10 Years of Timepix in Space - How CERN Detectors are Supporting Human Spaceflight

Introduction

- Artemis 1 launch Wednesday Nov 16
- Carrying 4 Timepix detectors from the Medipix2 collaboration at CERN on board to measure radiation
- Part of a larger program at NASA using Timepix based instruments for radiation measurement
- Why do we care about space radiation?
- How did we get here?
- How do we use these detectors
- How will we use them in the future?

Complete List of NASA Timepix Based Flight Hardware

Name	Date Flown	Mission	Location	Objective	Vehicle	Number TPX
REM	2012	ISS	LEO	Demo	ISS	5
BIRD	2014	Orion EFT-1	LEO/MEO	Demo/Science	Orion	2
REM2	2018	ISS	LEO	Ops	ISS	7
MPT	2017	ISS	LEO	Science	ISS	2
Biosentinel	2020	ISS	LEO	Science	ISS	1
ISS-HERA	2018	ISS	LEO	Demo	ISS	3
AHOSS	2020	ISS	LEO	Demo/Ops	ISS	3
LETS(1)	2023	Astrobotic 1	Lunar Surface	Science	Peregrine	1
LETS(2)	2024/5	Berensheet 2*	Lunar Surface	Science	Berensheet 2	1
HERA	2022	Artemis 1	Lunar Orbit	Ops	Orion	3
Biosentinel	2022	Artemis 1	Solar Orbit	Science	Cubesat	1
HERA	2023	Polaris Dawn	MEO	Science	Crew Dragon	1
HERA	2024	Artemis 2	Lunar Orbit	Ops	Orion	6
HERA	2025	Artemis 3	Lunar Orbit	Ops	Orion	6
ARES	2025	Artemis 3	Lunar Surface	Ops	Starship	>=1
LEIA	~~2024	CLPS Lander	Lunar Surface	Science	TBS Lander	1
ARES	2026	Artemis	Lunar Orbit	Ops	Lunar Gateway	2

***Evaluating mission possibility**

7 missions flown, 4 missions next six months, 6 missions manifested, > 23 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

People involved

- **NASA JSC** - Stuart George*, Tom-Campbell-Ricketts, Martin Leitgab, Ryan Rios, Nic Stoffle, Dan Fry, Ramona Gaza, Mena Abdelmelek, Sergiy Rozhdestvenskyy, Amir Bahadori, Eddie Semones, Susan Gavelas, Catherine McLeod, Michael Ecord, Maddy Vandewalle, Tim Sweet, Scott Wheeler, Hank Jones, Ron Moore, Aaron Schram, Hieu Nguyen, Robert Hirsch, Neil Townsend, Justin Yang, Shawn Li, Karly O'Connor, Carlos De Los Santos, Trish Caffey
- **University of Houston** - Larry Pinsky, Son Hoang, John Idarraga, Toni Empl
- **CERN** - Xavier Llopart Cudie, Jerome Alozy, Lukas Tlustos, Rafael Ballabriga, Michael Campbell
- **Advacam** - Jan Jakubek, Martin Jakubek, Pavel Soukup, Carlos Granja,
- **Daniel Turecek**
- **IEAP** - Stanislav Pospisil, Zdenek Vykydal
- **NASA Ames** - Sergio Santa-Maria, Jack Miller
- **HIMAC -** Satoshi Kodaira, Hisashi Kitamura
- **Astrobotic, Pittsburgh** - Jodi Coletti, Michael Chahin
- **SpaceX** - Marissa Rosenberg, Neil Banarjee
- **Los Alamos National Laboratory** - Martin Kroupa
- **NASA Space Radiation Laboratory** - Mike Sievetz, Adam Ruskin,
- **Brookhaven National Laboratory Tandem** - Dannie Steskie, Chuck Carlson
- **TRISH/Baylor College of Medicine** - Jimmy Wu

*Presenter

Funding

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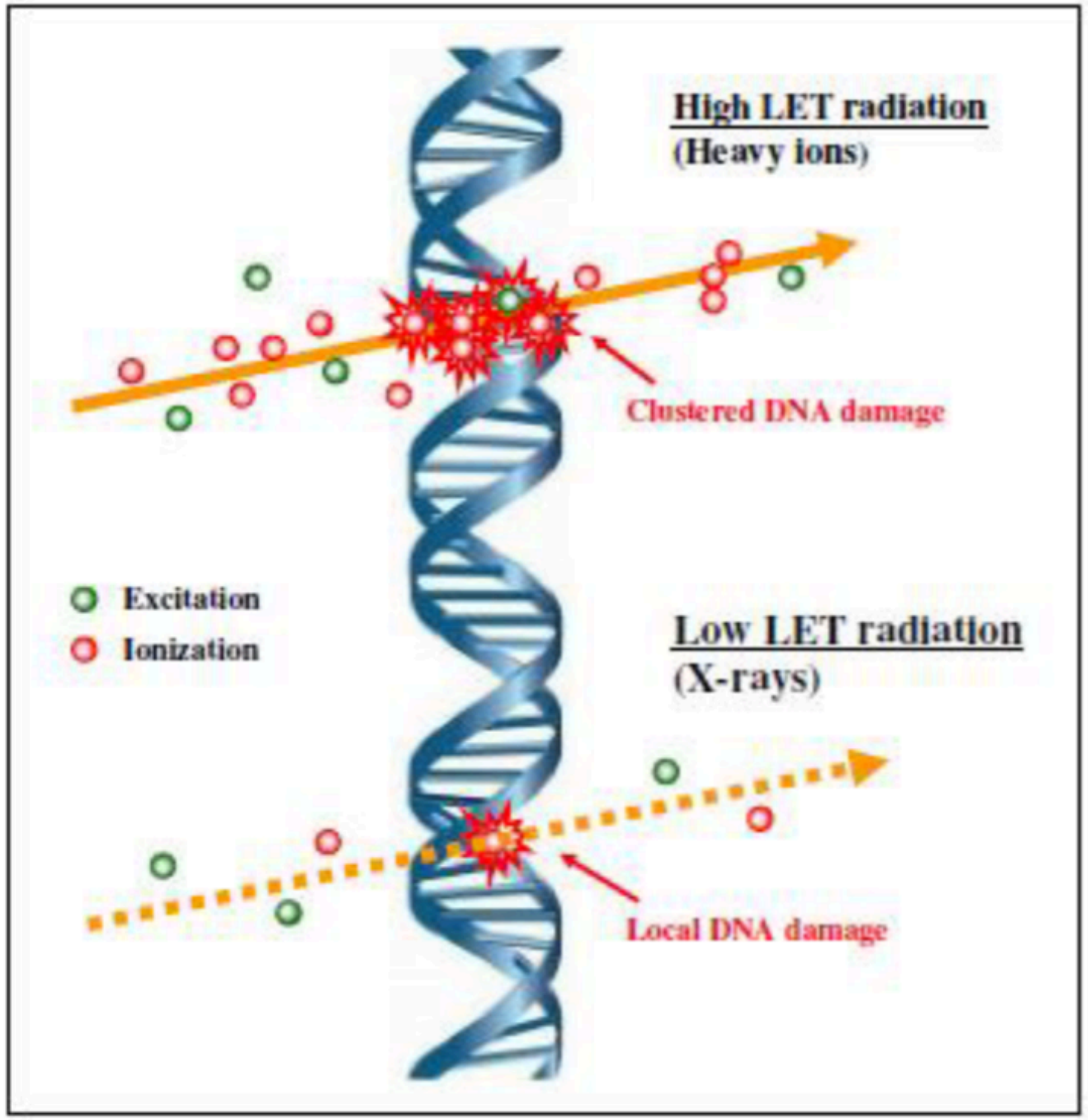
- Work to develop the HERA for the SpaceX Polaris Dawn mission was funded by the Translational Institute for Space Health

- It is important to acknowledge that vehicles we fly on, including the International Space Station, Orion Spacecraft and Lunar Gateway all have significant contributions from ESA and other International partners.

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.

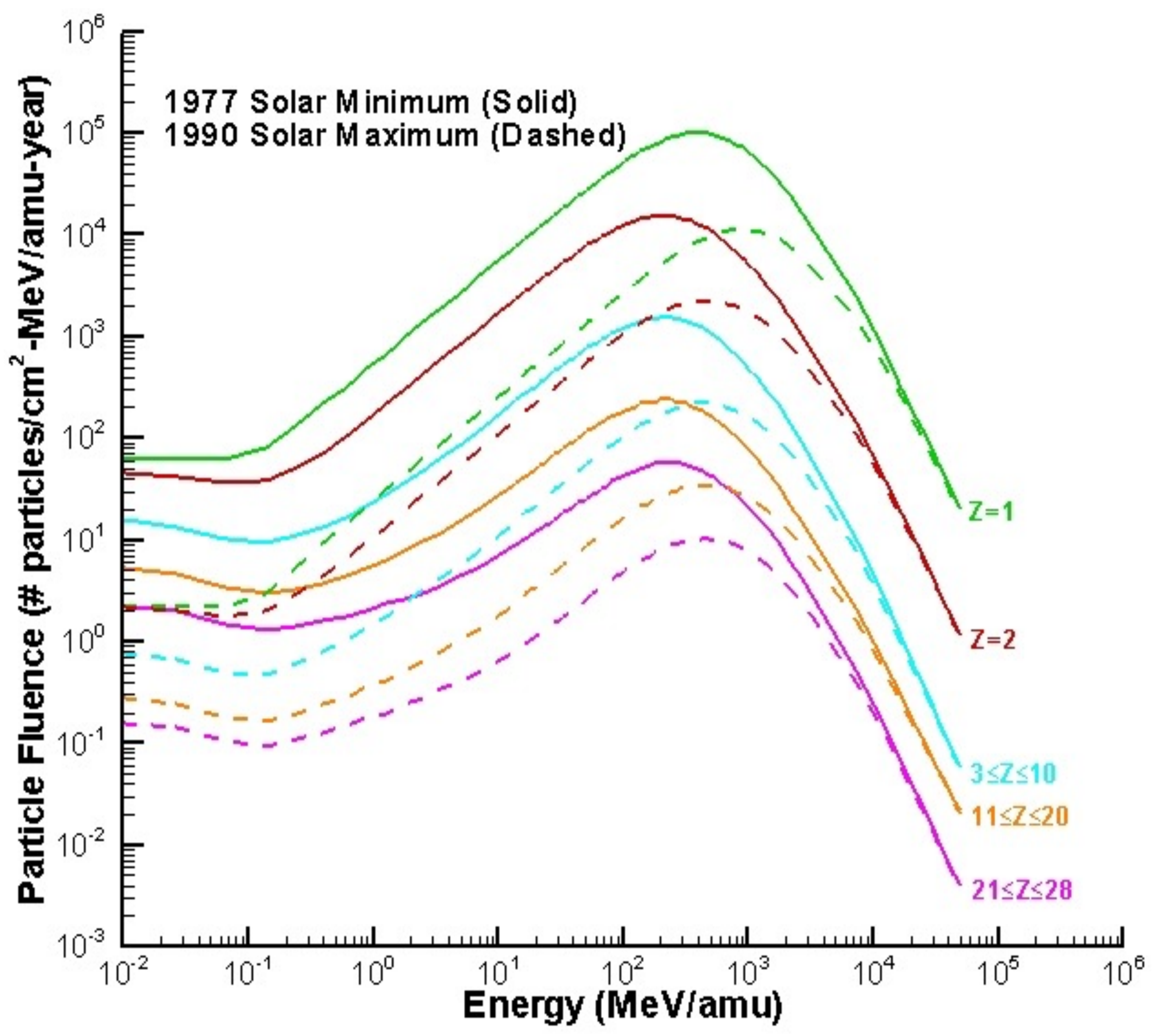


Heavy ions cause clustered damage along their tracks, causing outsize biological effect compared to terrestrial radiation sources like x-rays. From Tinganelli and Durante (2020)

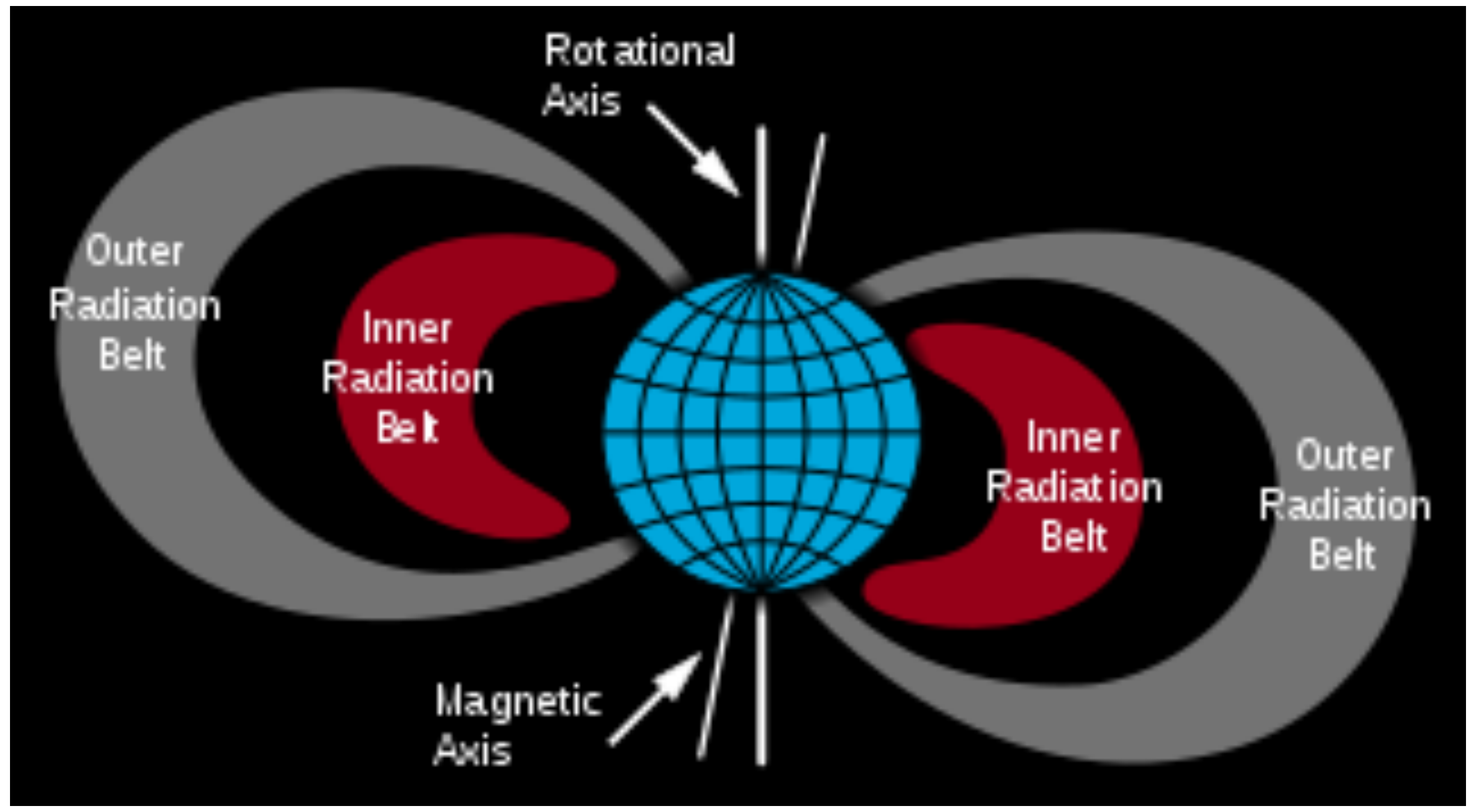
Protect crew, keep crew ALARA, enable longer and more complicated missions, understand risks of radiation

What Sort of Radiation is there in Space?

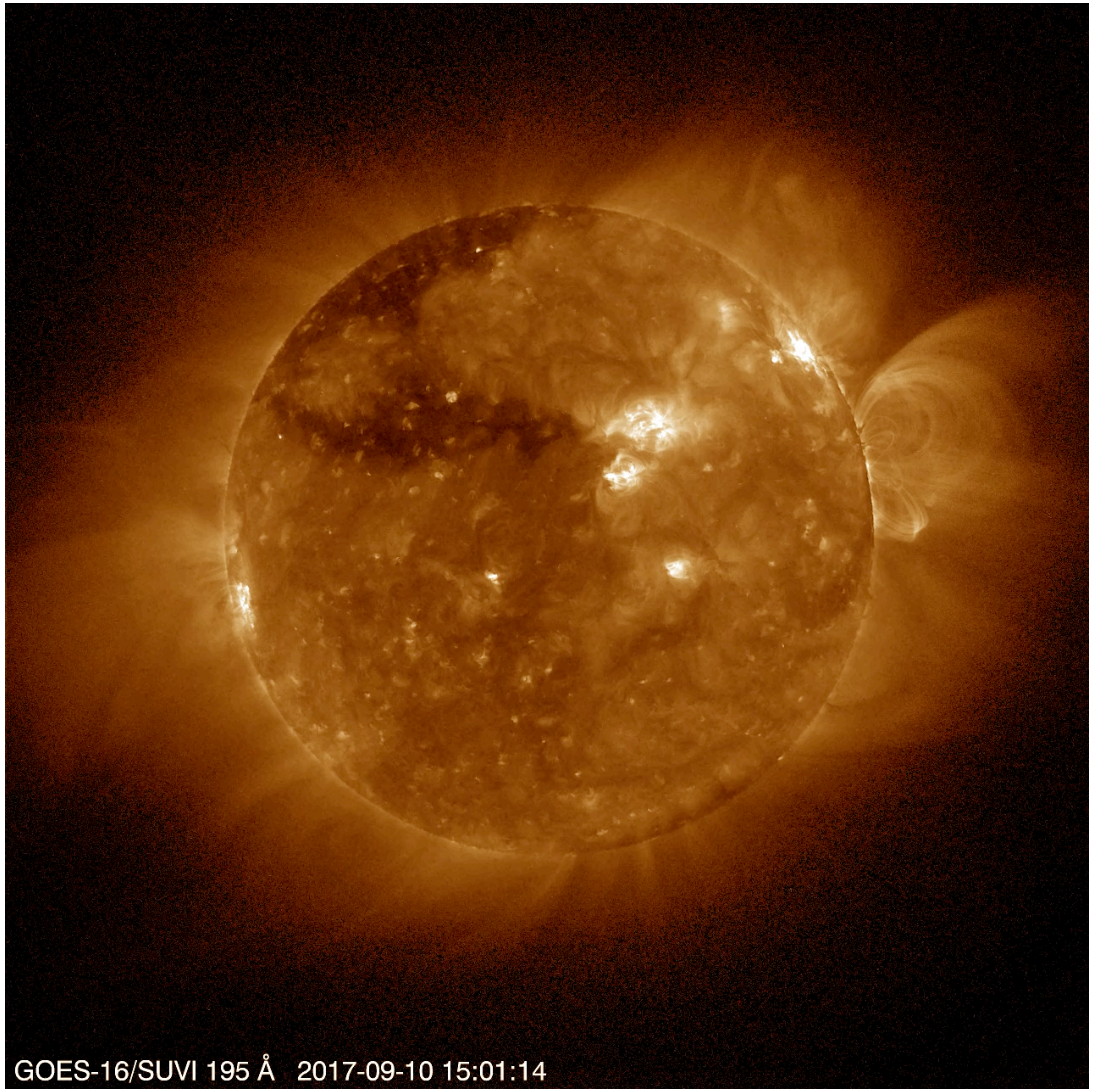
	Composition	Energies of interest	Spectral Shape	How Many/ cm^2	How Long
Galactic Cosmic Rays (GCR)	Mixed ion	100 MeV/a - 10 GeV/a (of interest)	See right	A few/ second	Constant
Surfaces	Like GCR, with albedo/ attenuation	As GCR	See right	As GCR	Constant
Particle Belts	Protons/ Electrons	Protons < 200 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

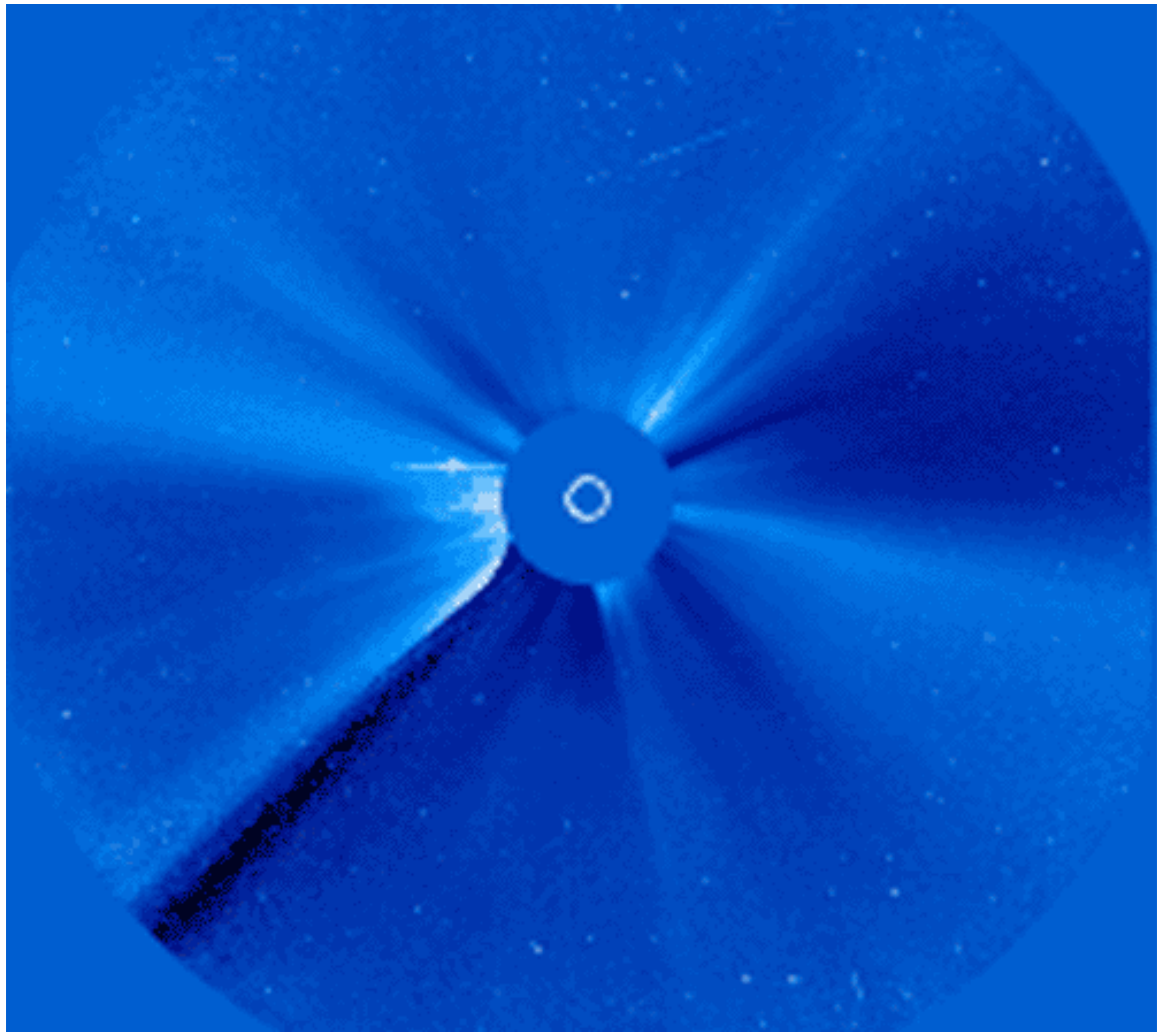


Galactic Cosmic Rays



Solar Particle Events





- (Left) Sept 10 2017 flare and CME measured with GOES-16 SUVI
- (Right) Oct 28 2003 CME imaged with LASCO coronagraph

What can we do about space radiation

	Effectiveness of Shielding*	Predictability	Primary Mitigation	Risks
Galactic Cosmic Rays, Surfaces	Low	Constant (ish)	Mission length	Chronic
Particle Belts	High	Known quantity	Optimised Trajectory	Chronic
Solar Particles	High	Low Think extreme rare weather events	Forecasting/ nowcasting Shelter	Potentially acute. Esp if poorly shielded

A bit of History and Serendipity

CERN/Medipix Collaboration

- 1988 - Develops pixel detectors to replace crossed strips for vertexing in particle physics experiments after LEP era.
- 1999 - Pixel detectors designs for LHC experiments
- Medipix collaboration formed to bring pixel technology out of particle physics
- 1997 - Original Medipix detectors conceived of as photon counters for x-ray applications
- 2007 - The energy measuring Timepix originally conceived for gas detector readout applications
- 2011 - Miniaturization of Timepix readout systems at IEAP

NASA/Space Radiation Analysis Group

- Shuttle missions to LEO used a standardized set of hardware (TePC) for crew radiation monitoring.
- ISS instruments were successors to these detectors
- As NASA moved towards exploration missions it became clear that **smaller, more robust systems would be needed** to support exploration goals.
- It was also clear that there would be a gap between Shuttle and next generation exploration systems
- Timepix brought to the attention of NASA by Lawrence Pinsky at the University of Houston in 2008 via Erik Heijne

2012 - 5 Timepix (IEAP Minipix) flown on International Space Station

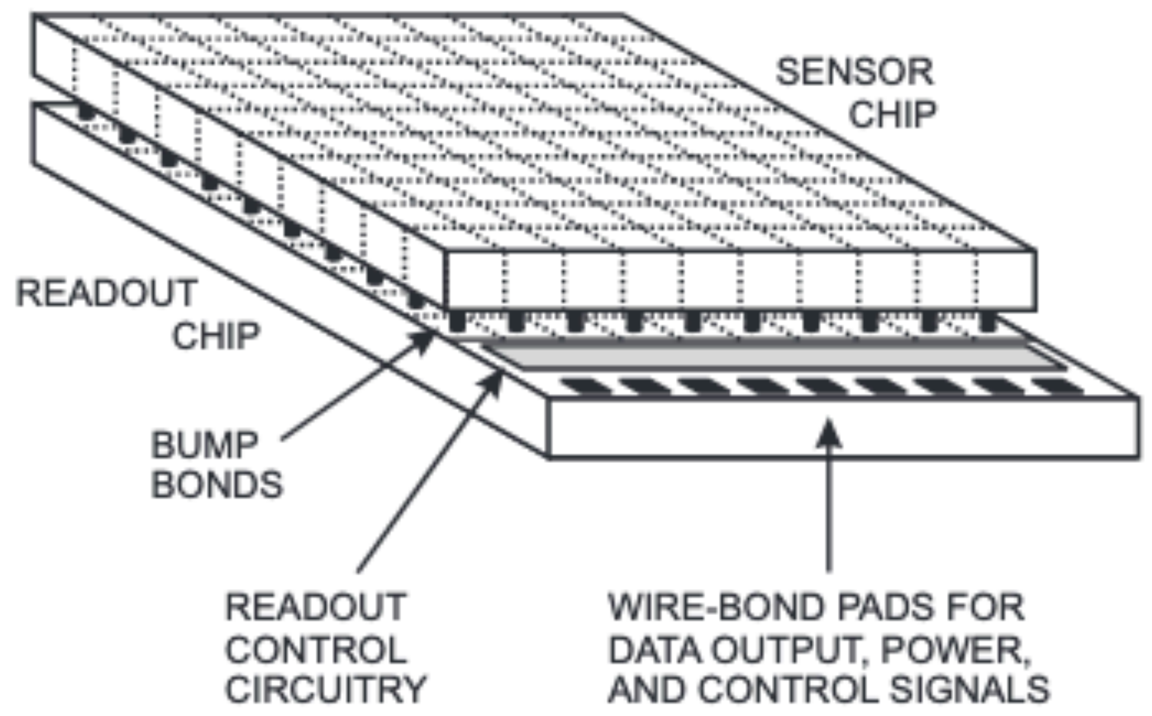
Old Shuttle engineering hardware from the “SRAG Museum”

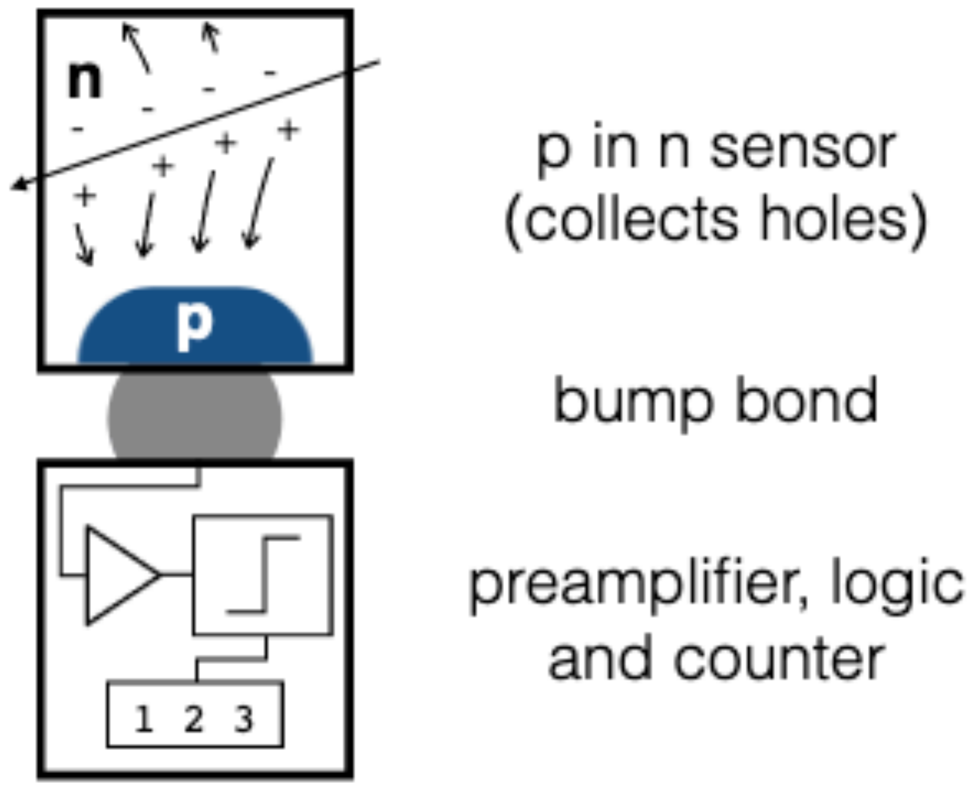
Timepix

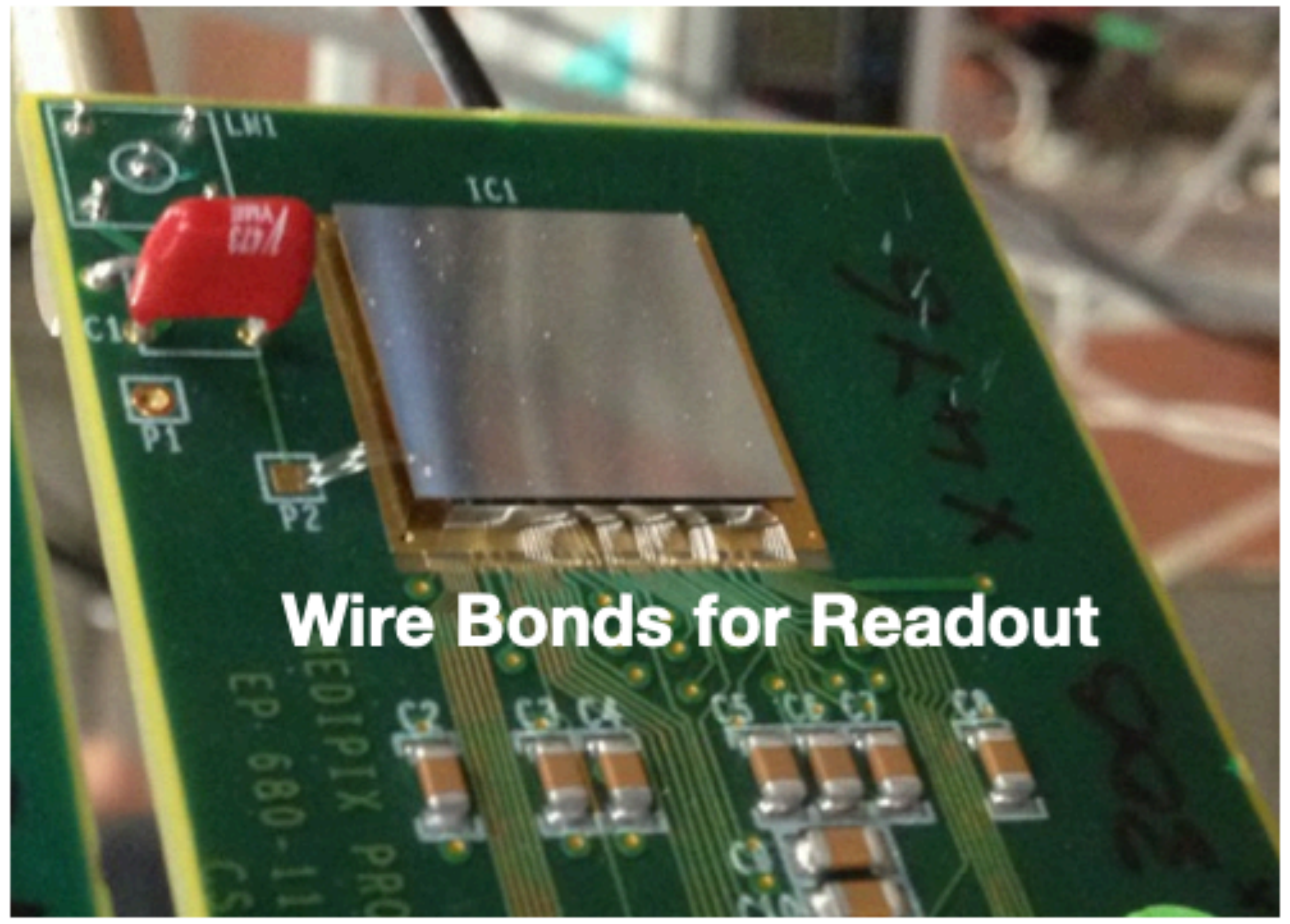
(Actually this unit - Minipix from IEAP Prague)

Timepix Hybrid Pixel Detectors

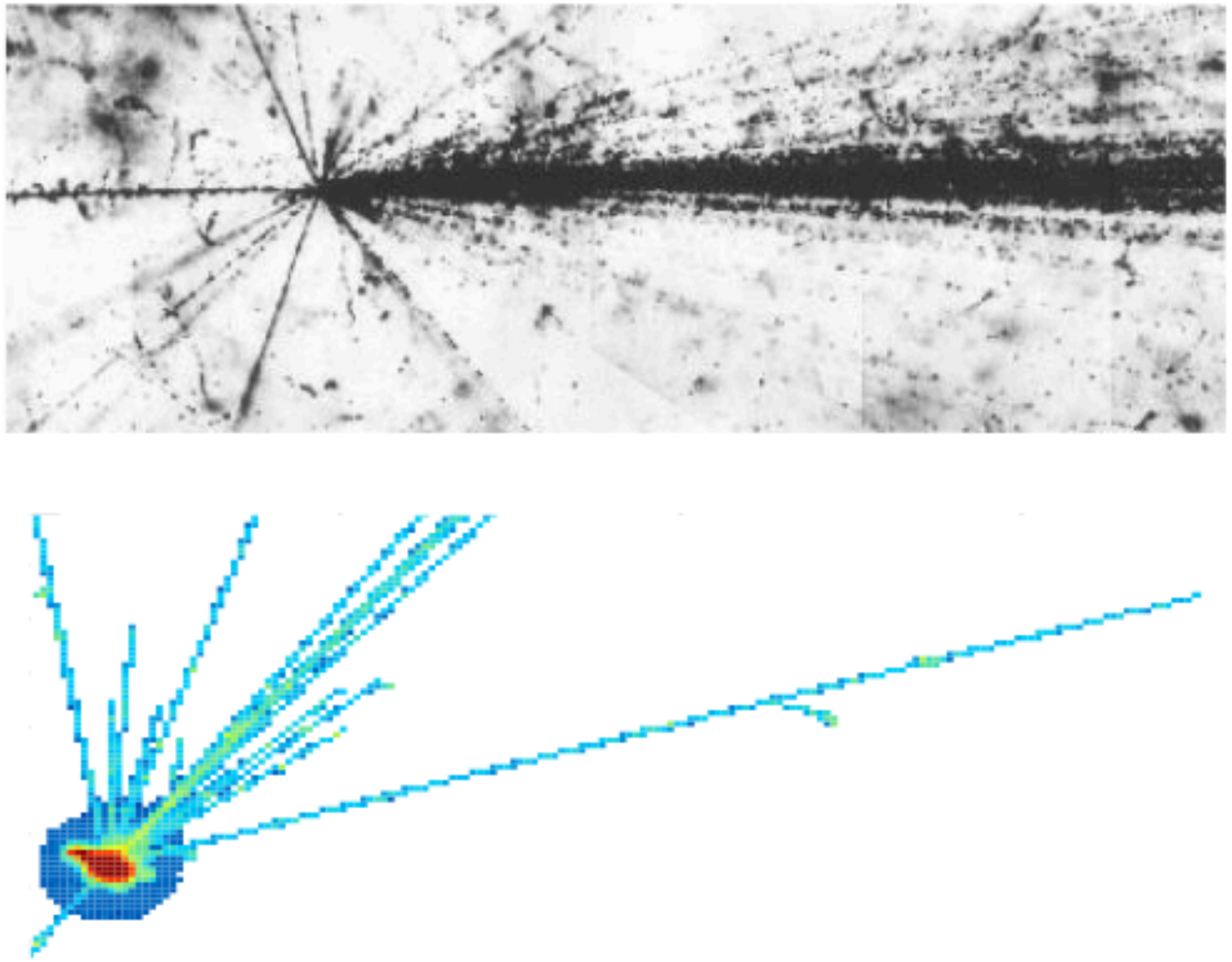
- Hybrid pixel detectors like Timepix consist of a pixellated semiconductor sensor connected to an underlying signal processing ASIC
- Each pixel contains a shaper circuit to shape the charge pulse from the semiconductor into a triangular pulse where length ~ charge
- The time over threshold is measured by and the resultant clock counts can be converted to an energy deposit in the pixel
- In the case of our Timepix detectors, the sensor is 256 x 256 pixels of 55um pitch and 500um thickness.
- When particles traverse a Timepix detector, the effect is much like solid state nuclear emulsion.



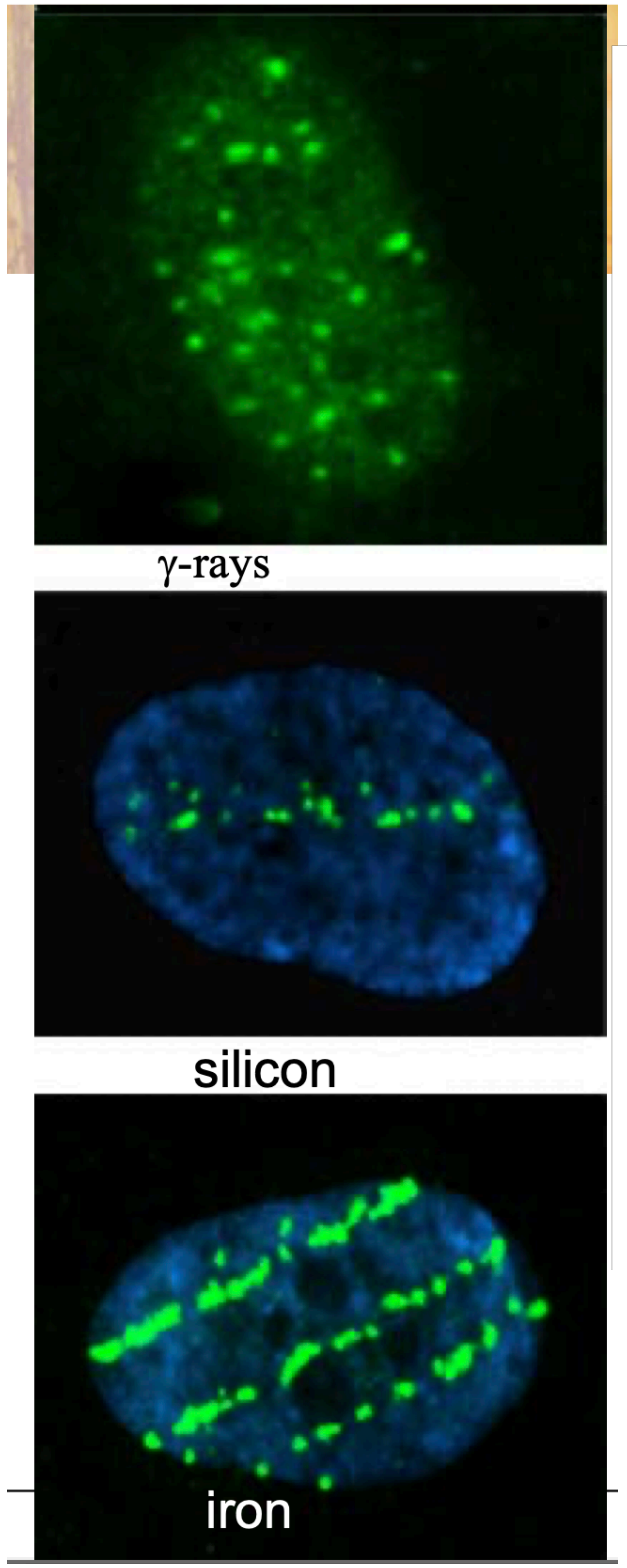


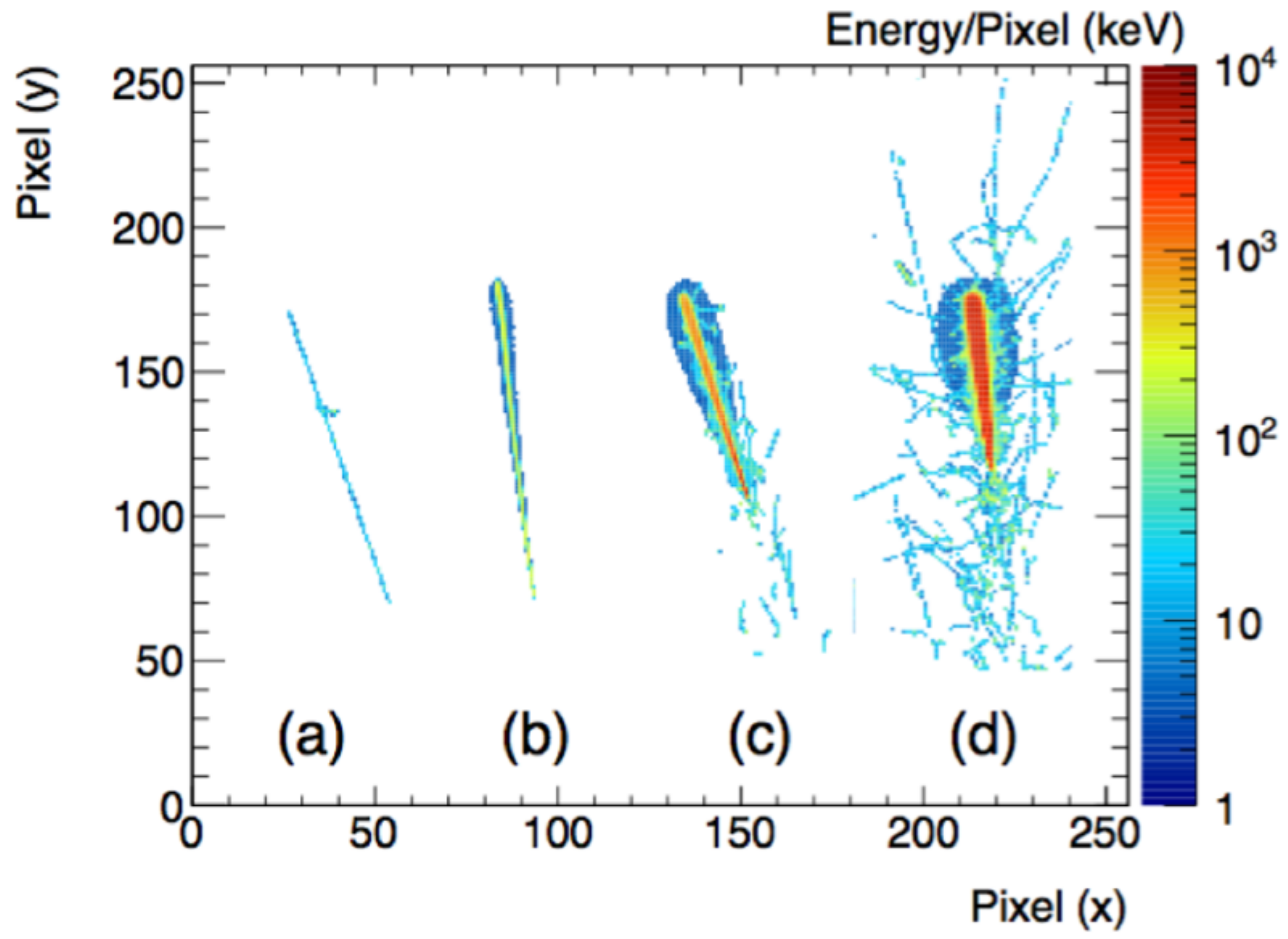


Timepix on Probe Board



Cosmic ray fragmentation interaction in nuclear emulsion (top) and measured by Timepix detector (bottom)





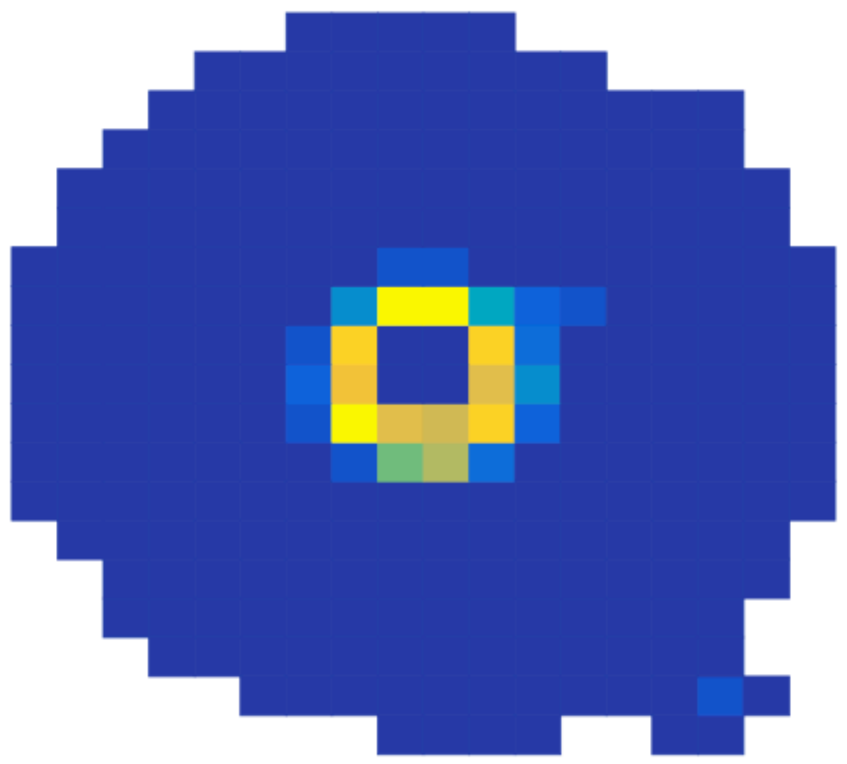
(a)	$\mathrm{LET_{Si}} = 0.52\,\mathrm{keV\,\mu m^{-1}}$	Alt. = 71.0°	Az. = 84.6°
(b)	$\mathrm{LET_{Si}} = 5.45\,\mathrm{keV\,\mu m^{-1}}$	Alt. = 82.0°	Az. = 84.0°
(c)	$\mathrm{LET_{Si}} = 54.8\,\mathrm{keV\,\mu m^{-1}}$	Alt. = 66.7°	Az. = 81.4°
(d)	$\mathrm{LET_{Si}} = 233\,\mathrm{keV\,\mu m^{-1}}$	Alt. = 84.2°	Az. = 81.1°

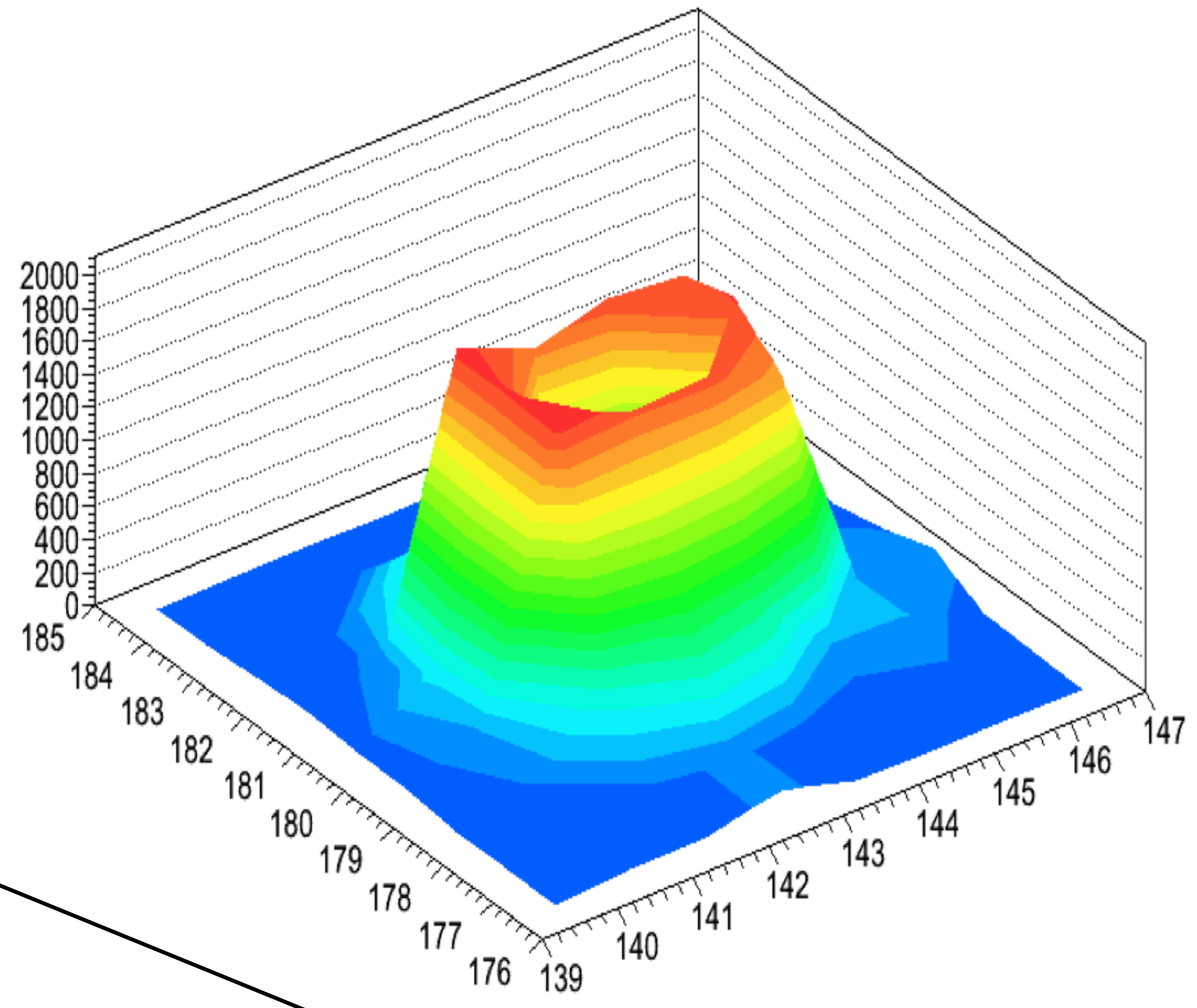
Heavy ion tracks in cells (left) and Timepix (right). (c) Would be the closest analogue to Is and (d) to Fe. Left adapted from Cucinotta and Durante (2006)

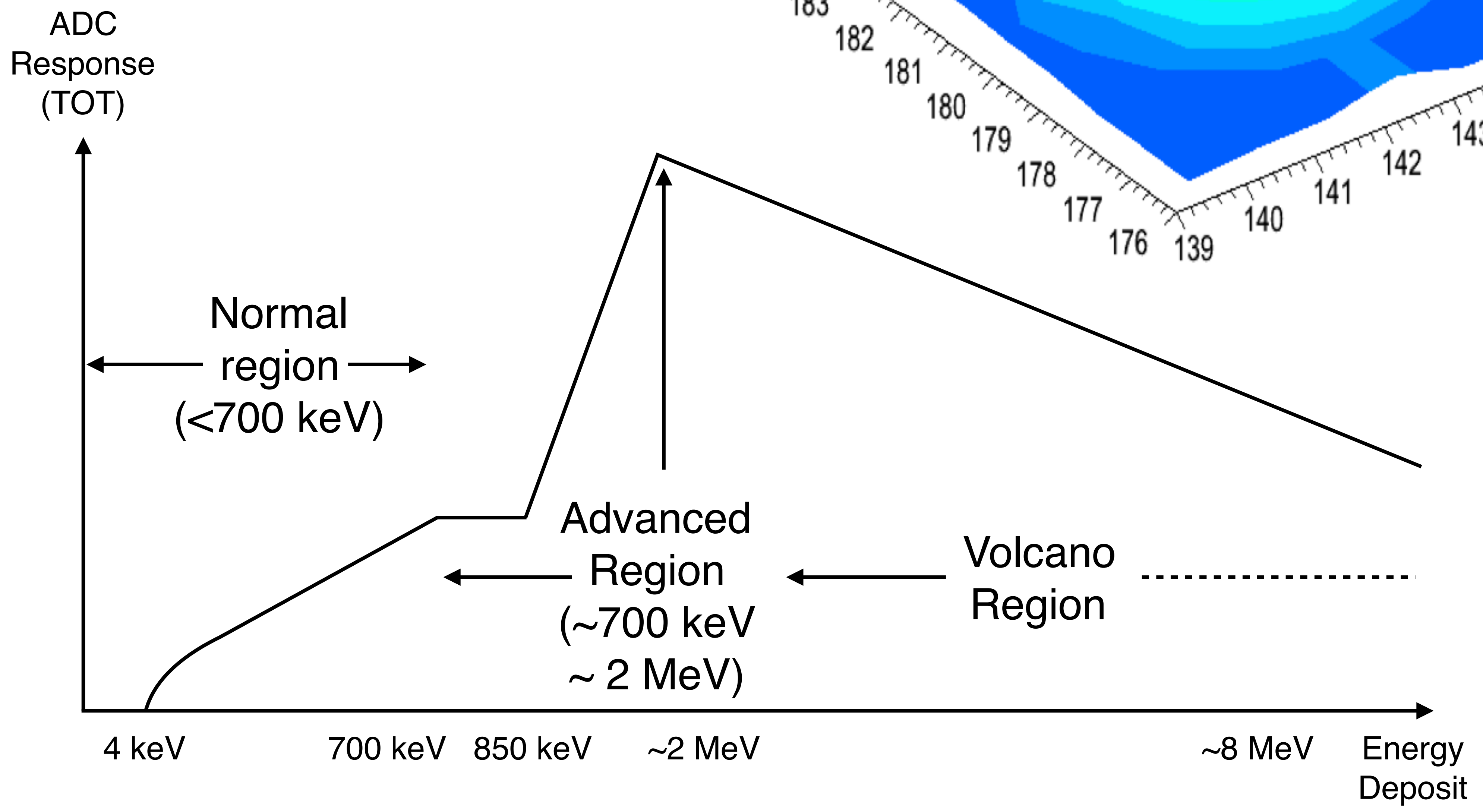
- **The essential point of a Timepix detector for particle tracking applications is that the pixels give you highly resolved access to the track structure -> you can use this to determine relevant properties of the particle**

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.





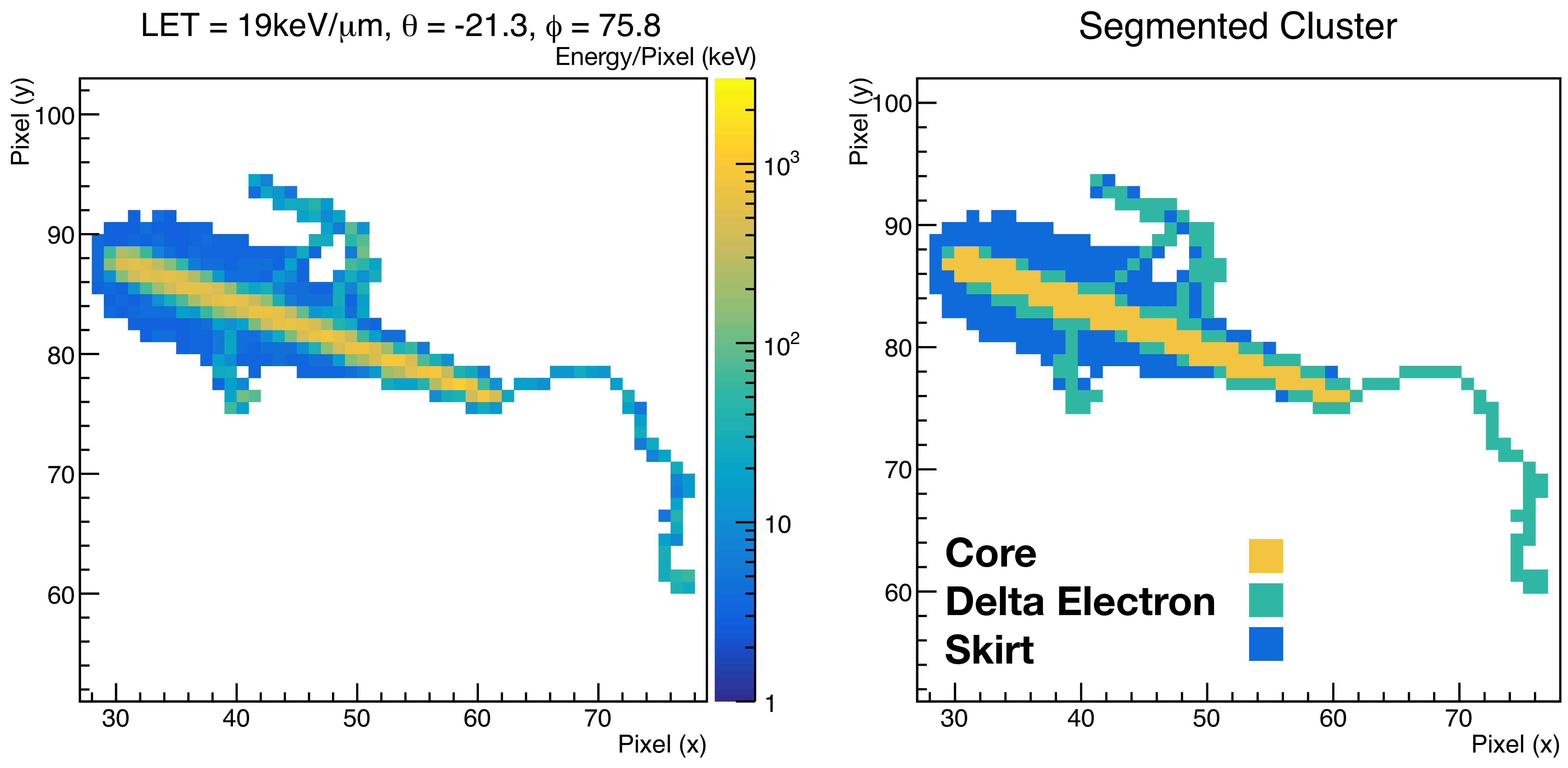


Top - “volcanos” as measured with a heavy ions at an accelerator (bottom) - Timepix calibration curve 4 keV - 8 MeV

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.



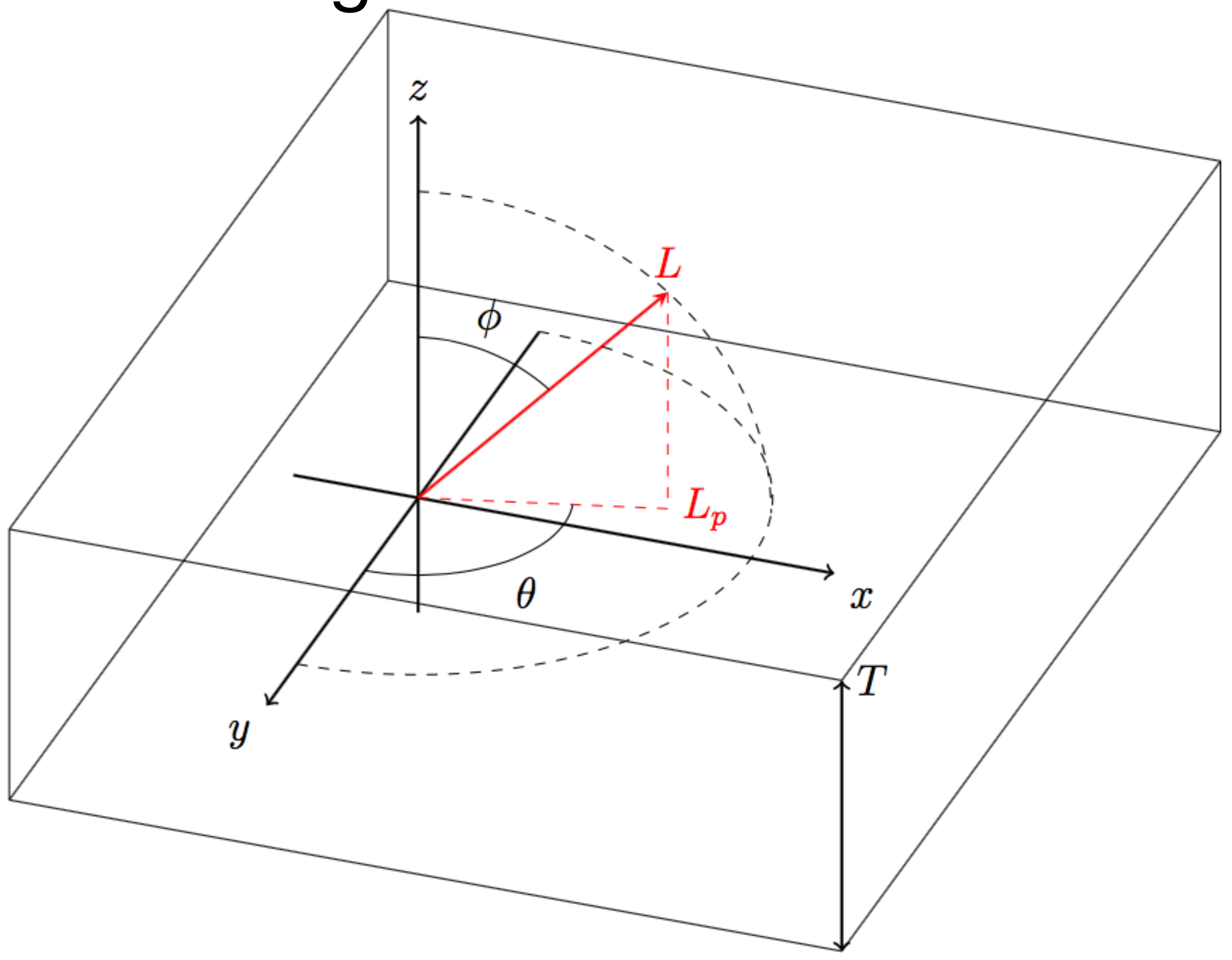
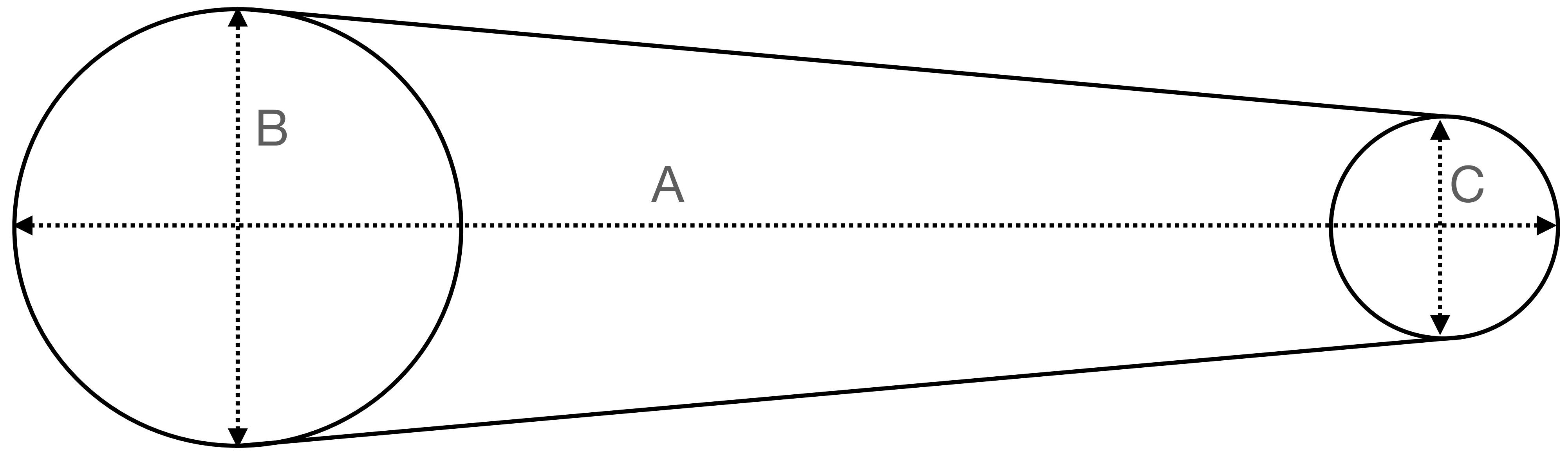


Figure 3.6: Measurement of the azimuth angle θ and altitude ϕ relative to the sensor axes from a penetrating track of length L over a sensor of thickness T.

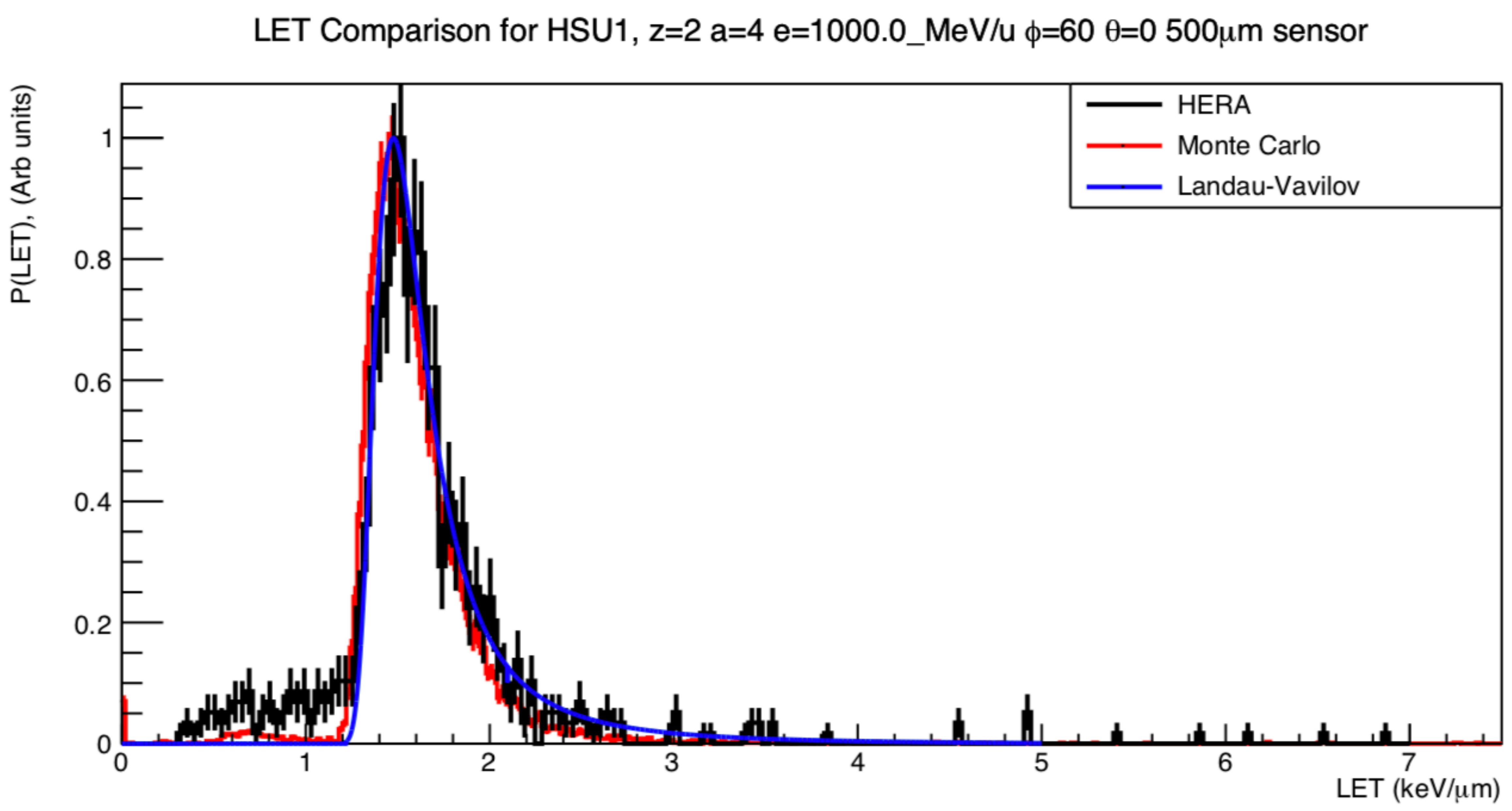


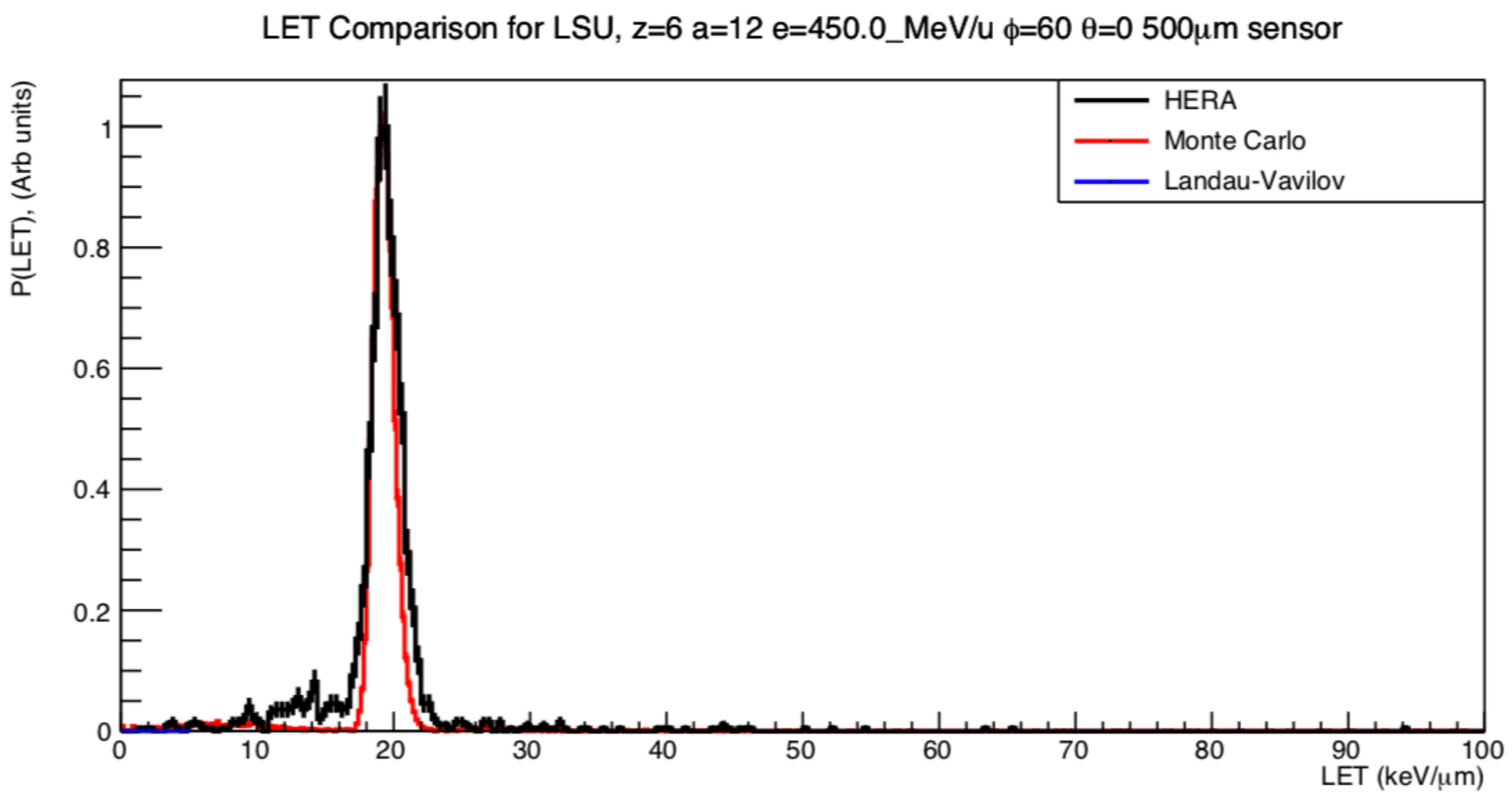
- Disentangle charge sharing effects - charge sharing in track causes characteristic 'comet' shape

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

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

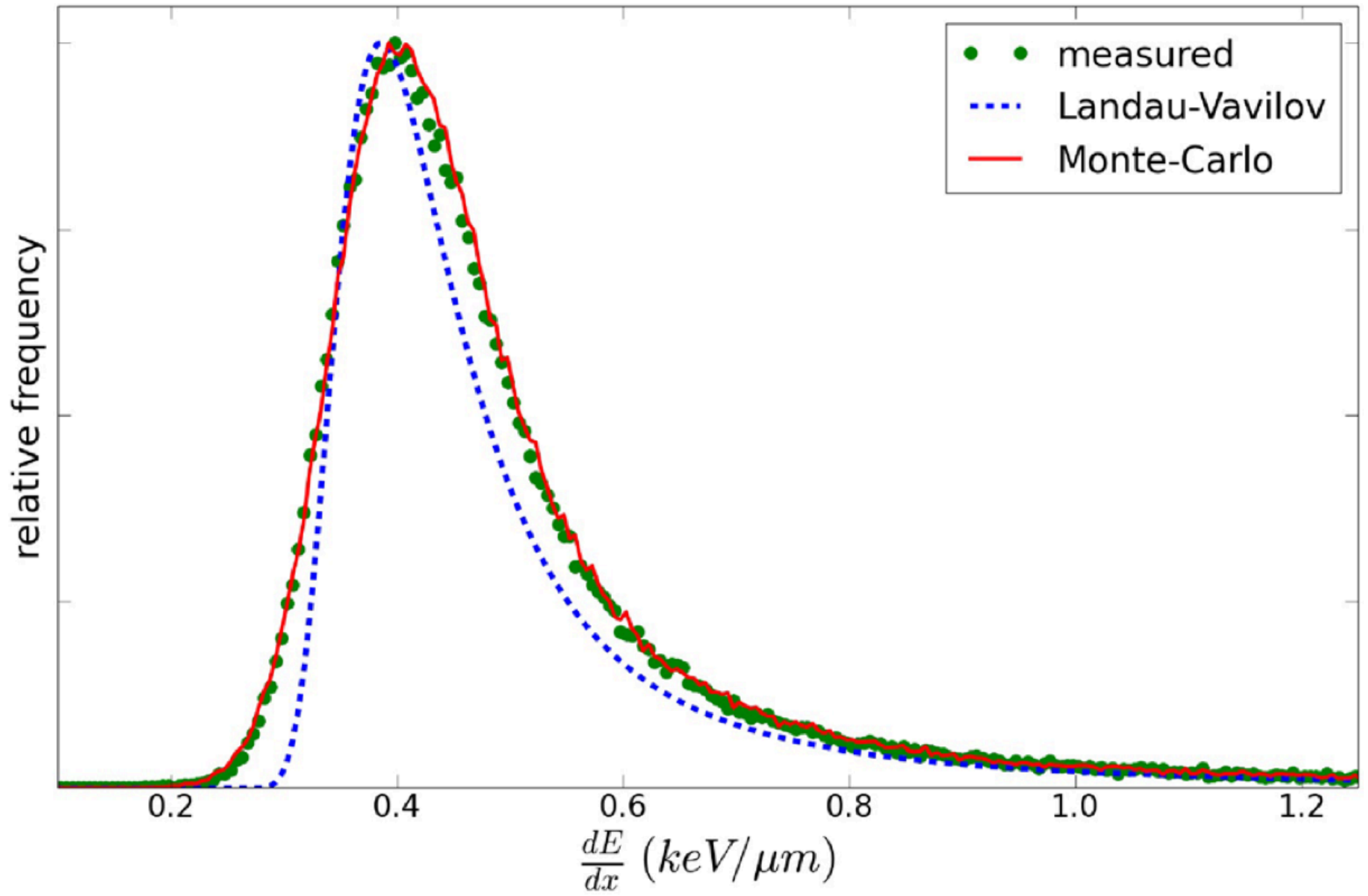
Example LET/Stopping Power Measurements





Top left - Alpha (1 GeV/a)
Top right - Carbon (450 MeV/a)
Right - Protons (400 MeV)

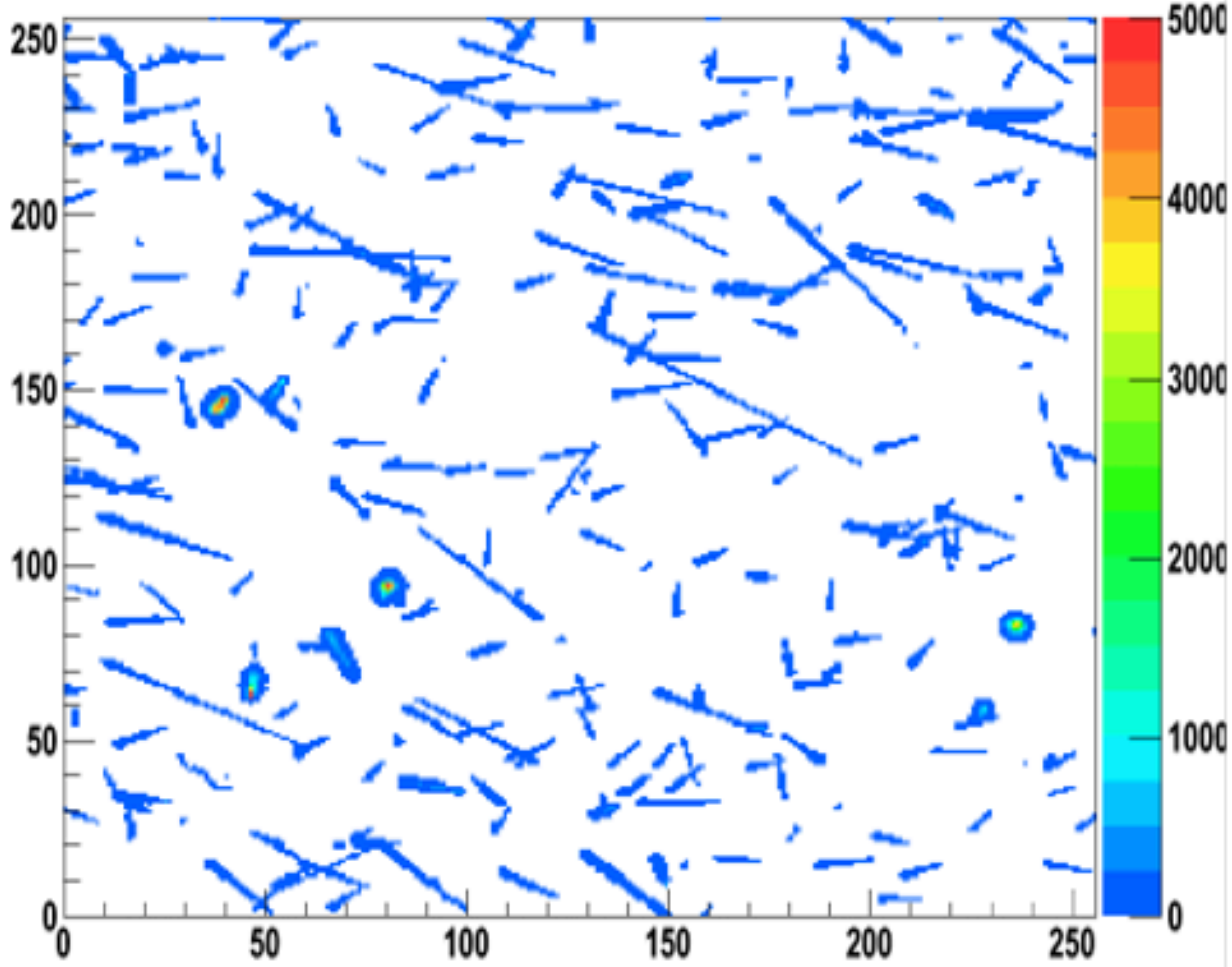
Compared with Landau-Vavilov calculation and Geant4 Monte Carlo simulation of LET in 500um silicon sensor. Livermore electromagnetic physics and INCLXX hadronic with 2um physics cut.



2012 - First Flights of Timepix on ISS

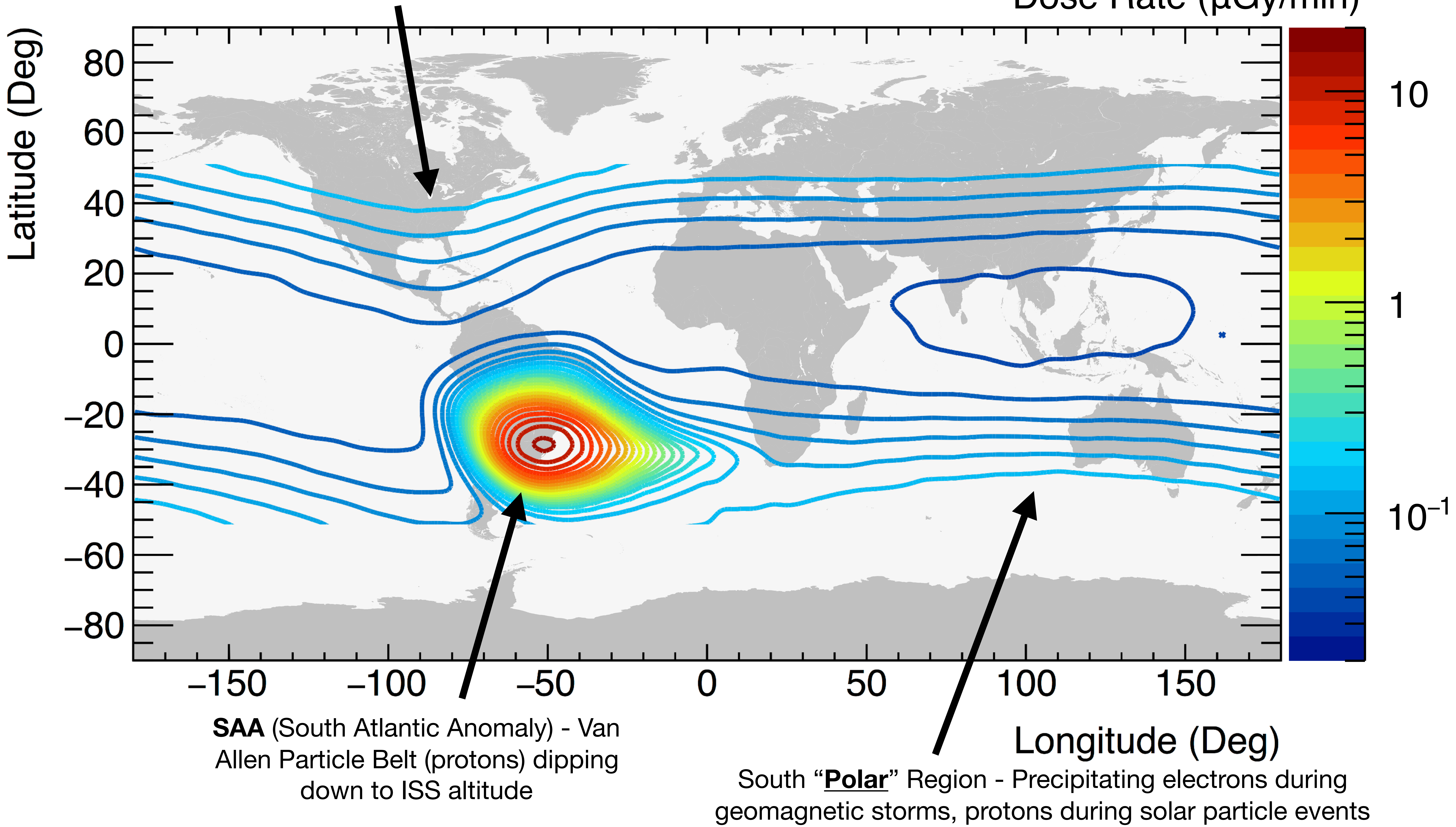
- In 2012 the first set of 5 REM detectors (IEAP Minipix) flew to ISS
- These detectors were plugged into space station laptops, acquisition software running on laptops
- Laptop software would load configs into units, take frames, apply calibration and display dose rate
- All other data analysis done on the ground, e.g LET, binned dose etc etc

First Frames from ISS per Larry Pinsky



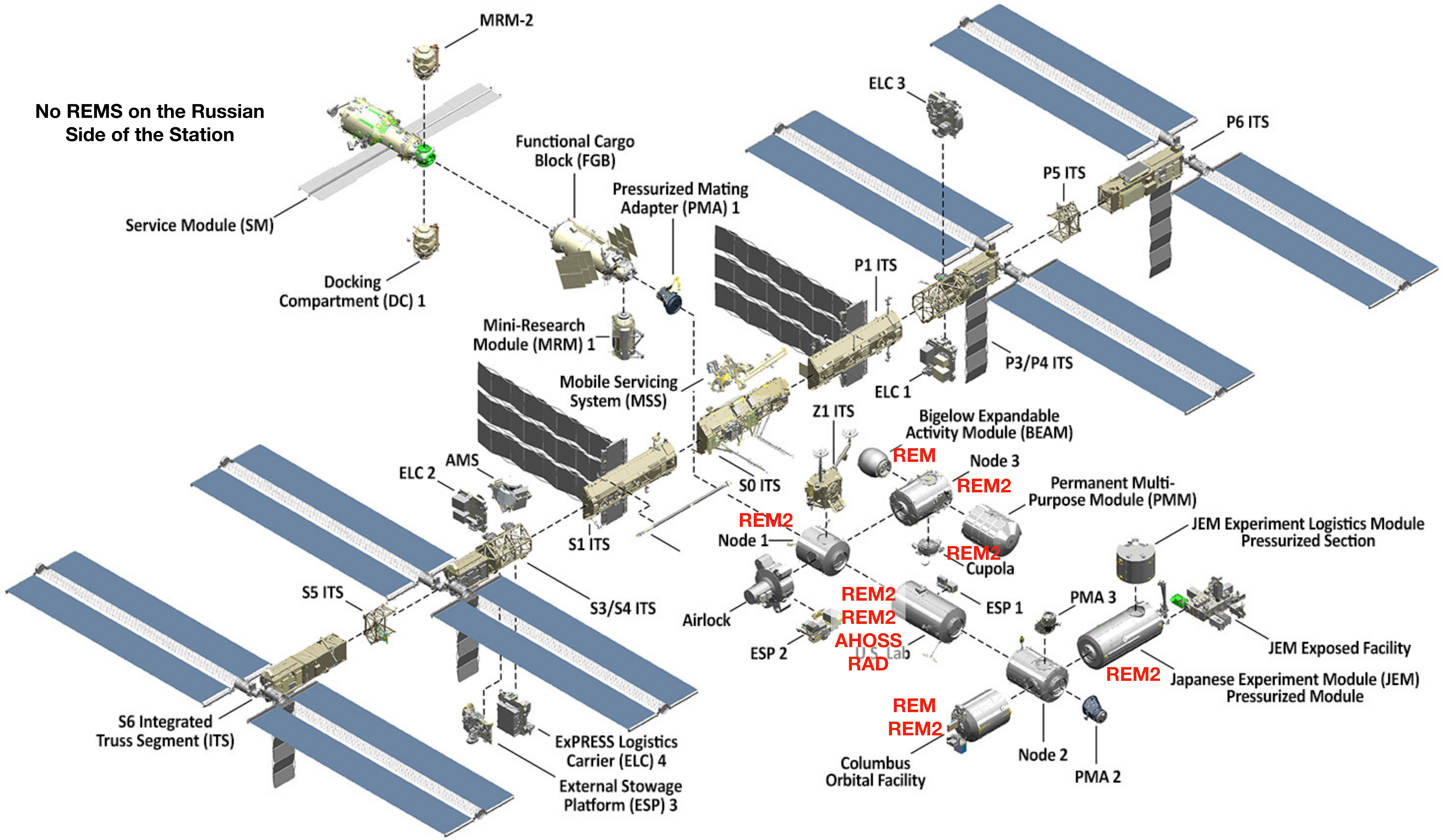
This is the first SAA image from the ISS seen during the SRAG team weekly meeting at NASA JSC. There was a unanimous gasp in the room. They all knew the numbers from other calculations and earlier detectors, but the room was silent for a few seconds until one of the onlookers exhaled and said, “Geeez, I knew that the SAA was bad, but this…”

Measured ISS Dose Rates from Timepix - 2014



ISS Deployment -> Towards the Modern REM2 Network

- Operational experience with the first REM (IEAP Minipix) instruments
- Science data was perfect, and impressive enough to progress to other instruments
- Some failures in early units, one electronics based, the others based on ‘crew interaction’.
- REM2 - New network of Advacam Minipix, 500um Si Timepix installed in 2019, now with USB cables. Software as a windows service to improve uptime.
    - Current operational experience of REM2 - detectors have been reliable, some interesting performance hiccups that needed software/processing work to solve (noisy frames etc, likely candidate radiation events in FPGA)
    - USB cables seemed to have solved attrition issues
    - Because of the shared nature of the resource (laptop USB ports) these take up perhaps more crew time than originally anticipated.


No REMS on the Russian
Side of the Station
MRM-2
Service Module (SM)
Docking
Compartment (DC) 1
Functional Cargo
Block (FGB)
Pressurized Mating
Adapter (PMA) 1
Mini-Research
Module (MRM) 1
Mobile Servicing
System (MSS)
ELC 3
P6 ITS
P5 ITS
P1 ITS
P3/P4 ITS
ELC 1
Z1 ITS
Bigelow Expandable
Activity Module (BEAM)
REM
Node 3
REM2
Permanent Multi-
Purpose Module (PMM)
JEM Experiment Logistics Module
Pressurized Section
REM2
Cupola
AMS
ELC 2
S0 ITS
S1 ITS
REM2
Node 1
S5 ITS
S3/S4 ITS
Airlock
REM2
REM2
AHOSS
RAD
U.S. Lab
ESP 1
ESP 2
PMA 3
JEM Exposed Facility
REM2
Japanese Experiment Module (JEM)
Pressurized Module
S6 Integrated
Truss Segment (ITS)
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Platform (ESP) 3
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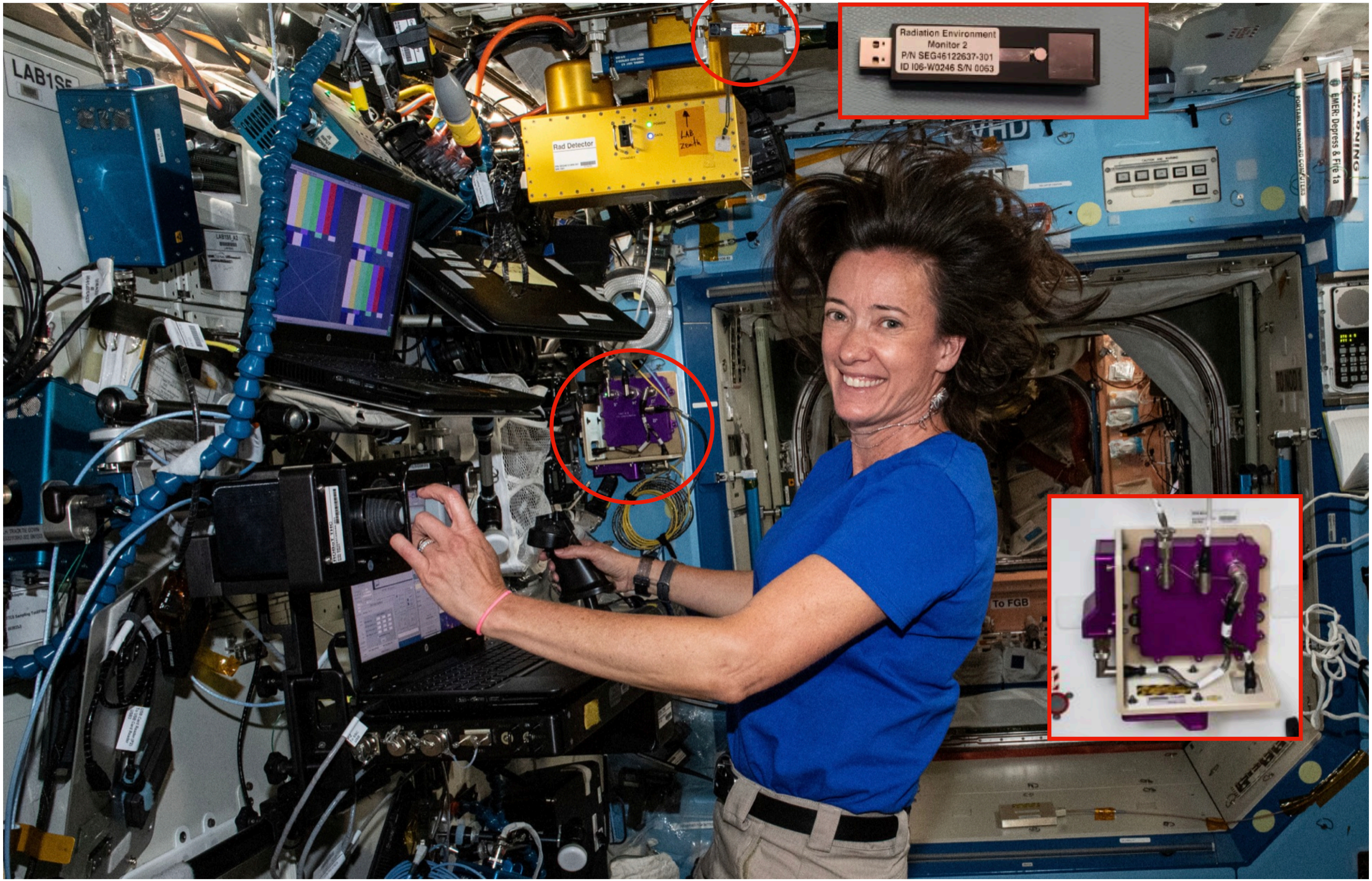
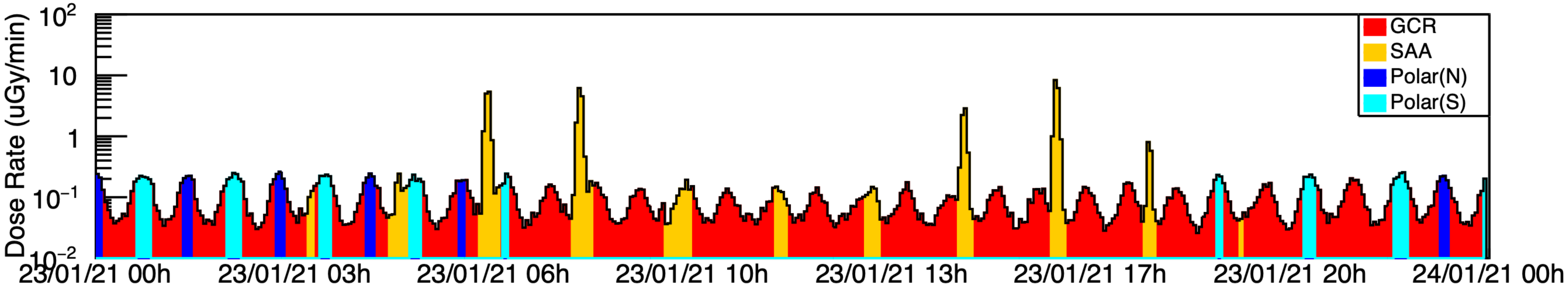
REM2
Columbus
Orbital Facility
Node 2
PMA 2

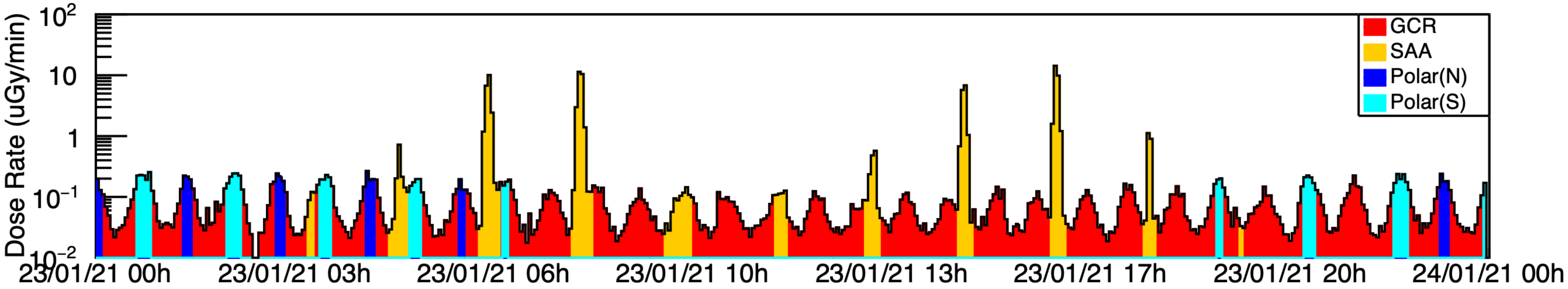


Radiation Environment
Monitor 2
P/N SEG46122637-301
ID I06-W0246 S/N 0063
Rad Detector
LAB
Zenith
LAB1S
EMER: Depress & Fire 1a
To FGB

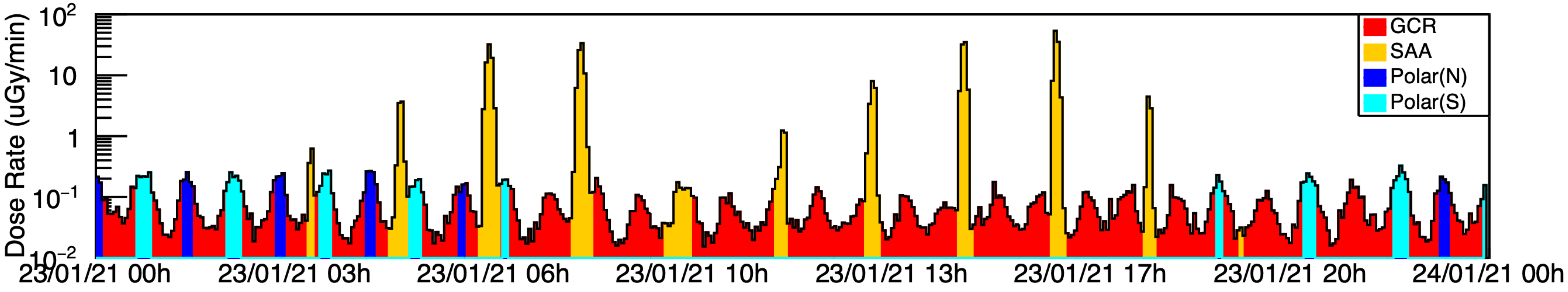
2021 GMT023 I06-W0246



2021 GMT023 G05-W0246

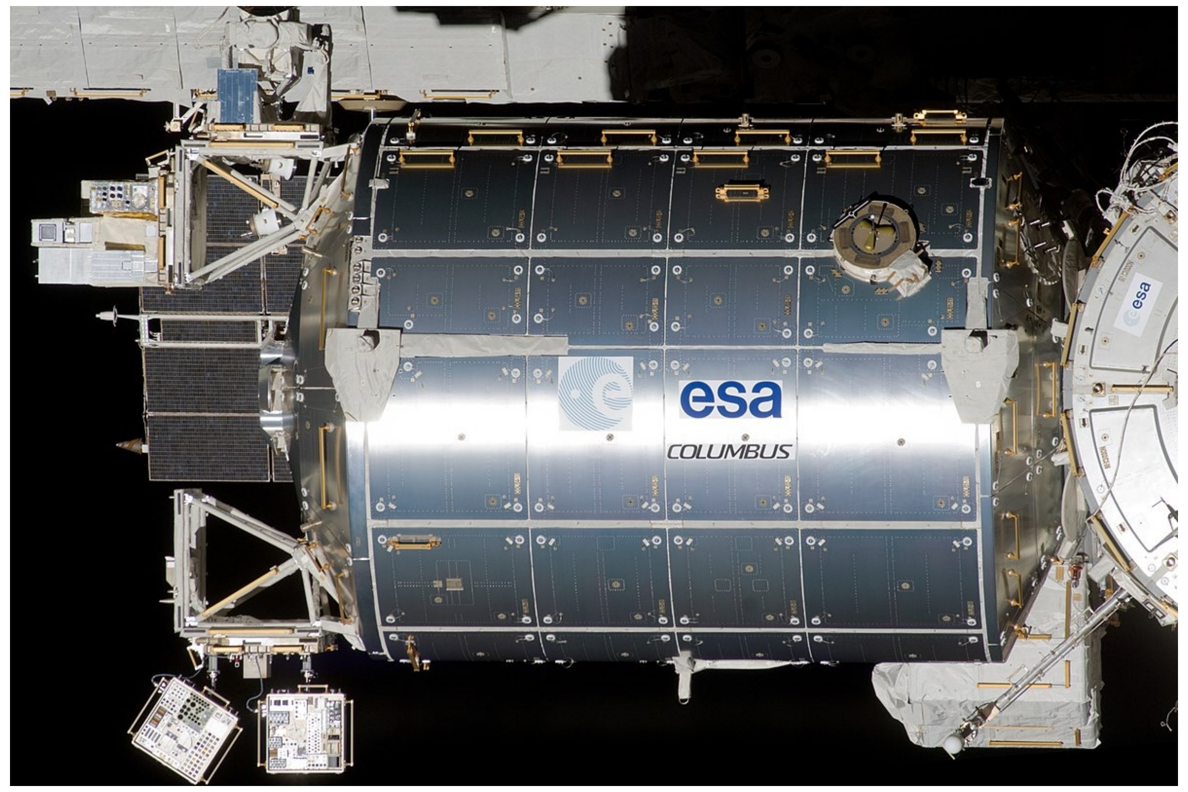


2021 GMT023 H10-W0099



Destiny Module/US Lab

Columbus Module



BEAM (Inflatable module)

Short term dose rates

REM2 Science Report - 10/02/22 - 10/09/22 (2022 GMT 275 - 2022 GMT 282)

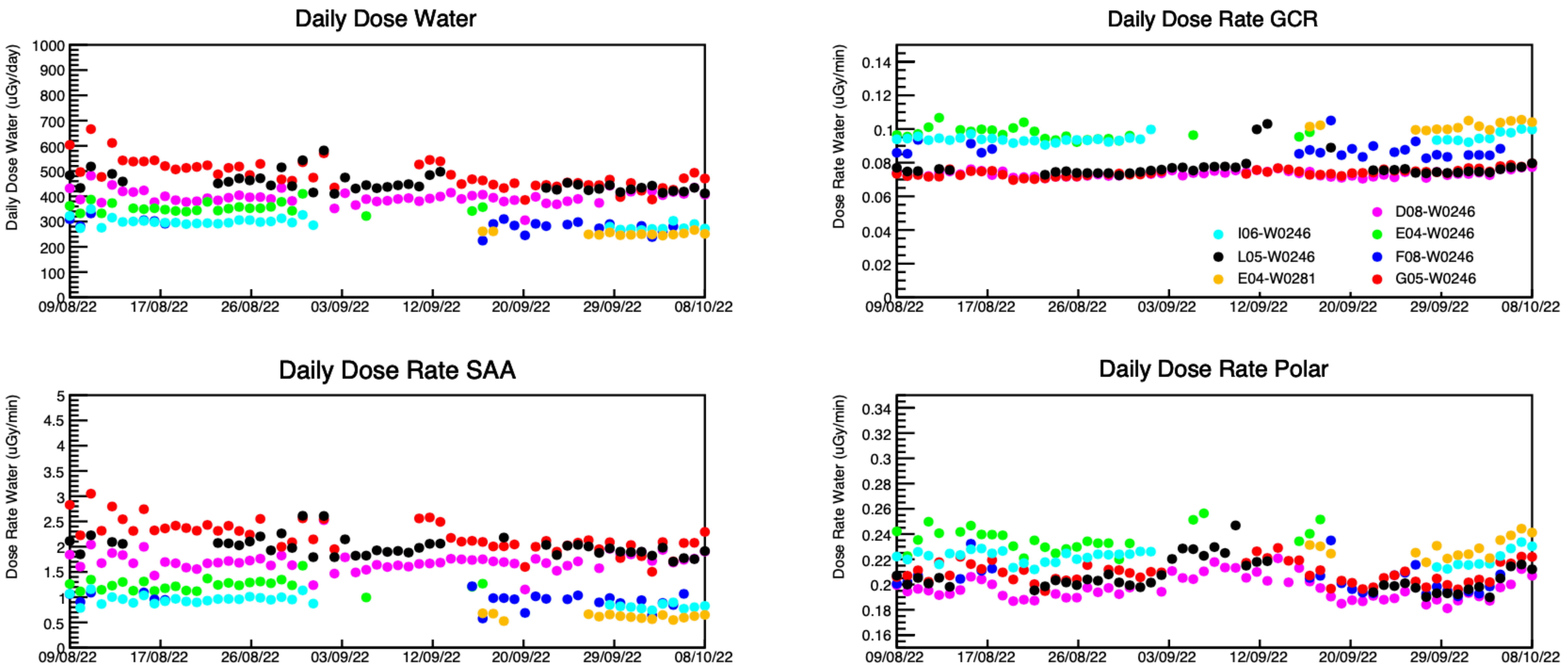
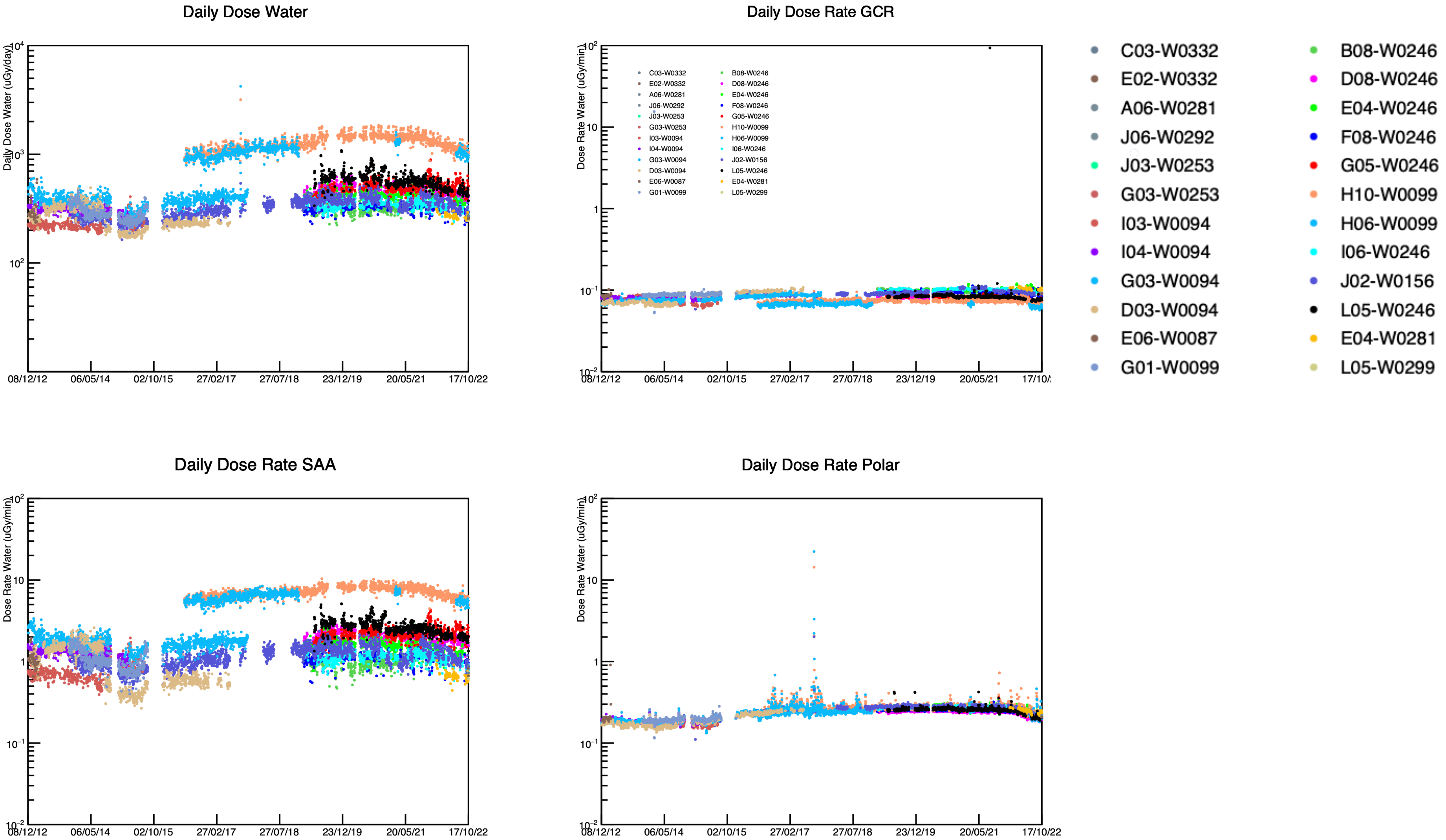


Figure 1: REM2 Daily absorbed dose rates in water for last 60 days. SAA : McIlwain L < 3, B < 23000 nT, Polar : L > 3, GCR : not SAA (includes Polar).



Daily Dose Water
Daily Dose Water (uGy/day)
Daily Dose Rate GCR
Dose Rate Water (uGy/min)
Daily Dose Rate SAA
Dose Rate Water (uGy/min)
Daily Dose Rate Polar
Dose Rate Water (uGy/min)
08/12/12
06/05/14
02/10/15
27/02/17
27/07/18
23/12/19
20/05/21
17/10/22
C03-W0332
E02-W0332
A06-W0281
J06-W0292
J03-W0253
G03-W0253
I03-W0094
I04-W0094
G03-W0094
D03-W0094
E06-W0087
G01-W0099
B08-W0246
D08-W0246
E04-W0246
F08-W0246
G05-W0246
H10-W0099
H06-W0099
I06-W0246
J02-W0156
L05-W0246
E04-W0281
L05-W0299

LET Spectra

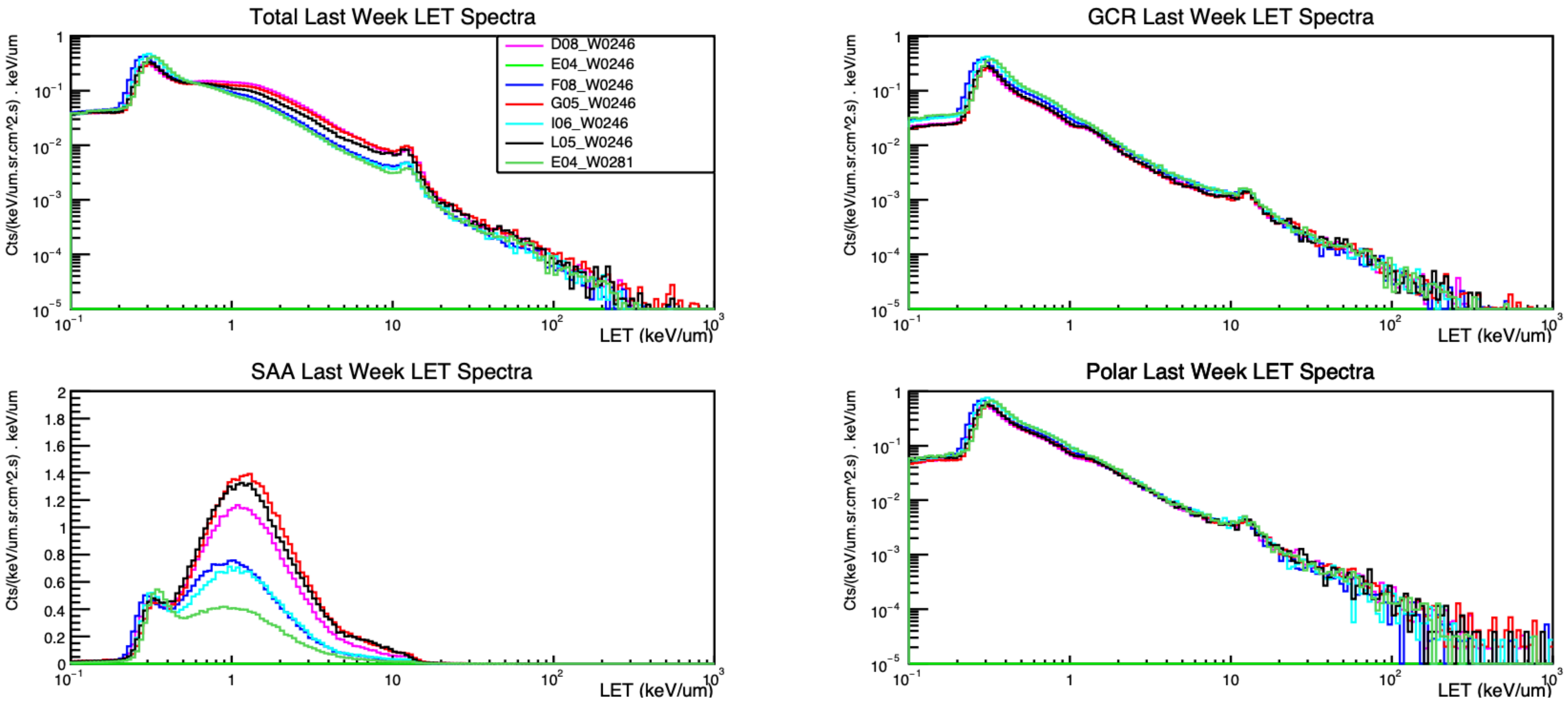
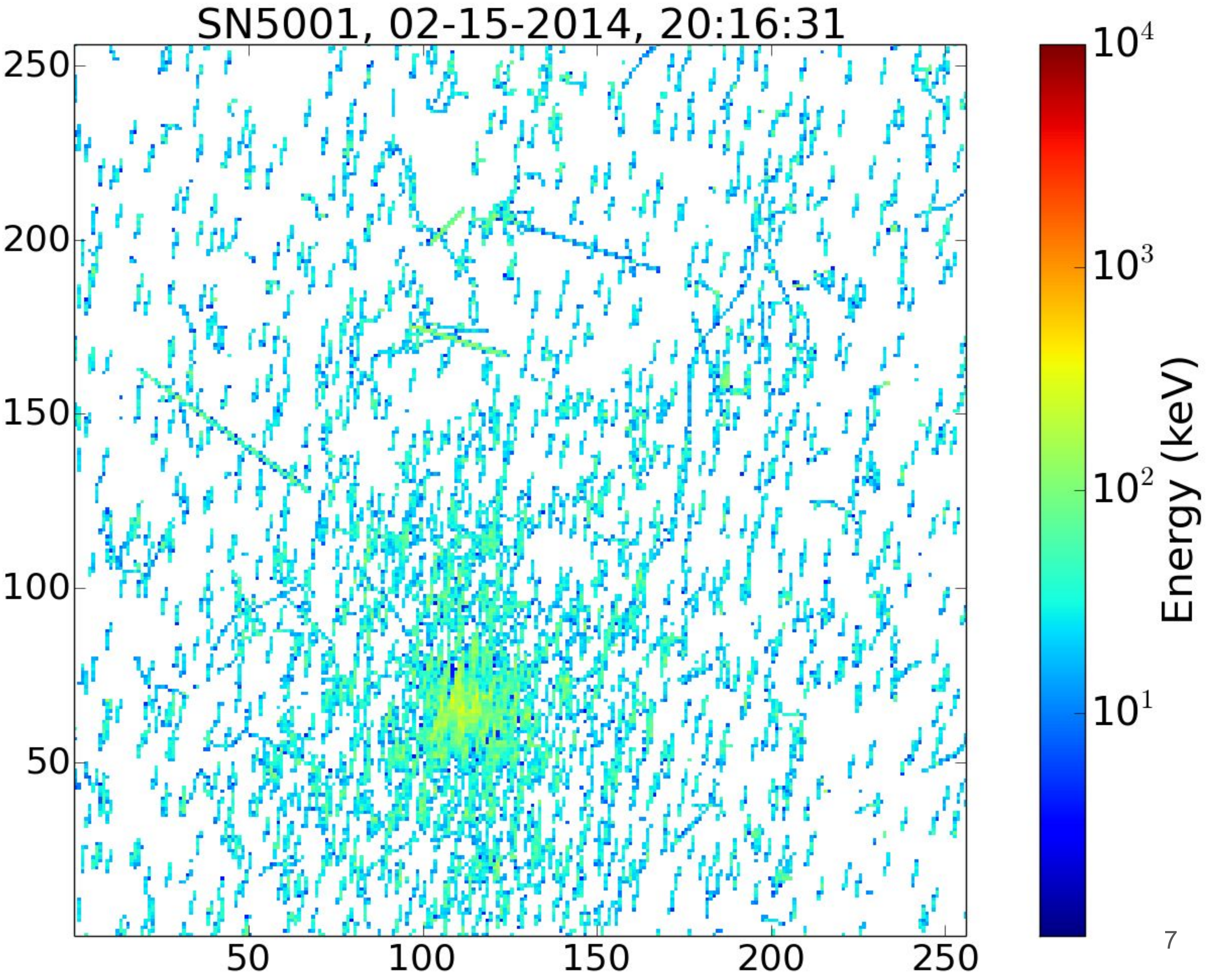


Figure 2: REM2 LET Spectra in silicon over last week (flux * LET to preserve visual area with log(x) scale).

Hadron showers!

3 image types:

- with core



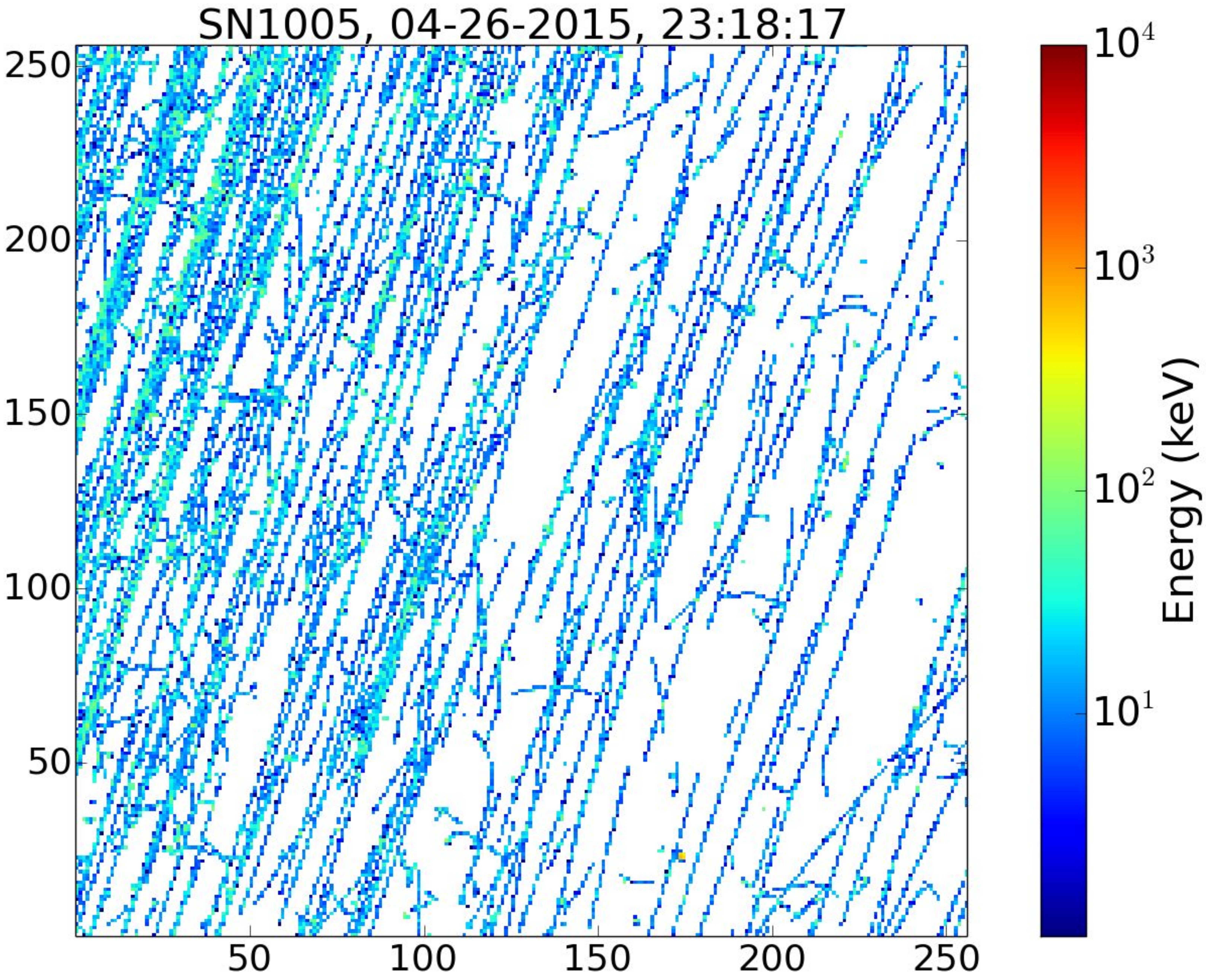
Slides on hadron showers courtesy T. Campbell-Ricketts, in submission to LSSR

Hadron showers!

3 image types:

- with core

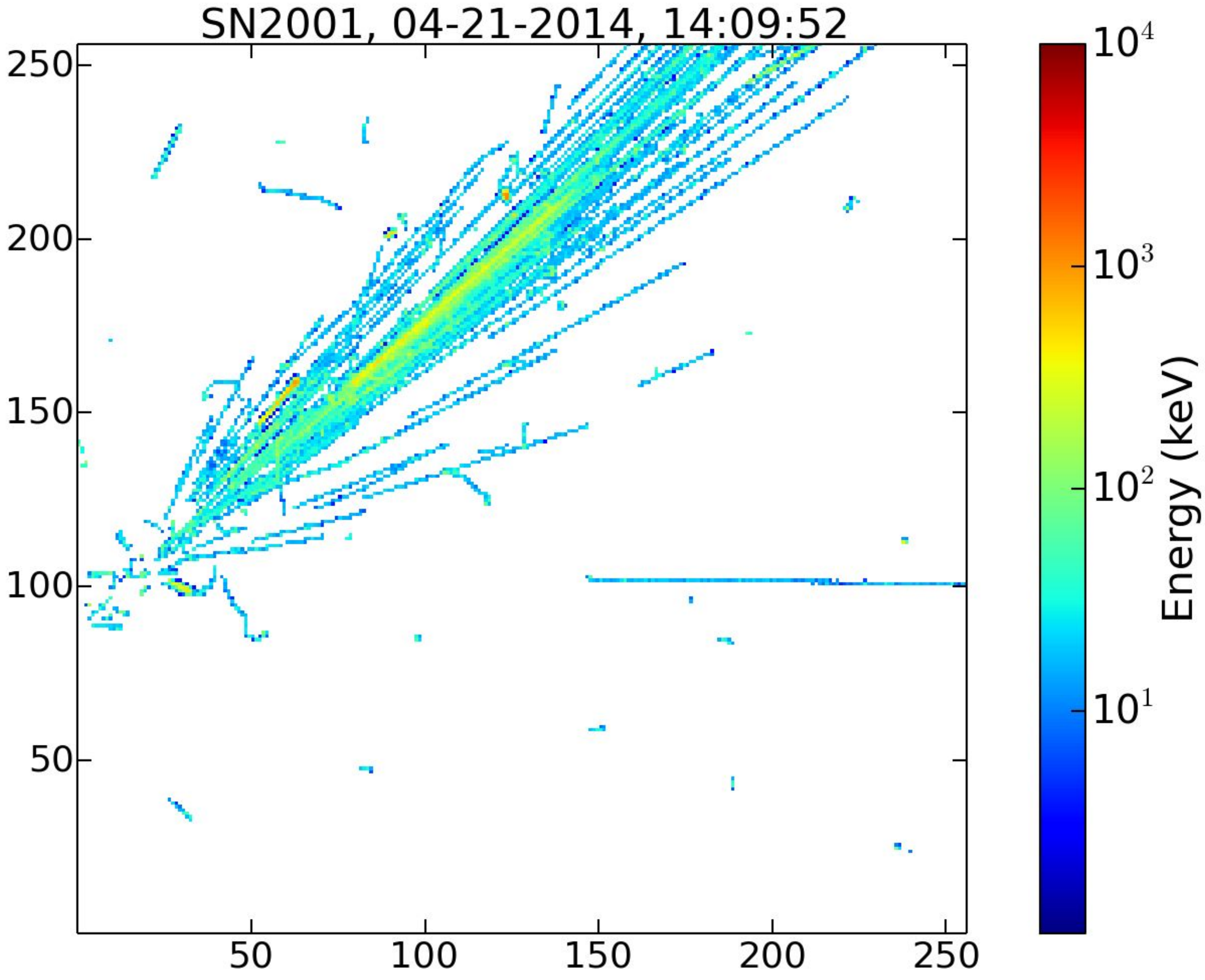
- without core

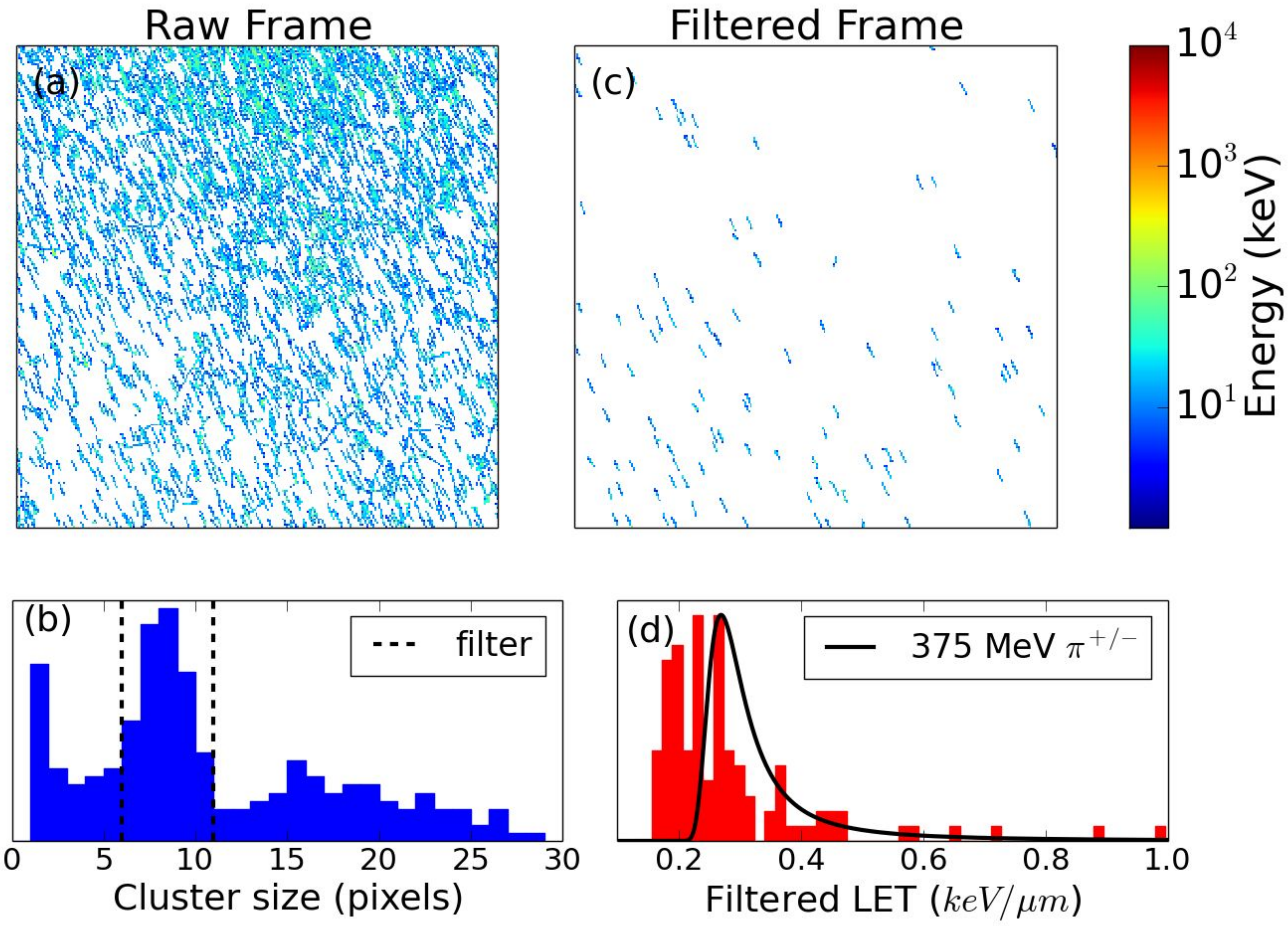


Hadron showers!

3 image types:

- with core
- without core
- originating in detector





Conservatively, at least 6 times as many particles generated, as were incident on the detector.

- ~4124 particles
- E > 20 TeV

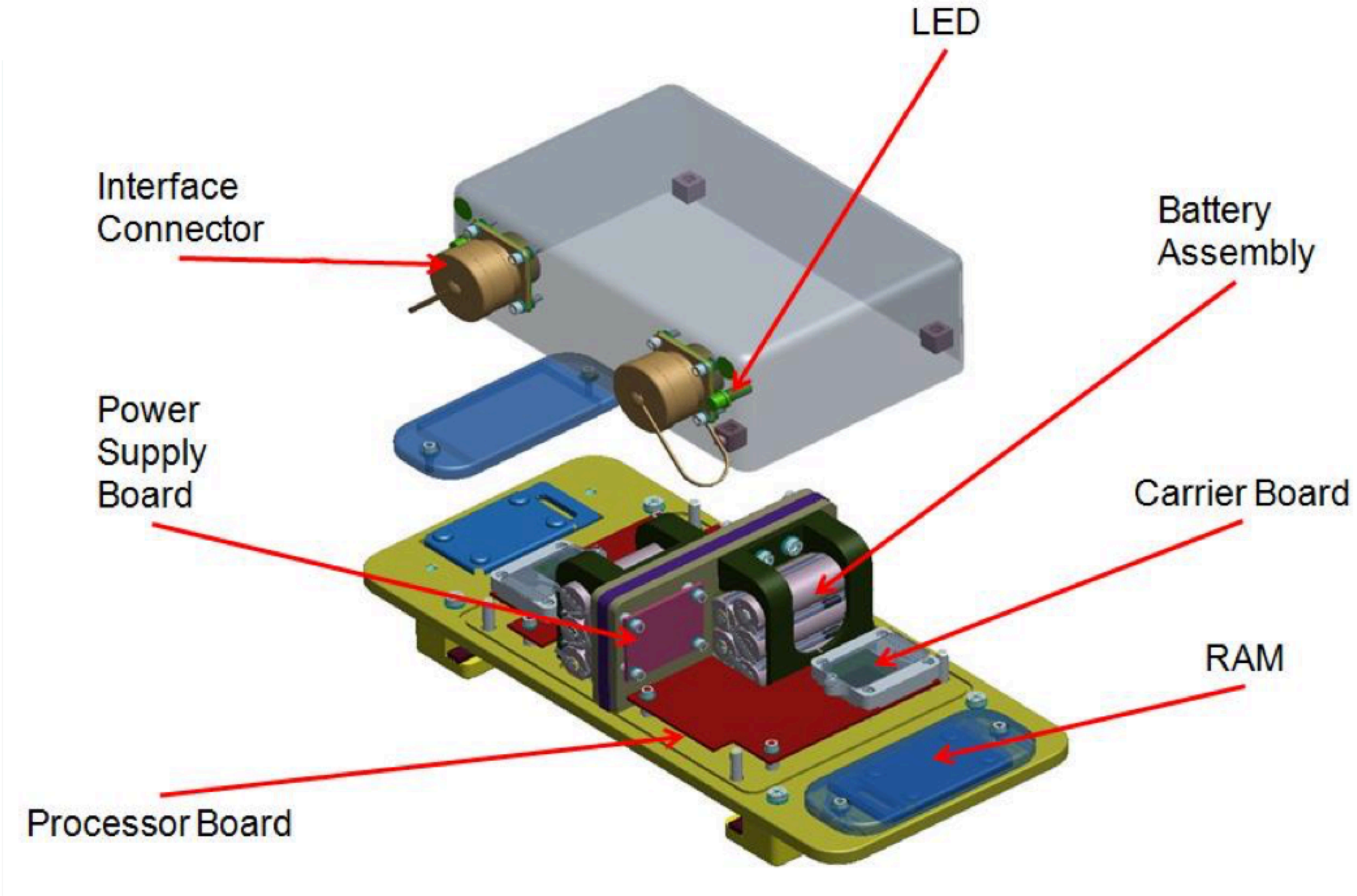
Human health implications

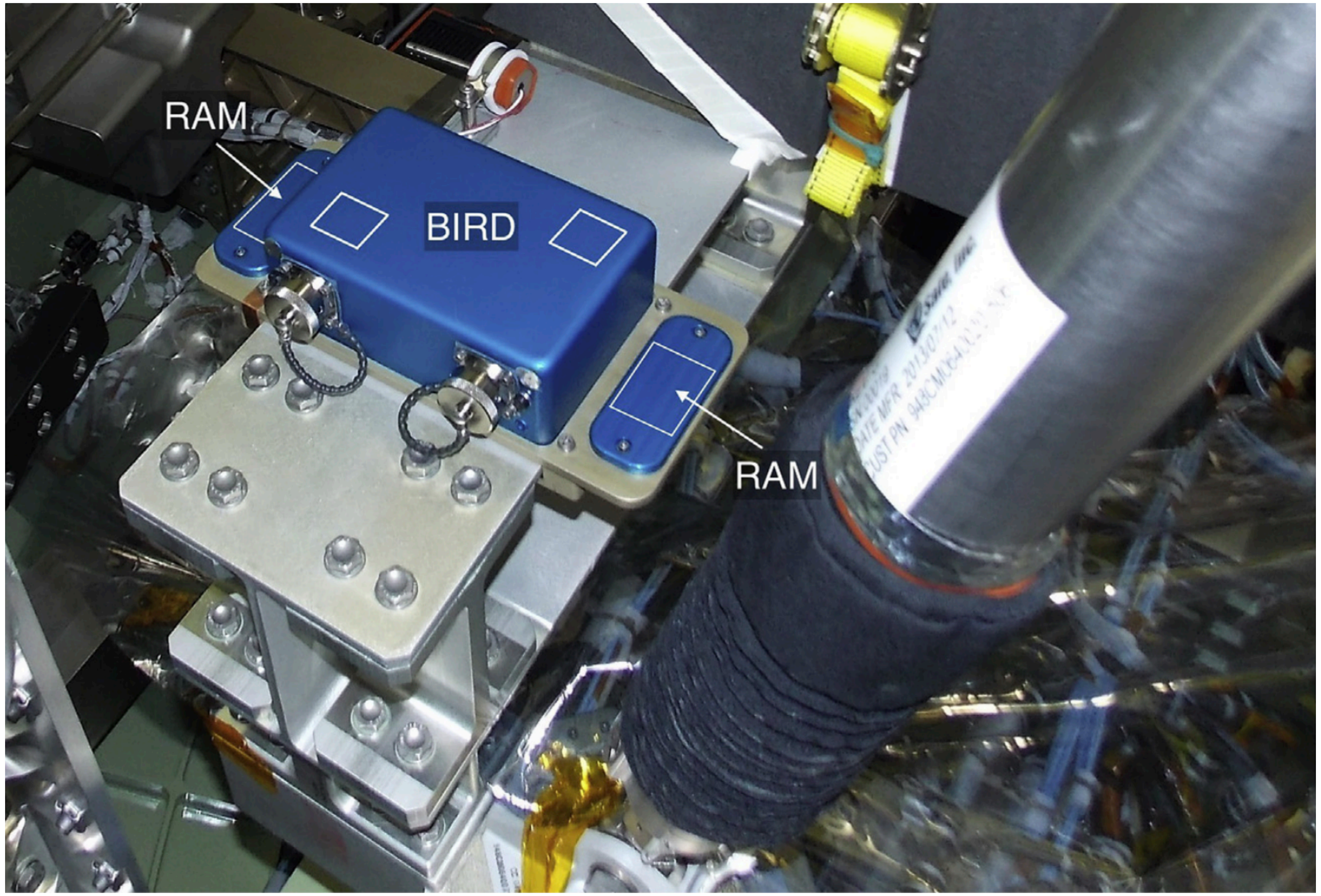
- Compact & near-instantaneous mode of dose delivery doesn't seem to correspond to epidemiological data and medical effects may not be well understood

- Hadron showers grow as they propagate through condensed matter, each daughter can produce more daughters, thus dose measured in a thin wafer of silicon may greatly underestimate dose to human

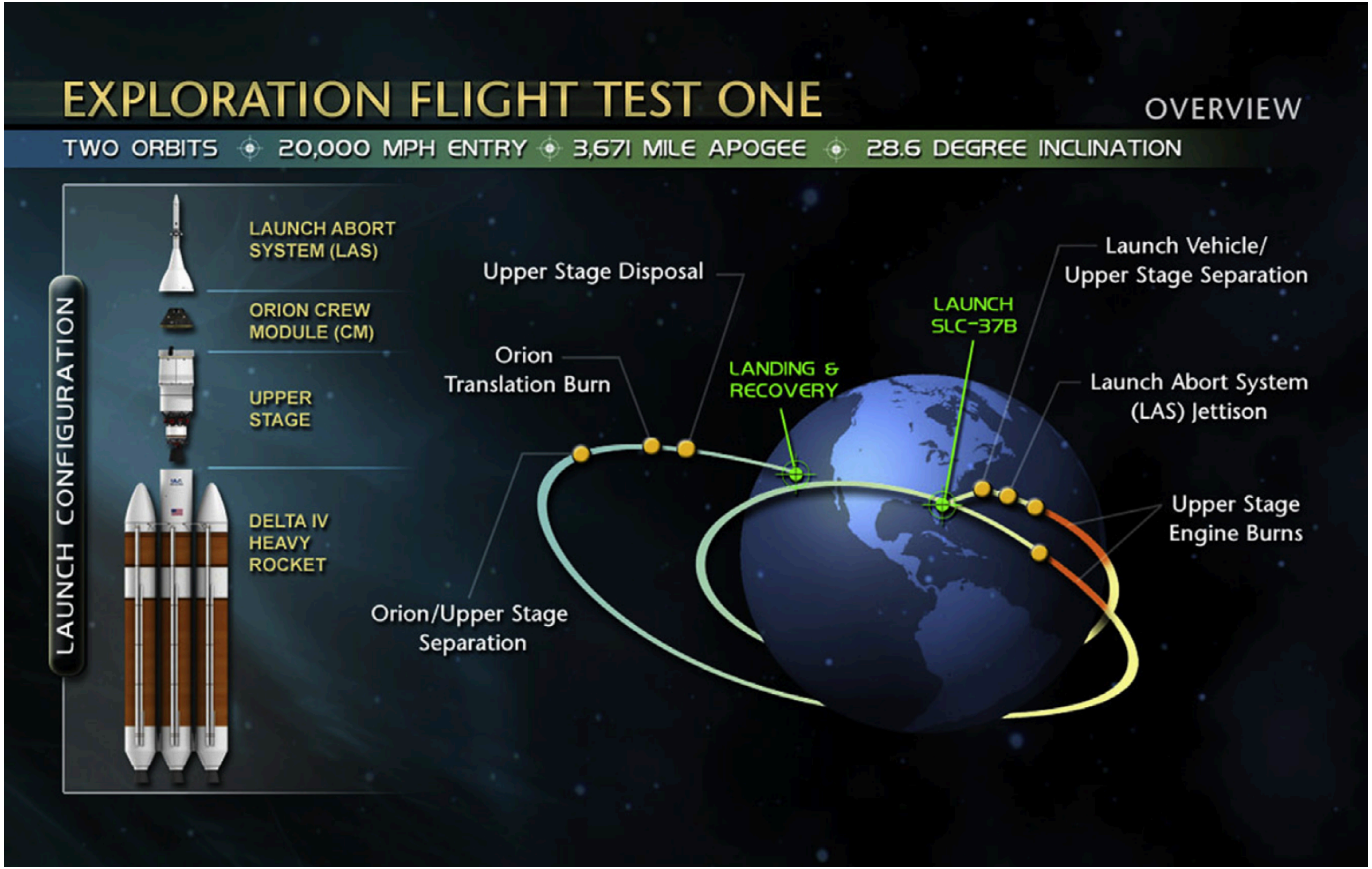
- Average yearly fluency in a $2cm^2$ detector is ~100/year. The surface area of a person is ~$18000cm^2$ - Its quite reasonable to assume a person will see ~100k of these showers per year.

BIRD - Battery Operated Radiation Dosimeter

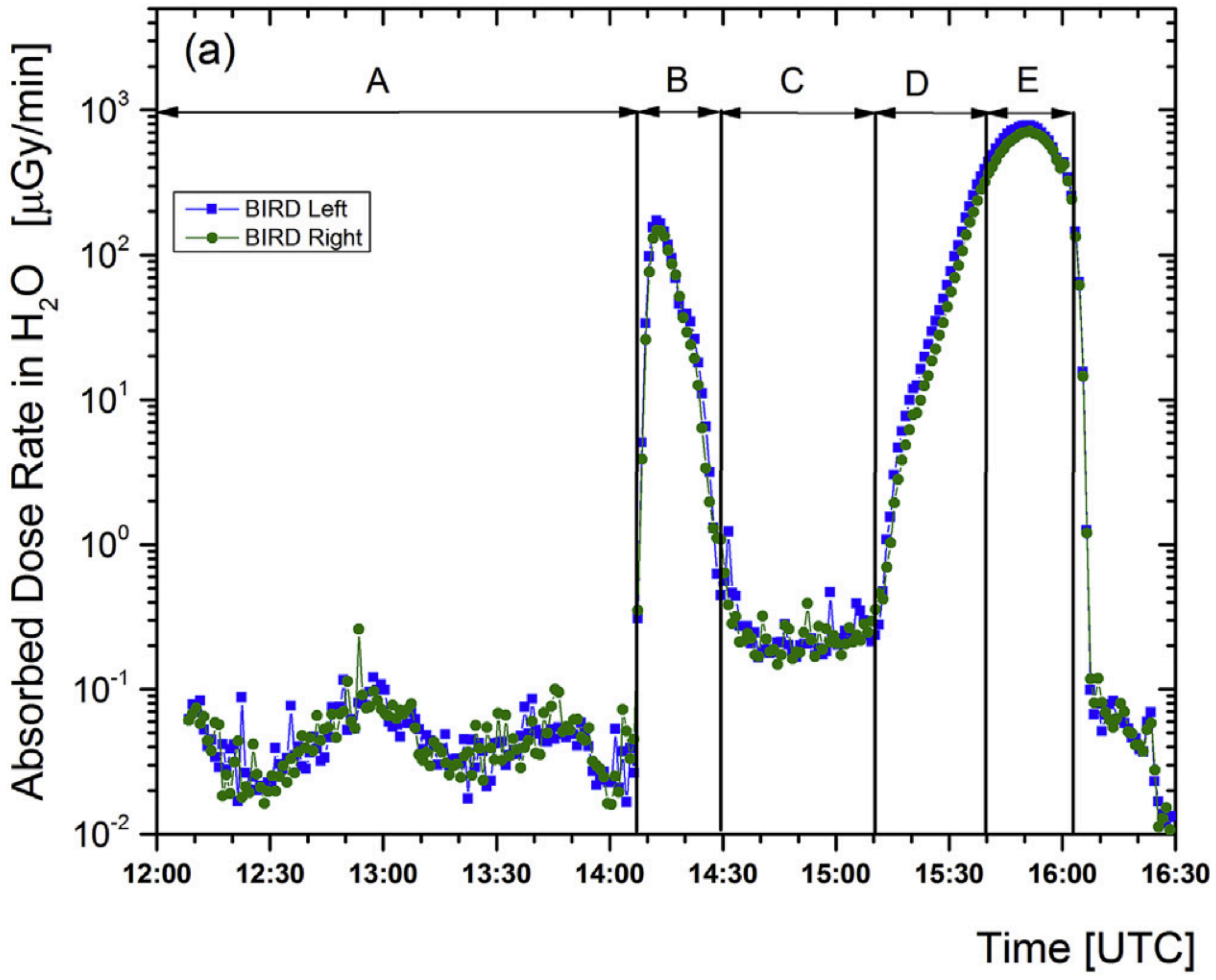


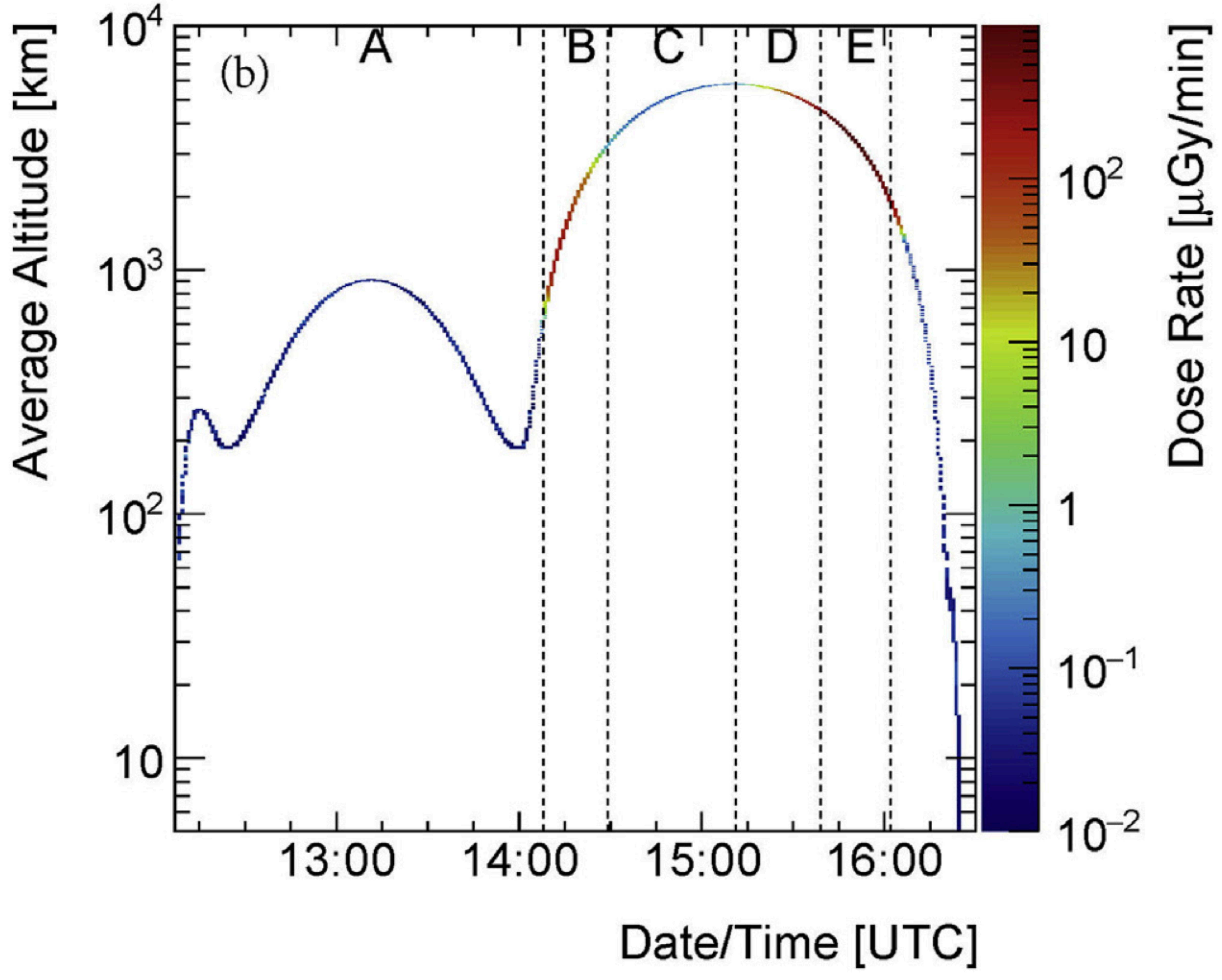


- The BIRD was our first piece of standalone Timepix based flight hardware. Battery powered it triggered measurements off a built in accelerometer and saved the resultant frames to onboard storage


EXPLORATION FLIGHT TEST ONE
OVERVIEW
TWO ORBITS
20,000 MPH ENTRY
3,671 MILE APOGEE
28.6 DEGREE INCLINATION
LAUNCH CONFIGURATION
LAUNCH ABORT SYSTEM (LAS)
ORION CREW MODULE (CM)
UPPER STAGE
DELTA IV HEAVY ROCKET
Upper Stage Disposal
Orion Translation Burn
LANDING & RECOVERY
LAUNCH SLC-37B
Launch Vehicle/ Upper Stage Separation
Launch Abort System (LAS) Jettison
Upper Stage Engine Burns
Orion/Upper Stage Separation

BIRD - Measurements



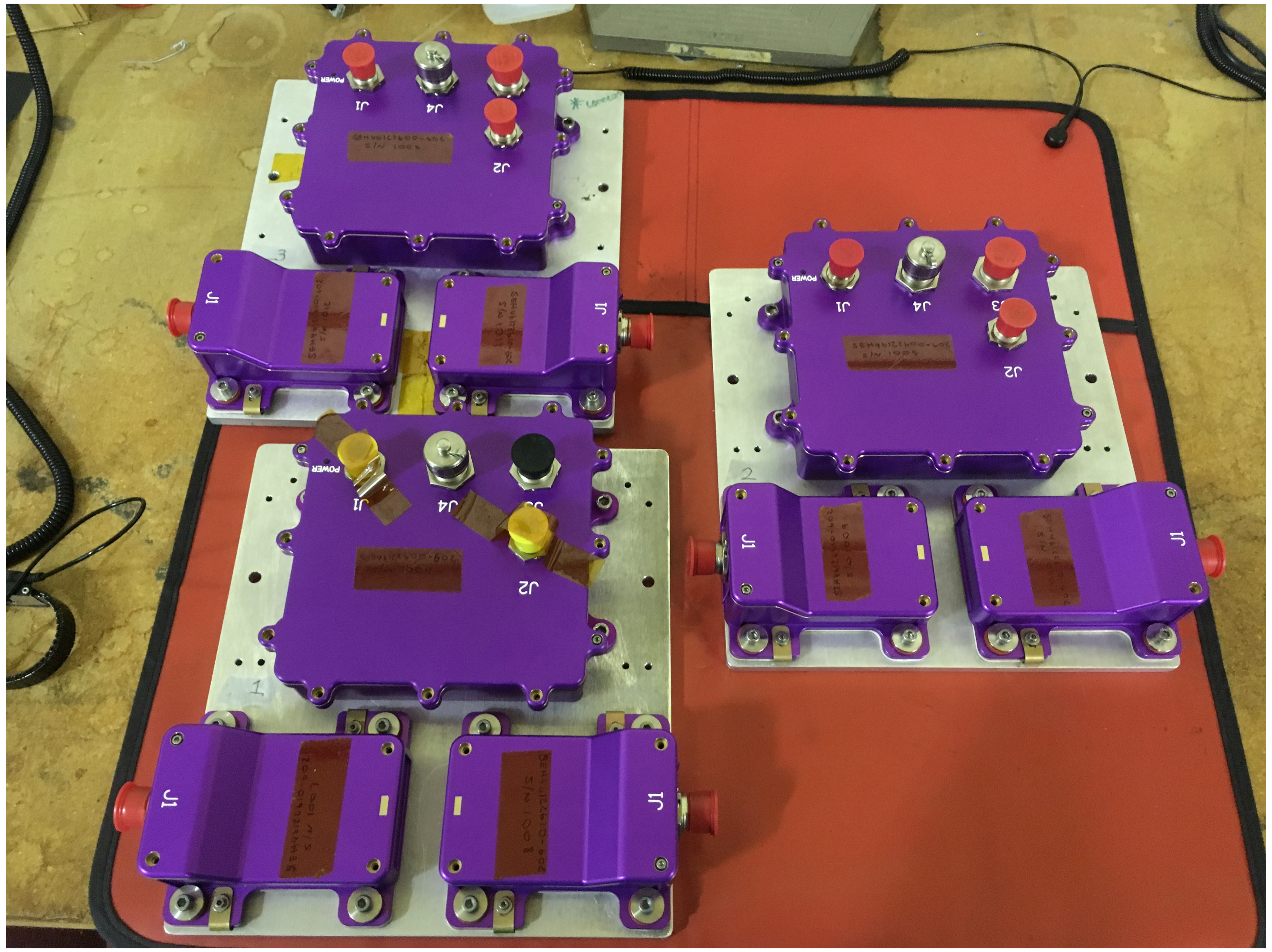


AA Bahadori et al (2015), R Gaza et al (2017)

HERA - A Fully Autonomous Instrument

HERA Top Level Overview

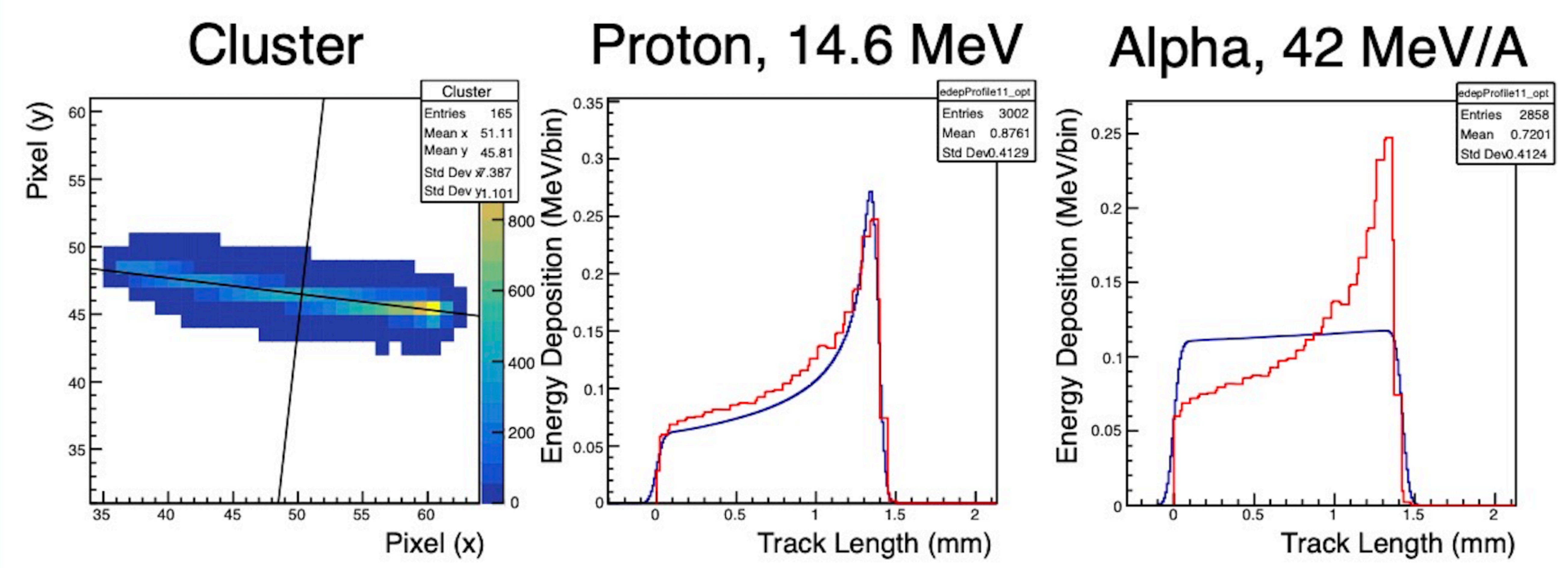
- HERA was the first effort to build a fully autonomous radiation monitoring instrument for NASA exploration programs, specifically the Orion spacecraft
- HERA performs real time onboard calibration and PID/binning
- Each HERA consists of an HPU (HERA processing unit) and two HSU's (HERA Sensor Unit),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

Techniques for particle ID and data analysis with Hybrid Pixel Detectors

- Based on measured track polar angles and stopping power and can construct hypothesis - e.g. is Proton 14 MeV or Alpha 42 MeV/A



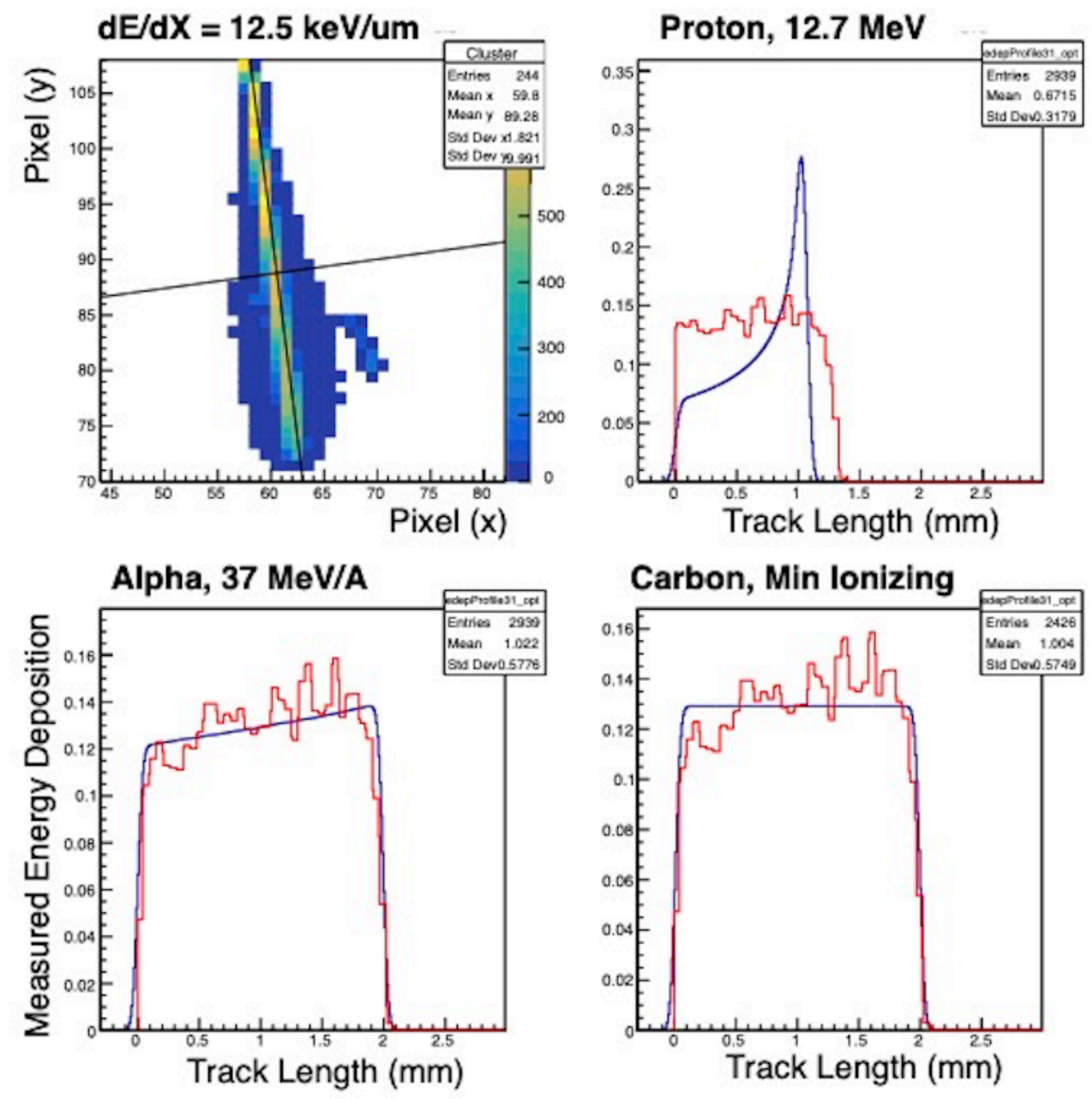
- Construct theoretical energy deposition curve and compare to measurement

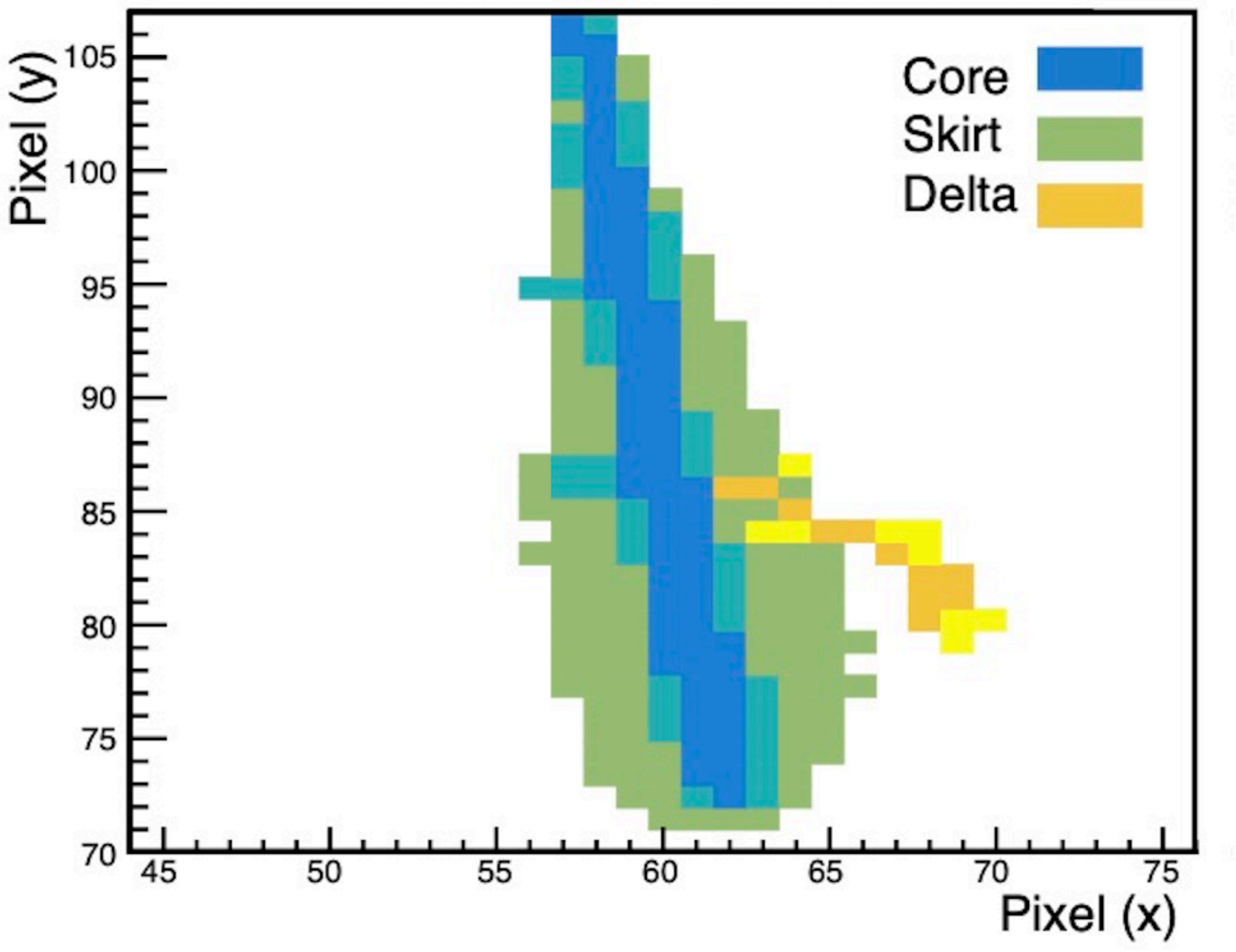
- Pick best hypothesis

- Delta electron production kinematically restricted

$$\beta > \sqrt{\frac{T}{2m_e + T}}$$

- Identification of delta ray allows further hypothesis rejection.





EM2 Science Binning and V&V Campaign

- ***HERA performs real time onboard calibration and binning utilizing the techniques outlined in the previous section (also see supplementary slides)***
- HERA telemeters a 500 byte science message every minute
- Contains **per sensor dose rates** and **per sensor spectroscopic flux binning.**
- Flux bins on a 5 minute rotating schedule
- Science V&V testing at NSRL and CPC
- NSRL testing verifies spectroscopic capabilities
- CPC testing verifies dosimetry and flux measurements in a continuous charged particle beam.

Bins	Contents
1	Protons
2	CNO
3	APE
4	LET (1) (0.1 - 10 keV/um)
5	LET (2) (10 keV/um - 1 MeV/um)

HERA Telemetry Binsets

Bin	nBins	Energy Range	
Proton	21	5 MeV, 1 GeV+	~Log
Alpha	6	0 - 100 MeV+	Lin
CNO	19	100 MeV/A - 1.5 GeV/A	Log
Neon+	1	Inclusive	
Interaction	1	Inclusive	
Photon	13	5 keV - 50 keV	~Lin
Electron	1	Inclusive	

Environmental Qualification Campaign

- More stringent environmental constraints than before due to hard mount in Orion on SLS

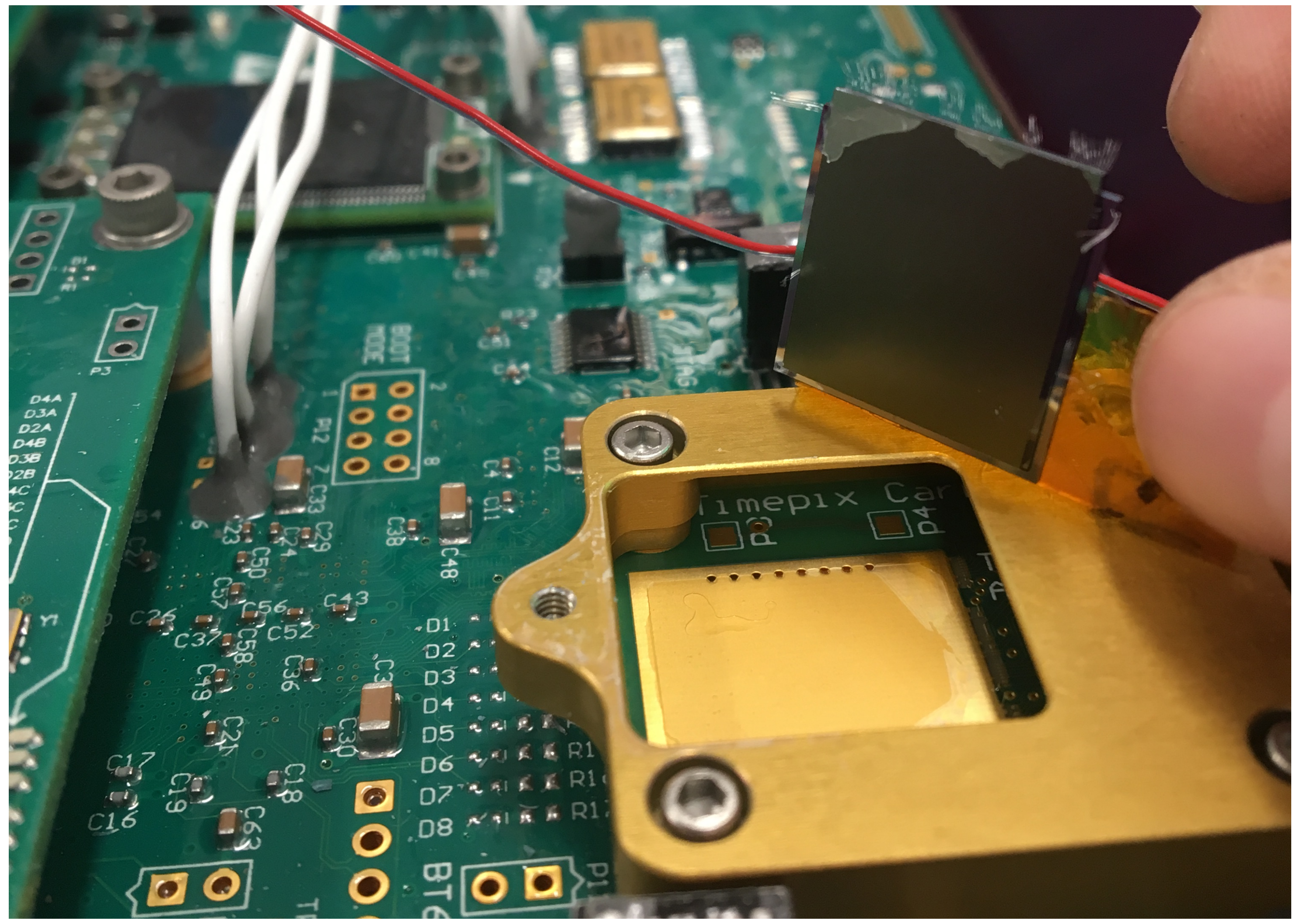
- Random Vibration - Placed on table and shaken, qualification vibration level at 12.1 G's (RMS), Vibration spectrum from 20-2000 HZ

- Shock test (Pyro decoupling simulation). 5380g's at 10000 Hz.

- Timepix chips popped off board during shock. Issue with epoxy, which was 2 part cured at room temperature. Heating 'advanced the cure' which made it brittle. Switched to a softer epoxy that cures at an elevated temperature.

- Thermal Vacumn testing - 32F (-36 C) to 162 F (72 C) and 10^{-5} Torr (1 mPa).

- 8 cycles of 6 to 8 hours per cycle. 1 hour cold soak, 2 hour hot soak.



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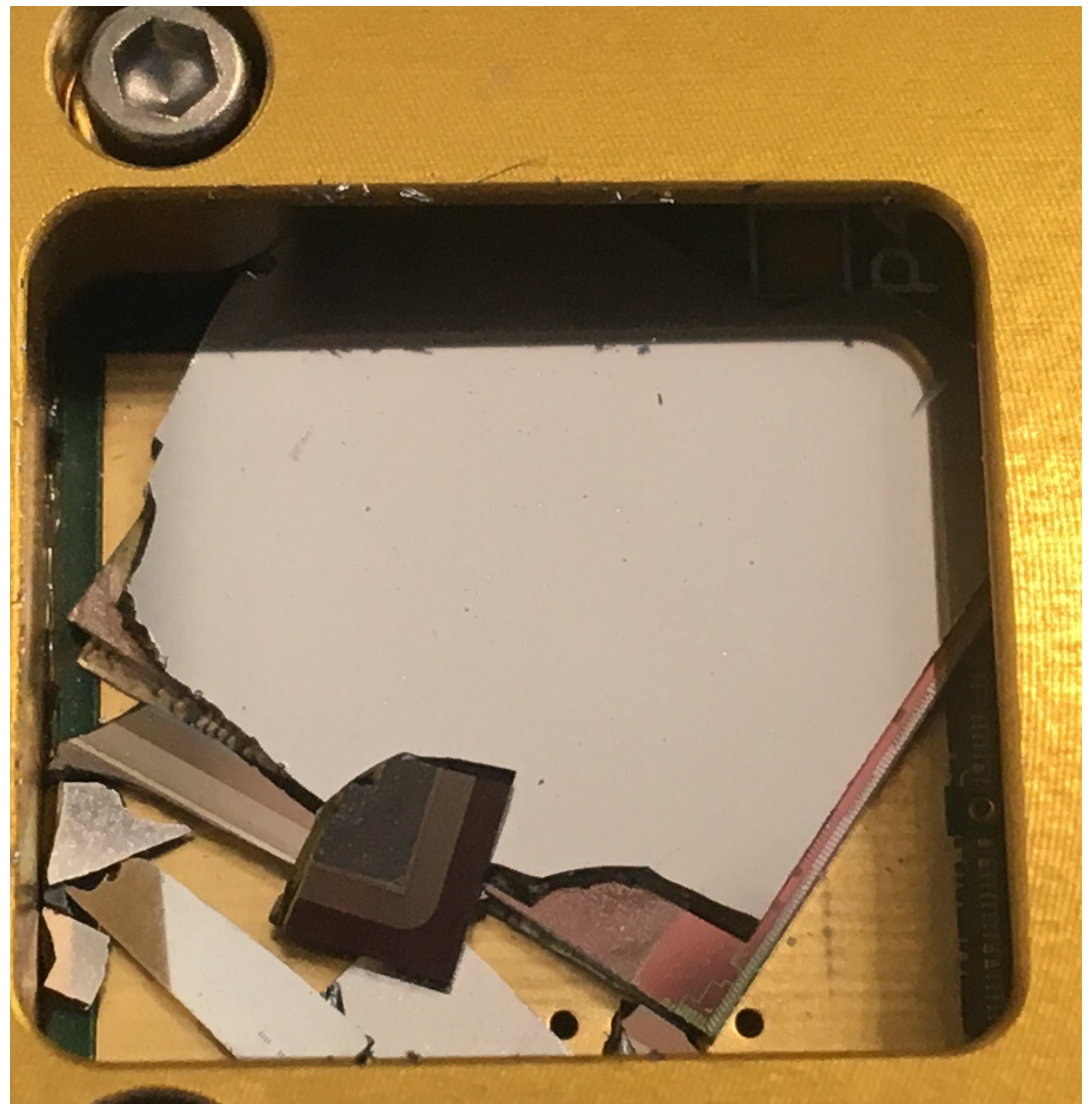
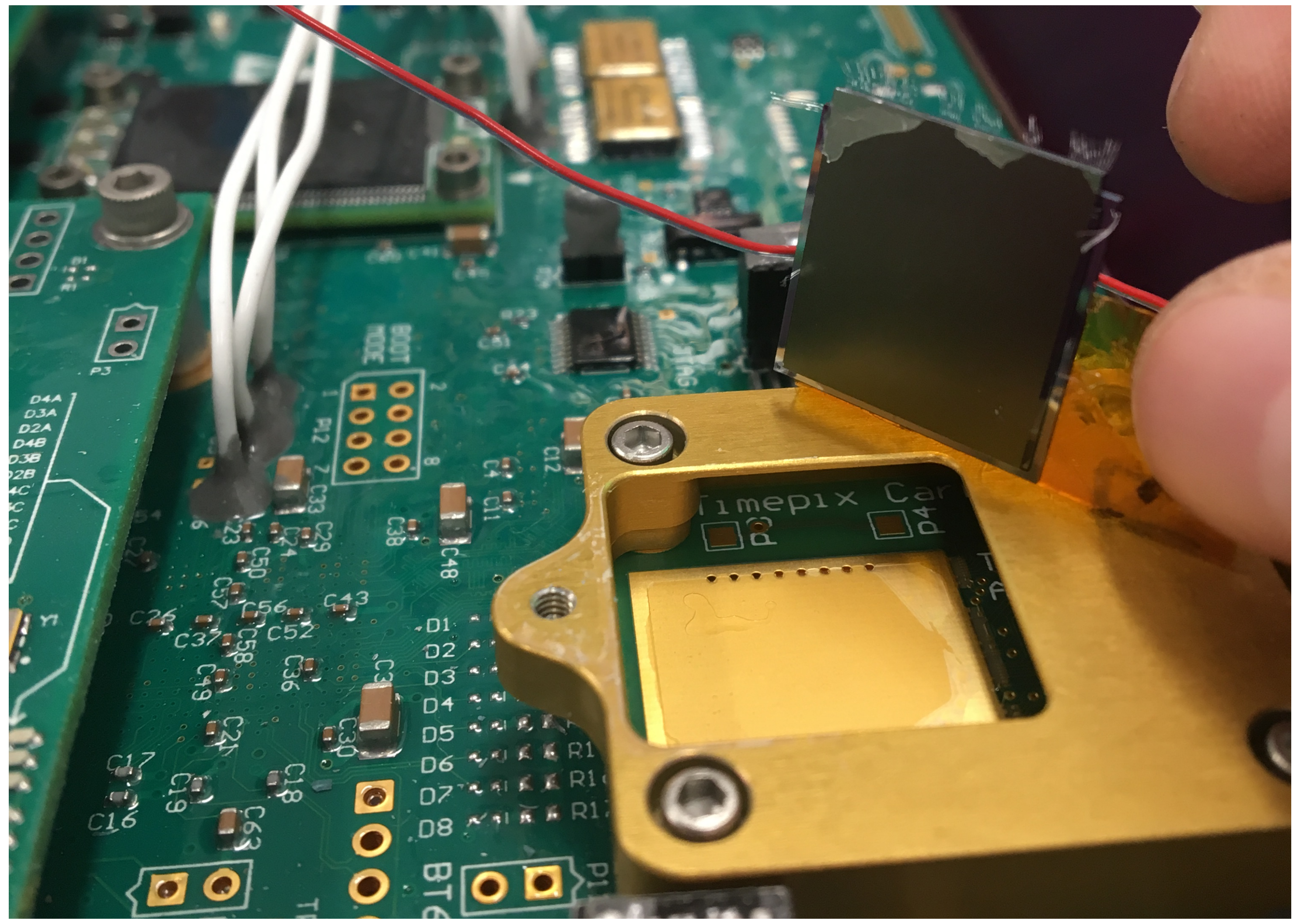
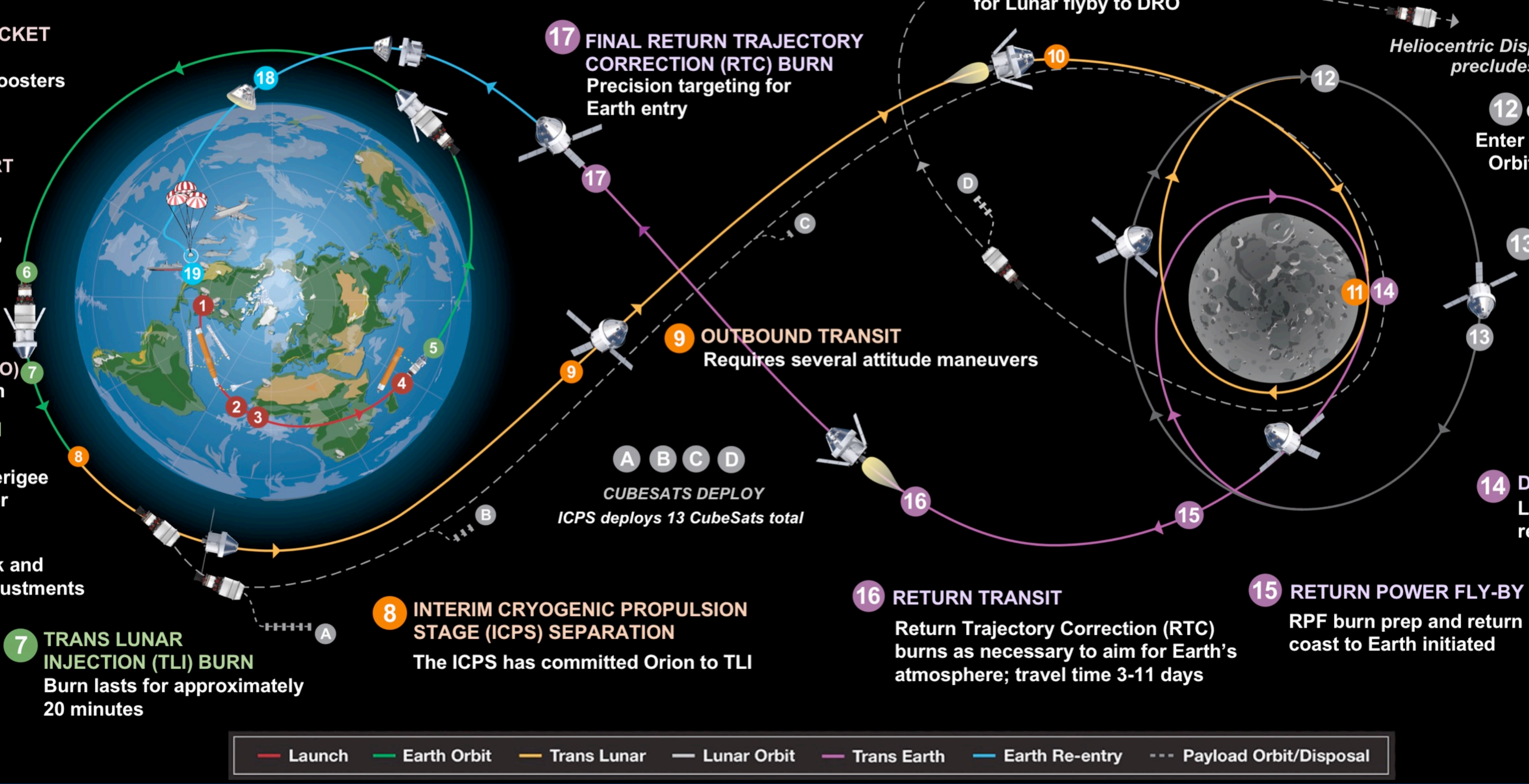




ARTEMIS I

The first uncrewed, integrated flight test of NASA's Orion spacecraft and Space Launch System rocket, launching from a modernized Kennedy spaceport



1 LAUNCH
SLS and Orion lift off from pad 39B at Kennedy Space Center

2 JETTISON ROCKET BOOSTERS
Solid rocket boosters separate

3 JETTISON LAUNCH ABORT SYSTEM (LAS)
The LAS is no longer needed, Orion could safely abort

4 CORE STAGE MAIN ENGINE CUT OFF (MECO) and separation

5 ENTER EARTH ORBIT
Perform the perigee raise maneuver

6 EARTH ORBIT
Systems check and solar panel adjustments

7 TRANS LUNAR INJECTION (TLI) BURN
Burn lasts for approximately 20 minutes

8 INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION
The ICPS has committed Orion to TLI

9 OUTBOUND TRANSIT
Requires several attitude maneuvers

10 OUTBOUND TRAJECTORY CORRECTION (OTC) BURNS
As necessary adjust trajectory for Lunar flyby to DRO

11 OUTBOUND POWERED FLYBY (OPF)
62 miles from the Moon; targets DRO insertion

12 ORBIT INSERTION
Enter Distant Retrograde Orbit for next 6-23 days

13 DISTANT RETROGRADE ORBIT (DRO)
Orbit Maintenance burns and solar panel adjustments; 38,000 nmi from the surface of the Moon

14 DRO DEPARTURE
Leave DRO and start return to Earth

15 RETURN POWER FLY-BY (RPF)
RPF burn prep and return coast to Earth initiated

16 RETURN TRANSIT
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time 3-11 days

17 FINAL RETURN TRAJECTORY CORRECTION (RTC) BURN
Precision targeting for Earth entry

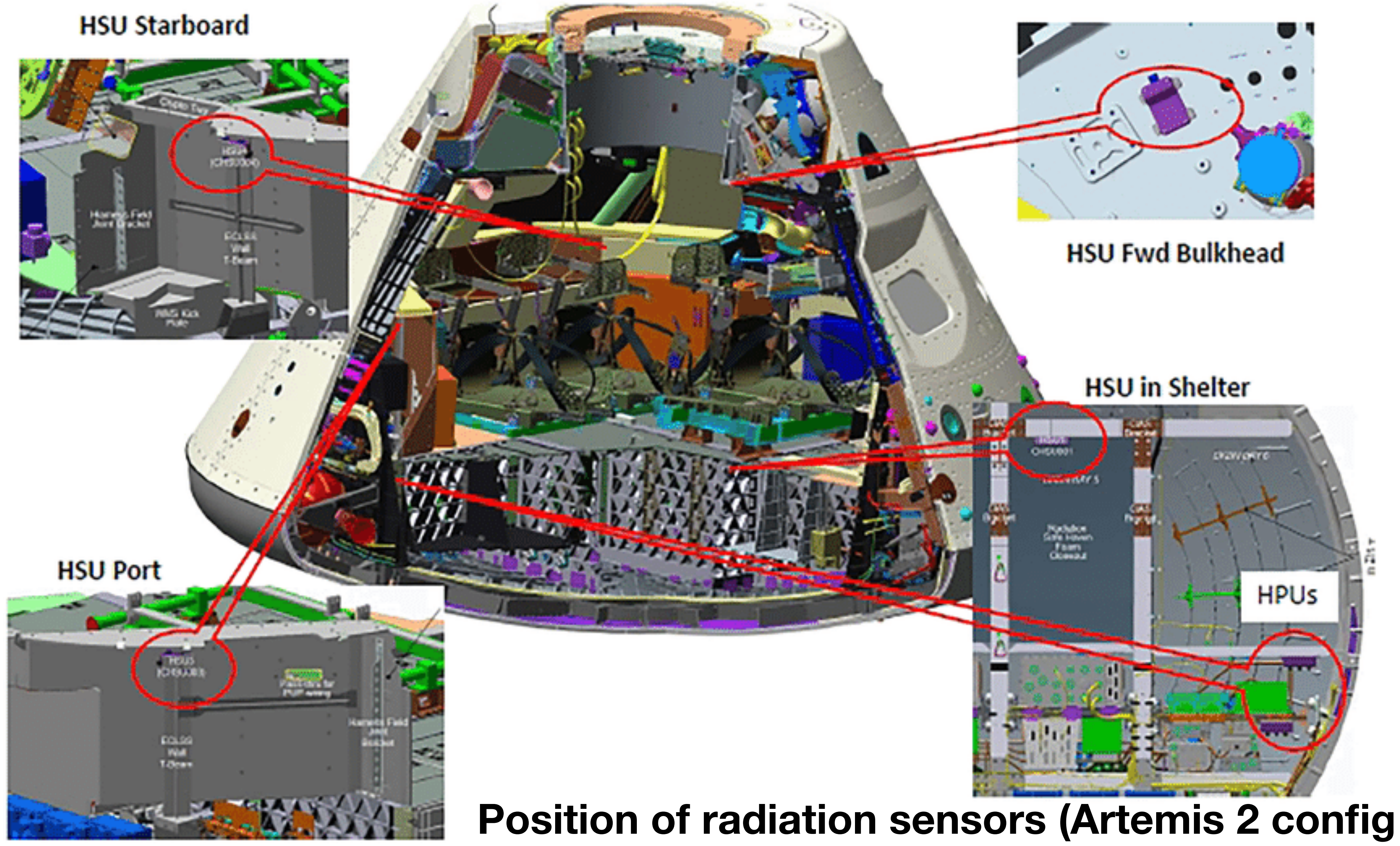
18 ENTRY INTERFACE (EI)
Enter Earth's atmosphere

19 SPLASHDOWN
Pacific Ocean landing within view of the U.S. Navy recovery ships

ARTEMIS

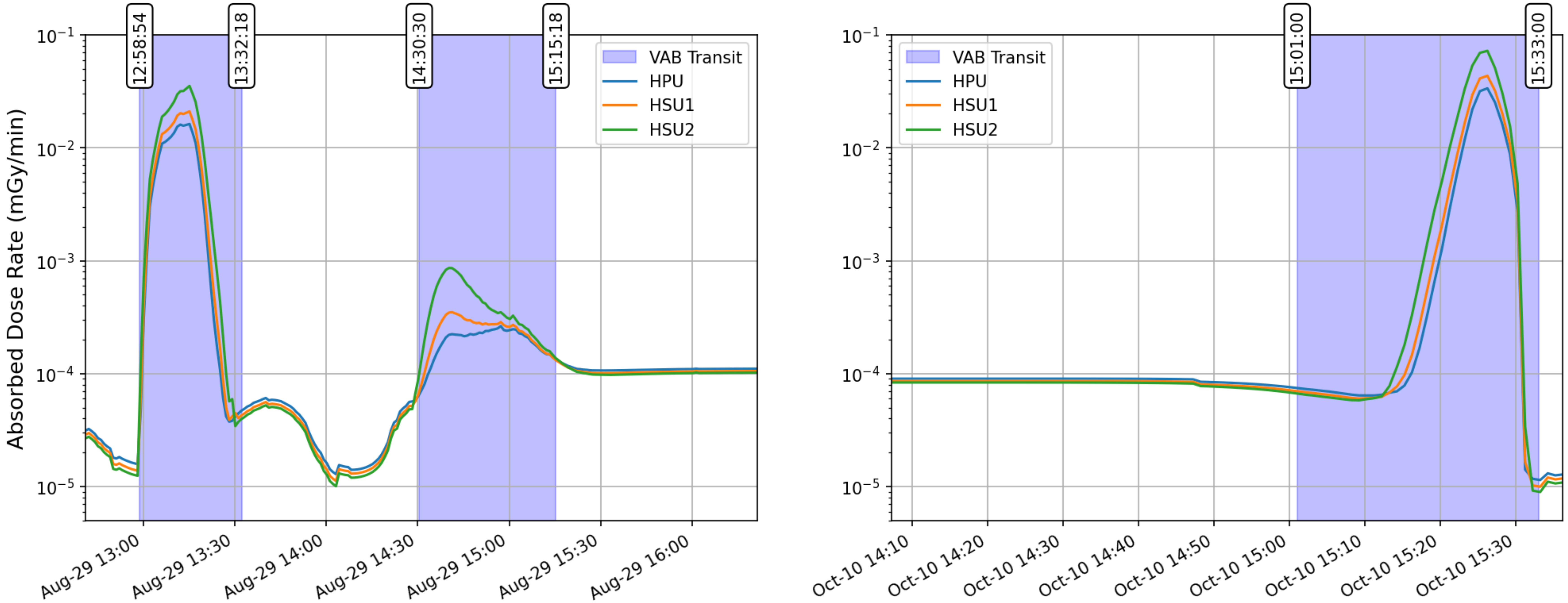
ARTEMIS I

Total distance traveled: 1.3 million miles – Mission duration: 26-42 days – Re-entry speed: 24,500 mph (Mach 32) – 13 CubeSats deployed



Position of radiation sensors (Artemis 2 config with 2x HERA)

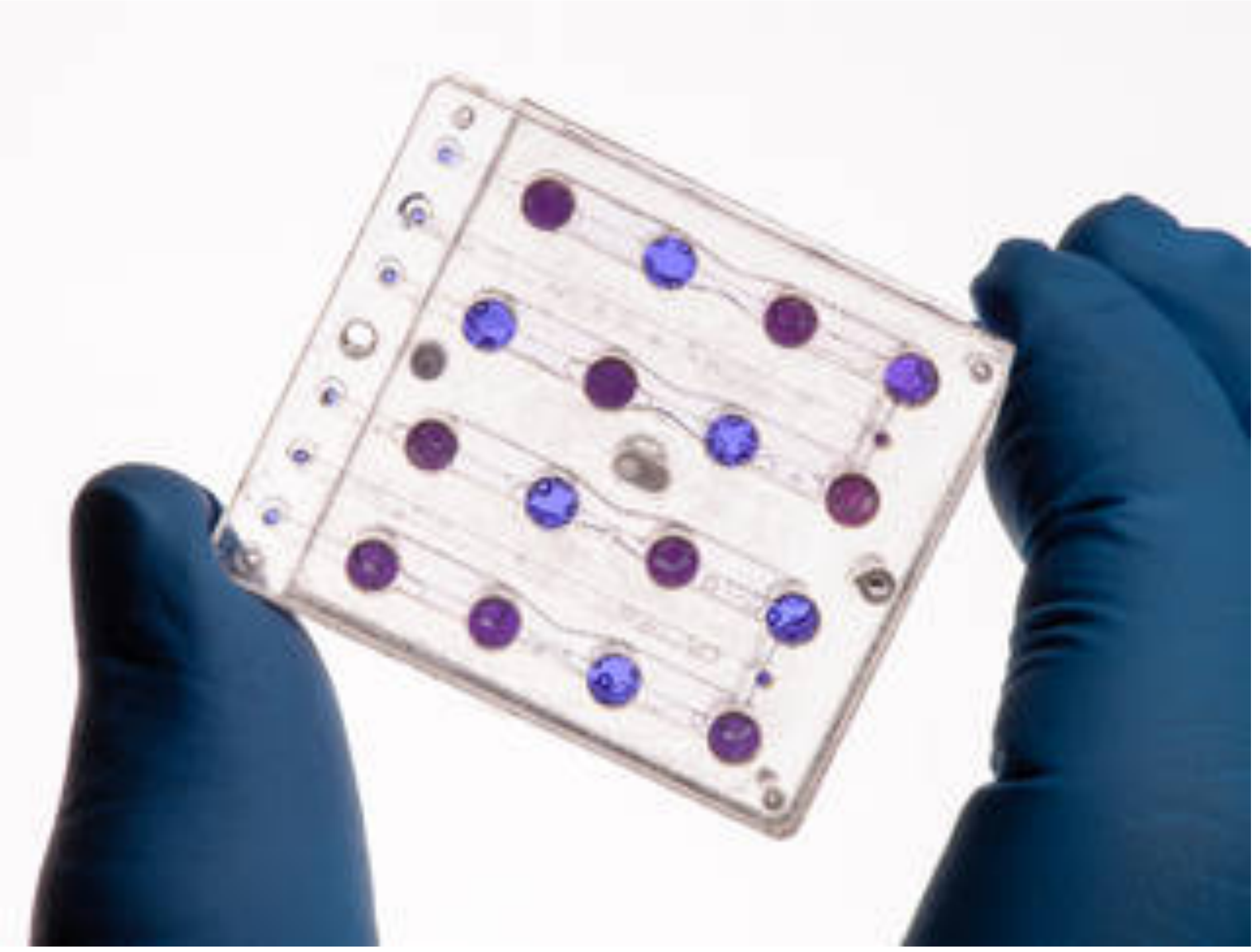
Helga and Zohar phantoms in Artemis 1 capsule

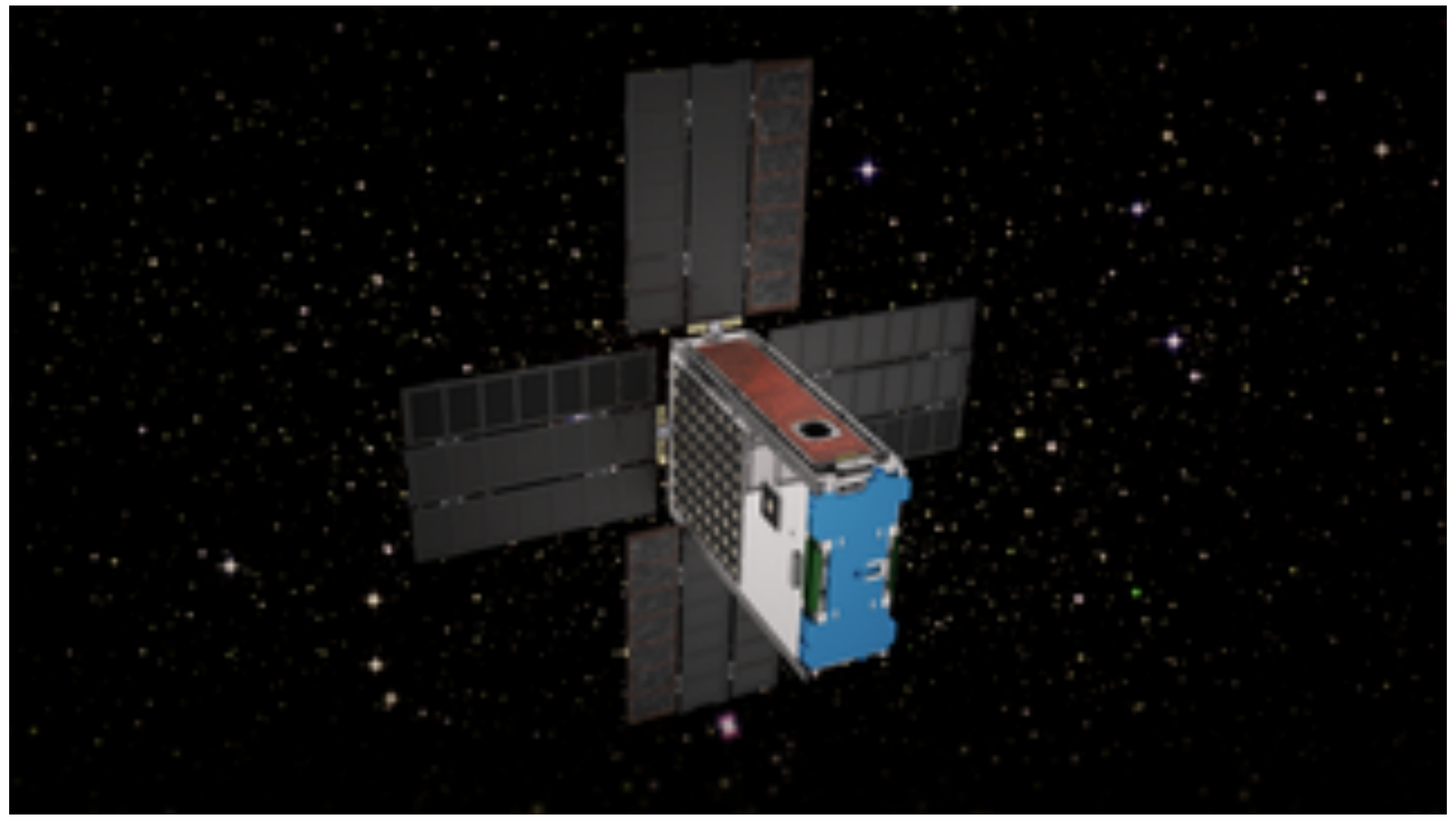


Simulation of predicted HERA dose rates during notional Artemis 1 mission

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
- Launched into a heliocentric (solar) orbit on Artemis 1
- Nominal operations for 6 months, radiation data (dose, LET spectra etc) on 1 hour cadence.
- Good chance to see space weather events etc



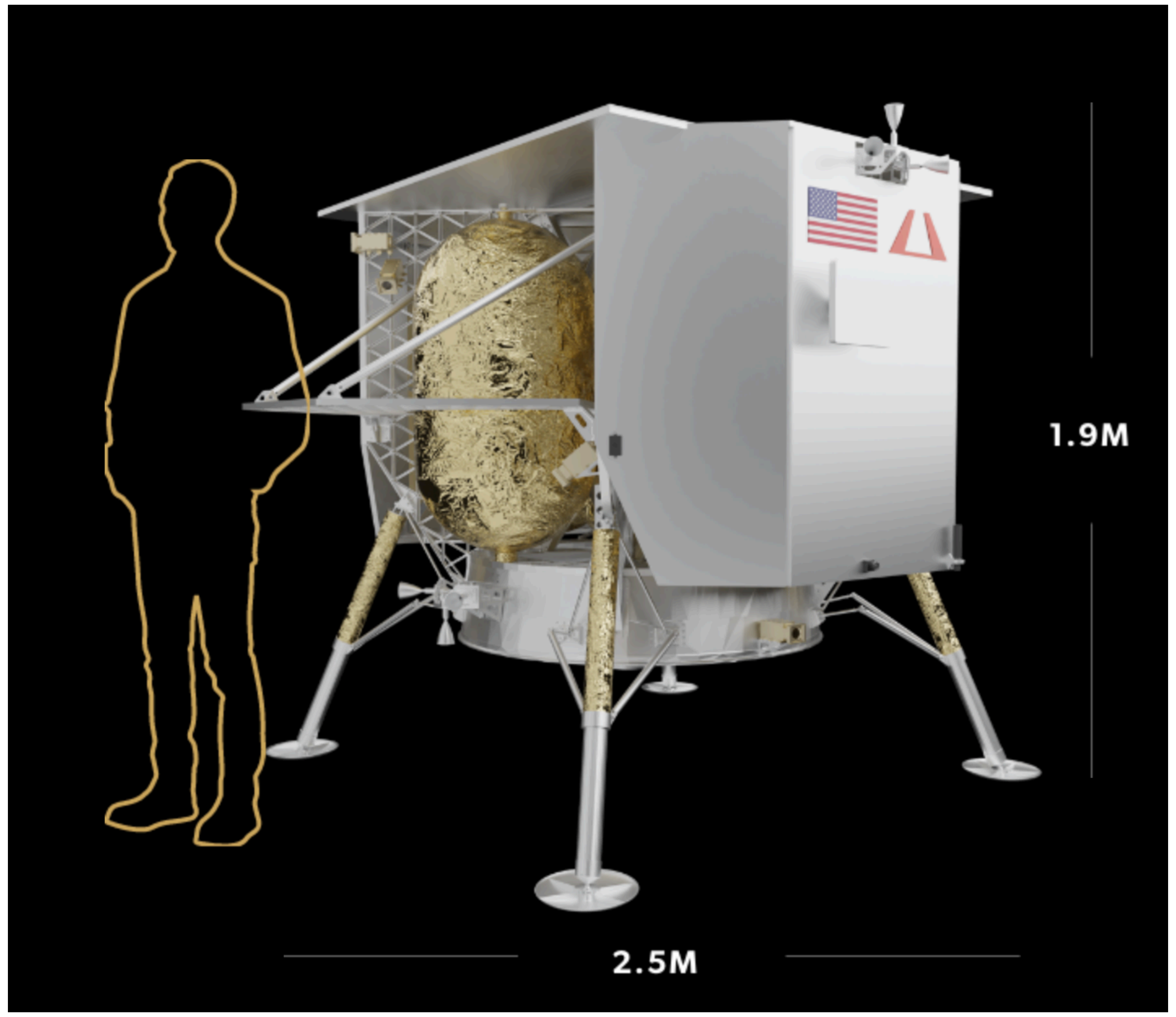


AJ Ricco et al (2020)

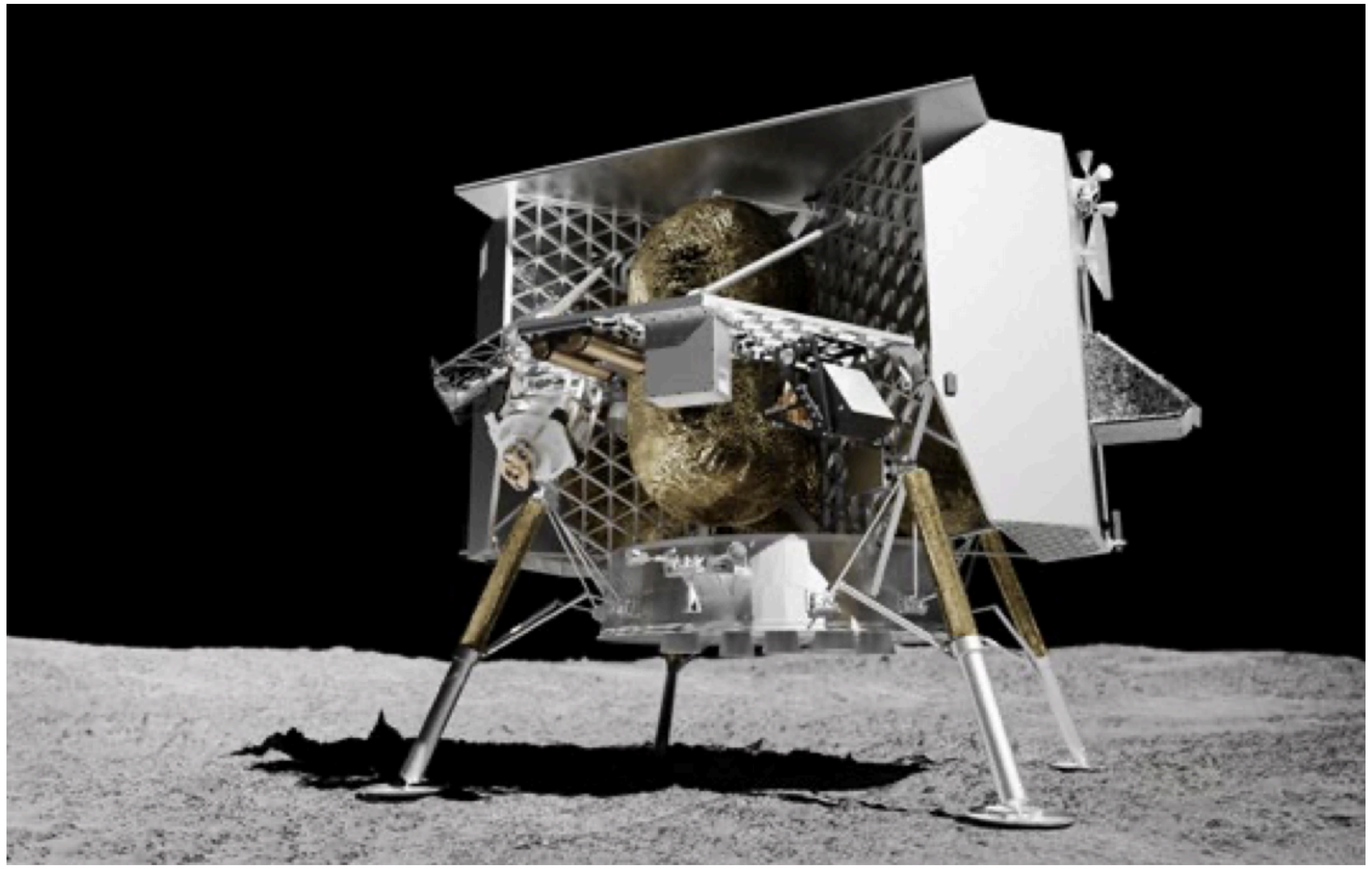
Current Status

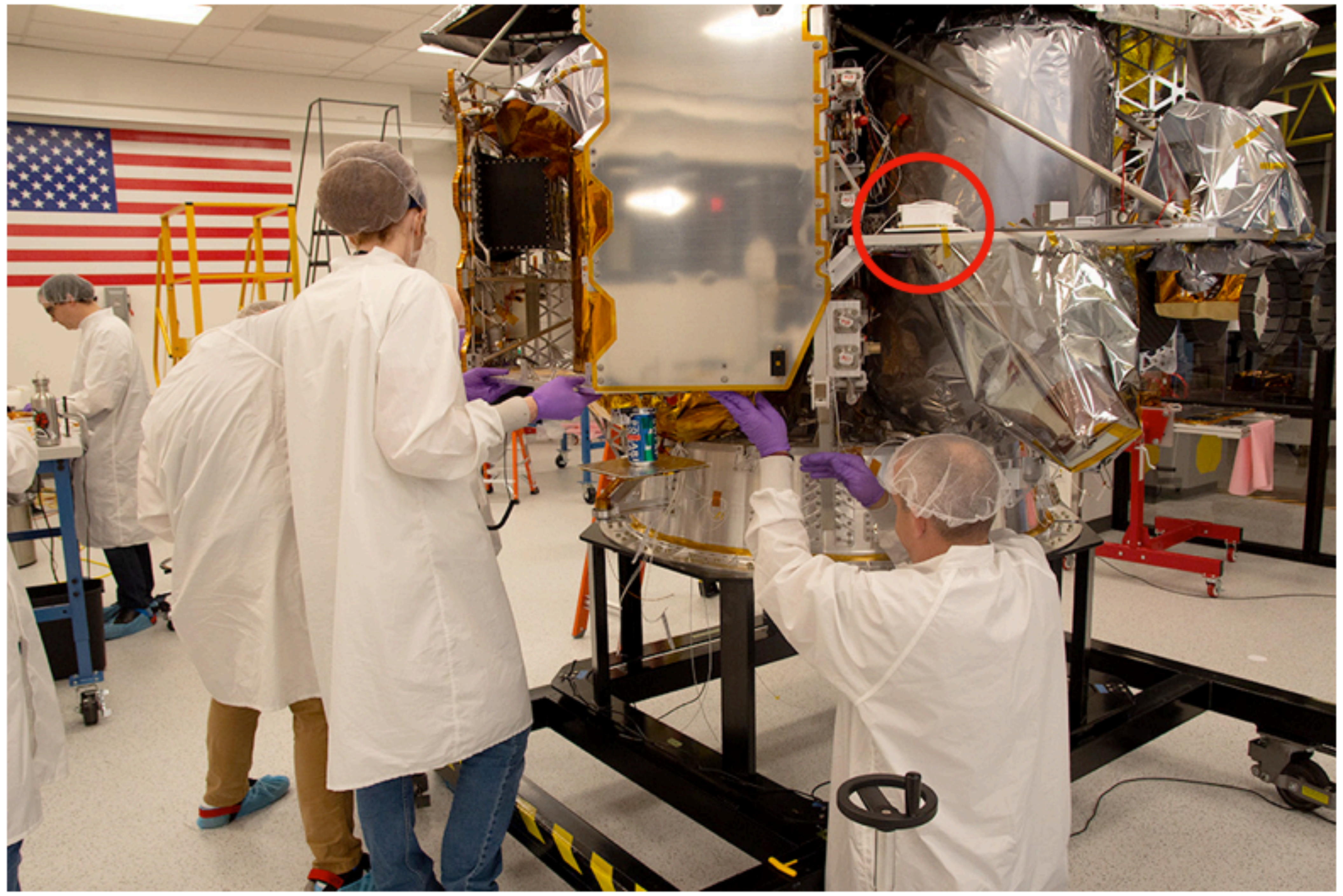
- Artemis 1 launched November 16th (wednesday) morning at ~7:50 Geneva time
- **HERA successfully turned on at 50,000 ft as planned**
- **Sending back (sensible looking) real time telemetry on a minute wise cadence to MCC radiation console**
- Artemis 1 successfully performed Trans Lunar Injection burn 1.5 hours after launch - on its way to the moon now (177,309 miles from Earth this morning).
- Biosentinel deploy ~ 2 hours after launch (no updates on status, run out of NASA AMES)

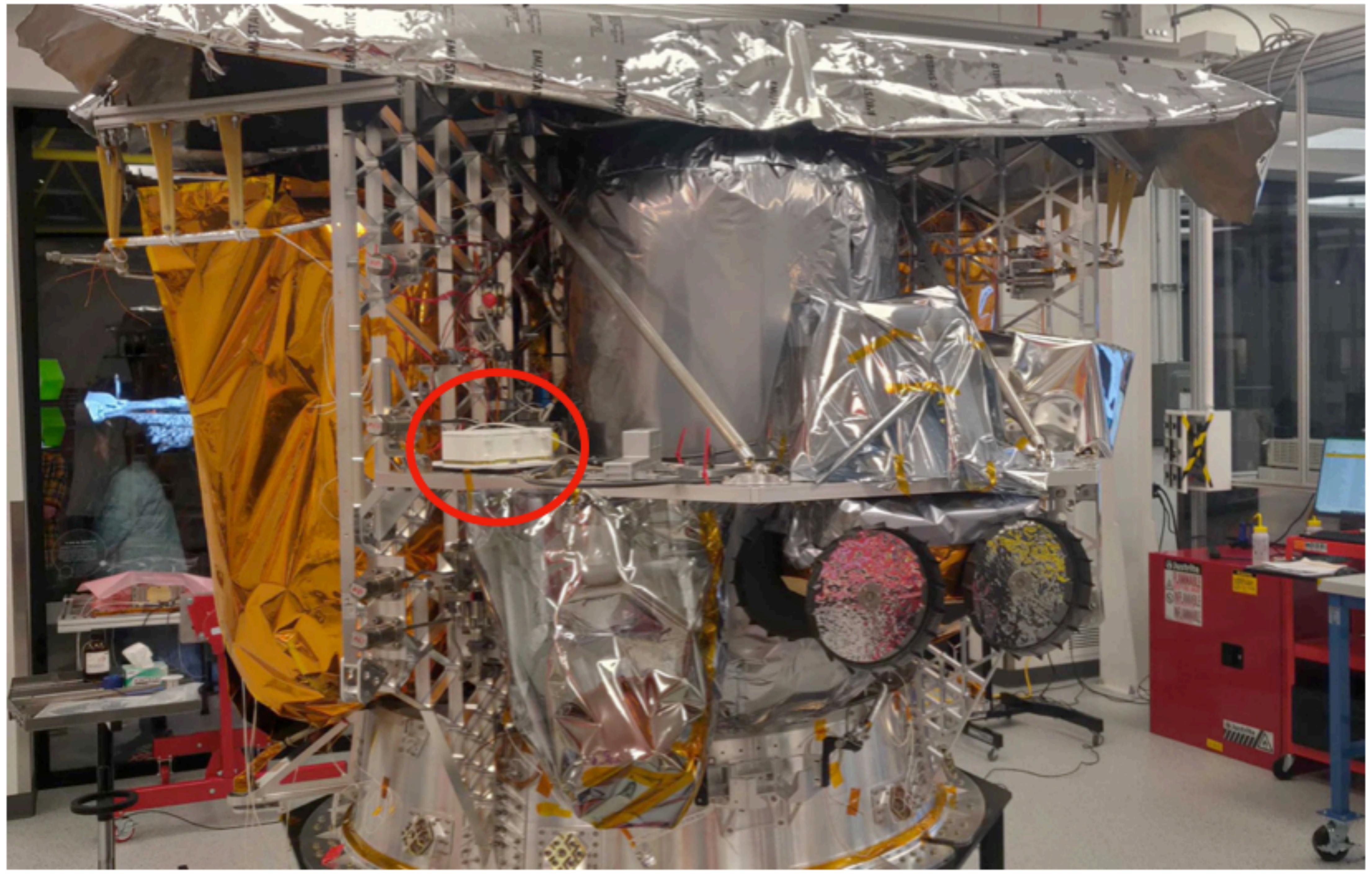
LETS on Astrobotic Peregrine

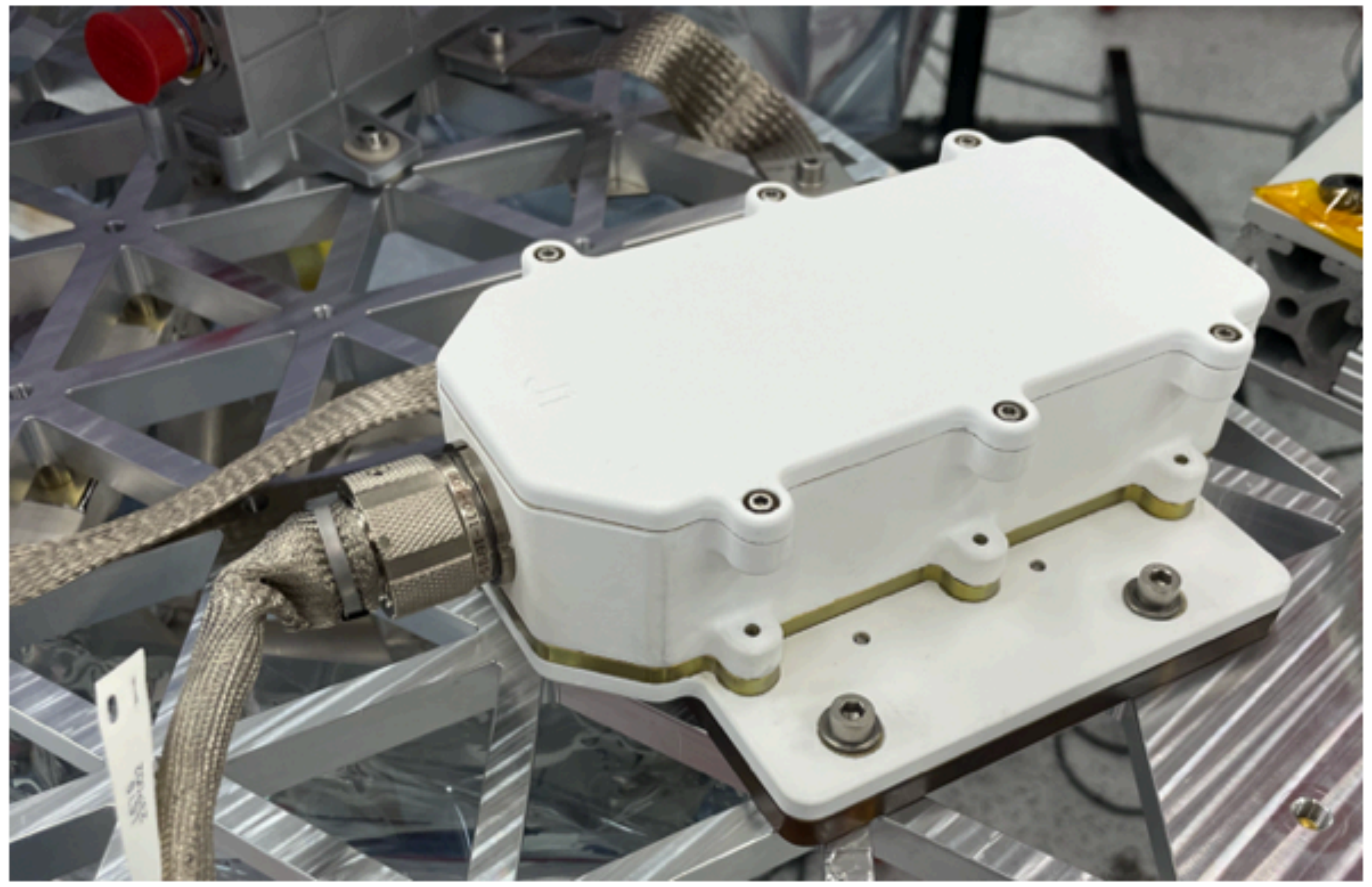


- LETS stands for the "Linear Energy Transfer Spectrometer"
- Goals - measure radiation environment on moon as precursor to lunar missions, measure dynamic environment during cruise, measure space weather events if we are lucky enough to observe one.
- Small, single Timepix instrument on the top deck of the Astrobotic Peregrine (unmanned) lander
- Scheduled for launch of first flight of ULA Vulcan Centaur, Q1 2023
- Cruise phase ~40 days to moon
- During cruise phase telemetry data on 60 minute cadence, same as HERA with higher resolute LET/Stopping power spectrum
- 10 days operations on lunar surface
- During surface phase telemetry data on 1 minute cadence, same as HERA with higher resolute LET/Stopping power spectrum
- Thermal main constraint for mission - we are sun facing during some phases. Biggest concern lunar noon (may need to siesta). Optimized Timepix for stable operation up to 80C ambient.







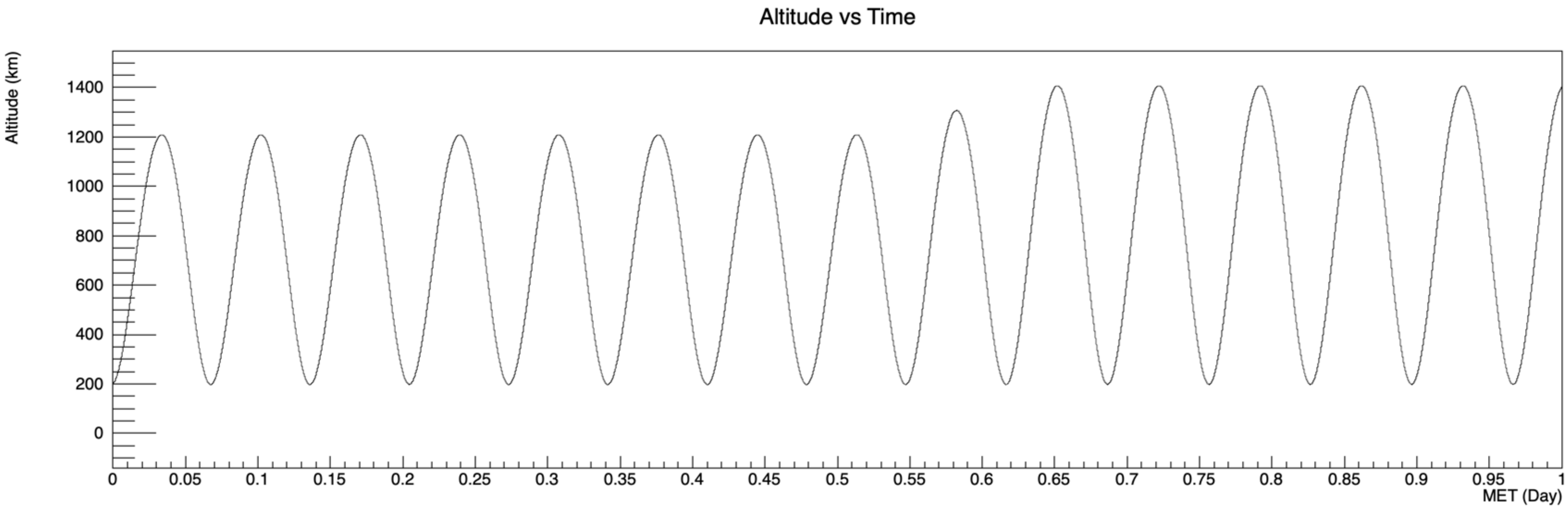


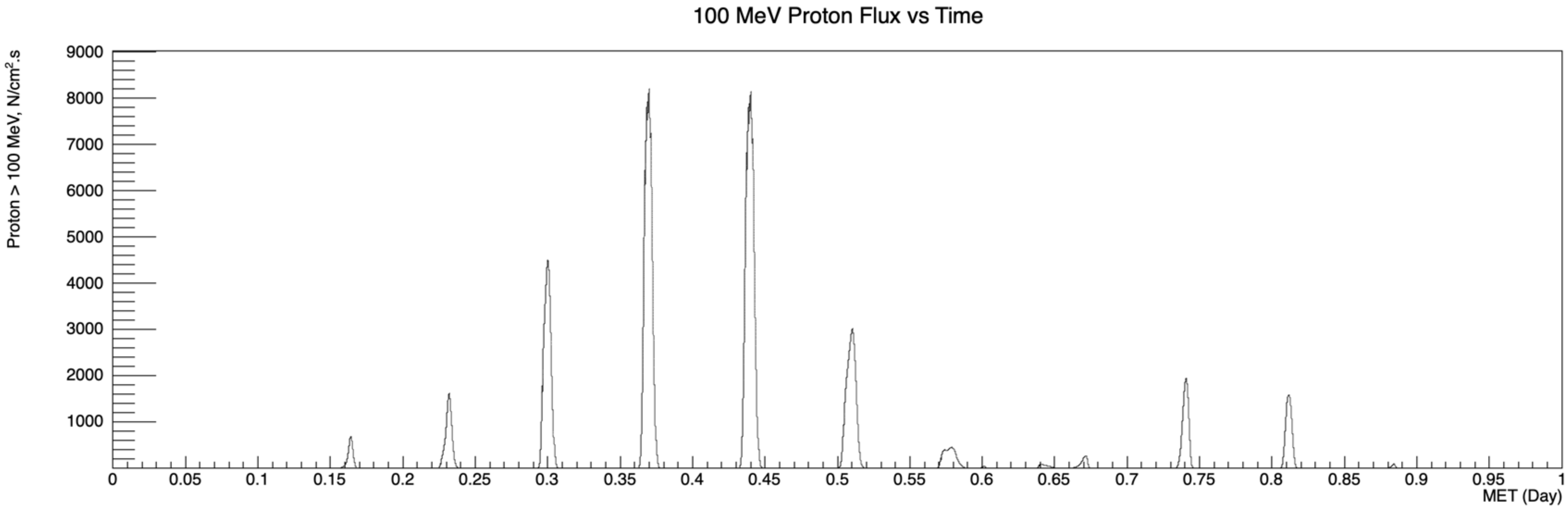
<u>Peregrine (and LETS) will launch in the first quarter of 2023 on the first launch of the ULA Vulcan Centaur rocket</u>


EVICTION NOTICE
Violation of the Lease Agreement
End of Tenancy

Polaris Dawn

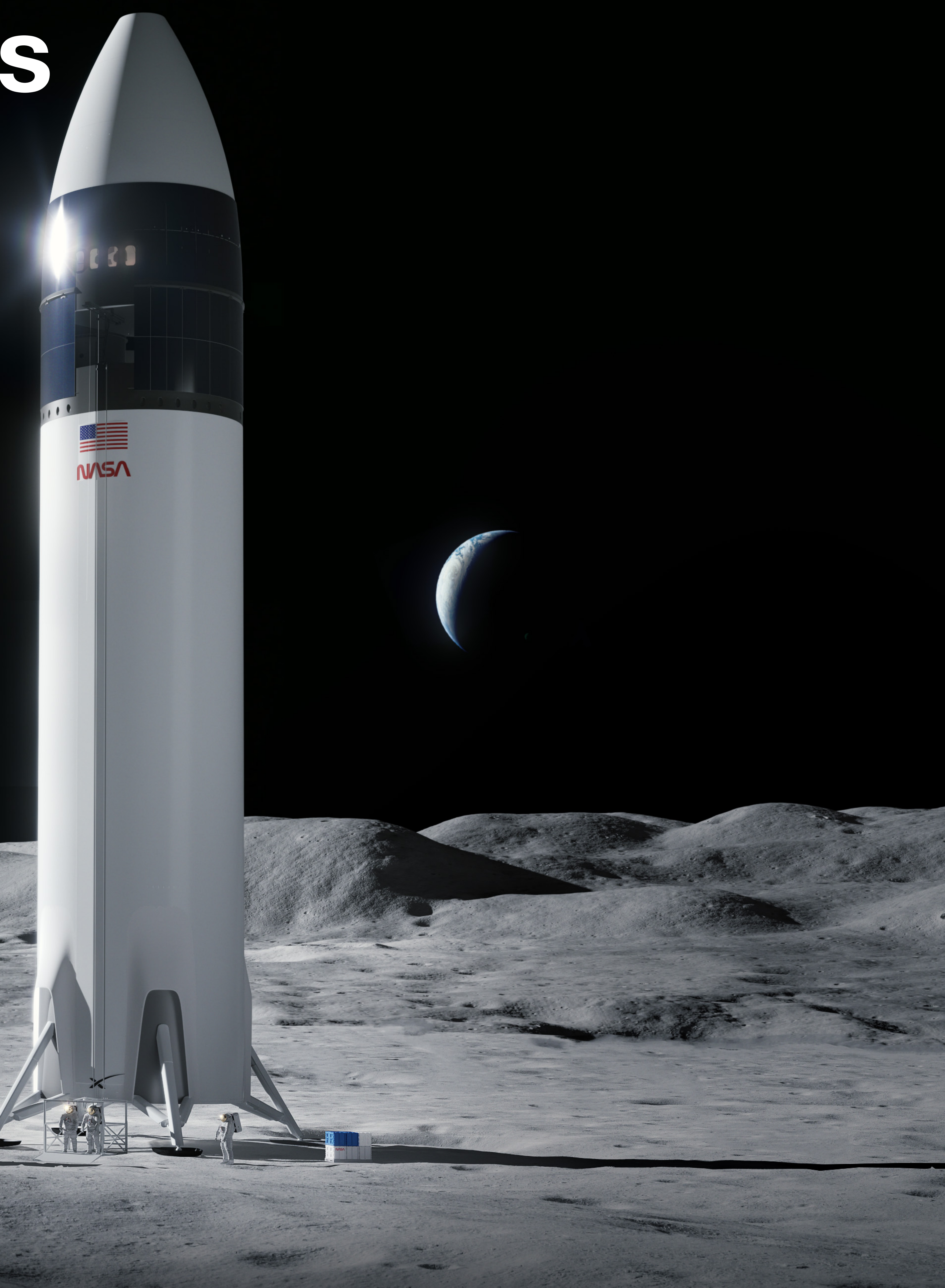
- Polaris Dawn is the second free flying private spaceflight from SpaceX following the “Inspiration 4” flight in 2021. It is being privately funded by Jared Isaacman.
- This is a significant free flying spaceflight. The Polaris Dawn crew has a full roster of science for their 5 day flight. They will ascend to a 1400 km altitude and perform a spacewalk.
- From a radiation point of view, the high flight path includes several high altitude Van Allen Belt traversals with significantly higher proton fluxes
- We are flying a space HERA instrument (HPU only) to support Polaris Dawn.


Altitude vs Time
Altitude (km)
1400
1200
1000
800
600
400
200
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
MET (Day)

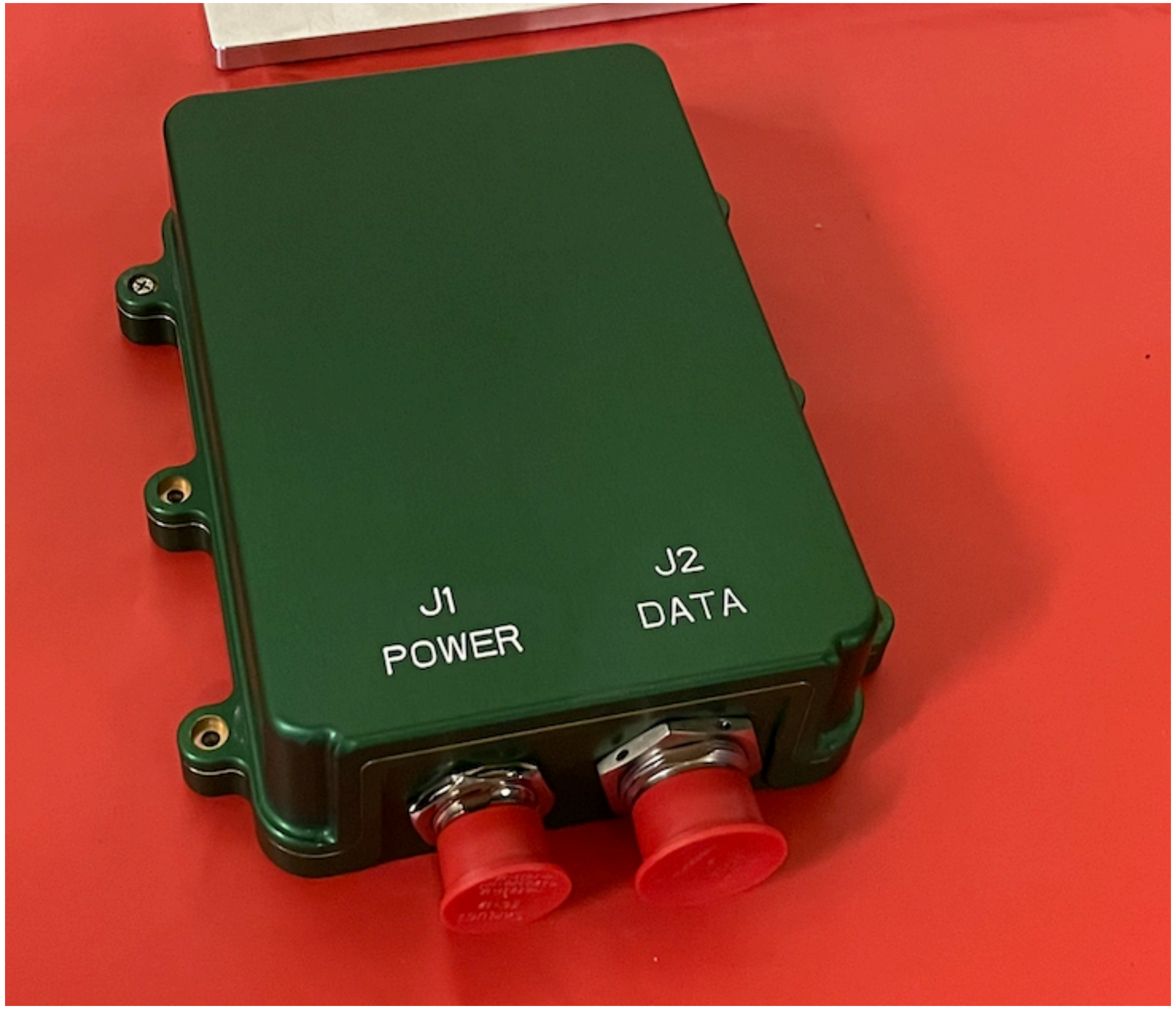

100 MeV Proton Flux vs Time
Proton > 100 MeV, N/cm².s
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
MET (Day)

ARES, CEPS Future Missions

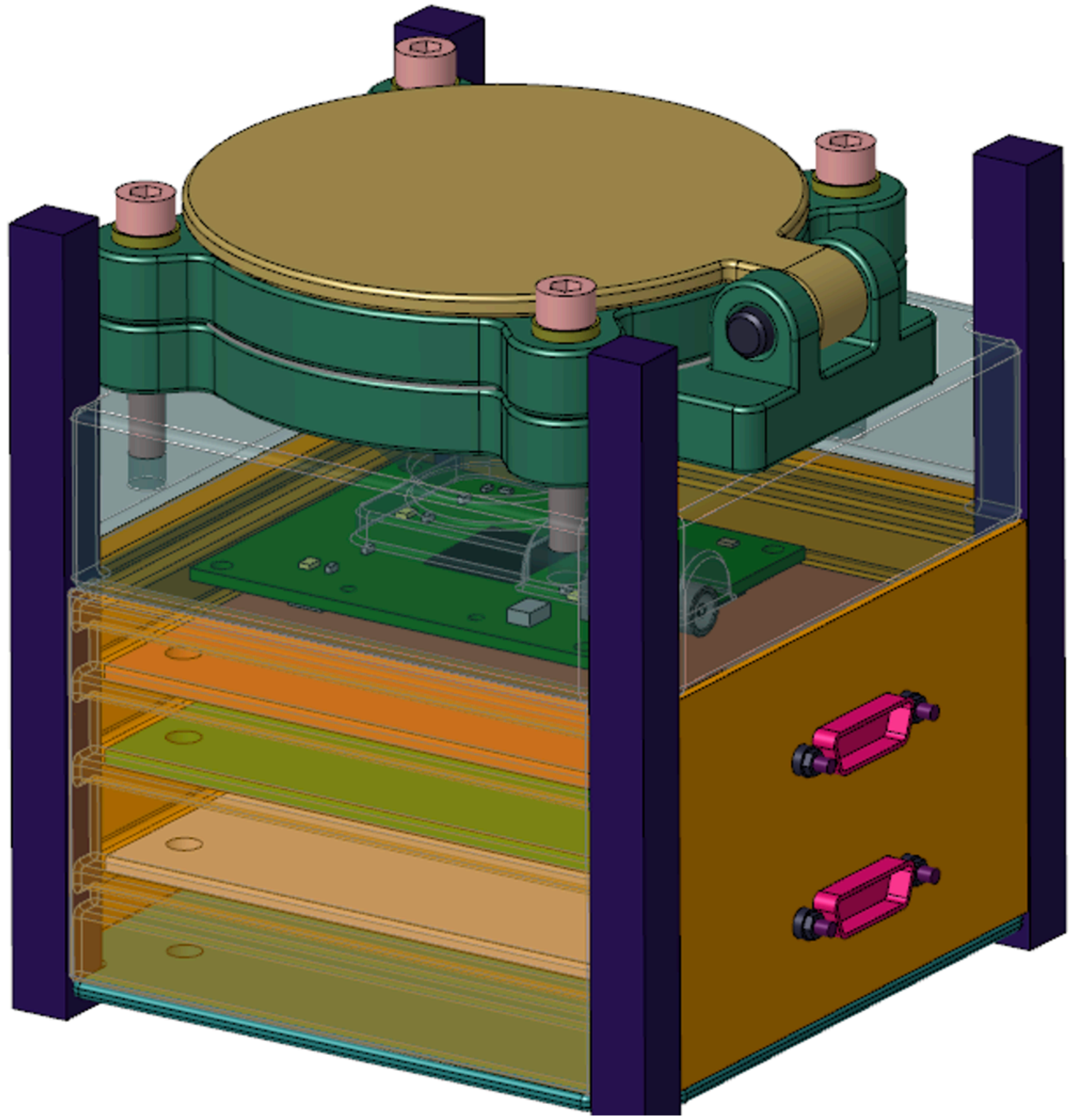
- ARES is the NASA's next Timepix based instrument for IV monitoring
- Currently manufacturing 20x flight units to support HLS (SpaceX starship), NASA Gateway (planned lunar space station hosting a number of ESA Timepix payloads) and future CLPS missions
- Future CLPS flights include LEIA, a biology experiment similar to Biosentinel destined for the lunar surface.
- CEPS (Compact Electron Proton Spectrometer) is an EV instrument for electron spectroscopy 0.2 - 2 MeV, and proton spectroscopy 10 - 150 MeV
- Rad hard Hi-Z Timepix2 based instrument targeting 10 year lifespan in free space
- Space weather protection and early warning for crew, heliophysics science missions, planetary magnetosphere missions.



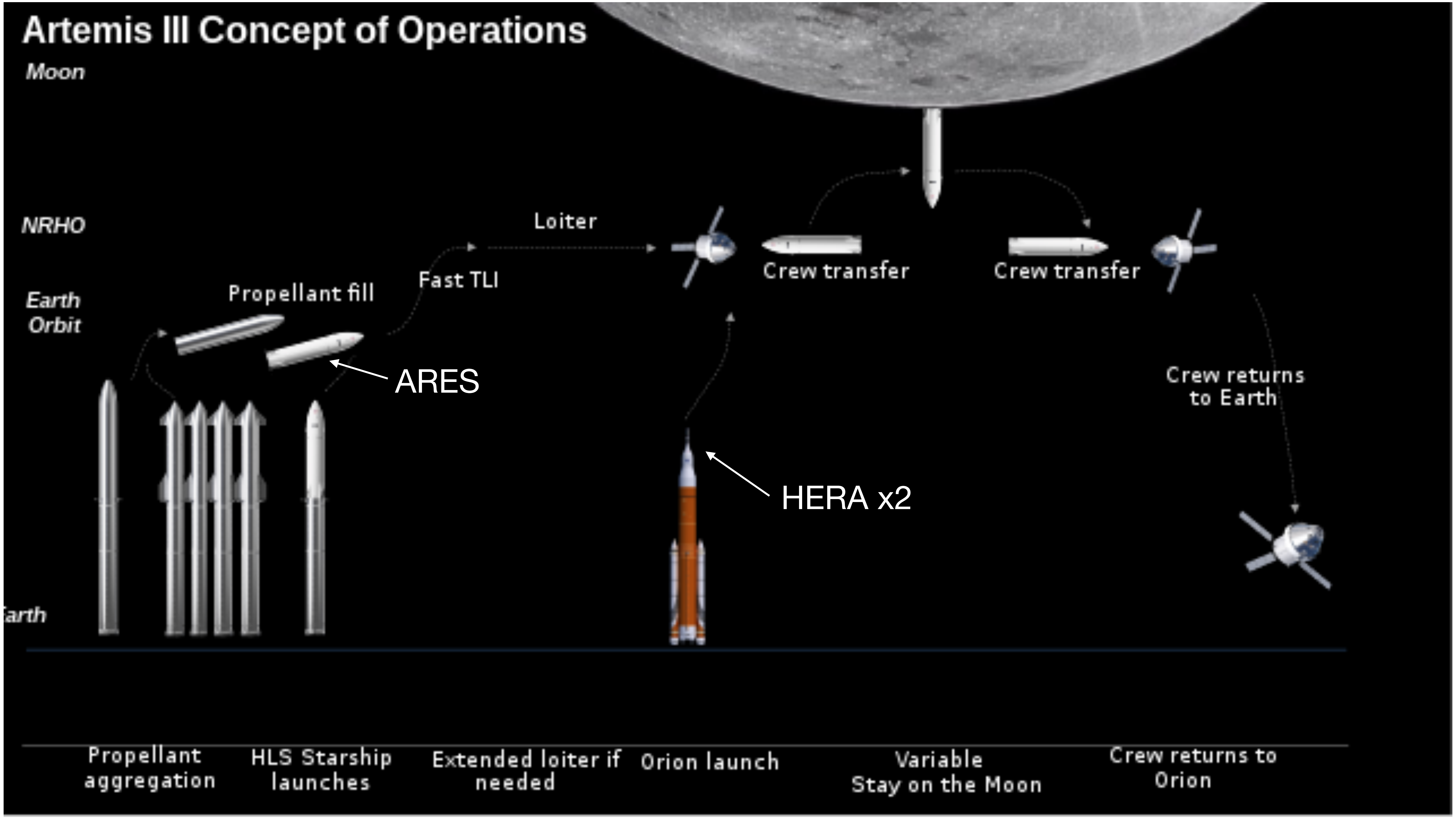
ARES



CEPS



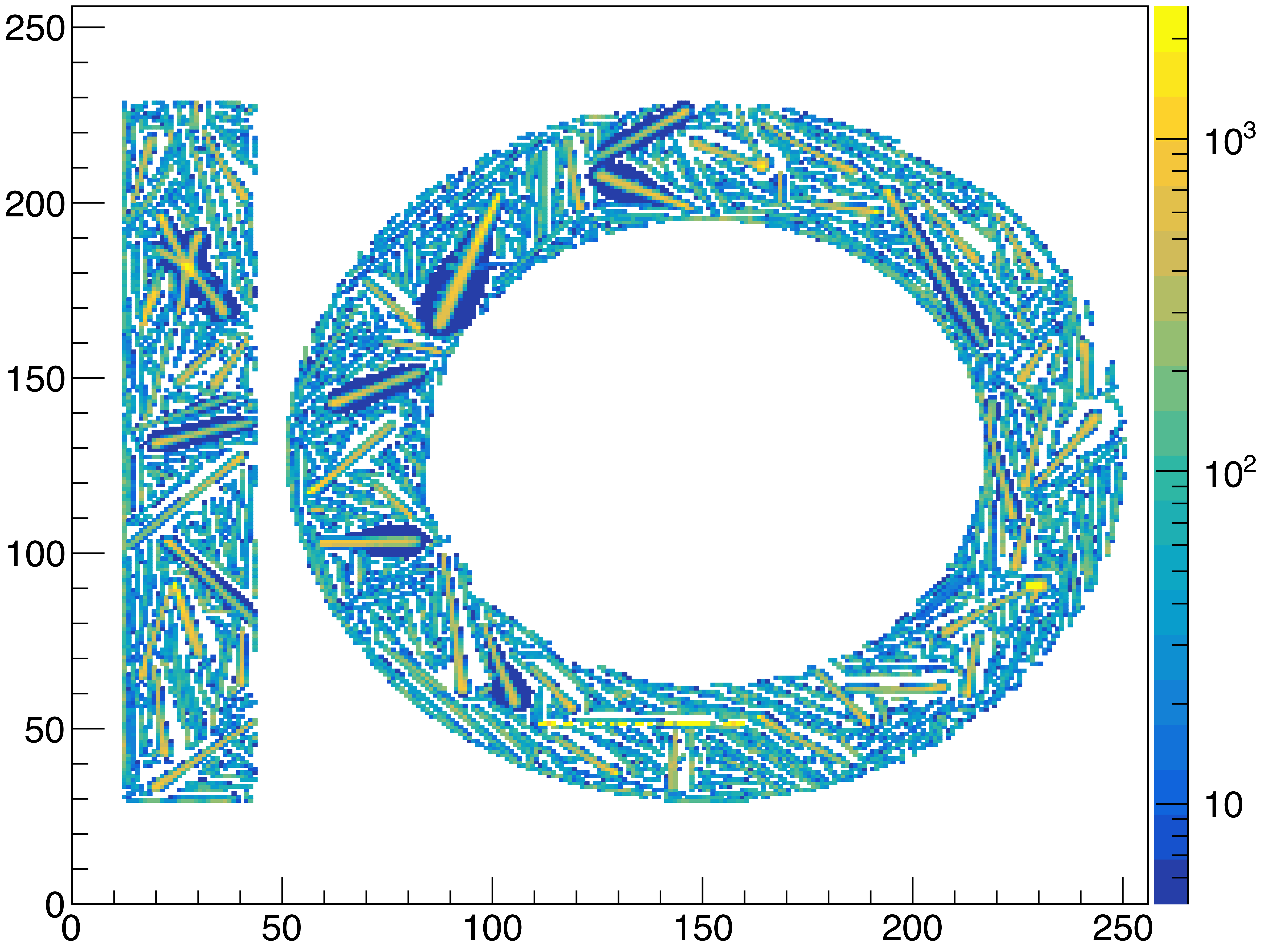
HERA and the future Artemis Vehicles



Thank you for your attention

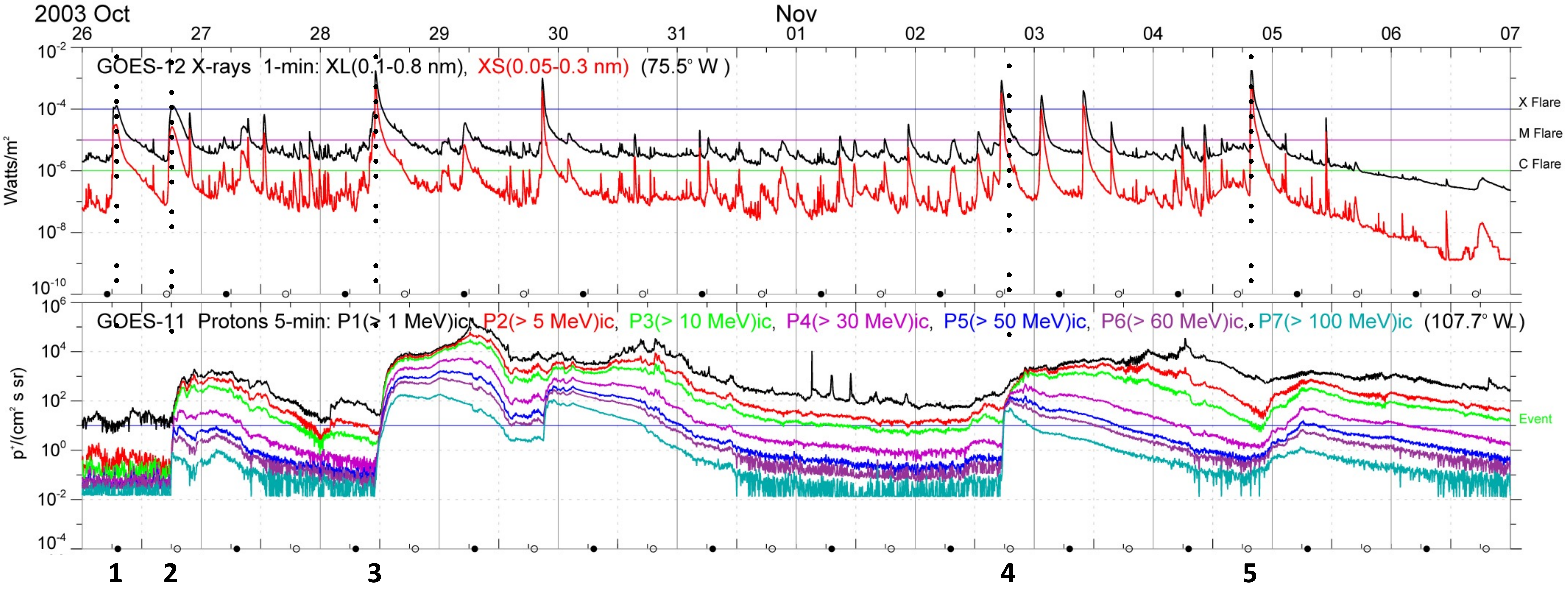
And thanks to everyone here (there are many) who helped make this program the success it is today

10 Years of Timepix in Space



Supplemental Slides

Extreme Event: 2003-10-26 00h - 2003-11-06 24h



1 - A big flare, but no particles

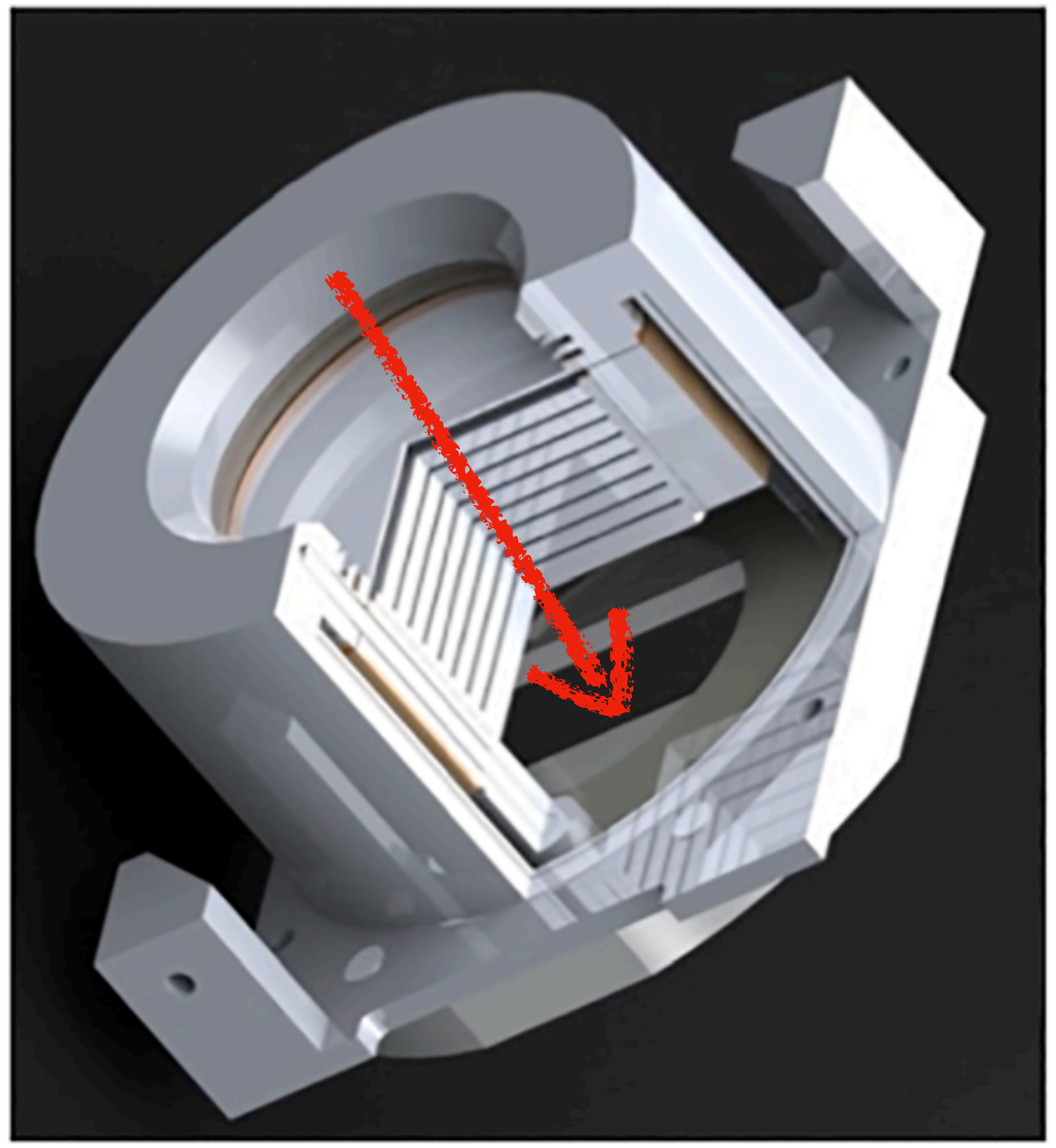
2 - A similar flare, but significant particle levels.

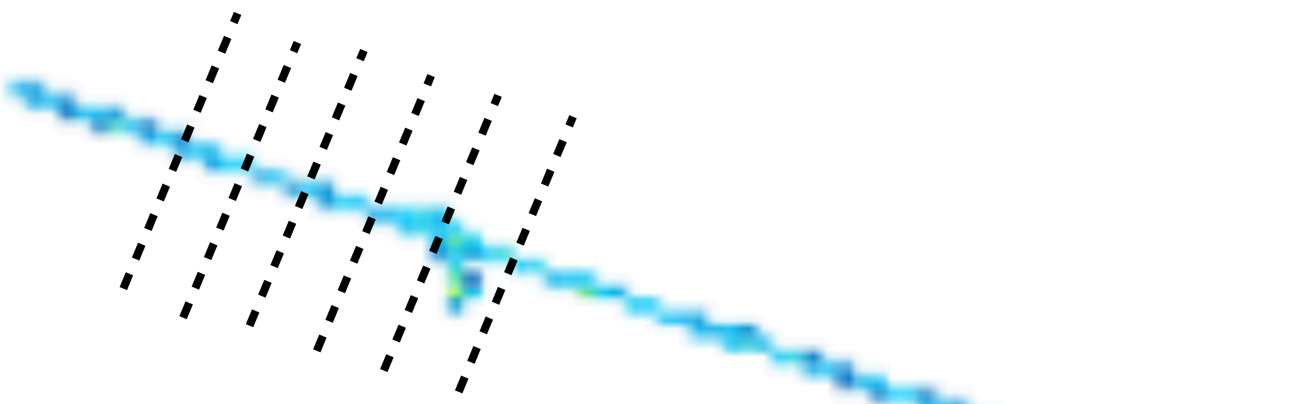
3 - A very large flare, with very high particle fluxes

4 - Note fast onset time of > 100 MeV

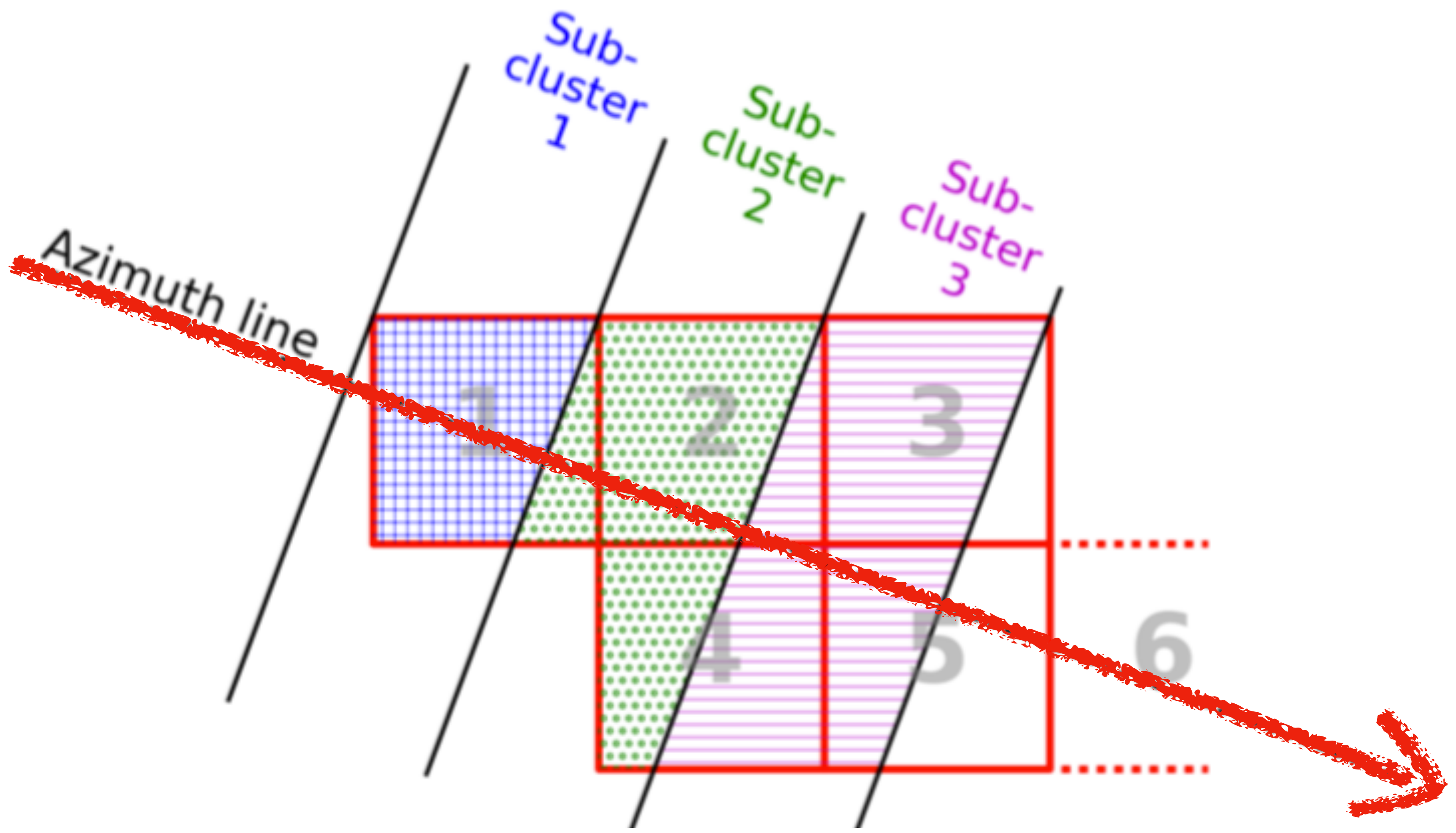
5 - Final large flare, modest particle enhancements

Single Layer Telescope





Example “Virtual telescope layers”



Dividing pixels into virtual telescope layers
(Subclusters)

- Most space instrumentation is some form of particle telescope - stacks of monolithic detectors - e.g. MERiT on left (from Kanekal et al, “JGR Space Physics” (2019)

- One insight that helped to bridge the gap between imaging detectors like the Timepix and more conventional space instrumentation is that the tracks in the Timepix can be thought of as passing through a large number of ‘virtual telescope layers’ - a so called “Single Layer Telescope”.

Maximum Likelihood for Proton Energy ID

- Utilizing all the information in the 'virtual telescope' layers can be used to dramatically improve the measurement of proton energy

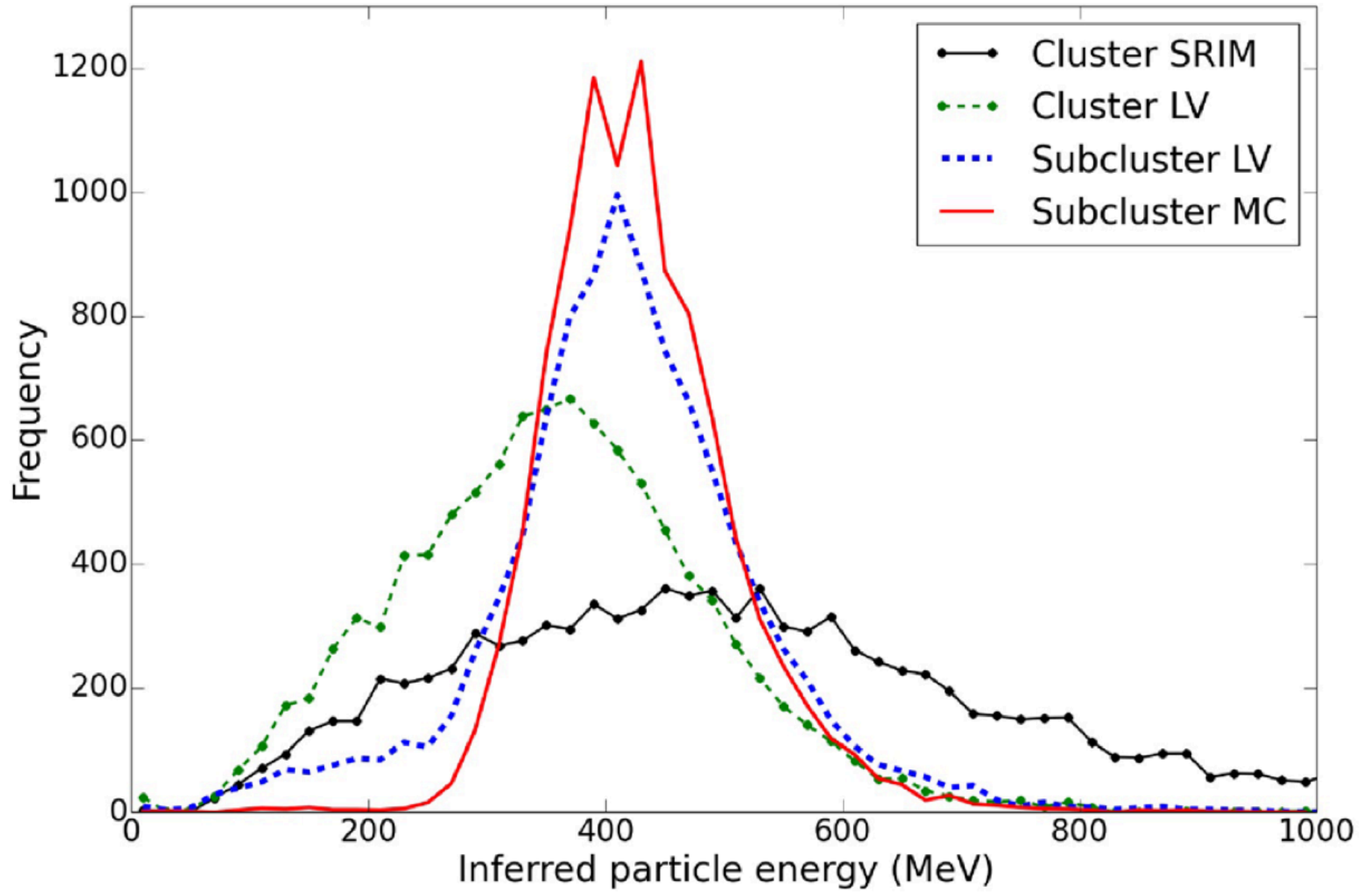
- Calculate likelihood of measuring sub cluster dE/dX for given energy

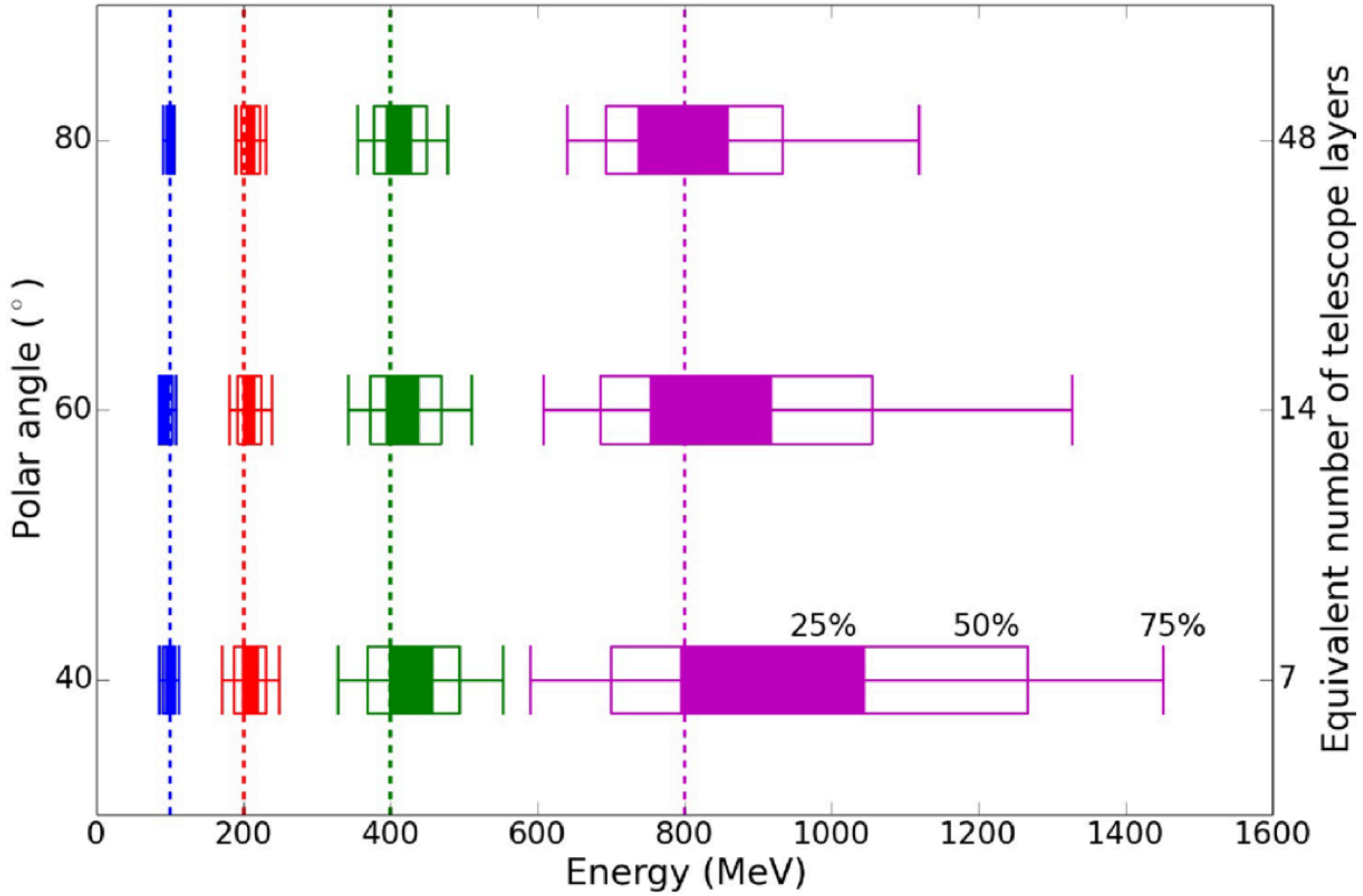
$$P(E|\Delta E, \Delta x) \propto P(E) \times P(\Delta E|E, \Delta x).$$

- Maximise likelihood by calculating product of likelihoods over range of energy

$$P(E_j|\Delta E_1, \ldots, \Delta E_n, \Delta x) \propto \prod_{i=2}^{n-1} P(E_j) \times P(\Delta E_i|E_j, \Delta x).$$

- Good results for likelihood of sub cluster dE/dX from theoretical calculation, best for Monte Carlo model w. charge sharing

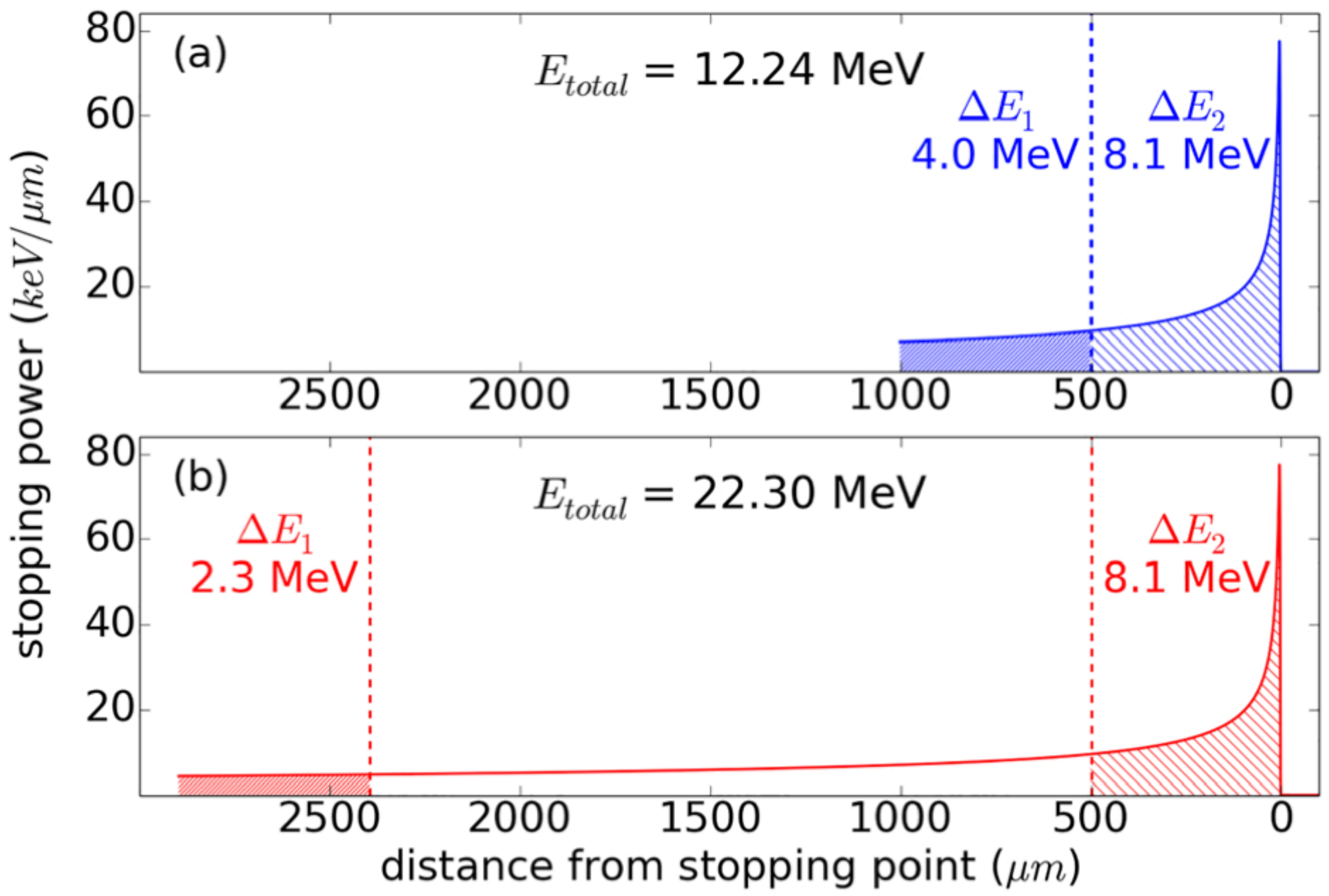




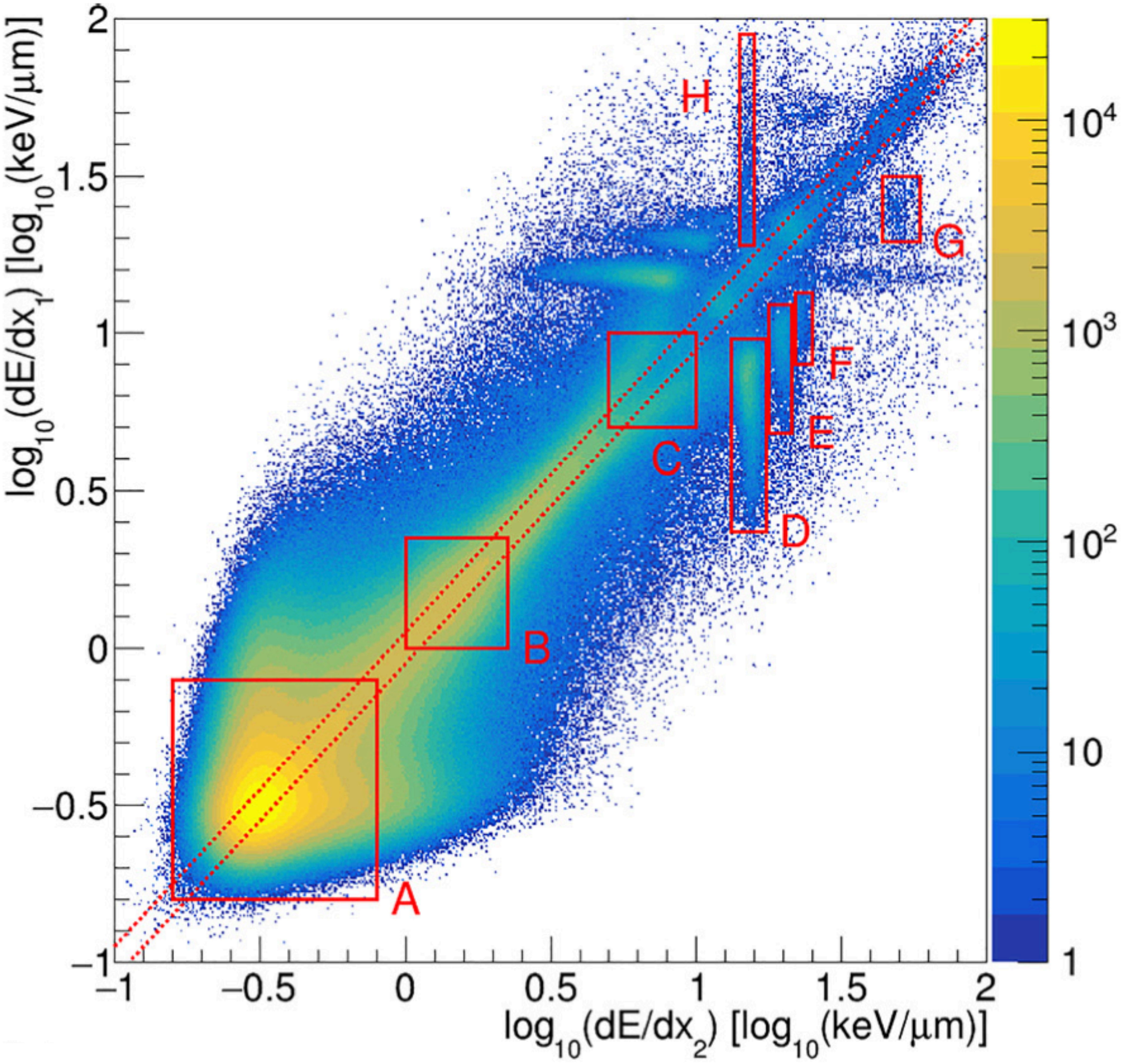
Appl. Phys. Lett. 112, 134103 (2018); https://doi.org/10.1063/1.5024920

dE/dE Plots

- Plot sum of sub clusters energies in first 500um of track against sub cluster energy in last 500um of track
- ID technique for H/He isotopes

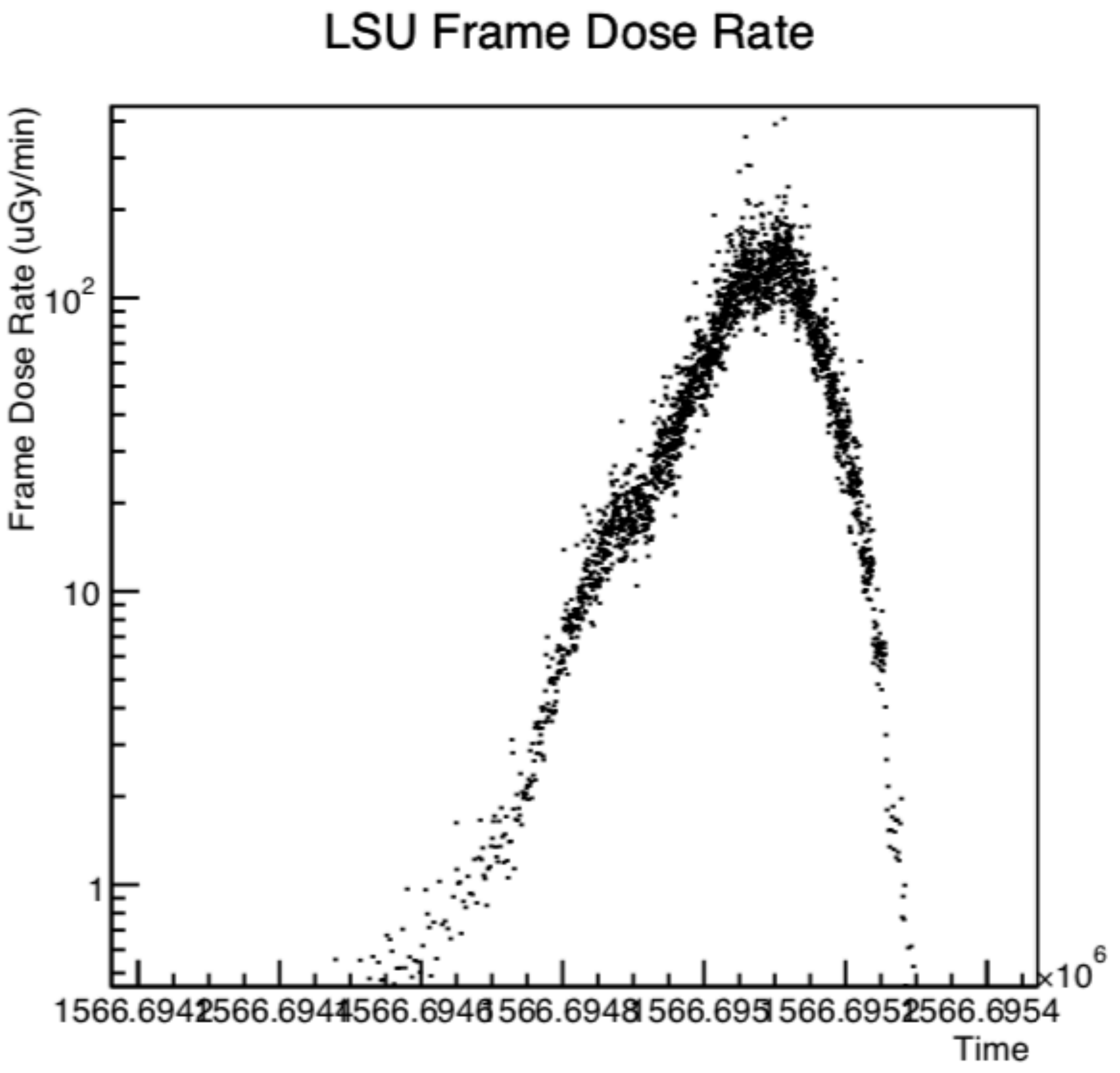


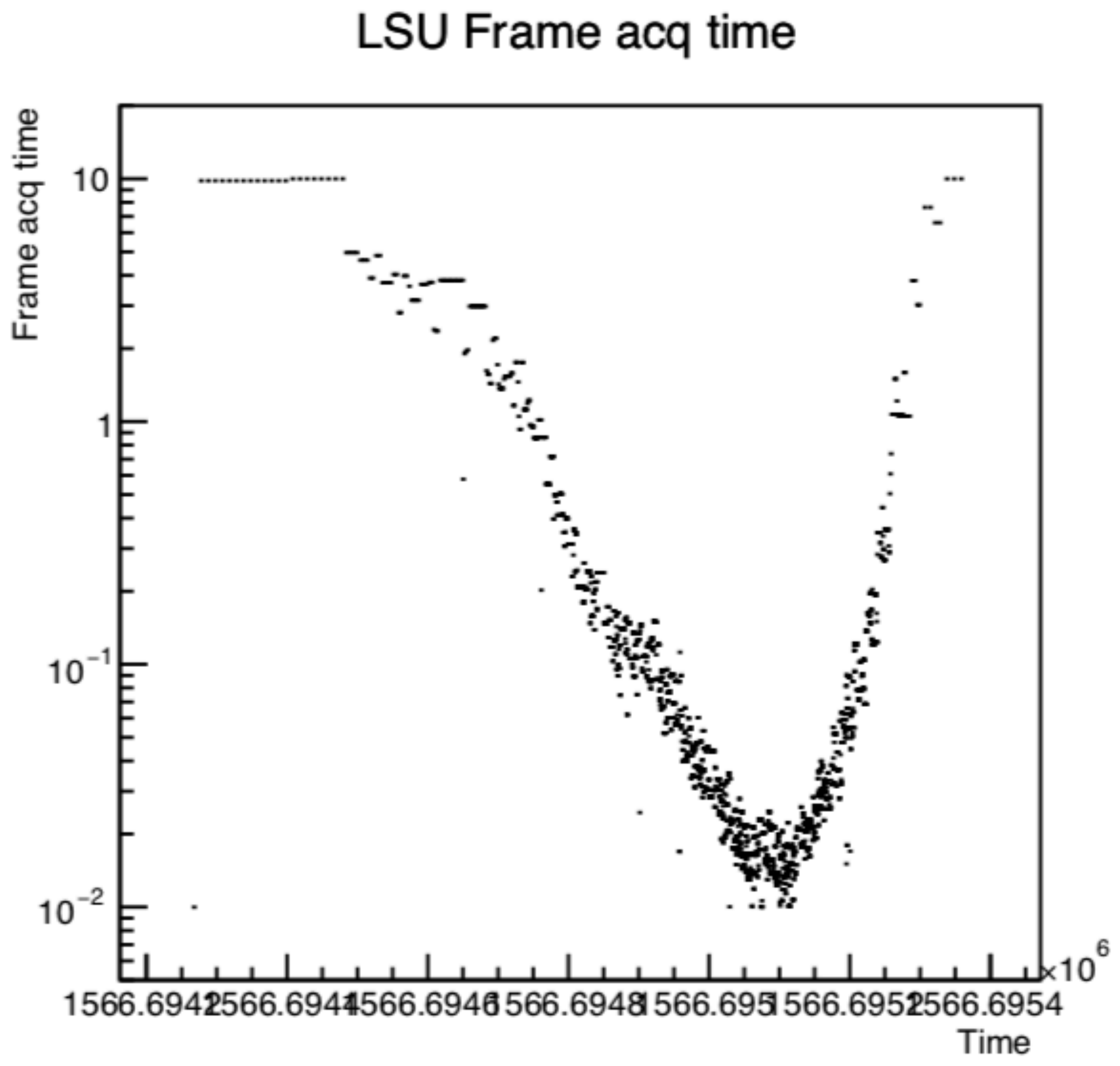
Appl. Phys. Lett. 113, 174101 (2018); https://doi.org/10.1063/1.5052907



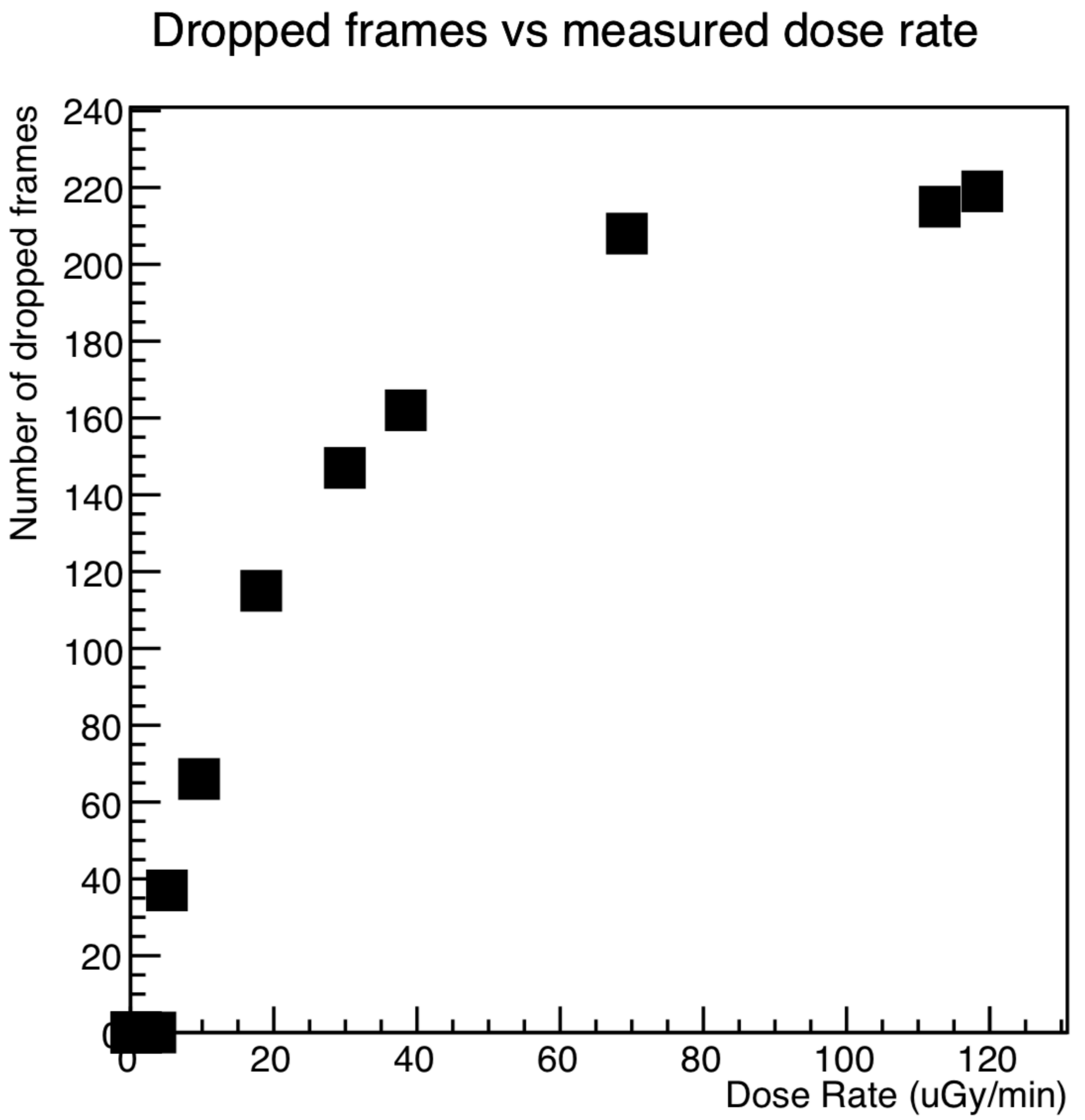
A - MIP Proton, B - Slow Proton/MIP He, C -
D - Stopping Hydrogen, E - Stopping Deuterium, F - Stopping Tritium
G - He3/He4
H - Nuclear interactions from proton

Dosimetry V&V at Chicago Proton Center (2 Slides)



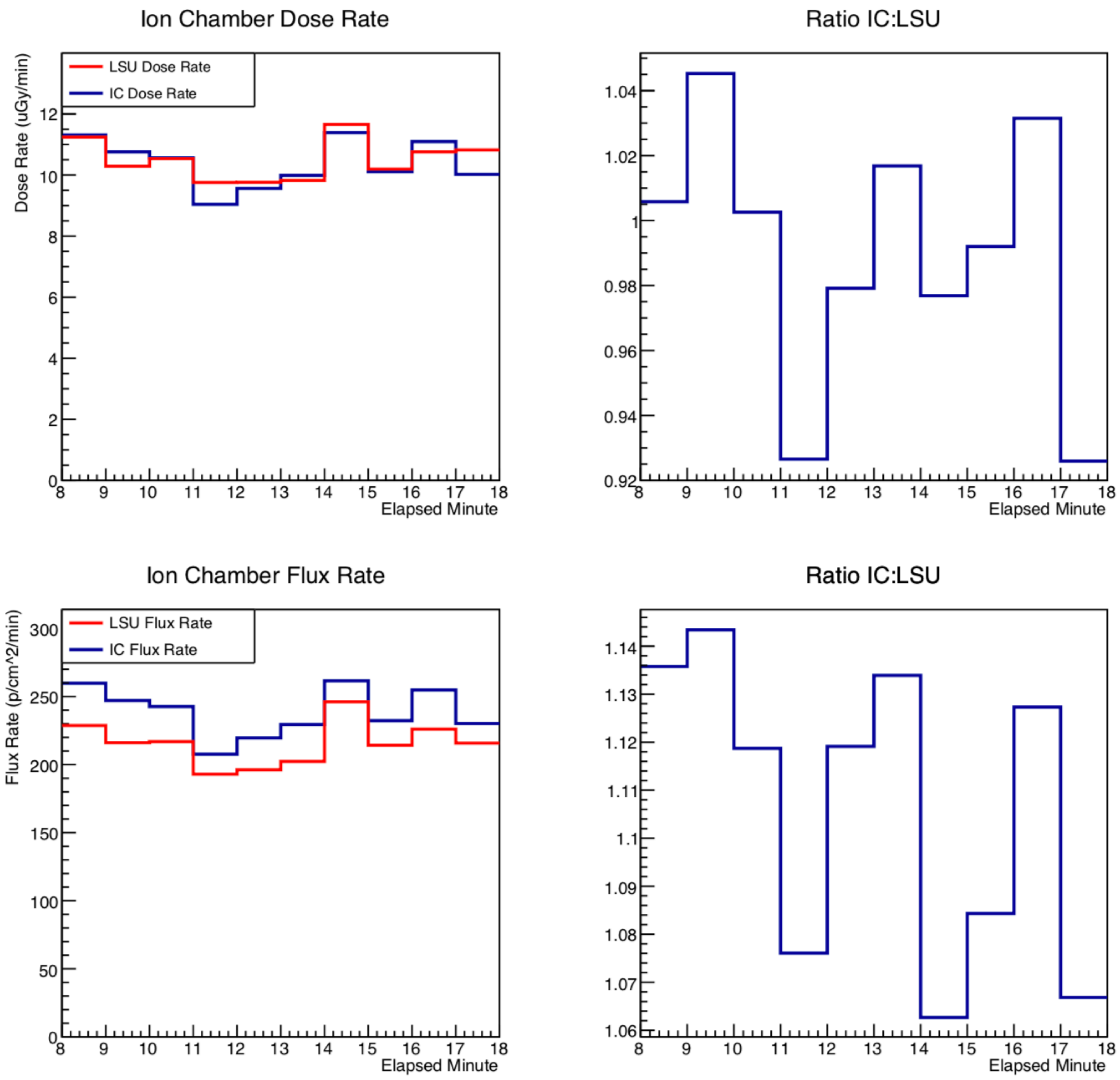


Simulated Belt/SAA pass at CPC showing frame acquisition time dynamic ramping

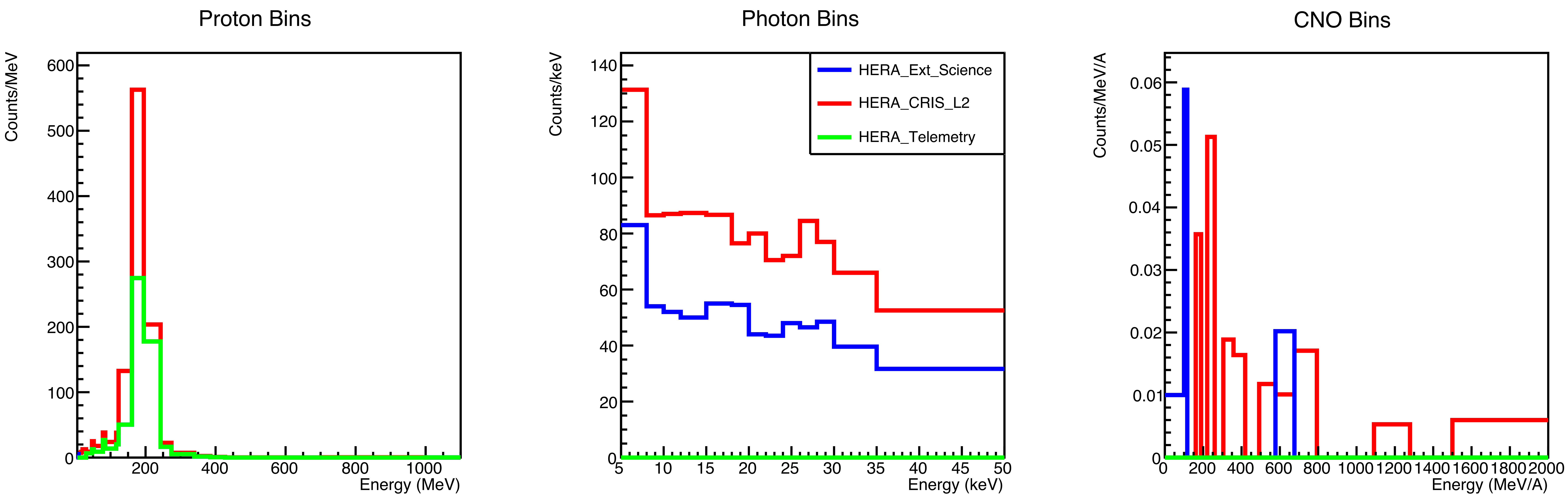


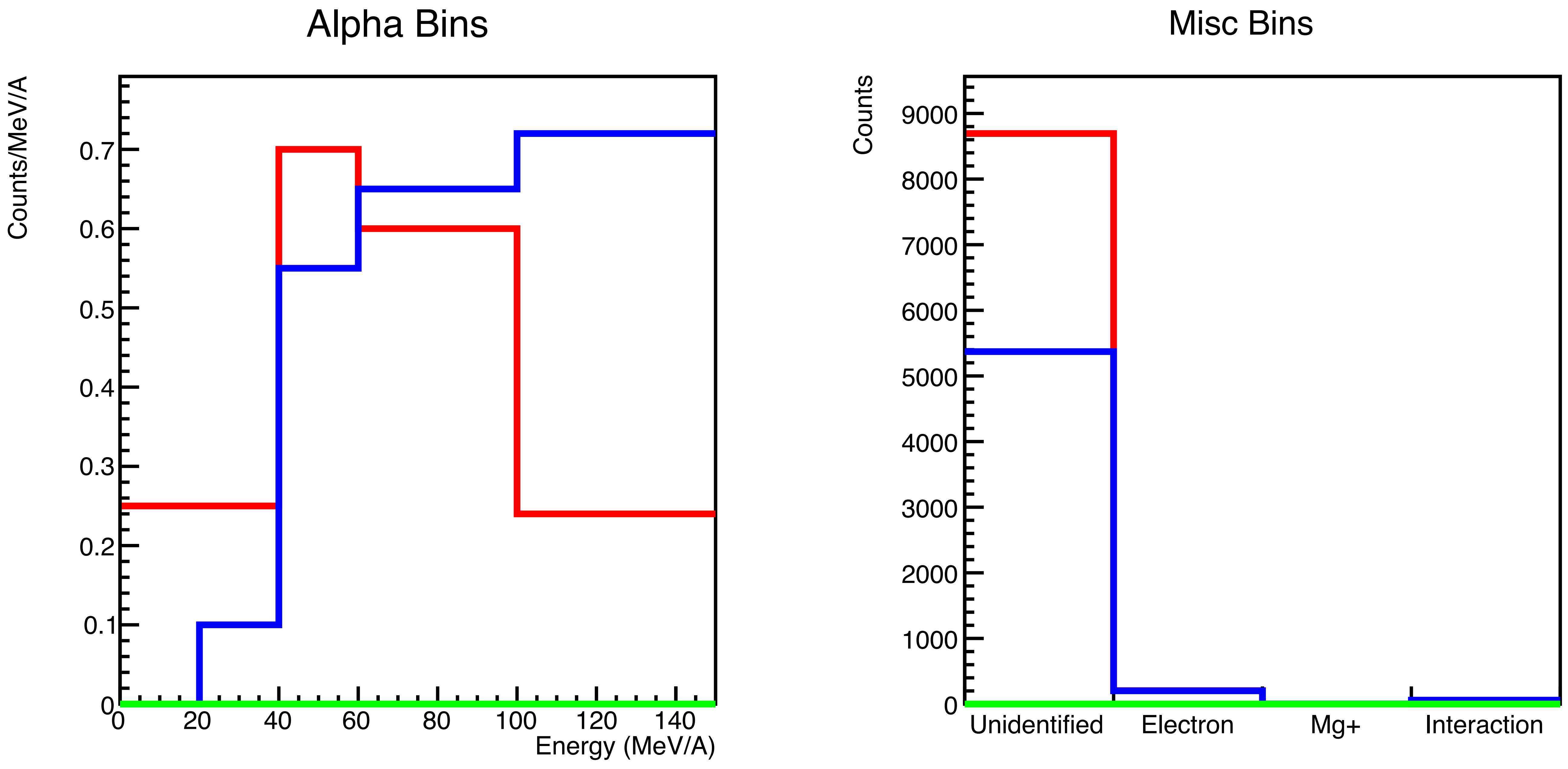
Number of 'dropped' frames (only dose computed, no particle binning) at CPC as a function of dose rate - shows system dynamically adjusting to increased load

Dosimetry V&V at Chicago Proton Center



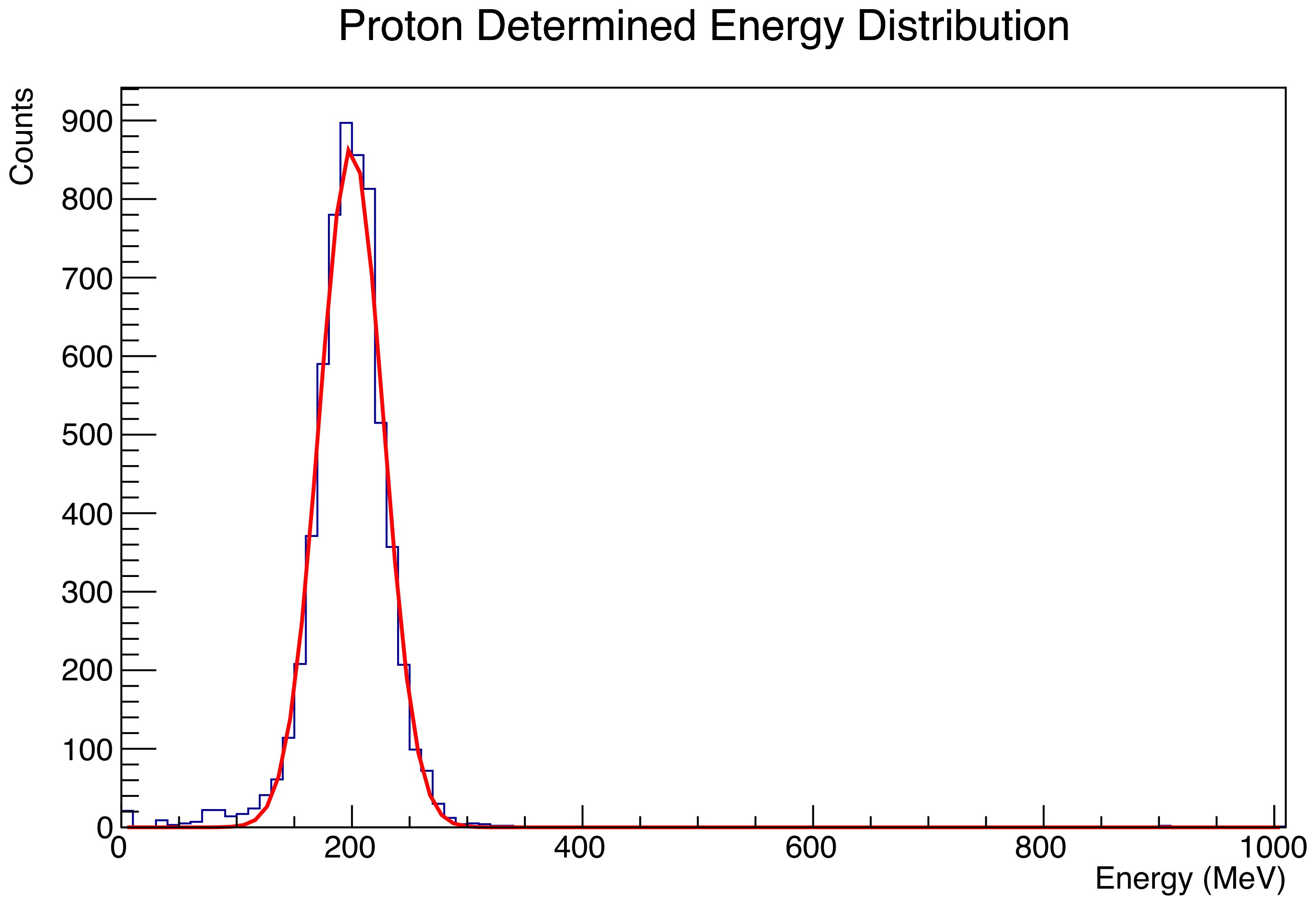
10 uGy/min rate, 200 MeV Protons
Flux calculated only from particles identified as protons



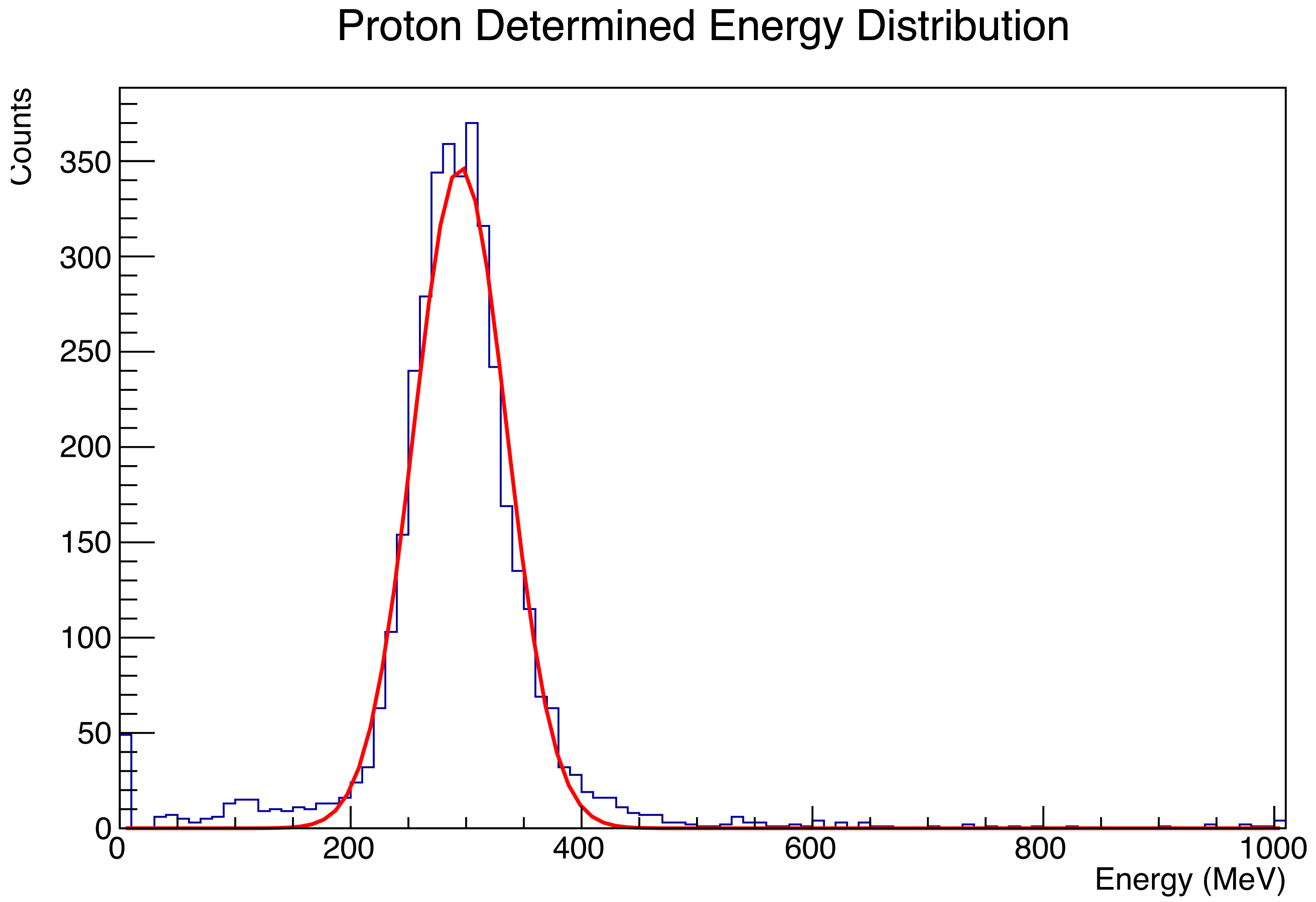


Example of "raw" telemetry output from CPC run

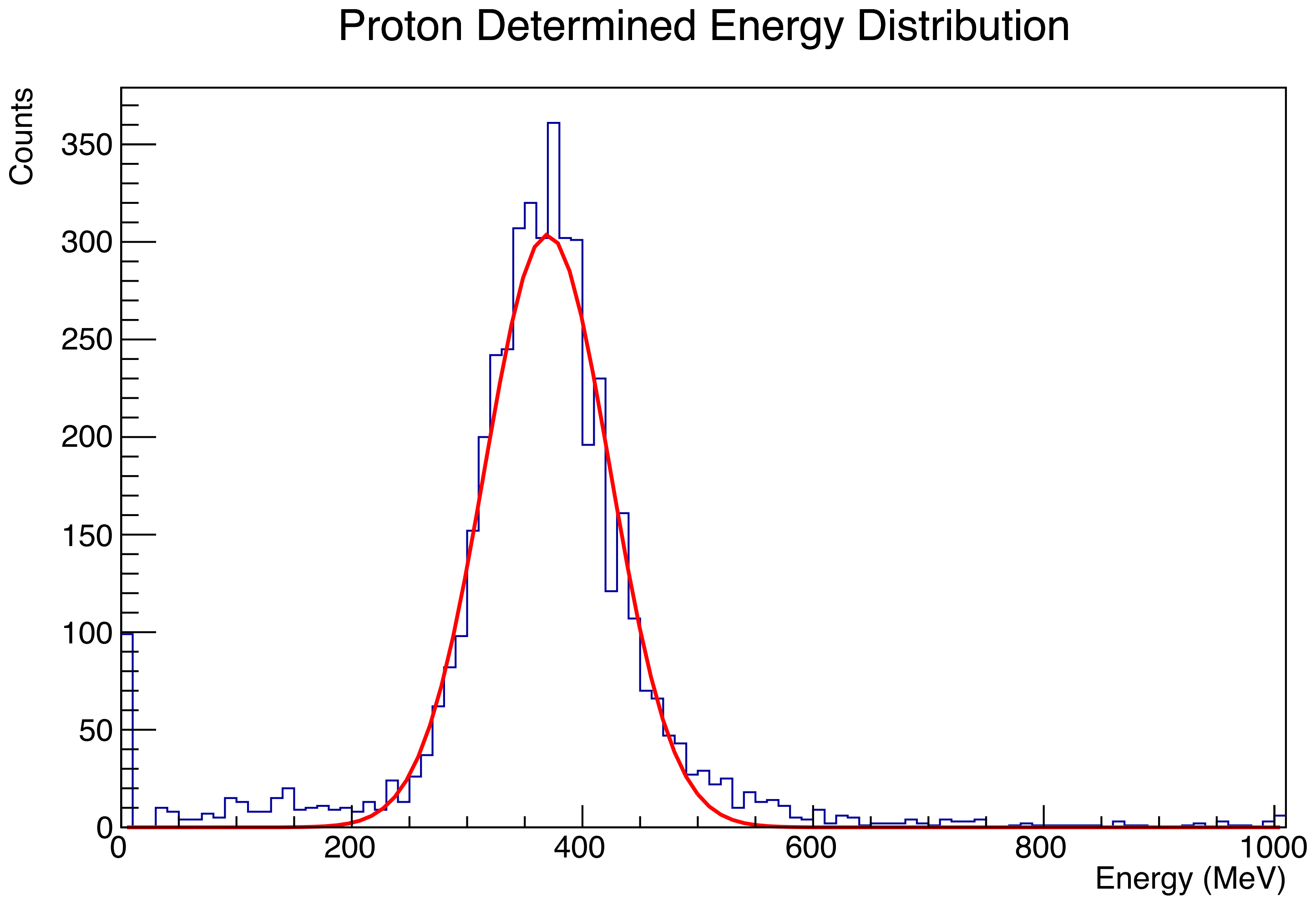
Particle Binning V&V at NSRL



200 MeV Proton @ 60 Degrees



300 MeV Proton @ 70 Degrees



400 MeV Proton @ 70 Degrees