DUNE overview and MeV-scale Calibration

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

I. DUNE Status

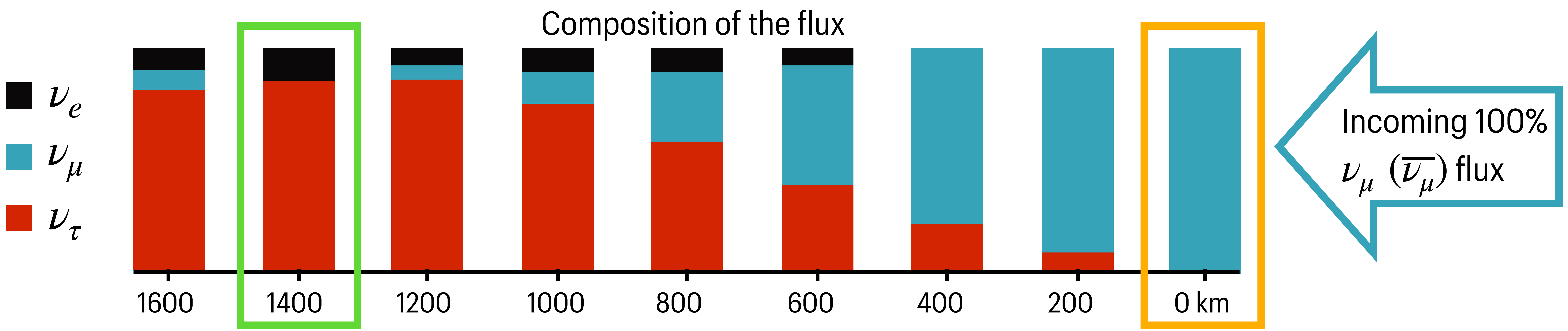
1. DUNE construction status
2. DUNE production status
3. Prototyping phase

II.ProtoDUNE-HD calibration

1. Few MeV energy spectrum
2. ^{232}Th energy range
3. Calibration factor and recombination

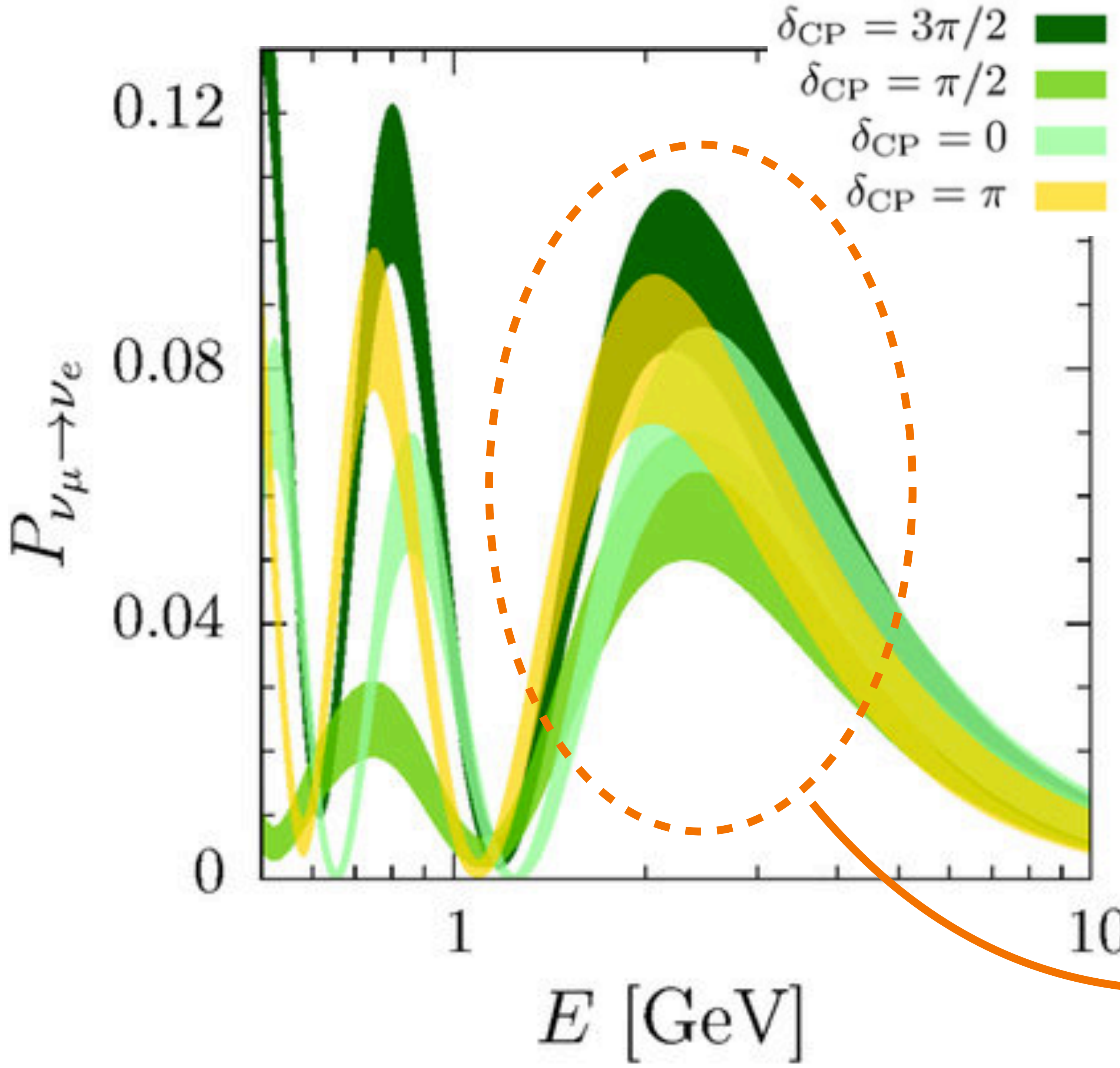
Conclusion

- DUNE is composed of three parts : **Far Detector**, **Near Detector** and **Accelerator**



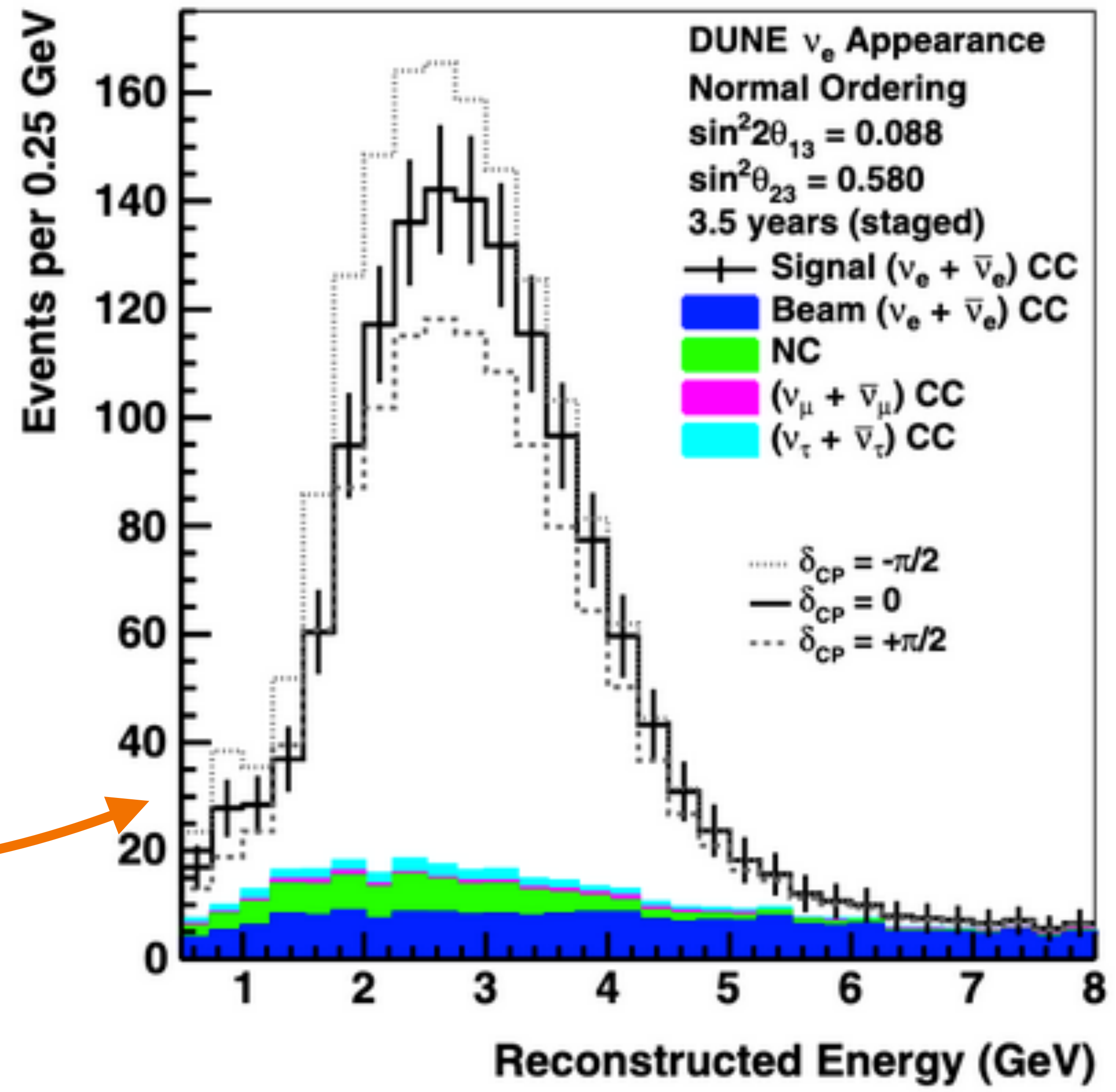
- Measure ν_e ($\overline{\nu_e}$) appearance or disappearance in ν_μ ($\overline{\nu_\mu}$) beam

- Measure the second oscillation peak with **E > 1 GeV**



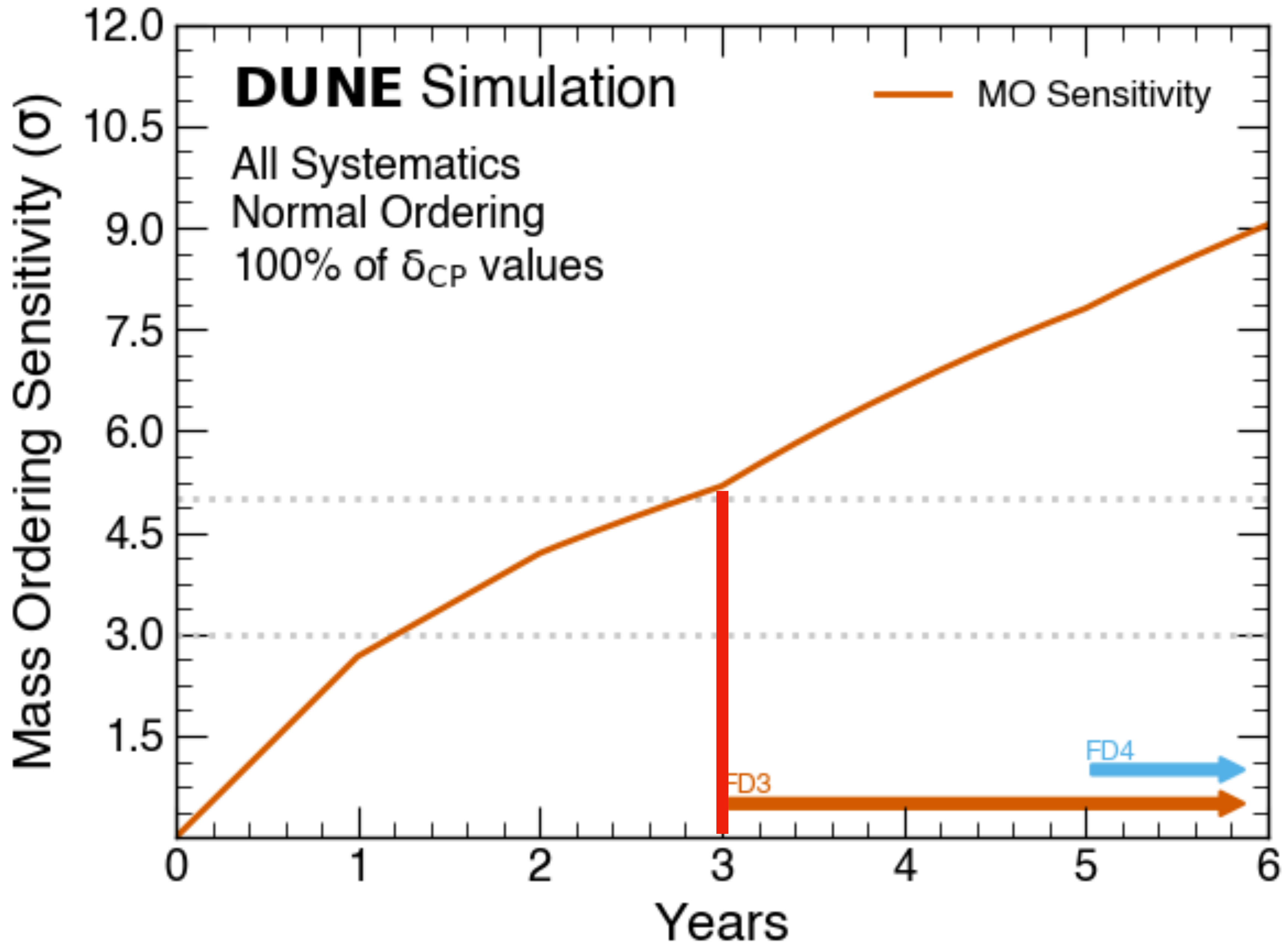
Example with appearance

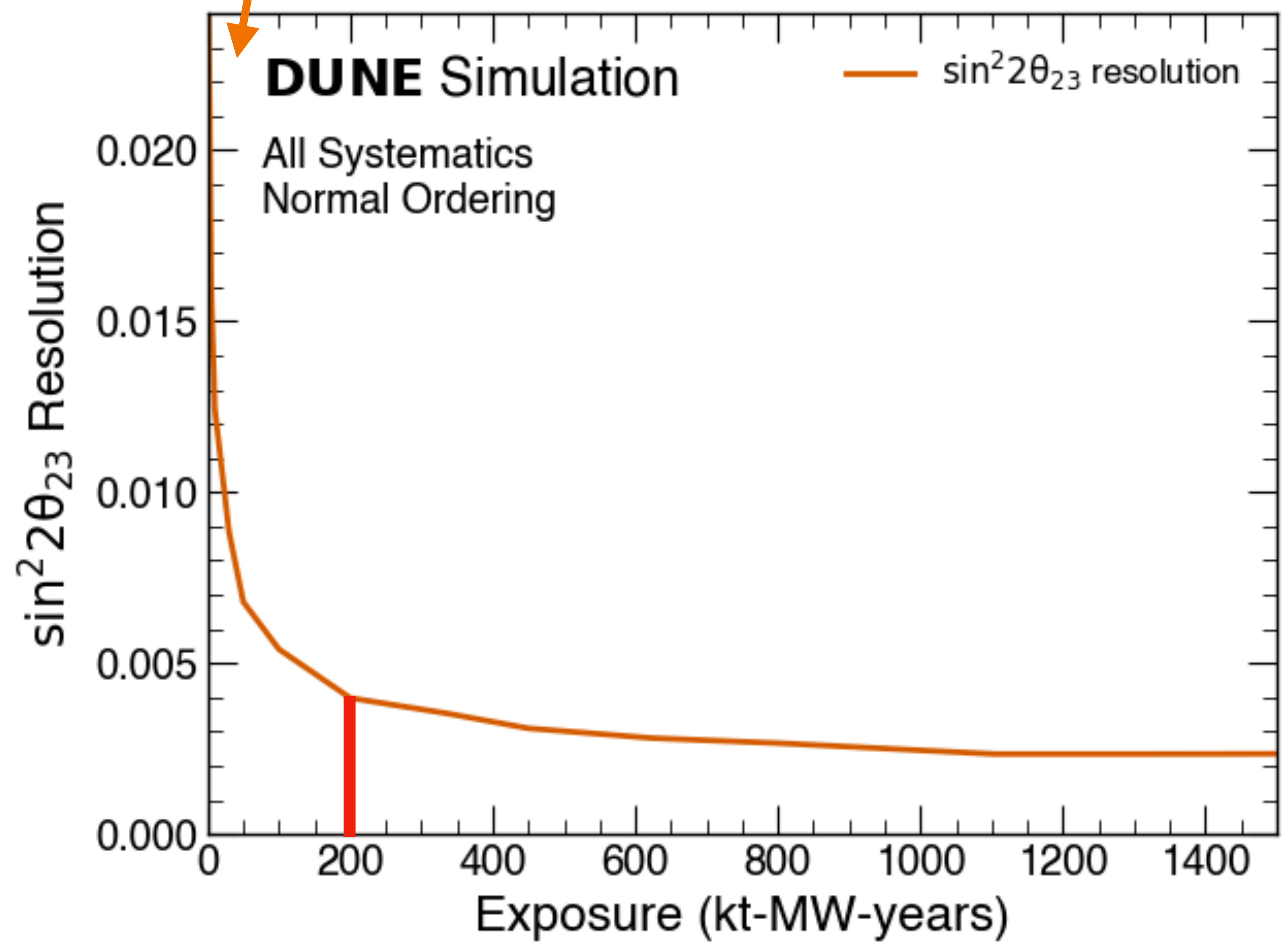
Expected signal

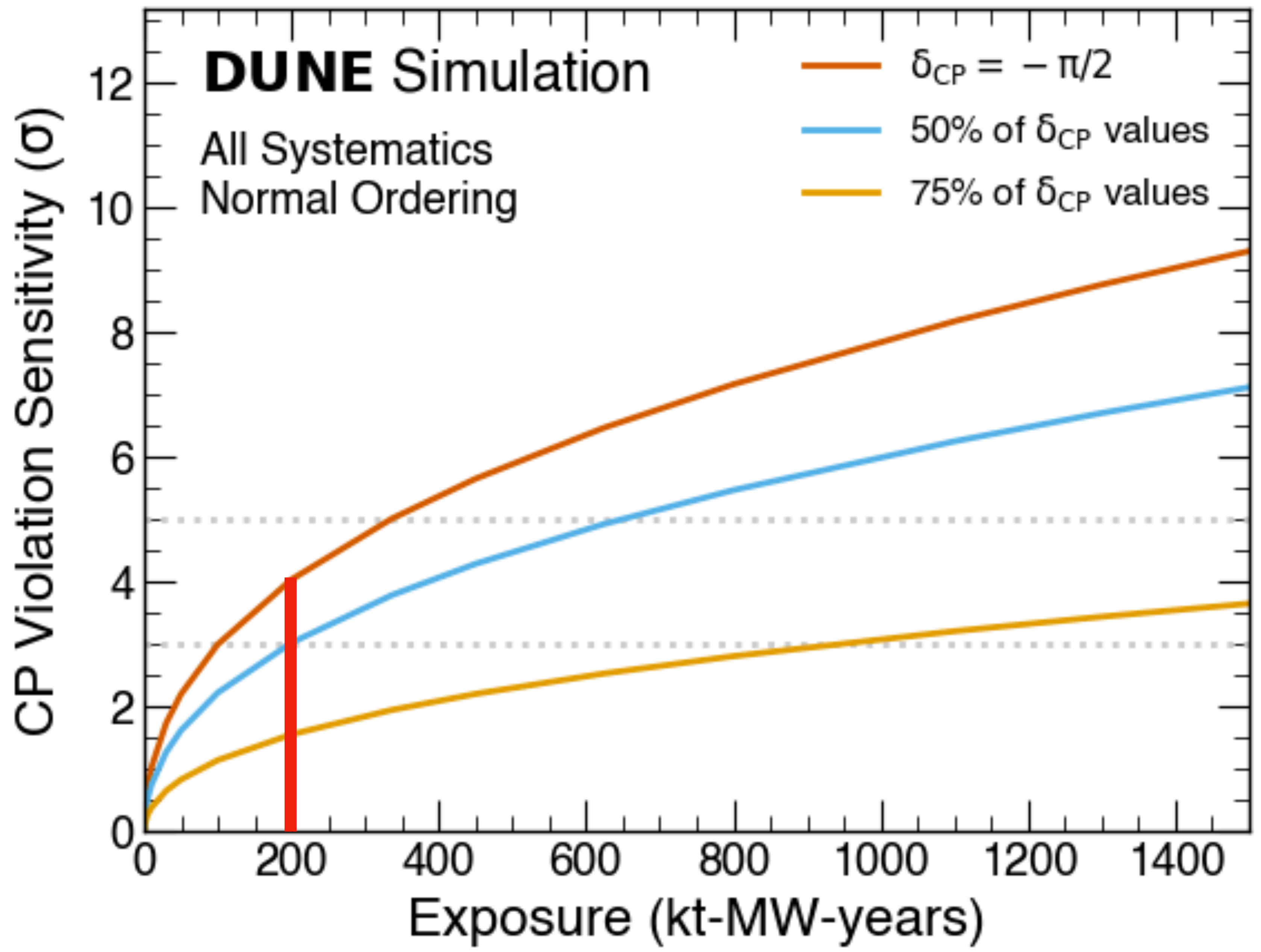


Main goals:

- Measure of the neutrino **mass ordering**
- Measure of the **CP-phase value,** Is there a CP-violation in the leptonic sector?
- Measure with precision some of PMNS parameters: θ_{23} (octant), Δm^2_{23},θ_{13}





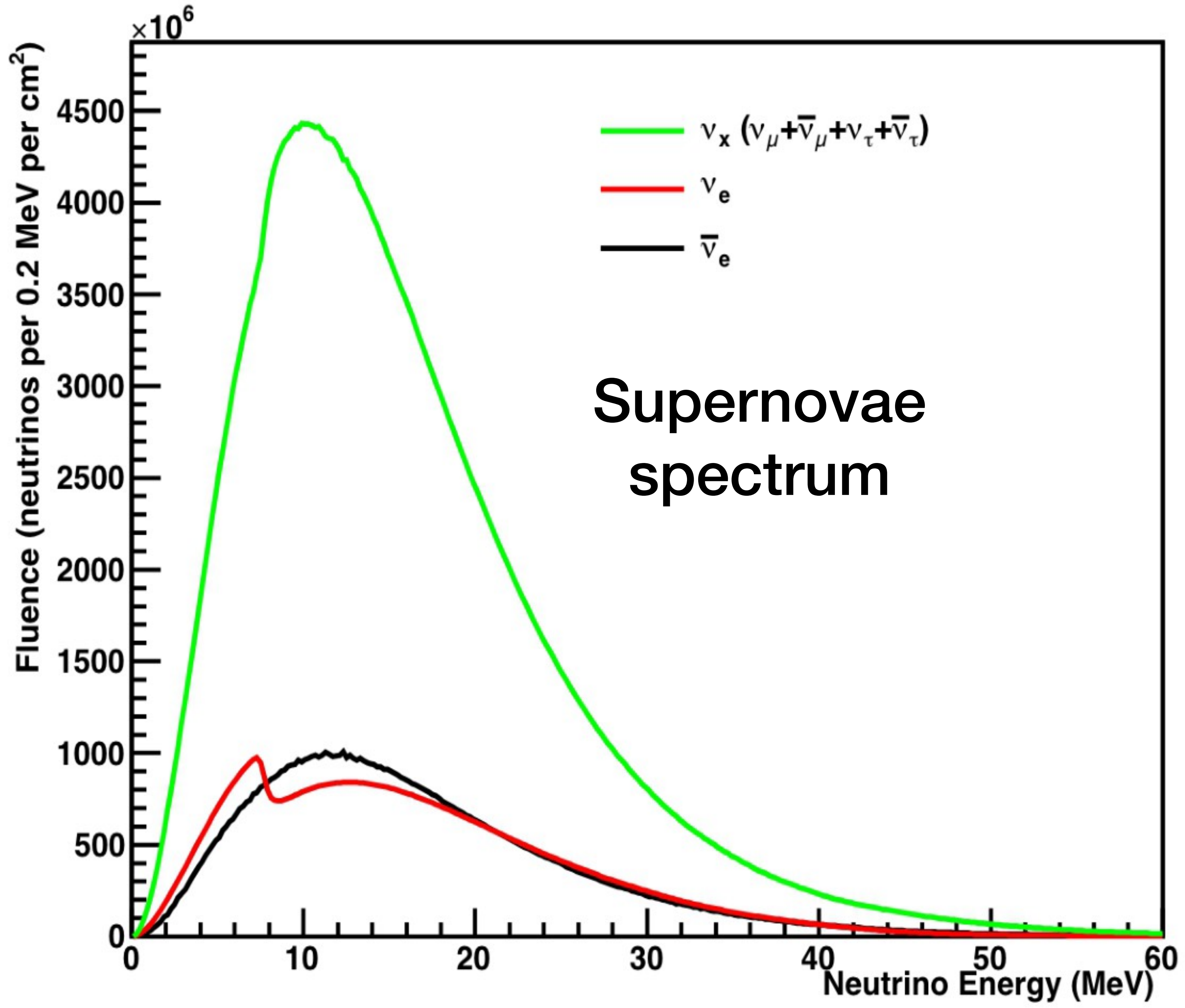


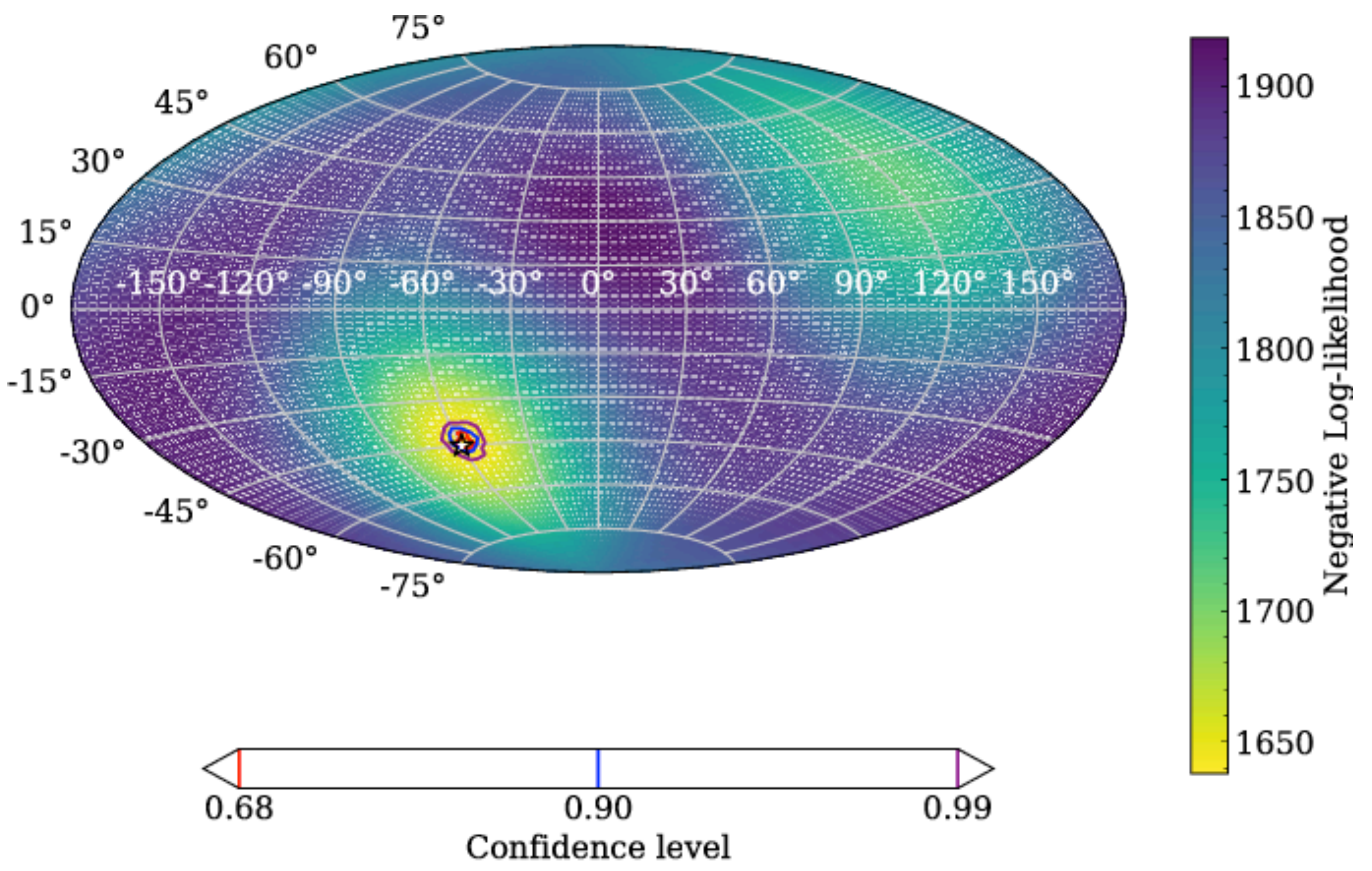
200 kt-MW-years ≈ 3 years of data taking with full-scale detector

Low energy physics program (~MeV):

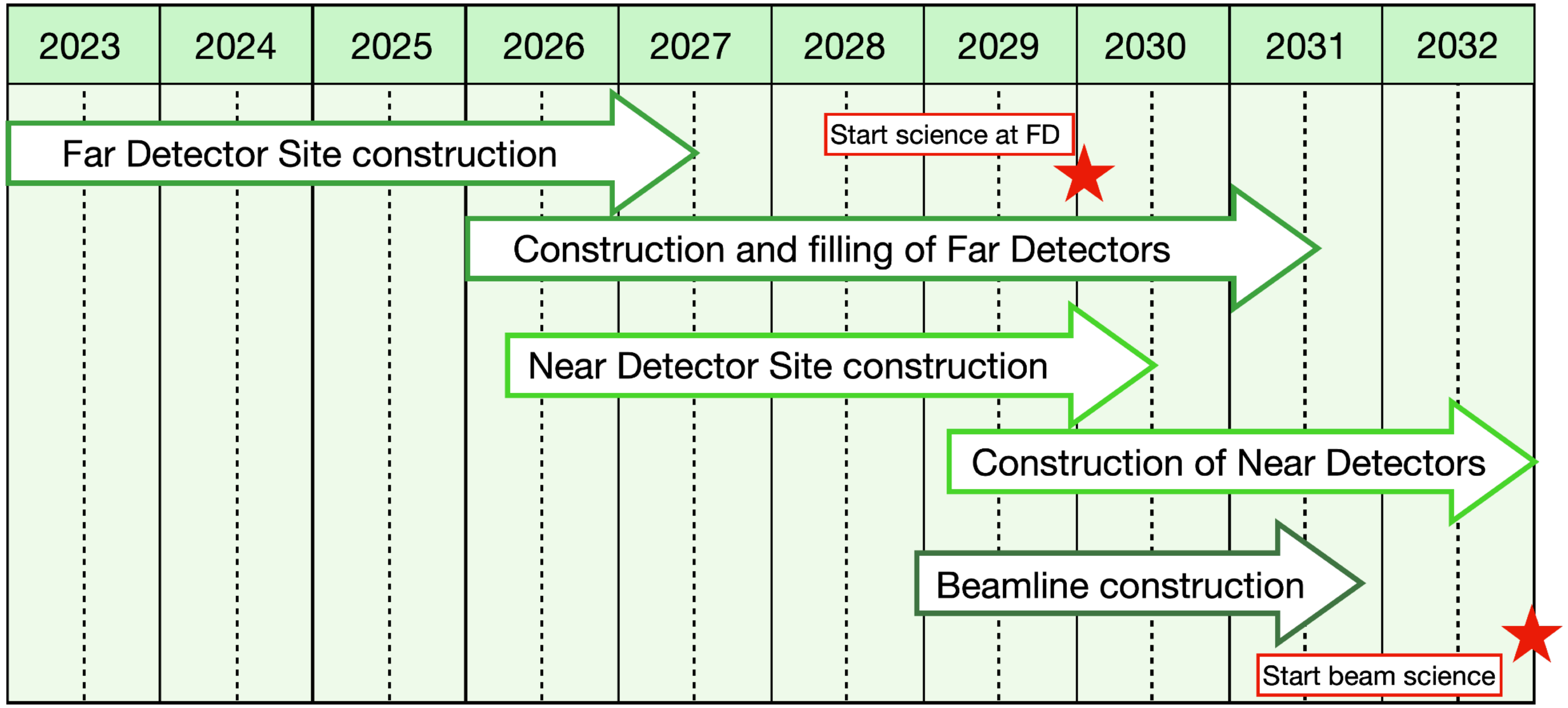
- SuperNova Burst detection
  - Important information on birth of black-holes
  - Multi-messenger astrophysics: Gravitational waves, neutrinos then photons
- Solar neutrino detection (hep neutrino)
- Diffuse SuperNova Background

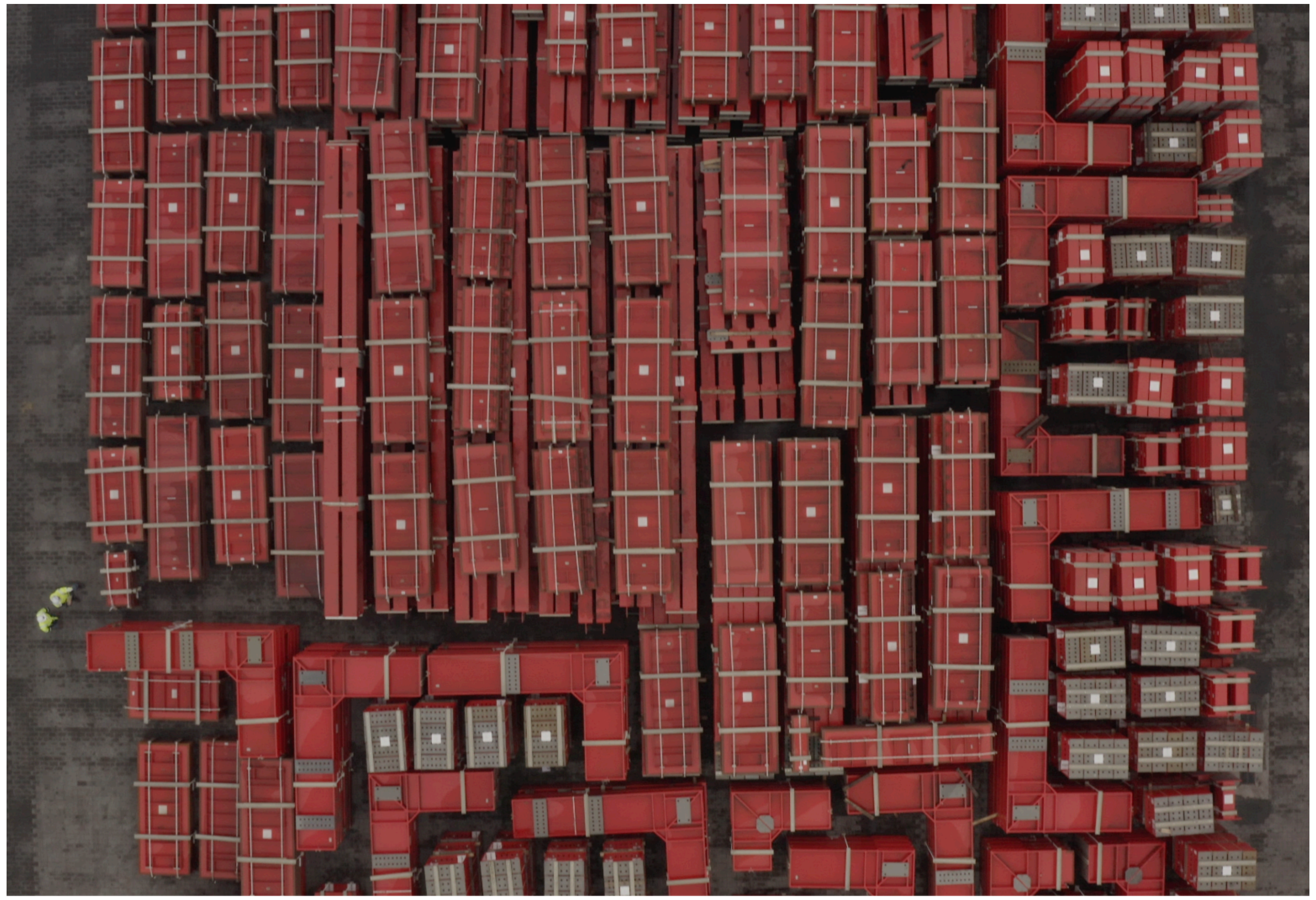
- **Challenging range of energy** with lower cross-section and more sensitive to detector or reconstruction effects like background or noise level. Need a dedicated Trigger and dedicated reconstruction.





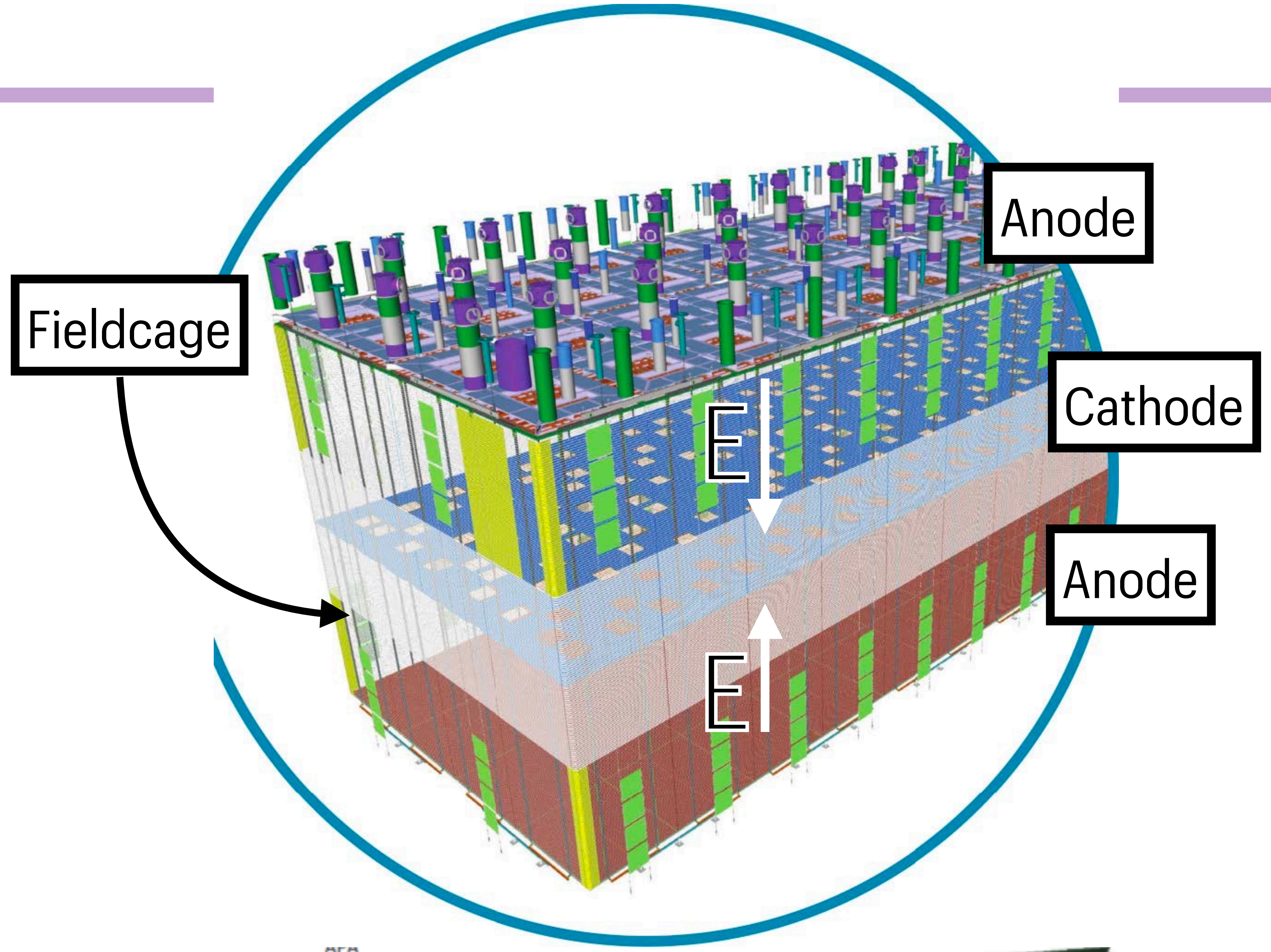
- Excavation of Far Detector site finished
- Cavern available → 01/01/26
- Cryostat delivery completed

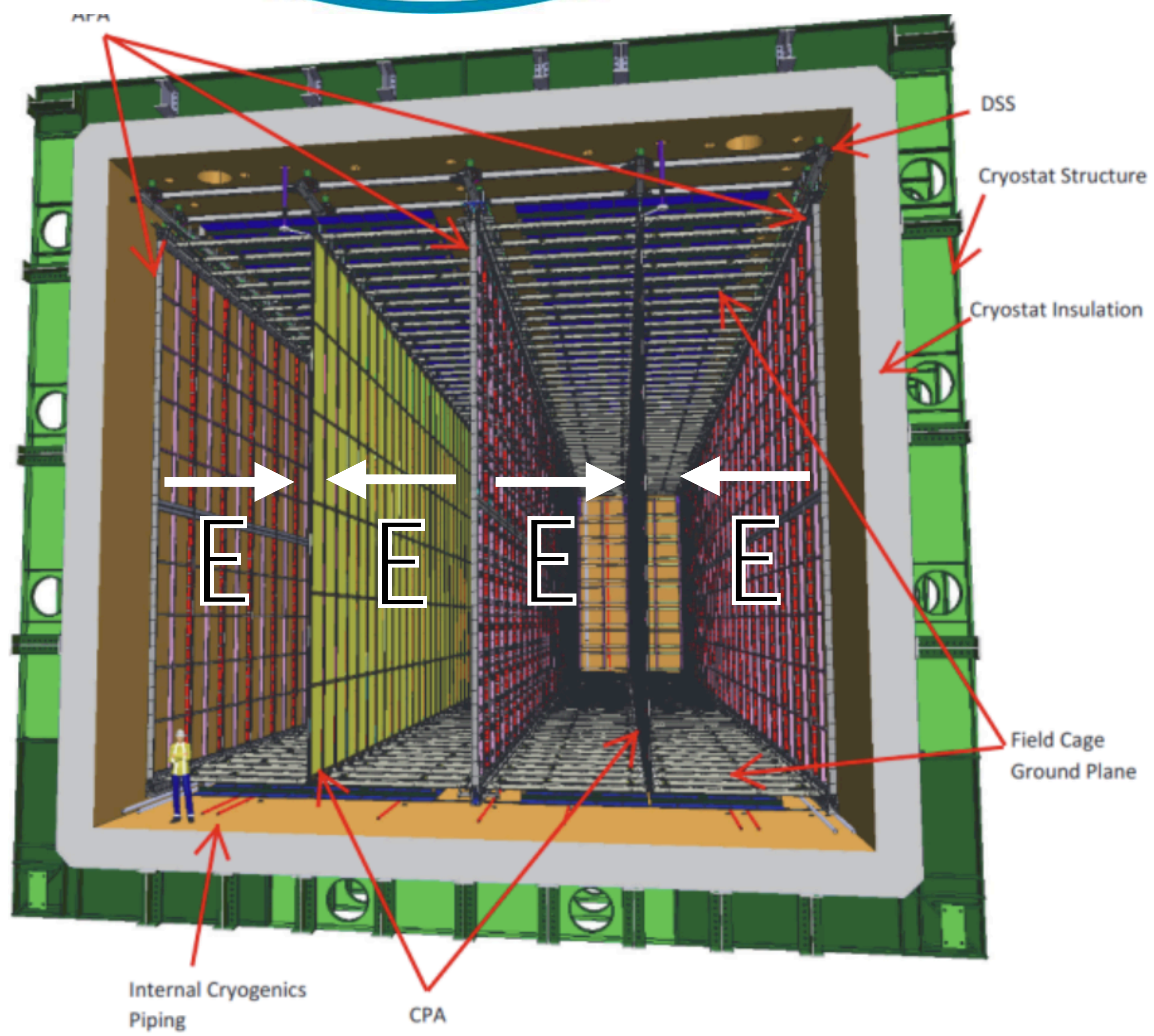




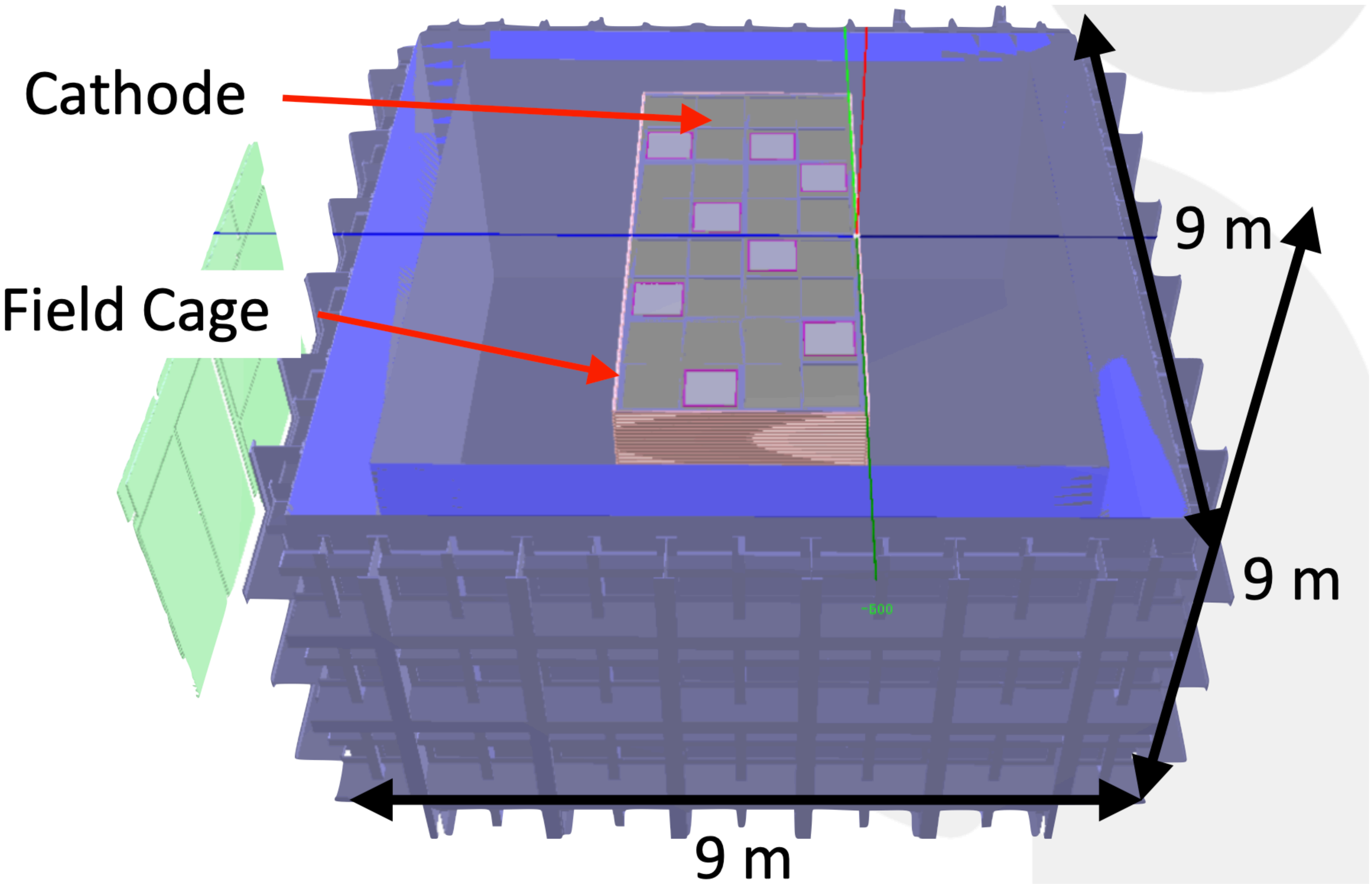
DUNE Status

- Two Far Detectors (LArTPC):
  - **Vertical Drift** (French effort):
    - starting the production phases of different detector components (cathode, anode, photon detection system, top drift electronics)
    - starting the installation test at Cern (1:1 size)
  - **Horizontal Drift:**
    - production of the anode unit near full-speed (~30 anodes produced)
- Near Detector and Beam:
  - Near detector: 100% completed designs
  - 0.9 MW NuMI beam already achieved for NOvA



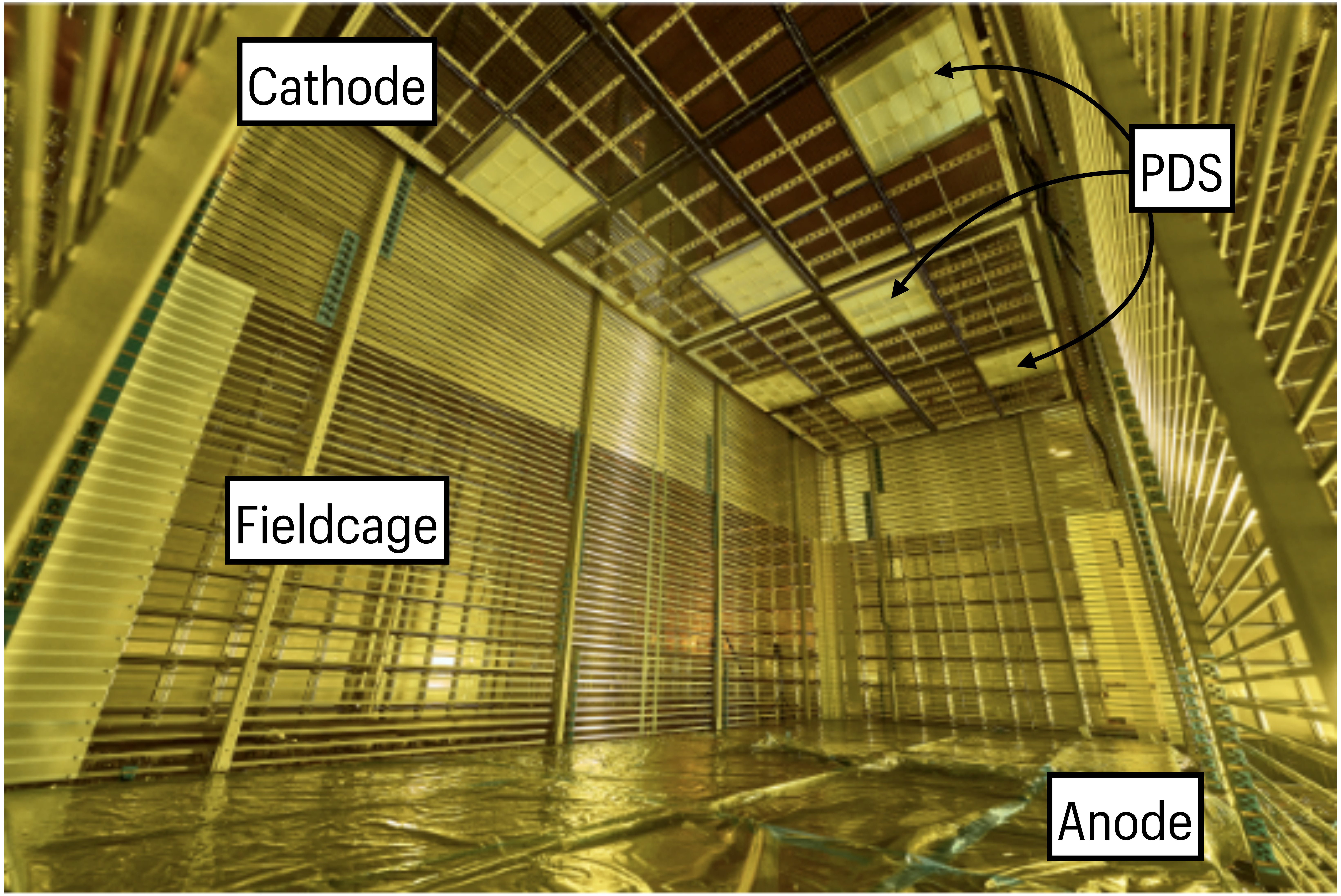


ProtoDUNE Vertical Drift (PDVD)



- Prototype at CERN on surface
- **Full with liquid Argon**
- Under commissioning
- **Same design as FDVD (anode and cathode)**

- Two drift volumes
- **~3 meter drift length**
- **Only two cathode units**



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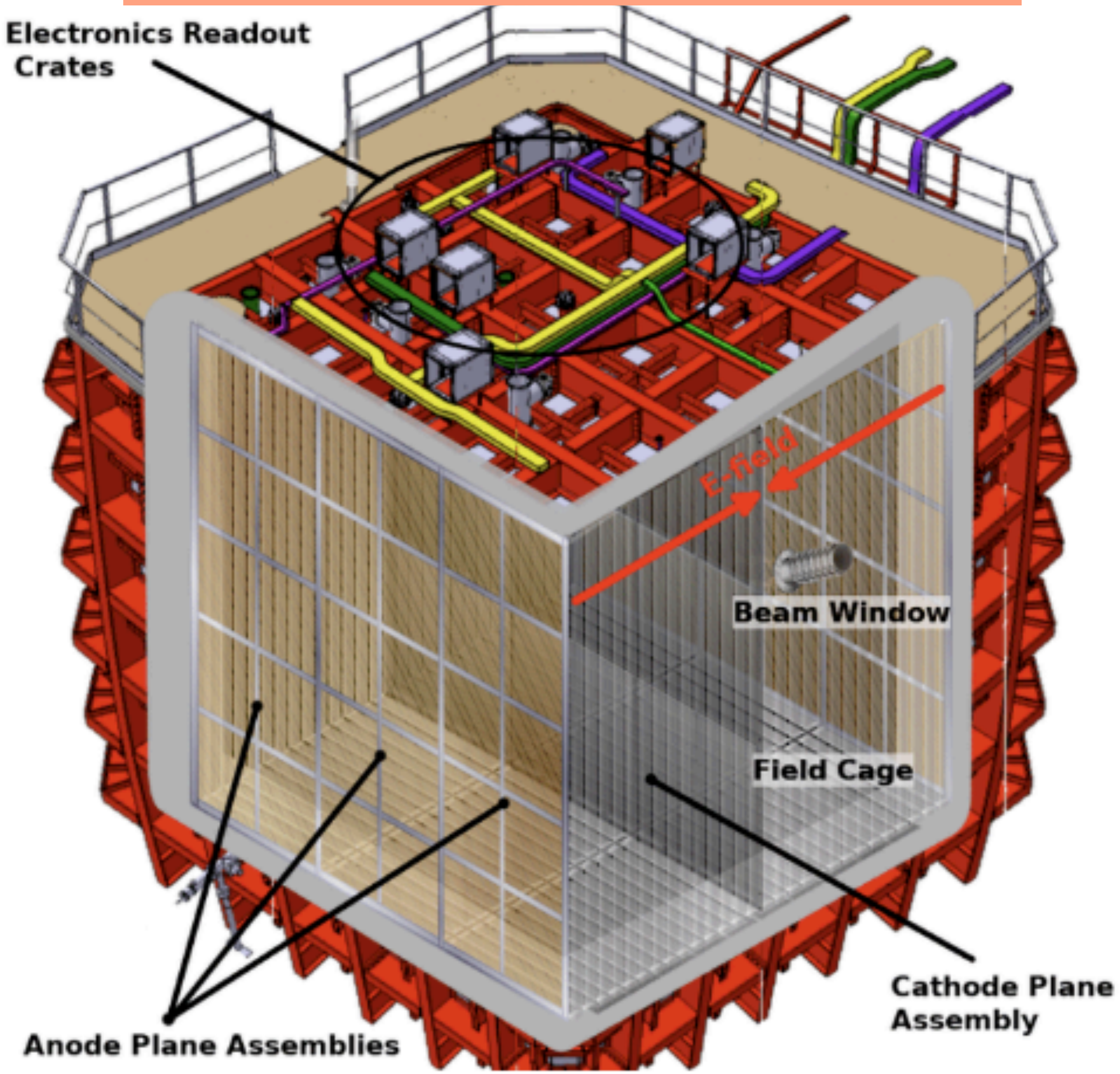
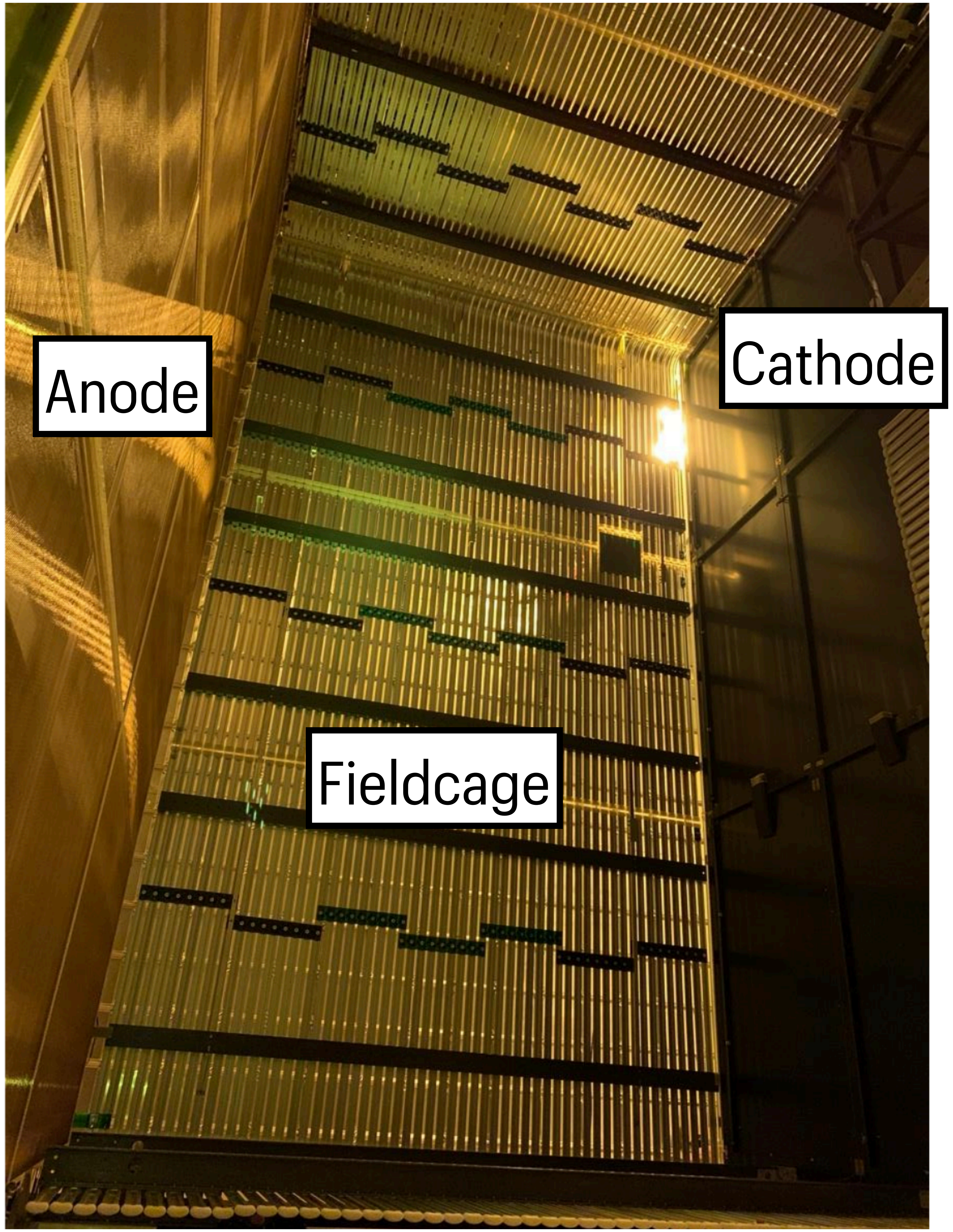
ProtoDUNE Horizontal Drift (PDHD)



- Prototype at CERN on surface
- **Only two drift volumes**
- **~3.5 meter drift length**
- **took data (May→November 2024)**
- Detector full of LAr in April 2024
- Stabilized needed purity level (>30 ms) achieved in June
- 10 weeks of beam run
- beam energy from 1 to 7 GeV (mainly pions)

Context of DUNE



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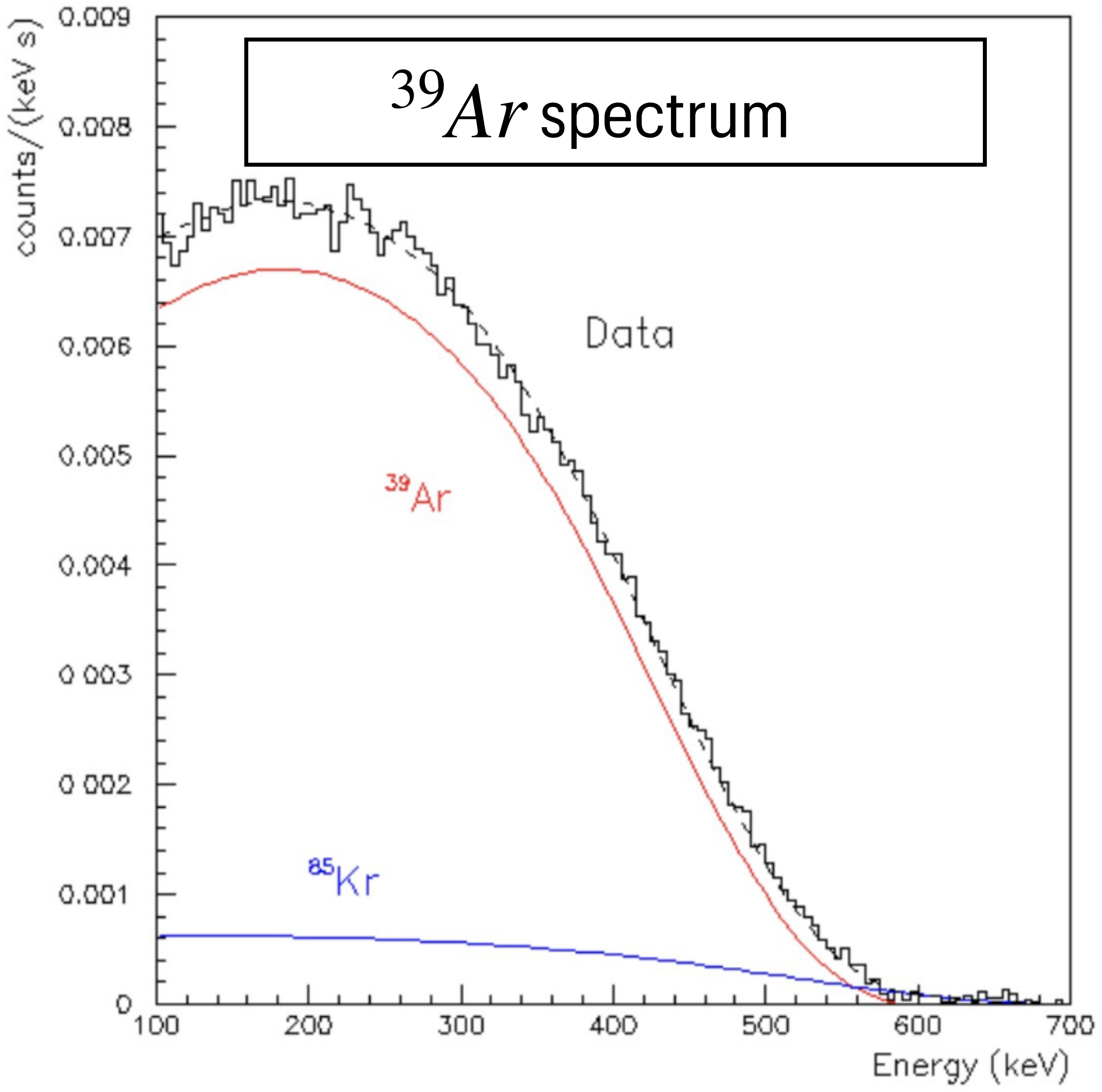
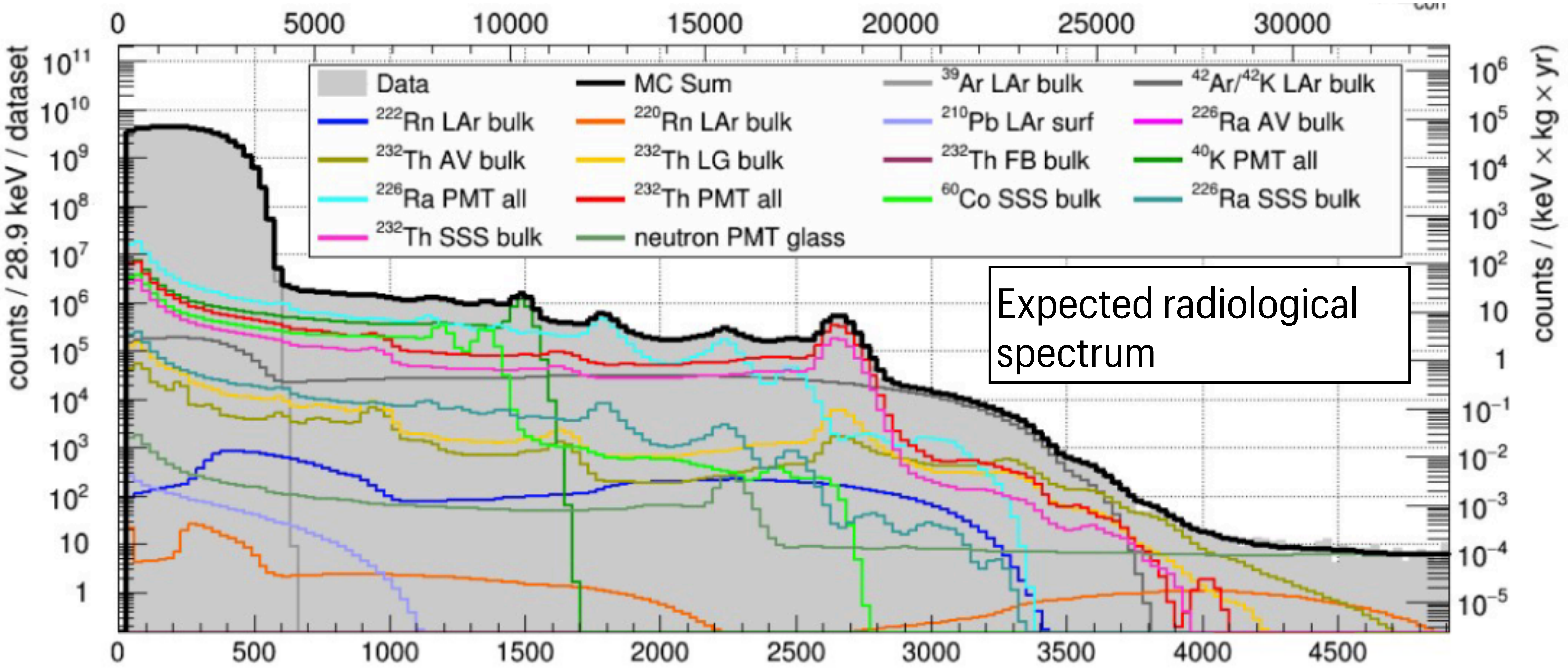
MeV calibration of ProtoDUNE-HD

ProtoDUNE-HD calibration

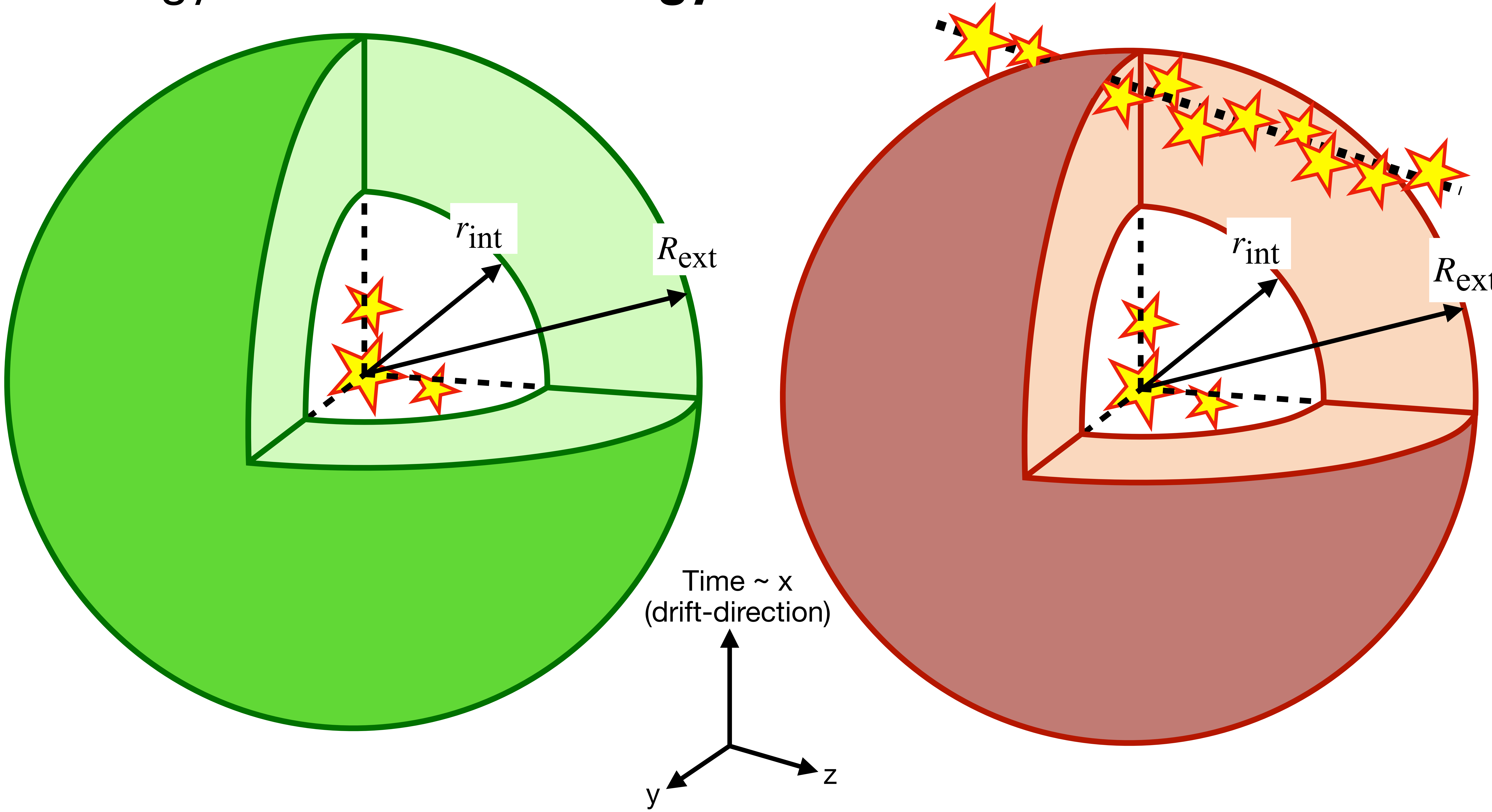
- **Use radiologic decays (radiologicals) for calibration**:
  - ^{39}Ar in volume (**main background for Low Energy studies**: expect ~10^5decays/s for prototypes)
  - Natural contribution from detector components (^{232}Th,^{238}U chains)
  - additional ^{207}Bi source



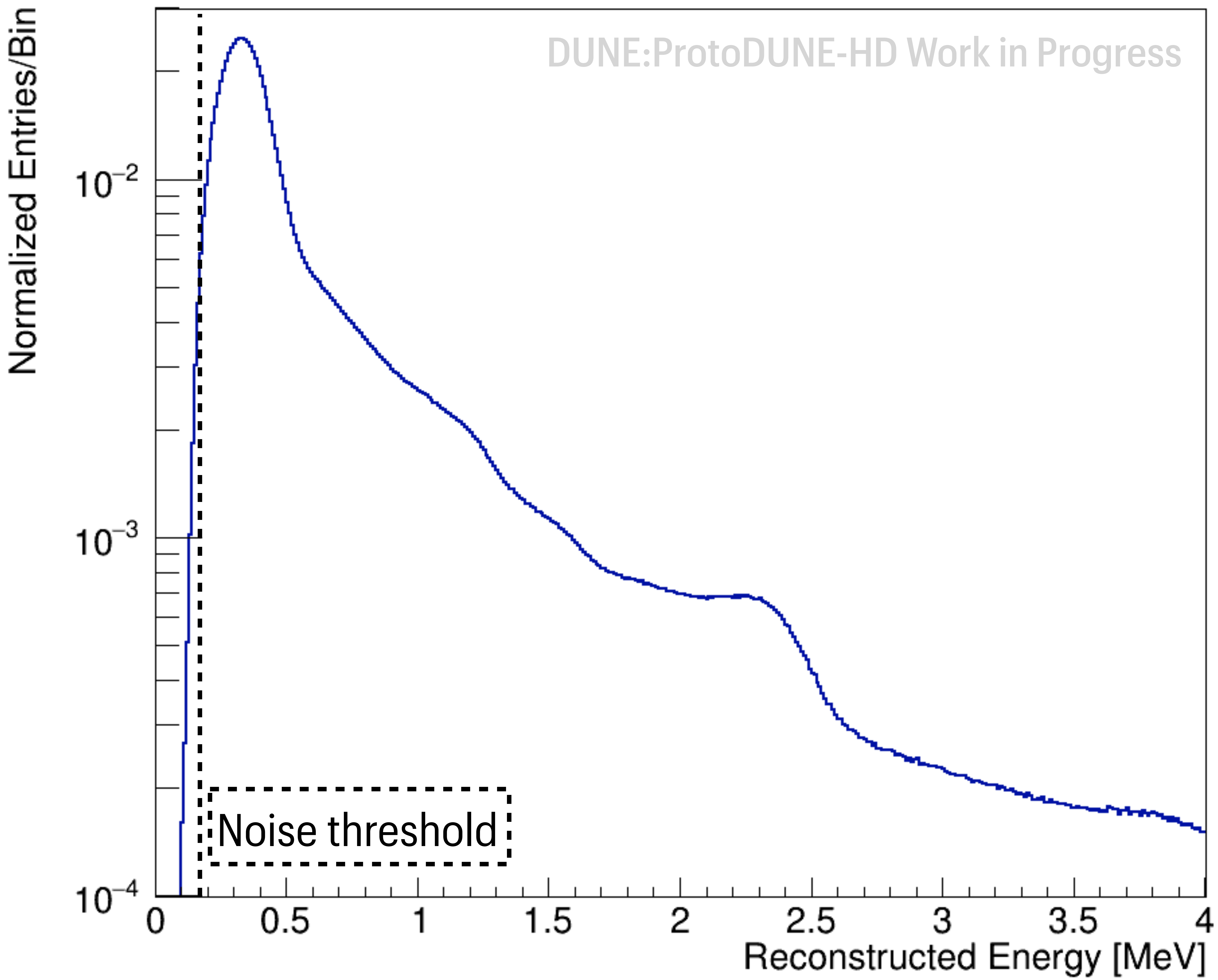
Example: Background measurement with DEAP-3600 (3.3 tonne LAr dark matter detector at SNOLAB)



- Signal signature: **point-like events isolated in the detector** (with few MeV energy)
- **But:** ProtoDUNE's are surface detectors → **lots of cosmics**
- Made a **dedicated analysis tool** (available for the collaboration) to reconstruct **isolated hits** position and energy and make **Low Energy clusters**



- Reconstructed **~36 min of data taking → ~50 To** (only ~1% of all set)



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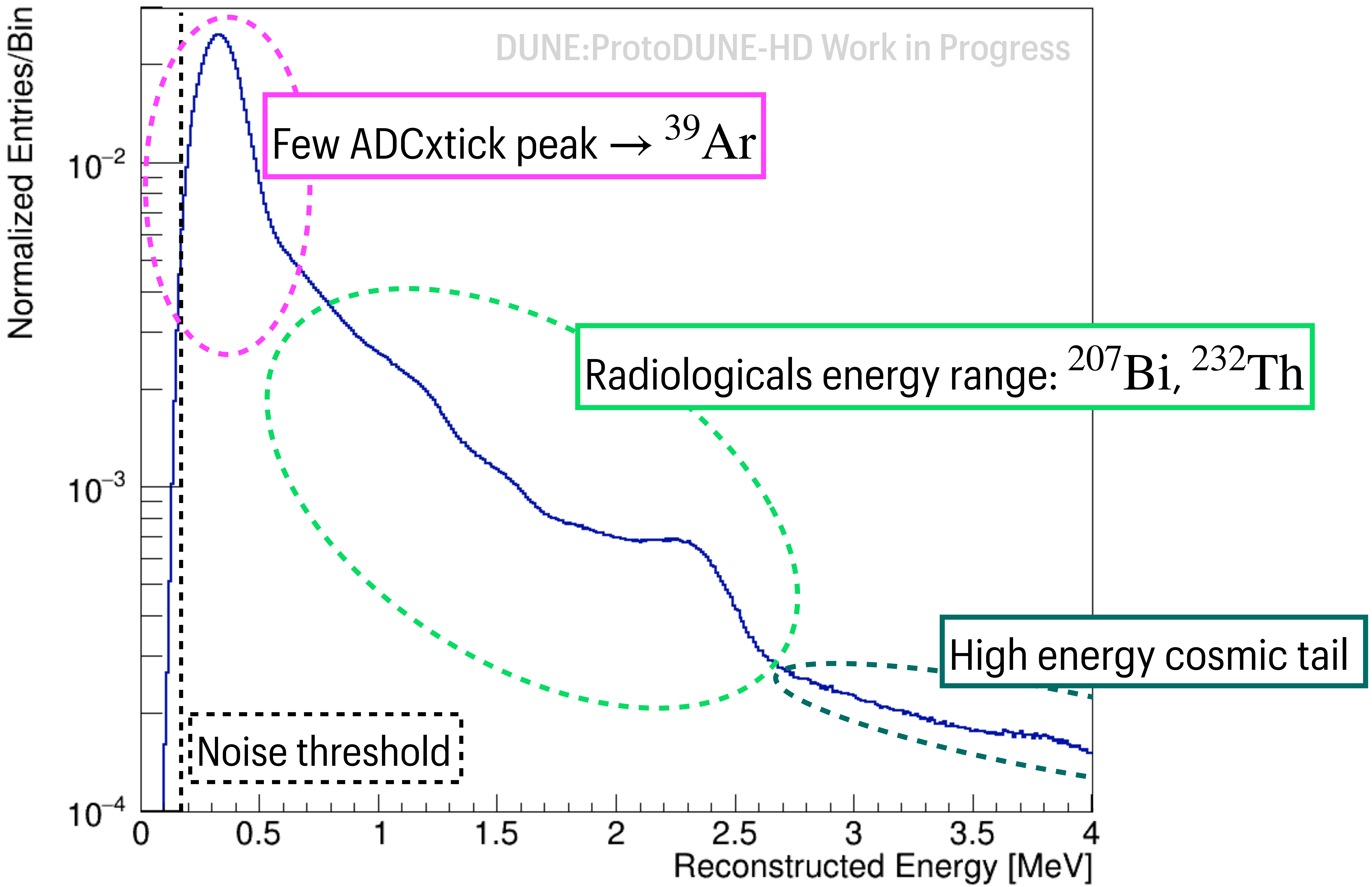
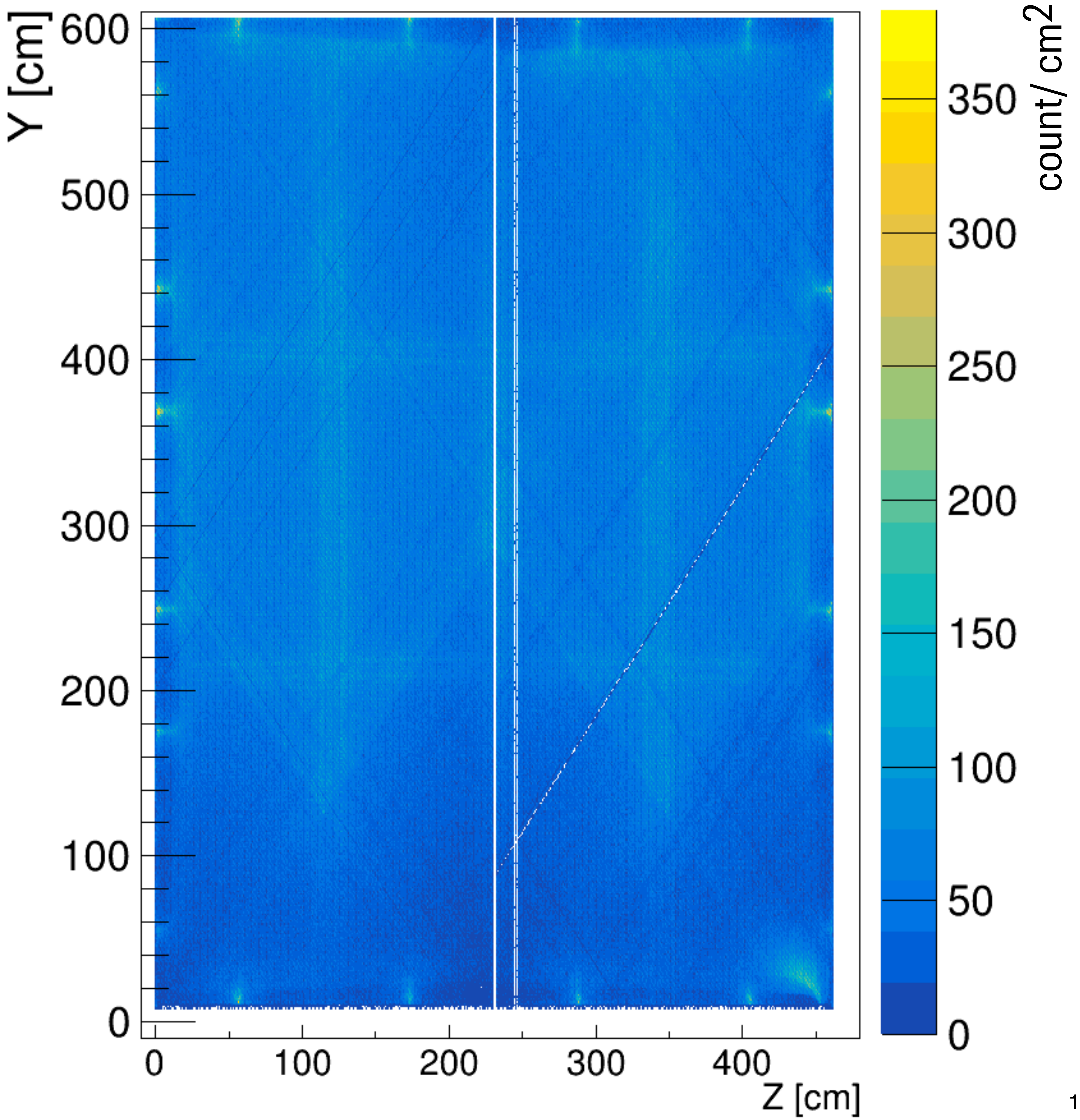
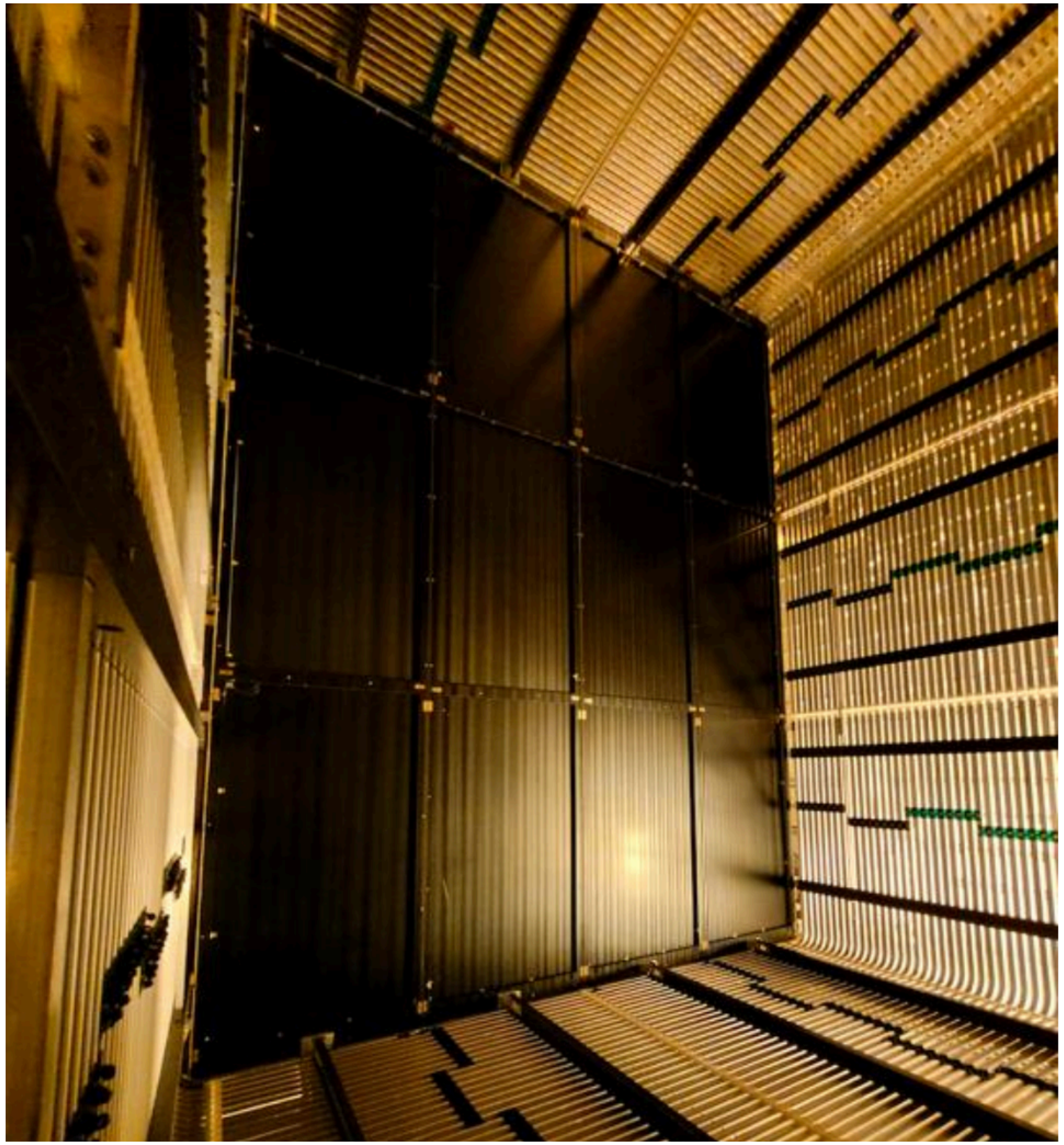
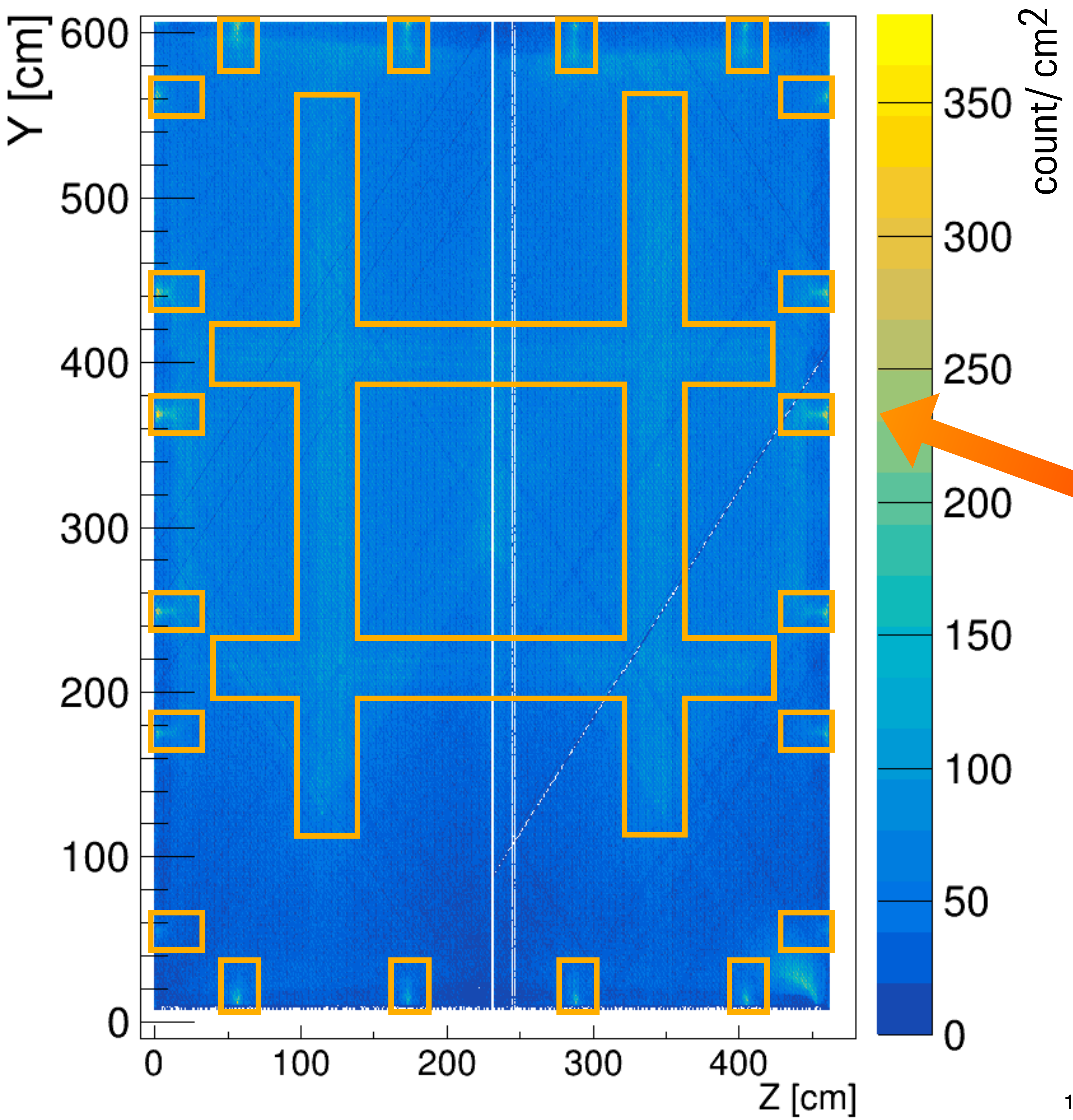




- We recognize **cathode and field cage structure**





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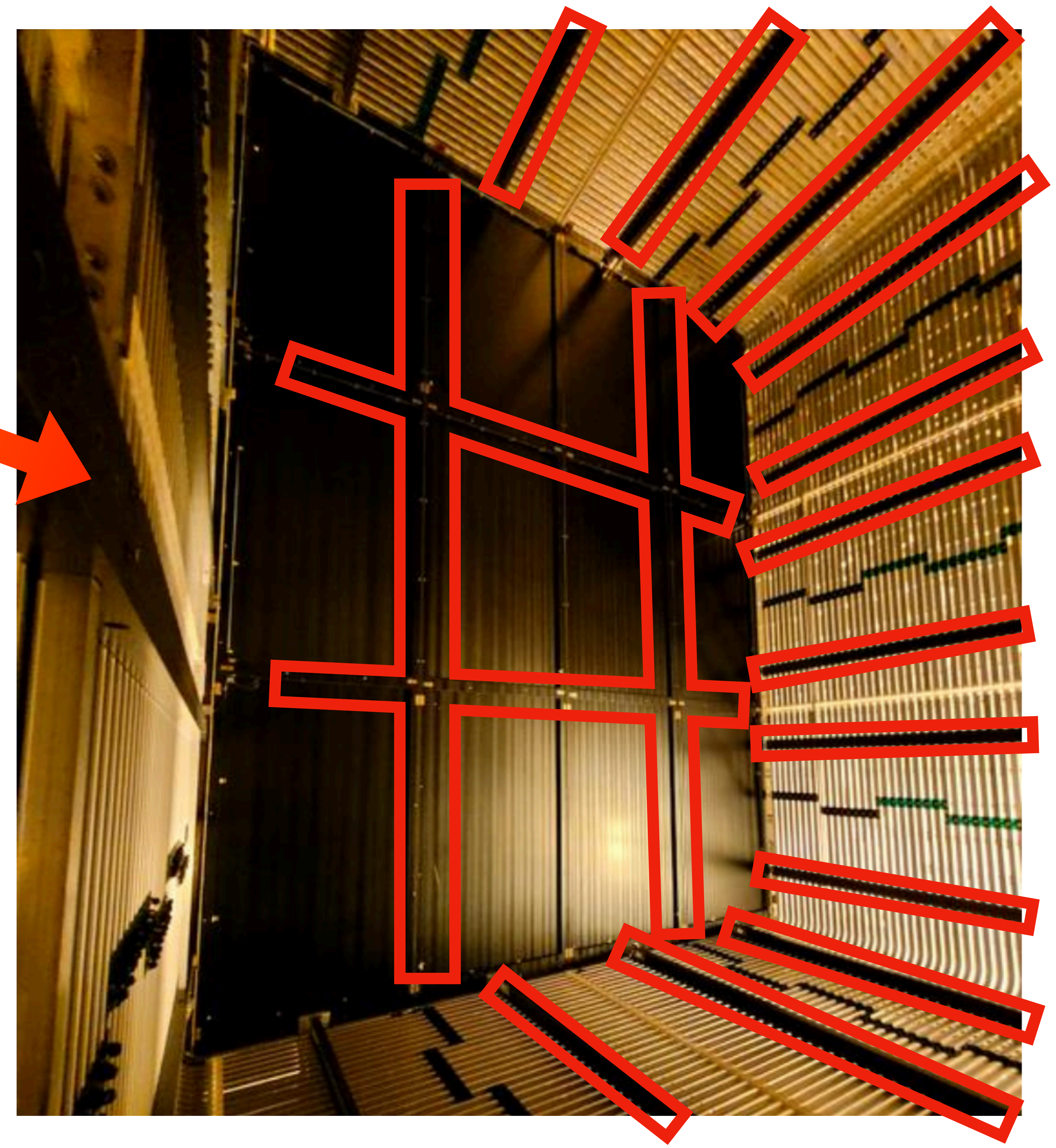
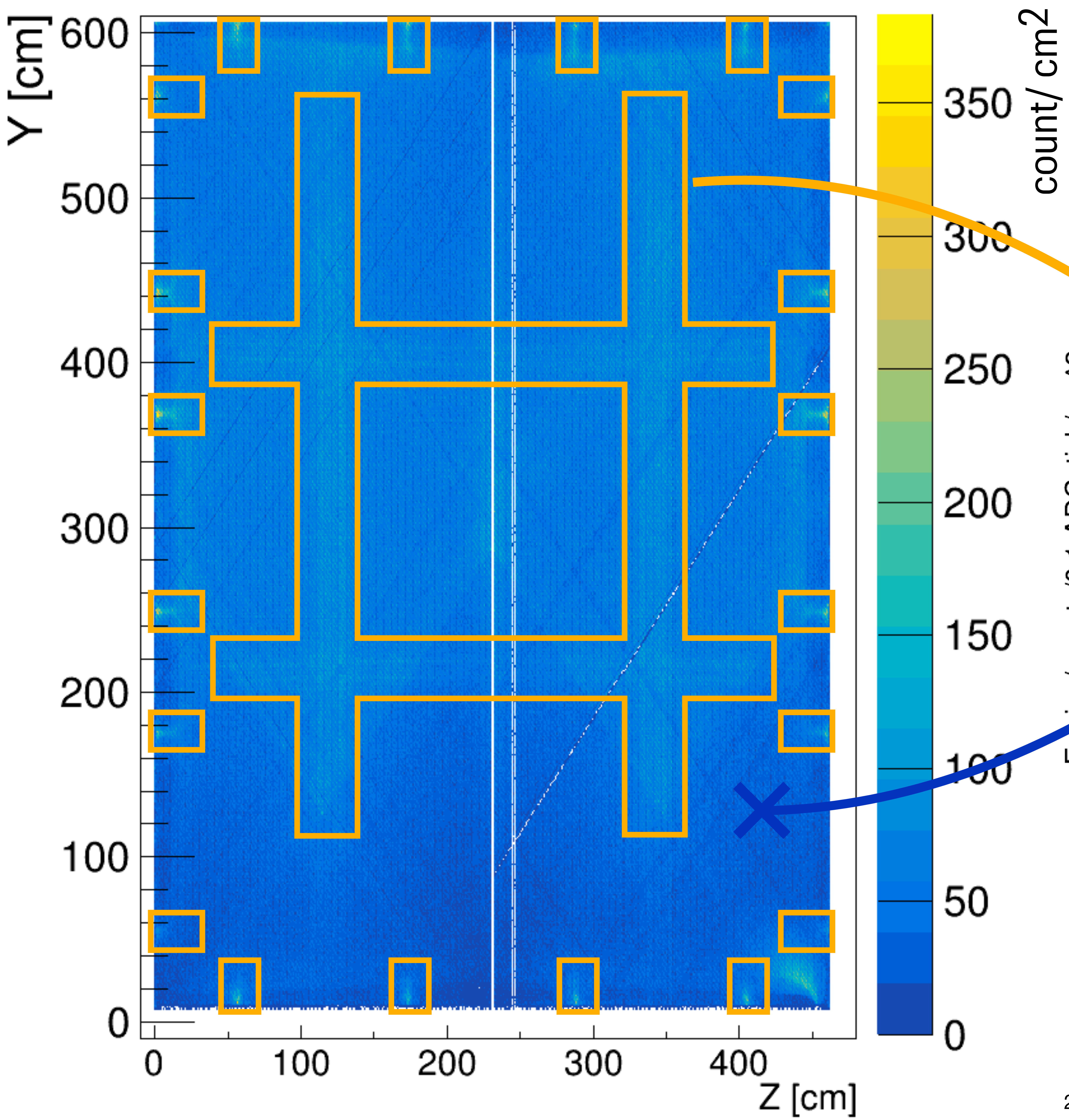
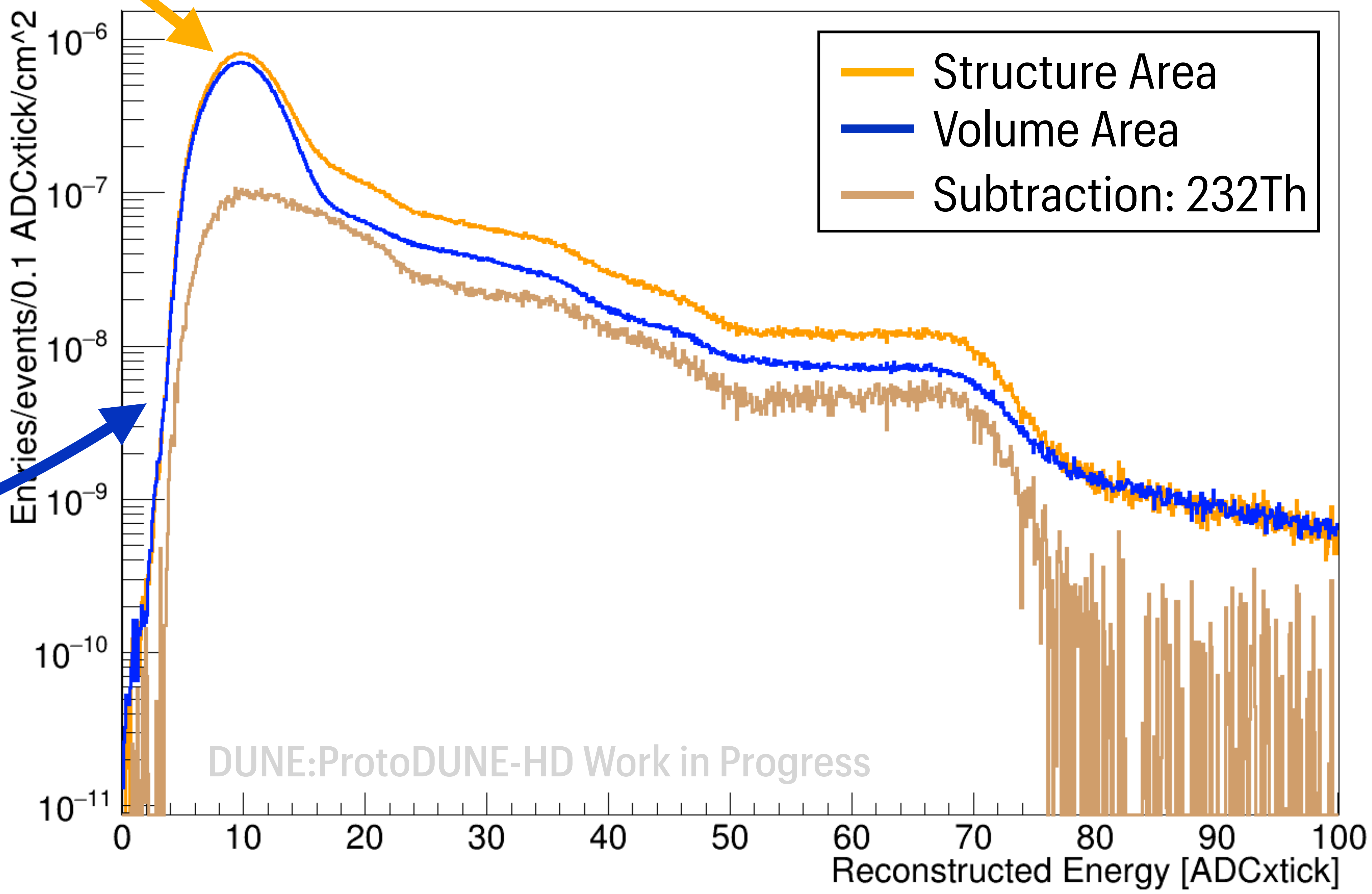


ProtoDUNE-HD calibration

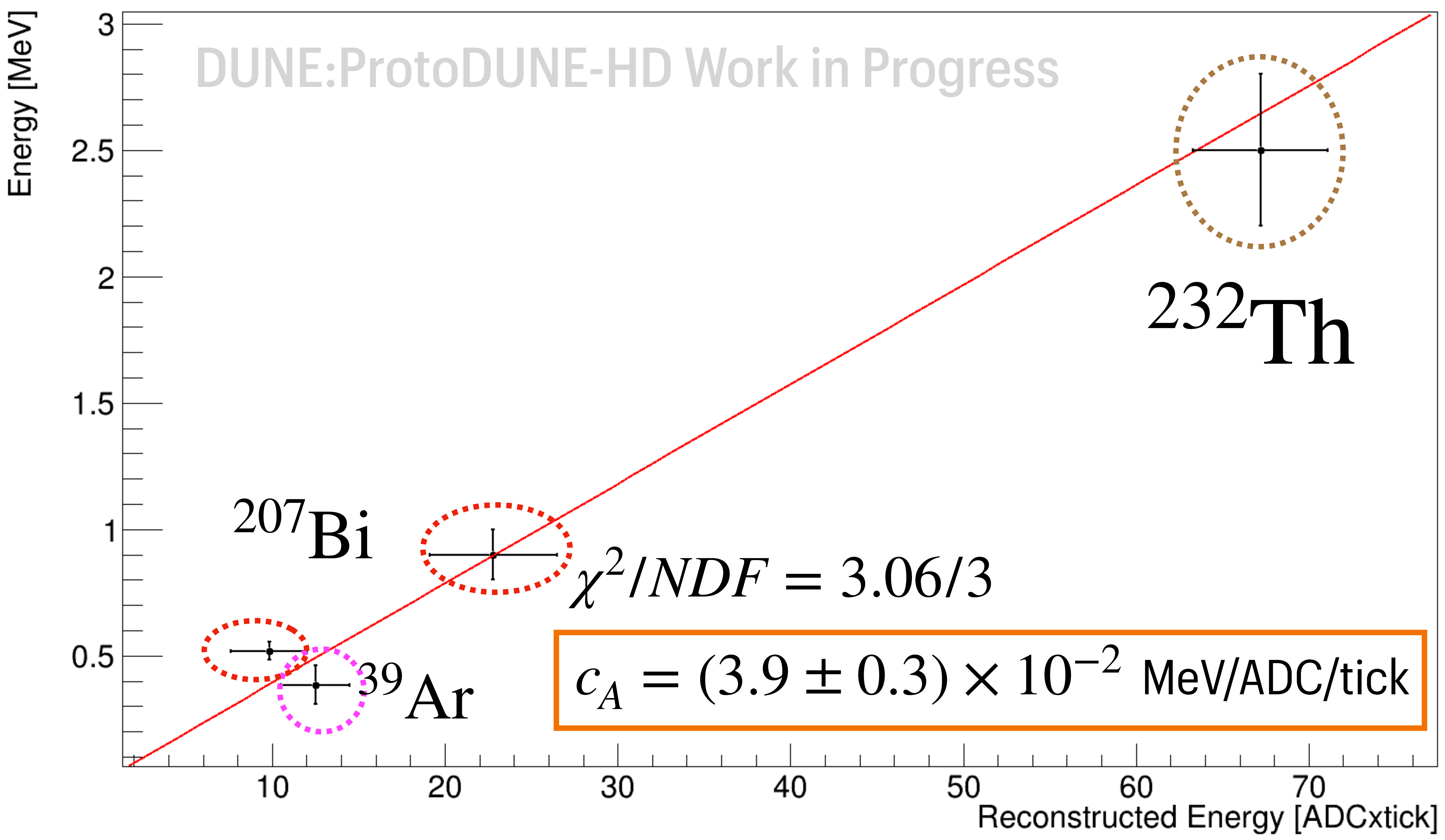


- ^{232}Th is a well known natural radioactive component with a prominent **2.6 MeV gamma line** from ^{208}Tl decay

NB: spectrum is normalised by area



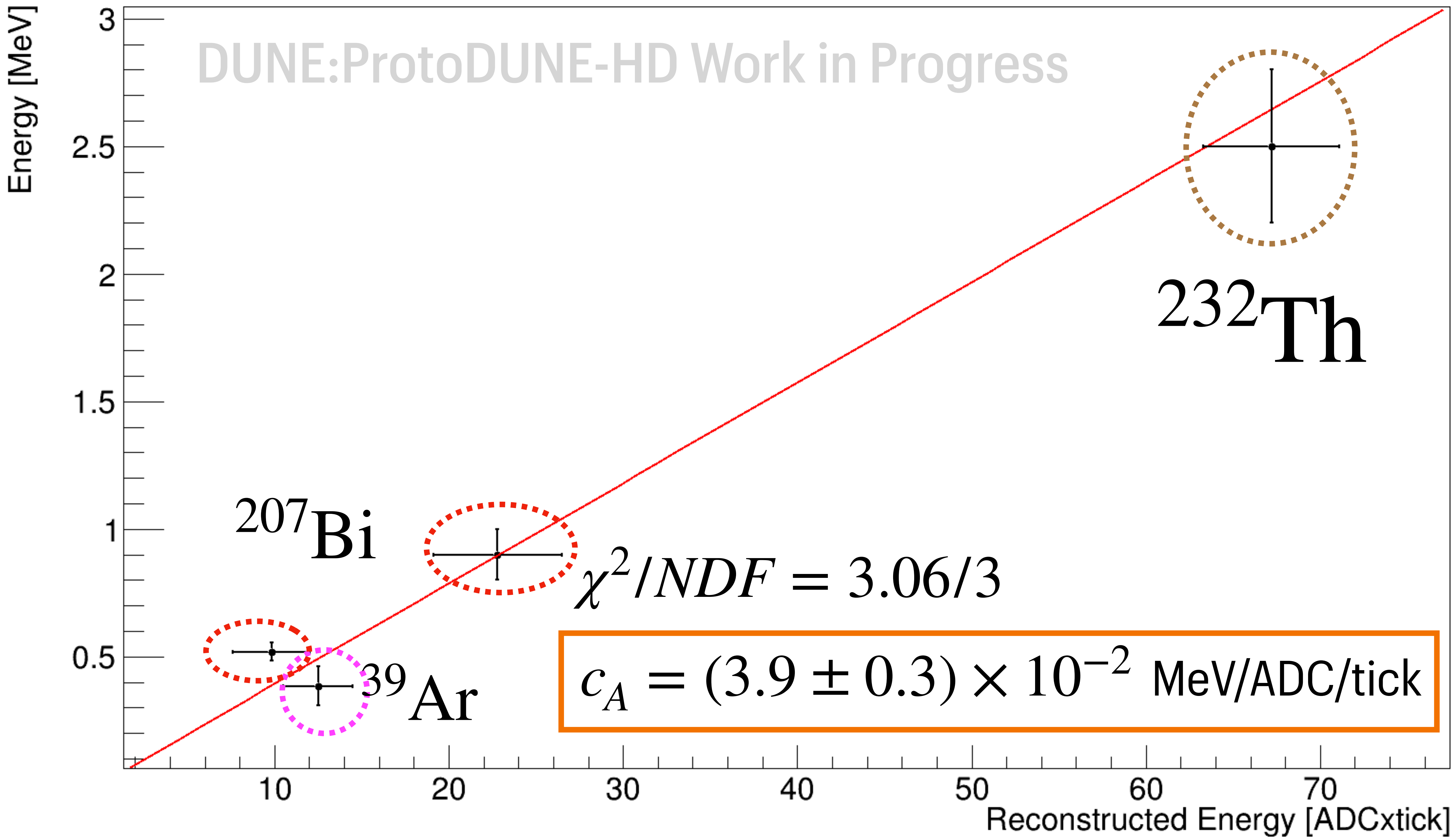
Consistent with literature: MicroBoone https://doi.org/10.1103/PhysRevD.111.032005



- Calibration factor is consistent with higher energy:

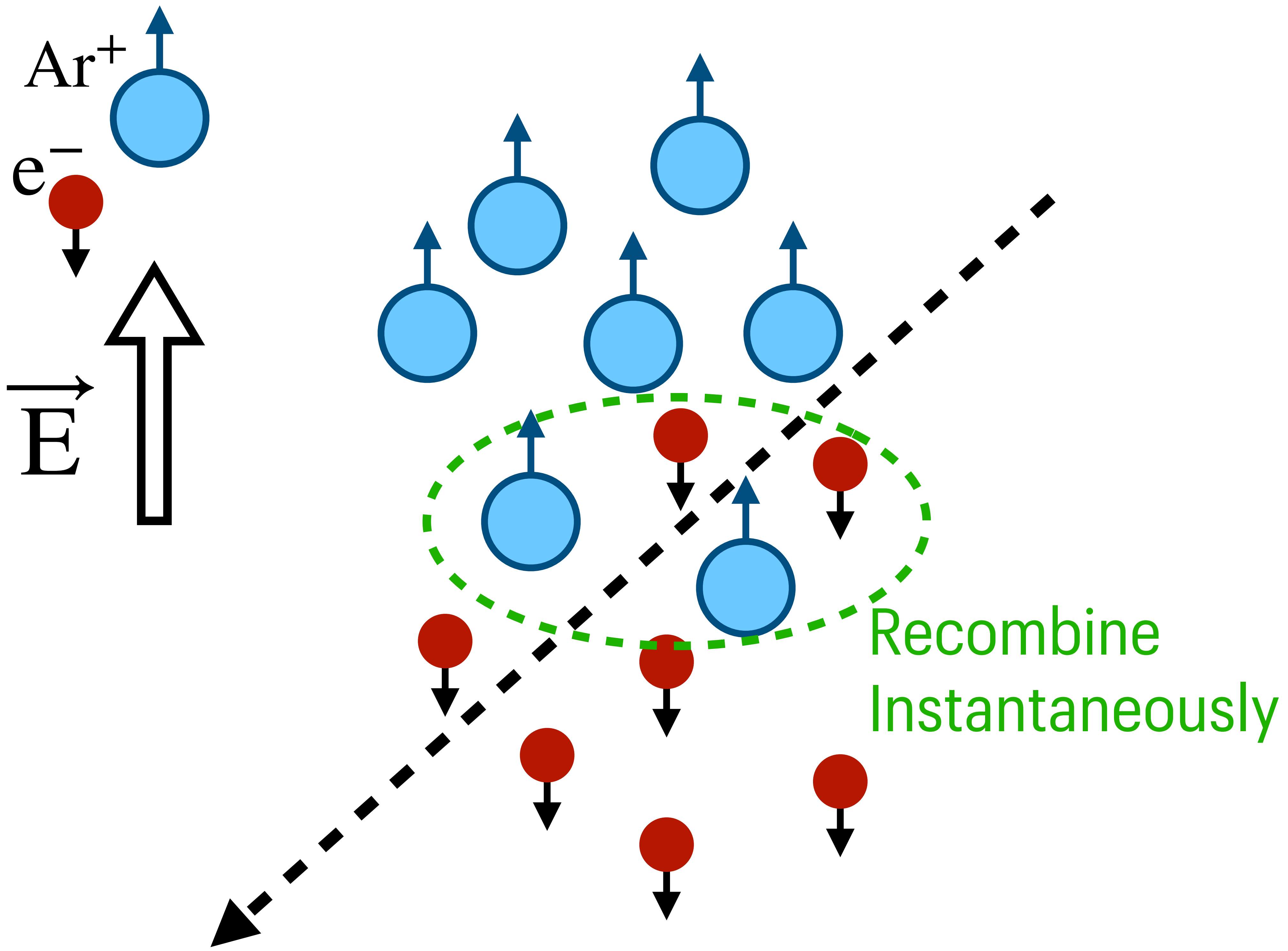
$$c_A^{\mathrm{HE}} \approx 0.036 \text{ MeV/ADC/tick}$$

- From calibration **we can compute the recombination R :**



- Important features of LArTPC is recombination R:

$$R = \frac{E_{\text{visible}}\ [\text{MeV}]}{E_{\text{true deposited}}\ [\text{MeV}]}$$



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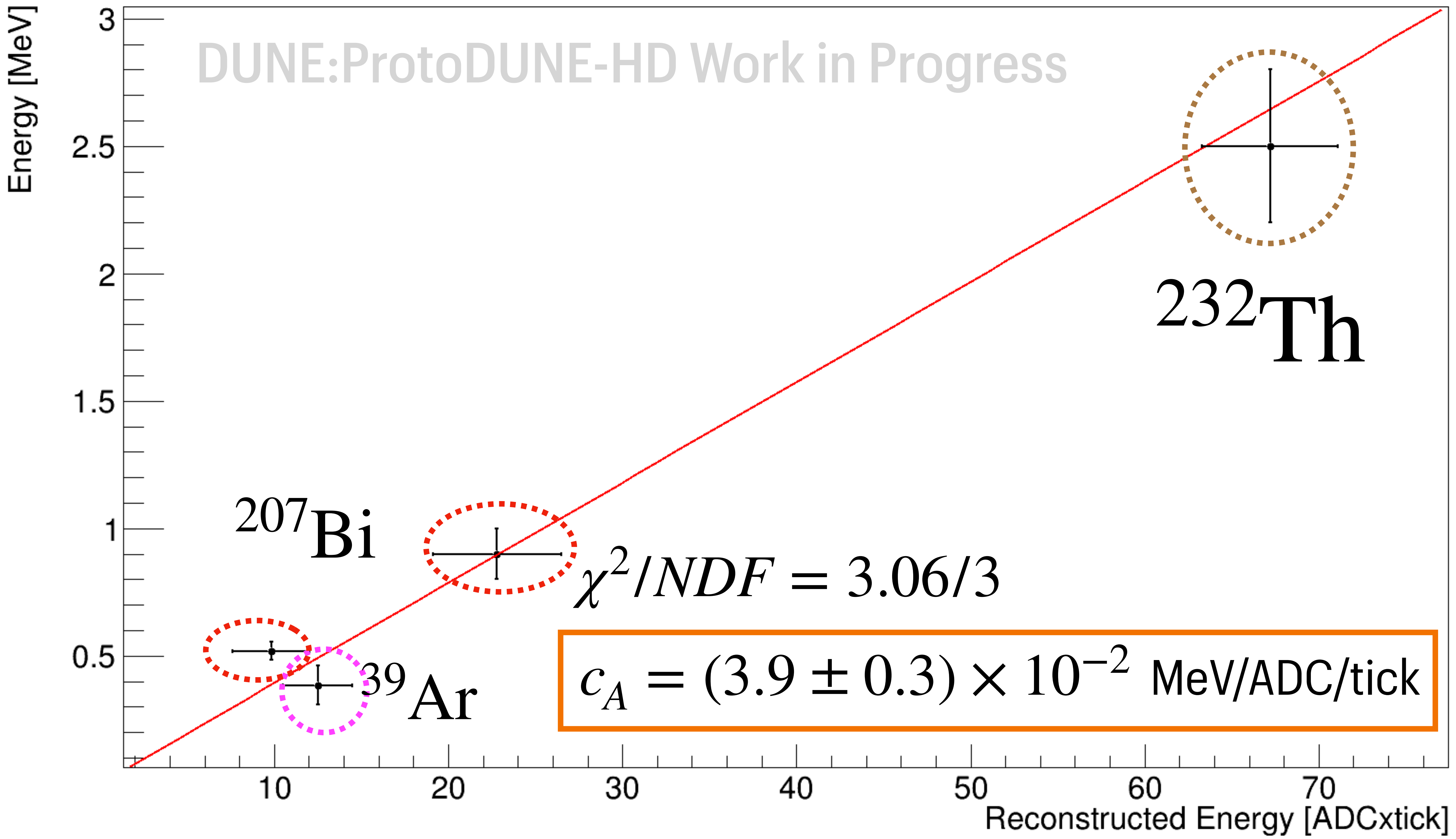

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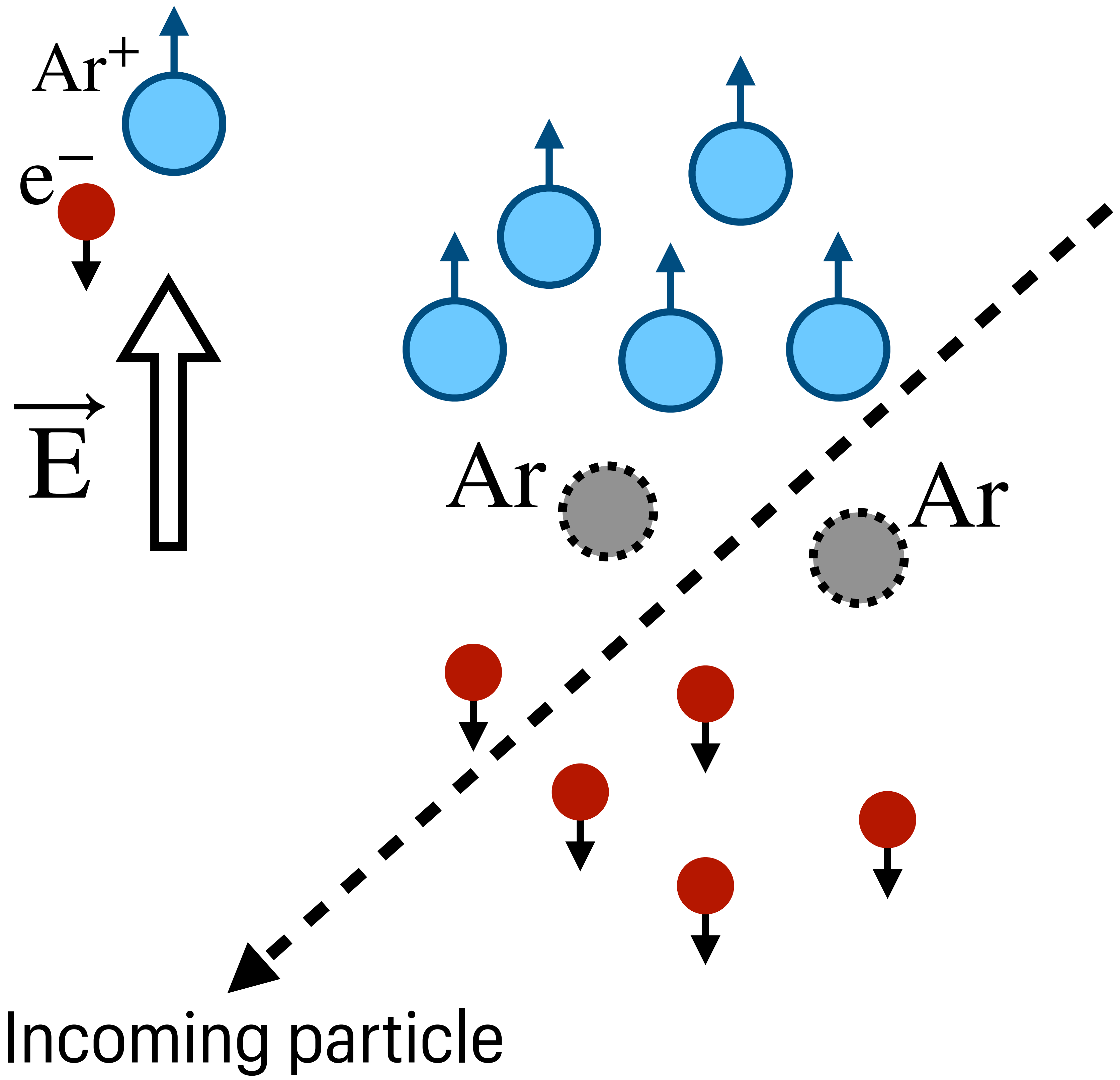

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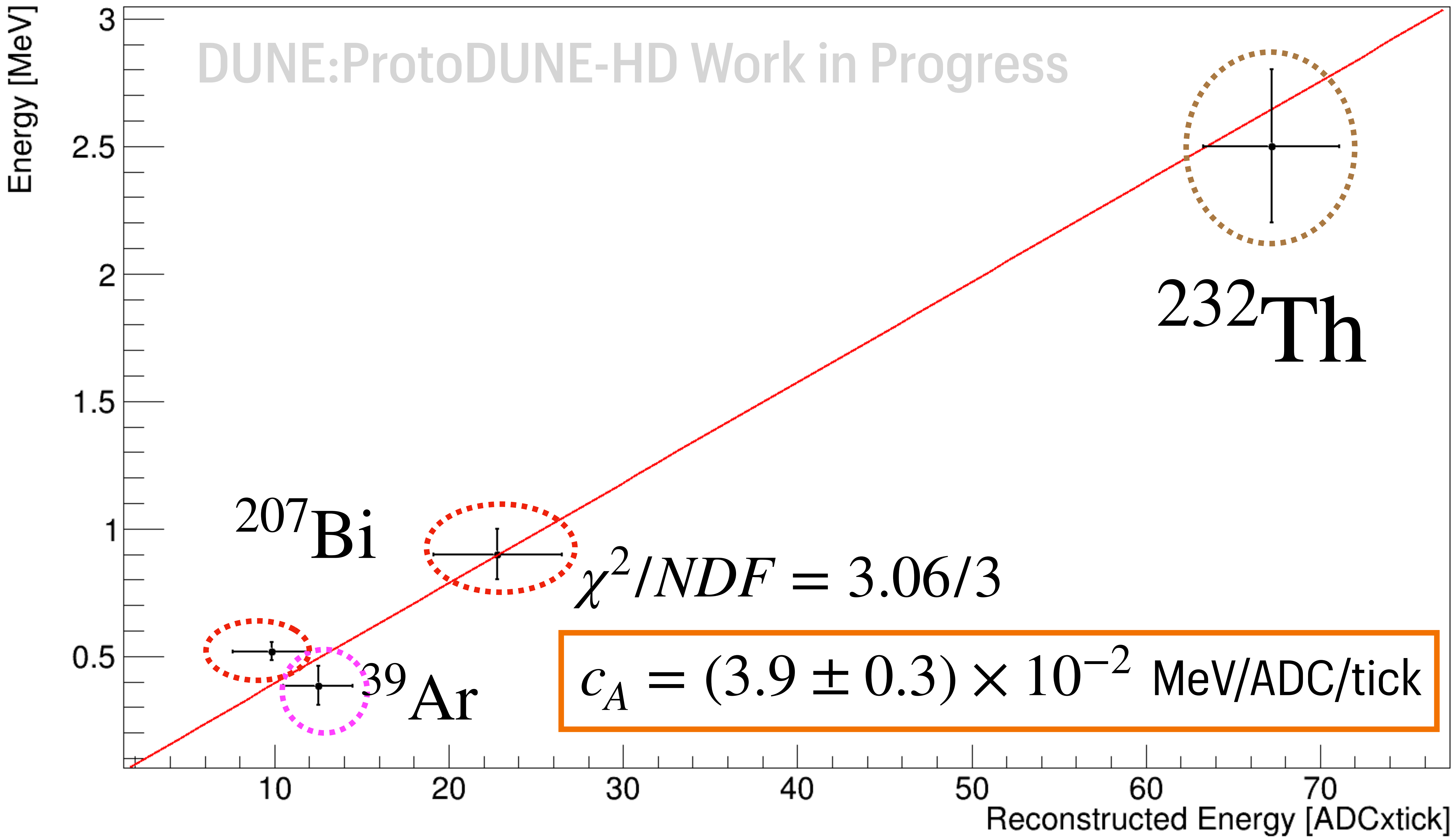

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- Predicted with Modified Box Model at higher energy but **not well tuned at MeV scale**

$$\boxed{R = \frac{W_{ions}}{g_e \times c_A} = 0.60 \pm 0.05}$$

CONCLUSION

- DUNE is in a intense phase of production
- The prototypes showed good result on HD (soon on VD)

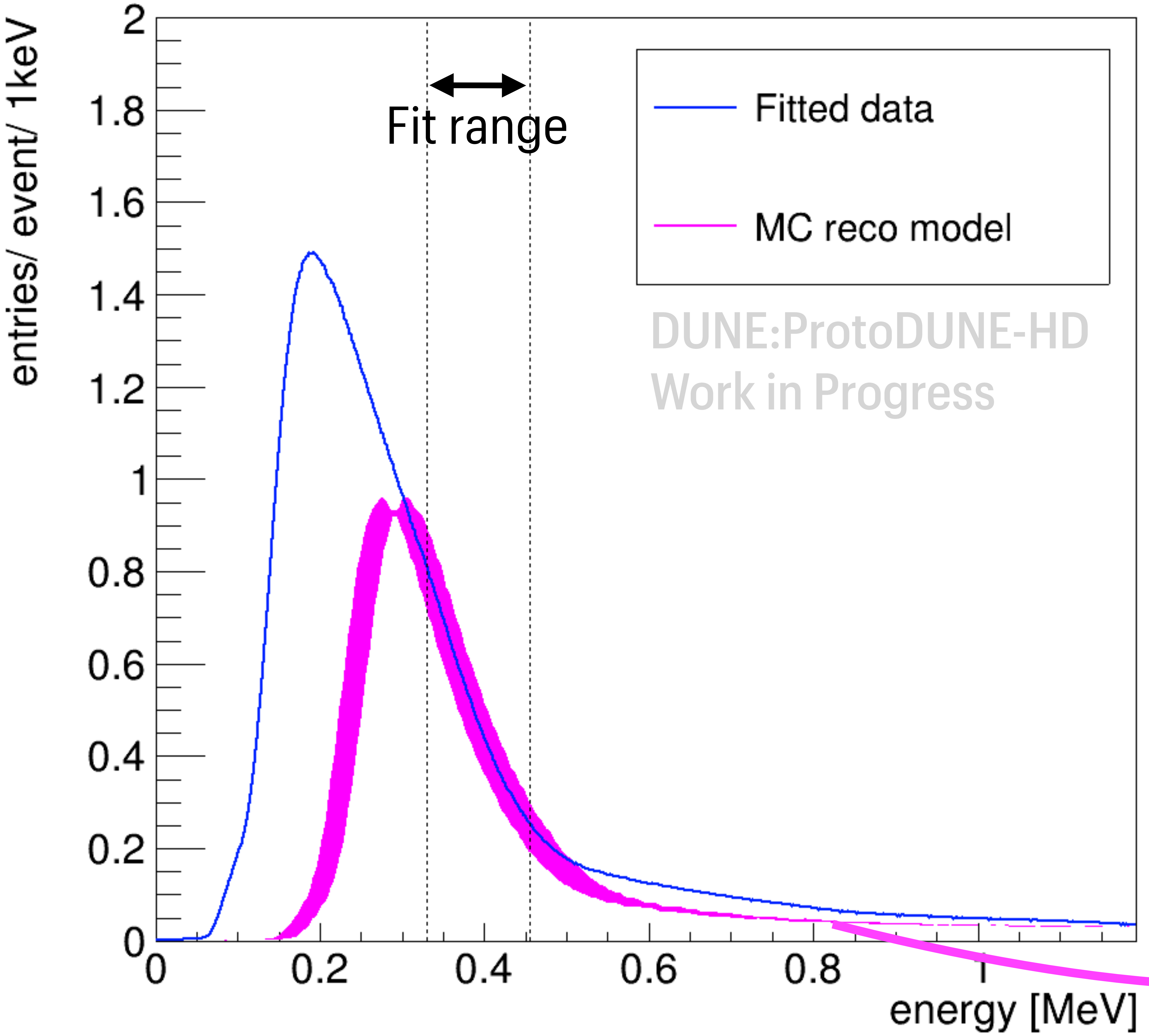
- **Developed an analysis tool for the collaboration available in DUNE's software**

- **Very good spatial resolution:** cm level (Bi source, field cage structure)
- **Shown that MeV scale physics is possible for ProtoDUNE-HD (DUNE Far Detector ?)**

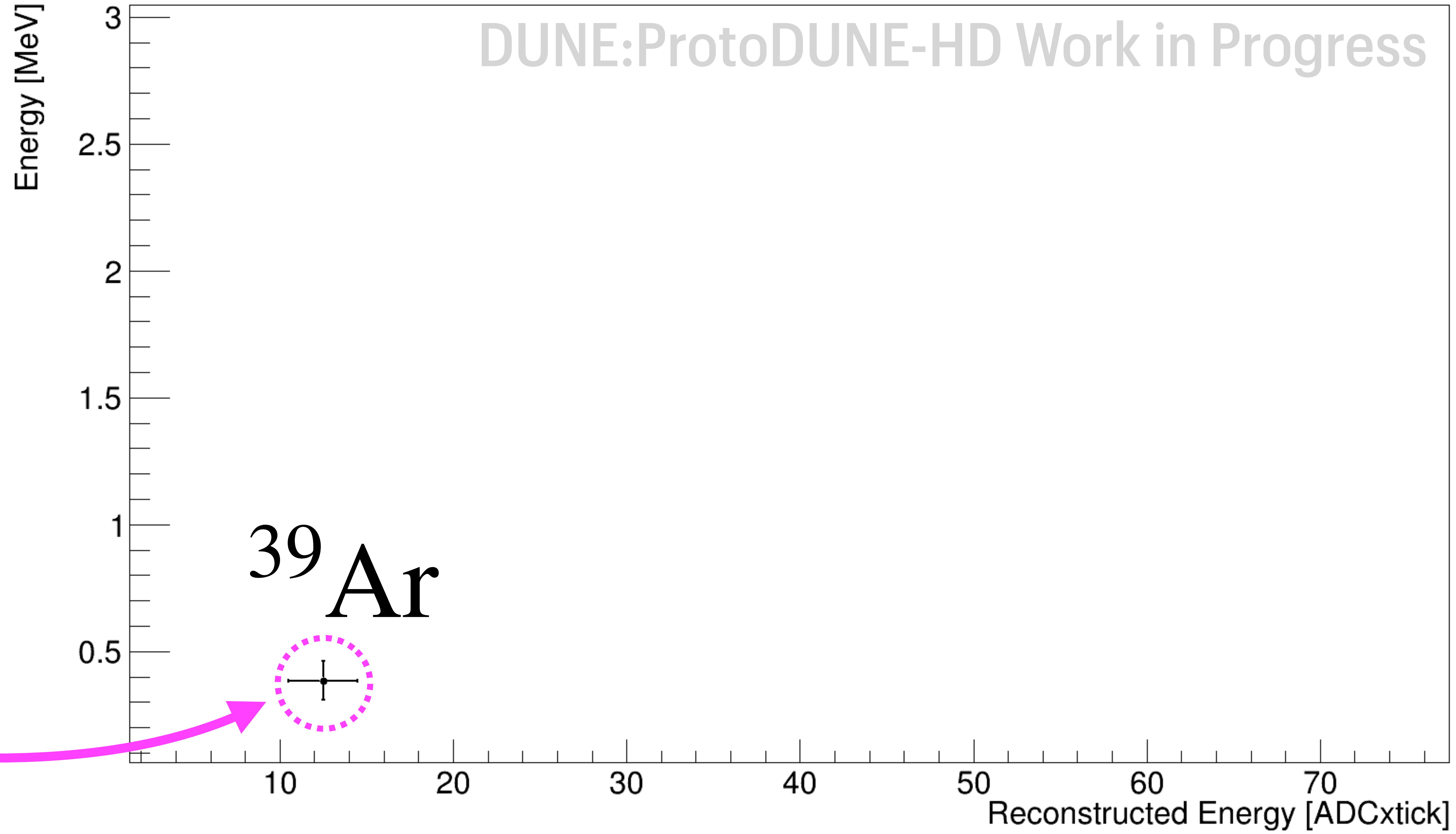
- Several radiological sources identified → **used for first calibration at low energy made on PDHD data**
- Find **recombination** value consistent with other experiments at low energy

Annexe

- **Identification of the peak as ^{39}Ar**
- **Official DUNE Monte Carlo**: cosmics + ^{39}Ar + 1 GeV electron beam + ^{85}Kr + ^{222}Rn
- Fit ^{39}Ar end of spectrum region → [10.5 , 14.5] ADCxticks

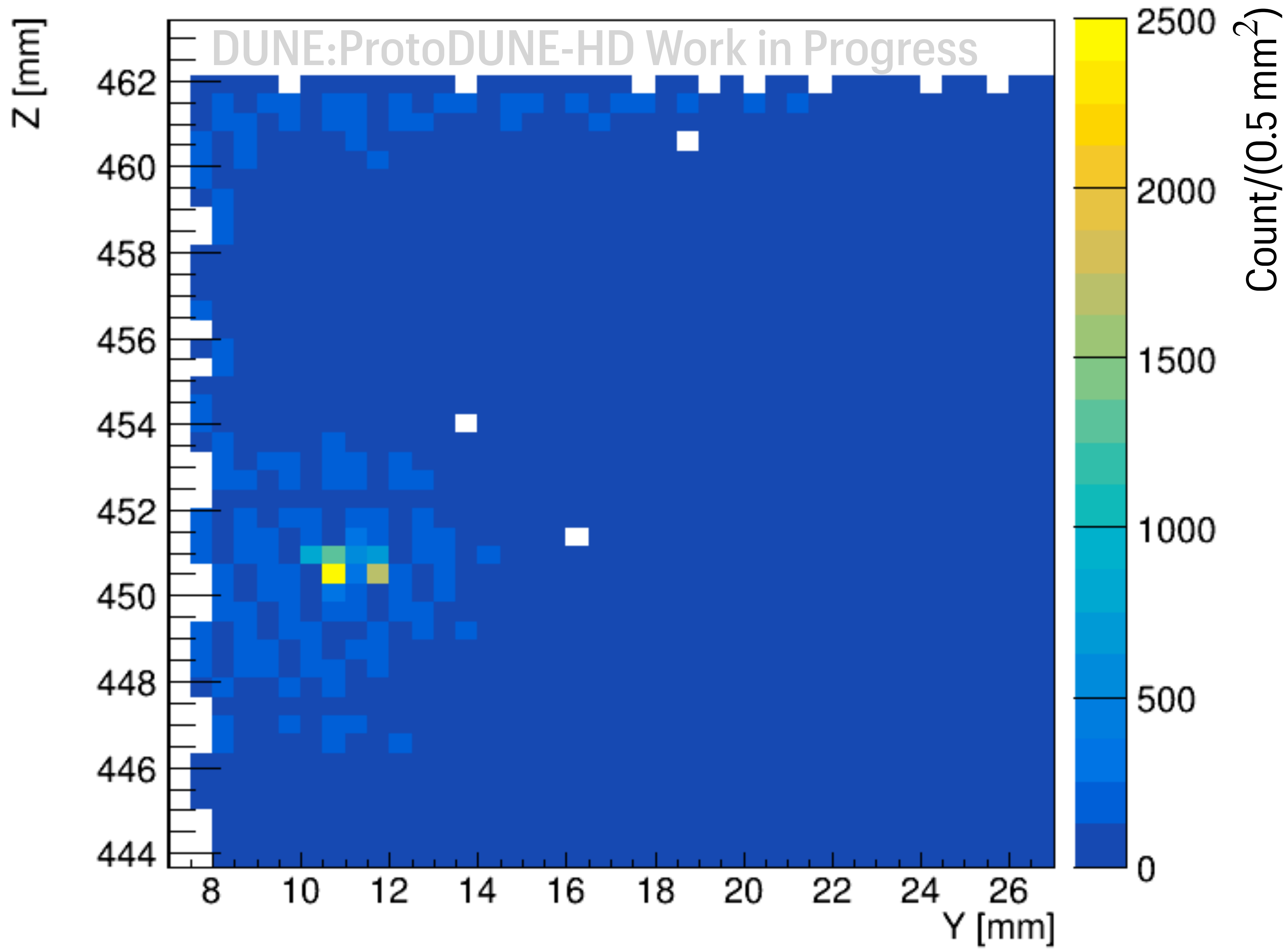


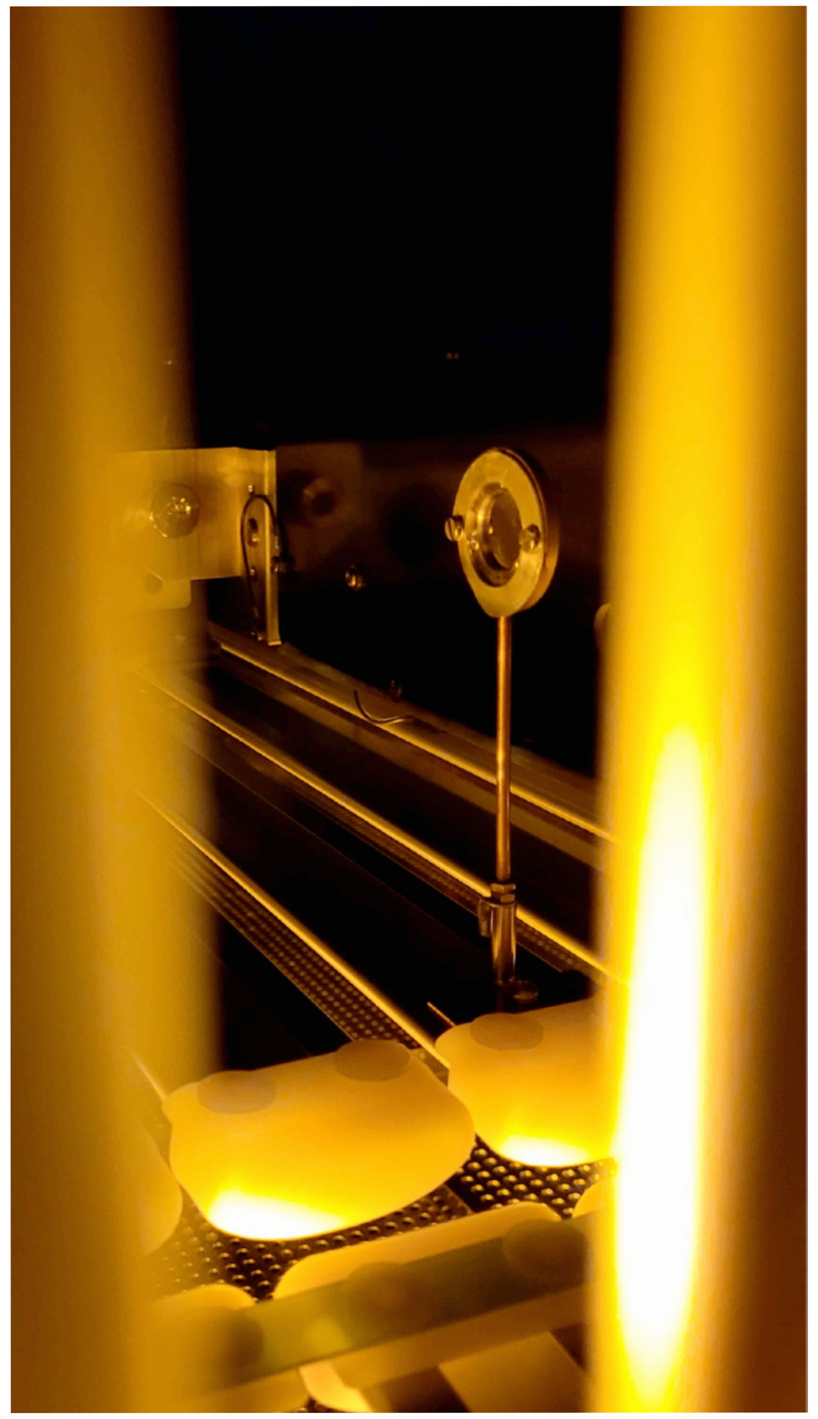
- c_A is the fitted calibration factor in MeV/ADC/ticks
- we find $c_A = 0.031 \pm 0.001$

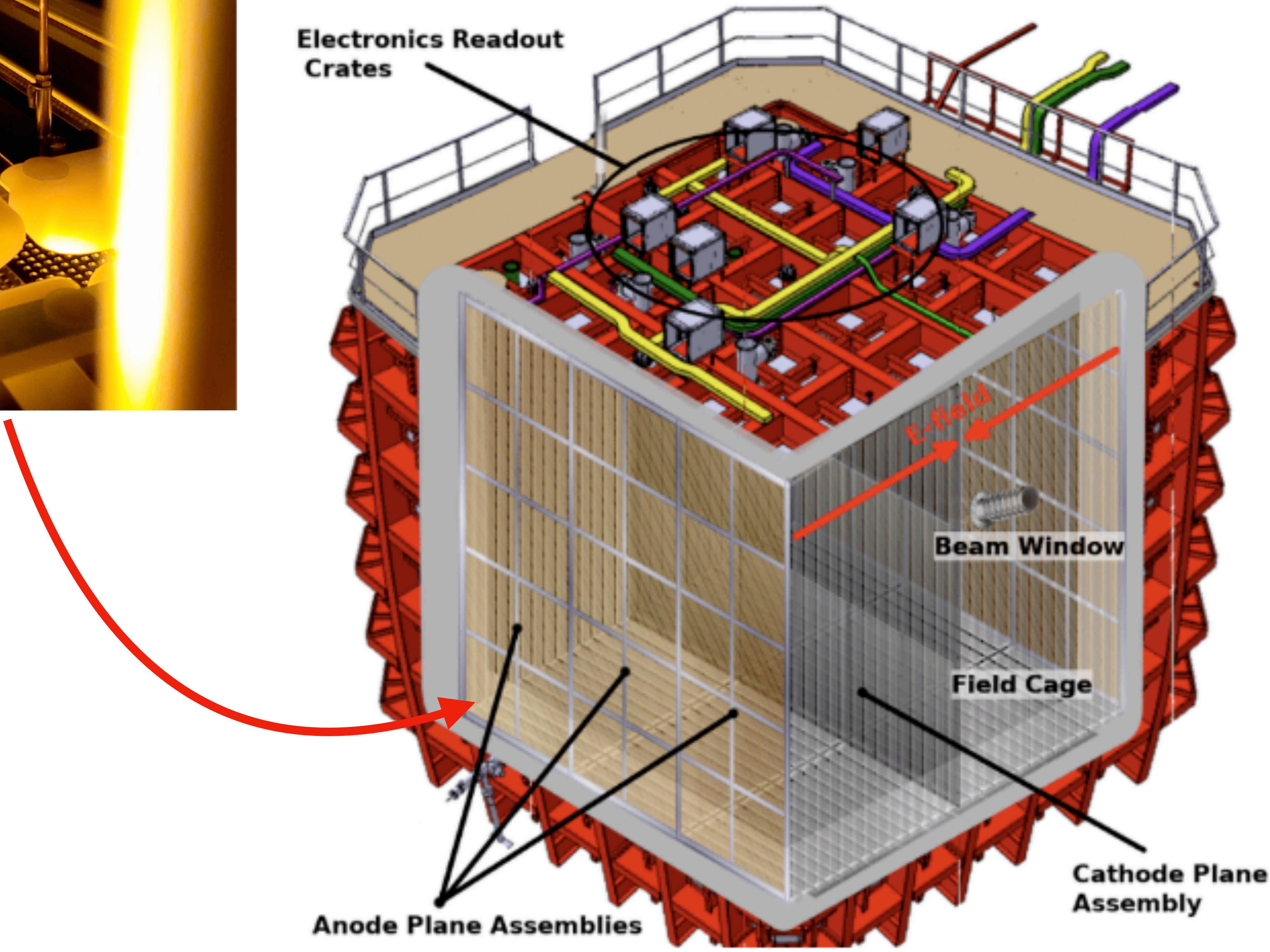


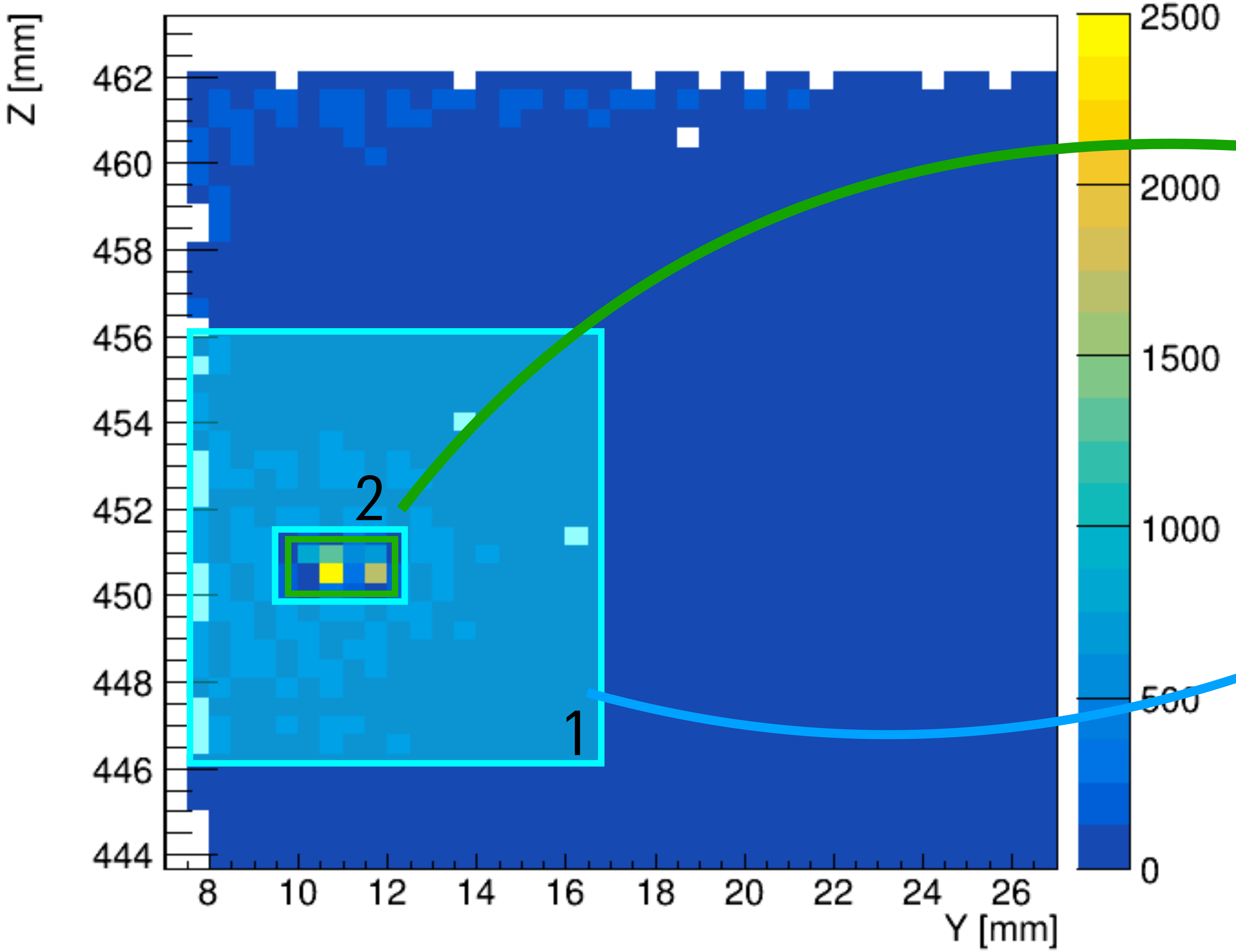
ProtoDUNE-HD calibration

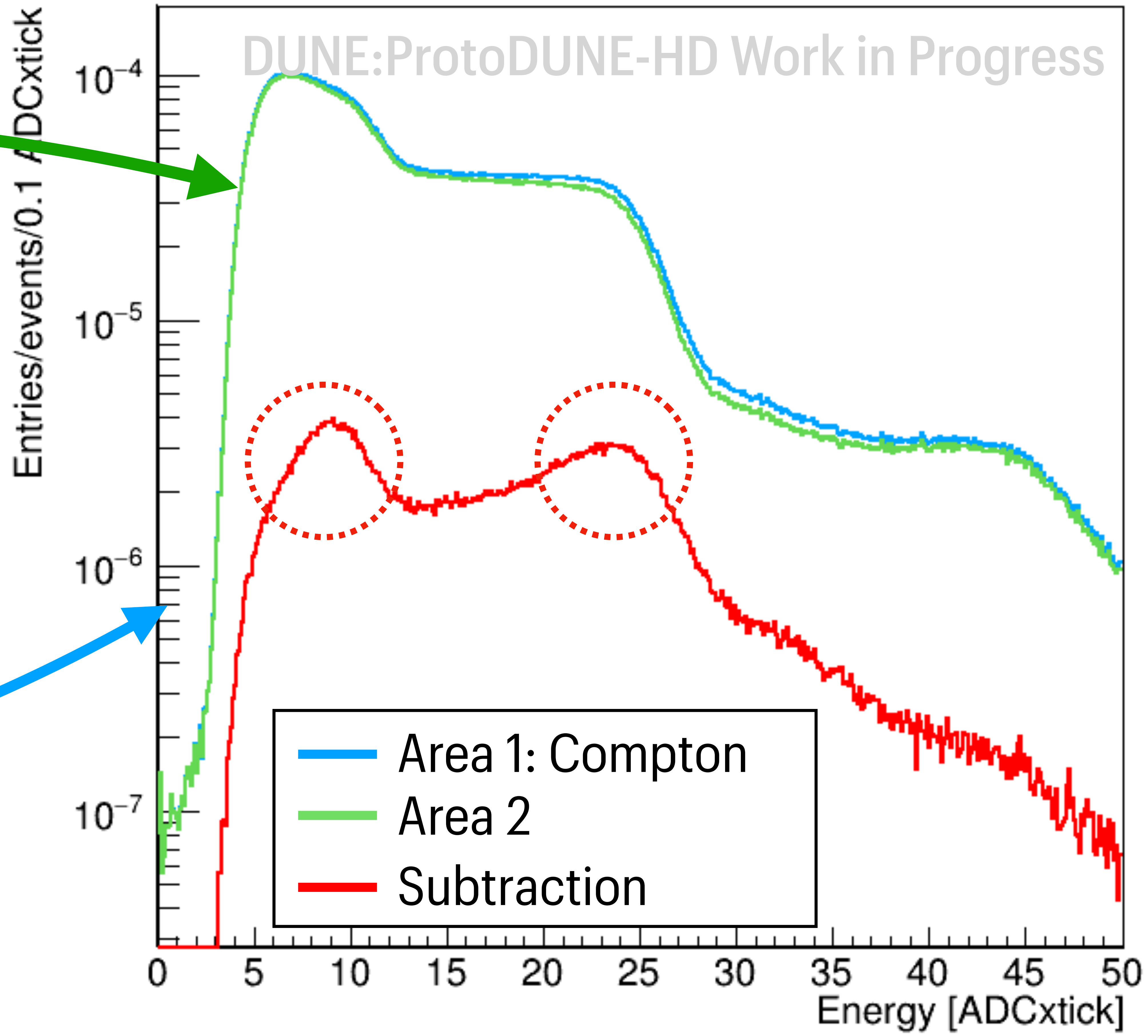
- For calibration purpose a source of $^{207}\mathrm{Bi}$ has been added in PDHD
- Position is reconstructed **at the cm level**







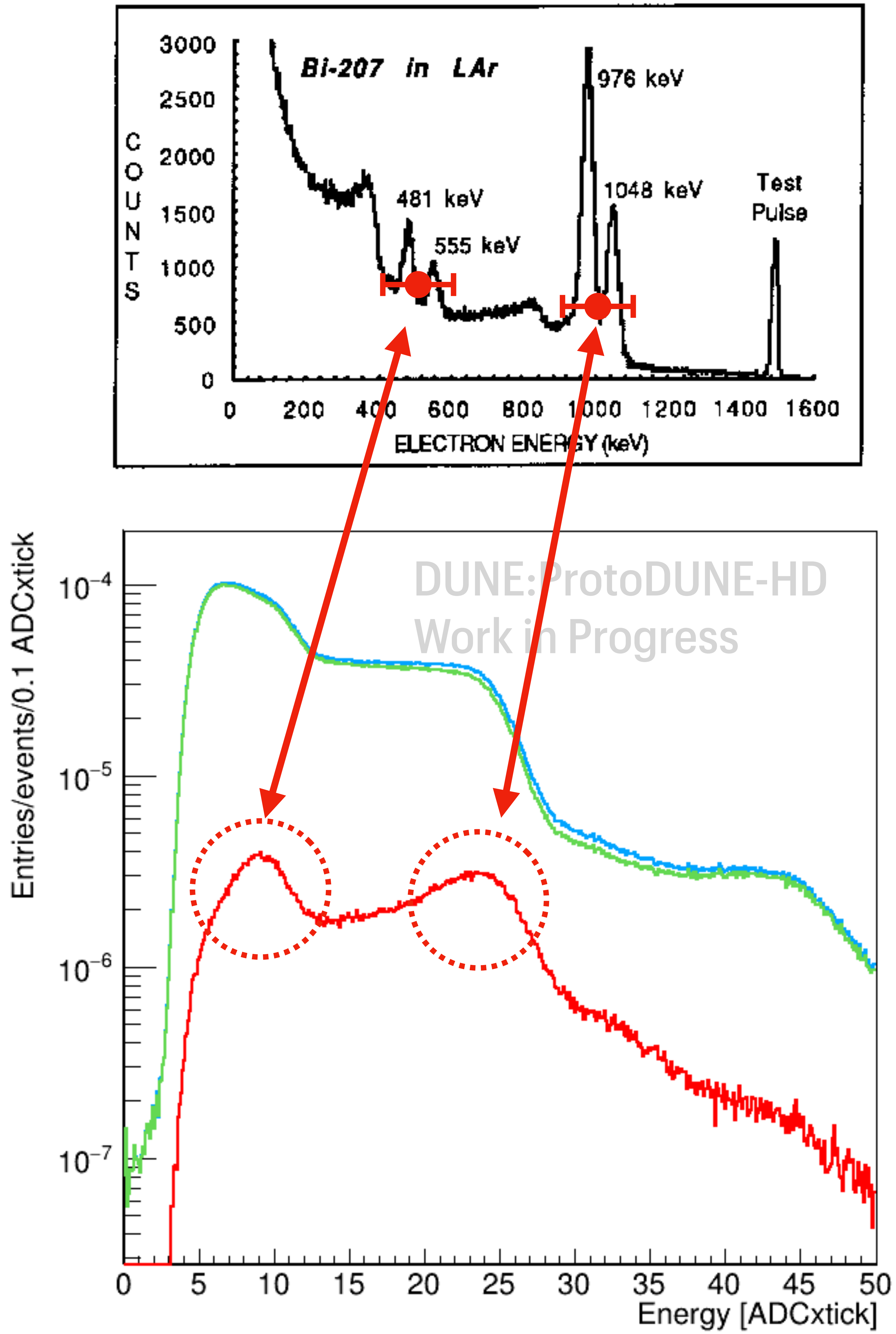




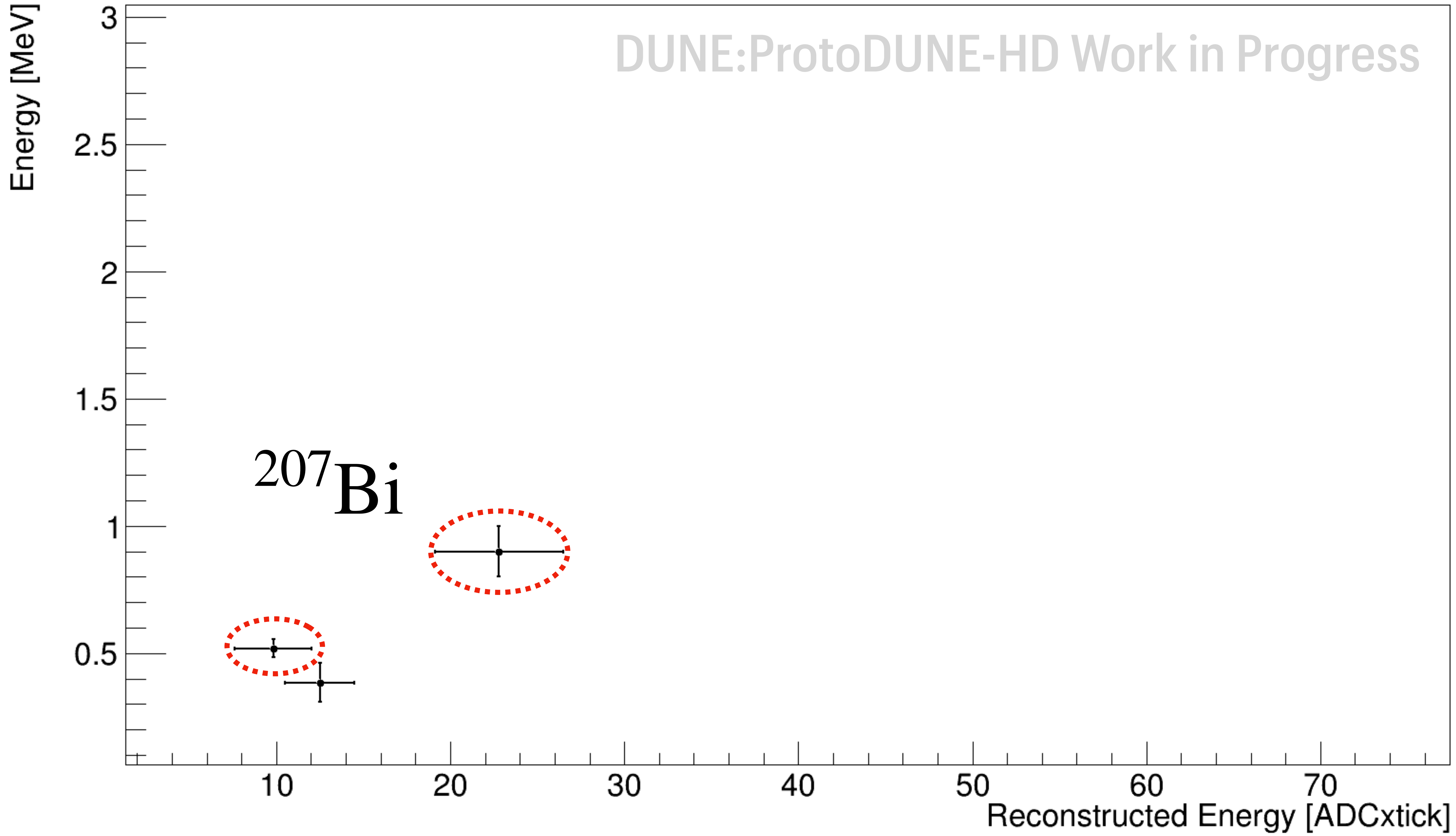
- Soustract the Compton front from the gamma
- Clear appearance of **the conversion electron peak**

ProtoDUNE-HD calibration

DOI:10.1109/23.12669

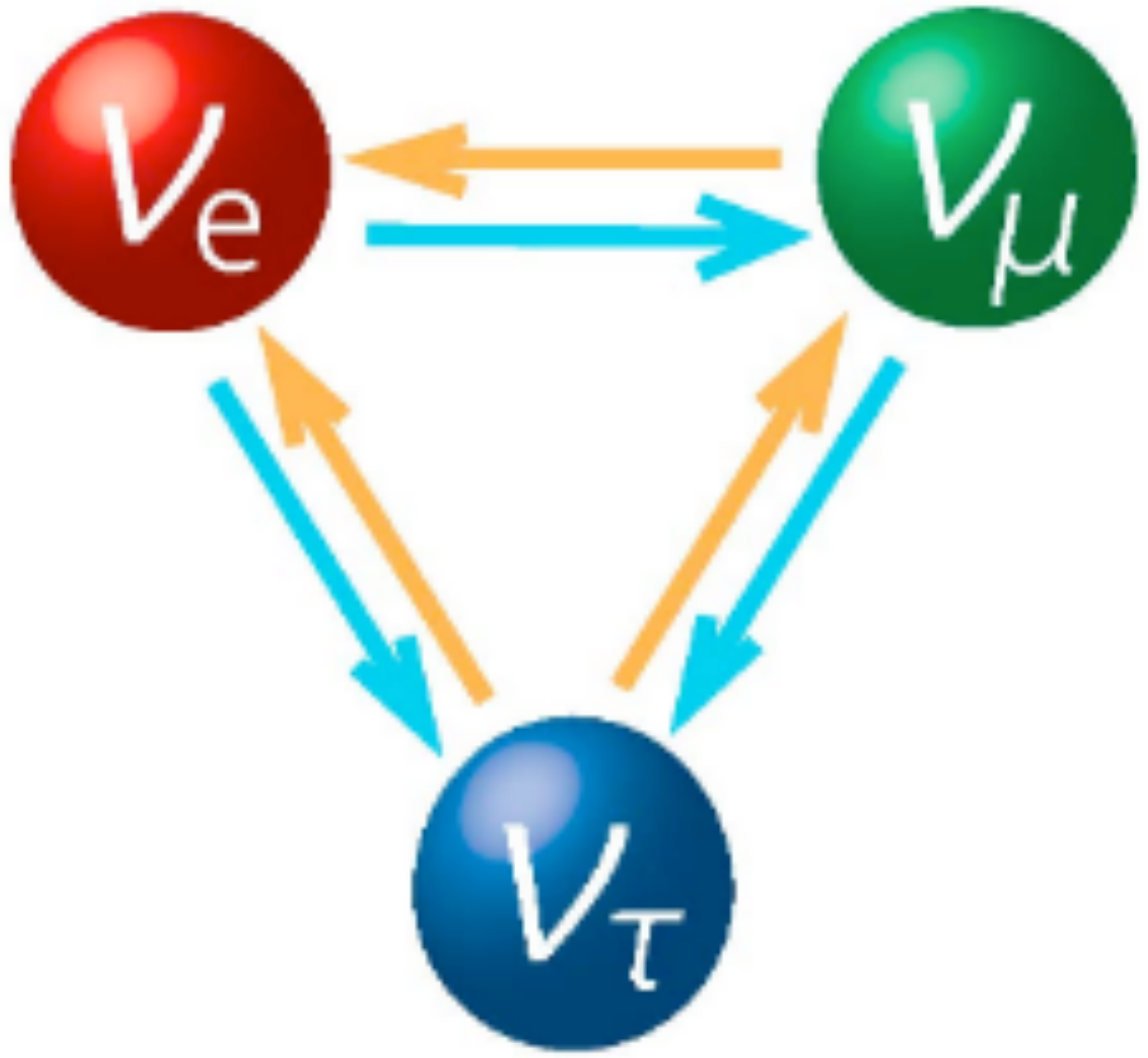


- ^{207}Bi is complex source (several gamma rays and conversion electrons)
- **Identification of two electrons peaks**



Context of DUNE

- Neutrino are **neutral right-handed leptons** with **3 flavours**
- They are predicted to be mass-less within Standard Model
- Flavour oscillation measured* → **first evidence of physics Beyond Standard Model**



PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix ↔ CKM

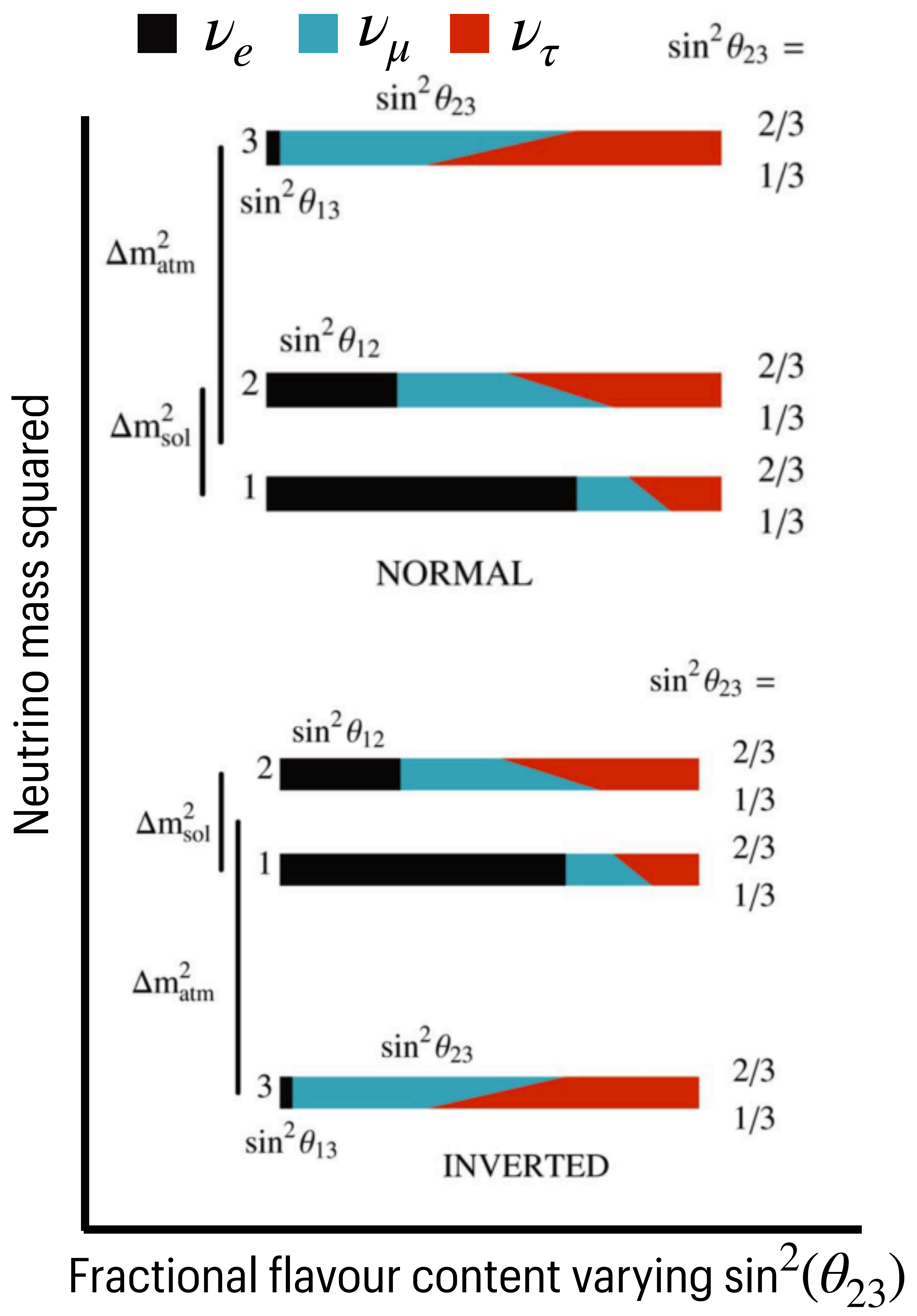
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

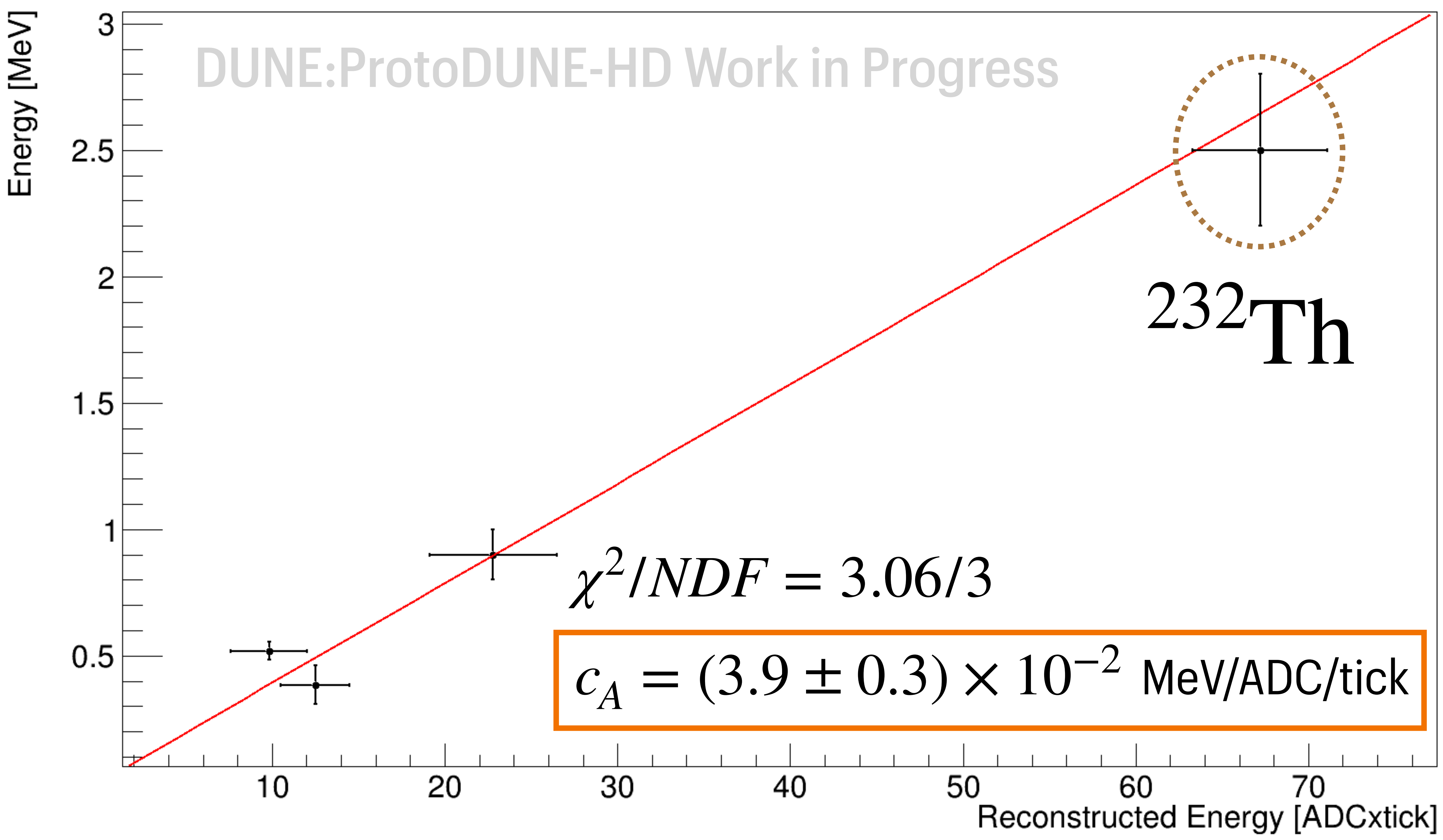
Long baseline accelerator + atmospherics Solar + reactor

δ_{CP} is the Charge-Parity violating phase in leptonic sector

*at SNO with solar neutrinos in 2001: https://link.aps.org/doi/10.1103/PhysRevLett.87.071301

- In neutrino field there are **fundamental unanswered questions**:
  - Is there CP violation in the lepton sector? **CP-phase value?**
  - Where does the neutrino mass come from ?
  - What is the neutrino **mass ordering?**
  - Are neutrinos their own antiparticle? Dirac or Majorana?
  - Are there any sterile neutrino states? If so, what are their masses?
  - Deviations from unitarity of the PMNS matrix?





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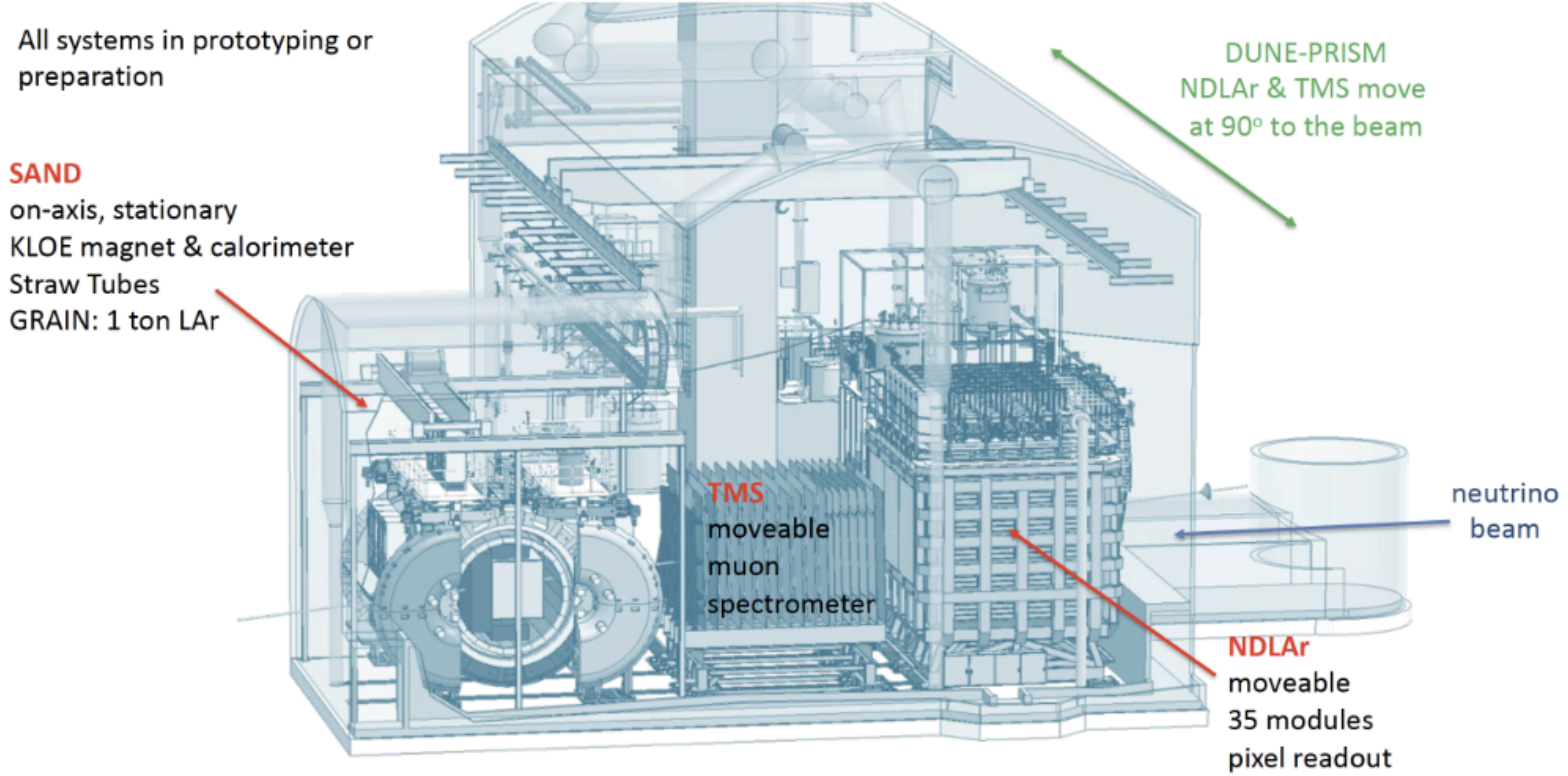
Data set	Particle		Topic	$\mathscr{R}$ at 0.5 kV/cm
3 ton	Stopping	μ, p	$\mathscr{R}_{3t}$ vs. $\frac{dE}{dx}$ 3 $\mathscr{E}$ values	mip: 0.70 ± 0.02
Scalettar[3]	^{113}Sn source	364 keV e^-	$\mathscr{R}_S$ vs. $\mathscr{E}$	0.58 ± 0.01
	^{241}Am source	5.64 MeV α	$\mathscr{R}_\alpha$ vs. $\mathscr{E}$	$0.014 \pm ?$
Aprile[4]	^{207}Bi source	976 keV e^-	$\mathscr{R}_A$ vs. $\mathscr{E}$	0.64 ± 0.05
T600	Stopping	μ	$\mathscr{R}_{T600}$ vs. $\frac{dE}{dx}$	mip: 0.71 ± 0.04

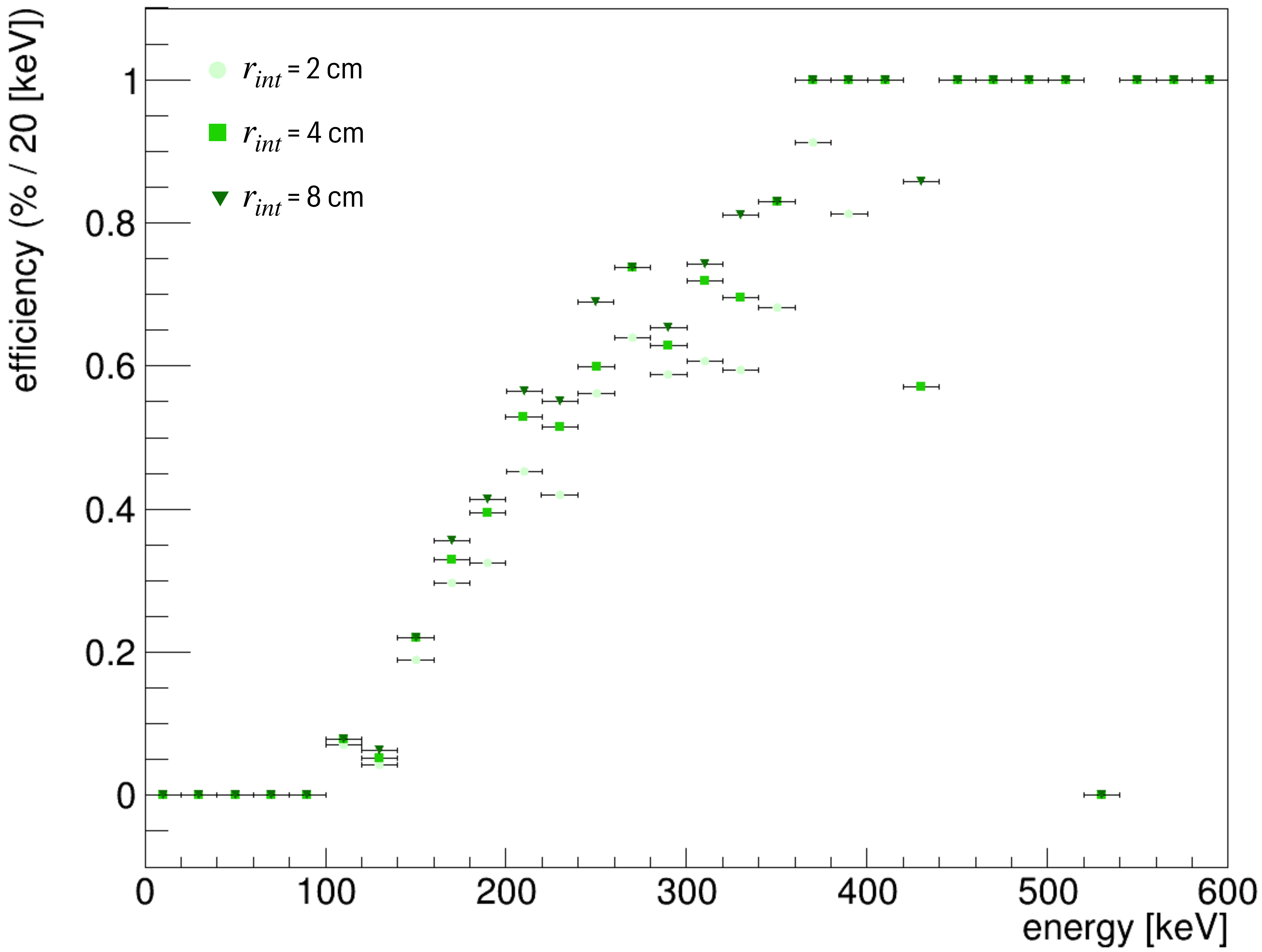
From: Study of electron recombination in liquid argon with the ICARUS TPC

- **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

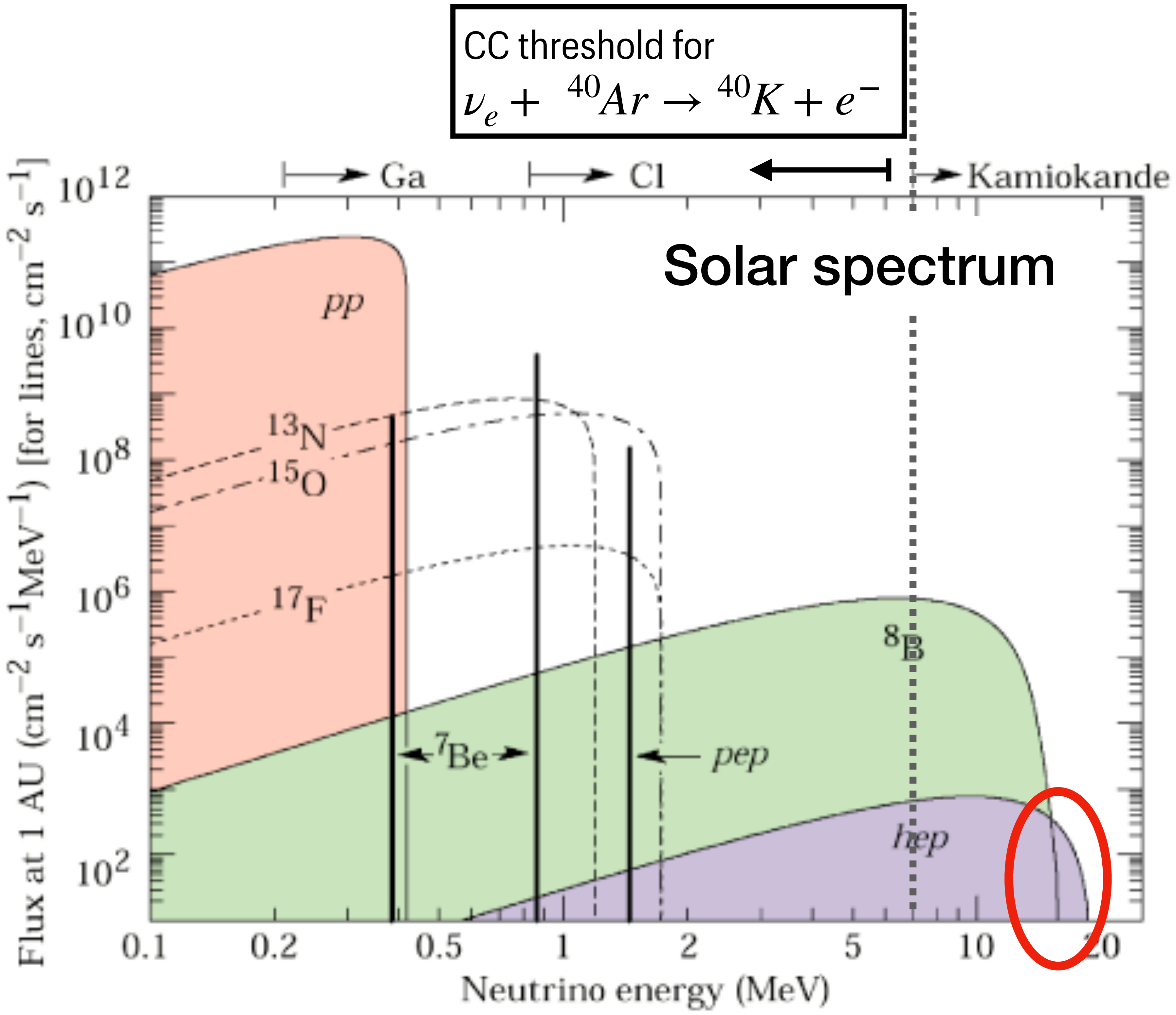


Efficiency

- **Mean efficiency: ~40 % for 39Ar (MC)**
- i.e. decays with < 3 hits and < 1 MeV
- Huge improvement wrt Pandora



Context of DUNE

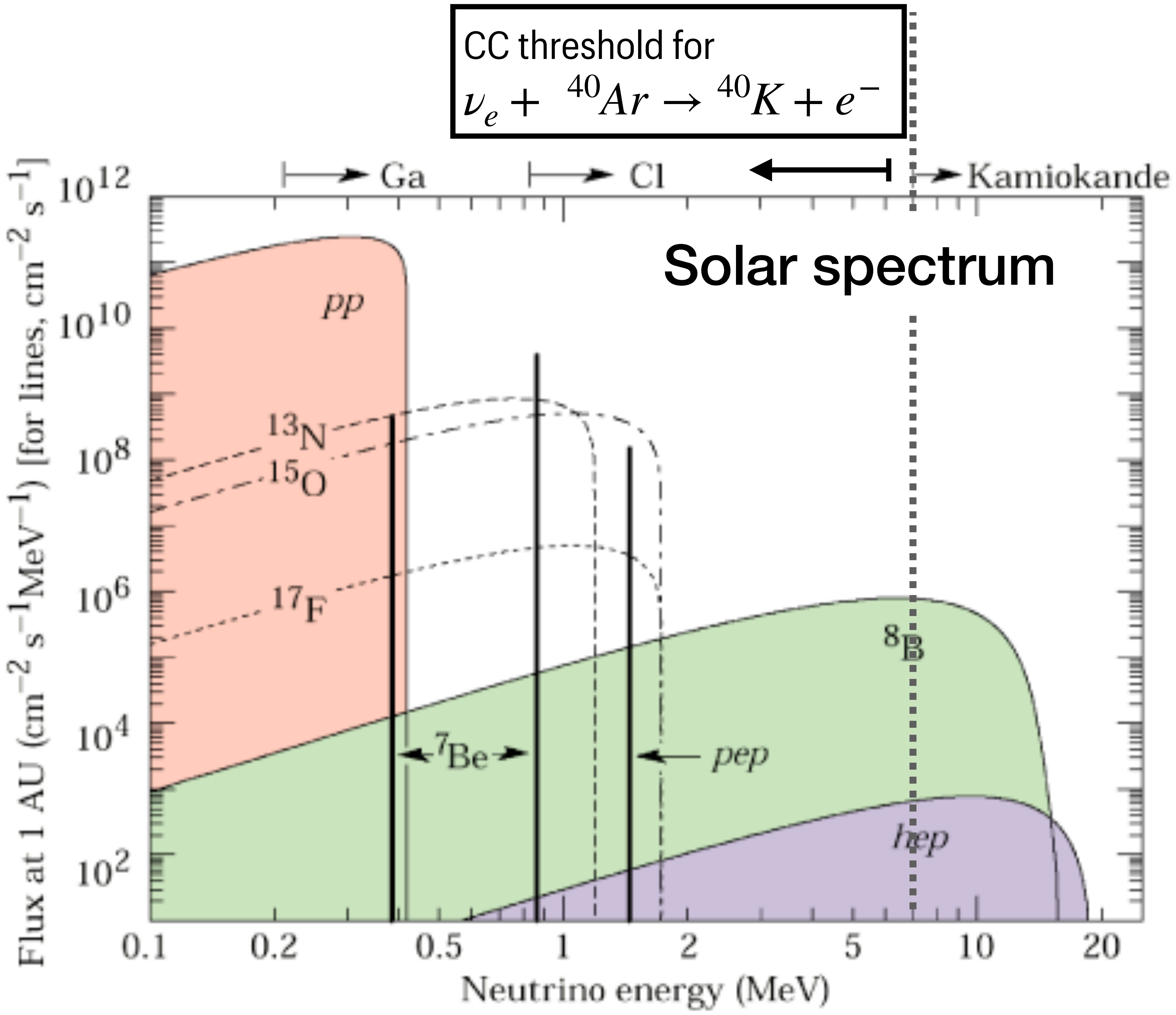


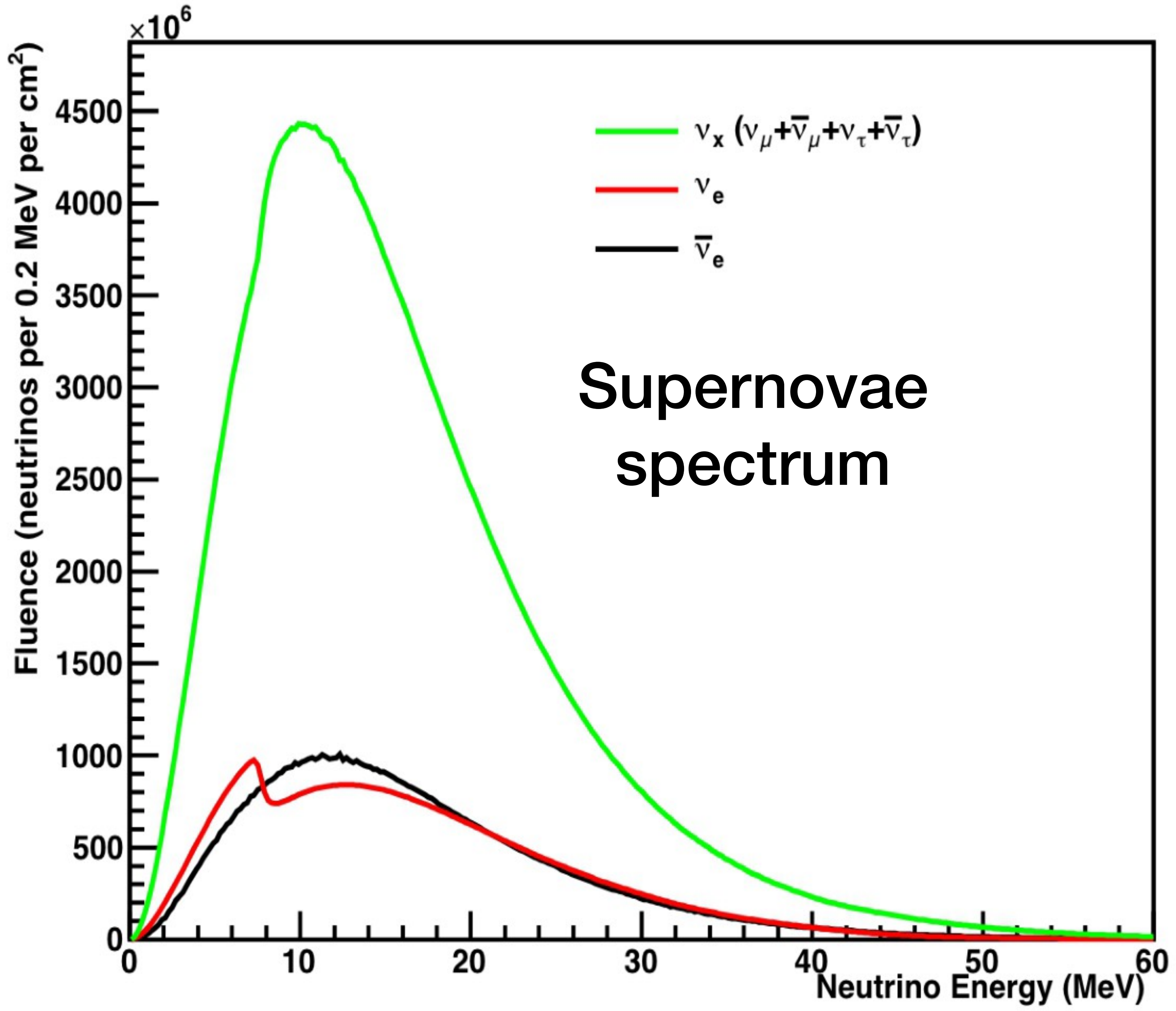
- Measure **hep neutrino** for the first time
- Neutrino fluxes carry important information about the interior of the Sun: hep → Outer Core

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

arXiv:2207.09632 [astro-ph.HE]
Figure from arXiv:1205.6003 [astro-ph.IM]

Context of DUNE





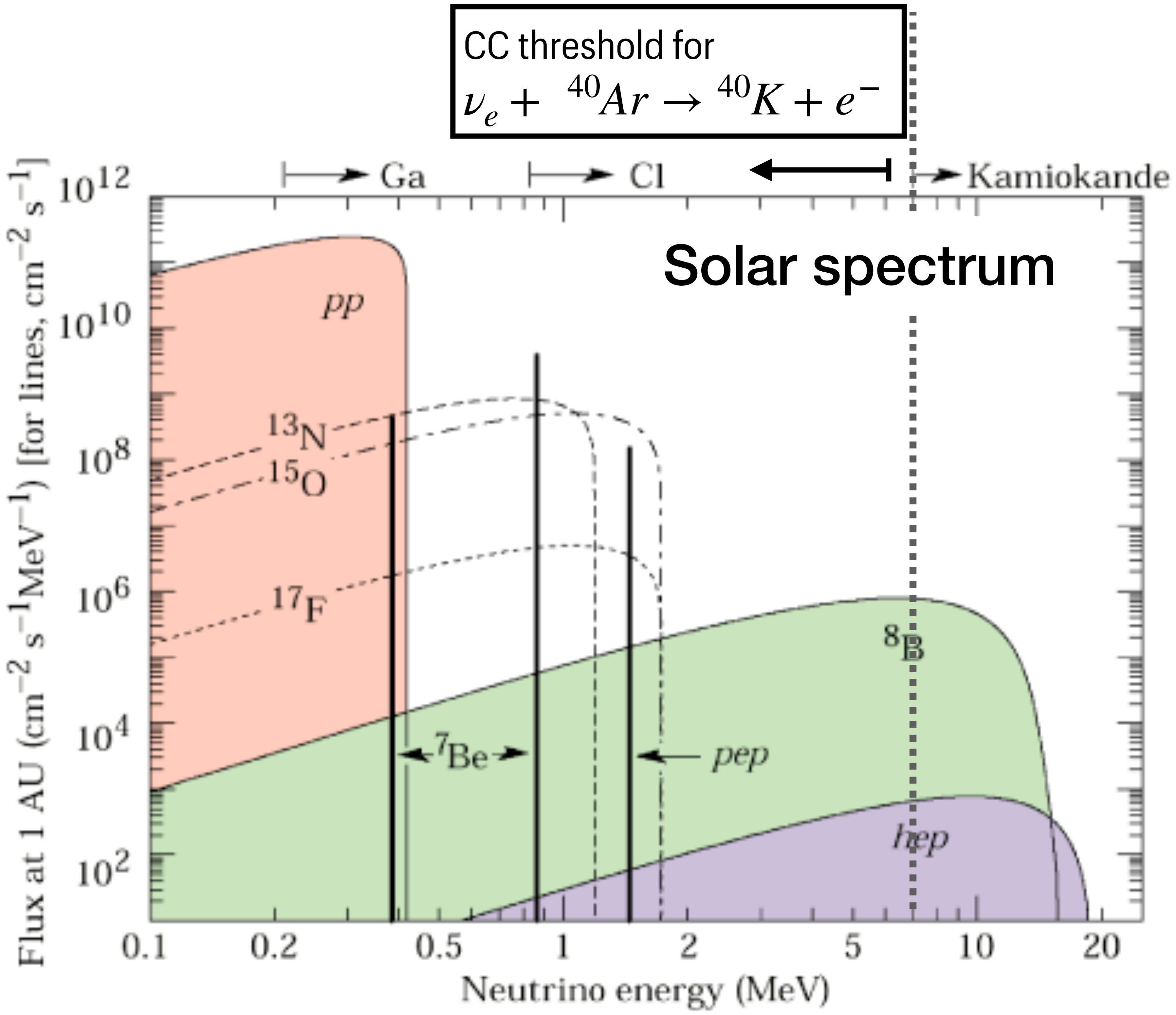
- Neutrino carry up to **99% of gravitational energy**
- Important information on birth of black-holes
- **Multi-messenger astrophysics:** Gravitational waves, neutrinos then photons

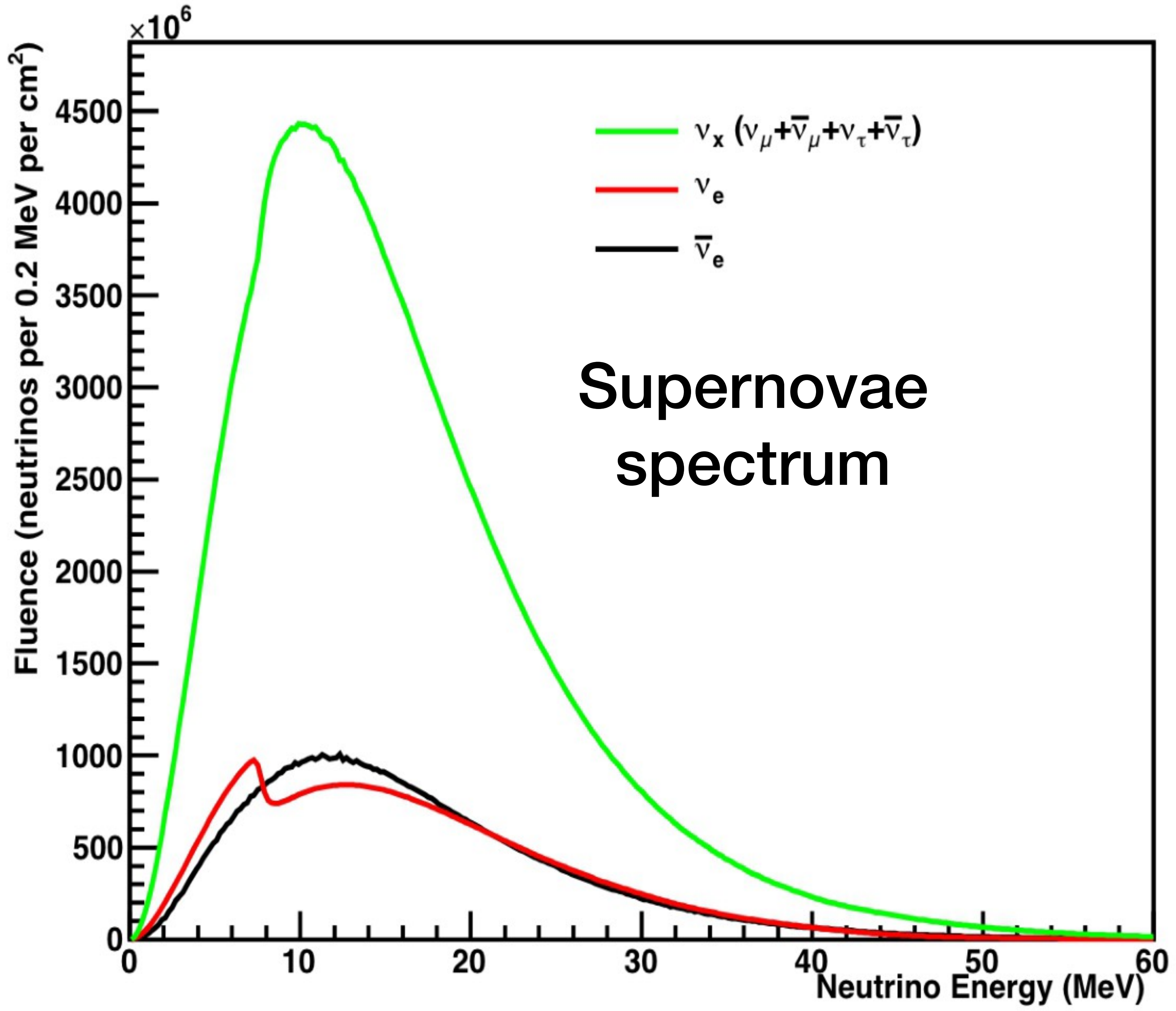
the energy spectrum of solar neutrinos. Image reprinted from J. Bahcall, A.M. Serenelli, and S. Basu Ap. J. 621, L85 (2005)

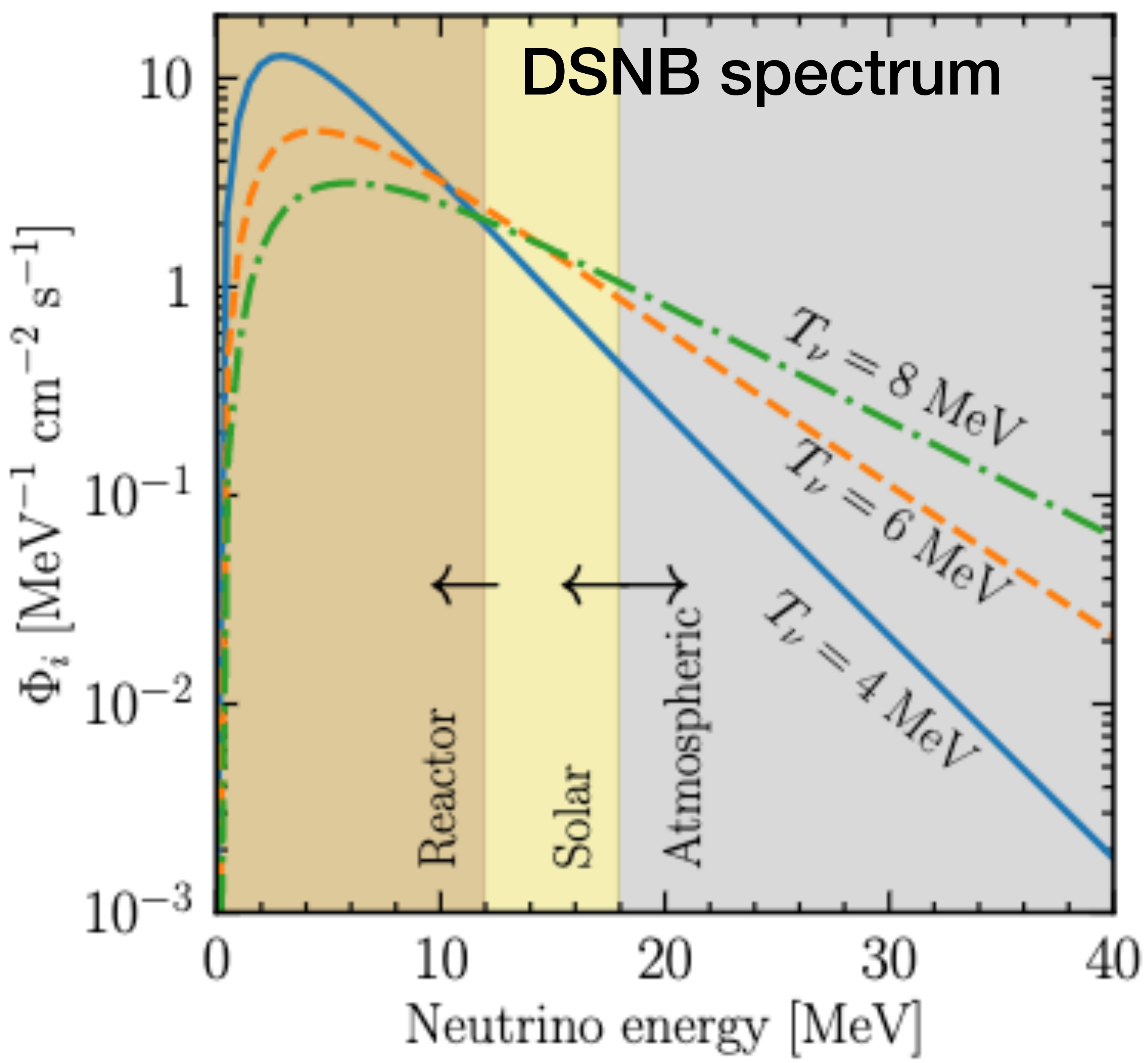
arXiv:2207.09632 [astro-ph.HE]
Figure from arXiv:1205.6003 [astro-ph.IM]

Context of DUNE

Low Energy (LE) neutrino physics







- Addition of all SN's neutrinos in the universe
- **Never been observed**

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

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Context of DUNE

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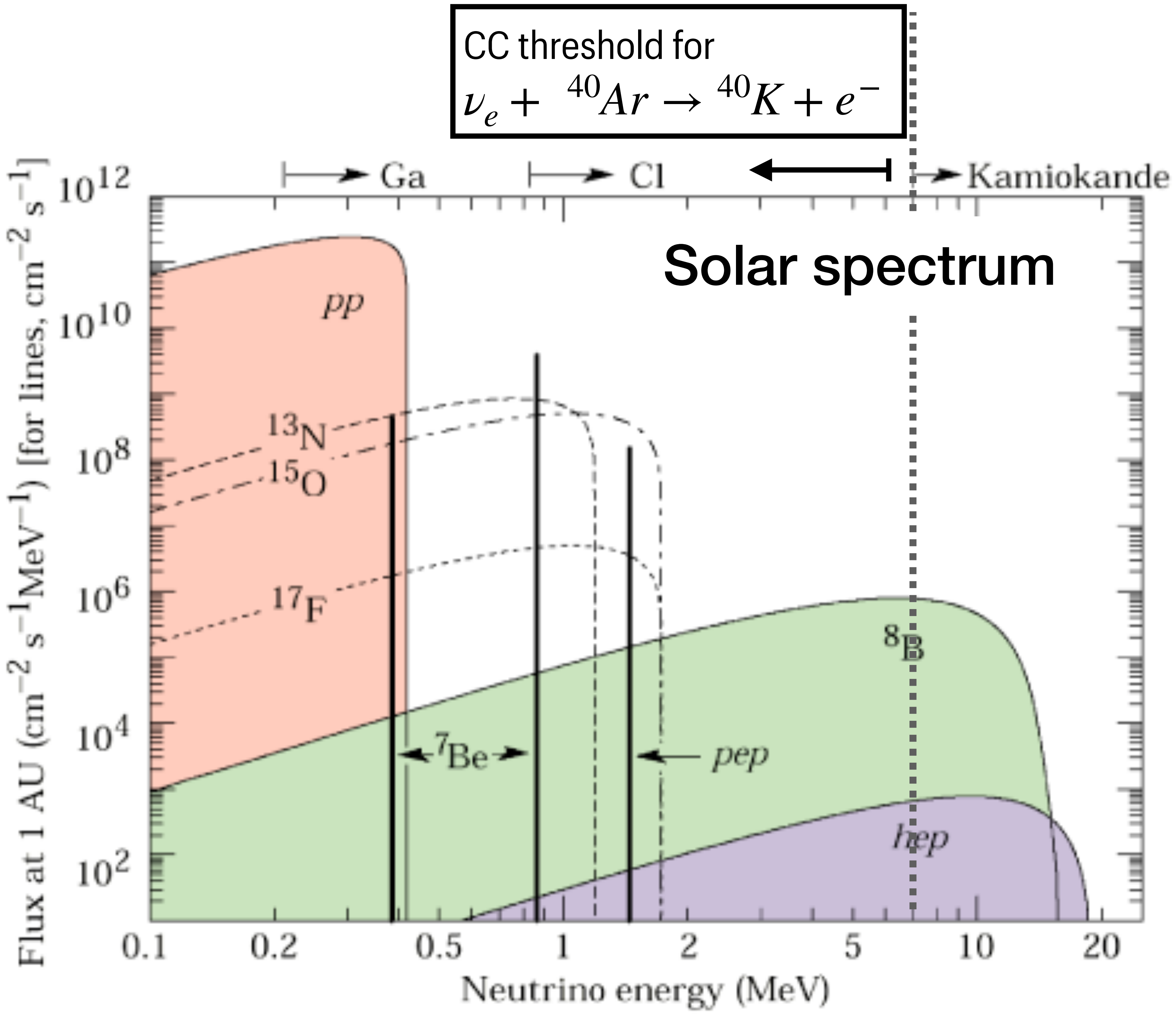
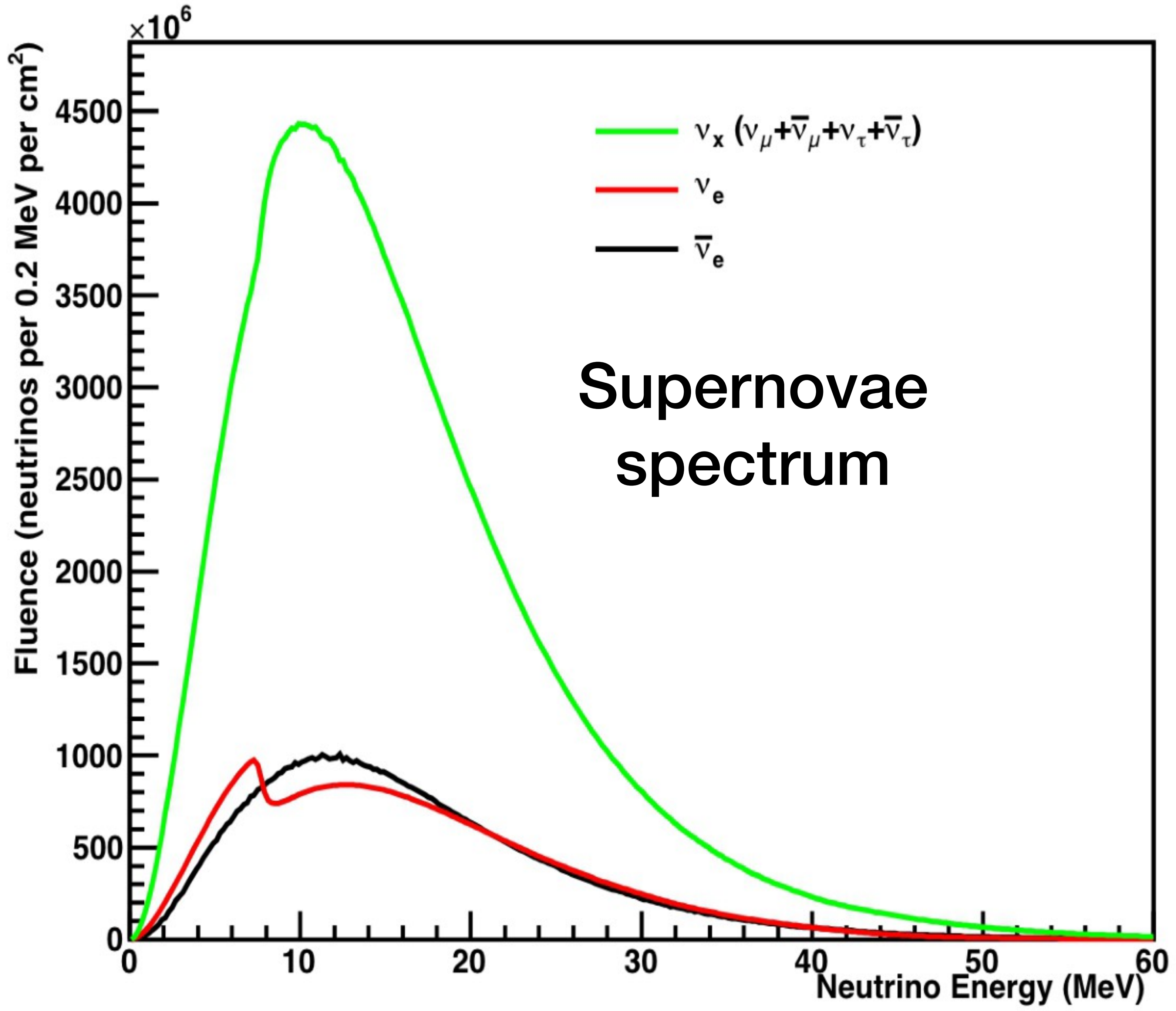
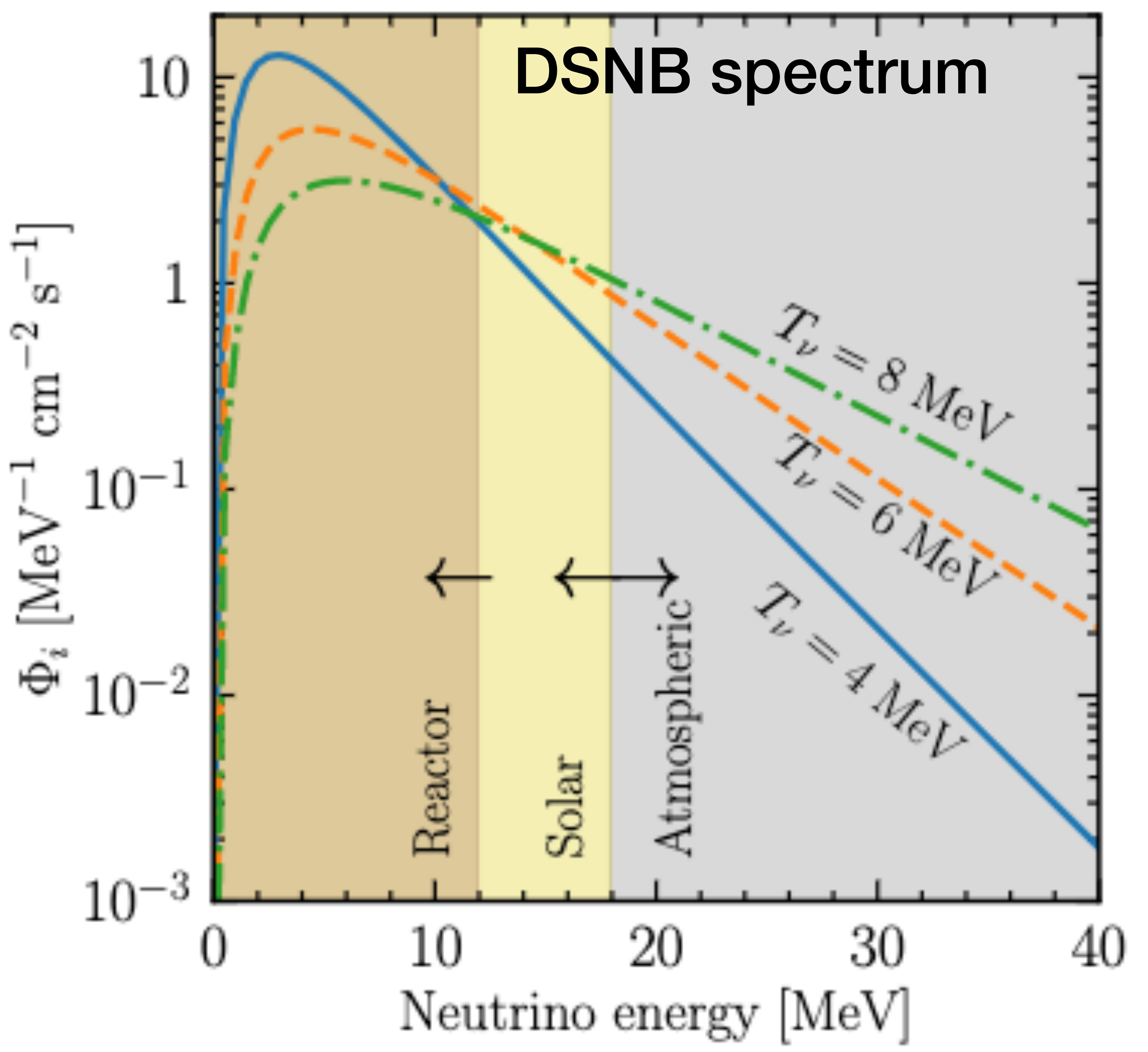




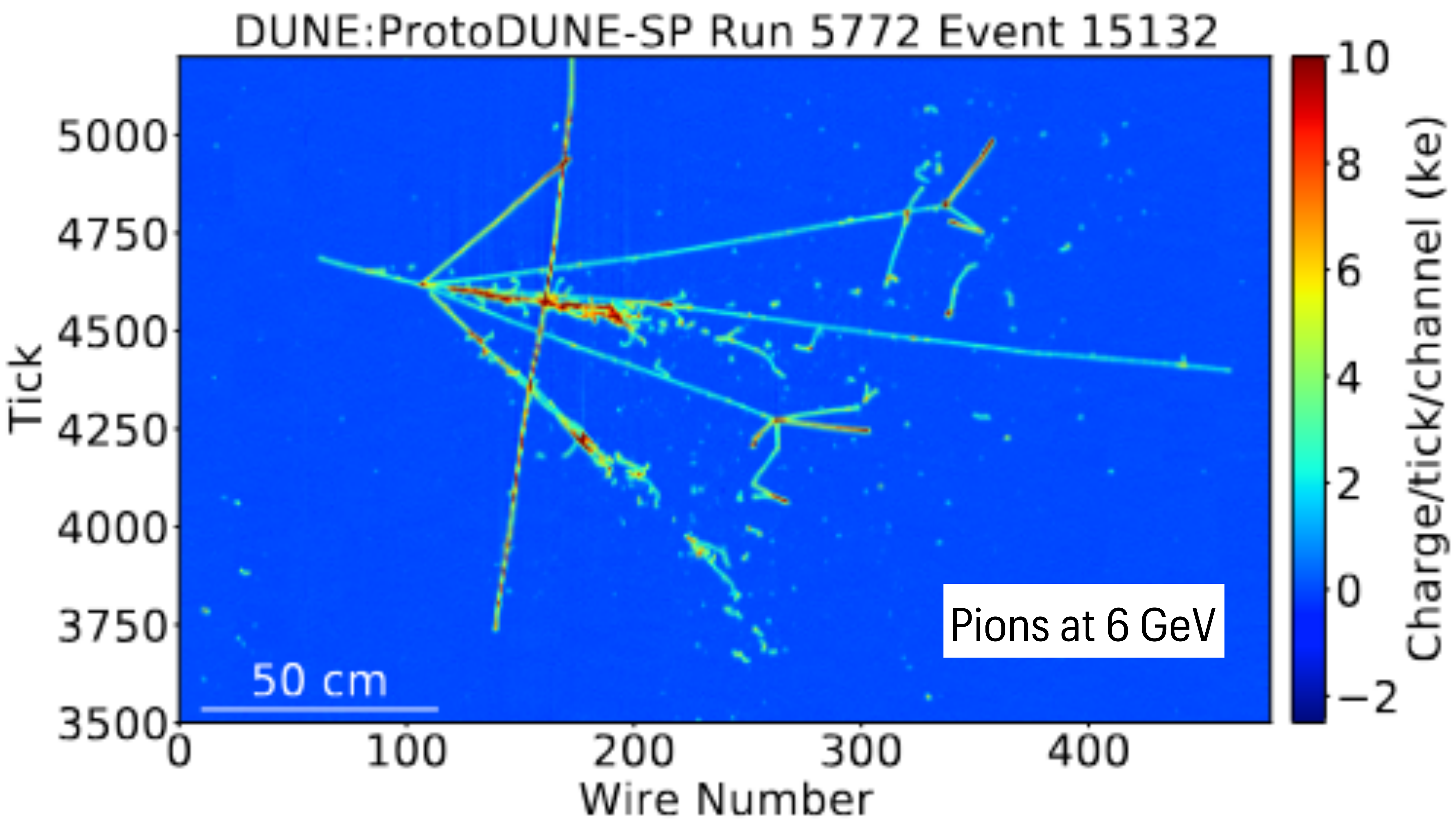


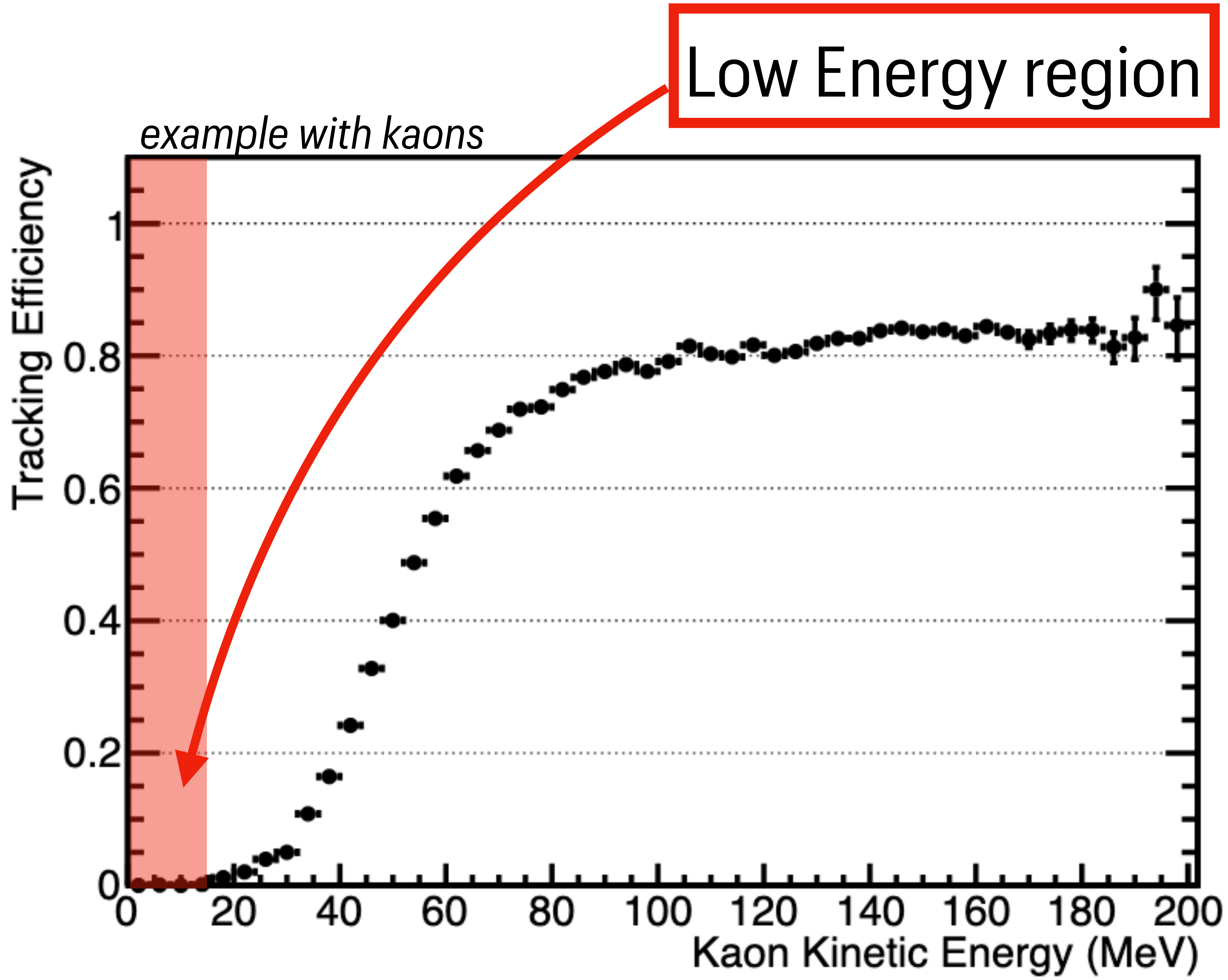
- **Challenging range of energy** with lower cross-section and more sensitive to detector or reconstruction effects like background or noise level.

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

arXiv:2207.09632 [astro-ph.HE]
Figure from arXiv:1205.6003 [astro-ph.IM]

- Detector performance better **for track/shower like event at GeV**
- **Default reconstruction/PID (Particle Identification) suboptimal for MeV signals**

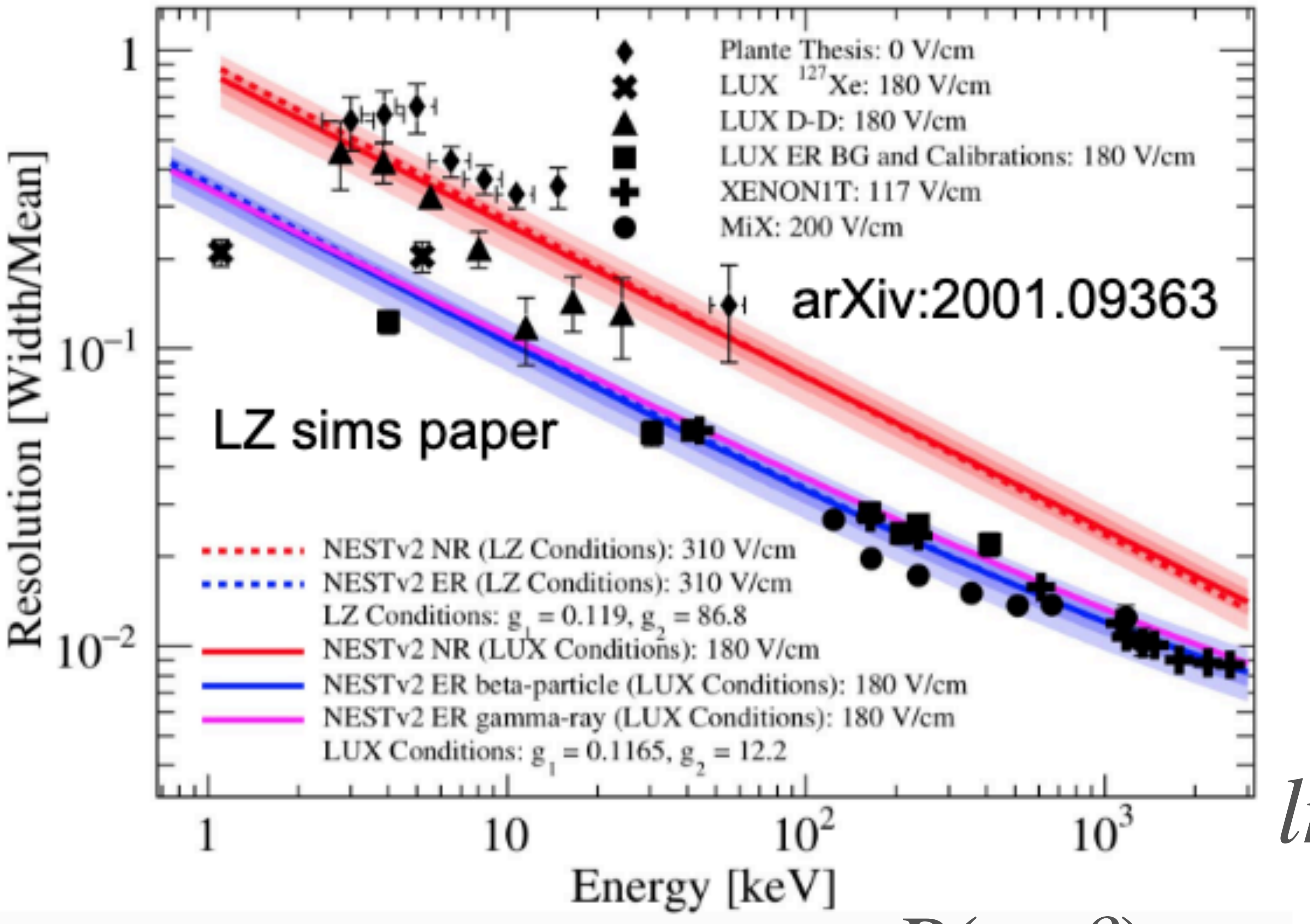


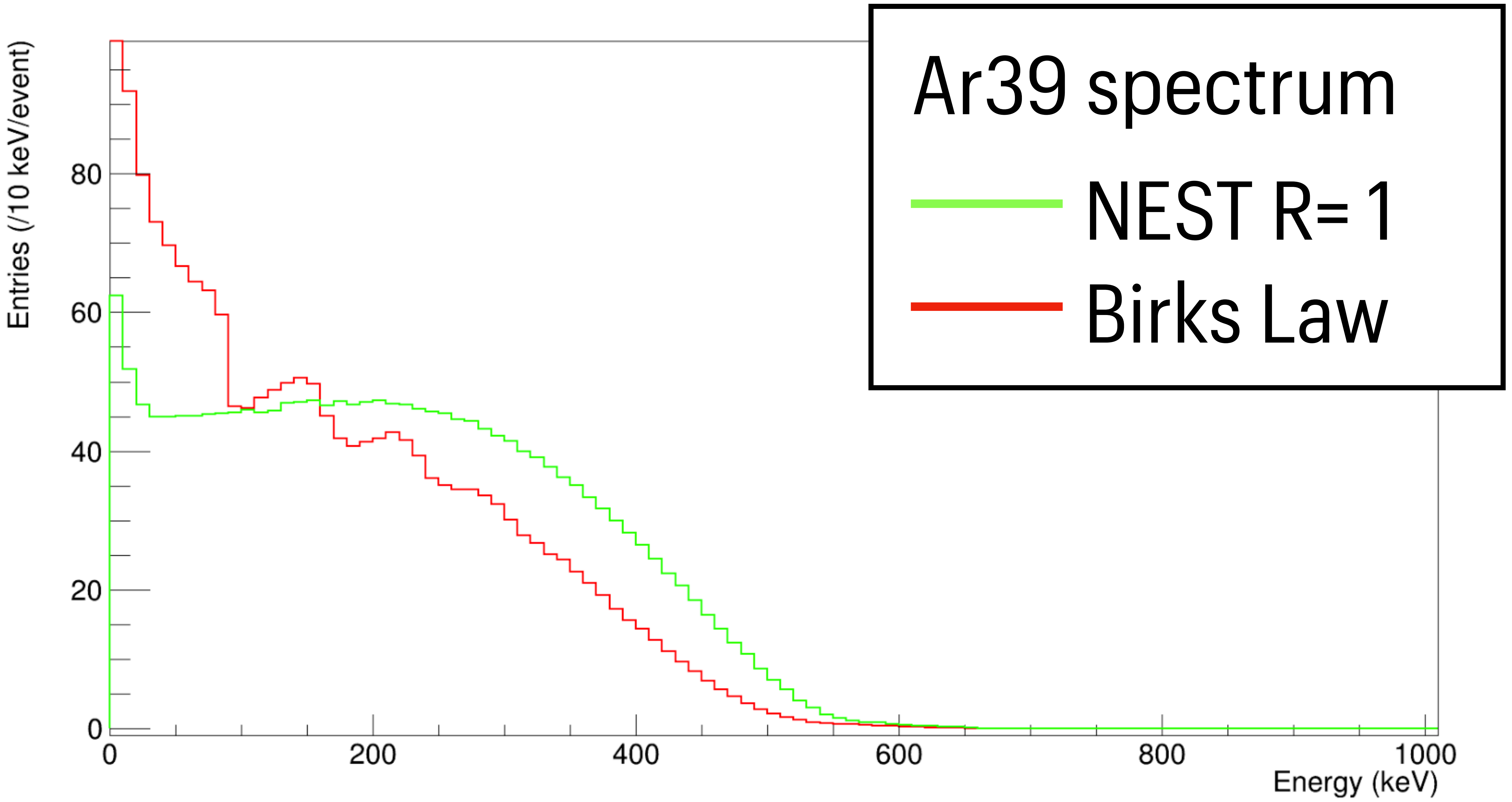


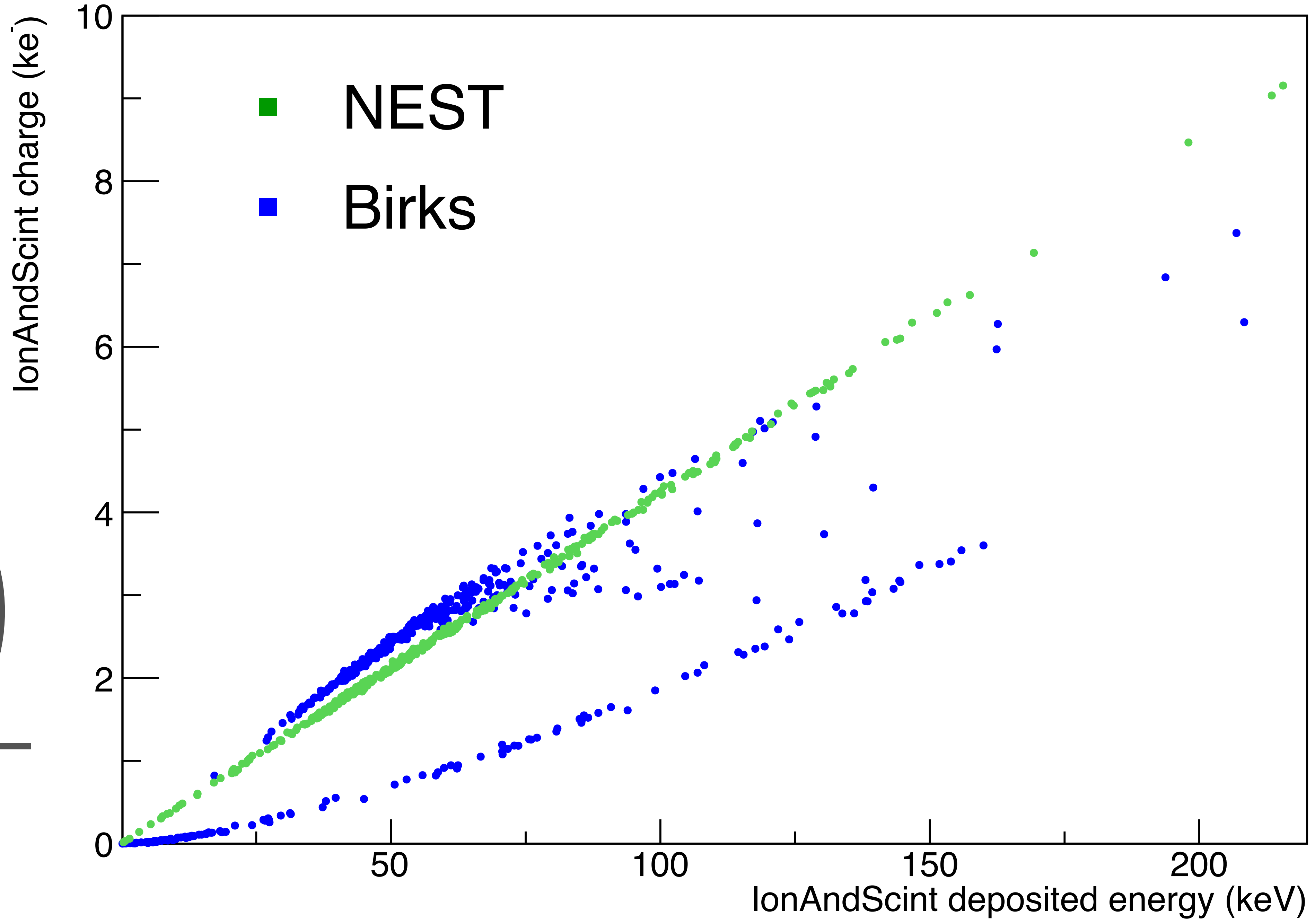
DUNE TDR: https://doi.org/10.48550/arXiv.2002.03005

ProtoDUNE-HD calibration

- Data driven simulation tool
- Perfect for low energy
- Allows **flat recombination** for simulation
- Allow to find the expected shape of the spectrum







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

- For calibration purpose a source of ^{207}Bi has been added in PDHD
- Position is reconstructed **at the cm level**

NB: spectrum is normalised by area

Fiducialization allows us to clearly identify ^{207}Bi

- Made a **dedicated analysis tool** to reconstruct **isolated hits** position and energy and make **LE clusters**
- Reconstructed **~36 min of data taking → ~50 To** (only ~1% of all set)

- Analysis tools included in **duneana branch in the Calibana method**
- Will be run in the reco 1 step for PDVD data

- https://github.com/emilelavaut/protoduneana/tree/develop/protoduneana/verticaldrift/singlehit
- https://github.com/emilelavaut/duneana/tree/develop/duneana/CalibAna