20th International Workshop on Radiation Imaging Detectors

Resolving Power of Pixel Detector Timepix for Wide-Range Electron, Proton and Ion Detection

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Motivation + Goals + Challenges + Approach

- Timepix detectors increasingly used to detect, monitor and characterize **mixed radiation fields** such as those found in the **upper atmosphere, outer space, ion beam radiotherapy, HEP/accelerator experiments, …**
- Of particular value is the detector **response** and **resolving power** in terms of **particle-type, deposited energy (stopping power)** and **direction (particle tracking** in **wide FoV).**
- The challenge is to provide discrimination, high/photon-counting sensitivity and wide dynamic range in terms of **particle types, stopping power/energy loss** and **direction** with a single compact device
- Experimental study – tests and calibration – with a **single Timepix** (300 μm Silicon): evaluation of detection response in **defined fields** of charged particles (electrons, protons, ions) in defined/wide range of fluxes, energies and incident directions

https://crreat.eu

Origin of Secondary Cosmic Rays

CRREAT

RESEARCH CENTRE OF COSMIC RAYS
AND RADIATION EVENTS IN THE ATMOSPHERE

G. Reitz, K. Kudela, O. Ploc, et al., CRREAT-UJF

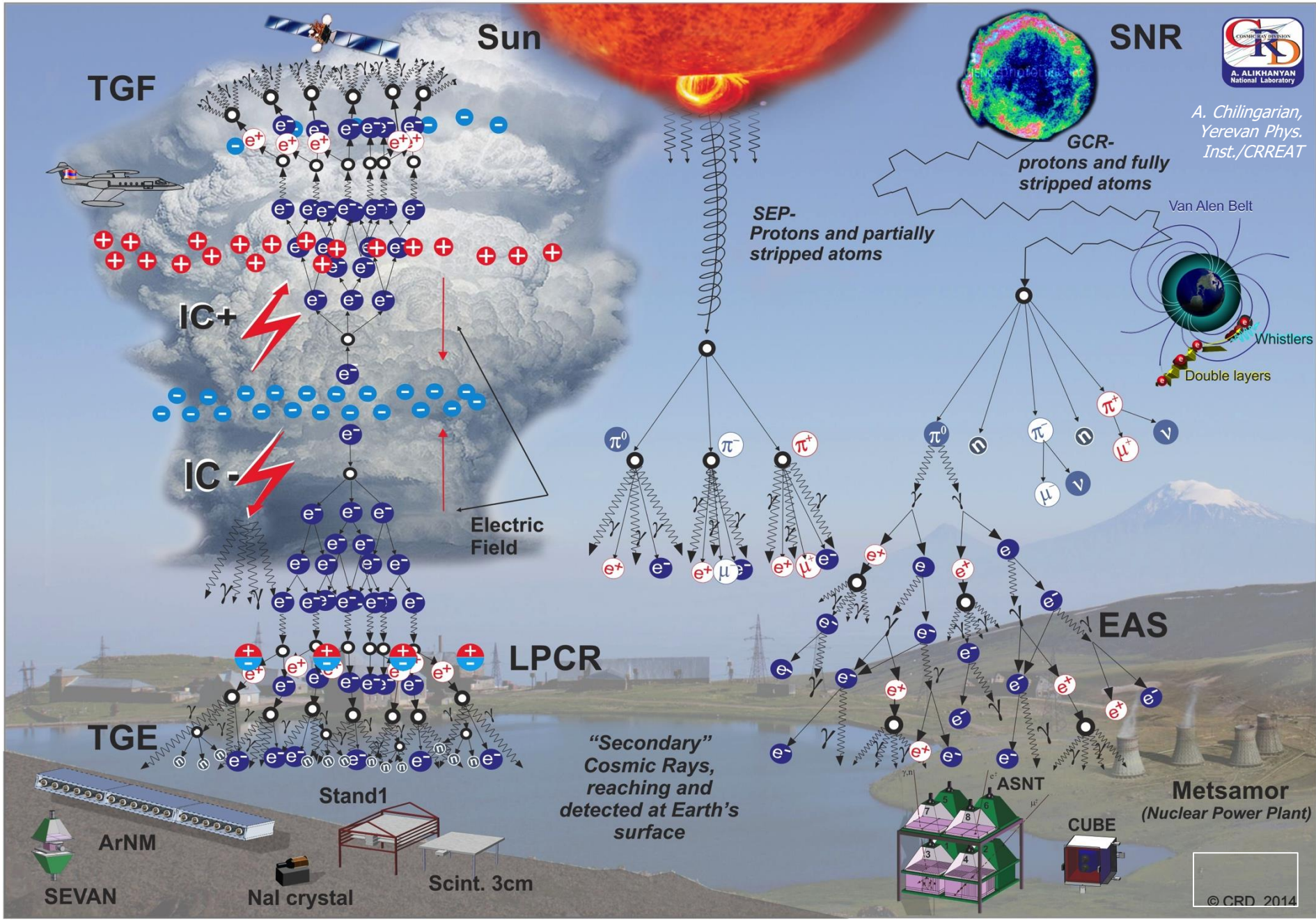
Research area/topics

- Atmospheric phenomena & ionizing radiation
- Sources, variation, characterization of primary & secondary cosmic rays
- Radiation instrumentation/methodology

Experiments/projects/deployment

- Atmospheric balloons
- UAV/drones, remote/terrain vehicles
- DLR aircraft flights
- Dosimetry experiments on board ISS
- Satellite borne payloads/experiments
- Return satellite capsule
- High-altitude radiation stations

Return capsule BION-M1, LEO orbit, IBMP RAS Moscow → space radiobiology research



Timepix deployments in Outer Space: Heritage + ongoing developments

Human flight/Dosimetry: LEO/on board ISS/2012, Radiation effects/Space Weather: spacecraft/satellite payloads/Proba-V/2013

Orbit	Launch	
		Spacecraft payloads: Micro-satellites
LEO, 820 km	May 2013	❑ **SATRAM-Timepix** on board **ESA Proba-V satellite** QinetiQ ESA (in LEO orbit since May 2013), successful commissioning, continuous data taking
LEO, 600 km	July 2014	❑ **LUCID-5xTimepix array payload** on board **TechDemoSat-1 SSTL-UK satellite** Langton Ultimate Cosmic-ray Intensity Detector, successful commissioning, continuous data taking
LEO, 600 km	1Q-2019	❑ **Particle telescope/2x stack Timepix** for **RISESAT satellite** Tohoku U./Japan (ongoing, FM delivery 3Q 2018, launch 4Q 2018/1Q2019)
		Spacecraft payloads: nanosatellites/cubesats
LEO, 500 km	June 2017	❑ **Focal plane X-ray detector 1xTimepix/X-ray telescope 1D optics** on board **Cubesat VZLUSAT-1**, successful commissioning continuous data taking
CIS-lunar/deep space	2020	❑ **Timepix radiation monitor payload** on board **BioSentinel cubesat** for **NASA-ORION flight EM1**, NASA Ames
		Spacecraft payloads: large satellites
GEO 36000 km	>2020	❑ **Miniaturized Radiation Monitor MIRAM**, for **ESA/ARTES telecommunication satellites at GEO orbit**
		Sub-orbital sounding rockets
LEO, 200 km	April 2018	❑ **Focal plane X-ray detector 2xTimepix/X-ray telescope 2D optics REX** payload Penn State U. for **NASA WRX-R sounding sub-orbital rocket**, launched 4th April 2018, successful operation, data collected, payload retrieved
		Pressurized/manned space modules
LEO, 420 km	Aug 2012	❑ Miniaturized **Quantum imaging on-line space radiation dosimeters/Radiation Environment Monitors REM 5xTPX** on board **ISS-NASA**, successful commissioning, continuous data taking, NASA JSC
MEO, 6000 km	Dec 2014	❑ **2x Battery Operated Radiation Detectors BIRD-Timepix** fully autonomous operation, **NASA Orion Exploration Flight Test EFT-1**, successful commissioning, continuous data taking , NASA JSC
LEO, 420 km	May 2017	❑ **Energetic Particle Telescope EPT-Timepix 2x stack** on board **ISS-NASA**, successful commissioning continuous data taking, NASA JSC
CIS-lunar/deep space	2020	❑ **Hybrid Electronic Radiation Assessor HERA-Timepix** for **NASA-ORION flights EM1** and **EM2**, NASA JSC

The isochronous cyclotron U-120M

Center of Accelerators and Nuclear Analytical Methods (CANAM)
http://canam.ujf.cas.cz

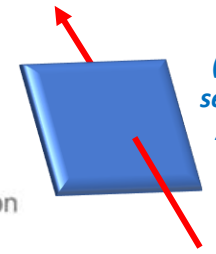
Nuclear Physics Institute of the CAS
public research institution

U-120M Cyclotron accelerator

Ions		Energy [MeV]	Max. current [μA]
H^+	Internal beam	1 - 37	> 200
H^+	External beam	6 - 25	5
H^-/H^+	External beam	6 - 37	50 - 30
D^+	Internal beam	2 - 20	> 80
D^+	External beam	12 - 20	5
D^-/D^+	External beam	11 - 20	35 - 20
$^3He^{+2}$	Internal beam	3 - 55	20
$^3He^{+2}$	External beam	18 - 52	2
$^4He^{+2}$ (α)	Internal beam	4 - 40	40
$^4He^{+2}$ (α)	External beam	24 - 38	5

Note: Energy range of internal beams is for the probe radii from 20–50 cm.

Timepix/miniPIX



Timepix assembly (300 um Si sensor + TPX ASIC chip)

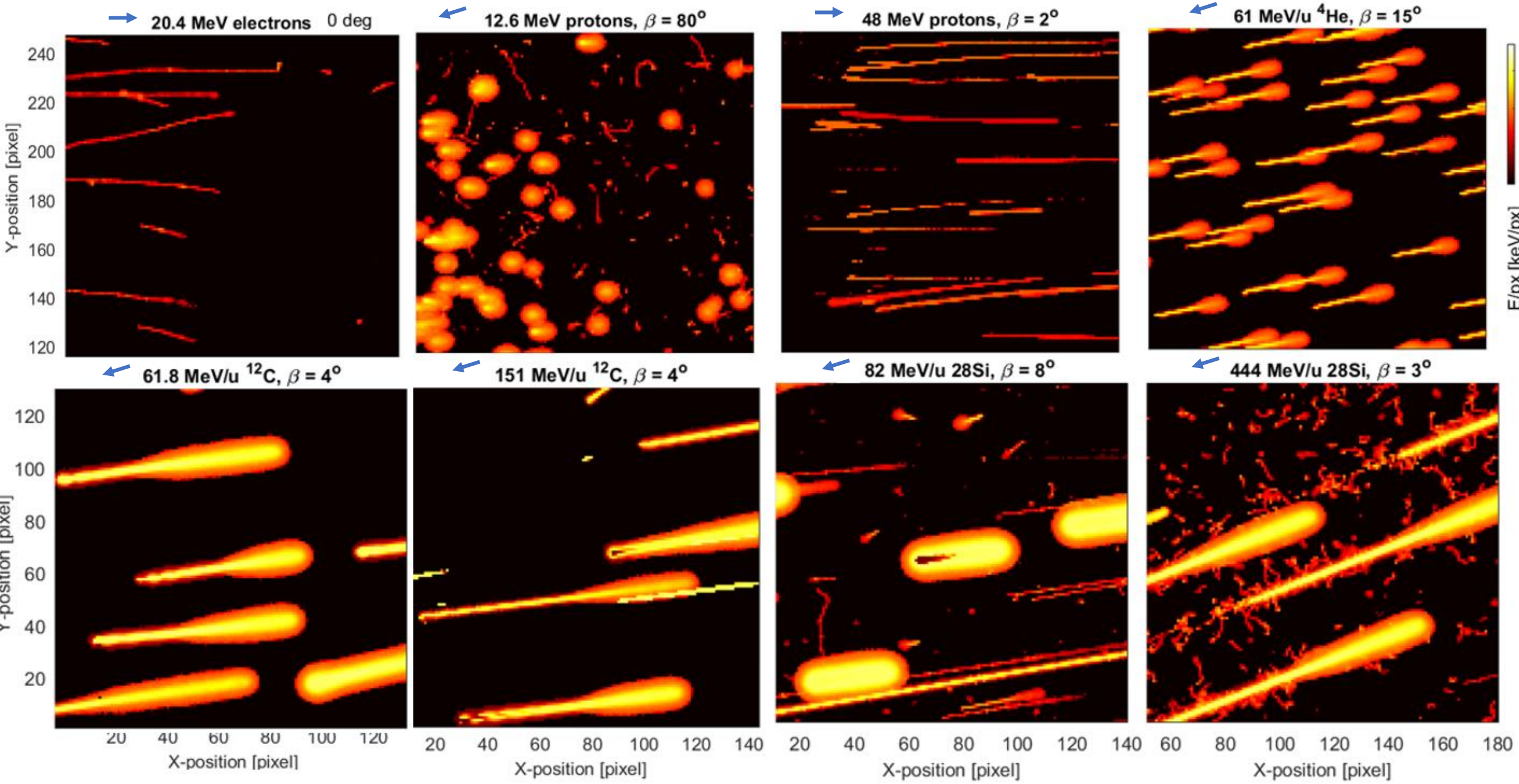
Incident beam

Electron microtron accelerator MT-25

Maximum energy	25 MeV
Energy range	6 - 25 MeV
Electron current	25 μA
Tunable magnetron	2 796 ± 5 MHz
Peak power	3 MW
Pulse lenght	3 μs
Repetition rate	max. 425 s^{-1}
Resonator freq.	2 796 MHz
Power supply freq.	50 Hz

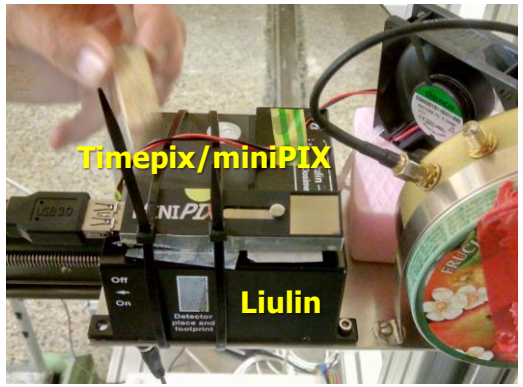
NPI-CAS, Rez near Prague
Electron Microtron Accelerator

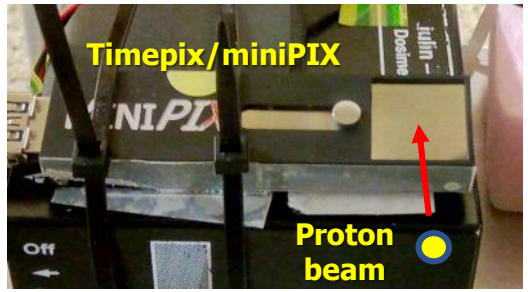
Quantum imaging detection, spectrometry, tracking: Charged particles

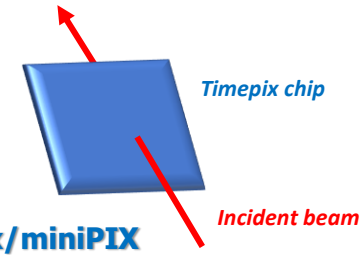


protons: varying E + raw data

Medium-energy protons
Cyclotron accelerator, NPI-Czech Ac.Sc. Rez/Prague



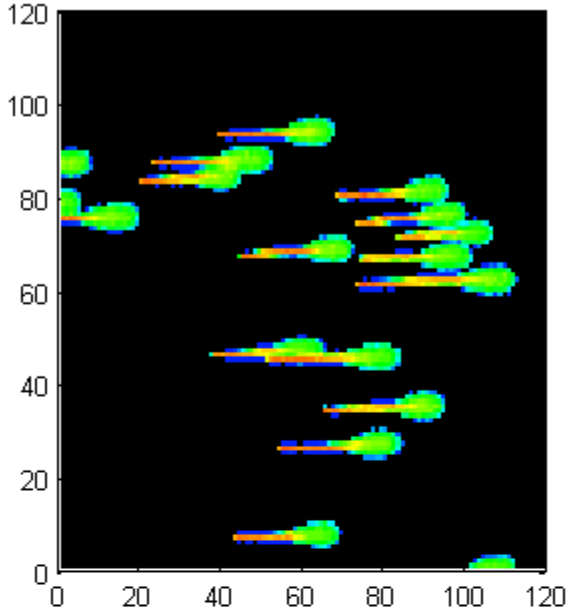




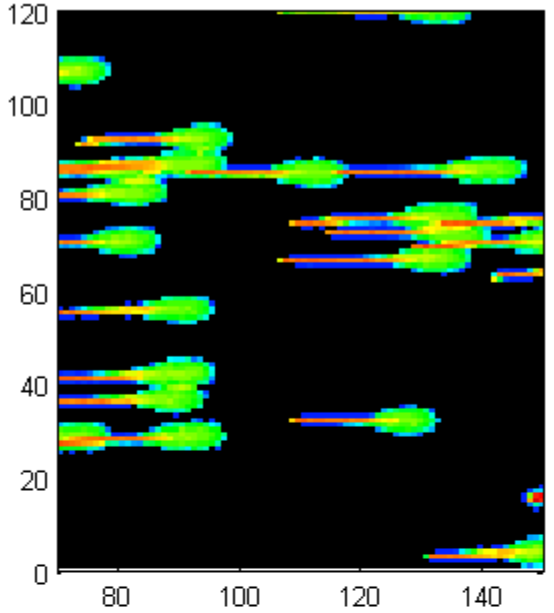
Timepix/miniPIX

ADVACAM
Imaging the Unseen

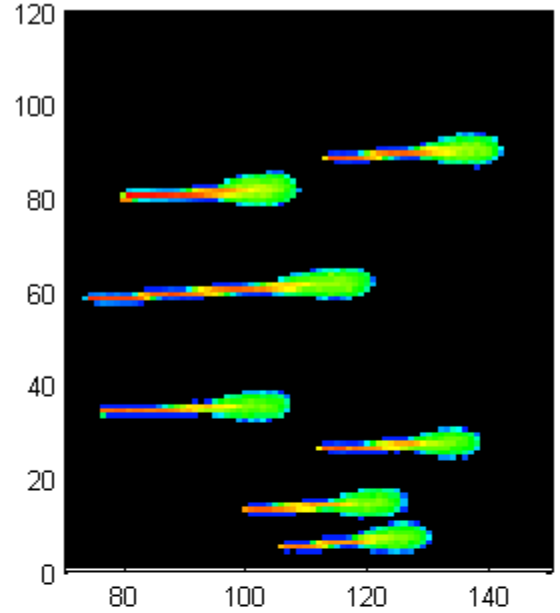
30.9 MeV protons



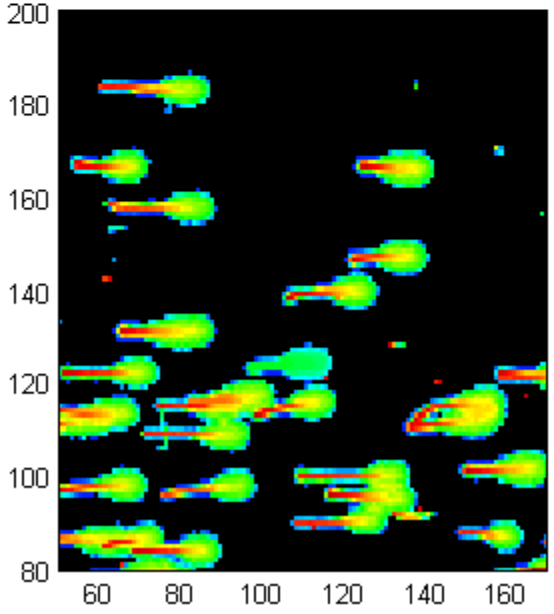
b) 28.8 MeV protons



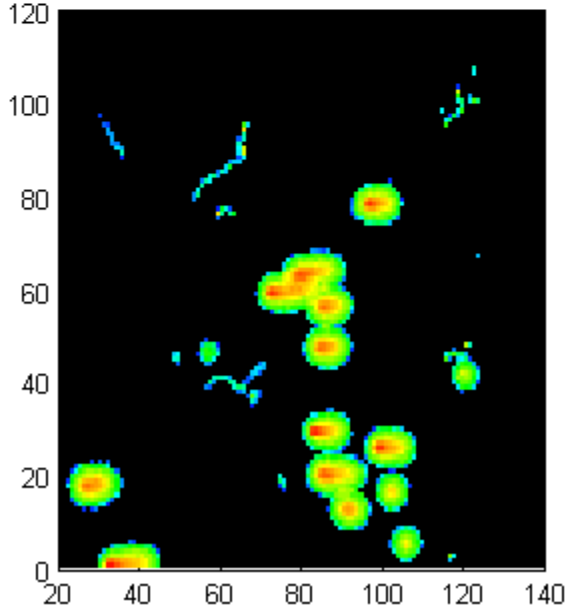
c) 26.6 MeV protons



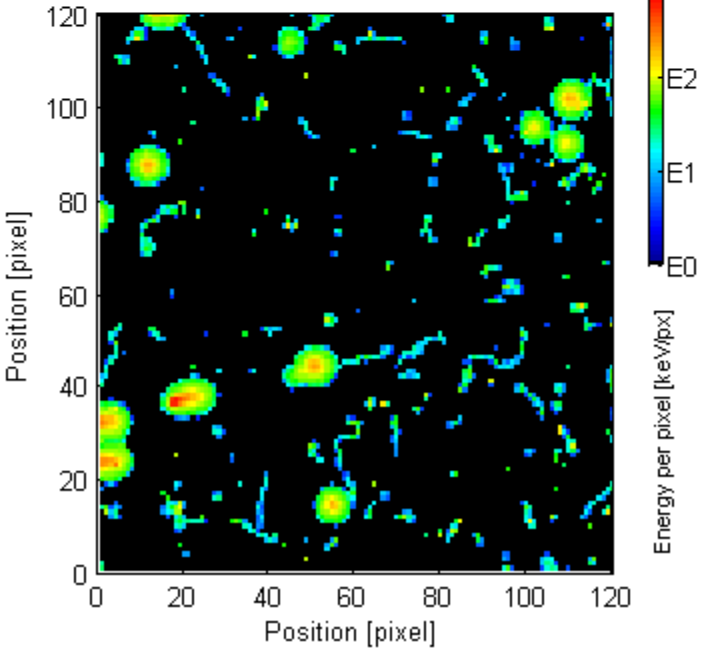
d) 19.6 MeV protons



e) 12.7 MeV protons



f) 6.2 MeV protons



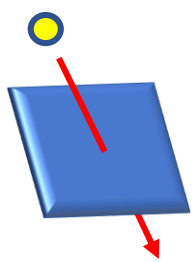
CREAT

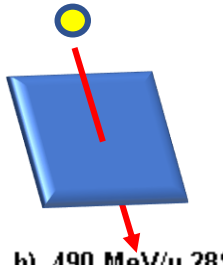
ujf

Quantum imaging detection, spectrometry, tracking

Energetic charged particles: relativistic ions, secondaries/reaction/fragmentation products

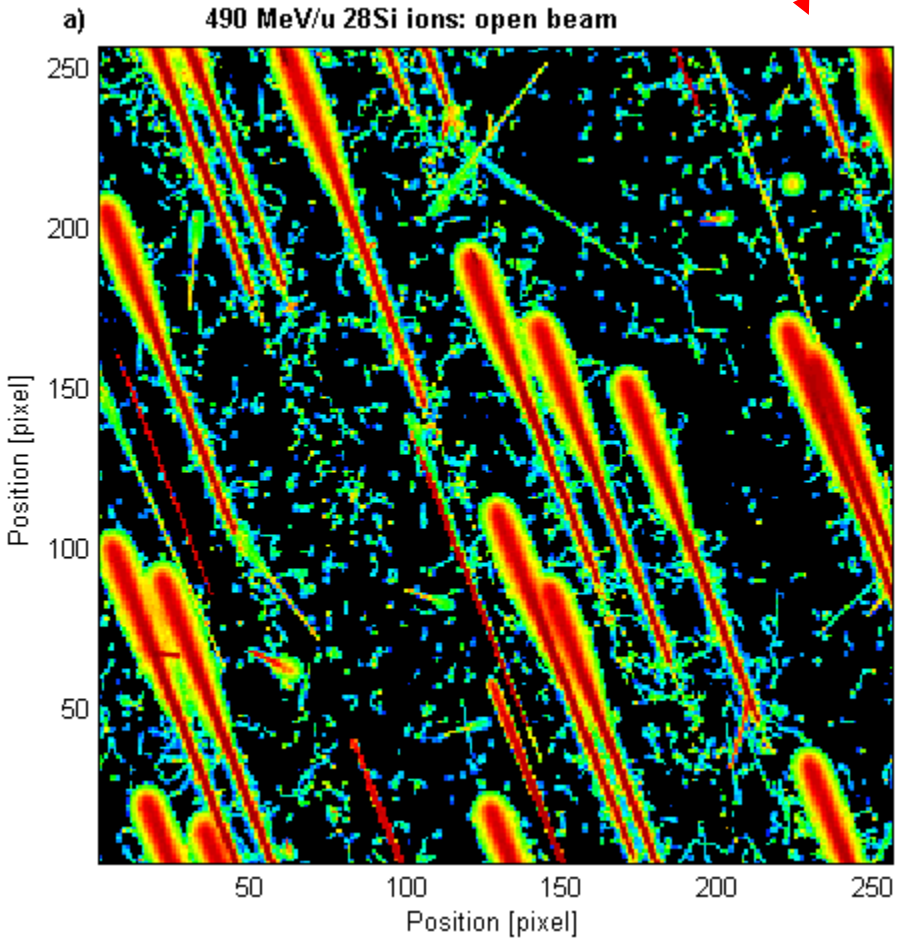
490 MeV/u ^{28}Al ions

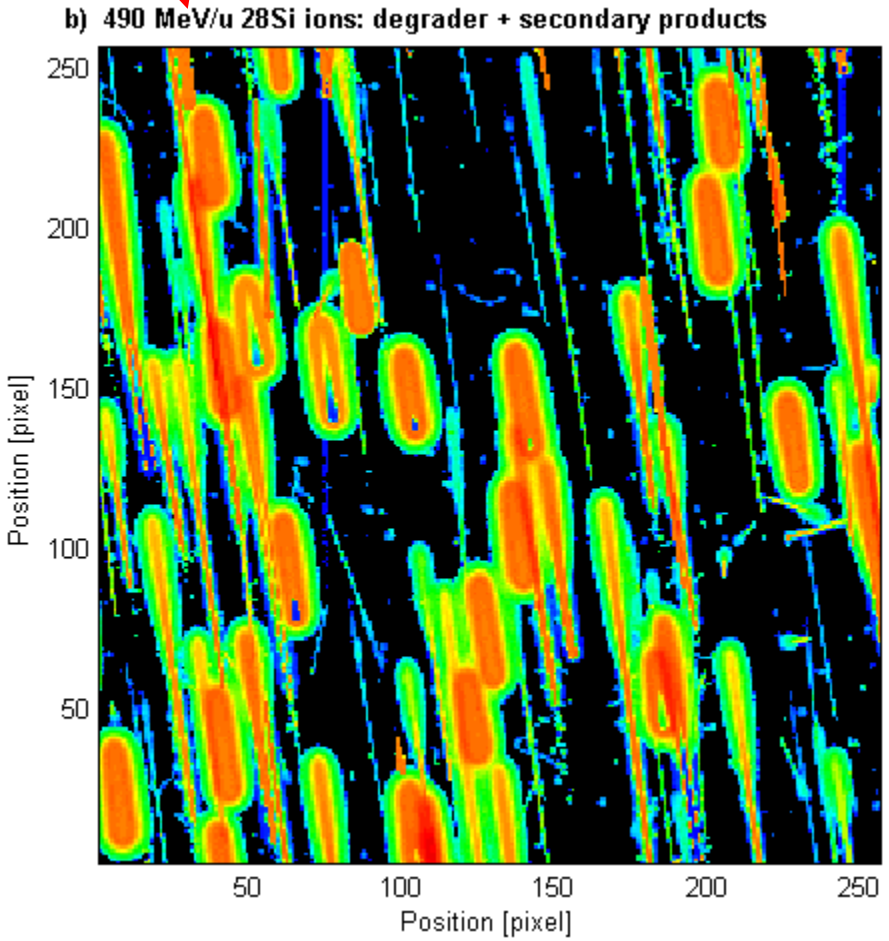




85 MeV/u ^{28}Al ions
& secondary reaction products

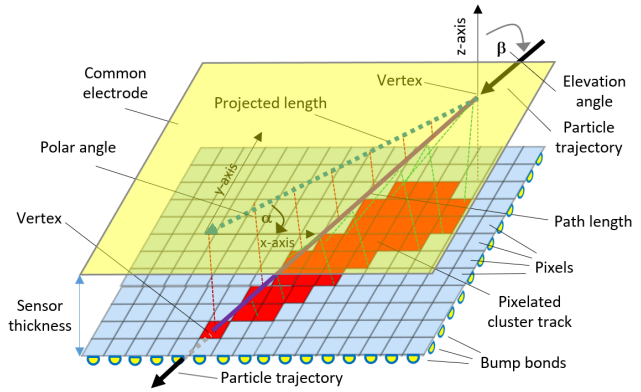
Micro-scale particle tracking + high-resolution pattern recognition of single particle tracks





Energetic (penetrating) charged particles:

- **Deposited energy**
- **Position of interaction + Path tracking**
- **→ dE/dx → LET, stopping power**
- **Direction: Wide FoV + ang res ≈ 1°-10°**



α = Azimuth angle
β = Elevation angle

Quantum imaging detection, spectrometry, tracking

Energetic charged particles: relativistic ions, secondary reaction/fragmentation products

label	Parameter	Value in cluster	Range#	Units
A	Area	# of pixels	1 – few 100's	px
E	Deposited energy	Sum of energies of all pixels	5 – 1×10^6 $	keV
H	Height	Largest per-pixel energy	5 – 1×10^3 $@	keV
R	Roundness	Extent of circular shape	0 – 1	a.u.
Lin	Linearity	Extent of track length approaching a straight line	0 – 1	a.u.
L	Length	Path length of track across sensor	1 – 256	px
C	Curliness	Transversal distance from lineal track	1 – 50	px
LET	Linear energy transfer	Ratio of energy to length	0.1 – 10^3	keV/µm
α	Polar angle	Projected angle on the sensor plane	0 – 180	°
β	Elevation angle	Elevation angle to the sensor plane	0 – 90	°
HEA	Ratio H to β	Height to elevation angle	0.1 – 10^3	keV/°
HL	Ratio H to L	Height to track length	0.1 – 10^3	keV/px

#: Upper limit approximate level

$: Lower limit given by the detector sensitivity and calibration, typically at the level of few keV/px

@: Upper limit typically up to 1 MeV (linear range of calibration) and 2 MeV (distorted region).

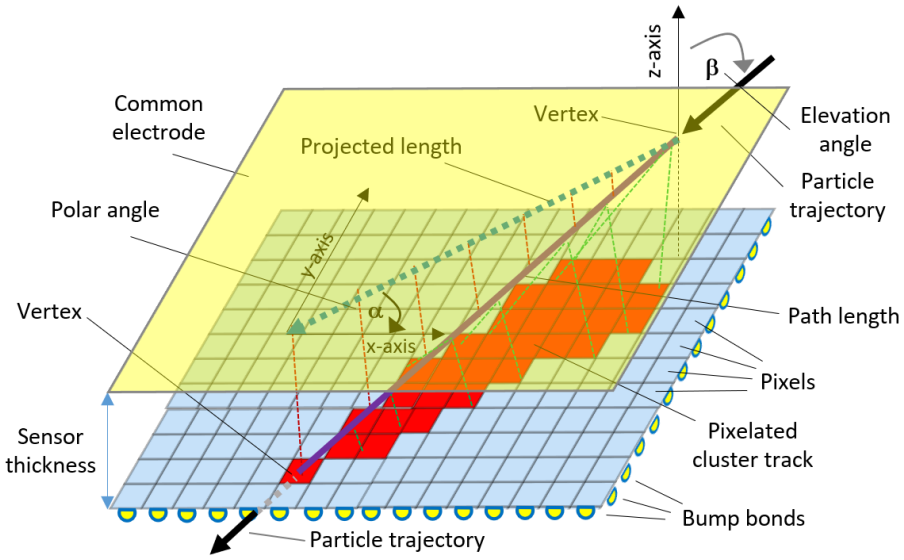
a.u.: arbitrary units

Degrees of freedom:
- **Particle type**
- **Particle energy, stopping power**
- **Particle direction**

Pixel clusters + convolution of sensor bias and detector/DAC settings

Micro-scale particle tracking + high-resolution pattern recognition of single particle tracks

Energetic (penetrating) charged particles:
- **Deposited energy**
- **Position of interaction + Path tracking**
- **→ dE/dx → LET, stopping power**
- **Direction: Wide FoV + ang res ≈ 1°-10°**



α = Azimuth angle
β = Elevation angle

SINGLE-PARAMETER ANALYSIS

Response of cluster analysis parameters: Varying particle energy

^{4}He beam: 5 energies in 20-150 MeV/u range + raw/unfiltered data (all particles)

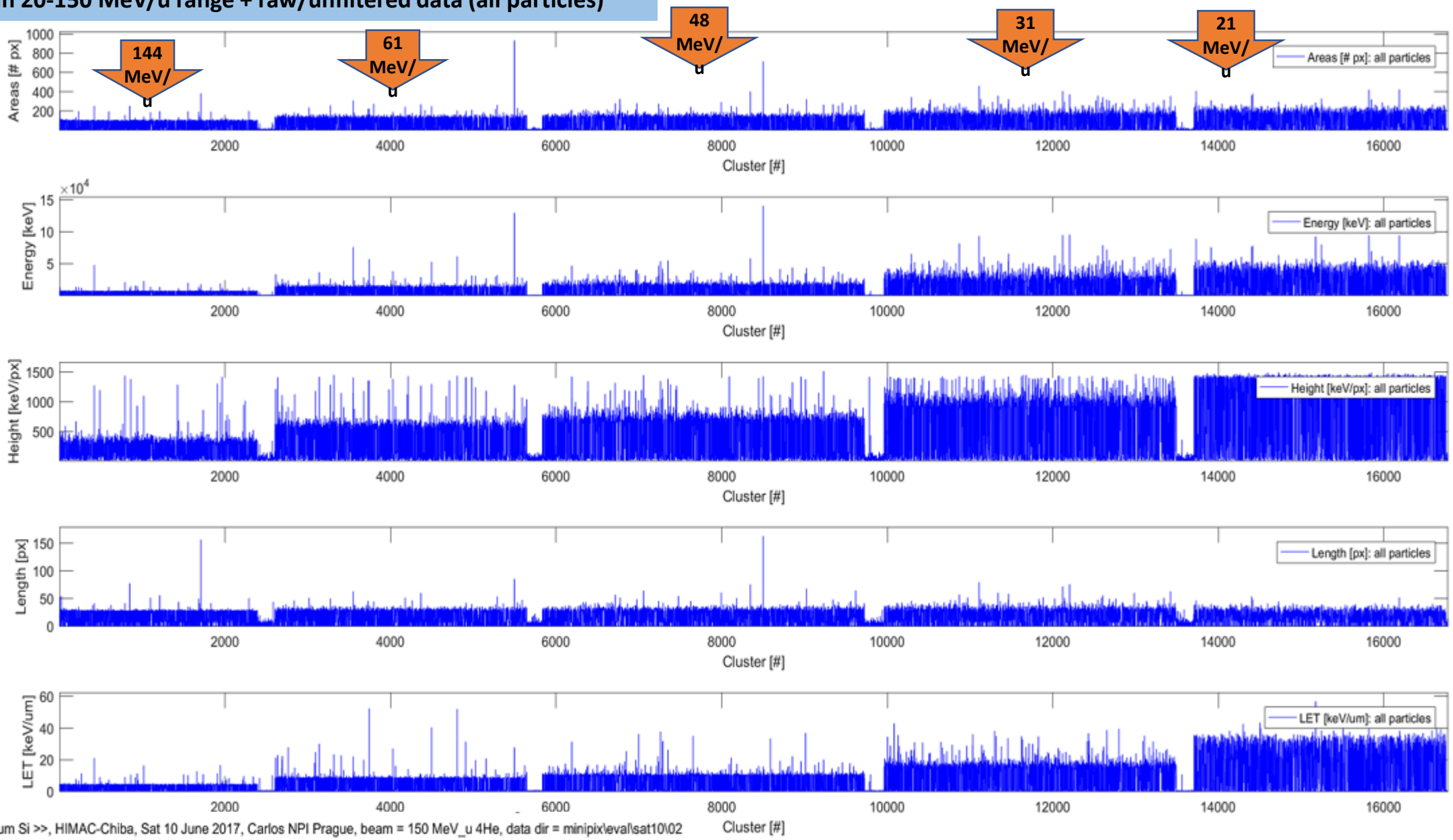
Area [# px]

Energy/volume [keV]

Height [keV]

Track length [um]

LET [keV/um]

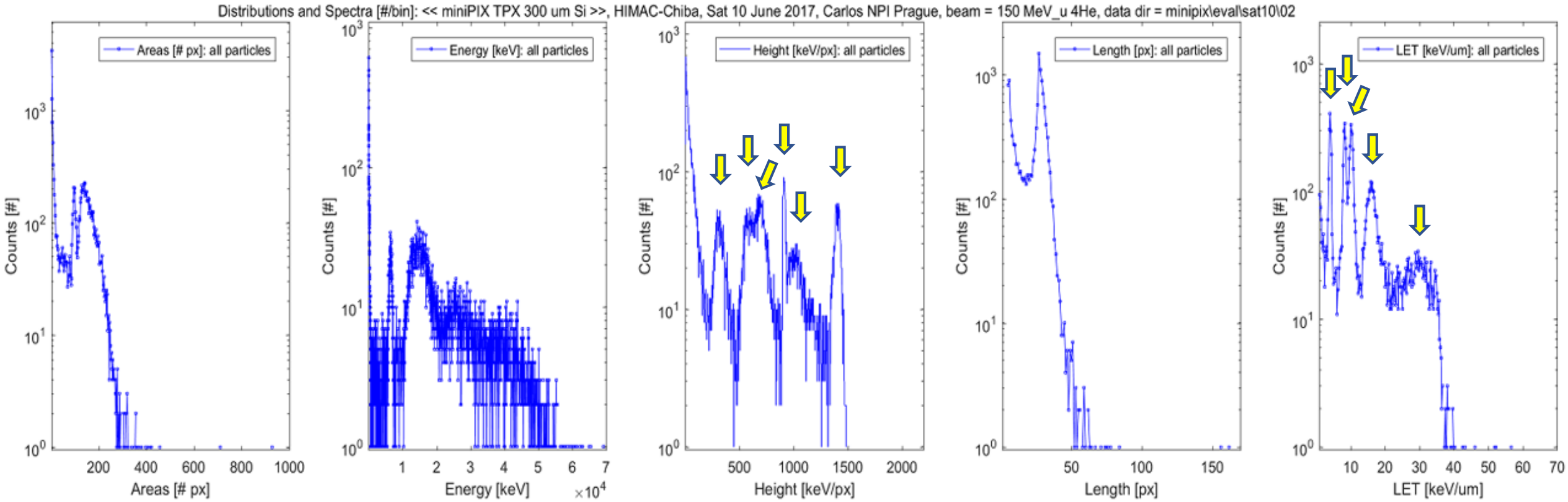


<< miniPIX TPX 300 um Si >>, HIMAC-Chiba, Sat 10 June 2017, Carlos NPI Prague, beam = 150 MeV_u 4He, data dir = minipix\eval\sat10\02

Response of cluster analysis parameters: Varying particle energy

^{4}He beam: 5 energies in 20-150 MeV/u range + raw/unfiltered data (all particles)

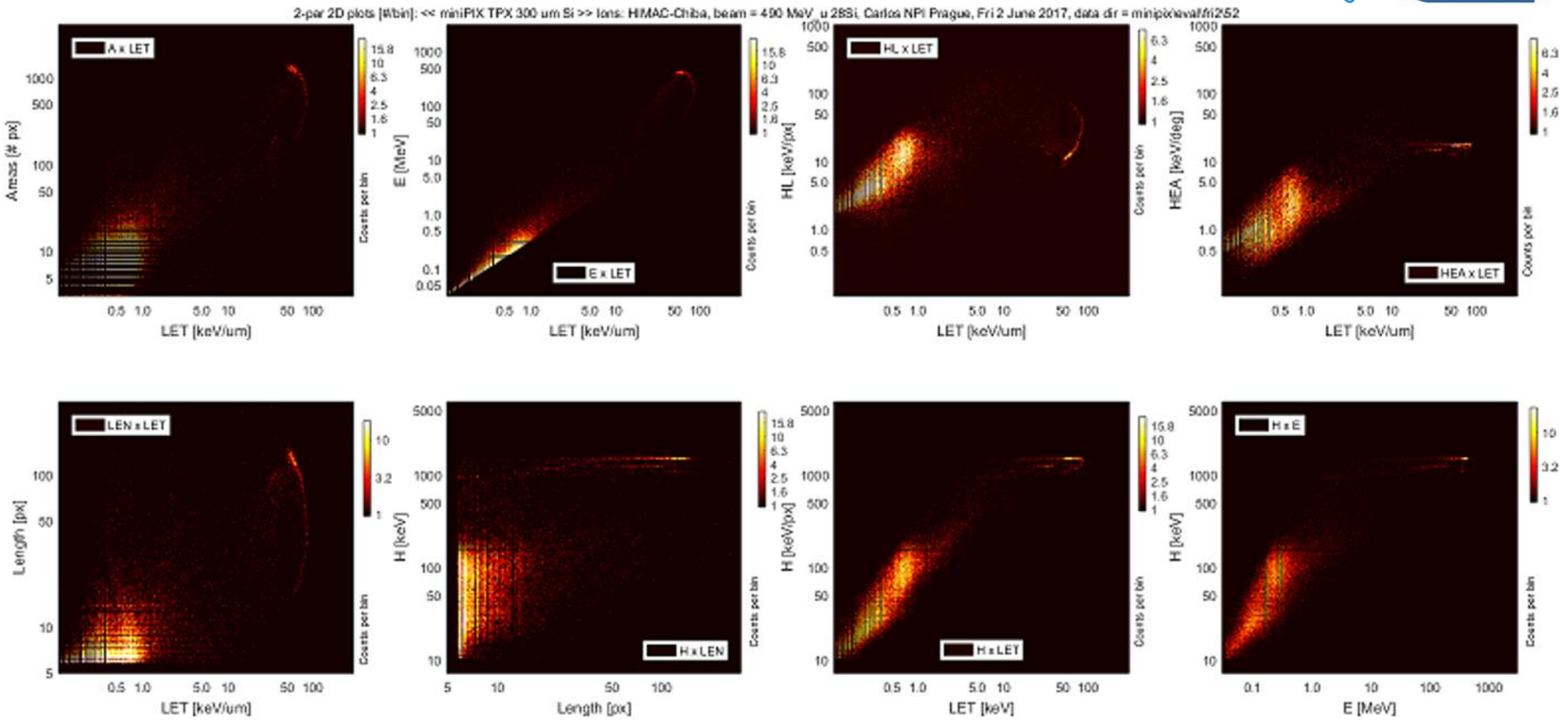
Area [# px] | Energy (volume) [keV] | Height [keV] | Track length [um] | LET [keV/um]



TWO-PARAMETER ANALYSIS

^{28}Si beam: 490 MeV/u: all particles

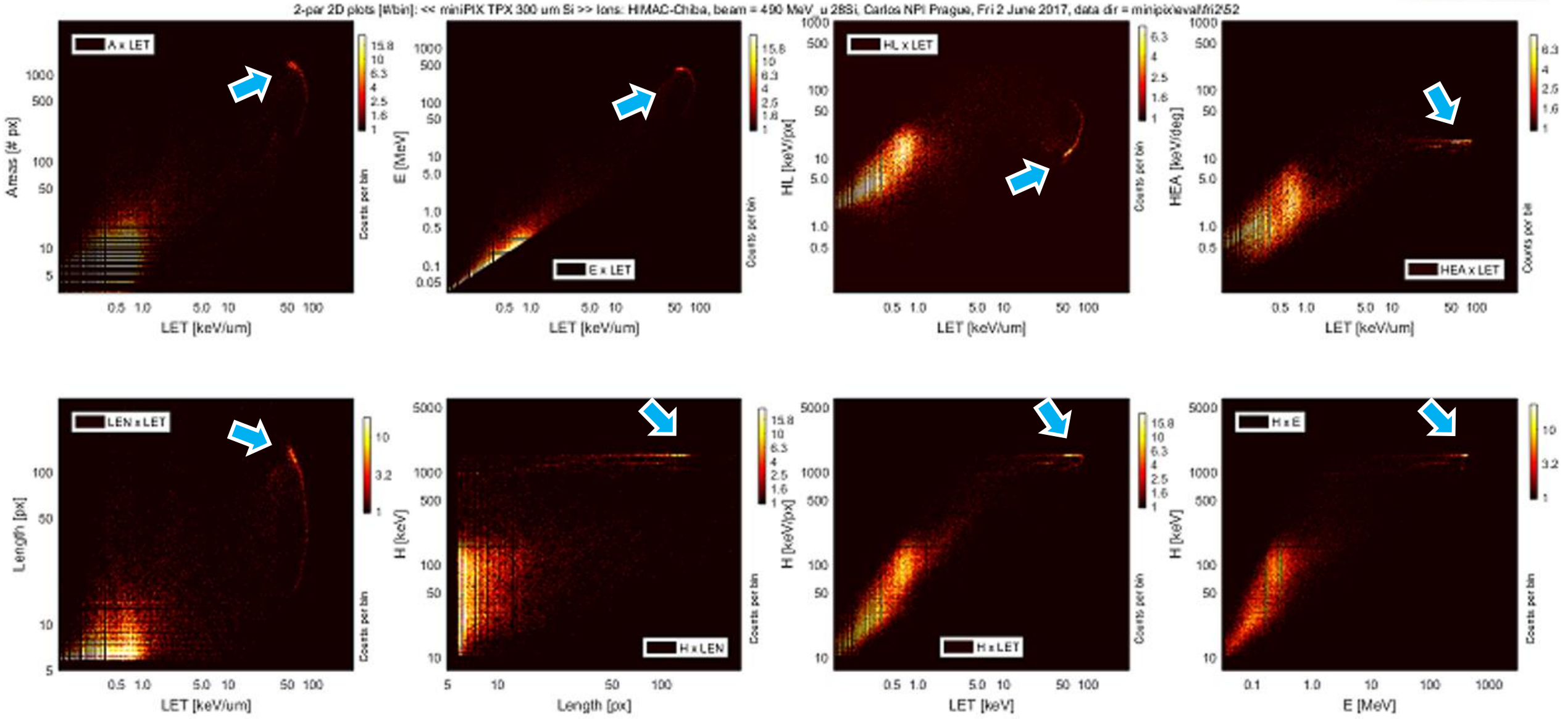
490 MeV/u ^{28}Si



TWO-PARAMETER ANALYSIS

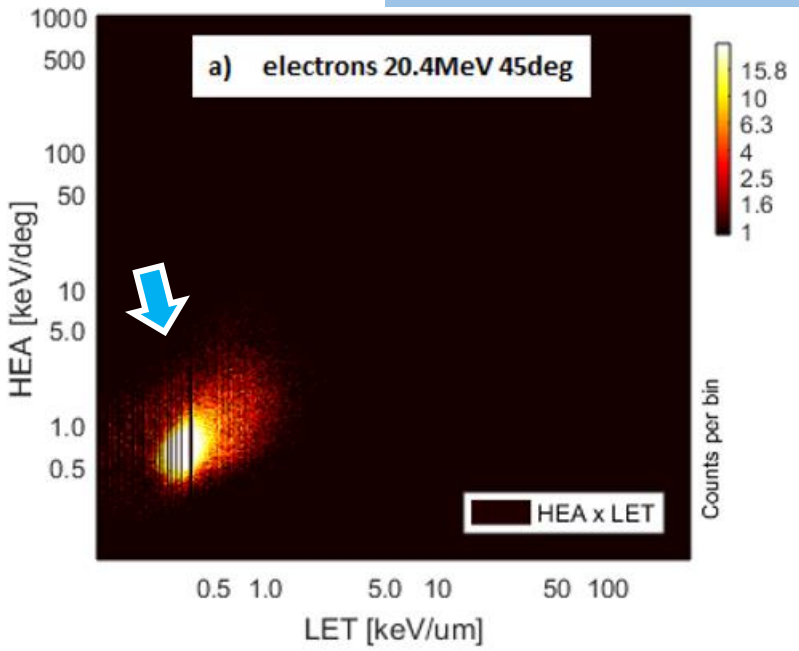
^{28}Si beam: 490 MeV/u: all particles

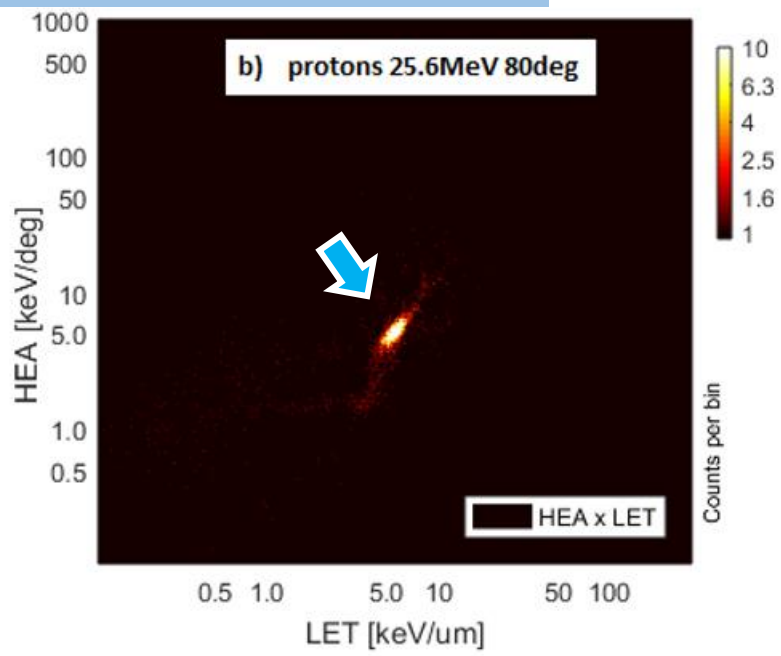
490 MeV/u ^{28}Si

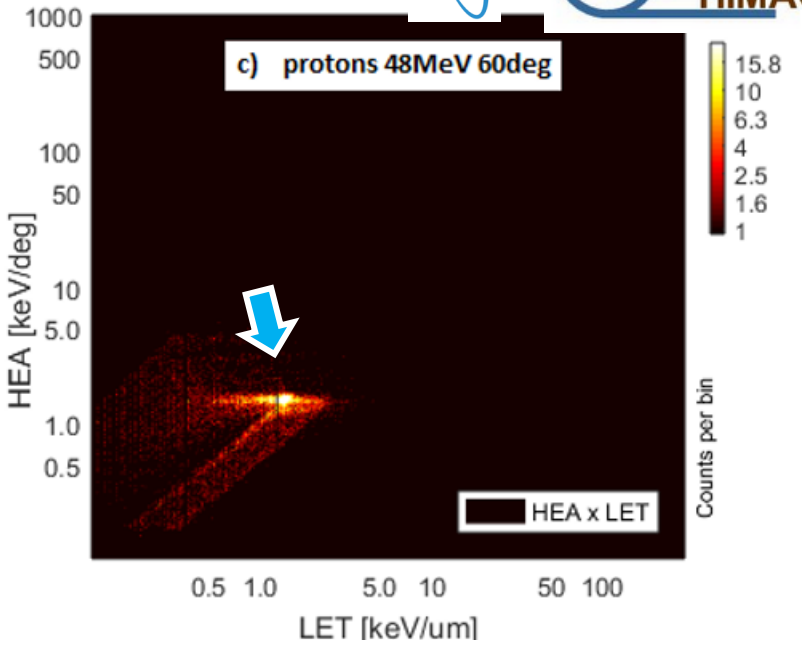


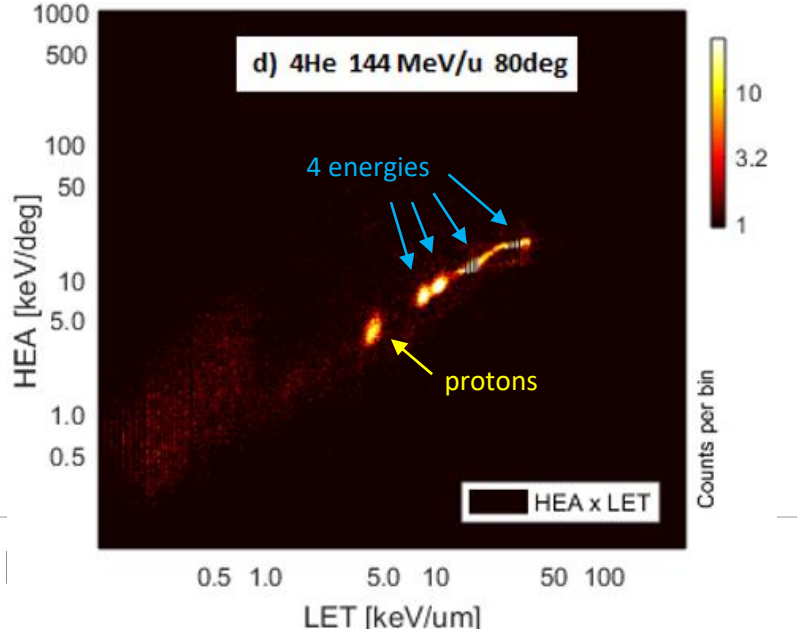
TWO-PARAMETER ANALYSIS

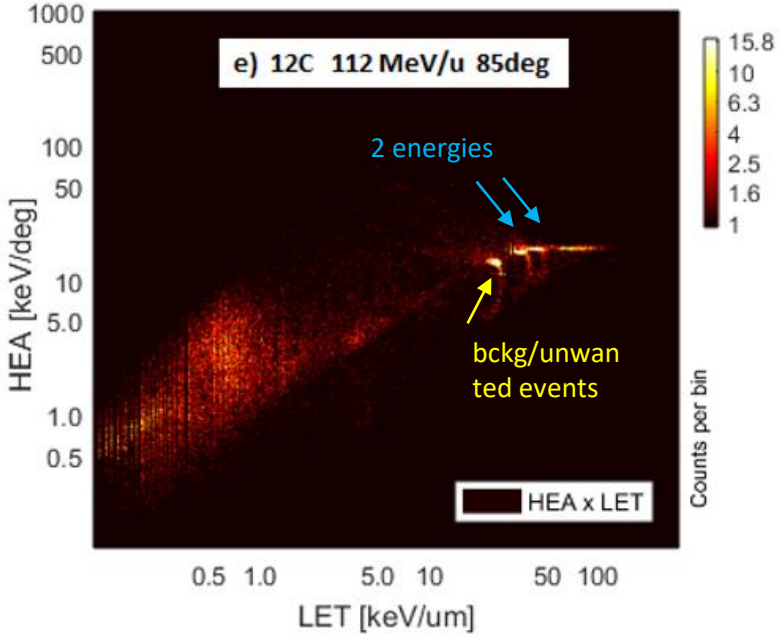
Electrons, protons, ions: all particles

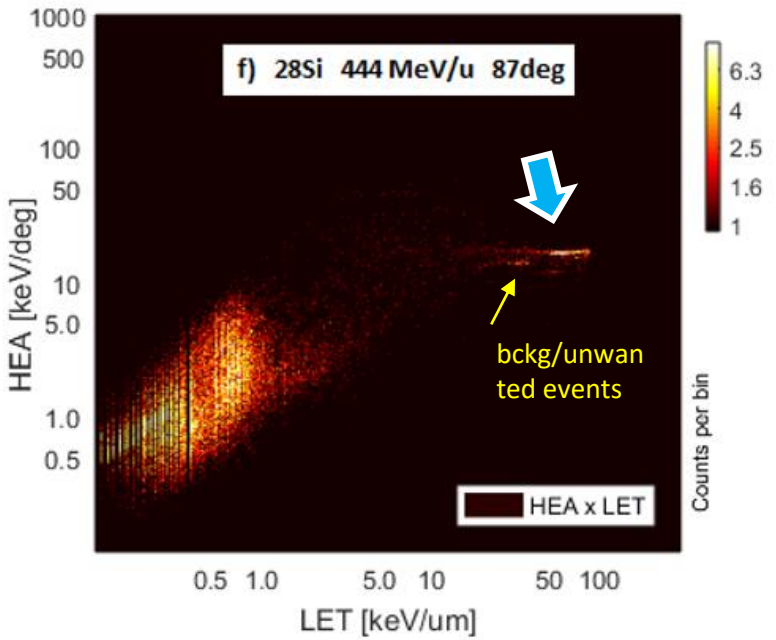










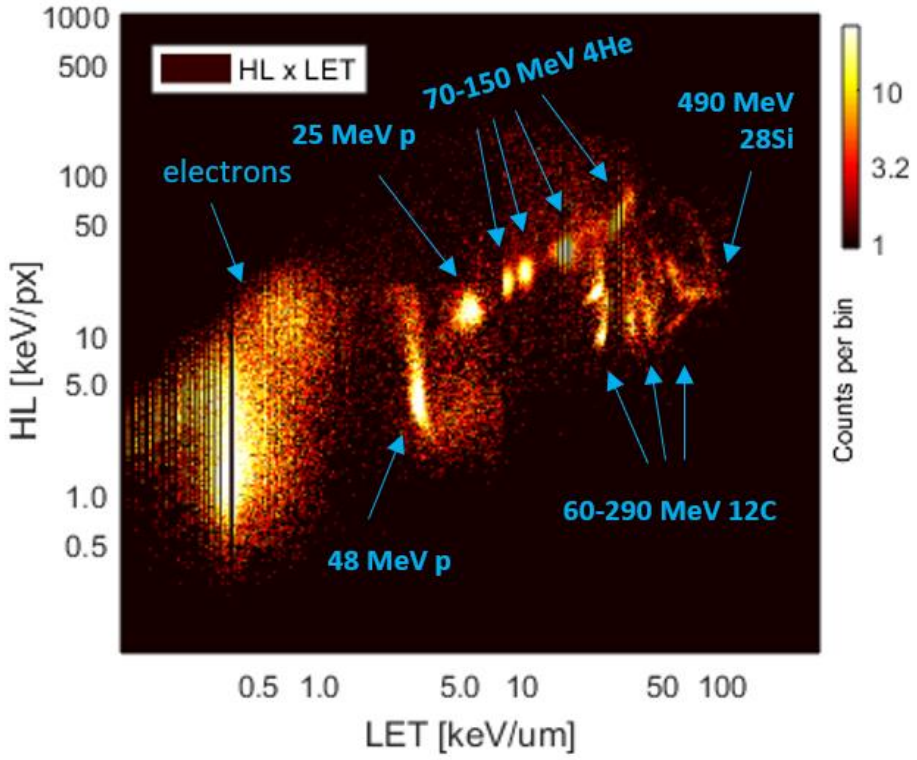


Timepix resolving power for energetic charged particle detection

Particle type/species + Spectral dE/dx range + Direction → Physics-based event classification → 8 groups

TWO-PARAMETER ANALYSIS

Electrons, protons, ions



Physics-based classification of radiation events by a single Timepix detector. Event types are listed with filters/proposed range/selected values of cluster parameters.

#	Event	CAP 1	CAP 2	CAP 3
1	X rays; LE e OD; HE e, μ PP	A≤3	Lin<0.72	
		H<140; C<2.8	β<20	LET < 1.6
		0.9<C<2.8	β>20; Lin<0.83	LET < 1.6
		R<0.70	C > 2.5	LET < 1.6
2	LE p's PP	140<H<700; C≥2.8	8<HL<30; R>0.87	3.0 < LET < 8.0
3	LE light ions PP	700<H<2500	40<HL<70; R>0.87	15< LET<42
4	LE heavy ions PP	2500<H	70<HL; R>0.87	90< LET
5	HE e's, μ's nP	A>3; H<60	β>20; Lin≥0.65	LET < 0.9
6	HE p's nP	140<H<400	2<HL<8; Lin≥0.65	1.85 < LET < 3.0
		25<H≤140	2<HL<8; Lin≥0.85	0.50 < LET ≤ 1.85
7	HE light ions nP	400<H<1050	15<HL<40	4.0< LET<15
8	HE heavy ions nP	800<H<2500	10<HL<50	42<LET<90

LE = low energy, HE = energetic, PP = Perpendicular (β<20), CAP = cluster analysis parameter
A = area [# px], R = roundness [a.u.], H = height [keV/px], LET = linear energy transfer [keV/μm]
e = electrons, μ = muons, p = protons, OD = omnidirectional, nP = non-perpendicular (β≥20)
C = curliness.

Next/future work: implement/merge the physics methodology with advanced processing, neural networks, …