New Concepts with Pixelated Detectors in the Search for the Neutrinoless Double Beta Decay

16th October 2012

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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RTS Colloquium

Fermi National Accelerator Laboratory

Friedrich-Alexander-Universität Erlangen-Nürnberg

IMPRS physics of light

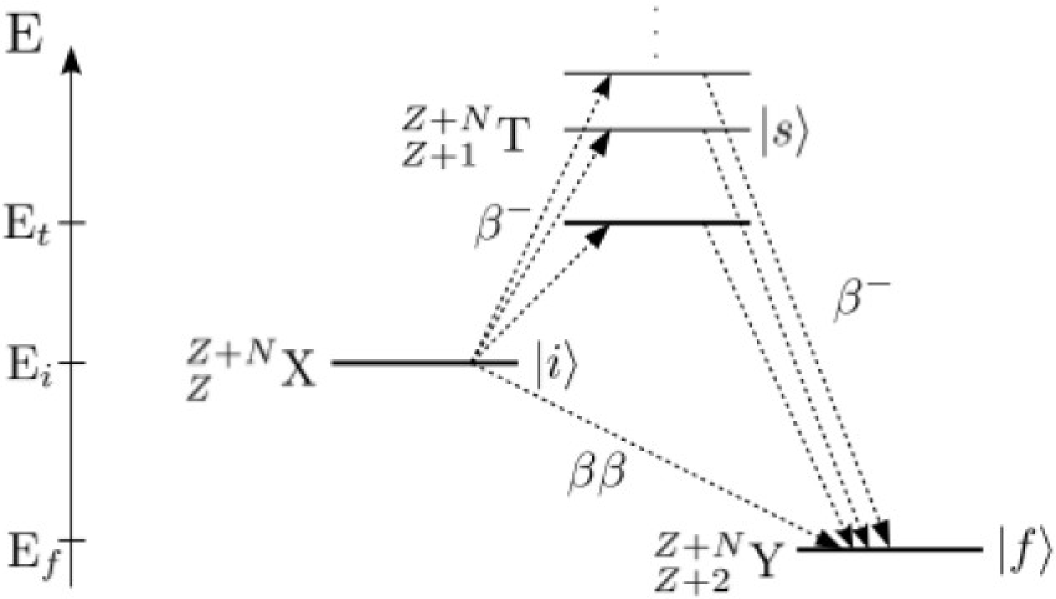
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

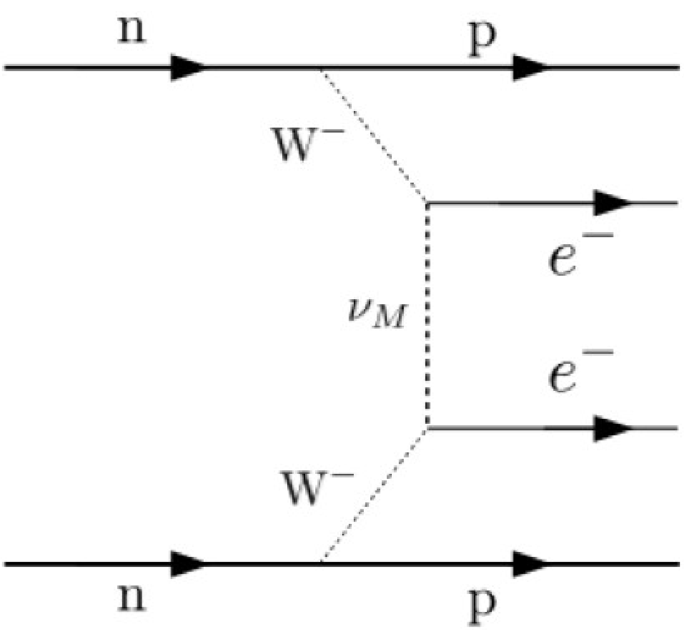
I. Short Introduction to the Neutrinoless Double Beta Decay

About the Neutrinoless Double Beta Decay

Neutrinoless Double Beta Decay (0vbb):

$$2n \rightarrow 2p + 2e^-$$





$$(T_{\frac{1}{2}})^{-1}_{0\nu\beta\beta} = G_{0\nu}(Q_{\beta\beta}, Z)\, |M_{0\nu}|^2 \,\langle m_\nu \rangle^2$$

$$T_{0\nu} > 2 \cdot 10^{25} a$$

About the Neutrinoless Double Beta Decay

Consequences:

The neutrino is a Majorana particle.
(→ Direct evidence for Physics beyond the SM !)

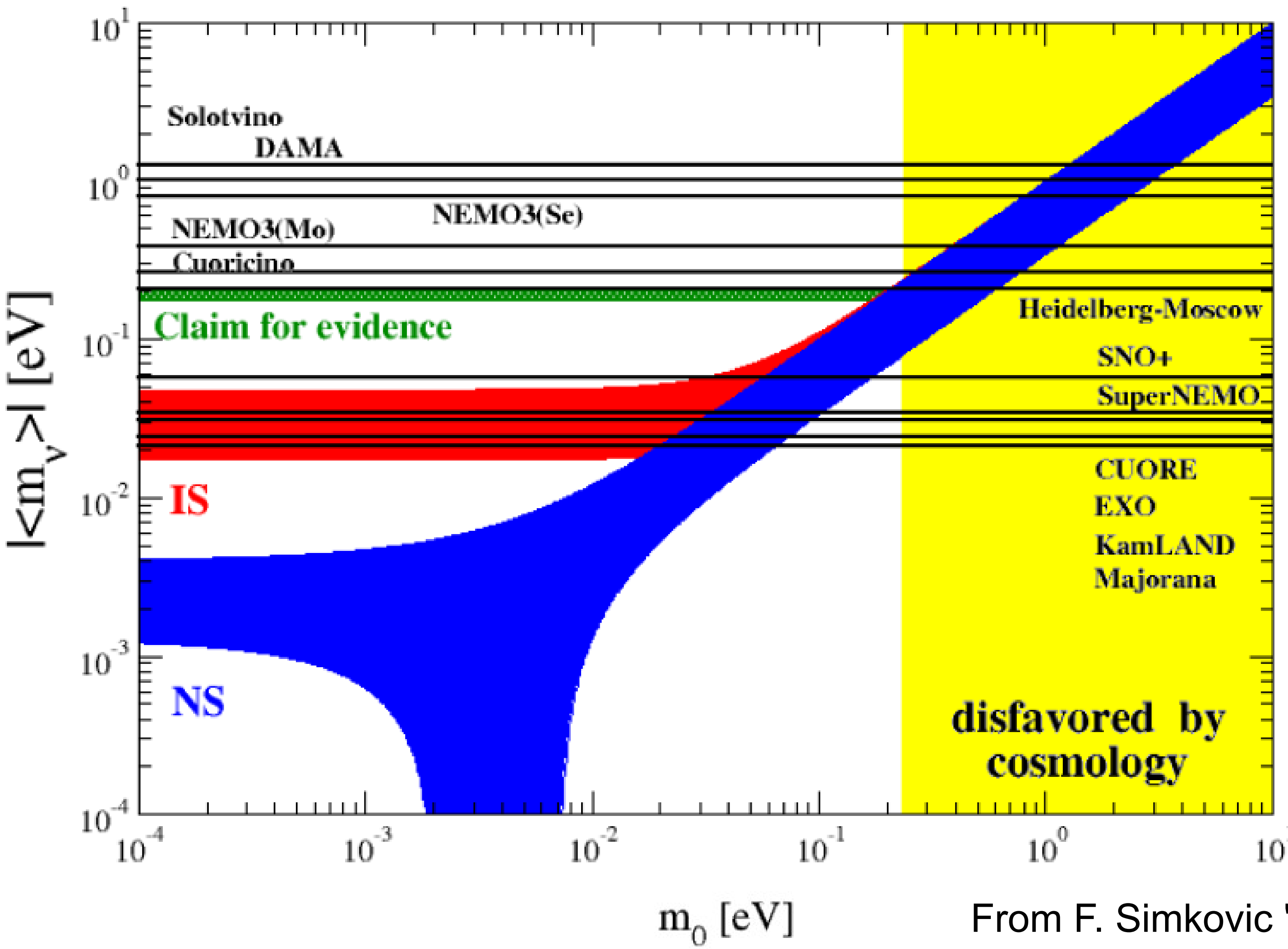
The neutrino (a Lepton !) is its own anti-particle.

Measurement of the effective neutrino mass.

$$\langle m_\nu \rangle = \sum_i |U_{ei}|^2 \, m_i$$

About the Neutrinoless Double Beta Decay

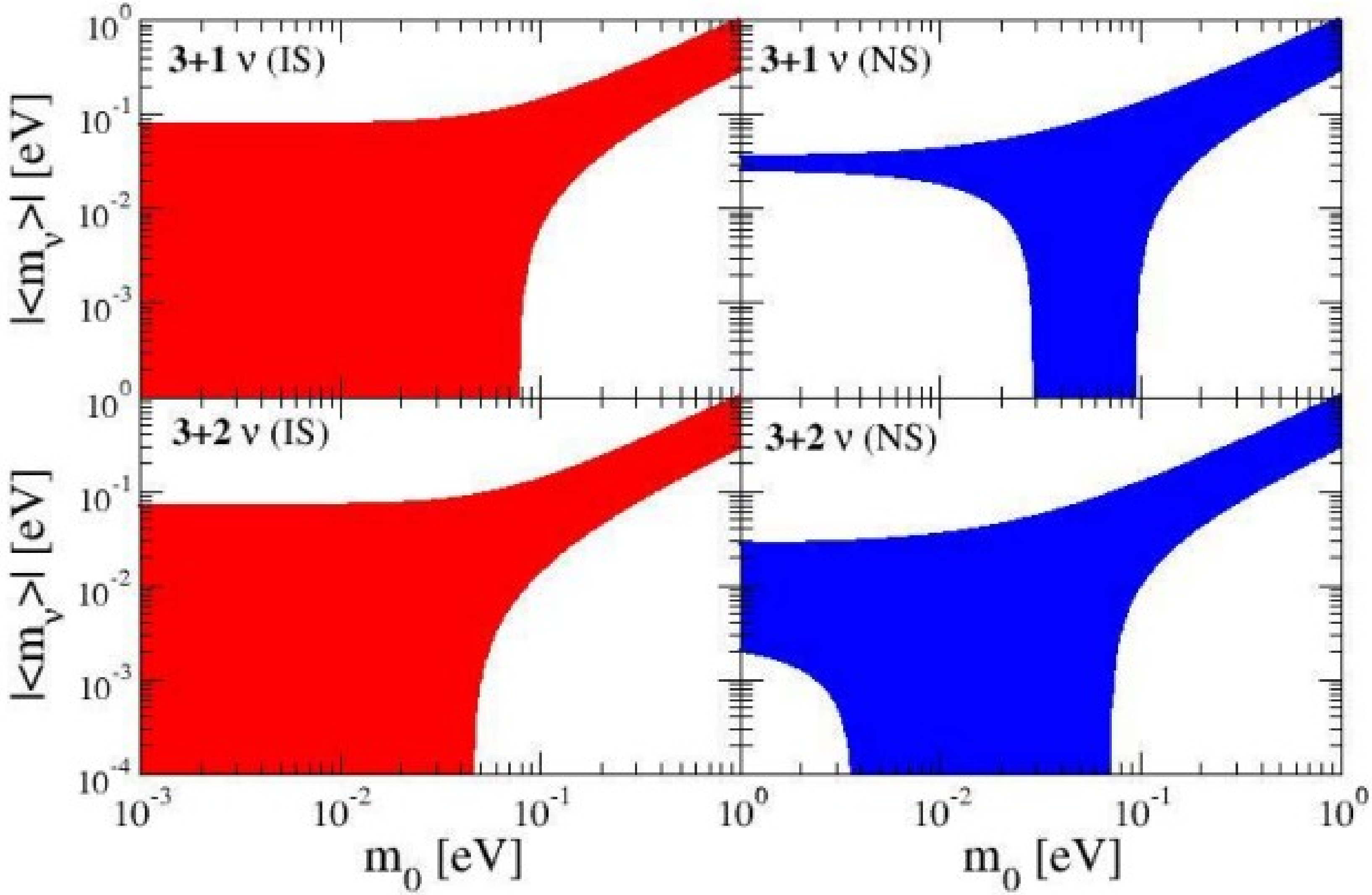
Solving the neutrino-mass hirarchie problem.



From F. Simkovic '12

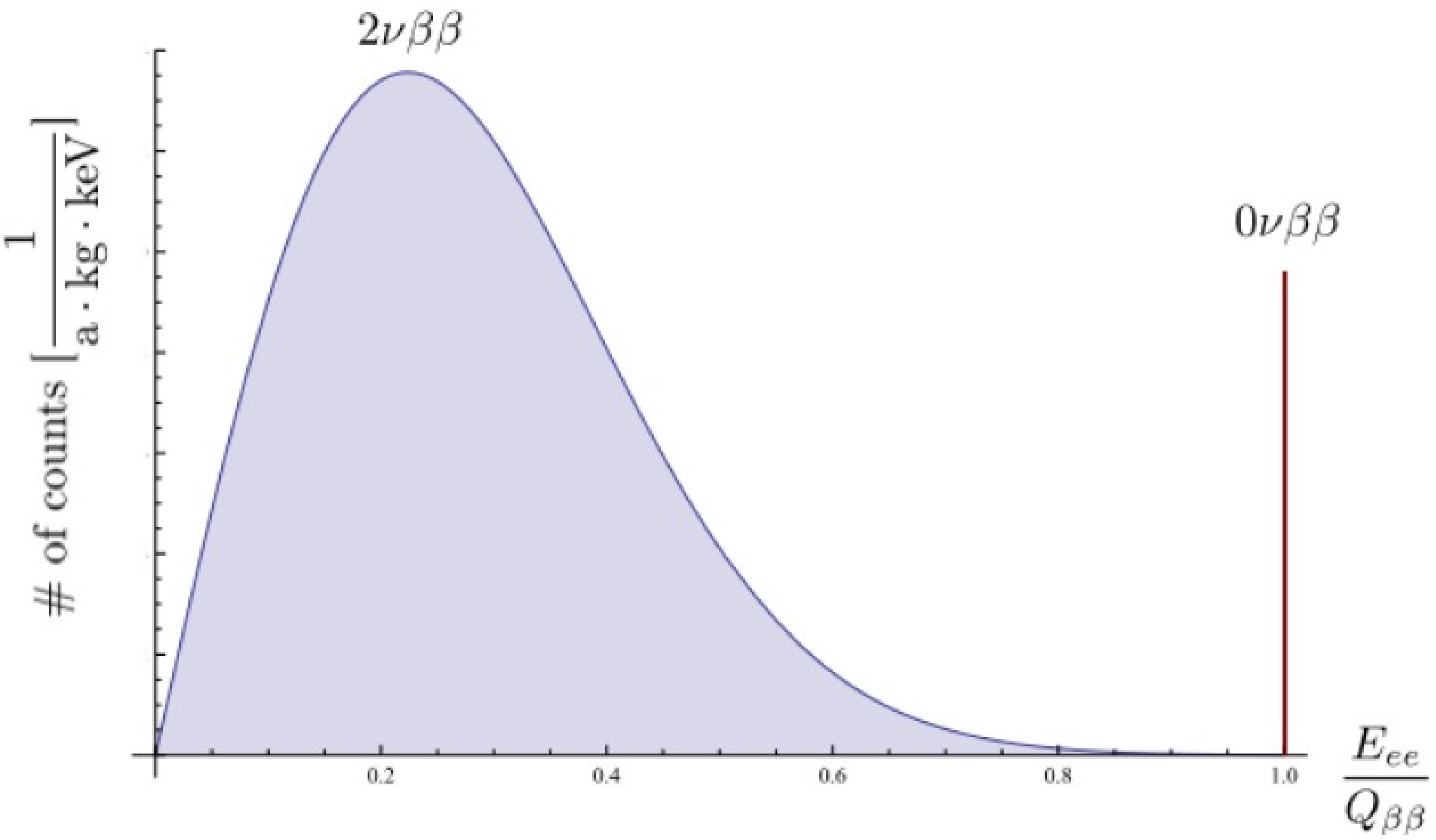
About the Neutrinoless Double Beta Decay

What happens with sterile neutrinos?



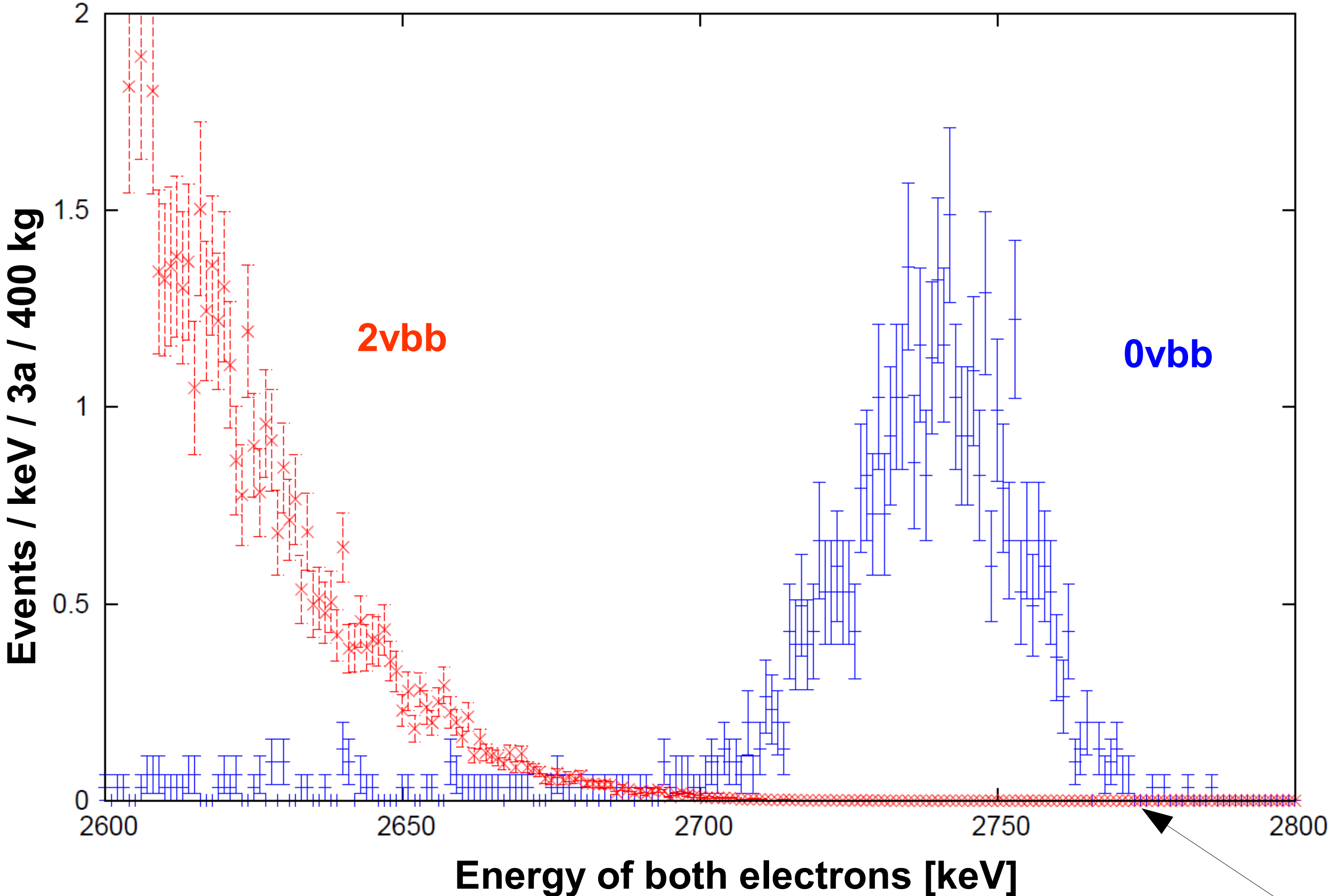
From F. Simkovic '12

The Experimental Approach to the 0vbb: The Energy Signature



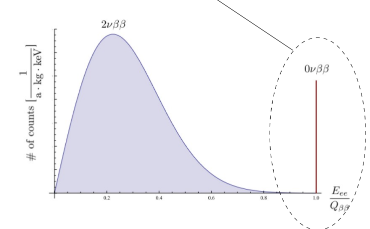
The Experimental Approach to the 0vbb: The Energy Signature

From T.Gleixner '11

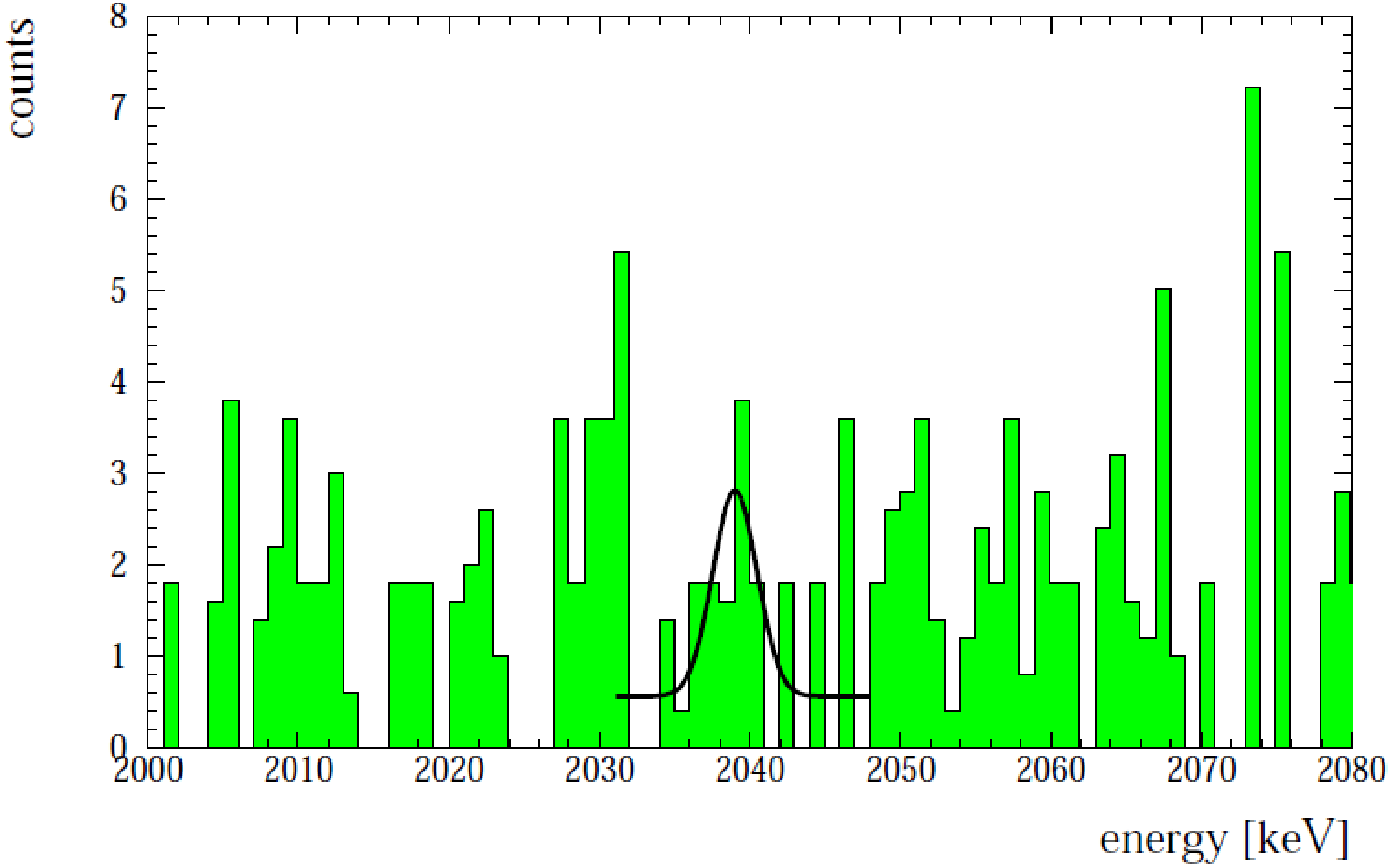


Main Idea:

Build a highly precise particle calorimeter.

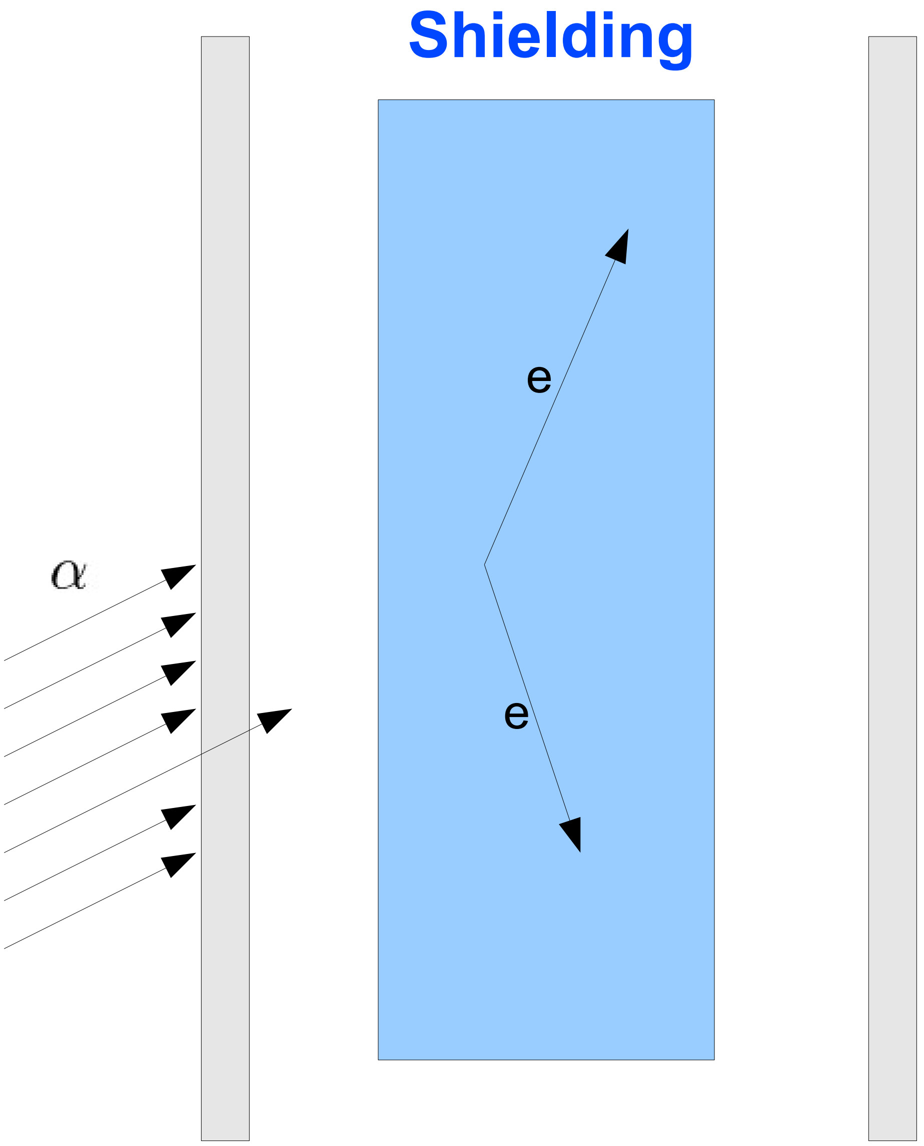


Main Problem: Background Reduction



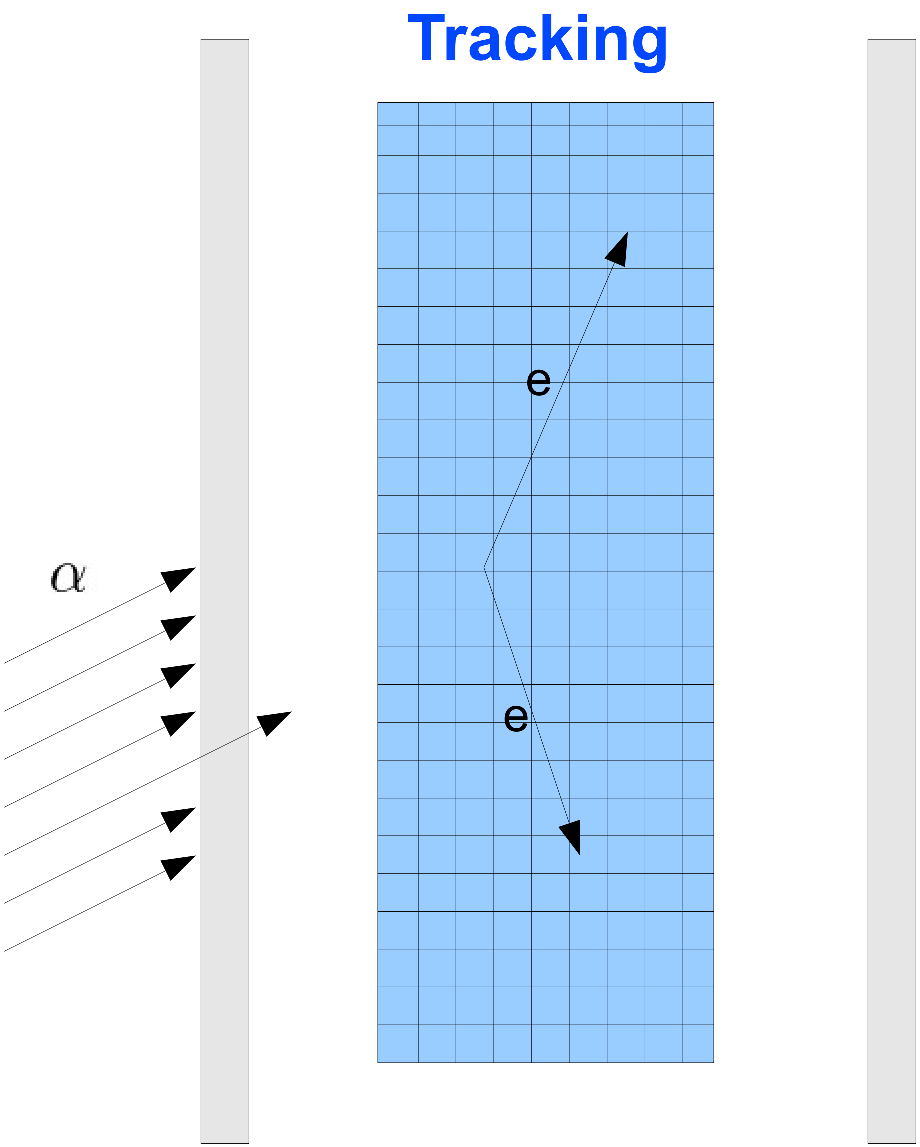
Result of the Heidelberg-Moscow Experiment with a Germanium Calorimeter ['02 H.V. Klapdor-Kleingrothaus].

Idea: Background Reduction by Tracking



decay material = detector sensor material

Idea: Background Reduction by Tracking



decay material = detector sensor material

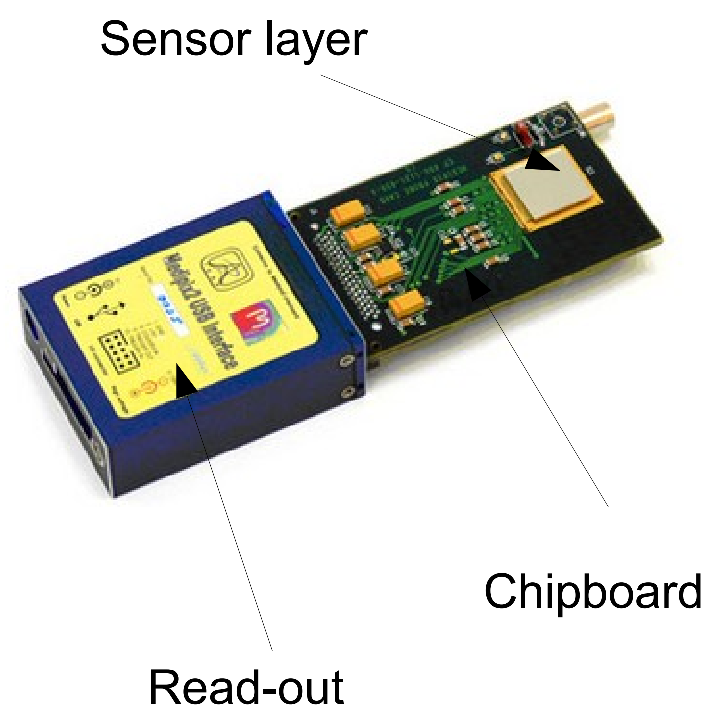
II. How Well Does Tracking Actually Work?

The Timepix Detector

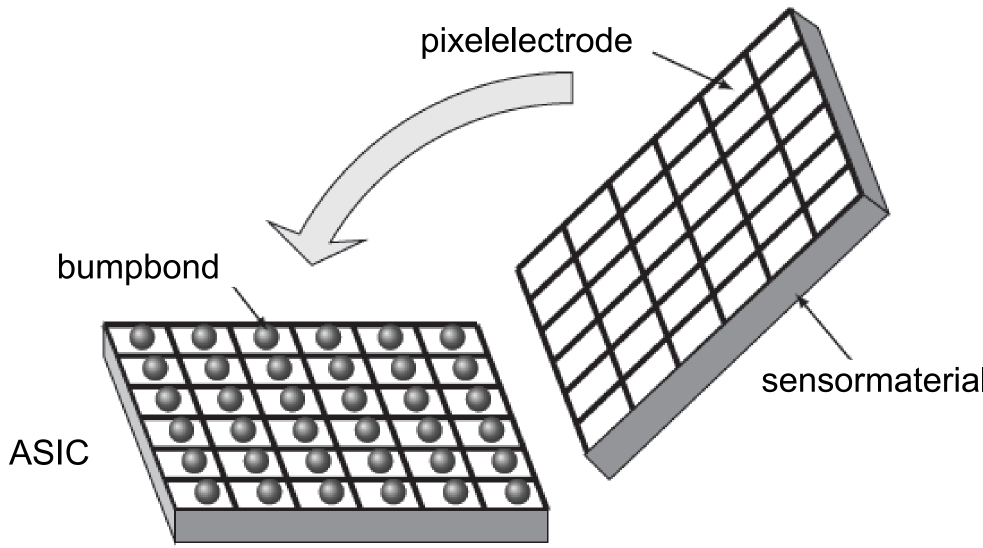
Timepix:
Pixelated Semiconductor X-ray Imaging Detector

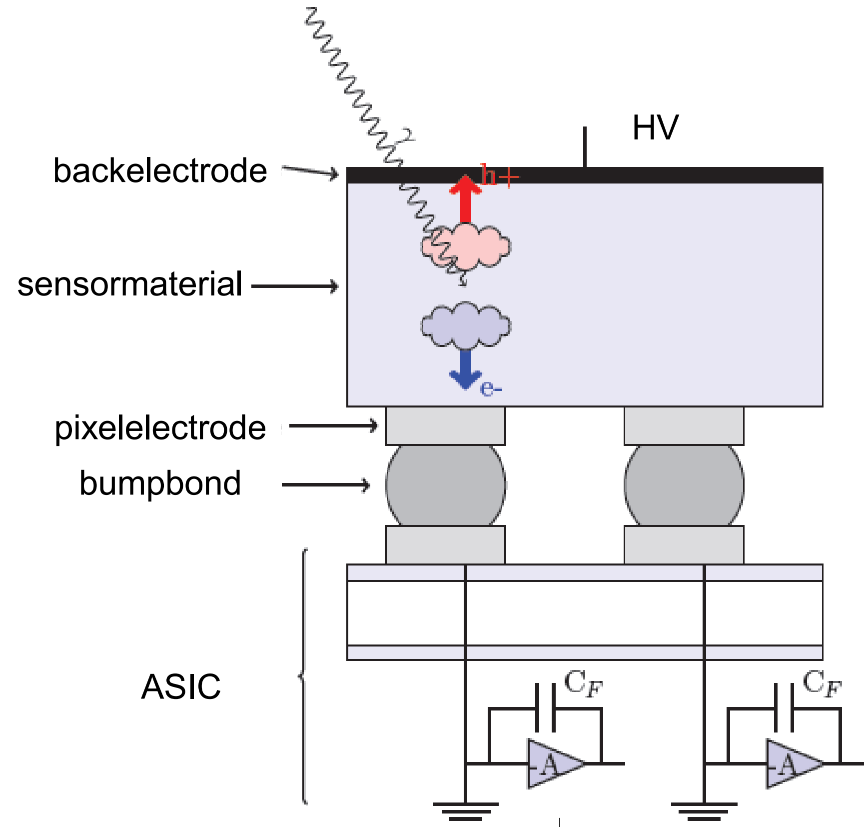
Facts:
256 x 256 pixels per chip
55μm, 110 μm or 220 μm pixelsize
Si or CdTe Sensors
Energy measurement for each pixel
Threshold limit at about 5 keV

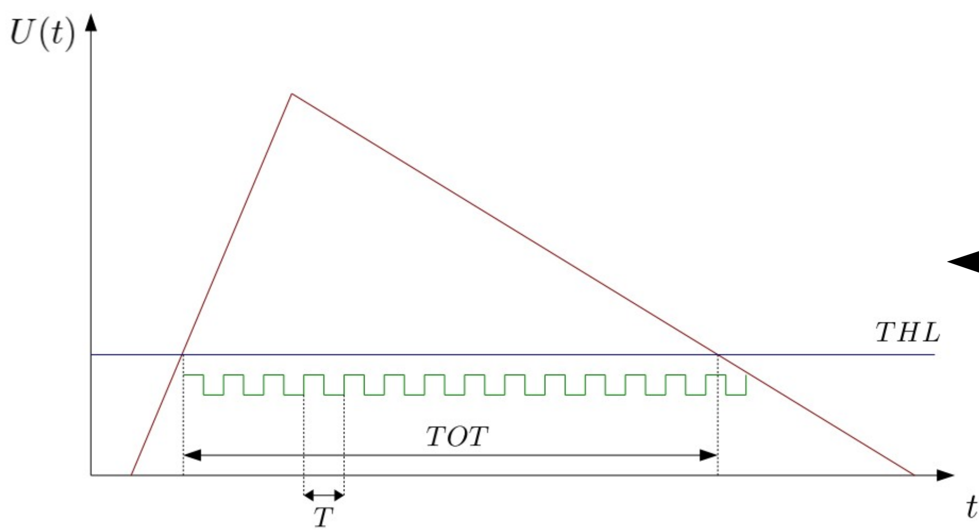
Conceptual:
Cd-116, Te-128 and Te-130 are 0vbb isotopes.



Timepix Functionality

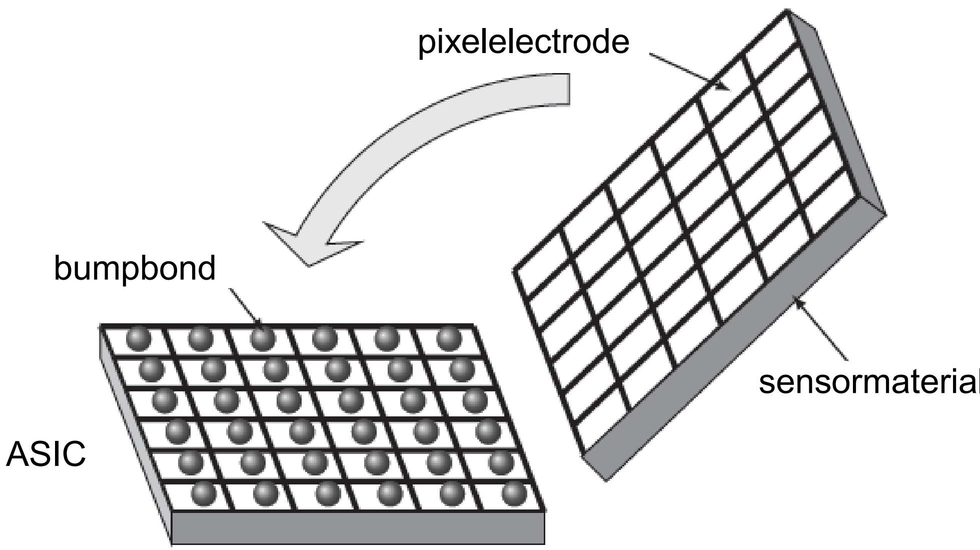


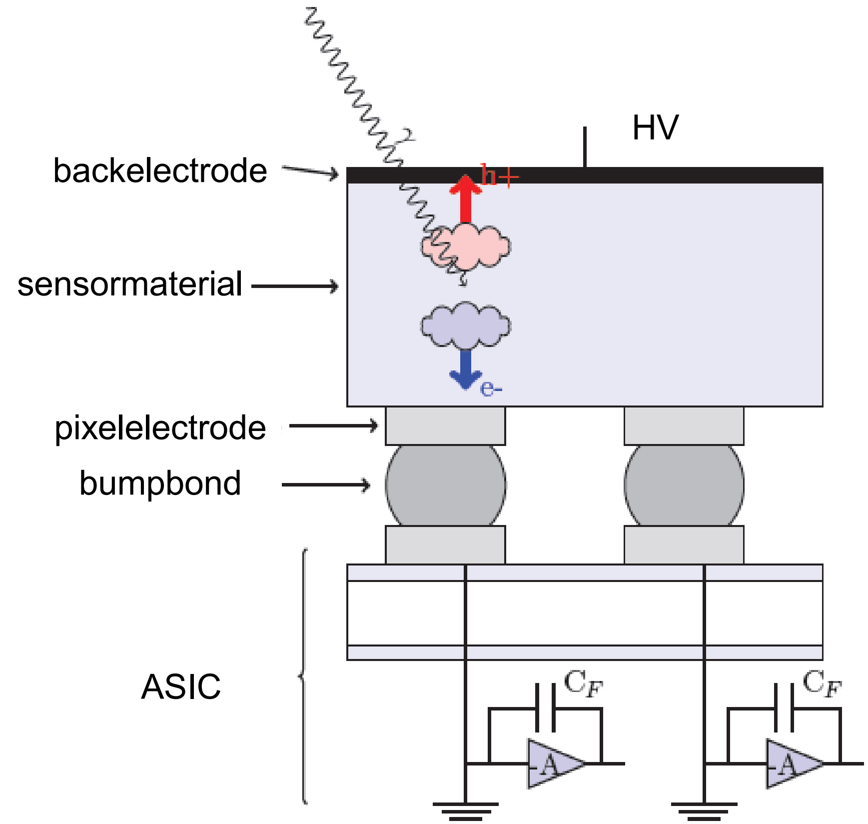




From E. Guni (Dissertation '12)

Timepix Functionality

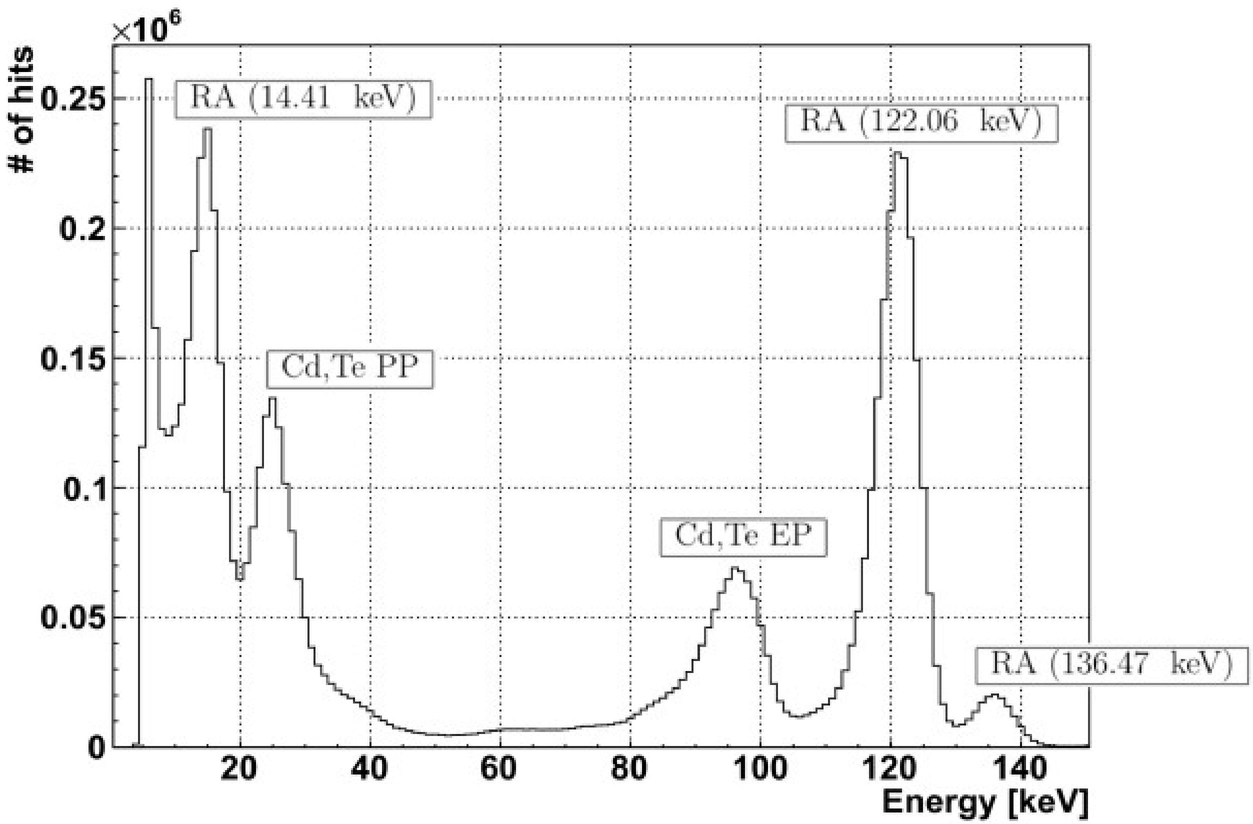




From E. Guni (Dissertation '12)

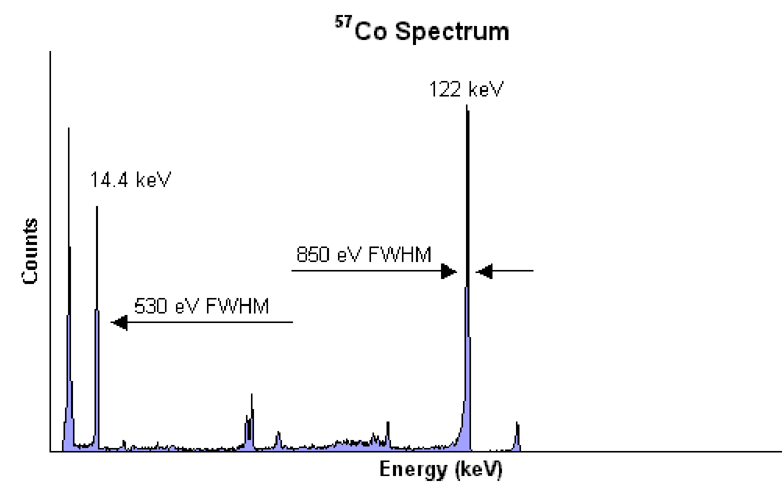
„Intelligent Pixels"
→ **Can be** way faster compared to a CCD.
Readout @ ~ 60 fps; Timing resolution ~ 20ns.

The Spectrum of a Co-57 source

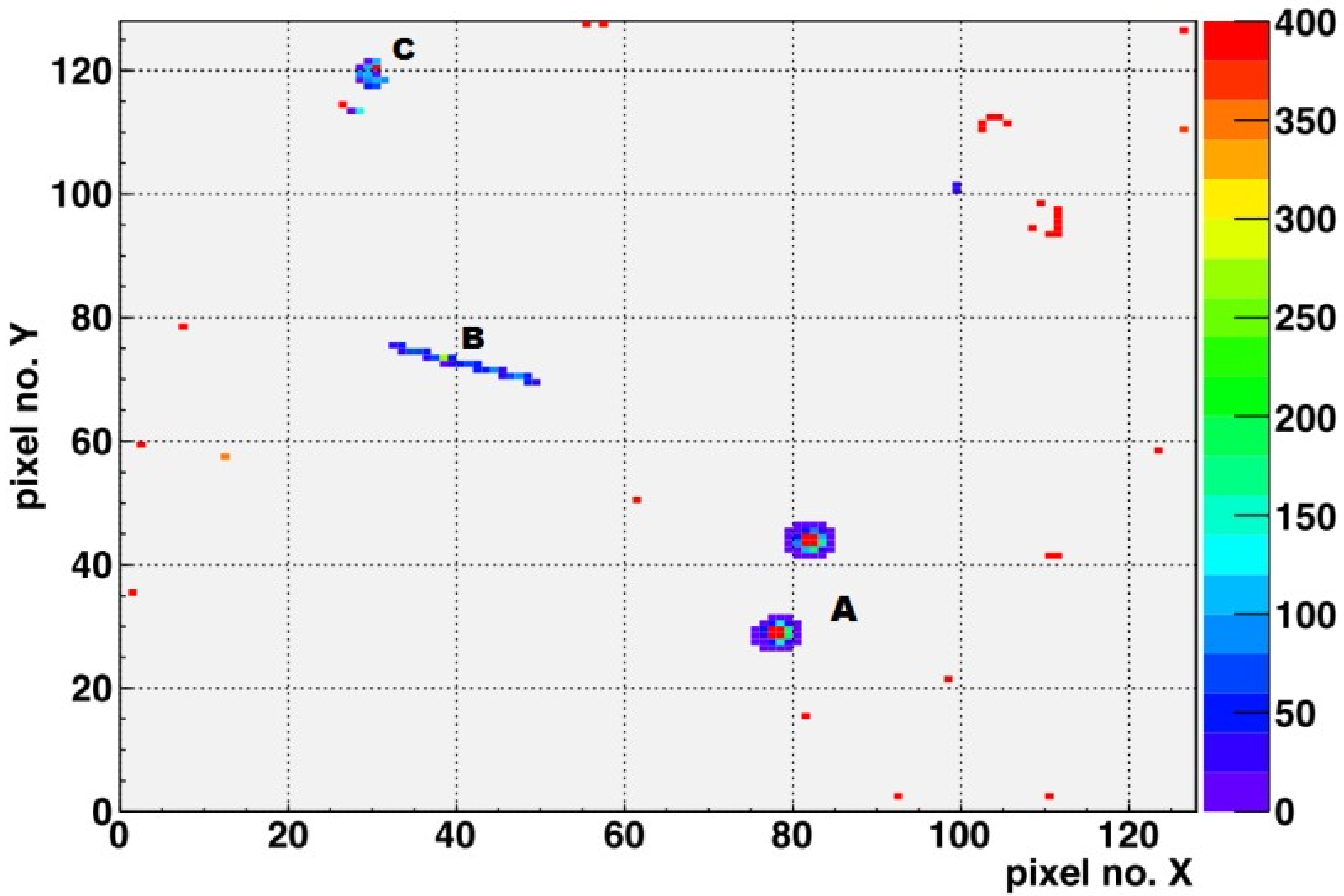


Timepix
FWHM: 6.31 keV

CdZnTe-CPG-Calorimeter
FWHM: 850 eV



Tracks measured by a Timepix detector

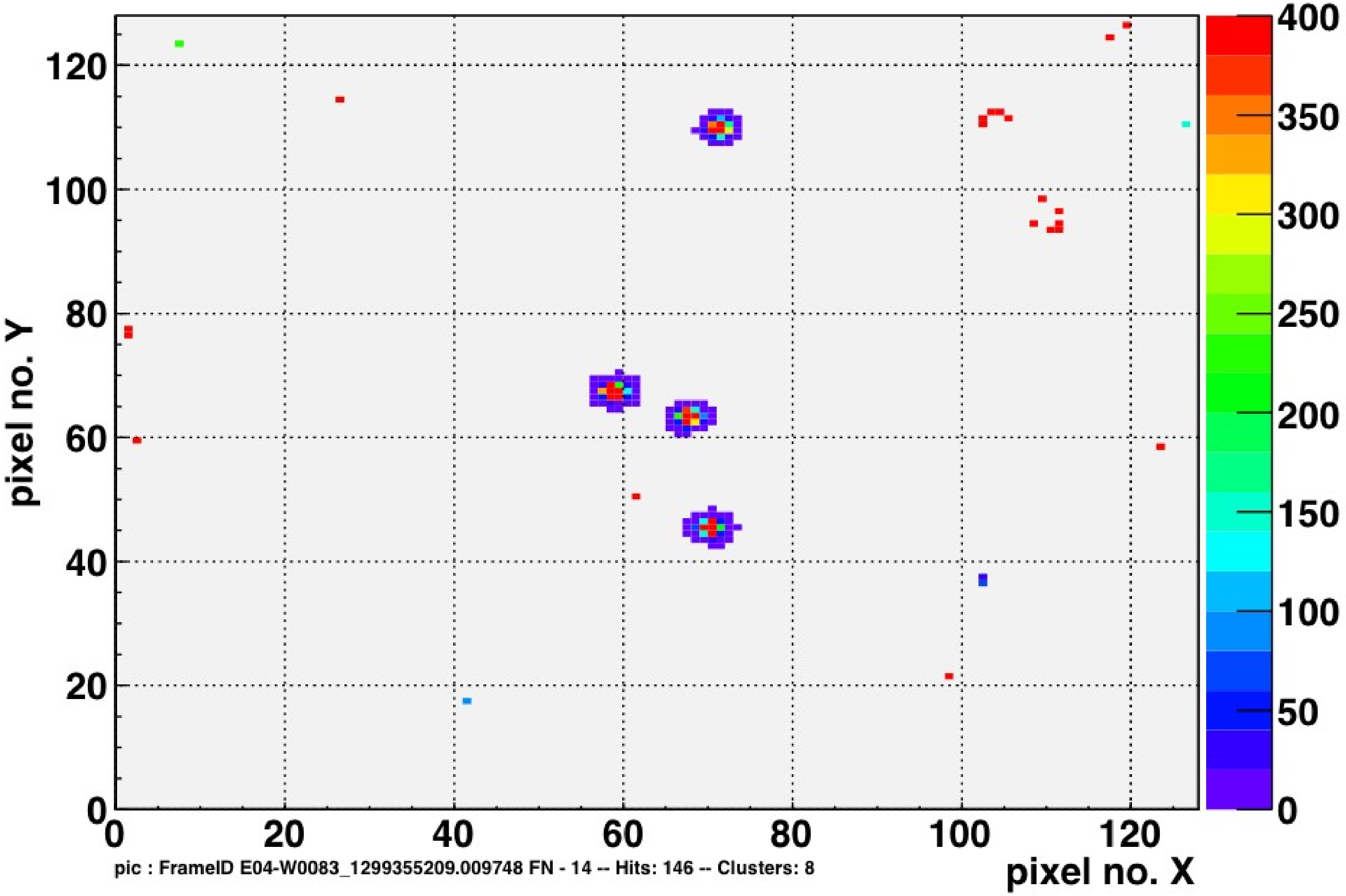


Question: How good can different sorts of background be identified?

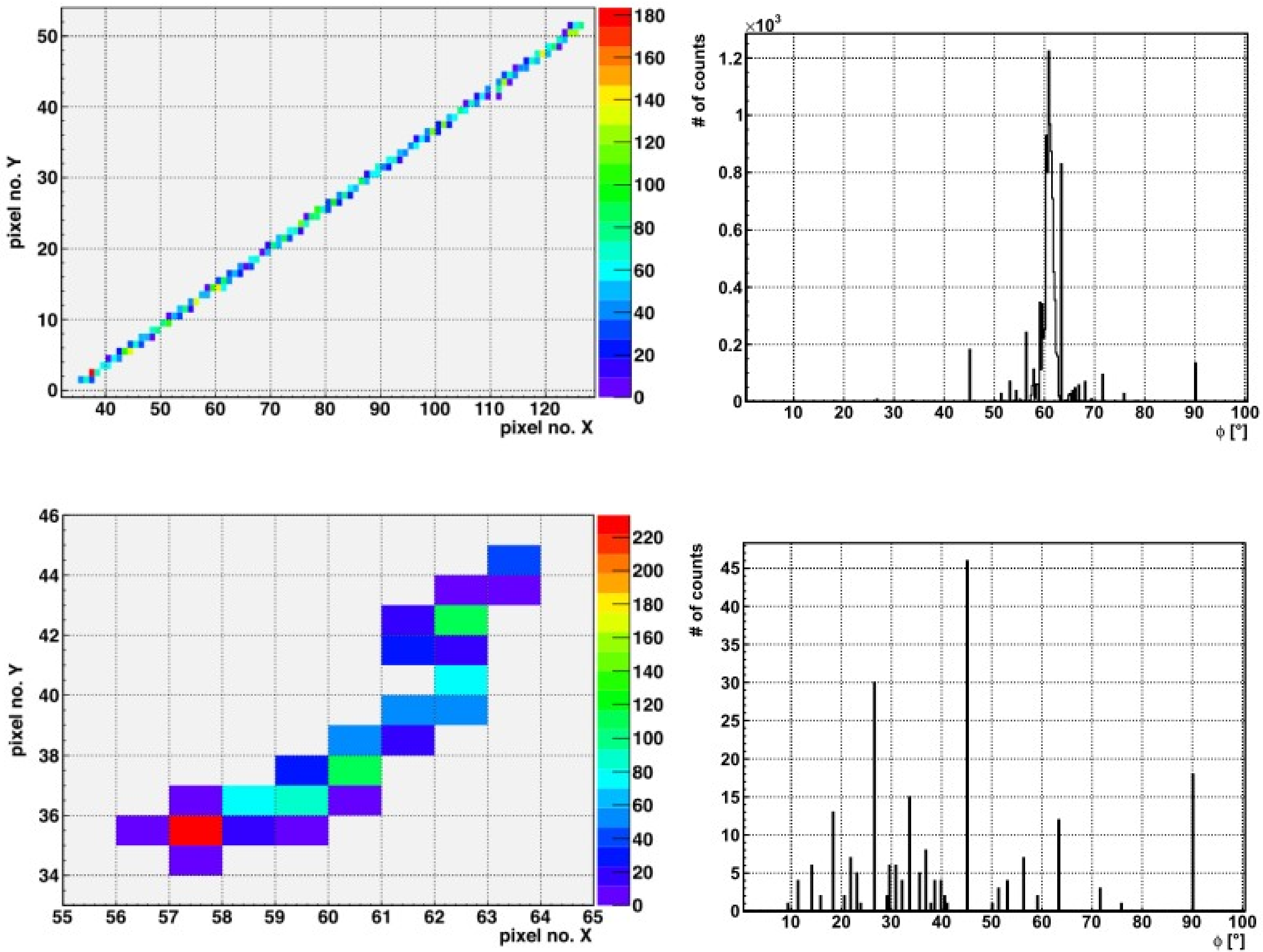
Identification of Alphas

Alphas:

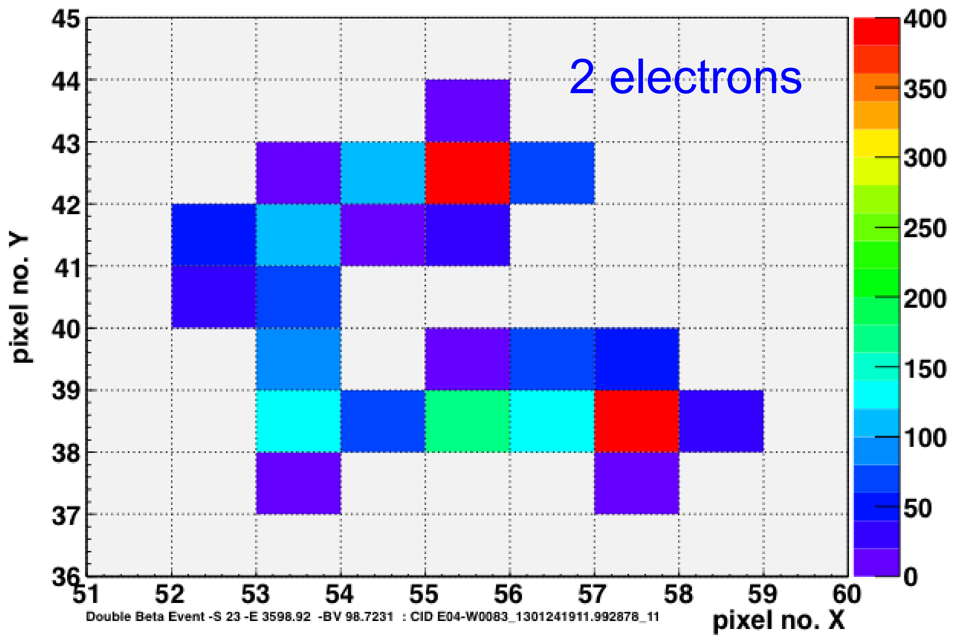
Clusters of 20 – 30 pixels size with the pixels located around the energy deposition maximum.

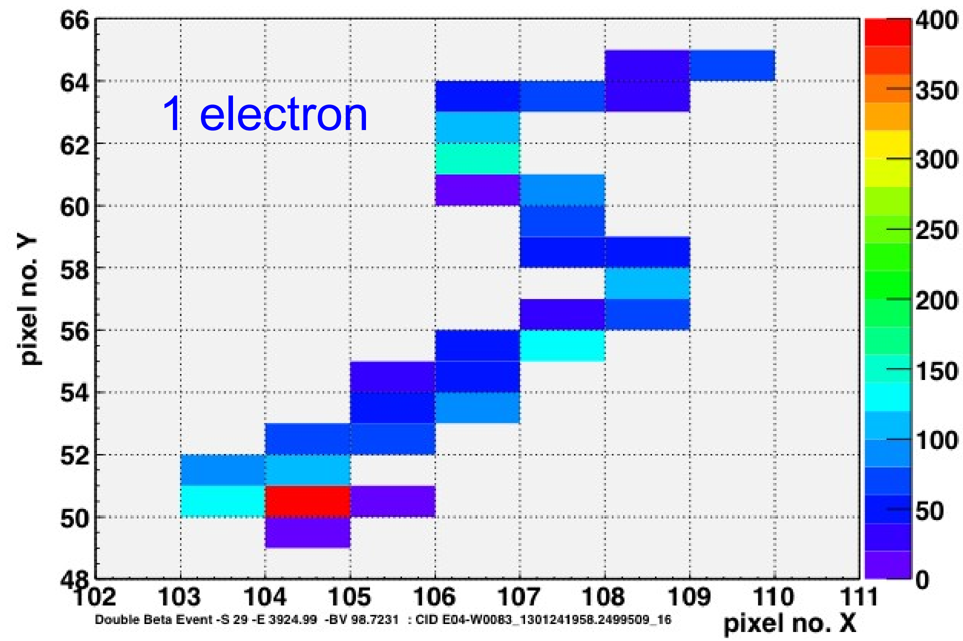


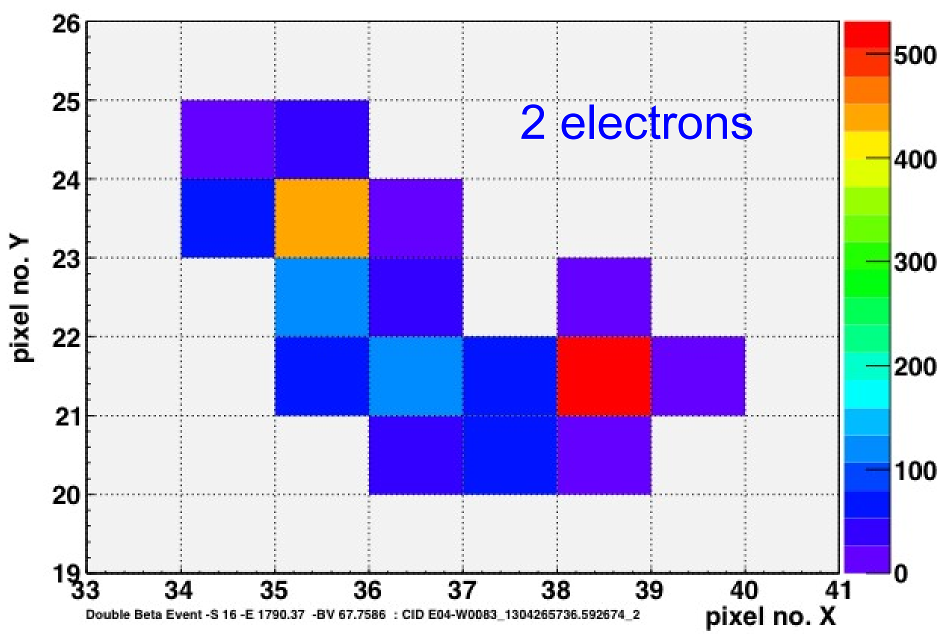
Identification of Muons

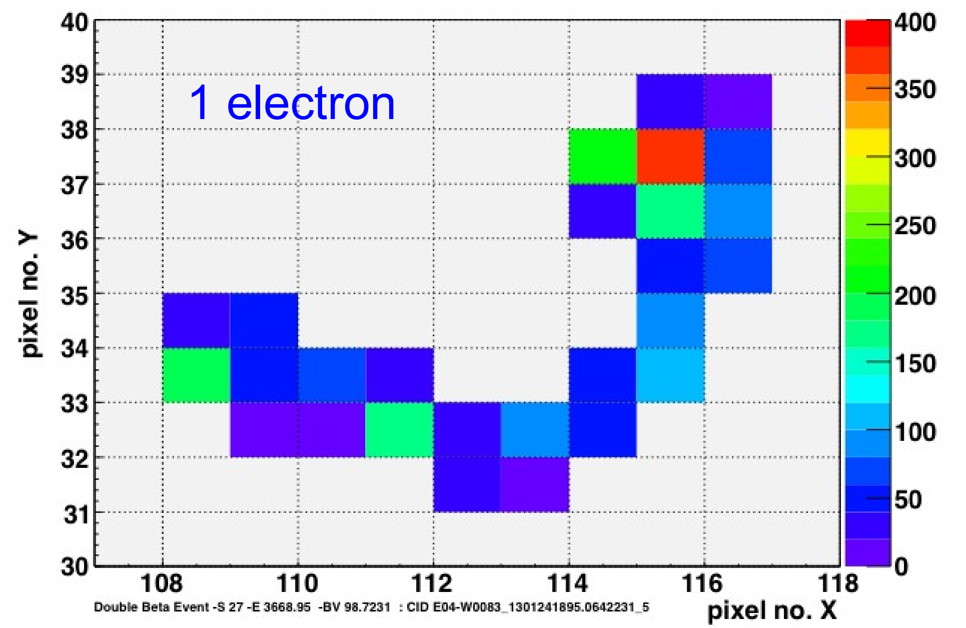


Identification of Single Electron Tracks









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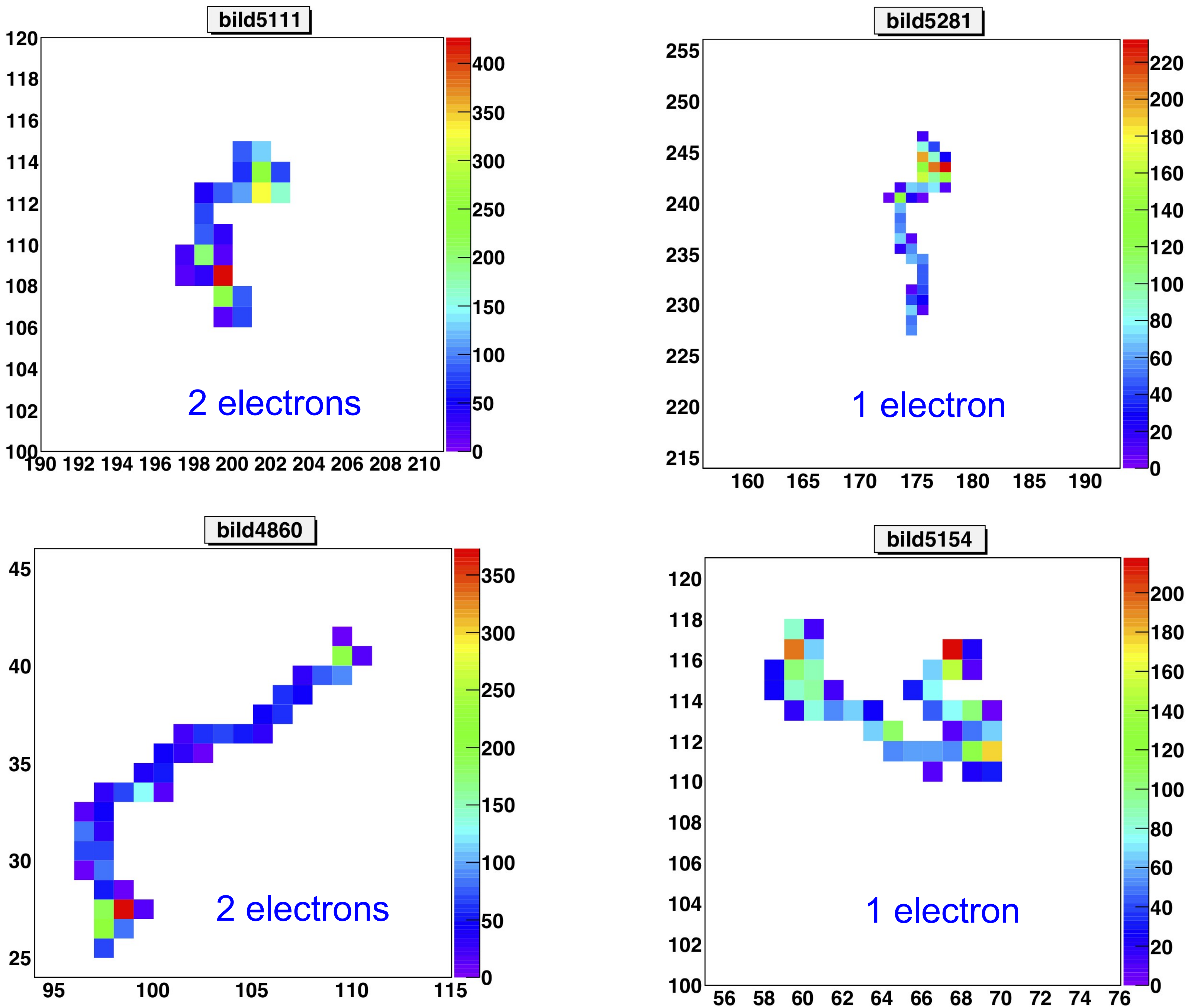
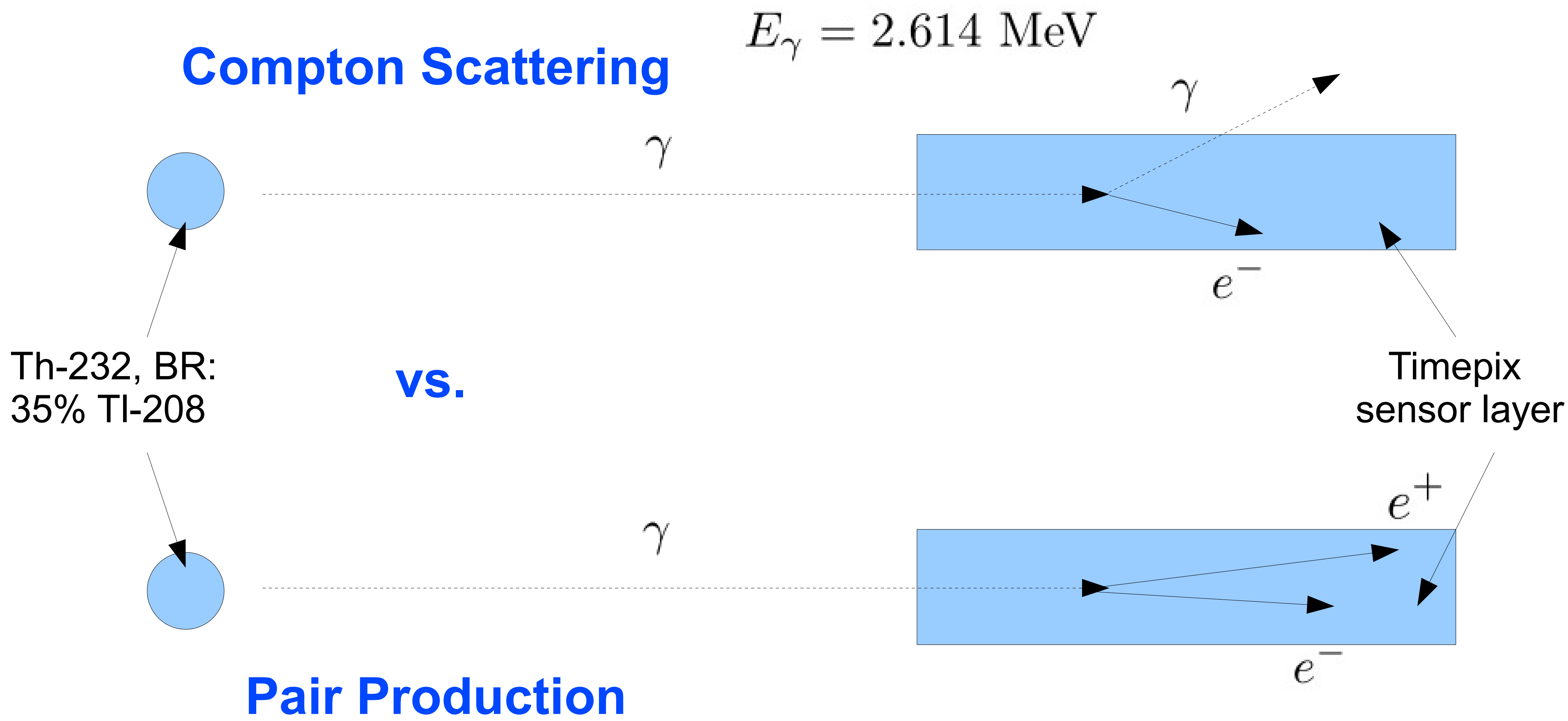


The Main Experiment with Thallium-208

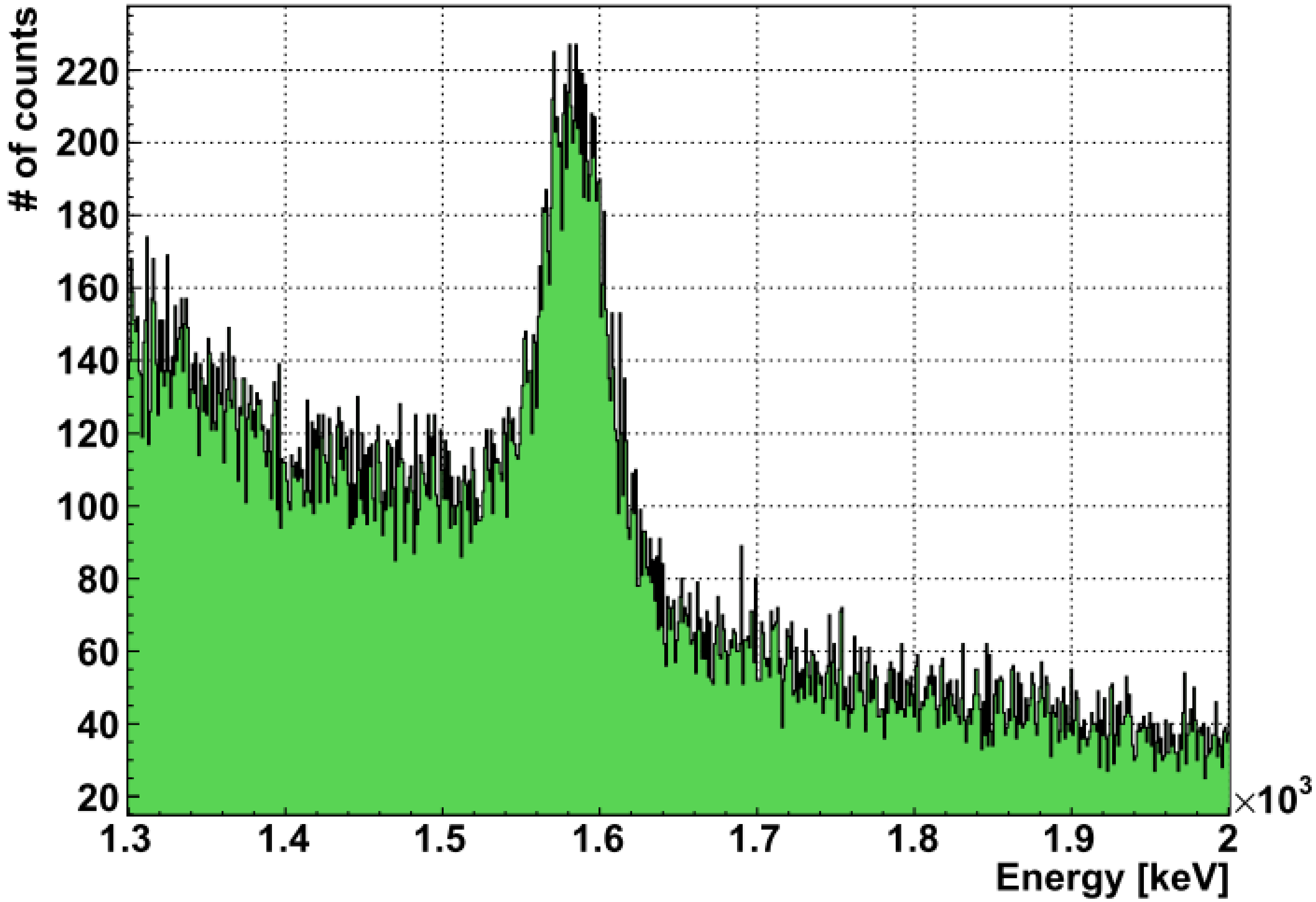
Idea:

Electron-Positron pair production events produce the same tracking signature as 0vbb events.

Use Tl-208 to induce pair production within the sensor.

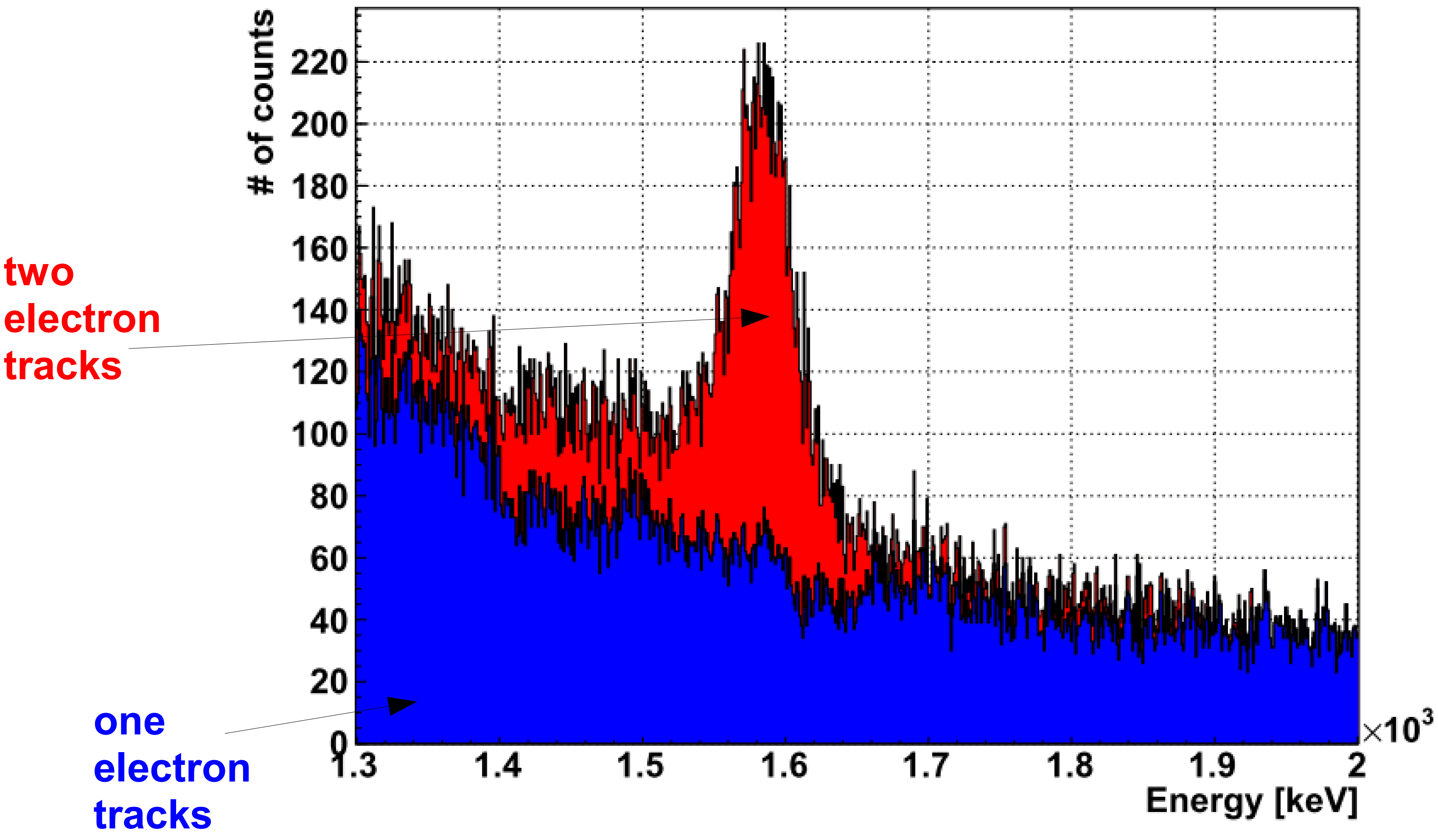


The Event Spectrum in the Region of Interest



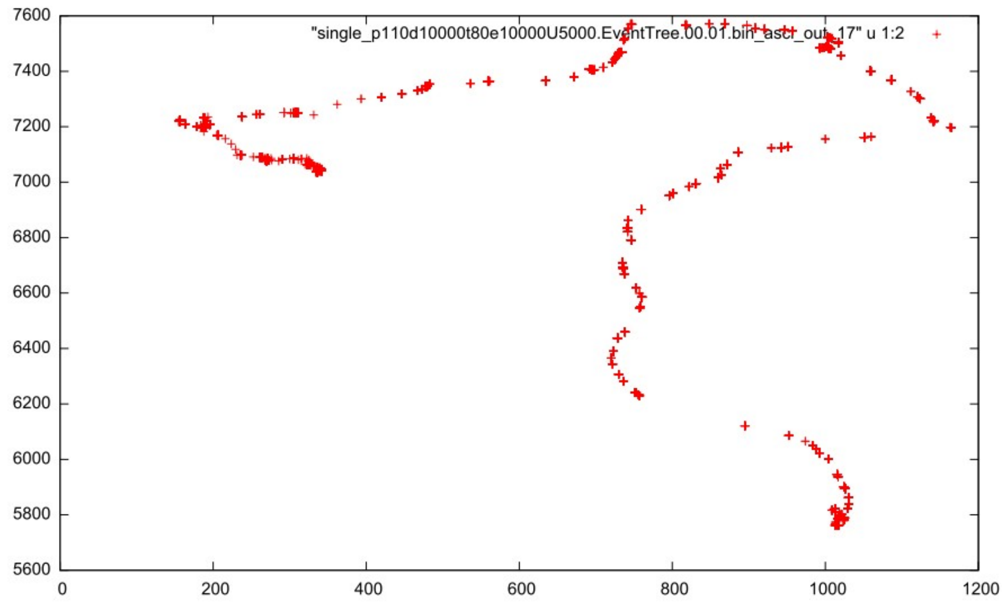
Before event classification with **artificial neural networks**. Resolution: 1.6 %

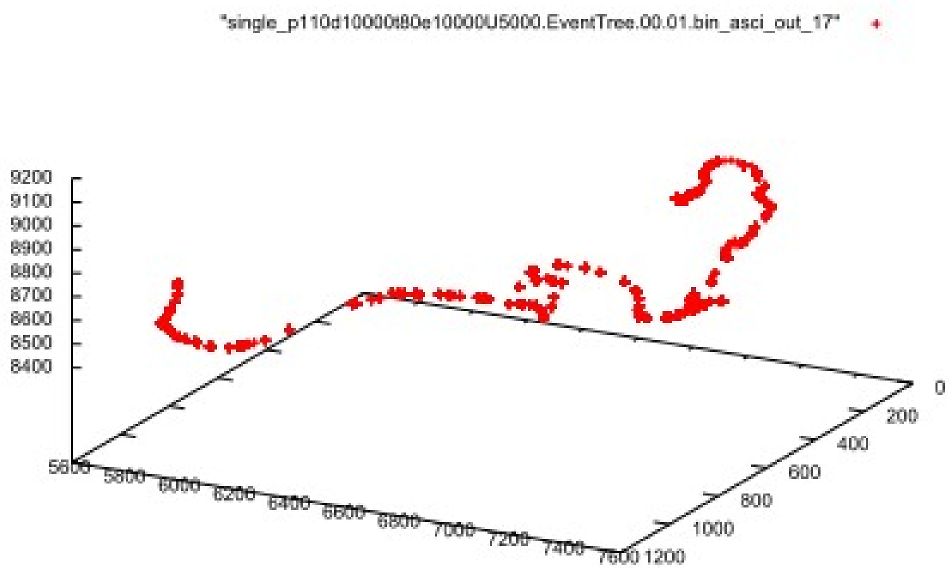
The Reconstructed Spectrum in the Region of Interest



After event classification with **artificial neural networks** and taking into account misclassification errors.

An Outlook on 3D Tracks





What do we have so far?

Tracking is a valuable tool for background rejection, especially for alphas and muons.

Electron tracking can also increase the sensitivity significantly.

3D tracking is desirable, escpecially for fiducializing.

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3D tracking is desirable, escpecially for fiducializing.

BUT

Semiconductor detectors are difficult to scale up..

III. A New Detector Concept Based on Solid Xenon

In Collaboration with the
Fermi National Accelator Laboratory
Jonghee Yoo

Fermilab

Why Xenon?

Inert Gas
→ Easy to enrich (Xe-136) and scale up in mass
(NEXT, EXO target mass 1t of Xenon)

No Beta emitting isotopes.

Q-value at about 2.5 MeV.

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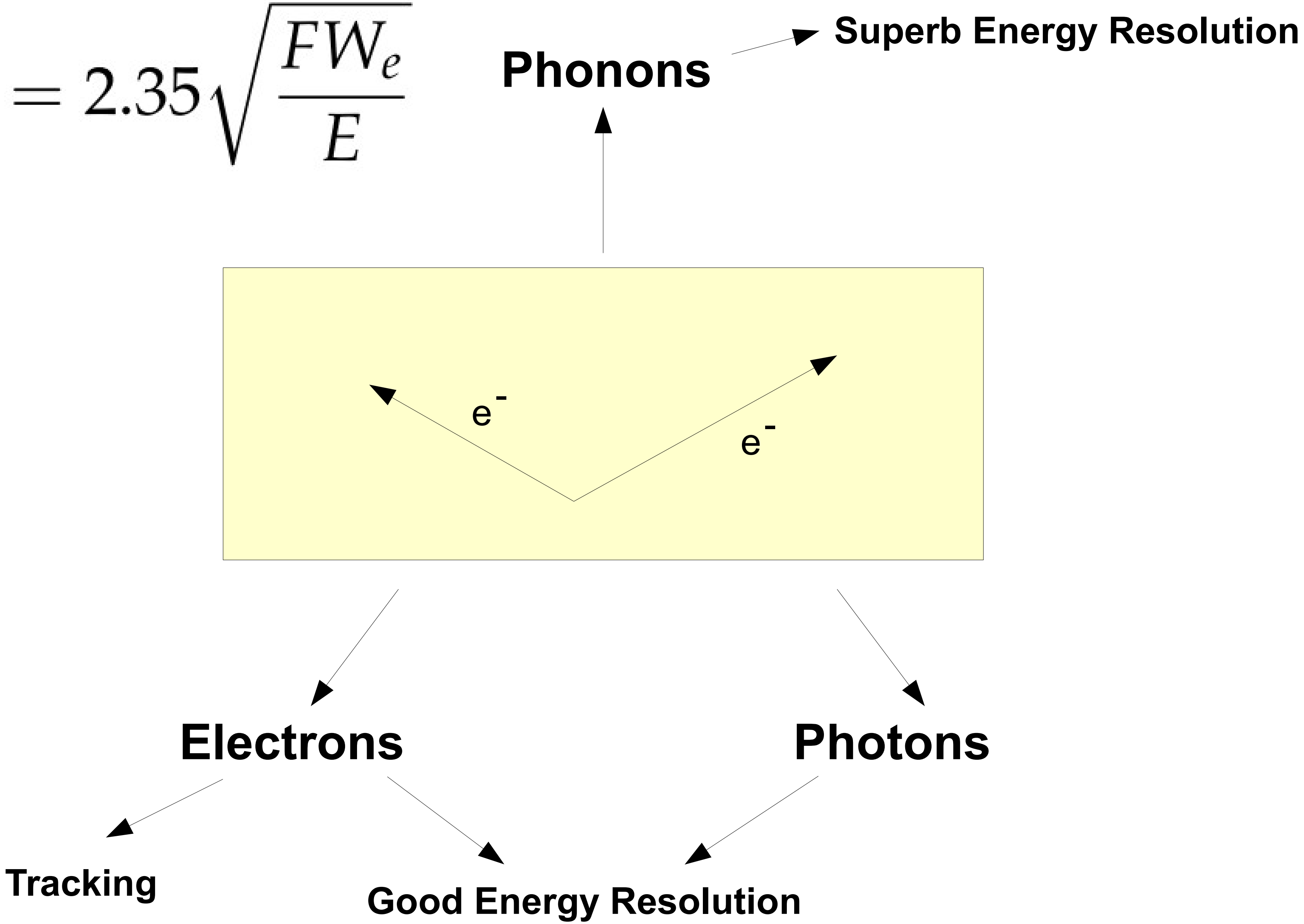
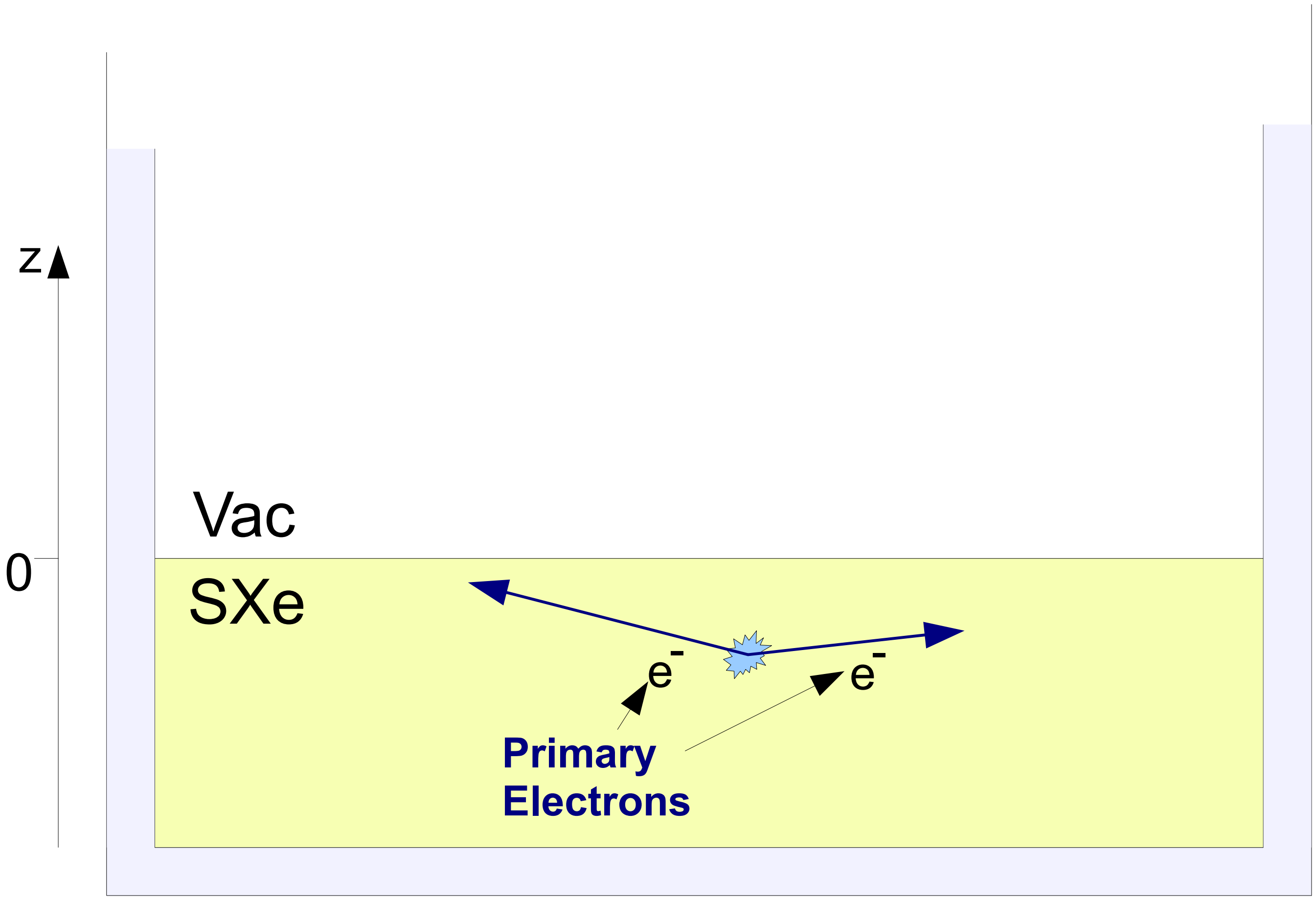
Why Solid?

Three Signals in Solid Xenon

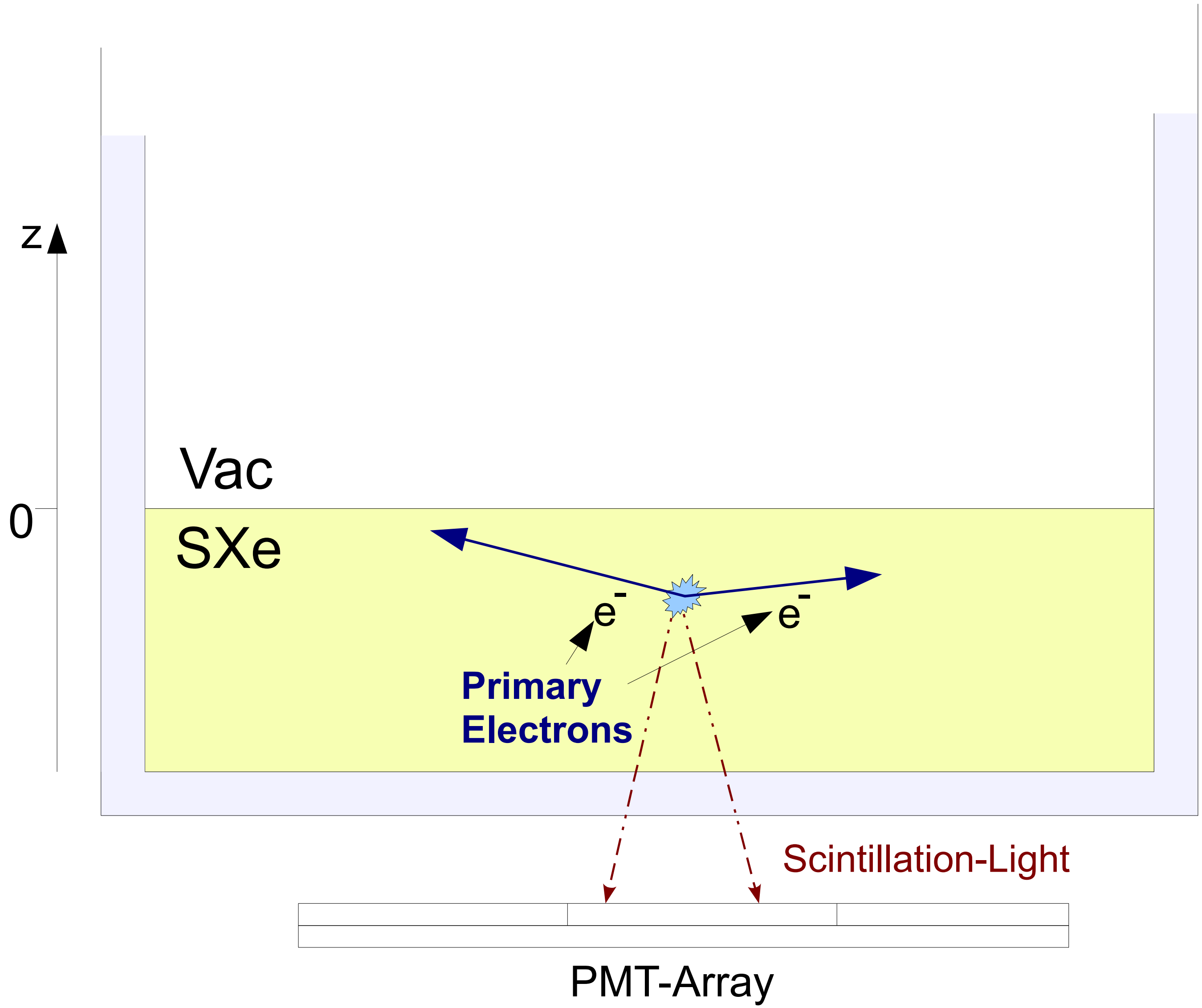
$$R = 2.35\sqrt{\frac{FW_e}{E}}$$



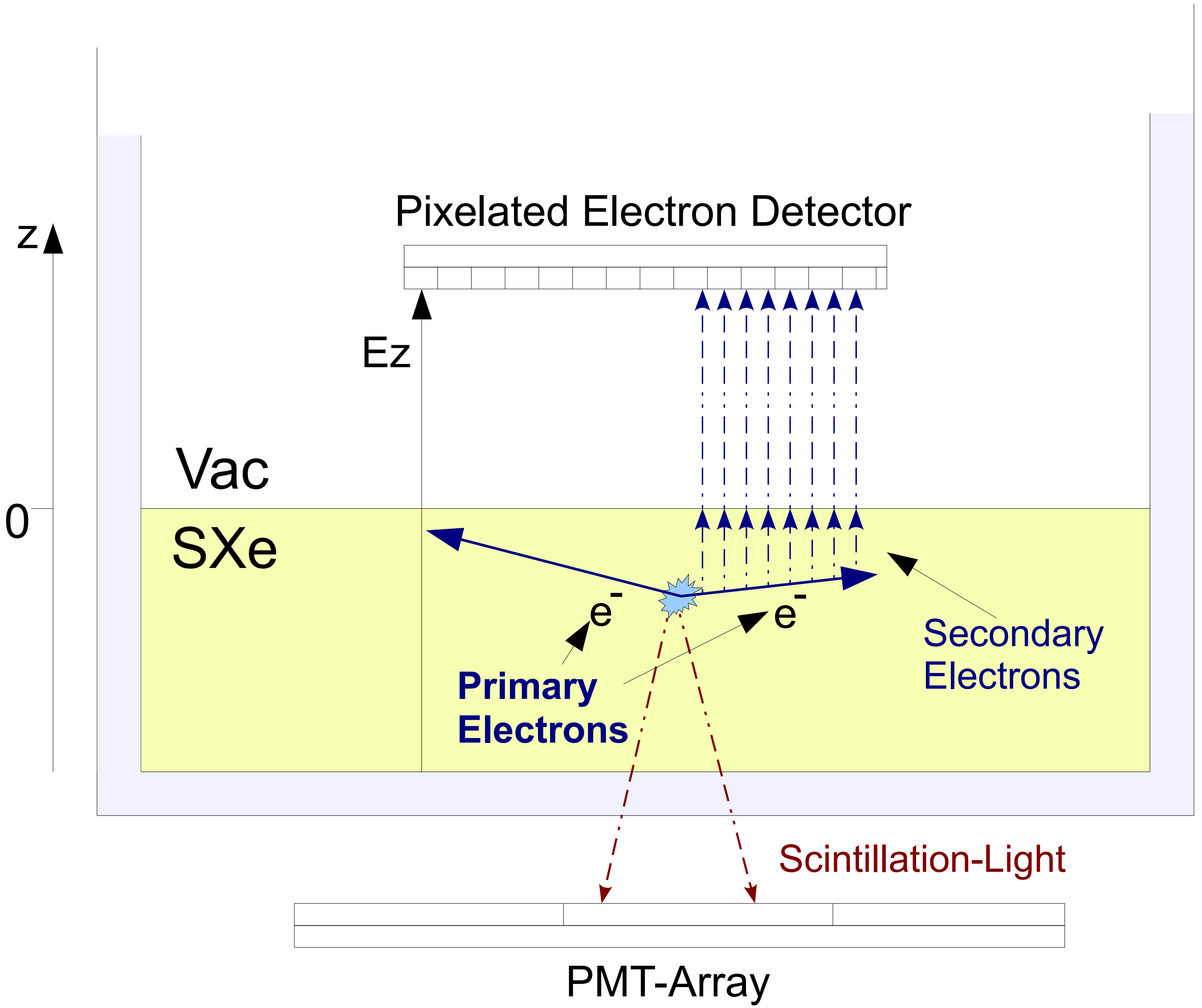
Electron and Scintilliation Signal Readout



Electron and Scintilliation Signal Readout



Electron and Scintilliation Signal Readout



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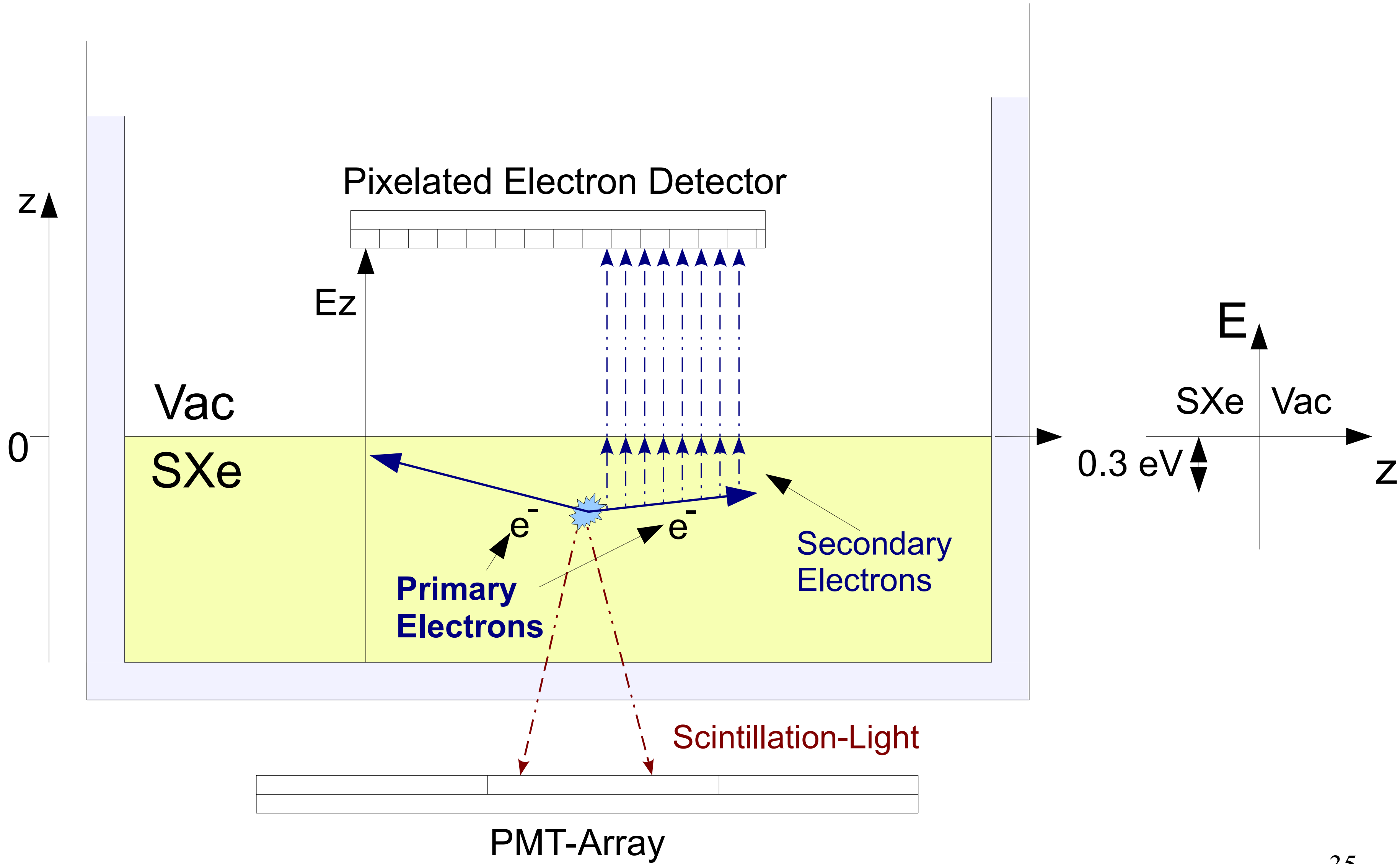

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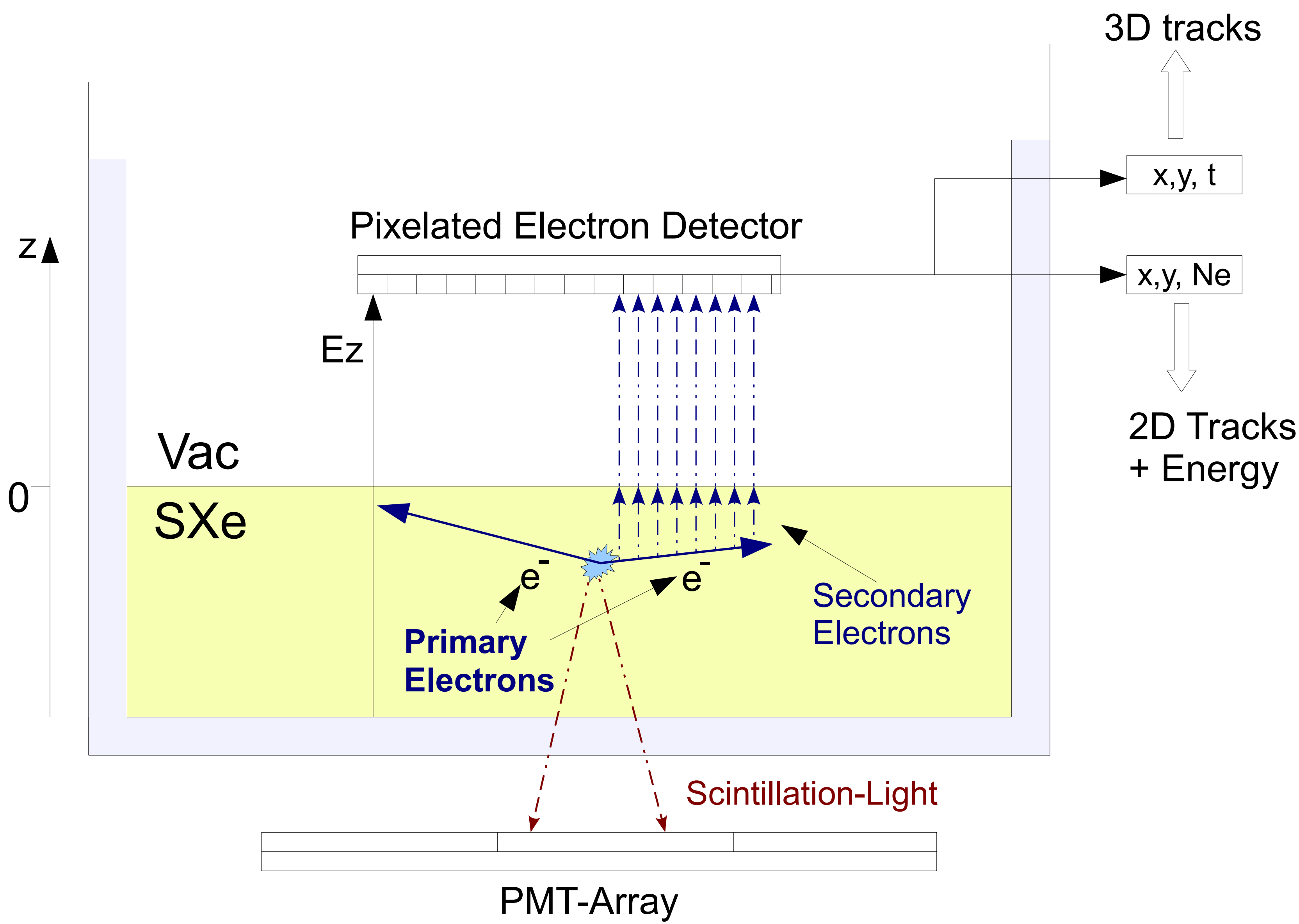
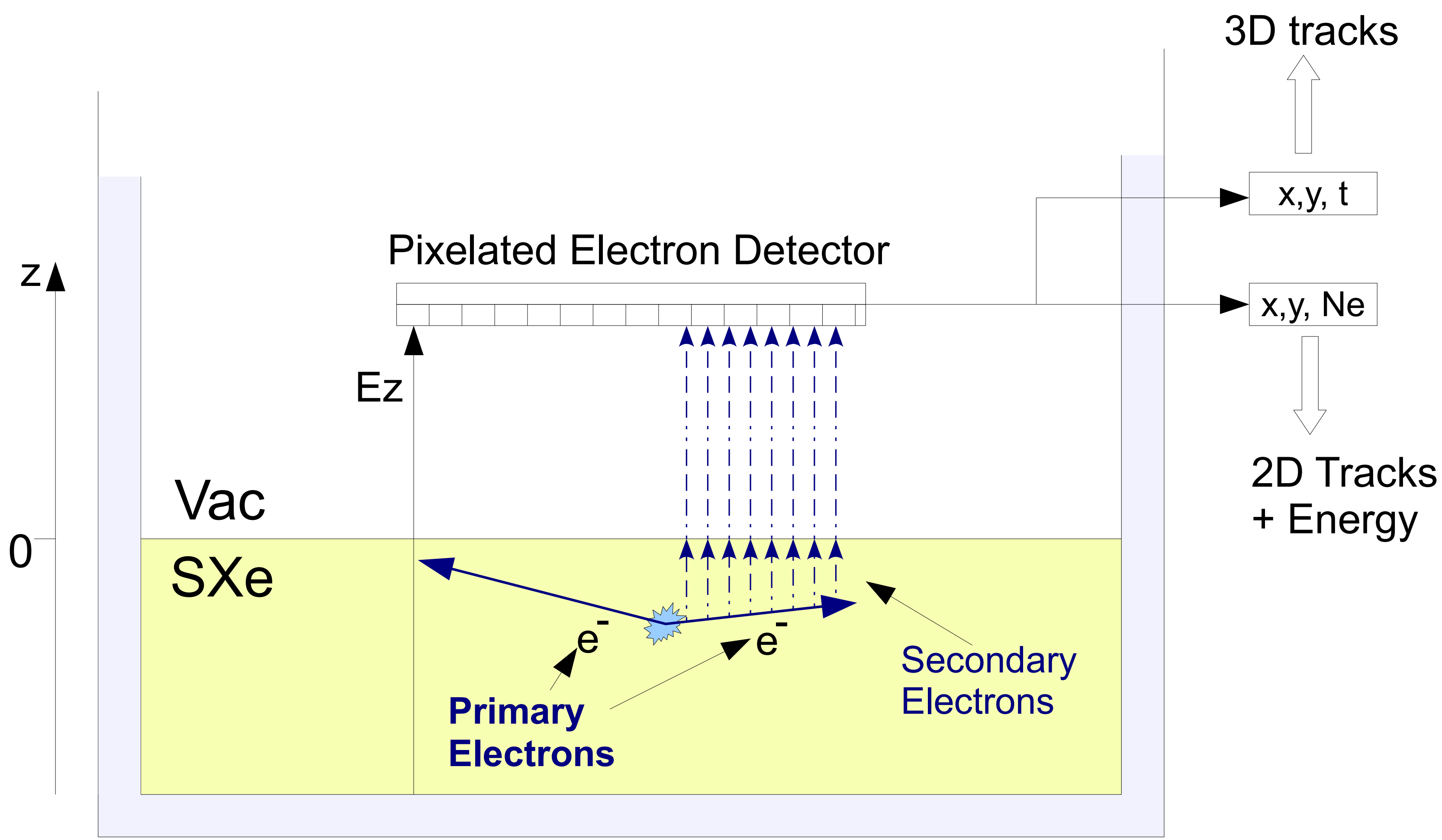


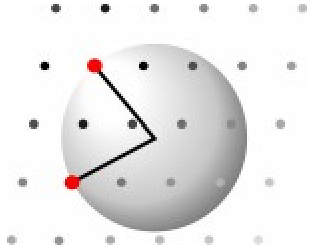
Electron and Scintilliation Signal Readout



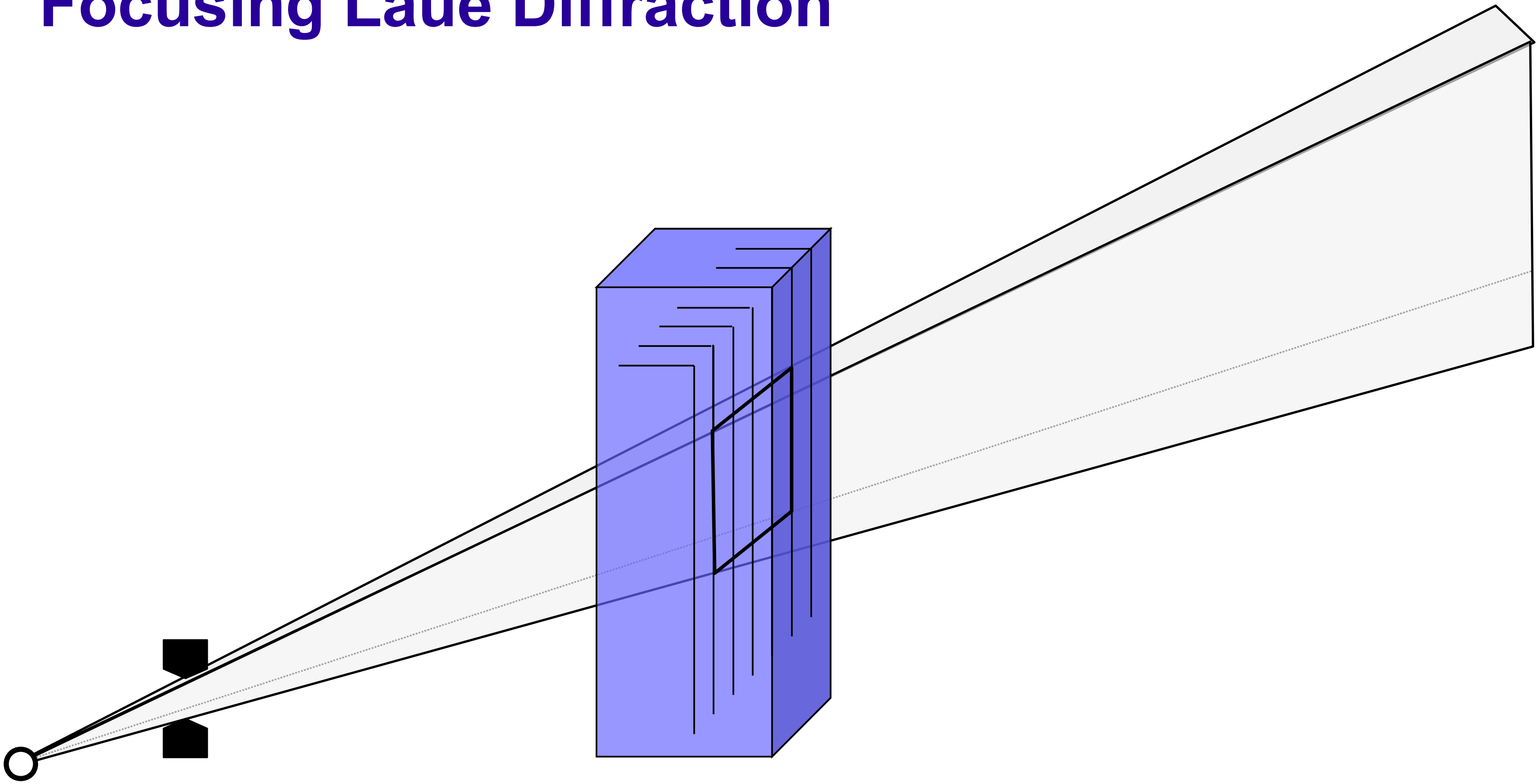
The signal quality could be highly increased by the quality of the xenon crystal → **Crystollography**

IV. Crystallographic Measurements on SXe

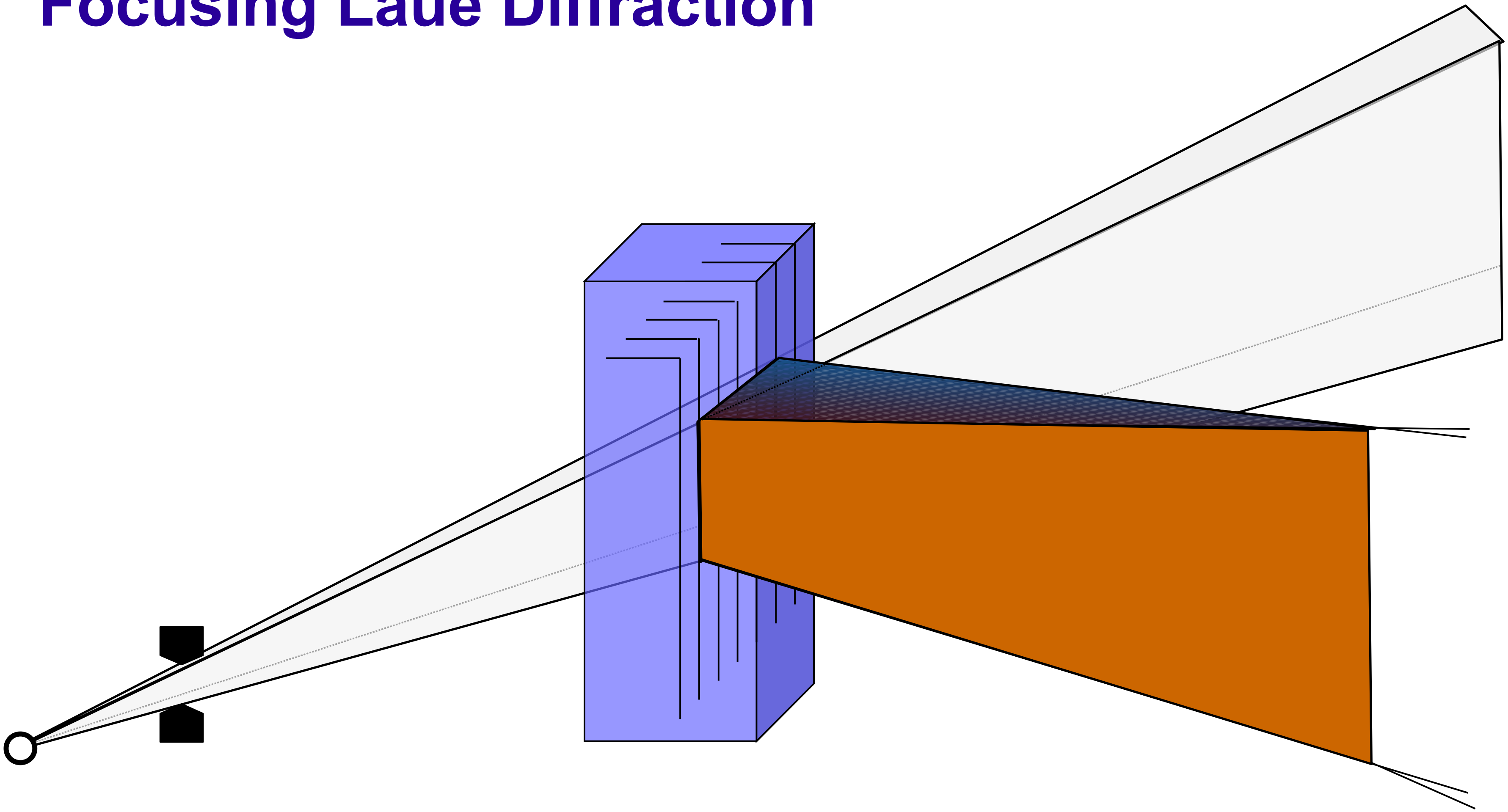
In Collaboration with the
Crystalloraphy Institute Erlangen
M. Weißer, A. Magerl



Focusing Laue Diffraction



Focusing Laue Diffraction

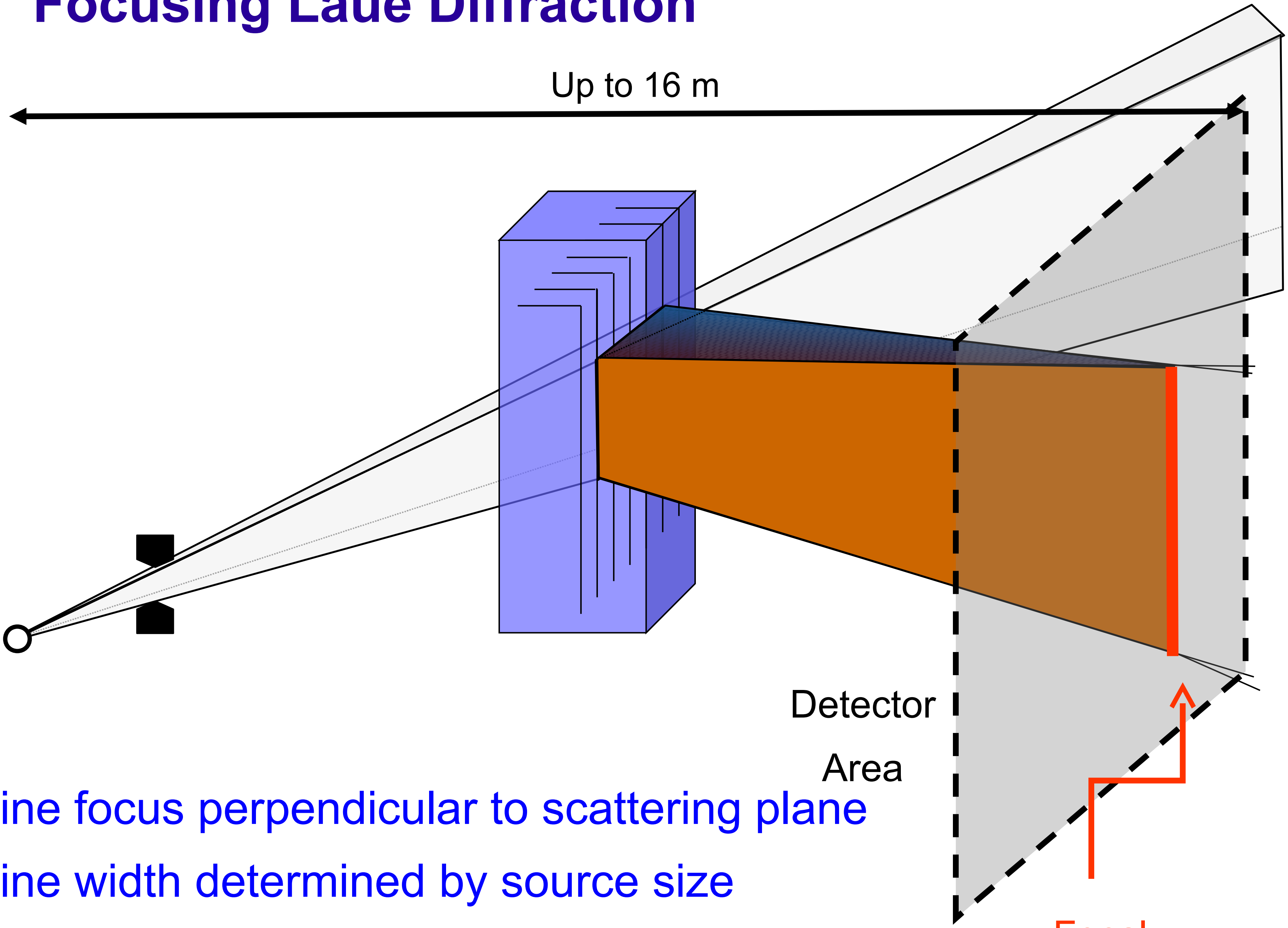


Line focus perpendicular to scattering plane

Line width determined by source size

Vertical spatial resolution

Focusing Laue Diffraction

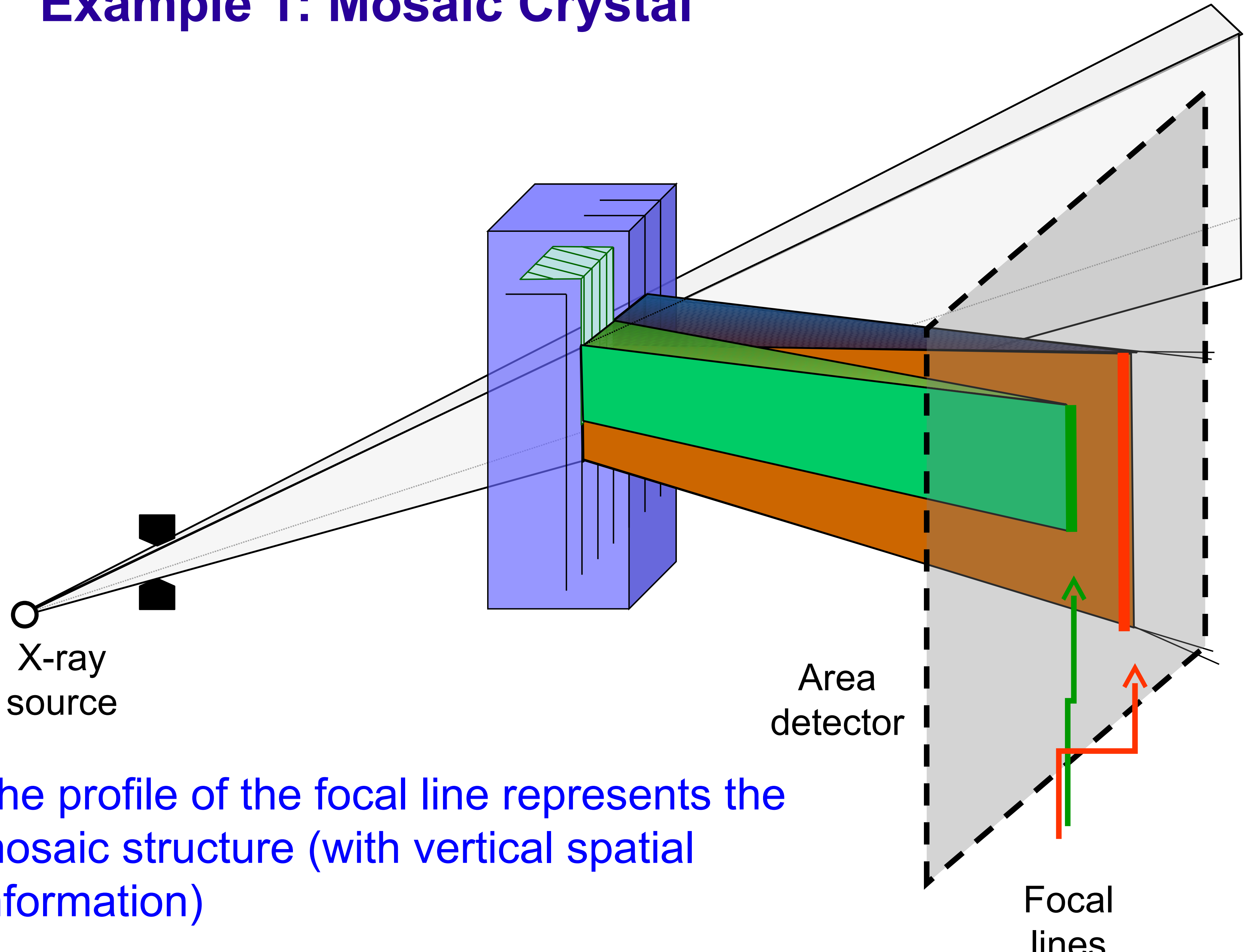


Line focus perpendicular to scattering plane

Line width determined by source size

Vertical spatial resolution

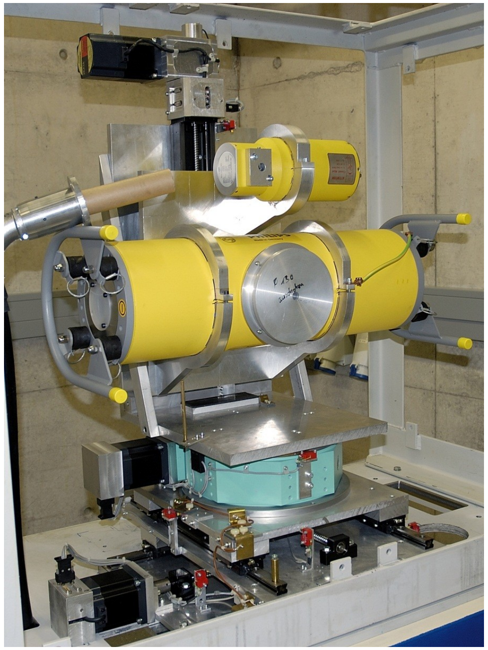
Example 1: Mosaic Crystal

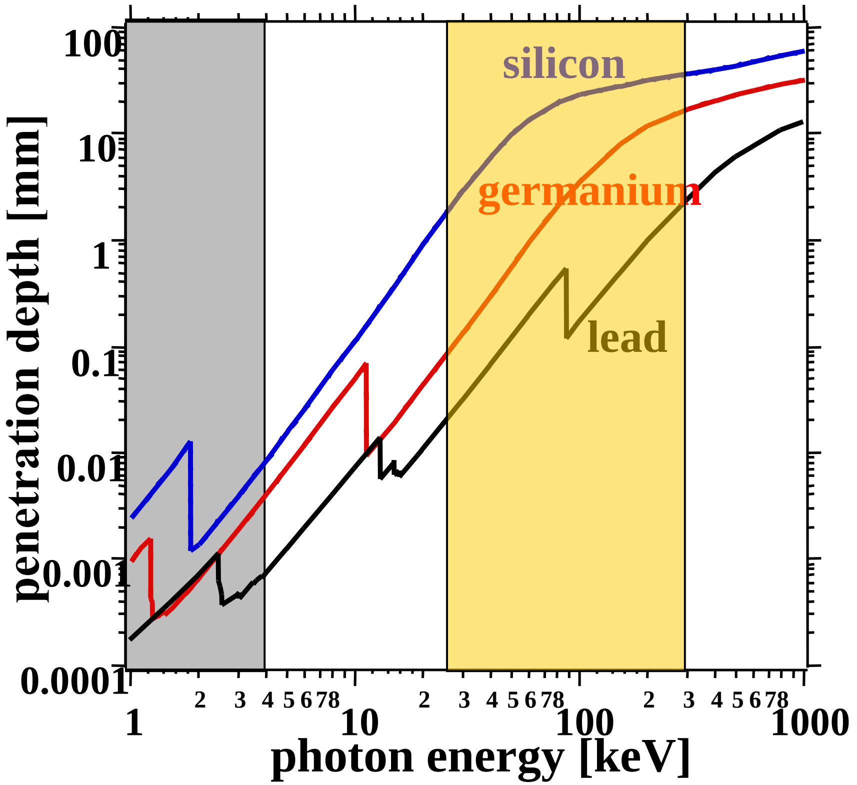


The profile of the focal line represents the mosaic structure (with vertical spatial information)

Resolution ~0.005°

HEXBay Lab

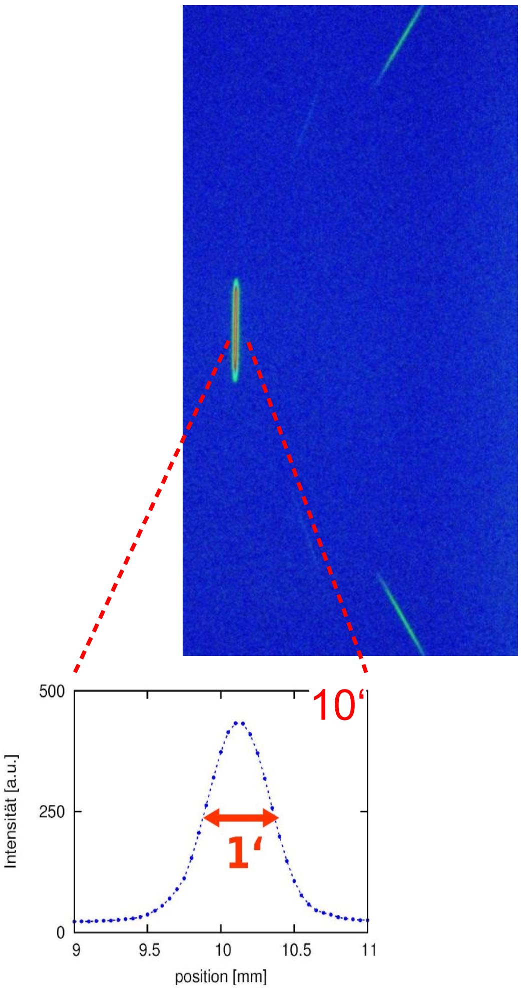




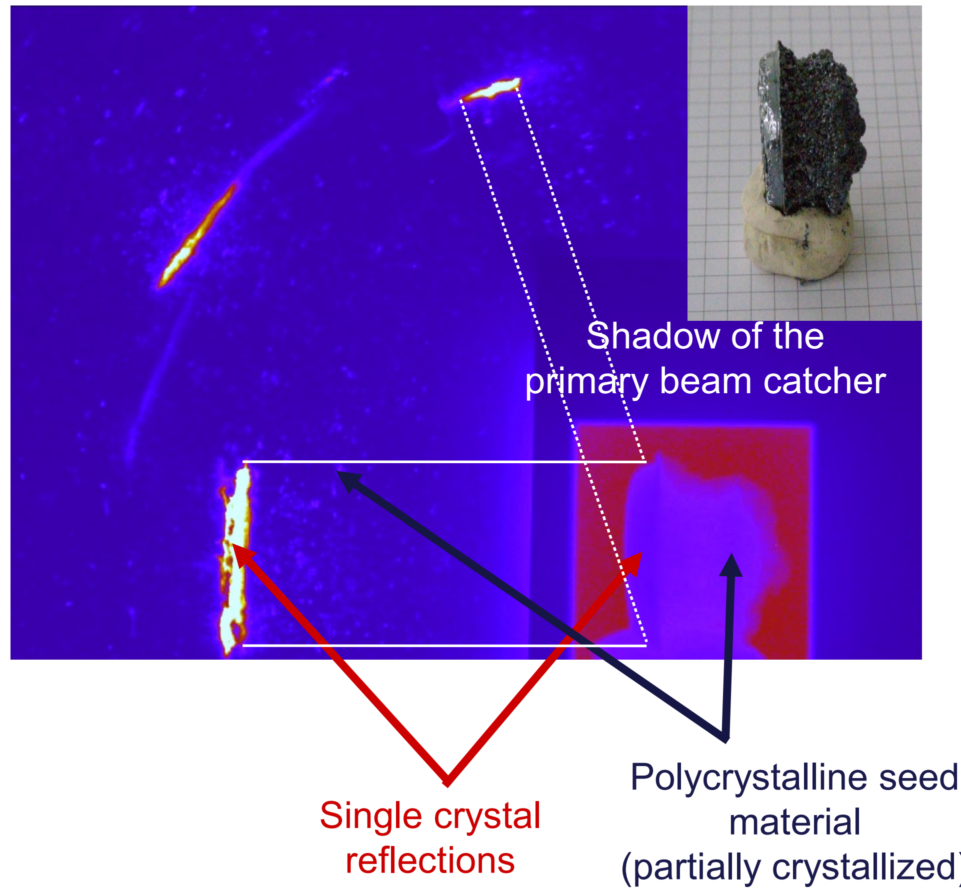
Instruments can be changed without loosing alignment of the beam-path

Example 2: Silicon and SiGe Crystals

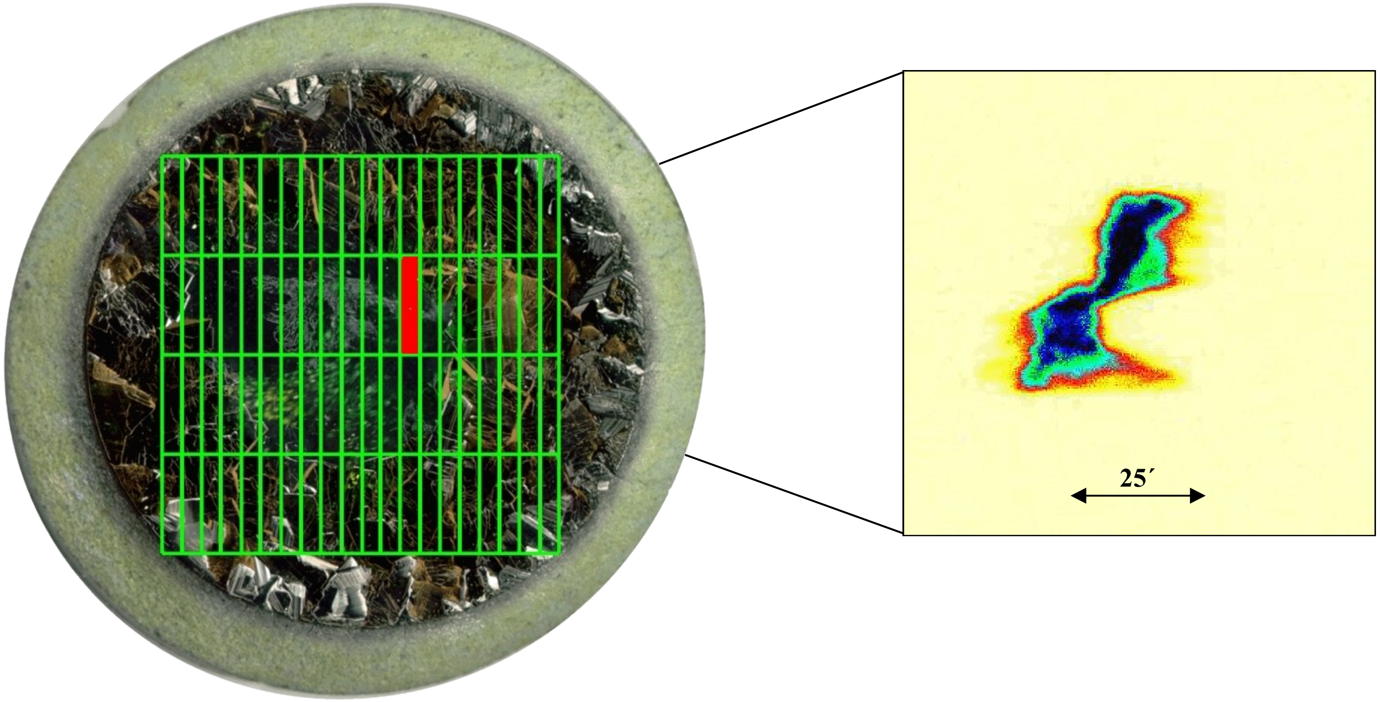
Ideal Si
CCD-detail: 20 x 10 cm²



SiGe by gas phase transport reaction
CCD-detail: 20 x 30 cm²

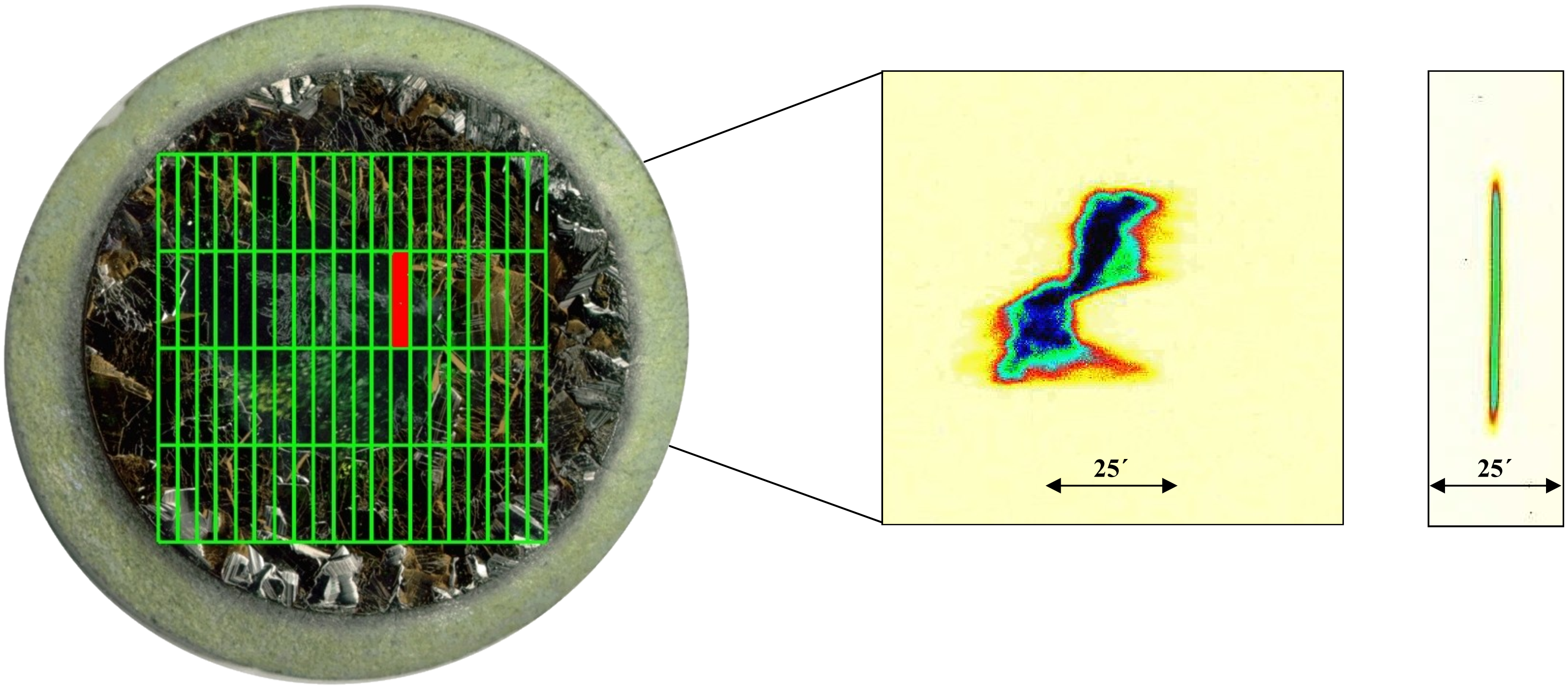


Example 3: 6H SiC grown in inhomogeneous temperature field



- exposure time 10min
- single mesh size 2 x 12 mm2
- Overall diameter 70mm
- Thickness about 20mm

Example 3: 6H SiC grown in inhomogeneous temperature field



- exposure time 10min
- single mesh size 2 x 12 mm2

- Overall diameter 70mm
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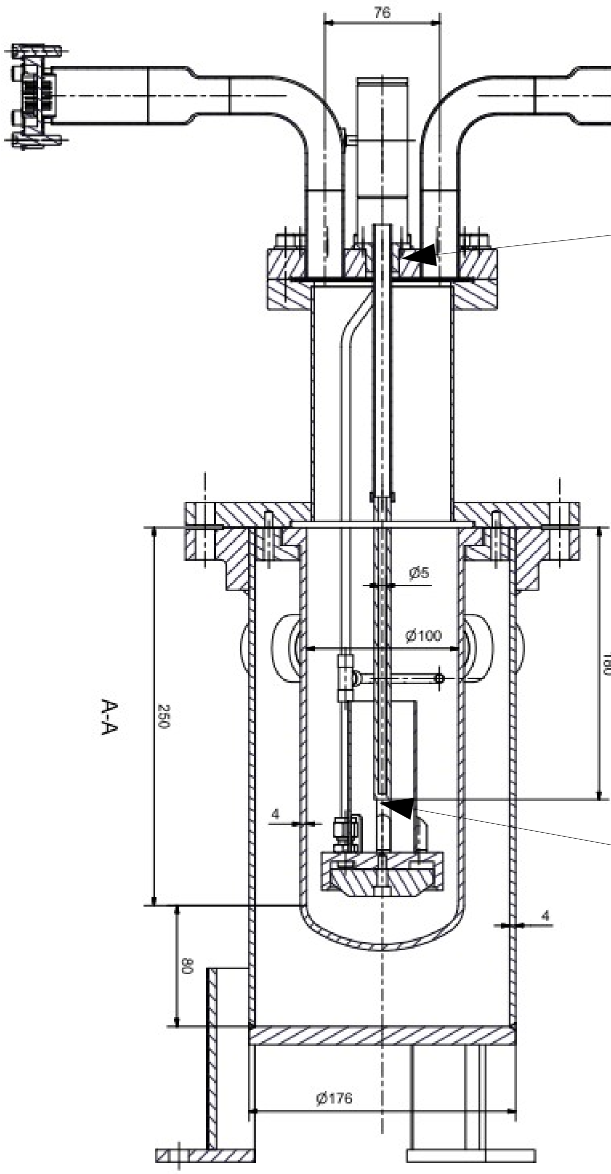
Cryostat for Crystallography



Inner Vessel designed to be removable, in order to test different seed crystals

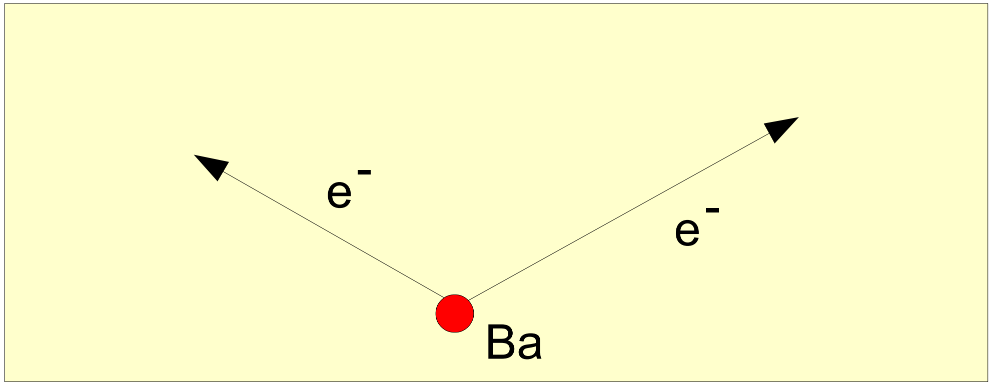
Easielly available crystals could be perfect for the job:
BaF
KCl

Small SXe Crystall, Ø ~ 1.0 cm

V. An Outlook on Barium Tagging

Barium Tagging

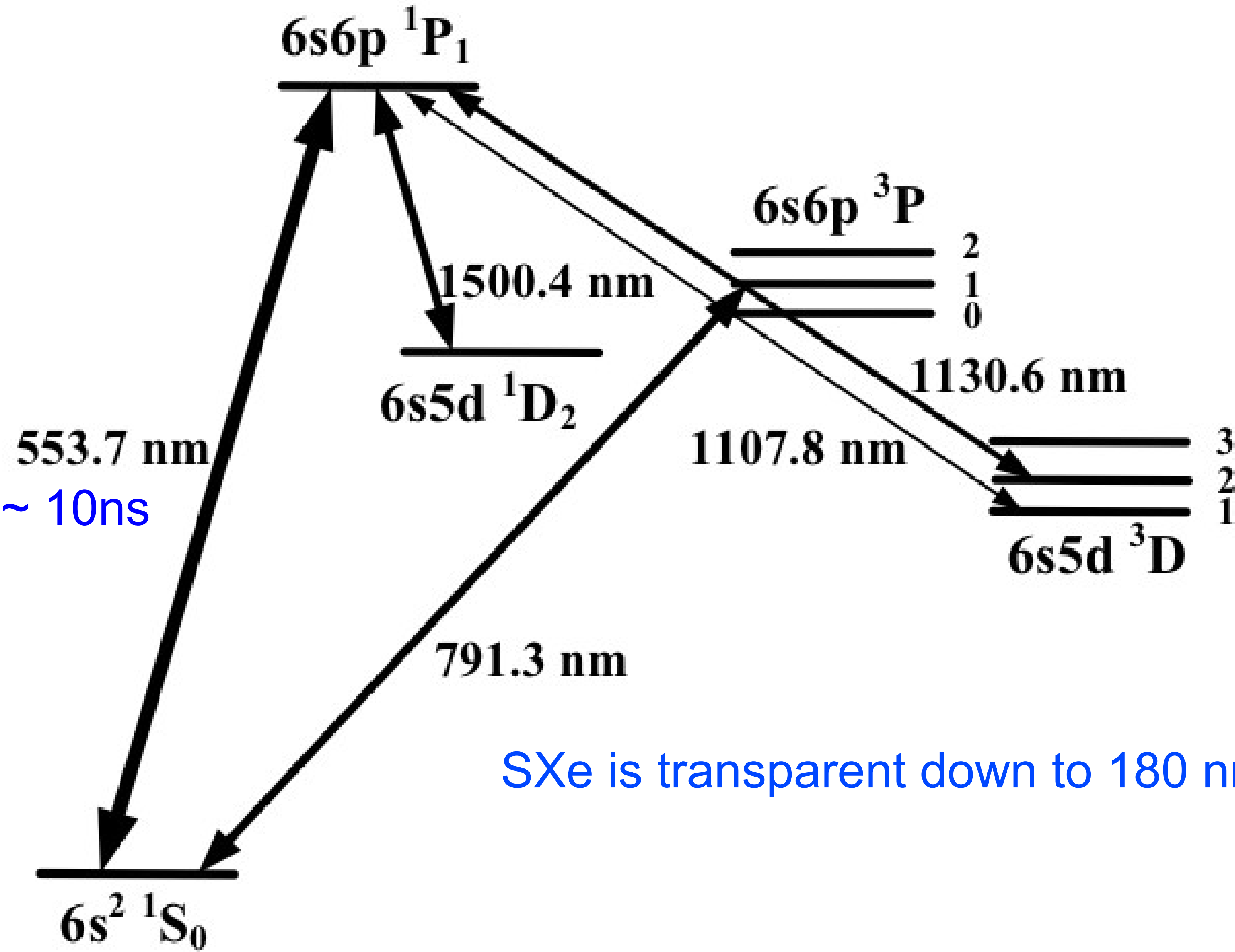
$$^{136}\mathrm{Xe} \quad \rightarrow \quad {}^{136}\mathrm{Ba} + 2e^{-}$$



→ Barium Colour Center in a Solid Xenon Matrix !

Question:
Can you see a single Barium atom in a Xenon crystal?

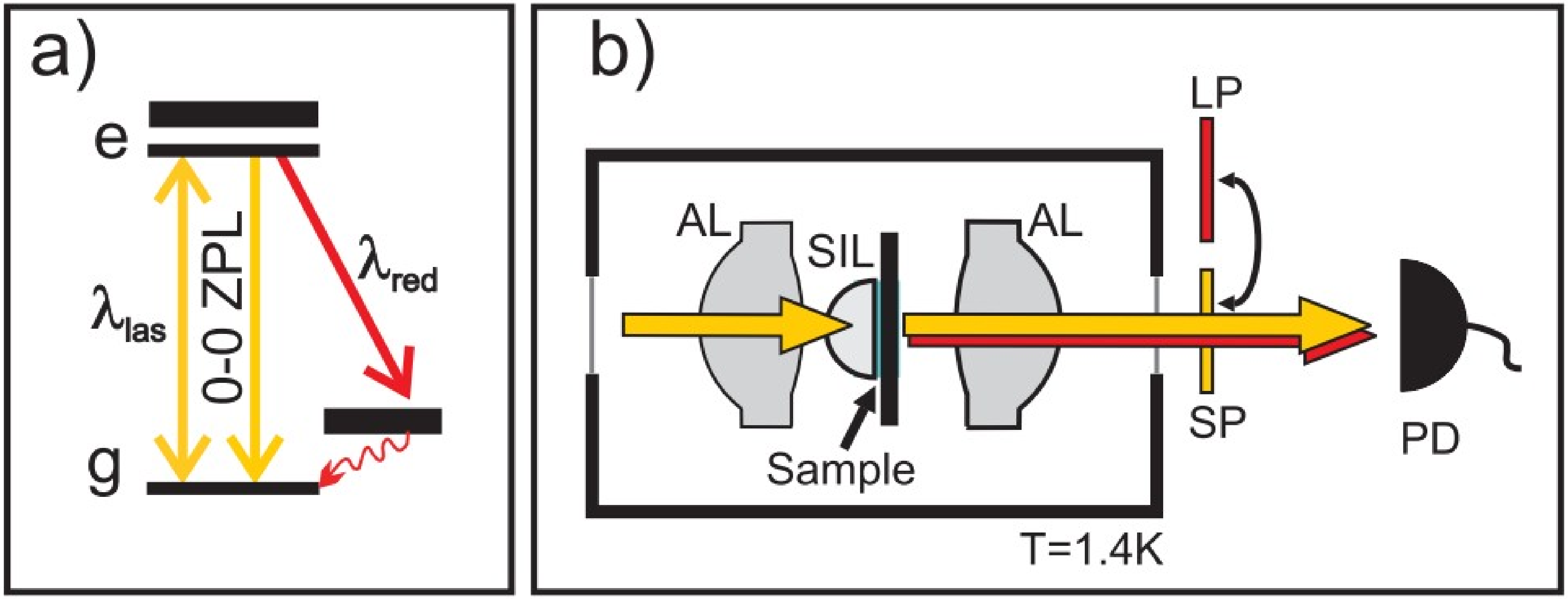
Barium Jablonksky Diagram



Γ ~ 10ns

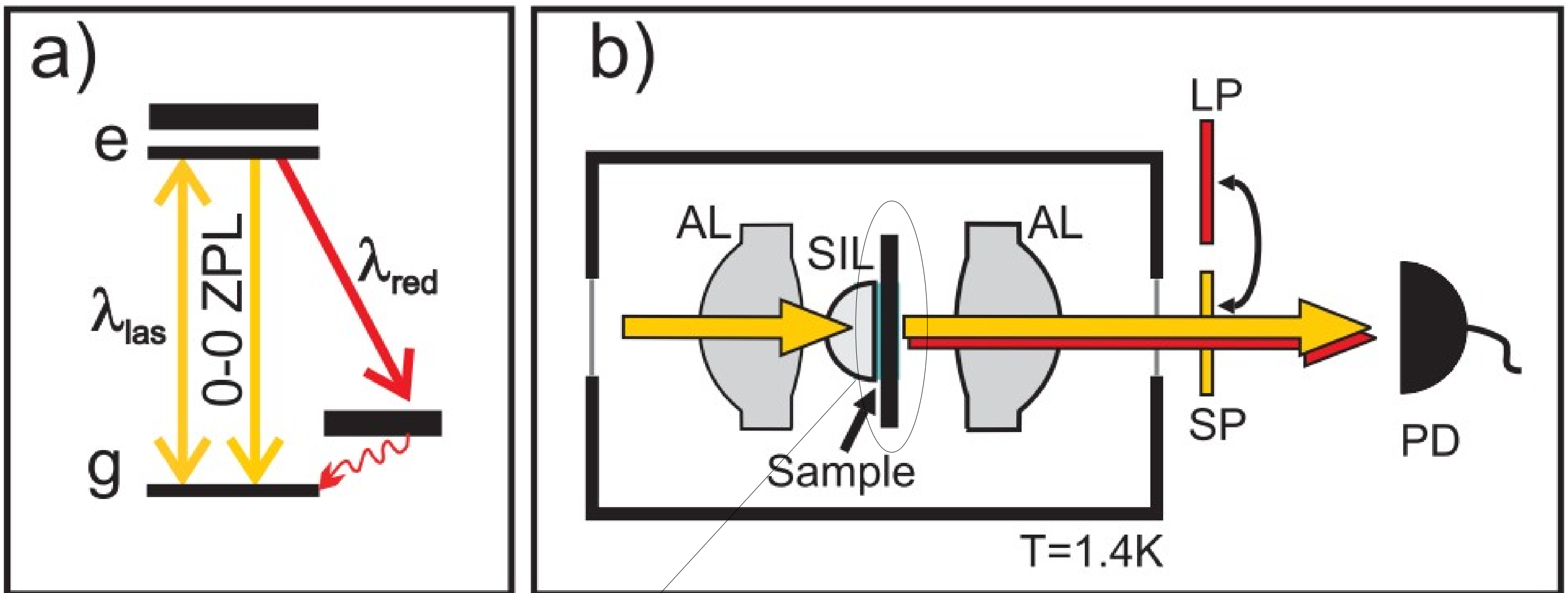
SXe is transparent down to 180 nm!

Single Atom Tagging Principle



Taken from arXiv:0808.3300v1 (I. Gerhardt, V.Sagdoghdar et al. '08)

Single Atom Tagging Principle



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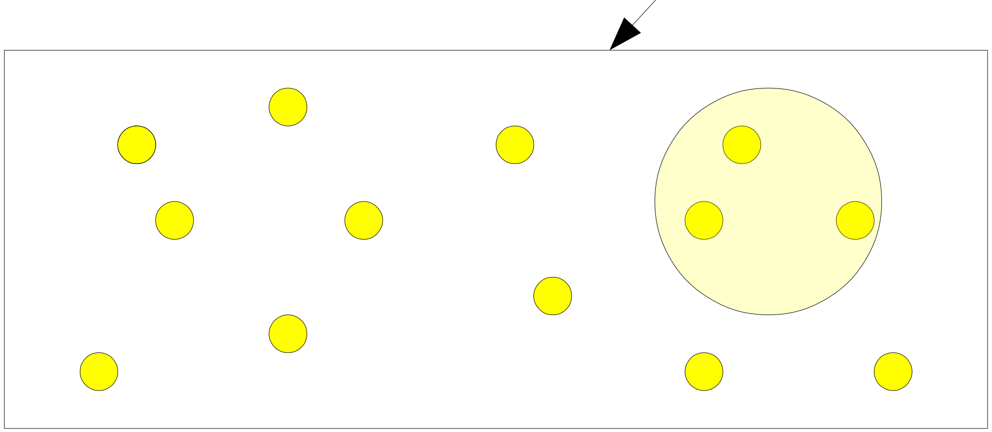
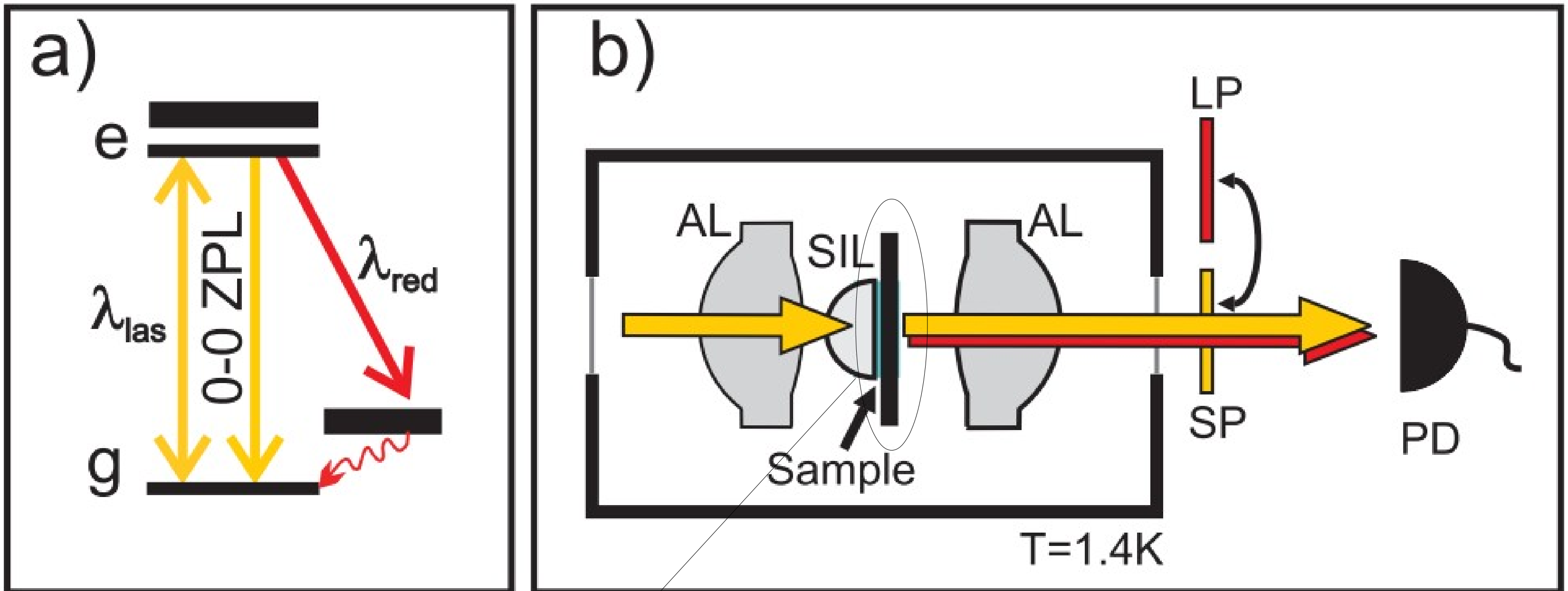


Sample thickness ~ 500 nm

Single Atom Tagging Principle



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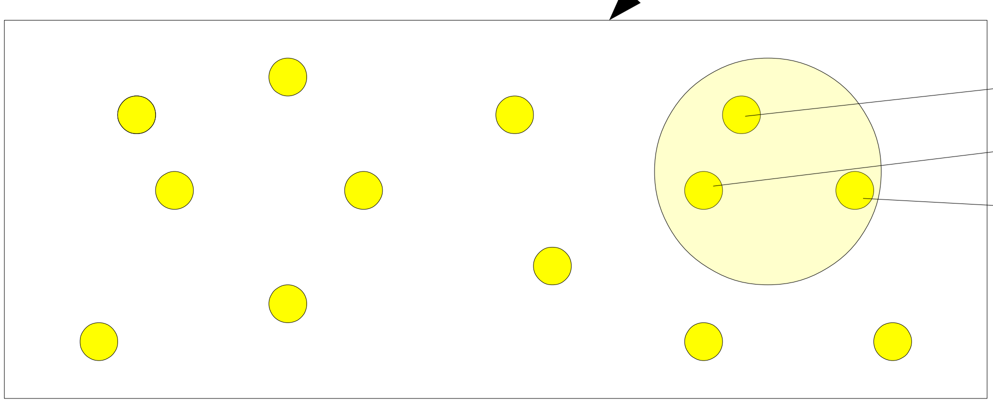

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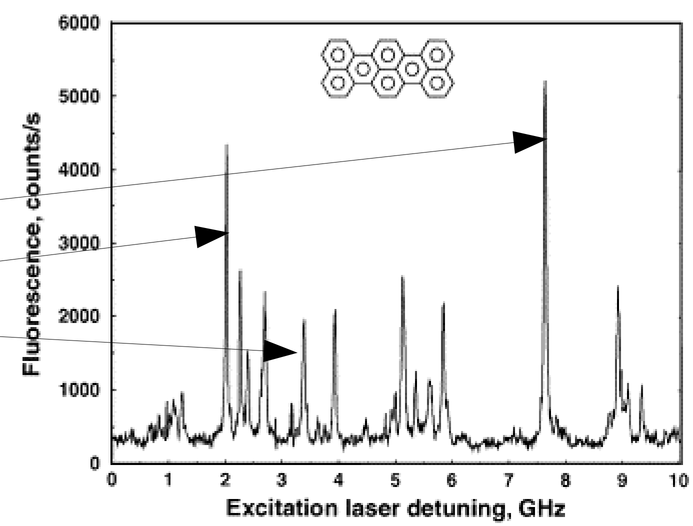
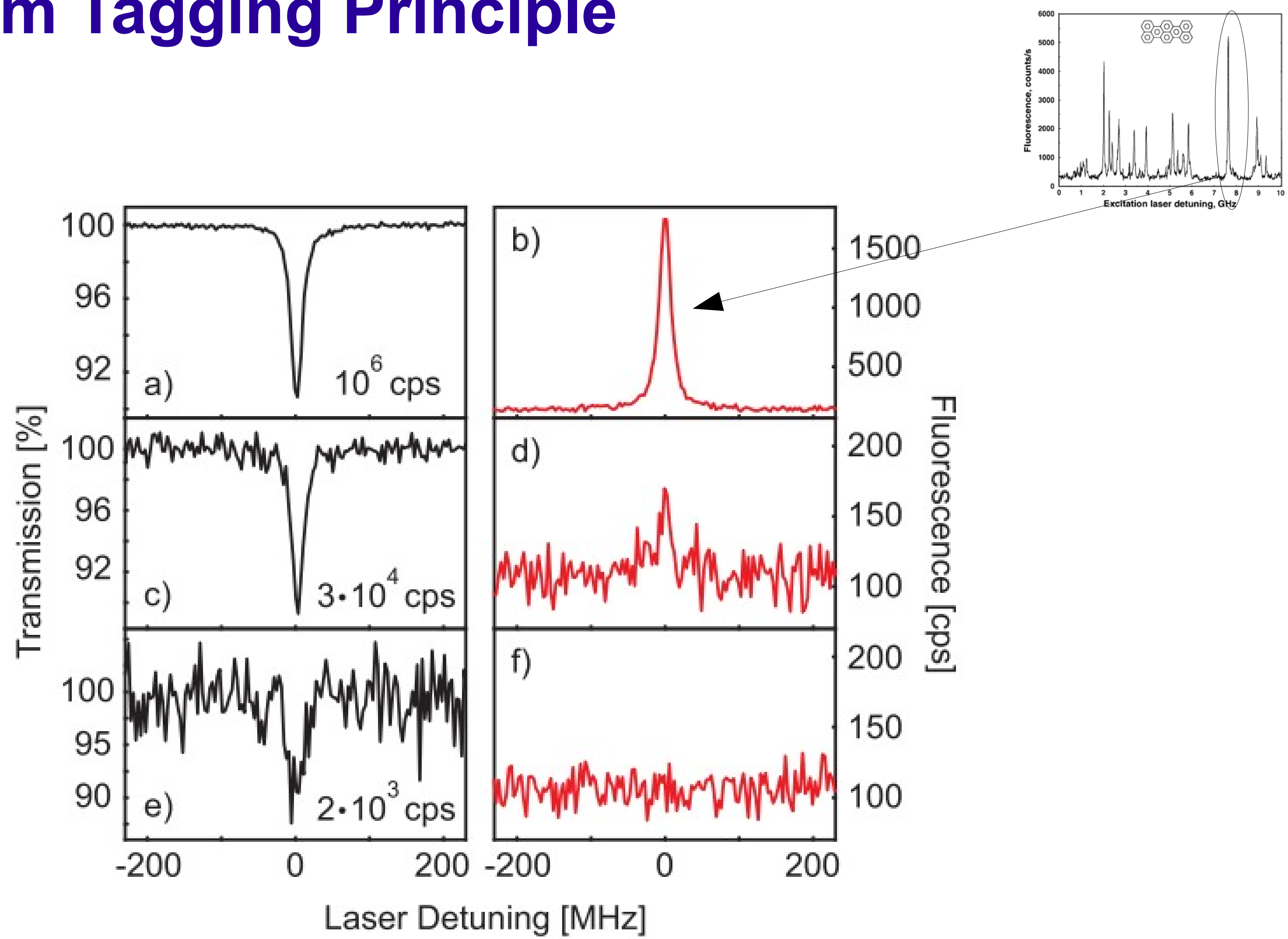


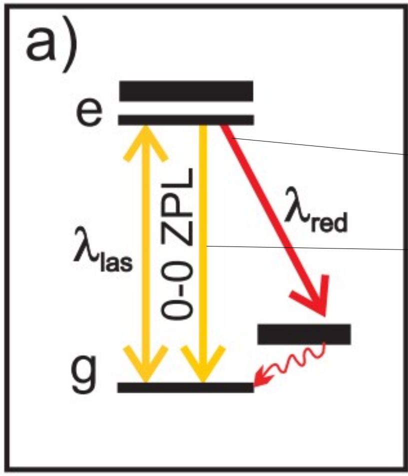
Taken from JLu: K. Rebane '02,
DOI 10.1016/S0022-2313(02)00455-6

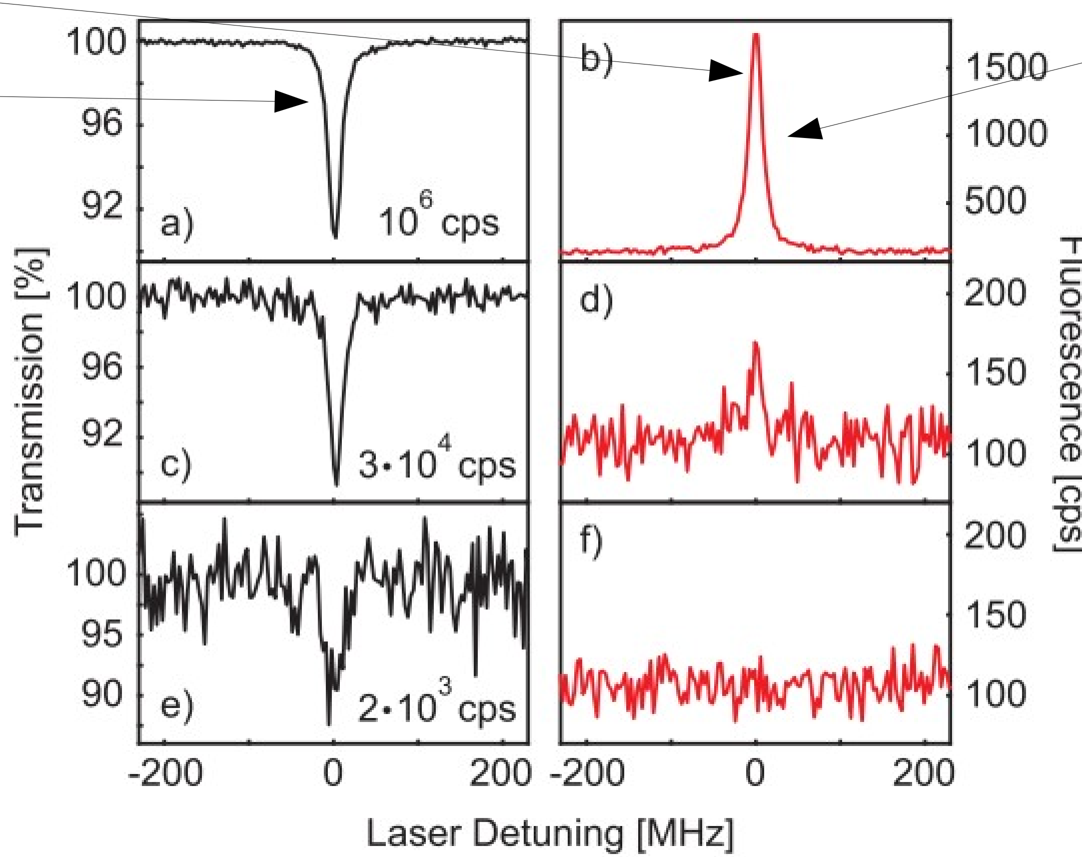
Single Atom Tagging Principle

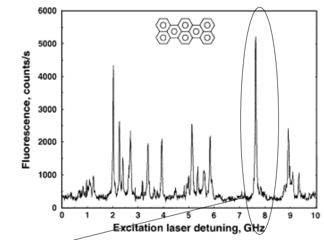


Taken from arXiv:0808.3300v1 (I. Gerhardt, V.Sagdoghdar et al. '08)

Single Atom Tagging Principle



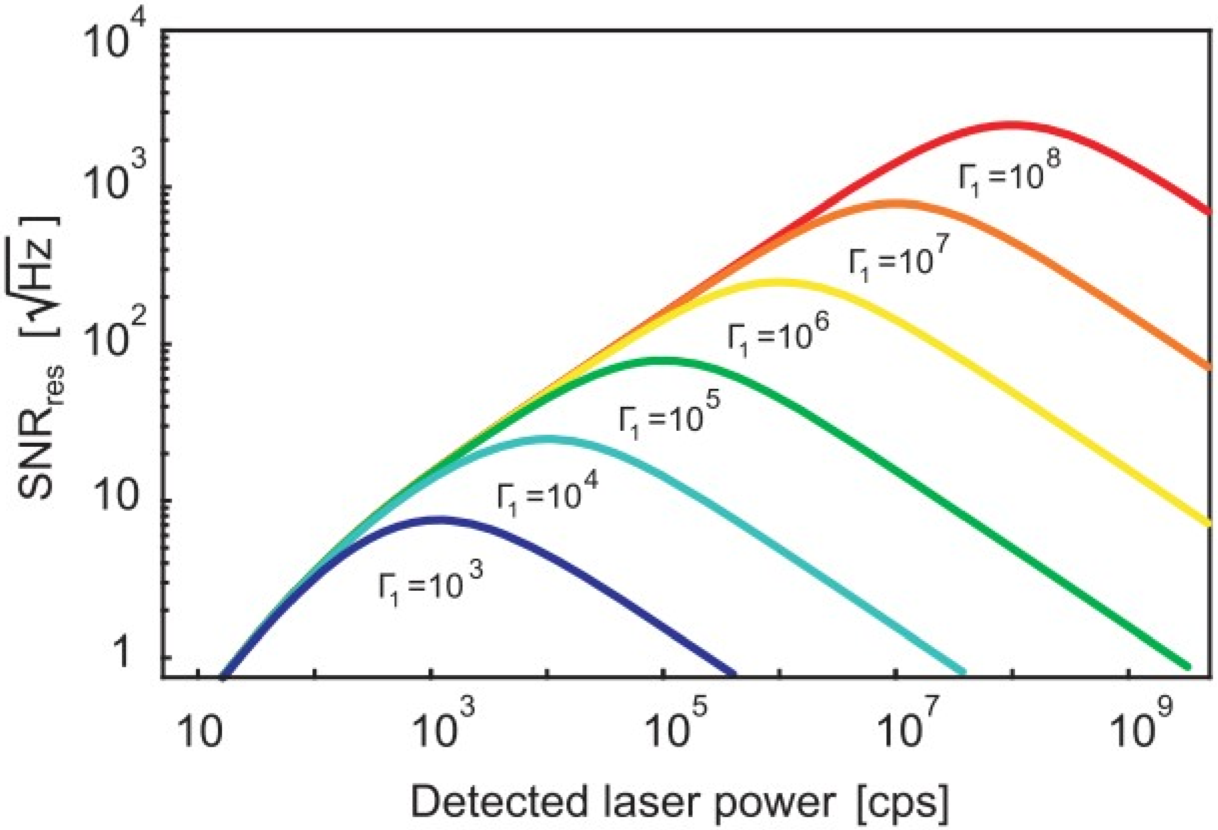




Taken from arXiv:0808.3300v1 (I. Gerhardt, V.Sagdoghdar et al. '08)

Extinction tagging gives a stronger signal

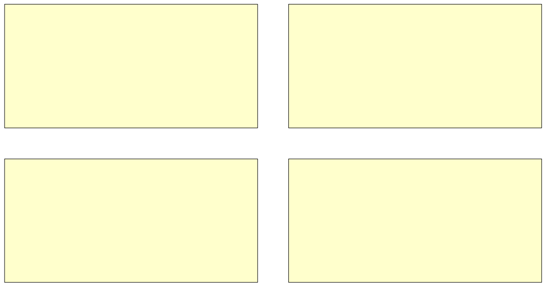
Single Atom Tagging Principle



The barium transition has a width of Γ ~ 10ns
→ Promising even with a „thick (~ 0.5 mm)“ xenon-layer

The Big Plan

1t of SXe divided into
smaller detection blocks



The Big Plan

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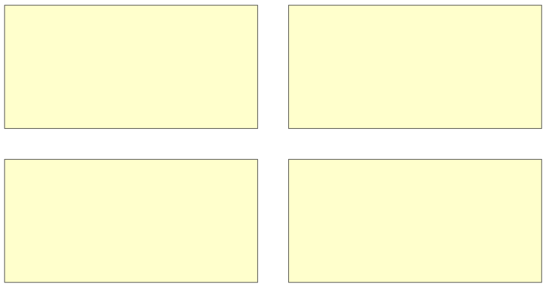
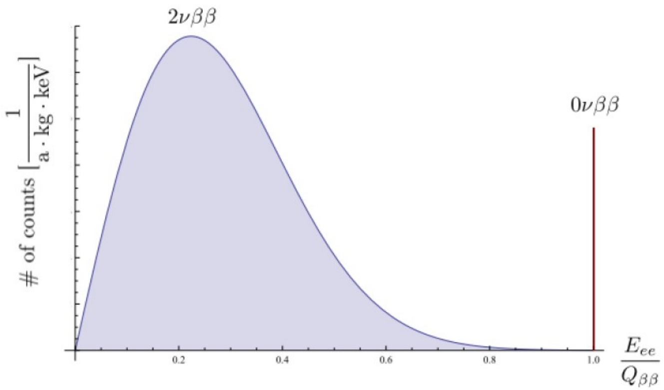


I. Energy Signature



The Big Plan

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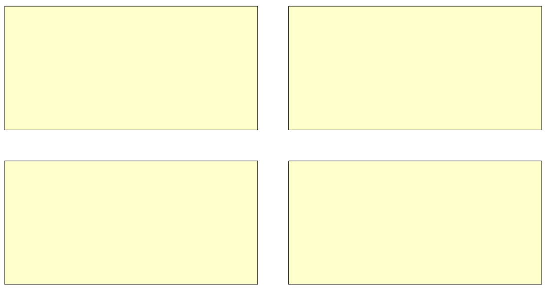

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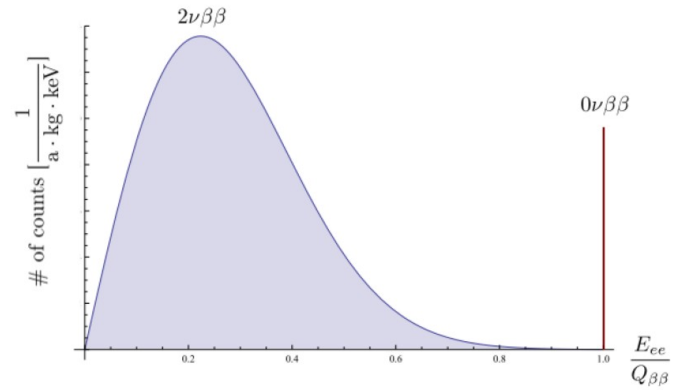
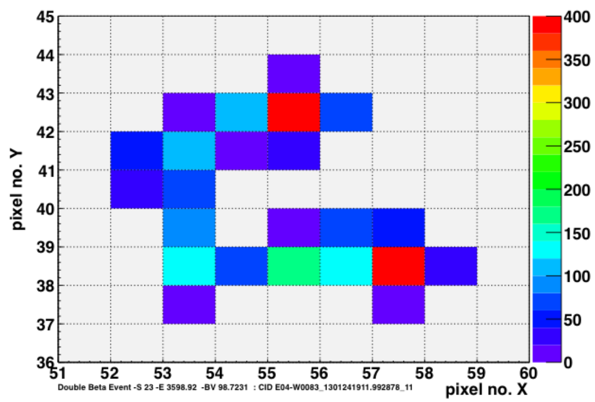


II. Tracking Signature



The Big Plan

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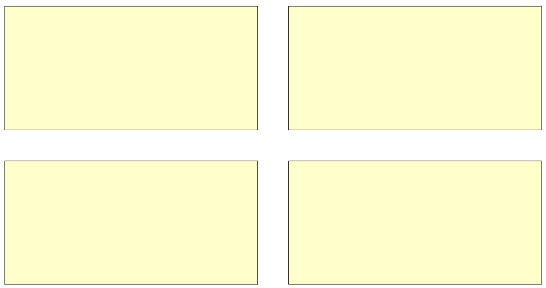

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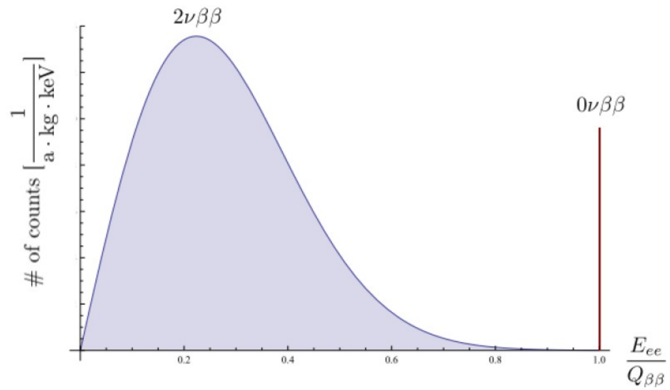

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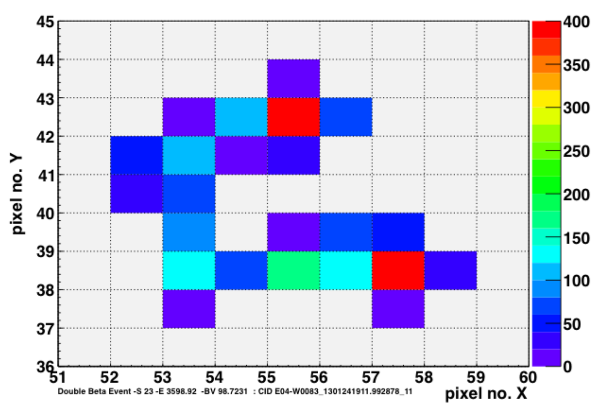
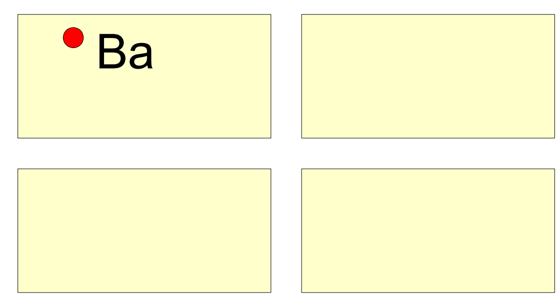
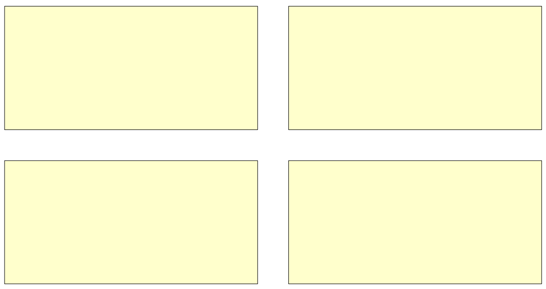


III. Barium Tagging



The Big Plan

1t of SXe divided into smaller detection blocks



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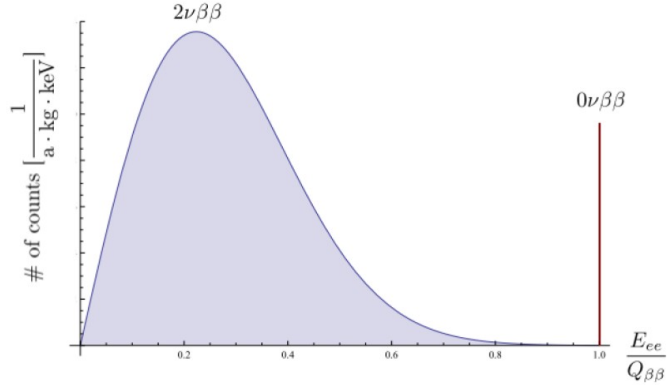
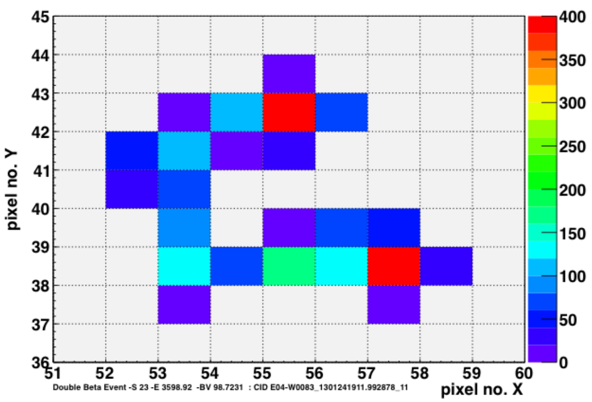


II. Tracking Signature



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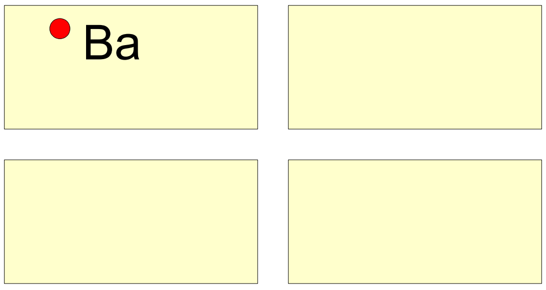
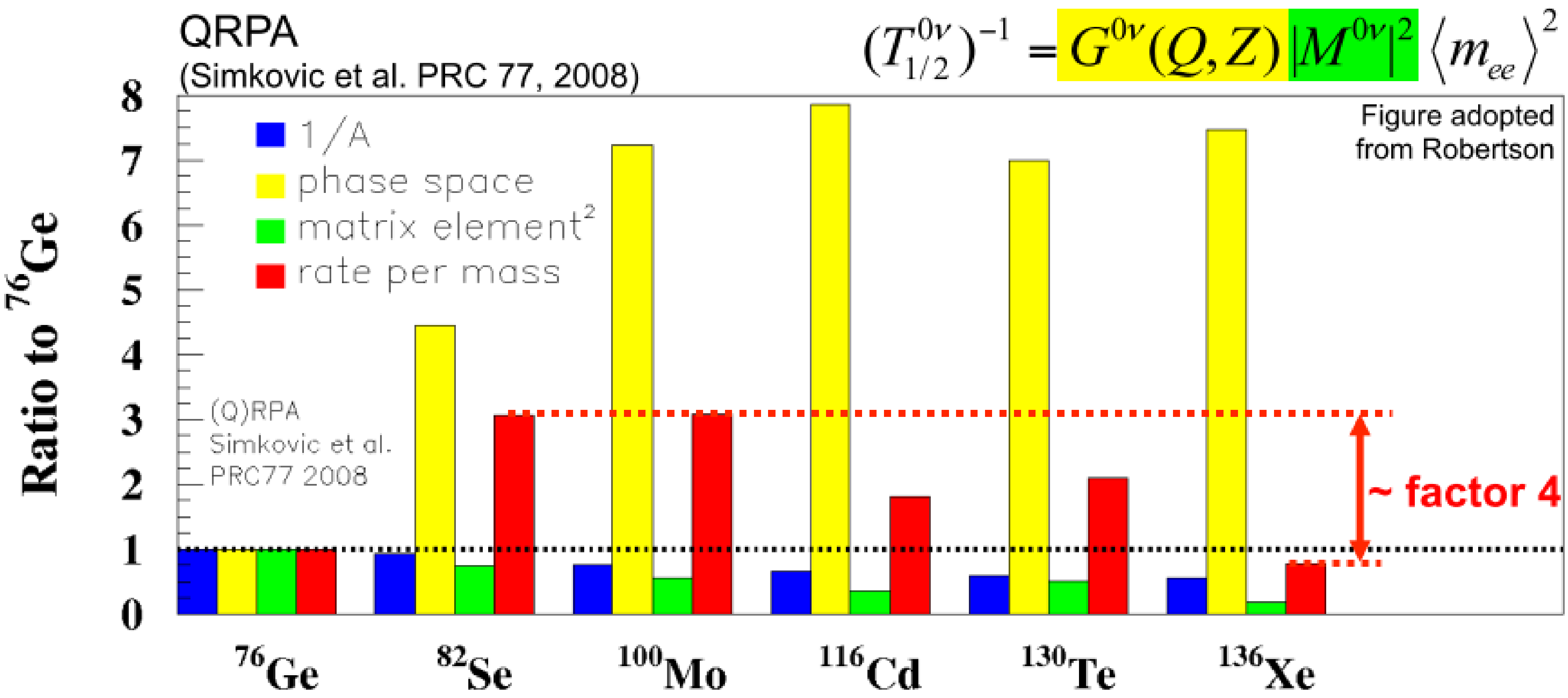


Solid Xenon has the potenial to give more than just evidence for 0vbb !!

Thank You
and
Good Appetite!

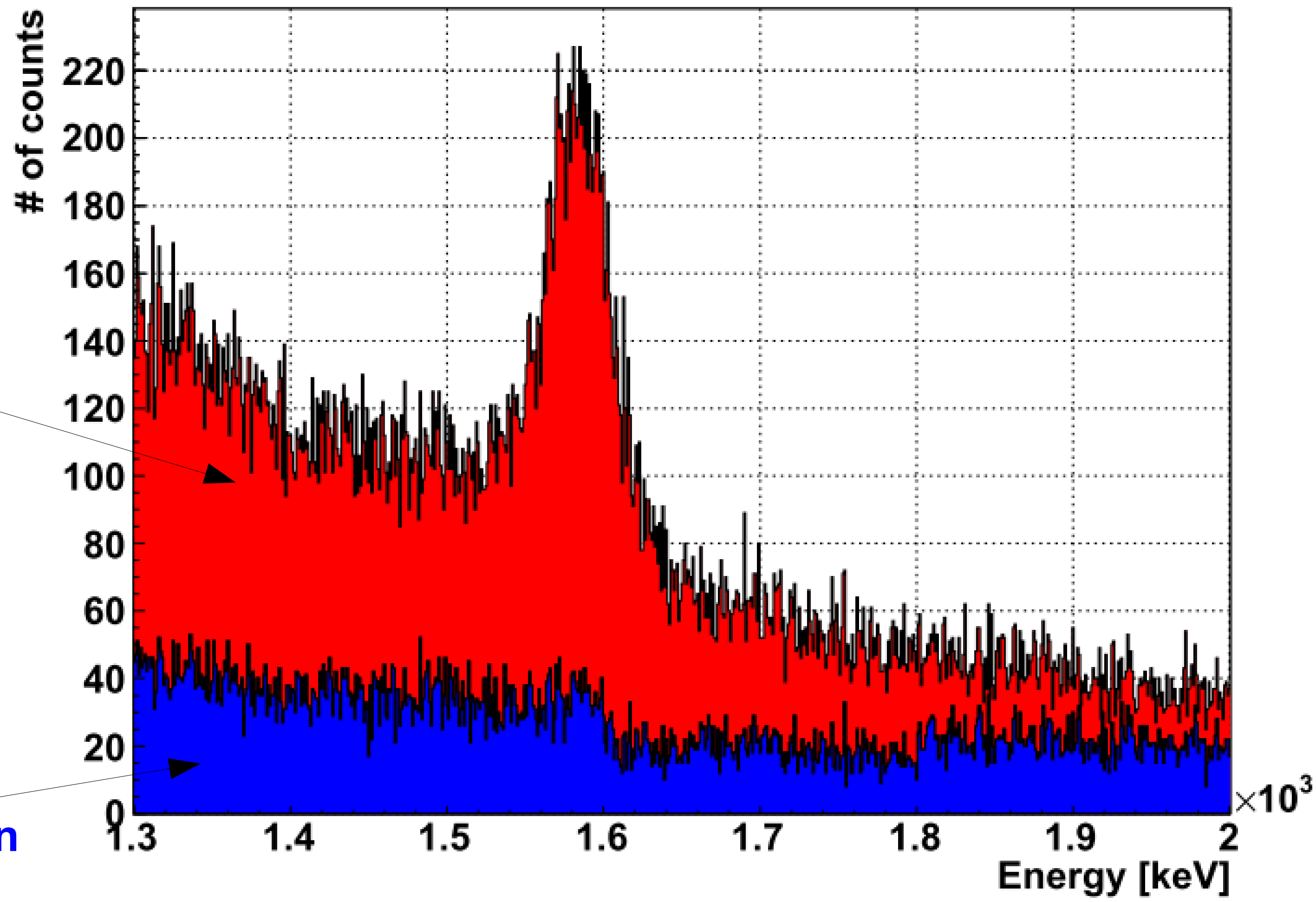
Isotope properties of Xe-136



Maybe not the best isotope but what's about practical issues?

The Event Spectrum in the Region of Interest

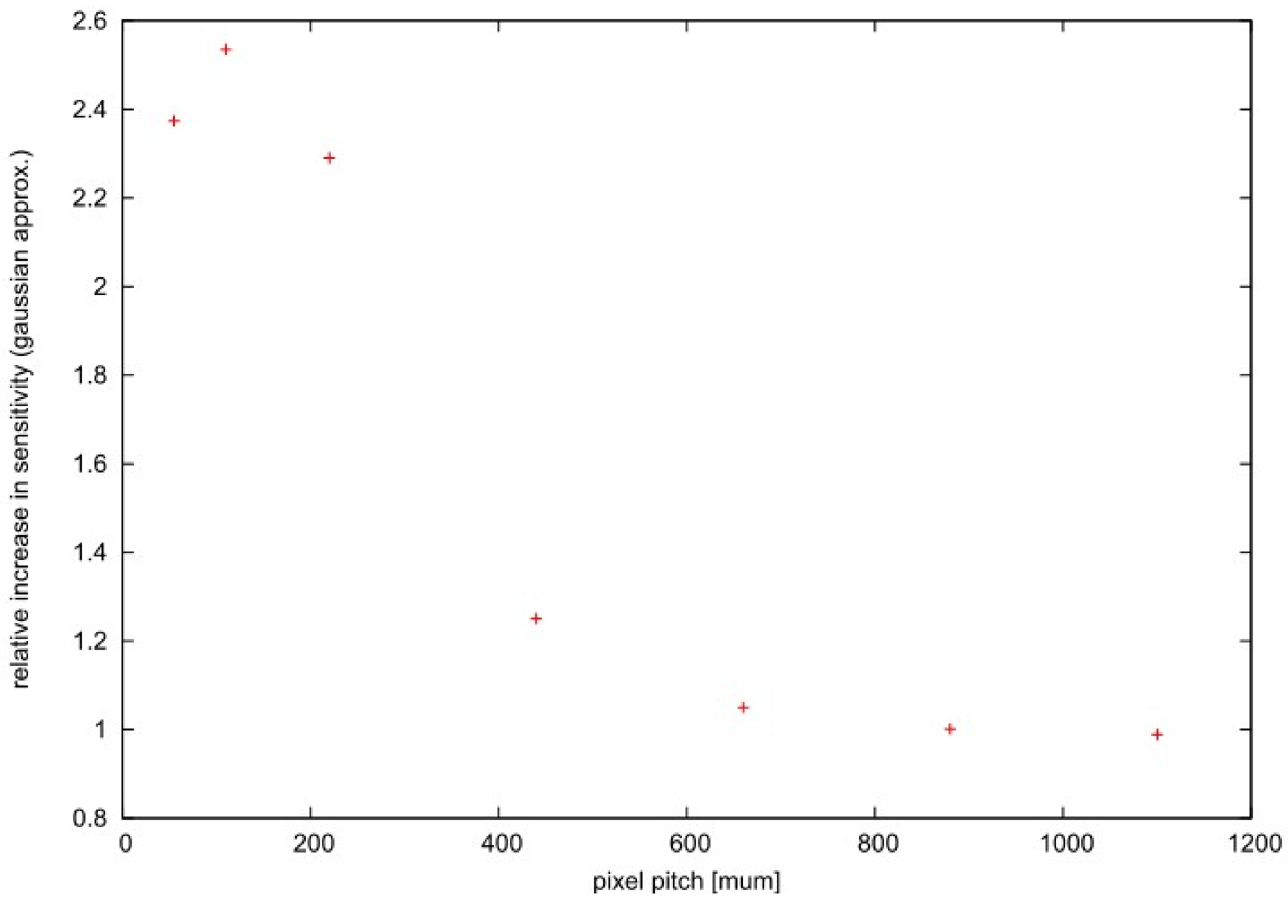
two
electron
tracks



one
electron
tracks

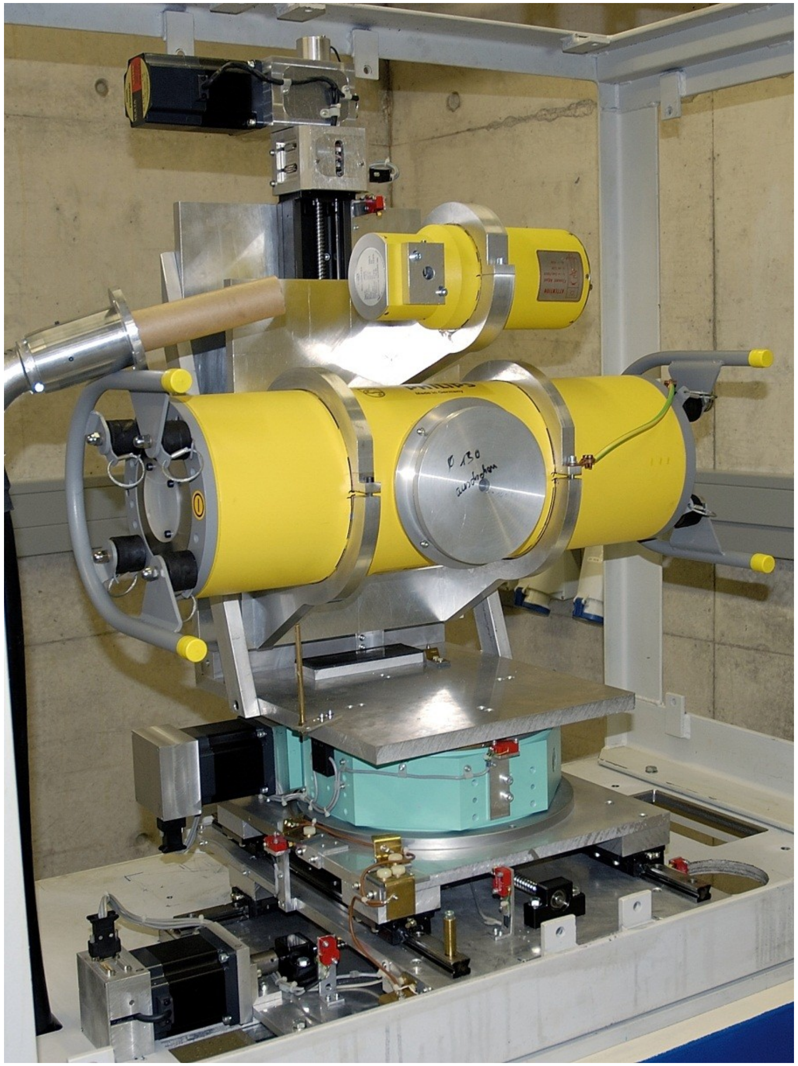
After event classification with **artificial neural networks**.

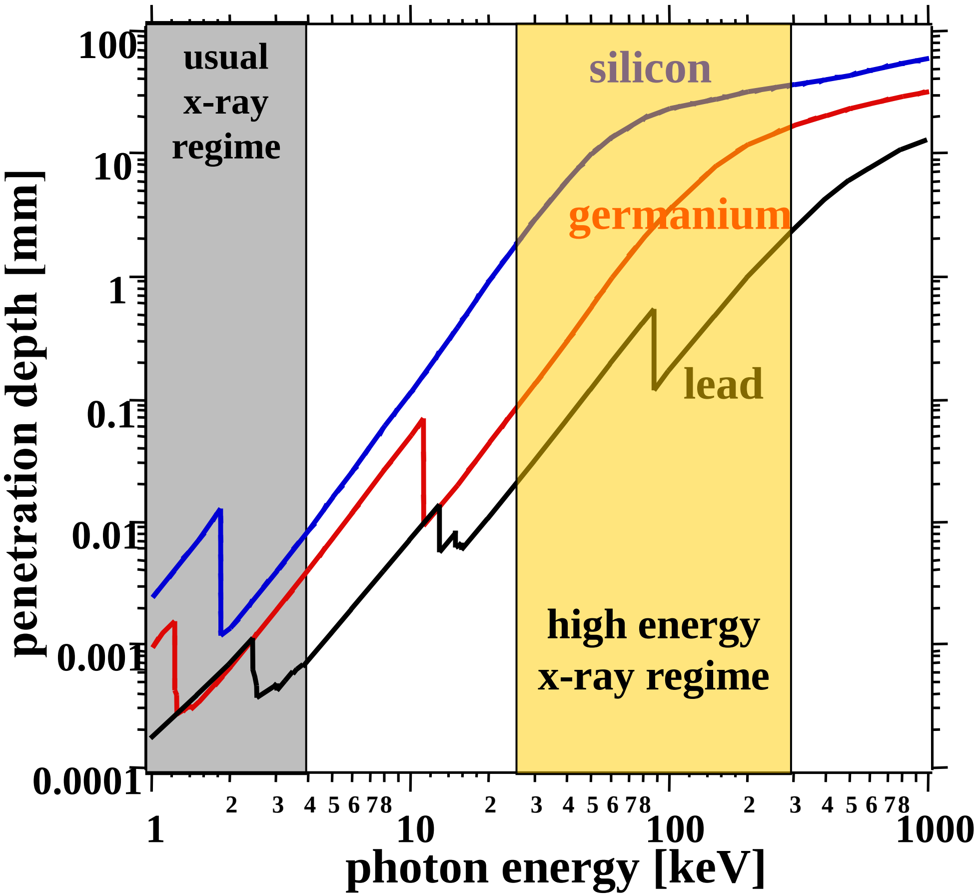
Sensitivity



A rough evalutation of 3D tracks with ANNs gives an improvement of about a factor of 6 in sensitivity!

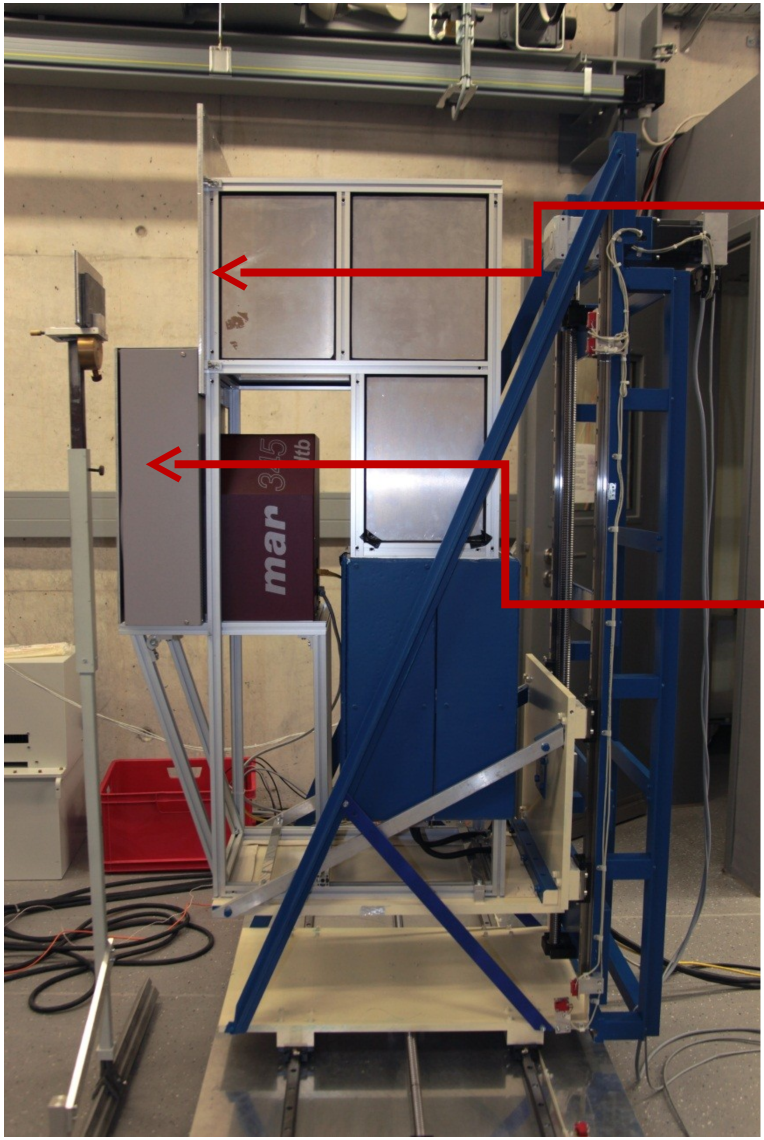
HEXBay X-ray sources





	Voltage	Power	Source size
Tube 1	225 keV	2,25 kW	0,4 x 0,4 mm2 or 1,5 x 1,5 mm2
Tube 2	450 keV	4,5 kW	1,0 x 1,0 mm2 or 6,0 x 6,0 mm2

HEXBay Detector-Systems



2 Area detectors:

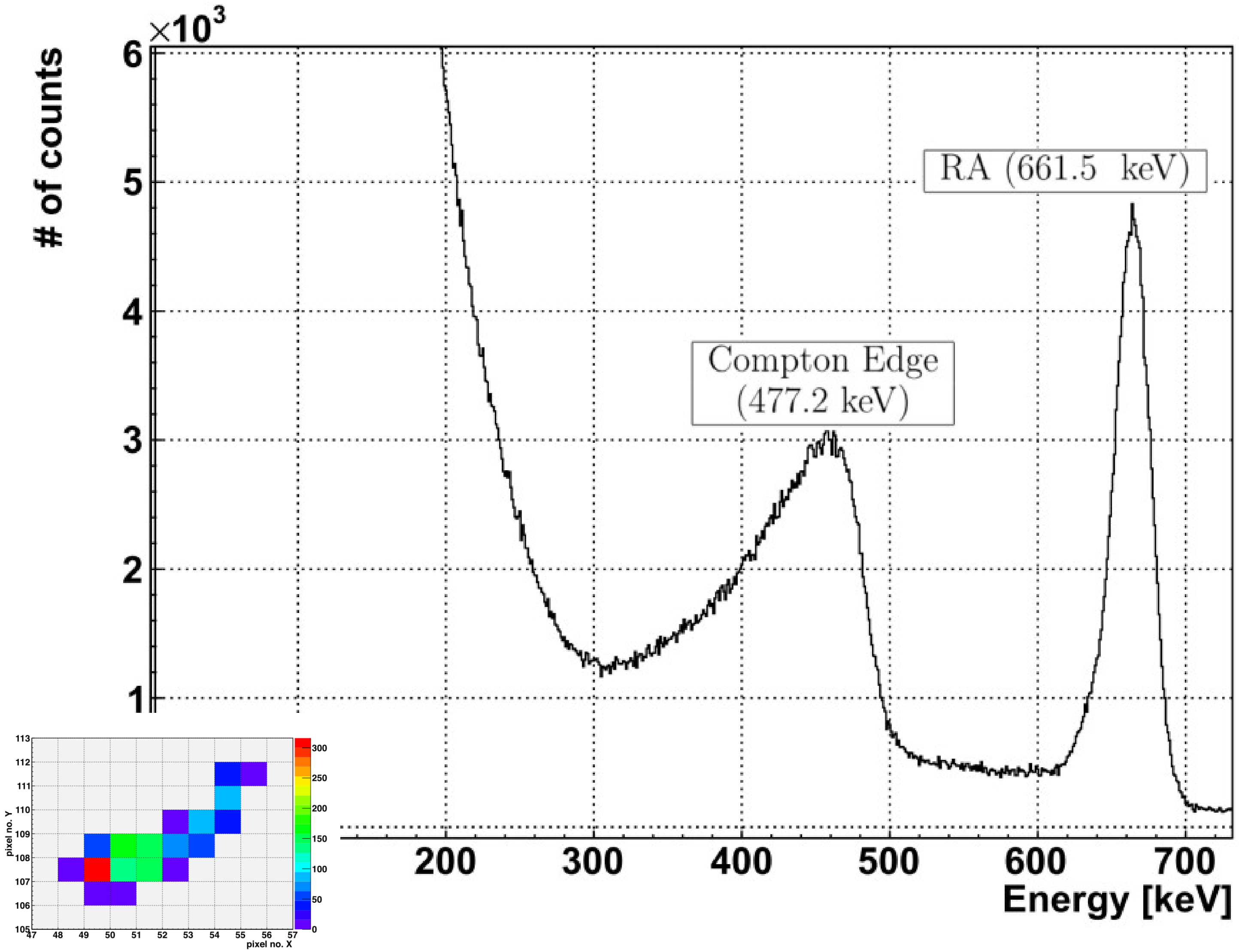
Scintillator with a System of cooled CCD-Cameras

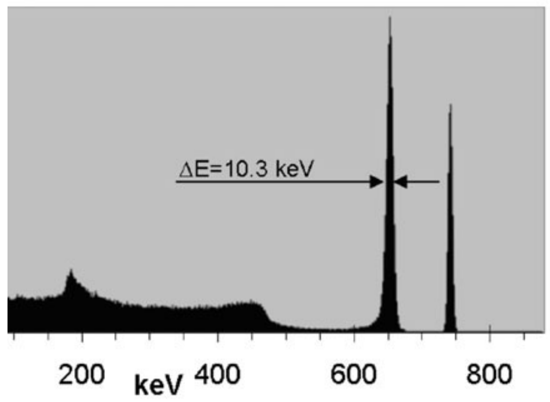
Active area 30 x 20 cm2
2 x 14 bit CCD- with 1280 x 1024 pixel
Resolution ~ 150 µm
Read out = 125 ms

Image plate System MAR 345

Active area Ø 345 cm
Resolution ~ 100 µm
Read out incl. delay time = 2 min

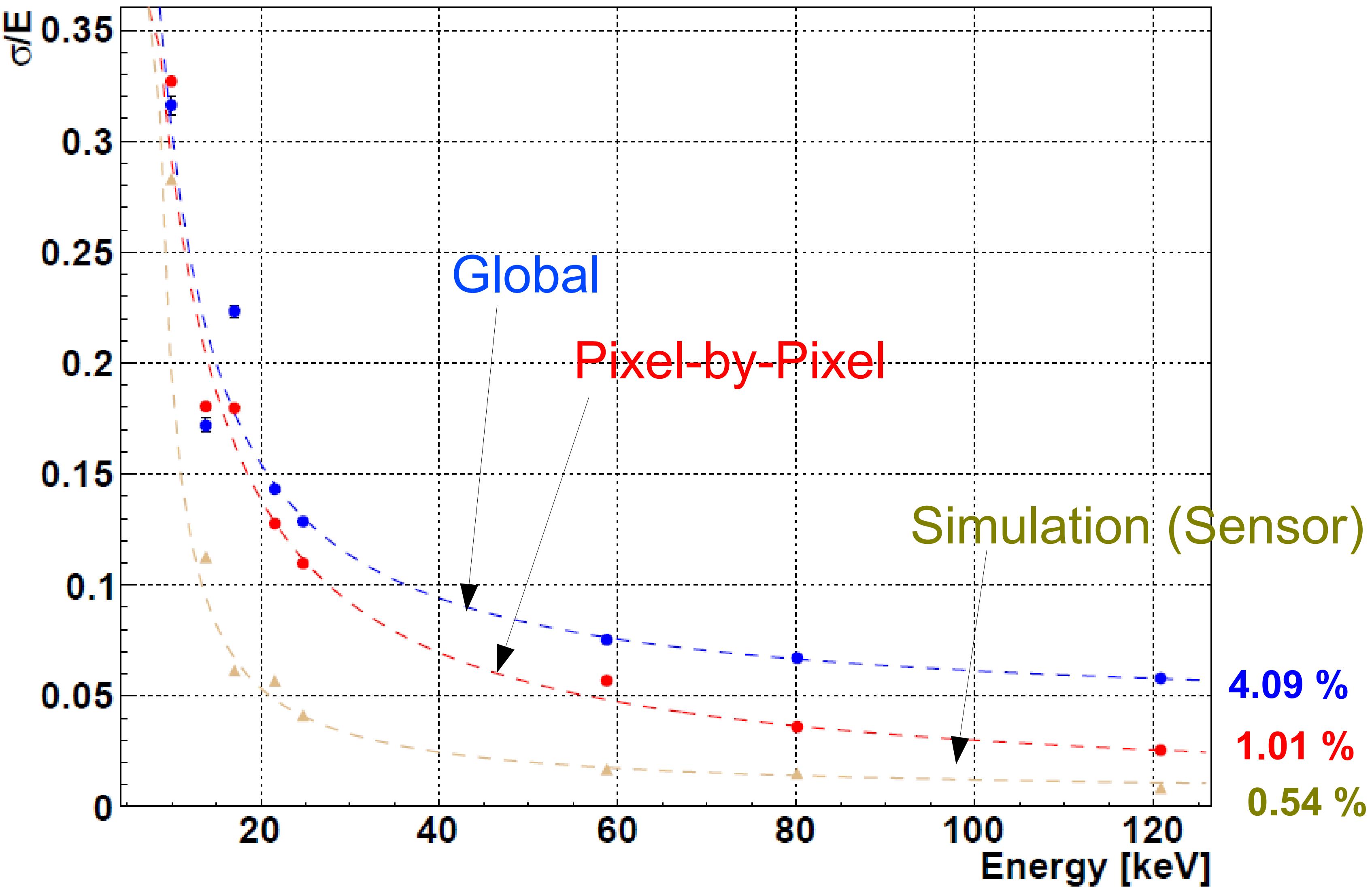
Spectrum of a Cs-137 source





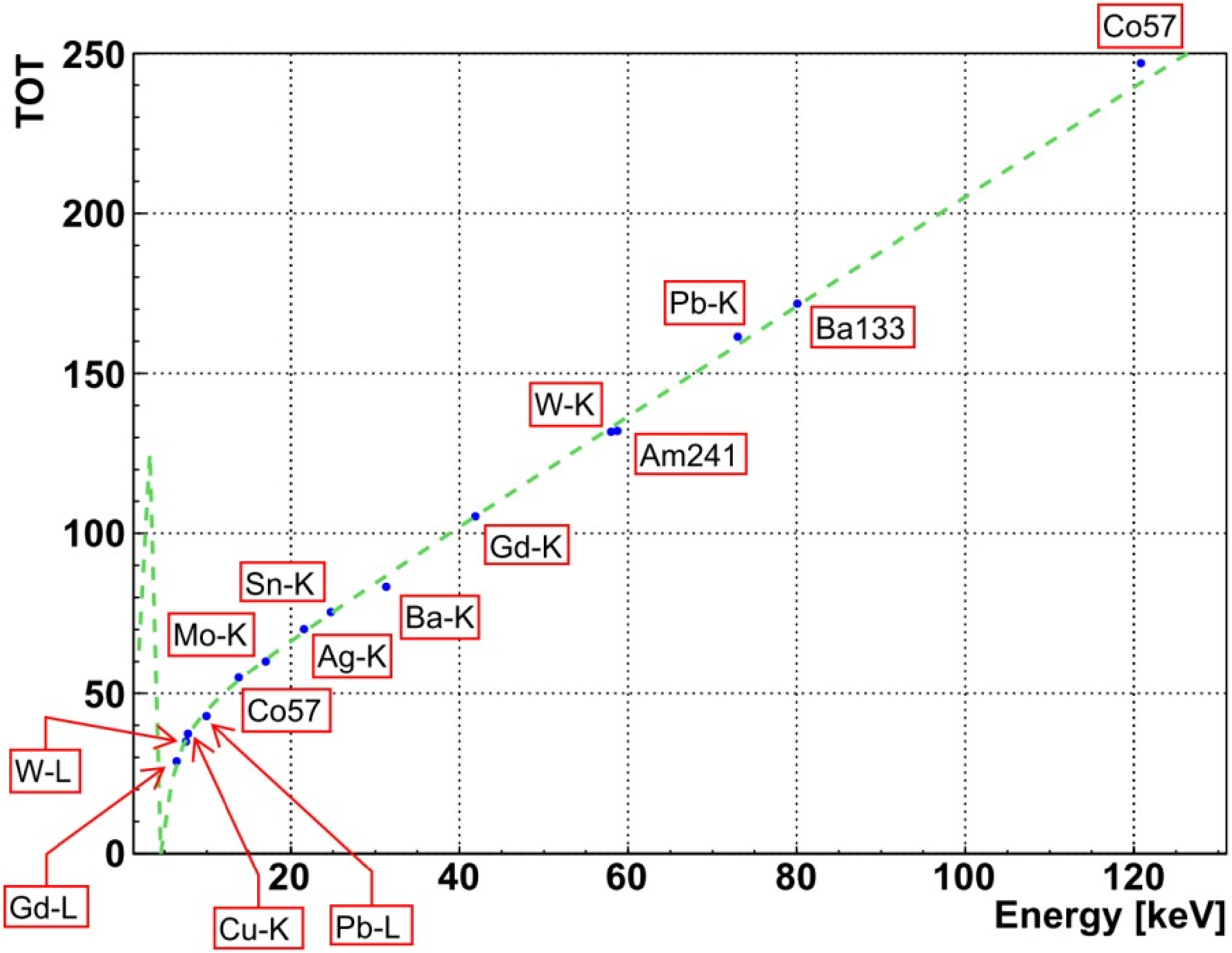
Energy resolution (FWHM) at **661.5** keV (Cs-137): **4.45** %

Energy Resolution (σ/E) for Global Calibration, Pixel-by-Pixel Calibration and Simulation



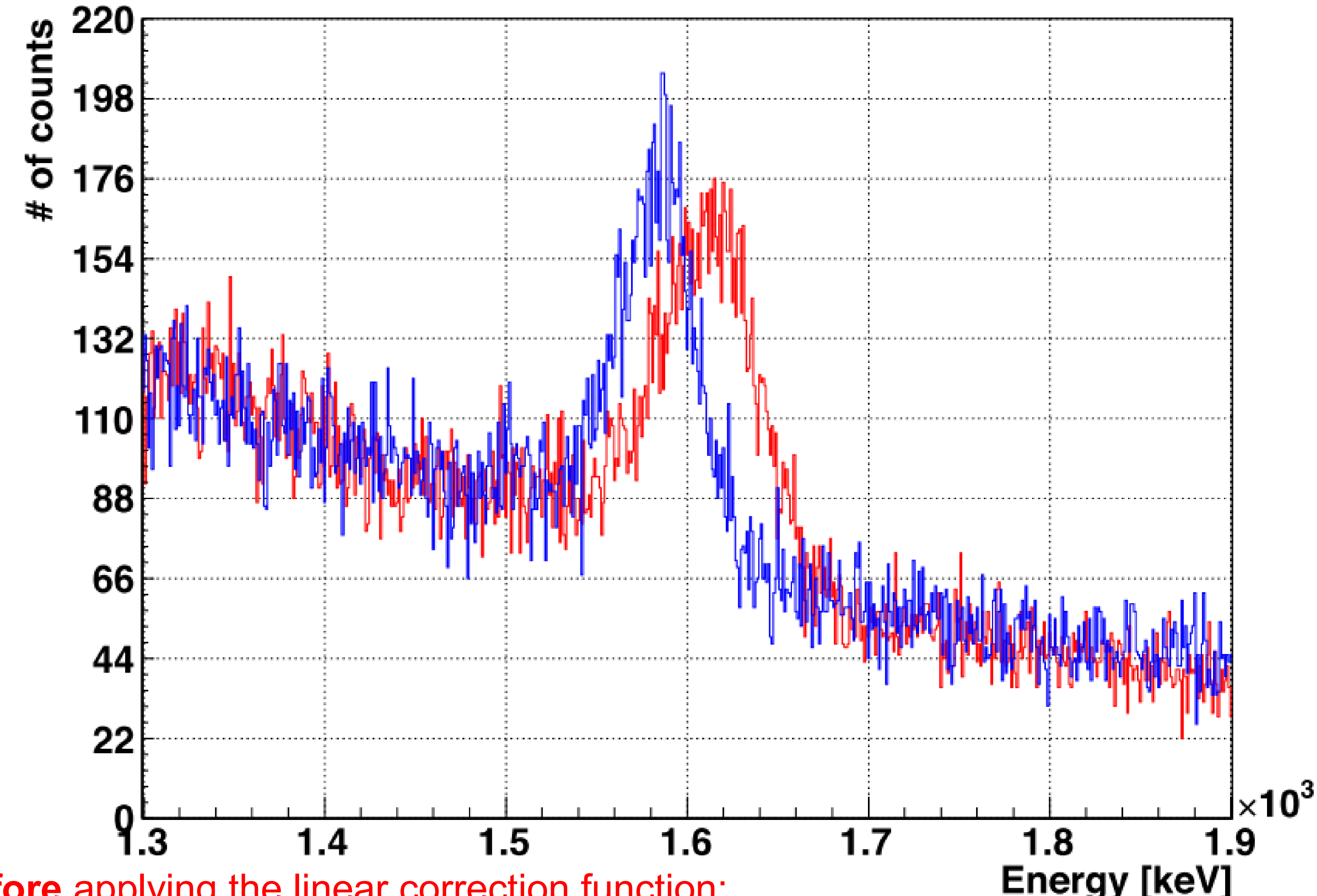
$$\frac{\sigma}{E}(E) = \alpha + \frac{\beta}{(E-\gamma)^{\delta}}$$

The Calibration Curve



$$TOT(E) = a \cdot E + b + \frac{c}{E - t}.$$

Energy Resolution (σ/E) for Pair Production at 1588.53 keV (Tl-208)



Before applying the linear correction function:
E = ~ 1610 keV, σ/E = 2.2 %

After applying the linear correction function:
E = ~ 1588 keV, σ/E = 1.6 %

Expected Position:
1588.53 keV

Recognizing electrons: Neuronal artificial networks

Idea:

I. Every event is classified by a vector of N quantities

$$\vec{x} = (x_1, ..., x_N)$$

II. For every vector a number v can be calculated due to the formula

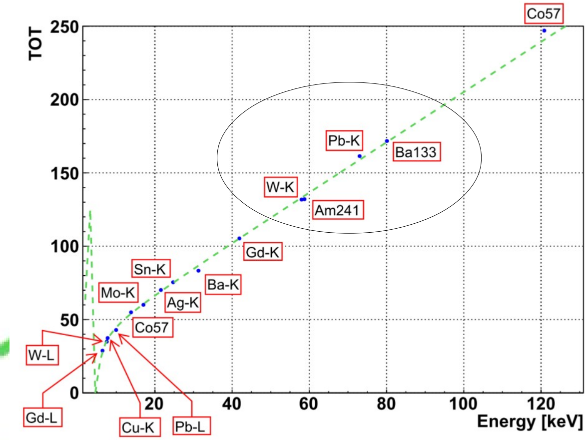
$$v_j = \sum_{i=1}^{N} w_i \cdot x_i$$

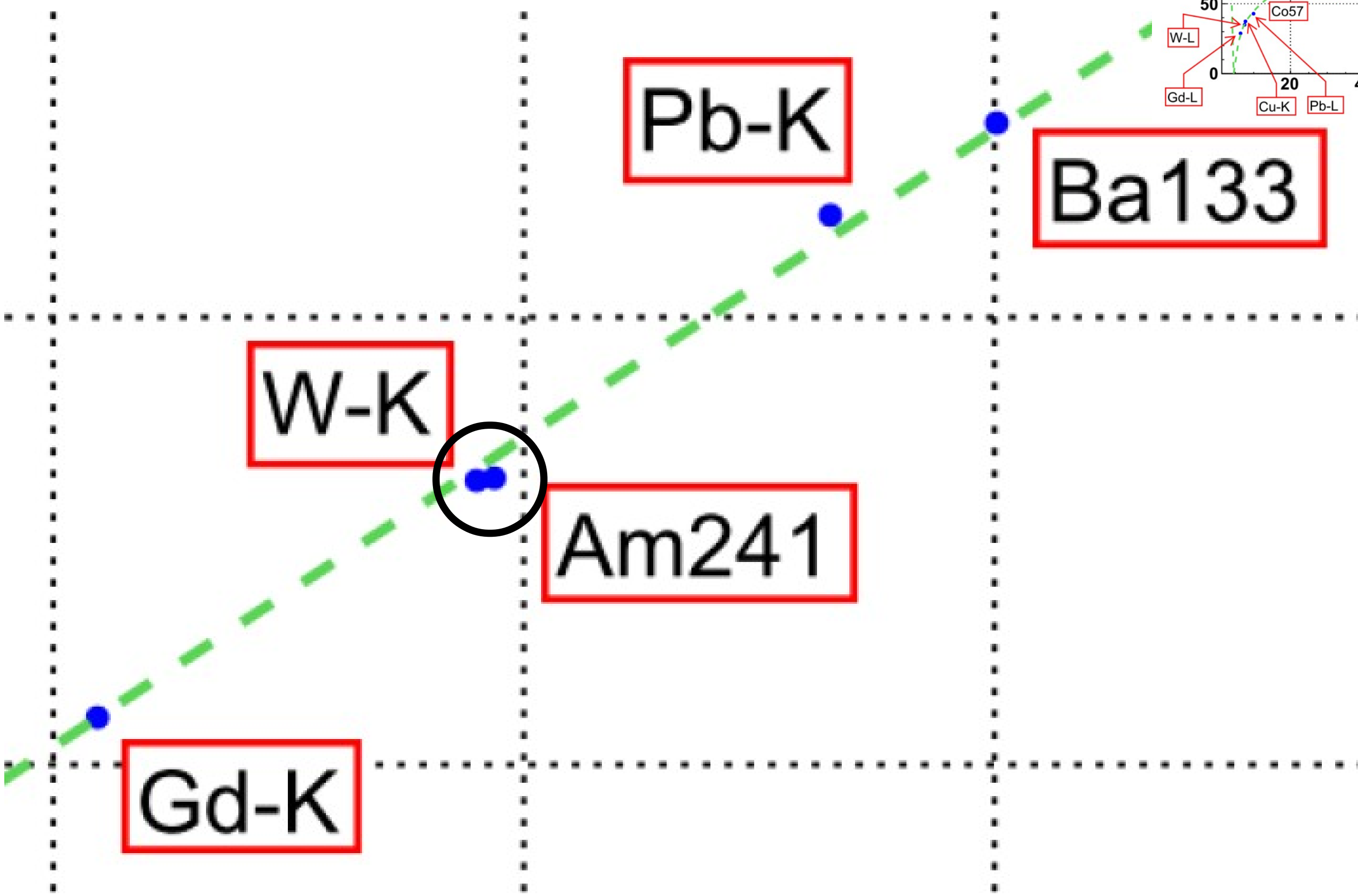
III. If v is bigger than a particular value v', the picture is identified as a 0vbb event otherwise as a single electron

$$v_j > v' \quad \rightarrow \quad 0\nu bb$$

IV. Train the networks by simulations to optimize the weighting factors

Calibration Curve (Global Calibration)





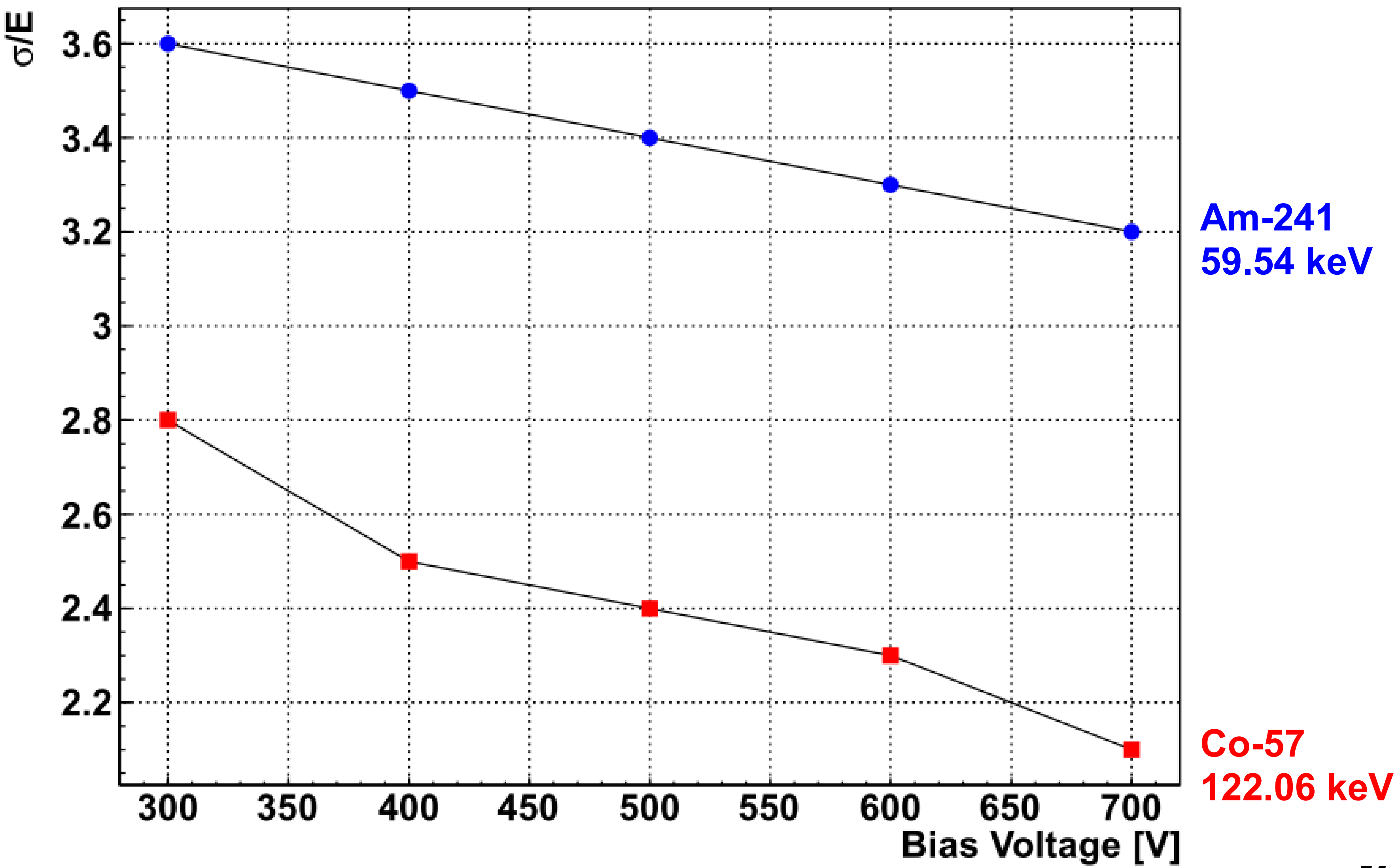
Totally out of error bars!

Energy Resolution under Various DAC Settings - Pixel-by-Pixel Calibration

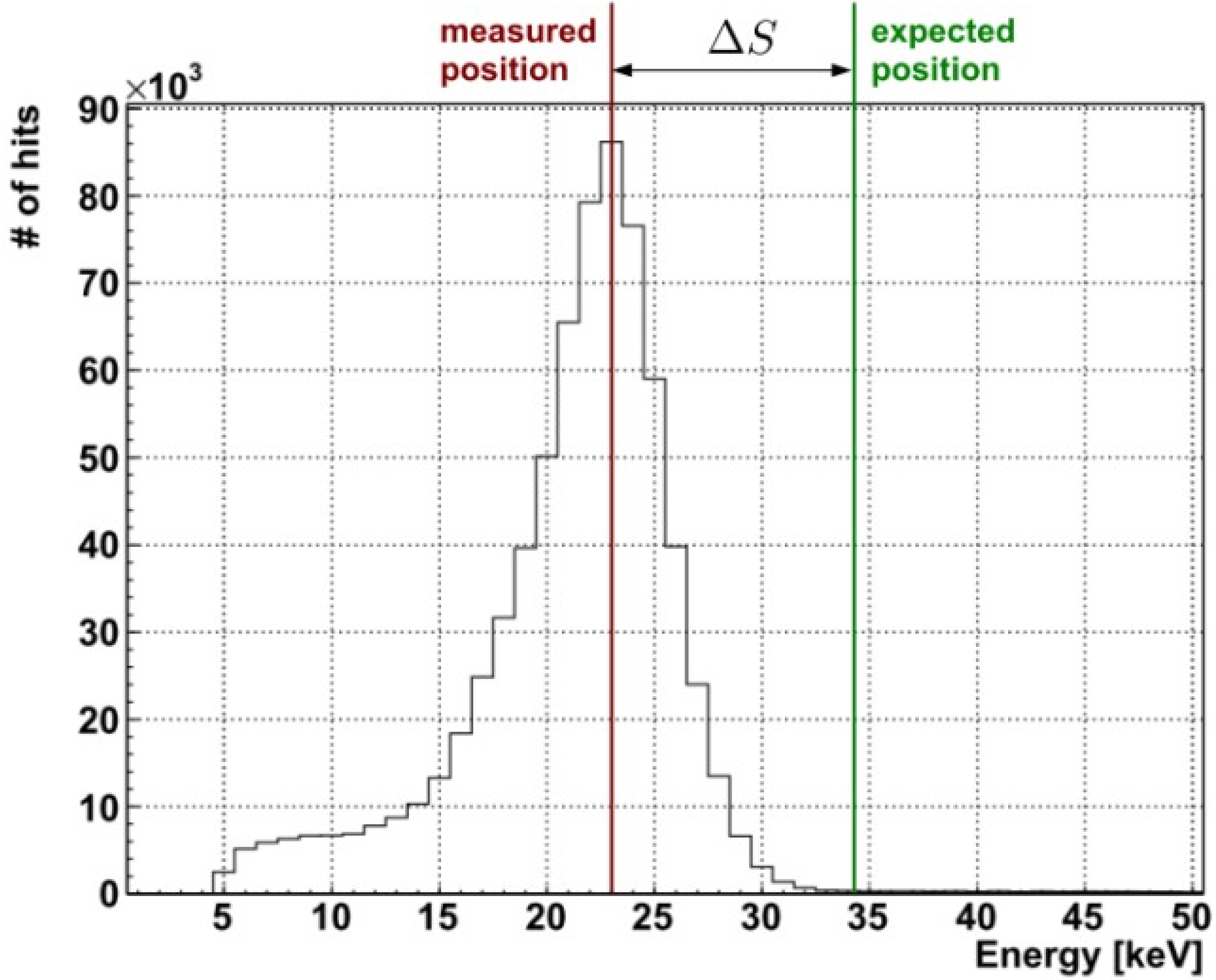
DACs	^{241}Am	^{133}Ba	^{57}Co
Ik 10, THL 190	5.6	3.5	2.5
Ik 04, THL 210	3.4	3.2	2.3

Energy Resolution with Different Bias Voltages

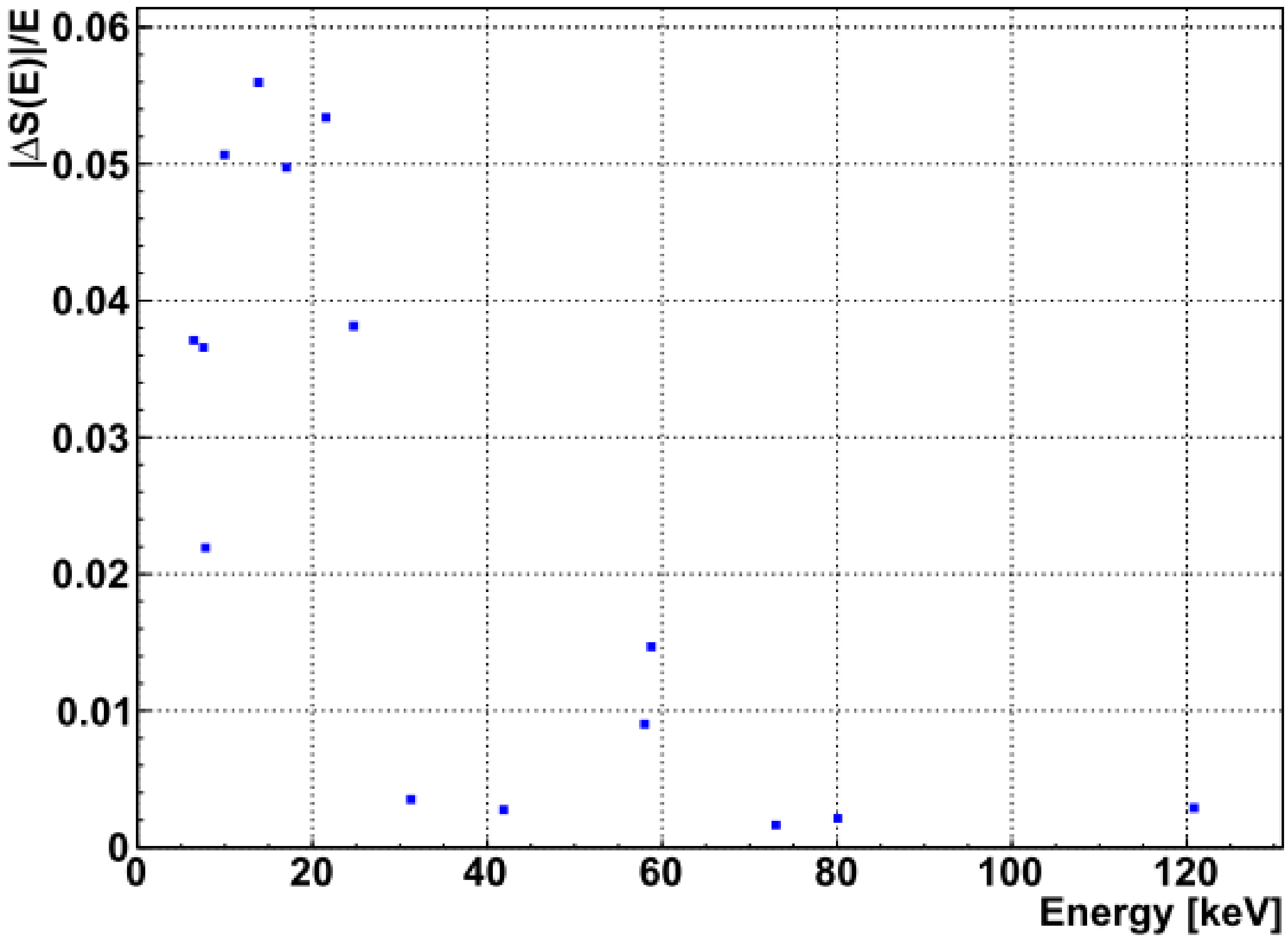
Highest voltage tested: ~800 V (leakage current ~13 μm)



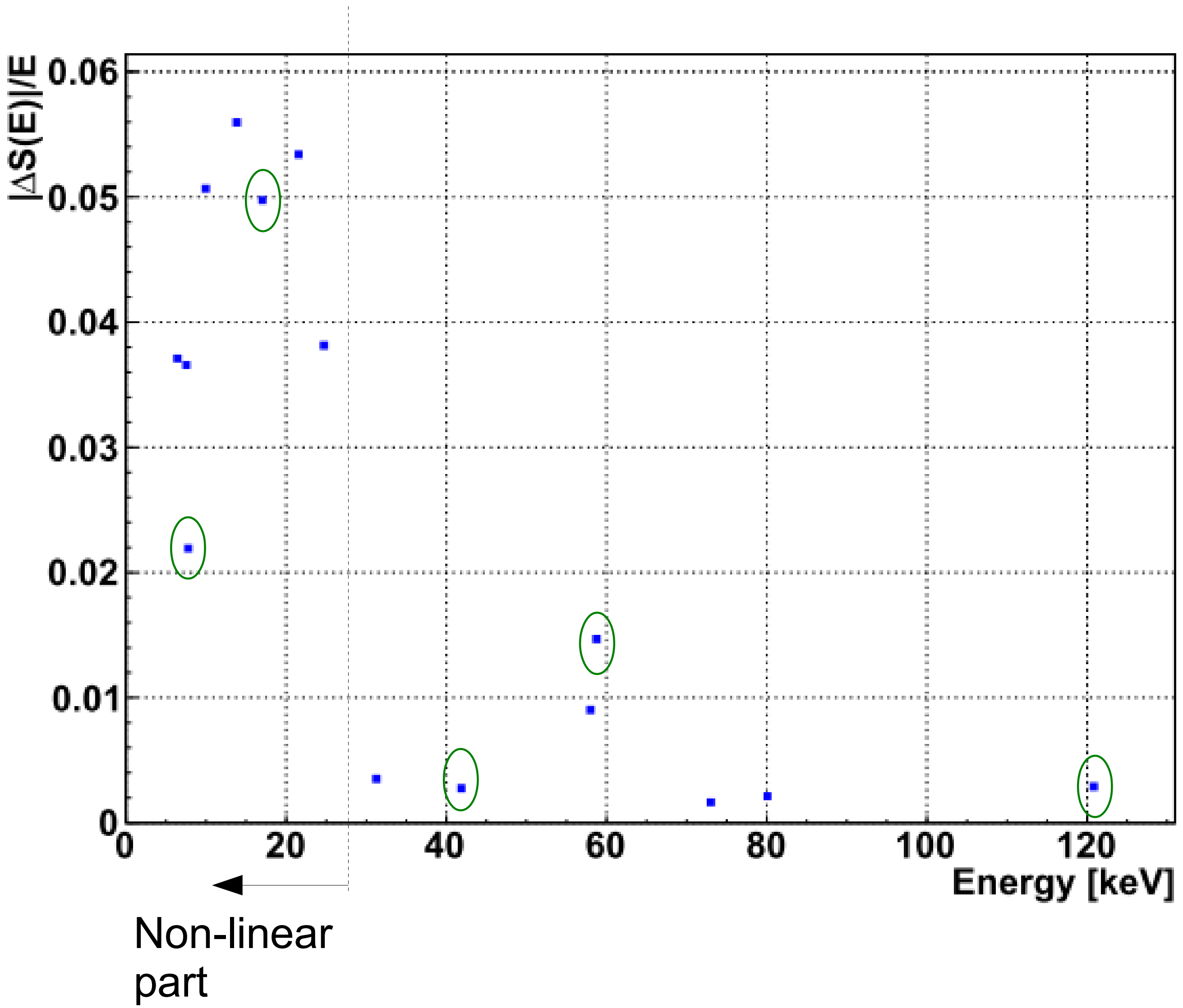
Calibration Curve Reliability Quantity



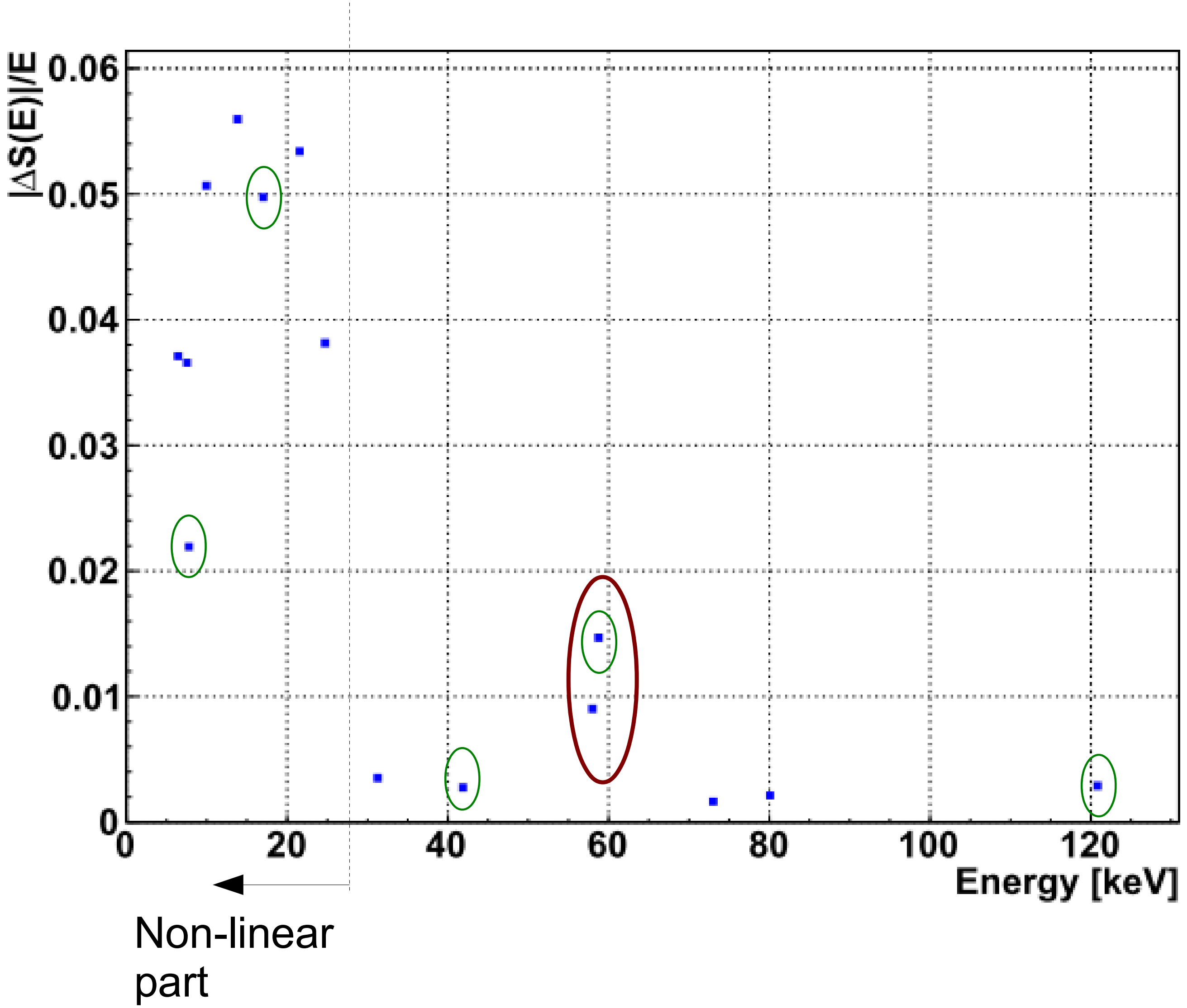
Calibration Curve Reliability within the calibration range



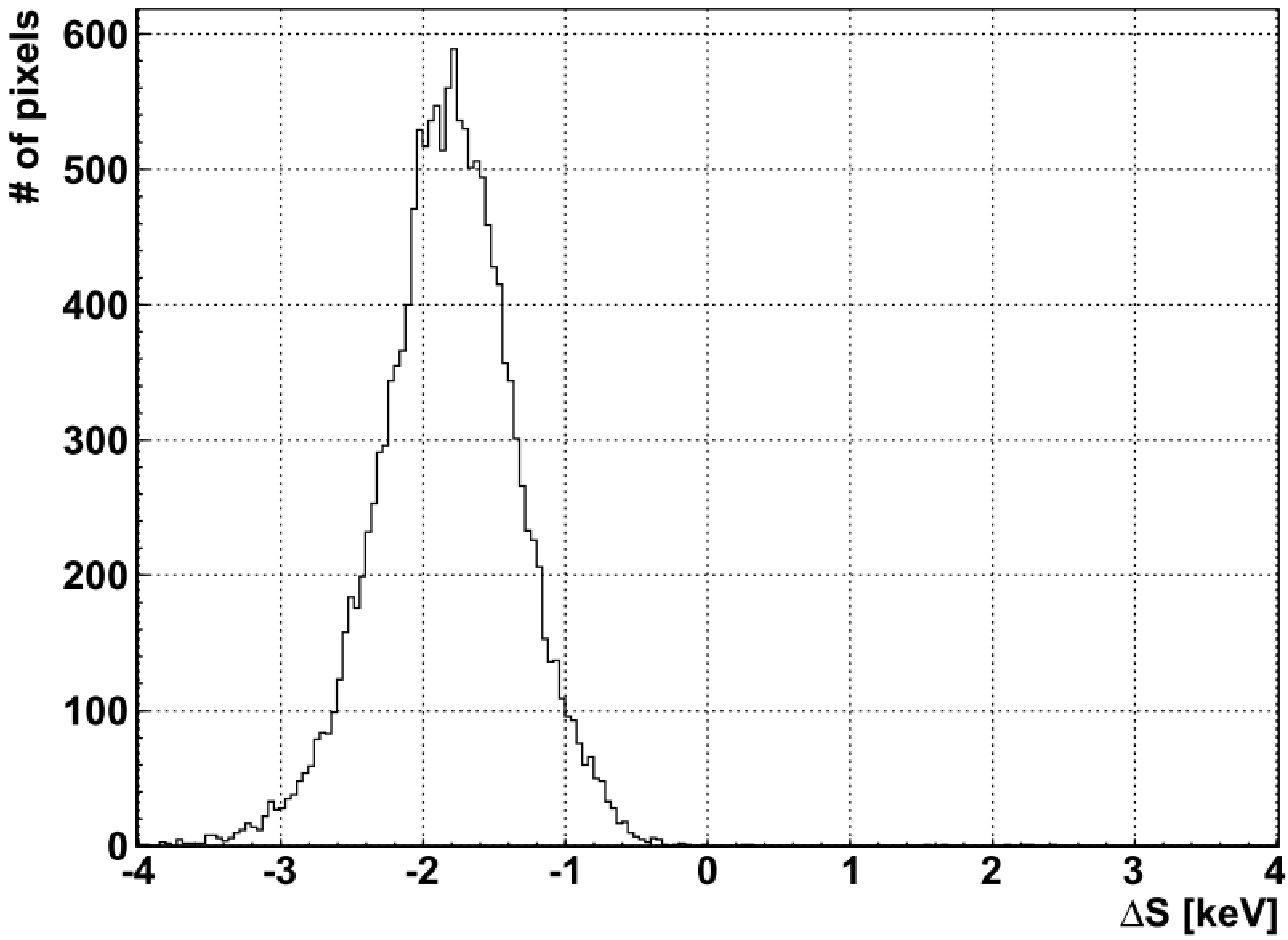
Calibration Curve Reliability within the calibration range



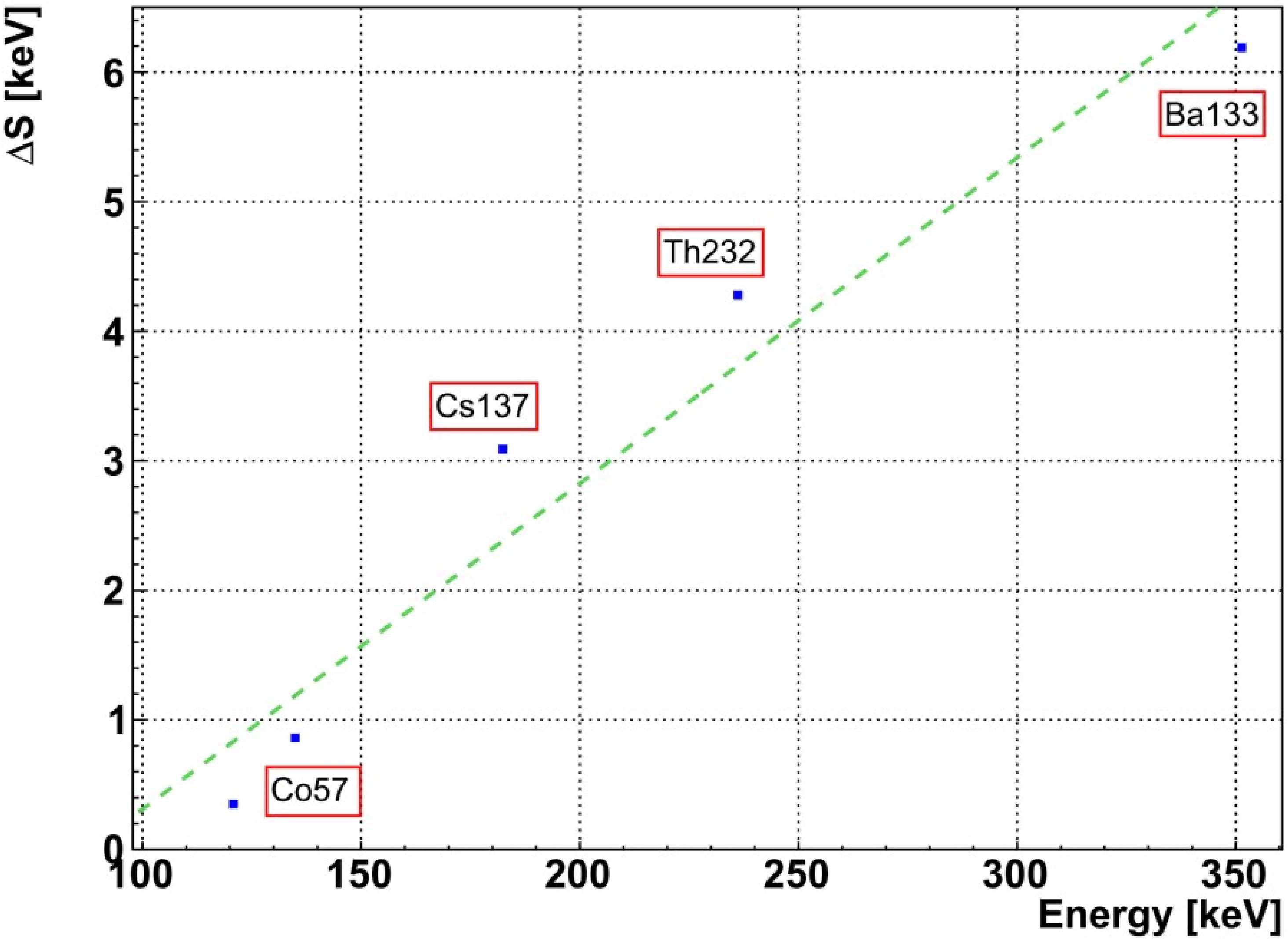
Calibration Curve Reliability within the calibration range



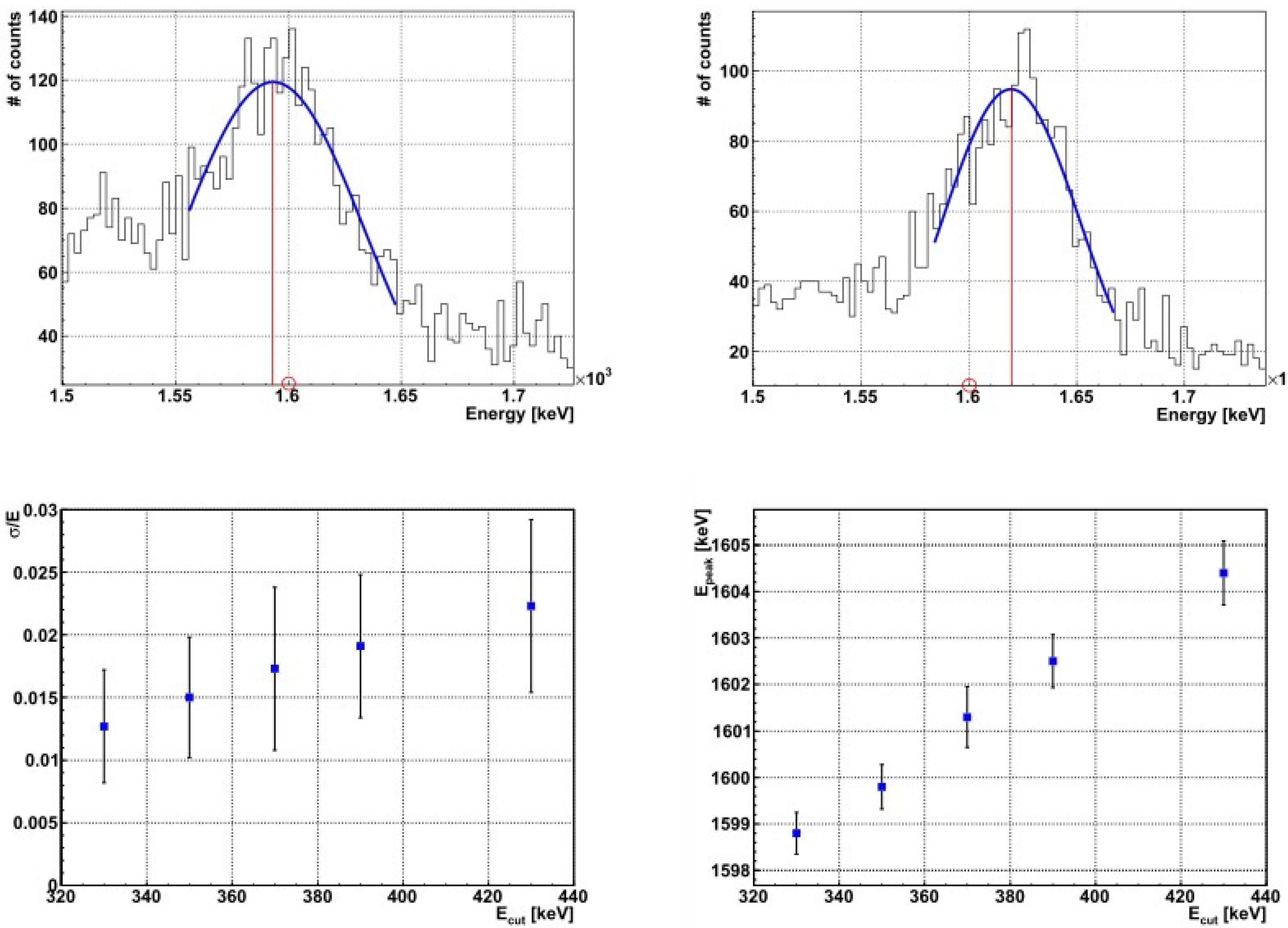
Calibration Error Distribution for Am-241



Calibration Error on Extrapolation



Energy Resolution (σ/E) for Tracks (TI-208)



Experimental Approach to the 0vbb

Cadminum Zinc Telluride **0**-Neutrino Double **B**eta **R**esearch **A**pparatus (COBRA):

Use a CdZnTe calorimeter with enriched Cd-116.

$$Q_{0\nu} = 2.809 \text{ MeV}$$
$$T_{0\nu} \approx 10^{27} a$$

Large scale Experiment:

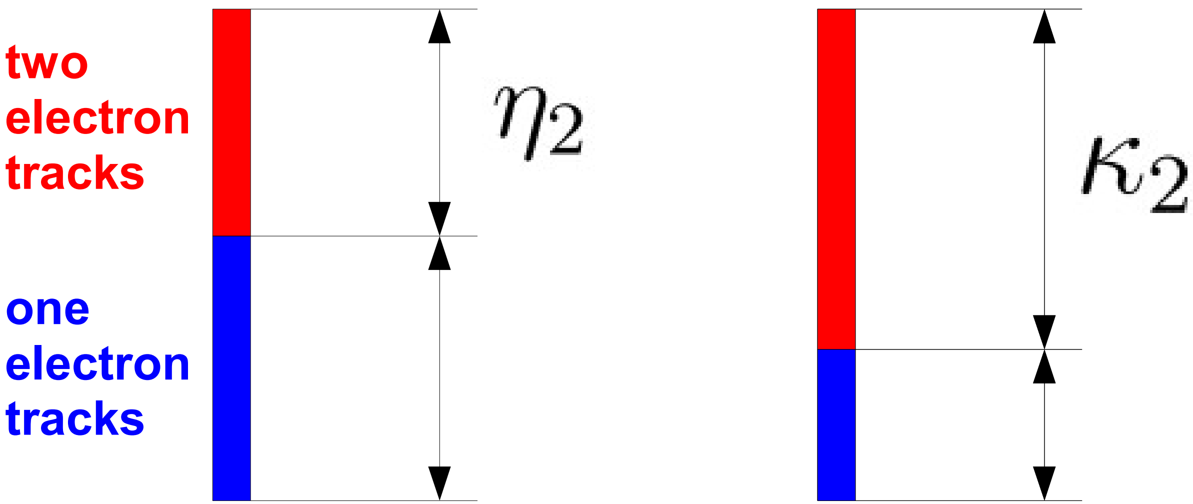
400 kg of Cd-116 observed for 5 years.

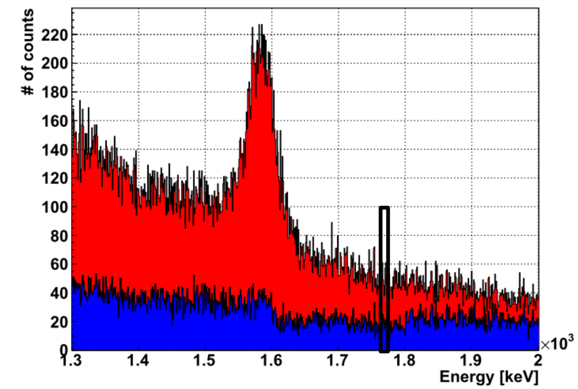
3 – 6 0vbb events are expected (for recent assumptions about the neutrino mass).

Main Task: Elimination of background.

Taking into Account Classification Errors

one energy bin



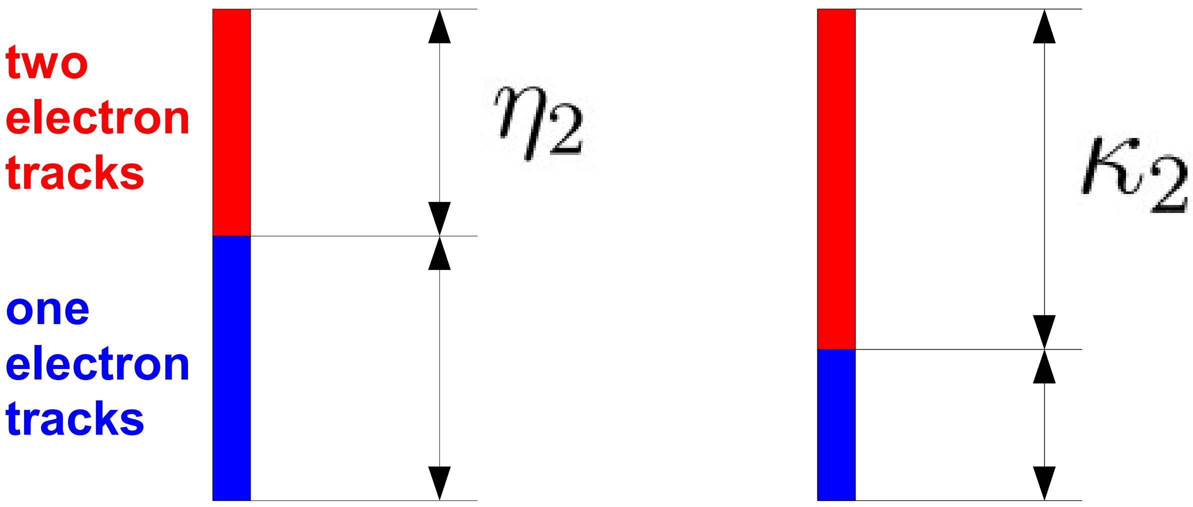


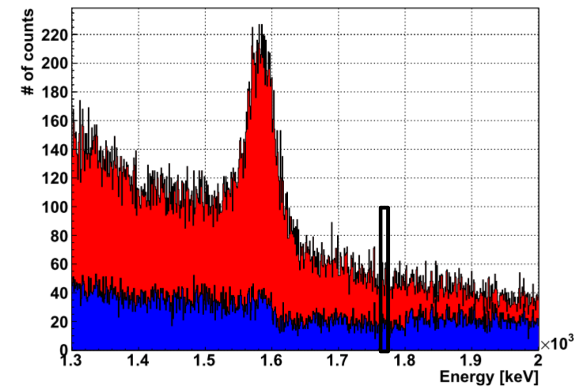
reality after classification

π_2 Number of correctly identified two electron tracks

Taking into Account Classification Errors

one energy bin





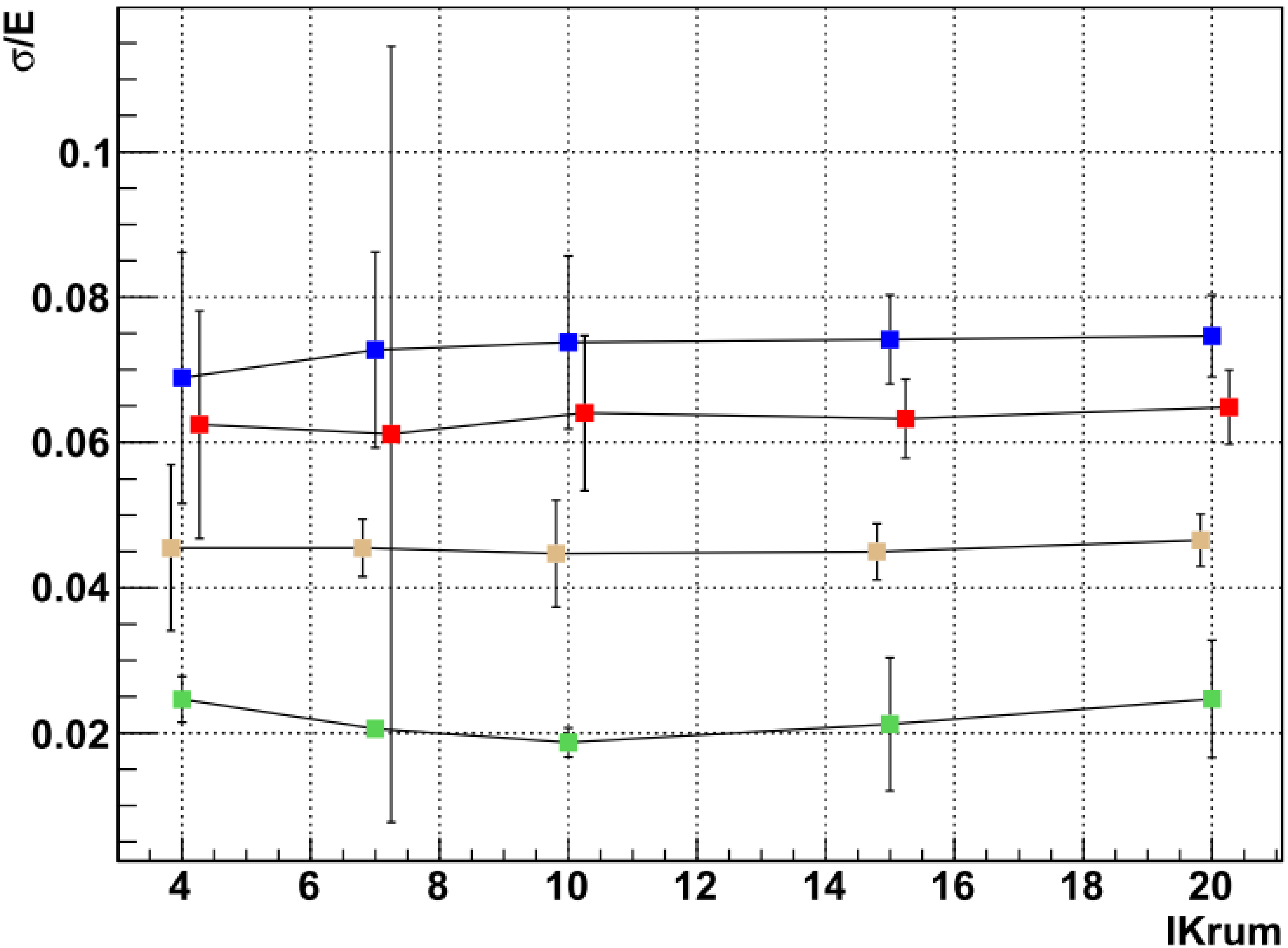
reality after classification

π_2 Number of correctly identified two electron tracks

$$\kappa_2 = \pi_2 \cdot \eta_2 + (1 - \pi_1) \cdot \eta_1$$

$$\eta_2 = \frac{1}{\pi_2}(\kappa_2 - (1 - \pi_1) \cdot \eta_1)$$

Energy resolution under various DAC settings - GC



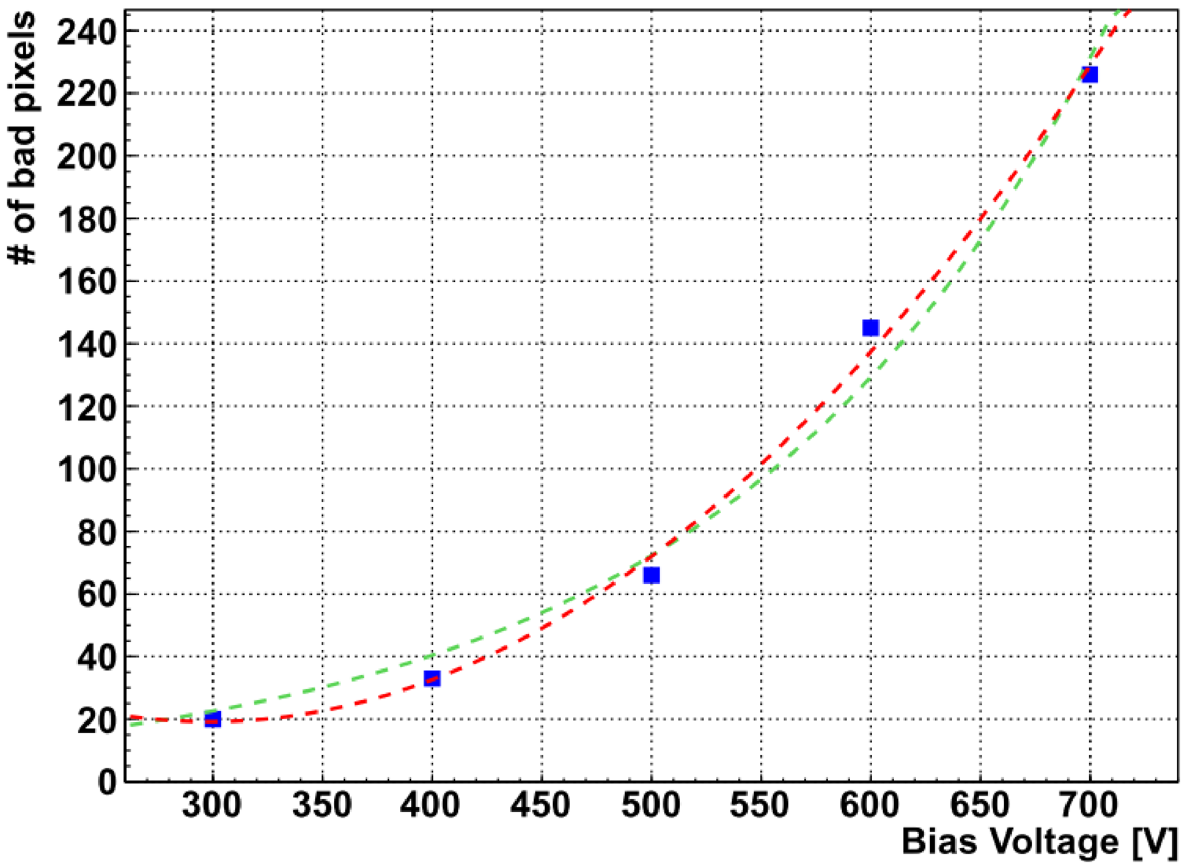
Am-241
59.54 keV

Ba-133
80.99 keV

Co-57
122.06 keV

α

Number of bad pixels with different bias voltages

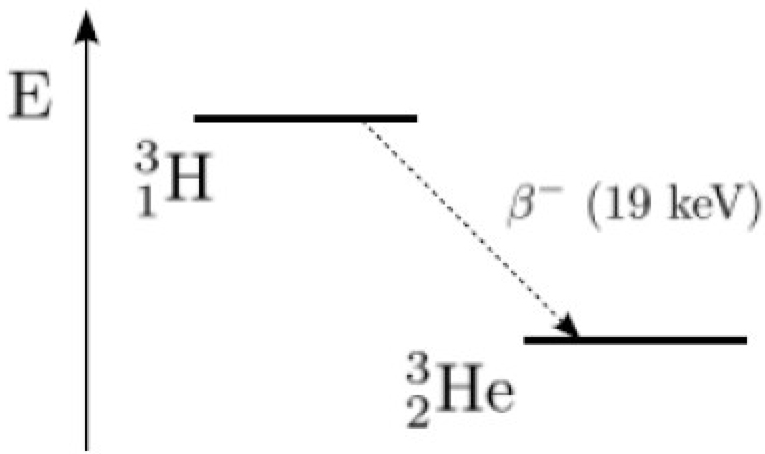


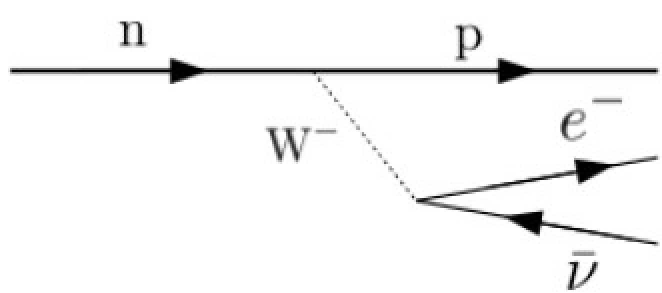
The interdependency between the number of bad pixels on the matrix and the bias voltage. A power law (red) of the form N(V) = $a \cdot (V - b)^2 + c$ and an exponential function (green) of the form N(V)= $a \cdot \exp(-b \cdot V)$ are shown as possible fit functions. The parameters are a = $1.3 \cdot 10^{-3} \pm 2.67202 \cdot 10^{-05}$, b = 298.4 ± 4.3 and c = 1.91 ± 0.95 (power law); a = 3.94±0.11 and b = $-5.81705 \cdot 10^{-03} \pm 4.51922 \cdot 10^{-05}$ (exponential).

About the Neutrinoless Double Beta Decay

Regular Beta Decay:

$$n \rightarrow p + e^- + \bar{\nu}_e$$



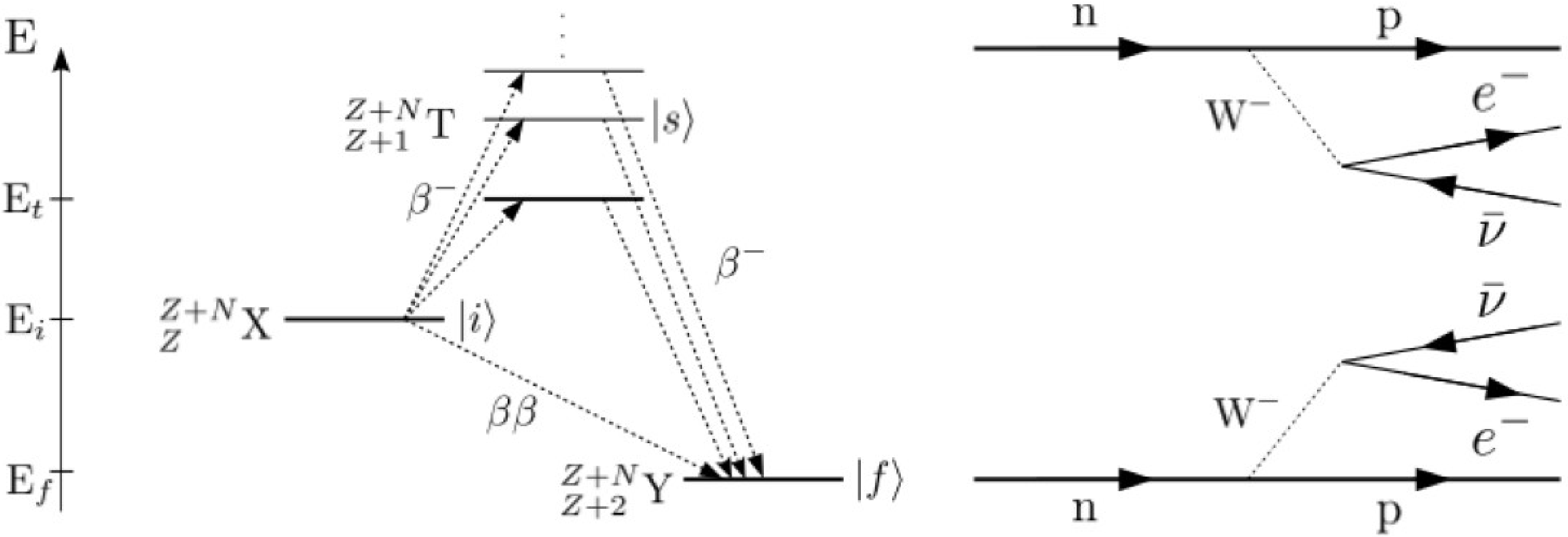


$$(T_{\frac{1}{2}})^{-1}_{1\nu} = \frac{2\pi}{\hbar} \left|H_{fi}\right|^2 G(E_f)$$

About the Neutrinoless Double Beta Decay

Double Beta Decay (2vbb):

$$2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$$



Identification of Muons

Muons:

Straight lines with homogeneously distributed energy deposition per pixel.
Identification by the reduced Hough Transformation.