JRJC 2024

Study of 39Ar Beta Decays in DUNE's Prototypes

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Emile LAVAUT

I. Context of DUNE

1. Neutrino physics
2. DUNE's Low Energy (LE) goals
3. DUNE's Far Detector (FD)
4. DUNE's prototypes (PDHD/VD)

II.Low Energy Calibration

1. Challenge : background
2. External source of calibration : 207Bi
3. DONUT Analysis

III. Results on PDHD

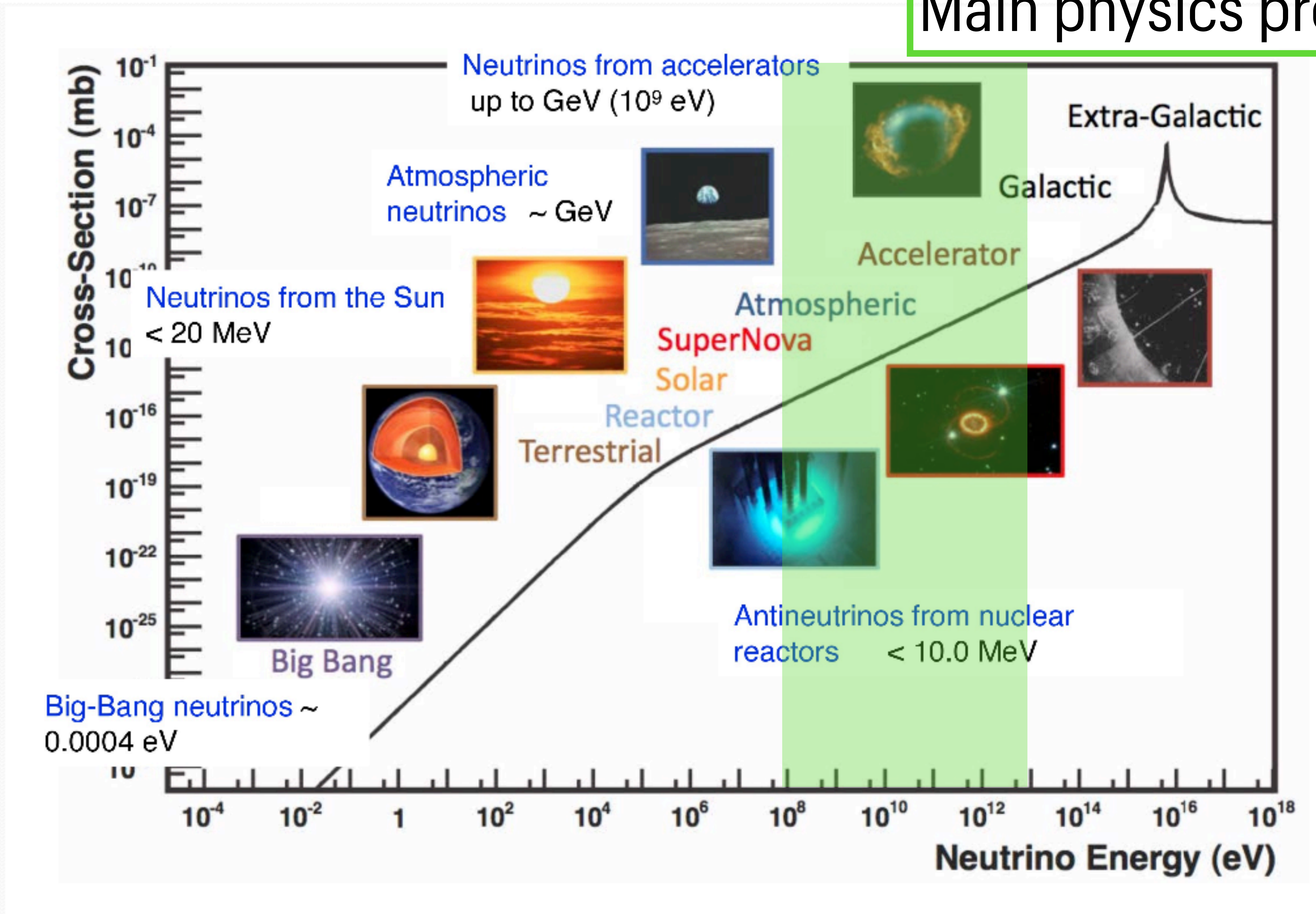
1. PDHD MC
2. PDHD calibration
3. PDHD data
4. PDHD 207Bi

Conclusion

I. DUNE’s context

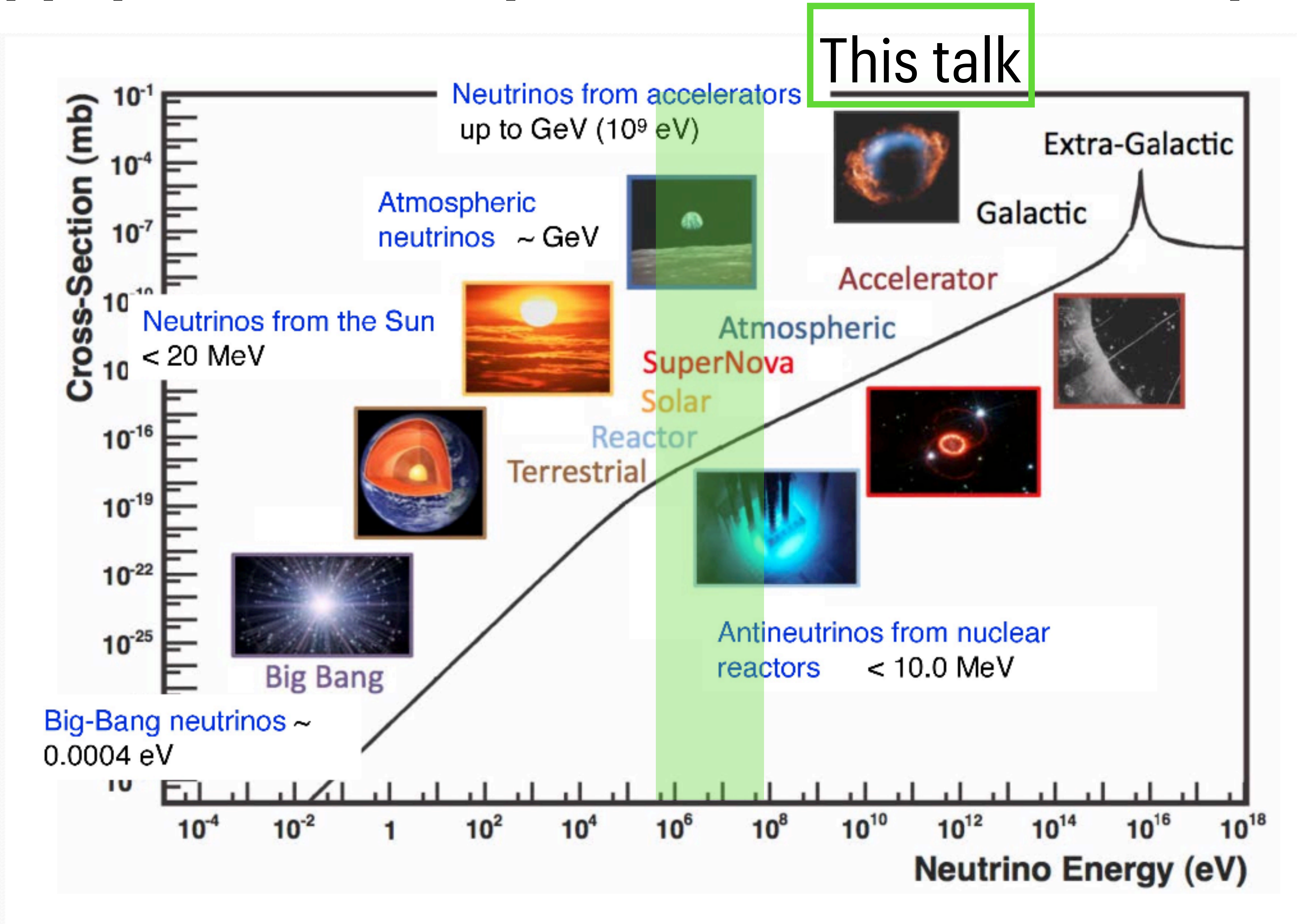
- Neutrino can be produced from very **different sources** in a **large range of energy**
- DUNE → **Accelerator,** atmospheric

Main physics program



I. Context of DUNE

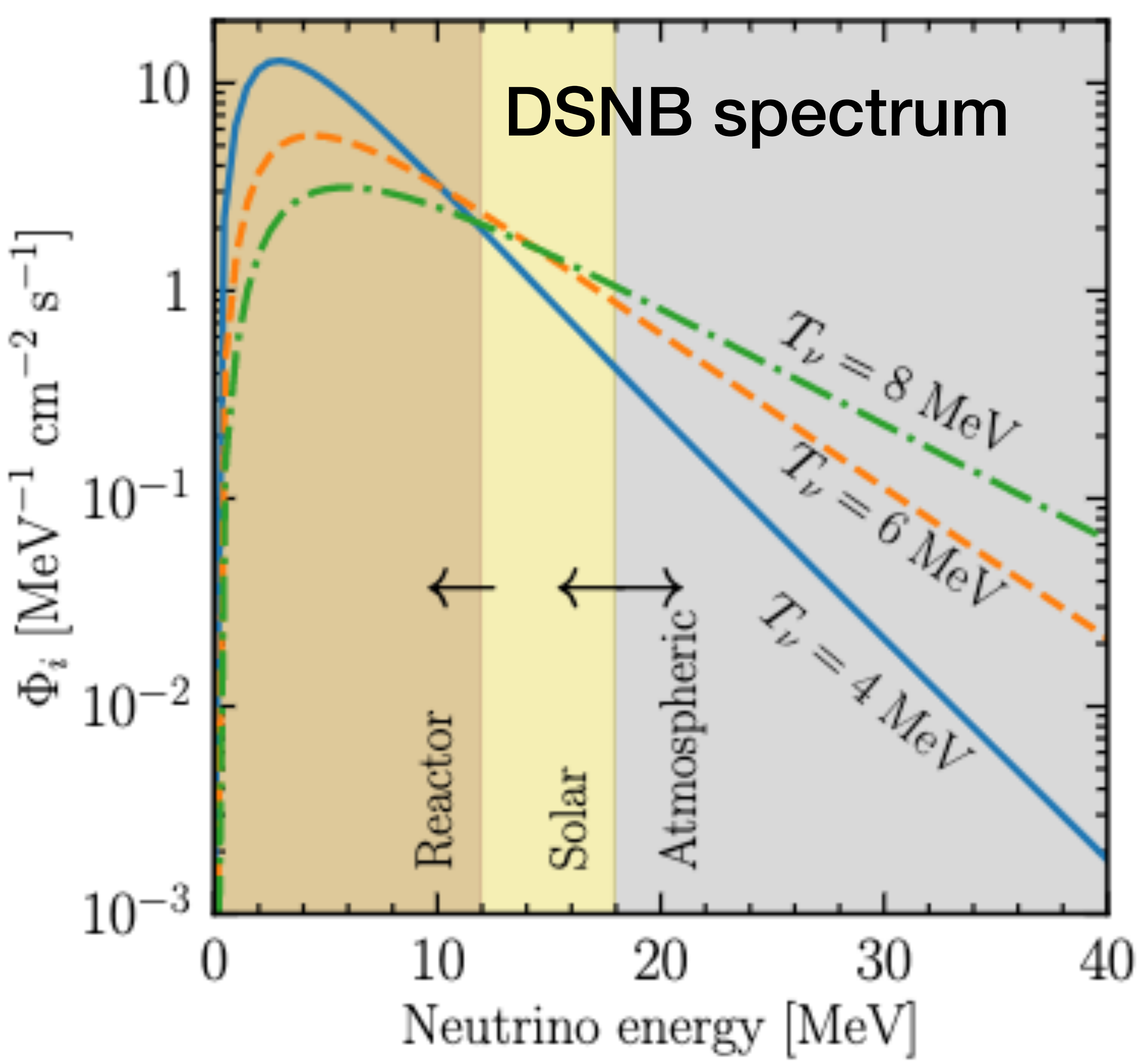
- Neutrino can be produced from very **different sources** in a **large range of energy**
- DUNE → **Low Energy physics : Solar, SuperNova (SN) and Diffuse SuperNova Background**

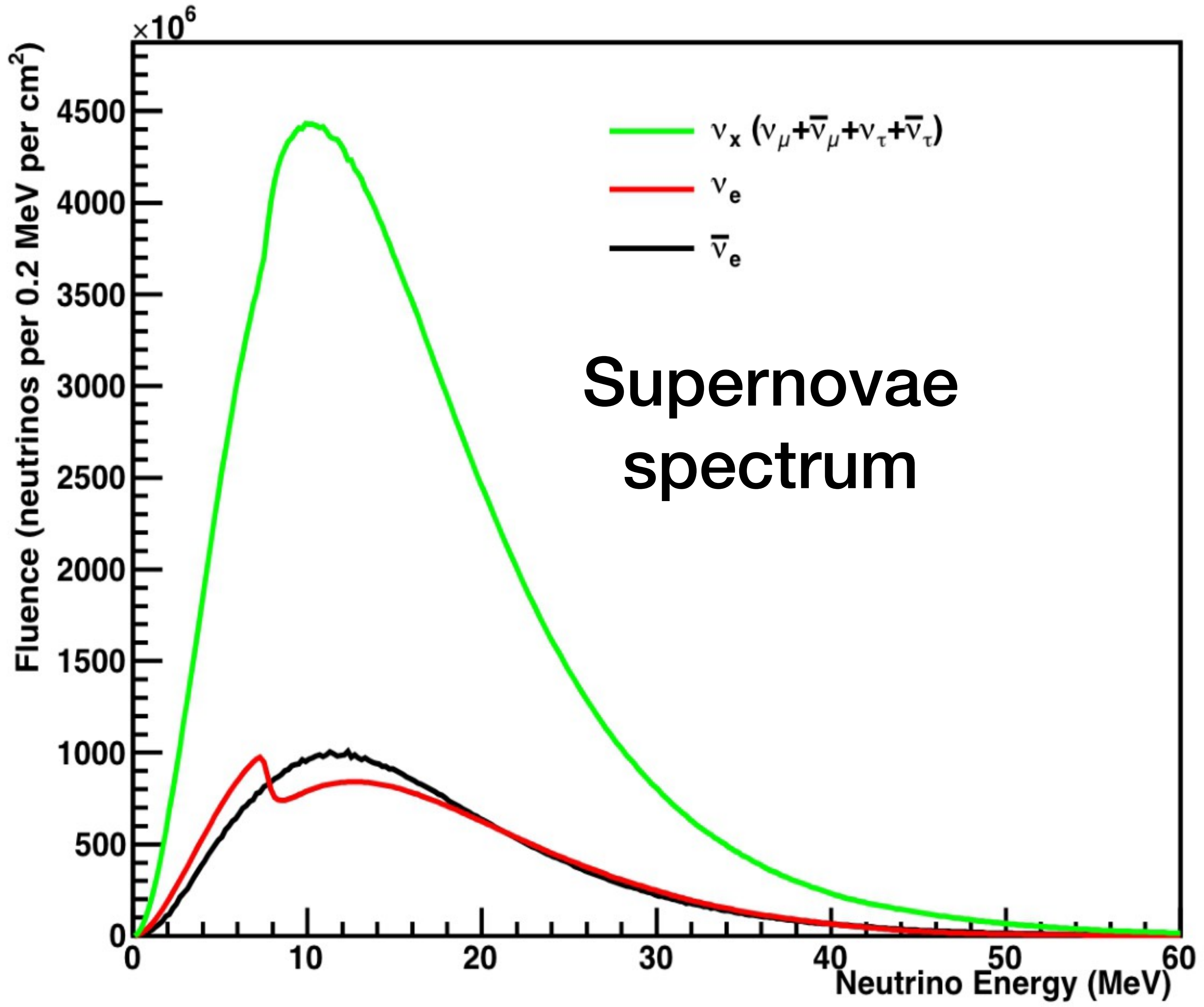


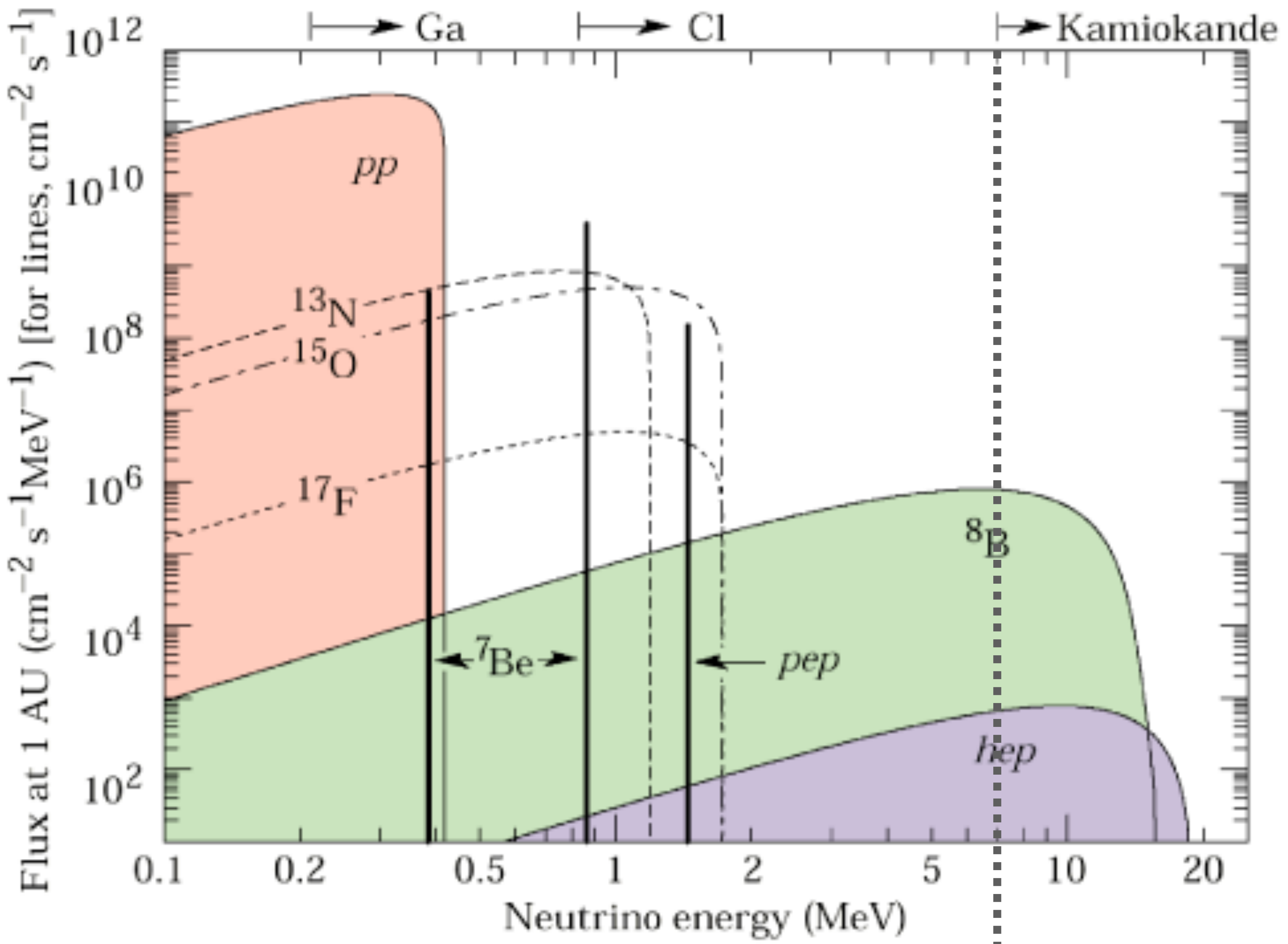
DUNE

I. Context of DUNE

- Solar neutrino's : may see **hep neutrino** for 1st time
- Supernovae :
  - **Supernovae burst**
  - Diffuse Supernovae Background (DSNB)







CC threshold for
$\nu_e + {}^{40}Ar \rightarrow {}^{40}K + e^-$

Neutrino physics
in the 0 to 10 MeV range

the energy spectrum of solar neutrinos.
Image reprinted from J. Bahcall,
A.M. Serenelli, and S. Basu Ap. J. 621, L85 (2005)

Figure from arXiv:1205.6003 [astro-ph.IM]

arXiv:2207.09632 [astro-ph.HE]

I. Context of DUNE

- DUNE is composed of three parts : **Accelerator**, **Near Detector** and **Far Detector**
- Long baseline neutrino experiment → Oscillation oriented experiment
- For **Low Energy Neutrino Physics (LE)** the **Far Detector** is very well suited

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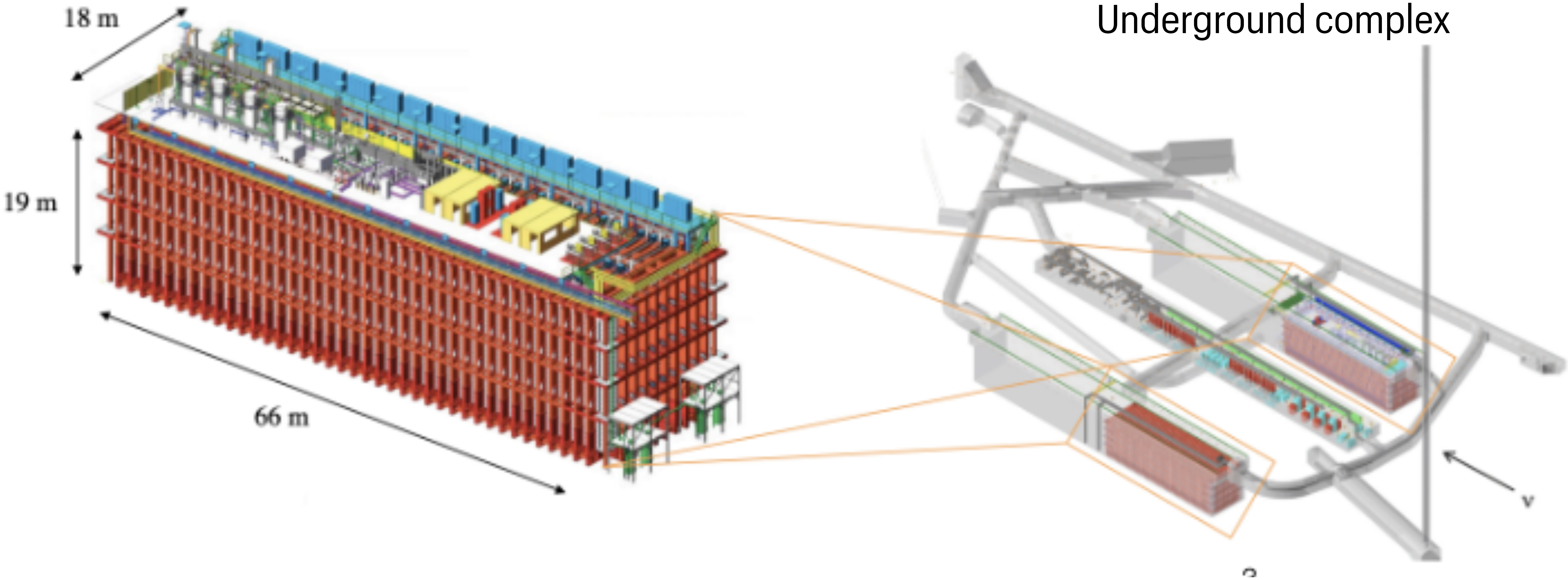
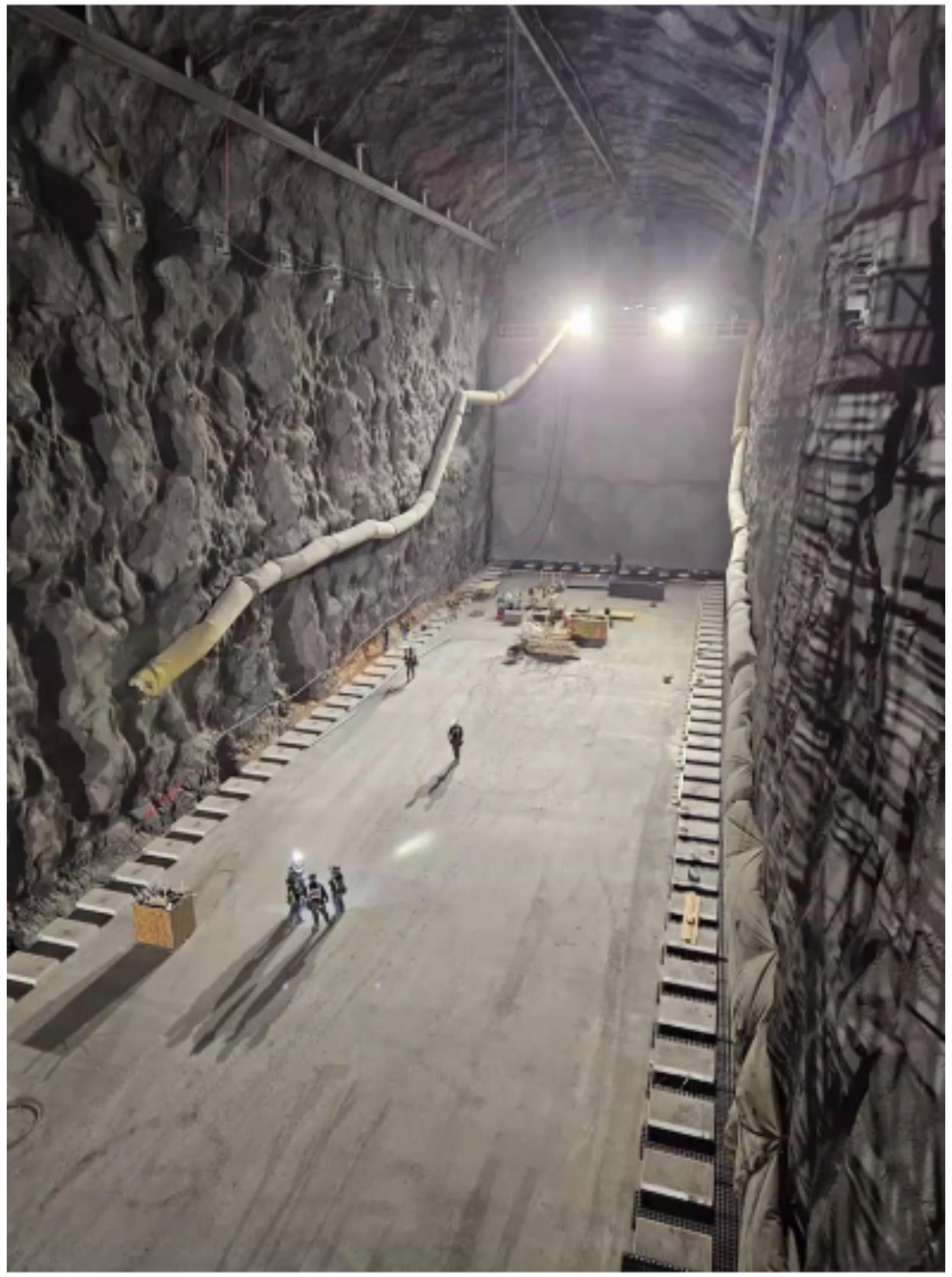
- DUNE is composed of three parts : **Accelerator**, **Near Detector** and **Far Detector**
- For **Low Energy Neutrino Physics (LE)** the **Far Detector** is very well suited:
  - Huge volume (20 kt each): good statistic
  - Underground: good cosmic rejection
  - Spatial and angular resolution (SuperNova Pointing)

- **Far Detector** = 4 cryostats with **LArTPC based technologies** with dimensions 66m x 18m x 19m
    - Cryostats 1 & 3 → **Vertical Drift design**
    - Cryostat 2 → **Horizontal Drift design**
    - Cryostat 4 → to be defined



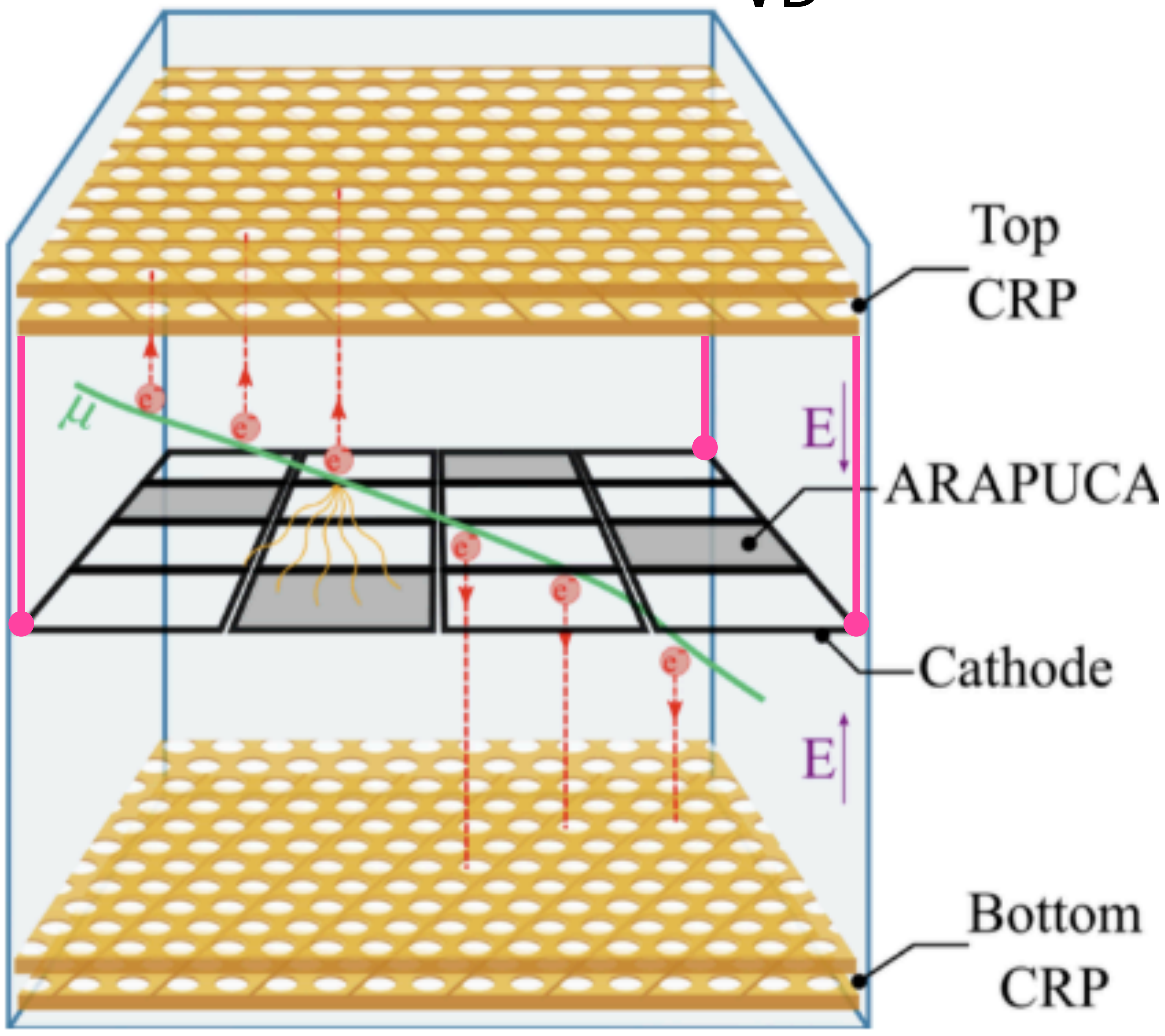


800 ktons of rock

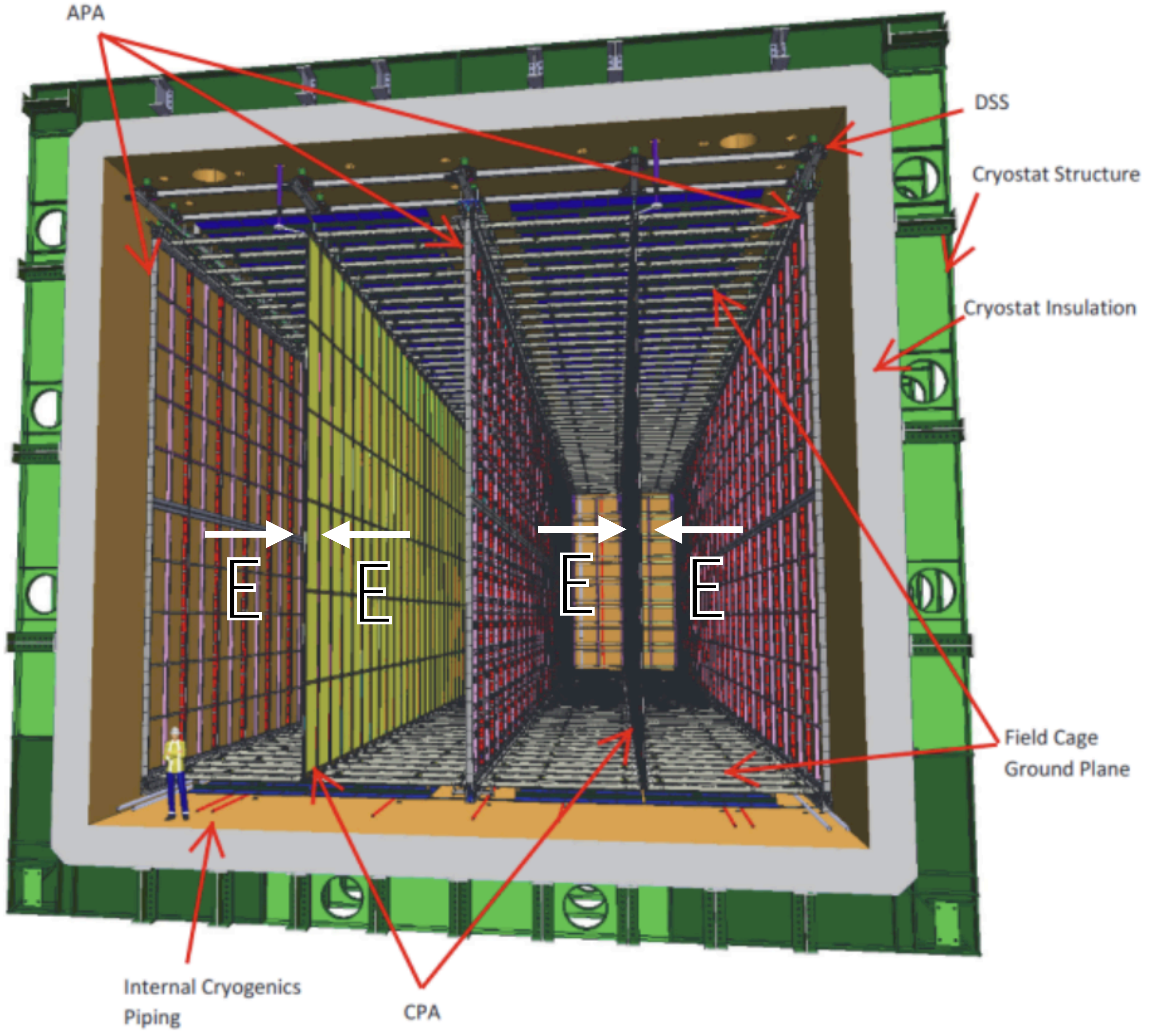
I. Context of DUNE

3. DUNE's Far Detectors (FD)

VD

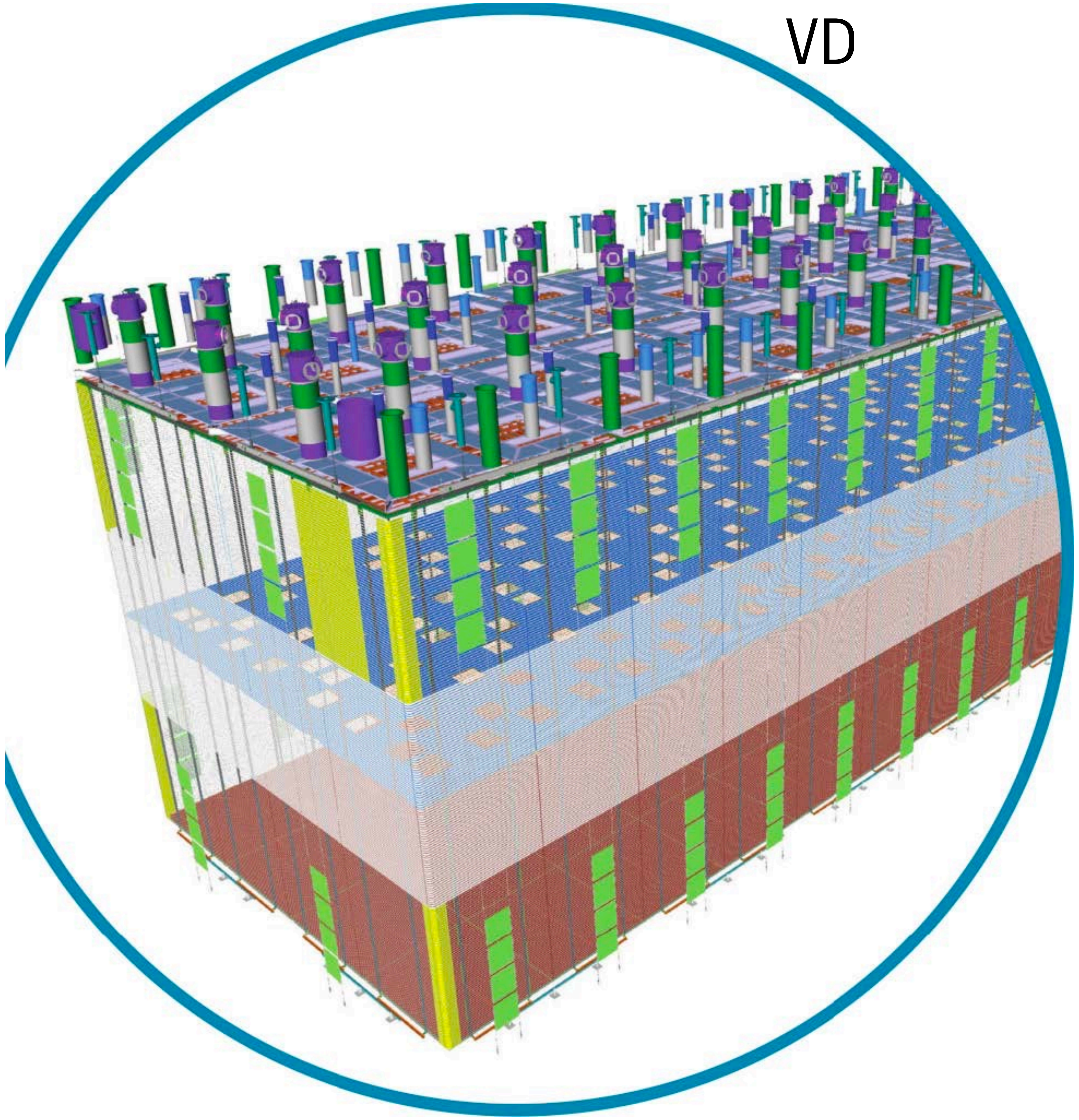


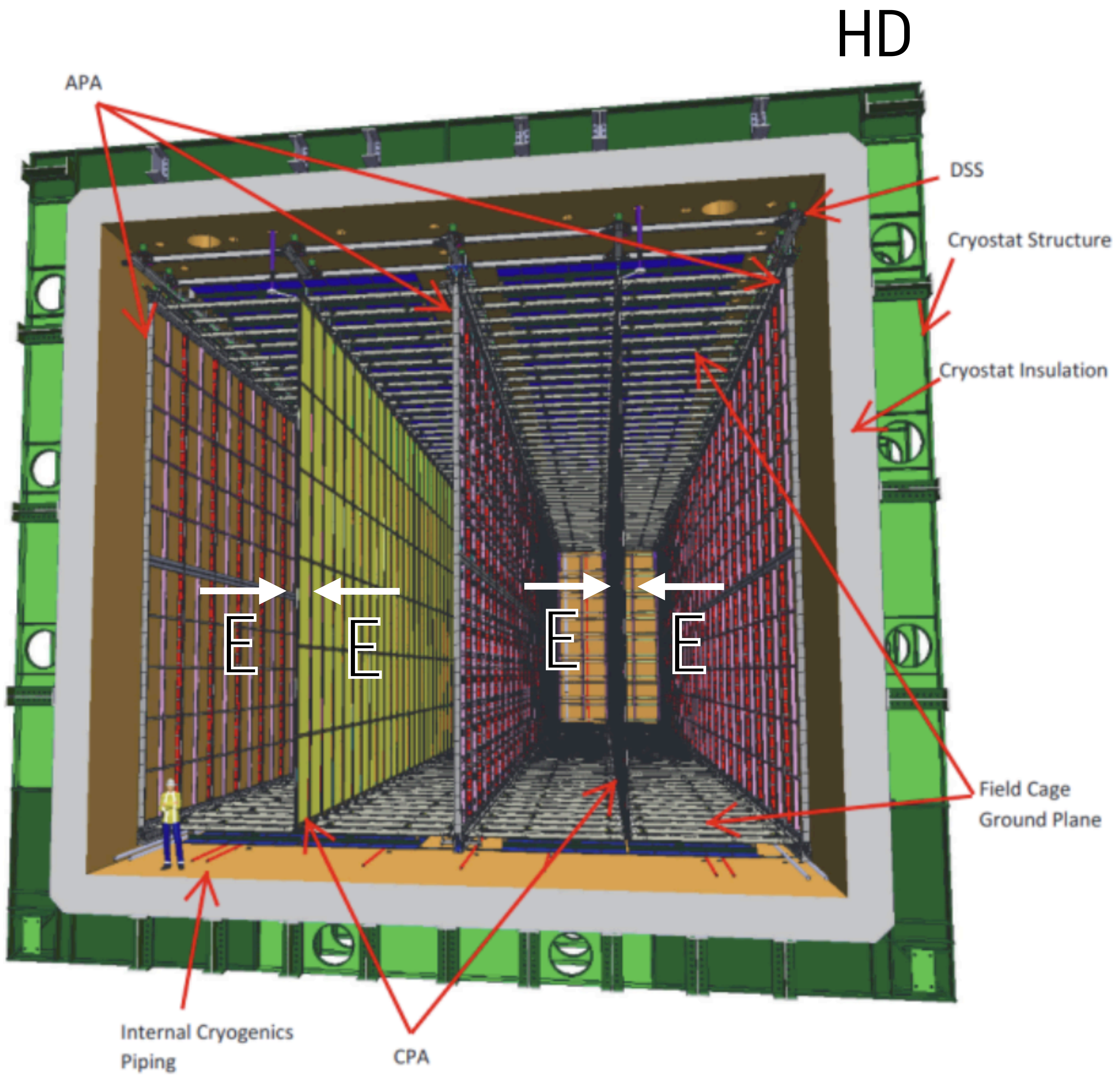
HD



IJCLAB is producing the cathodes for VD

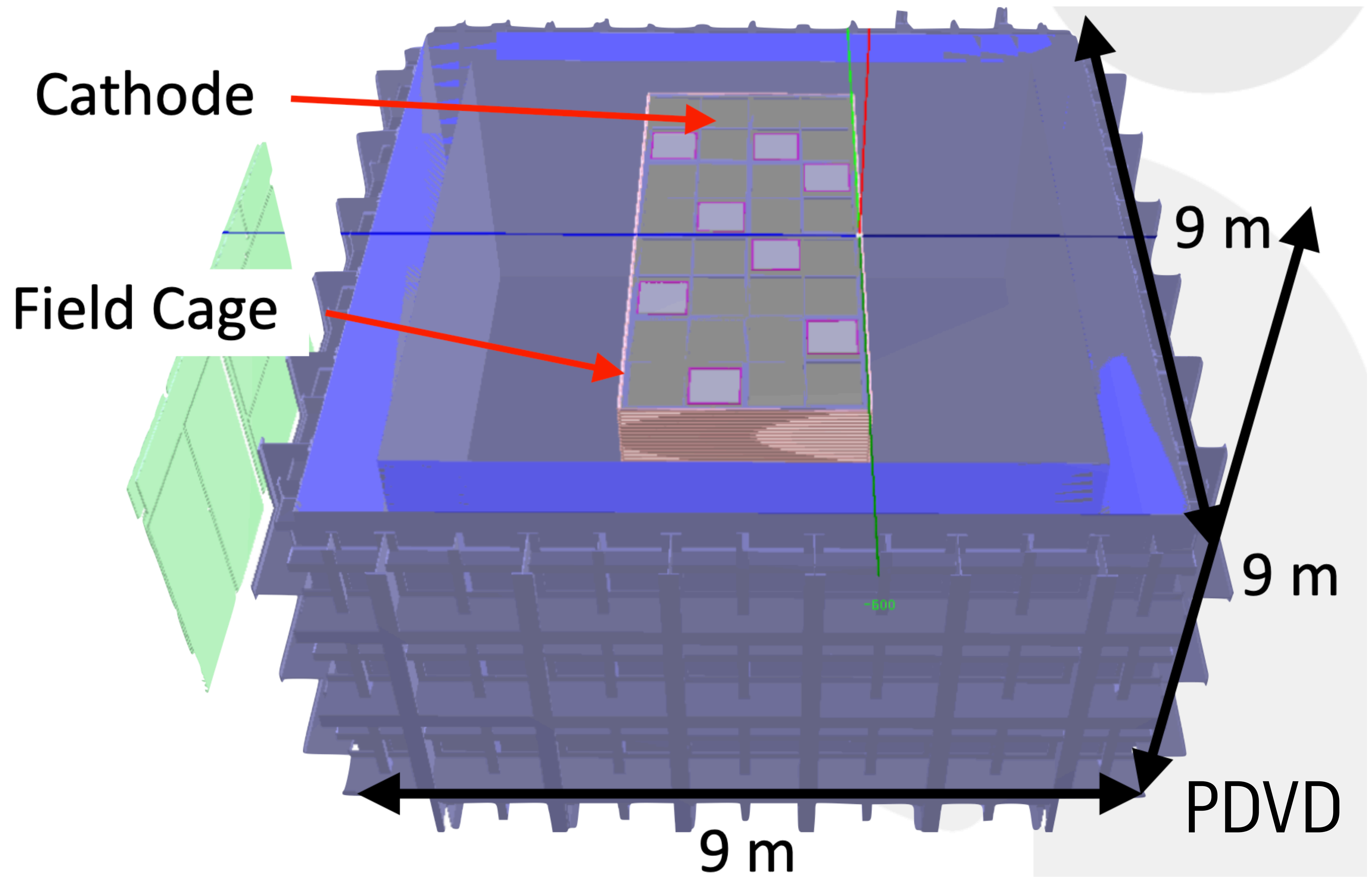
I. Context of DUNE

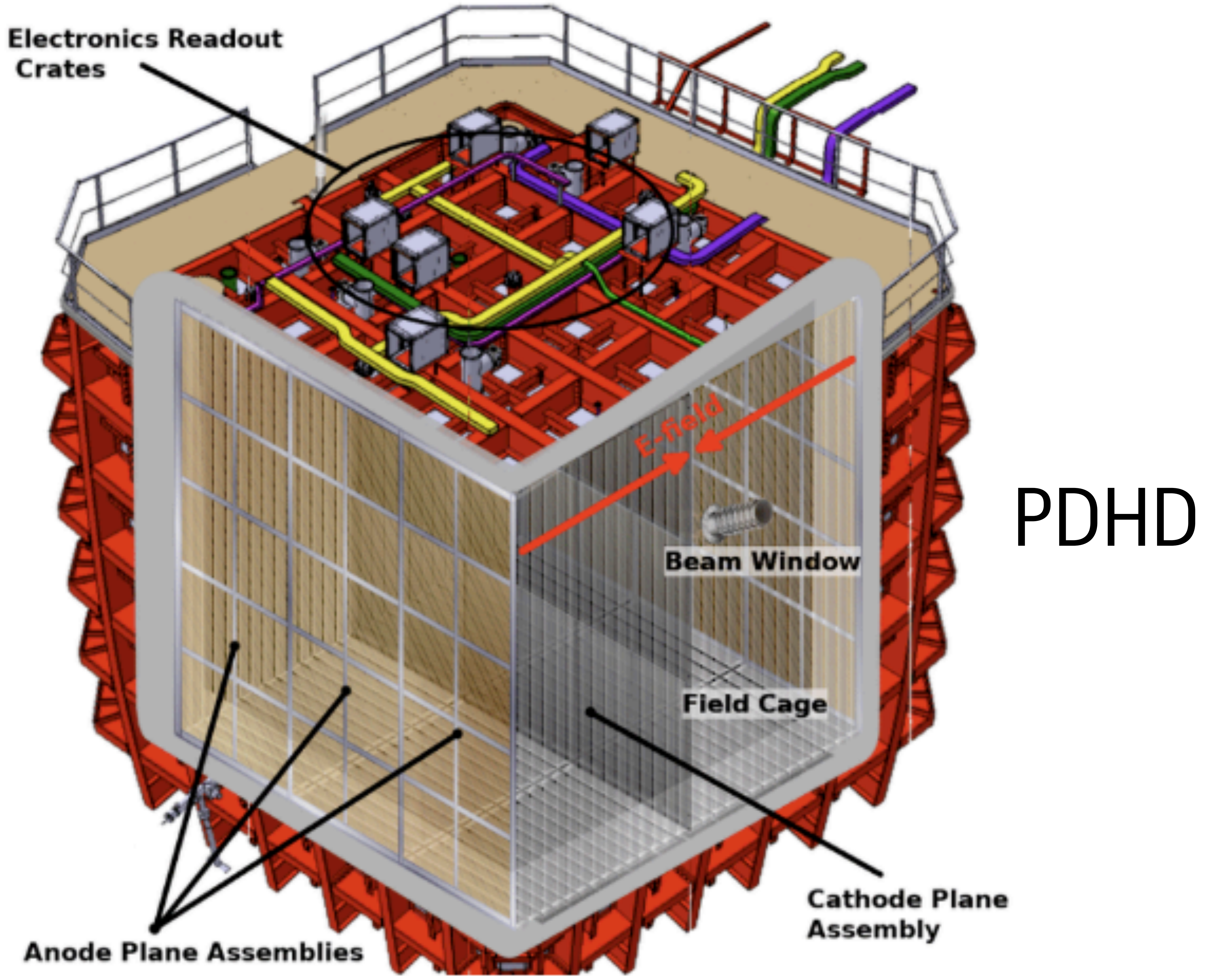




I. Context of DUNE

- 2 Prototypes @CERN on surface in 2 (9m x 9m x 9m) cryostats :
  - **ProtoDune Vertical Drift (PDVD)** → ready for LAr filling
  - **ProtoDune Horizontal Drift (PDHD)** → took data (May→November 2024)





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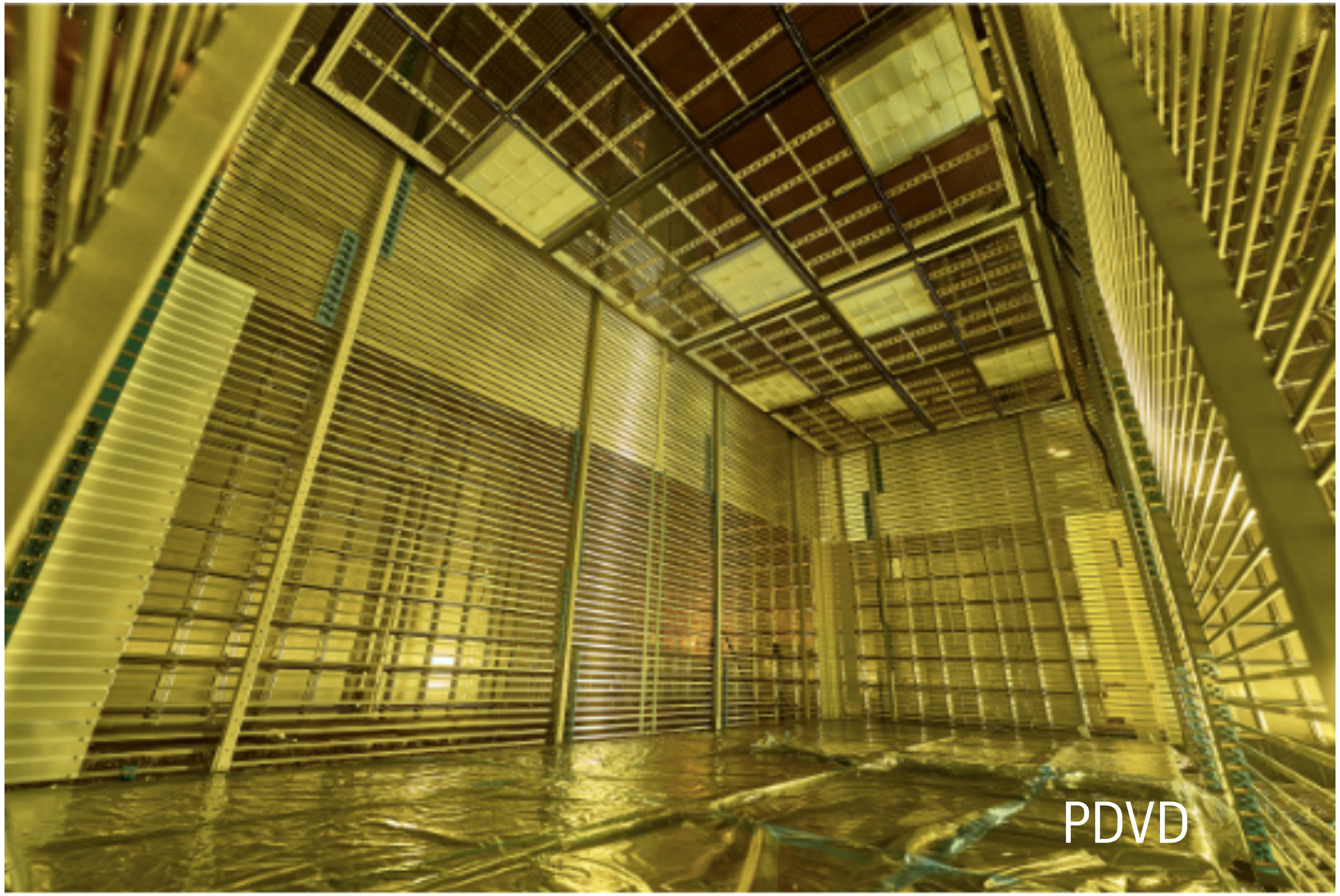
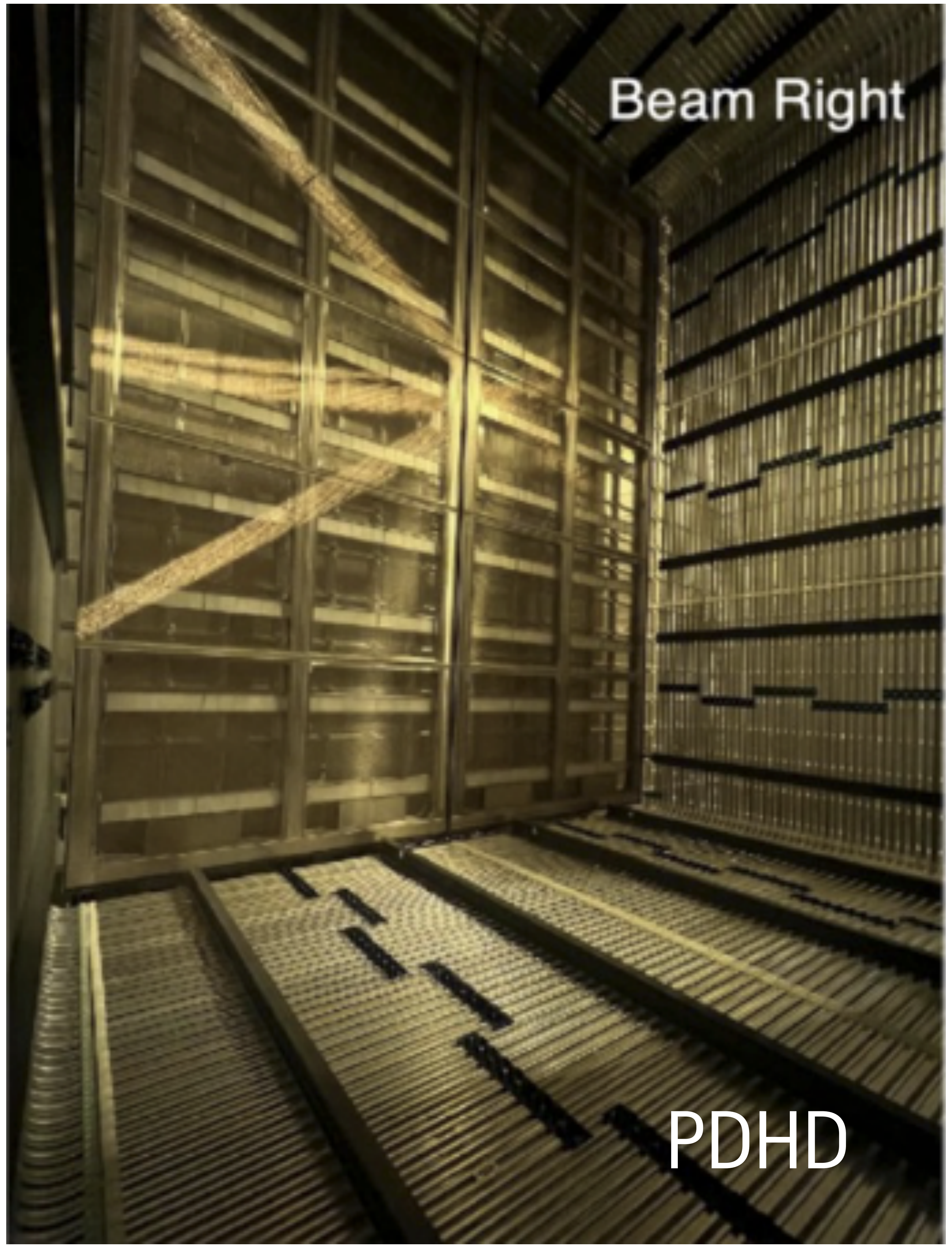


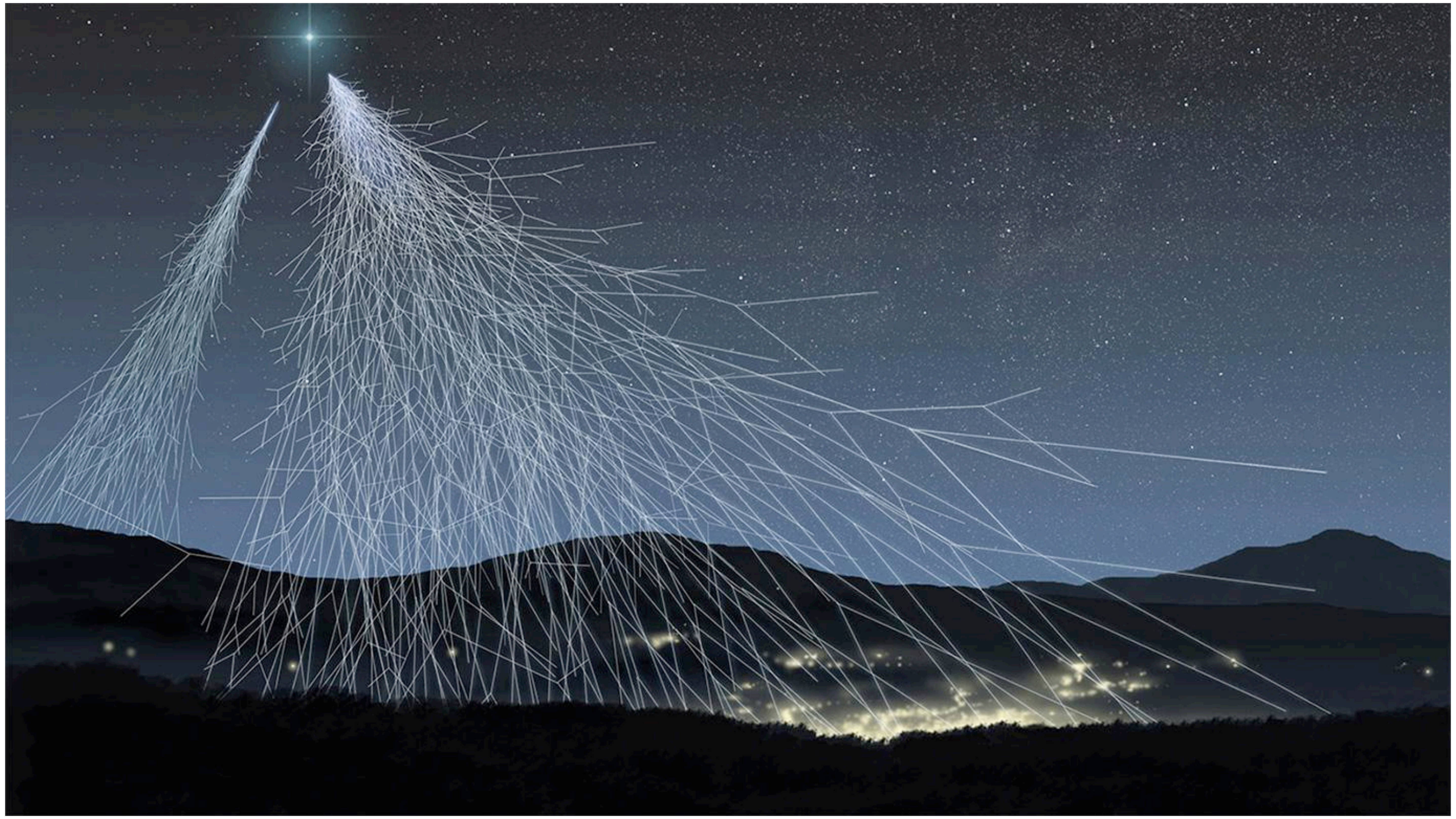


II. Low Energy calibration

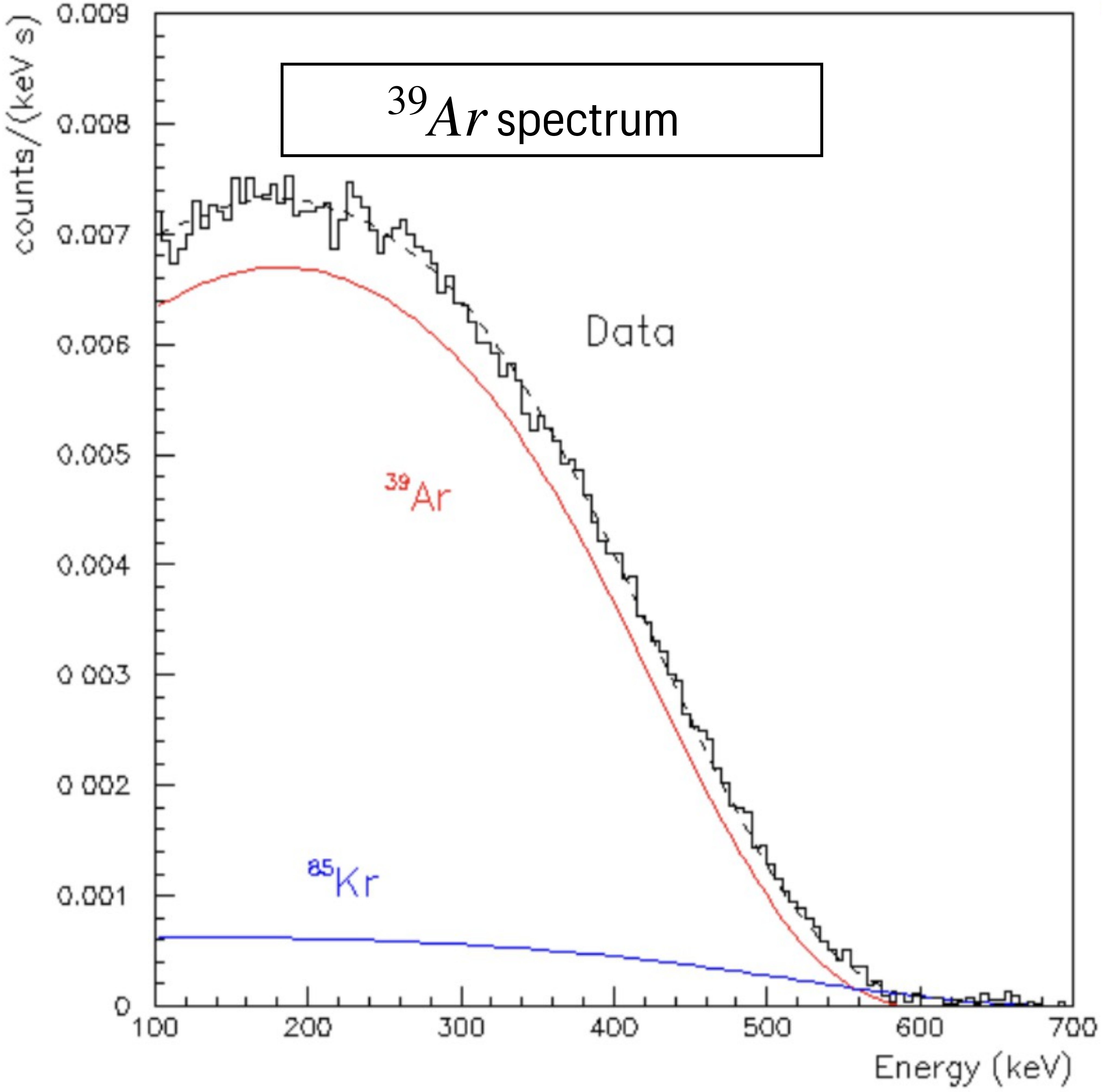
II. Low Energy at DUNE

- **Cosmics :**
  - **O(2000)/second** for surface detector → **ProtoDUNEs (PDVD/HD)** (0.75 kt detector)
  - O(0.01)/second ie **O(4000)/days** for underground detector → **FD** (20 kt detector)

If we want to perform Low Energy analysis we need to differentiate signal from cosmics events



- **Cosmics** (suppressed a lot in FD)/**radiologicals** but important for prototypes (PD) @CERN
- **point-like signals : (radioactive decays) :**
  - Internal radioactivity, in LAr mainly ^{39}Ar (+^{85}Kr)
    - FD : ~10^7 decays/s
    - PD : ~10^5decays/s

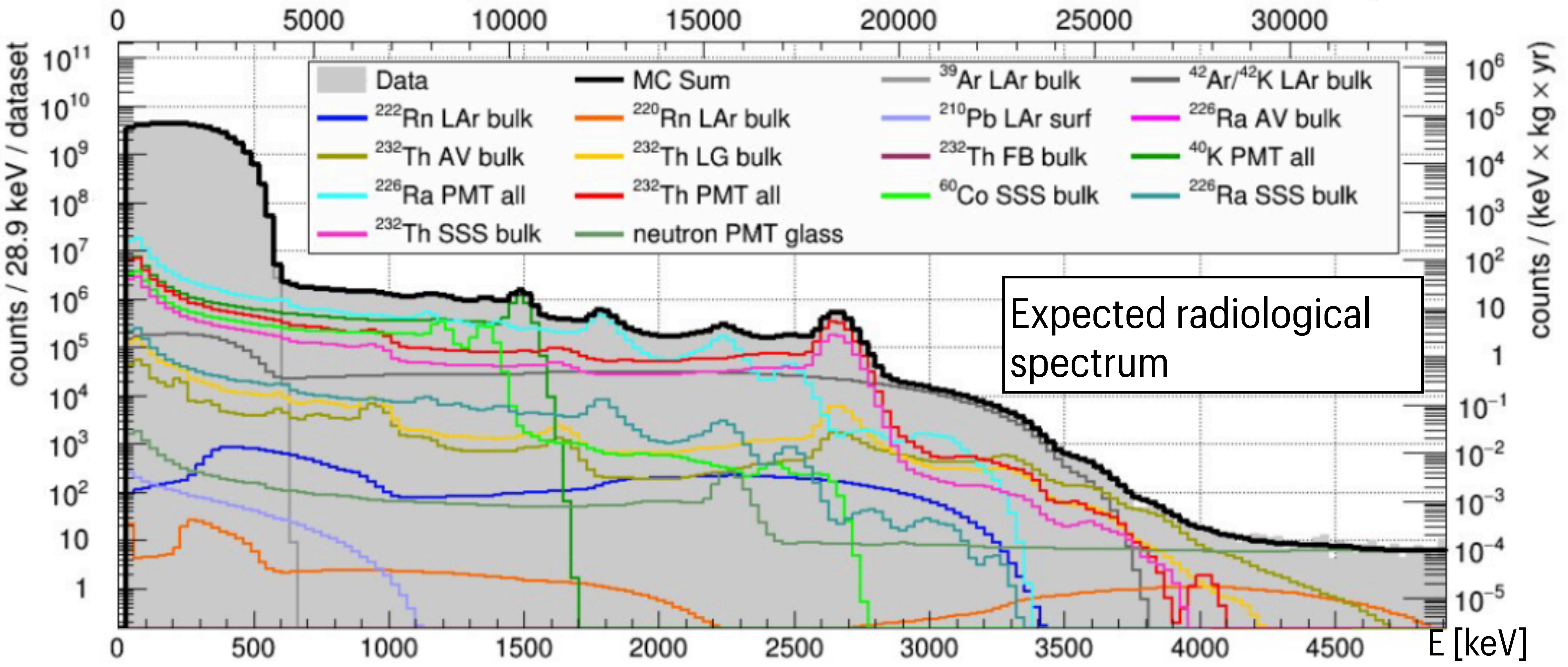


With its huge statistic ^{39}Ar is a good source of calibration for LE

- Cosmics
- **point-like signals : (radioactive decays) :**
    - Intern radioactivity, in LAr mainly ^{39}Ar (+^{85}Kr)
    - ^{42}K, ^{232}Th, ^{222}Rn chain, ^{238}U chain from detector component (anode, cathode, field cage …)

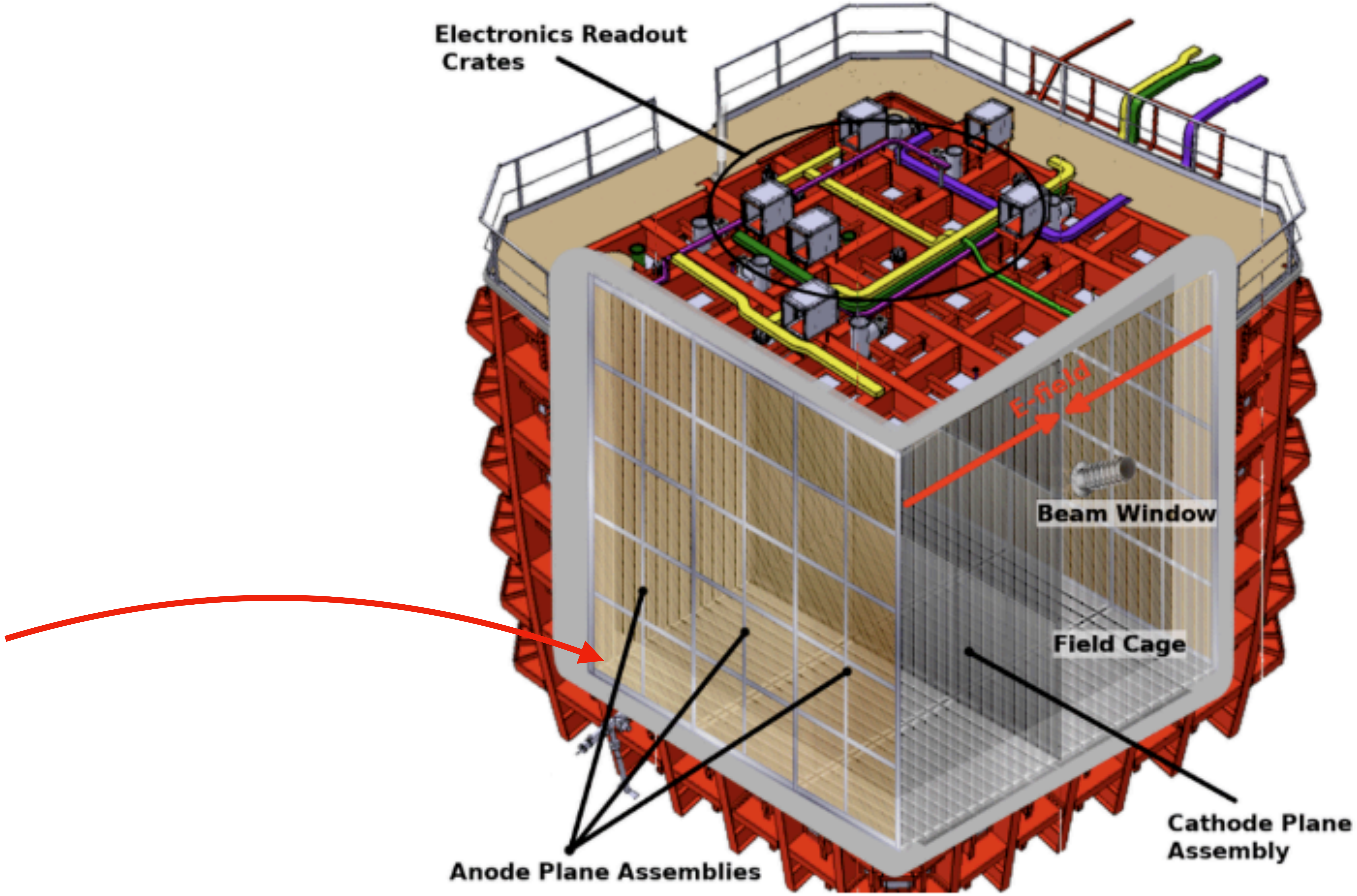
Example: Background measurement with DEAP-3600 (3.3 tonne LAr dark matter detector at SNOLAB)

If good suppression of cosmics this kind of spectrum can be used for calibration



DUNE

- A **207Bi** source has been placed in PDHD on APA 2 in bottom left corner



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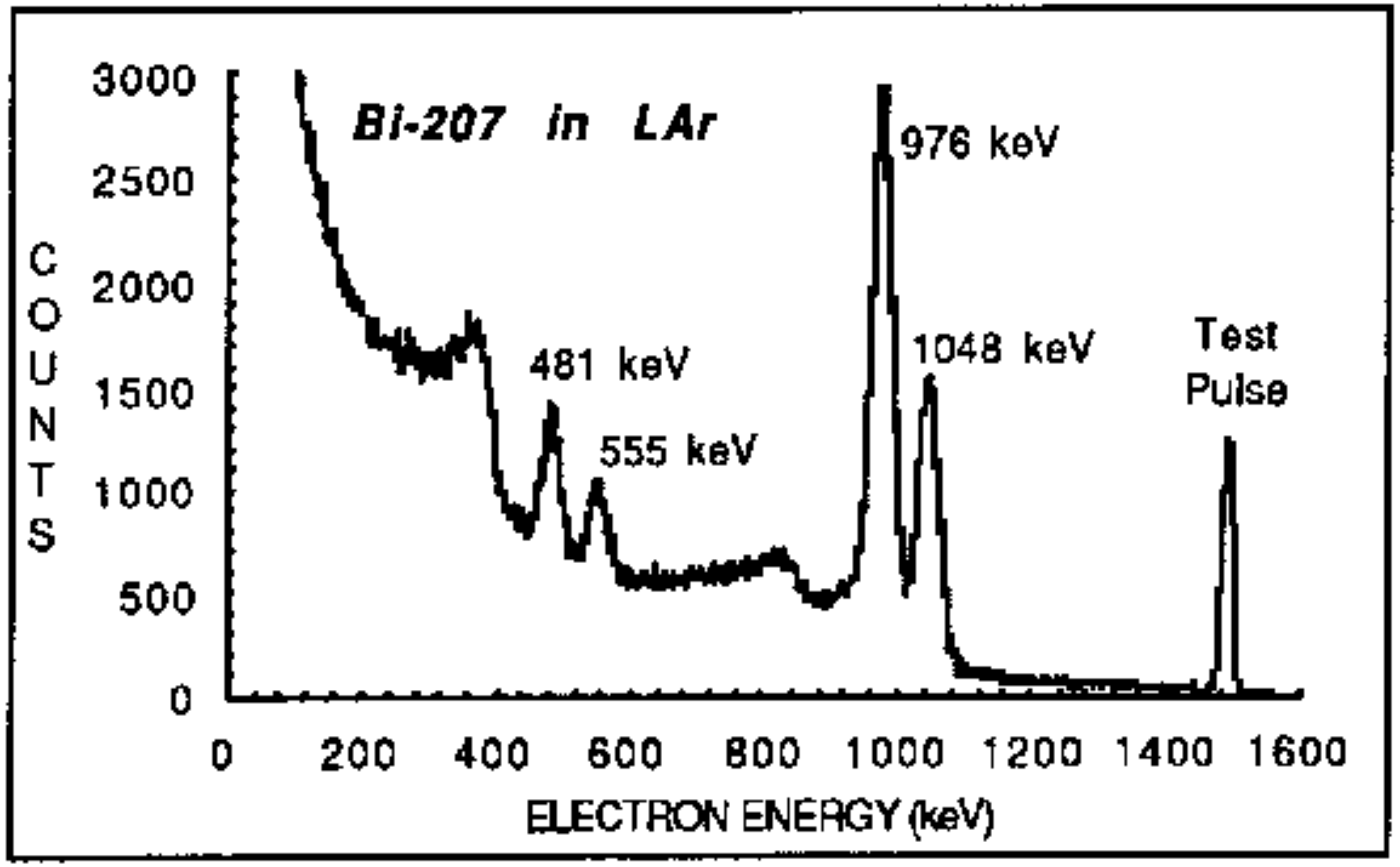
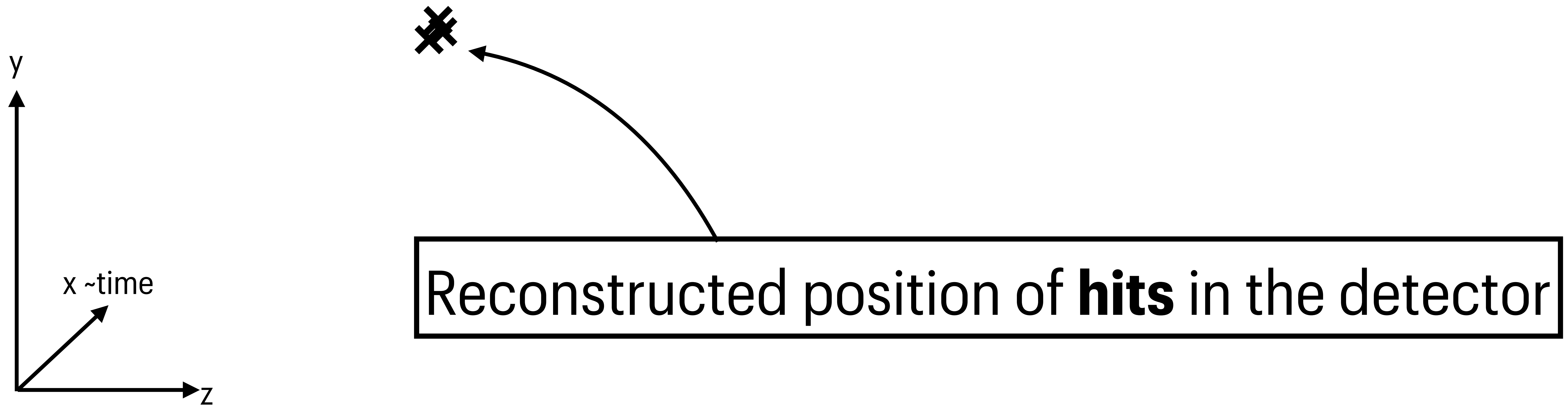


II. Low Energy at DUNE

- Identify radioactive decays (^{39}Ar) in PDHD data/simulation
- I'm looking for **localised and isolated** signals in PDHD



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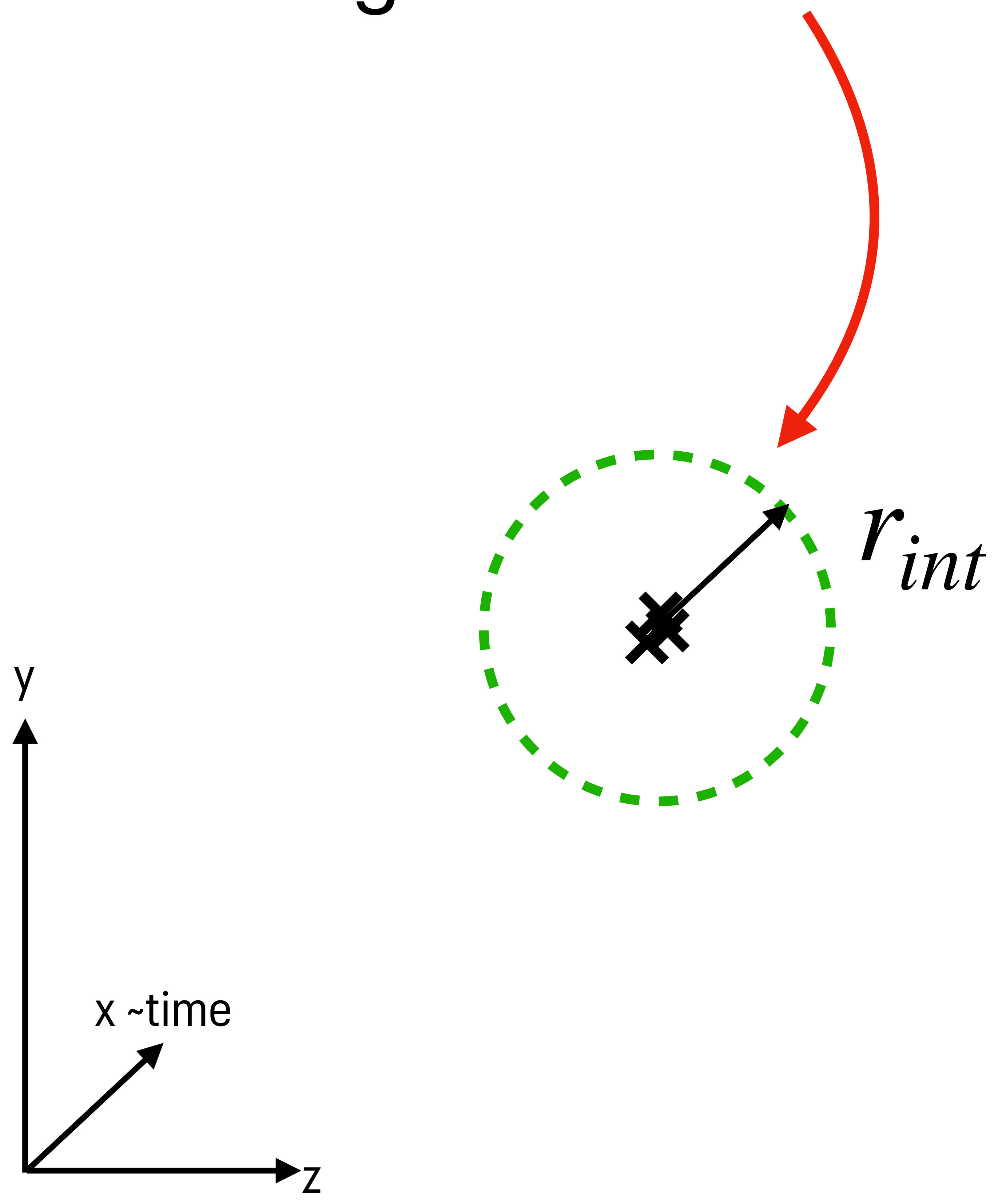

It insures a **veto against high energy deposits** → in TPC the electron cloud due to ionisation (and its spreading) is correlated to the initial energy deposit

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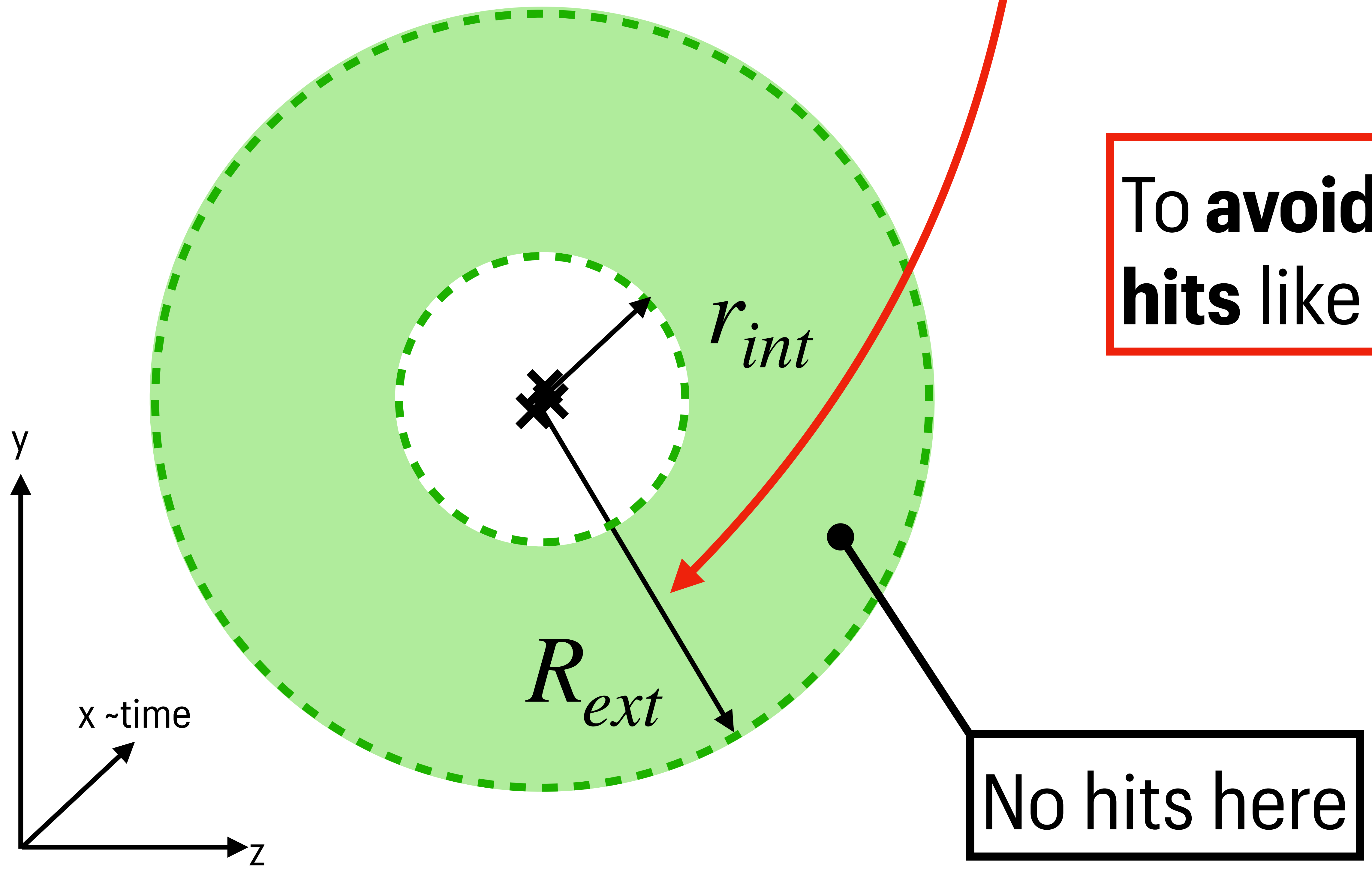
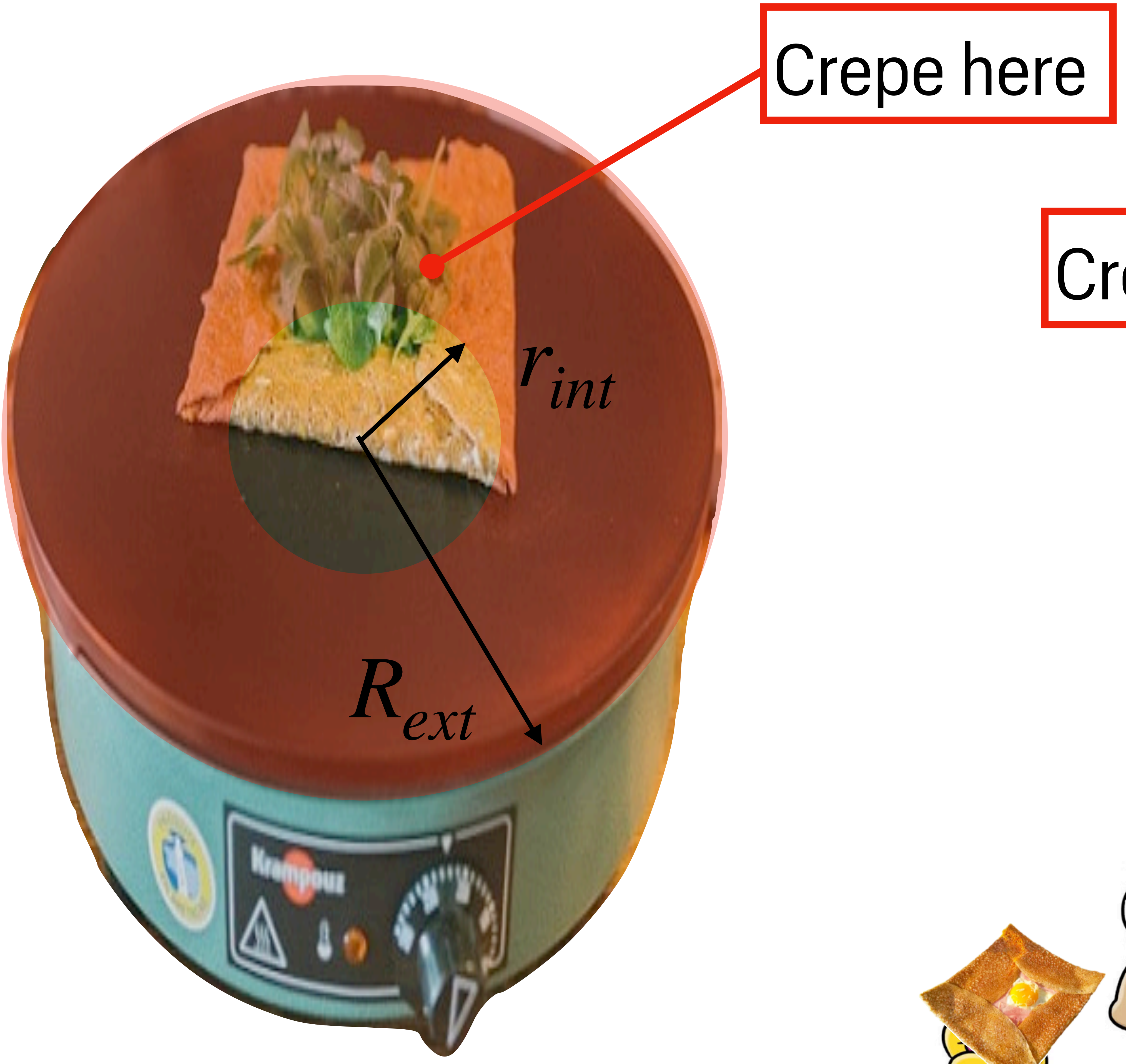
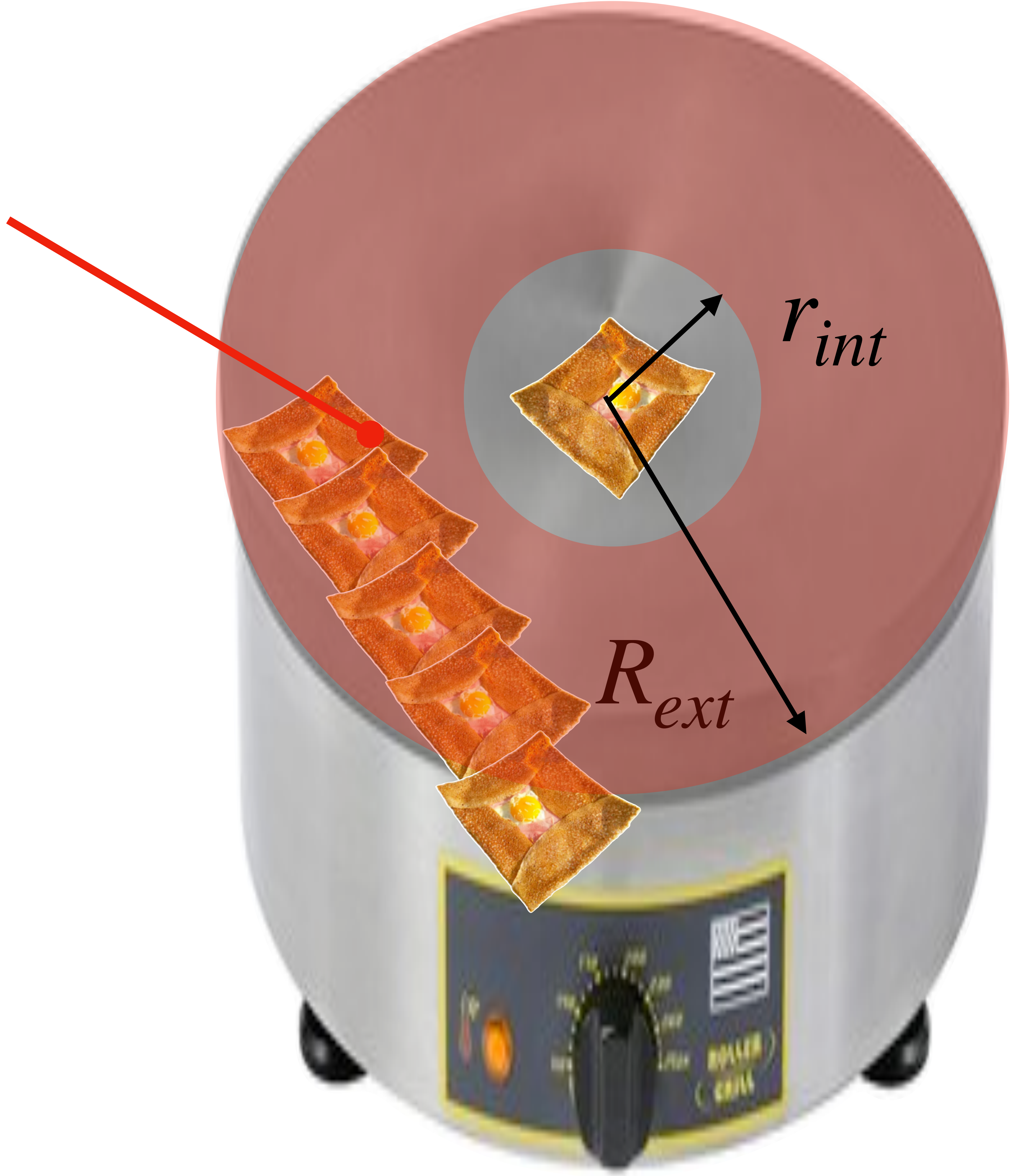


To **avoid selecting cosmic induced hits** like delta-rays or broken tracks


Crepe here
r_{int}
R_{ext}


Crepe here
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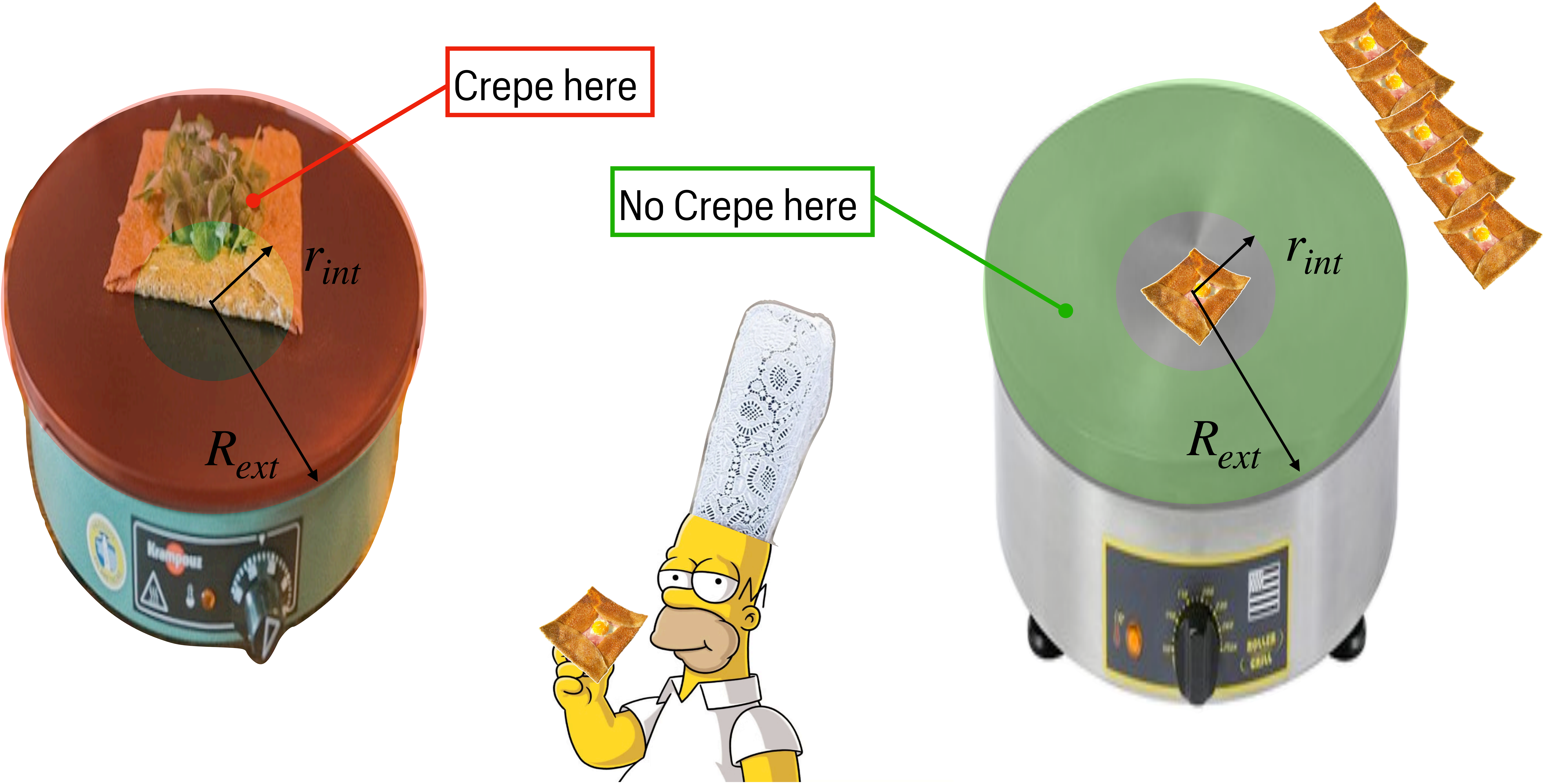
Crepe here
r_{int}
R_{ext}
No Crepe here
r_{int}
R_{ext}

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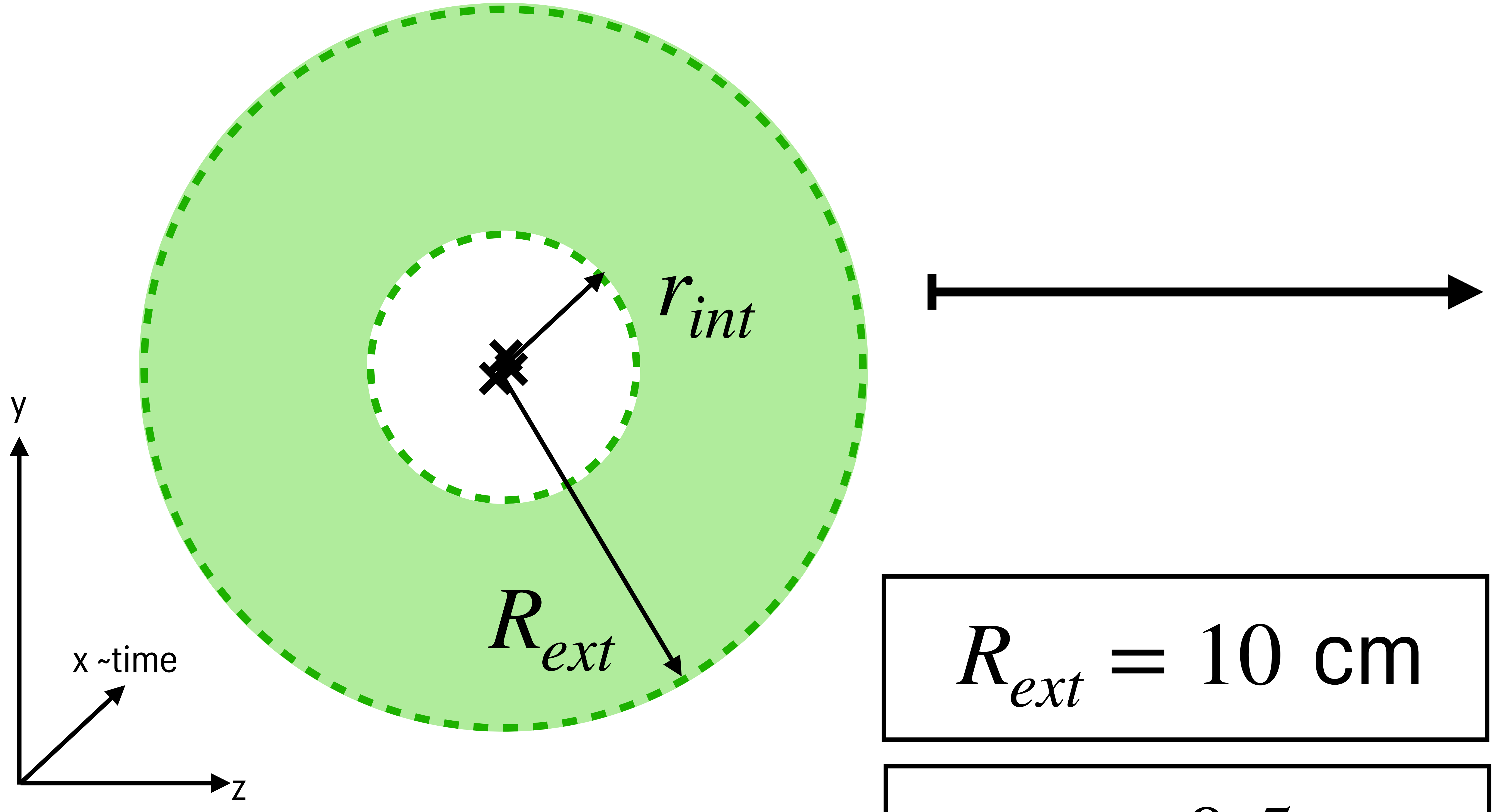
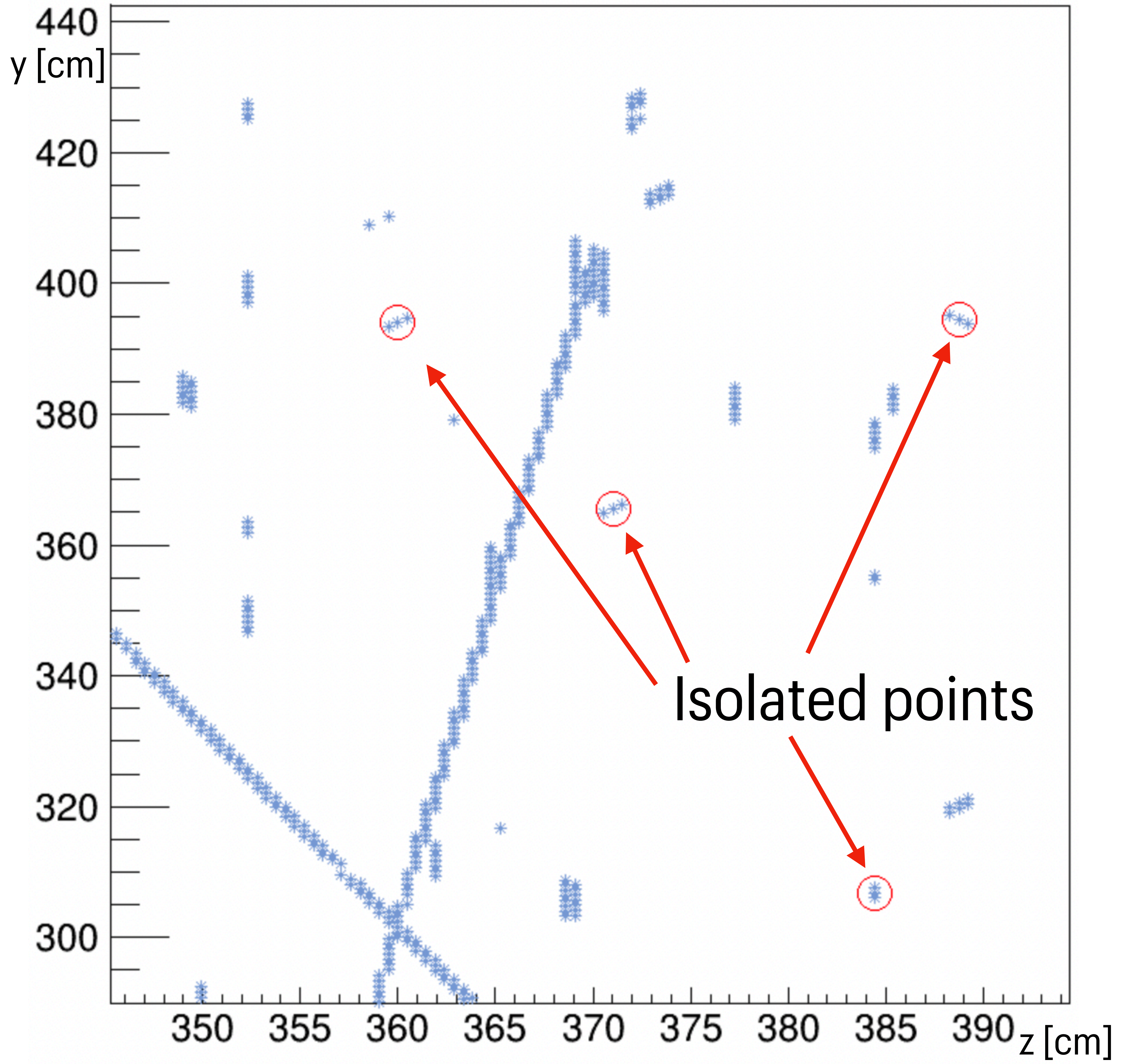


$R_{ext} = 10$ cm

$r_{int} = 0.5$ cm

PDHD data event display



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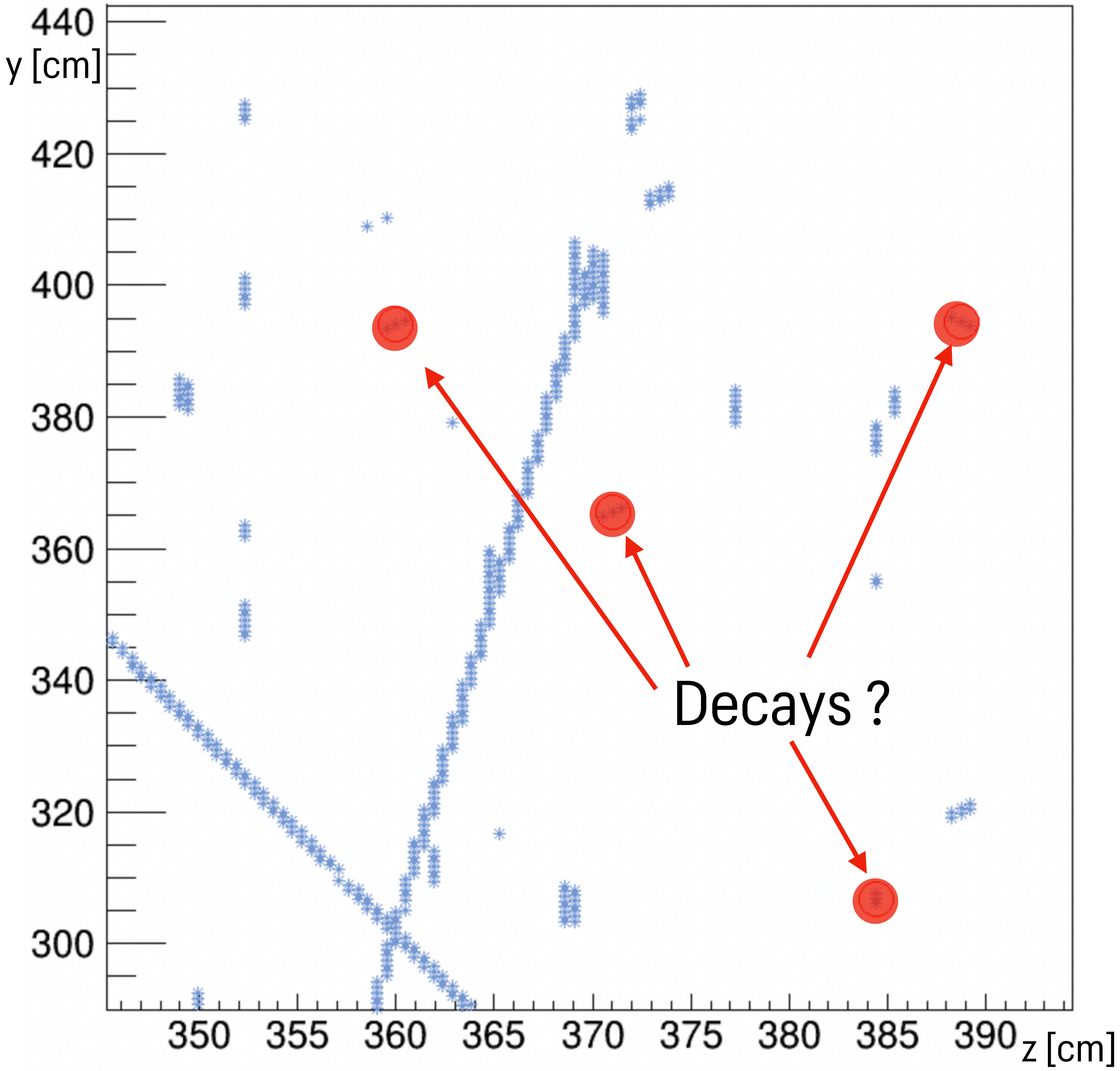

Then these points are clustered with the philosophy :

1 cluster = 1 decay

III. Results on PDHD

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- Monte-Carlo composition :
  - Cosmics
  - 1 GeV electron beam
  - $^{39}Ar + {}^{85}Kr + {}^{222}Rn$
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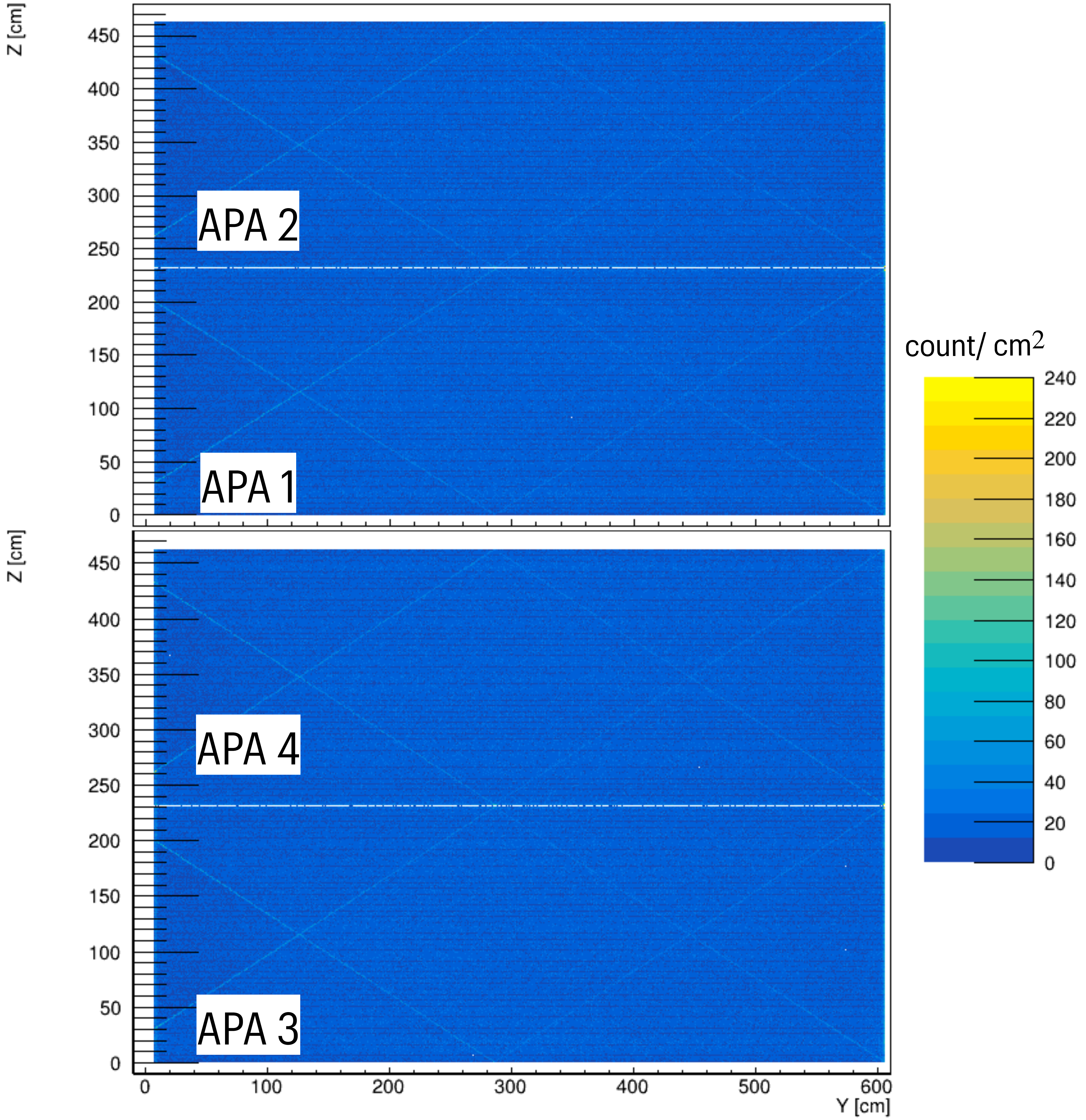
After <u>reconstruction and DONUT veto</u>:

- The spatial distribution of LE clusters is **uniform**

$$R_{ext} = 20 \text{ cm}$$

$$r_{int} = 2 \text{ cm}$$



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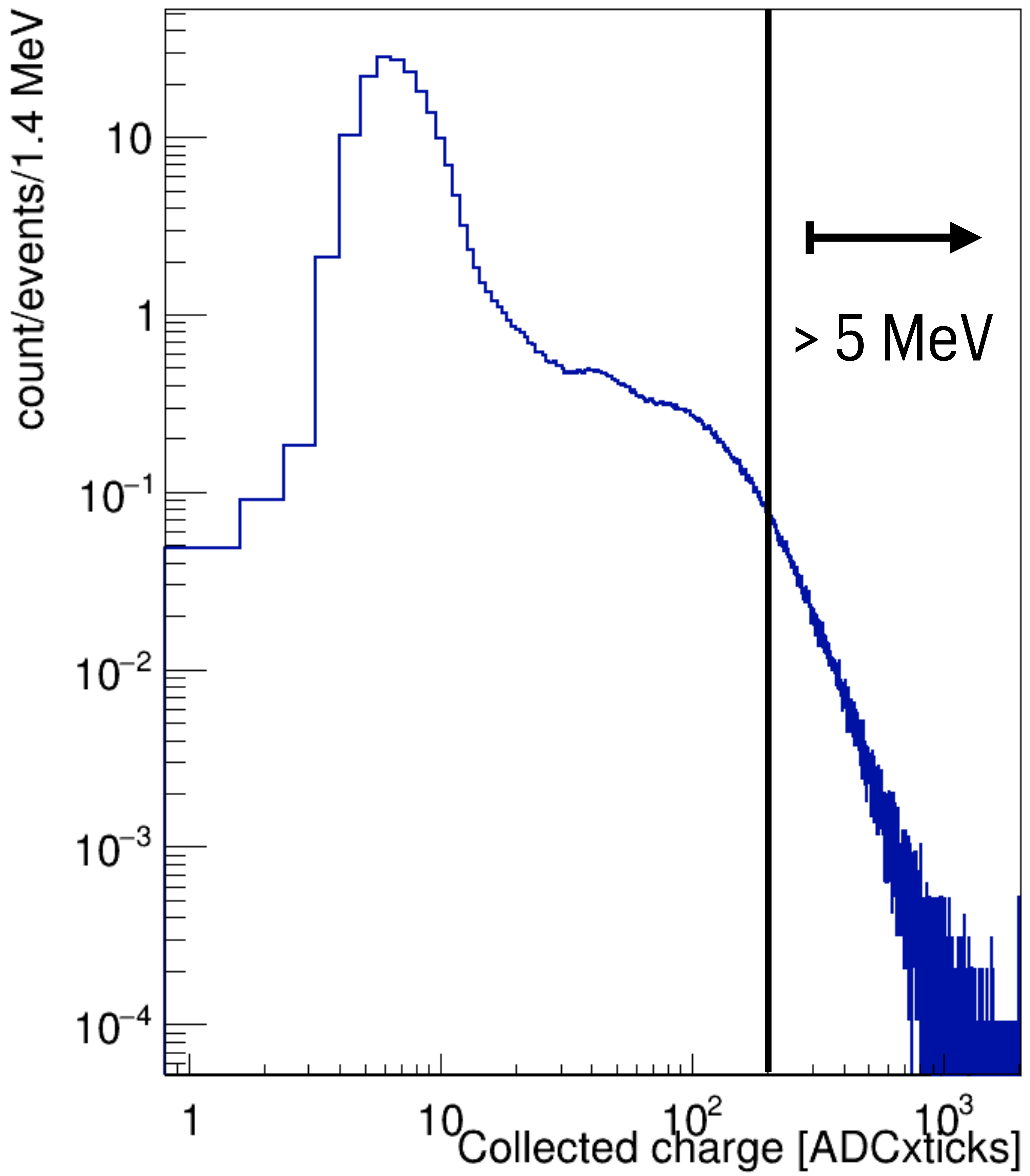
- The spatial distribution of LE clusters is **uniform**

- **Suppression of High Energy** (>10 MeV) signals



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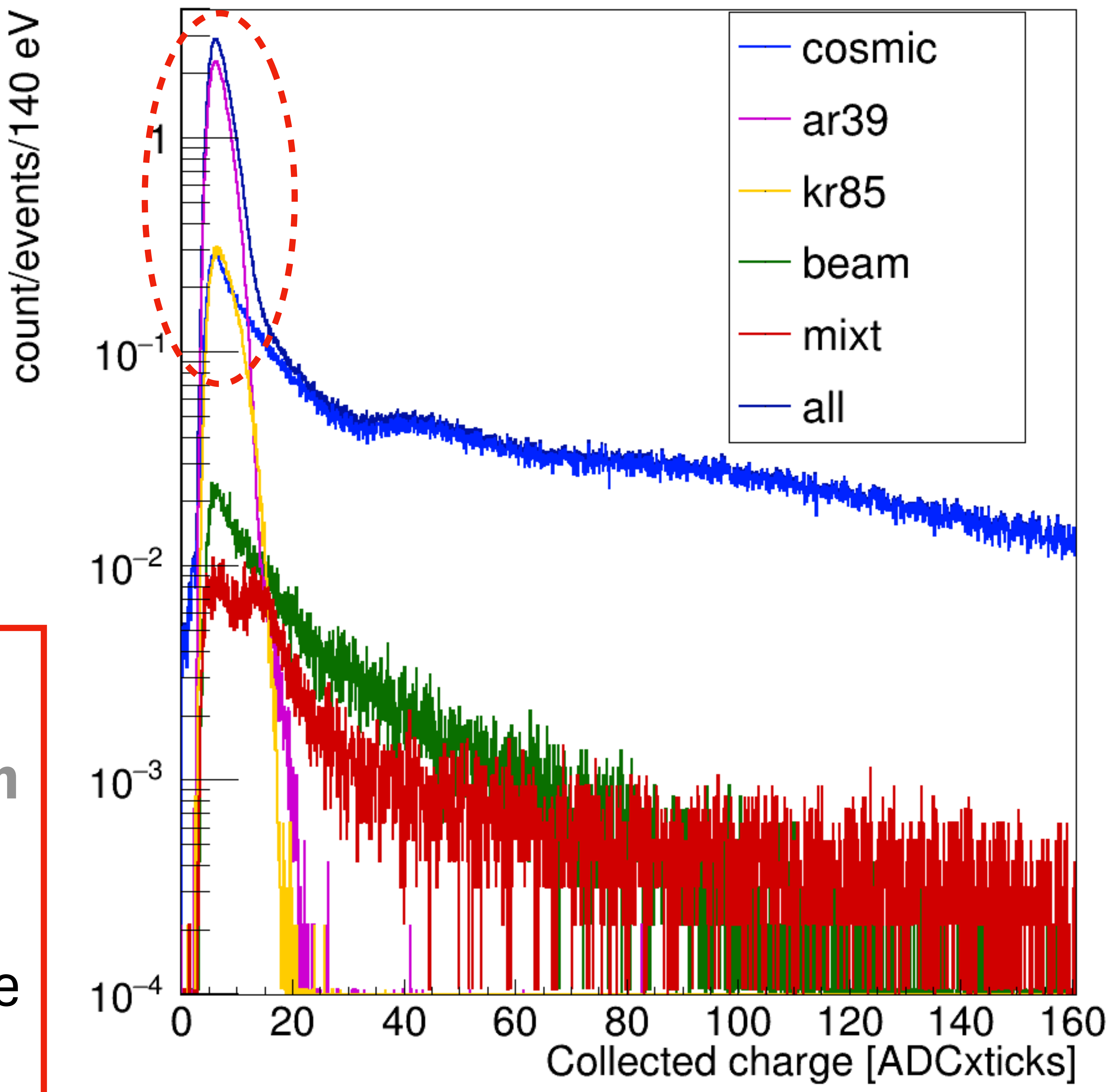
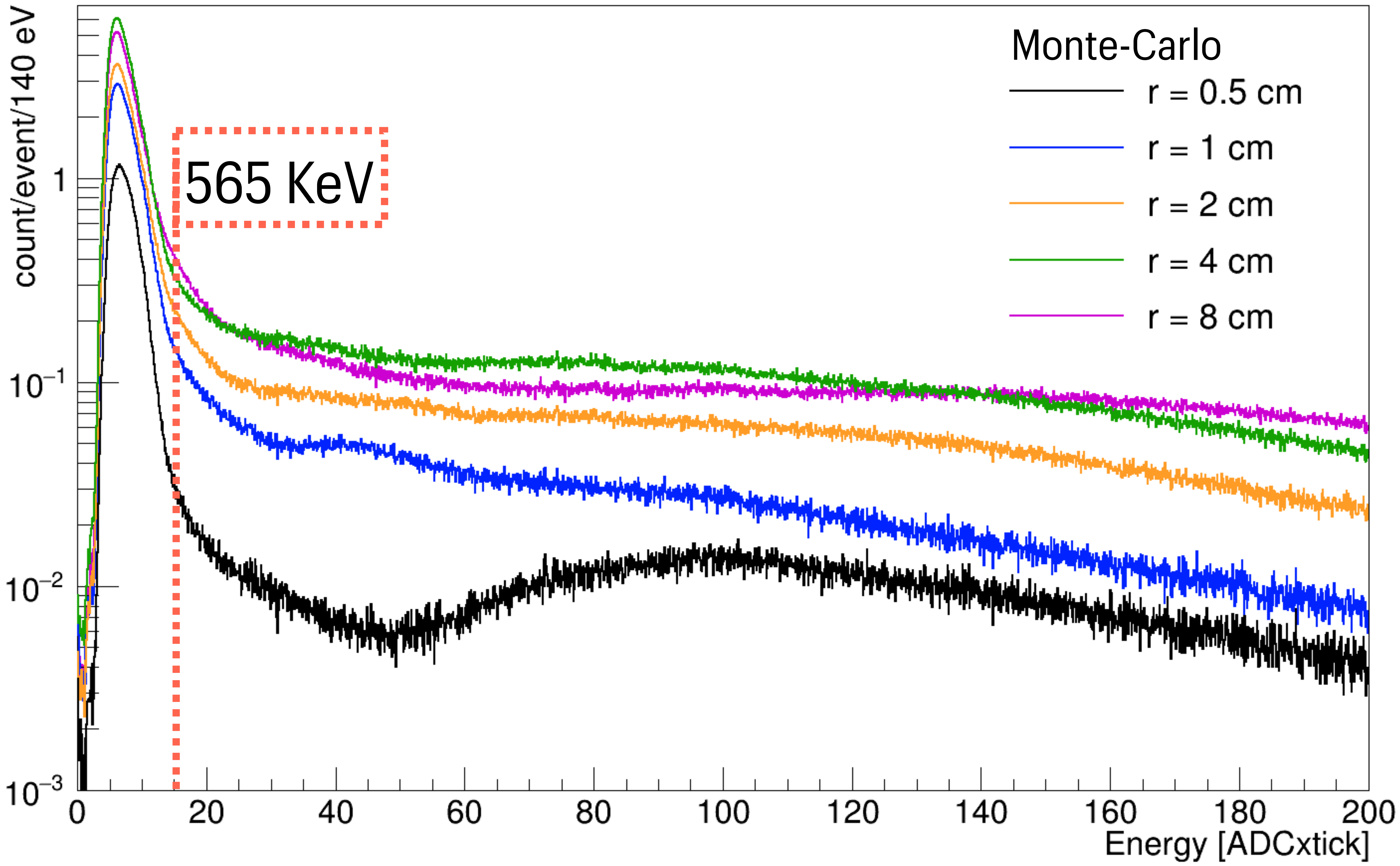
- **Suppression of High Energy** (>10 MeV) signals

- **Identification of ^{39}Ar peak** with signal to noise ratio of about 10



DUNE

- $r_{int} = 2$ cm → good compromise between distinction of the ^{39}**Ar** β**-spectrum queue** and the **suppression of cosmics**



III. Results on PDHD

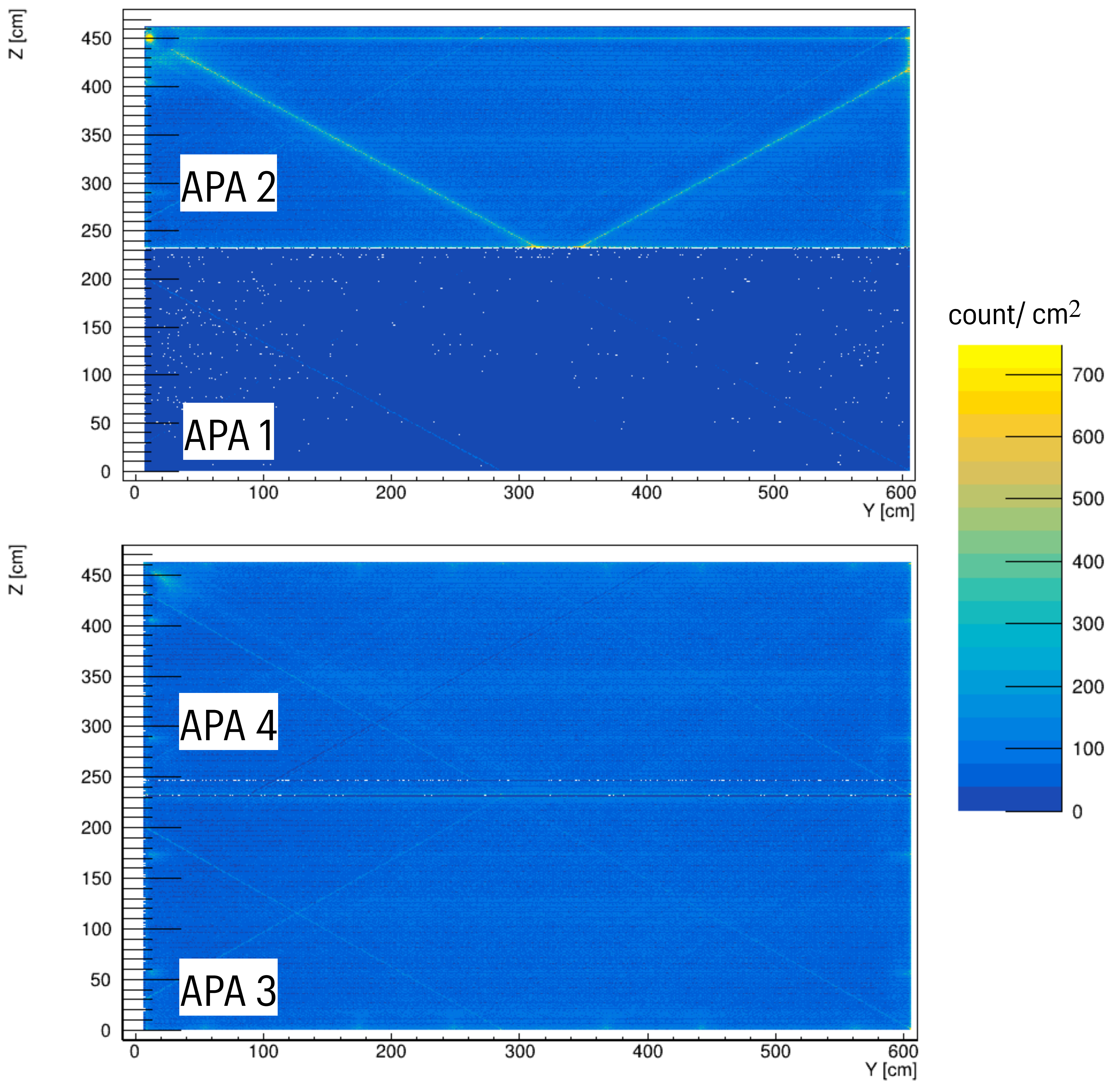
- **ROUGHT CALIBRATION:**
- **With the identification of the Ar39** queue value on MC:
  - $Q_{value}(0.565\ MeV) = 16.5\ ADC \times ticks \rightarrow f_{MC} = 3.4 \times 10^{-2}$
- **With evaluation of electronics response :**
  - $$Q_{collected}[ADC \times tick] = \frac{E_{deposited}[MeV] \times W_{ions}[\#e^-/MeV]}{g_e[\#e^-/ADC \times tick] \times R}$$
    $\rightarrow f_{elec} = 3.5 \times 10^{-2}$
- With $W_{ions} = 23.6 \times 10^{-6}\ MeV^{-1}, g_e = 10^{-3}$ and $R \approx 0.67$*
- But at this energy scale several effects (**purity, recombination, electronics gain, noise level**) compete and make this calibration complicated without standard candles.

* from « Study of electron recombination in liquid argon with the ICARUS TPC »

- Run with 1 GeV beam and cosmics
- Surface divided in 4 :
  - APA 1 : electronics connection issue
  - APA 2/4 : Bismuth source
  - **APA 3 is the one that we can compare to Monte-Carlo**

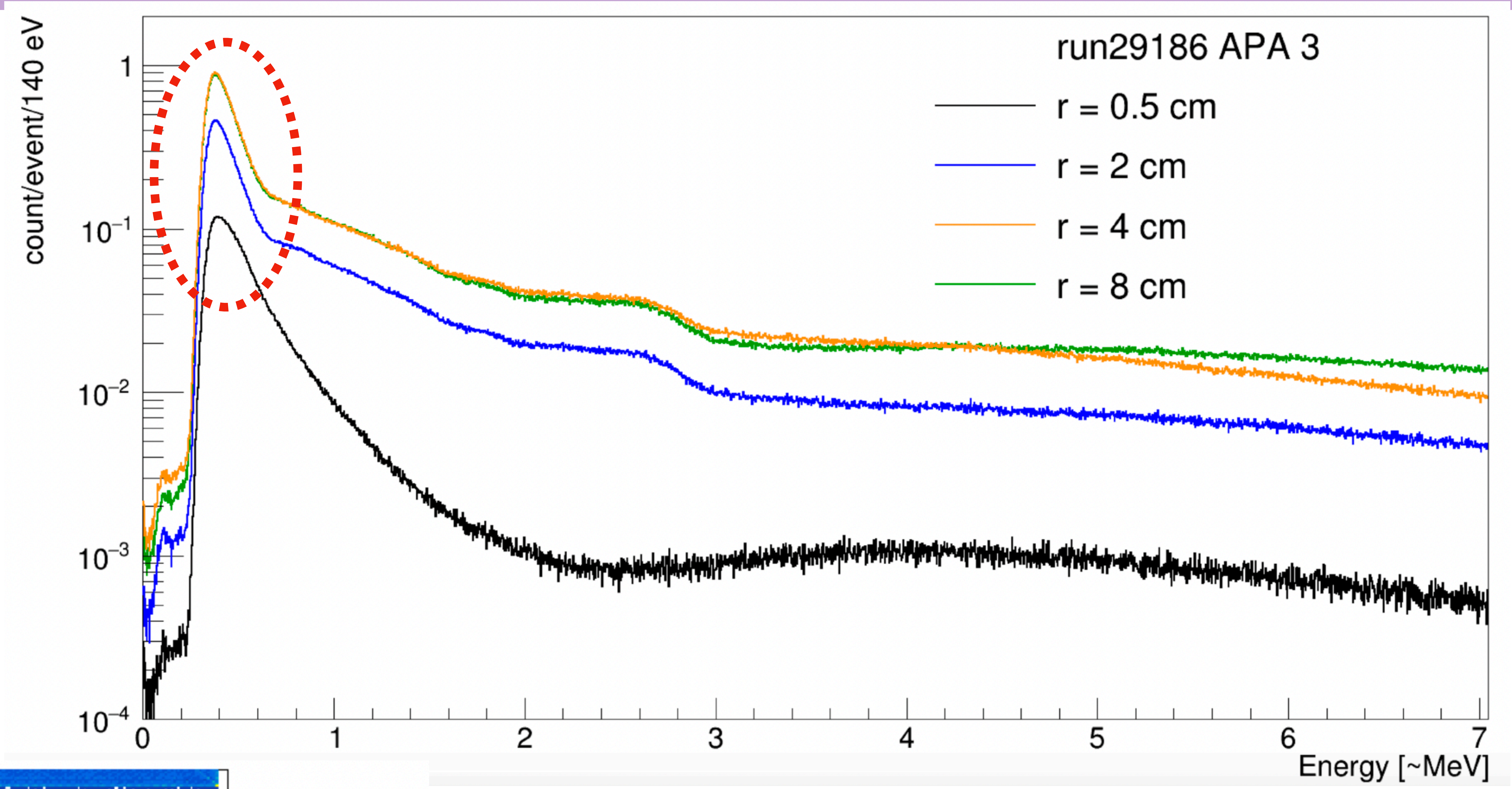
$$R_{ext} = 20 \text{ cm}$$

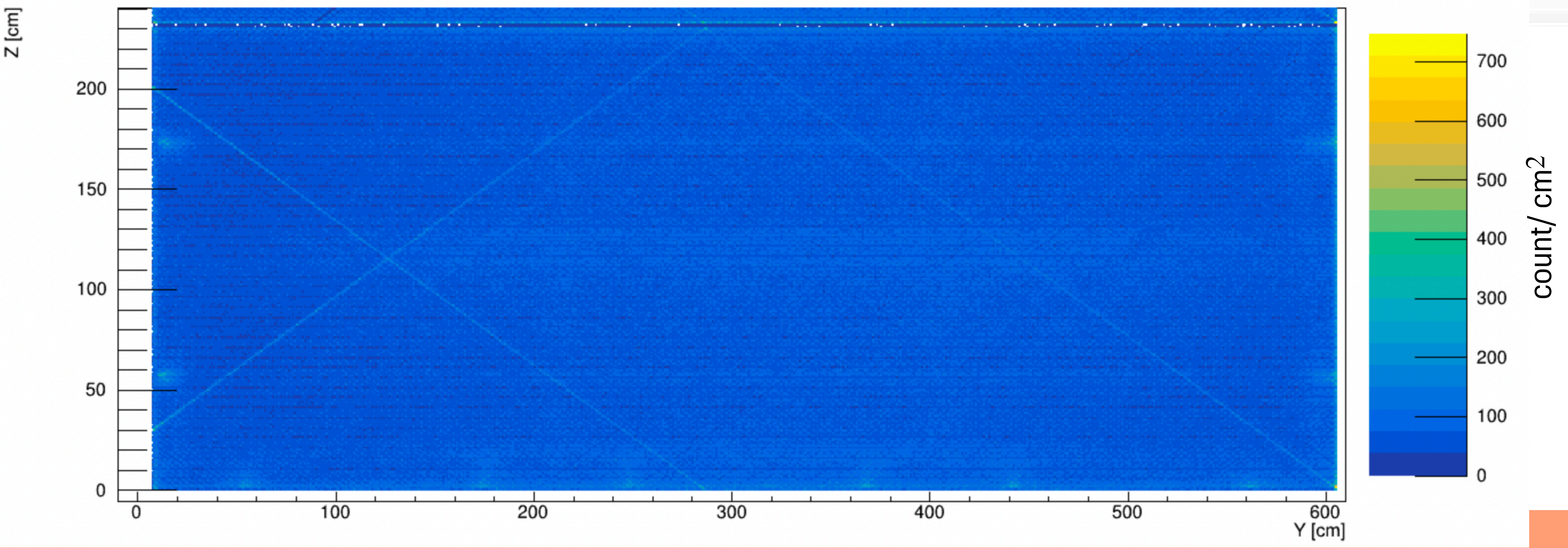
$$r_{int} = 2 \text{ cm}$$



III. Results on PDHD

- Shape agreement with MC
- See the **Ar39 peak rise**





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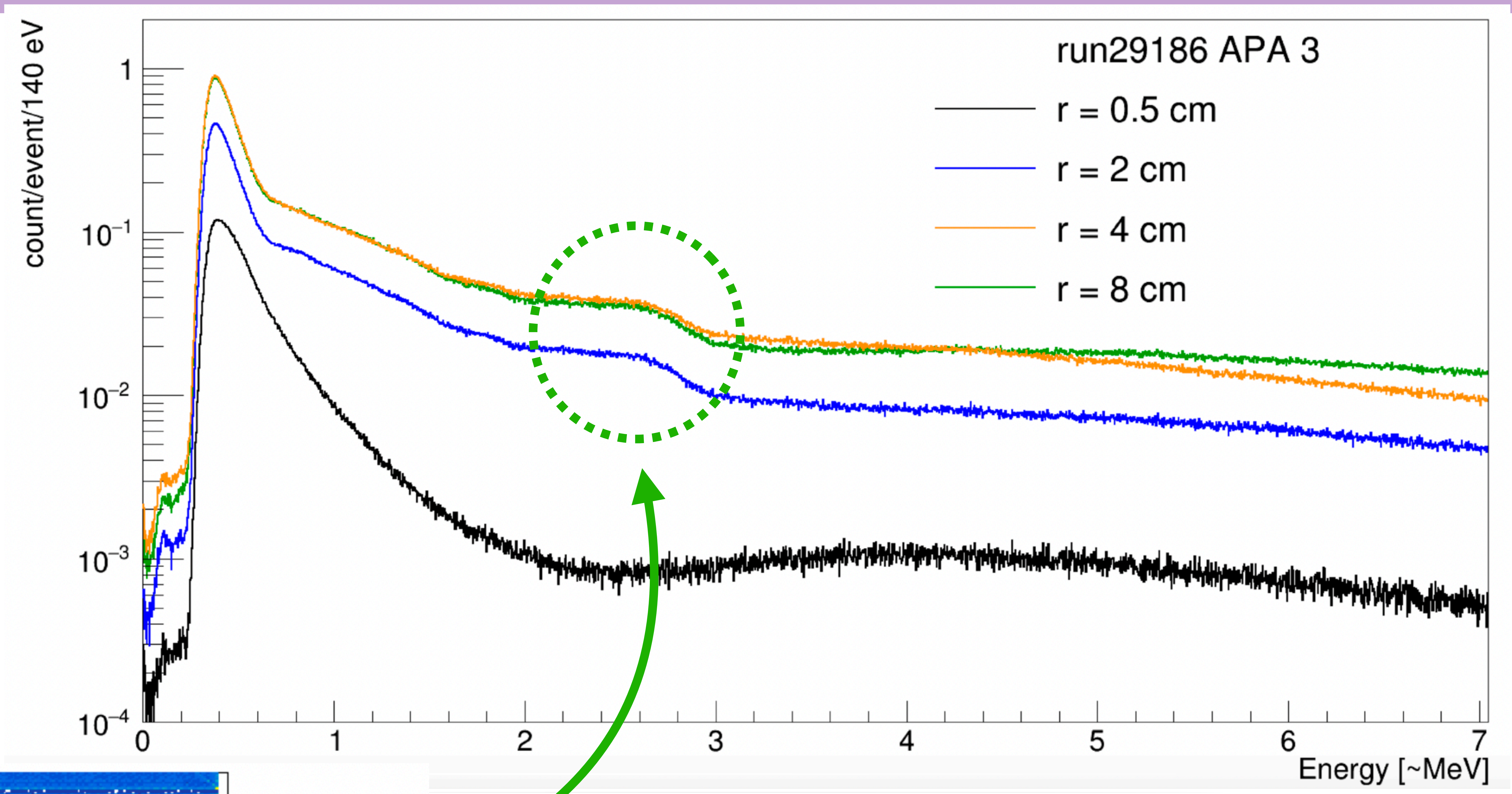
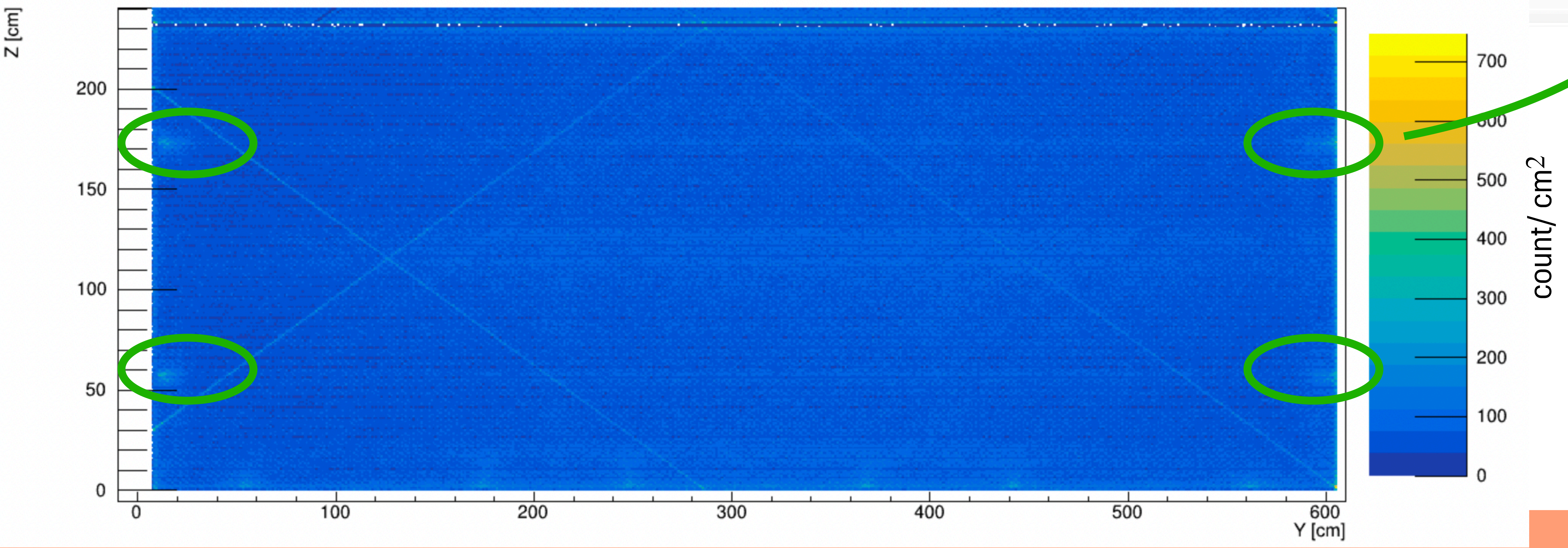
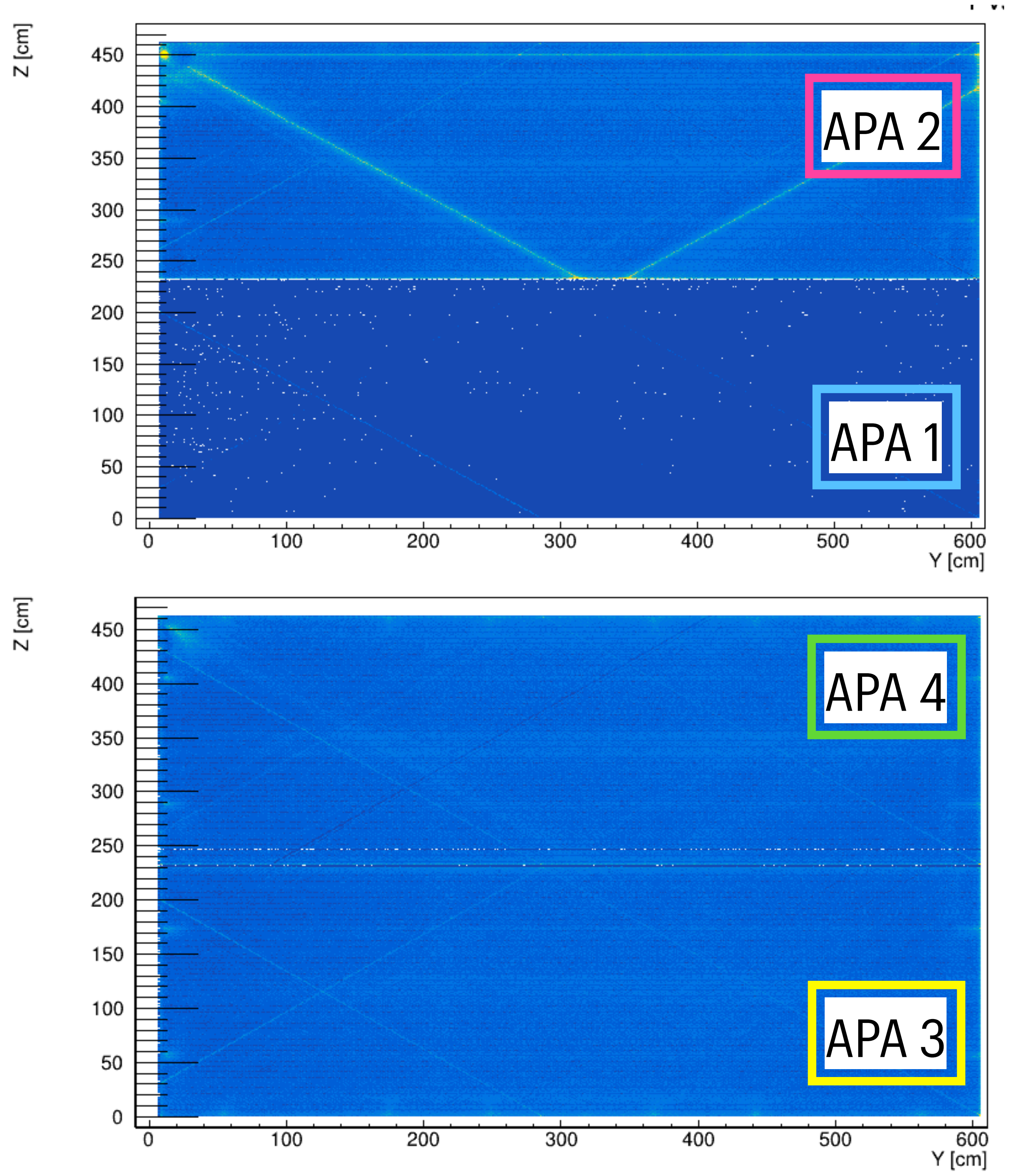
- Indices of **sensitivity to Thorium** from field cage beam

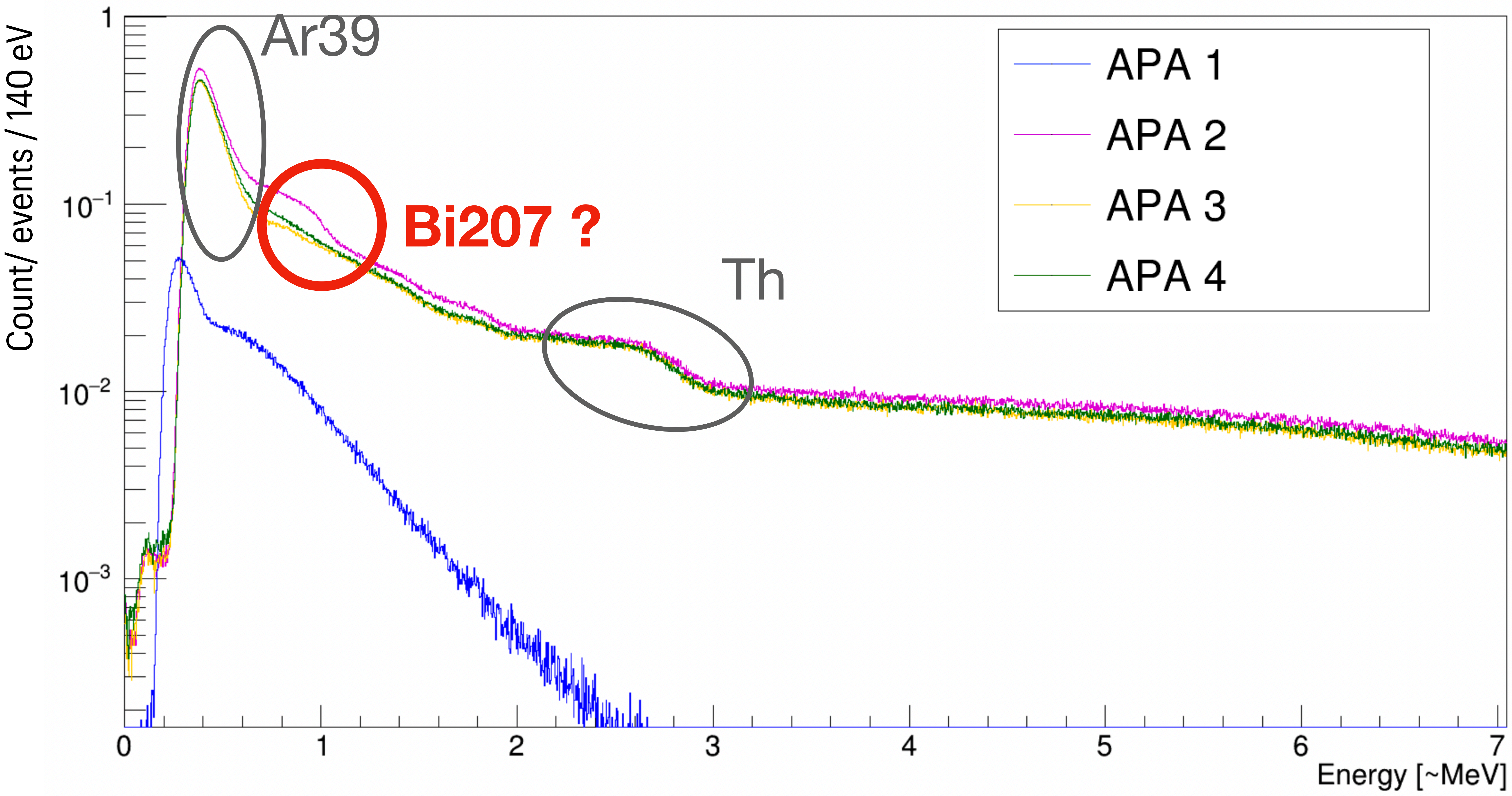




III. Results on PDHD

- Energy comparison between APA → sensitive to the ^{207}Bi





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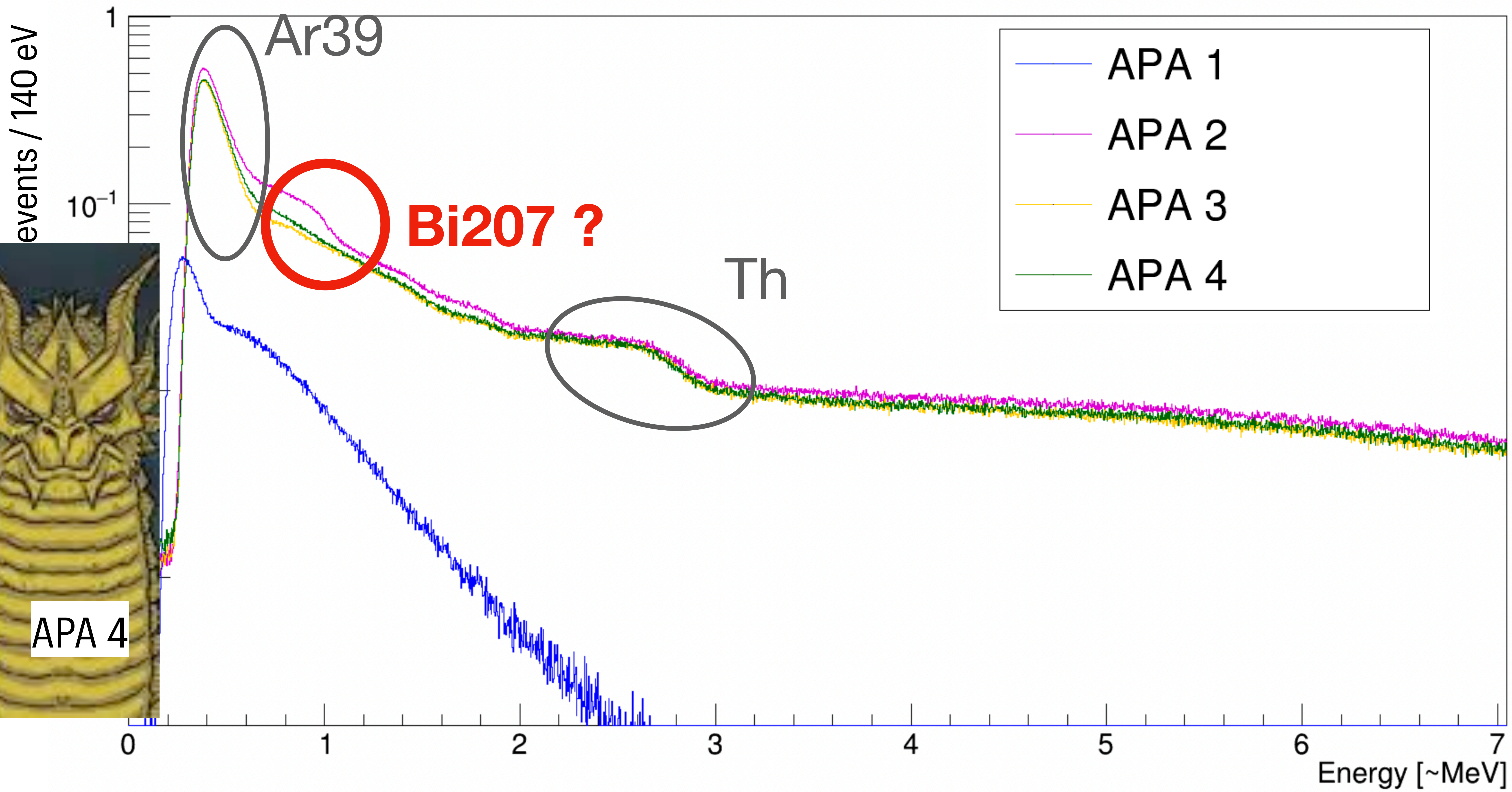

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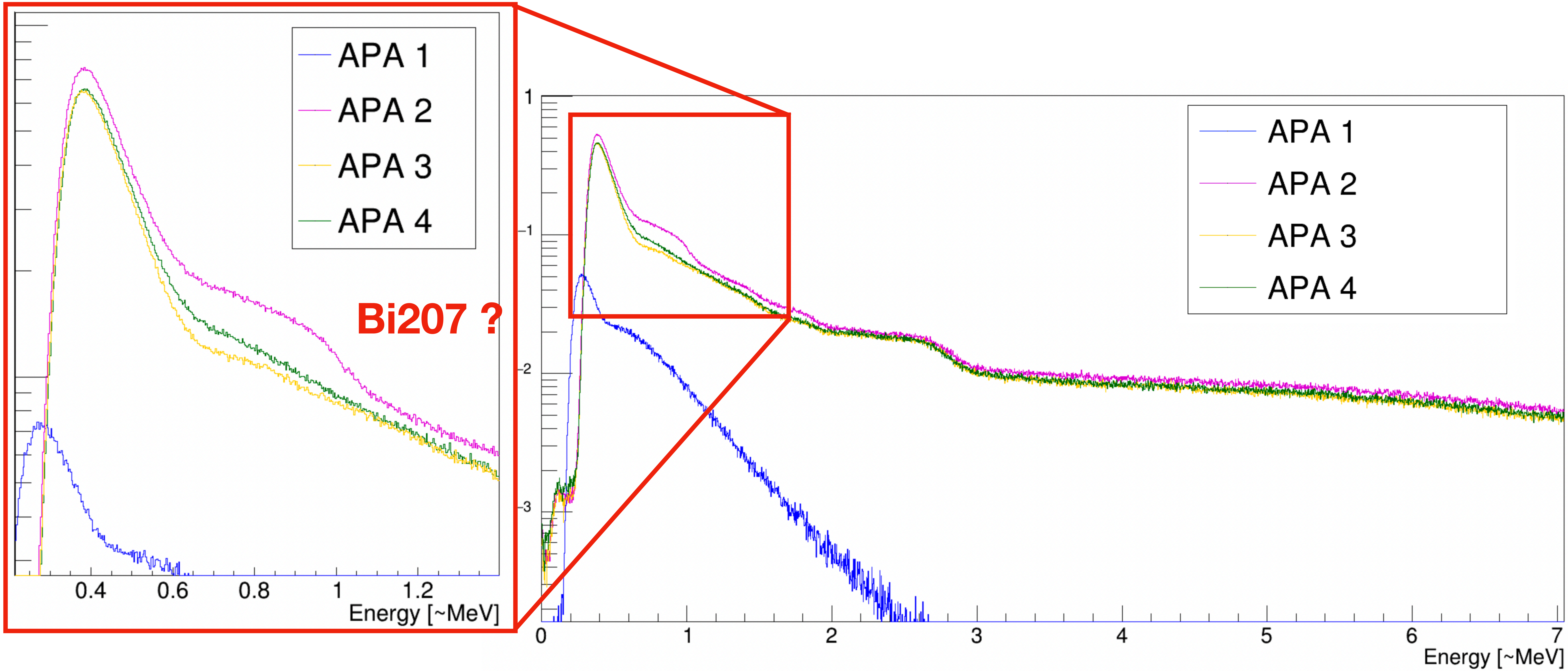
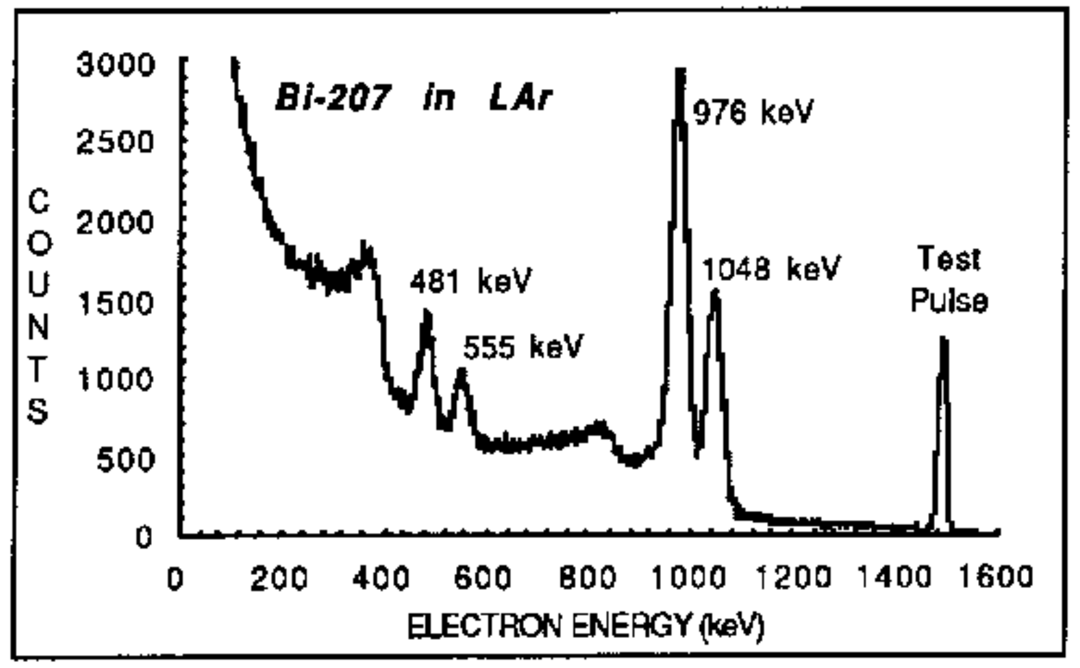
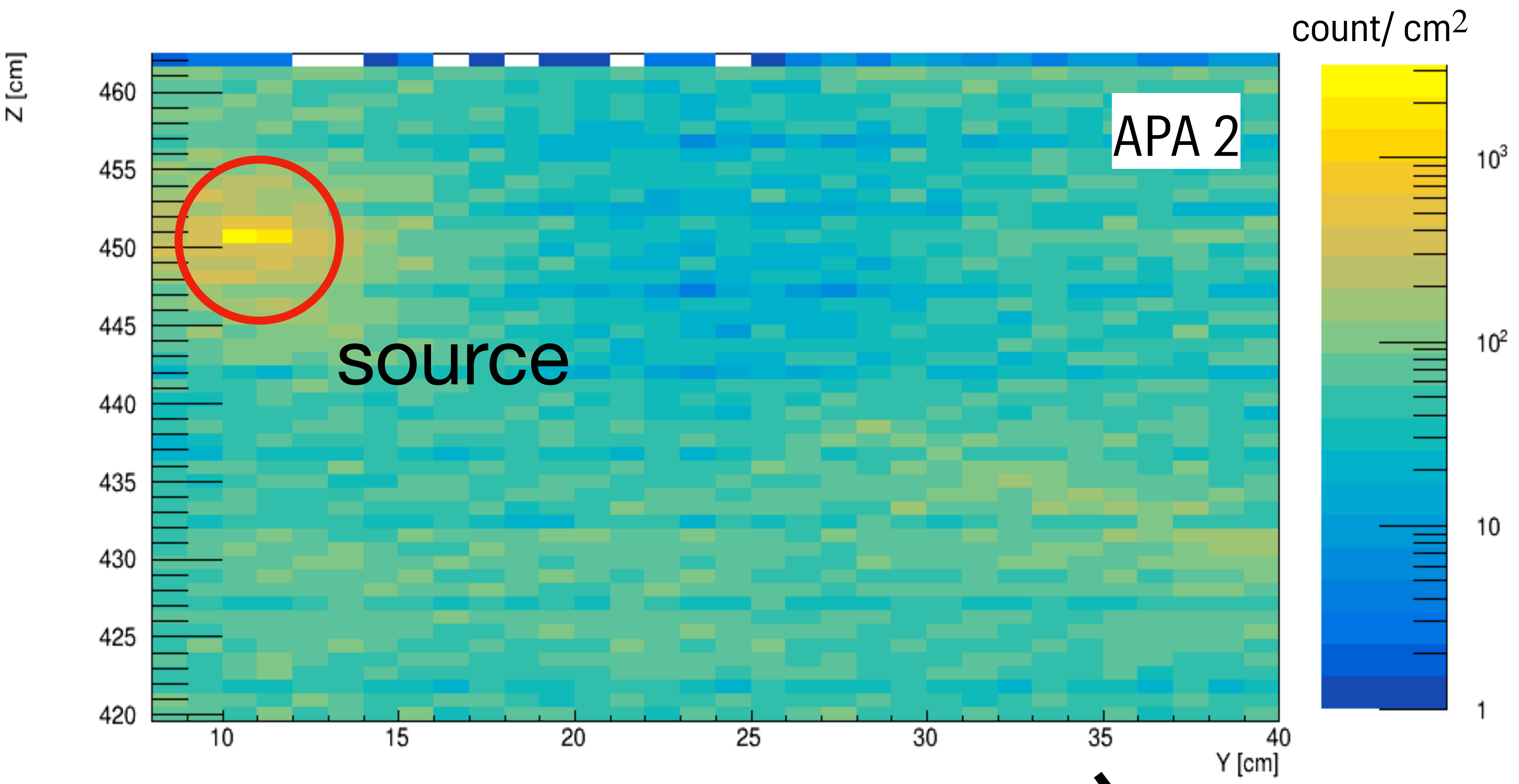


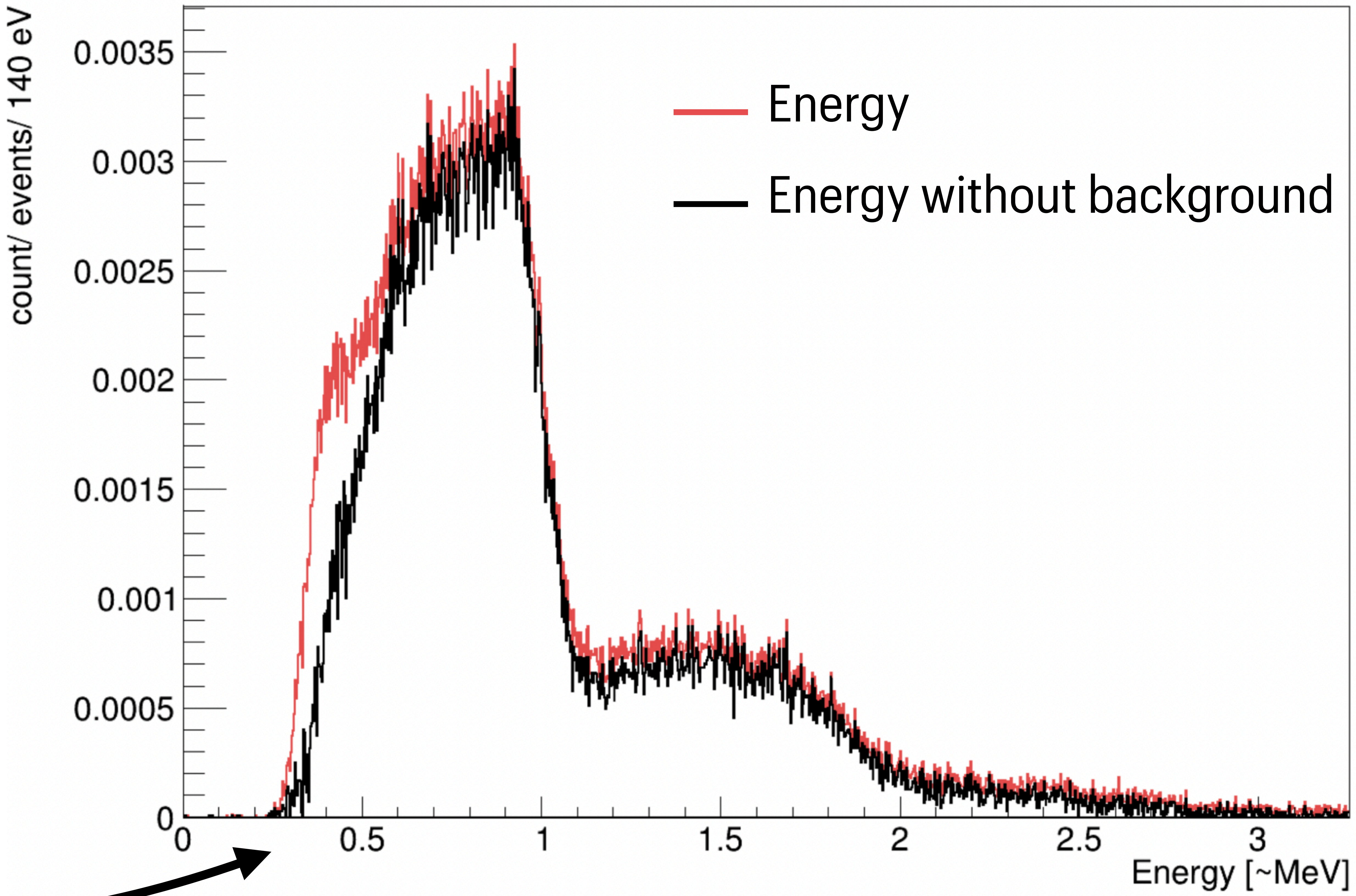
III. Results on PDHD

- Spatial reconstruction **precise at the cm level**
- **Observation of 1 MeV** peak with rough calibration factor

- **need simulation** to understand better the spectrum:
  - Gamma scattering
  - Recombination effect ...







DUNE

Conclusion

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- Implementation of a powerful calibration tool useful for the collaboration
- Identification of 39Ar with one order of magnitude w/r to cosmic in MC
- First analysis at low energy on **PDHD data** and **identification of Bismuth source**
- **Monte-Carlo / data shape comparison performed**
- Need simulation of 207Bi for better understanding of data
- Purity analysis to be perform on 39Ar spectrum
- Signal (solar neutrino) over background identification analysis to be done

I. Context of DUNE

- ν's can be produced in **3 flavours states** (ν_e , ν_μ , ν_τ) and **3 mass states** (ν_1 , ν_2 , ν_3)
- ν's can **oscillate** from one state to an other along their paths

$$P(\nu_e \rightarrow \nu_\alpha) = |\Sigma\ U_{ei} U^*_{\alpha i}\ e^{-iE_i t}|^2_{i=1,\,2,\,3}$$

- where **U = PMNS matrix** (~CKM matrix)

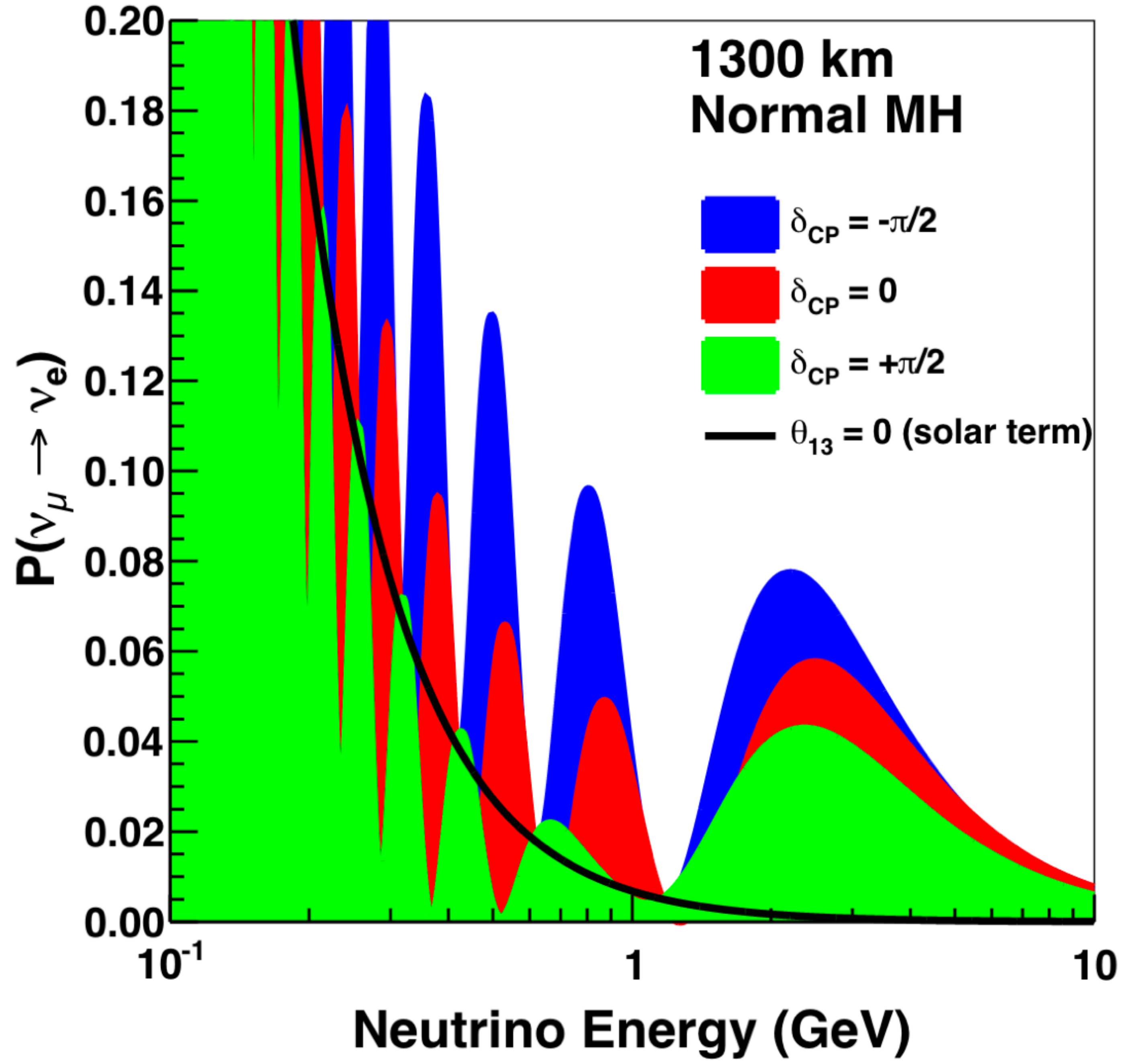
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$

atmos+LBL(dis): $P(\nu_\mu \rightarrow \nu_\mu)$

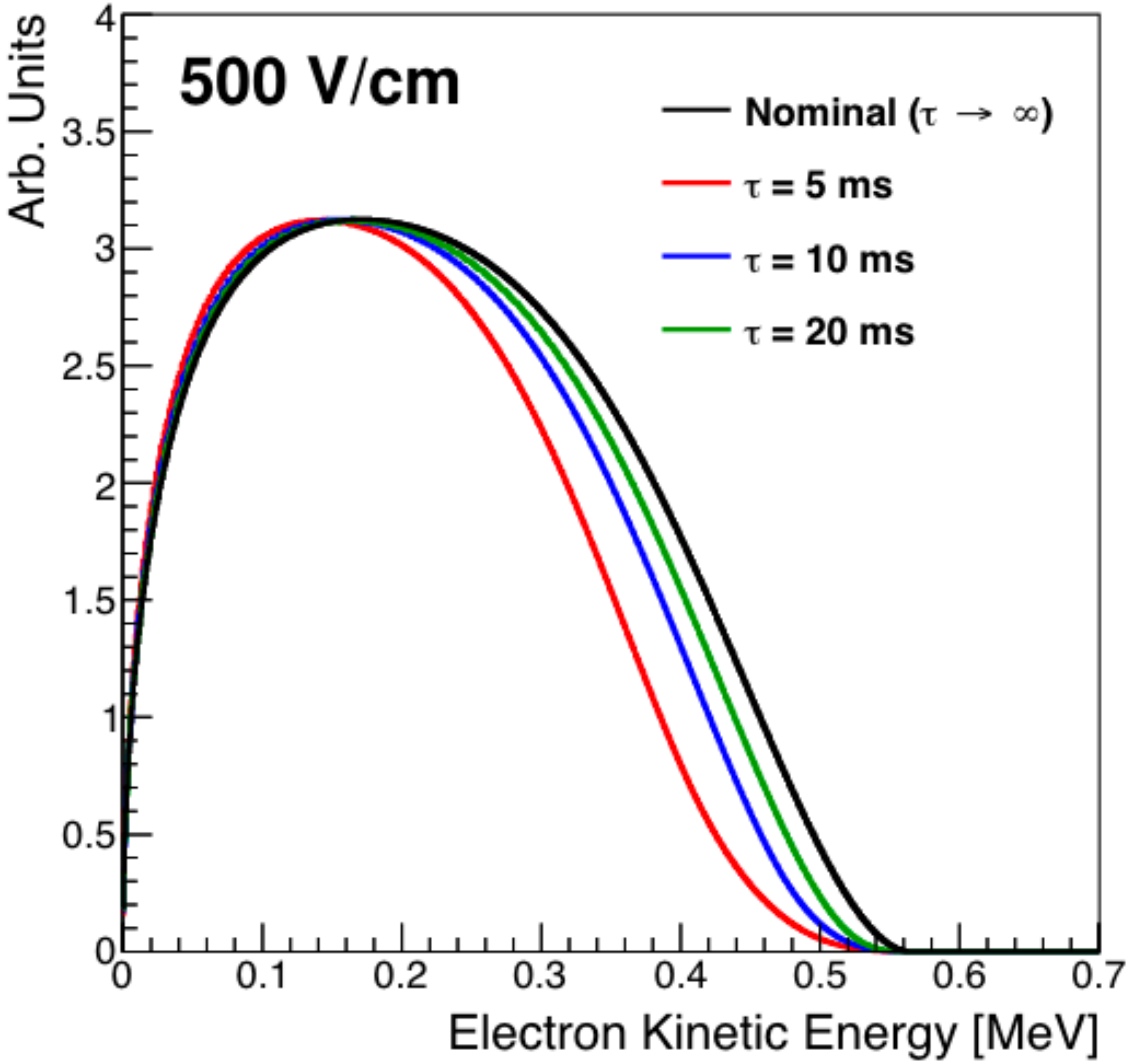
Chooz+LBL(app): $P(\nu_e \rightarrow \nu_e)$ & $P(\nu_\mu \rightarrow \nu_e)$

solar+KamLAND: $P(\nu_e \rightarrow \nu_x)$

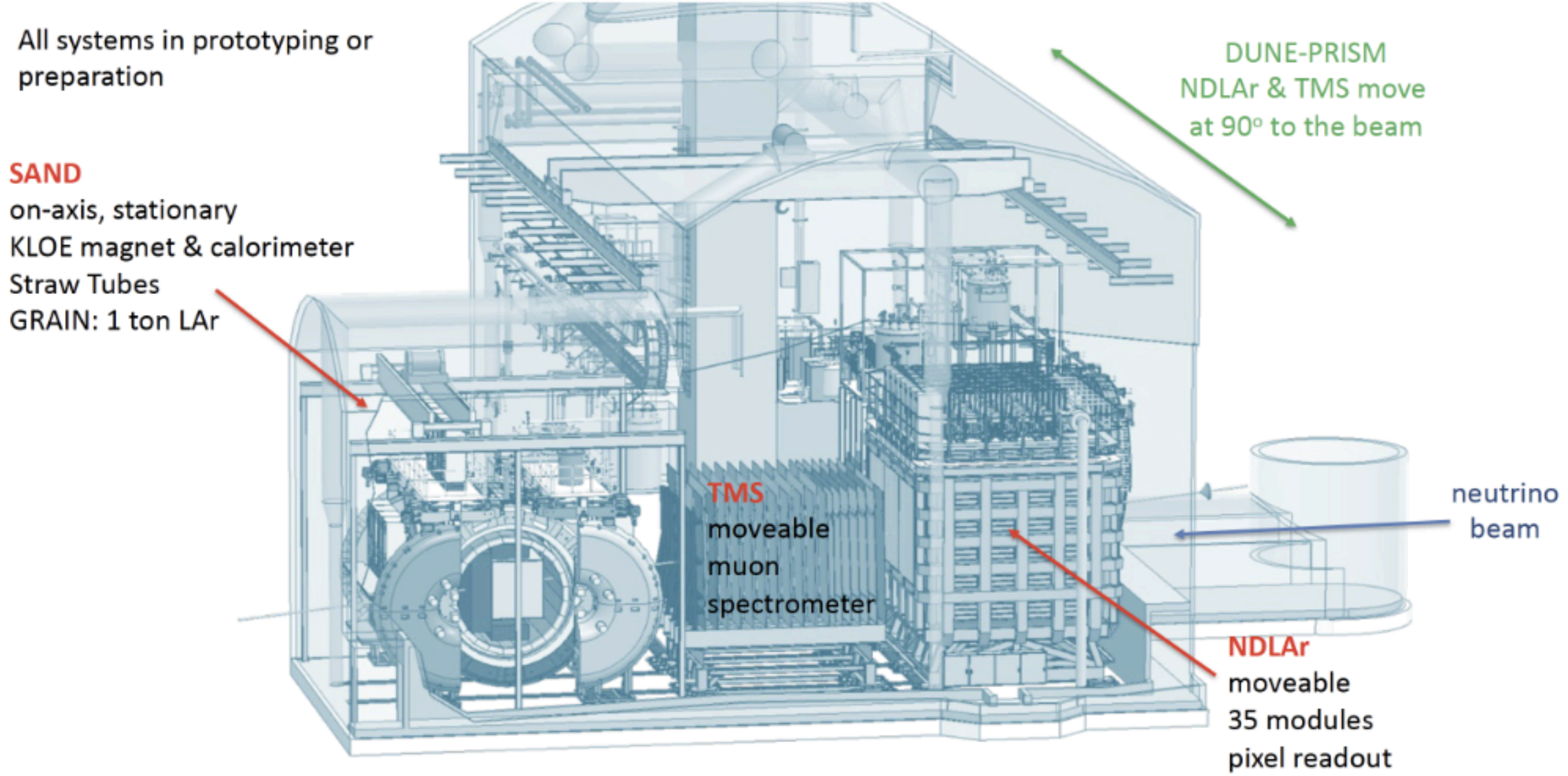


DUNE

- Ar39 distributed uniformly in the volume



- **Near Detector** (ND) measurements shall be of sufficient precision to ensure that when extrapolated **to predict the FD event spectra**, the associated systematic error must not dominate the measurement precision



1. Recombination - Theory

- **R is modelling the immediate « re-attachment » of ionisation induced electrons with the nearby ions ***

- $Q_{recomb}^{\{\#e^-\}} = \mathrm{R} \times Q_{true}^{\{\#e^-\}} = \mathrm{R} \times \frac{E_{dep}^{\{eV\}}}{W_{ion}^{\{eV\}}}$

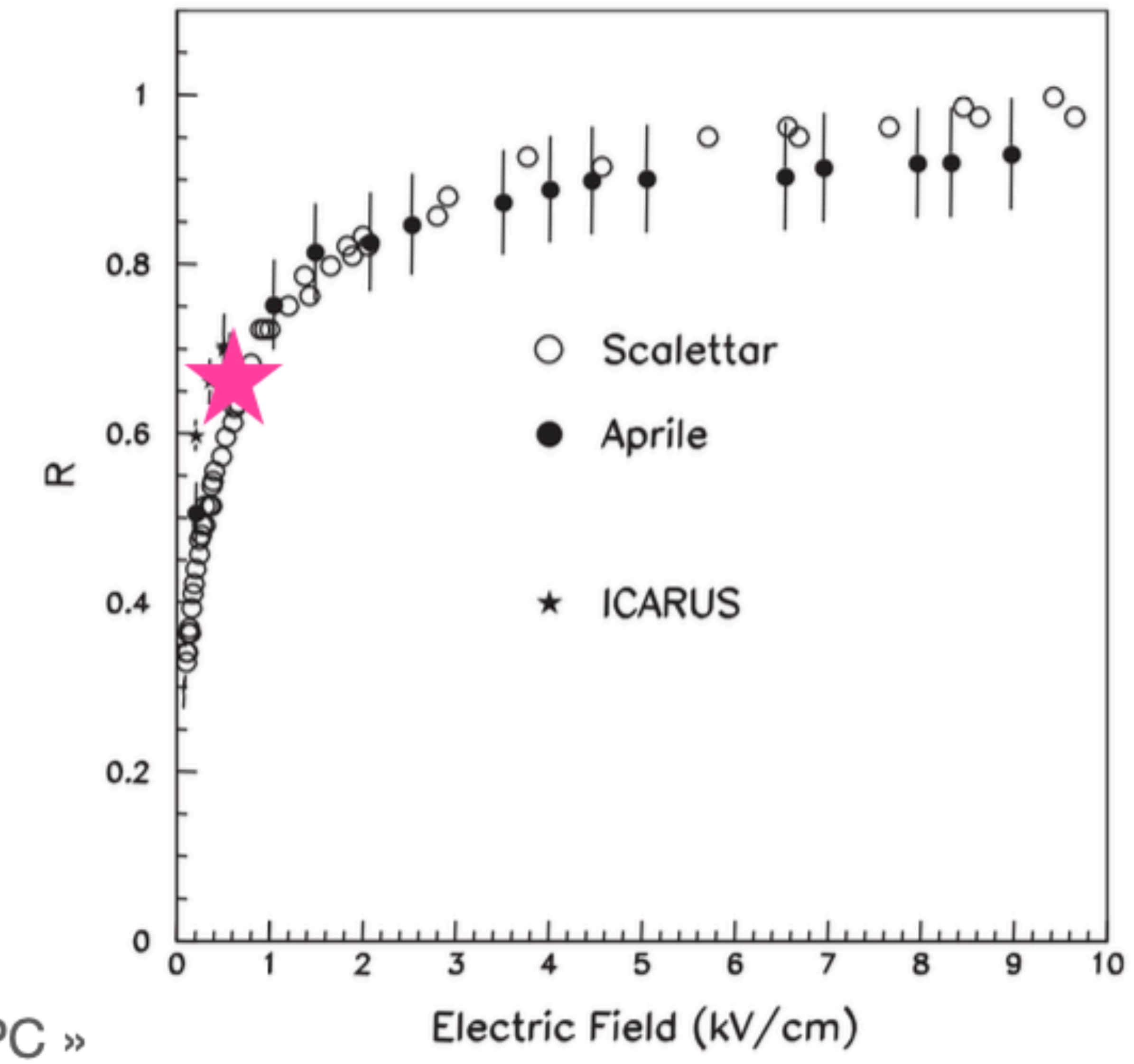
- Two empiric models: Birks(not used here) and Modified box model

$$R(\alpha,\beta) = \frac{ln\left(\frac{dE}{dx} \times \frac{\beta}{\rho E_f} + \alpha\right)}{\frac{dE}{dx} \times \frac{\beta}{\rho E_f}}$$

- With $\rho =$ LAr density $E_f =$ Electric field norm $\alpha, \beta =$ parameters

- Actual value of $\alpha = 0.93 \pm 0.02$ and $\beta = 0.2 \pm 0.02$ from Argoneut (proton and deuton at ~10 MeV)**

- Also measured with Michel e⁻ in PDSP ***



*arXiv:1306.1712v1 [physics.ins-det] 7 Jun 2013

** Acciarri et al., « A Study of Electron Recombination Using Highly Ionizing Particles in the ArgoNeuT Liquid Argon TPC »

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*** DUNE Collaboration et al., « Identification and Reconstruction of Low-Energy Electrons in the ProtoDUNE-SP Detector »