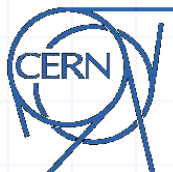
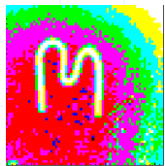




# Application of semiconductor pixel detectors for high resolution X-ray and neutron imaging, particle tracking and in space

*Stanislav Pospíšil*

*on behalf of former and present Medipix/Timepix team  
of the Institute of Experimental and Applied Physics  
Czech Technical University in Prague*





# Main goals of the lecture

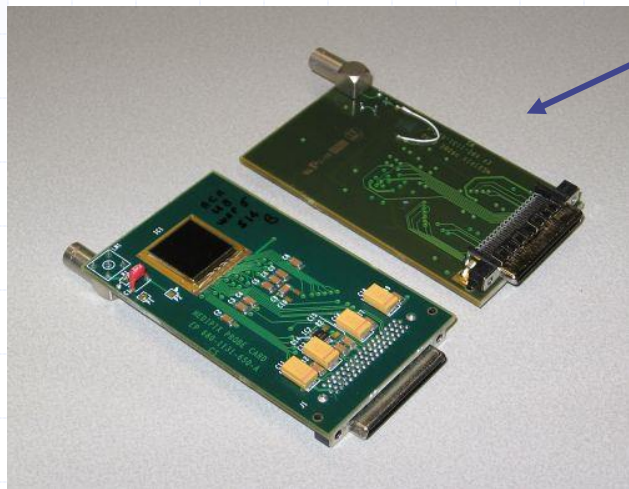
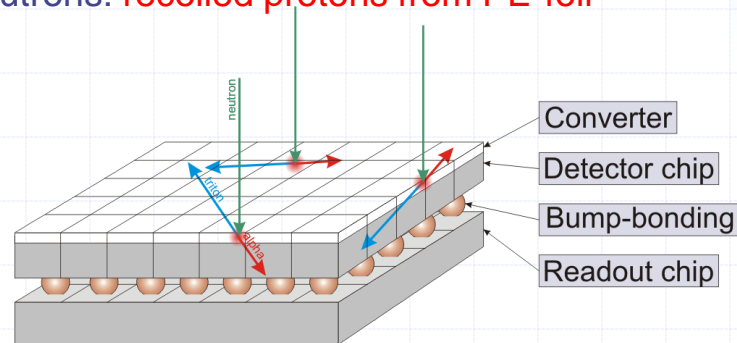
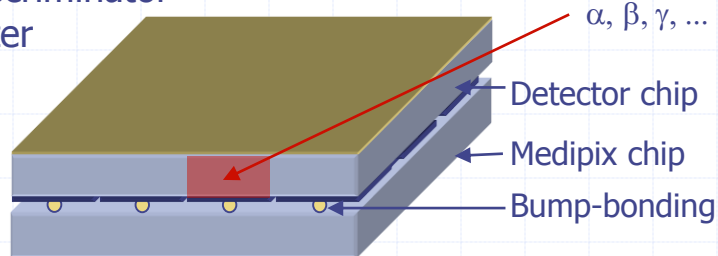
- To describe shortly family of ***Medipix2, Timepix and Timepix3 semiconductor pixel detectors*** including corresponding R/O electronics.
- To document ability of Timepix pixel detector to ***visualize individual particle tracks in solid state*** similarly to nuclear emulsions, cloud chambers, bubble chamber, Micro-Pattern Gaseous Detectors etc.
- To demonstrate capability of the devices for ***high resolution (micrometric and nearly nanometric) radiography, nondestructive testing and 3D imaging*** by means of ***X-rays and neutrons***.
- To present results of investigation of ***neutron interactions in silicon*** sensors in a broad energy range (500 keV up to GeV region) by means of ***Time-of-Flight (ToF) technique***.
- To show examples of broad ***applications*** of the Timepix detectors for ***measurements of composition and spectral characteristics of mixed radiation fields around physics experiments, in medicine and in space research***.



# Medipix/Timepix hybrid pixel detector device

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

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

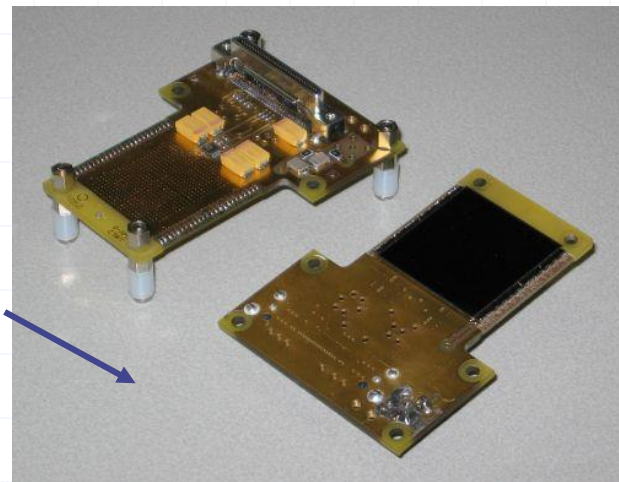


## Medipix2/Timepix

Pixels: 256 x 256  
Pixel size: 55 x 55  $\mu\text{m}^2$   
Area: 1.5 x 1.5  $\text{cm}^2$

## Medipix2/Timepix Quad

Pixels: 512 x 512  
Pixel size: 55 x 55  $\mu\text{m}^2$   
Area: 3 x 3  $\text{cm}^2$





# TIMEPIX3



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.

It can be effectively used for simultaneous measurement

- of Time-of-Flight of detected particle,
- Energy of this particle deposited in the sensor and
- a drift time of charge in the sensor

- ◆ Thickness: 300 $\mu$ m
- ◆ Bias: 90 V
- ◆ Triggered
- ◆ Data driven mode
- ◆ T0 synch when trigger signal was received



Timepix3 CERN chip board



# About development of R/O interfaces for Medipix/Timepix devices



## HISTORY 1995-2011:

### MAMOGRAPHY

- CAMAC/VME
- MUROS (NIKHEF)
- USB1 (IEAP)
- USB Lite (IEAP)
- RUIN (IEAP)
- MARS (NZ)
- USB2 (IEAP)
- TPX Lite (IEAP)



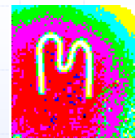
**CAMAC**



**MUROS 1**



**USB Lite**

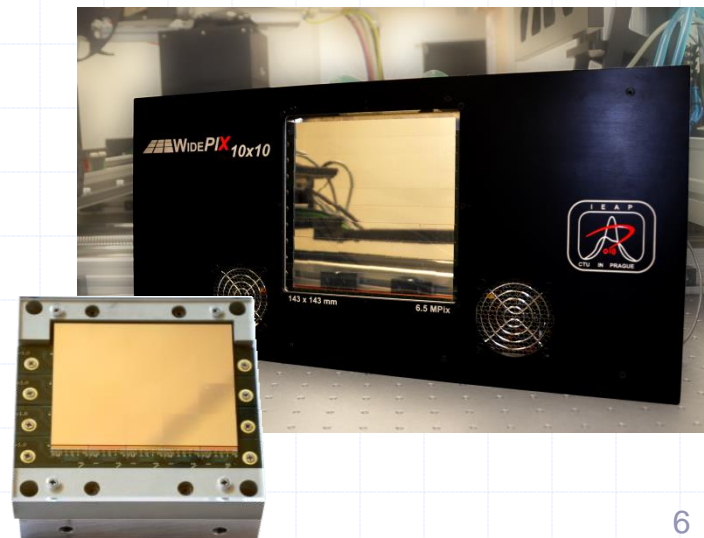
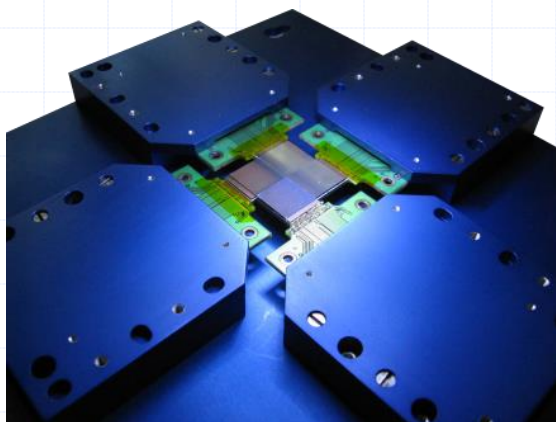
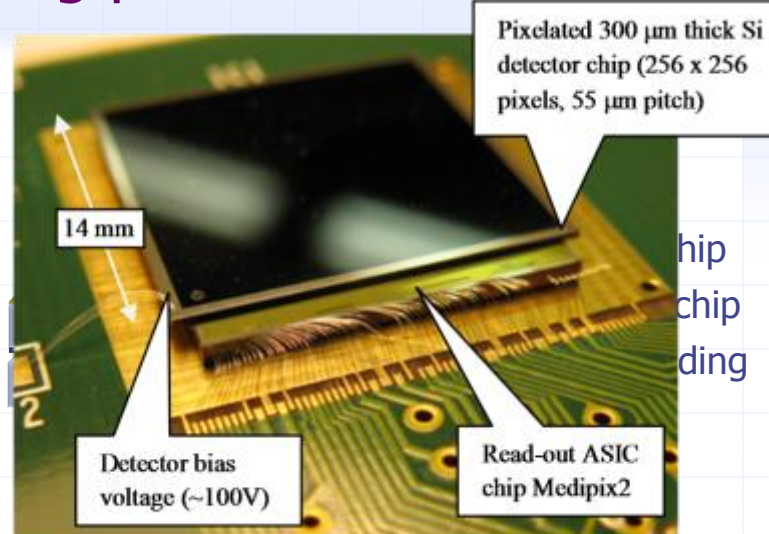


# Timepix pixel device

## operating as single particle counting pixel detector

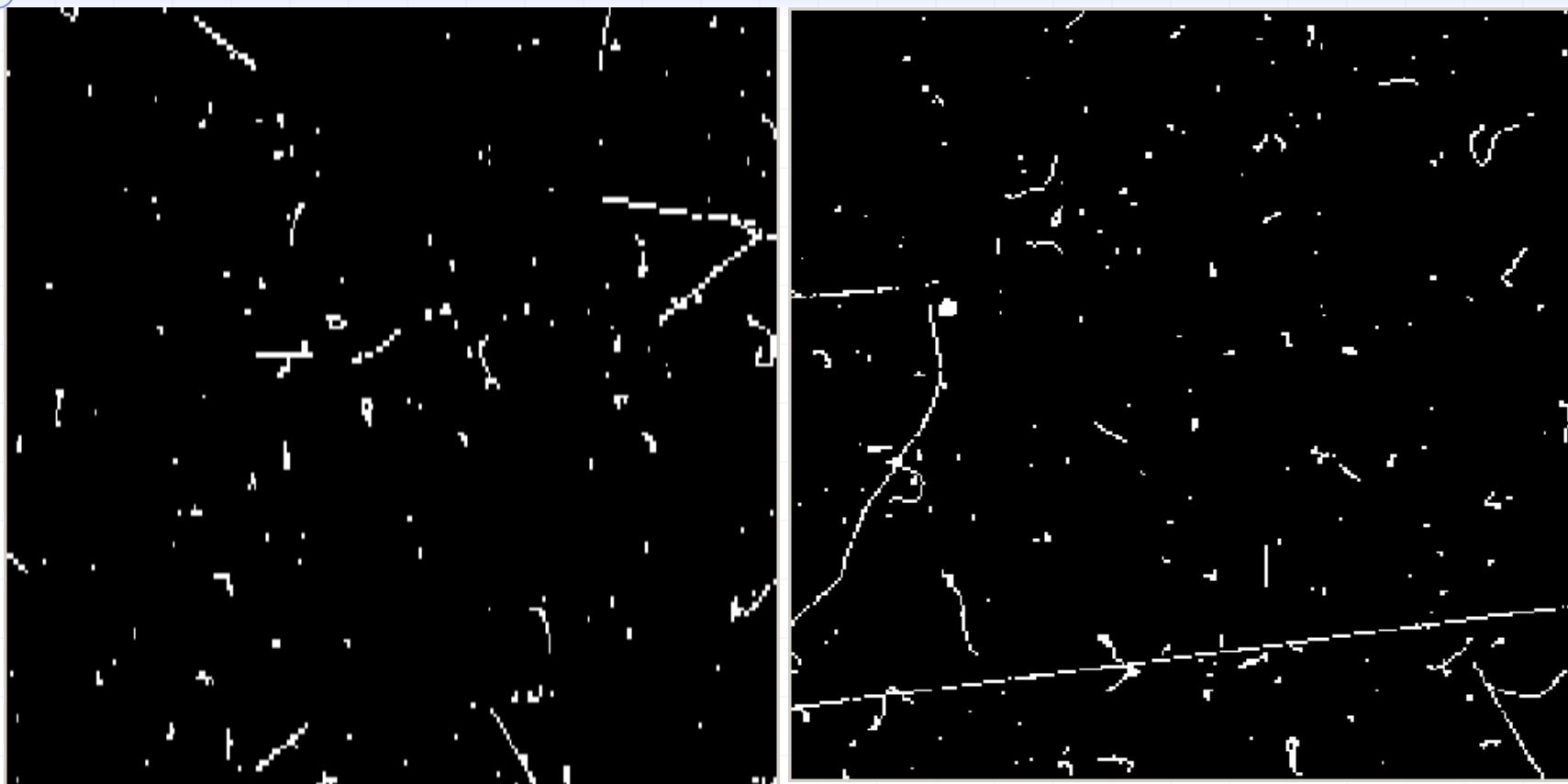
Institute of Experimental and Applied Physics  
Czech Technical University in Prague

- Planar pixelated detector (Si, GaAs, CdTe, thickness: 150/300/700/1000mm ...)
- Bump-bonded to readout chip containing in each pixel cell: amplifier, discriminator, Counter or ADC or **Timer**
- Multichip assemblies with common sensor: **Quad** (30 x 30 mm), **Hexa** (45 x 30 mm)
- Multichip detectors with edgeless sensors: **WidePIX<sub>10x10</sub>** (143x143 mm)





# Response of Medipix2 device to natural background radiation



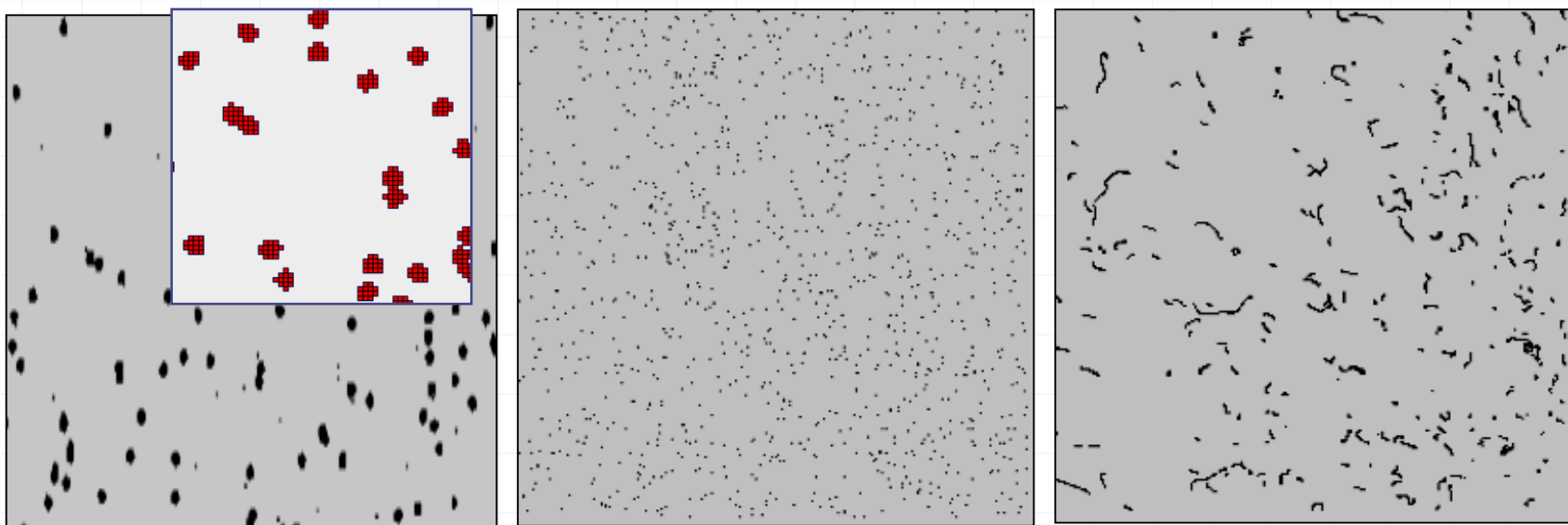
Clearly recognizable tracks and traces of X-rays, electrons generated mostly by gamma rays, alpha particles, muon, ... . Muon tracks can be recognized by submicrometric precision.



# Noiseless particle detection

## Tracking mode of pixel detector operation

(On-line imaging of tracks and traces of single radiation quanta)



- ◆  $^{241}\text{Am}$  alpha source gives clusters of  $\sim 5 \times 5$  pixels measured with the MEDIPIX-USB device and a  $300 \mu\text{m}$  thick silicon sensor. The clusters are shown in detail in the inset. The cluster sizes depend on particle energy and threshold setting.
- ◆ Signature of X-rays from a  $^{55}\text{Fe}$  X-ray source. Photons yield single pixel hits or hits on 2 adjacent pixels due to charge sharing.
- ◆ A  $^{90}\text{Sr}$  beta source produces curved tracks in the silicon detector.
- ◆ A pixel counter is used just to say "YES" if individual quantum of radiation generates in the pixel a charge above the pre-selected threshold.



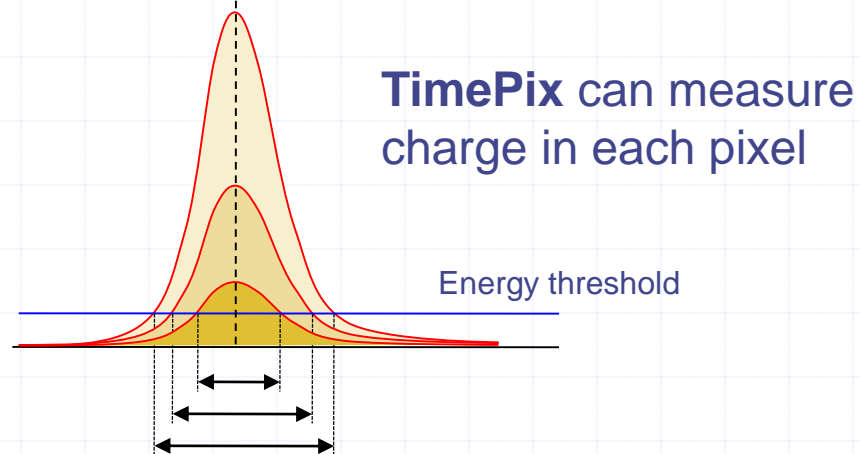
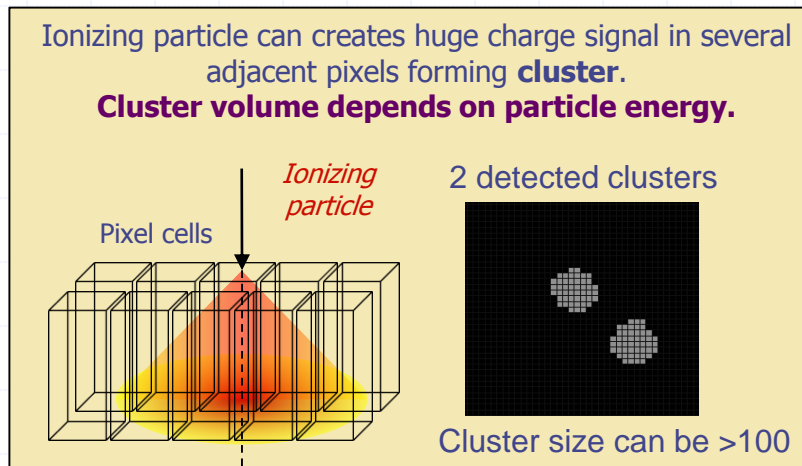


# Charge sharing effect - clusters

- ◆ Ionizing particle creates a charge in the sensor.
- ◆ The charge is collected by external electric field => the process takes some time
- ◆ Due to charge diffusion the charge cloud expands
- ◆ The charge cloud can overlap several adjacent pixels => **CLUSTER**
- ◆ Pixels in a cluster will detect the charge if it is higher than certain threshold

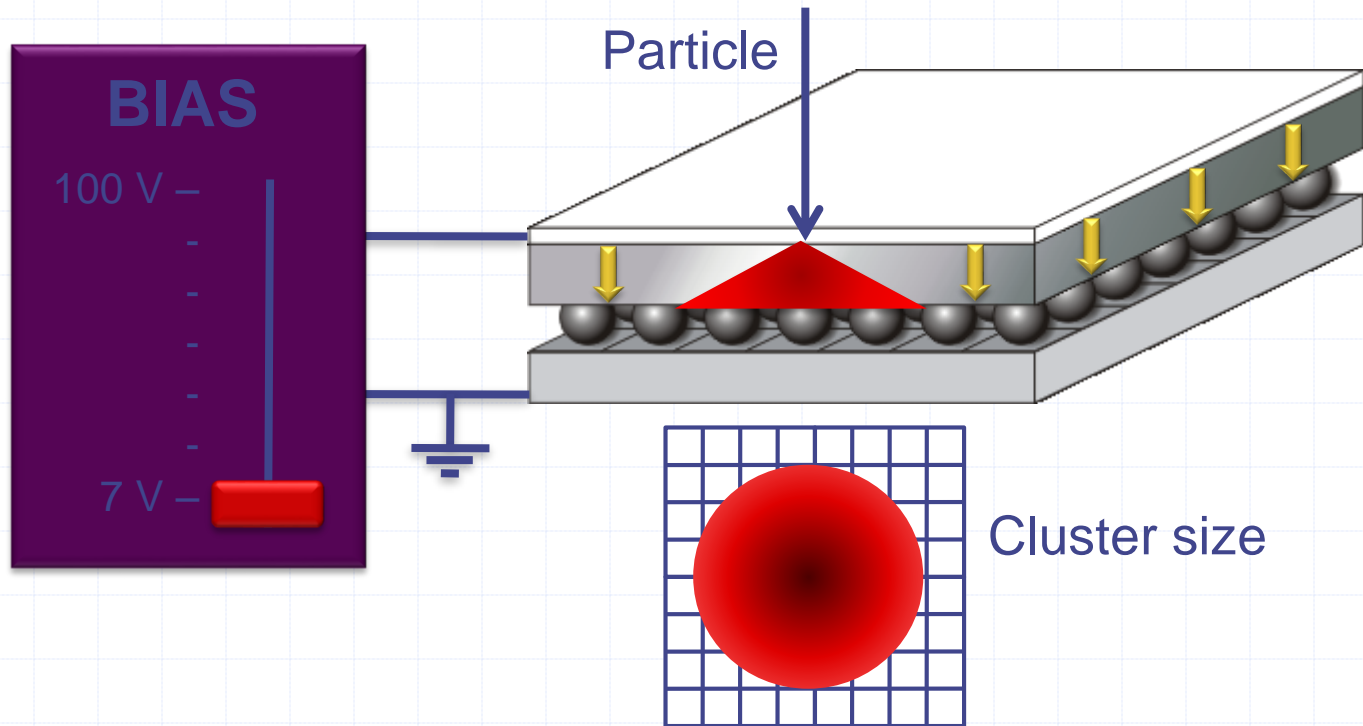
## The Cluster size depends on:

- ◆ Particle energy and range
- ◆ Depth of interaction
- ◆ Detector Bias Voltage
- ◆ Local CCE (e.g. due to a material inhomogeneities and radiation damage)



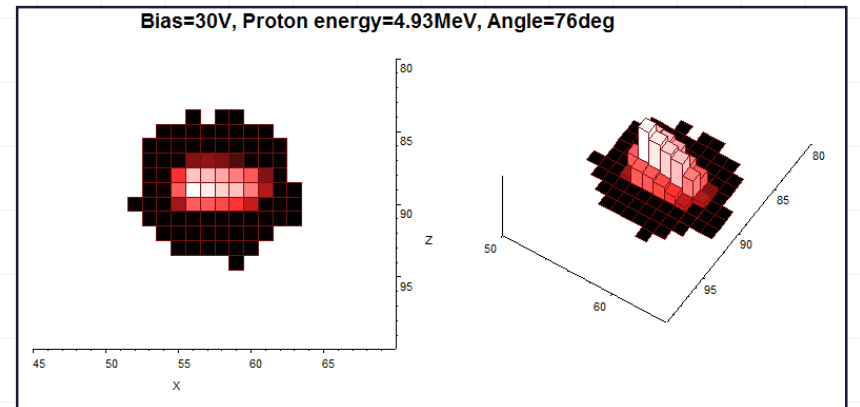
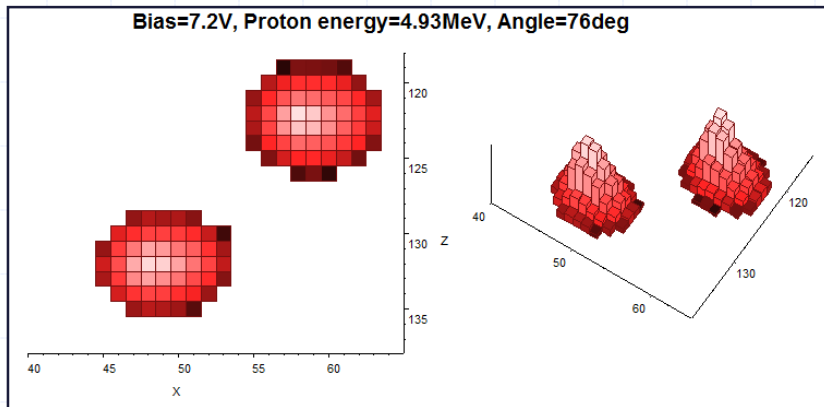
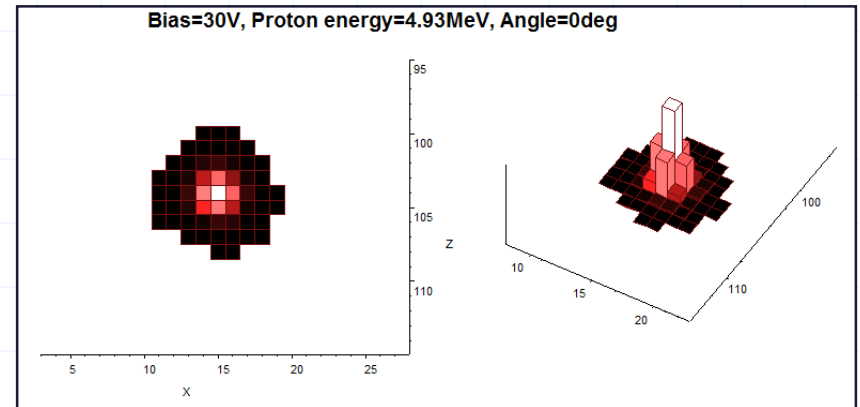
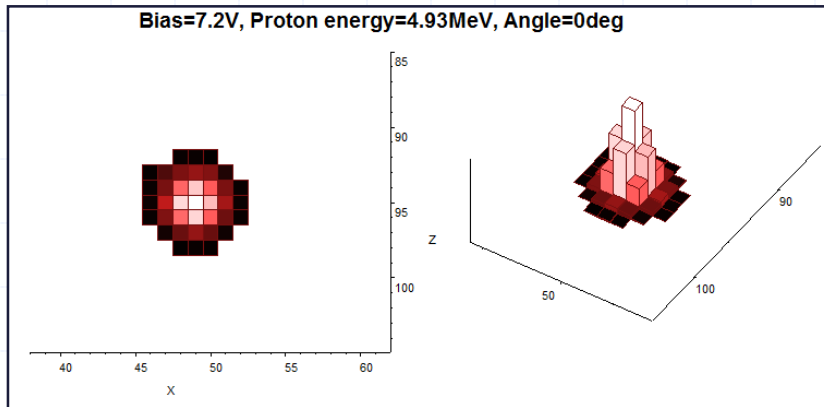


# Dependence of cluster size on applied bias (on electric field in semiconductor)





# 3D-visualization of proton tracks in Timepix silicon pixel detector. Illumination under different angles and different applied biases

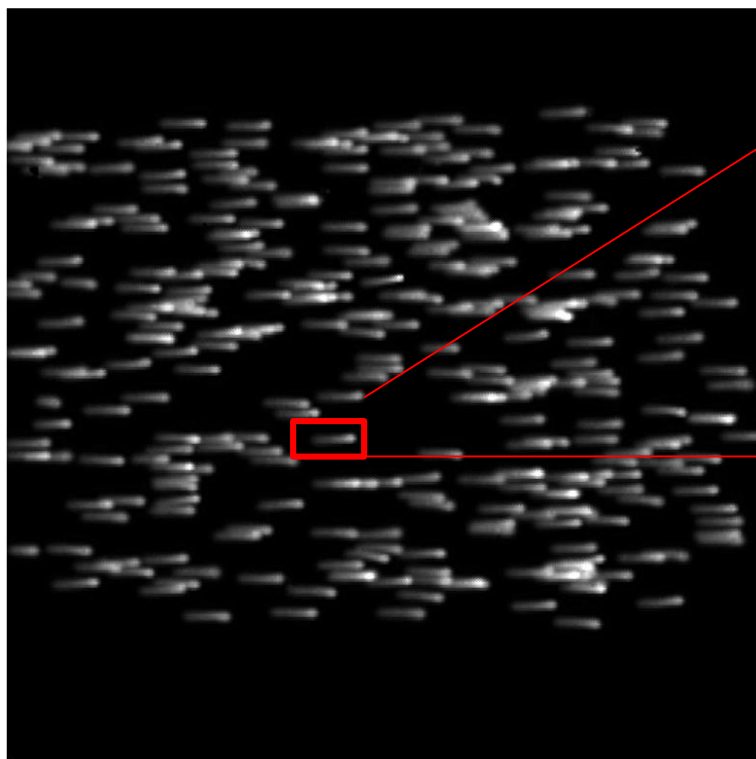


What is the spatial resolution? X- and Y-coordinates are determined with a precision of about 500nm. Determination of angle is with a precision of about 1°. It needs additional experiments.

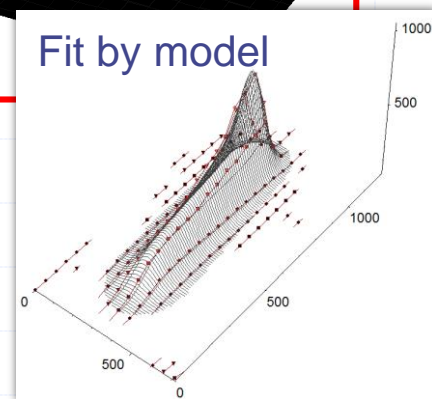
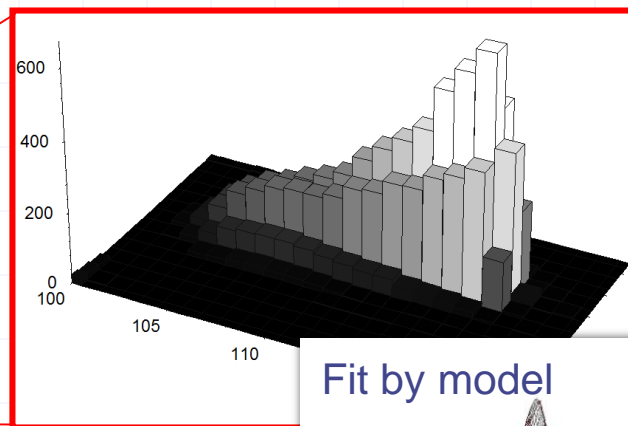


# Flock of 11 MeV protons entering the silicon sensor under 85°

11 MeV protons, 85 degrees



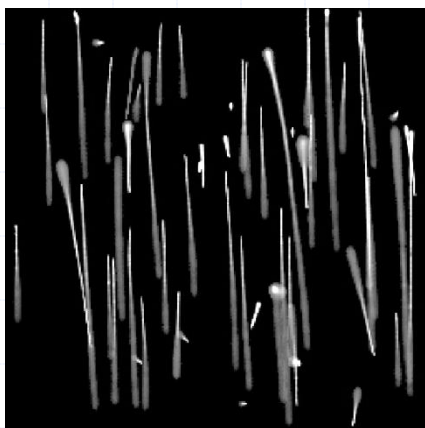
$\Delta E/\Delta x$  Bragg profile nicely pronounced, proton range about 960  $\mu\text{m}$





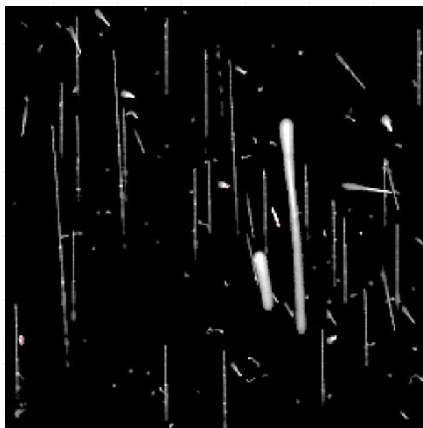
# Typical observed tracks of particles used for hadron therapy beam

Protons 48 MeV



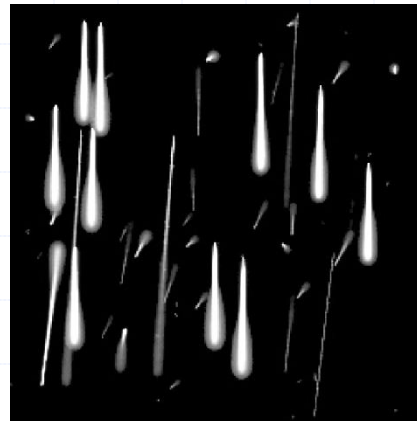
Only protons and their scattering, no secondaries.

Protons 221 MeV



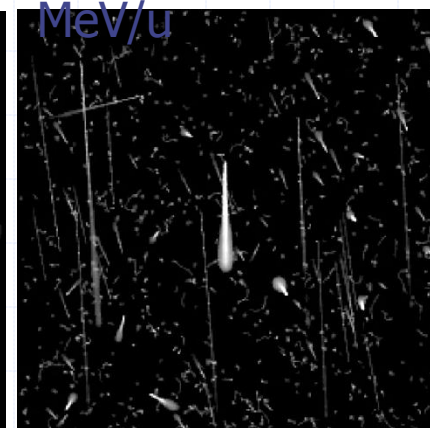
Many secondaries, (delta electrons fragments).

Carbons 89 MeV/u



Carbons and protons and their scattering, no secondaries.

Carbons 430 MeV/u



Carbons and many secondaries.

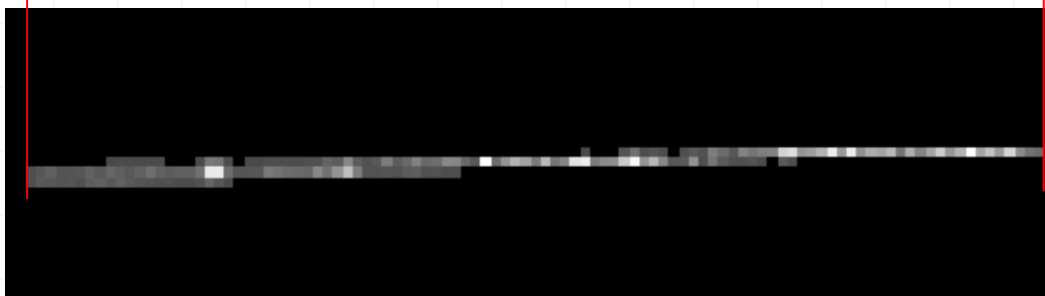
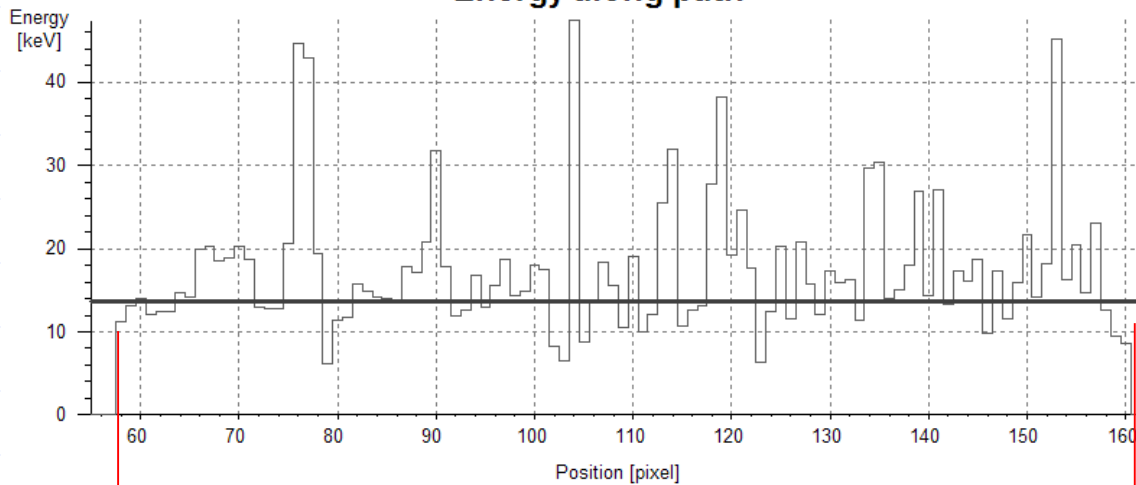


# Track of MIP particle – cosmic muon



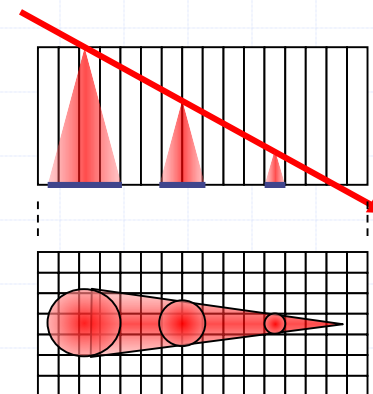
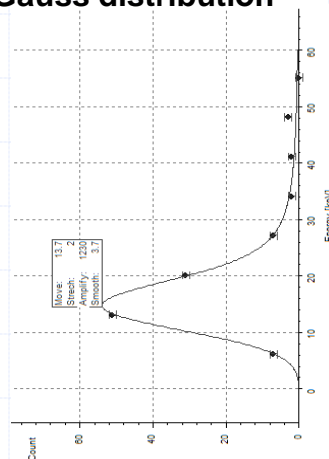
Charge sharing effect helps to determine all three track coordinates with quite high resolution (deeply submicrometric in case of x and y)

### Energy along path



Track recorded by TimePix device



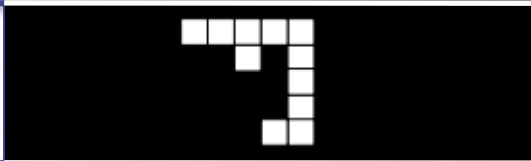
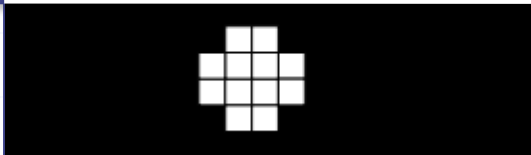
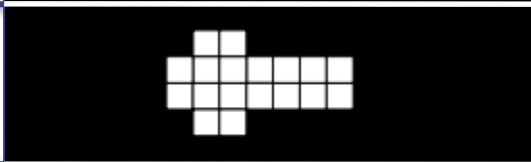
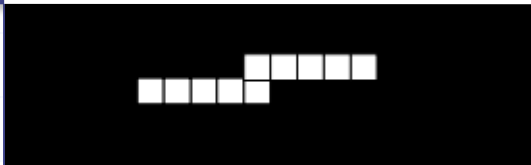
### Energy distribution fit by convolution of Landau and Gauss distribution





# Review of the characteristic patterns

## Event by event processing

1) Dot		Photons and electrons (10keV)
2) Small blob		Photons and electrons
3) Curly track		Electrons (MeV range)
4) Heavy blob		Heavy ionizing particles with low range (alpha particles,...)
5) Heavy track		Heavy ionizing particles (protons,...)
6) Straight track		Energetic light charged particles (MIP, Muons,...)



# X-ray imaging



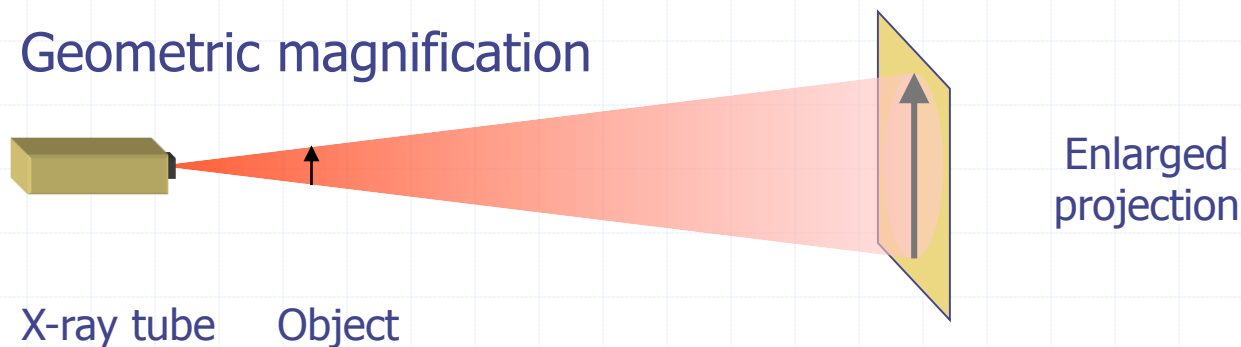


# High resolution X-ray radiography

## Experimental setup

### Requirements:

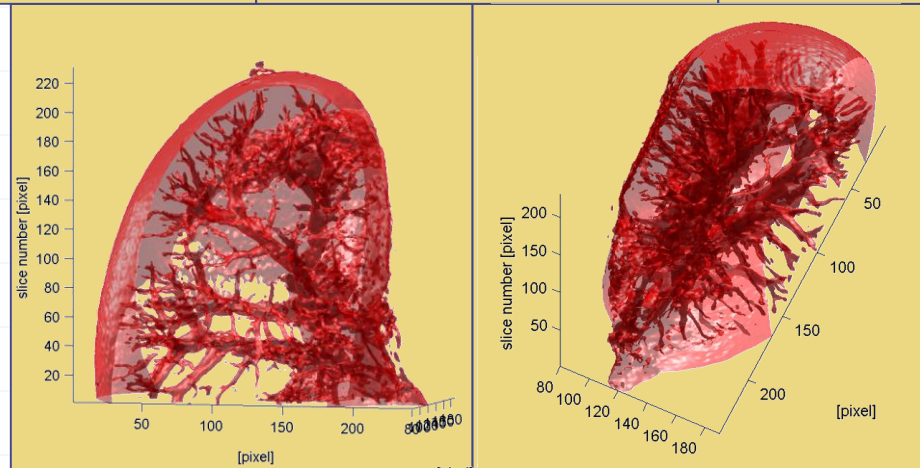
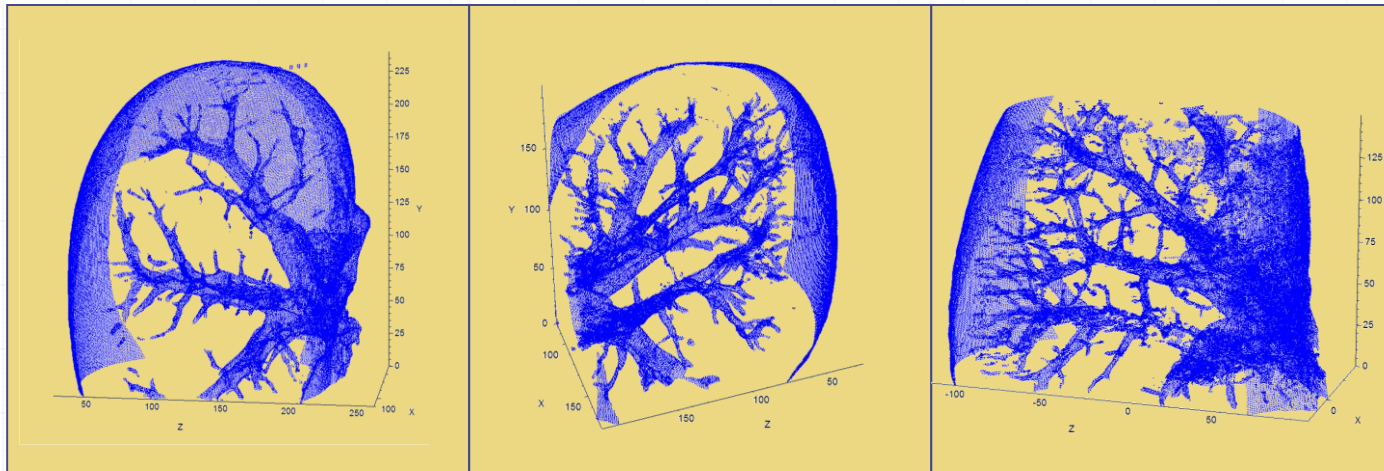
- Microfocus X-ray source to enable geometrical magnification
- Adjustable object holder (three translations + rotation)
- Sample stabilization (temperature, humidity)
- Equipment for automatic calibration of pixel responses
- Detector holder and detector stabilization (temperature, condensing point)





## Mouse Kidney Tomography

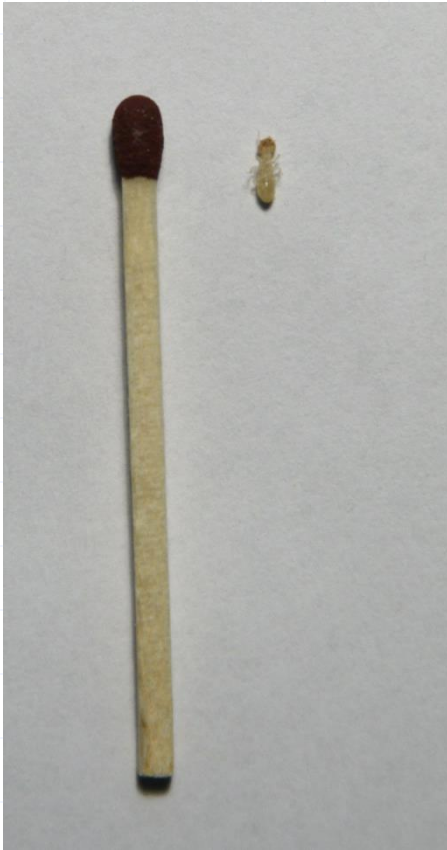
Missing angles => Iterative algorithm instead of Filtered back projection (3 iterations in OSEM 5)





High resolution X-ray radiography:

# Imaging of Termites



The imaging of termites as a model **soft tissue organism** is particularly difficult due to their **poorly sclerotized** cuticle making difficult to observe the anatomic structures with an optimal contrast.

Moreover, they are vulnerable to damage when they are manipulated or treated during sample preparation.

Thus, the termites represent an ideal model to optimize the accuracy and sensitivity of the developed method.



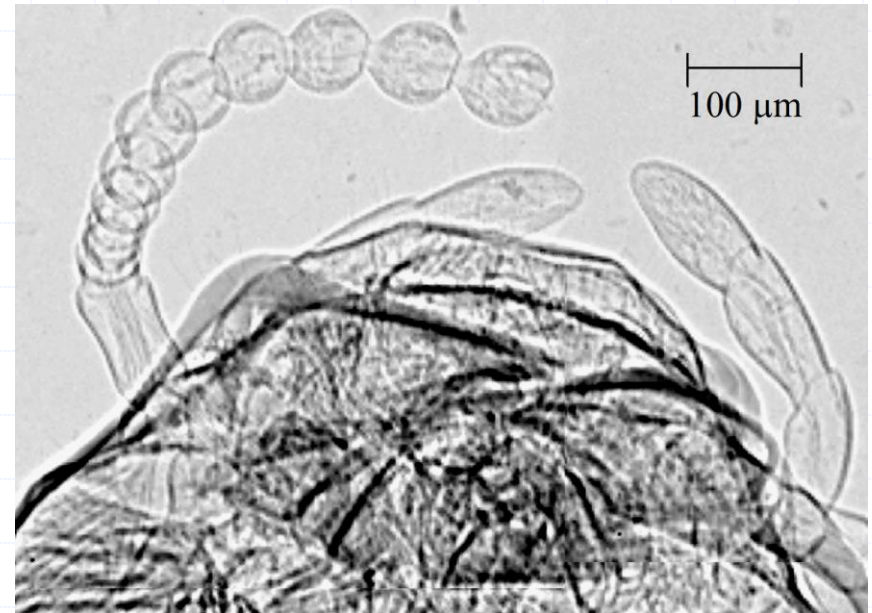
High resolution X-ray radiography:

# Imaging of Termites



X-ray transmission image of termite worker body (left) and detail of its head (bottom). Even fine internal structure of the antennae is recognized.

(Magnified 15x, time=30s, tube at 40kV and 70 $\mu$ A)



# Imaging of Living Termites



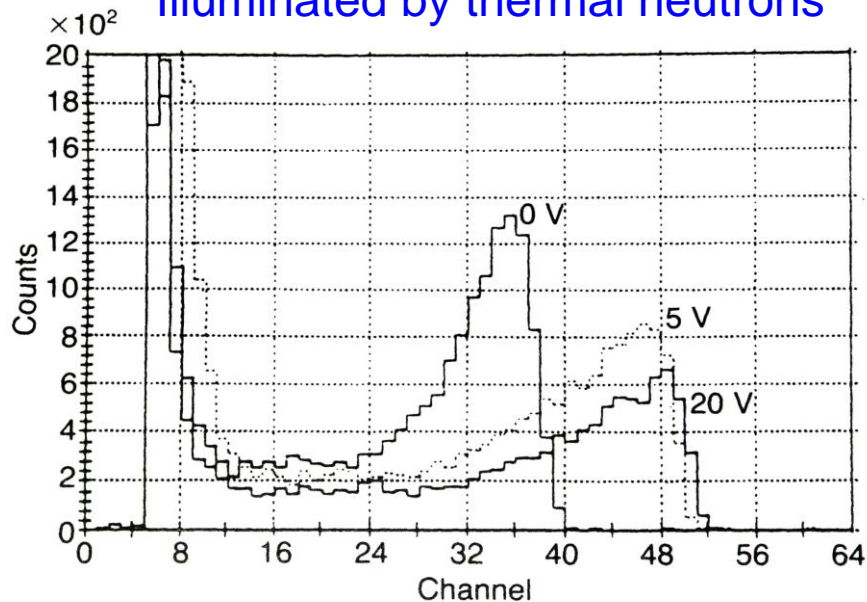
Images of a termite worker before (left) and after (right) its metamorphosis toward the soldier caste (5s exposure  $\sim 0.7\text{mGy}$  dose)



# About neutrons

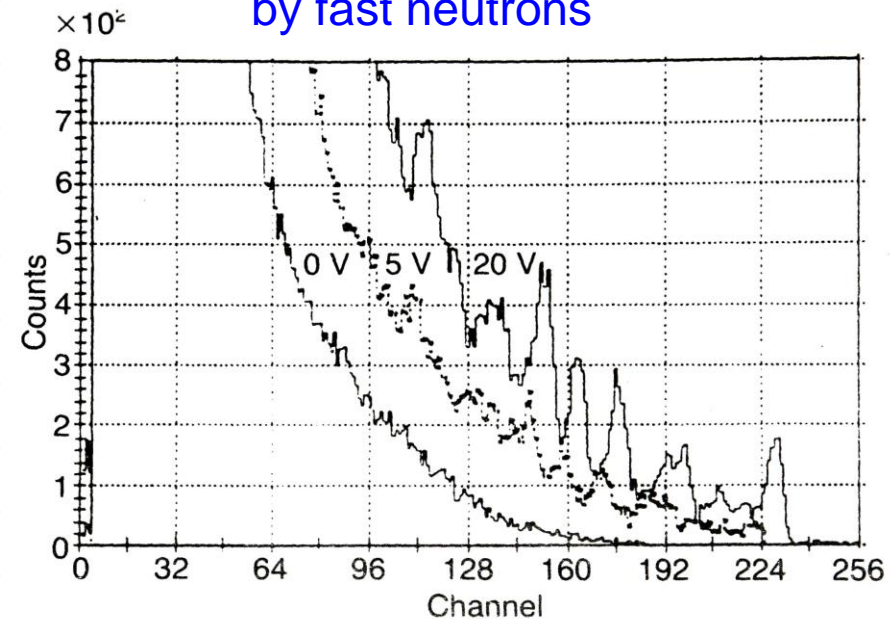
# Responses of silicon detectors to neutrons

Silicon diode +  ${}^6\text{LiF}$  converter  
Illuminated by thermal neutrons



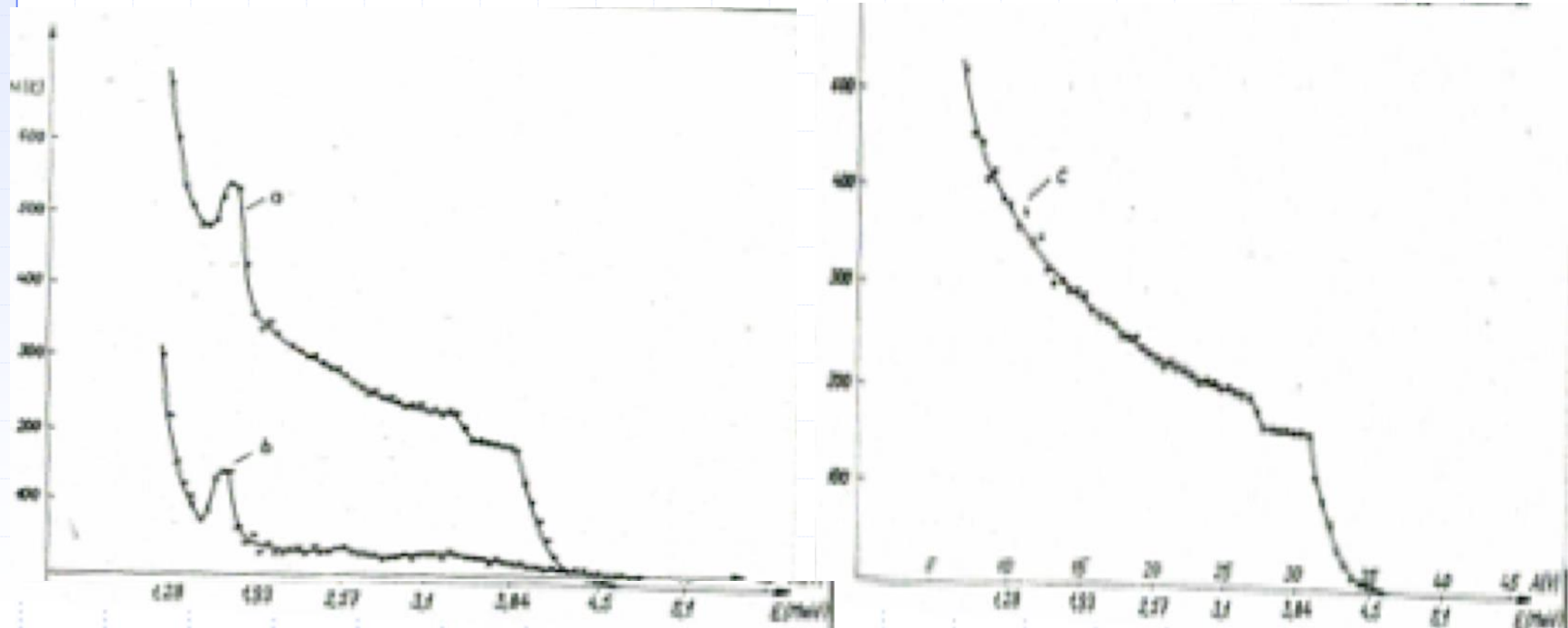
Pulse height distributions of neutron detector on thermal neutrons at different bias (0, 5, 20 V). Detector operates well in the self-biased regime.

Silicon diode illuminated  
by fast neutrons



Pulse height distributions of neutron detector when illuminated by fast neutrons (14.8 MeV) at different bias (0, 5, 20 V). Peaks from interaction of fast neutrons with  ${}^{28}\text{Si}$  are clearly seen

# Response of silicon diode with CH<sub>2</sub> converter to protons recoiled by 3.8 and 4.2 MeV neutrons



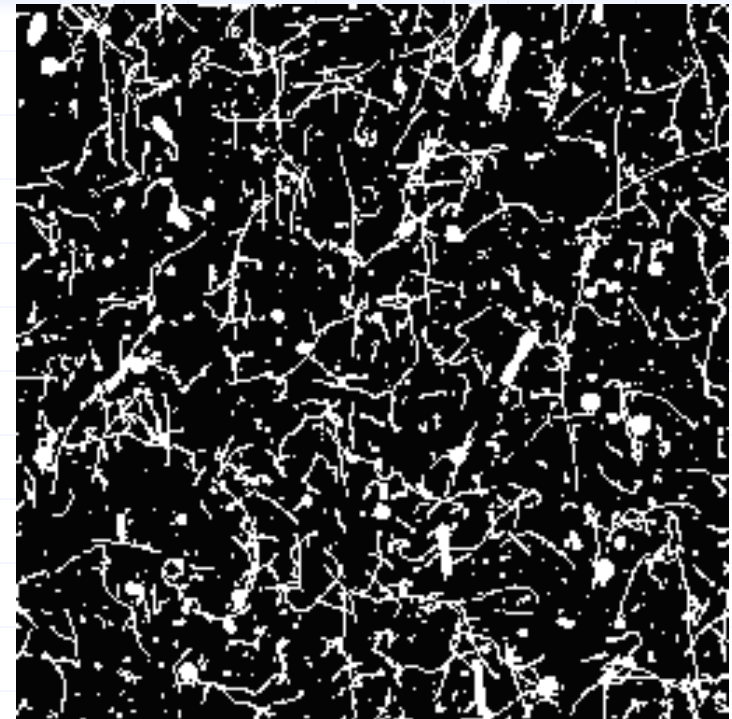
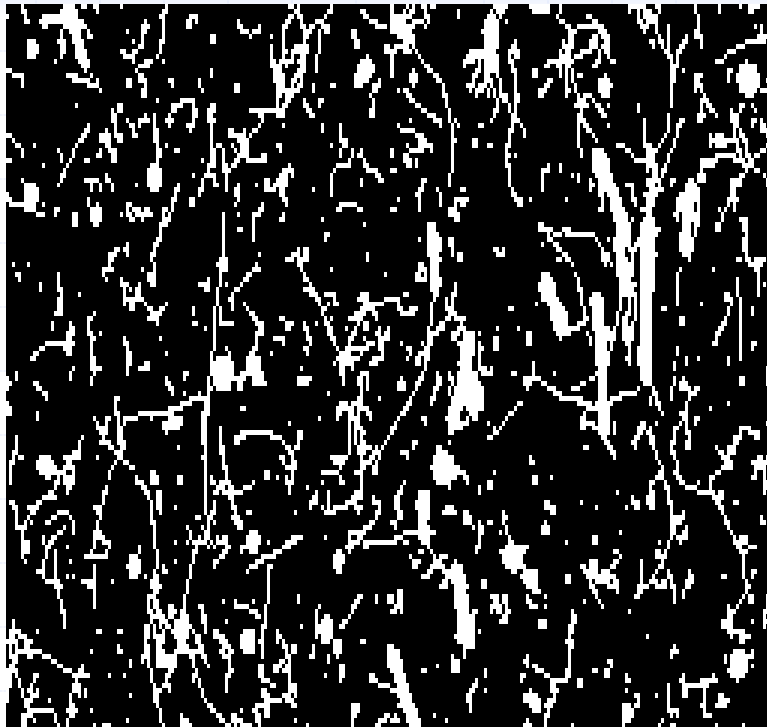
a) PH spectrum measured by the diode with CH<sub>2</sub> converter (up)

b) PH spectrum measured by the diode without CH<sub>2</sub> representing background caused by  $^{28}\text{Si}(n,\alpha)^{25}\text{Mg}$  (down)

c) Pure spectrum of recoiled protons (background subtracted)



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

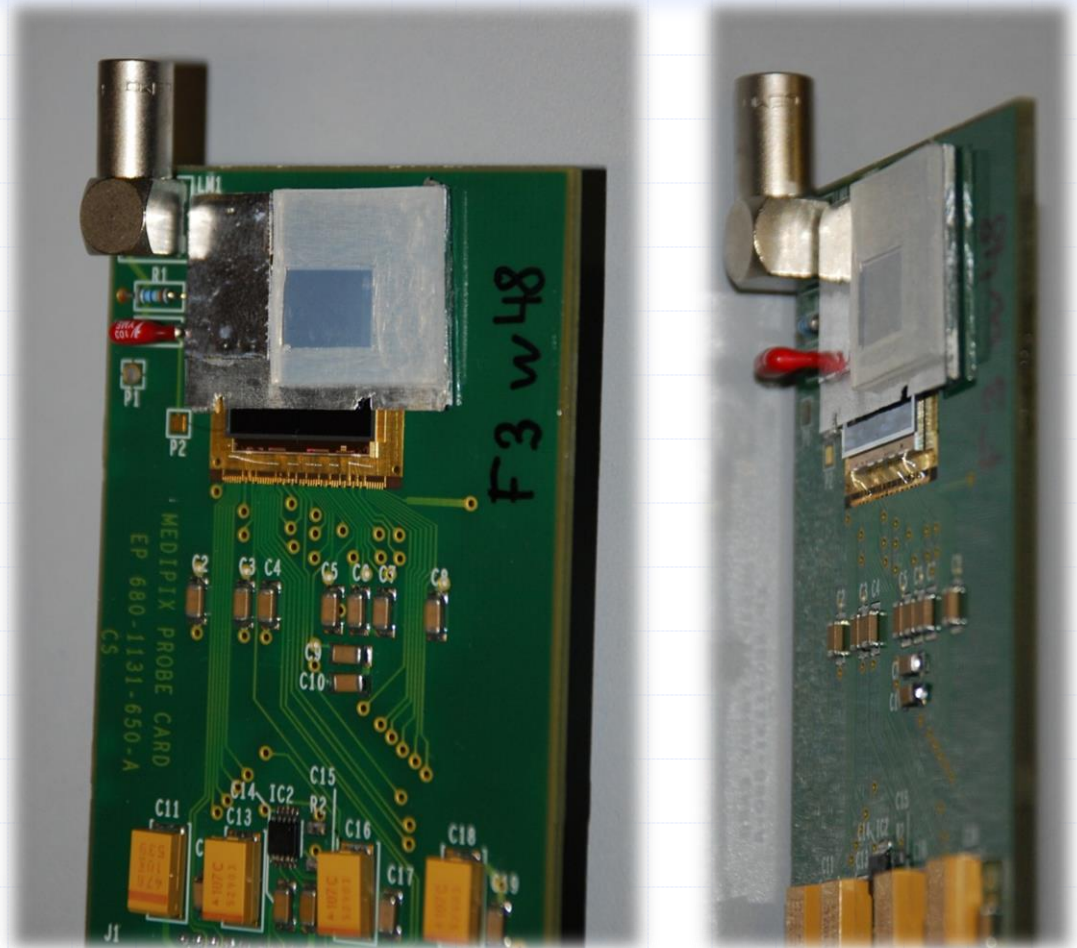
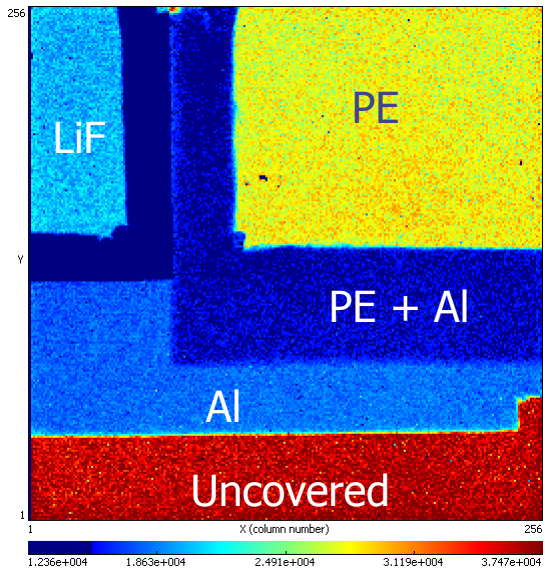


- ◆ The direction of the neutrons with respect to the image was upstream (from bottom to top). The huge background is due to gamma rays which accompany neutrons. Half of the sensor (the right-hand side) was covered with a CH<sub>2</sub> foil about 1.3 mm thickness.
- ◆ One can clearly recognize long and rather thick tracks of recoiled protons (up to 2 mm, vertically oriented) and big tracks and clusters generated via  $^{28}\text{Si}(n,\alpha)^{25}\text{Mg}$ ,  $^{28}\text{Si}(n,p)^{28}\text{Al}$  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.

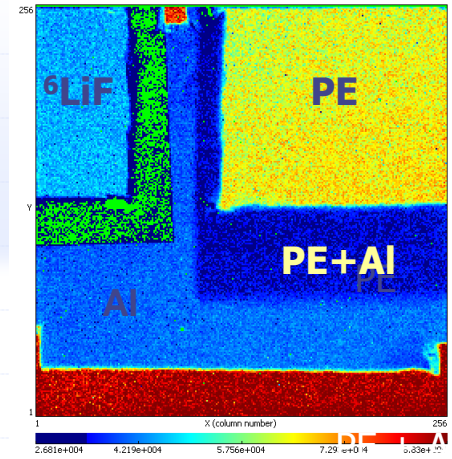
# Detail view on conversion layers added for a neutron detection in mixed radiation fields

Several different regions:

- ◆ LiF+50 $\mu$ m Al foil area
- ◆ 100 $\mu$ m Al foil area
- ◆ PE area
- ◆ PE+50 $\mu$ m Al foil area
- ◆ 50 $\mu$ m Al foil area
- ◆ Uncovered area



# $^{252}\text{Cf}$ neutrons measured in counting mode of operation at different thresholds



$^{252}\text{Cf}$ , low threshold (8 keV)



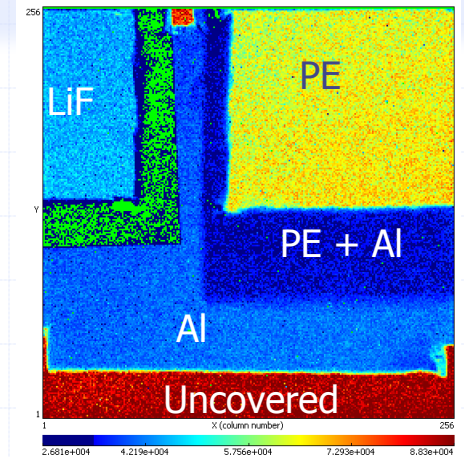
$^{252}\text{Cf}$ , high threshold (300 keV)



# Responses to neutrons of different energies measured at high threshold in counting mode

Identification of spectral composition of incoming neutron radiation can be done by comparing responses of different sensitive regions.

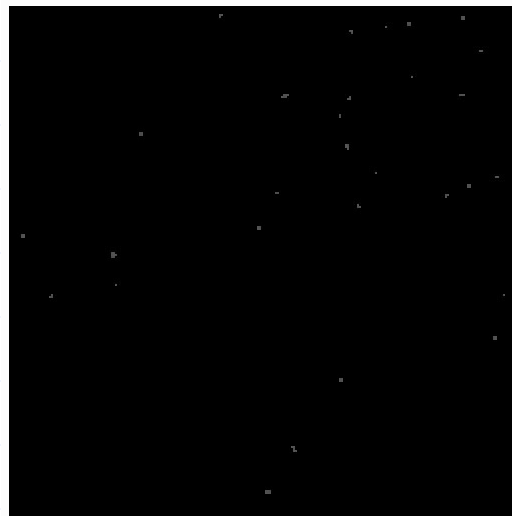
Thermal neutrons – 500s



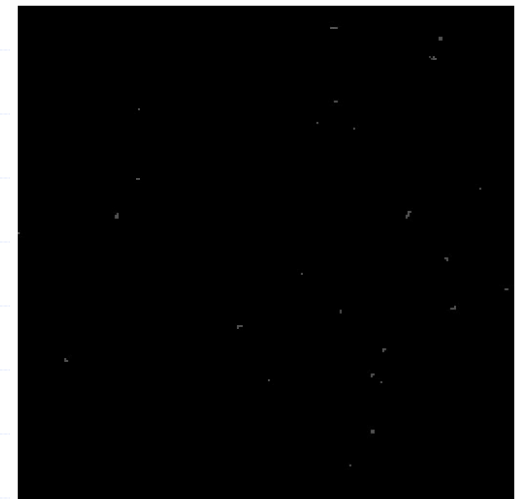
252Cf – 2000s



AmBe – 2000s



17 MeV neutrons at 0°





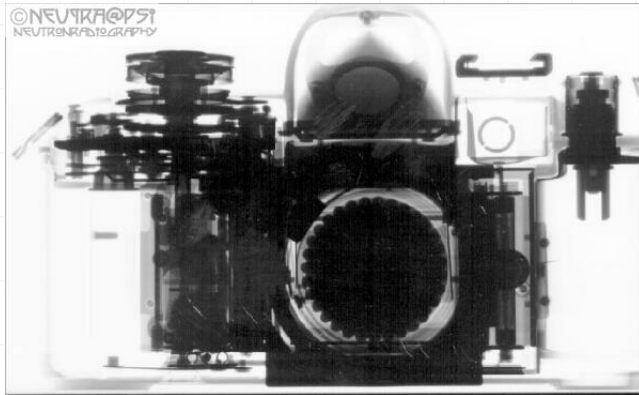
# Neutron imaging



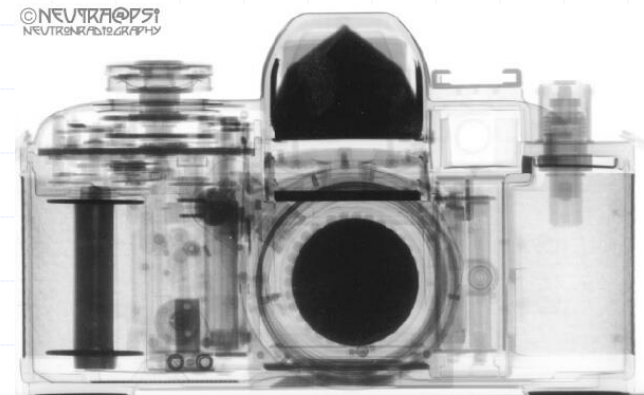
# Motivation – neutron radiography



- While X-rays are attenuated more effectively by heavier materials like metals, neutrons allow to image some light materials such as hydrogenous substances with high contrast.
- Neutron radiography can serve as complementary technique to X-ray radiography



X-rays



Neutrons

In the X-ray image, the metal parts of the photo camera are seen clearly, while the neutron radiogram shows details of the plastic parts (Courtesy of E. Lehmann, PSI)

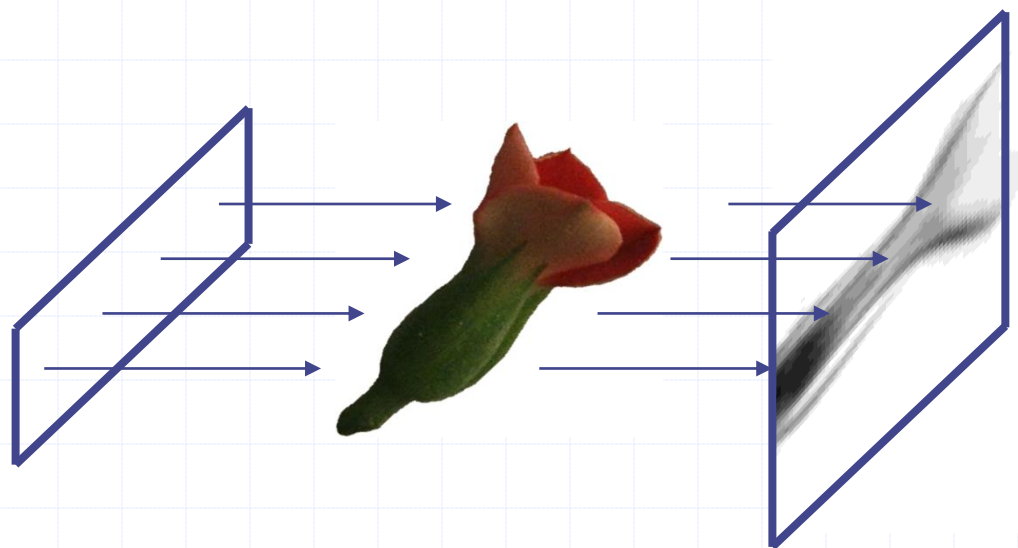


# The Neutronography based on



${}^6\text{Li}(n,\alpha)\text{T}$ ,  $Q=4.78\text{MeV}$  and  ${}^{10}\text{B}(n,\alpha){}^7\text{Li}$ ,  $Q=2.78\text{MeV}$

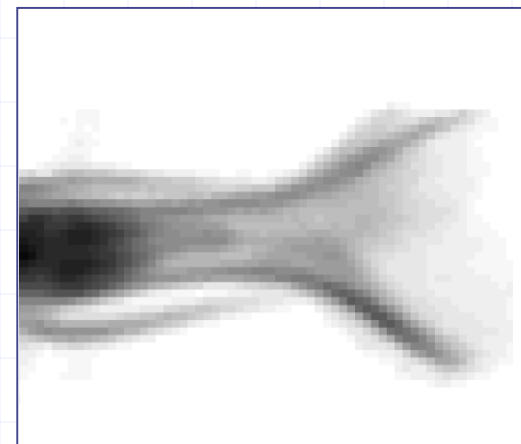
(energetic charged products define interaction with deeply subpixel resolution)



Parallel beam  
of thermal  
neutrons

Specimen  
attenuating  
the beam

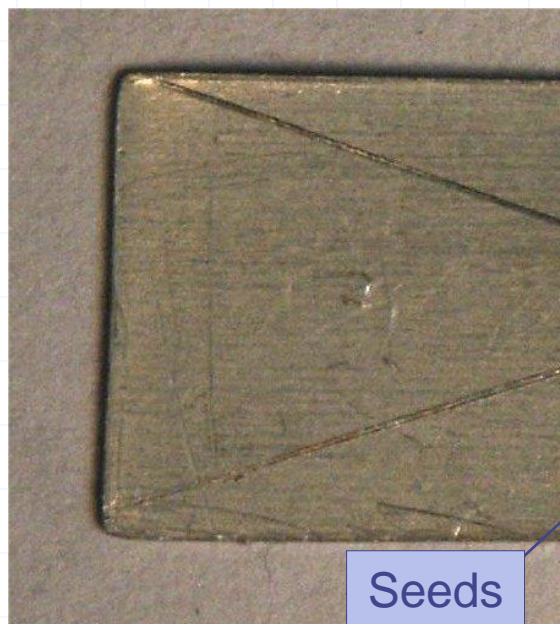
Shadow  
on  
detector  
plane



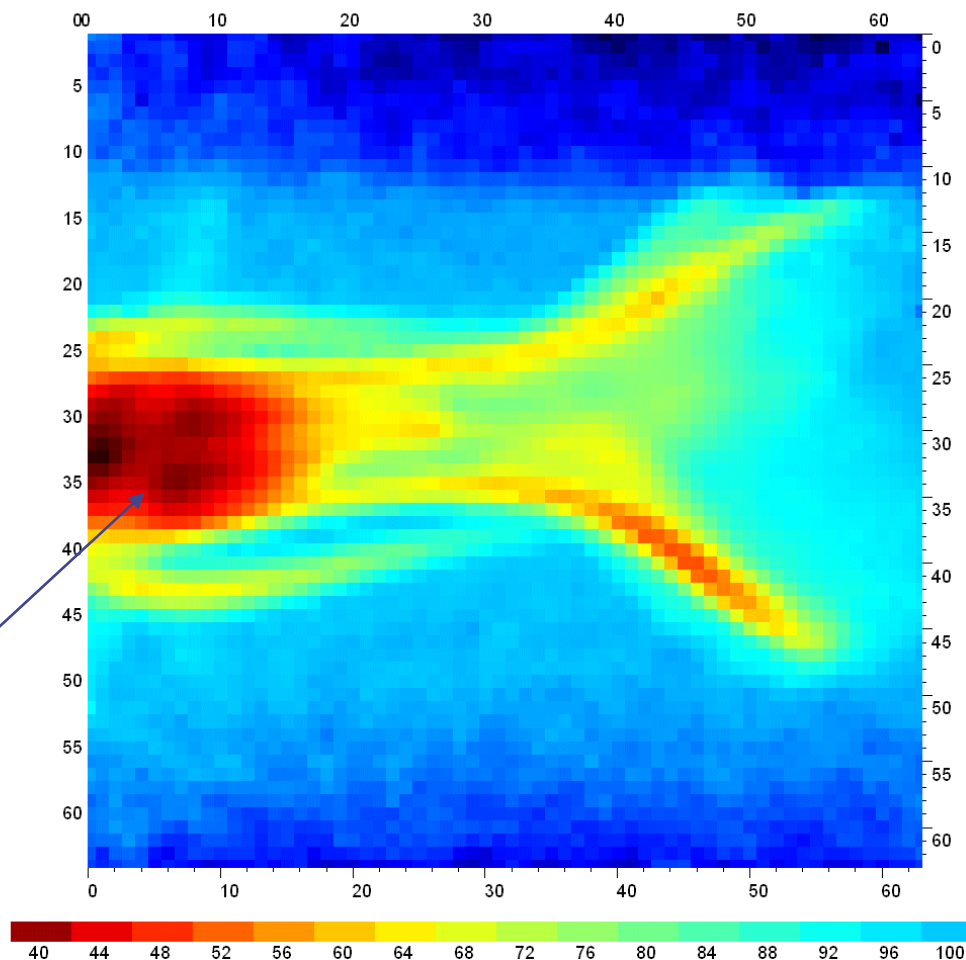
Neutronogram

# Flower behind Al plate

Look through metal with thermal neutron beam at NPI Rez



Seeds

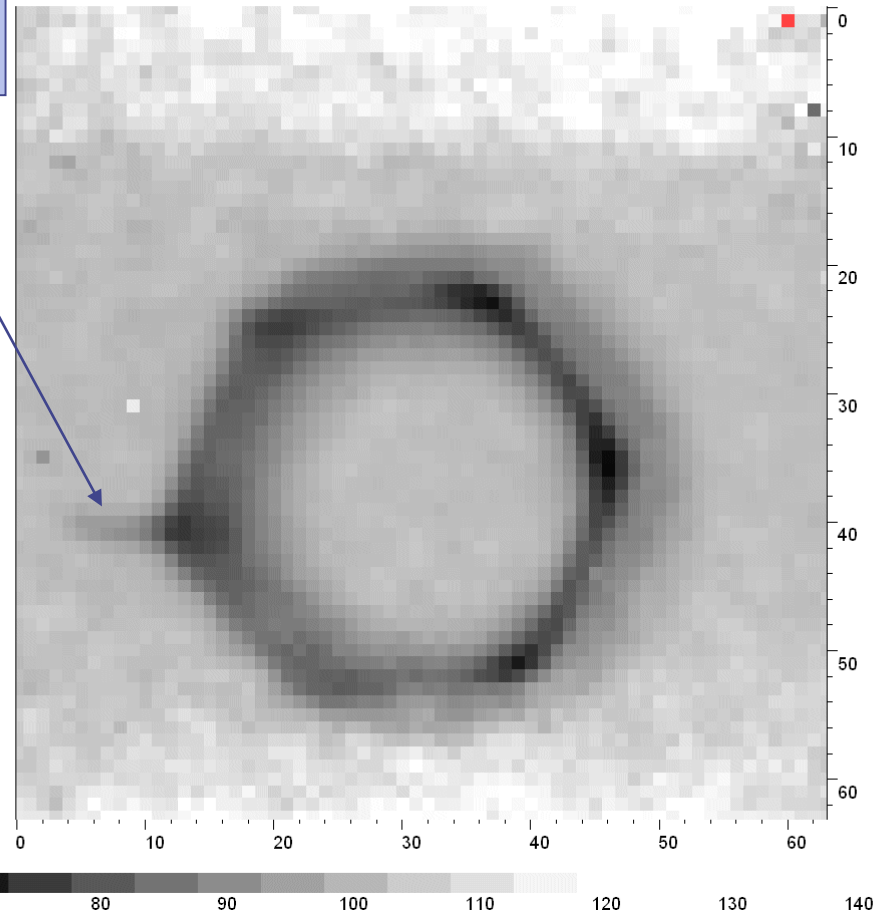




# Glued Al pieces

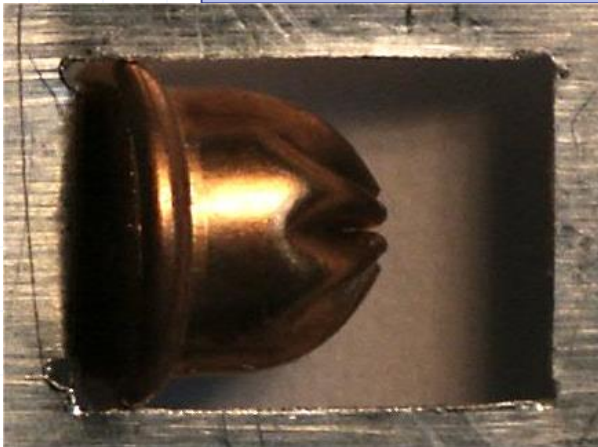
(measured at NPI Rez)

Glue raised through capillary attraction



# Neutron radiography with Medipix coated by $^6\text{LiF}$ : Blank cartridge. Look through metals!

Photography

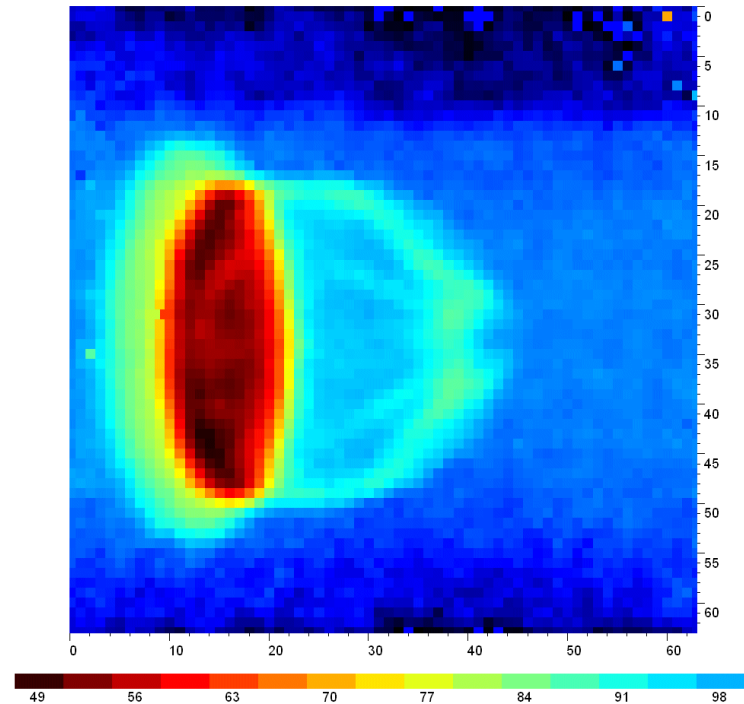


Blank shell  
(cartridge)

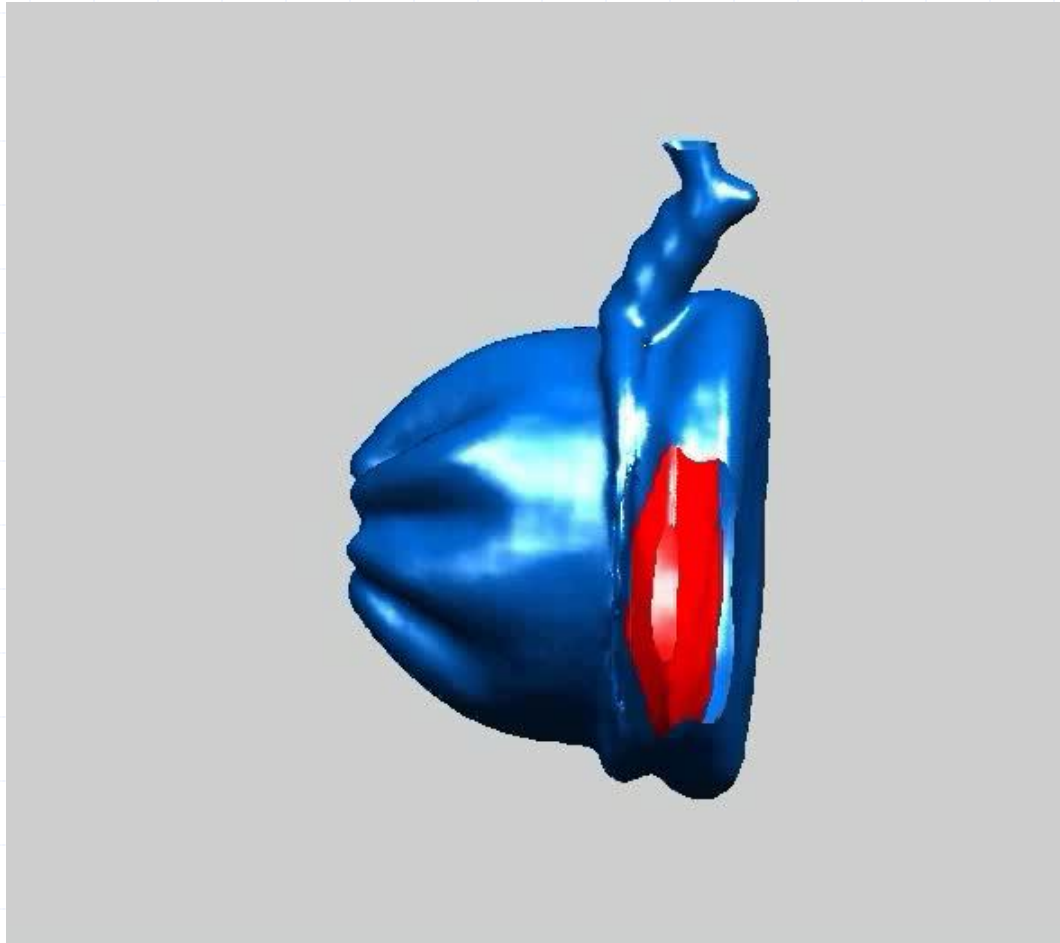
Roentgenogram



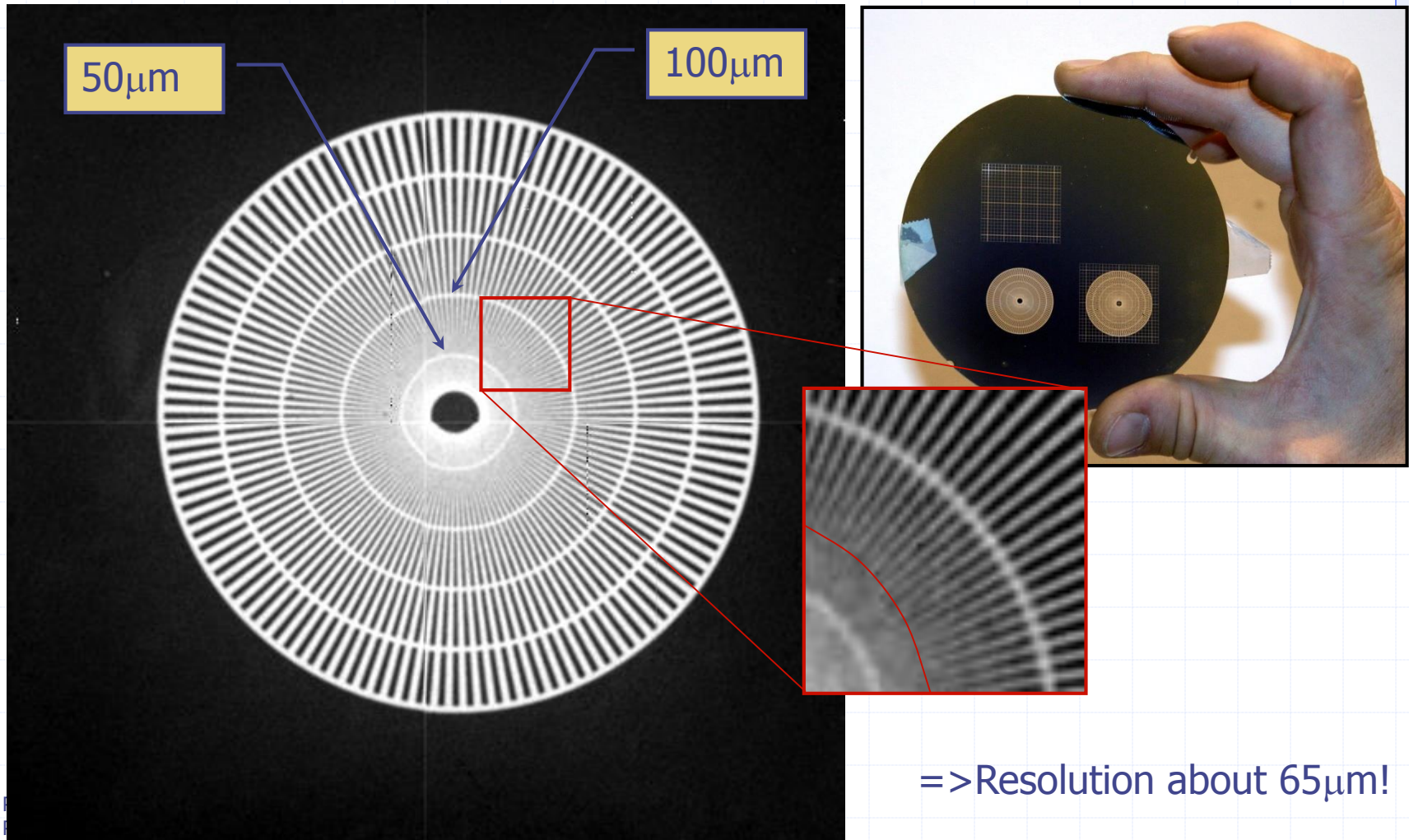
Explosive filling



# 3D neutron tomography



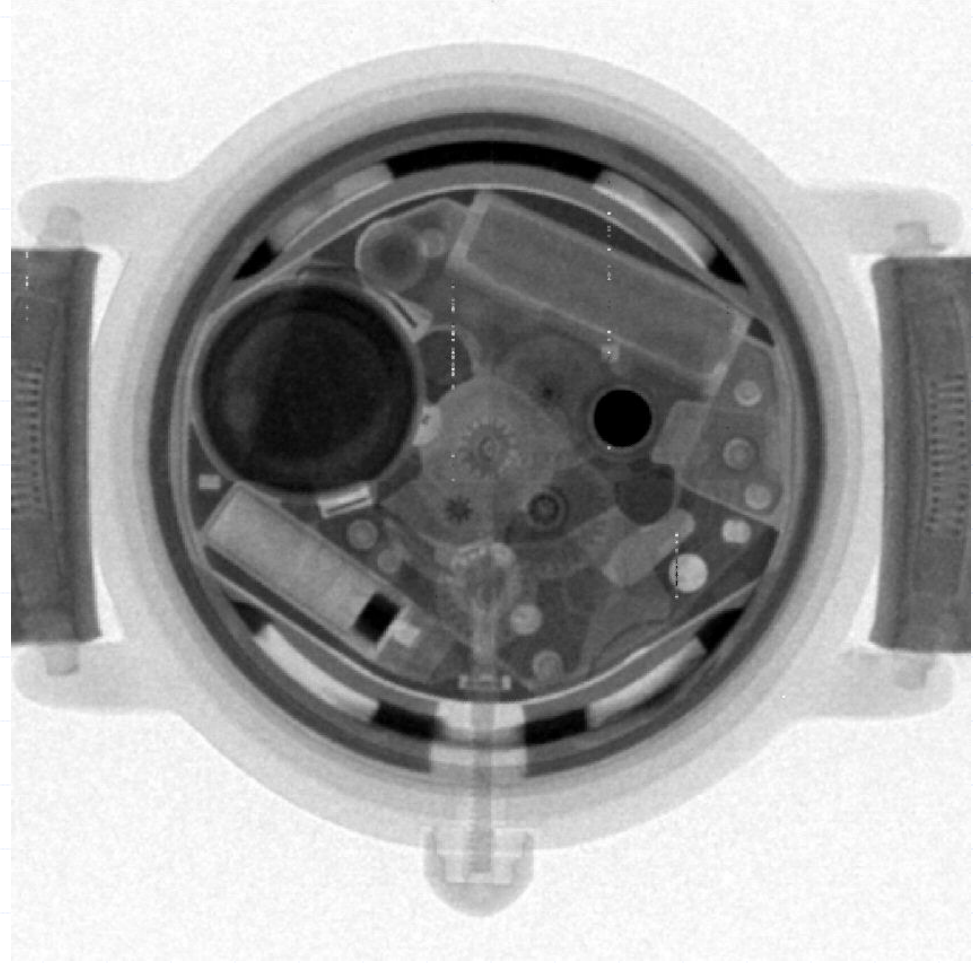
# Neutron transmission radiography (counting mode) Test of Spatial Resolution (Medipix2 Quad system and cold neutrons)



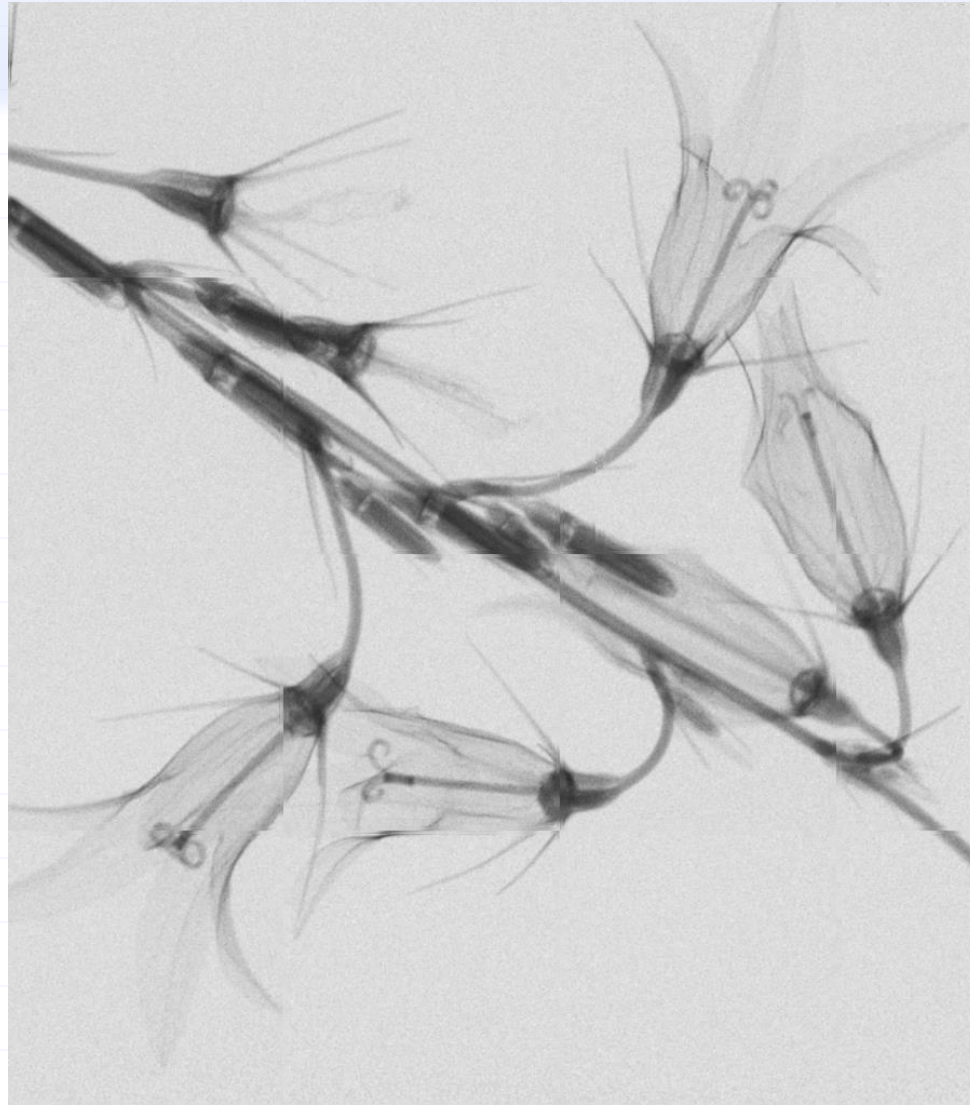
=>Resolution about 65µm!

# Cold neutron radiography performed at PSI

## Wrist watch



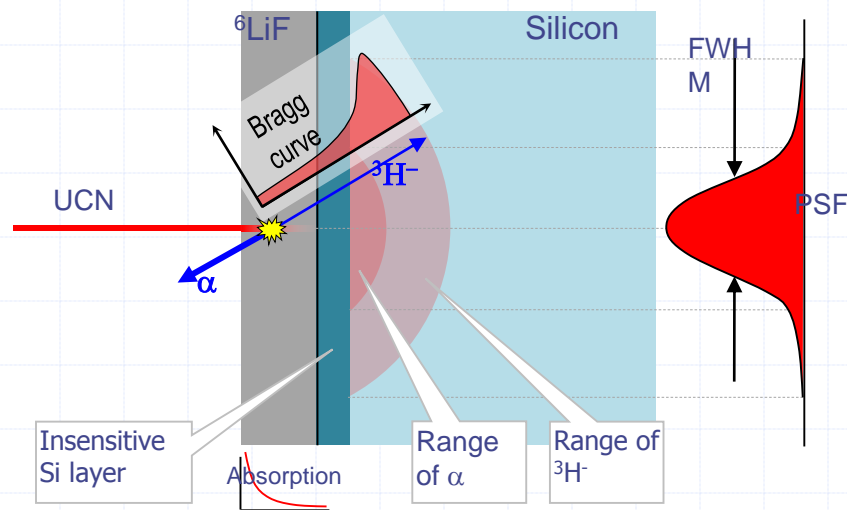
# Bellflower



# About detection efficiency and position resolution

## Monte-Carlo simulations and experiments

- ◆ Simulations performed using MCNP, SRIM and Matlab
- ◆ Aim: To estimate detection efficiency and spatial resolution



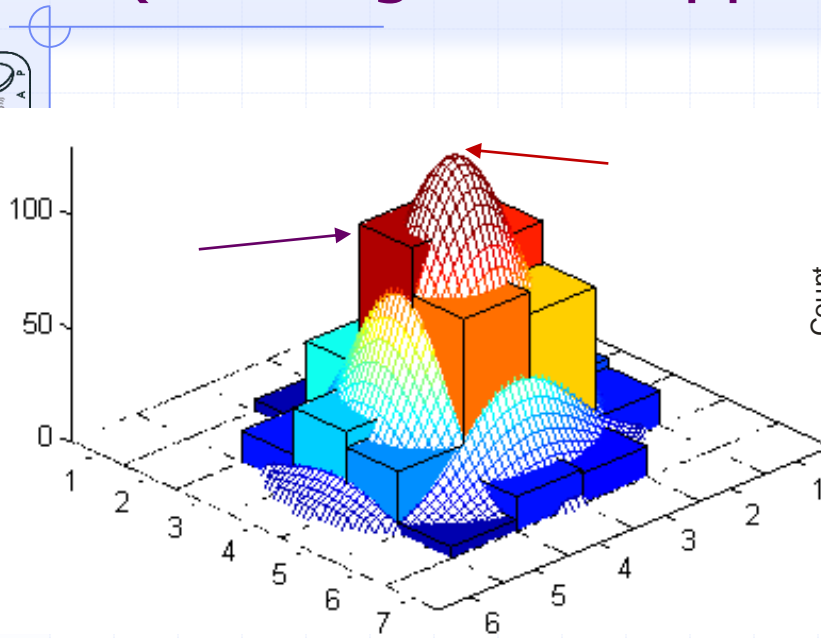
Expected UCNs velocity: 500 cm/s. For such neutrons the cross section of  ${}^6\text{Li}$  increases to **0.34 Mbarn**. The cross section of  ${}^{10}\text{B}$  reaches **1.67 Mbarn**.

50% of such UCNs are fully absorbed in  ${}^6\text{LiF}$  layer of  $85 \text{ ug/cm}^2$  ( $\sim 320 \text{ nm}$  thickness). For  ${}^{10}\text{B}$  it is layer of  $7 \text{ ug/cm}^2$  ( $\sim 30 \text{ nm}$  thickness).

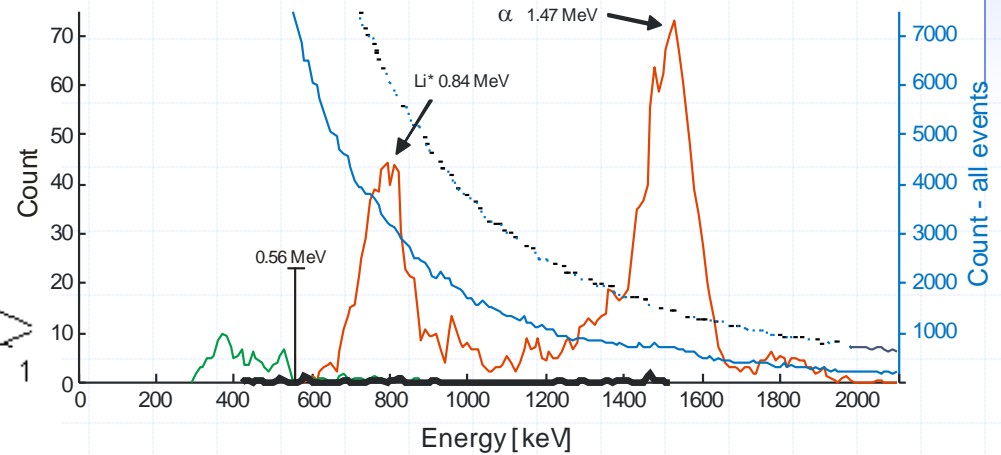
Used  ${}^6\text{LiF}$  density of  $2.65 \text{ g/cm}^3$  and  ${}^{10}\text{B}$  density of  $2.35 \text{ g/cm}^3$ .

### Geometry used in simulations

# Detail view on individual clusters resulting from (n, $\alpha$ ) reaction in $^{10}\text{B}$ converter (tracking mode applicable for neutron imaging)



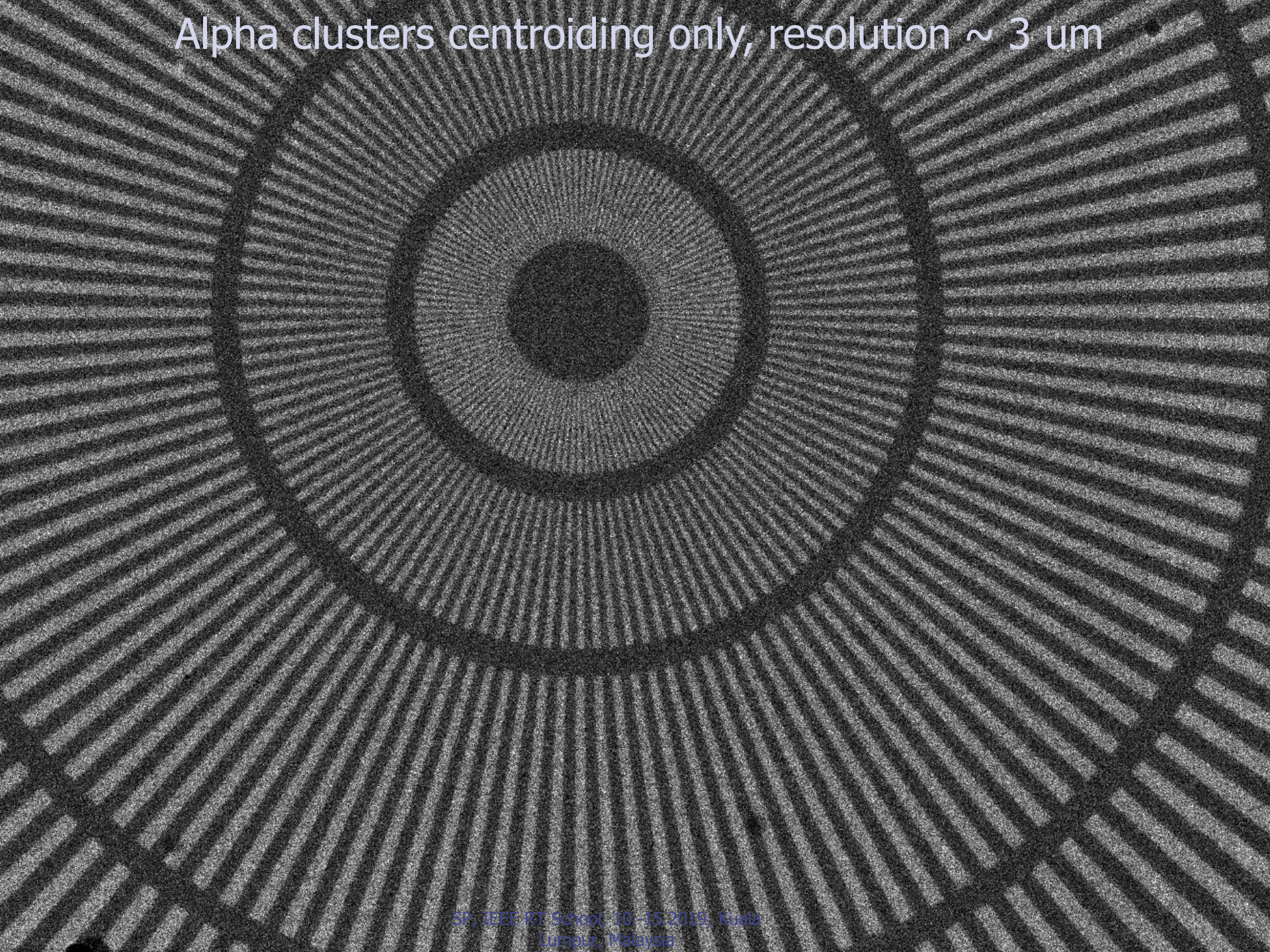
Pixel detector response to every charged article (alpha and  $^7\text{Li}$ ) in a form of 3D-cluster with a shape corresponding to convolution of Gaussian and individual pixel responses



Corresponding amplitude spectrum measured by integration of cluster volumes.  $^{10}\text{B}$  converter thickness  $1.8 \mu\text{g}/\text{cm}^2$  ( $\sim 36 \text{ nm}$ )



Alpha clusters centroiding only, resolution  $\sim 3 \mu\text{m}$

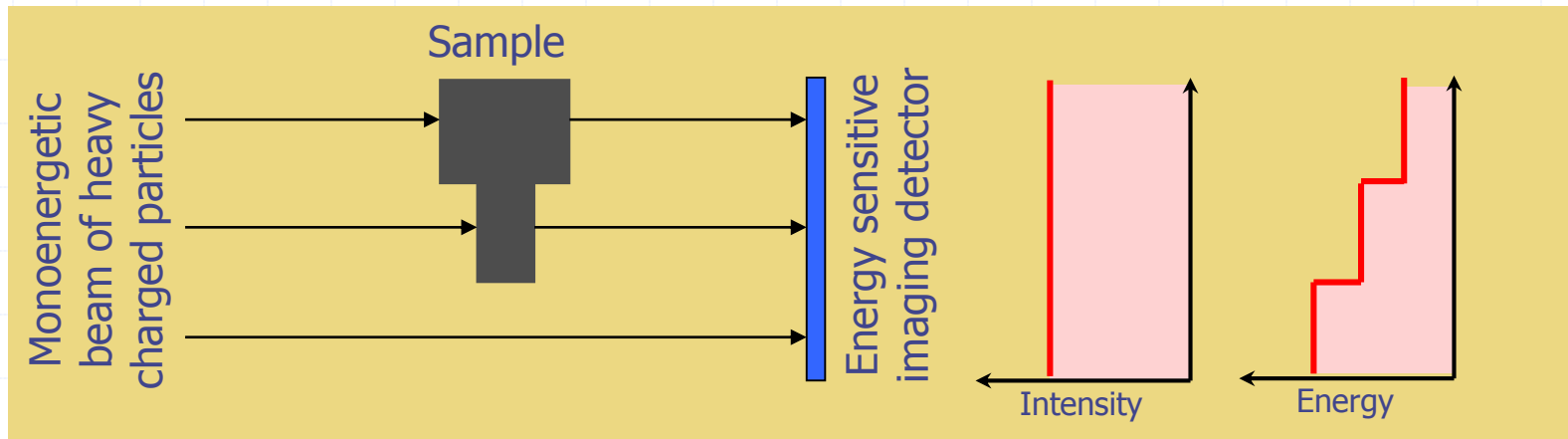


# Alpha radiography



Application:

# Radiography with highly ionizing particles



- ◆ **Heavy charged particles** (protons, deuterons, tritons, alphas, ions) can be used (impossible with photons, difficult with electrons due to huge change of direction).
- ◆ Instead of transmitted beam intensity the **energy losses** of individual particles are measured.
- ◆ Just single particle is needed to measure material "density".
- ◆ With common sources of heavy charged particles (isotopes, ion beams) it is feasible to inspect just small (thin) objects (thin layer, foils, cellular structures)
- ◆ **Precision of thickness measurement can be in nanometer scale.**

# Radiography with heavy charged particles with Medipix2



By cluster analysis it can be determined:

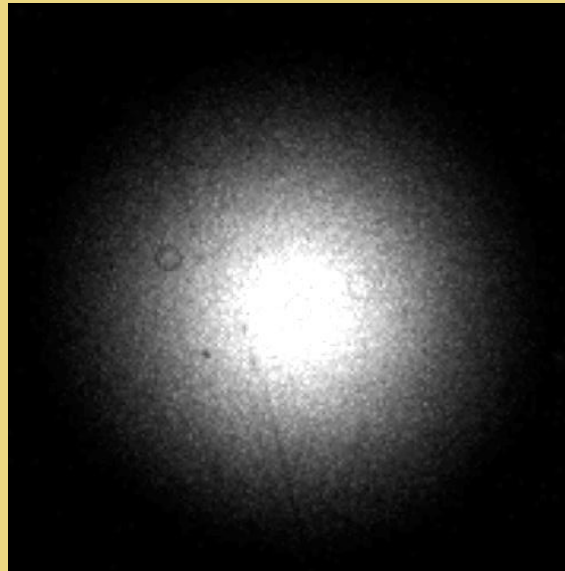
- **Centroid** to increase spatial resolution (subpixel resolution)
- **Size** as a measure of particle energy

**Wing of fly**

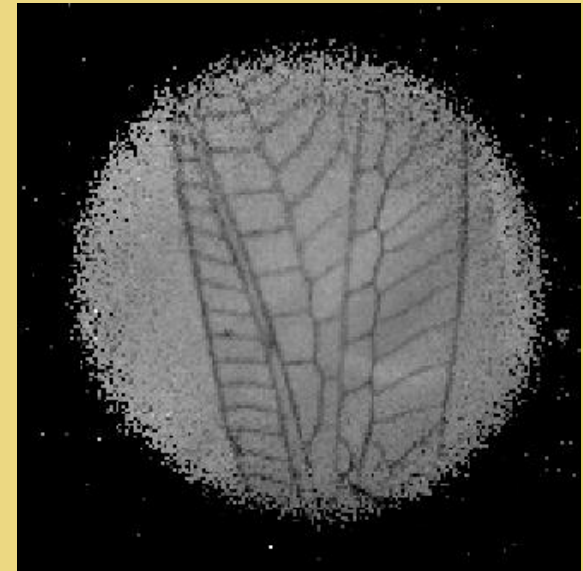
(less than 20 particles per pixel)



Photo



Intensity

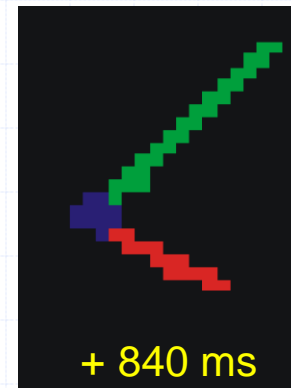
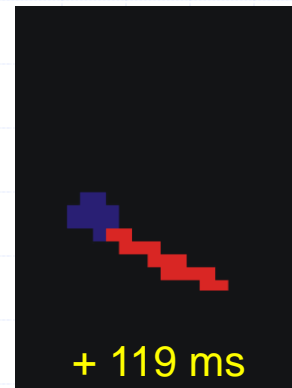
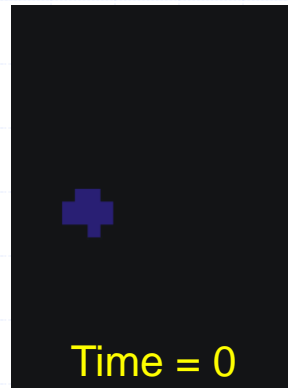
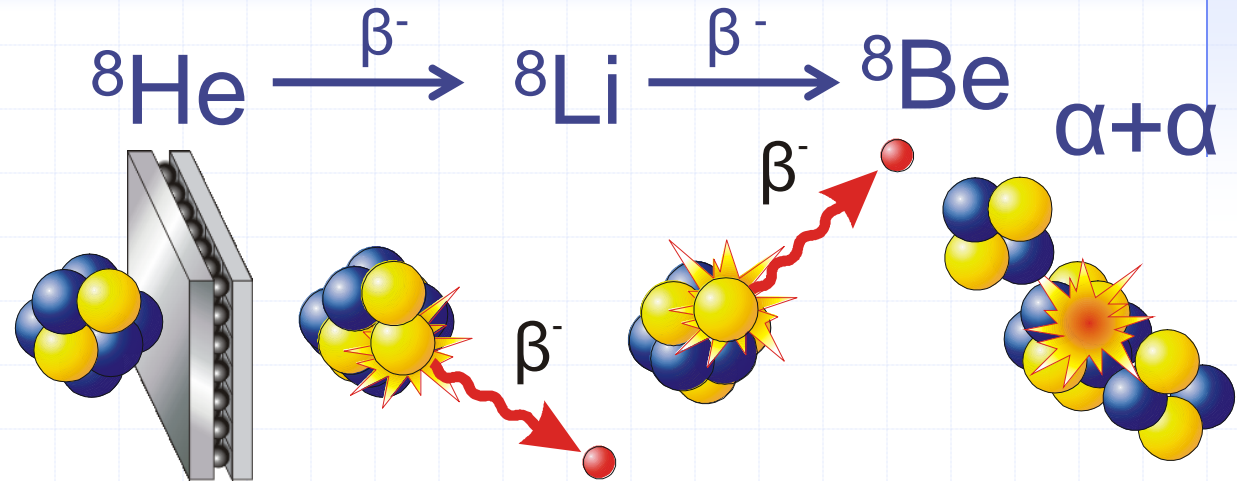


Energy

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

$^8\text{He}$  ion hits the Timepix sensor where undergoes  $\beta^-$ -decay

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

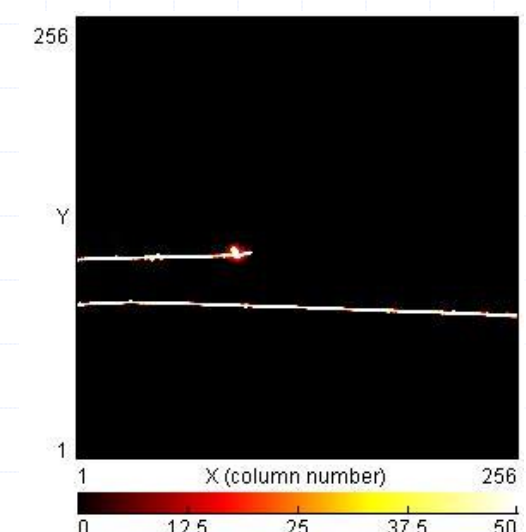
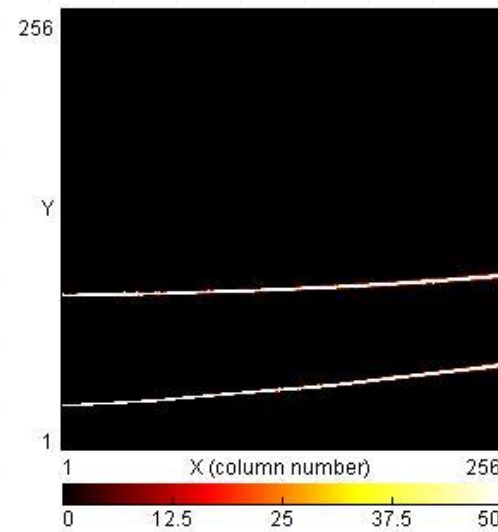
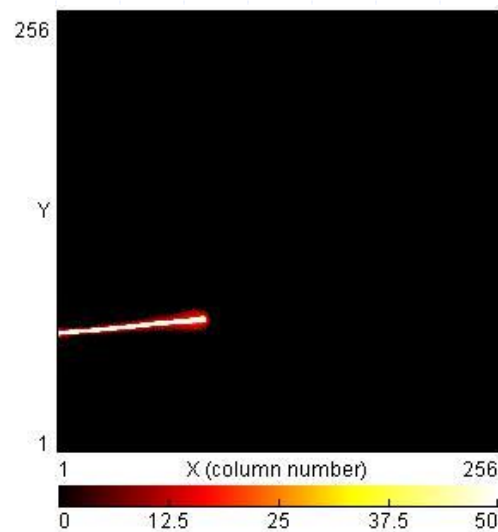
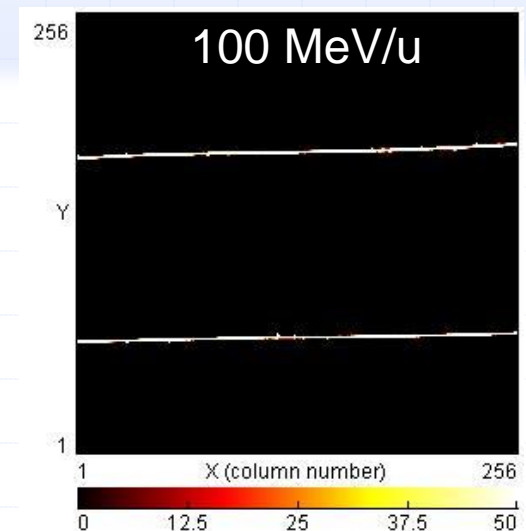
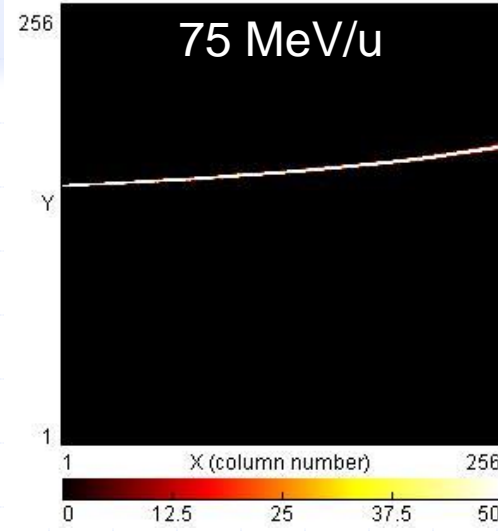
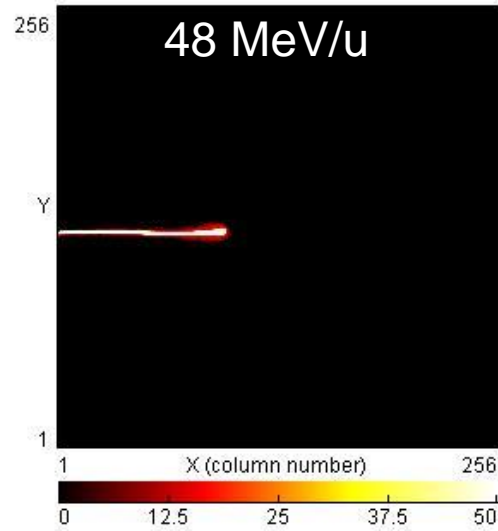




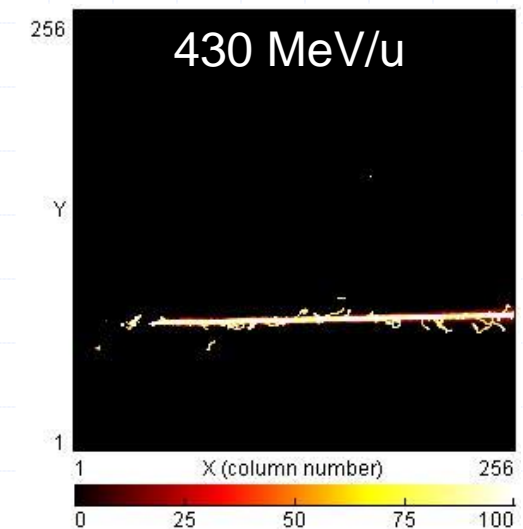
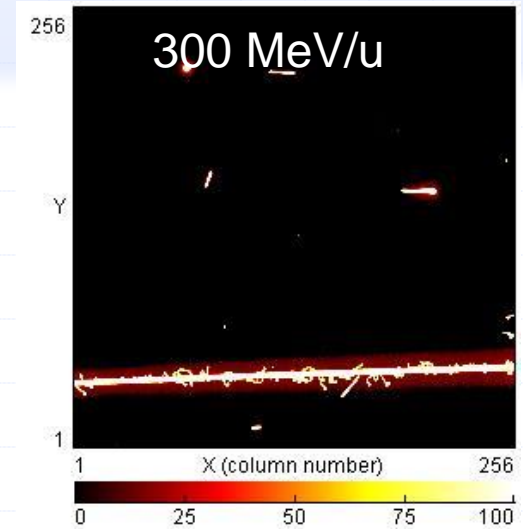
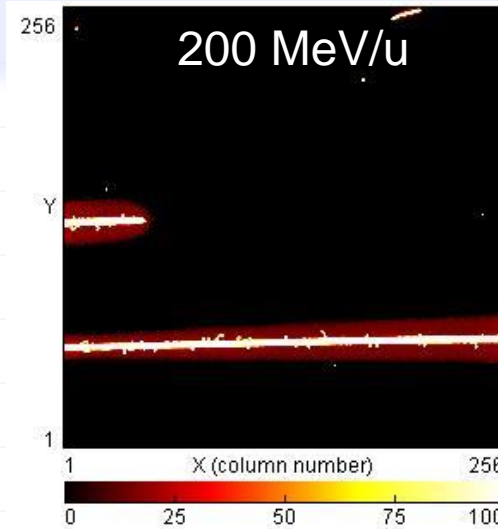
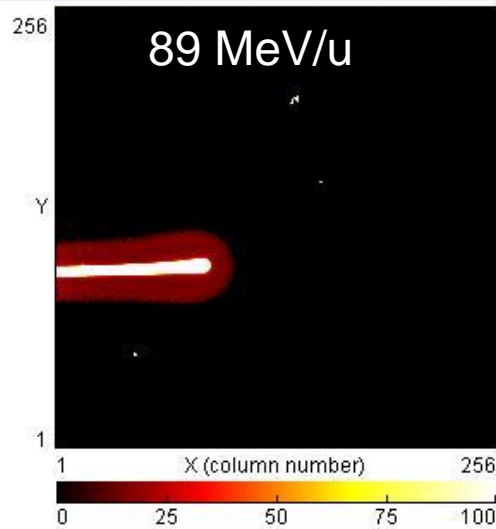
# About use of Timepix pixel detectors for measurement of composition and spectral characteristics of complex radiation fields

**Calibration of detector responses to all  
available particles is required!**

# Protons with different energies: 90 degree



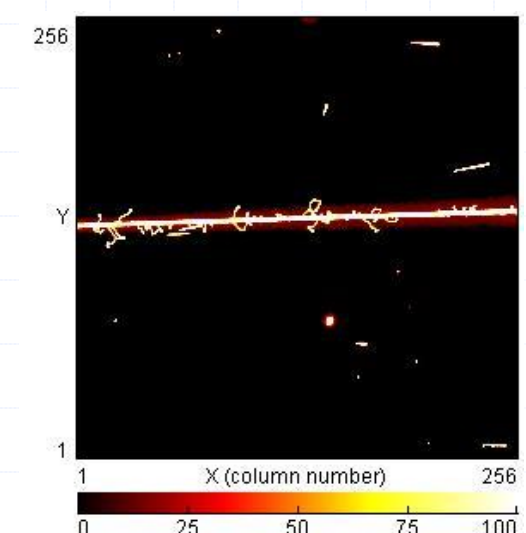
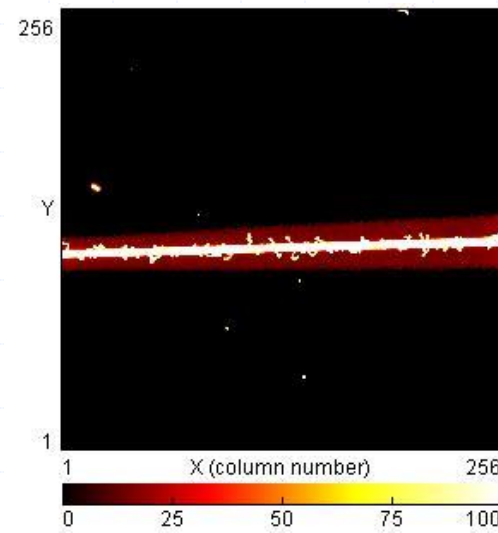
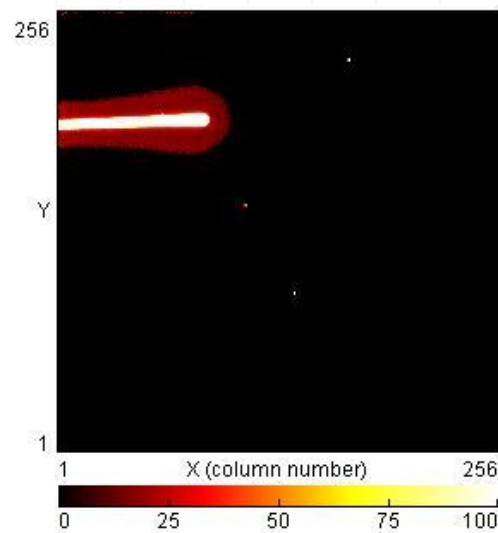
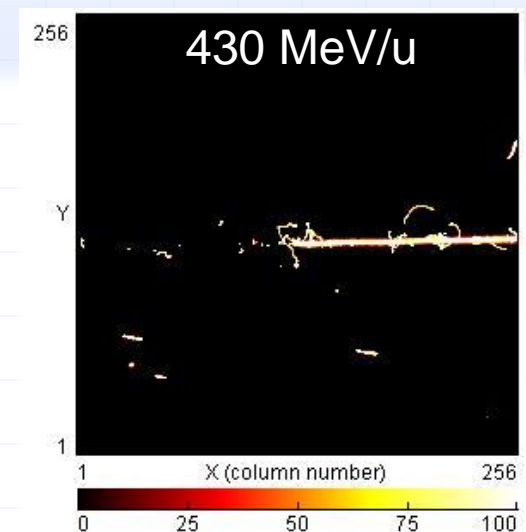
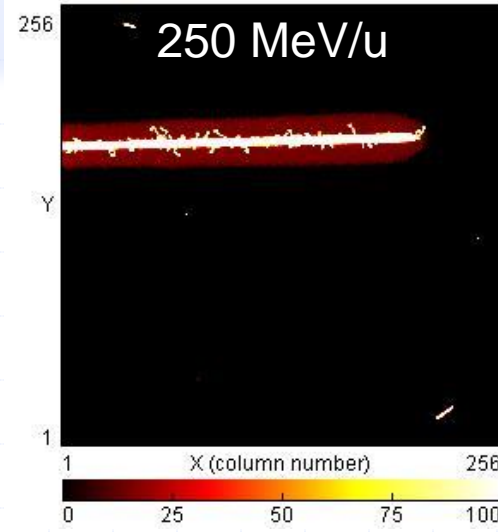
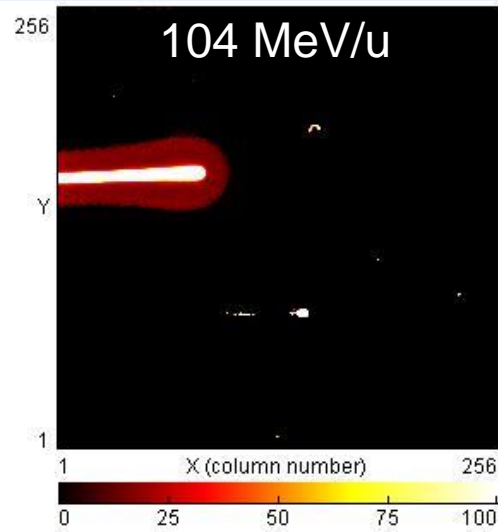
# Carbon ions with different energies: 90 degrees



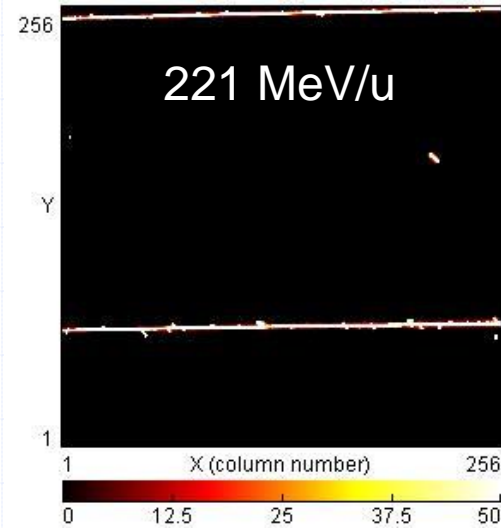
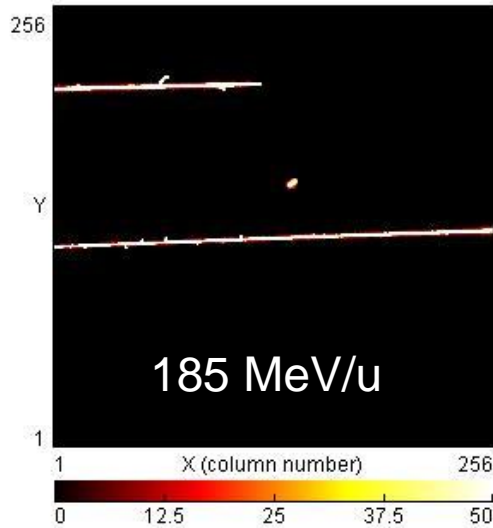
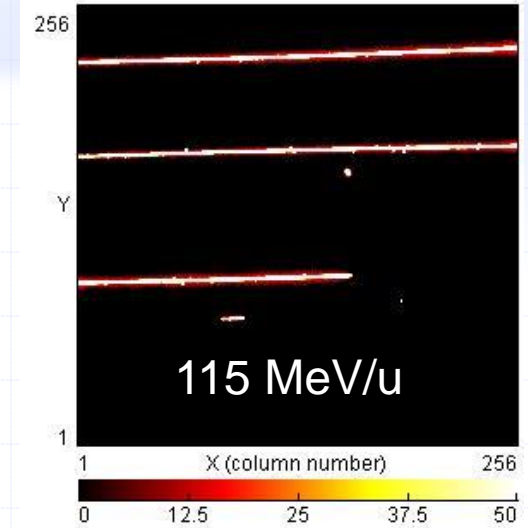
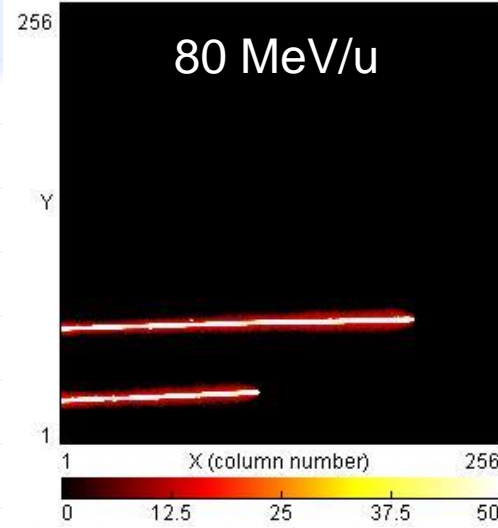
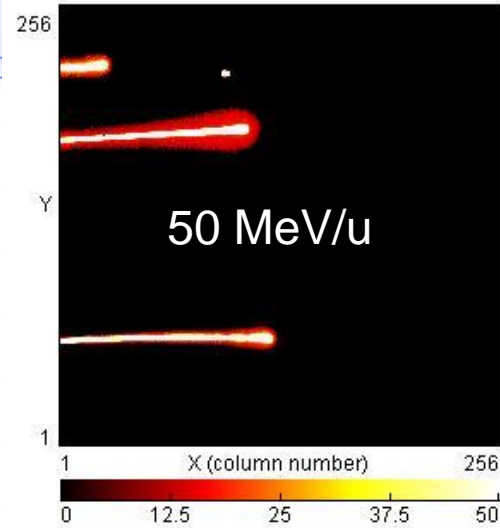
- ❑ Halo of pixel with low energy deposition around track - less pronounced for higher energies.
- ❑ Number of delta rays increases with increasing energy.



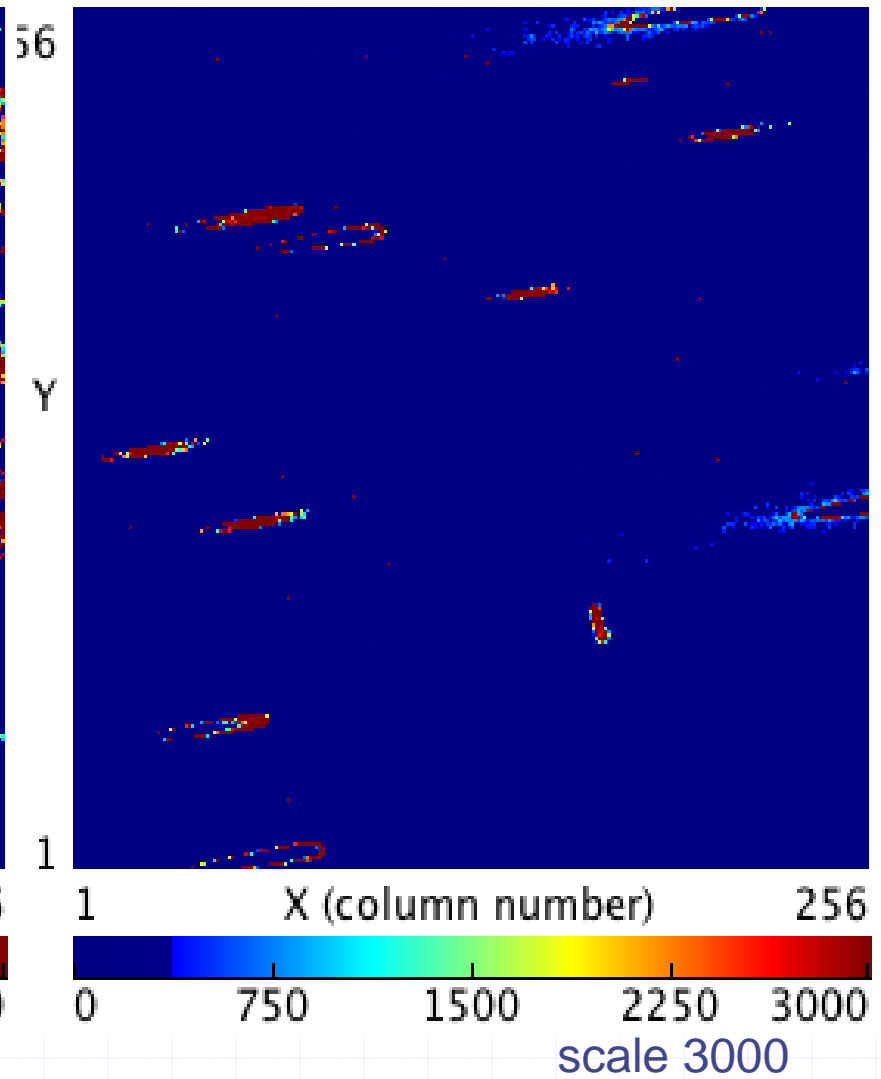
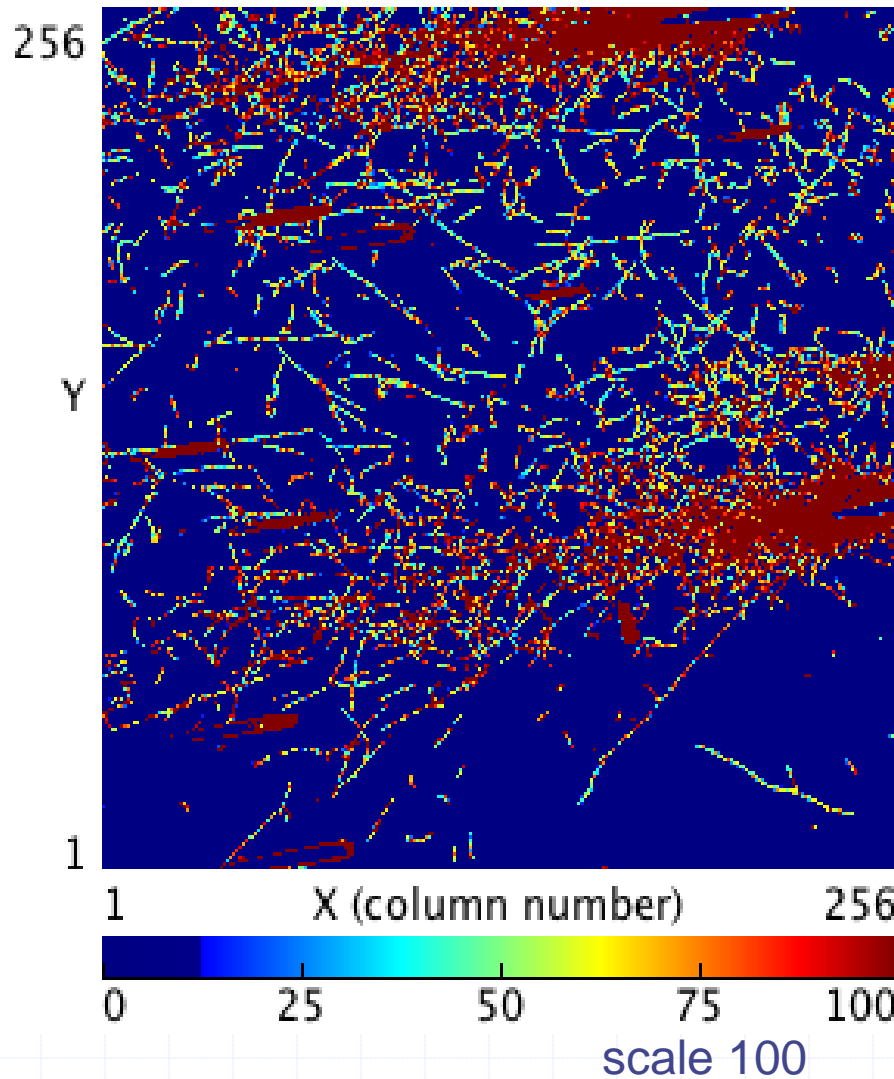
# Oxygen ions with different energies: 90 degrees



# Alphas with different energies: 90 degrees



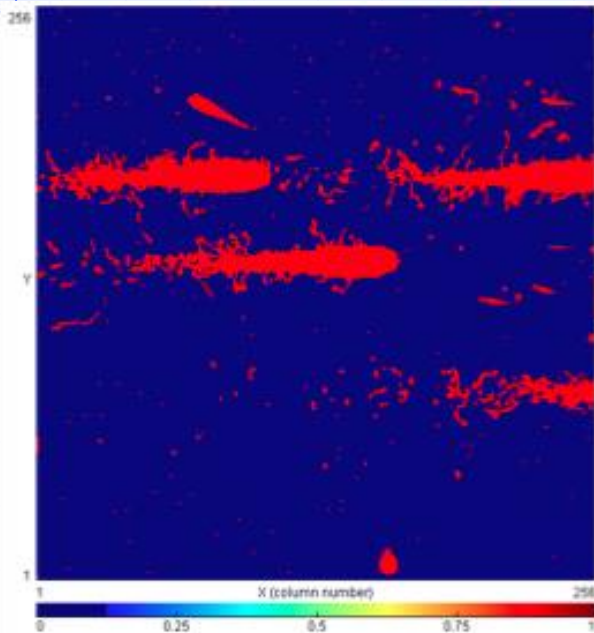
# Tracks of Pb ions as measured on SPS beam at CERN (rear-side glancing angular incidence about 4.1 degree)



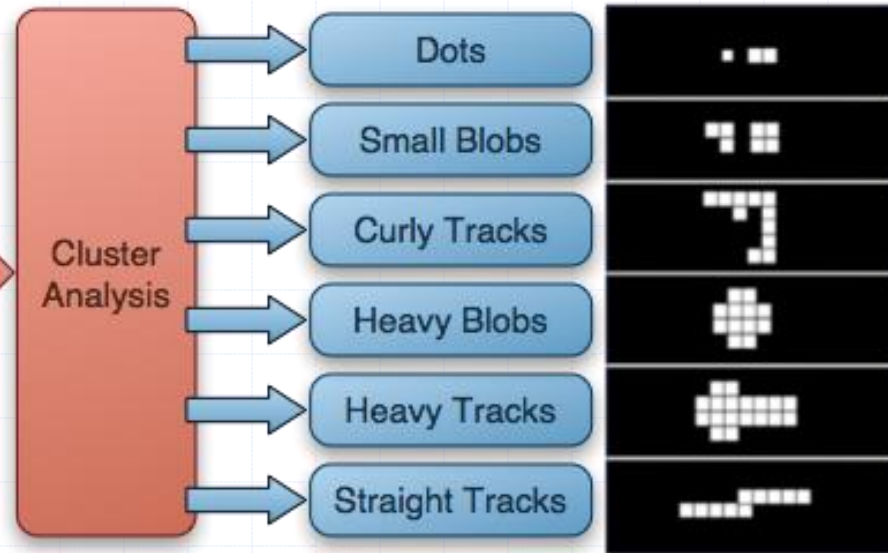
Imaged with low threshold on the left and with high threshold on the right

# Online miniaturized Timepix Quantum Dosimeter

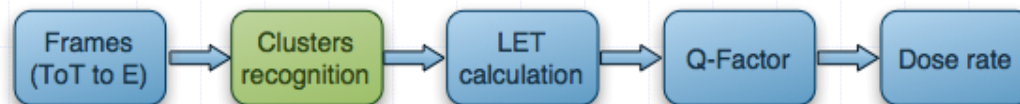
## Single particle visualization & tracking



Frame containing 400 MeV 56Fe,  
85°, measured at HIMAC, Japan



Cluster analysis algorithm is successfully  
working in ATLAS-MPX network



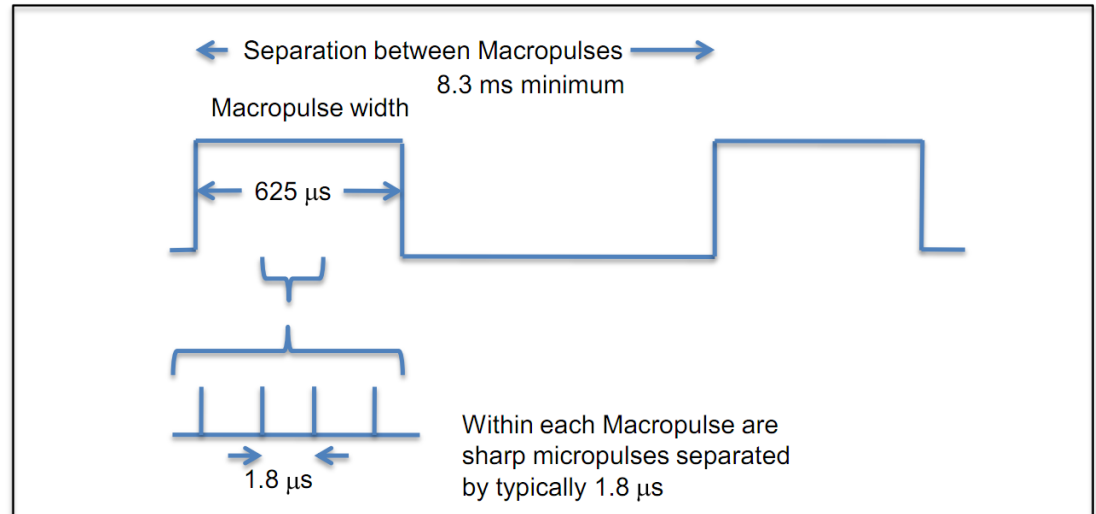
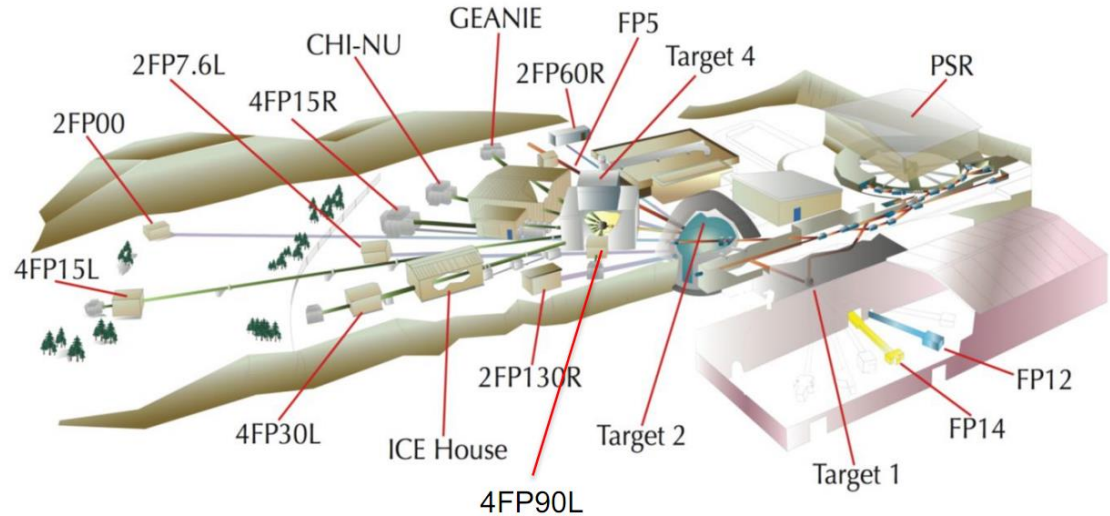
# Fast neutron ToF measurement with TIMEPIX

## LANSCCE neutron sources and nuclear science flight paths

### (combined ToA and ToT modes)



The layout of the LANSCCE neutron sources and Nuclear Science flight paths

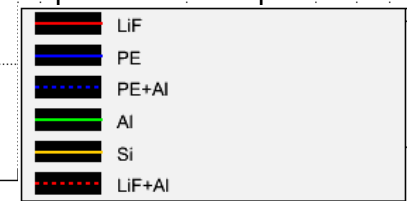
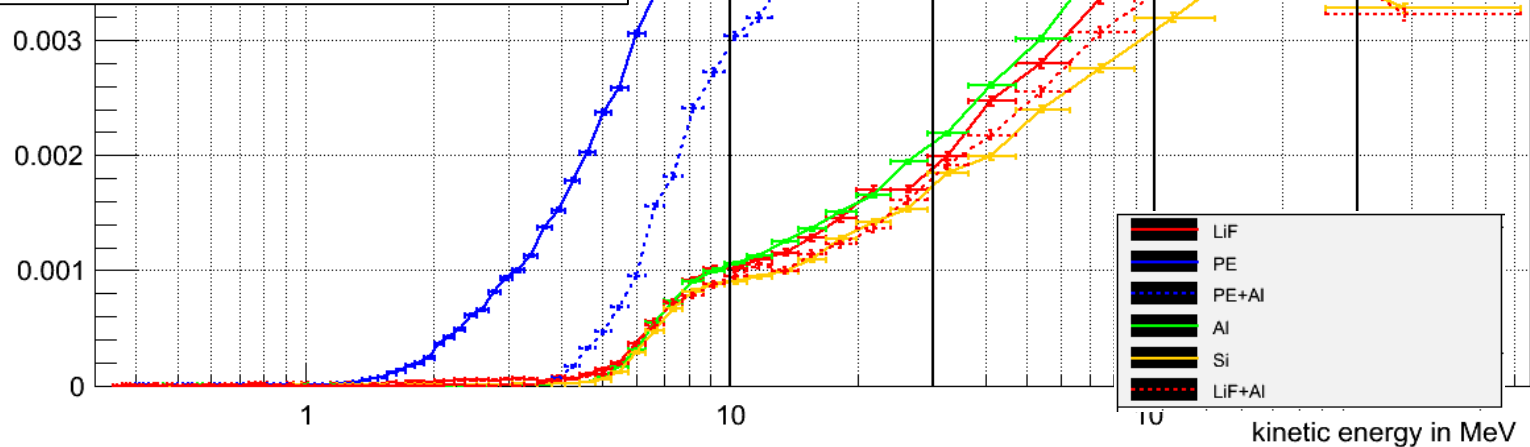
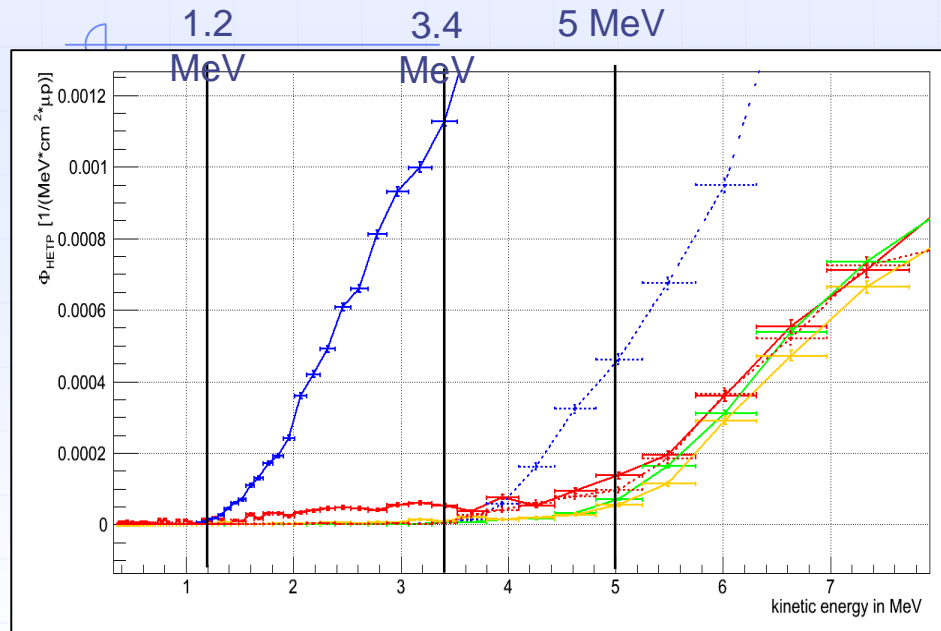


# Fluences below different conversion layers



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  $\sim 3.4$  MeV
- Enhanced signal below LiF up to 4 MeV
- Recoiled protons visible above 1.2 MeV

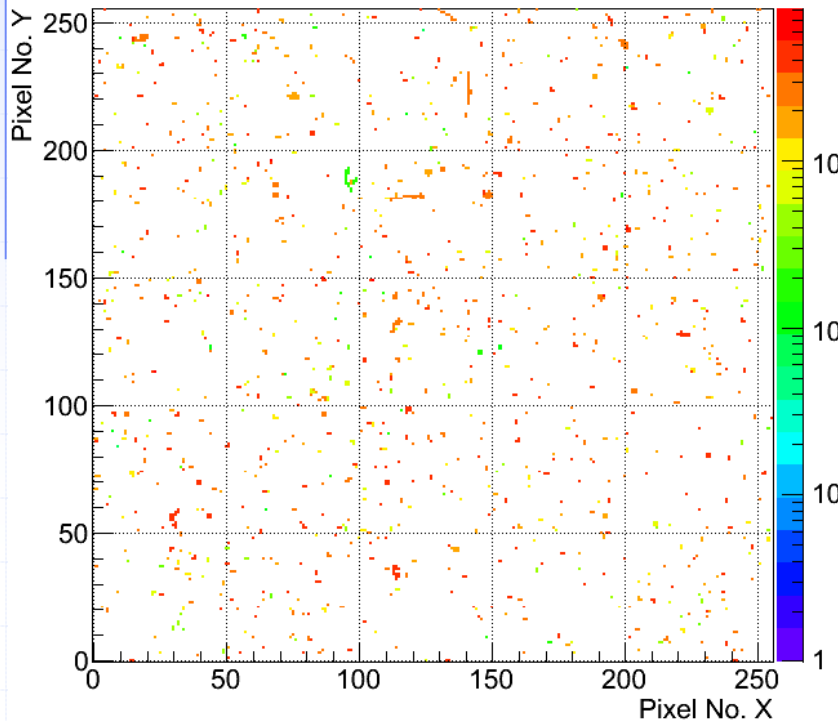


# Response of Timepix:

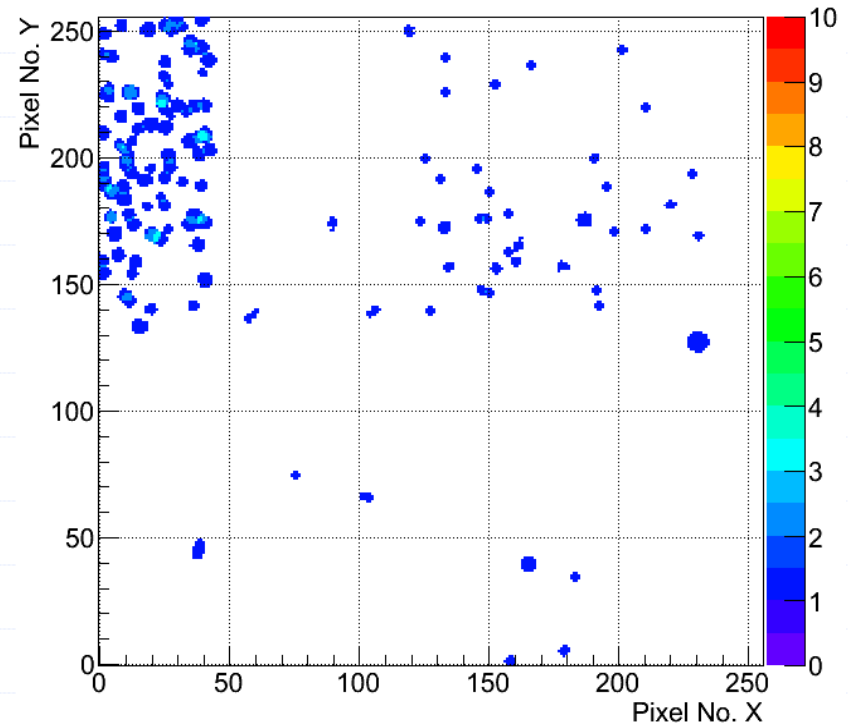
## Energy region 0.4 – 1.2 MeV



- ◆ Mainly dots, curly tracks are found in this energy region
- ◆ Heavy blobs below LiF indicate presence of slow/thermal neutrons
- ◆ Also PE region shows slightly enhanced count rate



All types of clusters in this energy region integral picture (1000 events were considered)



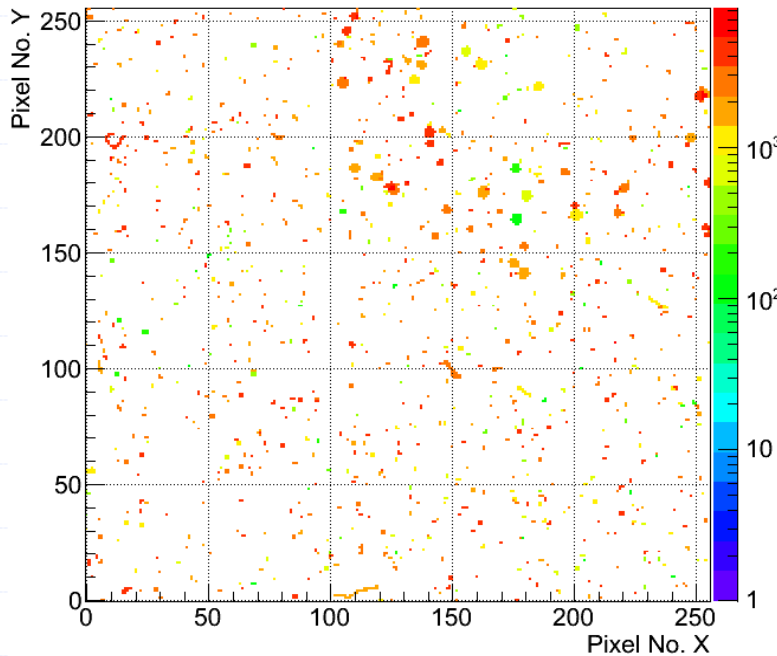
Heavy tracks and heavy blobs in this energy region (139 events were found)

# Response of Timepix:

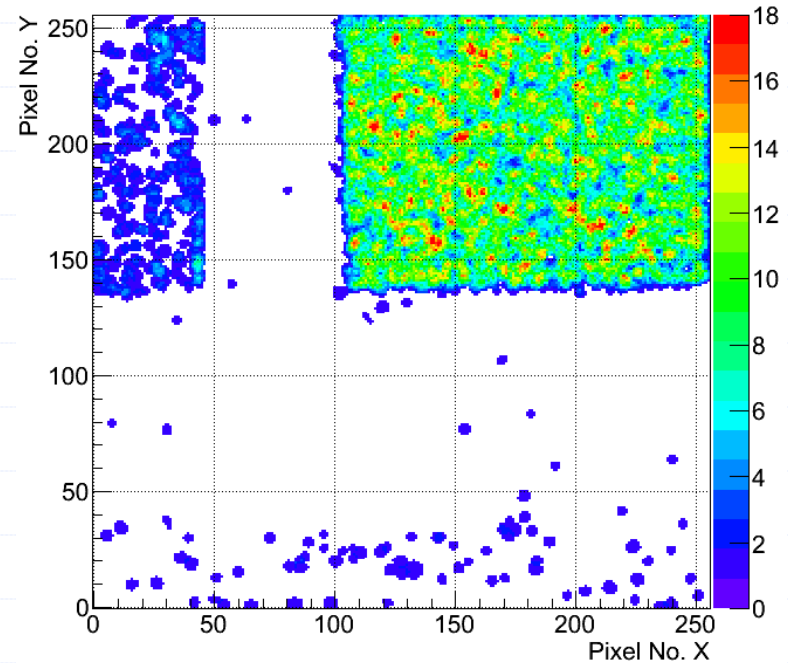
## Energy region 1.2 – 3.4 MeV



- ◆ Heavy blobs below LiF indicate presence of slow/thermal neutrons
- ◆ Clear signal of High Energy Transfer Particles (HETP) below PE
- ◆ uncovered area shows also a few events



All types of clusters in this energy region integral picture (1000 events were considered)



Heavy tracks and heavy blobs in this energy region (full statistics - 10259 events were found)

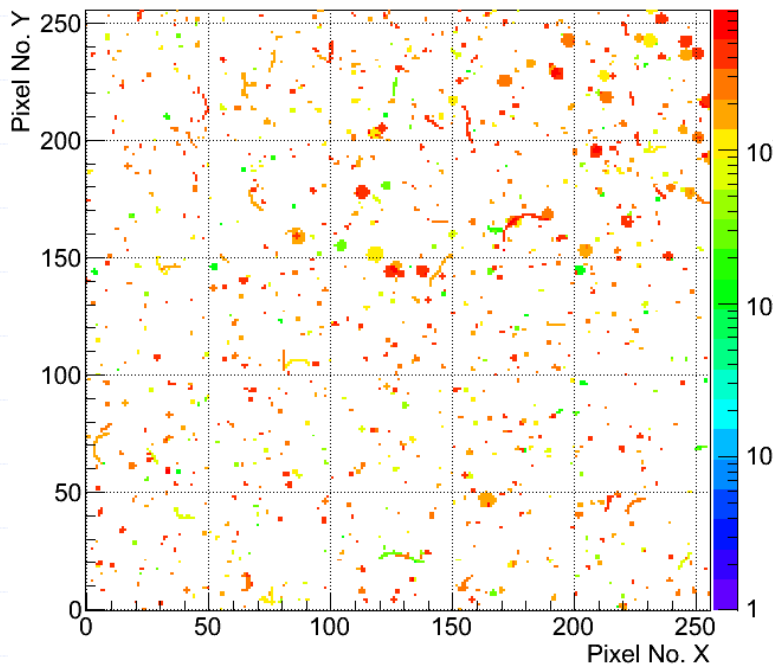


# Response of Timepix: Energy region 3.4 – 5.0 MeV

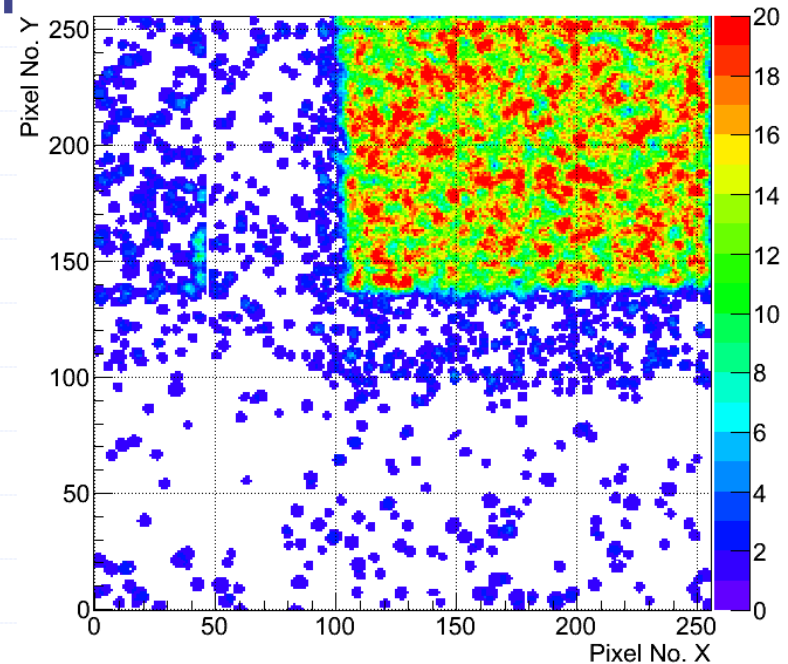


## Clear signal of HETP below PE

### Analysis of PE and HETP in Timepix



All types of clusters in this energy region integral picture (1000 events were considered)

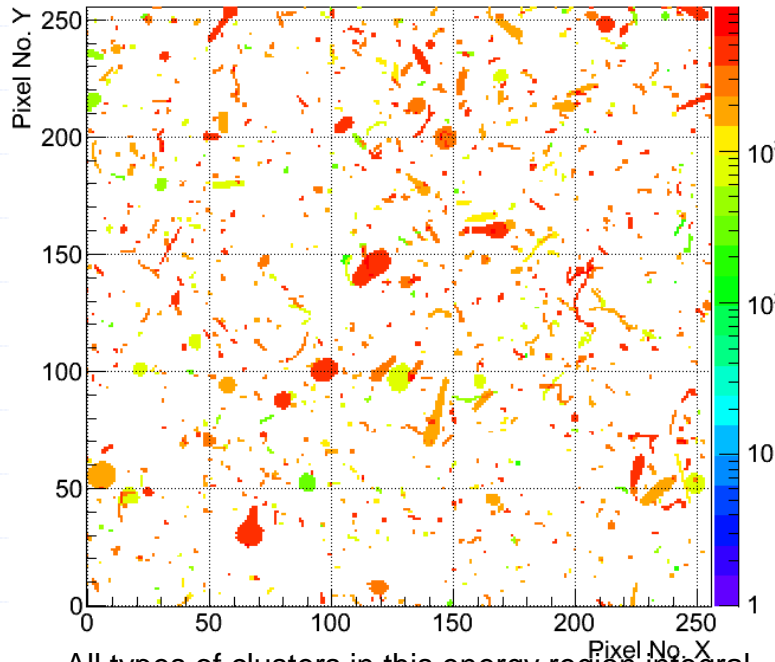


Heavy tracks and heavy blobs in this energy region (full statistics – 13406 events were found)

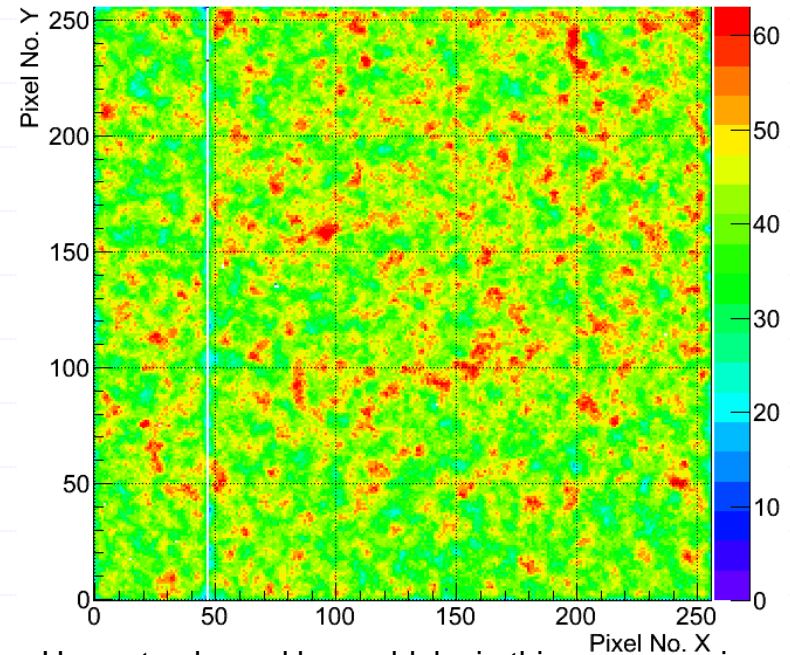
# Response of Timepix: Energy region 100 – 300 MeV



- ◆ HETP nearly equally distributed below all regions
- ◆ HETP Cluster shapes
  - Are getting bigger and more and more asymmetric
  - Round clusters with outgoing tracks are seen

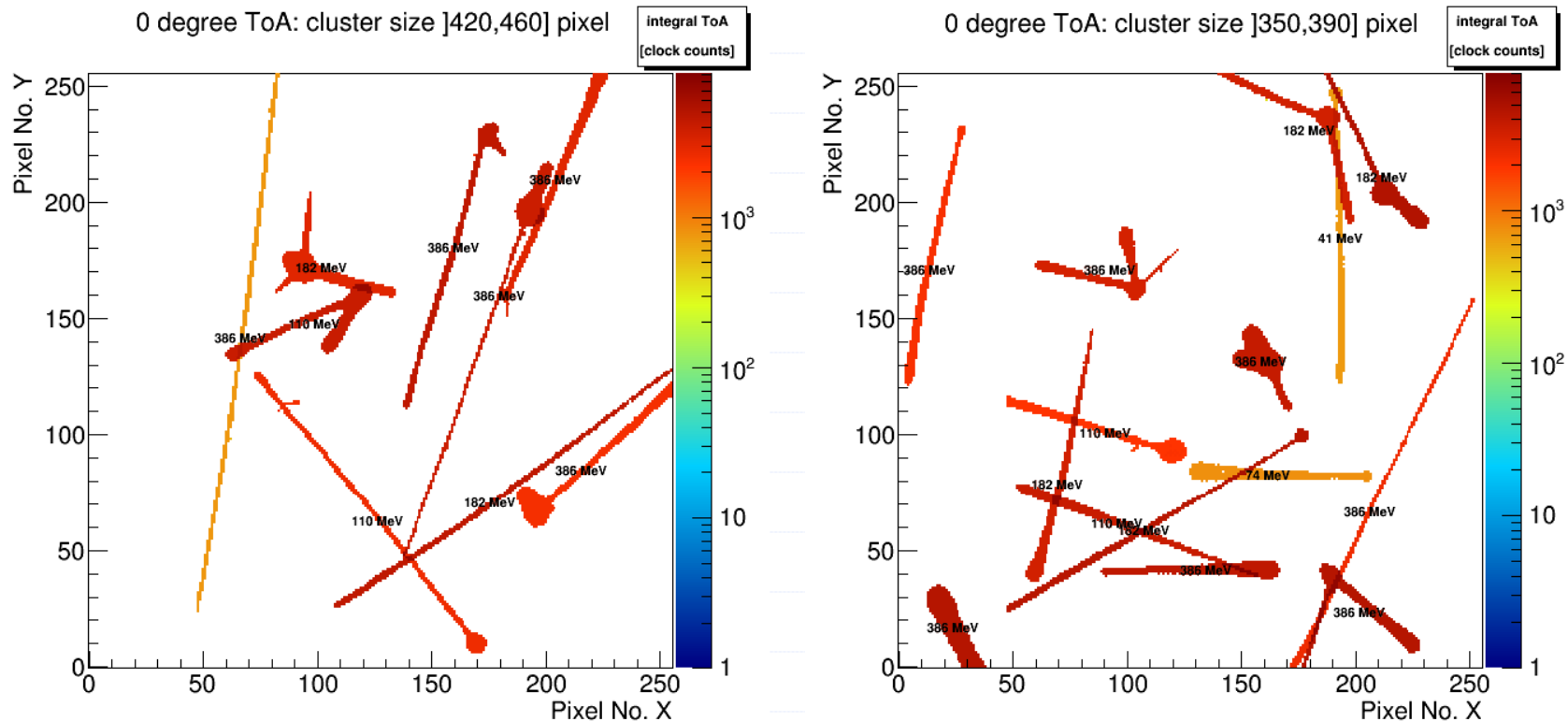


All types of clusters in this energy region integral picture (1000 events were considered)



Heavy tracks and heavy blobs in this energy region (full statistics - 64755 events were found)

# Examples of heavy ionizing events induced by neutrons of different energies selected according their cluster sizes

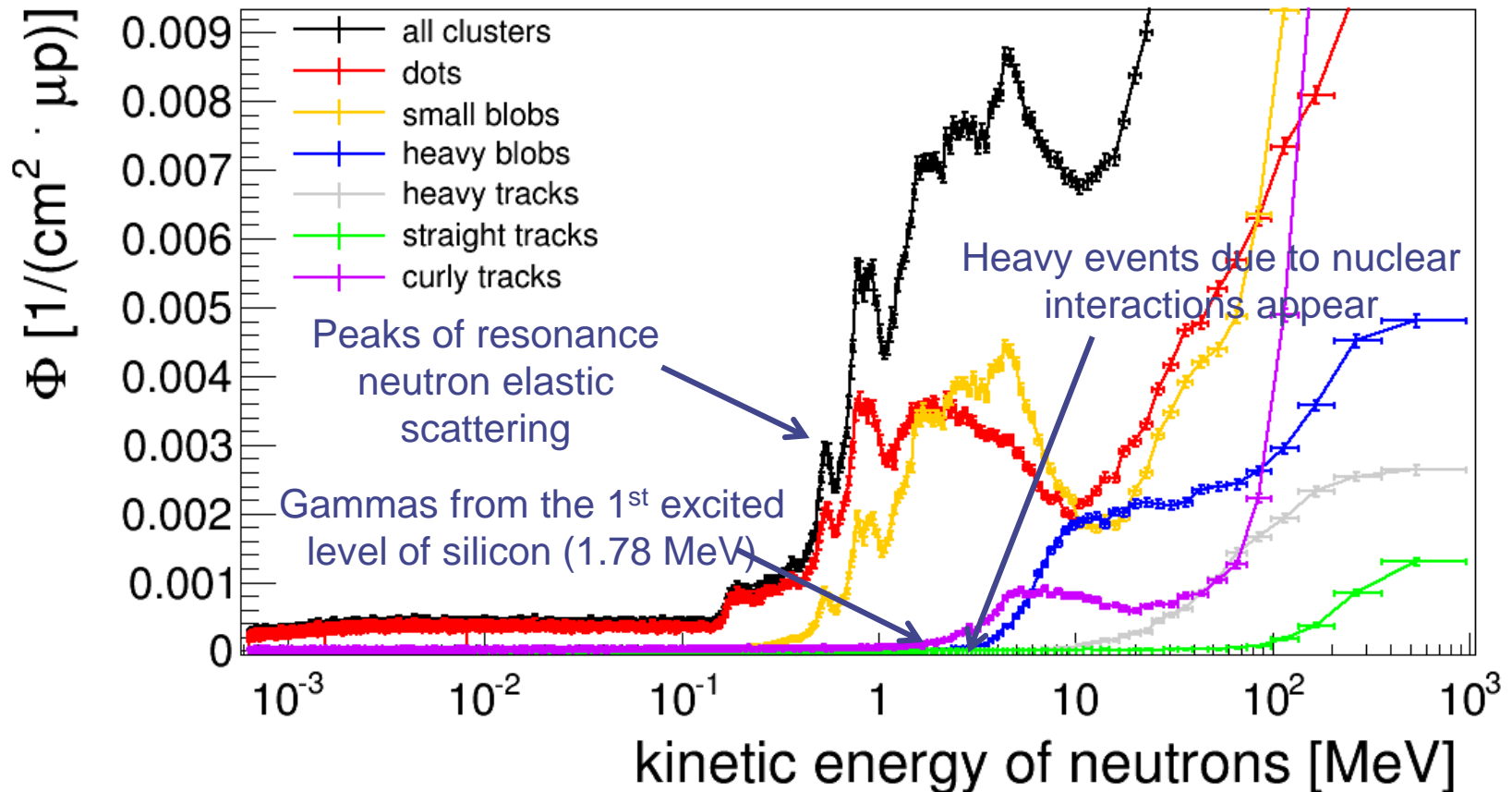


Different colors and black numbers assigned to individual clusters indicate the energy of incoming neutrons as measured by means of the TOF technique

# Cluster shapes

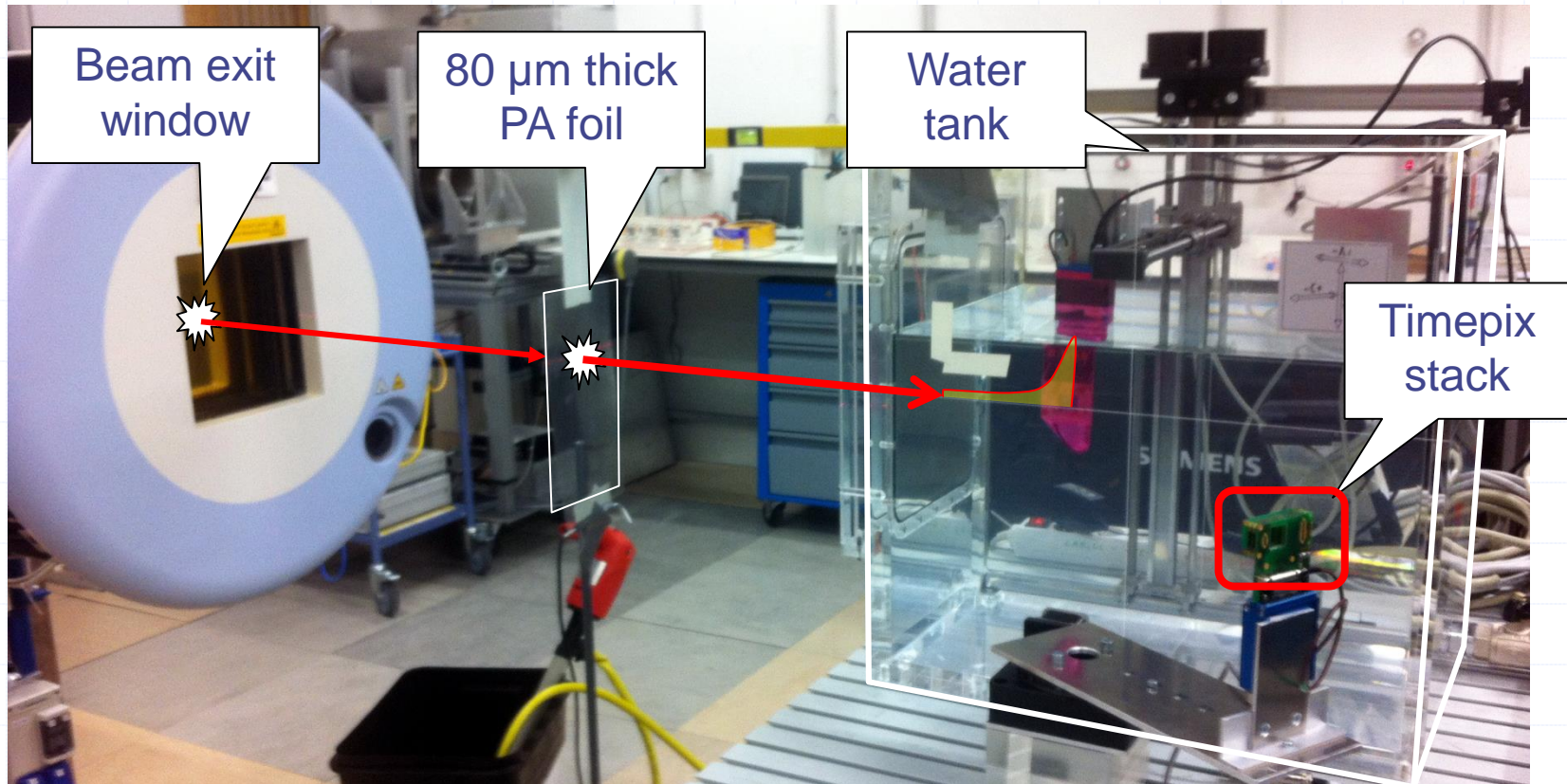
## Timepix detector responses as a function of neutron kinetic energy

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



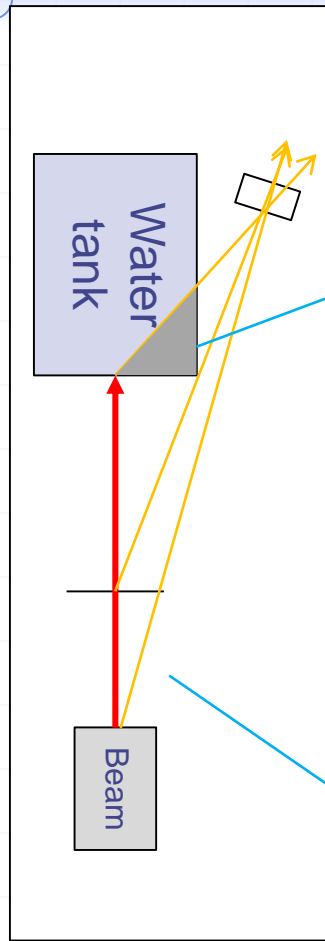
\*) see: B Bergmann *et al* 2014 *JINST* **9** C05048

# Medical application: Hadron therapy - Experimental setup

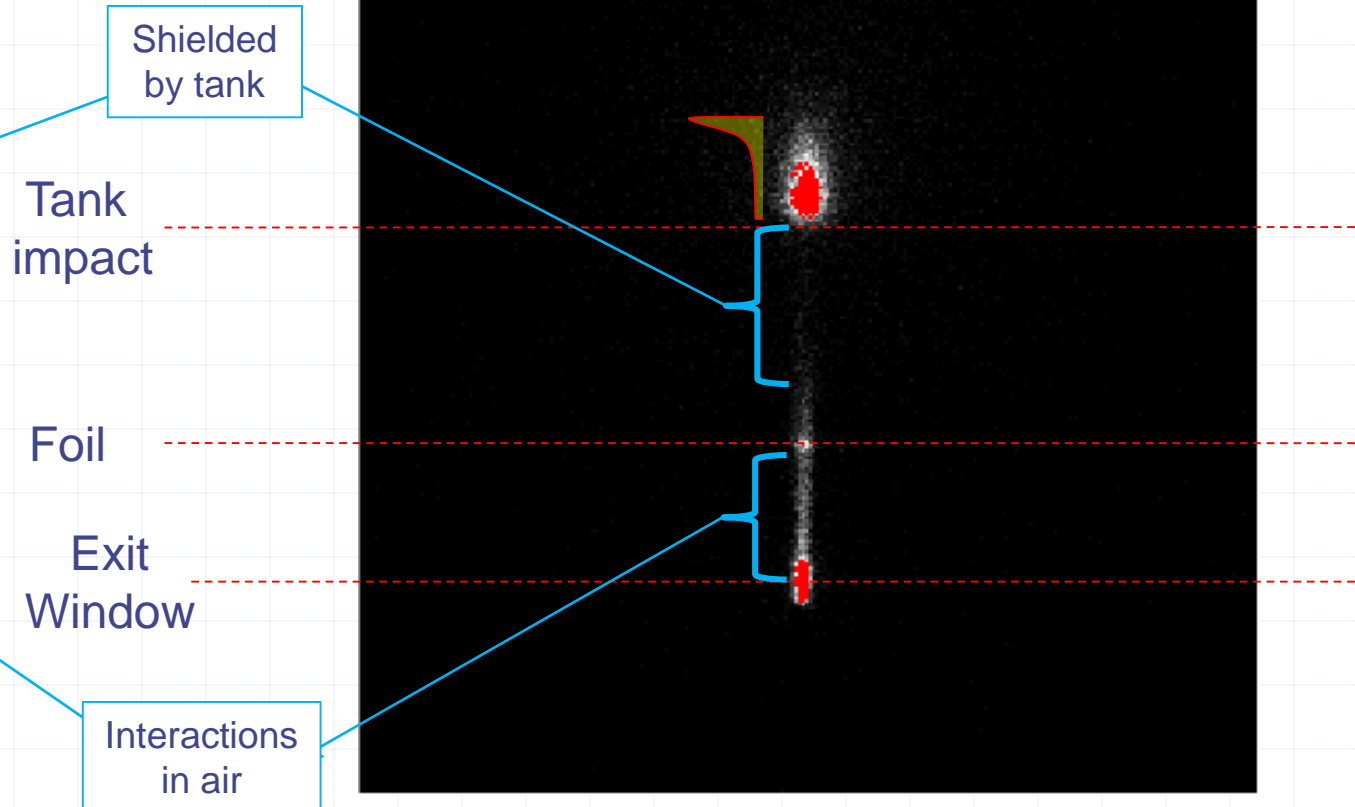


Visualization of secondary particles produced by the beam

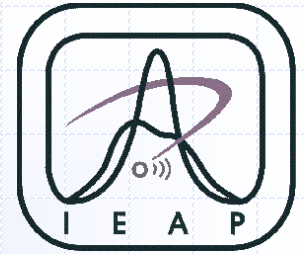
# in air and in the phantom



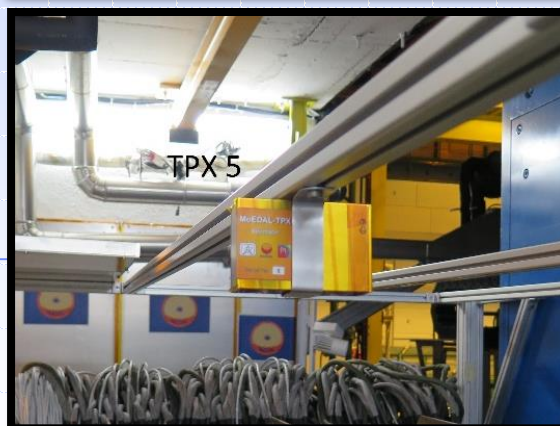
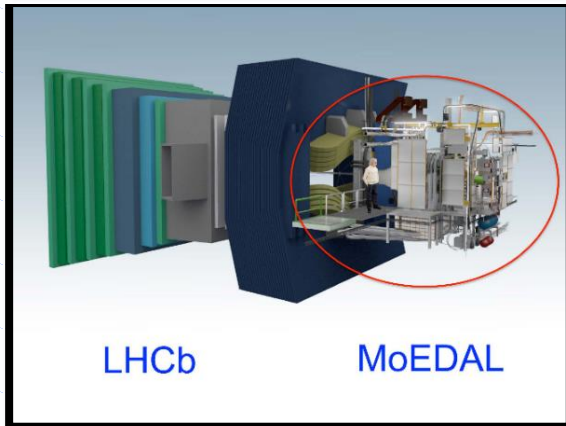
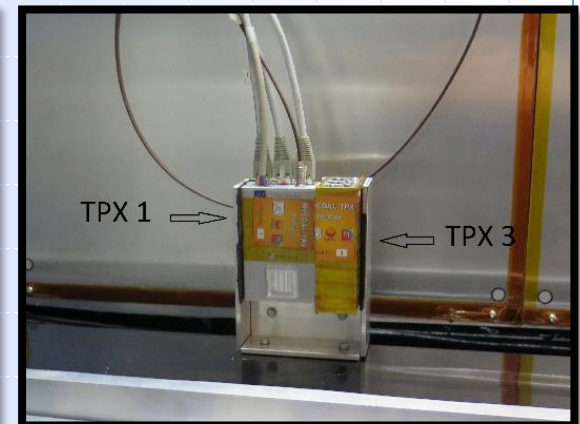
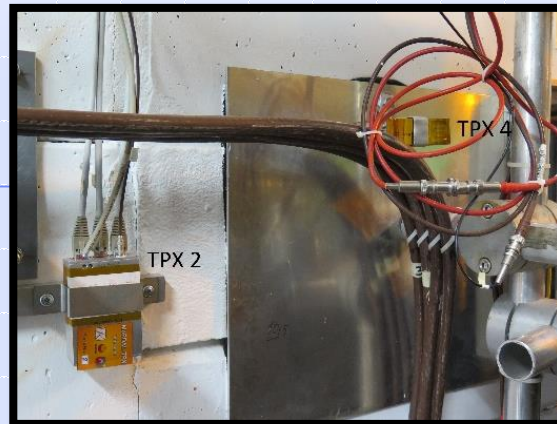
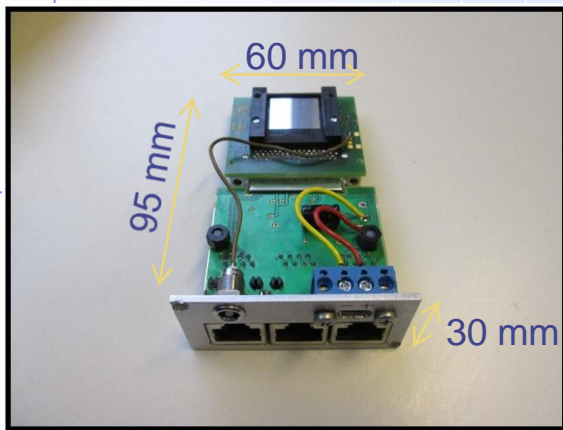
Reconstructed image (all coincident events)



# The TPX devices in the MoEDAL network



5 Timepix detectors of different thicknesses (300  $\mu\text{m}$  and 1000  $\mu\text{m}$ , 1 of them equipped with neutron converters) placed in chipboards with radiation tolerant electronics installed in the MoEDAL at LHC



Timepix devices in the MoEDAL experiment

# Selected tracks observed with MOEDAL TPX03

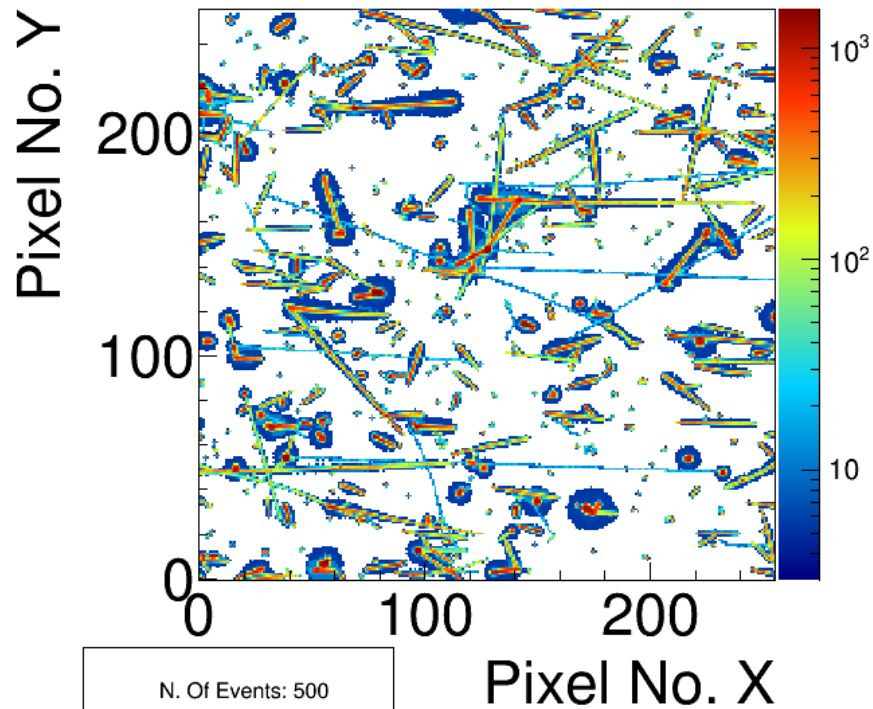
12/09/2015



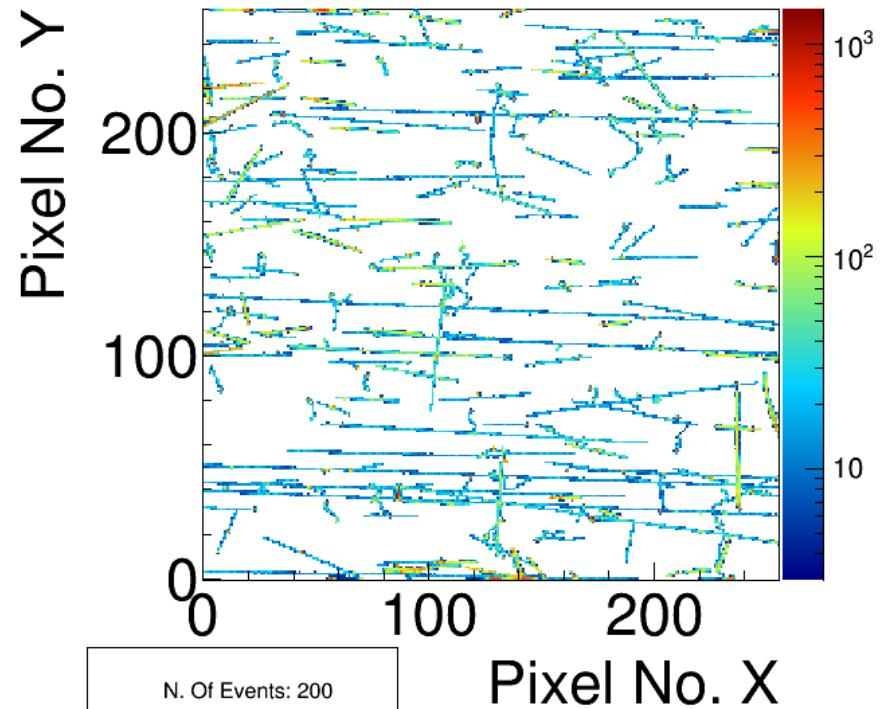
*High Energy Transfer Events  
(Min Clstr Height: 300 keV)*

*Long Tracks  
(Min Clstr Height: 300 keV)*

MOEDAL TPX03 HETs Energy [keV]



MOEDAL TPX03 L Trcks Energy [keV]





# Selected tracks observed with MOEDAL TPX04

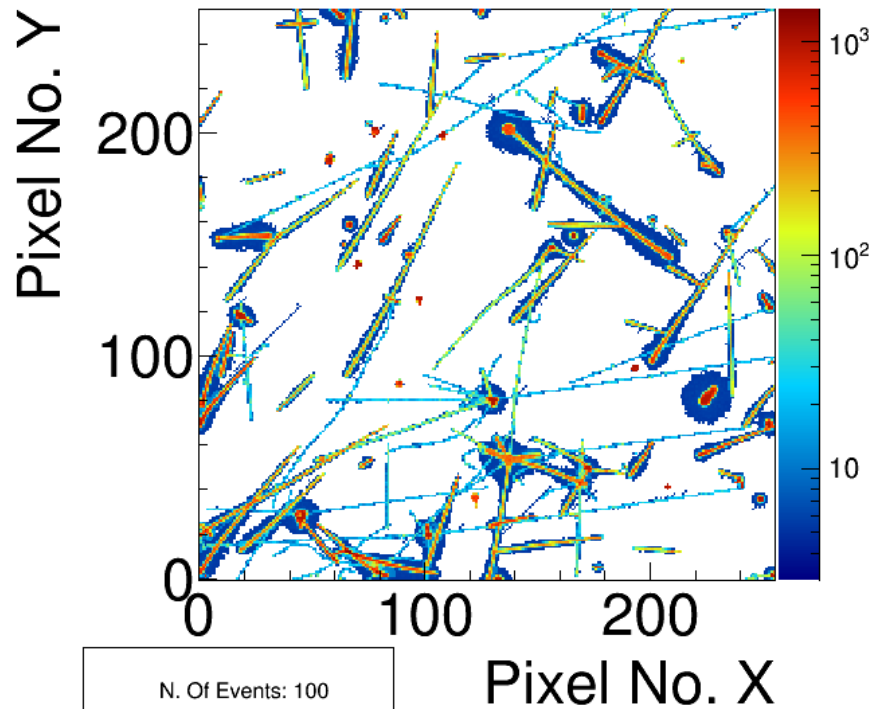
12/09/2015



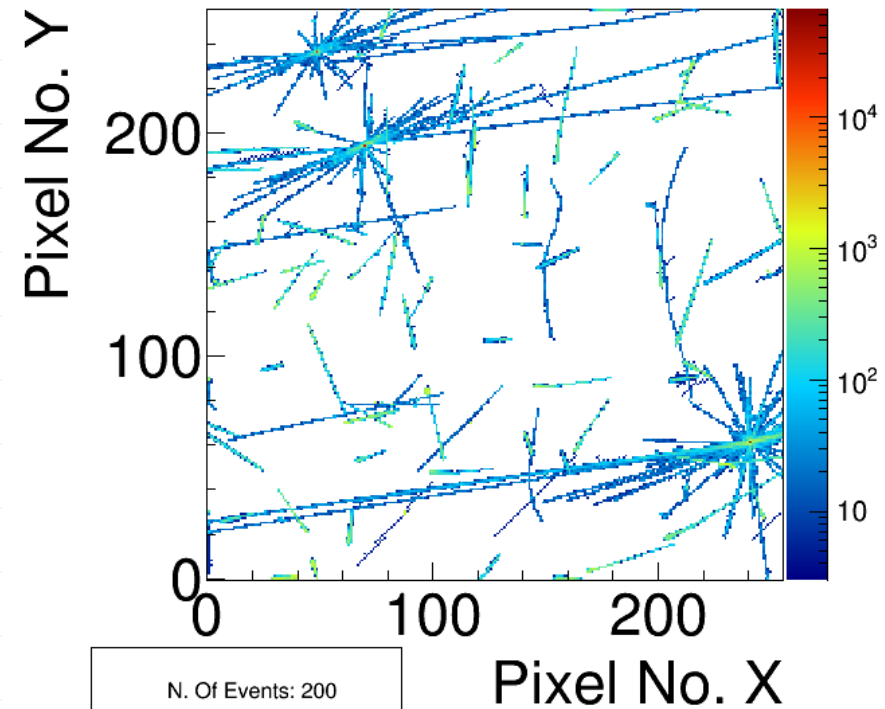
*High Energy Transfer Events  
(Min Clstr Height: 300 keV)*

*Long Tracks  
(Min Clstr Height: 300 keV)*

MOEDAL TPX04 HETs Energy [keV]

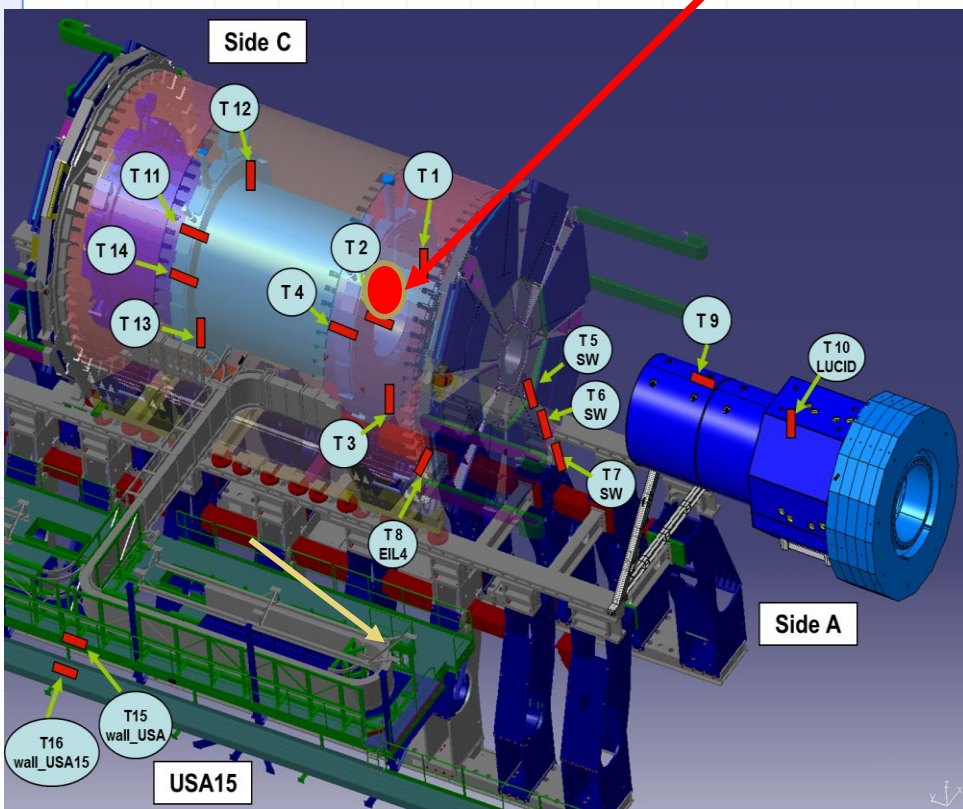


MOEDAL TPX04 L TrcksEnergy [keV]

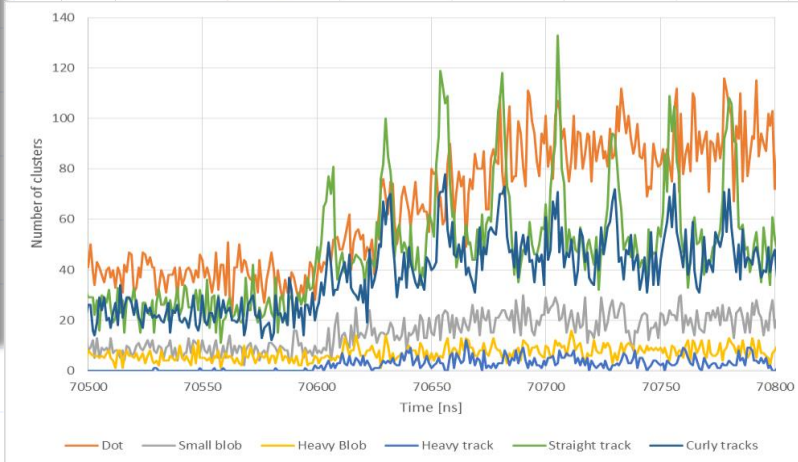
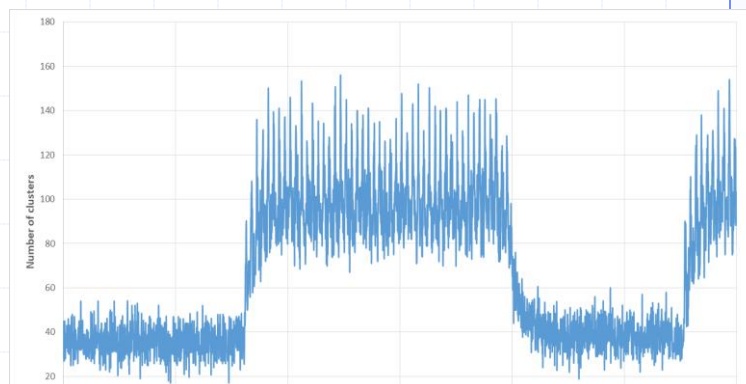


# Timepix3 in ATLAS

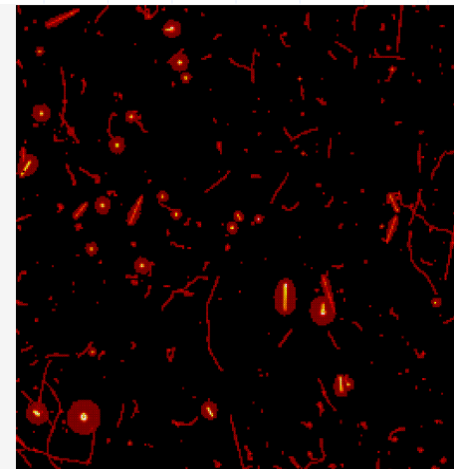
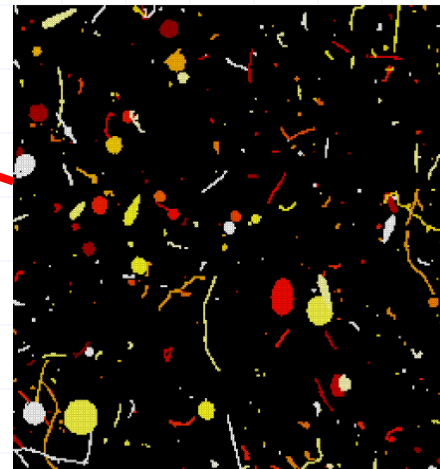
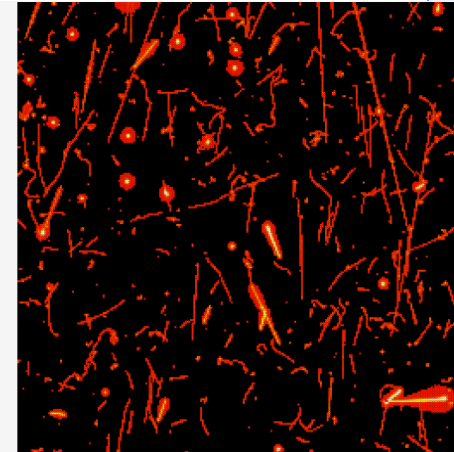
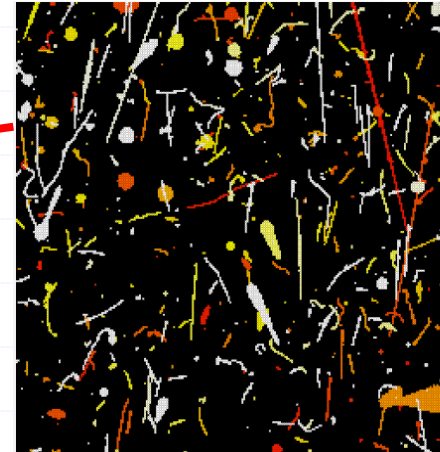
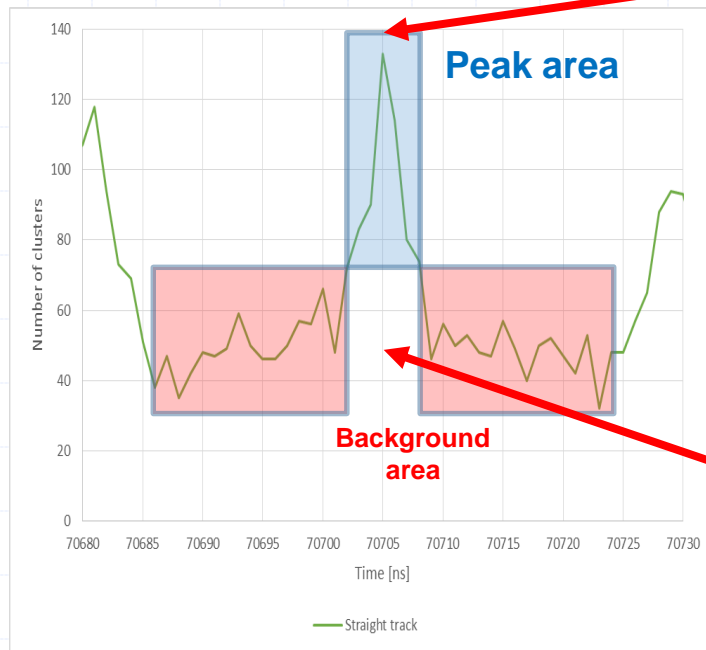
## synchronized with LHC clock



Detail view on bunch-bunch collisions recorded by TPX3



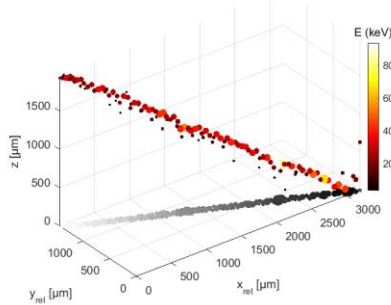
# Clusters corresponding to particles generated in the LHC bunch-bunch collisions and recorded according their ToF



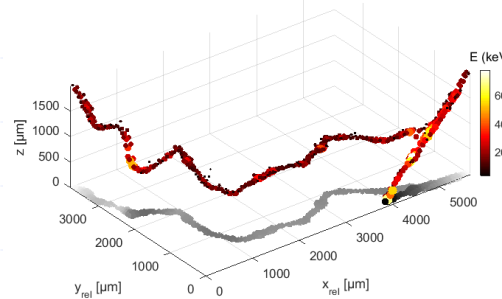
# 3D-visualisation of particle tracks in CZT detector measured at SPS

(z-coordinate determined from the drift time of charge carriers)

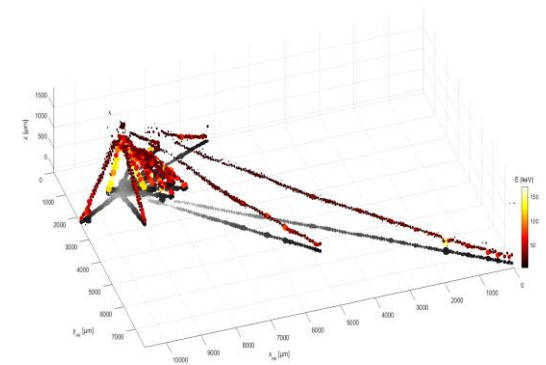
Muon



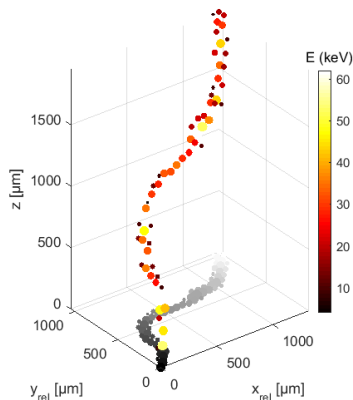
Pion + delta electron



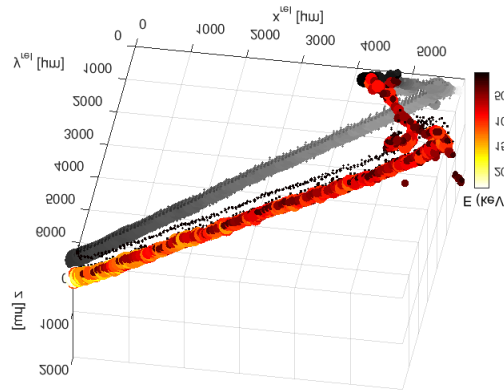
Fragmentation



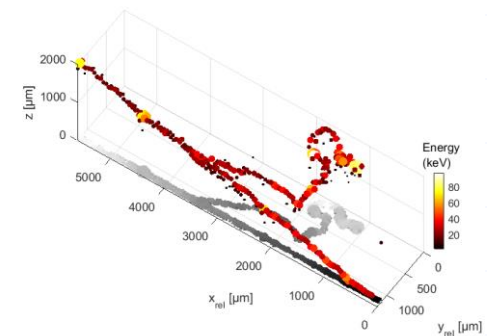
Electron



Heavy track

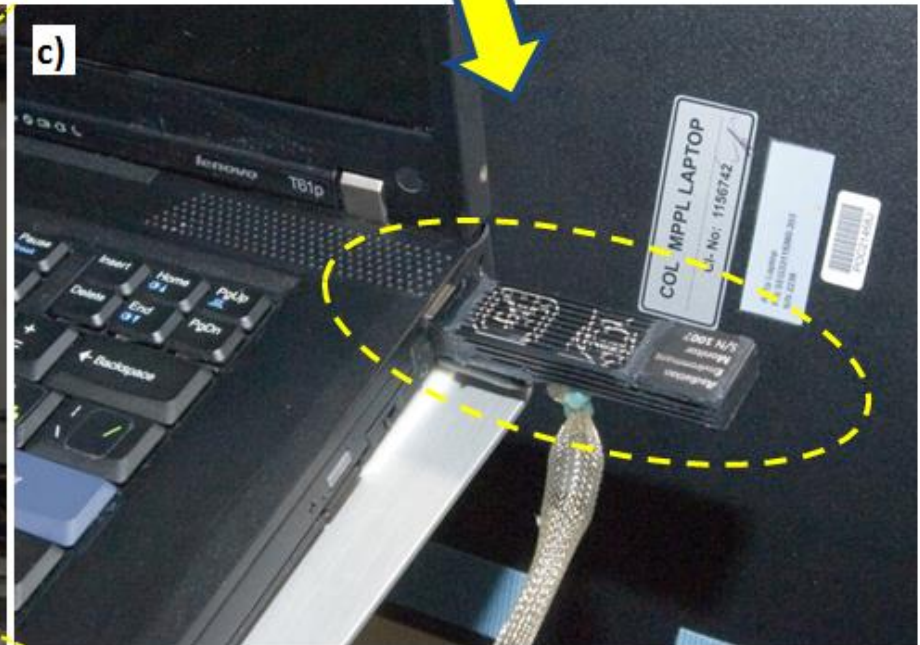
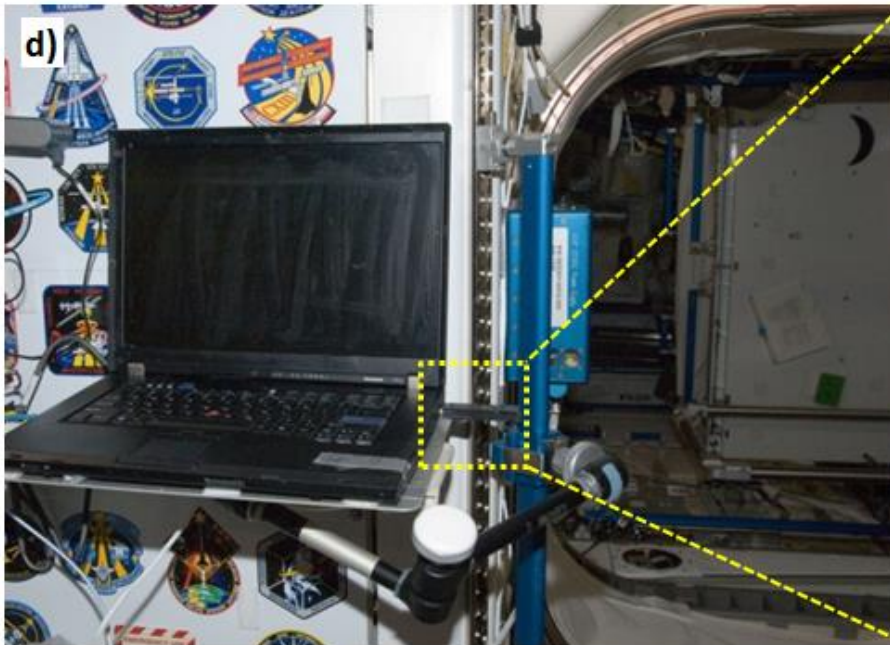
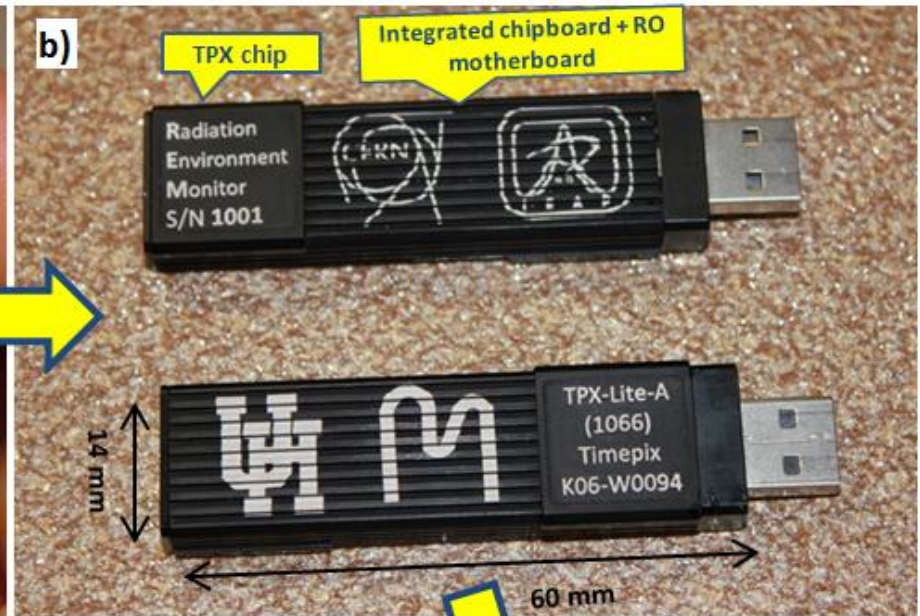
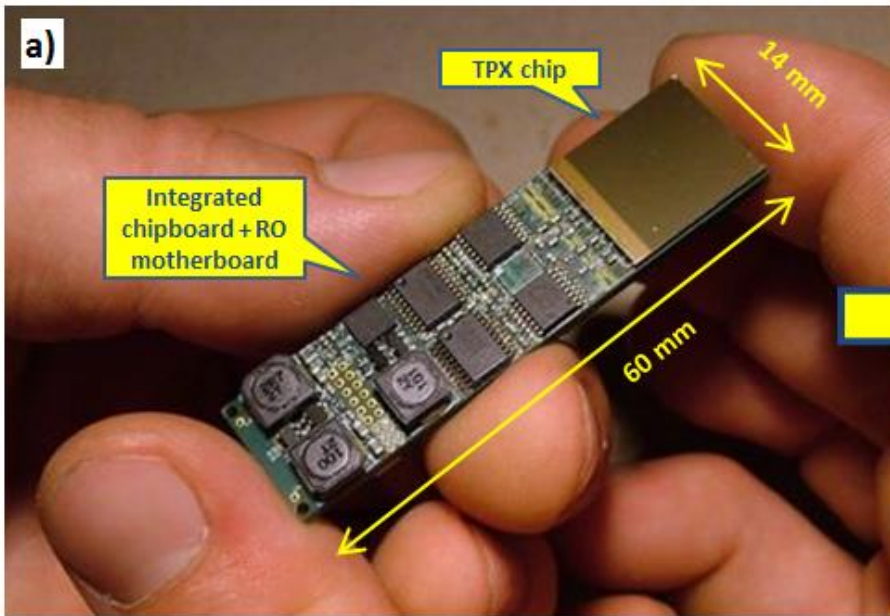


Pion + delta electron





# Space applications



Timepix detector in the highly miniaturized LITE architecture (a) customized for the ISS (b) as deployed with an on-board laptop via USB port (c) in a NASA Module at the ISS (d). Work done in cooperation with NASA and the University of Houston.



# The IEAP CTU Timepix based device used by NASA astronauts on ISS (courtesy of L.Pinsky, UoH)

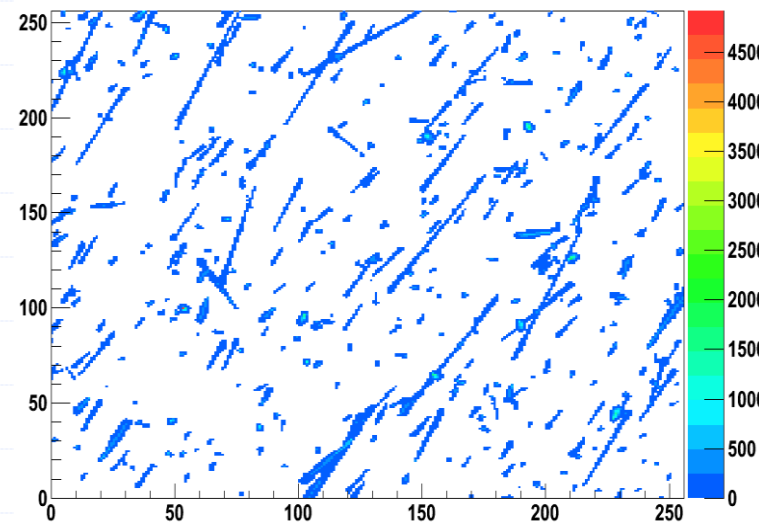
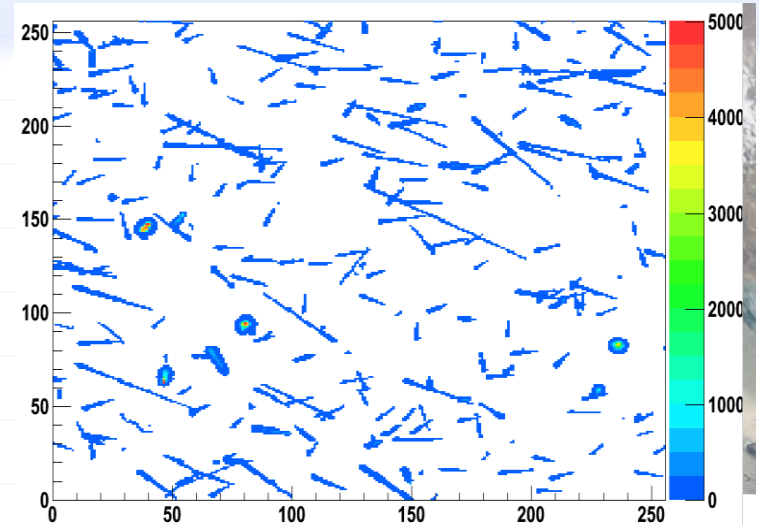




# Dosimetry in space on ISS



- Timepix for the first time in the space on the altitude  $\sim 400\text{km}$
- 5 detectors deployed on ISS from October 2012



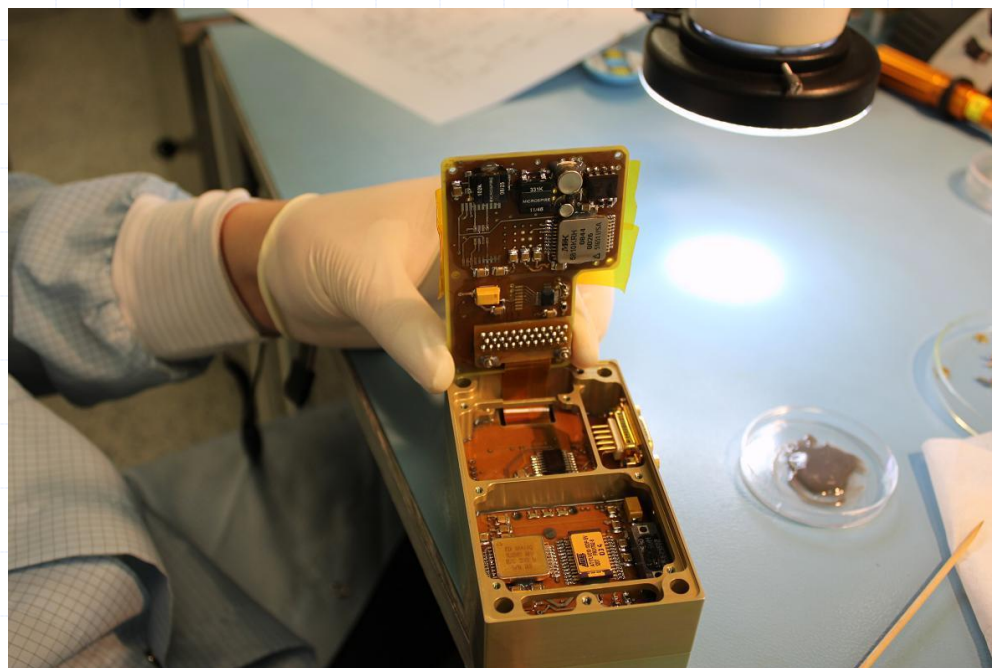




# Dosimetry in space: SATRAM – ESA Proba-V satellite

## Characterization of mixed radiation field on low orbit of PROBA-V satellite

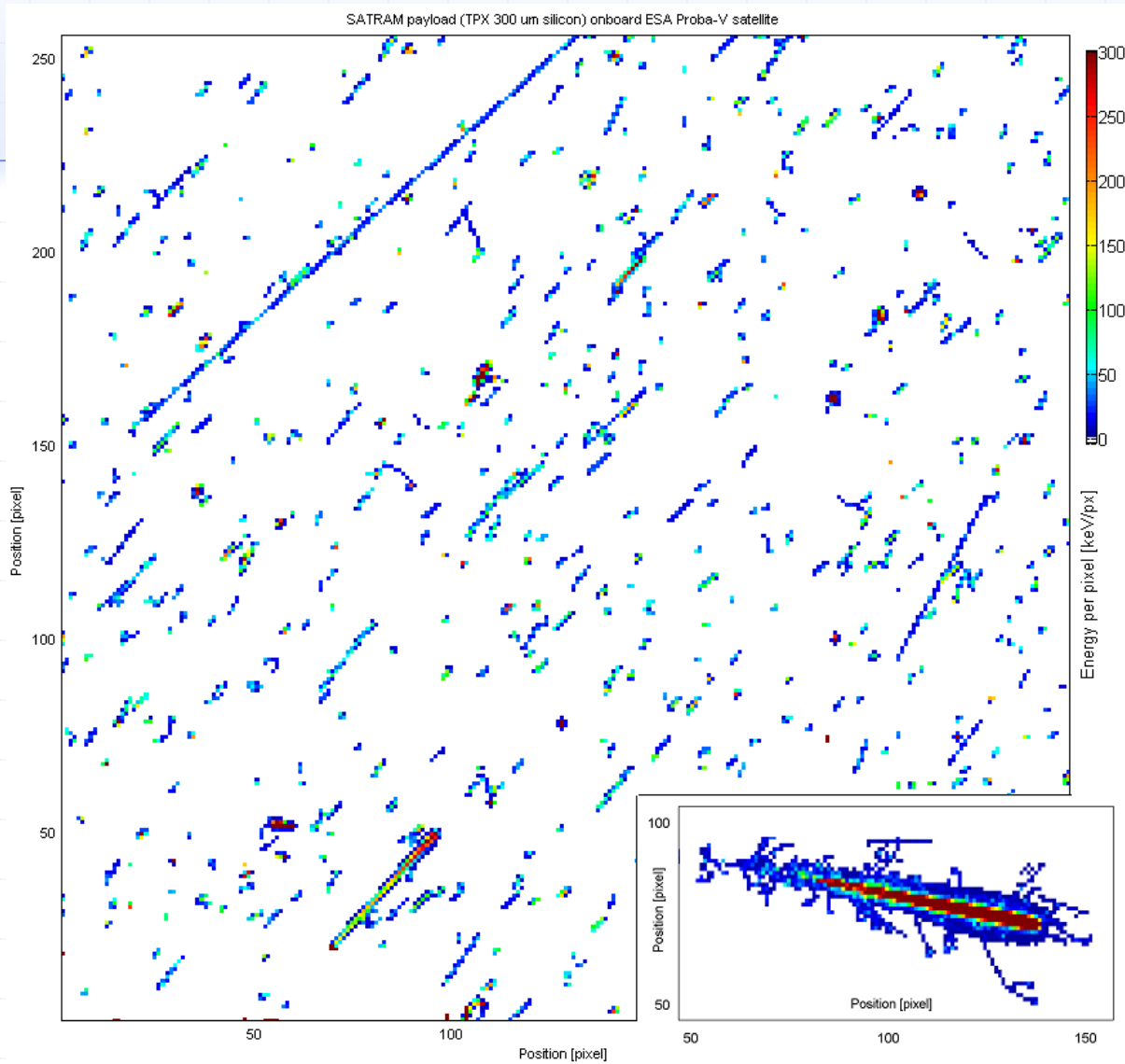
- ◆ Altitude ~ 800 km
- ◆ Timepix for the first time outside in the space
- ◆ Launched in May 2013





ESA Vega-2 rocket

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





# Timepix/ESA Proba-V: LEO space radiation @ 820 km

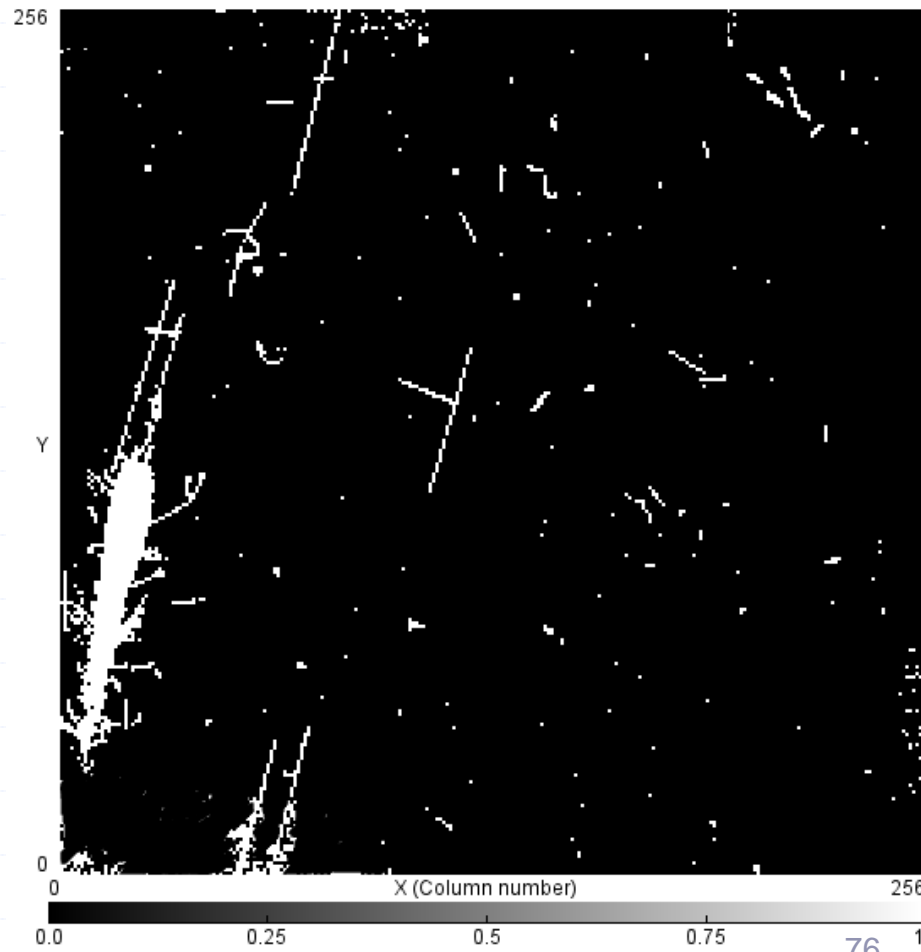


ysics  
ague

Energetic heavy charged particles (ions)

11.11.2013 10:24:53

11.11.2013 11:16:59



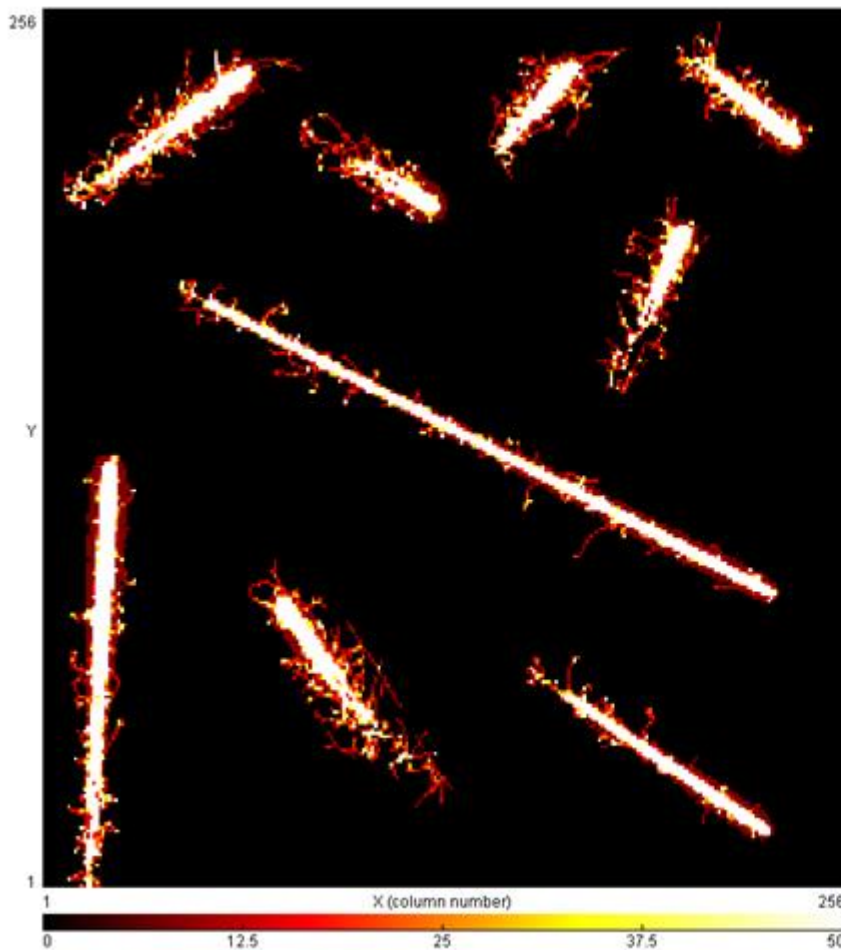


Timepix/ESA Proba-V:



# LEO space radiation @ 820 km

HETPs: Highly energetic heavy charged particles (ions) → HZE's





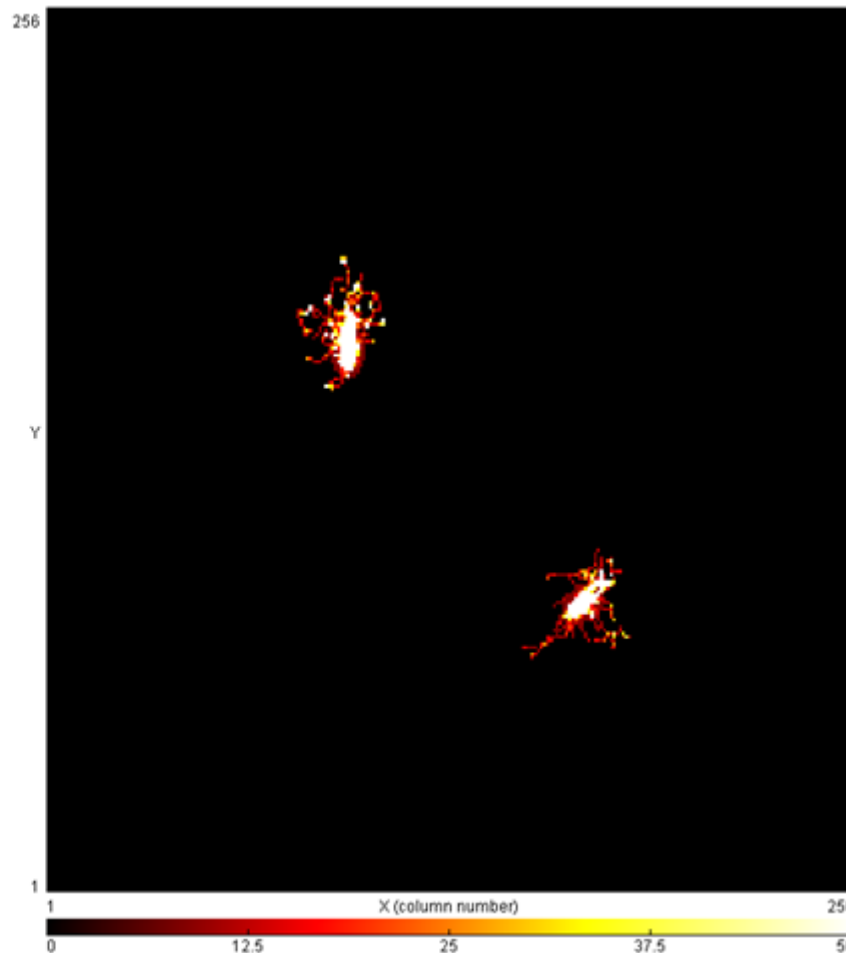
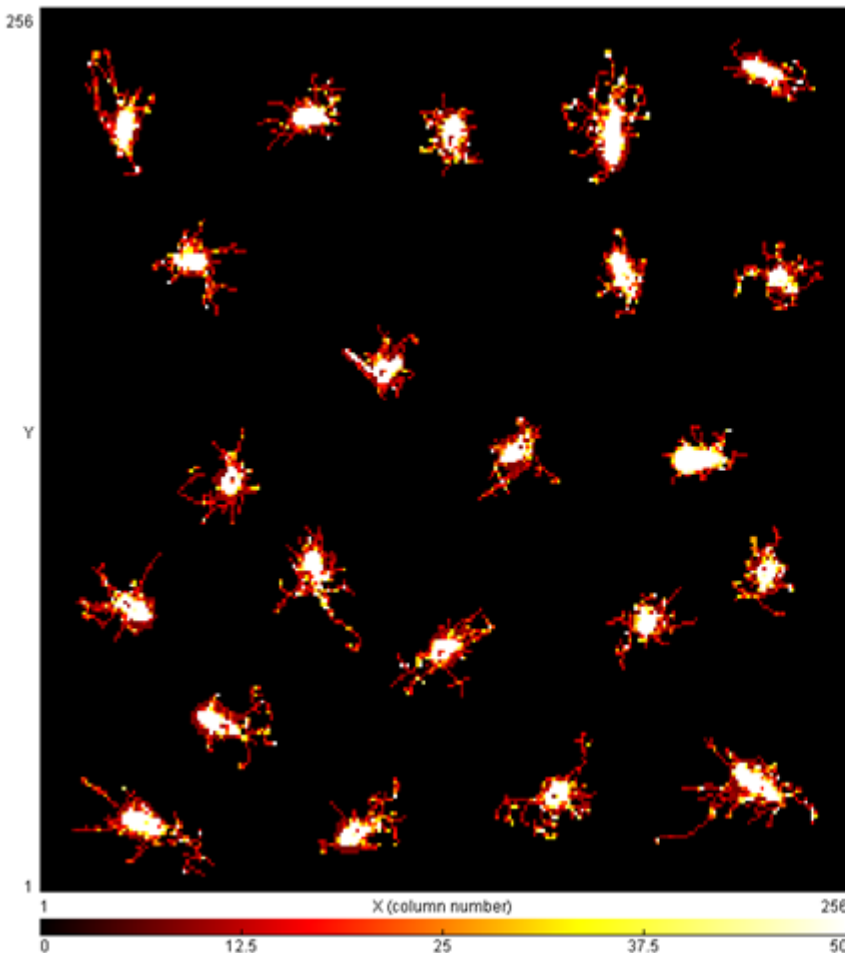
Timepix/ESA Proba-V:

# LEO space radiation @ 820 km



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HETPs: Highly energetic heavy charged particles (ions) → HZE's





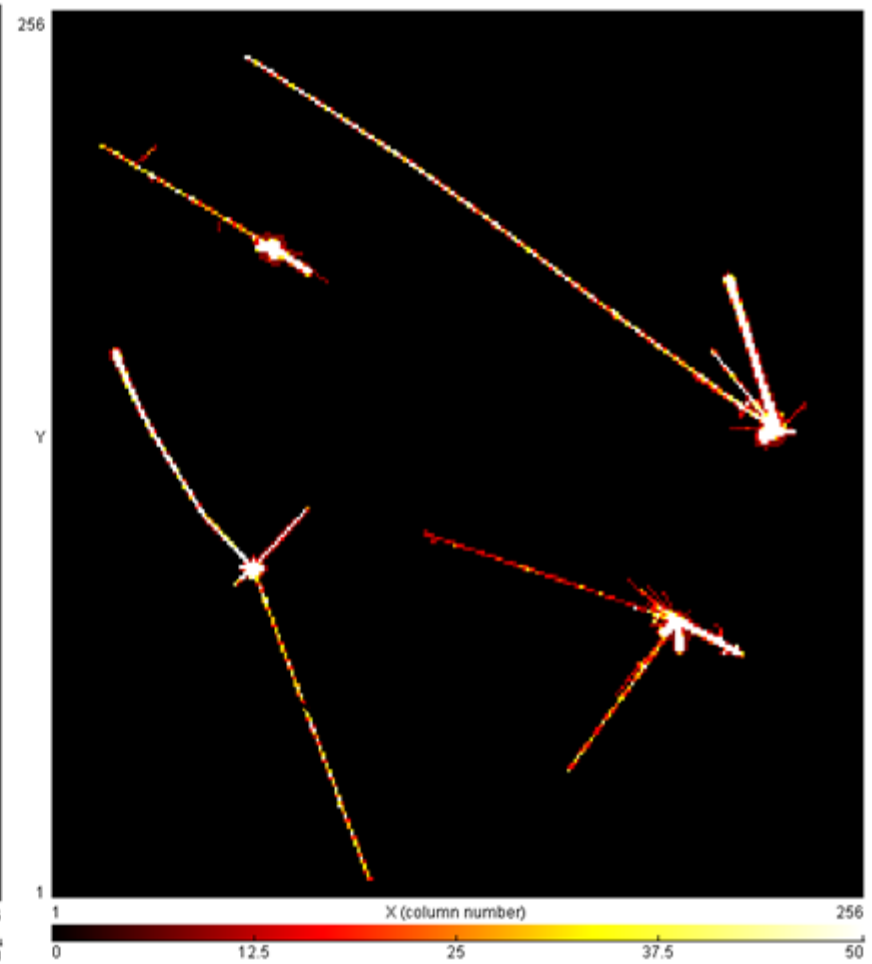
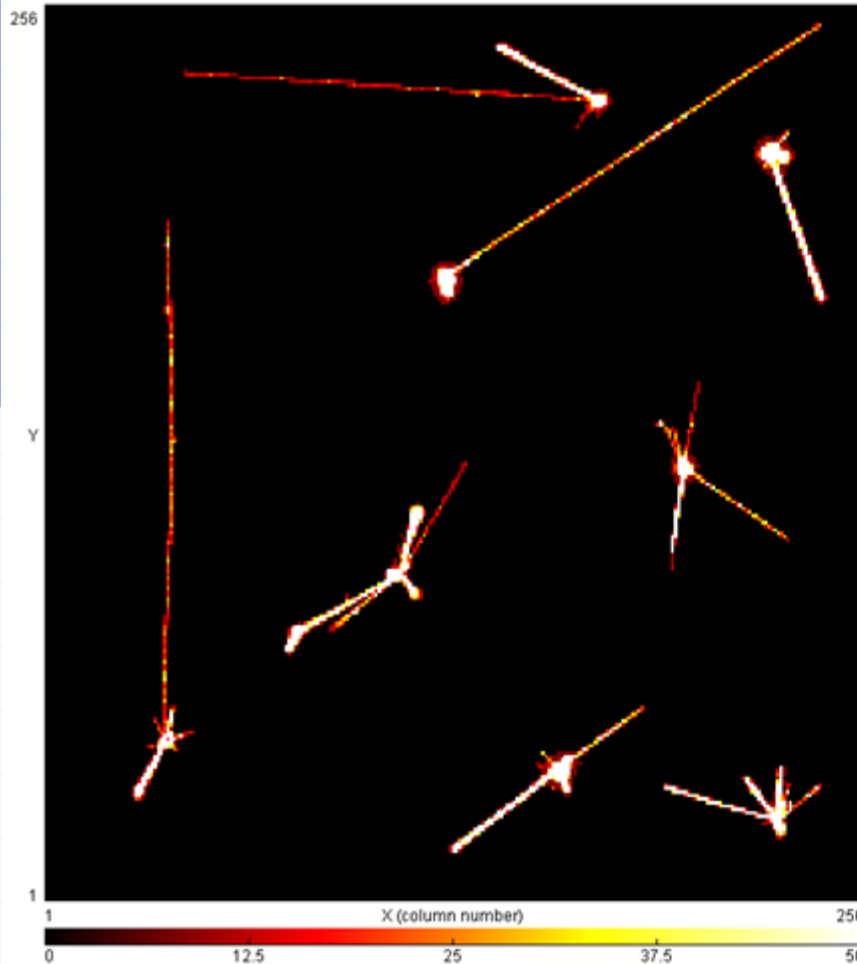
Timepix/ESA Proba-V:

# LEO space radiation @ 820 km



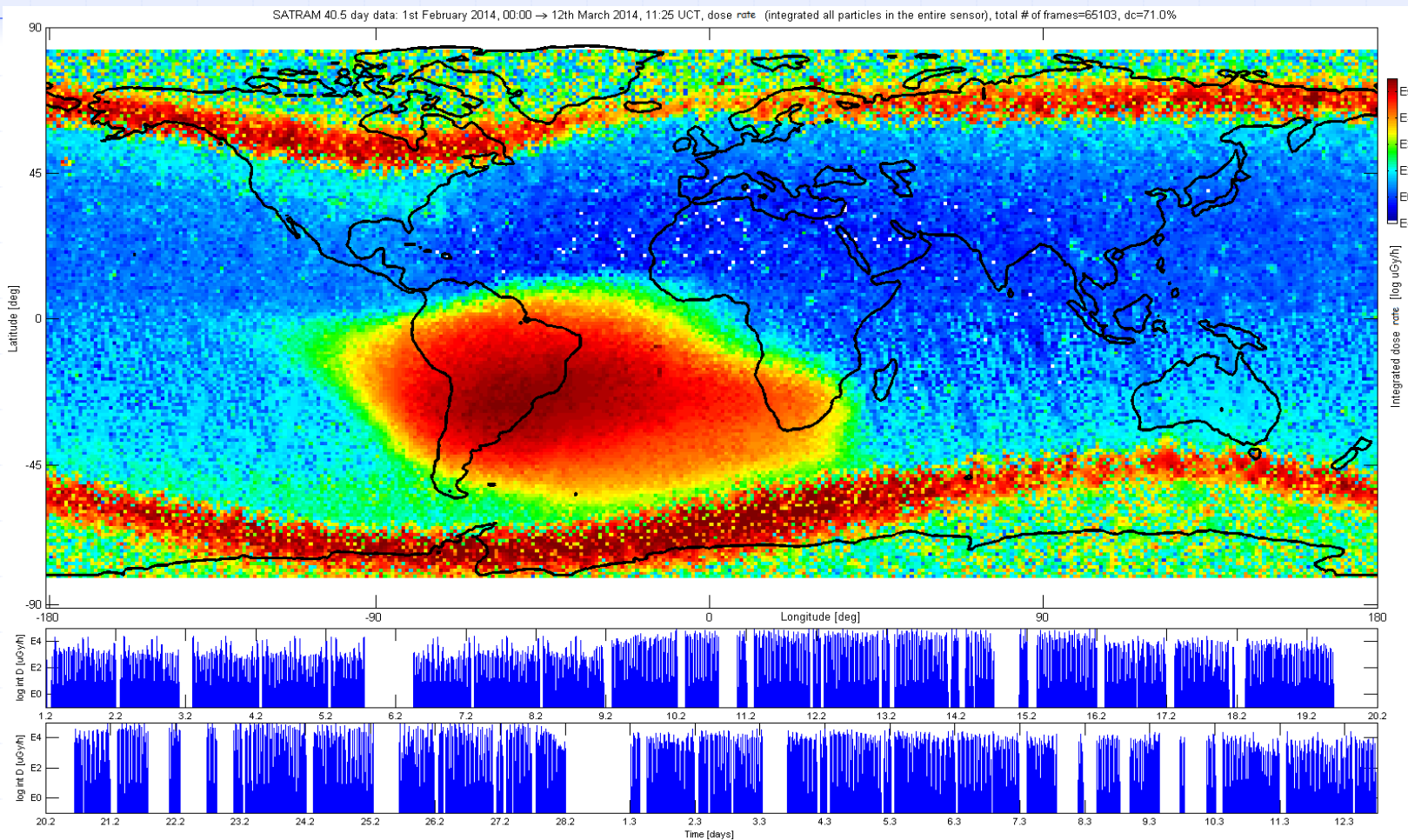
LETPs: Energetic light charged particles (l) + nuclear interactions

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# Measured radiation map by Satram device in orbit around the Earth at an altitude of 820 km from the earth's surface obtained within 36 days from January 1, 2014 to February 7, 2014 logarithmic scale in $\mu\text{G/hr}$ .







# RISESAT

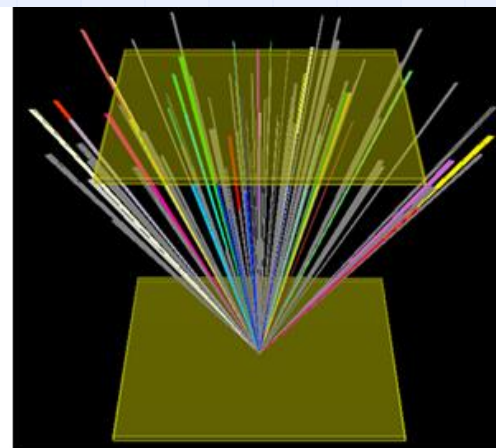
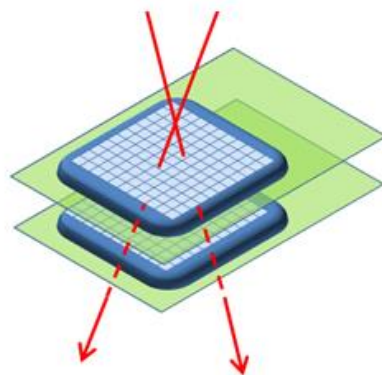
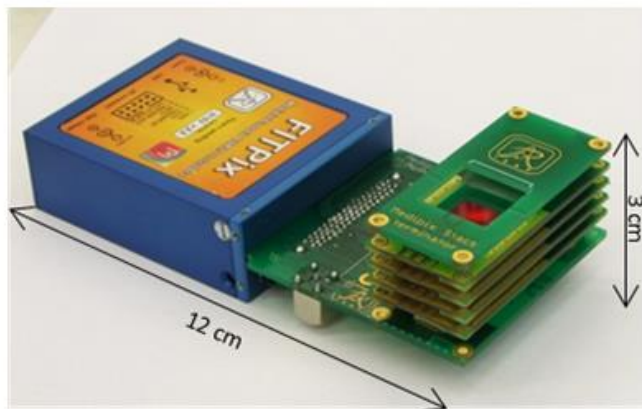
(Rapid International Experimental Satellite)

東北大学  
TOHOKU UNIVERSITY

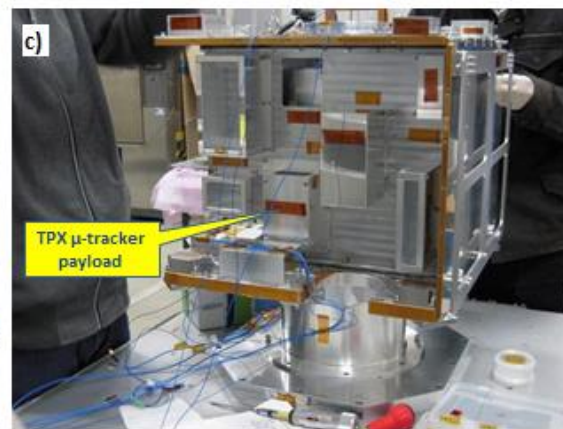
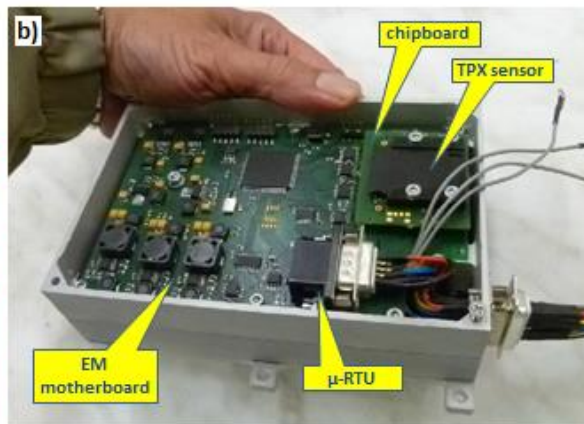
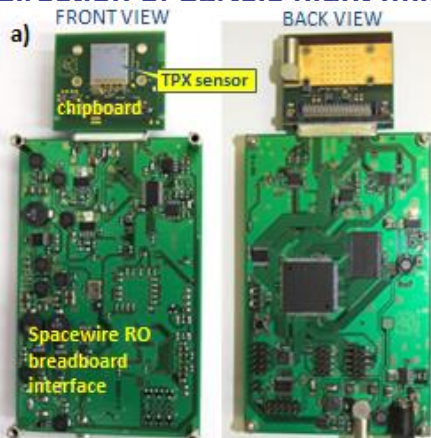


Timepix particle  $\mu$ -tracker particle telescope – launched on Feb 2019

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Czech Technical University in Prague



Particle micro-tracker of a stack of Timepix detector chipboards with common motherboard and single integrated R/O interface (left). Illustration of particle telescope on two pixelated sensors determining the direction of particle flight (middle) providing spatial visualization of particle trajectories (right).



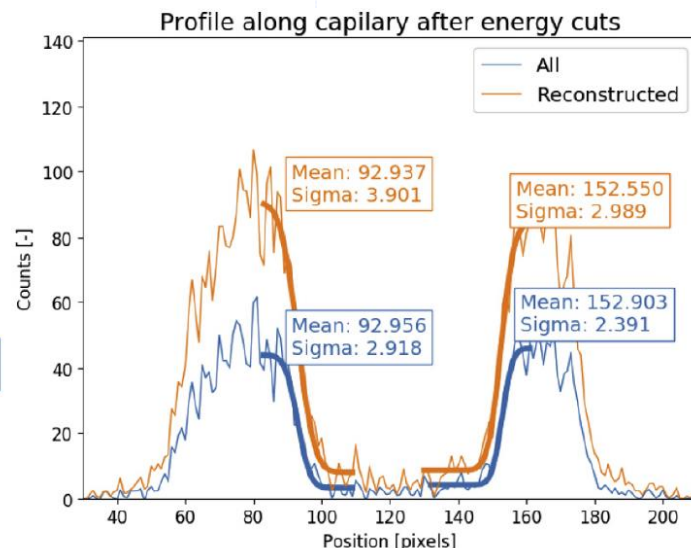
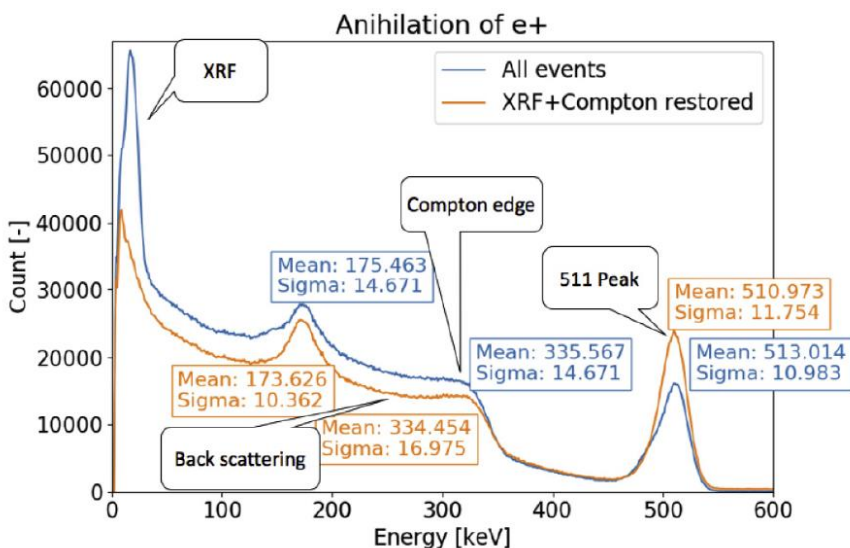
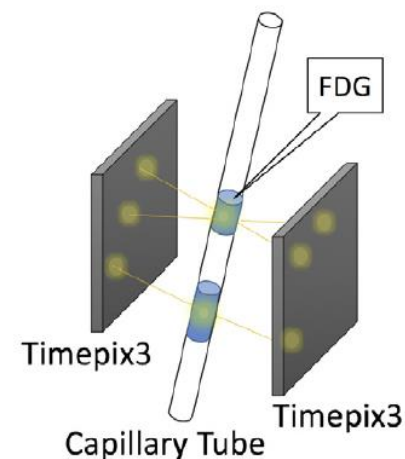
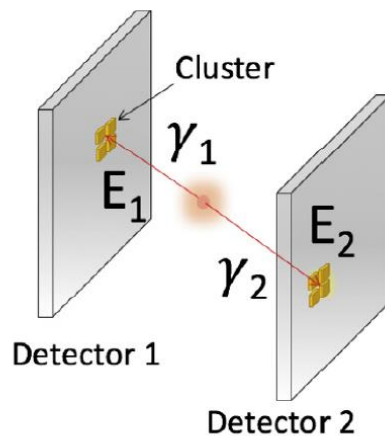
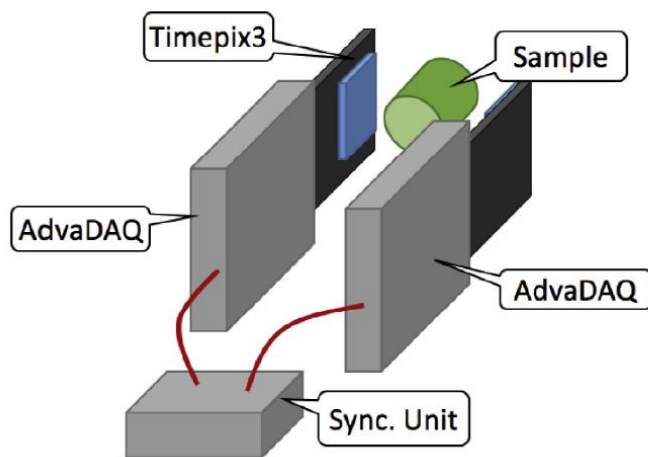
Timepix  $\mu$ -tracker for the RISESAT satellite consisting of two separate devices with synchronized operation. Spacewire interface (a), payload engineering model (b) and its position in the 50 Kg micro-satellite (c).



# Timepix3 for coincidence gamma ray spectroscopy PET – with TPX3 CdTe detectors



D. Tureček et.al.: NIMA 895 (2018) 84-89

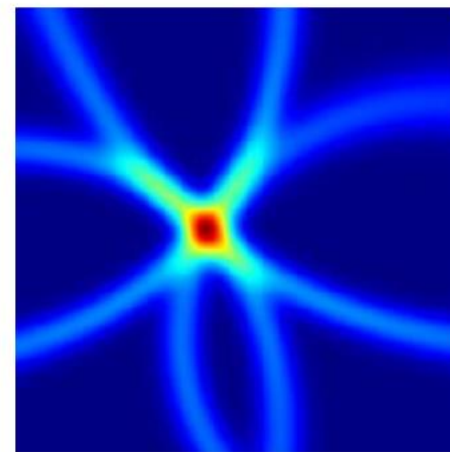
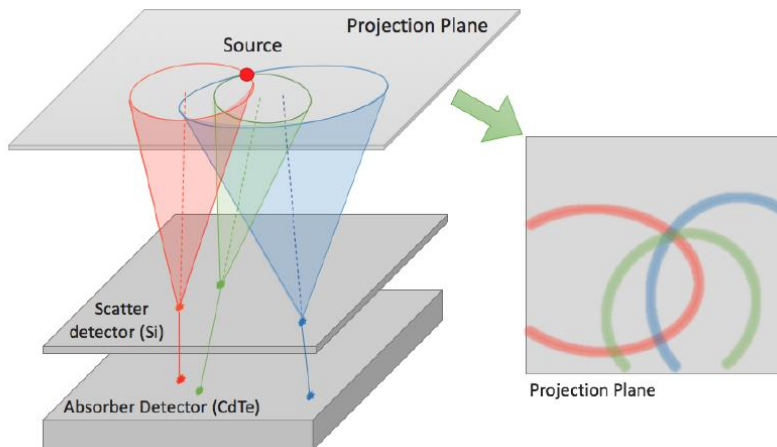
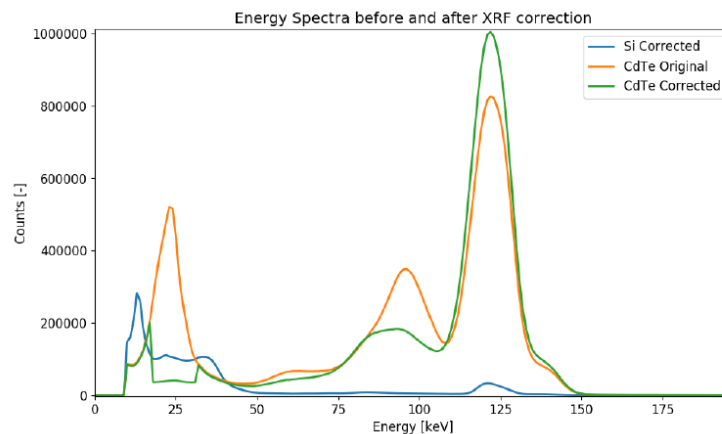
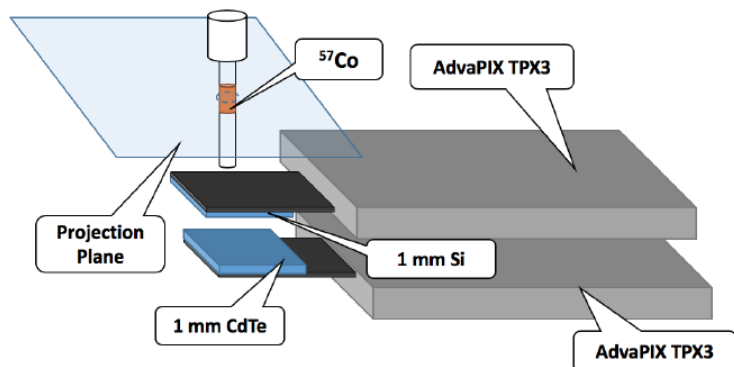




# Timepix3 for coincidence gamma ray spectroscopy Compton camera with CdTe and Si detectors



D. Tureček et.al.: 2018 JINST 13 C11022



chosen 4 events



# Acknowledgement

The presented results have been achieved within research activities cultivated at IEAP CTU in Prague. They result from extensive partnerships in frame of the Medipix2@3 collaboration with significant contributions of the following colleagues:

**R. Ballabriga<sup>2</sup>, B. Bergmann<sup>1</sup>, P. Burian<sup>1,12</sup>, I. Caicedo<sup>1</sup>, M. Campbell<sup>2</sup>, J. Dammer<sup>1</sup>, C. DaVia<sup>8</sup>, J. Dudák<sup>1</sup>, C. Froejdh<sup>9</sup>, E. Froejdh<sup>2</sup>, V. Georgiev<sup>12</sup>, C. Granja<sup>1</sup>, E. Heijne<sup>1,2</sup>, M. Holík<sup>1,12</sup>, R. Hall-Wilton<sup>10</sup>, M. Holík<sup>12</sup>, T. Holý<sup>1</sup>, J. Jakůbek<sup>1</sup>, M. Jakůbek<sup>1</sup>, J. Kirstead<sup>7</sup>, V. Kraus<sup>1,12</sup>, F. Krejčí<sup>1</sup>, E. Lehmann<sup>11</sup>, C. Leroy<sup>4</sup>, X. Llopart<sup>2</sup>, J. M. O'Donnel<sup>3</sup>, R. Nelson<sup>3</sup>, M. Nessi<sup>2</sup>, A. Owens<sup>5</sup>, L. Pinsky<sup>6</sup>, S. Petersson<sup>9</sup>, S. Pospíšil<sup>1</sup>, M. Platkevič<sup>1</sup>, K. Smith<sup>13</sup>, T. Slavíček<sup>1</sup>, P. Soukup<sup>1</sup>, M. Suk<sup>1</sup>, J. Šolc<sup>1</sup>, H. Takai<sup>7</sup>, G. Thungstroem<sup>9</sup>, D. Tureček<sup>1</sup>, J. Uher<sup>1</sup>, D. Vavřík<sup>1</sup>, Z. Vykydal<sup>1</sup>, S. Wender<sup>7</sup>, J. Žemlička<sup>1</sup>**

<sup>1</sup> *Institute of Experimental and Applied Physics, CTU in Prague, Czech Republic*

<sup>2</sup> *CERN, Switzerland*

<sup>3</sup> *LANSCE, LANL, USA*

<sup>4</sup> *Université de Montréal, Canada*

<sup>5</sup> *ESA*

<sup>6</sup> *NASA/University Houston, USA*

<sup>7</sup> *BNL, USA*

<sup>8</sup> *Manchester University, UK*

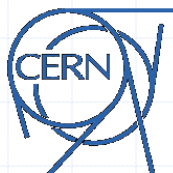
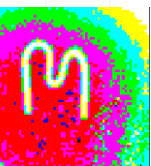
<sup>9</sup> *MidSweden University, Sundsvall, Sweden*

<sup>10</sup> *ESS, Sweden*

<sup>11</sup> *PSI, Switzerland*

<sup>12</sup> *WBU Pilsen, Czech Republic*

<sup>13</sup> *Glasgow University*





**Thank you for your attention!**