Experimental Physics Division Seminar

Institute of High Energy Physics, CAS

Measurement of ^{136}Xe DBD Half-life with PandaX-4T

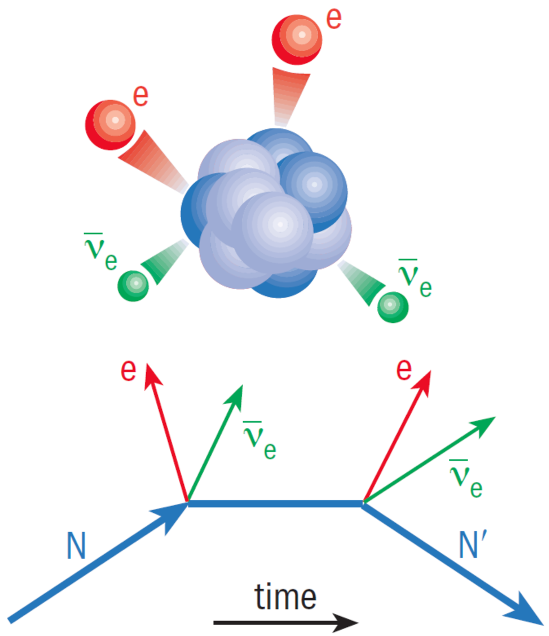
Ke Han (SJTU)

For the PandaX Collaboration

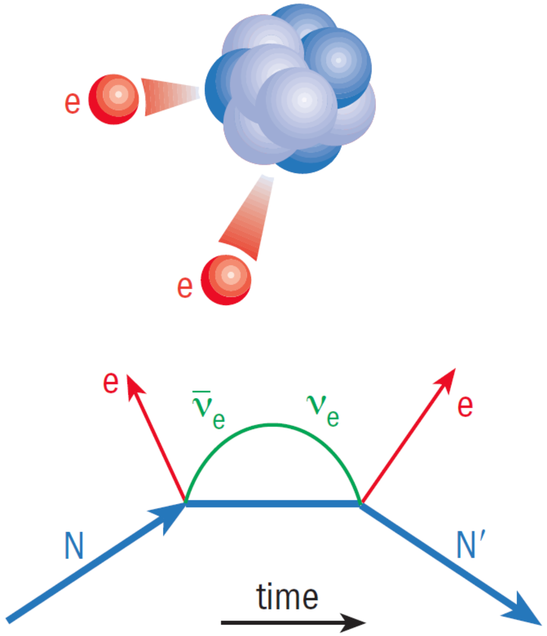
2022/6/7

Arxiv:2205.12809

Majorana neutrino and 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

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

NLDBD probes the nature of neutrinos

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

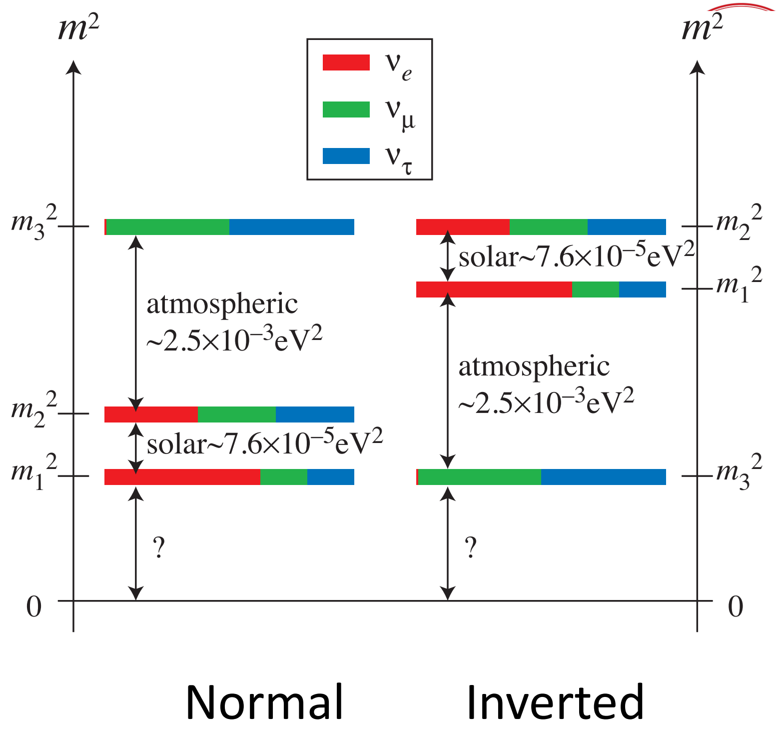
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

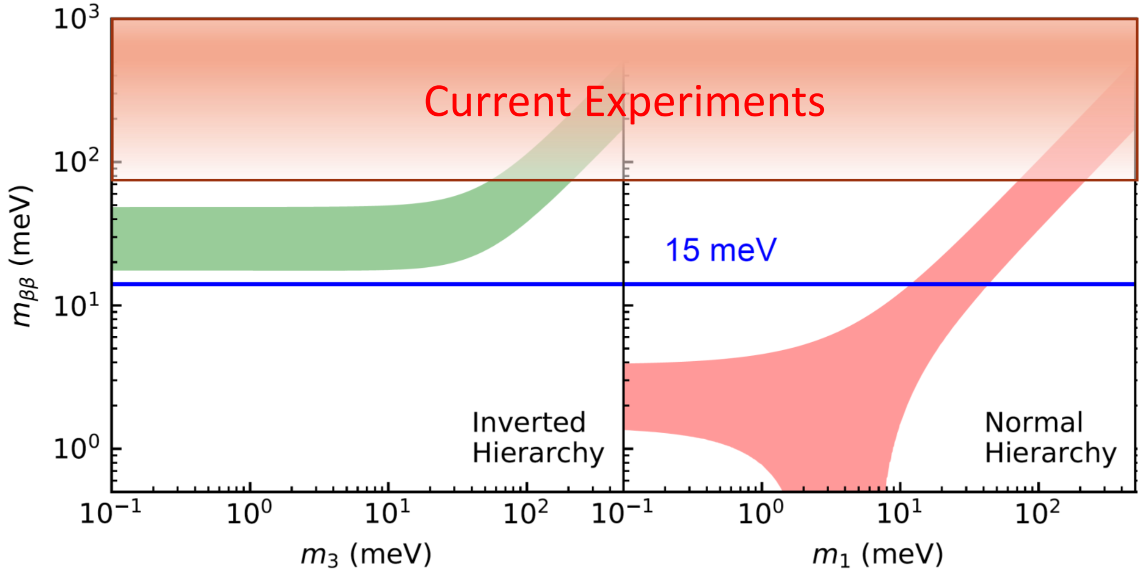
Phase space factor

Nuclear matrix element

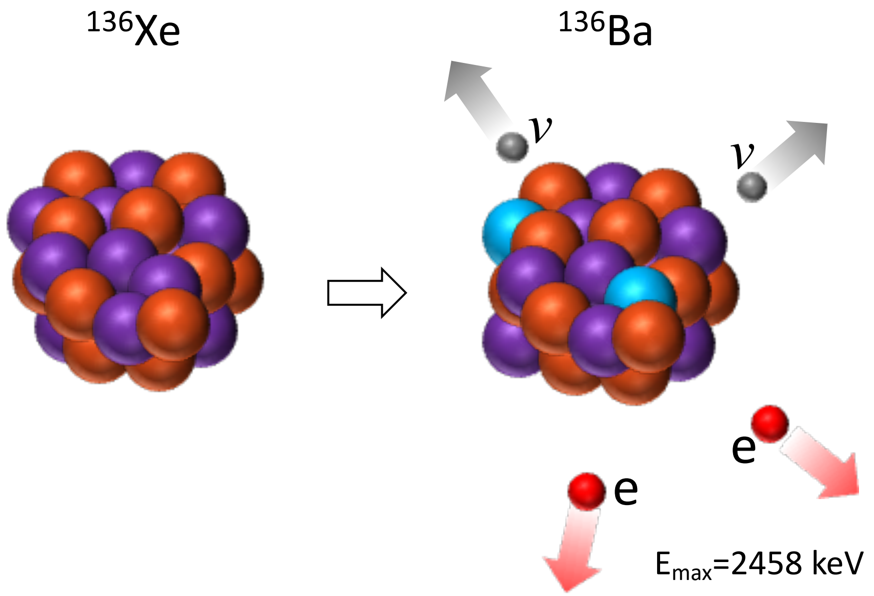
Effective Majorana neutrino mass:

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

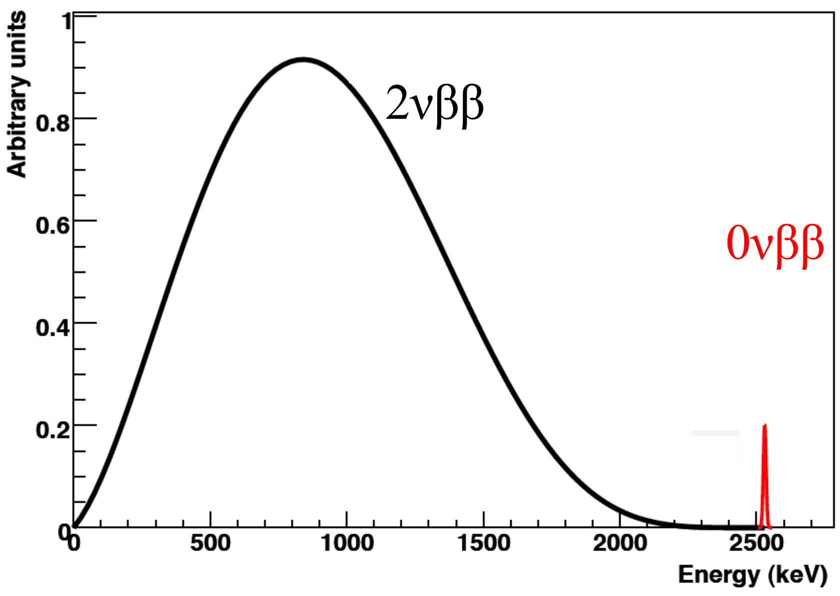




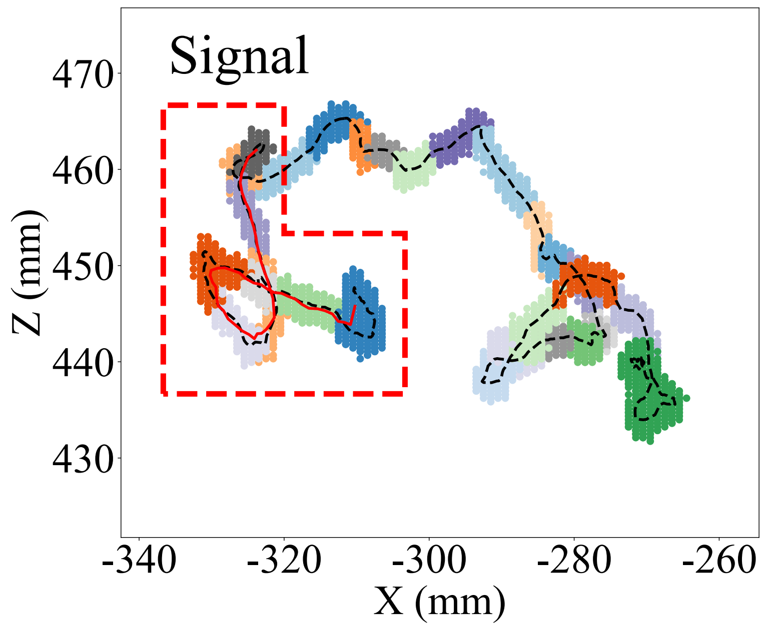
Detection of double beta decay



- Measure energies of emitted electrons
- Electron tracks are a huge plus
- Daughter nuclei identification



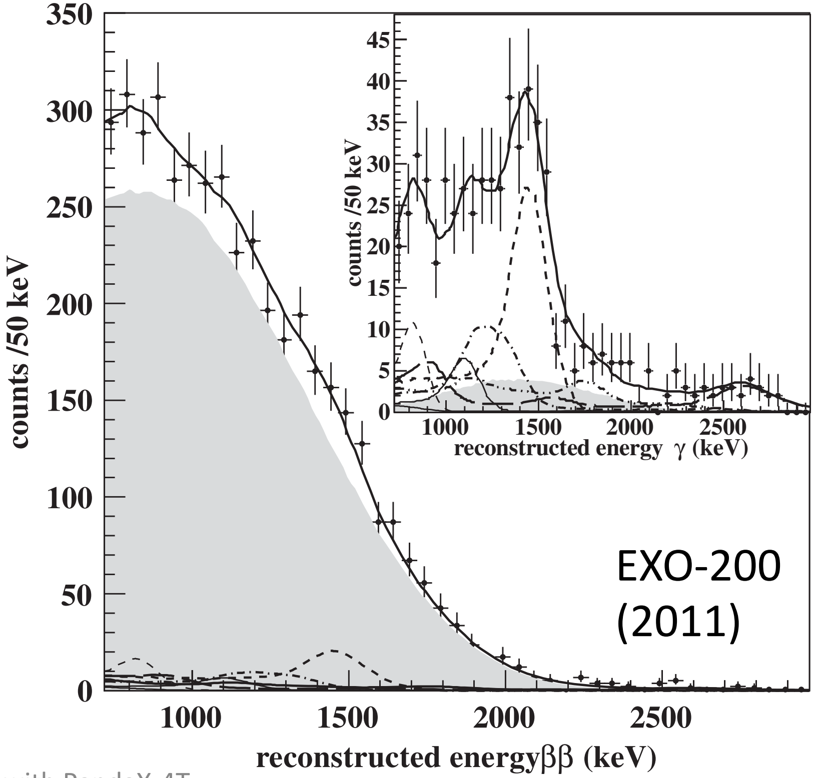
Sum of two electrons energy



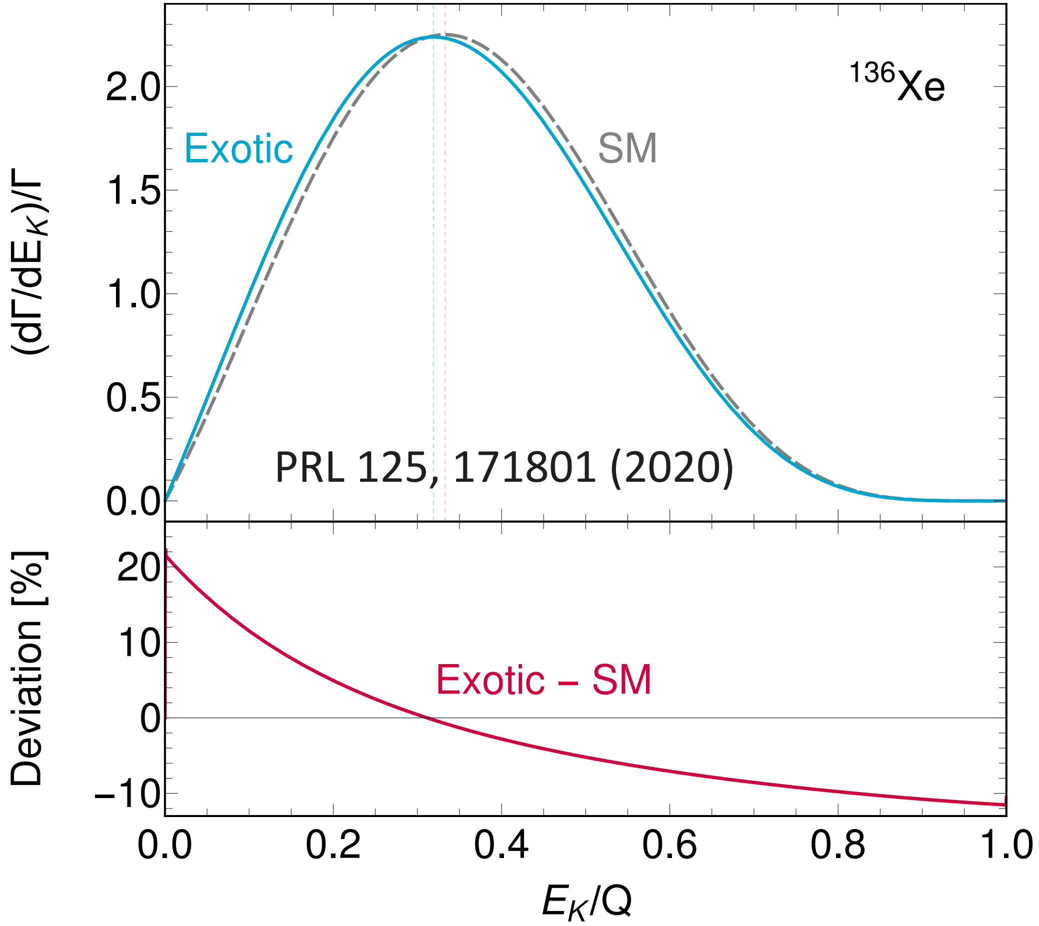
Simulated track of 0νββ in high pressure Xe

Measuring the DBD half-life

- Precision measurement of DBD is a major first step for any NLDBD experiment
- Understand better the background for more rare searches

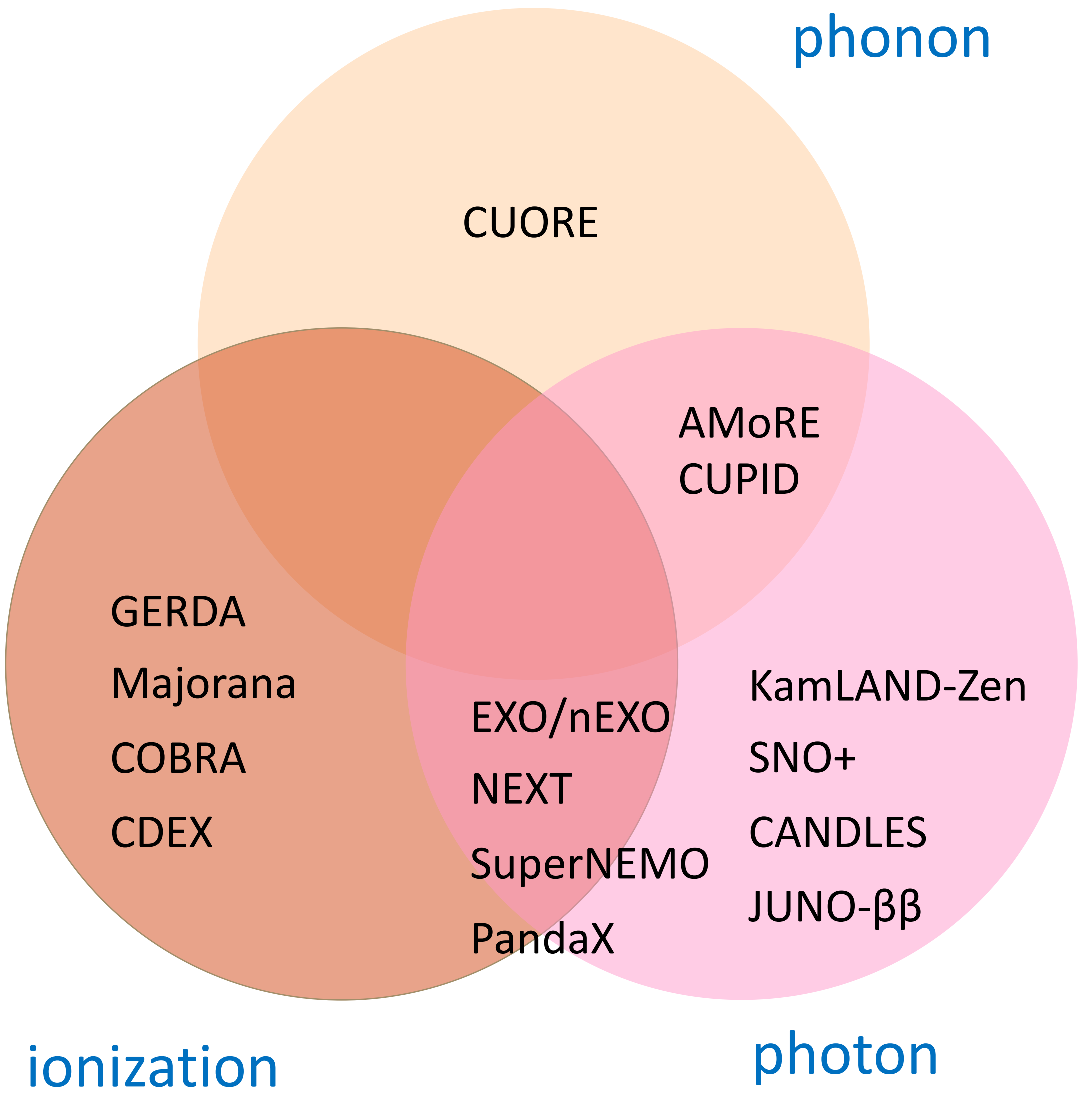


- Searching for possible shape distortion for new BSM physics



Detector techniques

Giuliani, TAUP 2021



GERDA $T_{1/2} > 1.8\times10^{26}$ y
Phys. Rev. Lett. 125, 252502 (2020)

KamLAND-Zen 400 $T_{1/2} > 1.07\times10^{26}$ y
Phys. Rev. Lett. 117, 082503 (2016)

EXO-200 $T_{1/2} > 3.5\times10^{25}$ y
Phys. Rev. Lett. 123, 161802 (2019)

MAJORANA dem. $T_{1/2} > 2.7\times10^{25}$ y
Phys. Rev. C 100, 025501

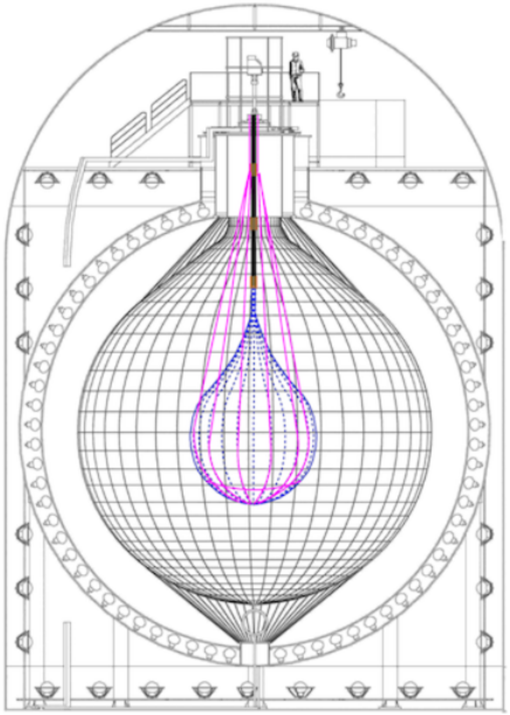
CUORE $T_{1/2} > 2.2\times10^{25}$ y
arXiv:1907.09376

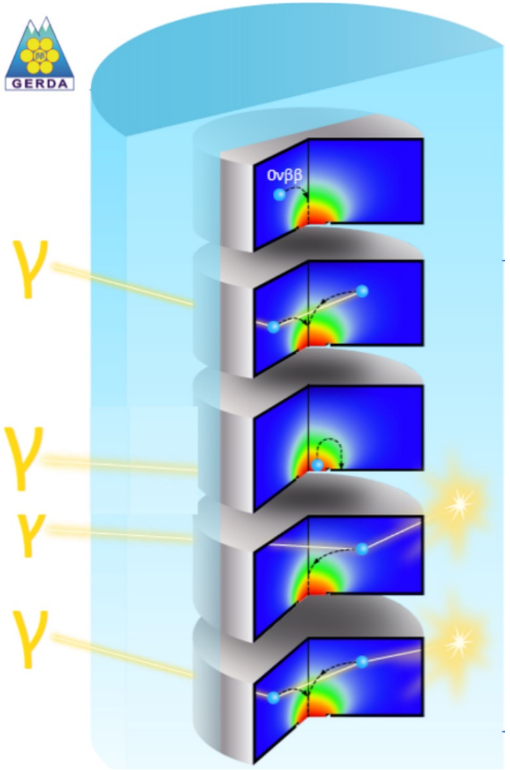
CUPID-0 NEW $T_{1/2} > 4.7\times10^{24}$ y
L. Pagnanini, this conference

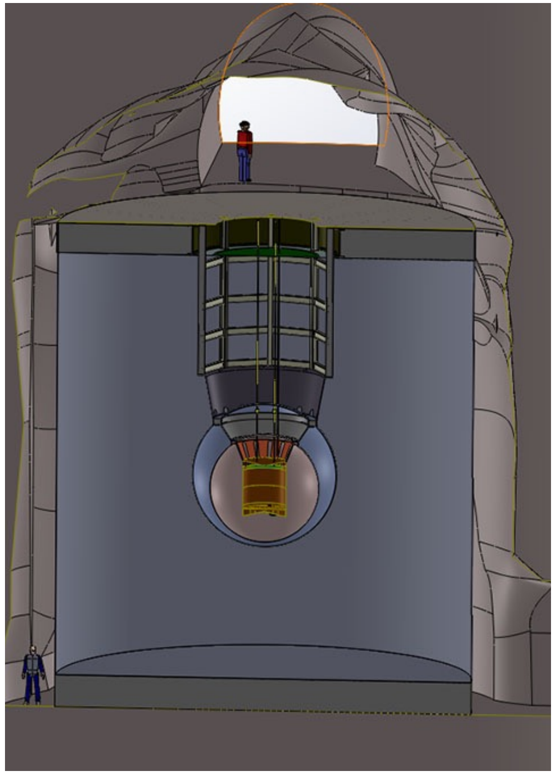
CUPID-Mo NEW $T_{1/2} > 1.8\times10^{24}$ y
B. Welliver, this conference

NEMO-3 $T_{1/2} > 1.1\times10^{24}$ y
Phys. Rev. D 92, 072011 (2015)

The big four







CUORE/CUPID

Bolometer

KamLAND-ZEN

Doped LS

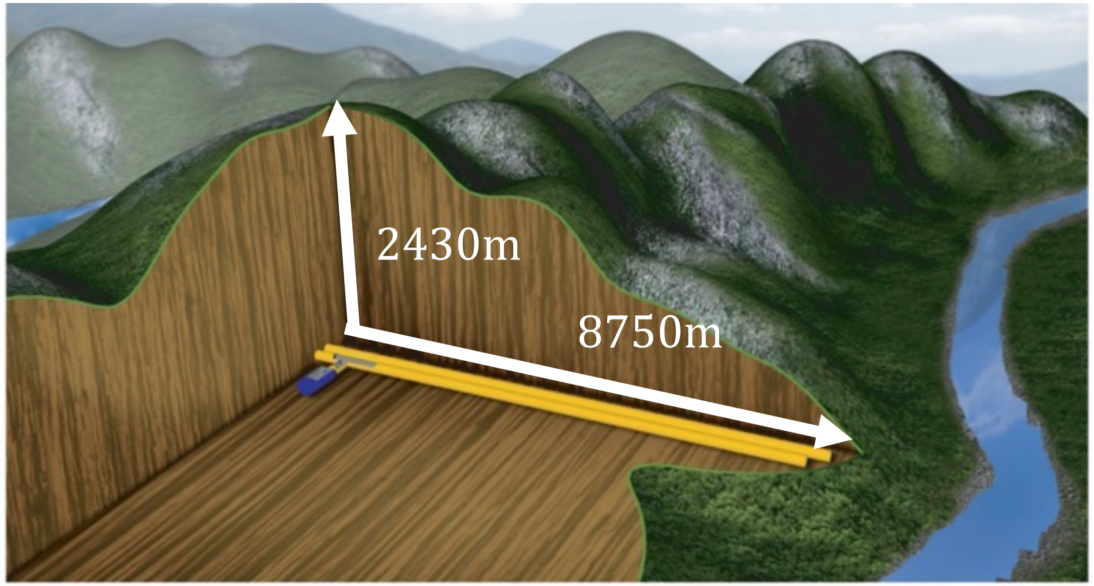
LEGEND family

HPGe

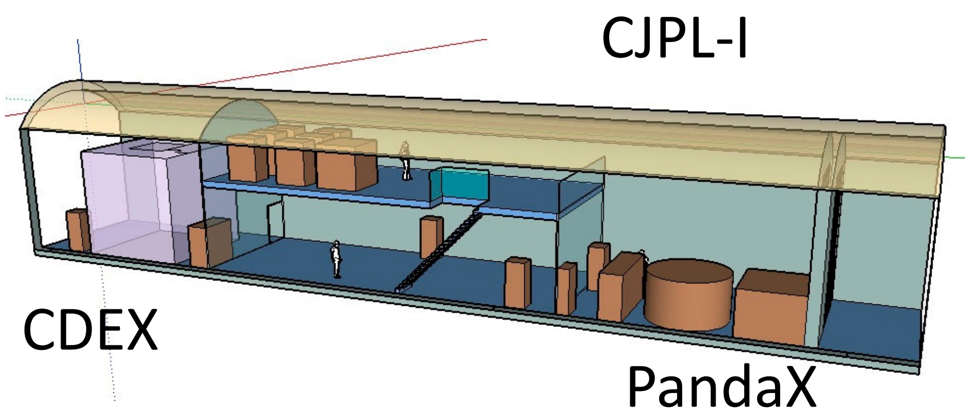
EXO/nEXO

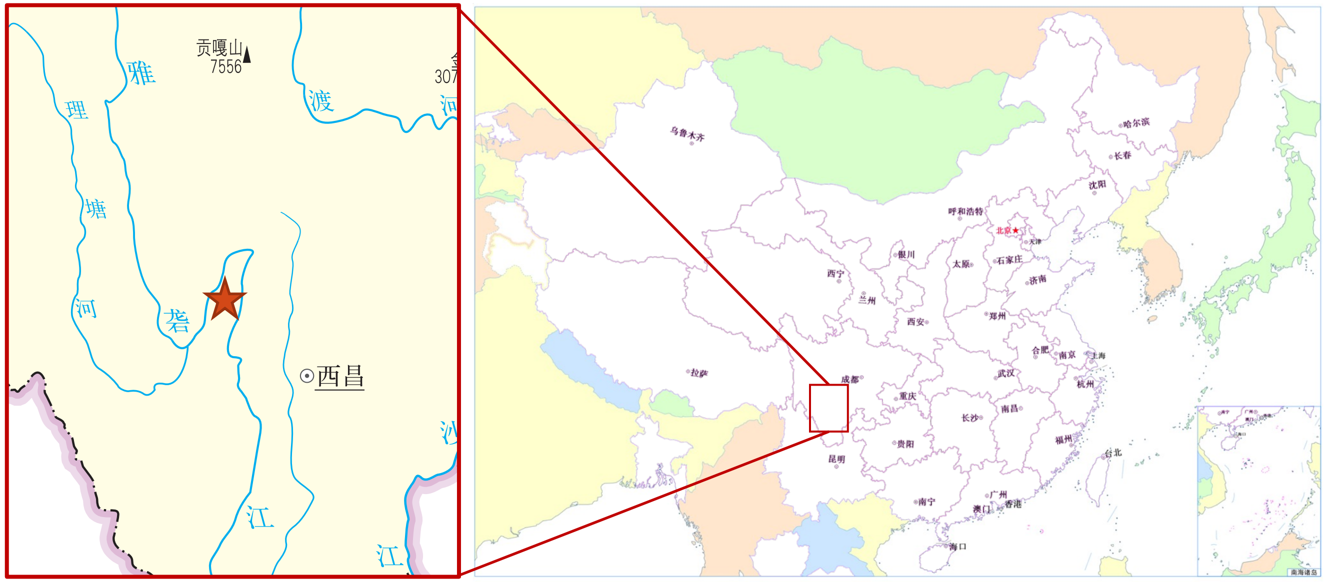
LXe TPC

CJPL: Deepest underground lab

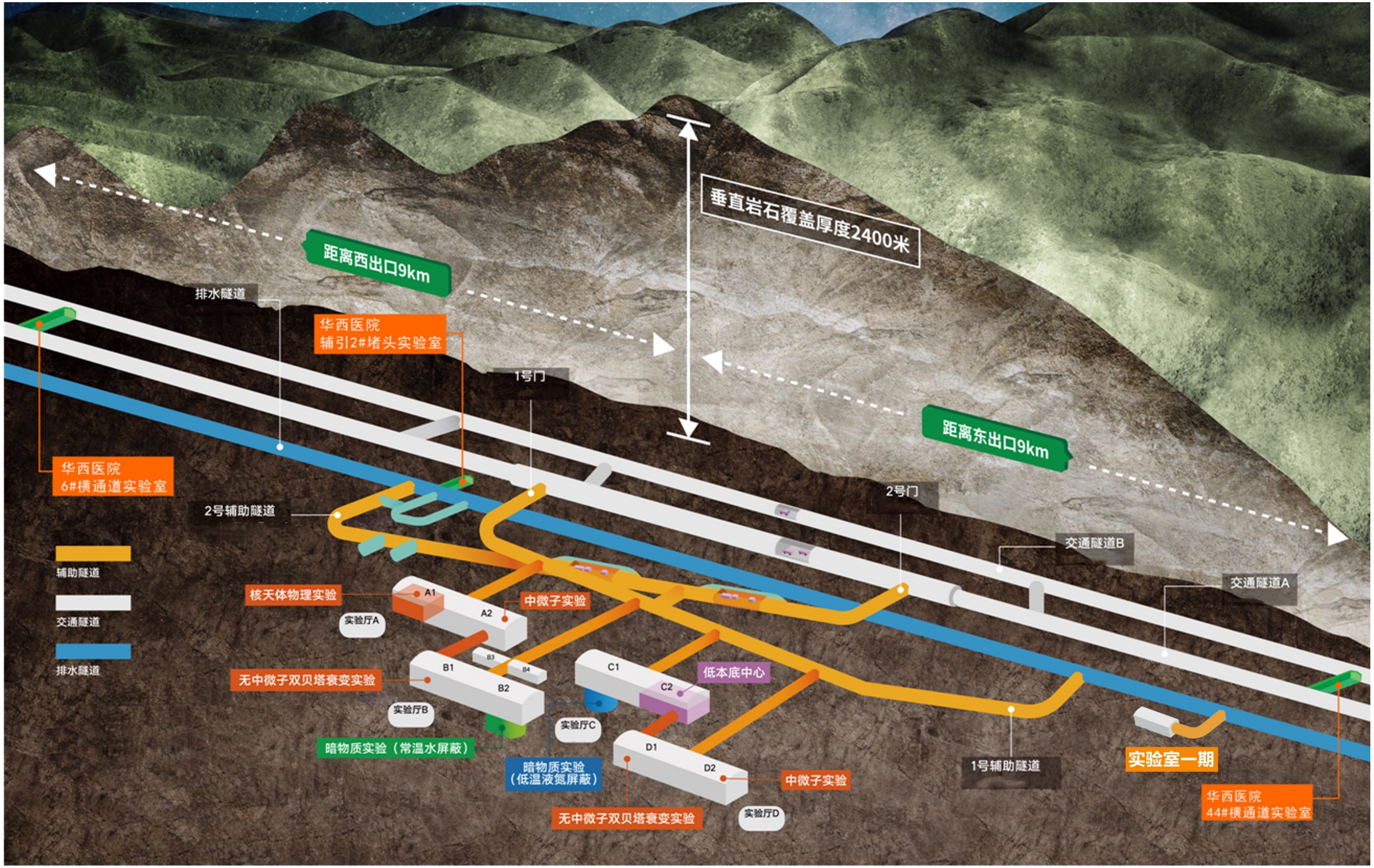


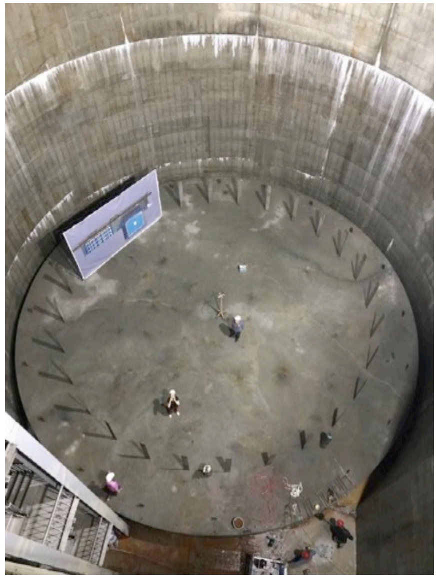
- Deepest (6800 m.w.e): < 0.2 muons/m^2/day
- Horizontal access with ~9 km long tunnel: large truck can drive in.
- National key science research facility for dark matter searches, neutrino physics, and astroparticle physics, etc.



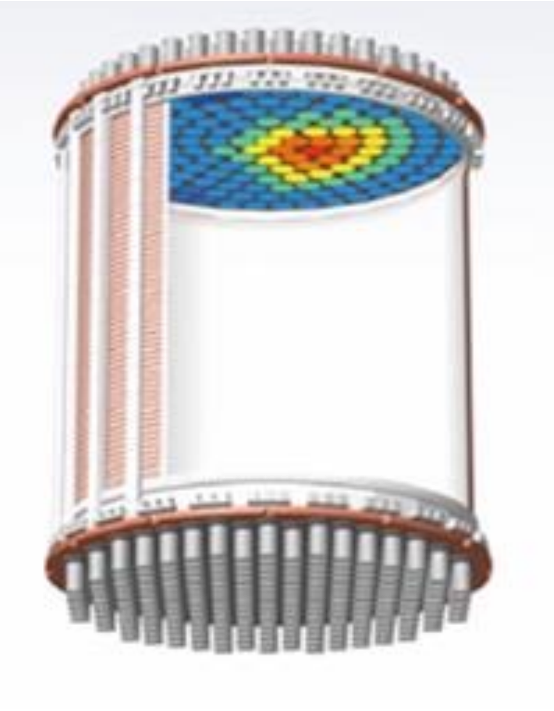


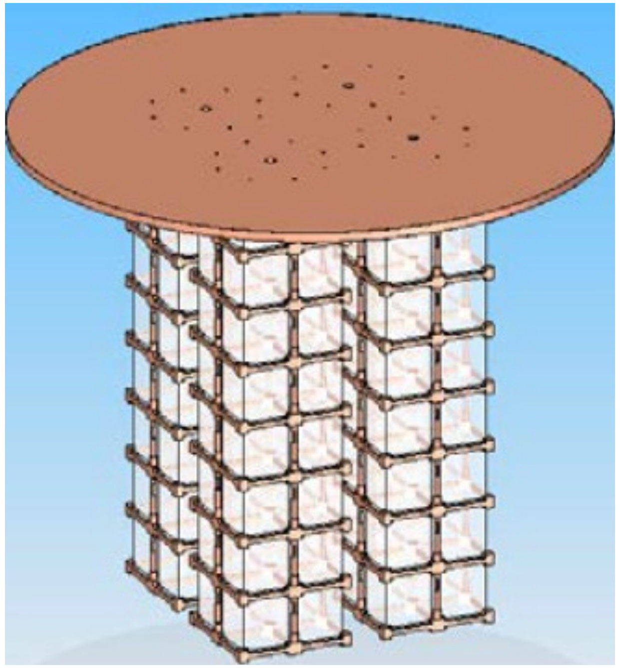
CJPL-II: much enlarged underground lab space

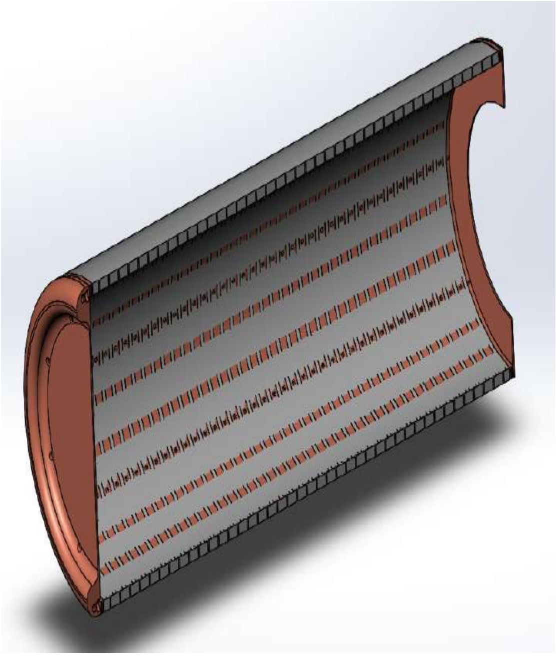




Expected DBD experiments at CJPL-II







PandaX

Xe TPC

CUPID-China

Bolometer

CDEX

HPGe

NvDEx

Ion TPC

PandaX Collaboration

- Particle and Astrophysical Xenon Experiment; started in 2009; now ~80 authors

SINAP

CNNC

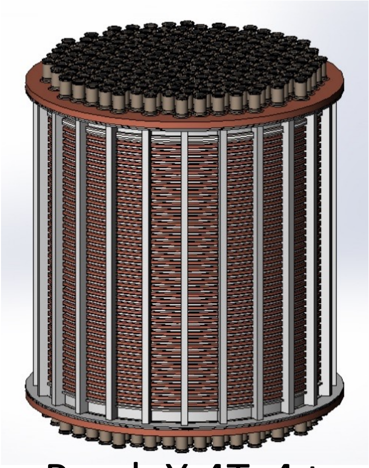
雅砻江水电

Universidad Zaragoza

PandaX detectors

PandaX-I: 120kg LXe
(2009 – 2014)

PandaX-II: 500kg LXe
(2014 – 2018)

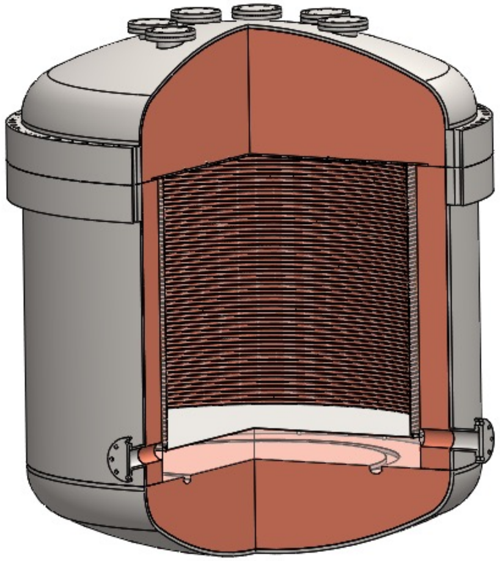


PandaX-4T: 4 ton
(2019-)

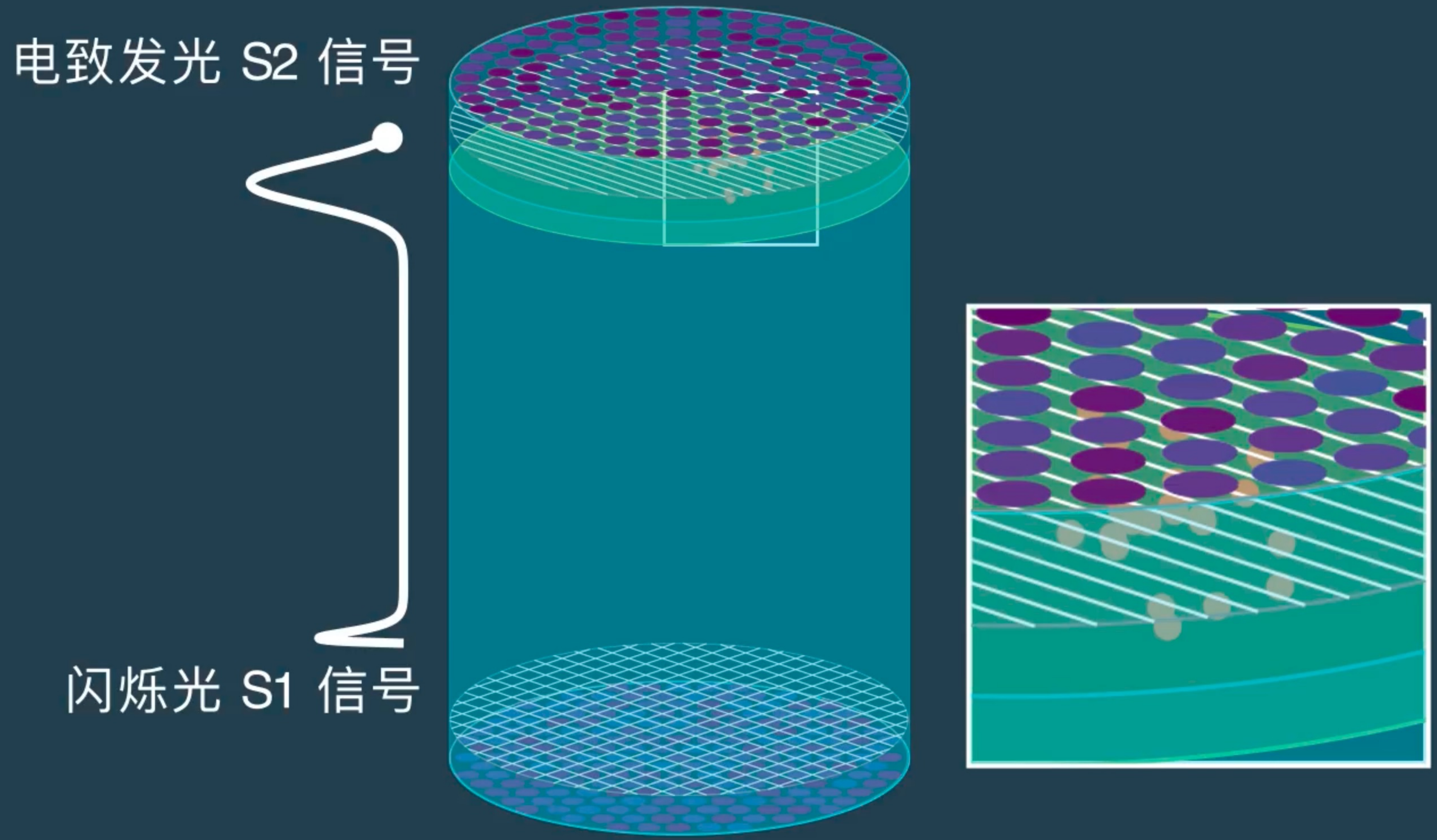
WIMP searches
(DBD as well)

PRL 117, 121303 (2016)
…
…

PandaX-III: 100kg - 1 ton
HPXe for DBD (future)



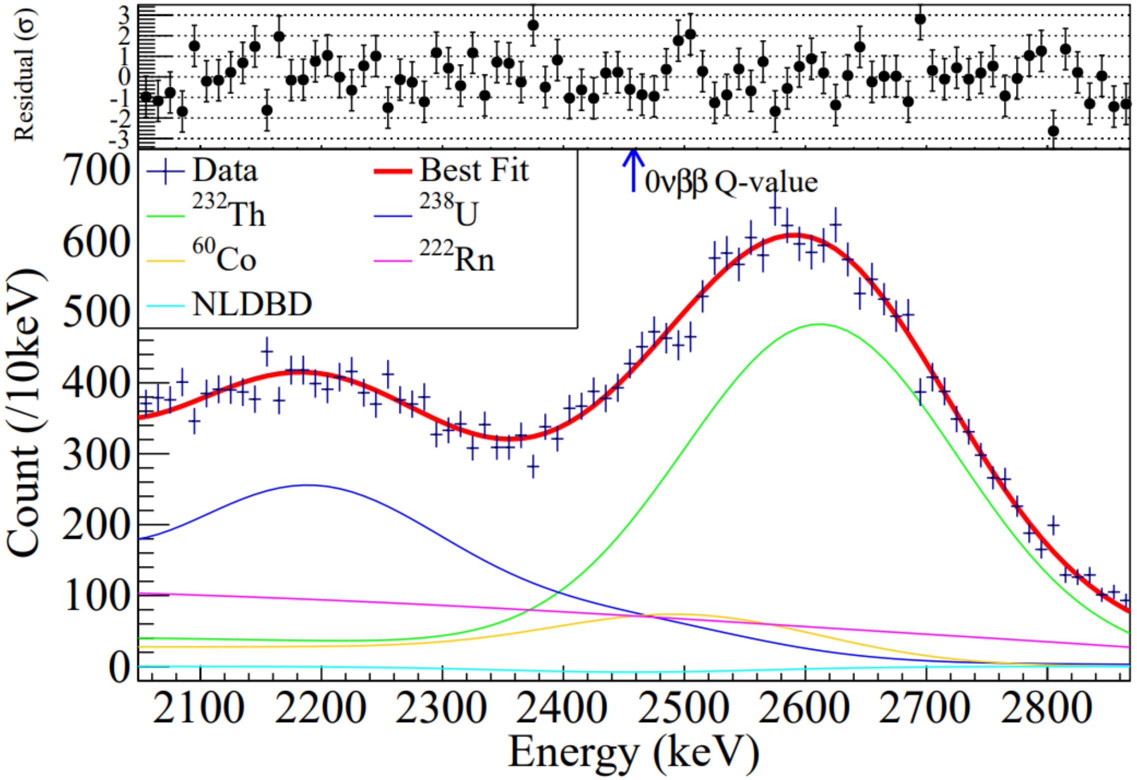
PandaX 多物理探测器



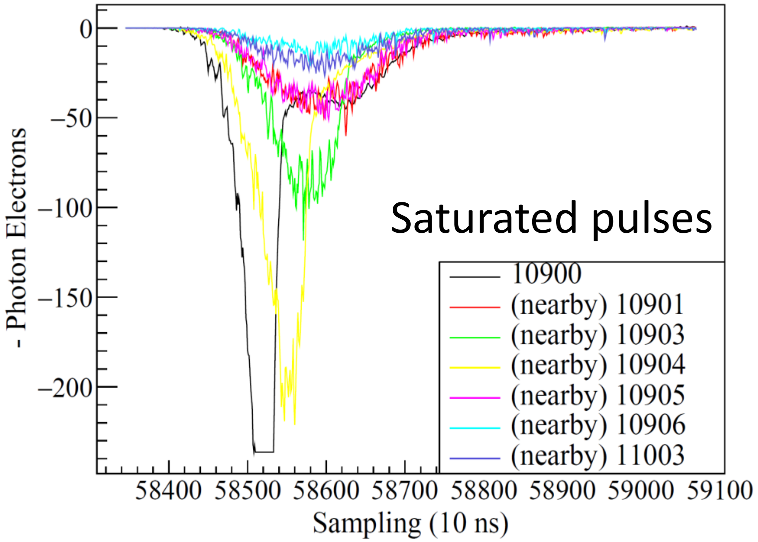
NLDBD search at PandaX-II

- 580 kg natural xenon; ~50 kg of ^{136}Xe.
- 403.1 day of dark matter physics data
- Null results; Lower limit for decay half-life: 2.4×10^{23} yr at 90% CL
- Effective Majorana mass upper limit: 1.3-3.5 eV.

- First NLDBD result reported from a dual-phase xenon experiment
- Proof of Principle

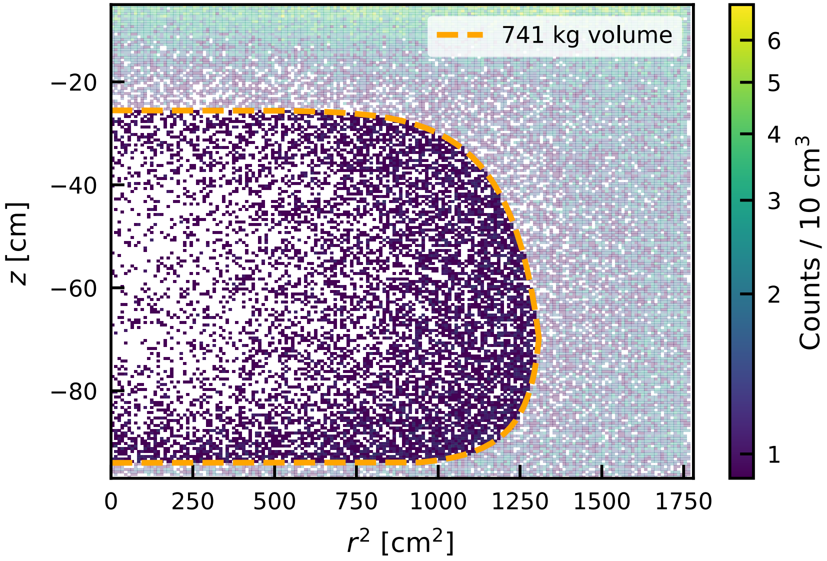


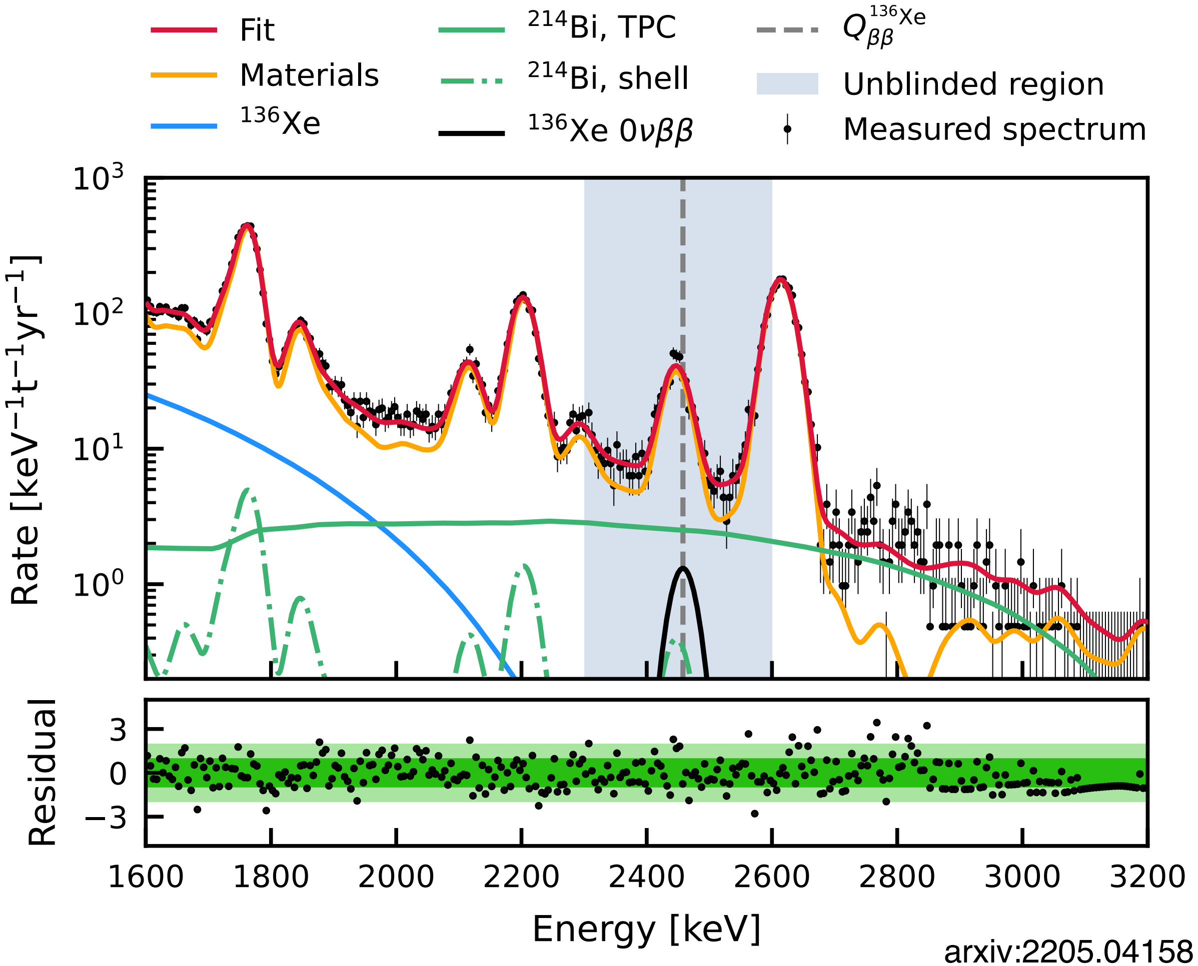
arXiv:1906.11457; Chinese Physics C 43, 113001 (2019)



NLDBD searches at XENON1T

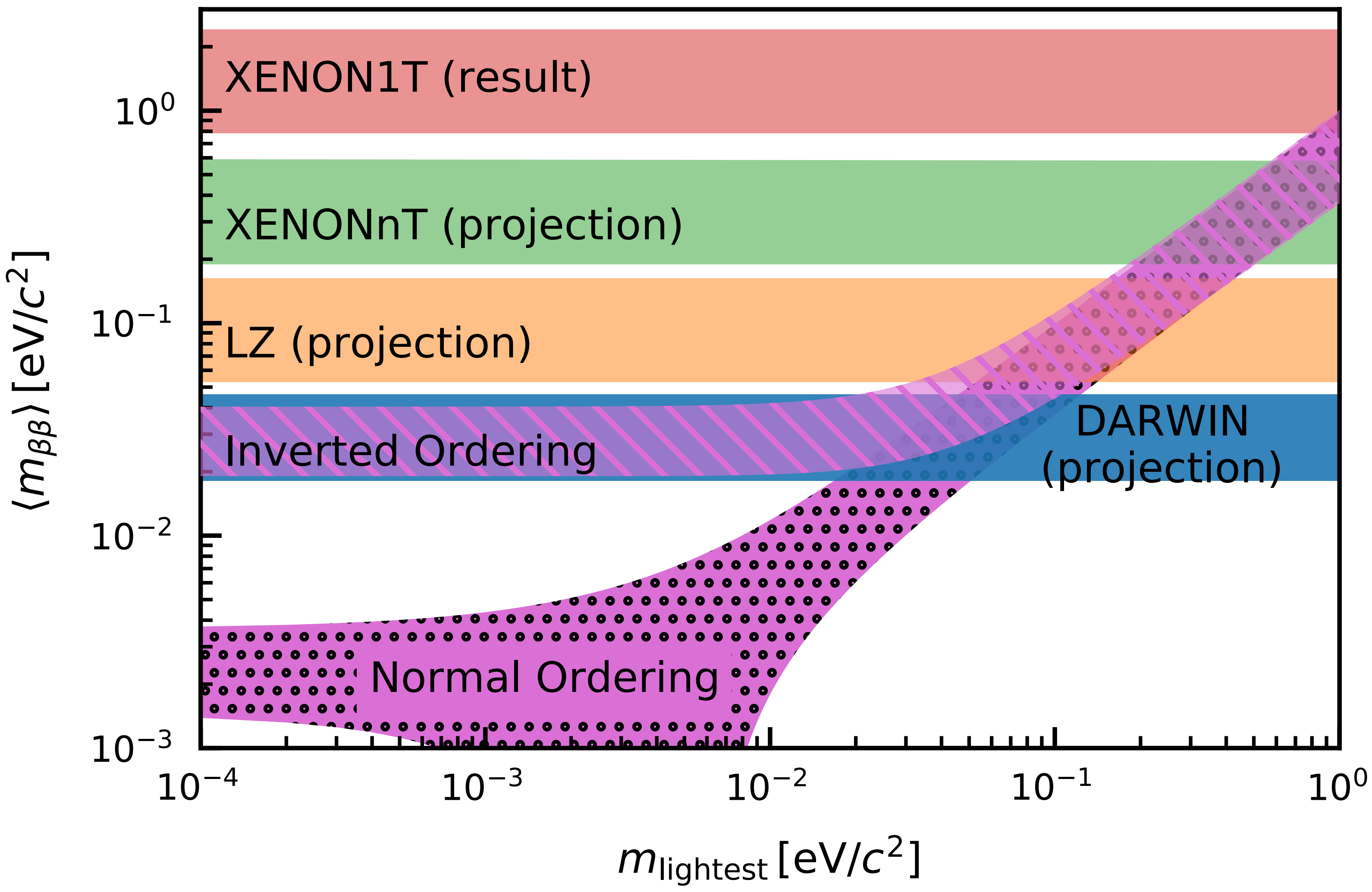
- Data between 2300 and 2600 keV
- Lower limit at 90% CL from profiled likelihood
- $T > 1.2 \times 10^{24} yr$





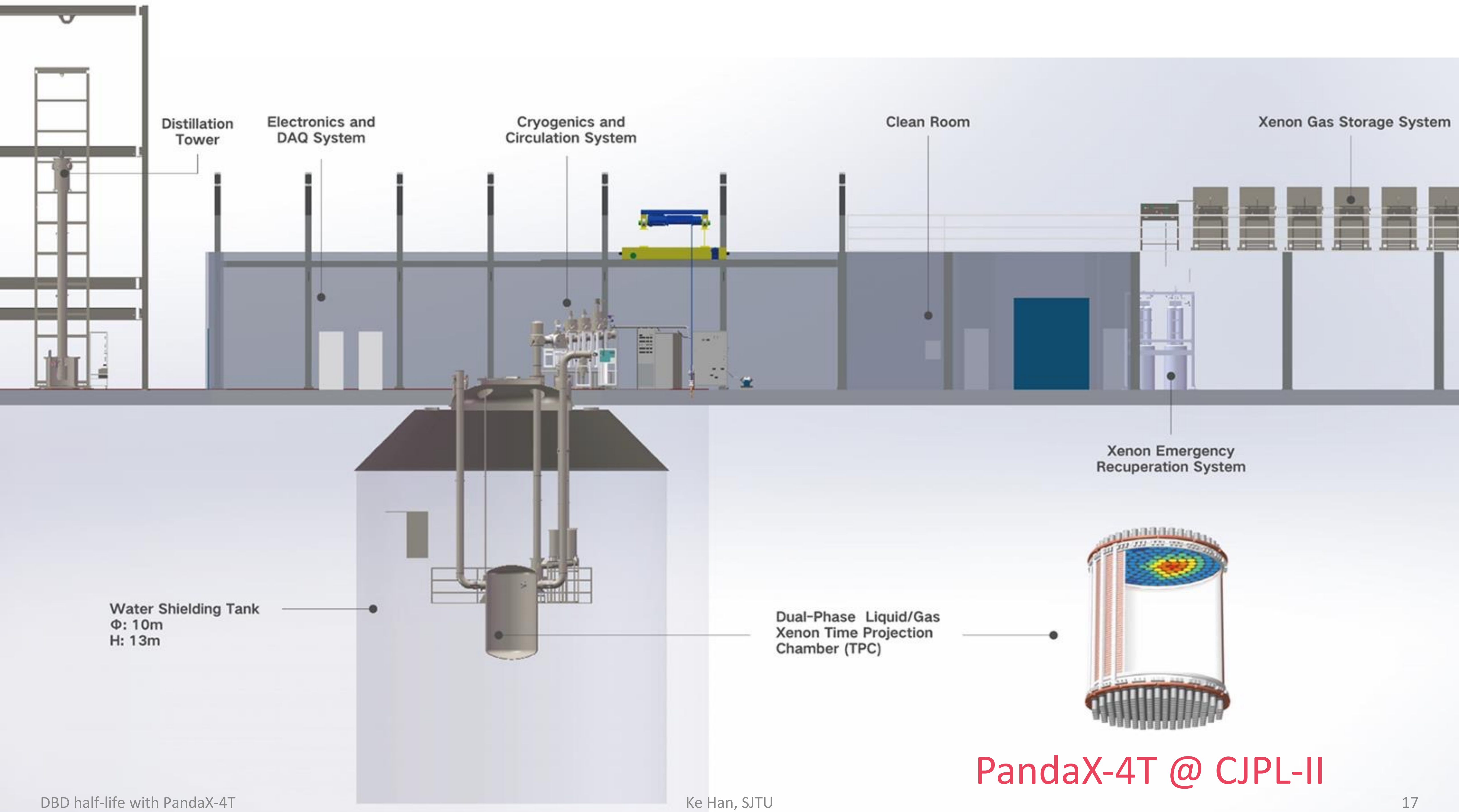
arxiv:2205.04158

Ambitious natural LXe TPC can achieve competitive NLDBD sensitivity



The multi-physics game is on

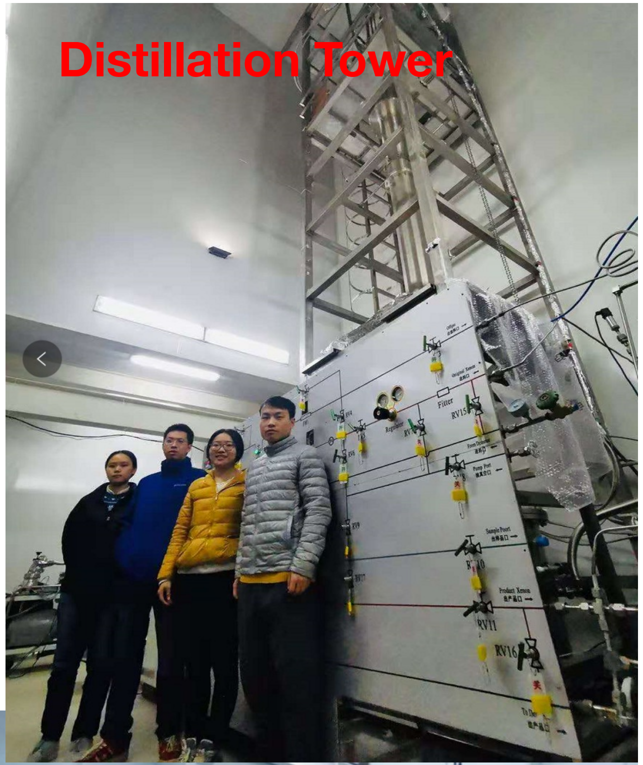
T. Wolf, Neutrino2022



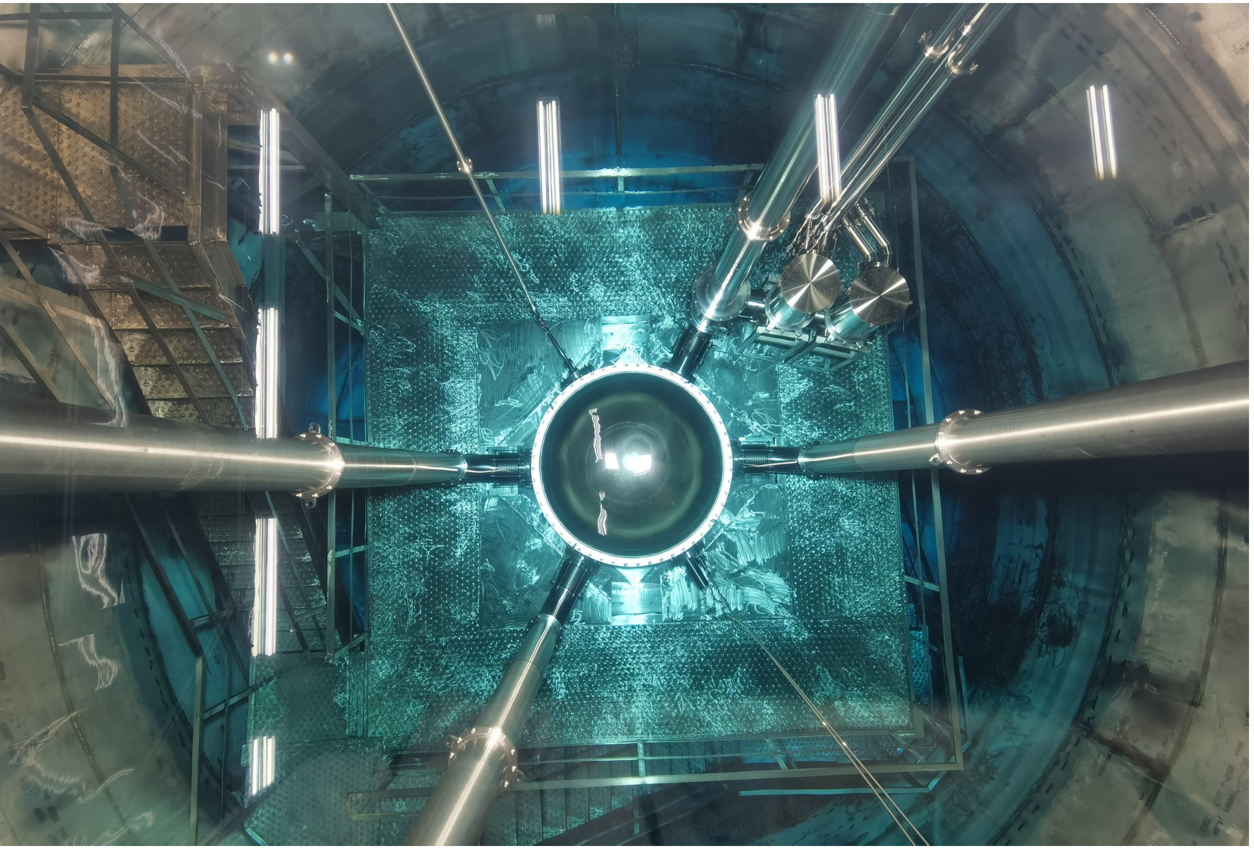
PandaX-4T @ CJPL-II

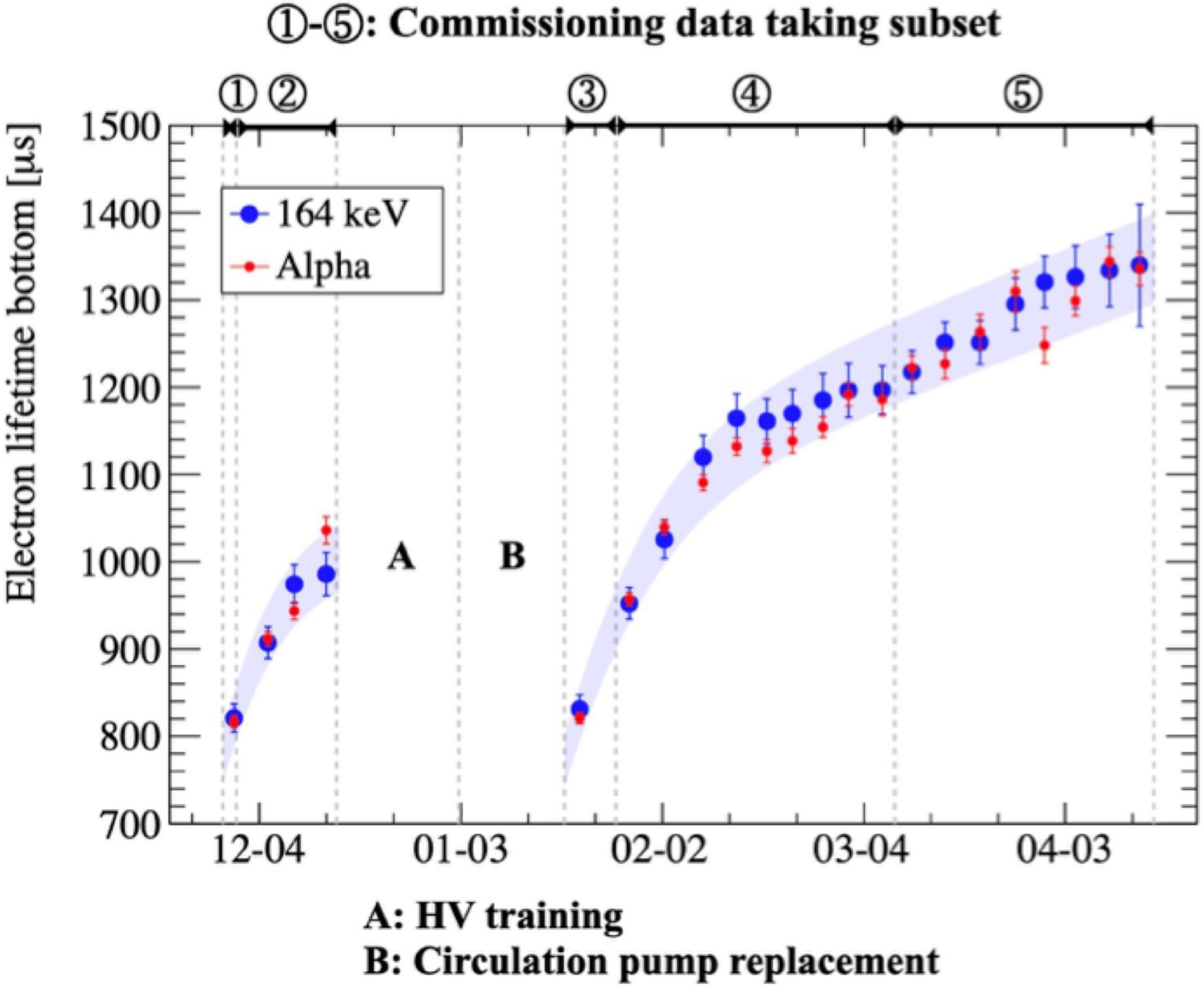

上海交通大学PandaX暗物质与中微子实验平台

PandaX-4T Commissioning onsite



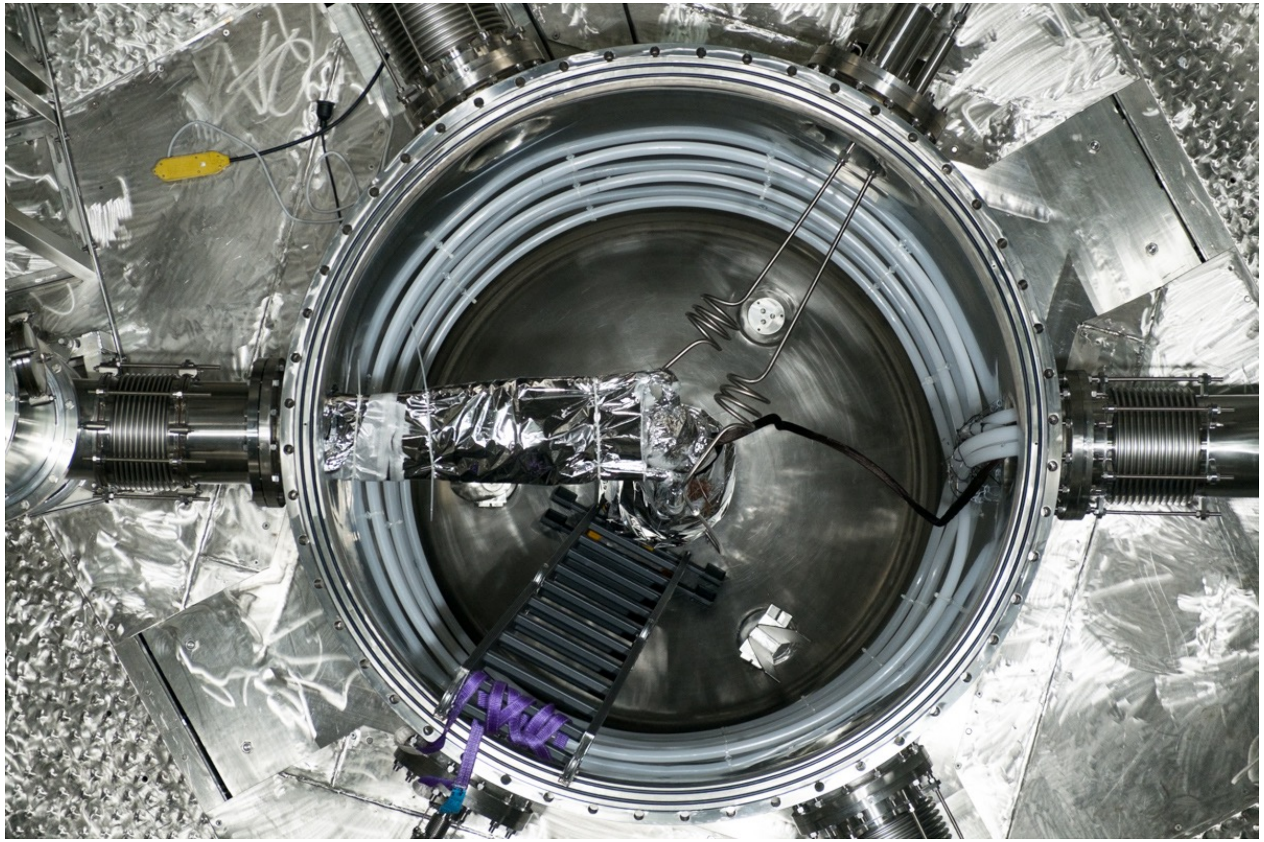
Stable data taking during commissioning runs: 94.9 days for DBD analysis

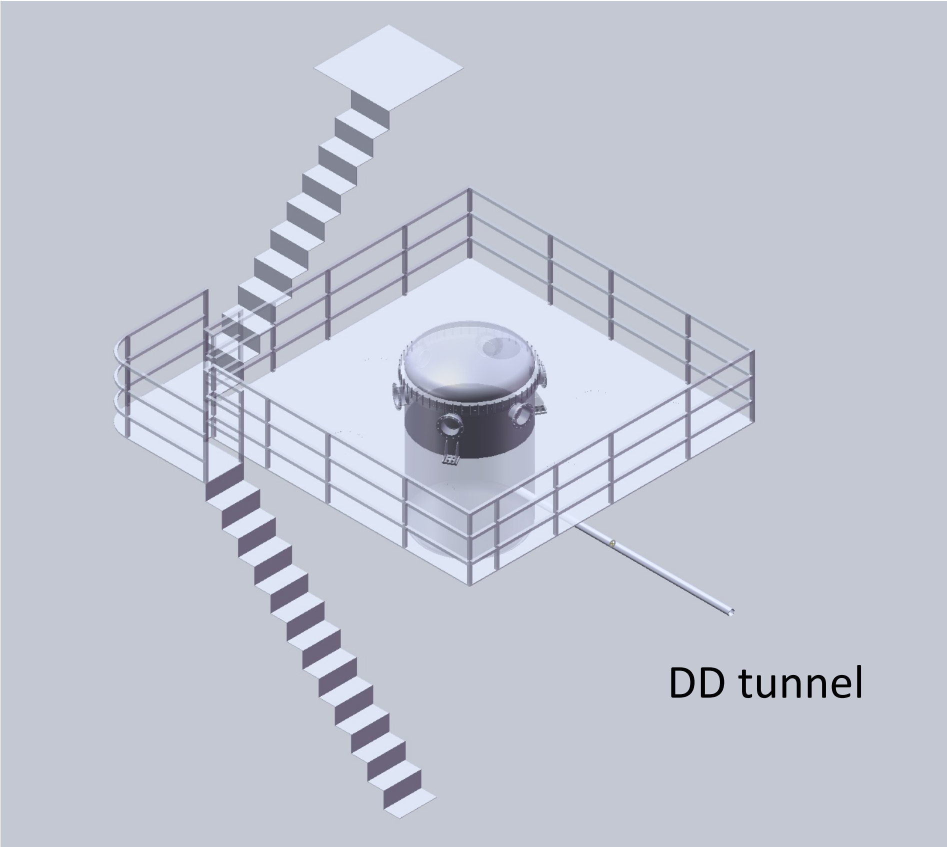




- Nov. 28, 2020 to Apr. 16, 2021

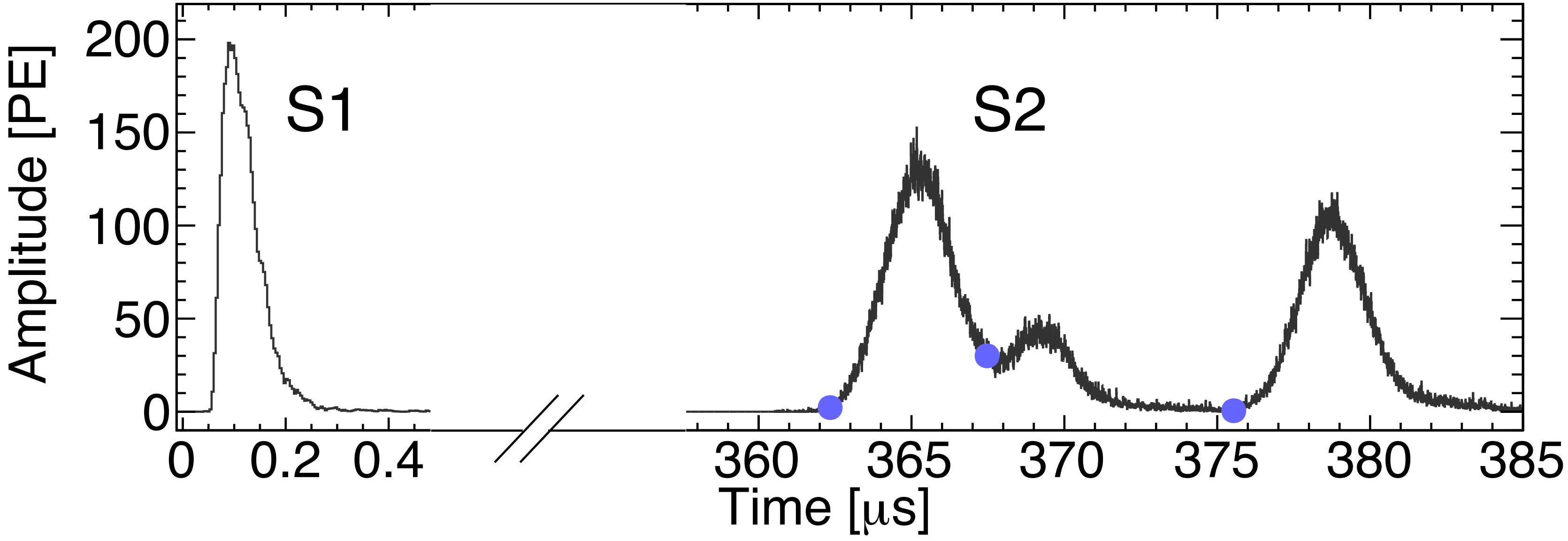
External calibration sources for high energy detector response: ^{232}Th (loops), ^{127}Cs, and ^{60}Co (DD tunnel)

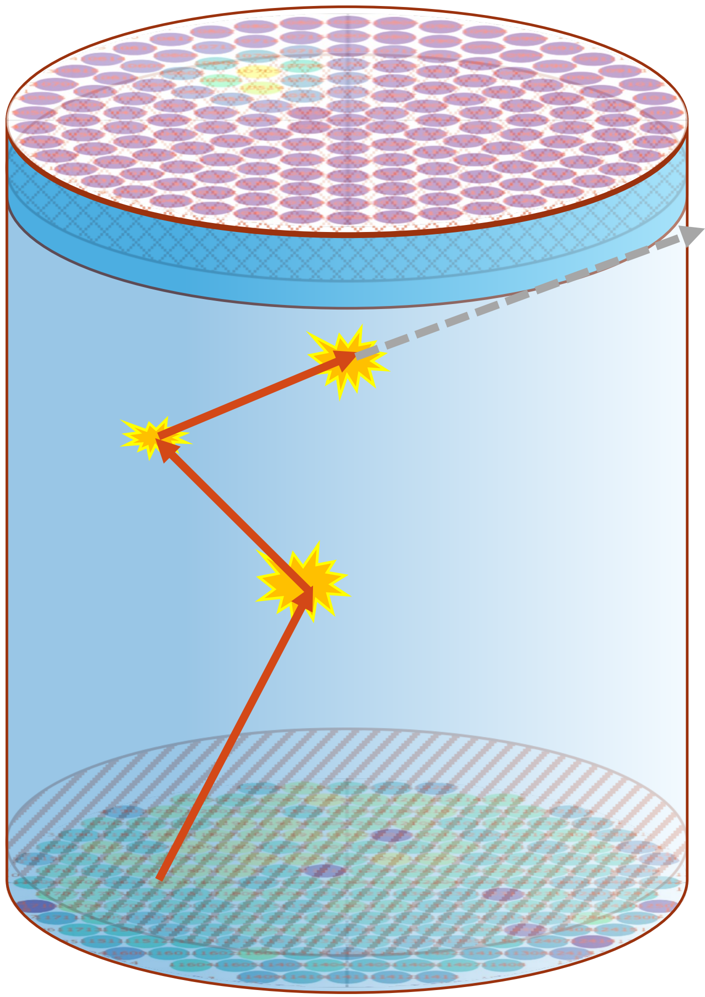




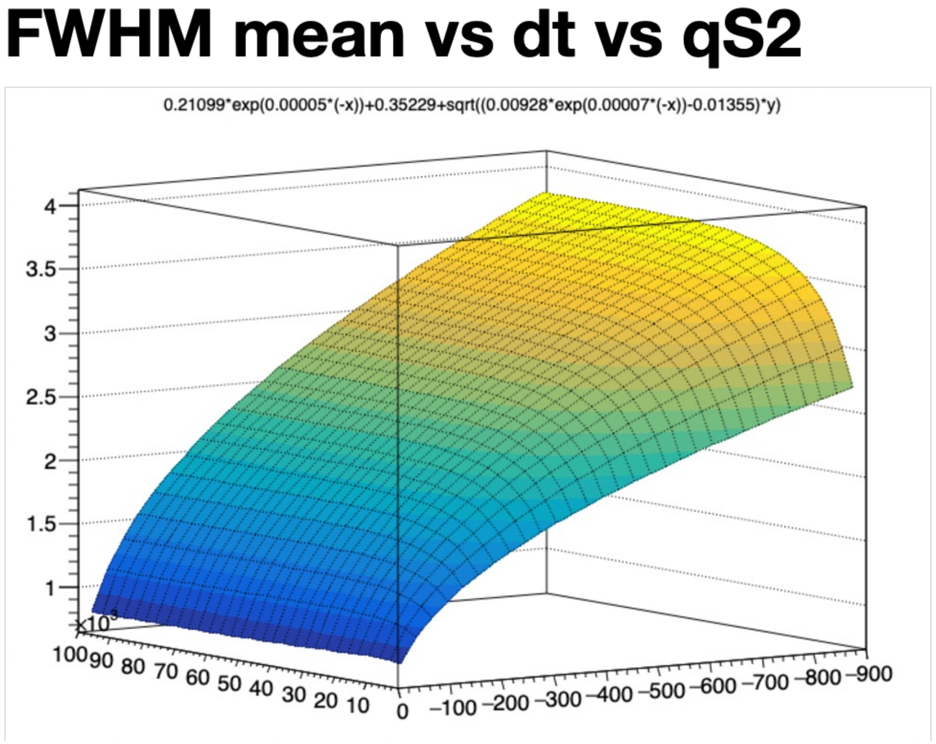
Extending DM detector response to MeV range

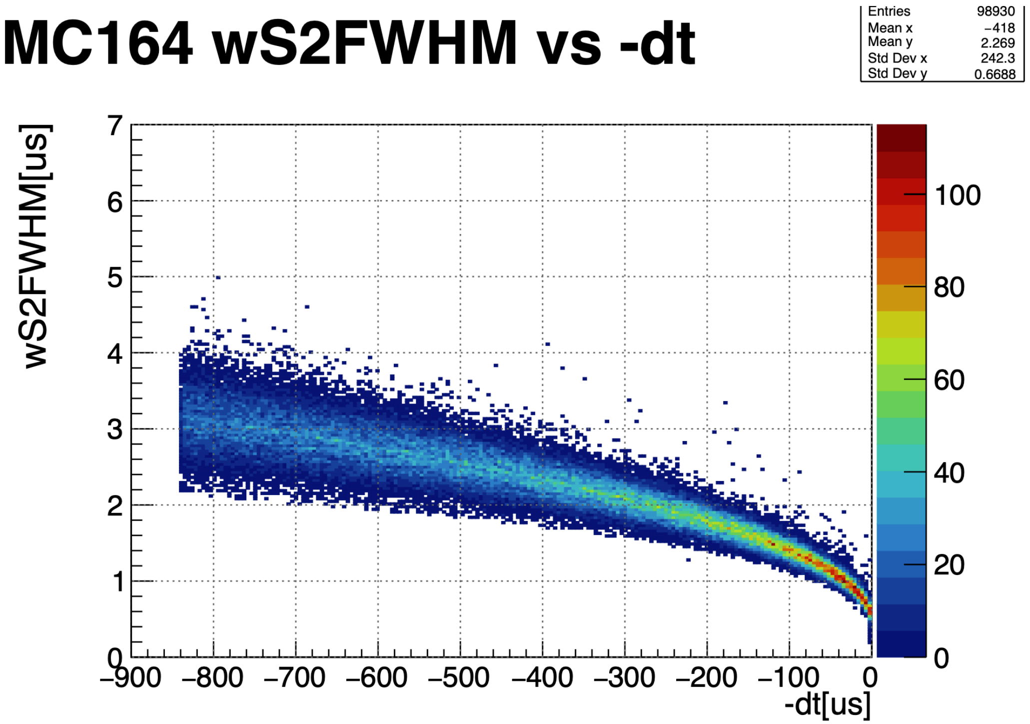
- MeV gamma events are mostly multiple-scattering events; while signals (DBD) are mostly single site (SS)
- Identifying Multi-Site (MS) events with PMT waveforms
- Width of waveforms dominated by Z (electron diffusion)





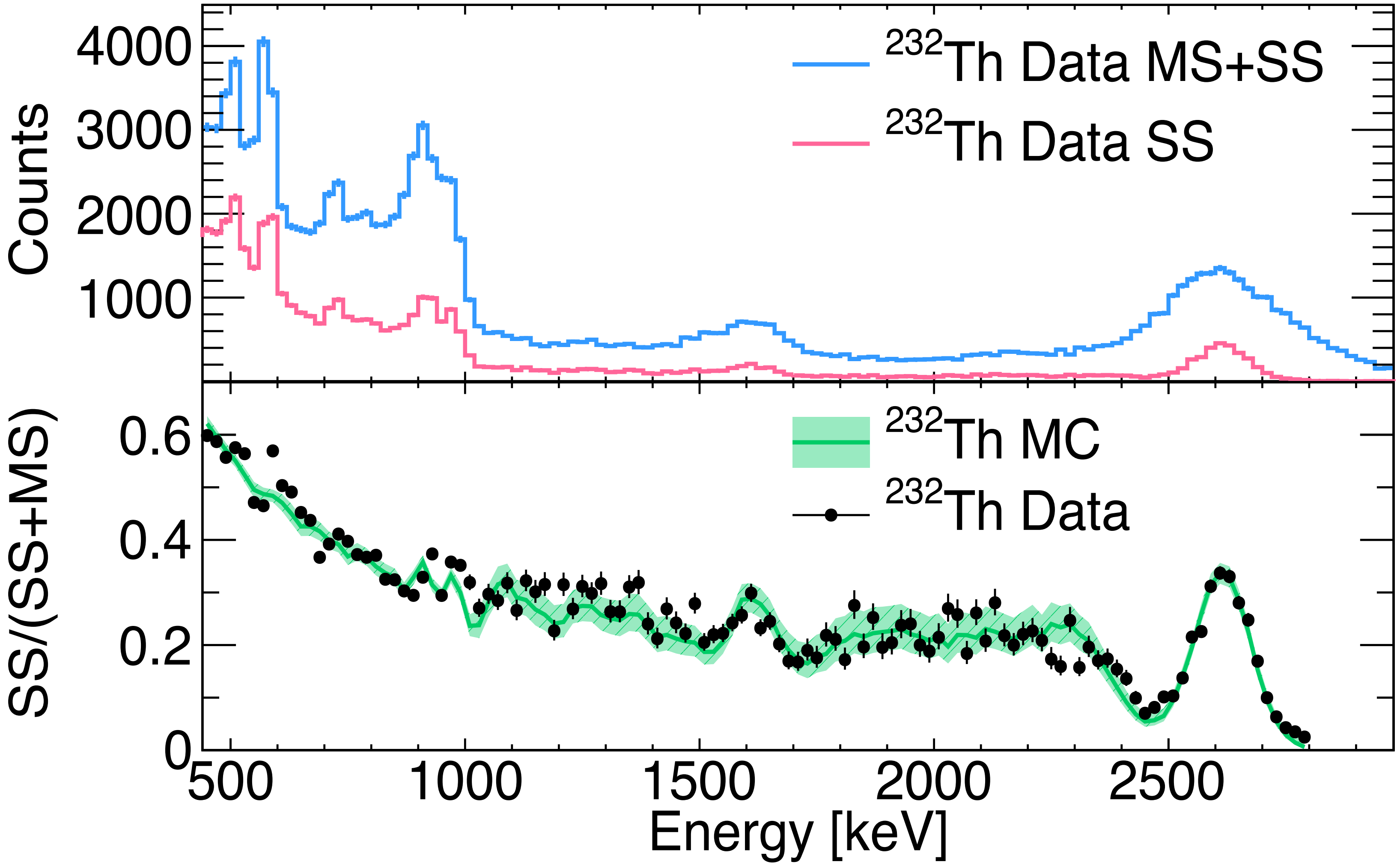
Data-driven diffusion width as input for simulation





- Pulse width of SS events are calculated from data
- Used for simualtion of waveforms after Geant4 output

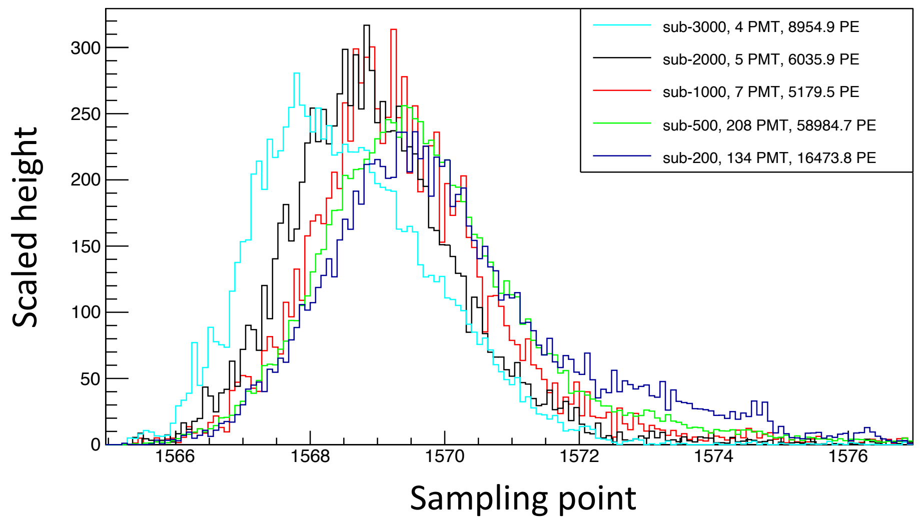
Validation with calibration data

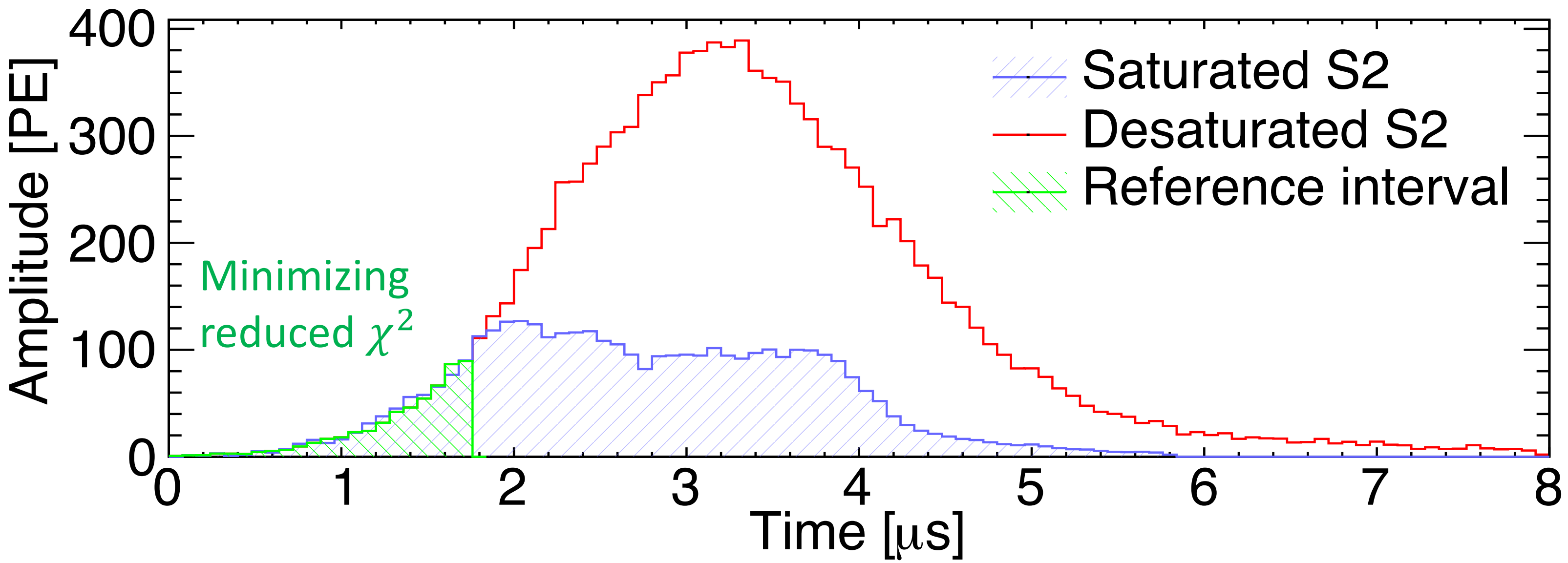


The overall agreement is at 1.7% level

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



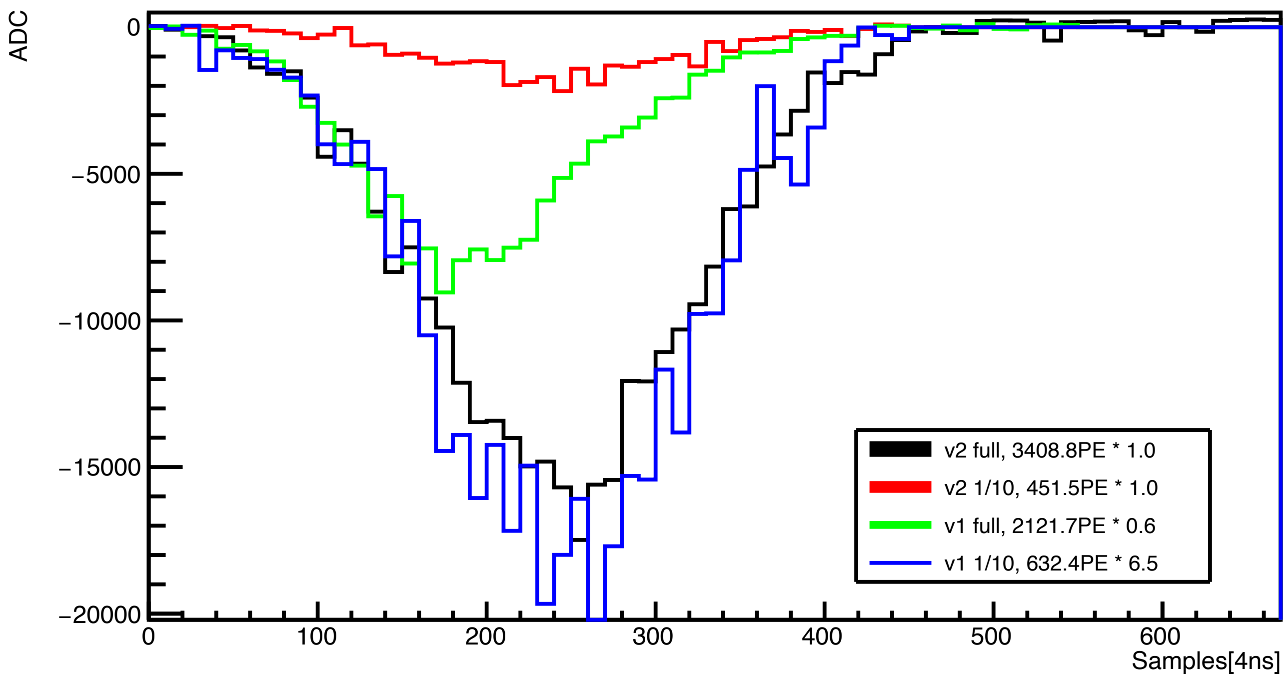


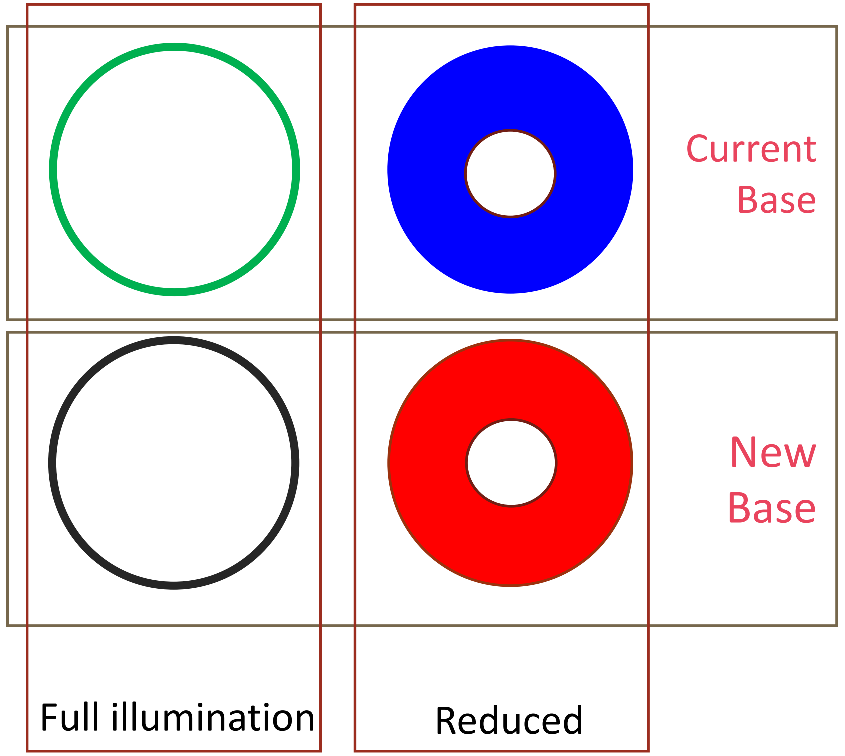
>900 PE

Unsaturated WFs (50-500 PE) as templates

Validation with bench tests and improvement of PMT bases

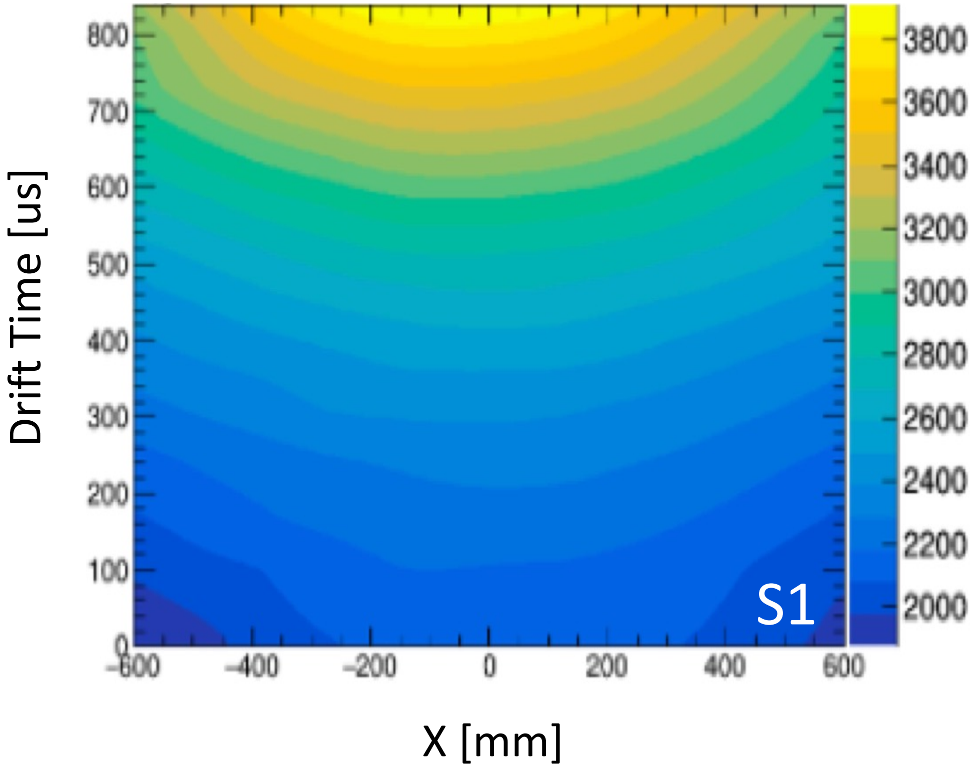
- Desaturation algorithm validated with a bench measurement
  - PMTs illuminated by high intensity photons with S2 timing profiles
- Newly designed PMT bases can improvement the linear dynamic range by >30

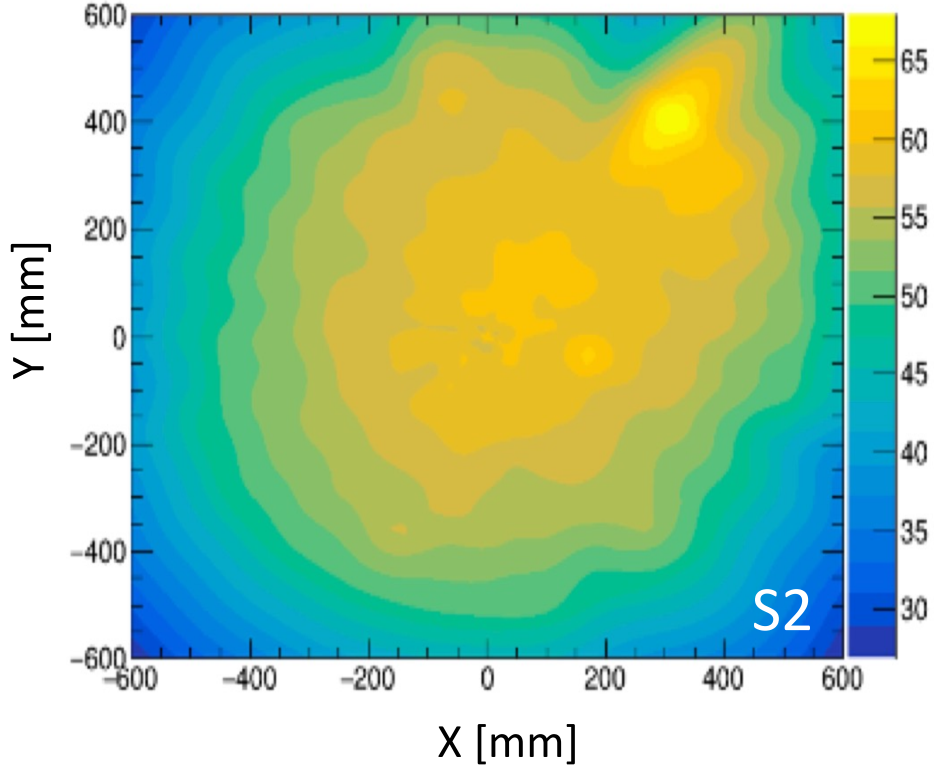




Data-driven detector response and correction

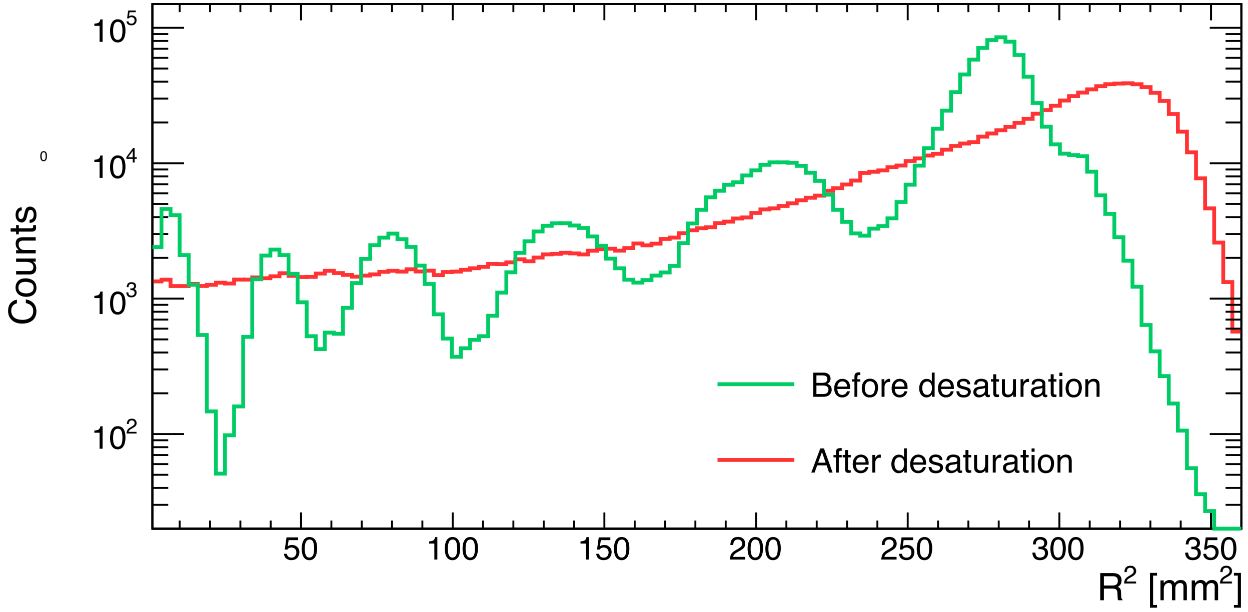
- Gaseous ^{83m}Kr feed into the TPC → uniformly distributed 41.5 keV events → 3D detector response
- S1 (3D) and S2 (2D) signals are corrected respectively; E-lifetime correction done for S2 before this
- Also validated with higher energy peaks (164 keV and even 2615 keV)

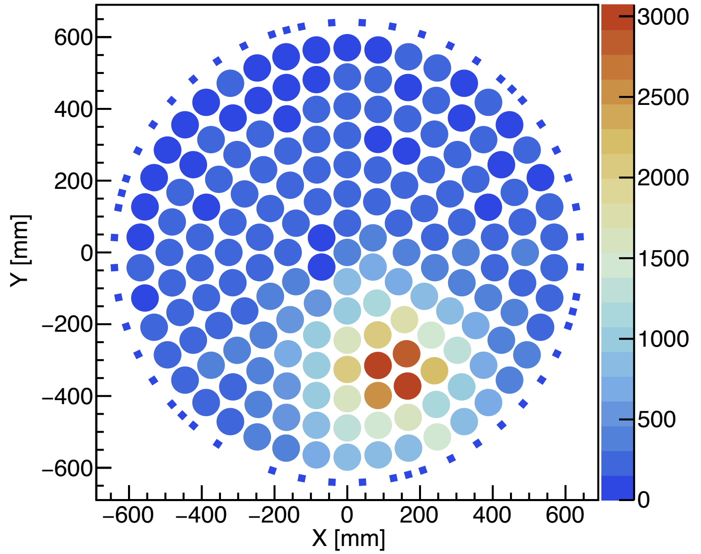




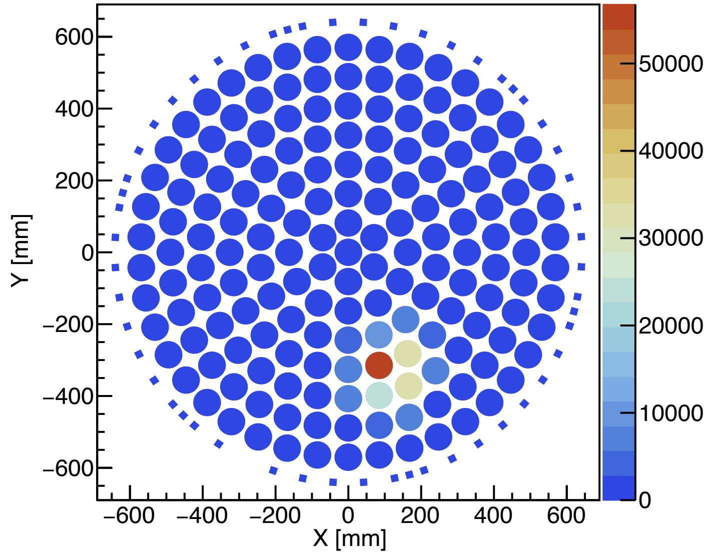
Position reconstruction improvement with desaturation

- 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





Before



After

Energy reconstruction

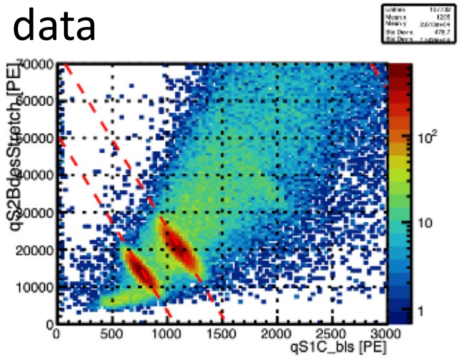
- Energy reconstruction: E = 13.7 eV × (S1/PDE + $S2_b$/(EEE × SEG_b))
- High energy peak positions off by ~10% with inputs from DM analysis
- Further tune S1 and $S2_b$ vs. energy and position → deviations of peak positions to the percent level.

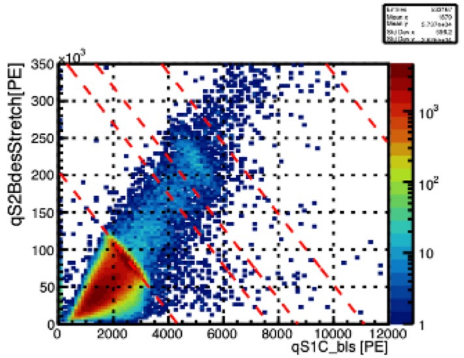
PDE: photon detection efficiency for S1

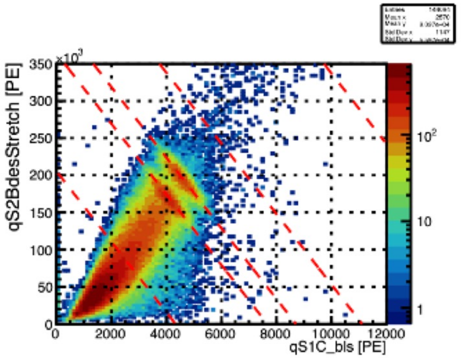
EEE: electron extraction efficiency

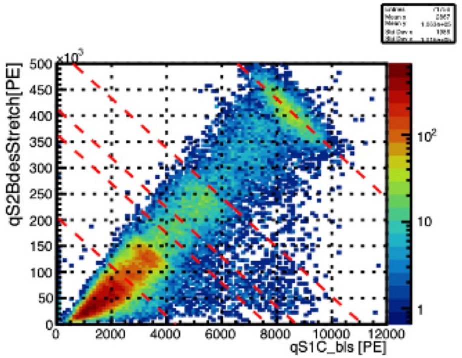
SEG_b: single-electron gain for $S2_b$

Calibration data







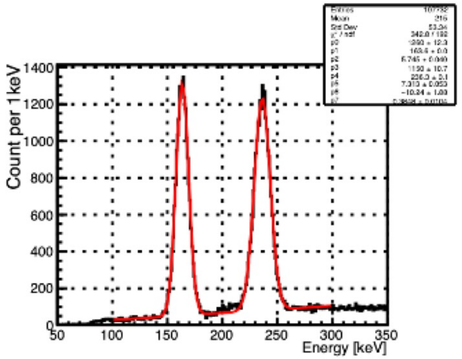


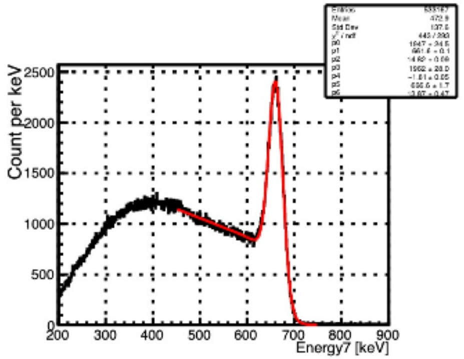
^{131m}Xe (164 keV), ^{129m}Xe (236 keV)

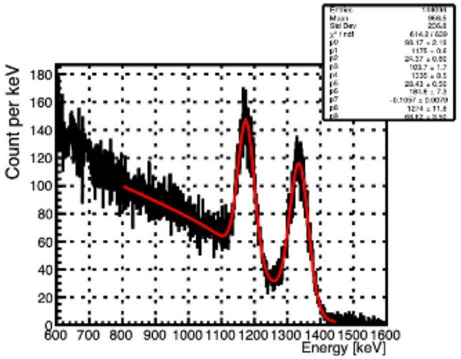
^{137}Cs

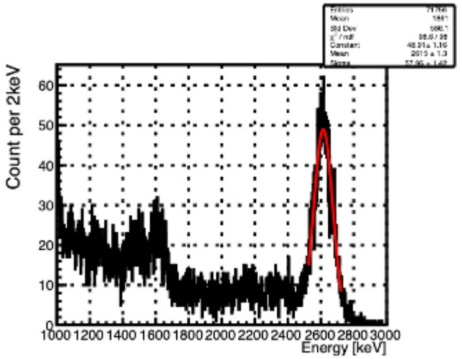
^{60}Co

^{208}Tl



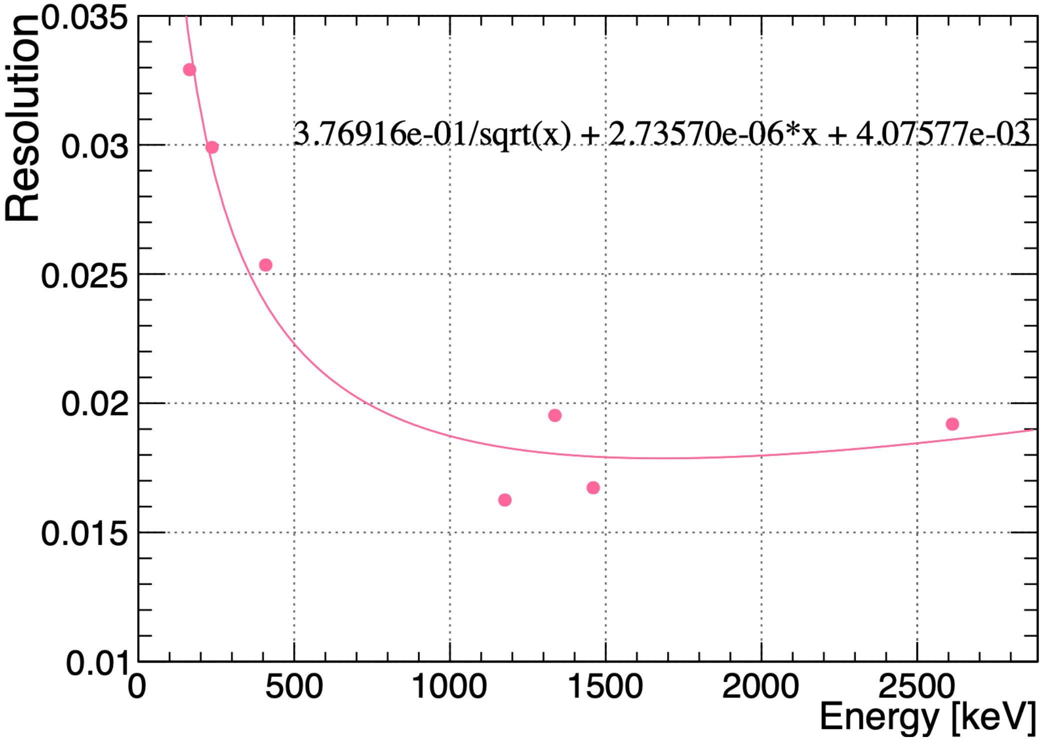




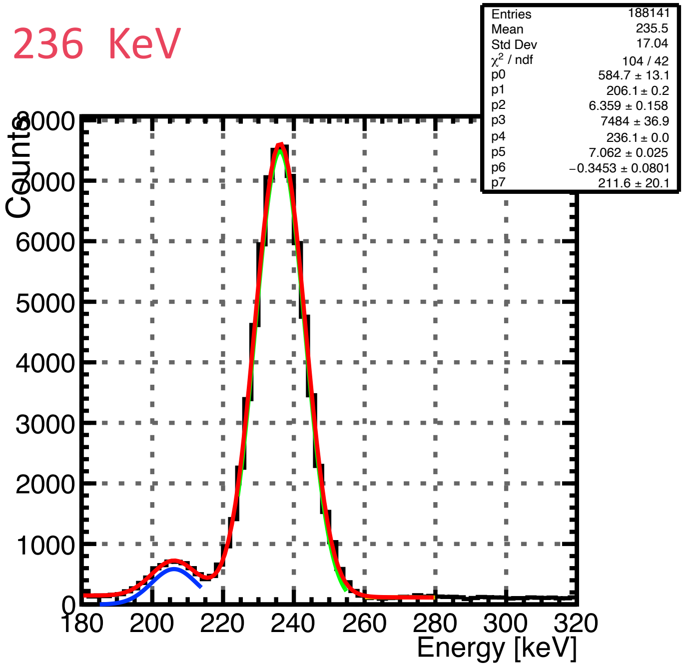


Background peaks

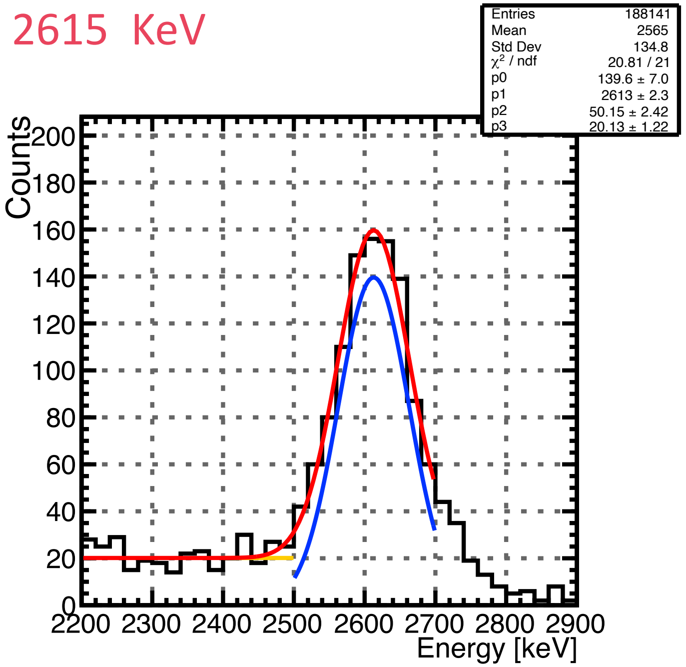
- Resolution of background data: 1.9% at 2615 keV; 3.0% at 236 keV
- Resolutions from different peaks as input for simulated spectrum



236 KeV

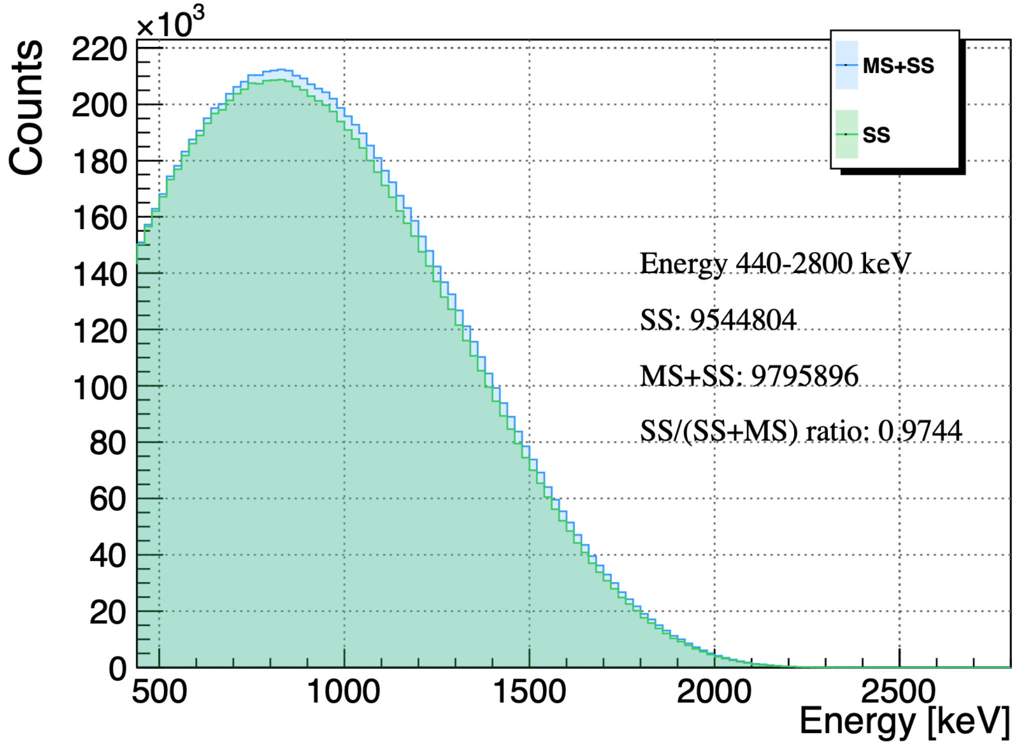


2615 KeV



Signal Efficiencies

- SS efficiency: 97.4% for DBD events > 440 keV
- DBD events generated with DECAY0 package and went through PandaX-4T simulation and data processing chain.

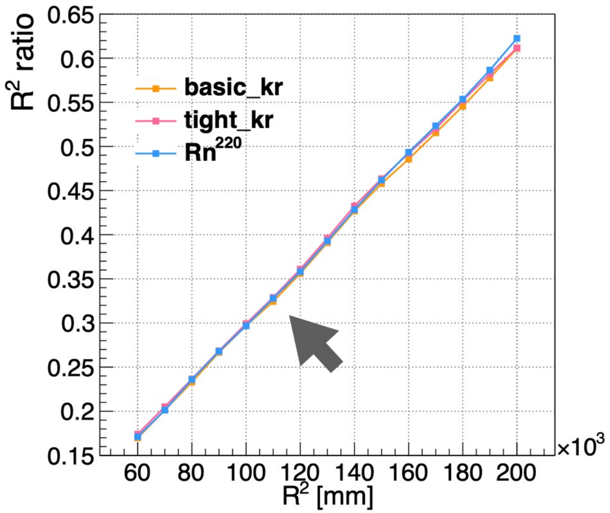


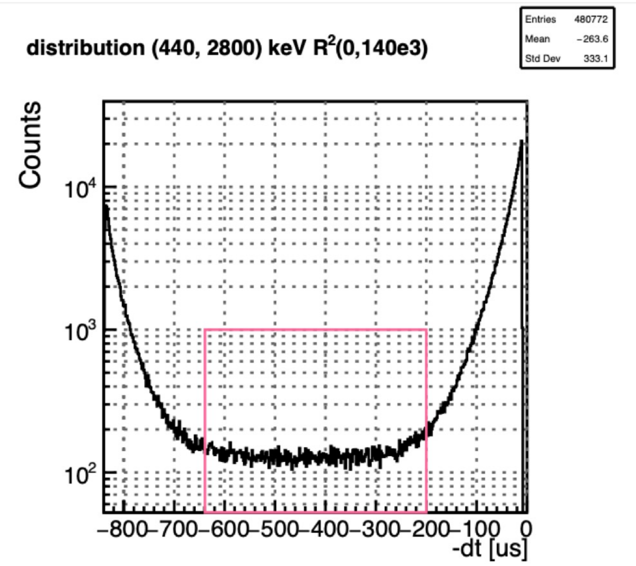
- (Very mild) Data quality cut efficiencies: (99.4 ± 0.4)%
  - S1, S2, S1/S2: remove non-electron recoil and alpha events
  - Top and bottom S1 charge asymmetry vs. drift time: reject accidental coincidence events and events originating from the gate electrode.
  - Calculated by region
- Calculated from 9.6 days of physics data; validated with full data
- Validated with 164 and 236 keV peaks

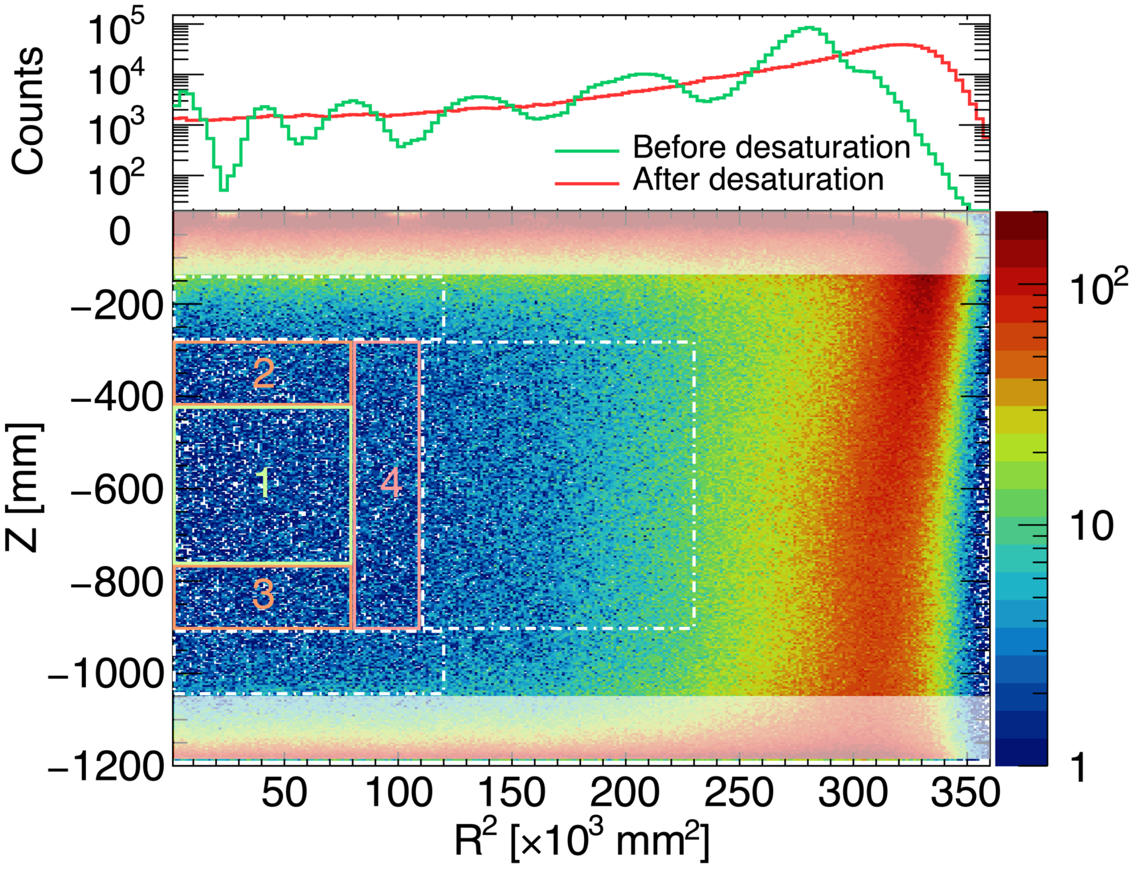
Fiducial Volume: emphasis on systematics, not statistics

- 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

FV mass



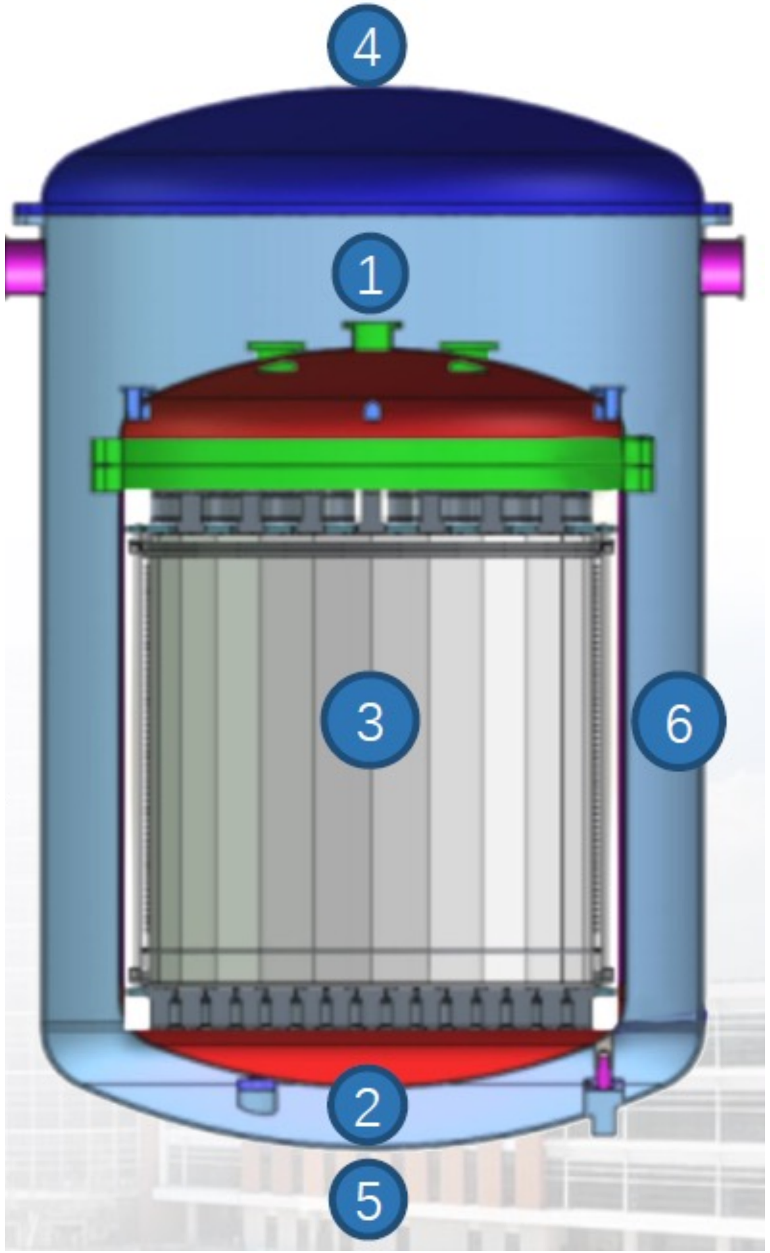




Background components

- Grouped detector components into three categories: 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

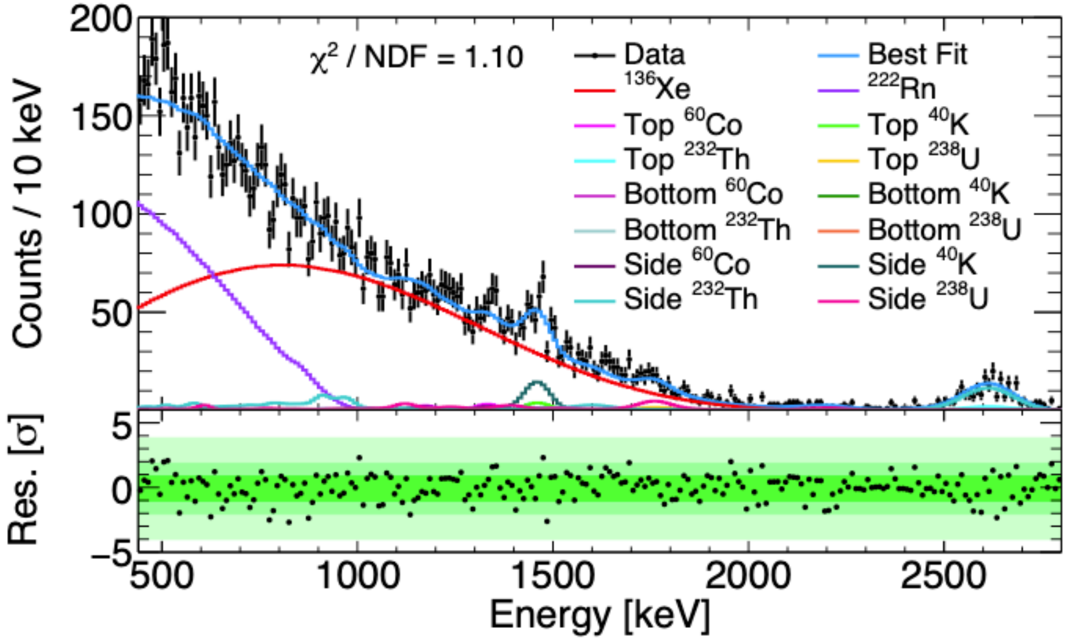
Detector part	Contamination	Expected counts
Top	^{238}U	334 ± 127
	^{232}Th	397 ± 131
	^{60}Co	322 ± 137
	^{40}K	296 ± 155
Bottom	^{238}U	143 ± 52
	^{232}Th	240 ± 120
	^{60}Co	161 ± 97
	^{40}K	90 ± 85
Side	^{238}U	469 ± 697
	^{232}Th	777 ± 945
	^{60}Co	1227 ± 938
	^{40}K	1498 ± 822
LXe	^{222}Rn	8951 ± 186



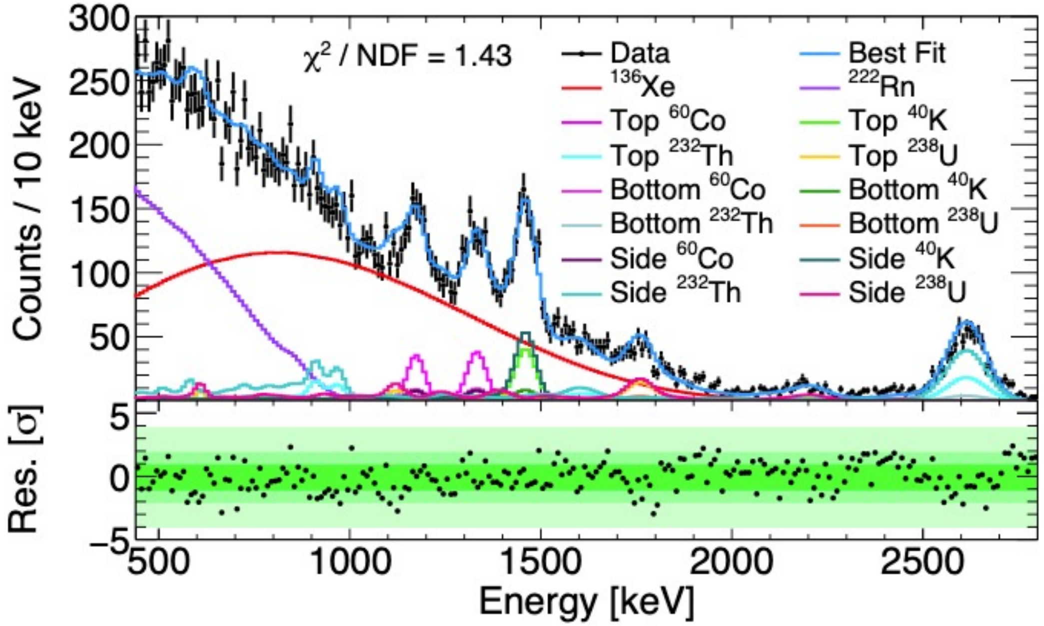
Simultaneous binned likelihood fit in four regions

$$L=\prod_{i=1}^{N_{\mathrm{R}}}\prod_{j=1}^{N_{\mathrm{bins}}}\frac{(N_{ij})^{N_{ij}^{\mathrm{obs}}}}{N_{ij}^{\mathrm{obs}}!}e^{-N_{ij}}\prod_{k=1}^{N_{\mathrm{bkgs}}}\frac{1}{\sqrt{2\pi}\sigma_k}e^{-\frac{1}{2}(\frac{\eta_k}{\sigma_k})^2}\,,\qquad N_{ij}=n_{\mathrm{Xe}}S_{ij}^{\mathrm{Xe}}+\sum_{k=1}^{N_{\mathrm{bkgs}}}(1+\eta_k)n_{ij}^{k}B_{ij}^{k}\,,$$

Region 1



Region 234

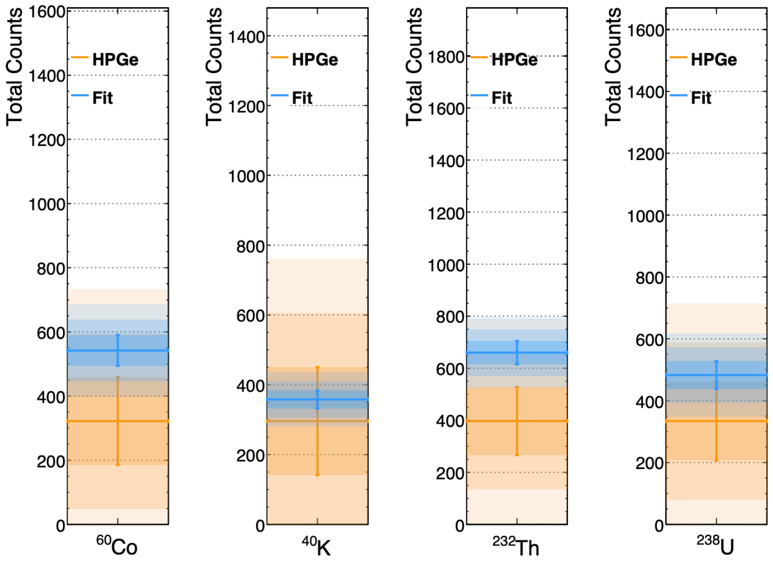


^{136}Xe fit results: 17468±243; 2.27 ± 0.03(stat.) ± 0.09(syst.) × 10^{21} year half-life

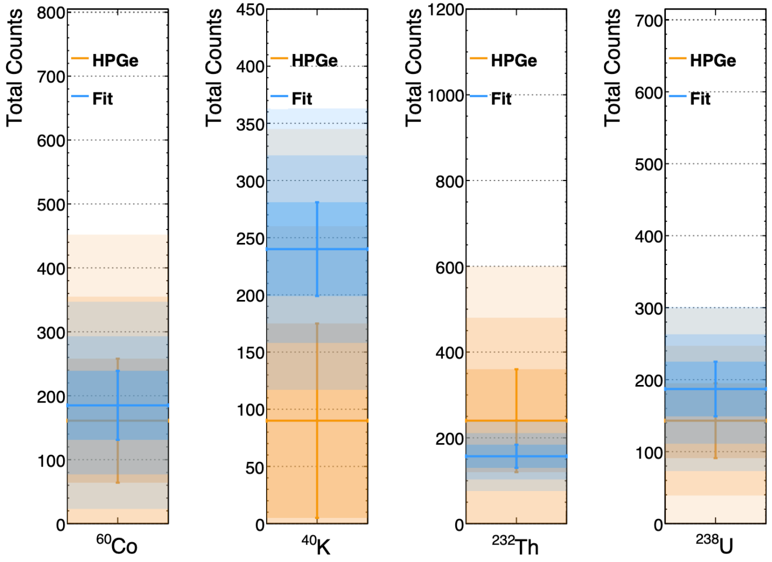
Cross check with RooFit likelihood fit

Background results

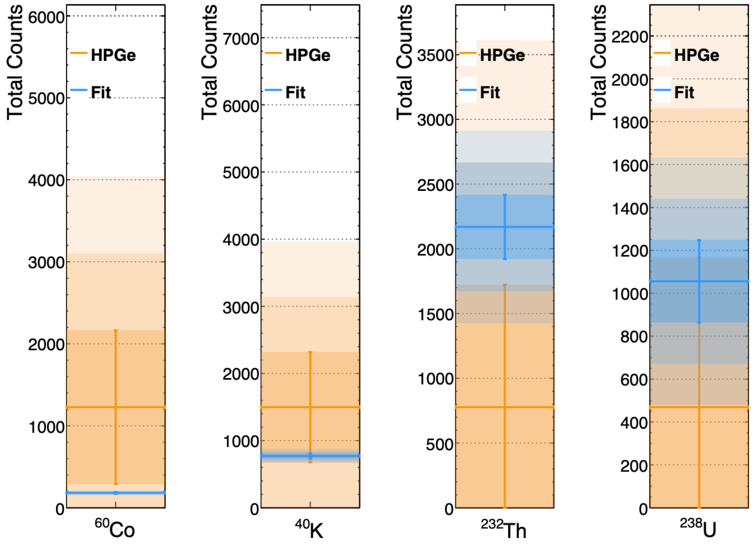
Top



Bottom

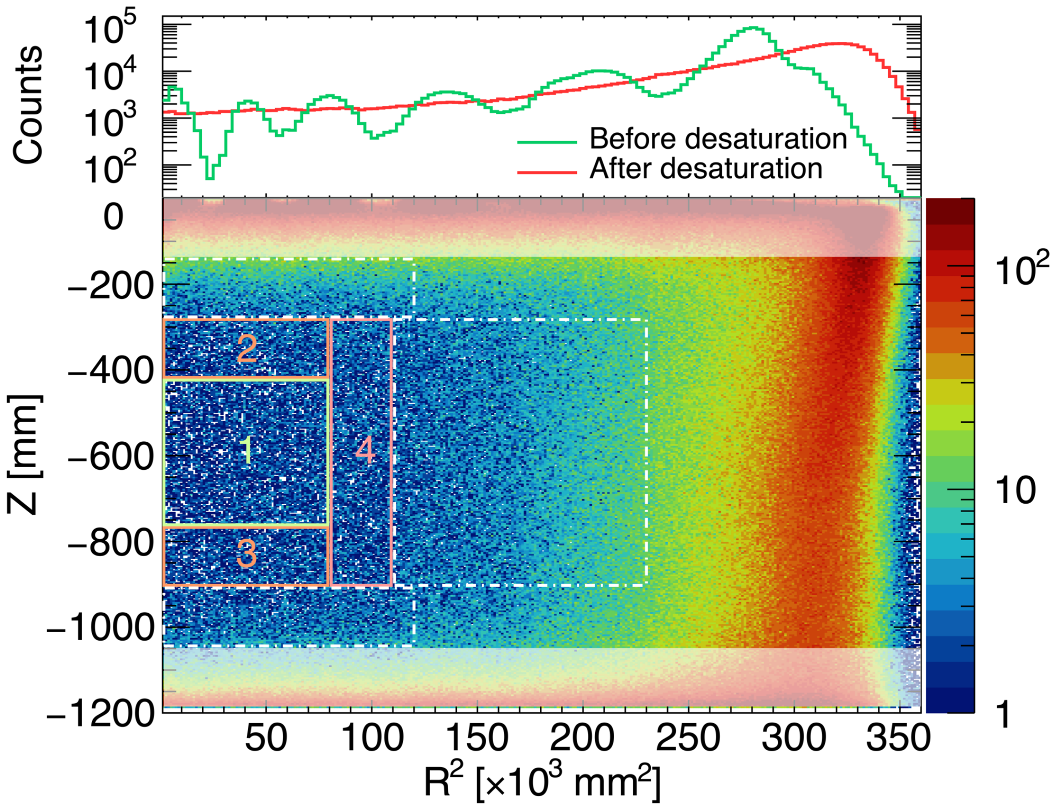


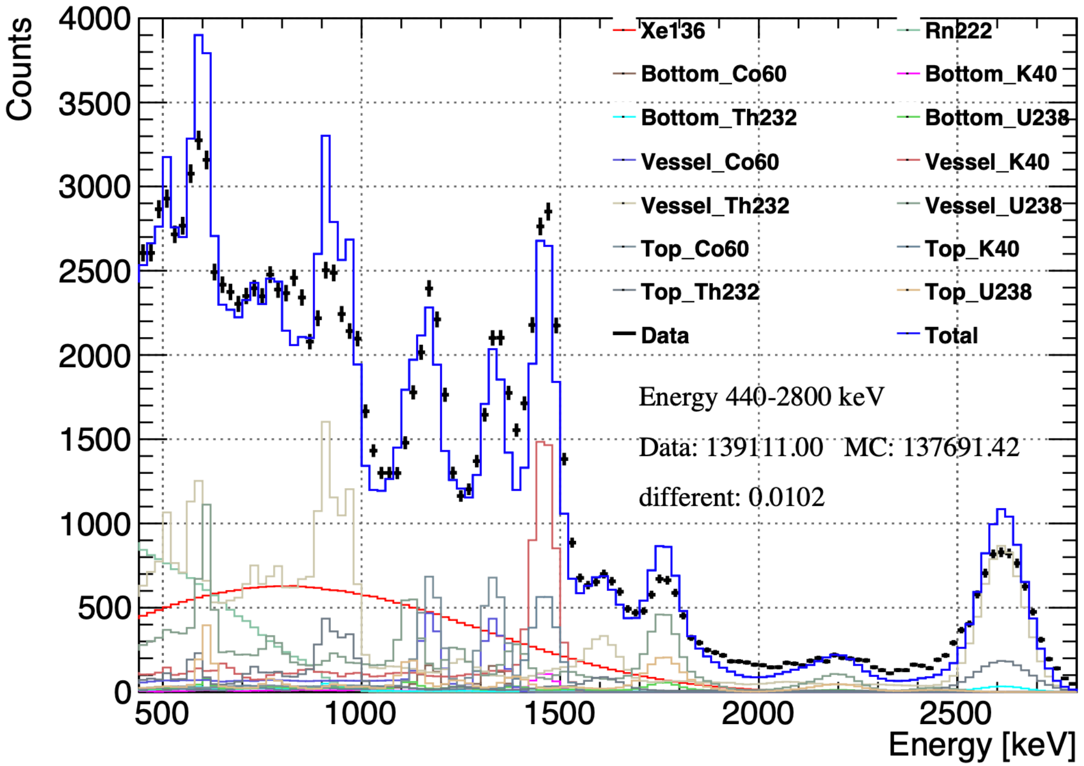
Side



- Compatible and more precise results from PandaX-4T than HPGe
- ^{214}Pb is only (78.2 ± 1.7)% of the input value of ^{222}Rn, as measured by high energy alphas: depeletion

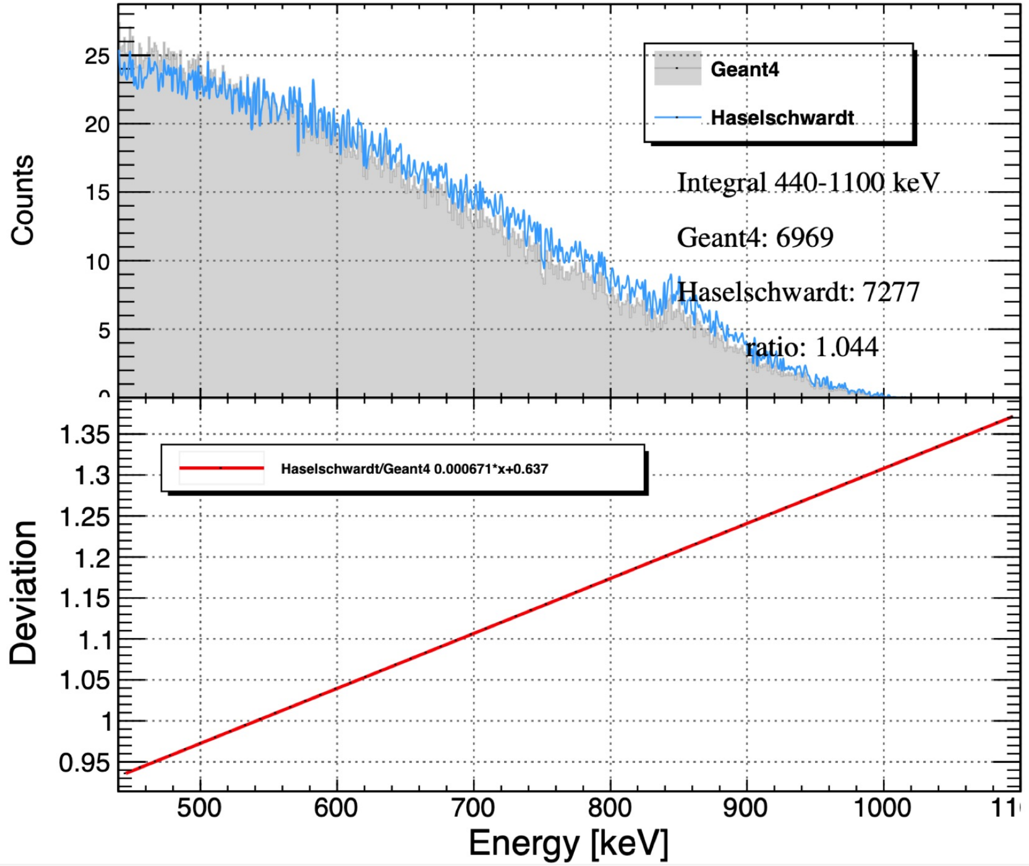
Cross validation in the outer region





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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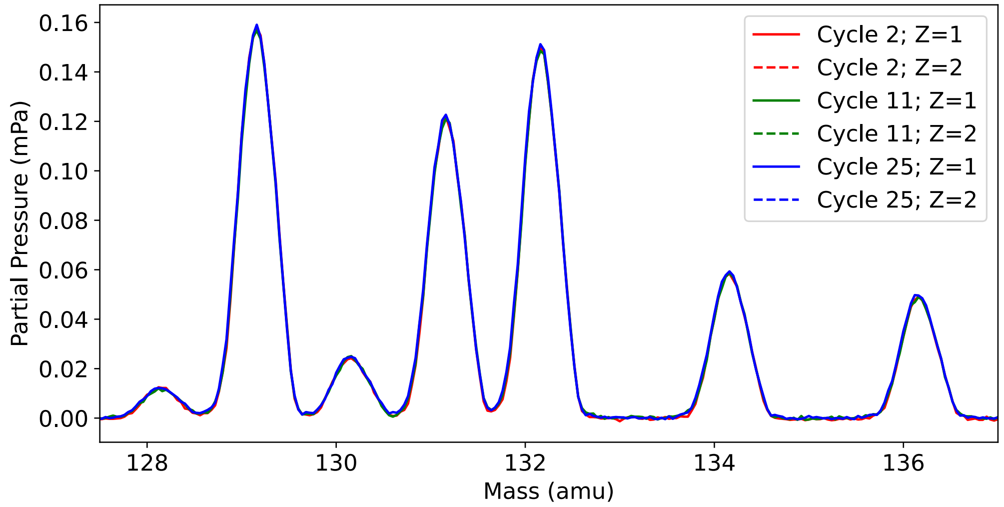
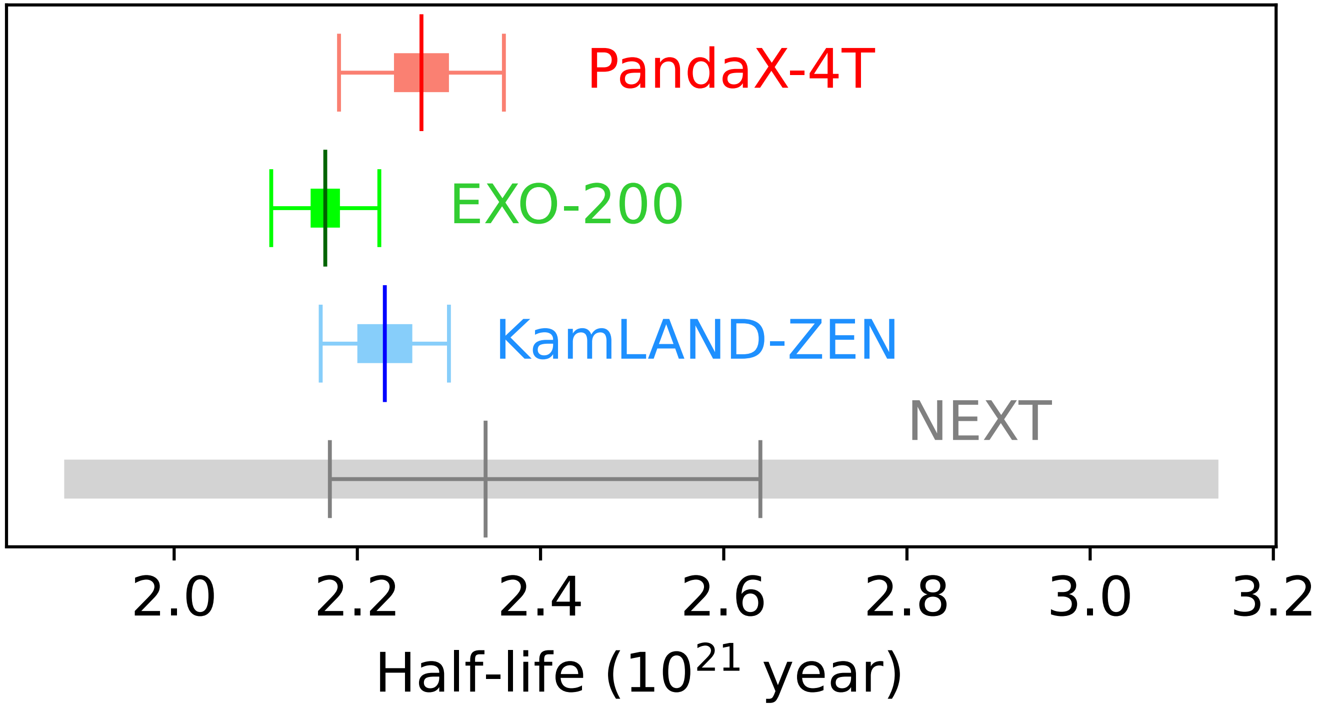


- ^{136}Xe IA: 8.79% if ionization efficiencies not corrected; 9.03% if corrected with NIST values
- Taken nominal value 8.86% as input and difference to our measurement as uncertainties

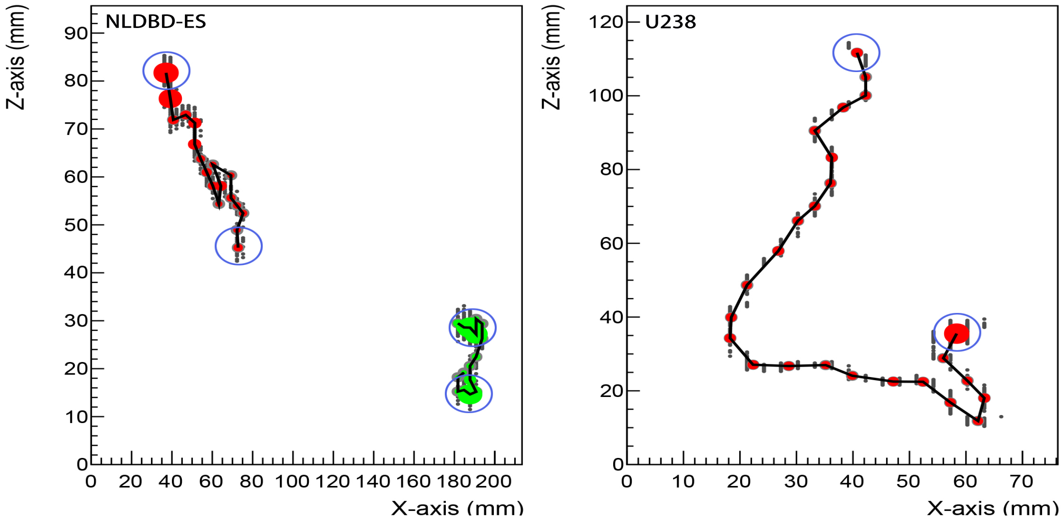
Final results

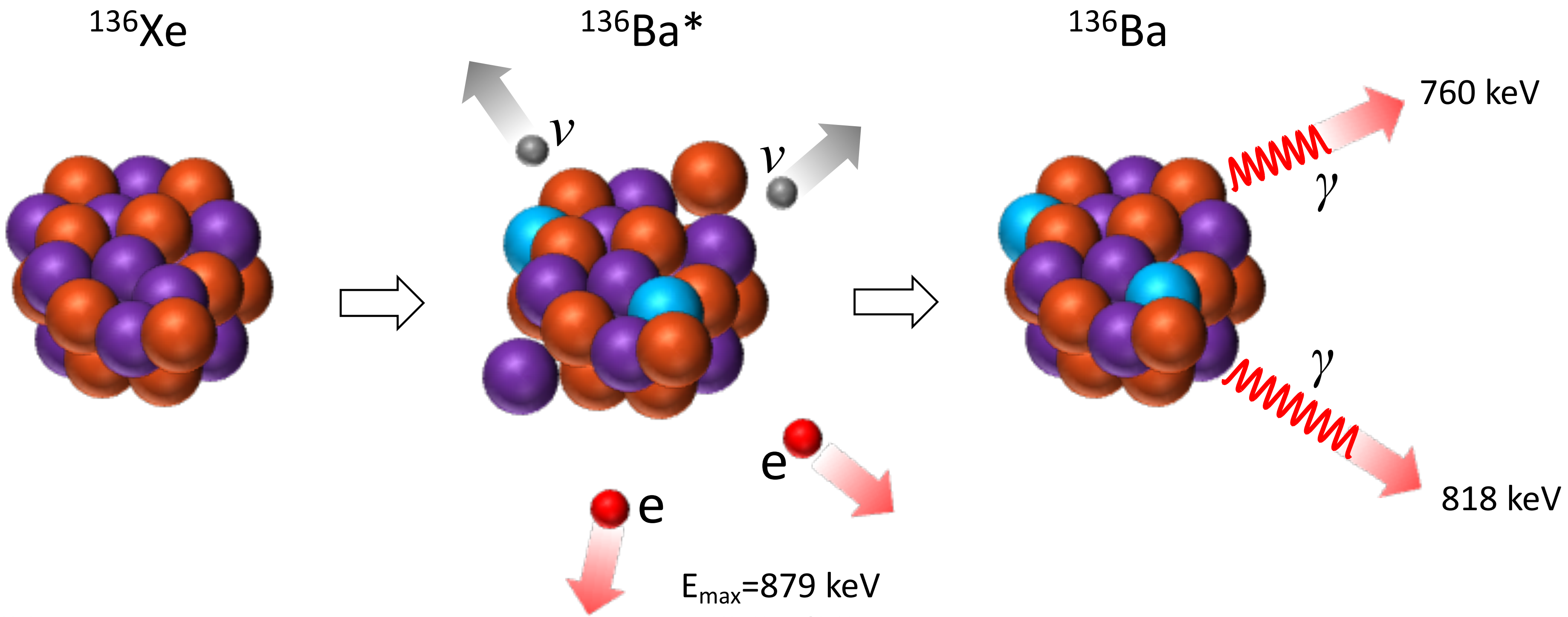
- ^{136}Xe DBD half-life measured by PandaX-4T: 2.27 ± 0.03(stat.) ± 0.09(syst.) × 10^{21} year
- Comparable precision with leading results
- First such measurement from a DM detector with natural xenon
- 440 keV – 2800 keV range is the widest ROI



PandaX-4T for more neutrino physics

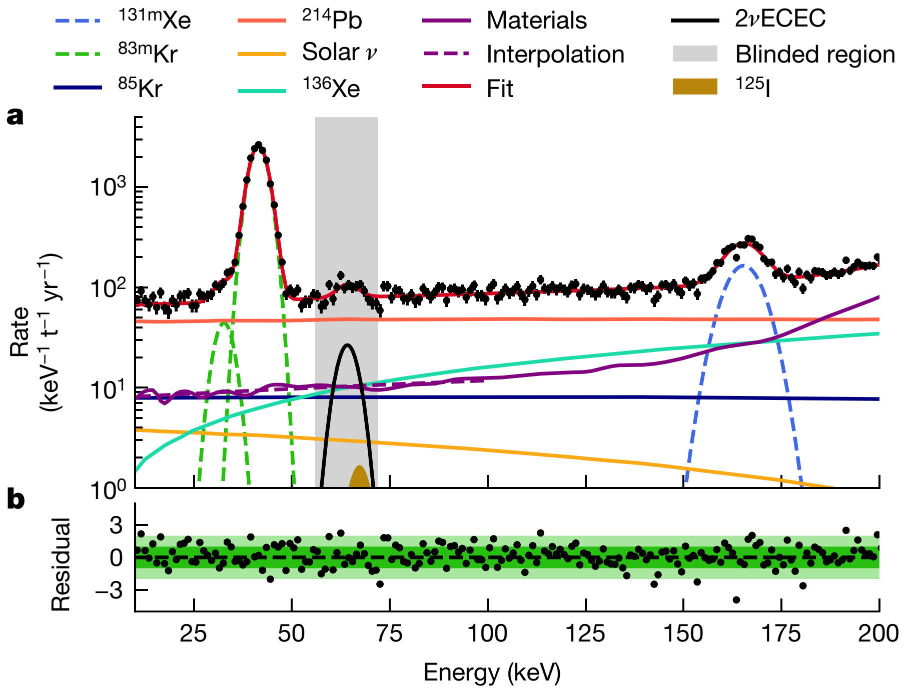
- Double beta decay to excited states of daughter nuclei
- Dual-electron + Gamma emission: clearer signature
- $^{136}Xe \rightarrow ^{136}Ba^*$ to be discovered; half-life measurement would help understand the nuclear physics of DBD





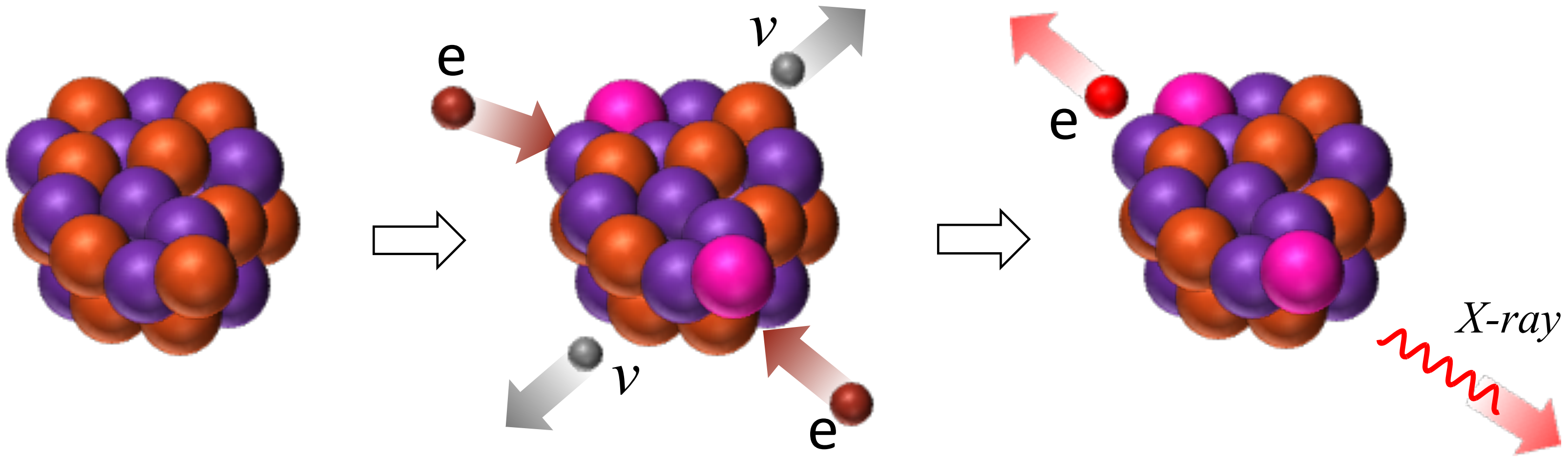
PandaX-4T for more neutrino physics

- (Neutrinoless) Double electron capture (DEC) is an equivalent 2nd-order weak process
- XENON1T recently reported the first observation of DEC of ^{124}Xe: very nice bonus feature for natural xenon detectors
- Neutrinoless DEC can be enhanced if mass difference between intial and intermediate states. (Admittedly still very long half-life)



XENON1T

^{124}Xe ^{124}Te ^{124}Te

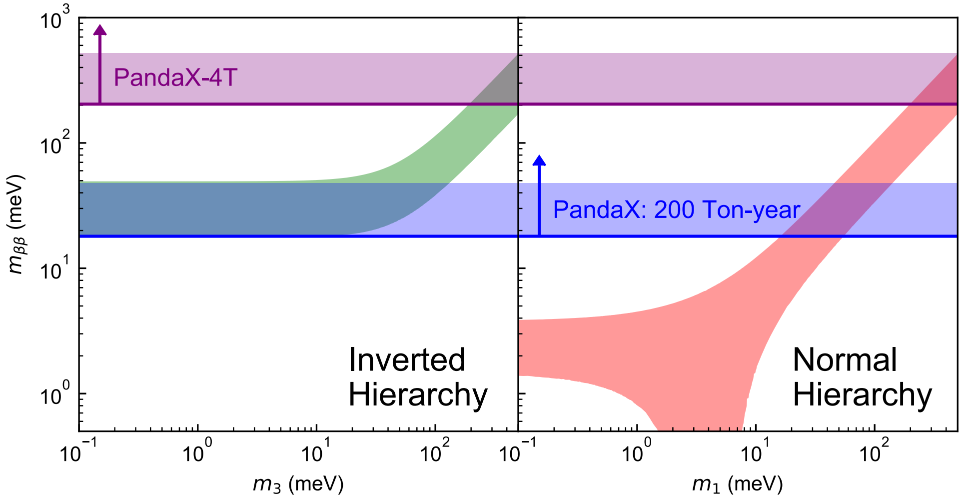


Comparison with other LXe TPC

	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}
XENONnT	~2	0.8%	1128	1000 days	2.1×10^{25}
LZ	~0.1	1%	967	1000 days	1.06×10^{26}
DARWIN	~0.004	0.8%	5000	10 years	2.4×10^{27}

Upgrade of PandaX-4T with improved PMT bases is planned

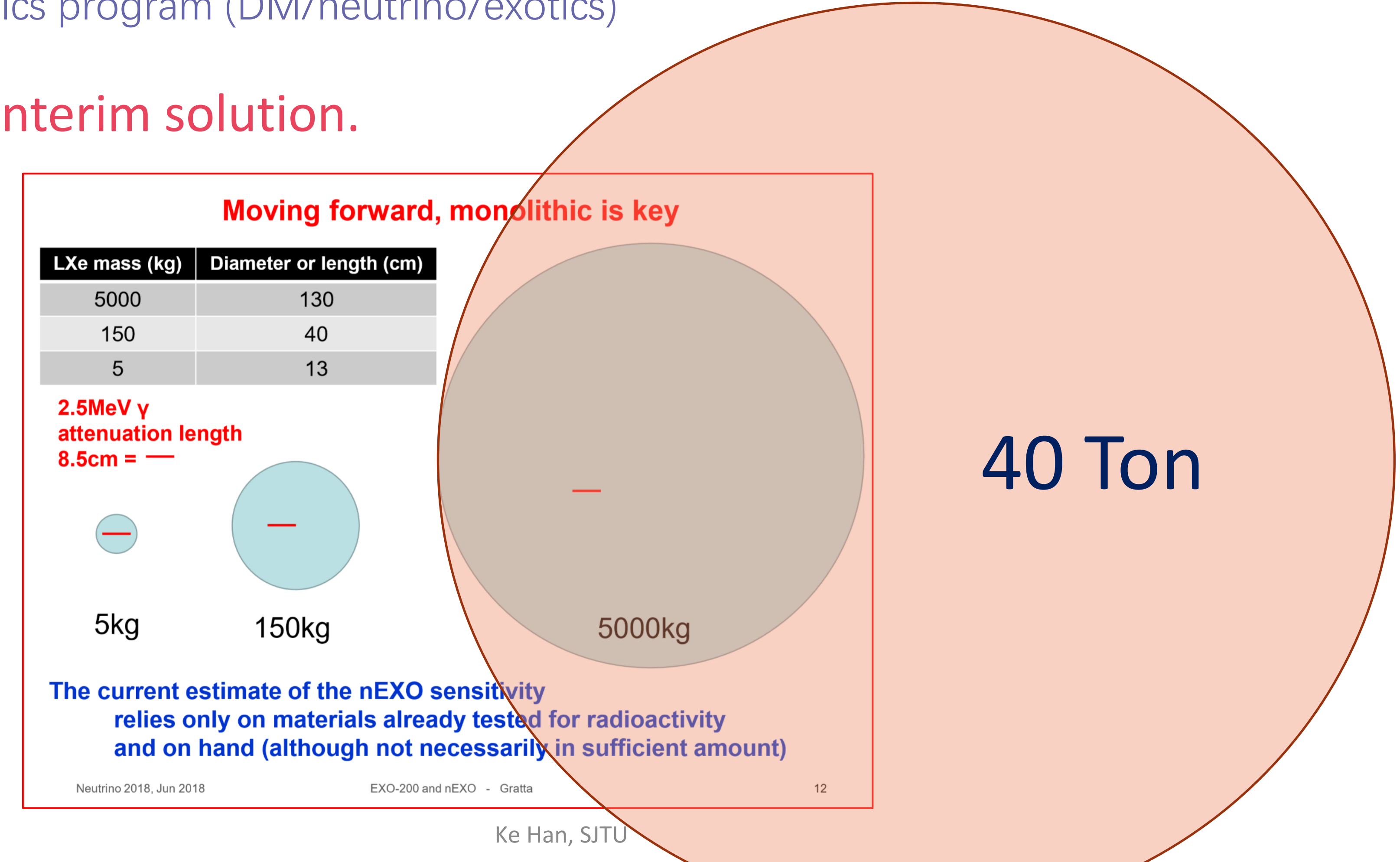
- Better energy resolution
- Better SS/MS discrimination



Major advantages of natural xenon measurement

- Fiducialization (and MS/SS discrimination) to suppress background.
- Robust determination of background throughout the FV
- Extremely versatile physics program (DM/neutrino/exotics)

⇒ A very appealing interim solution.

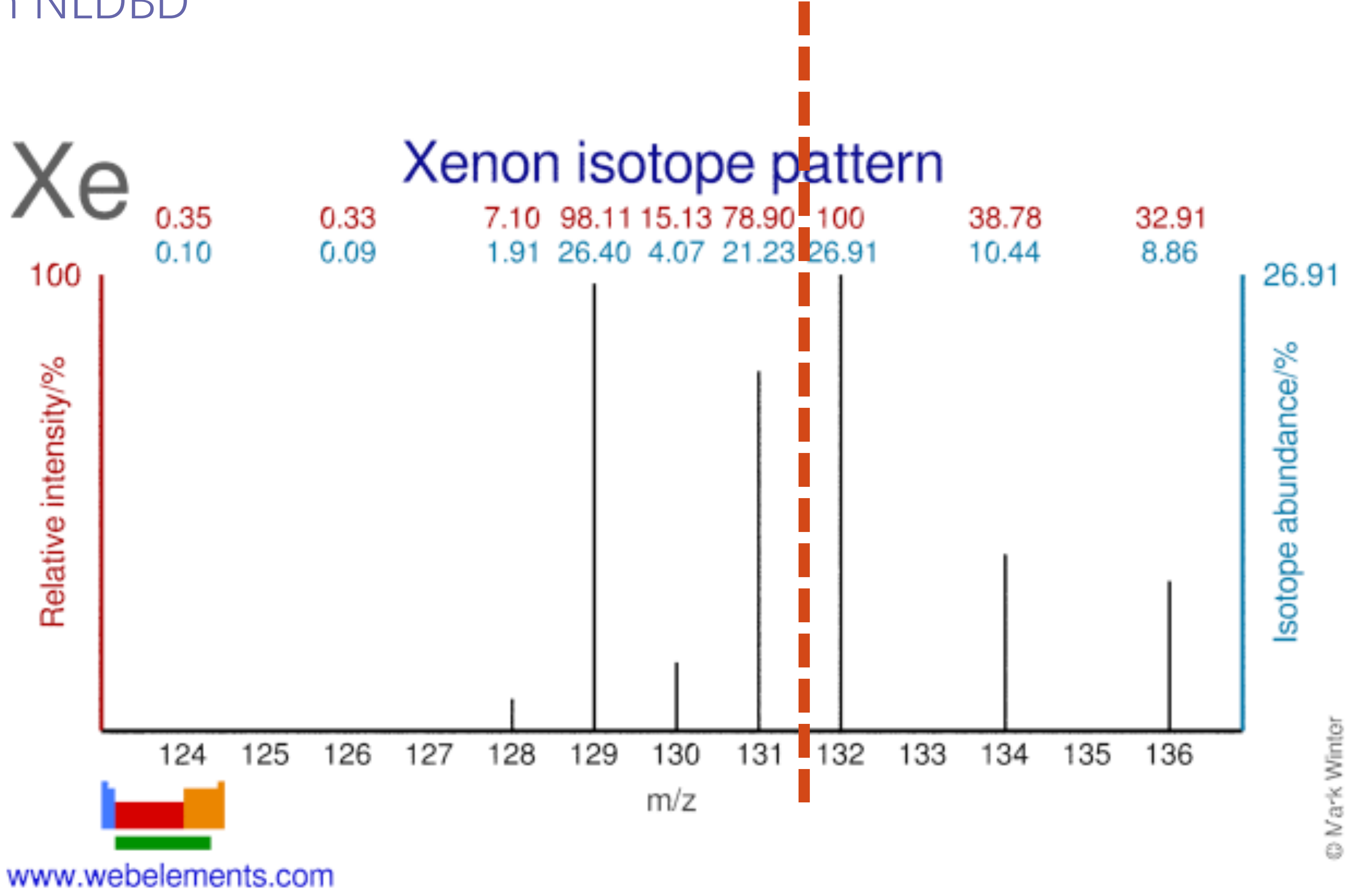


LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

Possible isotope seperation/enrichment

A separation of even/odd nucleus would already have huge advantage (beam on-off experiment)

- SI/SD dark matter interaction, combating neutrino floor
- Significant boost in NLDBD



Stay tuned for multi-physics program with PandaX!