Double Beta Decay and Neutrino Physics in PandaX-4T

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on behalf of the PandaX Collaboration

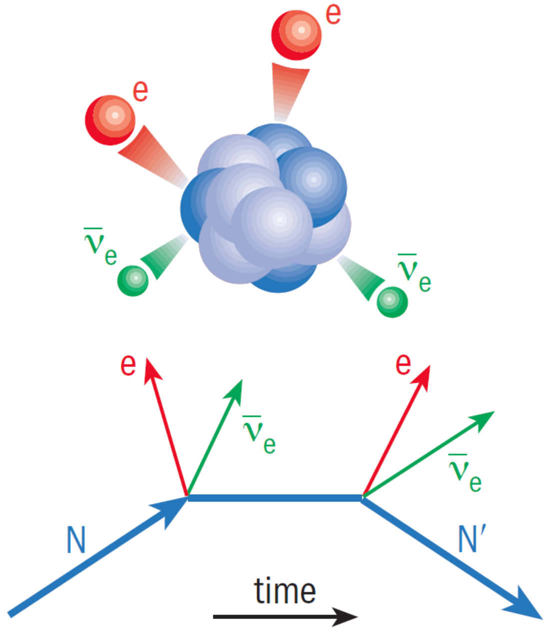
May 20, 2023

第二届无中微子双贝塔衰变及相关物理研讨会

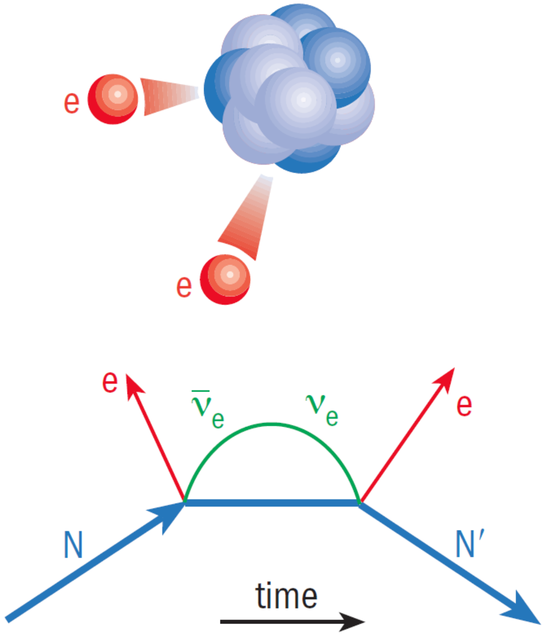
Outline

- Introduction to double beta decay (DBD)
- PandaX experiments
- ^{136}Xe DBD in PandaX-4T
  - Detector response at MeV range
  - Half-life measurement
- More neutrino physics in PandaX-4T
  - ^{136}Xe DBD to excited states
  - ^{124}Xe double electron capture (DEC)
- Summary and outlook

(Neutrinoless) double beta decay



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



From Physics World

1935, Goeppert-Mayer
Two-Neutrino double beta decay

1937, Majorana
Majorana Neutrino

1939, Furry
Neutrinoless double beta decay

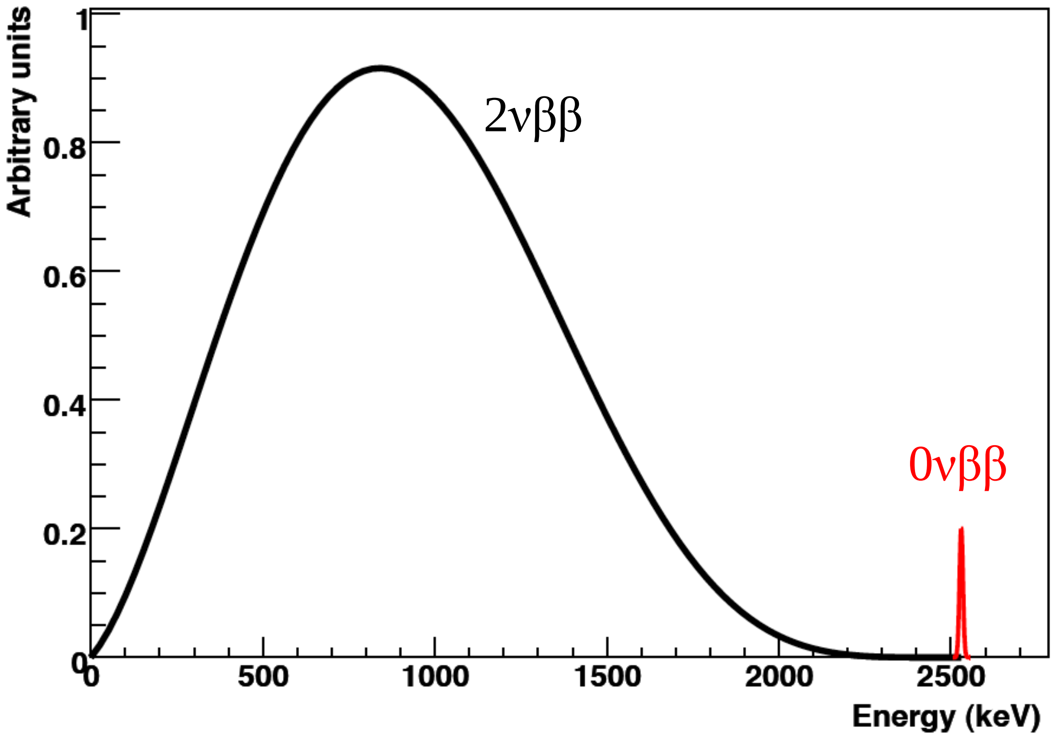
1930, Pauli
Idea of neutrino

1933, Fermi
Beta decay theory

$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba + 2e^- + (2\bar{\upsilon})$$

Detection of NLDBD and 2νDBD

$$^{136}_{54}Xe \rightarrow\, ^{136}_{56}Ba + 2e^{-} + (2\bar{\nu})$$



- Detect NLDBD and 2νDBD through energies of emitted electrons
- Precision measurement of DBD is a major first step for any NLDBD experiment
- Understand better the background

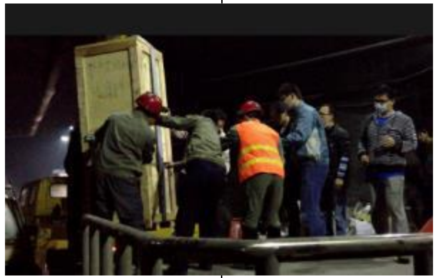
PandaX collaboration

- Particle and Astrophysical Xenon Experiment
- Now 15 institutions, ~80 authors

PandaX experiments

2009.3 — **Collaboration formed**

2012.7 — **PandaX-I apparatus moved to CJPL-I**



2014.3 — **PandaX-I started**

2014.5-10 — **PandaX-I, 120 kg xenon operation**

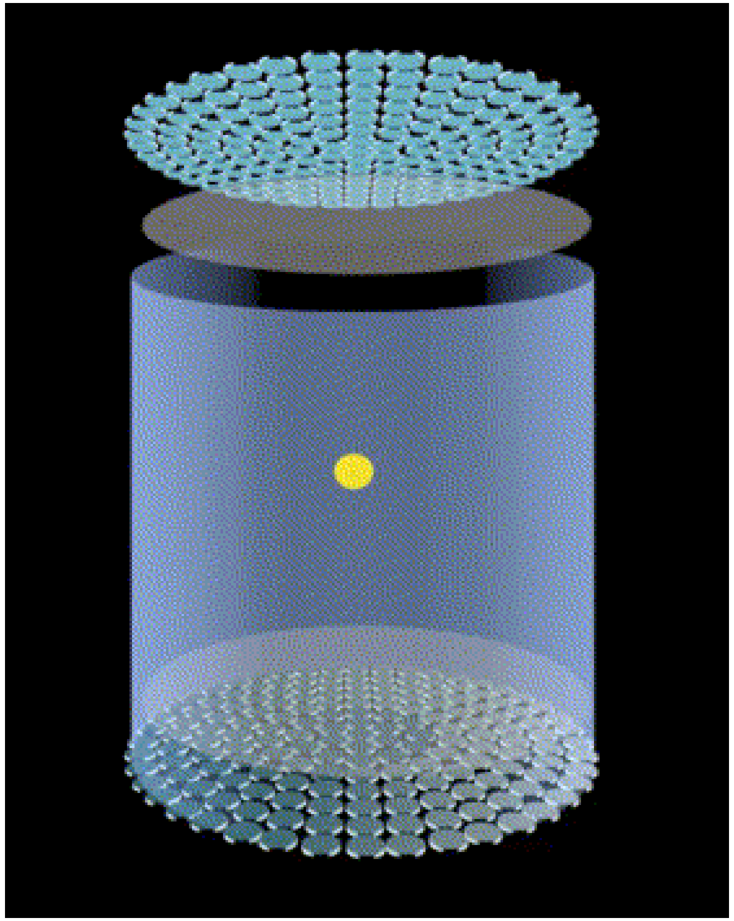
2016.7-2019.7 — **PandaX-II, 580 kg xenon operation**

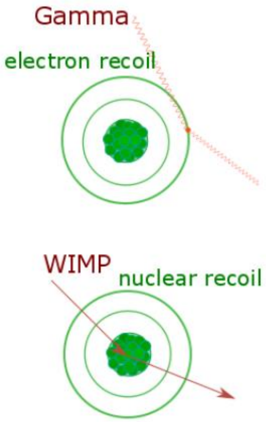
2019.8 — **PandaX-4T, 3.7 ton moved to CJPL-II**

2020.11- — **PandaX-4T online**

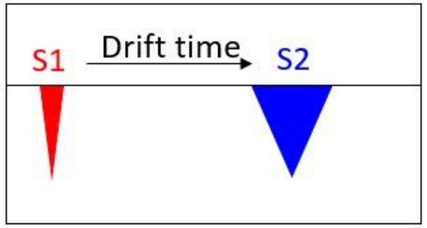
Dual phase xenon TPC

- S1: prompt scintillation signal
- S2: delayed ionization signal

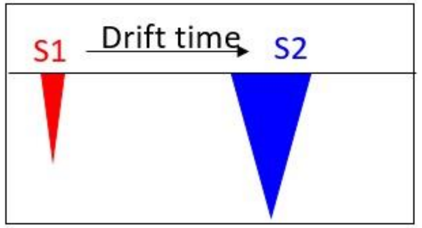




Dark matter: nuclear recoil (NR)

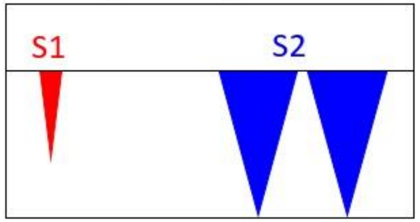


γ background: electron recoil (ER)



$(S2/S1)_{NR} << (S2/S1)_{ER}$

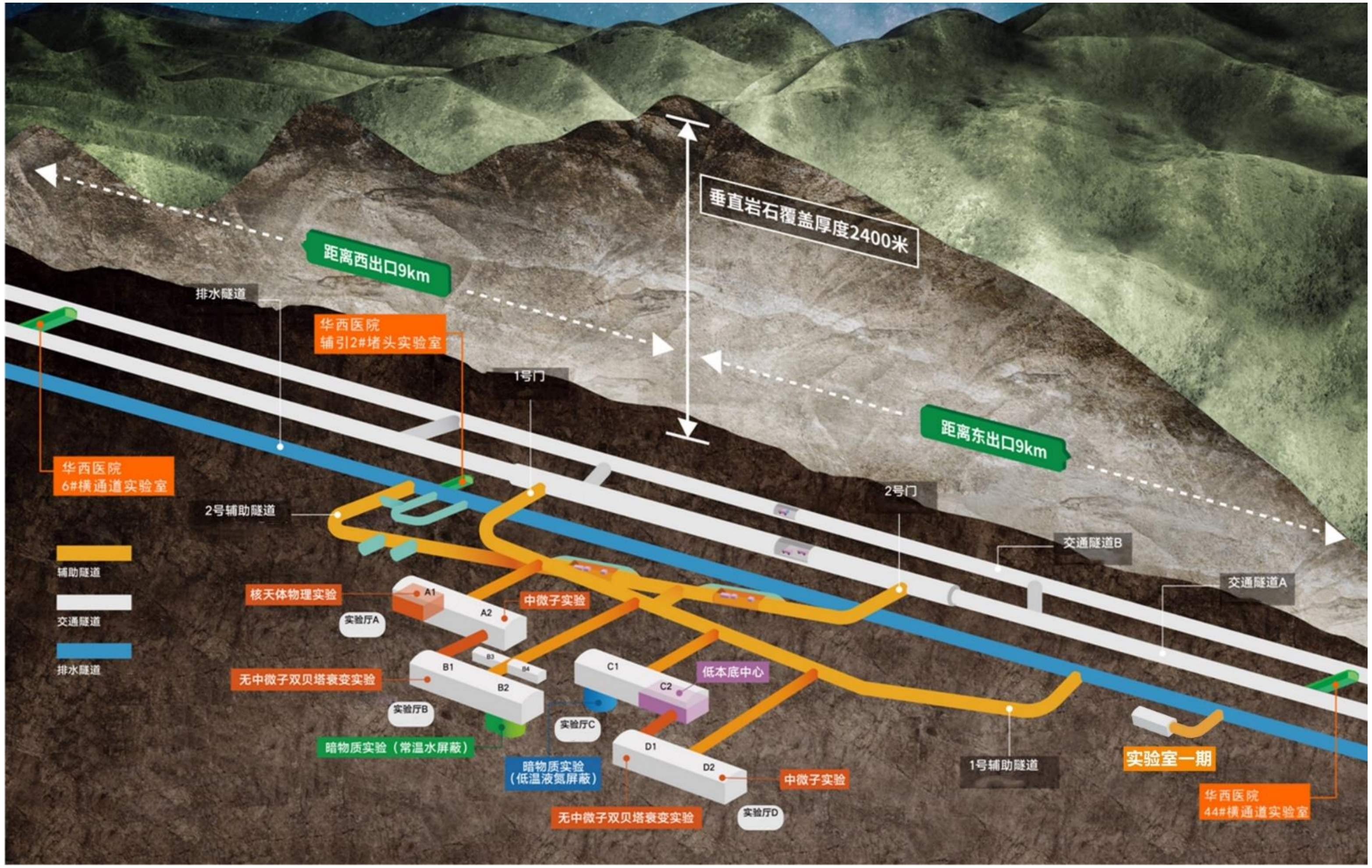
Multi-site scattering background (ER or NR)



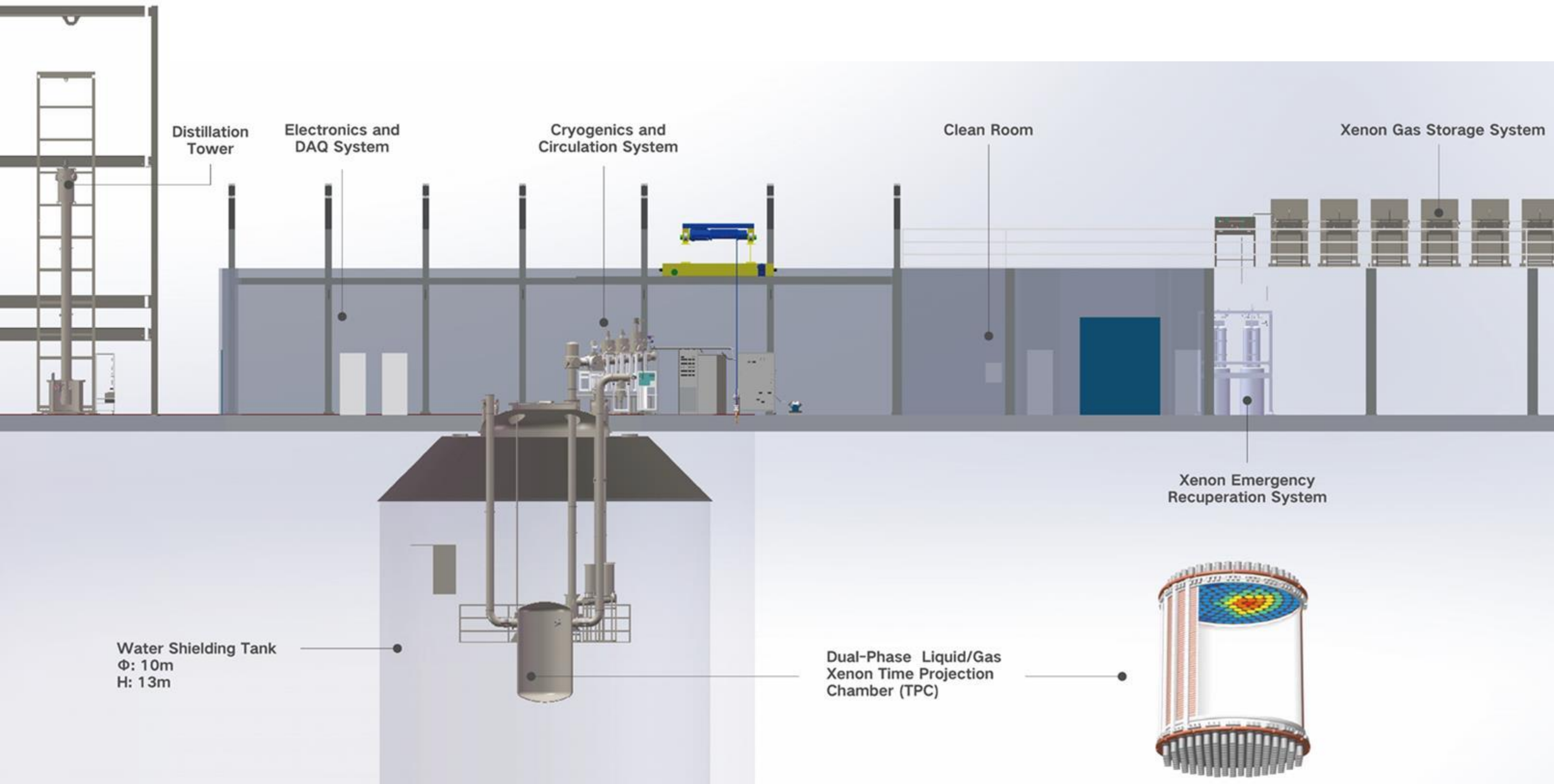
Dual phase xenon detector capability:

- ER/NR identification
- Single / multi-site identification
- 3D reconstruction and fiducialization
- Calorimeter from sub keV to MeV

CJPL and CJPL-II: deepest underground lab

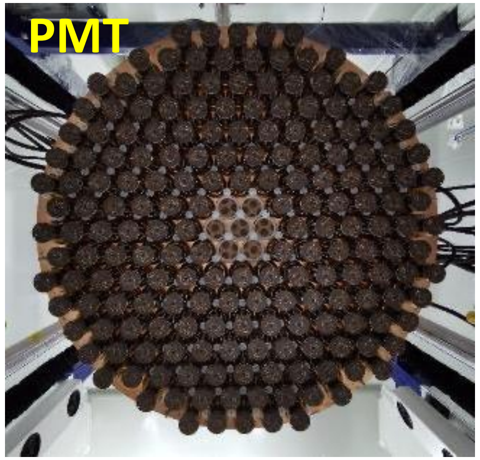


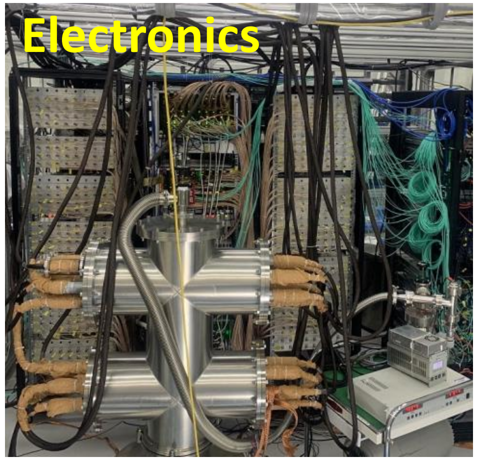
- Deepest (6800 m.w.e)
  - < 0.2 muons/m^2/day
- Much larger space in CJPL-II
- National key science research facility for dark matter searches, neutrino physics, and astroparticle physics, etc.



PandaX-4T @ CJPL-II

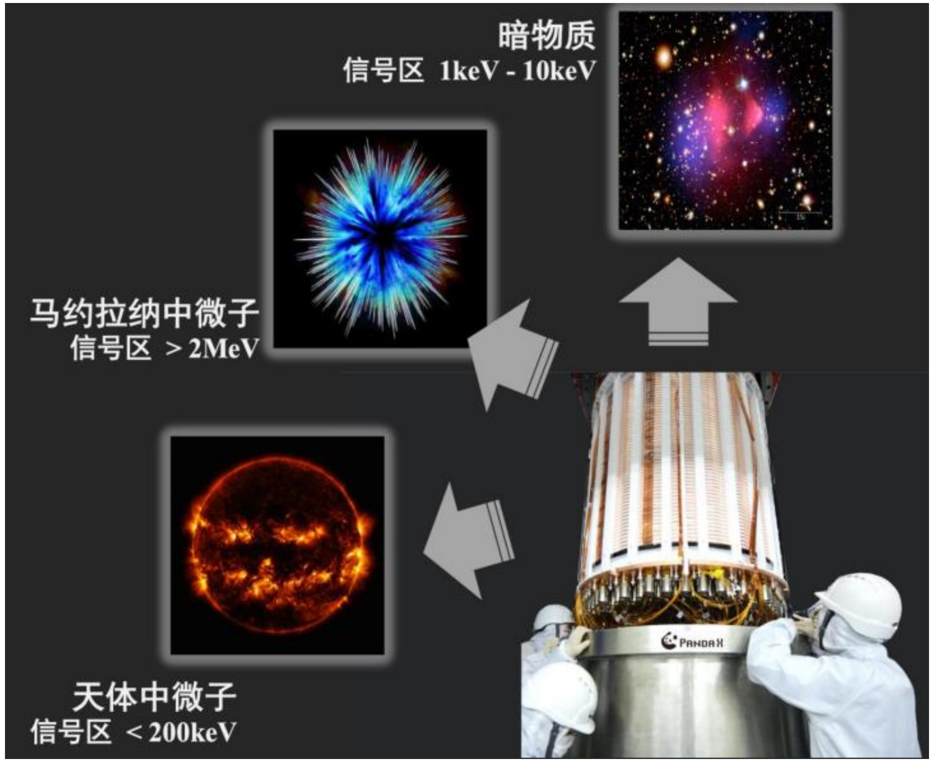
PandaX-4T subsystems





PandaX-4T runs and multiple physics topics

Commissioning (Run 0)	Calibration	Distillation	Physics Run (Run 1)	Calibration	Detector Upgrade
2020/11/28 – 2021/04/16	2021/04/17 – 2021/06/09		2021/11/15 – 2022/05/15	2022/05/16 – 2022/07/08	



- Have completed data-taking of
  - commissioning Run 0 (~ 95 d)
  - physics Run 1 (~ 154 d)
- Detector upgrade and more physics runs are on-going
- Multiple physics topics are being studied now
- Commissioning run is chosen for following ^{136}Xe DBD analysis

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  - ^{136}Xe DBD to excited states
  - ^{124}Xe DEC
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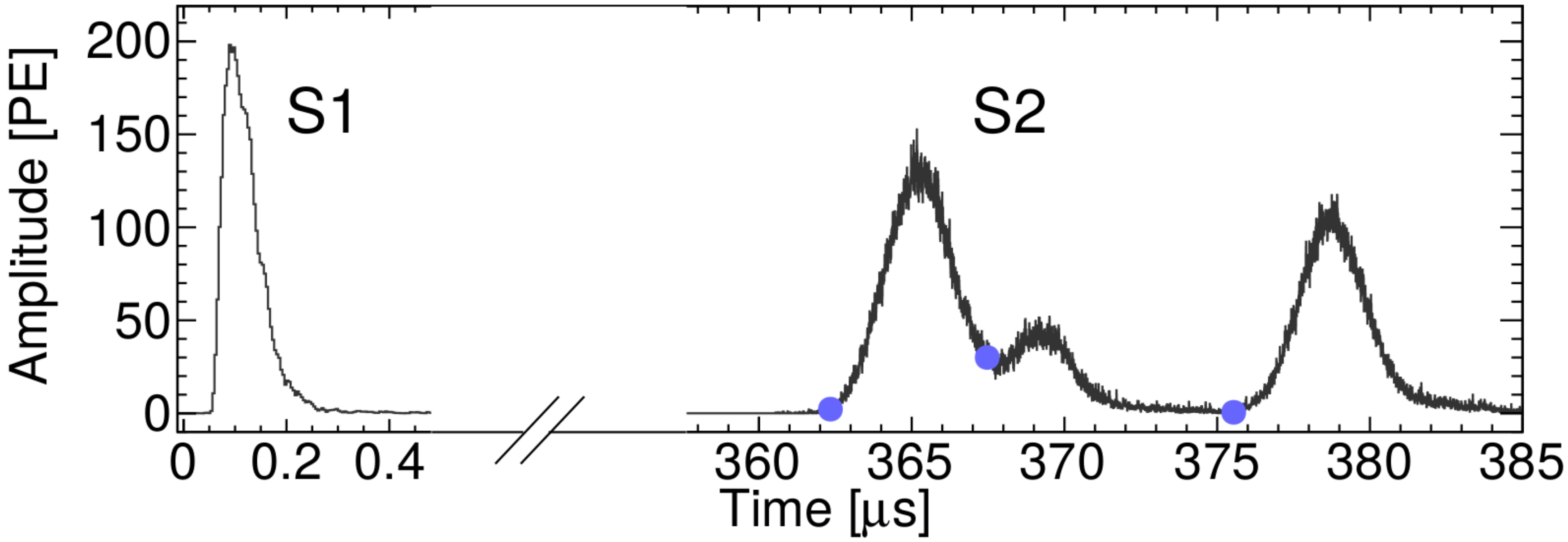
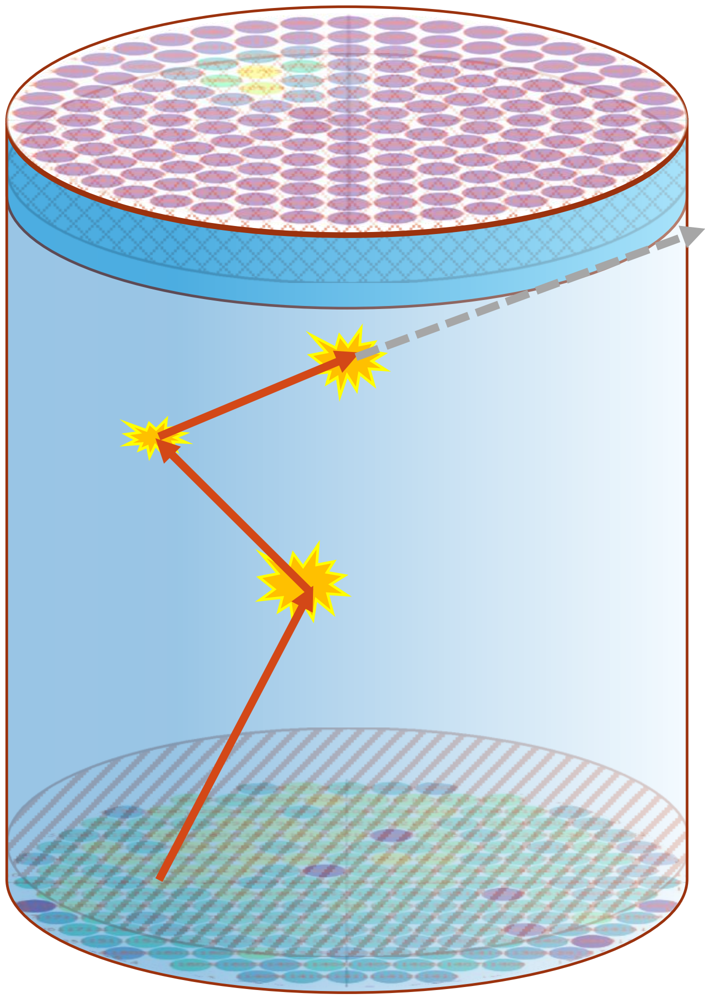
Identifying SS and MS

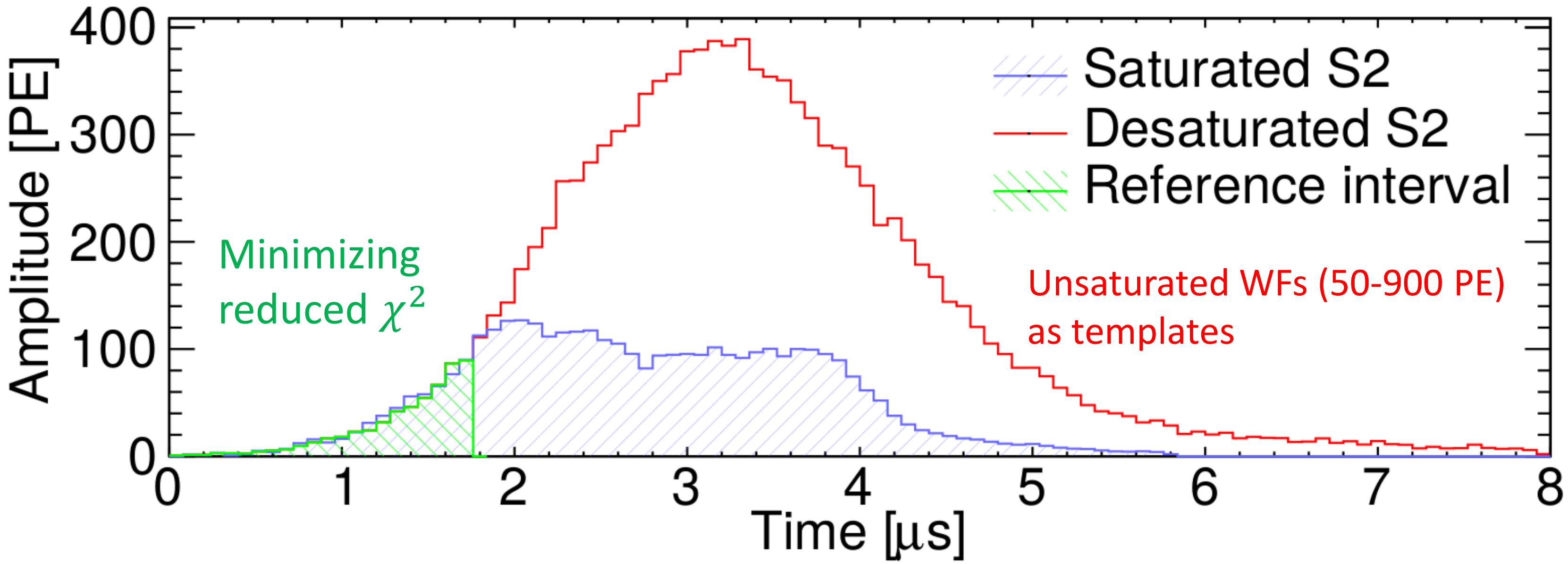
- MeV gamma events are mostly multi-site (MS) events; while signals (DBD) are mostly single site (SS)
- Identifying MS events with PMT waveforms
- Width of waveforms dominated by Z (electron diffusion)





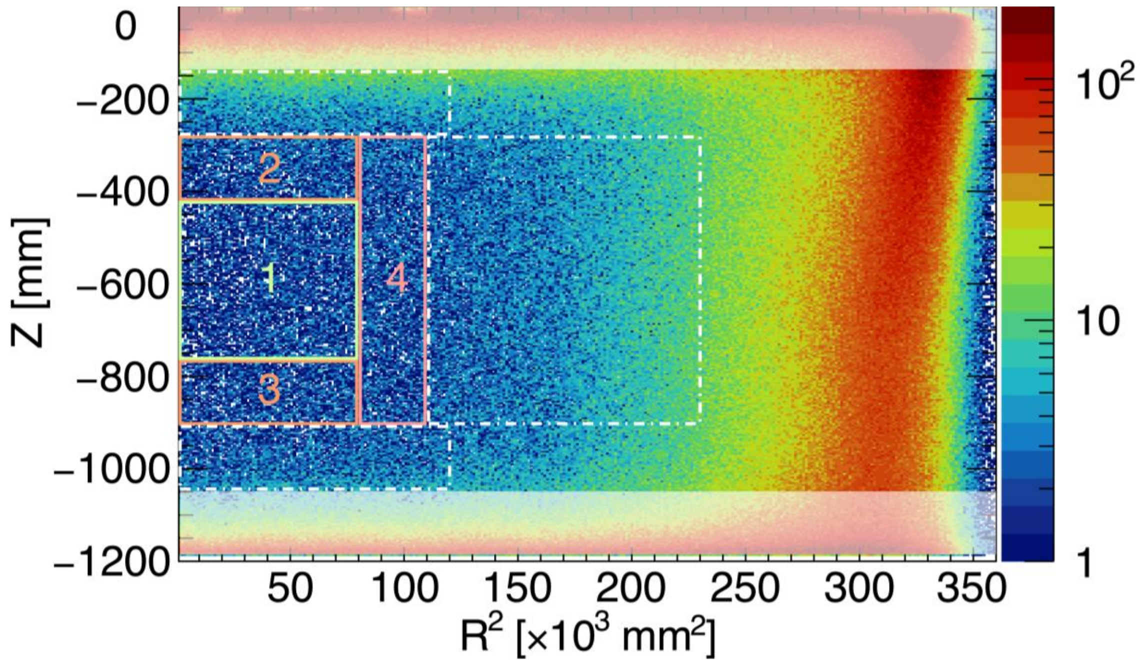
PMT pulse saturation and desaturation

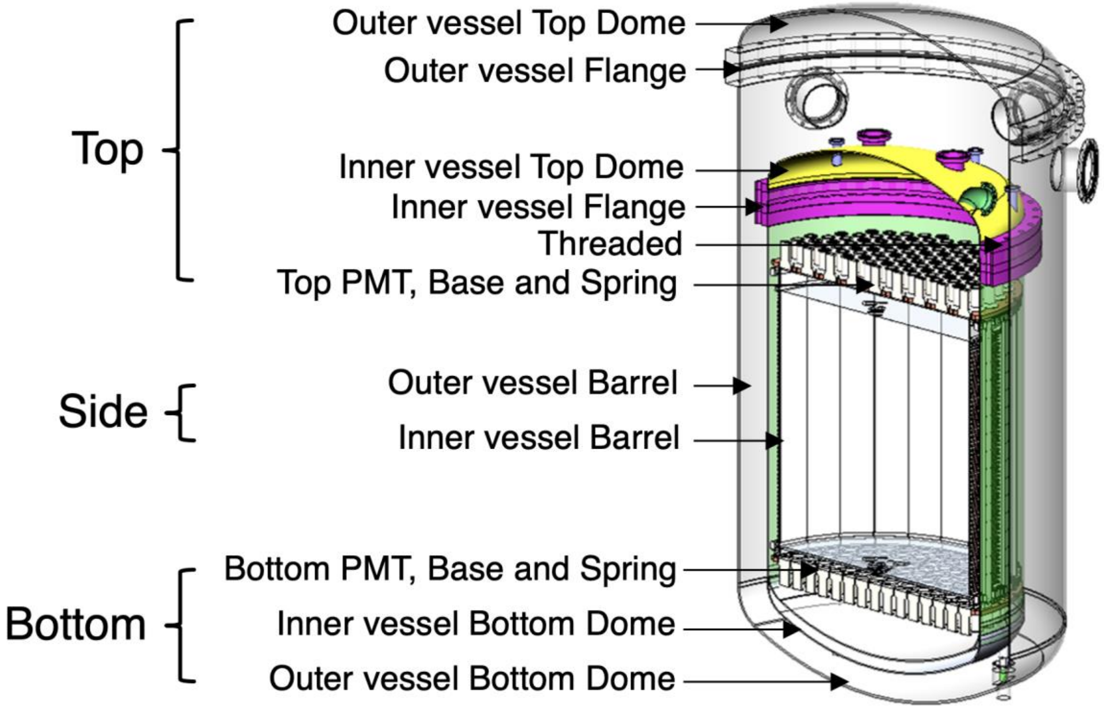
- PMT bases suffer serious saturation for MeV range events.
- Match the rising slope of the saturated to the non-saturated templates in the same events → True charge collected
- For events in the energy range of 1 to 3 MeV, the average correction factor is ~3.0 for the top PMT array



Establish an accurate background model

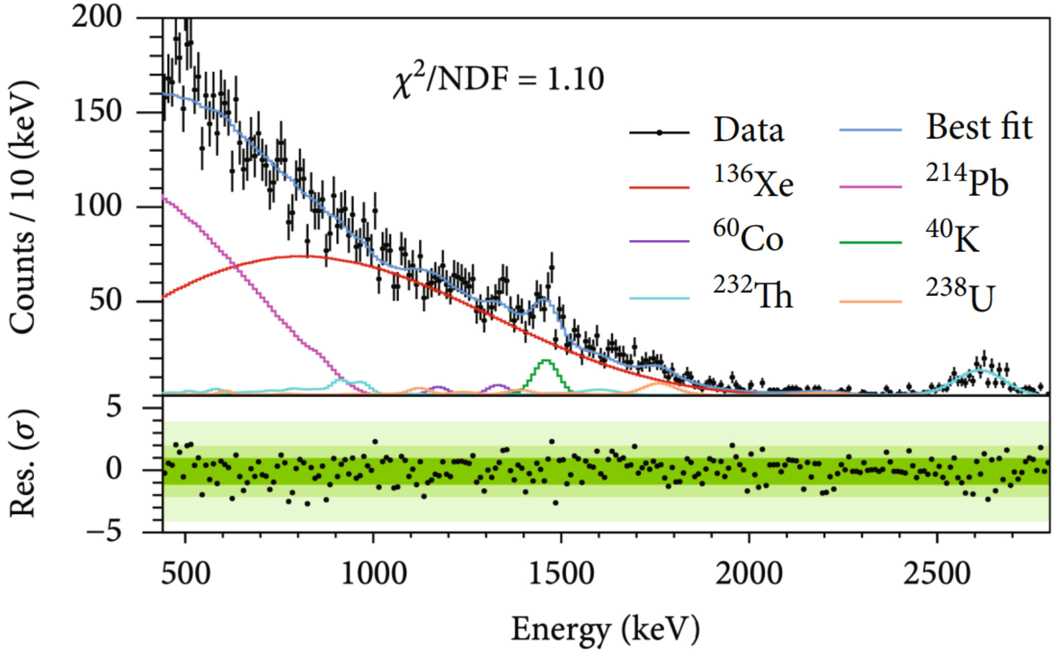
- Robust estimation of backgrounds in fiducial volume (4 regions)
  - Three categories of backgrounds: top bottom and side, based on weight and relative contribution to background counts in the ROI
  - Input values based on HPGe assay results and high energy alpha events

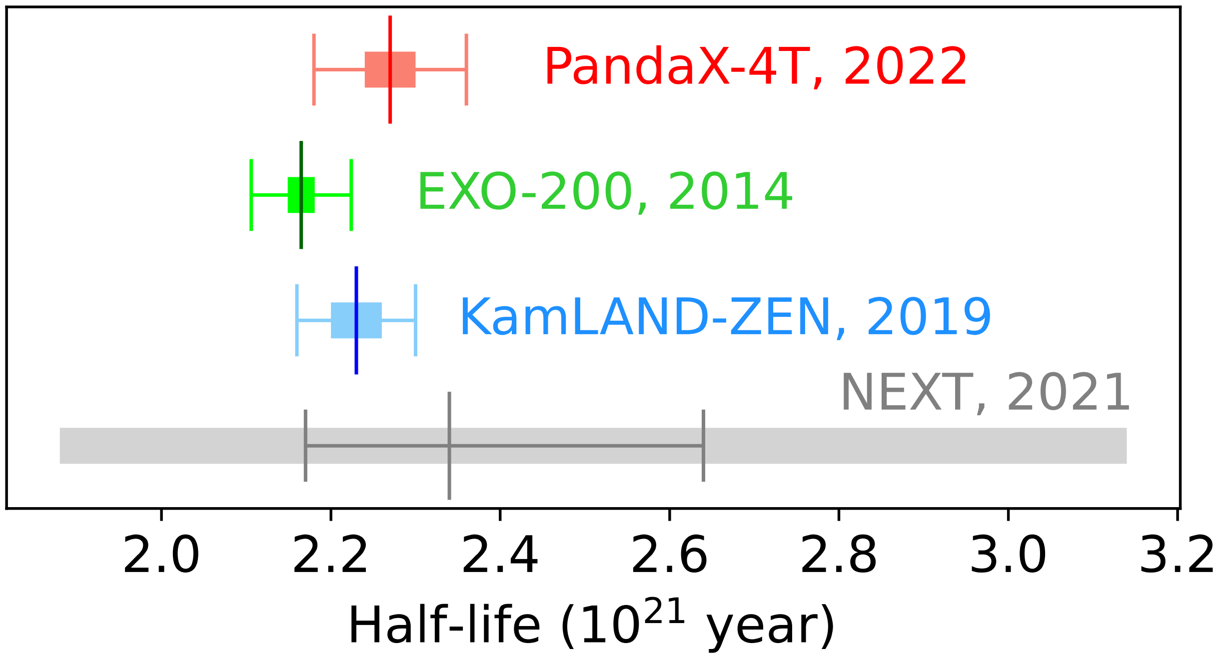




^{136}Xe 2νDBD half-life measurement

Research.10.34133/2022/979872



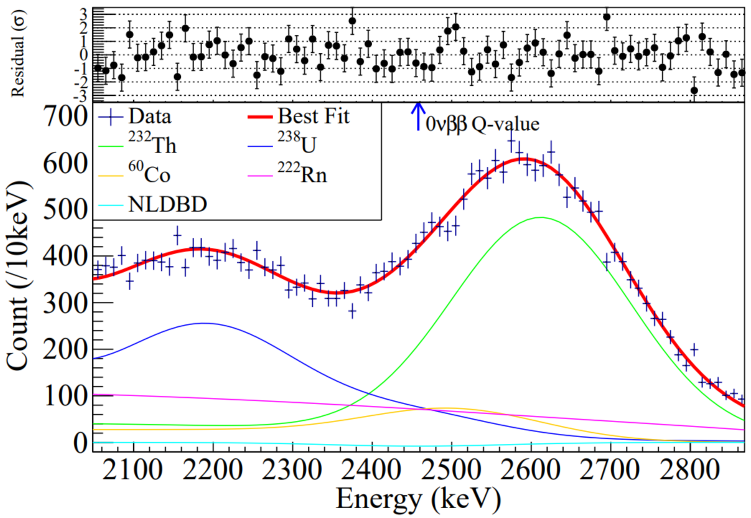


- First such result from a DM detector with natural xenon
  - ^{136}Xe DBD $T_{1/2}$ = 2.27 ± 0.03(stat.) ± 0.10(syst.) × 10^{21} year
  - Comparable with enriched ^{136}Xe experiments
  - The widest ROI from 440 keV to 2800 keV

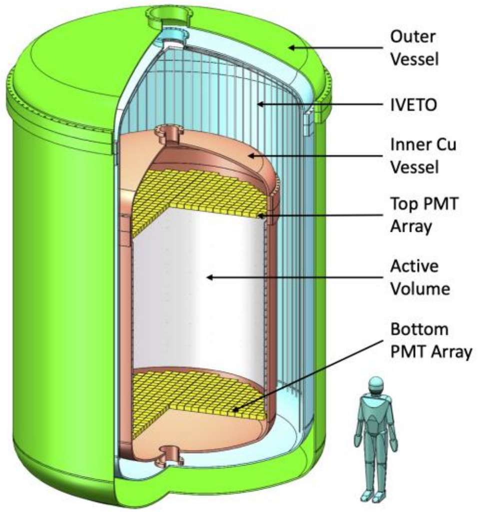
Expected NLDBD search in PandaX-4T

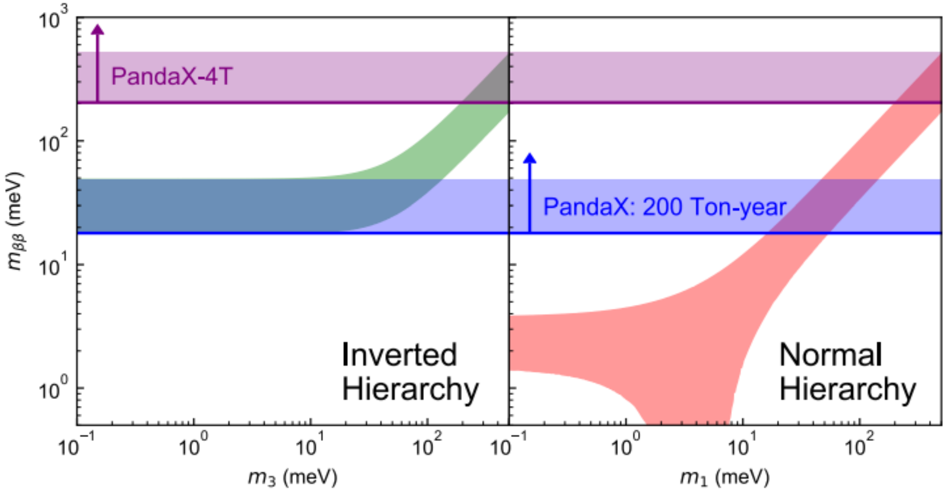
	Bkg rate (/keV/ton/y)	Energy resolution	FV mass (kg)	Run time	Sensitivity/Limit (90% CL, year)
PandaX-II	~200	4.2%	219	403.1 days	2.4×10^{23}
PandaX-4T	9	1.9%	649.7 ± 6.5	94.9 days	$> 10^{24}$
XENON1T	~20	0.8%	741 ± 9	202.7 days	1.2×10^{24}
Next Generation	~0.004	0.8%	5000	10 years	2.4×10^{27}

NLDBD search in PandaX-II



Future PandaX-xT





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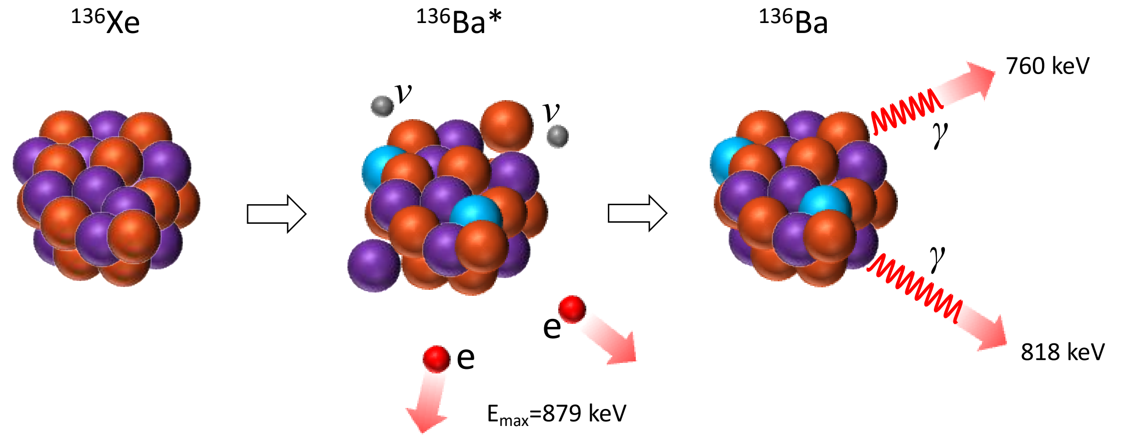
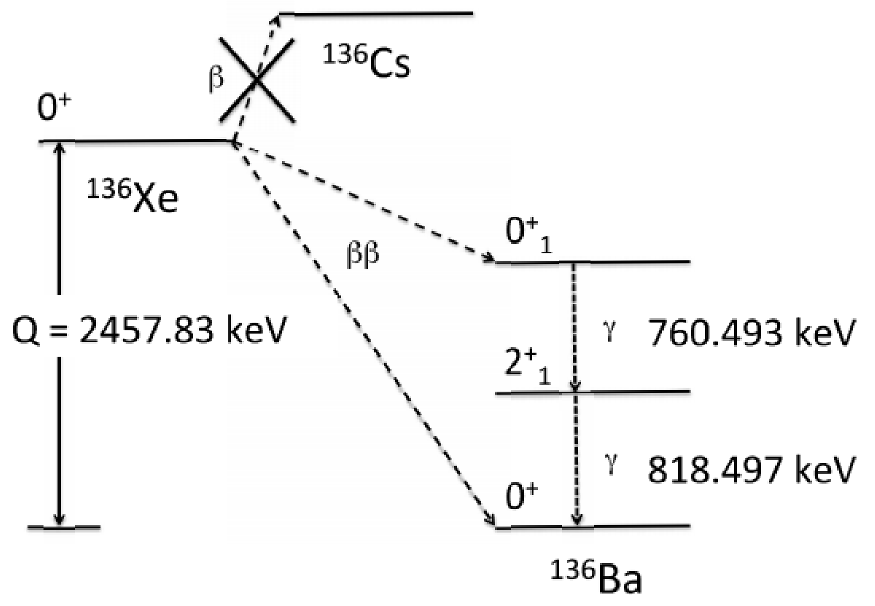
^{136}Xe DBD to excited states (ES)

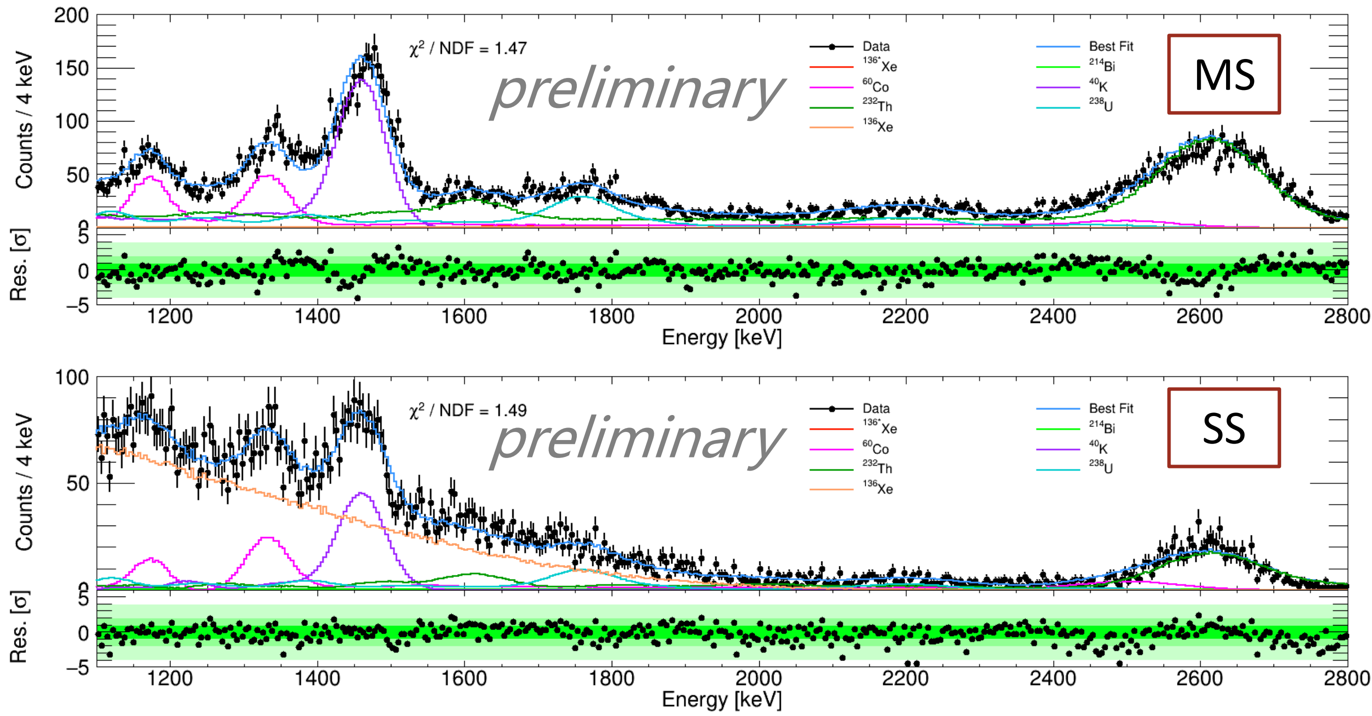
- Double beta decay to excited states of daughter nuclei
- Present limit: $T_{1/2} > 1.4\times10^{24}$ yr from EXO-200
- Theoretical prediction: $10^{23} \sim 10^{26}$ yr
- More clear signature: double e^- + double γ

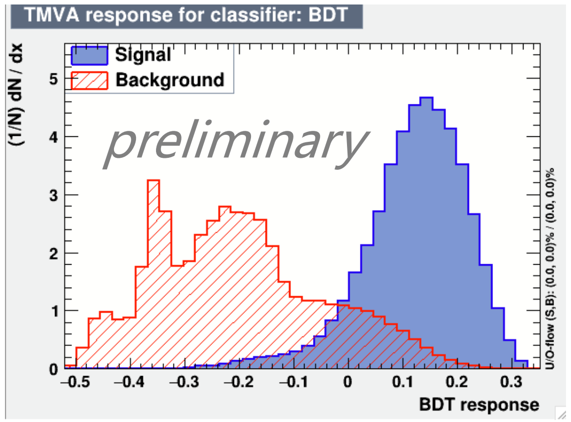


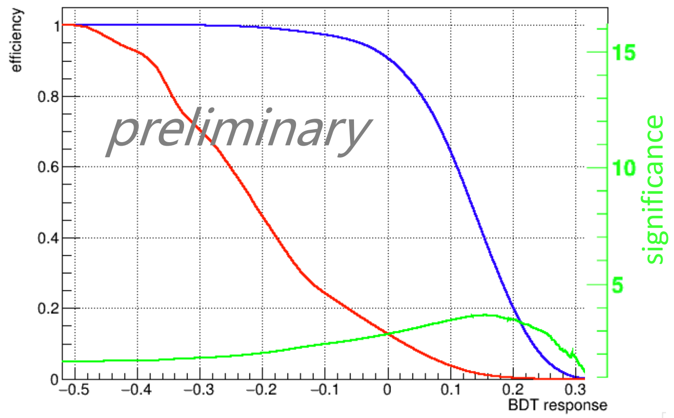


^{136}Xe DBD to ES in PandaX-4T

- Multi-site event energy reconstruction
  - Energy resolution: ~ **3% at 2615keV**
- DBD-ES signals are not inapparent in the spectrum fit only
- Need to take account of the signature and use TMVA (Toolkit for Multivariate Data Analysis) to improve signal/background ratio
  - Total γ energy (760.5+818.5 keV)
  - Energy of first site
  - Max energy among all sites
  - Minimum distance to detector boundary

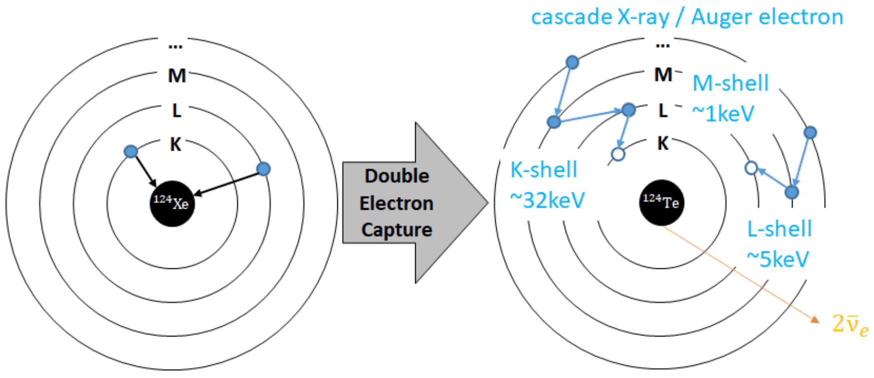


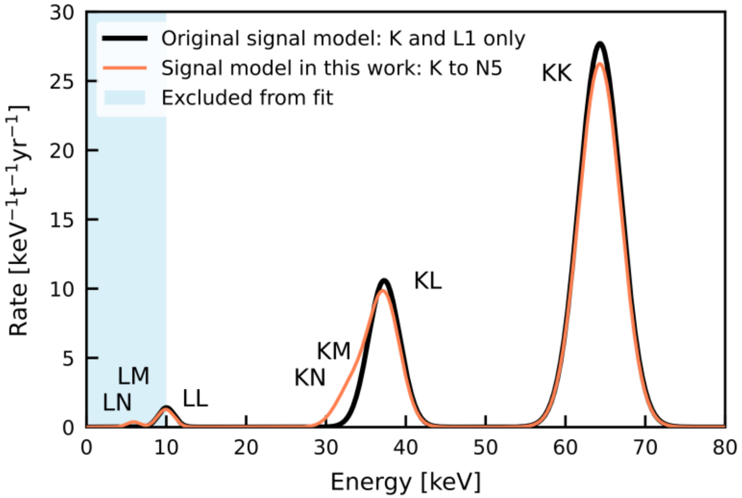




^{124}Xe double electron capture (DEC)

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

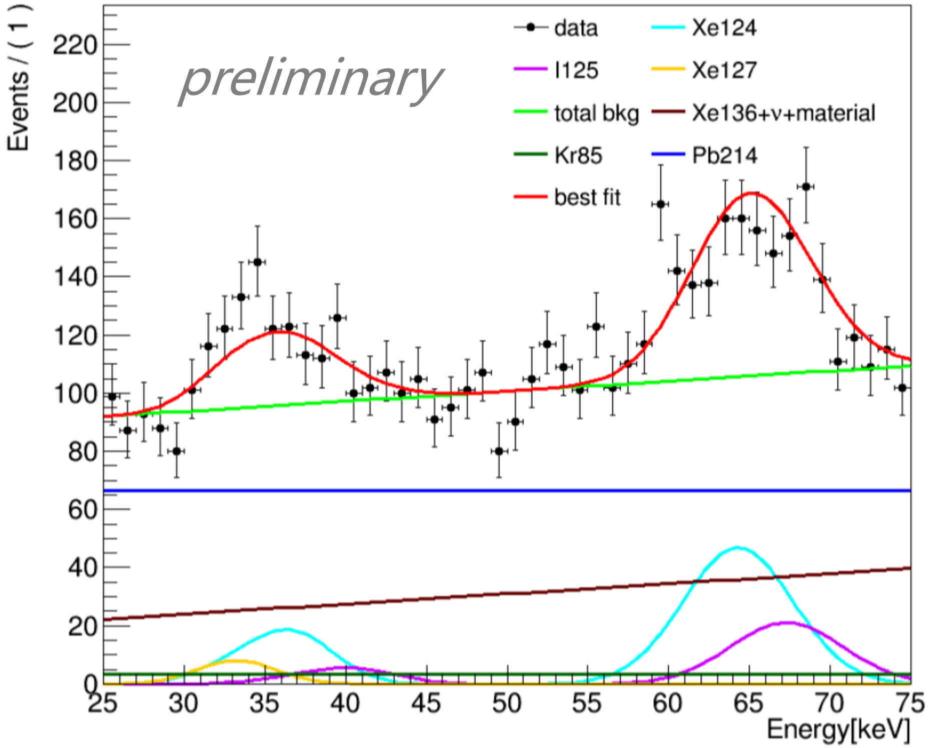


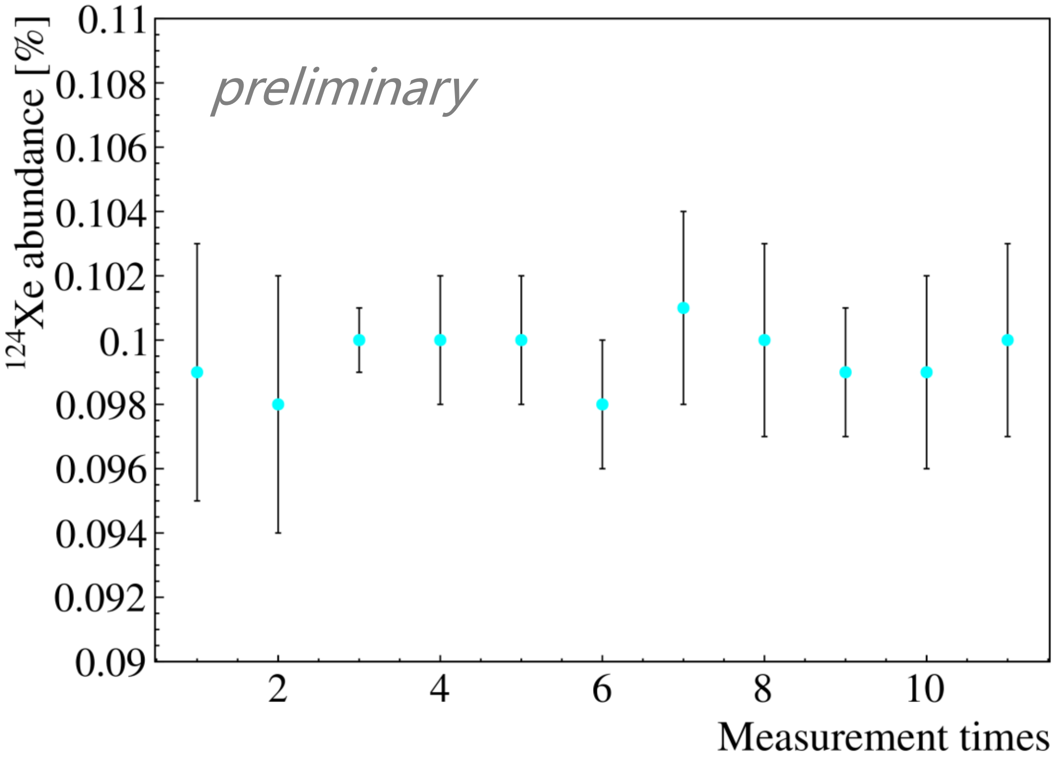


XENON1T, Physical Review C 106, 024328 (2022)

- Two-neutrino / neutrinoless double electron capture (DEC)
  - Q = 2857 keV
  - KK electron capture: ~72.4%, 64.3 keV
  - KL electron capture: ~20%, 36.8 keV
  - KM electron capture: ~4.3%, ~33 keV
- 2nd order weak process, $T_{1/2}=(1.18\pm0.13_{stat}\pm0.14_{sys})\times10^{22}$ yr from XENONnT

^{124}Xe DEC: spectrum fit to PandaX-4T data

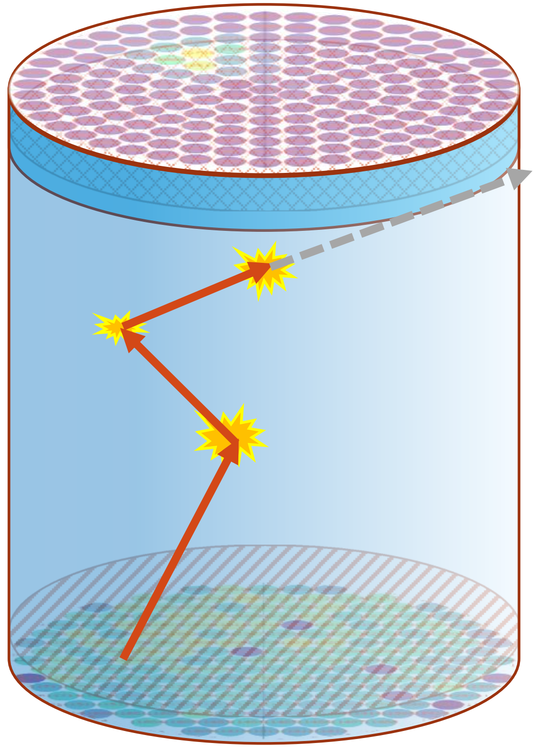




- Energy resolution at 64.3keV: (5.4±0.4)%
- Spectrum fit to Run 0 + Run 1 data: obvious ^{124}Xe DEC signal peaks
- Measurement of ^{124}Xe abundance in PandaX-4T: (0.099±0.001)%

Summary and outlook

- PandaX-4T has completed its commissioning run and first physics run, upgrade and more runs are on-going
- PandaX-4T as multi-physics program
  - Extend DM detector response to MeV range
  - Provide leading measurement on ^{136}Xe DBD half-life
- Studying more neutrino physics in PandaX!
  - NLDBD
  - ^{136}Xe DBD to excited states
  - ^{124}Xe DEC, …



Thanks very much for your attention!

Backup slides

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NLDBD probes the nature of neutrinos

- Majorana or Dirac
- Lepton number violation
- Measures effective Majorana mass: relate 0νββ to the neutrino oscillation physics

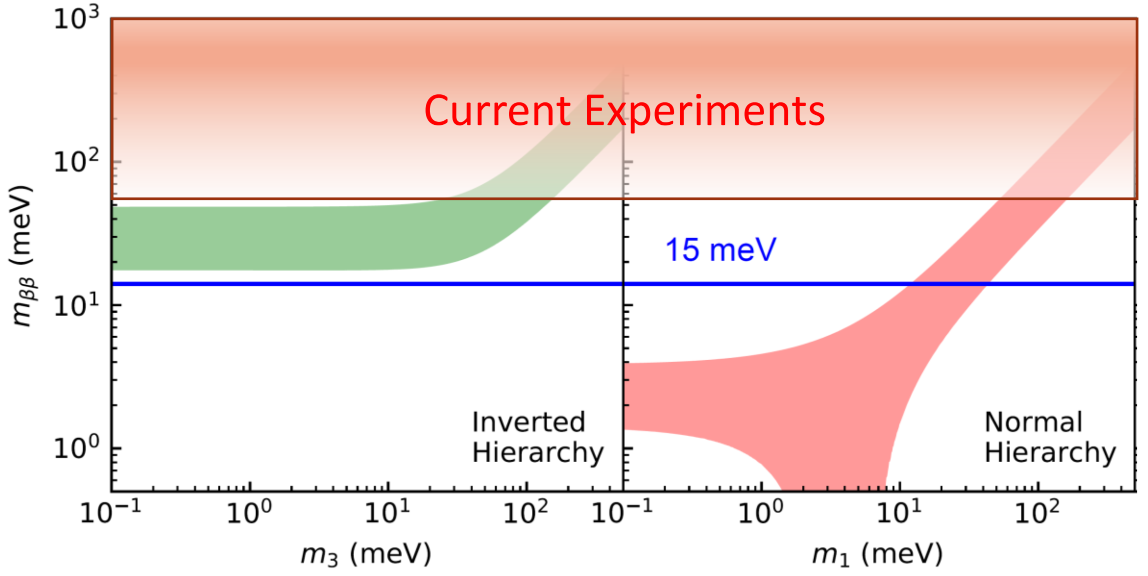
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phase space factor

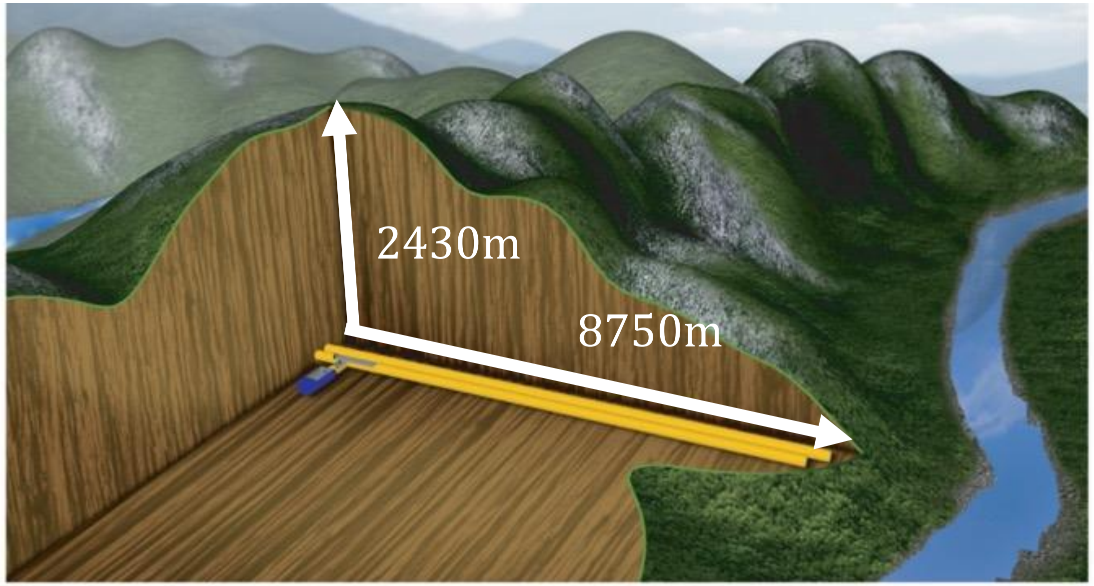
Nuclear matrix element

Effective Majorana neutrino mass:

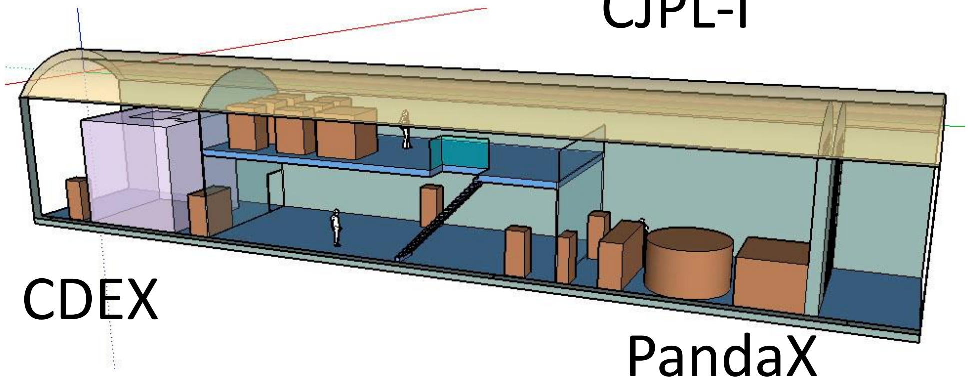
$$|\langle m_{\beta\beta}\rangle| = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

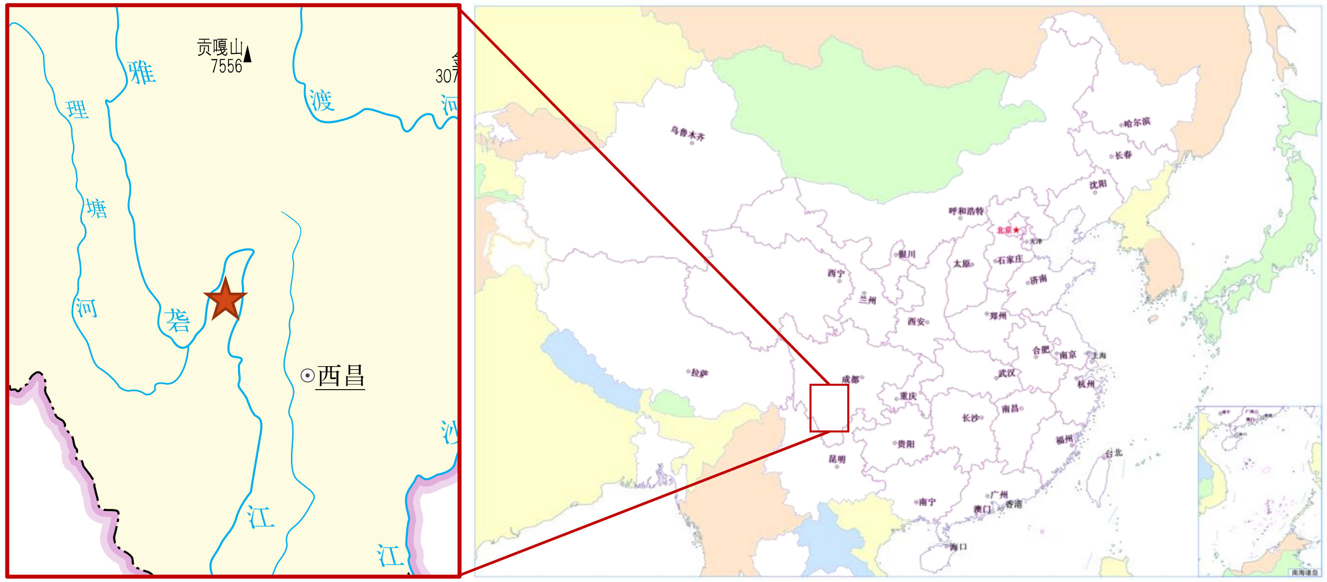


CJPL: Deepest underground lab



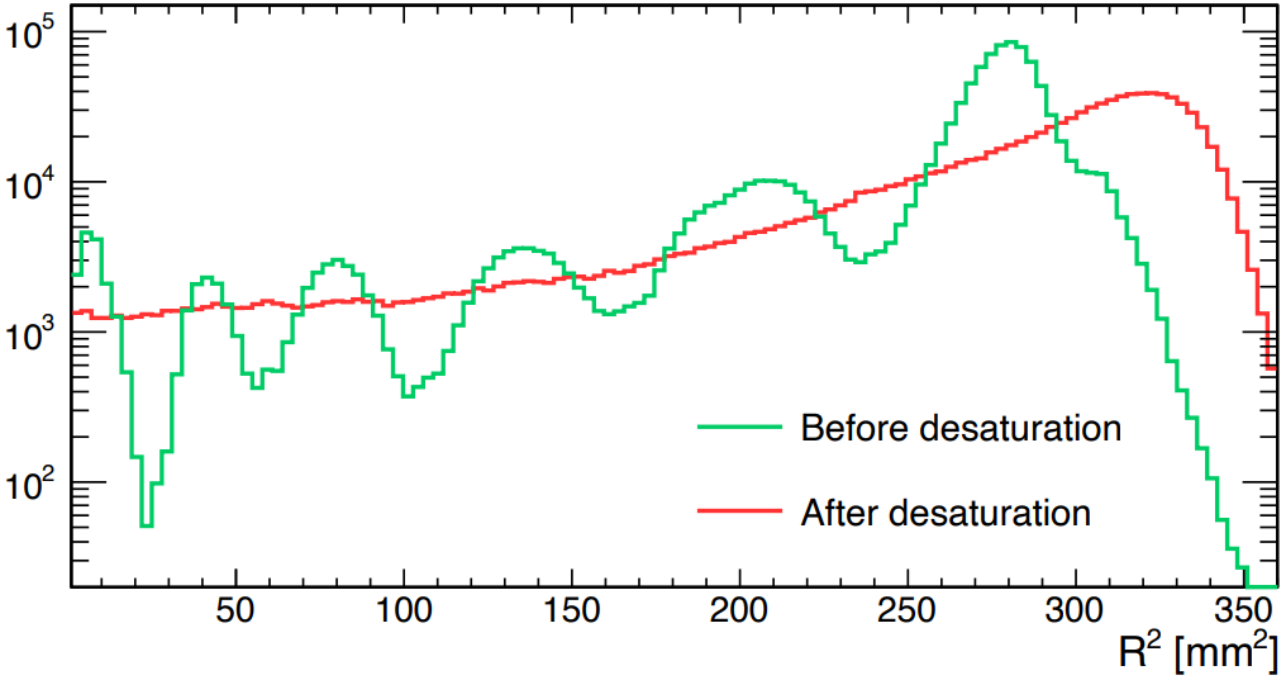
- Deepest (6800 m.w.e): < 0.2 muons/m^2/day
- Horizontal access with ~9 km long tunnel: large truck can drive in.
- National key science research facility for dark matter searches, neutrino physics, and astroparticle physics, etc.

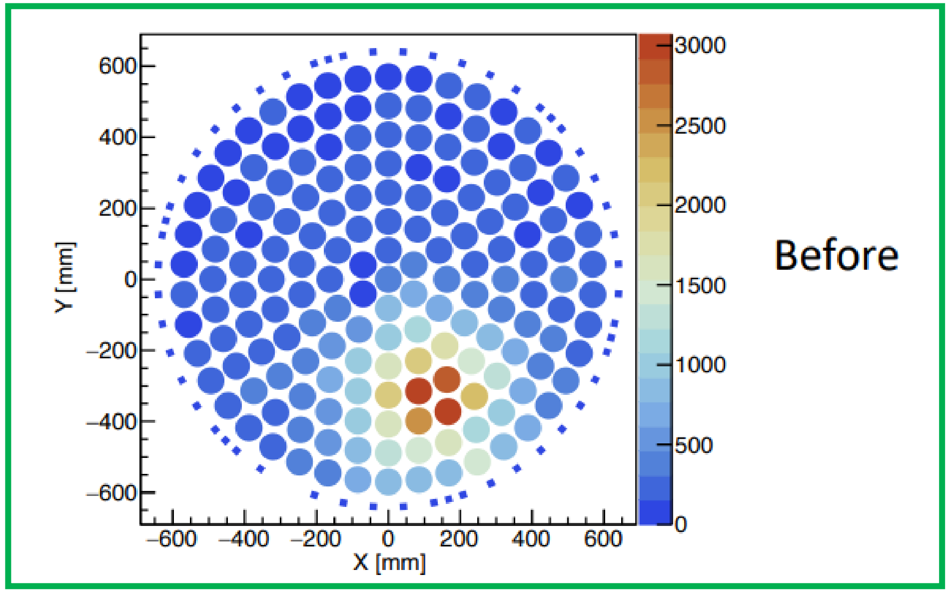


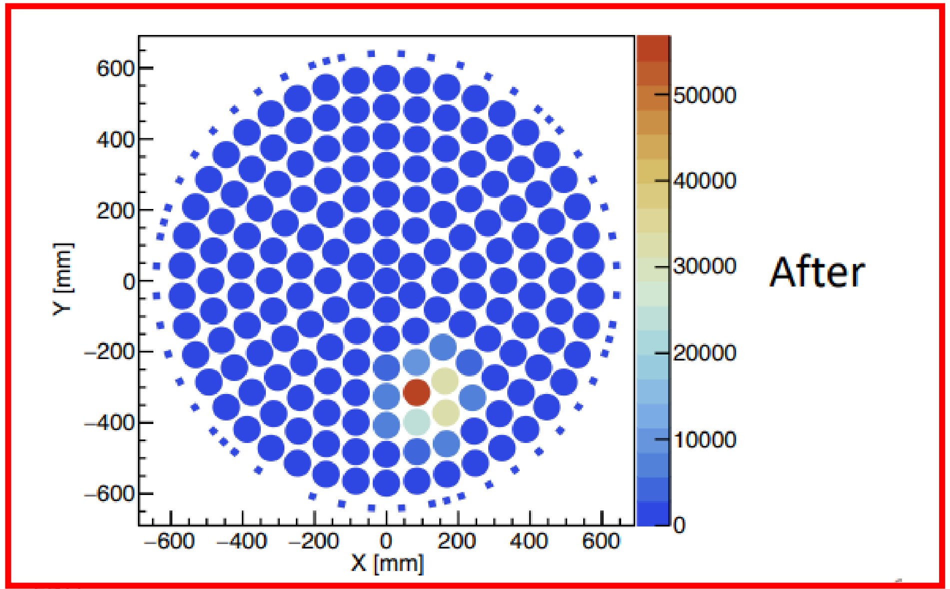


Position reconstruction improvement with desaturation

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

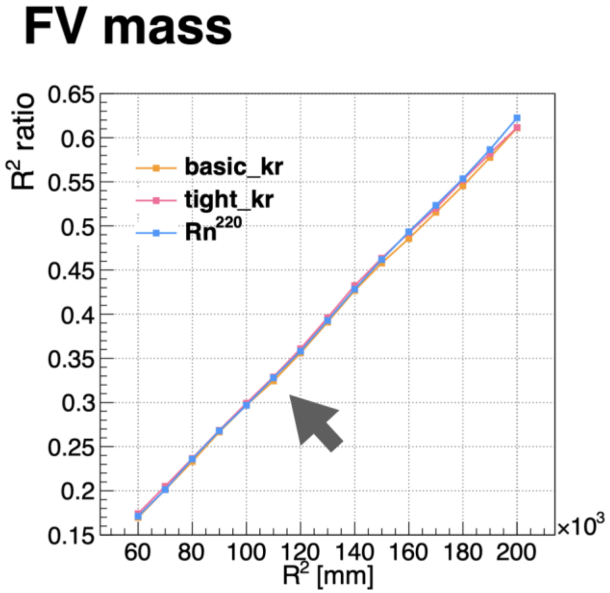


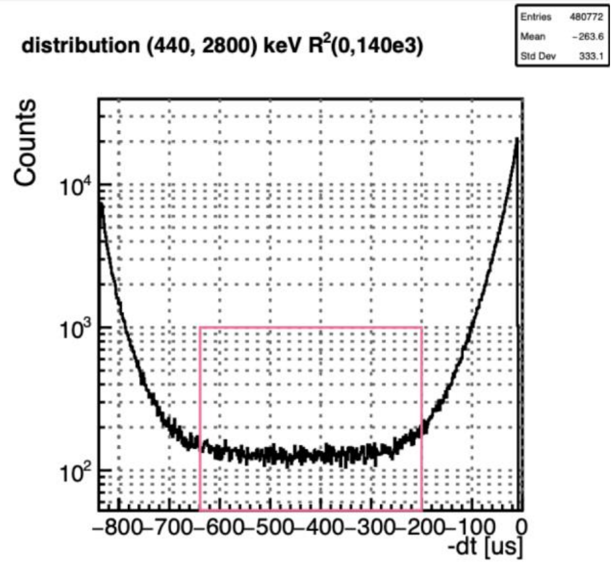


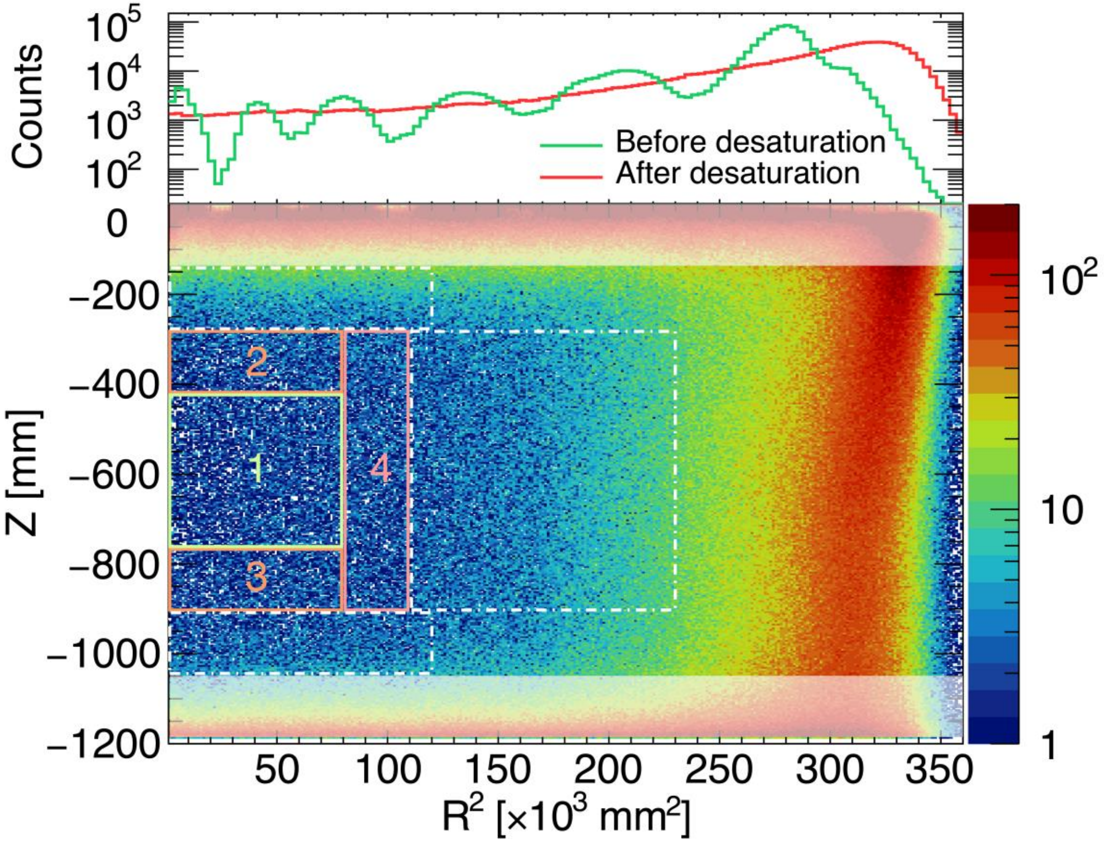


Fiducial volume

- Compare the number of events of ^{83m}Kr and ^{220}Rn with geometric volume; the non-linearity between the two <0.5% defines the cut in R direction
- Z direction: smaller background rate
- Outer (dashed) region for cross-validation

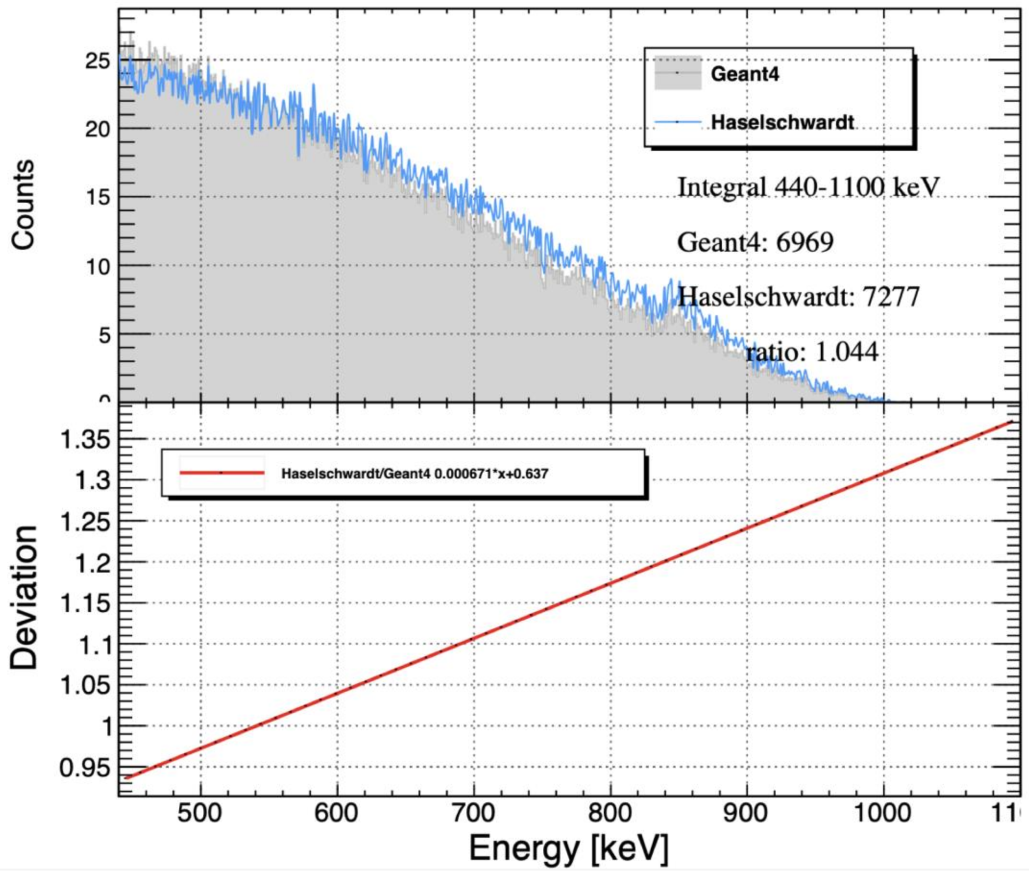






Systematic uncertainties

systematic source	Uncertainty [%]
Quality cut	0.39
FV cut	0.99
SS cut	1.75
LXe density	0.13
Pb214 spectrum correction	2.03
Bin size	0.05
Xe136 abundance	1.92
Energy range	1.23
Region difference	1.58
resolution	0.58
shift MC spectrum	0.26
total	4.05



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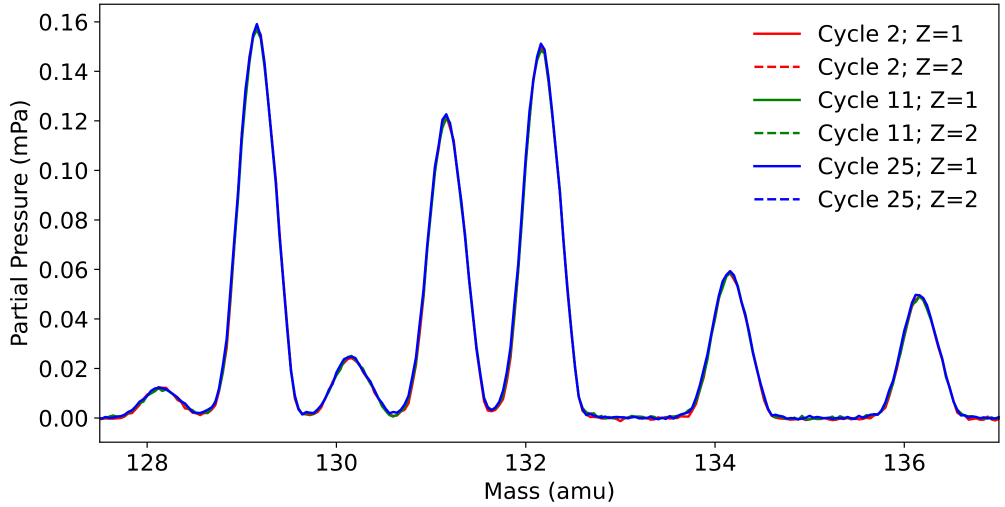

- ^{136}Xe IA: 8.79% if ionization efficiencies not corrected; 9.03% if corrected with NIST values
- Taken nominal value 8.86% as input and difference to our measurement as uncertainties