Latest Radiation Results from the Biosentinel and Astrobotic Peregrine Missions

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Medipix Collaboration Meeting

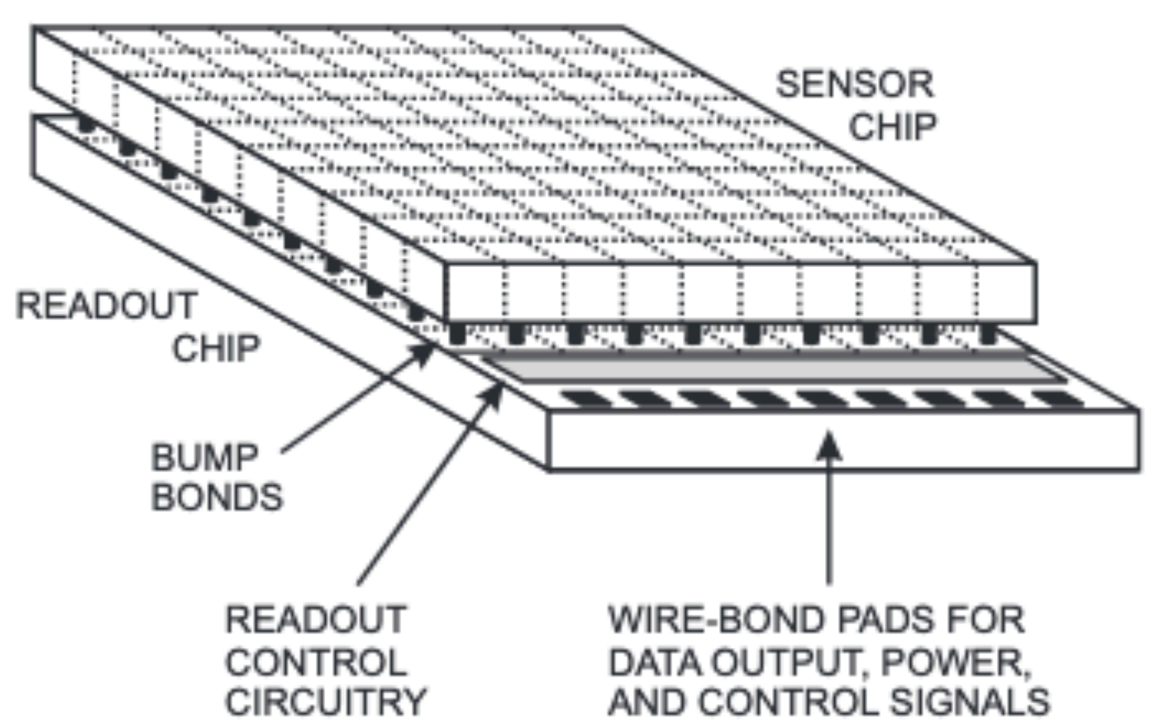
On Behalf of the LETS team (NASA JSC) and the Biosentinel Team (NASA Ames)

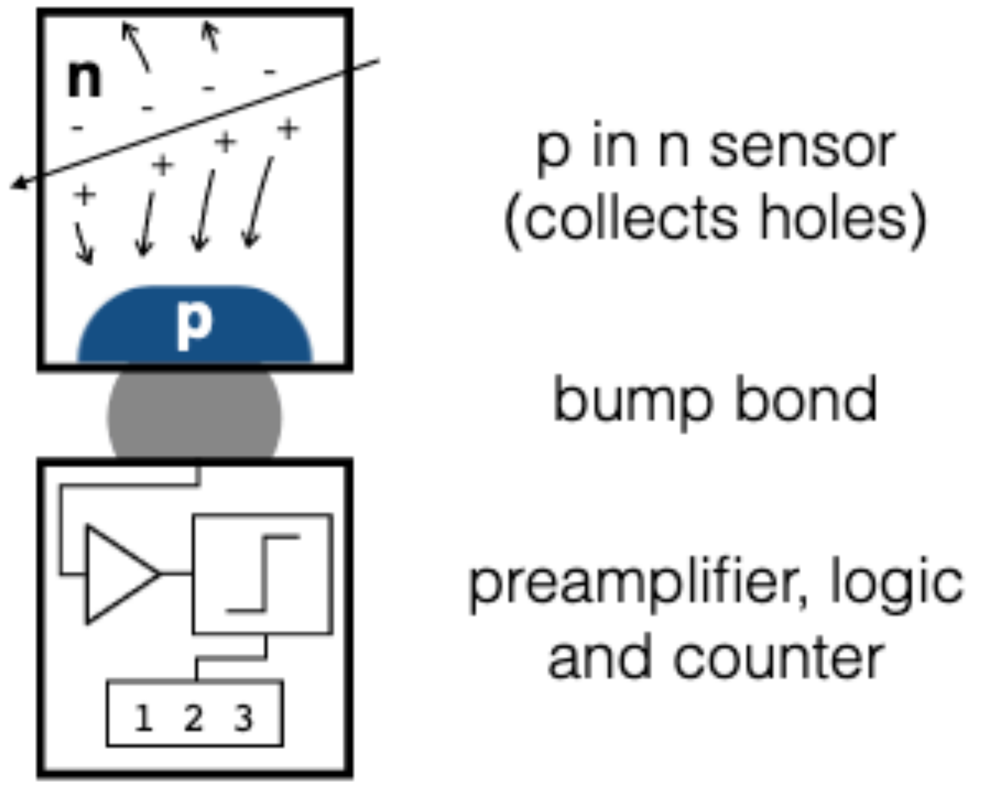
Introduction

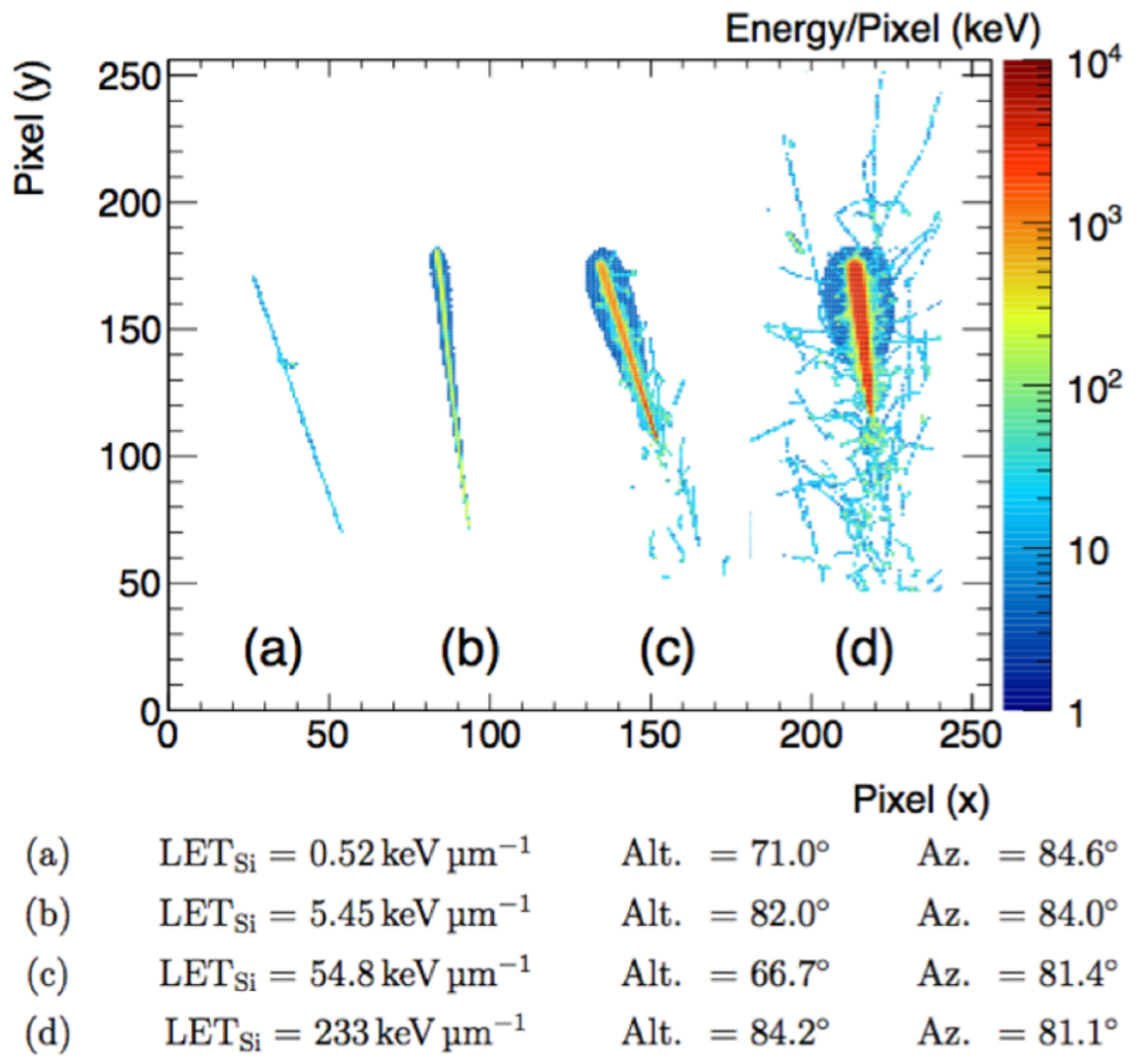
- This talk outlines radiation results from two uncrewed scientific radiation measurement missions - “Biosentinel” and “Astrobotic Peregrine”.
- Both missions feature LETS detectors designed by the NASA Radworks and Space Radiation Analysis Group
- Both these detectors use a Timepix detector designed by the Medipix2 collaboration for radiation measurements (>25 Timepix in space to date)
- Part of wider NASA program using Timepix detectors for crewed and uncrewed space radiation monitoring
- Both missions suffered significant problems - however are at least partially successful thanks in no small part to Timepix based instrumentation

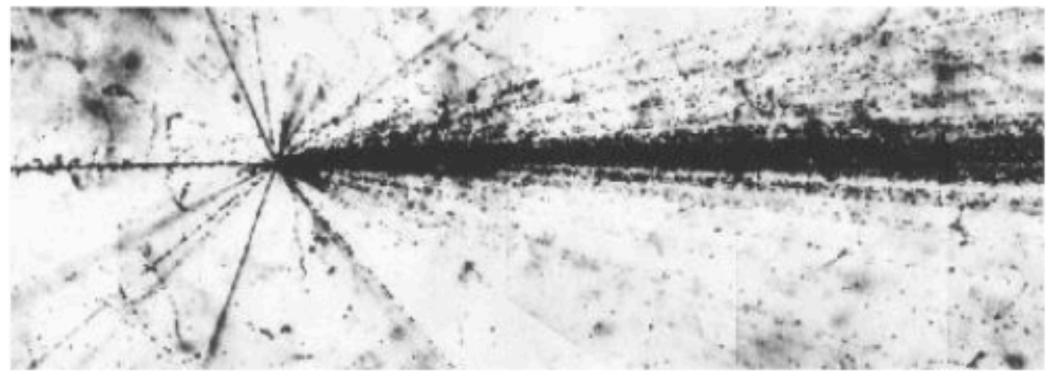
Why Use Timepix in Space

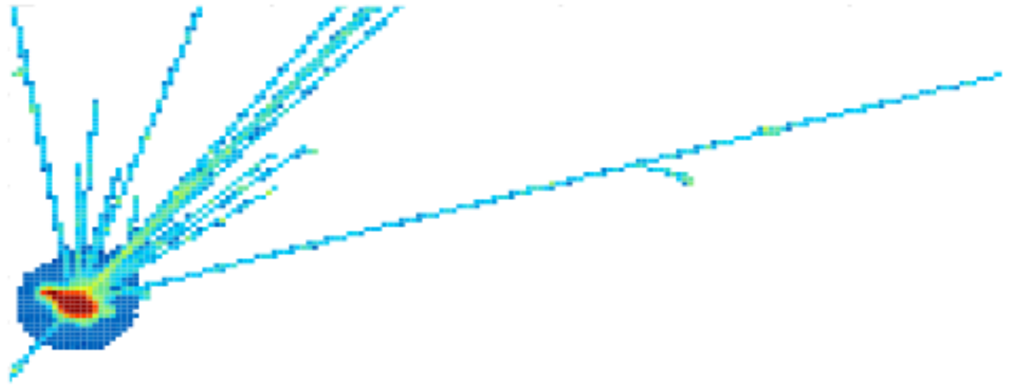
- 256 x 256 hybrid pixel detector array, Wilkinson type ADC where time over threshold can be calibrated to energy deposit. Min threshold 5 keV
- High energy range, with appropriate calibration can measure from 5 keV deposit in sensor to GeV deposits from heavy ions
- Analogue electronics integrated into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





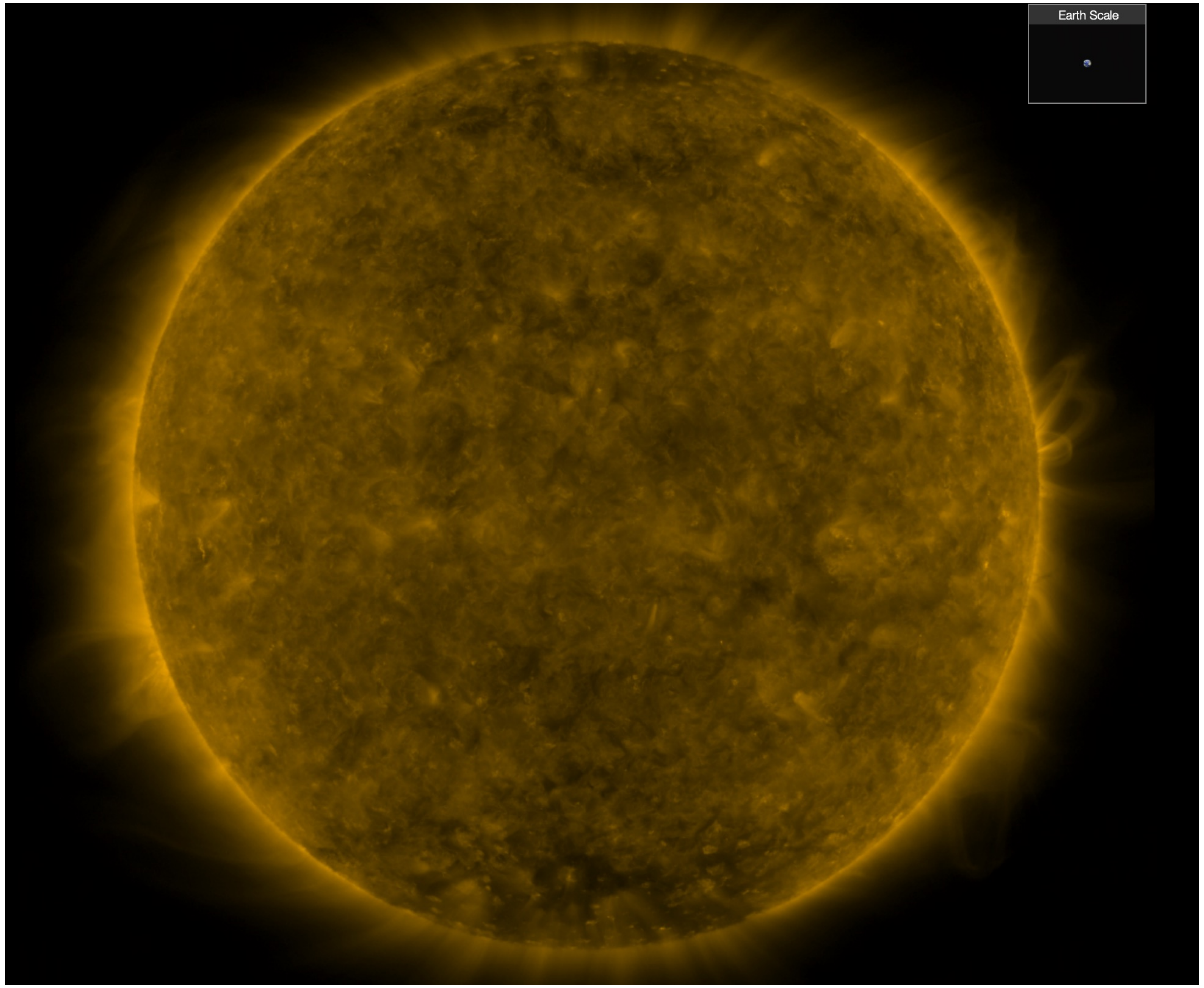




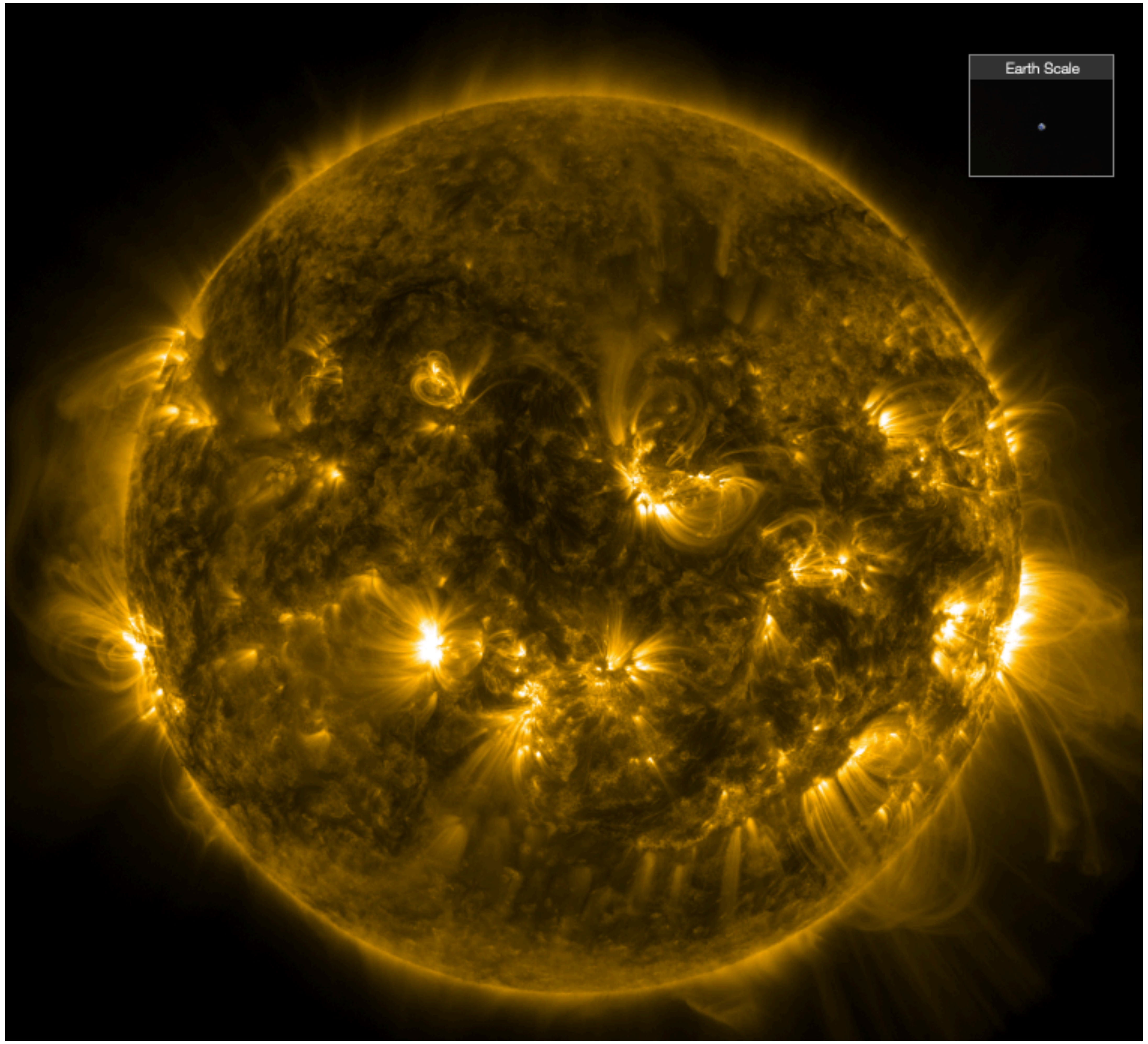


(Top) Schematic of Timepix Detector and individual pixel, (bottom left) example tracks in Timepix detector from ions (bottom right) example nuclear fragmentation in nuclear emulsion and Timepix showing analogy with ‘solid state nuclear emulsion’

Magnetically Quiet and Active Sun



Spotless Disk During Solar Min
Feb 2019 (SDO AIA Imagery, 171 nm)



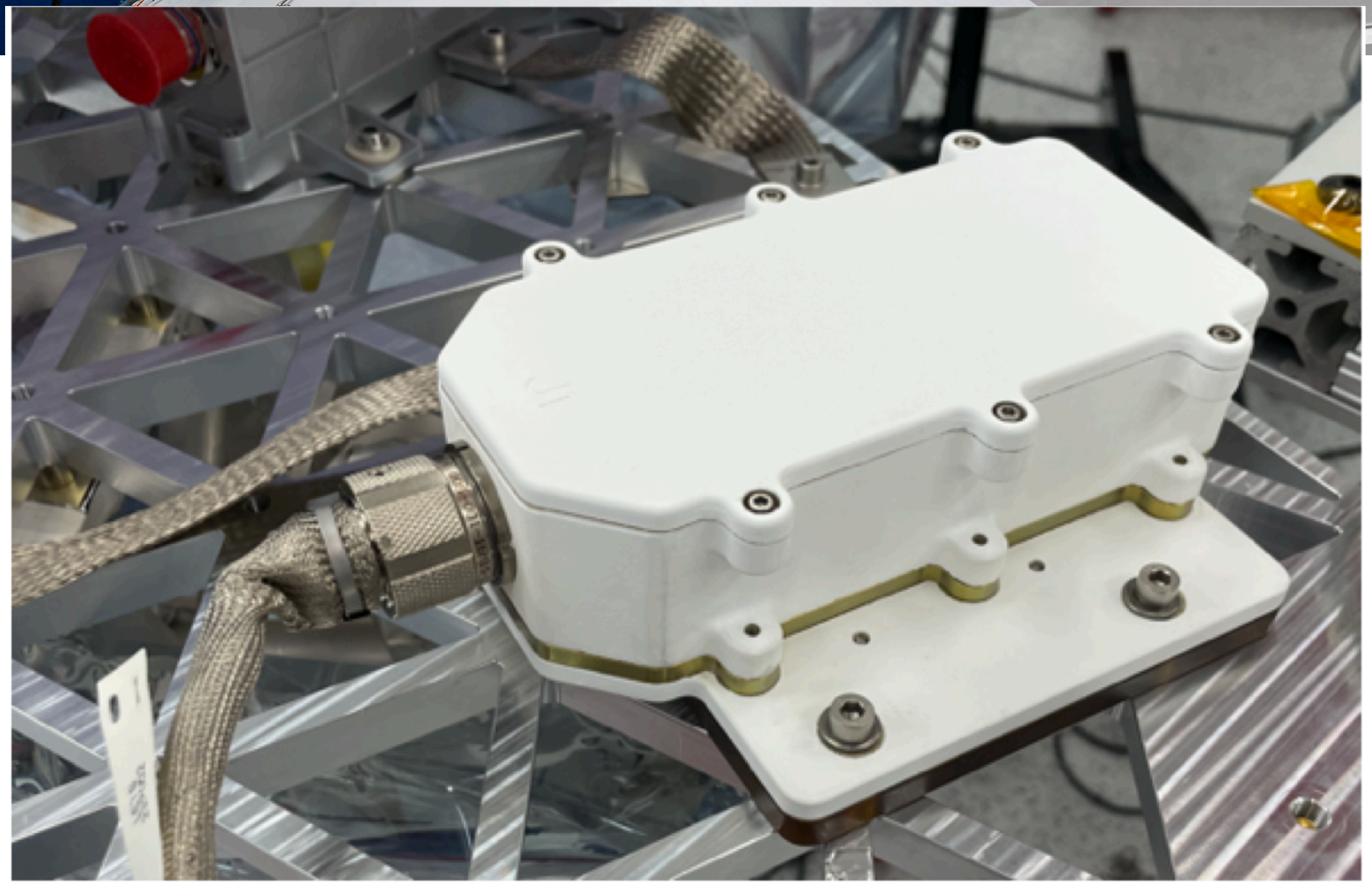
~Solar Max, Aug 2024 (SDO AIA 171 nm)

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
    - Various methods of calculations, but stopping power/LET based most amenable to measurement using ICRP60 method, Q = f(LET)
    - Results in average quality factor <Q> - **H = <Q>.D**
    - <Q> values for free space cosmic rays and **especially inside shielding** of wide scientific interest.
- Flux **F** - Found by multiplying measured count rates for detector by “Geometry Factor”. For Timepix Geometry Factor in isotropic field = 13.34 $cm^{-2}sr$, Flux units - $N.cm^{-2}sr^{-1}s^{-1}$

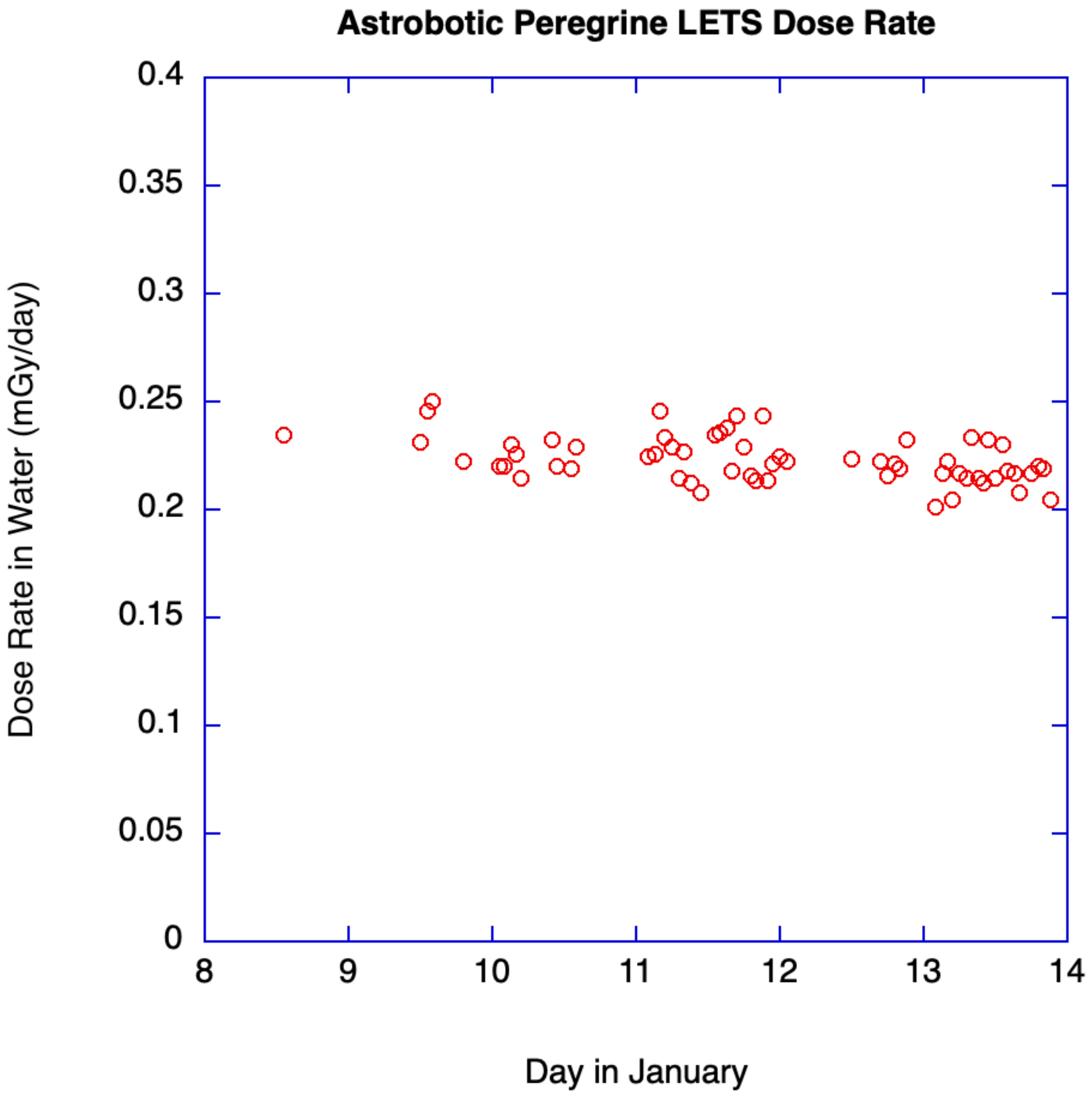
LETS on Astrobotic Peregrine

- First NASA “Commercial Lunar Payload Services” mission
- Feature 5 NASA science payloads include “LETS” detector
- LETS placed next to DLR M-42
- Goals of LETS detector - measure lunar surface environment (primary), measure cruise environment (secondary)
- LETS detector = power + processing/data reduction + thermal system + timepix
- Launched January 8th 2024 on Vulcan Centaur Rocket
- Suffered failure of propulsion system shortly after separation of Vulcan Centaur
- Maintained power and data (somewhat intermittently) until reentry August 18th



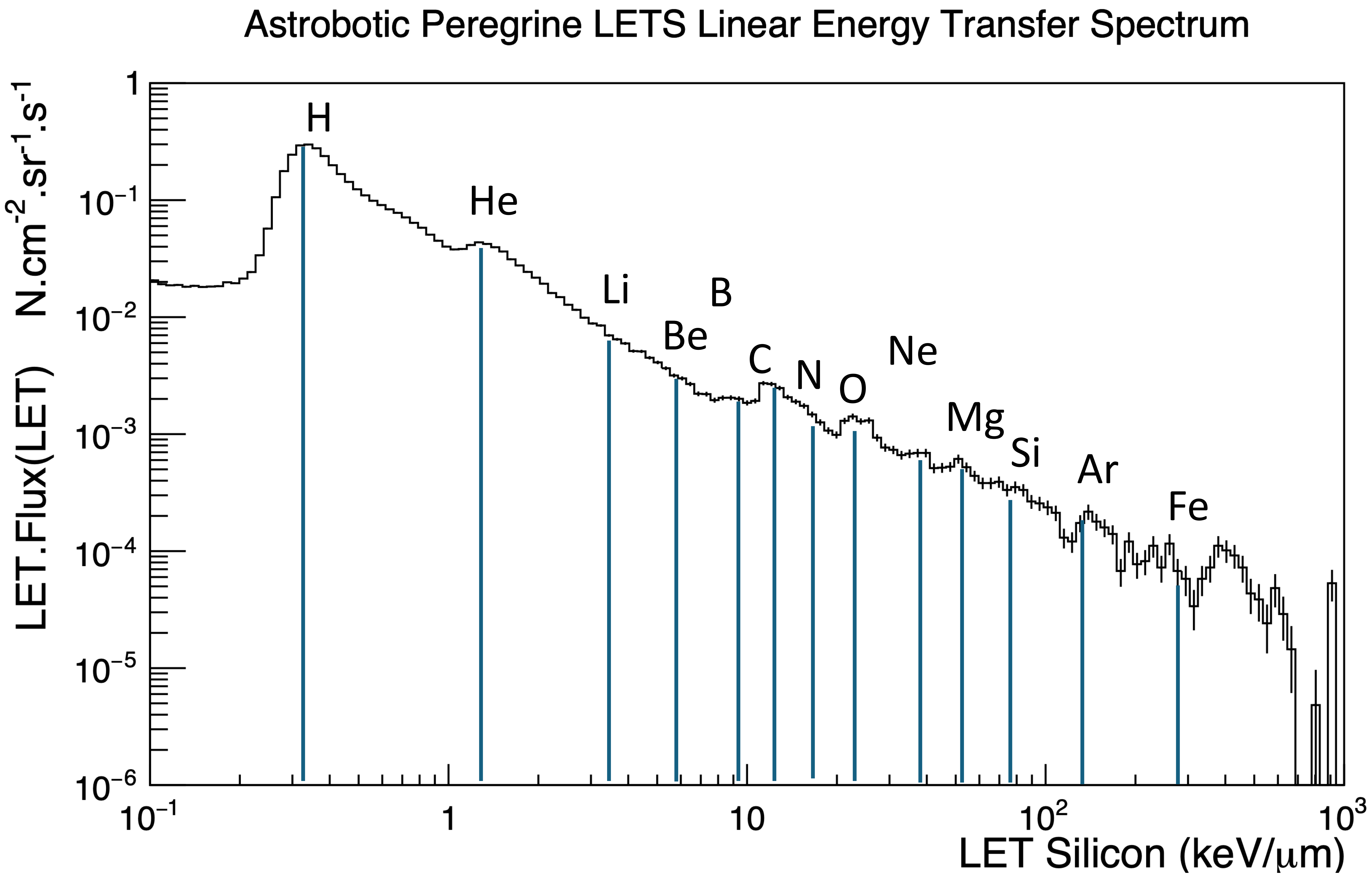
Peregrine Measurement Results

- Data at '1 hour' cadence - needed due to stringent data constraints during mission (1.5 kB/hr)
- Most downlinked in intermittent telemetry windows
- Measured absorbed dose rate (converted into "water/tissue")
- Shows slight downward trend inline with reducing solar protons over mission
- Average mission dose of 0.223 mGy/day.
- Average mission dose equivalent of 1.12 mSv/day

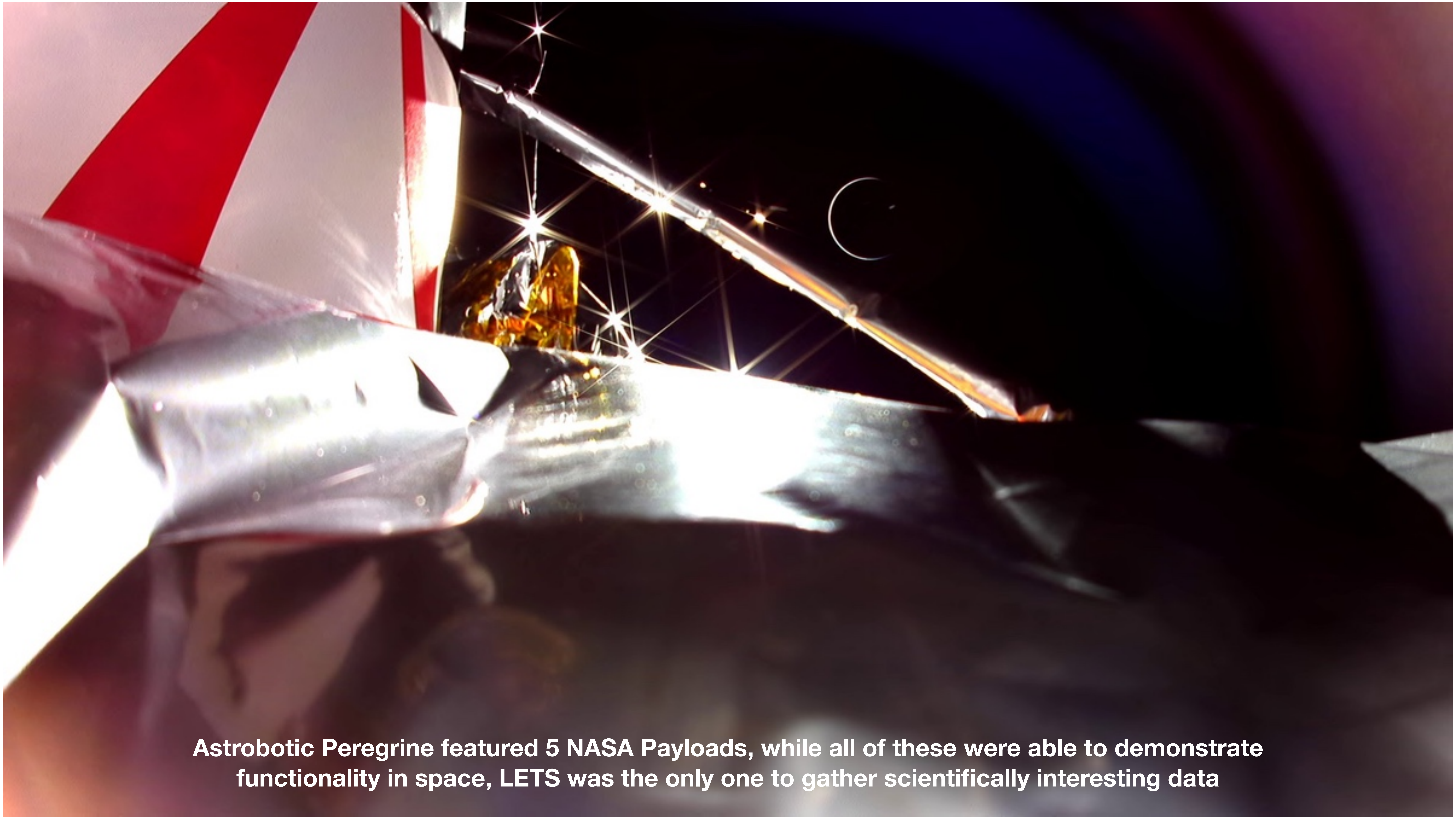


LETS Linear Energy Transfer Spectrum

- Measured LET spectrum for the deep space portion (all) of the AB mission.
- One of the primary quantities we set out to measure.
- Peaks in spectrum from different components of cosmic ray spectrum (hydrogen, helium etc)
- From it we can calculate a quality factor of 5.2.
- This is how much more biologically detrimental the space radiation is than common terrestrial sources.
- From this and the dose rate measurements on the instrument we can have measured the interplanetary dose equivalent rate (Which is how biologically bad the radiation is) for a lightly shielded vehicle/instrument at close to the maximum of the solar cycle.



Lines show the theoretical expectation for the Minimum Ionizing MPV for GCR heavy ions



Astrobotic Peregrine featured 5 NASA Payloads, while all of these were able to demonstrate functionality in space, LETS was the only one to gather scientifically interesting data

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 ~35M km away

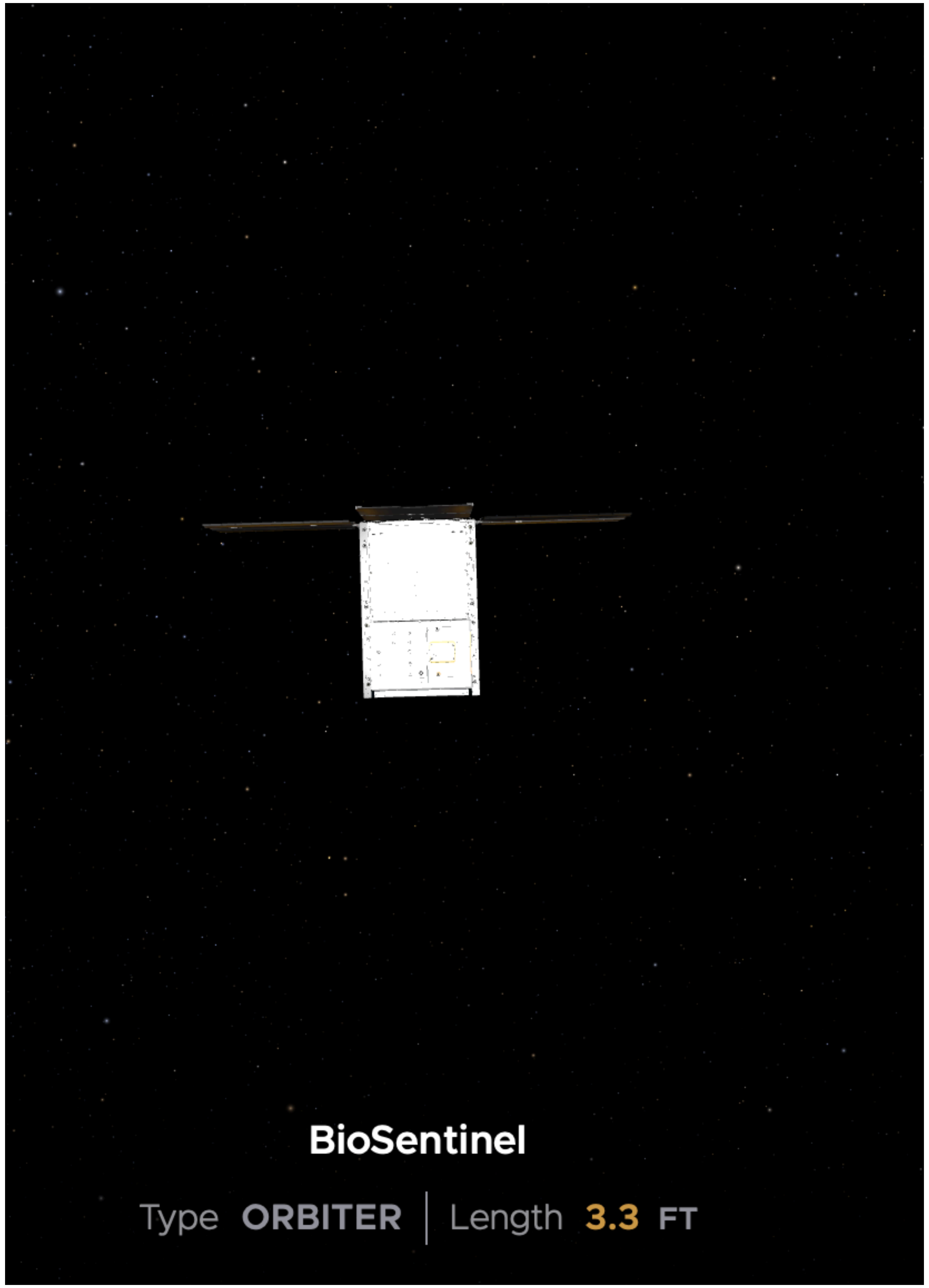
- Originally intended as a six month radiation biology experiment the biology part failed to function most likely due to the long pad stay of Artemis I. Radiation hardware is an early LETS board supplied by JSC Radworks

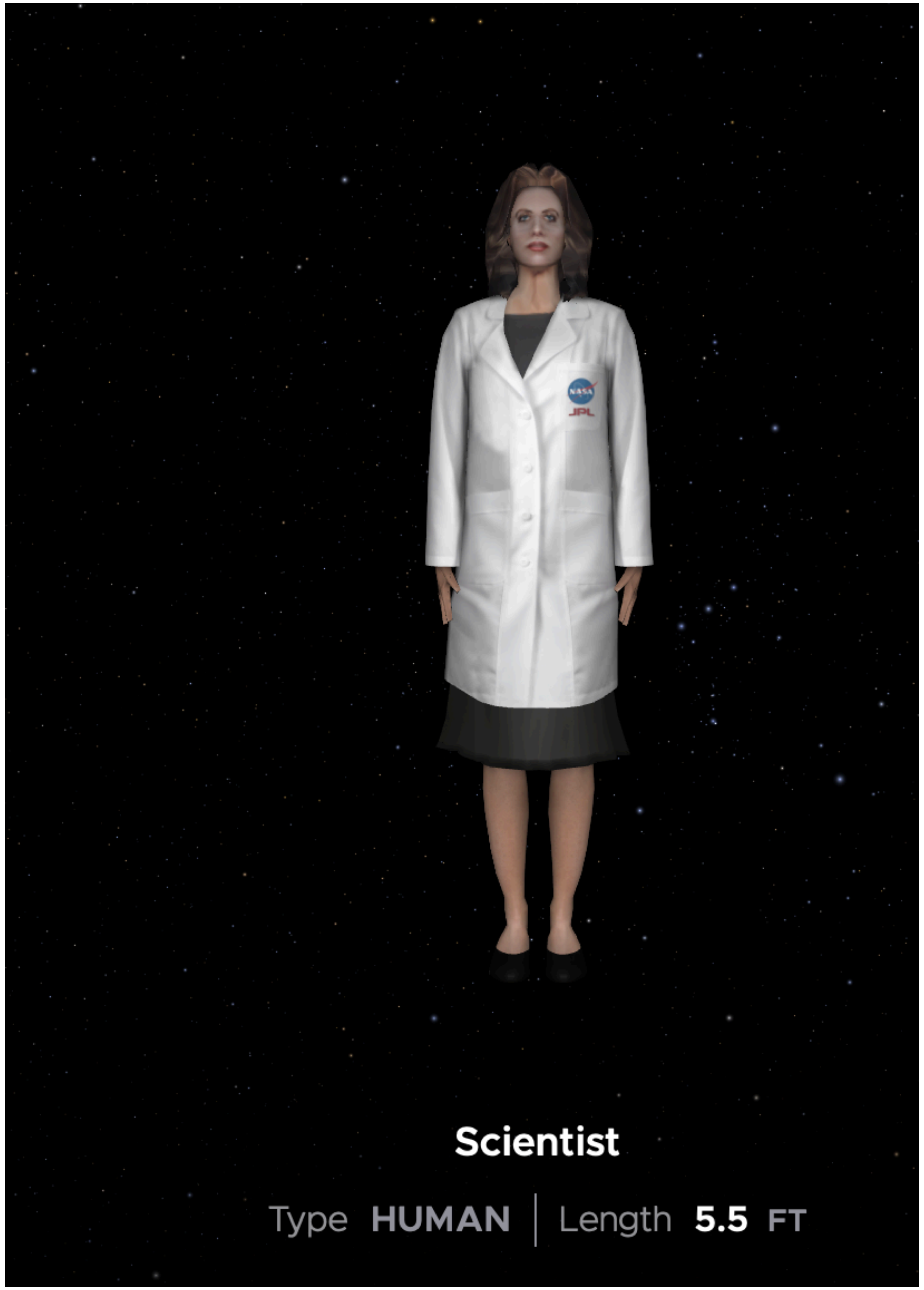
- Mission extended twice, once by NASA Moon to Mars program and once by NASA Heliophysics, end date now Dec 2024 (we hope for more extensions)

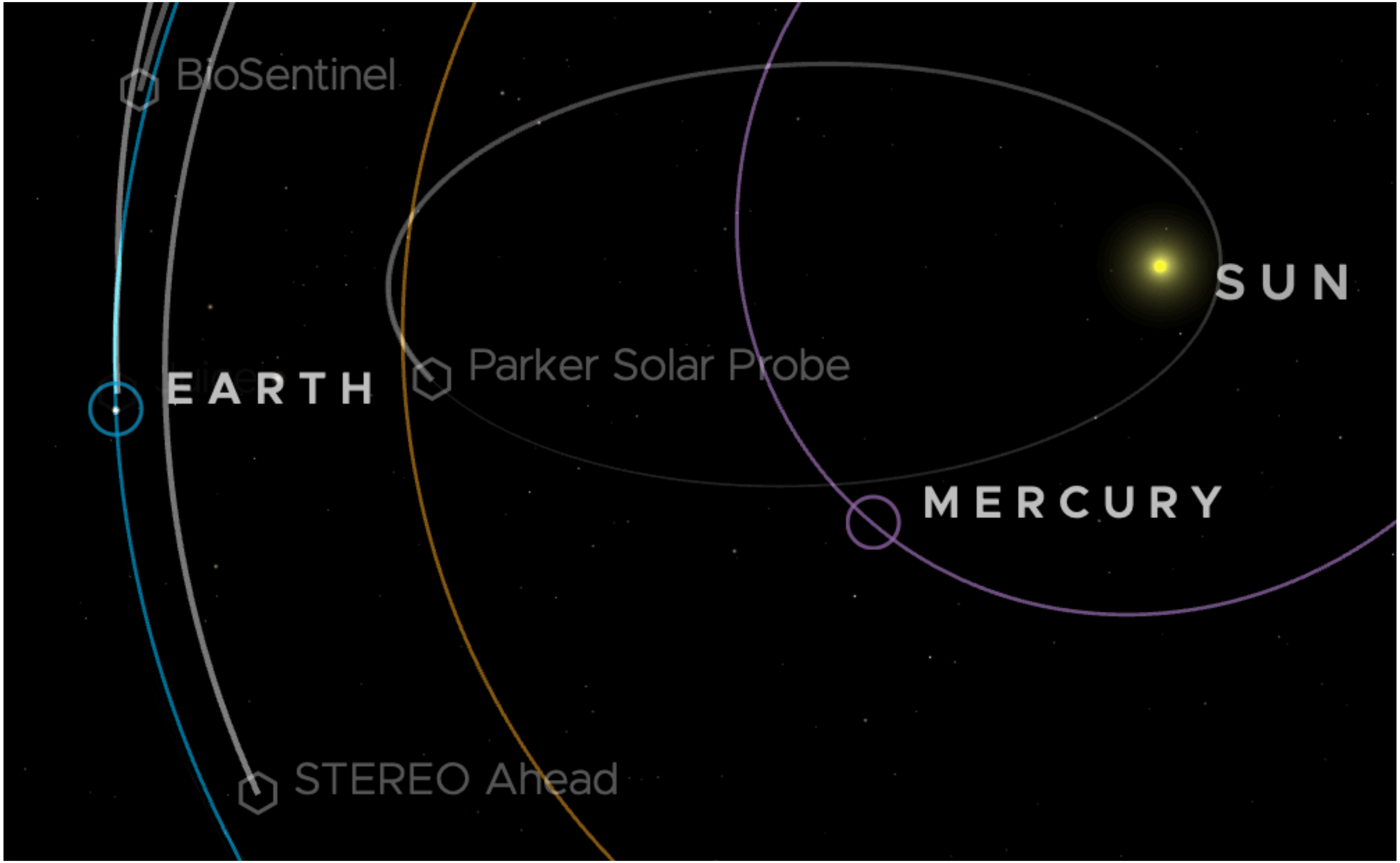
- Biosentinel is the only energetic particle measurement asset (or space weather asset) in its position in the heliosphere

- Long term goal - adapt Biosentinel data products (dose, LET etc) to Heliophysics objectives

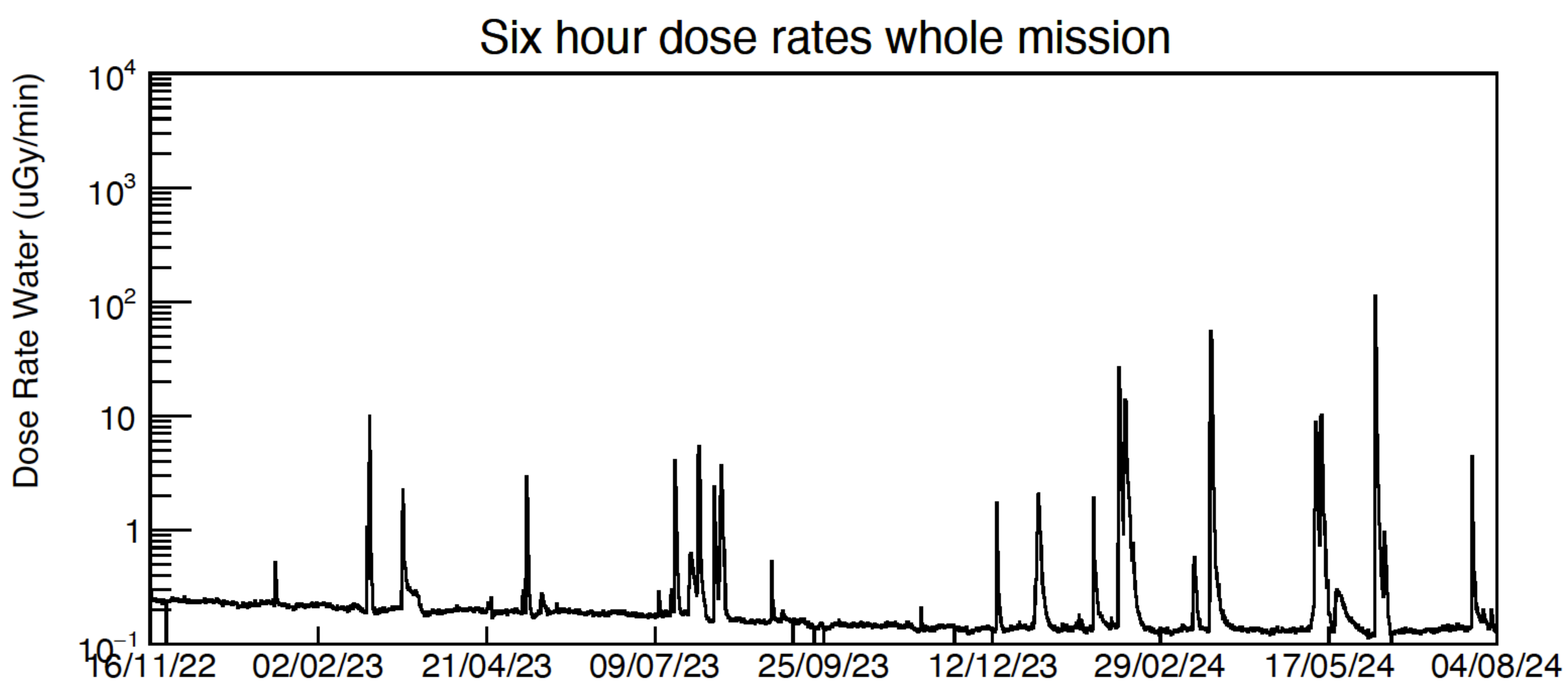
- Biosentinel gathers minute wise dose and stopping power data, downlinked once weekly over DSN

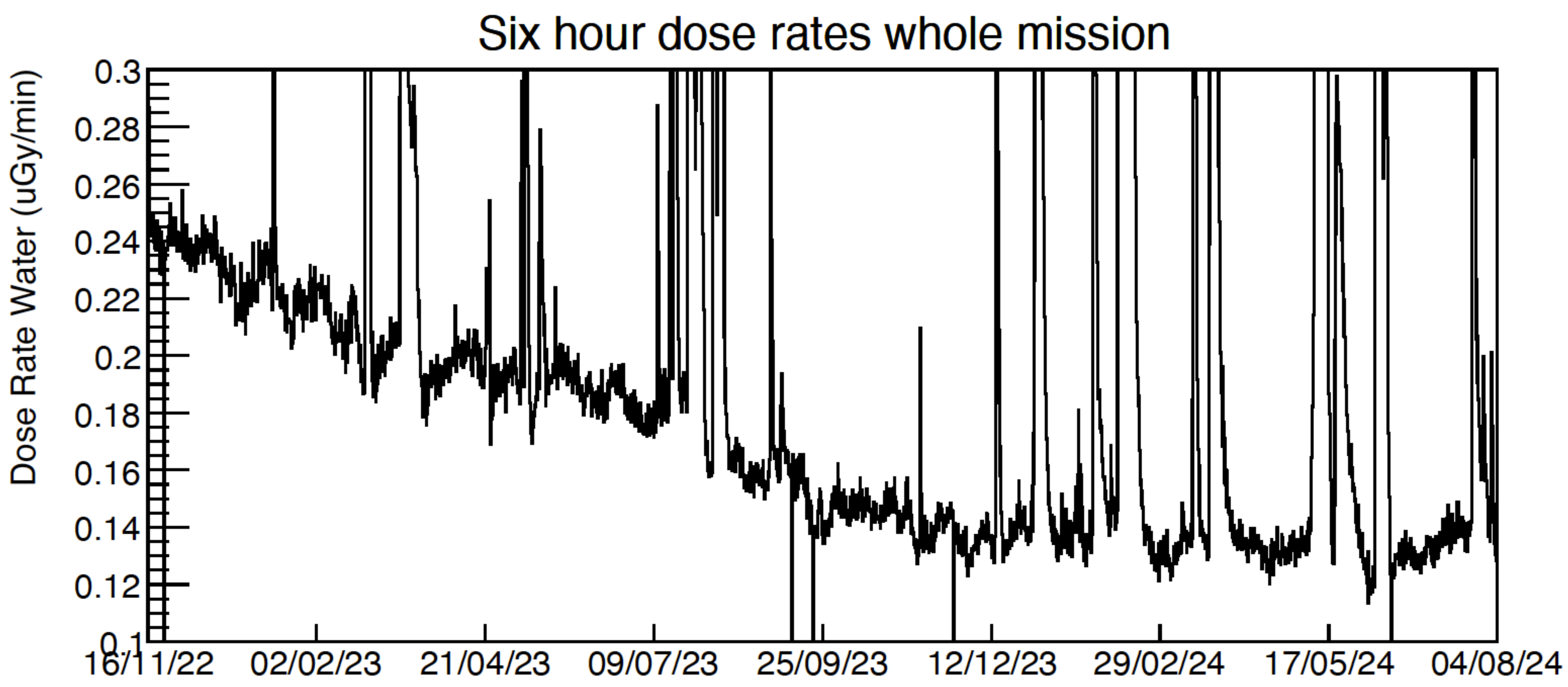

BioSentinel
Type ORBITER | Length 3.3 FT


Scientist
Type HUMAN | Length 5.5 FT



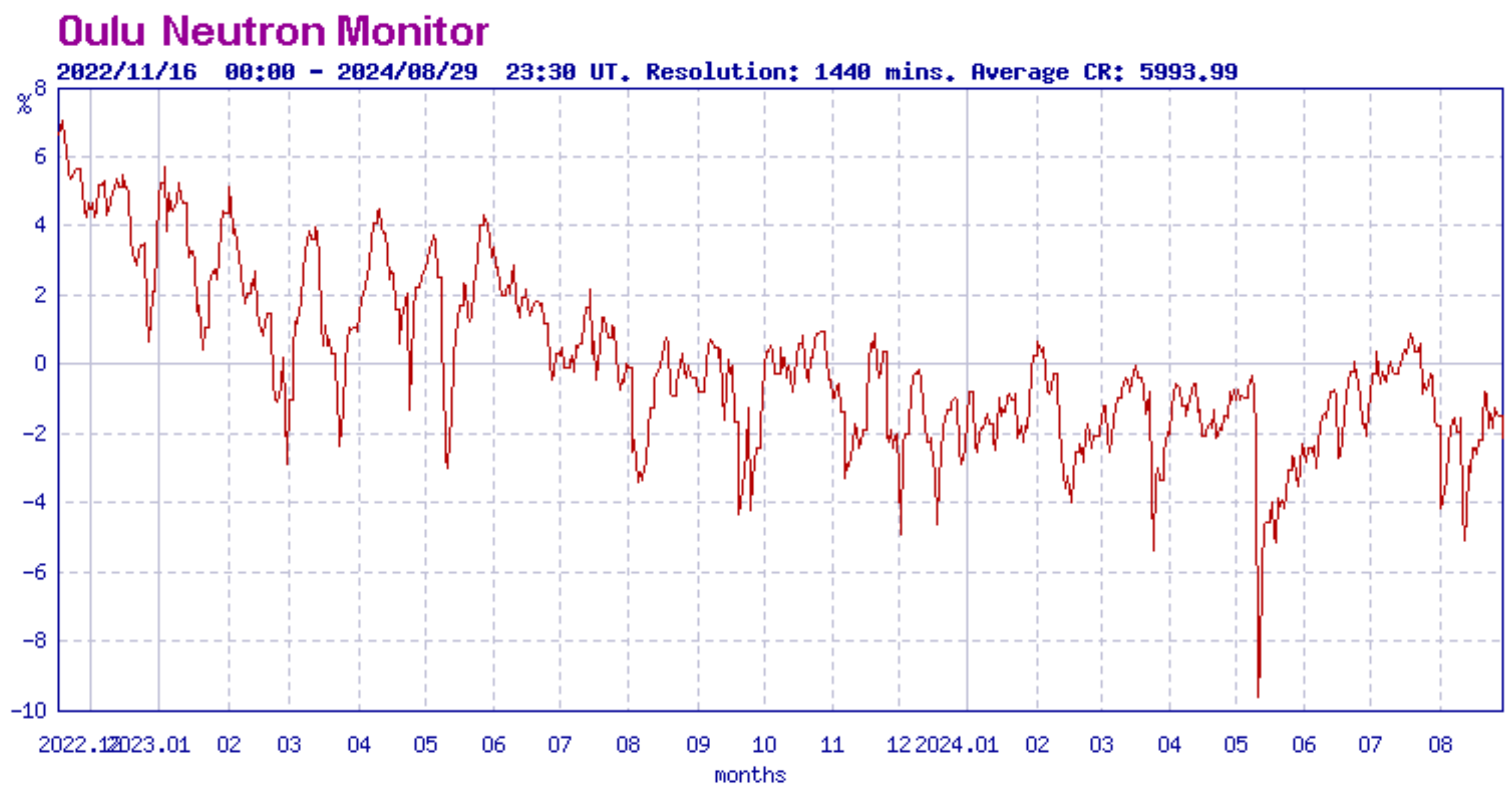
Biosentinel now ~50M km from Earth, in operation for 652 days (far exceeding its design mission of 6 months)



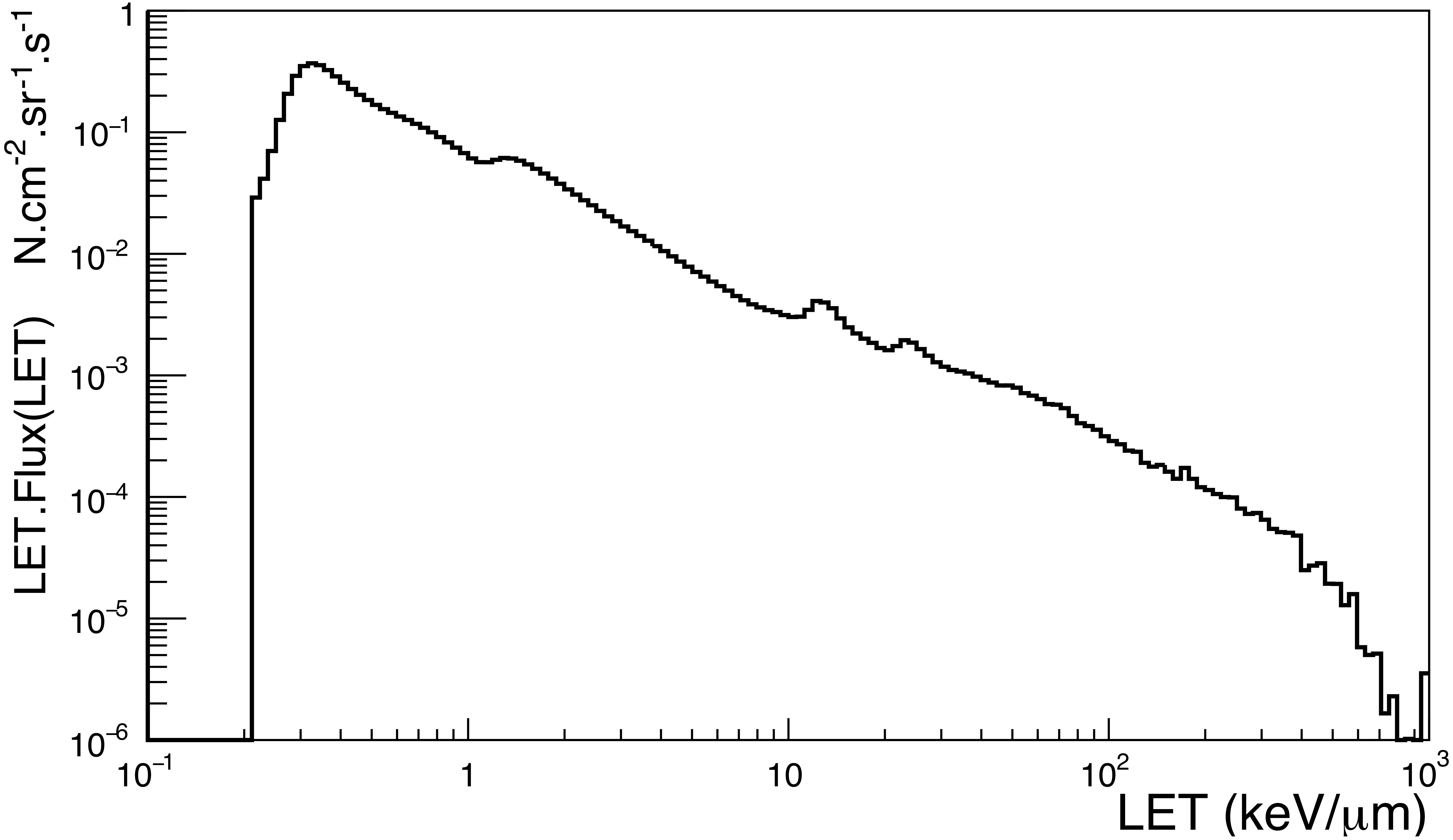


Dose Measurements Heading into Solar Maximum

- Dose rate approximately 60% of what it was in November 2022
- Now largely flat
- 27 solar particle events (of varying size)
- Largest was S3 storm from June 2024, ~85 mGy total event dose
- Big Forbush decrease in Oulu NM after May CMEs only slightly visible in Bios - confusion from prior SPE?

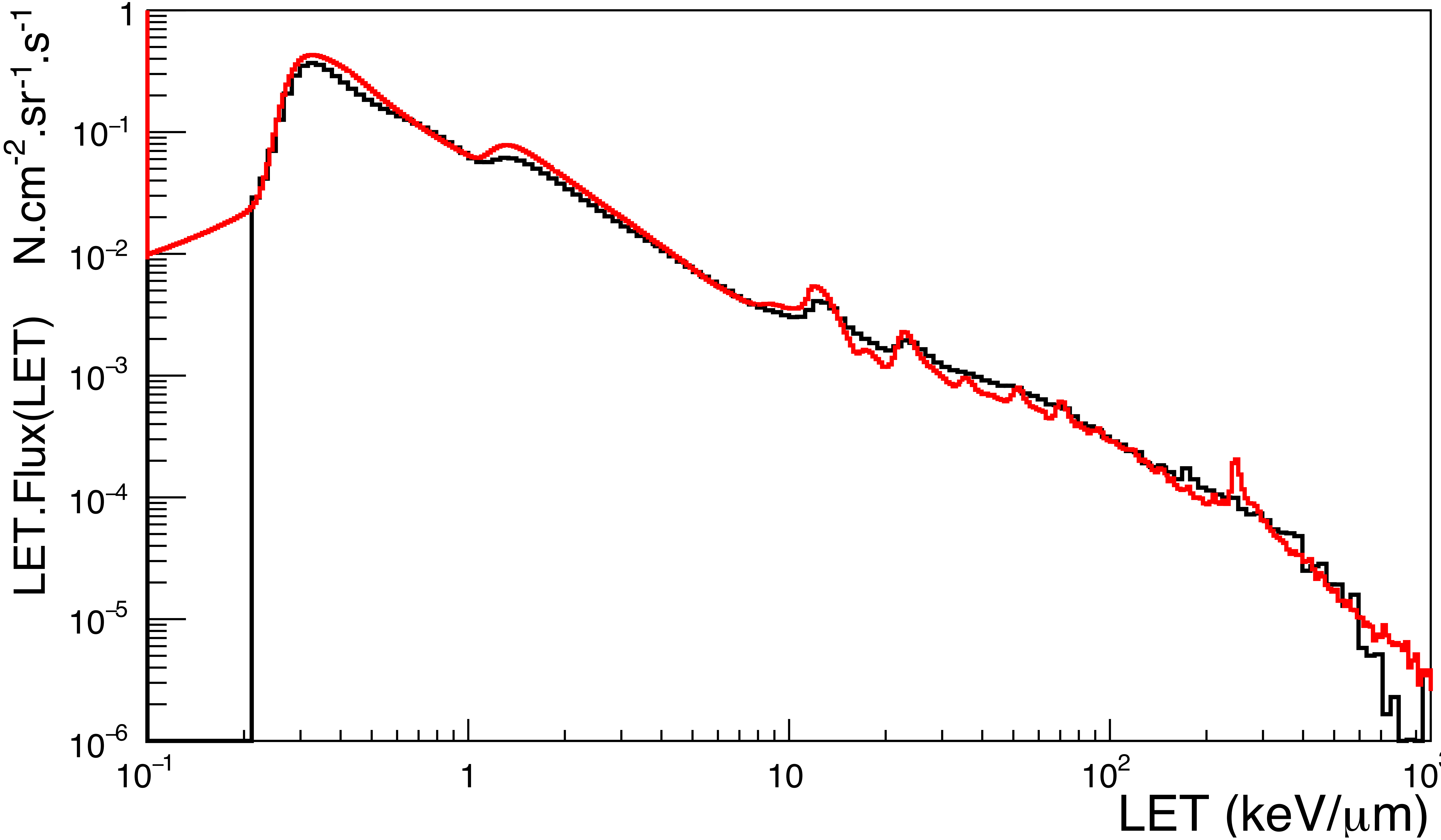


GCR LET Spectra Measurements



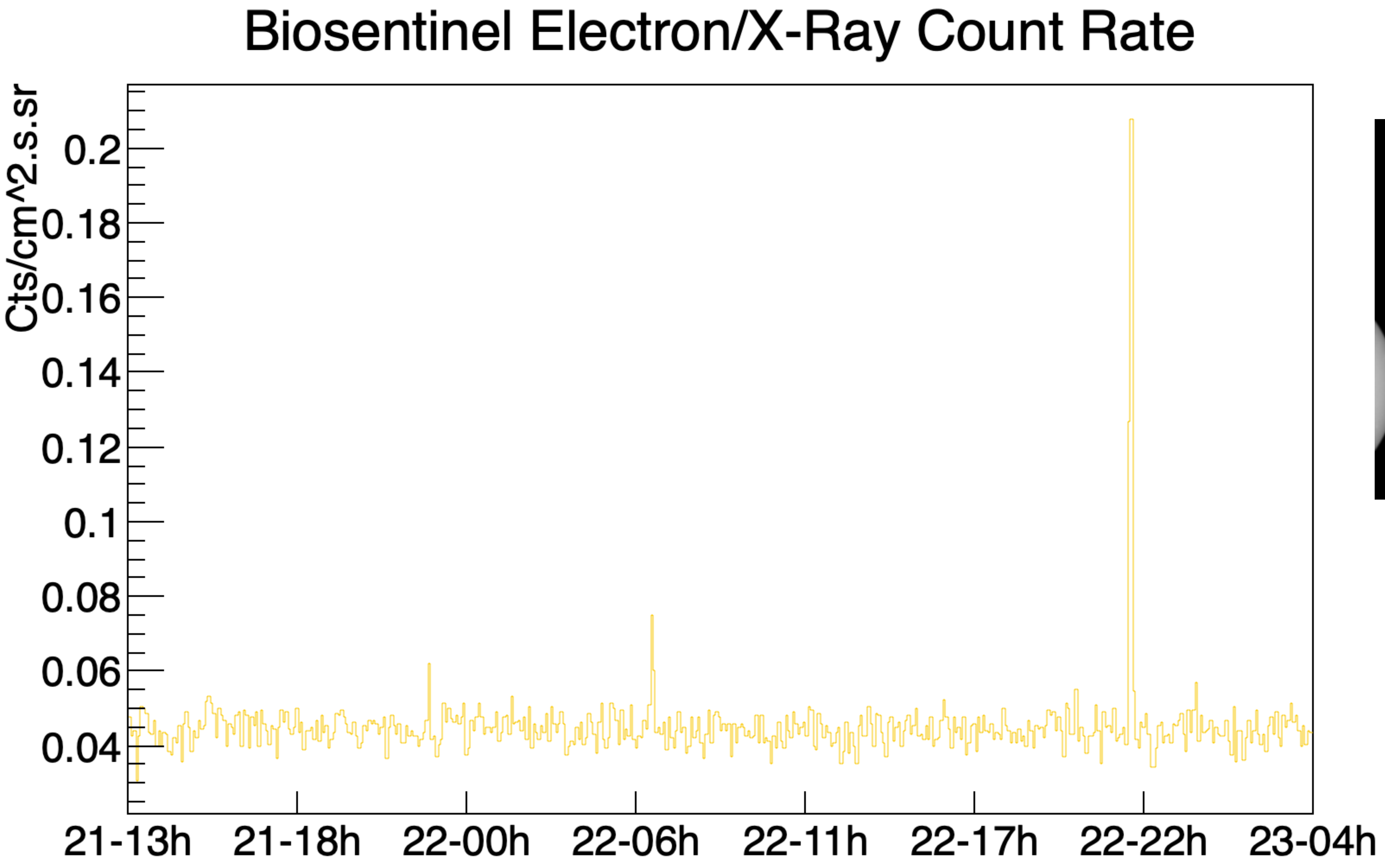
<u>GCR LET Spectra <Q> = 4.1 (compare to Astrobotic Q = 5.2, why? Biosentinel is more shielded, ~8g/cm2 vs 2g/cm2)</u>
<u>Biosentinel and Astrobotic Peregrine provide key data for benchmarking free space GCR flux models and transport models through shielding</u>

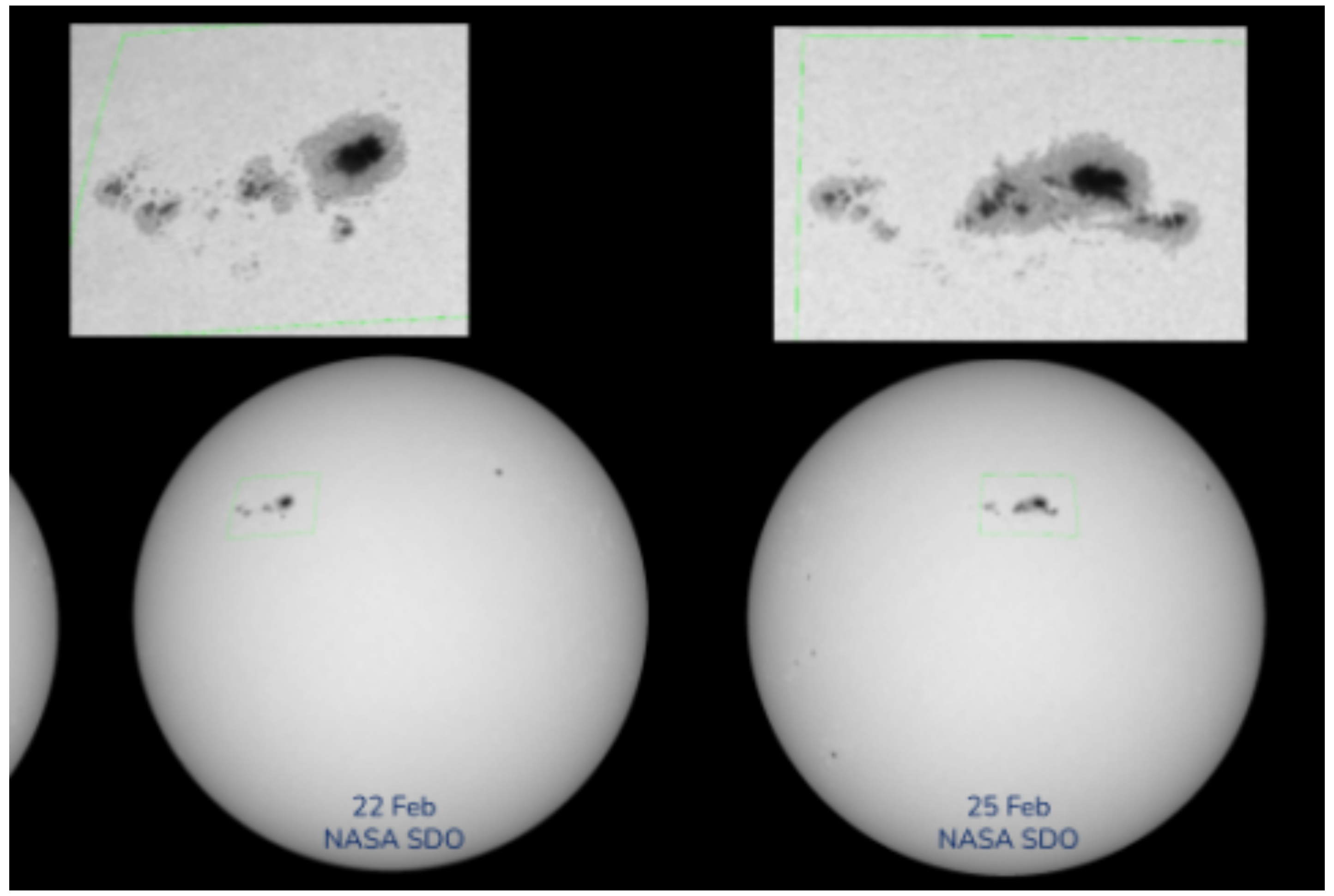
Biosentinel v2 HZETRN All Particles

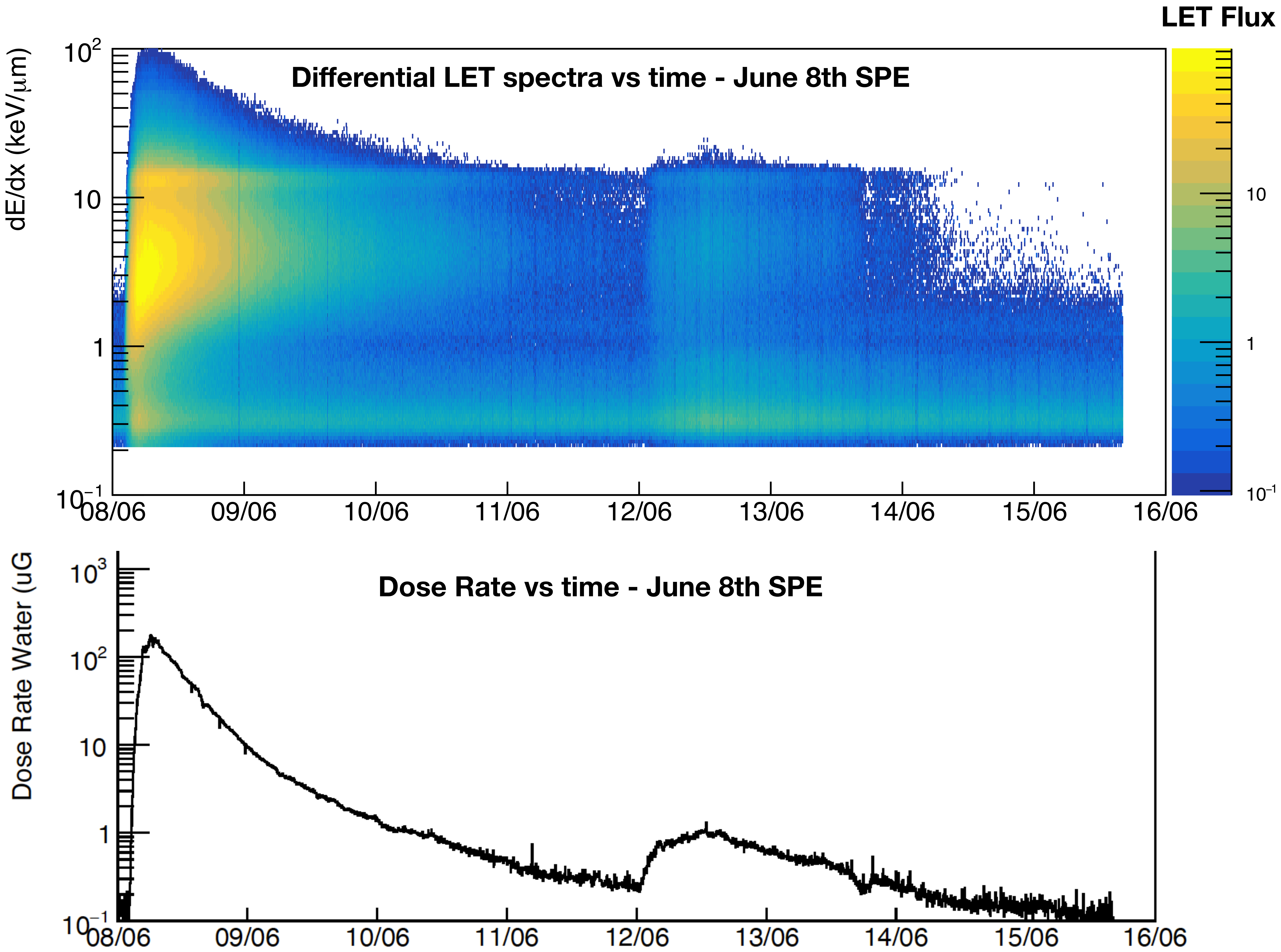


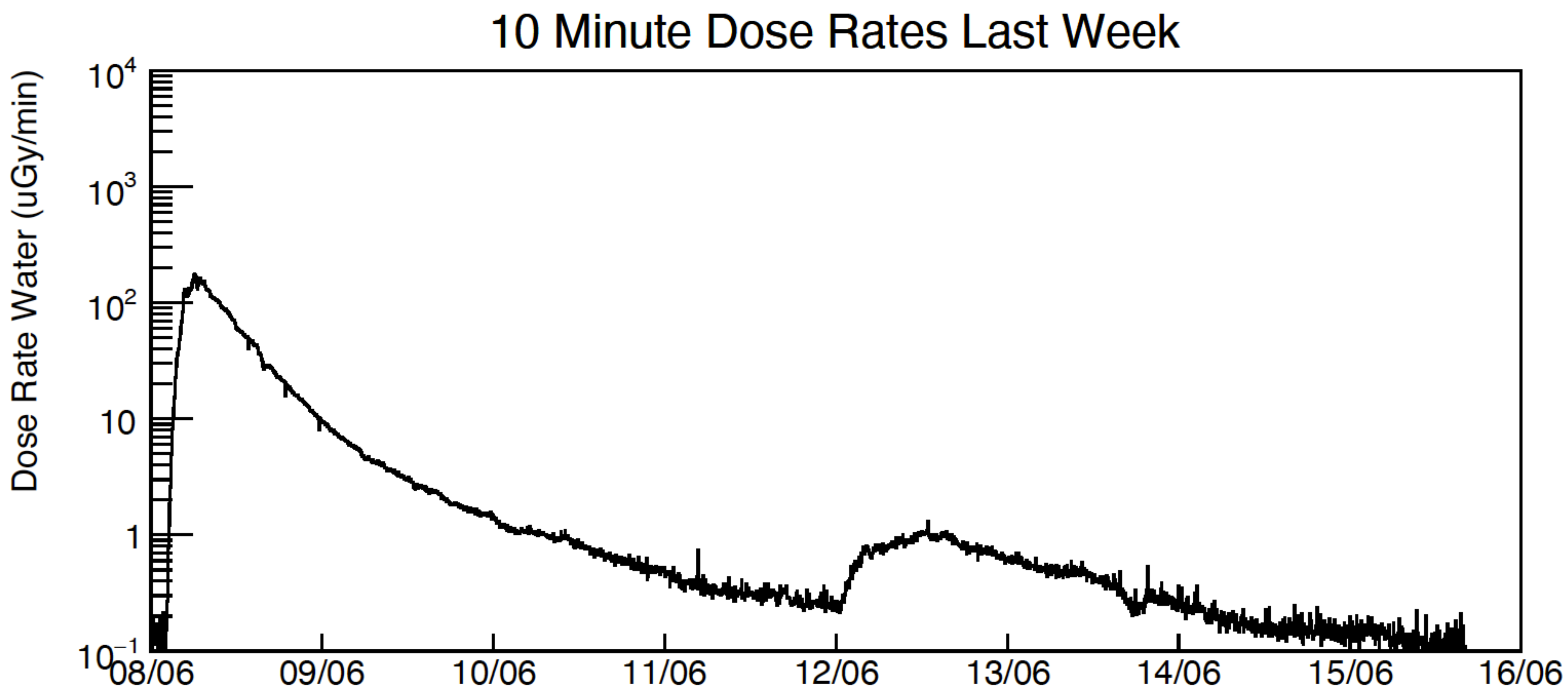
HZTRN Validation (T. Slaba and S. George) - HZETRN for transport through ray traced shielding distribution and Geant4 (INCLXX Hadronic Physics, Livermore EM, 2um cut) for LETS response

Multiple X Flares - Region 3590






LET Flux
Differential LET spectra vs time - June 8th SPE
dE/dx (keV/μm)
08/06
09/06
10/06
11/06
12/06
13/06
14/06
15/06
16/06
Dose Rate vs time - June 8th SPE
Dose Rate Water (uG



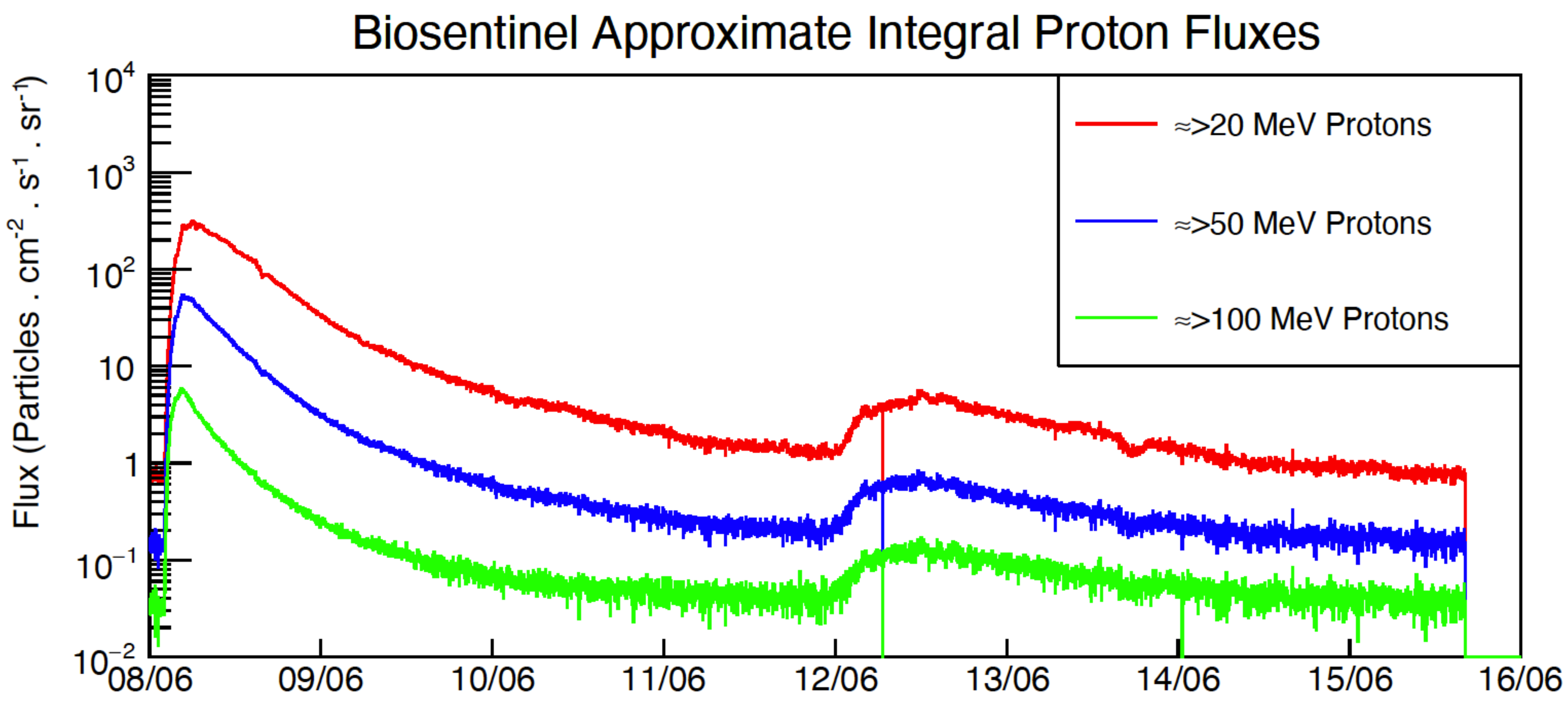


Figure 3: Biosentinel Integral Proton Flux Counts (Uncalibrated)

Dose Rates Feb ESPE

- Proton fluxes based (at present) on dE/dX cuts
- More sophisticated 'response function' based on Monte Carlo simulations with ray traced shielding distributions in work
- Very comparable to NOAA GOES data
- Now that Biosentinel is getting further away significant differences emerging.
- Biosentinel data helping to disentangle the record of complex events on an active sun

Biosentinel Future Developments

- **Long term goal - adapt Biosentinel data products (dose, LET etc) to Heliophysics objectives**

- Biosentinel can see - energetic protons, electrons and large (x-class) solar flares

- It will be positioned to do so from a unique vantage point in the Heliosphere during solar maximum

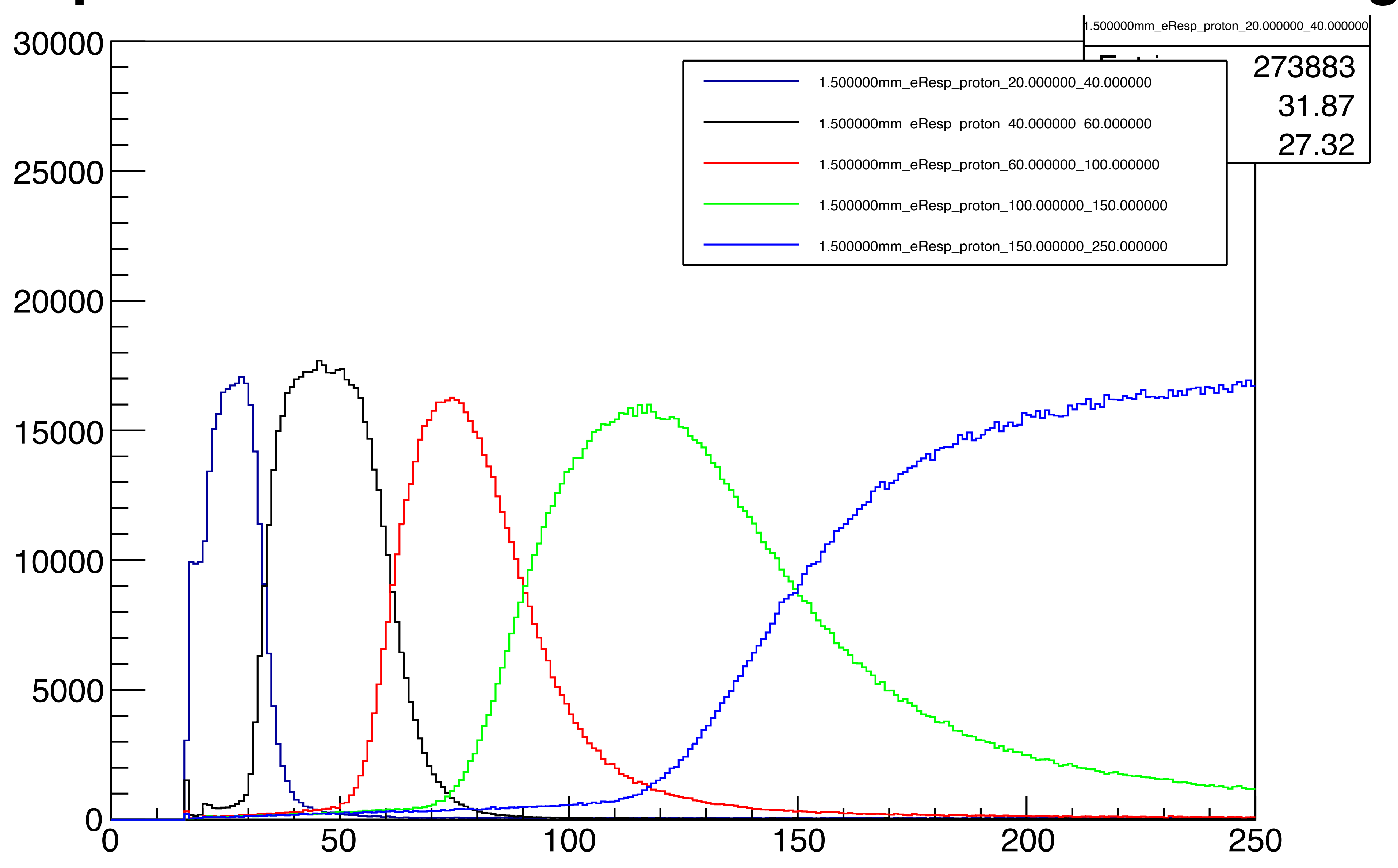
- Future work will focus on calibration of the above quantities

Thank you for your attention

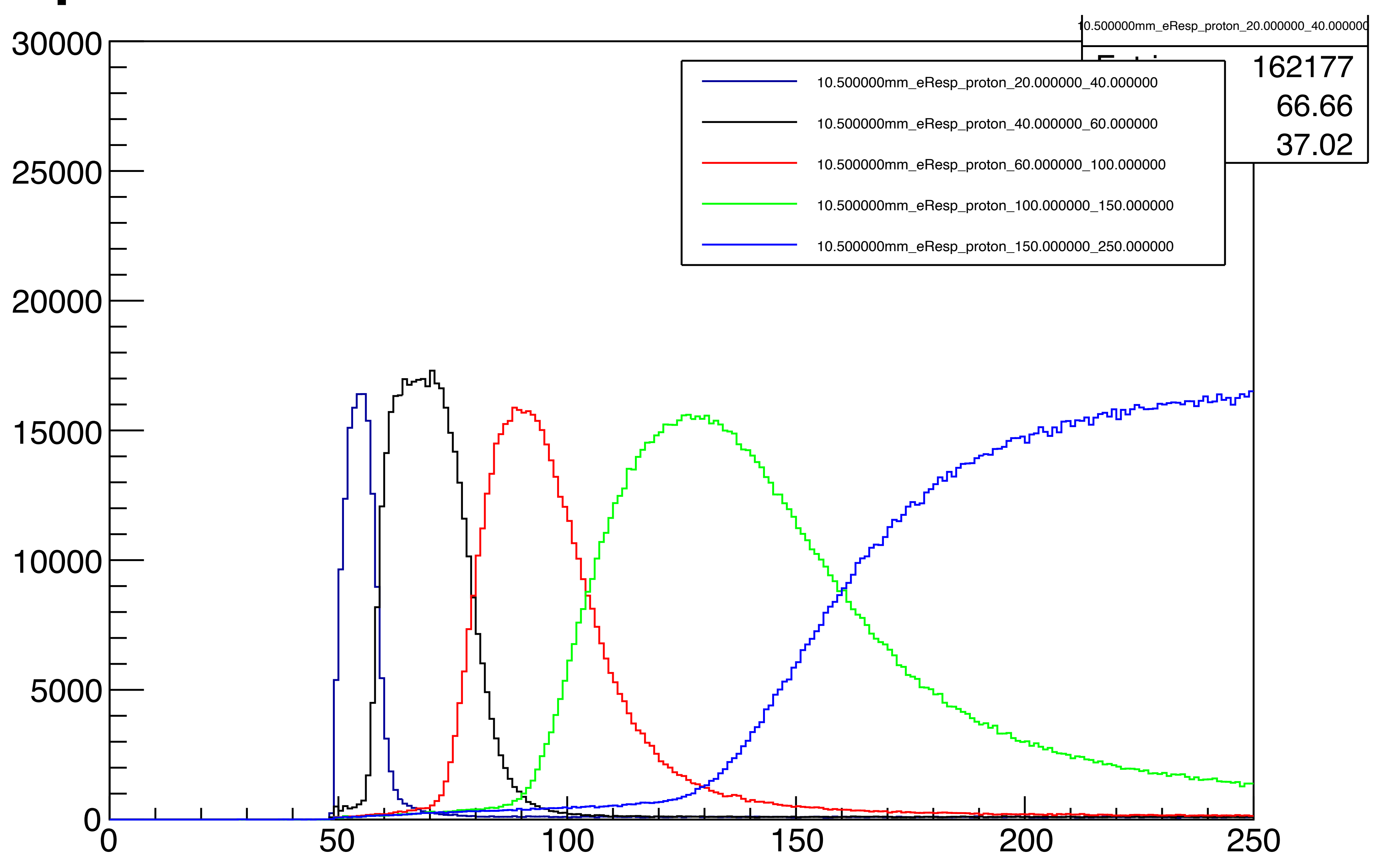
- We look forward to the following future flights of Timepix based hardware
  - Polaris Dawn, MEO (summer 2024)
  - Artemis II, Lunar Orbit (2025)
  - Artemis III, Lunar Orbit + Surface (2026)
  - LEIA, Lunar Surface (2026)
  - Gateway, Lunar Orbit (2027)
  - Berensheet II, Lunar Surface (2027)
  - And a mystery flight (wooo)!

- As well as other flights of non NASA Timepix on CLPS missions and Gateway
- And future flights of a dedicated Space Weather instrument - the **Timepix2** based "Compact Electron Proton Spectrometer", now funded for high TRL development by NASA Planetary Science and Mars Campaign Office

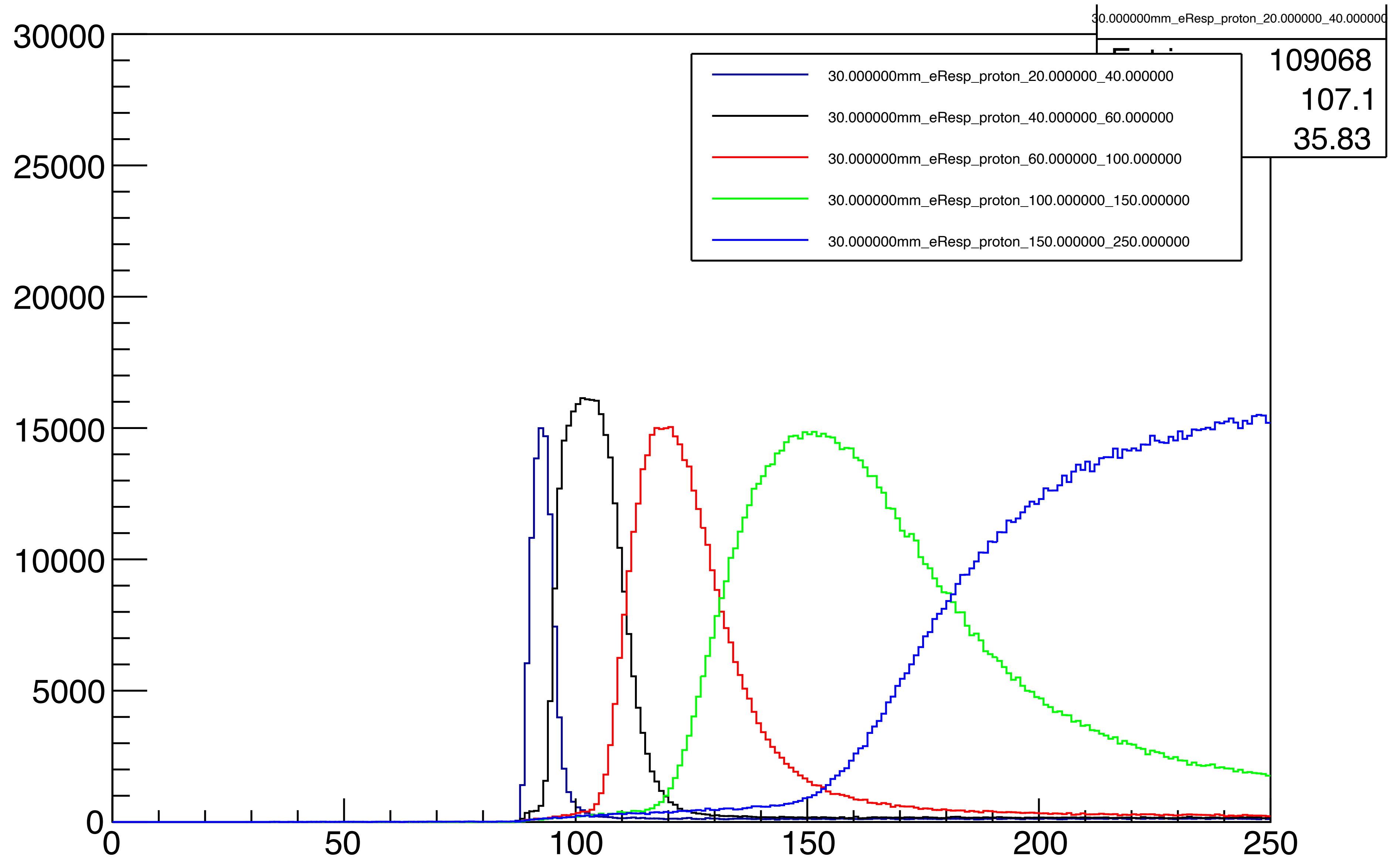
Response Functions for 1.5mm Aluminum Shielding



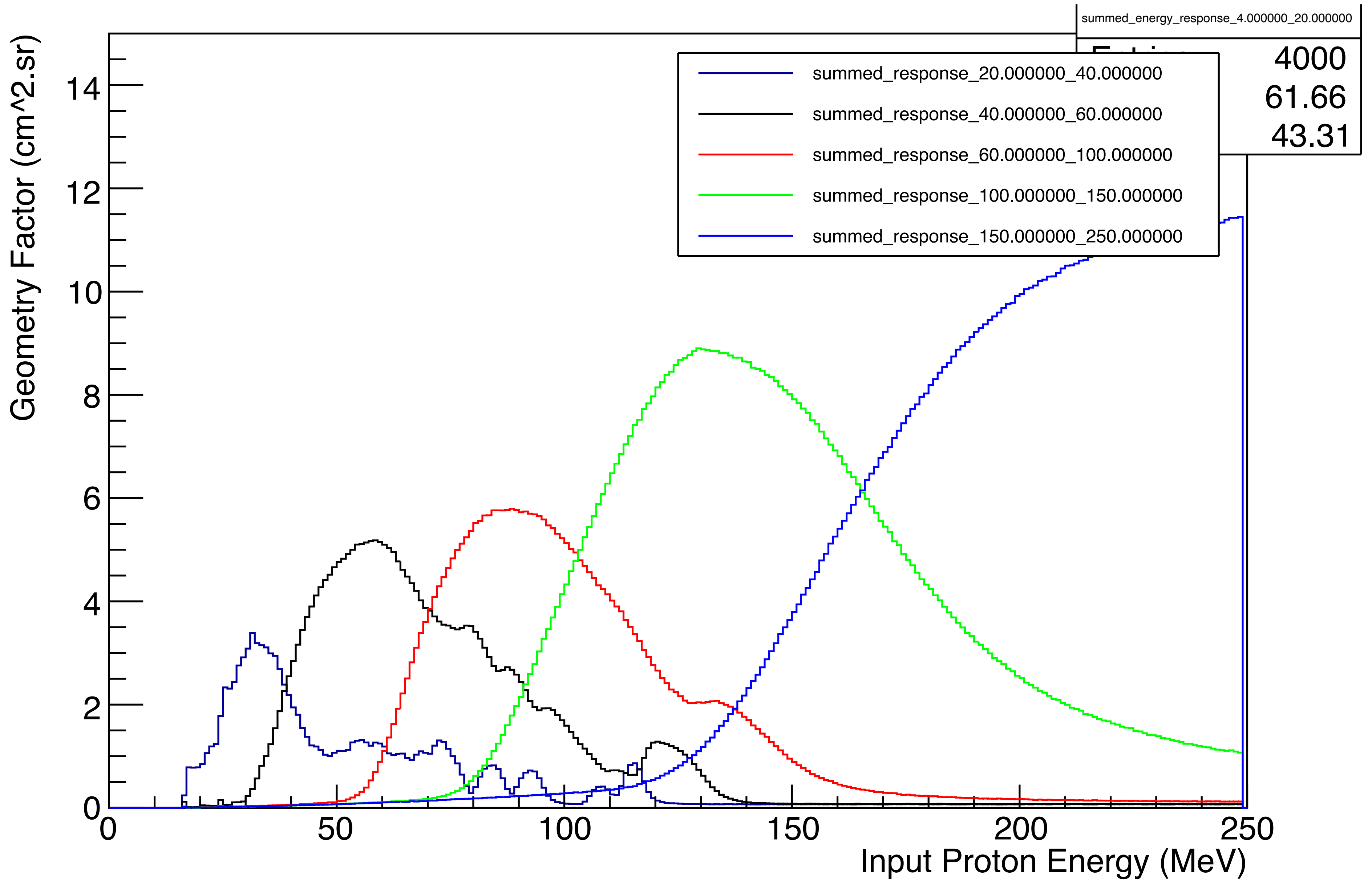
Response Functions for 10.5mm Aluminum Shielding



Response Functions for 30mm Aluminum Shielding

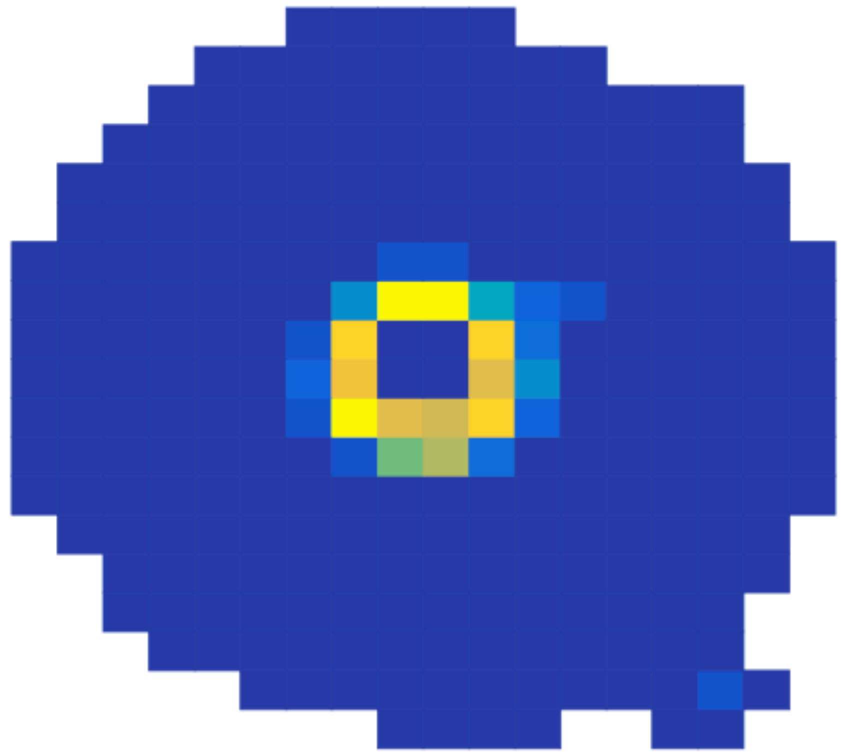


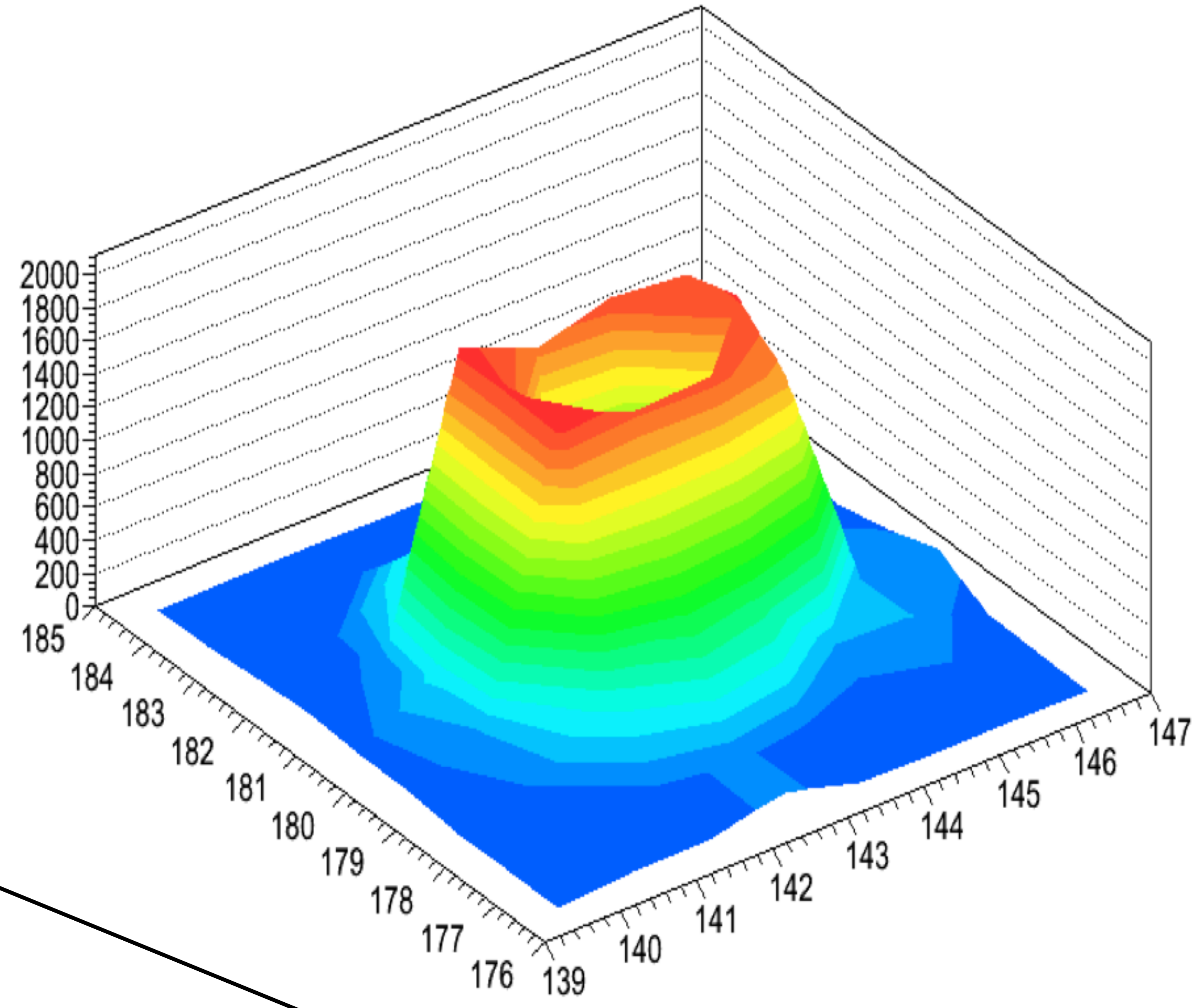
Omnidirectional Response for whole shielding distribution

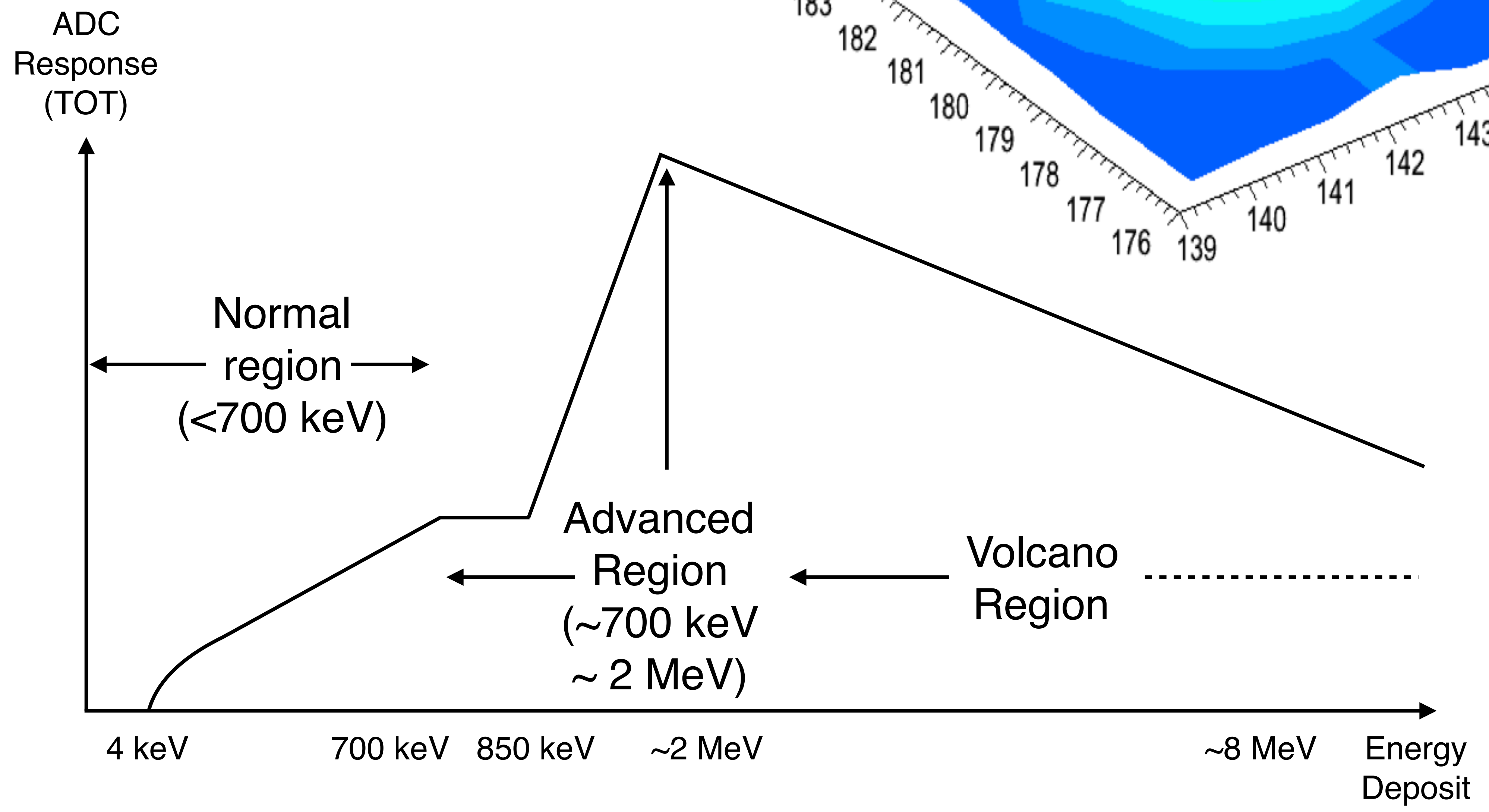


Timepix Energy Calibration and “The Volcano Effect”

- 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.





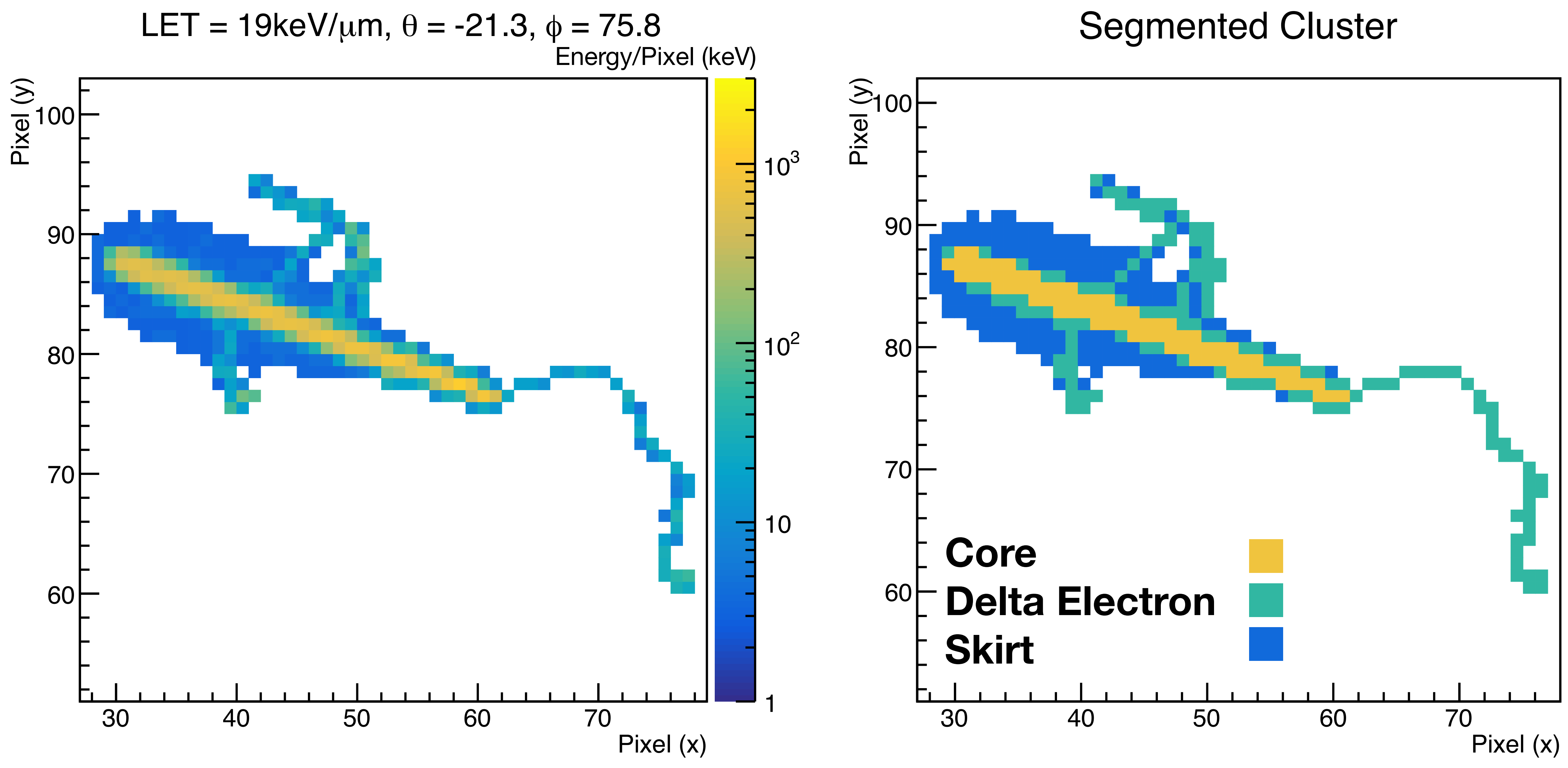


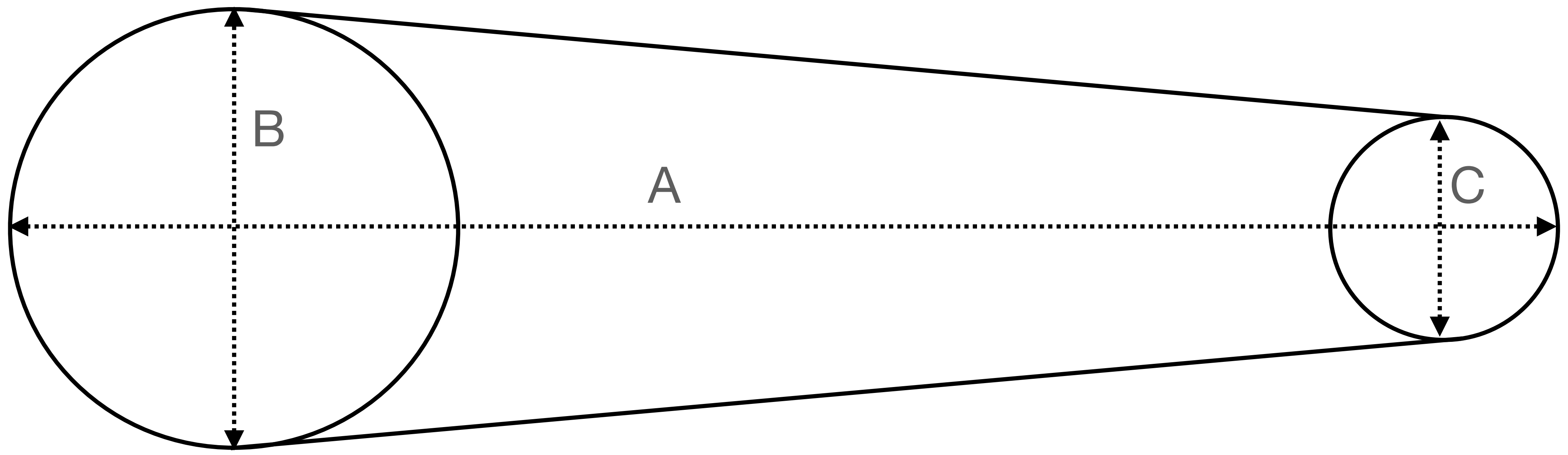
Top - “volcanos” as measured with a heavy ions at an accelerator (bottom) - Timepix calibration curve 4 keV - 8 MeV

M Kroupa et al (2017)
SP George et al (2018)

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.





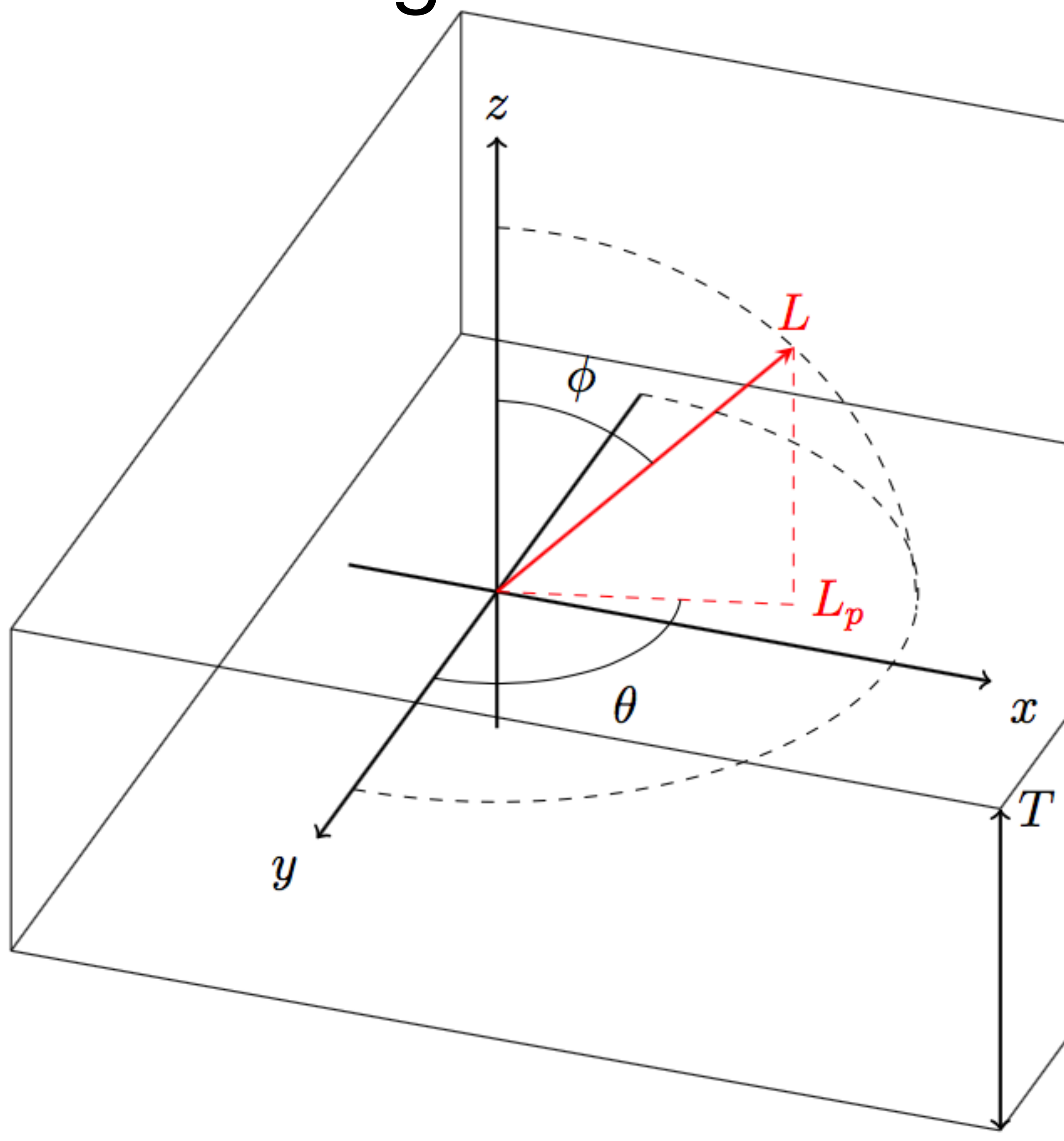


Figure 3.6: Measurement of the azimuth angle θ and altitude ϕ relative to the sensor axes from a penetrating track of length L over a sensor of thickness T.

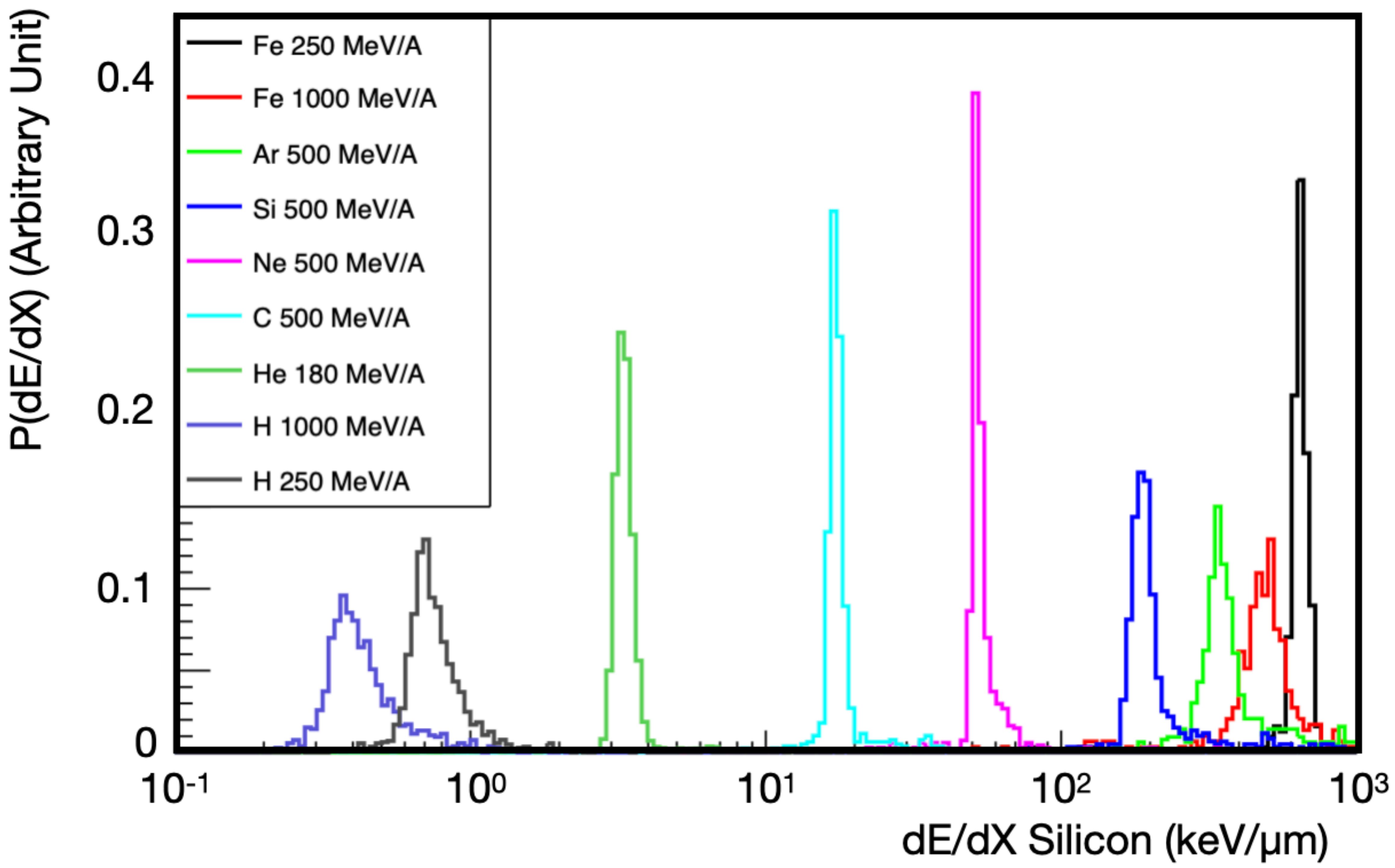
- Disentangle charge sharing effects - charge sharing in track causes characteristic ‘comet’ shape

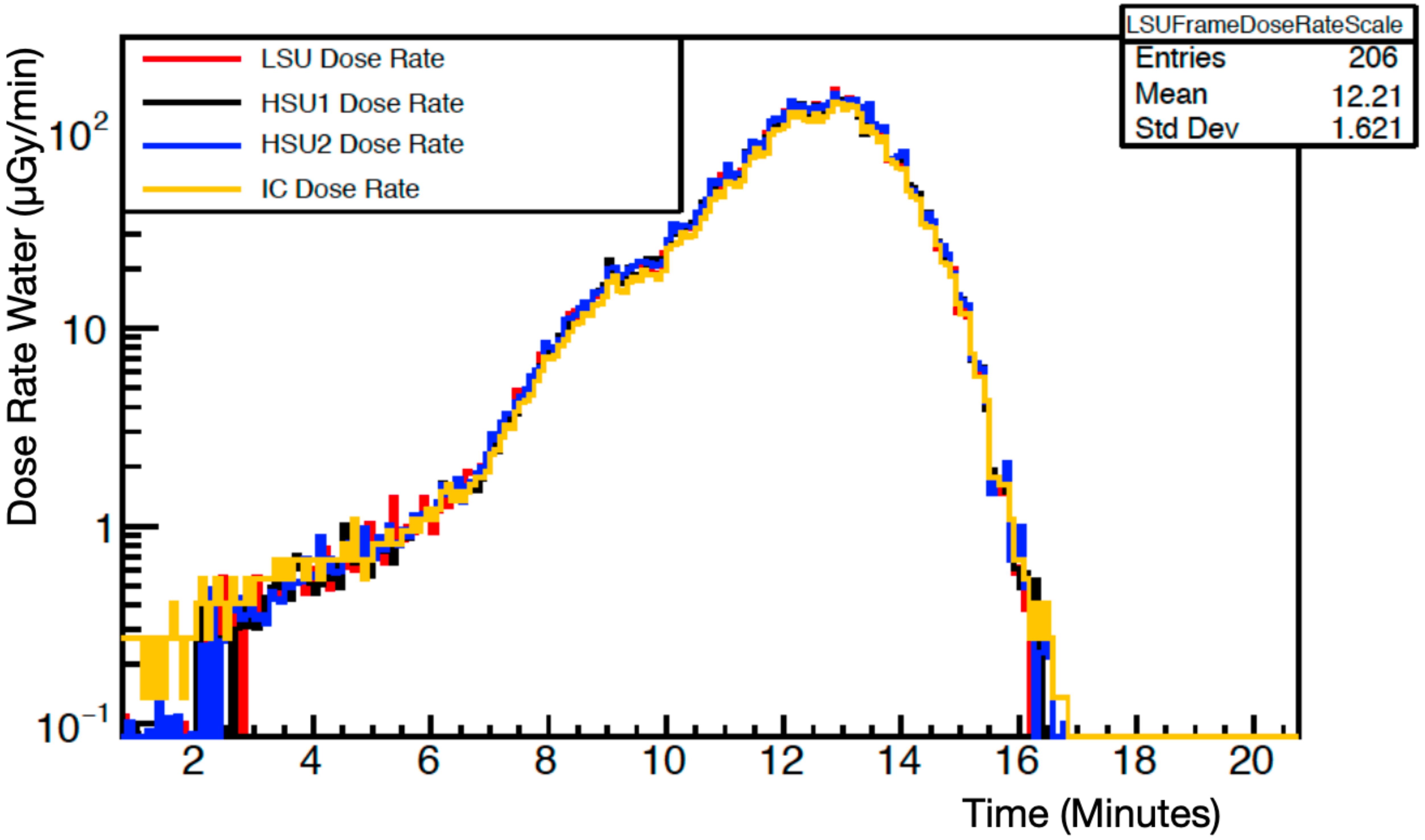
$$L_p \sim A - B/2 - C/2$$

- 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.