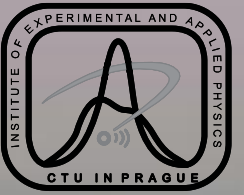


Measurement of the space radiation environment characteristics with Timepix-based detection setups

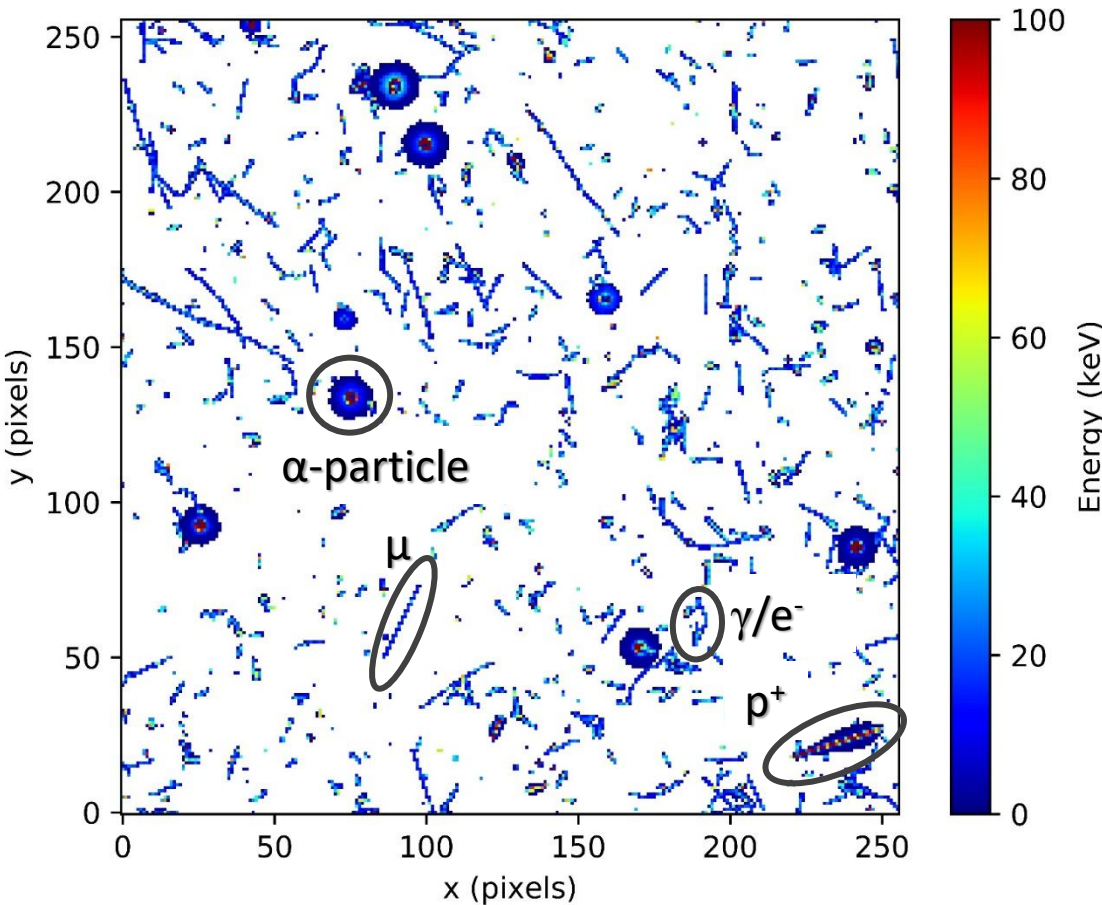


Benedikt Bergmann, Institute of Experimental and Applied Physics, CTU in Prague
Benedikt.Bergmann@cvut.cz







Pattern recognition

Pattern recognition together with dE/dx information allows determination of incident particle type - and energy?

T. Holy, et al. *Pattern recognition of tracks induced by individual quanta of ionizing radiation in Medipix2 silicon detector*, Nucl. Inst. Meth. Phys. Res. A, 591(1):287 – 290, 2008.



60 minutes measurement at an altitude of 2 700 m

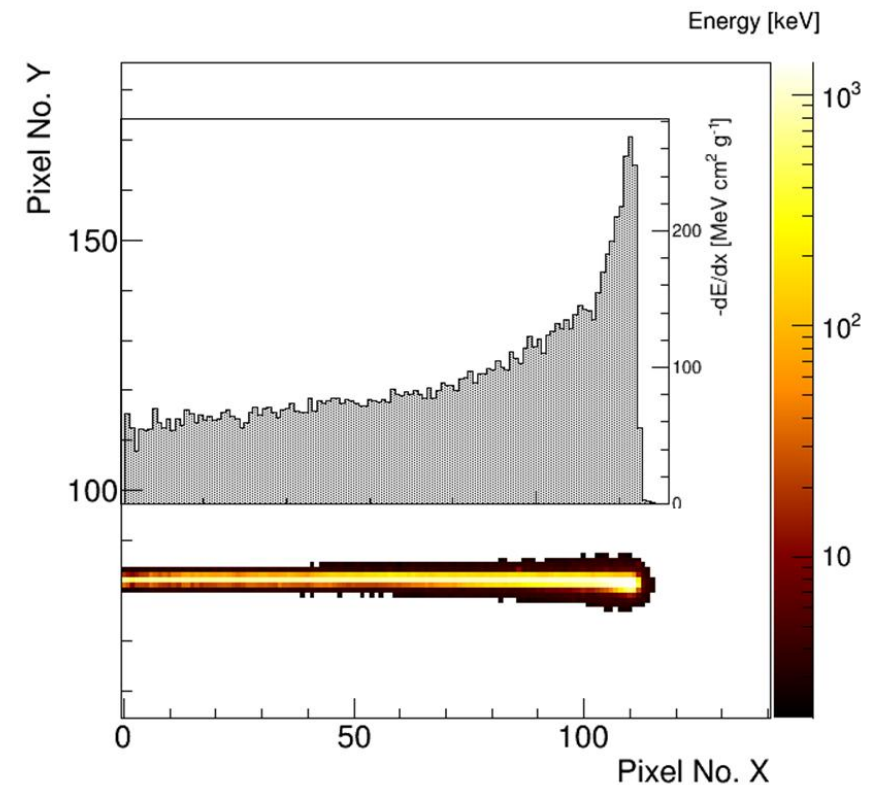
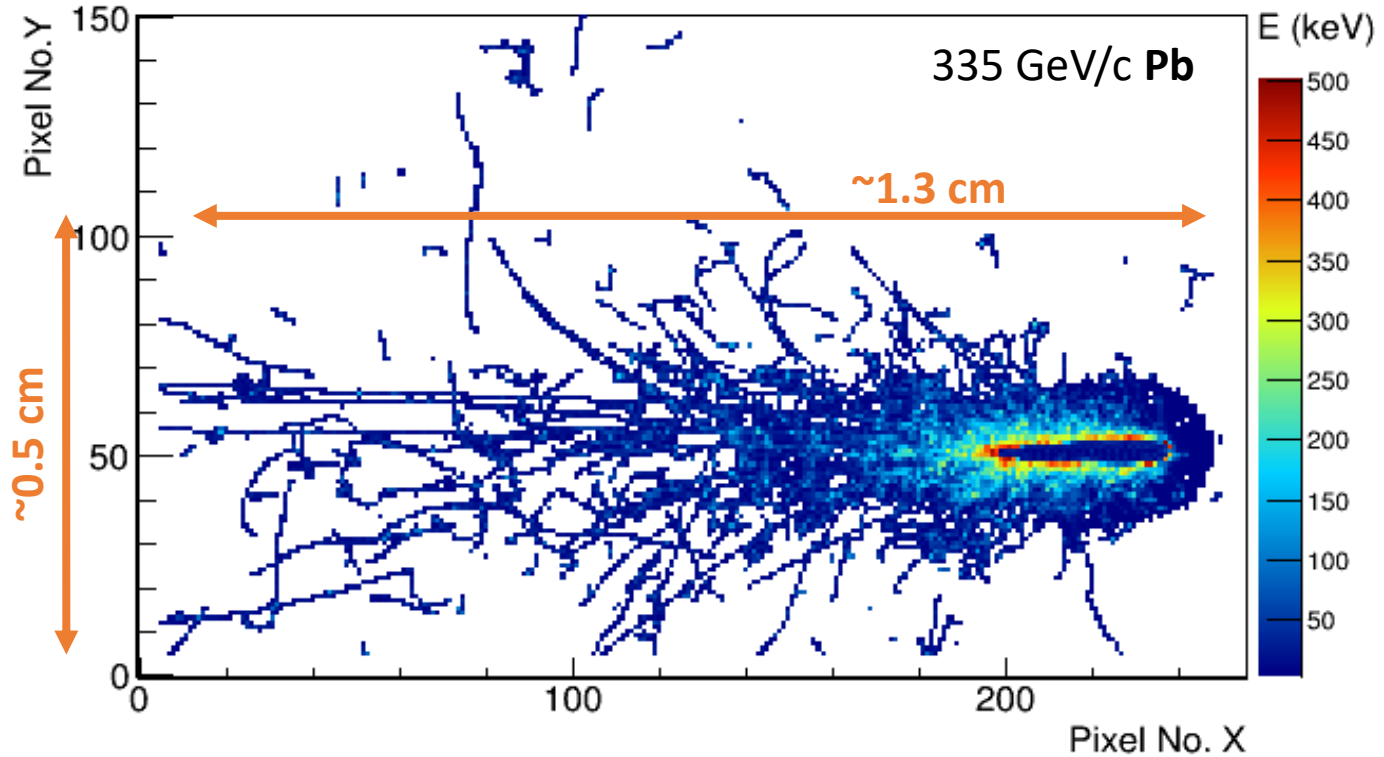
- (1) Dot  Low energy X- and γ -rays, low energy electrons
- (2) Small blob  X- and γ -rays, electrons
- (3) Curly track  γ -rays and electrons (MeV)
- (4) Heavy Blob  Highly ionizing particles with short range (α , protons, ...)
- (5) Heavy track  Highly ionizing particles (protons, ions, ...)
- (6) Straight track  Energetic light charged particles (μ , minimum ionizing light ions, ...)

Working principle

Detector response to ionizing radiation

High energy deposition either for particles with high Z or at low velocity $\beta \ll 1$
 → Use Bragg-behavior or δ -ray appearance for classification

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



Increased energy deposit in the medium at the end of its range (**Bragg-Peak**)
 Example: **350 MeV/A He track.**

The Timepix family

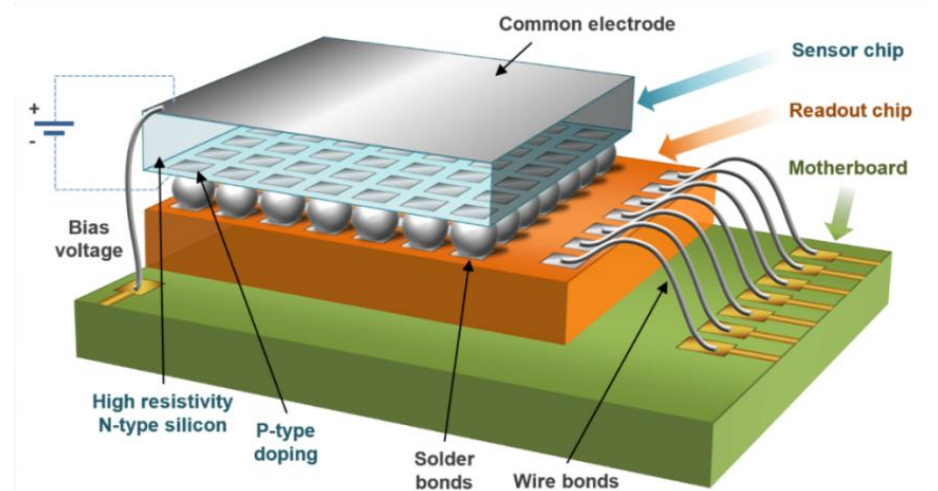
- 256 x 256 pixels with 55 μm pitch (1.98 cm^2)
- Sensor layer (Silicon, GaAs, CdTe, ...) flip-chip bump bonded to the ASIC

Timepix:

- Frame based readout (92 fps) – dead time > 11 ms
- Measurement of **energy or time** (Δt up to 10 ns)
- Minimal detectable energy for noise free measurement 3-5 keV

Timepix3

- Data-driven readout (max. count rate 40 Mhits $\text{cm}^{-2} \text{s}^{-1}$)
- Simult. measurement of **energy and time** ($\Delta t = 1.56$ ns)
- Minimal detectable energy per pixel ~ 3 keV



Timepix3 with chipboard.

Japanese Satellite Hitomi: Lost in Space?

“A scientific tragedy”

Witze, A. Software error doomed Japanese Hitomi spacecraft. *Nature* **533**, 18–19 (2016).
<https://doi.org/10.1038/nature.2016.19835>



16 March 2026

SpaceX – Sailing Close to the Space Weather?

“The 3 February **2022** launch of 49 of SpaceX's Starlink satellites has provided a fascinating example of how even modest space weather can have **significant practical and financial consequences.**”

<https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022SW003074>

Planes grounded after Airbus discovers solar radiation could impact systems

<https://www.bbc.com/news/articles/c8e9d13x2z7o>

Toulouse, France, 28 November 2025 – Analysis of a recent event involving an A320 Family aircraft has revealed that **intense solar radiation may corrupt data critical to the functioning of flight controls.** Airbus has consequently identified a significant number of A320 Family aircraft currently in-service which may be impacted.

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The Space radiation environment

Particles trapped in Van-Allen radiation belts (continuous)

- Electrons up to 7 MeV
- Protons up to 400 MeV

- Spacecraft charging
- TID (permanent device degradation)
- SEE
- Astronaut dose

Solar particle events (transient)

- A few days at a time, a few per year on average but correlated to solar activity
- Particle energy usually < 100 MeV, rare GeV storms

- Potentially dangerous to electronics and humans on space missions

Solar Wind (continuous)

- Plasma released from the sun (eV – few keV)

- Mostly spacecraft charging

Galactic Cosmic Rays (continuous flux)

- 98% Baryonic component: 87% protons, 12% alpha-particles, 1% heavy ions ($Z > 2$)
- 2% Electrons and positrons
- Energies > 0.5 GeV/nucleon (penetrating particles)

- SEE in electronics
- Main driver of the astronaut dose (e.g., 50% astronaut dose on ISS)

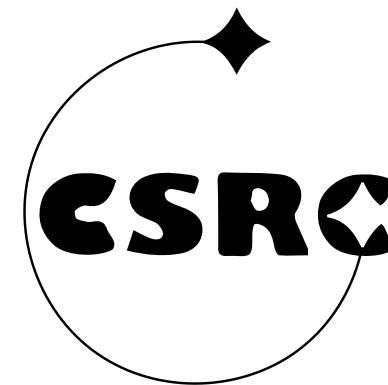
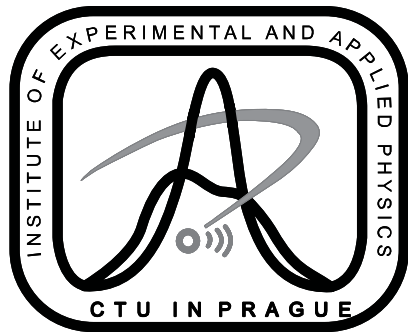
Timepix

- 256 x 256 pixels
- pixel pitch 55 μm
- Energy measurement in each pixel
- Sensor: Si 300 μm

12 years of successful radiation monitoring in LEO

SATRAM

Space Application of Timepix Radiation Monitor



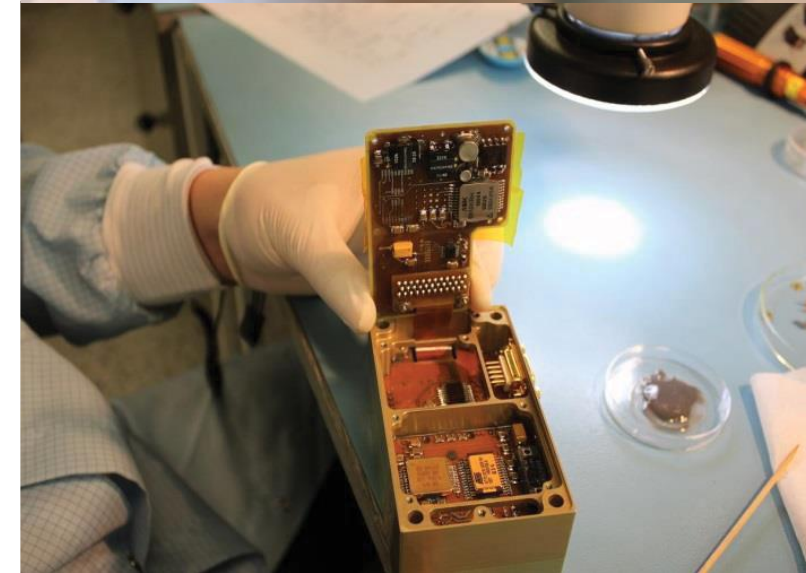
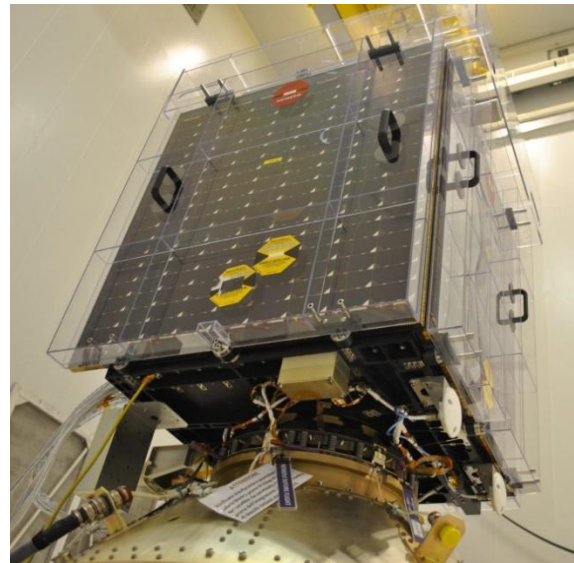
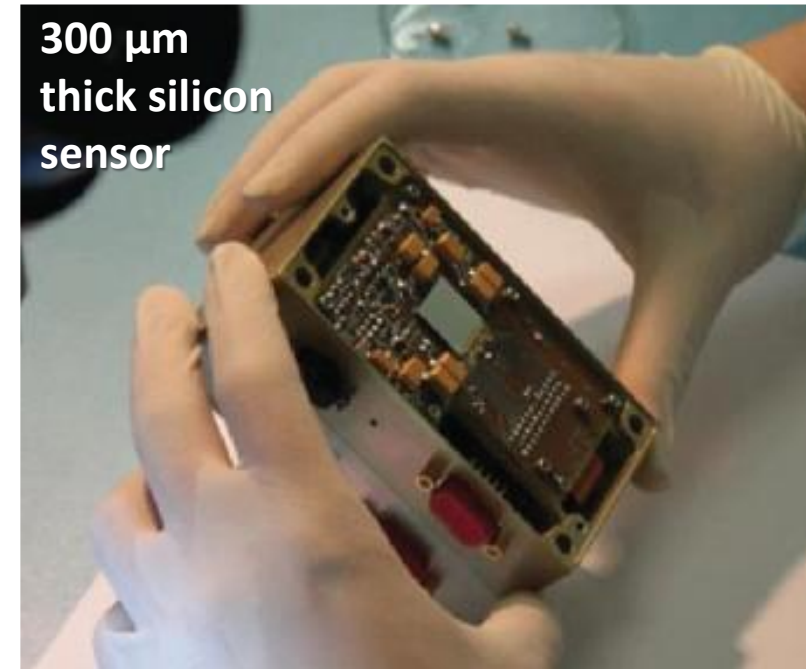
Space Application of Timepix Radiation Monitor (SATRAM)

- **First Timepix in open space**
- Power consumption of **2.5 W**
- Total mass **380 g** (107 x 70 x 55 mm)
- Platform technology demonstrator

Proba-V

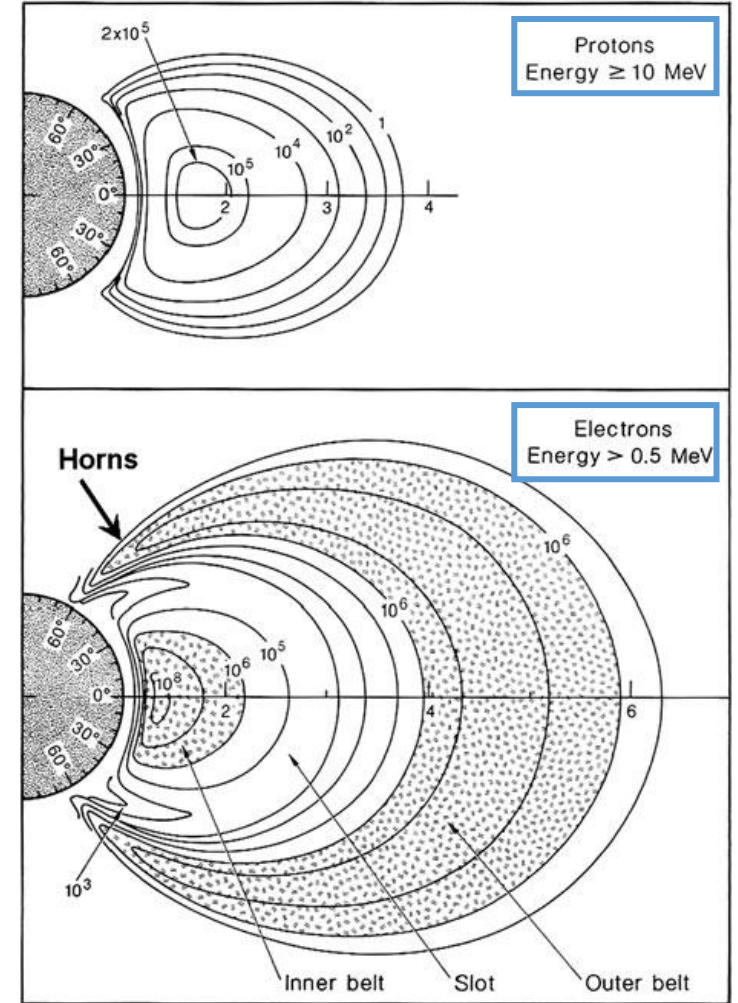
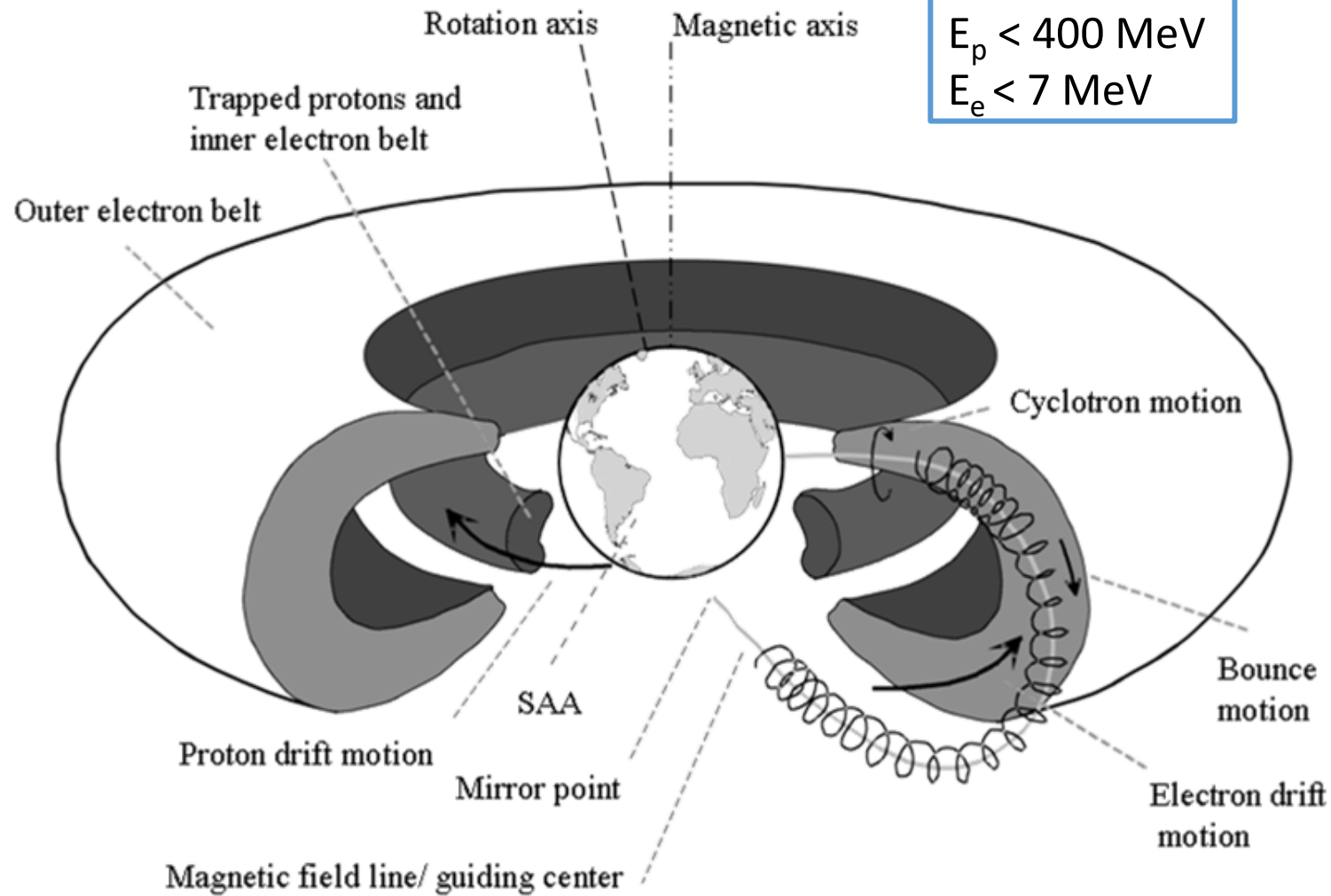
- Minisatellite (158 kg)
- Altitude ~ 820 km (LEO)
- 101.21 minutes orbit duration
- Inclination 98.6°
- Sun-synchronous
- Launched 7th March 2013

10 x times lower mass budget than space environment monitors with similar capabilities



Radiation environment in LEO

Trapped particles



Mauk, B.H., Fox, N.J., Kanekal, S.G. et al. Space Sci Rev (2013) 179: 3.

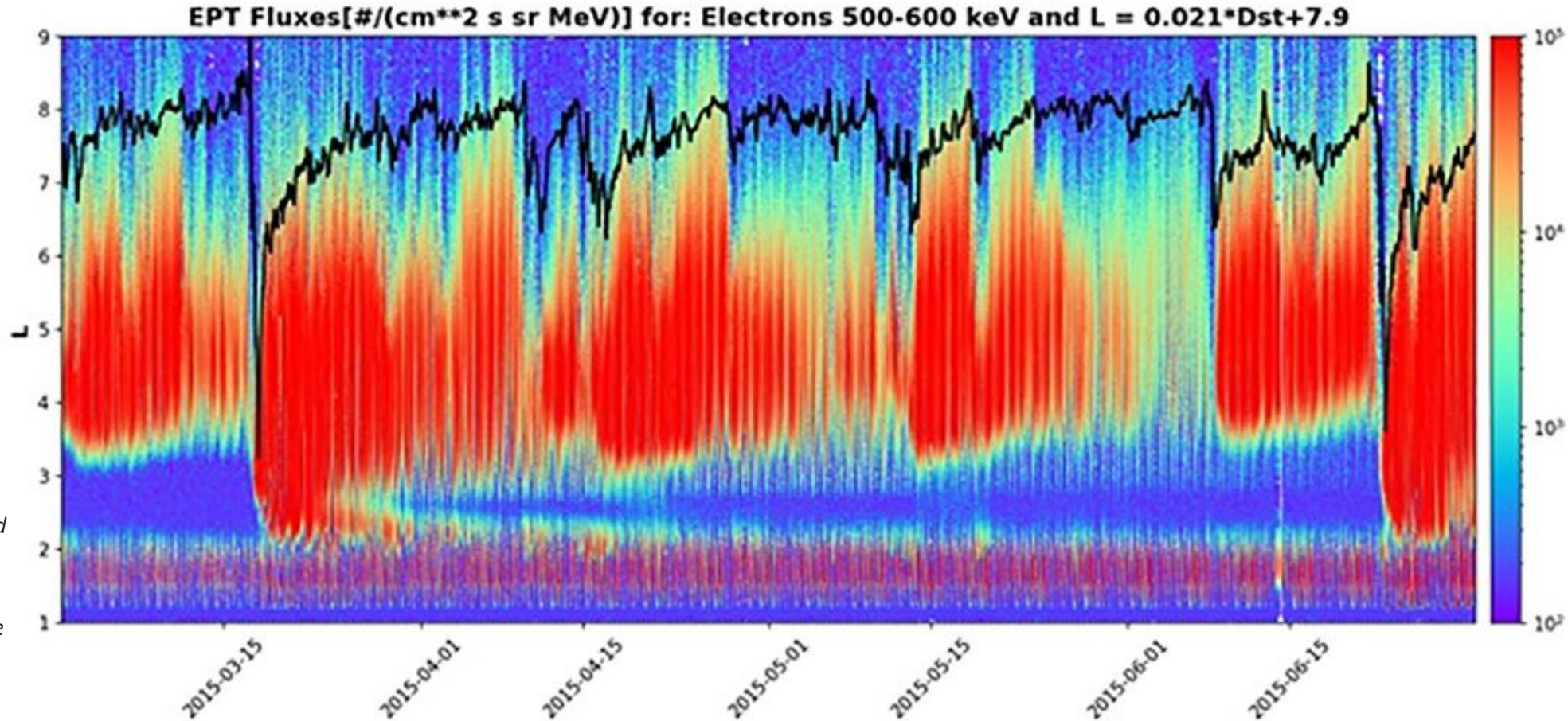
Radiation environment in LEO

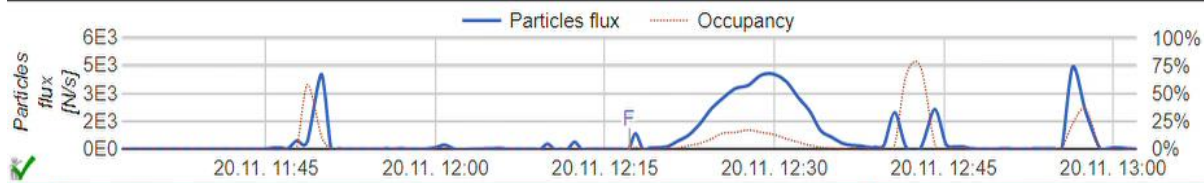
Dynamics of the radiation belt structure

Radiation belts structure highly dynamic.

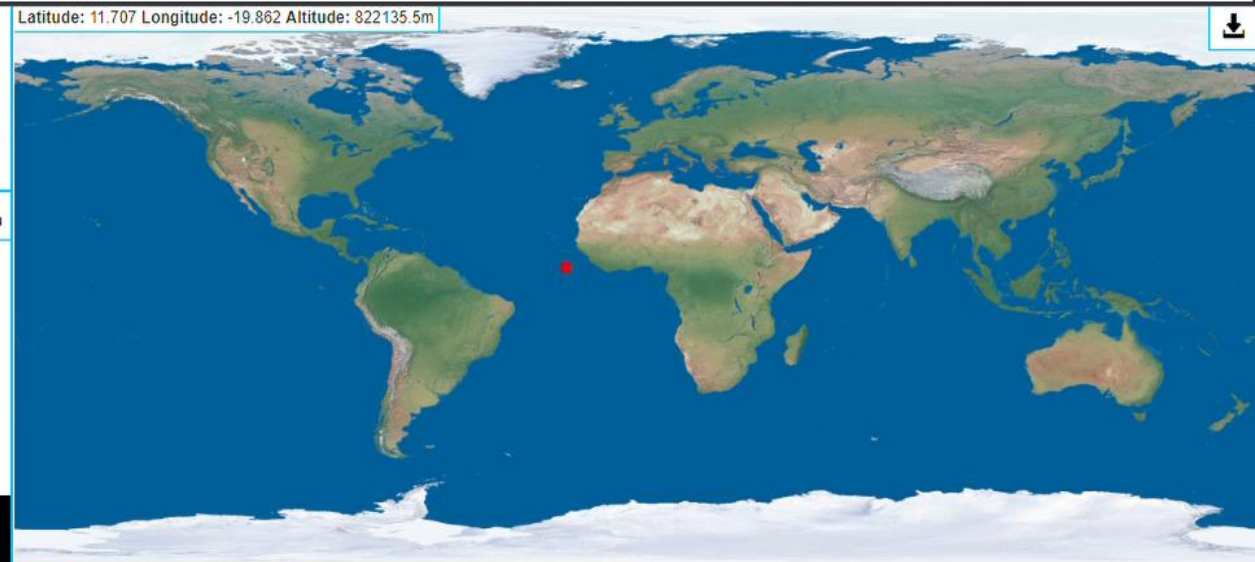
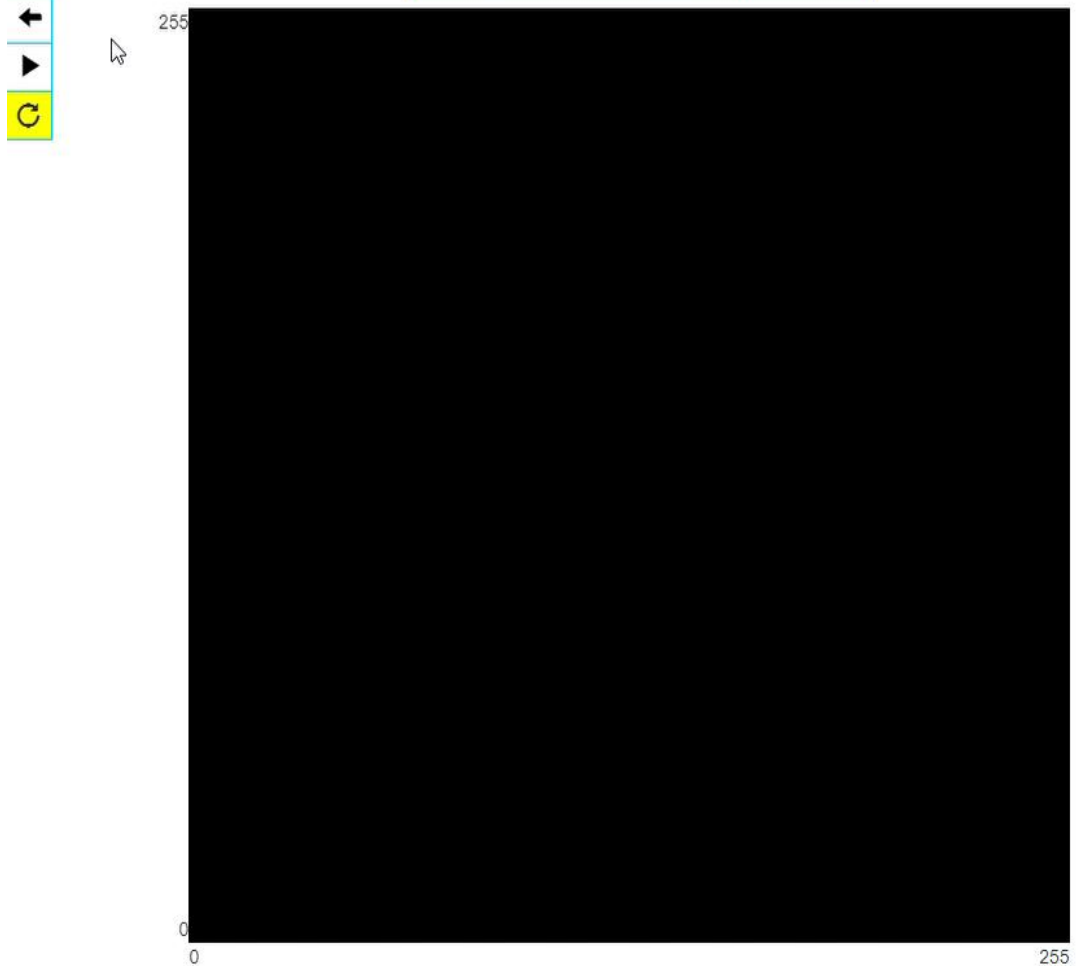
- Solar Flares
- Solar Particle Events
- Interplanetary shock waves
- ...

V. Pierrard et al., "Electron dropout events and flux enhancements associated with geomagnetic storms observed by PROBA-V/Energetic Particle Telescope from 2013 to 2019", *Journal of Geophysical Research: Space Physics* **125**, e2020JA028487 (2020).
<https://doi.org/10.1029/2020JA028487>





© 2014-11-20 12:17:07 UTC Acq. time: 0.2s



Energy [keV]

Cluster type	Sum	Particles flux	Energy flux [MeV]	H
Dot	0	0	0	
Small blob	0	0	0	
Heavy blob	0	0	0	
Heavy track	0	0	0	
Straight track	0	0	0	
Curly track	0	0	0	
Sum:	0	0	0	

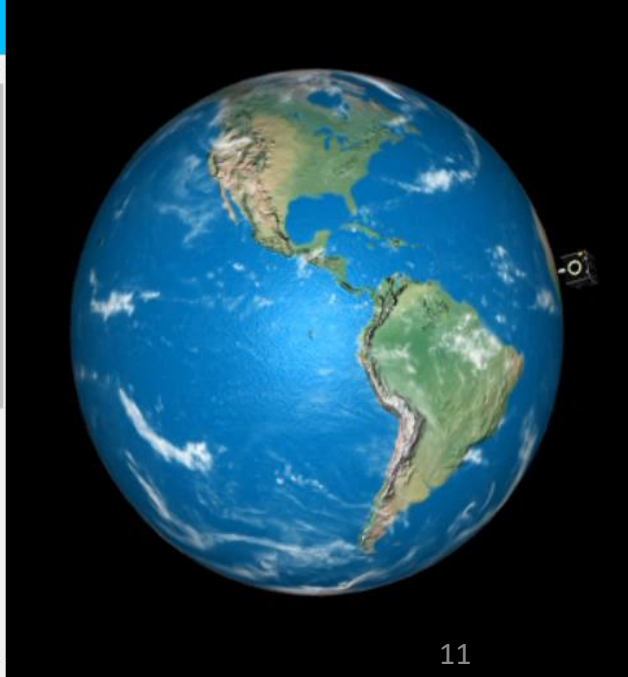
Histograms

Type of histogram: Volume [keV]

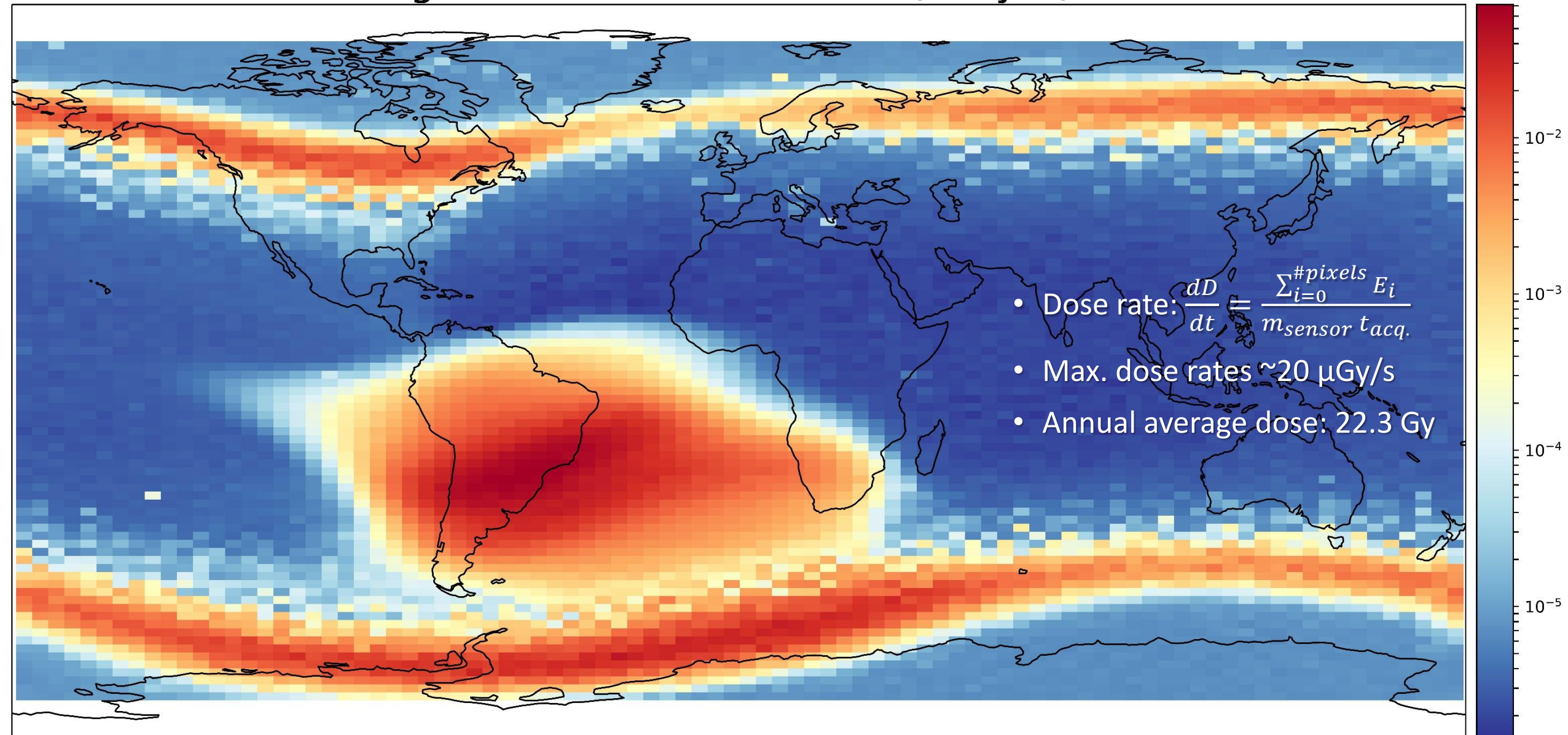
Max number of bins:

Min. value:

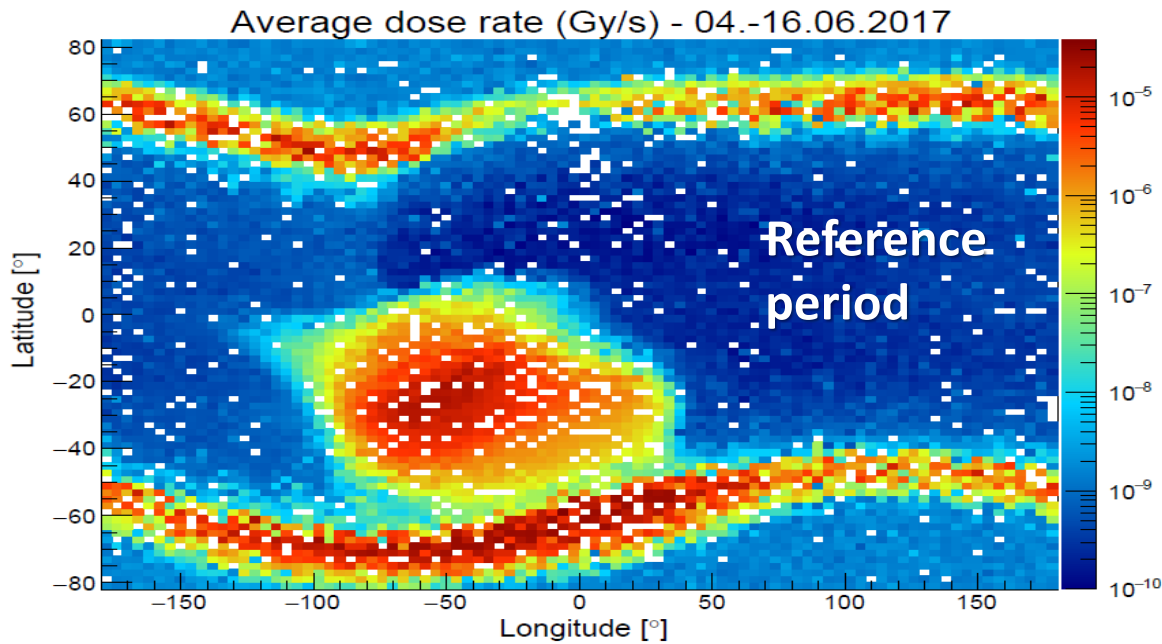
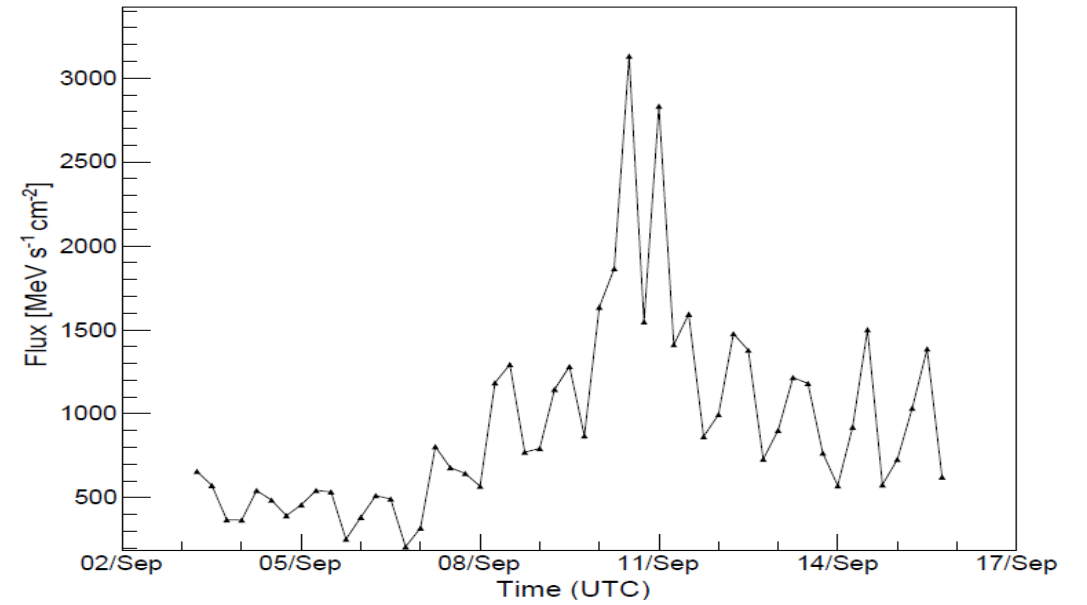
Max. value:



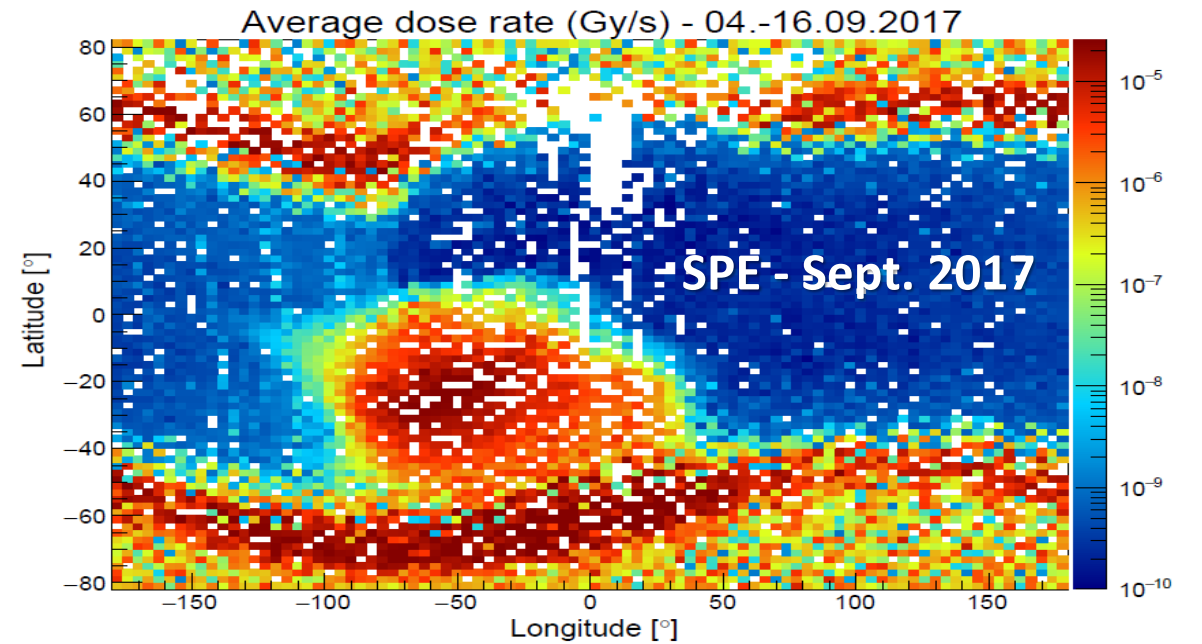
SATRAM - Average dose rate 2015-2018 (mGy/h) - Orbit: 820 km



Transient effect Solar proton event (SPE) on September 10, 2017



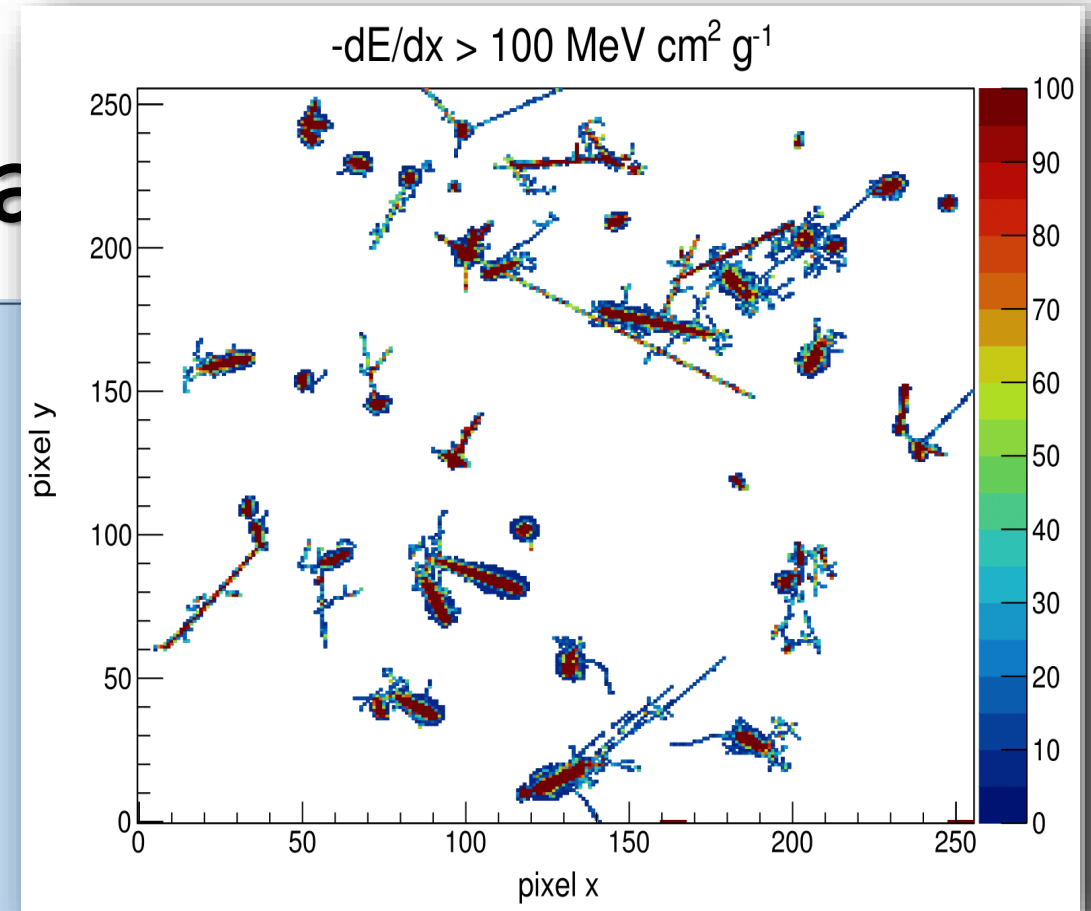
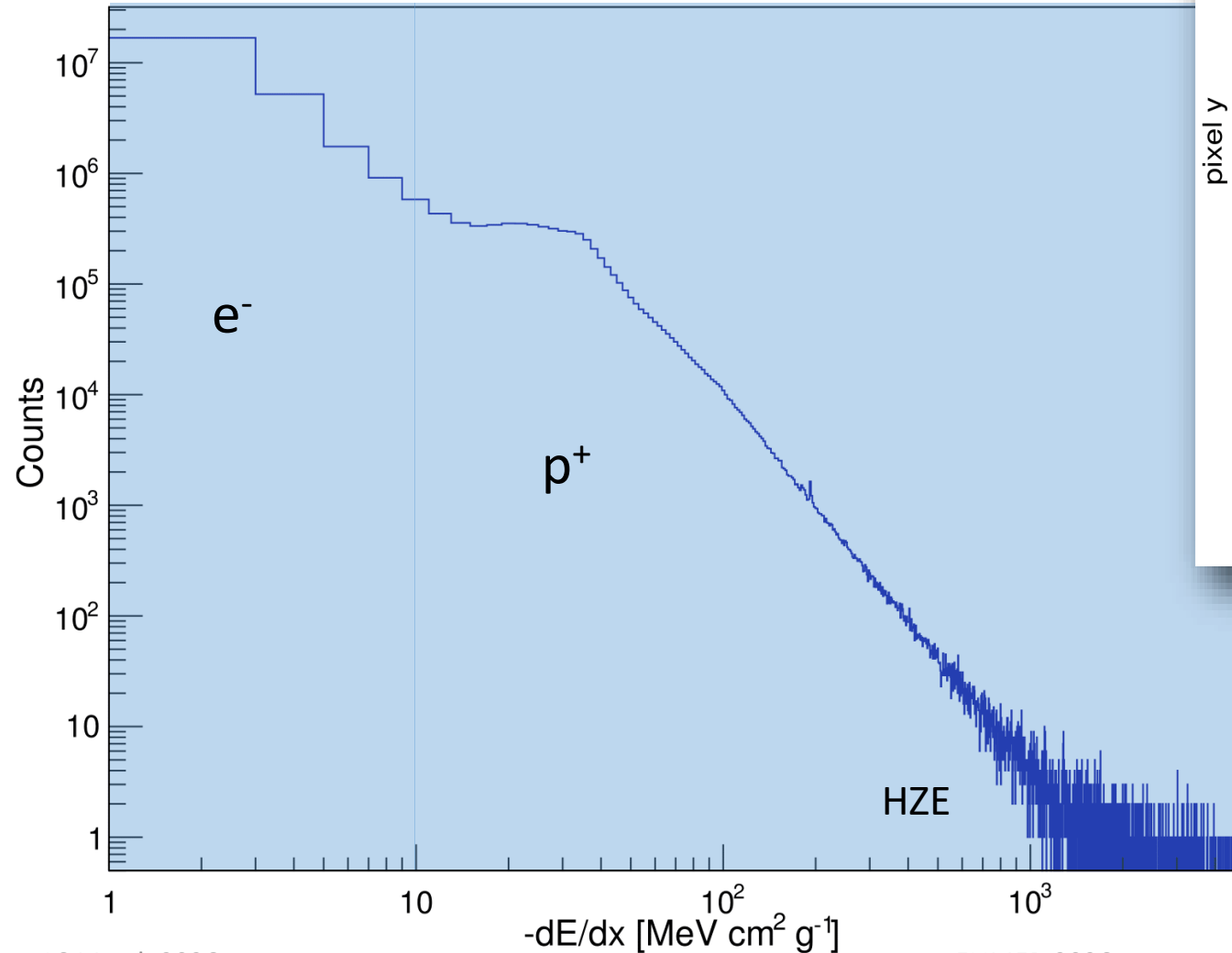
16 March 2026



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dE/dX and particle classification



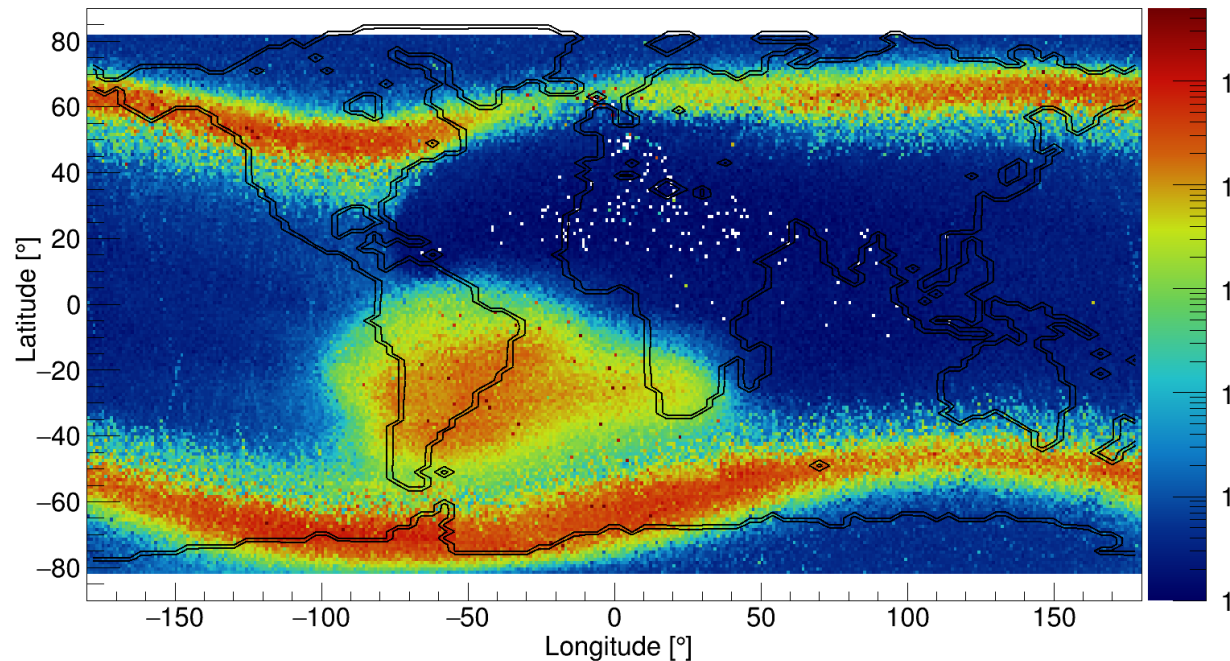
St. Gohl et al., "Study of the radiation fields in LEO with the Space Application of Timepix Radiation Monitor (SATRAM)", Advances in Space Research 63, Issue 5, pp. 1646-1660, (2019).

Electron and proton flux maps

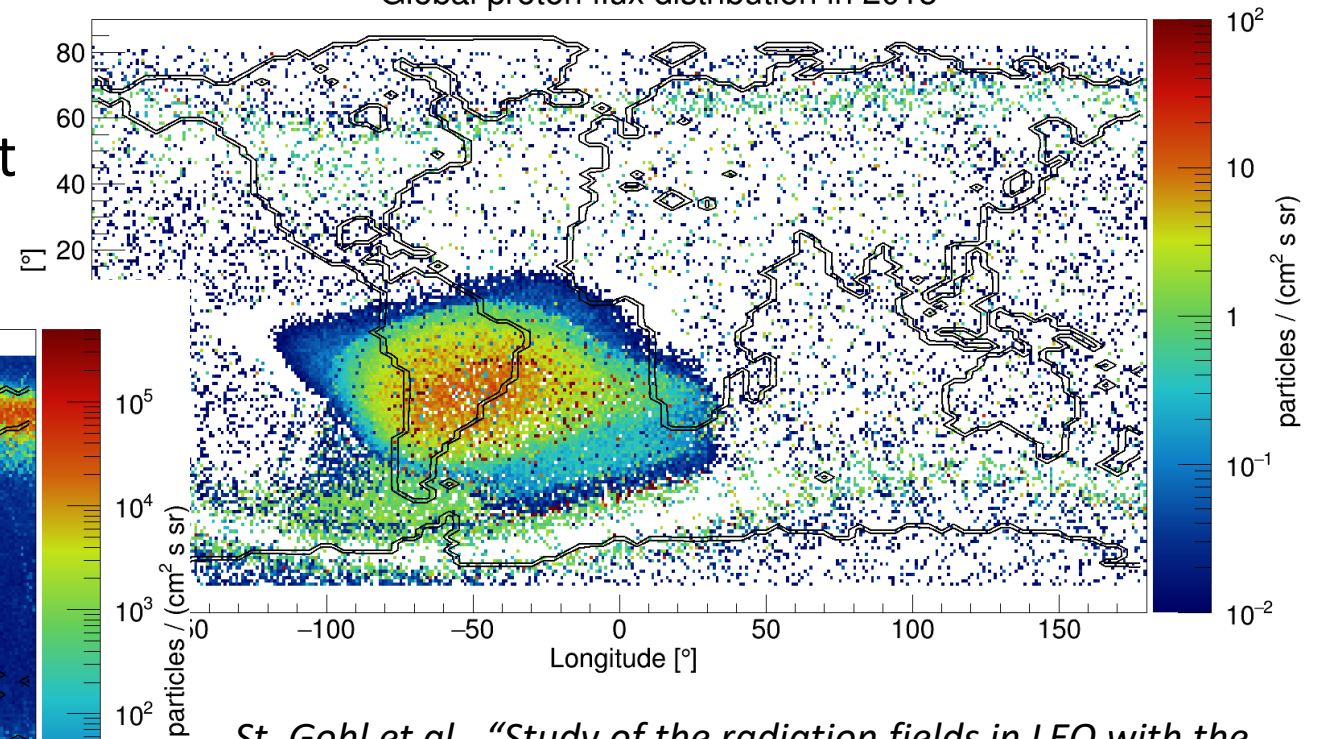
e^- fluxes 3 orders of magnitude larger than p^+ fluxes

→ Even small e^- misclassification distort p^+ flux measurement

Global electron flux distribution in 2015

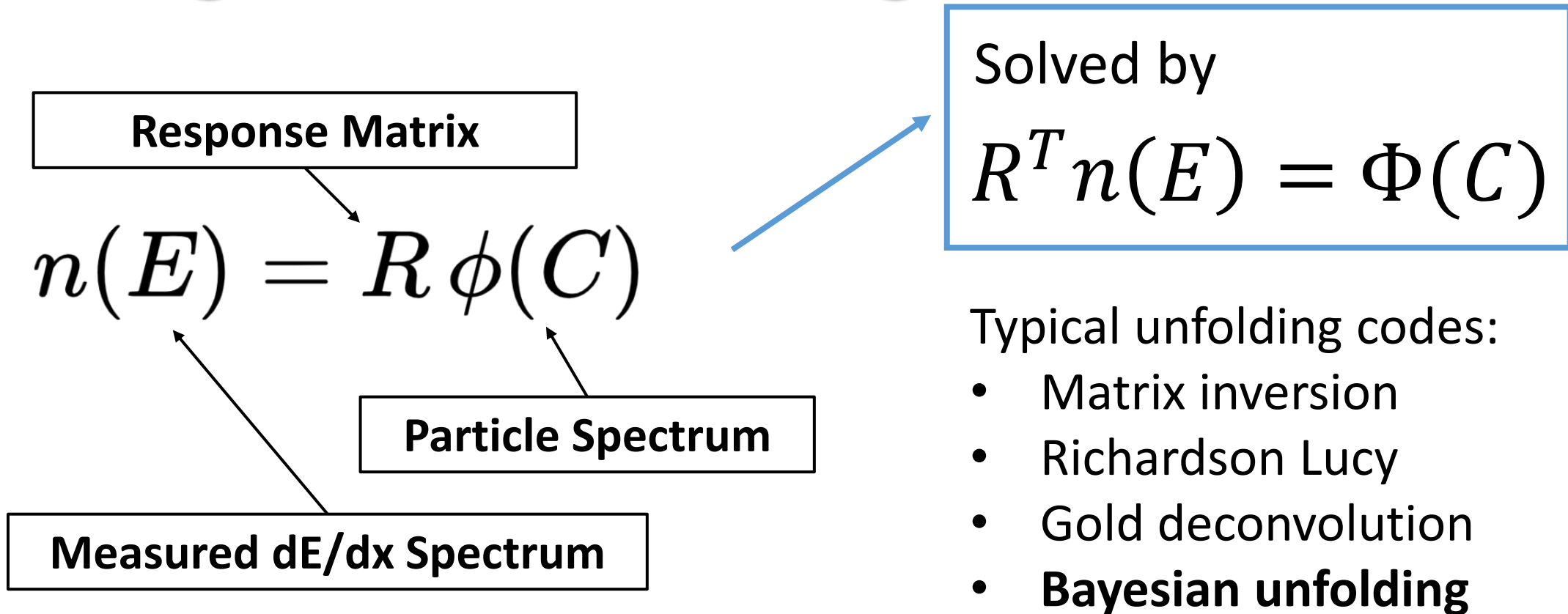


Global proton flux distribution in 2015



St. Gohl et al., "Study of the radiation fields in LEO with the Space Application of Timepix Radiation Monitor (SATRAM)", Advances in Space Research 63, Issue 5, pp. 1646-1660 (2019).

Incident particle energy reconstruction using dE/dX unfolding



dE/dX unfolding:

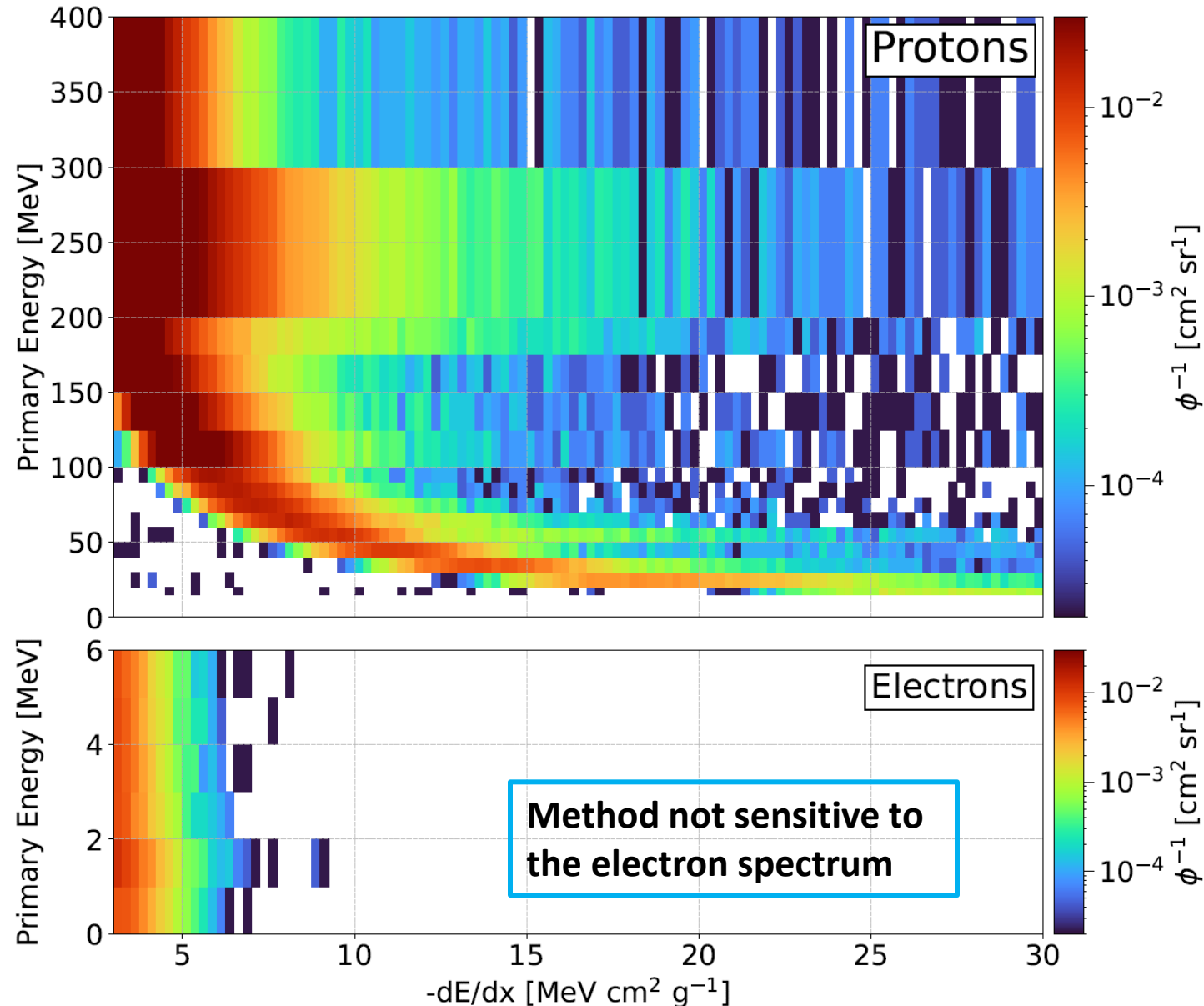
Response matrix

- Simulated in omnidirectional particle field for e^- ($E_e < 6$ MeV) and p^+ ($E_p < 400$ MeV)
- Methodology verification in monoenergetic proton beams

Energy (MeV)	125	175	225
σ (MeV)	17	25	42

Resolution averaged over polar angles of 0, 45, 70 and 85 degrees

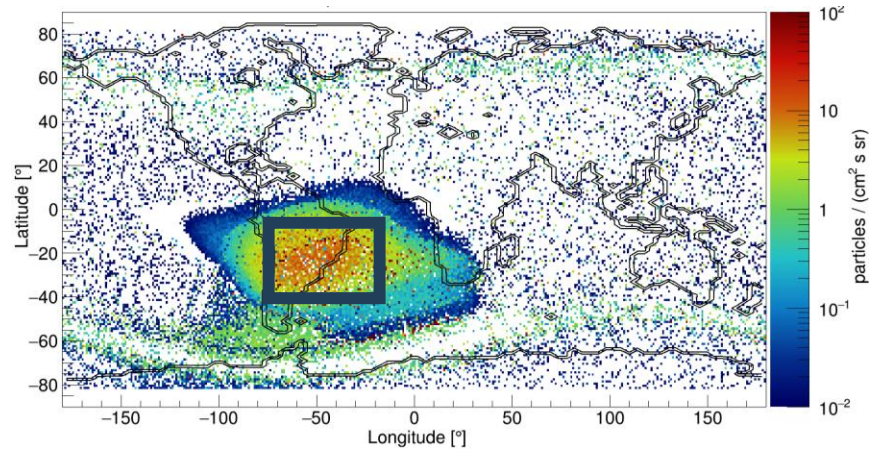
16 March 2026



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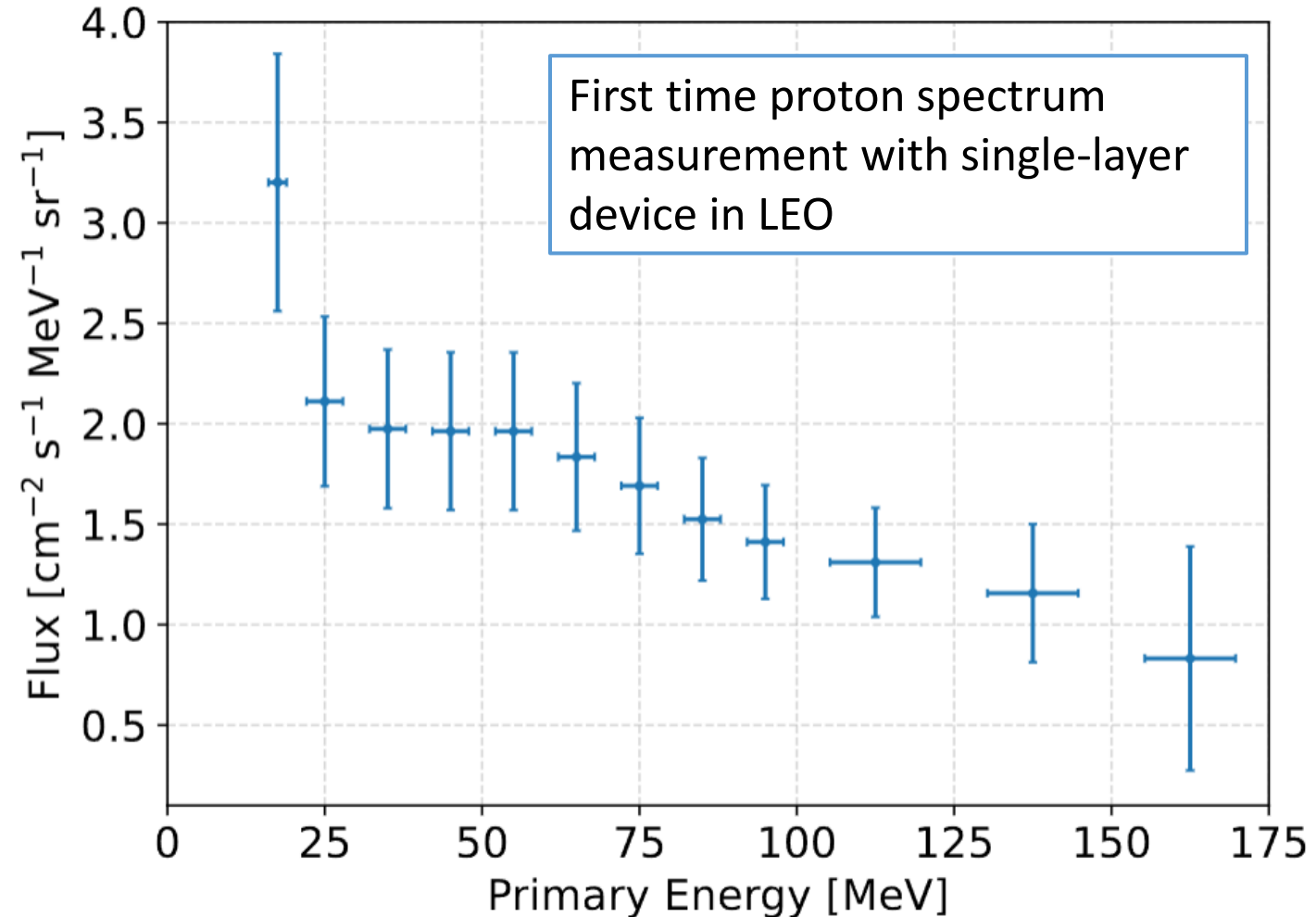
17

Application to measured SATRAM data



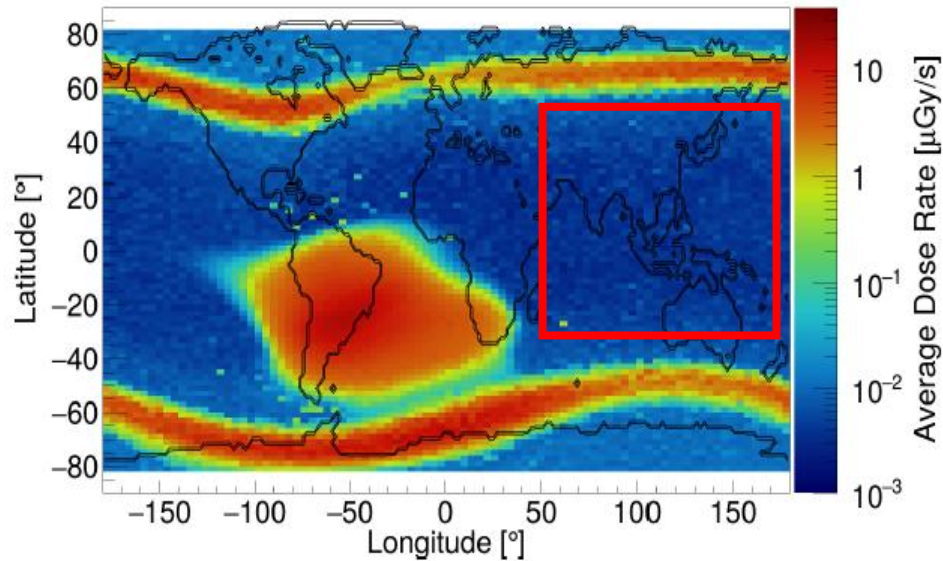
22,784 frames of 2 ms ($t_{\text{meas}} = \sim 46$ s) were found in the selected geographic region in the years 2014-2018.

Single-layer electron spectrum reconstruction remains a key challenge for future development



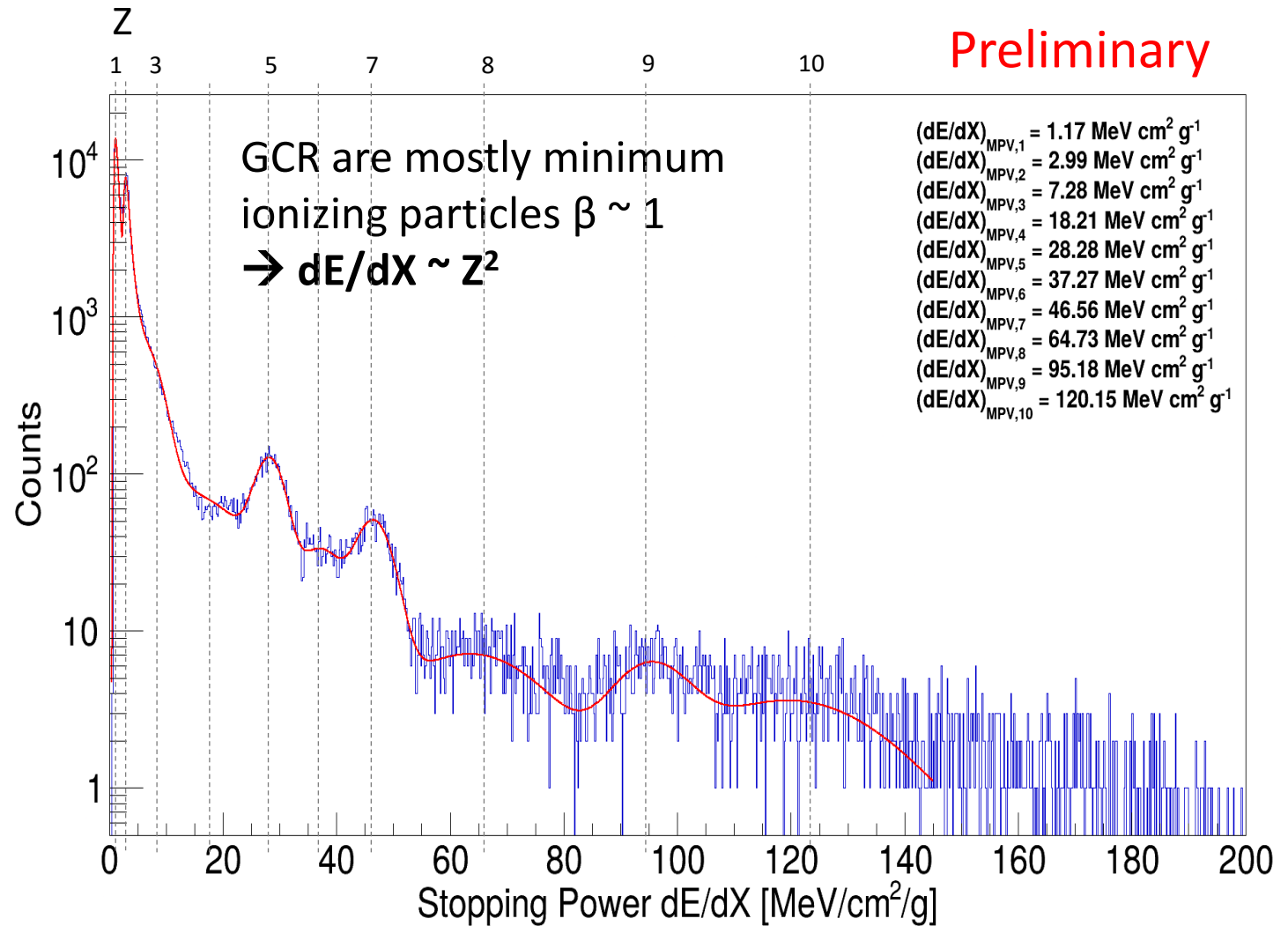
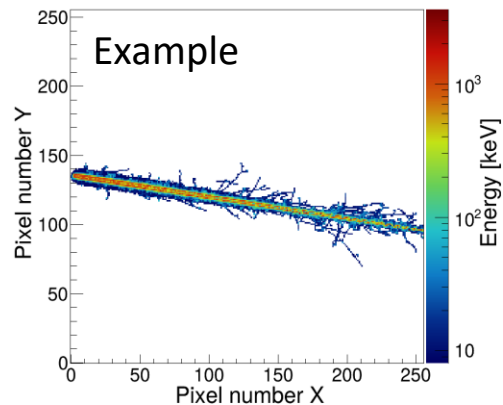
Bergmann et al. *Instruments* 2024, **8**(1), 17; <https://www.mdpi.com/2410-390X/8/1/17>

GCR Measurement with SATRAM



Tracks at grazing angles in the region shielded by Earth Magnetic field

Analysis is ongoing





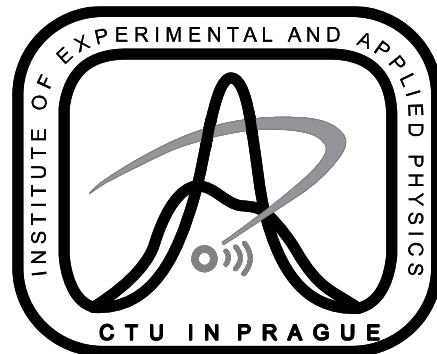
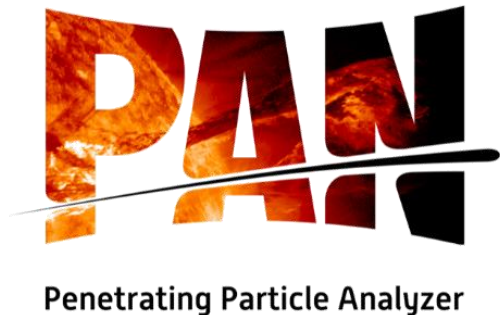
Horizon 2020
European Union Funding
for Research & Innovation

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 862044.

X.Wu et al., Penetrating Particle ANalyzer (PAN), *Adv. Space Res.* 63, 8, 2672-2682 (2019) <https://doi.org/10.1016/j.asr.2019.01.012>

<http://www.pan-space.eu/>

Development of a demonstrator penetrating particle analyzer (mini.PAN) for deep space missions

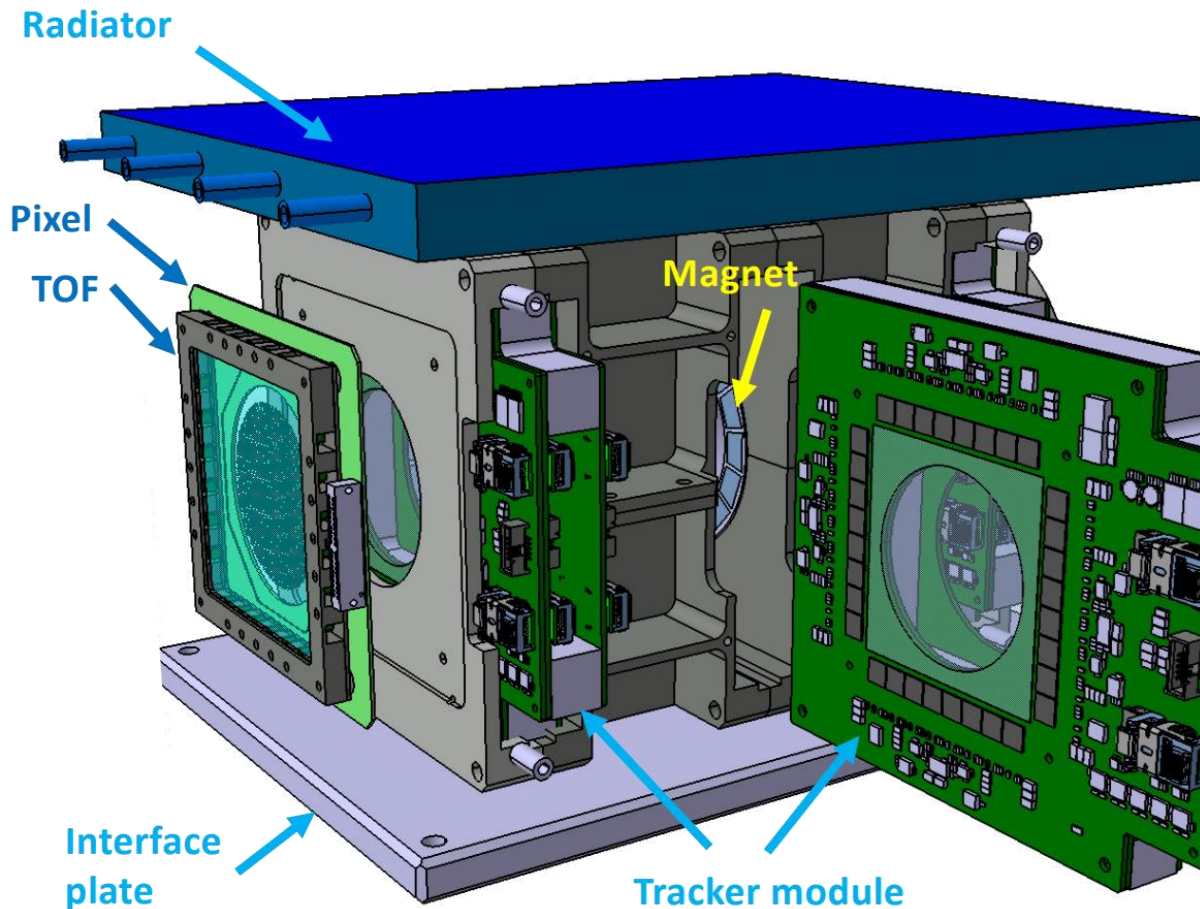


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DE GENÈVE

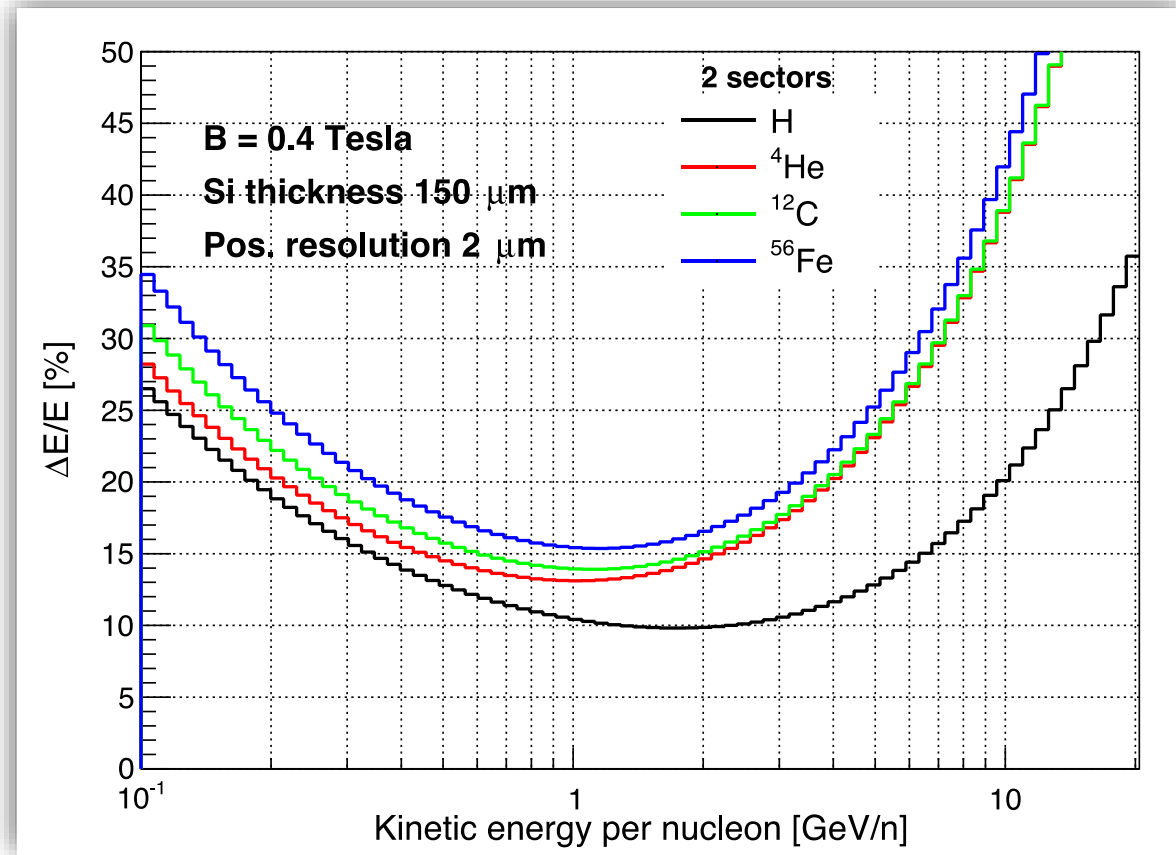


Mini.PAN:

Conceptual design



Expected performance:



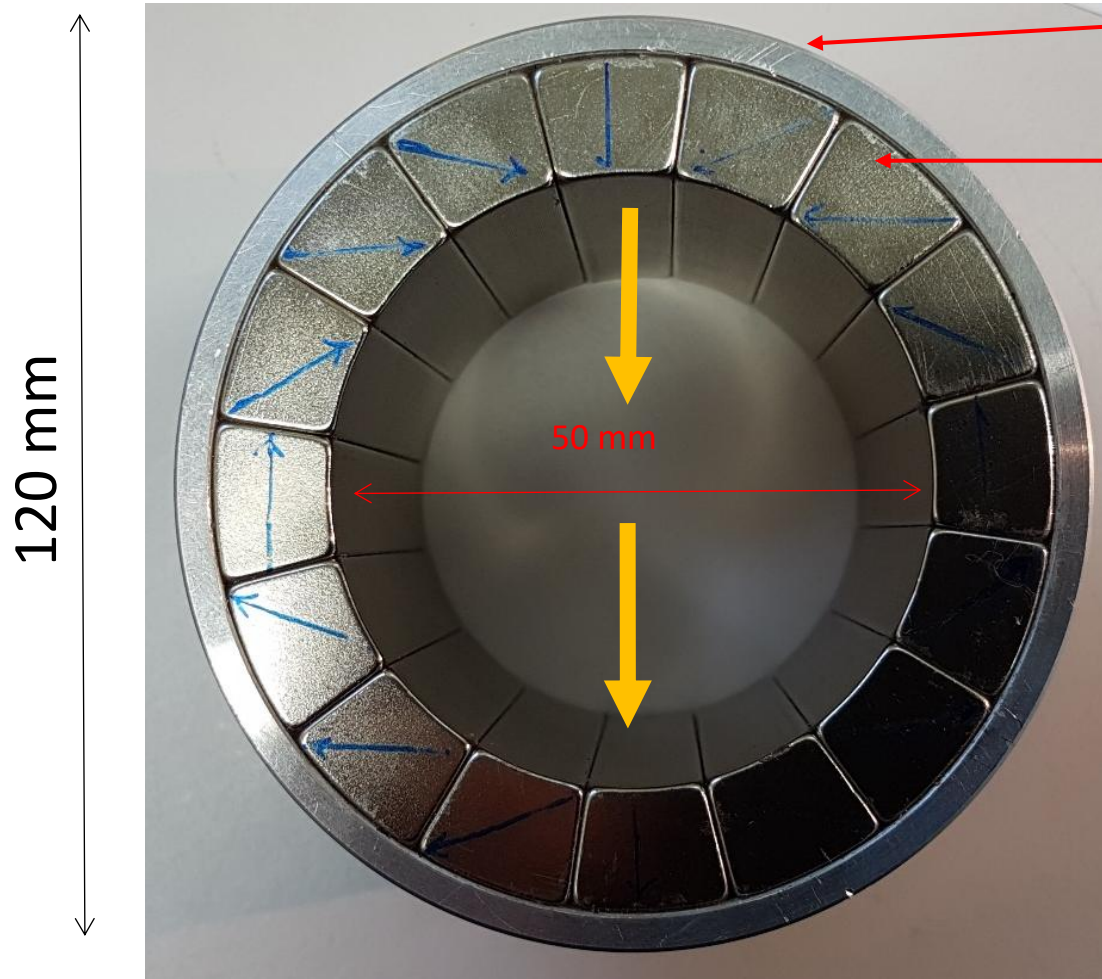
2 ToF modules (time resolution < 100 ps):

- Scintillators (EJ230) coupled with SiPMs

Mini.PAN ~10 kg, ~20-30 W

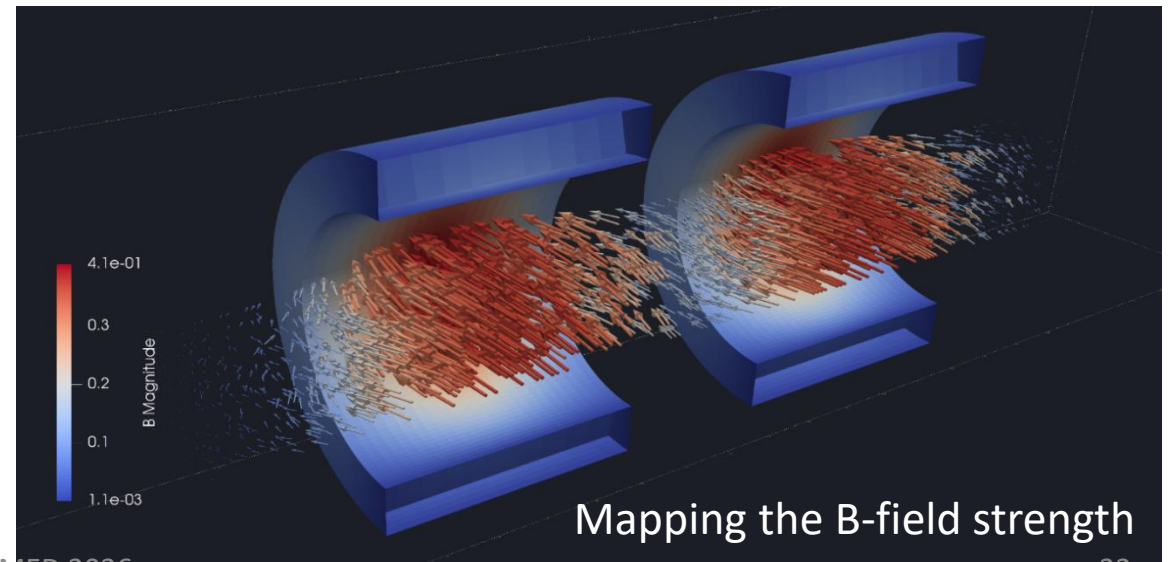
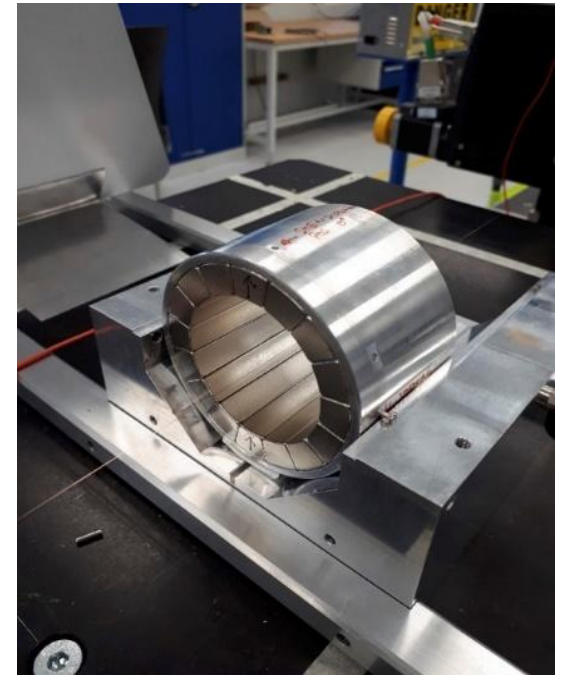
Mini.PAN:

Magnet sectors



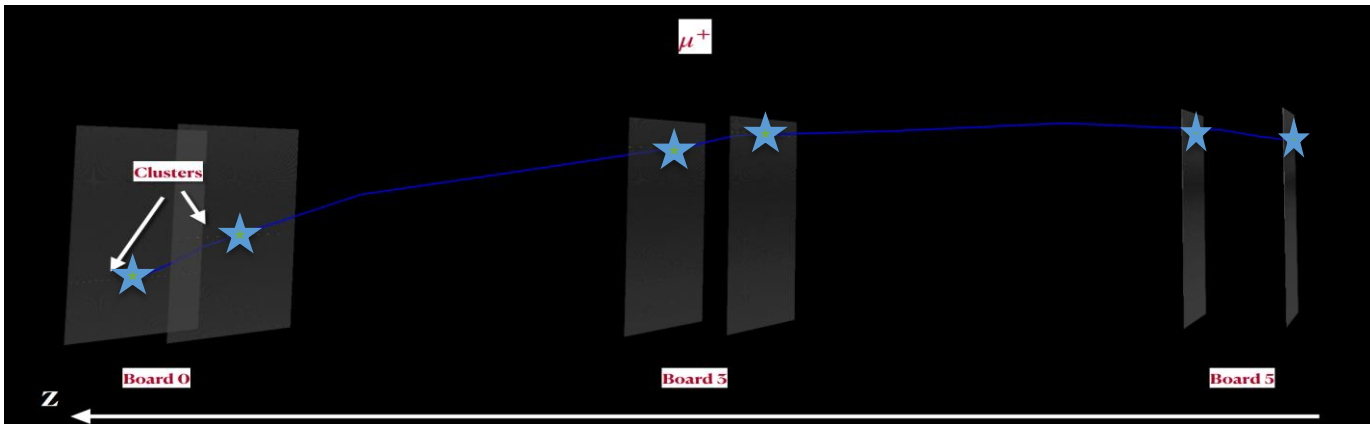
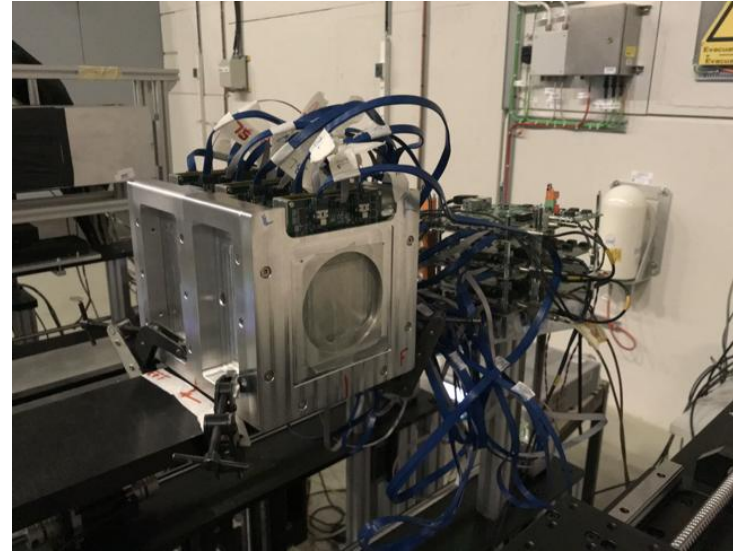
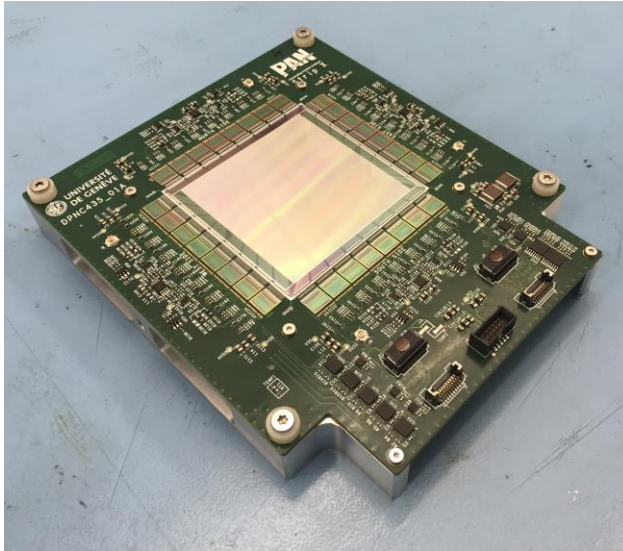
Ring, aluminium

Permanent magnet block, NdFeB



Mini.PAN:

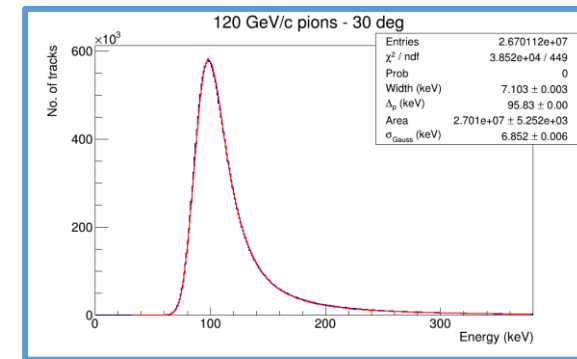
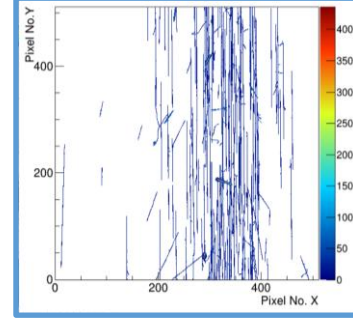
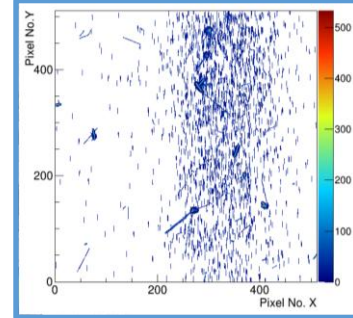
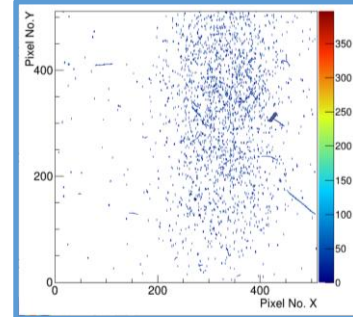
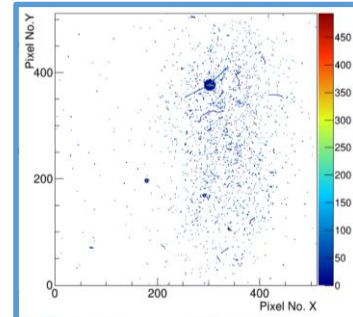
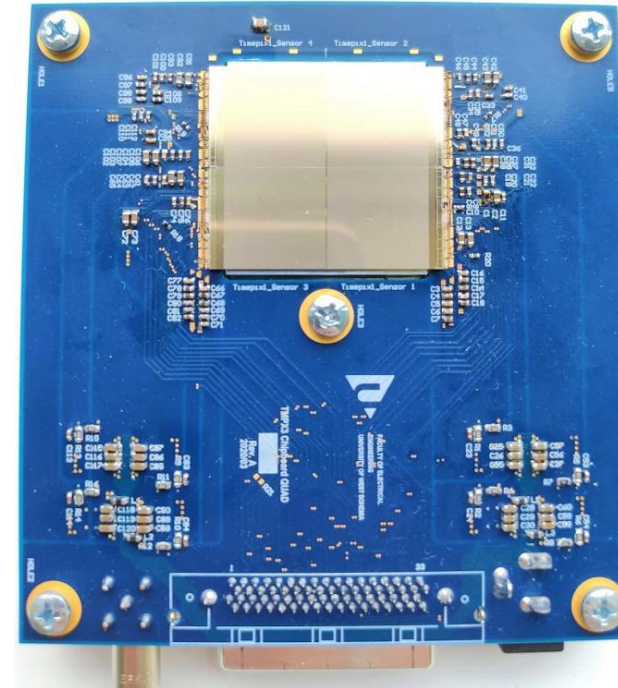
Tracking modules



16 March 2026

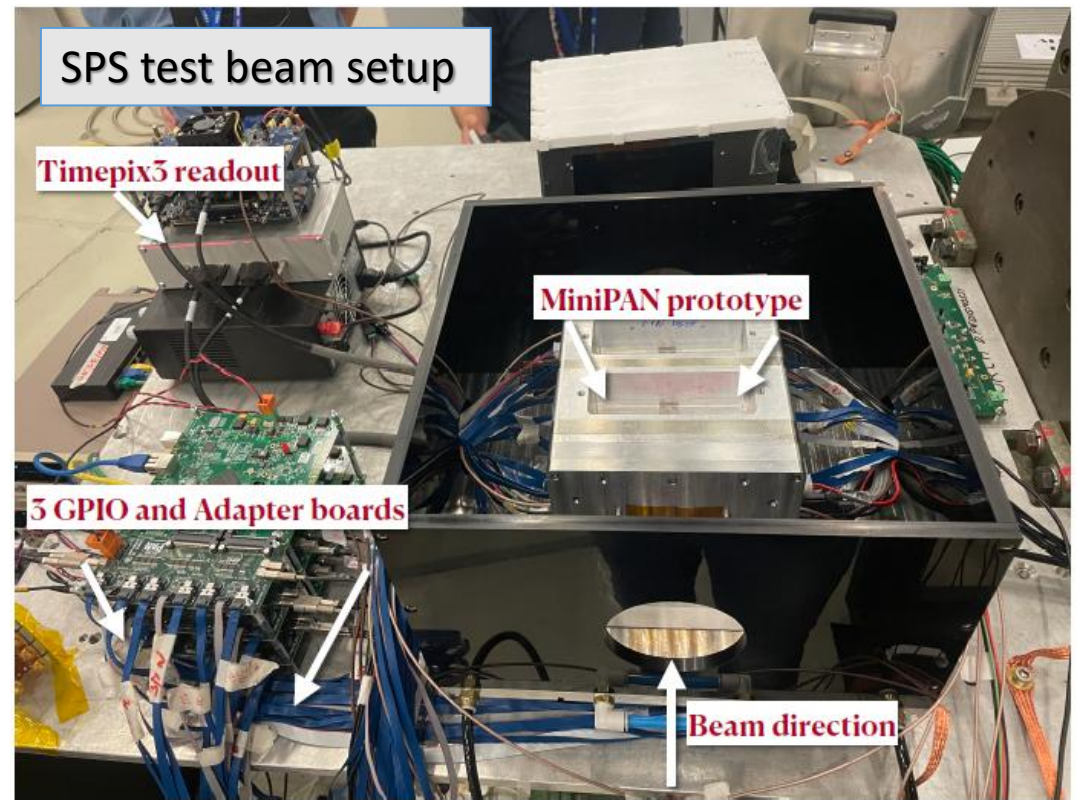
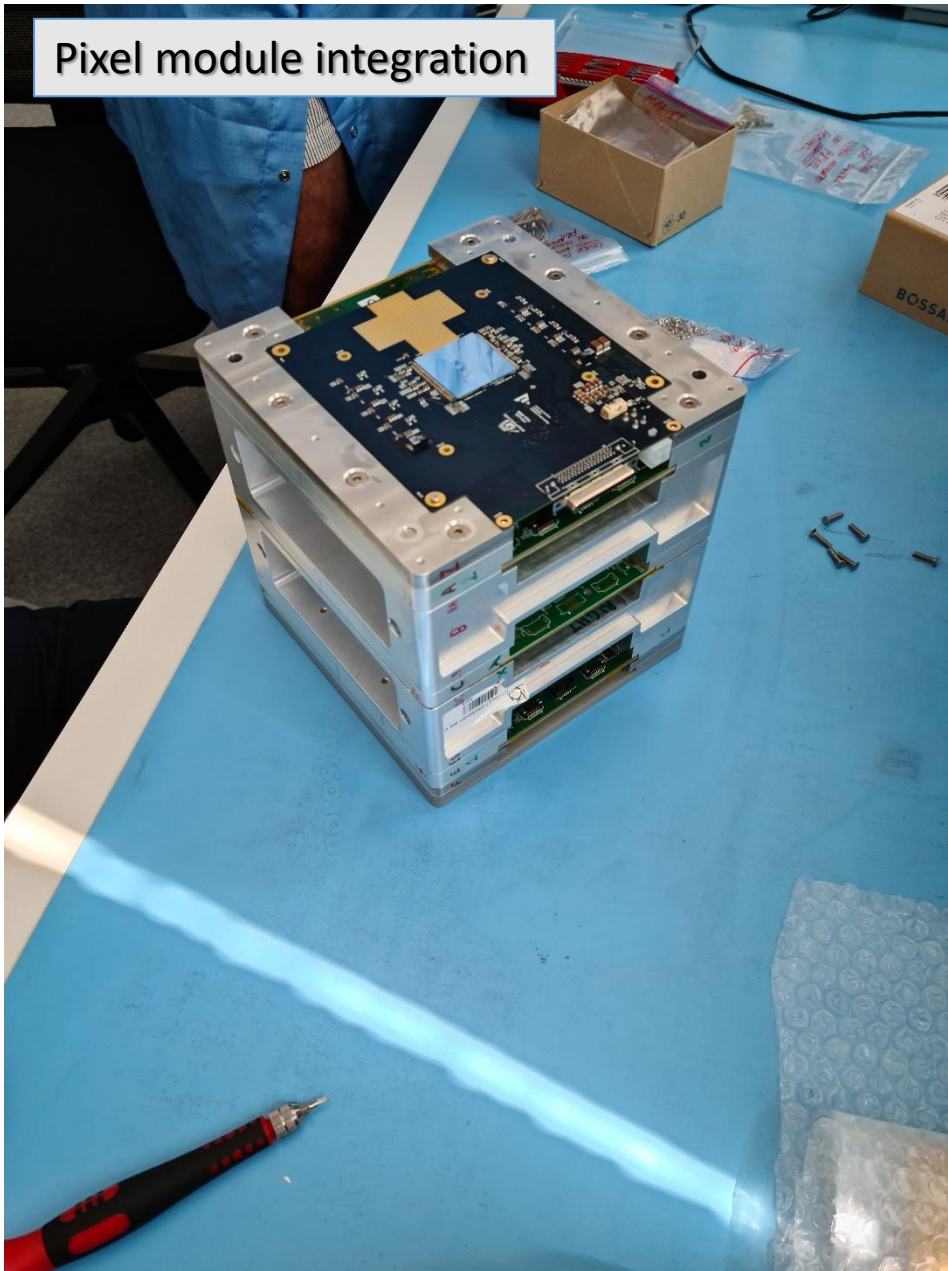
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Pixel detector prototype
for functional testing



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Mechanics integration and functional testing



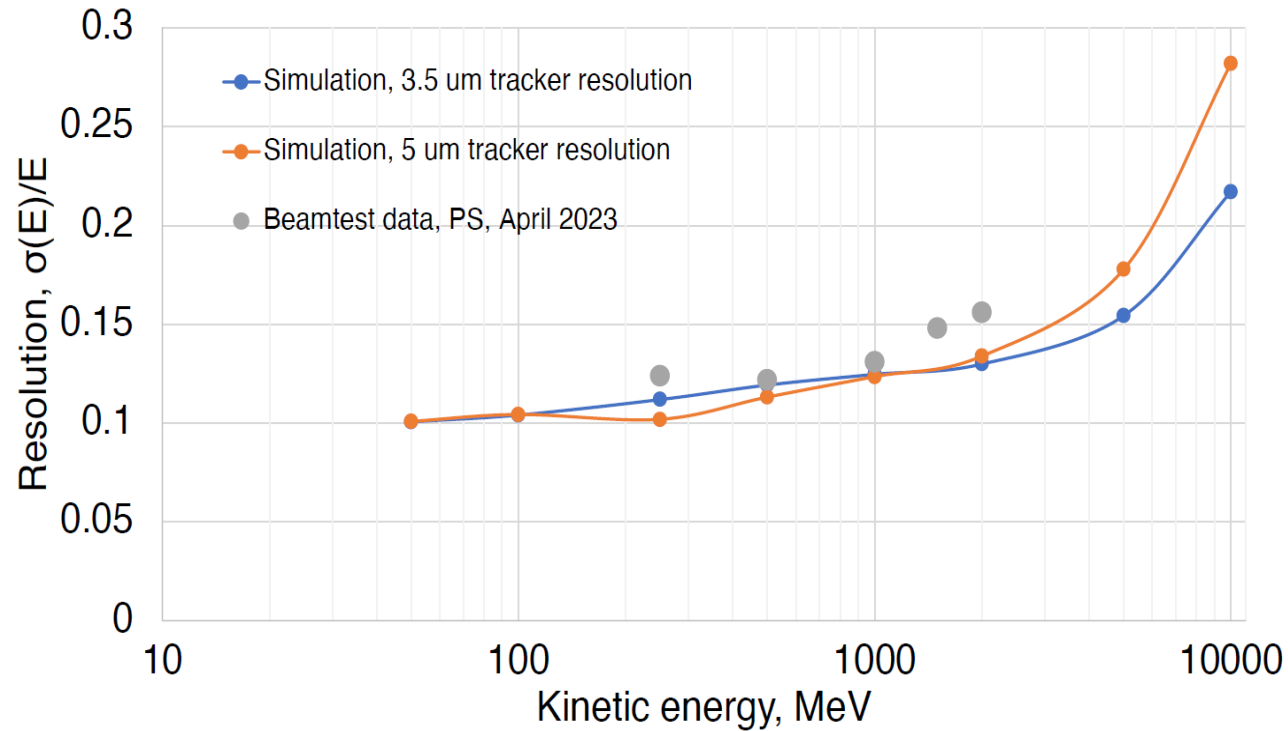
Particle beams:

- μ^- (160 GeV/c) – CERN SPS
- p^+ (60 MeV – 10 GeV/c) – CNAO, CERN PS
- e^+/e^- (0.25 – 2 GeV/c) – CERN PS
- Carbon (100 – 400 MeV/n) - CNAO
- Fragmented ion beam with $A/Z = 2.2$ – CERN SPS

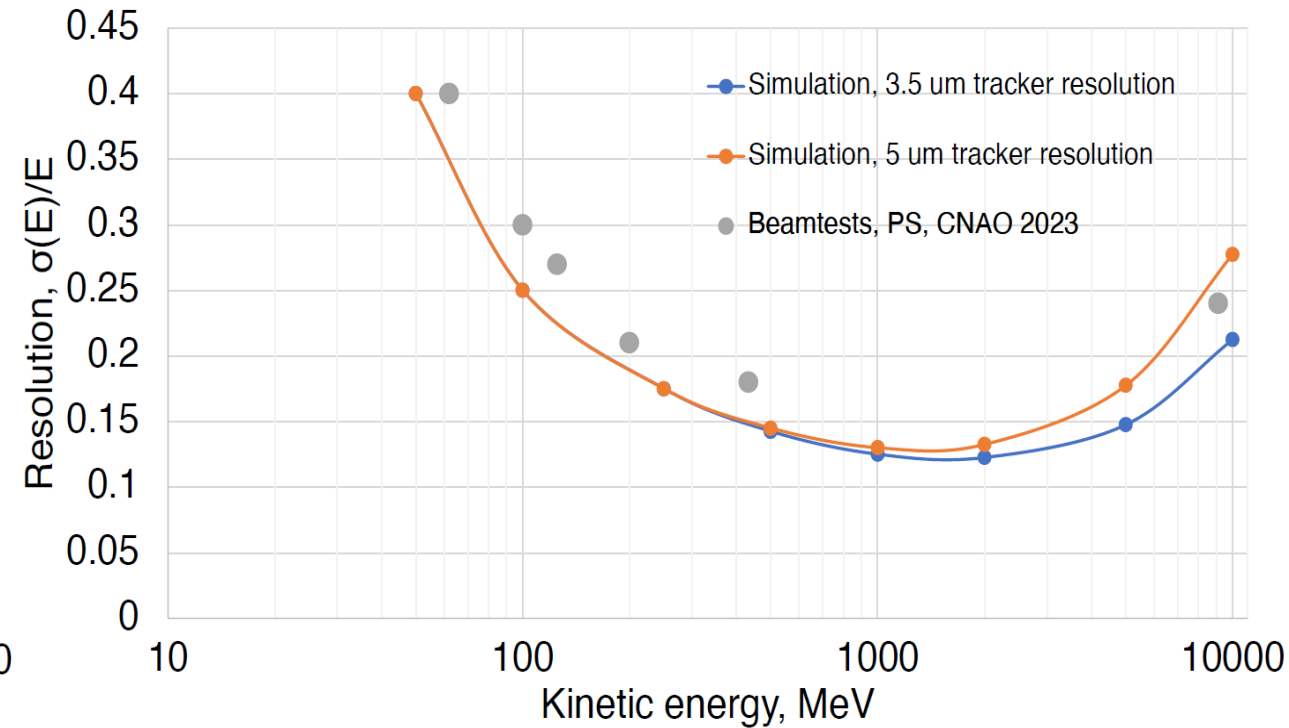
Mini.Pan prototype – functional testing:

Kinetic energy reconstruction - resolution

Electrons, MiniPAN, 150 μm thickness, realistic magnetic field map



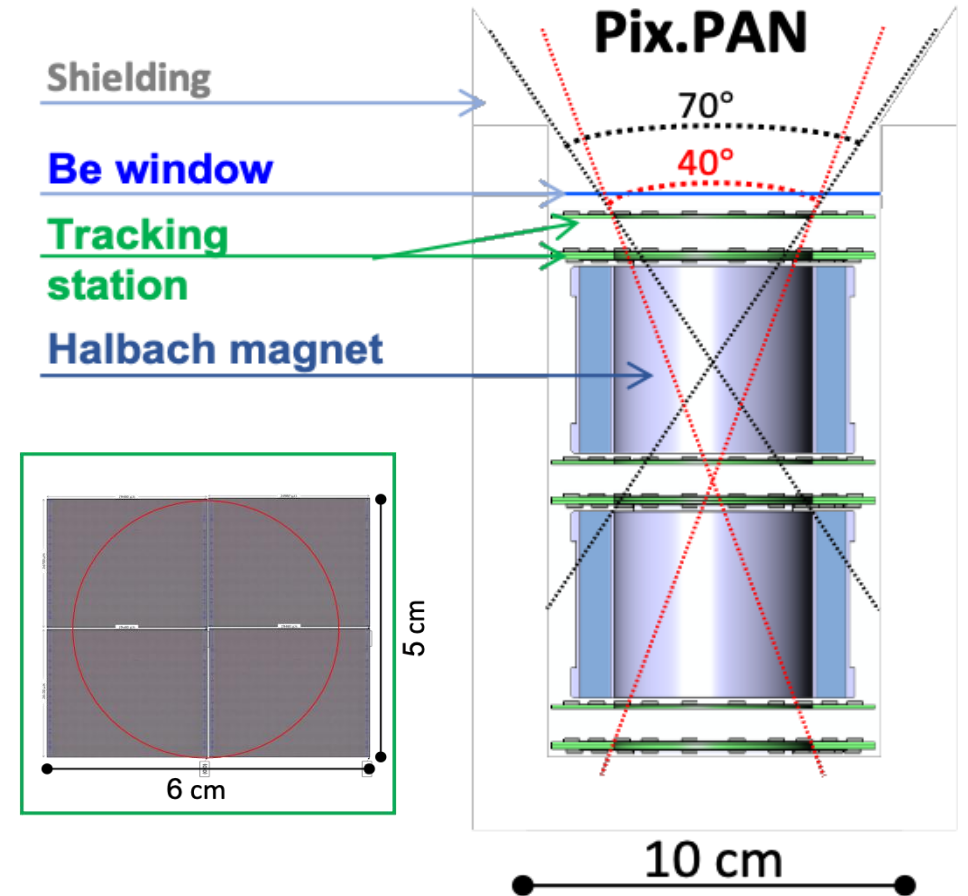
Protons, MiniPAN, 150 μm thickness, realistic magnetic field map



Magnetic spectrometer based on Timepix4

From Mini.PAN to Pix.PAN

- 512 x 448 pixels at 55 μm pitch (7 cm^2)
 - Time binning of **200 ps** (resolution ~ 60 ps)
 - Data-driven measurement with up to 3.5 Mpixel/ mm^2/s
- Significant **simplification of integration**
- Add **high rate capability** self-triggered operation
- **Desired power consumption < 20 W (vs 60 W)**
 - **Improved spatial resolution in bending direction required**
- **Baseline pixel dimension of 27.5 x 880 μm**



Conclusion and outlook

- The Timepix detector's capability of **single-layer particle tracking and particle discrimination and spectroscopy** allows production of competitive radiation monitors with one order of reduction in mass
 - Flux, beam profile (spatial resolution down to ~ 500 ns), and energy measurement (with 5-20% resolution) for ion beams up to ~ 200 MeV/u
- Timepix-based detection systems are part or baseline design of compact magnetic spectrometers for **energy-dispersive measurement of 1-20 GeV/n particles**
 - Energy-dispersive flux measurement of wakefield-accelerated electrons with 10% resolution for the energy range from 1-10 GeV
- Space radiation is a key concern for safety in space missions and aerospace
 - Laser-created electron and ion beams can provide reference fields for electronics and detector testing for space application?

Thank you for your attention!

<https://radecs2026.org/>



“Northern lights brightened Czech skies” – Prague morning, Jan. 2026



The “magic” of
Space radiation

Space radiation

is not just an abstract risk –
It can impact everyday life!

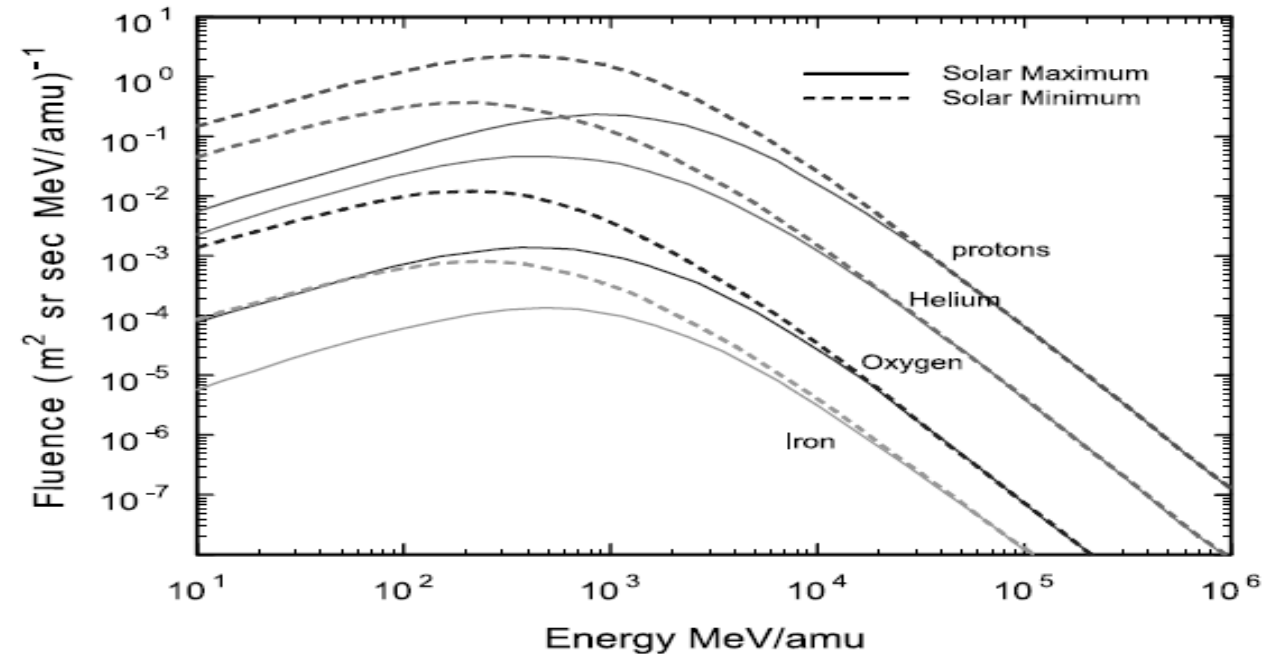
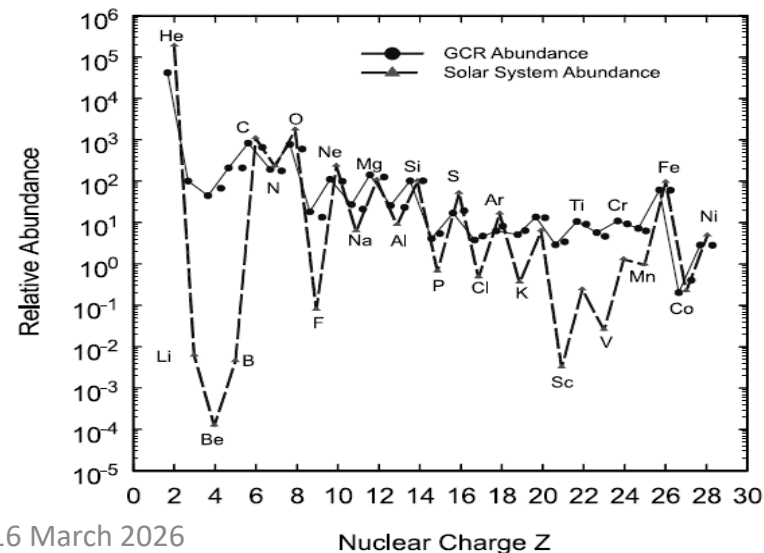


Galactic Cosmic Rays

98% Baryonic component

- 87% protons
- 12% alpha-particles
- 1% heavy ions ($Z > 2$)

2% Leptons (electrons and positrons)



GCR are penetrating particles: flux peaks > 0.5 -1 GeV/nucleon and thus difficult to shield

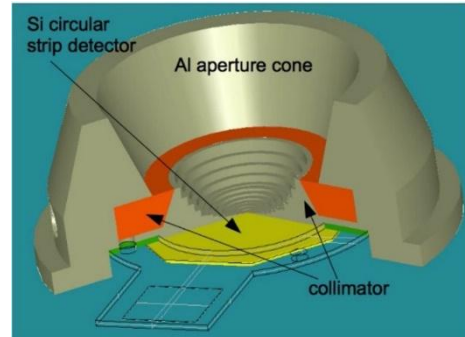
→ GCR are a major source of the astronaut dose on interplanetary missions

Instruments for measurements in LEO



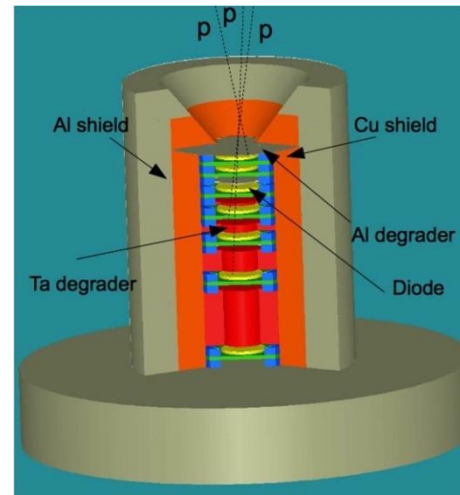
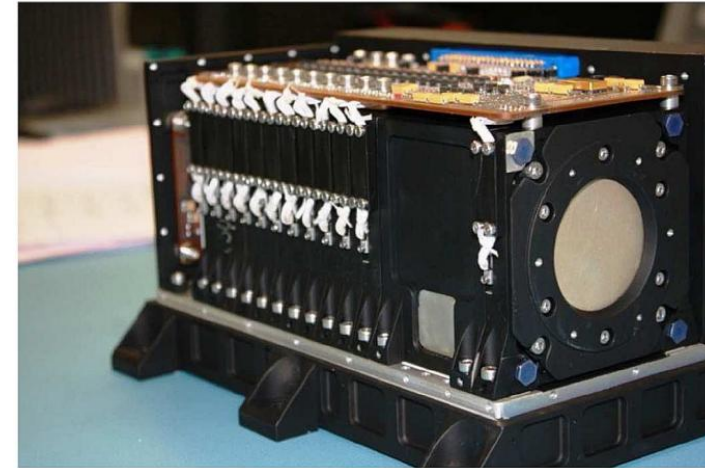
Next Generation Radiation Monitor (NGRM)

- Mass ~ 1 kg
- Consumption ~1-2 W



EPT (Energetic Particle Telescope)

- Mass: **4.6 kg**
- Consumption: 5.6 W



ICARE-NG:

- Mass: **2.4 kg**
- Consumption: 3 W



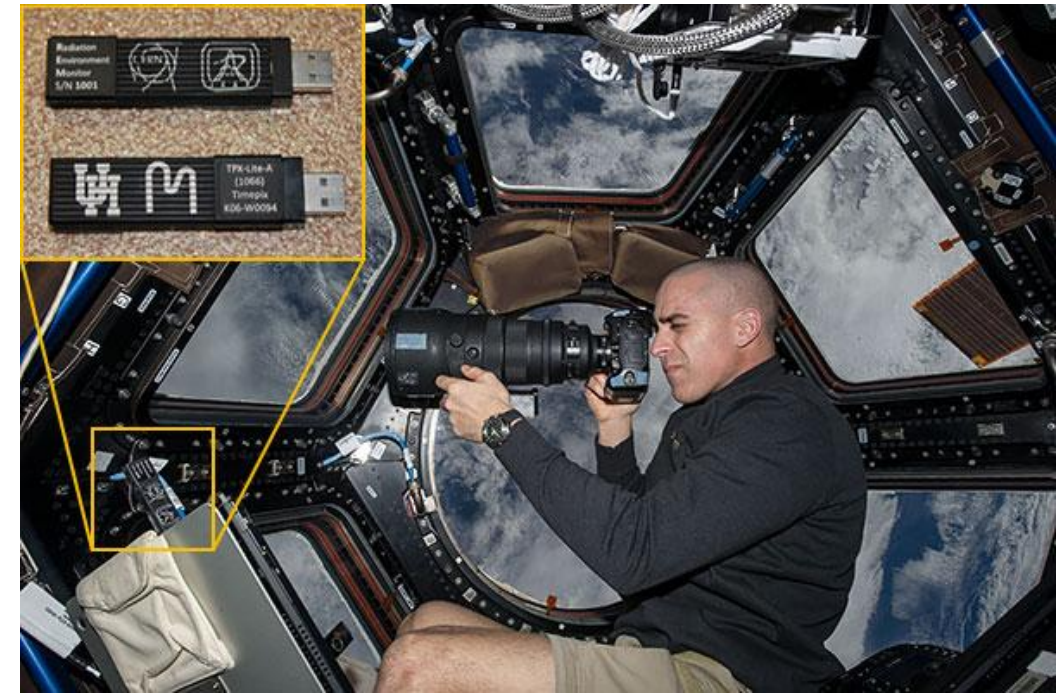
Timepix devices in LEO

- Single-layer particle discrimination
- Small dimensions and low mass
- Large field of view

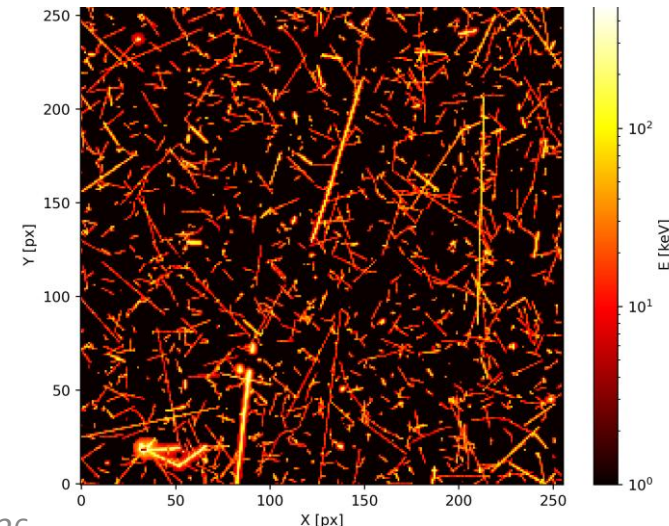
Short historical perspective:

- REM on ISS (since 2012: different versions; MiniPIX TPX3 by Advacam deployed in 2021)
- **SATRAM on Proba-V (launch in 2013, 820 km)**
- LUCID-Timepix (2014-2017, 635 km)
- VZLUSAT-1 (launch in 2017, 510 km)
- RISESAT (launch in 2019, 500 km)
- VZLUSAT-2 (launch in 2022, 500 km, CdTe 2 mm)
- In recent years significant increase of missions with Timepix due to commercial availability

16 March 2026



Space radiation in LEO measured by TPX3, integrated frame, 200 s, energy display



Minipix TPX3 and shielding by ADVACAM



ADVACAM^{*}
Imaging the Unseen

First deployment of TPX3 detector in space

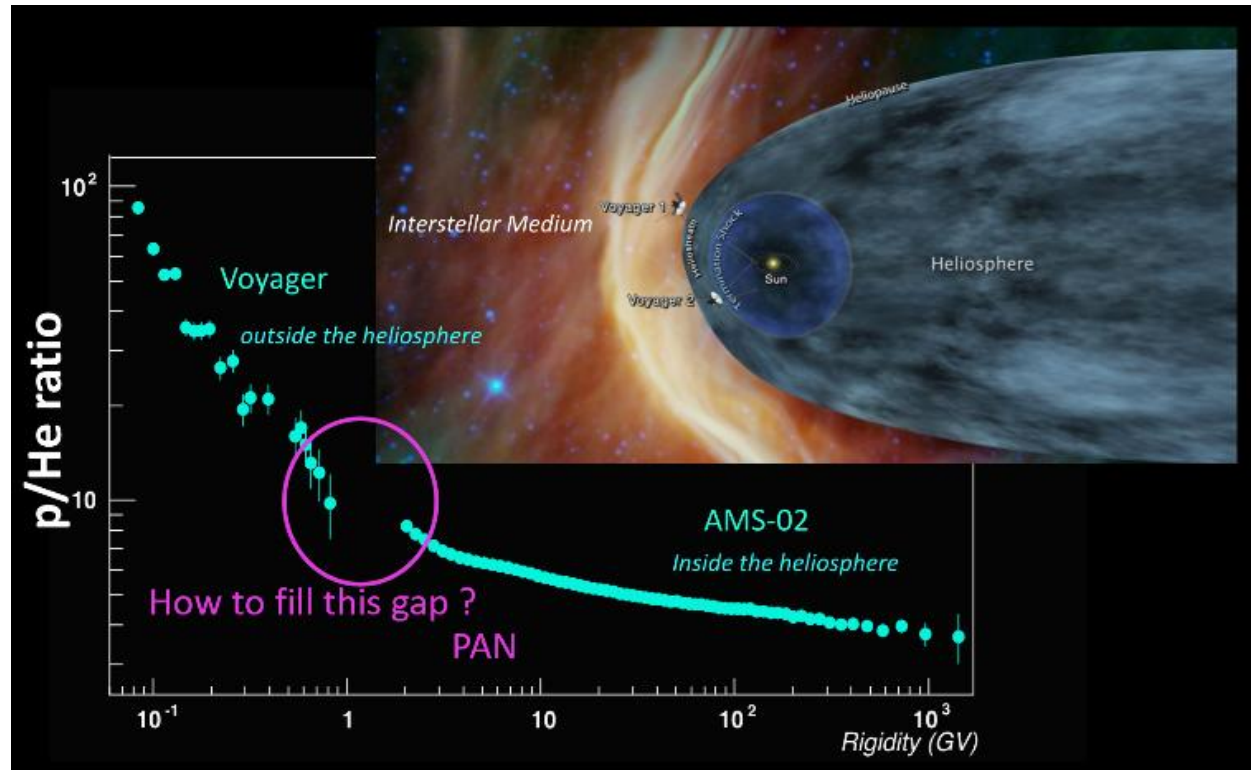
34

ELIMED 2026

Mini.PAN:

Scientific objectives

Precisely measure and monitor flux, composition, and direction of penetrating particles (up to ~ 20 GeV/nucleon)



Galactic cosmic ray (GCR) physics:

- Understand origin, acceleration mechanisms and propagation properties
- Antimatter content

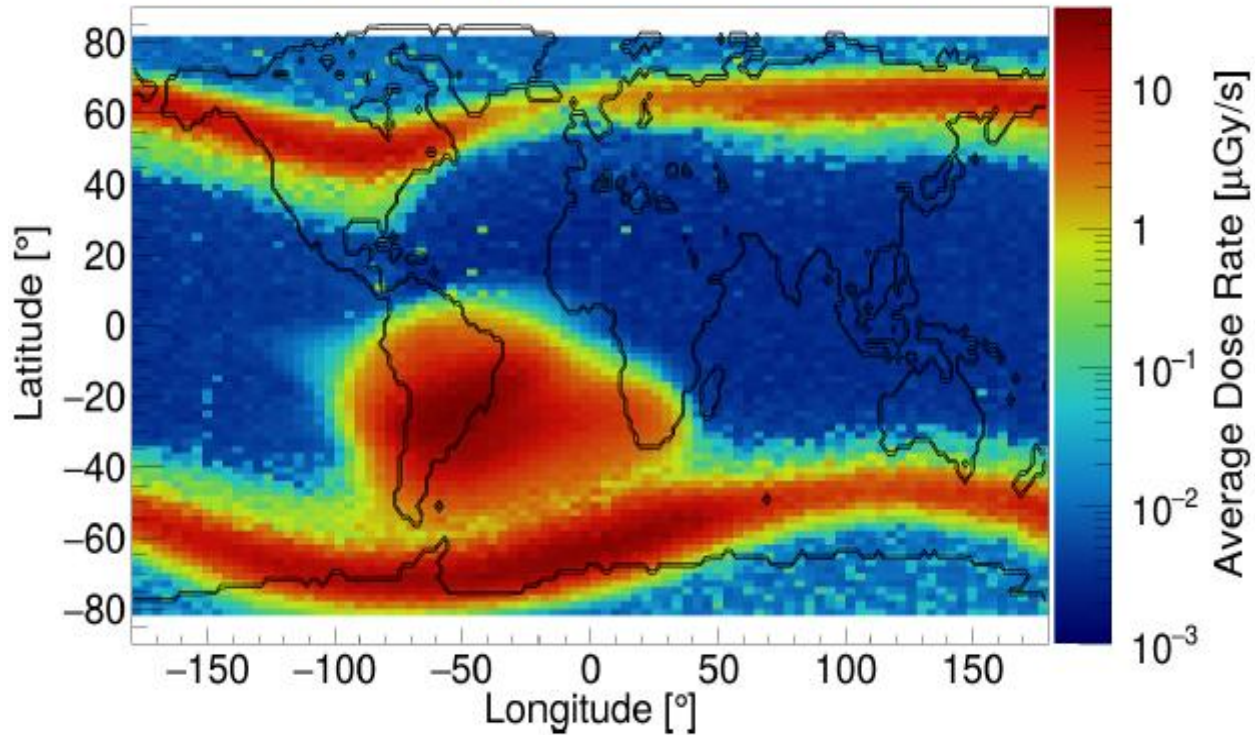
$\sim 50\%$ of astronaut dose from penetrating GCR

Dosimetric aspect:

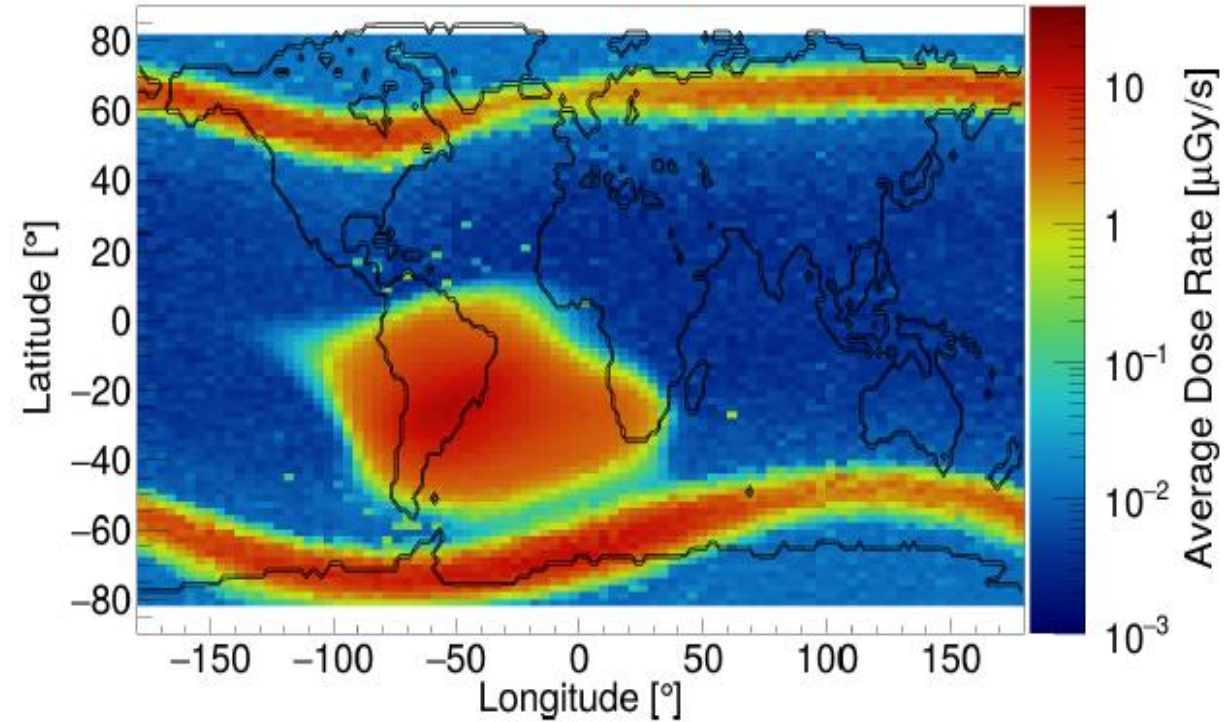
- GCR major source of dose for astronauts on (interplanetary) missions

Comparison of dose during Solar Maximum and Minimum

2015 (right after) Maximum



2019 Minimum



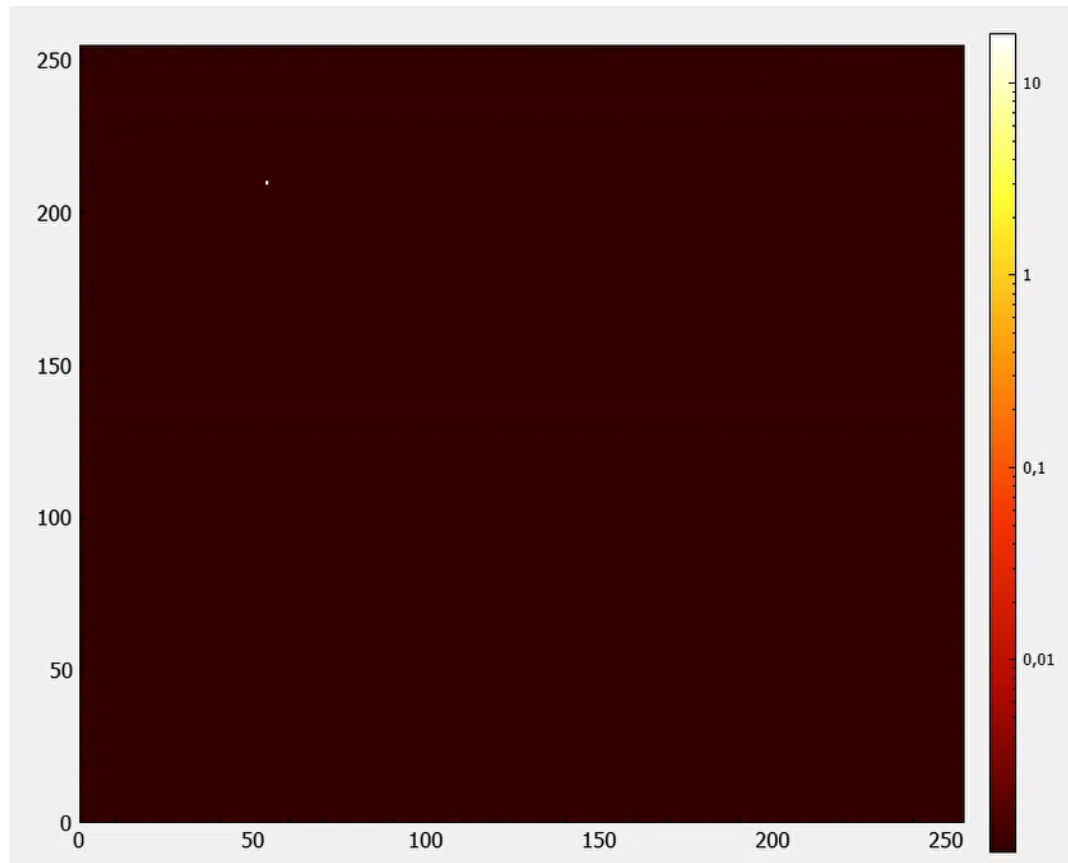
Dose rate average for the entire year

Working principle

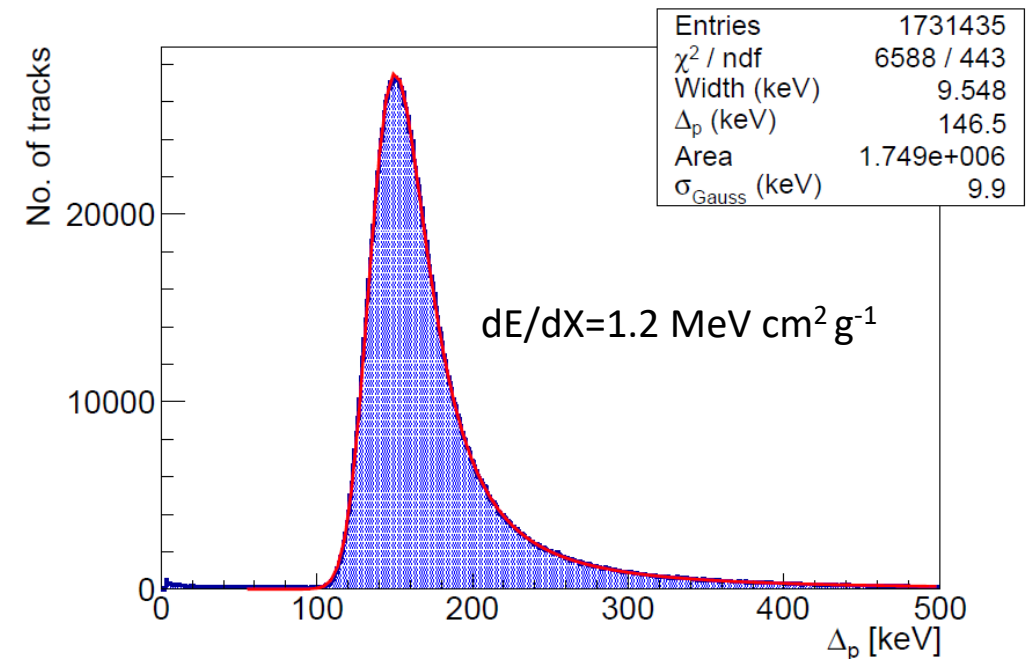
Detector response to ionizing radiation

120 GeV/c pion beam

Singly-charged relativistic particles (μ , pions, ...)



$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



Fluctuations of the energy depositions are described by a Landau-Vavilov distribution (physics) convolved with Gauss (detector energy resolution).

Ion resolving and particle separation capability

Relativistic fragmented ion beam

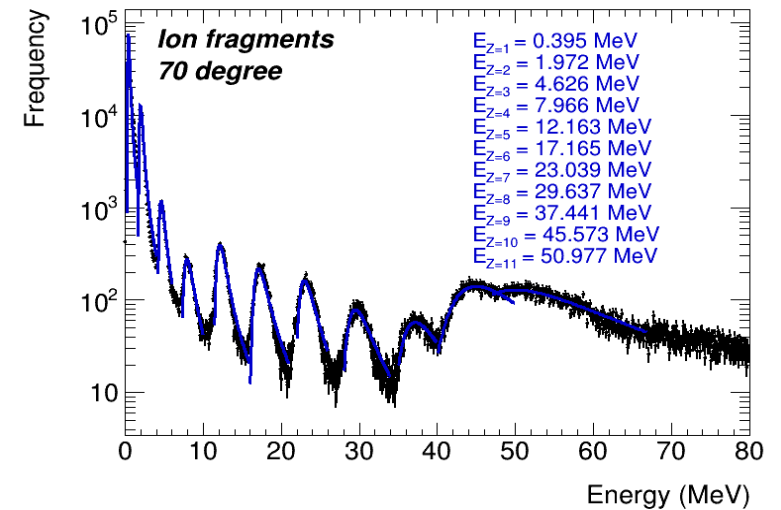
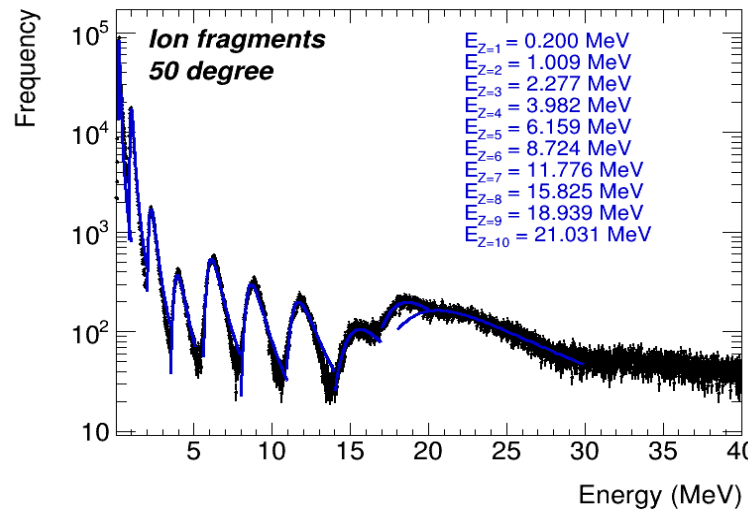
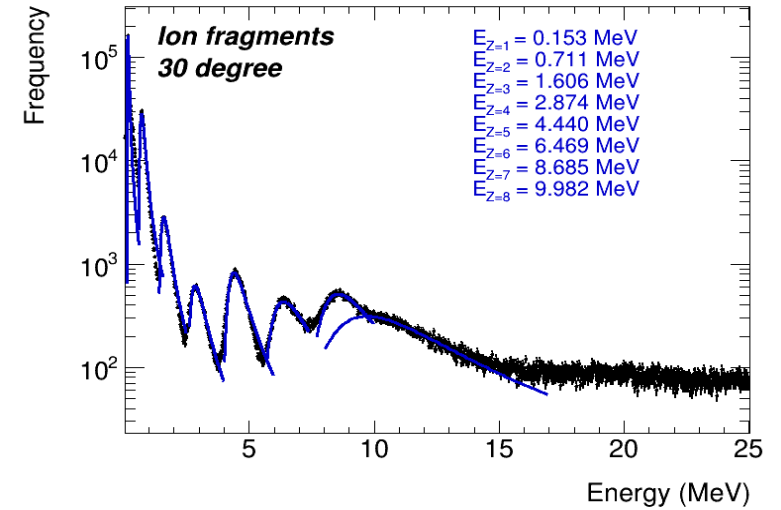
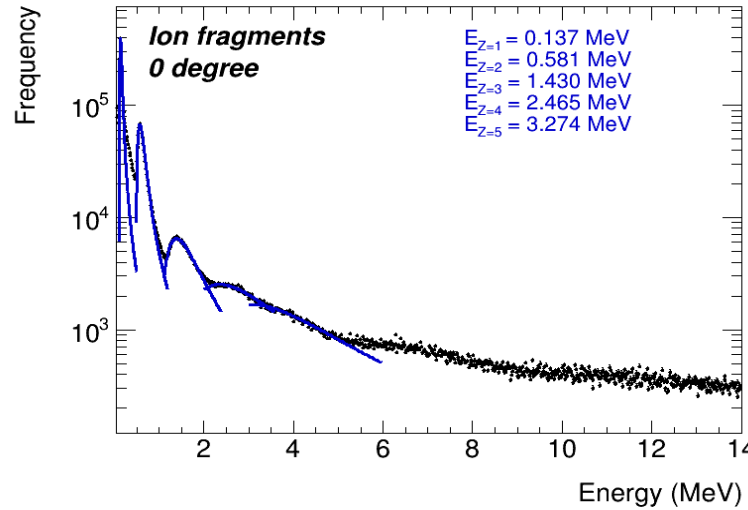
Mixed field of relativistic ion fragments created by Pb beam on target.

Observed peaks relate to different ion charge:

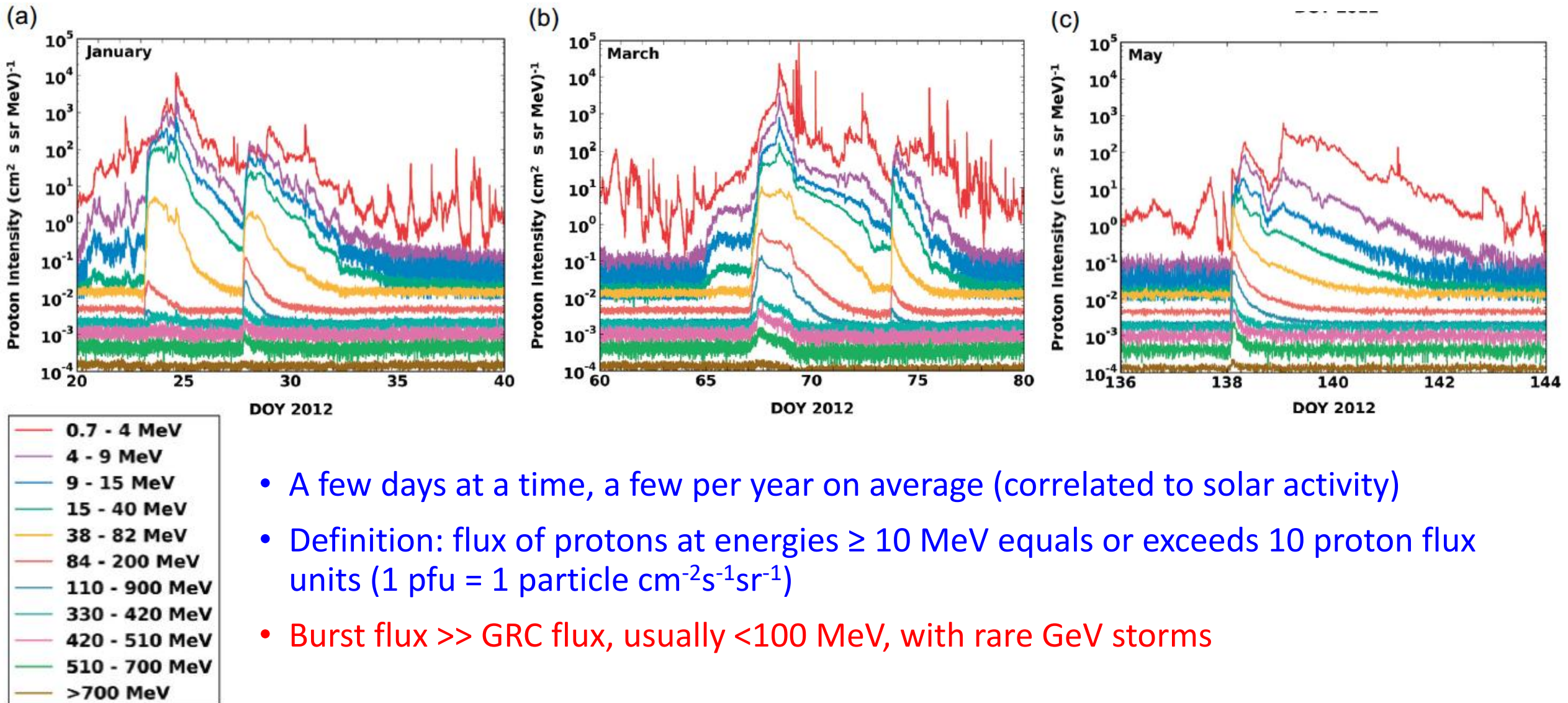
$$\frac{dE}{dX} = \frac{dE_{Z=1}}{dX} Z^2$$

Resolving power up to Z=11

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



Transient flux: Solar Particle Events (SPE)



- A few days at a time, a few per year on average (correlated to solar activity)
- Definition: flux of protons at energies ≥ 10 MeV equals or exceeds 10 proton flux units (1 pfu = 1 particle $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$)
- Burst flux \gg GRC flux, usually <100 MeV, with rare GeV storms

Solar Radiation Storms

			Flux level of \geq 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	<p><u>Biological</u>: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. ***</p> <p><u>Satellite operations</u>: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible.</p> <p><u>Other systems</u>: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.</p>	10^5	Fewer than 1 per cycle
S 4	Severe	<p><u>Biological</u>: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***</p> <p><u>Satellite operations</u>: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded.</p> <p><u>Other systems</u>: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.</p>	10^4	3 per cycle
S 3	Strong	<p><u>Biological</u>: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***</p> <p><u>Satellite operations</u>: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely.</p> <p><u>Other systems</u>: degraded HF radio propagation through the polar regions and navigation position errors likely.</p>	10^3	10 per cycle
S 2	Moderate	<p><u>Biological</u>: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.***</p> <p><u>Satellite operations</u>: infrequent single-event upsets possible.</p> <p><u>Other systems</u>: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected.</p>	10^2	25 per cycle
S1	Minor	<p><u>Biological</u>: none.</p> <p><u>Satellite operations</u>: none.</p> <p><u>Other systems</u>: minor impacts on HF radio in the polar regions.</p>	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles $\cdot s^{-1} \cdot ster^{-1} \cdot cm^{-2}$ Based on this measure, but other physical measures are also considered.

** These events can last more than one day.

*** High energy particle (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

Orbit	Radiation Environment	Particle Energy	Particle Flux
LEO	The Low Earth Orbit environment is characterized by high-energy radiation-belt trapped protons. This region is dominated by the South Atlantic Anomaly. Flux of cosmic rays and solar energetic particles is reduced by the Geomagnetic Shielding but the shielding is not total. LEO orbits also encounter outer-belt trapped electrons at high latitudes.	<u>Electrons:</u> 100 keV to 7 MeV <u>Protons:</u> 100 keV to 400 MeV	<u>Electrons</u> E> 500 keV: up to $5 \cdot 10^4$ (/cm ² /sec) <u>Protons</u> E>10 MeV: up to 10^4 (/cm ² /sec)
MEO	These orbits encounter mostly an electron-dominated environment, but also the inner, proton radiation belt.	<u>Electrons:</u> 100 keV to 7 MeV <u>Protons:</u> 100 keV to 400 MeV	<u>Electrons:</u> E> 500 keV up to 10^7 (/cm ² /sec) <u>Protons:</u> E > 10 MeV up to 10^3 (/cm ² /sec)
GEO	This orbit encounters an environment dominated by energetic electrons. Solar protons and cosmic rays have unrestricted access to this orbit.	<u>Electrons:</u> 100 keV to 7 MeV <u>SEP (protons):</u> 100 keV to 400 MeV <u>Cosmic rays:</u> $10\text{-}10^{13}$ MeV.	<u>Electrons:</u> E> 500 keV up to $5 \cdot 10^6$ (/cm ² /sec) <u>SEP (protons):</u> E>10 MeV up to 10^4 (/cm ² /s)
Interplanetary	The interplanetary environment is characterised by cosmic rays and occasional solar energetic particle events. Missions to the giant planets must consider their intense magnetospheres	<u>Cosmic rays:</u> $10\text{-}10^{13}$ MeV. <u>SEP (protons):</u> 100 keV to 400 MeV	<u>Cosmic Rays:</u> 2-4 (/cm ² /sec) <u>SEP (protons):</u> E>10 MeV up to 10^4 (/cm ² /s)

Near Earth Orbits:

→ electrons (< 7 MeV) and protons (< 400 MeV)

Interplanetary and deep space

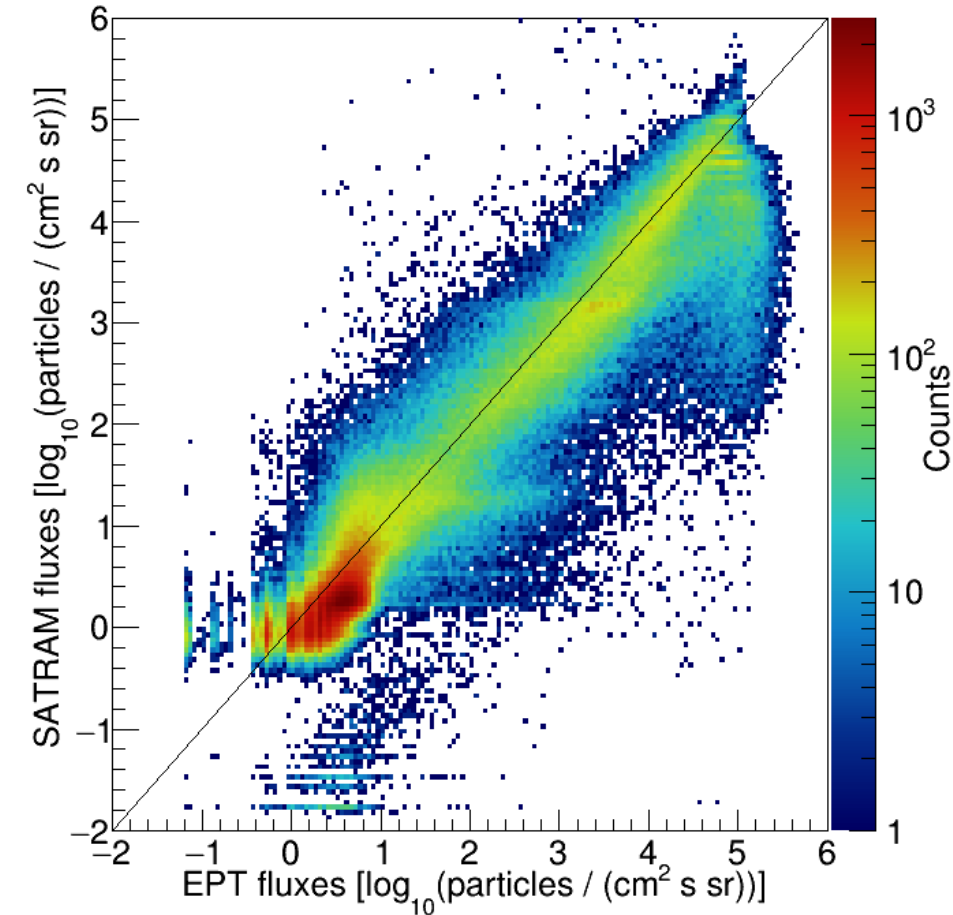
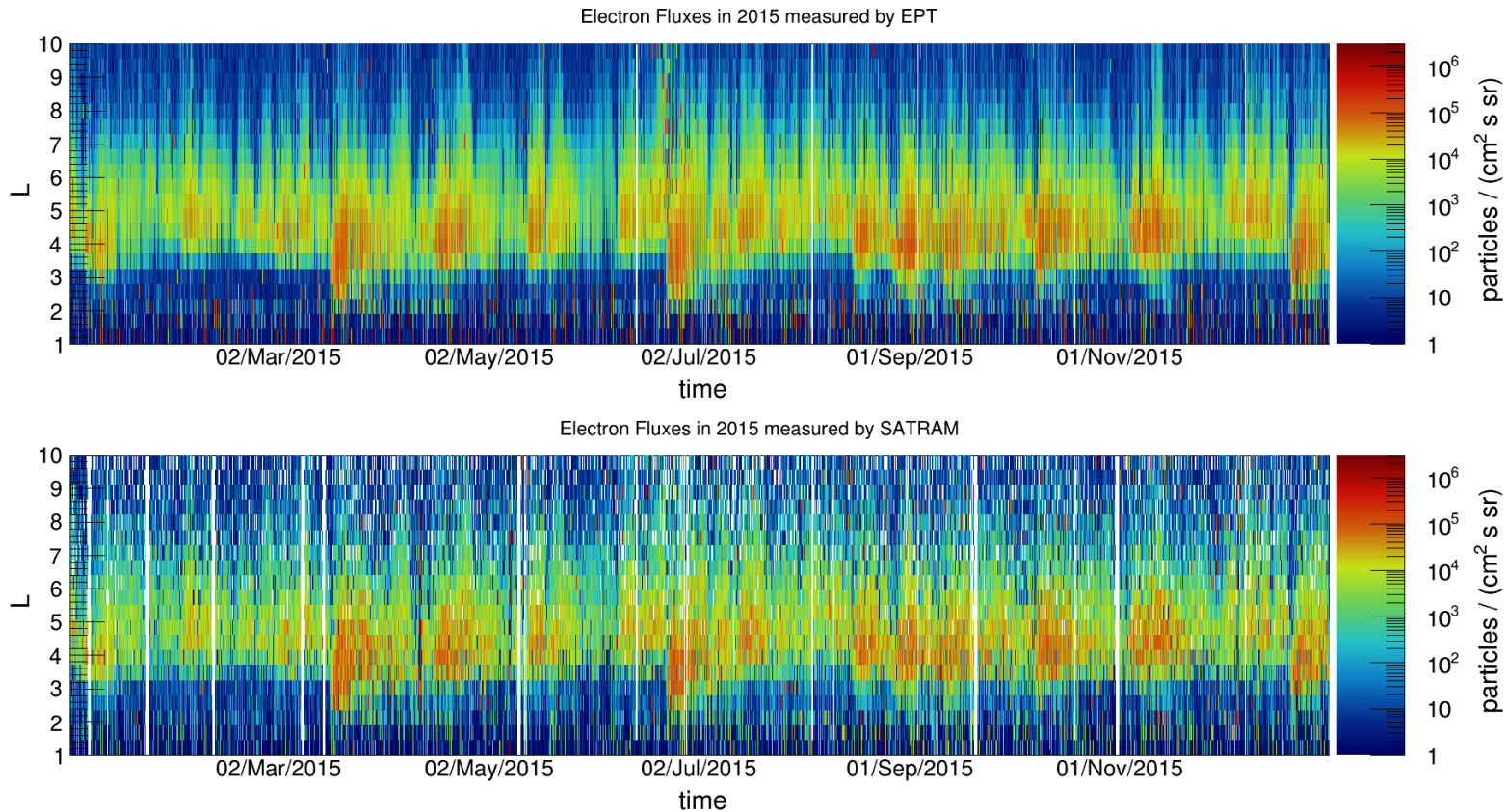
→ Galactic cosmic rays (GCR) – origin and acceleration mechanism unknown of today

Table 1: Characteristics of space radiation environment for typical satellite orbits [AD11].

Comparison with other radiation detectors in LEO

SATRAM vs. EPT (Energetic Particle Telescope)*): Electron fluxes

S. Gohl, B. Bergmann, M. Kaplan et al., "Measurement of electron fluxes in a Low Earth Orbit with SATRAM and comparison to EPT data", *Adv. Space Res.*, <https://doi.org/10.1016/j.asr.2023.05.033>



*) EPT and SATRAM are both on Proba-V.

60 seconds integration time

SATRAM vs. ICARE-NG:

Proton fluxes

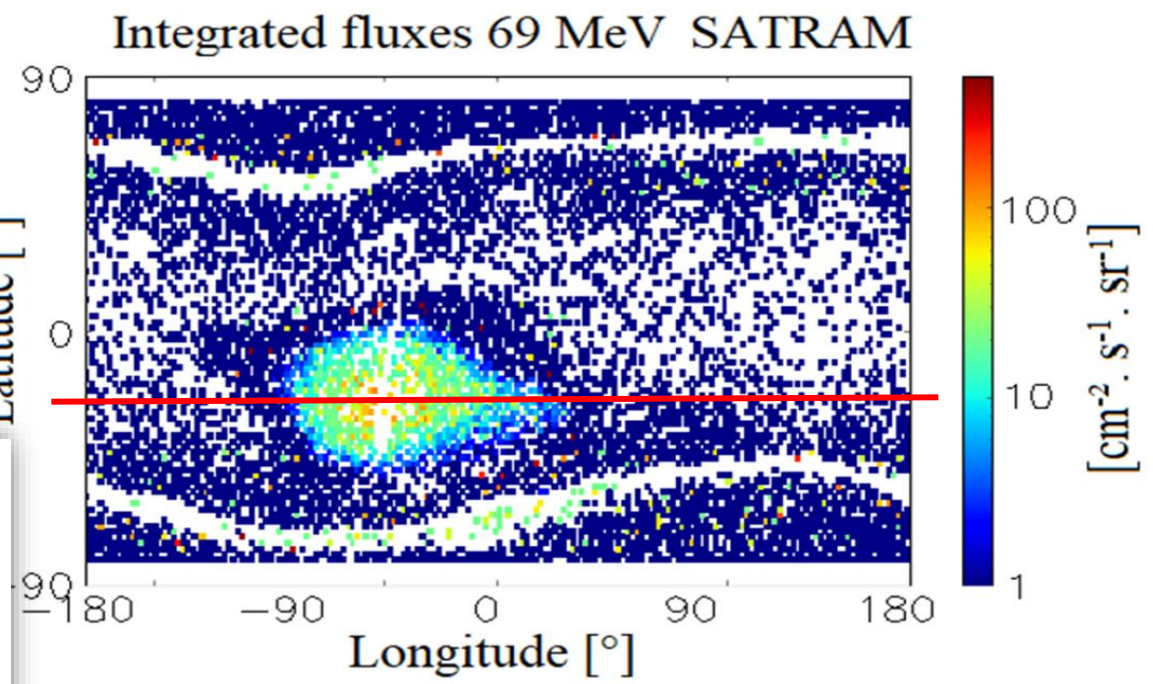
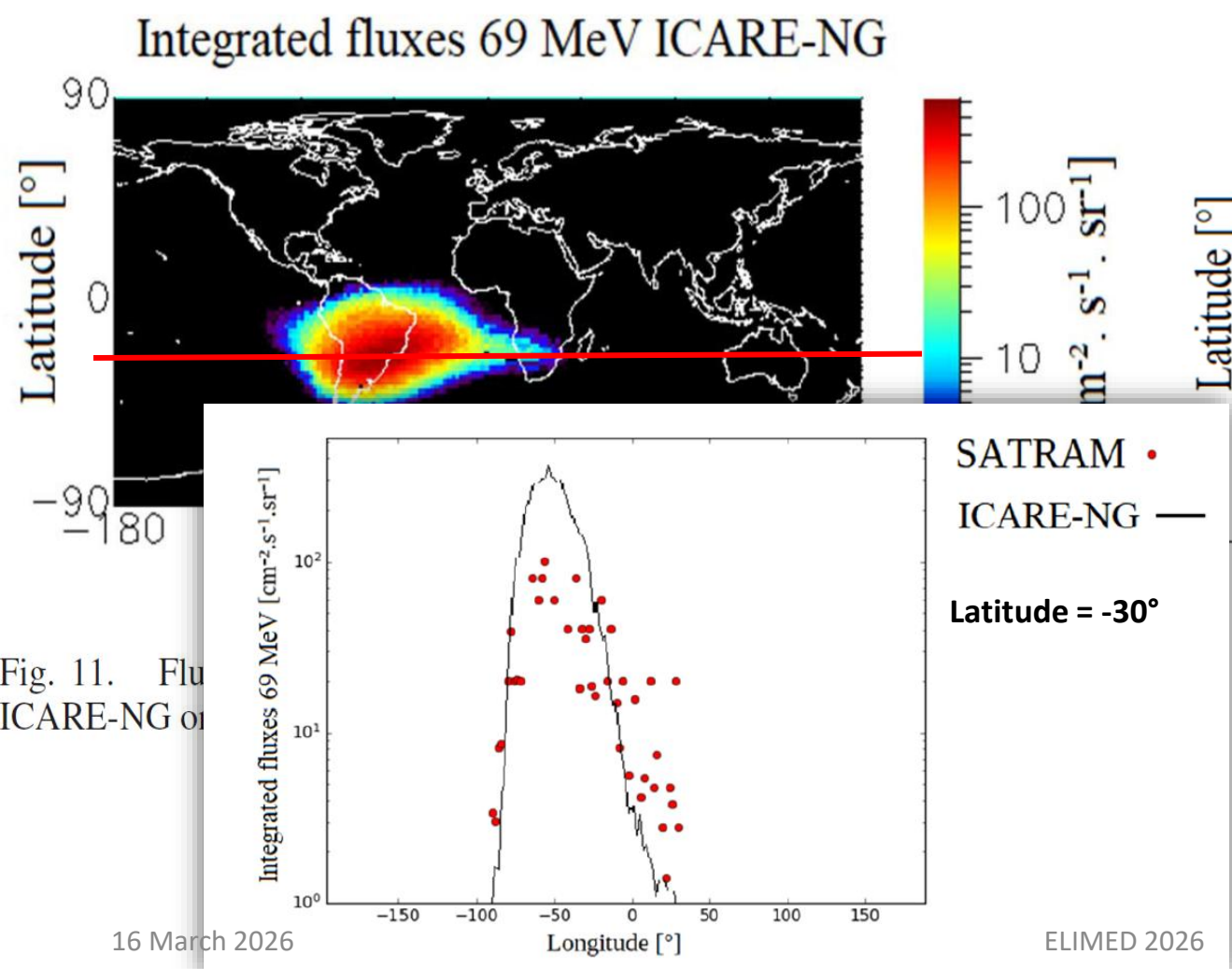


Fig. 11. Fluxes measured by ICARE-NG or

M. Ruffenach et al., "A new technique based on convolutional neural networks to measure the energy of protons and electrons with a single Timepix detector", in IEEE TNS, 68, 8, pp. 1746-1753, (2021). doi: 10.1109/TNS.2021.3071583

Development of the next-generation Timepix space radiation monitors - HardPix

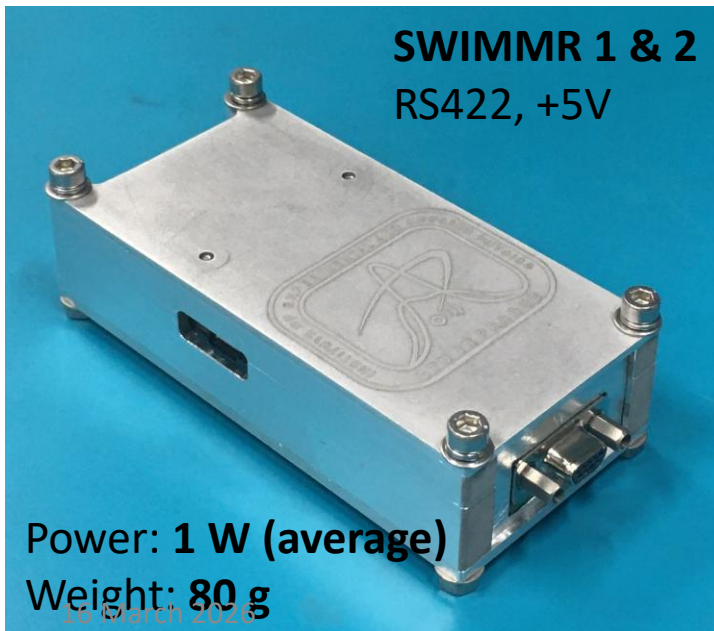
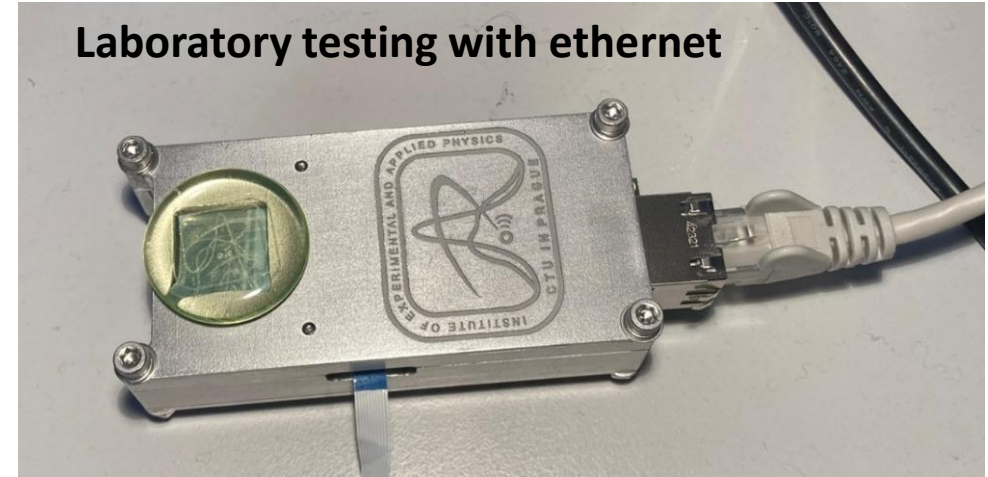
Development done in collaboration with ESA.

HardPix - Timepix3

- **Data-driven readout** for quasi-continuous measurement (max. count rate $40 \text{ Mhits cm}^{-2} \text{ s}^{-1}$)
- Simult. measurement of **energy and time**
- Minimal detectable energy per pixel: **6 keV**
- Low power mode (Timepix3 ASIC @ 0.2-0.5 mW)

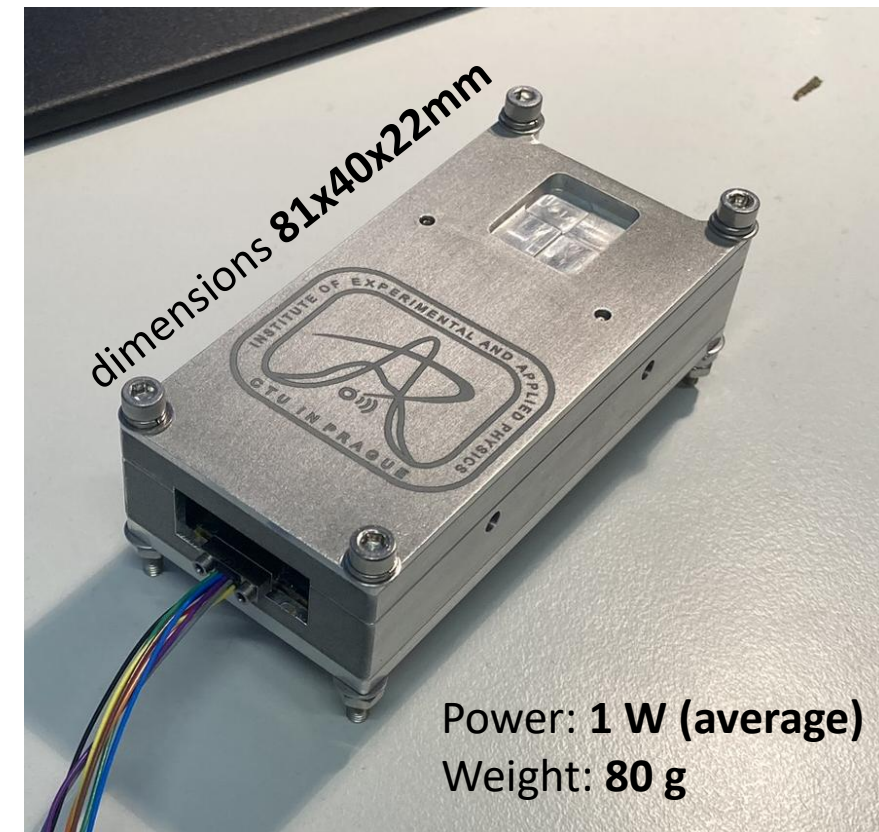
Based on: Zynq 7020 SoC

Laboratory testing with ethernet

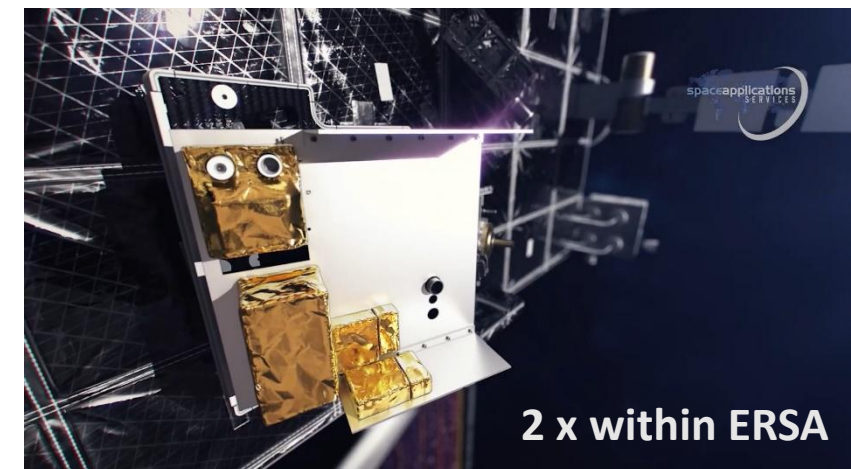


HardPix – Missions

- **SWIMMR1** (Space Weather Instrumentation, Measurement, Modelling and Risk) D-Orbit ION satellite, 525 km altitude – June 2023 – (first Timepix3 in data-driven operation in space)
- **SWIMMR 2** D-Orbit satellite orbit 330 - 1200 km - launched in January 2025
- **HEKI** - study radiation field influence on a superconducting magnet by Robinson-Paihau research institute in New Zealand using 2x HardPix detectors. Launched to ISS/Nanoracks in September 2025.
- **Cassini** - European Commission In-orbit demonstration mission. Managed by ESA and provided by ISISPACE 6U Cubesat - Test of 2-layer Timepix3 – Launch in **2026**
- 2 modules outside of the Lunar Gateway as a part of the ESA **ERSA** (European Radiation Sensors Array)
- **MAGPIE** equipped with neutron converters → neutron detection for water mapping (<https://ispace-inc.com/news-en/?p=7621>)



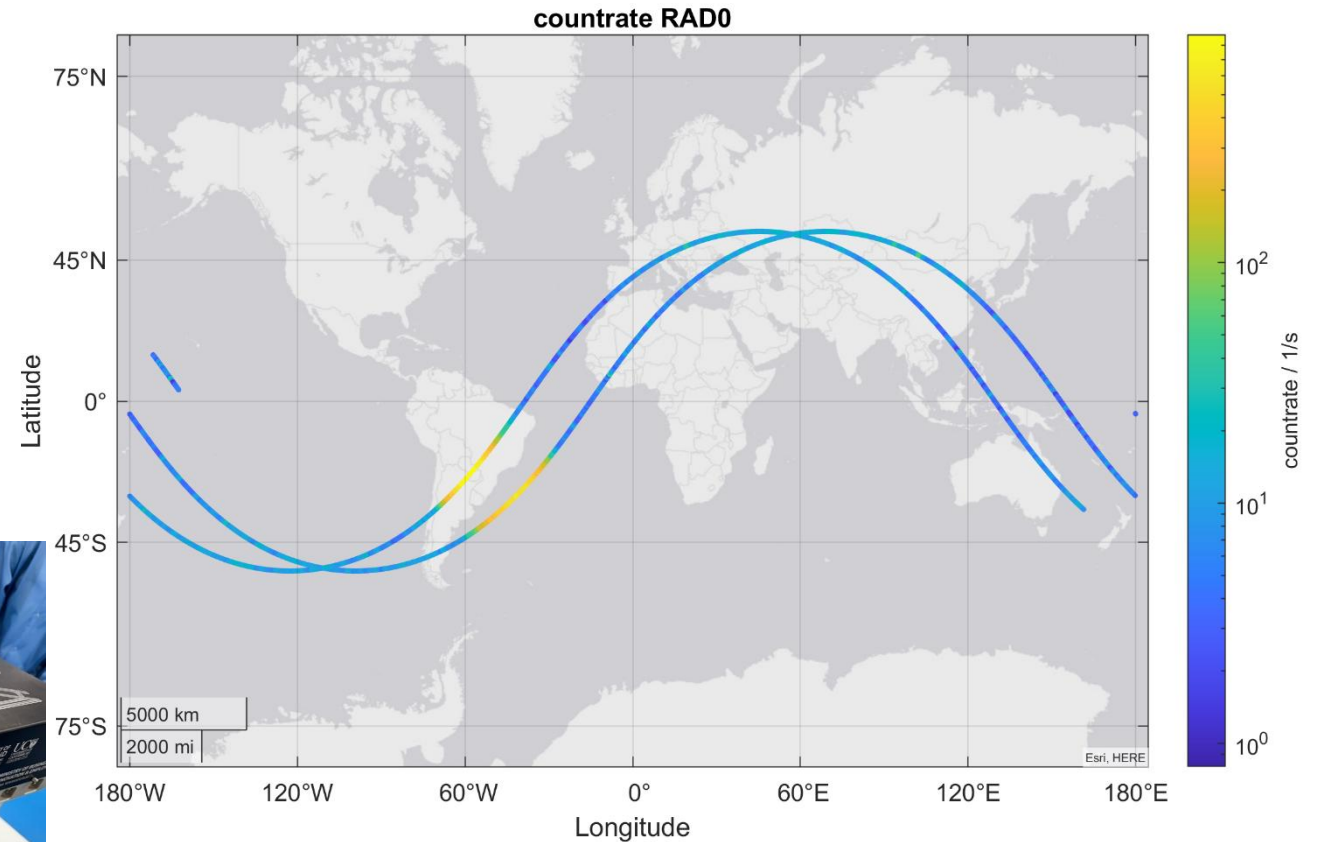
HardPix was developed with ESA projects



HardPix at ISS within HEKI Installation and first results



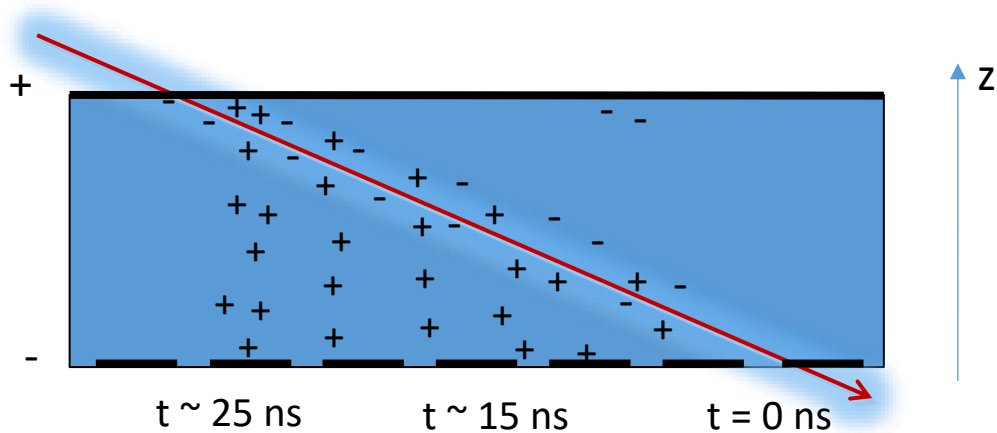
The HEKI experiment contains 2 HardPix with Timepix3 detectors.



First results from Timepix3 radiation monitor (data-driven operation)

Solid-state Time-Projection Chamber: 3D reconstruction of particle tracks

Enabled by the nanosecond-scale time measurement



Charge carrier drift motion:

e^- and h^+ drift described by

$$v_e = -\mu_e \times E(z)$$

$$v_h = \mu_h \times E(z)$$

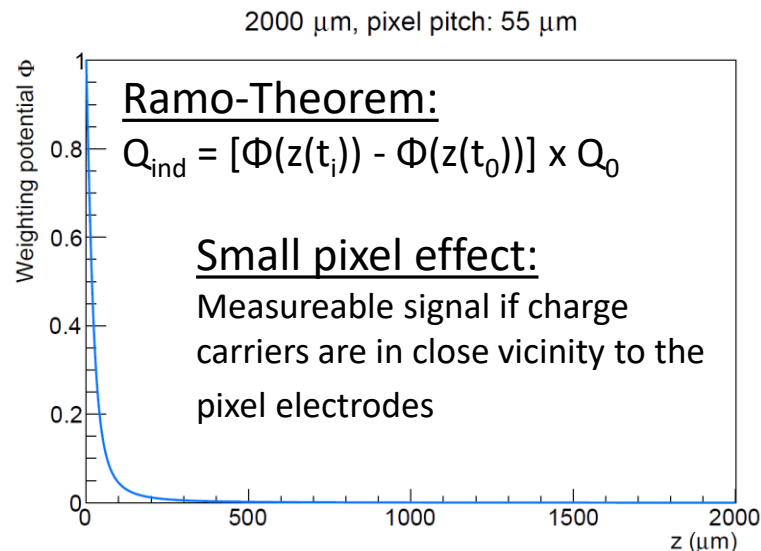
$\mu_{e/h}$: Mobility of e^-/h^+

Electric field parametrization:

Si: $\vec{E}(z) = \frac{U_B}{d} \vec{e}_z + \frac{2U_{dep}}{d^2} \left(\frac{d}{2} - z\right) \vec{e}_z$;

CdTe: $\vec{E}(z) = \frac{U_B}{d} \vec{e}_z$

U_B : Bias voltage; U_{dep} : Depletion voltage; d : Sensor thickness



→ Look-up table: $z(t_{meas.}, E_{meas.})$

Bergmann et al. Eur. Phys. J. C (2017) 77: 421. <https://doi.org/10.1140/epjc/s10052-017-4993-4>

Bergmann et al., Eur. Phys. J. C (2019) 79: 165. <https://doi.org/10.1140/epjc/s10052-019-6673-z>

3D track reconstruction – 500 μm thick silicon

120 GeV/c pion tracks accompanied by δ -rays:

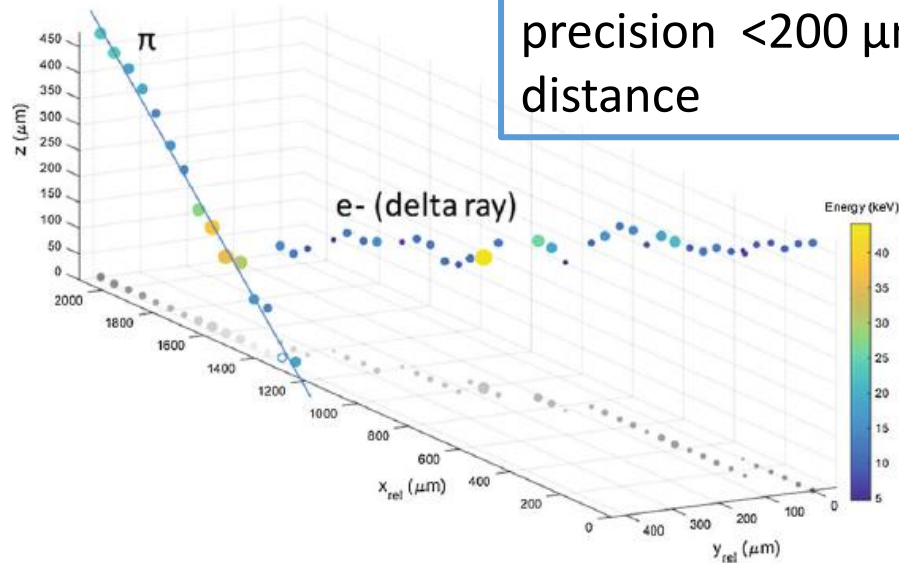
z-resolution:

$$\sigma_z \sim 30 \mu\text{m}$$

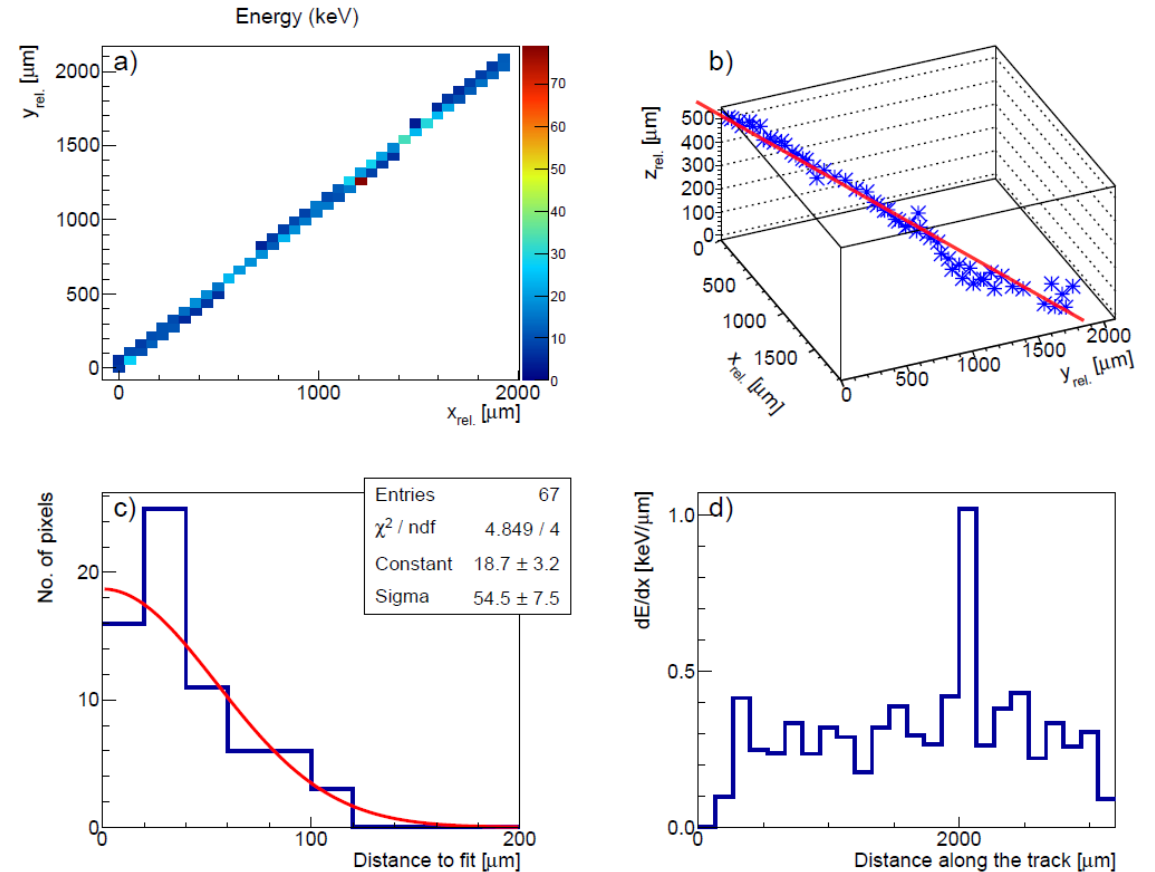
→ Improved determination of track directions

→ Improved separation of different particle classes

Trajectory reconstruction precision $< 200 \mu\text{m}$ at 1 m distance



A cosmic μ measured in the Prague laboratory:



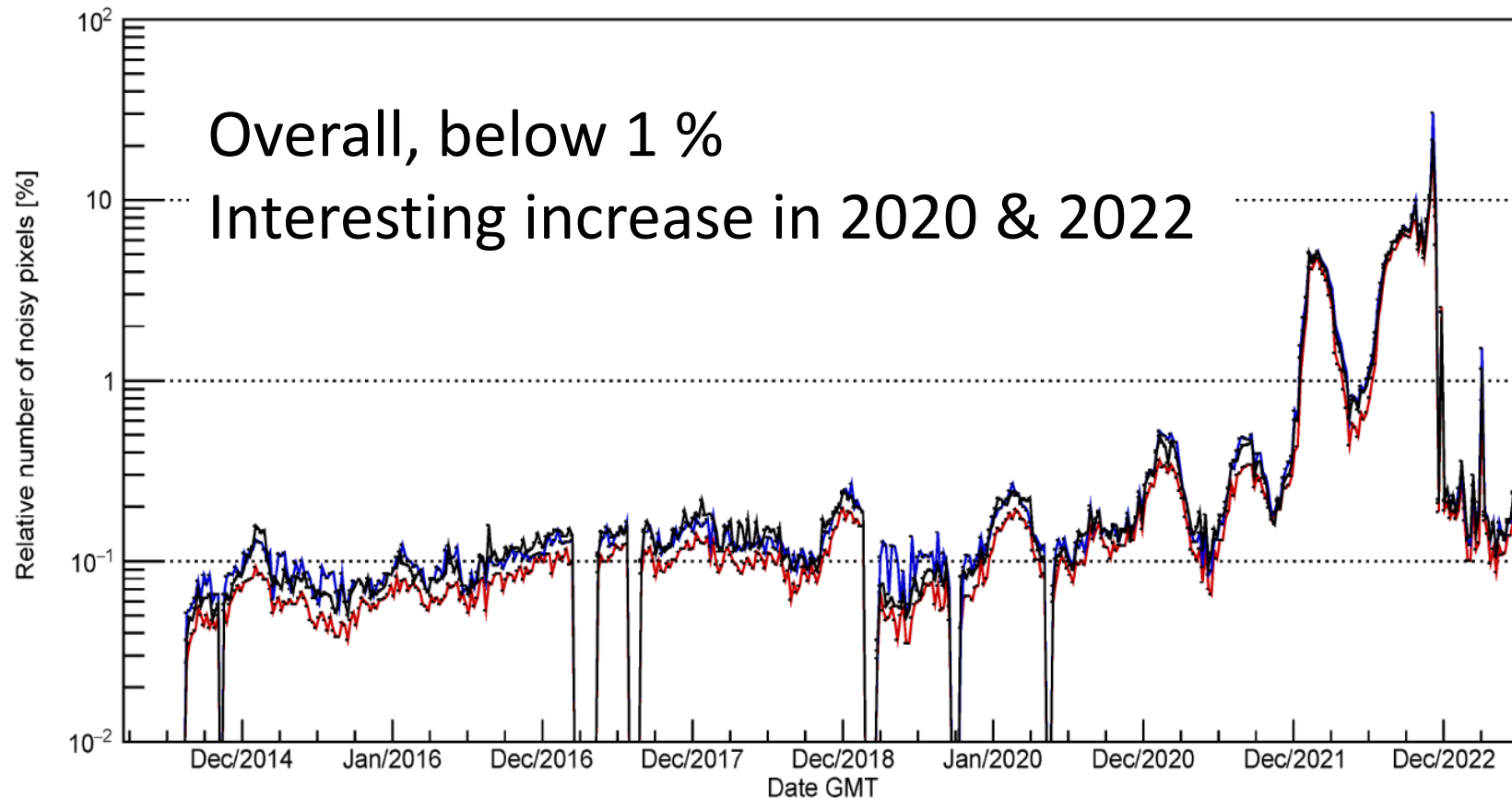
Bergmann et al. Eur. Phys. J. C (2017) 77: 421.

<https://doi.org/10.1140/epjc/s10052-017-4993-4>

What about radiation effects?

12 years of radiation monitoring with SATRAM

Effects of Space Radiation on device performance? – Noisy pixel appearance



Noisy pixel = pixel counting stat. sign. more than others (5 sigma) or with abnormal energy value

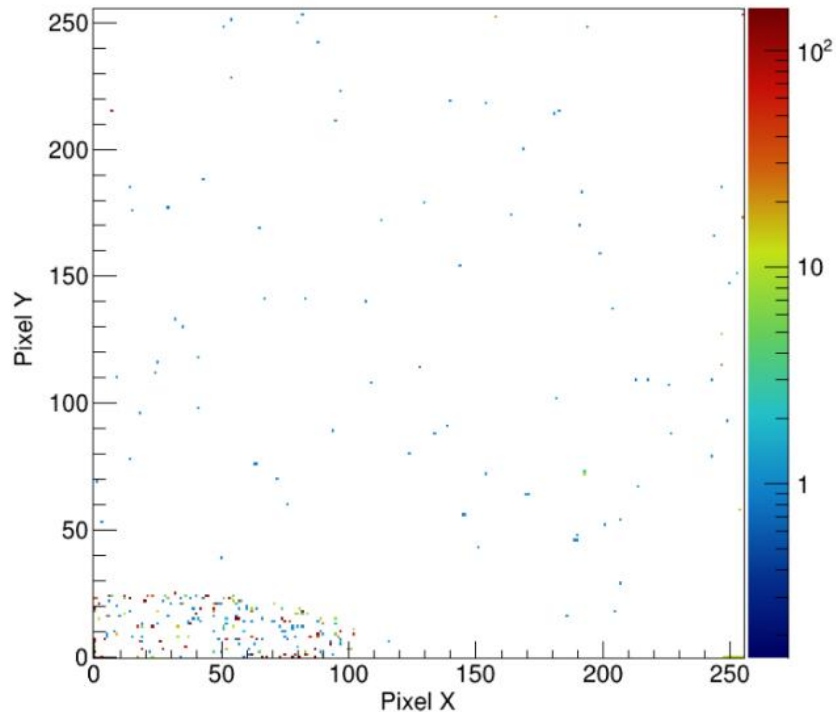
Noisy pixels appear due to bit-flips changing local THL bit flip in digital counter when measuring ToT

→ Recovered by pixel configuration reset

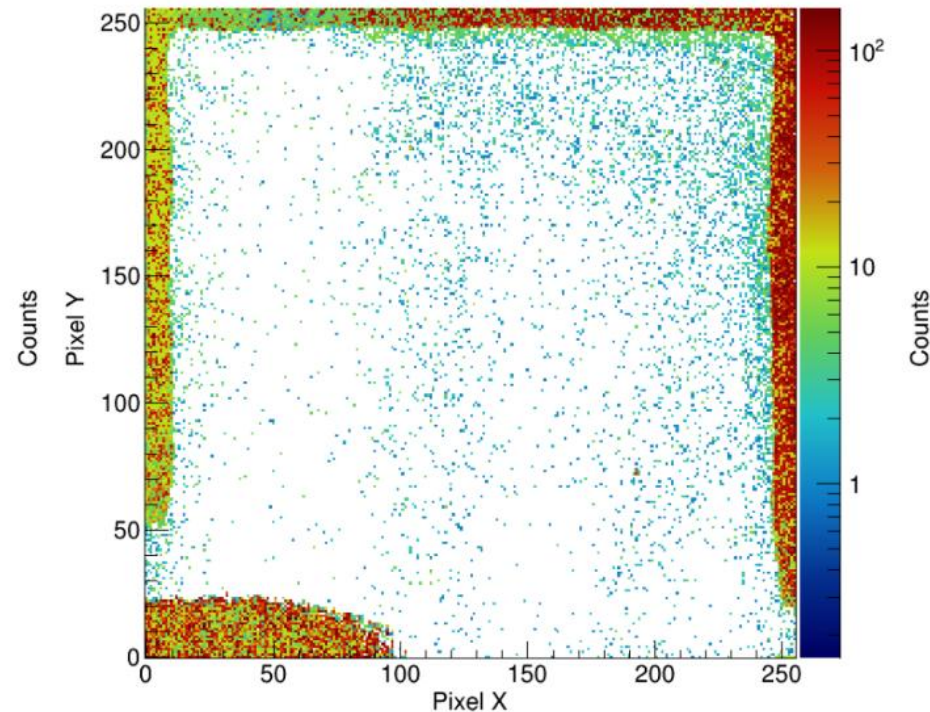
→ No effect on data quality identified and omitted

12 years of radiation monitoring with SATRAM

Effects of Space Radiation on device performance? – Noisy pixel appearance



Noisy pixel map in 2015



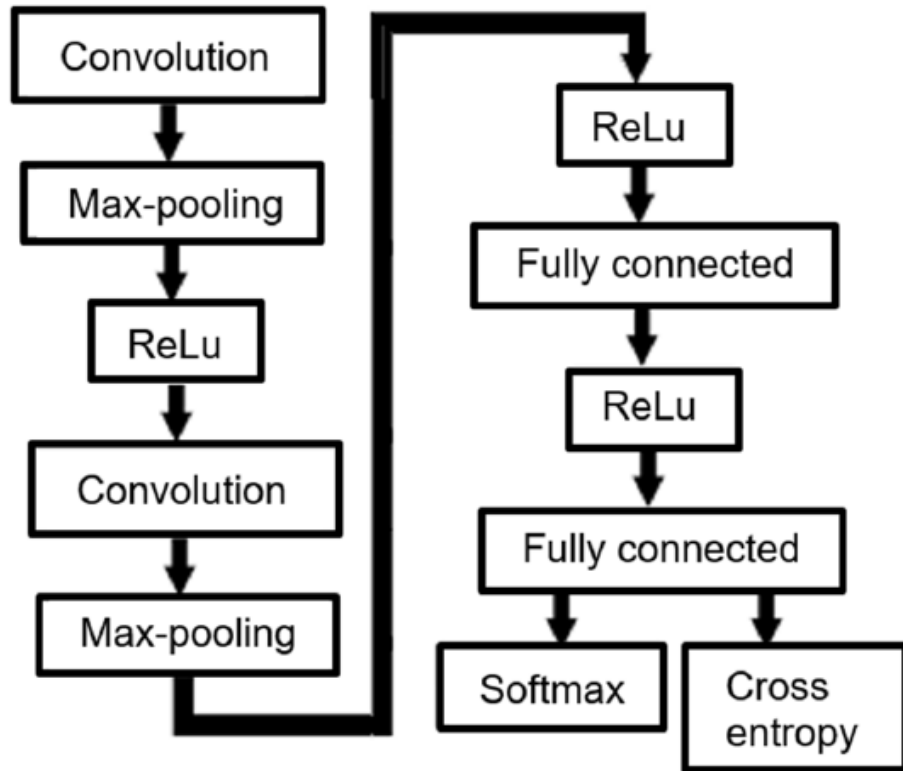
Noisy pixel map in 2022

Noisy pixels growing from the edge indicates issues with the reverse bias supply

→ Masking of edge pixels mitigates this issue

Improving particle identification and spectroscopy with machine learning

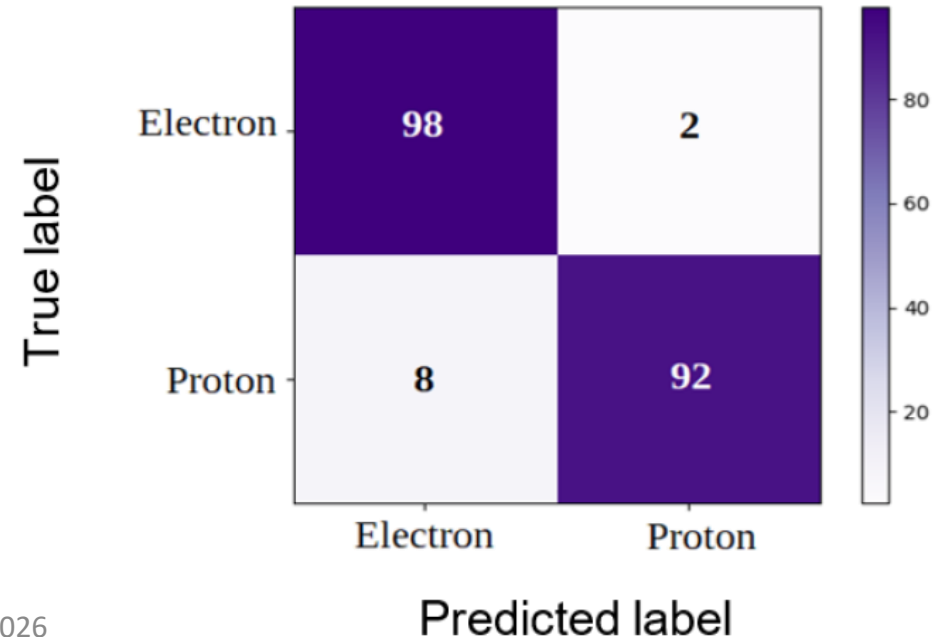
CNN – convolution neural network for separation of electrons and protons



Ground truth - simulation:

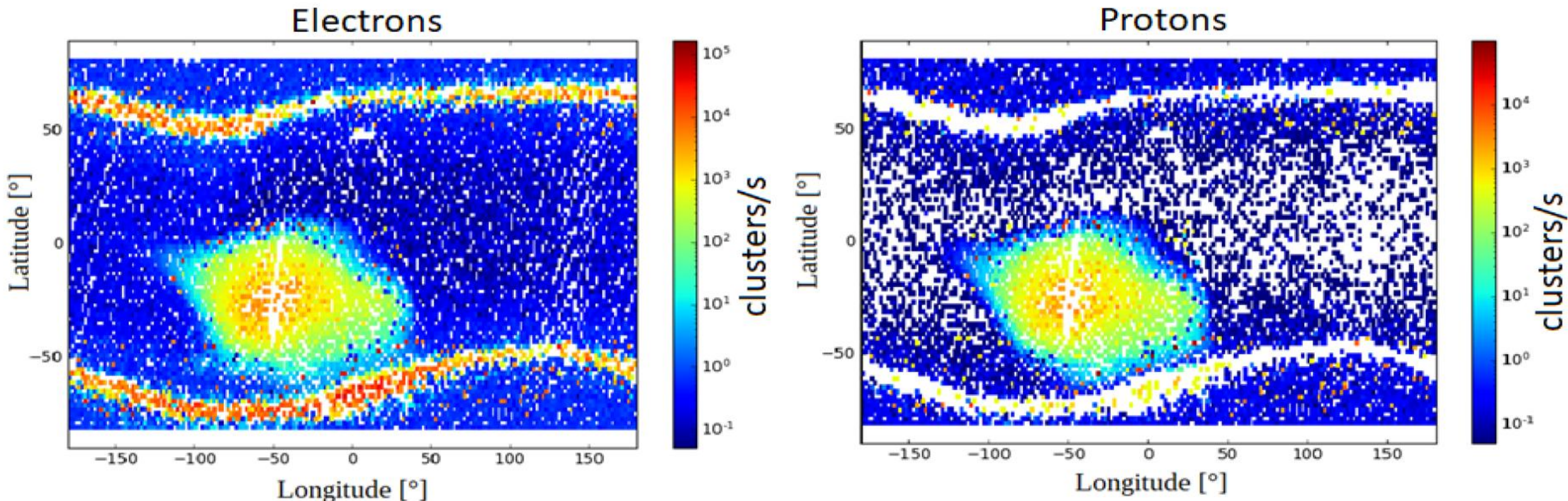
- Spherical source with cosine distributed angles
- 10 Mio electrons from 0.4 to 5 MeV
- 10 Mio protons from 17 to 200 MeV

Normalized confusion matrix



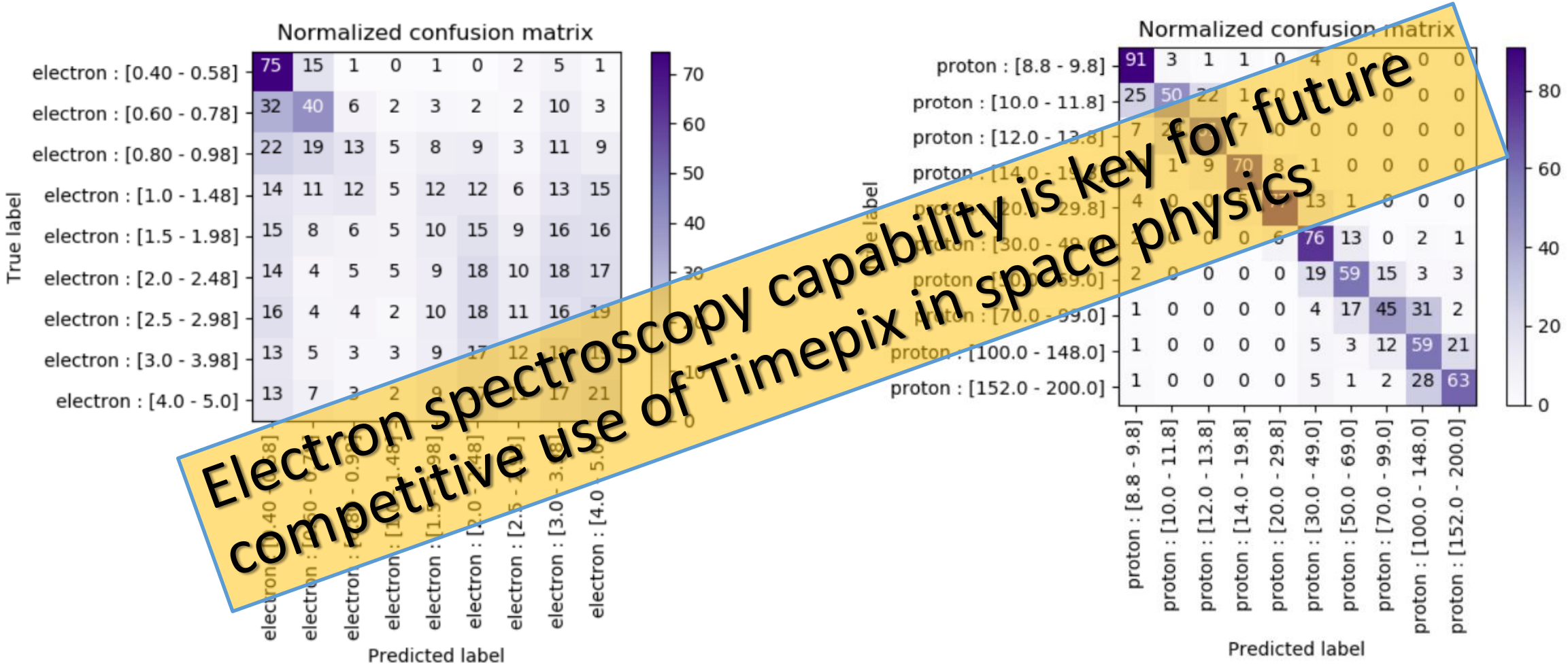
M. Ruffenach et al., "A new technique based on convolutional neural networks to measure the energy of protons and electrons with a single Timepix detector", in *IEEE TNS*, **68**, 8, pp. 1746-1753, (2021). doi: 10.1109/TNS.2021.3071583

CNN – convolution neural network for separation of electrons and protons



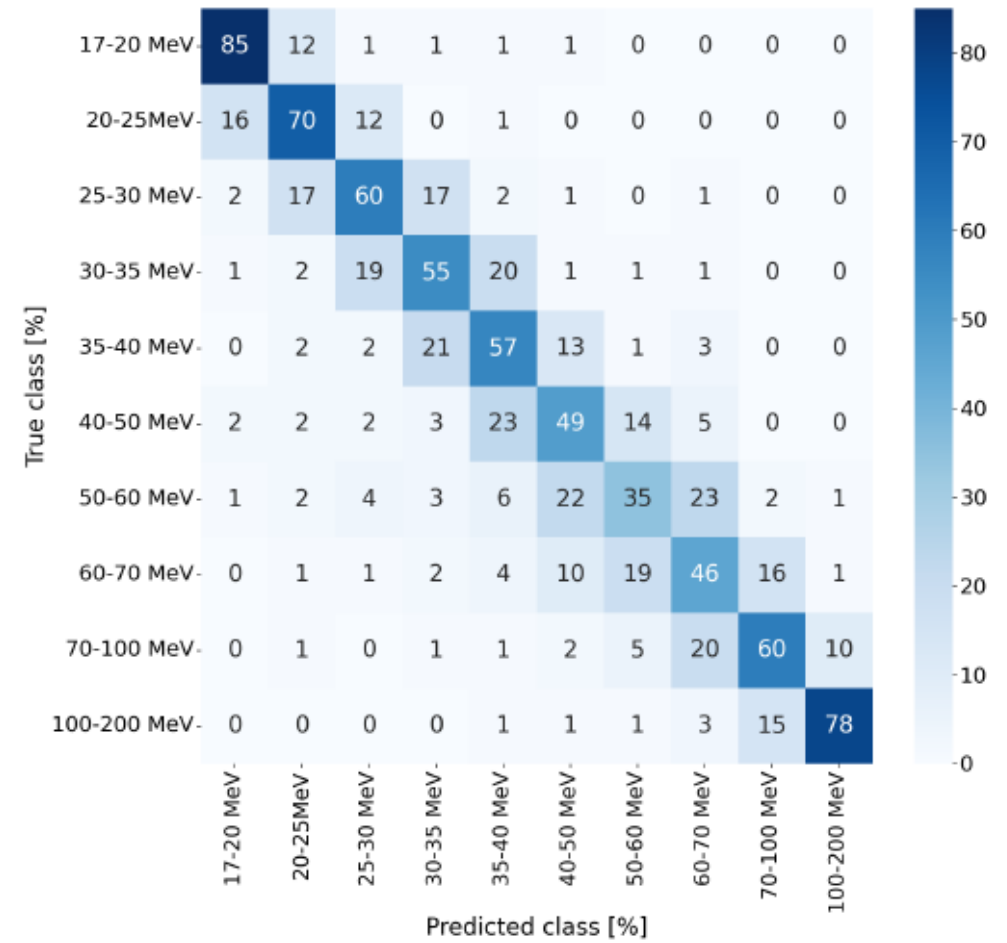
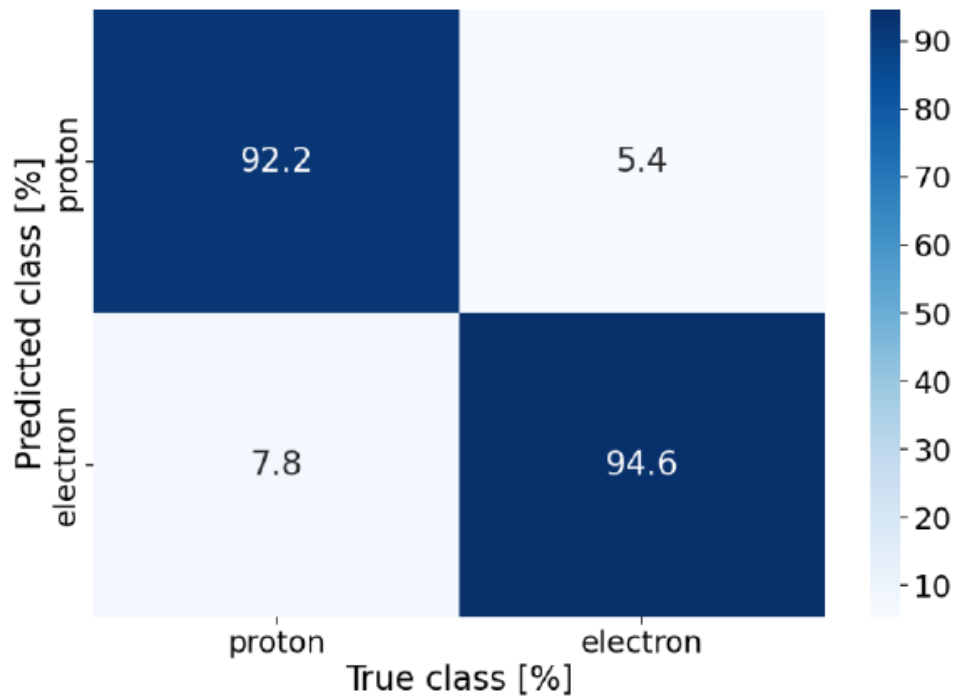
M. Ruffenach et al., "A new technique based on convolutional neural networks to measure the energy of protons and electrons with a single Timepix detector", in IEEE TNS, 68, 8, pp. 1746-1753, (2021). doi: 10.1109/TNS.2021.3071583

CNN – convolution neural network for incident energy determination

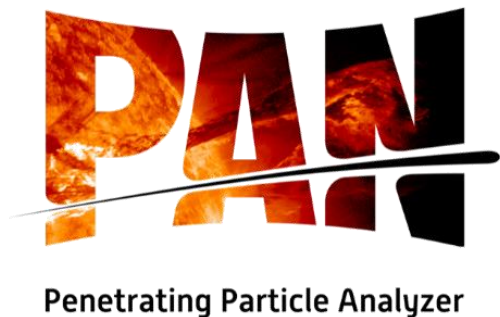


CNN U-Net results

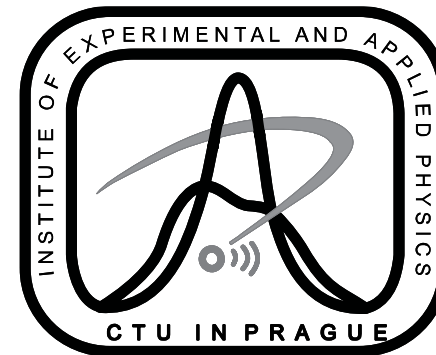
93.4% accuracy can be improved by neglecting small clusters



Development of a compact magnetic spectrometer based on Timepix4 - From mini.PAN to Pix.PAN



**UNIVERSITÉ
DE GENÈVE**

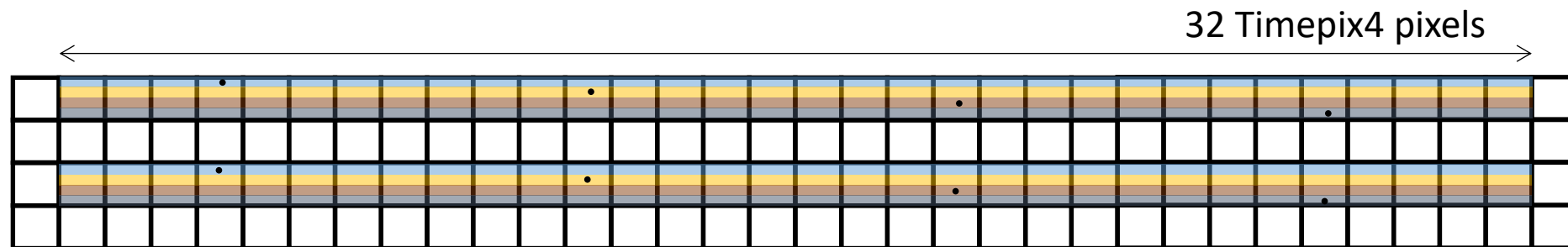


Magnetic spectrometer based on Timepix4

Rectangular pixel design as solution?

Pitch in non-bending direction is not crucial for particle kinetic energy determination

Use asymmetric “long thin” pixels with a “pitch adapter” for oversampling in one direction and connect only 1/8 pixels!



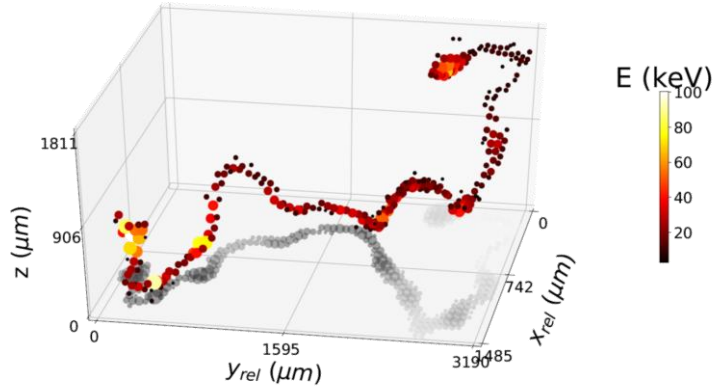
→ Pixel $13.75 \times 1760 \mu\text{m}$ - creates a matrix of 8224 in bending by 56 pixels in non-bending direction with $dx = 3.7 \mu\text{m}$

→ Power consumption reduced to **~25 W**. Further reduction by exploiting chip configurations (operation at reduced clock, ...)

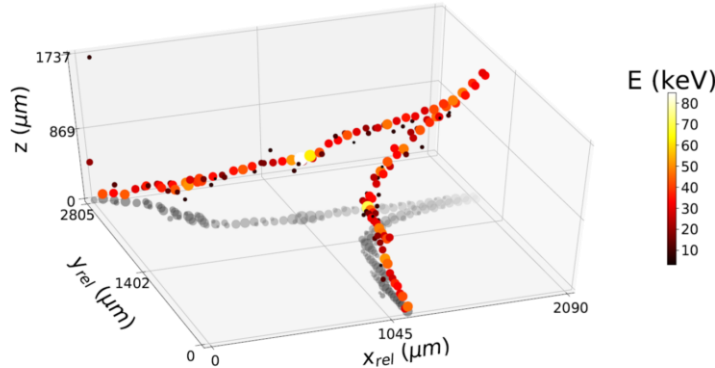
Assemblies have been produced and are now being tested in lab and test beams (SPS, PS)

3D track reconstruction – 2 mm CdTe

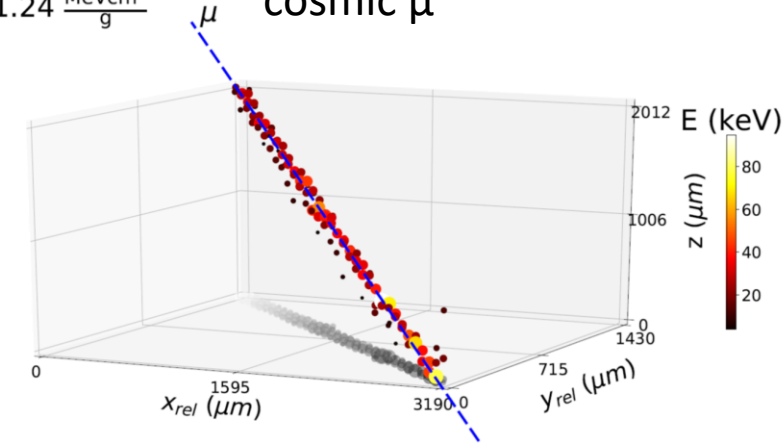
$E_{\text{dep}} = 5.66 \text{ MeV}$ $e^{-/+}$ like event



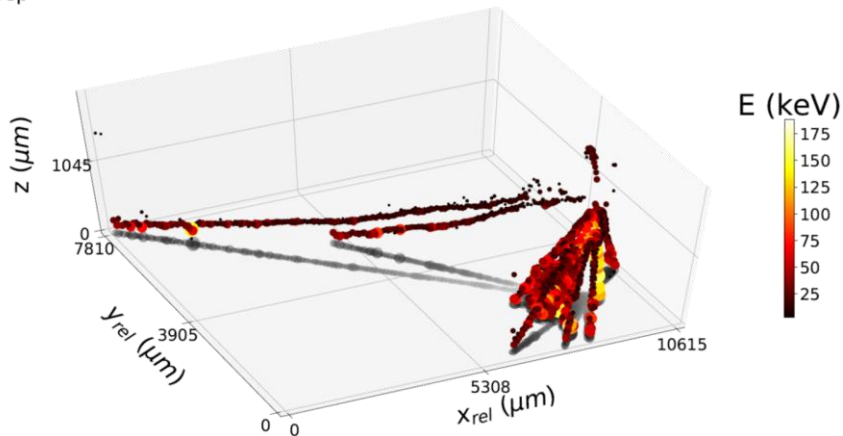
$E_{\text{dep}} = 3.96 \text{ MeV}$ pair production (!?)



$\frac{dE}{dx} = 1.24 \frac{\text{MeVcm}^2}{\text{g}}$ cosmic μ



$E_{\text{dep}} = 37.06 \text{ MeV}$ fragmentation



Trajectory reconstruction precision $< 200 \mu\text{m}$ at 1 m distance

z-resolution: $\sigma_z \sim 60 \mu\text{m}$

→ Improved determination of track directions

→ Improved separation of different particle classes

Bergmann et al., Eur. Phys. J. C (2019) 79: 165.

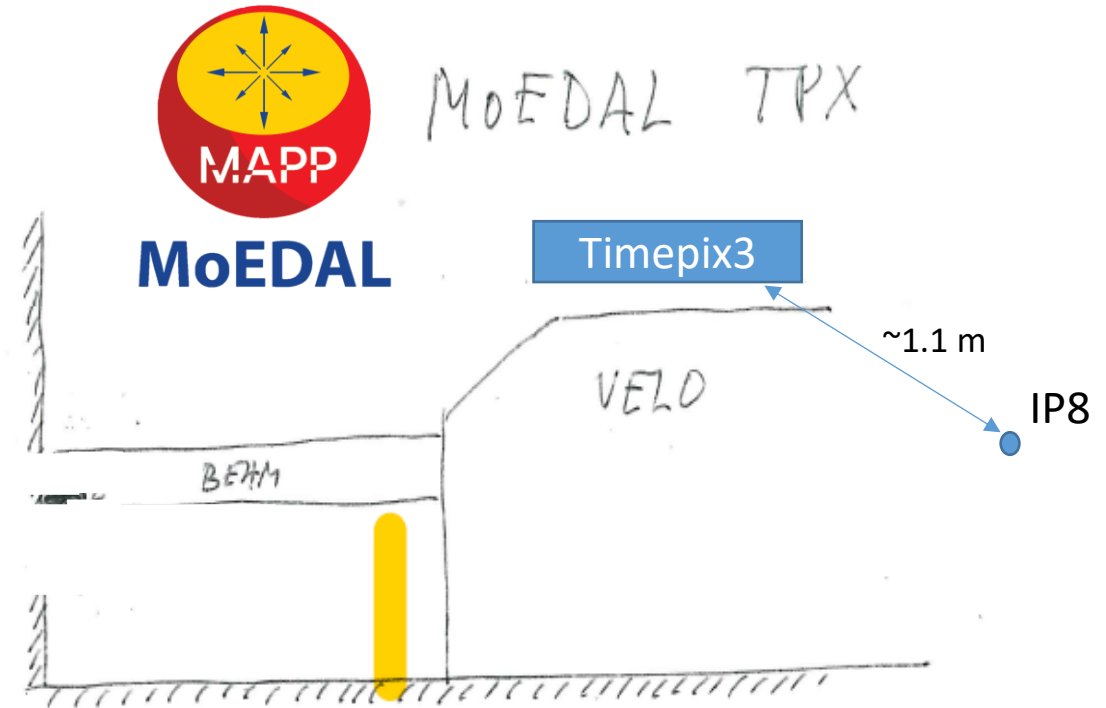
<https://doi.org/10.1140/epjc/s10052-019-6673-z>

LHC Experiments - MoEDAL Timepix3

Single-layer particle tracking for radiation field
characterization at IP8

Timepix3 within MoEDAL

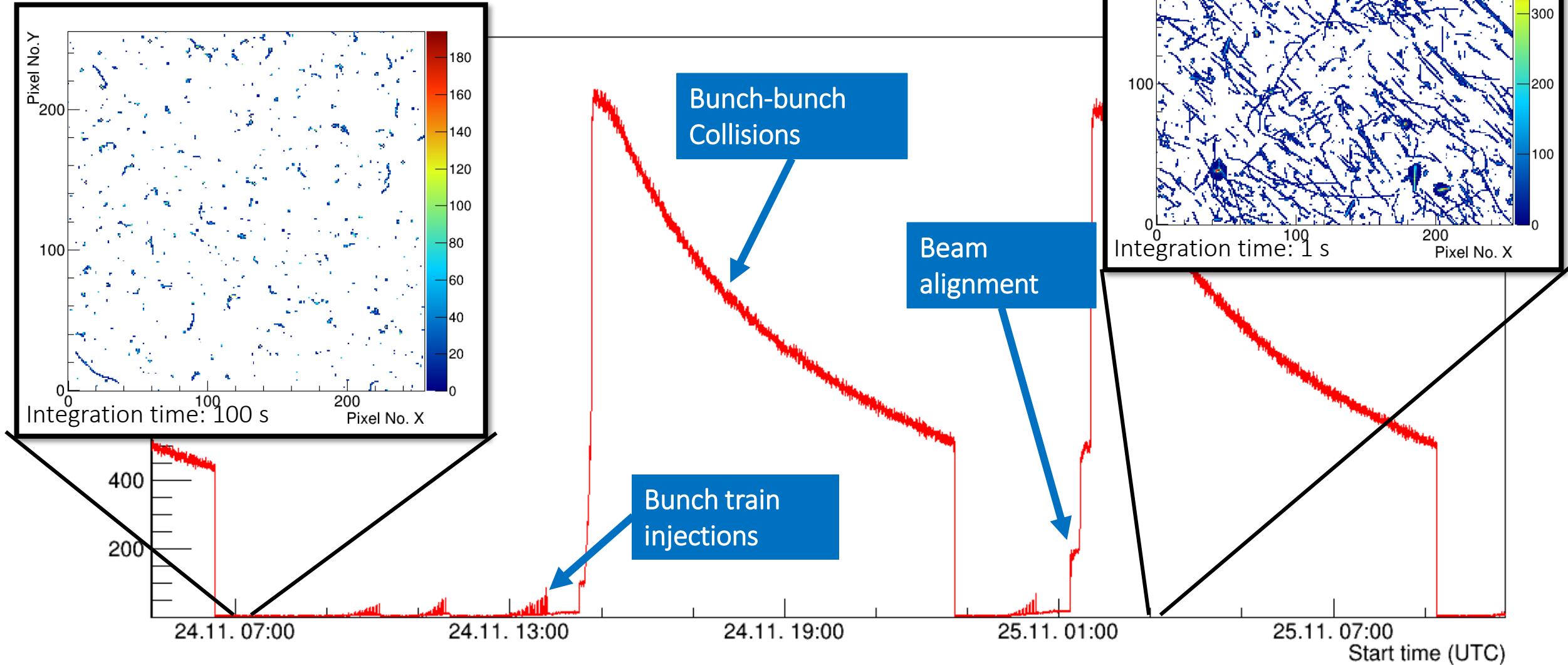
Installation of 2 Timepix3 detectors in MoEDAL in **September 2018**. Timepix3 are placed at 1.1 m distance to IP8 with a relatively unobstructed view



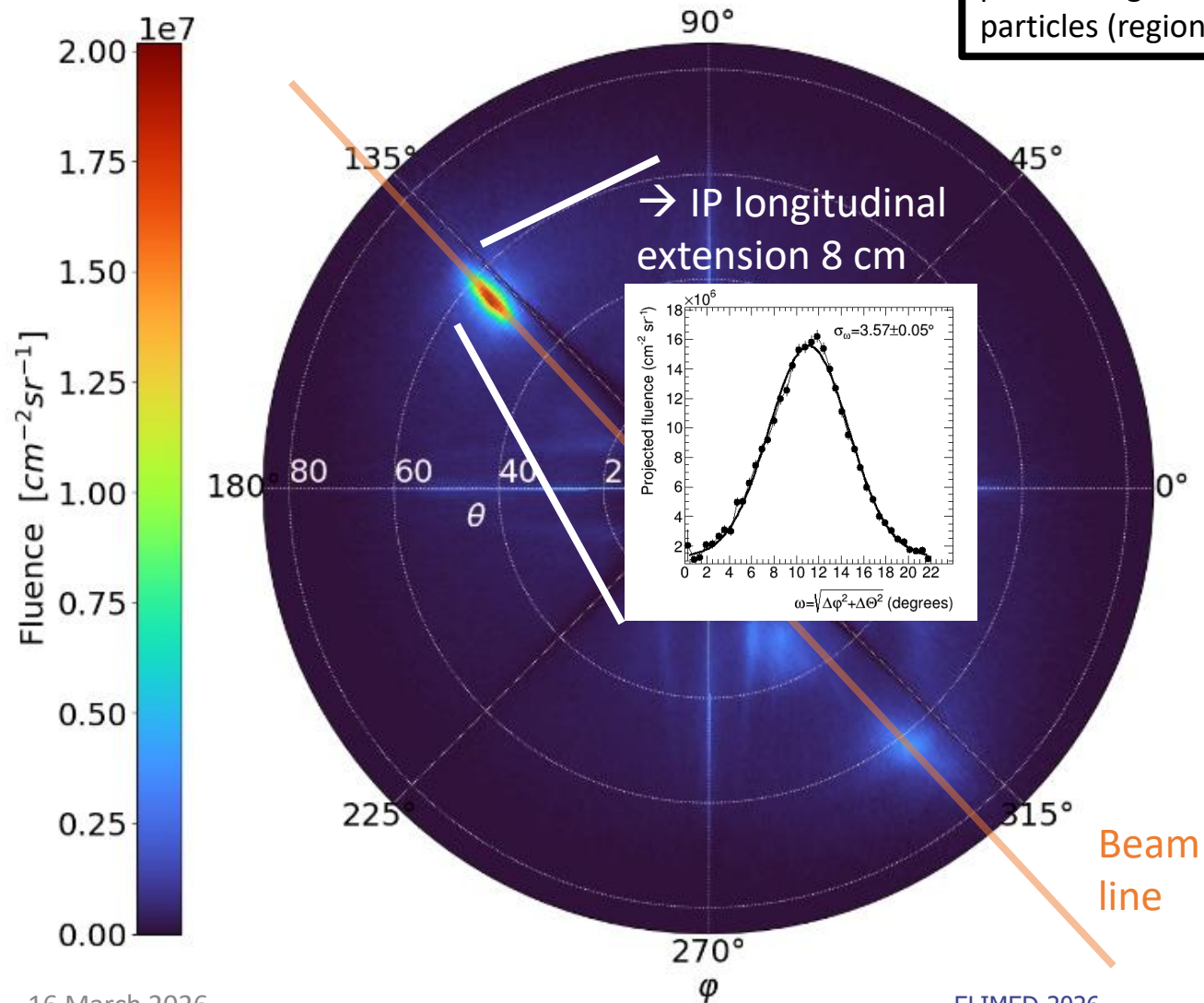
Continuous quasi dead-time free measurement (in real time) keeping a permanent record of **all particle traces**

- Tracking and identification of **all** particles
- Online outlier detection to search for exotics (highly ionizing events)

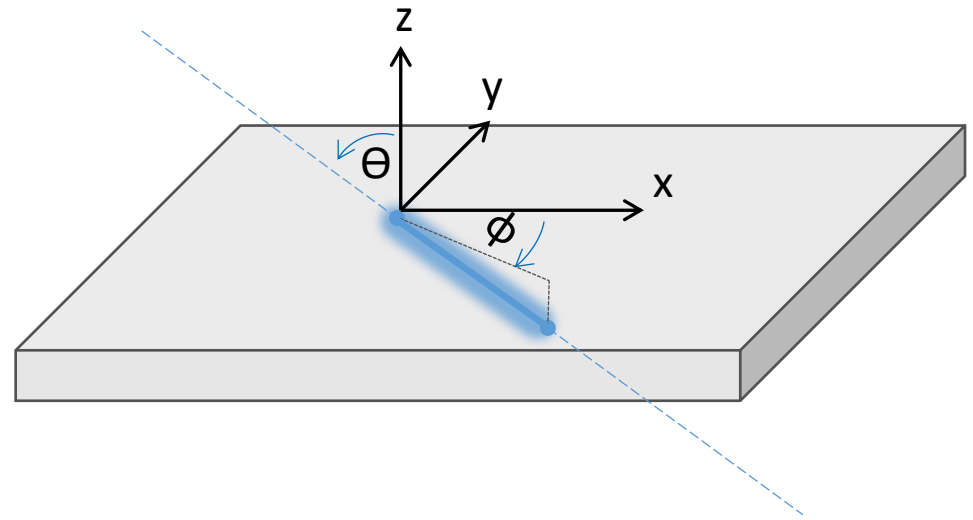
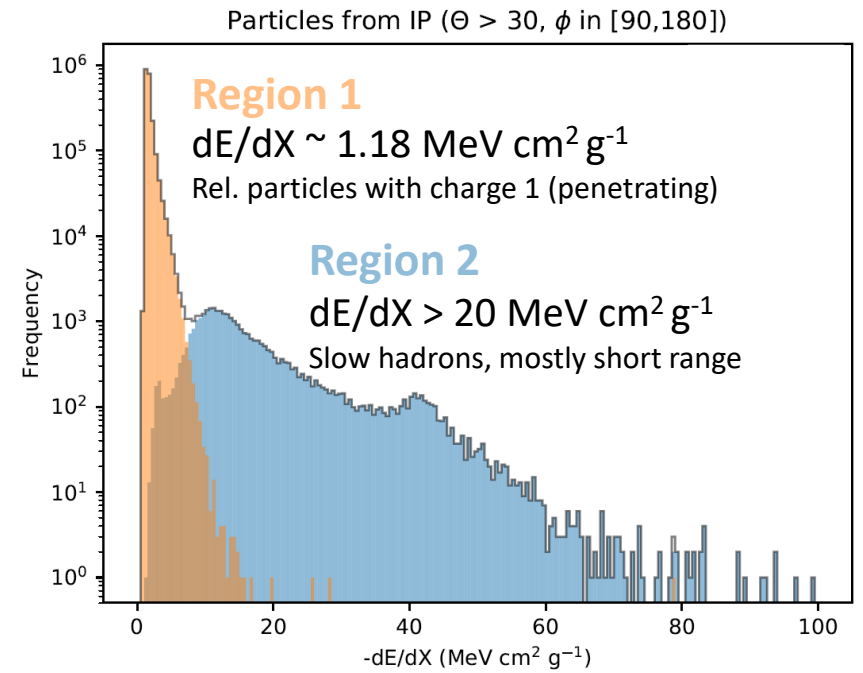
Radiation Levels and radiation Field within MoEDAL



Directionality map

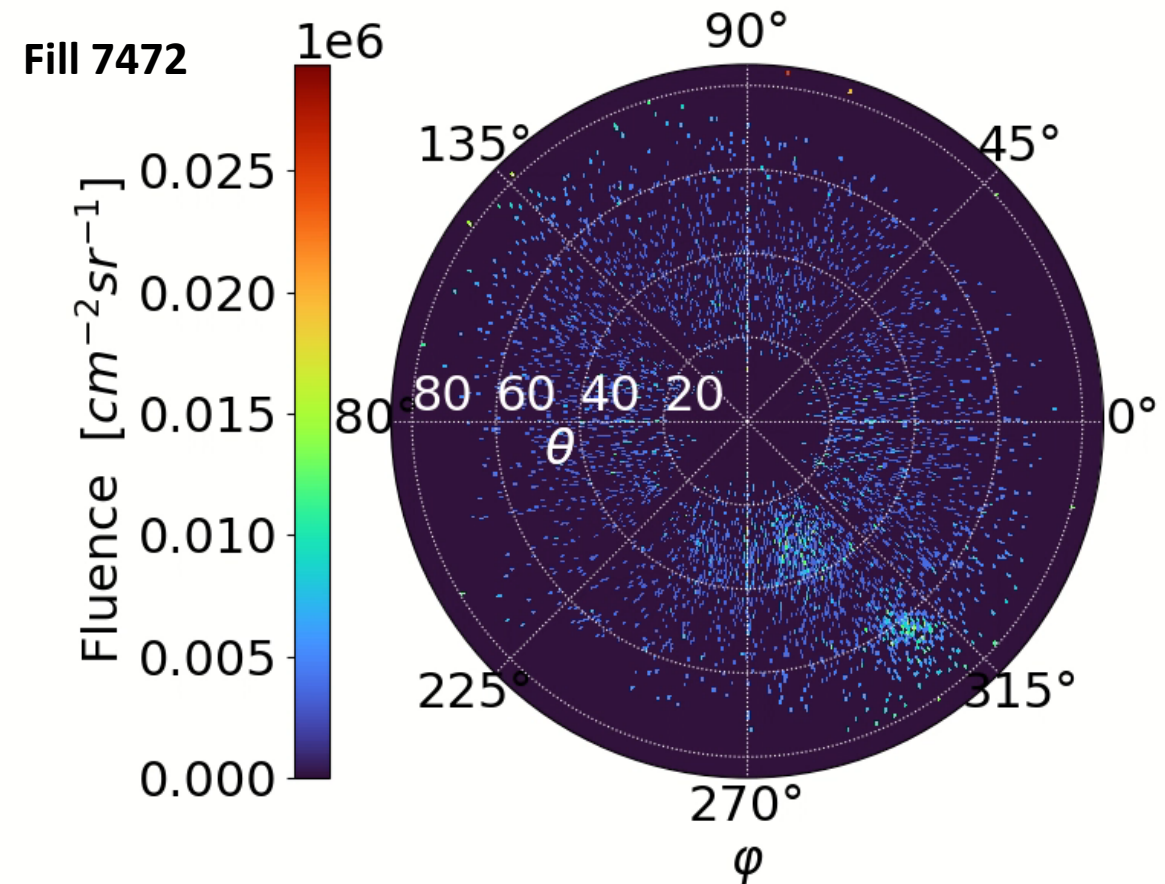
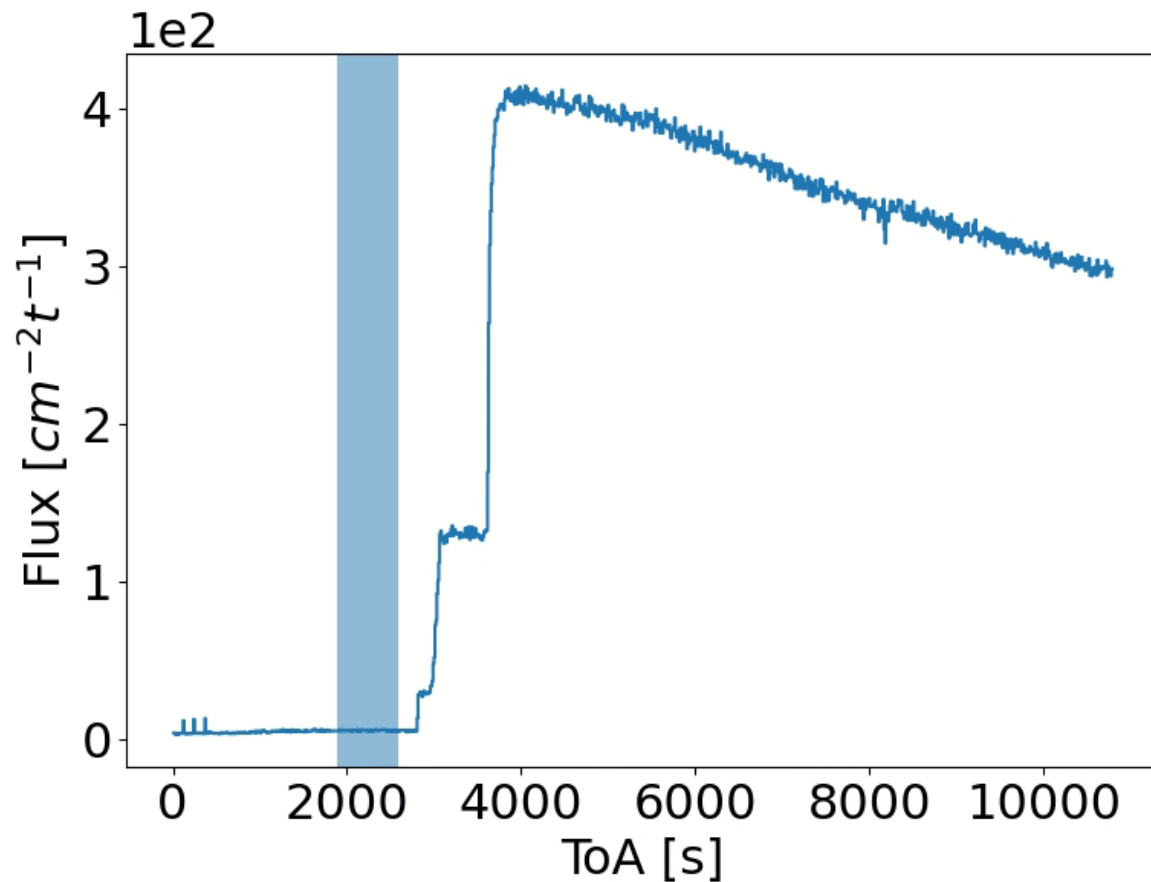


Directionality evaluated for penetrating particles (region 1)



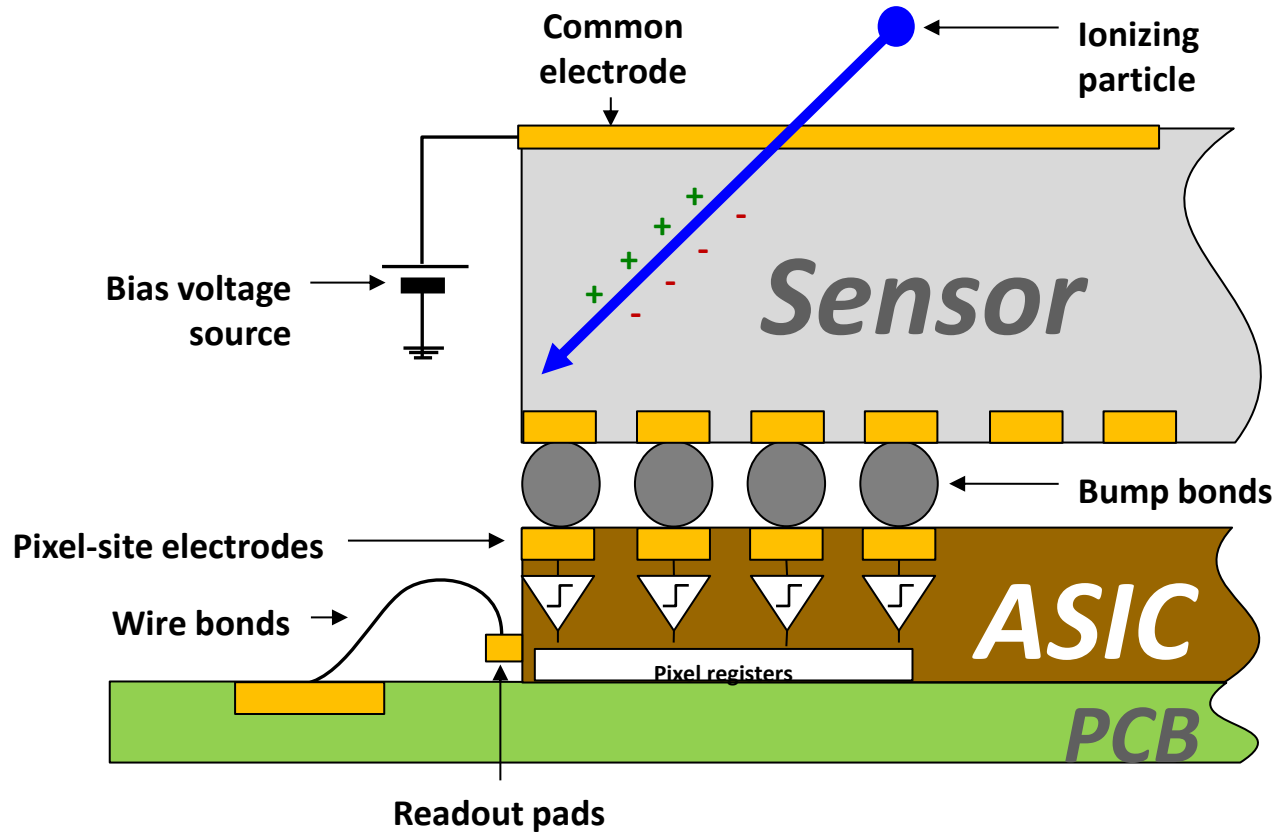
Time-resolved measurement of the directionality map $Pb-Pb$ collision period

Continuous
dead-time free
measurement

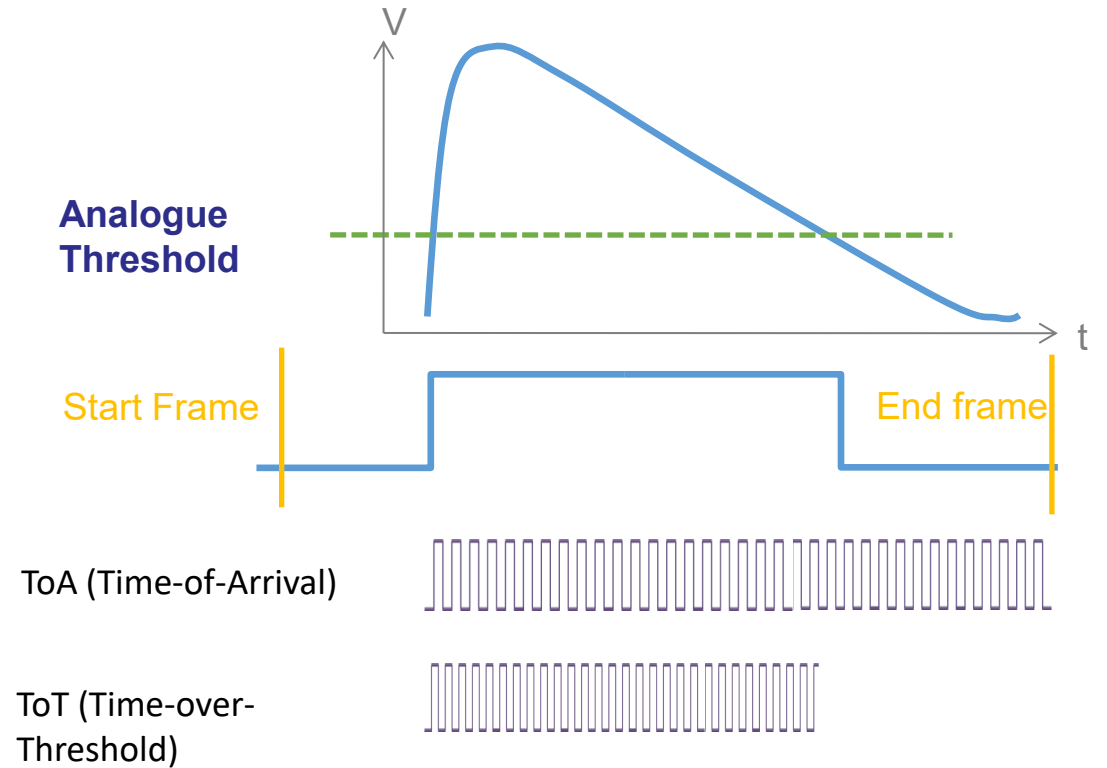


Working principle:

Modes of operation - Timepix



Timepix pixel processing:



Working principle:

Timepix3

- **Data-driven** readout with continuously running 40 MHz base clock
- **Simultaneous** measurement of ToT and ToA
- Local oscillator creates **640 MHz** clock for precise time stamping

