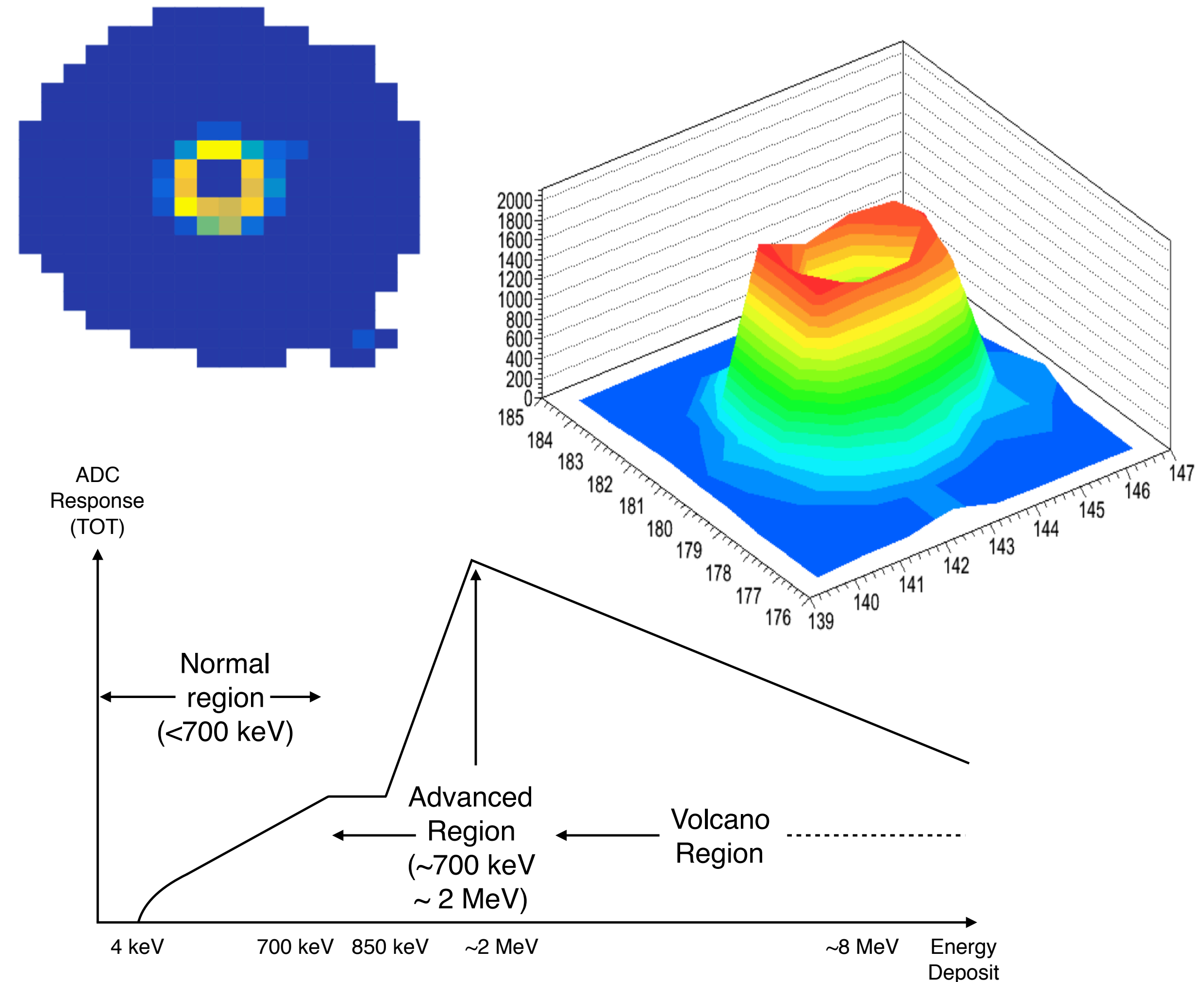


Thank you for your time and attention - October 2024 Geomagnetic Storm at Brookhaven National Lab, NY



Timepix Energy Calibration and “The Volcano Effect”

- The energy calibration of Timepix detectors was not so straight forward at first
- Initial tests with heavy ions revealed dramatic, hollowed out cluster shapes dubbed Volcanos (or sarcophagi by some)
- For measurement of energies deposited by particles up to Iron, we needed to manage from 5 keV per pixel, to 10 MeV per pixel, 3 orders of magnitude.
- A side effect of the instruments heritage as an x-ray instrument. No-one in the Medipix collaboration considered measuring such large input charges
- Front end worked fine up to 700 keV
- After 700 keV the response continues monotonically up and can be calibrated with low energy protons
- After 2 MeV, the response goes down, but we were lucky - monotonically again, can be corrected pixel wise or “on the whole cluster”
- The radiation dose, is the sum of the deposited energy in the sensor divided by the sensor mass.



**Top - “volcanos” as measured with a heavy ions at an accelerator
(bottom) - Timepix calibration curve 4 keV - 8 MeV**

Track Length Calculation

- Tracks in Timepix detectors contain a number of distinct features including the track skirt and delta electrons (top)
- Skirt detector artefact from charge induction interaction with front end in distant pixels.
- To calculate track length, remove skirt and delta electrons to reveal core. Process core to get projected track length.

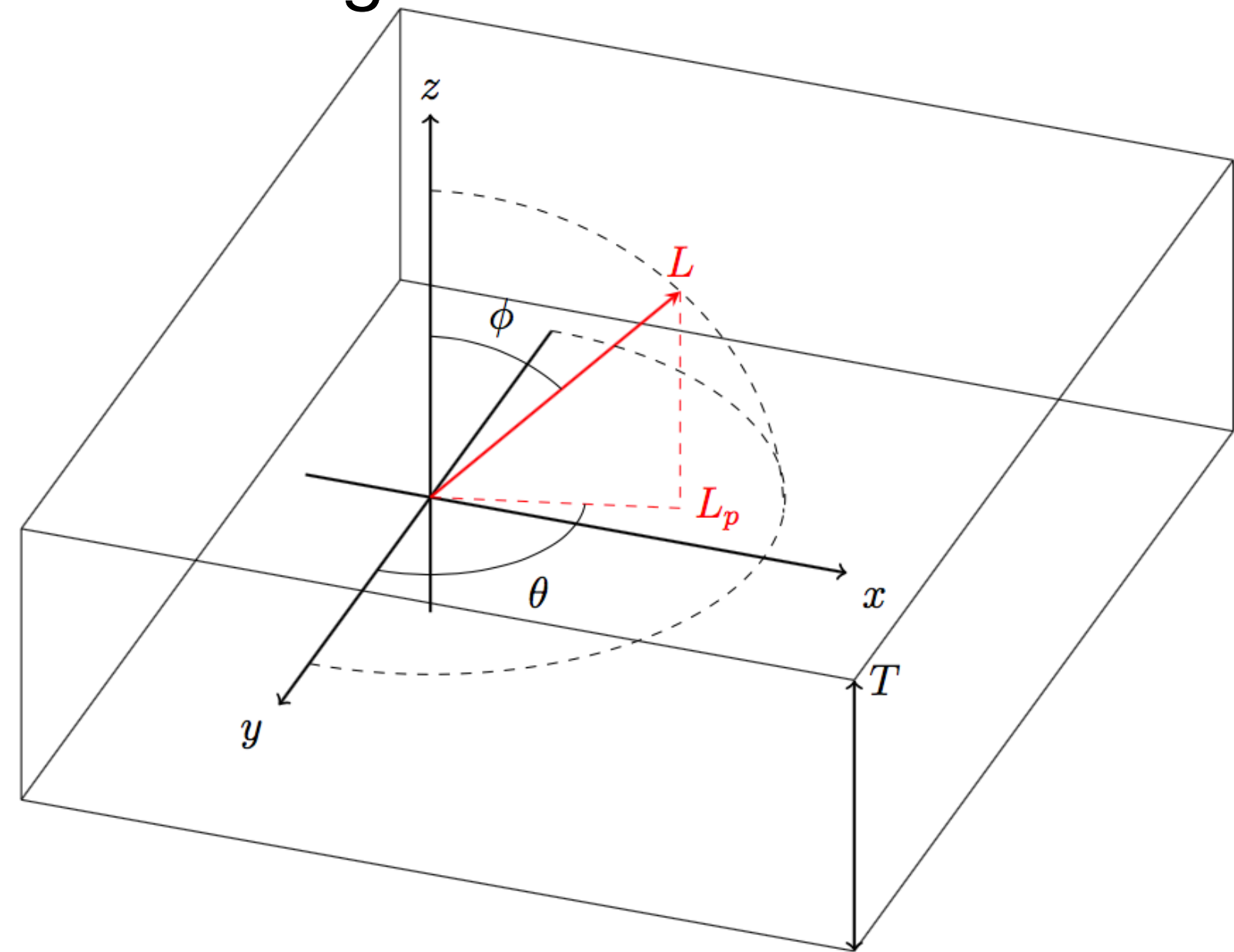
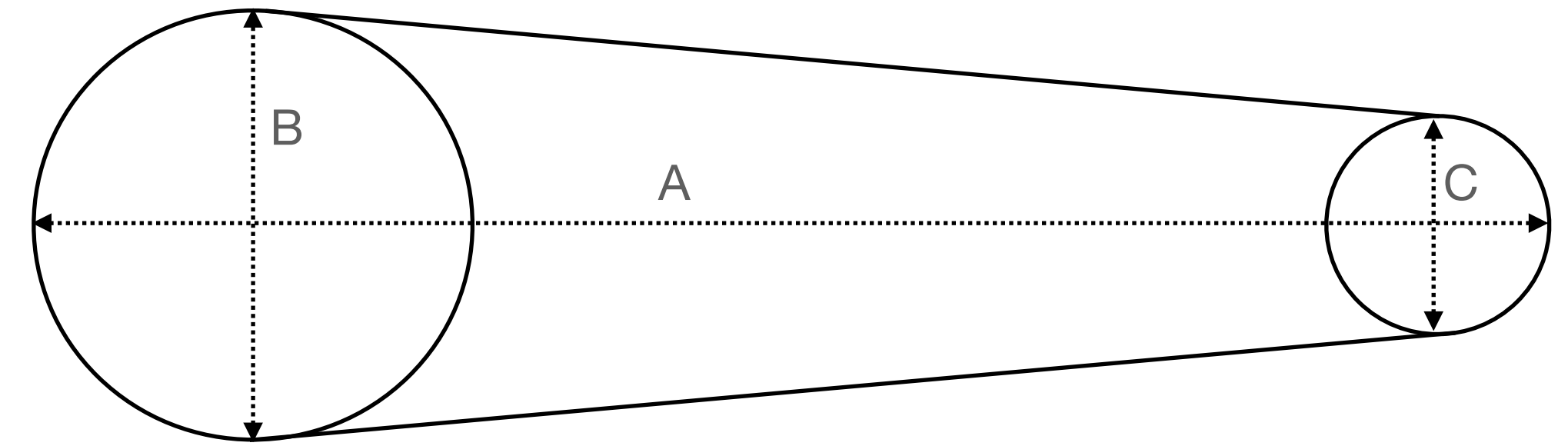
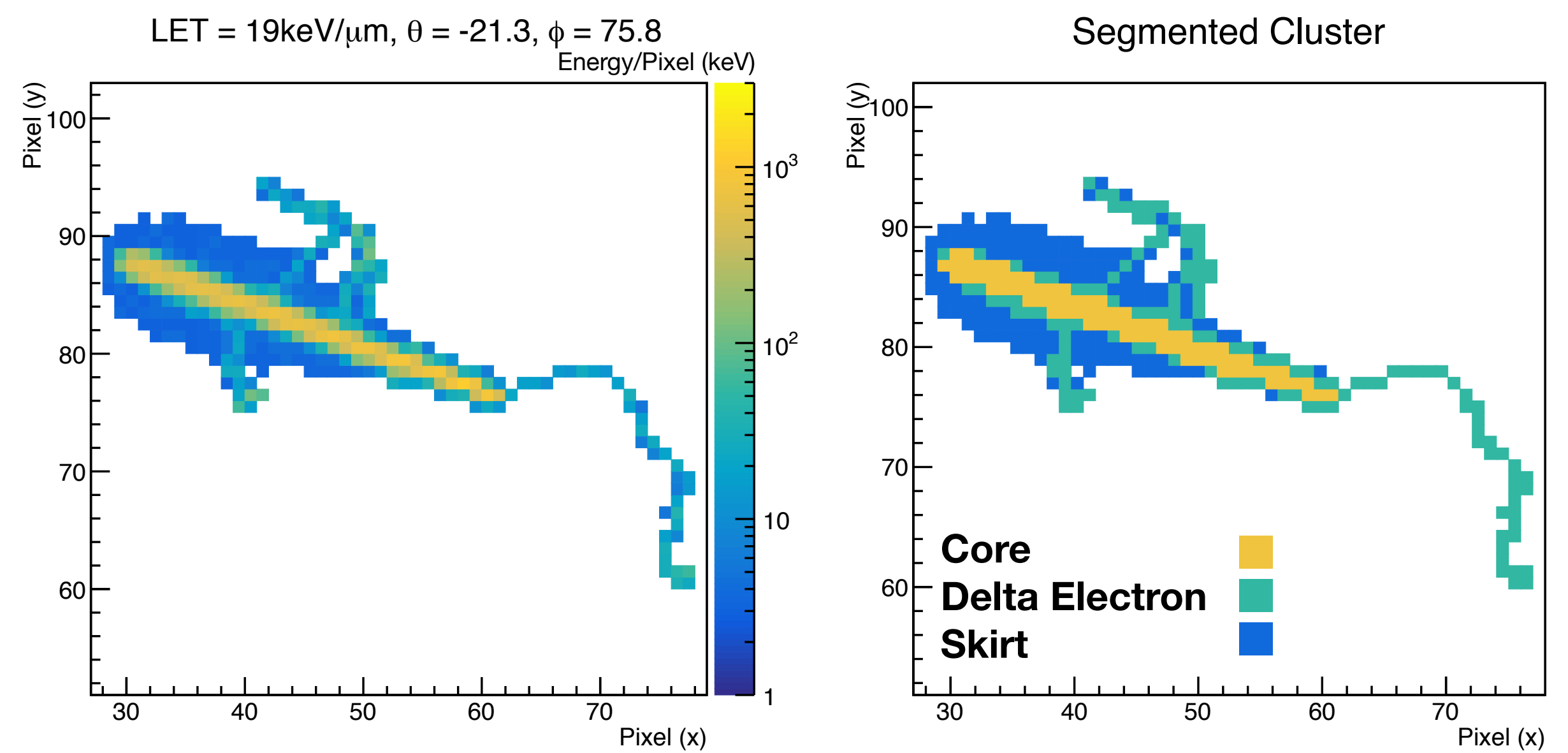


Figure 3.6: Measurement of the azimuth angle θ and altitude ϕ relative to the sensor axes from a penetrating track of length L over a sensor of thickness T .



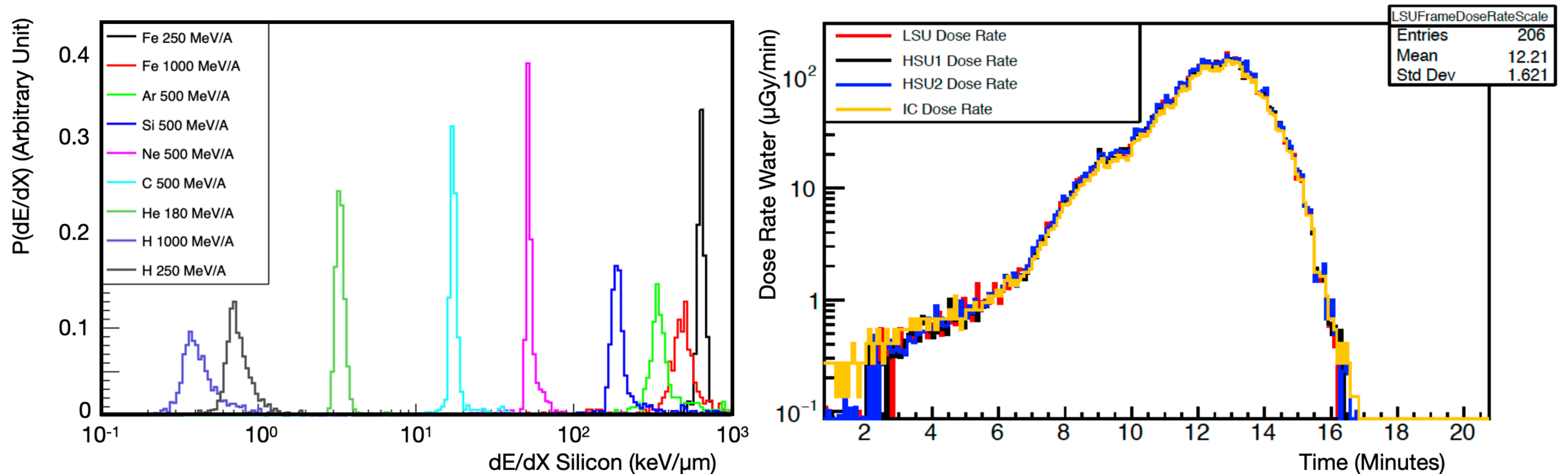
- Disentangle charge sharing effects - charge sharing in track causes characteristic 'comet' shape

$$L_p \sim A - B/2 - C/2$$

- Finally calculate track polar angles based on assumption that track penetrates sensor (left)

Calculation of dE/dX and Example Performance

- The track LET or dE/dX is important because it tells you about the biological effectiveness or “quality” of the radiation
- This can be calculated with the ICRP60 quality factor formalism



(Left) Example Timepix stopping power measurements at 75 degree polar angle carried out with a variety of ion beams at the NASA Space Radiation Laboratory in Brookhaven, New York,
(Right) simulated ‘belt pass’ carried out with three different Timepix sensors on HERA (LSU, HSU1 and HSU2) compared to external ion chamber. Measurement was carried out with a 200MeV proton beam at a cyclotron at Northwestern Proton Center in Naperville, IL.