Neutrinoless Double Beta Decay with PandaX

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For the PandaX Collaboration

2025/1/20

Outline

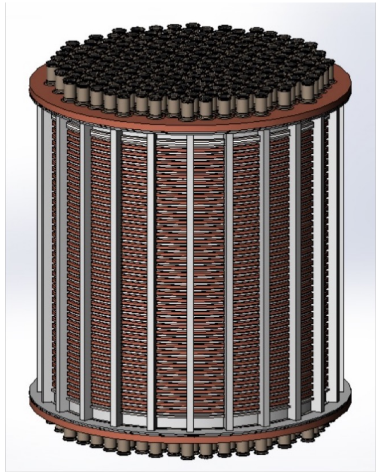
1. Introduction to PandaX and liquid xenon TPC
2. PandaX-4T ^{134}Xe 2νββ (0νββ) results
3. PandaX-4T ^{136}Xe 0νββ limits
4. PandaX-4T ^{136}Xe 2νββ half-life measurement and spectrum fit
5. Future: PandaX-xT

PandaX: Particle and astrophysical Xenon Experiment

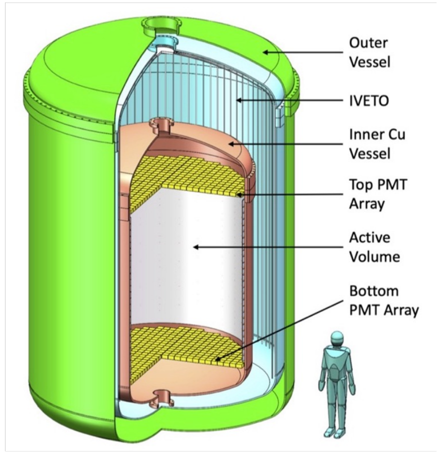
PandaX detectors

PandaX-I: 120kg LXe (2009 – 2014)

PandaX-II: 500kg LXe (2014 – 2018)

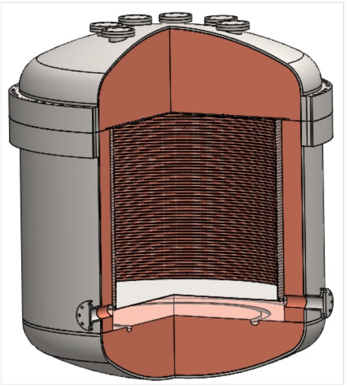


PandaX-4T LXe (2020-)



PandaX-xT LXe (future)

PandaX-III: 100kg - 1 ton HPXe for $0\nu\beta\beta$ (future)

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Underground Laboratory
China
Beijing
北京
Tianjin
天津
Jinan
济南市
Dalian
大连市
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평양
South Korea
Japan
Tokyo
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Osaka
大阪
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East China Sea
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酒泉市
Yinchuan
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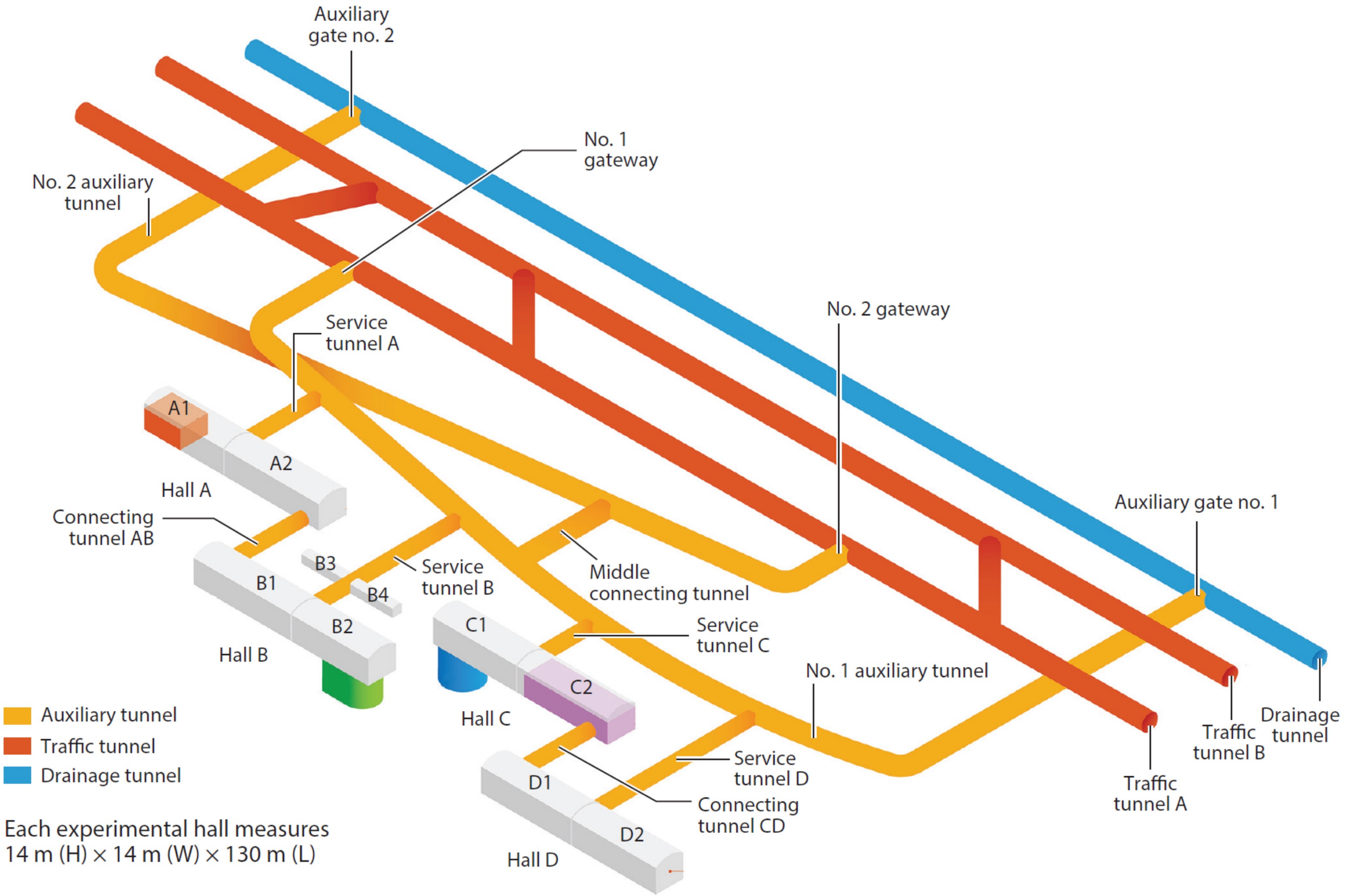
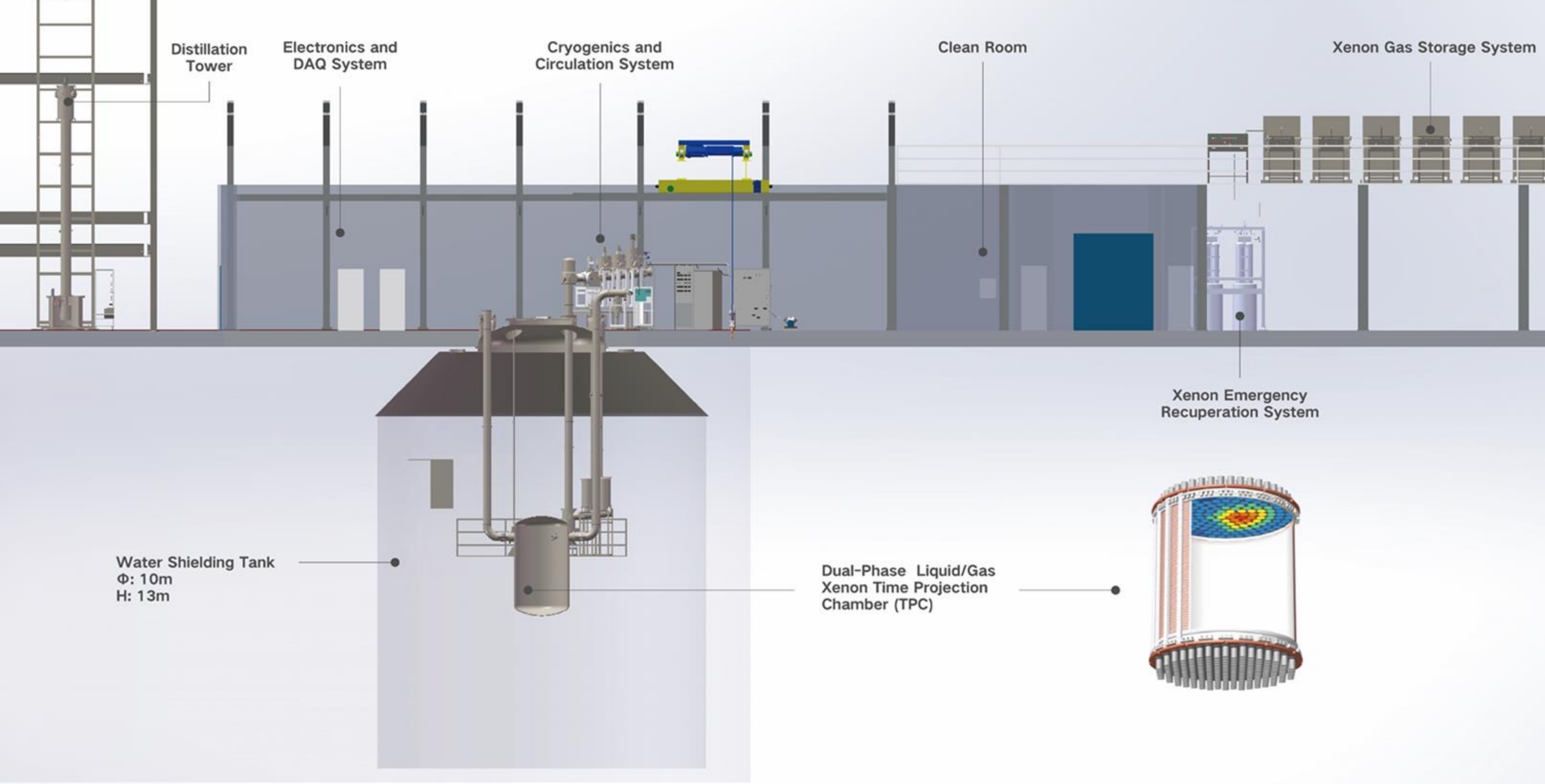
FUJIAN
Kunming
昆明市
YUNNAN
GUANGXI
GUANGDONG
Hong Kong
香港
Myanmar
(Burma)
Hanoi
Haiphong
2430m
8750m

CJPL-II



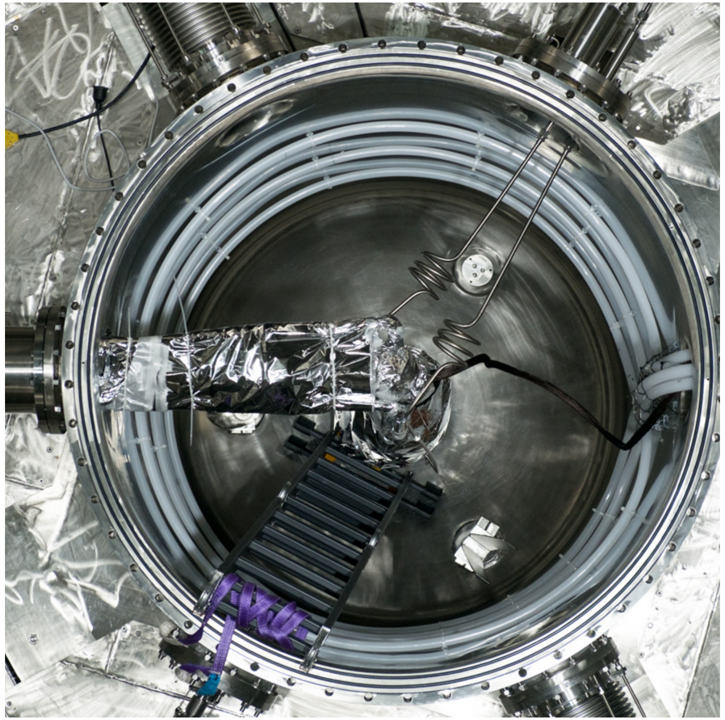
Each experimental hall measures 14 m (H) × 14 m (W) × 130 m (L)

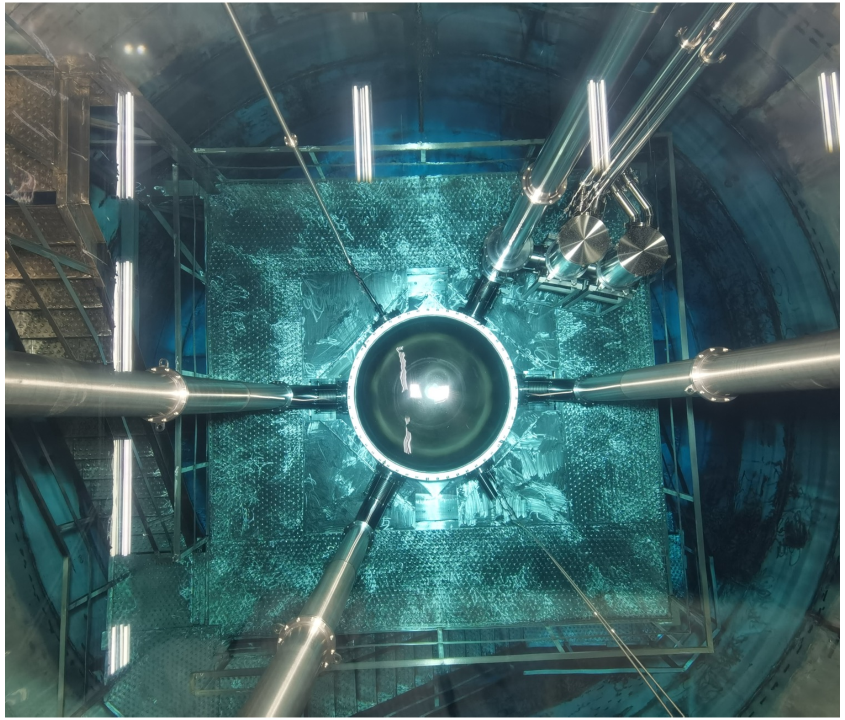
PandaX-4T @ Hall B2 of CJPL-II



PandaX-4T

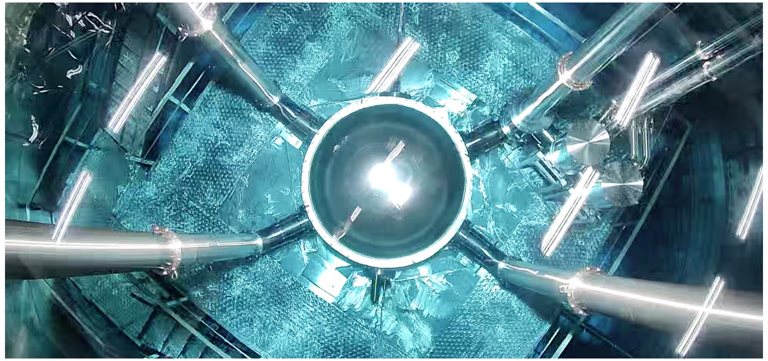
- A multi-ton dual-phase xenon TPC at B2 hall of China Jinping Underground Laboratory
- 1.2 m (D) ×1.2 m (H); Sensitive volume: 3.7-ton LXe; 3-inch PMTs: 169 top / 199 bottom
- Water shielding





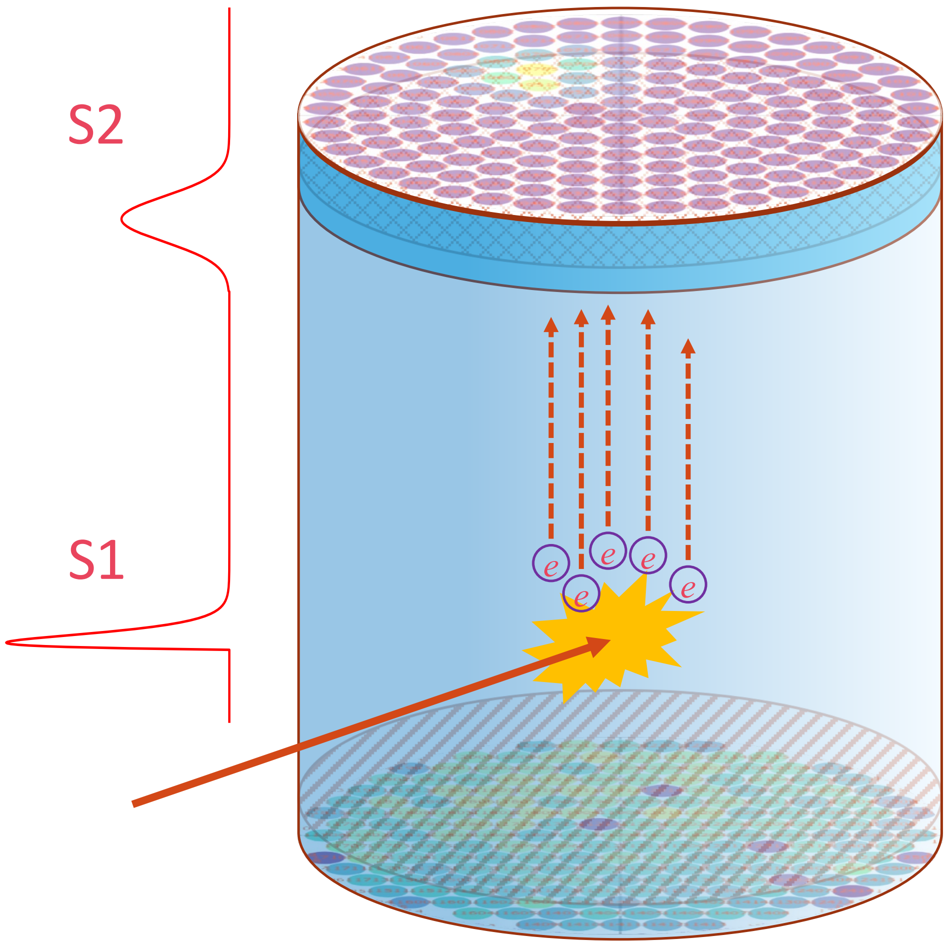
PandaX-4T timeline

2020/11 – 2021/04	**Commissioning (Run 0)** 95 days data
2021/07 – 2021/10	**Tritium removal** xenon distillation, gas flushing, etc.
2021/11 – 2022/05	**Physics run (Run 1)** 164 days data
2022/09 – 2023/12	**CJPL B2 hall construction** xenon recuperation, detector upgrade
Detector is taking Run 2 data	

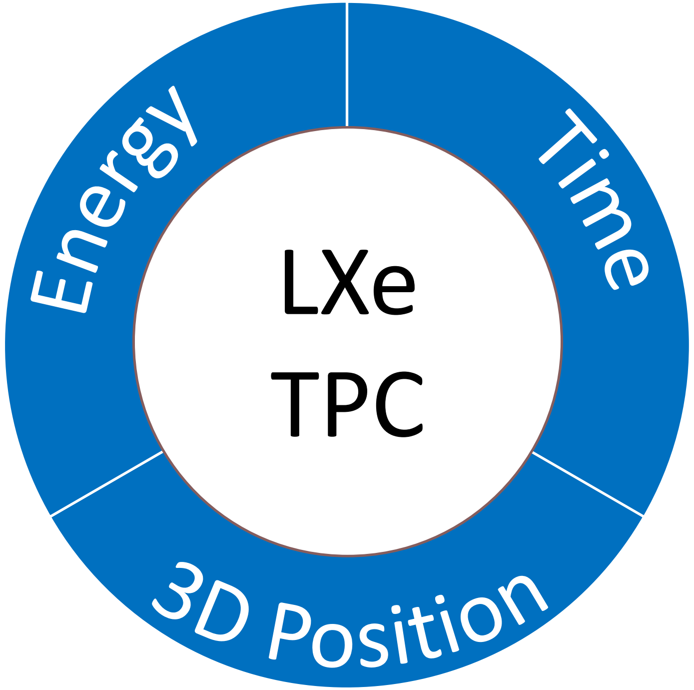


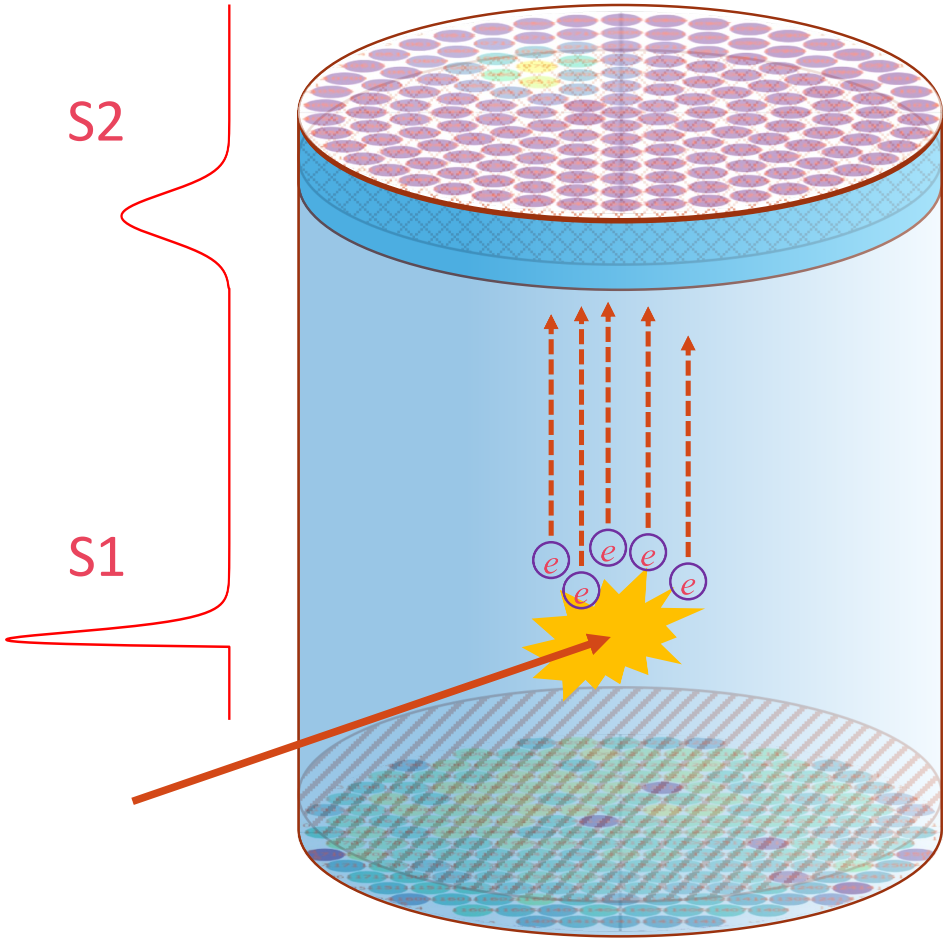
Liquid Xenon Time Projection Chamber (LXe TPC)

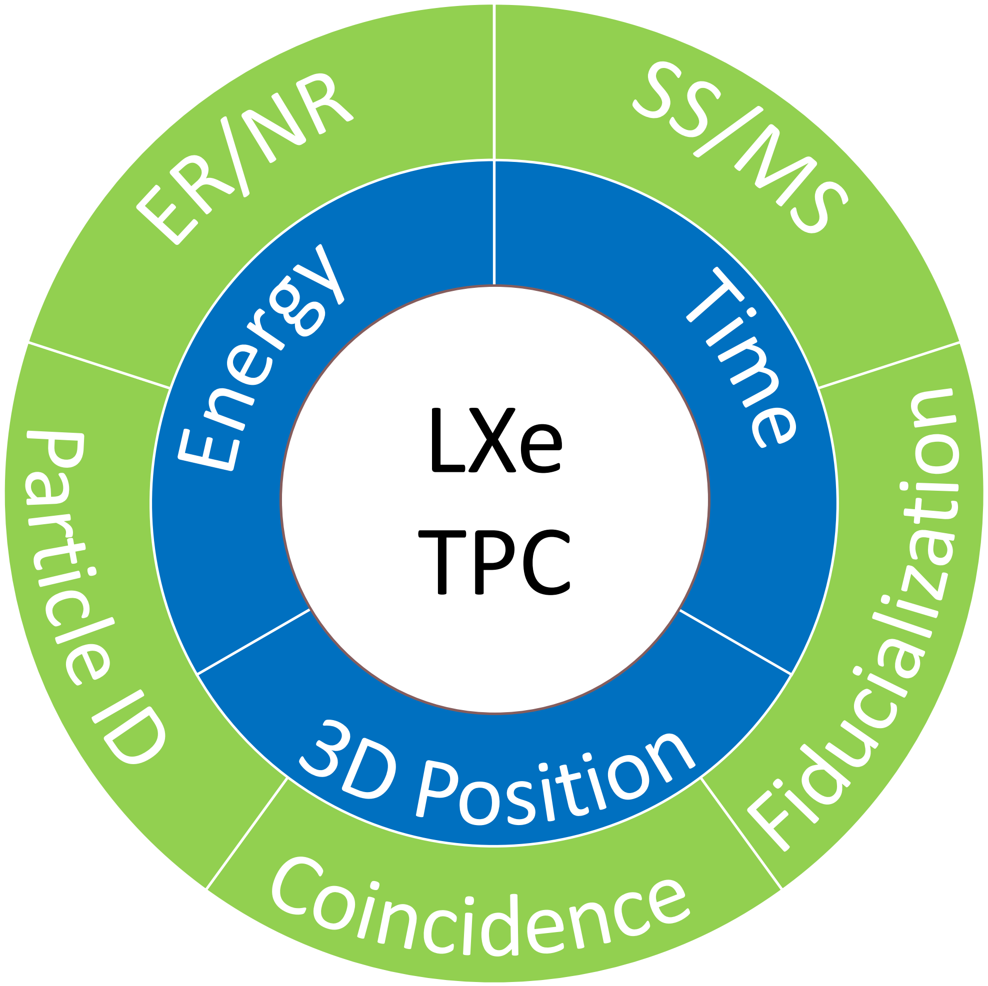
- Prompt scintillation signal (S1) followed by drift electron signal (S2)
- Measures the 3D position, energy, and time
- Nuclear Recoil (NR) and electron recoil (ER) discrimination
- Single-site (SS) and multi-site (MS) event discrimination
- Large monolithic target: High signal efficiency and effective self-shielding

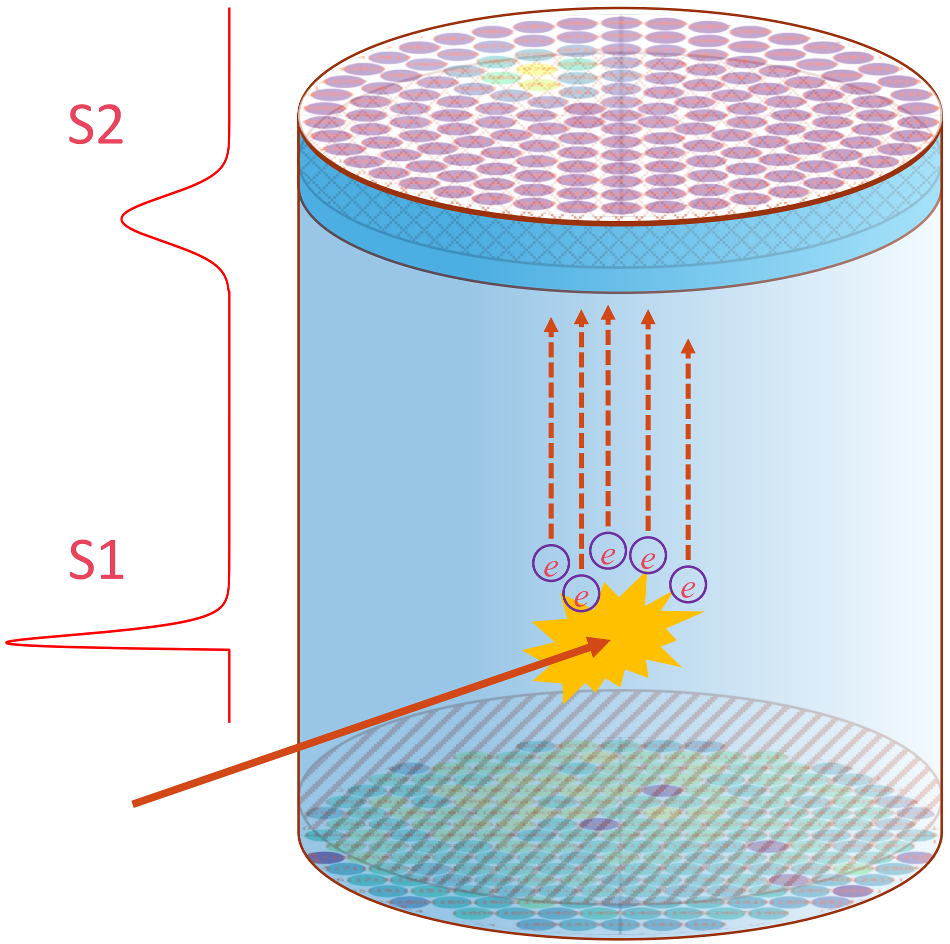


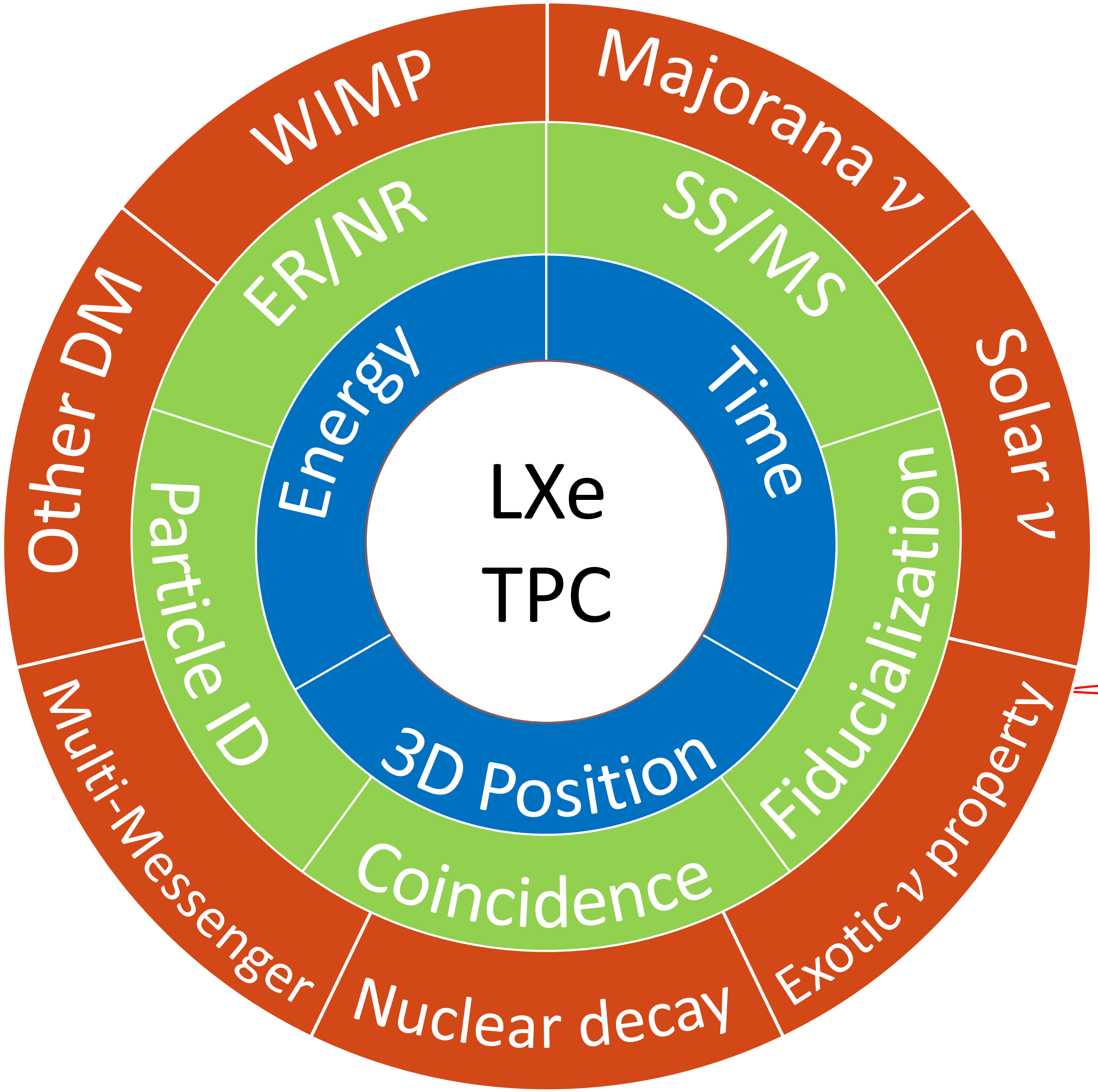
- LXe TPC as a Total-Absorption 5D Calorimeter

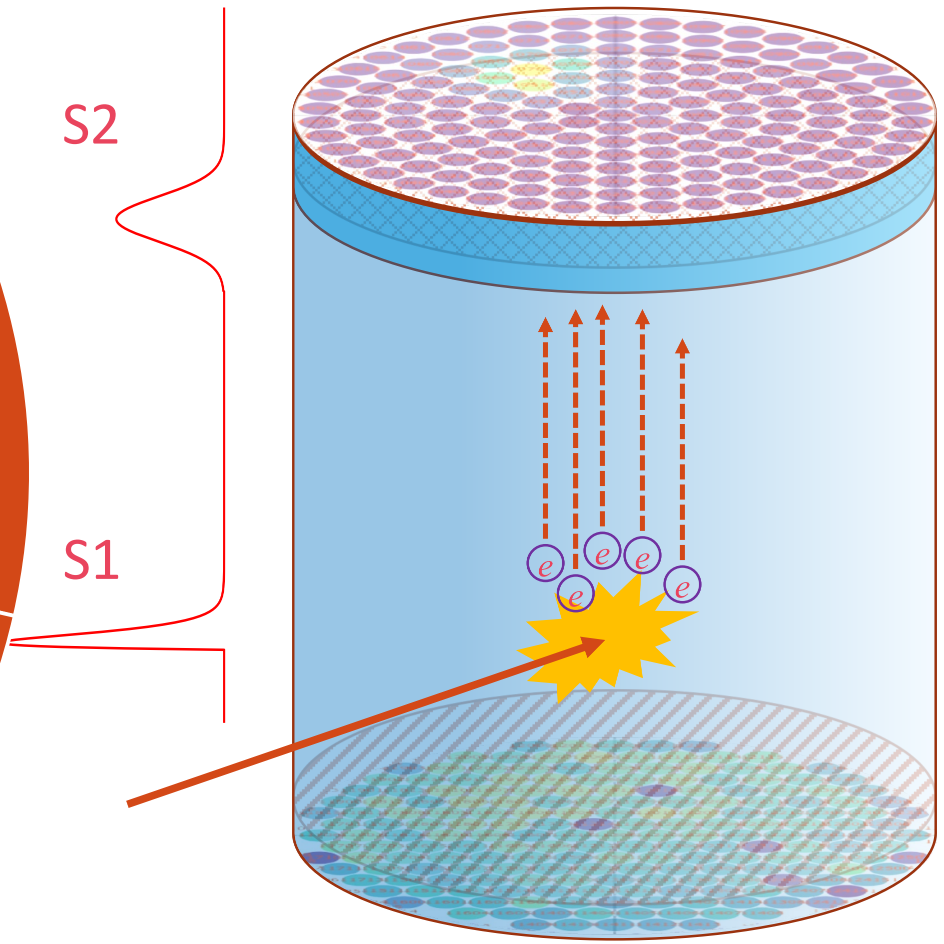

Energy
Time
3D Position
LXe
TPC


S2
S1

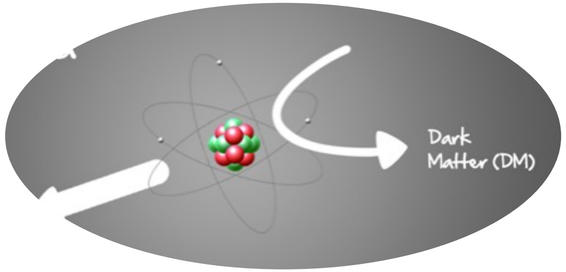

LXe
TPC
Energy
Time
3D Position
ER/NR
SS/MS
Fiducialization
Coincidence
Particle ID


S2
S1
e


LXe
TPC
Energy
Time
3D Position
ER/NR
SS/MS
Particle ID
Fiducialization
Coincidence
WIMP
Majorana ν
Solar ν
Other DM
Multi-Messenger
Nuclear decay
Exotic ν property


S2
S1
e

Multiple physics goals in one detector



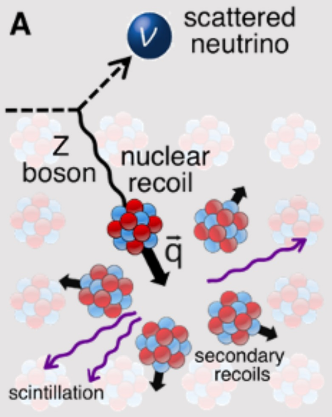
keV | 10 keV | 100 keV | 1 MeV

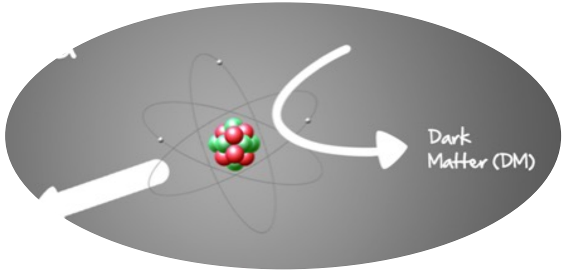
WIMP signals

- Large target mass
- Great energy threshold
- NR and ER discrimination

Multiple physics goals in one detector

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC





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CEνNS (NR)

- Large target mass
- Better energy threshold
- NR and ER discrimination

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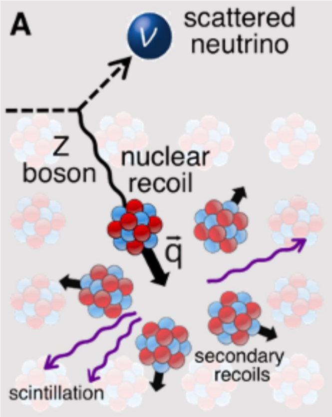
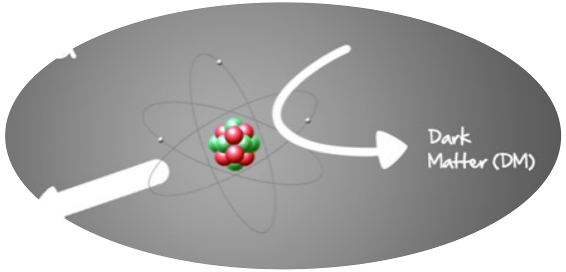
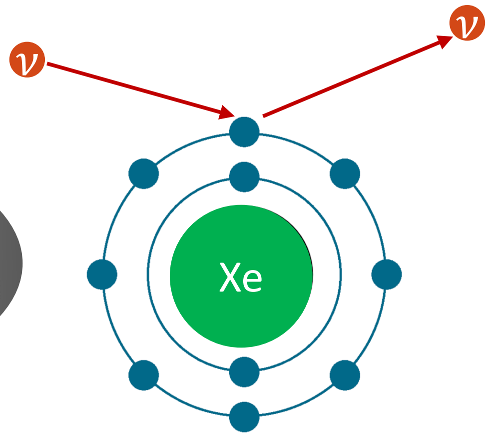
Multiple physics goals in one detector







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Neutrino-electron scattering

- Large target mass
- Energy threshold and resolution

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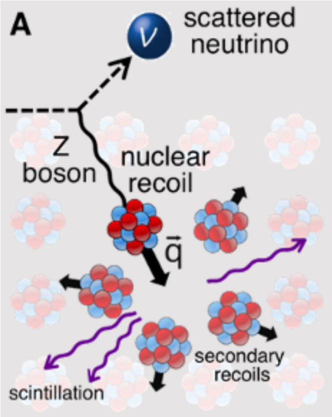

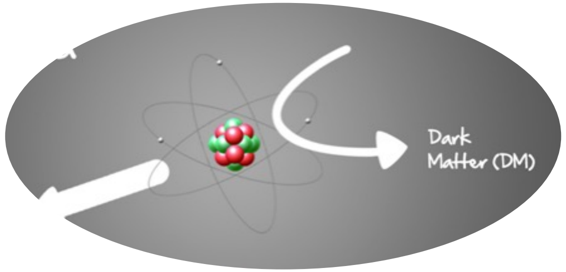

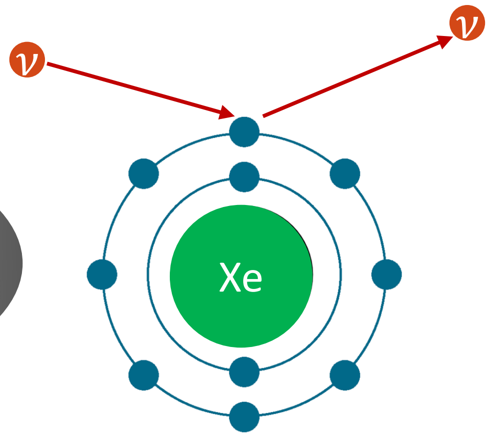

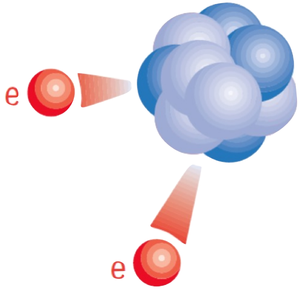

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- Large target mass
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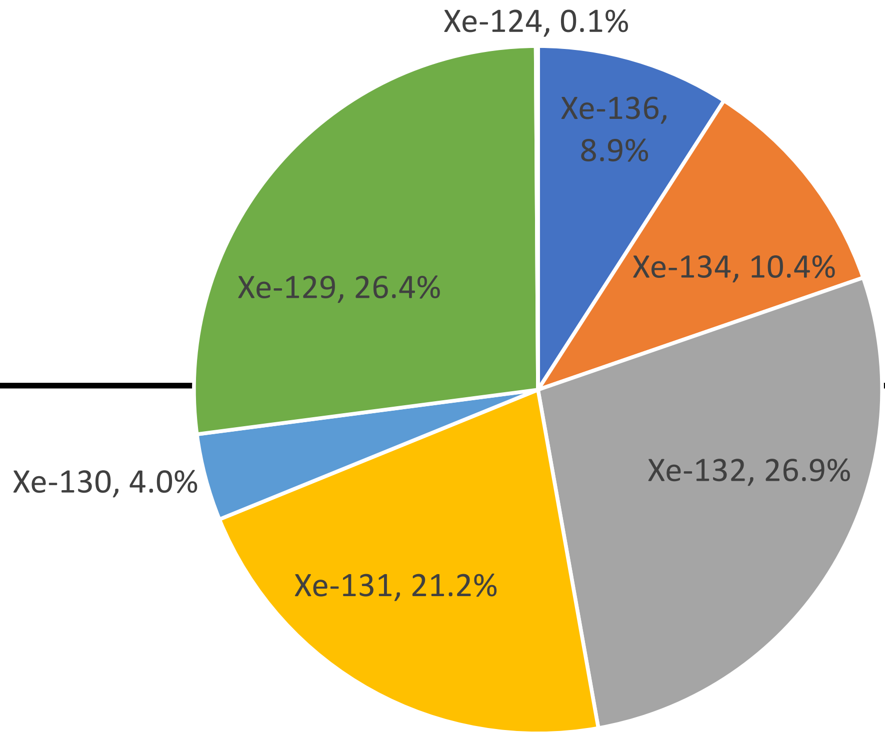
Double beta decay

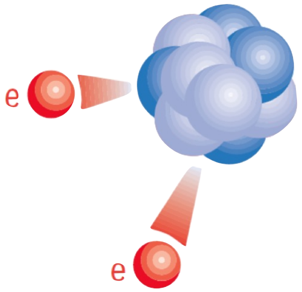
- Large target mass
- Excellent energy resolution
- Single vs multiple site event

Multiple physics goals in one detector



keV

1 MeV



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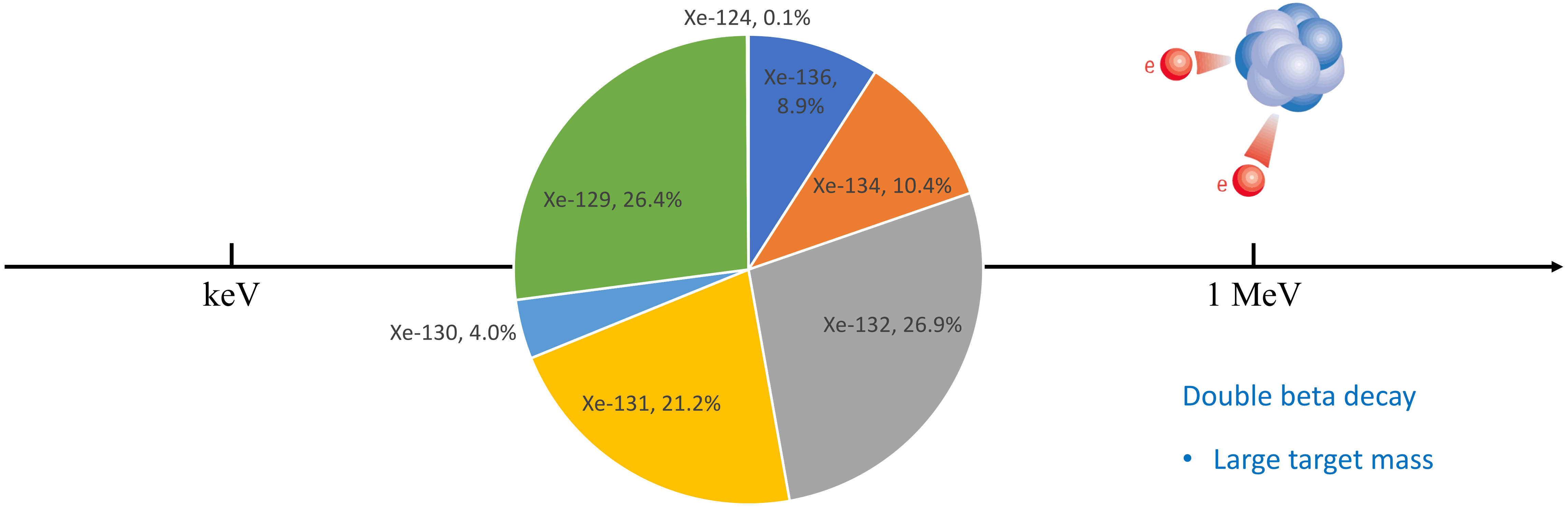

Double beta decay

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- Excellent energy resolution
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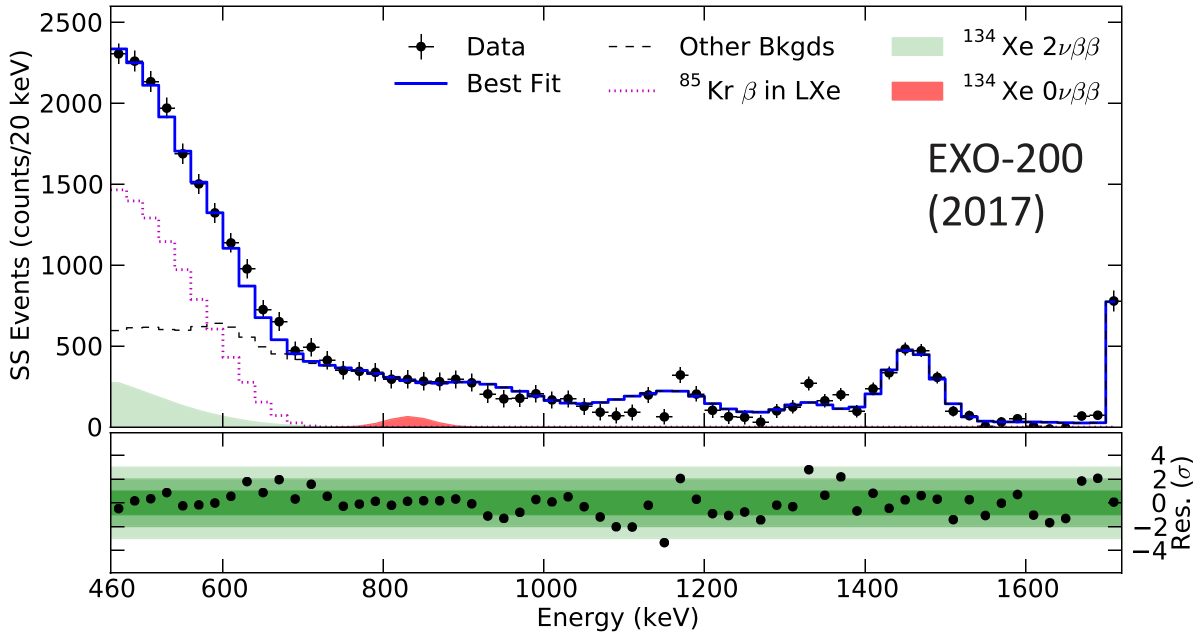
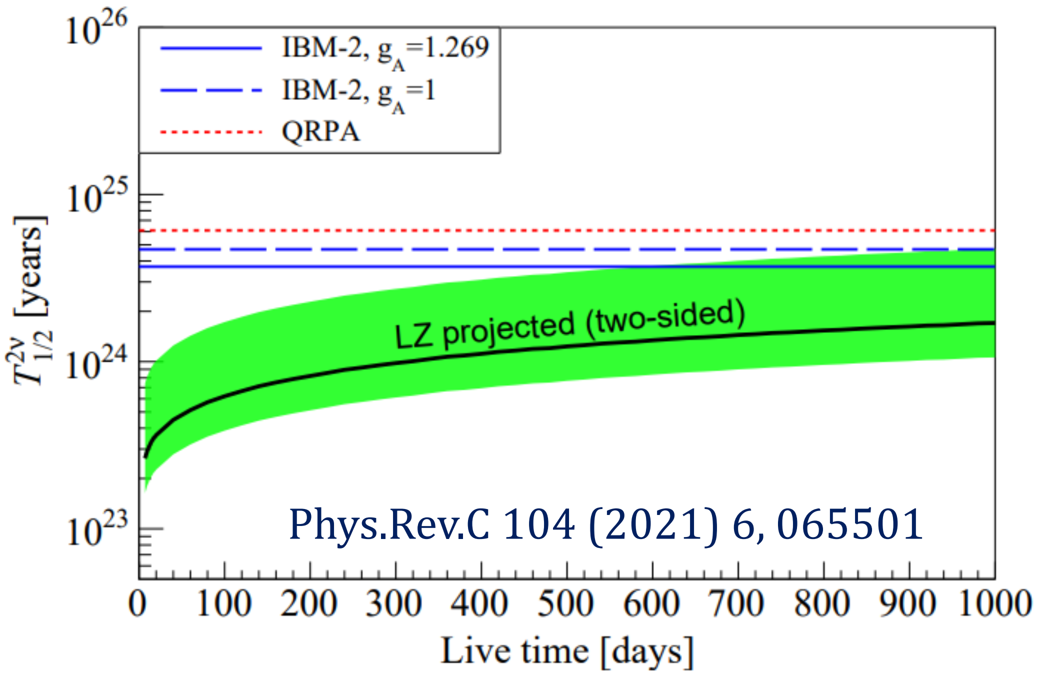
^{134}Xe 2νββ and 0νββ

- Q=826 keV; 2νββ half-life from theoretical predictions: 10^{24}-10^{25} yr; Never been observed
- Previous 2νββ (0νββ) half-life limit from EXO-200 : T >8.7x10^{20} yr (1.1x10^{23} yr) at 90% CL

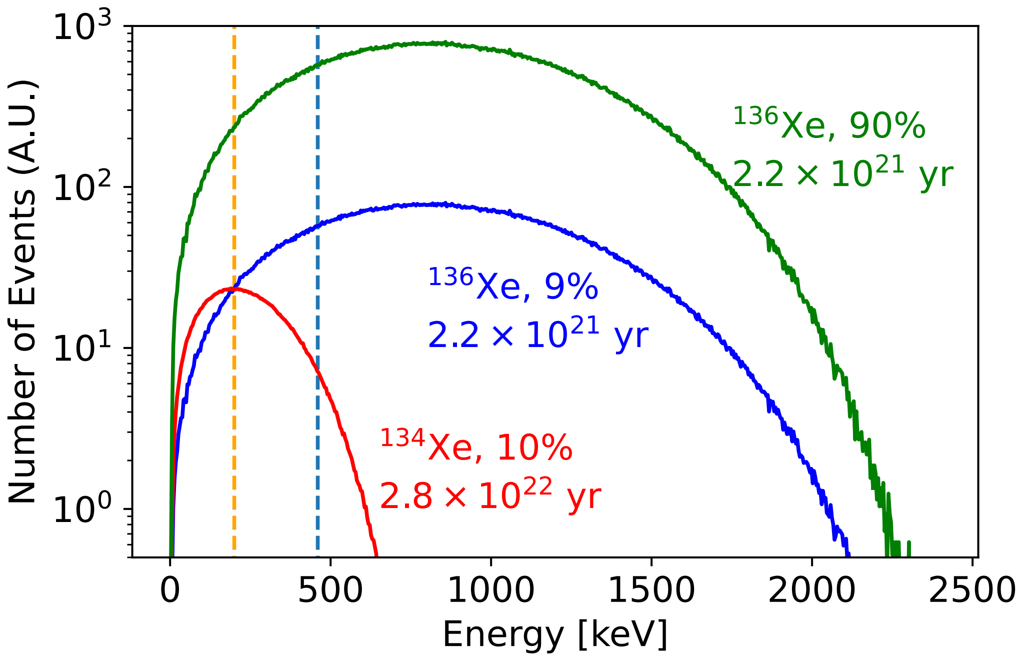




^{134}Xe 2νββ and 0νββ searches at PandaX-4T

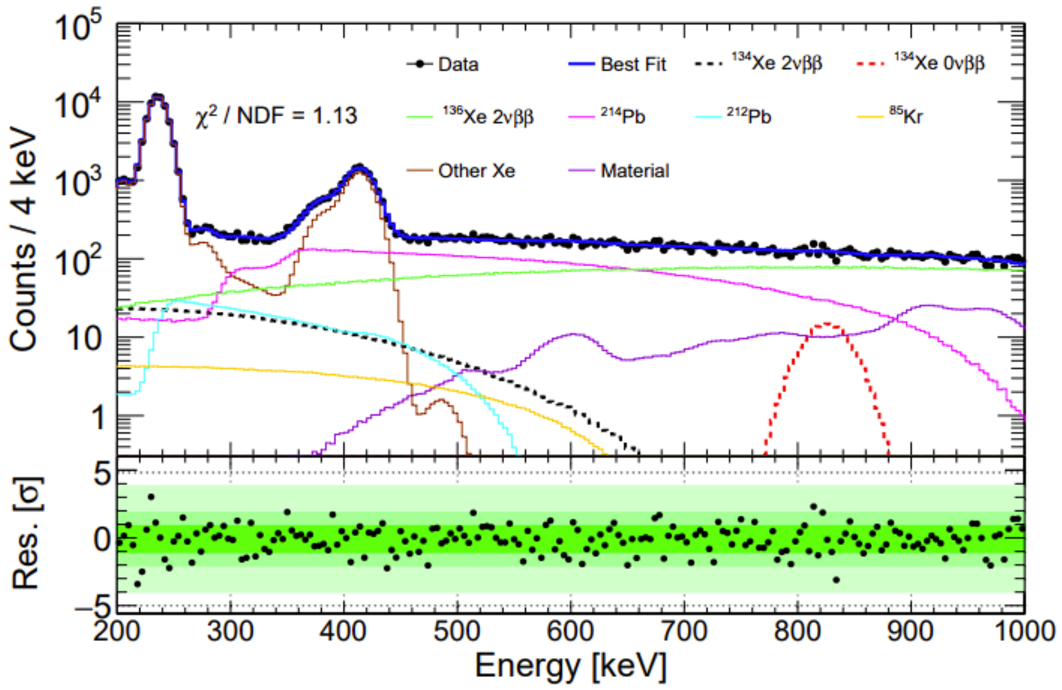
- Q=826 keV; 2νββ half-life from theoretical predictions: 10^{24}-10^{25} yr; Never been observed
- Previous 2νββ (0νββ) half-life limit from EXO-200 : T >8.7x10^{20} yr (1.1x10^{23} yr) at 90% CL
- PandaX-4T: more ^{134}Xe; much less ^{136}Xe; wider energy range

	PandaX-4T	EXO-200
^{134}Xe mass	68.7 kg	18.1 kg
^{136}Xe abundance	8.90%	81%
Analysis threshold	200 keV	460 keV
Live Time	94.9 days	600 days

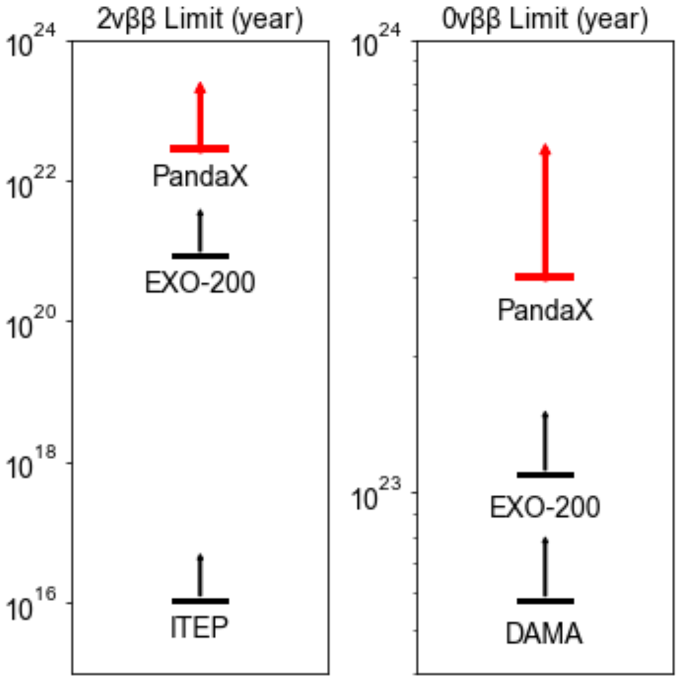


^{134}Xe half-life limits @ PandaX-4T

- Simultaneous fit for ^{134}Xe $2\nu\beta\beta$ and $0\nu\beta\beta$
- Final counts of $2\nu\beta\beta$ and $0\nu\beta\beta$: 10±269(stat.)±680(syst.) and 105±48(stat.)±38(syst.)
- 90% CL lower limits on the half-life: $T_{1/2}^{2\nu\beta\beta} > 2.8 \cdot 10^{22}$ yr and $T_{1/2}^{0\nu\beta\beta} > 3.0 \cdot 10^{23}$ yr



PRL 132, 152502 (2024)



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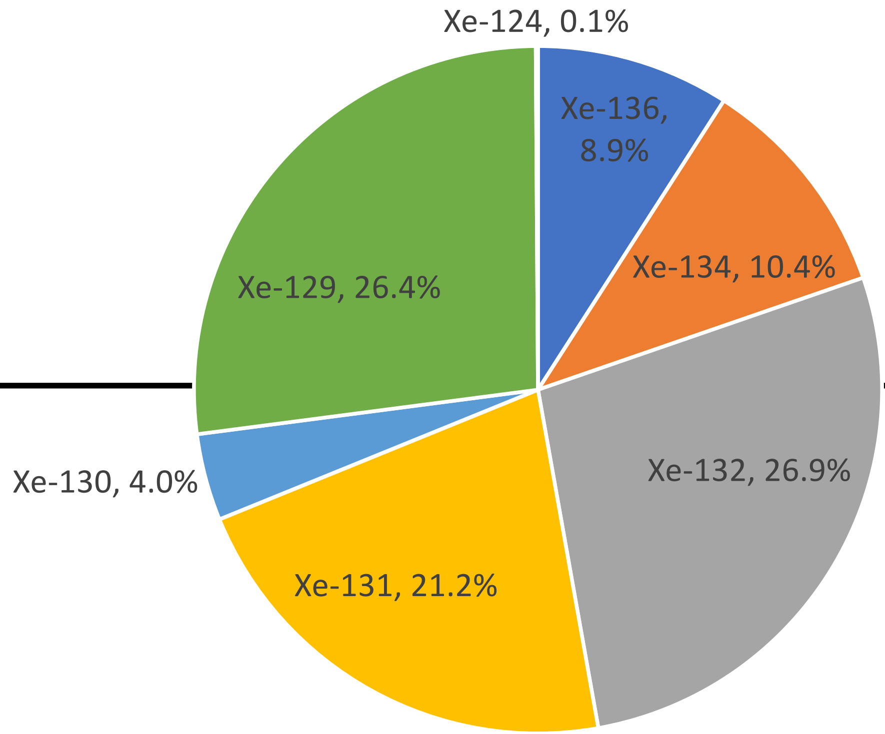
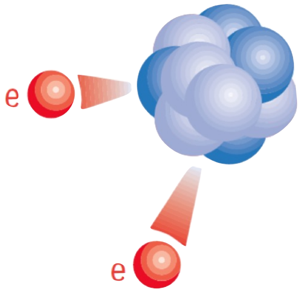


keV

1 MeV

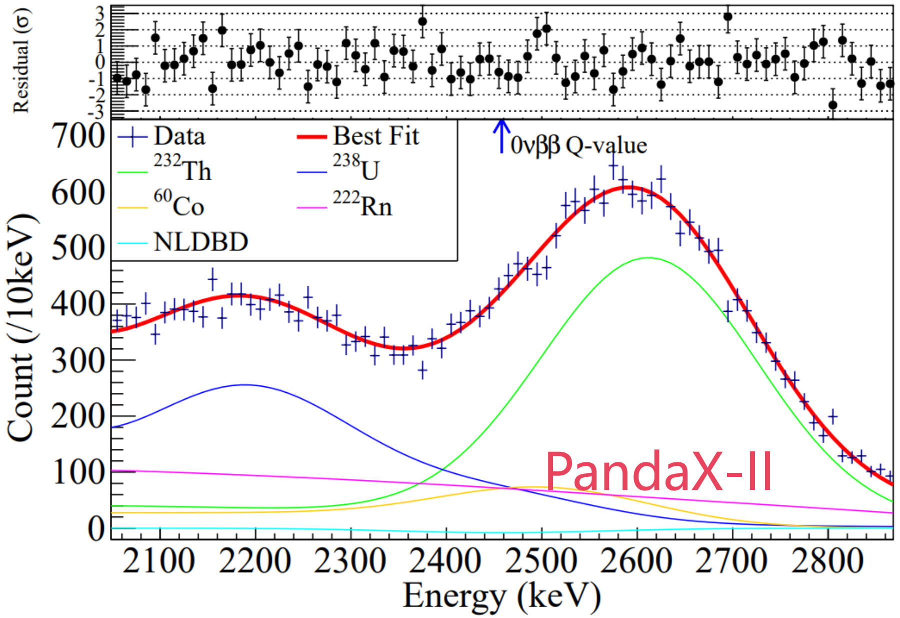


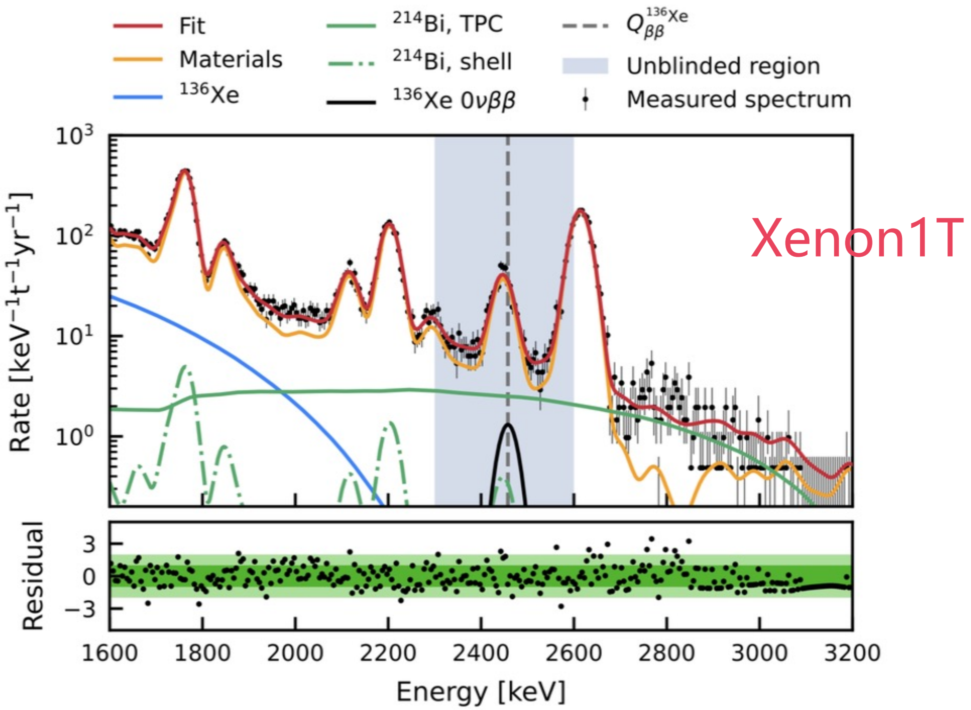
Double beta decay

- Large target mass
- Excellent energy resolution
- Single vs multiple site event

Search for ^{136}Xe 0νββ with natural Xe TPC

	Bkg rate (/keV/ton/y)	Energy resolution	FV mass (kg)	Live time	Sensitivity/Limit (90% CL, year)	Year
PandaX-II	~200	4.2%	219	403 days	2.4×10^{23}	2019
XENON1T	~20	0.8%	741	203 days	1.2×10^{24}	2022
PandaX-4T	~10	2.0-2.3%	735	258 days	2.1×10^{24}	2024

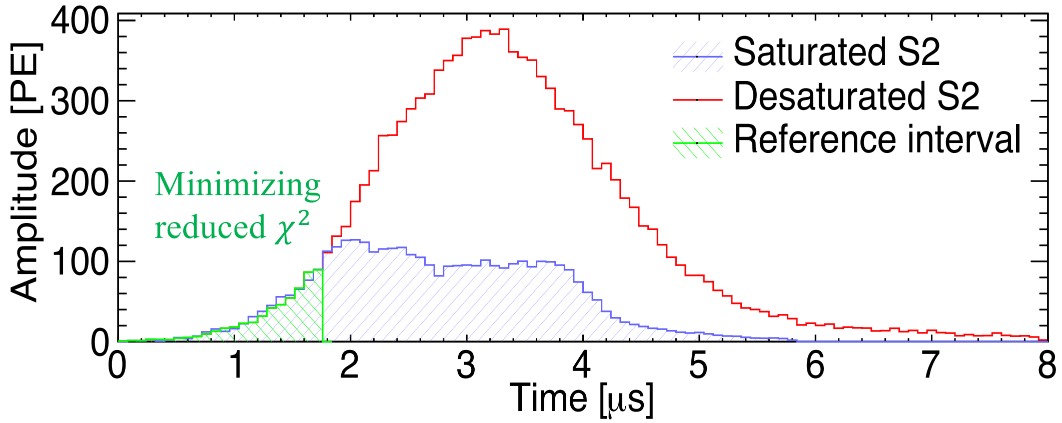


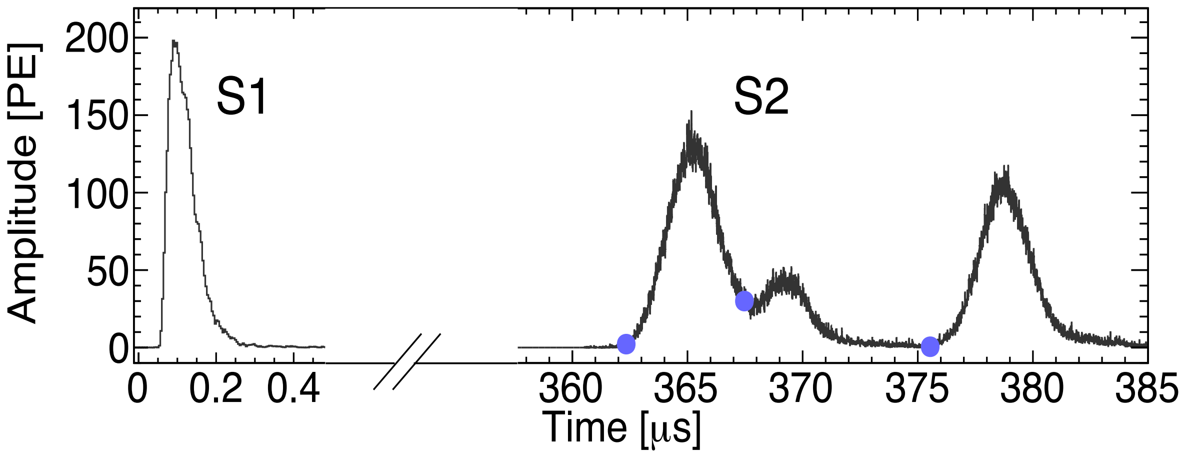


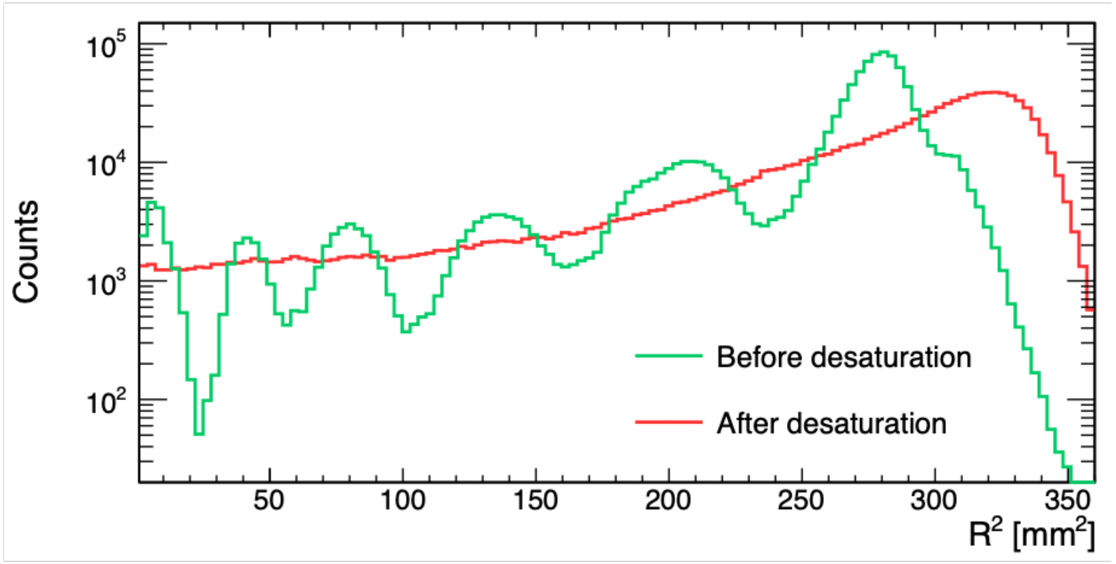
Extending energy from keV to O(100 keV) – O(MeV)

- S2 waveform slicing to improve SS and MS identification
- PMT desaturation for large S2 signals
- Improvement of X-Y position reconstruction, energy linearity and energy resolution

Research 2022 9798721 (2022)

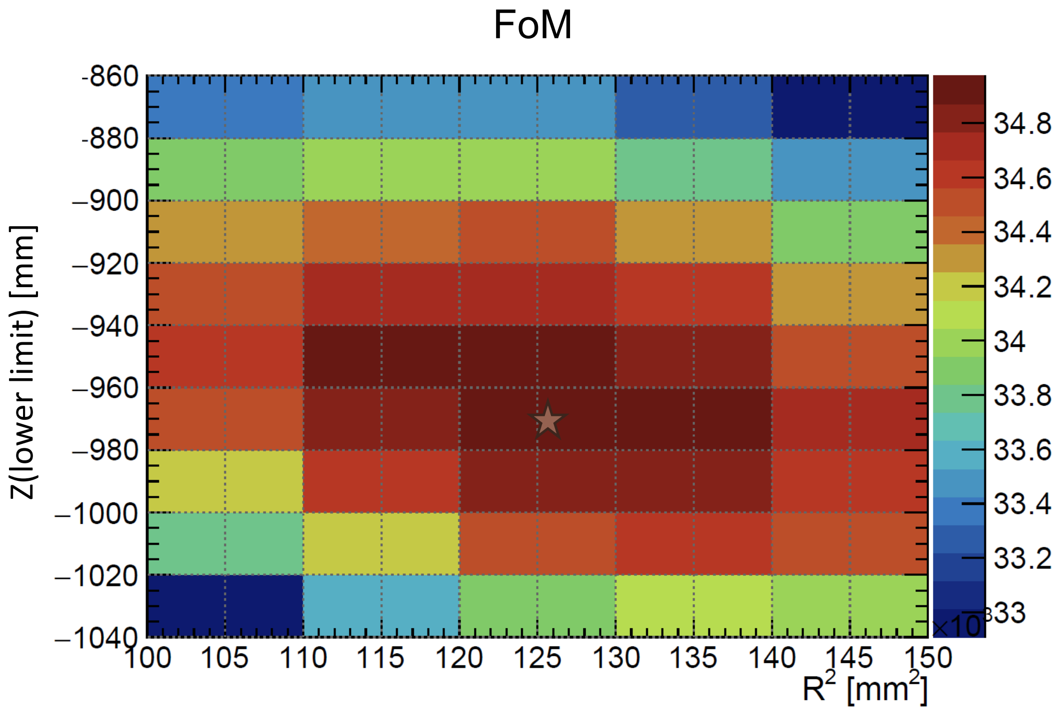


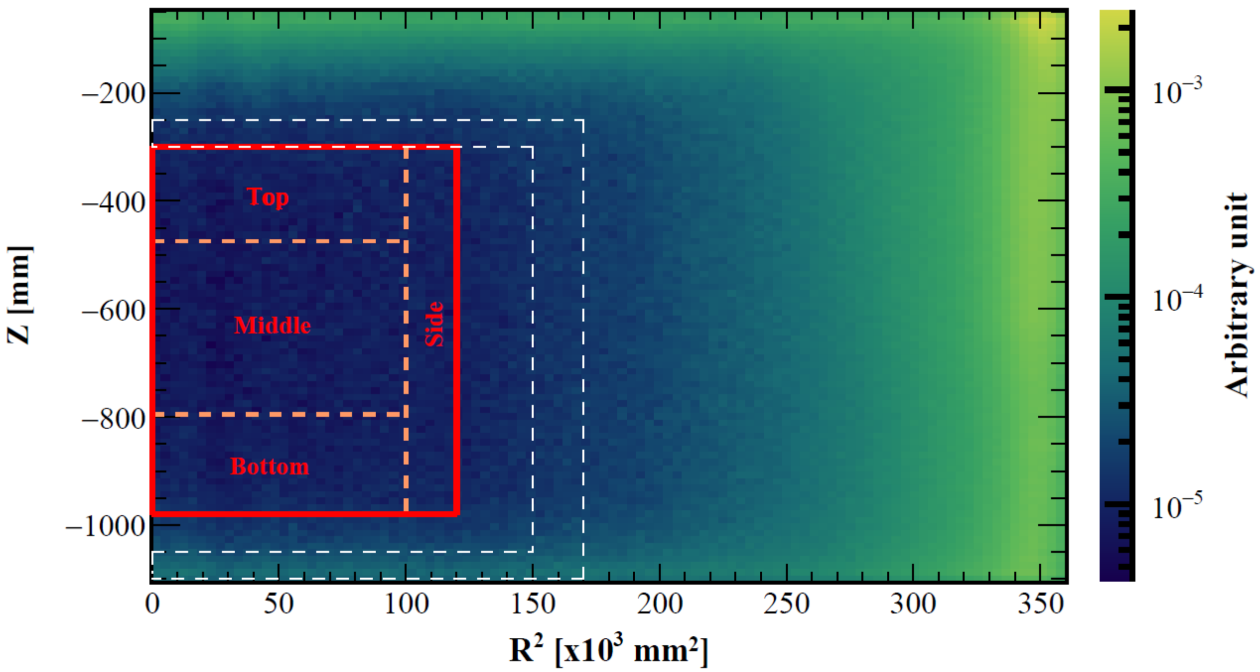




Fiducial Volume (FV)

- FV is optimized by maximizing the FoM $FoM \propto \frac{m}{\sqrt{B}}$
- FV is further divided into four regions to better constrain detector material background from top, side, and bottom parts



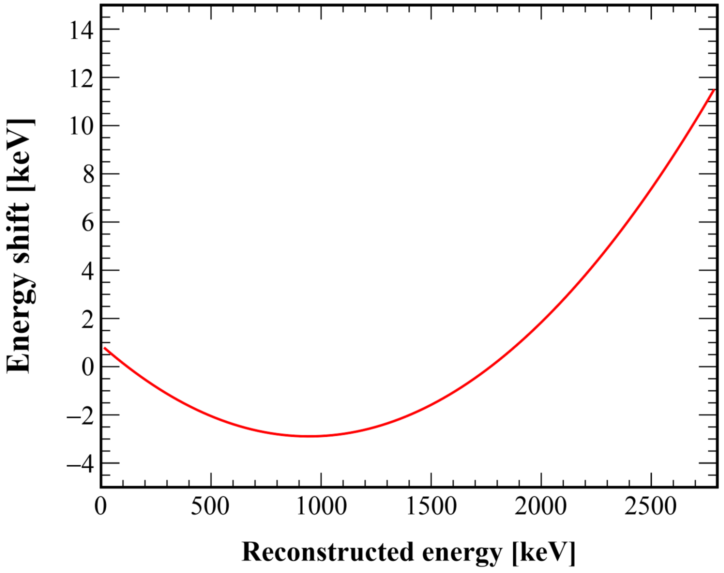


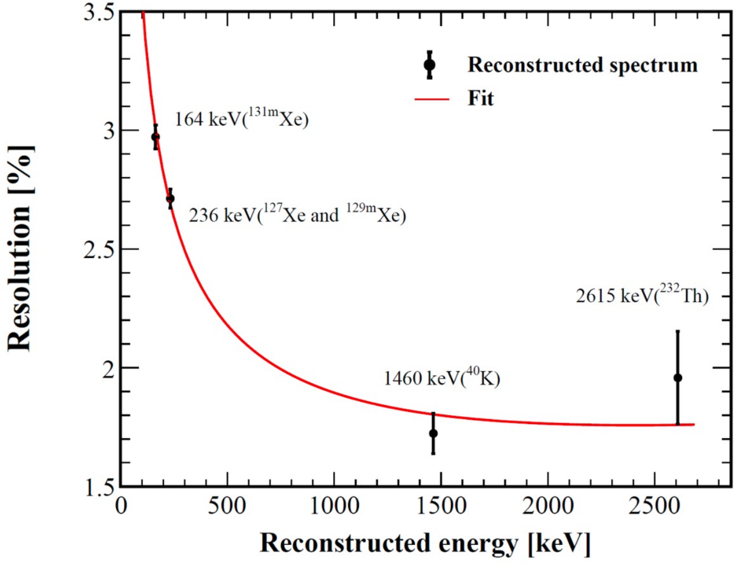
Energy Response Model

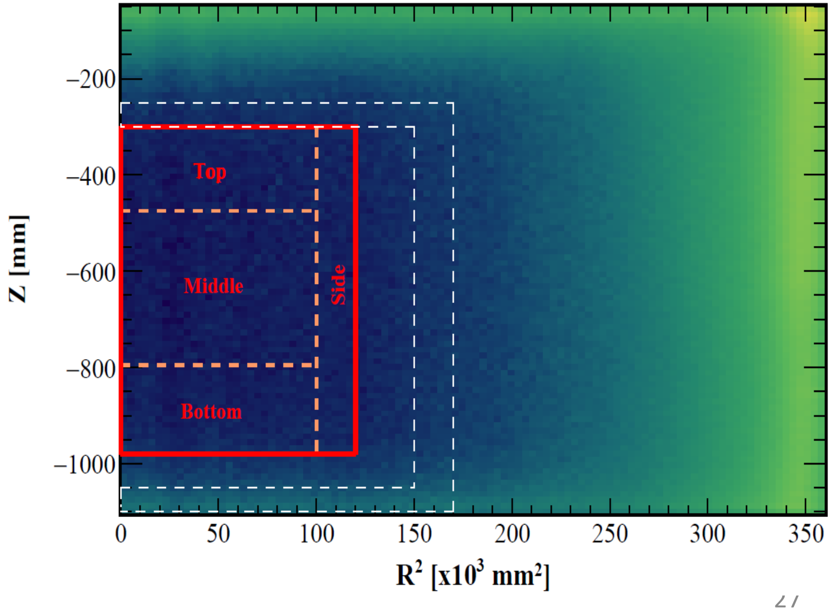
- Residual shift between simulated energy and reconstructed energy
- Energy resolution vs. reconstructed energy
- Response model from physics data in slim regions outside FV
- Model parameters naturally included in the likelihood fitting

$$E = a \cdot \hat{E}^2 + b \cdot \hat{E} + c.$$

$$\frac{\sigma(E)}{E} = \frac{d}{\sqrt{E}} + e \cdot E + f.$$

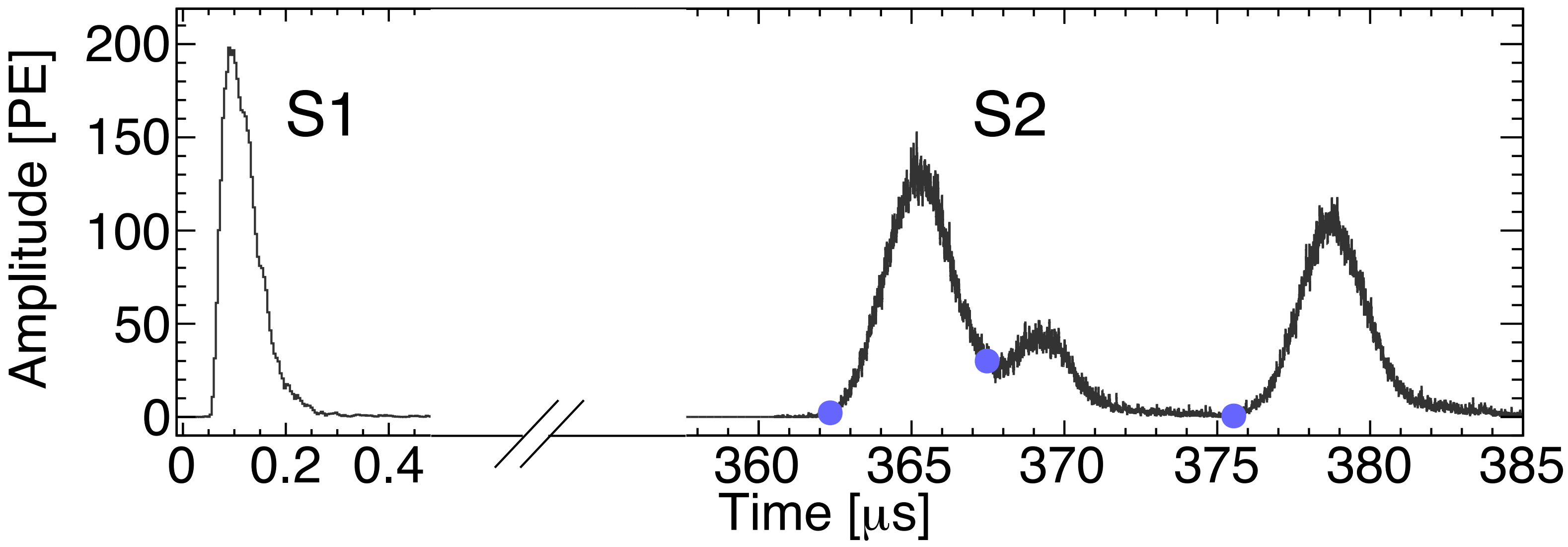


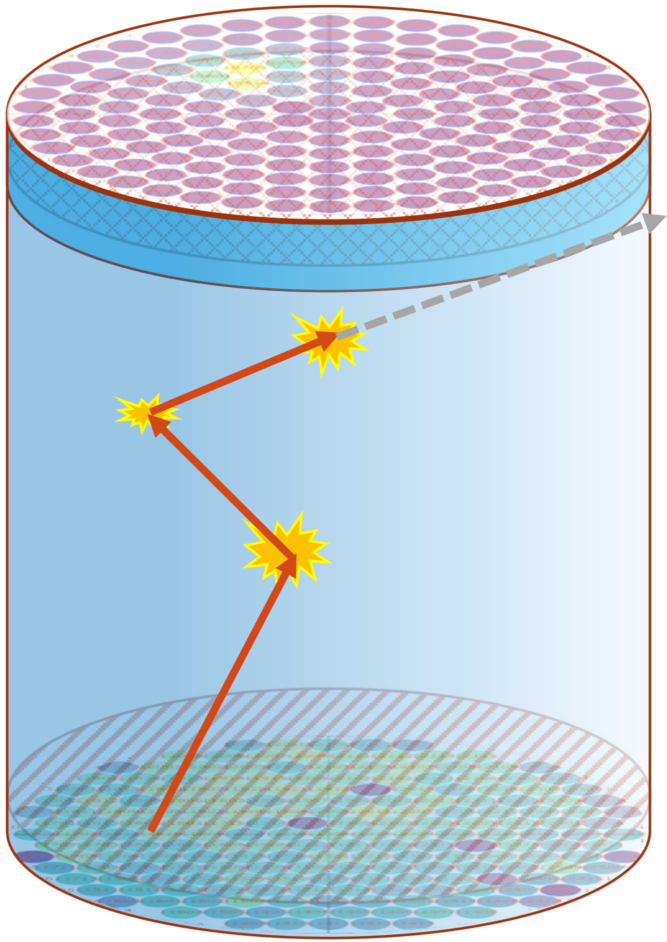




SS vs. MS

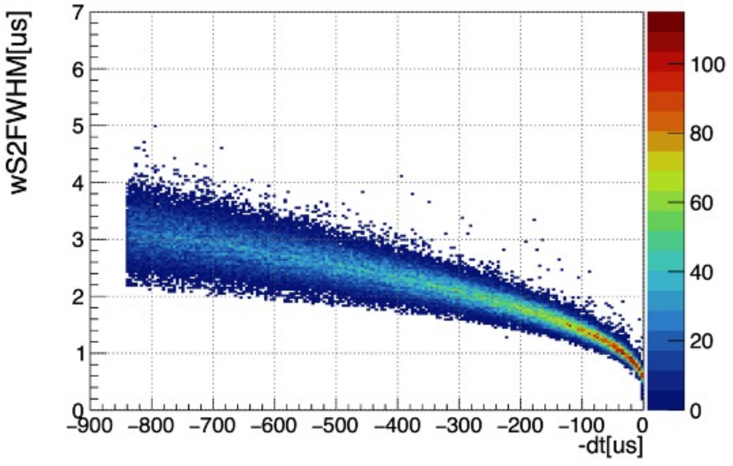
- MeV gamma events are mostly multiple-scattering events; while signals (DBD) are mostly single site (SS)
- Identifying Multi-Site (MS) events with PMT waveforms
- Width of waveforms dominated by Z (electron diffusion)

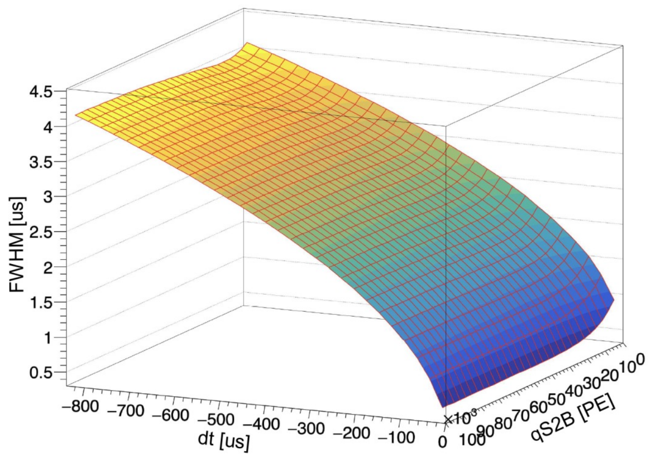


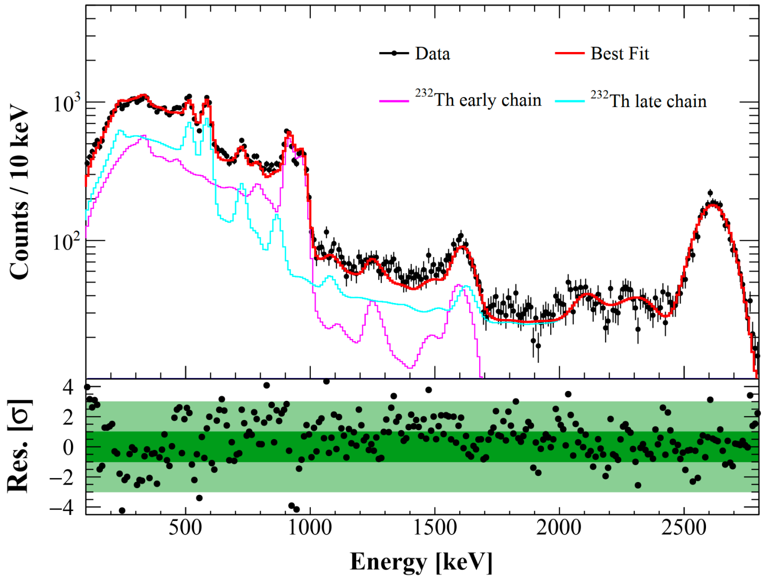


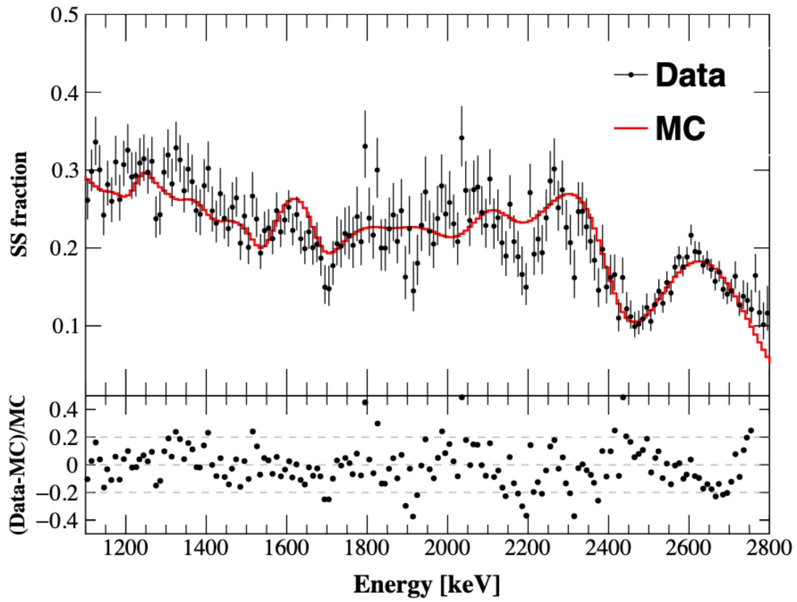
SS Fraction (SS/Total) determination

- Data-driven S2 waveform simulation + data processing
- SS fraction uncertainty is estimated by comparison MC/data of ^{232}Th calibration
- Spectrum average of the absolute bin-by-bin deviation between data and MC taken as SS fraction uncertainty



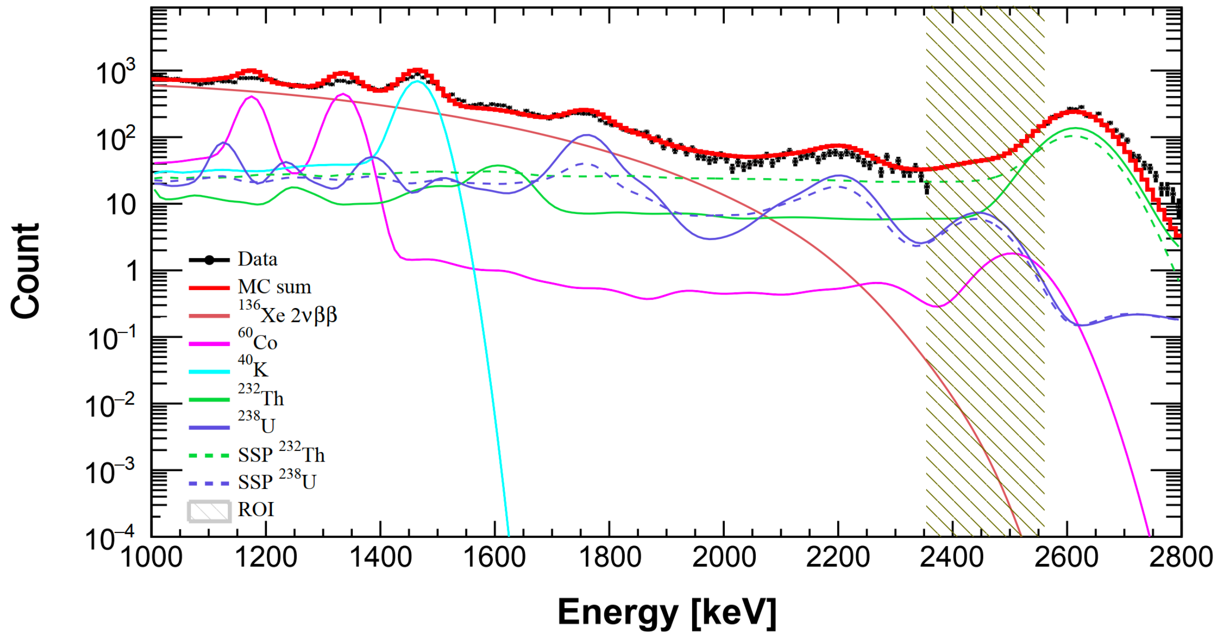


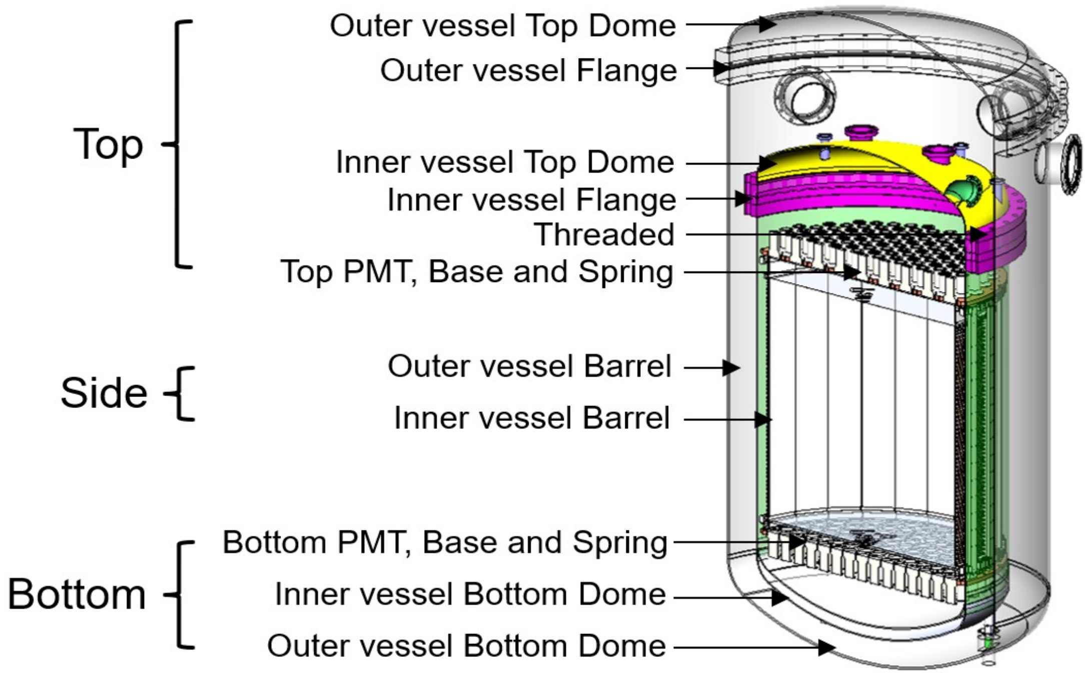




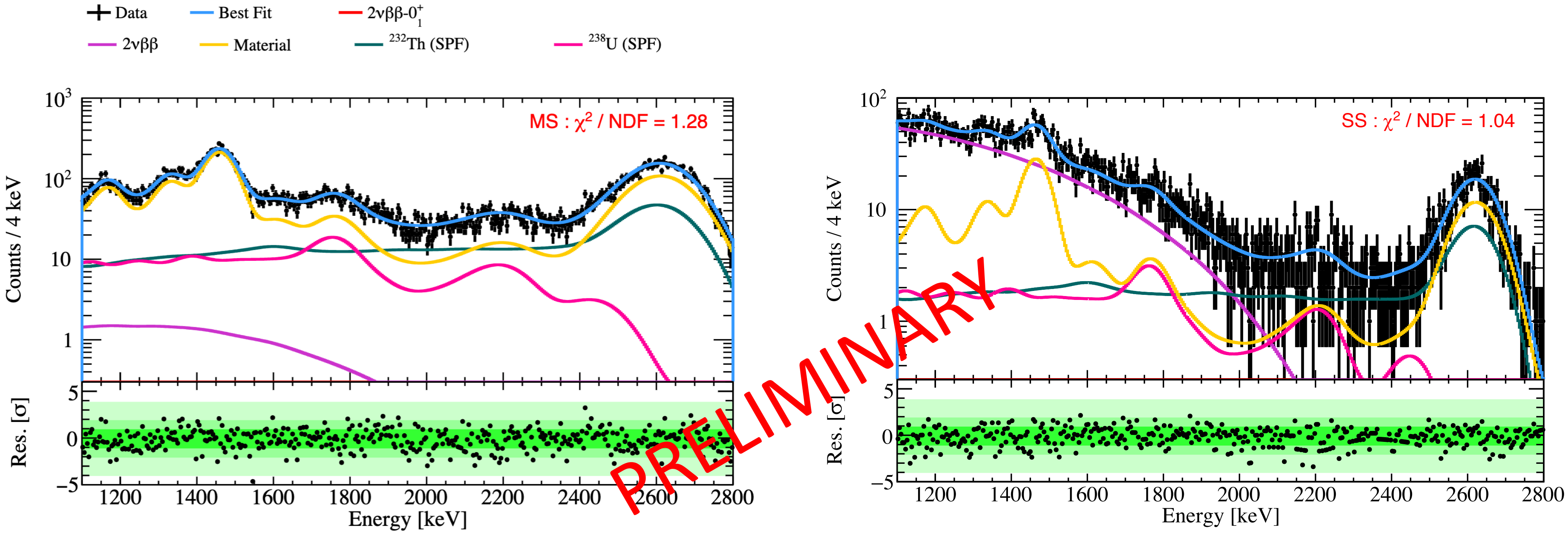
Background Model

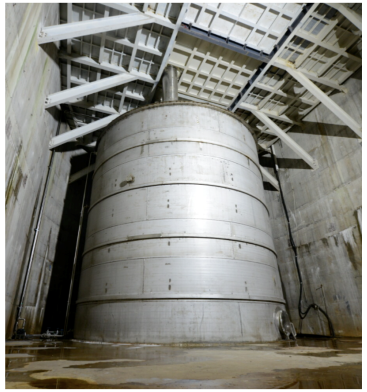
- ^{136}Xe $2\nu\beta\beta$ (from PandaX measured ^{136}Xe half-life)
- Detector material: ^{60}Co, ^{40}K, ^{232}Th, ^{238}U (from HPGe material assay), and grouped into top, side, and bottom parts
- Stainless steel platform (SSP): ^{232}Th, ^{238}U (from MS fitting)

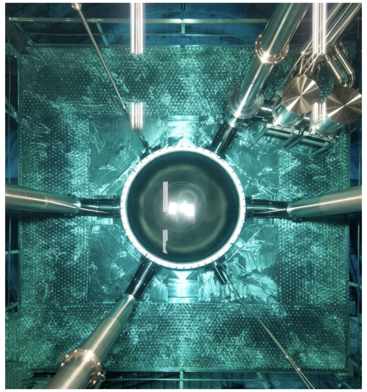


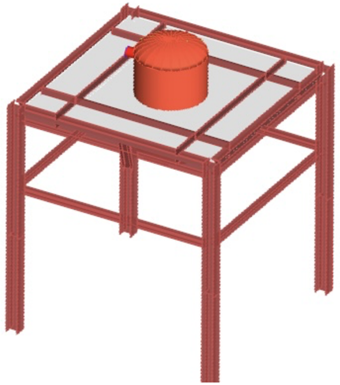


Stainless steel platform (SSP) contribution









Likelihood and Systematics

- Binned Poisson likelihood with Gaussian penalty terms to constrain nuisance parameters
- Systematics include three categories: energy response, overall efficiency, ^{136}Xe mass
- ^{136}Xe mass uncertainties: abundance from RGA measurement; FV mass from the non-uniformity of ^{83m}Kr + LXe density fluctuation

$$L = \prod_{r}^{N_{run}} \prod_{i}^{N_{region}} \prod_{j}^{N_{bins}} \frac{(N_{rij})^{N_{rij}^{obs}}}{N_{rij}^{obs}!} e^{-N_{rij}}$$

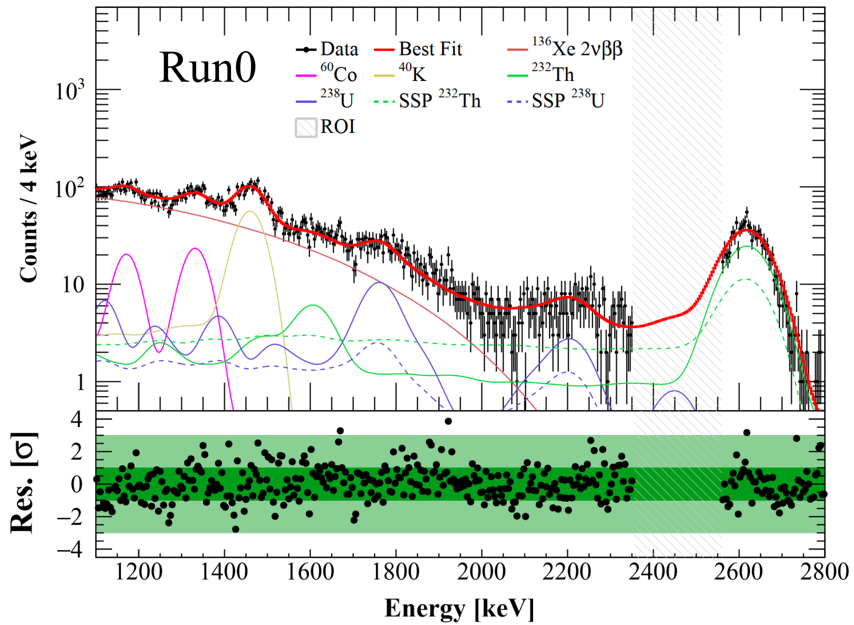
$$\cdot \prod_{r}^{N_{run}} [\mathcal{G}(\mathcal{M}_r; \mathcal{M}_r^0, \Sigma_r^{\mathcal{M}}) \cdot \prod_{k}^{N_{eff}} G(\eta_r^k; 0, \sigma_r^k)]$$

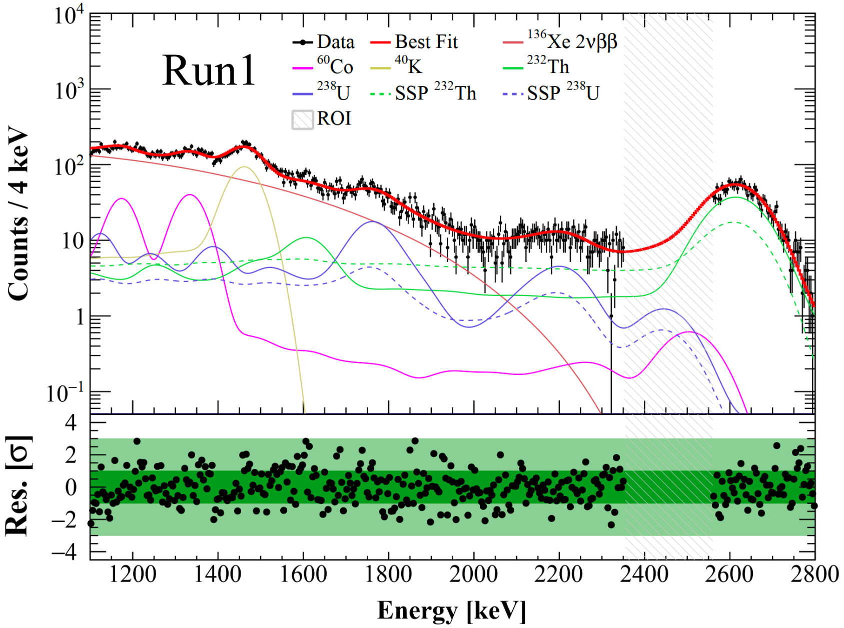
$$\cdot \prod_{b}^{N_{bkg}} G(\eta^b; 0, \sigma^b)$$

$$N_{rij} = (1 + \eta_r^o) \cdot [(1 + \eta_r^s) \cdot n_r^s \cdot S_{ijr} + \sum_{b}^{N_{bkg}} (1 + \eta^b) \cdot n_r^b \cdot B_{ijr}^b]$$

Sources		Values: Run0	Values: Run1
Energy response	a [keV^{-1}]	$(4.2 \pm 1.0) \times 10^{-6}$	$(1.1 \pm 1.4) \times 10^{-6}$
	b	0.992 ± 0.002	0.997 ± 0.004
	c [keV]	0.90 ± 0.32	1.4 ± 1.5
	d [$\sqrt{\text{keV}}$]	0.259 ± 0.046	0.46 ± 0.25
	e [keV^{-1}]	$(1.1 \pm 1.5) \times 10^{-6}$	$(8.8 \pm 22.2) \times 10^{-7}$
	f	$(9.7 \pm 3.5) \times 10^{-3}$	$(7.4 \pm 10.0) \times 10^{-3}$
Overall efficiency	^{136}Xe $0\nu\beta\beta$ SS fraction	$(87.1 \pm 11.3)\%$	$(87.3 \pm 7.0)\%$
	Quality cut	$(99.89 \pm 0.10)\%$	$(99.97 \pm 0.02)\%$
^{136}Xe mass	^{136}Xe abundance	$(8.58 \pm 0.11)\%$	
	FV mass [kg]	735 ± 3	735 ± 14
Background model		Table. 2	

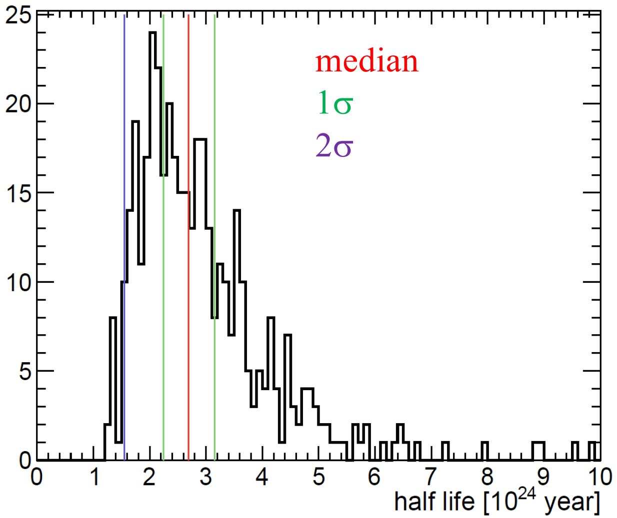
Blinded Fit and Sensitivity





Goodness-of-fit:

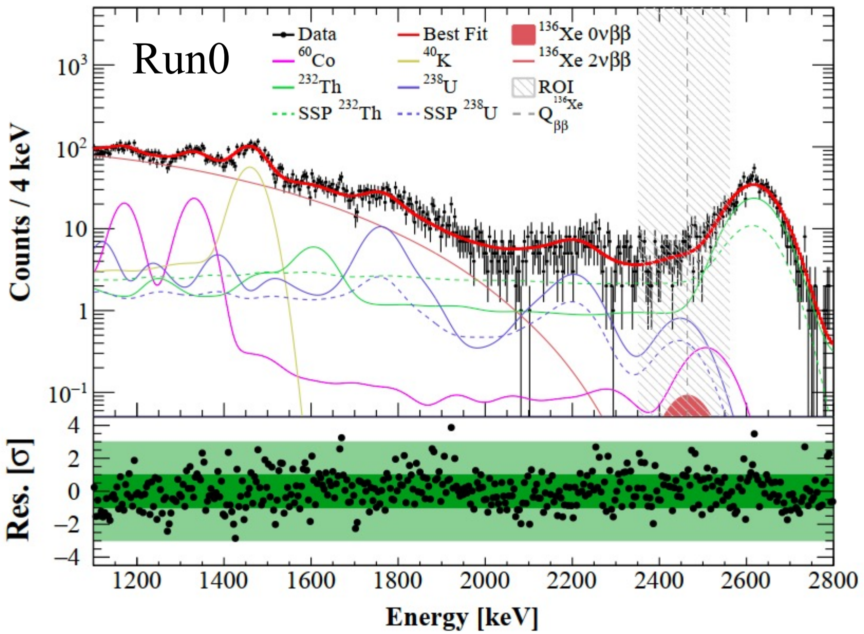
$\chi^2/NDF = 1.14$

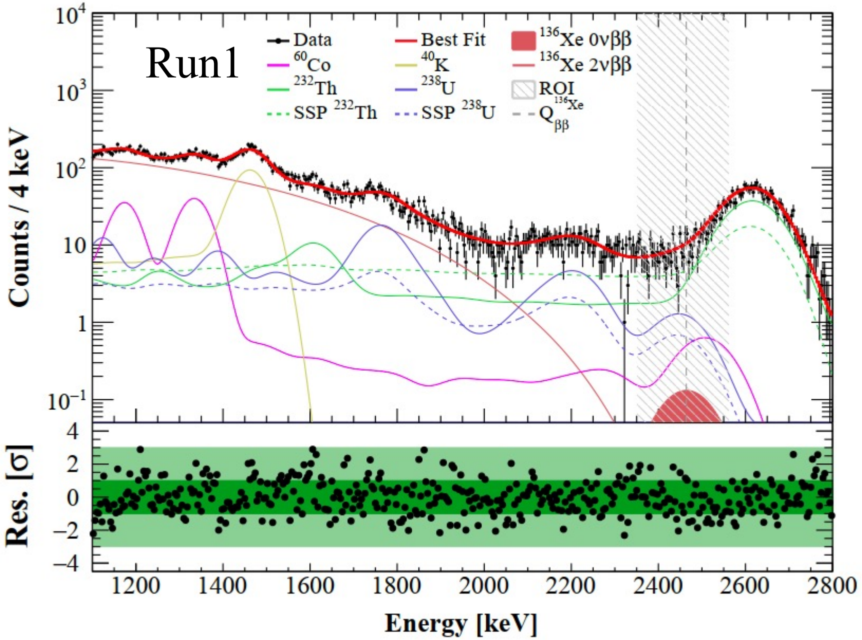


Median sensitivity is estimated by fits to toy-data, generated from background model.

$$T^{0\nu\beta\beta}_{1/2,\,sensitivity} > 2.7\times 10^{24}\ yr \text{ at 90\% C.L.}$$

Unblinded Fit and Results





- ^{136}Xe exposure: 44.6 kg-yr
- Energy resolution @ 2615 keV: 2.0% in Run0 and 2.3% in Run1
- ^{136}Xe $0\nu\beta\beta$ event rate: $14\pm55\ t^{-1}yr^{-1}$, <111 $t^{-1}yr^{-1}$ at 90% C.L.
- $T_{1/2}^{0\nu\beta\beta} > 2.1\times 10^{24}\ yr$ at 90% C.L. $\langle m_{\beta\beta}\rangle = (0.4 - 1.6)\ \mathrm{eV/c^2}$

arXiv:2412.13979

Search for ^{136}Xe 0νββ with natural Xe TPC

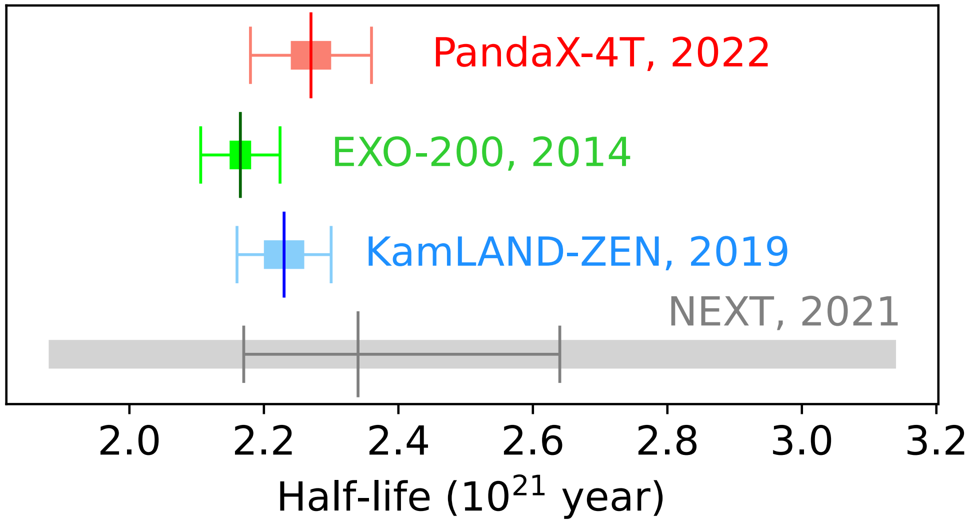
	Bkg rate (/keV/ton/y)	Energy resolution	FV mass (kg)	Live time	Sensitivity/Limit (90% CL, year)	Year
PandaX-II	~200	4.2%	219	403 days	2.4×10^{23}	2019
XENON1T	~20	0.8%	741	203 days	1.2×10^{24}	2022
PandaX-4T	~10	2.0-2.3%	735	258 days	2.1×10^{24}	2024

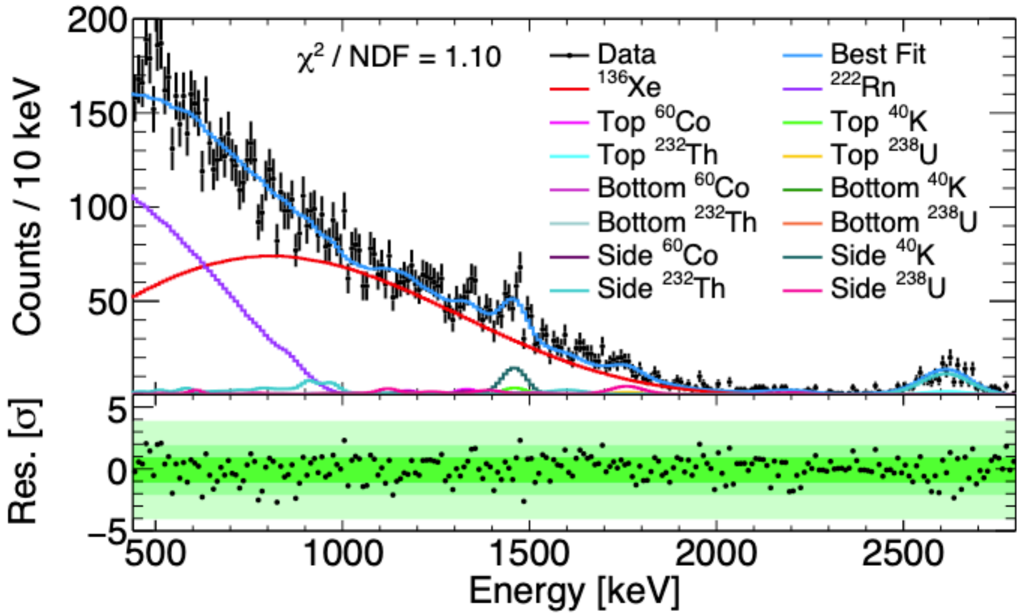
- The most stringent constraint from a natural xenon detector
- Improvement w.r.t PandaX-II by an order of magnitude and XENON1T by a factor of 1.8
- Demonstrating the potential of ^{136}Xe 0νββ search with next-generation multi-ten-tonne natural xenon detectors

Published ^{136}Xe 2νββ half-life measurement

- ^{136}Xe 2νββ half-life measured by PandaX-4T: 2.27 ± 0.03(stat.) ± 0.09(syst.) × 10^{21} year
- 440 keV – 2800 keV range is the widest ROI
- Comparable precision with leading results
- First such measurement from a natural xenon TPC

Research, 9798721 (2022)



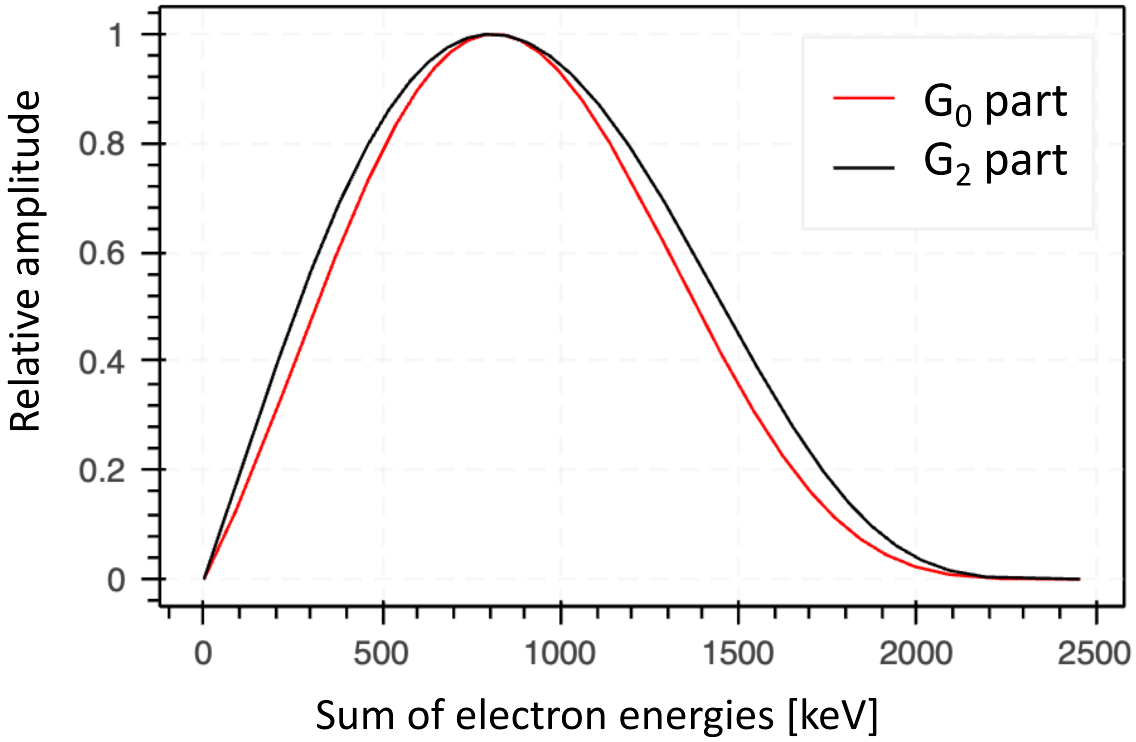


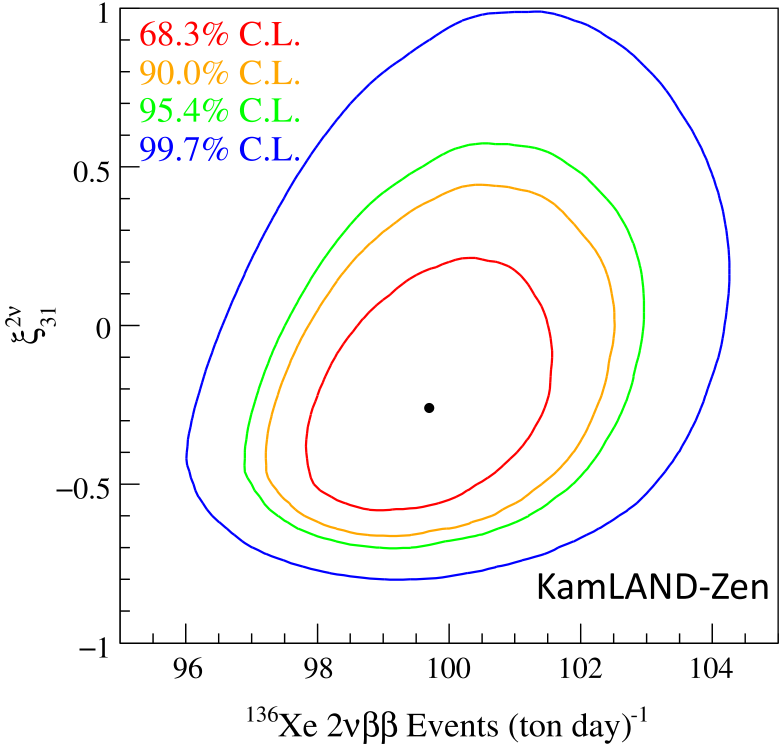
Current effort: decode the higher order contribution to NME

- Higher order $2\nu\beta\beta$ NME impact the shape of the DBD double-electron energy, especially at the low and high energy.
- Precise DBD spectrum may help determine the contribution

$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} \simeq \left(g_A^{\mathrm{eff}}\right)^4 \left|M_{GT-3}^{2\nu}\right|^2 \frac{1}{\left|\xi_{31}^{2\nu}\right|^2} \left(G_0^{2\nu} + \xi_{31}^{2\nu} G_2^{2\nu}\right)$$

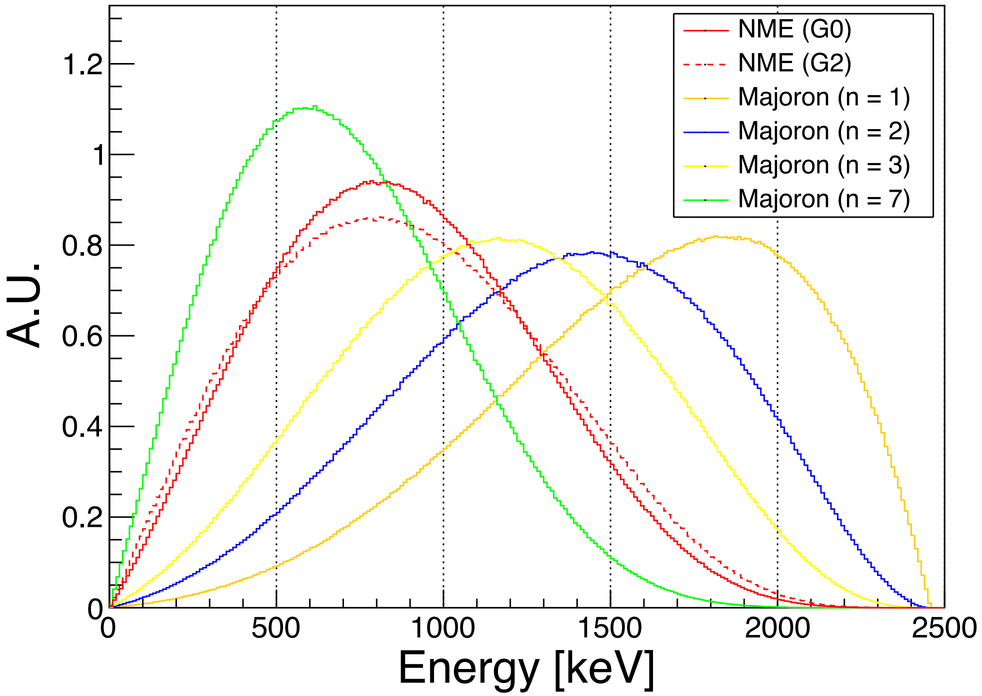
$$\xi_{31}^{2\nu} = \frac{M_{GT-3}^{2\nu}}{M_{GT-1}^{2\nu}}$$

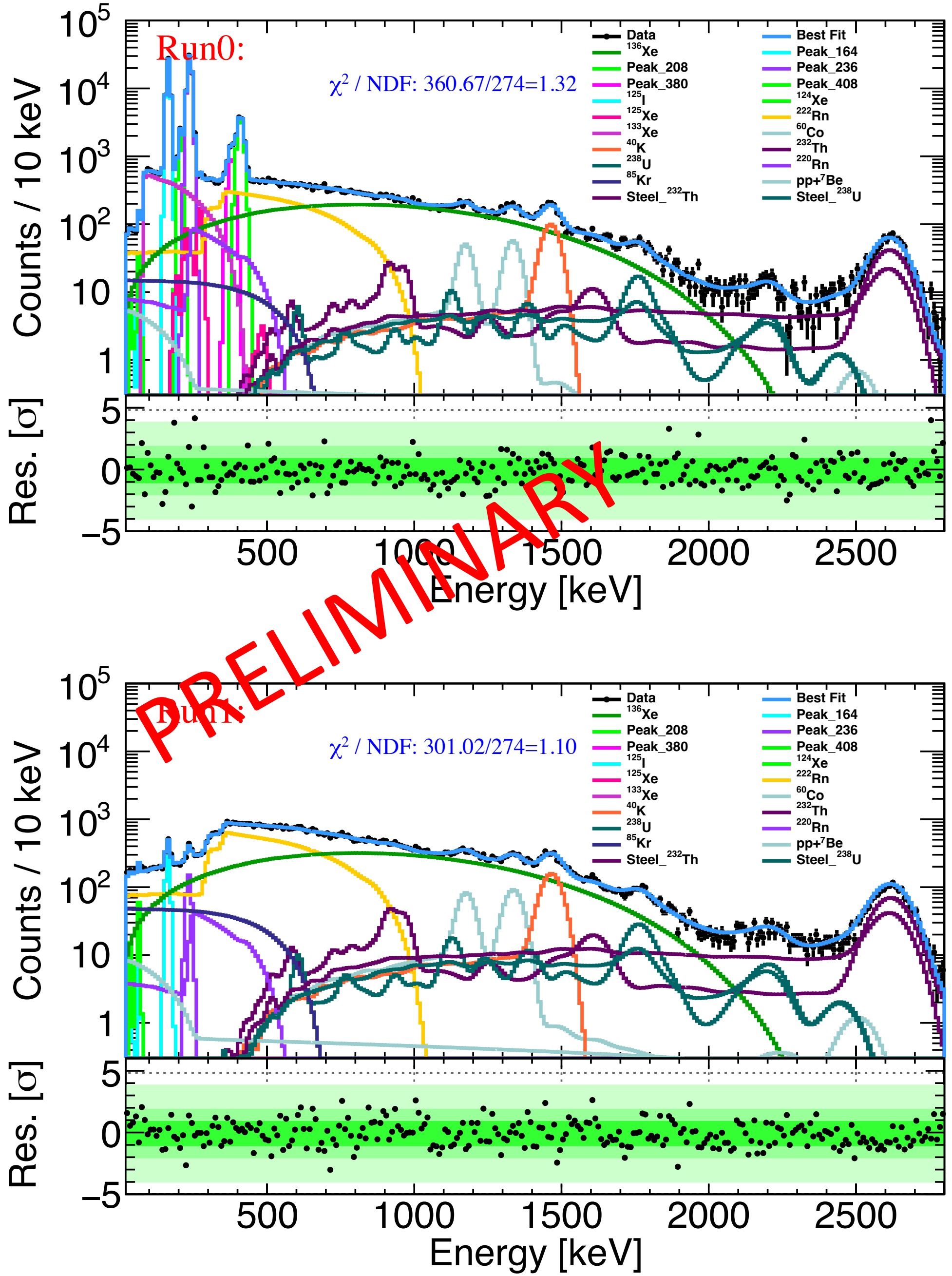


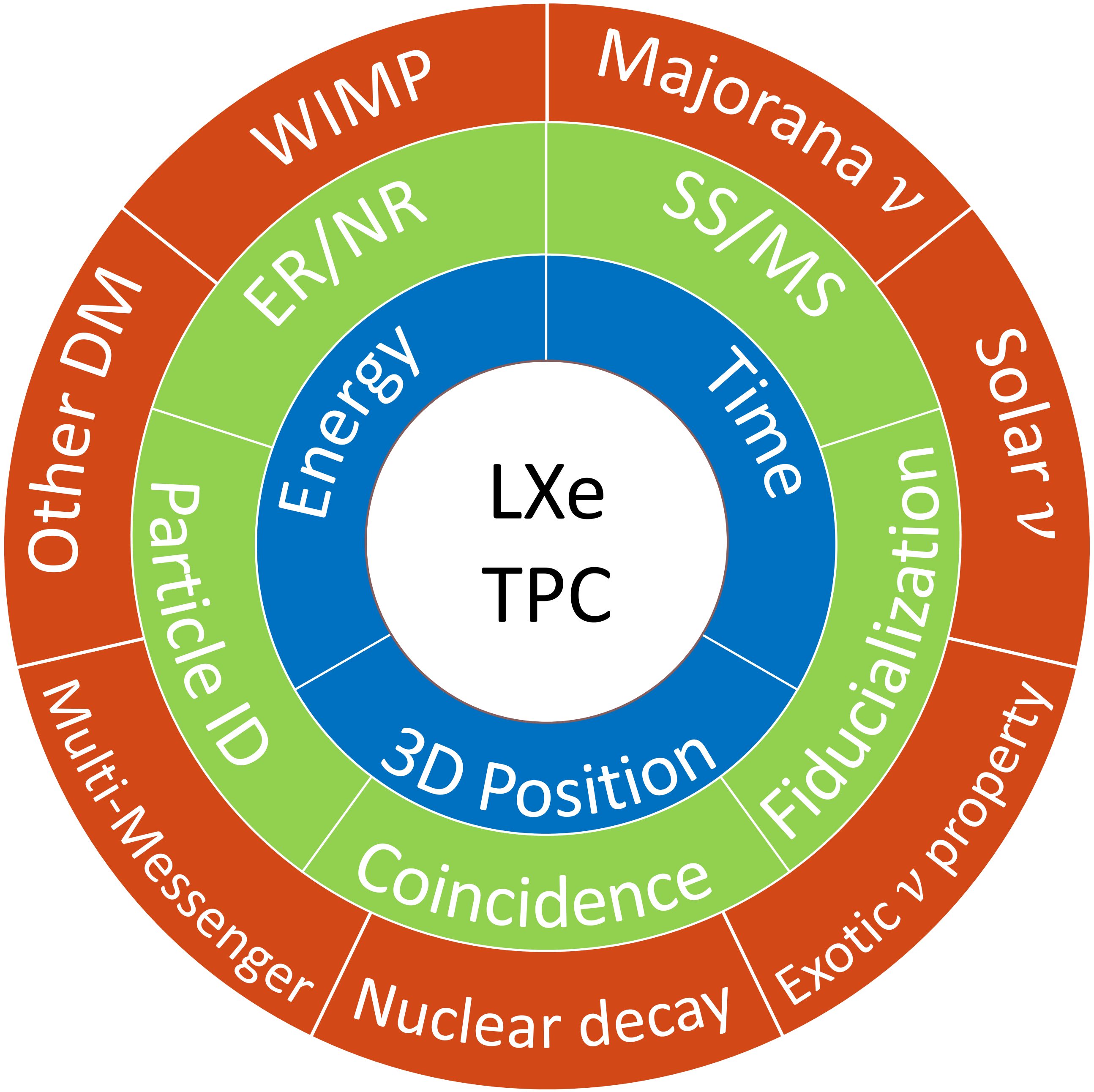


Analysis with PandaX-4T

- Combined Run0+1 data analysis with a low-energy threshold of 20 keV
- Better resolution/worse background than KamLAND-ZEN



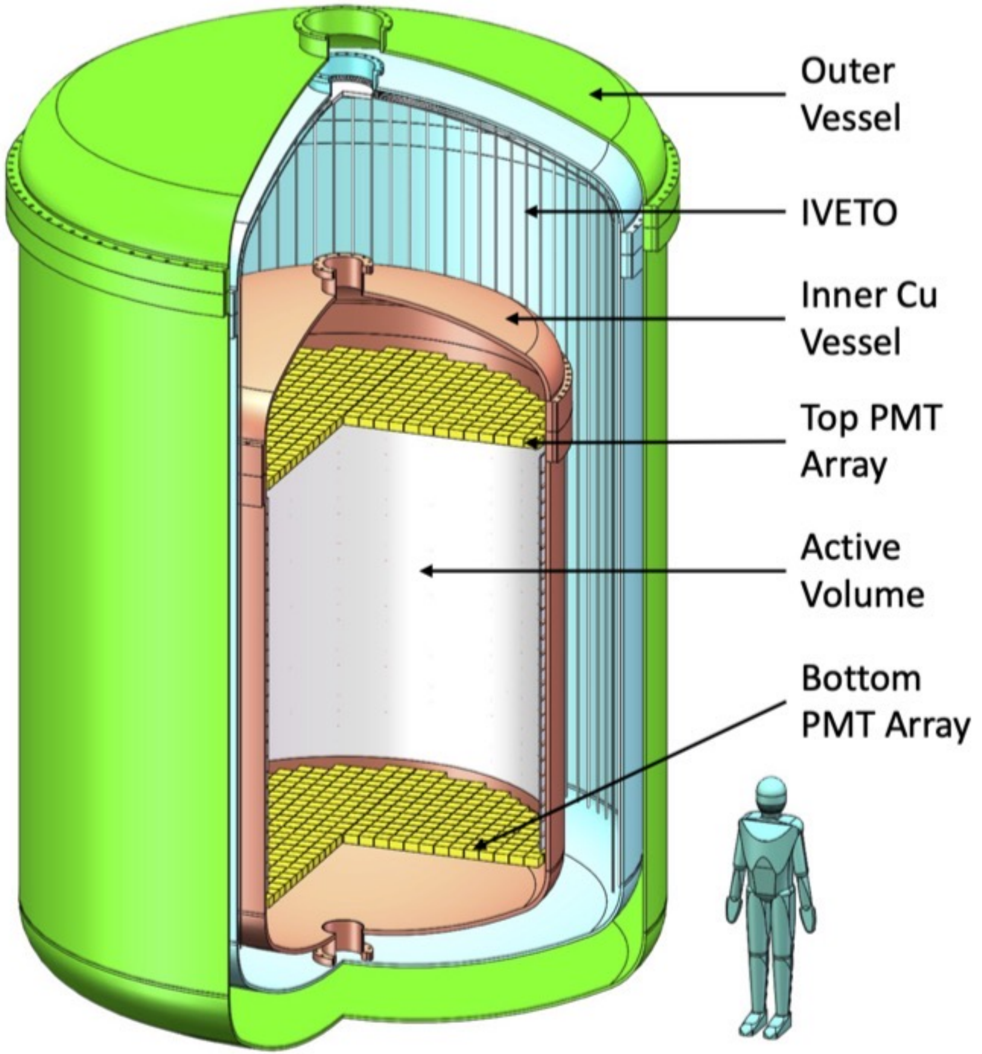




\+ Larger Cleaner Detector

PandaX-xT: Multi-ten-tonne Liquid Xenon Observatory

- Active target: 43 tons of Xenon
  - Test the WIMP paradigm to the neutrino floor
  - Explore the Dirac/Majorana nature of neutrino
  - Search for astrophysical or terrestrial neutrinos and other ultra-rare interactions
- Notable detector improvements:
  - High-granularity, low-background 2-in PMT array
  - Cu/Ti vessel for improved radiopurity
  - Inner liquid scintillator veto



SCPMA 68, 221011 (2025)

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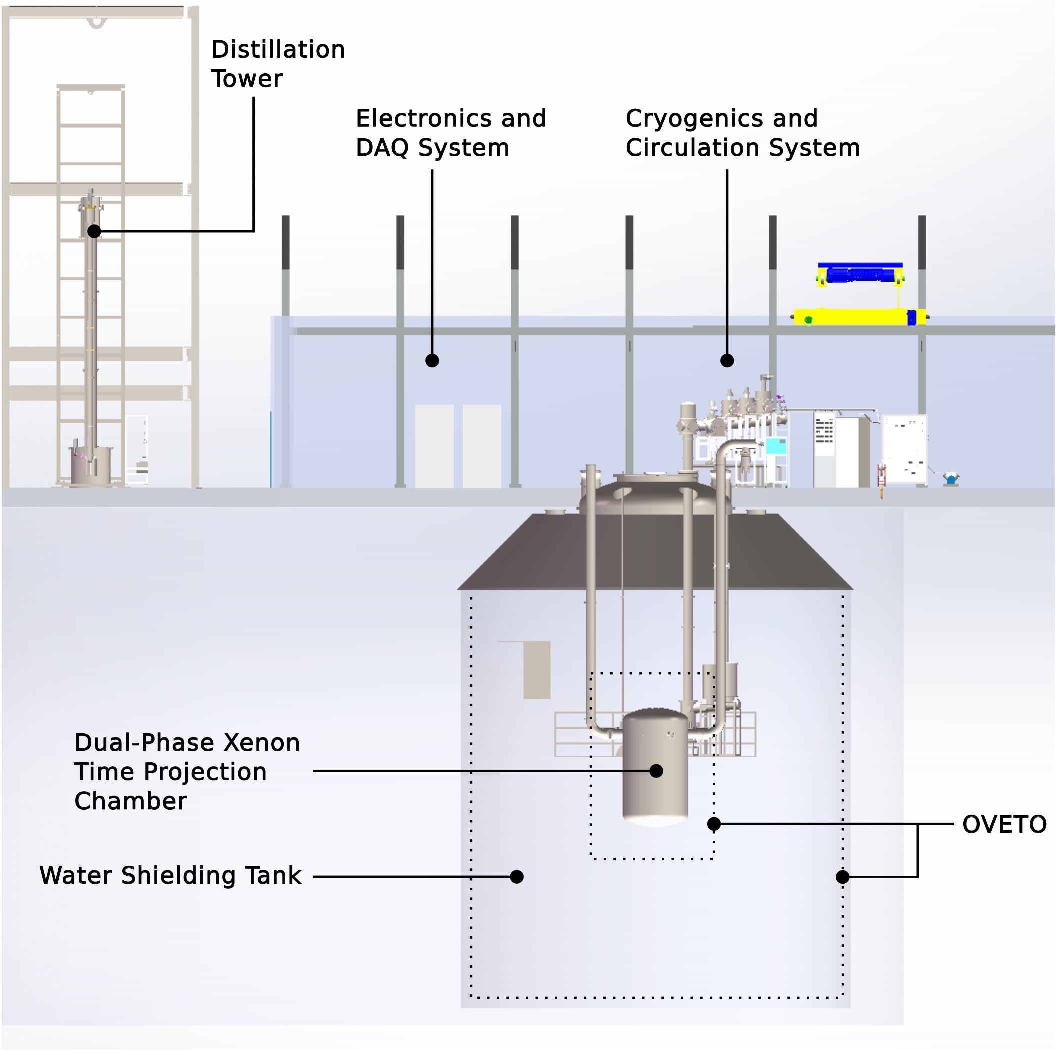

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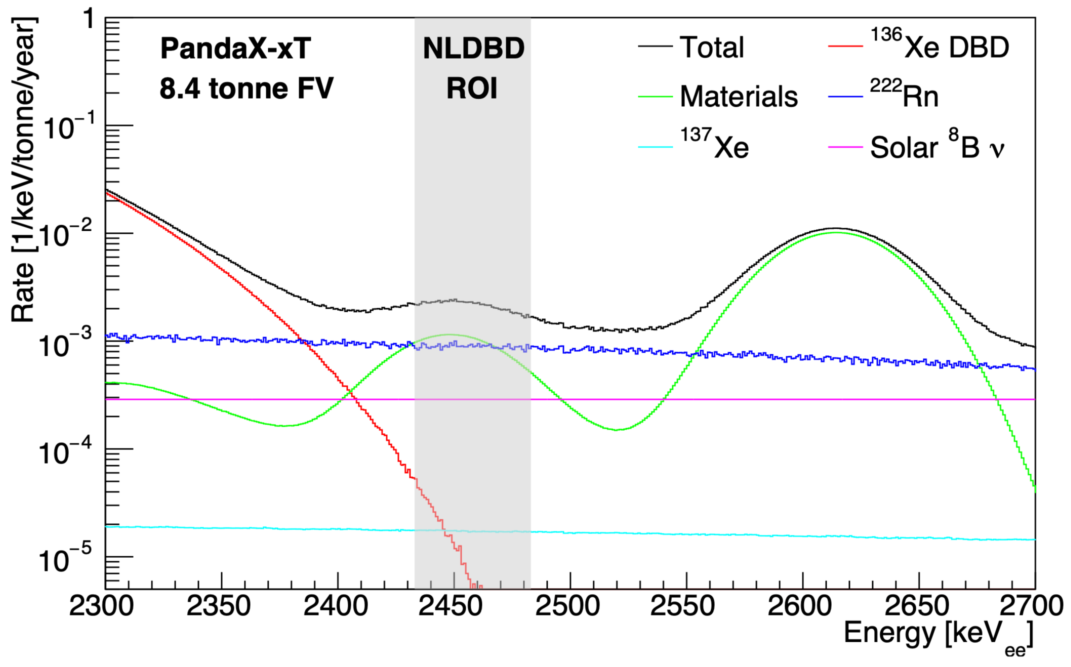
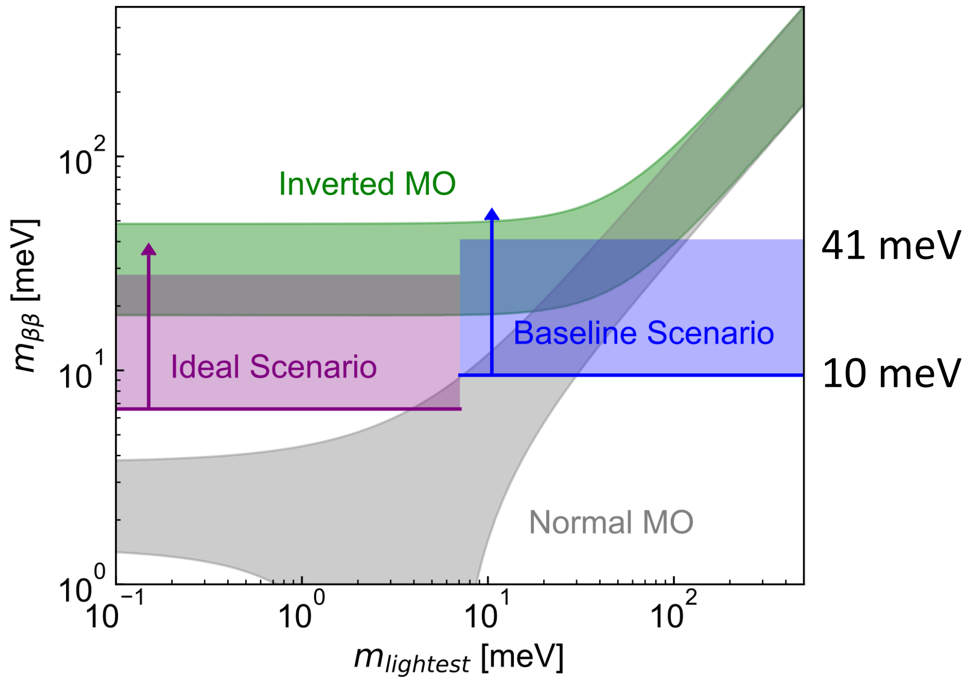
PandaX-xT for 0νββ

- 4 ton of ^{136}Xe: one of the largest 0νββ experiments
- Effective self-shielding: Xenon-related background dominates in the 8.4-tonne center FV

	Baseline (1/tonne/year)	Ideal (1/tonne/year)
Photosensors	1.4×10^{-2}	2.8×10^{-3}
Copper vessel	3.2×10^{-2}	6.3×10^{-3}
^{222}Rn	4.5×10^{-2}	-
^{136}Xe DBD	5.2×10^{-4}	5.2×10^{-4}
^{137}Xe	8.7×10^{-4}	8.7×10^{-4}
Solar ^{8}B ν	1.4×10^{-2}	1.4×10^{-2}
Total	$\mathbf{1.1\times10^{-1}}$	$\mathbf{2.4\times10^{-2}}$





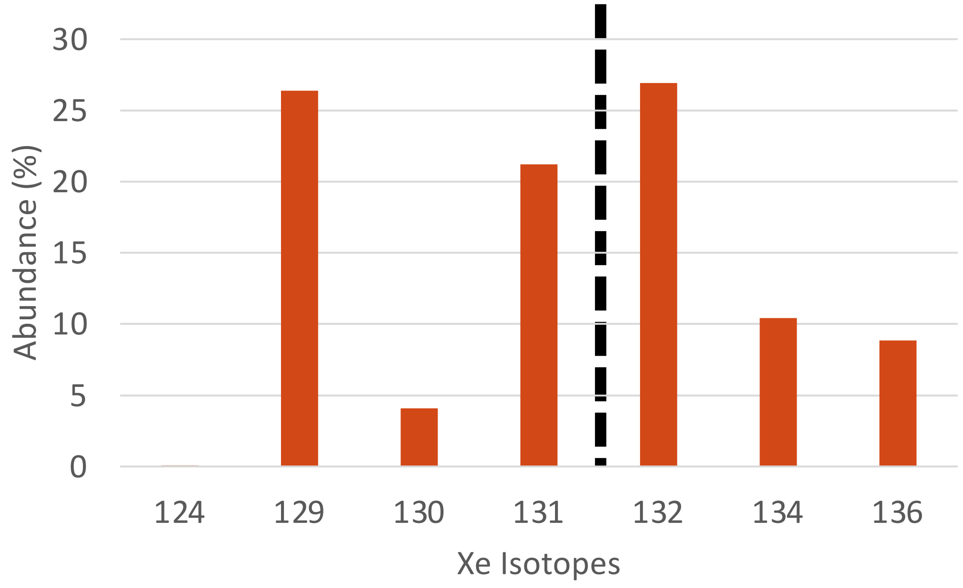
Head-to-head with other DM/0νββ experiments

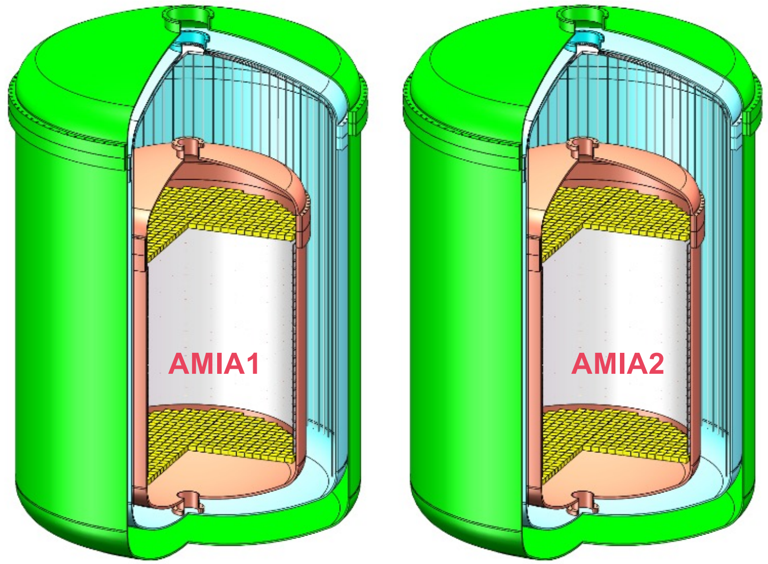
	Bkg rate (/keV/ton/y)	Energy resolution	Mass (ton)	Run time	Sensitivity/Limit (90% CL, year)
PandaX-4T	6	1.9%	4	94.9 days	$> 10^{24}$
XENONnT	1	0.8%	6	1000 days (expected)	2×10^{25}
LZ	0.3	1%	7	1000 days (expected)	1×10^{26}
KamLAND-ZEN	0.002	5%	0.8 (^{136}Xe)	1.5 years	2.3×10^{26}
nEXO	0.006	1%	5 (^{136}Xe)	10 years	1.35×10^{28} **
DARWIN	0.004*	0.8%	40	10 years	2×10^{27}
PandaX-xT	0.002*	1%	43	10 years	3×10^{27}

* Major difference from cosmogenic ^{137}Xe; ** $\frac{S}{\sqrt{B}}$ sensitivity is 6×10^{27} yr, for detector performance comparison in the table.

Possible isotope seperation/enrichment

- Xenon with artificially modified isotopic abundance (AMIA) for smoking gun discovery
  - A split of odd and even nuclei
  - Further enrichment of ^{136}Xe
  - to improve sensitivity to spin-dependence of DM-nucleon interactions and $0\nu\beta\beta$





Neutrinoless double beta decay with PandaX

- PandaX is a multi-physics program with xenon TPCs
- PandaX-4T presented competitive results on double beta decays with natural xenon
  - ^{134}Xe and ^{136}Xe 2νββ (0νββ)
- PandaX-xT will be one of the most competitive 0νββ experiments
- "Wish-list" for NME: More concrete half-life prediction for ^{134}Xe

Thank you very much

We welcome new collaborators

at PandaX-xT

PandaX
PARTICLE AND ASTROPHYSICAL XENON TPC