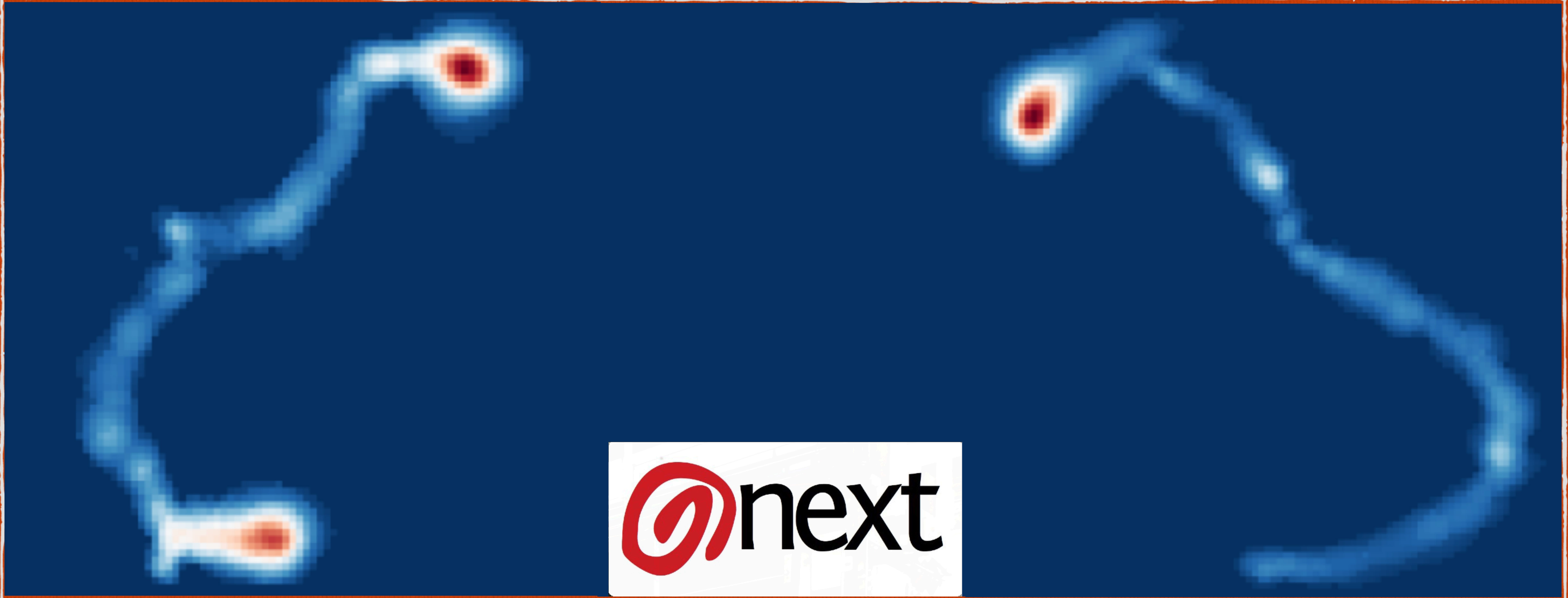
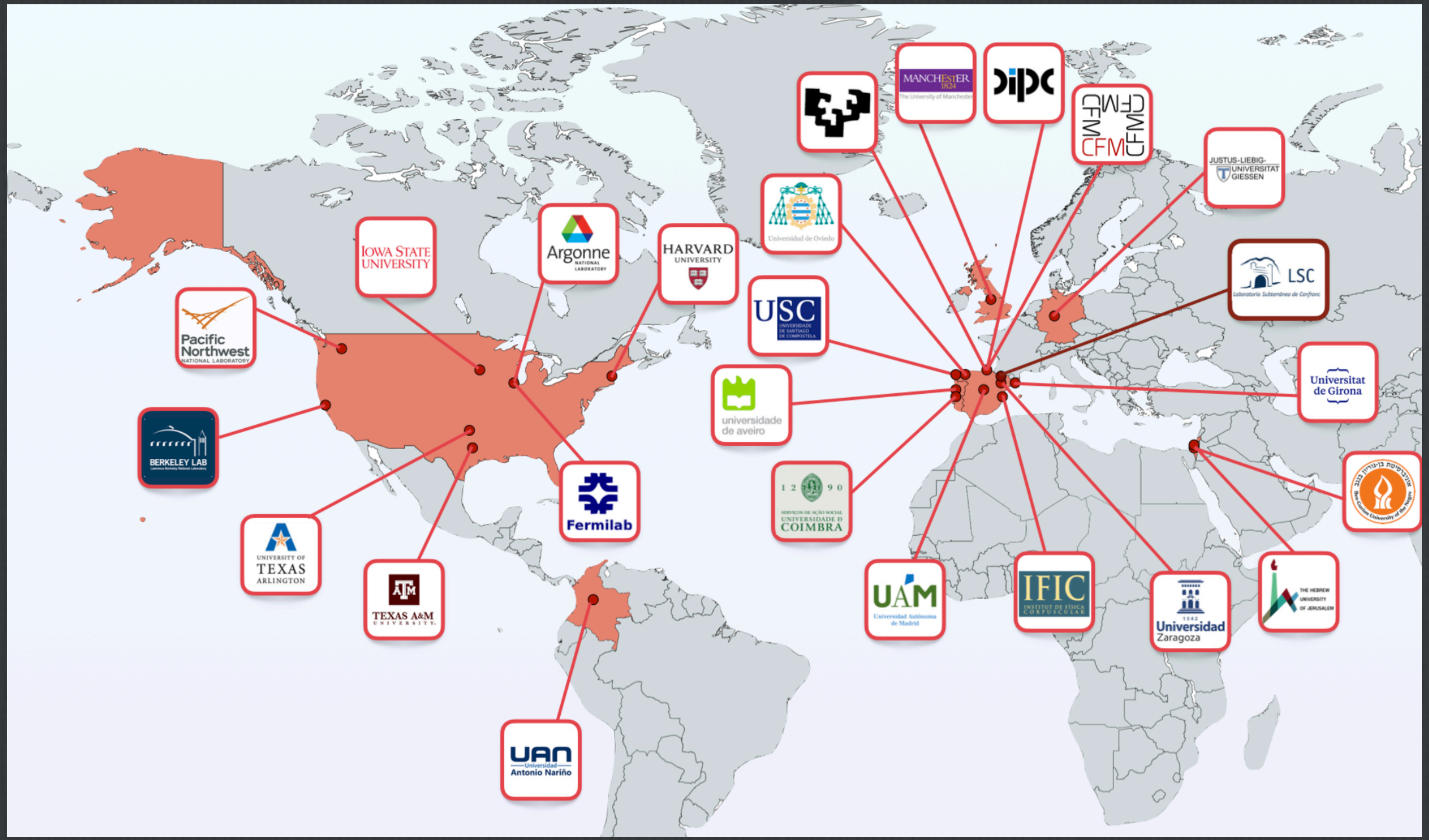


Topological Event Discrimination using Deep Convolutional Neural Networks for the NEXT Experiment

Fabian Kellerer on behalf of the NEXT Collaboration

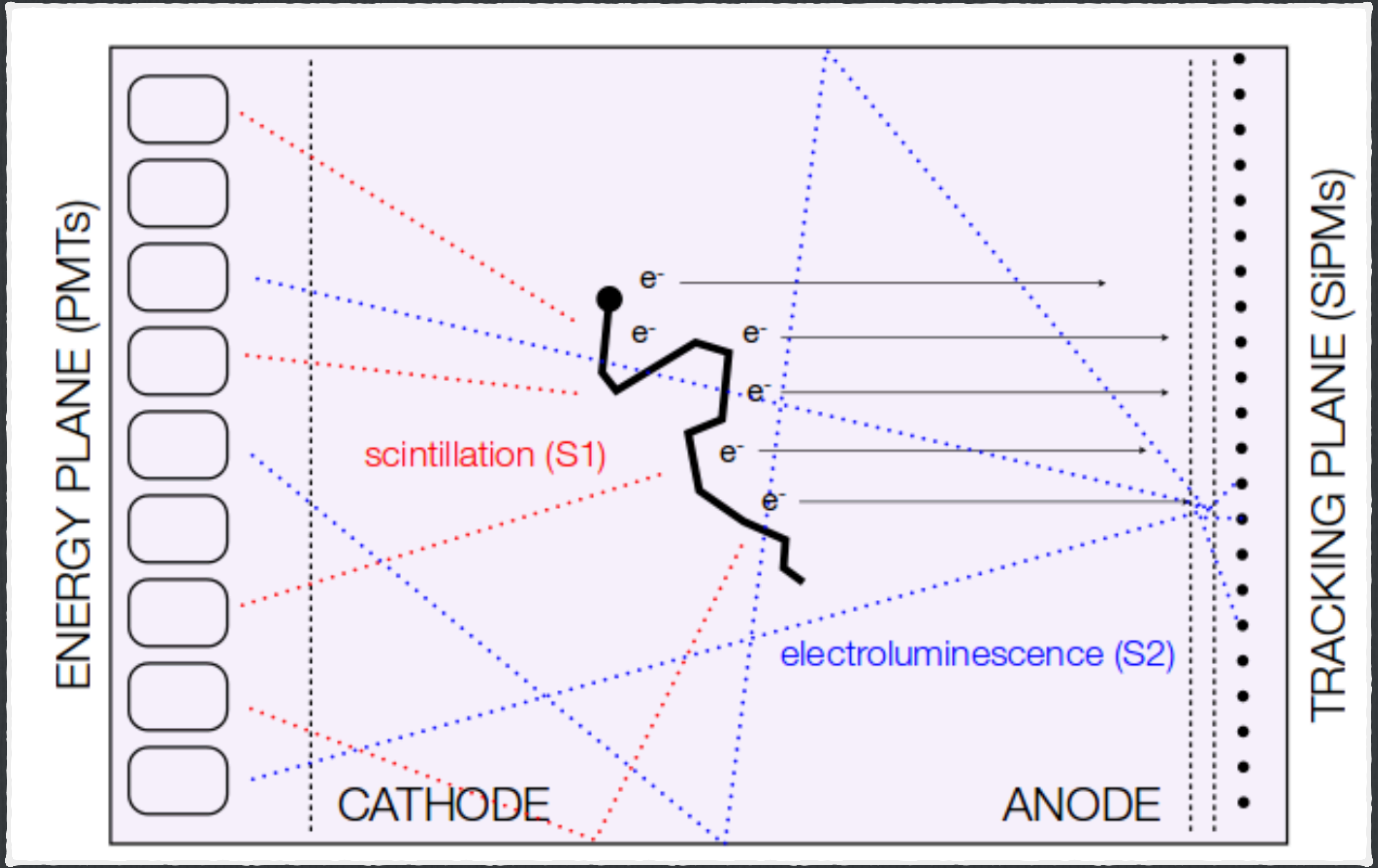
The NEXT Collaboration



- ☐ 100+ people from 20+ institutions
- ☐ Hosted at the LSC in the Spanish Pyrenees

<3

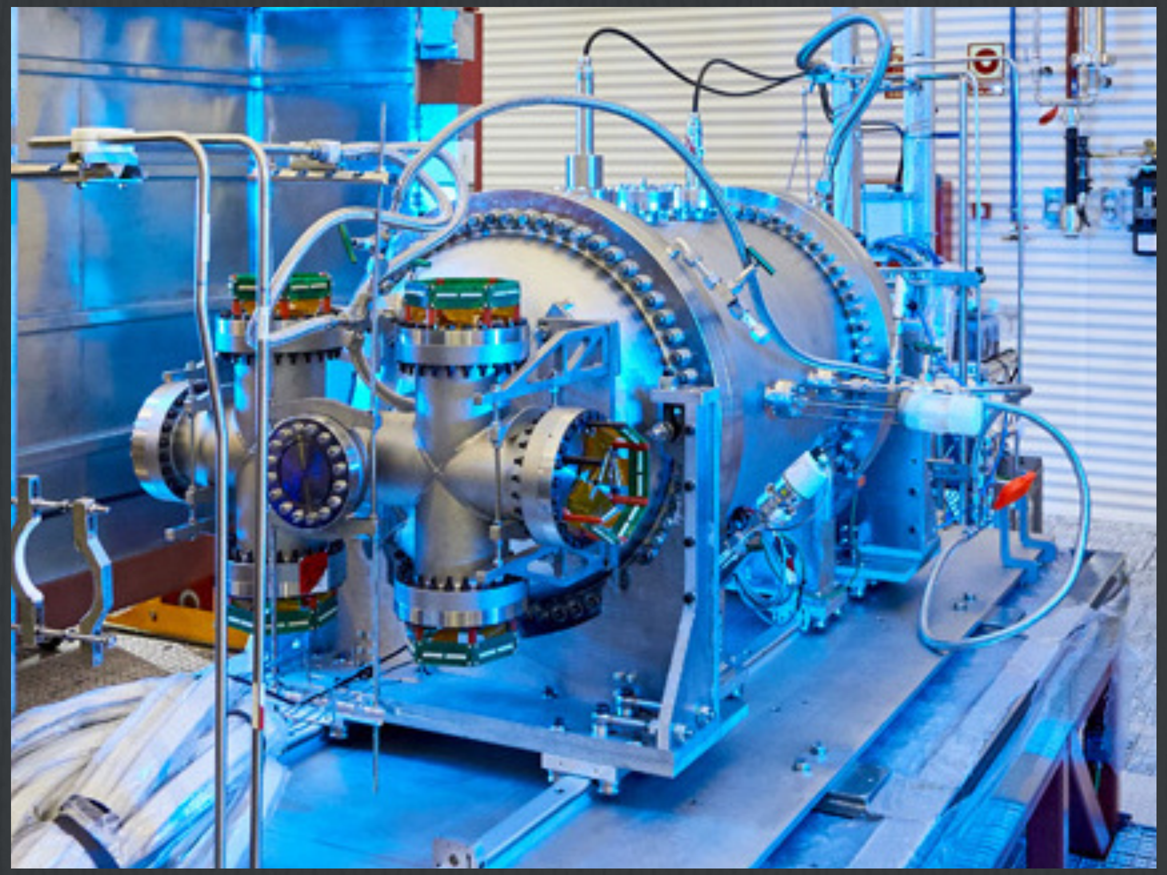
0νββ Search with NEXT

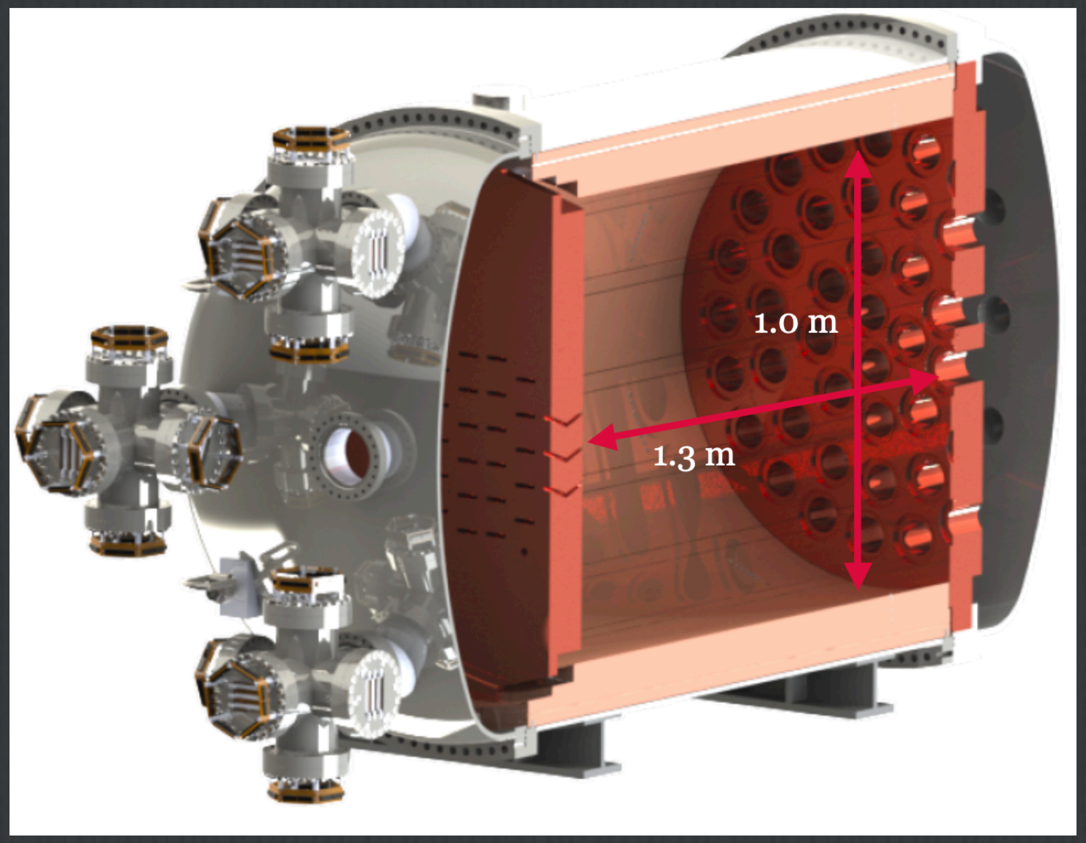


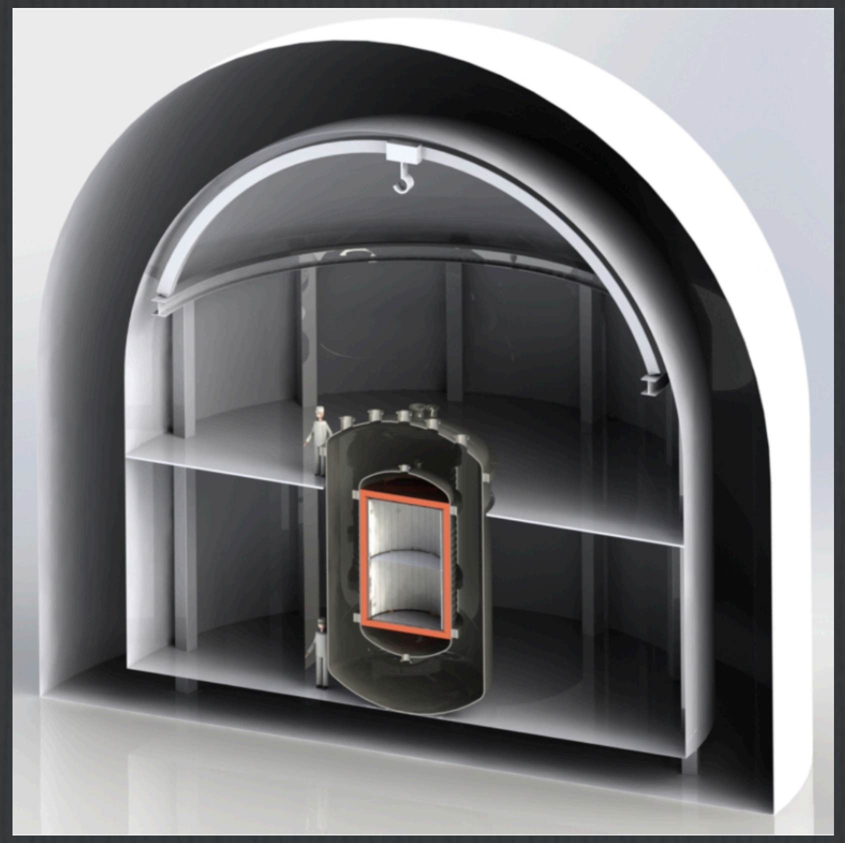
Schematic of a NEXT TPC

- Neutrino Experiment with a Xenon TPC (Time Projection Chamber)
- Detector material: enriched gaseous Xe^{136}
  - Less nuclei per volume, but better energy resolution and track reconstruction compared to liquids
- S1: primary scintillation, detected by PMTs
- S2: from electroluminescent amplification. Used for track reconstruction and x/y position
- Δt between S1 and S2 used for z position

NEXT Timeline







2009-2014

Small prototypes (~1kg of Xenon)

2015-2021

NEXT-White (NEW) (~5 kg). Background and 2νββ

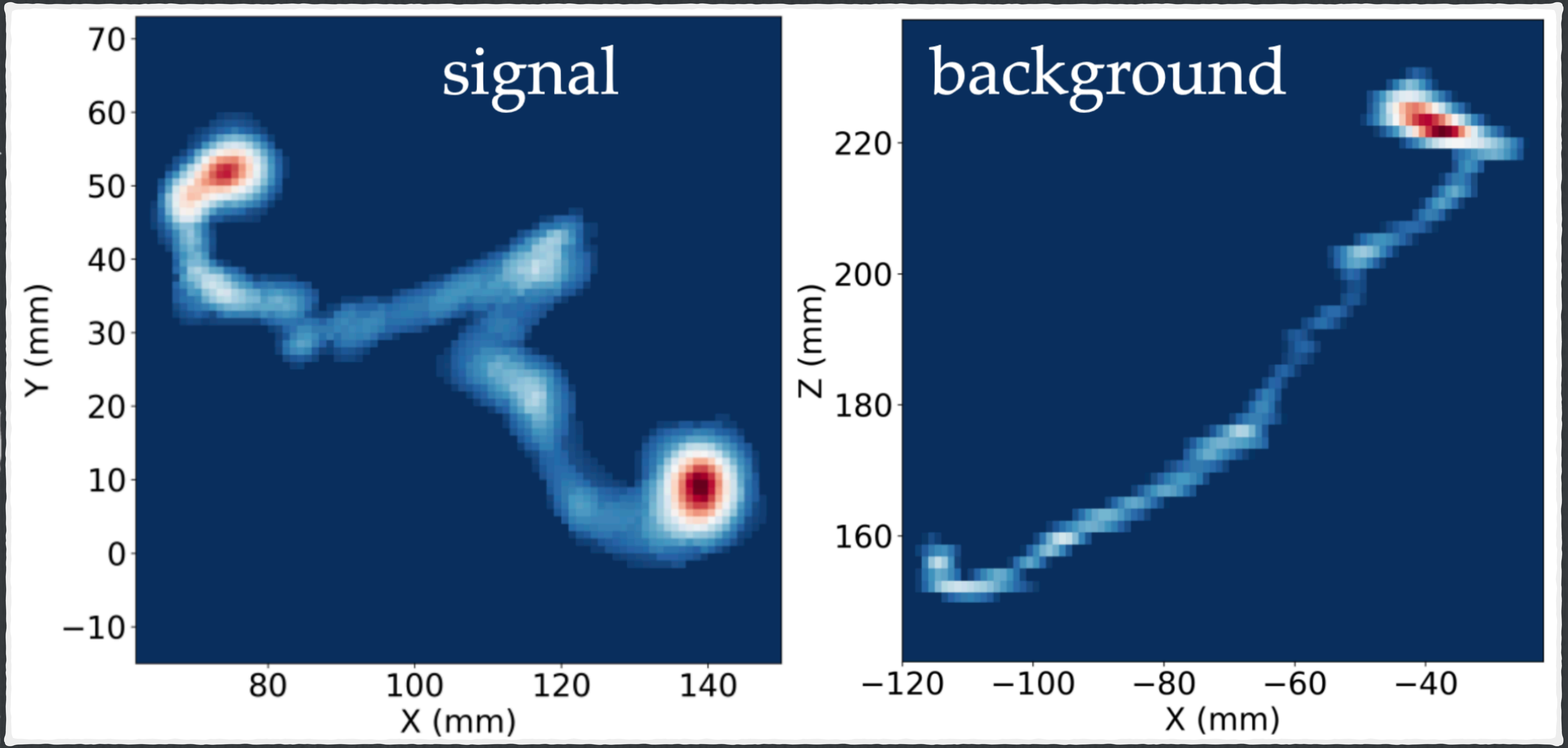
2024-202?

NEXT-100 (~100 kg). 0νββ limit setting.

20??

NEXT-HD/BOLD (~1 ton). 0νββ detection…?

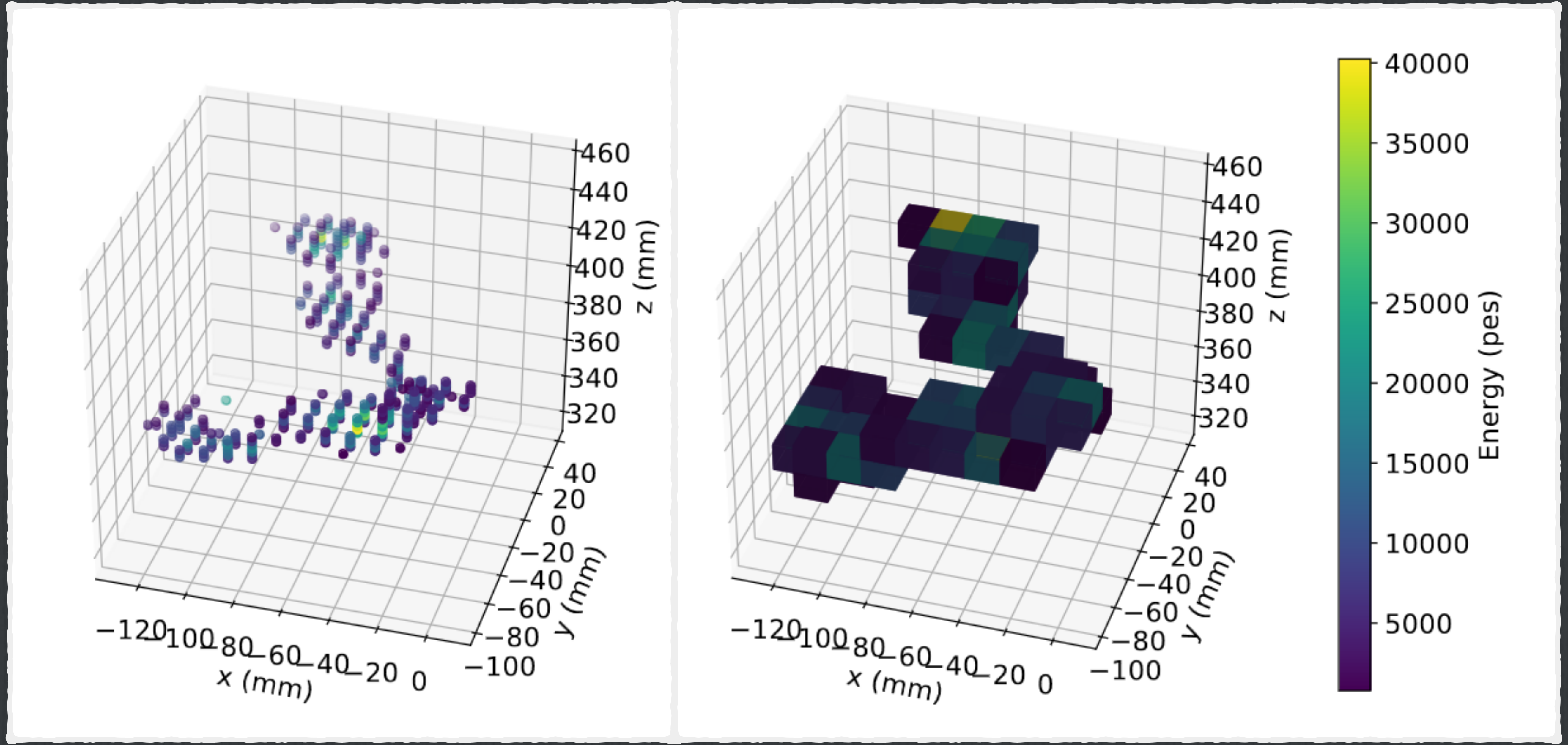
Topological Event Discrimination



An example of real data from NEW, showcasing a signal and a background candidate event

- Bragg peak at the end of an electron track -> manifests as 'blob' that allows for topological background rejection
- Use 'double escape' events from Tl^{208} decays: e^+/e^- pair production from a single high-energy γ where the subsequent 511 keV annihilation γ-rays escape the active volume
  - For Tl^{208}: at 1592 KeV
  - -> Same topological signature as $0\nu\beta\beta$ decay
- Continuous background of single-electron Compton scattering events

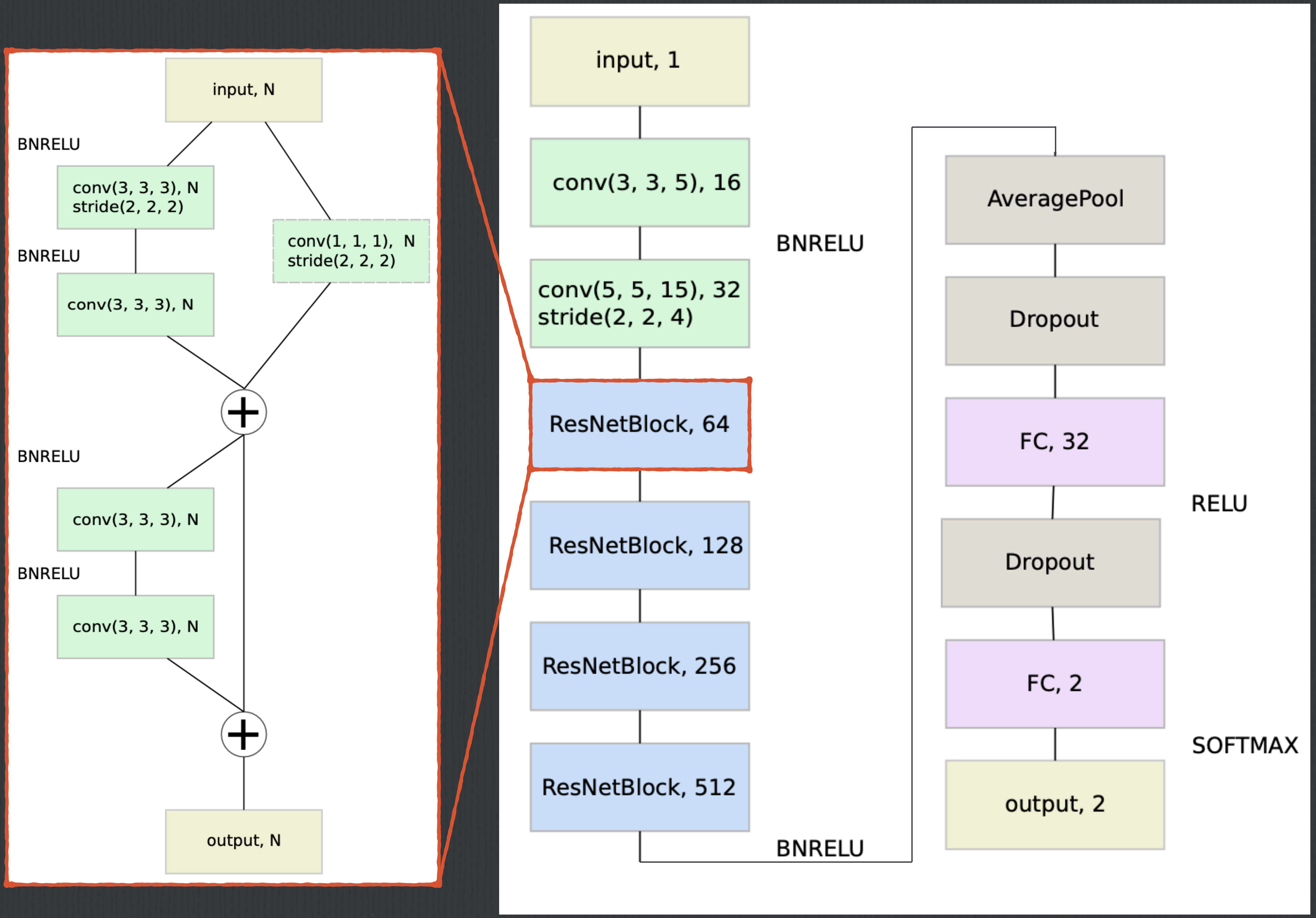
‘Traditional’ Approach [1]



Left: hits at their reconstructed positions in 3D; right: voxelised track

- ☐ Reconstruct each sensor hit position from the sensor position and drift time between S1 and S2
- ☐ Group hits into voxels
- ☐ Use Breadth First Search (BSF) algorithm to cluster neighbouring voxels into tracks
- ☐ Sum over track ends to get blob energies and cut on the second blob energy to reject background

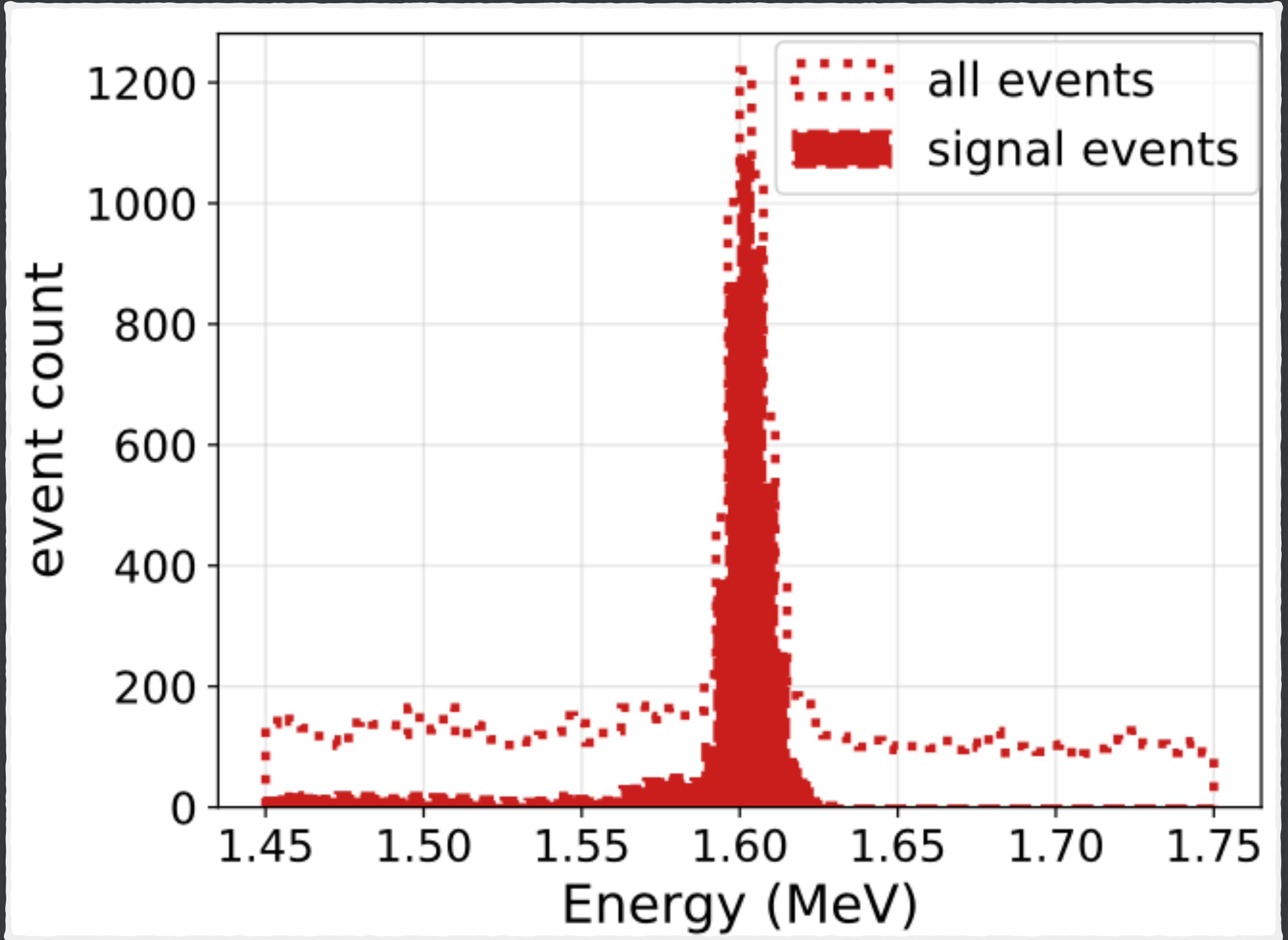
DCNN Approach [2]



The network architecture used in this study

- Deep Convolutional Neural Network
- Developed for image recognition
- Convolution filters: tensors of learnable parameters that are applied linearly over an image in steps ('stride')
- Here: sparse 3D convolutional network with 2 output classes: signal and background
- conv(x,y,z), N: convolution using N filters of size x,y,z
- FC: fully connected layer

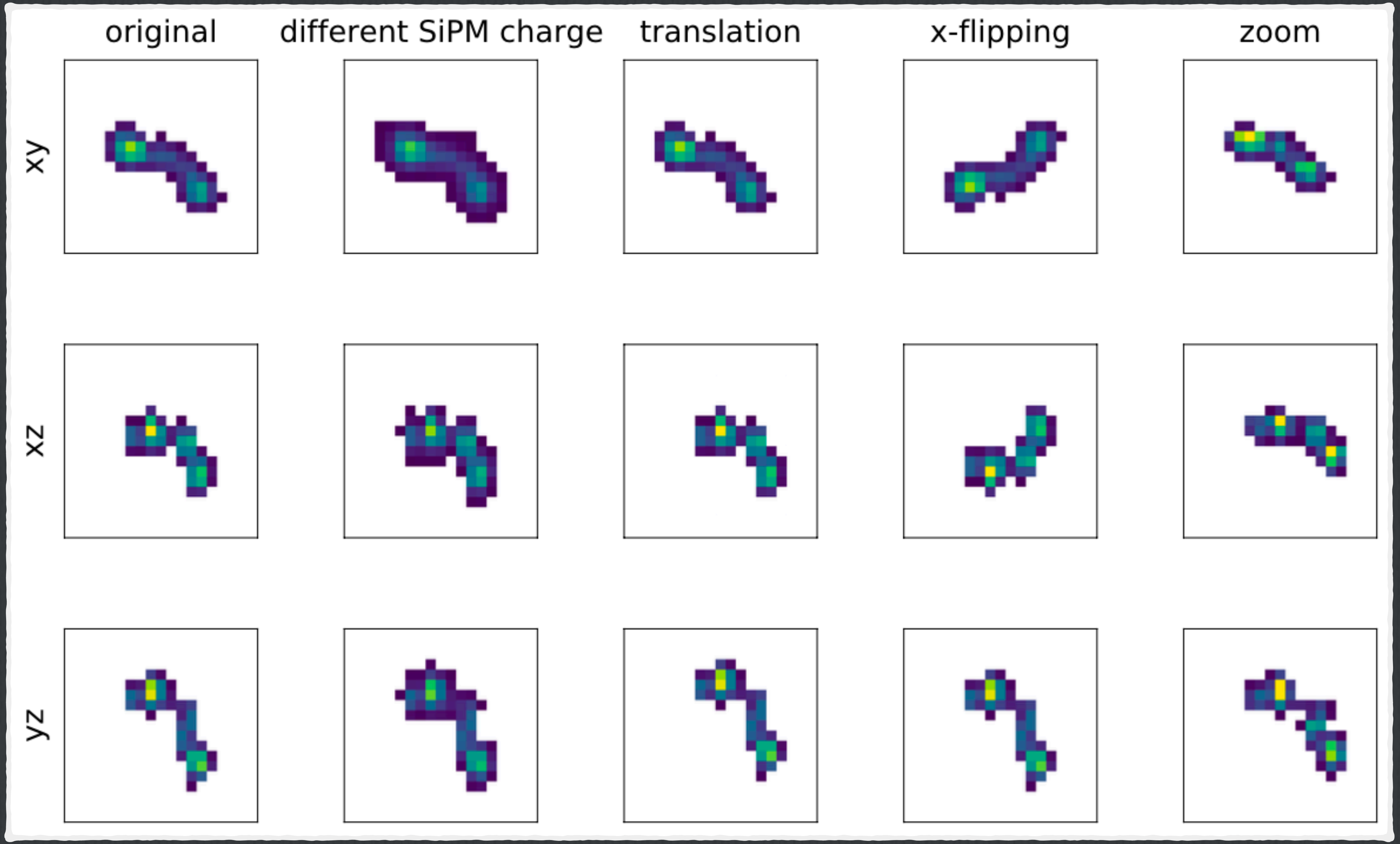
Data Preparation [2]



Energy spectrum of the simulated events

- MC simulation of Tl^{208} double escape events using our Geant4 application Nexus
- Run same reconstruction chain as for traditional approach, except for:
  - Total event energy normalised to one
  - Custom voxel size applied to re-voxelise hits after original track reconstruction

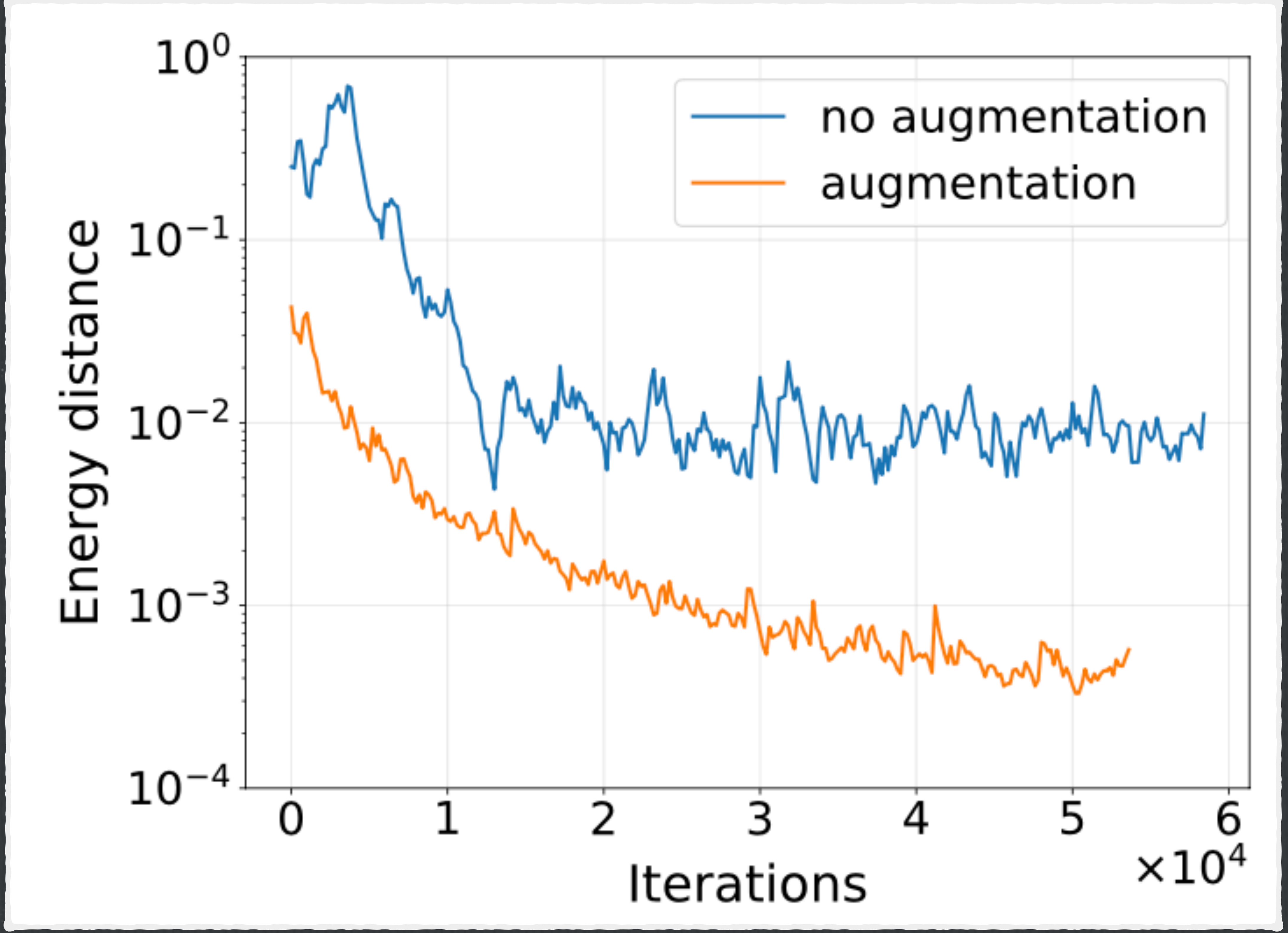
Training Procedure [2]



An example of data augmentation in 3 axes

- 500k training events, 30k validation
- Cross-entropy loss
- L2 weight regularisation
- On-the-fly data augmentation:
  - Track flipping, translating, zooming and SiPM charge cut variation

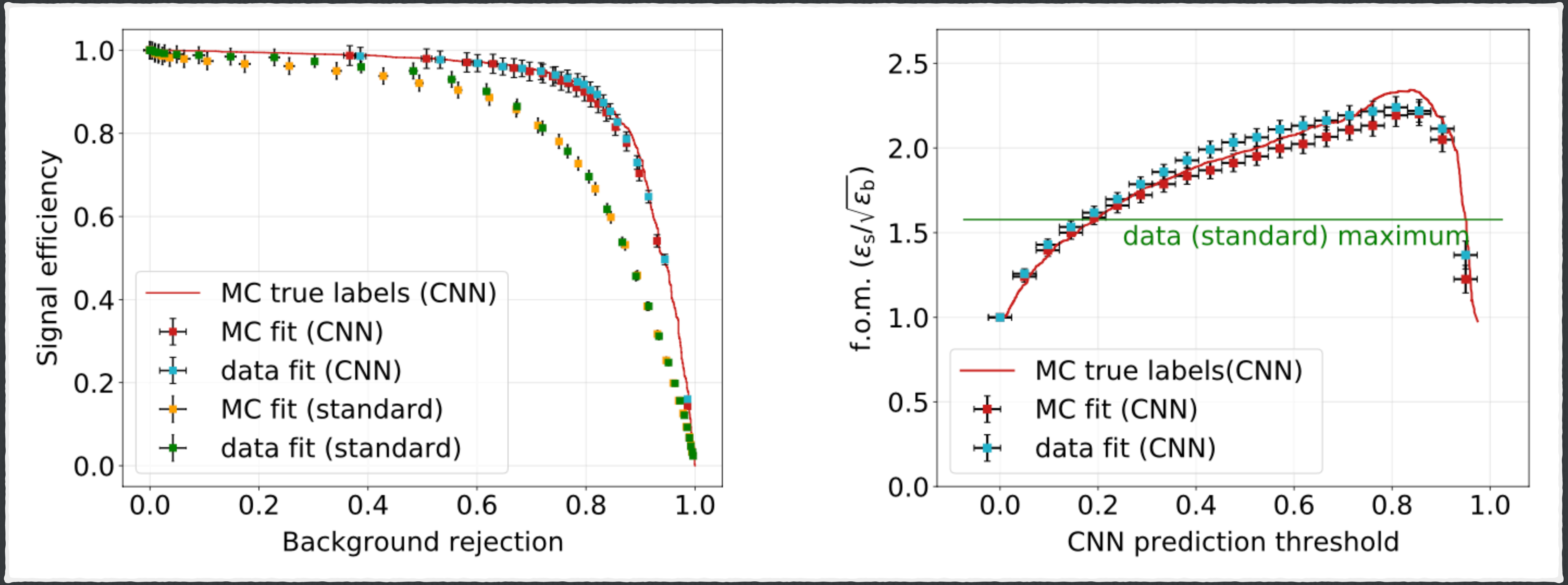
Data Augmentation [2]



The energy distance between data and MC, with and without data augmentation

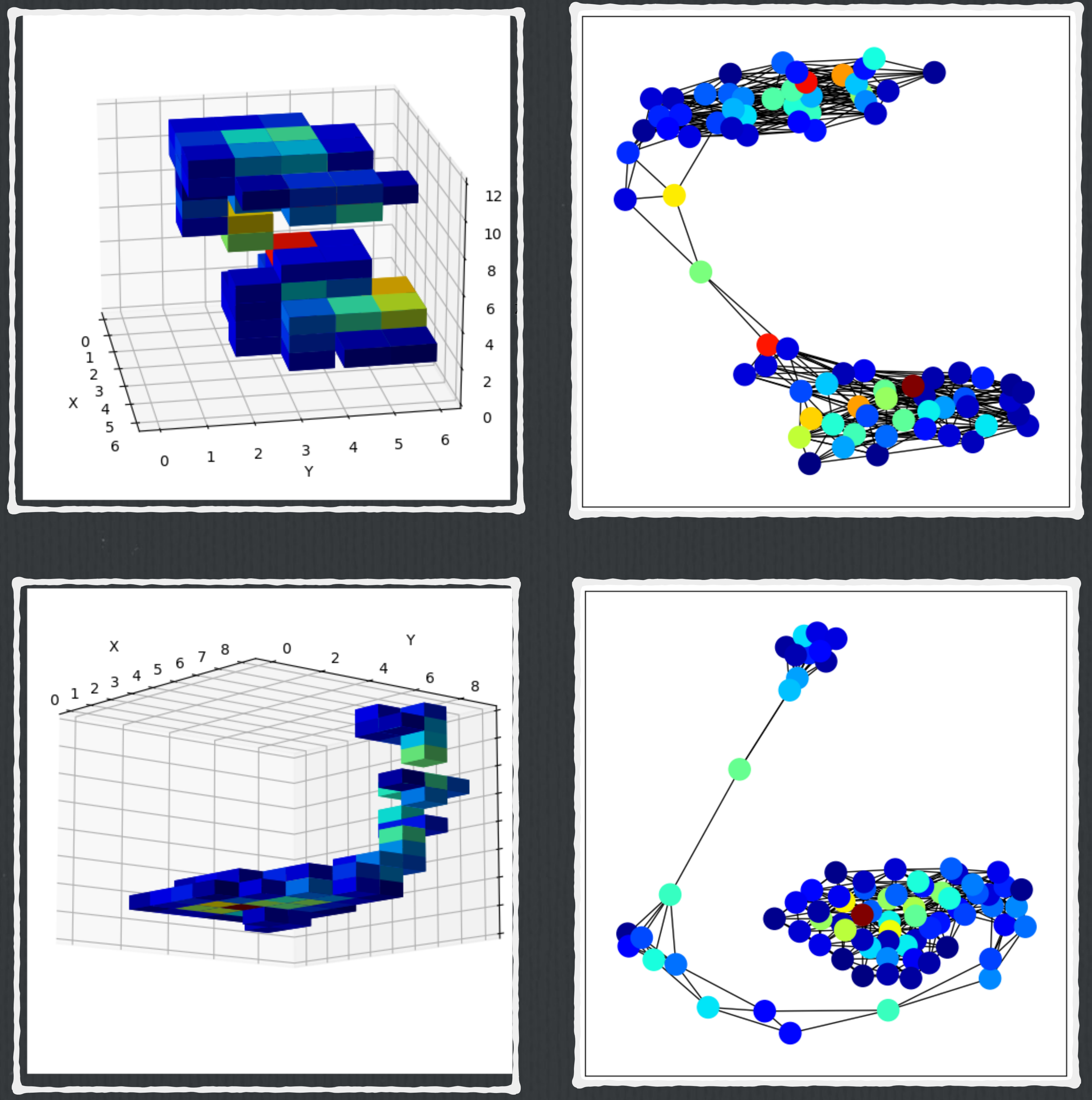
- ☐ Data and MC have some known differences in NEXT; not all are understood
- ☐ Data augmentation does not correct our MC but makes the model more robust to data-MC differences
- ☐ After average pooling layer: calculate Energy distance [3] between data/MC using the network feature vector (512 features)
  - ☐ -> probability that data/MC follow the same distribution can be calculated to be more that 95% with data augmentation

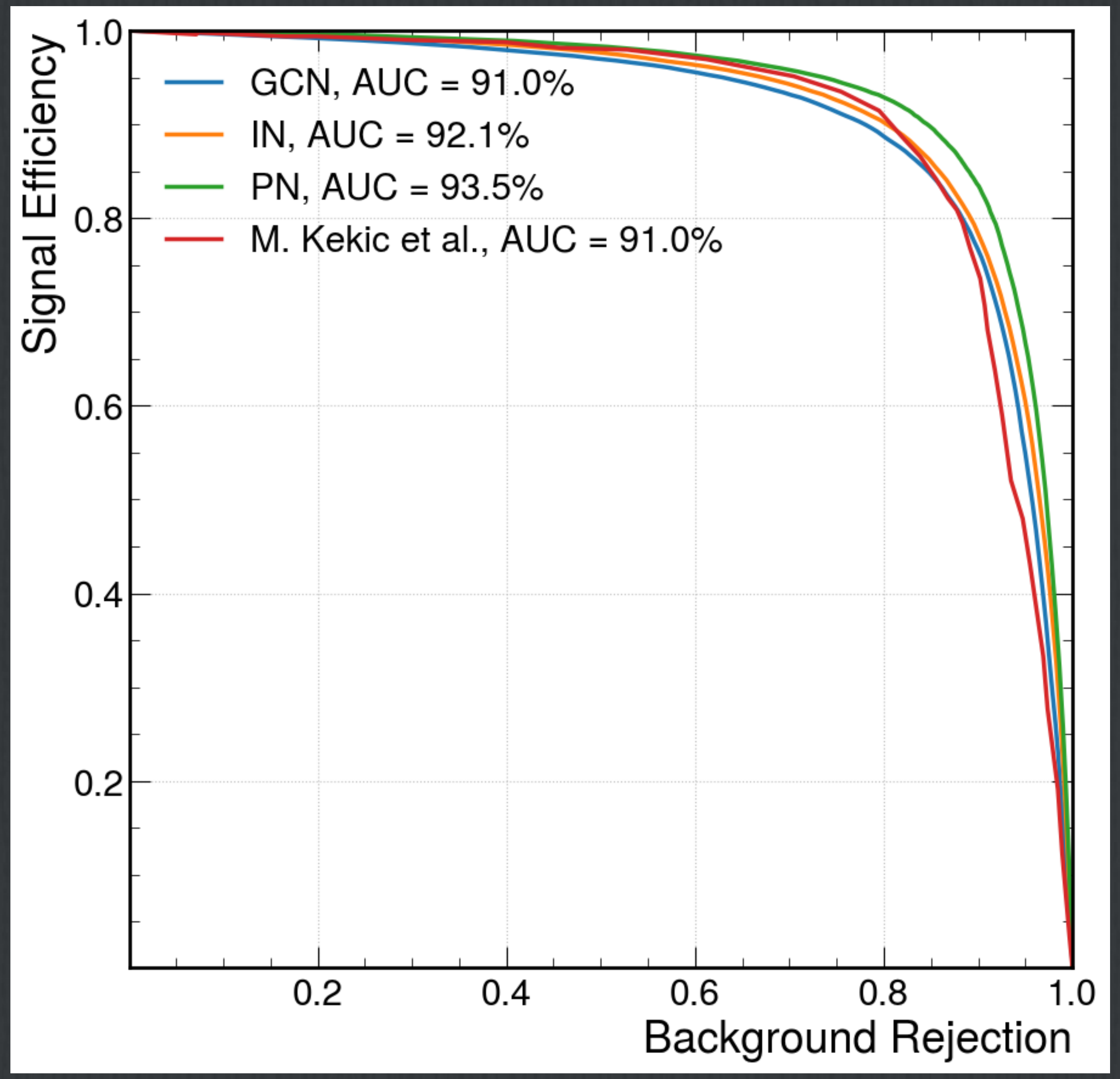
Results [2]



Signal acceptance vs background rejection and figure of merit ($\varepsilon_{s/b}$: fraction of signal/background events labeled as signal). Fit curves are obtained from fitting the energy spectrum with a gaussian + exponential background to estimate the number of true signal/background events. Standard curves are obtained using the non-CNN based approach described above. A significant improvement is apparent.

Next Steps: Upgrade to Graphs





A signal (top) and background event converted to graphs, and the signal efficiency - background rejection curves of three different GNN network architectures compared to the CNN curve (M. Kekic et al.)

- Graph neural network (GNN): generalisation of CNN
- Voxelised tracks are converted to nodes with a feature vector (i.e. energy, position…) and connections
  - -> Additional degree of freedom in graph architecture
  - Removal of unnecessary information, data is inherently sparse
- First tries on MC look to improve over CNNs
- Suitable data-MC compatibility strategies such as data augmentation to be developed

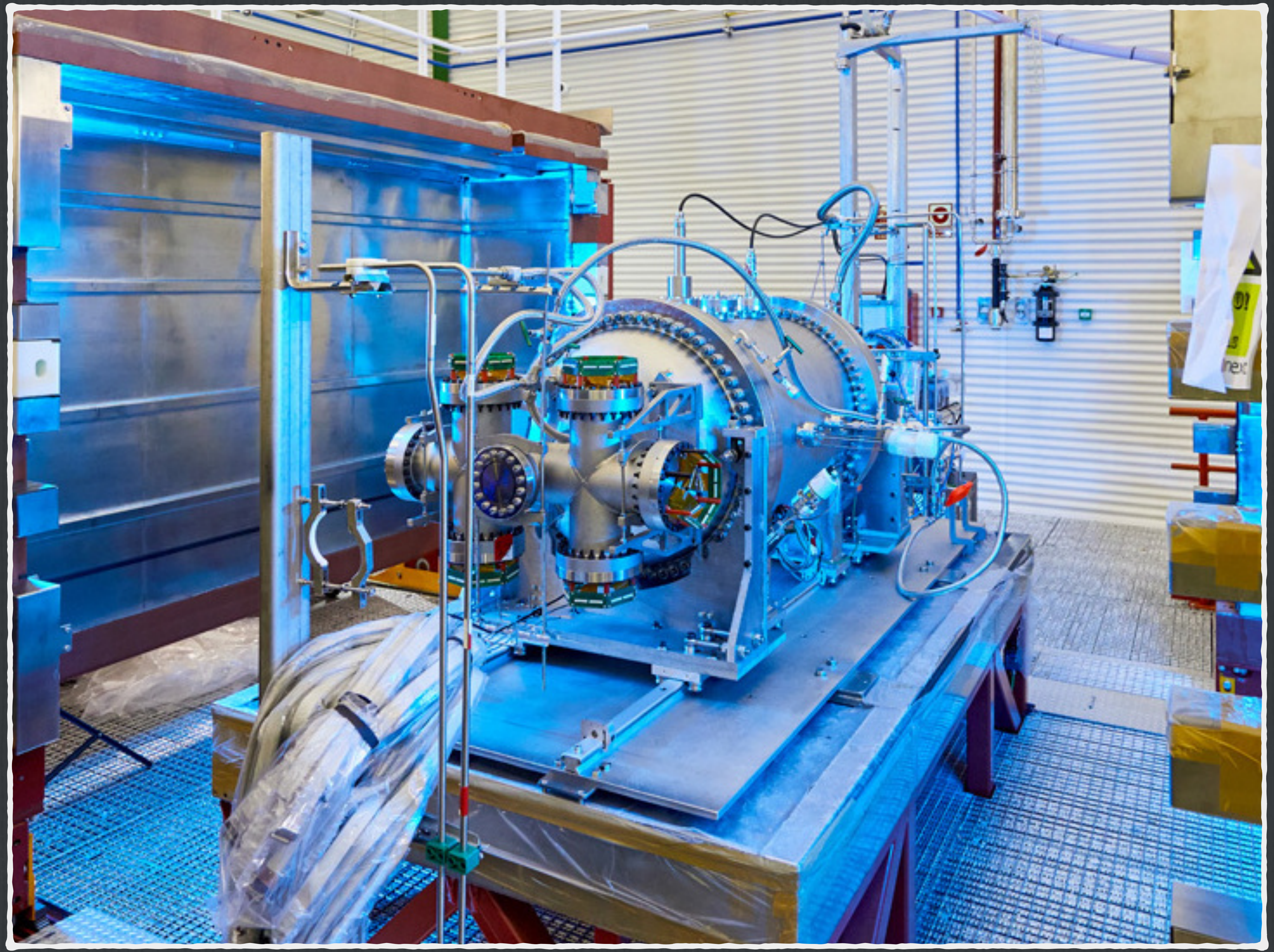
Summary

- Gaseous TPCs provide a strong tool to reject single-electron background events in $0\nu\beta\beta$ searches
- Convolutional neural networks can be used successfully for this task, even in the case of non-perfect data/Monte Carlo compatibility
- Even better background rejection might be possible using graph neural networks

Questions?

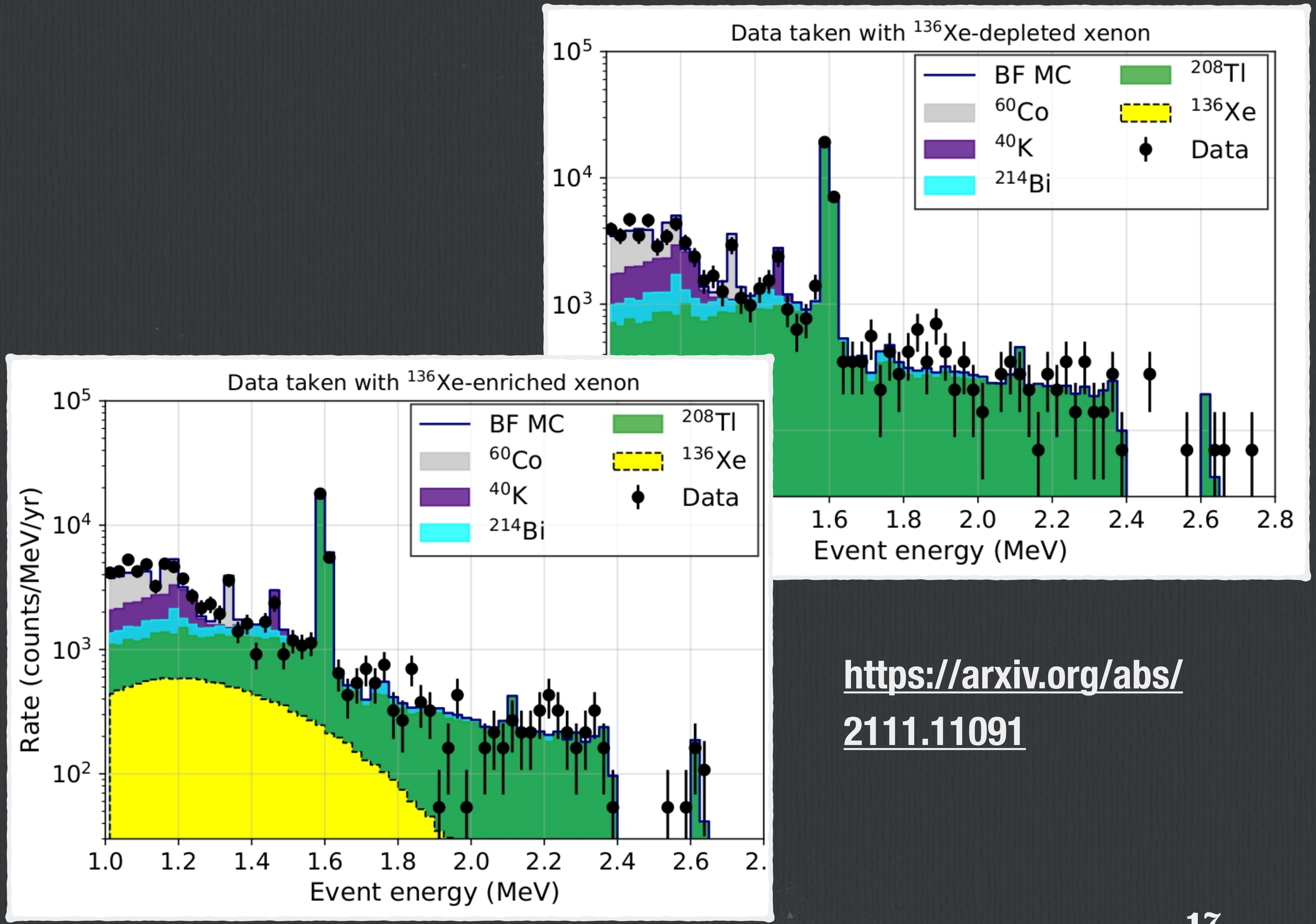
BACKUP

NEW



- ☐ First radiopure realisation of a NEXT TPC

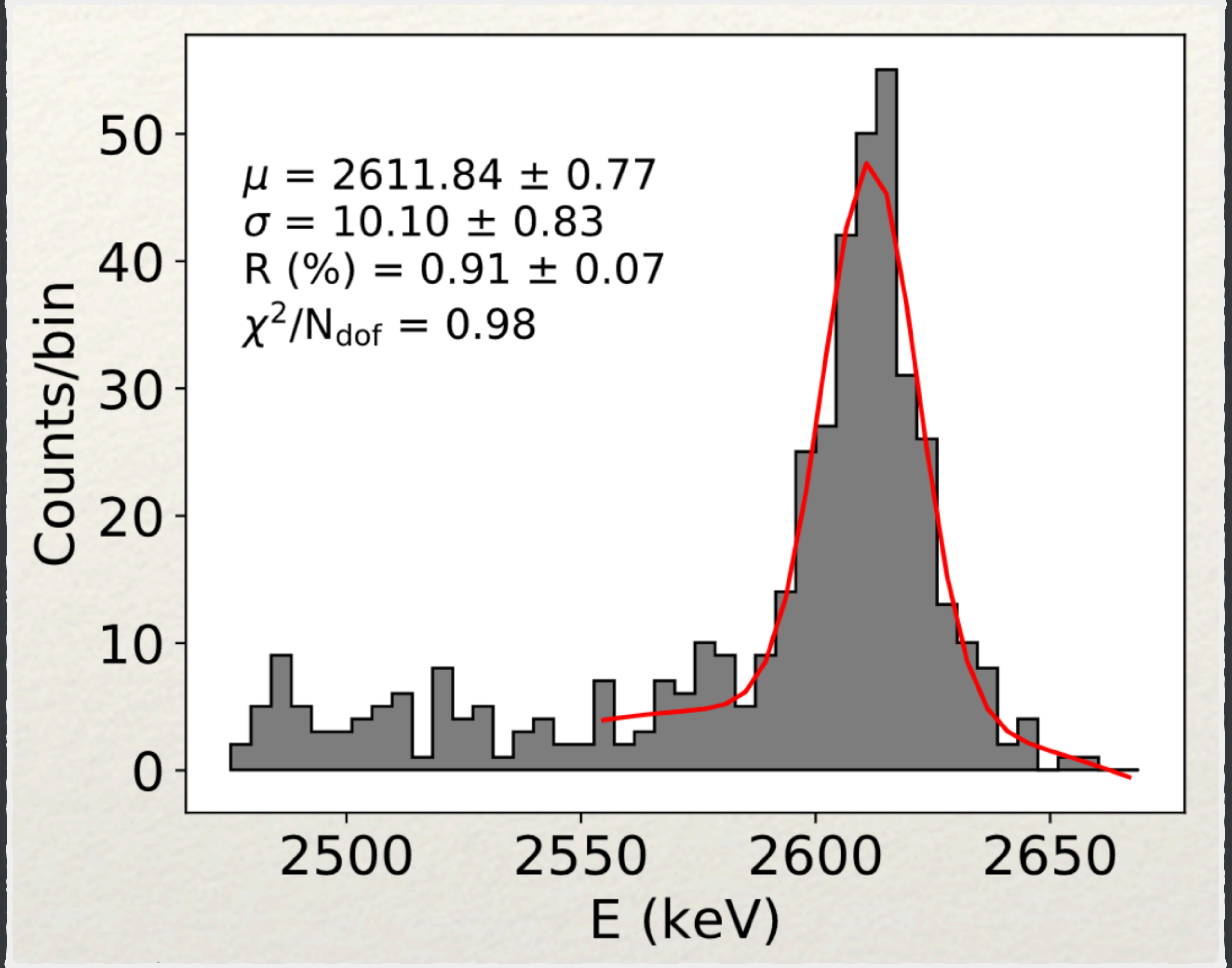
NEW



- First radiopure realisation of a NEXT TPC
- Purpose:
  - Characterise background at LSC

https://arxiv.org/abs/2111.11091

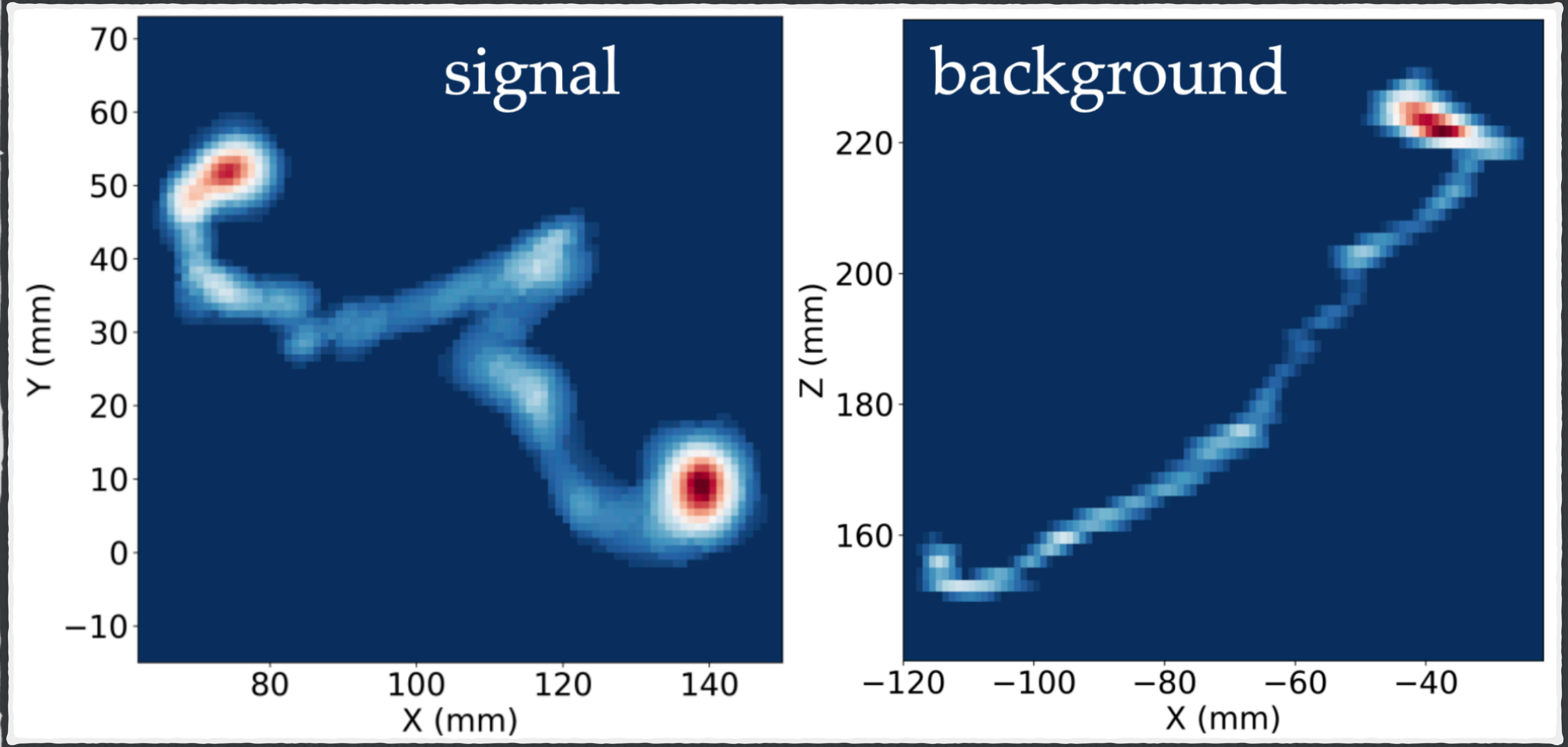
NEW



- First radiopure realisation of a NEXT TPC
- Purpose:
  - Characterise background at LSC
  - Demonstrate energy resolution

Better than 1% at 2.6 MeV! [2]

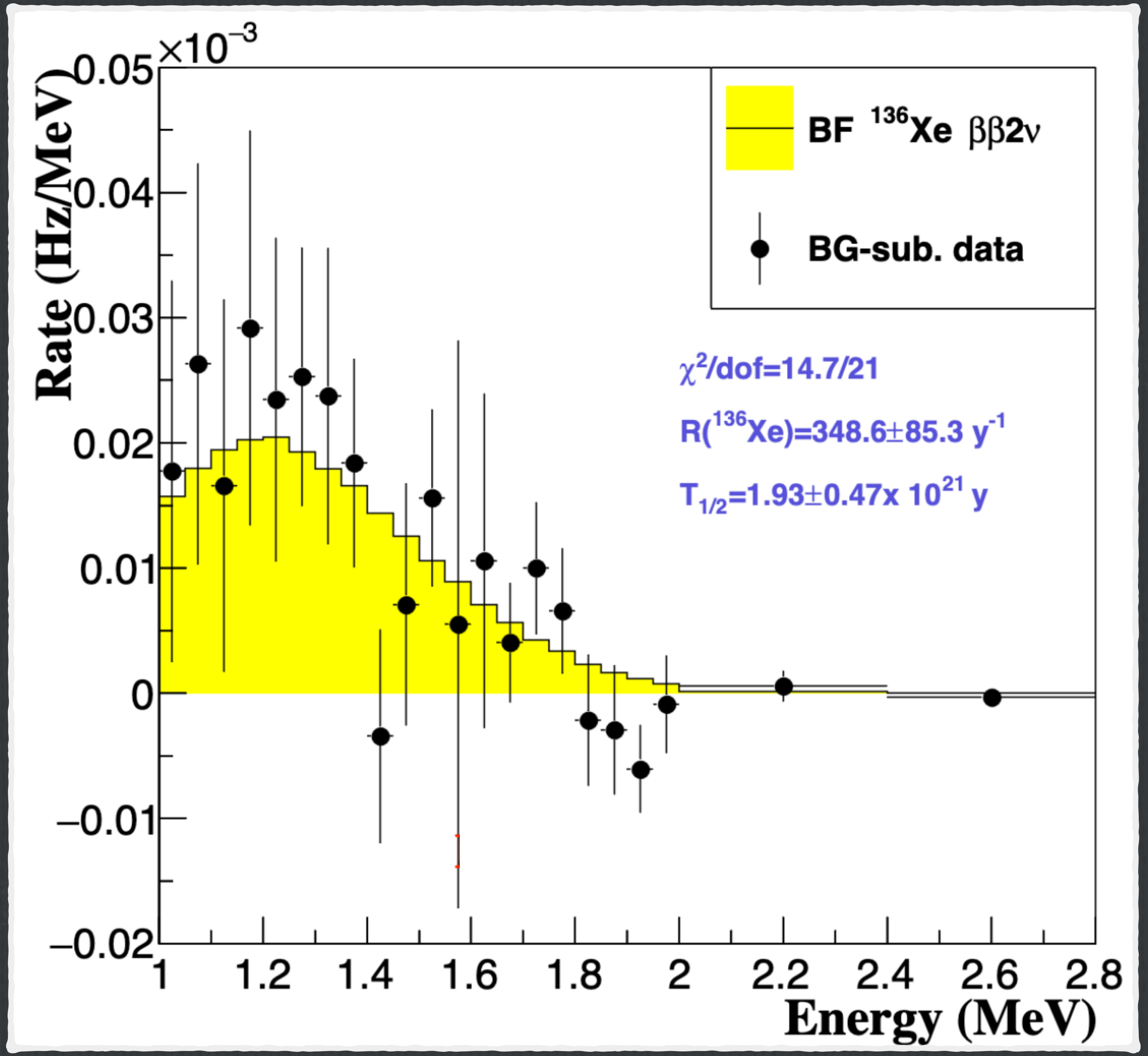
NEW



- First radiopure realisation of a NEXT TPC
- Purpose:
  - Characterise background at LSC
  - Demonstrate energy resolution
  - Achieve topological event discrimination

Bragg peak at the end of an electron track -> manifests as 'blob' and allows for topological signal detection

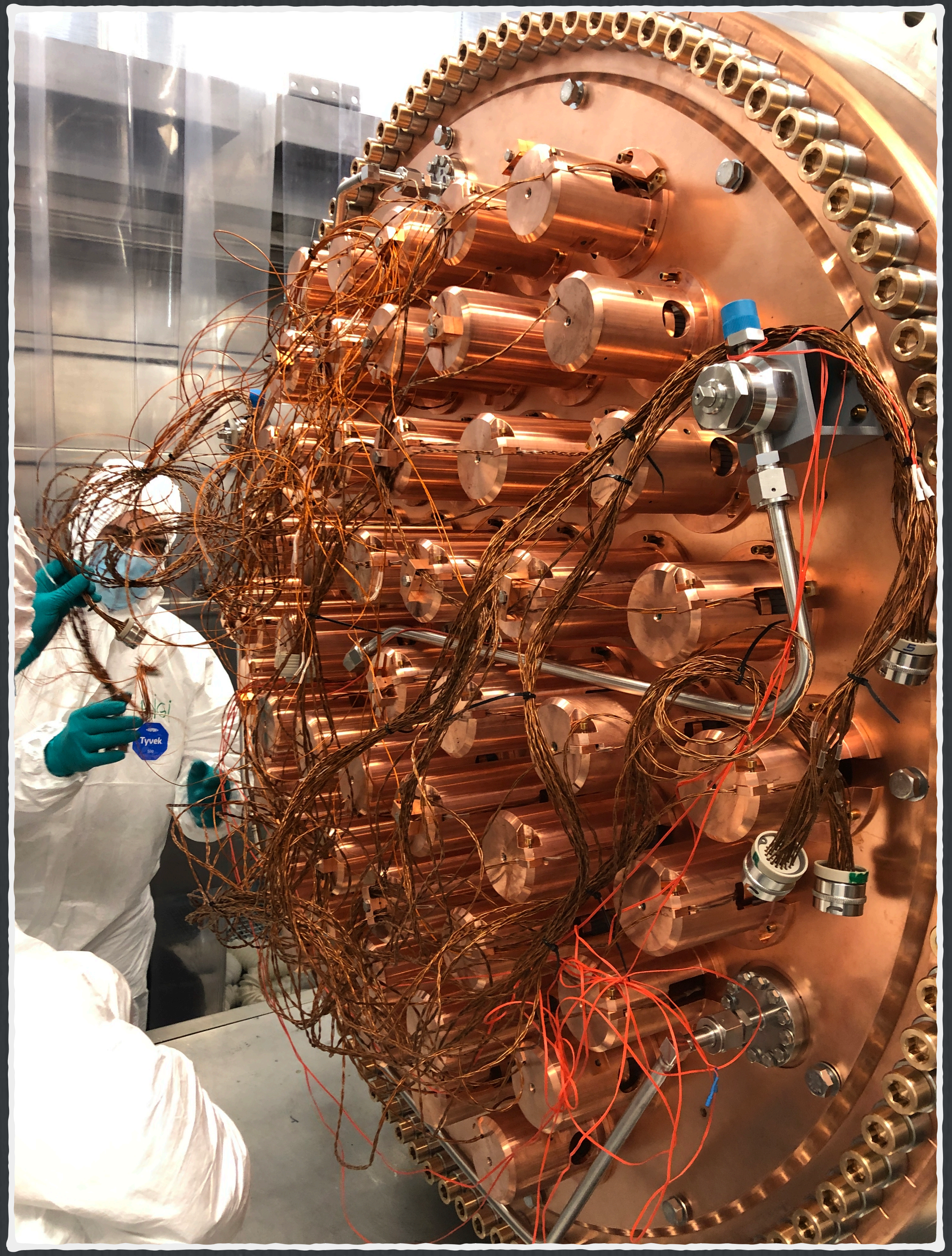
NEW



- First radiopure realisation of a NEXT TPC
- Purpose:
  - Characterise background at LSC
  - Demonstrate energy resolution
  - Achieve topological event discrimination
  - Measure the regular 2vββ decay mode

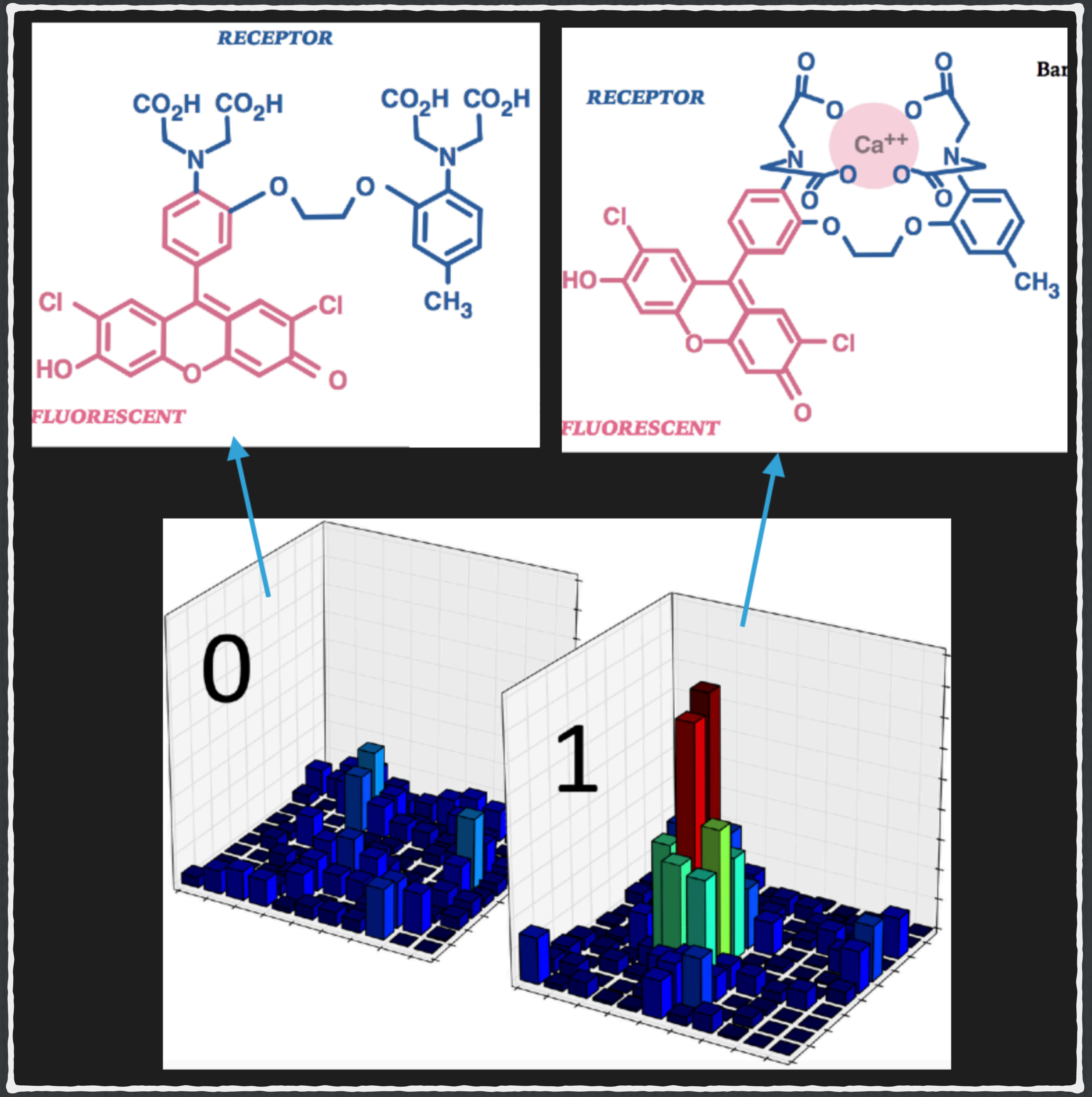
$T_{1/2}$=(1.93 ± 0.47)·10^{21} years [3] - Compatible with literature!

NEXT-100



- Situated at LSC
- Will provide a competitive limit on the 0νββ decay: $4.1 \cdot 10^{25}$ years after 3 years of data taking
- 60 PMTs and 3583 SiPMs in a 1.3 m long TPC
- Shielded by 12 cm of pure copper, a 20 cm thick lead castle and an active muon veto
- Already online!

NEXT-BOLD



- PMTs to be replaced by another system
  - Dense SiPM tracking plane
  - Optical fiber barrel
  - Camera readout [4]
- Symmetric TPC -> Shorter drift lengths to mitigate diffusion
- Could probe half-lives above 10^{27} years!
- With Ba tagging: up to 10^{28} years!

https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.120.132504