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Study of the Ionizing Energy Depositions After Fast Neutron Interactions in Silicon

Bartoloměj Biskup
on behalf of
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BNL
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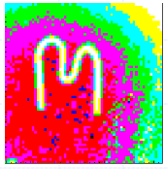

Main goals of the talk

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- To describe briefly family of ***Medipix2 and Timepix semiconductor pixel detectors*** including corresponding R/O electronics.
- To document ability of Timepix pixel detector to ***visualize individual particle tracks in solid state*** similarly to nuclear emulsions, cloud chambers, bubble chamber, Micro-Pattern Gaseous Detectors etc.
- To demonstrate capability of the devices for ***high resolution (micrometric and nearly nanometric) radiography and 3D imaging*** by means of ***X-rays and neutrons.***
- To show examples of broad ***applications*** of the Timepix detectors for ***measurements of composition and spectral characteristics of mixed radiation fields around physics experiments (ATLAS, MoEDAL).***
- To reveal ***interactions of individual fast neutrons in silicon*** sensor by means of ***Time-of-Flight (ToF) technique*** in a broad energy range (180 keV up to 800 MeV region).
- By comparing the ionizing energy loss of elastically or inelastically recoiled silicon nuclei with its energy obtained in this process according the kinematics of neutron scattering, ***the ratio between (IEL) and (NIEL) of silicon nuclei in silicon lattice was determined in the range 20-900 keV.***

Medipix/Timepix hybrid pixel detector device

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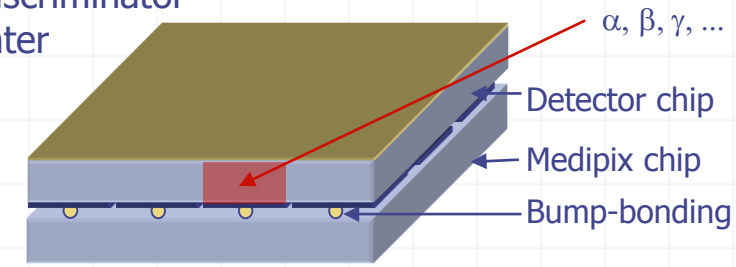
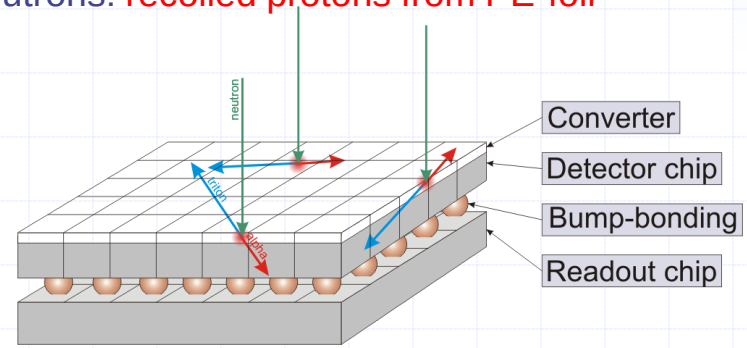
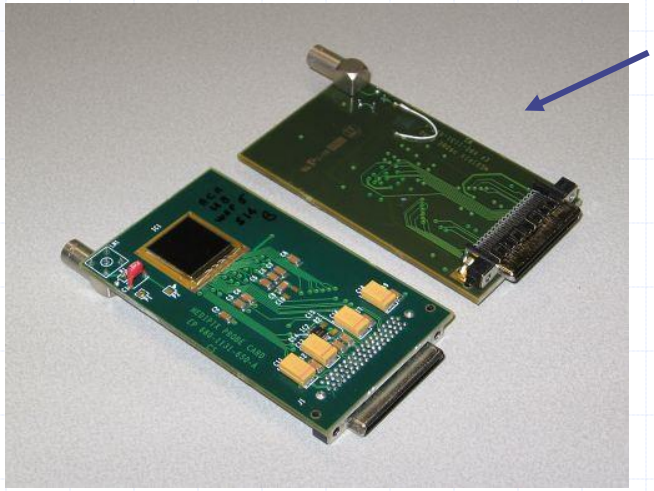
- Planar pixellated detector (Si, GaAs, CdTe, thickness: 300/700/1000μm)
- Bump-bonded to Medipix readout chip containing in each pixel cell:
  - amplifier,
  - double discriminator
  - and counter



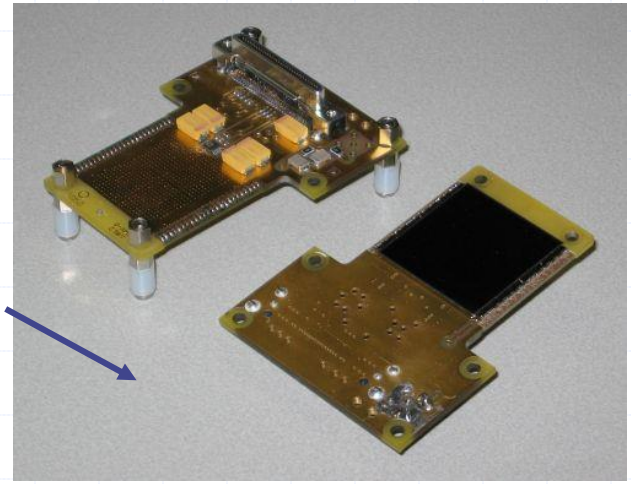
- Converter materials to detect
  - thermal neutrons: 6Li(n,α)T, Q=4.78MeV
    10B(n,α)7Li, Q=2.78MeV
  - fast neutrons: recoiled protons from PE-foil





Medipix2/Timepix
Pixels: 256 x 256
Pixel size: 55 x 55 μm^2
Area: 1.5 x 1.5 cm^2

Medipix2/Timepix Quad
Pixels: 512 x 512
Pixel size: 55 x 55 μm^2
Area: 3 x 3 cm^2



Medipix – single quantum counting detector
Timepix - spectroscopic pixel detector with ToT and ToA modes of operation

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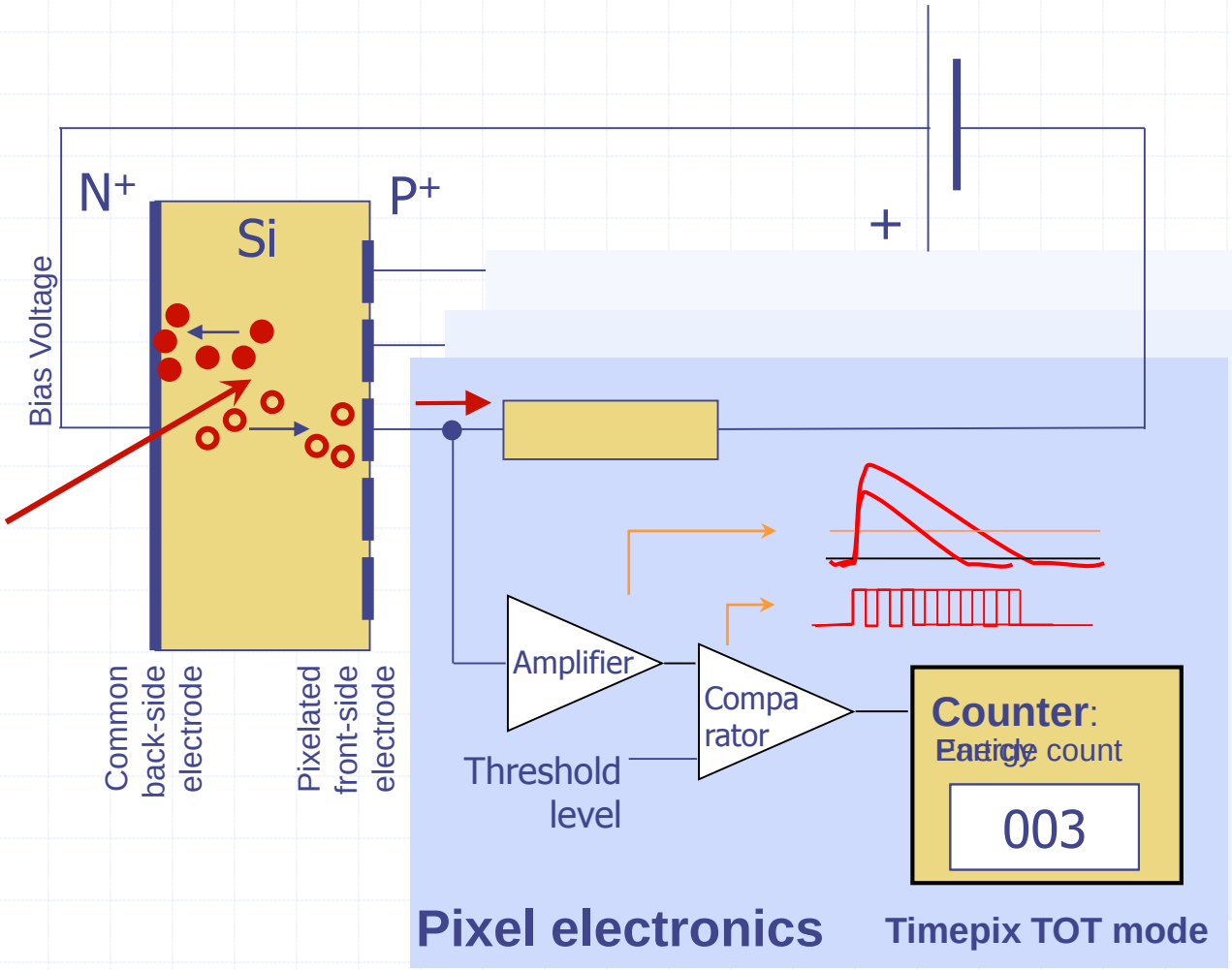

Threshold level above electronic noise
⇒ **No false counting**.

Digital integration (counting)
⇒ **No dark current**.

Unlimited dynamic range and exposure time. Counts obey poissonian distribution.

65k spectroscopic chains:
- SCA in case of Medipix
- MCA in case of Timepix
- MCA+TDC with Timepix3

Energy calibration
(Calibration of 65k MCA!
Question: how to deposit defined energy into a volume 55x55x300 μm^3?)

Medipix/Timepix – USB2 controlled portable device

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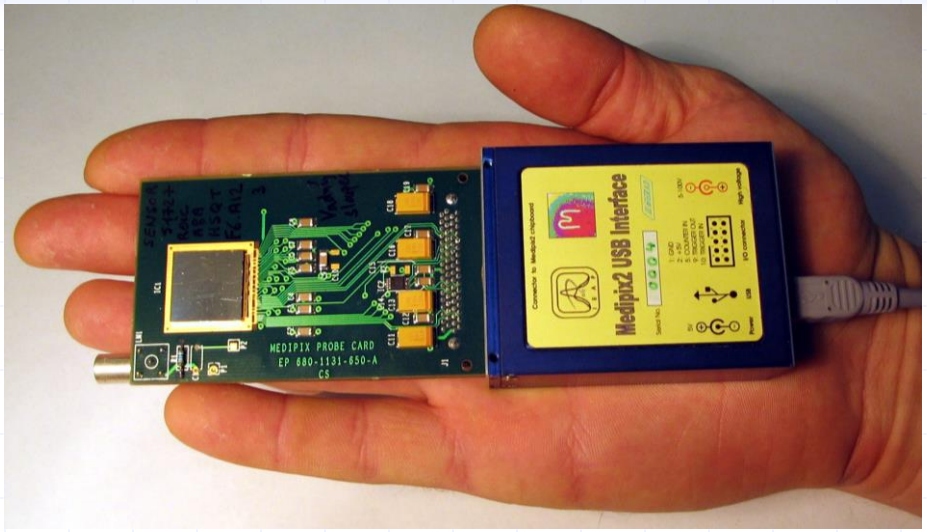

- Medipix/Timepix motherboard (R/O chip developed at CERN in frame of Medipix2 collaboration) assembled to USB2 interface board (developed with Pixelman software package at IEAP CTU in Prague), http://www.utef.cvut.cz/MEDIPIX.
- The MEDIPIX/Timepix-USB device connected to the portable PC. Up to 80 frames per second (USB2 serial connection) or 800 f/s (parallel connection). One PC can effectively run up to 50 devices.
- Light version of the Medipix-USB interface (on the right).

Soft tissue high resolution X-ray imaging and tomography – mouse kidney (the best achieved resolution up to 700 nm)

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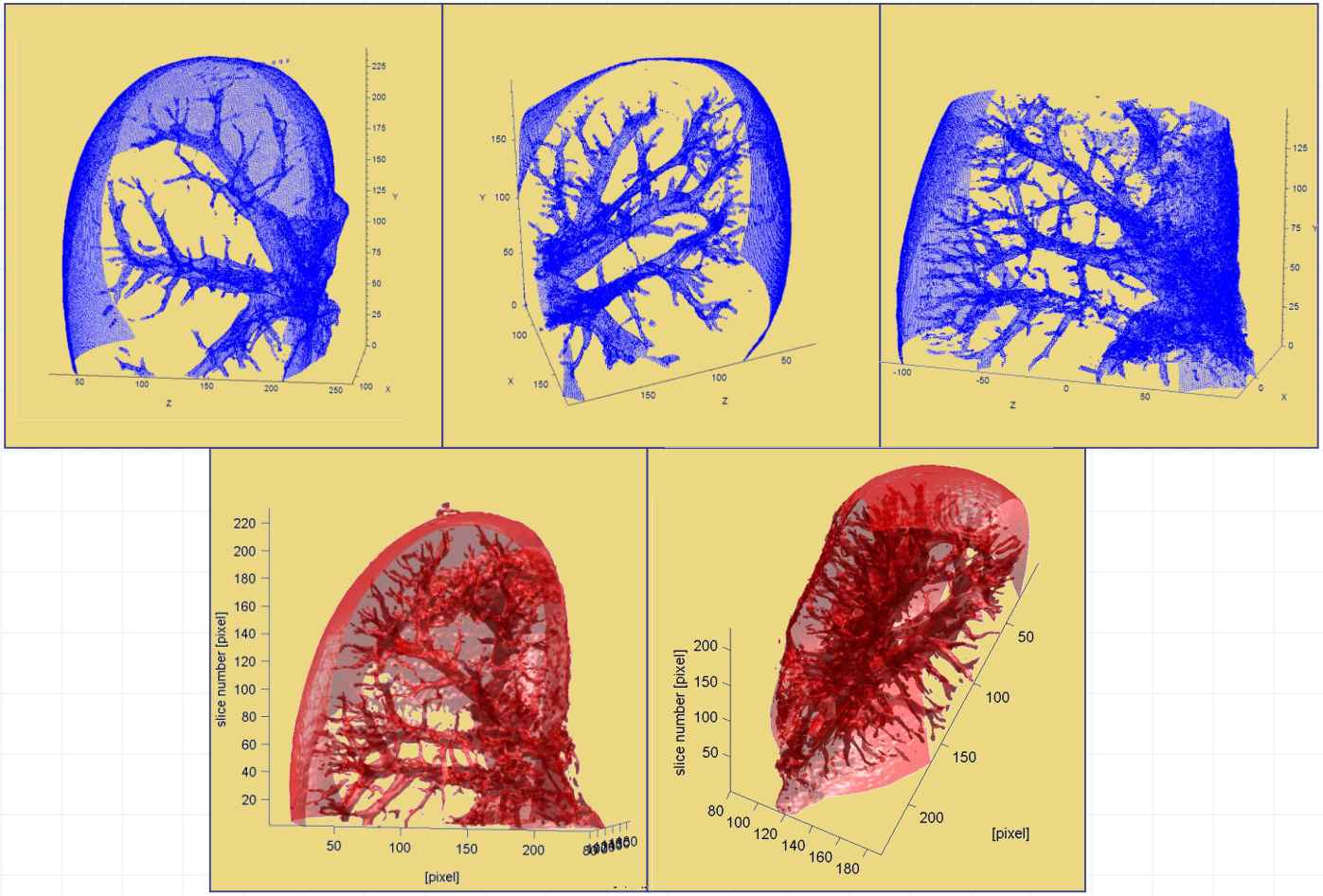
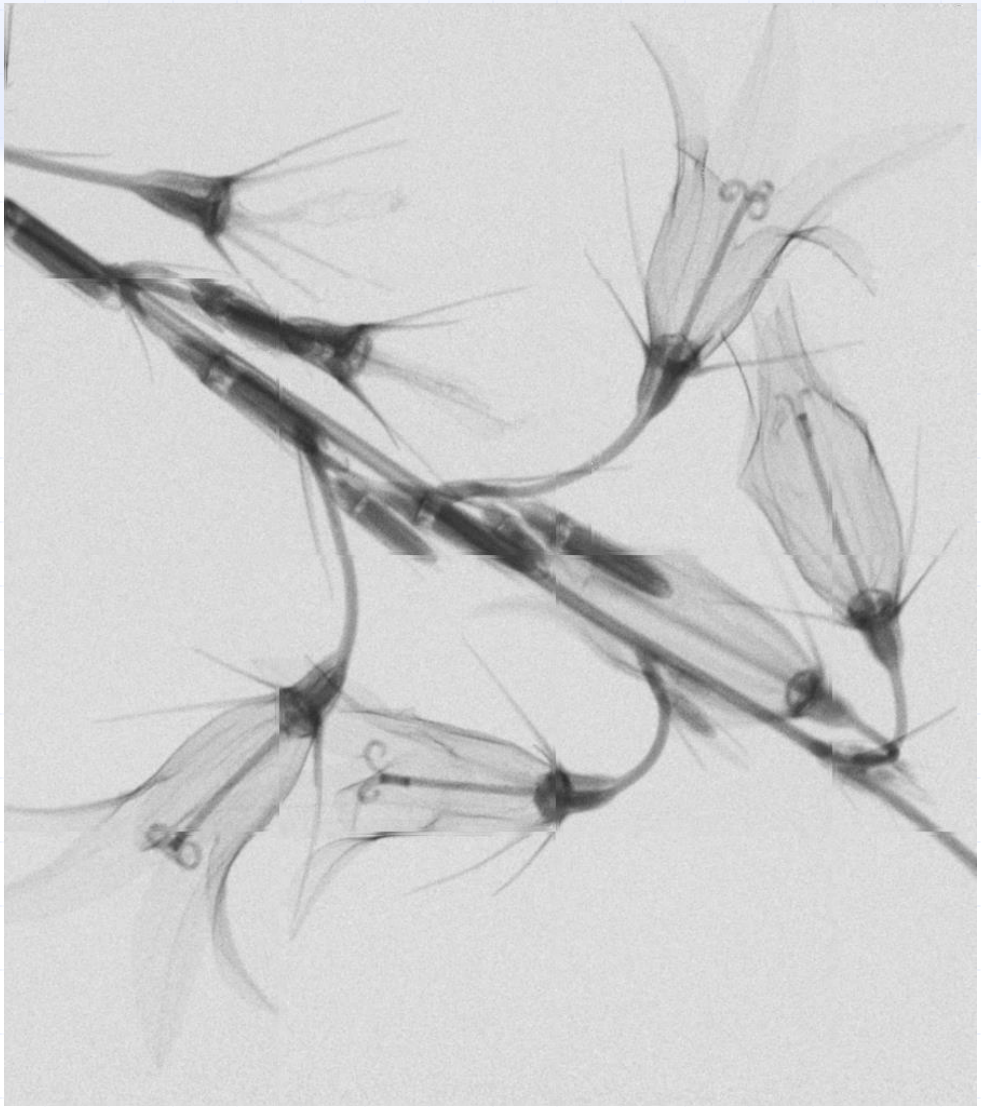
Missing angles => Iterative algorithm instead of Filtered back projection (3 iterations in OSEM 5)



High resolution neutron radiography of bellflower



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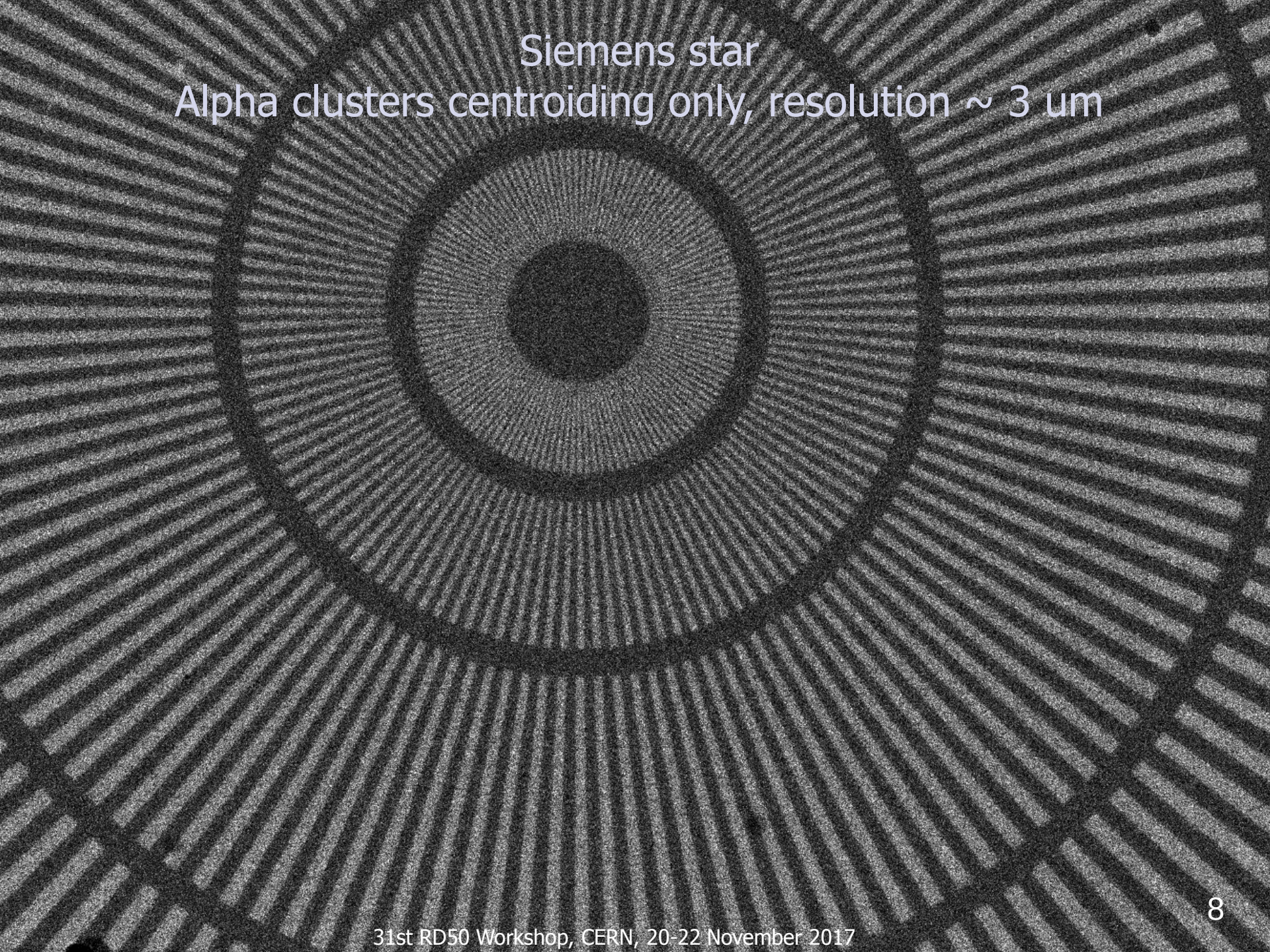
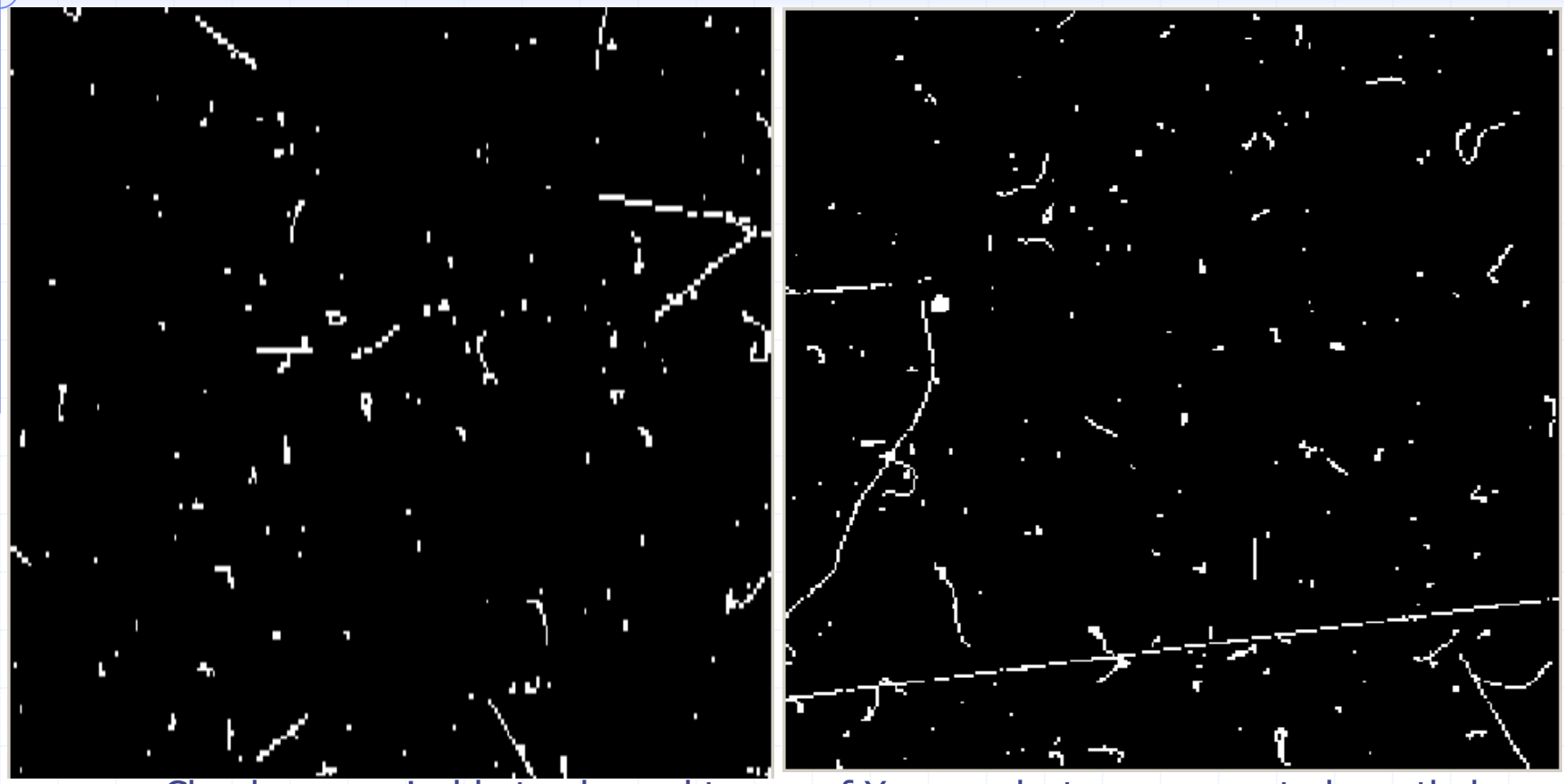

Siemens star
Alpha clusters centroiding only, resolution ~ 3 um

Response of Medipix2 device to natural background radiation



Clearly recognizable tracks and traces of X-rays, electrons generated mostly by gamma rays, alpha particles, muon, … . Muon tracks can be recognized by submicrometric precision.

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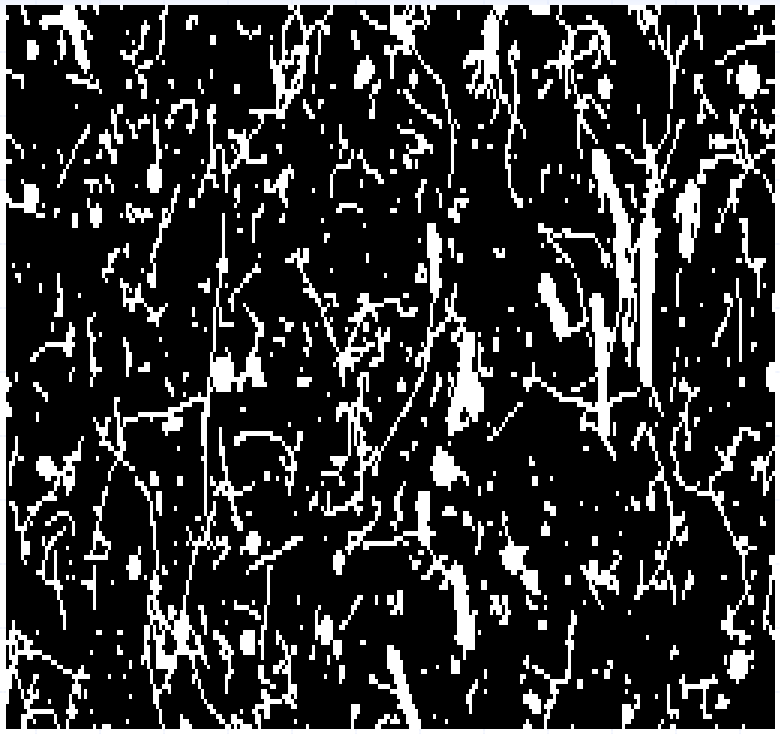
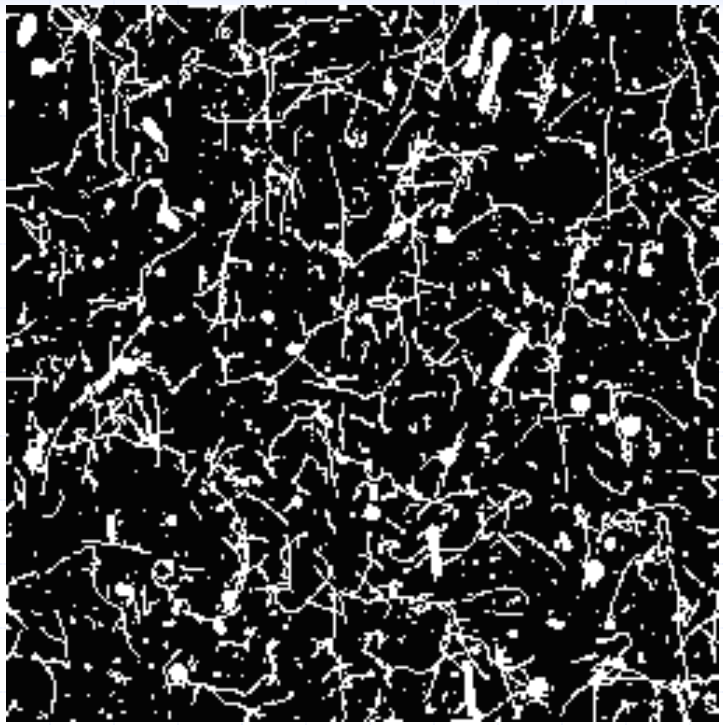
Response of MEDIPIX-USB device with polyethylene converter (on the right hand side) to fast monochromatic neutrons (17MeV)





- The direction of the neutrons with respect to the image was upstream (from bottom to top). The huge background is due to gamma rays which accompany neutrons. Half of the sensor (the right-hand side) was covered with a CH2 foil about 1.3 mm thickness.
- One can clearly recognize long and rather thick tracks of recoiled protons (up to 2 mm, vertically oriented) and big tracks and clusters generated via 28Si(n,α)25Mg, 28Si(n,p)28Al nuclear reactions in the body of the silicon detector. These events are displayed on the dense background caused by tracks and traces of electrons from interactions of gamma rays. One can even recognize that proton tracks shapes follows a Bragg law.

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Flight of 11 MeV protons entering the silicon sensor under 85°

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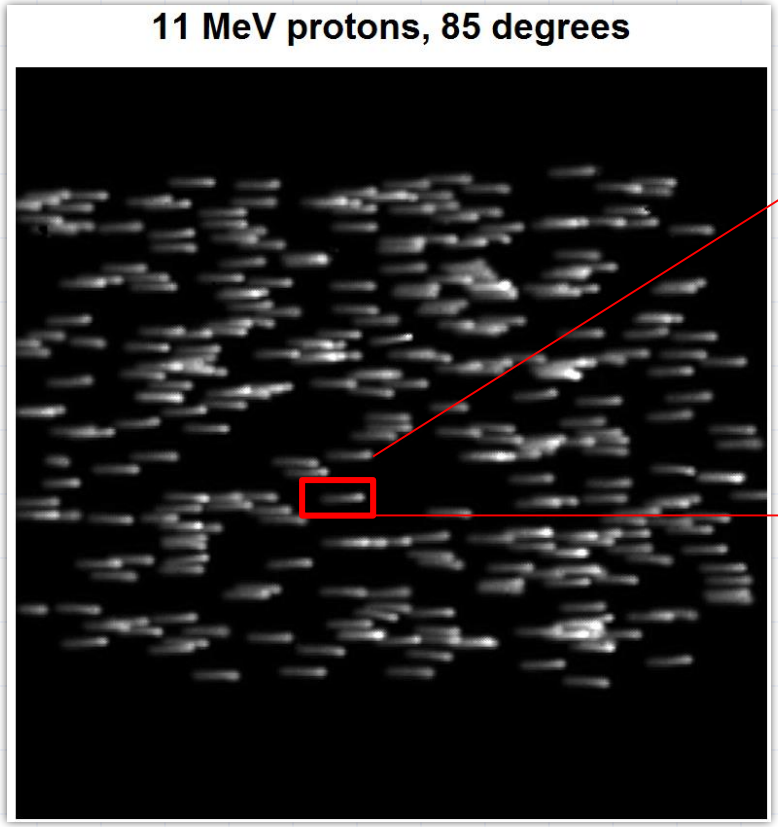
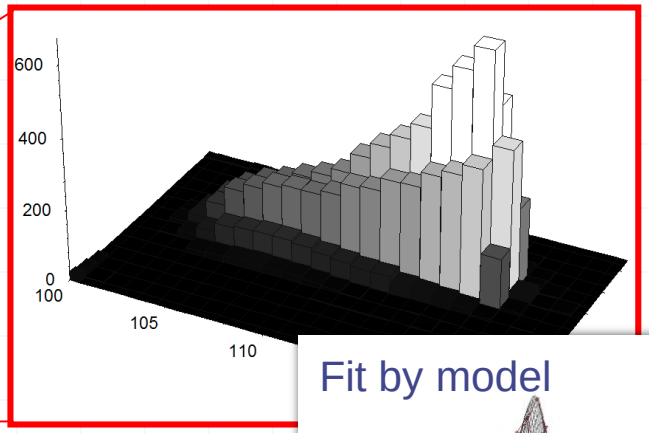
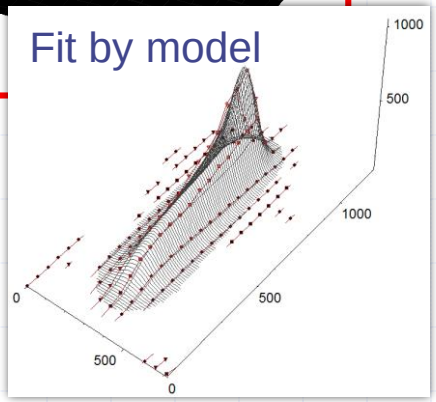


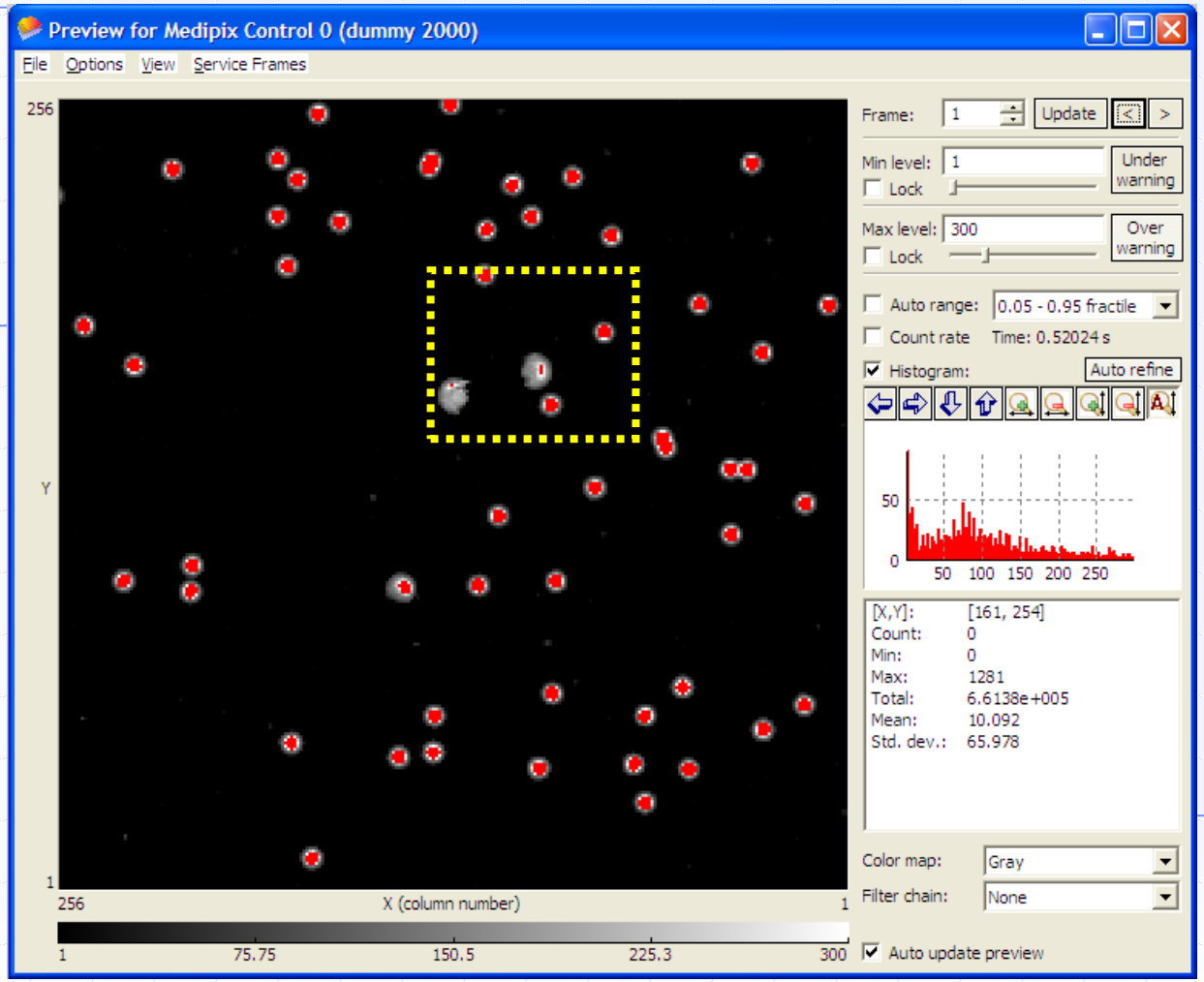
ΔE/Δx Bragg profile nicely pronounced, proton range about 960 μm



Fit by model



Response of TimePix damaged regions to 5.9 MeV α's (^{244}Cm)



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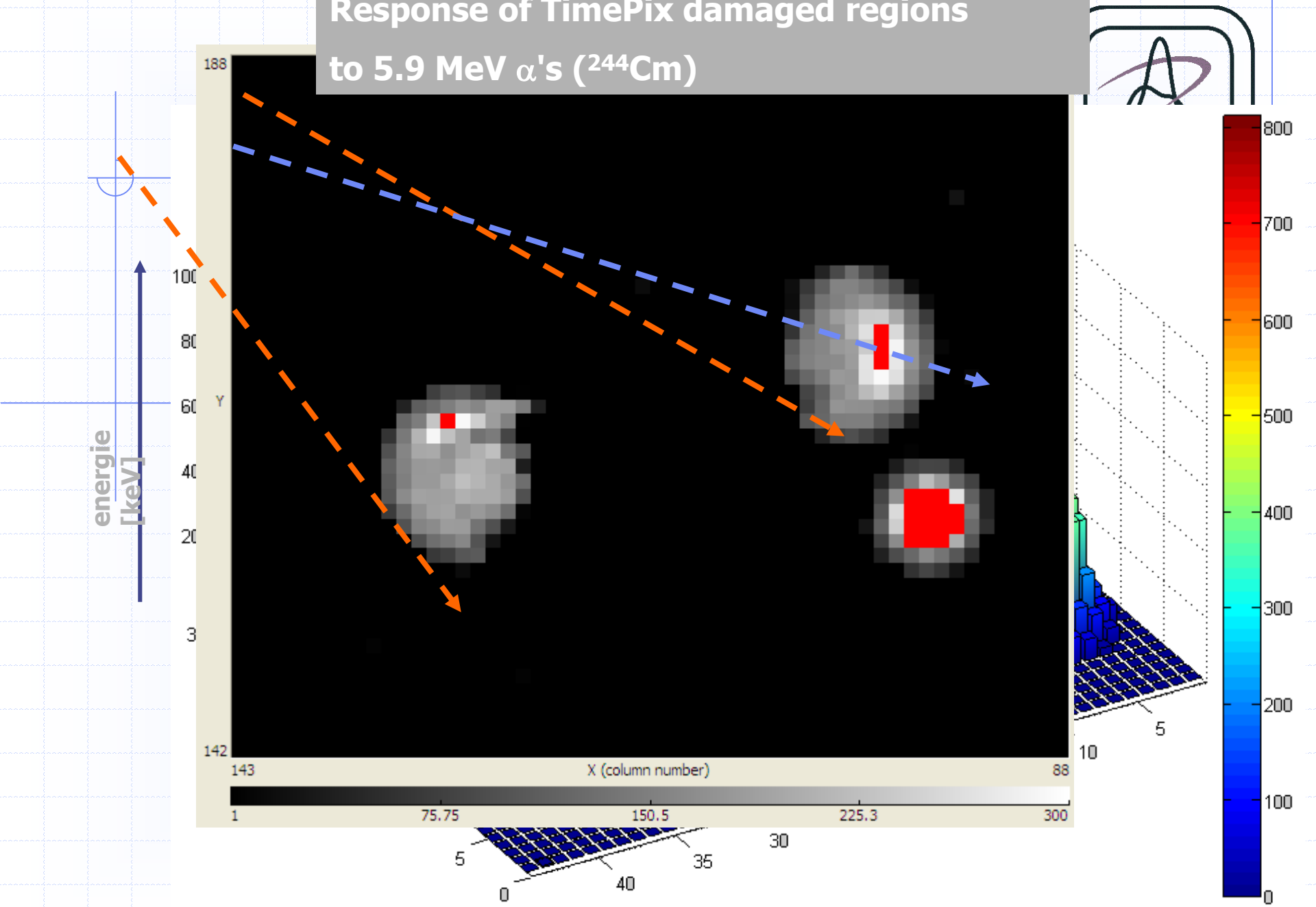

Single ^{8}He ion decay sequence recorded by Timepix operating in ToA mode

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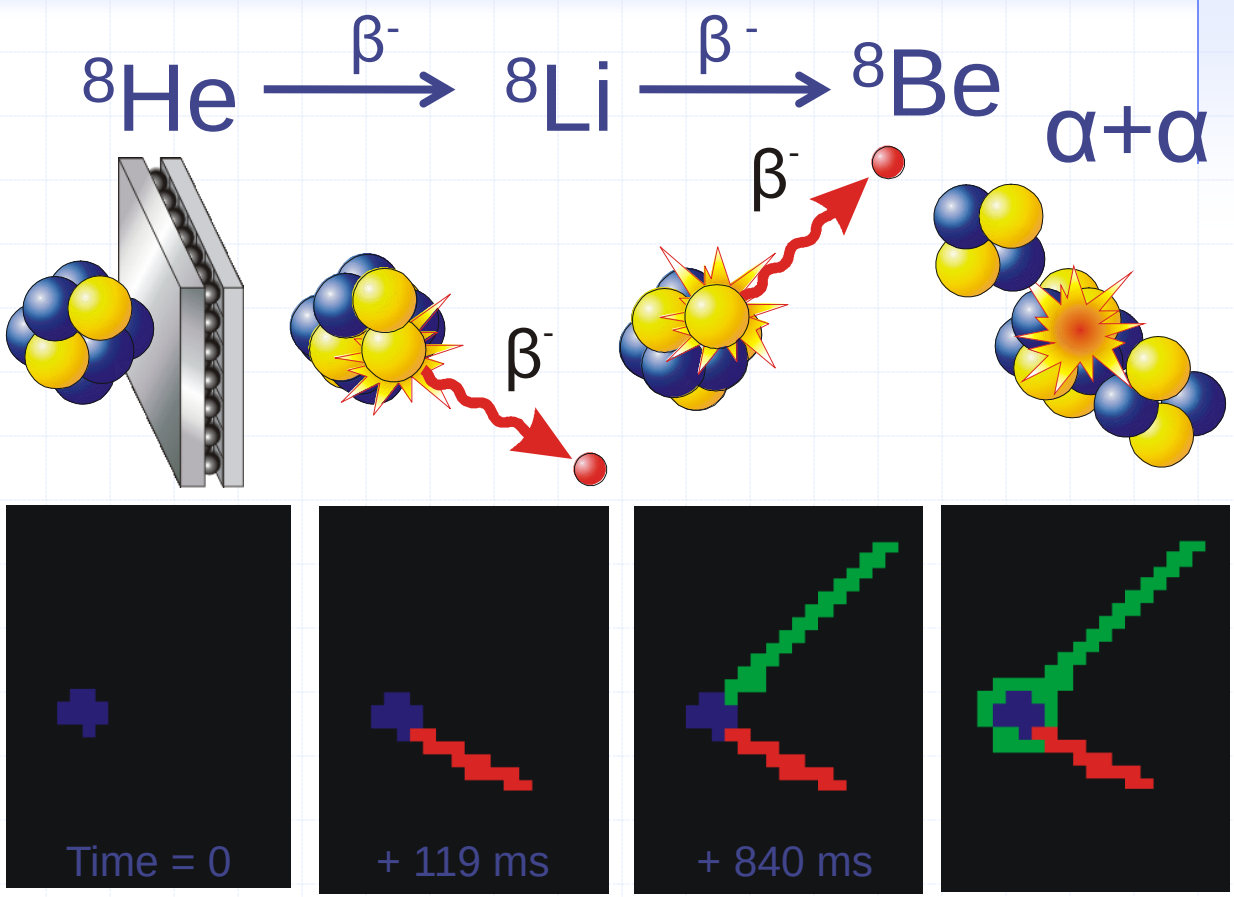
^{8}He ion hits the Timepix sensor where undergoes β-decay

Subsequent decays of the daughter nuclei by emission of one beta and two alpha particles follows



Typical observed tracks of particles used for hadron therapy beam

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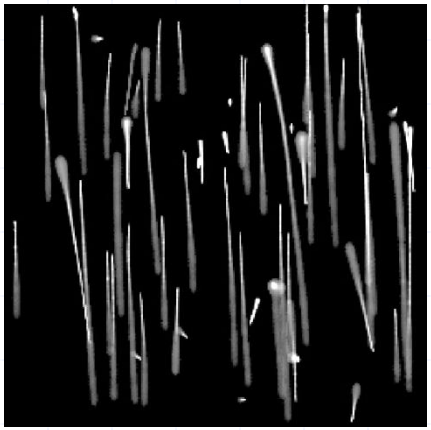
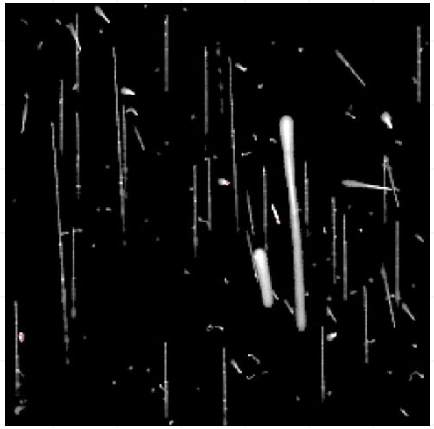
Protons 48 MeV



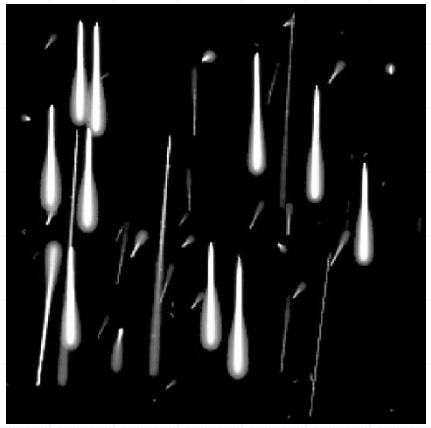
Only protons and their scattering, no secondaries.

Protons 221 MeV



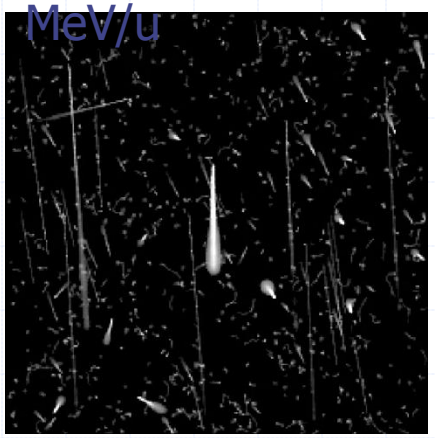
Many secondaries, (delta electrons fragments).

Carbons 89 MeV/u



Carbons and protons and their scattering, no secondaries.

Carbons 430 MeV/u



Carbons and many secondaries.

Detailed visualization of interactions in the Silicon sensor

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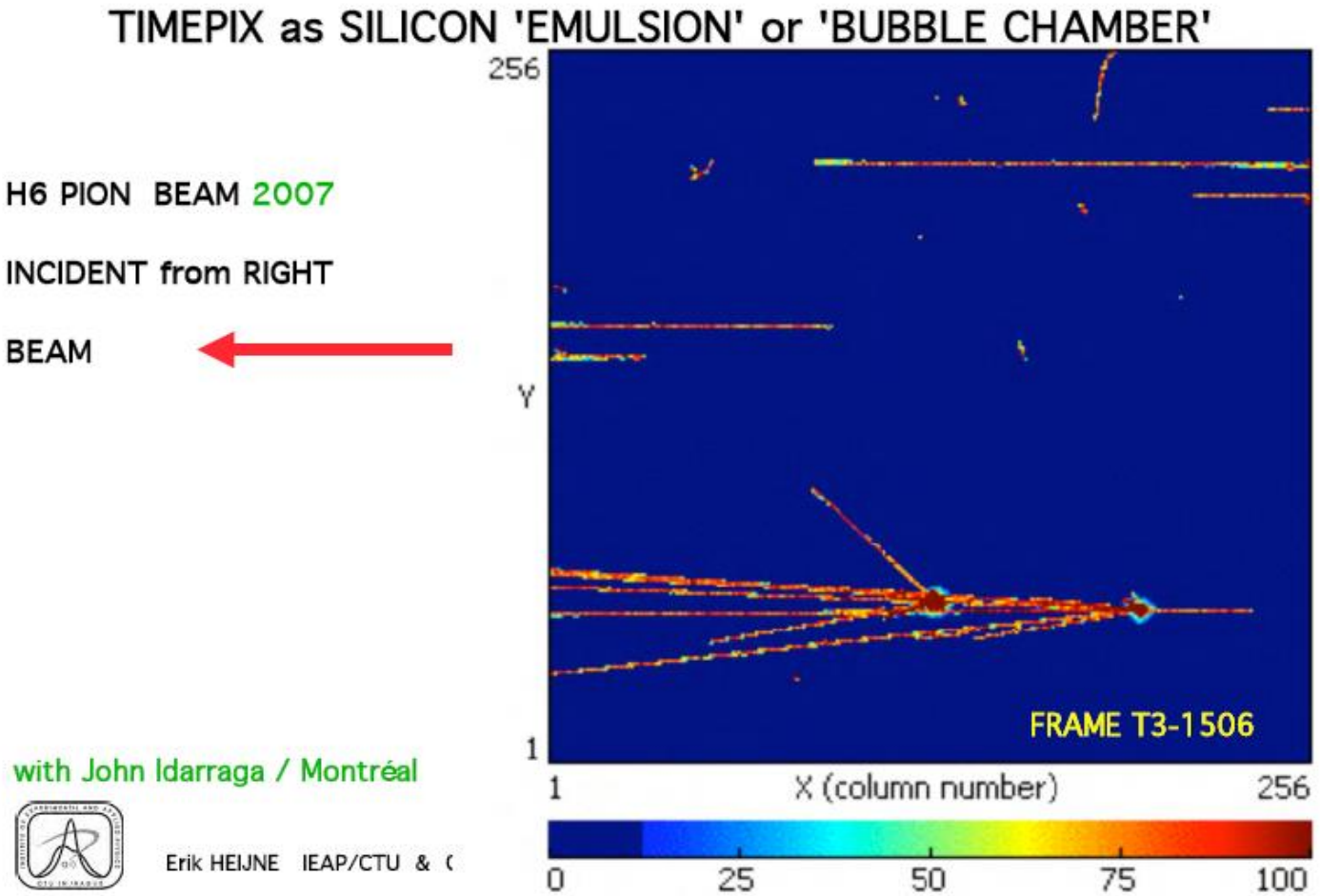

Relativistic Ions @ small (grazing) angles

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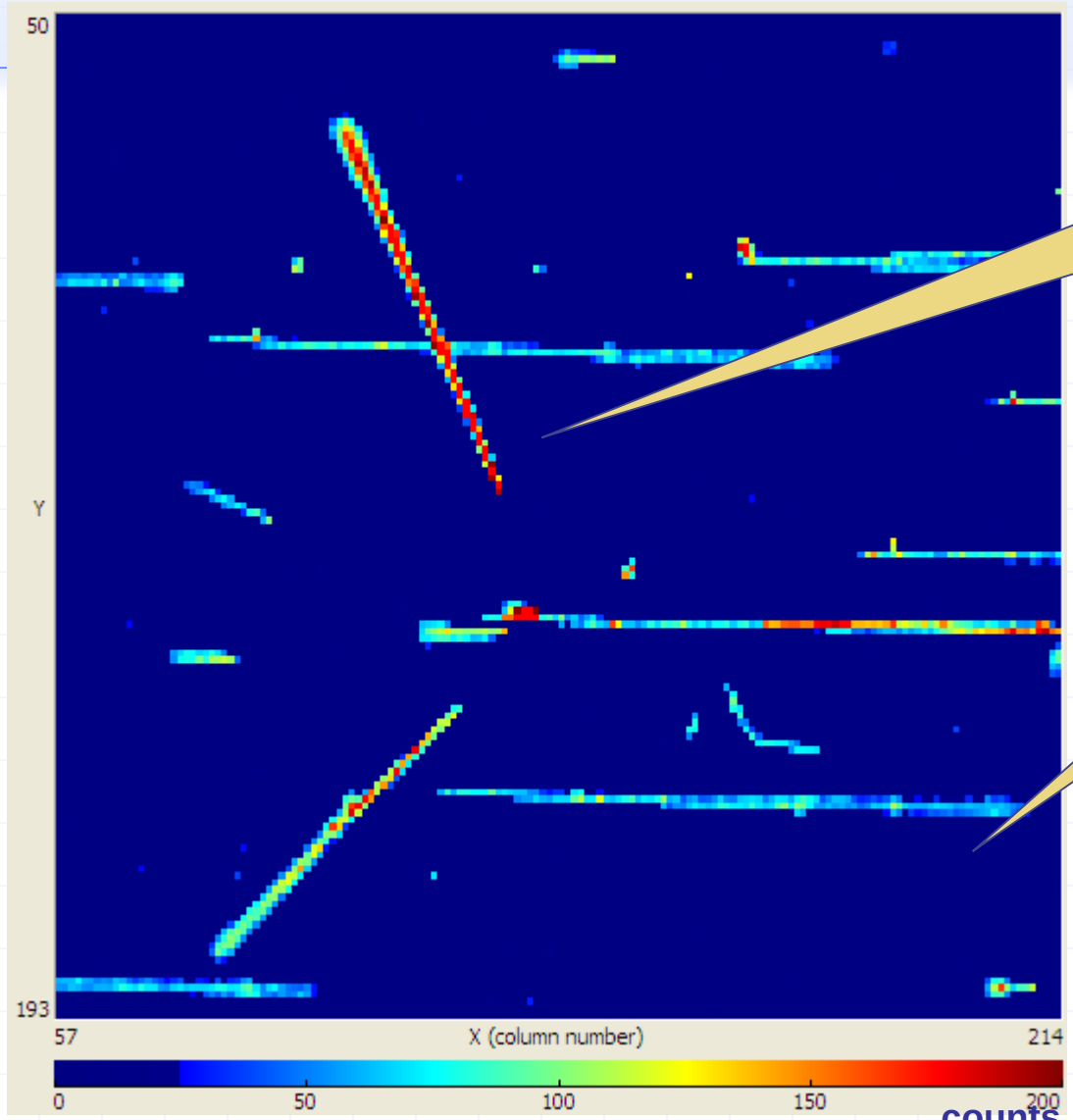
^{2}H

angle = 3°



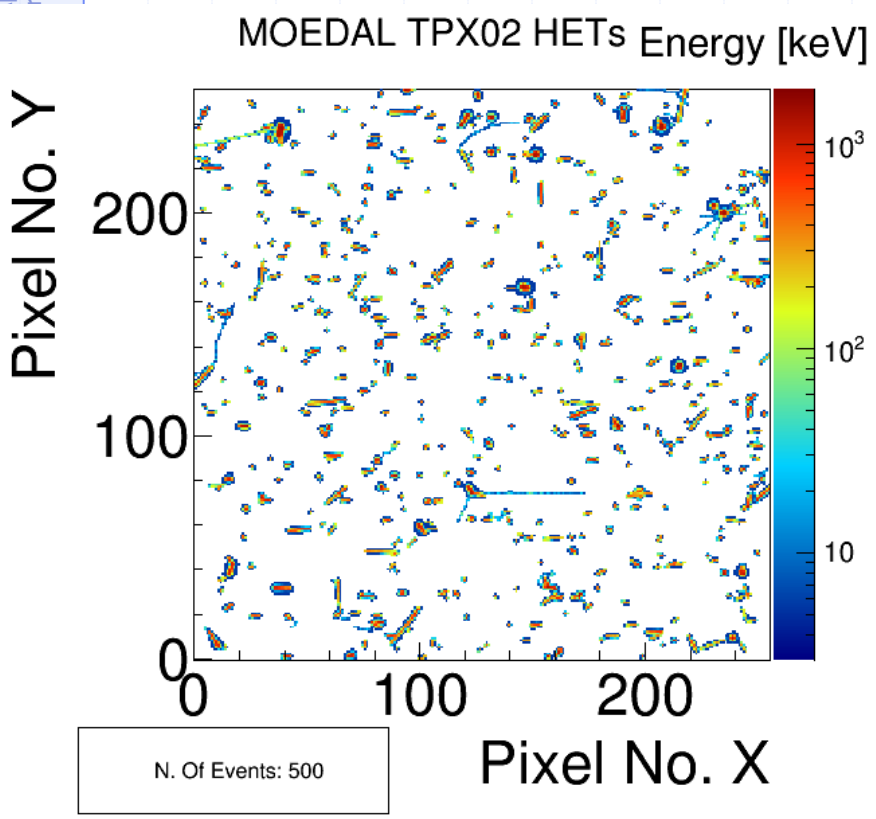
Nuclear reaction product

Beam ions

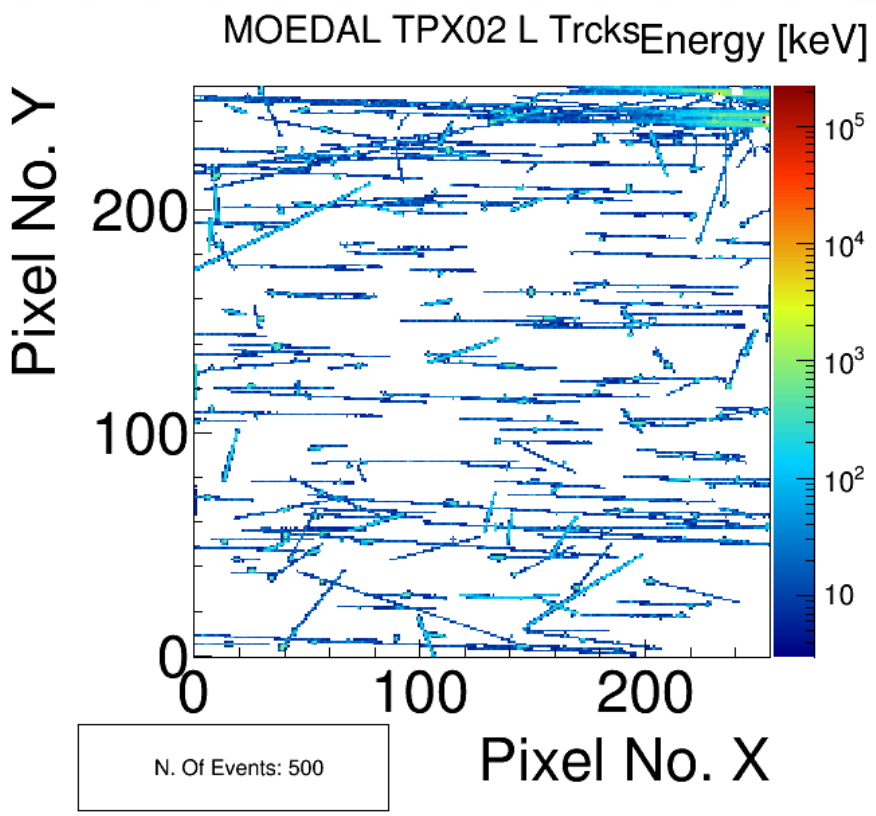
MoEDAL experiment at LHC

Selected tracks observed with TPX02 - 12/09/2015

High Energy Transfer Events
(Min Clstr Height: 300 keV)

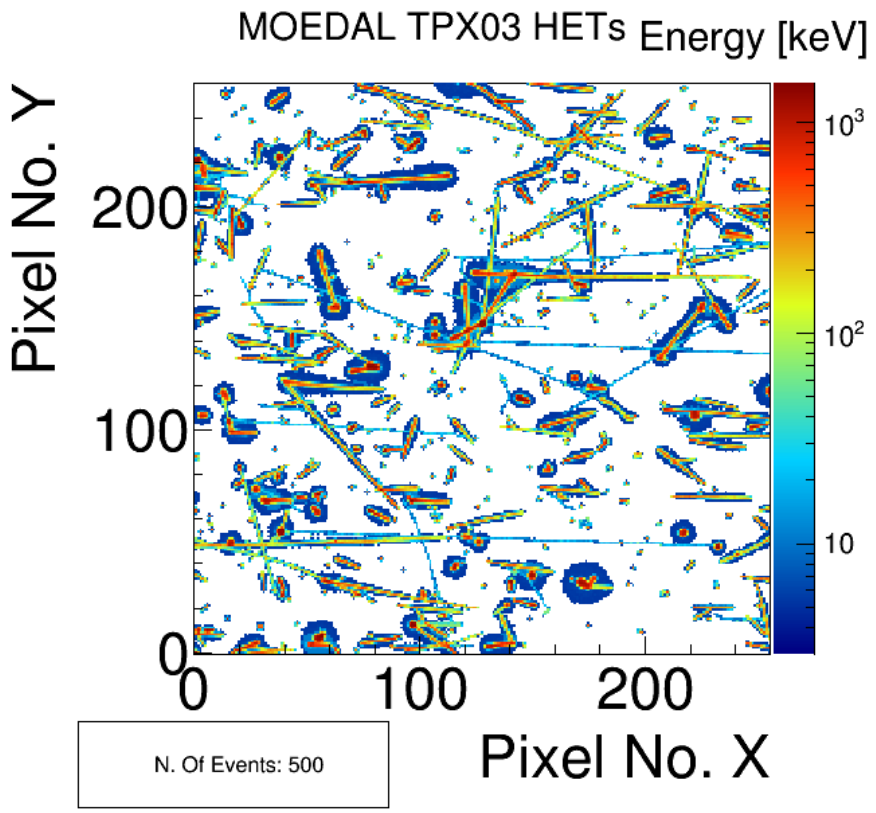


Long Tracks
(Min Clstr Height: 300 keV)

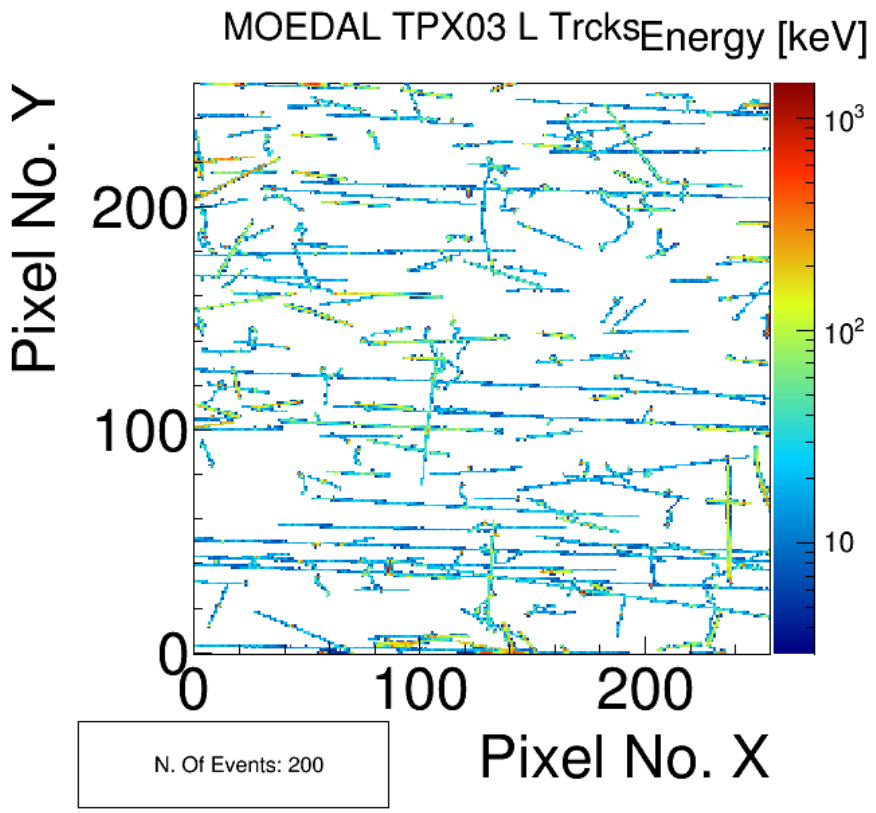


Selected tracks observed with MOEDAL TPX03
12/09/2015

High Energy Transfer Events
(Min Clstr Height: 300 keV)

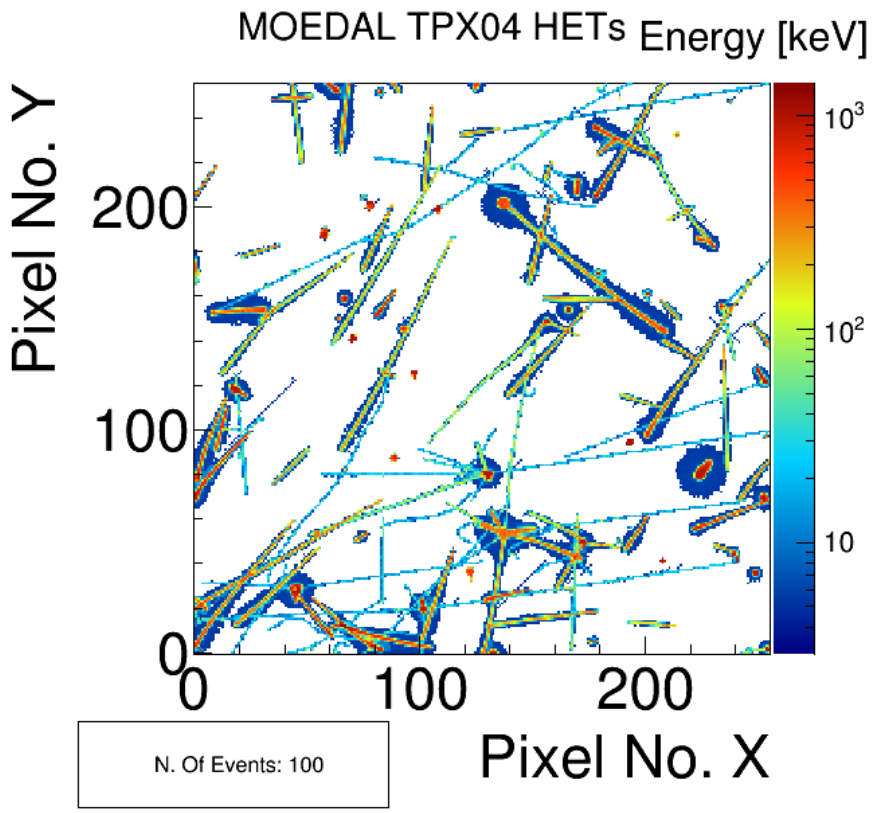


Long Tracks
(Min Clstr Height: 300 keV)

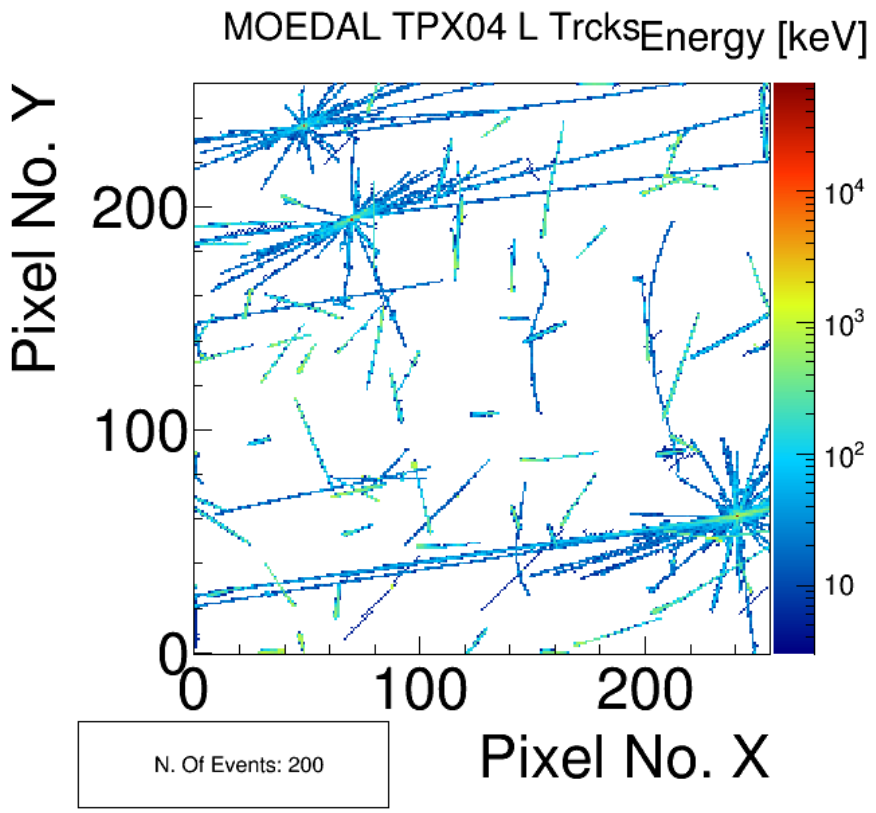


Selected tracks observed with MOEDAL TPX04
12/09/2015

High Energy Transfer Events
(Min Clstr Height: 300 keV)

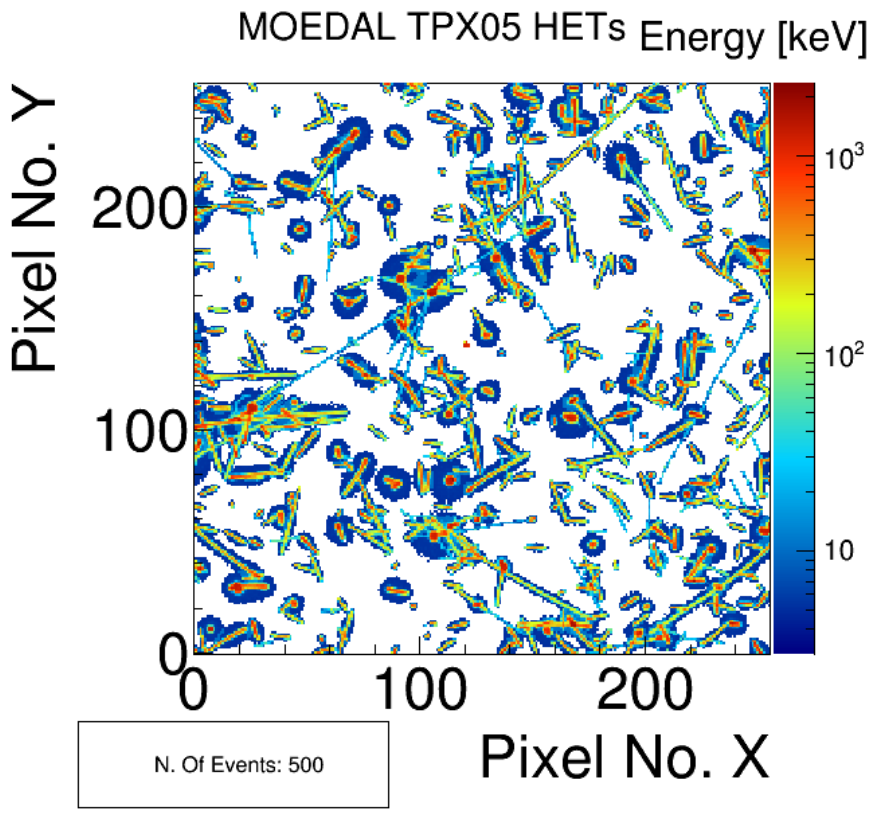


Long Tracks
(Min Clstr Height: 300 keV)

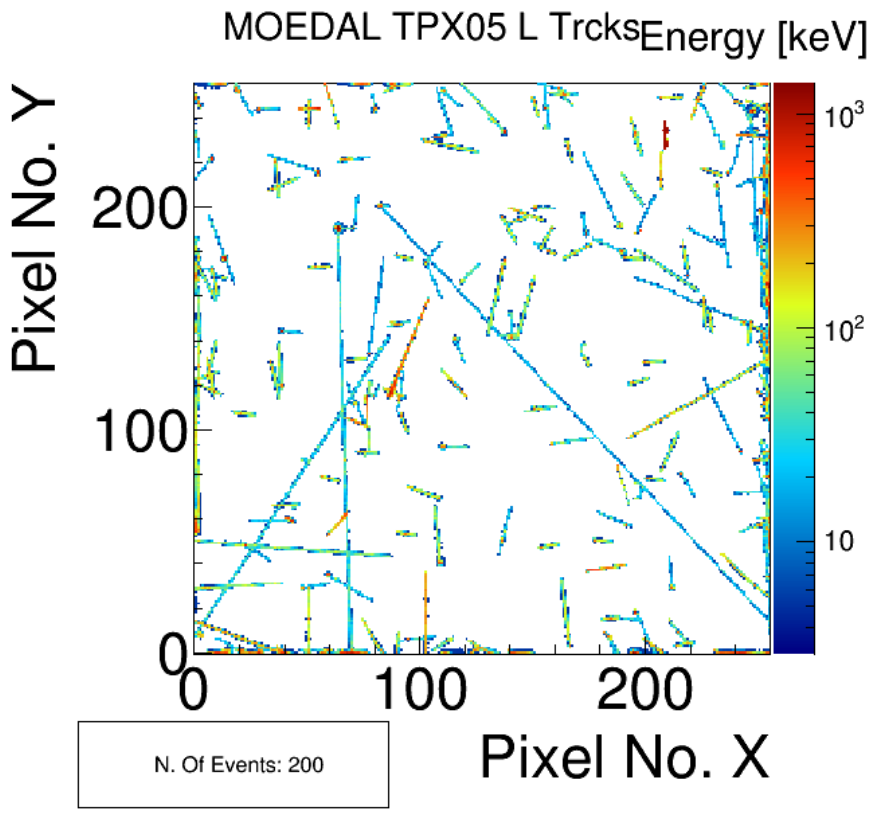


Selected tracks observed with MOEDAL TPX05
12/09/2015

High Energy Transfer Events
(Min Clstr Height: 300 keV)

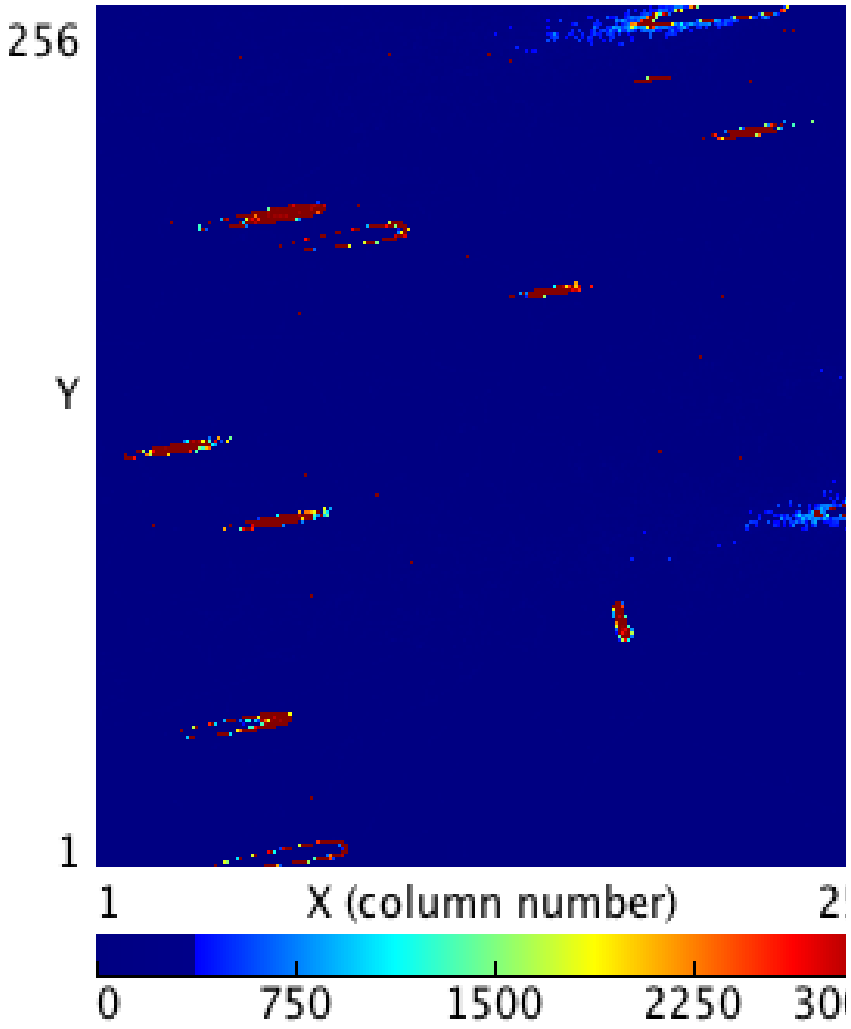


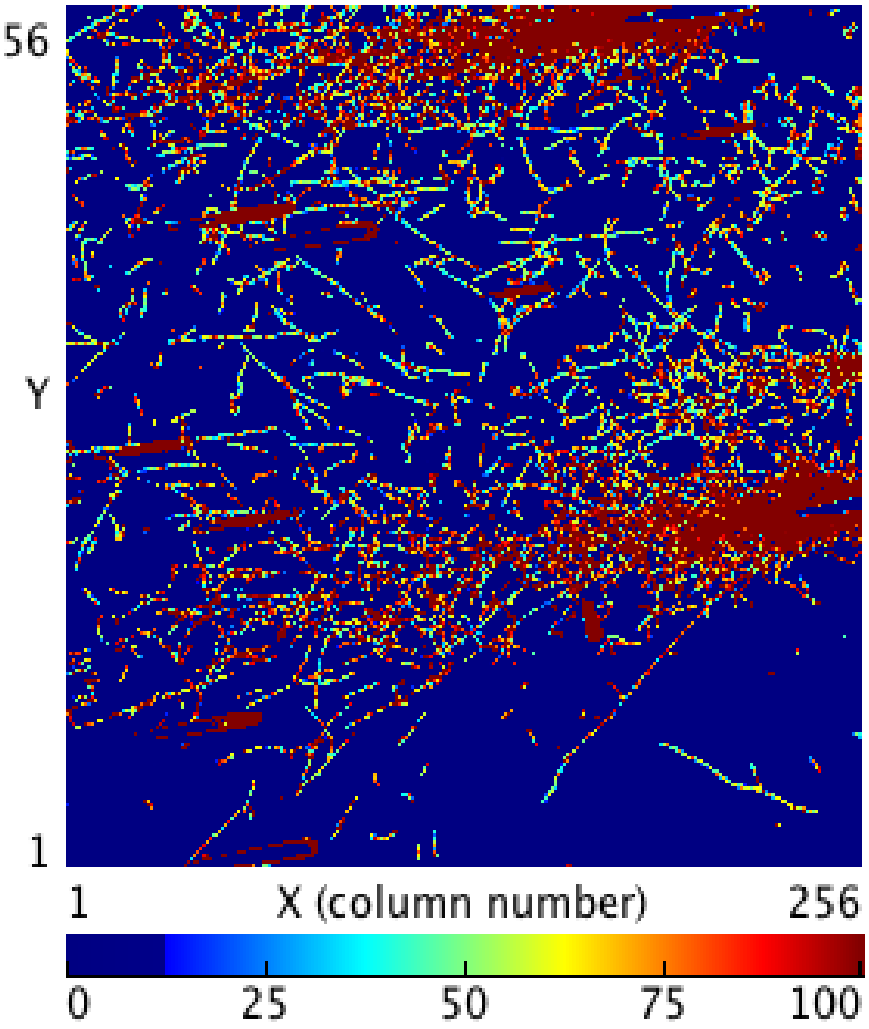
Long Tracks
(Min Clstr Height: 300 keV)



Tracks of Pb ions as measured on SPS beam at CERN

(rear-side glancing angular incidence about 4.1 degree)





scale 100 scale 3000

Imaged with high threshold on the left and with low threshold on the right

ATLAS-TPX: Composition of the radiation field at different places (during collisions)

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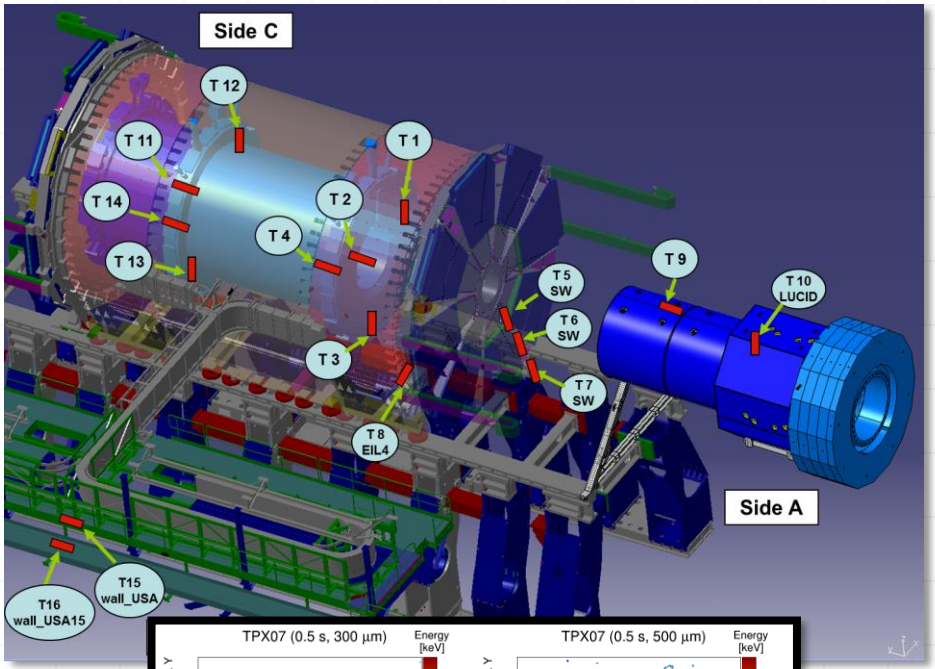
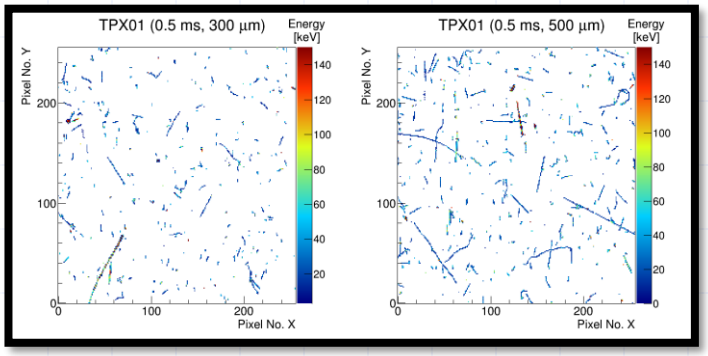
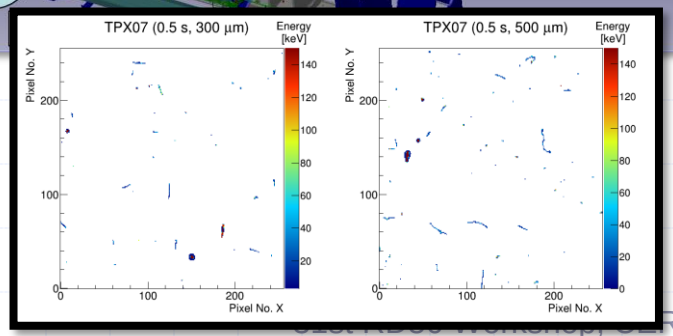
Setup: 16 ATLAS-TPX two-layer devices installed in the ATLAS detector at different places (during collisions on May 31, 2016)

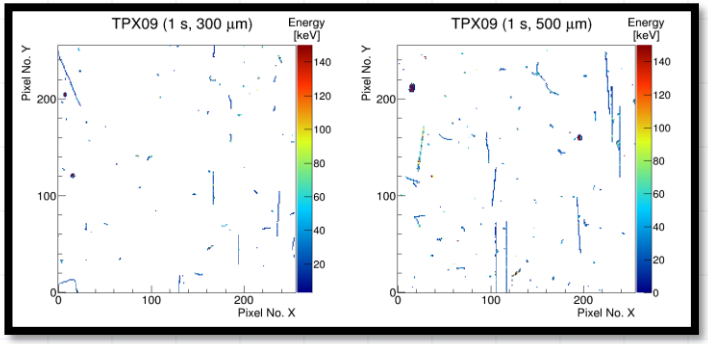




TPX04: Frame of 0.1 sec. measured on May 31, 2016



TPX07: Frame of 0.5 s.



TPX09: Frame of 1 sec.

Fast neutron ToF measurement with TIMEPIX

LANSCE neutron sources and nuclear science flight paths

(combined ToA and ToT modes)

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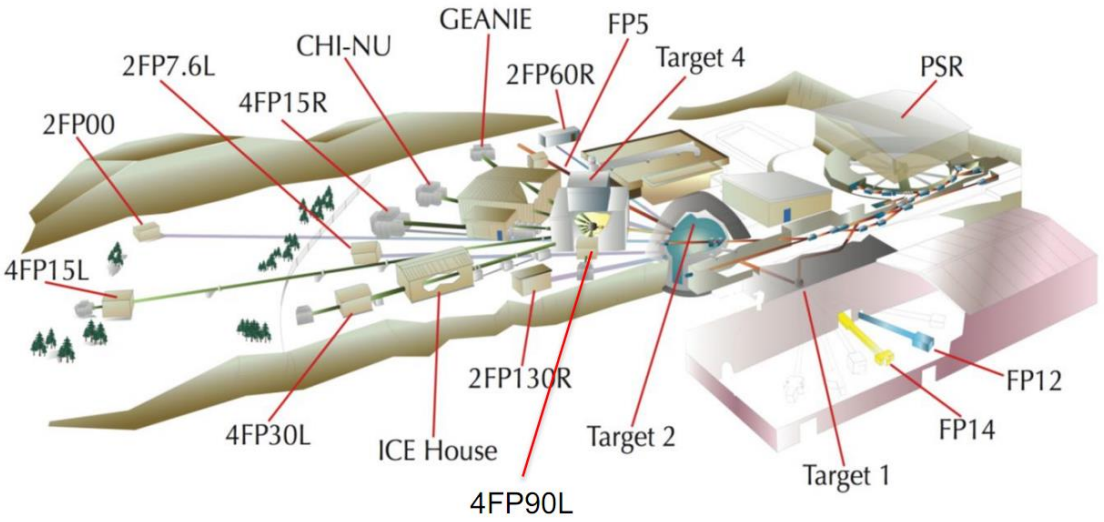
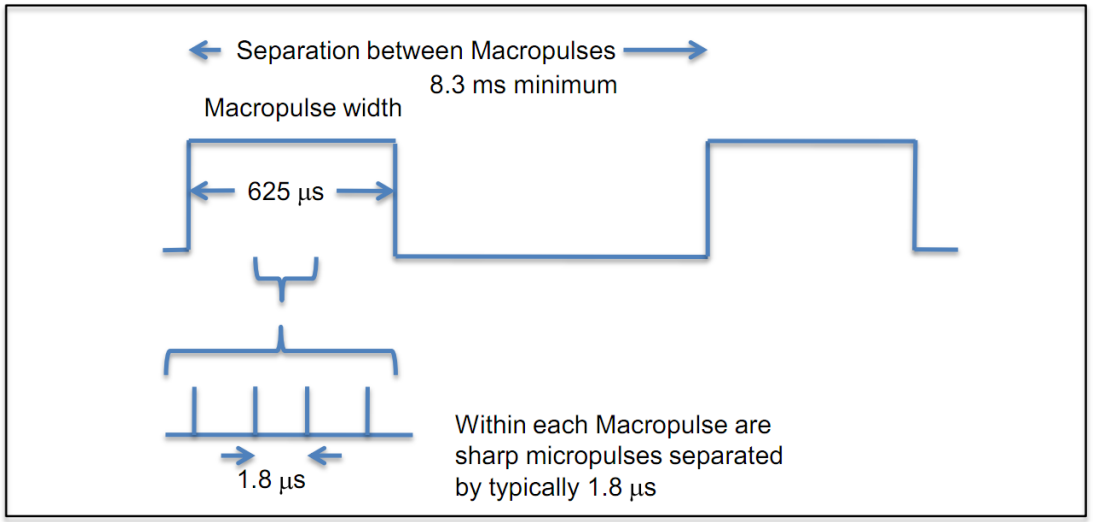
- The layout of the LANSCE neutron sources and Nuclear Science flight paths



- Time structure of the proton beam for typical Target-4 operation 1.8 ns pulses every 1.8 μs



Fluences of different cluster types over energy

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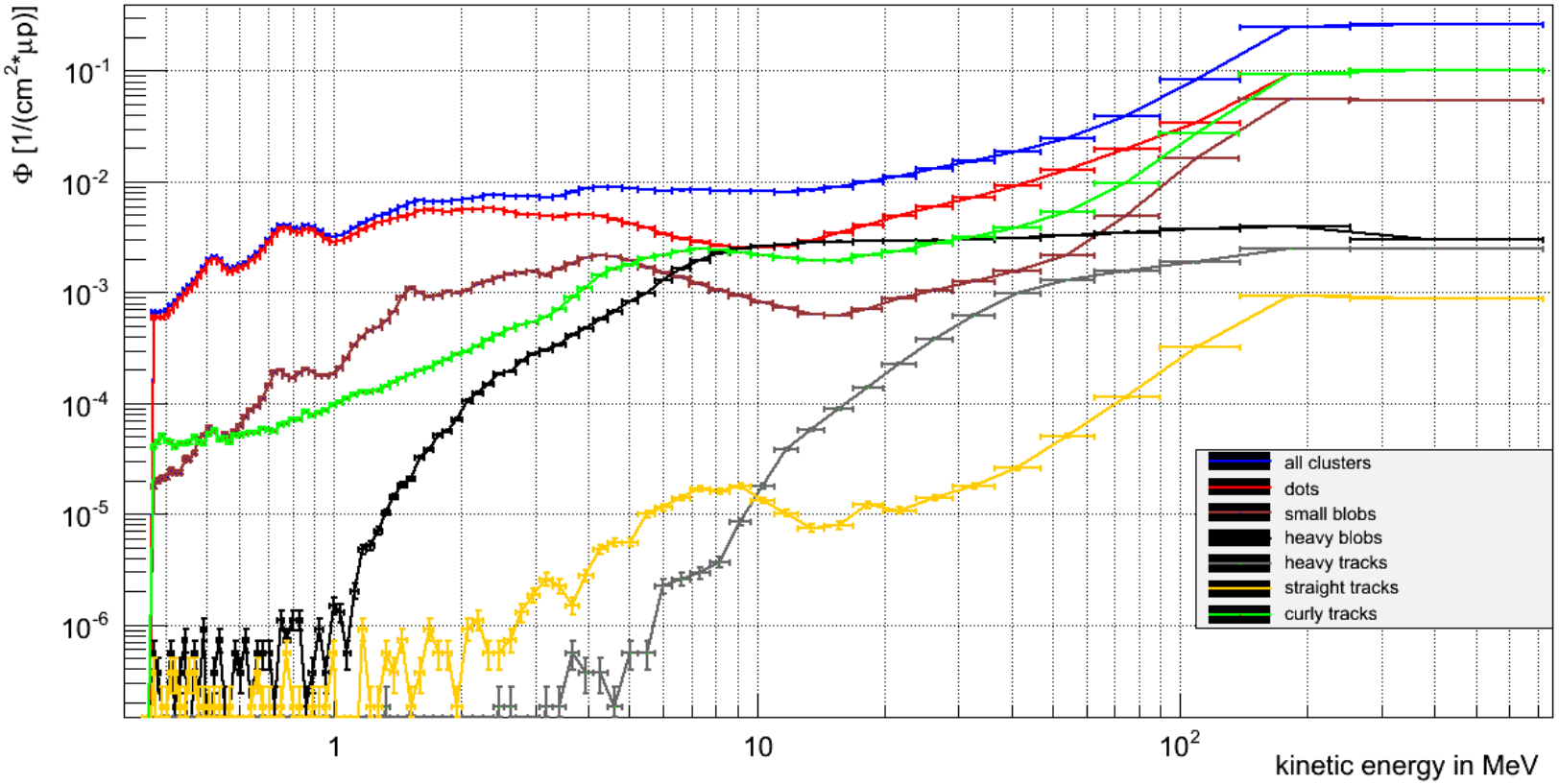
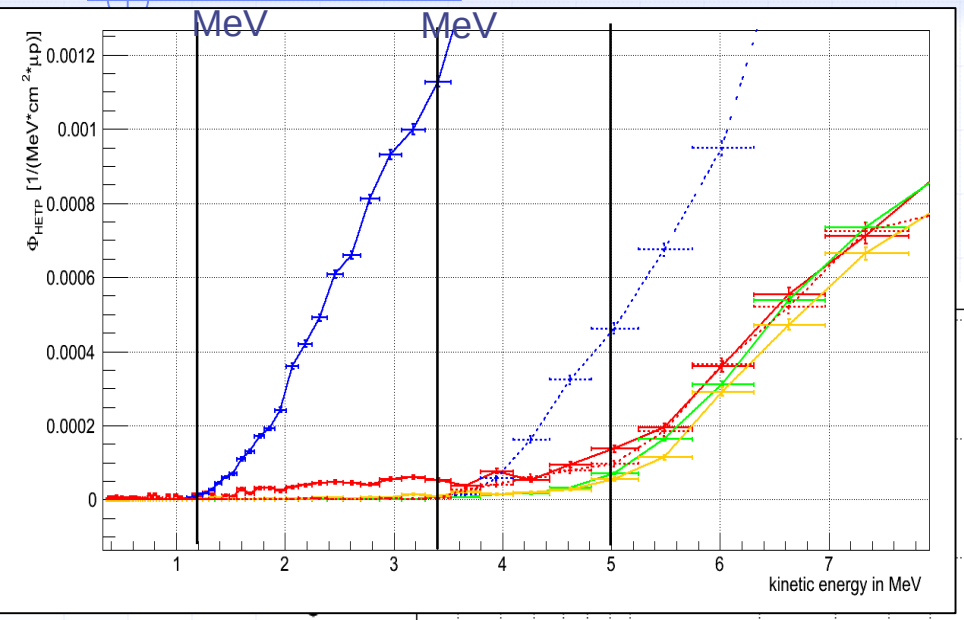
- Curly tracks, dots and small blobs dominate nearly over the whole energy range
- Asymmetric errorbars in x-direction due to binning of the measurement
- Three humps are present at lower fast neutron energies (<1 MeV) -> dots

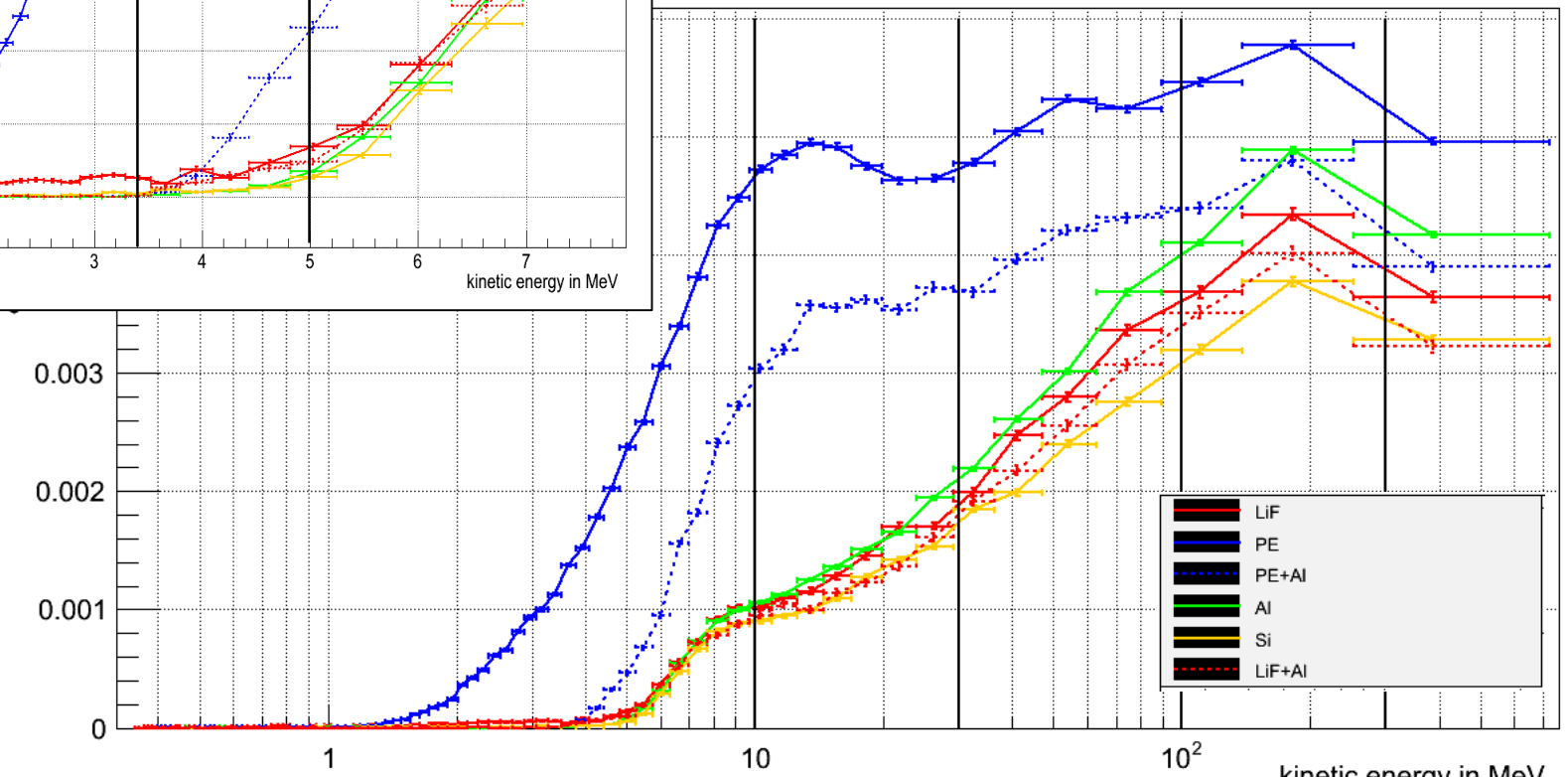


Fluences below different conversion layers

In the lower energy region responses below LiF, PE, PE+Al seem to be a good indicator for neutron energies

- Threshold for PE+Al at ~ 3.4 MeV
- Enhanced signal below LiF up to 4 MeV
- Recoiled protons visible above 1.2 MeV





Cluster shapes
Timepix detector responses as a function of neutron kinetic energy

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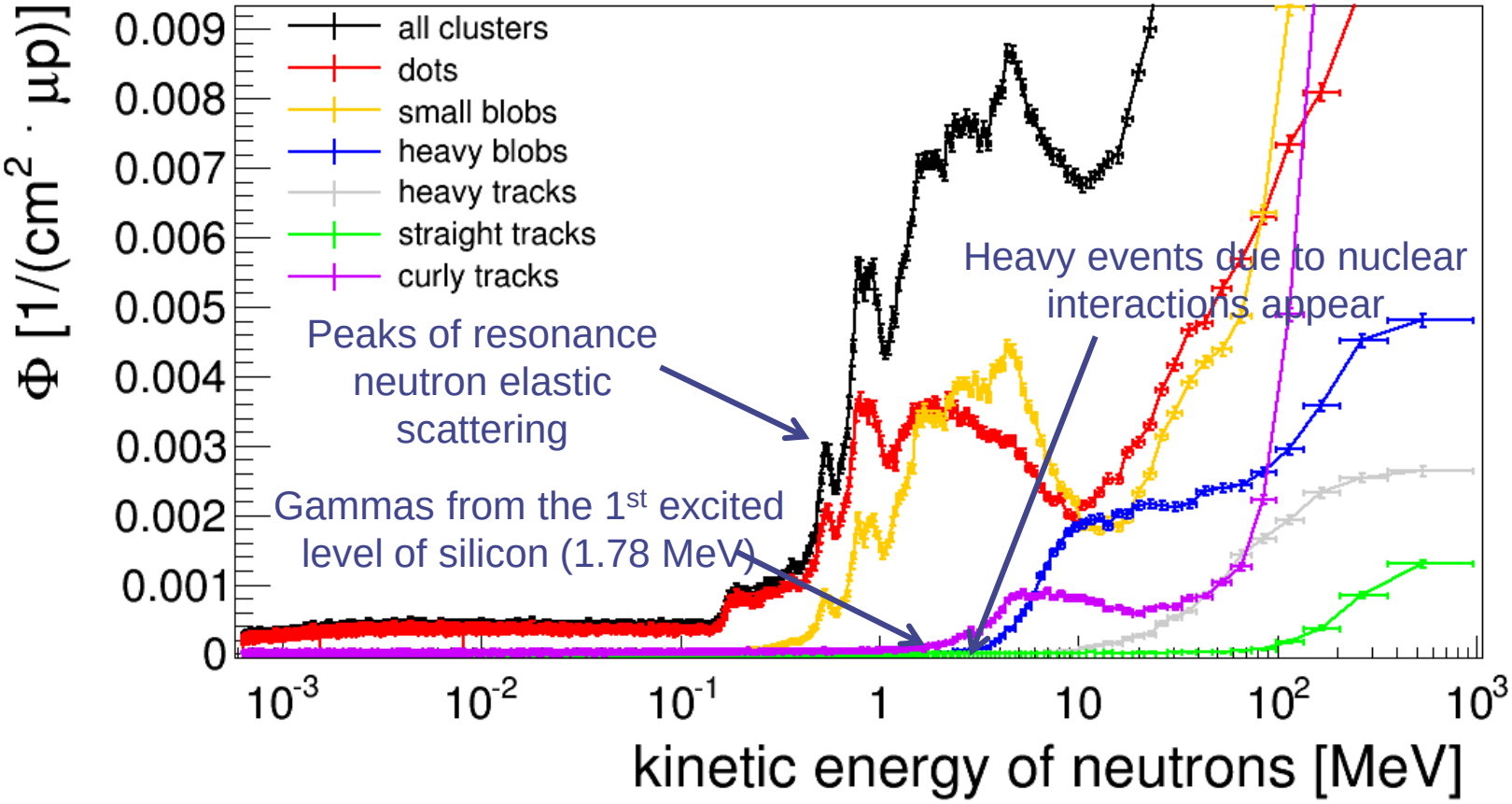
- The ToF technique*) was used to assign the detector responses to the corresponding neutron energies (track by track).



*) see: B Bergmann *et al* 2014 *JINST* **9** C05048

TIMEPIX3

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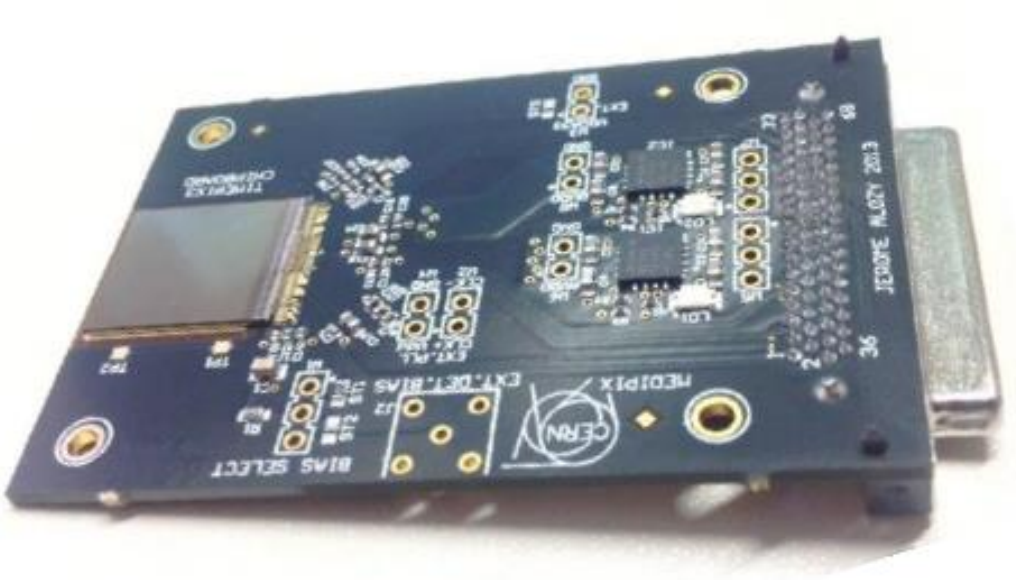
The pixel device permitting simultaneous measurement of Time over Threshold (ToT - collected charge) and Time of Arrival (ToA) of the signal in every pixel with resolution 1.6 ns.

- Thickness: 300μm
- Bias: 90 V
- Triggered
- Data driven mode
- T0 synch when trigger signal was received



Timepix3 CERN chip board

Number of detected neutron interactions (clusters) in 300 μm thick silicon sensor as a function of neutron kinetic energy.

Up to 4 MeV they mostly correspond to elastic or inelastic neutrons on silicon nuclei.

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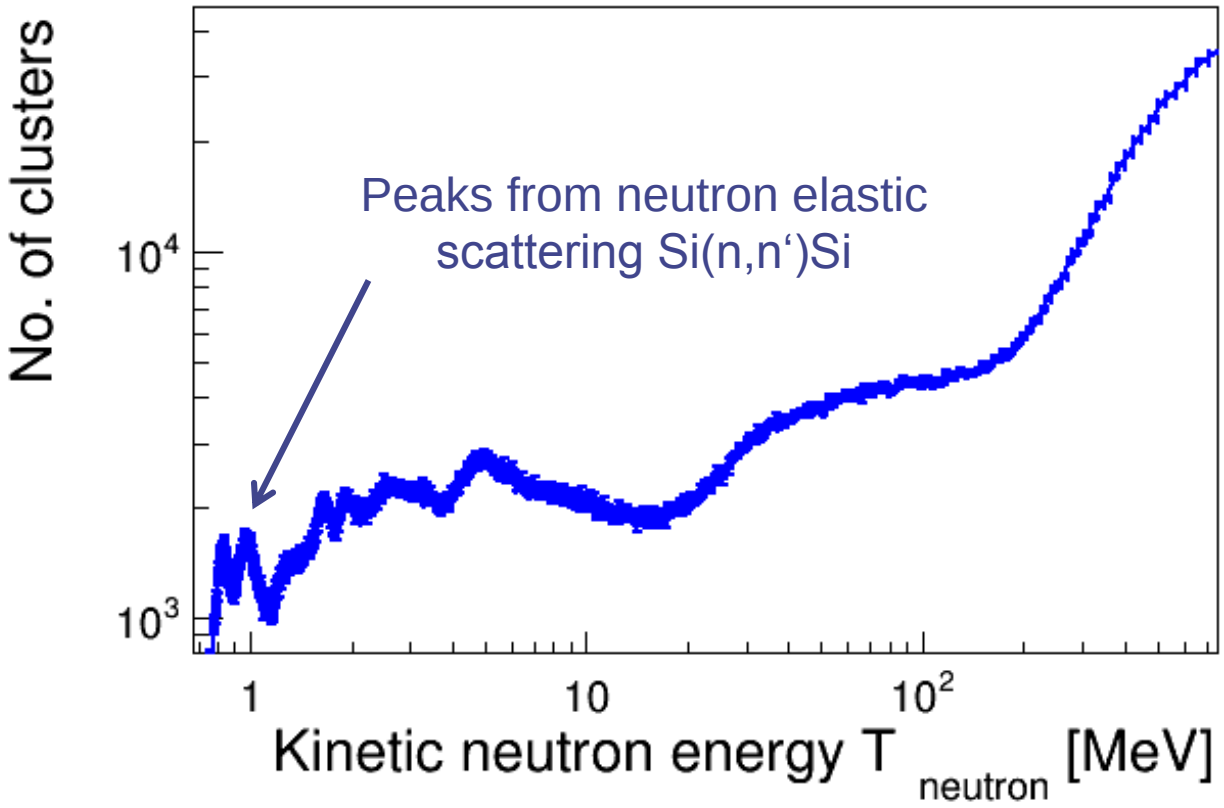

Energy spectra corresponding to elastic and/or inelastic scattering of neutrons on Si nuclei

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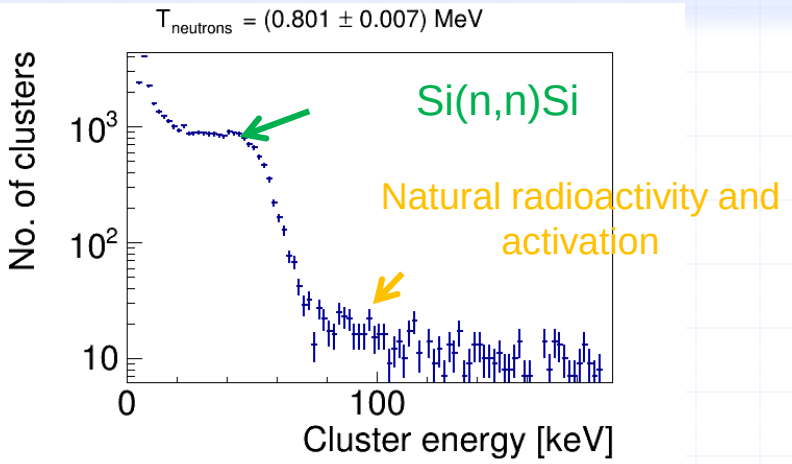

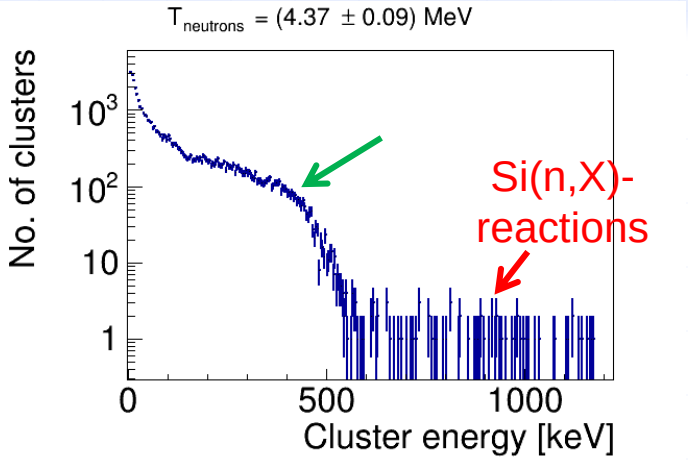

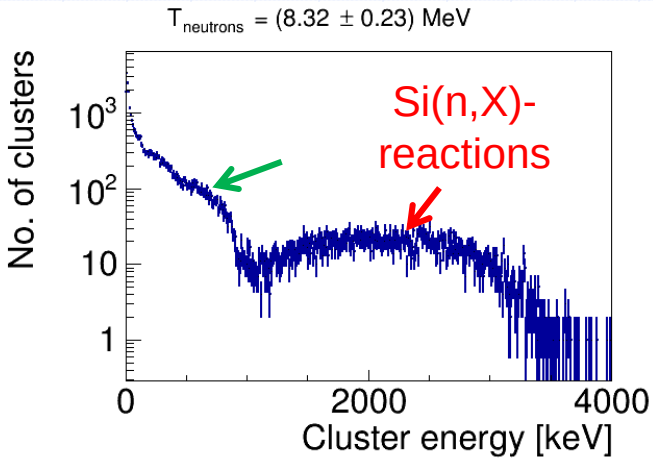

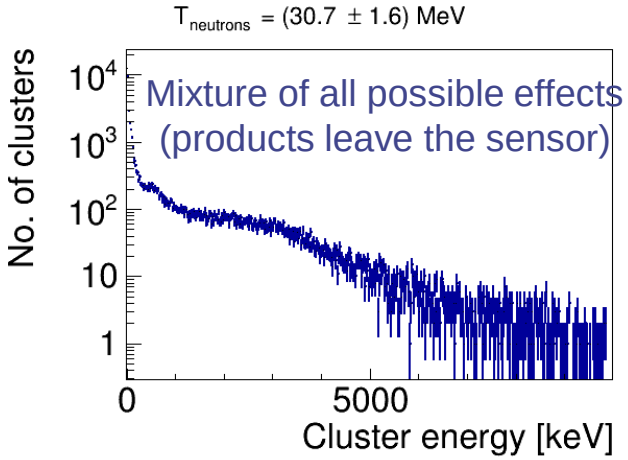

The edges correspond to head-head collisions. Analysis of spectra brings IEL of recoil Si nuclei in the silicon sensor

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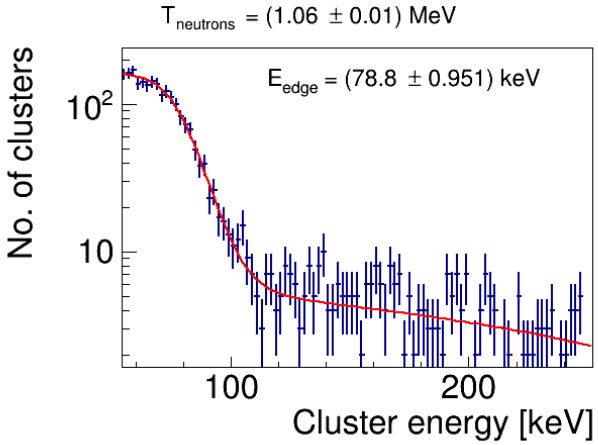
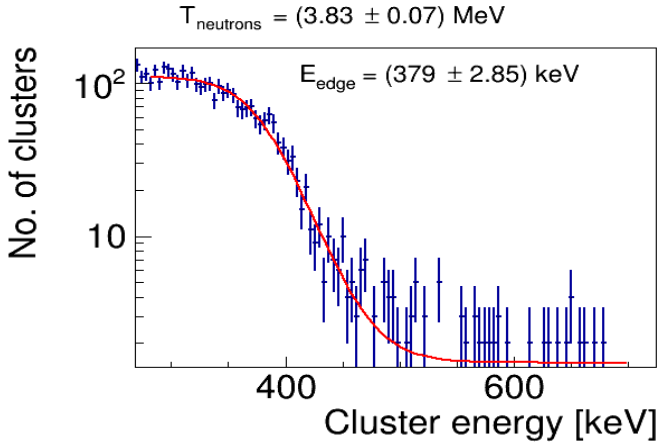
- Fit Fermi-function with background: $f(E) = \frac{A}{e^{(E-E_{edge})}+1} + B + C \cdot E$





Energy transfer to the silicon nucleus:

→ Energy goes partly into displacement (NIEL) and ionization

Energy measured:
→ Fraction of ionizing energy losses:

Neutron scattering: Losses by ionization vs losses due to displacement

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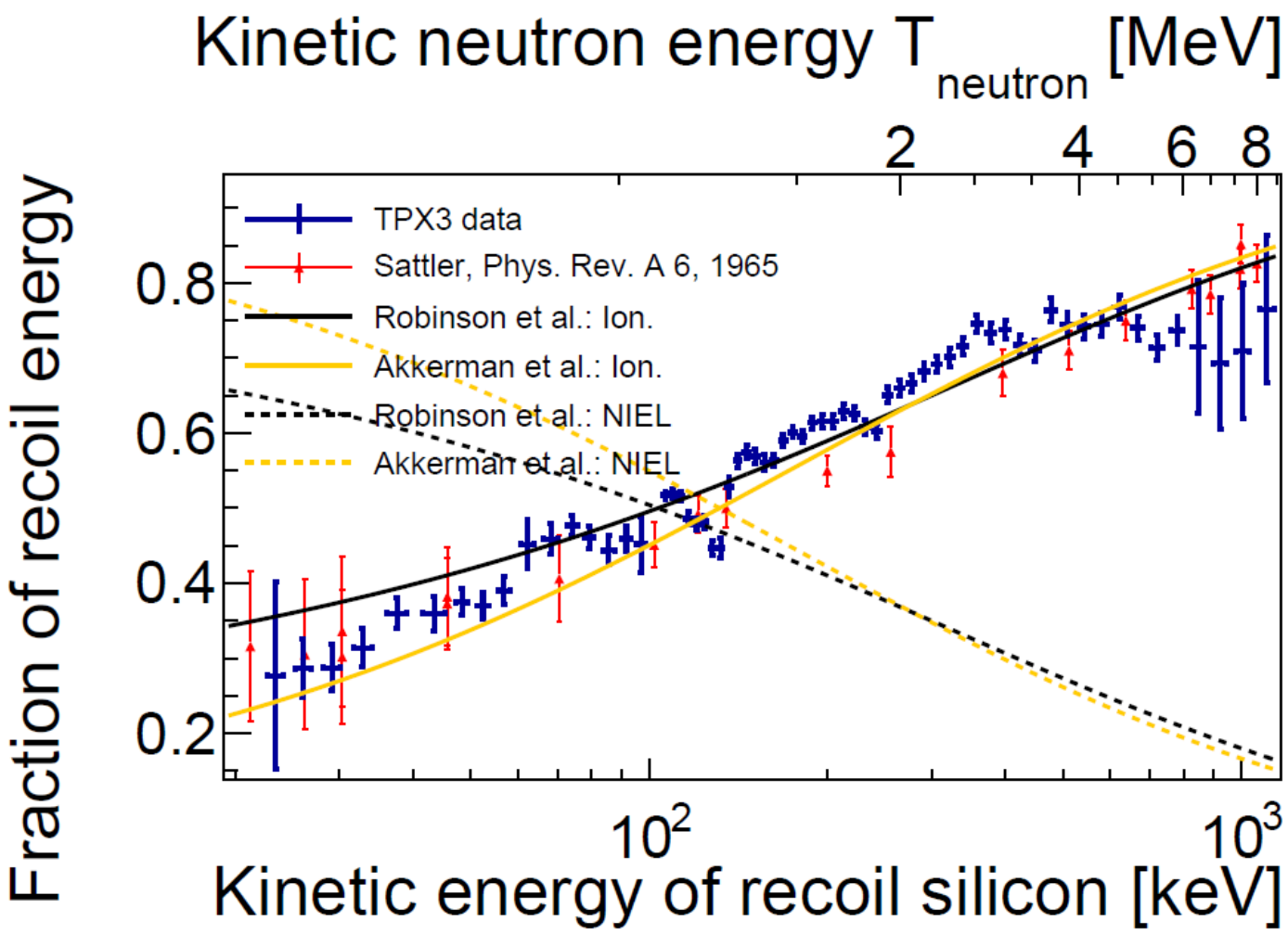

Conclusion

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- Example spectra of ionzing energy depositions of charged products after fast neutron impact were presented
- By spectrum analysis the competition of ionizing versus non ionizing energy losses was studied
- The results agreed with the calculations of Norgett-Torrens-Robinson, the Akkerman predictions and a previous measurement by Sattler

Impact:

- Knowledge of ionizing energy depositions essential for single event effect estimation/simulations
- Knowledge of non ionizing energy depositions necessary for understanding permanent radiation damage

Results published:

http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7482701

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Thank you!