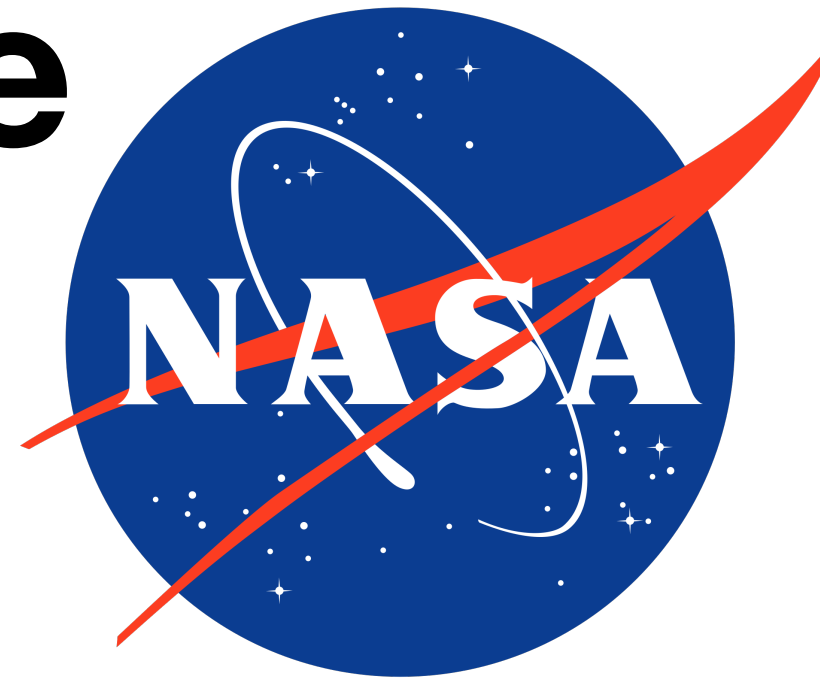




Radiation Measurements with the Timepix based HERA Instrument on Artemis I and Biosentinel



Dr. Stuart George, IWORID 2023, Oslo

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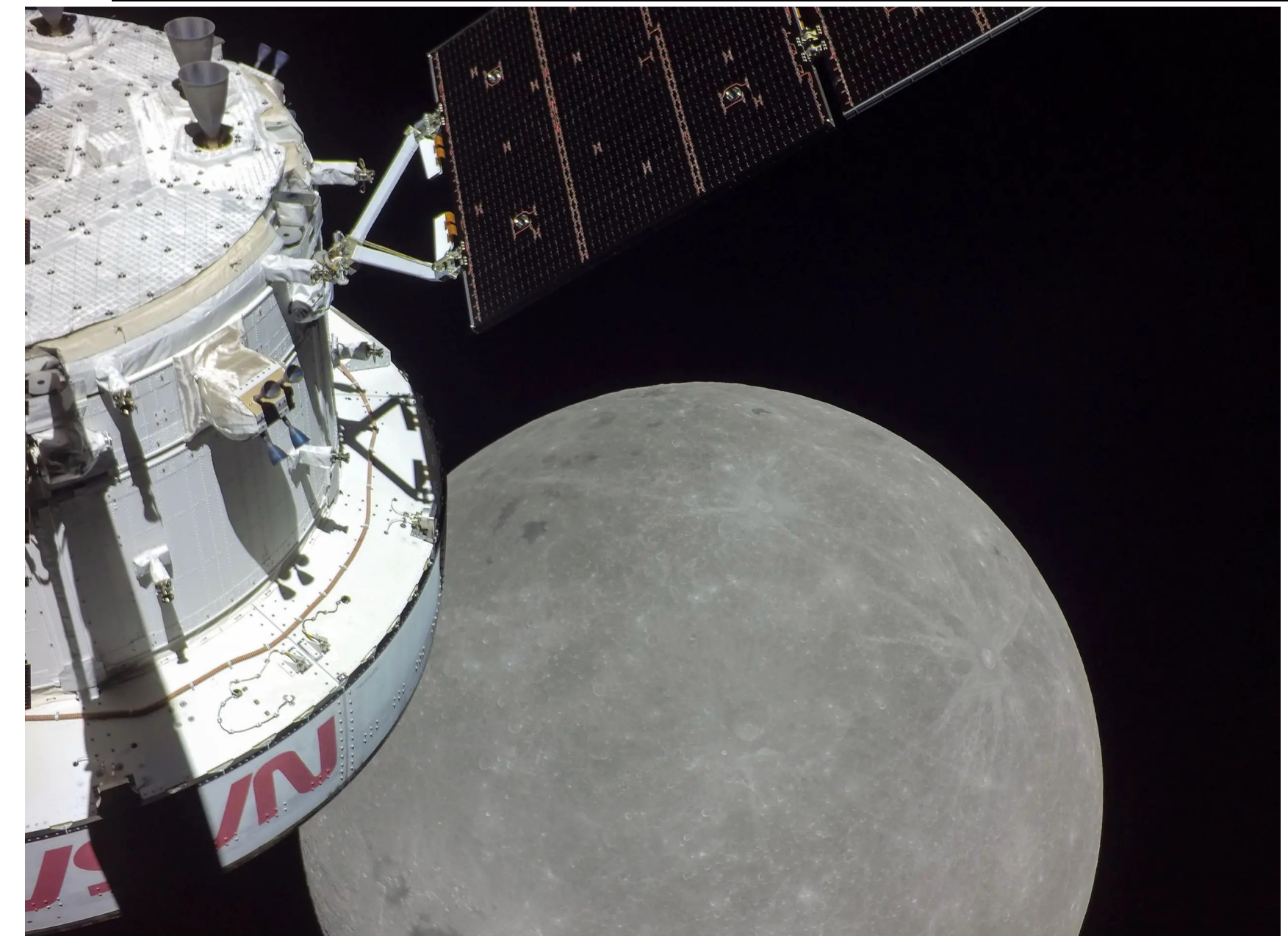


Funding and Acknowledgements

- **This work has been supported by NASA Advanced Exploration Systems and the Orion Program. Much of this work was carried out under the NASA Human Health and Performance Contract .**
- **The Timepix detector was developed by the Medipix collaboration at CERN**
- **IEAP Prague, the University of Houston and the Medipix collaboration were instrumental in our first flights of Timepix detectors on the International Space Station. Especially S Popisil, X. Llopart, R. Ballabringa, L Tlustos and M. Campbell.**
- **The Artemis I Orion vehicle and SLS rocket were developed by NASA, the Orion Service module was developed by the European Space Agency**

Introduction

- Artemis 1 launched Wednesday Nov 16, the first mission of the Artemis Program - NASA's manned return to the moon
- Carried 4 Timepix hybrid pixel detectors from the Medipix2 collaboration at CERN on board to measure radiation
- Three in the HERA instrument returned to Earth with the Orion spacecraft, one is still in deep space measuring radiation
- Part of a larger program at NASA using Timepix based instruments for radiation measurement
- Why do we care about space radiation?
- How are we using Timepix to address these goals?
- What did we measure on Artemis I?
- What does the future look like?



Complete List of NASA Timepix Based Flight Hardware

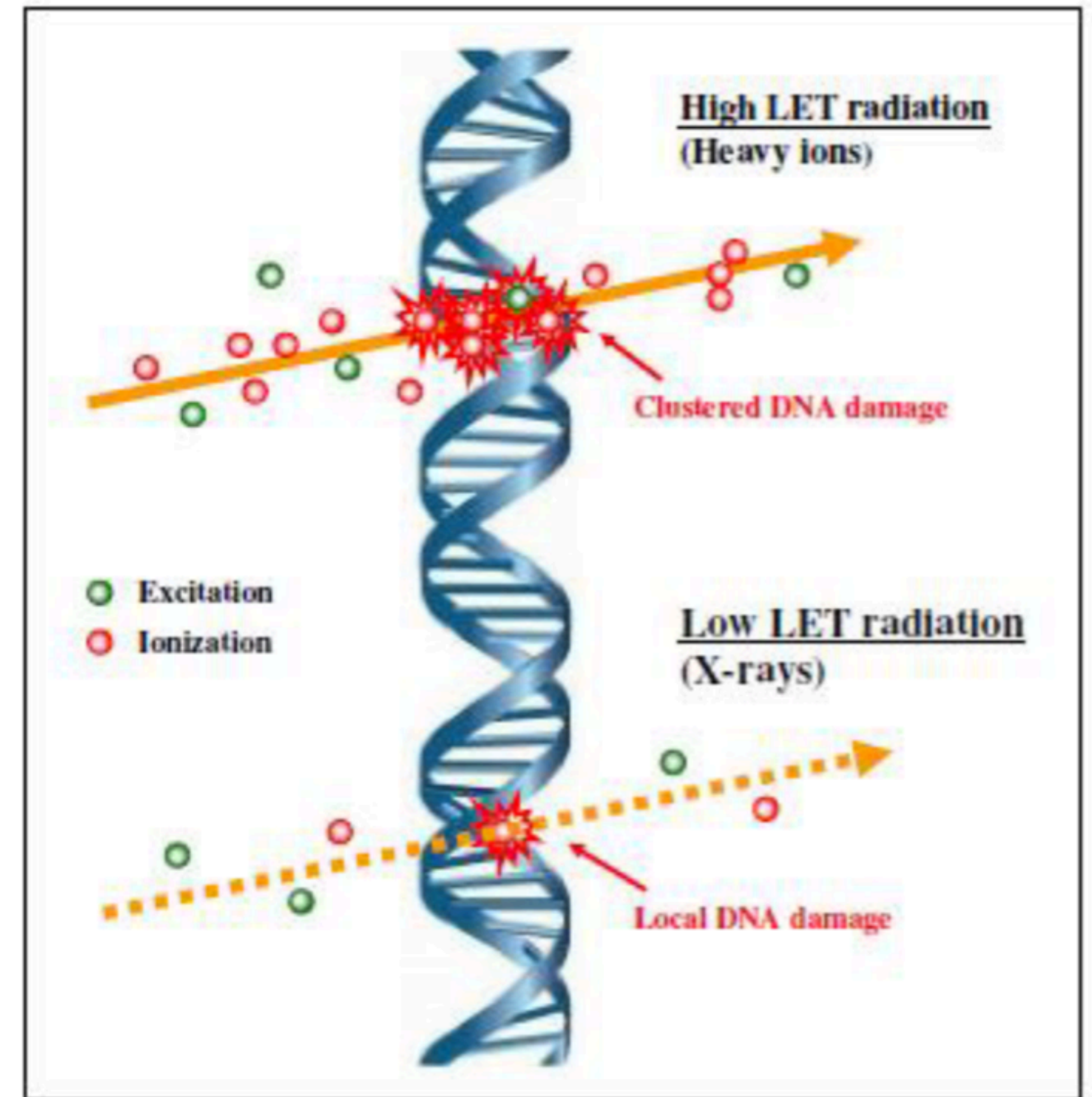
Name	Flight Date	Mission	Location	Objective	Vehicle	Number Timepix
REM*	2012	ISS	LEO	Demo	ISS	5
BIRD	2014	Orion ETF-1	LEO/MEO	Demo/Science	Orion	2
MPT	2017	ISS	LEO	Science	ISS	2
ISS-HERA	2018	ISS	LEO	Demo	ISS	3
REM2*	2018	ISS	LEO	Ops	ISS	7
Biosentinel	2020	ISS	LEO	Science	ISS	1
AHOSS*	2022	ISS	LEO	Demo/Ops	ISS	3
HERA EM-1	2022	Artemis I	Lunar Orbit	Ops	Orion	3
Biosentinel*	2022	Artemis I	Heliocentric Orbit	Science	Cubesat	1
HERA EM-1	2023	Polaris Dawn	LEO/MEO	Science	Crew Dragon	1
LETS 1**	2023	Astrobotic 1	Lunar Surface	Science	Peregrine	1
LETS 2	2024/5	Beresheet 2	Lunar Surface	Science	Berensheet 2	1
HERA EM-2**	2024	Artemis II	Lunar Orbit	Ops	Orion	6
LETS 3	2025	TBD	Lunar Surface	Science	TBS	1
HERA EM-2	2025	Artemis III	Lunar Orbit	Ops	Orion	6
ARES	2025	Artemis III	Lunar Surface	Ops	HLS	>1
LEIA	2025/6	CLPS Lander	Lunar Surface	Science	TBS Lander	>1
ARES	2026	Artemis IV	Lunar Surface	Ops	Gateway	>1

Table 1: Flown, flying, and manifested Timepix based radiation measurement hardware produced by NASA AES Radworks. *Presently flying/operating, **Installed in vehicle. LEO refers to Low Earth Orbit, MEO to Medium Earth Orbit.

9 missions flown, 2 missions next six months, 6 missions manifested, > 25 Timepix in Space to date
Highly successful technology transfer from CERN, powering NASA missions for the last 10 years, and likely for the next 10

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.

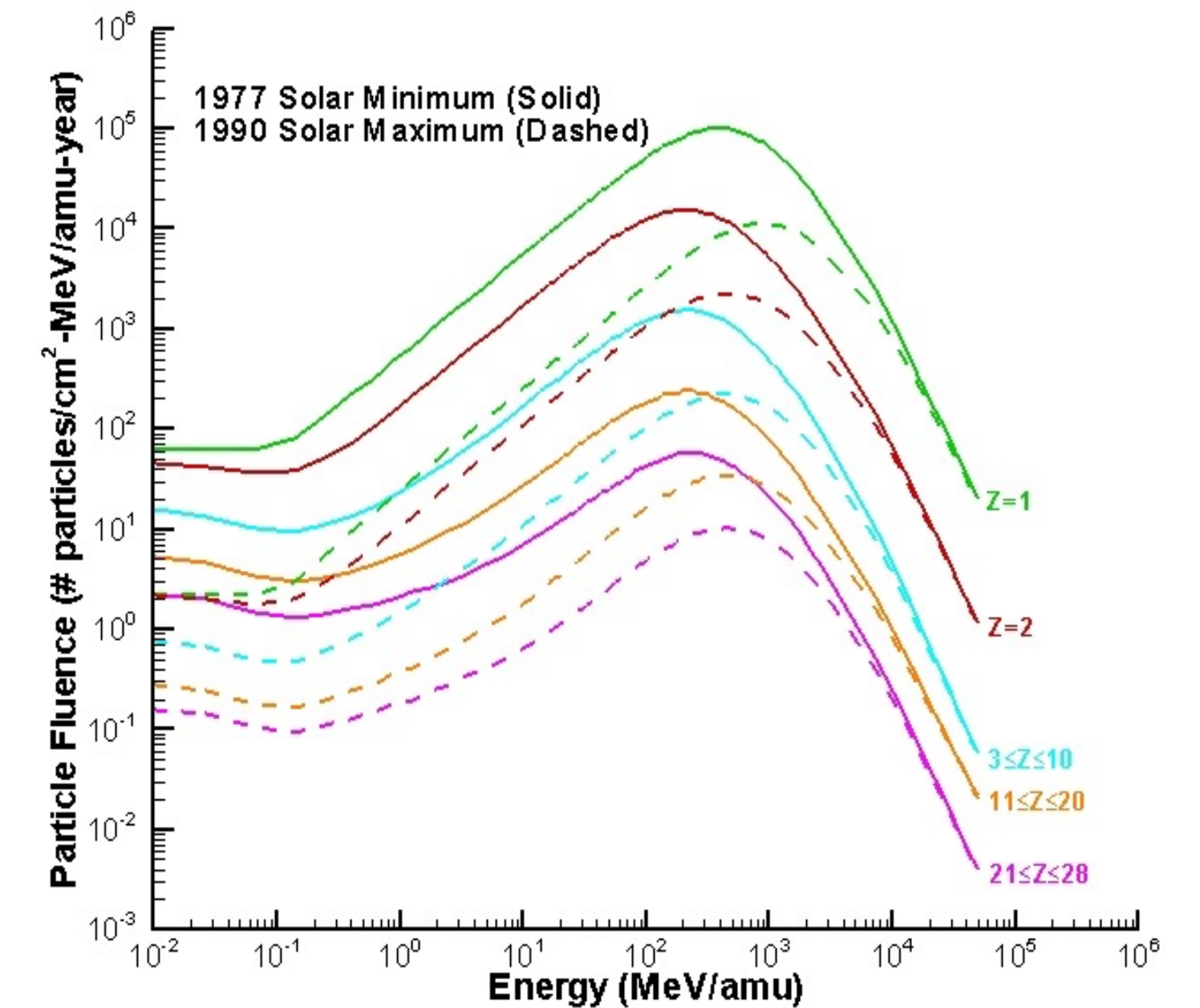


Heavy ions cause clustered damage along their tracks, causing outside biological effect compared to terrestrial radiation sources like x-rays. From Tinganelli and Durante (2020)

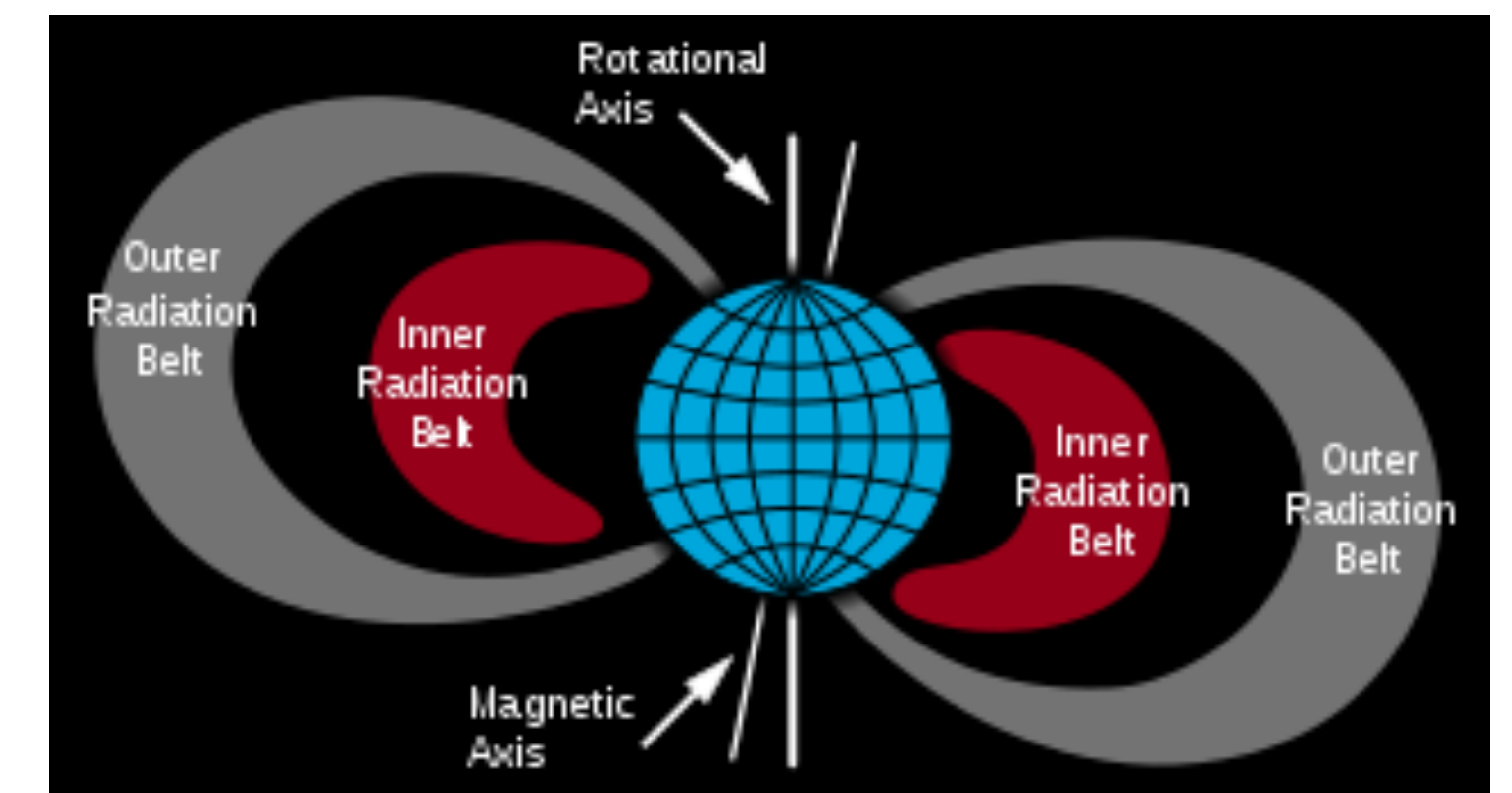
What Sort of Radiation is there in Space?

	Composition	Energies of interest	Spectral Shape	How Many/cm ²	How Long
Galactic Cosmic Rays (GCR)	Mixed ion	100 MeV/a - 10 GeV/a (of interest)	See right	A few/second	Constant
Surfaces	Like GCR, with albedo/attenuation	As GCR	See right	As GCR	Constant
Particle Belts	Protons/ Electrons	Protons < 200 MeV Electrons < 10 MeV	Decreasing power law	> 10 ² /s for ISS > 10 ⁵ /s high altitude	A few mins/transit
Solar Particles	Protons/ Electrons	Protons < 1 GeV Electrons < 4 MeV	Decreasing power law	Bad event > 10 ⁵ /s high	Up to a few days

Bold Text = Artemis I environment

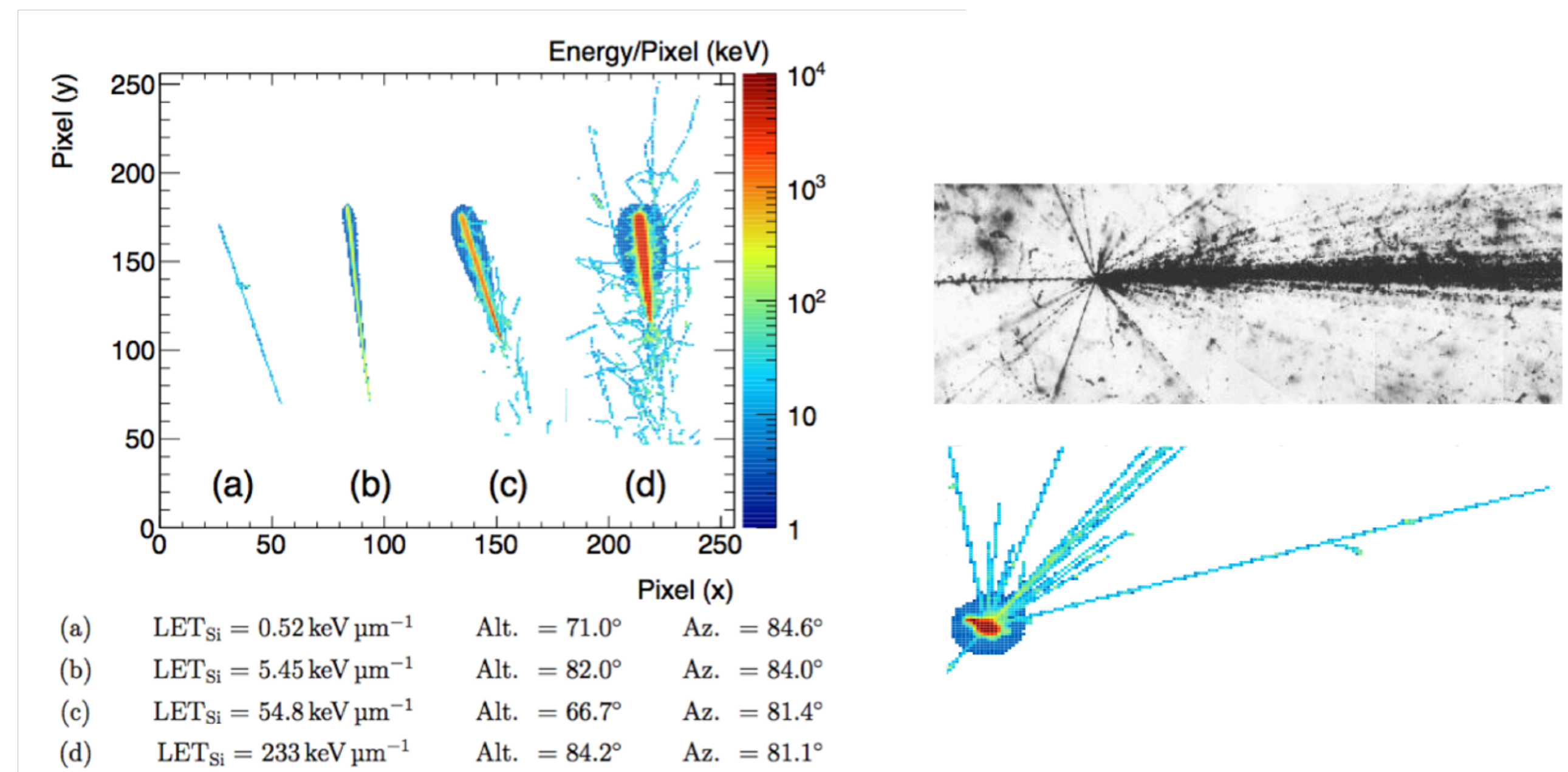
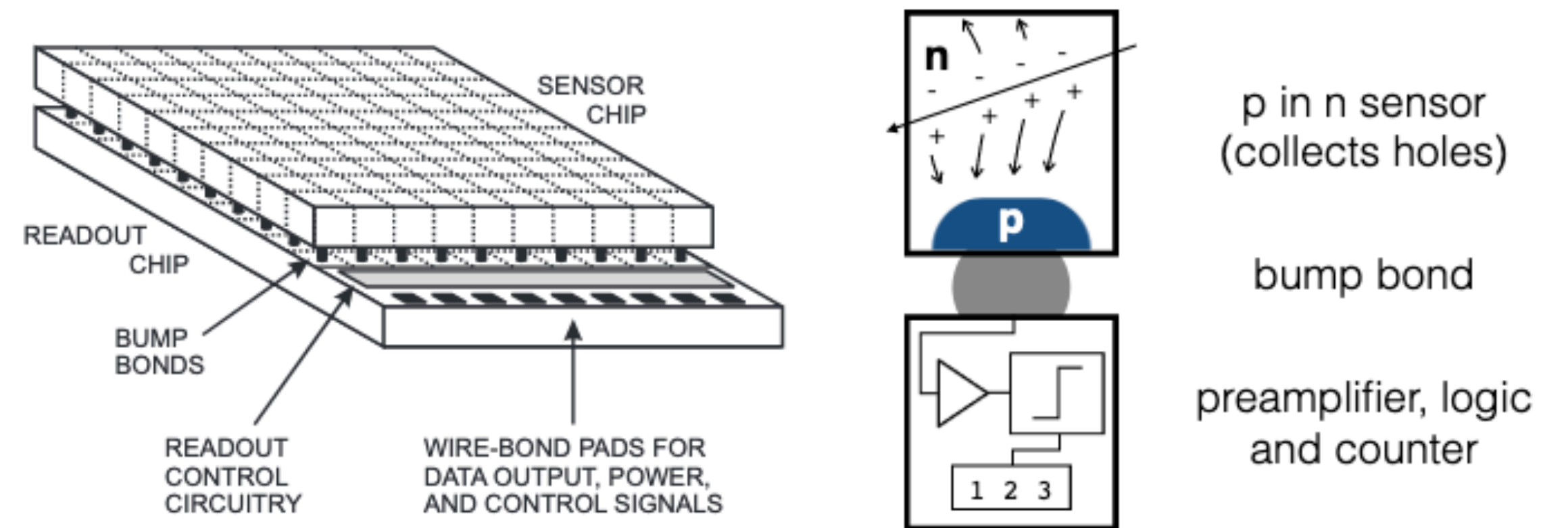


Galactic Cosmic Rays



Why Use Timepix in Space

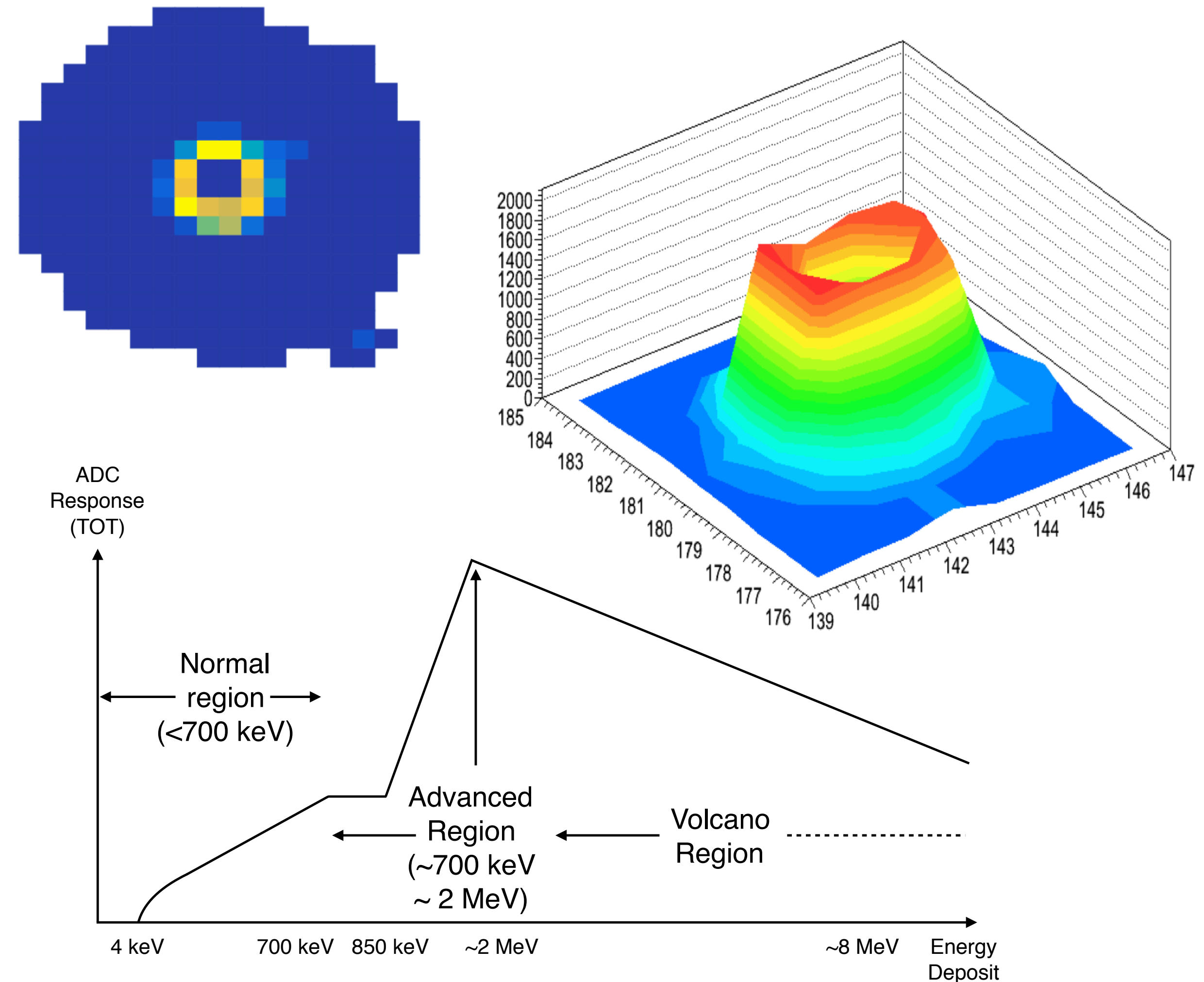
- 256 x 256 hybrid pixel detector array, Wilkinson type ADC where time over threshold can be calibrated to energy deposit. Min threshold 5 keV
- High energy range, with appropriate calibration can measure from 5 keV deposit in sensor to GeV deposits from heavy ions
- Analogue electronics integrated into 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'

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.

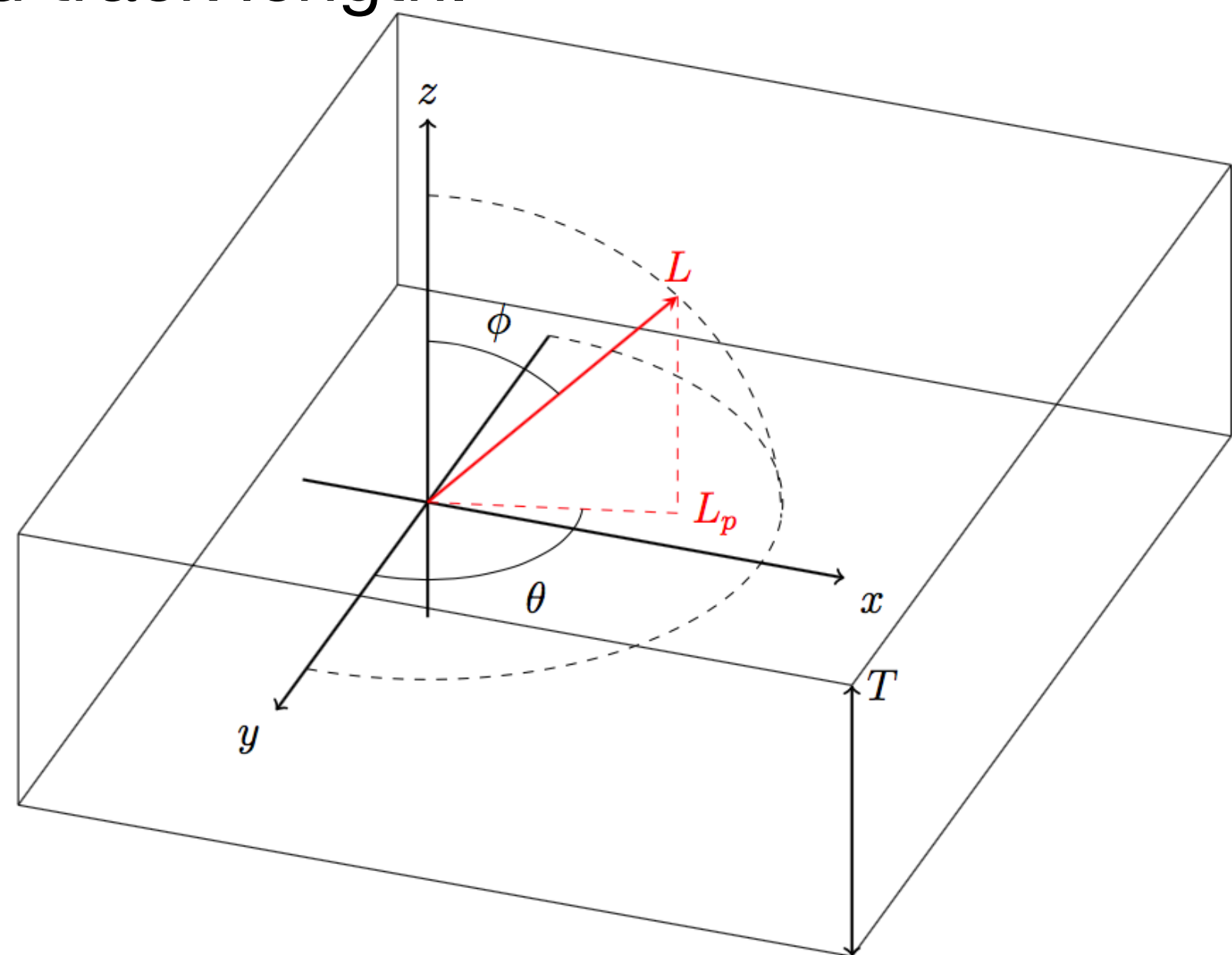
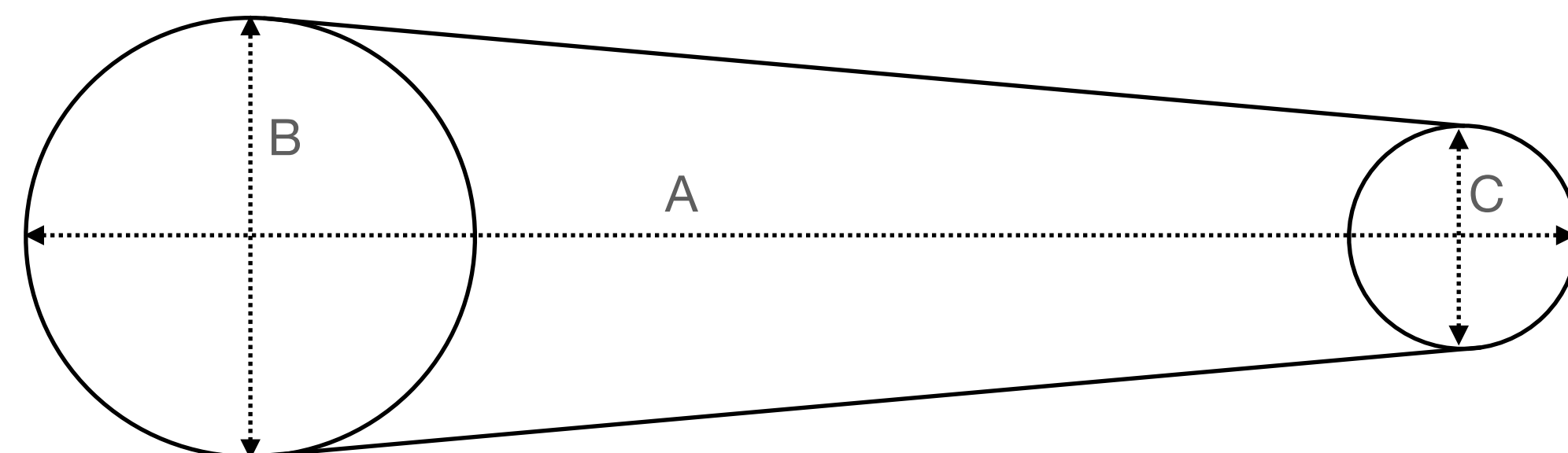
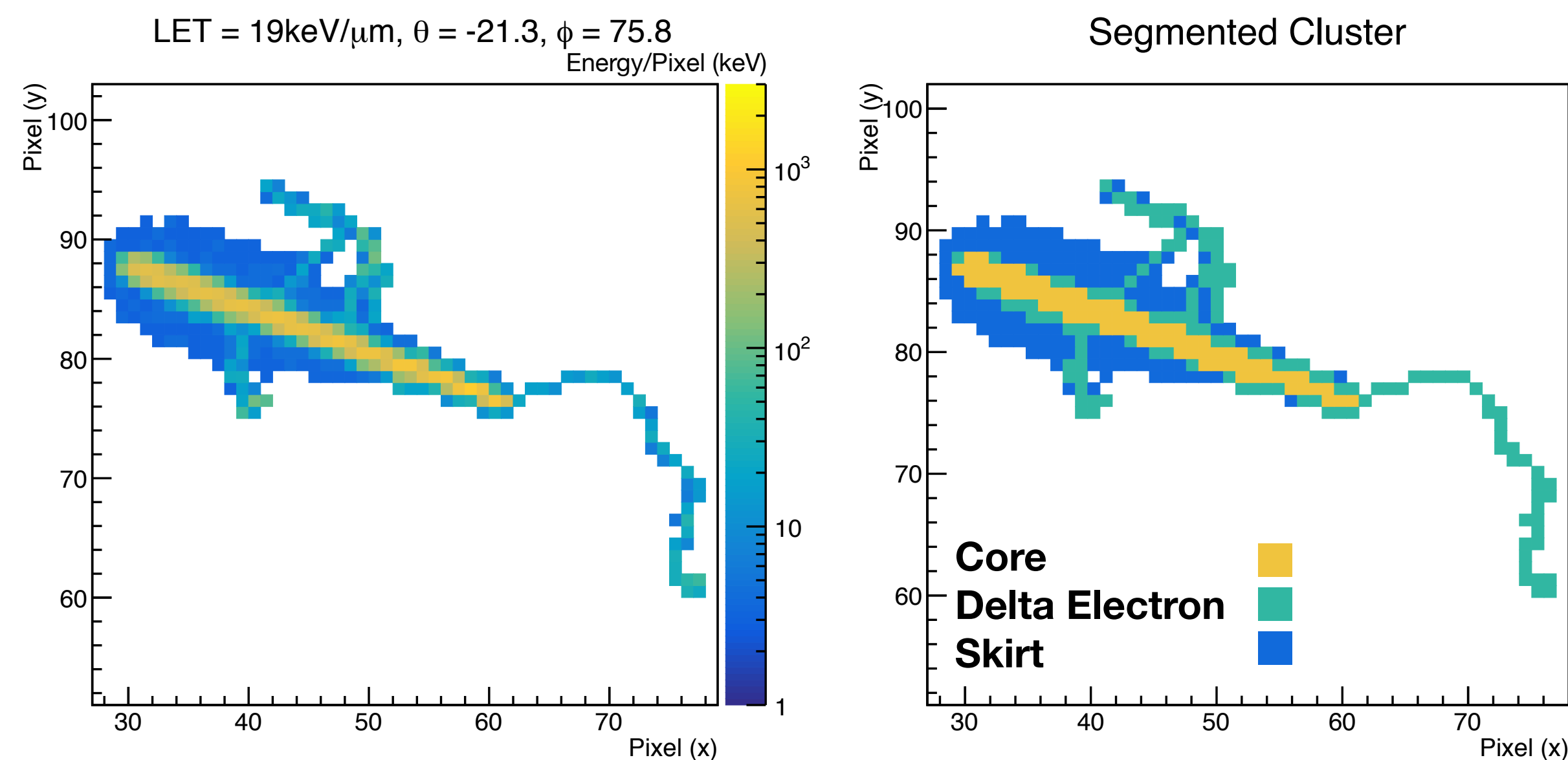


Figure 3.6: Measurement of the azimuth angle θ and altitude ϕ relative to the sensor axes from a penetrating track of length L over a sensor of thickness T .



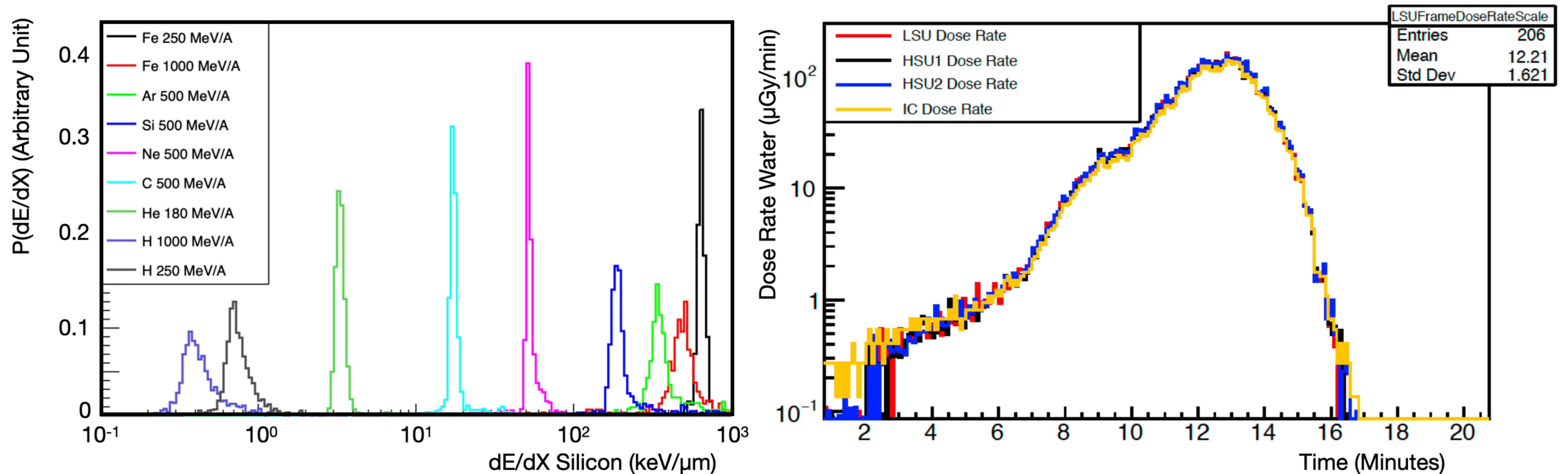
- Disentangle charge sharing effects - charge sharing in track causes characteristic 'comet' shape

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

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

Calculation of dE/dX and Example Performance

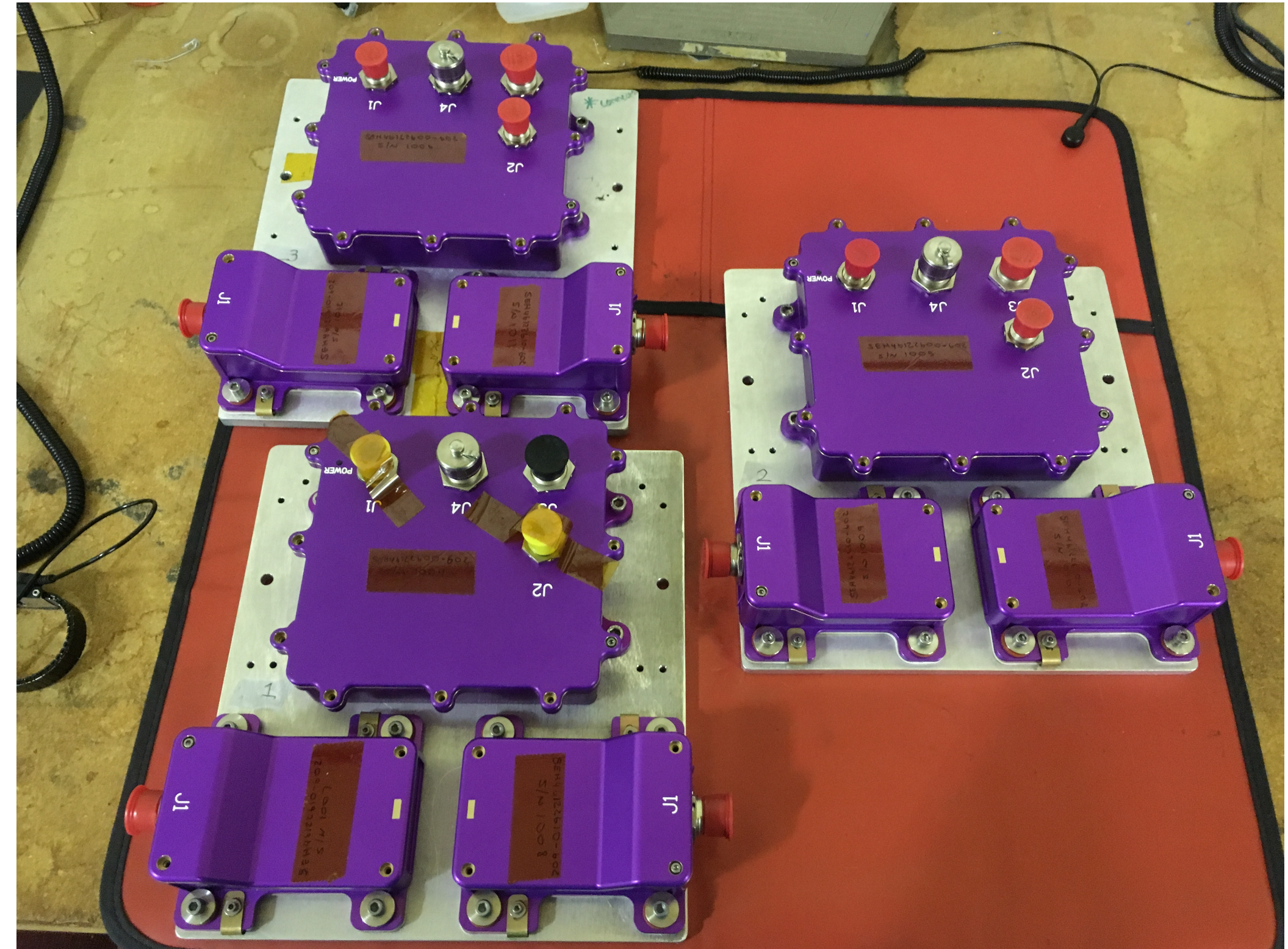
- The track LET or dE/dX is important because it tells you about the biological effectiveness or “quality” of the radiation
- This can be calculated with the ICRP60 quality factor formalism



(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.

HERA Is Our Instrument

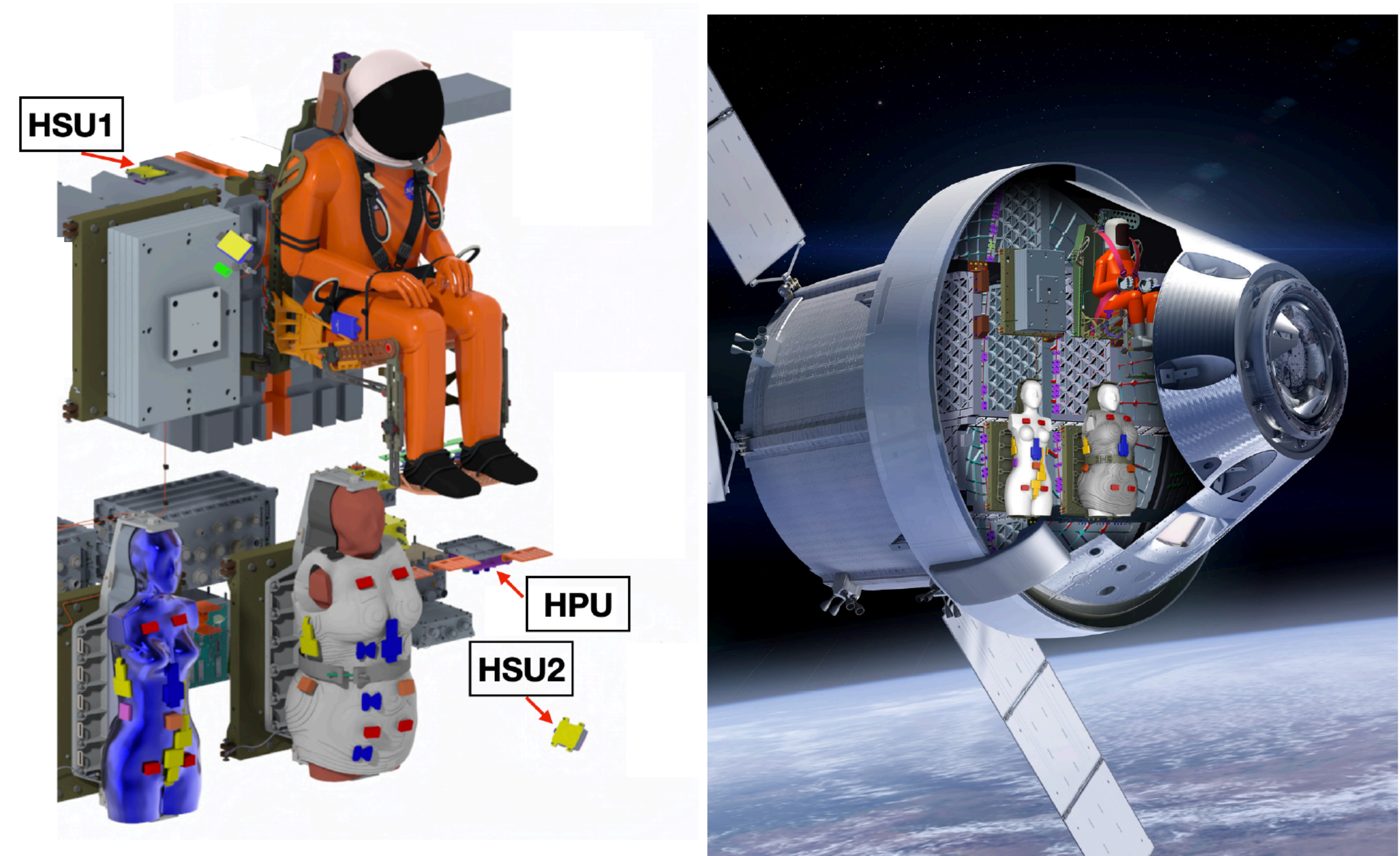
- HERA is a fully autonomous radiation monitoring instrument for NASA exploration programs, specifically the Orion spacecraft
- HERA performs real time onboard calibration and PID/binning
- Each HERA consists of an HPU (HERA processing unit) and two HSU's (HERA Sensor Unit), each containing a timepix 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**

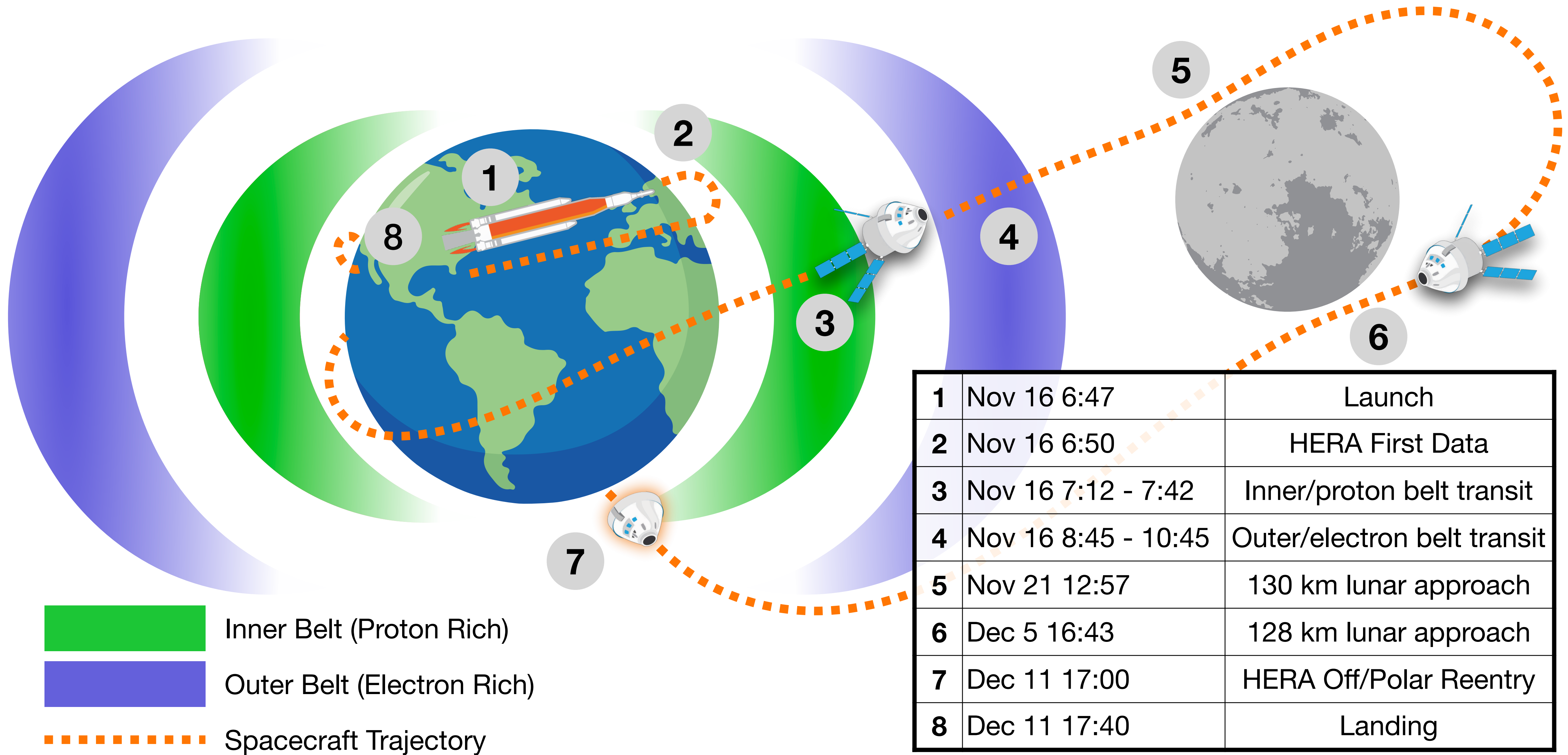
HERA in Orion

- The HERA detector (comprising 3 timepix) is hard mounted into the Orion spacecraft, placed around the crew capsule
- Different sensors are placed at different ‘shielding depths’ around the crew capsule. Especially important for determination of human solar particle event dose which is very strongly affected by shielding.
- Real time telemetry sent back to support mission control, frames saved on device for post mission analysis

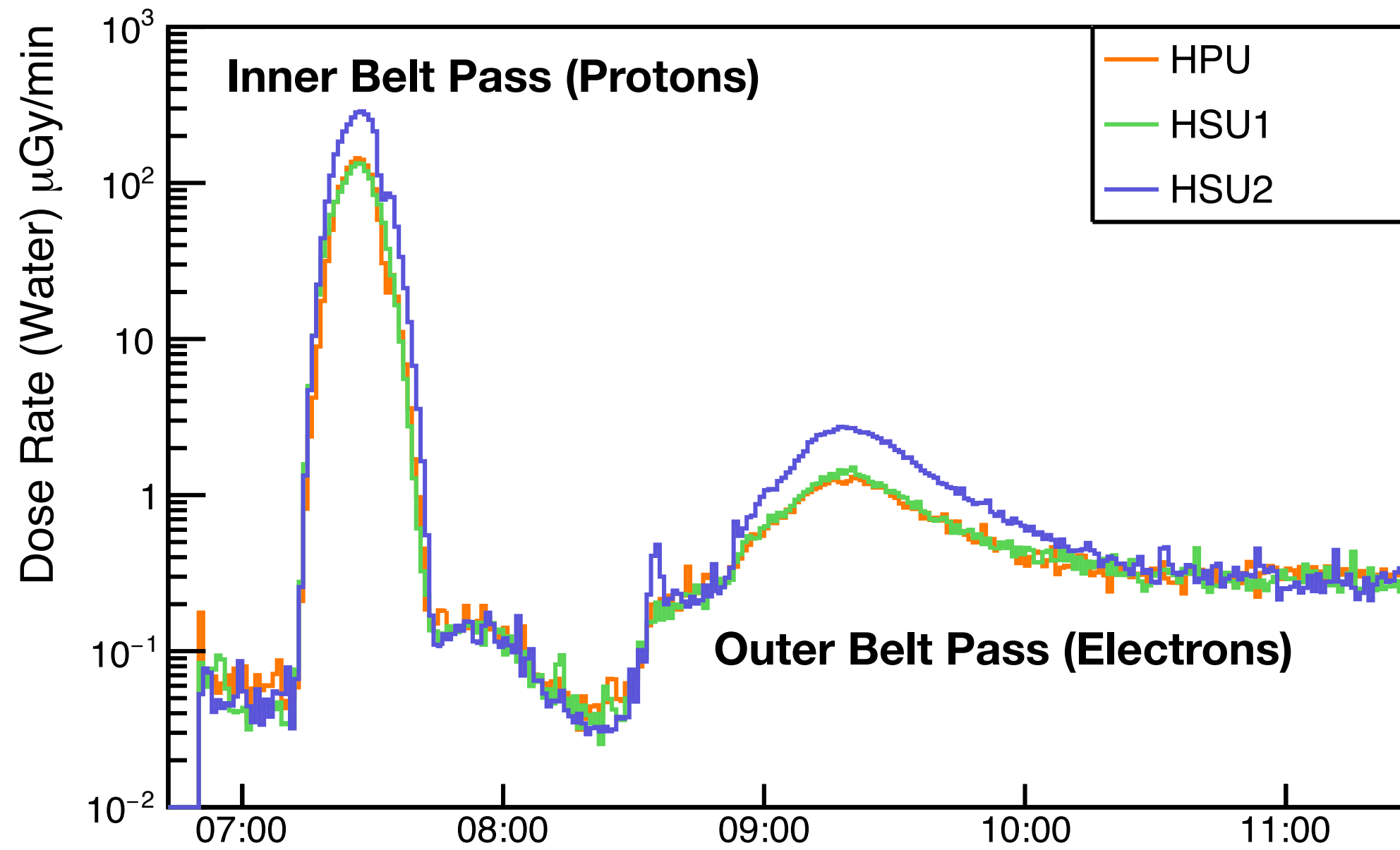


Sensor	Mean Depth (g/cm ²)	Median Depth (g/cm ²)
HPU	52.4	43.6
HSU1	45.7	34.4
HSU2	38.3	27.0

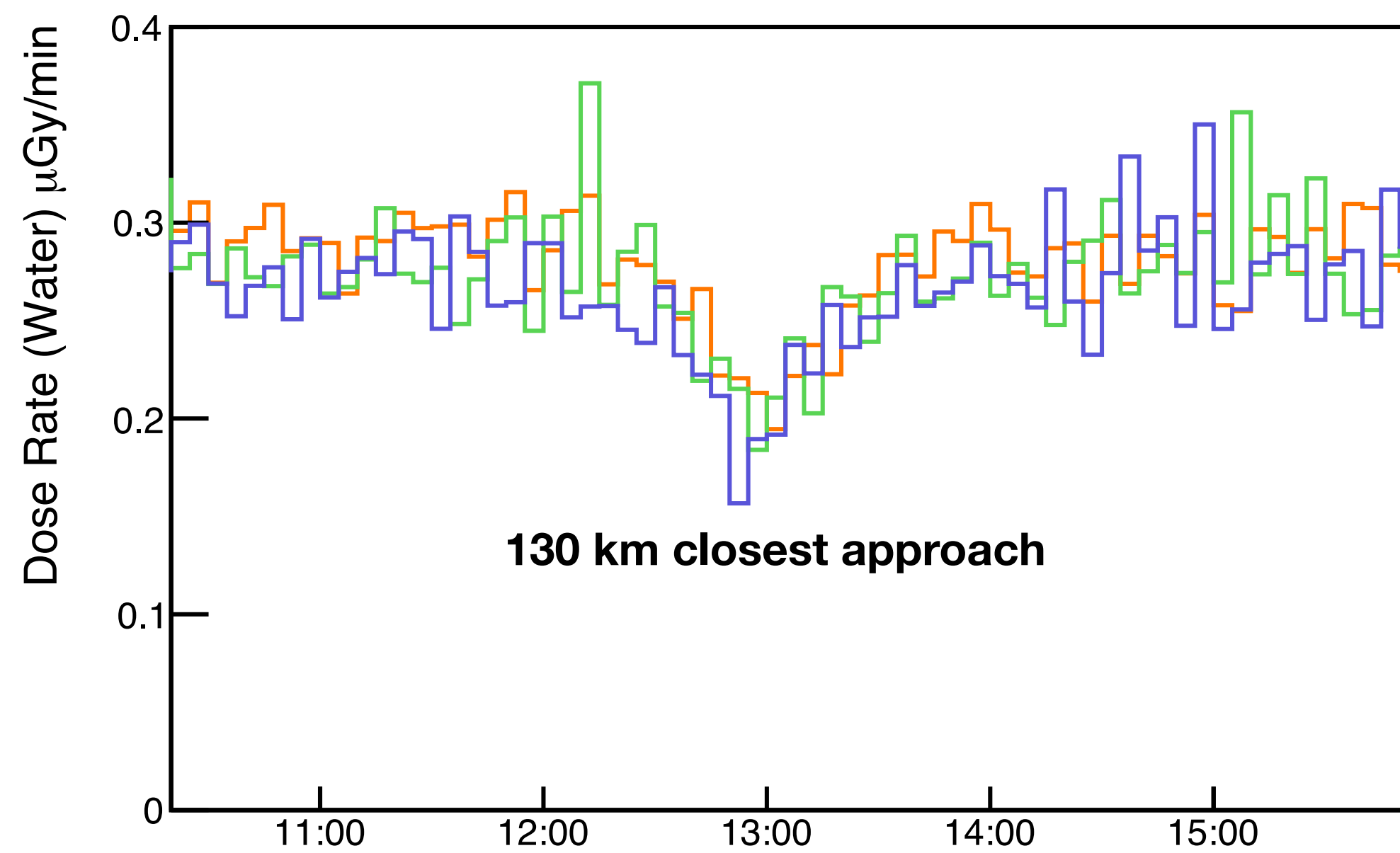
Artemis I - The Radiation Perspective



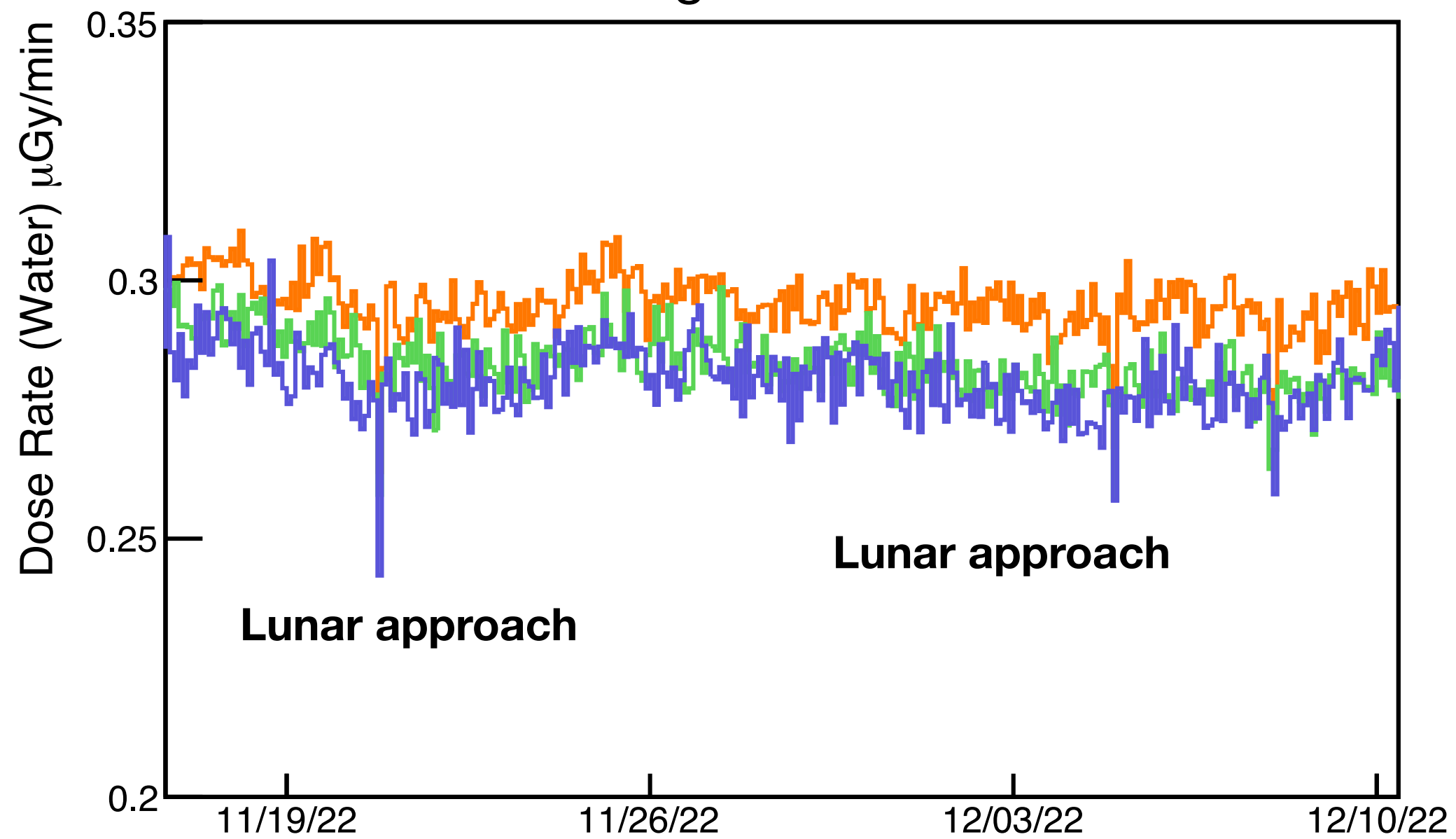
Belt Pass Nov 16 2022



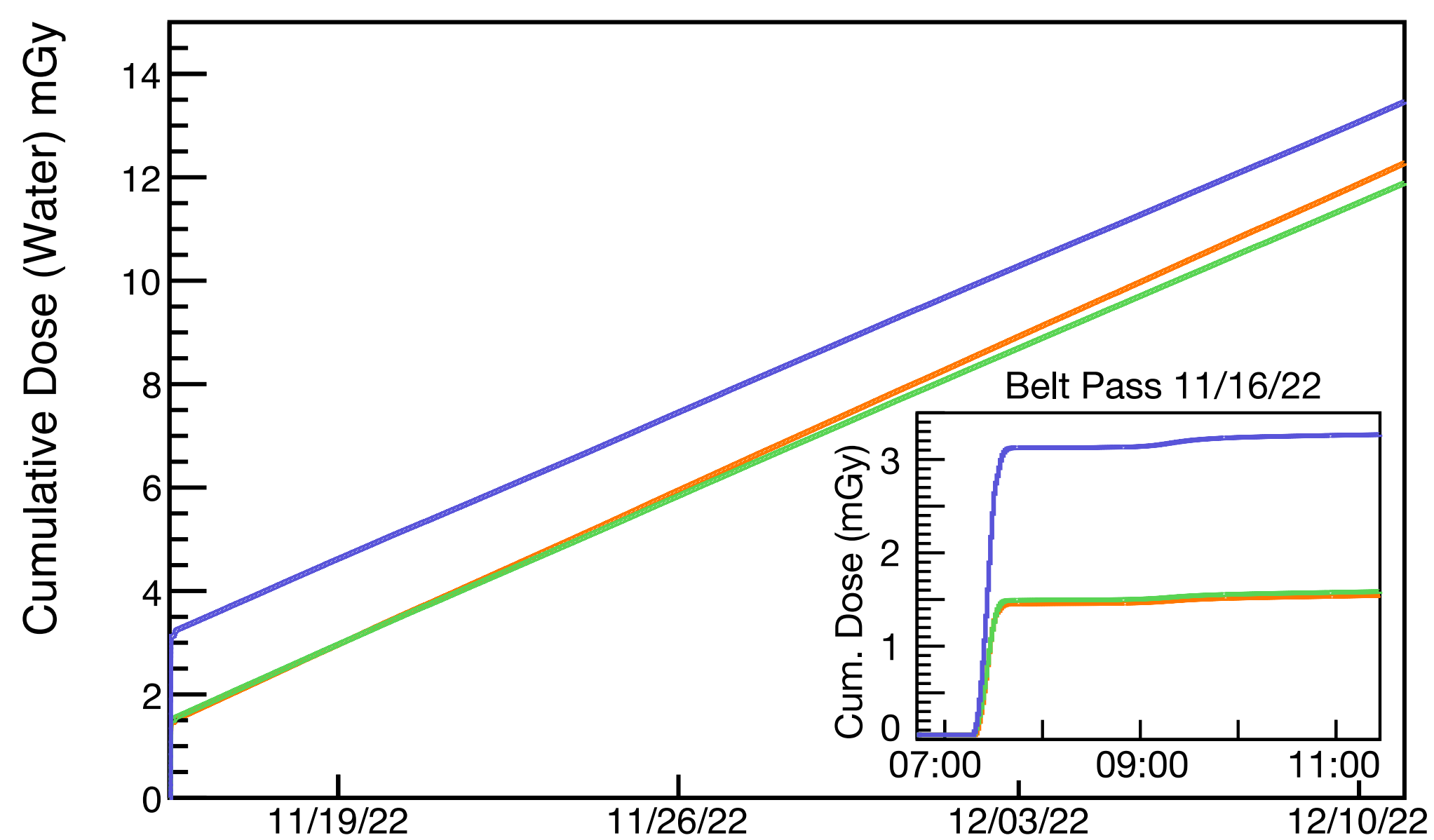
GCR Dose Rates During Lunar Flyby



6 Hour Average GCR Dose Rates

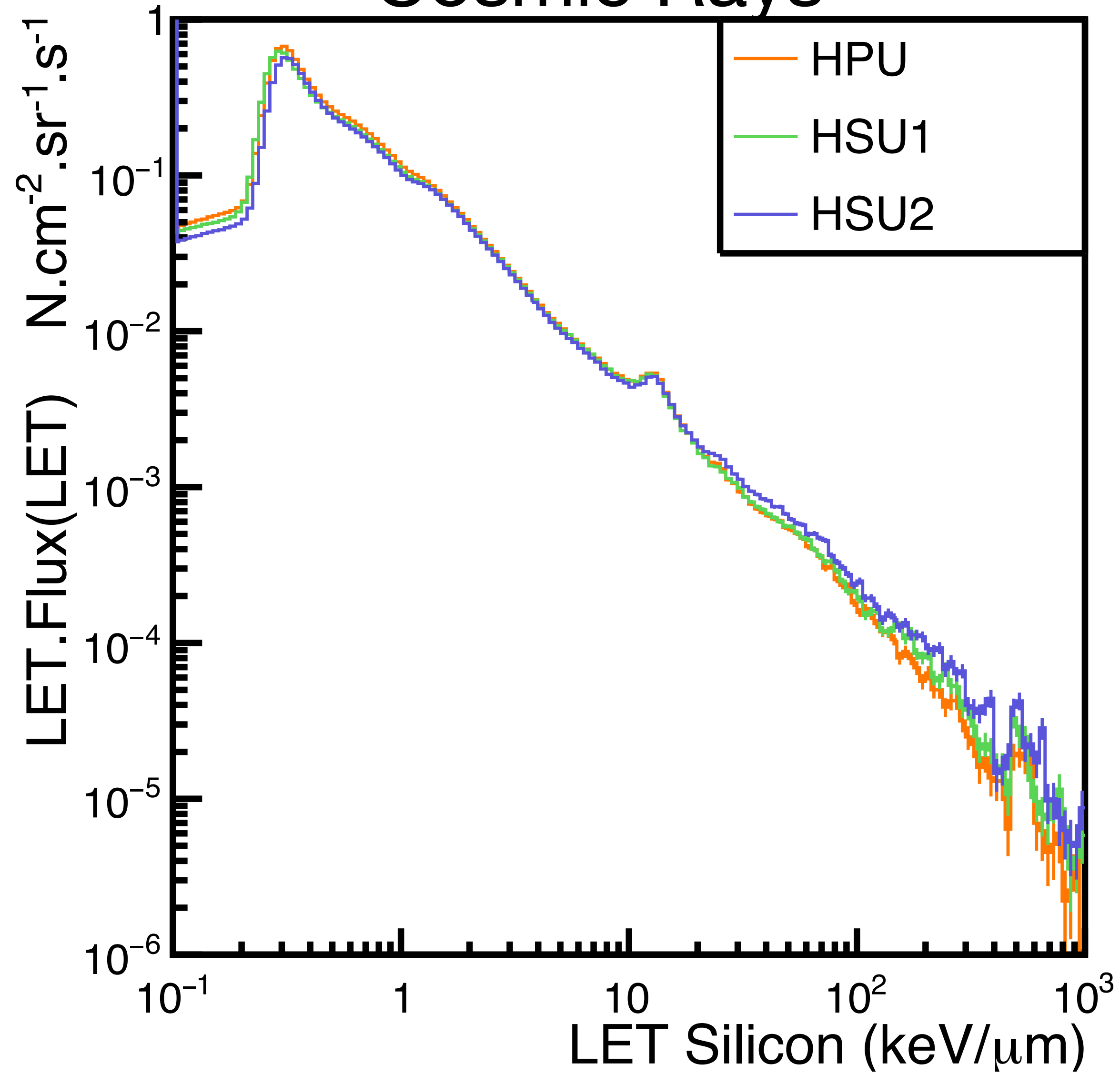


Whole Mission Cumulative Dose

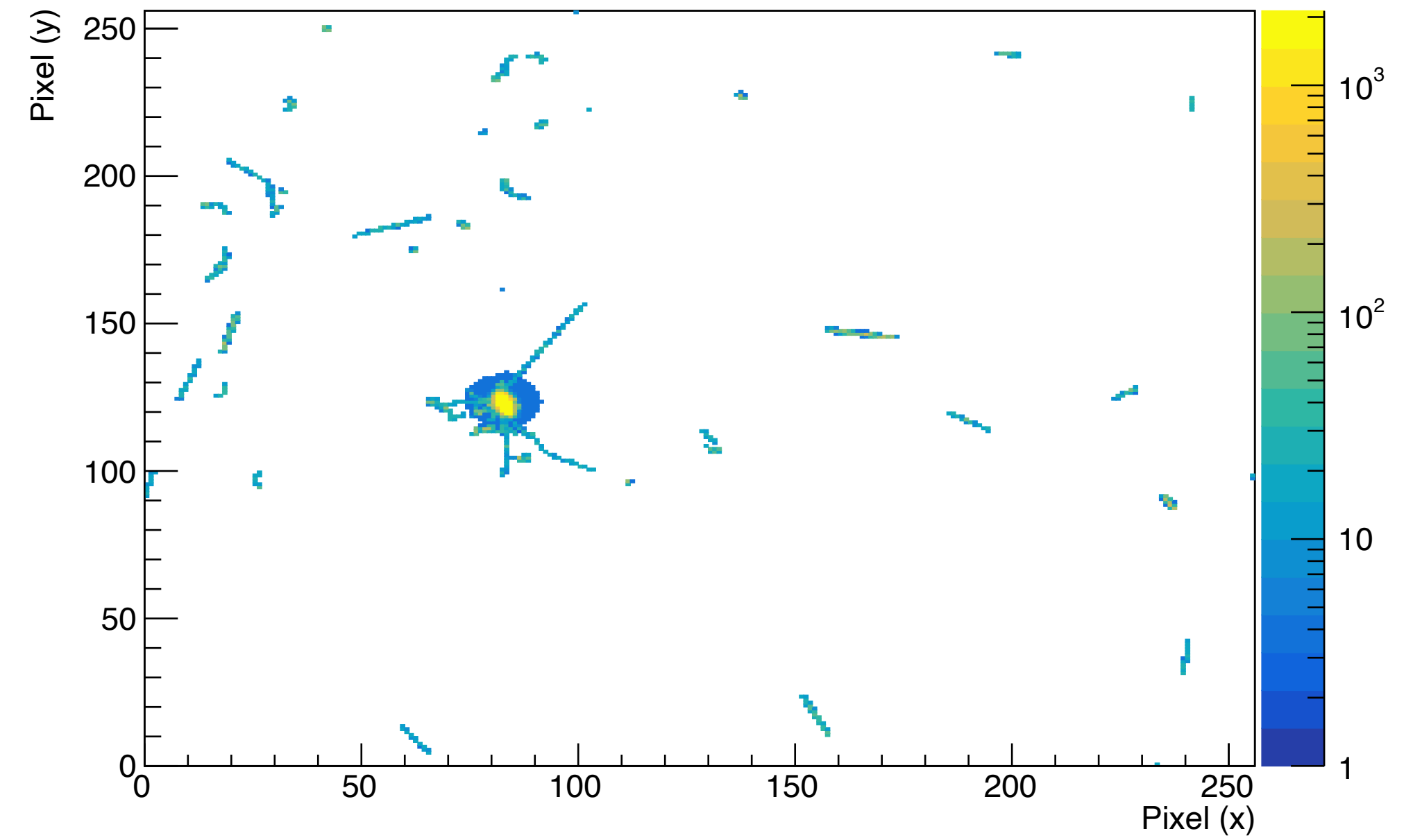


HSU2 is the least shielded detector, HPU is the most shielded detector

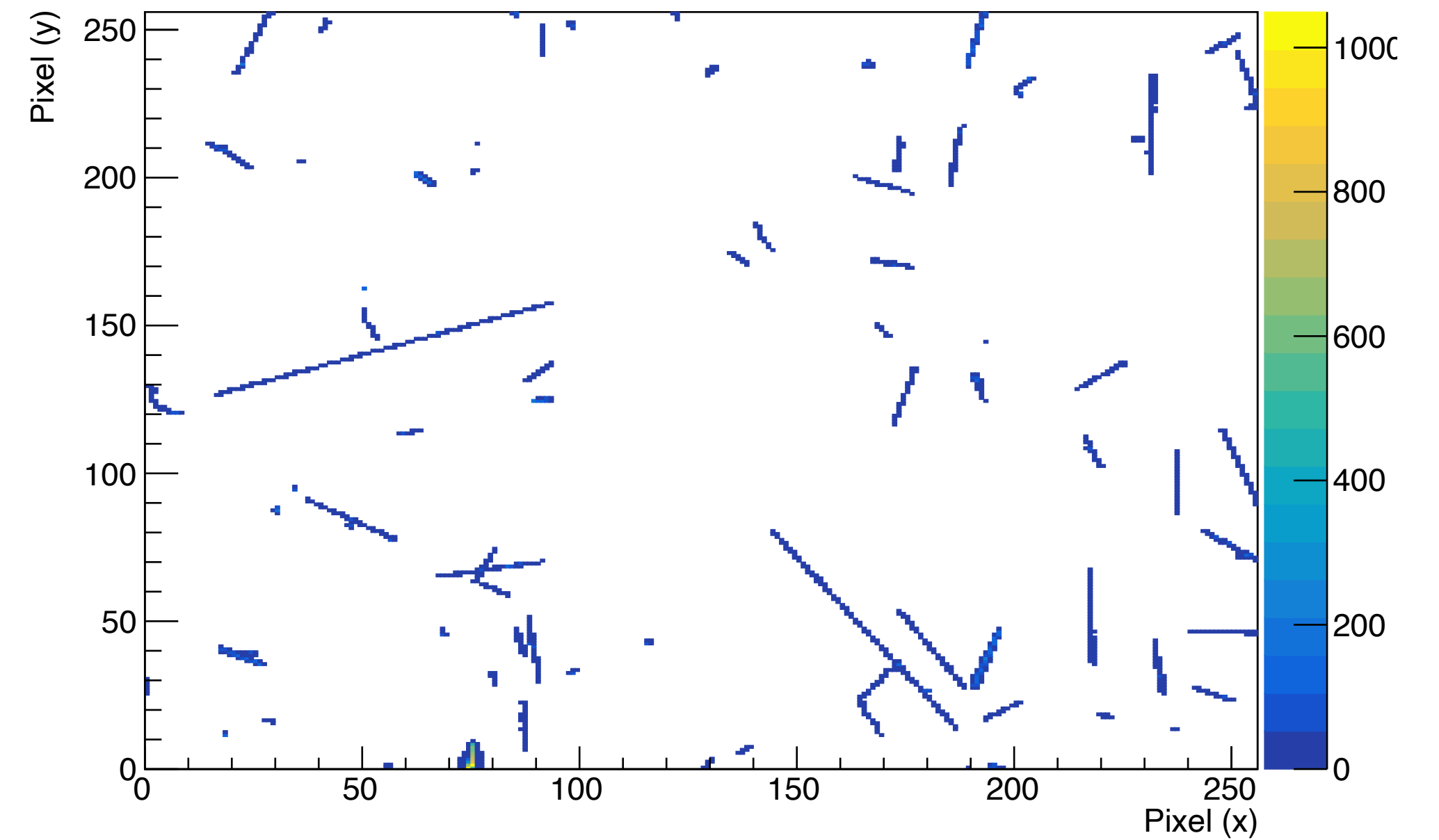
LET Spectra Galactic Cosmic Rays



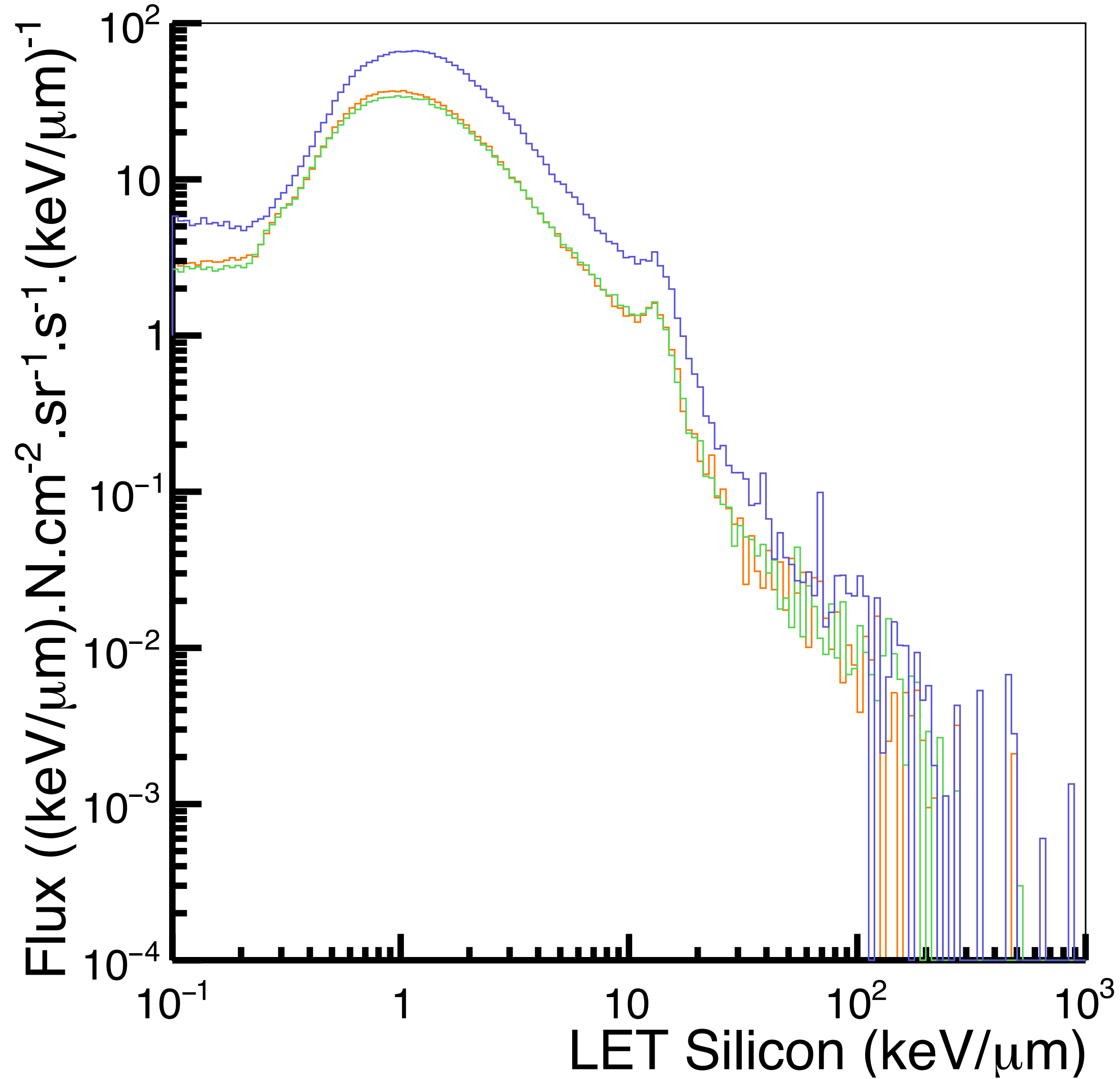
Dose Rate = 1.846634 $\mu\text{Gy}/\text{min}$



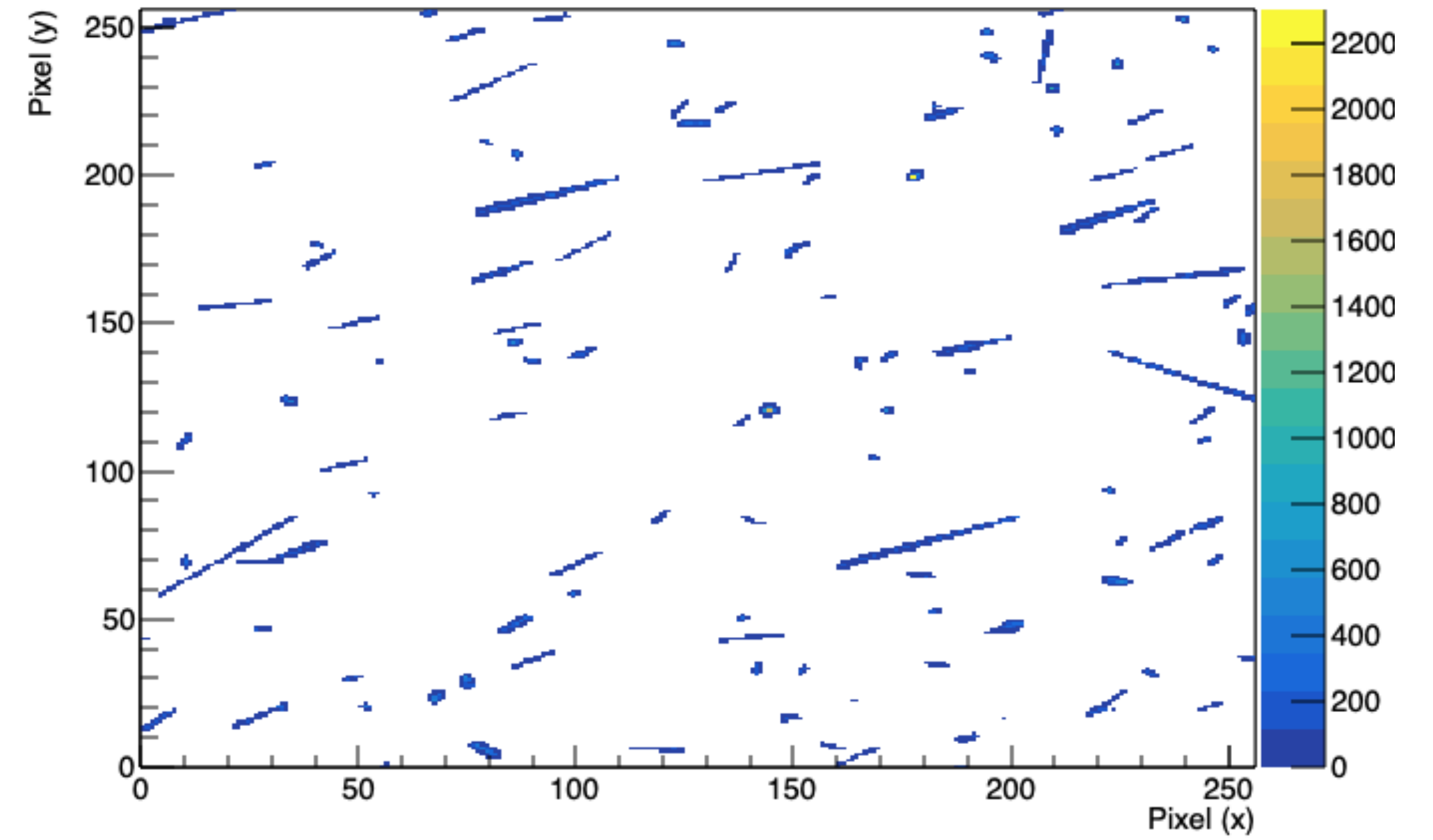
Dose Rate = 0.209512 $\mu\text{Gy}/\text{min}$



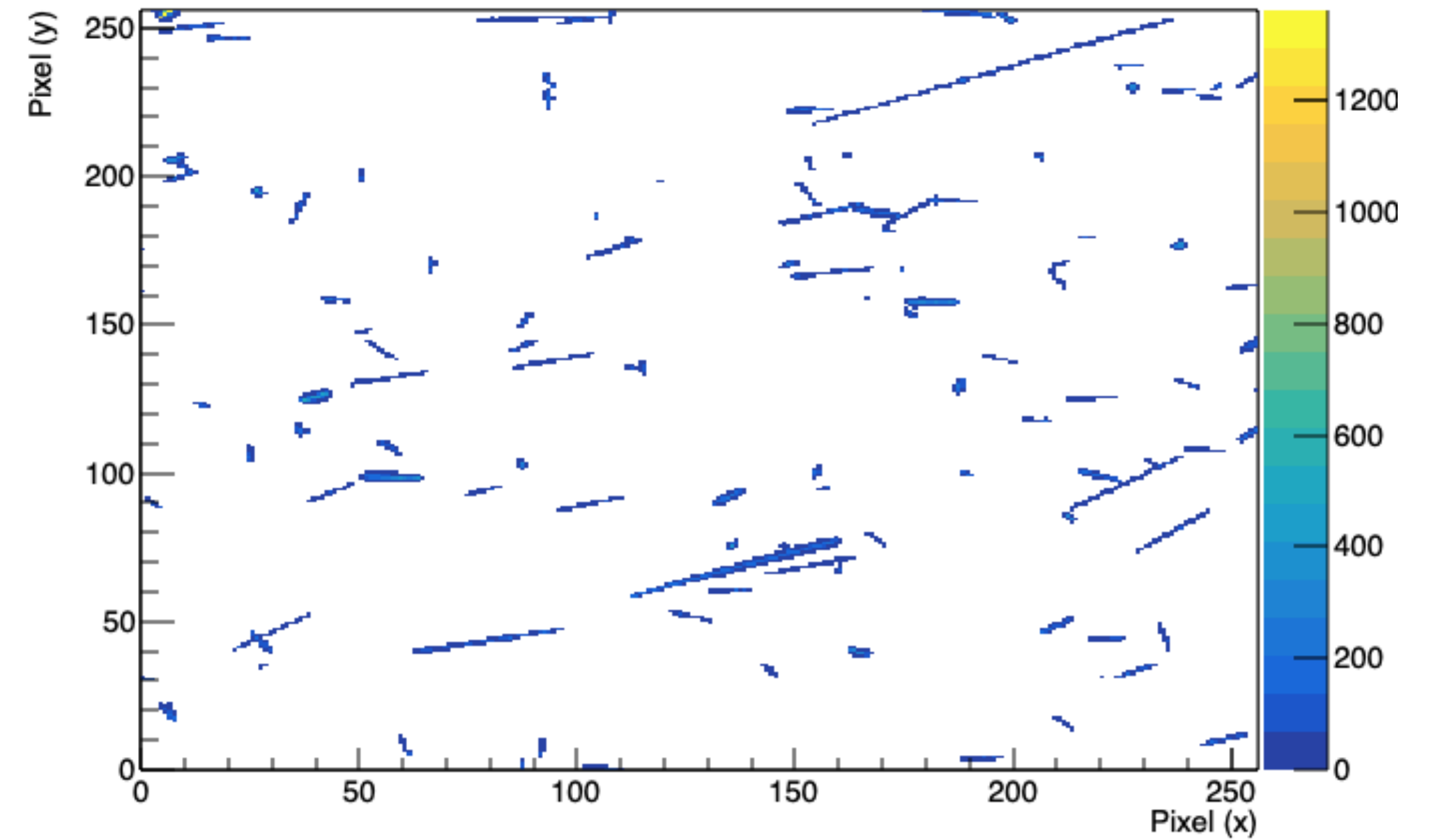
LET Spectra Inner Belts



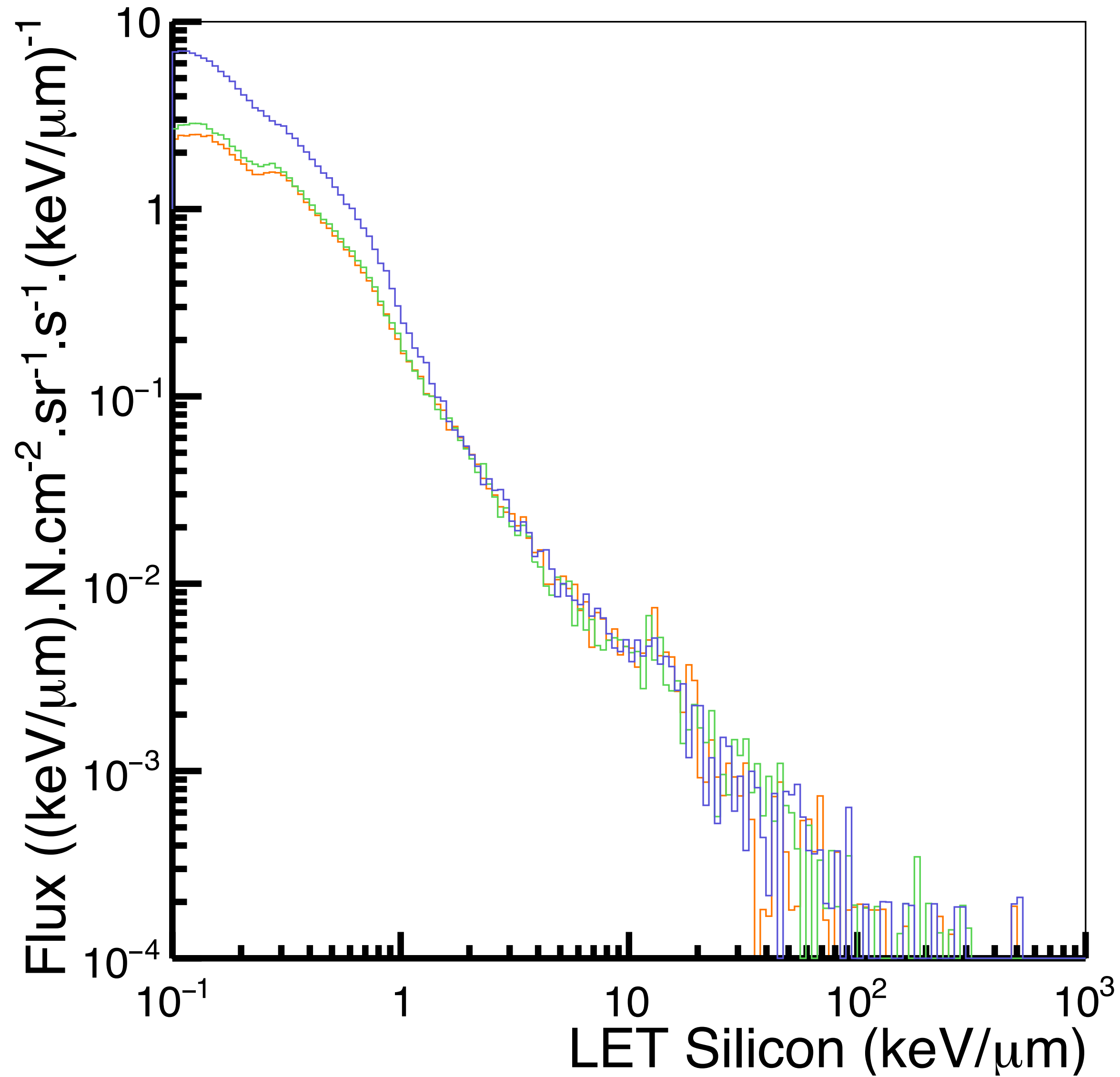
Dose Rate = 138.876852 uGy/min



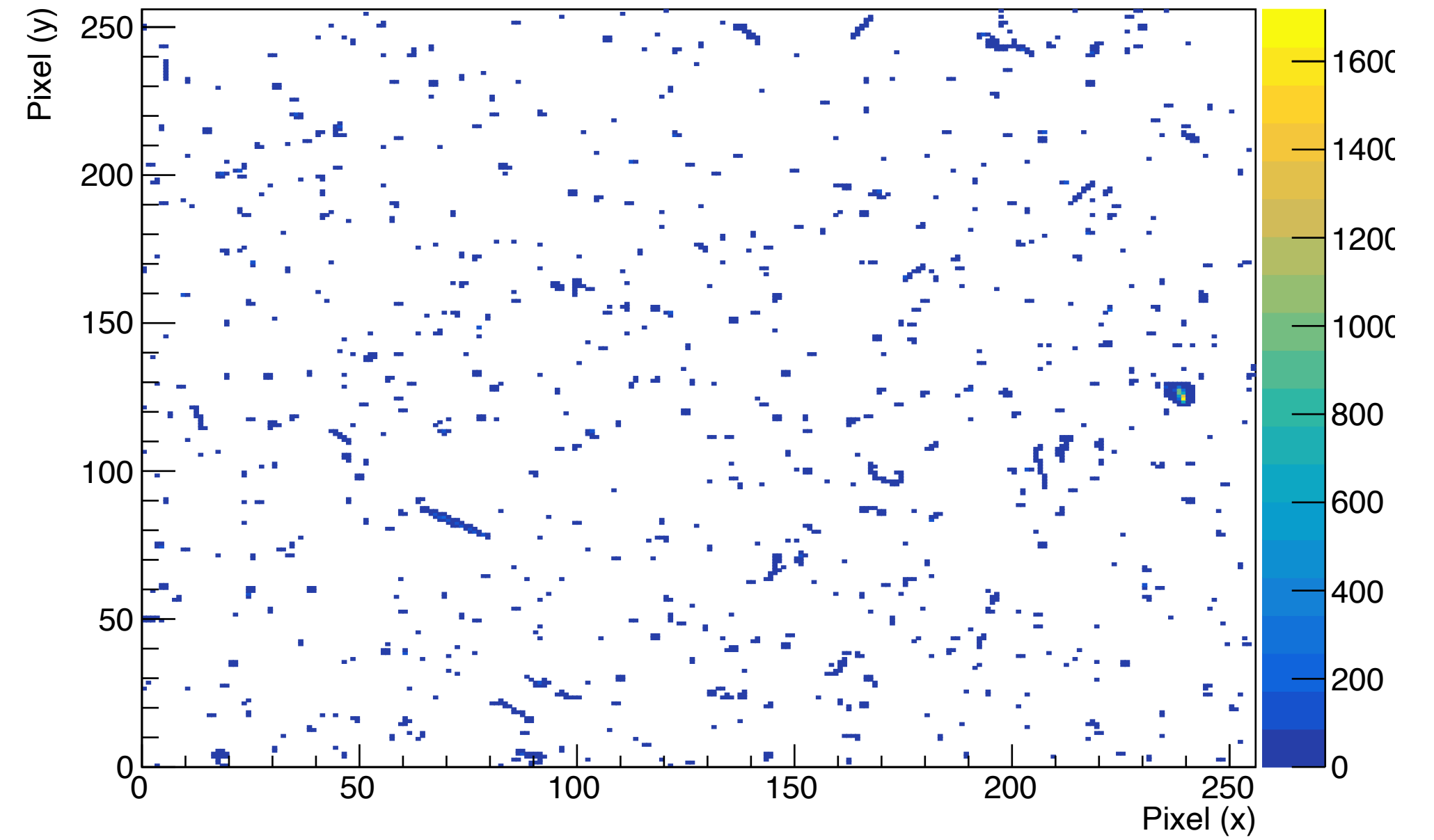
Dose Rate = 176.717545 uGy/min



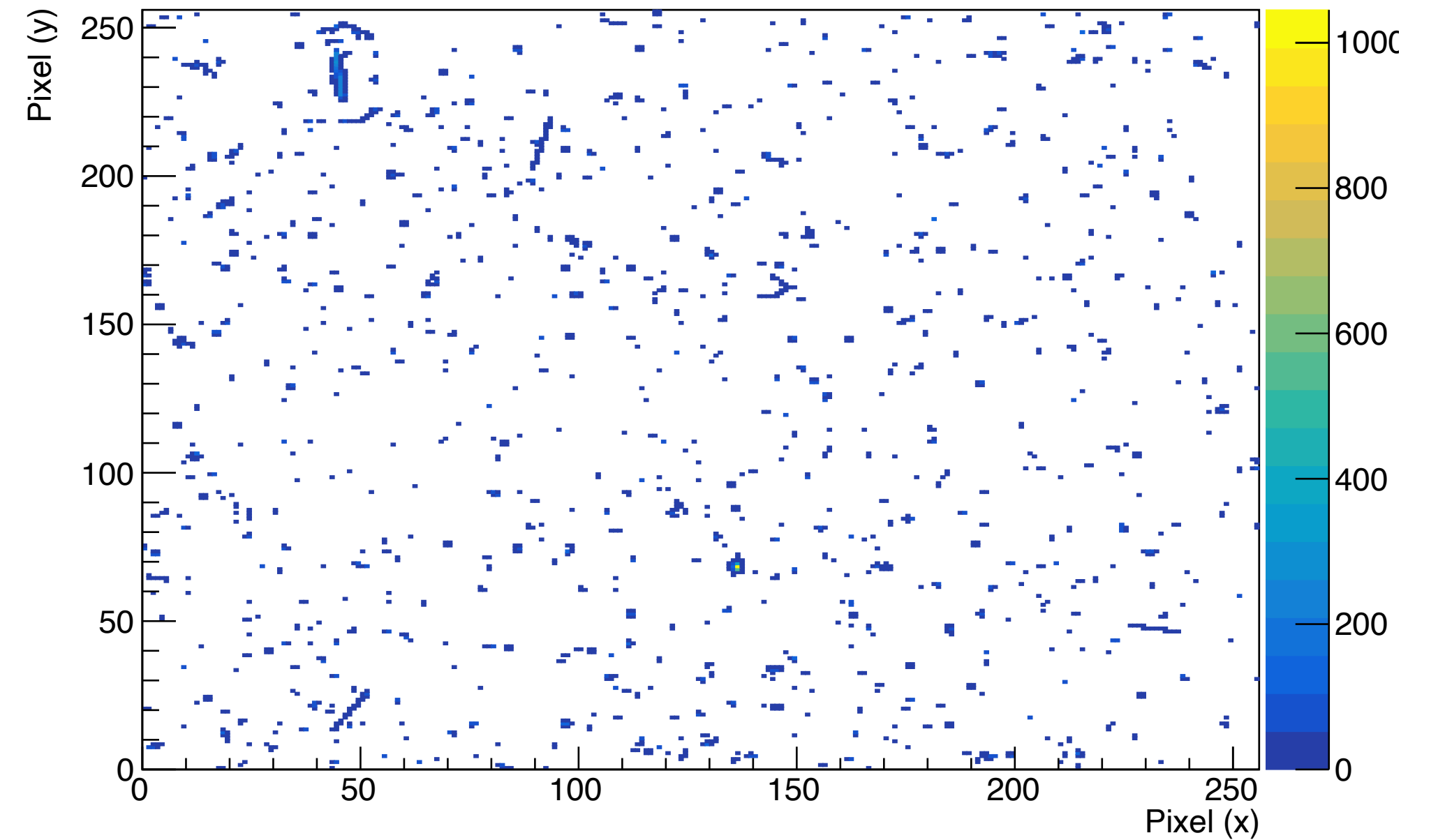
LET Spectra Outer Belts



Dose Rate = 2.421711 uGy/min

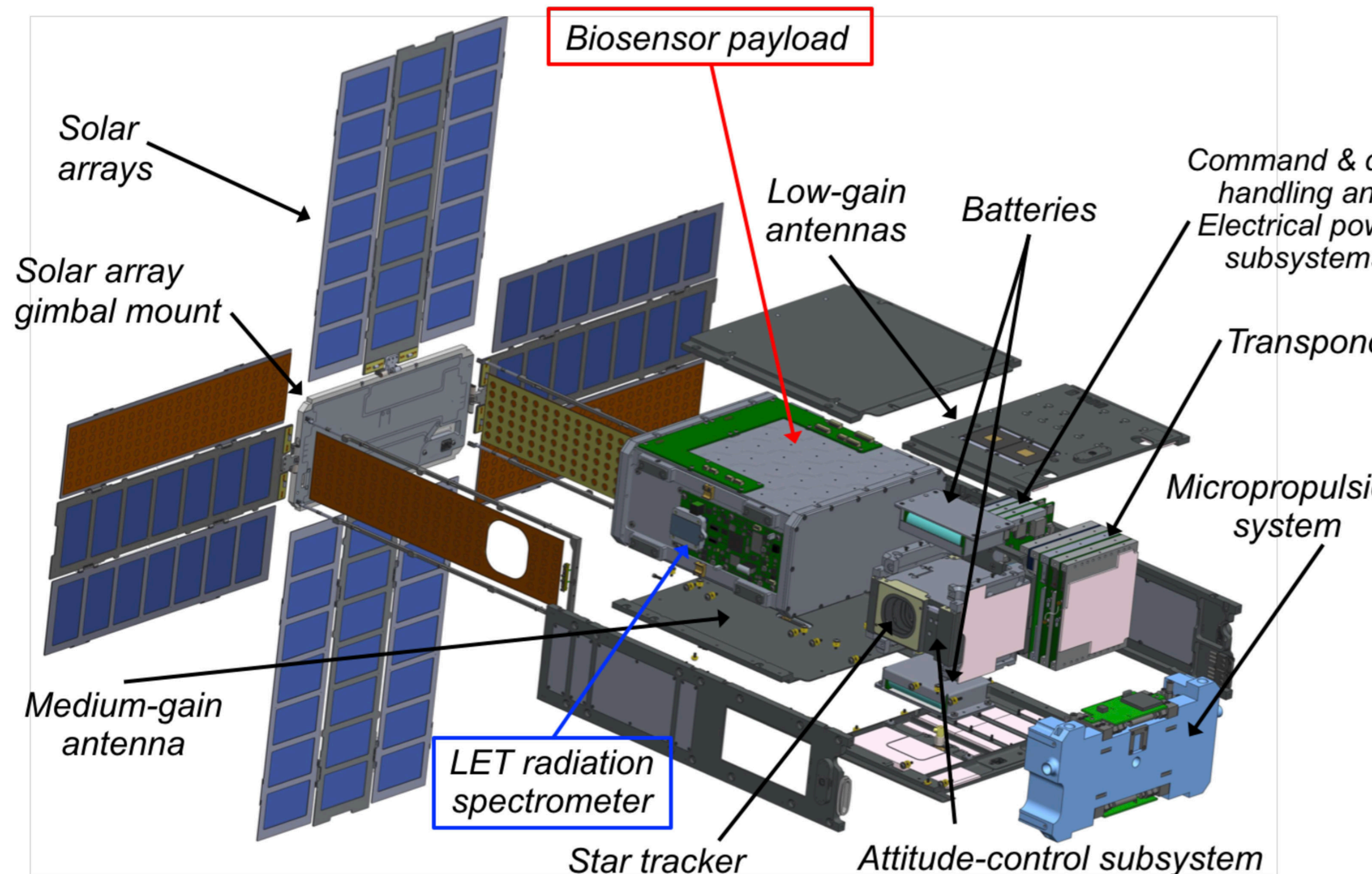
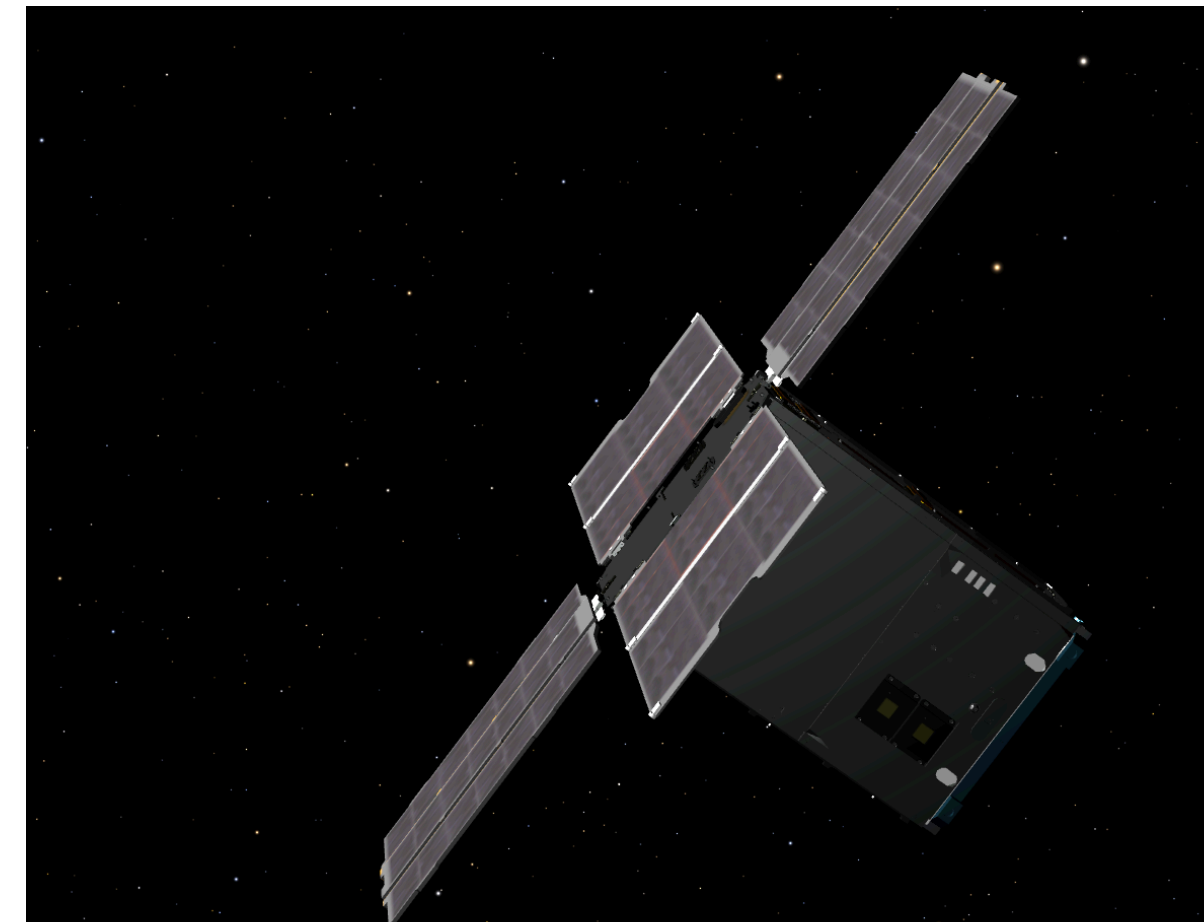


Dose Rate = 2.437818 uGy/min

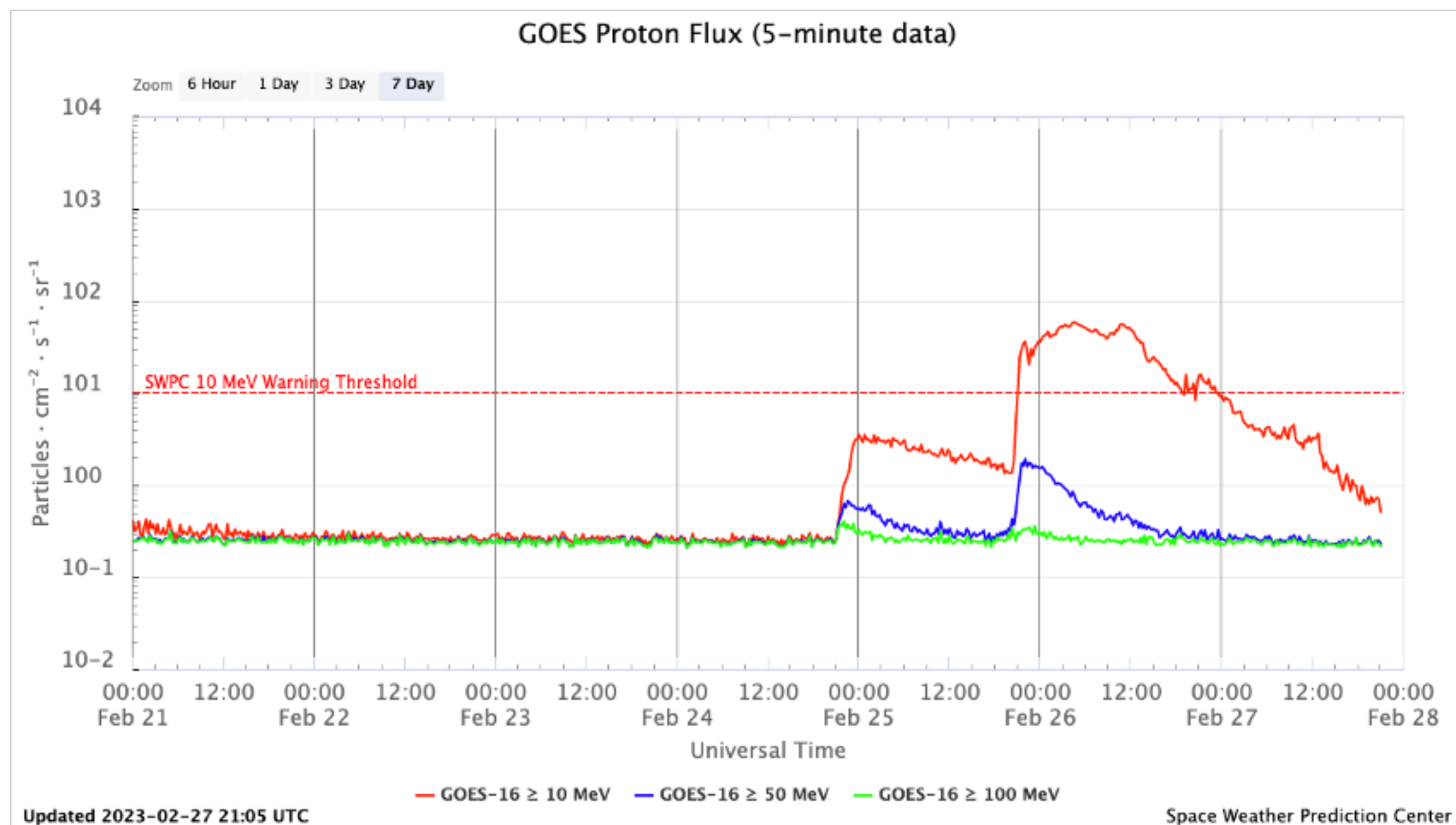


Biosentinel

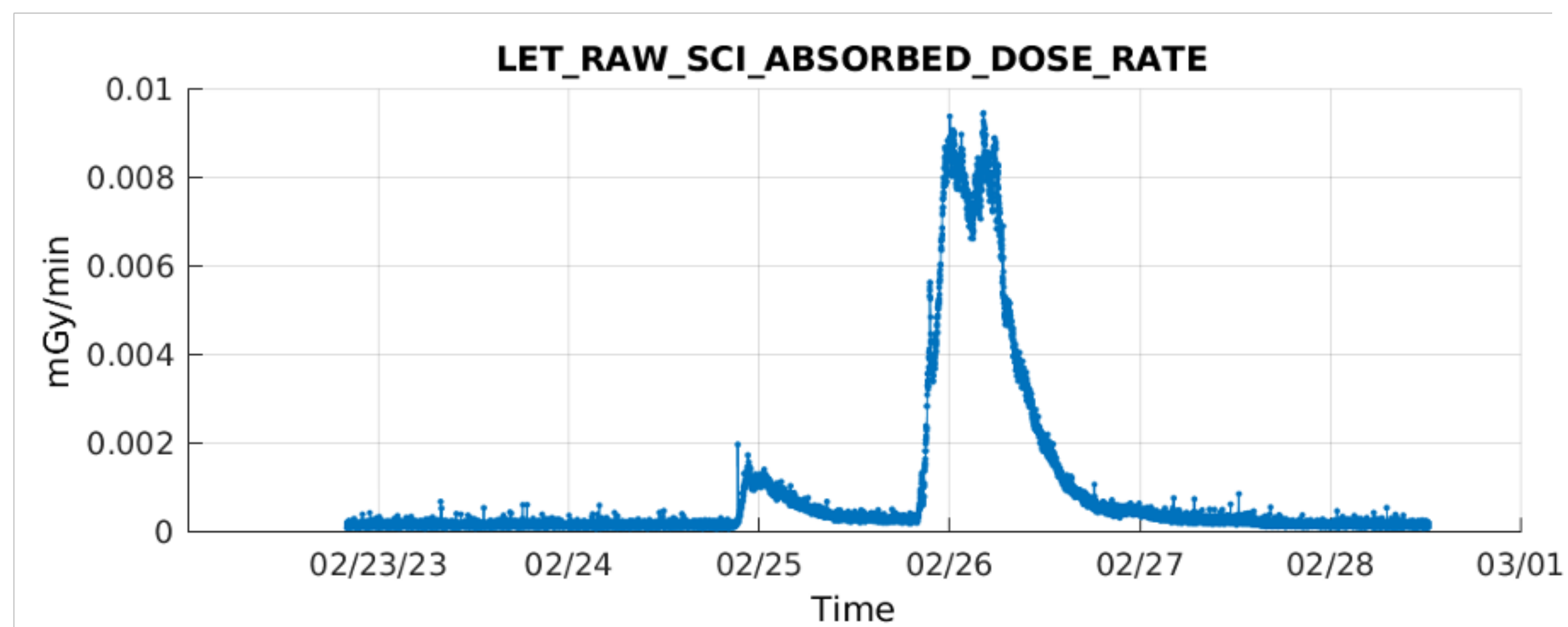
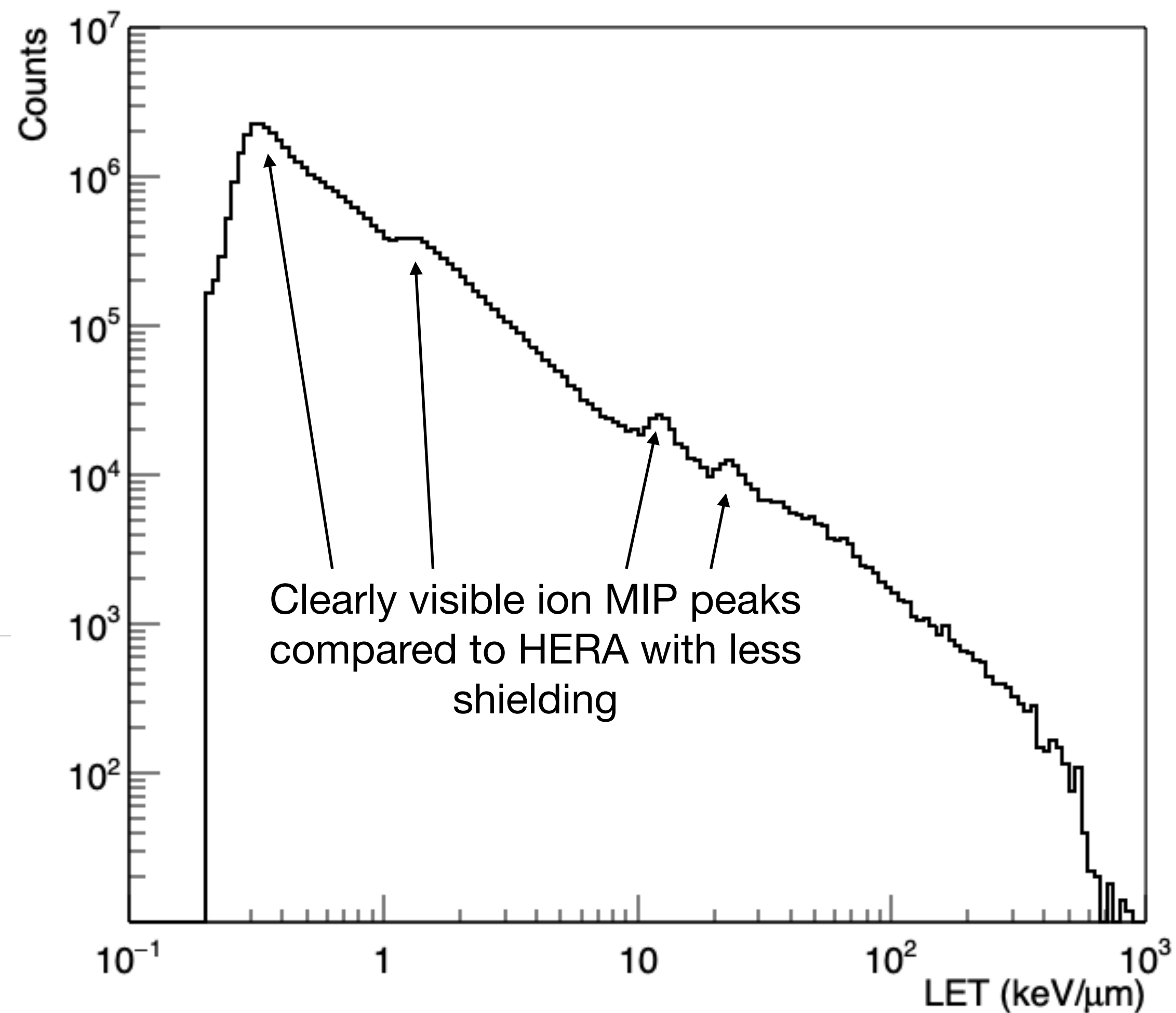
- Biosentinel was one of 10 cubesats launched by Artemis I
- It was launched into a heliocentric (solar) orbit by the SLS after Orion separation
- Biosentinel contains a Timepix on an “LET” board providing much of the same functionality as HERA as well as a biological payload
- Biosentinel will be 20 million km from Earth the last day of this conference (June 29th). It will transmit back dose and LET flux until the end of this year at which point it will be 27 million km away.
- Compared to HERA it is much more lightly shielded and so much more sensitive to low energy protons and small space weather events



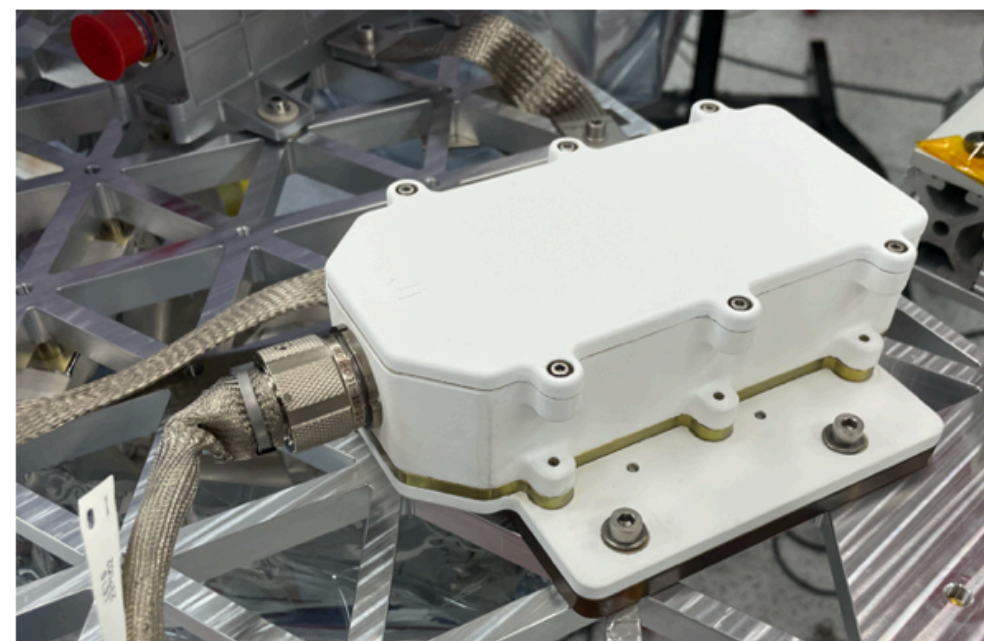
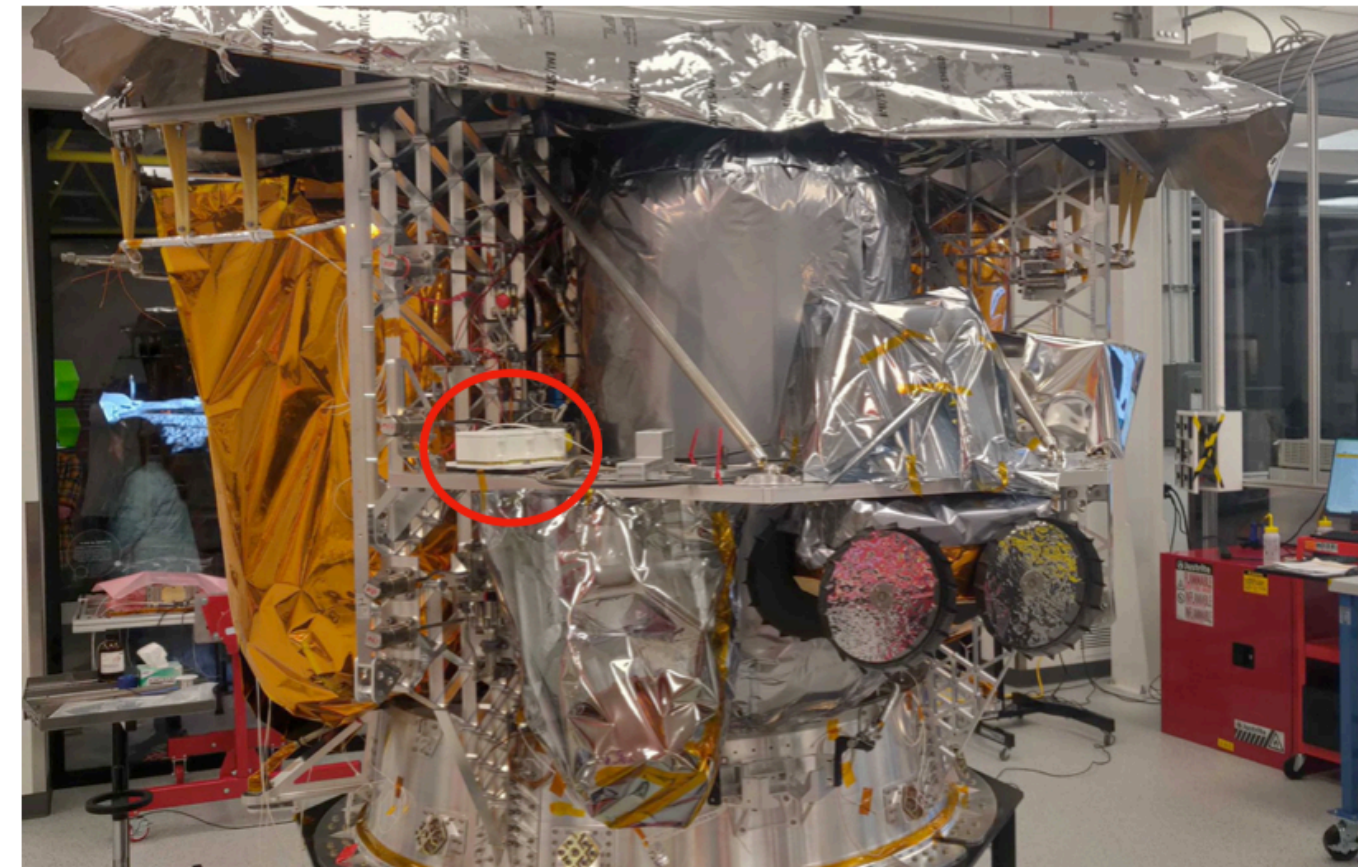
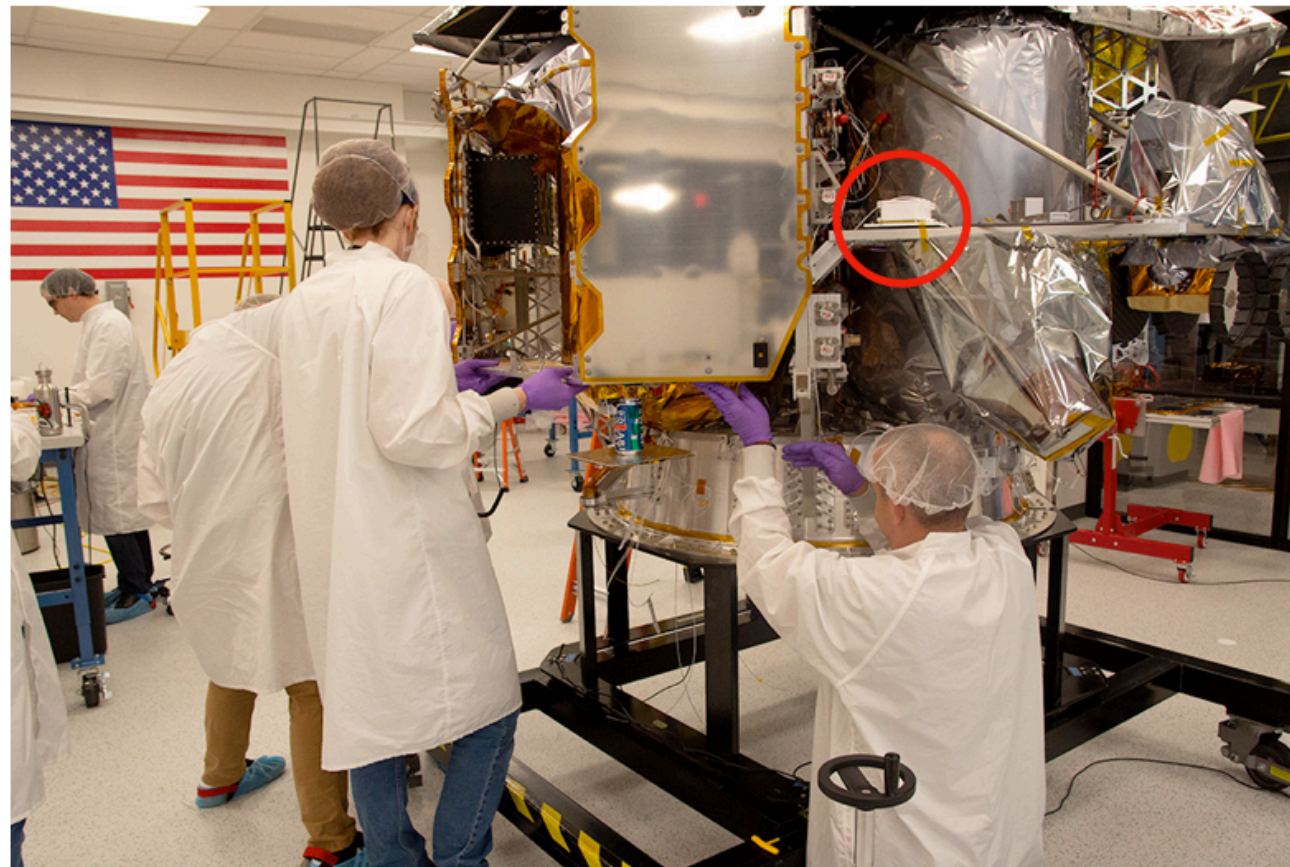
Some Preliminary Biosentinel Results



Biosentinel LET Spectra Jan 2023



Thank you for your attention



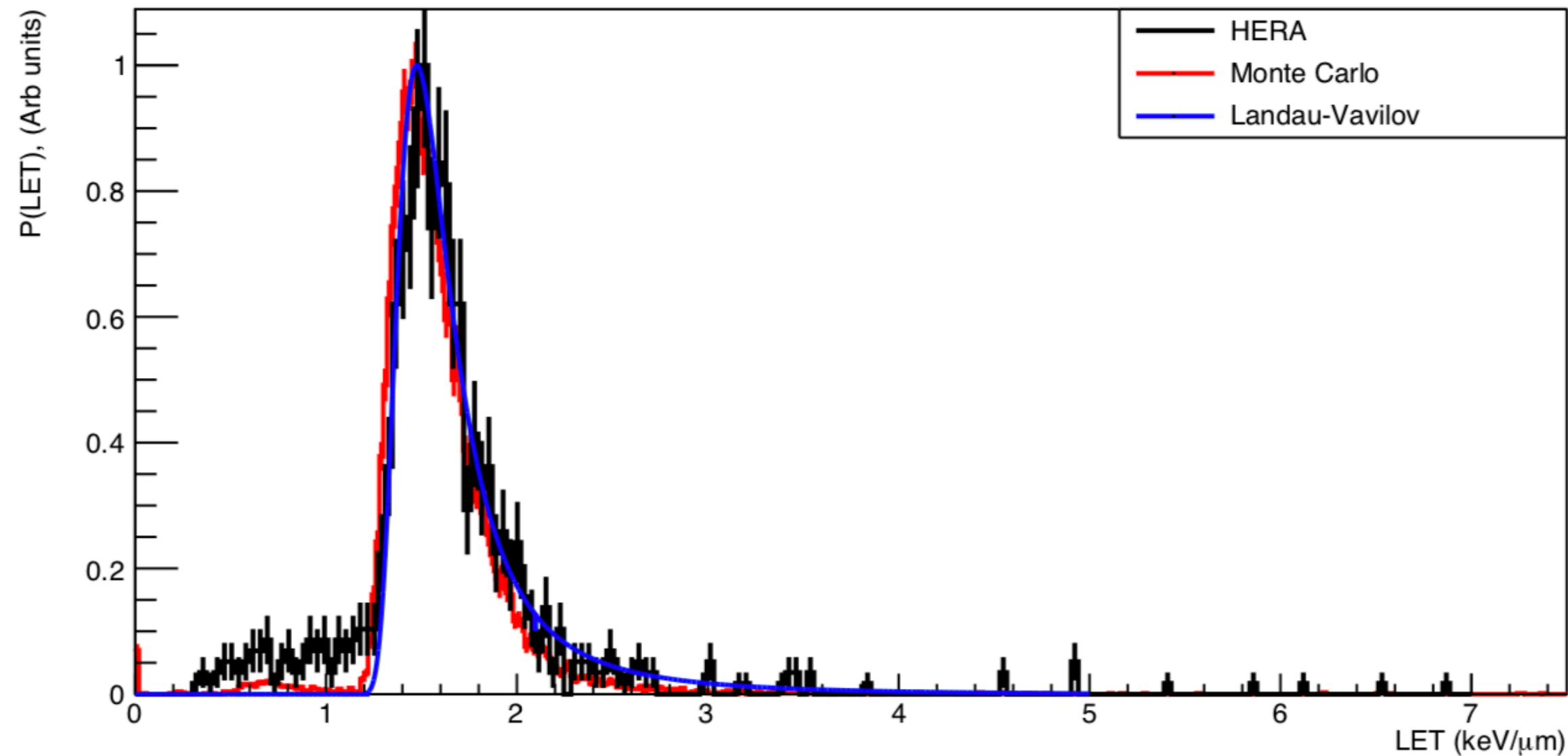
(Left) Timepix based "LETS" detector integrated into Astrobotic Peregrine lunar lander

(Right) SpaceX promo image of spacewalk during "Polaris Dawn" where a HERA will provide radiation monitoring

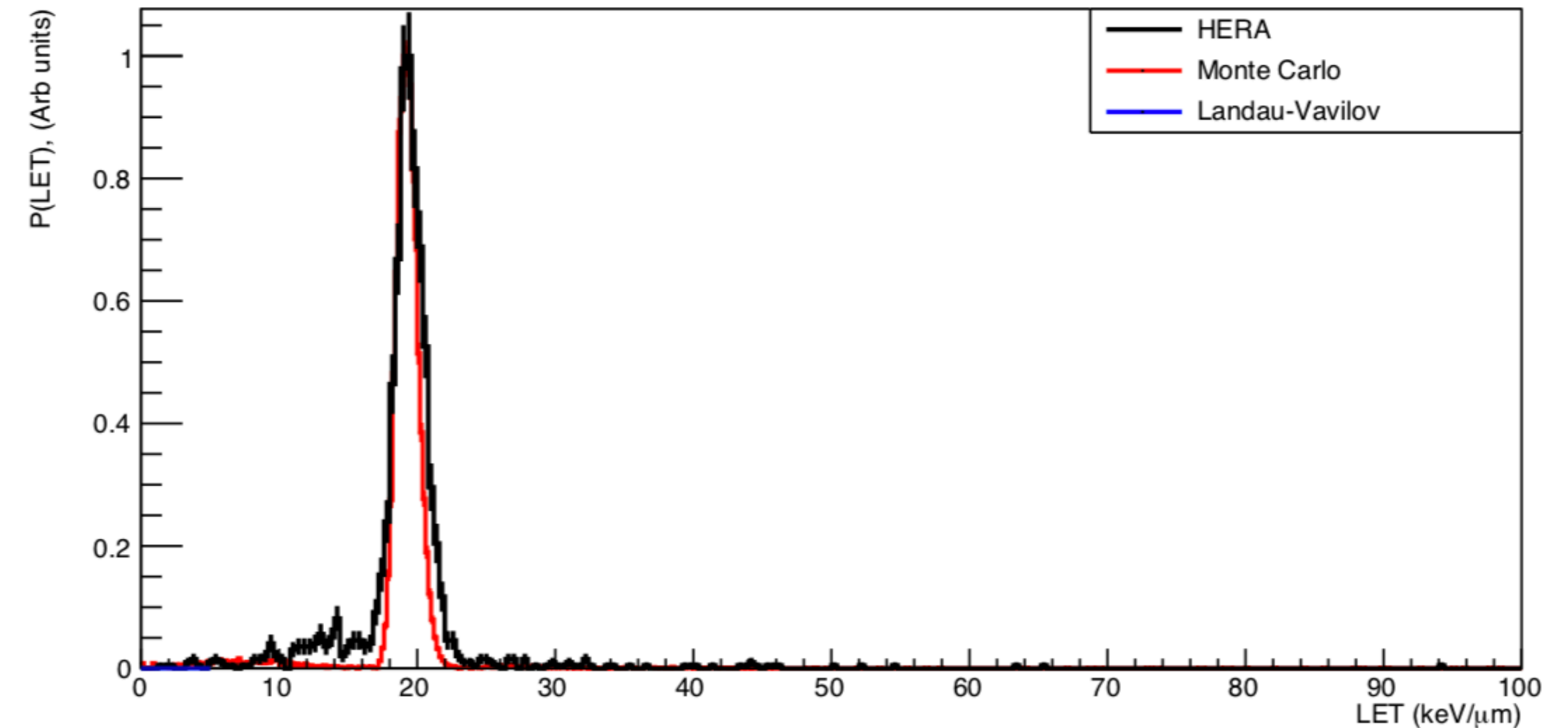
Both flights scheduled for later in 2023

Example LET/Stopping Power Measurements

LET Comparison for HSU1, z=2 a=4 e=1000.0_MeV/u $\phi=60$ $\theta=0$ 500 μ m sensor



LET Comparison for LSU, z=6 a=12 e=450.0_MeV/u $\phi=60$ $\theta=0$ 500 μ m sensor



Top left - Alpha (1 GeV/a)

Top right - Carbon (450 MeV/a)

Right - Protons (400 MeV)

Compared with Landau-Vavilov calculation and Geant4 Monte Carlo simulation of LET in 500 μ m silicon sensor. Livermore electromagnetic physics and INCLXX hadronic with 2 μ m physics cut.

