PandaX

ICHEP 2024 | PRAGUE

Measurement of Solar *pp* Neutrino Flux with PandaX-4T Commissioning Run Data

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2024/07/18

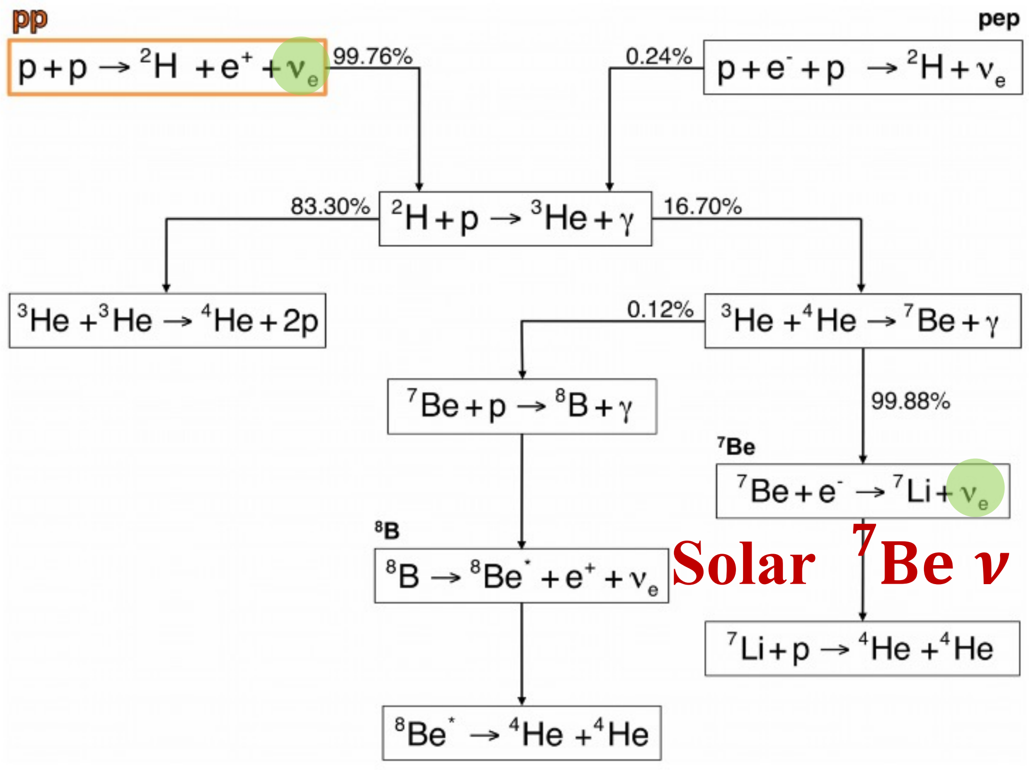
Outline

- Introduction to solar *pp* neutrinos
- PandaX-4T experiment
- Data reconstruction
- Background model
- Results and outlook

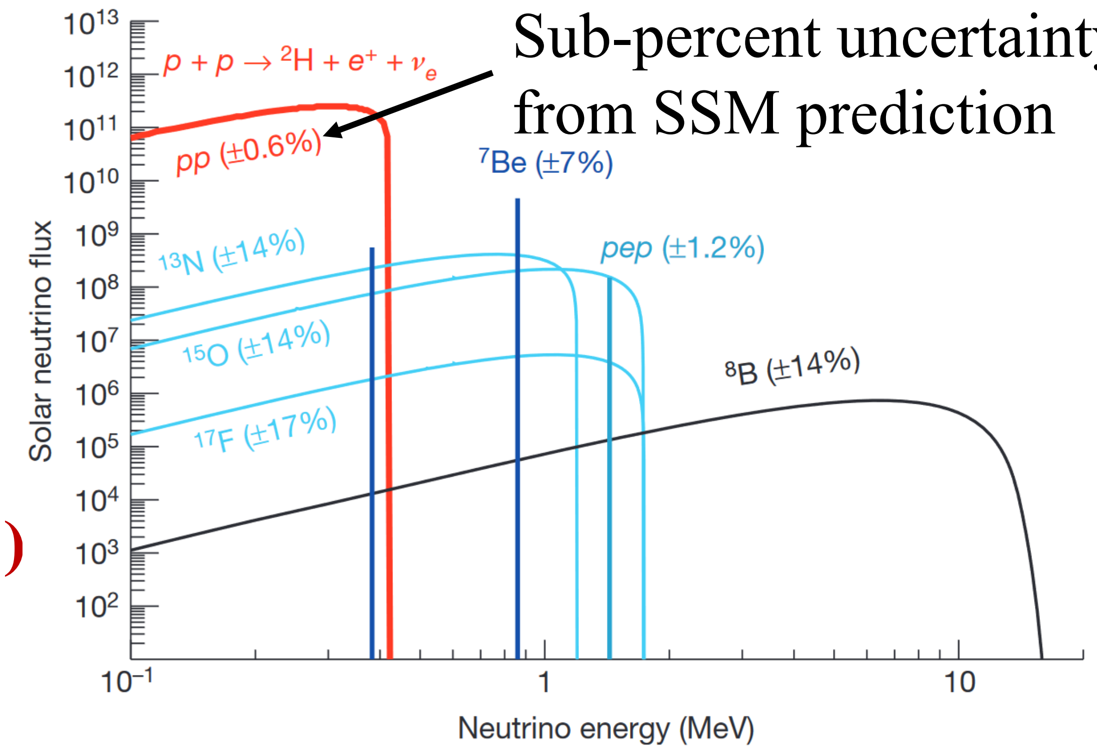
Solar *pp* neutrinos

Solar *pp* neutrinos (~91%)
E < 420 keV

Precise measurement in the future is essential for understanding the stellar mechanism and the matter effect of neutrino oscillation.



Solar ^{7}Be *ν* (~7%)



Sub-percent uncertainty from SSM prediction

[Nature volume 512, pages 383–386(2014)]

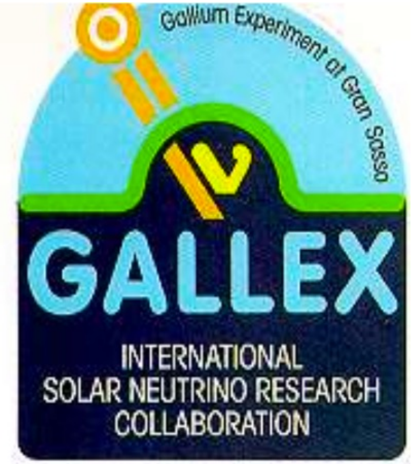
Detection of Solar *pp* neutrinos

- Radiochemical experiment

$$^{71}\text{Ga} + \nu_e \rightarrow e^- + {}^{71}\text{Ge}$$

EC decay

$T_{1/2} = 11.4$ days

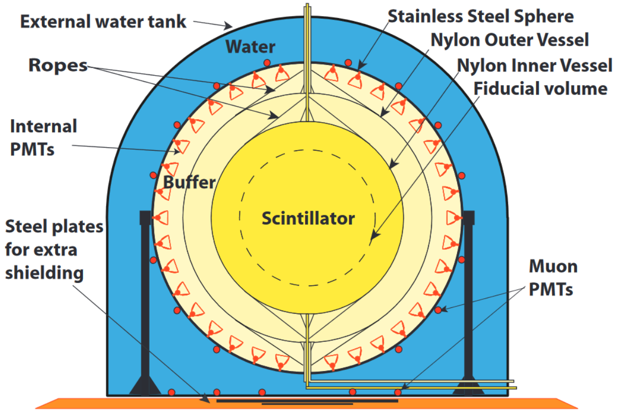


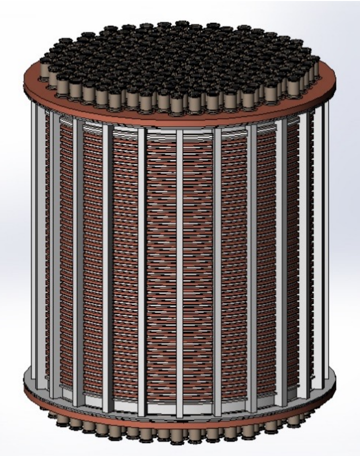
- GALLEX/GNO and SAGE
- 13.3% uncertainty in 2009

- Real-time experiment

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

- Maximum Electron Recoil energy is 264 keV

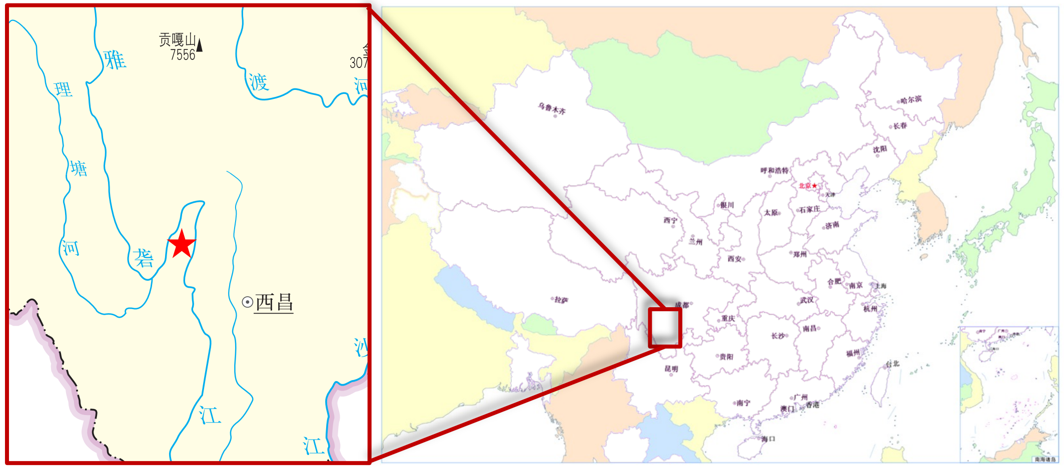




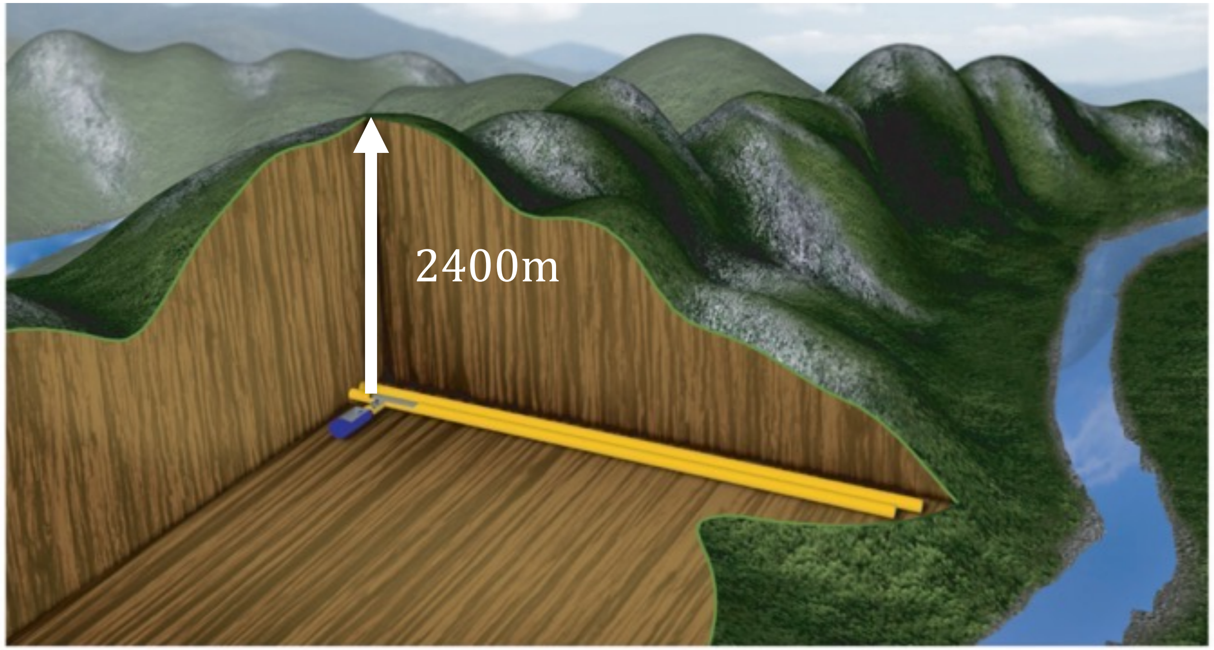
- Borexino using LS
- Energy window is 165 ~ 590 keV
- First direct measurement in 2014 with 10.6% uncertainty

- LXe (liquid xenon) experiments
- Lower threshold

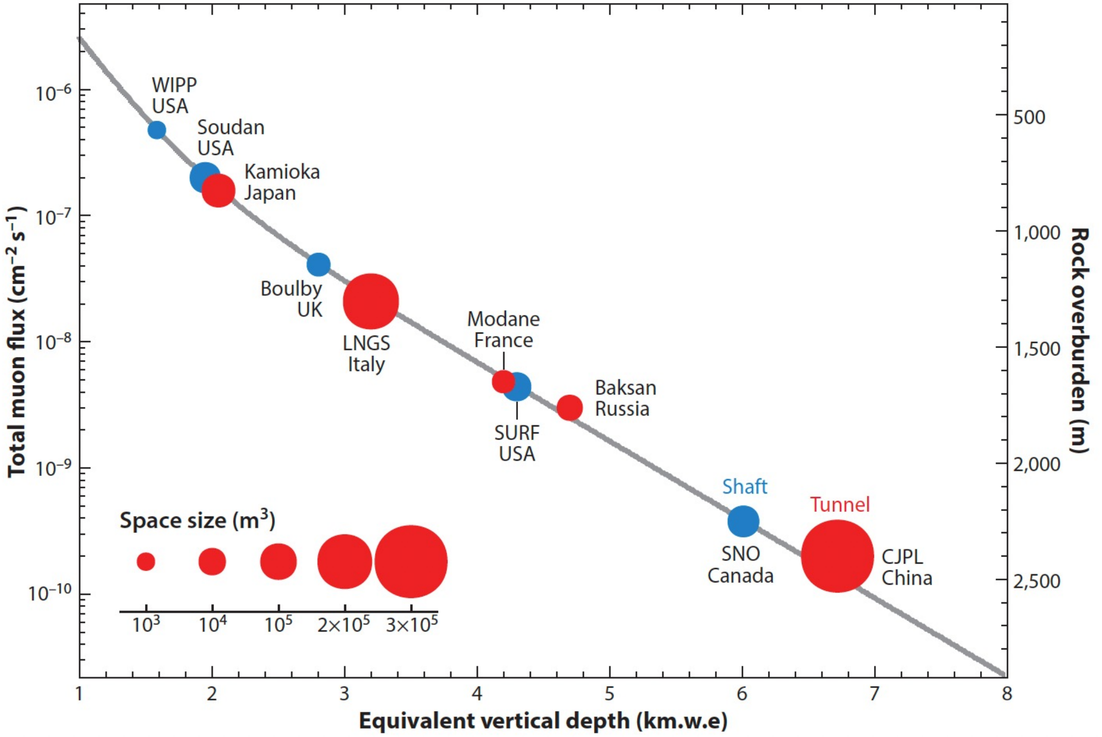
CJPL: Deepest underground lab



- China Jinping Underground Laboratory
- Deepest (6720 m.w.e): $< 0.2\ \text{muons}/\text{m}^2/\text{day}$
- Horizontal access with ~18 km long tunnel

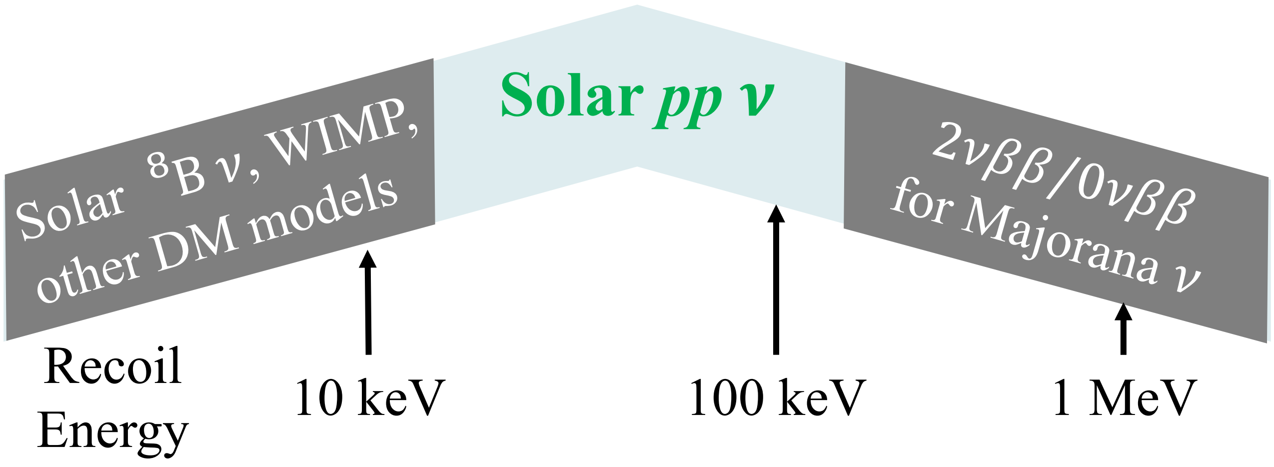


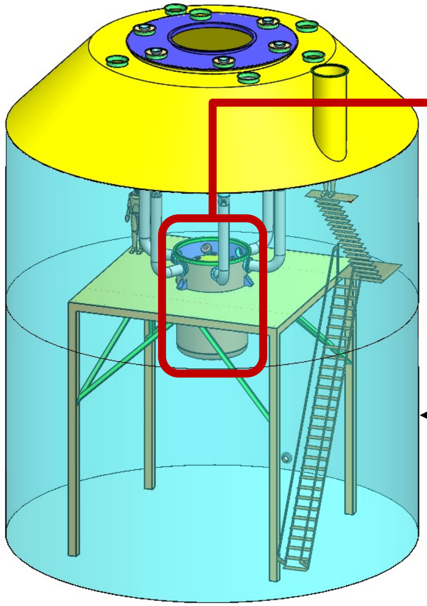
https://doi.org/10.1146/annurev-nucl-102115-044842



PandaX-4T Experiment

Multi-ton scale LXe experiment





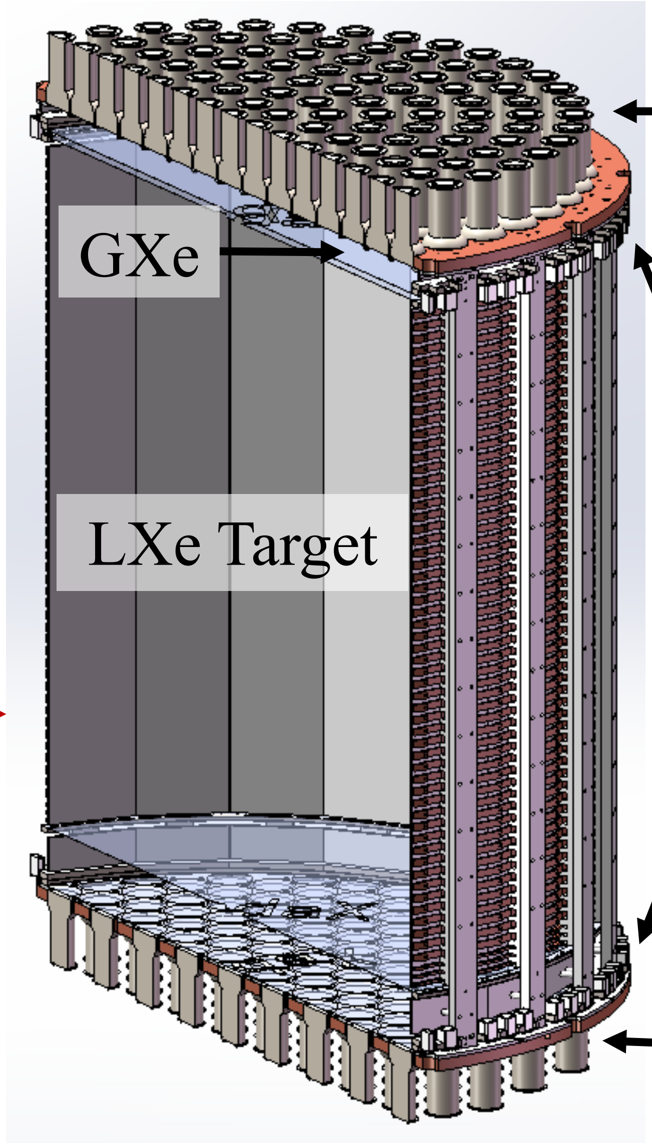
TPC

(Time projection chamber)

1.2 m (D) ×1.2 m (H)

Water shielding

10 m (D) ×13 m (H)

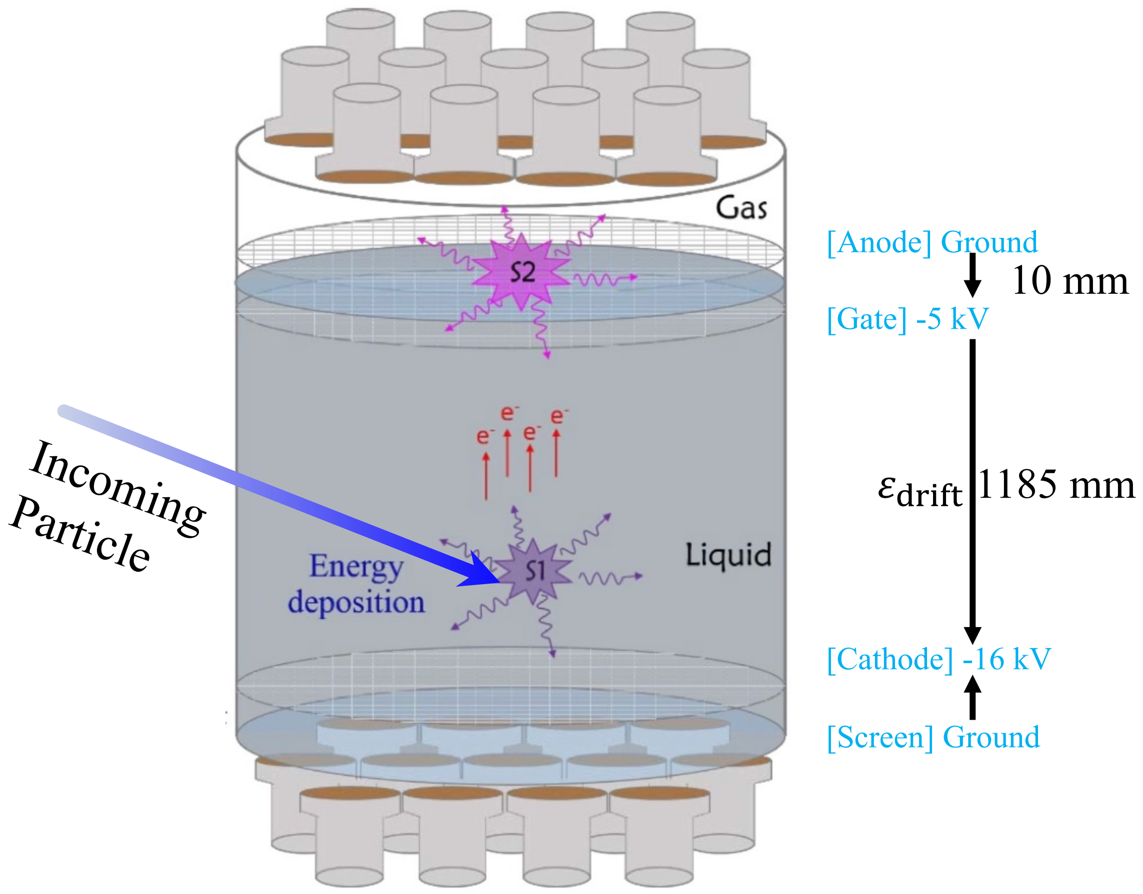


Top PMT array

Veto PMTs

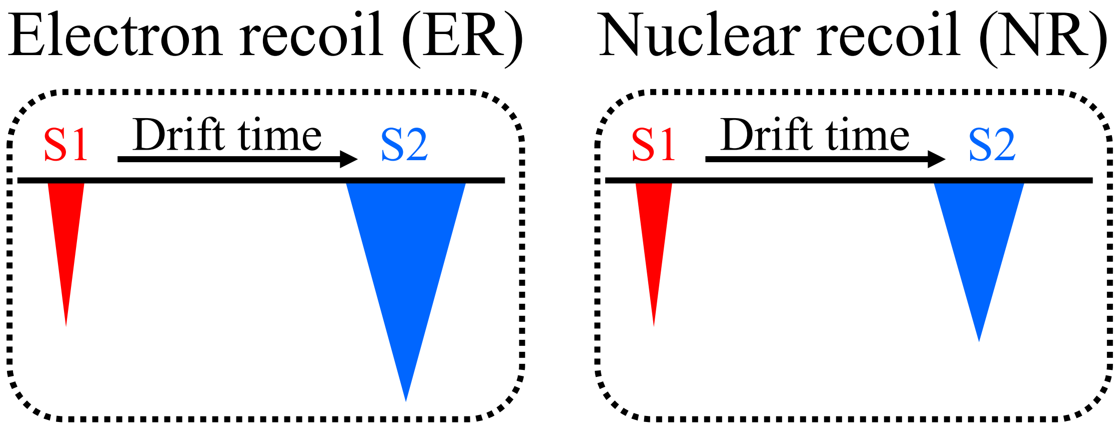
Bottom PMT array

Dual-phase xenon TPC



3-D position reconstruction

- Vertical: time difference between S1 and S2
- Horizontal: light pattern on top PMT array



S2/S1: ER >> NR

Electron Recoil of Solar *pp* + ^{7}Be neutrinos

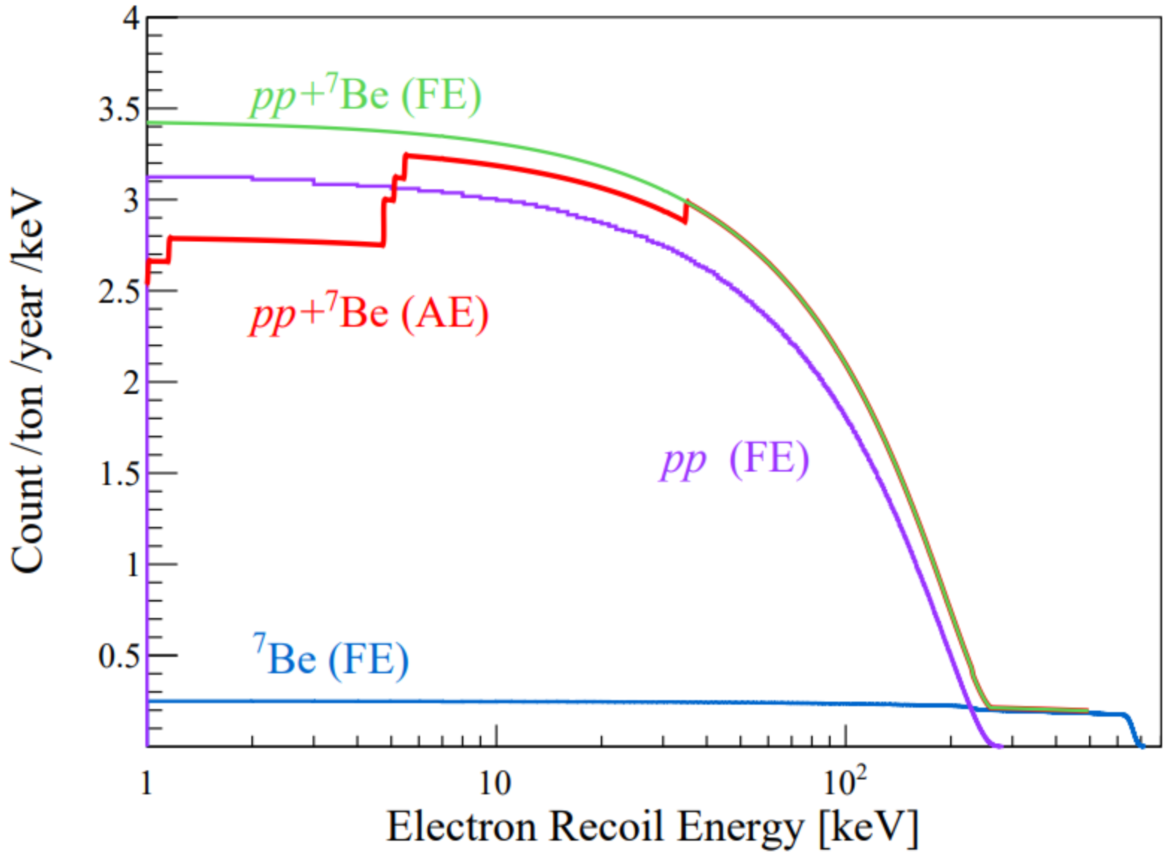
- ER energy < 264 keV

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

- Expected event rate per unit recoil energy

$$\frac{dR}{dE_r} = N \sum_j \int \phi(E_\nu) P_{ej} \frac{d\sigma_j(E_\nu, E_r)}{dE_r} dE_\nu$$

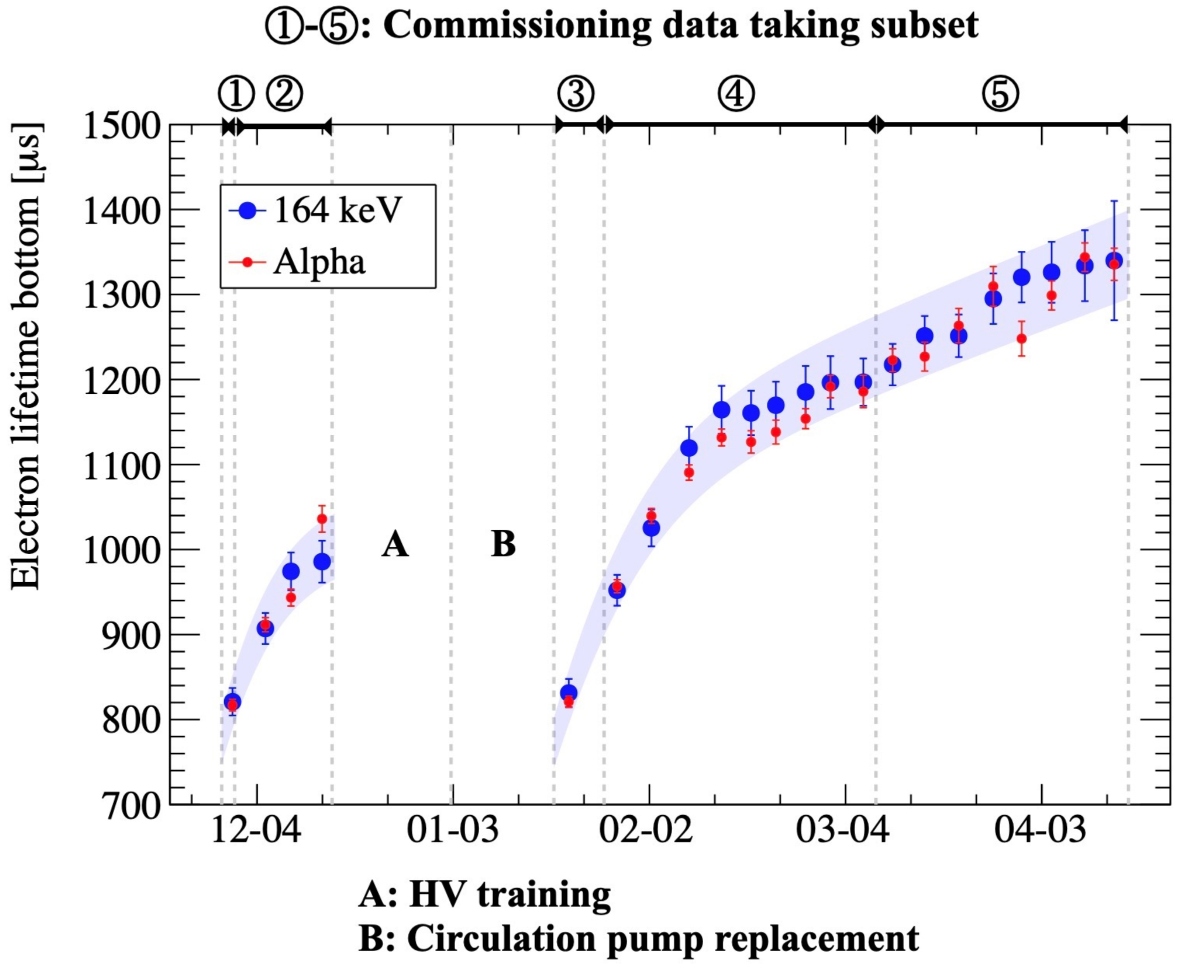
  - N: the number of target electrons
  - $\phi(E_\nu)$: the neutrino flux
  - P_{ej}: the oscillation probabilities
  - $d\sigma_j$: the differential cross-section



- FE: Free electrons
- AE: atomic electrons

[Physics Letters B 774 (2017) 656–661]

PandaX-4T Commissioning data taking



- Electronegative impurity S in LXe

$$e^- + S \rightarrow S^-$$

- Electron lifetime represents the impurity concentration

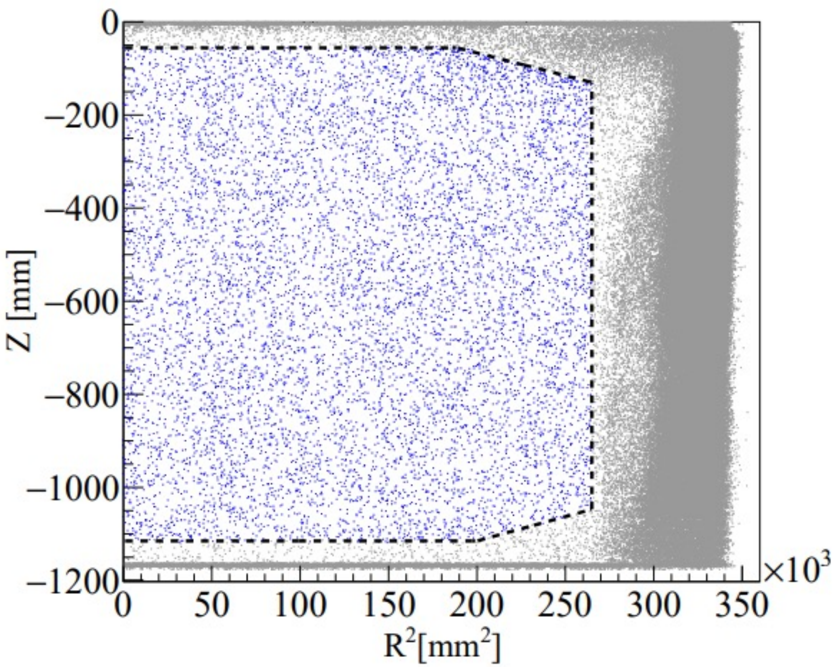
Subset	1	2	3	4	5
Gate (kV)	-4.9		-5	-5	
Cathode (kV)	-20	-18.6	-18	-16	

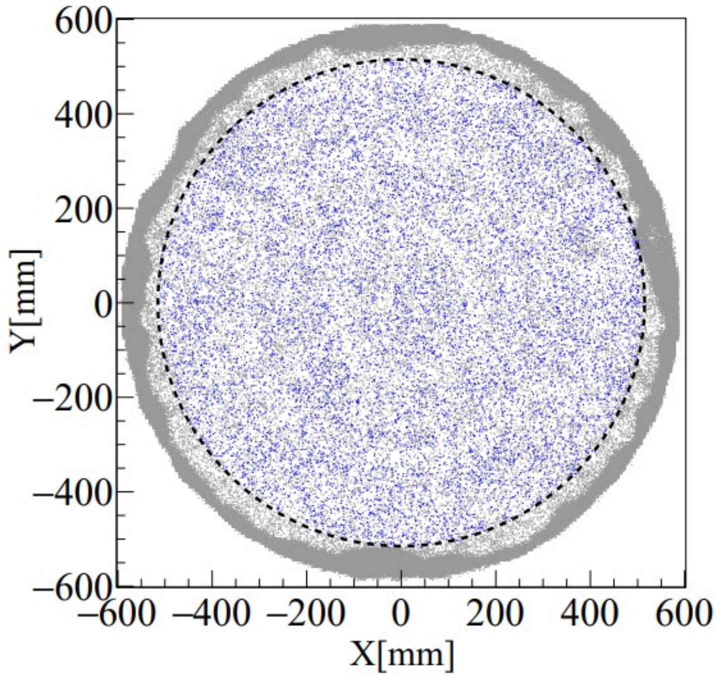
➢ 95.0 days of commissioning data taken from 2020.11 to 2021.04

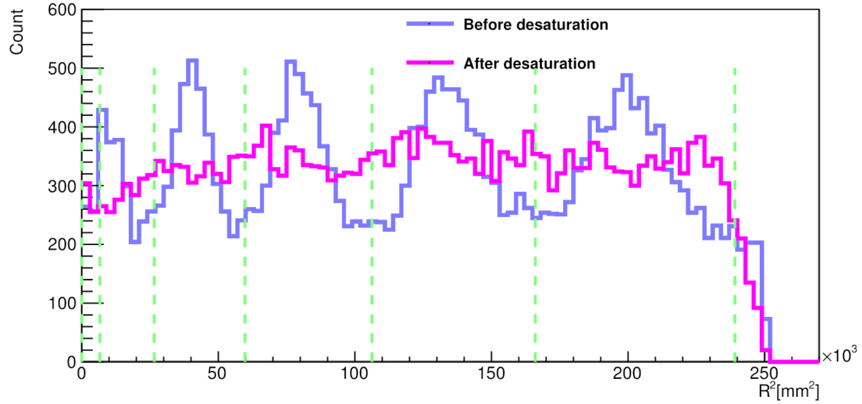
➢ 0.63 tonne×year exposure

Position reconstruction

- Horizontal: light pattern on top PMT array with desaturation algorithm
- Vertical: time difference between S1 and S2







- ➢ Sensitive volume: 3.69±0.01 tonne
- ➢ FV (fiducial volume) mass: 2.66±0.02 tonne

- ➢ Desaturation improved uniformity of horizontal position reconstruction

Energy reconstruction and resolution

$$E = 13.7\ \text{eV} \times \left(\frac{S1}{\text{PDE}} + \frac{S2_B}{\text{EEE} \times \text{SEG}_\text{B}} \right)$$

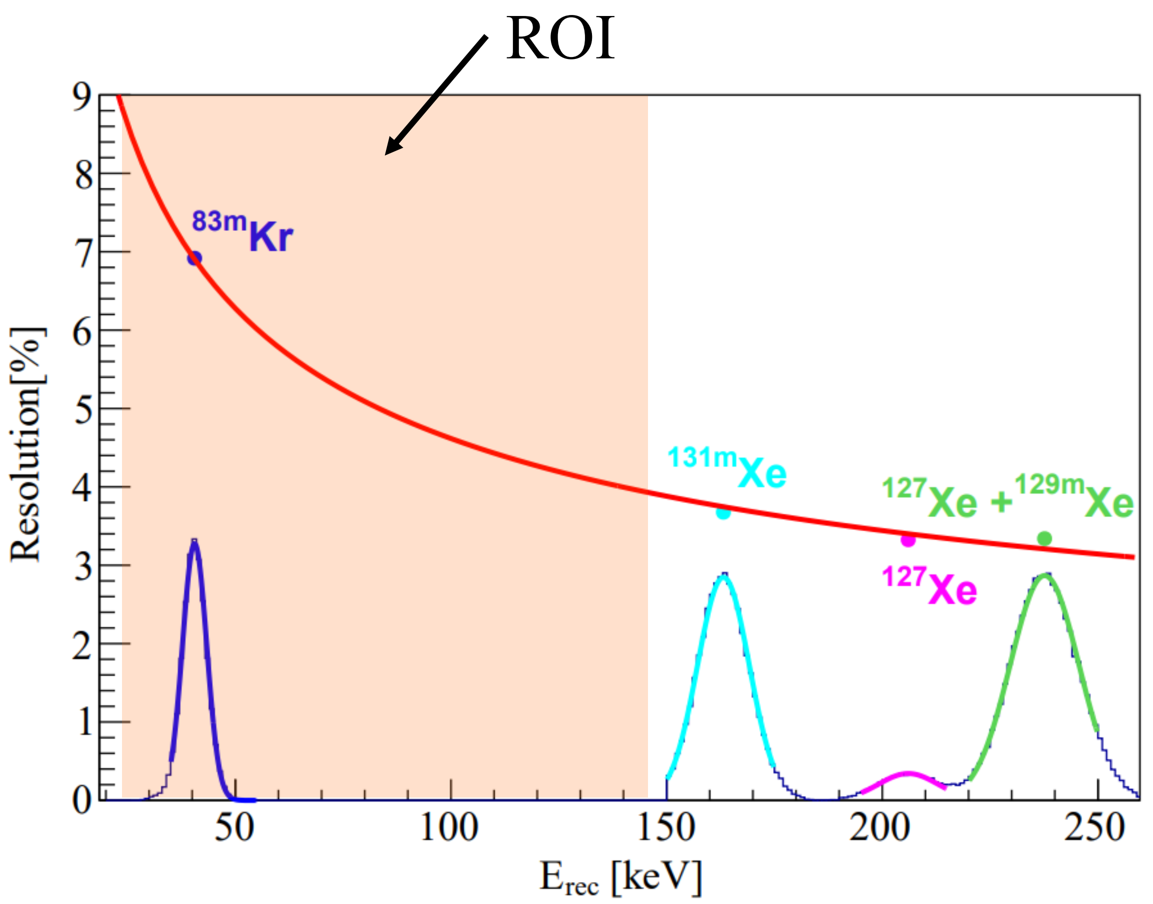
- 13.7 eV: energy required to produce an exciton or ion
- PDE: photon detection efficiency for S1
- EEE: electron extraction efficiency
- SEG_B: single-electron gain for S2_B

Subset	1	2	3	4	5
PDE(%)	9.0 ± 0.2		9.0 ± 0.2		
EEE(%)	90.2 ± 5.4		92.6 ± 5.4		
SEG_B(PE/e)	3.8 ± 0.1		4.6 ± 0.1		

➢ ROI(region of interest): 24~144 keV

- Above dark matter search region
- Avoid 163.9 keV peak of ^{131m}Xe from neutron calibration

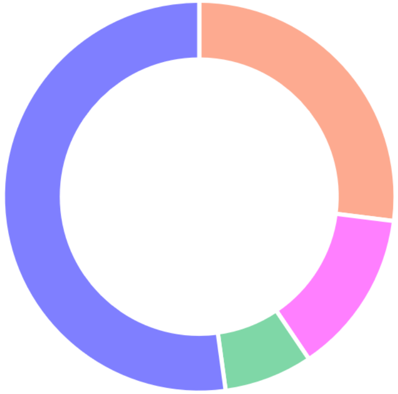
➢ Offset in the ROI < 1 keV



➢ Fit curve: $\frac{\sigma}{E} = \frac{a}{\sqrt{E}} + b$

➢ Resolution at 24 keV (144 keV) is 8.8% (3.9%)

Background model

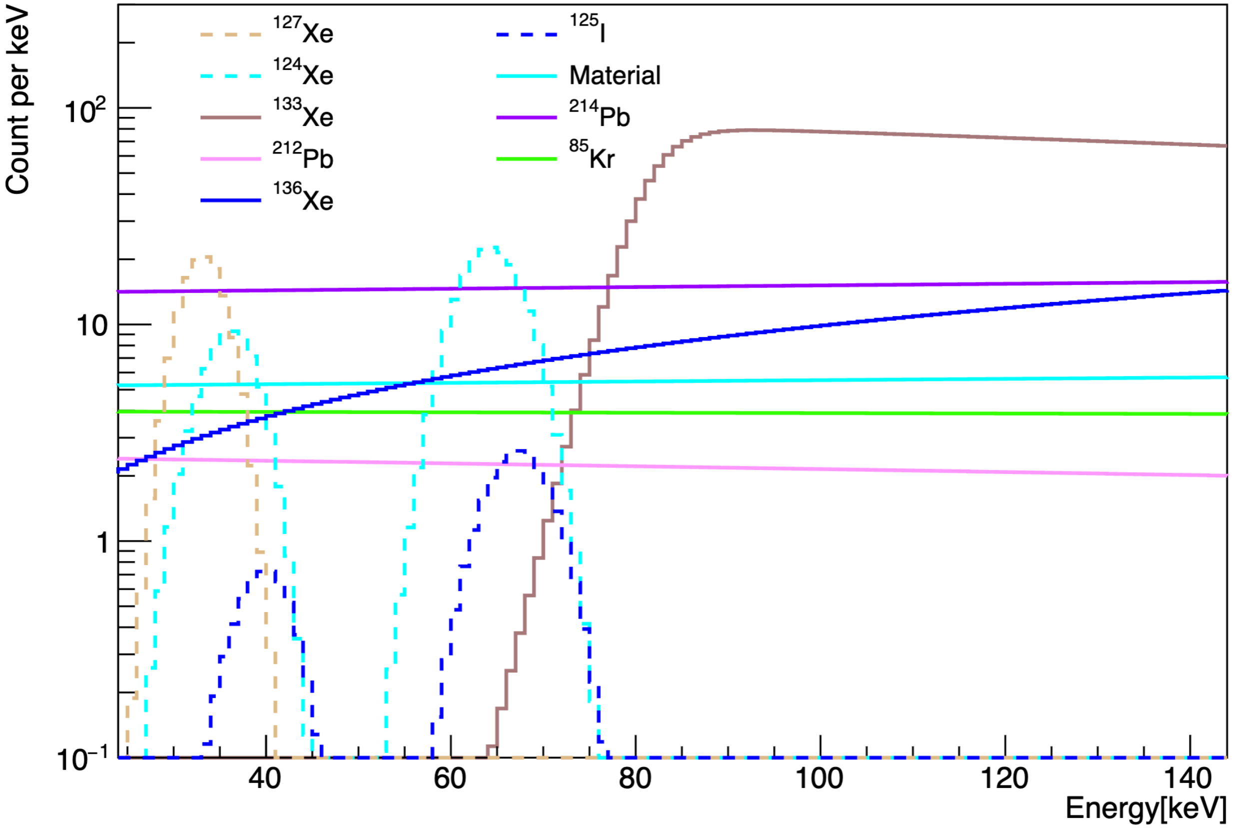


Activation
- I-125
- Xe-127
- Xe-133

Impurity
- Pb-214
- Pb-212
- Kr-85

Intrinsic
- Xe-136
- Xe-124

Material



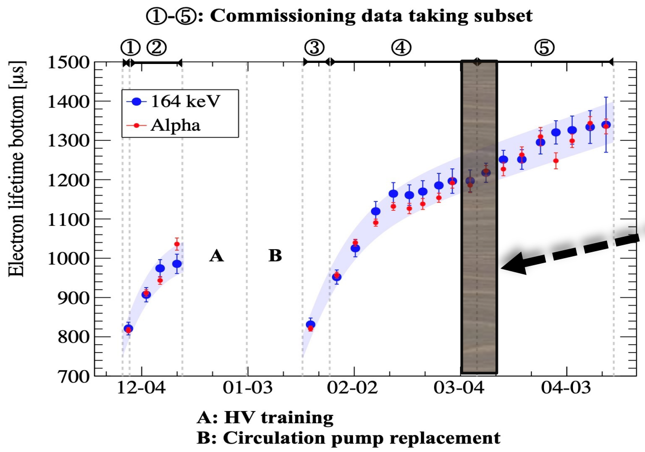
Primary challenge:

Estimation of backgrounds with smooth energy spectrums that resemble the signal spectrum

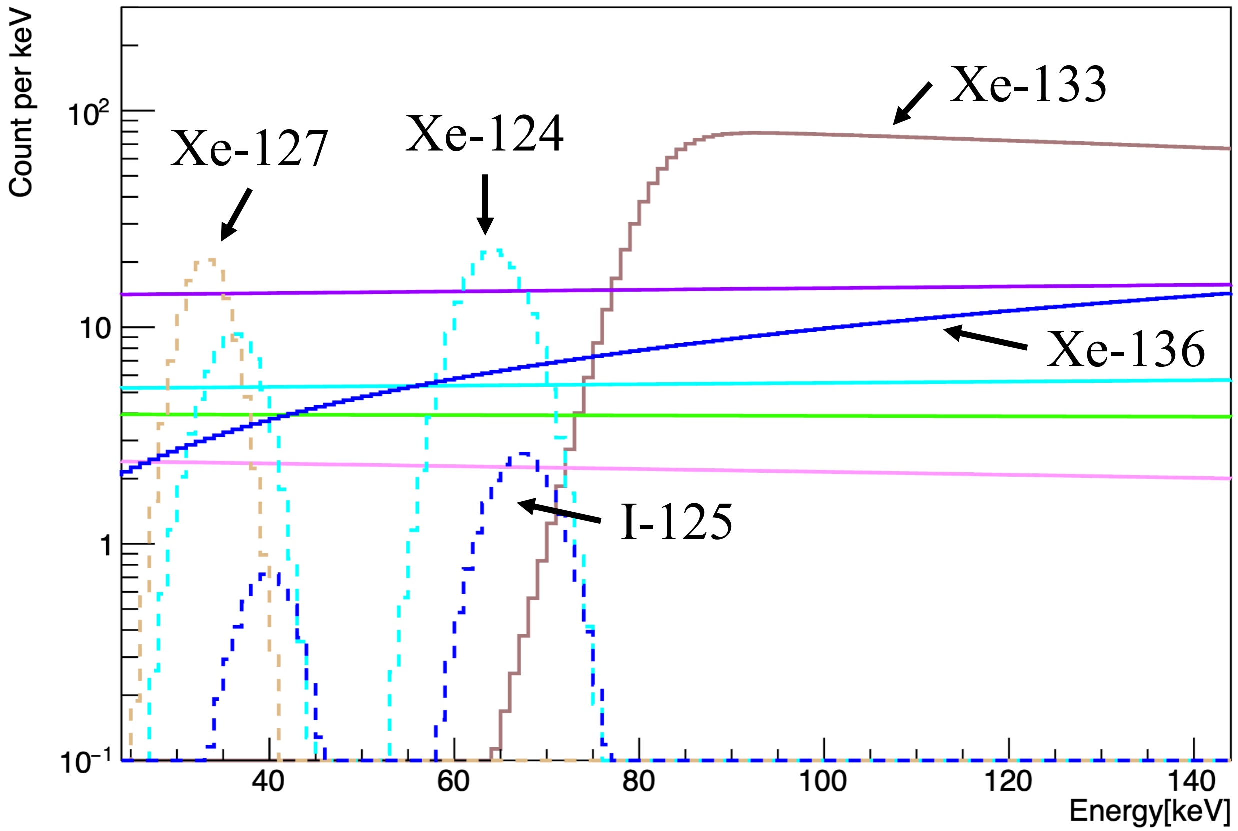
Backgrounds: Activation + Intrinsic

➢ Xe-133

- β decay with Q value 427.4 keV



Remove 8.4 days data following neutron calibration with high ^{133}Xe concentration



➢ Xe-136

- $2\nu\beta\beta$ Q value 2457.8 keV
- Half-life from ^{136}Xe $2\nu\beta\beta$ analysis

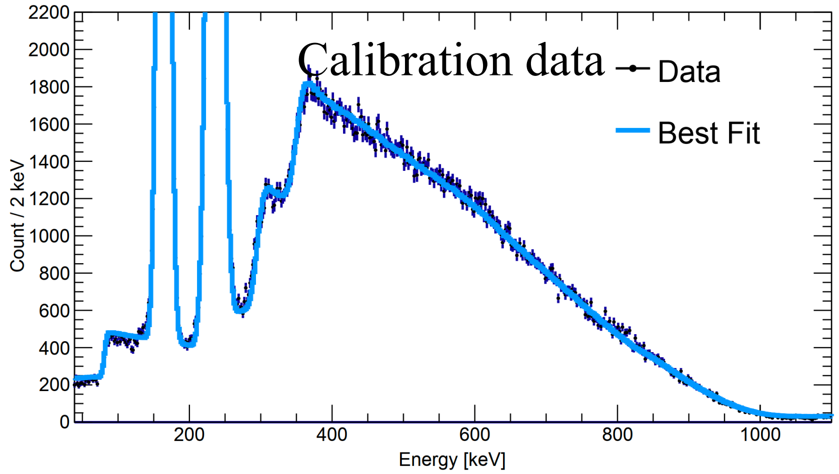
[Research 25 Nov 2022, 9798721]

Gaussian Backgrounds

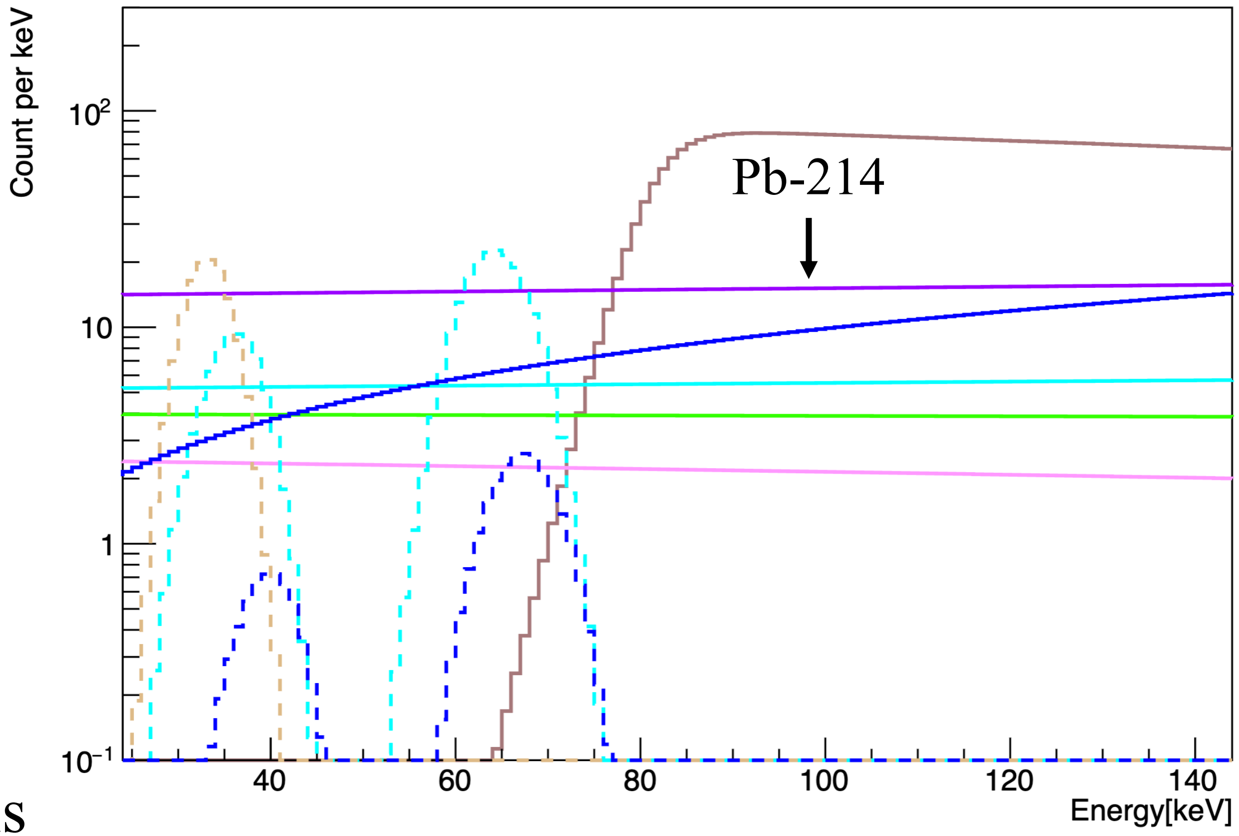
- ➢ **Xe-124** ECEC (KK/KL/KM/KN)
- ➢ **I-125** EC (K/L/M + γ)
- ➢ **Xe-127** EC (K)

Backgrounds: Impurity

- **Pb-214:** Main background
  - β decay with Q value 1018 keV

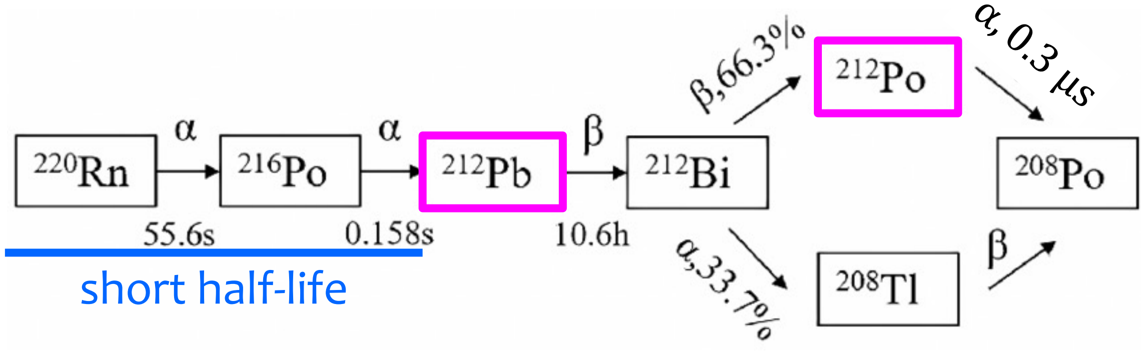


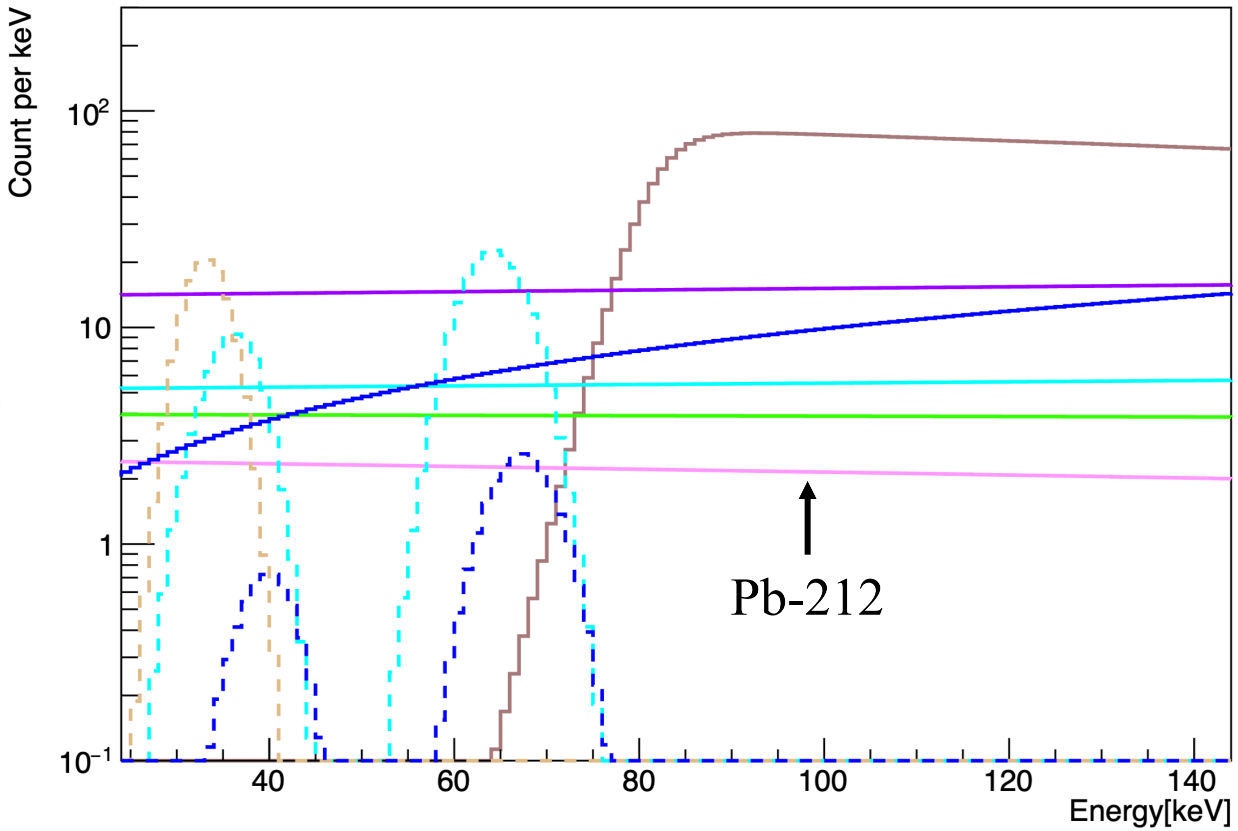
- Extrapolation ratio
- 4.5 ± 0.2 μBq/kg from the DBD analysis [PhysRevLett.132.152502]



Backgrounds: Impurity

- **Pb-212**
  - β decay with Q value 569 keV



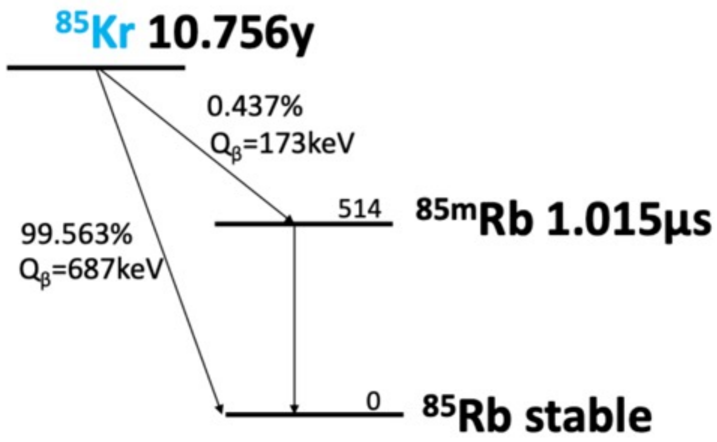


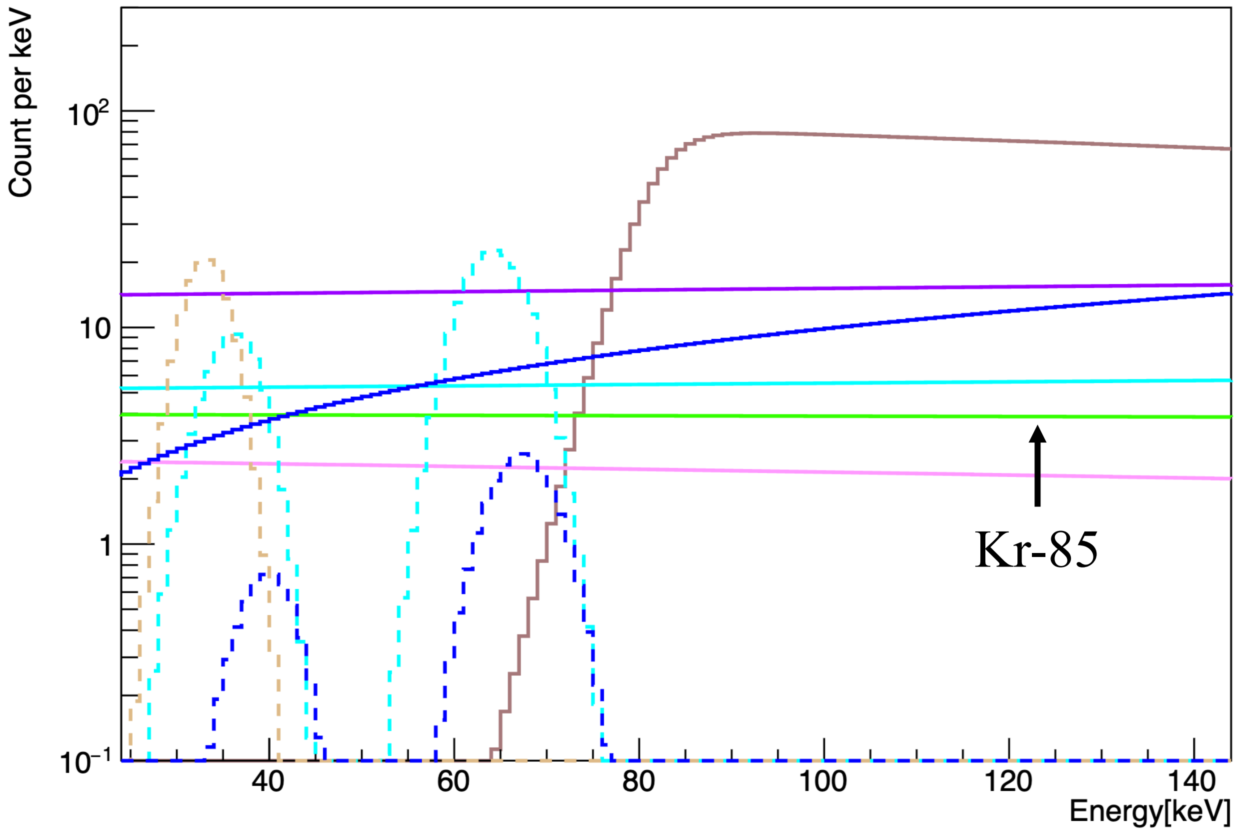
- Rate of ^{212}Po
- ^{212}Pb/^{212}Po using calibration data
- Rate of ^{212}Pb 0.30 ± 0.08 μBq/kg

Backgrounds: Impurity

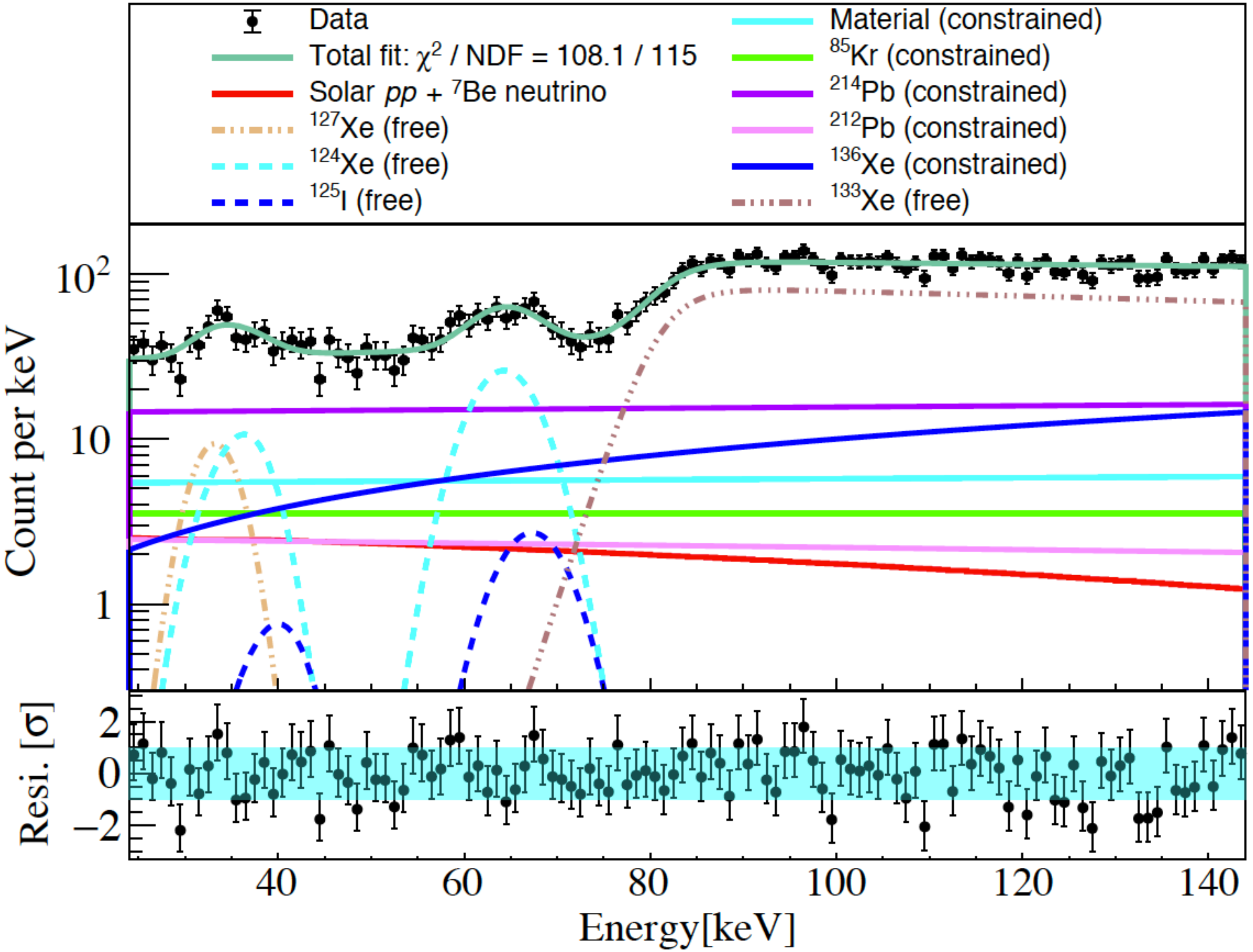
➢ Kr-85

- $\beta - \gamma$ coincidence
- Kr/Xe[ppt(10^{-12})]: 0.52 ± 0.27

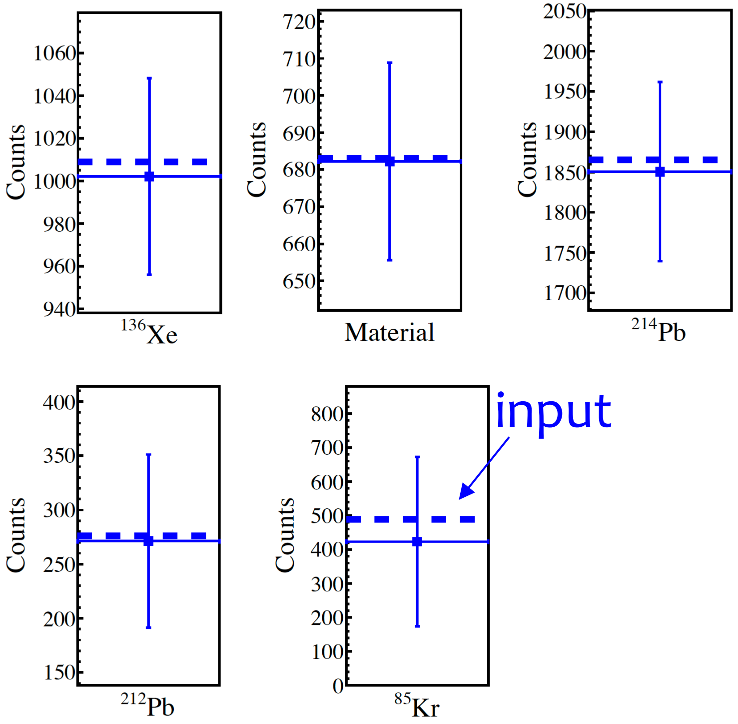




Best-fit



Nuisance parameters are constrained using expected uncertainties



➢ Fitted pp + ^{7}Be ν: 231 ± 257

Uncertainties

① σ_{stat}: Statistical uncertainty

- Fix all nuisance parameters to best-fit values, and re-fit

② σ_{sys1}: On nuisance parameters

- Subtotal = $\sqrt{\sigma^2 - \sigma_{stat}^2}$
- Loose i-th nuisance parameter and fix others, and re-fit

$$\sqrt{\sigma_i^2 - \sigma_{stat}^2}$$

③ σ_{sys2}: Evaluated manually

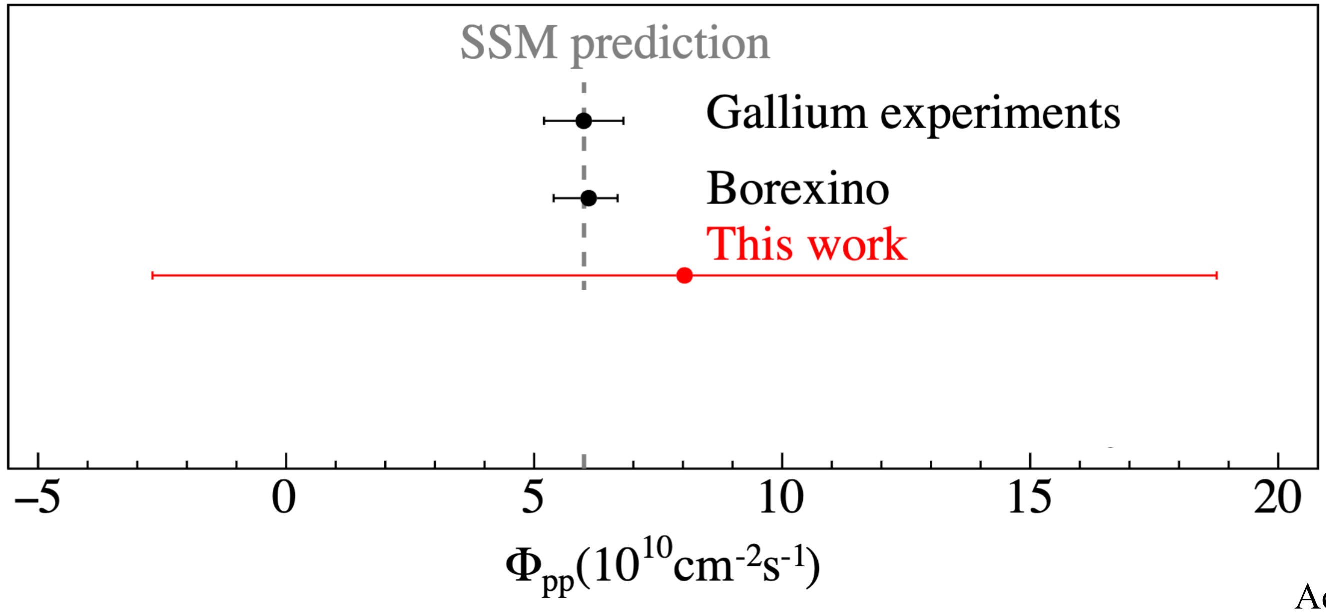
	Components	Counts
σ_{stat}	-	113
σ_{sys1}	^{85}Kr	202
	^{214}Pb	87
	^{212}Pb	69
	Material	21
	^{136}Xe	19
	Data selection	29
	Subtotal	**231**
σ_{sys2}	Energy scale	142
	Energy resolution	19
	Fit range	29
	^{214}Pb spectrum	84
	^{212}Pb spectrum	18
	^{85}Kr spectrum	5
	^{136}Xe $2\nu\beta\beta$ half-life	16
	Subtotal	**170**
	Total	**287**

Future improvement

➢ Fitted pp + ^{7}Be ν: $231 \pm 113(\text{stat}) \pm 287(\text{syst})$

Results

- In the 24~144 keV electron recoil energy range
  - Flux: $8.0 \pm 3.9(\text{stat}) \pm 10.0(\text{sys}) \times 10^{10}\text{s}^{-1}\text{cm}^{-2}$
  - Upper limit at 90% C.L.: $23.3 \times 10^{10}\text{s}^{-1}\text{cm}^{-2}$
- The first solar *pp* neutrino measurement using liquid xenon

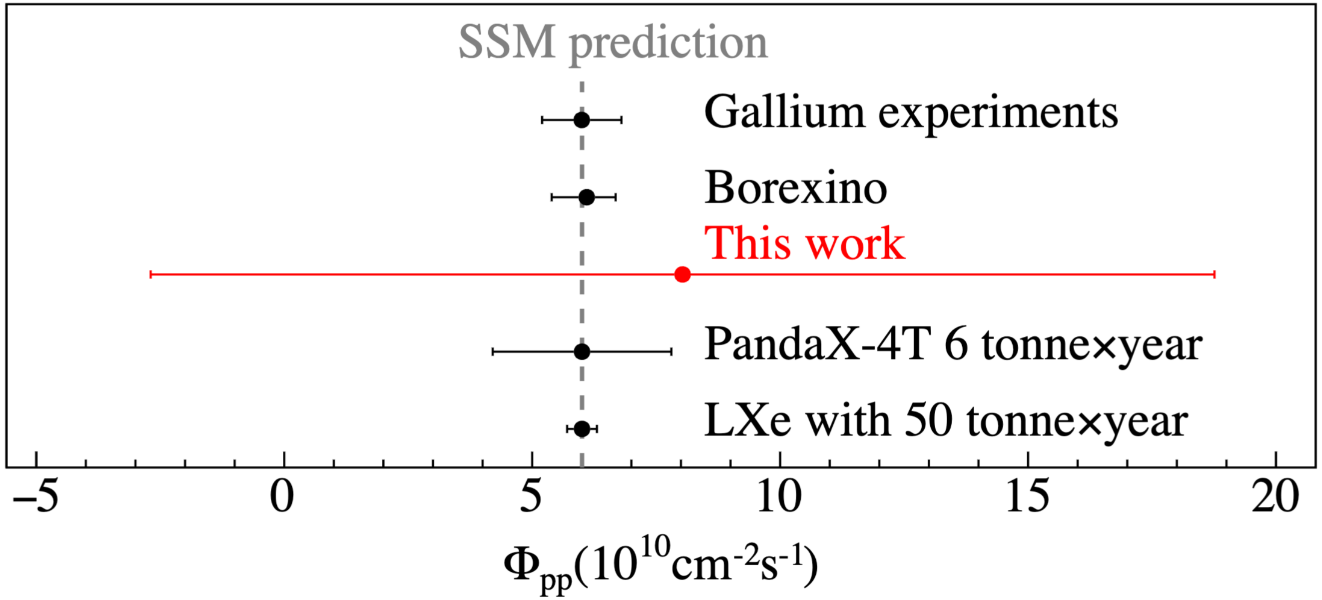


[arXiv:2401.07045]
Accepted by Chinese Physics C

Outlook

- PandaX-4T with assumptions
  1. No induced activation of xenon isotopes
  2. Reduction of radon and krypton by a factor of 2
  3. Control of the background uncertainty within 5%

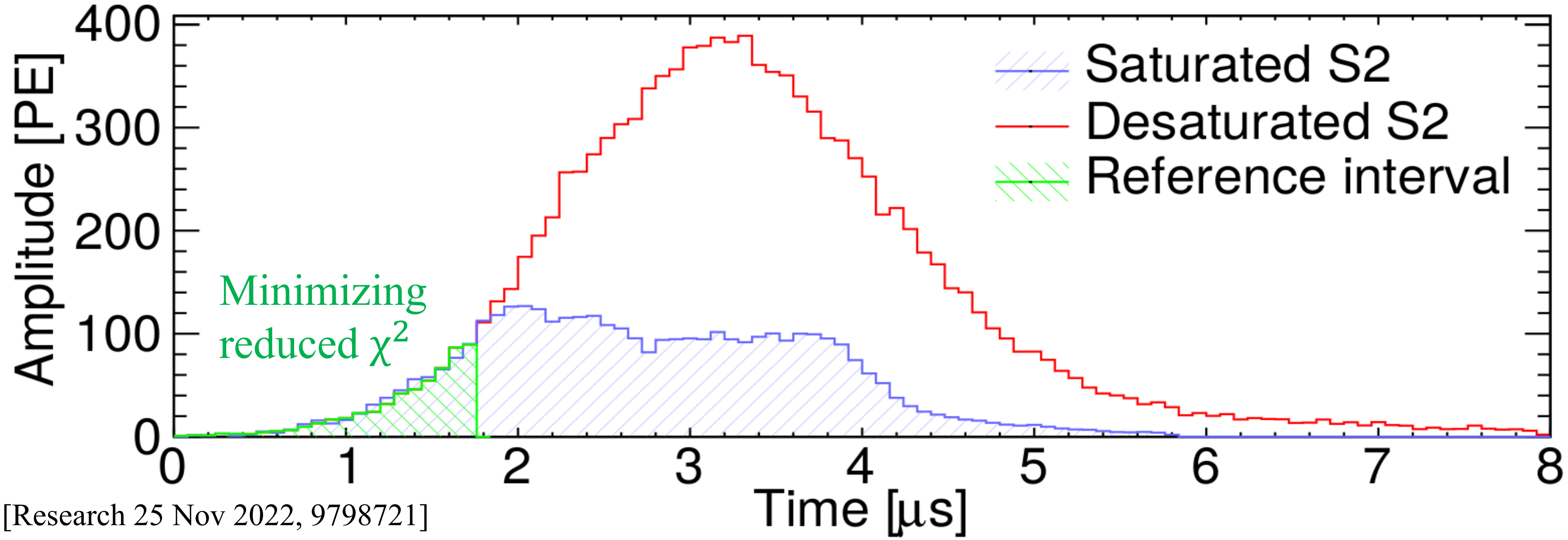
  → ~30% uncertainty @ 6 tonne×year
- Future LXe experiments, larger targets, and lower backgrounds
  → ~5% uncertainty @ 50 tonne×year exposure
- Multi-tonne-scale LXe experiments open a window for solar *pp* neutrino detection



Thanks for your attention!

Back Up

PMT pulse desaturation

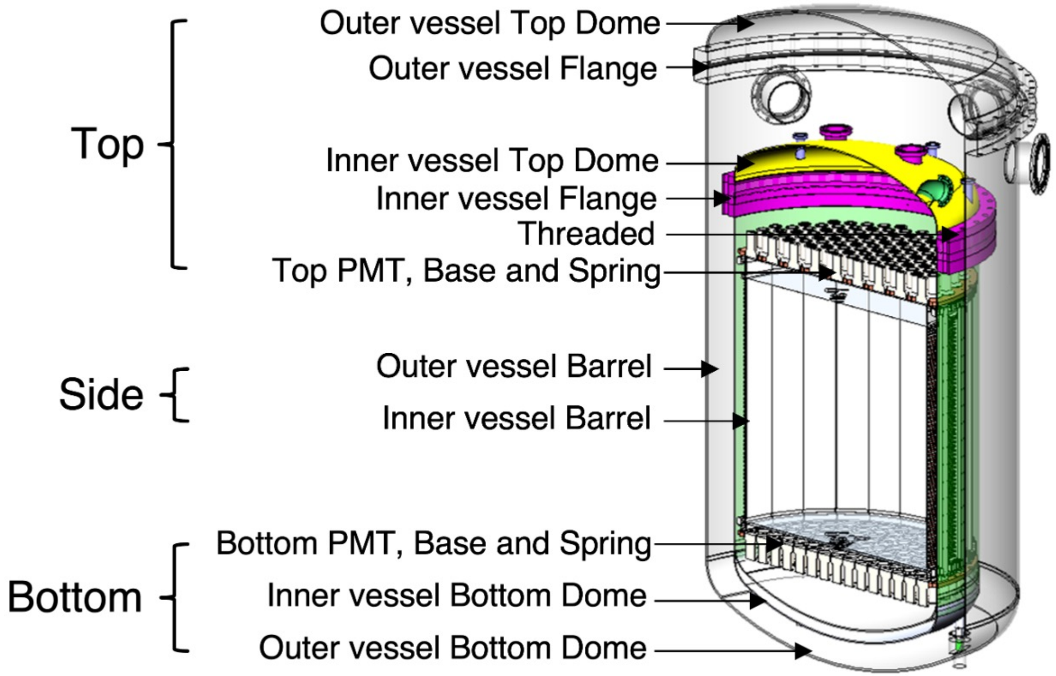


[Research 25 Nov 2022, 9798721]

- Desaturation algorithm
  - Match the rising slope of the saturated waveforms to the non-saturated templates in the same events → True charge collected

Backgrounds: material

- Long-lived radioactive isotopes K-40, Th-232, U-238 and Co-60
- Simulated using BambooMC, Geant4-based MC simulation package
- Using Xe-136DBD analysis fit result.
- In ROI: 683±27



[JHEP06(2022)147]

Remove leaked Bi-214 events

- Scan Po-214 α events within 5 ms by waveform characters
  - charge > 30e3 PE
  - height > 1000 PE
  - wFWHM < 200 ns
- Not include in bkg model