SpacePix3: A Radiation-Hardened Pixel Detector for Orbital Dosimetry

VZLUSAT-2 Flight Results and SpacePix3 Lab Characterization

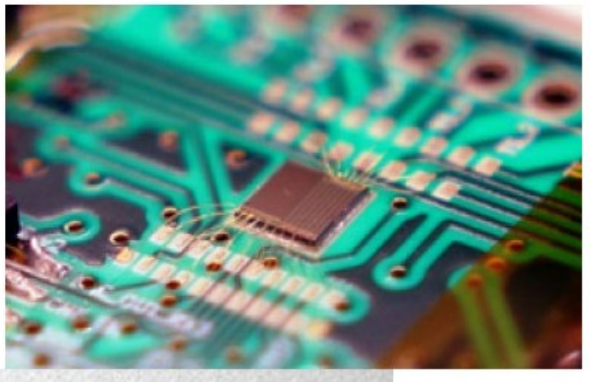
3.9.2026

Radek Novotný
for the CAPADS team

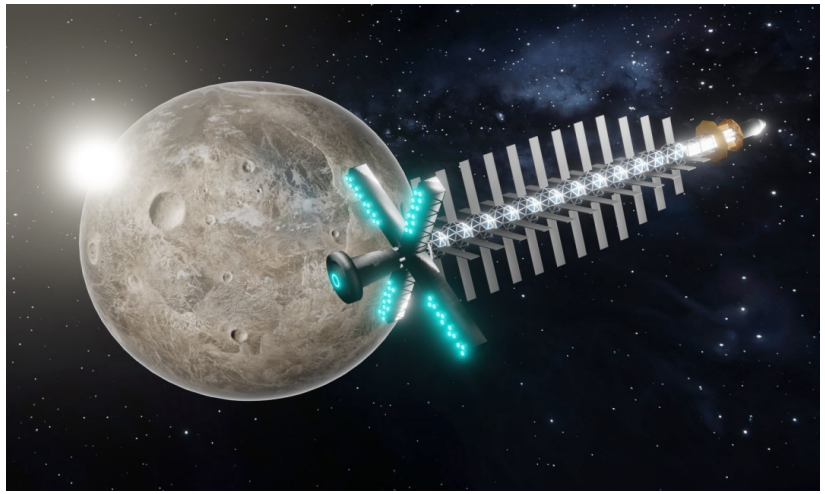
Zdenko Janoška, Vladimír Kafka, Josef Knápek, Anhelina Kostina, Jiří Kulda,
Monika Kuncová, Mária Marčišovská, Michal Marčišovský,
Radek Novotný, Marek Strnad, Peter Švihra, Lukáš Tomášek

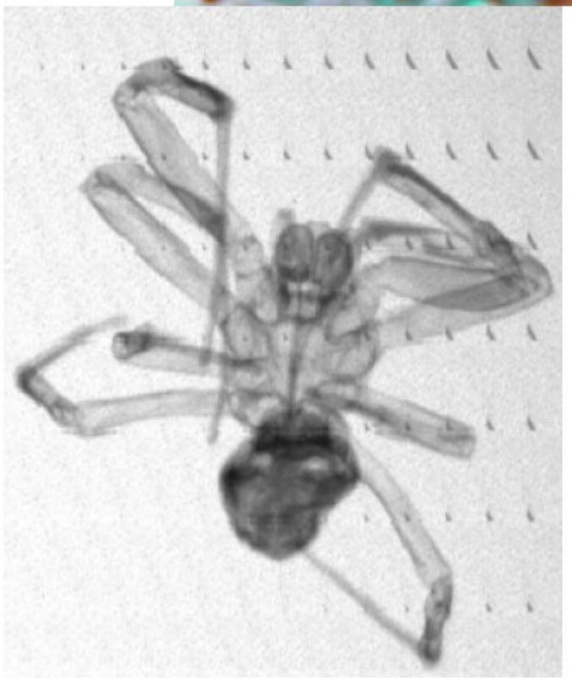
Who are we

The Center of Applied Physics and Advanced Detection Systems (CAPADS) is a research group at the Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague.



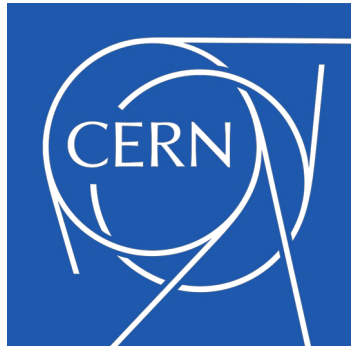
- Group size: ~ 25 people
- Research topics:
  - Monolithic and hybrid detector-chip design for future high-energy physics experiments, medical and space applications, and plasma diagnostics
  - Silicon carbide detectors
  - Quantum astrometry
  - Space nuclear propulsion studies





Participation in international research projects

- CERN, Switzerland
  - ATLAS
  - RD50, RD53, DRD3
  - Medipix
- Brookhaven National Laboratory, USA
  - sPHENIX
  - STAR
  - Future Electron–Ion Collider (ePIC)
- FAIR - GSI, Germany
  - PANDA

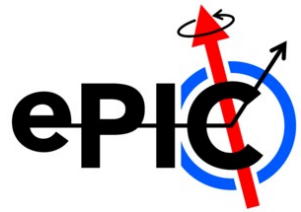








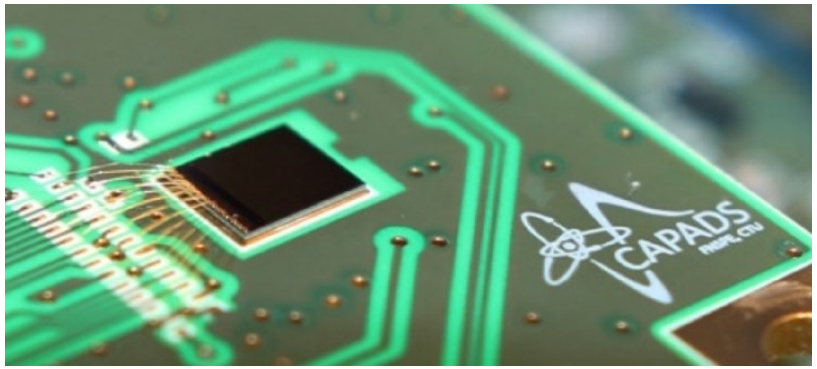
Brookhaven
National Laboratory





Overview of previous submissions

- Measurement of X-rays, beta radiation, and ions
  - Radiology, dose-rate measurement, spectroscopy, and space weather
  - **Since 2012 (preceded by CERN R&D)**
- **Technologies:**
  - onsemi - Proprietary sensors (Si, SiC - own process flow)
  - LFoundry 150 nm CMOS (LF150)
  - AMS 180 nm CMOS (C18, aC18)
  - TSI 180 nm CMOS (H18)
  - **X-FAB SoI 180 nm (XT018)**
  - **TSMC 65 nm CMOS LP**
- All submissions use Analog-on-Top

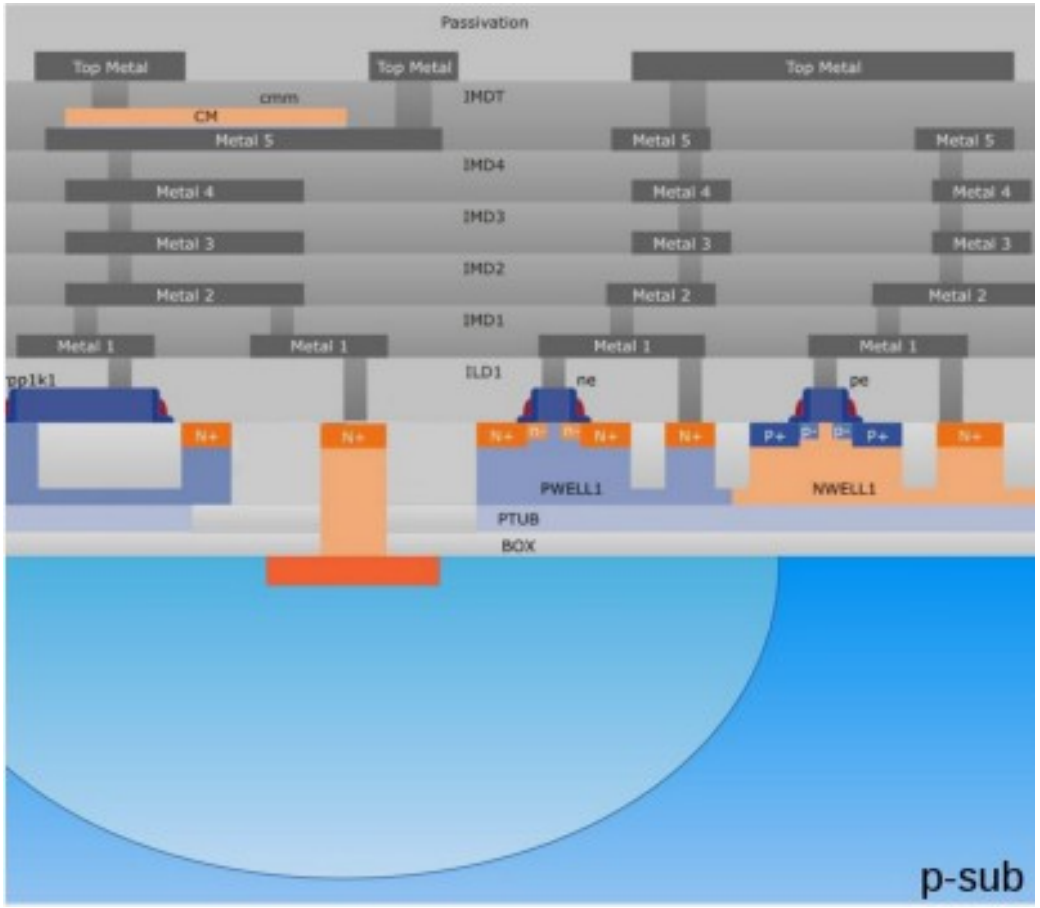


ASICs: 30+ tape-outs (4 ERs)
Sensors: silicon (20 ERs)
CZT
(prototyping) SiC
(prototyping)

Introduction to SpacePix

- The SpacePix family uses monolithic sensors for space-dosimetry measurements
- It uses a 180 nm SOI MAPS process

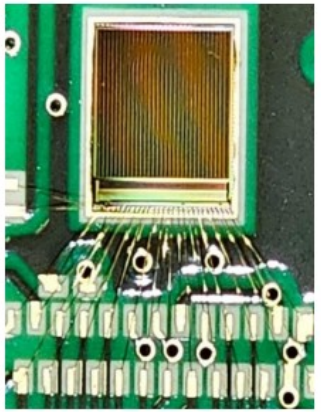
- Monitoring space radiation is important for:
  - terrestrial and space-based technological infrastructure (especially electronic systems)
  - human health protection, space dosimetry
  - space radiation research



The SpacePix family

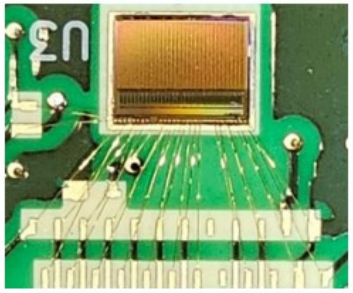
XCHIP-03 → **SpacePix1** → **SpacePix2** → **SpacePix3**

2018



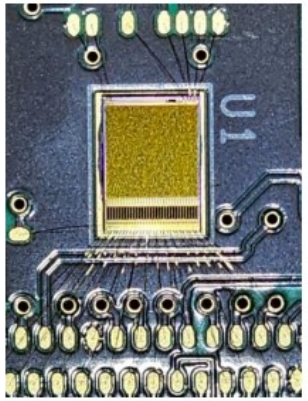
- 180 nm SOI CMOS process
- 1 - 10 ke⁻ signal range
- 10-bit single-ended column-parallel SAR ADCs
- Soft X-ray imaging

2020



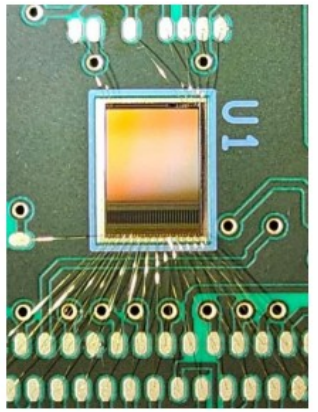
- The first SpacePix test chip
- Extended dynamic range 1 ke⁻ - 65 ke⁻
- 8 – bit asynchronous column-parallel SAR ADCs with differential architecture

2022



- Digitization signal from backside channel extending signal range up to 30 Me⁻
- 10 – bit asynchronous column-parallel SAR ADCs with differential architecture

2023

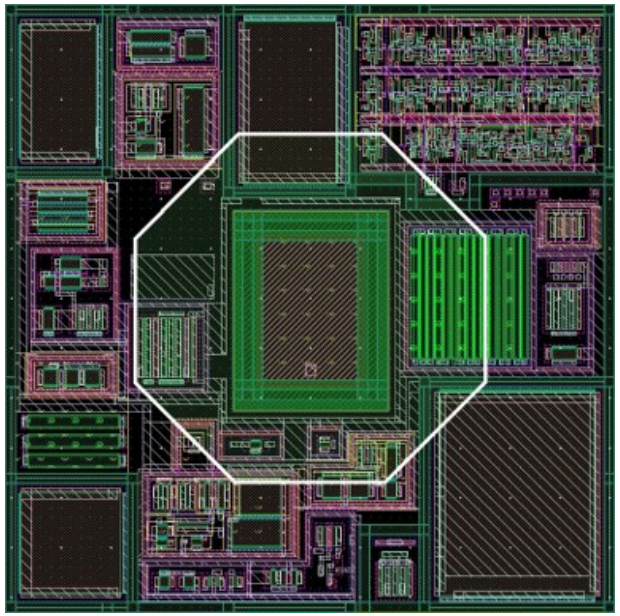


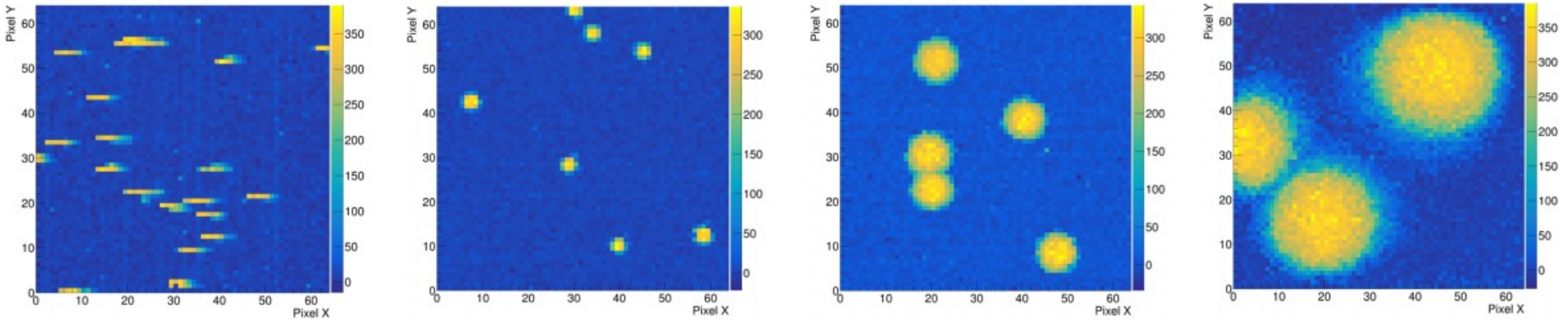
- Improved version of SpacePix2
- SAR ADC bugfix
- New feature: user defined data sampling at falling or rising edge
- optimized CSA, PDH and ADC ranges

Two parallel branches share the technology: **SpacePix** for dosimetry and wide dynamic range, **X-CHIP** for soft X-rays — now at version 4.

SpacePix2 main parameters

- It features a 64 × 64 pixel matrix with a 60 µm pixel pitch
- Digitization uses a fast 10-bit asynchronous differential SAR ADC
- Dynamic range — pixel side: 2–80 ke^-; backside: 0.25–30 Me^-
- Low power (<50 mW); processes 10^5–10^6 pixel hits $cm^{-2}\ s^{-1}$
- Total-ionizing-dose (TID) threshold: ~2 kGy at 15 Gy/min
- dE/dx measurement for electrons, protons, and heavy ions





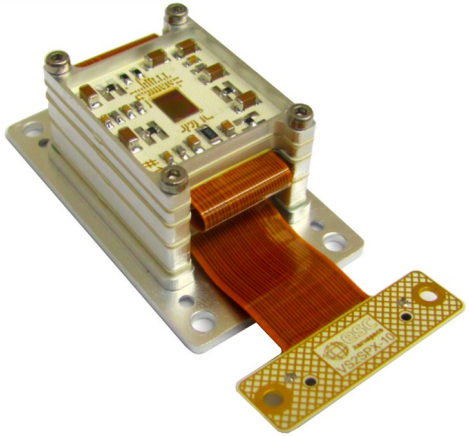
(a) ^{1}H ions @ PTC (b) ^{22}Ne ions @ U400M (c) ^{40}Ar ions @ U400M (d) ^{136}Xe ions @ U400M

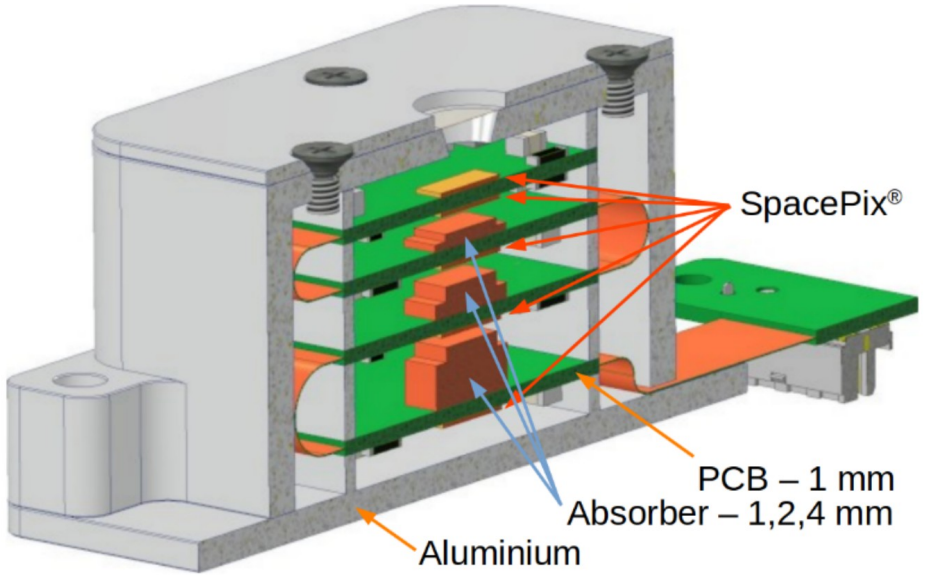
Visualization of the deposited energy (in ADC units) for the accelerated ions. The visualized ion hits are pedestal-subtracted (except for (a)) and the axes show the pixel coordinates.

The SpacePix Radiation Monitor (SXRM)

- SpacePix2 is designed for standalone operation, for use in a particle telescope, or with a scintillator
- The SXRM consists of five SpacePix2 sensors separated by absorbers
- SXRM envelope dimensions: 41 × 32 × 26 mm³
- Weight: less than 60 g (Al case) or 135 g (Inconel)
- The detector modules connect to a radiation-tolerant microcontroller unit
- Supply voltage: 1.8 V, with an HV bias of −150 V
- **Projected GEO lifetime: 10 years**

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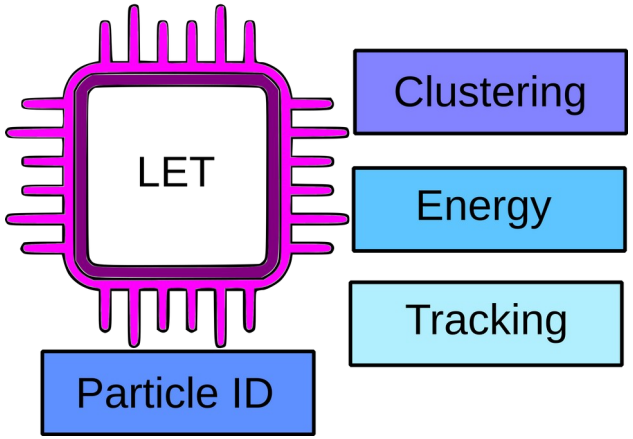


On-board processing: bandwidth is the real limit

- On a CubeSat, the downlink - not the sensor - determines what a dosimeter can deliver
- In flight, the 2SD processing unit performs clustering, topological event classification, and partial trajectory reconstruction
- Several readout modes trade spatial resolution against bandwidth

Result: autonomous characterization of the radiation environment from a small fraction of the raw frames - and maps by particle species rather than a single counter

On-board processing



On-board: clustering, energy, coarse tracking and particle ID — so the downlink carries physics, not raw frames.

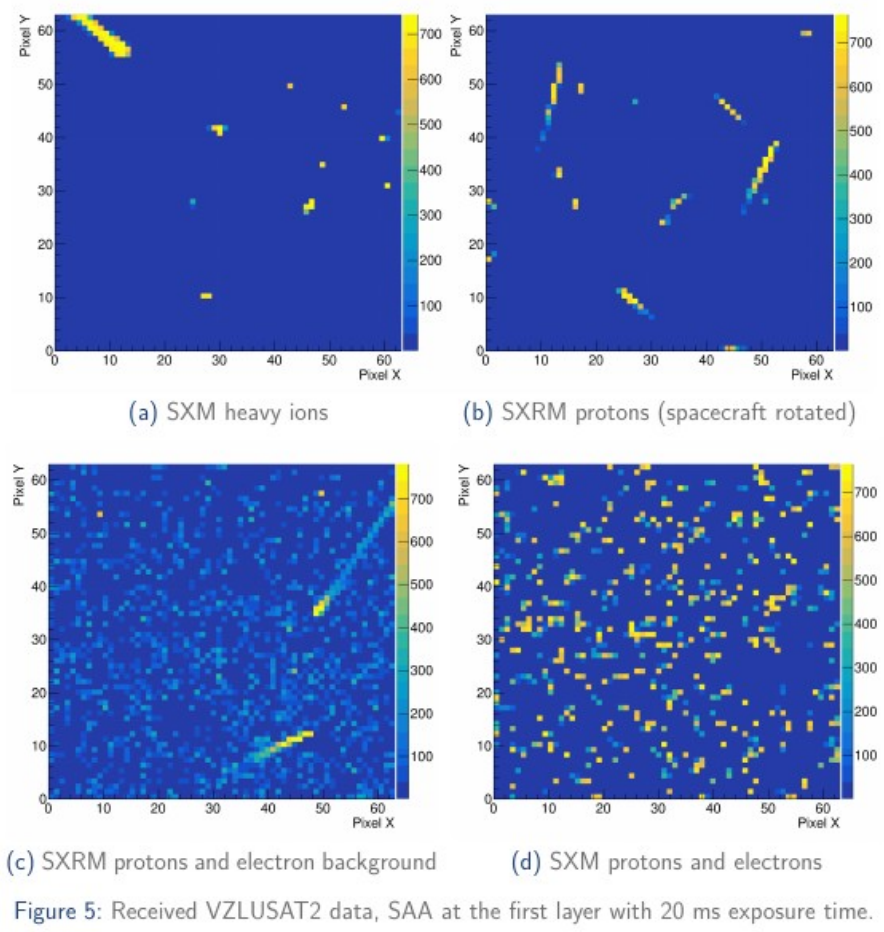
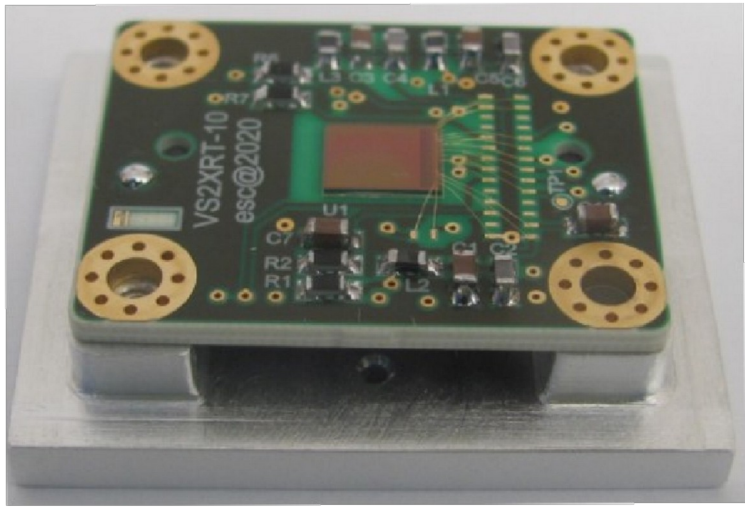


Figure 5: Received VZLUSAT2 data, SAA at the first layer with 20 ms exposure time.

Measured signatures at 20 ms exposure—the classifier input.

Soft X-ray Monitor (SXM)

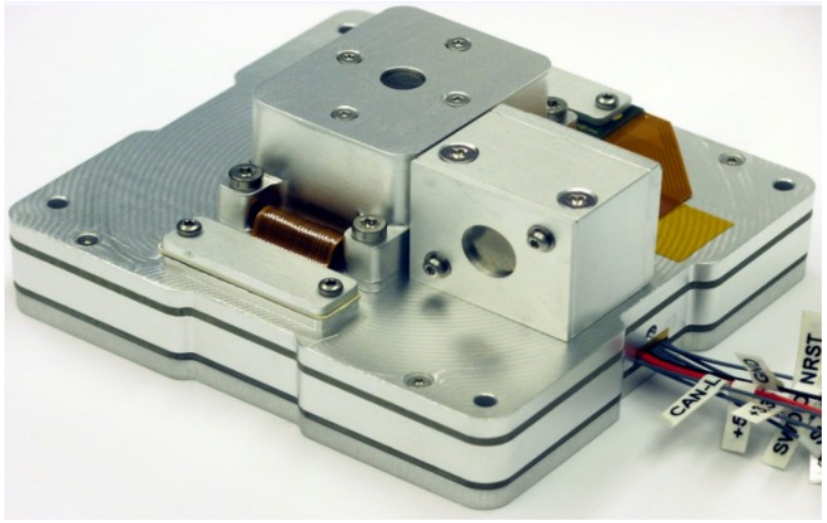
- The SXM detector is based on a single XCHIP-03 chip
- XCHIP is a parallel branch of the SpacePix detector family (now at version 4)
- It targets a different energy range and particle type (soft X-rays), with hit-counting and ADC modes
- Photon energy range: 3–30 keV
- Shielding: Al block with a drilled-cone input aperture

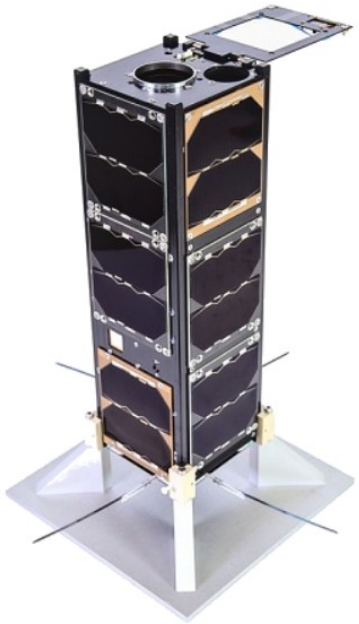


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VZLUSAT-2 mission

- The SXRM and SXM are part of the Czech VZLUSAT-2 nanosatellite mission as components of the Space Dosimetry System Demonstrator (2SD)
- VZLUSAT-2 was launched in 2022 aboard a SpaceX Falcon 9
- Sun-synchronous polar orbit: inclination ≈ 97.3°; initial altitude 521–543 km (de-orbited on 30 November 2025)

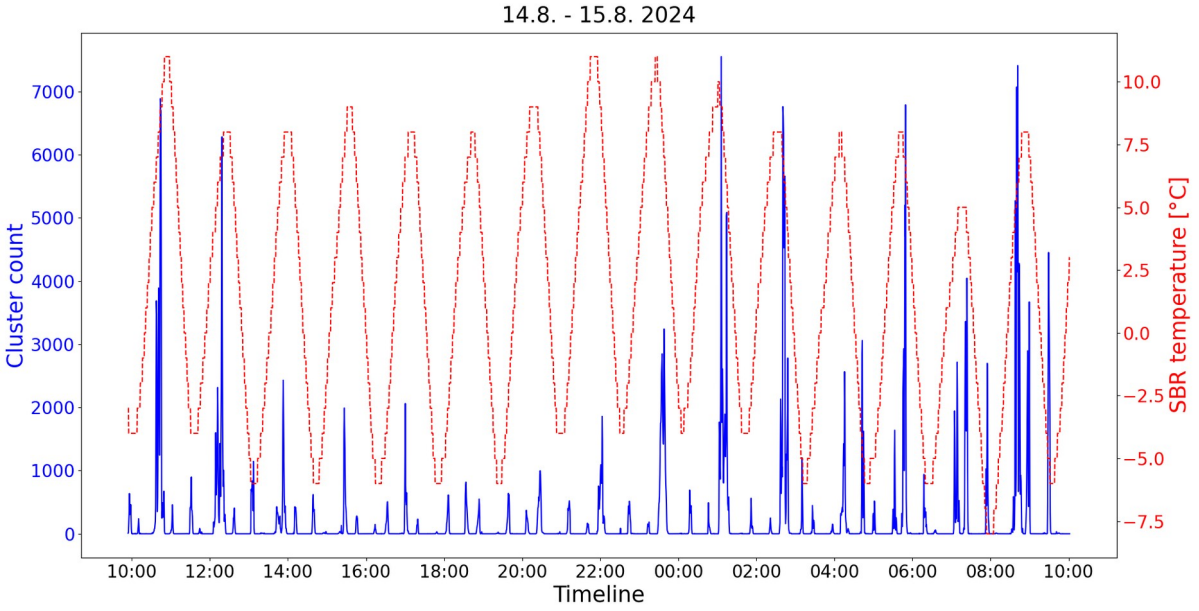






SpacePix2: one day in orbit

- **One day of in-orbit data (14–15 August 2024): cluster count and detector temperature over several orbits.**
- Representative 20 ms frames show distinct heavy-ion, proton, and electron-background signatures.



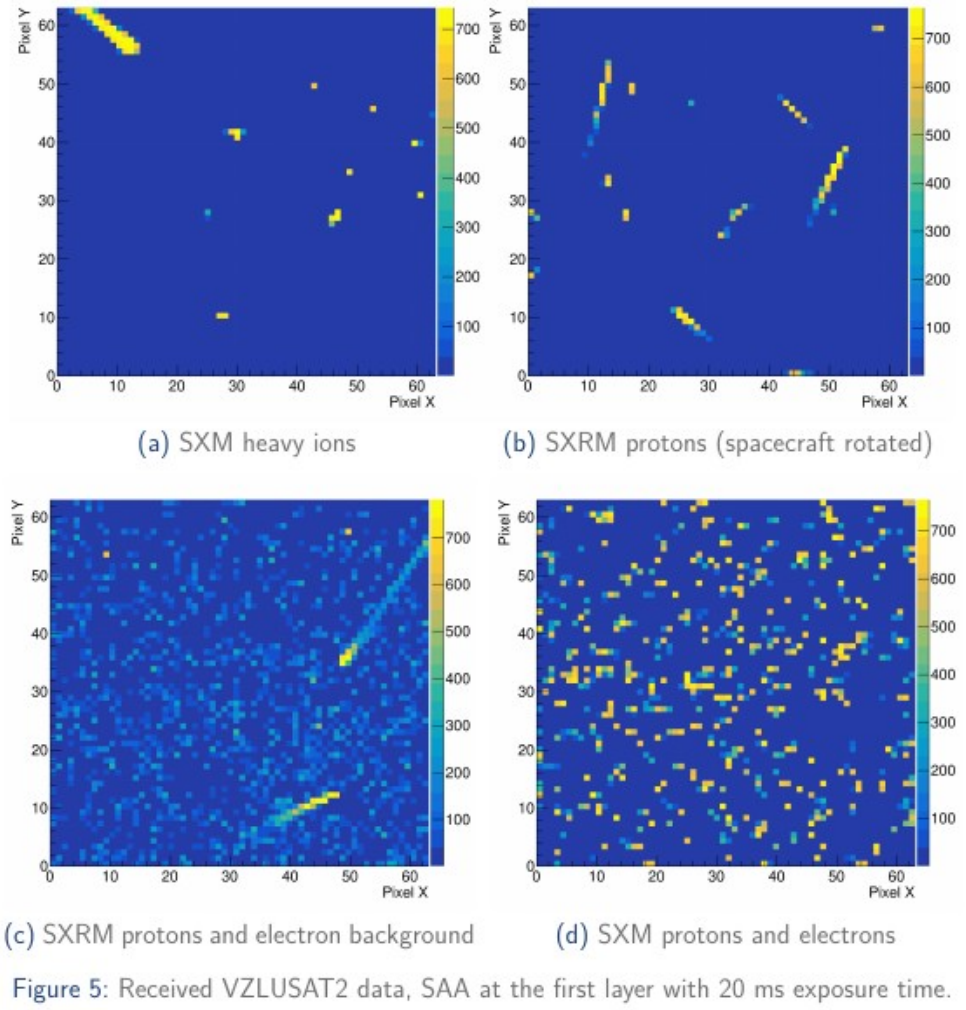
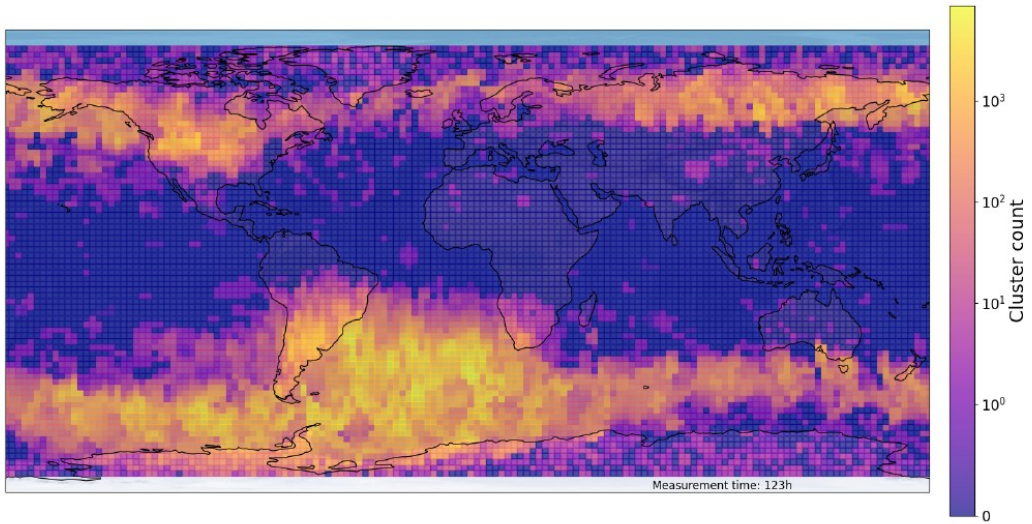


Figure 5: Received VZLUSAT2 data, SAA at the first layer with 20 ms exposure time.

VZLUSAT-2: flight-path correlation

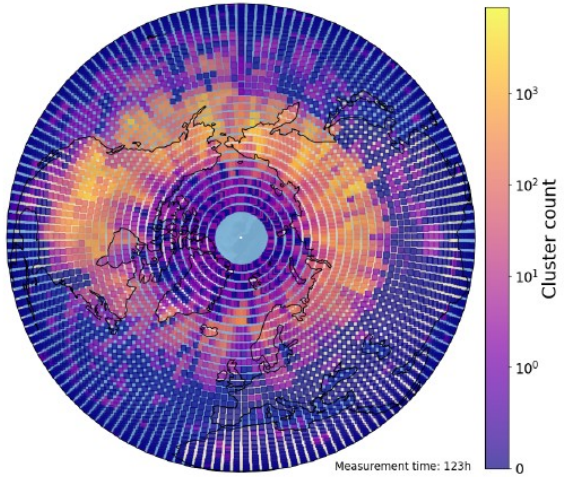
- Correlating detector data with the flight trajectory produces a global radiation map.
- **The South Atlantic Anomaly (SAA) appears clearly as enhanced particle counts.**
- Elevated particle flux is also visible at high latitudes.

Global projection



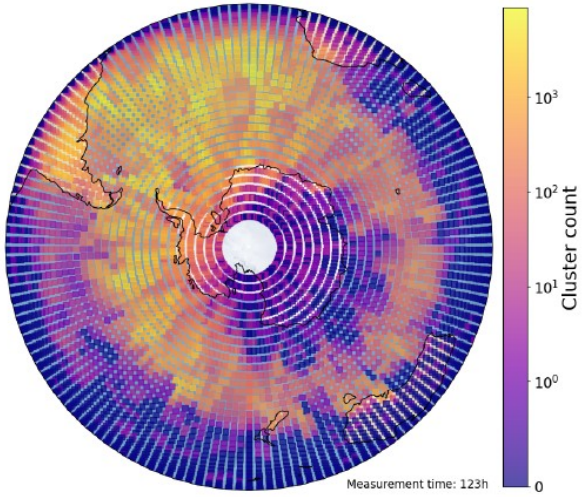
(a)

Northern polar projection



(b)

Southern polar projection

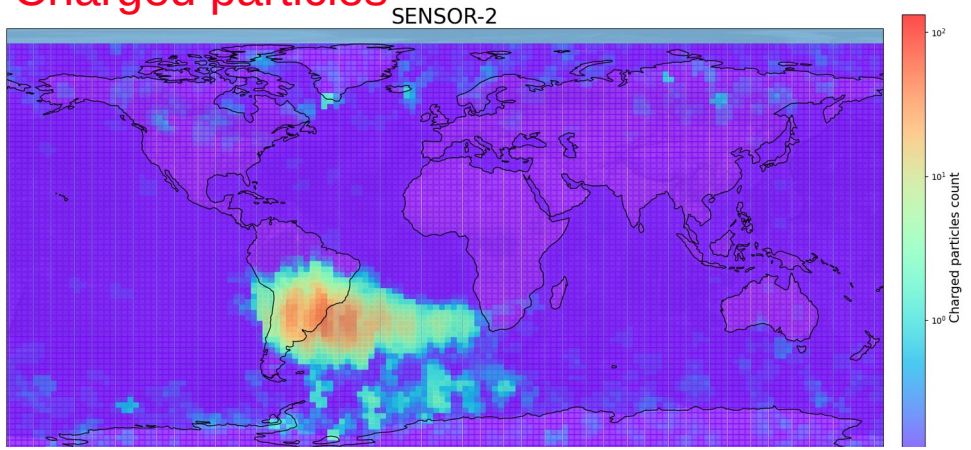


(c)

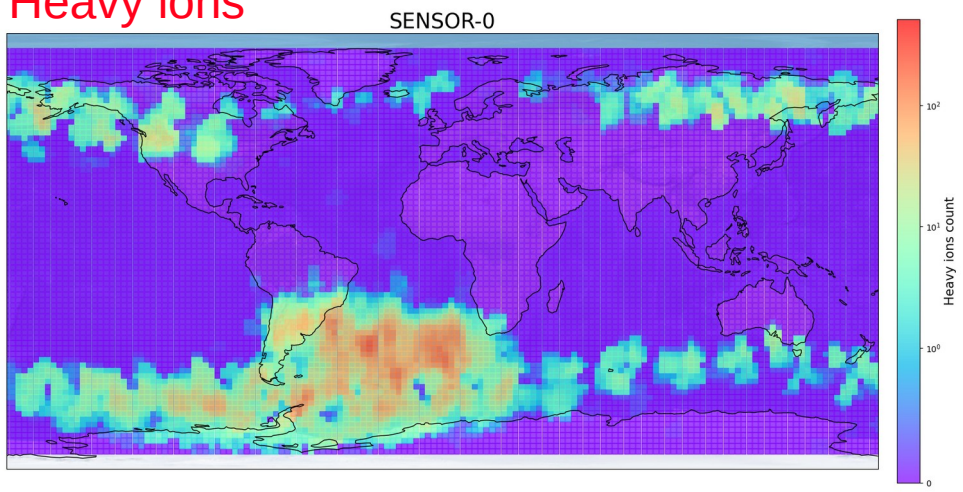
On-board processing and particle ID

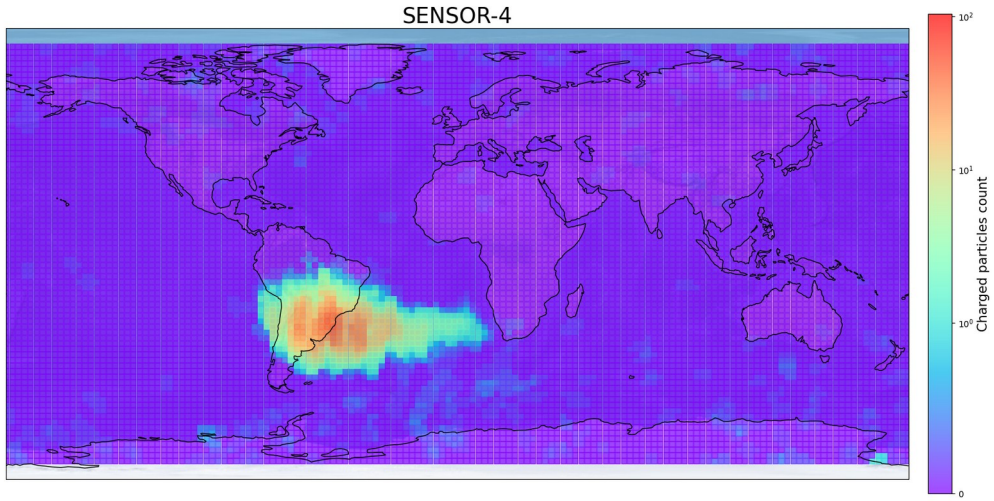
- On-board processing uses clustering, topology-based classification, and partial particle-trajectory reconstruction.
- SENSOR-1 was damaged during launch, reducing the tracking baseline and complicating particle identification.

Charged particles



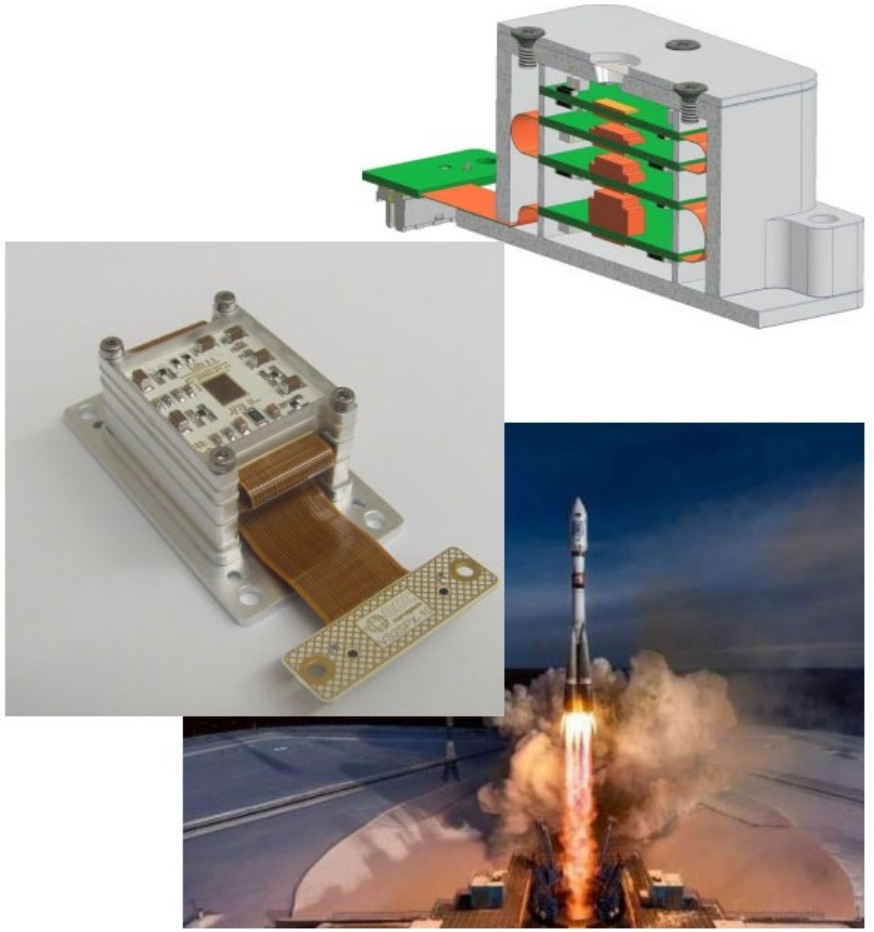
Heavy ions





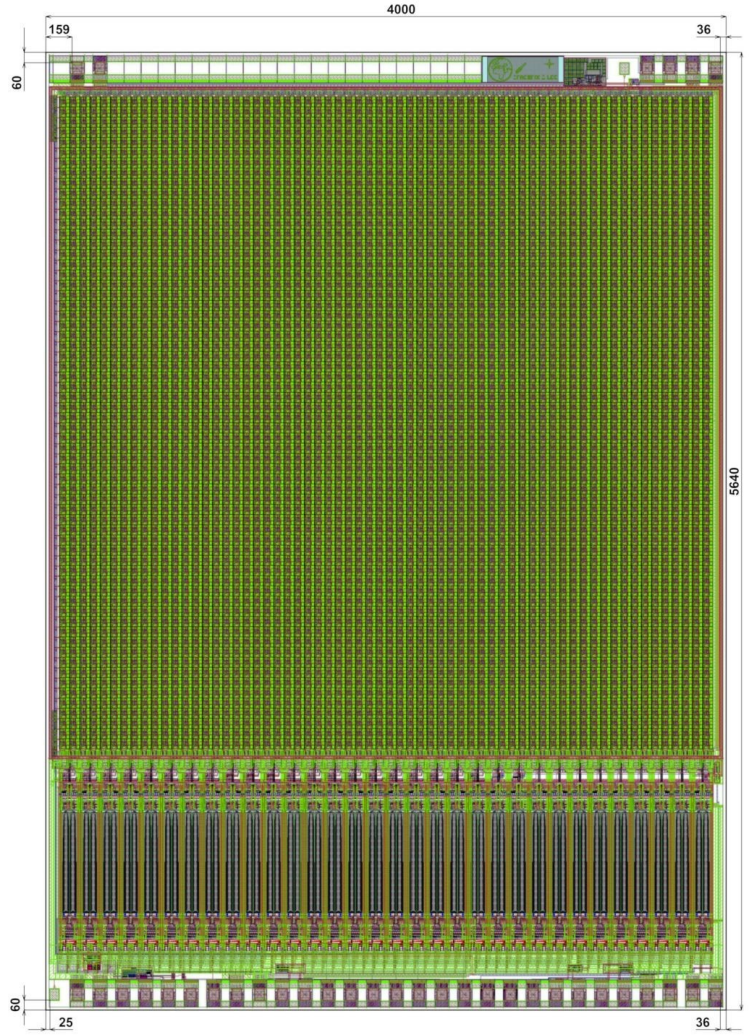
Flight validation and SpacePix3 inputs

- **SpacePix2, SXRM, and SXM were validated in orbit aboard VZLUSAT-2, achieving TRL 9.**
- Flight data revealed the limits of the original DAQ ranges and directly guided SpacePix3 development: improved ADC linearity, reoptimized ranges, and lower-power operation.



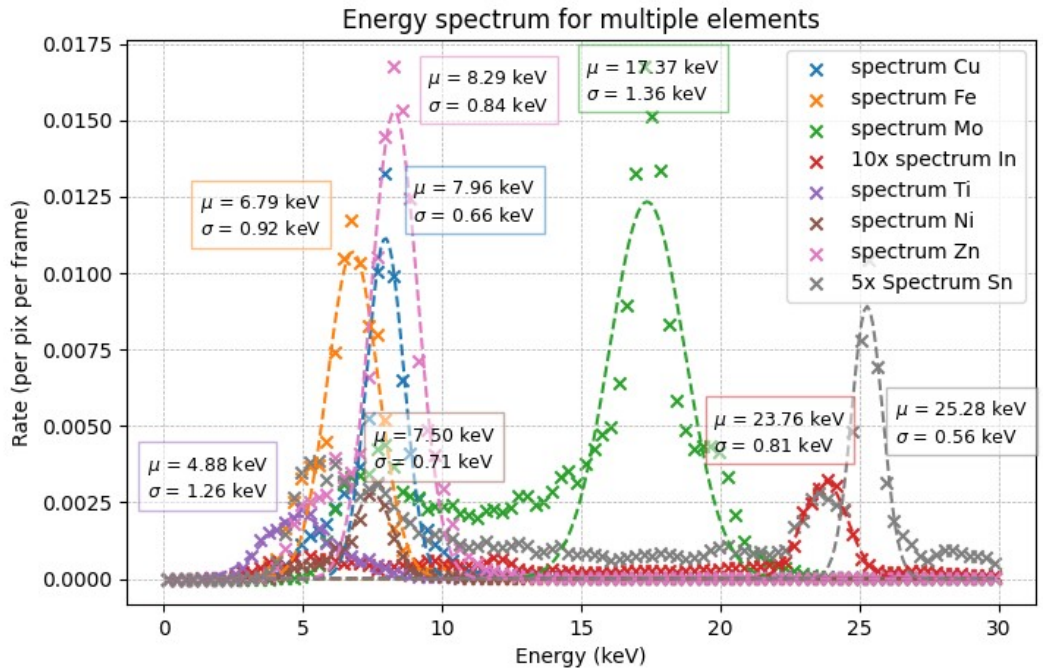
From flight data to SpacePix3

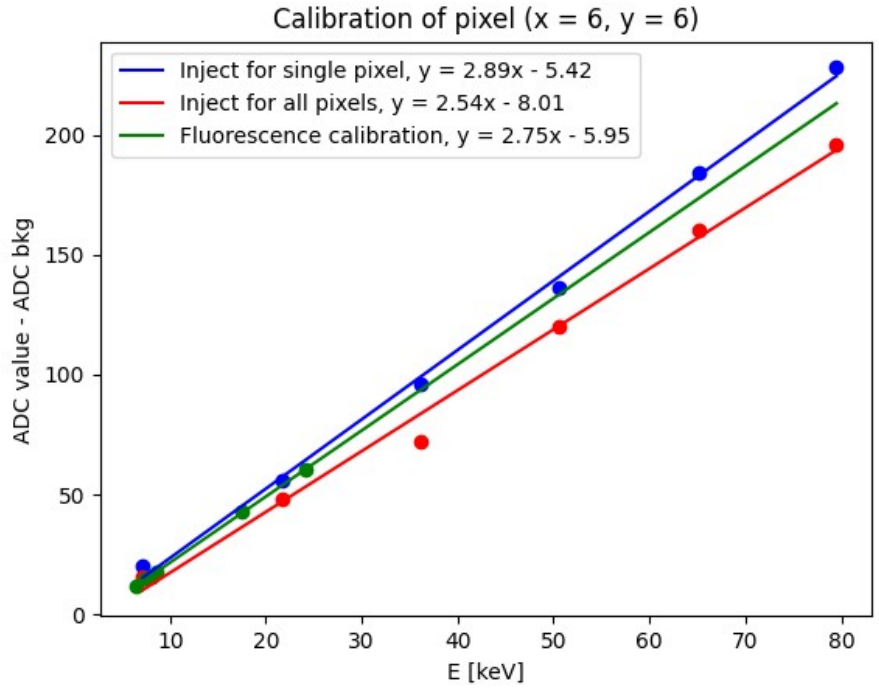
- VZLUSAT-2 confirmed that SpacePix2 worked, but exposed real limits—some DAQ ranges were too narrow because pre-flight simulations and in-orbit operation disagreed
- SAR ADC redesigned to suppress missing codes → more linear response and better measurement precision
- CSA, PDH, and ADC ranges reoptimized; current draw reduced to ≈ 31 mA in SPI mode
- New: user-defined sampling on either the rising or falling clock edge
- Produced in an engineering run with X-CHIP-04 → many samples in hand; manufacturing cost ≈ US$100 per chip
- **The takeaway: fly the chip, then trust the ranges.**



SpacePix3 calibration

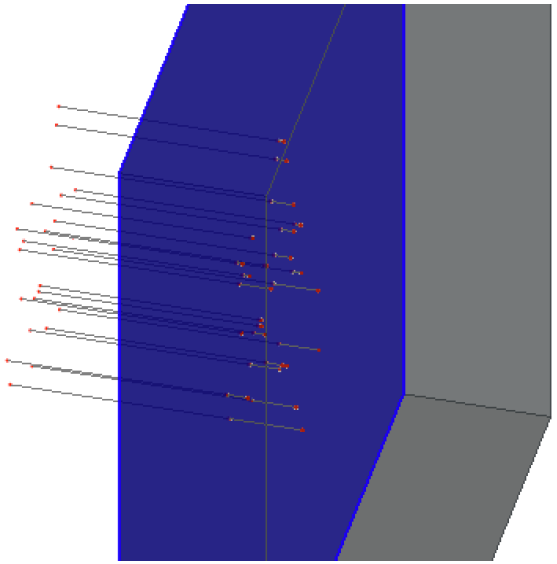
- Calibration based on X-ray fluorescence (very low detection probability due to the thin silicon sensitive layer)
- Built-in charge injection enables calibration of one pixel or all pixels at once
- **Good linearity up to 80 keV (but very low interaction probability)**

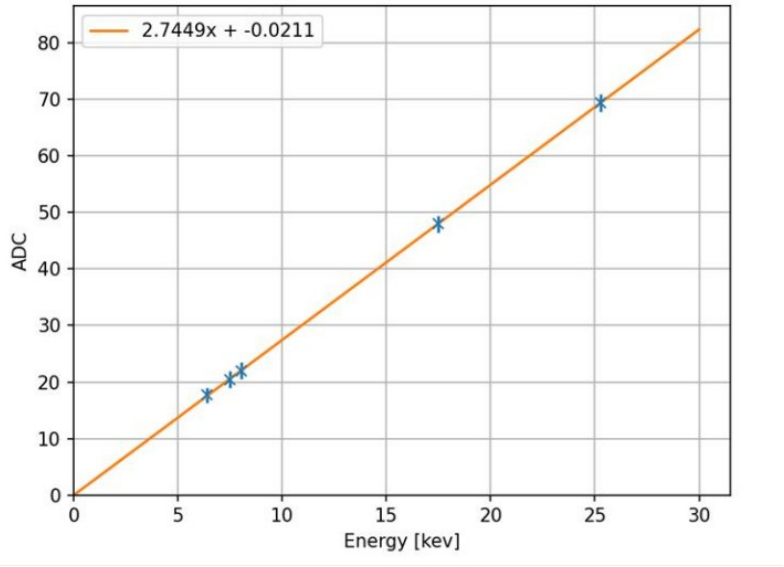


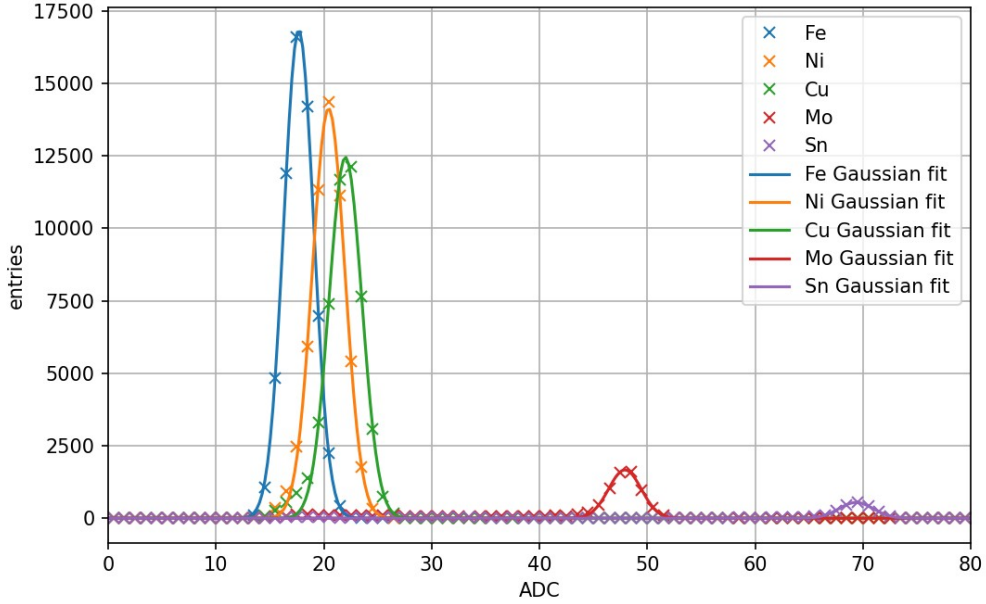


SpacePix3 simulation

- Improved simulation based on the VZLUSAT-2 mission
- Introducing Allpix Squared for detector-response simulation (https://allpix-squared.docs.cern.ch)
- Next: ADC validation → MIP/alpha studies

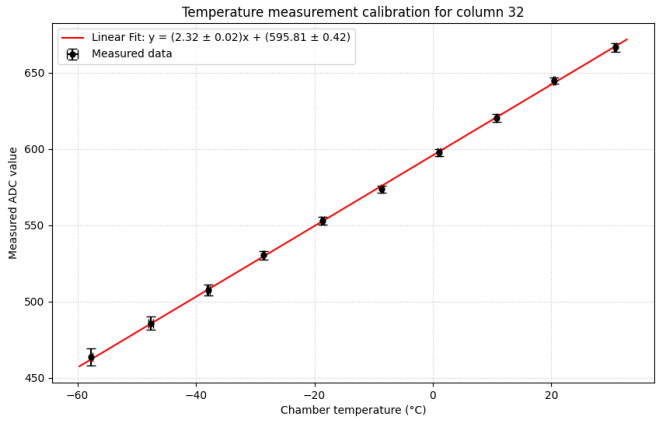


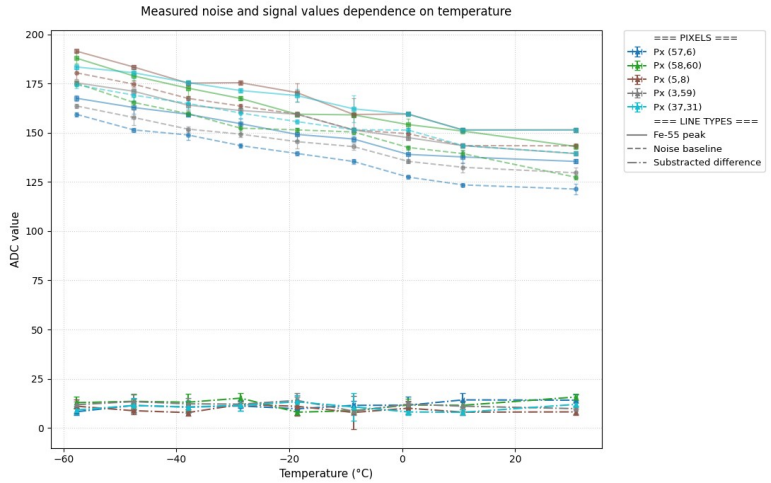


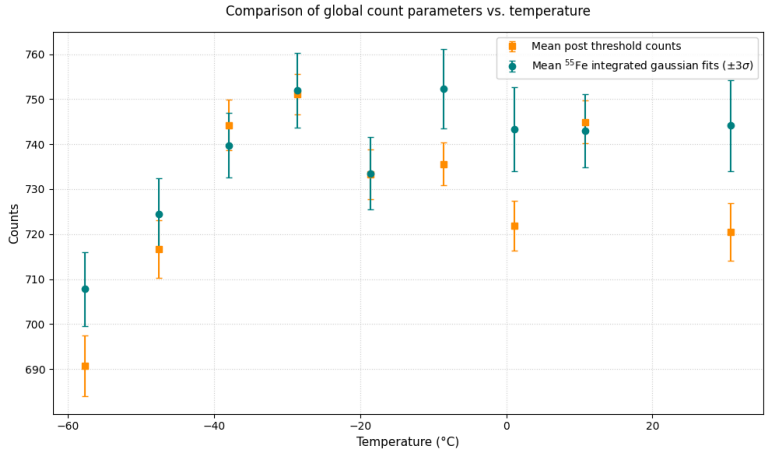


Temperature characterization

- Environmental-chamber measurement at the Institute of Physics, CAS: −60 °C to +30 °C, eight set points, 10 000 frames each, with and without a ^{55}Fe source
- On-chip thermometer calibrated per ADC channel against a reference probe—linear across the whole range at (2.32 ± 0.02) ADC counts/°C
- ^{55}Fe peak and noise baseline **shift down together** with rising temperature, but their difference is constant → **gain is temperature-stable, only the offset moves**
- Detection efficiency flat from **−40 °C to +30 °C**, with a possible small decrease below −40 °C; ≈ 20 % of pixels rejected by the automatic peak fit at most temperatures





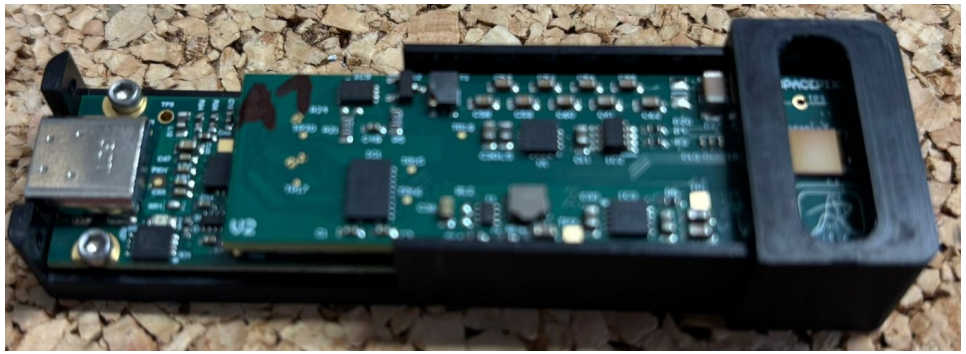


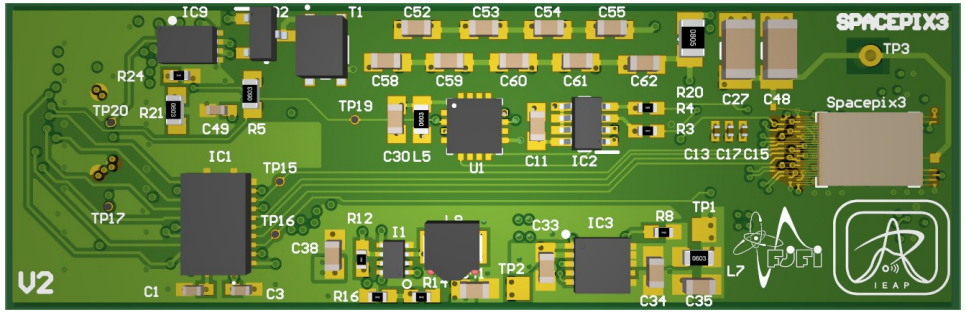
Data: J. Knápek, research project, CTU FNSPE, 2026

SpacePix-Lite: a bench system

- Based on the **Timepix-Lite** readout developed by IEAP Prague (Two stratospheric balloon missions – ASTRABAX (34.4 km) and OURANOS (27.3 km))
- Not rad hard by design - a deliberately low-cost COTS route to getting SpacePix3 onto a bench
- **USB-C for testing and Nano-D for flights**, integrated HV supply, STM32 firmware with Python host software over UDP
- Purpose: let an external group evaluate SpacePix3 without building any infrastructure - the chips are free, so the readout should not be the barrier

The chips are free for non-commercial R&D.
SpacePix-Lite means the readout is not the barrier either.

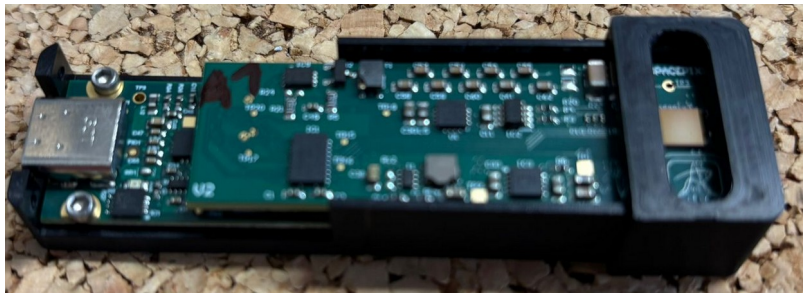




Above: assembled module. Below: sensor-board render.

Availability and next steps

- We are a university group, so **SpacePix3 and X-CHIP-04 are available free of charge for non-commercial R&D** — engineering-run samples are in hand
- Manufacturing cost estimate ≈ US$100 per chip; SpacePix-Lite provides a turnkey bench setup



- **What we are looking for at WRMISS:**
  - flight opportunities — LEO, GEO or a crewed platform
  - cross-calibration against an ISS-class instrument
  - partners for a compact or wearable dosimeter demonstration

Get in touch
radek.novotny@fjfi.cvut.cz
CAPADS · FNSPE CTU in Prague

Summary

- **SpacePix2 flew** on VZLUSAT-2 inside the 2SD: 123 h of data, stable throughout, no measurable degradation, the SAA and polar structure reconstructed
- **SpacePix3 fixes what the flight exposed** — ADC linearity, DAQ ranges, power — and is calibrated from 4.9 to 25.3 keV with σ down to ≈ 0.5 keV
- **Gain is temperature-stable from −60 to +30 °C; only the offset moves, and the on-chip thermometer tracks it at 2.32 ADC counts/°C**
- **SpacePix-Lite** makes the chip usable on any bench

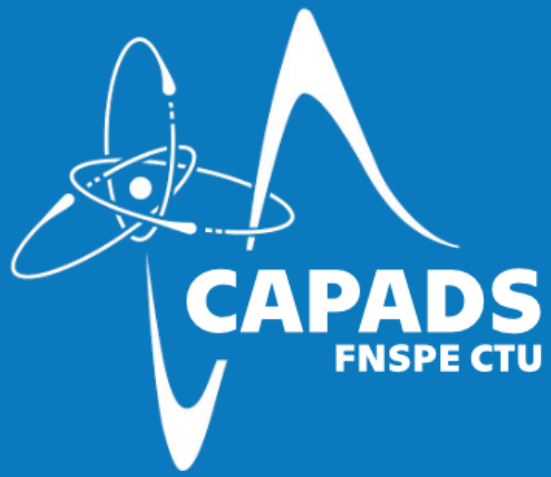
- **Chips are free** for non-commercial R&D and we are looking for missions
  - **What we still owe you:** dose-rate and LET numbers from the flight data, and a SpacePix3 radiation-tolerance campaign.

Our Team*

* most of it at least!



Thank you for your attention!





https://capads.fjfi.cvut.cz