Radiation Results from the Biosentinel Cubesat

WRMISS 2023, Rome, Italy

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On Behalf of the Biosentinel Team (PI Sergio Santa-Maria, PM Matthew Napoli NASA Ames)

All results in this presentation should be considered preliminary

The Biosentinel Mission

- We are all (or we certainly will be) very familiar with the Artemis I mission
- First flight of the SLS and Orion on November 16th 2022
- As well as the MARE payload and HERA instruments to measure radiation also carried another radiation payload …
- The **BIOSENTINEL** satellite
- Biosentinel was lofted into a heliocentric orbit by SLS and has been measuring the interplanetary radiation environment ever since

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.

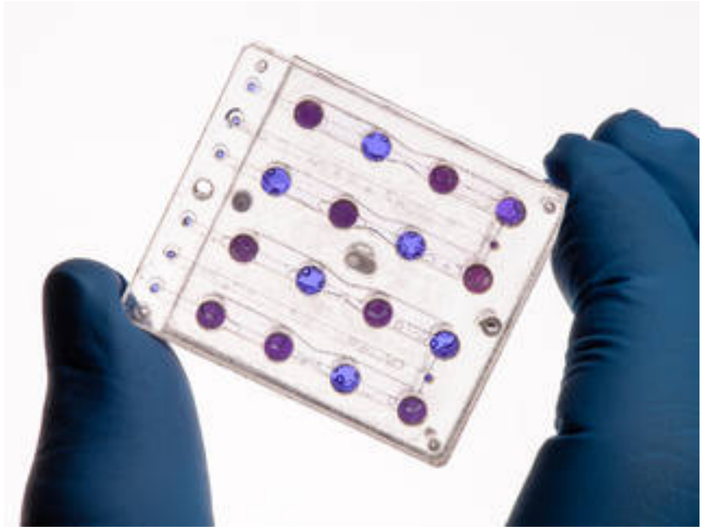
9 missions flown, 2 missions next six months, 6 missions manifested, > 25 Timepix in Space to date

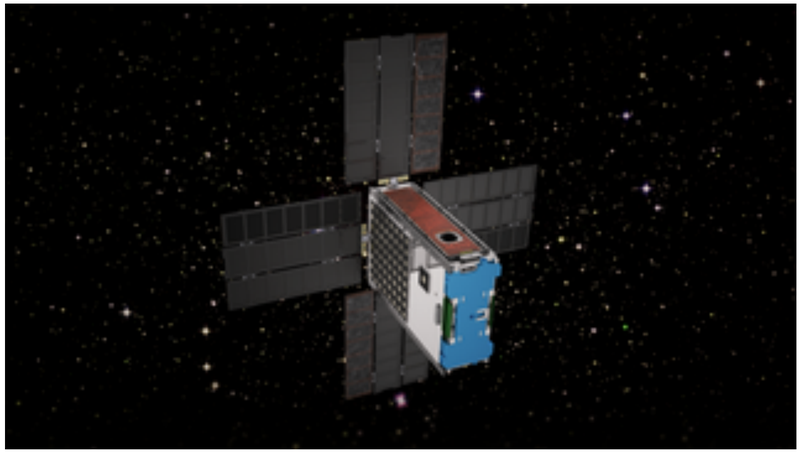
Highly successful technology transfer from CERN, powering NASA missions for the last 10 years, and likely for the next 10

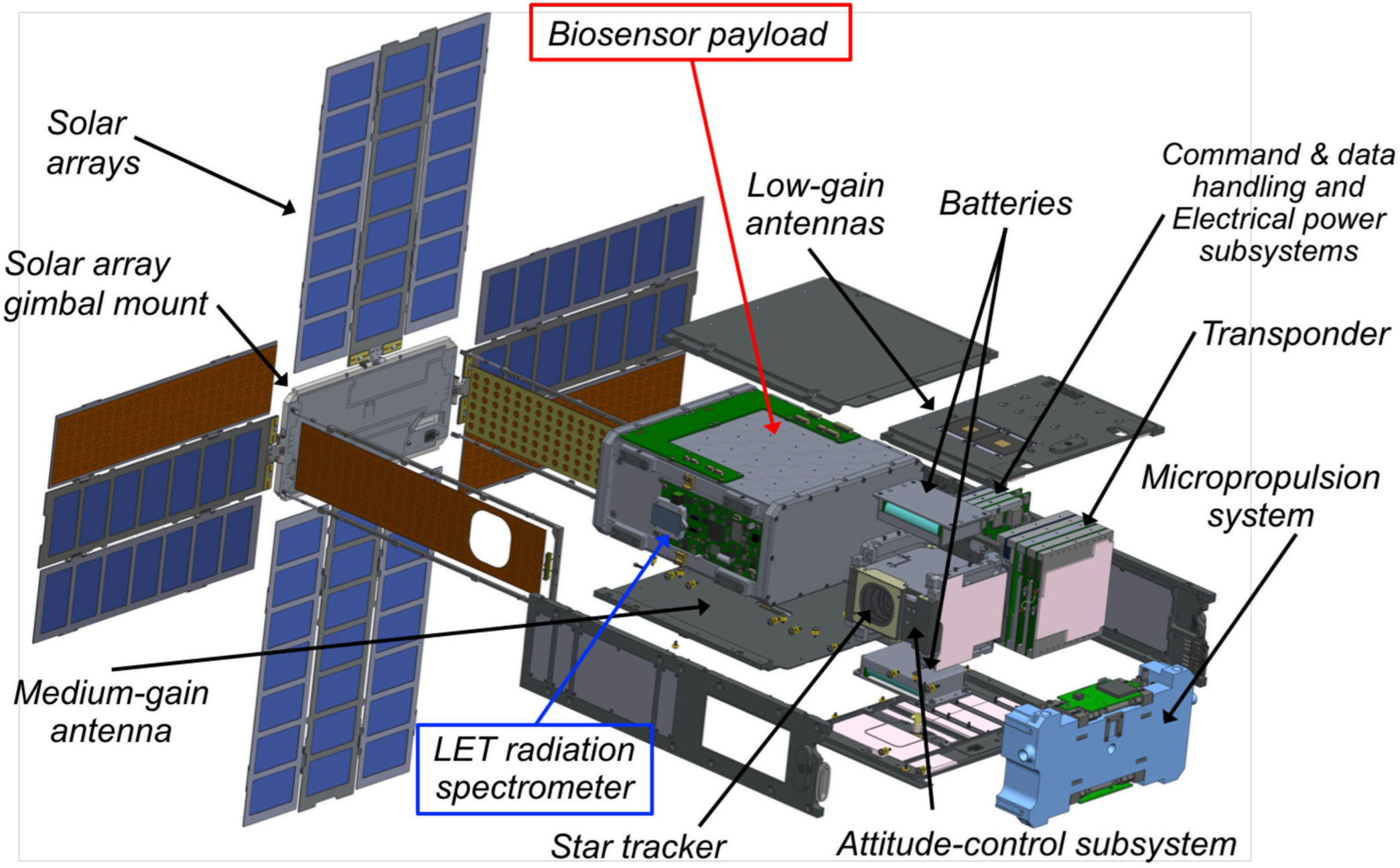
Biosentinel

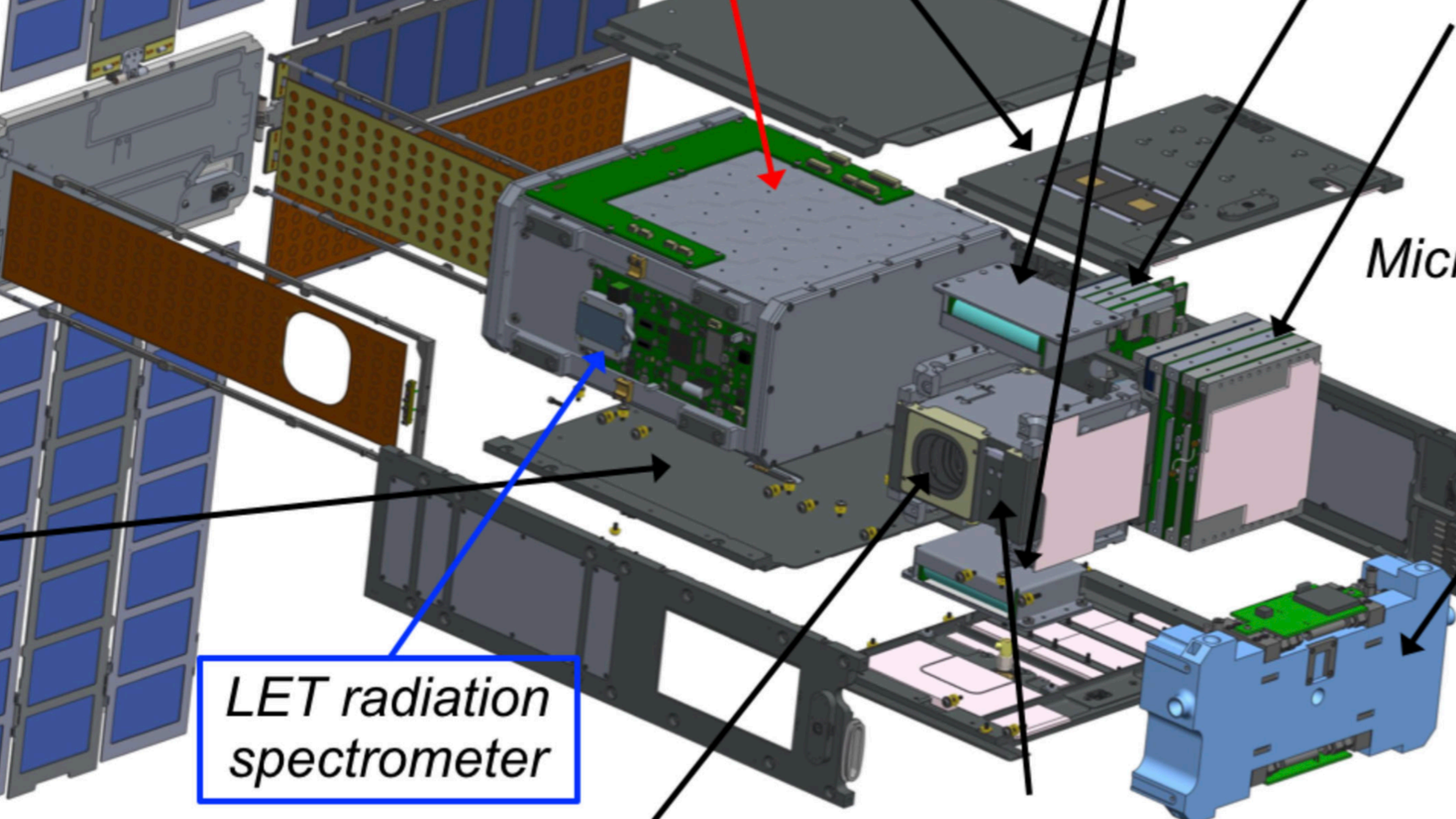
- Biosentinel is a radiation biology experiment
- Contains dehydrated micro wells of yeast, including variety that does not repair DNA damage well
- Yeast will accumulate radiation damage throughout flight and be rehydrated through flight to measure growth rates
- First study of biological response to space radiation outside LEO since Apollo
- Timepix based radiation sensor included in cubesat, similar capability to HERA
- Unfortunately (likely) due to the long time between cubesat loading and Artemis I launch the Biosentinel yeast did not grow
- **<u>Biosentinel is now exclusively a radiation experiment</u>**

AJ Ricco et al (2020)

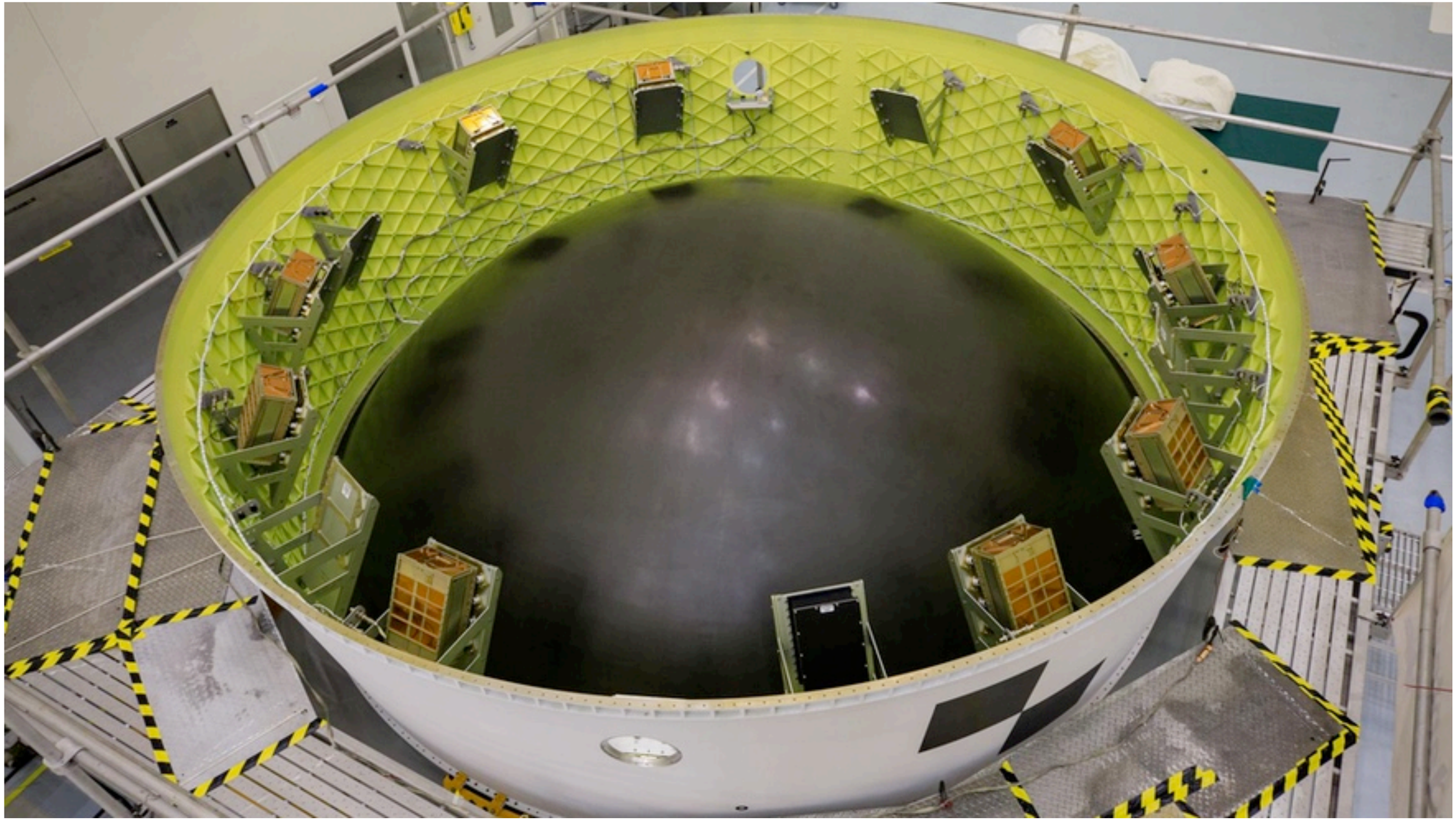





Biosensor payload
Solar arrays
Low-gain antennas
Batteries
Command & data handling and Electrical power subsystems
Solar array gimbal mount
Transponder
Micropropulsion system
Medium-gain antenna
LET radiation spectrometer
Star tracker
Attitude-control subsystem

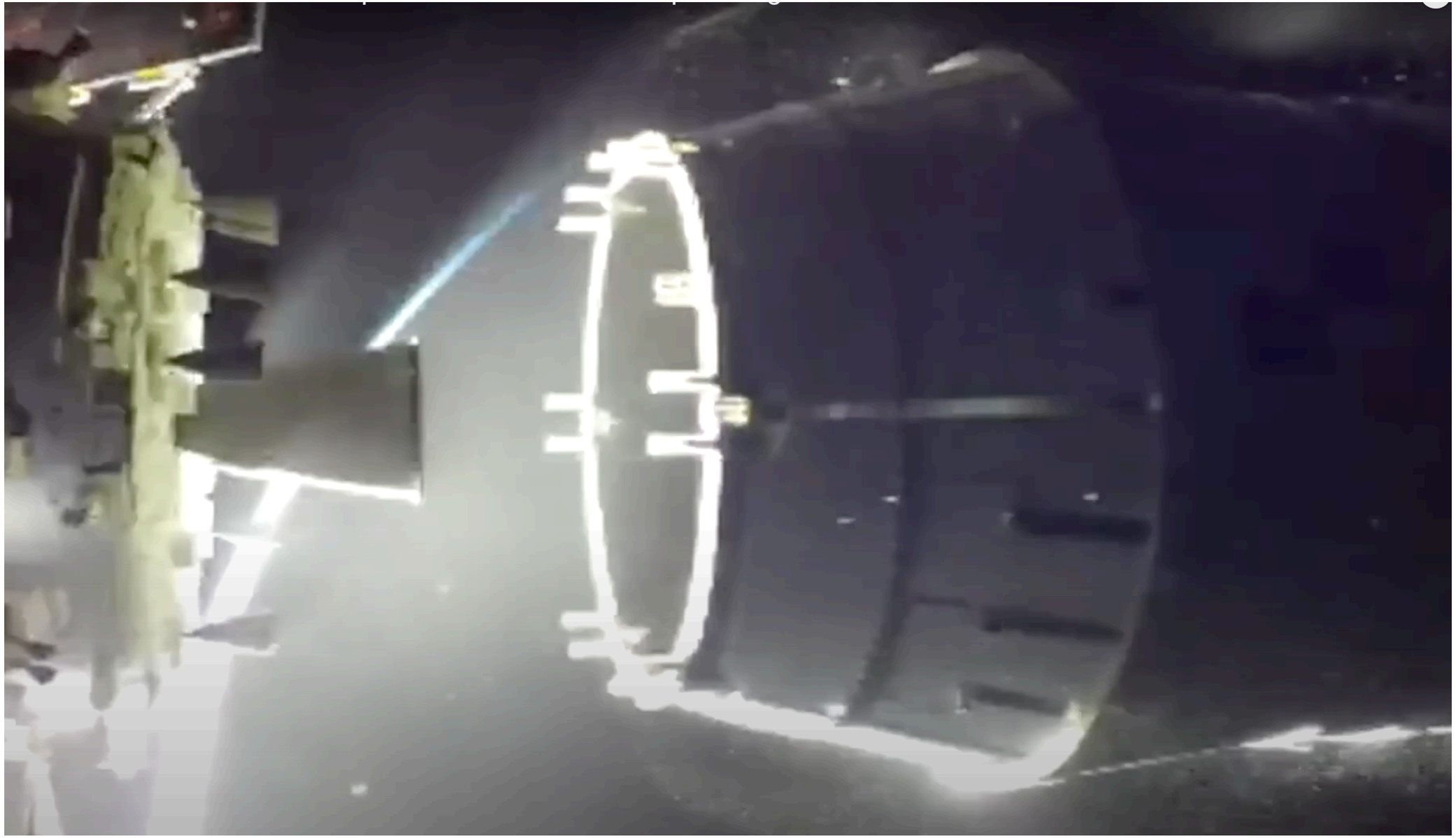

LET radiation
spectrometer

Biosentinel Cubesat EMI Testing



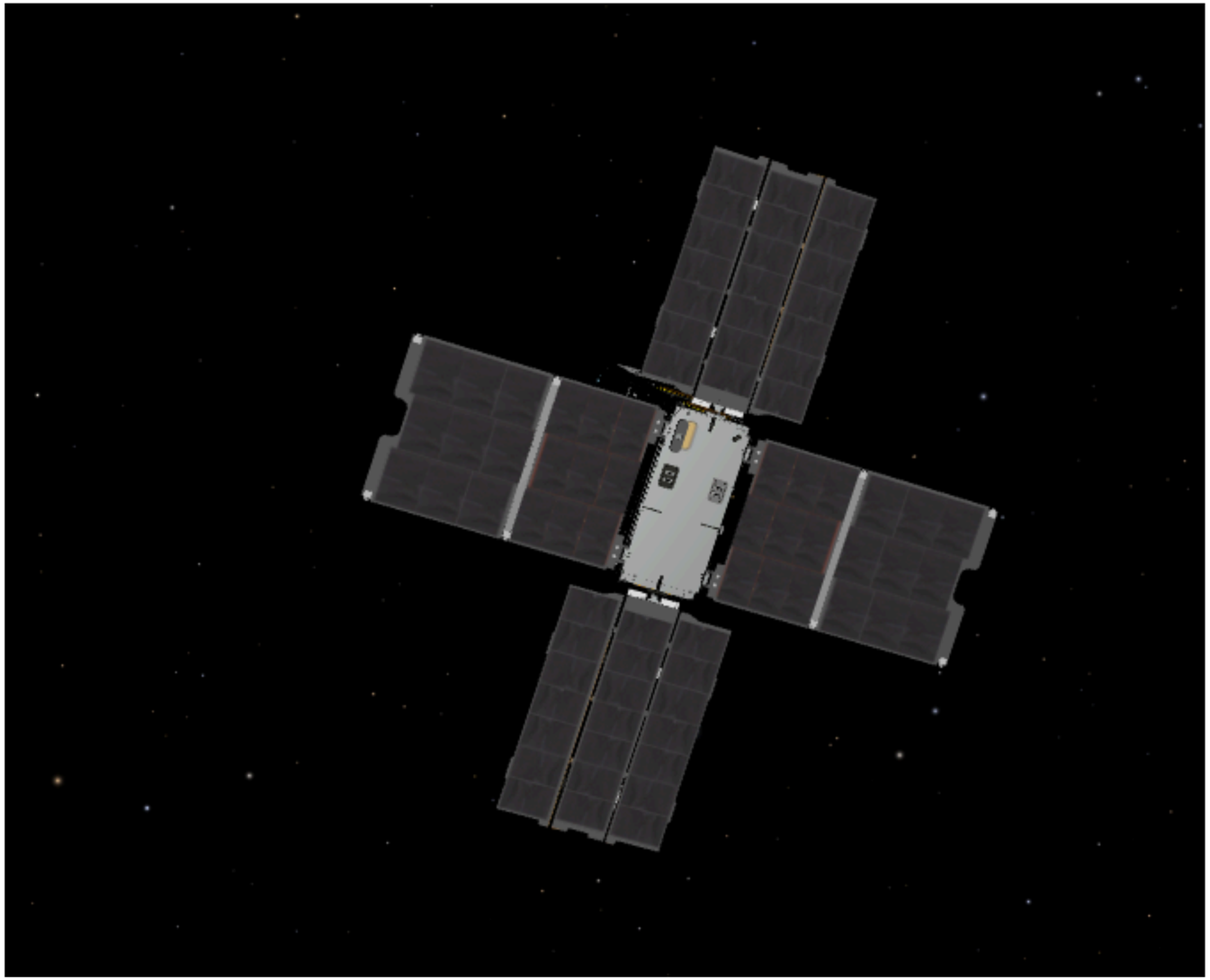
Artemis I cubesats installed in Cubesat ring

Artemis I Launch

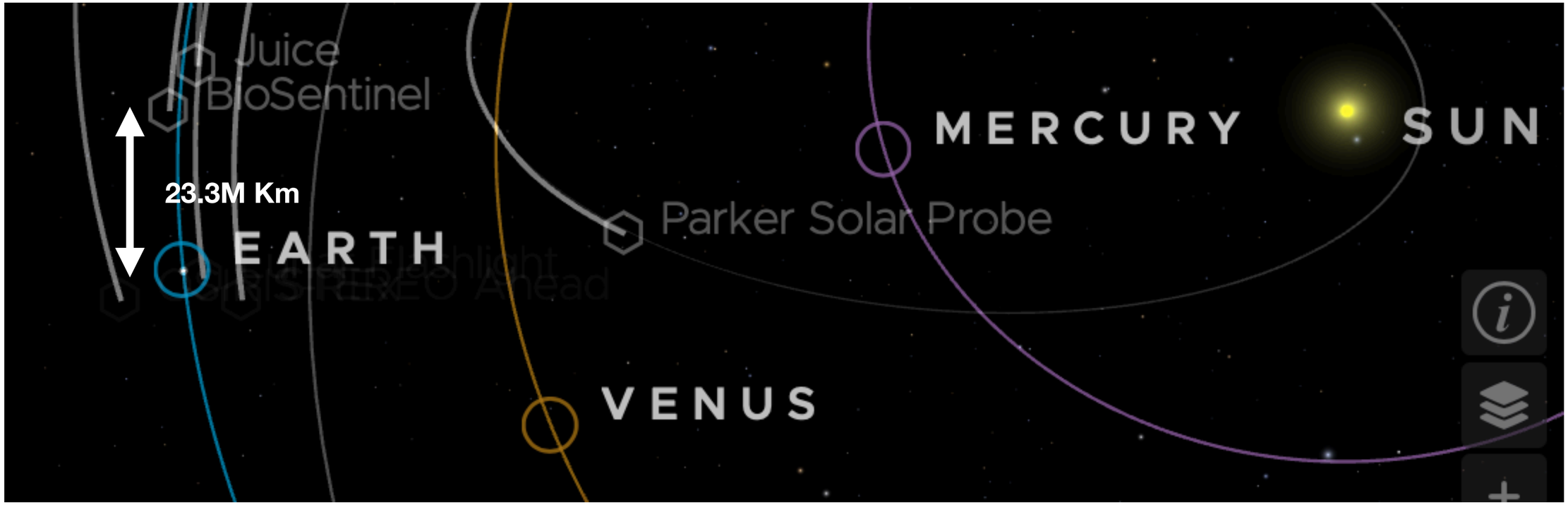


ICRS Separation from Orion, disposal burn for ICPS to heliocentric orbit, Biosentinel deploy from ICPS

Where is Biosentinel Now?



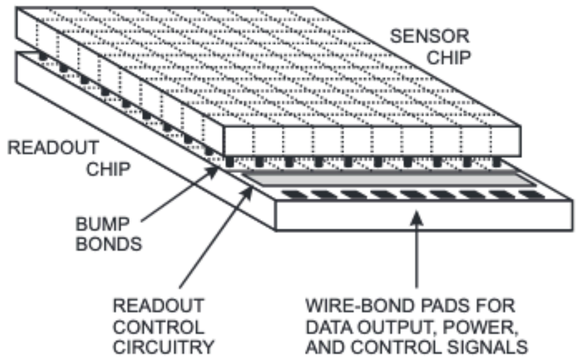
Where is Biosentinel Now?

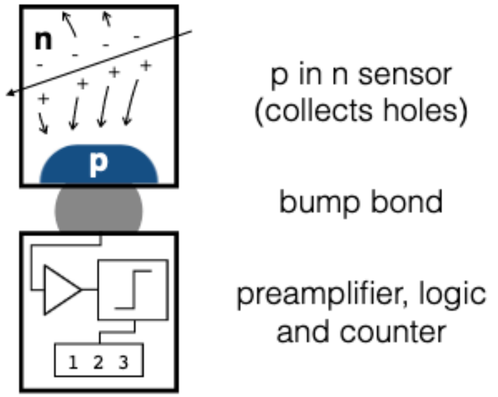


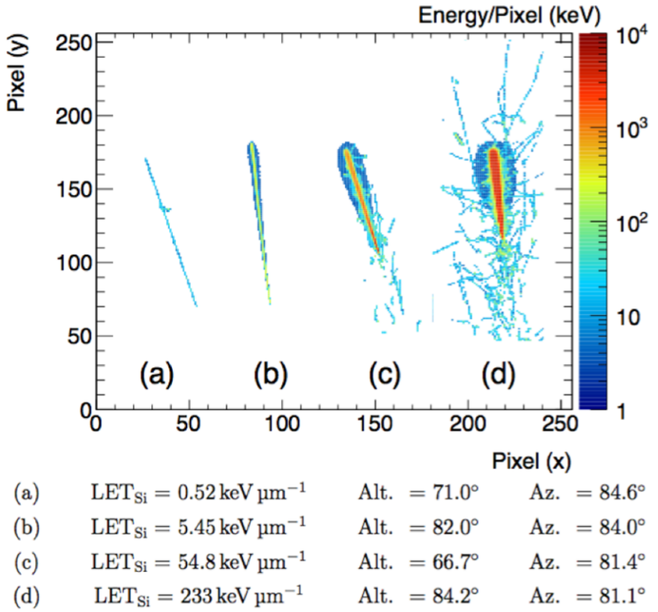
September 4 2023 from the Tool “Eyes on the Solar System”, eyes.nasa.gov

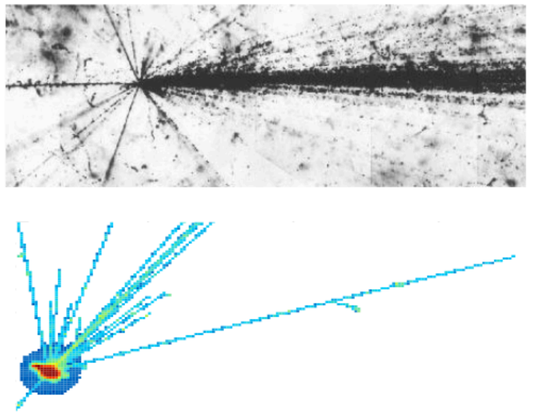
Why Use Timepix in Space

- 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’





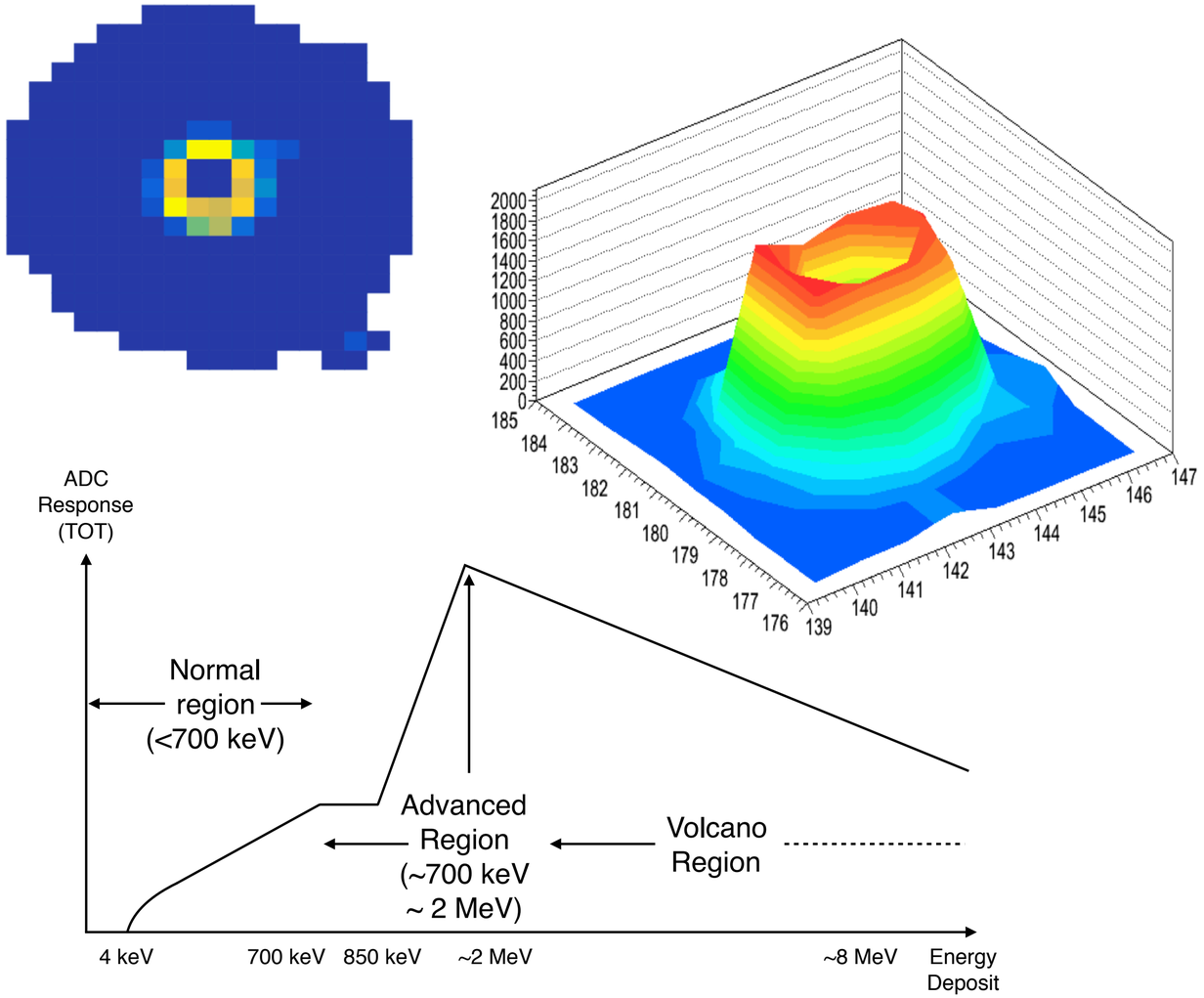




(Top) Schematic of Timepix Detector and individual pixel, (bottom left) example tracks in Timepix detector from ions (bottom right) example nuclear fragmentation in nuclear emulsion and Timepix showing analogy with ‘solid state nuclear emulsion’

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

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.

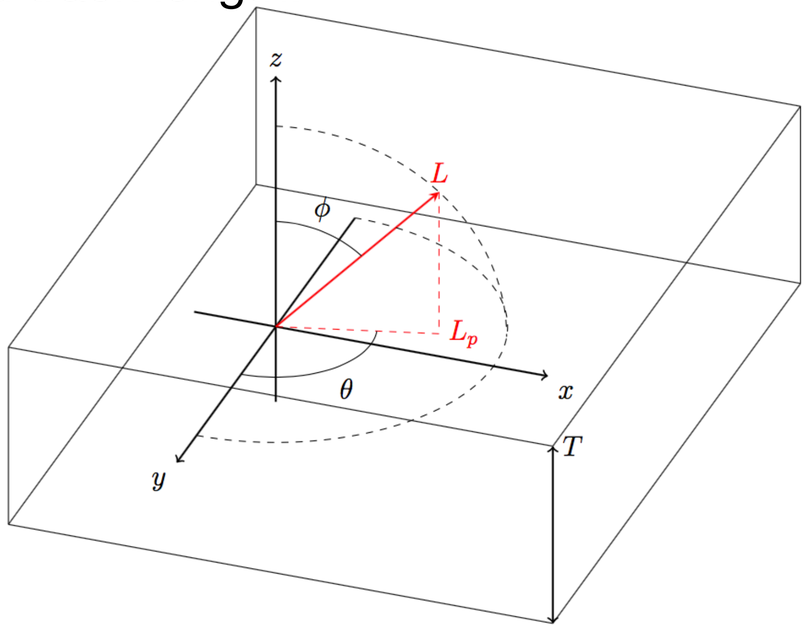
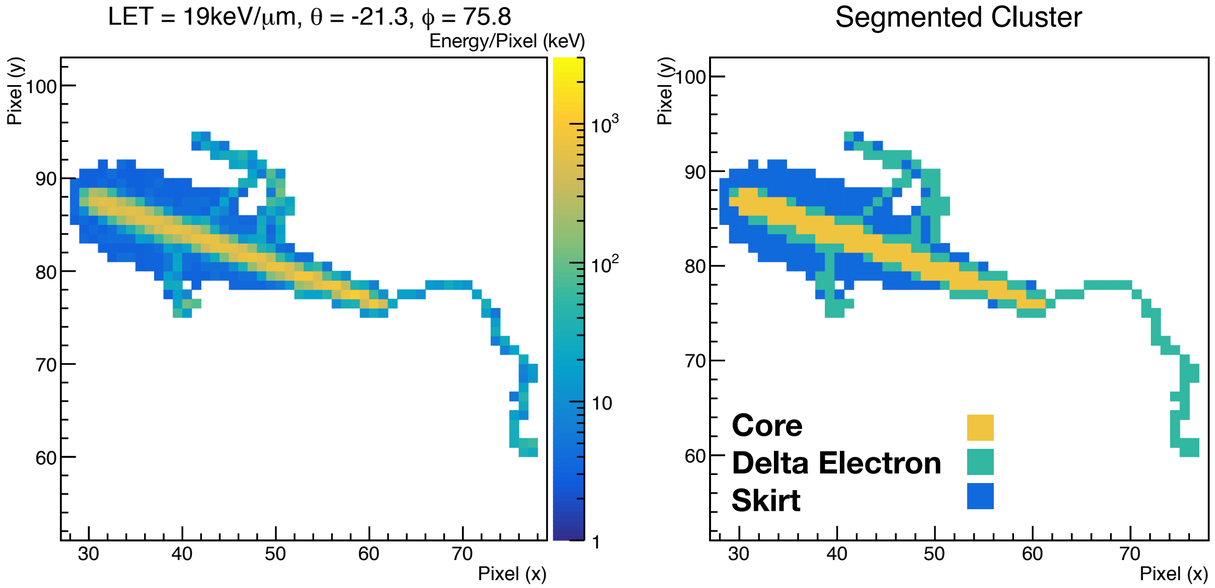
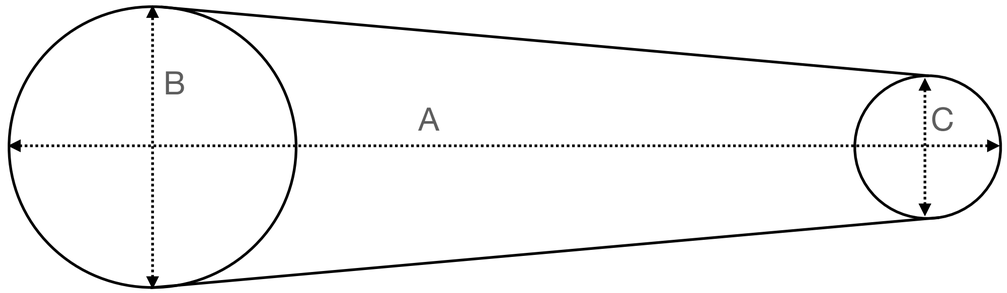


Figure 3.6: Measurement of the azimuth angle θ and altitude ϕ relative to the sensor axes from a penetrating track of length L over a sensor of thickness T.





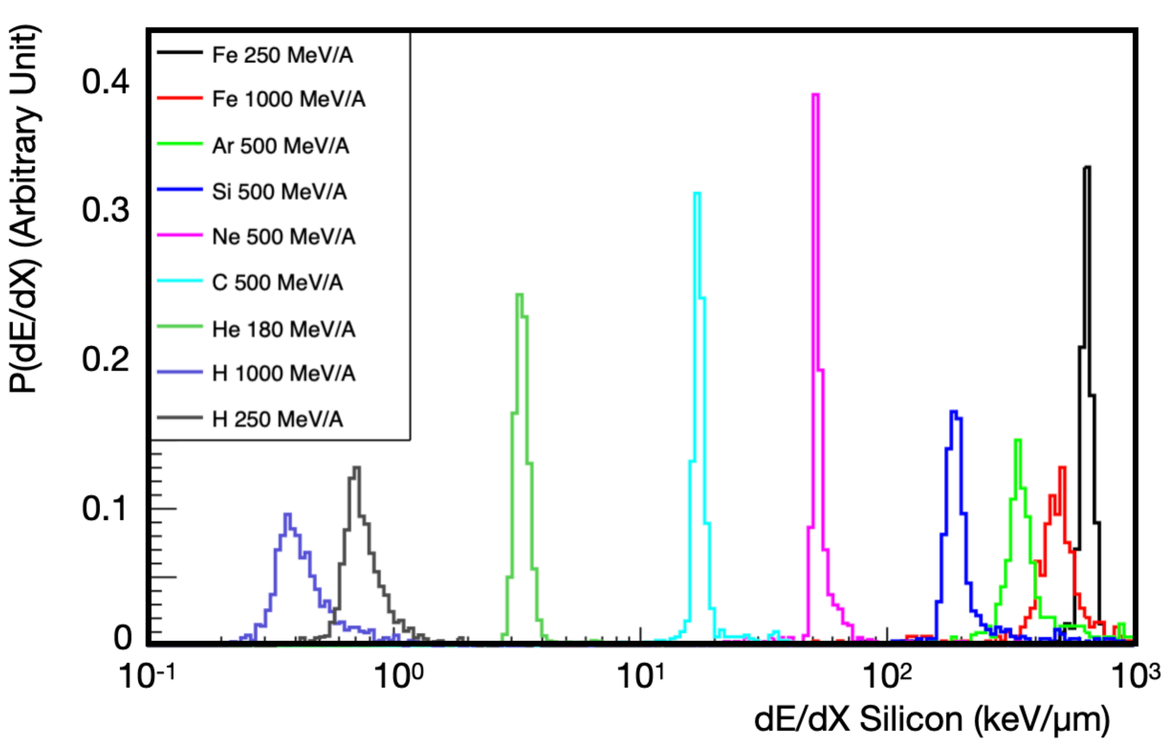
- Disentangle charge sharing effects - charge sharing in track causes characteristic ‘comet’ shape

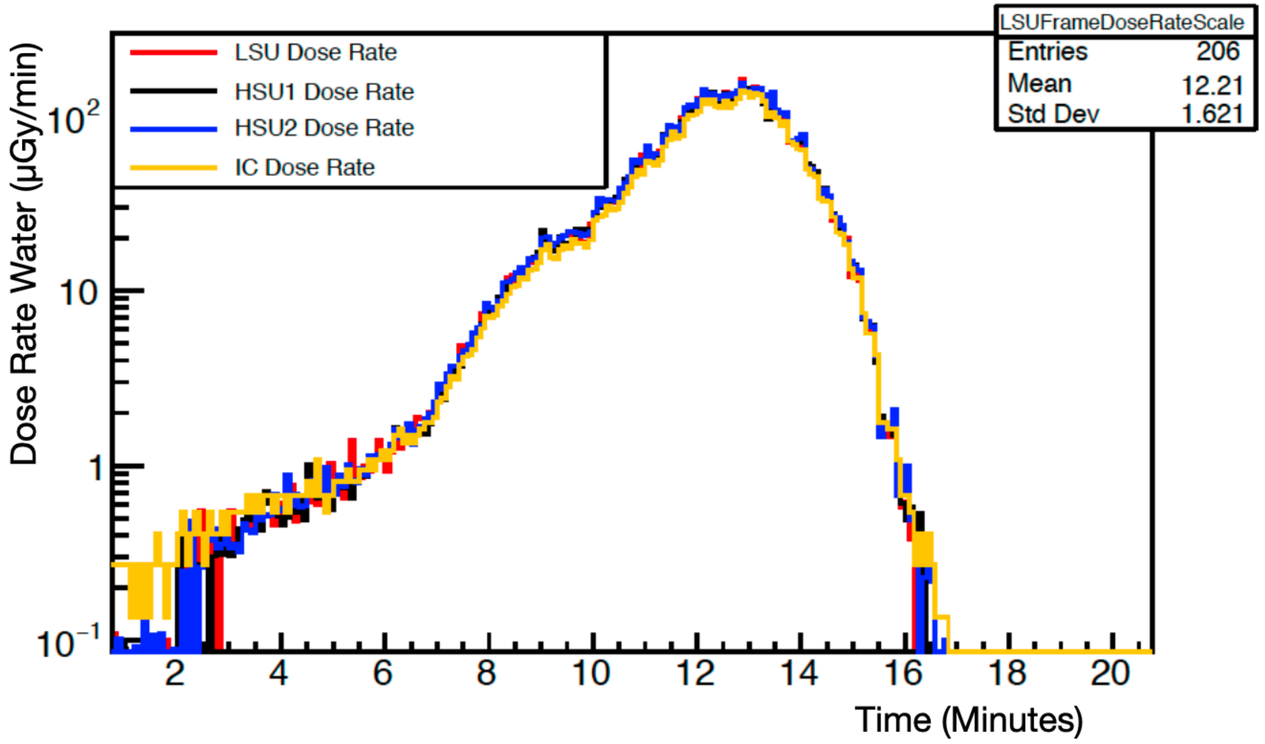
$$L_p \sim A - B/2 - C/2$$

- 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



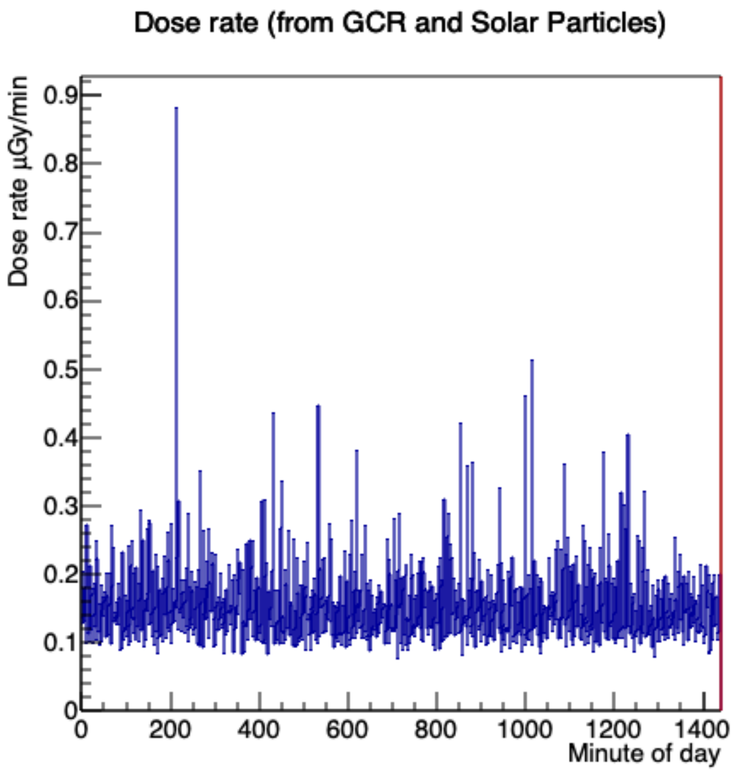


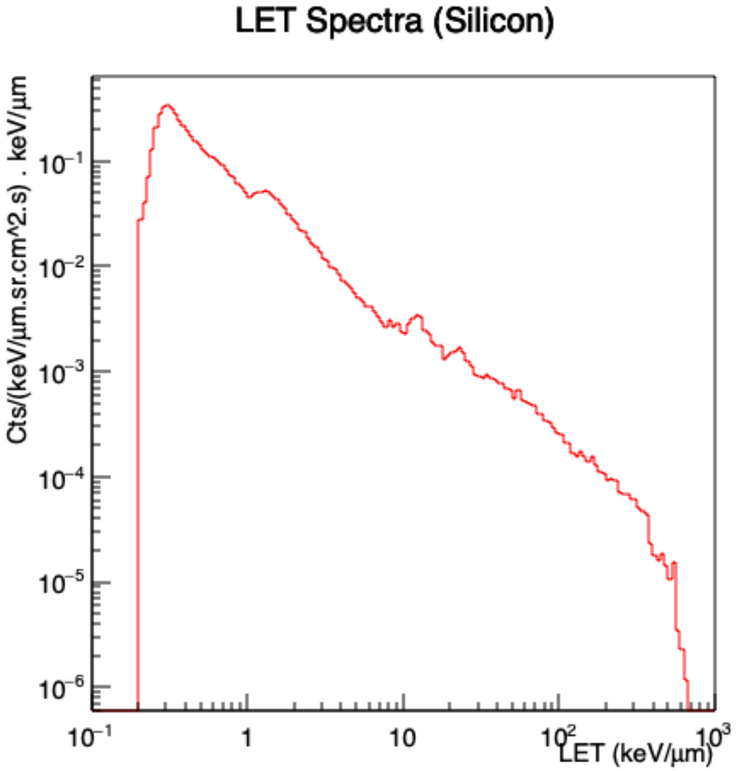
(Left) Example Timepix stopping power measurements at 75 degree polar angle carried out with a variety of ion beams at the NASA Space Radiation Laboratory in Brookhaven, New York,
(Right) simulated ‘belt pass’ carried out with three different Timepix sensors on HERA (LSU, HSU1 and HSU2) compared to external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

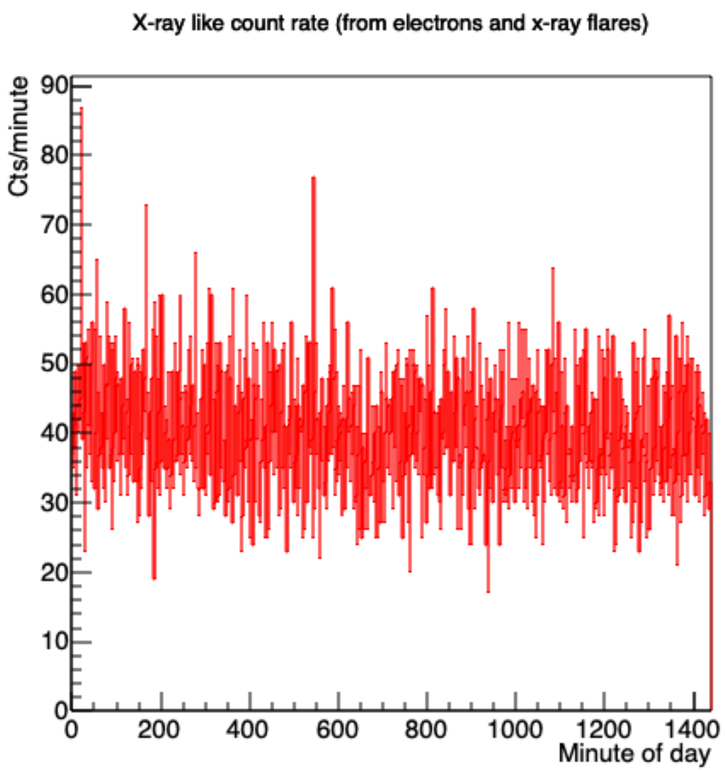
What Does Biosentinel Report?

- **Dose**
- **LET Flux Spectrum (0 - 50 keV/um, 50 - 500 keV/um bootstrapped using our improved knowledge of Timepix response since we built LETS board**
- **Integral counts 5 - 100 keV**
- **All processing done on board**
- **1 message per minute, not including satellite downtime, DSN outages etc**

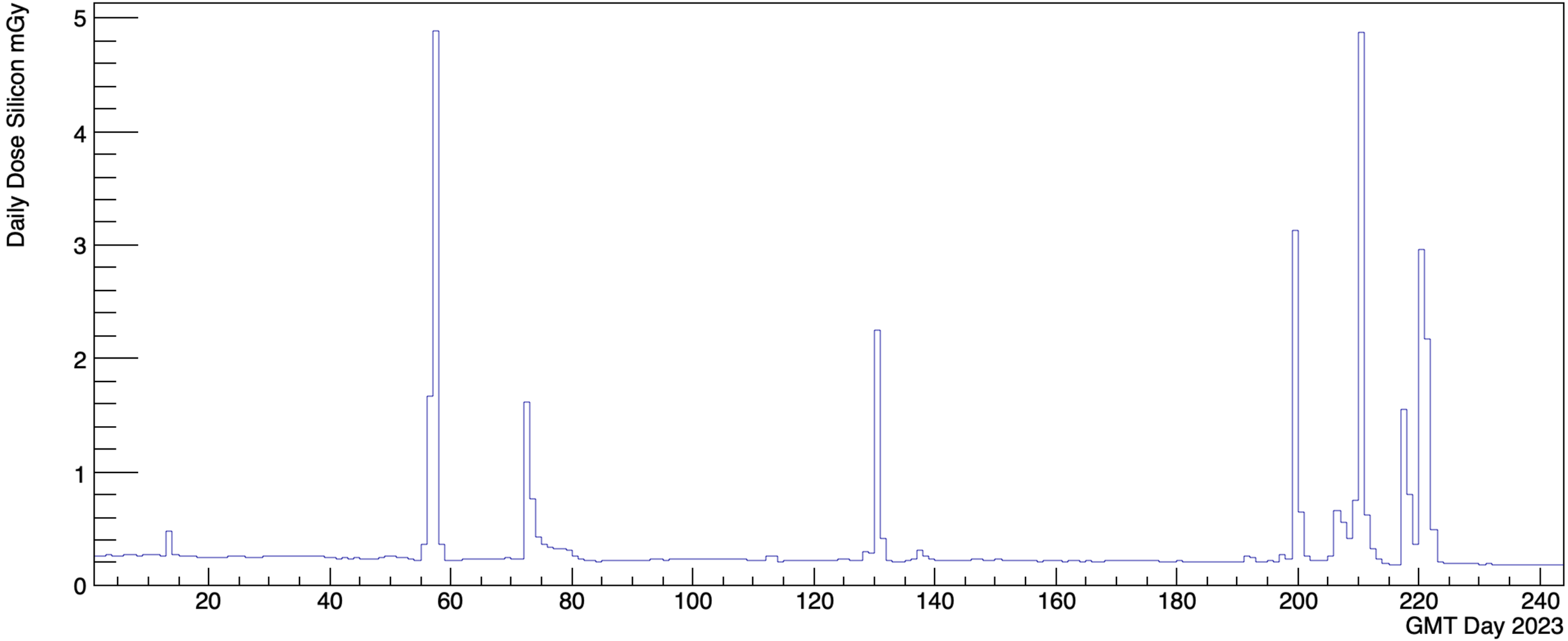
Example One Day Doses and Flux





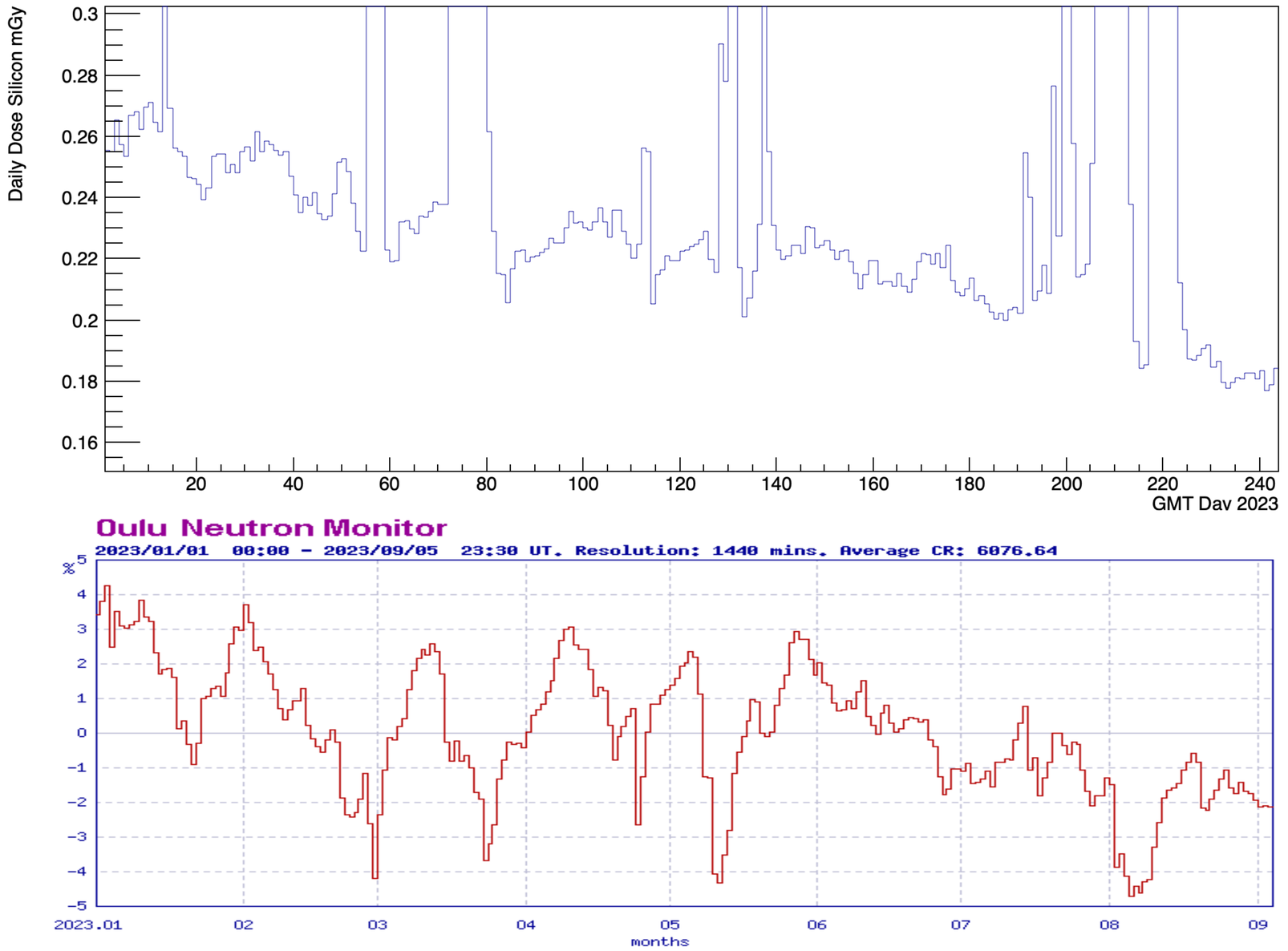


Long Term Daily Doses



Total Si dose GMT 1-244 = 83.4 mGy
~~0.34 mGy/day

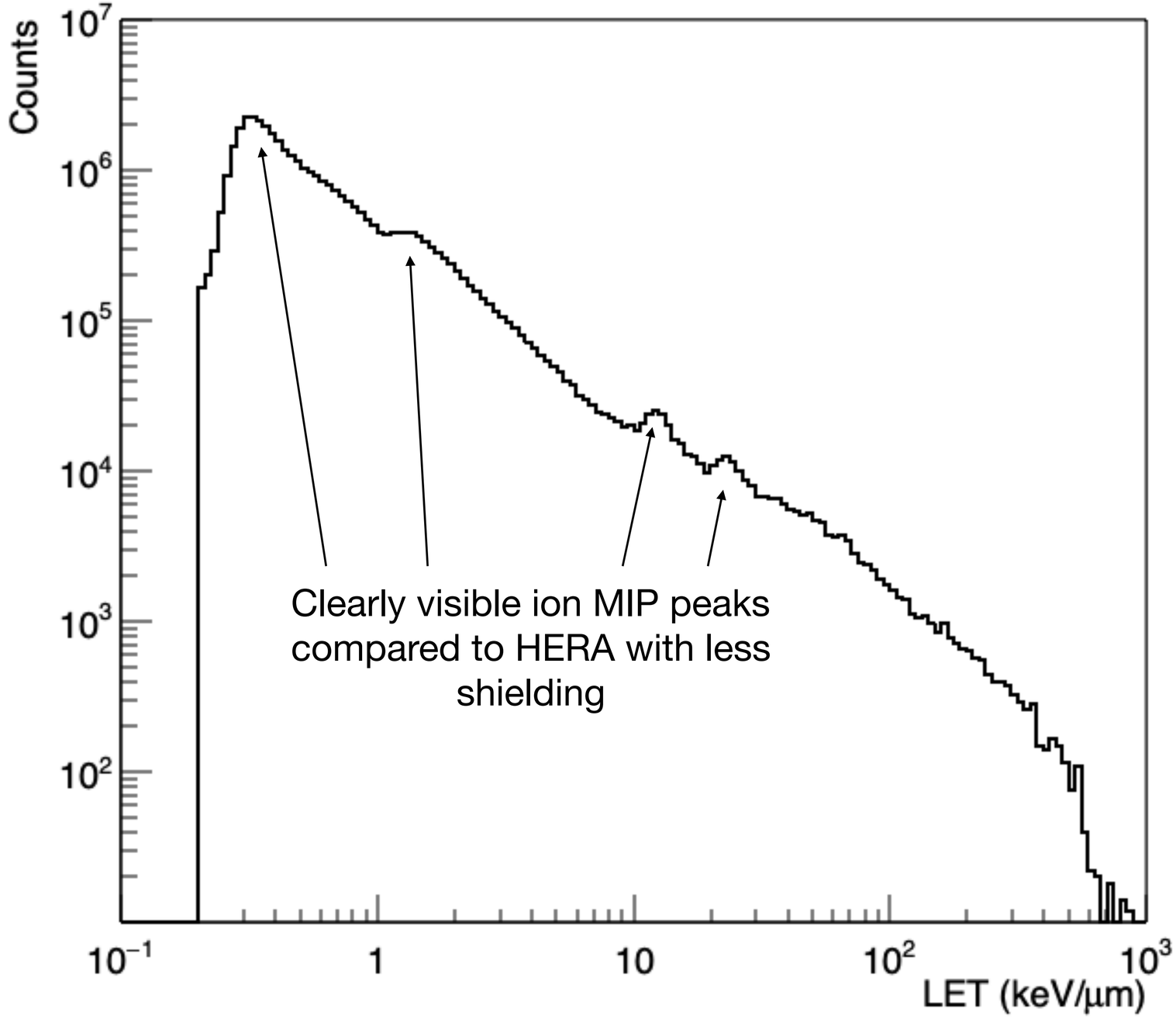
Zoomed in dose rates vs Oulu Neutrons



Compare to Simulation based on extrapolated phi for Nov 22 - May 23 = 0.25 mGy/day (Rahmanian et al 2023)

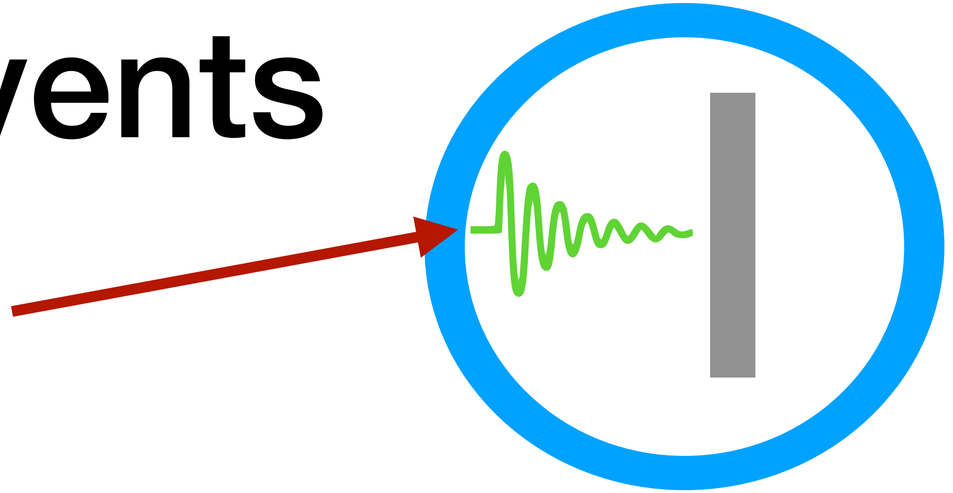
So over 2023 SPE contribution to absorbed dose ~~ extra 60%

Biosentinel LET Spectra Jan 2023 (No SPE in Jan 23)

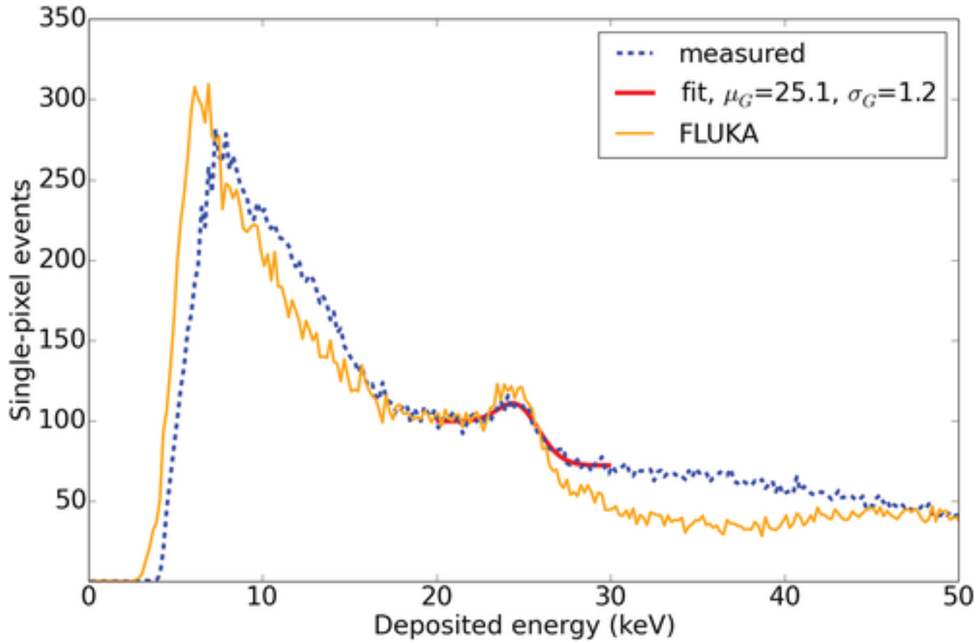


Solar Particle Events

- 2023 has been had several small solar particle events
- Mostly non affective on ISS - soft energy spectra/small events
- But very visible in lightly shielded BioSentinel
- Additionally, BioSentinel has access to an (integral) electron channel via its < 100 keV

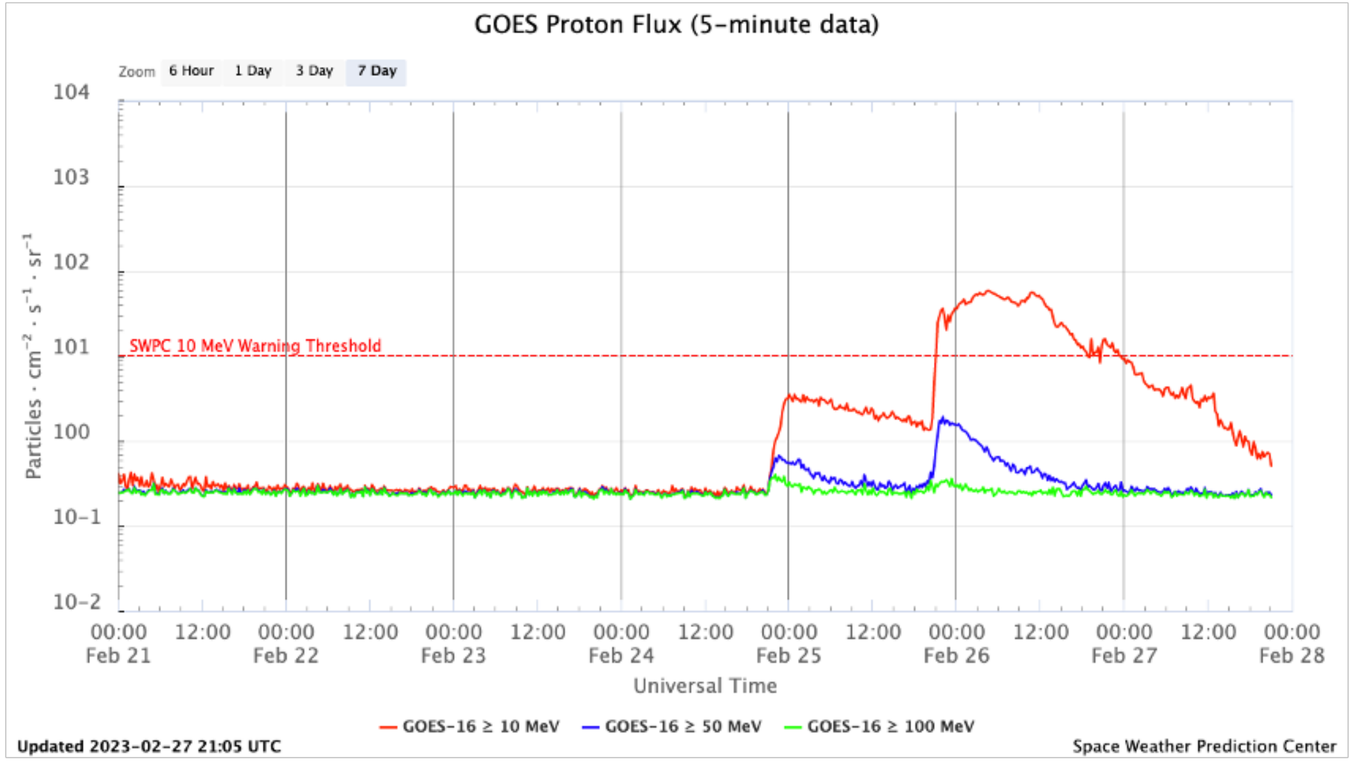


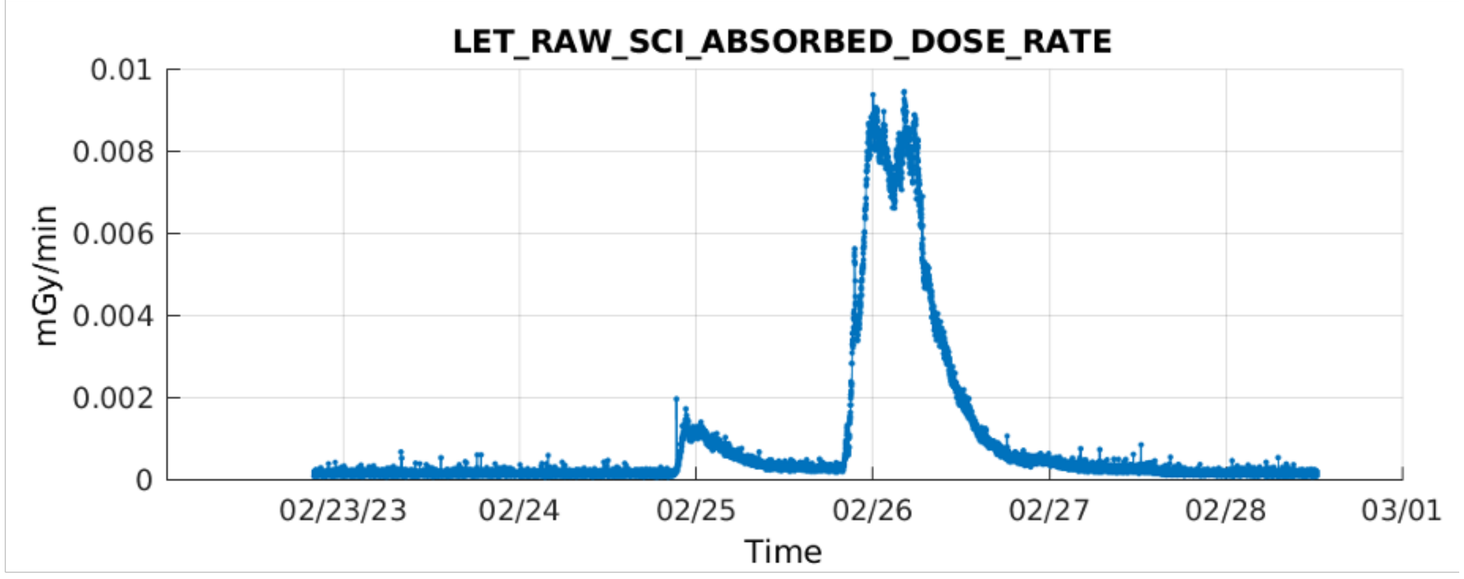
(Top) EV Electrons Create Bremsstrahlung in vehicle walls - fill vehicle with low energy x-rays. Also seen NASA EFT-1 (Timepix) and Artemis I (bottom) - simulation of EV electron effect



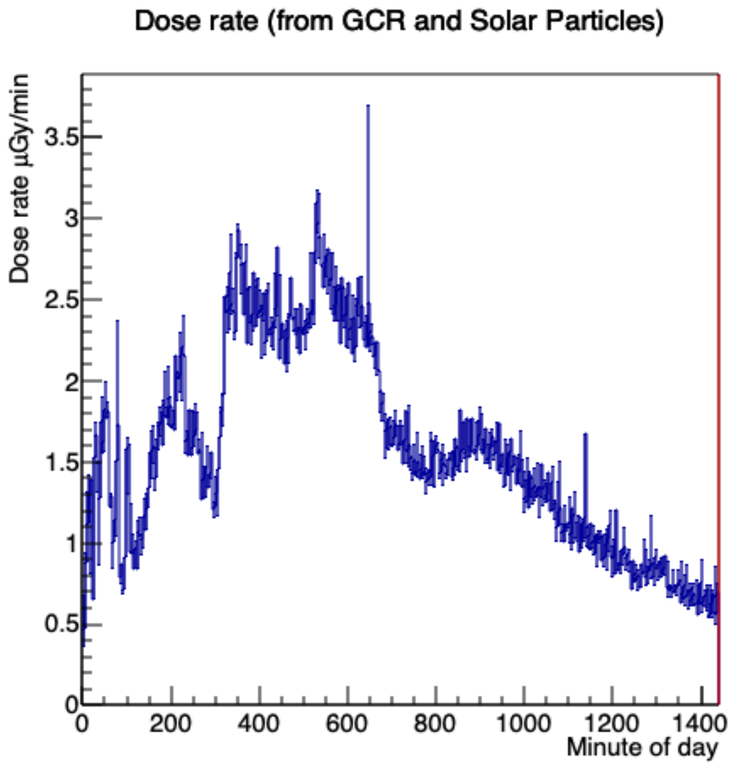
M. Kroupa et al JGR Space Physics Oct 2019

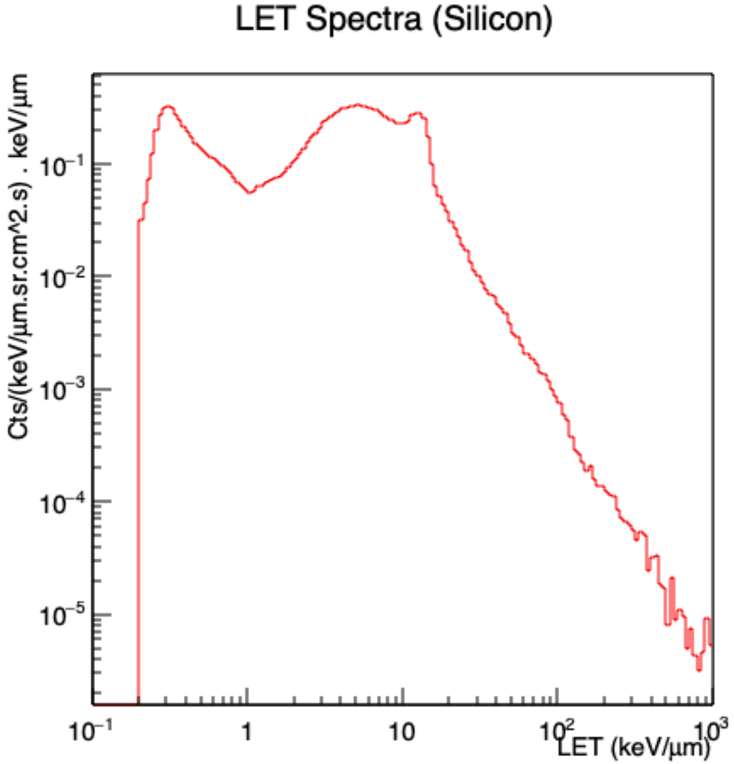
Solar Particle Events

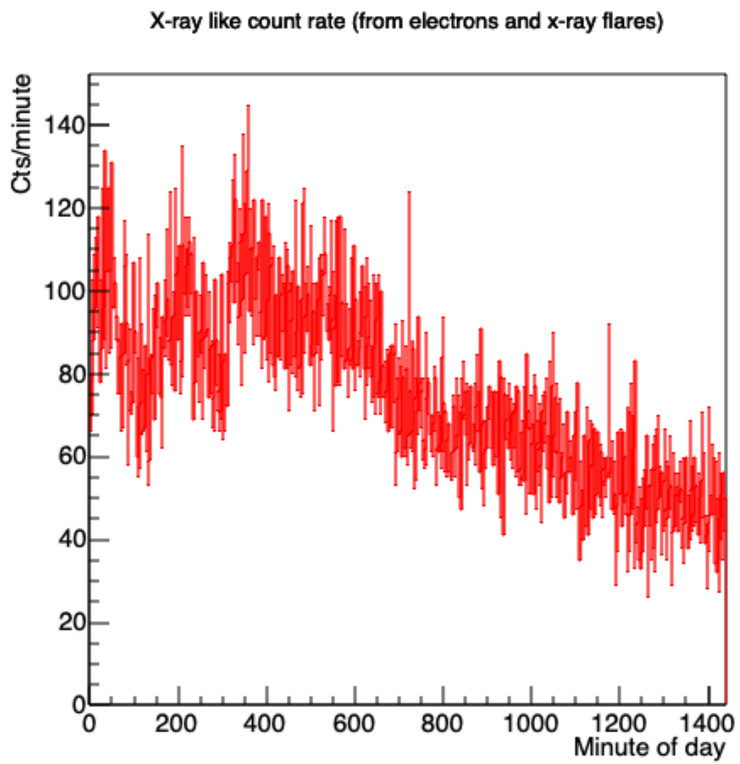

GOES Proton Flux (5-minute data)
Zoom 6 Hour 1 Day 3 Day 7 Day
Particles · cm⁻² · s⁻¹ · sr⁻¹
104
103
102
101
100
10−1
10−2
SWPC 10 MeV Warning Threshold
00:00 Feb 21
12:00
00:00 Feb 22
12:00
00:00 Feb 23
12:00
00:00 Feb 24
12:00
00:00 Feb 25
12:00
00:00 Feb 26
12:00
00:00 Feb 27
12:00
00:00 Feb 28
Universal Time
GOES-16 ≥ 10 MeV
GOES-16 ≥ 50 MeV
GOES-16 ≥ 100 MeV
Updated 2023-02-27 21:05 UTC
Space Weather Prediction Center


LET_RAW_SCI_ABSORBED_DOSE_RATE
mGy/min
0.01
0.008
0.006
0.004
0.002
0
02/23/23
02/24
02/25
02/26
02/27
02/28
03/01
Time

Example Solar Activity GMT130 SPE

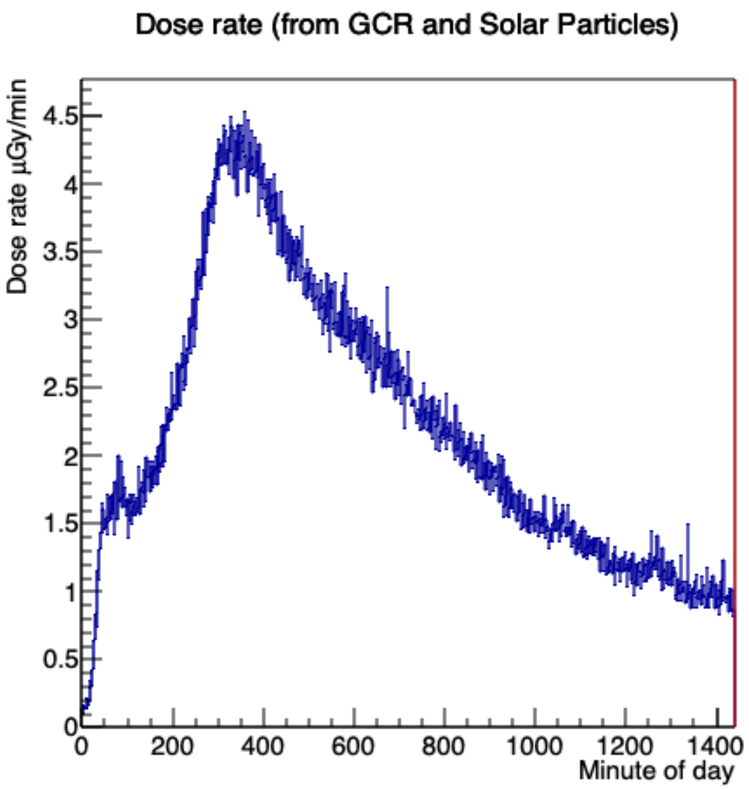


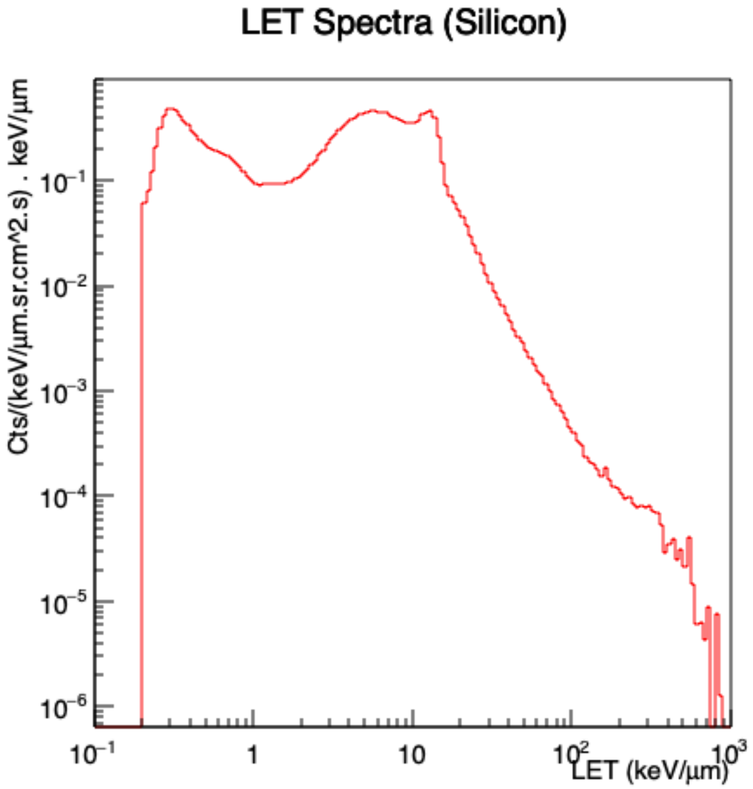


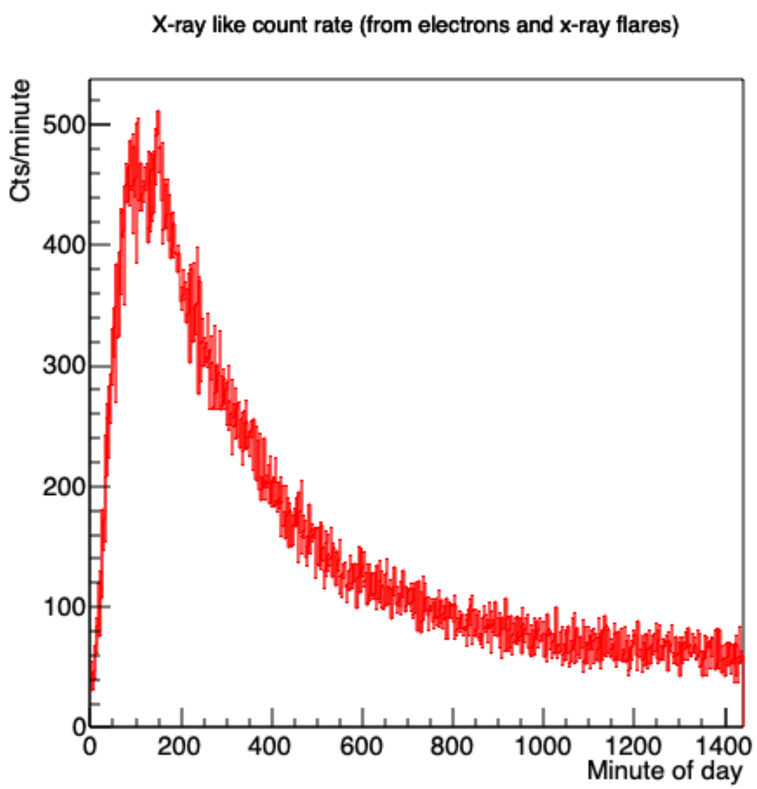


Spikes in dose rate on left from high Z GCR hits (like REMS/HERA), LET spectra in middle uses experimental volcano correction
X-ray counts on right mostly associated with electron flux, but occasionally with solar x-ray flares

Example SPE – July 2023

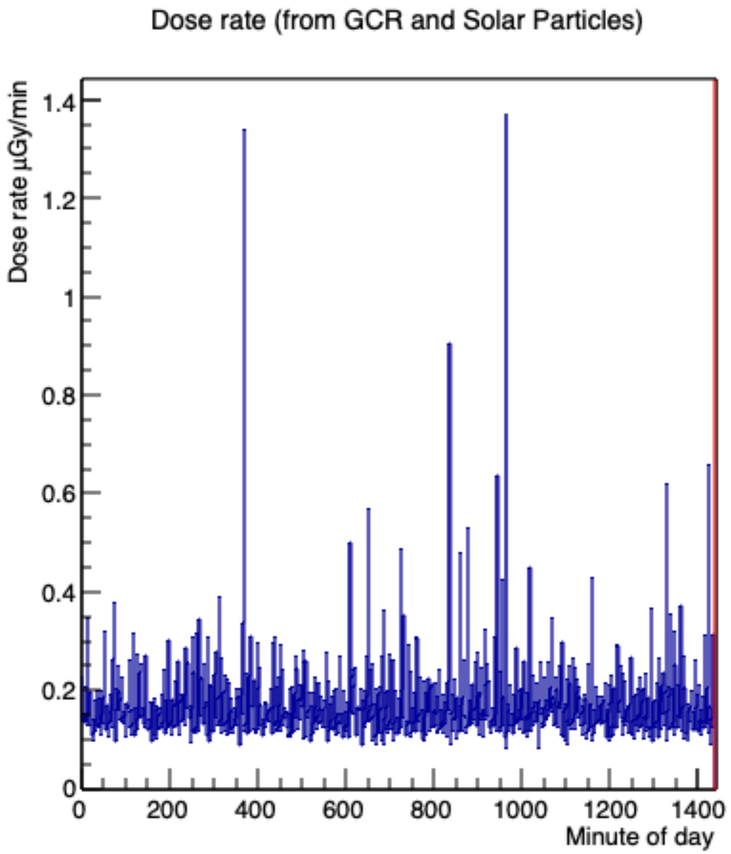


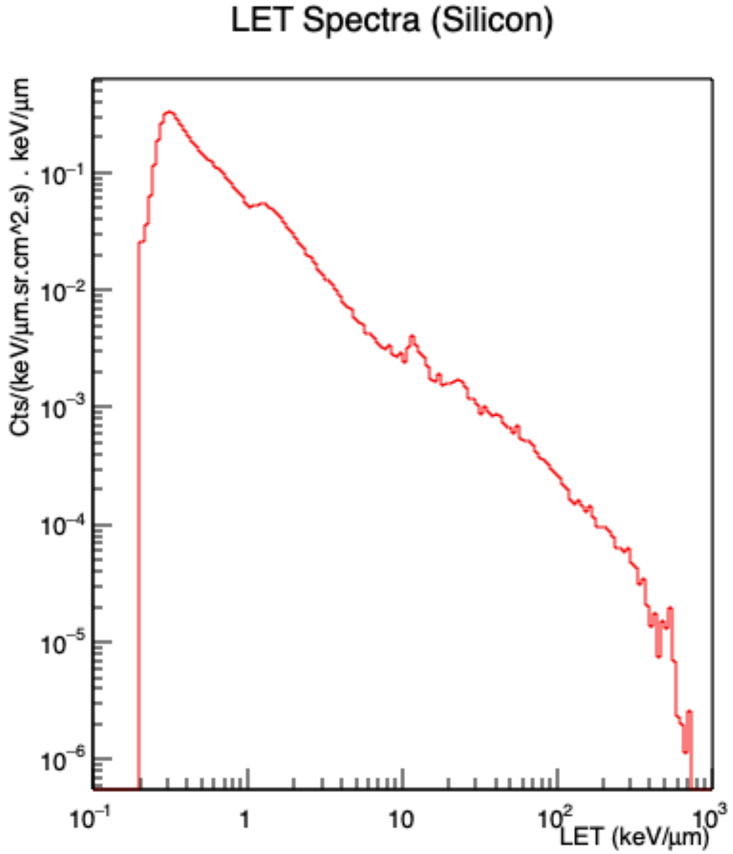


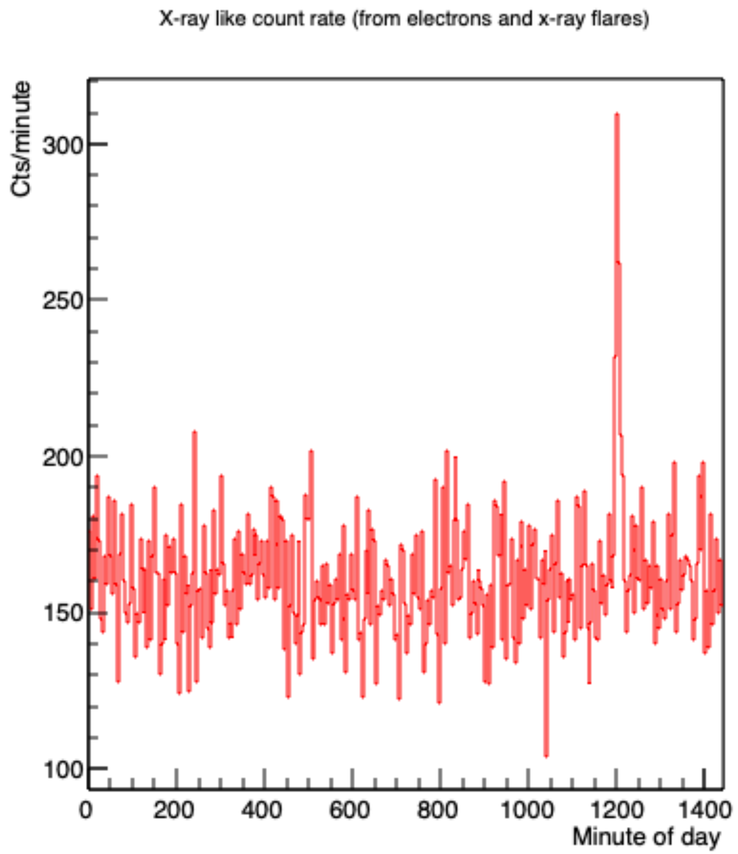


Spikes in dose rate on left from high Z GCR hits (like REMS/HERA), LET spectra in middle uses experimental volcano correction
X-ray counts on right mostly associated with electron flux, but occasionally with solar x-ray flares

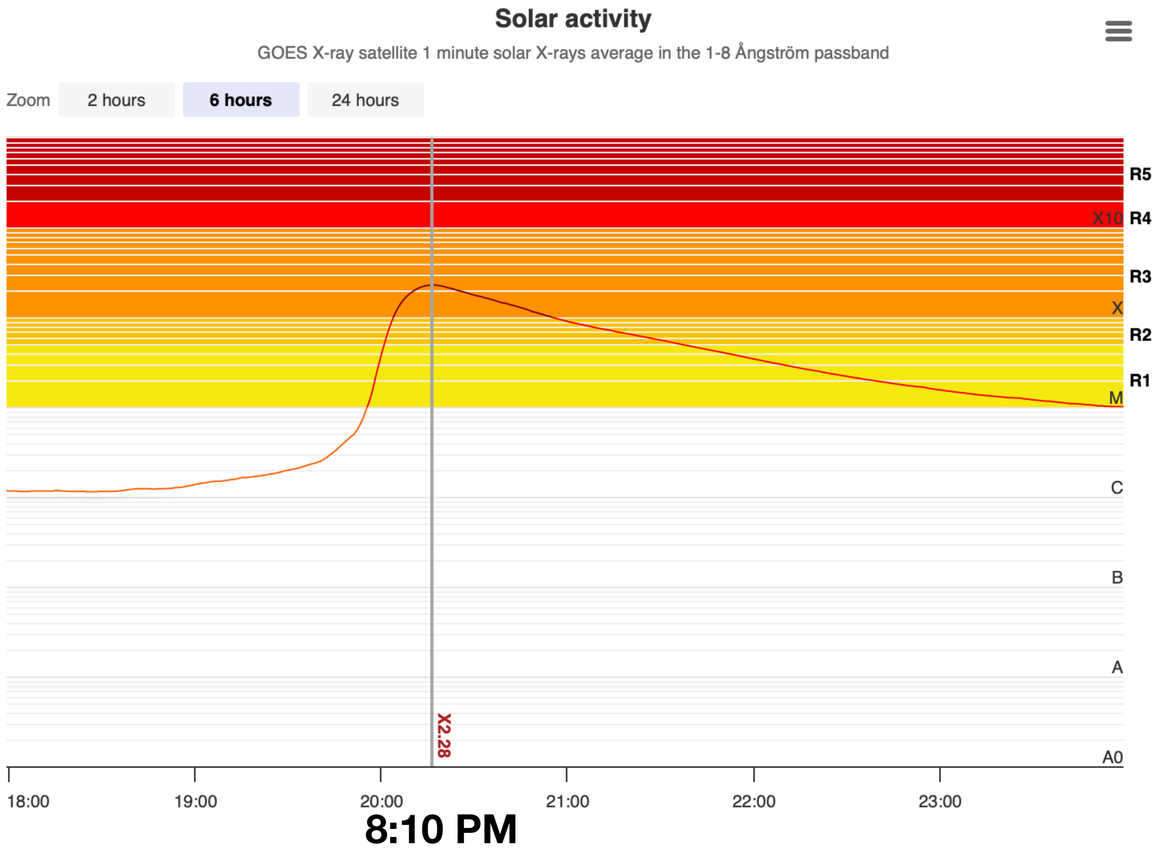
Example solar flare – X2.2 Feb 17 2023 (Rebinned 4 min data)







Spikes in dose rate on left from high Z GCR hits (like REMS/HERA), LET spectra in middle uses experimental volcano correction
X-ray counts on right mostly associated with electron flux, but occasionally with solar x-ray flares



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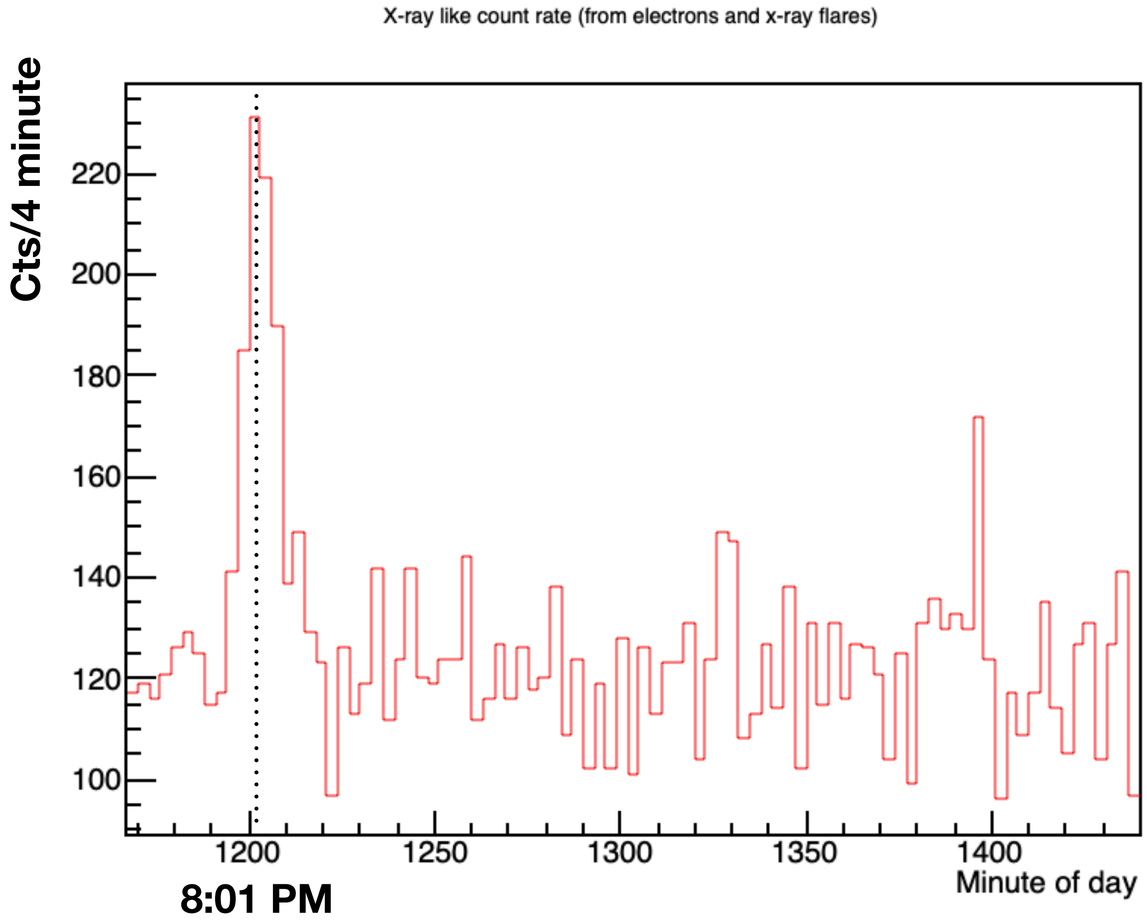


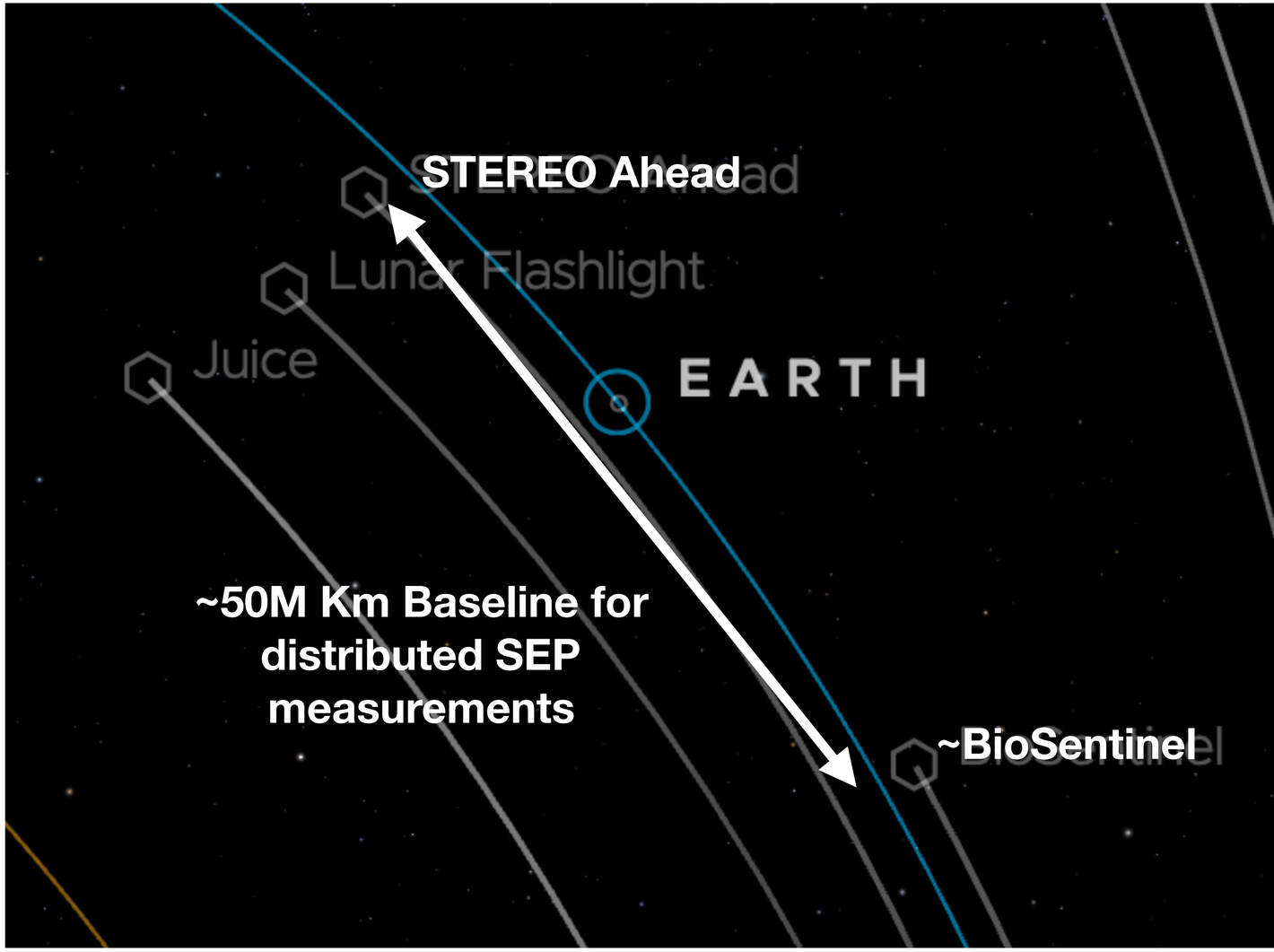
8:01 PM

Note - the peak of the flare on Biosentinel comes ~10 minutes before the peak in the GOES 1-8 A Wideband channel (1.5 - 12 keV). This is likely because the Biosentinel is only sensitive to quite high energy external x-rays, e.g. > 50 keV due to its shielding. It is well known that solar flares x-ray emission peaks in higher energy earlier than lower energies.

Also - this X2.2 solar flare is the only solar flare we have been able to find so far in the Biosentinel data - unclear if this is a size effect, (e.g. it needed to be this big to see it), the x-ray spectrum was particularly hard or something else.

The Future

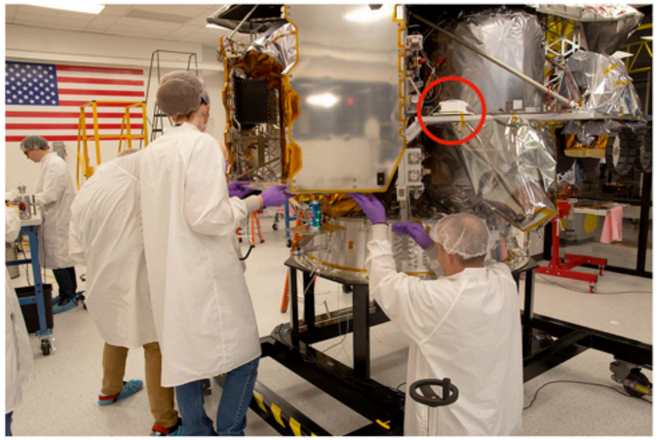
- Big to do list including calibration of LET channels to STEREO proton data and more comparisons with other SWx instruments
- Shielding studies, comparison to modeling etc
- How good really is that GCR high LET bootstrap?
- Towards the end of the year STEREO ahead and Biosentinel fortuitously positioned either side of Earth assets - ideal for studies of longitudinal spread of SEP

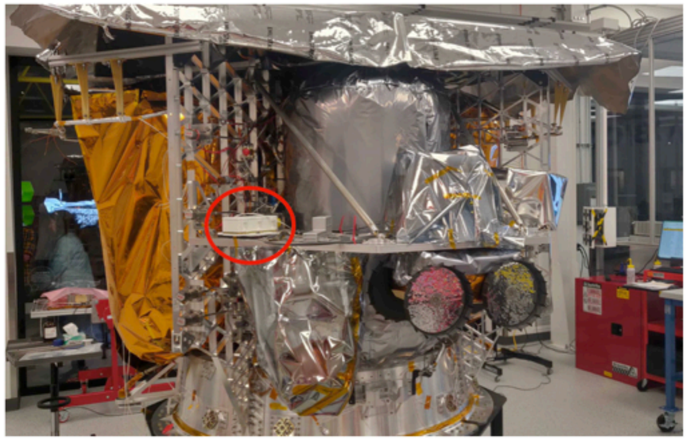


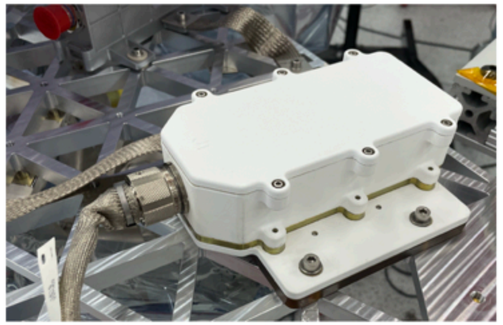
Conclusions

- Biosentinel is still delivering valuable data on the deep space radiation environment including the GCR environment into solar max and solar particle events
- Efforts are underway to increase the science take including the electron environment and some proton flux bins
- Biosentinel will be fortuitously positioned with STEREO A for distributed SEP measurements at the end of this year
- Much analysis work still to be done

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