Novel detection techniques and space radiation research in orbit with Timepix detectors onboard satellites, the International Space Station and the Lunar Space Station Gateway

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ADVACAM *
Imaging the Unseen

www.advacam.com

*Spinoff of the Medipix Collaboration/IEAP CTU Prague

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MiniPIX Timepix3 Space

- ESA Gateway IDA
- One Web satellite LEO
- NASA Moon Orbiter

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Vladimir Daniel, et al.,

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E. Semones, et al.,

- ***NASA-ARC***, *USA*

L. Liddell, et al.,

- ***ESA***, *ESTEC, Noordwijk*

A. Owens, M. Vuolo

- ***LIP***, ***Coimbra Univ.***, *Portugal*

R. Silva et al.,

- ***One Web***, *UK-USA*

V. Colas, M. Sabia, et al.,

- ***Louisiana st. Univ.***, *USA*

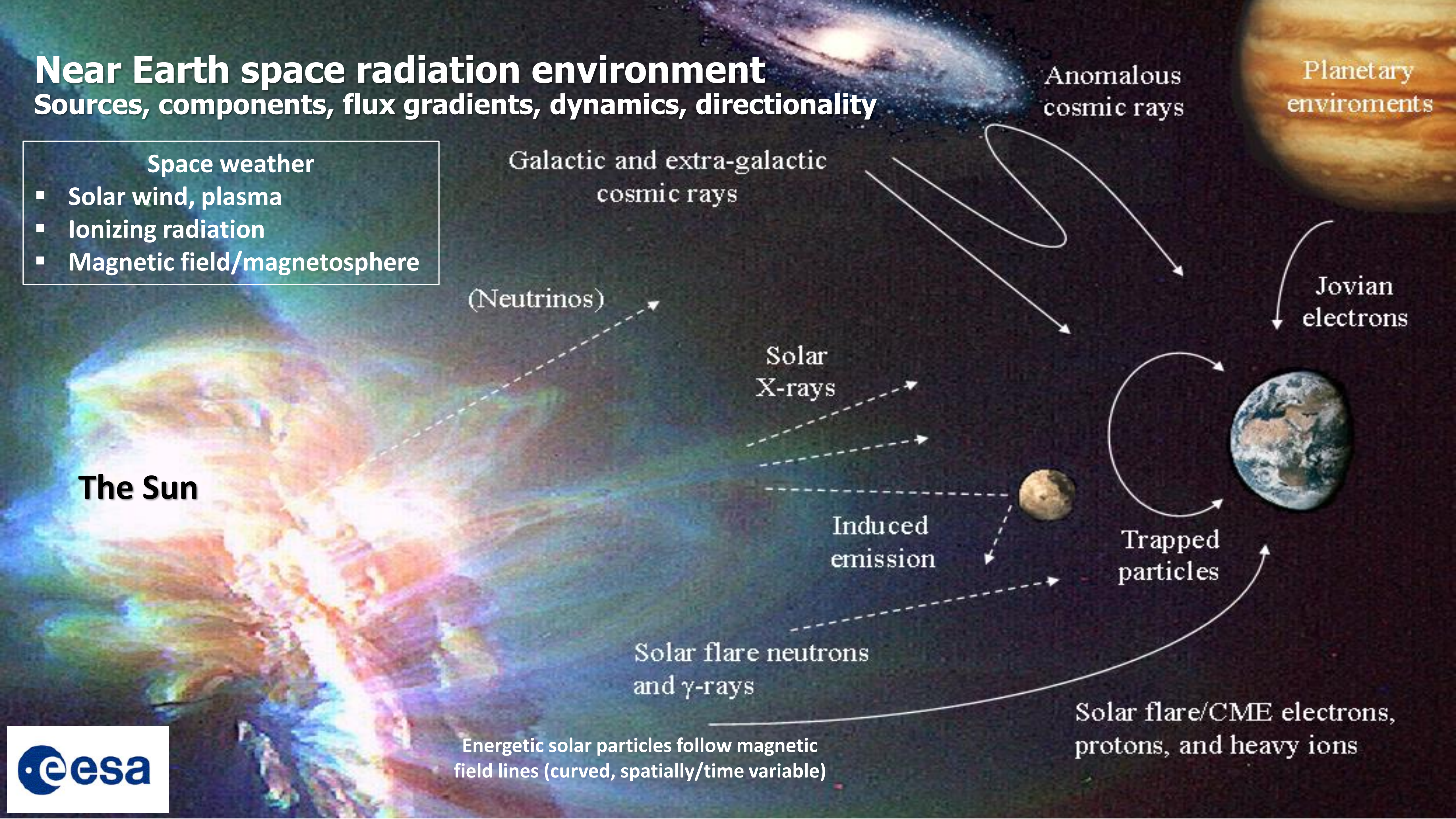
J. Chancellor, et al.,

Near Earth space radiation environment

Sources, components, flux gradients, dynamics, directionality

Space weather

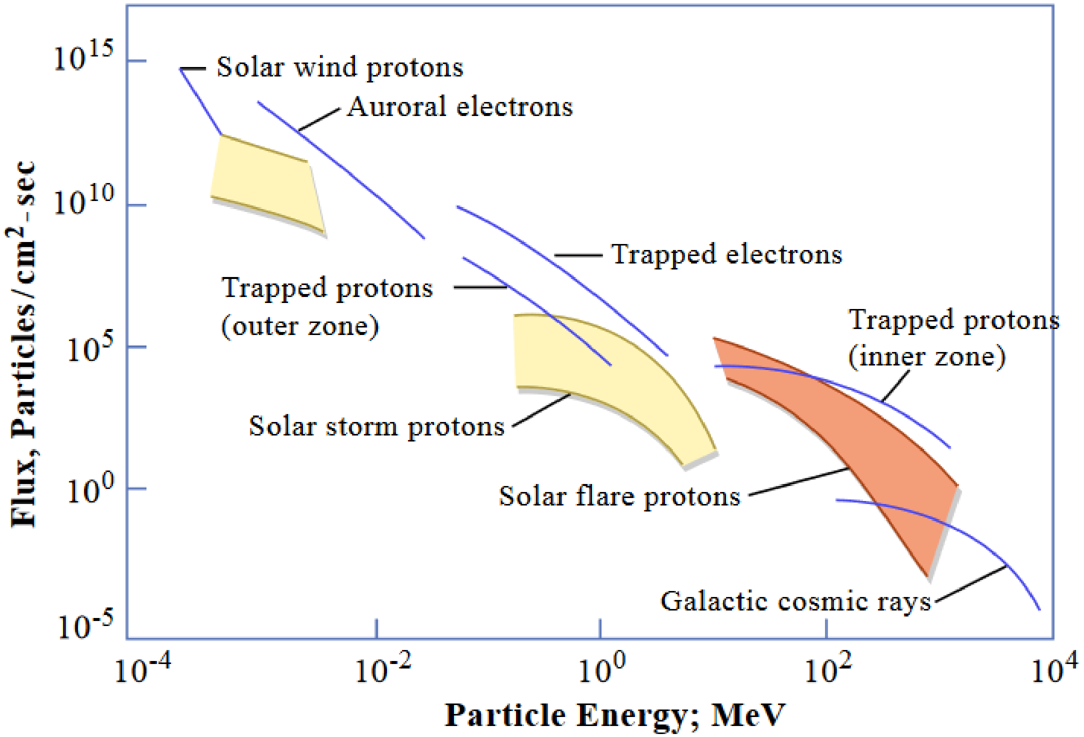
- Solar wind, plasma
- Ionizing radiation
- Magnetic field/magnetosphere



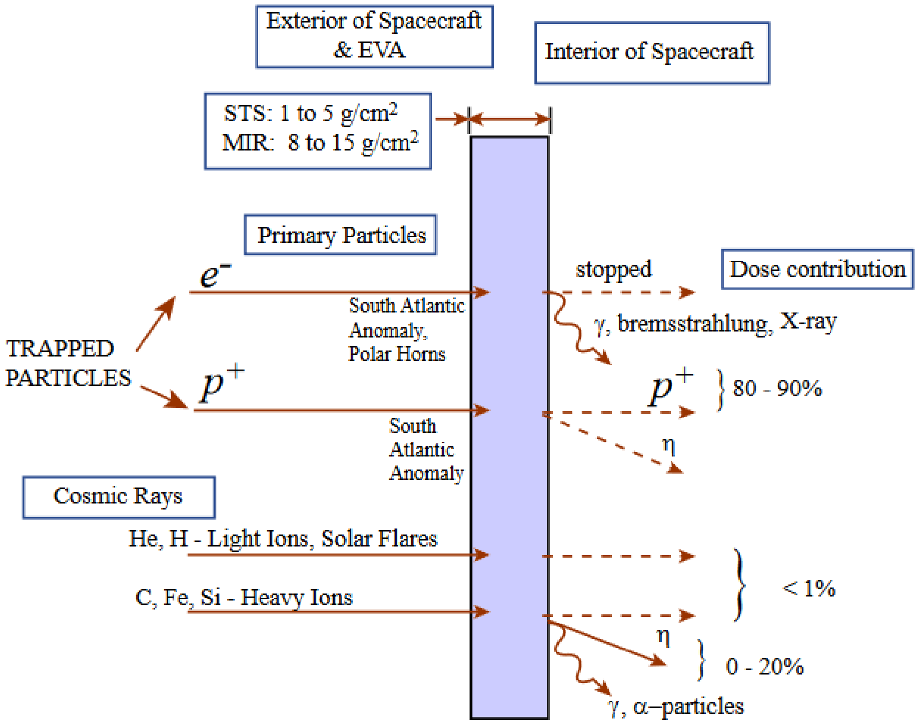
Space radiation

Composition, variability (intensity, time, orbit, location), directionality

Spectra and flux range of charged particles in space



Space radiation environment inside and outside spacecraft



Primary radiation

Secondary radiation

Space radiation

Composition, variability (intensity, time, orbit, location), directionality

- ❑ Components (e, p, ions, X, gamma, n)
- ❑ Wide energy range (keV, MeV, 100's MeV)
- ❑ Wide intensity range (6x - 9x orders of magnitude)
- ❑ Directional (2π Field-of-view/omnidirectional)
- ❑ Dynamic ← time variability (s, min, h, days, weeks)
- ❑ Location/orbit specific
- ❑ Primary ←→ secondary radiation

Composition characterization of mixed-radiation fields

Particle-event-type classification

Single chip Timepix3
500 um Silicon:

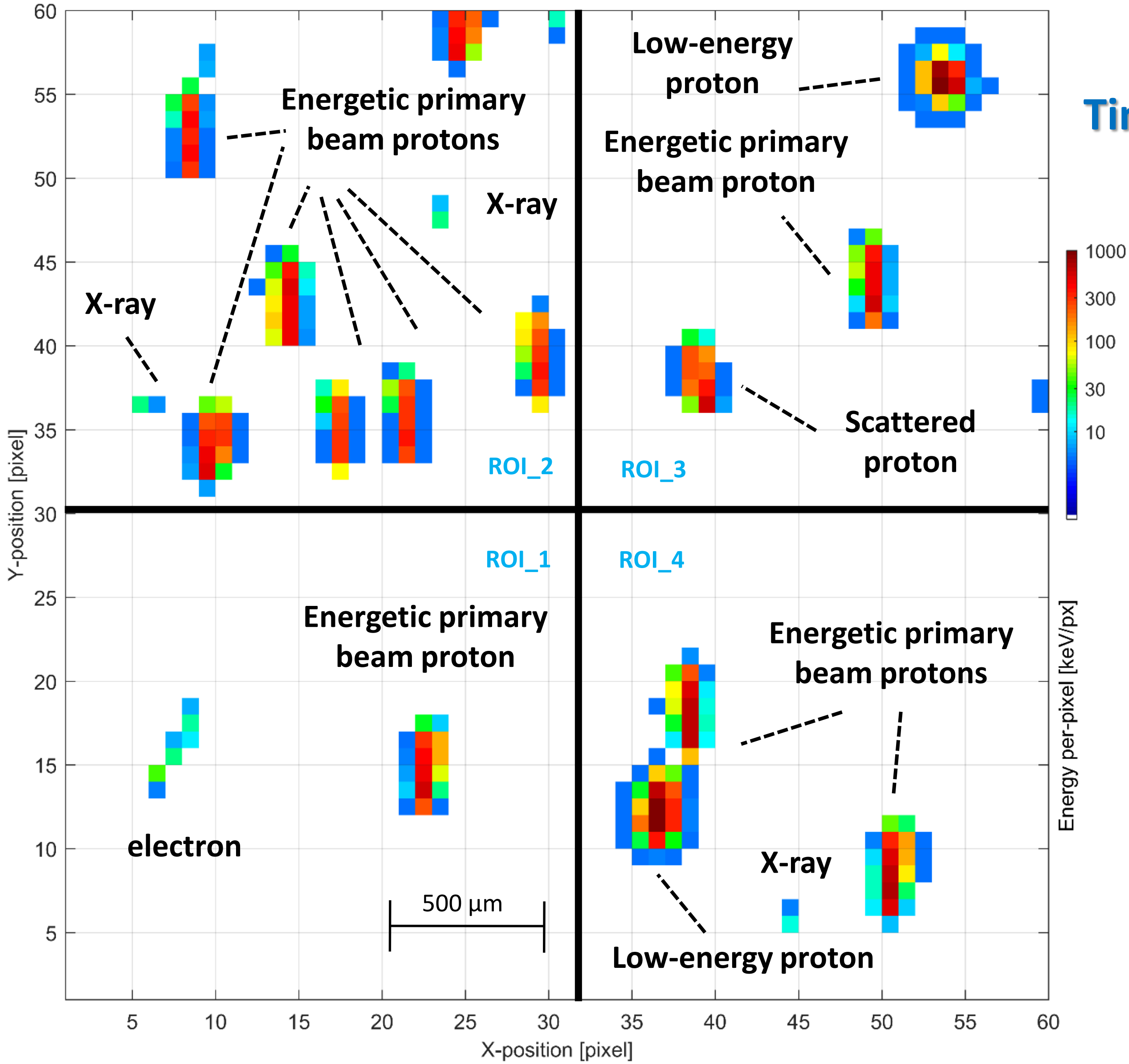
Composition and spectral characterization of mixed-radiation fields / space radiation

#	Class	Morphology	Interaction	Particle	Energy (direction)
1	A	Round	HETP	protons ions neutrons	1–50 MeV (< 10°), 1–4 MeV (OD) > 2 MeV/u (< 10°), 2–8 MeV/u (OD) fast ≥ MeV (OD), thermal[⊠] (OD)
2	*B*			protons ions neutrons	100 keV–1 MeV (OD), > 50 MeV (< 10°) 0.2–2 MeV/u (OD) fast ≈ MeV (OD); thermal[⊠] (OD)
3	*C*	Elongated		protons ions neutrons	4–50 MeV (> 10°) > 8 MeV/u (> 10°) fast ≥ MeV (OD)
4	*D*			protons neutrons	50–150 MeV (> 10°) fast ≥ MeV (OD)
5	*E*			protons	> 150 MeV (> 10°)
6	F[&]	Elongated	LETP	electrons	< 3 MeV (OD)
7	G[&%]			electrons	> 3 MeV (OD)
8	H[•]	Small		X rays	3–30 keV (OD)
9	I[@]	1–2 px	noisy px	---	---

HETP = high-energy transfer particles, LETP = low-energy transfer particles, OD = omnidirectional, ⊠ = in the region of the thermal converter mask, & = including gamma rays (low-energy <1 MeV), % admixture of muons and MIP protons >250 MeV) (>10°), ● admixture of muons, MIP protons >250 MeV (<10°), @ admixture of slow (≈ MeV) neutron (short-range low-energy) interactions.

Spectral tracking & quantum-imaging detection of single particles

Single chip radiation camera MiniPIX-Timepix3



Resolving power/classification of particle-type events

Timepix3 Si 500 µm: charged particles (e, p, ions), X rays, gamma rays

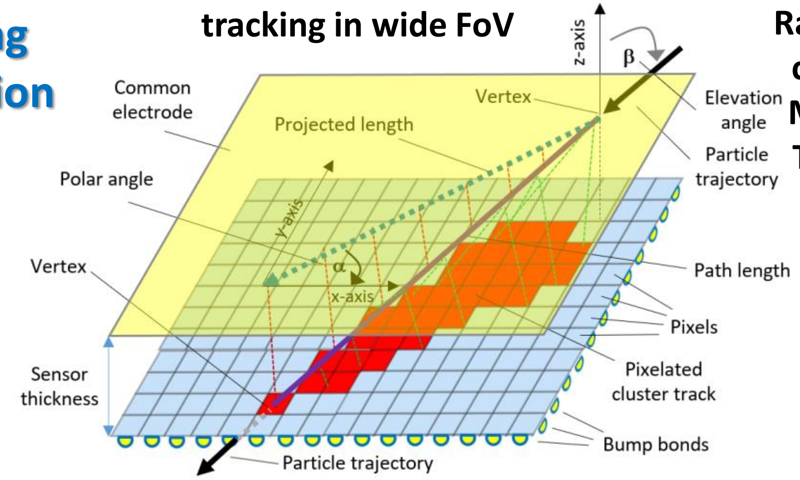
- ❑ Decomposition of mixed-radiation field
- ❑ Energy loss ΔE
- ❑ Particle track Δd
- ❑ LET = ΔE/ Δd
- ❑ Direction
- ❑ Timing
- ❑ Position

TPX3 ASIC chip
Si 500 µm sensor

Radiation camera MiniPIX TPX3 Si

Spectral-sensitive particle tracking in wide FoV

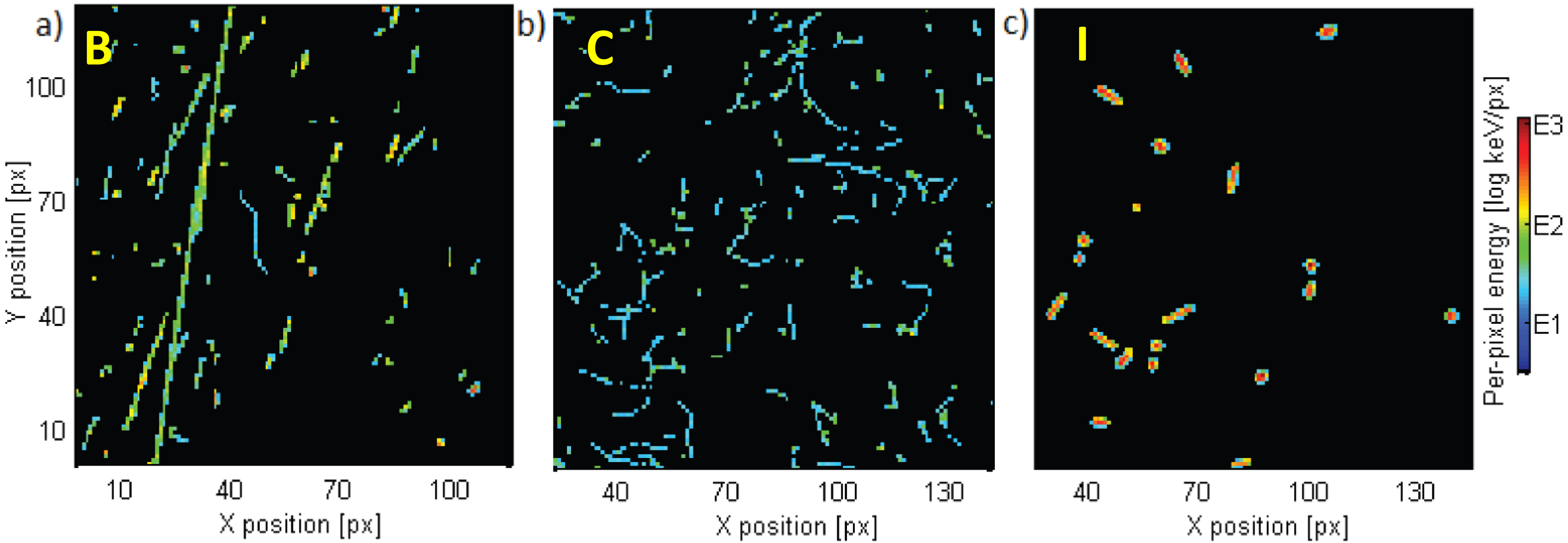
Active nuclear emulsion



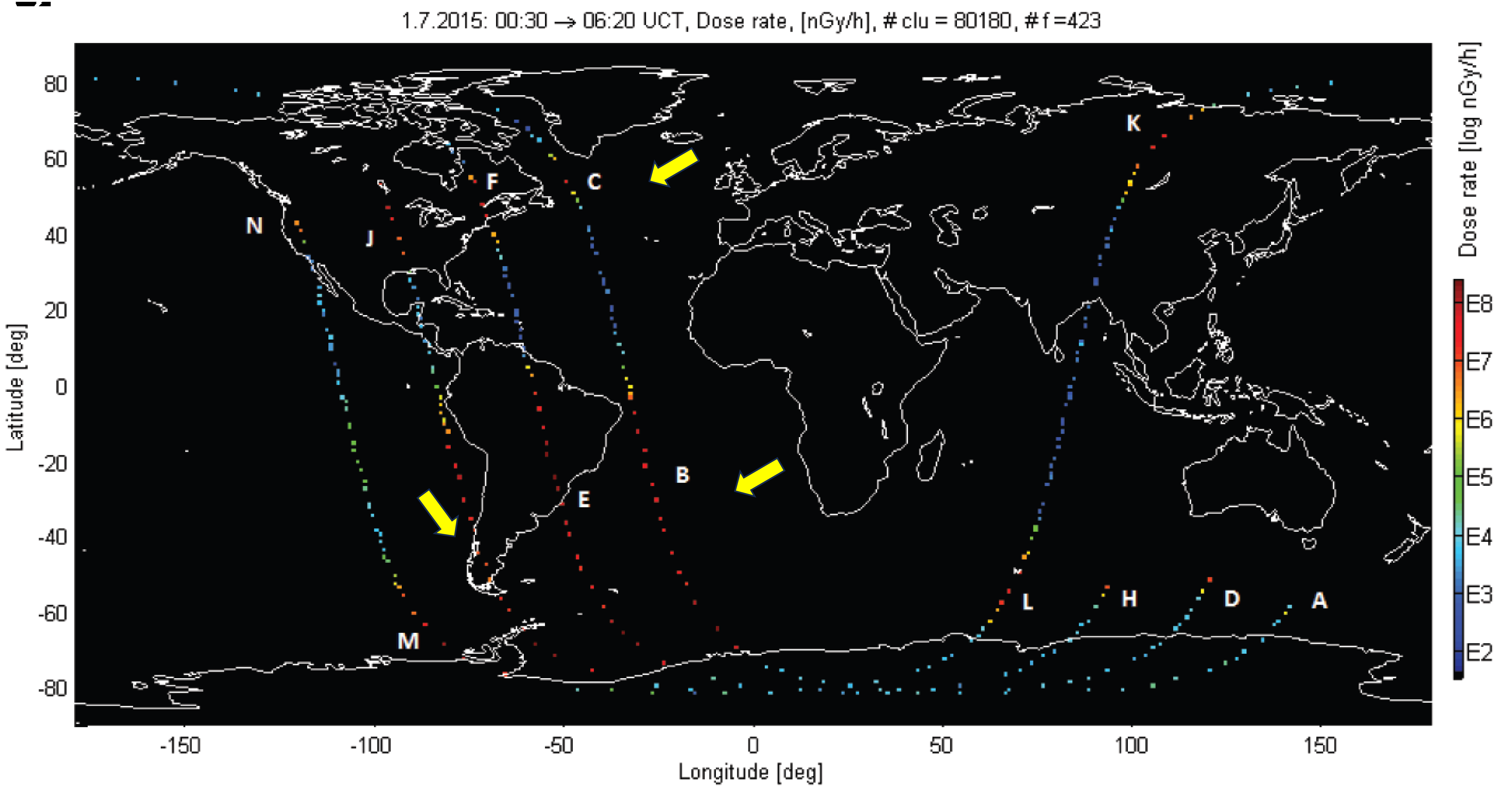
Space radiation: characterization by Timepix

SATRAM-Timepix payload onboard ESA's Proba-V satellite, LEO orbit, launch 2013

Energetic protons > 70 MeV | **MeV electrons** | **Low-energy protons < 70 MeV**



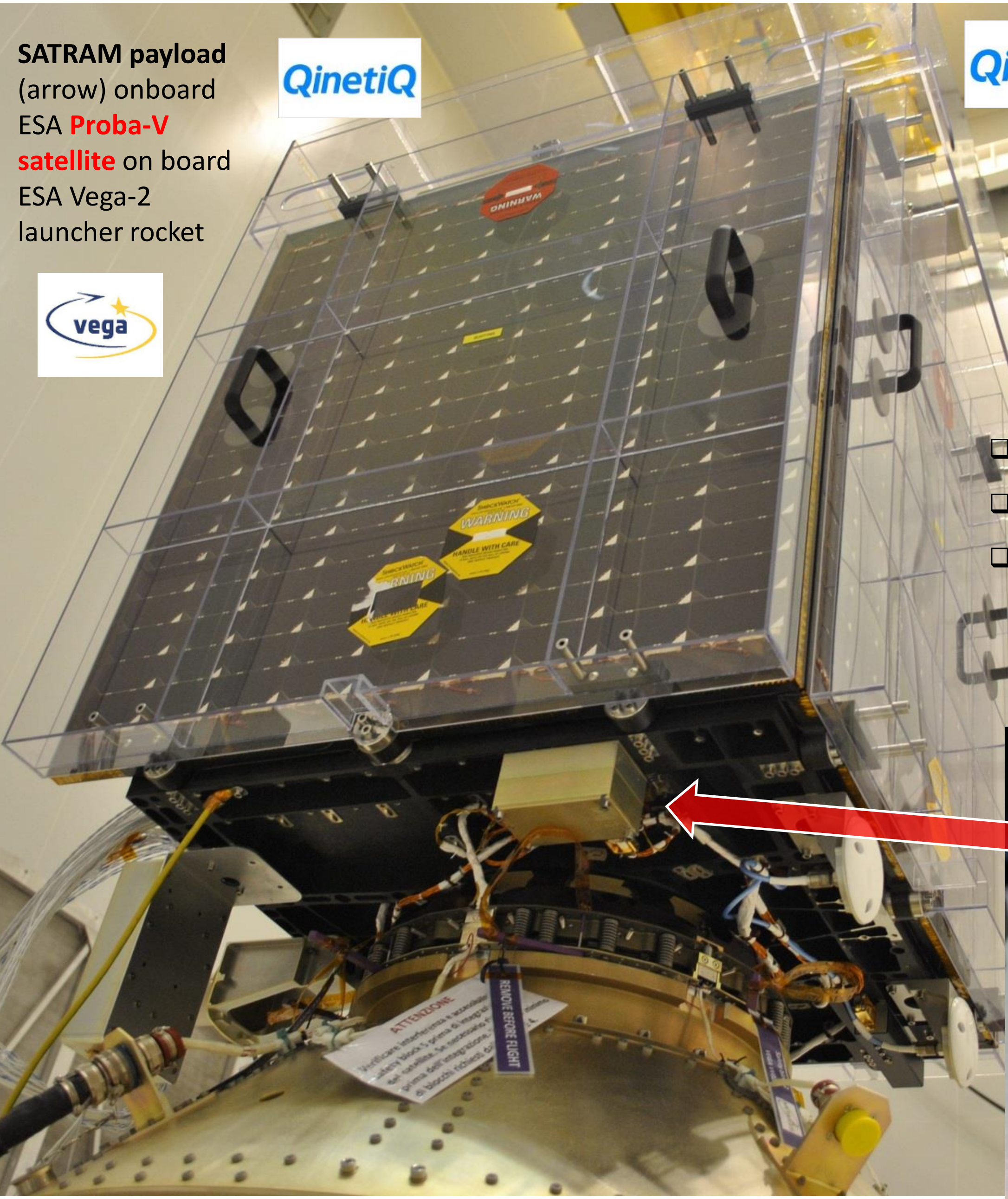
SSA center | **Polar horns northern hemisphere** | **SSA mid**


1.7.2015: 00:30 → 06:20 UCT, Dose rate, [nGy/h], # clu = 80180, # f =423
Latitude [deg]
Longitude [deg]
Dose rate [log nGy/h]
E8
E7
E6
E5
E4
E3
E2
80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150
A
B
C
D
E
F
H
J
K
L
M
N

Heritage: SATRAM: Space Application of Timepix Radiation Monitor

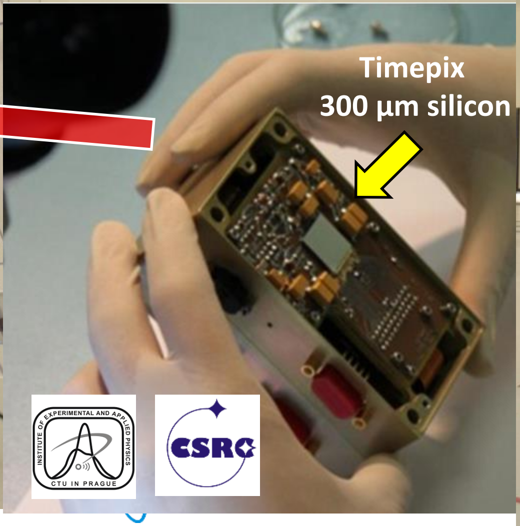
C. Granja, IEAP CTU Prague 2015

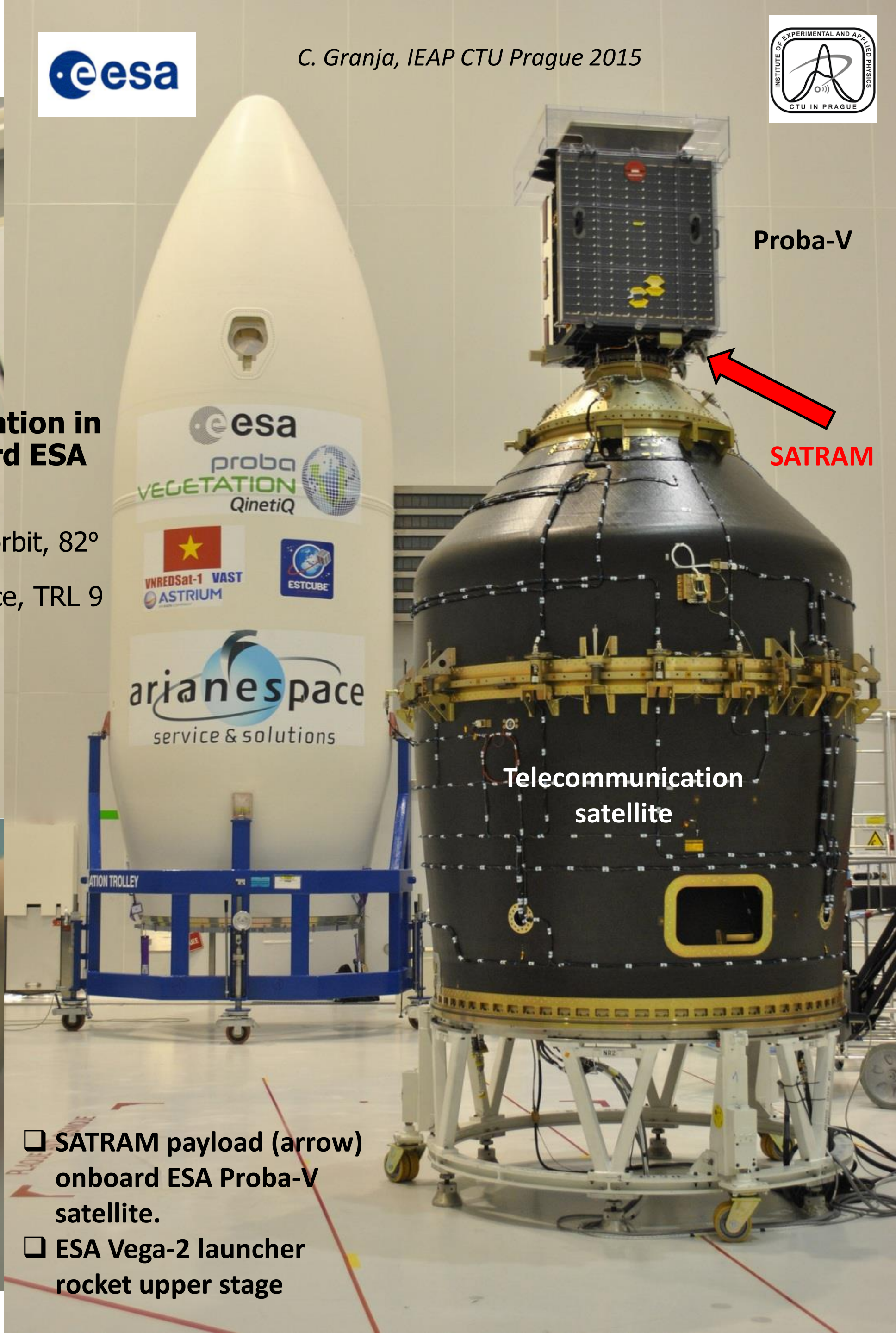
SATRAM payload (arrow) onboard ESA **Proba-V satellite** on board ESA Vega-2 launcher rocket



Characterization of space radiation in Low Earth Orbit (LEO) onboard ESA PROBA-V satellite

- LEO 820 km, polar sun synchronous orbit, 82°
- Timepix first deployment in open space, TRL 9
- Launched 7th May 2013





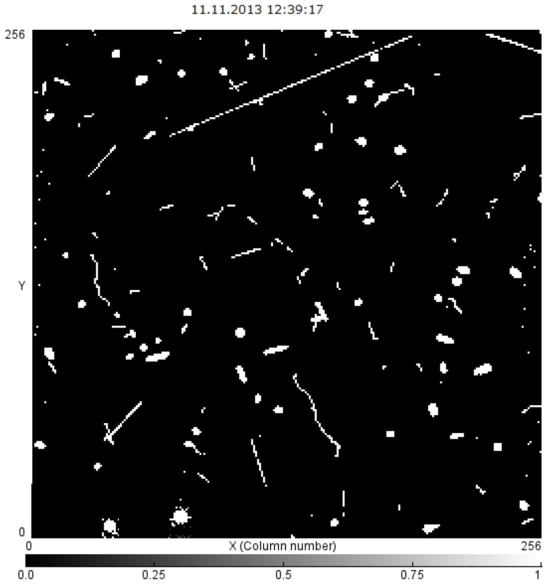
- SATRAM payload (arrow) onboard ESA Proba-V satellite.
- ESA Vega-2 launcher rocket upper stage

C. Granja, IEAP CTU Prague 2015

SATRAM/Timepix on board Proba-V
Quantum imaging detection/monitoring of space radiation in LEO orbit 820 km

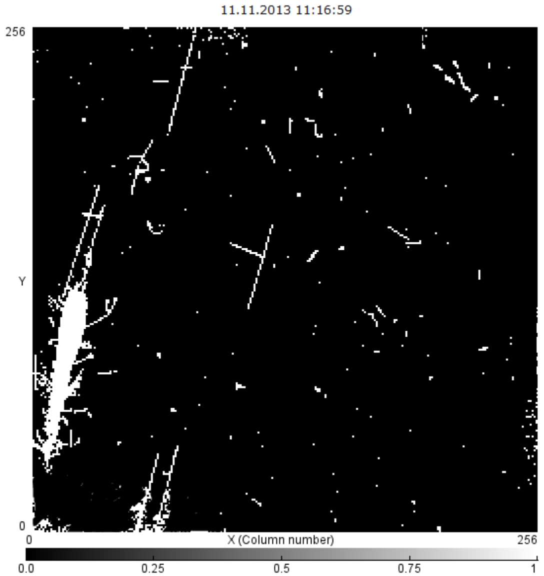
Timepix 300 µm silicon sensor

Timepix operated in **counting mode**
Space radiation along Proba-V 820 km LEO orbit.
Data from different orbit locations



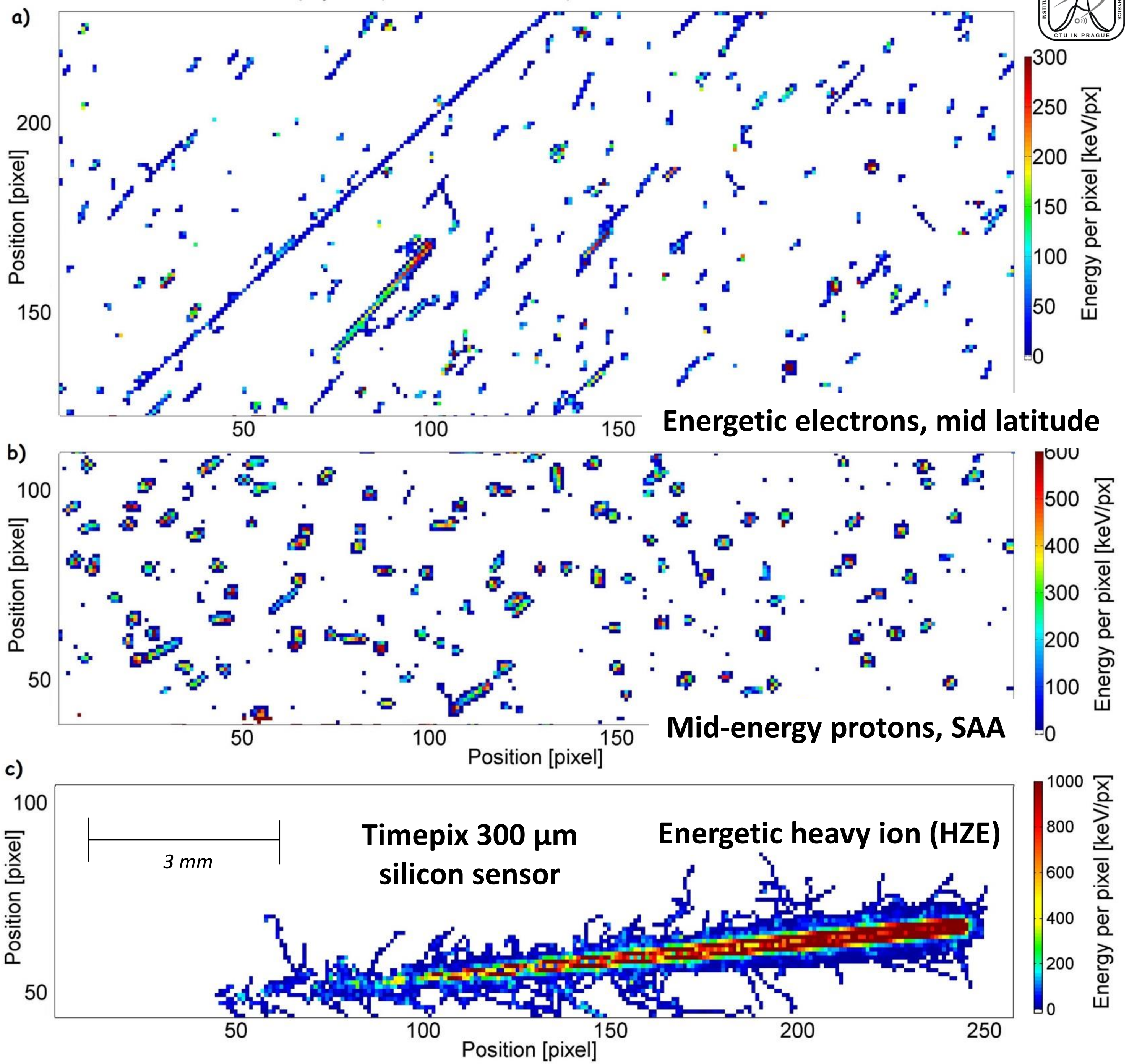
SAA

Beyond belt crossing



Timepix (operated in **energy mode**) recorded at different orbit locations

SATRAM payload (TPX 300 um silicon) onboard ESA Proba-V satellite

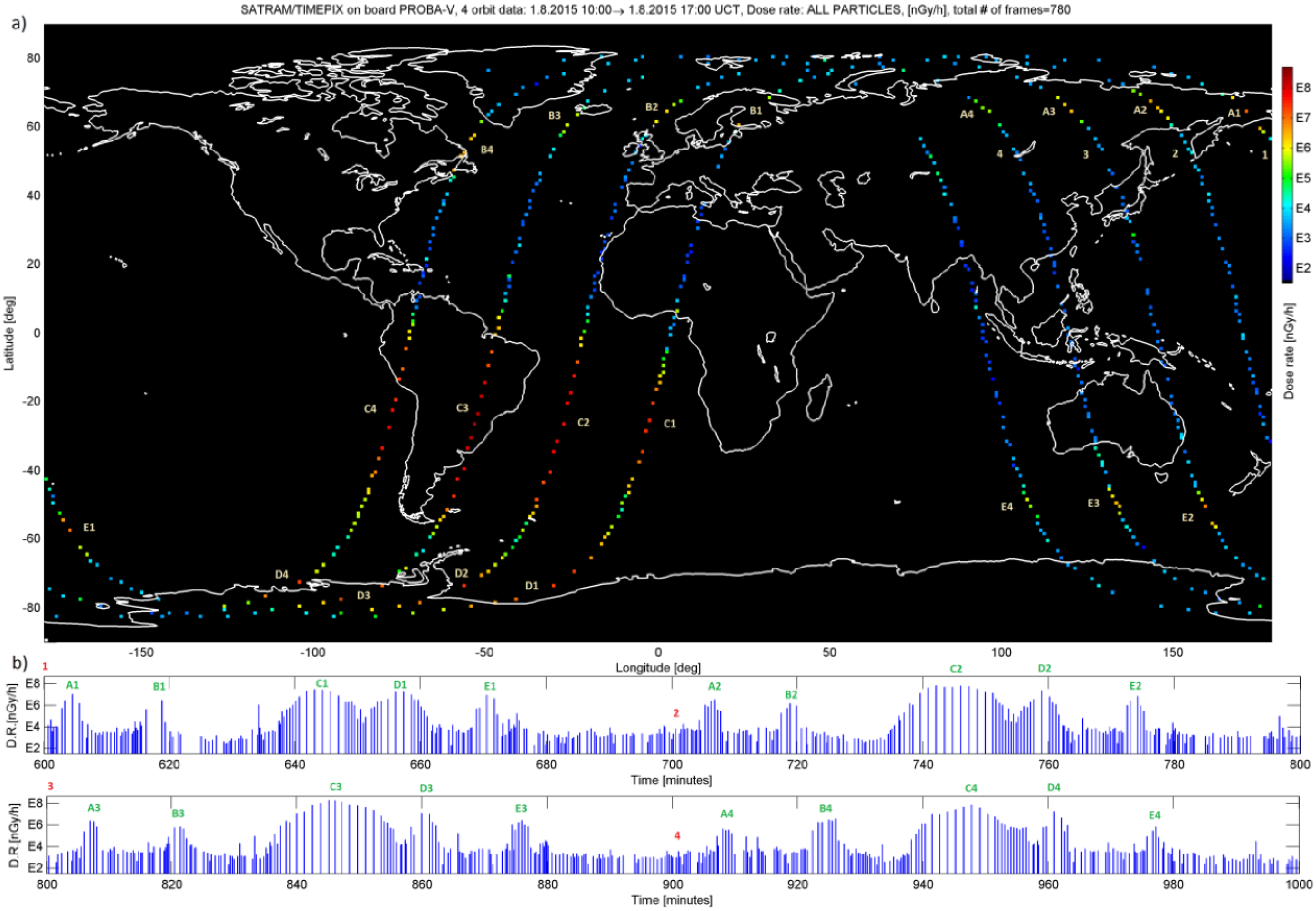


SATRAM/Timepix on board Proba-V → Mapping of Space Radiation along Proba-V Orbit

C. Granja,
IEAP CTU Prague 2015

Distribution along satellite orbit: dose rate

6 h 45 min
4 orbits



Time histogram: dose rate

6 h 45 min
4 orbits

SATRAM/Timepix on board Proba-V → Mapping of Space Radiation along Proba-V Orbit

C. Granja,
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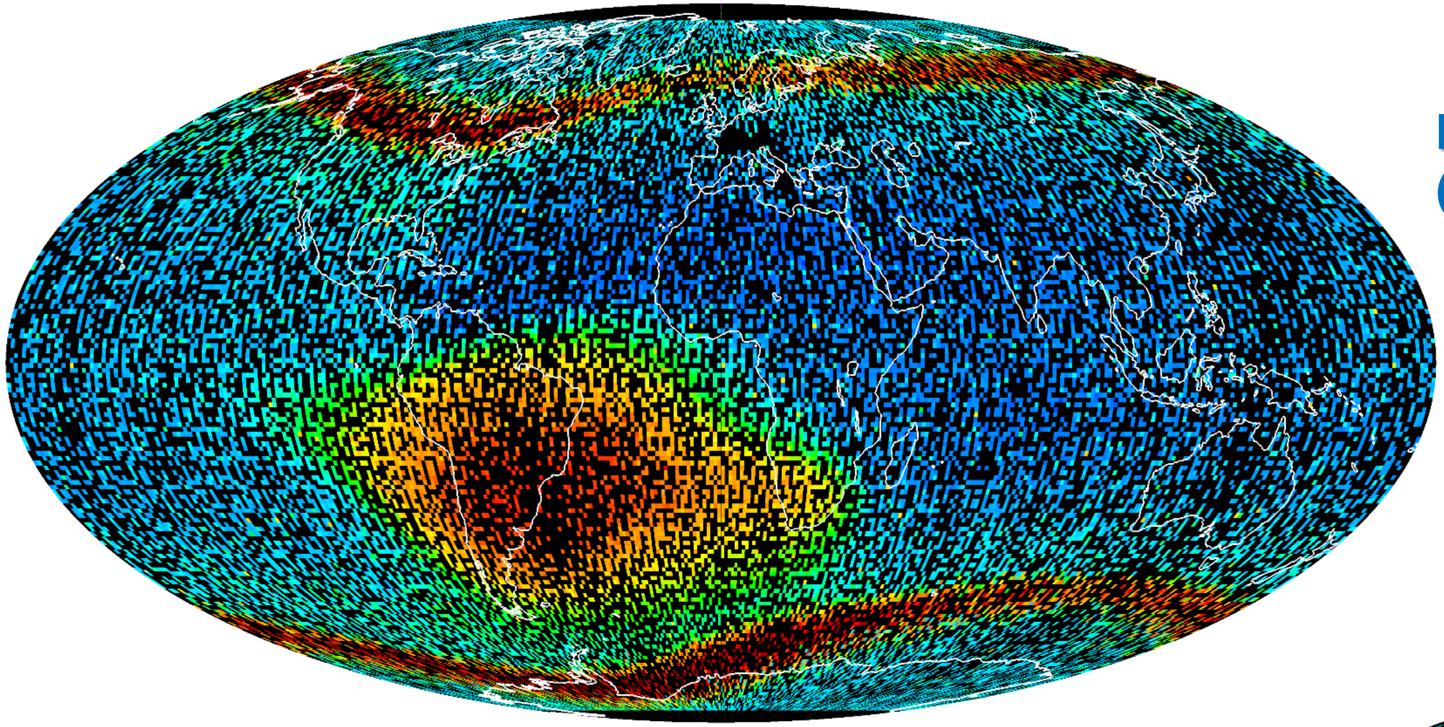
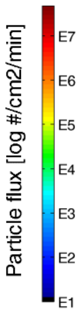


Map: Particle Flux (all particles)

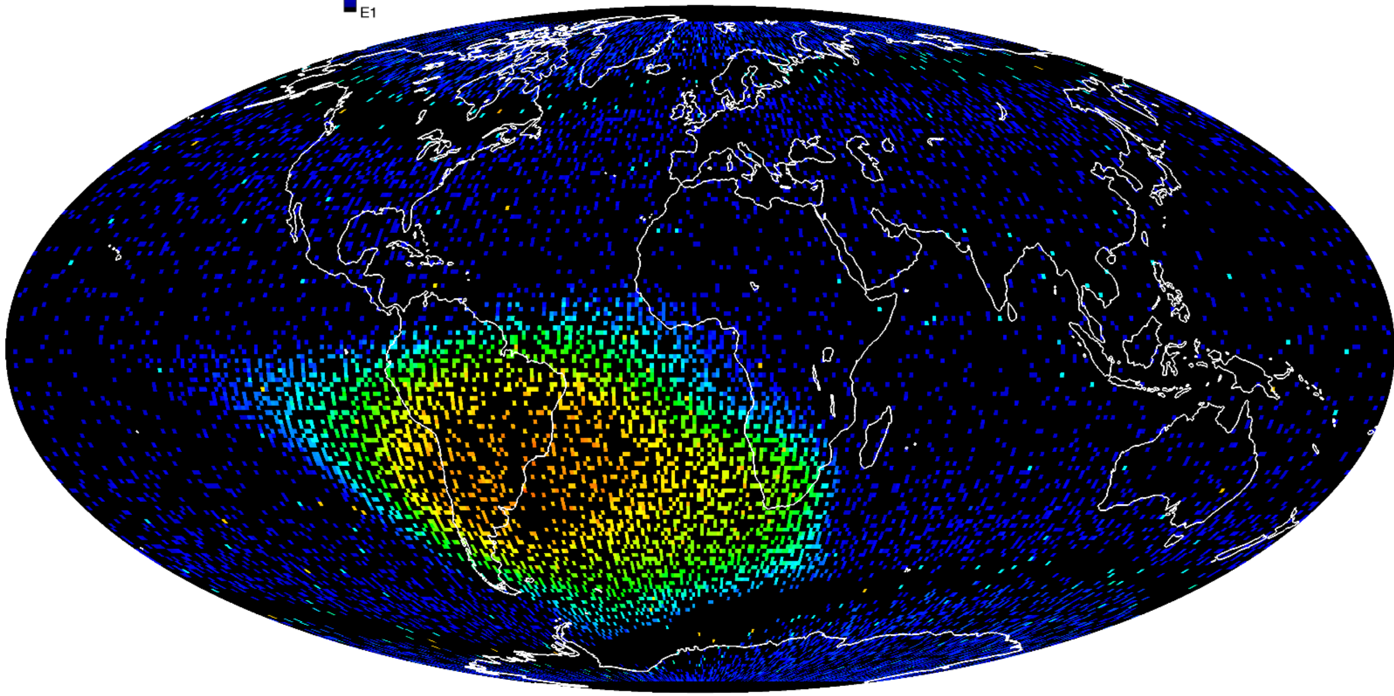


Particle count rate shown in color in log scale spanning over 6 orders of magnitude.

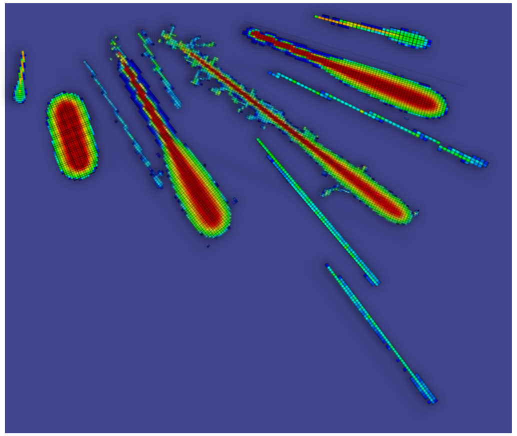
SATRAM/Timepix on board Proba-V

Data shown for 19 days (1-19 Oct 2014)

Map: Particle Flux (protons)



Orbit distributions of particle flux in Proba-V SATRAM Timepix:
All particles (top left), **Heavy charged particles** (bottom right)



Timepix detector visualizes and recognizes each particle of cosmic radiation

Areas/Applications

- Radiation effects
- Spacecrew dosimetry
- Space Weather
- Space Physics, science

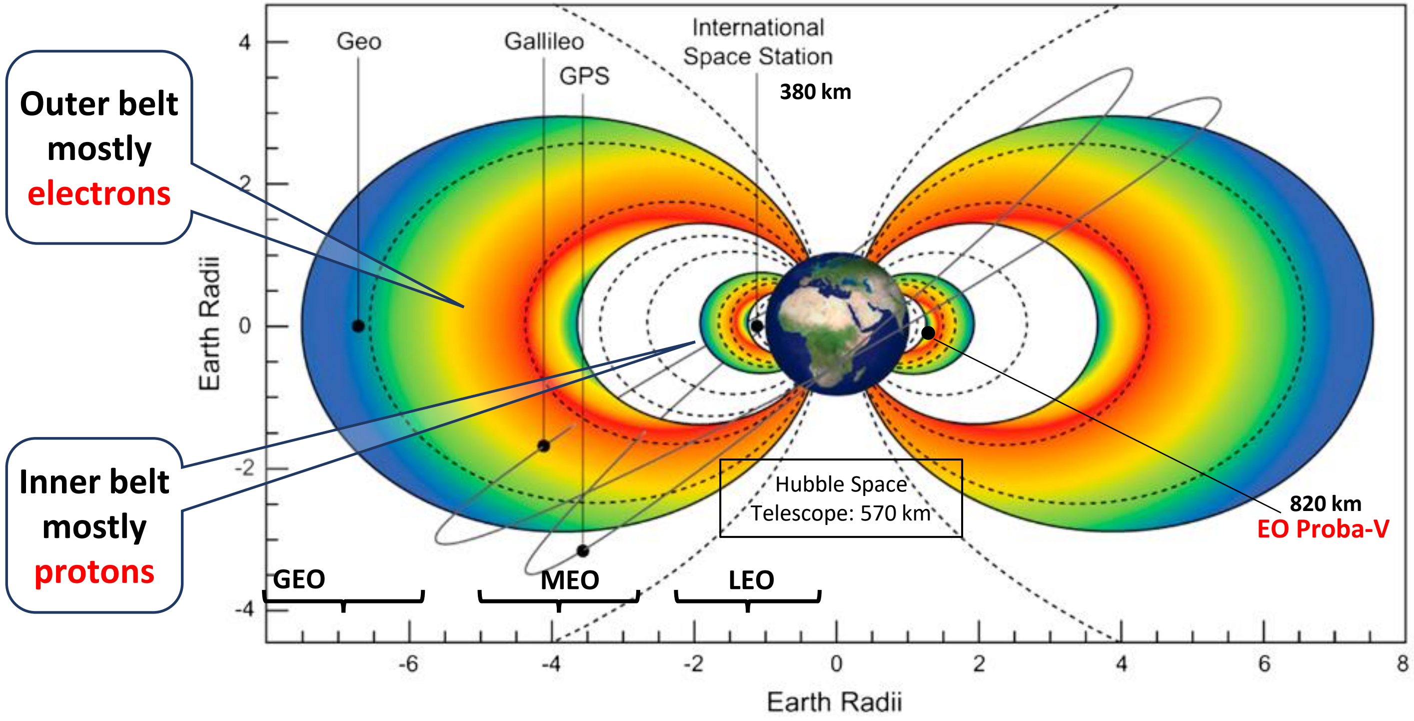
Space radiation → hazards & risk for biological and electronic systems

The risks are much higher beyond the shield of the Earth magnetic field

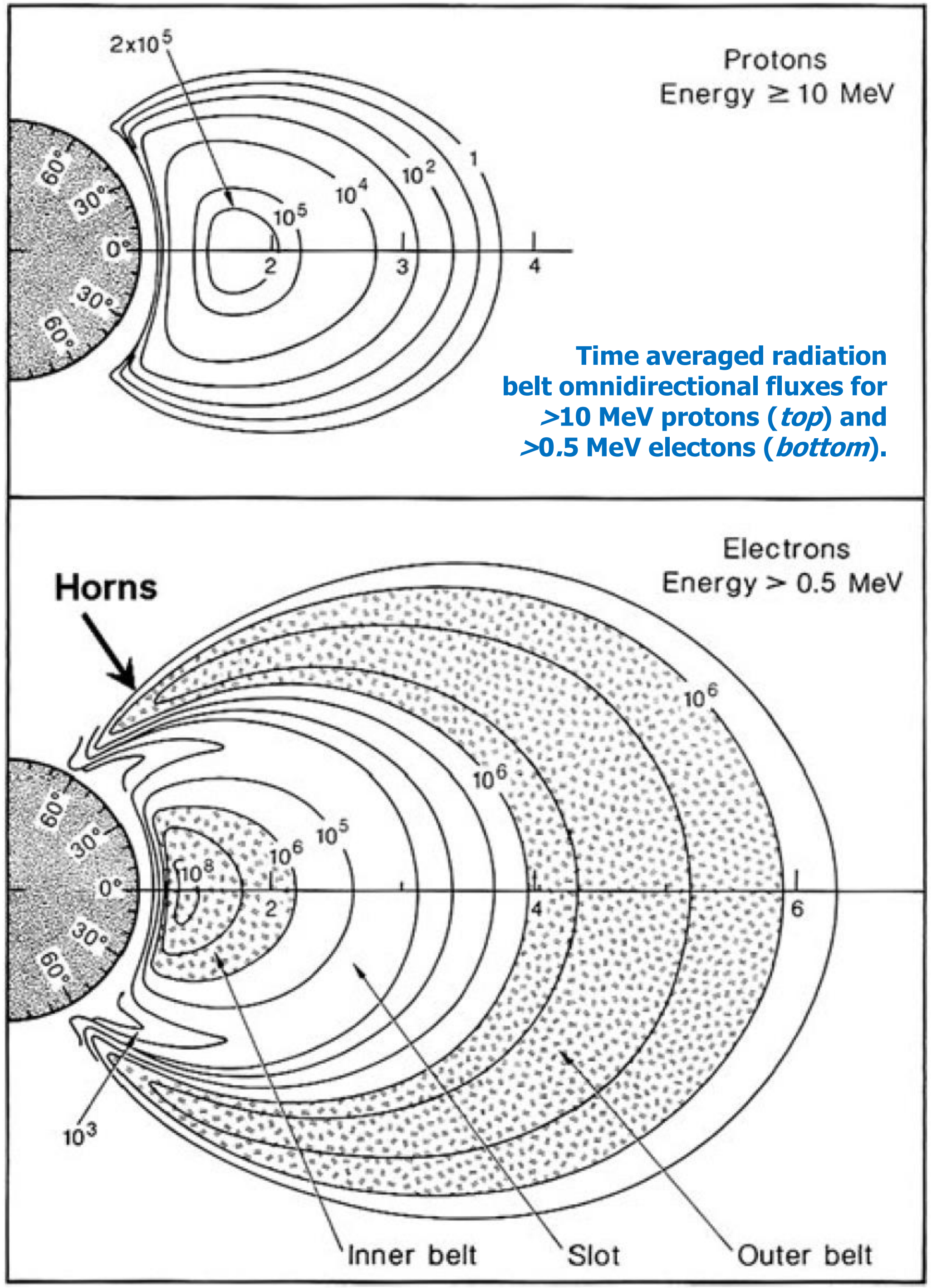
Earth radiation belts
Trapped radiation: charged particles

As of May 2012, there are 994 operational satellites on orbit of which 419 are in geosynchronous orbit (GEO), 69 in medium earth orbit (MEO), 35 in elliptical orbit, and 471 in low earth orbit (LEO) [*SIA*, 2012]. This represents a large growth in the satellite industry since 2002 when the number of satellites at GEO was approximately 200

Earth radiation belts

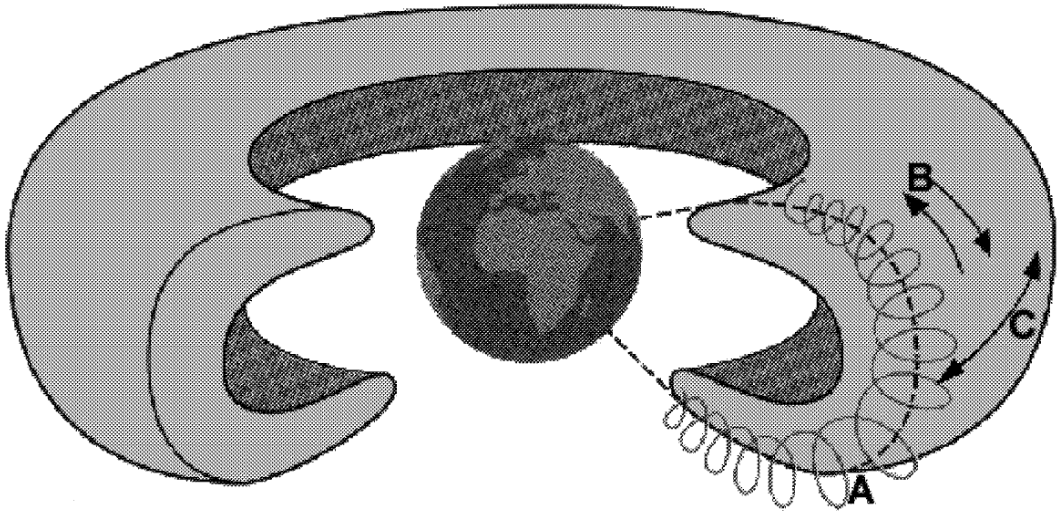


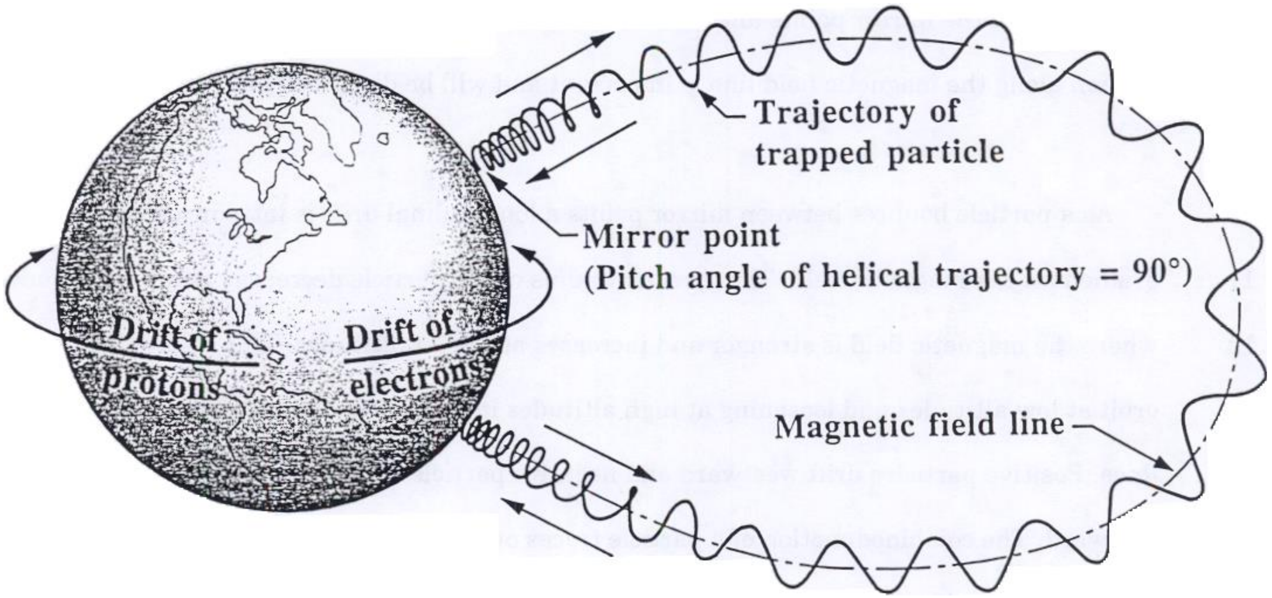
Different types of satellite orbits in relation to the Earth and the Earth's r… belts. Most telecommunications satellites are in GEO, GNSS satellites such as Gali… GPS are in MEO, and the international space station is in low Earth orbit (LEO). … region lies between the inner and outer radiation belts.



Time averaged radiation belt omnidirectional fluxes for >10 MeV protons (*top*) and >0.5 MeV electons (*bottom*).

Earth radiation belts
Trapped radiation (charged particle): dynamics

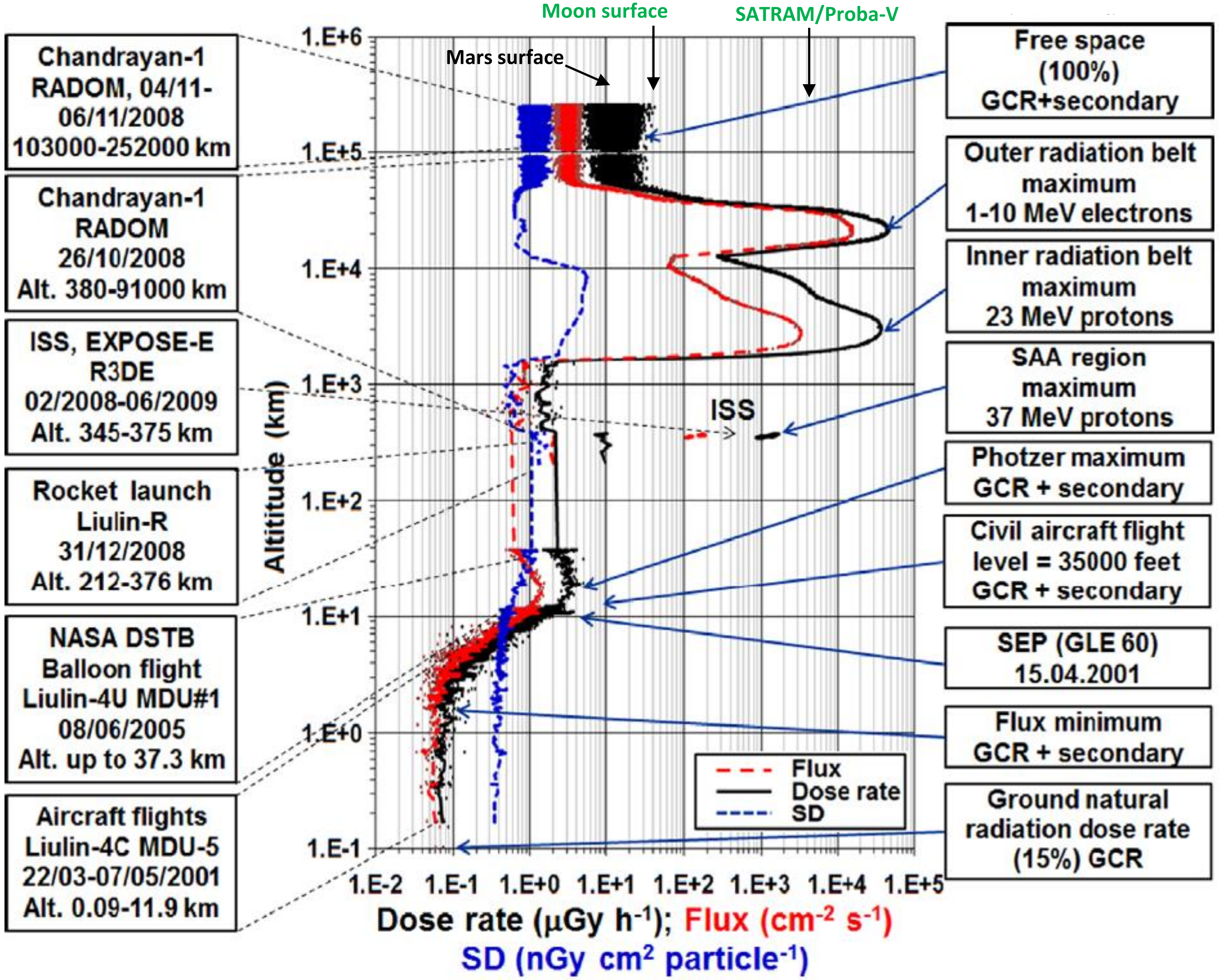




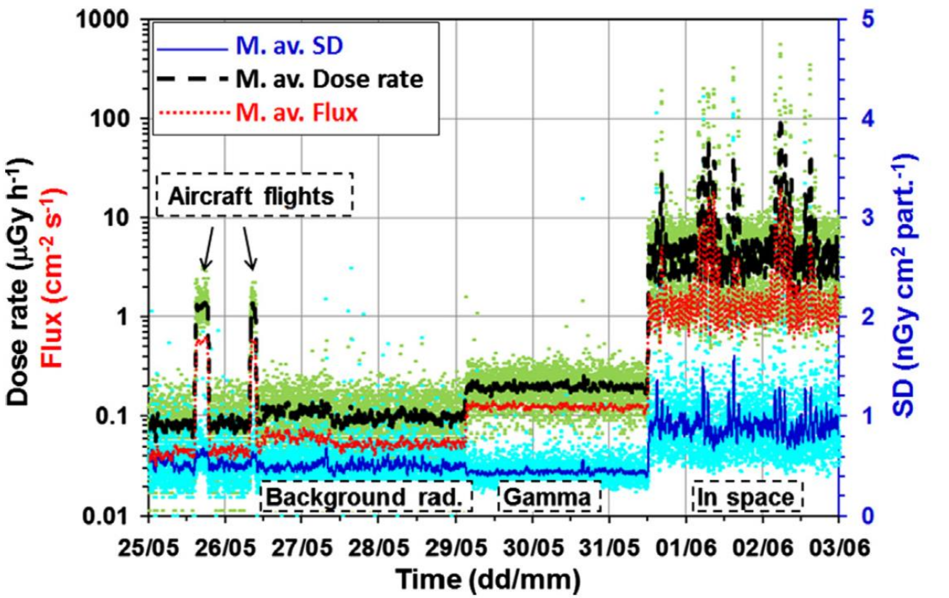
Motion of charged particles in the geomagnetic belts. A) gyration B) bouncing C) drift.

Near-Earth space radiation environment

Intensity/flux profile between Earth and outer space



Radiation Risks Radiometer-Dosimeter (R3D) (82x57x25 mm, 129 g) for Biopan (R3D-B) with 256 channels ionizing radiation monitoring spectrometer known as R3D-B2 flown inside the ESA Biopan5 facility on the FotonM2 satellite: LEO orbit



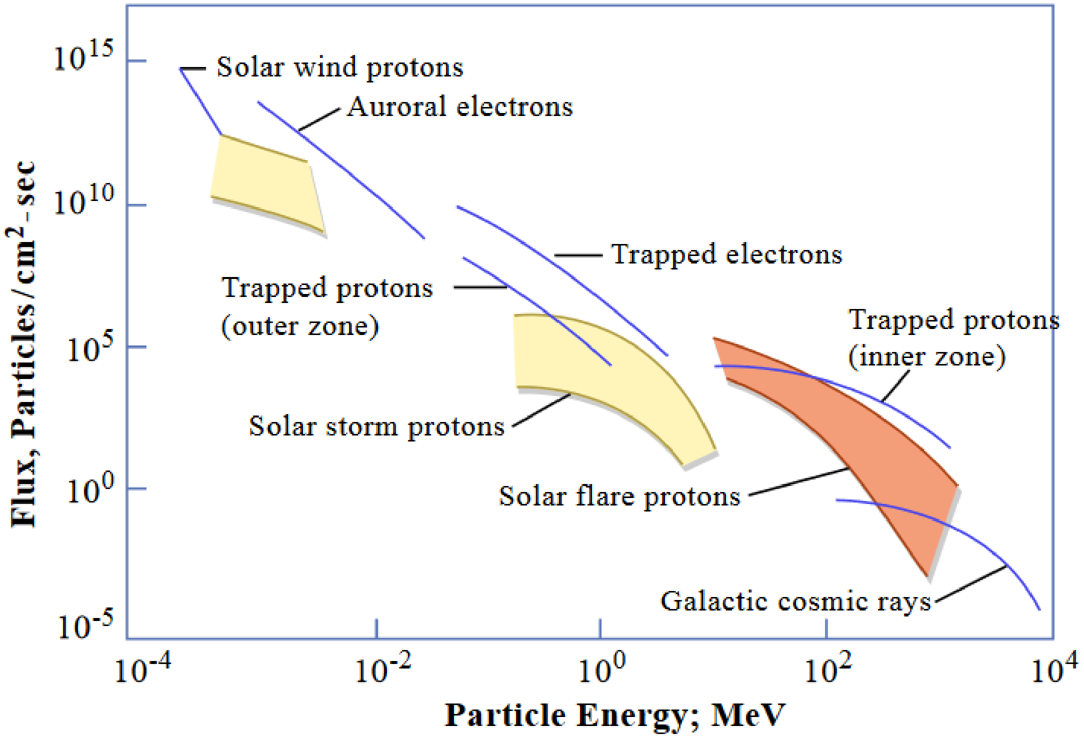
Variations of the flux, dose rate and specific dose (SD = ratio of dose to flux)

Variations of the absorbed dose rate, flux and specific dose for altitudinal range from 0.1 to 250.000 km

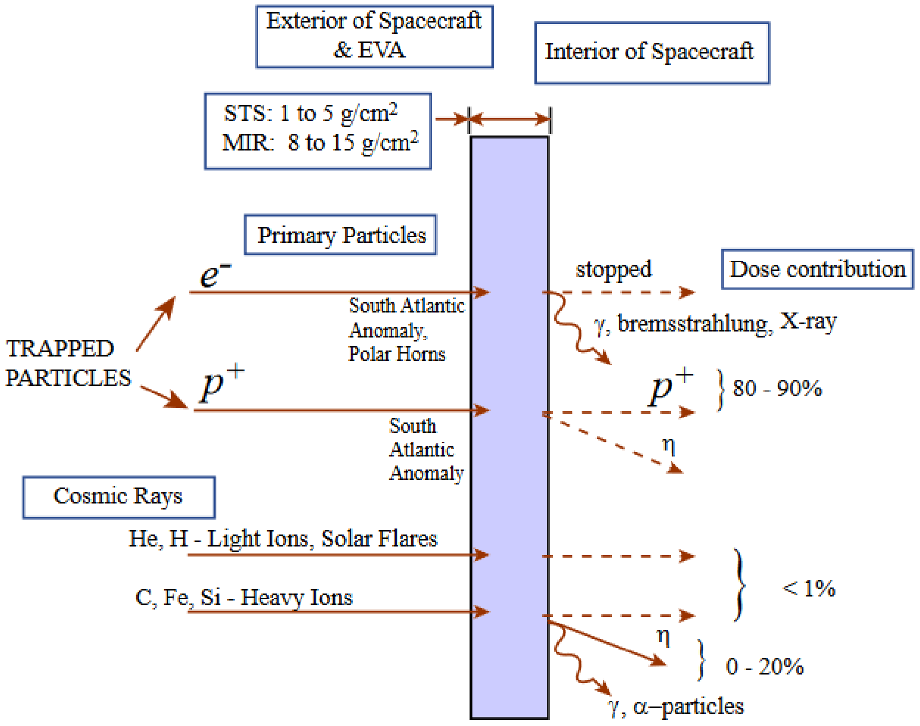
Space radiation

Composition, variability (intensity, time, orbit, location), directionality

Spectra and flux range of charged particles in space



Space radiation environment inside and outside spacecraft

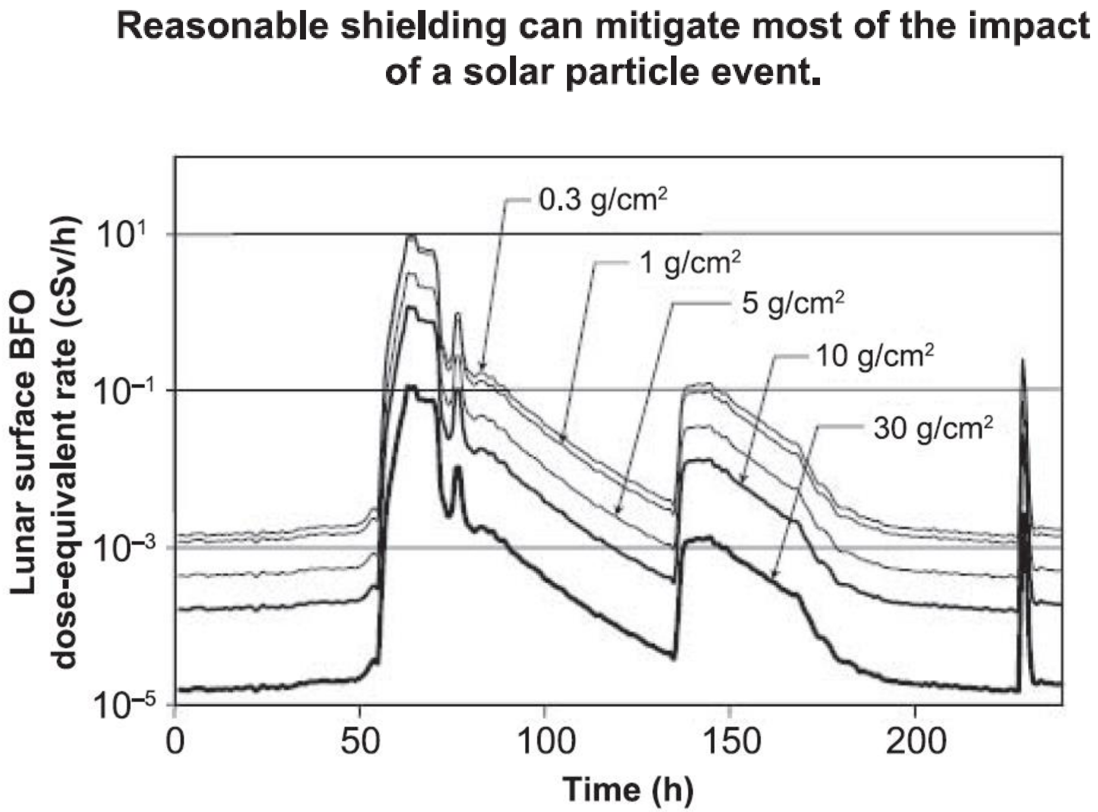


Primary radiation

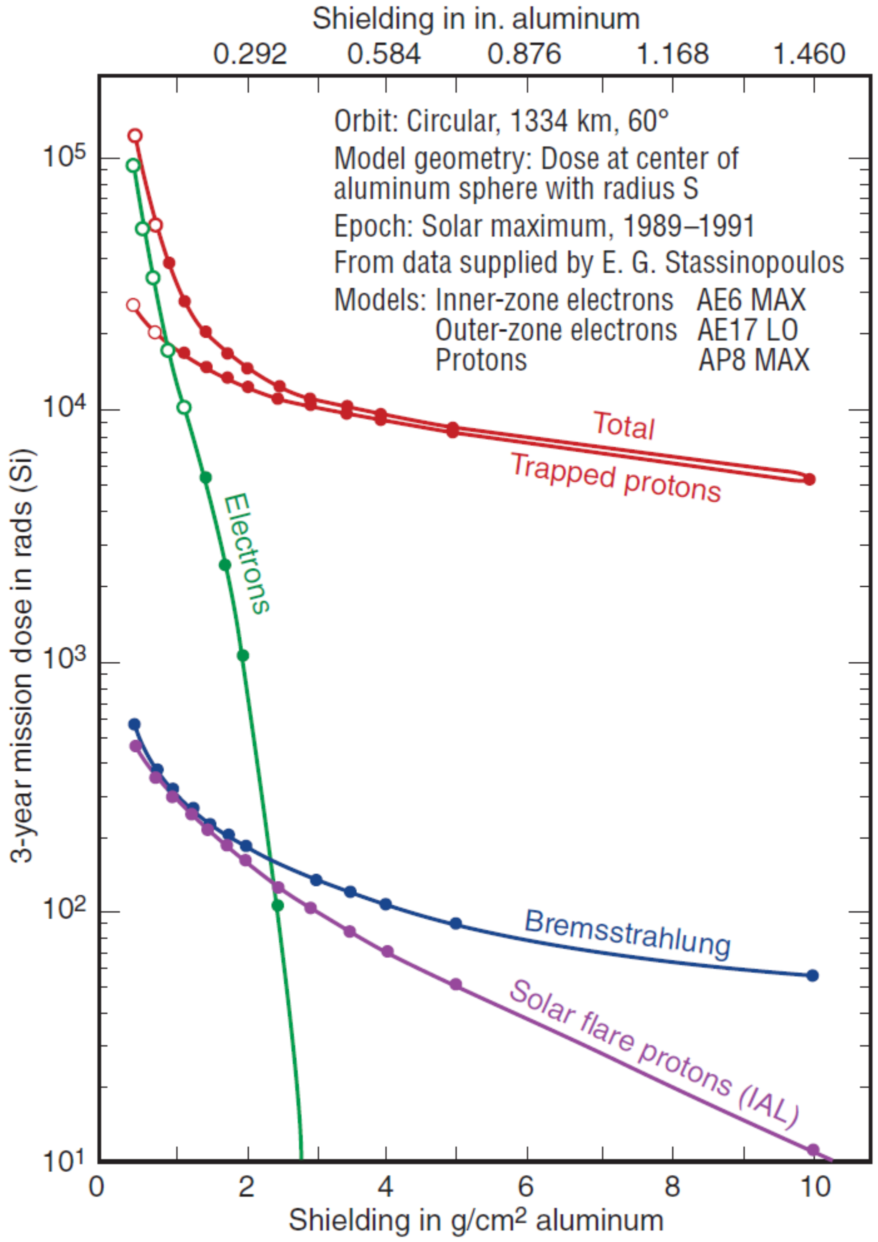
Secondary radiation

Space radiation & shielding

Biologic/human exposure, dose rate, dose equivalent



Lunar surface dose equivalent rate for blood-forming organs and effects of aluminum shielding for the large SPE on August 2, 1972. This event occurred between the Apollo 16 and 17 missions. Blood-forming organs dose equivalents are based on NCRP Report No. 132 recommendations. Note the high-dose-rate period of ’20 h immediately after arrival of charged particles



Dose–depth curve. The curve shows the effectiveness of shielding the electrons and the penetrating capability of the protons. The quasi-asymptotic total dose curve at the larger depths sets a floor of ~10,000 rad (Si) below which it is impractical to shield.

Timepix on Artemis-1

- Artemis-1 flight 16 Nov 2022

→ Carrying **4 Timepix detectors** on board to measure radiation

- Part of a long term program at NASA-JSC using Timepix based instruments for space radiation measurement and online spacecrew dosimetry

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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	ISaS	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**

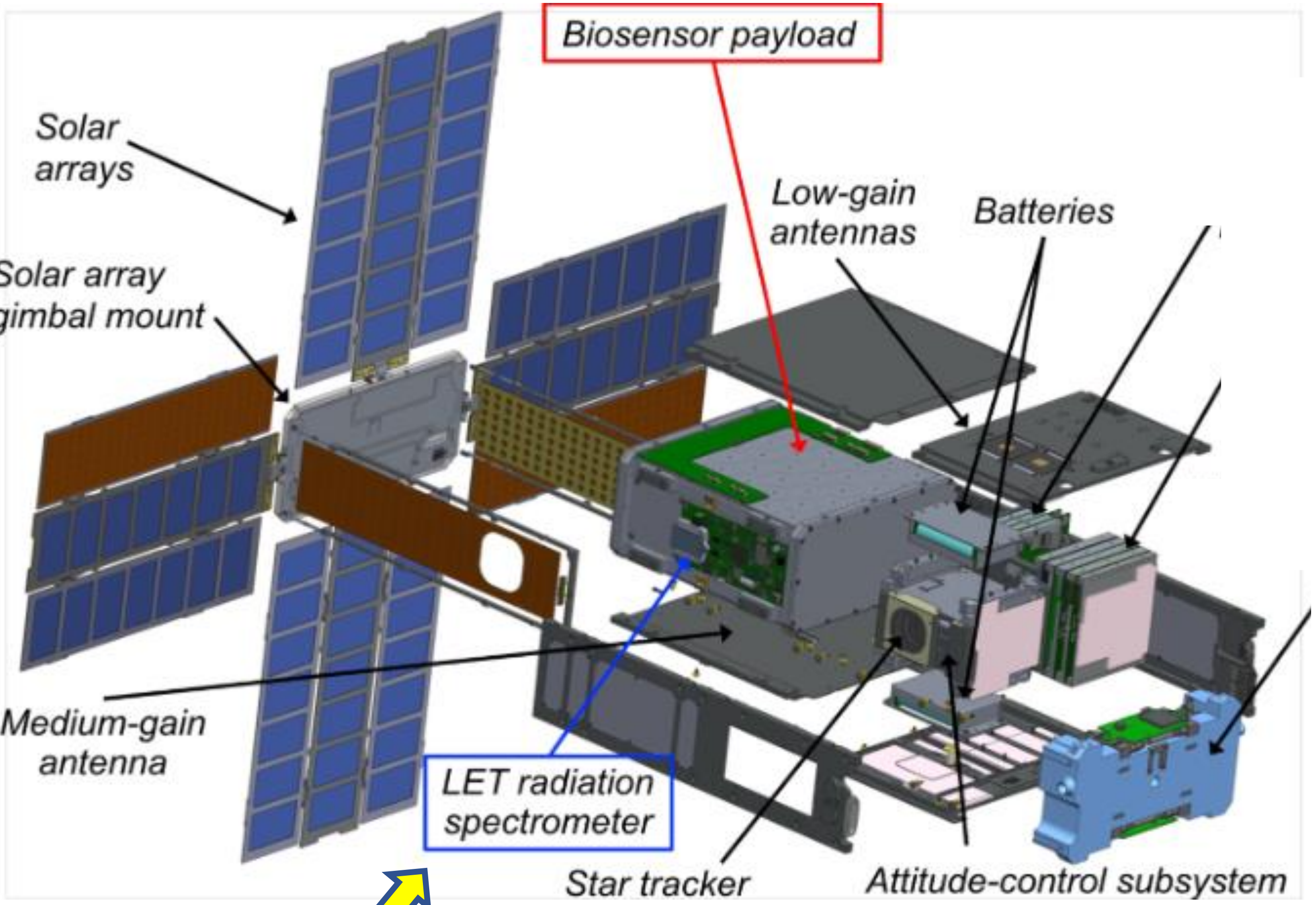
7 missions flown, 4 missions next six months, 6 missions planned → 23 Timepix devices in space/in orbit to date/Nov 2022

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

A.J. Ricco, et al., IEEE A.S. mag. (2020) 6-18

BioSentinel Cubesat Deep Space Radiobiology Experiment

Timepix: LET radiation spectrometer

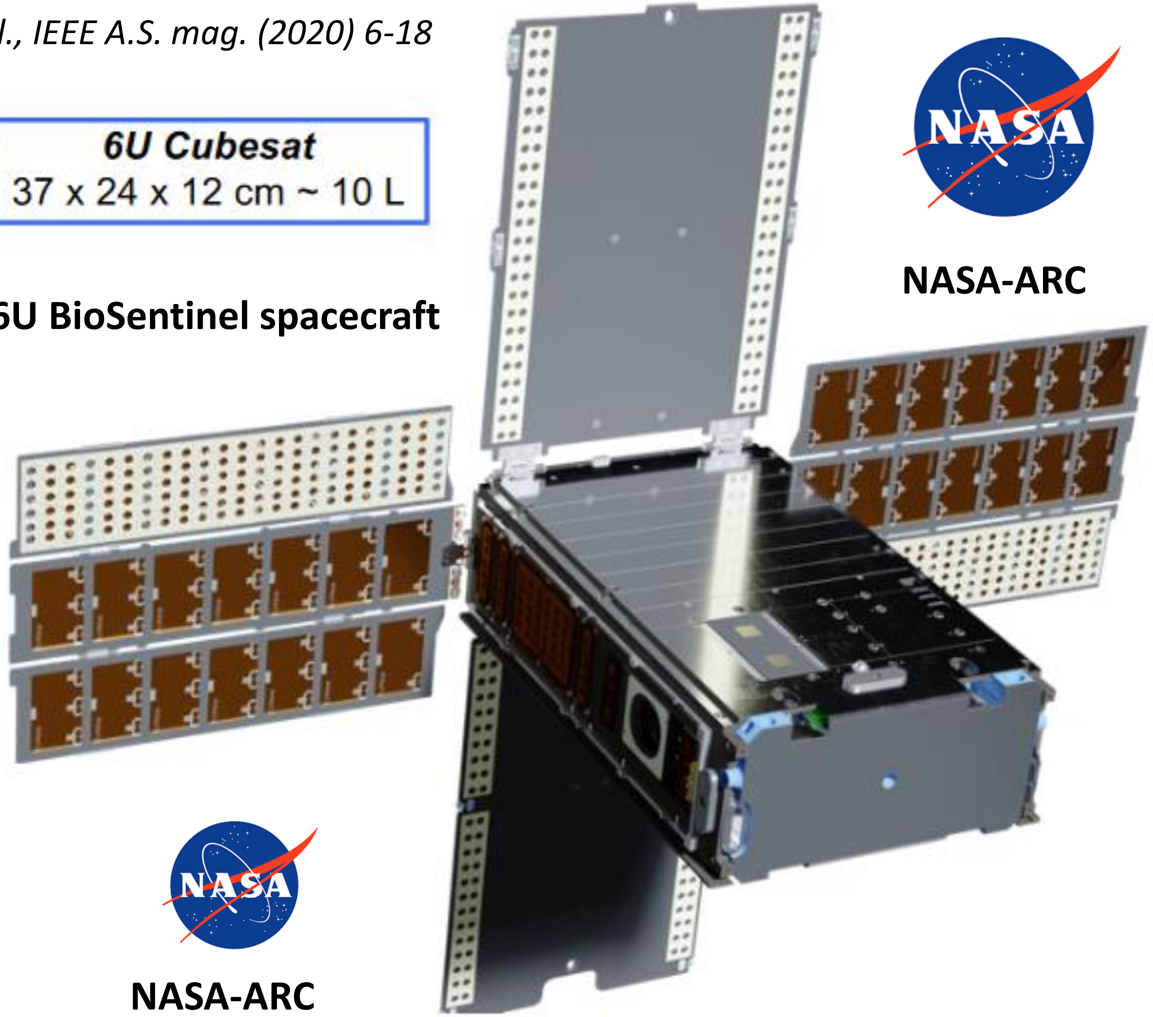


Timepix

NASA-JSC

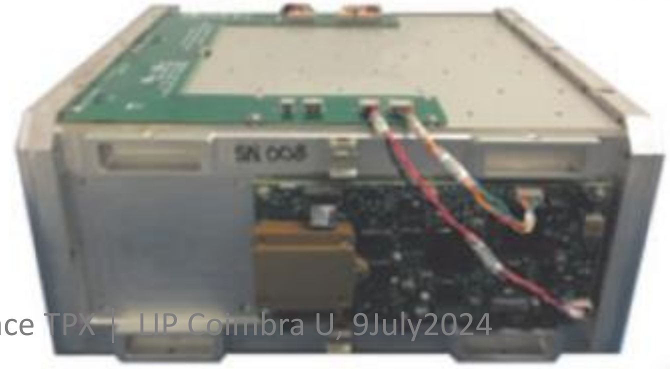
6U Cubesat
37 x 24 x 12 cm ~ 10 L

6U BioSentinel spacecraft



NASA-ARC

NASA-ARC



4U BioSentinel payload

BioSentinel Cubesat Deep Space Radiobiology Experiment
Timepix: LET radiation spectrometer

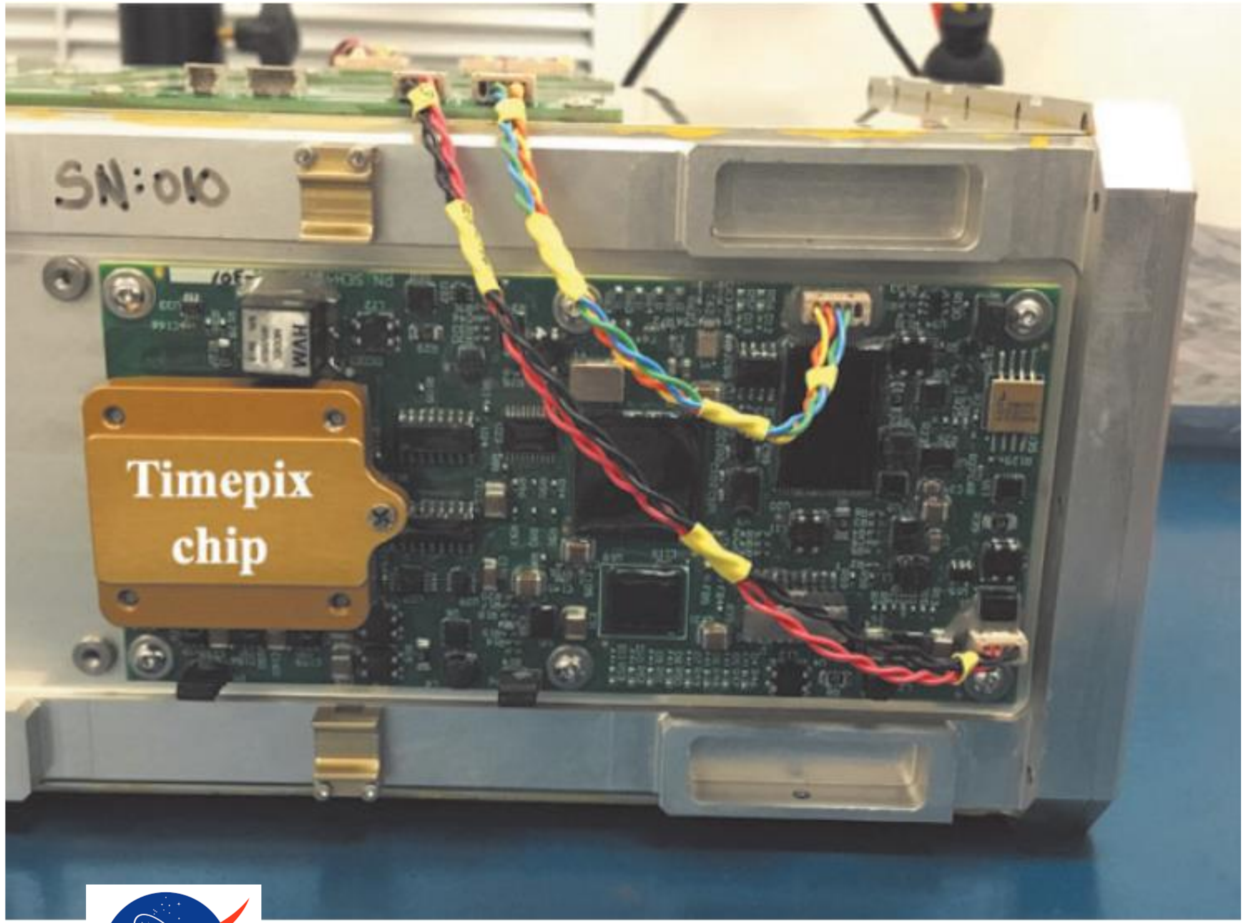
S.Massaro Tieze, et al., Astrobiology 20 (2020) 1-6

M.R. Padgen, et al., Astrobiology 21 (2020) 1-11

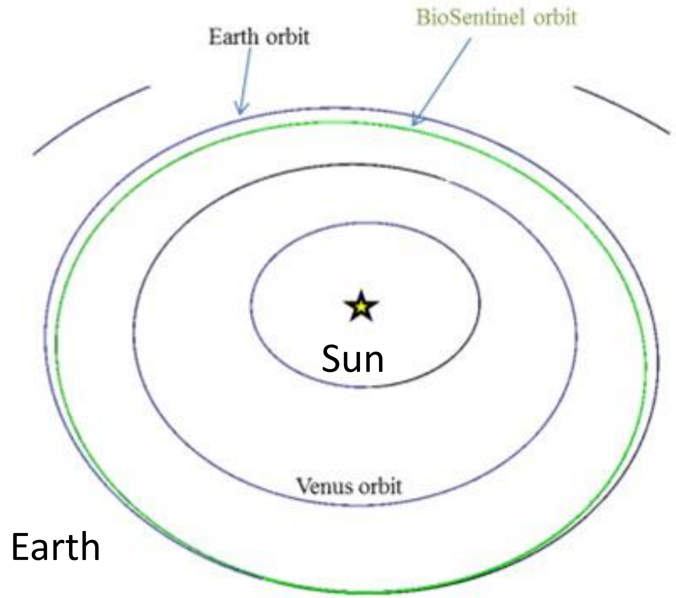
NASA-ARC

Study the effects of deep space radiation on biological sample (yeast)

4U BioSentinel payload



Readout electronics NASA-JSC, Radworks group



BioSentinel is one of 10 cubesats carried with the Artemis 1 (Orion CM-002) mission into a **heliocentric orbit** in CIS-lunar space on the maiden flight of the SLS (Block 1) iCPS launch vehicle in November 2022

Flight certification of Advacam MiniPIX-TPX
7 units flown to ISS LEO orbit
on SpaceX-16, Dec 2018, 6 spares

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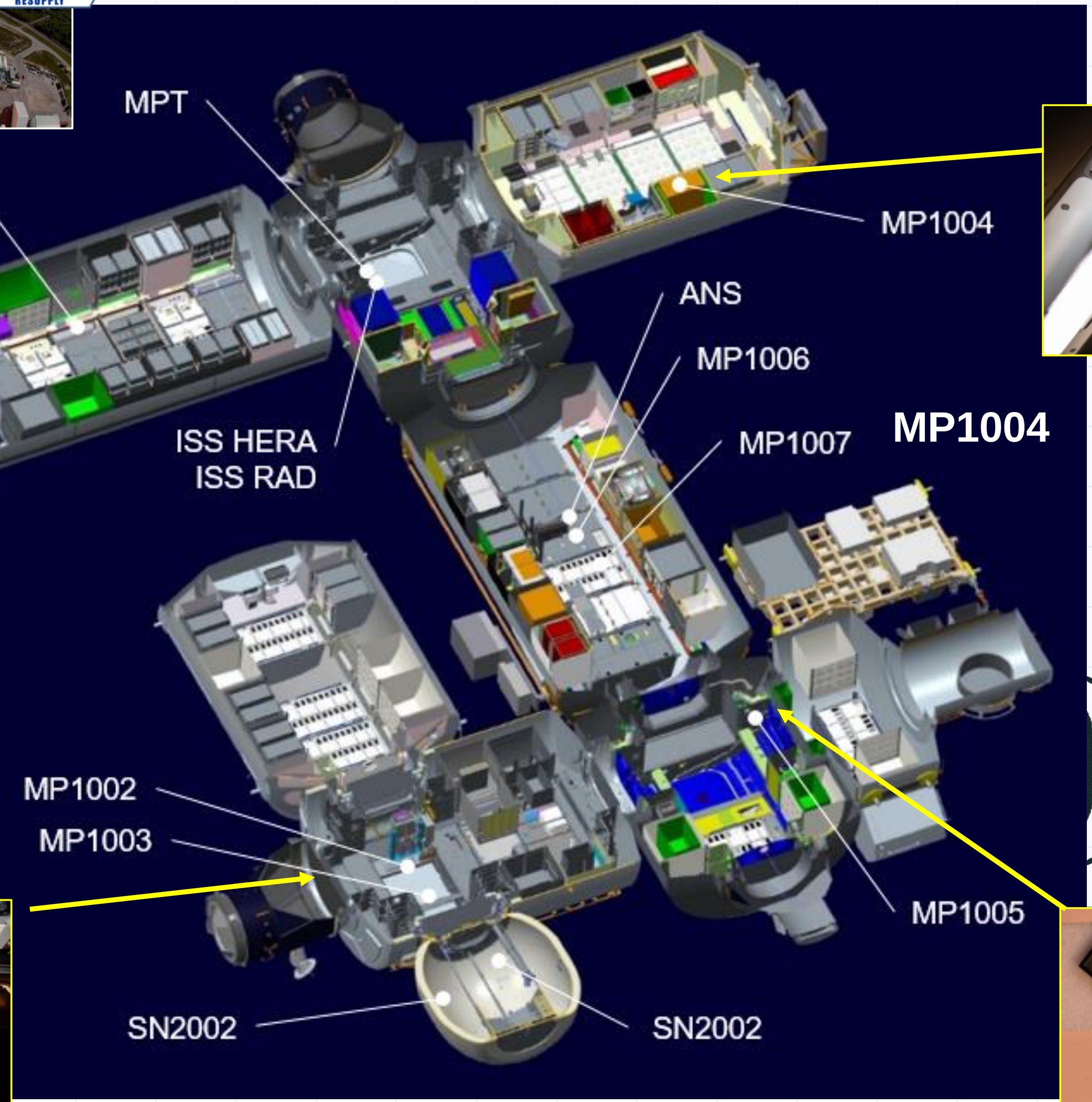
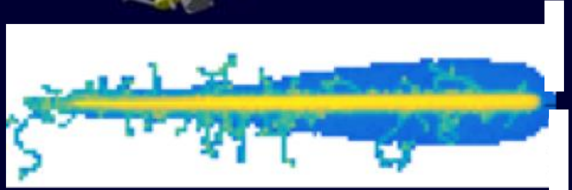
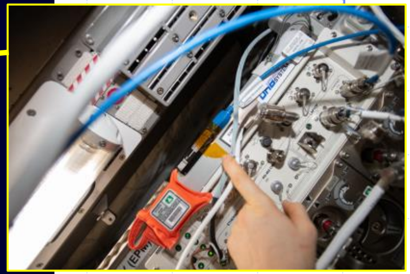
E. Semones, NASA,-JSC
CERN, MPX 2019





Example measured track of SINGLE Si ion. Color is a calibrated energy scale.



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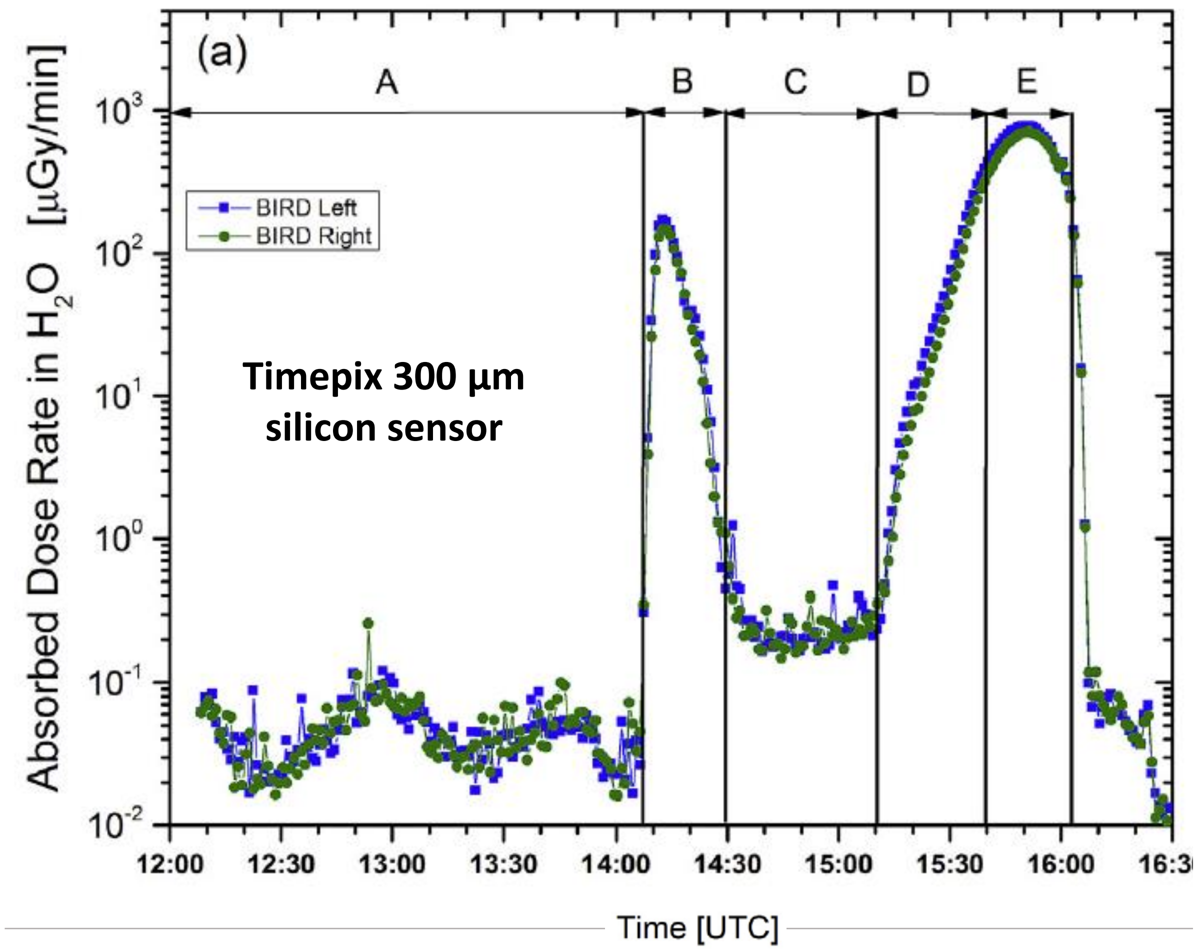
R. Gaza, M. Kroupa, et al., *Comparison of novel active semiconductor pixel detector with passive radiation detectors during the NASA Orion Exploration Flight Test 1 (EFT-1)*, Rad. Meas. 106 (2017) 290–297

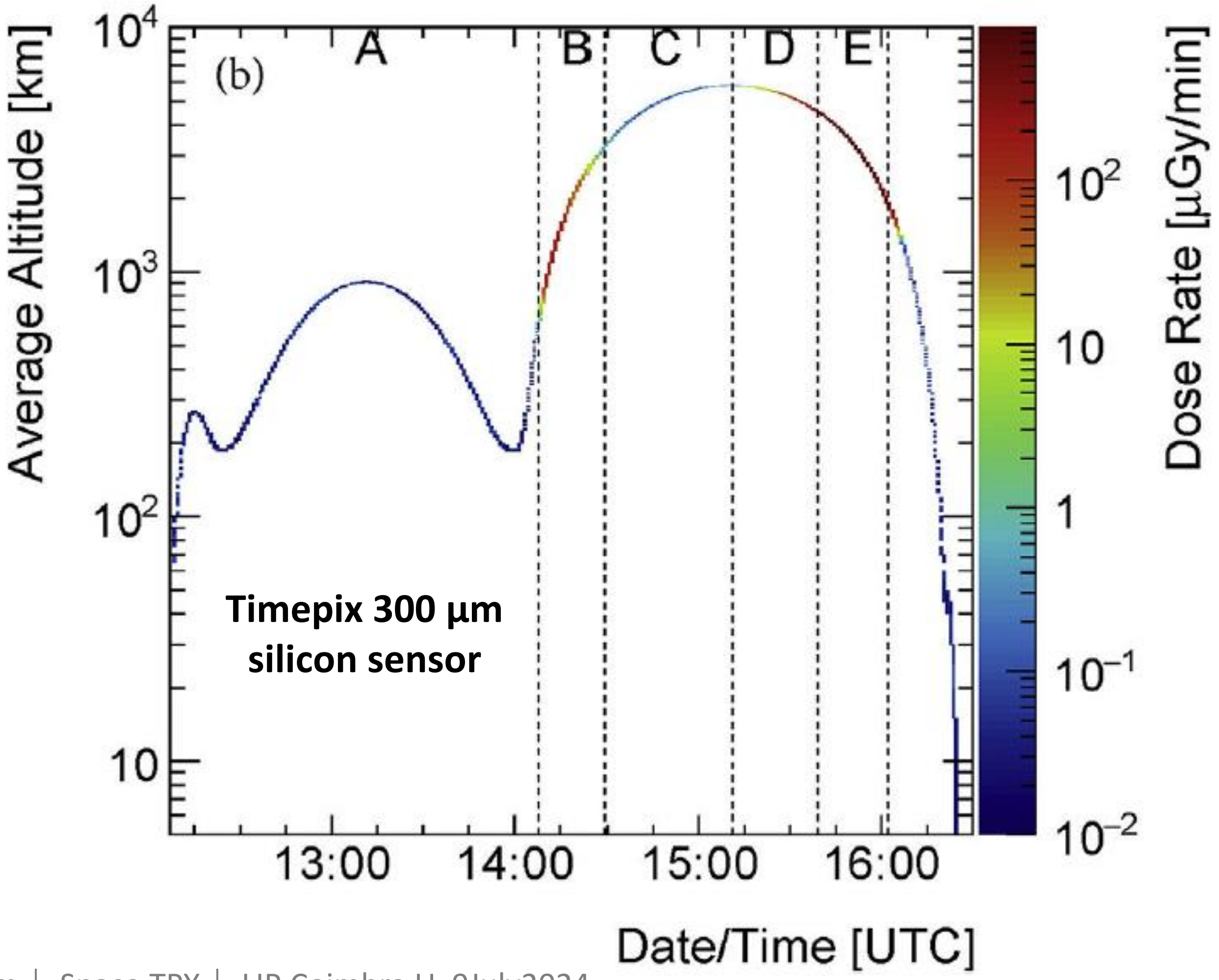
BIRD-Timepix payload on board ORION EFT-1: Dec 2014

Wide-range radiation detection and dosimetry in LEO/MEO

Dose rate time profile along the EFT-1 orbit trajectory.



Dose rate altitude/time profile



Space Radiation and Mixed-Field Characterization in LEO orbit with miniaturized MiniPIX-Timepix3 Space radiation monitor

onboard One-Web Joeysat satellite

- Field decomposition: protons, electrons, X rays, gamma
- Charged-particle dosimetry
- Dose/TID, LET spectrometry
- Wide field-of-view directional tracking
- LEO: 600 km, 1200 km, transfer orbit

MiniPIX Timepix3 Space

OneWeb

oledcomm

esa

ADVACAM Imaging the Unseen

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ADVACAM, Prague, Czech Republic

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IEAP medipix collaboration CERN

*Spinoff of the Medipix Collaboration/IEAP CTU Prague

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Tomas Baca

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Victor Colas, Marco Sabia

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Maxime L'Huillier, E. Plascencia, B. Azoulay

- ***ESA**, ESTEC, Noordwijk, NL*

Marco Vuolo, et al.

One Web, UK

Experimental micro-satellite Joeysat – LEO 1200 km

Carlos Granja, ADV, Prague, 2023

OneWeb

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Imaging the Unseen

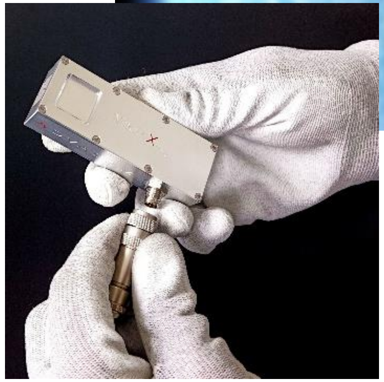
Radiation effects

High-resolution wide-range radiation monitor: Timepix3 Si sensor, UART/RS-422

Data products:

- ❑ Mixed-field/space radiation composition characterization
- ❑ Particle fluxes: total, partial
- ❑ Dose rates: total, partial
- ❑ LET spectra
- ❑ Directional fluxes, wide FoV

Micro-satellite Joeysat – LEO 1200 km, launch 2024



MiniPIX TPX3 Space

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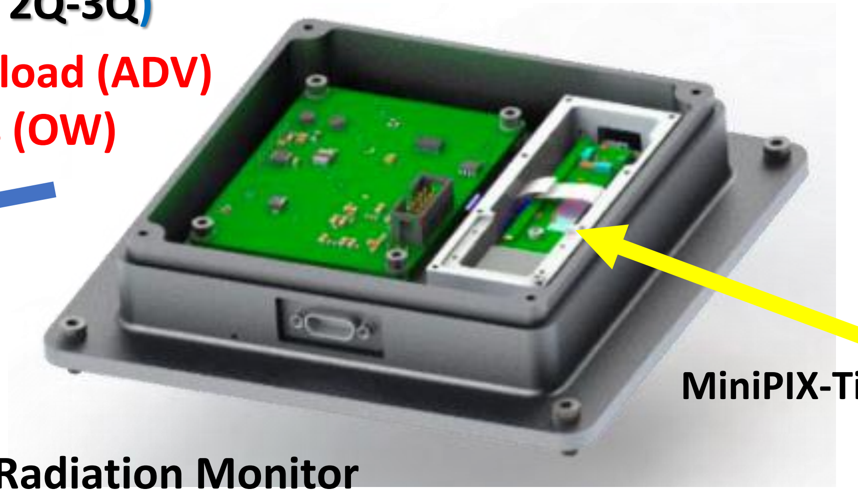
RADIATION MONITOR INTEGRATION

Telecommunication satellite Joeysat
Launched to LEO 600 km (May 2023)
+ transfer to 1200 km (2024 2Q-3Q)

on board JoeySat MPX radmon payload (ADV)
+ Computer (OC) + SOCAN bus (OW)

JoeySat FLIGHT MODEL MOUNTED EXTERNALLY (Mx PANEL)



MiniPIX-Timepix3 Space

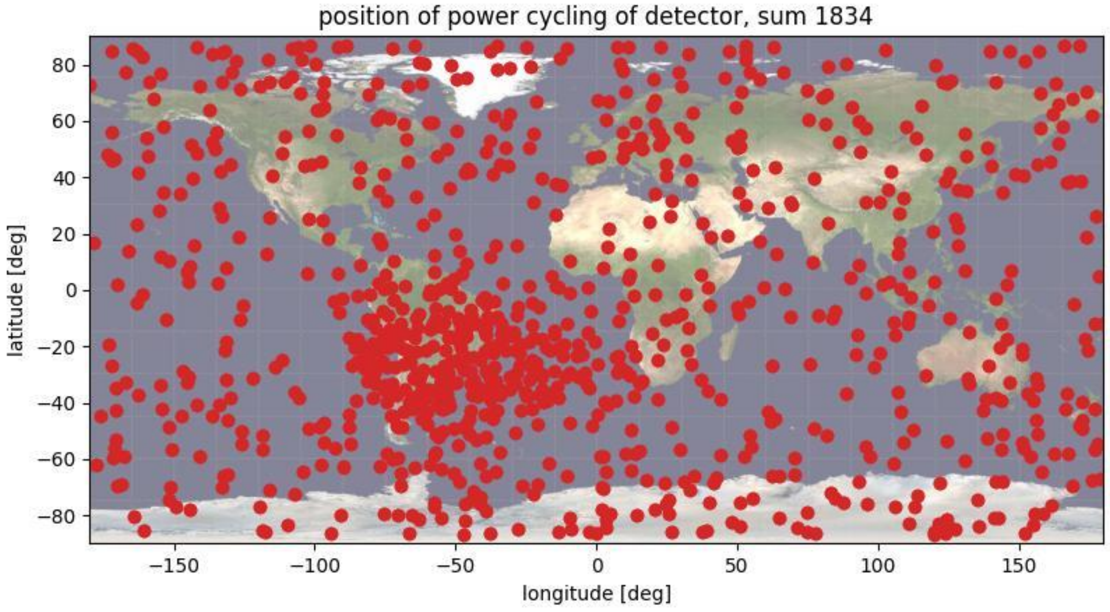
MPX Radiation Monitor

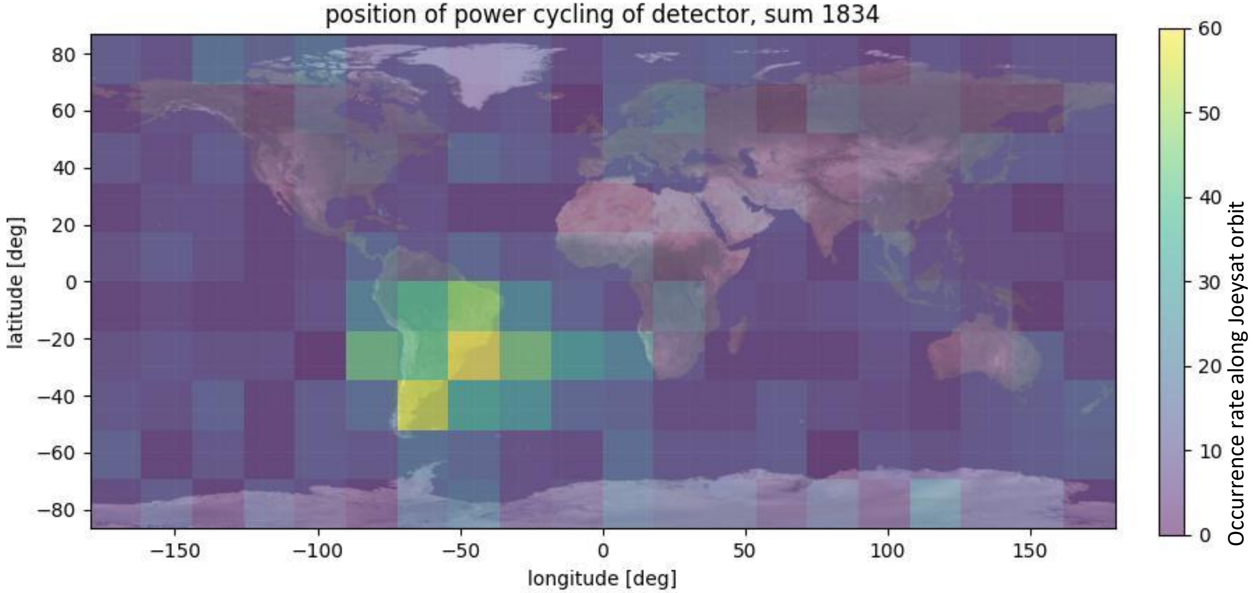
Control/DAQ/interface computer

POWER CYCLING OF MPX ON JOEYSAT IN-ORBIT OPERATION

MPX payload + Computer + SOCAN bus

- Power cycling of detector – evaluated period from 1.12.2023 trhu 30.1.2024 = 60 days
- ≈ 1200 MPX data frames per day
- Carried out if error of MPX operation encountered
- There were ≈ 1800 of power cycles due to errors mainly in SAA → Occurrence rate ≈ 30 per day
- → ≈ 2.5 % per day





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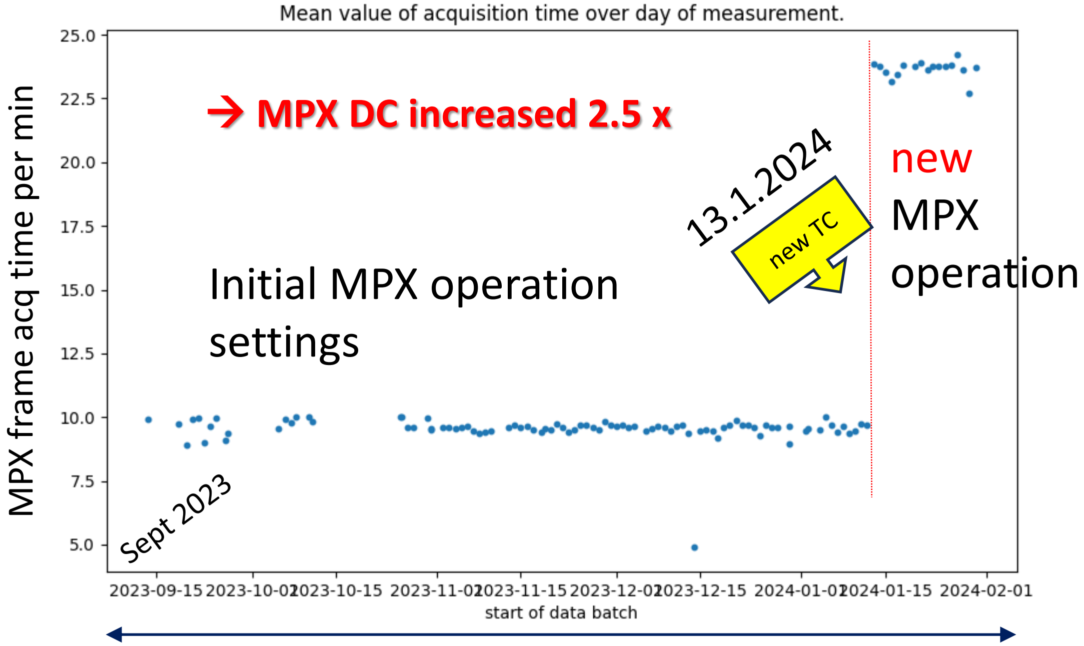
L. Marek,ADV, 2024

COMMISSIONING OF MPX IN-ORBIT JOEYSAT OPERATION

MPX TC OPTIMIZATION (uplink January 2024)

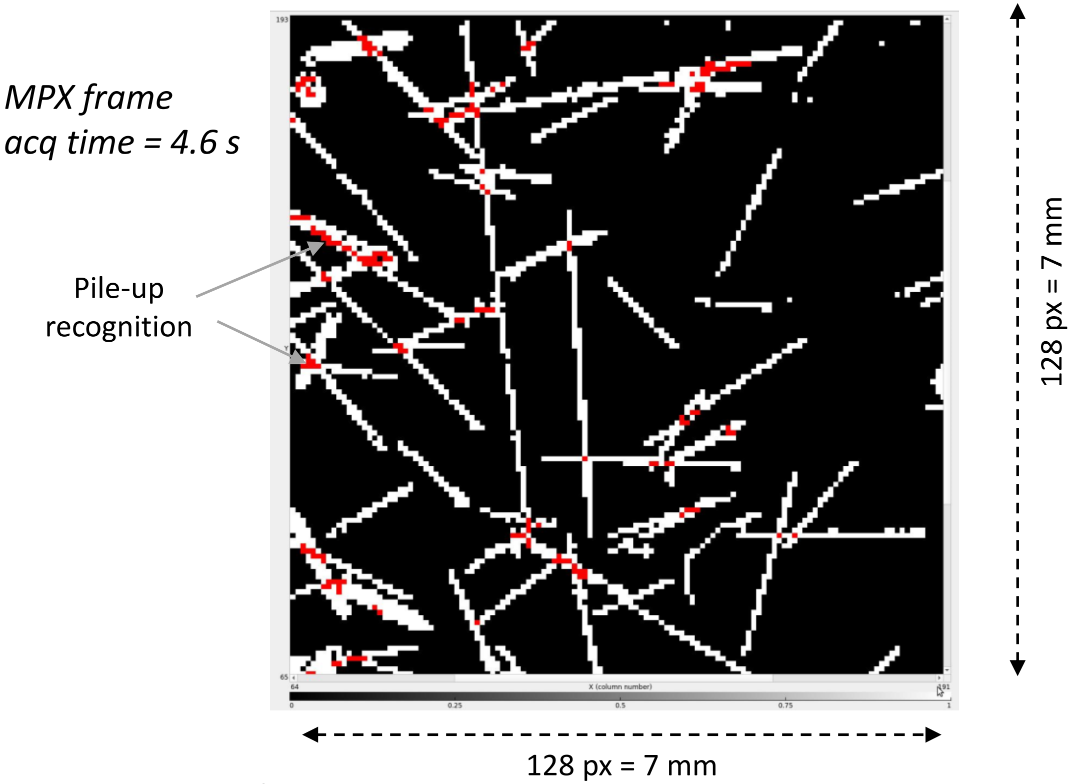
MPX OPERATION DUTY CYCLE: **MPX frame acq time per min**



Entire period of in-orbit operation/data collection of MPX on board Joeysat in LEO

- Tuning and optimization of MPX detector operation to achieve high duty cycle, higher MPX frame acq time
- Increase the MPX frame max acq time from 10s to 25s
- Increase the frequency of MPX measurement from 3 min to 1 min
- Overall MPX operation duty cycle increased from ≈ 5% to ≈ 30%

One Web **Joeysat MPX TPX3 in-orbit LEO 600 km**
Timepix3: per-px **counting mode**



- Occurrence of pile-ups in in-orbit data, especially over the SAA
- Based on collected data analysis → **suppression of pile-up occurrence**, further optimization of MPX operation settings underway
- New MPX TC → MPX per-px lowered occupancy & decreased pile-up rate

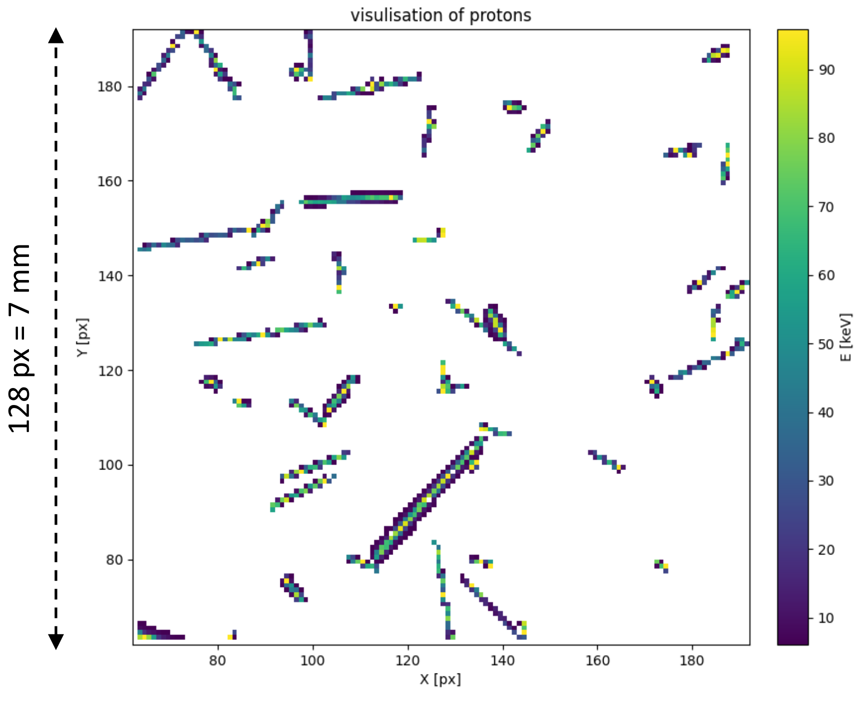
L. Marek, C. Granja, ADV, 2024

MPX radiation monitor on JoeySat in LEO 600 km

Space radiation decomposition: particle-event types

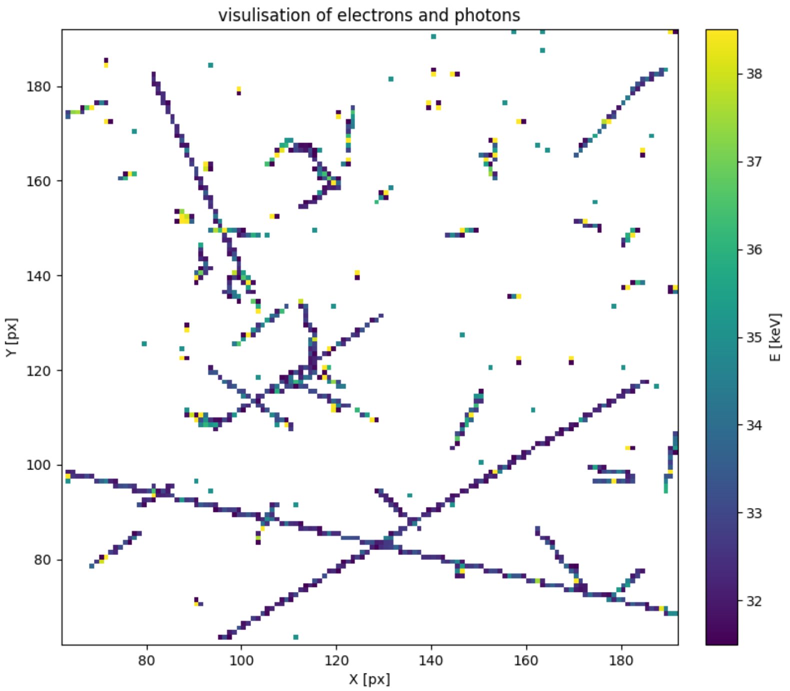
Spectral visualization of tracks by single particles
in the **Timepix3 sensor 500 µm silicon**

High-energy protons

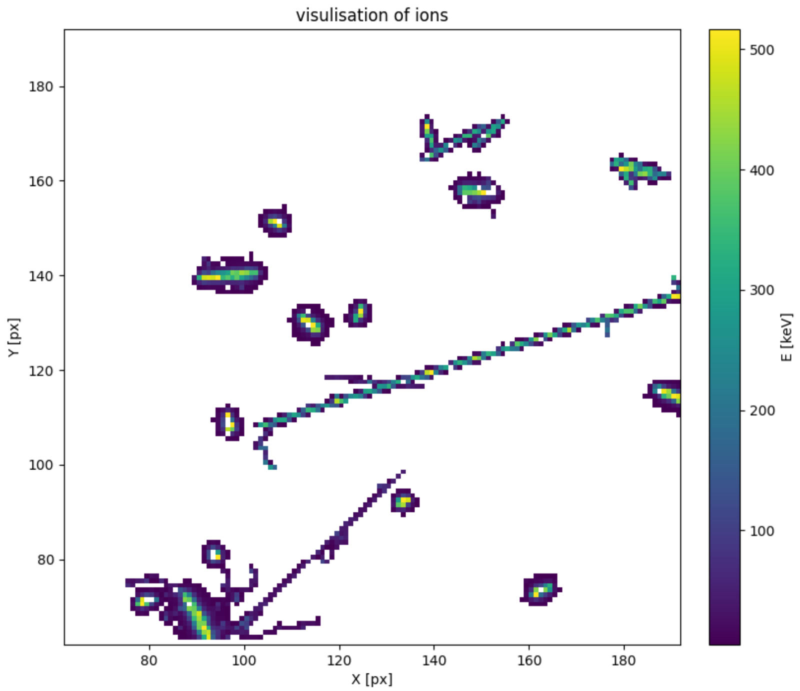


128 px = 7 mm

Electrons, X rays, LE gammas



Low-energy protons, ions

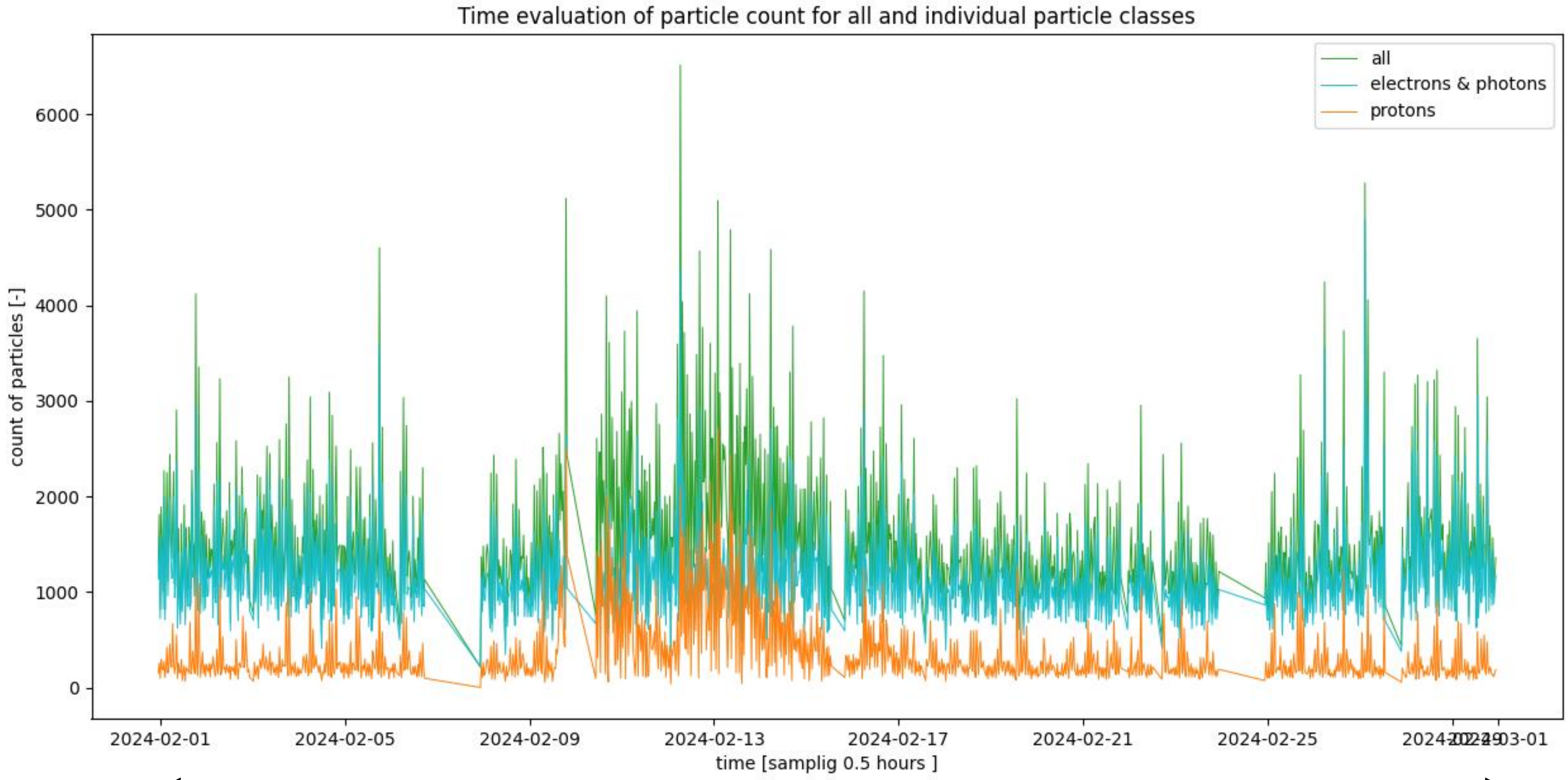


L. Marek,ADV, 2024

MPX radiation monitor on JoeySat in LEO 600 km

Space radiation decomposition: particle-event types

Preliminary: Time histogram of event counts: all, protons, electrons/X rays



1 month data = Feb 2024

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MPX radiation monitor on JoeySat in LEO 600 km

Space radiation decomposition: particle-event types

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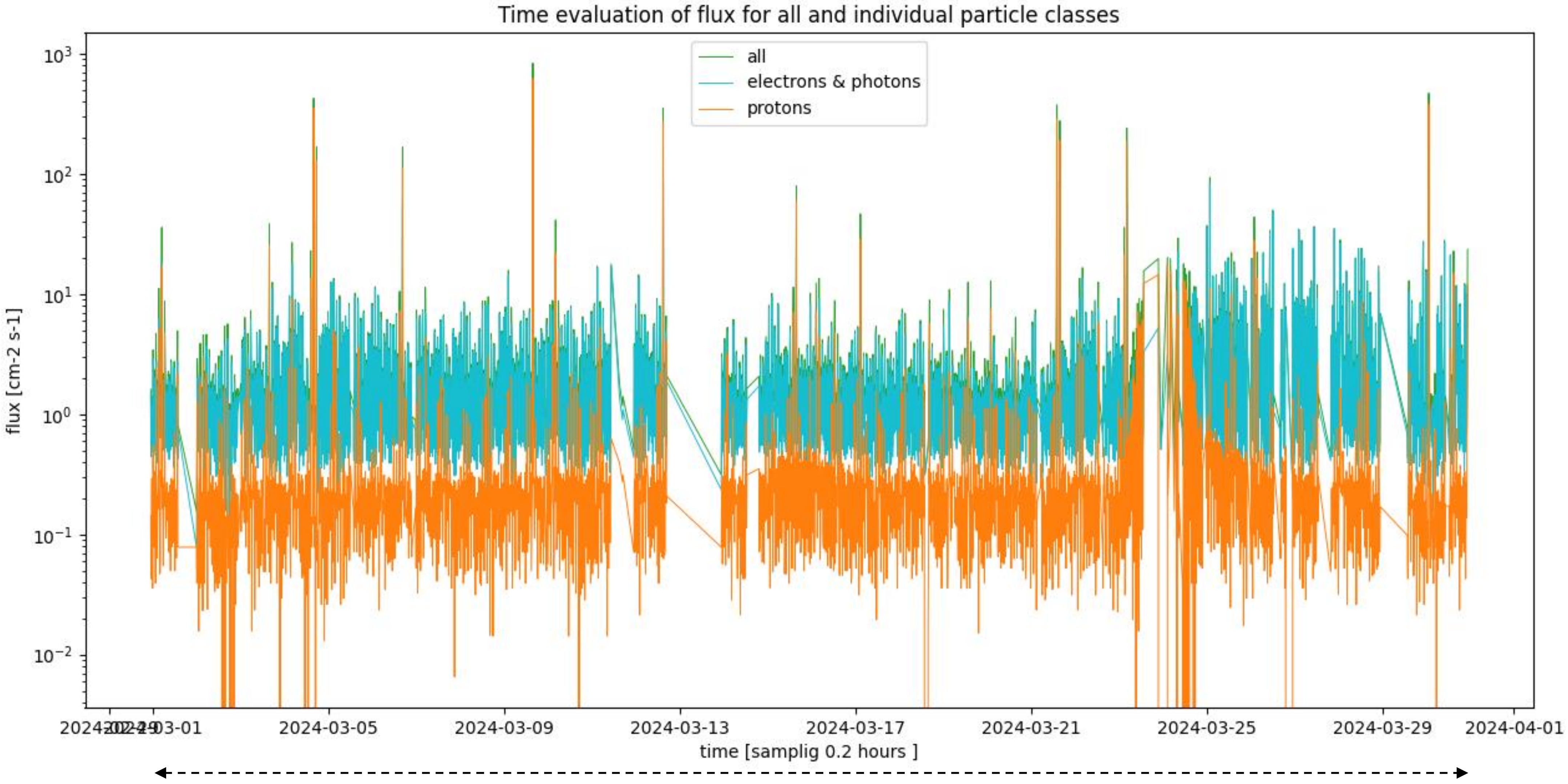
Preliminary: **Time histogram of particle flux: all, protons, electrons/X rays**



1 month data = March 2024

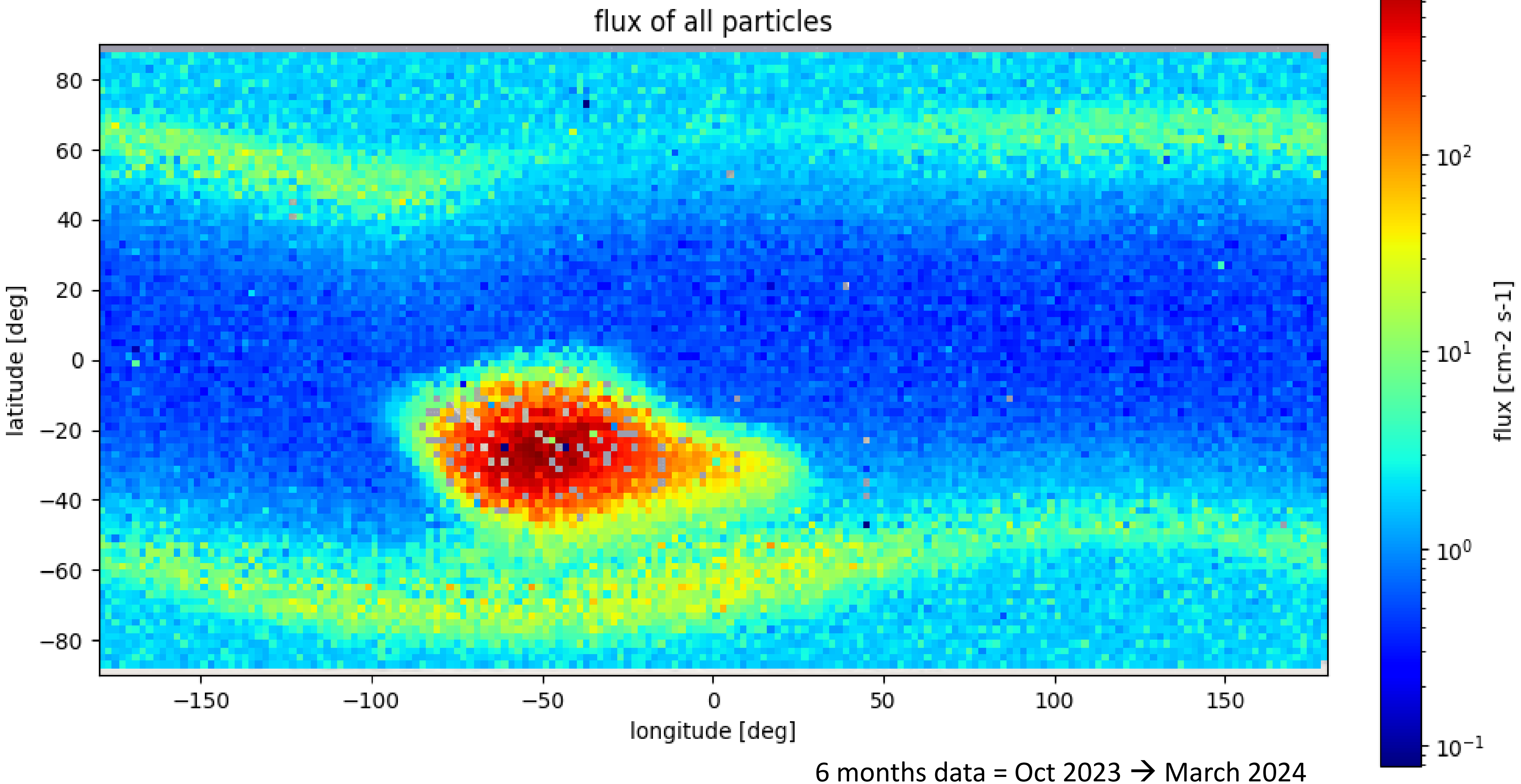
L. Marek,ADV, 2024

MPX radiation monitor on JoeySat in LEO 600 km

Space radiation decomposition: particle-event types

Preliminary:

Orbit maps of particle flux: all particles



6 months data = Oct 2023 → March 2024

MPX radiation monitor on JoeySat in LEO 600 km

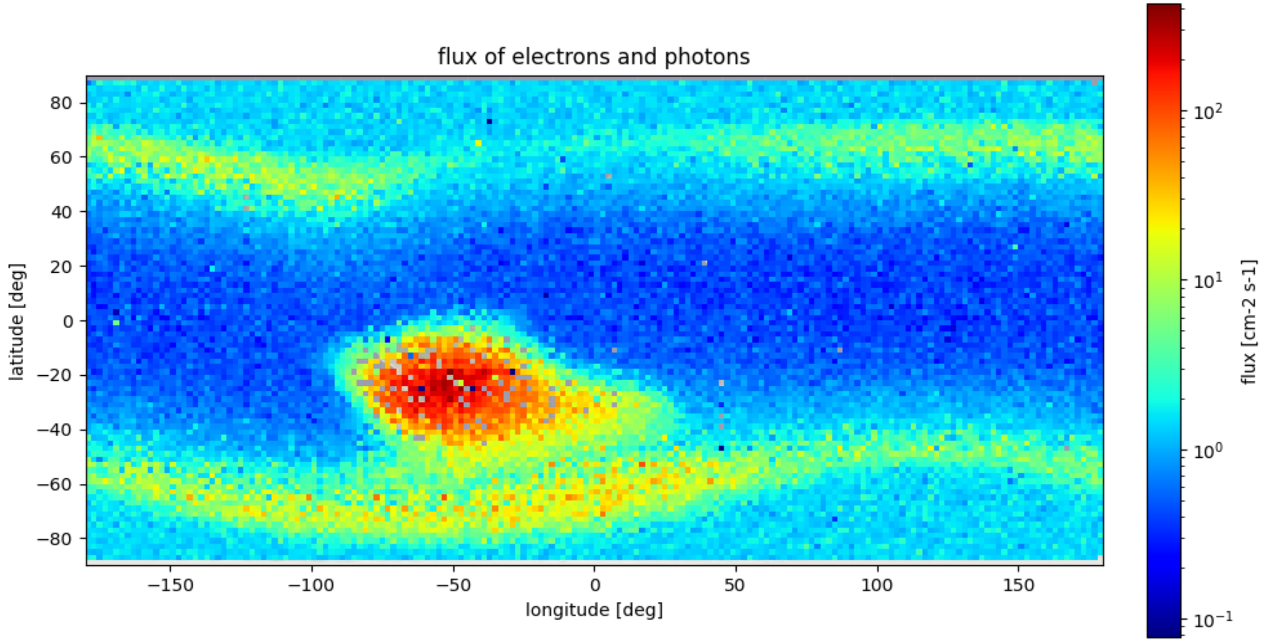
Space radiation decomposition: particle-event types

L. Marek,ADV, 2024

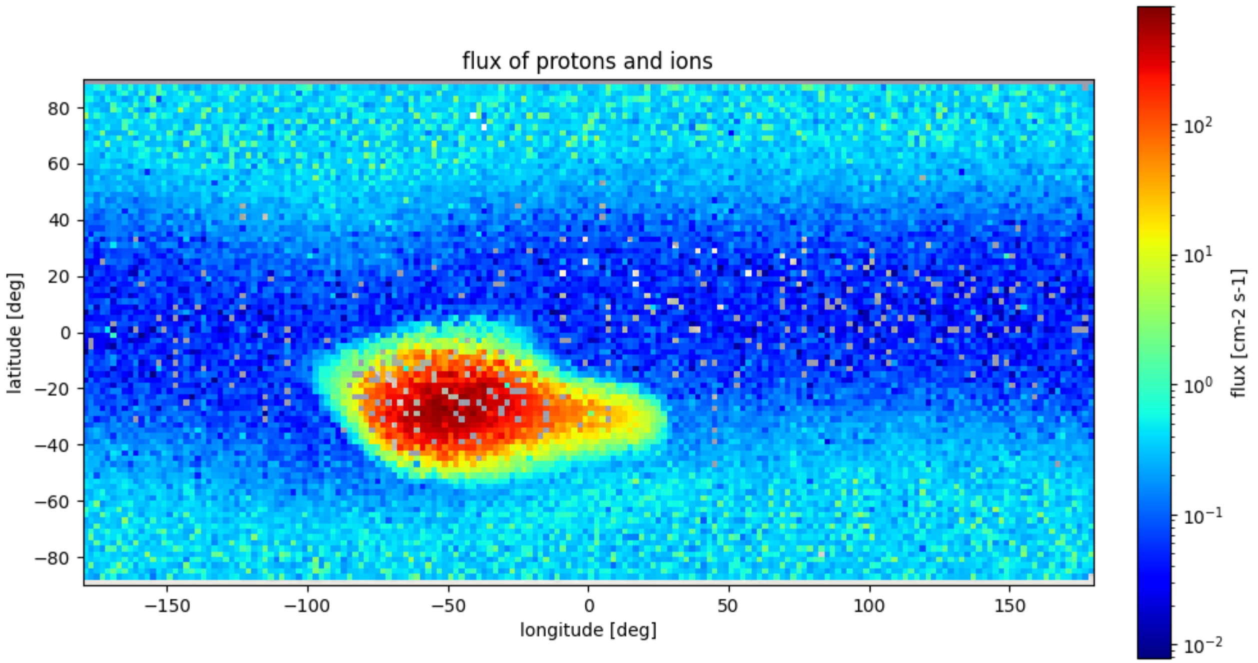
Preliminary:

Orbit maps of particle flux: partial

Electrons + X rays + low-E gamma rays



Protons + ions

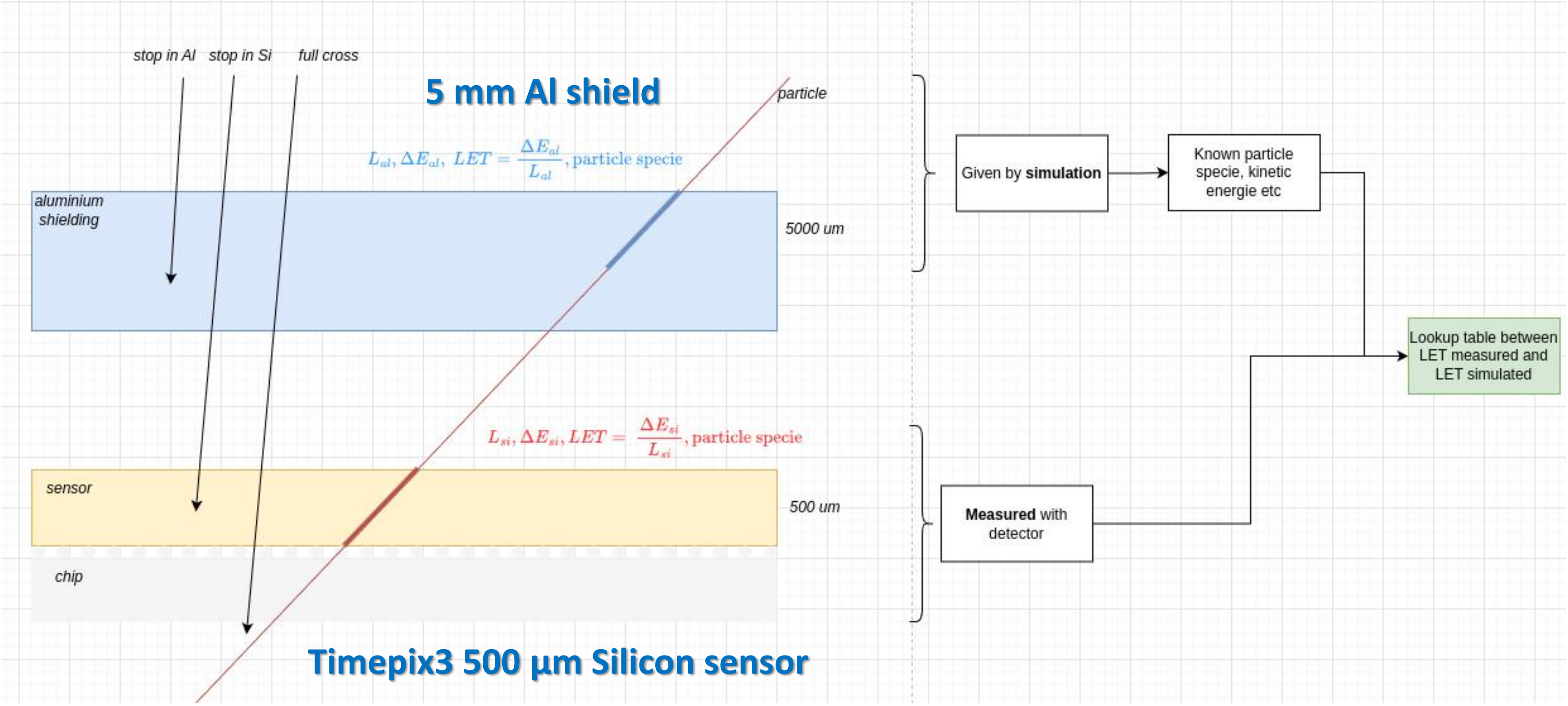


6 months data = Oct 2023 → March 2024

Space radiation characterization in LEO orbit

Effect of shielding

- Goal - estimate particle specie and kinetic energy before crossing shielding
- Model - estimating of LET and particle specie form detector and then derive based on simulation original particle specie and kinetic energy
- In progress:
    - CNN model for E_kin, particle track length improvement
    - E_dep corrections

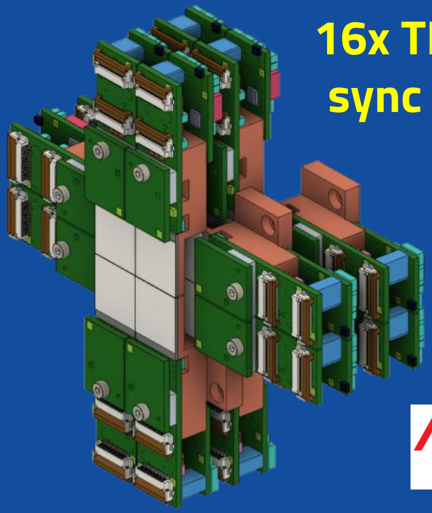


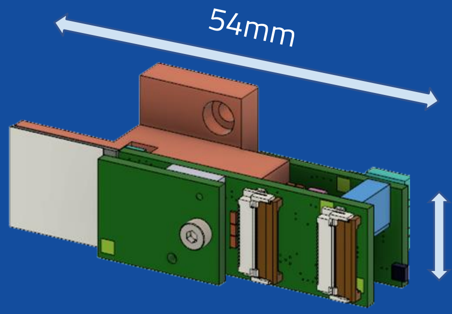
ESA simulation tools:

https://www.spenvis.oma.be/ to calculate the environment, fluxes and doses from the orbit
https://essr.esa.int/project/search/gras for download
https://spitfire.estec.esa.int/trac/GRAS/ for GRAS wiki and instructions

Space Rider - TGF Monitor
THOR-SR experiment

Directional gamma-ray tracker array in wide field-of-view





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TPX3 CdTe Finger board

Rui C. Silva, Jorge M. Maia,
LIP-Coimbra, Portugal

PRODEX, 2022-4
Launch 2024-5

Space Rider

esa

Space **R**eusable **I**ntegrated **D**emonstrator for **E**urope **R**eturn

LEO orbit
400 km
2 month mission
recoverable

LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

FACULDADE CIÊNCIAS
Departamento de Física

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UNIVERSIDADE D COIMBRA

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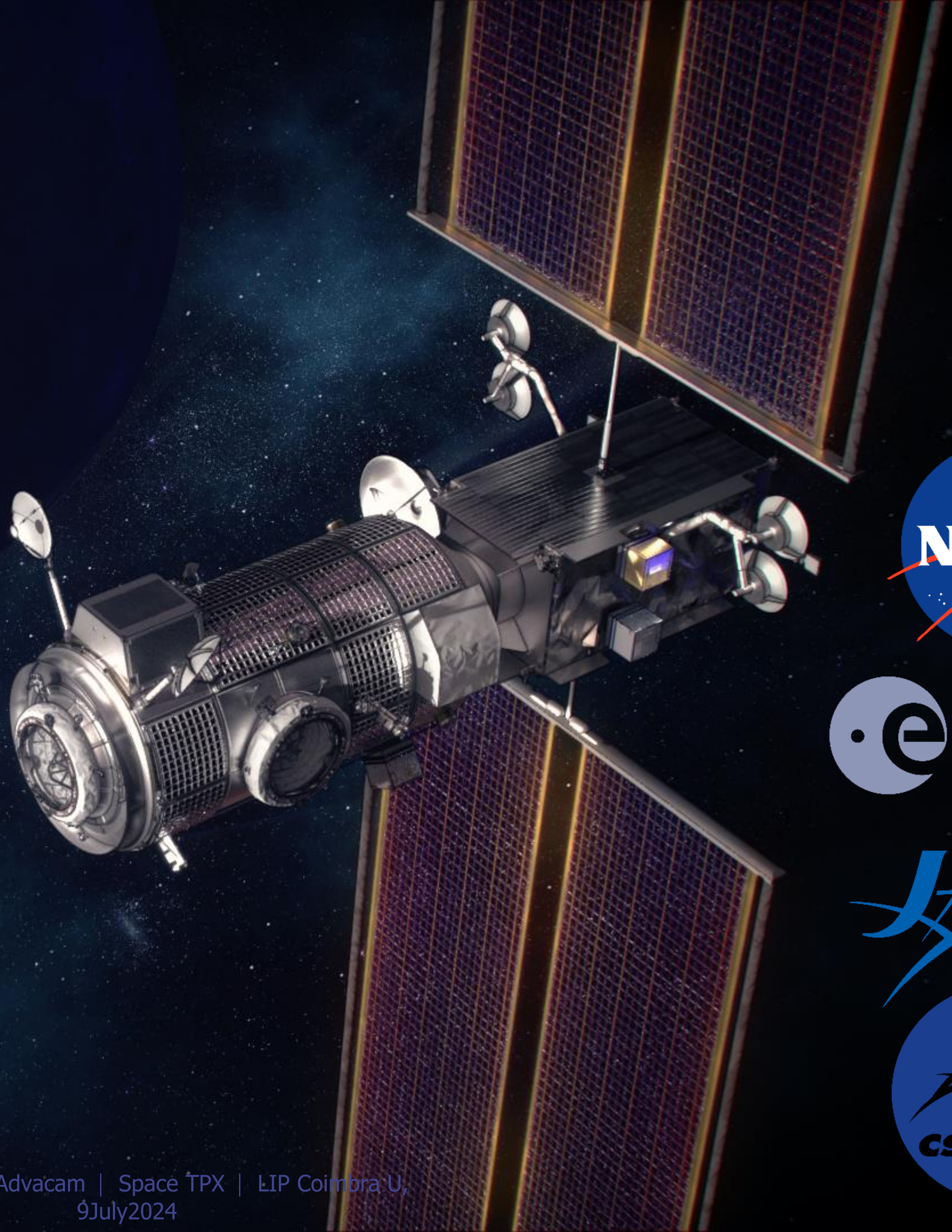
Next step in space exploration:

Lunar GATEWAY

Space station in lunar orbit



"Gateway will be critical in expanding a human presence to the Moon, Mars, and deeper into the Solar System."

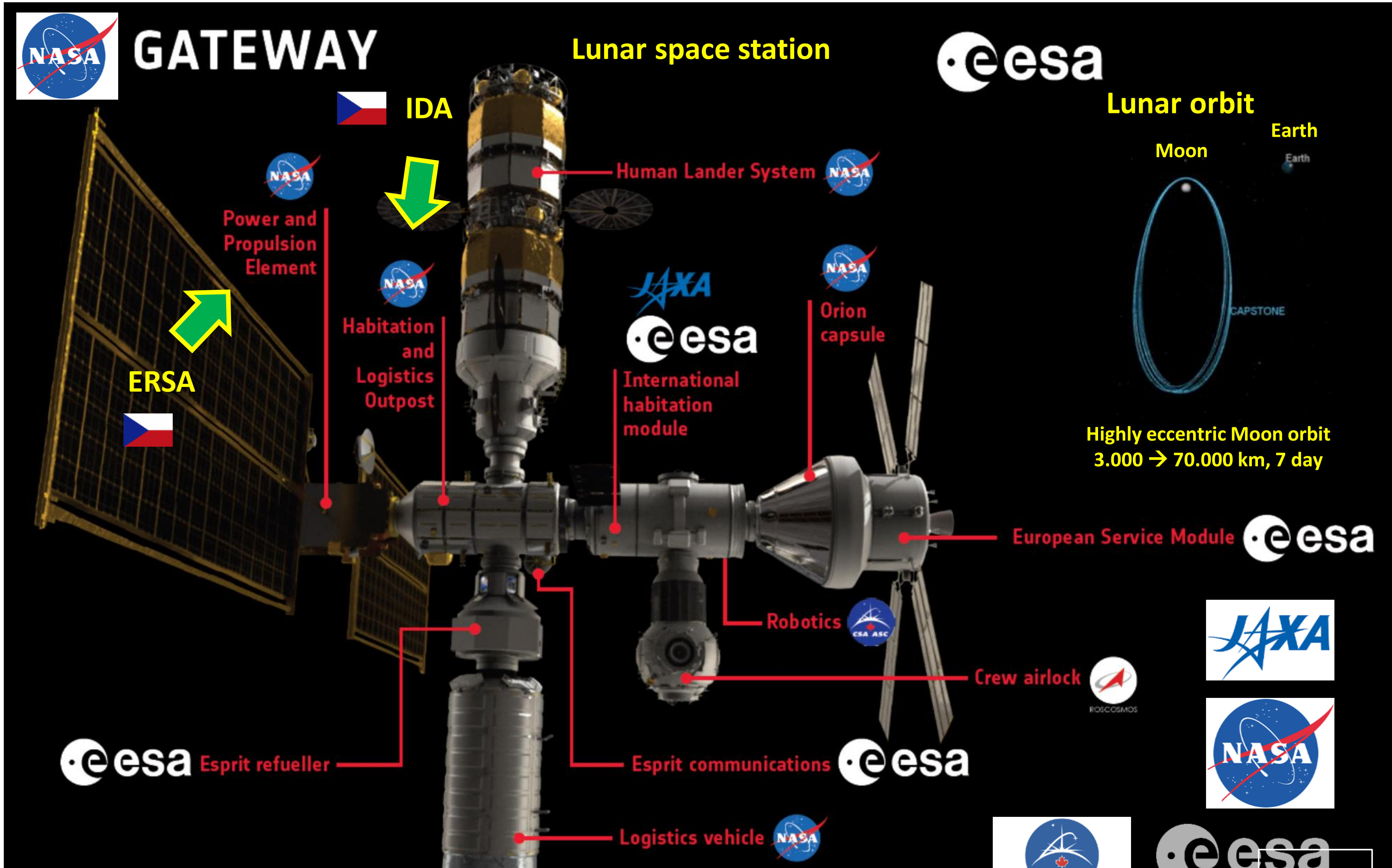
NASA-ESA Lunar Space Station Gateway

European Radiation Instruments Deployments → ERSA + IDA

Gateway is an in-development **mini-space station** in **lunar orbit**.

European Space Radiation Deployments

- ESA-IDA = Internal Dosimetry Array → TPX Advacam
- ESA-ERSA = European Radiation Sensor Array → TPX IEAP CTU Prague



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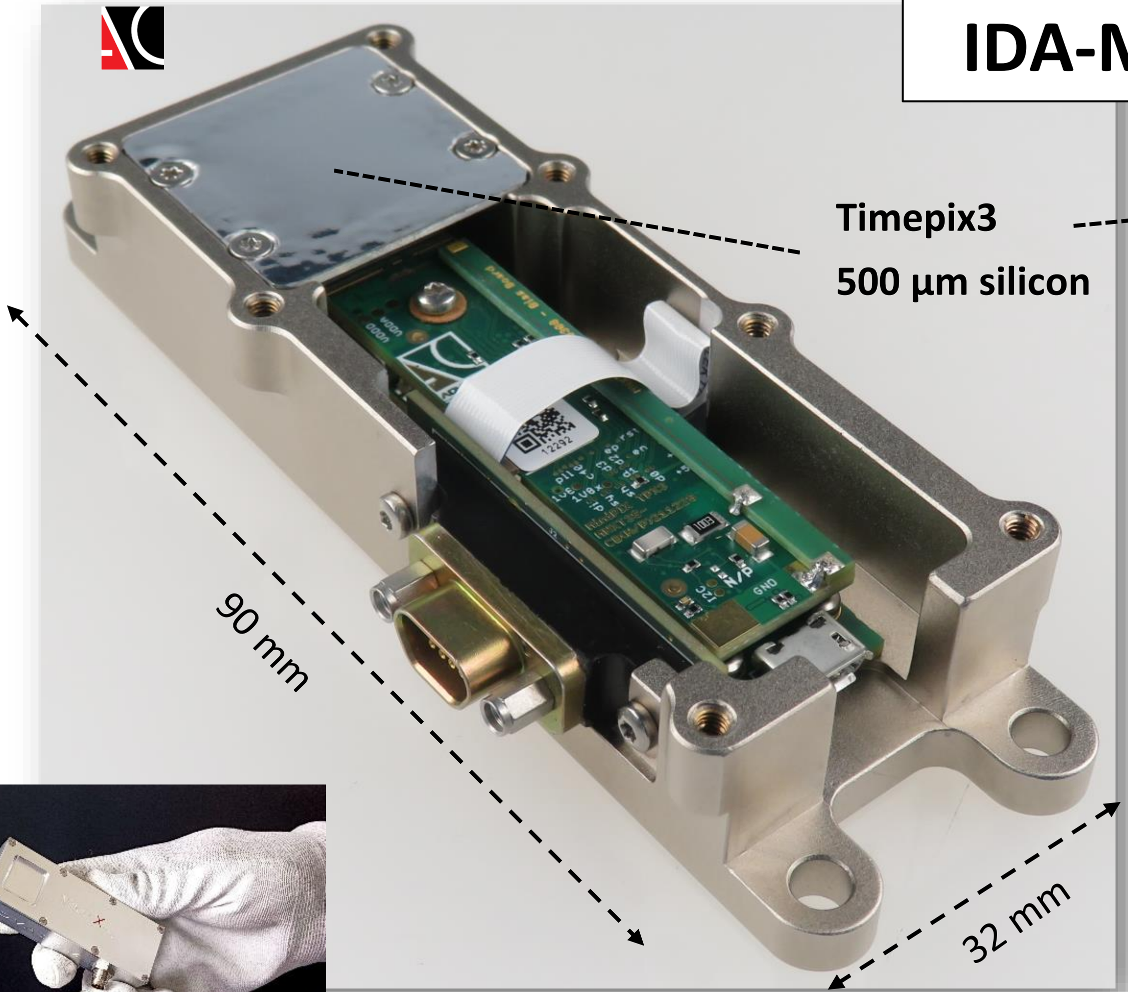
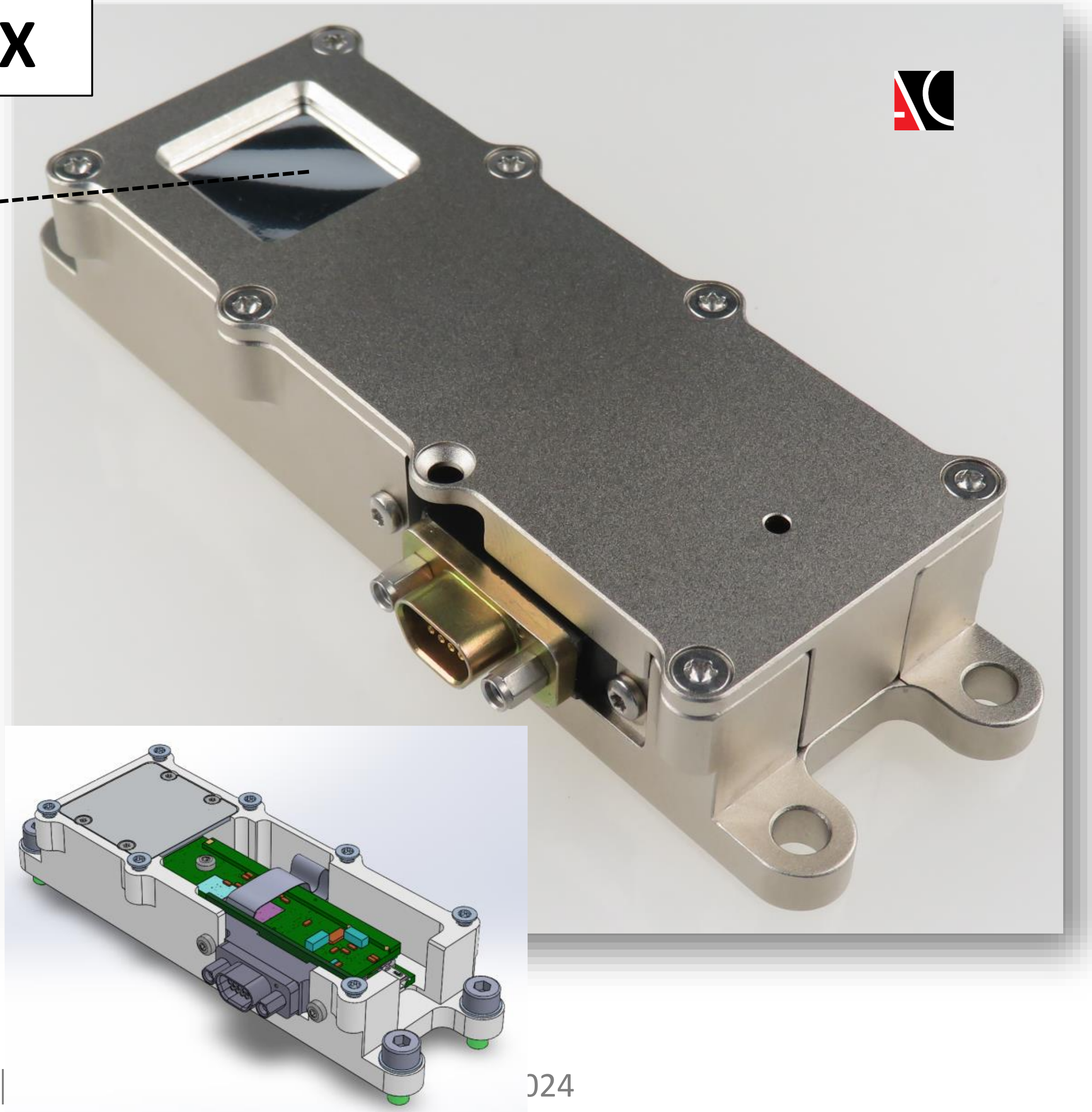
M. Kasal, J. Jakubek, ADVACAM, Prague 2023

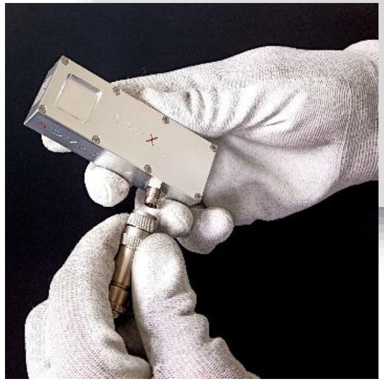
NASA-ESA Lunar Space Station Gateway

European Internal Dosimetry Array IDA: Medipix payload IDA-MPX

IDA-MPX







MiniPIX-Timepix3

Space

3U CubeSat VZLUSAT-2, Czech Aerospace Center VZLU

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X-ray/gamma imaging payload Timepix CdTe

Daniela Doubravova
ADVACAM, 2022

- X-ray optics (Rigaku)
- Focal-plane X-ray imager (Advacam)
  Timepix CdTe 1000 μm

http://vzlusat2.cz

Rigaku

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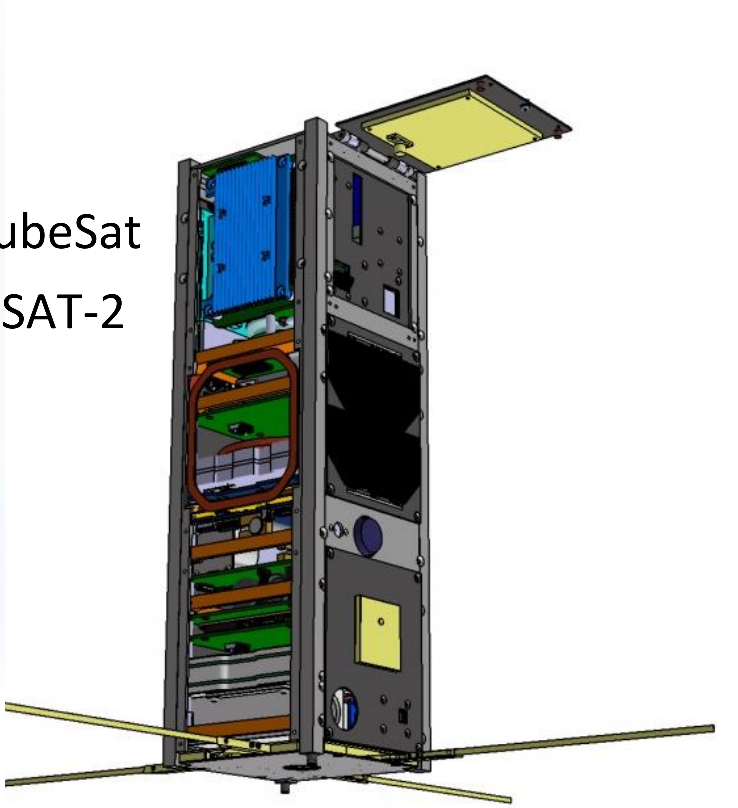
- LEO orbit, 500 km
- Launched January 2022
  Space-X, Cape Canaveral

SPACEX

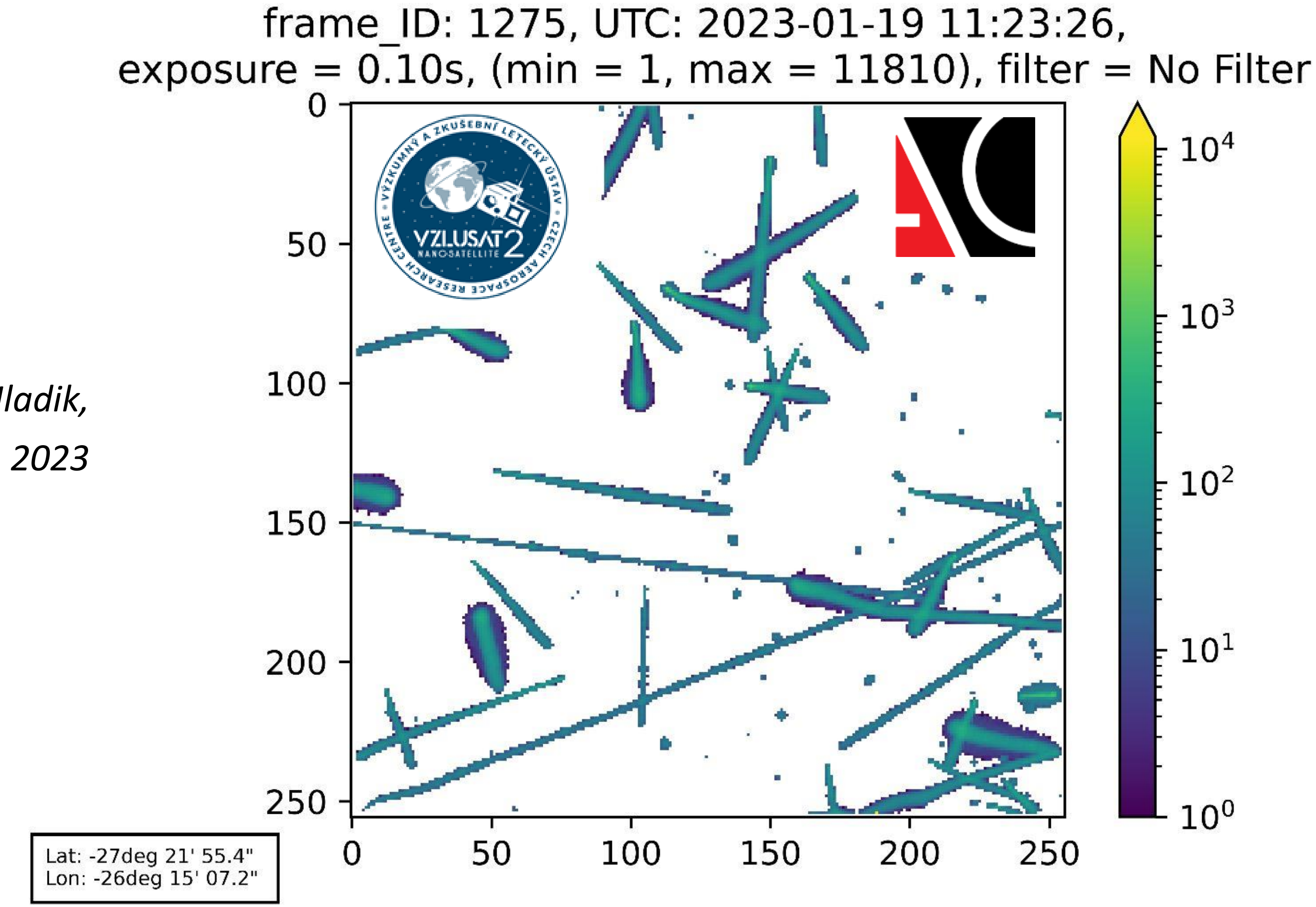
3U CubeSat
VZLUSAT-2



VZLUSAT 2

Space radiation, LEO orbit 500 km, Timepix CdTe 1000 µm

David Hladik,
ADVACAM, 2023



http://vzlusat2.cz

Timepix detectors in space, cosmic rays

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Timepix detectors: methods, techniques

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- C. Granja, et al., **Directional detection of charged particles and cosmic rays with the miniaturized radiation camera MiniPIX Timepix**, Nuclear Instr. Methods A 911 (2018) 142-152
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Timepix detectors: instrumentation

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