13TH INTERNATIONAL WORKSHOP ON ASTRONOMICAL X-RAY OPTICS

5 - 9th December 2022 | Prague, Czech Republic

AXR

ADVACAM
Imaging the Unseen

X ray imaging with spectral and photon counting response with Timepix3 and Timepix2 radiation cameras

Jan Jakubek, Eliska Trojanova, Daniela Doubrabova, Daniel Turecek, Stepan Polansky, Carlos Granja

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www.advacam.com

ADVACAM

Prague, Czech Republic

Start-up of the Medipix Collaboration/IEAP CTU Prague

Radiation camera MiniPIX TPX

carlos.granja@advacam.cz

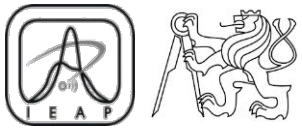
Acknowledgements, Cooperation

❑ ***ADVACAM**, Prague*

Pavel Soukup, Martin Jakubek, Michal Matous, et al.

❑ ***Institute of Experimental and Applied Physics, Czech TU, IEAP CTU,** Prague*

Stanislav Pospisil, et al.



❑ ***RIGAKU**, Prague*

Veronika Marsikova, Ada Inneman

❑ ***VZLU**, Prague*

Vladimir Daniel

❑ ***CERN Medipix/Timepix Group/Collaboration***

Michael Campbell, et al.

❑ ***ESA, ESTEC**, Noordwijk*

Alan Owens, Marco Vuolo

ADVACAM: Advanced Radiation Cameras
- Innovative radiation technology and applications
- Radiation payloads for satellites and space missions

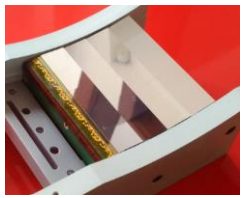
ADVACAM
Imaging the Unseen
www.advacam.com

- ADVACAM CZ, Prague: **imaging cameras and solutions** (since 2013)
  Spin-off from IEAP Czech TU Prague & CERN Medipix collaboration
  - 32 staff (engineers, researchers/scientists, technicians, students)
- ADVACAM FIN, Espoo: **semiconductor sensors & modules** (since 2012)
  Spin-off from VTT Technical Research Centre of Finland, 12 staff

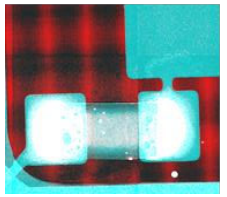
Over 30 customers & contractors

Miniaturized portable online radiation cameras

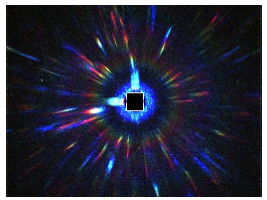
Custom devices



Color XRT



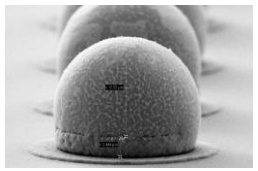
Color XRD

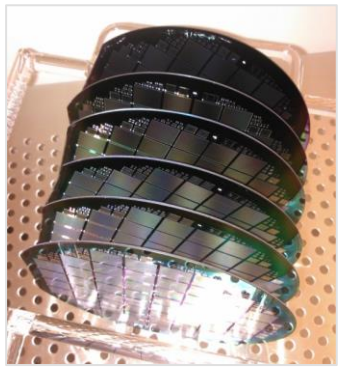


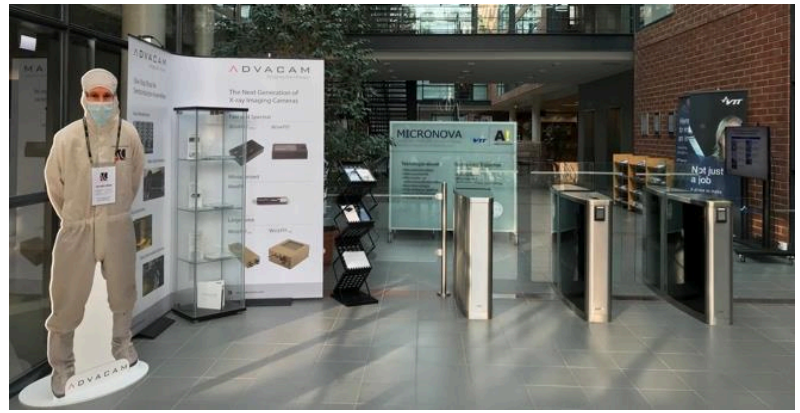
- ESA contracted development
- NASA Quality Certification

Industrial large area radiation imagers
6.5 Mpixel 14 cm x 14 cm

Semiconductor technologies and micropackaging







Advacam devices/deployments in space

High-resolution radiation spacecraft payloads
Miniaturized online space-crew dosimeters

ADVACAM Imaging the Unseen

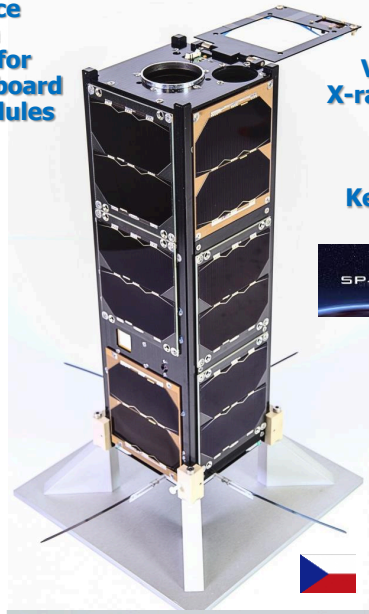
www.advacam.com

Online Space Radiation Dosimeters for spacecrew on board ISS NASA modules

SPACEX

NASA

7x units MiniPIX-TPX-space flown to ISS LEO orbit, Dec 2018
SpaceX-16, Falcon-9 rocket

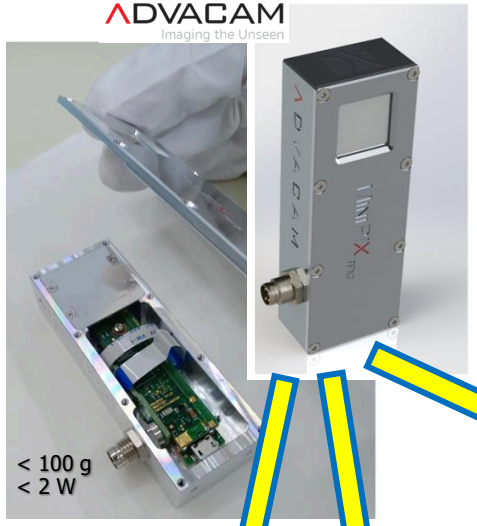


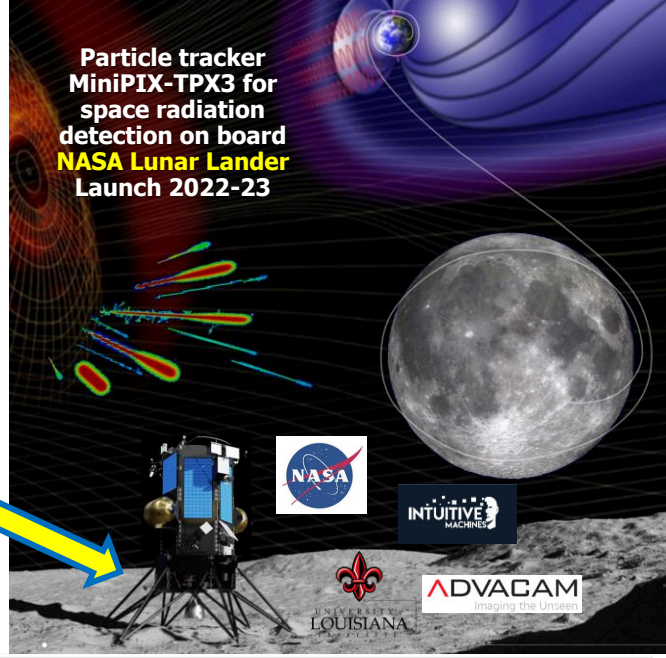
VZLUSAT-2 Cubesat
X-ray 2D optics telescope
LEO orbit, Launch
10 January 2022
SpaceX Falcon-9
Kennedy Space Center

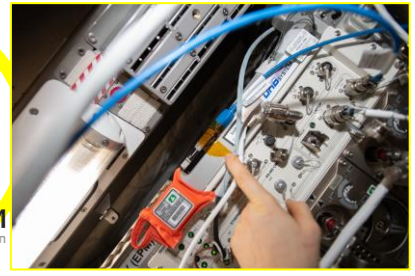
SPACEX

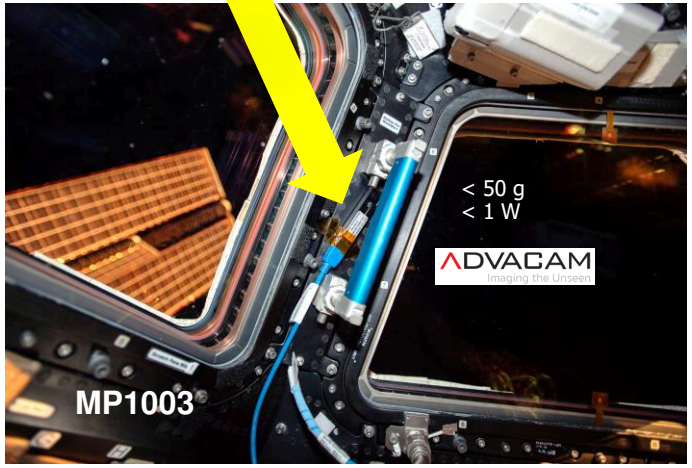
VZLU

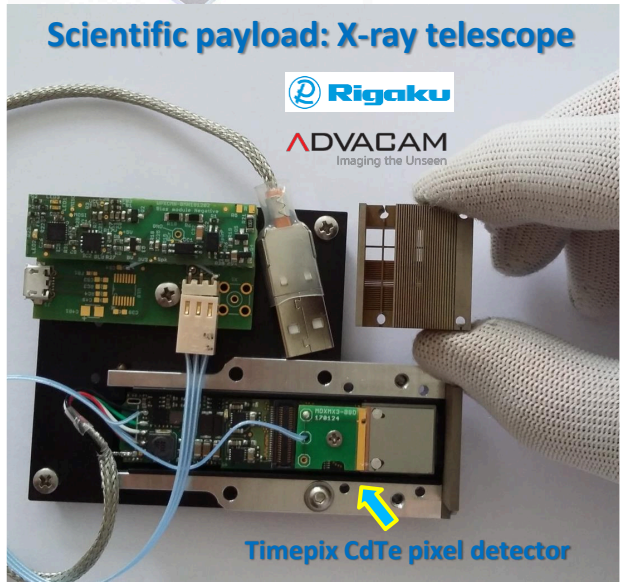
VZLUSAT 2 NANOSATELLITE

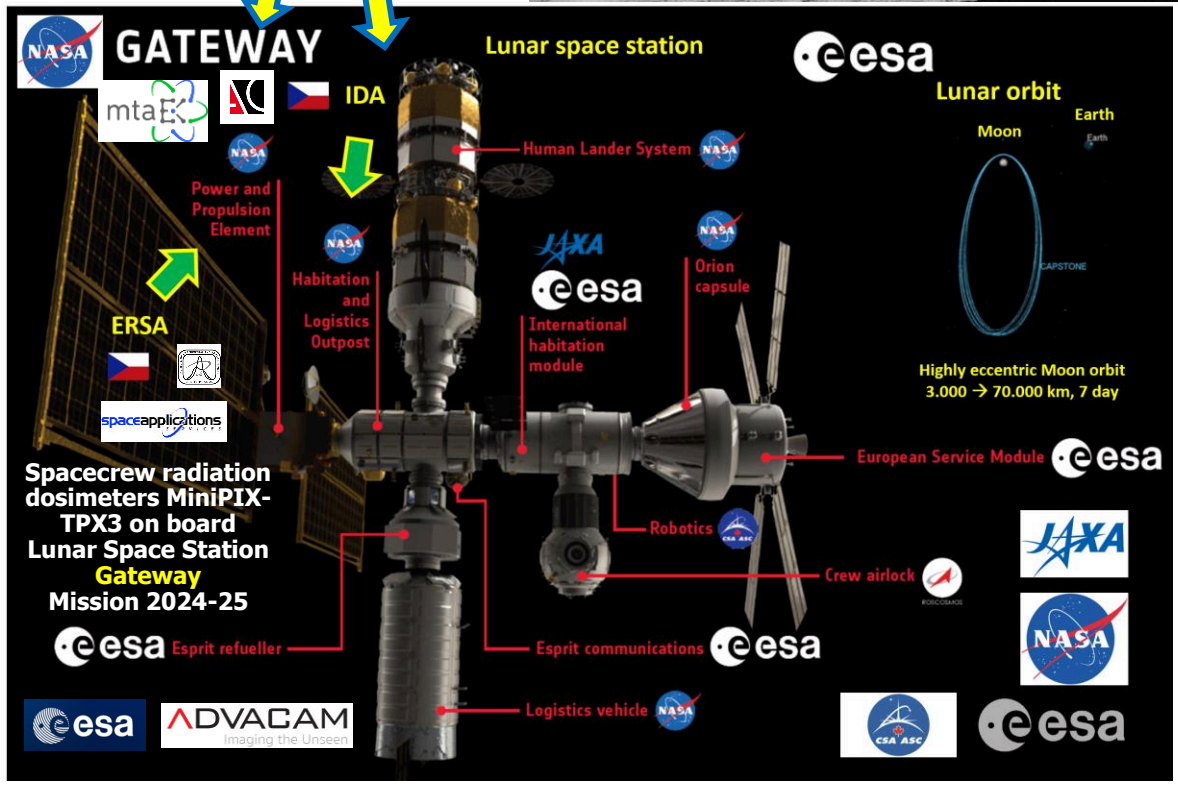












Hybrid semiconductor pixel detector Timepix
Per–pixel signal readout electronics

C. Granja, S. Pospisil,
IEAP CTU Prague 2012

Medipix Collaboration based at CERN
www.cern.ch/medipix

Hybrid architecture

Hybrid architecture: sensor is bump-bonded to the **Timepix readout ASIC chip**. Different semiconductor sensors can be used:

- material (Si, CdTe, GaAs)
- thickness (e.g. 100, 300, 500, 700, 1000, 1500 µm).

High signal electronics integration

High integration, 1-2 k transistors per pixel

Quantum imaging detection

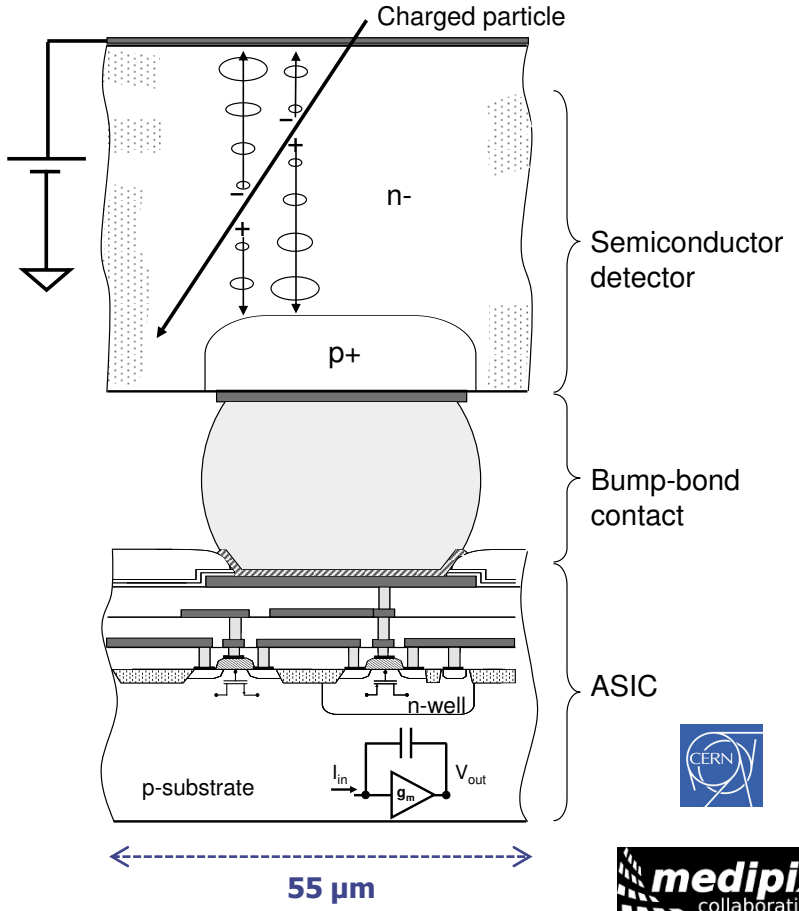
- Hybrid architecture
- Per-pixel signal processing electronics

- dark-current free detection
- threshold ~ 4 keV
- track visualization of single particles

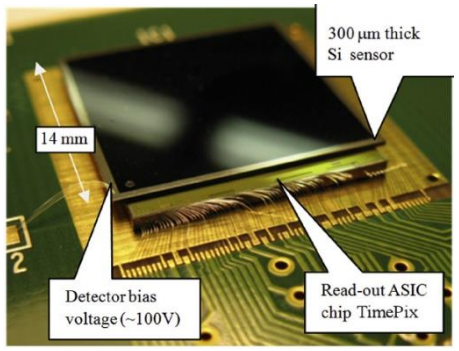
On line radiation camera

Digital spectral nuclear track emulsion

Illustration of per-pixel signal electronics



Pixel detector Timepix



256 x 256 pixels (pitch 55 µm)
14 mm x 14 mm = 2 cm²

Miniaturized radiation camera MiniPIX-TPX

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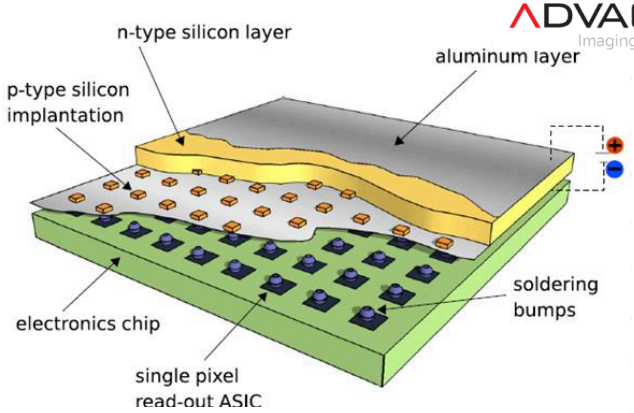

Integrated per-pixel signal readout electronics
MPX/TPX ASIC chip-sensor assembly

MiniPIX: integrated readout electronics

Timepix, TPX3, TPX2 with Si, CdTe, GaAs sensors

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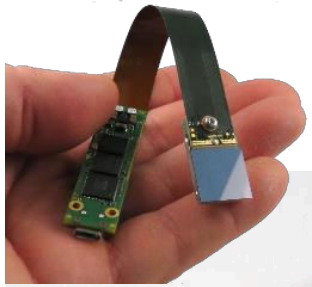
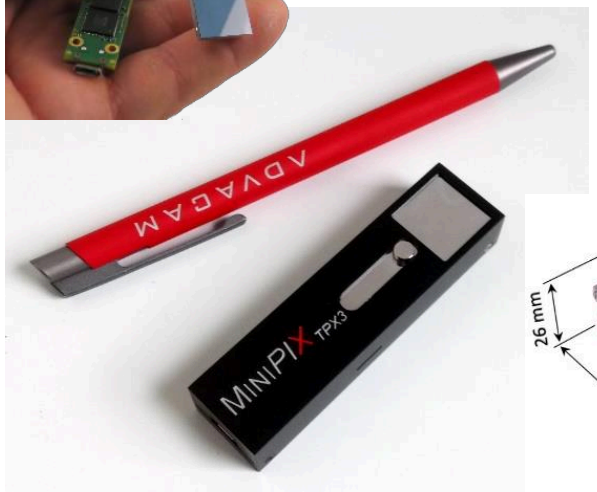
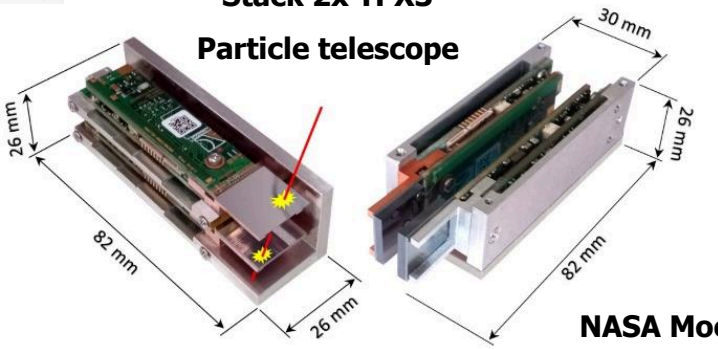




Gamma camera

Stack 2x TPX3

Particle telescope



NASA Moon Lander

Concept:

- Low power & Compact size
- Vacuum compatible
- Easy to integrate & Inexpensive

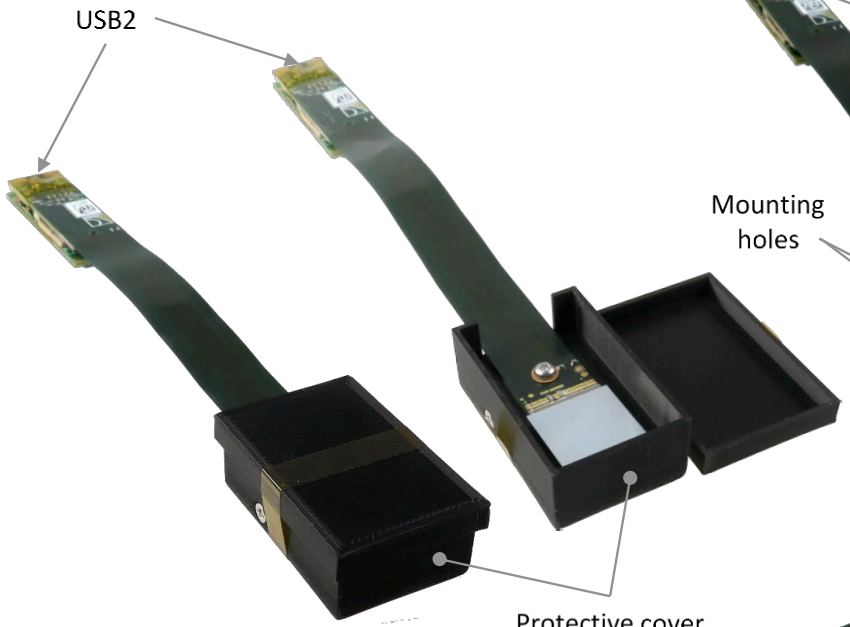
Popular product:

- Space: ISS, satellites, Moon …
- Electron microscopy
- XRD
- Gamma & Compton cameras
- Radiation monitors
- Medical: Thyroid
- Education

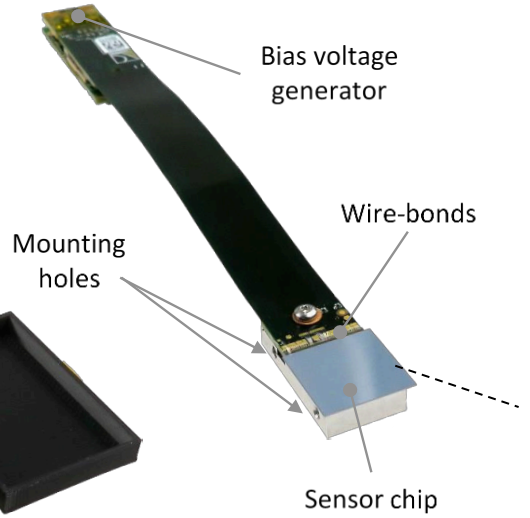
(few hundreds sold)

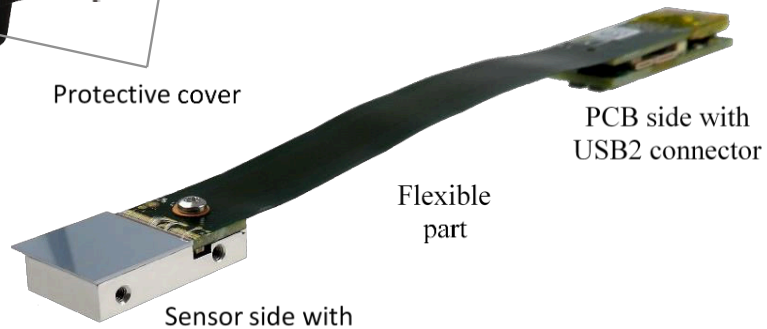
MiniPIX TPX3 flex: Module for integration to customized systems

Device with protective plastic cover
(left: as delivered, right: opened)

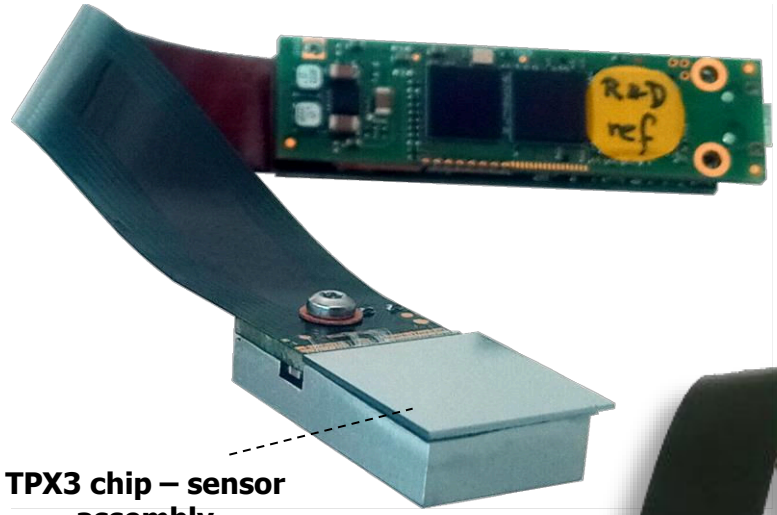


Plastic cover removed
(before installation)

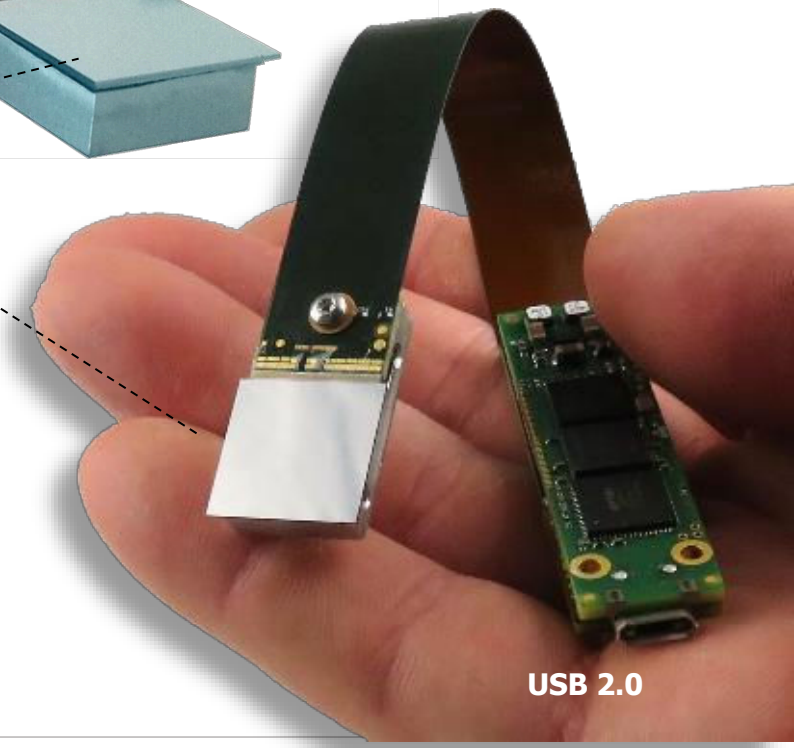




Photos of the device in its minimal configuration (without aluminum baseboard supporting PCB side).



TPX3 chip – sensor assembly



TPX3 detectors, radiation cameras: single chip, large area imagers

MiniPIX TPX3

USB2 interface, miniature

AdvaPIX TPX3 Quad

USB3 interface for 4 Timepix3 detectors. Detectors can be arranged as needed: Row, square, telescope …

AdvaDAQ TPX3

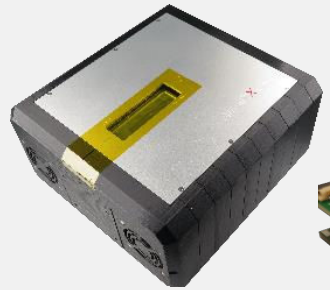
Full Timepix3 detector with USB3 interface. Versions with various sensors (Si, CdTe, CZT …).

AdvaPIX TPX3 Quad flex: Large area TPX3

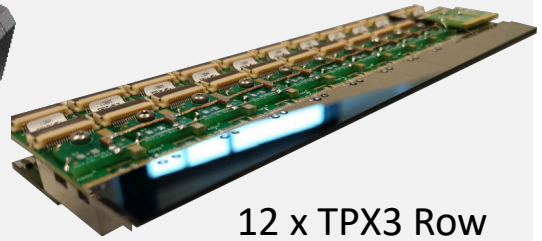
Solution for customized and OEM configurations.

Large area can be composed of multiple units.

Largest detectors created so far consist of 6 x 2 TPX3 tiles.



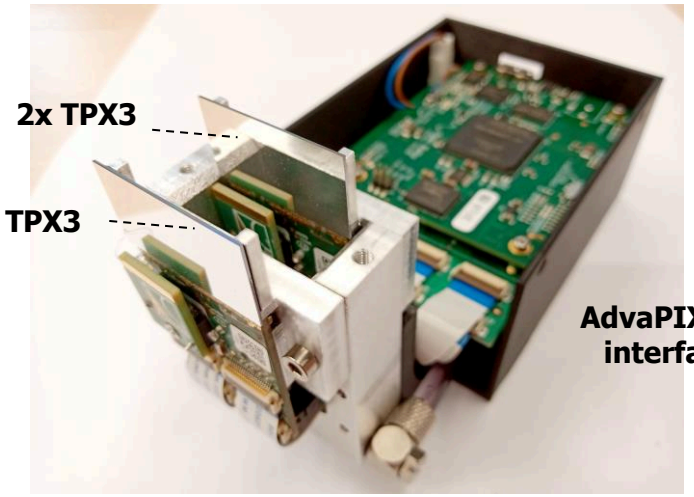
12 x Timepix3: 0.8 Mpixels

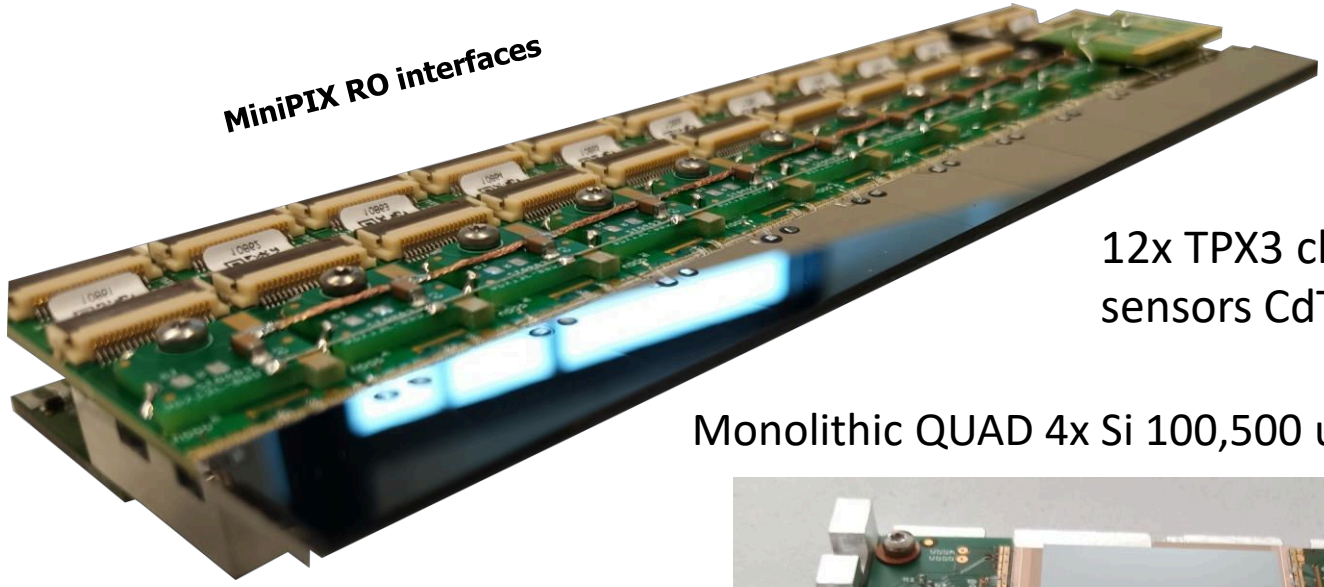


12 x TPX3 Row

TPX3 detectors, cameras: large area imagers, QUAD = 4x chips

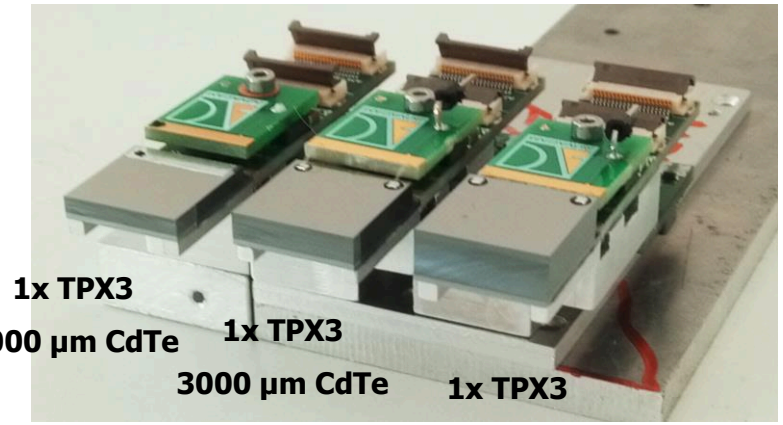
Monolithic twin 2x Si 500 um tracker



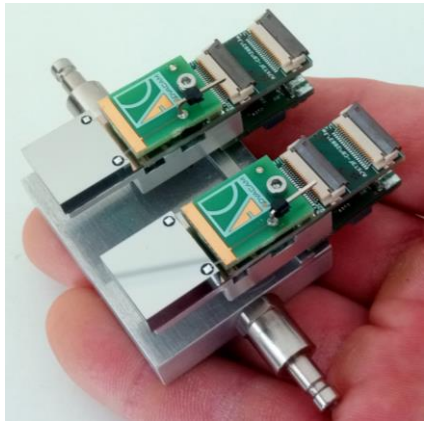


12x TPX3 chips
sensors CdTe 1 mm

CdTe: 1 mm, 2 mm, 3 mm, 5 mm



single 1x TPX3 500 µm Si



Monolithic QUAD 4x Si 100,500 um with opening

WidePIX 5x5 CdTe:

The first large area CdTe imaging detector with continuous sensitivity

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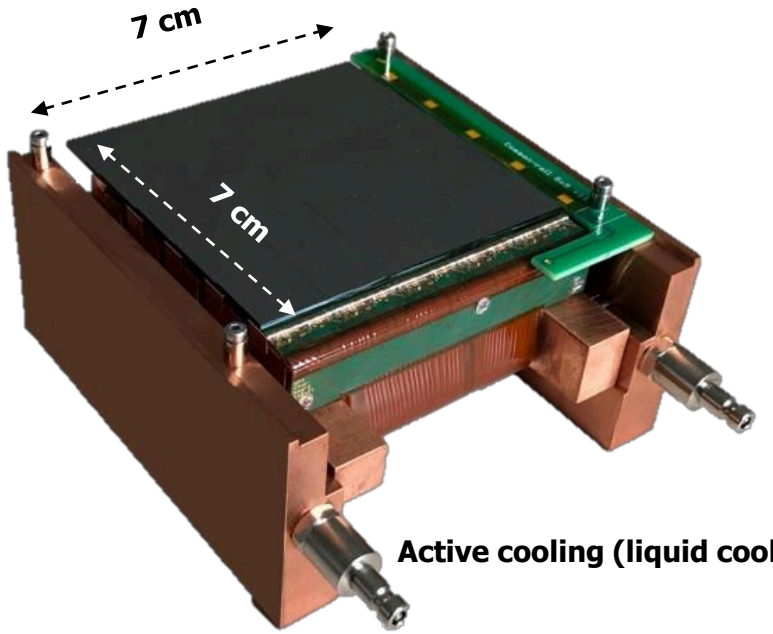
Features:

- Pixel size of **55 µm**
- 1280 x 1280 pixels = **1.6 Mega pixels**
- Sensitive area of **70 x 70 mm²**
- **Gap-less tilling**:
  - Gaps between modules smaller than quarter of the pixel
  - Edge pixels of 100 µm

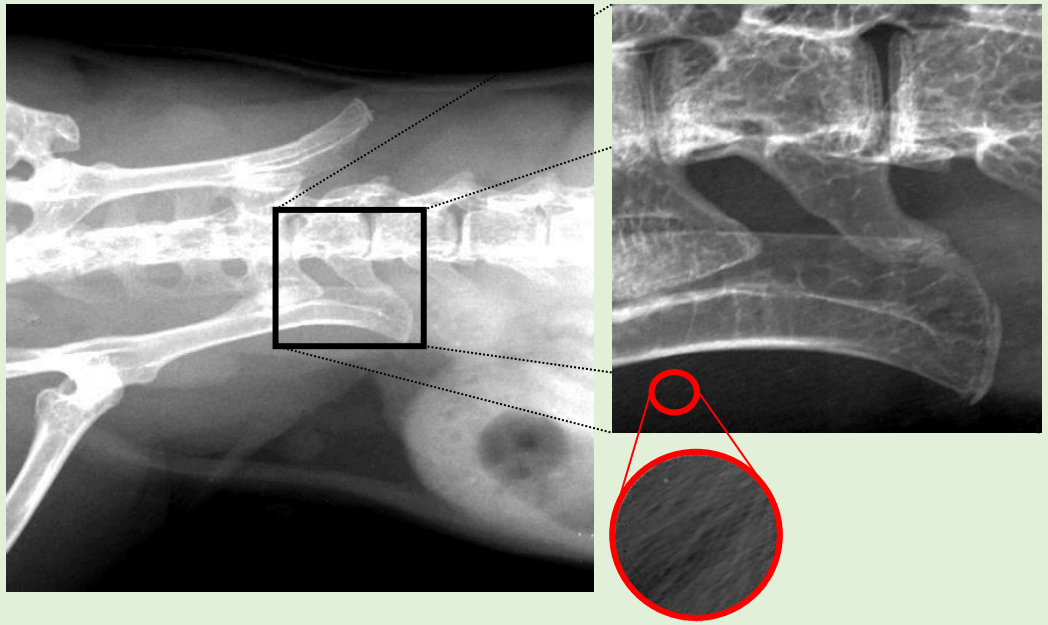
5x5 = 25 TPX3 chips



Active cooling (liquid coolant)

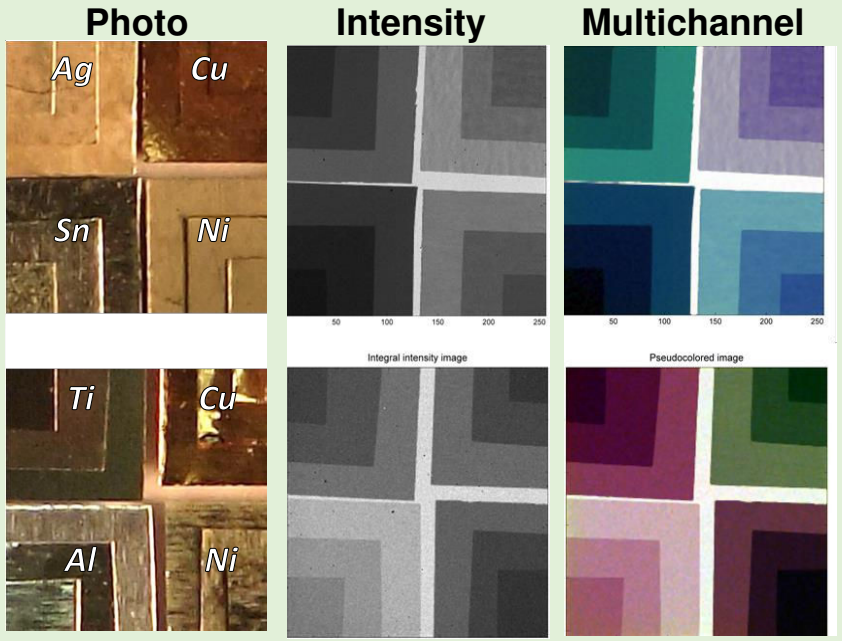
Photon counting imaging

Photon counting: Ultra-high contrast



Mouse: hair fibers are resolved through its body !

Multichannel: Material sensitivity



Metals: Material differences are identified !

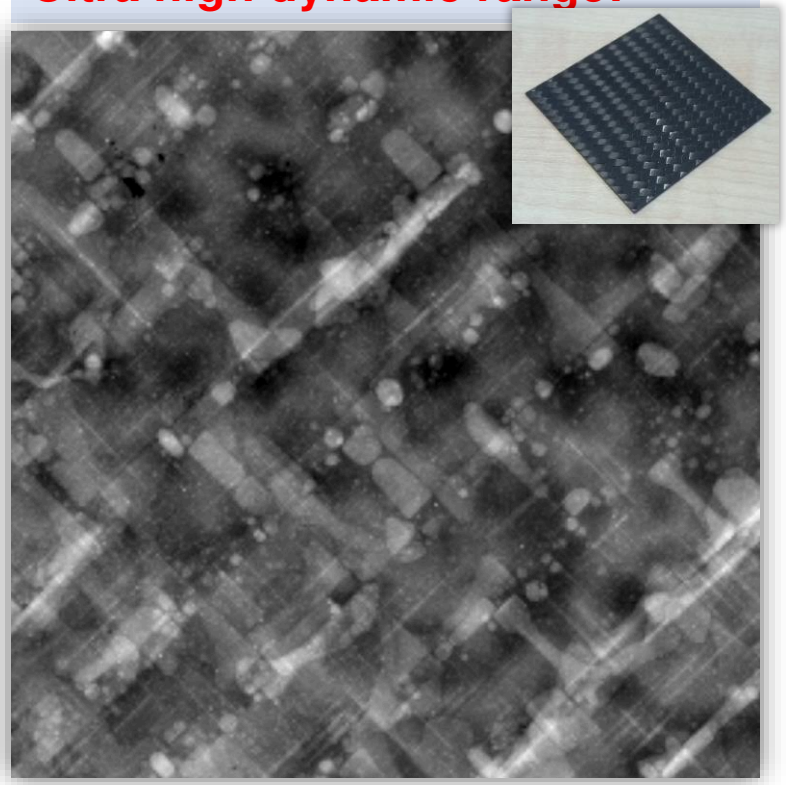
Signal to noise ratio can reach **2400** (noise of 0.04%) – measured with 2 mm thick CZT sensor

MiniPIX TPX2 camera

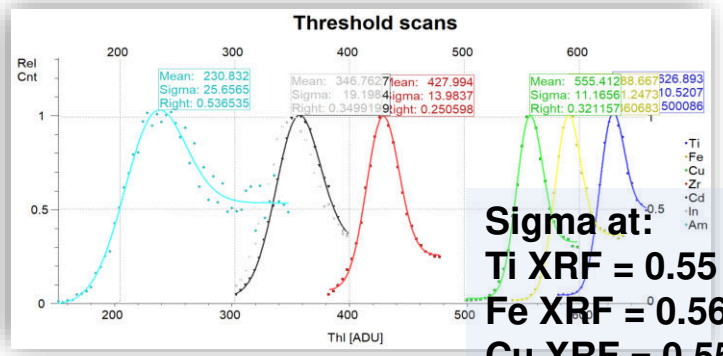
MiniPIX TPX2 properties:

- connected to the computer via micro USB2.0 connector
- **framerate**: **100 fps** at 10 bits, 60 fps at 14 bits, 30 fps at 28 bits.
- device is vacuum compatible
- eligible for space applications (same construction as MiniPIX TPX3 running on ISS already)

X-ray radiography:
Ultra high dynamic range!



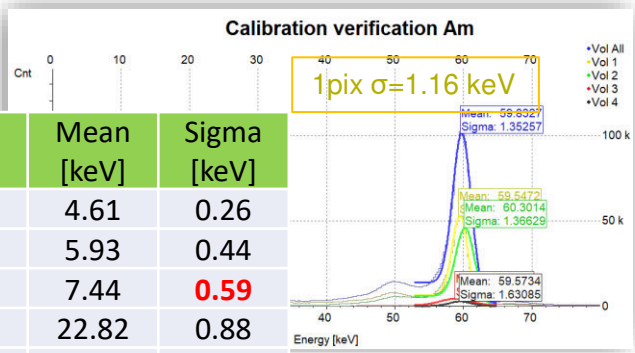
Threshold scans (Si sensor 300 µm):



Sigma at:
Ti XRF = 0.55 keV
Fe XRF = 0.56 keV
Cu XRF = 0.55 keV

Per pixel calibration in ToT mode:

All clusters	Mean [keV]	Sigma [keV]
Zero	4.61	0.26
Fe XRF	5.93	0.44
Cu XRF	7.44	**0.59**
Cd XRF	22.82	0.88
Am241	59.83	**1.35**



Excellent imaging properties!

Noise obeys Poissonian statistics even at very high counts:

- Global stability over 30 minutes:
  SNR = 5000
- Local stability over 1 hour:
  SNR = 2000

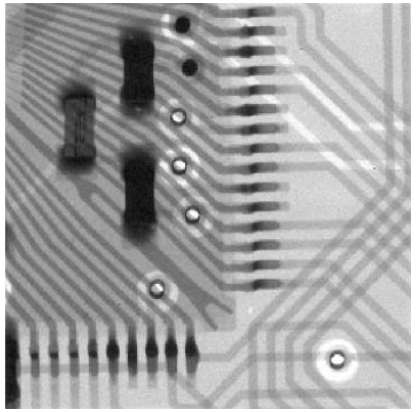
AdvaPIX TPX3: Applications & Examples

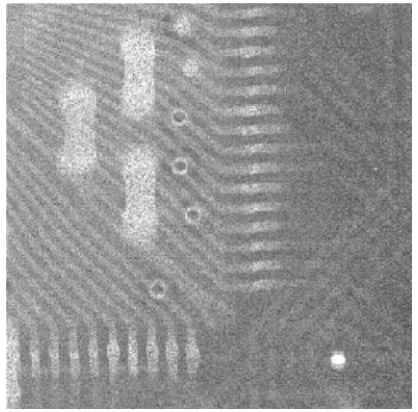
Fully spectral X-ray radiography:

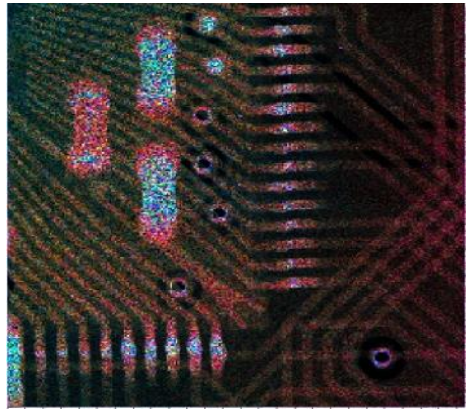
Fast fully spectral X-ray radiography of PCB sample without dead-time:

Minifocus 80 kVp, 150 uA
Tube-Det distance 20 cm
Exposure: 2 s

⇒ Even fully spectral CT is perfectly possible.





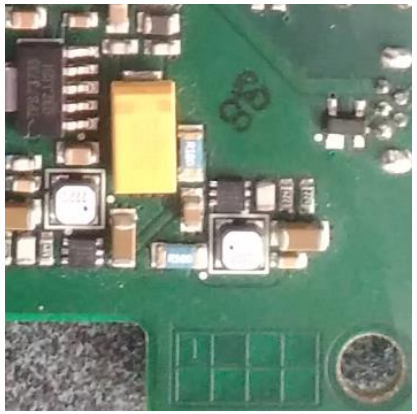


Energy dispersive
XRD analysis

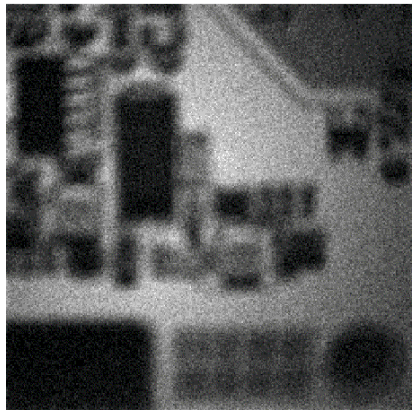
XRF imaging:

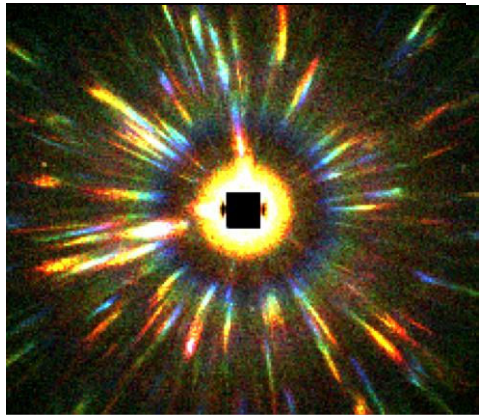
Example of XRF imaging with MiniX X-ray tube and pinhole.

Very low statistics with **less than one photon** per pixel for Sn and Ba lines. Result is still satisfactory.



XRF imaging





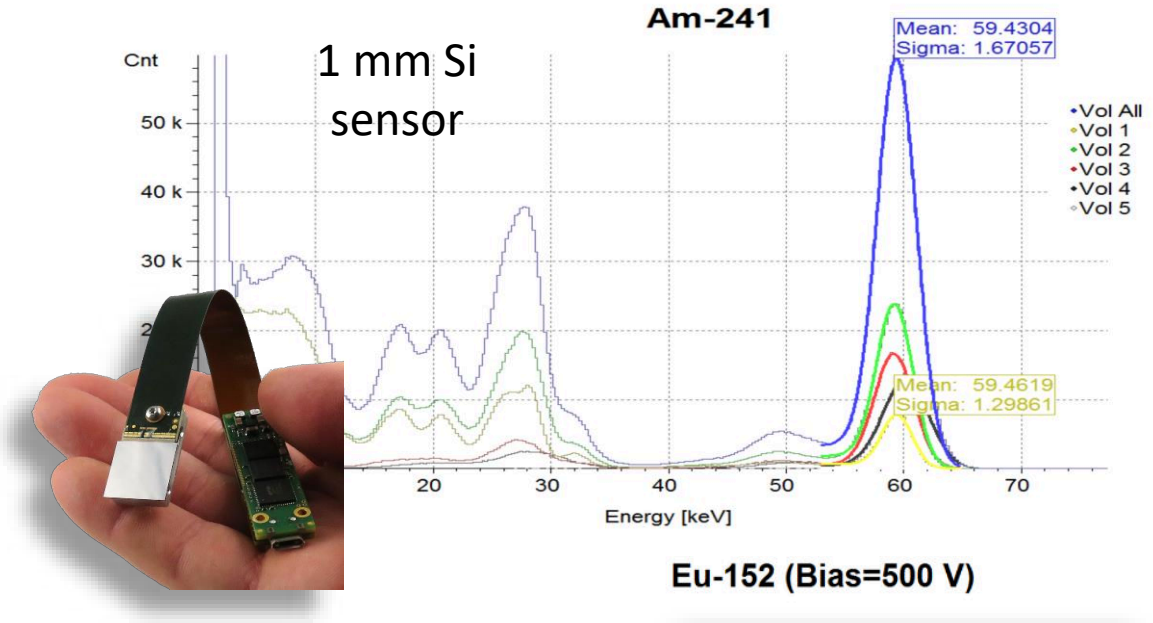
Timepix3 detector: spectral imaging: X rays, gamma rays

Timepix3:

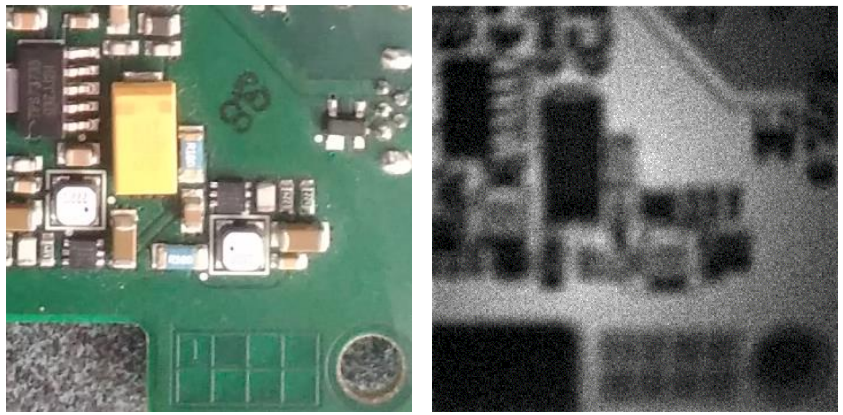
- Hybrid semiconductor pixel detector
- Successor of Timepix: **256x256 pixels, 55 µm pitch**
- **Event based readout**: Each hit pixel transmits the hit information immediately.

⇒ **No dead-time for readout of complete frame**.

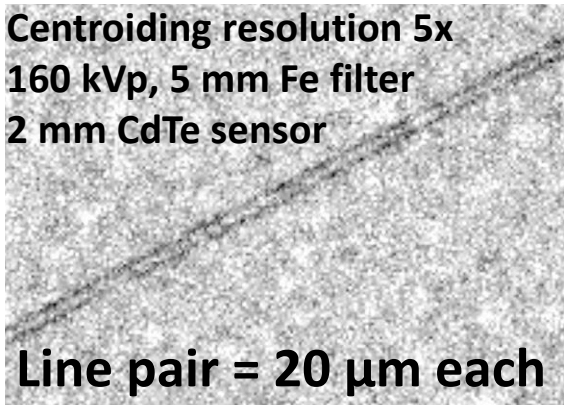
- Each hit pixel measures both: **Energy** and **Time of arrival**
- Time is measured with precision of 1.56 ns
- Chip can produce data stream of 5 Gbit/s.



Example: X-ray fluorescence (XRF) imaging



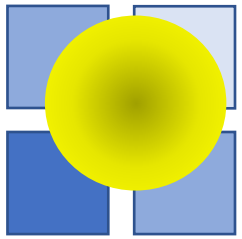
Subpixel resolution 9 µm:



ADVAPIX CdTe 2 mm: Subpixel resolution: photons ≈ 10 µm

Principle:

1. Single photon is creates signal in several adjacent pixels => cluster
2. The energy is measured by each hit pixel
3. Position can be calculated with better precission

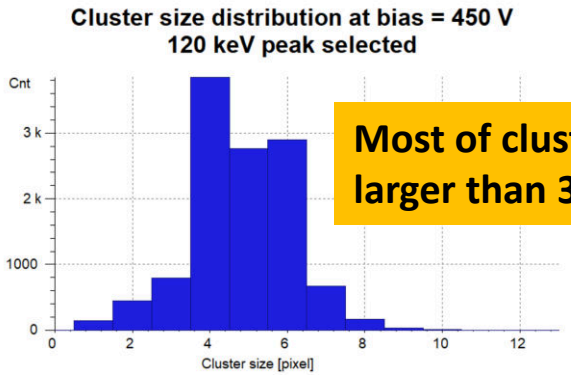


Real case:

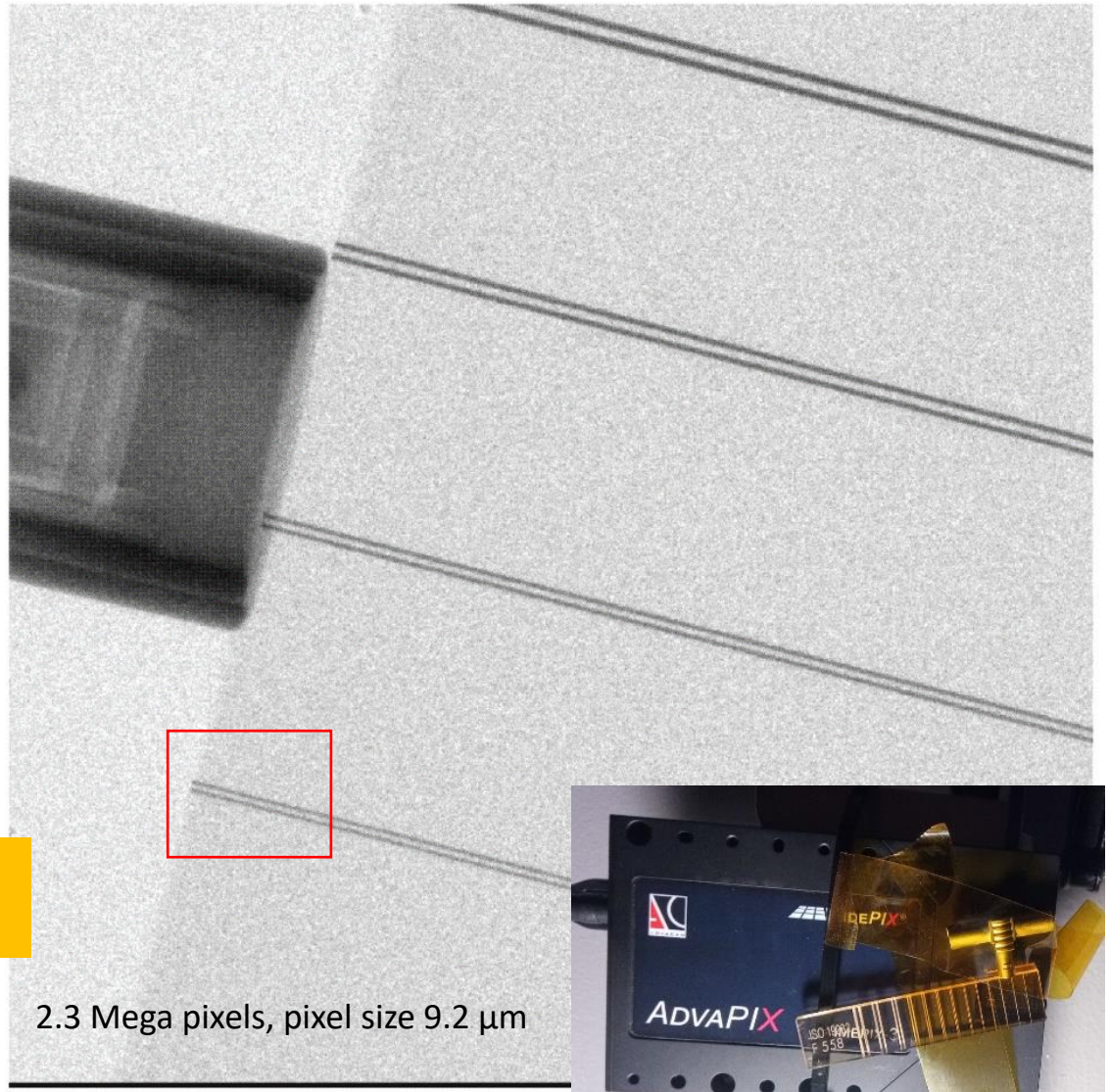
At 160 kVp with **5 mm steel filter**

⇒ Effective energy is 100-120 keV

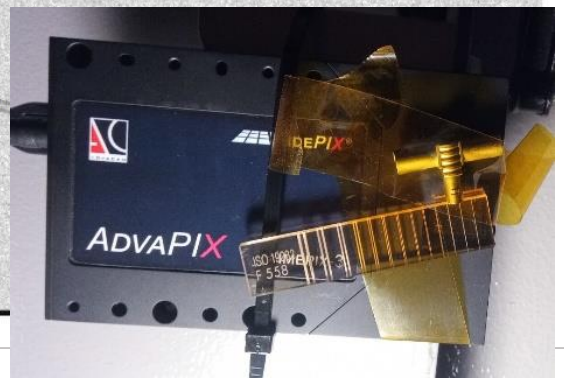
⇒ Average cluster of 5 pixels



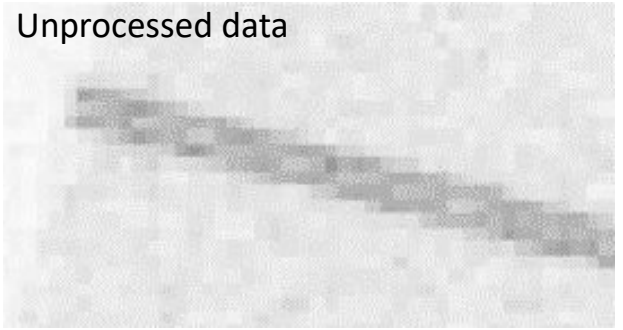
Most of clusters are larger than 3 pixels!



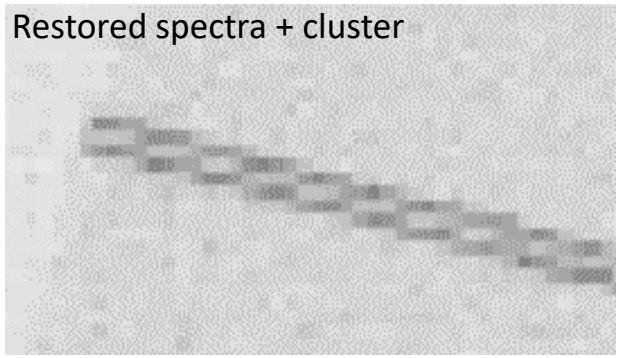
2.3 Mega pixels, pixel size 9.2 µm



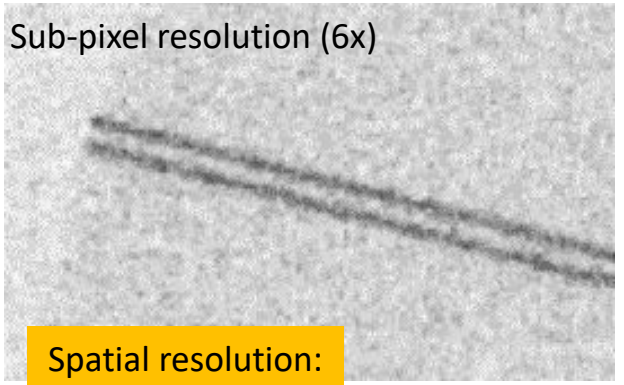
Unprocessed data



Restored spectra + cluster



Sub-pixel resolution (6x)

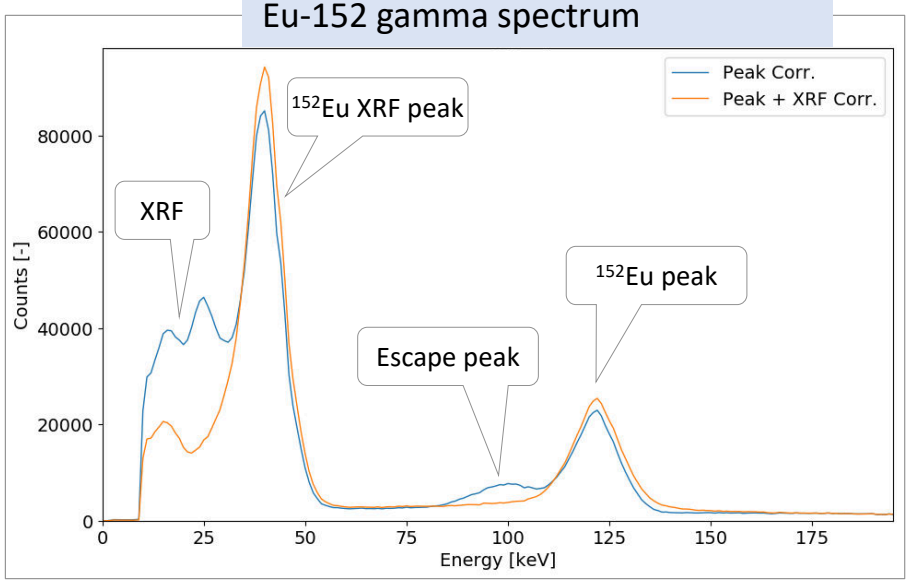


Spatial resolution:
9 µm (RMS)

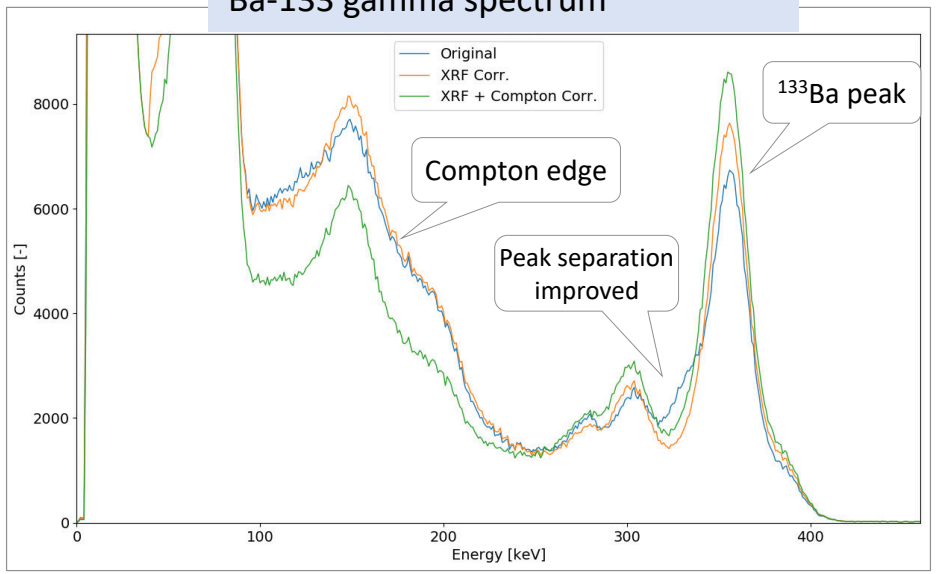
Gamma spectrum reconstruction for CdTe TPX3

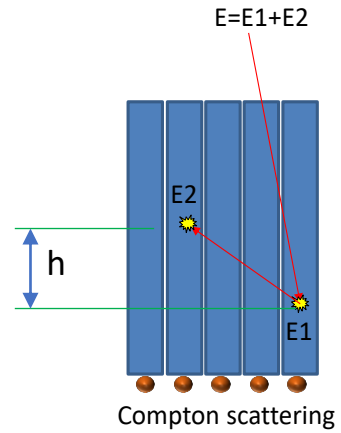
- 2 mm thick CdTe sensor: Efficiency for 120 keV of about 70%
- Coincidence technique removes artifacts and suppresses internal Compton scattering

Eu-152 gamma spectrum



Ba-133 gamma spectrum





Compton scattering or internal XRF

Internal XRF reconstruction:

1. Coincident events E1, E2 recognized
2. One of them fits to XRF energy of Cd or Te say E2
3. Event E2 is removed.
4. Energy E=E1+E2 is assigned to E1.

Compton effect reconstruction:

1. Coincident events E1, E2 recognized (distance ***d***, height ***h***)
2. Copmton and Klein-Nishina formula evaluated for E1 and E2
3. More likely scattering scenario is chosen
4. Energy E=E1+E2 is assigned to correct point.

Single layer Compton camera: TPX3 + 2 mm CdTe

Cosmic muon interaction in the CdTe sensor in TPX3. The particle crosses the entire sensor thickness from top to bottom, each hit pixel has a different charge collection time depending on the depth of the interaction

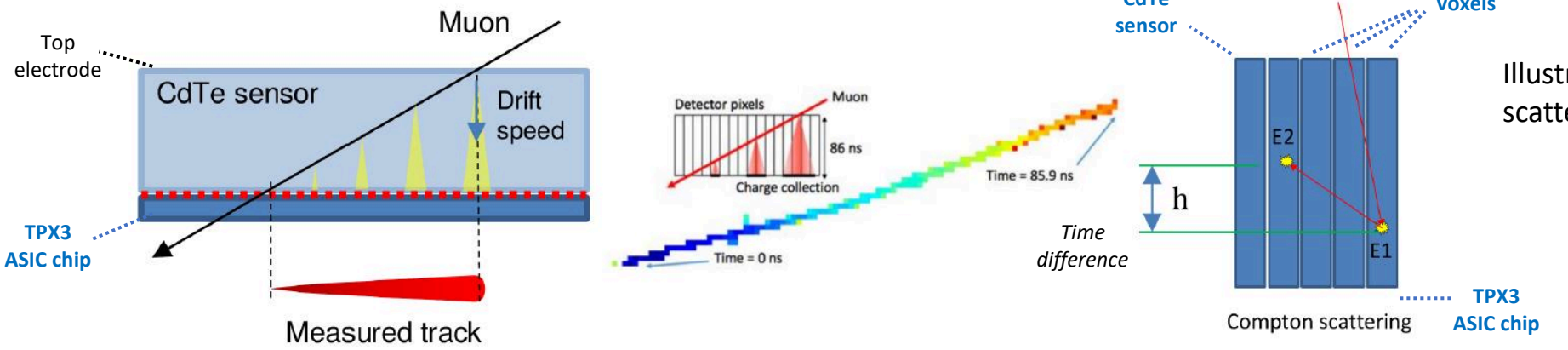
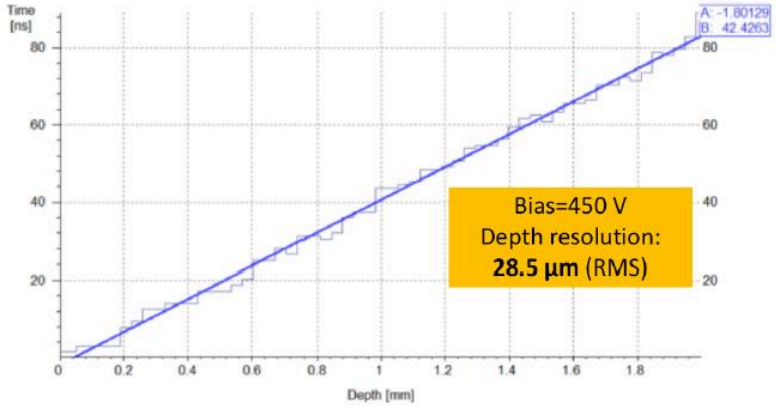
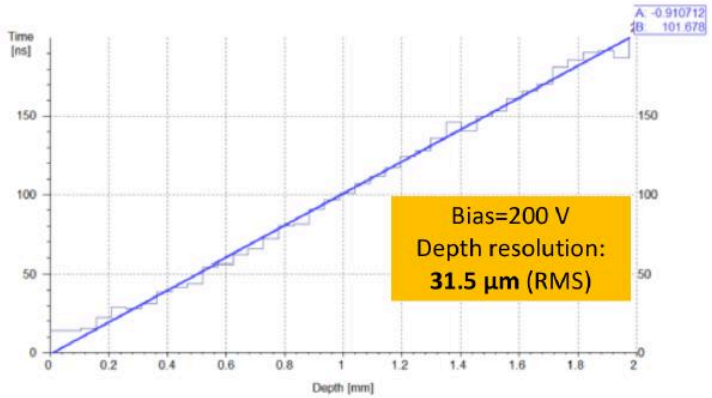
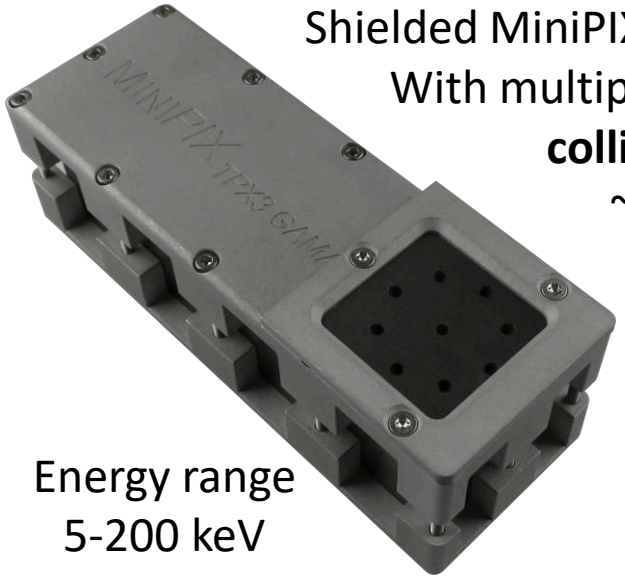


Illustration of Compton scattering in the sensor





Two recorded time profiles recorded along the tracks of two muons for two different bias voltages of 450V (left) and 200V (right) yielding about the same depth resolution ≈ 30 µm.



Shielded MiniPIX TPX3
With multipinhole
collimator
~ 500 g

Energy range
5-200 keV

FoV: 60 deg

MiniPIX TPX3
ultra compact
Compton camera
40 g

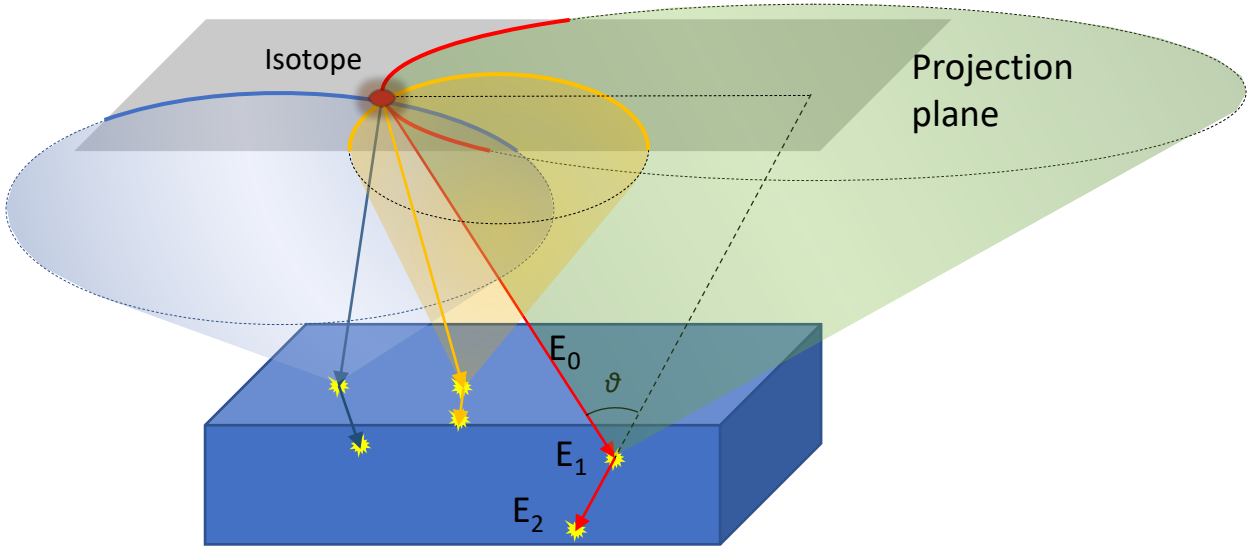
Energy range
150-700 keV

Wide FoV → 2π

Gamma camera: Timepix3 Compton camera

=> No large/heavy collimators

Single layer Compton camera: TPX3 + 2 mm CdTe



Timepix3 CdTe detector

JINST

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Single layer Compton camera based on Timepix3 technology

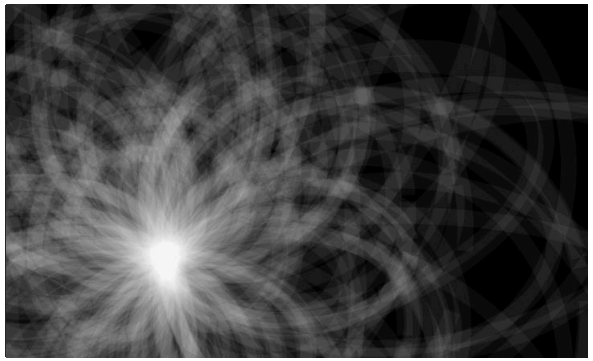
D. Turecek *et al* 2020 *JINST* **15** C01014

D. Turecek,[a,b,1] J. Jakubek,[b] E. Trojanova[a,b] and L. Sefc[a]

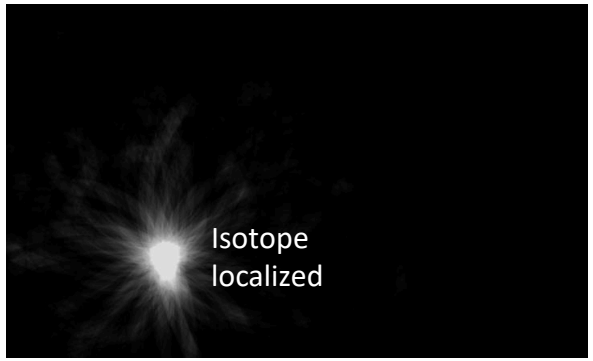
[a] *Center for Advanced Preclinical Imaging (CAPI), First Faculty of Medicine, Charles Univesity, Salmovska 3, Praha, 120 00 Czech Republic*

[b] *ADVACAM s.r.o., U Pergamenky 12, Praha, 17000 Czech Republic*

Image 100 events



Image



Single layer Compton camera: TPX3 + thick CdTe

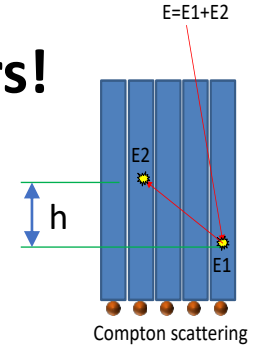
Gamma camera without collimators!

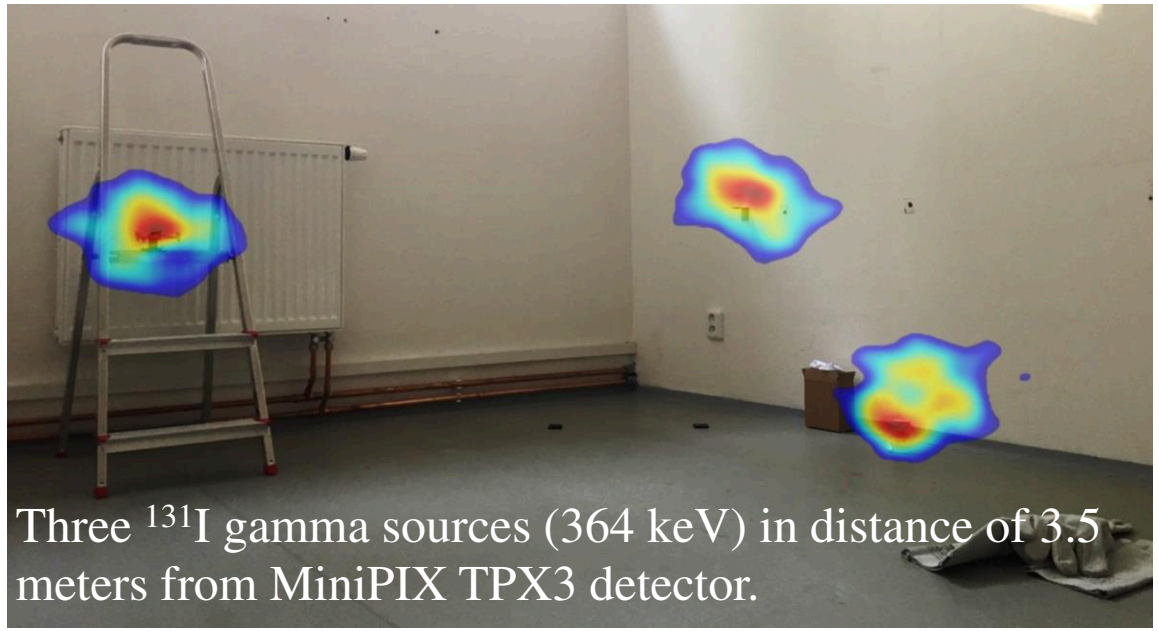
For each Compton scattering event we can:

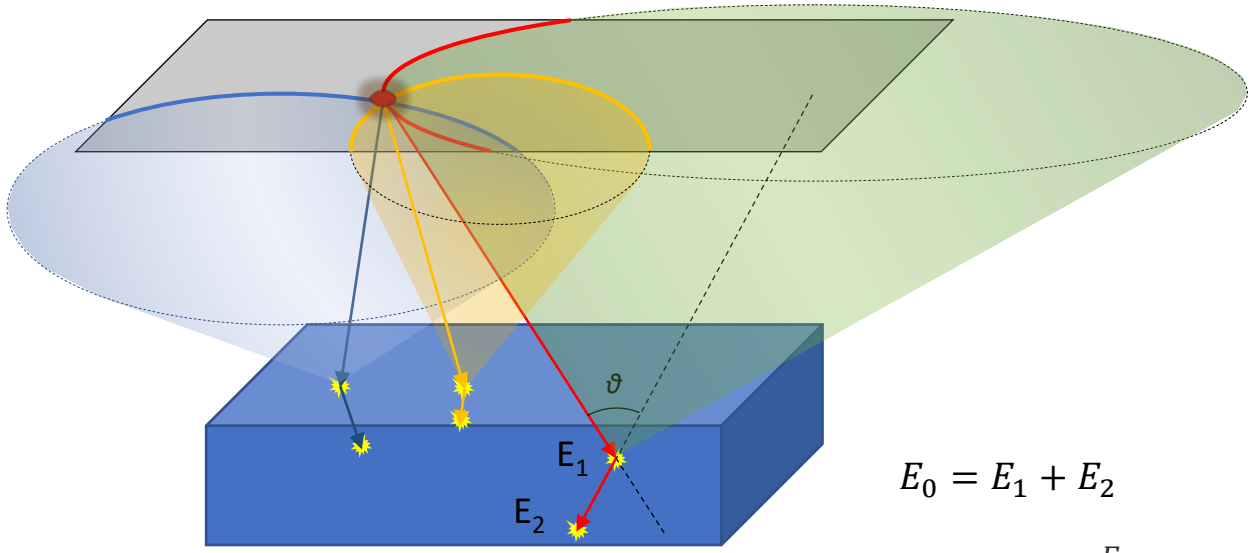
- Detect coincidence
- Measure both energies: E_1 and E_2
- Measure both positions in 3D

⇒ **We can reconstruct Compton cone**

⇒ **Combining many events we reconstruct an image**



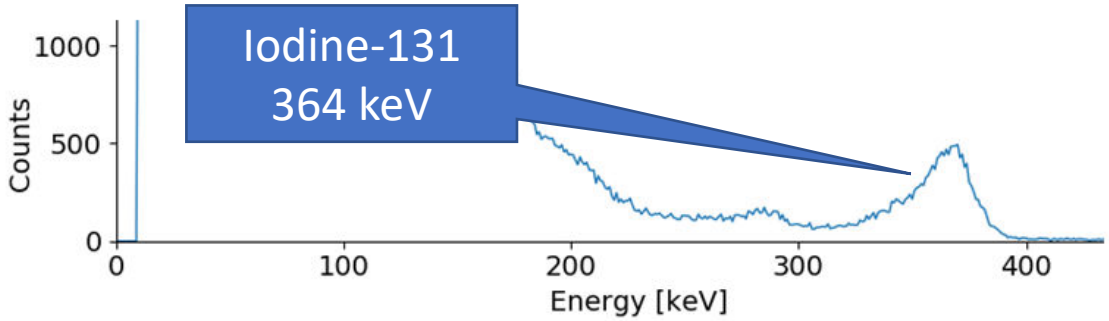




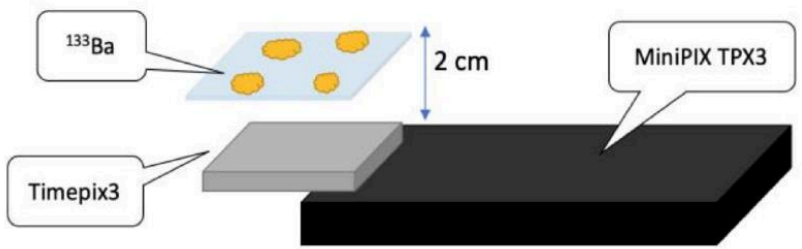
Timepix3 CdTe detector

$$E_0 = E_1 + E_2$$

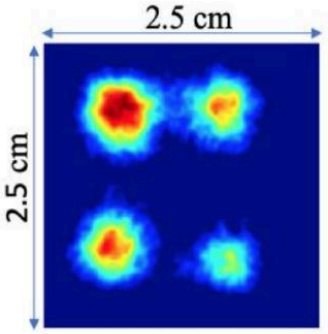
$$\cos\theta = 1 - m_e c^2 \frac{E_1}{E_2(E_1 + E_2)}$$



Single layer Compton camera: TPX3 + 2 mm CdTe



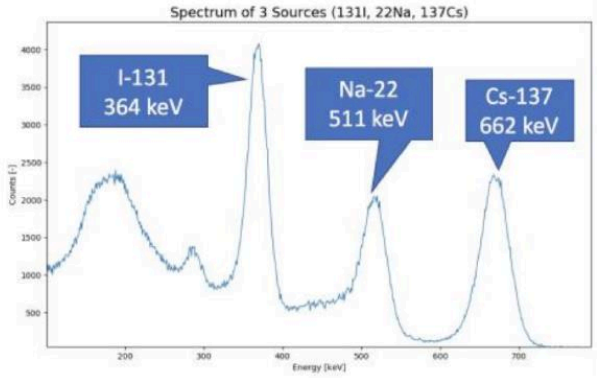
Scheme of measurement setup with ^{133}Ba source



Reconstructed image

Photo of the radionuclide sources above the detector

Energy spectrum of the measurement with 3 different gamma sources



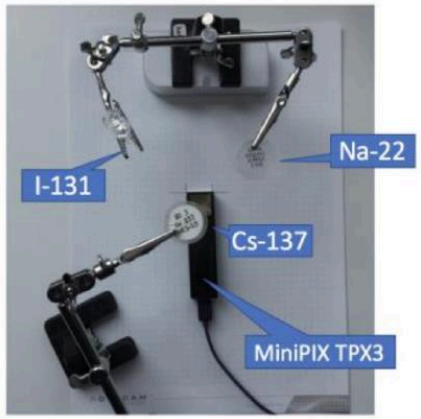
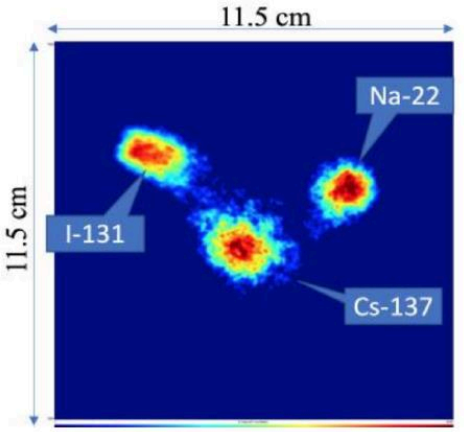


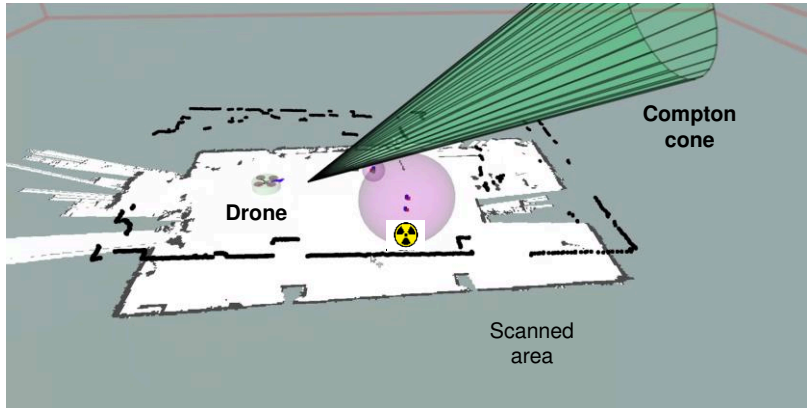
Photo of the measurement setup

Reconstructed image



- **Drone equipped with Compton camera**
  autonomous searching for radiation sources

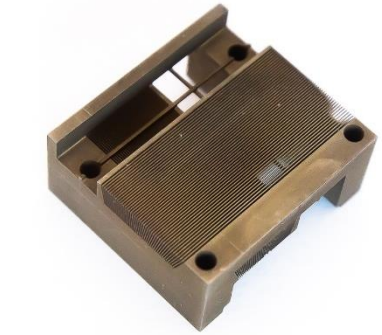
LIDAR + TPX3 Compton Camera event image map reconstruction principle



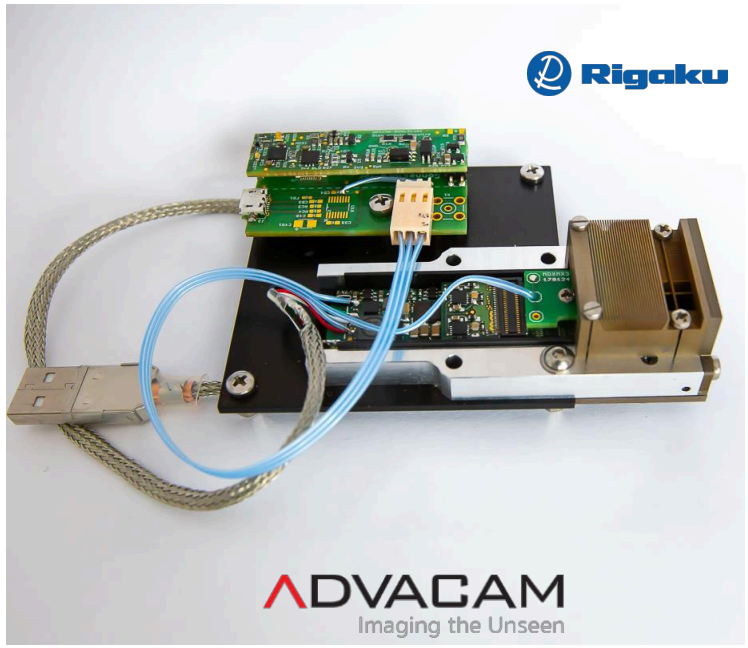
Composition map of radiation and optical image

- **Radiation environment monitor**
  monitoring of static scene
- **Mobile handheld Compton camera**
  operative inspection of radiation presence

- **Optický rtg. payload (TPX)**
  - optická část (Rigaku)
  - detektorová část (Advacam)



Rigaku



3U cubeSat

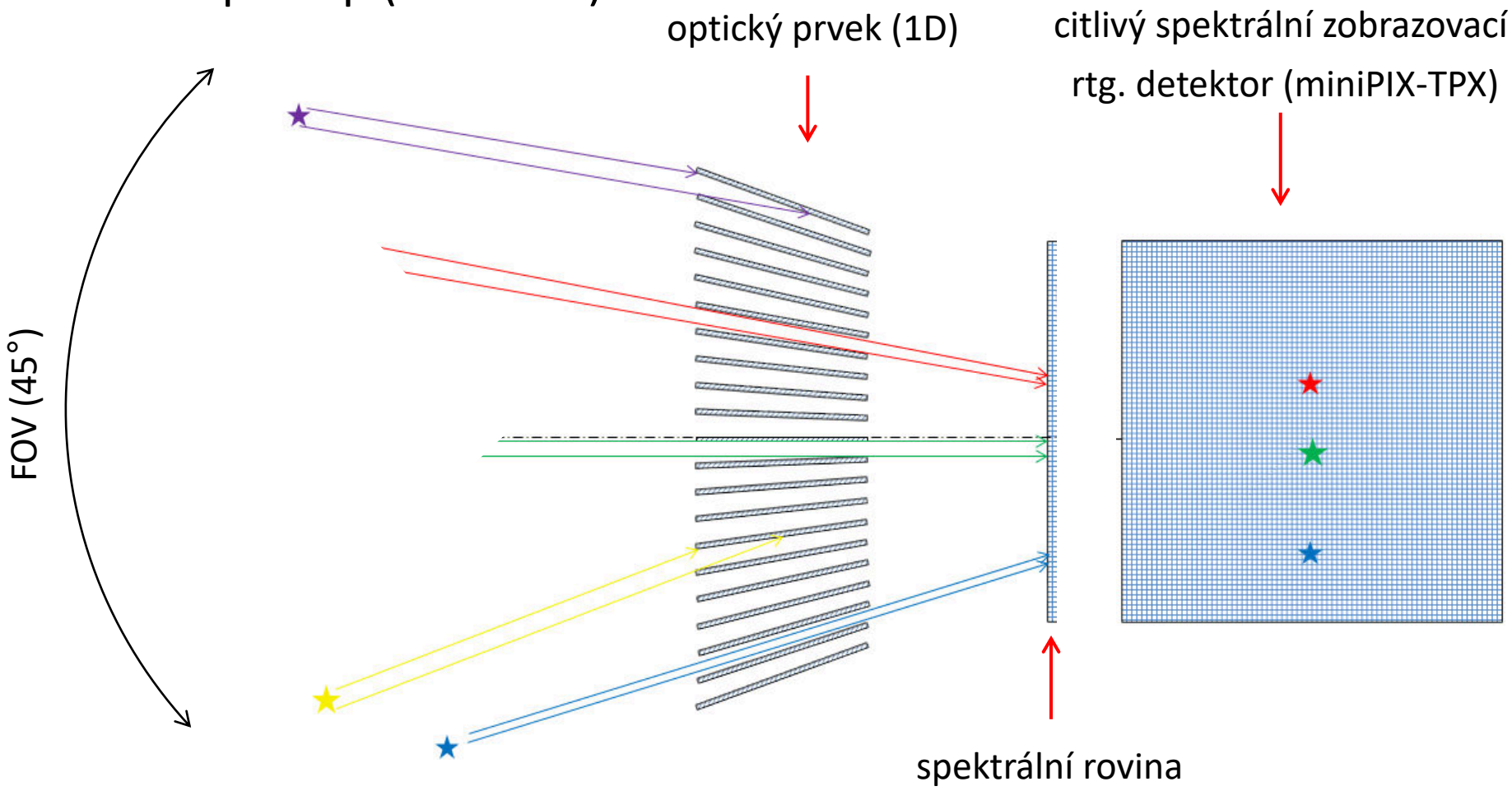
VZLUSAT-2

Rigaku

ADVACAM
Imaging the Unseen

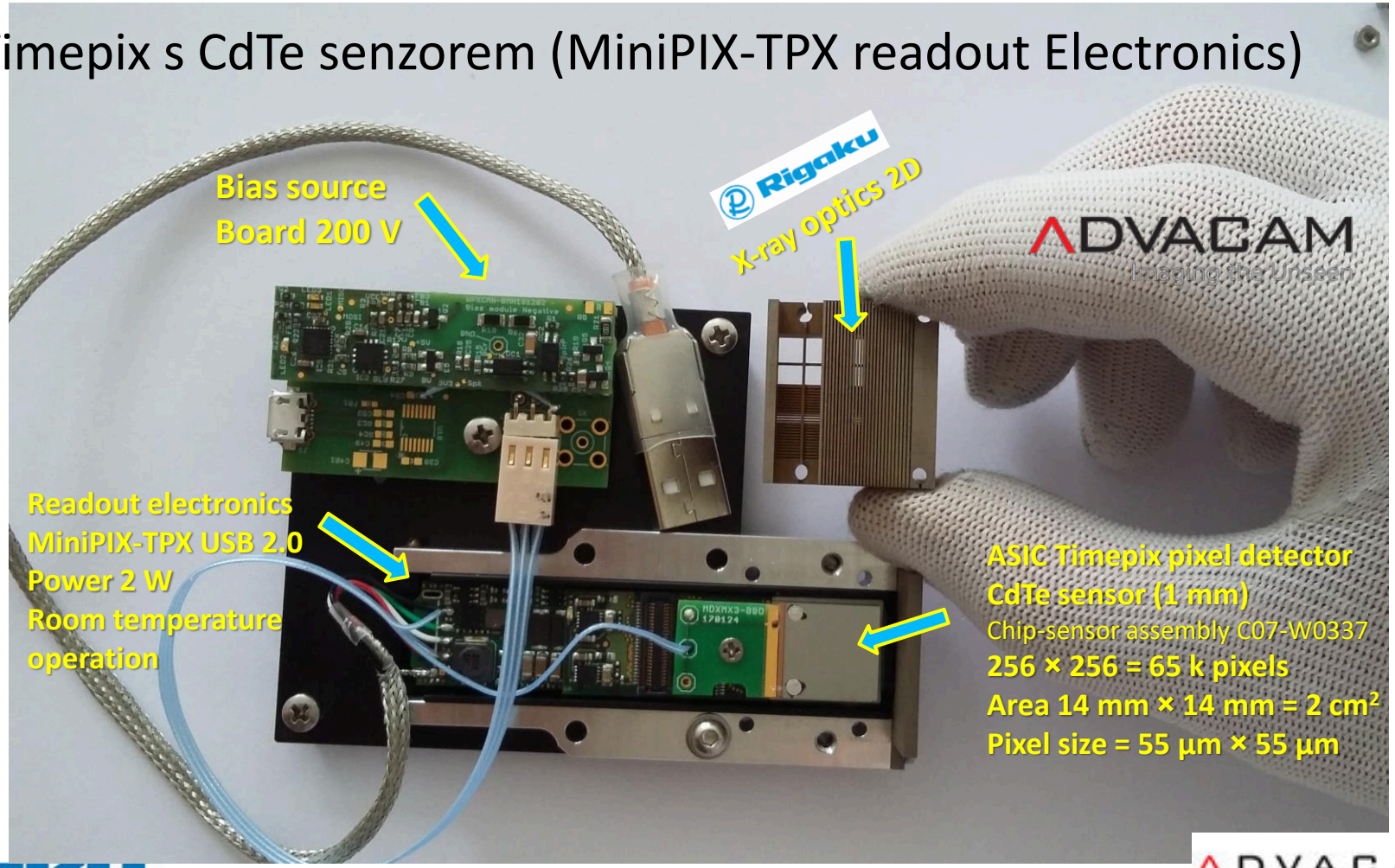
X-ray optický prvek

- princip (kolimace)

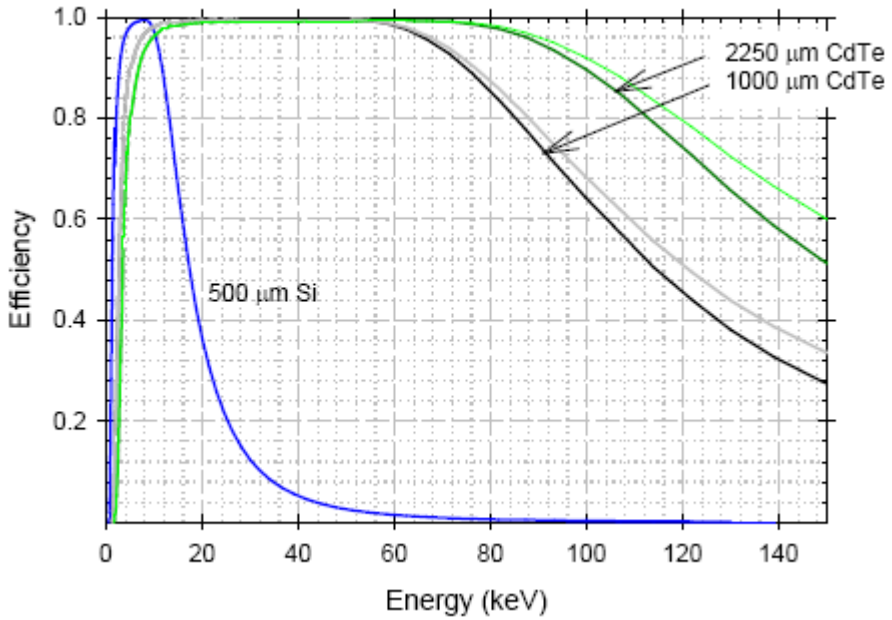


Detektorová část optického payloadu

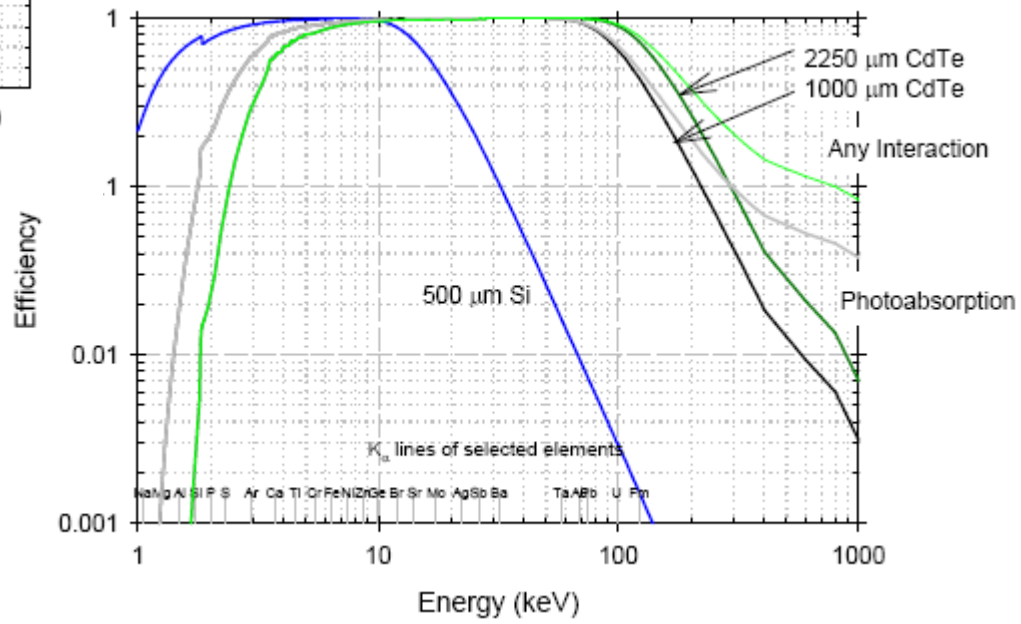
- Spektrální zobrazovač v fokální rovině: Hybridní pixelový detektor Timepix s CdTe senzorem (MiniPIX-TPX readout Electronics)

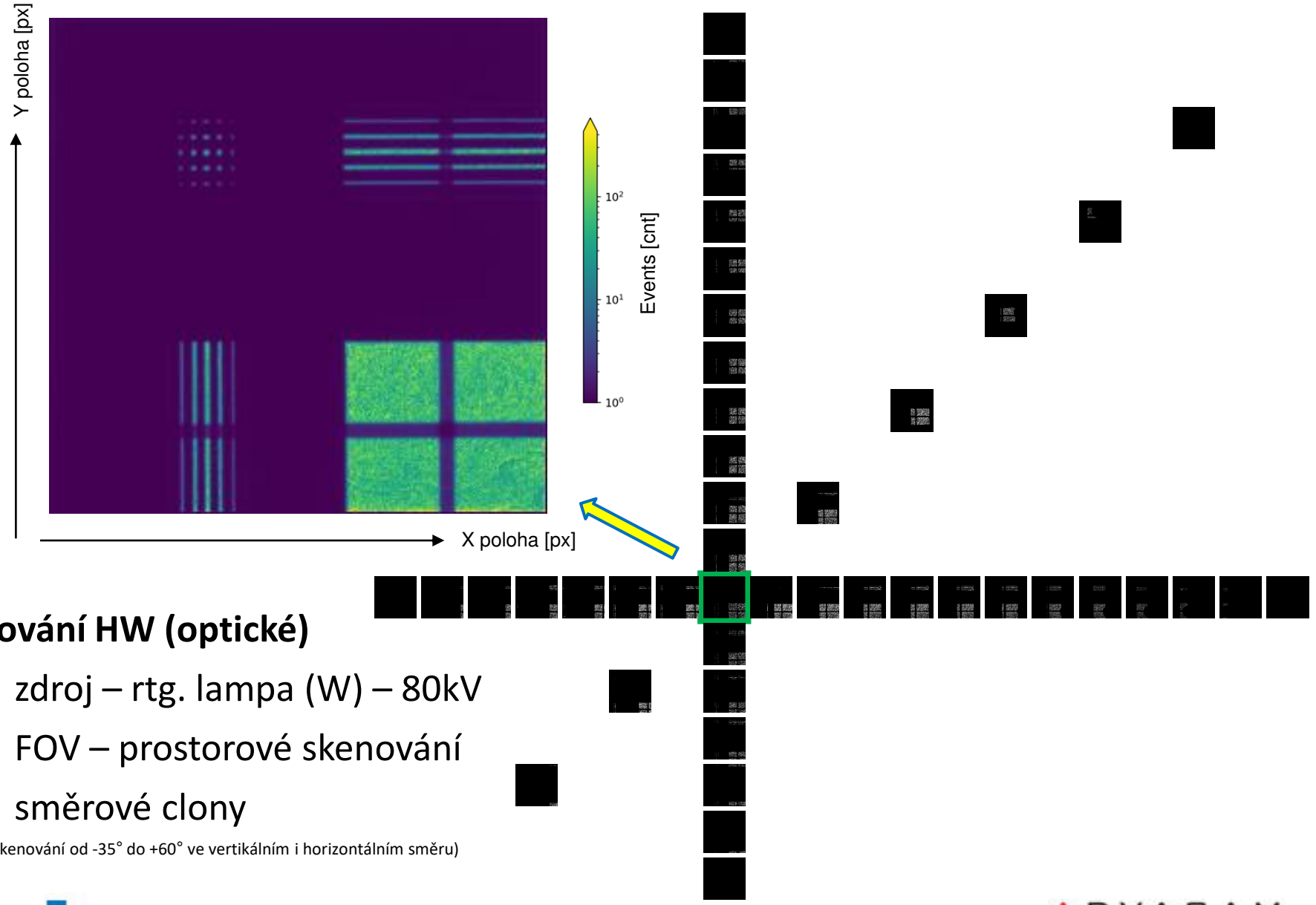


Účinnost CdTe vs Si senzoru



- koeficient lineárního útlumu - pravděpodobnost fotonové interakce je součinem pravděpodobnosti přenosu přes Be okénko pravděpodobnosti interakce v materiálu
- Data z web AMPTEK (https://www.amptek.com/internal-products/xr-100t-cdte-cadmium-telluride-detector-efficiency-application-note)





Testování HW (optické)

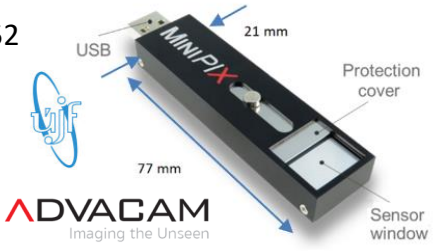
- zdroj – rtg. lampa (W) – 80kV
- FOV – prostorové skenování směrové clony

(skenování od -35° do +60° ve vertikálním i horizontálním směru)

C. Granja, K. Kudela, et al., *Directional detection of charged particles/cosmic rays with radiation camera MiniPIX Timepix*, NIM A 911 (2018) 142-152

Angular distributions of energetic light charged particles

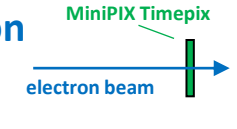
Single layer TPX + MiniPIX-Timepix camera + 1D angular distributions + wide FoV sky map



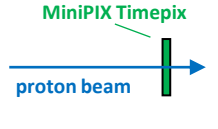
Angular distribution of a 12 MeV electrons beam incident at $\beta = 60°$ and $\alpha = 45°$. By single layer MiniPIX-Timepix camera.

Angular distribution of a 31 MeV proton beam along the (a) elevation and (b) polar angles for four incident geometries (collected separately) by a single layer MiniPIX-Timepix camera (sensor 300 µm silicon).

Electron beam 12 MeV – 1x direction
Microtron NPI-CAS Prague

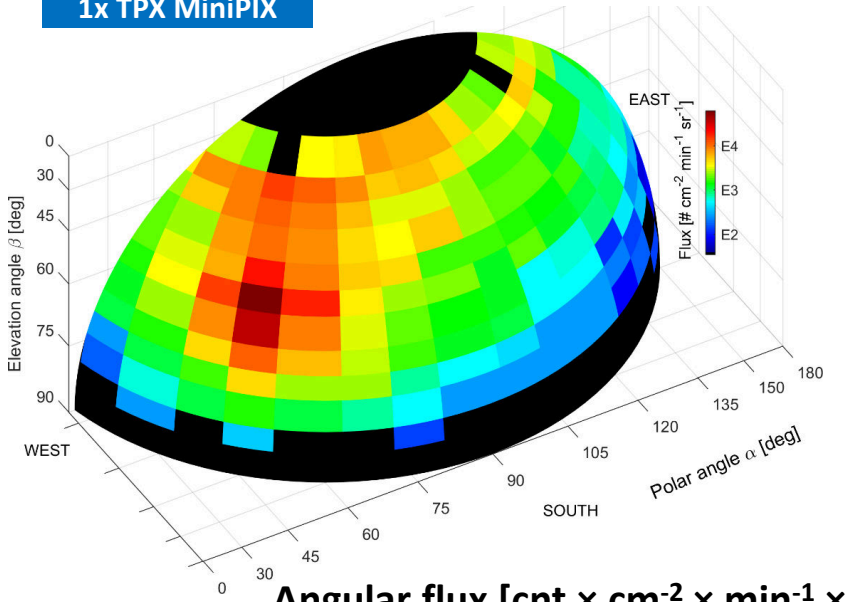


Proton beam 31 MeV – 4x directions
Cyclotron NPI-CAS Prague Rez

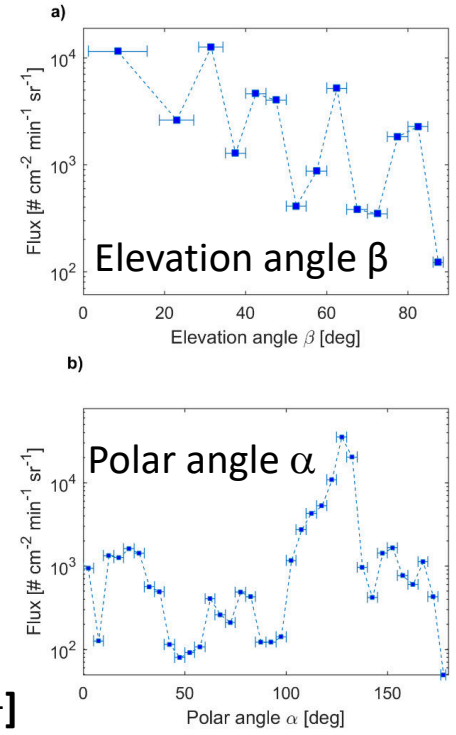


Directional sky map

1x TPX MiniPIX

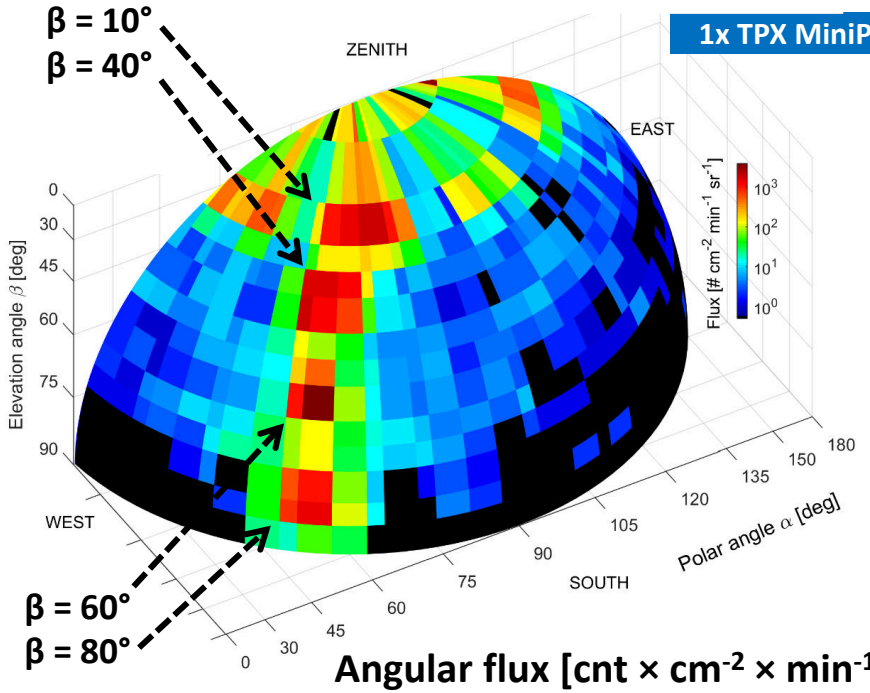


Angular flux [cnt × cm^{-2} × min^{-1} × sr^{-1}]



Directional sky map

1x TPX MiniPIX

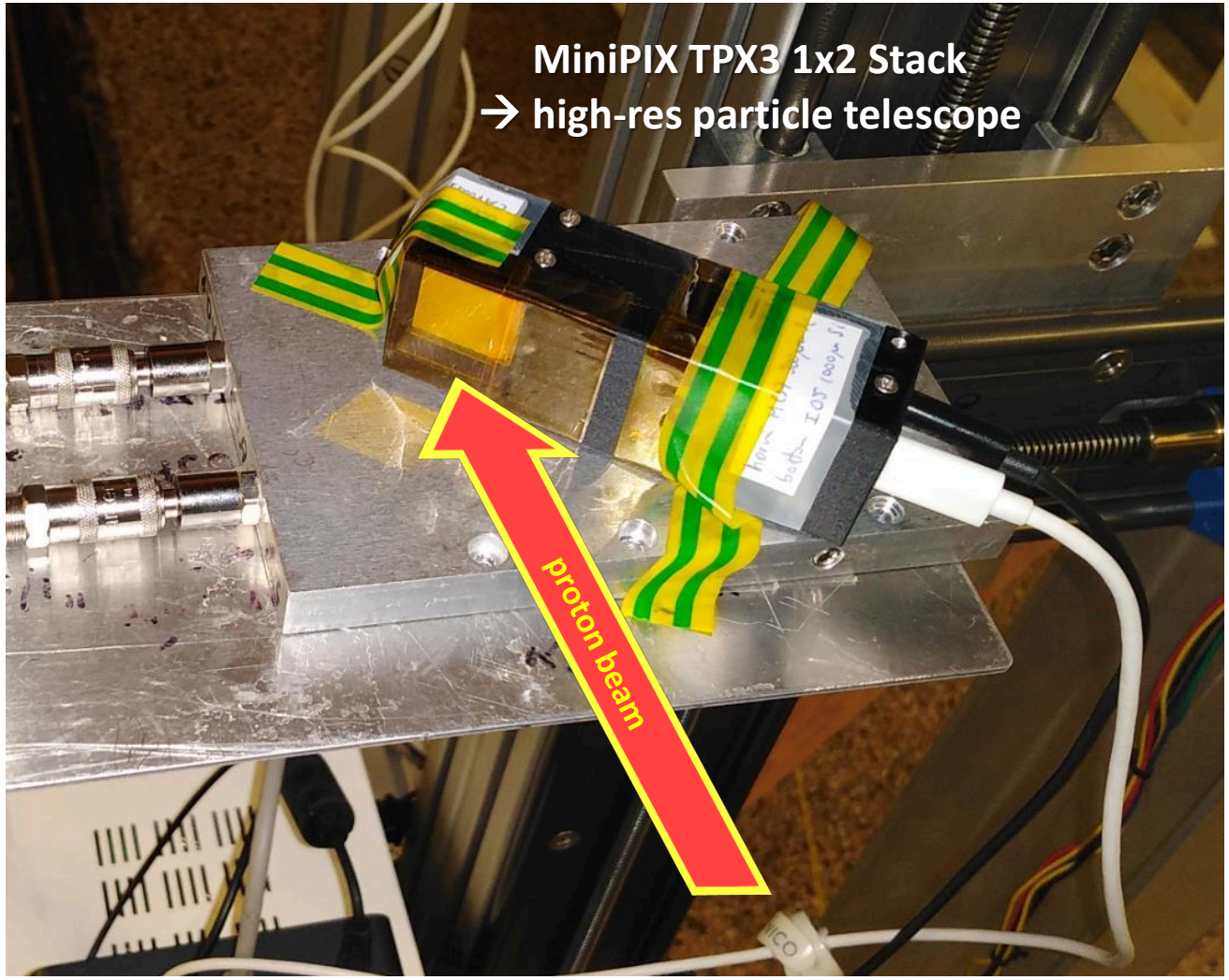


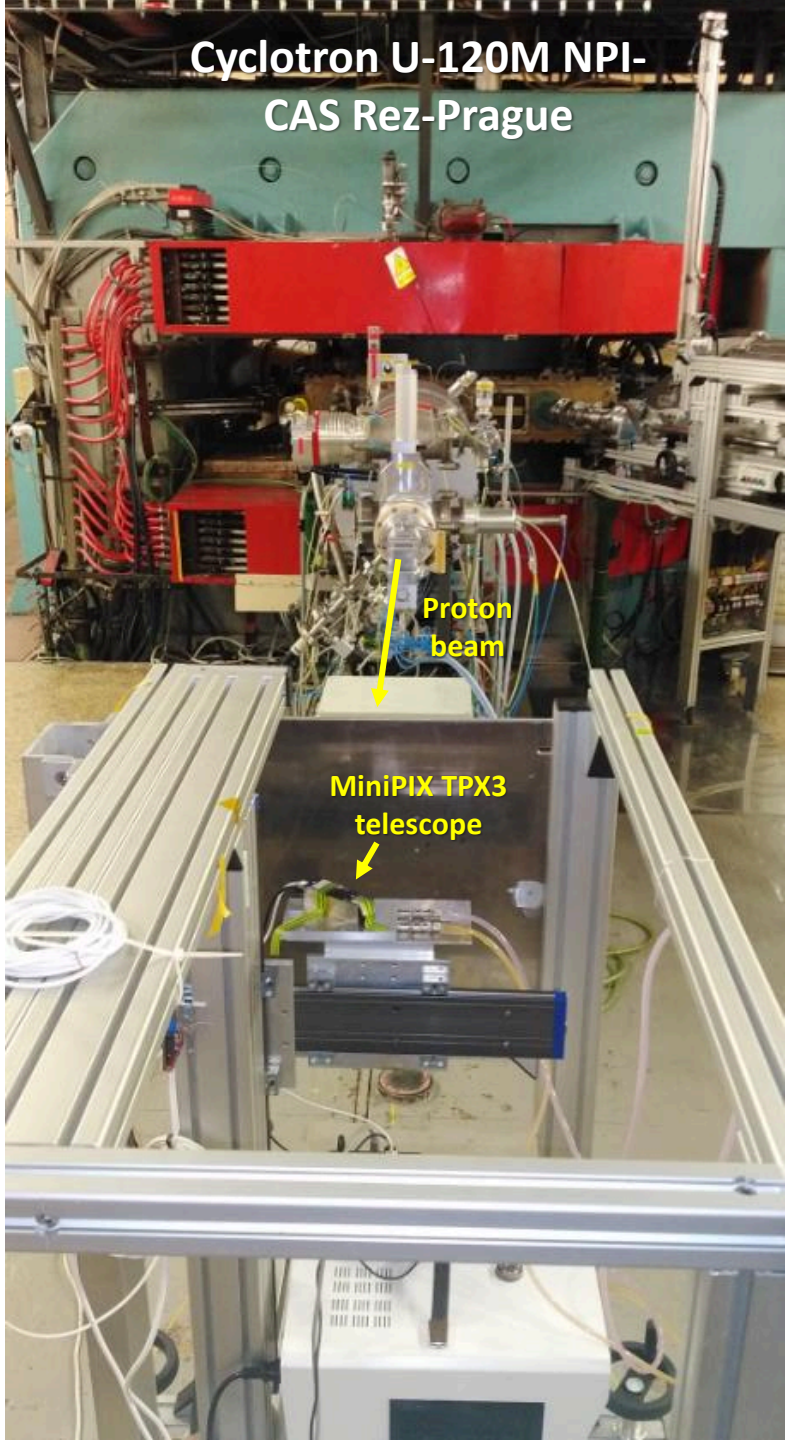
Angular flux [cnt × cm^{-2} × min^{-1} × sr^{-1}]

MiniPIX TPX3 Stack: High angular resolution tracking

8 – 30 MeV protons, Prague Cyclotron

ADVACAM
Imaging the Unseen

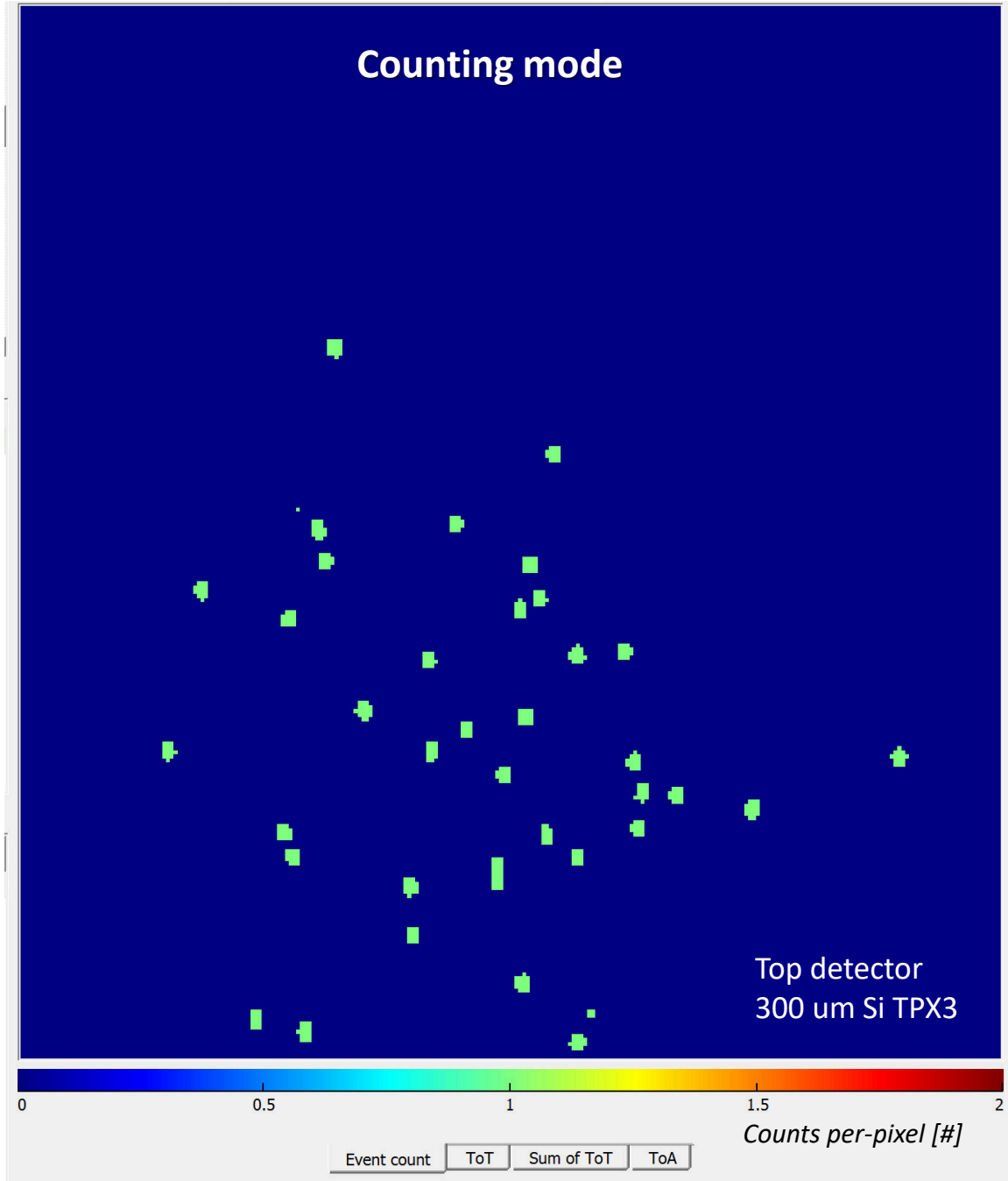




0.35 ms data stream

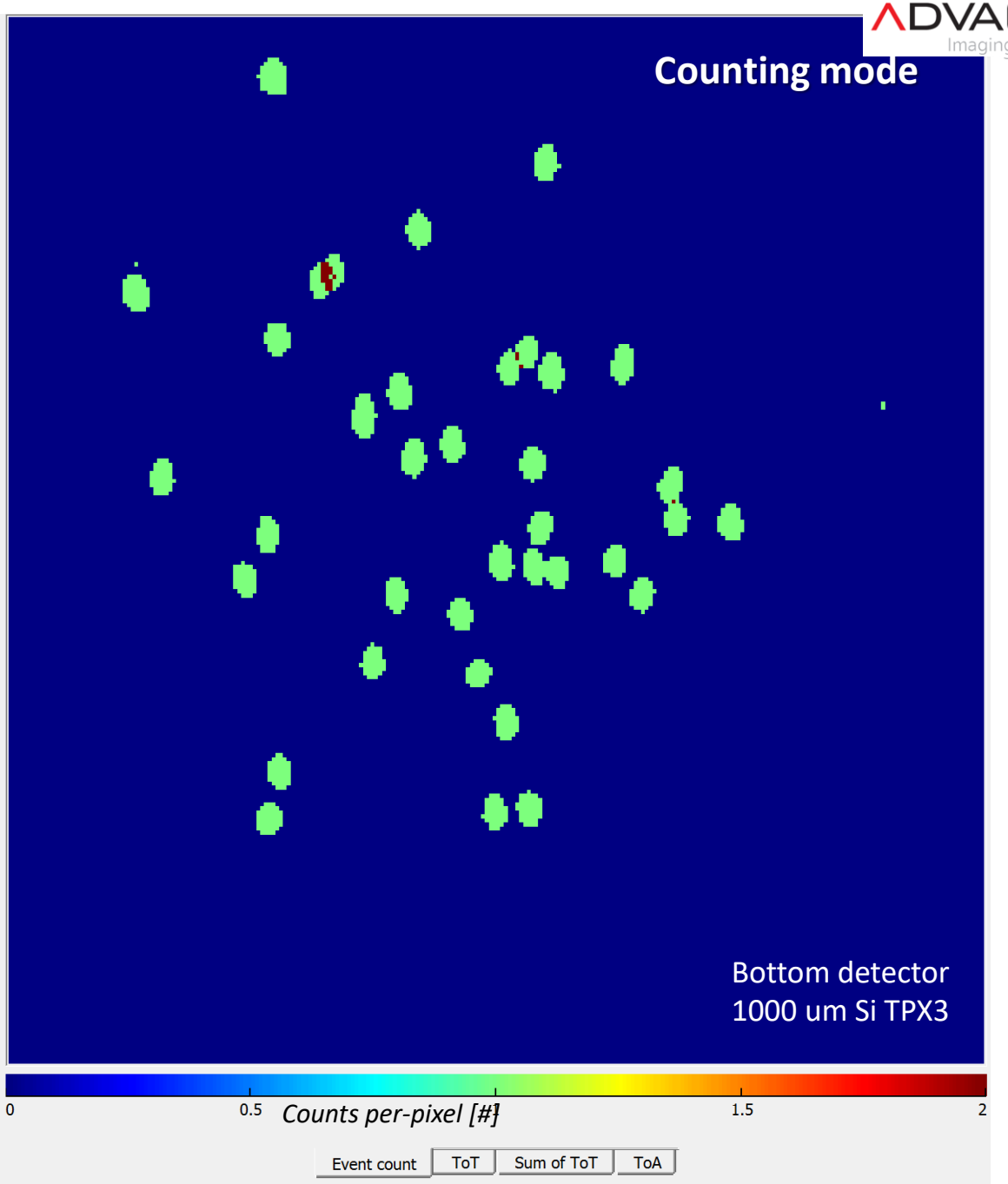
30 MeV protons, β = 15°, Cyclotron, NPI-CAS, Rez-Prague, Aug 2020

ADVACAM
Imaging the Unseen



TIC

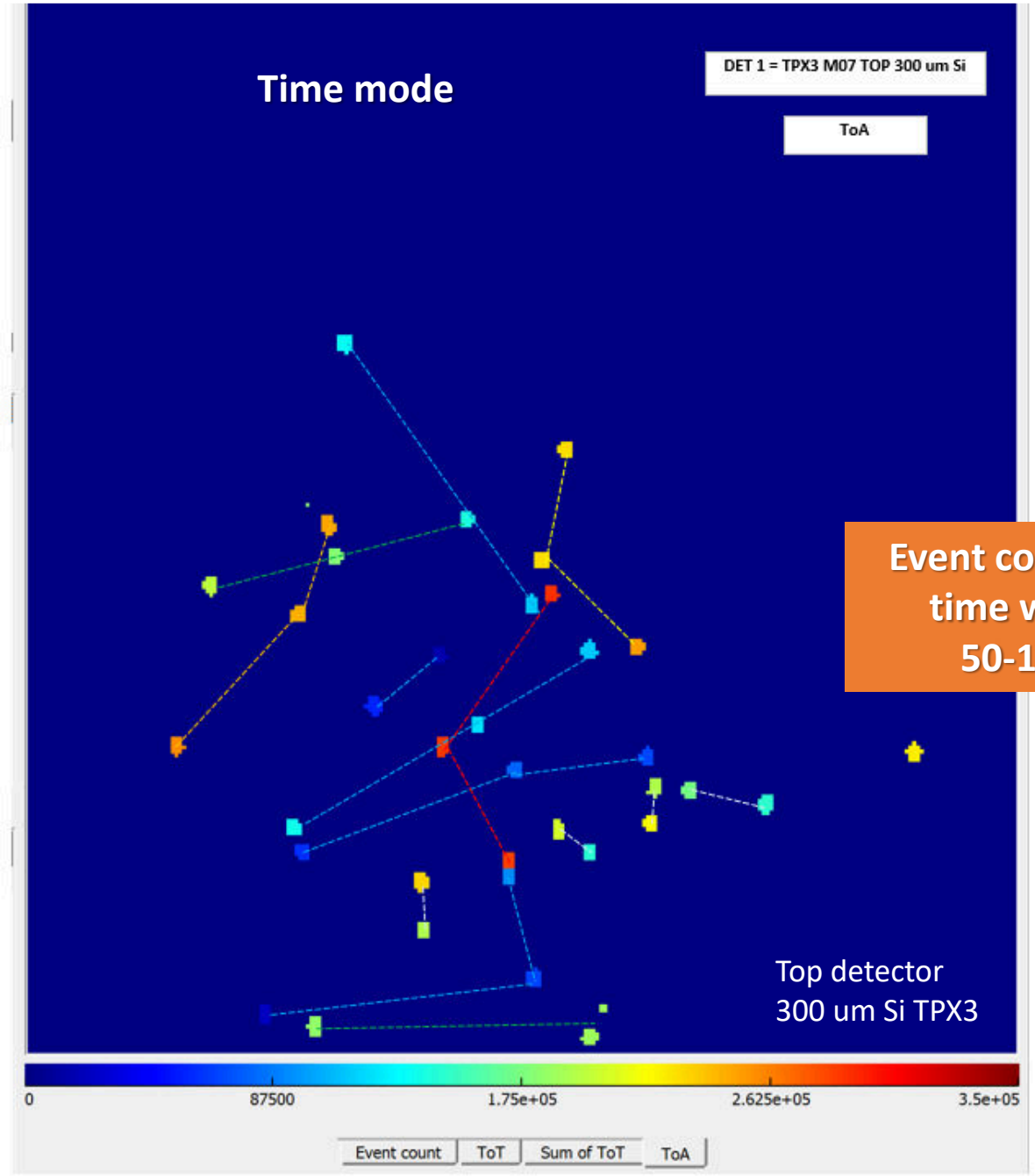
T, P



0.35 ms data stream

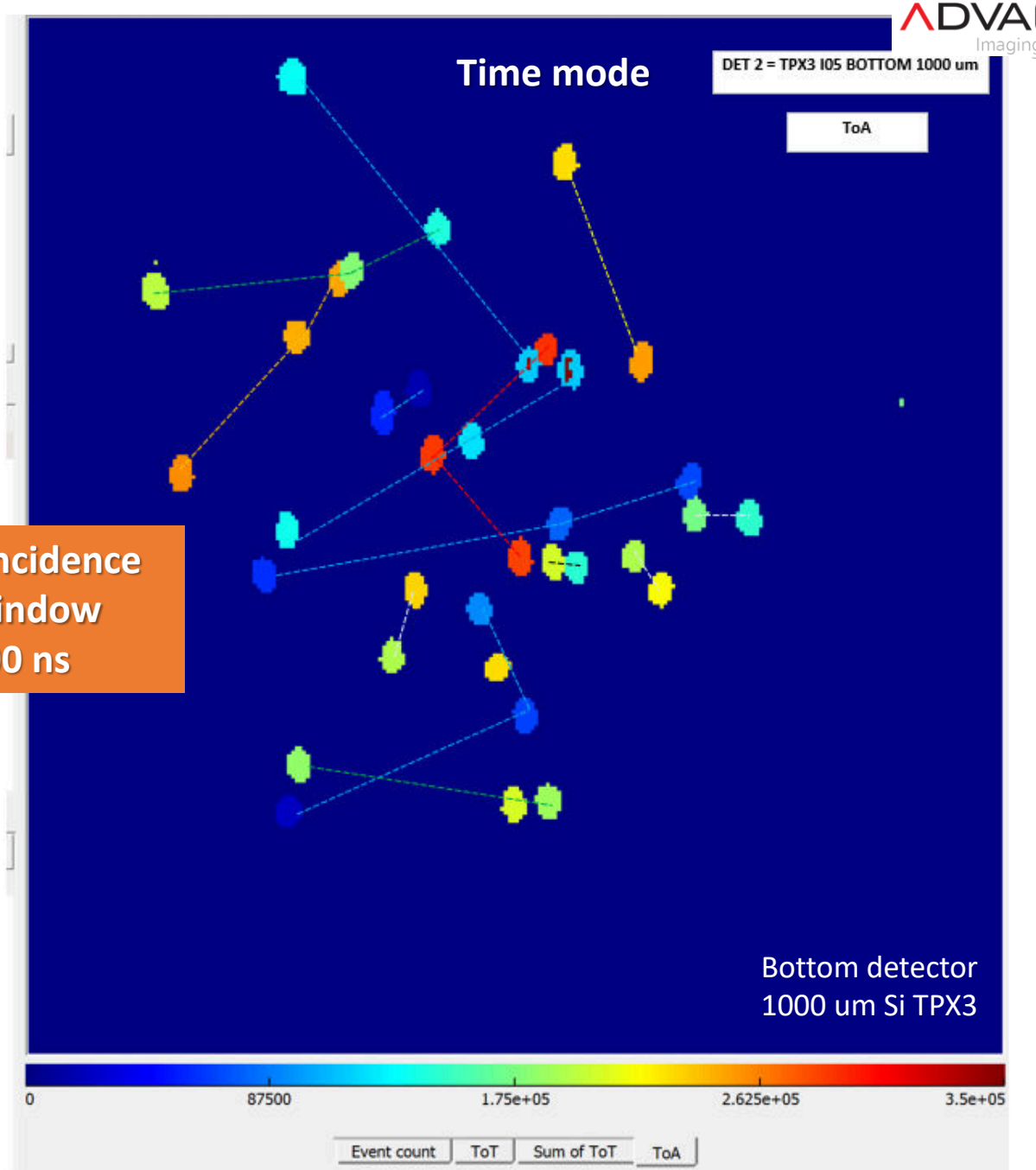
30 MeV protons, β = 15°, Cyclotron, NPI-CAS, Rez-Prague, Aug 2020

ADVACAM
Imaging the Unseen



Event coincidence time window 50-100 ns

Top detector
300 um Si TPX3



Bottom detector
1000 um Si TPX3

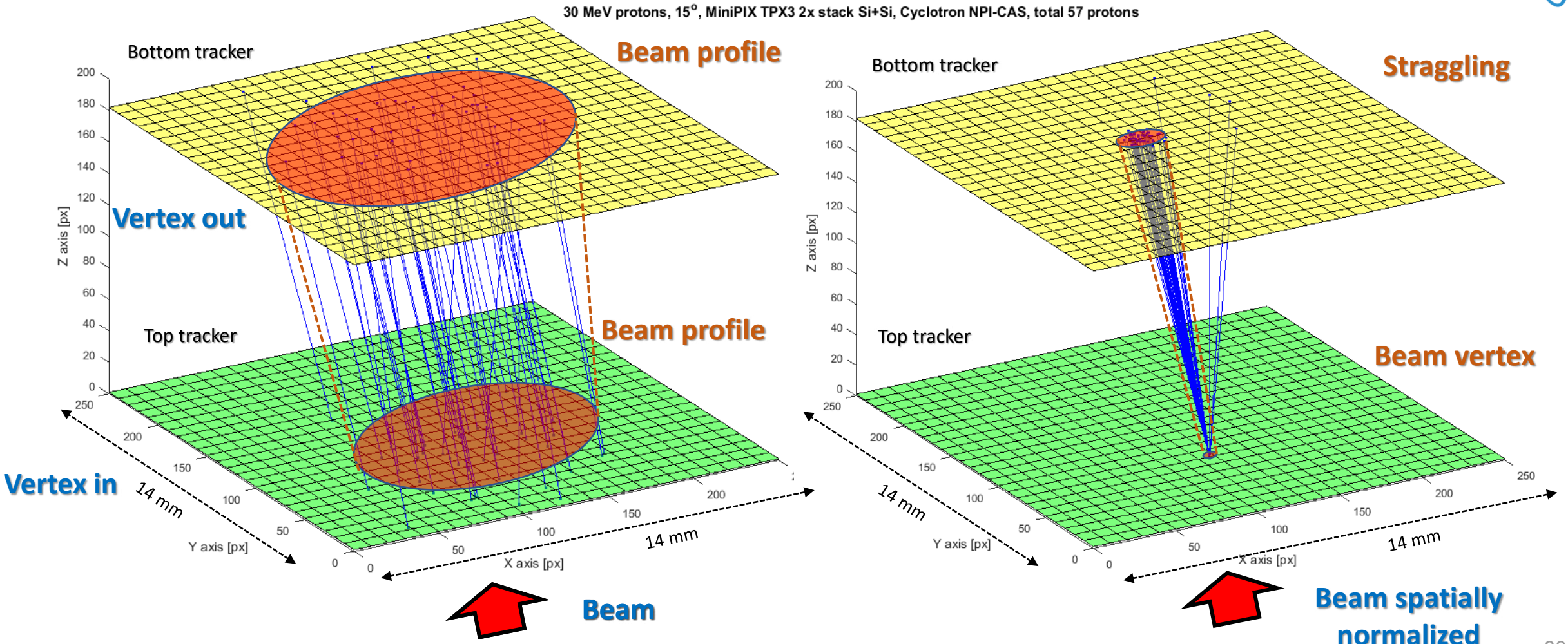
MiniPIX TPX3 Stack: High angular resolution tracking in wide FoV

Vertex registration with sub-pixel (≈10 µm) spatial resolution → directional vector in 3D

Spatial-directional mapping

3D directional vector

Directional-angular mapping



MiniPIX TPX3 Stack: High angular resolution tracking in wide FoV

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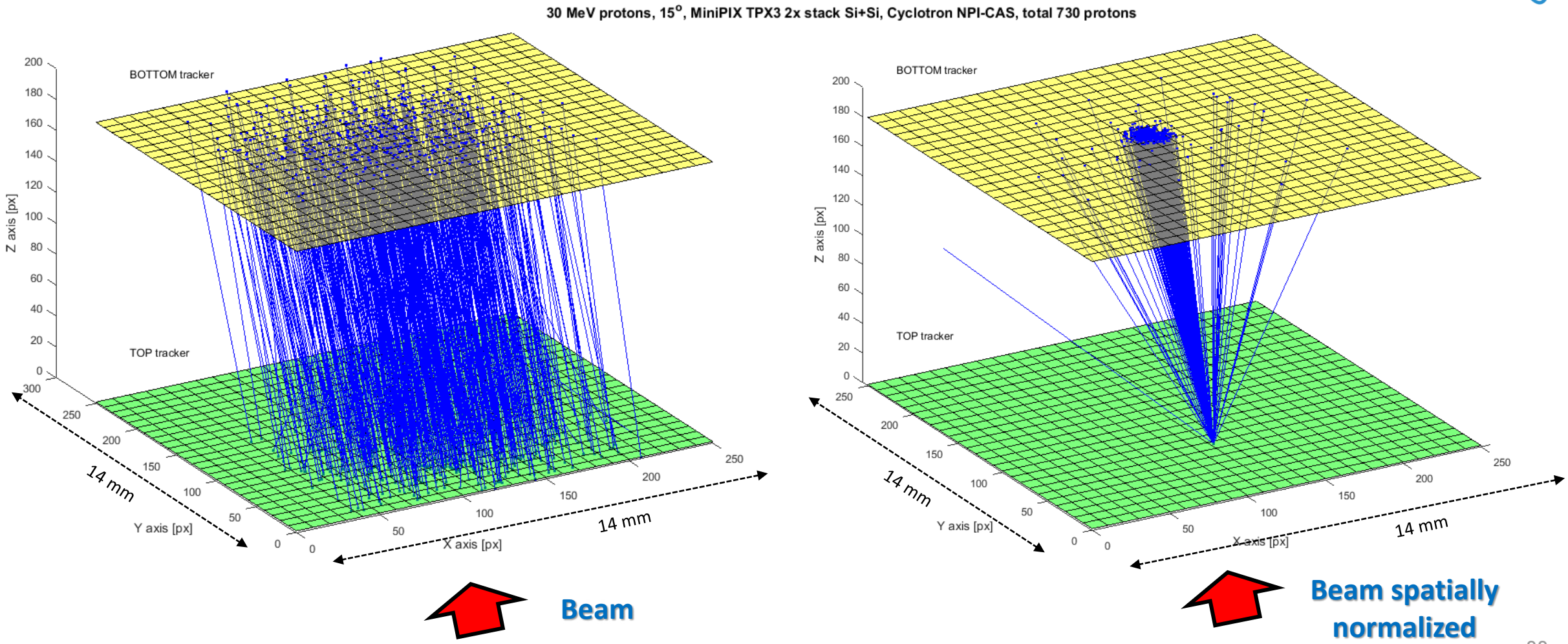
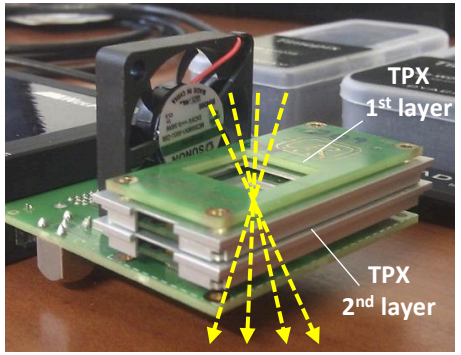


Beam

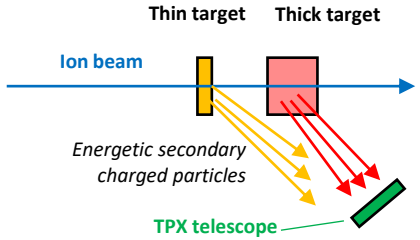
Beam spatially normalized

Wide range angular distributions of energetic charged particles

2x stack Timepix3 telescope → High angular resolution + wide FoV + enhanced discrimination

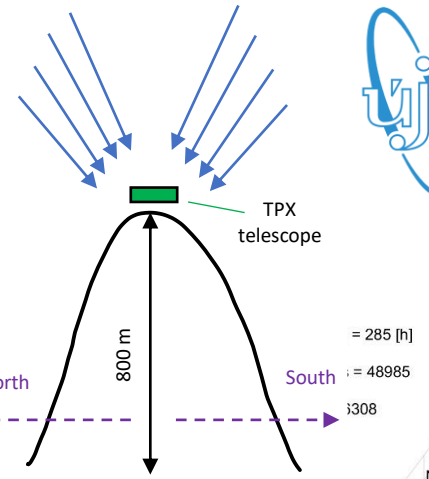


High angular resolution → sub-degree
Wide Field-of-View → 60-85% 2π



dkfz. HIT

^{12}C ion beam 213 MeV/u

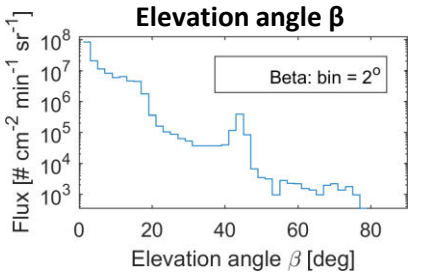


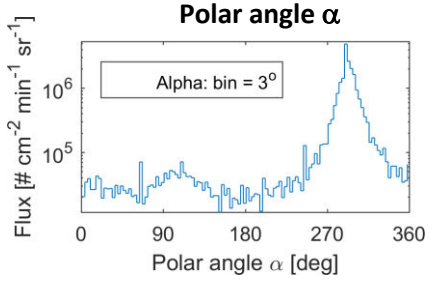
CRREAT
RESEARCH CENTRE OF COSMIC RAYS AND RADIATION EVENTS IN THE ATMOSPHERE

Milesovka mountain

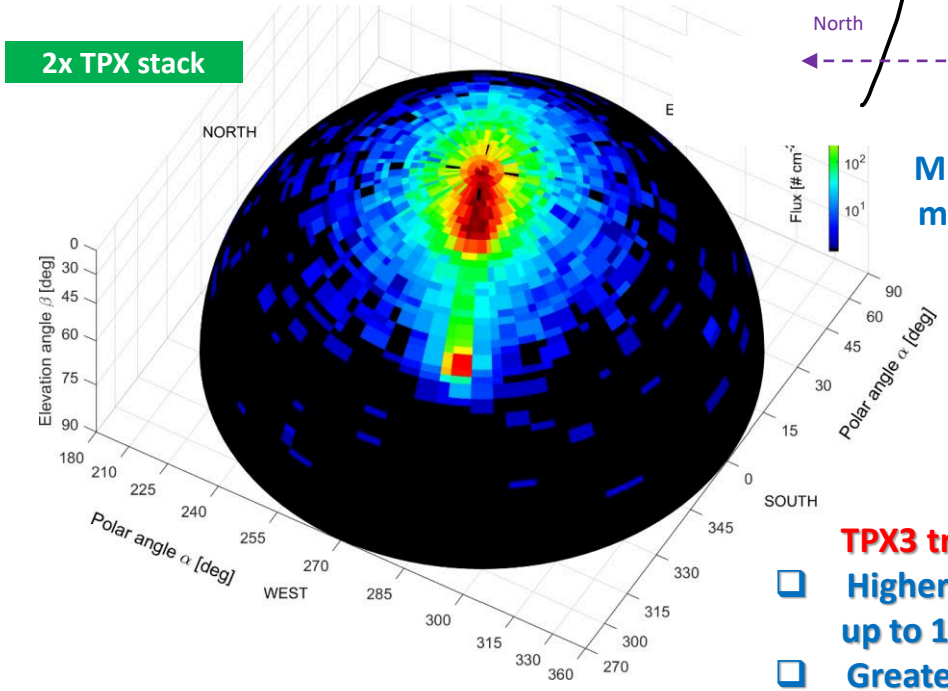
Secondary cosmic rays (muons) 800

Directional distribution/all sky map



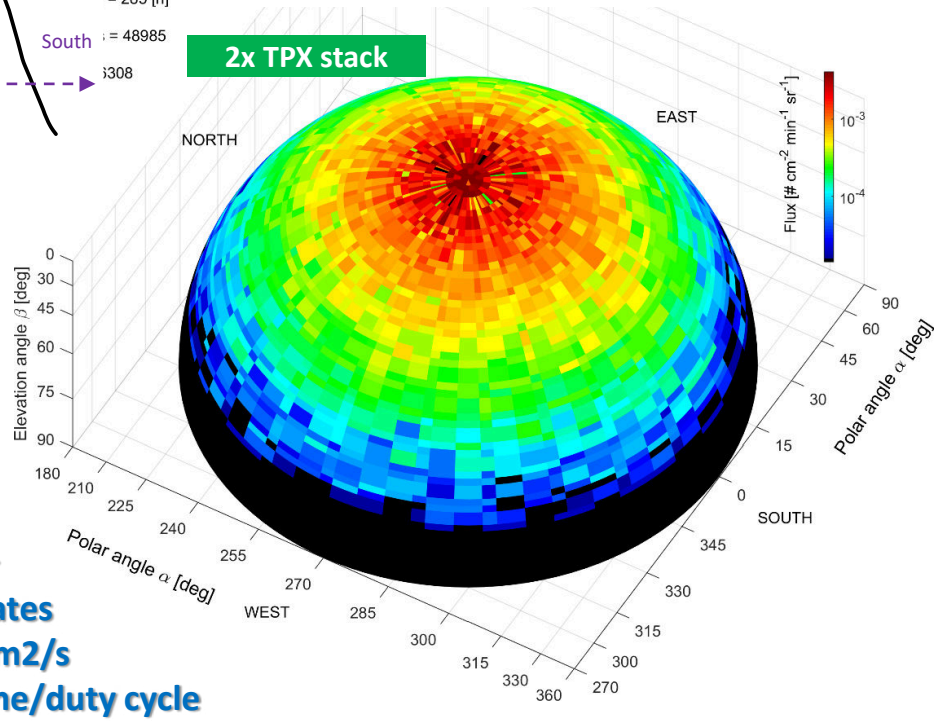


2x TPX stack



Directional distribution/all sky map

2x TPX stack



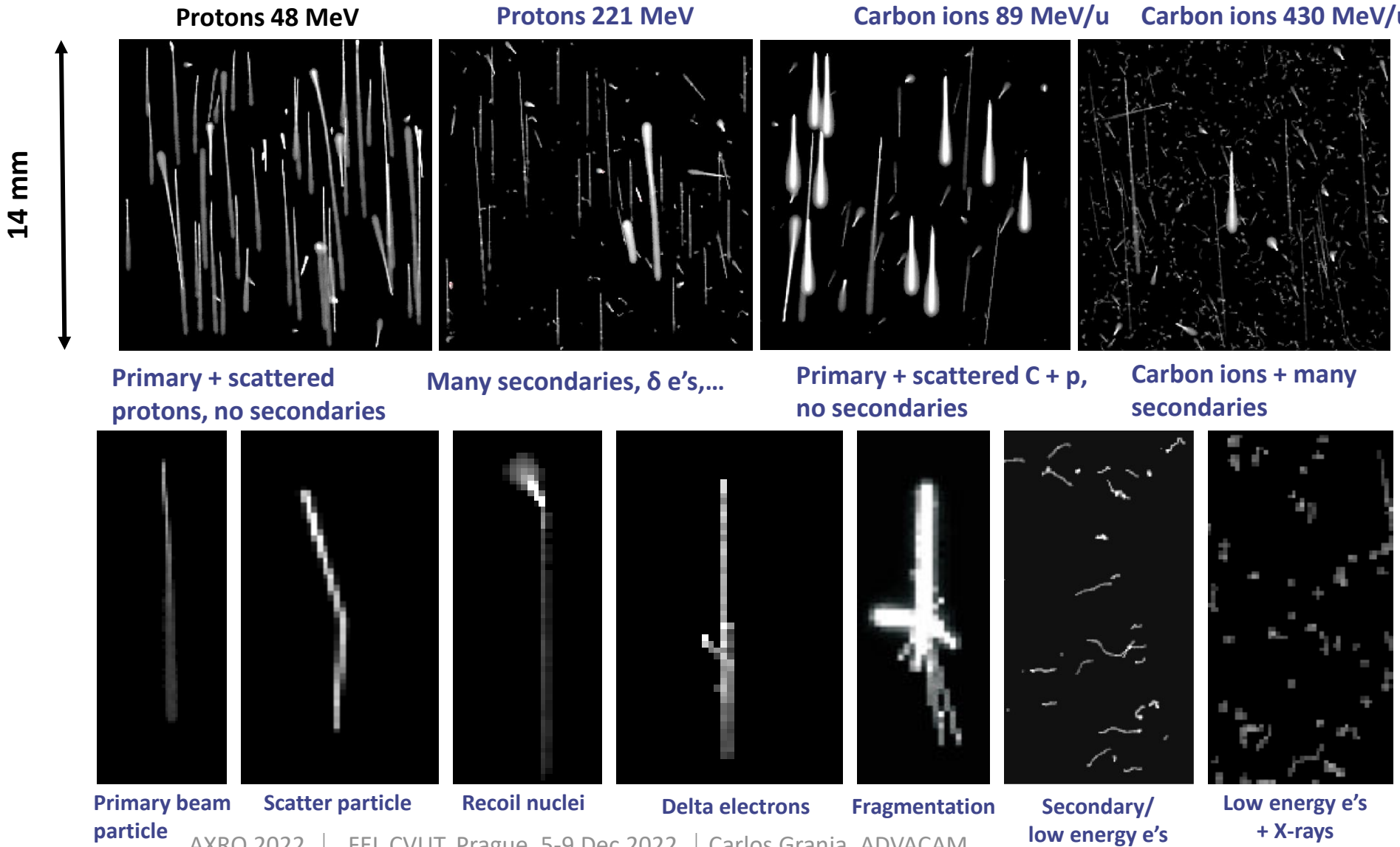
TPX3 tracker →

- Higher count rates up to 10^6 cnt/cm2/s
- Greater live time/duty cycle
- Combined spectrometry & tracking
- Enhanced resolving power/discrimination

Work in progress

Timepix

Active nuclear emulsion, per-px energy, time, counting response



Quantum imaging detectio and track visualization of single particles

High-resolution spectral-tracking with particle-event resolving power:

- **X rays (narrow E)**
- **Light charged particles (LE,HE)**
- **Protons (LE, HE)**
- **Heavy charged particles: protons, ions (LE, HE)**

Light ion U-120 cyclotron, Rez-Prague
Synchrotron HIT, Heidelberg, Germany
Synchrotron, HIMAC, Chiba, Japan

C. Granja, J. Jakubek, et al., ***Dynamic range and resolving power of the Timepix detector to Heavy Charged Particles***, J. of Instrum. JINST 13 (2018) C11003

a) 13 MeV ^{1}H 80° [REZ]
b) 31 MeV ^{1}H 80° [REZ]
c) 48 MeV ^{1}H 85° [HIT]
d) 140 MeV ^{1}H 85° [HIT]
e) 220 MeV ^{1}H 85° [HIT]
f) 31 MeV/u ^{4}He 80° [HIMAC]
g) 61 MeV/u ^{4}He 80° [HIMAC]
h) 144 MeV/u ^{4}He 80° [HIMAC]
i) 88 MeV/u ^{12}C 85° [HIT]
j) 270 MeV/u ^{12}C 85° [HIT]
k) 430 MeV/u ^{12}C 85° [HIT]
l) 82 MeV/u ^{28}Si 85° [HIMAC]
m) 118 MeV/u ^{28}Si 85° [HIMAC]
n) 444 MeV/u ^{28}Si 87° [HIMAC]
1 mm

Y-position [pixel]: 60, 80, 100, 120, 140, 160, 180, 200, 220, 240
X-position [pixel]: 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220
Per-pixel energy [keV/px]: 10^{1}, 10^{2}, 10^{3}

References

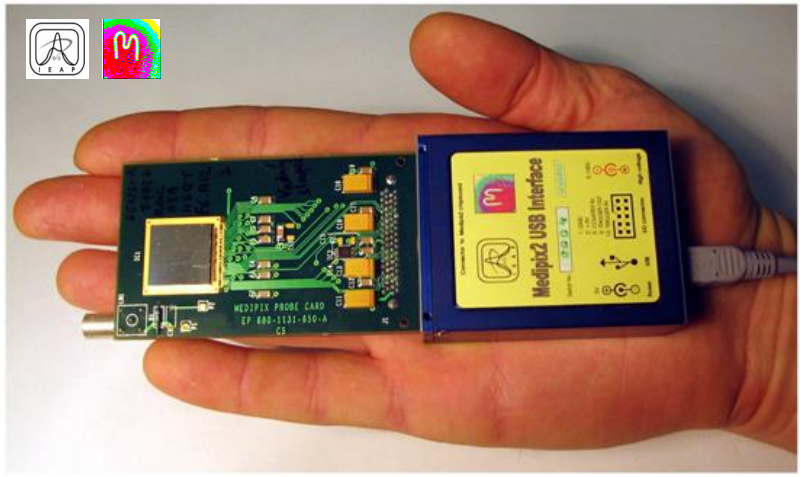
- D. Turecek *et al.,* Compton camera based on Timepix3 technology, *JINST* 13 (2018) C11022
- D. Turecek *et al.,* Single layer Compton camera based on Timepix3 technology, *JINST* 15 (2020) C01014
- E. Trojanova *et al.,* Evaluation of Timepix3 based CdTe photon counting detector for fully spectroscopic small animal SPECT imaging, *JINST* 13 (2018) C01001
- A. Modry, E. Trojanova, et al., SPECT imaging properties of the CdTe-Timepix3 detector used in a new prototype FullSPECT 3D multimodal preclinical imaging system: Comparison with scintillation gamma camera, NIM-A 1032 (2022) 166531
- C. Granja, J. Jakubek, P. Soukup, et al., Spectral and directional sensitive composition characterization of mixed-radiation fields with the miniaturized radiation camera MiniPIX Timepix2, J. of Instrumentation JINST (2022)
- C. Granja, R. Hudec, V. Marsikova, et al., Directional-Sensitive X-ray/Gamma-ray Imager on Board the VZLUSAT-2 CubeSat for Wide Field-of-View Observation of GRBs in Low Earth Orbit, Universe 8 (2022) 241
- C. Granja, J. Jakubek, P. Soukup, et. al., *Spectral tracking of energetic charged particles in wide field-of-view with miniaturized telescope MiniPIX Timepix3 1×2 Stack*, J. of Instrum. JINST 17 (2022) C03028
- C. Granja, J. Jakubek, P. Soukup, et. al., *MiniPIX Timepix3 — a miniaturized radiation camera with onboard data processing for online characterization of wide-intensity mixed-radiation fields*, J. of Instrum. JINST 17 (2022) C03019
- C. Granja, J. Jakubek, S. Polansky, et al., *Resolving power of pixel detector Timepix for wide-range electron, proton and ion detection*, Nuclear Instr. Methods A 908 (2018) 60-71

Integrated electronics, compact radiation cameras, online response

Hybrid semiconductor pixel detector: MPX/TPX ASIC chip + Si/CdTe sensors
Small size, miniaturization, integrated control/readout/data acquisition, online display

ADVACAM Imaging the Unseen

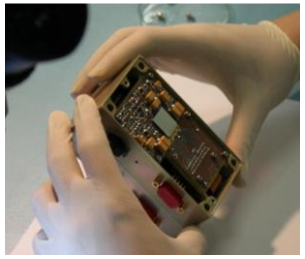
Radiation Camera



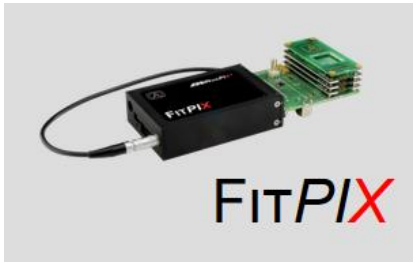
Portable wire-less camera

Large area radiation imager

SATRAM-Timepix payload on ESA Proba-V satellite



Stacked tracker Particle telescope



MX-10 Particle Camera

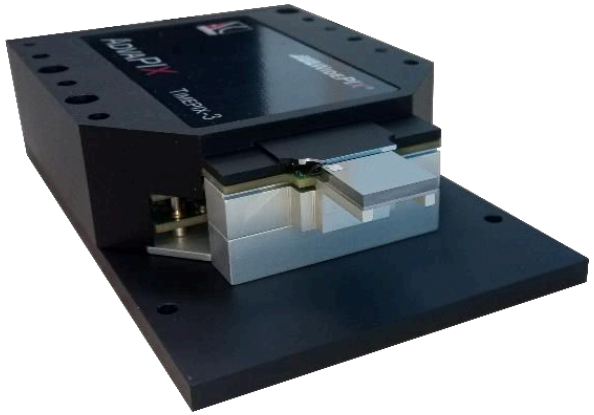
MiniPIX-EDU

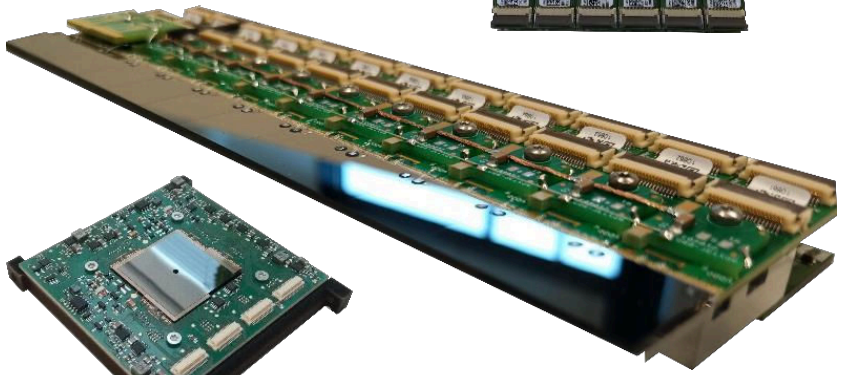
ADVACAM Imaging the Unseen HAWKEYE Spectral Imaging

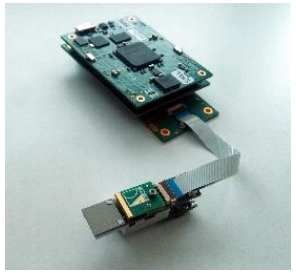
AdvaPIX + AdvaPIX Quad

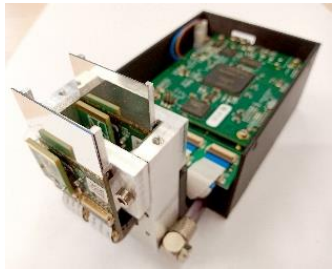
Timepix, **TPX3** all sensor types

ADVACAM
Imaging the Unseen









Concept:

- USB3.0 (USB C coming soon)
- Vacuum compatible
- Versatile & larger areas
- Quad with hole, rows, arcs …

Well-established product:

- Spectroscopic X-ray imaging
- SAXS & XRD
- Electron microscopy
- Gamma & Compton cameras
- Medical: OEM Thyroid
- Science & Research