NUCLEAR PHYSICS INSTITUTE
The Czech Academy of Sciences

29th WRMISS
Workshop on Radiation Monitoring to assess human exposures Inside the Solar System
1 - 3 September 2026

Detection sensitivity and specific tracking response to charged particles and neutrons by Timepix detectors with Si, SiC, GaAs and CdTe sensors

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VŠB TECHNICKÁ UNIVERZITA OSTRAVA

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STU SLOVENSKÁ TECHNICKÁ UNIVERZITA V BRATISLAVE

www.vsb.cz

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* until March 2026
ADVACAM*
Imaging the Unseen

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- **Institute of Experim. Physics**, Slovak Acad. Sci., Kosice/Slovakia
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  I. Chuprakov*, Y. Kopatch

Contents

- Motivation
- Instrumentation: Timepix
  - Hybrid architecture: ASIC chip – sensor assembly
  - Converter mask: neutrons (thermal, fast)
- Radiation response: imaging, particle tracking, dosimetry, resolving power
  - X rays, gamma rays
  - Charged particles: protons, ions
  - Charged particles: electrons
  - Neutrons: thermal, slow, fast
  - Mixed field: proton RT, cosmic rays/mountain altitude

Hybrid semiconductor pixel detector Timepix
Per–pixel signal readout electronics

S. Pospisil, J. Jakubek, C. Granja
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: TPX, TPX3, TPX2**
Different semiconductor sensors can be used:

- material (**Si, CdTe, GaAs, SiC**)
- thickness (100, 300, 500, 1000, 2000 µm)

High signal electronics integration

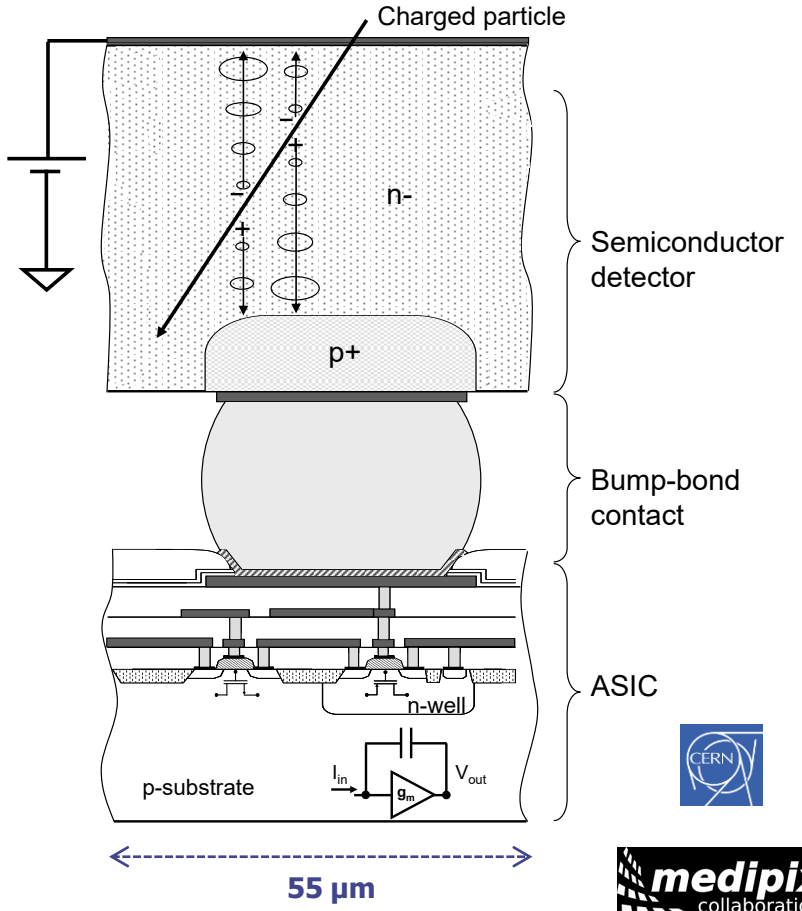
High integration, 1-2 k transistors per pixel

Quantum imaging detection

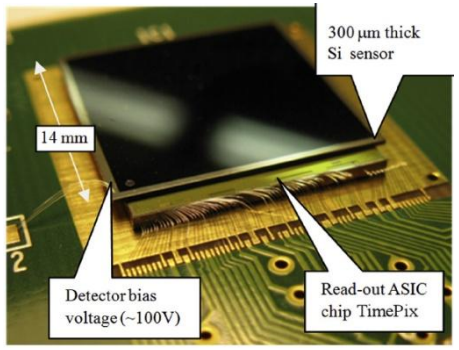
- Hybrid architecture
- Per-pixel signal processing electronics

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

Illustration of per-pixel signal electronics



Pixel detector Timepix



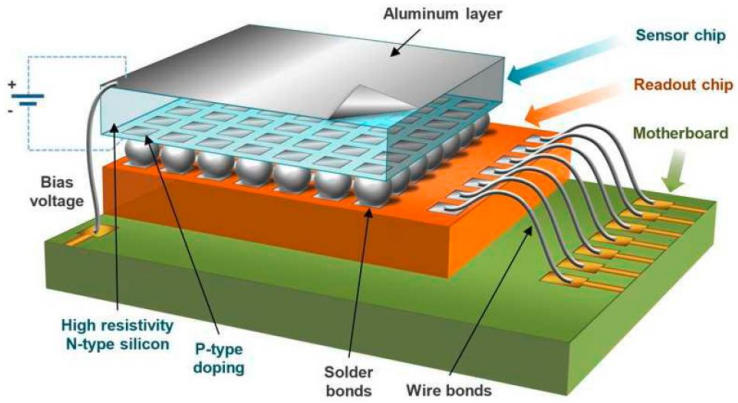
256 x 256 pixels (pitch 55 µm)
14 mm x 14 mm = 2 cm²

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

Miniaturized radiation camera MiniPIX-TPX



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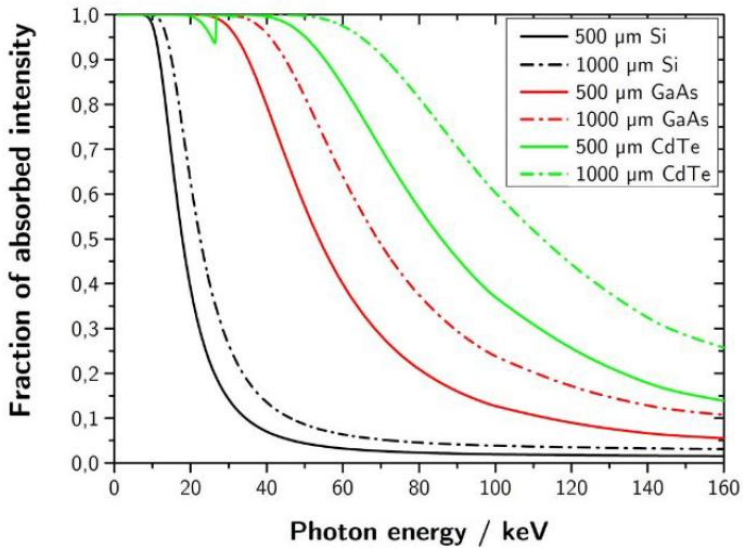
On line radiation camera

Digital spectral nuclear track emulsion

Motivation I

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Detection efficiency for X rays/gamma rays for **Si** + **GaAs** + **CdTe** of selected thickness, *P. Cardarelli, INFN 2026*



In the hybrid semiconductor detectors / Timepix

- The interaction and detection of radiation are determined by
  - The sensor material (**Si**, **SiC**, **GaAs**, **CdTe**), density, thickness
  - X rays/gamma rays: Limited detection efficiency
  - Neutrons: response specific to sensor material/isotopic
- The collection of the signal and its registration are determined by
  - The sensor properties + electric settings: charge diffusion + charge collection
  - The ASIC chip configuration, per-px signal electronics, threshold, linearity, range,…

Sensor material type/density, thermal stability, temperature effects/dependence, leakage current, noise, inhomogeneities, charge carrier loss/recombination, charge mobility, radiation hardness, sensor bias voltage → sensitive volume, electric field, saturation, …

Motivation II

In the hybrid semiconductor detectors / Timepix

- The extent, resolution and quality of the measured radiation data is determined by:
  - The sensor material (**Si**, **SiC**, **GaAs**, **CdTe**), density, thickness (bias)
  - The chip-sensor assembly equalization + per-px energy calibration
  - The sensor properties + electric settings
  - Onset/admixture of secondary radiation
  - Spectral-tracking resolving power
  - Radiation calibrations

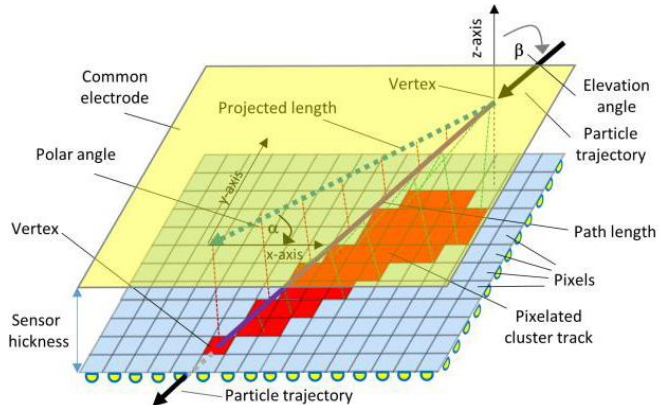
  → Particle-type resolving power
  → Discrimination

Motivation III

Pixel detectors Timepix of specific **ASIC chip – sensor configuration** in a wide range of applications: ● Nuclear physics ● neutron physics ● particle radiotherapy ● particle radiography ● cosmic rays ● space weather ● space radiation ● astrophysics ● …

- ❑ High-resolution experiments + complex/mixed-radiation fields + extended information
  - Composition characterization
  - Spectrometry (energy loss, LET)
  - Discrimination
  - Position
  - Direction

Spectral-tracking in high resolution and wide range



Degrees of freedom:

- Particle type/species
- Energy (energy loss)
- Direction

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

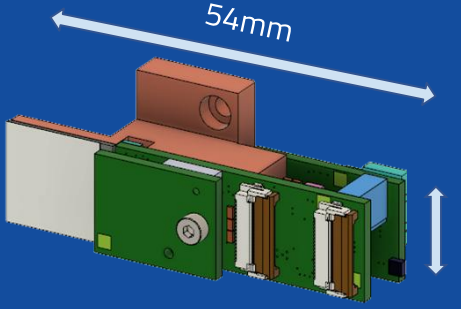
Space Rider - TGF Monitor THOR-SR experiment

Directional gamma-ray tracker array in wide field-of-view: 16x CdTe Timepix3

R. Silva/LIP, C. Granja + J. Jakubek/ADV, 2023



16x Timepix3
CdTe 2000 µm
finger boards

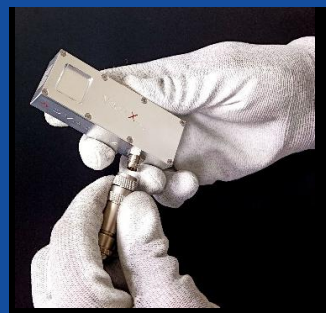


4x AdvaPIX space sync RO

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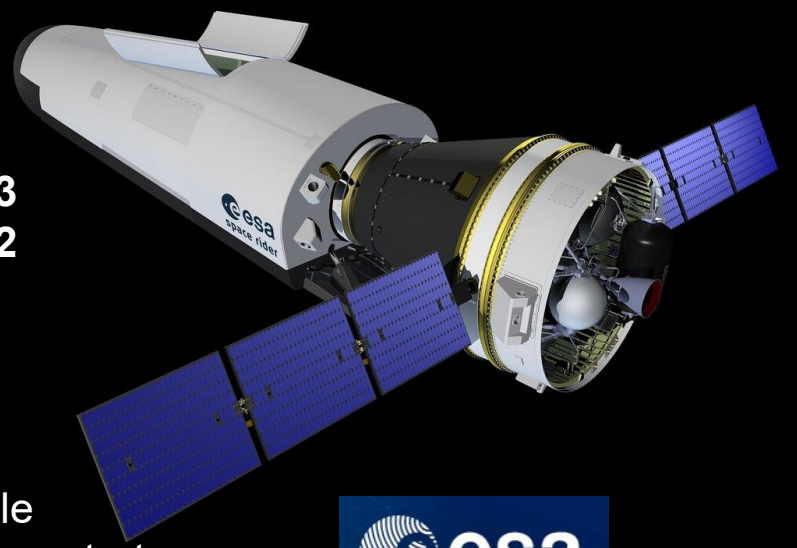
Wide FoV directional mapping of low-energy gamma rays
X-ray polarimetry from stellar objects
→ High discrimination & suppression of background/unwanted secondaries

Rui C. Silva, Jorge M. Maia, et al.
LIP, Univ. Coimbra, Portugal



1x MiniPIX TPX3
1x MiniPIX TPX2

Space Rider





Space **R**eusable
Integrated **D**emonstrator
for **E**urope **R**eturn

esa

LEO orbit
400 km
2 month mission
Recoverable
Launch 2027

LIP
LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

FACULDADE CIÊNCIAS
Departamento de Física

1 2 9 0
UNIVERSIDADE D COIMBRA

esa

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*

Charged particles

Heavy charged particles/light ions: ^{3}He ions 20-40 MeV

Light ion cyclotron accelerator, Nucl. Phys. Inst., CZ Acad. Sci. Rez n. Prague

Si, CdTe, GaAs Timepix/Timepix3

Chipboard + RO electronics MiniPIX Advacam

Radiation imaging, Particle tracking

Timepix ASIC chip – sensor assembly

C. Granja, J. Jakubek, Advacam, 2021

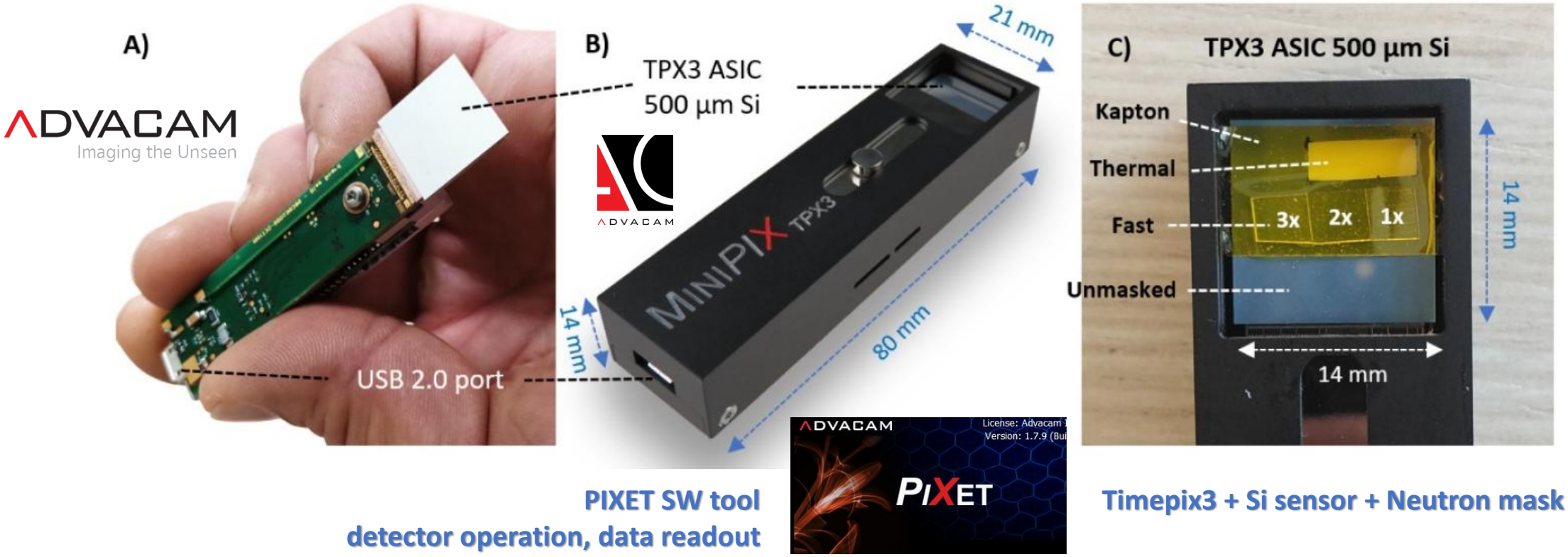
ADVACAM Imaging the Unseen

Miniaturized radiation camera: MiniPIX-TPX3 Si sensor + neutron converter mask

C. Granja, J. Jakubek, et al., ***MiniPIX Timepix3 radiation camera for characterization of mixed-radiation fields***, JINST 17 (2022) C03019

Radiation Camera MiniPIX Timepix3

Physics-customized neutron mask



PIXET SW tool
detector operation, data readout

Timepix3 + Si sensor + Neutron mask

Radiation sources/facilities, accelerators

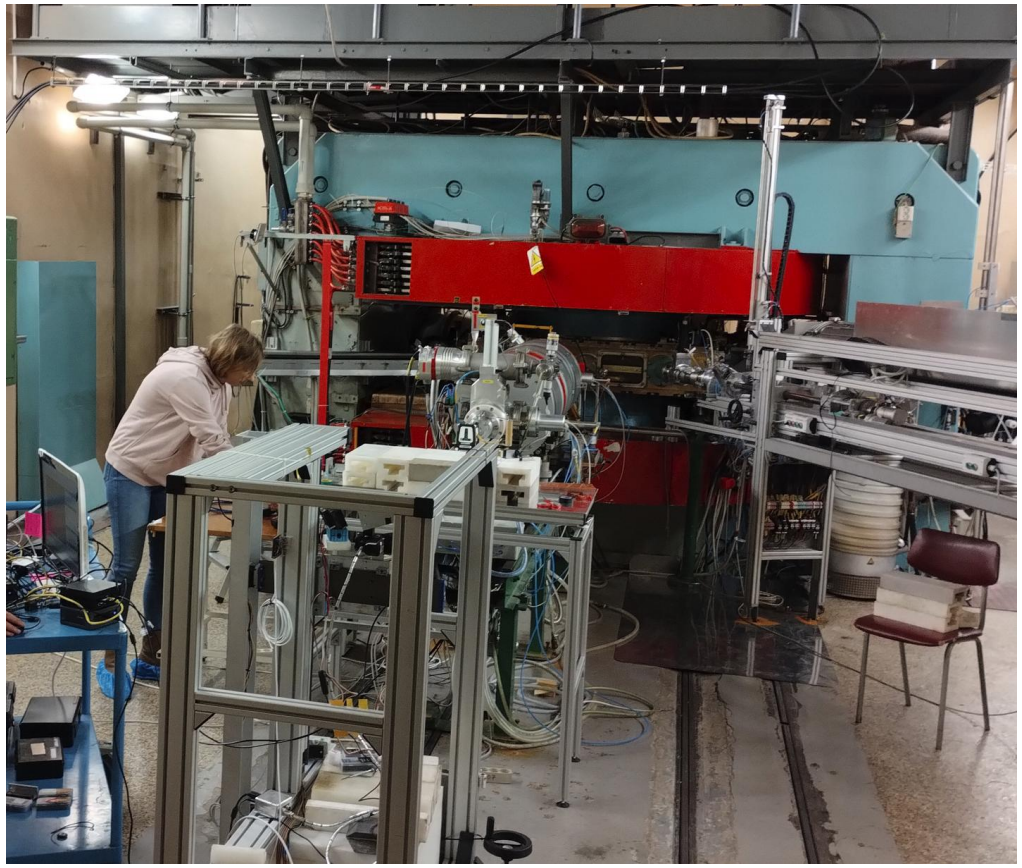
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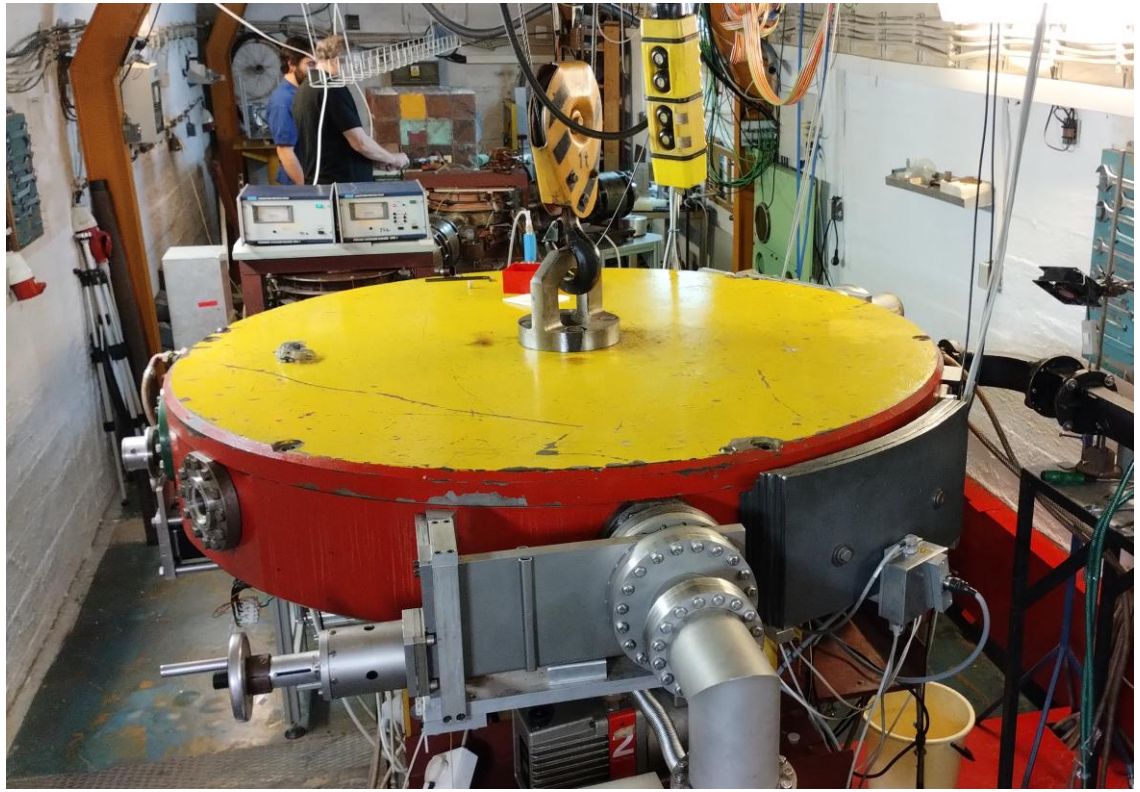
❑ ***Nucl. Phys. Inst, CZ Acad. Sci.**, Rez n. Prague, CZ: V. Zach, D. Chvatil, J. Stursa, D. Poklop, V. Olsansky, M. Stefanik*

Light ion cyclotron U-120M
8-35 MeV **protons, 3He ions**
Li/Be targets: 20-40 MeV **fast neutrons**

http://canam.ujf.cas.cz

MT-25 electron accelerator Microtron
3-22 MeV **electrons**
Secondary targets: gamma rays, ≈ MeV **fast neutrons**





Heavy charged particles: ^{3}He ions at 60^0

Carlos, Advacam, 2019

@ Light ion cyclotron U-120M, NPI-CZ AS Rez

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20 MeV ^{3}He ions @ 60^0

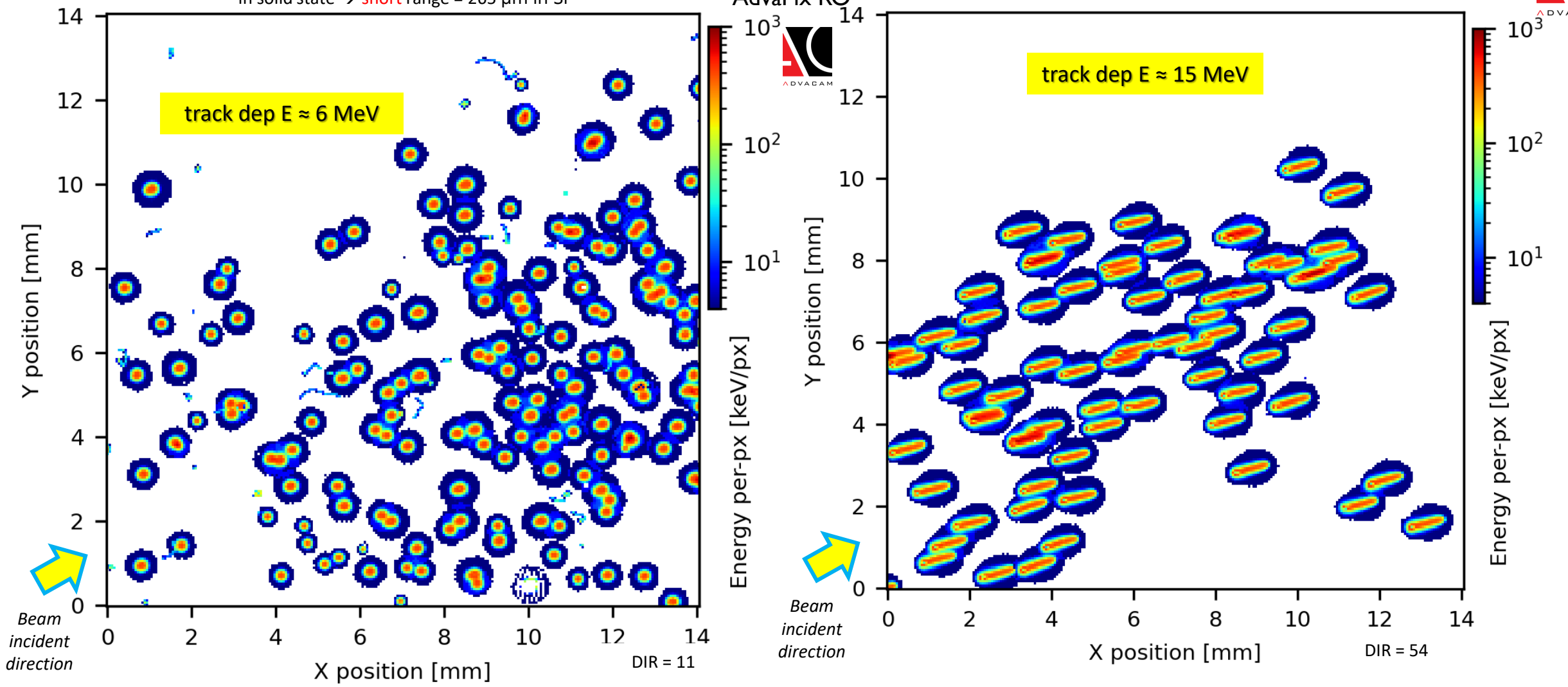
in solid state → short range = 265 µm in Si

Si 500 µm TPX3

AdvaPix RO

38 MeV ^{3}He ions @ 60^0

in solid state → long range = 880 µm in Si



Heavy charged particles: ^{3}He ions at 60^0

Carlos, Advacam, 2019

@ Light ion cyclotron U-120M, NPI-CZ AS Rez

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20 MeV ^{3}He ions @ 60^0

in solid state → short range

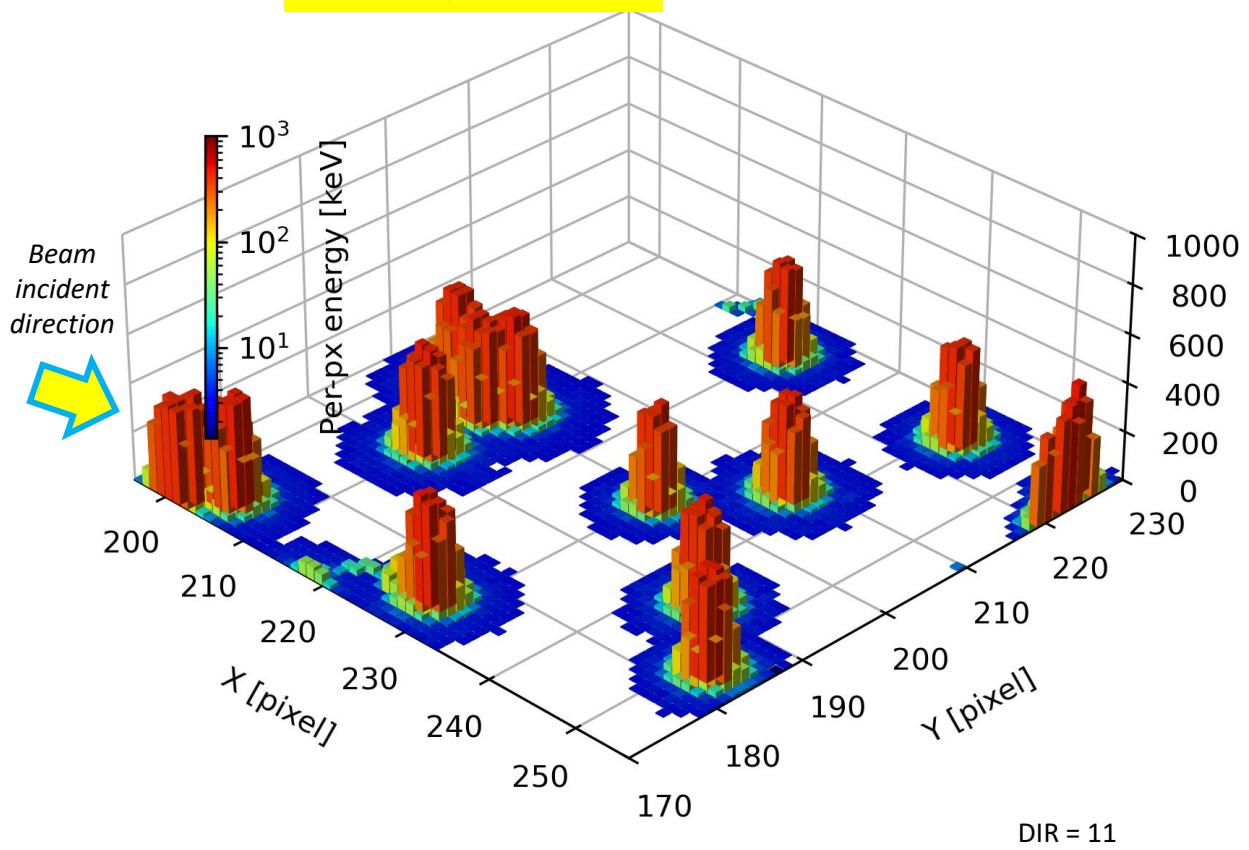
Si 500 µm TPX3

AdvaPix RO

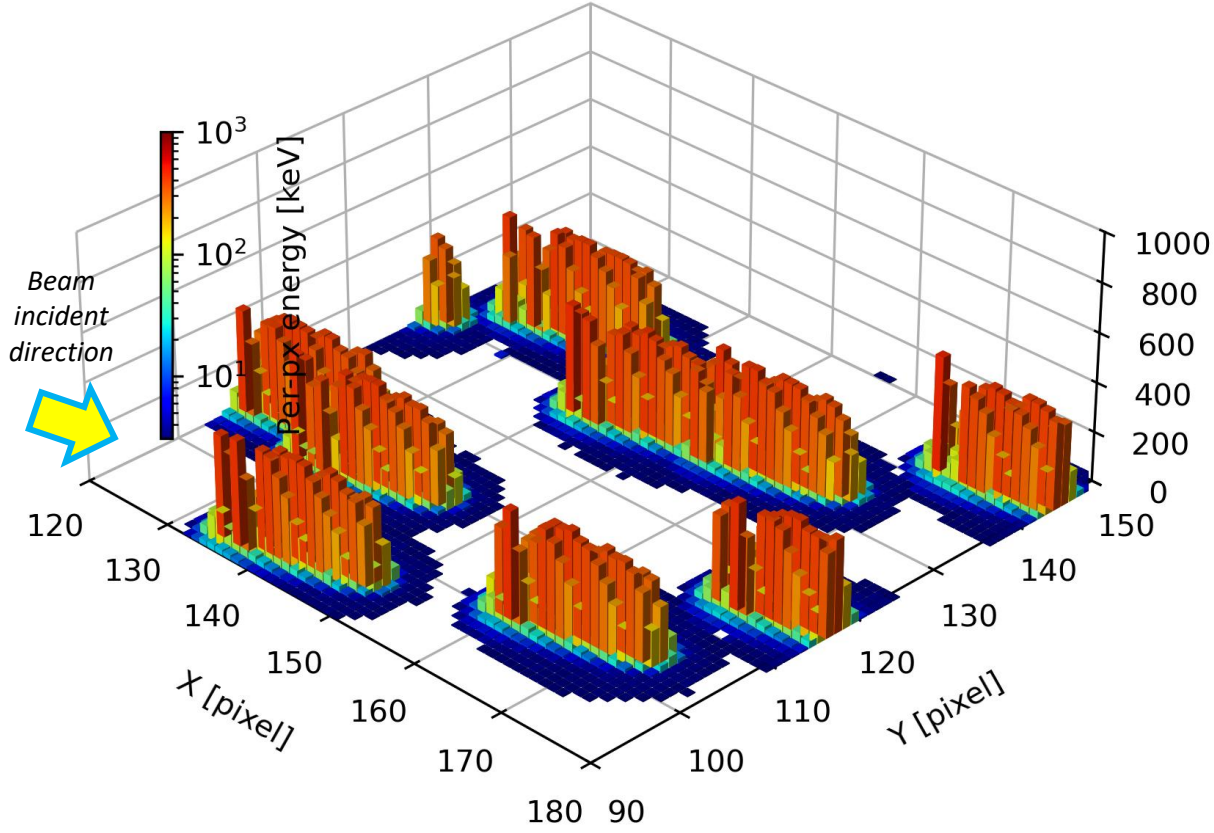
38 MeV ^{3}He ions @ 60^0

in solid state → long range

track dep E ≈ 6 MeV



track dep E ≈ 15 MeV



DIR = 11

Heavy charged particles: ^{3}He ions at 60^0

measured by Carlos, Advacam, 2019

@ Light ion cyclotron U-120M, NPI-CZ AS Rez

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ADVACAM

20 MeV ^{3}He ions @ 60^0

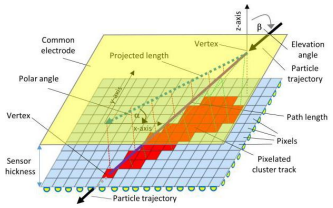
in solid state → short range = 265 µm in Si

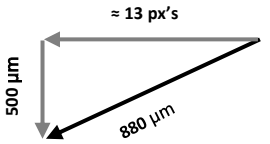
Si 500 µm TPX3

AdvaPix RO

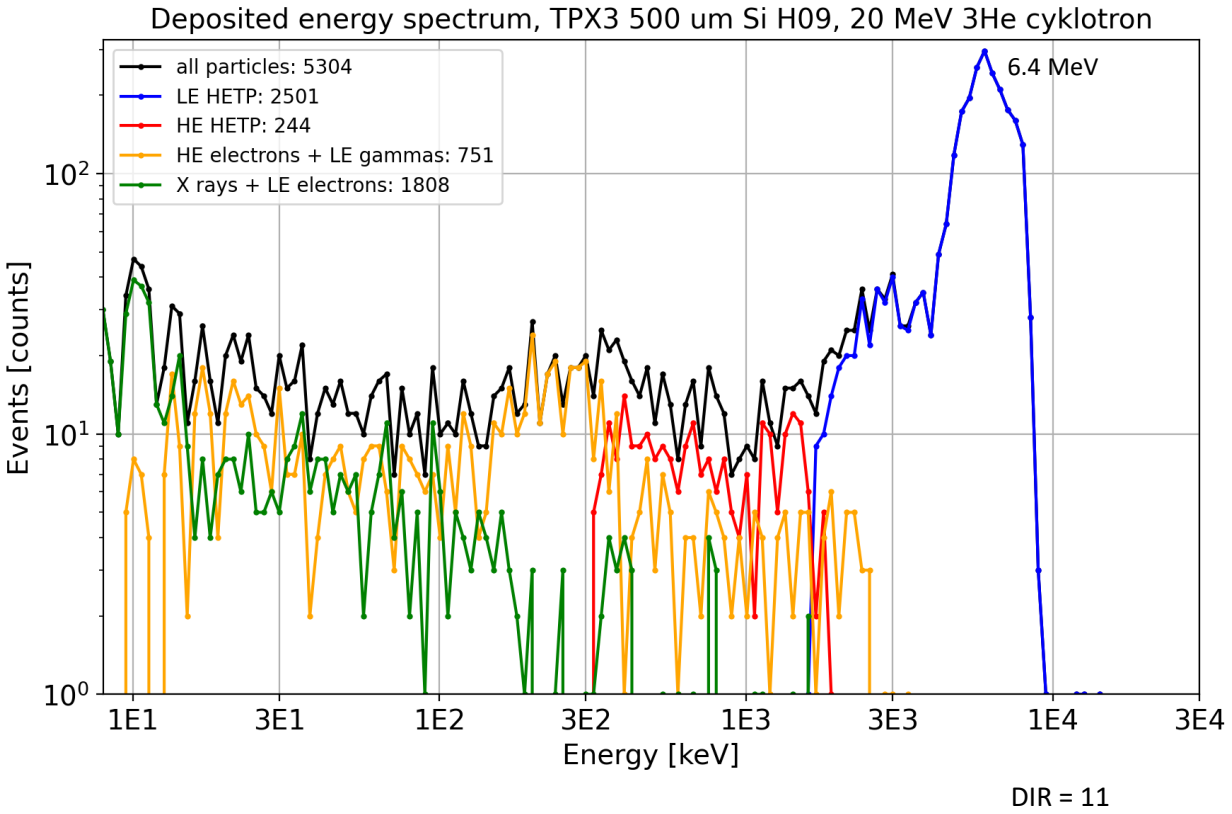
38 MeV ^{3}He ions @ 60^0

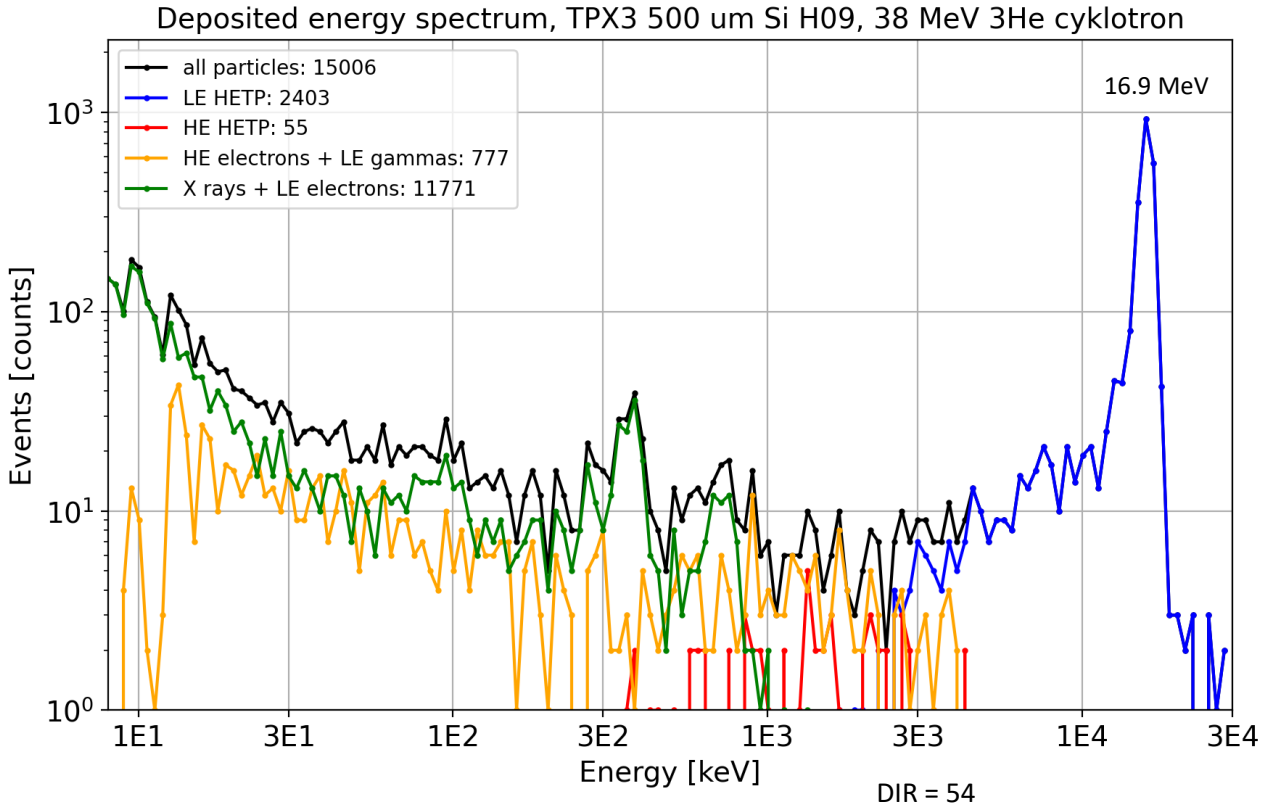
in solid state → long range = 880 µm in Si





SPECTROMETRY (DEP ENERGY) + DECOMPOSITION





Heavy charged particles: ^{3}He ions at 60^0

measured: Carlos, Advacam, 2019

@ Light ion cyclotron U-120M, NPI-CZ AS Rez

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20 MeV ^{3}He ions @ 60^0

in solid state → short range = 265 µm in Si

in solid state → high LET = 44 keV/µm in Si

Si 500 µm TPX3

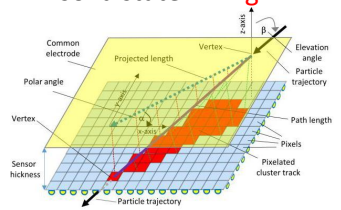
AdvaPix RO

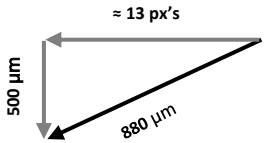
38 MeV ^{3}He ions @ 60^0

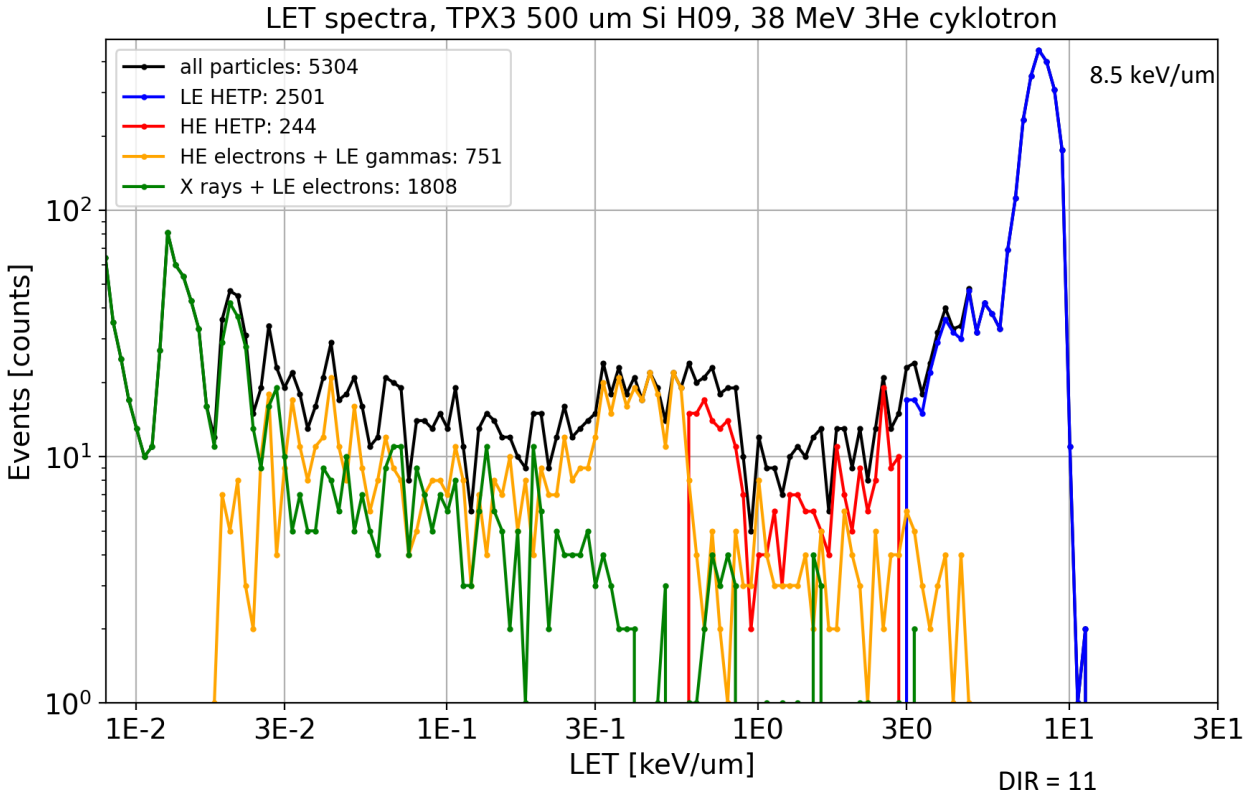
in solid state → long range = 880 µm in Si

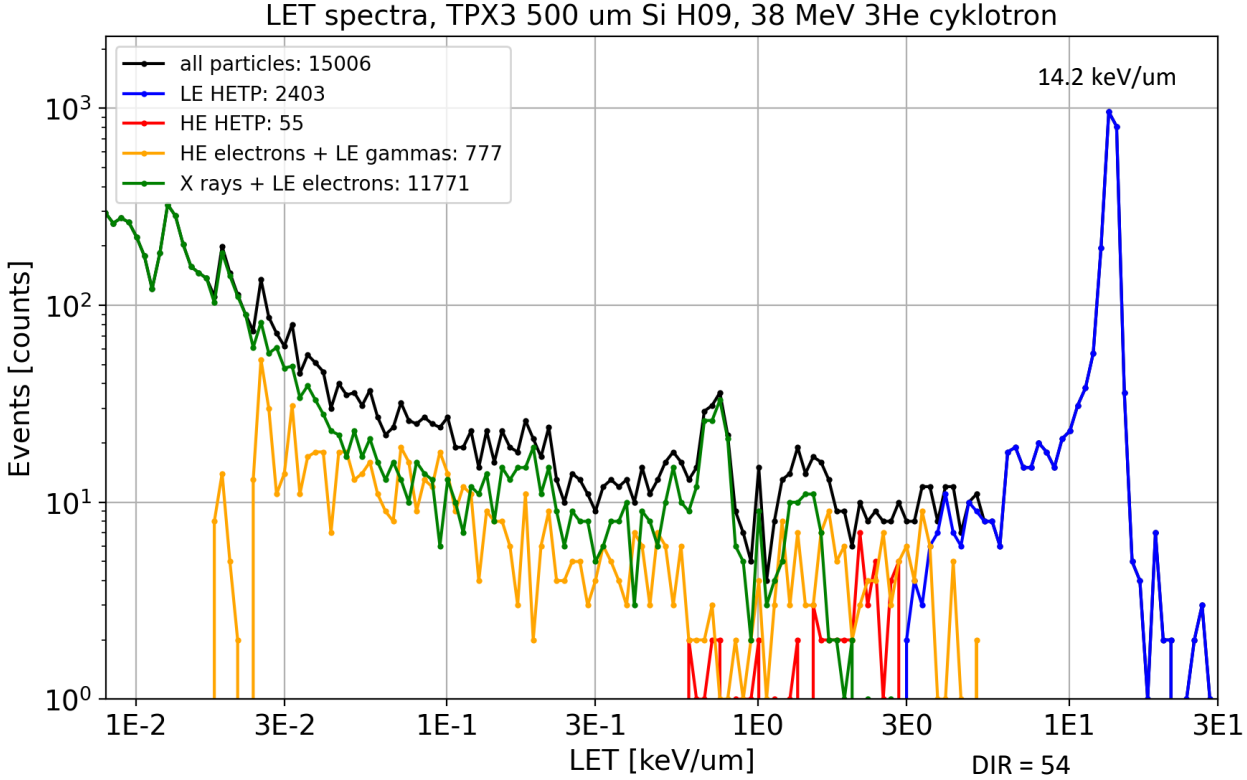
in solid state → high LET = 27.2 keV/µm in Si

SPECTROMETRY (LET SPECTRA) + DECOMPOSITION









Heavy charged particles: 38 MeV ^{3}He ions at 60^0

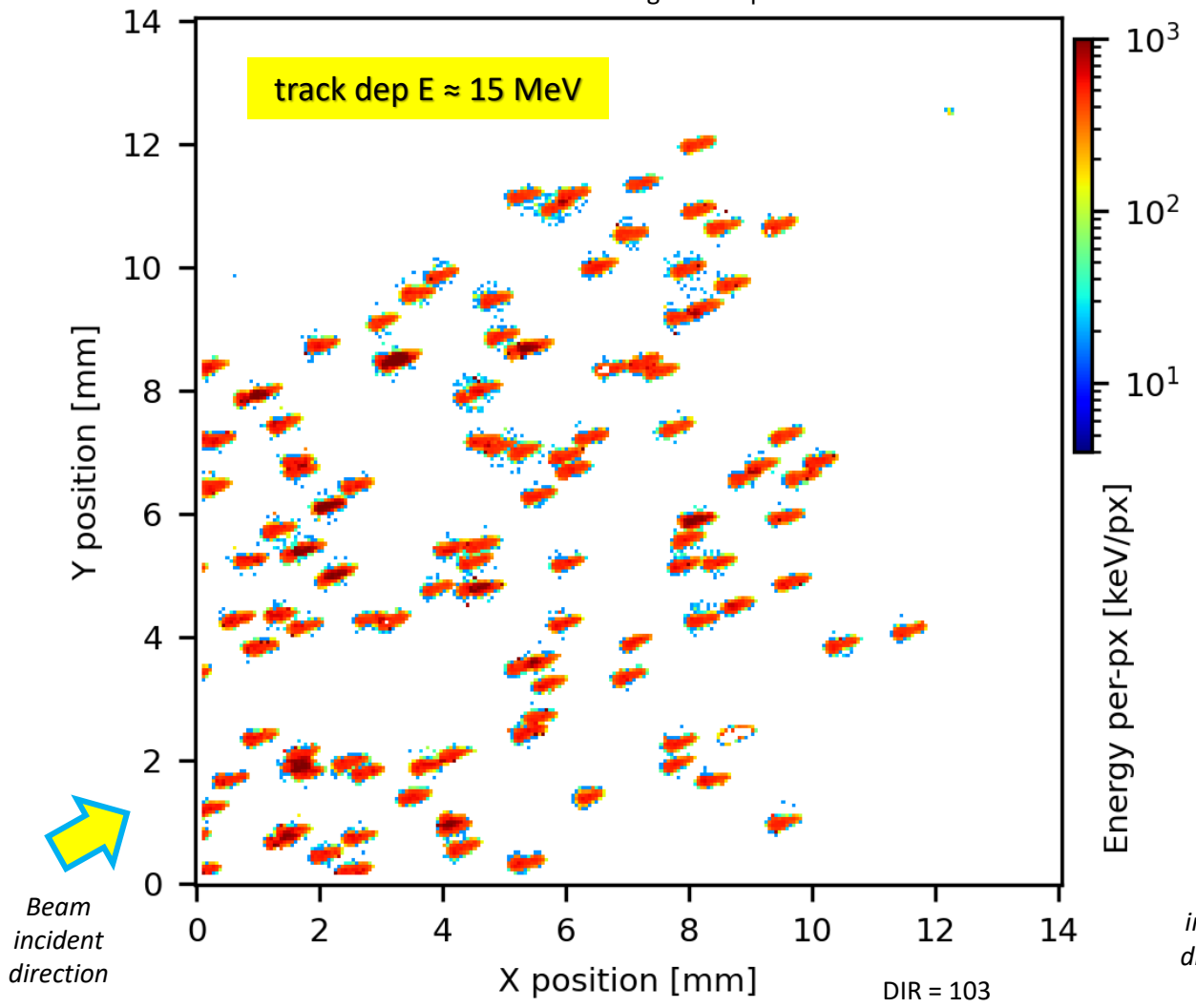
Carlos, Advacam, 2019

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@ Light ion cyclotron, Nucl. Phys. Inst., CZ Acad. Sci. Rez/CZ

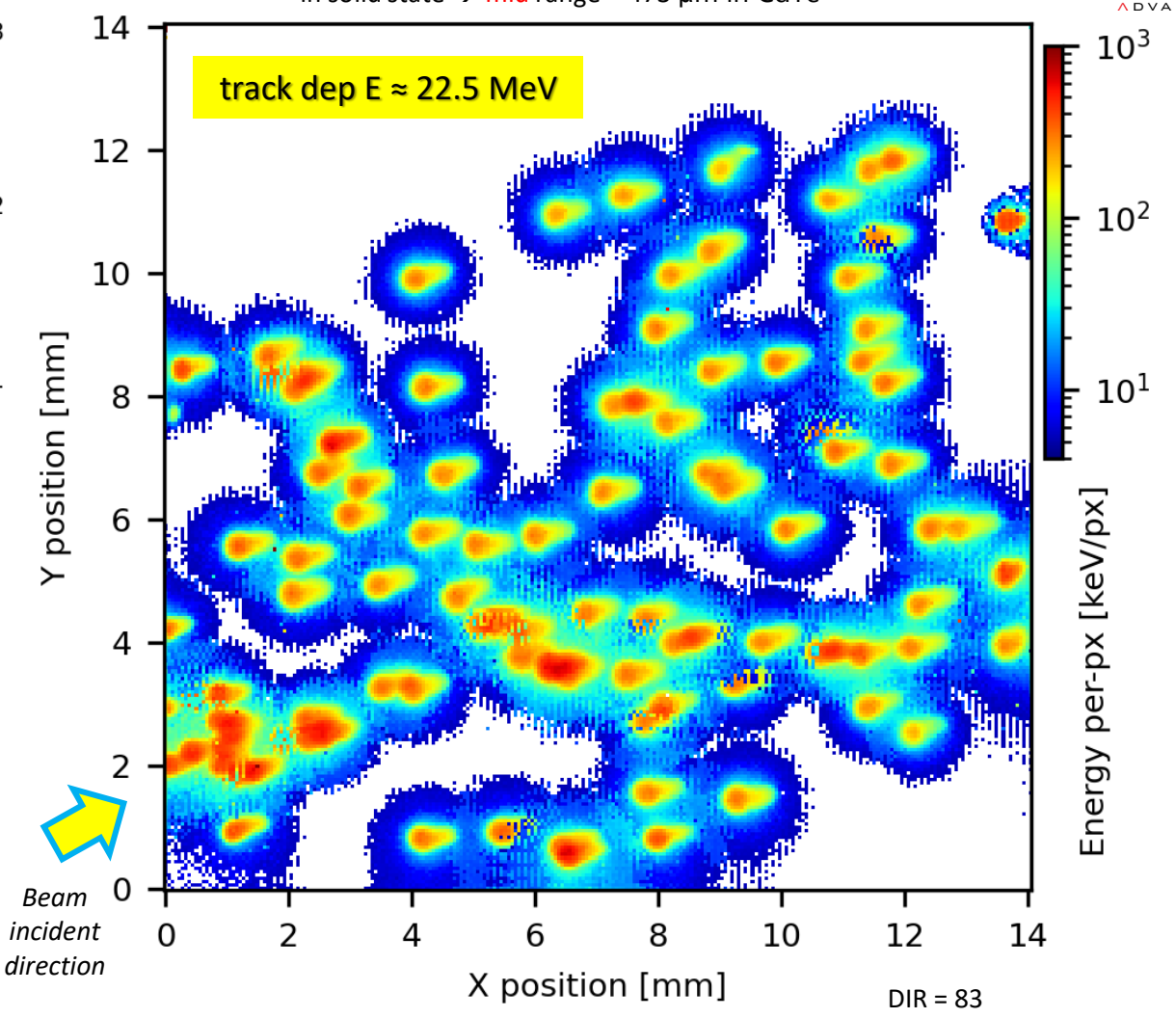
GaAs 500 um TPX3 AdvaPix RO

in solid state → mid range = 470 µm in Si



CdTe 2000 um TPX3 MiniPix RO

in solid state → mid range = 473 µm in CdTe



Heavy charged particles: 38 MeV ^{3}He ions at 60^0

Carlos, Advacam, 2019

@ Light ion cyclotron, Nucl. Phys. Inst., CZ Acad. Sci. Rez/CZ

GaAs 500 um TPX3 AdvaPix RO

in solid state → mid range = 470 µm in Si

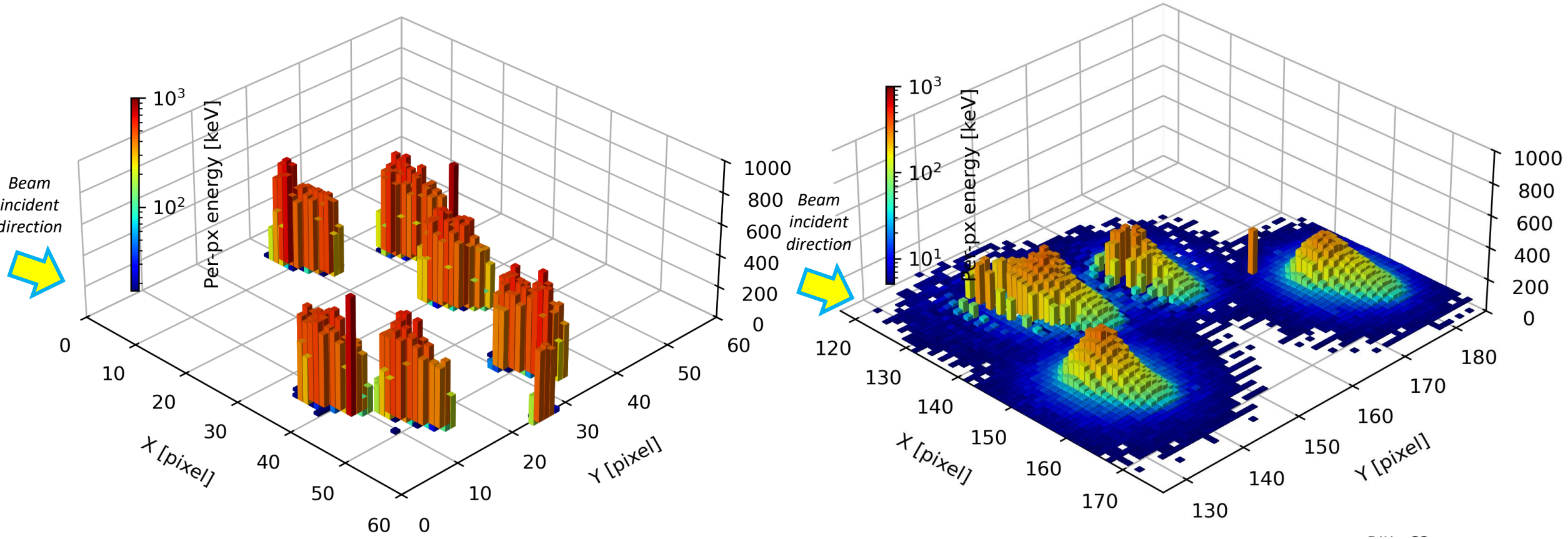
in solid state → high LET = 49 keV/µm in Si

CdTe 2000 um TPX3 MiniPix RO

in solid state → mid range = 473 µm in CdTe

in solid state → high LET = 47 keV/µm in CdTe

SPECTROMETRY (DEP ENERGY) + DECOMPOSITION



Heavy charged particles: 38 MeV ^{3}He ions at 60^0

Carlos, Advacam, 2019

@ Light ion cyclotron, Nucl. Phys. Inst., CZ Acad. Sci. Rez/CZ

GaAs 500 um TPX3 AdvaPix RO

in solid state → mid range = 470 μm in Si

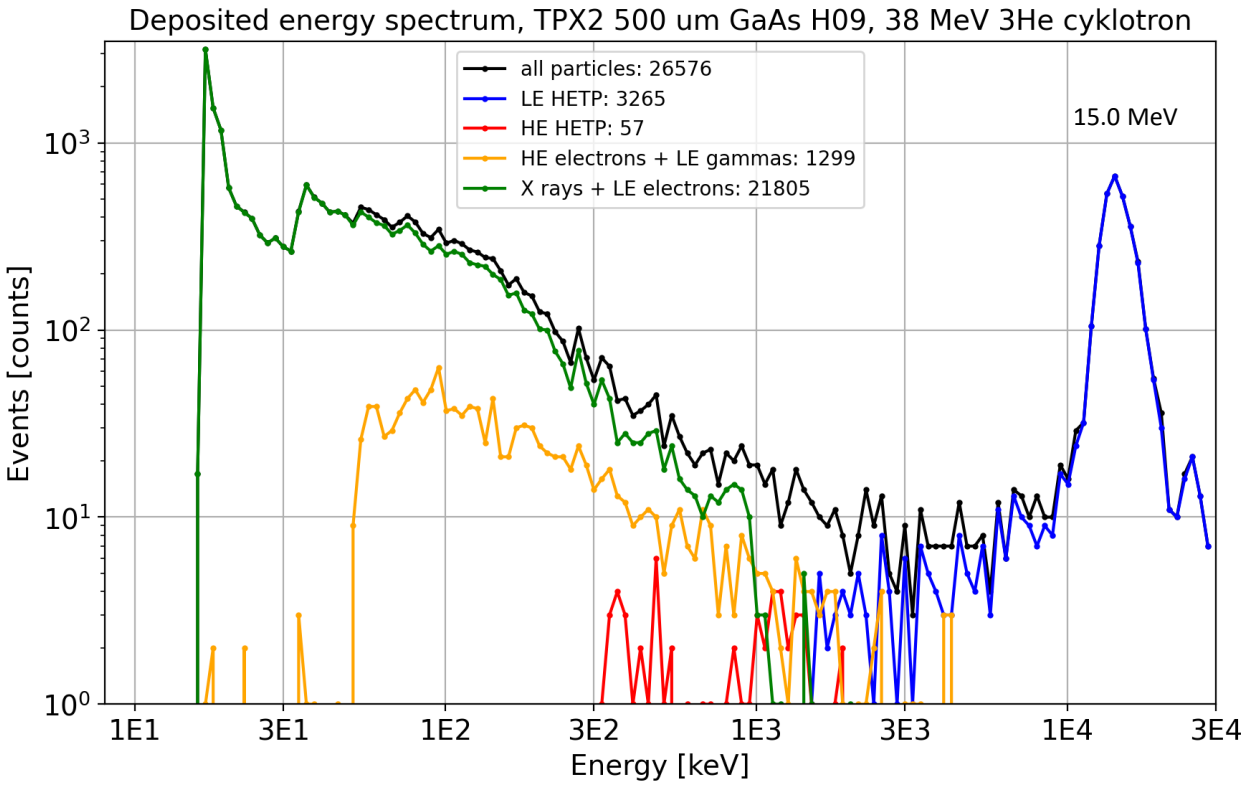
in solid state → high LET = 49 keV/μm in Si

CdTe 2000 um TPX3 MiniPix RO

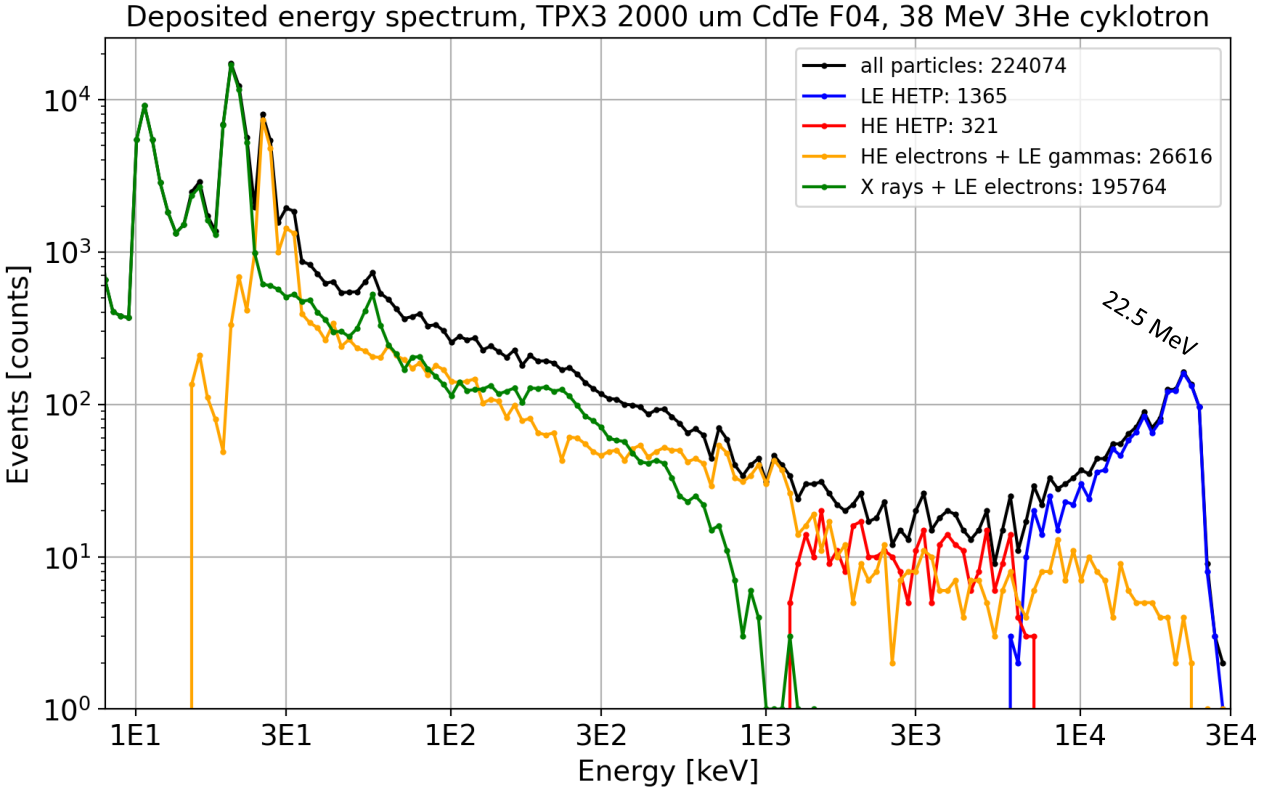
in solid state → mid range = 473 μm in CdTe

in solid state → high LET = 47 keV/μm in CdTe

SPECTROMETRY (DEP ENERGY) + DECOMPOSITION



DIR = 103



DIR = 83

Heavy charged particles: 38 MeV ^{3}He ions at 60^0

Carlos, Advacam, 2019

@ Light ion cyclotron, Nucl. Phys. Inst., CZ Acad. Sci. Rez/CZ

GaAs 500 um TPX3 AdvaPix RO

in solid state → mid range = 470 μm in Si

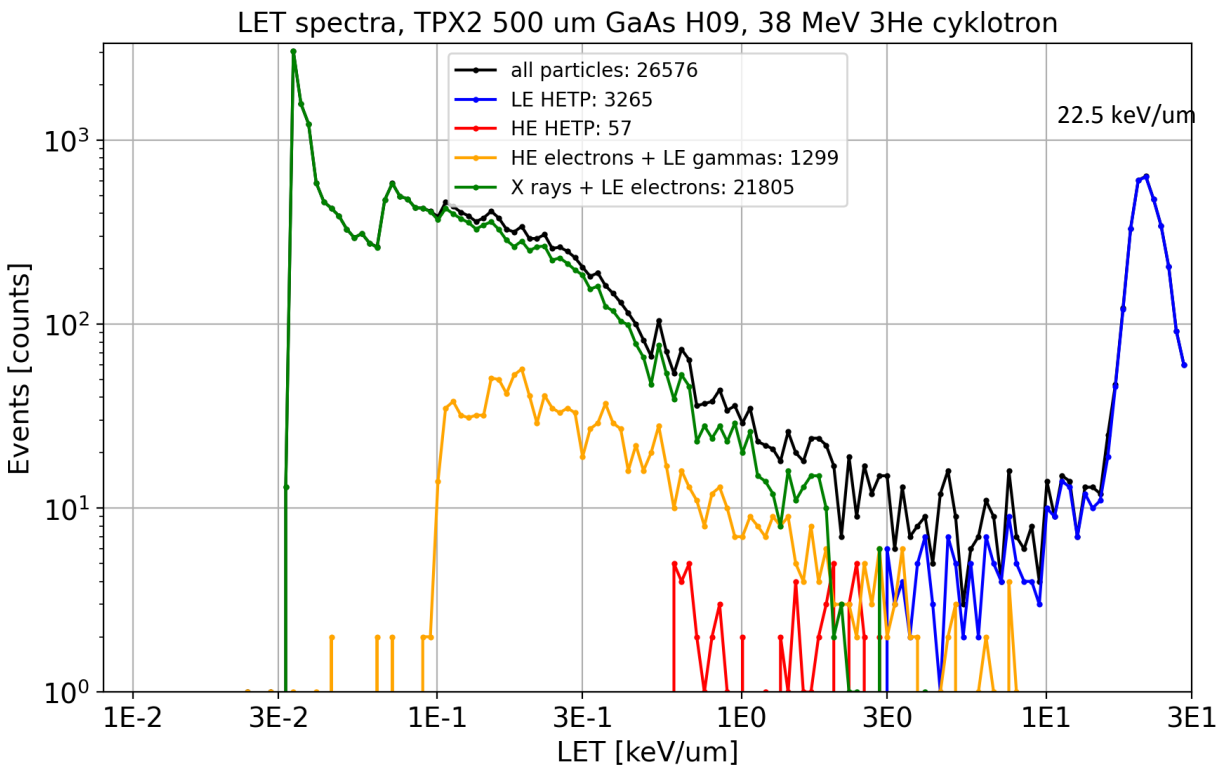
in solid state → high LET = 49 keV/μm in Si

CdTe 2000 um TPX3 MiniPix RO

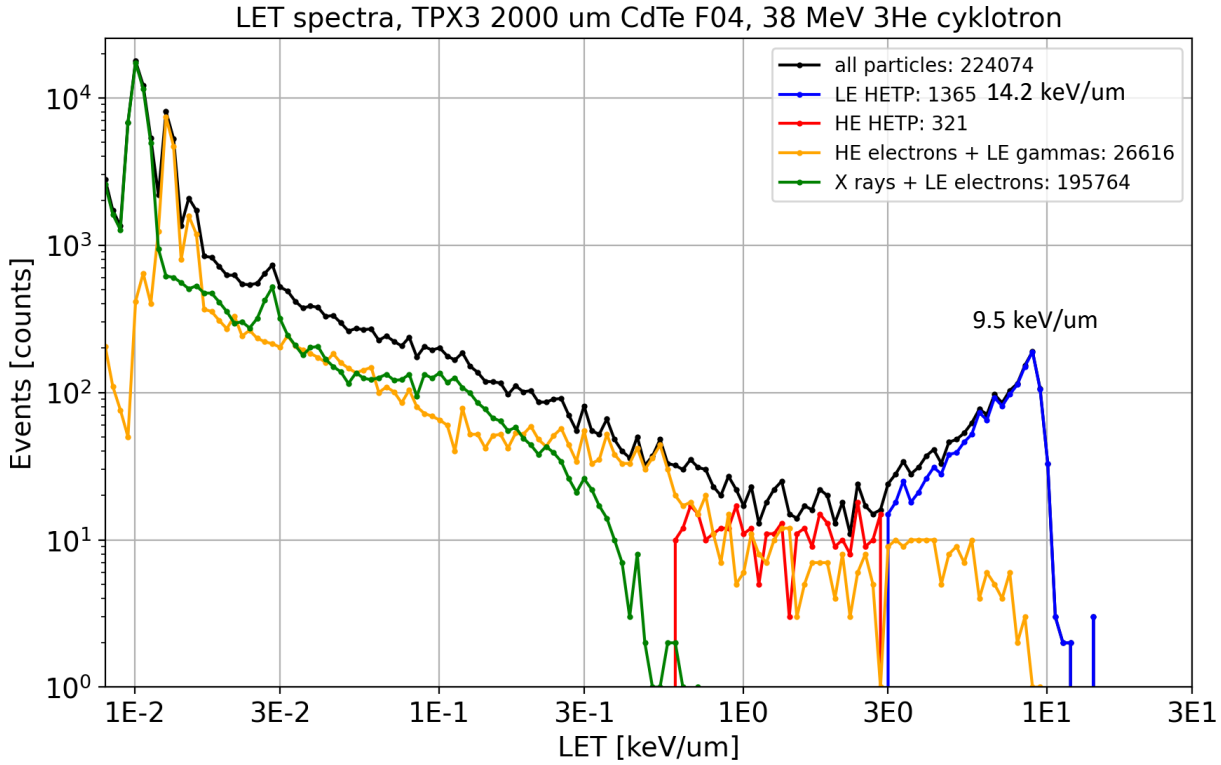
in solid state → mid range = 473 μm in CdTe

in solid state → high LET = 47 keV/μm in CdTe

SPECTROMETRY (LET SPECTRA) + DECOMPOSITION



DIR = 103

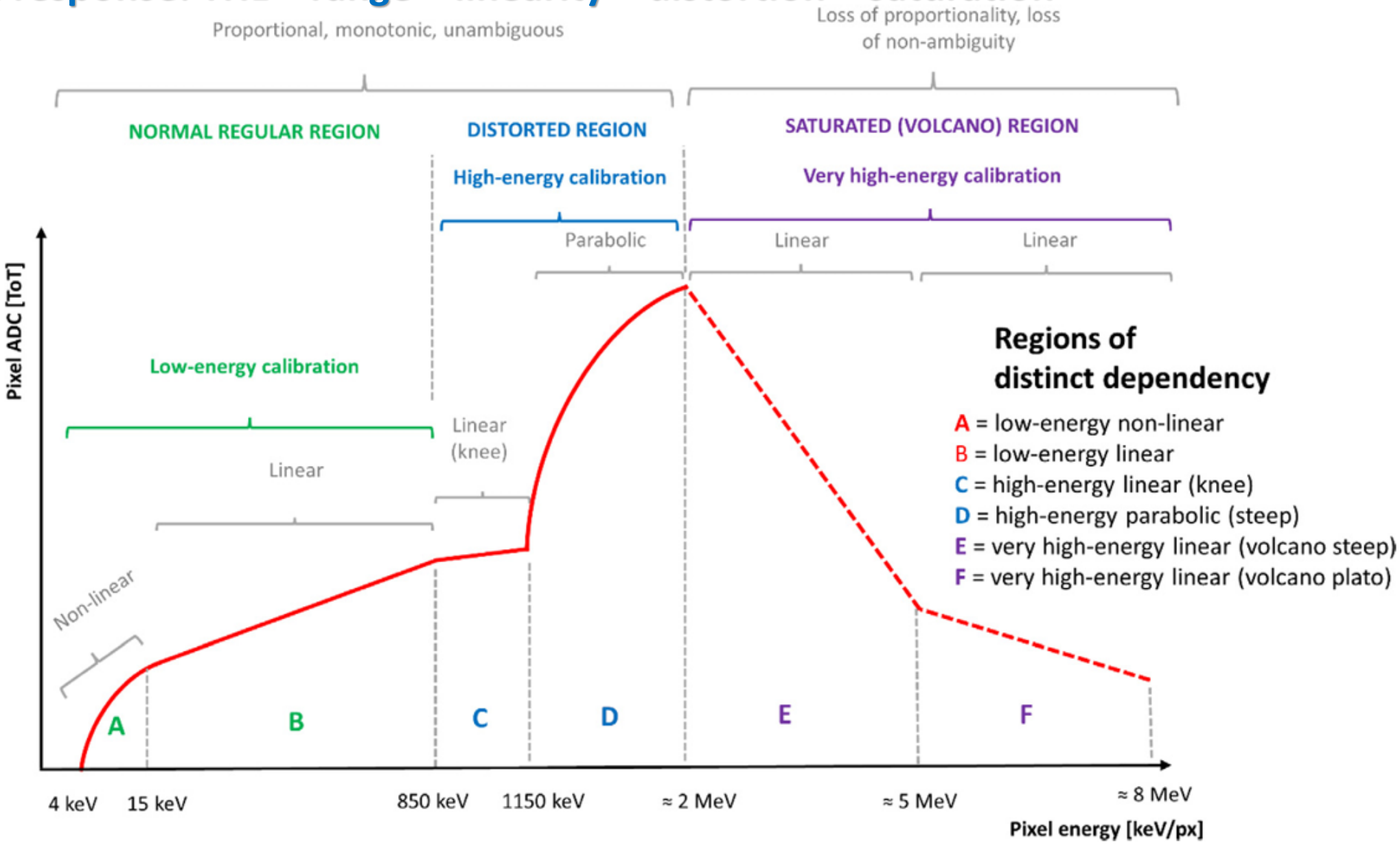


DIR = 83

Radiation spectrometry: Si sensor on Timepix

Per-px spectral response: THL + range + linearity + distortion + saturation

M. Sommer, C. Granja, et al., ***High-energy per-pixel calibration of pixel detector Timepix with laboratory alpha source***, NIM-A 1022 (2022) 165957



Light charged particles: electrons 22 MeV

Light ion cyclotron accelerator, Nucl. Phys. Inst., CZ Acad. Sci. Rez n. Prague

Si, CdTe, GaAs, SiC Timepix/Timepix3

Chipboard + RO electronics MiniPIX Advacam

Radiation imaging, Particle tracking

Light charged particles: 22 MeV electrons at 60°

measured: Carlos, Advacam, 2023

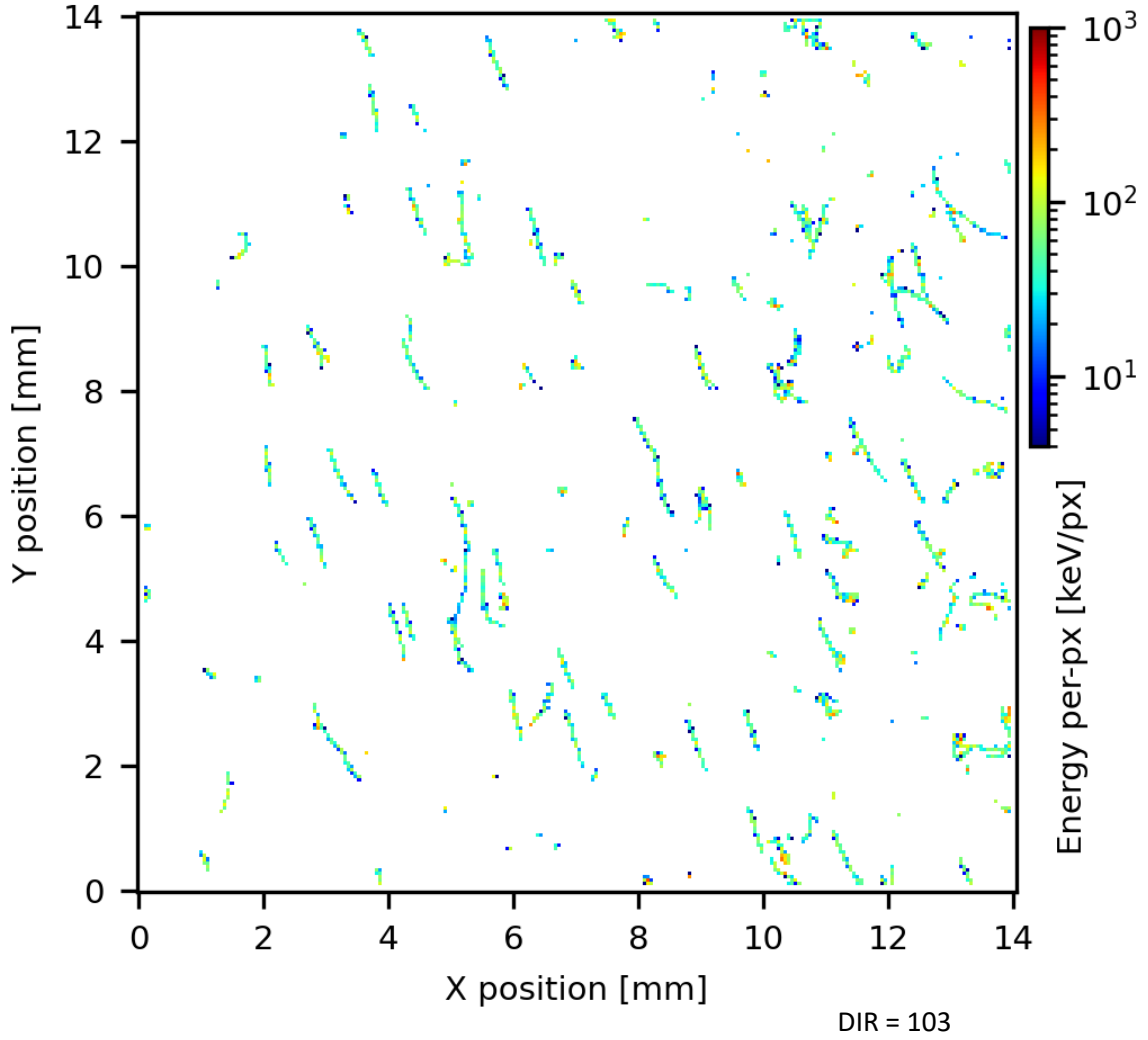
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The Czech Academy of Sciences

@ electron microtron accelerator, Nucl. Phys. Inst., CZ Acad. Sci. Rez/CZ

Beam incident direction

GaAs 500 um TPX3

MiniPix RO

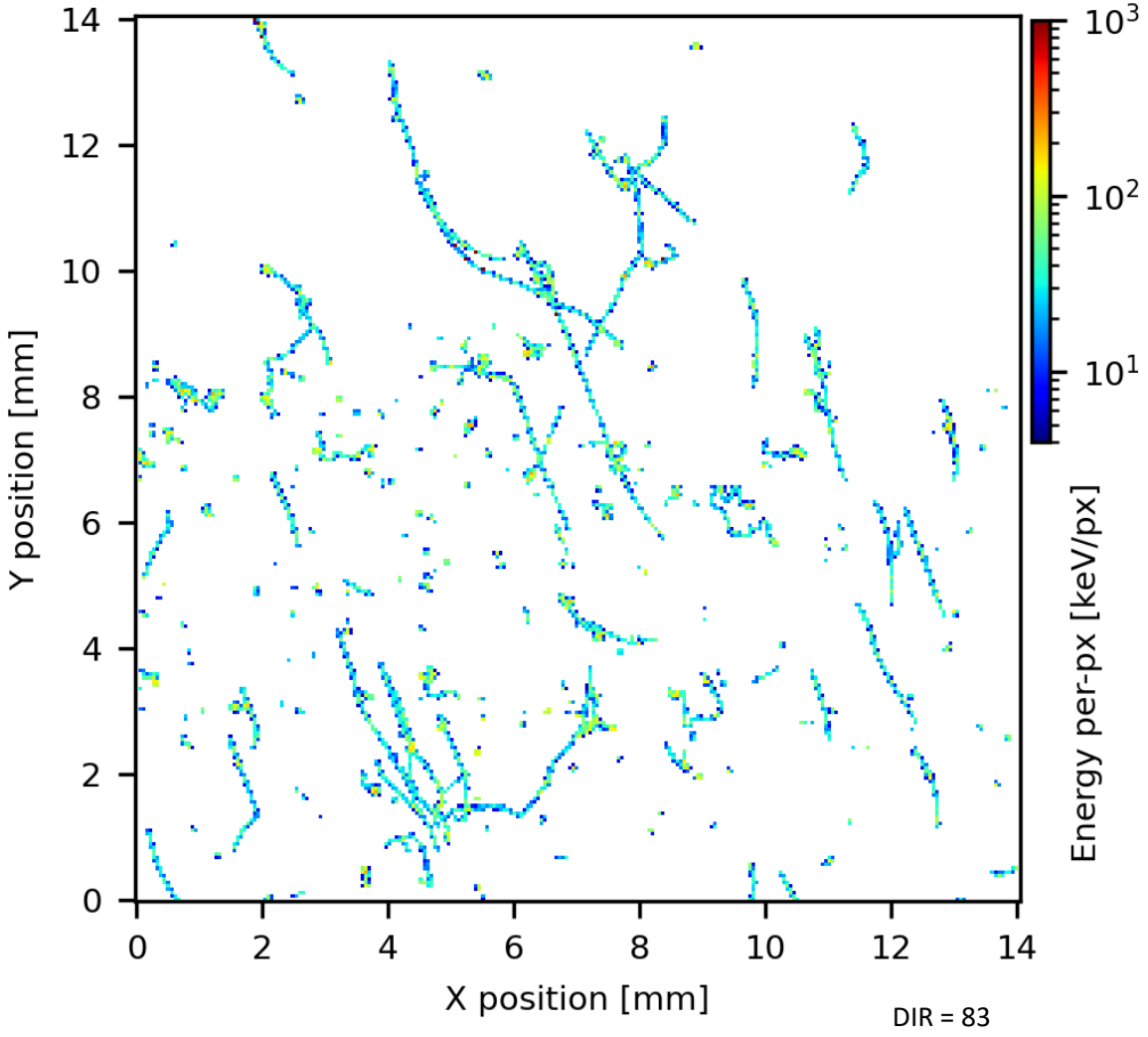


DIR = 103

Beam incident direction

CdTe 2000 um TPX3

MiniPix RO



DIR = 83

Light charged particles: 22 MeV electrons at 60^0

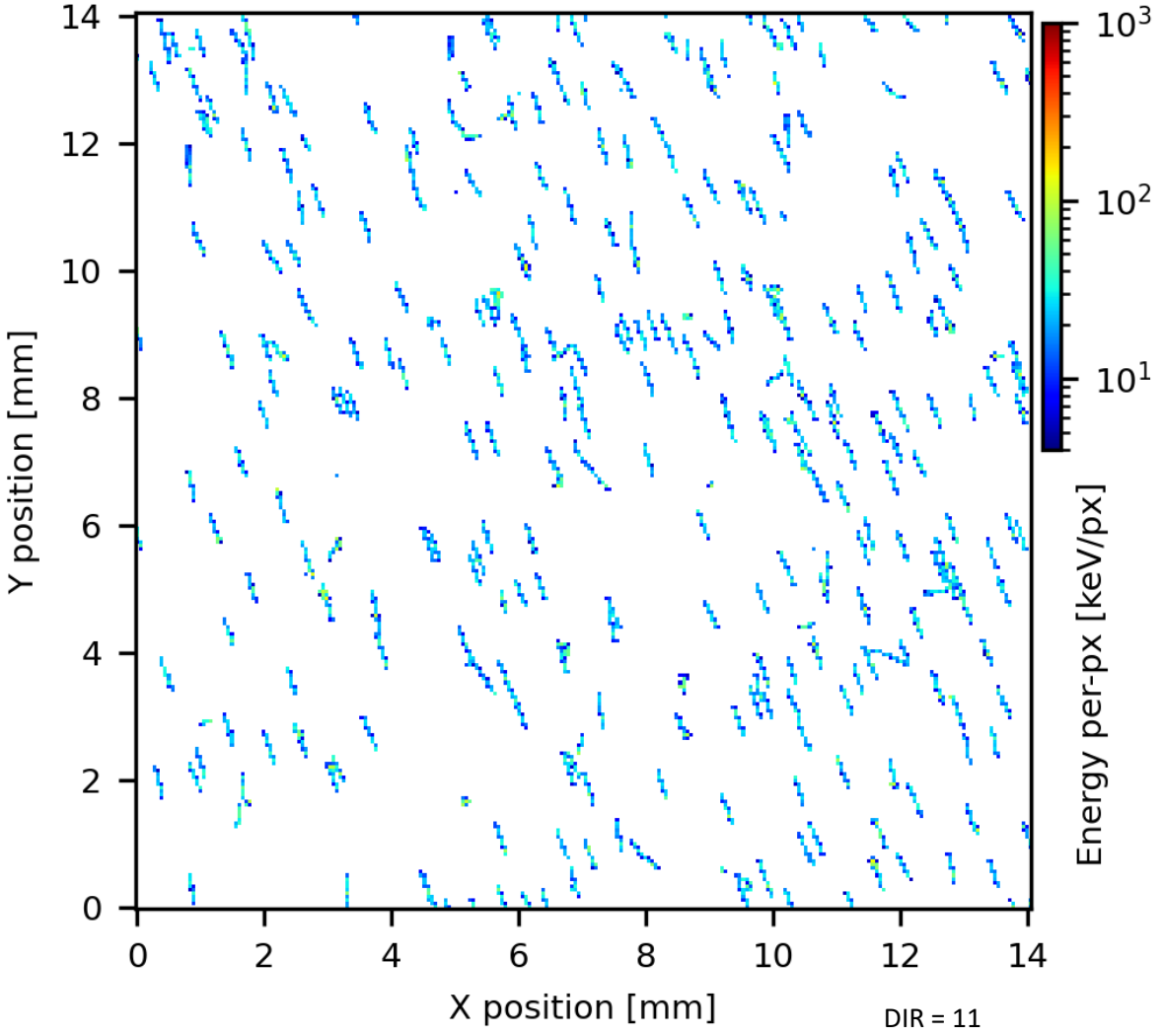
measured: Carlos, Advacam, 2023

NUCLEAR PHYSICS INSTITUTE
The Czech Academy of Sciences

Beam incident direction

Si 500 um TPX2

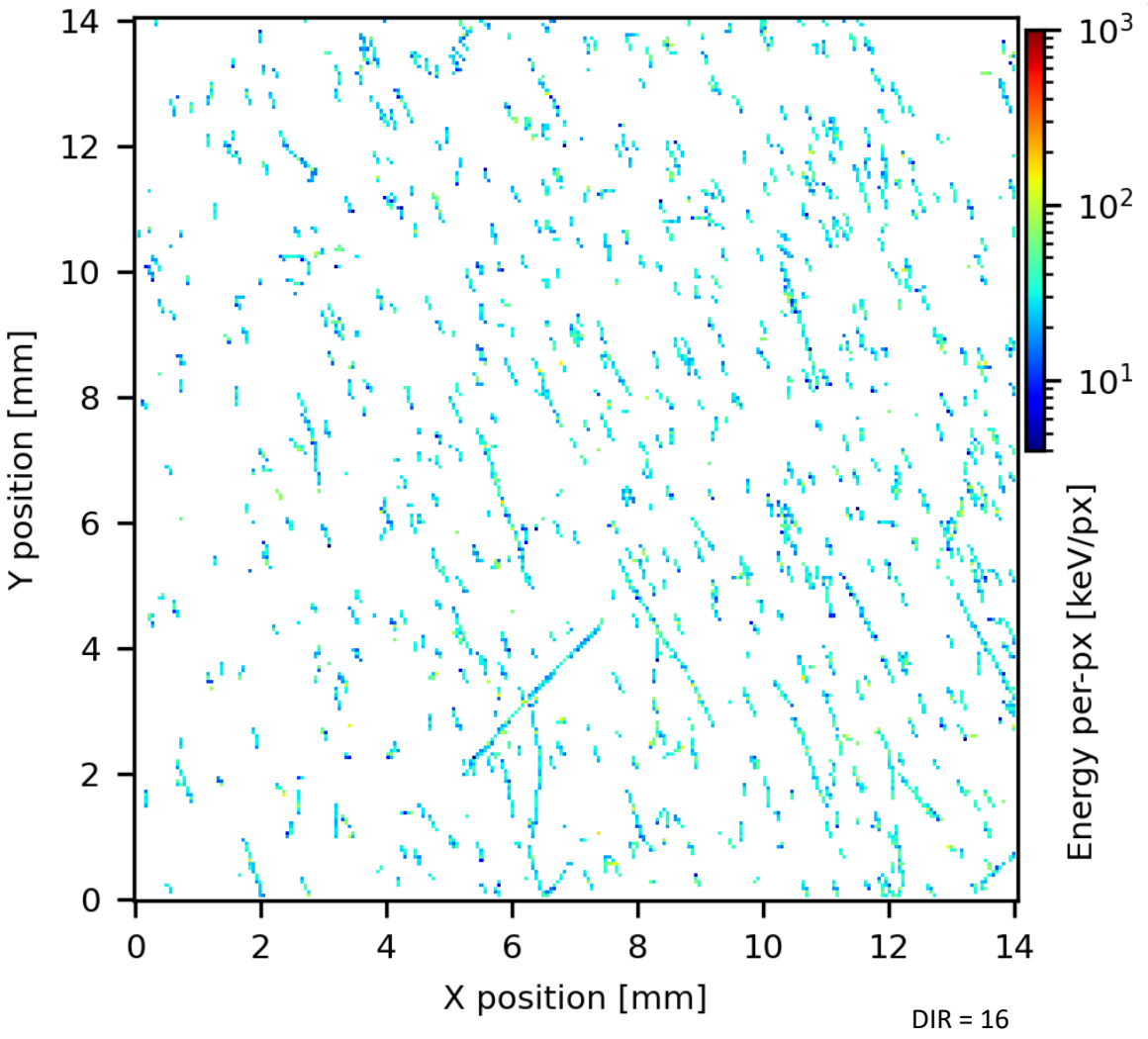
MiniPix RO



Beam incident direction

SiC 65 um TPX3

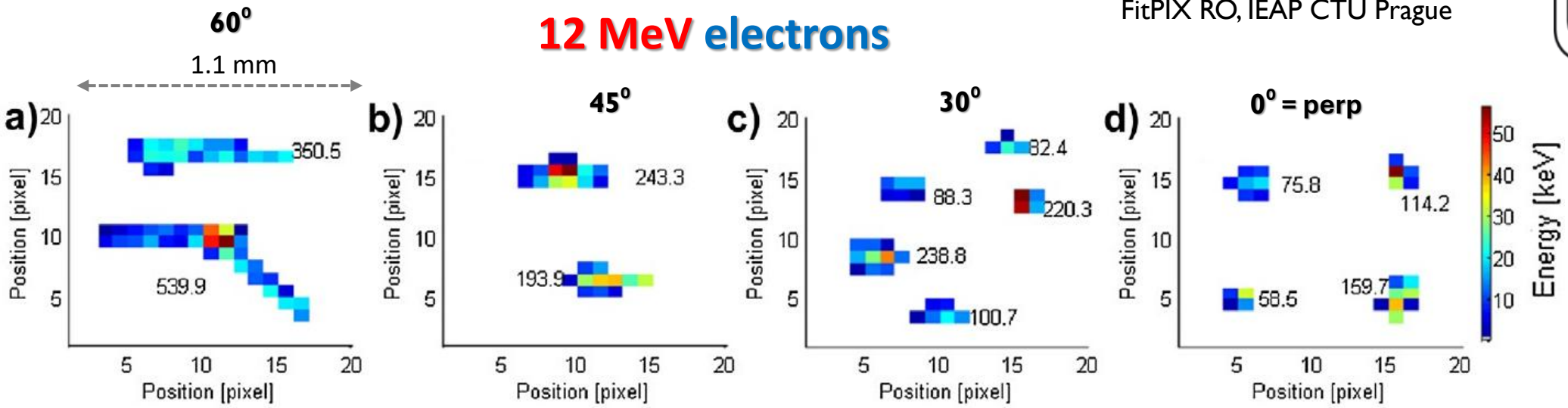
MiniPix RO



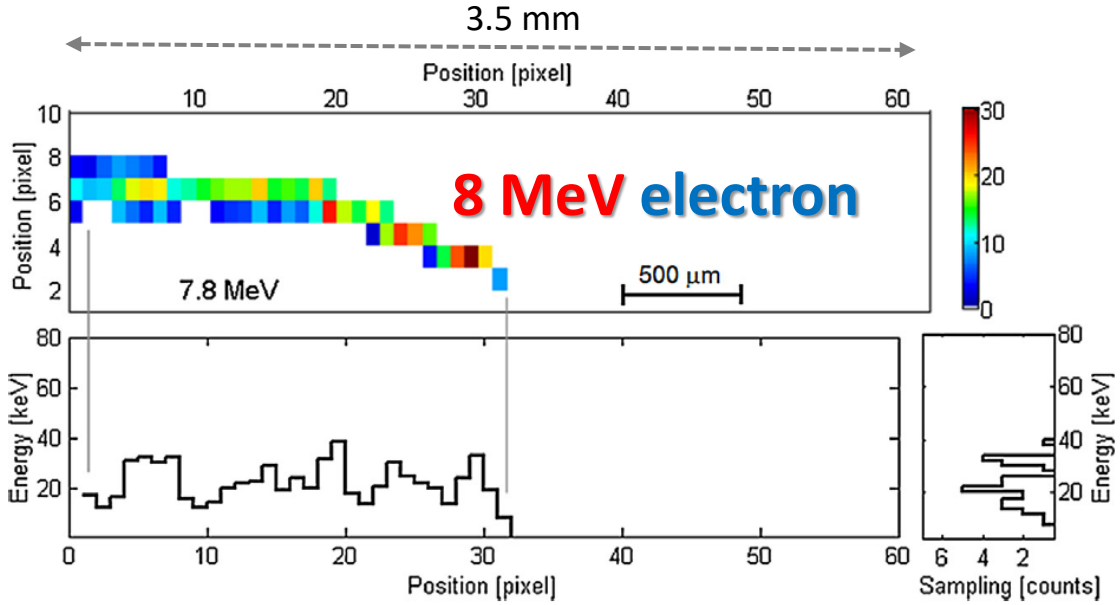
Light charged particles: fast electrons Si 300 um TPX

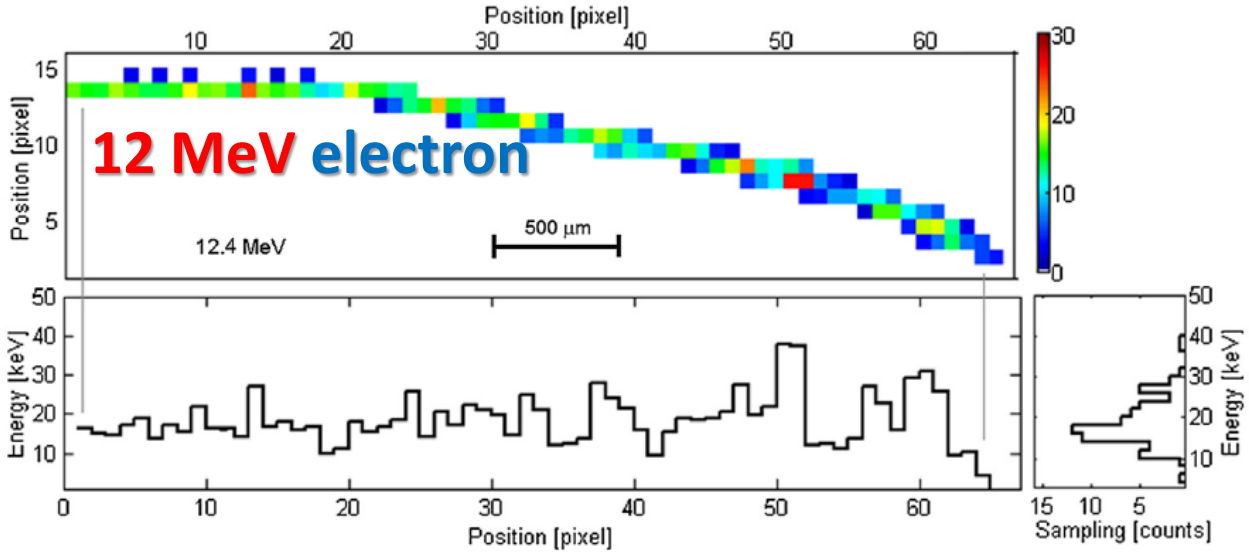
FitPIX RO, IEAP CTU Prague

12 MeV electrons



C. Granja, et al., ***Energy loss and online directional track visualization of fast electrons with the pixel detector Timepix***, Rad. Meas. 59 (2013) 245-261



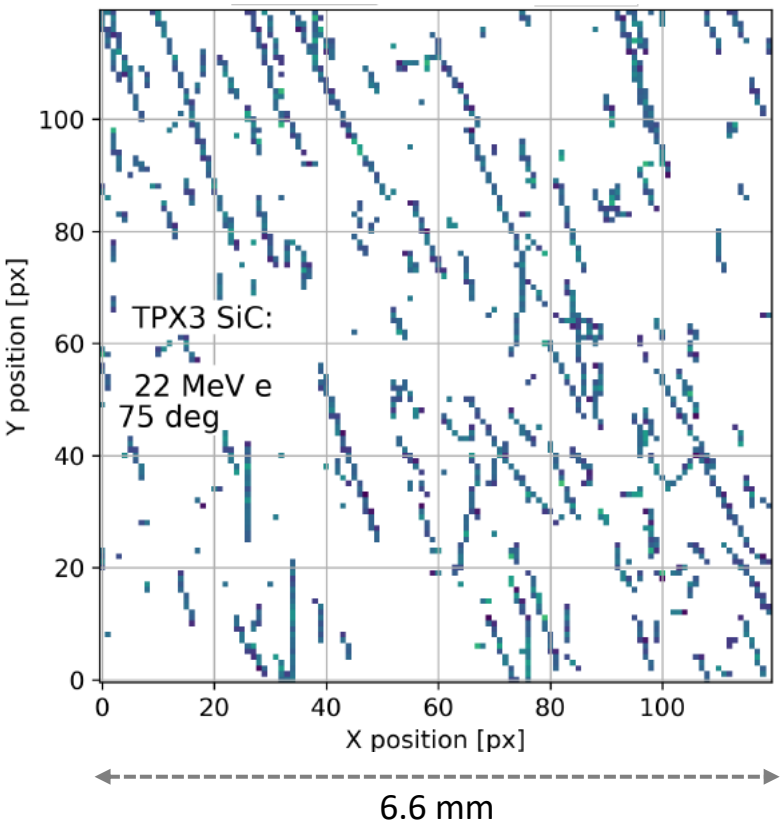


Electrons & protons: SiC 65 µm Timepix3

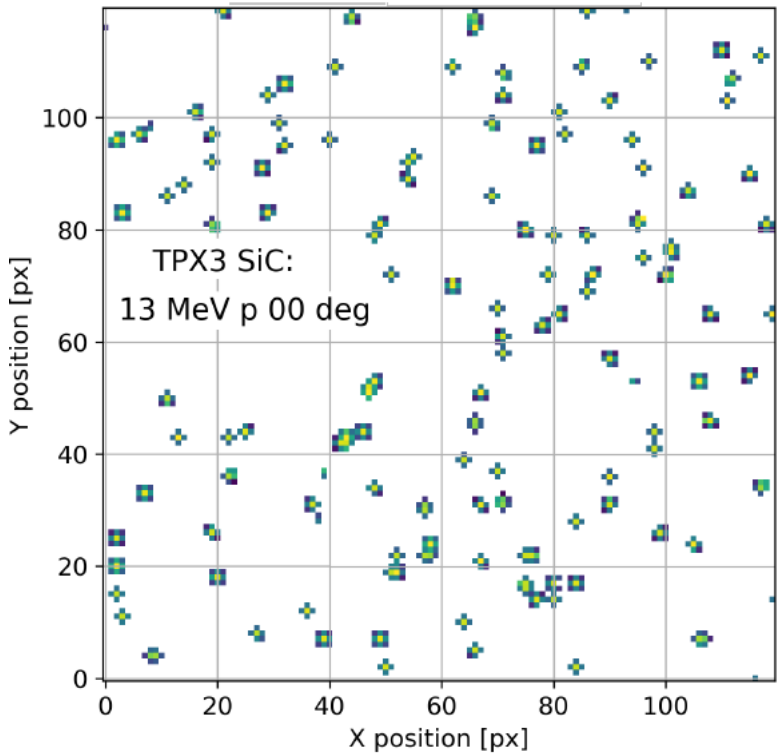
Radiation imaging, spectrometry, particle tracking

*C. Granja, et al., **Detection resolving power of SiC Timepix3 detector to electrons, neutrons, ions and protons**, JINST 19 (2024) C11007*

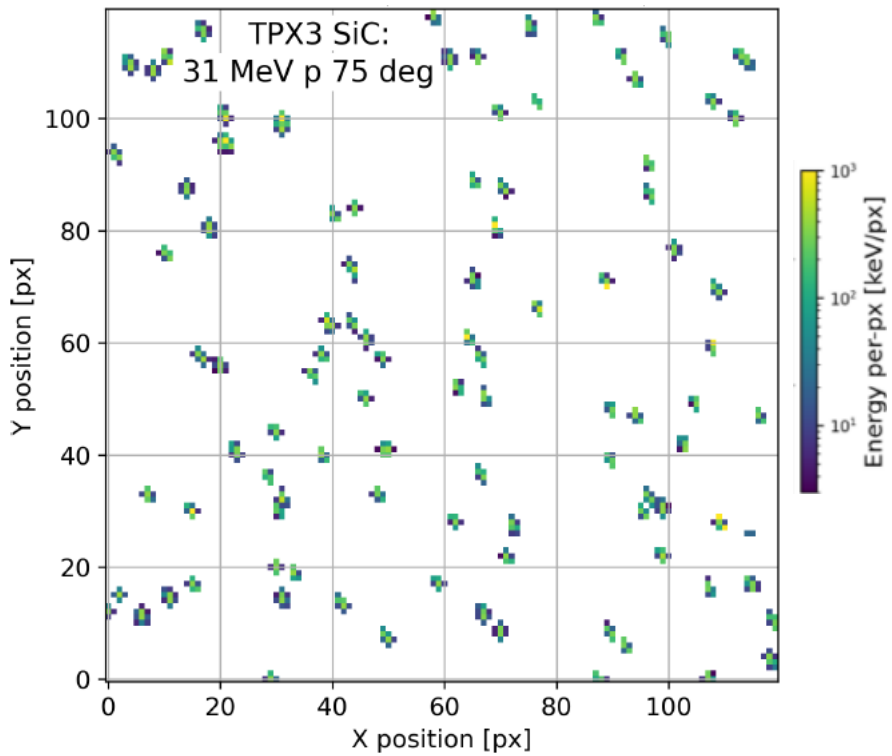
22 MeV electrons



13 MeV protons

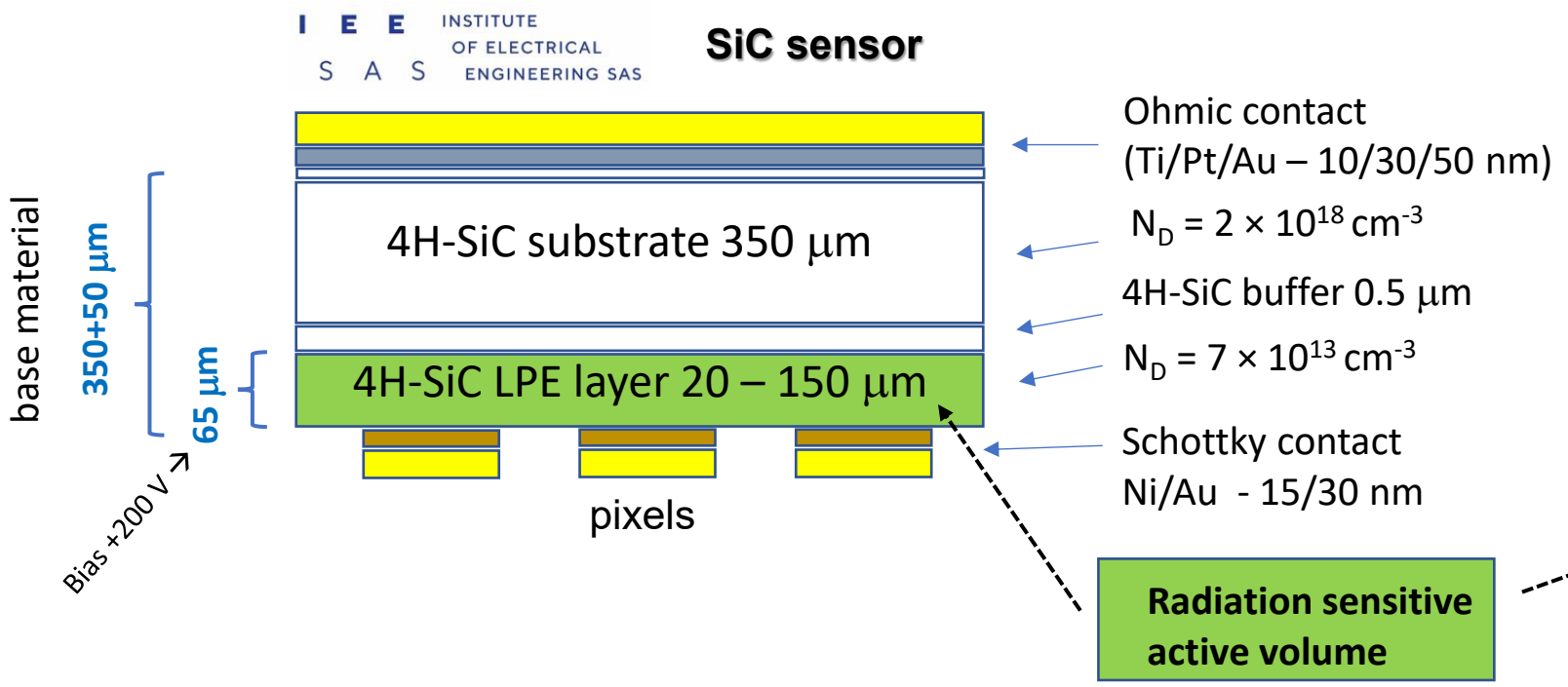


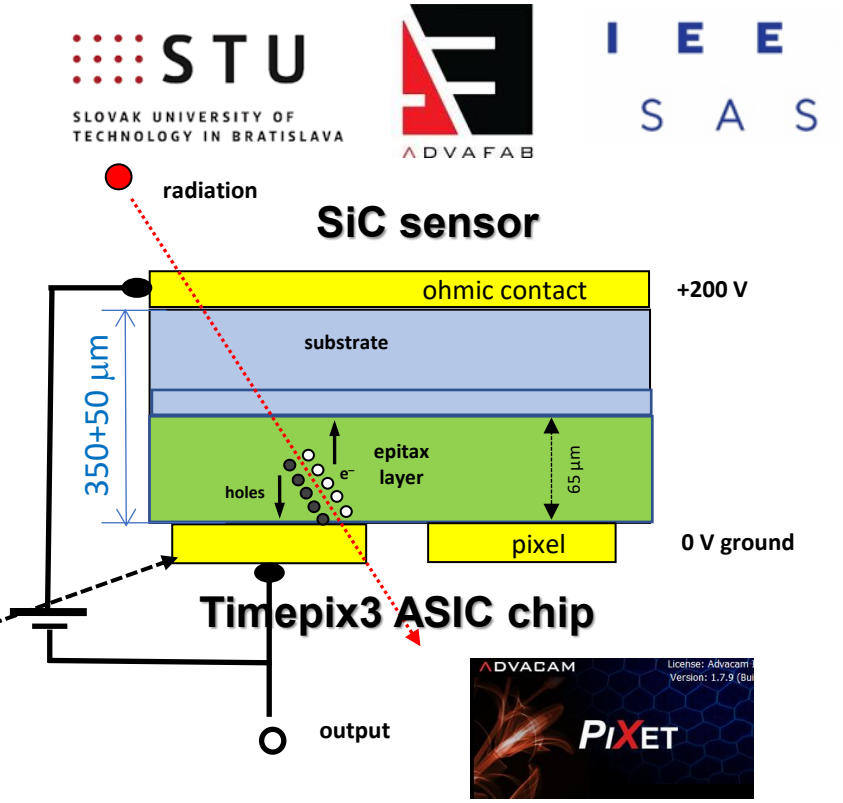
31 MeV protons



Silicon Carbide Timepix3 MiniPIX Radiation Camera

B. Zatko, A. Sagatova
J. Jakubek, S. Polansky, J. Kalliopuska





B. Zatko, A. Sagatova, et al., ***From a single silicon carbide detector to pixelated structure for radiation imaging camera***, JINST 17 (2022) C12005

SiC sensor, Schottky contact, EPITAX layer
Depletion thickness 65 um
on applied bias +200 V

ADVACAM
Imaging the Unseen

MiniPIX TPX3 SiC sensor
per-px Energy calibrated
ADVACAM, J. Jakubek, S. Polansky

ADVACAM



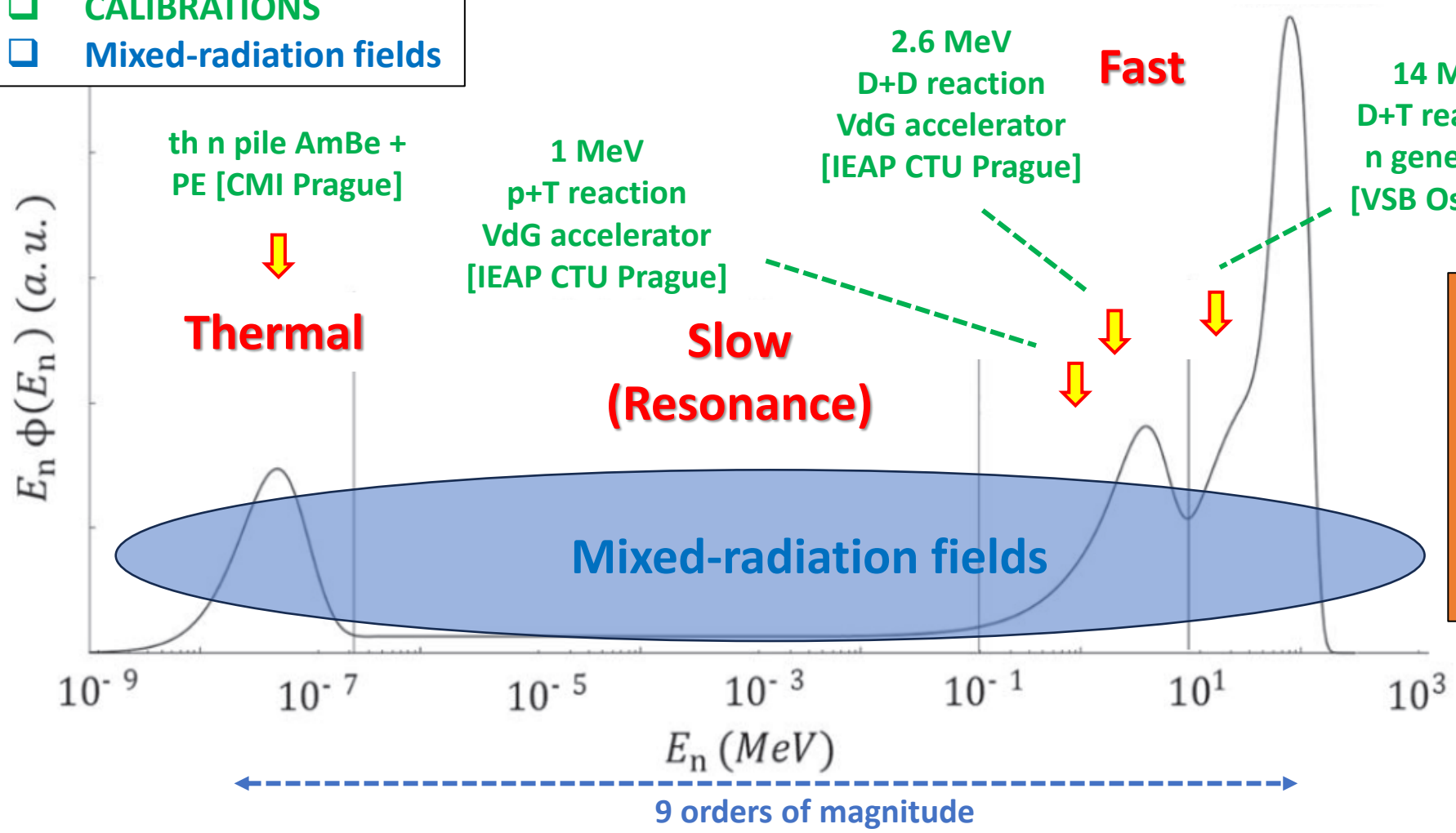
Wed POSTER # 398 B. Zatko **SiC** sensor

Neutrons

Neutron fields: accelerators, radiotherapy, outer space

Energy spectrum, wide range: 9 orders of magnitude → challenge

- ❑ CALIBRATIONS
- ❑ Mixed-radiation fields



Neutrons
- Interact **indirectly**
- Strong dependance on the sensor **material type** i.e. composition (isotopic)

Neutron spectrum at particle/proton radiotherapy environment

Neutrons: fast, thermal

Neutron generator D-T, VSB-Tech. Univ. Ostrava / CZ
Van-de-Graaff accelerator, FLNP, JINR Dubna / RU
Thermal neutron pile/AmBe, CZ Metrology Inst. Prague / CZ

Si, SiC, GaAs Timepix/Timepix3

Chipboard + RO electronics MiniPIX Advacam

Neutron converter mask: ^{6}Li, ^{10}B

$^{6}Li(n,\alpha)^{3}H$, Q = 4.78 MeV
$^{10}B(n,\alpha)^{7}Li$, Q = 2.31 MeV

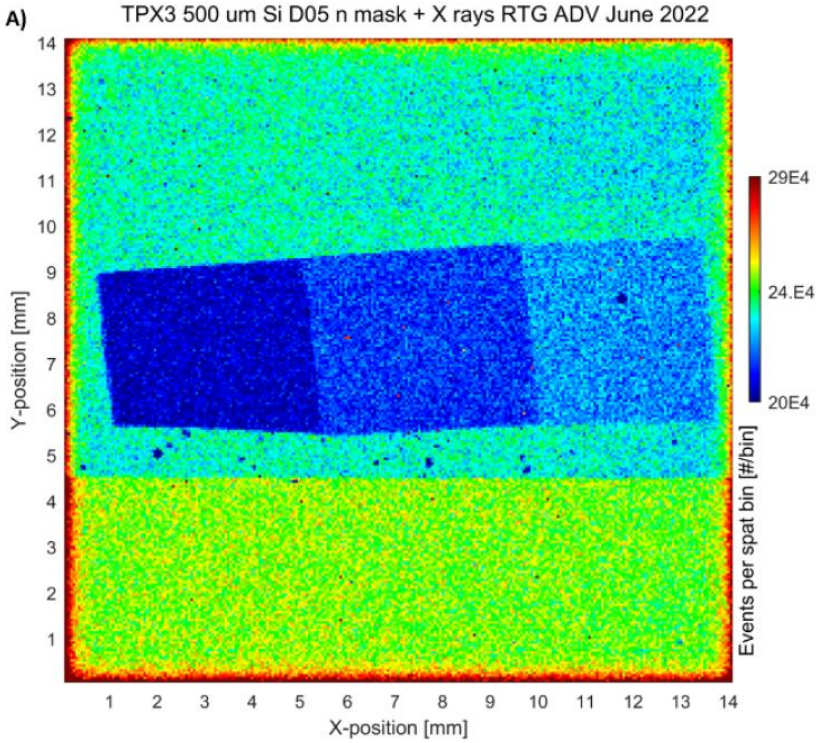
Radiation imaging, Particle tracking

Detection of neutrons (fast, thermal)

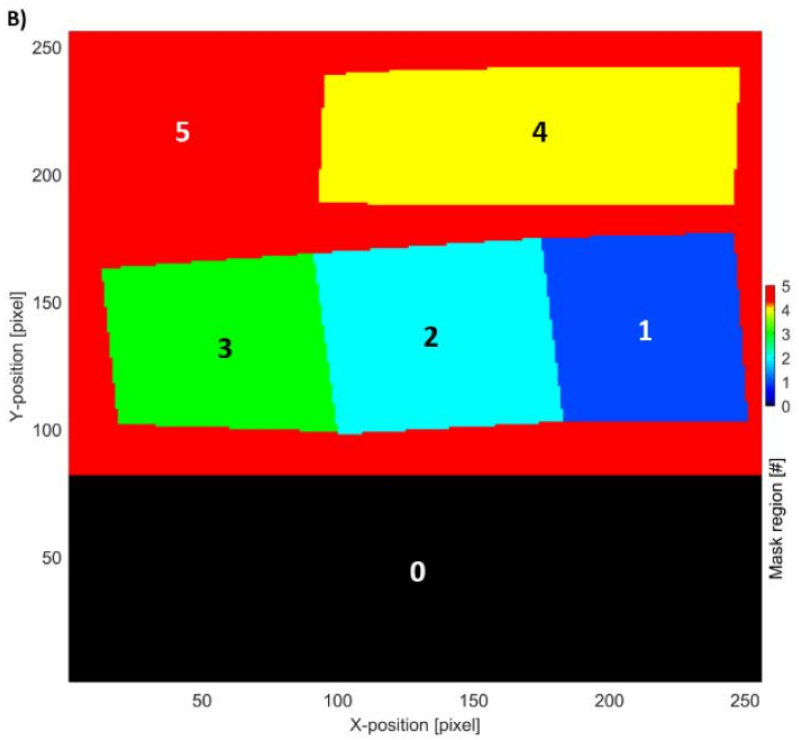
C. Granja, J. Jakubek, et al., *Detection of fast neutrons with the pixel detector Timepix3*, J. of Instrumentation JINST 18 (2023) P01003

ADVACAM * Imaging the Unseen

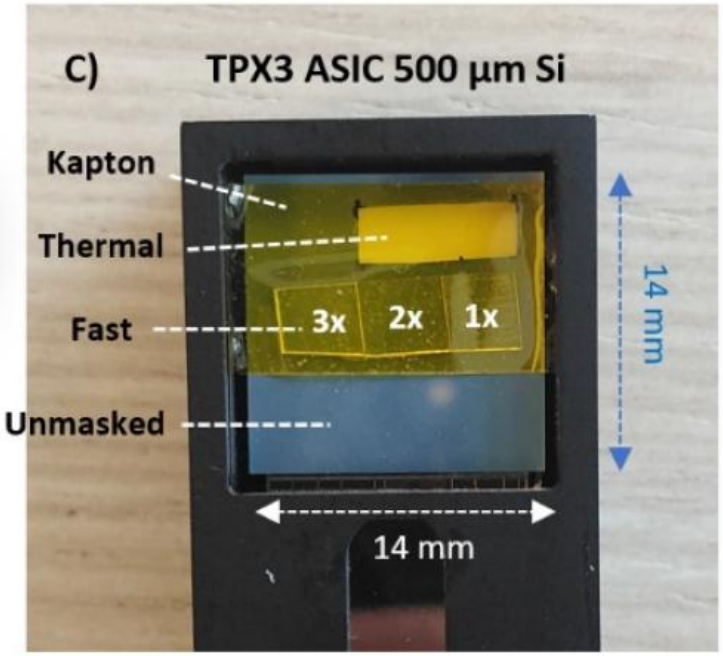
Radiation Camera MiniPIX Timepix3 Si sensor + neutron mask (thermal, fast)



X ray radiography



Neutron mask



Timepix3 + Si sensor + Neutron mask

Neutron mask segmented regions

Label	Material	Thickness	# of px	Area [%]	Area [cm^2]	Neutrons
0	—	—	20736	31.65	0.626	Fast BS
1	PE	50 µm	5080	7.75	0.153	Fast LE
2		100 µm	6016	9.18	0.182	
3		150 µm	5208	7.95	0.157	
4	^{6}LiF	≈ 1 µm	8150	12.44	0.246	Thermal
5	Kapton	10 µm	20346	31.05	0.615	Fast LE, BS

BS = broad spectrum

LE = low energy

Monoenergetic fast neutrons: 2.6 MeV, 14.1 MeV

Radiation imaging, spectrometry, particle tracking

C. Granja, P. Alexa, et al., ***Detection of fast neutrons with the pixel detector Timepix3***, J. of Instrumentation JINST 18 (2023) P01003

ADVACAM Imaging the Unseen

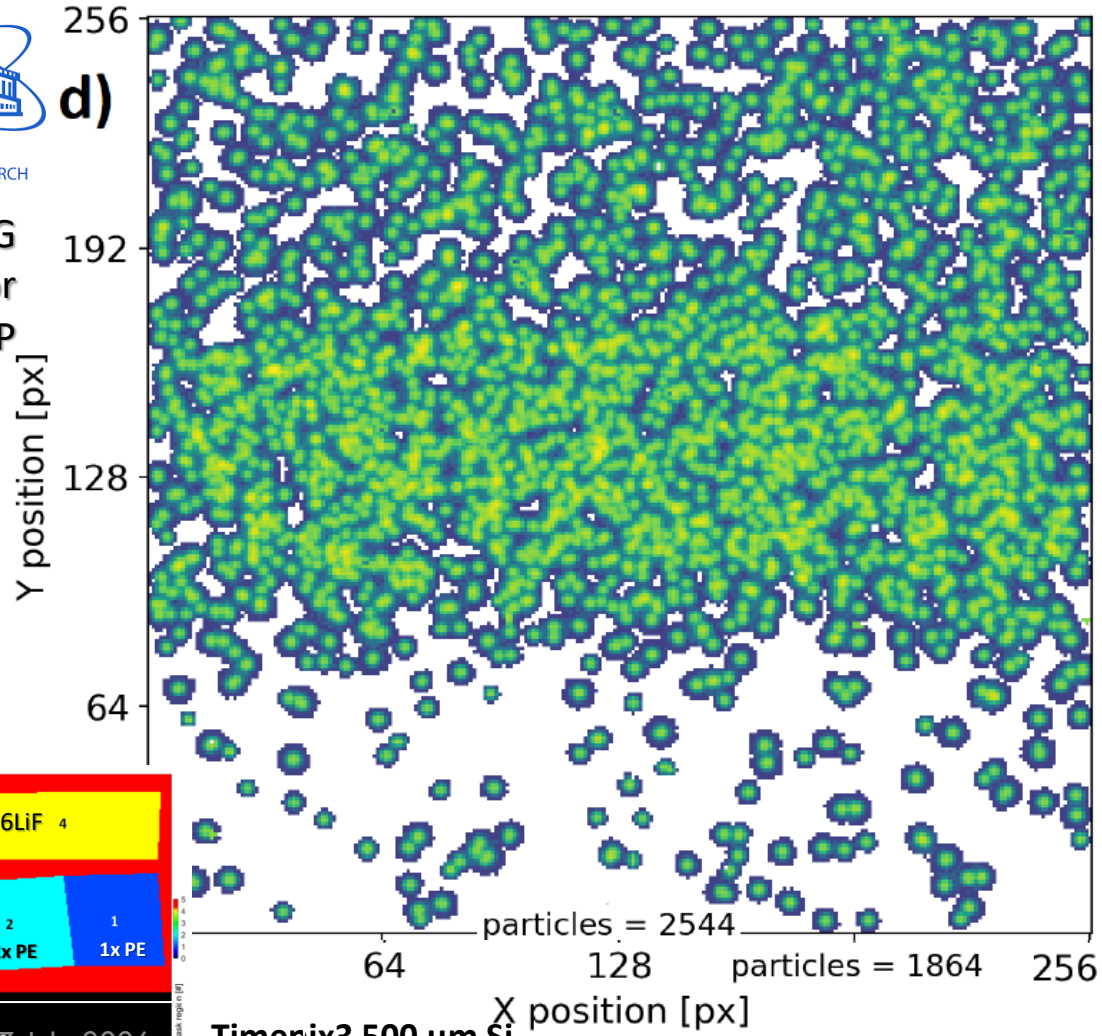
VSB TECHNICAL UNIVERSITY OF OSTRAVA

Radiation Camera MiniPIX Timepix3 Si sensor + neutron mask

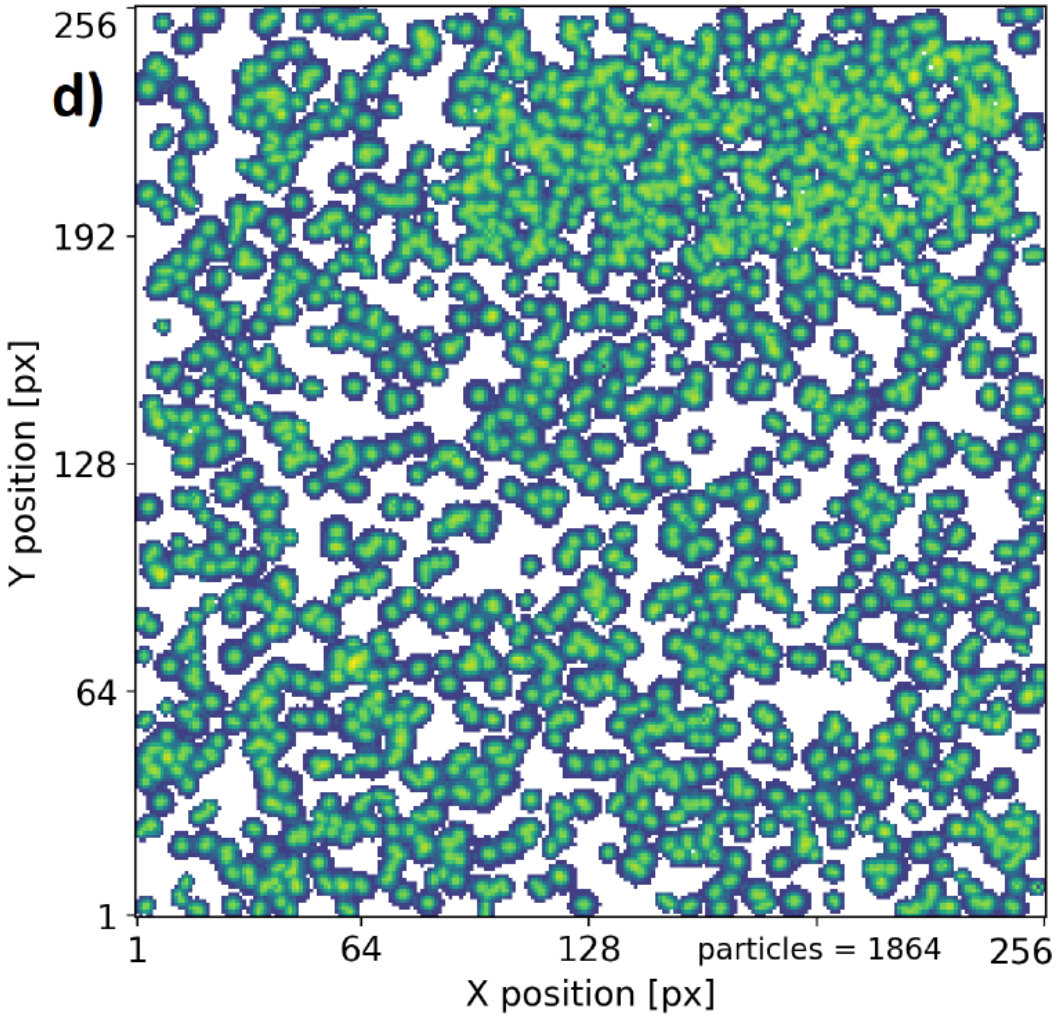
JOINT INSTITUTE FOR NUCLEAR RESEARCH

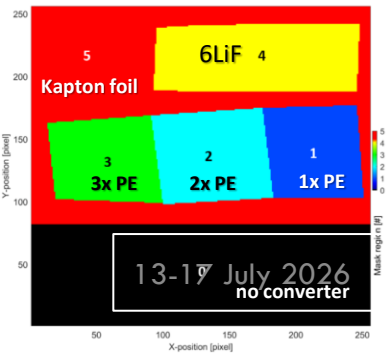
VdG accelerator JINR FLNP

D-D generator → 2.6 MeV n: HETP tracks



D-T generator → 14.1 MeV n + th n: HETP





Timepix3 500 µm Si

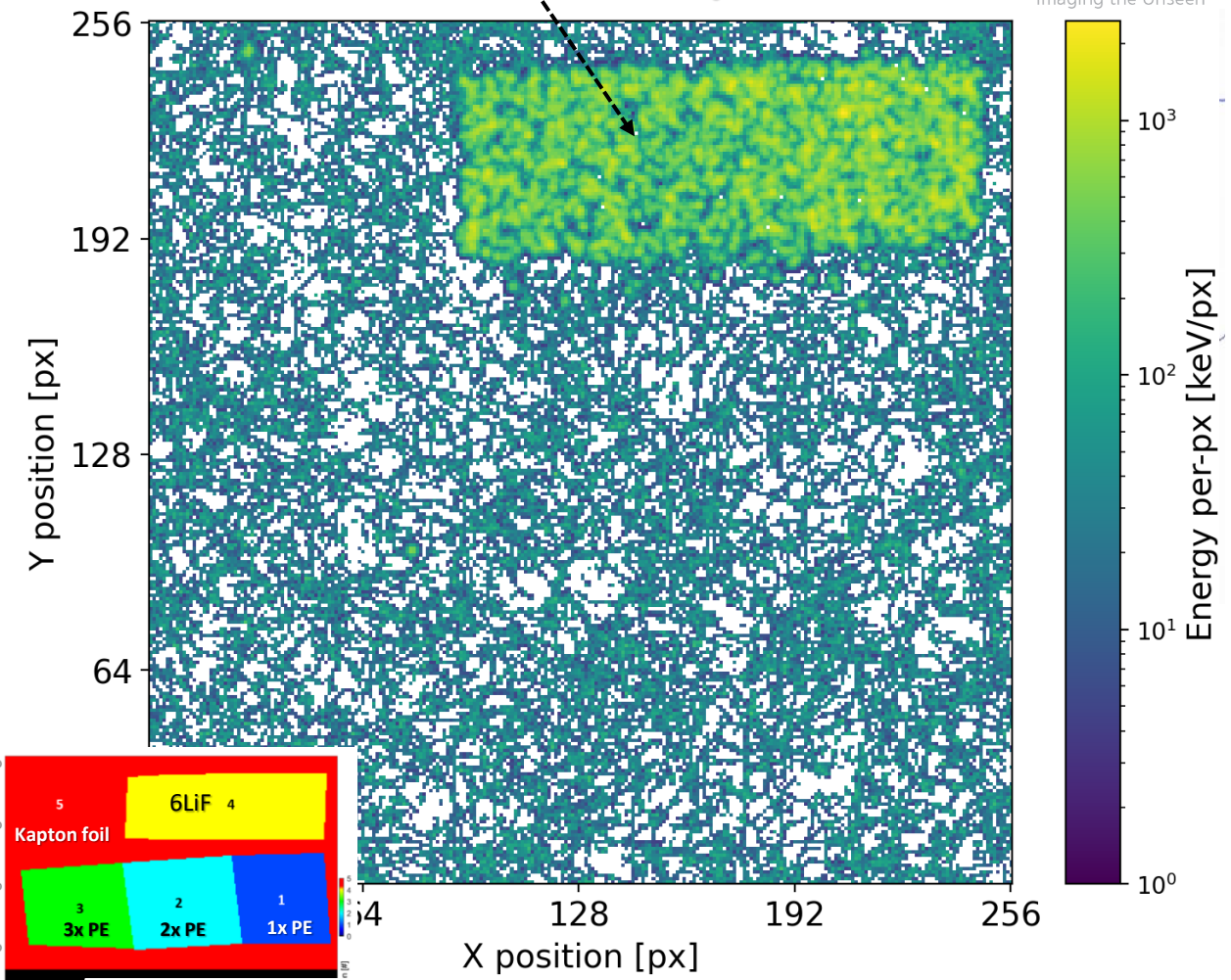
n mask (thermal, fast)

Thermal neutrons ← Thermal pile (Am-Be source + PE moderator)

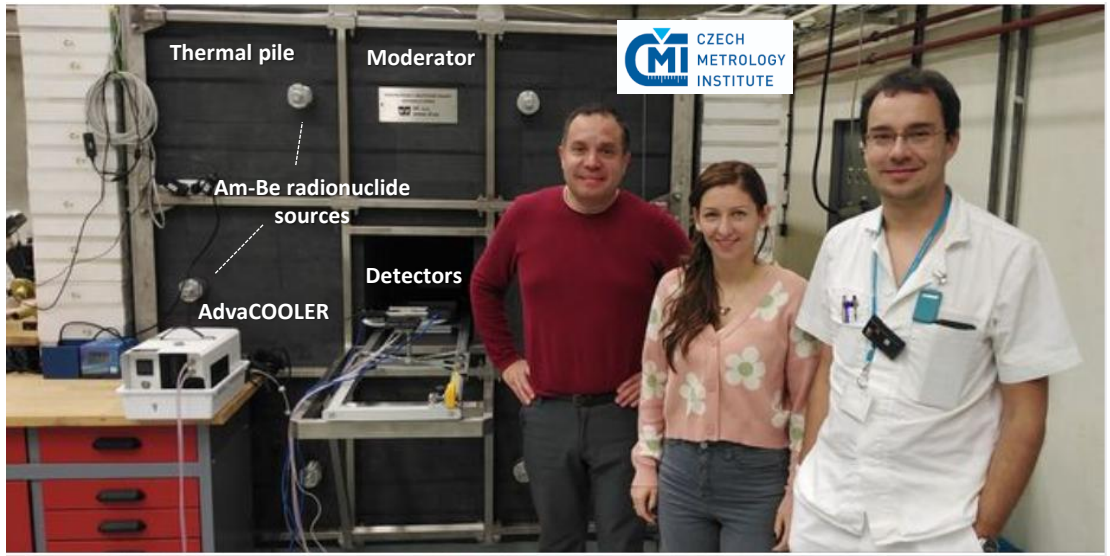
25 meV neutrons, gamma and X-ray background

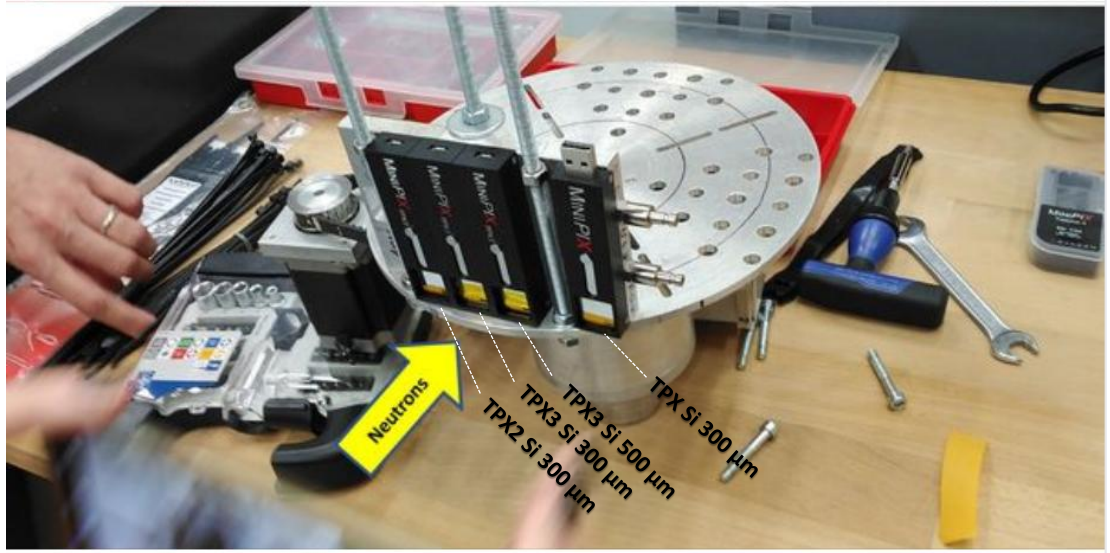
Radiation Camera MiniPIX Timepix3 Si sensor + neutron mask

Thermal neutrons: all particles



Timepix3 500 µm Si
n mask (thermal, fast)



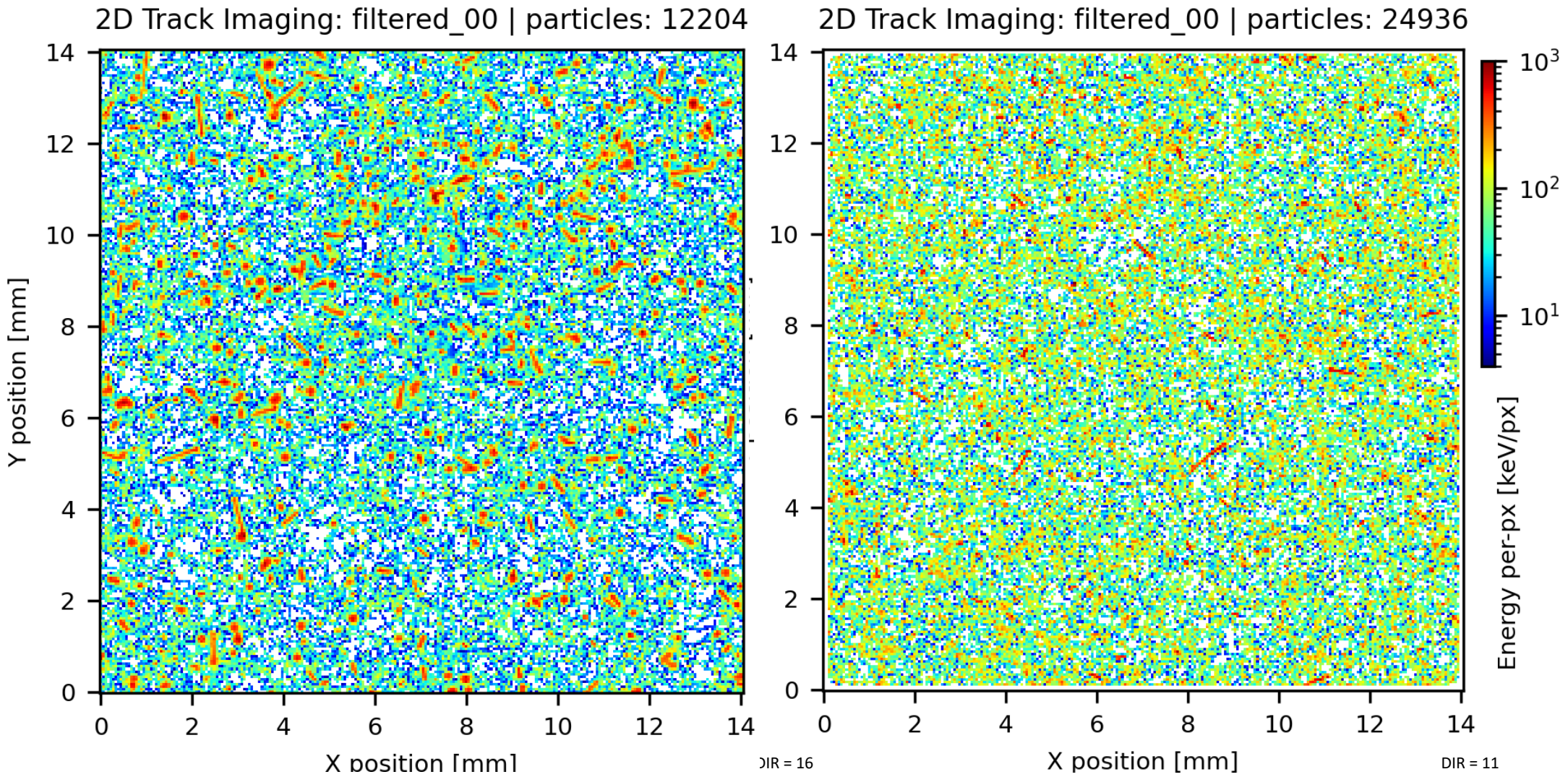


Fast neutrons: 14 MeV D-T generator @ VSB-TU Ostrava

All particles

Si 500 µm TPX3 MiniPix RO

GaAs 500 µm TPX2 MiniPix RO



Data acquired simultaneously with each detector over **4.24 s** int time (summed over 642 frames each of 6.6 ms acquisition time). No event filtering applied → the figures show:

All particles

Neutron interaction → cross sections

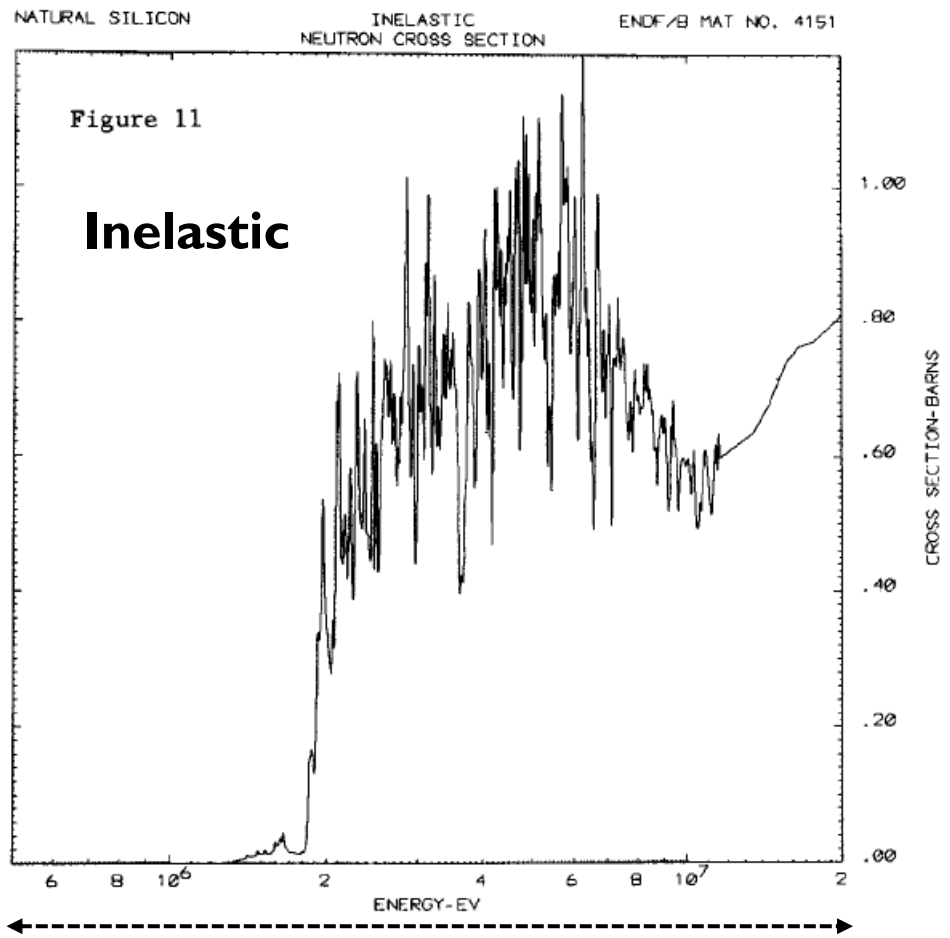
Neutron-induced nuclear reaction yields

→ strongly dependent on

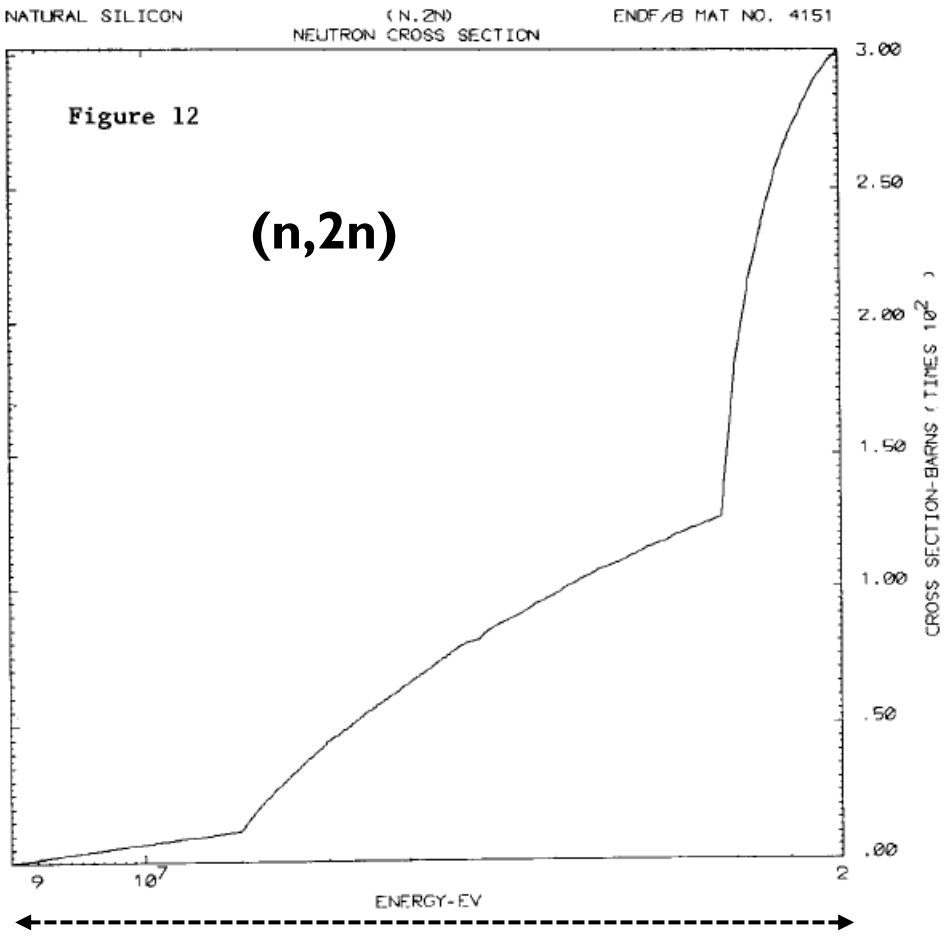
- **neutron energy**,
- **sensor material**
- **converter**

Radiation Detection / Nuclear Physics

Neutron-induced nuclear reaction cross sections on silicon ($^{28+29}$Si)

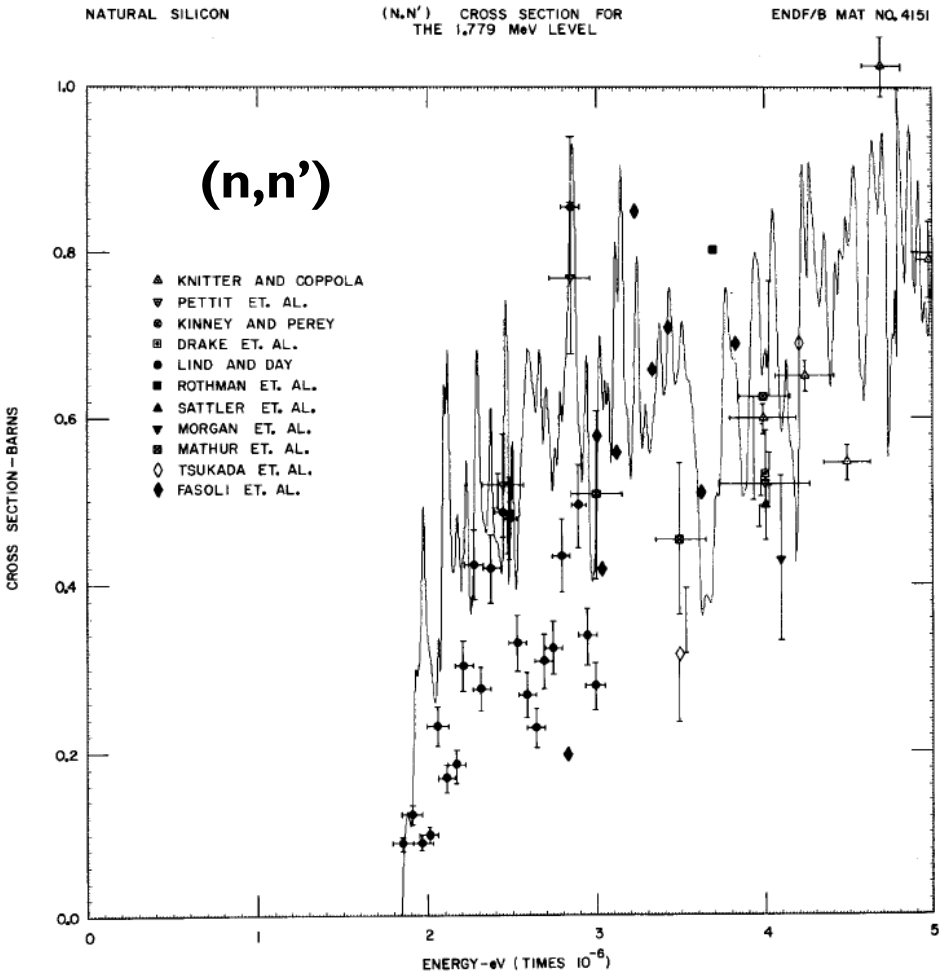


5 – 20 MeV

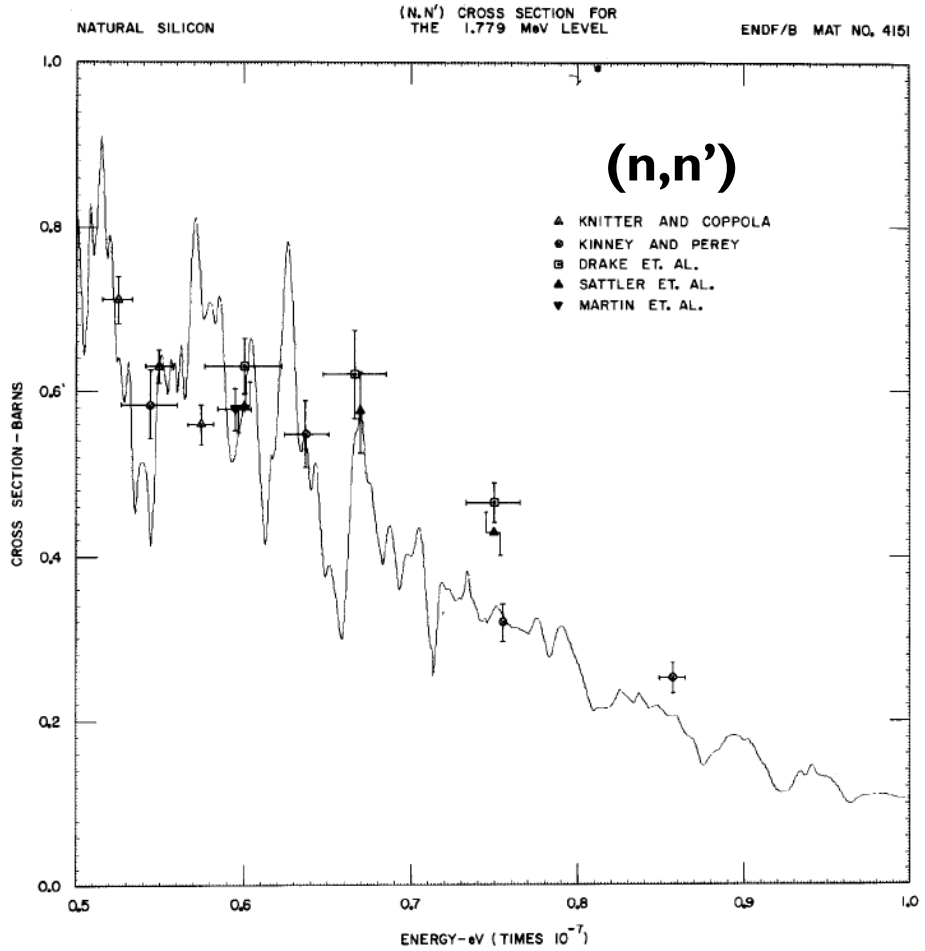


8 – 20 MeV

Neutron-induced nuclear reaction cross sections on silicon ($^{28+29}$Si)

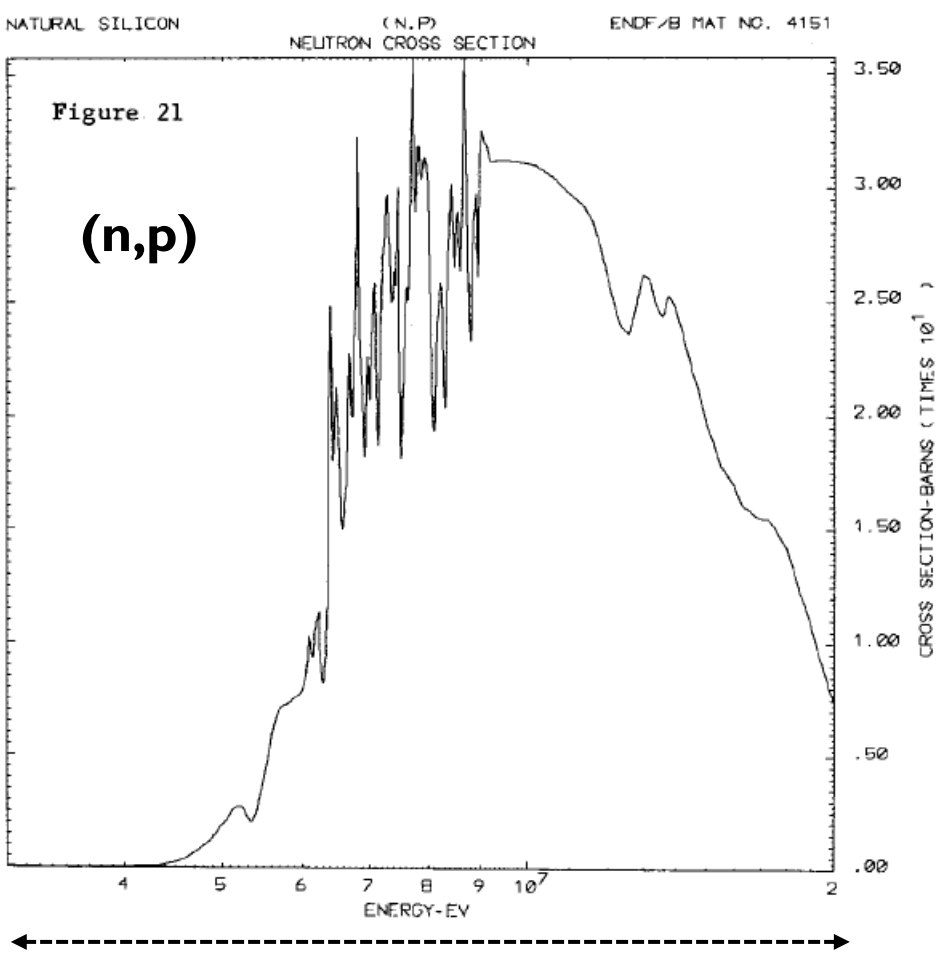


0 – 5 MeV

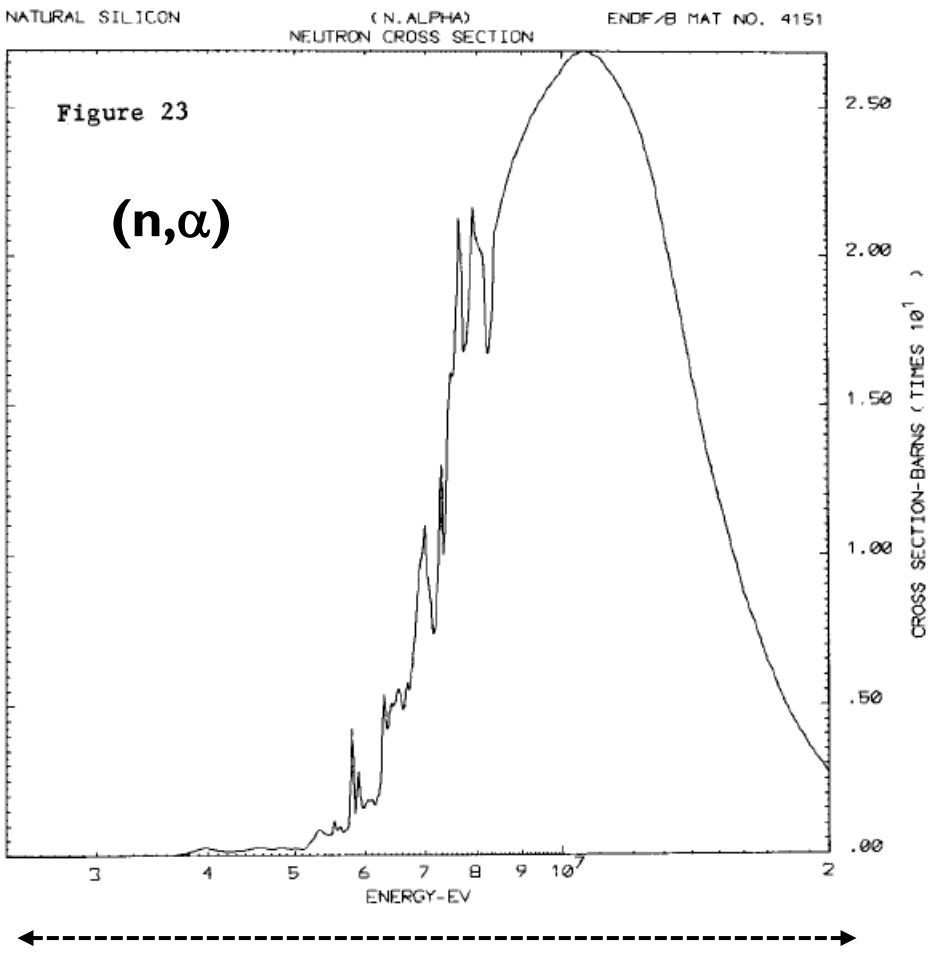


5 – 10 MeV

Neutron-induced nuclear reaction cross sections on silicon ($^{28+29}$Si)



I – 20 MeV



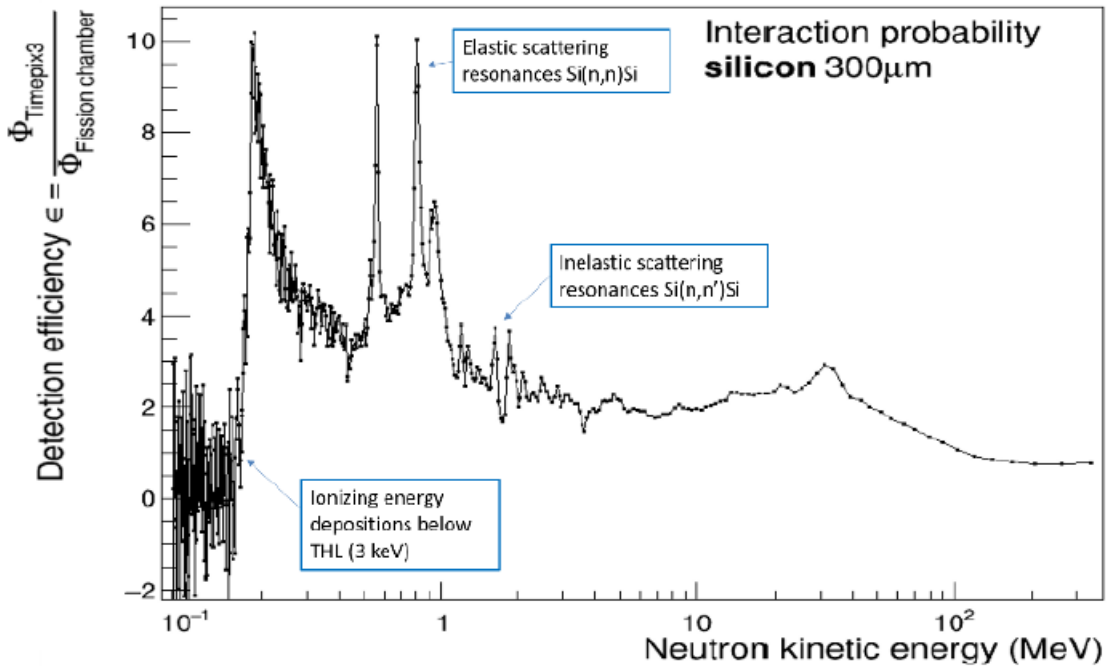
I – 20 MeV

Neutron detection in wide range: Timepix Si sensor

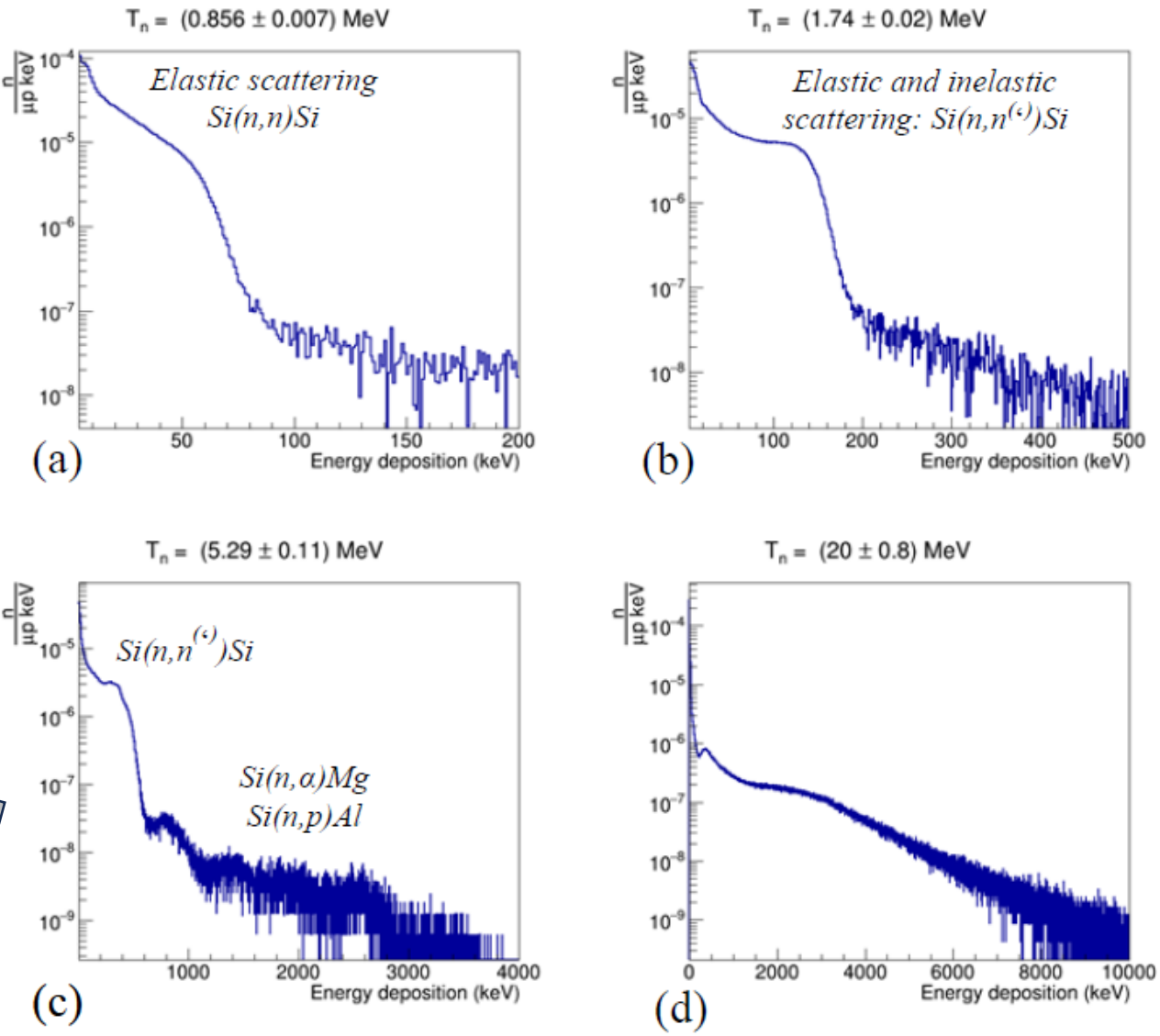
Wide range neutron energy T_n: 100 keV → 600 MeV

Understanding ionizing energy losses after charged particle and neutron impact in semiconductors with hybrid pixel detectors, ***B. Bergmann*** *(IEAP CTU Prague), Int. Conf. Appl. Electronics 2022, DOI: 10.1109/AE54730.2022.9920076*

Fast neutron interaction probability as a function of neutron incident energy for a 300 µm thick silicon sensor. Processes leading to the discernible interactions are labeled.



Ionizing energy deposition spectra after fast neutron interactions in silicon by monoenergetic neutrons



Measured at the Van-de-Graaff light ion accelerator, IEAP CTU Prague

Neutron interaction → cross sections

Neutron-induced nuclear reaction yields

→ strongly dependent on

- **neutron energy**,
- **sensor material**
- **converter**

Radiation Detection / Nuclear Physics

Neutron total cross section on hydrogen

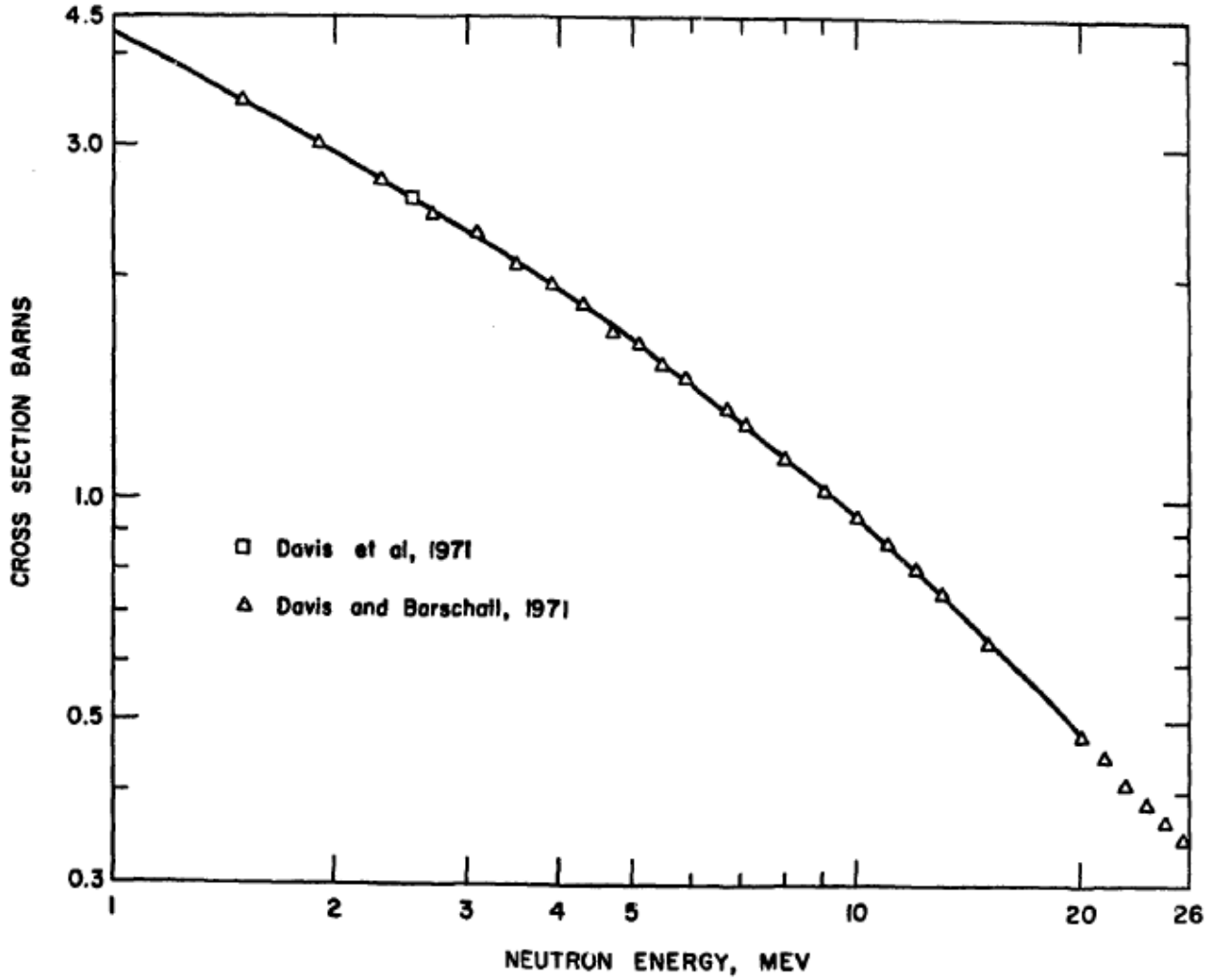


Fig. 4.
Total cross section for hydrogen from 1 to 26 MeV. The ENDF/B-V evaluation is compared to the Wisconsin measurements of Refs. 12 and 13. (Note that the symbols are larger than the experimental errors on these very precise measurements).

Neutron detection in wide range: Timepix Si sensor + neutron converter mask

Wide range of neutron energy ≈ keV → ≈ GeV

BROOKHAVEN NATIONAL LABORATORY

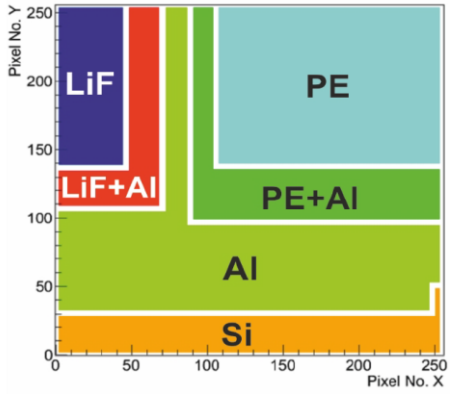
BNL-112485-2016-JA

Ionizing energy depositions after fast neutron interactions in silicon

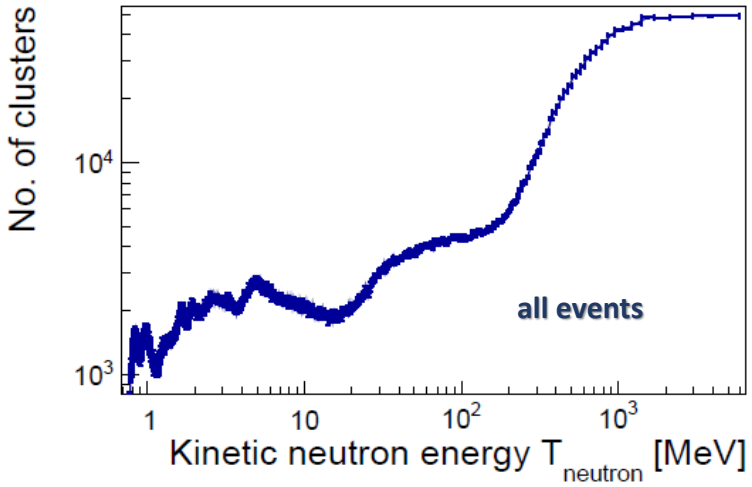
Benedikt Bergmann, Stanislav Pospisil, Ivan Caicedo, James Kierstead, Helio Takai, and Erik Frojdh

Submitted to IEEE Transaction on Nuclear Science

June 2016



Timepix n mask: Event rate on detector



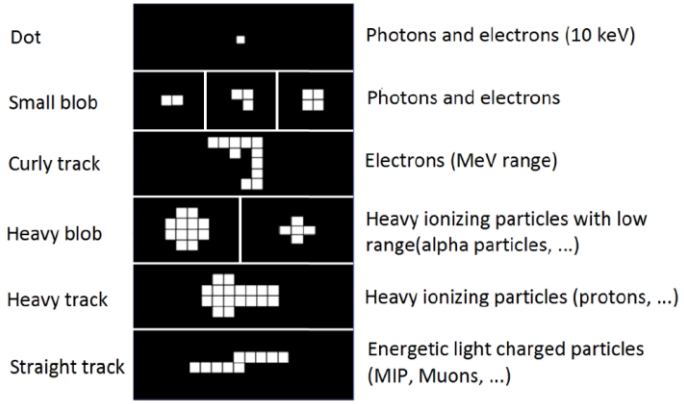


Fig. 3. Number of detected neutron interactions in the 300 μm thick silicon sensor as a function of neutron kinetic energy. The neutron energies were assigned with the ToF technique (see text for explanation).

Jinst

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15th INTERNATIONAL WORKSHOP ON RADIATION IMAGING DETECTORS
23–27 JUNE 2013,
PARIS, FRANCE

Time-of-flight measurement of fast neutrons with Timepix detectors

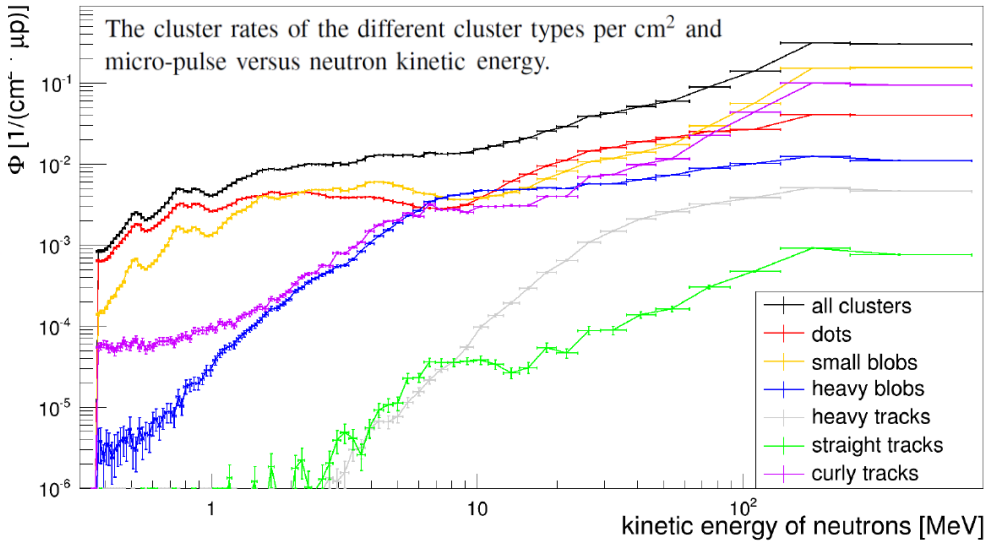
B. Bergmann,[a,1] R.O. Nelson,[b] J.M. O'Donnell,[b] S. Pospisil,[a] J. Solc,[a] H. Takai[c] and Z. Vykydal[a]

[a]*Institute for Experimental and Applied Physics, Czech Technical University in Prague, Horska 3a/22, 128 00 Praha 2, Czech Republic*
[b]*Los Alamos Neutron Science Center, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, United States*
[c]*Brookhaven National Laboratory, P.O. Box 5000, Upton, NY 11973-5000, United States*

E-mail: Benedikt.Bergmann@utef.cvut.cz

2014 JINST 9 C05048

Timepix n mask: Decomposition of event rate on detector



Detection of neutrons in wide energy range ↔ sensor & convertor

Neutron induced reaction mechanisms → detection channels

S. Pospisil, B. Bergmann, IEAP CTU
C. Granja, P. Alexa, VSB-TUO

^{6}Li, ^{10}B: ❑ Thermal neutrons
^{1}H: ❑ Slow/resonance neutrons

Converter

^{6}LiF-Region

Thermal neutrons through α-particles and ^{3}H from:

$n + {}^{6}Li \rightarrow \alpha + {}^{3}H, \quad T_n \approx 25\,meV$

Admixture channels

$n + Si \rightarrow n' + Si'$,	$T_n > 0.2$ MeV
$n + Si \rightarrow n' + Si' + \gamma$,	$T_n > 1.85$ MeV
$n + Si \rightarrow Mg + \alpha$,	$T_n > 2.75$ MeV
$n + Si \rightarrow Al + p$,	$T_n > 4$ MeV
$n + Si \rightarrow nX$,	$T_n > 20$ MeV
non-neutron field	

❑ Fast neutrons

Converter

PE-Region

Fast neutrons detection through protons from:

$n + p \rightarrow n' + p' \quad T_n > 1\,MeV$

Admixture channels

$n + Si \rightarrow n' + Si'$,	$T_n > 0.2$ MeV
$n + Si \rightarrow n' + Si' + \gamma$,	$T_n > 1.85$ MeV
$n + Si \rightarrow Mg + \alpha$,	$T_n > 2.75$ MeV
$n + Si \rightarrow Al + p$,	$T_n > 4$ MeV
$n + Si \rightarrow nX$,	$T_n > 20$ MeV
non-neutron field	

❑ Fast neutrons
- ❑ in silicon
- ❑ in SiC

Si-Region (uncovered)

—

Channels

$n + Si \rightarrow n' + Si'$,	$T_n > 0.2$ MeV
$n + Si \rightarrow n' + Si' + \gamma$,	$T_n > 1.85$ MeV
$n + Si \rightarrow Mg + \alpha$,	$T_n > 2.75$ MeV
$n + Si \rightarrow Al + p$,	$T_n > 4$ MeV
$n + Si \rightarrow nX$,	$T_n > 20$ MeV
non-neutron field	

Elastic scattering
Inelastic scattering
Direct reaction (n,α)
Direct reaction (n,p)

Radiation detection techniques

- ❑ Neutron spectroscopy based on proton recoil
- ❑ Neutron spectroscopy based on nuclei recoil ← Si, SiC

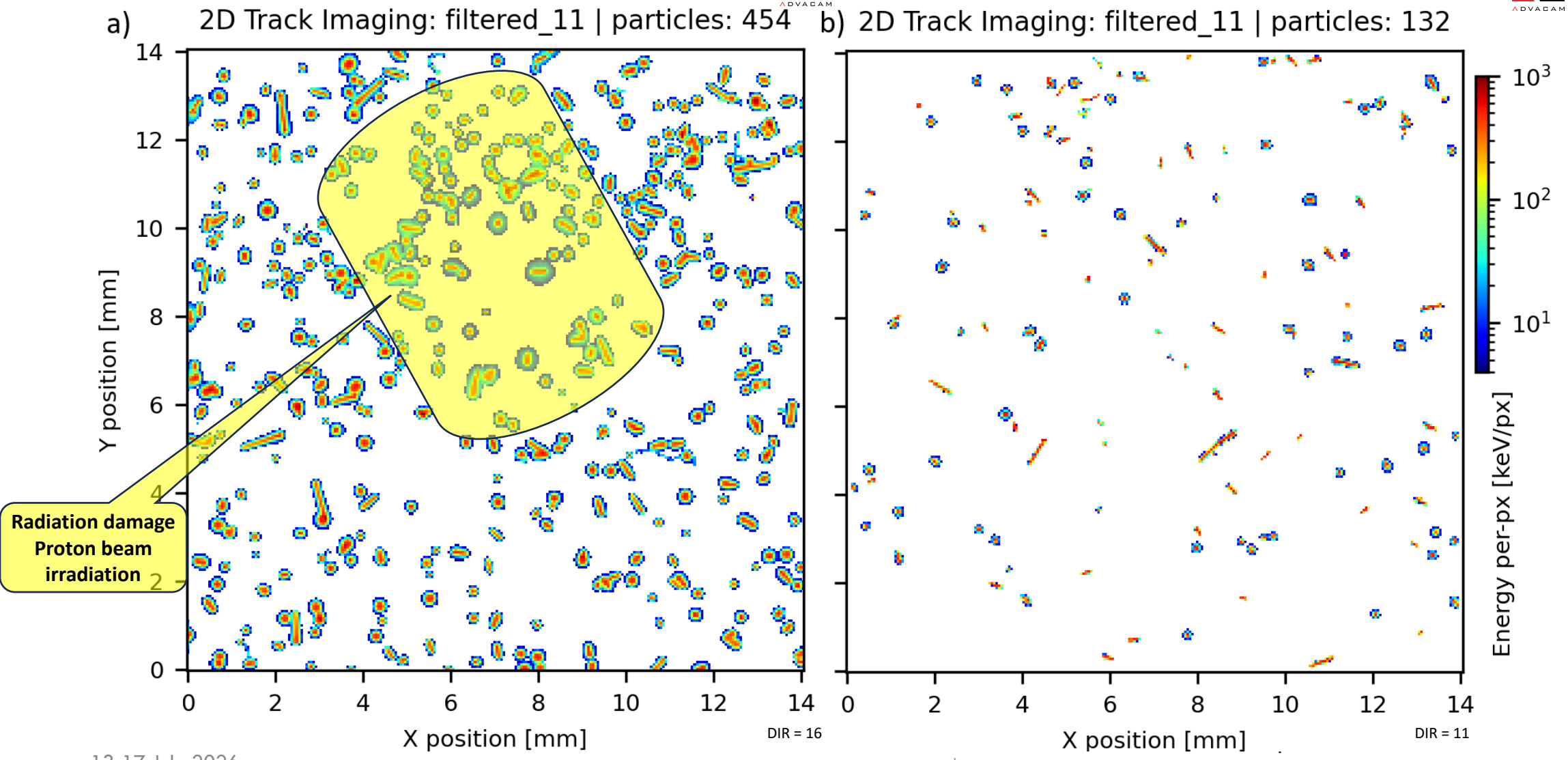
Fast neutrons: 14 MeV D-T generator @ VSB-TU Ostrava

VŠB TECHNICKÁ UNIVERZITA OSTRAVA

HETP particles

Si 500 µm TPX3 MiniPix RO

GaAs 500 µm TPX2 MiniPix RO



Data acquired simultaneously with each detector over **4.24 s** int time (summed over 642 frames each of 6.6 ms acquisition time). The figures show one of the radiation components resolved: **high-energy transfer particles**

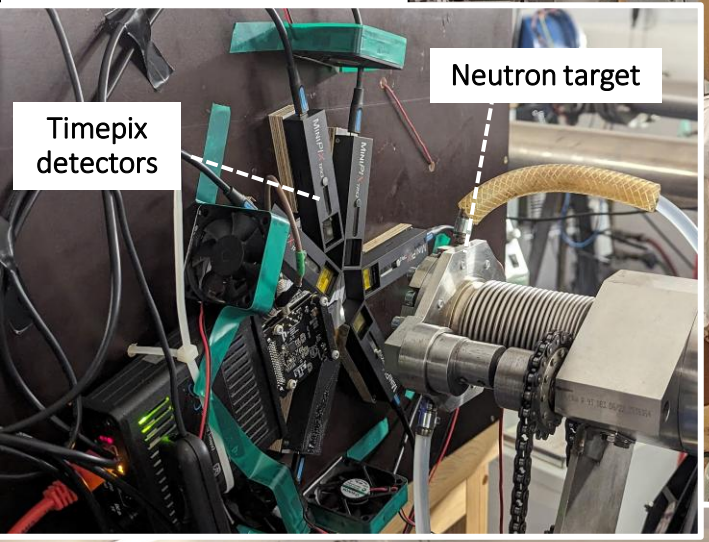
VdG accelerator IEAP CTU Prague

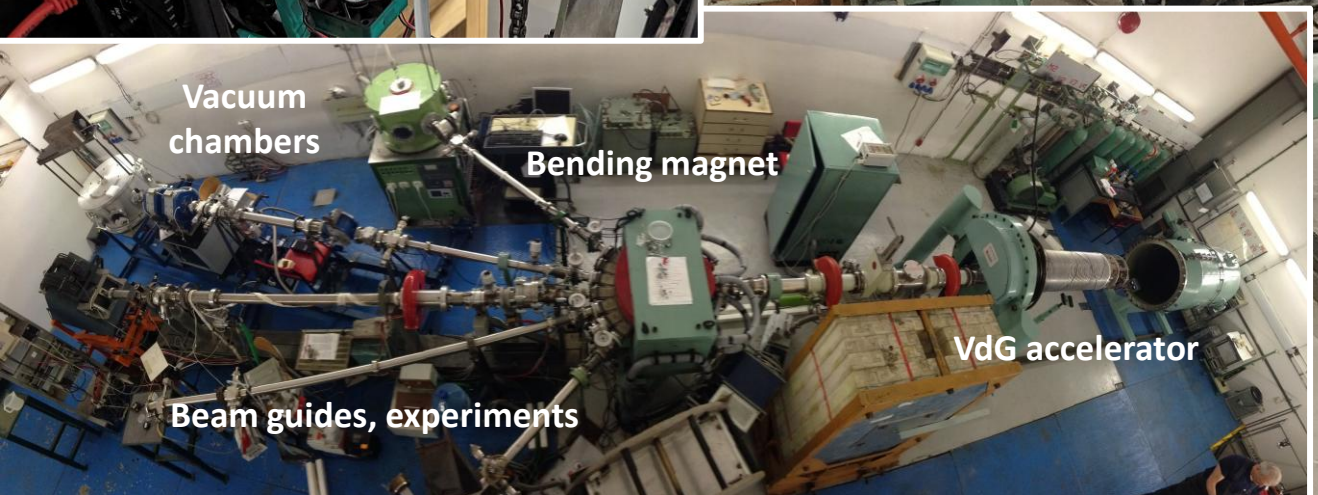
neutron sources reactions:

- ❑ P-T
- ❑ D-D
- ❑ D-T

http://vdg.utef.cvut.cz/

Carlos (2014), T. Slavicek (2025), UTEF CVUT





Van-de-Graaff electrostatic light ion accelerator

Neutron target

Particle beams
- protons
- light ions, ^{4}He

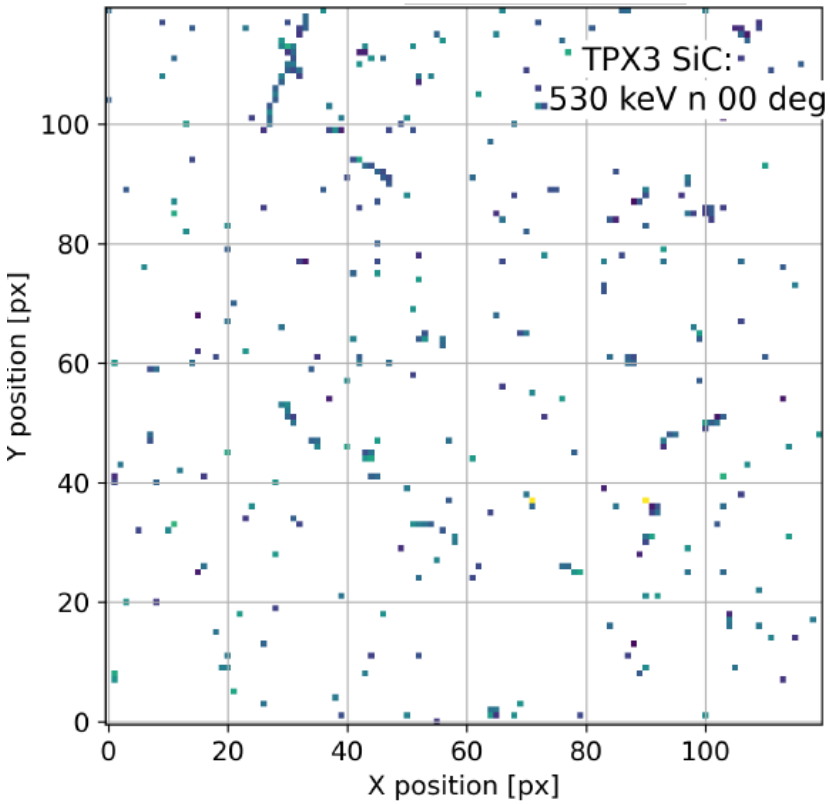
Tunable source of
- monoenergetic neutrons

Monoenergetic slow & fast neutrons: SiC 65 µm Timepix3

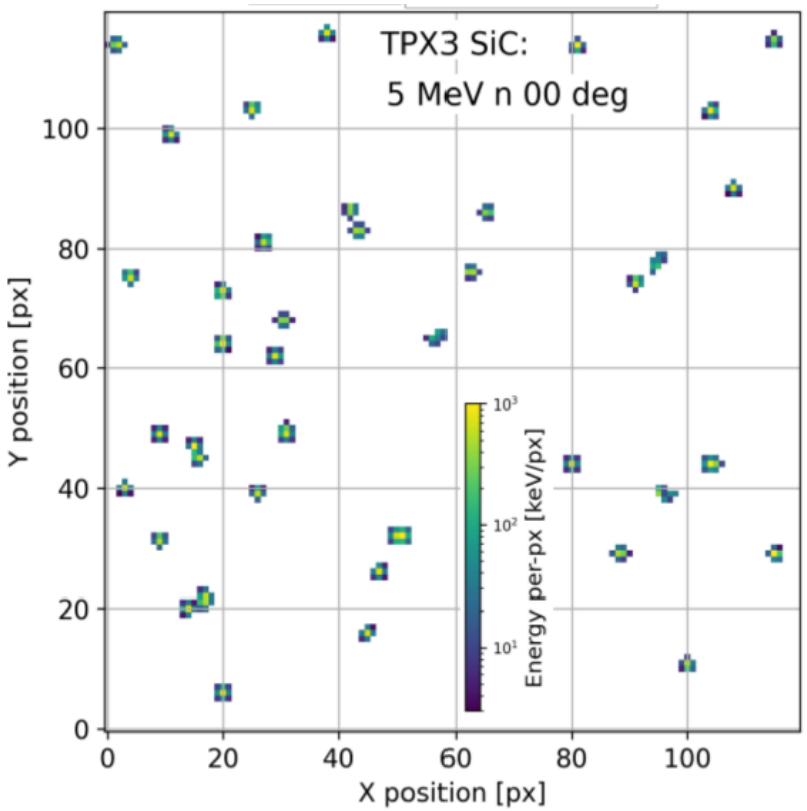
Radiation imaging, spectrometry, particle tracking

*C. Granja, et al., **Detection resolving power of SiC Timepix3 to electrons, neutrons, ions and protons**, J. Instrum. 19 (2024) C11007*

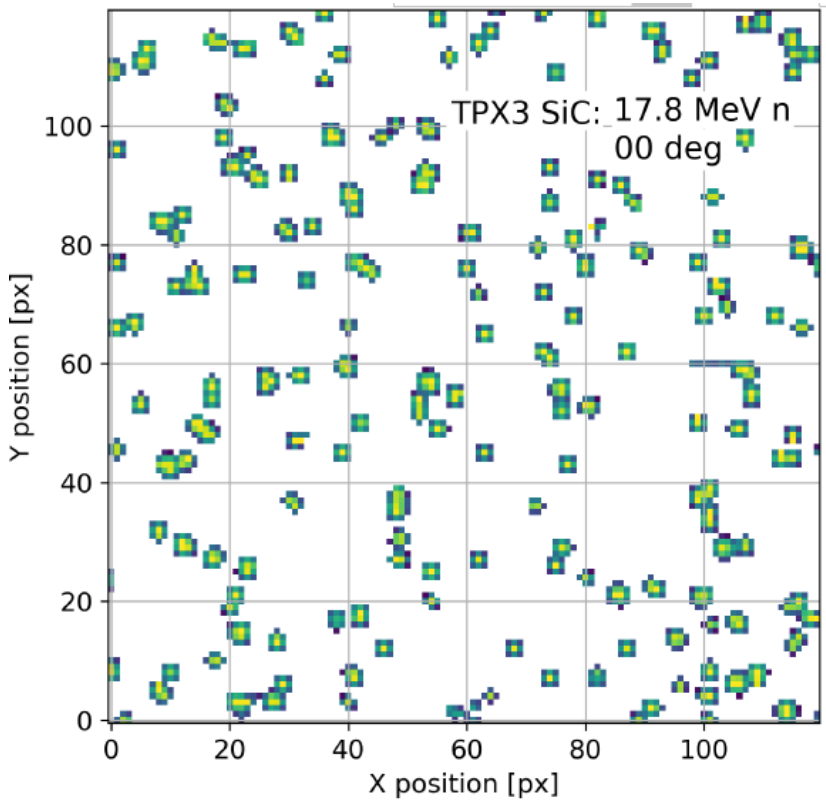
530 keV neutrons



5 MeV neutrons



18 MeV neutrons



Complex/mixed-radiation field: Cosmic rays

Earth’s atmosphere, high mountain peak Lomnicky Stit, Tatras, Slovakia

Si, CdTe Timepix2/Timepix3

MiniPIX-Timepix2/3 radiation camera: Advacam

Radiation imaging, Particle tracking

C. Granja, J. Kubancak

MiniPIX Timepix3 Telescopes: secondary cosmic ray detection

Tatra Mountains, Lomnicky Stit, 2700 m, Slovakia

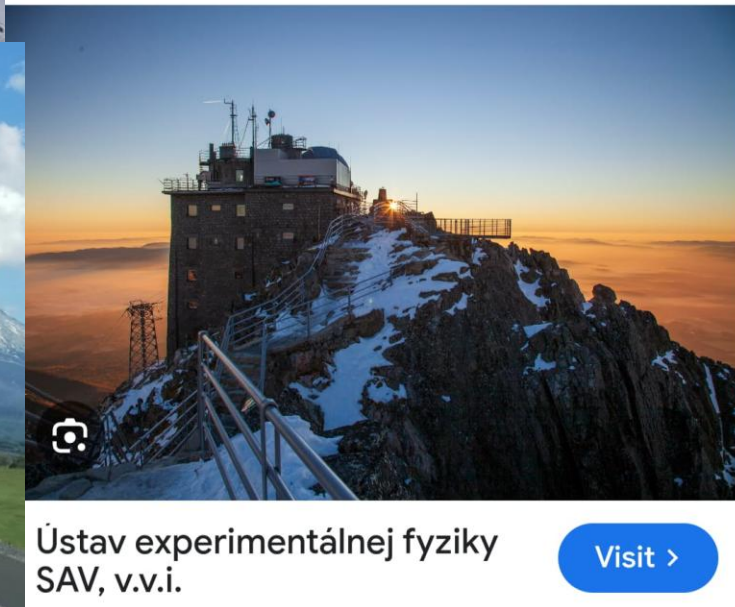
SLOVENSKÁ AKADÉMIA VIED

ADVACAM
Imaging the Unseen









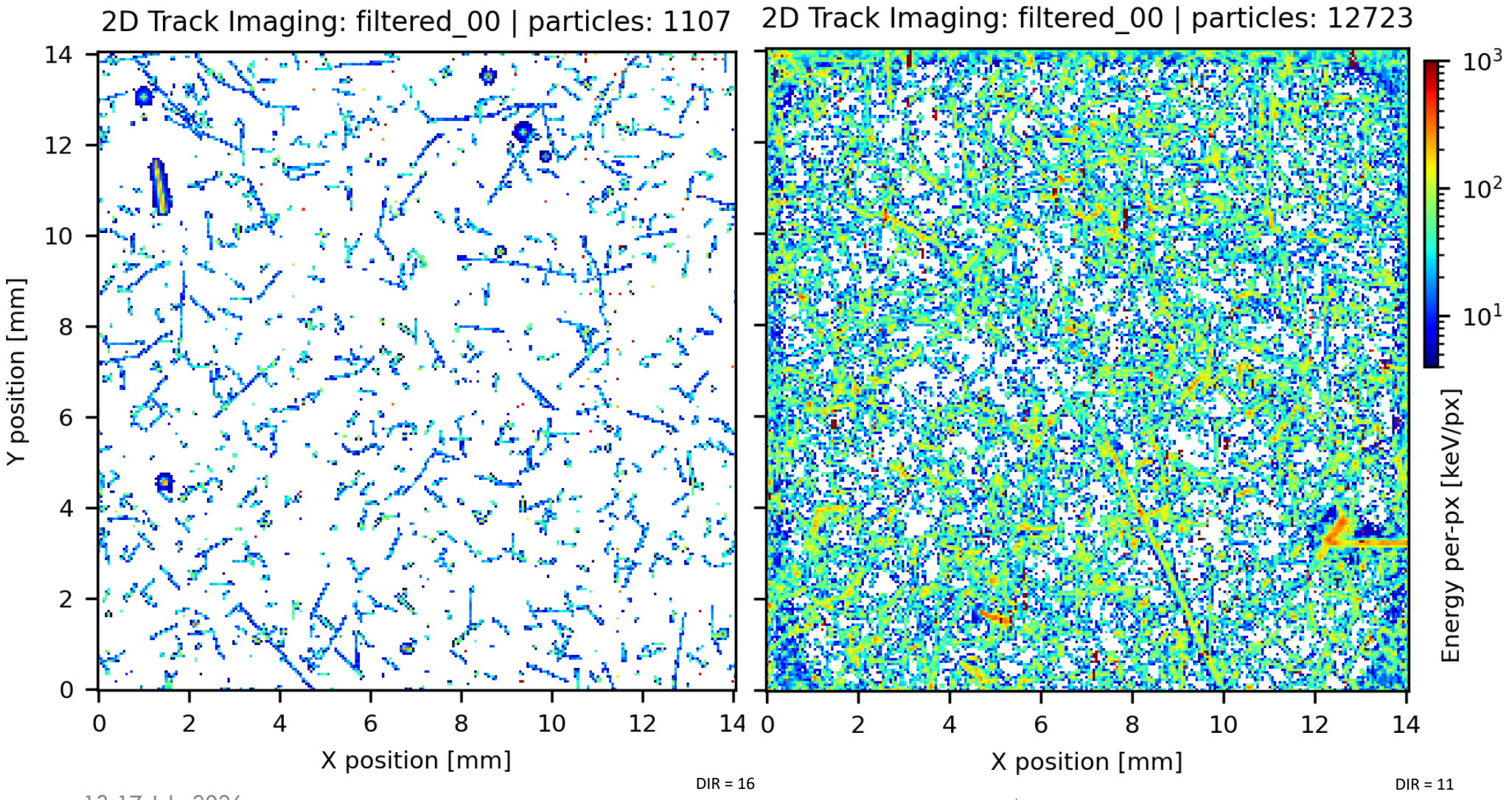
Cosmic rays: SCRs Lomnicky Stit, Tatras, IEP SAS SK

VŠB TECHNICKÁ UNIVERZITA OSTRAVA

Si 500 µm TPX3 MiniPix RO

All particles

CdTe 2000 µm TPX3 MiniPix RO



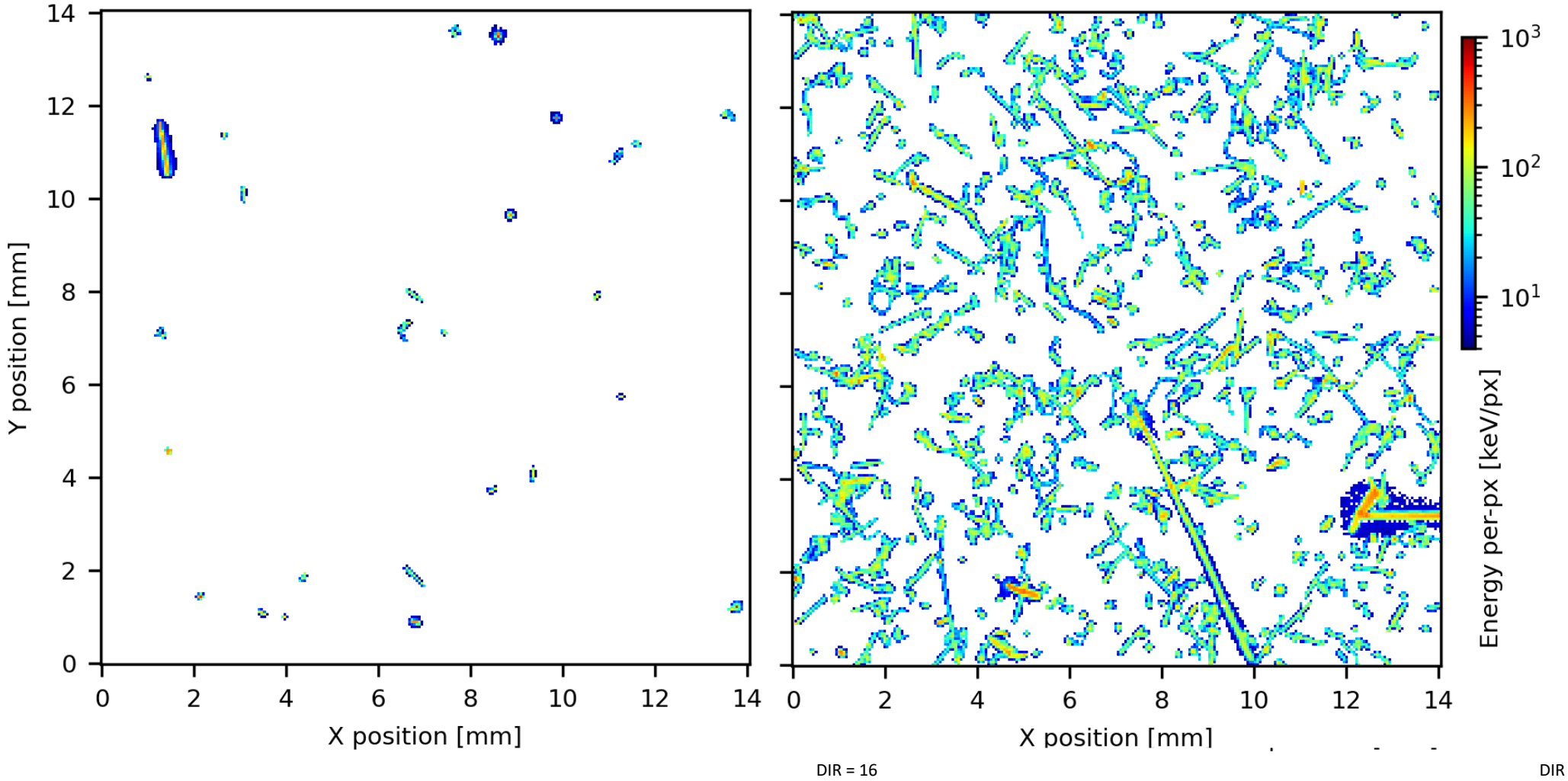
Measurement of secondary cosmic rays in the atmosphere by Timepix3 detectors. Data acquired simultaneously with each detector during **75 min** at Lomnicky Stit mountain at **2.6 km** altitude. No event filtering applied → all data shown:

All particles

Cosmic rays: SCRs Lomnicky Stit, Tatras, IEP SAS SK

VŠB TECHNICKÁ UNIVERZITA OSTRAVA

Si 500 µm TPX3 MiniPix RO **HETP component** **CdTe 2000 µm TPX3** MiniPix RO



Measurement of secondary cosmic rays in the atmosphere by Timepix3 detectors. Data acquired simultaneously with each detector during **75 min** at Lomnicky Stit mountain at **2.6 km** altitude. No event filtering applied → all data shown:

HETP particles

Complex/mixed-radiation field: Proton radiotherapy

Proton accelerator + tissue-equivalent / PMMA target

Si Timepix3 & neutron converter mask

Neutron mask + Chipboard + MiniPIX: Advacam

Radiation imaging, Particle tracking

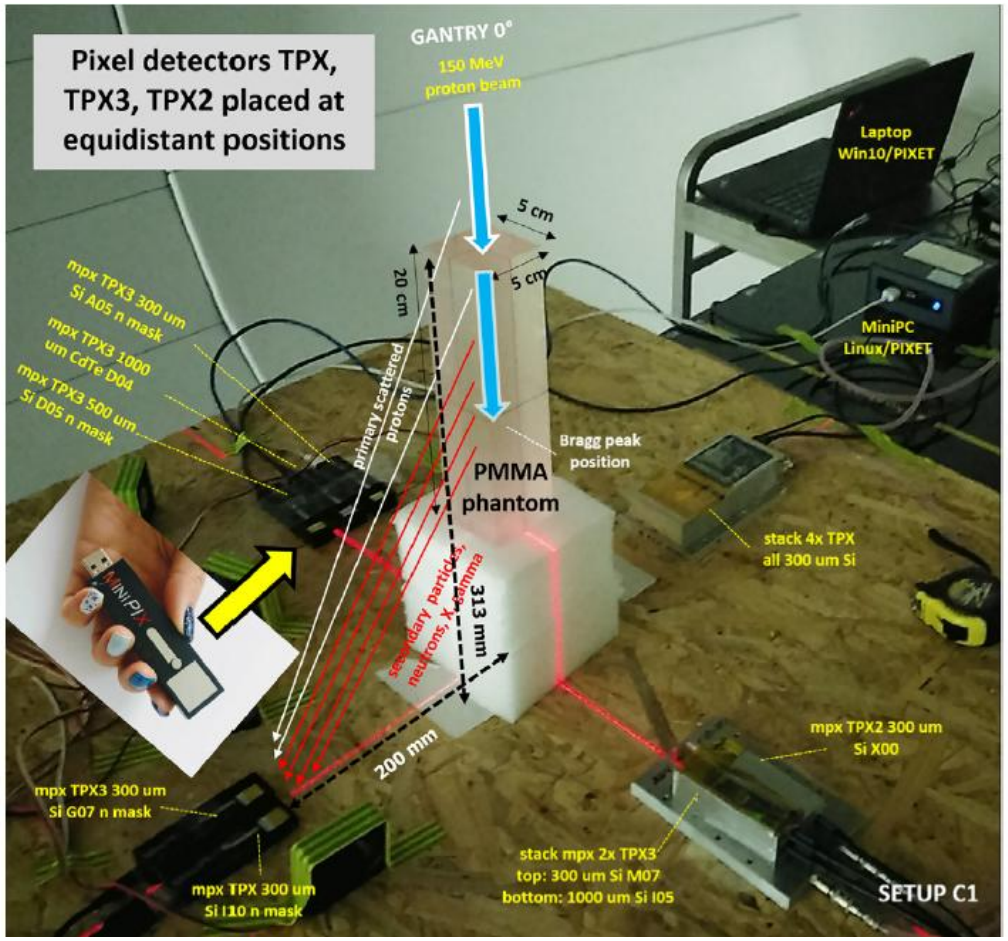
Mixed-radiation field characterization: Si TPX3

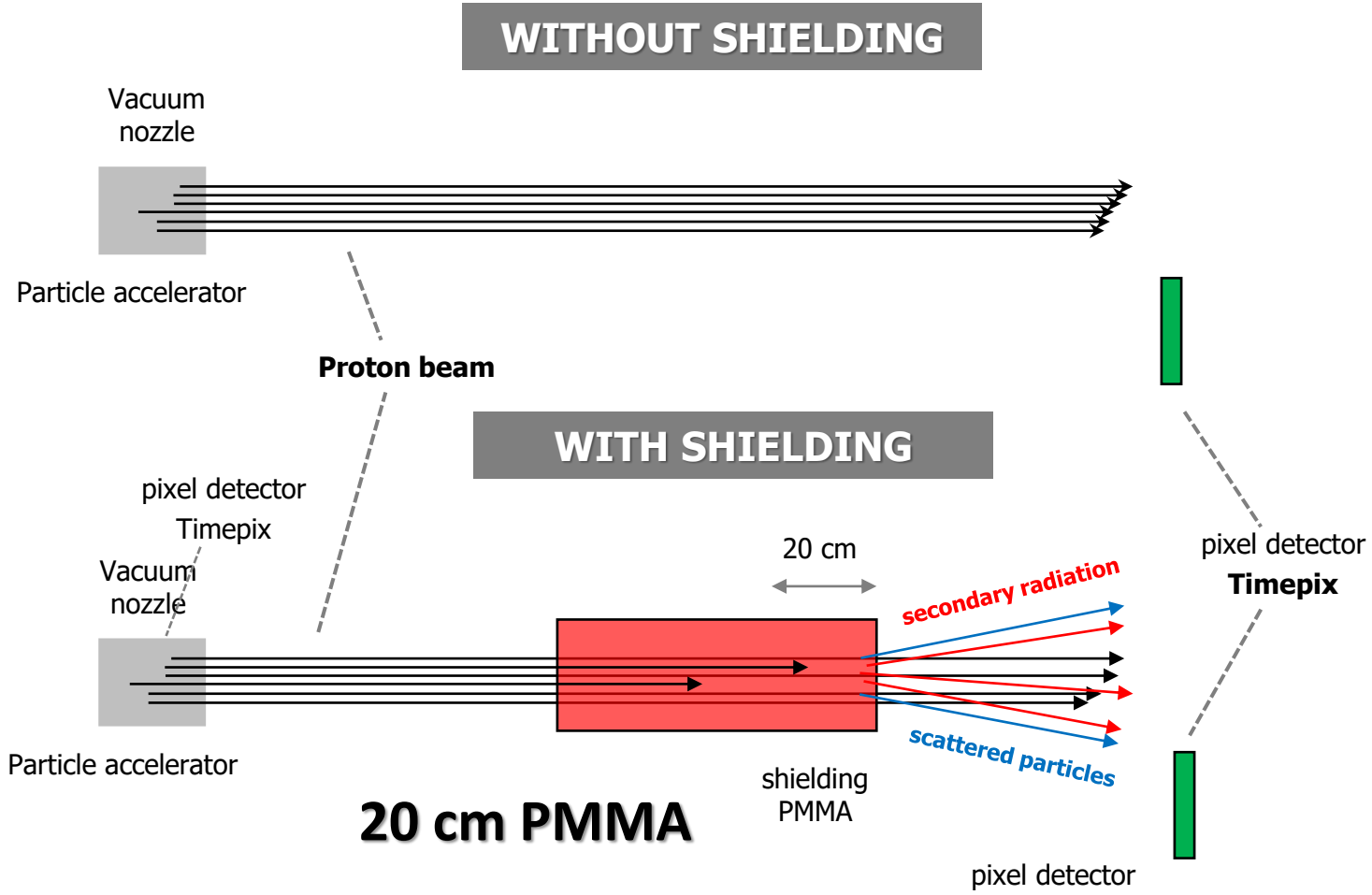
Complete & detailed characterization of the secondary radiation field

Cyclotron Centre Bronowice

150 MeV protons

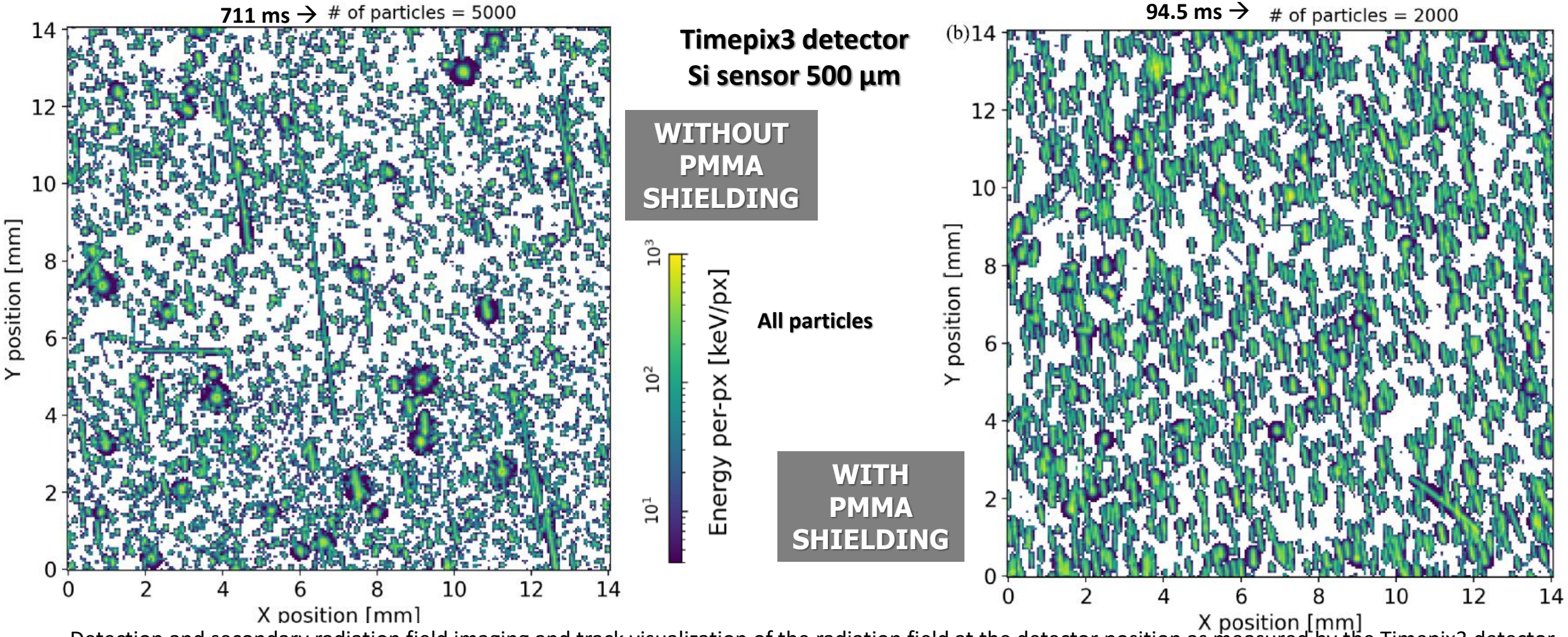
C. Granja, et al., Composition and Spectral Characterization of Mixed-Radiation Fields with Enhanced Resolving Power by Quantum Imaging Detection and Spectral-Sensitive Particle Tracking, IEEE Trans. Nucl. Sci. 71 (2024) 921-931





Characterization of complex/mixed-fields

Radiation field imaging + single particle track visualization

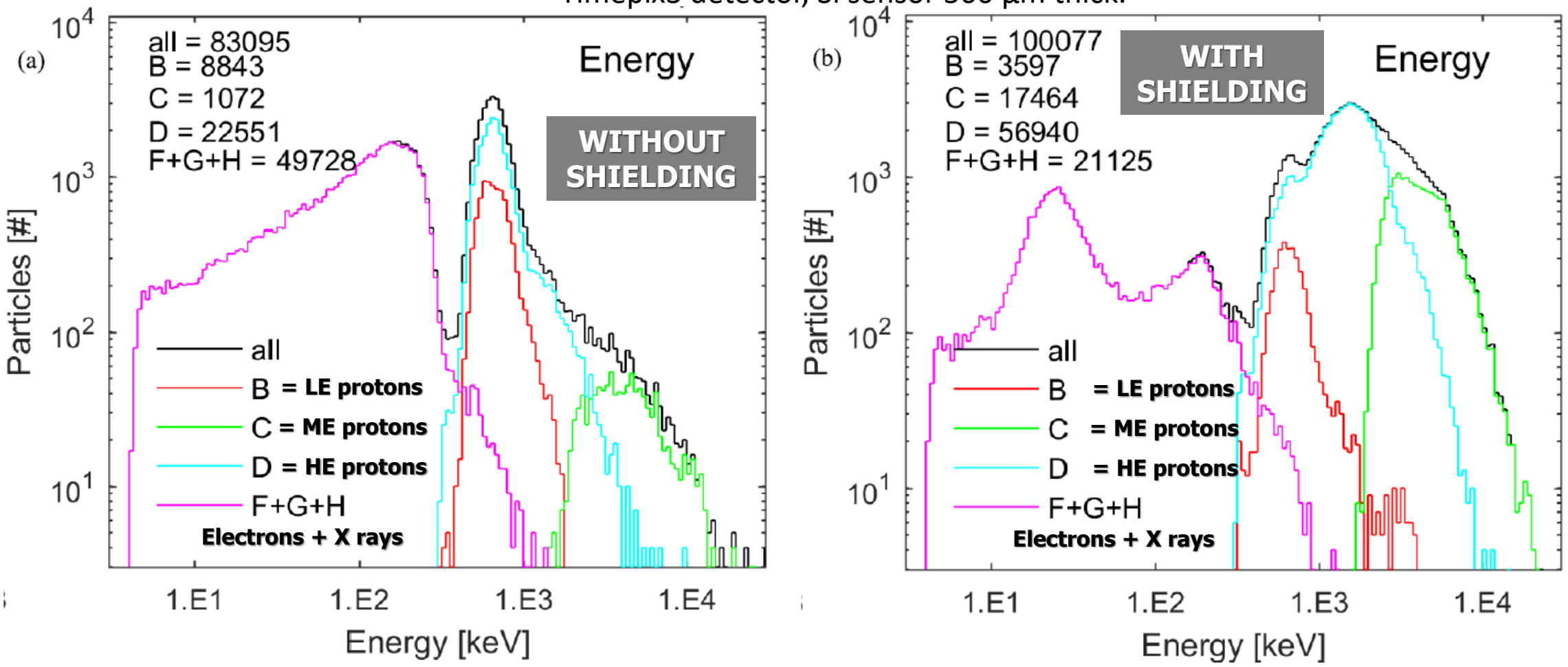


Detection and secondary radiation field imaging and track visualization of the radiation field at the detector position as measured by the Timepix3 detector, Si sensor 500 µm thick. The entire detector sensor area is displayed: 256 × 256 pixels = 65 k pixels = 14.1 × 14.1 mm = 1.98 cm2. The per-pixel energy response is displayed by the color bar in the log scale

Characterization of complex/mixed-fields

Decomposition + spectrometry (deposited energy, LET)

Timepix3 detector, Si sensor 500 µm thick.



Deposited energy spectra for the 150-MeV proton (a) without and (b) with the PMMA phantom. Data shown for all particles (black curve) and selected particle-type classes (color curves; see inset labels).



Comparison, conclusion

Timepix detectors: semiconductor sensors

According to radiation species

Quality of physics data

Suitability according radiation species

Sensor	Electrons	Protons	Ions	X rays#	Gamma rays#	Neutrons thermal*#	Neutrons fast#
Si	✓✓✓	✓✓✓	✓✓	Low-energy	☹	✓✓	✓✓
SiC	✓	✓	✓	☹	☹	☹	✓
GaAs	✓	☹	☹	✓✓	✓	☹	☹
CdTe	☹	☹	☹	✓✓✓	✓✓	☹	☹

- For extended gamma ray detection → thick CdTe sensors 2-5 mm
- For wide-range & detailed characterization → combination Si + SiC + GaAs/CdTe
- Specific radiation-sensor detection response matrices / look-up tables (under way)

*** With neutron converter mask**

 # Small detection efficiency

Timepix detectors: semiconductor sensors

According radiation techniques

Suitability according radiation techniques

Quality of physics data

Sensor	Imaging			Spectrometry		Particle tracking			Radiation dosimetry
	X rays	Y rays	e,p,ions	X rays, γ rays	e,p,ions	e,p,ions	neutrons	X, y	
Si	✓✓	☹	✓✓✓	✓	✓✓✓	✓✓✓	✓✓	😐	✓✓✓
SiC	😐	☹	✓	😐	✓✓	😐	✓	☹	✓✓✓
GaAs	✓	✓	😐	✓✓	✓	✓	☹	✓✓	✓
CdTe	✓✓✓	✓✓✓	☹	✓✓✓	😐	☹	☹	✓✓✓	✓

- For mixed-radiation field characterization → **Si sensor 500 µm/TPX2** ← **Outer space**
- For wide-range & detailed characterization → combination Si + SiC + GaAs/CdTe

Timepix + sensors + spectral-tracking analysis

References/articles (C. Granja)

- **C. Granja**, et al., Spectral-imaging response and particle tracking resolving power to charged particles by Timepix detectors with Si, SiC, GaAs and CdTe sensors, **JINST** (2026) *submitted*
- **C. Granja**, J. Solc, et al., Composition and Spectral Characterization of Mixed-Radiation Fields with Enhanced Resolving Power by Quantum Imaging Detection and Spectral-Sensitive Particle Tracking, **IEEE Trans. Nucl. Sci. 71** (2024) 921-931
- **C. Granja**, J. Swakon, P. Olko, Spatial Dosimetry Verification of Conformal Beams in Proton Radiotherapy by Spectral-Sensitive Imaging, **IEEE Trans. Rad. Plasma Med. Sci. 10** (2026) 611–618
- **C. Granja**, H. Chanal, et al., High-resolution mapping of secondary cosmic rays by miniaturized stacked pixel telescope, **Acta Polytechnica 65** (2025) 16-24
- **C. Granja**, et al, "Detection resolving power of SiC Timepix3 detector to electrons, neutrons, ions and protons", J. of Instrum. **JINST 19** (2024) C11007
- L. Marek, **C. Granja**, et al., Data Processing Engine (DPE): Data Analysis Tool for Particle Tracking and Mixed Radiation Field Characterization with Pixel Detectors Timepix, J. of Instrum. **JINST 19** (2024) 04026
- **C. Granja**, R. Uhlar, P. Alexa, et al., *Detection of fast neutrons with the pixel detector Timepix3*, **JINST** 18 (2023) P01003
- **C. Granja**, et al., Spectral and directional sensitive composition characterization of mixed-radiation fields with the miniaturized radiation camera MiniPIX Timepix2, **JINST** 17 (2022) C11014
- **C. Granja**, C. Oancea, et al., *Wide-range tracking and LET-spectra of energetic light and heavy charged particles*, **NIM-A** 988 (2021) 164901
- **C. Granja**, et al., *Resolving power of pixel detector Timepix for wide-range electron, proton and ion detection*, **NIM-A** 908 (2018) 60-71

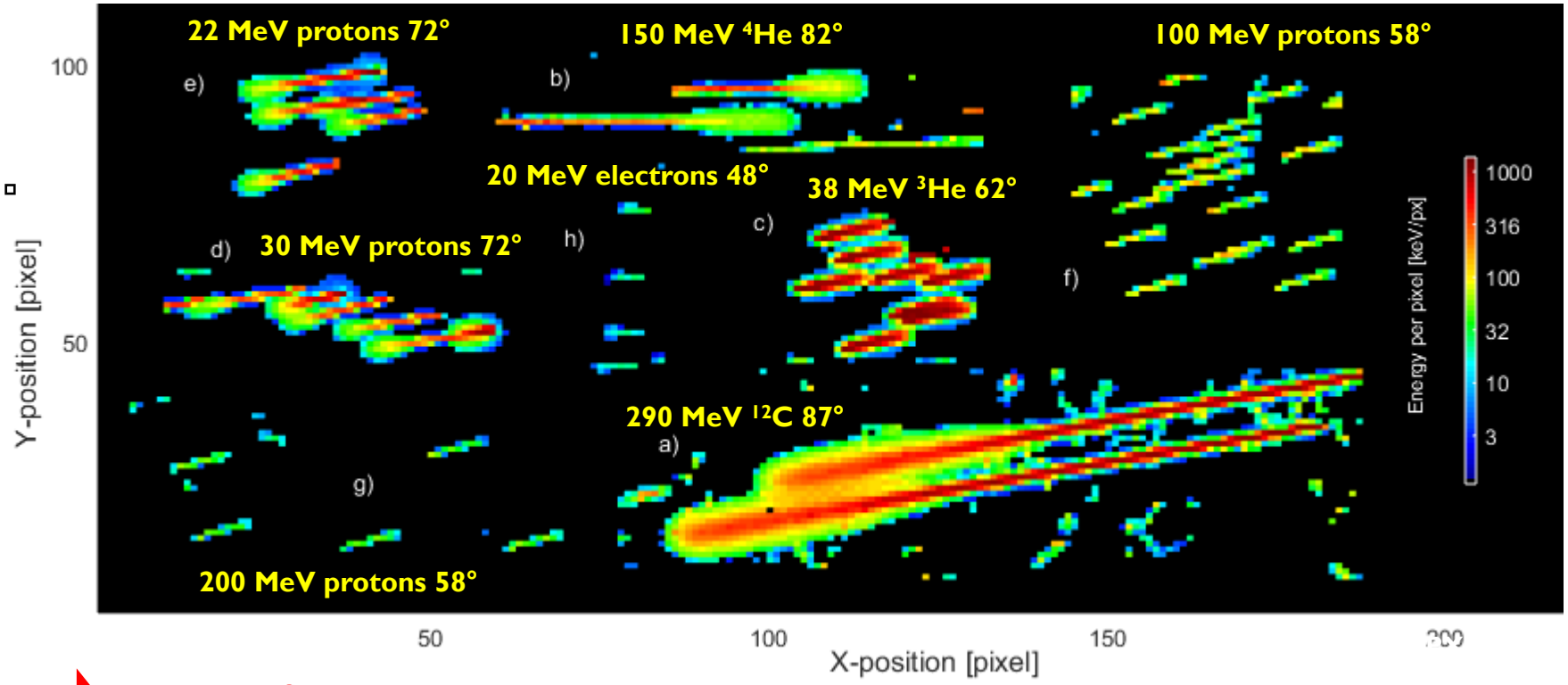
Hybrid semiconductor pixel detector Timepix

Quantum-imaging & Spectral-sensitive particle tracking: Si sensor 300 um

High-resolution spectral-sensitive particle tracking

Characteristic tracks ↔ particle-type species

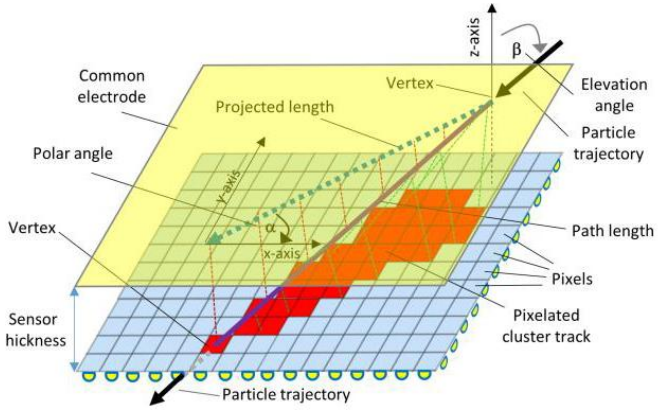
30, 100, 200 MeV protons, 38,150 MeV He ions, 20 MeV electrons



Particle-event type resolving power

C. Granja et al., Nucl. Instrum. Meth. A 908 (2018) 60-71

Particle tracking in wide FoV



Degrees of freedom:

- Particle type/species
- Energy (energy loss)
- Direction **2π FoV**