UC San Diego

XENON

Enhancing XENONnT's Sensitivity to $0\nu\beta\beta$ Decay with TextCNN

CoSSURF 2024

Min Zhong, UC San Diego

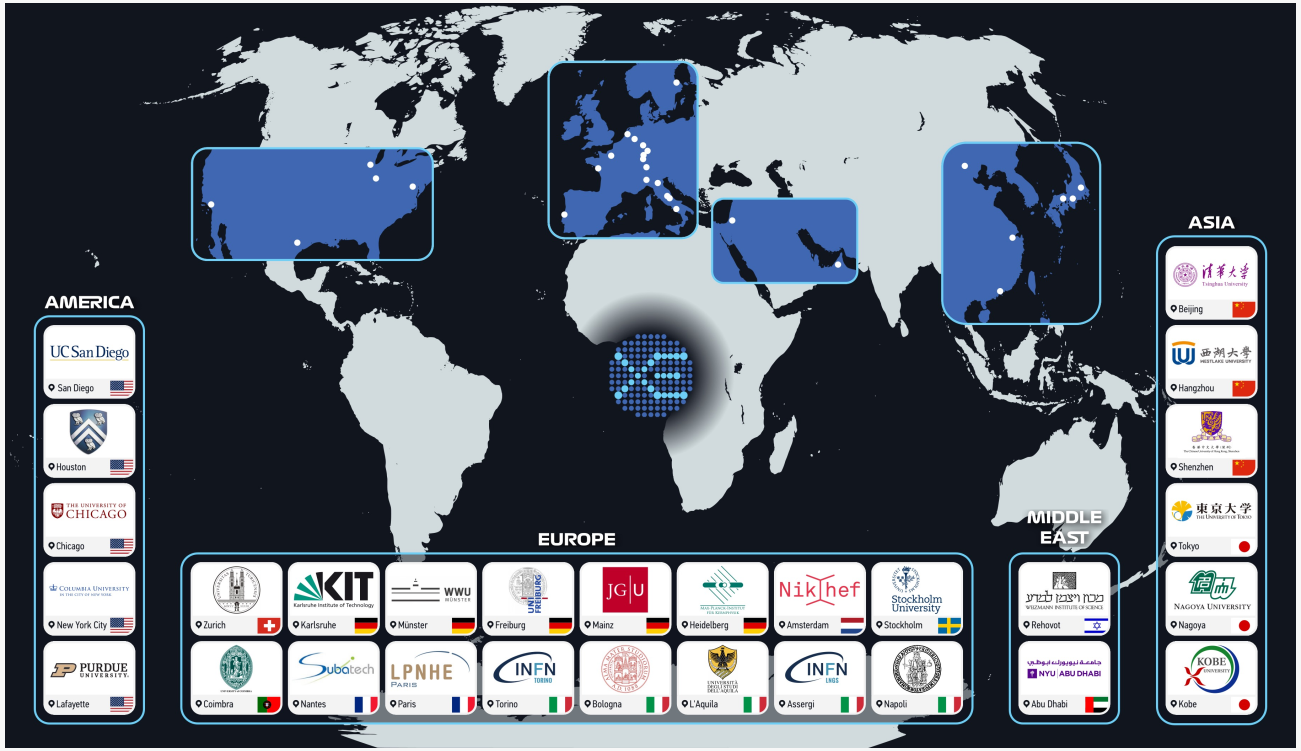
On behalf of the XENON collaboration

XENON Collaboration

www.xenonexperiment.org

instagram.com/xenon_experiment

twitter.com/xenonexperiment

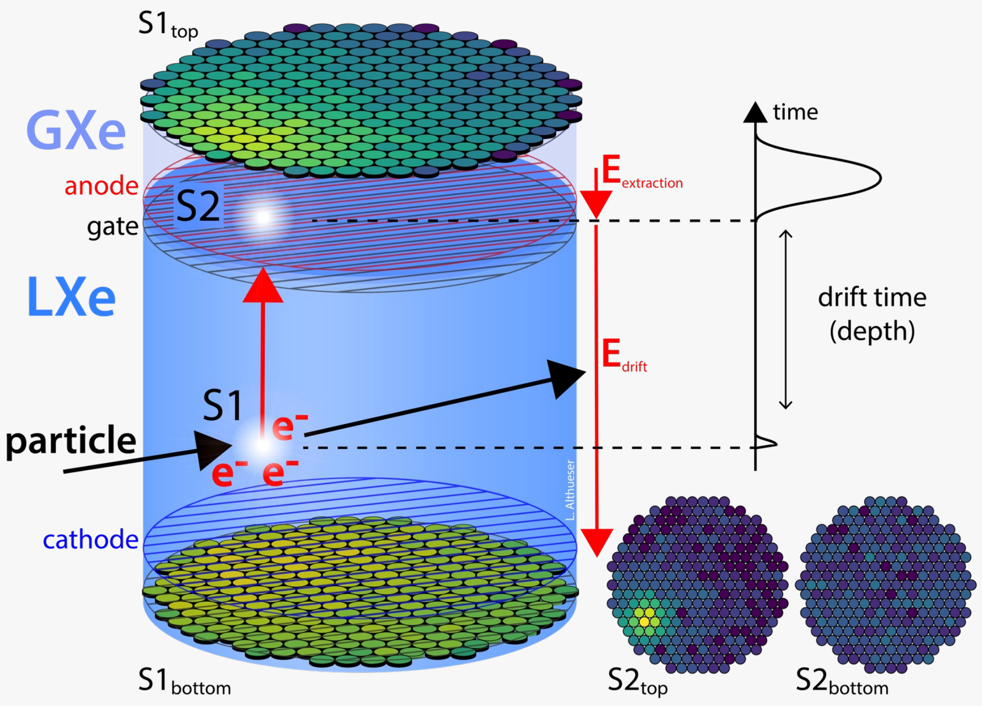


200+ Scientists

29 Institutions

Collaboration Meeting Sep. 2023, Paris

LXe Time Projection Chambers



Energy Reconstruction

From **combining S1** and **S2** signals

3D Position Reconstruction

x-y from PMTs **light pattern**, **z** from **drift time**

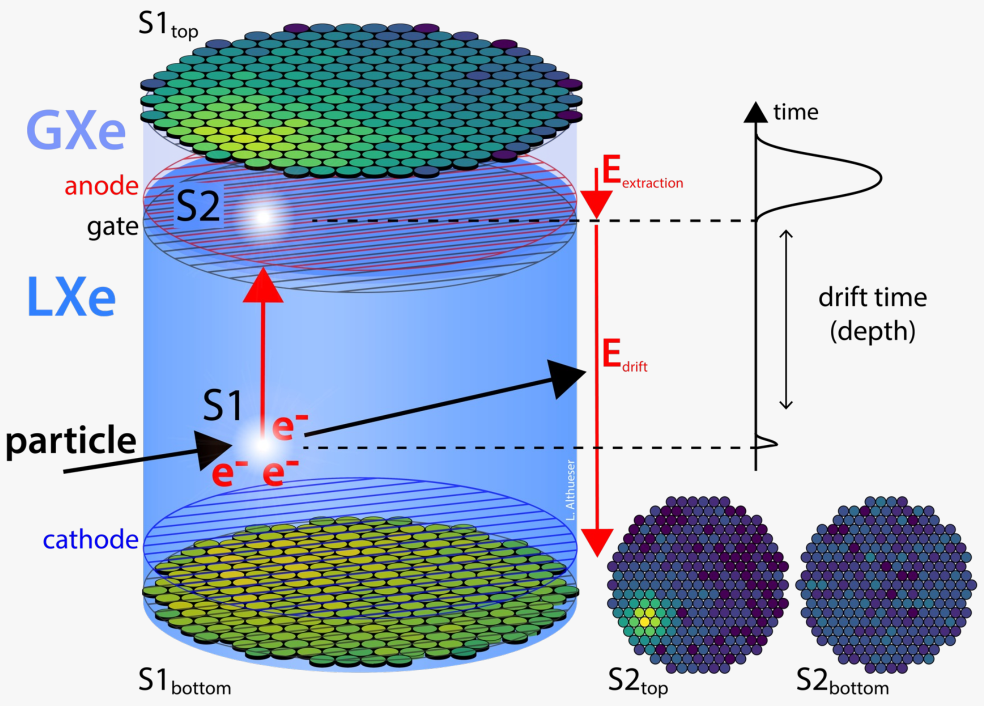
Recoil Type Identification

S2/S1 different for **Electronic Recoils** (**ER**) and **Nuclear Recoils** (**NR**)

Signals **in Dual-phase** Time Projection Chamber (**TPC**):

- Prompt scintillation light: **S1**
- Secondary scintillation proportional to drifted electrons: **S2**

LXe Time Projection Chambers



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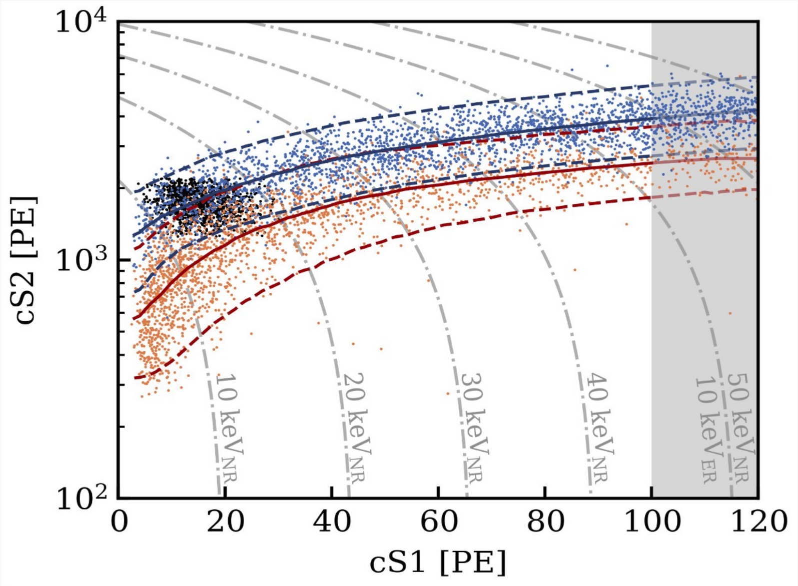
Electronic Recoils

Electrons, photons, neutrinos, (axions …)

Nuclear Recoils

Neutrons, neutrinos via coherent scattering, WIMPs…

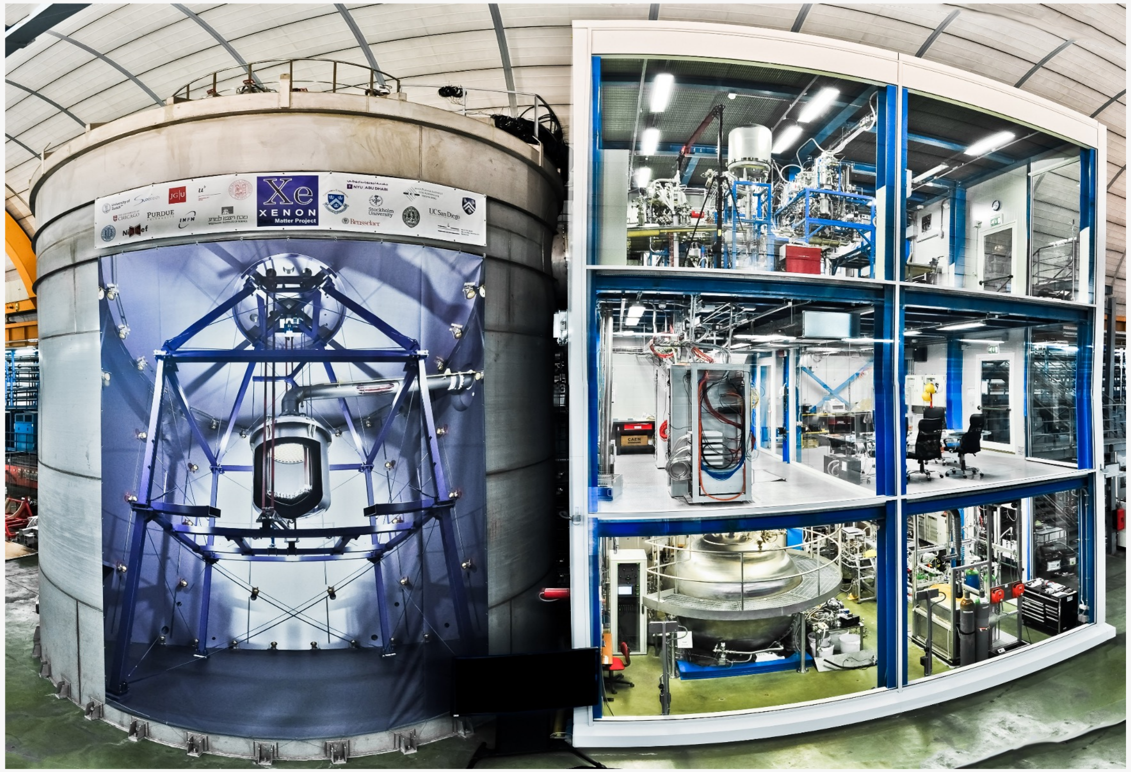


Phys. Rev. Lett. 131,041003, 2023

The XENONnT Experiment

Direct search for dark matter with **liquid xenon (LXe) TPC** deep underground at the INFN Laboratori Nazionali del Gran Sasso (LNGS) in Italy.

XENON10	XENON100	XENON1T	XENONnT
25 kg	161 kg	3.2 t	8.5 t
2005	2008	2016	2020



- 8.5 t LXe (5.9 t active mass)
- TPC: 494 Photomultiplier Tubes (PMTs)
- Neutron veto, muon veto
- GXe/LXe purification system, Rn distillation column

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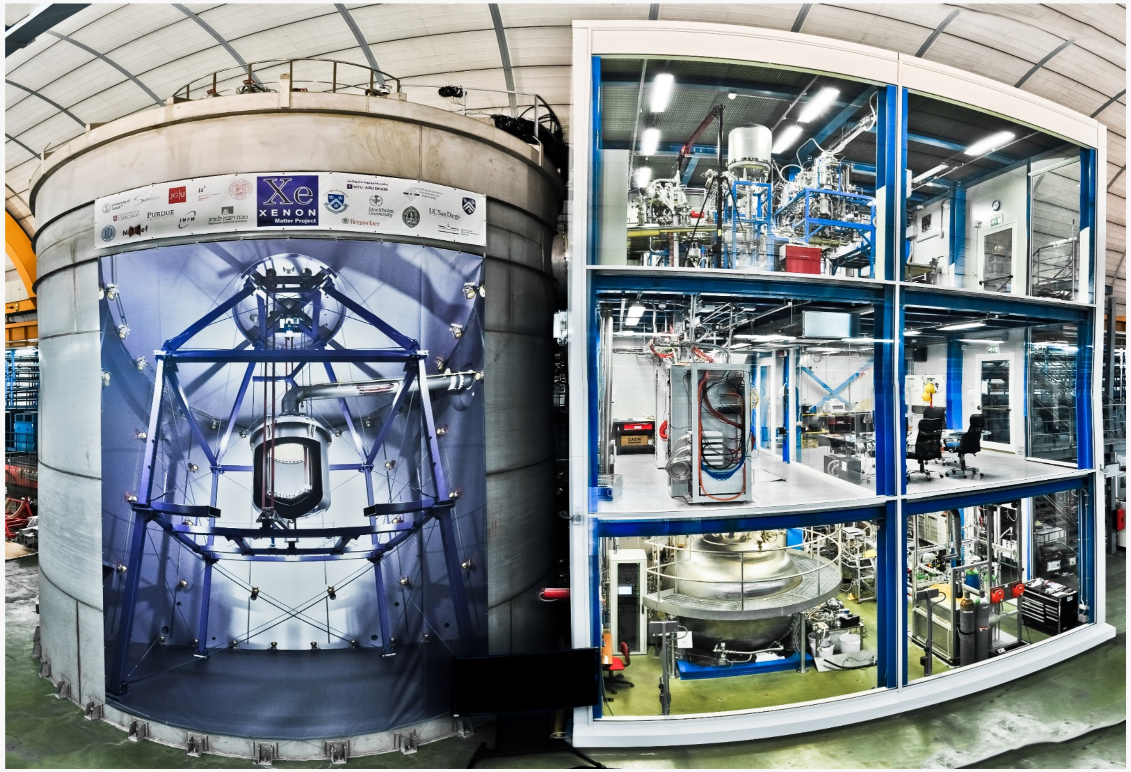
XENON1T → XENONnT

- x3 Larger target mass **(x4 fiducial mass**): lower material background, larger exposure
- Additional LXe purification: e-lifetime: **0.65 ms → ~15 ms**
- Radon distillation: ^{222}Rn suppressed to **< 1 μBq/kg**
- Triggerless data acquisition
- Open-source & faster processing software



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XENON Physics Program

WIMP Dark Matter

PRL 131, 041003
PRL 119, 181301
PRL 121, 111302

Light Dark Matter

PRL 123, 241803
PRL 123, 251801

Bosonic Dark Matter

PRD 102, 072004

Solar Axions

PRD 102, 072004

Solar ^{8}B CEvNS

PRL 126, 091301

Neutrino Magnetic Moment

PRD 102, 072004

Double Electron Capture

Nature 568, 532
PRC 106, 024328

Neutrinoless Double-Beta Decay

PRC 106, 024328
EPJC 80:785

$0\nu\beta\beta$ Search with XENON1T

XENON1T ^{136}Xe $0\nu\beta\beta$ search

- ~0.8% energy resolution at $Q_{\beta\beta}$
- $T_{1/2}^{0\nu\beta\beta} > 1.2 \times 10^{24}$ yr
- Main limitation: material background γ-rays

Detector Material γ-rays

Dominant background in ROI

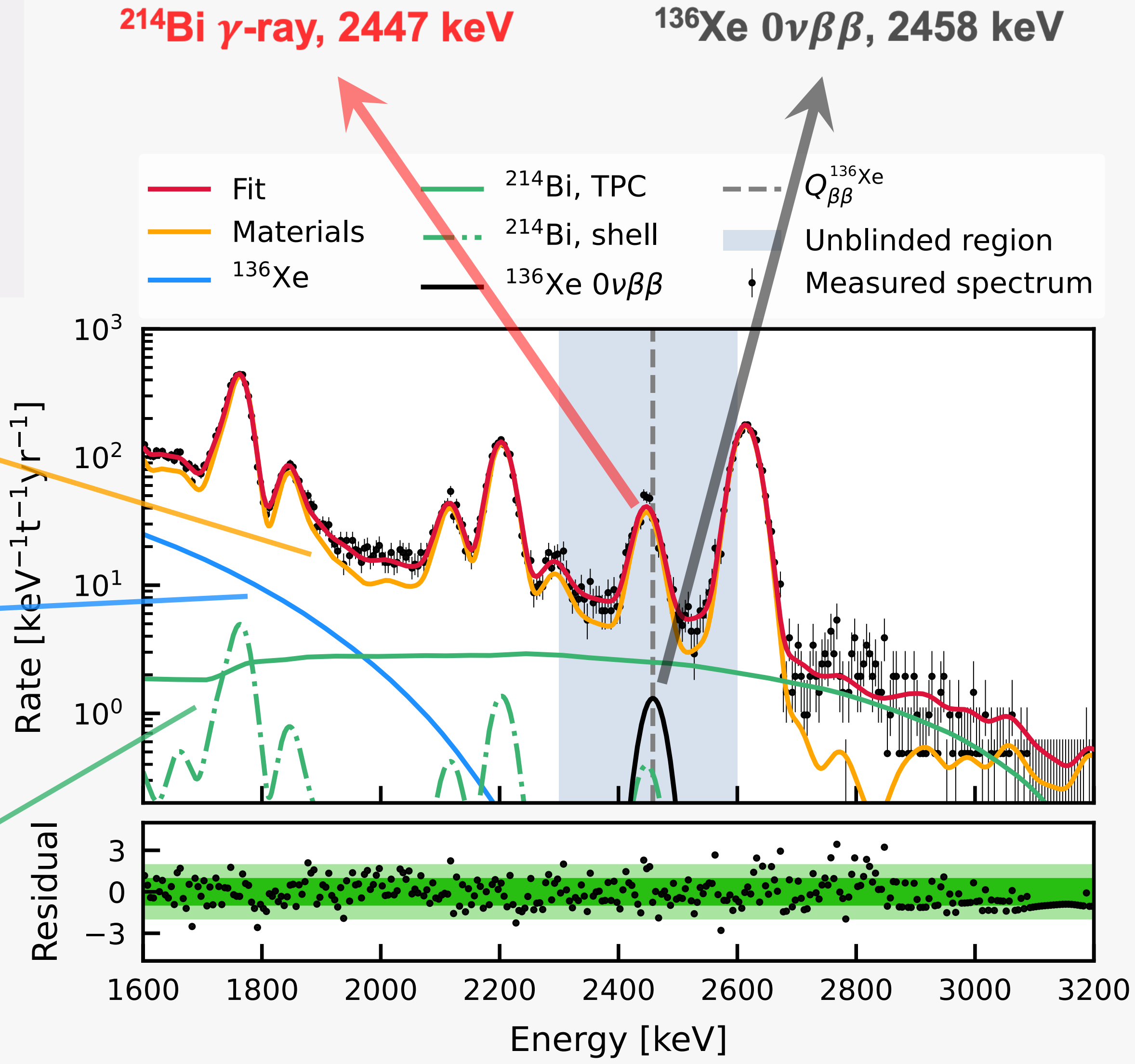
$2\nu\beta\beta$ of ^{136}Xe

Continuous spectrum ends at $Q_{\beta\beta}$, subdominant

^{214}Bi from ^{222}Rn emanation

TPC: Merged $\gamma + \beta$ signal from ^{214}Bi decay inside the active volume suppressed by ^{214}BiPo coincidence.

Shell: Decay of ^{214}Bi outside the active volume leads to additional γ -ray background.

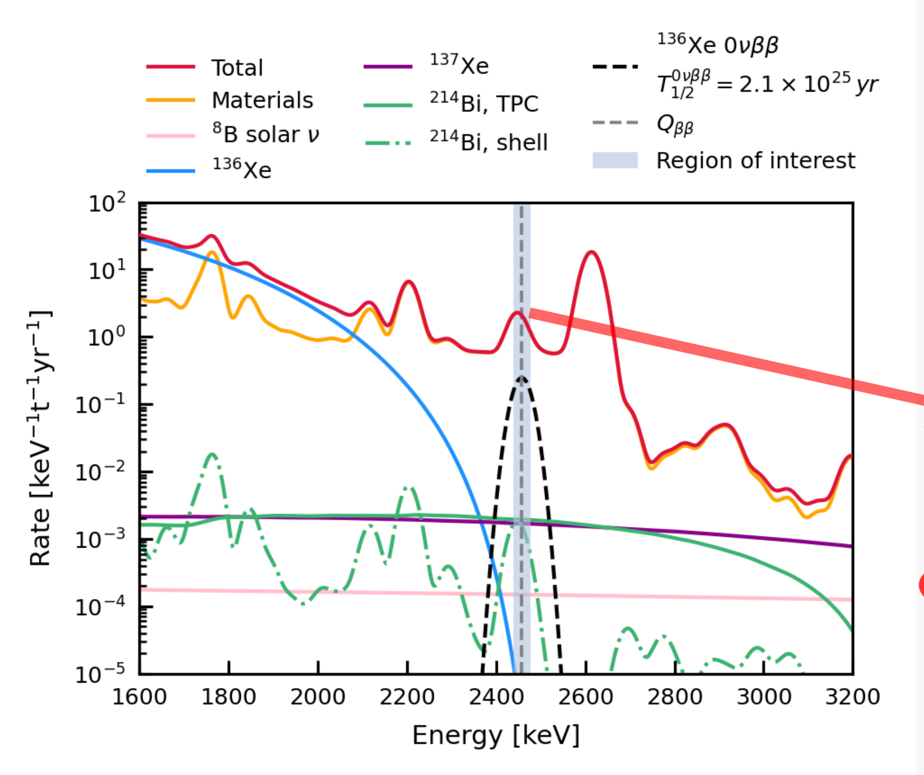


Phys.Rev.C. 106.024328, 2022

$0\nu\beta\beta$ Search with XENONnT

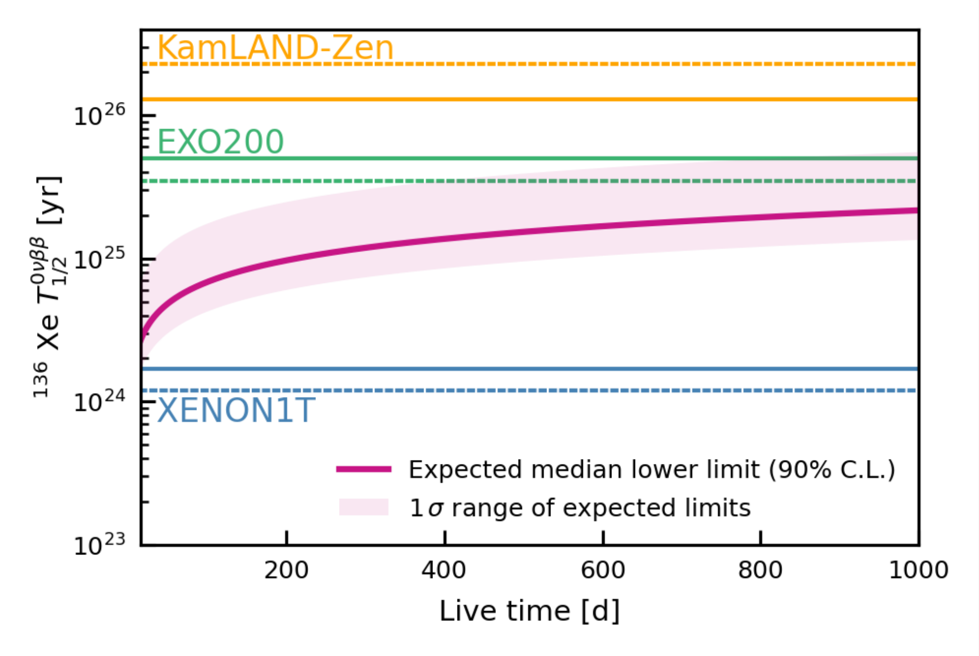
XENONnT ^{136}Xe $0\nu\beta\beta$ search

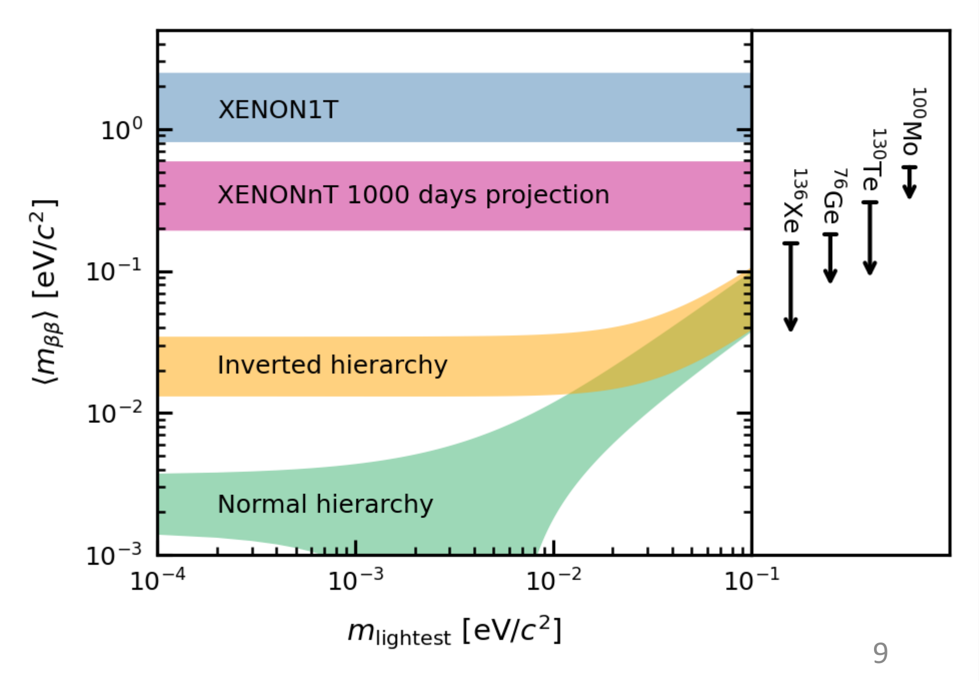
- Subpercent energy resolution at $Q_{\beta\beta}$
- Larger fiducial mass (5.9t active Xe, 8.9% ^{136}Xe)
- Lower material background level
- Expecting comparable sensitivity to EXO-200



Phys.Rev.C. 106.024328, 2022

Critical background
^{214}Bi γ-ray, 2447 keV

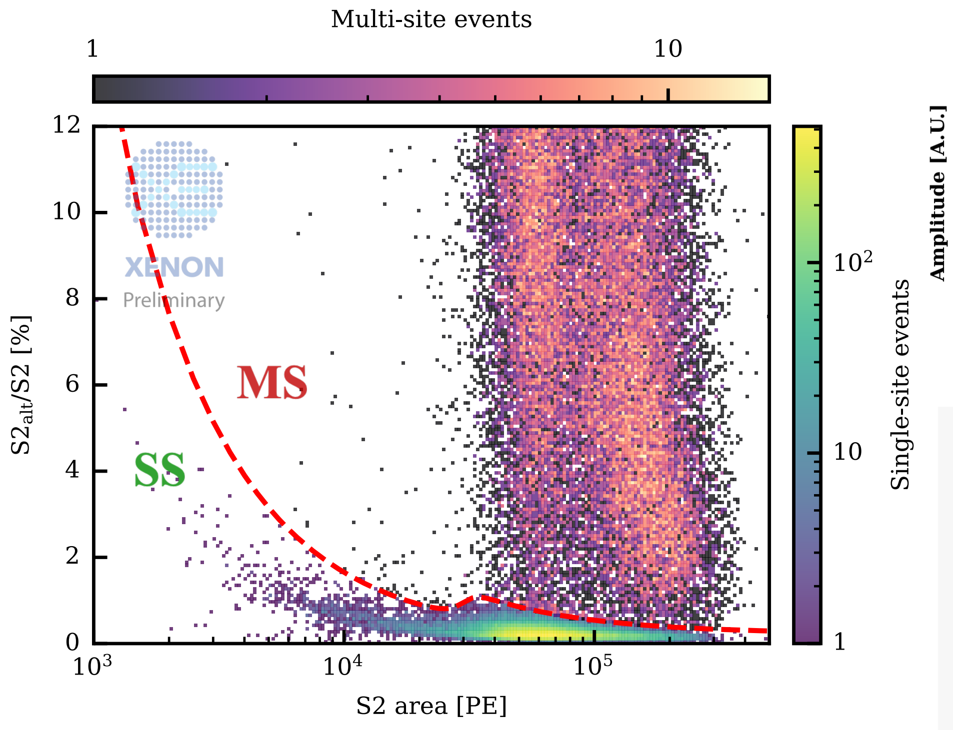


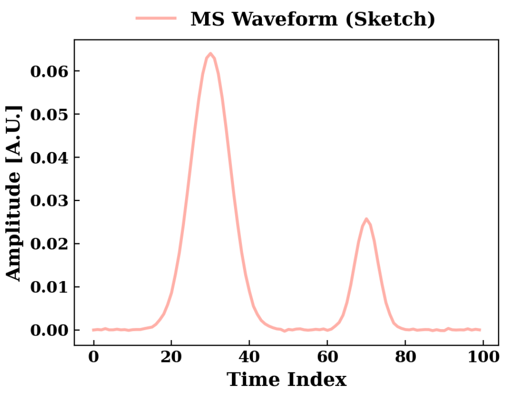


Tackle the Background with ML

Traditional Cut against Material γ-rays

- Hypothetical $\mathbf{0\nu\beta\beta}$ events mostly recorded as **single-site (SS)**
- **High energy γ-rays** more likely to be **multi-site (MS)** events
- Powerful for rejecting events with multiple S2s





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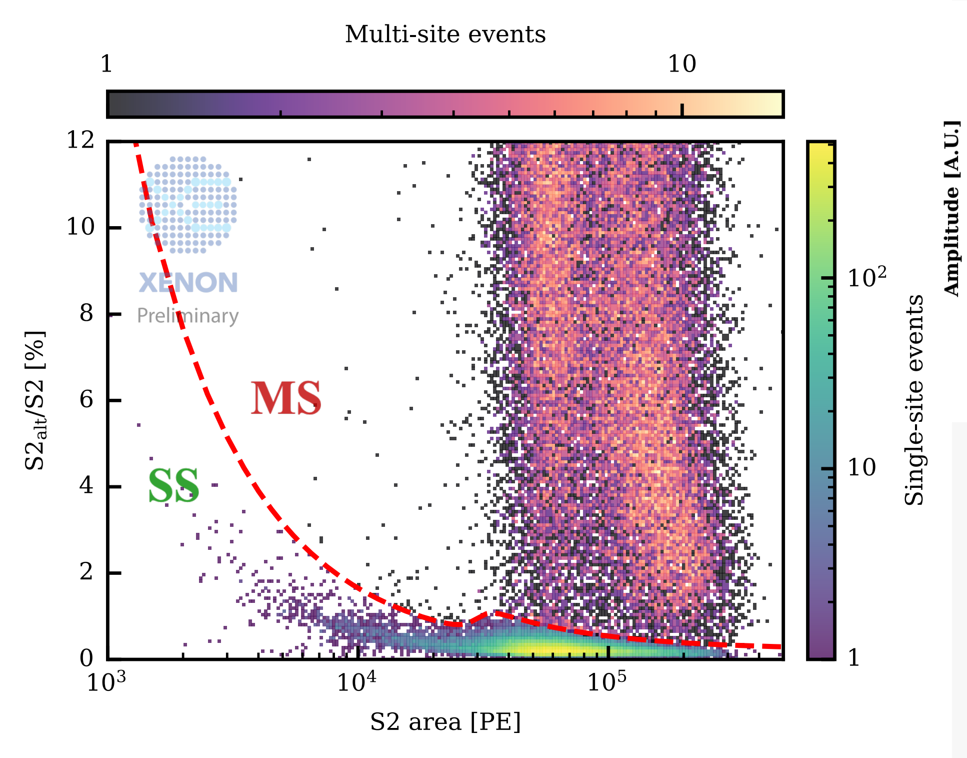
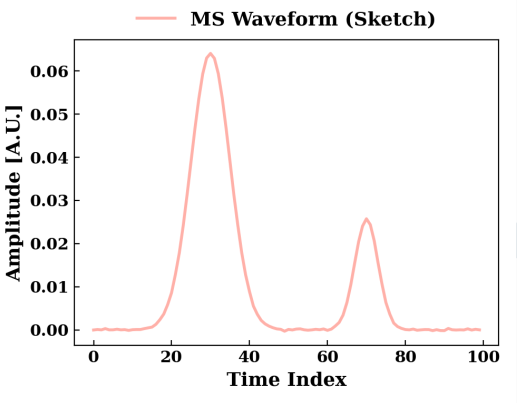
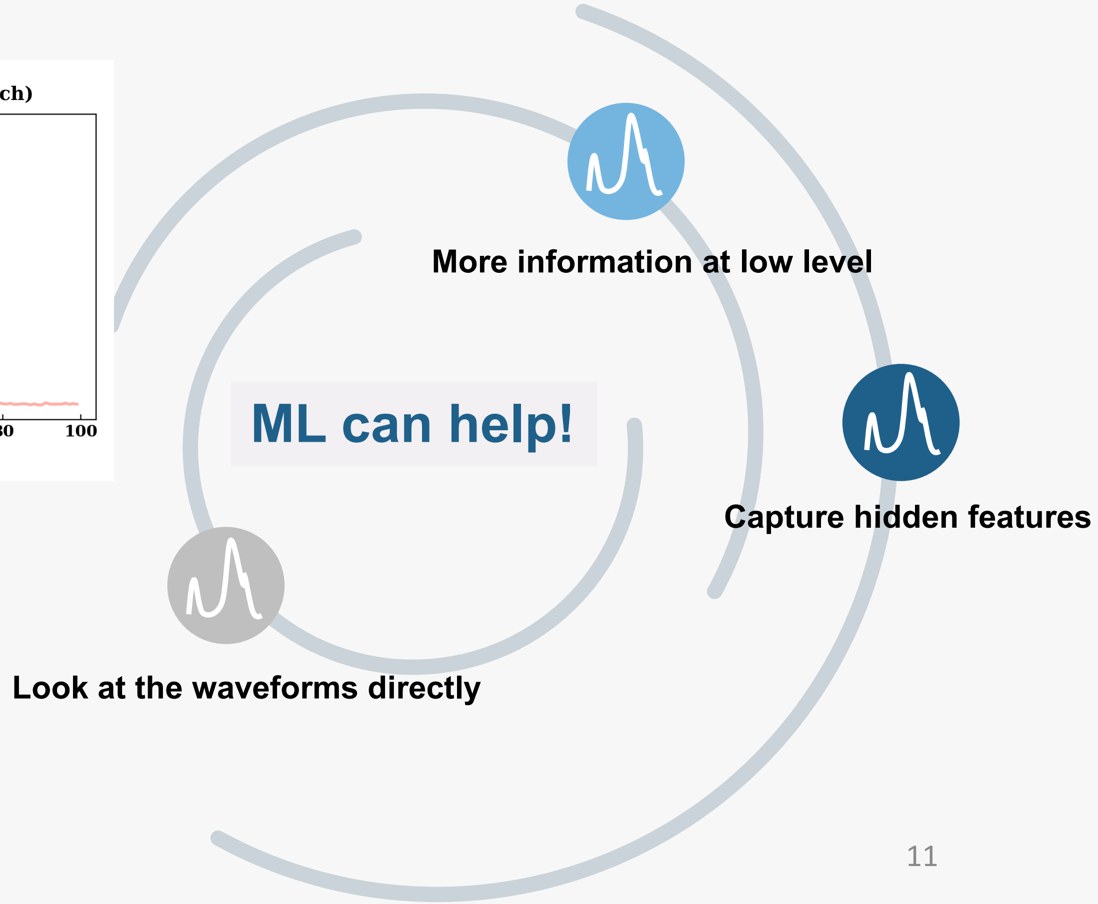
How about merged S2s?

- Events with only one dominant S2 signal
- **Difficult to be recognized by traditional cuts**







Inspiration: KamNet

KamLAND-Zen:

Xenon-loaded liquid scintillator for ^{136}Xe $0\nu\beta\beta$ search

World-leading limit on $0\nu\beta\beta$ half-life:

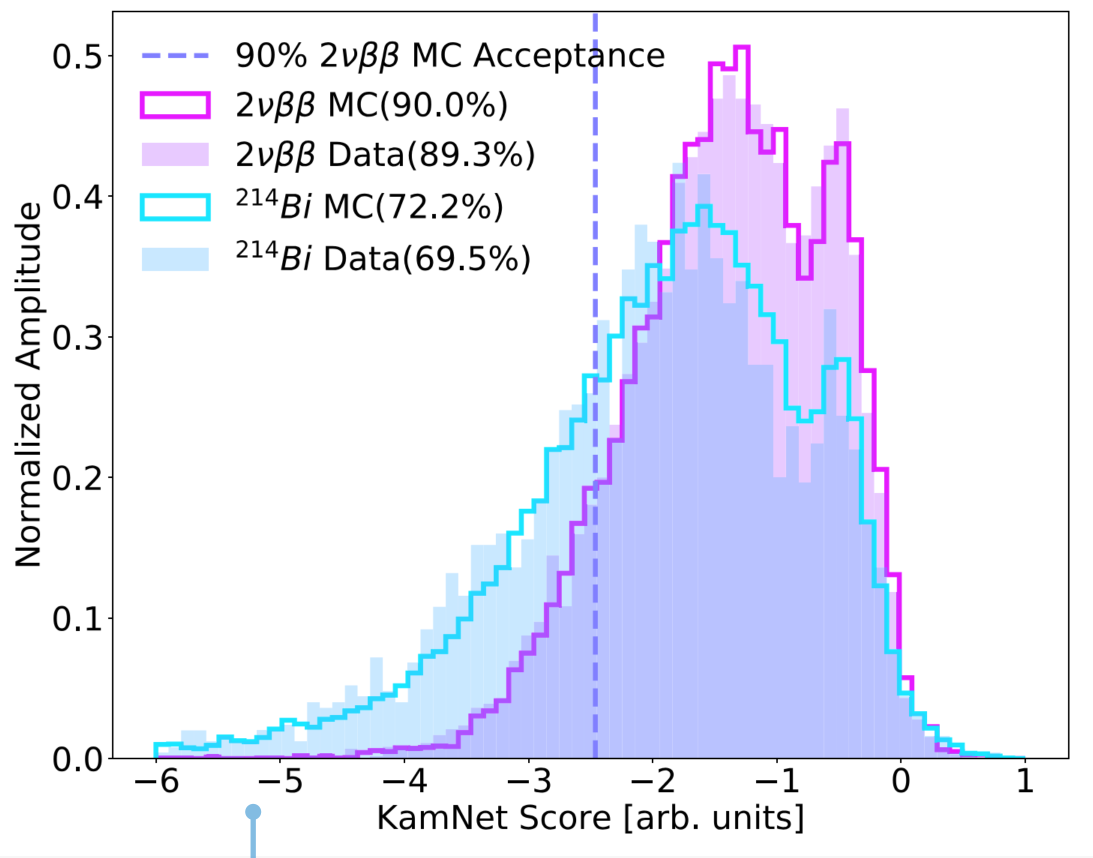
$T_{1/2}^{0\nu\beta\beta}$ > 2.3 x 10^{26} yr

KamNet: Spatiotemporal Deep Neutral Network

- KamLAND-Zen data is spatiotemporal (3D series)
- Rotational symmetry and temporal symmetry utilized
- Attention mechanism introduced

Sensitivity Boost

20/35% sensitivity boost based on background modeling



Phys.Rev.C. 107.014323, 2023

What can we do with XENONnT?

We don't have easily accessible spatiotemporal data

PMT signals are stored as 2D (hit patterns) and 1D (waveforms) data

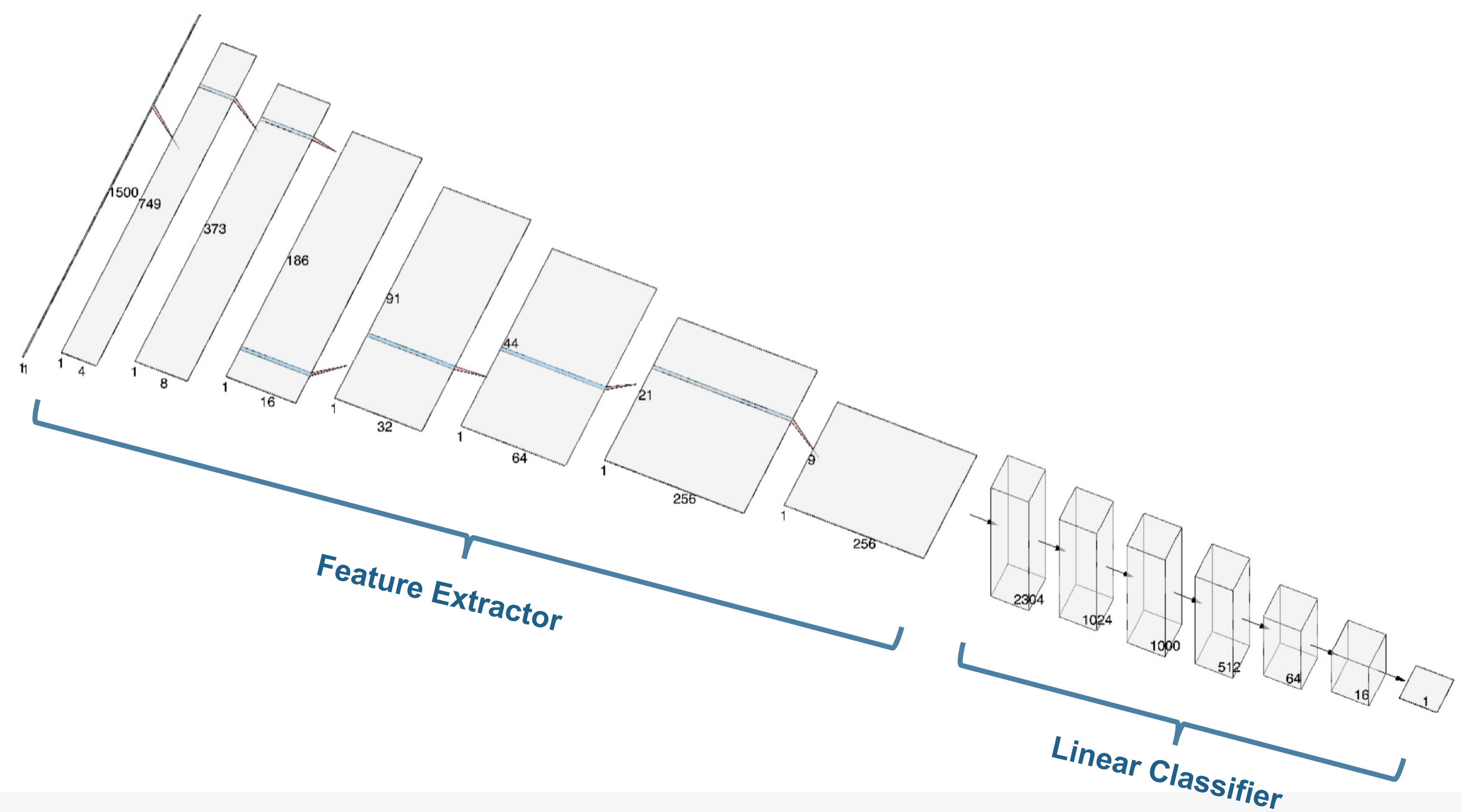
Powerful Classification

~30% background (^{214}Bi) rejection at 90% signal acceptance

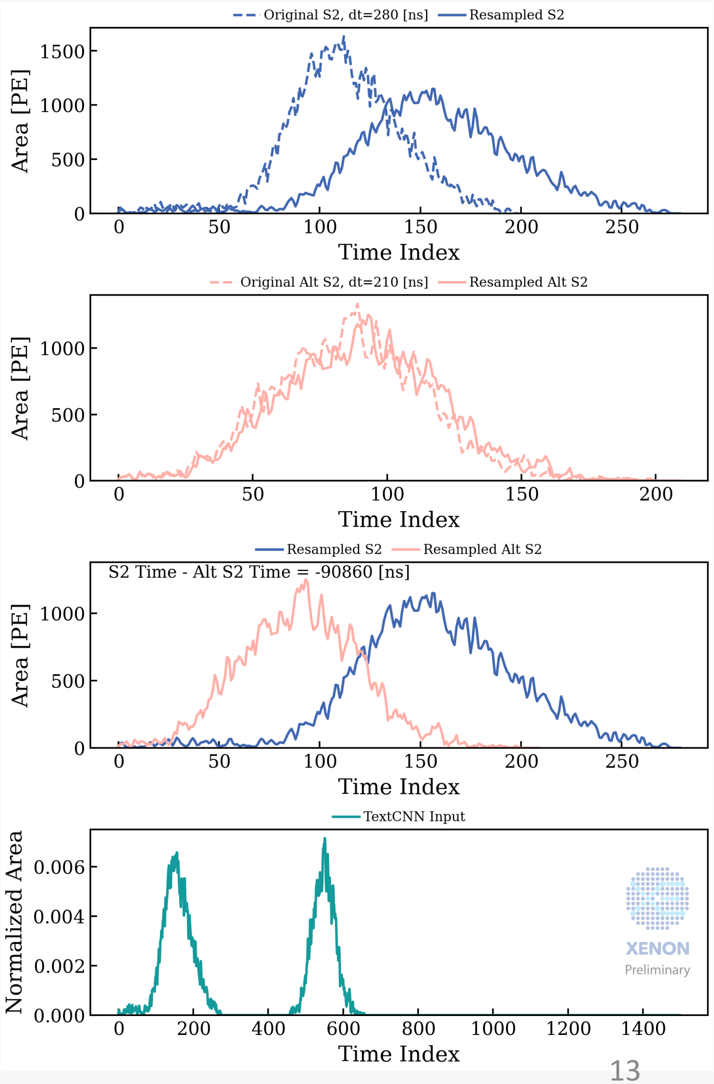
TextCNN Structure

TextCNN for 1D Time-series

- **Feature Extractor:** convolutional layers + activation layers + pooling layers + …
- **Linear Classifier:** gather features and make decision



Example Input Waveform



TextCNN Performance

Trained with 0-4 MeV e^{-} / γ:

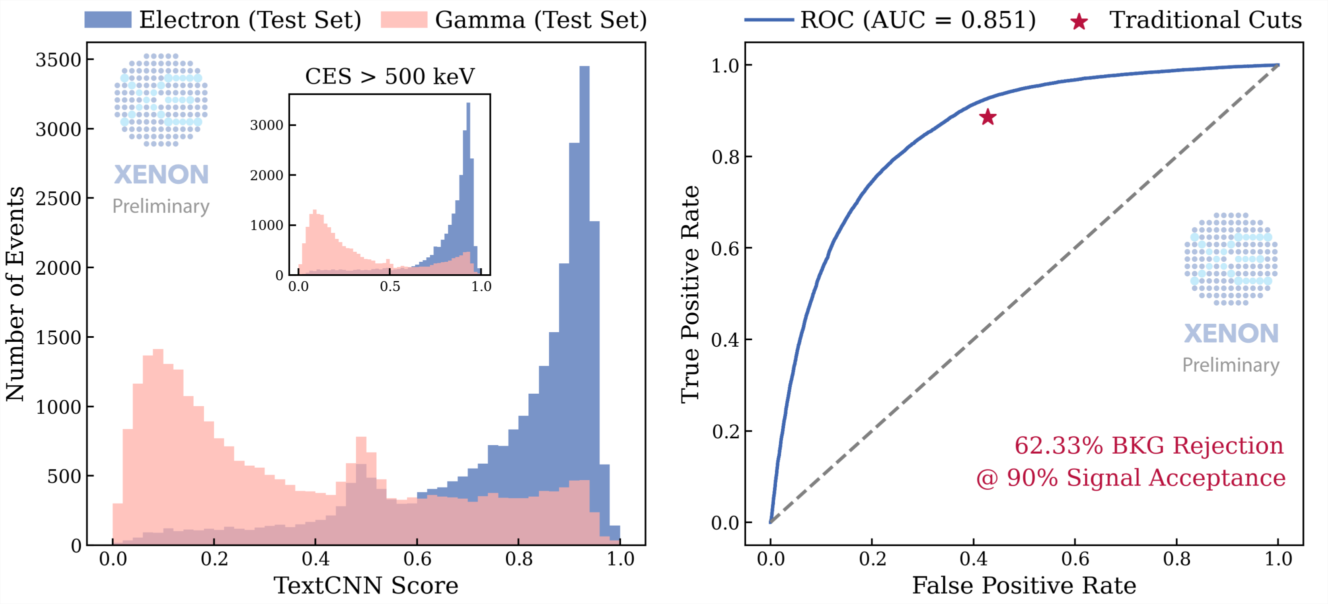
Uniform in energy and position

Outperforming traditional cuts

Rejecting > 60% background at 90% signal acceptance

Unique classification power

Rejecting > 40% background after traditional cuts



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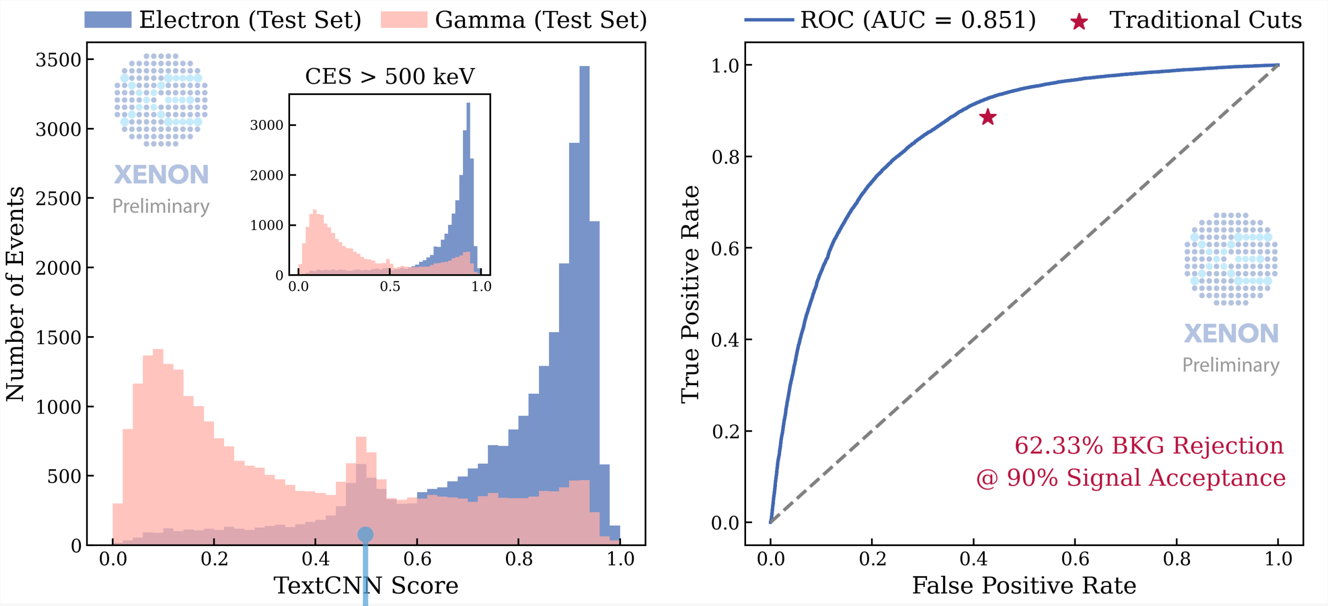

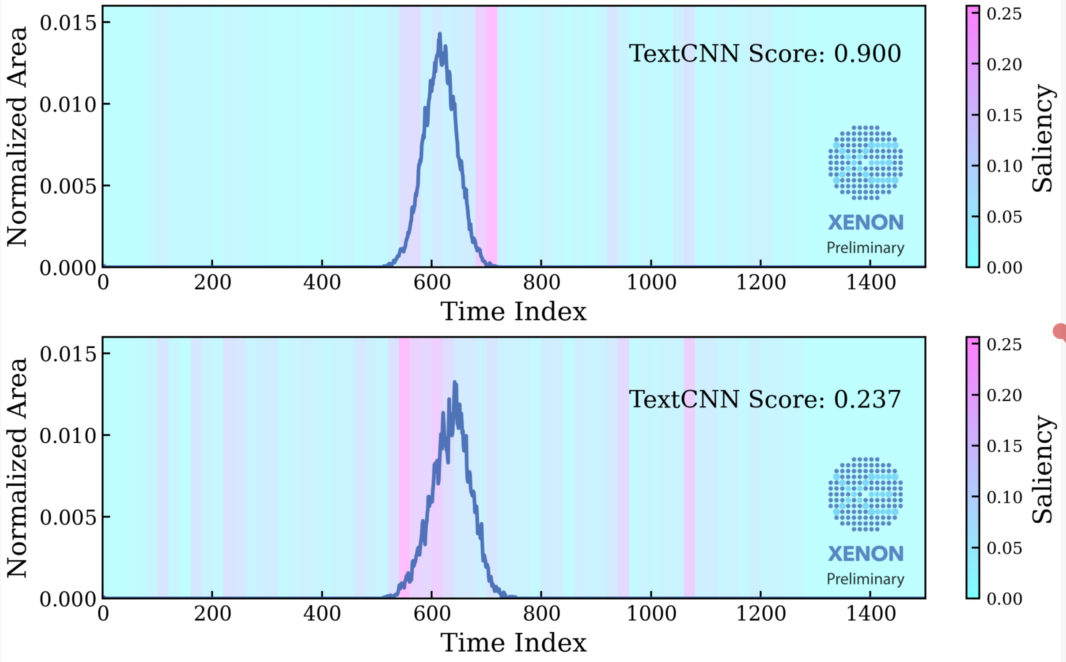

Faithful Classification

The TextCNN score is ~0.5 when the model has difficulty distinguishing between e^- and γ

Interpretability study with saliency map

The model is mostly looking at the rising / falling edges of the waveforms

Data-MC Matching w/ Augmentation

What is data augmentation?

- Apply various transformations to the original data
- Increase the size and diversity of the dataset

Why do we need augmentation?

- Account the mismodeling of the MC
- Make the model more **robust** and **adaptable**

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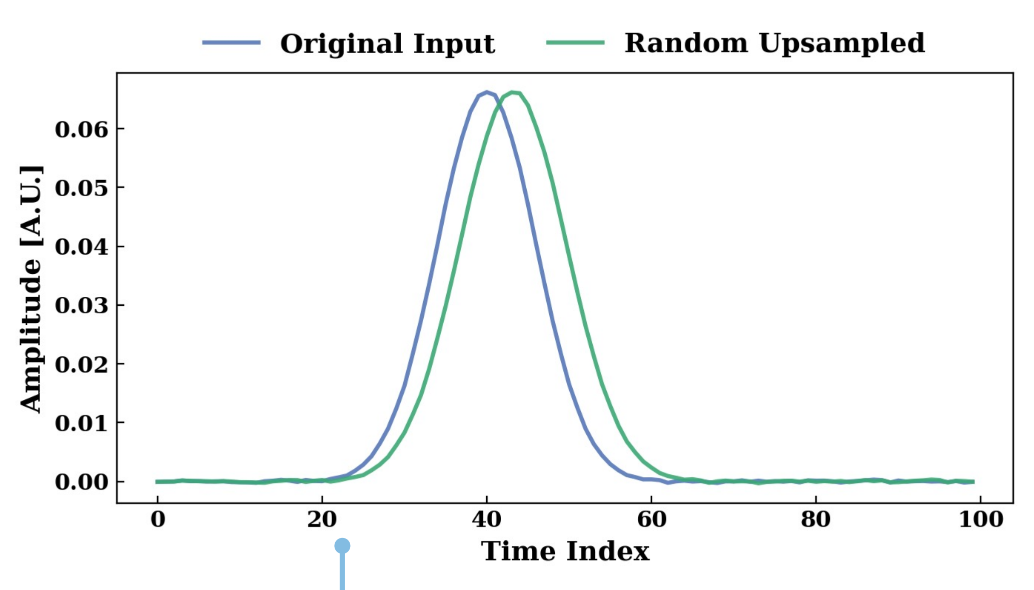
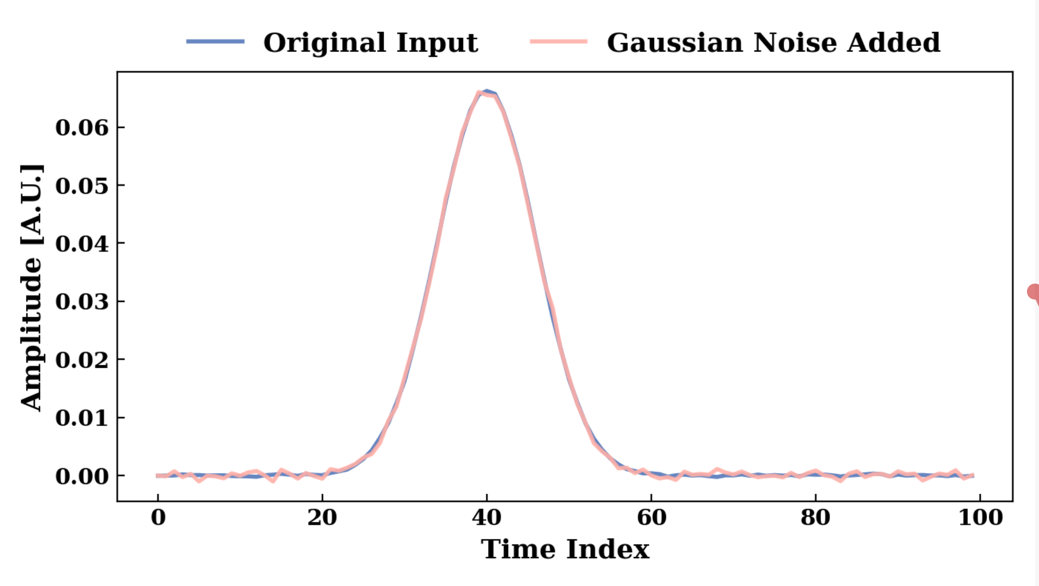


Random Upsampling

Account the mismodeling of the MC (mostly the S2 width)



Random Gaussian Noise

Erase energy information, increase adaptability and stability at different energies

Results & $0\nu\beta\beta$ Sensitivity Boost

Matching Strategy

- e^-: ^{136}Xe $2\nu\beta\beta$ (undistinguishable from $0\nu\beta\beta$)
- γ: ^{208}Tl (2614.5 keV γ peak)
- $e^- + \gamma$: ^{212}Pb (from ^{220}Rn calibration)

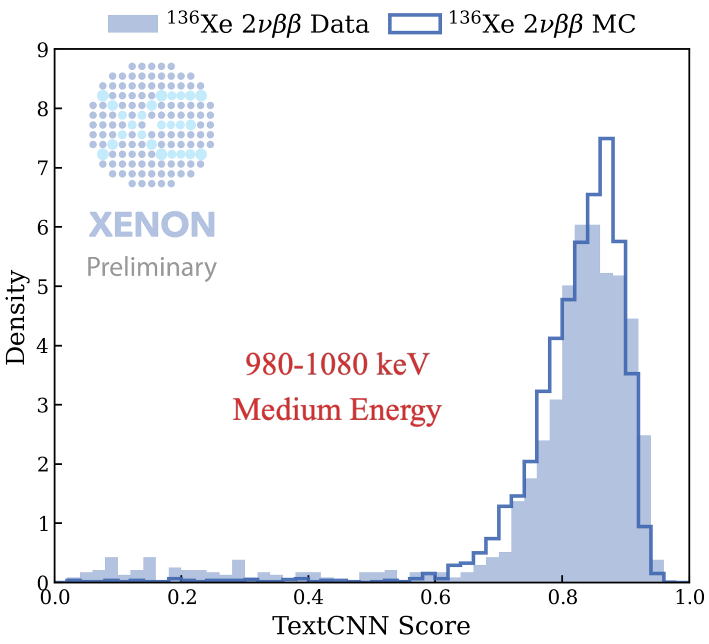
Preliminary Matching Result

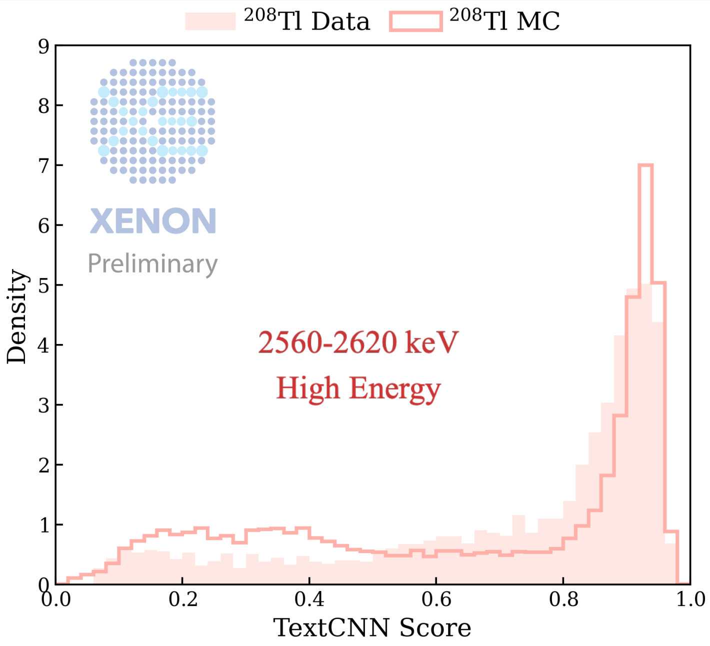
Three event categories matched

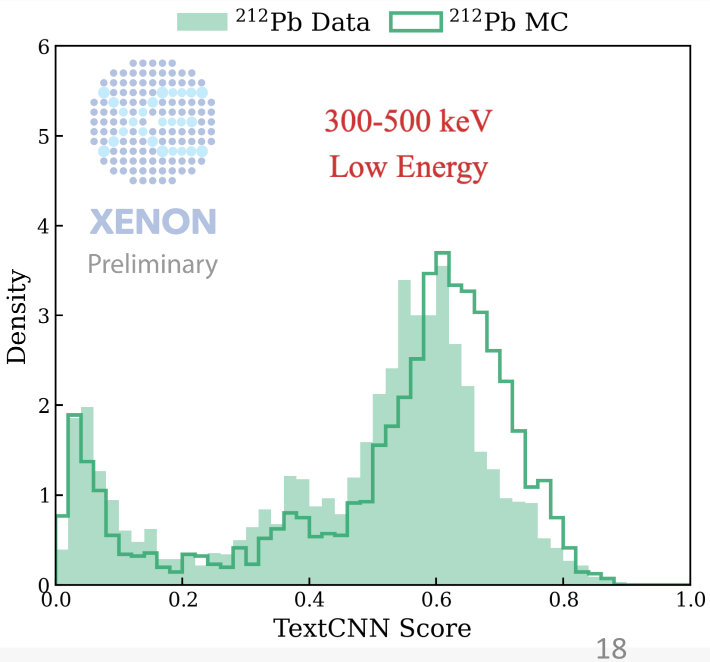
- e^-, γ, $e^- + \gamma$

Wide energy range matched

- Min 300 keV, Max 2.6 MeV







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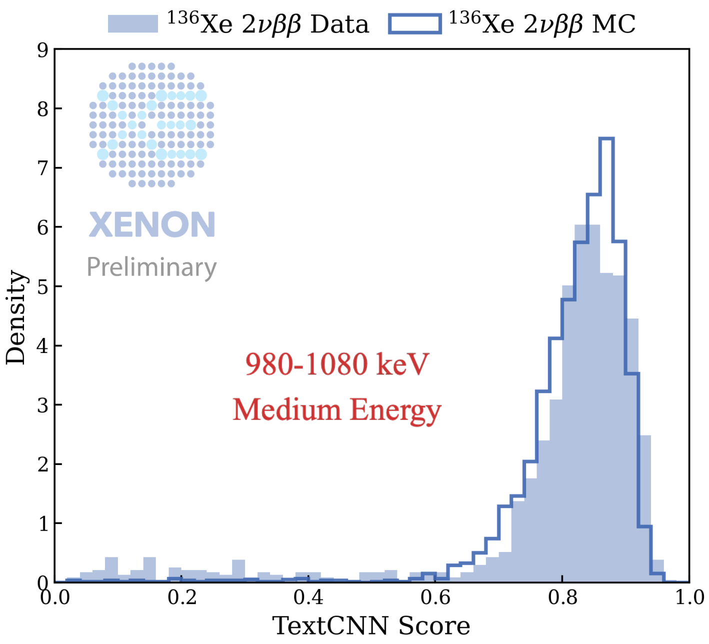

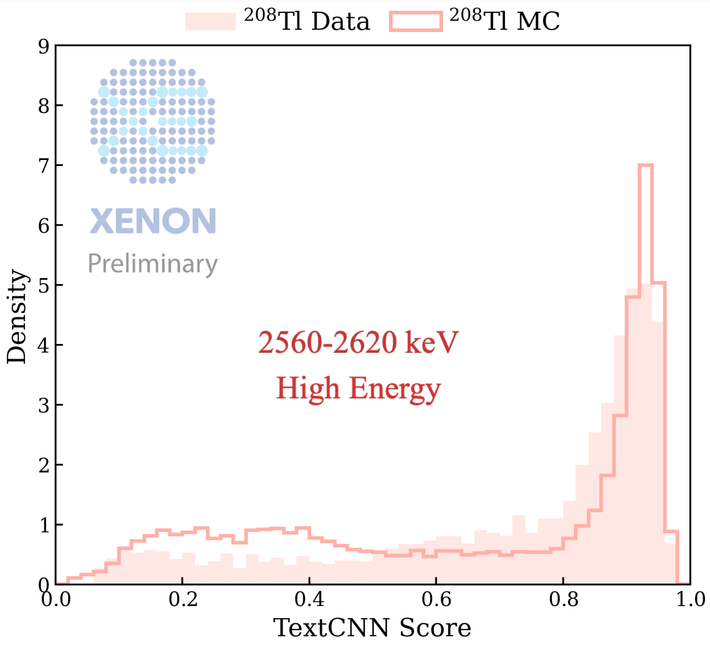

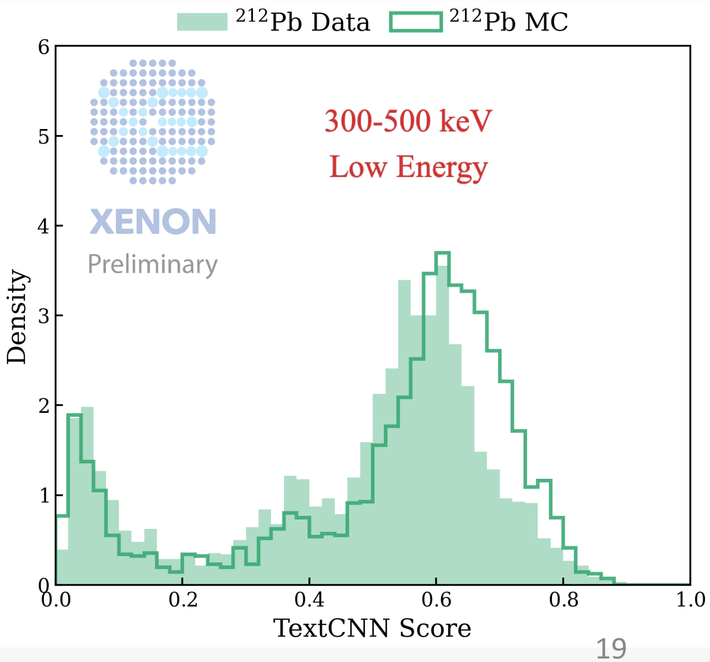

$0\nu\beta\beta$ Sensitivity Boost

Very preliminary ^{136}Xe $0\nu\beta\beta$ sensitivity boost based on counting experiment assumption

Model	Background Suppression	Fiducial Volume Expansion	Actual Boost
TextCNN	28.4%	27.5%	?
KamNet	2.2%	8.5%	20/35%

Very Preliminary

Phys.Rev.C. 107.014323, 2023

Phys.Rev.Lett. 130.151801, 2023

Summary and Outlook

$0\nu\beta\beta$ with XENONnT

Good sensitivity to $0\nu\beta\beta$ decays

High energy resolution, low background and large fiducial mass

Material background γ-rays dominant at $Q_{\beta\beta}$

Traditional cuts can help but have limitation

TextCNN Model Development

Utilize waveforms to decode more information

Great and unique classification power against background

Promising $0\nu\beta\beta$ sensitivity boost

Stay tuned!

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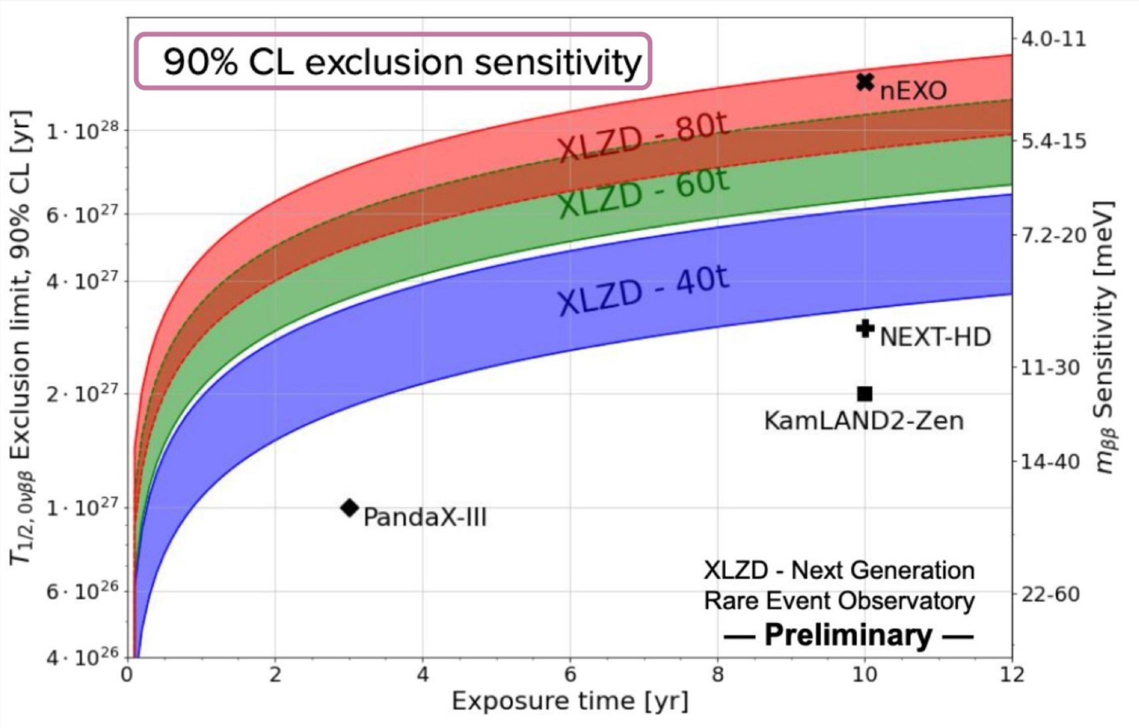


Alvine's talk on behalf of XLZD

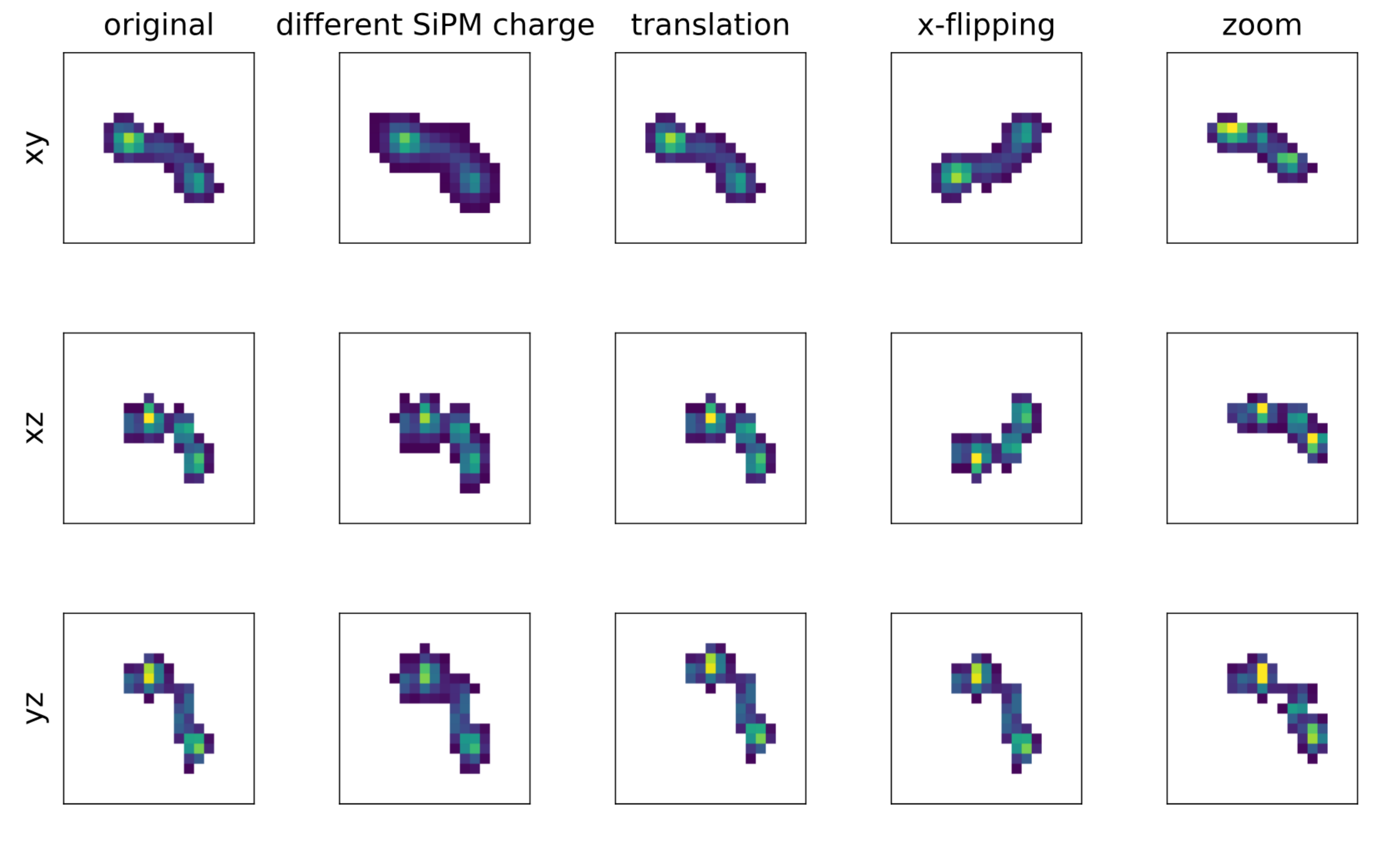
What's the future?

- Future LXe dark matter experiment (eg. XLZD) has larger fiducial mass
- Comparable sensitivity to that of $0\nu\beta\beta$ dedicated next-generation experiments
- **Machine learning can boost it further!**

TextCNN, Spatiotemporal Networks, …

Thanks for listening!

Backup: Augmentation in NEXT



JHEP01(2021)189,10.1007