PandaX Experiment: Double Weak Decays

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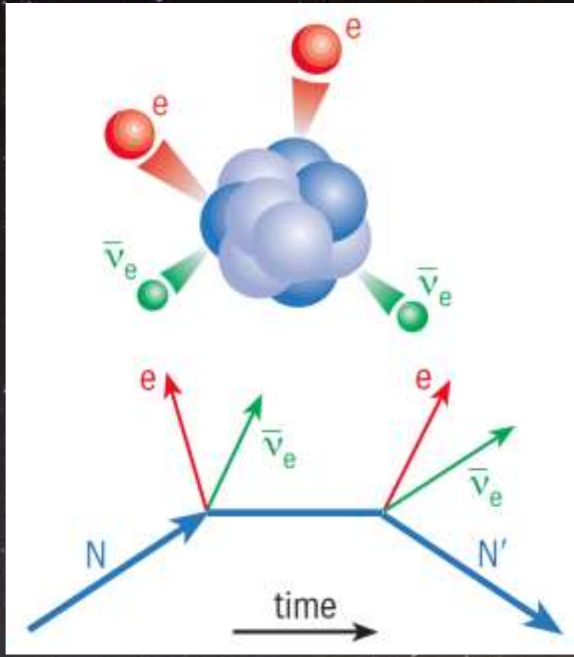
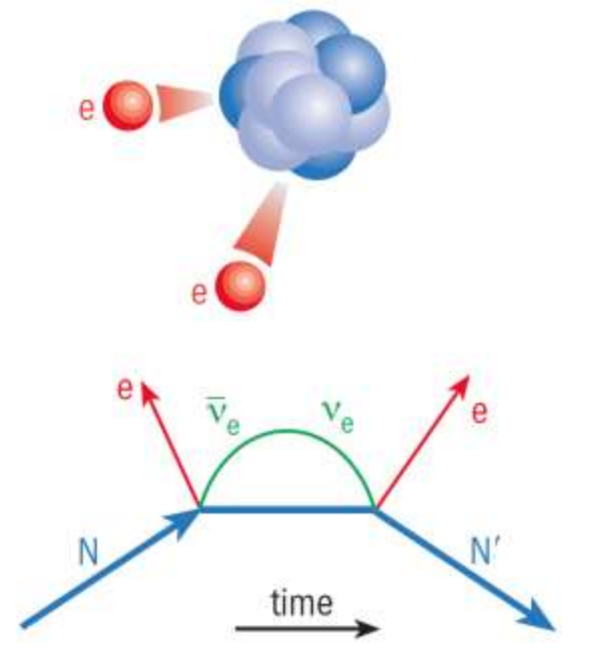
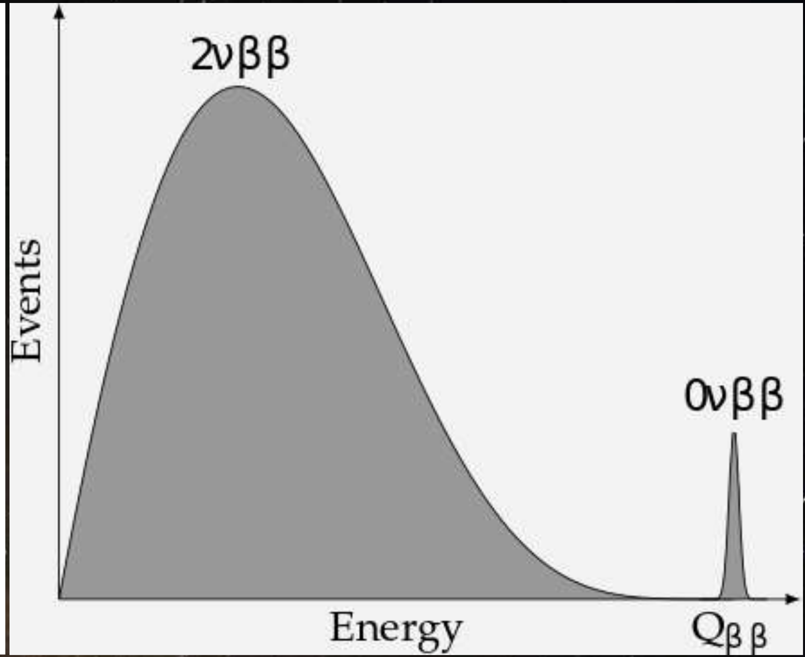
Neutrinos are Dirac or Majorana?

$$\bar{\nu} = \nu$$

Double Beta Decay ($2\nu\beta\beta$)
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)







Majorana neutrino may be an important link in connecting to matter-antimatter asymmetry in our universe

$0\nu\beta\beta$ probes the nature of neutrinos

- Majorana or Dirac
- Lepton number violation
- Measures effective Majorana mass: relate $0\nu\beta\beta$ to the neutrino oscillation physics

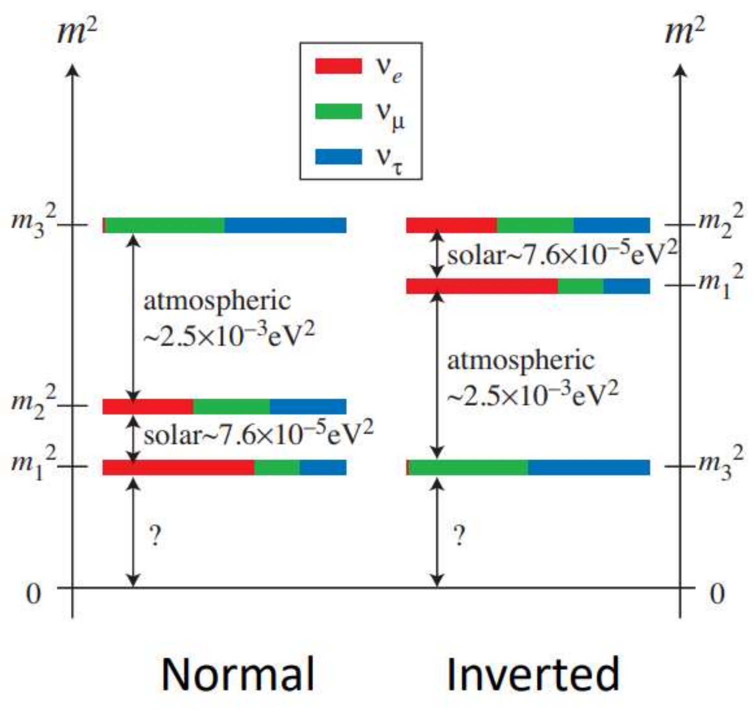
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

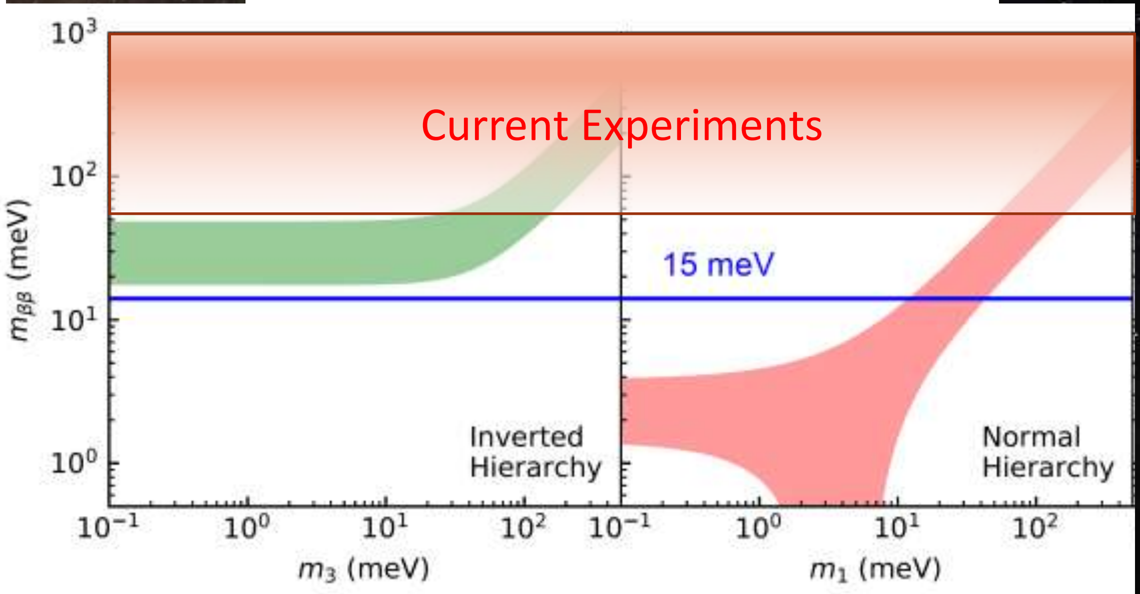
Phase space factor

Nuclear matrix element

Effective Majorana neutrino mass:

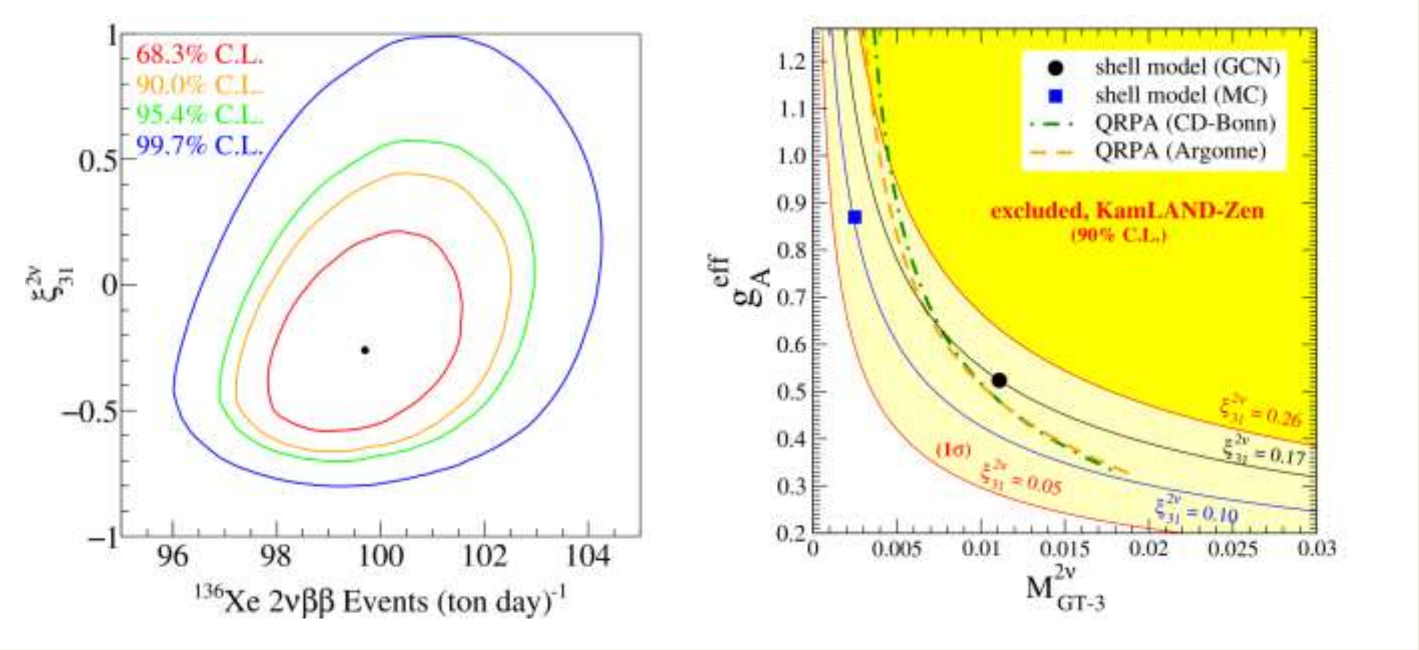
$$|\langle m_{\beta\beta}\rangle| = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$



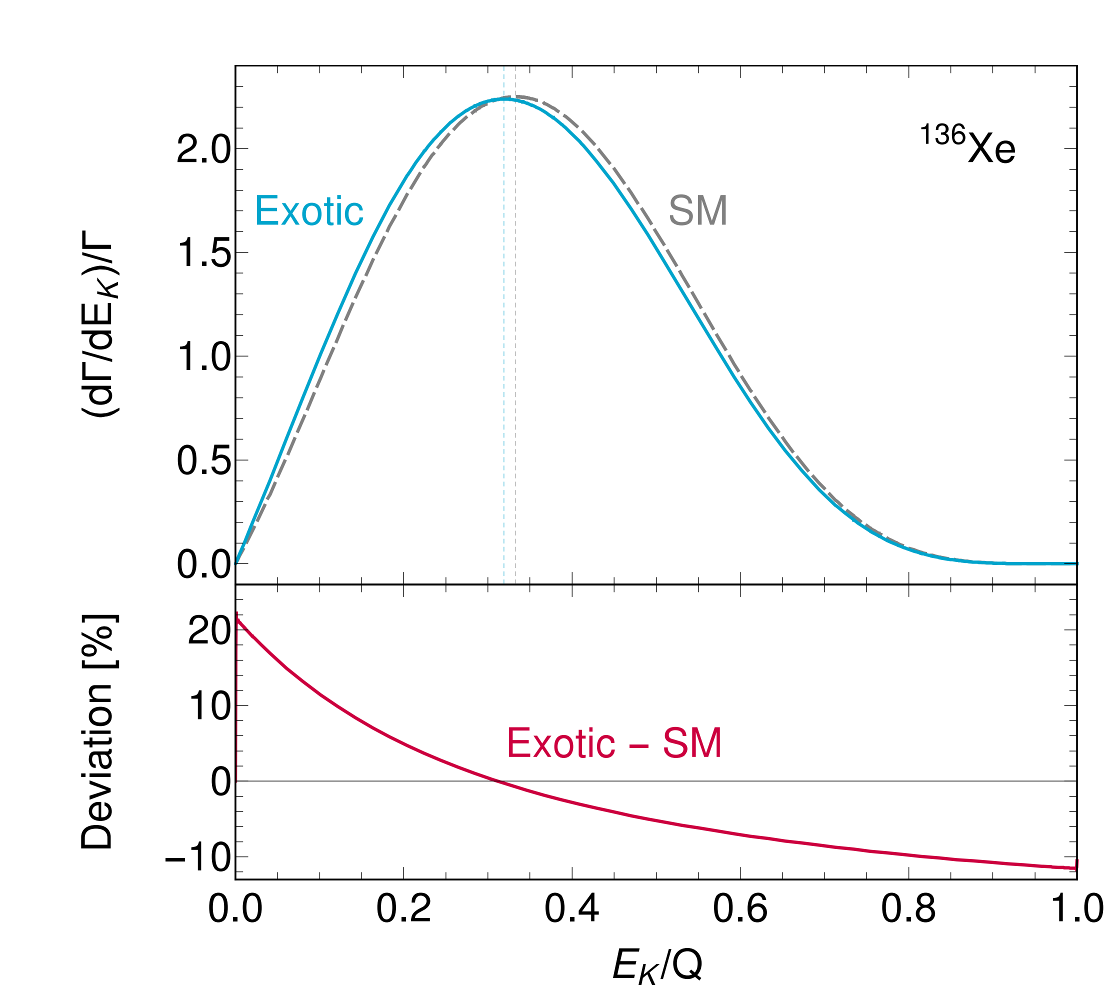


$2\nu\beta\beta$ probes the new physics

- Determination of Nuclear Matrix Elements (NME) of $2\nu\beta\beta$
- $0\nu\beta\beta$ half-life calculation
- New physics search with $2\nu\beta\beta$ spectrum



Phys.Rev.Lett. 122 (2019) 19, 192501



Phys.Rev.Lett. 125 (2020) 17, 171801

Overview of PandaX

Dark matter WIMP Searches

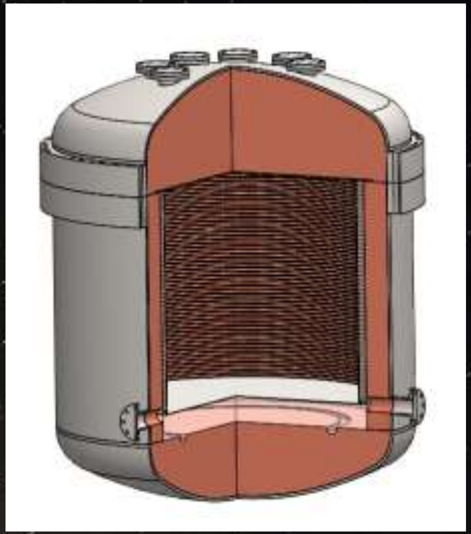
$2\nu\beta\beta$ and $0\nu\beta\beta$ Research

PandaX-I: 120kg LXe (2009 – 2014)

PandaX-II: 500kg LXe (2014 – 2019)

PandaX-4T: 3.7T LXe

PandaX-xT (future)

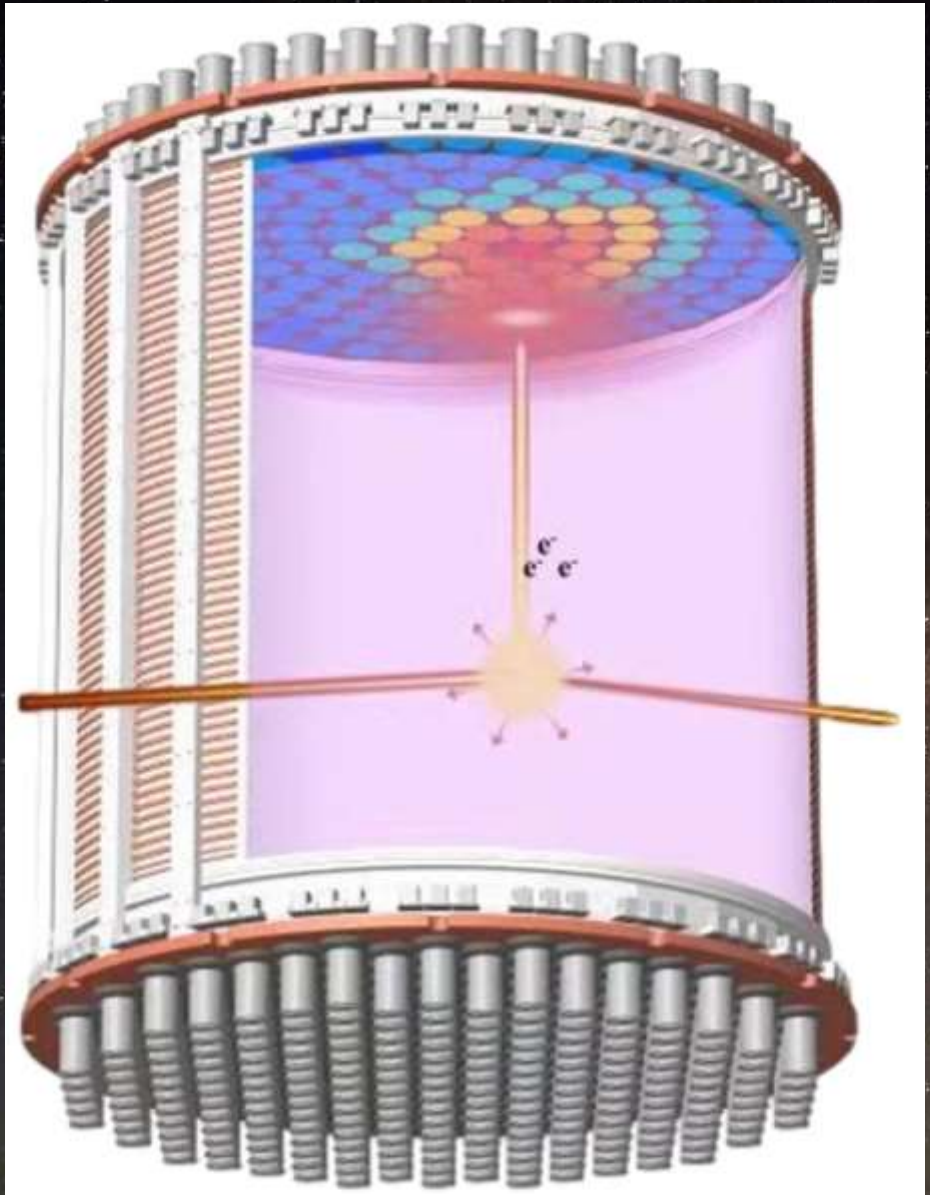


PandaX-III: HPXe 100 kg scale (R&D for the future)

Liquide natural Xe (8.9% ^{136}Xe)

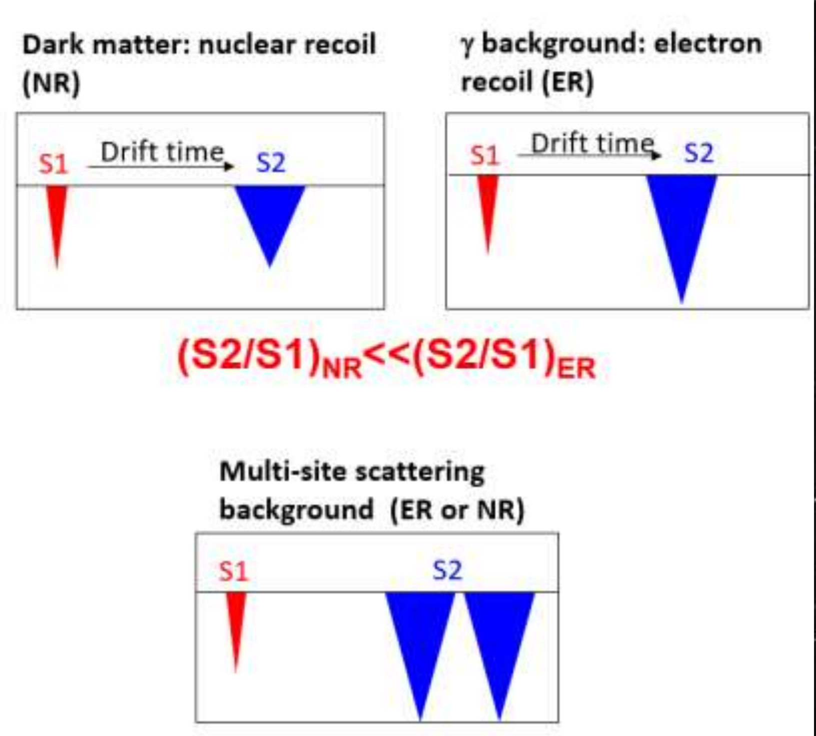
High pressure Xe (90% ^{136}Xe)

Dual-phase xenon time projection chamber (TPC)



Detector capability:

- 3D reconstruction and fiducialization (self-shielding)
- ER/NR PID
- Single-Site (SS) and Multi-Site (MS) discrimination
- Calorimeter from sub keV – few MeV



Multiple physics in a wide energy range

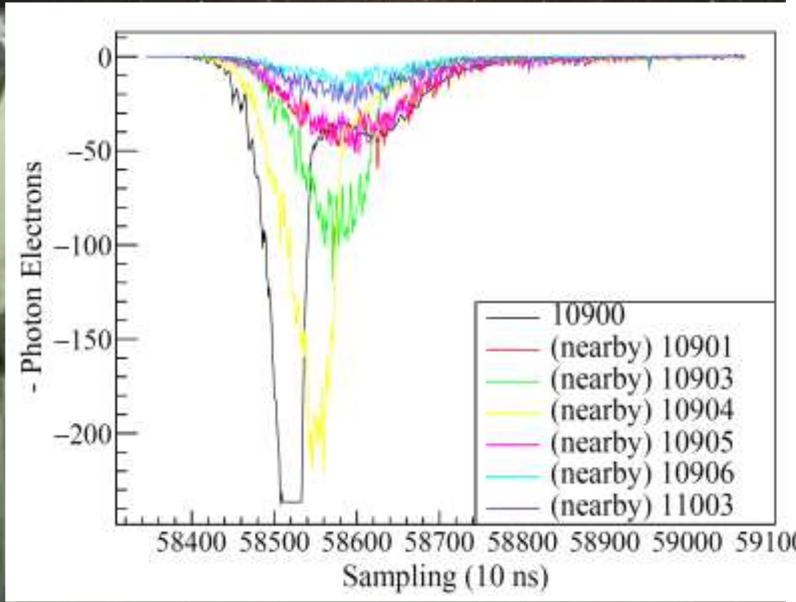
	Sub-keV	1 keV	10 keV	100 keV	1 MeV	10 MeV
Xe-136 (~9%)					2νββ / 0νββ	
Xe-134 (~10%)					2νββ / 0νββ	
Xe-124 (~0.1%)				2νECEC		
Xe all isotopes	^{8}B solar ν and light DM	WIMP and other DM models		solar pp ν		

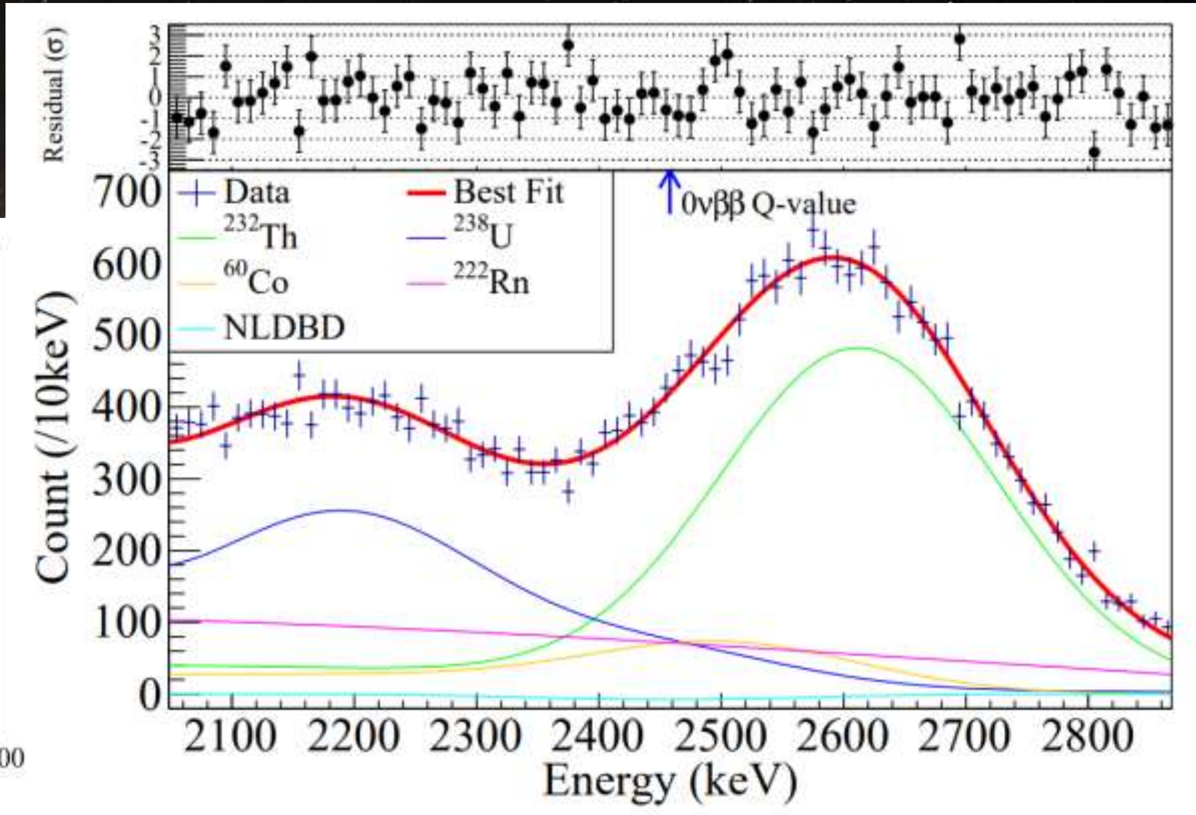
see Qing Lin's talk

this talk

$0\nu\beta\beta$ search with PandaX-II

- PandaX-II: 580 kg natural xenon, ~ 50 kg ^{136}Xe, 403.1 days' dark matter data
- ^{136}Xe half-life limit 2.4×10^{23} yr at 90% CL
- First $0\nu\beta\beta$ result with dual phase natural xenon detector (dark matter experiment)
- To verify the feasibility of $0\nu\beta\beta$ search
- Challenges:
  - Background level and detector
  - Energy resolution in MeV range





Chinese Physics C 43, 113001 (2019)

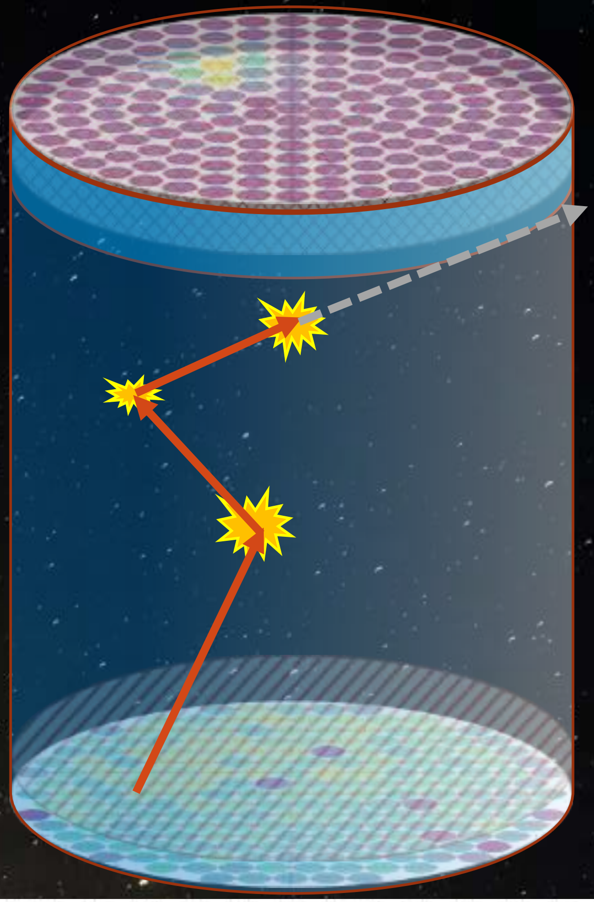
PandaX-4T experiment

- Third generation of the PandaX experiments located at CJPL-II
- Dual-phase Xe TPC: 1.2 m (D) ×1.2 m (H)
- Sensitive volume: 3.7 ton LXe
- Total volume: 5.6 ton LXe
- 3-inch PMTs: 169 top / 199 bottom
- Water shielding: 10 m (D) ×13 m (H)
- Data taking:
  - Commissioning Run0 : ~95 days
  - Physics Run1: ~164 days

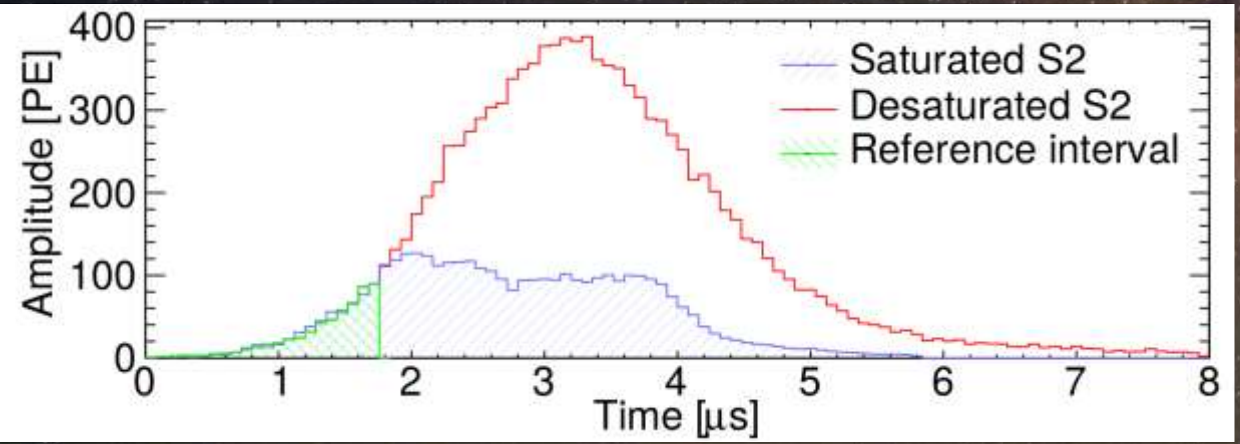
15 institutions and ~80 members

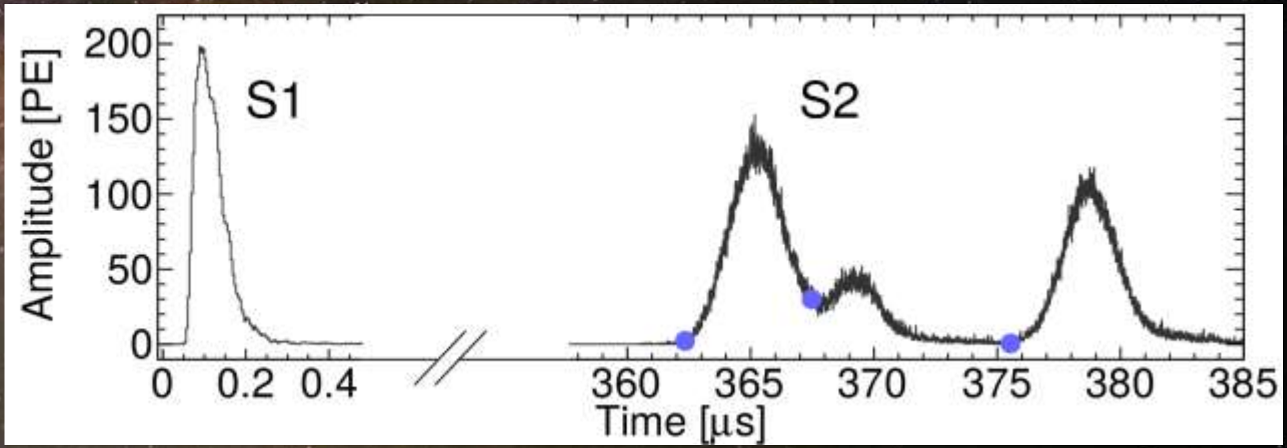
PandaX-4T @ CJPL-II B2

PandaX-4T: Extending DM detector response to MeV range



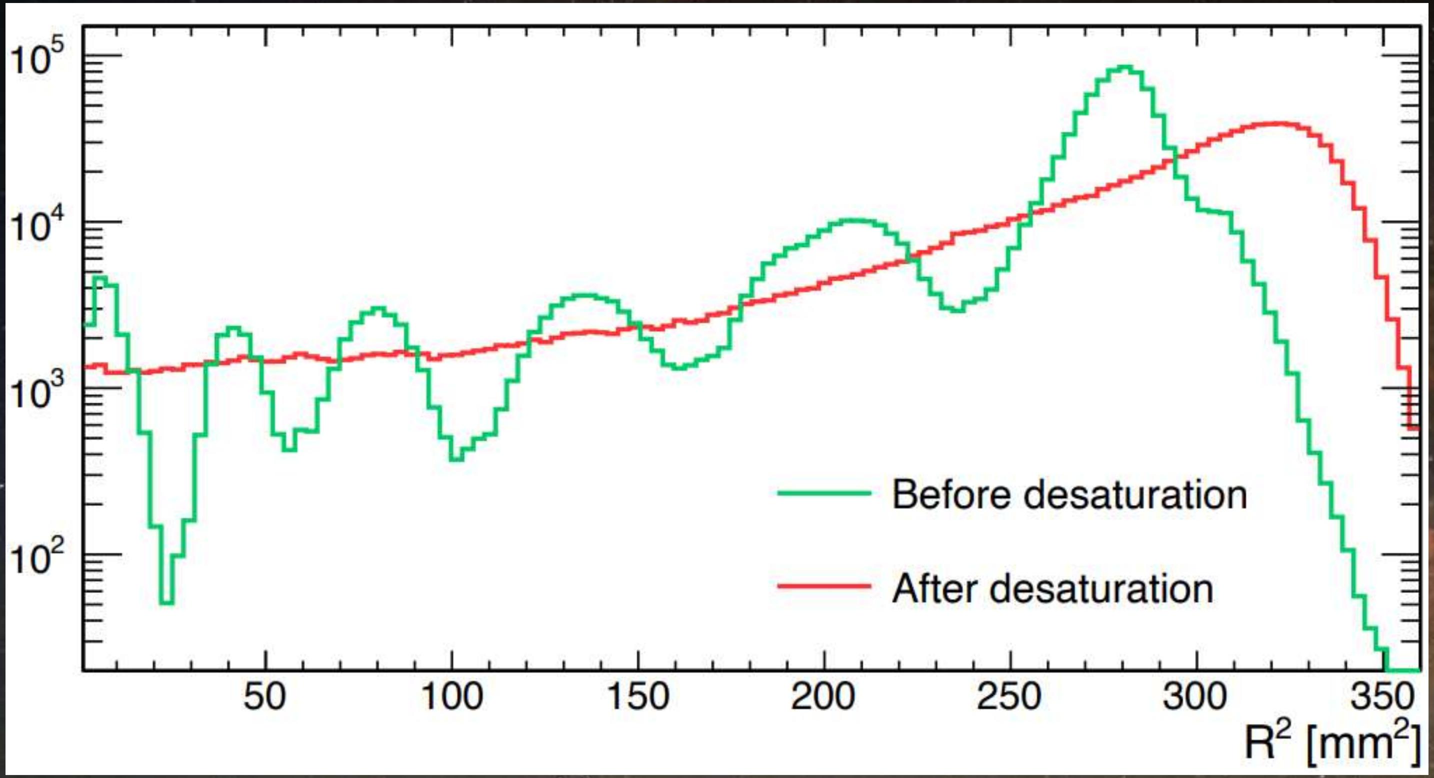
- PMT bases suffer serious saturation for MeV range events
- Match the rising slope of the saturated to the non-saturated templates in the same events→ True charge collected
- For events in the energy range of 1 to 3 MeV, the average correction factor is ~3.0 for the top PMT array
- MeV gamma events are mostly multiple-scattering events; while signals ($2\nu\beta\beta$ and $0\nu\beta\beta$) are mostly single site (SS)

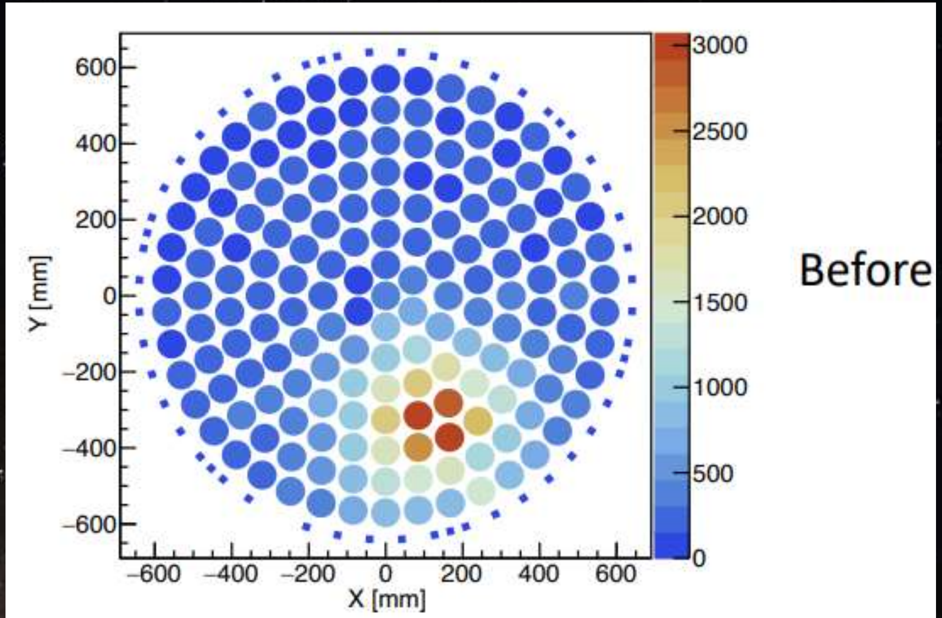


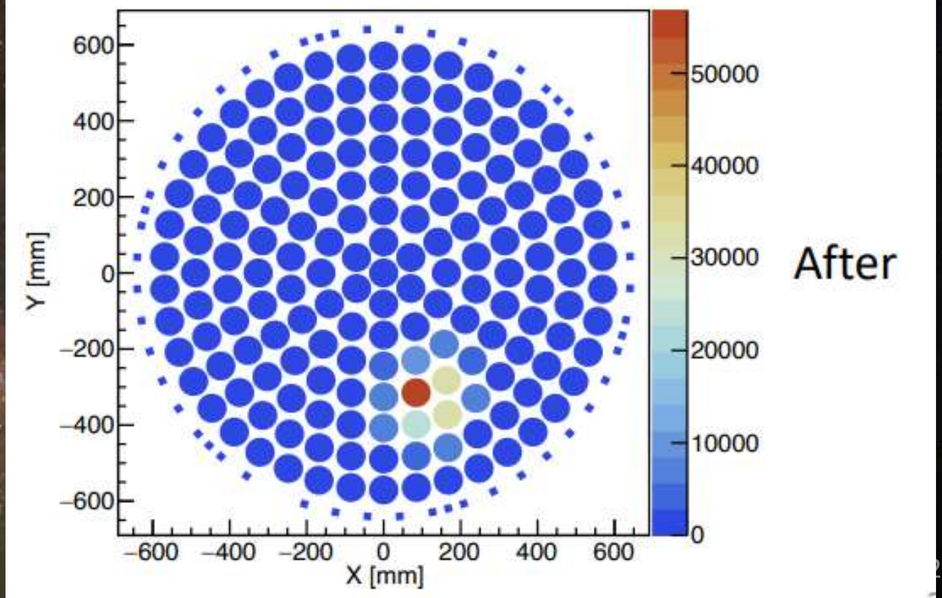


Position reconstruction improvement with desaturation

- Position reconstruction based on PAF (photon acceptance function) methods developed in DM analysis
- Reconstruction at MeV energy range is significantly improved with desaturation
- Removed the band structure in R^2 distribution

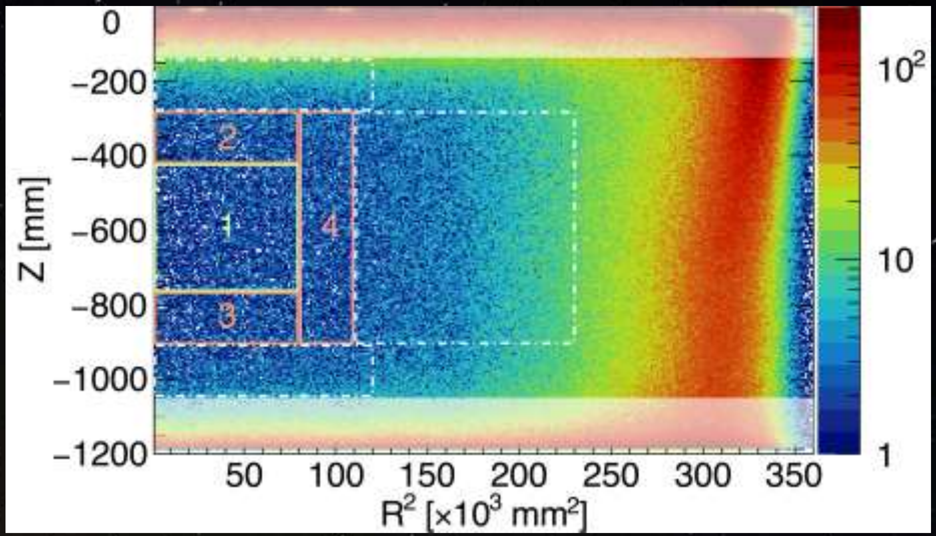


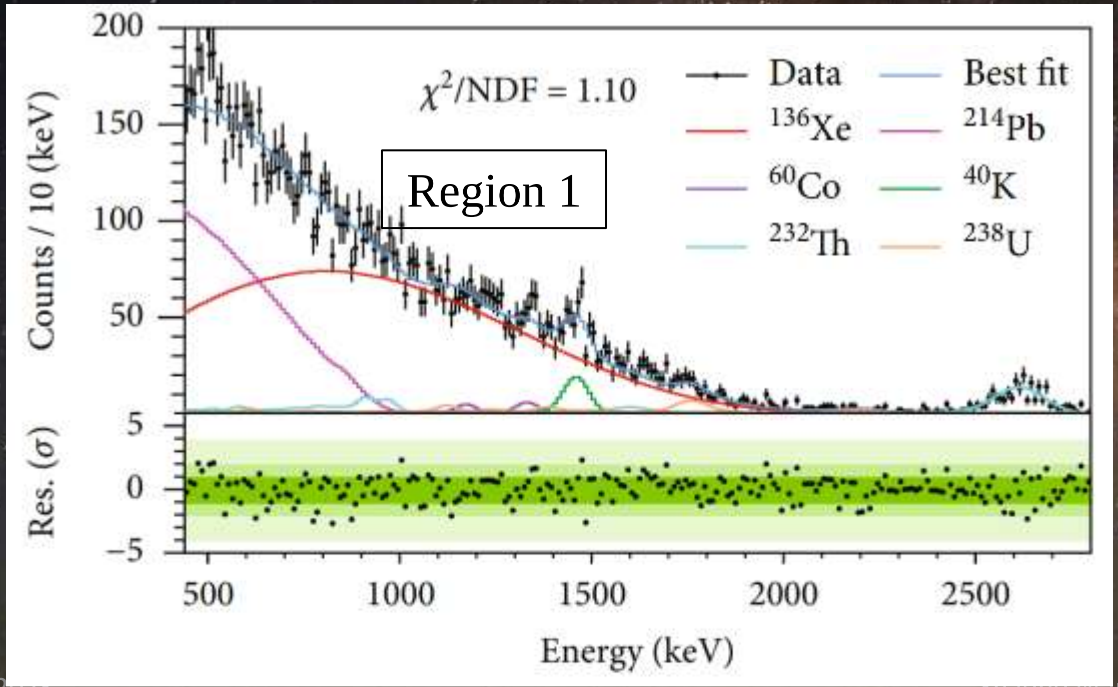


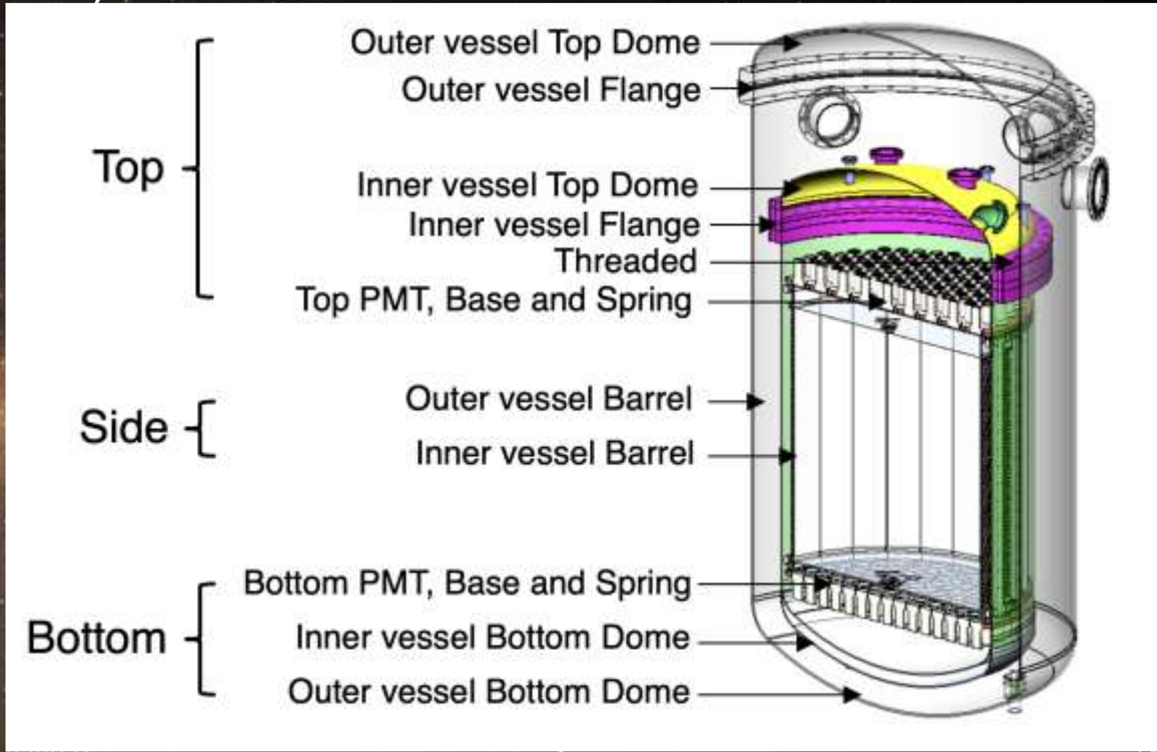


Segmented FV and simultaneous

- Material components are grouped into Top, Bottom and Side categories, each with ^{60}Co, ^{40}K, ^{238}U and ^{232}Th.
- FV is optimized based on both background level and position reconstruction non-linearity, then segmented into four regions.
- Binned Poisson likelihood fitting on SS energy spectrum is performed simultaneously in four regions.
- Outer regions are used to check material background model, and data-MC is consistent at 1% level.

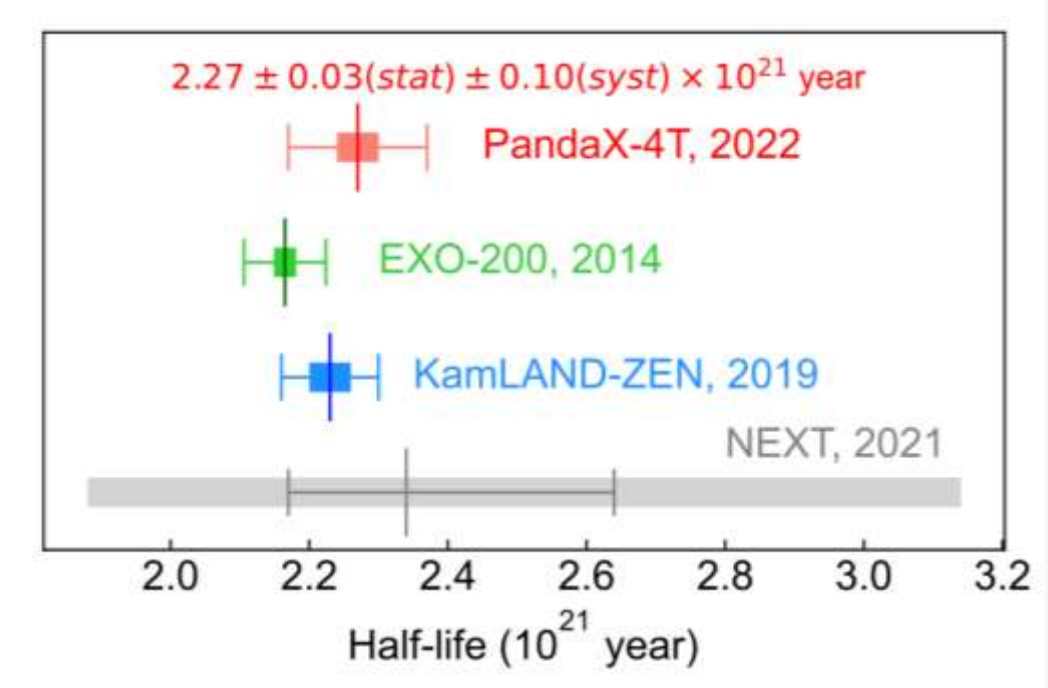






^{136}Xe $2\nu\beta\beta$ half-life measurement

- ^{136}Xe $2\nu\beta\beta$ half-life measured by PandaX-4T Run0: $2.27 \pm 0.03(\text{stat.}) \pm 0.10(\text{syst.}) \times 10^{21}$ year
- Comparable precision with leading results
- First such measurement from a dark matter detector with natural xenon
- 440 keV – 2800 keV range is the widest ROI
- The first step for $0\nu\beta\beta$ and the other new physics
- *"in-situ"* material background fitting results compatible and more precise than HPGe assay



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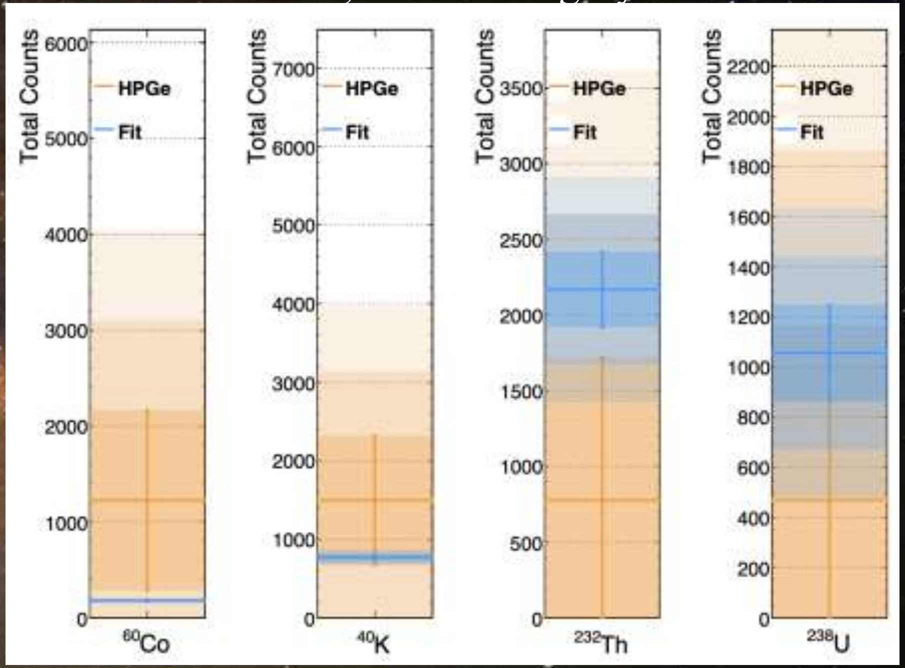
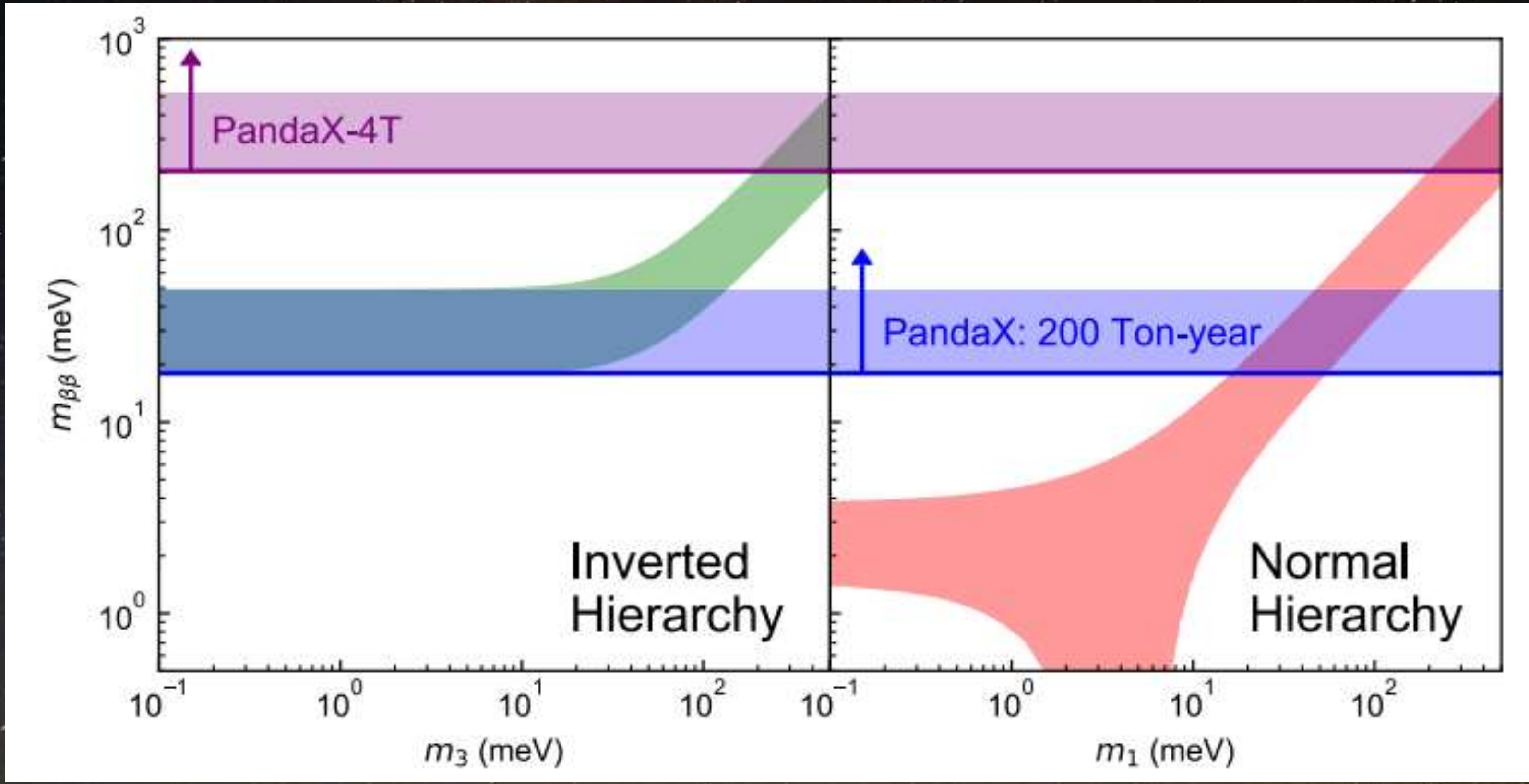
Material, "Side" category



$^{136}Xe\ 0\nu\beta\beta$ search in PandaX-4T

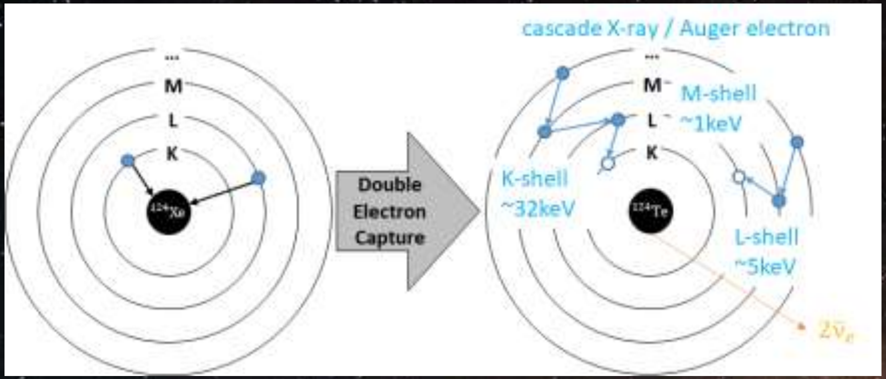
	Bkg rate (/keV/ton/y)	Energy resolution	FV mass (kg)	Run time	Sensitivity/Limit (90% CL, year)
PandaX-II	~200	4.2%	219	403.1 days	2.4×10^{23}
PandaX-4T-Run0	~10	~2%	~650	94.9 days	$> 10^{24}$

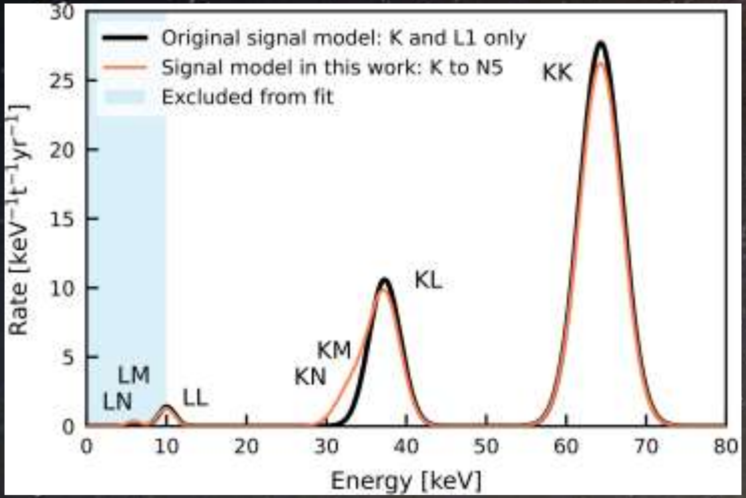


- Commissioning Run0 + Physics Run1 analysis on-going
- Improvement of the incoming Run2:
  - Better energy resolution and linearity
  - Better SS/MS discrimination

^{124}Xe 2νECEC half-life measurement

$$(A, Z) + 2e^- \rightarrow (A, Z-2) + (2\nu_e)$$





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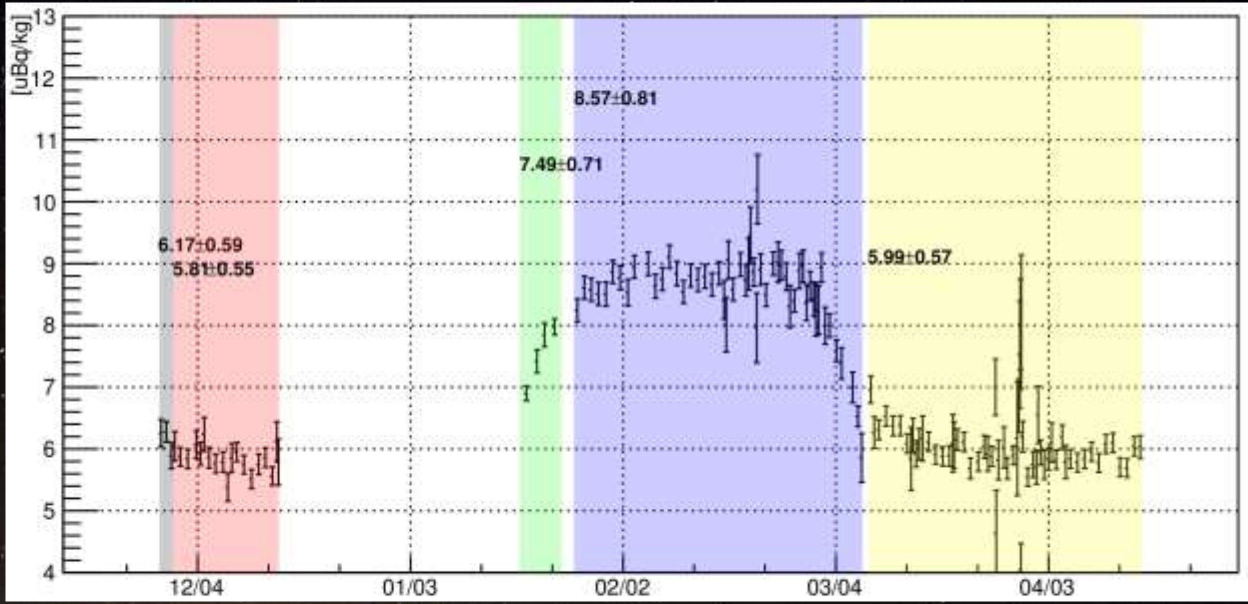
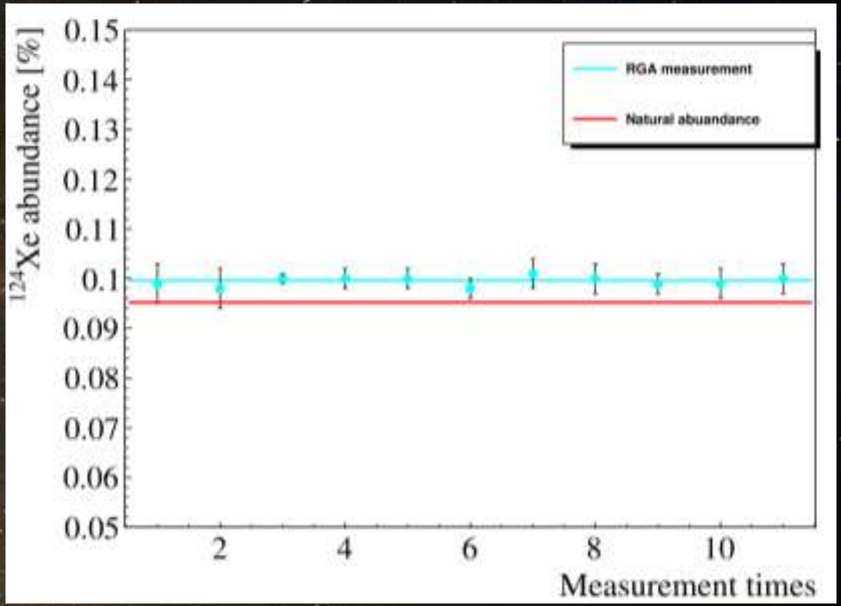
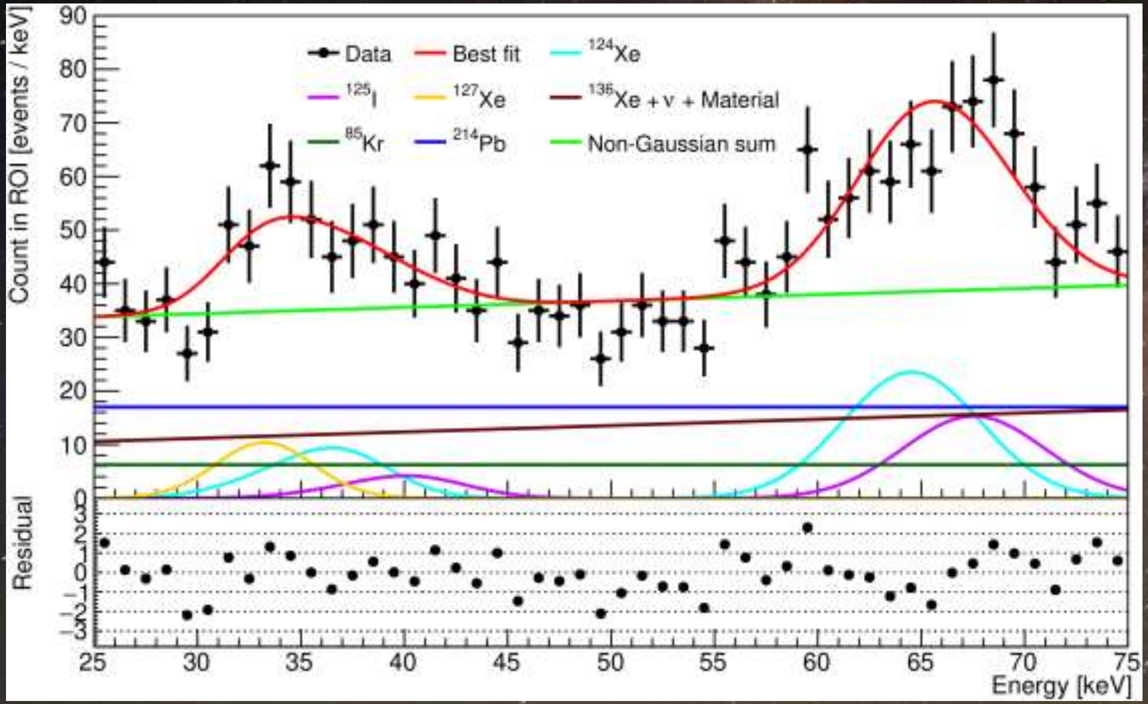


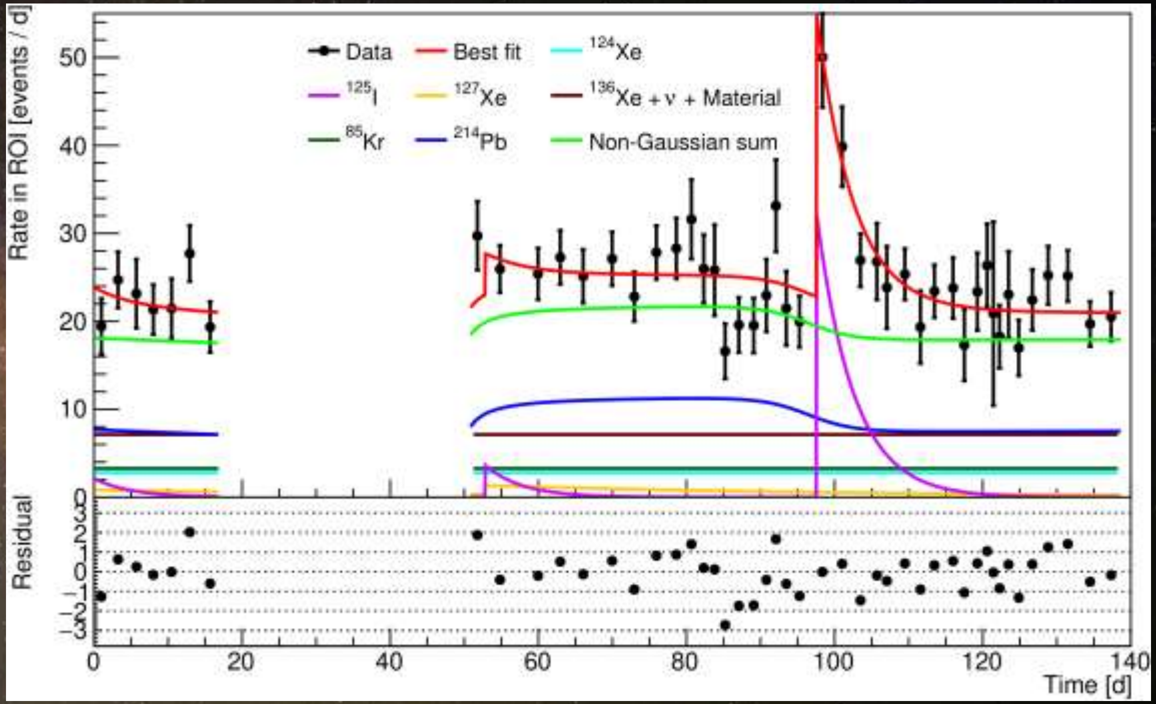
- Background time evolution is modeled and added to likelihood fitting
- Use commissioning Run0 open data to develop the method
- ^{124}Xe abundance measured as (0.100±0.001)%, larger than the natural abundance by ~5%



Energy spectrum + time evolution likelihood fit

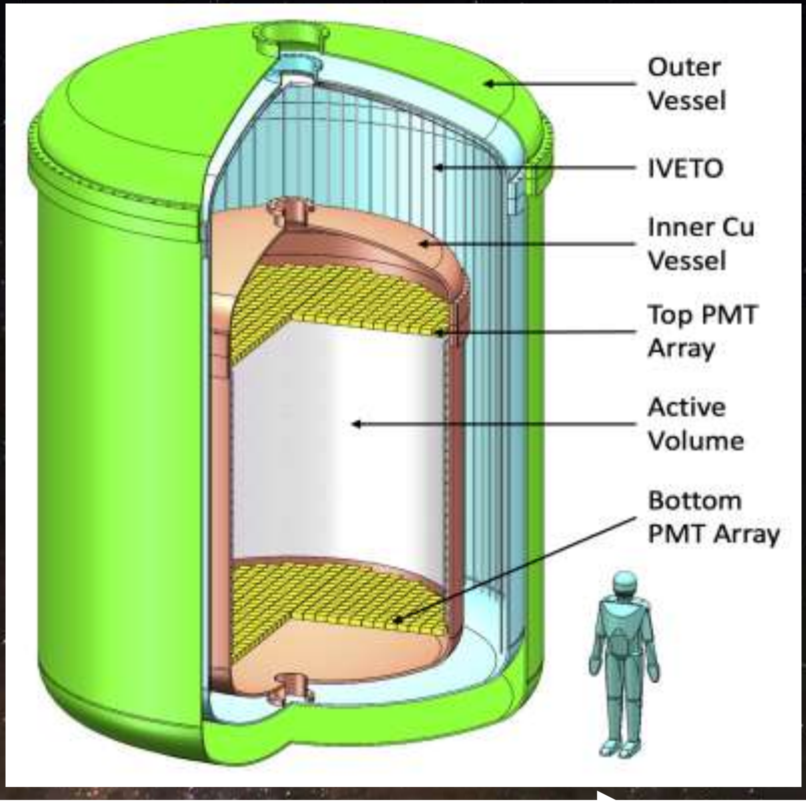
- Two fits were performed on Run0 open data for consistency check:
  - Unbinned 2-dimentional fit on parameter space of (energy, time)
  - Binned simultaneous fit on energy + time
- Fitting results are more precise compared to the fit on energy spectrum only
- Commissioning Run0 + Physics Run1 blind analysis on-going

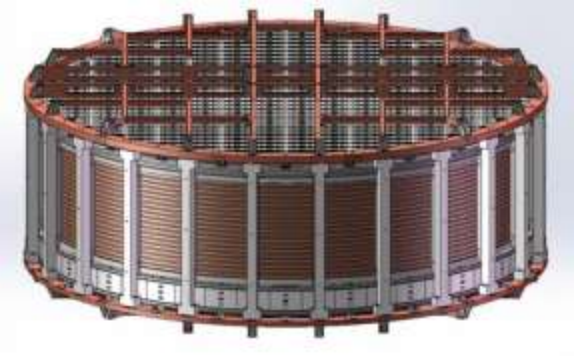


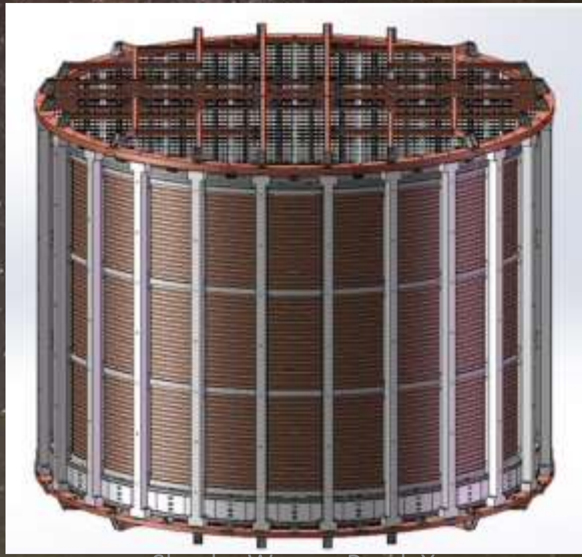


PandaX-xT

- 2.7 meters in diameter and height
- Total volume of 47-ton natural xenon
- Active xenon mass of 43-ton
- Upgradable based on the xenon amount in possession





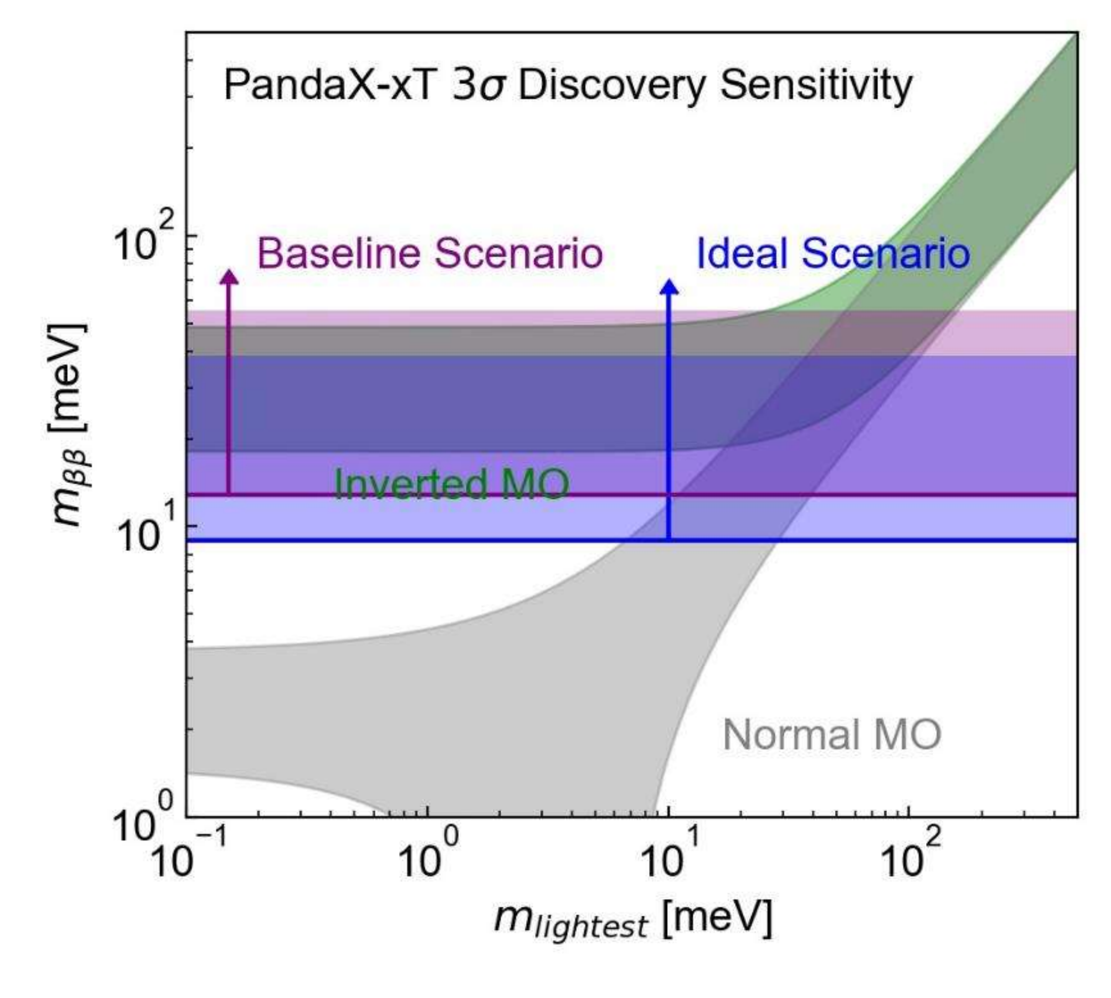


Sensitivity to $0\nu\beta\beta$ in PandaX-xT

Assumptions:

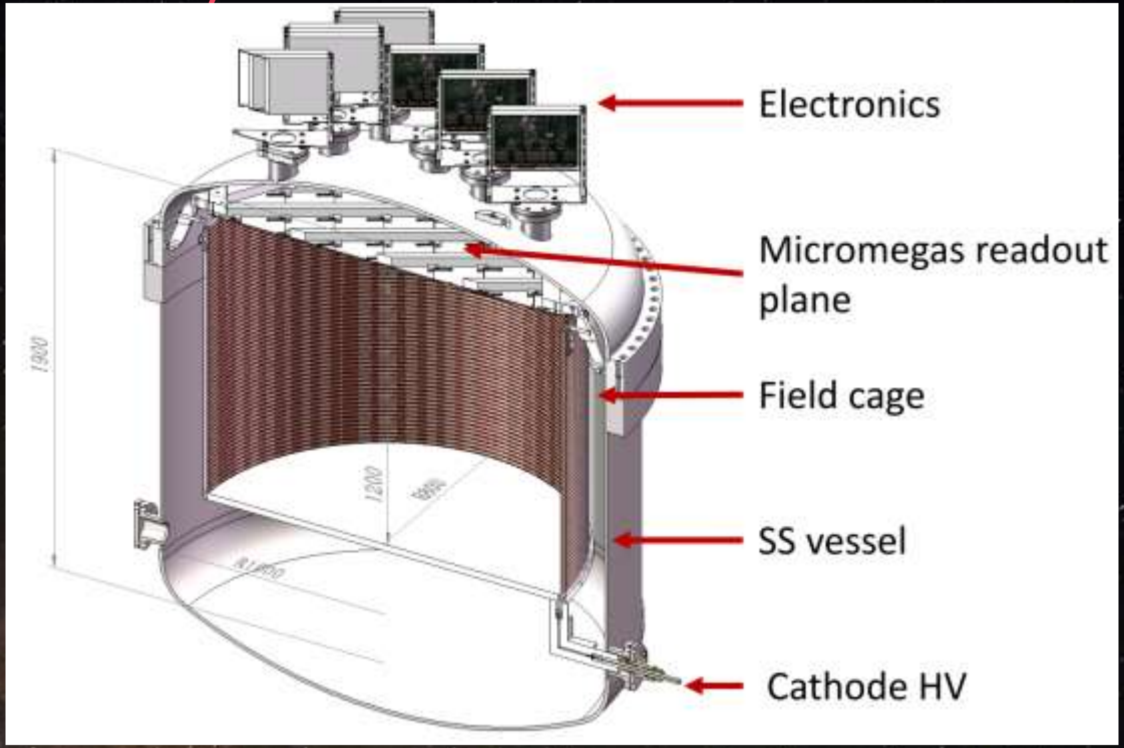
- 1% σ/E, RoI within 50 keV of Q value, two background assumptions
- 10 years × 8.4 ton FV (natural xenon, with 8.9% ^{136}Xe)
- 3σ discovery sensitivity to $m_{\beta\beta}$: 13-56 meV baseline, 9-39 meV ideal

	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	**1.1×10^{-1}**	**2.4×10^{-2}**

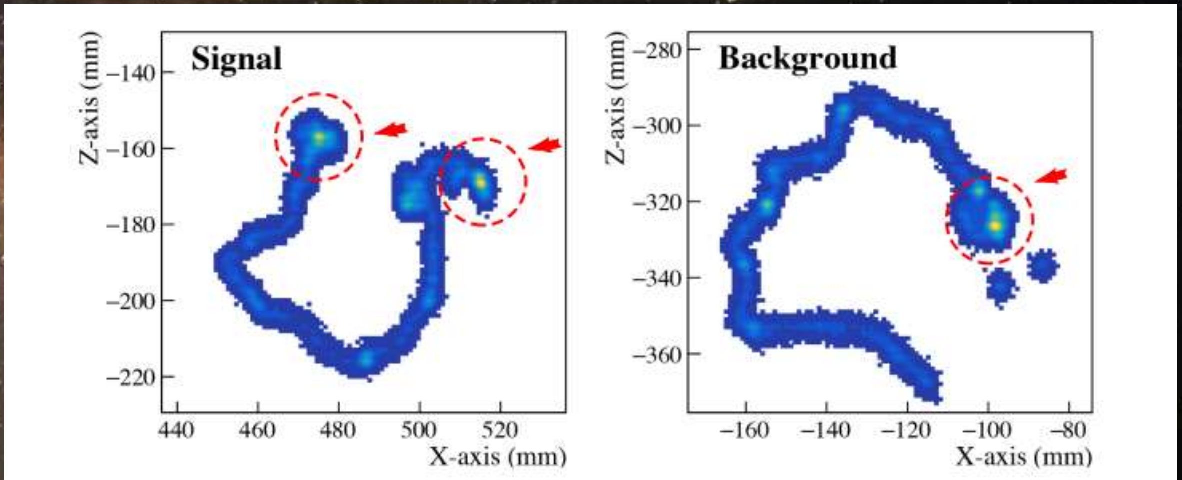


R&D towards a tracking calorimeter (PandaX-III)

- PandaX-III: 10 bar Xe-(1%)TMA (trimethylamine), ~100 kg enriched ^{136}Xe (90%)
- TPC : Single-end charge readout on the upper side, the cathode on the bottom
- 52 20X20 cm^2 Micromegas for charge readout
- Readout: 2 series of strips (x, y) of 3 mm
- Energy resolution: 3% FWHM expected at Q value of ^{136}Xe 0νββ
- Projection sensitivity: ~10^{26} yr with five years live time




Micromegas detector



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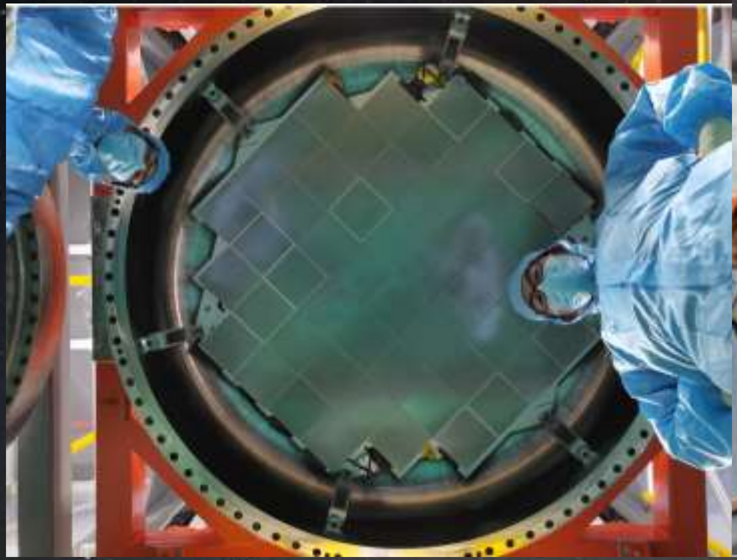
100 kg-scale demonstrator



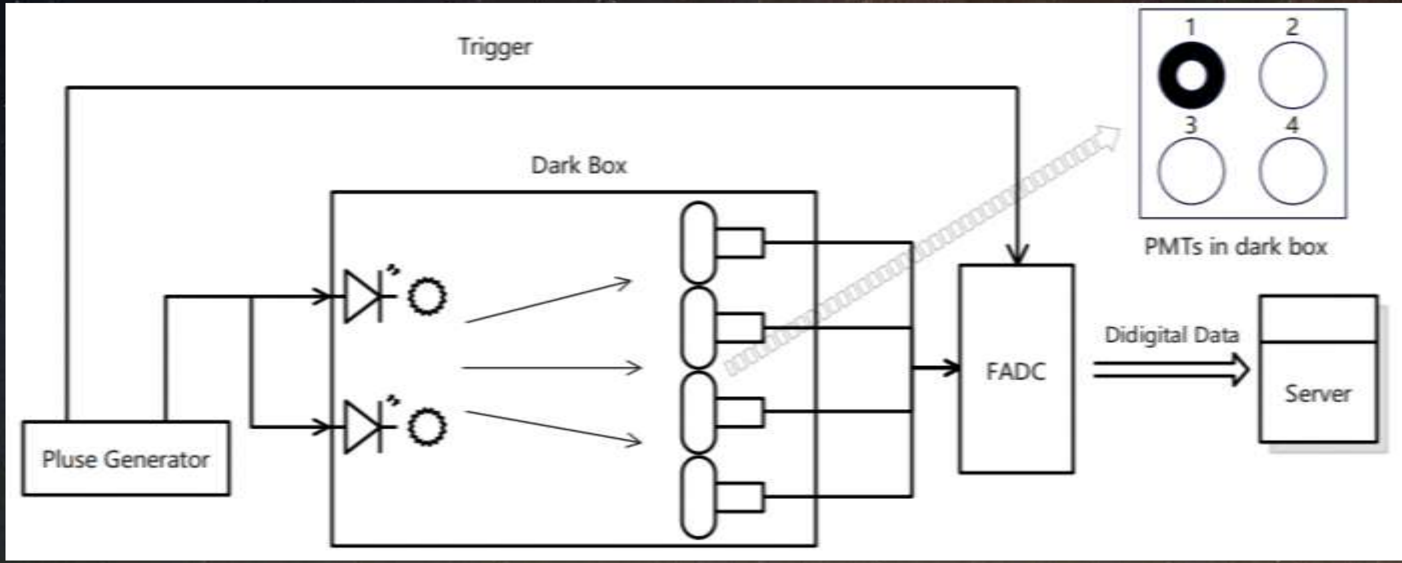
Summary

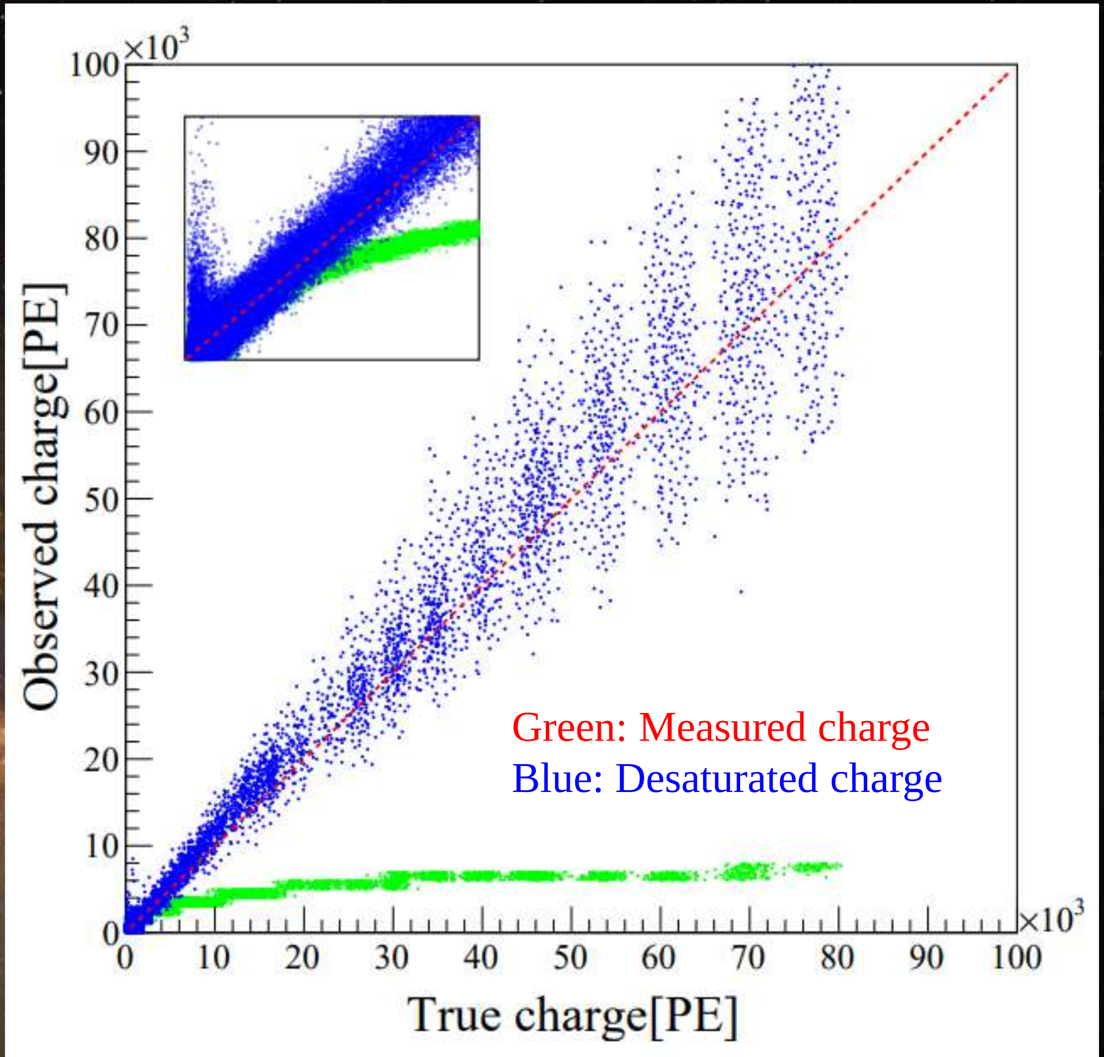
- PandaX-4T has extended the energy range from keV to MeV with dedicated analysis pipeline and calibration campaign, and therefore extended the physics reach from dark matter to double weak decays
- ^{136}Xe $2\nu\beta\beta$ half-life is precisely measured for the first time by a natural xenon detector, with much lower analysis threshold and robust background control, demonstrating the physics potential of large liquid xenon TPC on multiple fronts
- On-going analysis of double-weak decays: ^{124}Xe 2νECEC, ^{134}Xe $2\nu\beta\beta$ / $0\nu\beta\beta$, ^{136}Xe $0\nu\beta\beta$, etc
- PandaX-xT with active xenon mass of 43 tonnes is under R&D
- R&D work towards a future tracking calorimeter: 100-kg scale demonstrator in progress

Thanks！

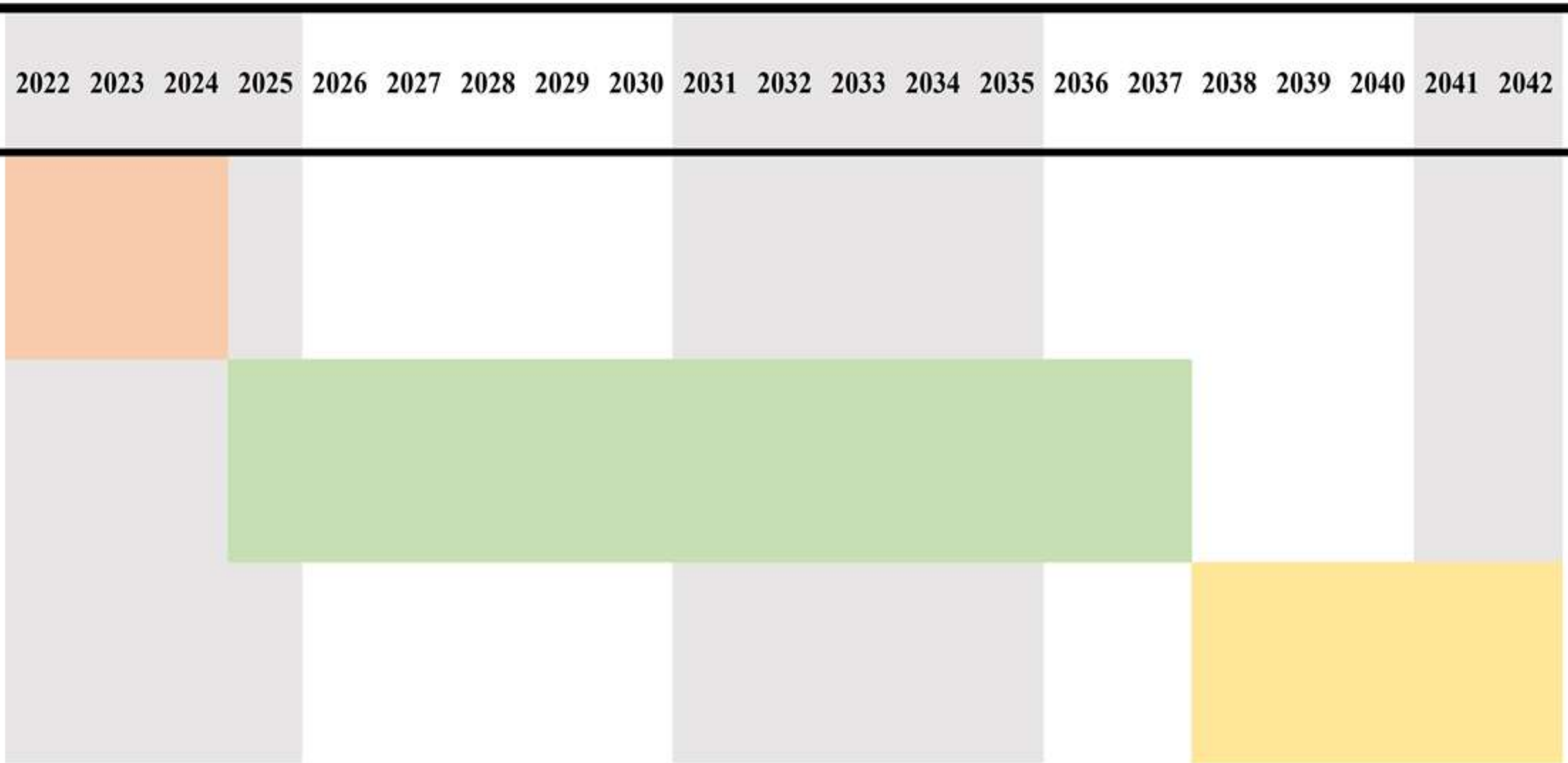
Improvement on the Energy Linearity Response

- PMT waveform saturation is studied by independent bench tests
- Desaturation algorithm is checked and verified





PandaX Project Timeline



Operation of PandaX-4T, and R&D for the upgrade

Project Phase-I：construct and operate PandaX-xT on the basis of PandaX-4T; procure xenon by stages and upgrade detector along the way till 43-ton target, and keep >50% of experimental live time

Project Phase-II: with isotopically separated xenon (versatile configurations)