上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

First Indication of Solar ^{8}B Neutrinos through Coherent Elastic Neutrino-Nucleus Scattering in PandaX-4T

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2026-07-15

饮 水 思 源 • 爱 国 荣 校

个人简介

- 2025至今，上海交通大学李政道研究所，博士后
- 2019-2025，上海交通大学李政道研究所，博士
- 2015-2019，上海交通大学，学士

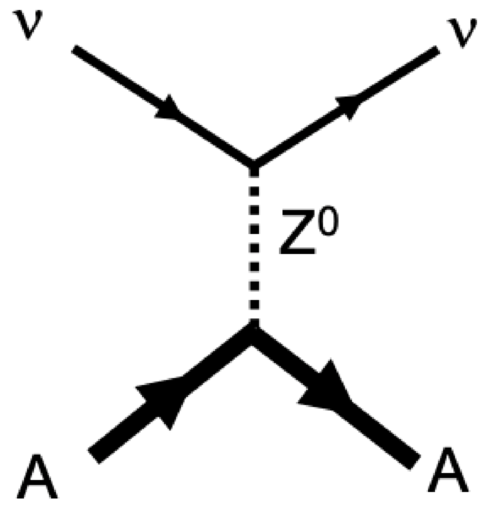
中微子-原子核相干弹性散射（CEνNS）

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

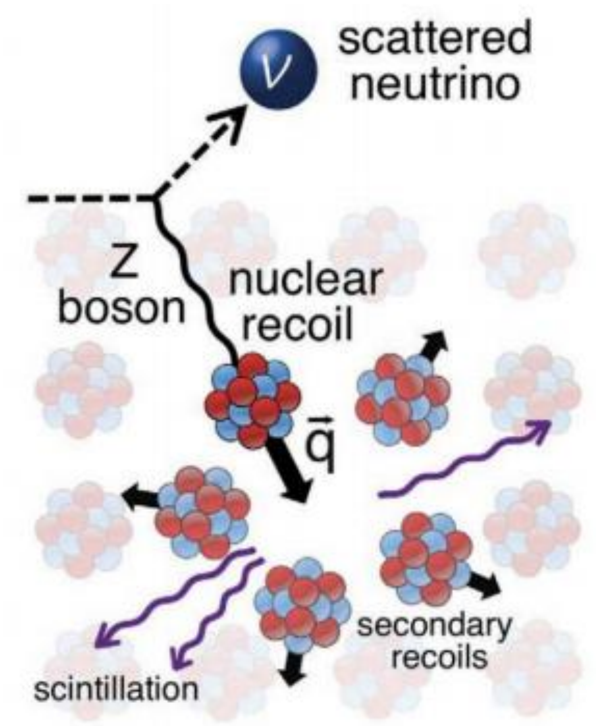
$$\nu + A \rightarrow \nu + A$$

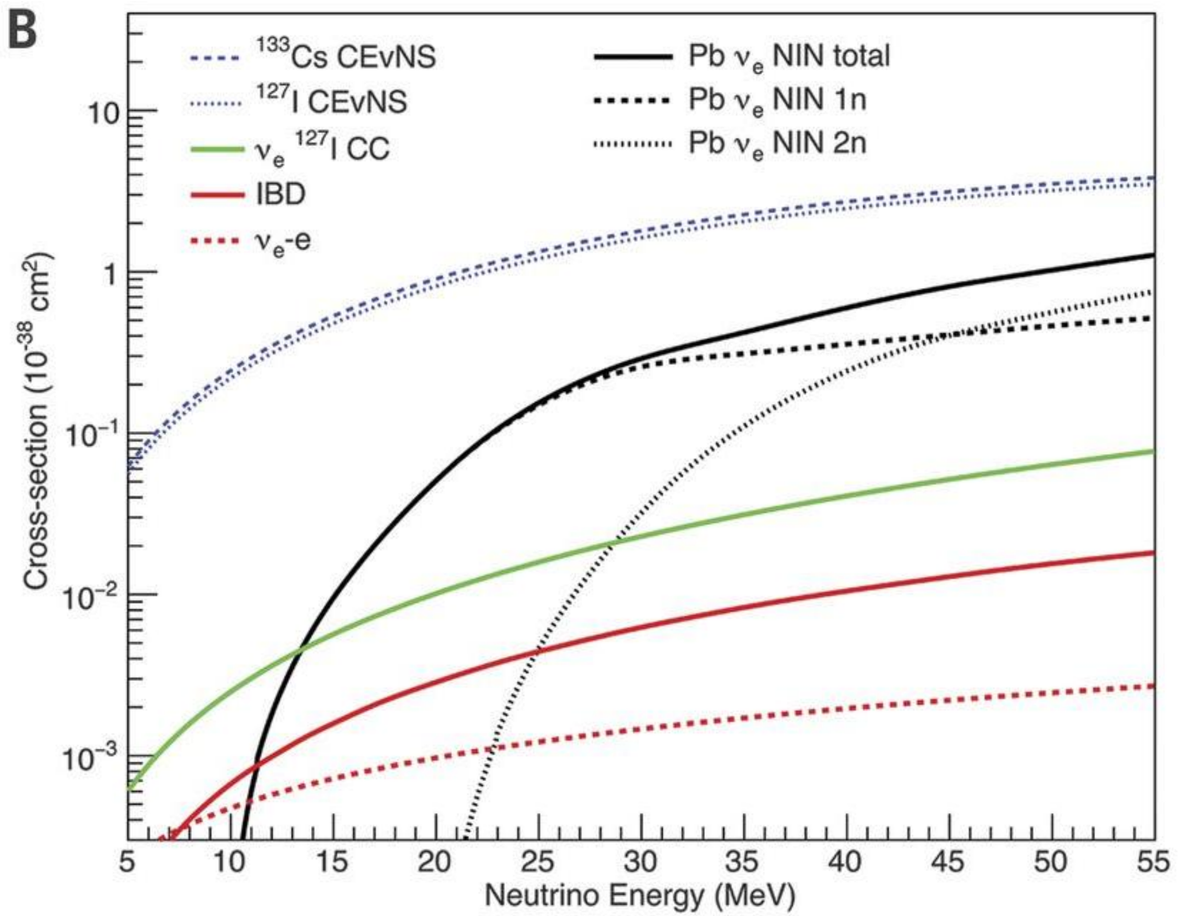


- **最早在1974年由Freedman提出**
- **当中微子波长接近或大于原子核尺度，中微子通过Z玻色子与原子核整体发生中性流相干散射**

中微子-原子核相干弹性散射（CEνNS）

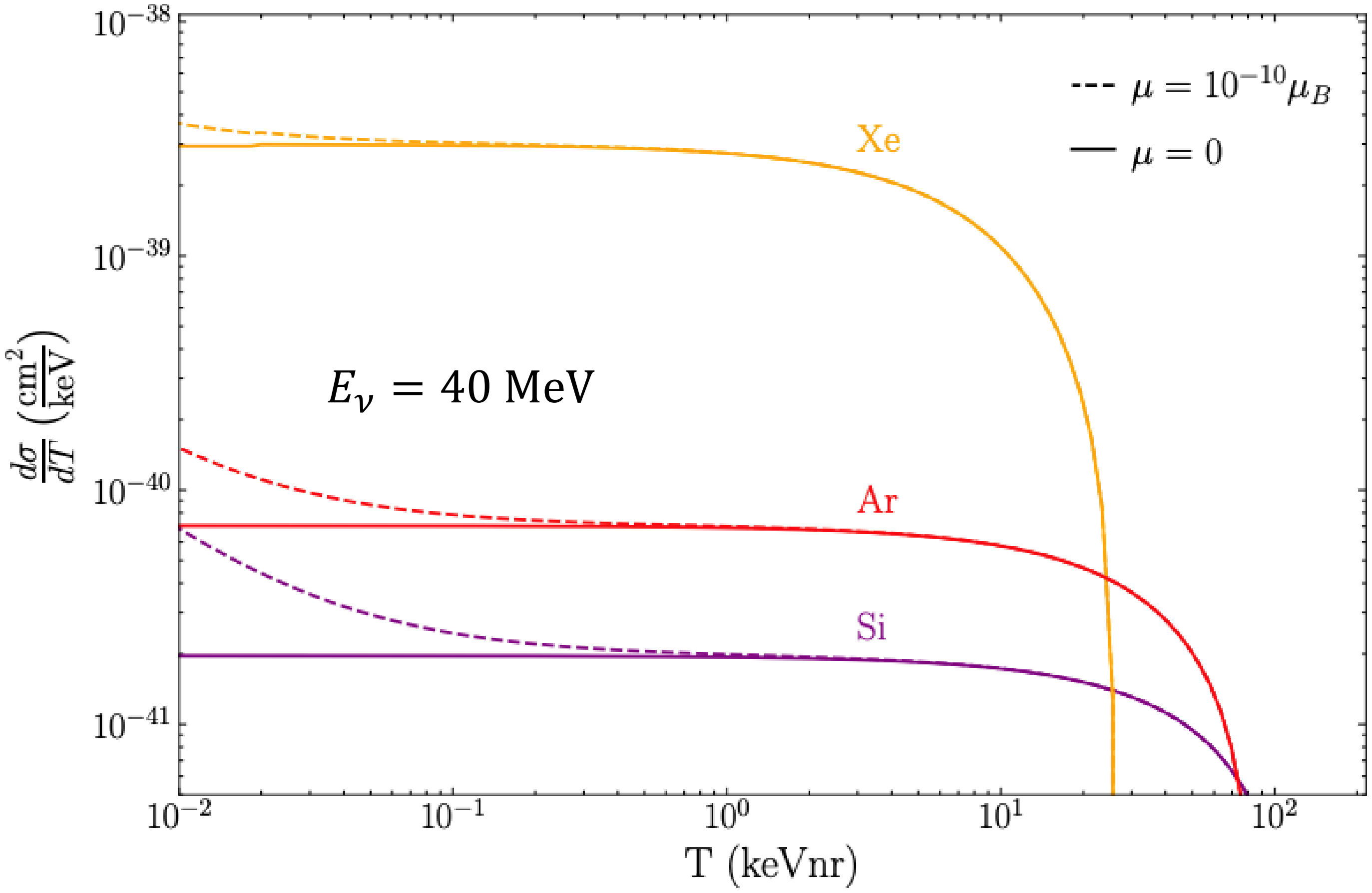
- **优势：散射截面与靶核中子数平方成正比，远大于其他中微子探测通道**





中微子-原子核相干弹性散射（CEνNS）

- 但是，信号反冲能量极低，对探测器灵敏度提出了极高的要求



JHEP 02 (2020) 123

暗物质直接探测实验

- 利用这种中微子探测器寻找宇宙中的暗物质粒子与靶原子核的相干弹性散射信号（Goodman and Witten，1985)

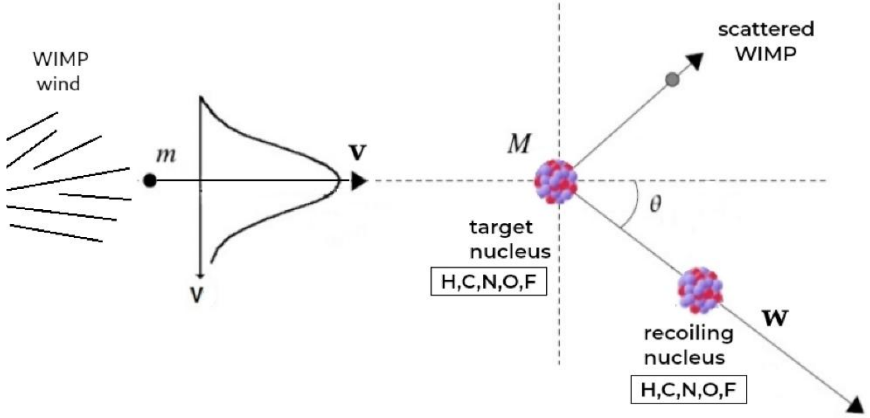
PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

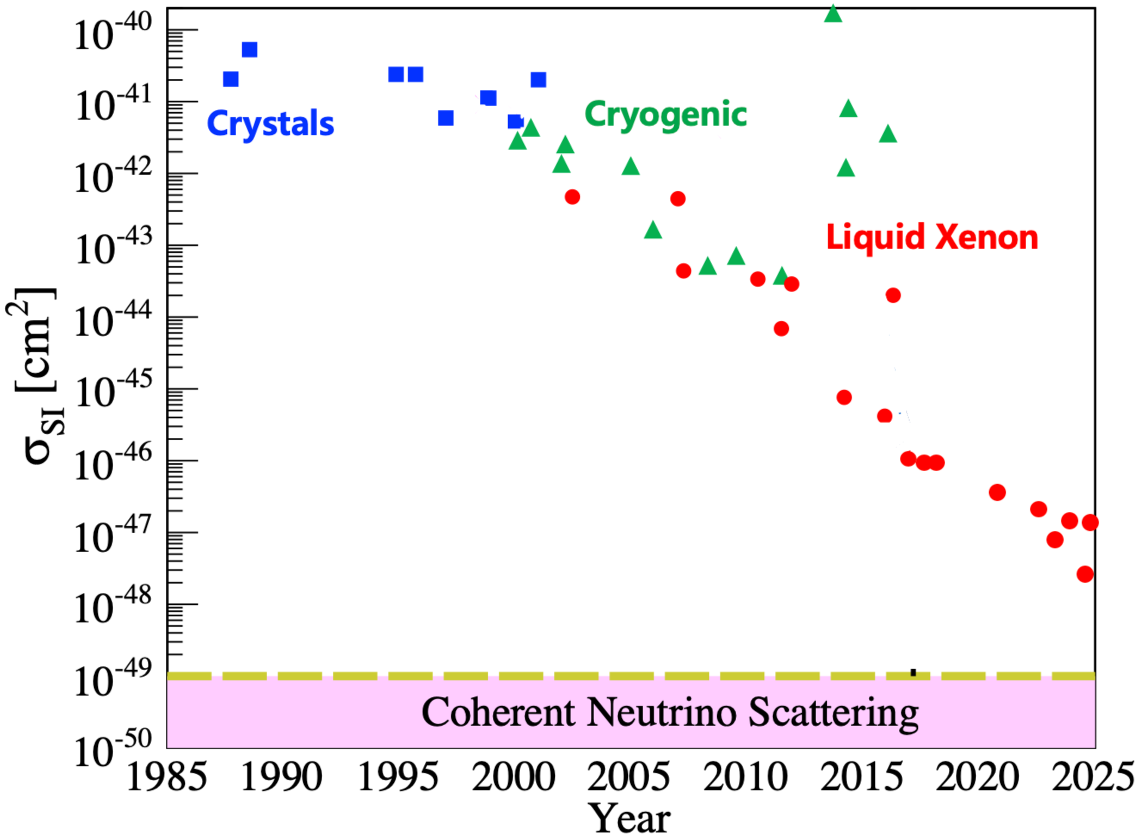
(Received 7 January 1985)

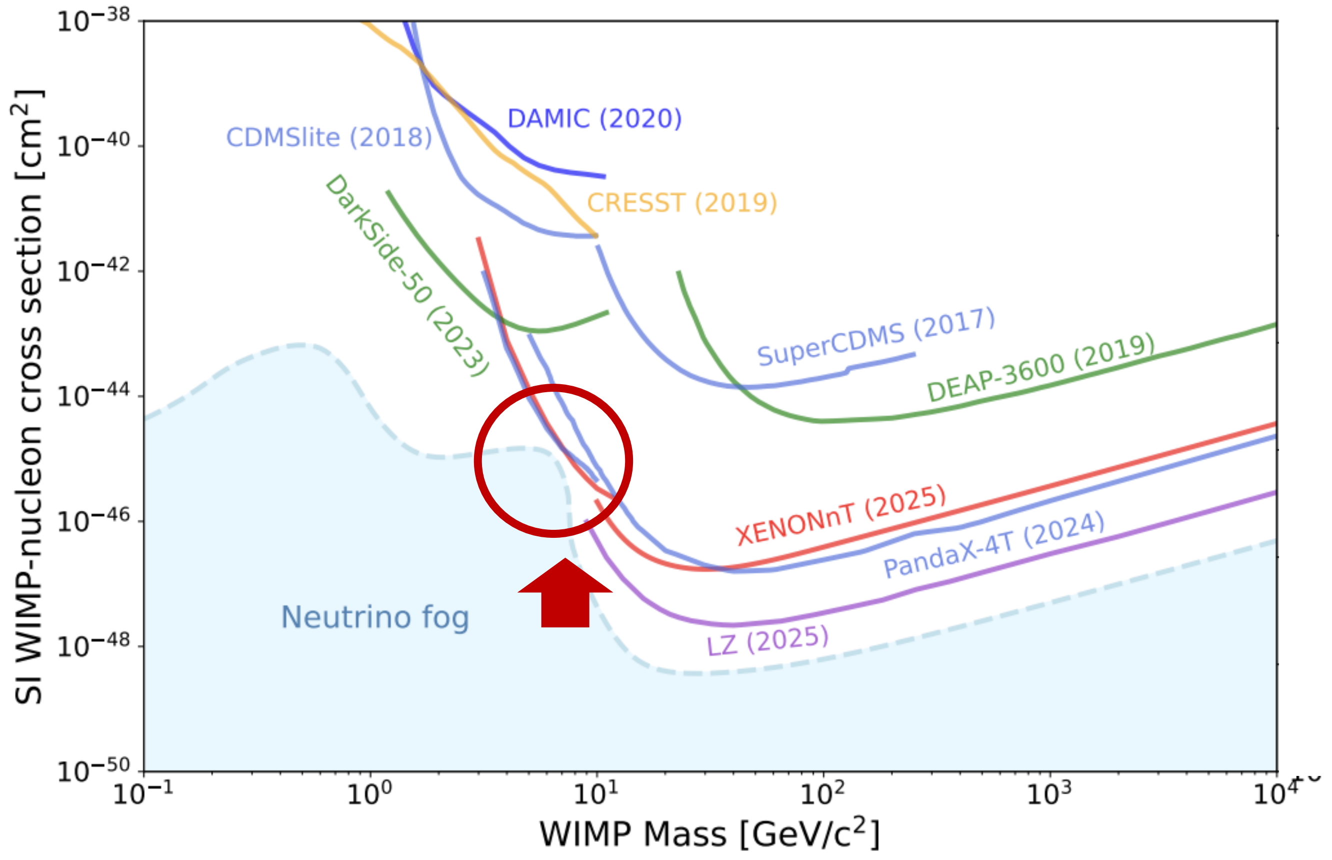
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses 1—10^6 GeV; particles with spin-dependent interactions of typical weak strength and masses 1—10^2 GeV; or strongly interacting particles of masses 1—10^{13} GeV.



暗物质直接探测的发展

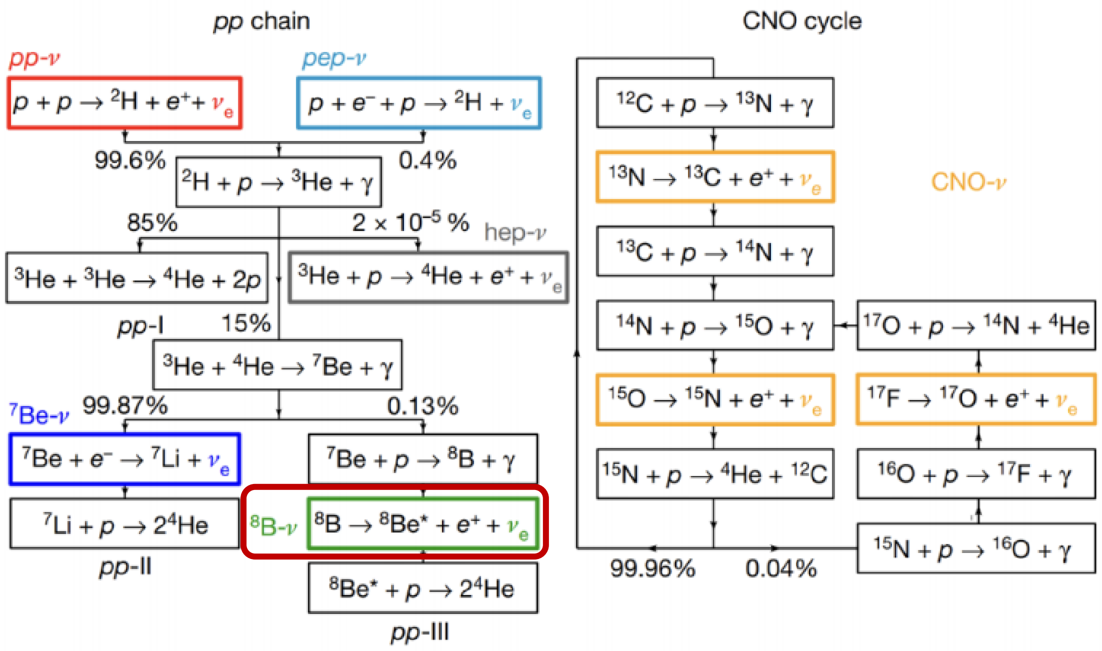
- 过去40年，暗物质探测灵敏度提升了7个数量级
- 终于开始接近中微子信号

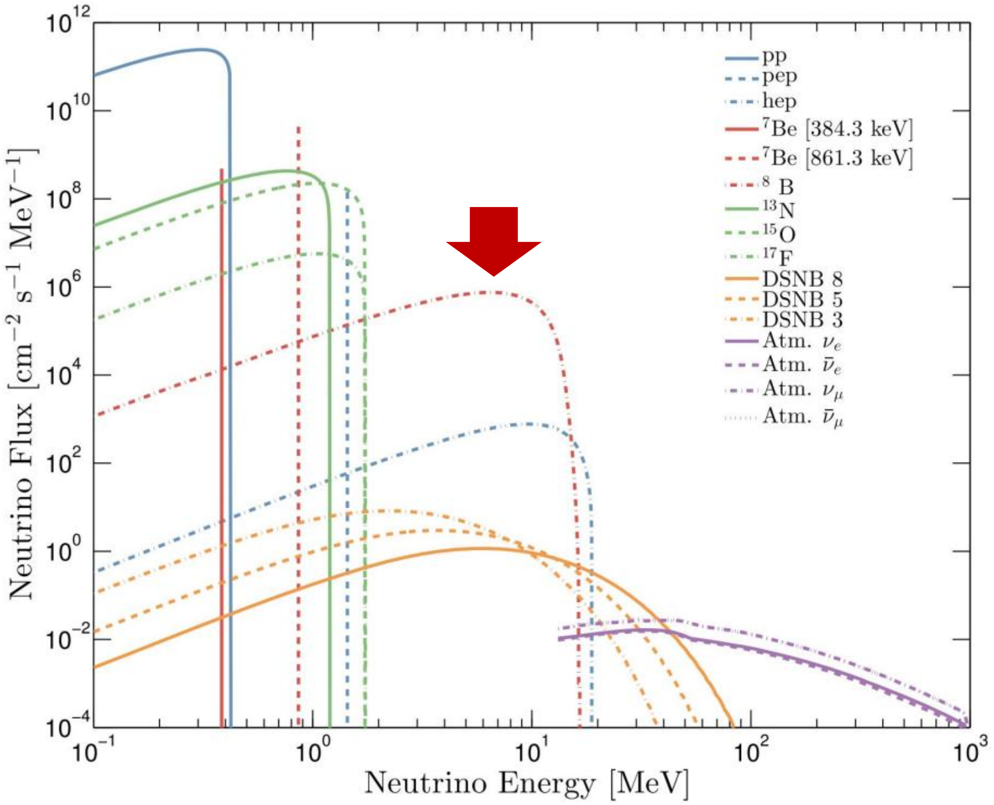




太阳 ^{8}B 中微子

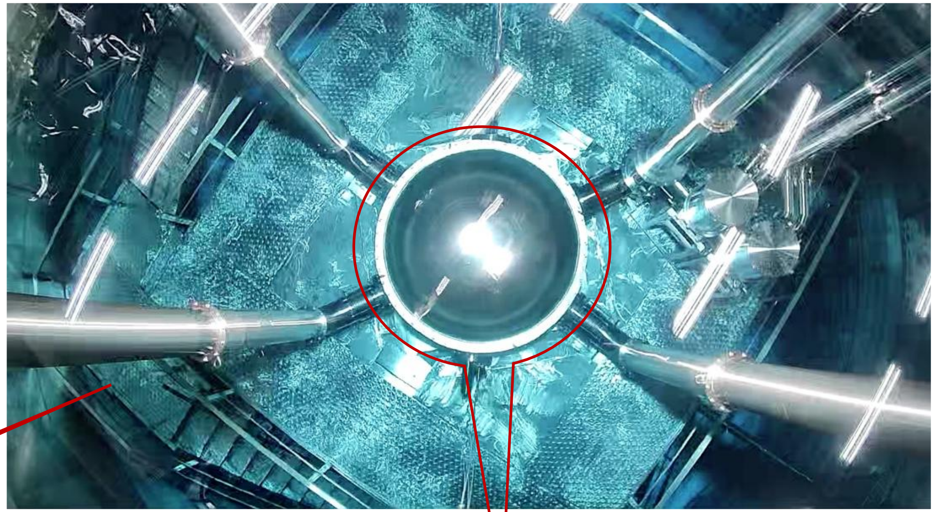
- 在高能区通量最大
- 是暗物质探测器最先遇到的中微子信号

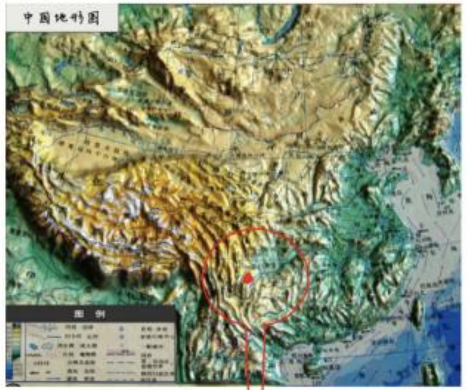


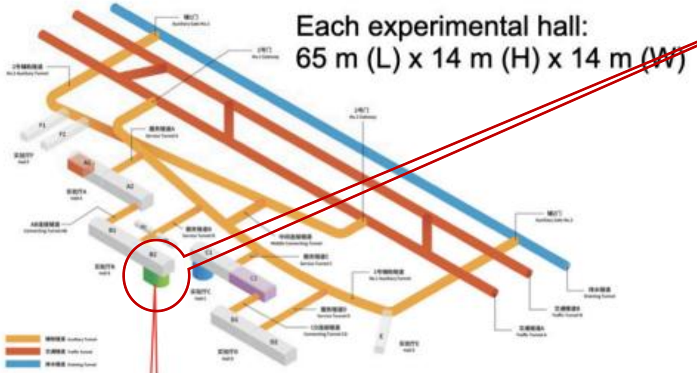


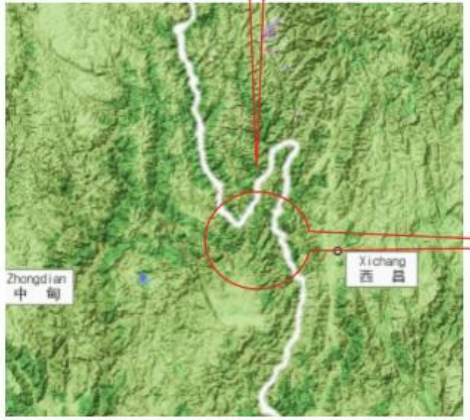
PandaX-4T 探测器

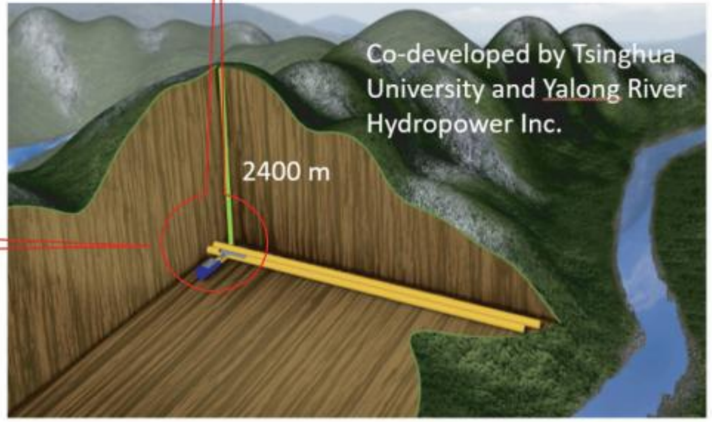
- 最灵敏的液氙暗物质探测器之一
- 3.7吨灵敏体积





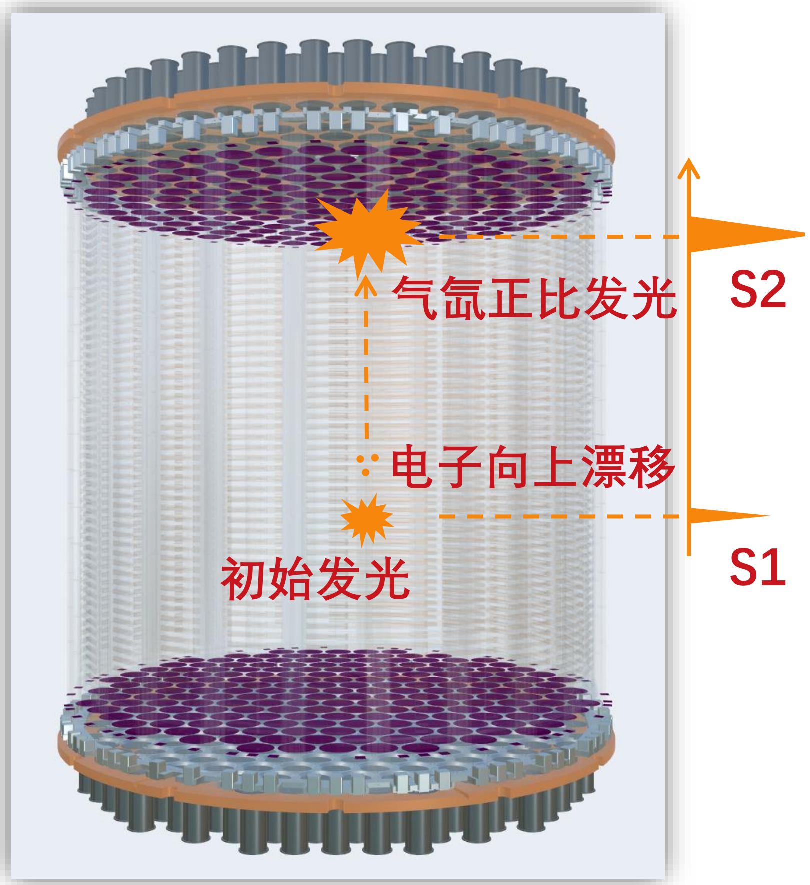




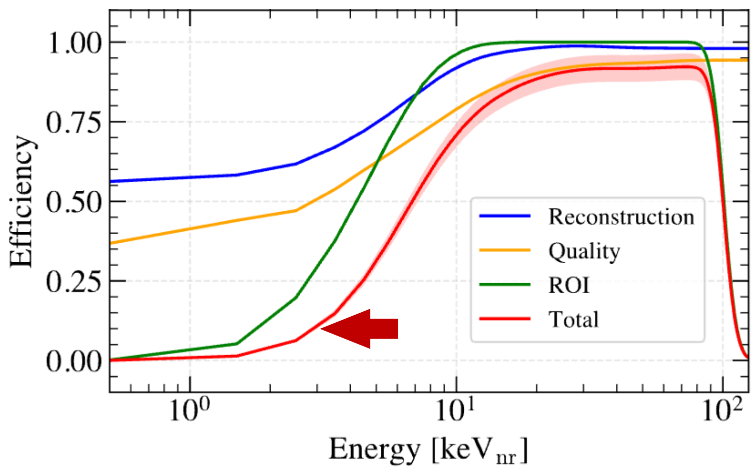


PandaX-4T 探测器

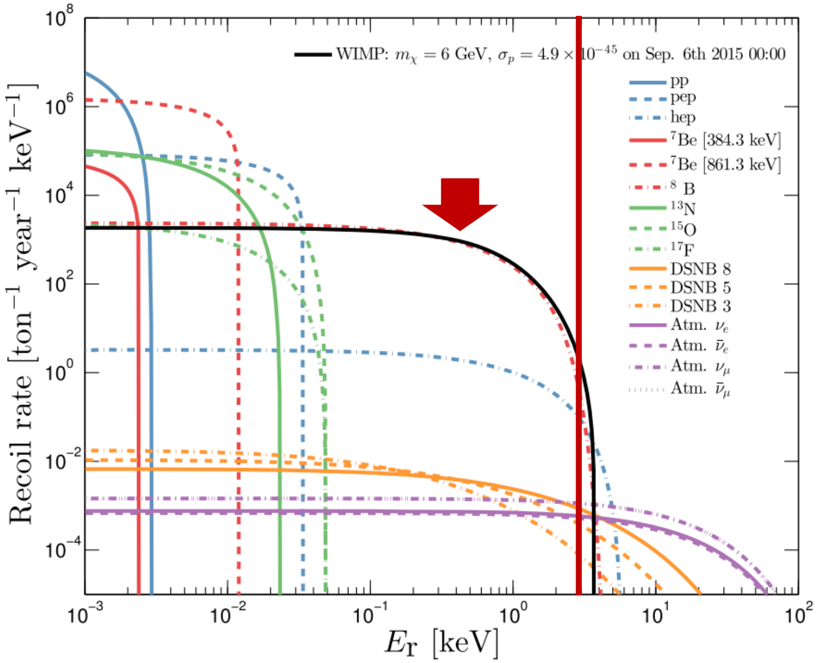
- **经典分析方法的局限：**
  - 结合S1与S2信号，能量阈值约在3keV左右，大量 ^{8}B 信号在有效能区之外
- **提升灵敏度的关键：进一步降低能量阈值**



经典探测能区信号效率

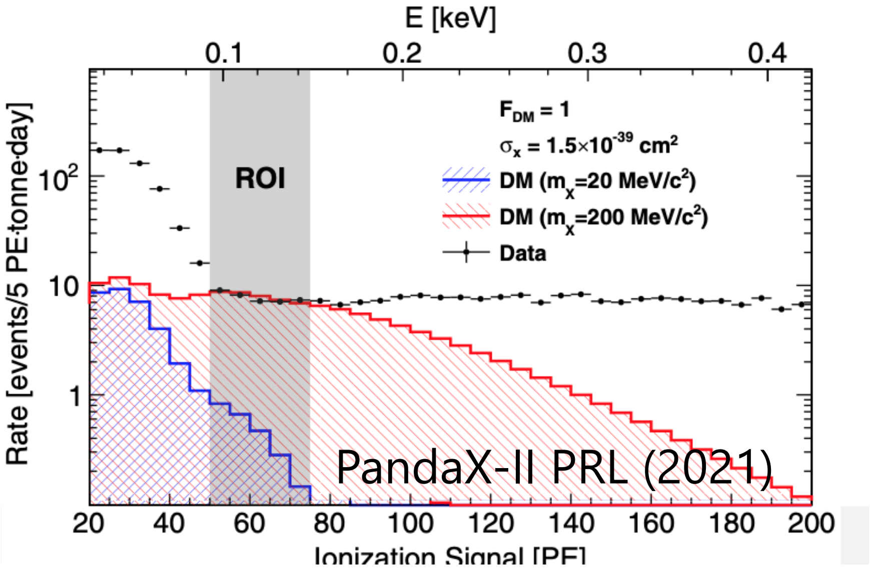


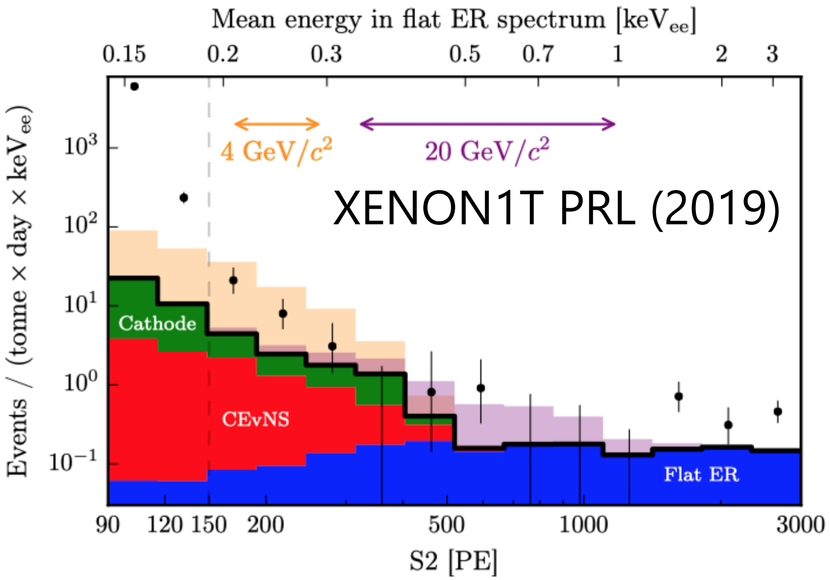
中微子在氙中的反冲能谱



单独电离信号

- 现有探测器对S1(~10%)的探测效率远低于S2(~90%)，能量阈值主要取决于S1的大小
- 无S1的单独电离信号能够显著降低能量阈值，提高信号事例率



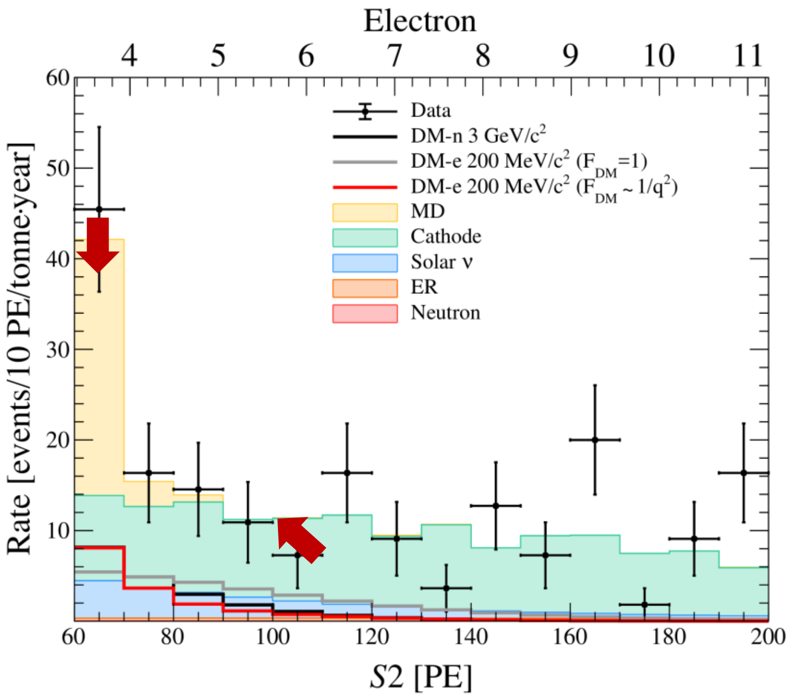


- 主要挑战: 极低能区的本底构成与信号模型 （个人主要工作）

本底成分

主要本底成分

- 延迟电子（MD）
  - ➢低能区占主导，迅速下降，来源尚不明确
- 阴极本底（Cathode）
  - ➢在较高能区占主导，来自阴极放射性，相较于物理事例信号宽度更大



PRL 130, 261001 (2023)

	Nominal
Cathode	41.6 ± 10.6
MD	$6.9^{+9.0}$
Solar ν	10.8 ± 3.7
ER	2.3 ± 0.6
Neutron	0.1 ± 0.1
Total	$61.7^{+14.4}_{-11.2}$

Nuisance parameters		Standard deviation.	Estimated by
Data selection efficiency	δ_ϵ	0.31	DS vs WS
Signal model rate	$\delta_s f_i$	f_i	NEST uncertainty
Cathode background rate	δ_{cat}	$\boxed{0.25}$	ROI sideband
MD background rate	δ_{MD}	$\boxed{^{+1.3}_{-0.0}}$	cut1 data

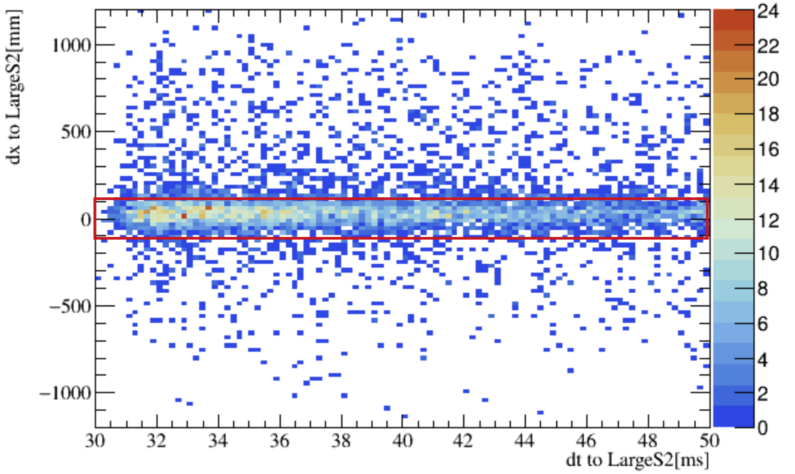
模型误差较大，尤其是延迟电子

延迟电子本底

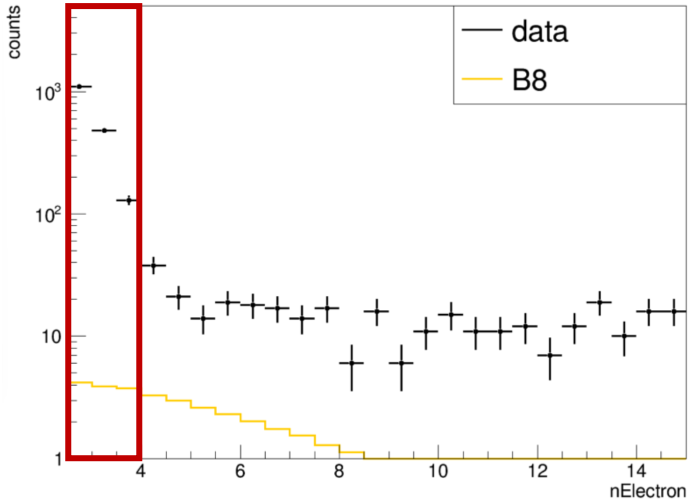
本分析中发现的特征

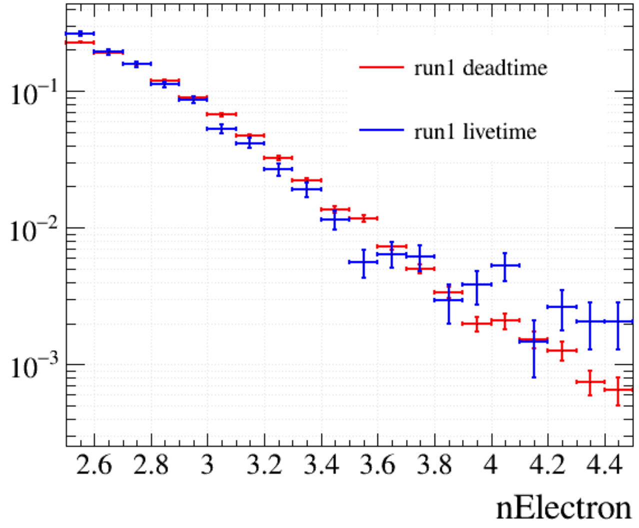
- 与单电子事例率相关
- 与前方的大信号有位置相关性

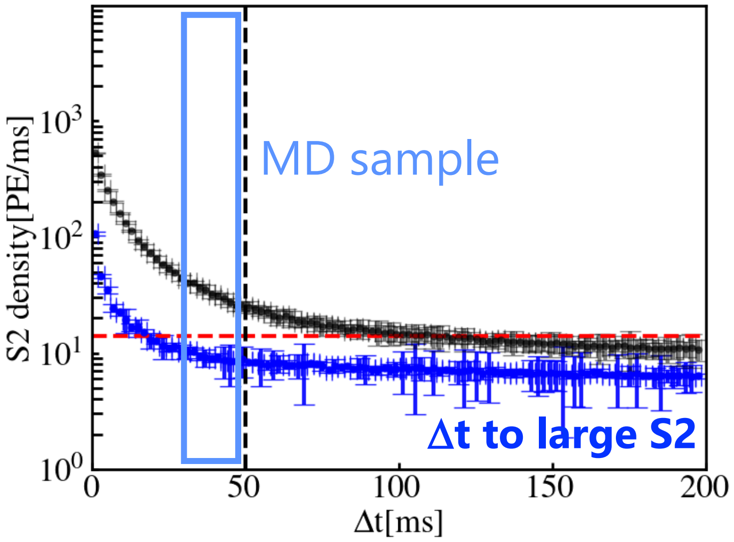
各类单电子聚合



从靠近大信号，单电子事例率极高的区域获得谱形，从低能区域获得事例率

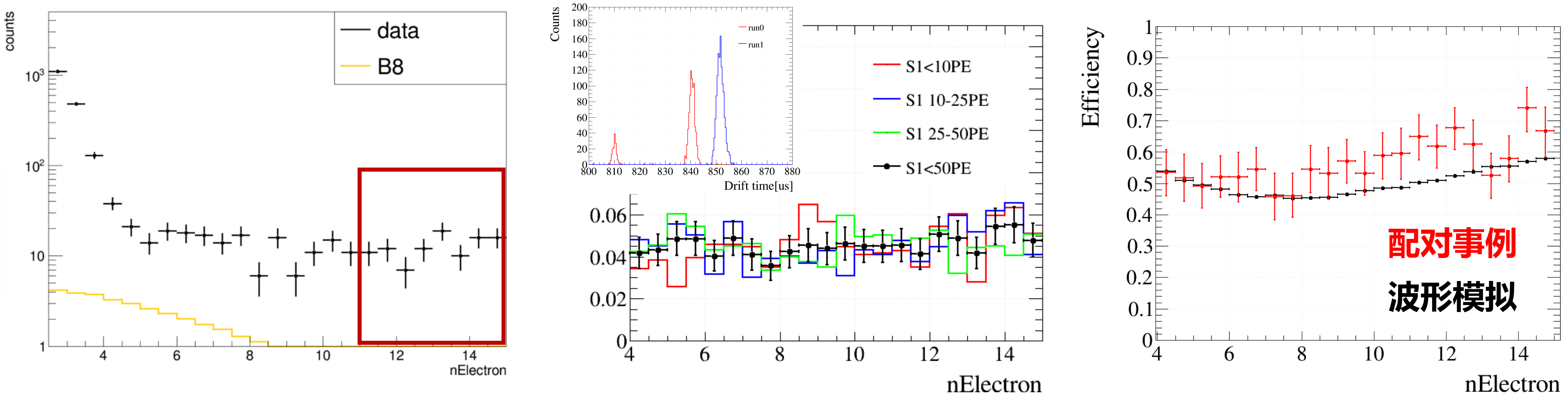






阴极本底

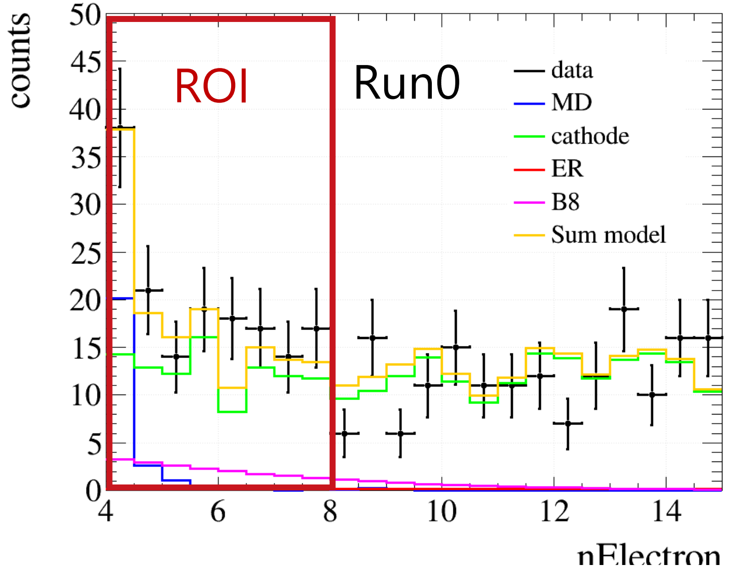
- 从配对事例挑选阴极附近事例获得谱形，从较高能区域获得事例率
- 数据驱动，统计量较少：
  - 在较宽松的筛选条件下获得谱形，乘以**波形模拟**给出的最终筛选效率

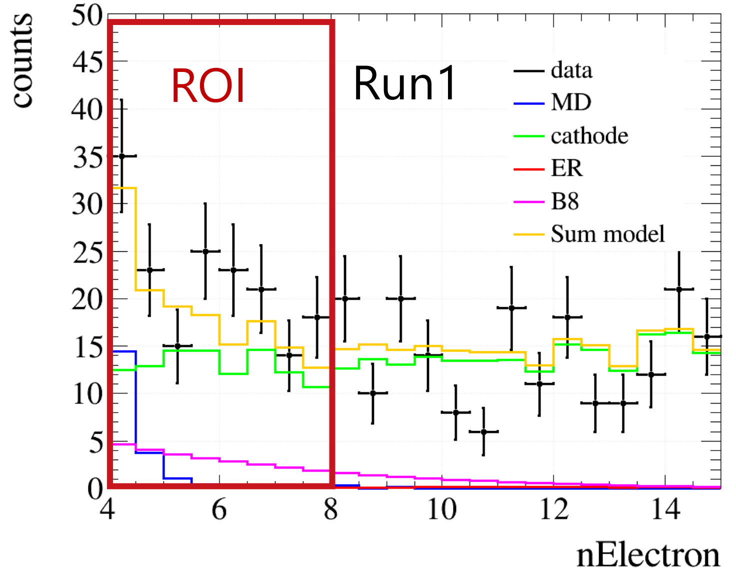


本底模型总结

- **将PandaX-4T Run1数据纳入分析**
- **延迟电子：**
  - 根本改良估计方法，显著降低模型误差
- **阴极本底：**
  - 利用波形模拟进一步降低模型误差
- **优化事例筛选条件，大幅提高了信号效率**

	PRL 2023 (Run0)	本论文 (Run0)	本论文 (Run1)
延迟电子误差	130%	13%	16%
阴极本底误差	25%	24%	20%
信号效率	~20%	~40%	~40%





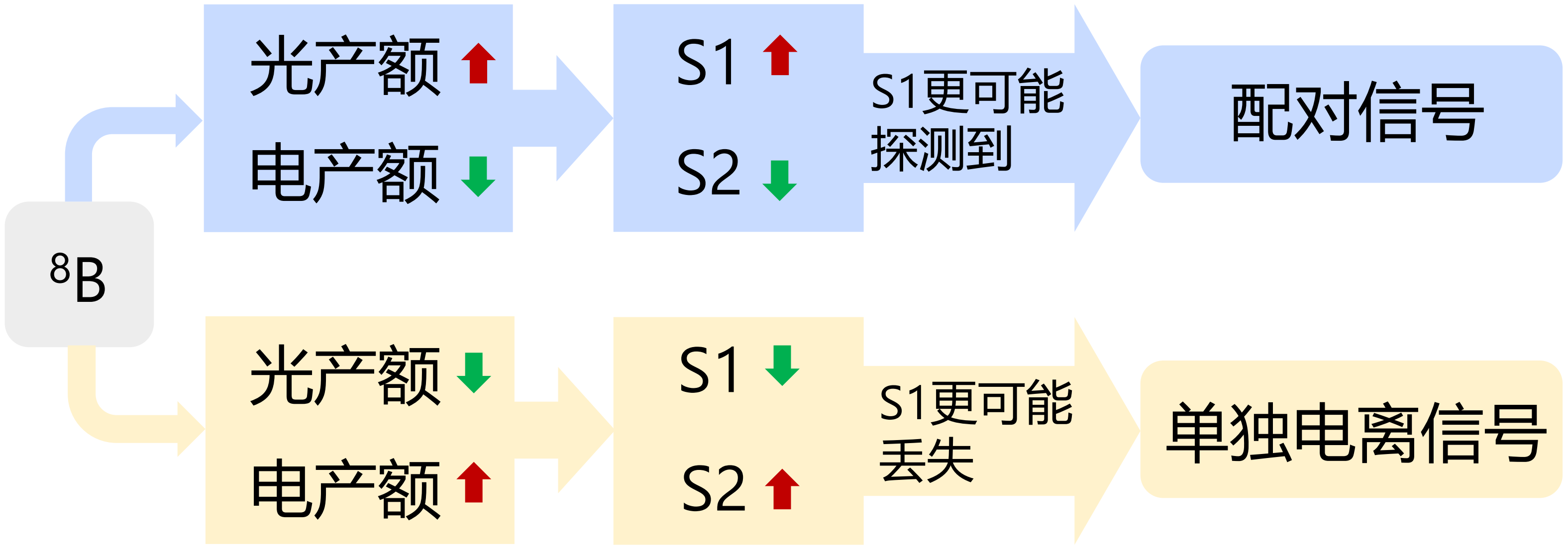
信号模型

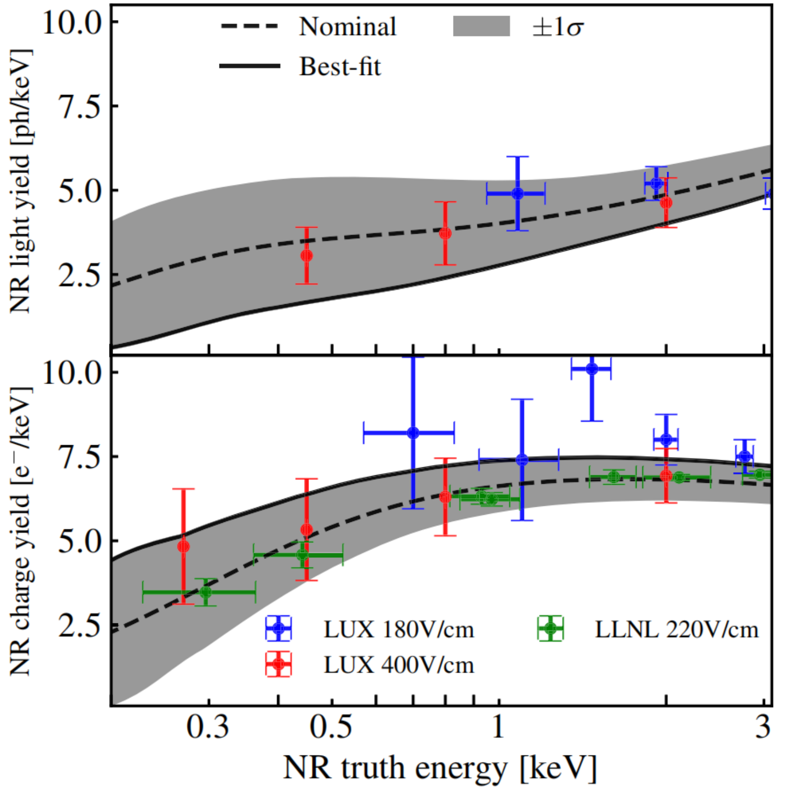
主要未知参数: 光产额与电产额

- 由于缺乏极低能刻度手段，使用来自 NEST v2.3.6 的国际测量结果

误差反相关浮动

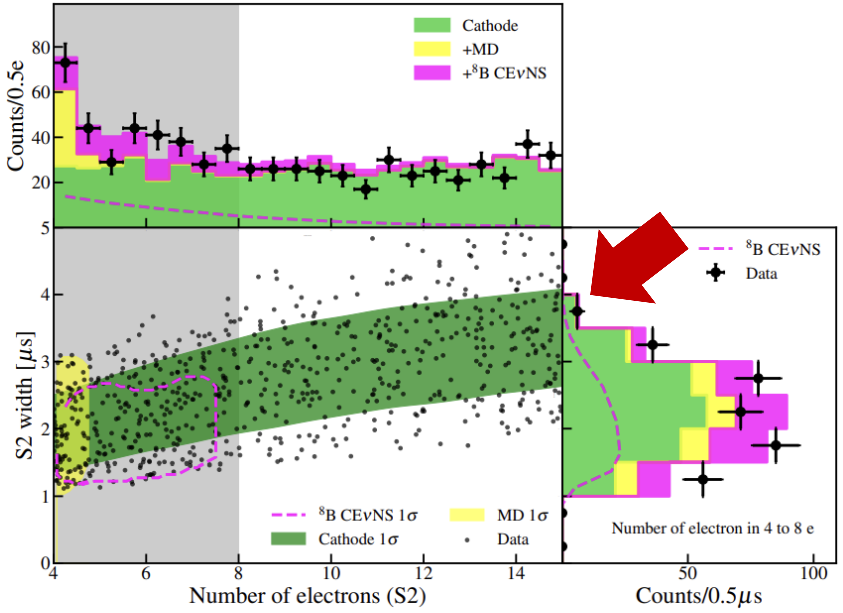
	配对信号	单独电离信号
预期事例数	6.22±0.74	294±33
观测事例数	3	332

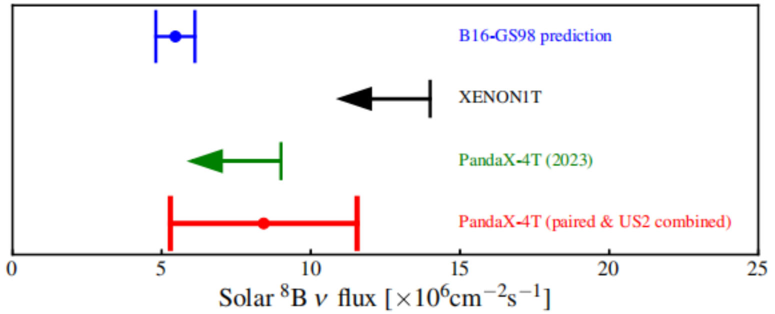




测量结果

- 配对信号与单独电离信号联合拟合
- 单独电离信号通过**电子数-宽度二维拟合**抑制阴极本底浮动
- 通量符合标准太阳模型预测，信号显著度达到**2.64σ**



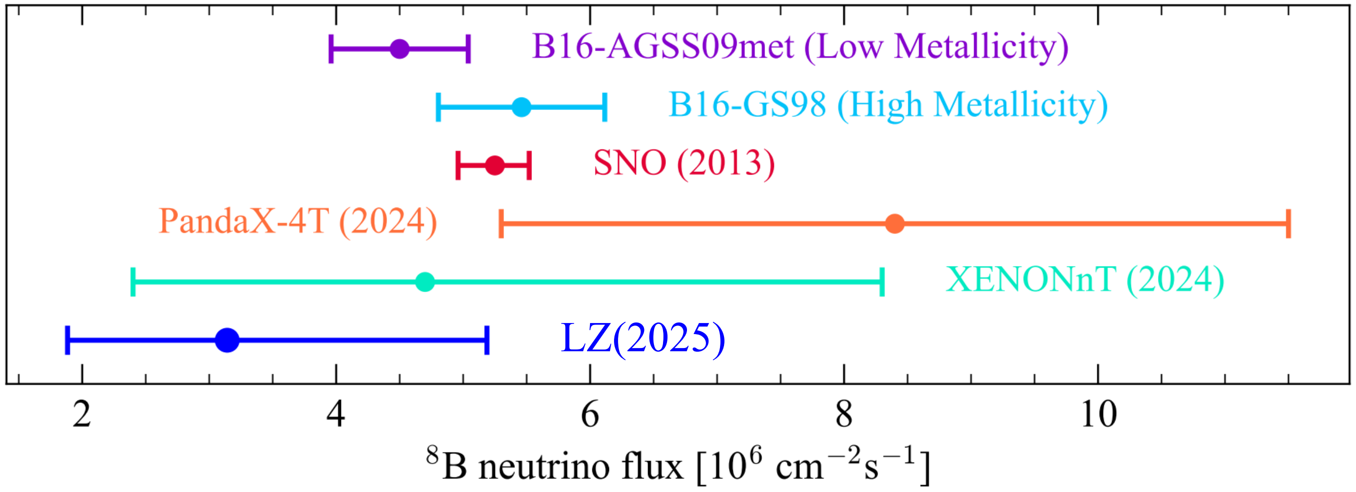


最佳拟合	单独电离信号	配对信号
^{8}B 信号数	75±28	3.5±1.3
^{8}B 通量	$8.4 \pm 3.1 \times 10^6 cm^{-2}s^{-1}$	

同类实验结果

- 单独电离信号将能量阈值降低到**0.33keV**，在同类实验中有显著优势
  - 能够实现能谱和通量的精确测量

	PandaX-4T（2024）	XENONnT（2024）	LZ（2025）
信号通道	单独电离信号	配对信号	配对信号
曝光量	1.04 吨·年	3.51 吨·年	5.7 吨·年
^{8}B 最佳拟合事例数	75 ± 28	$10.7^{+3.7}_{-4.2}$	$12.3^{+7.0}_{-5.4}$

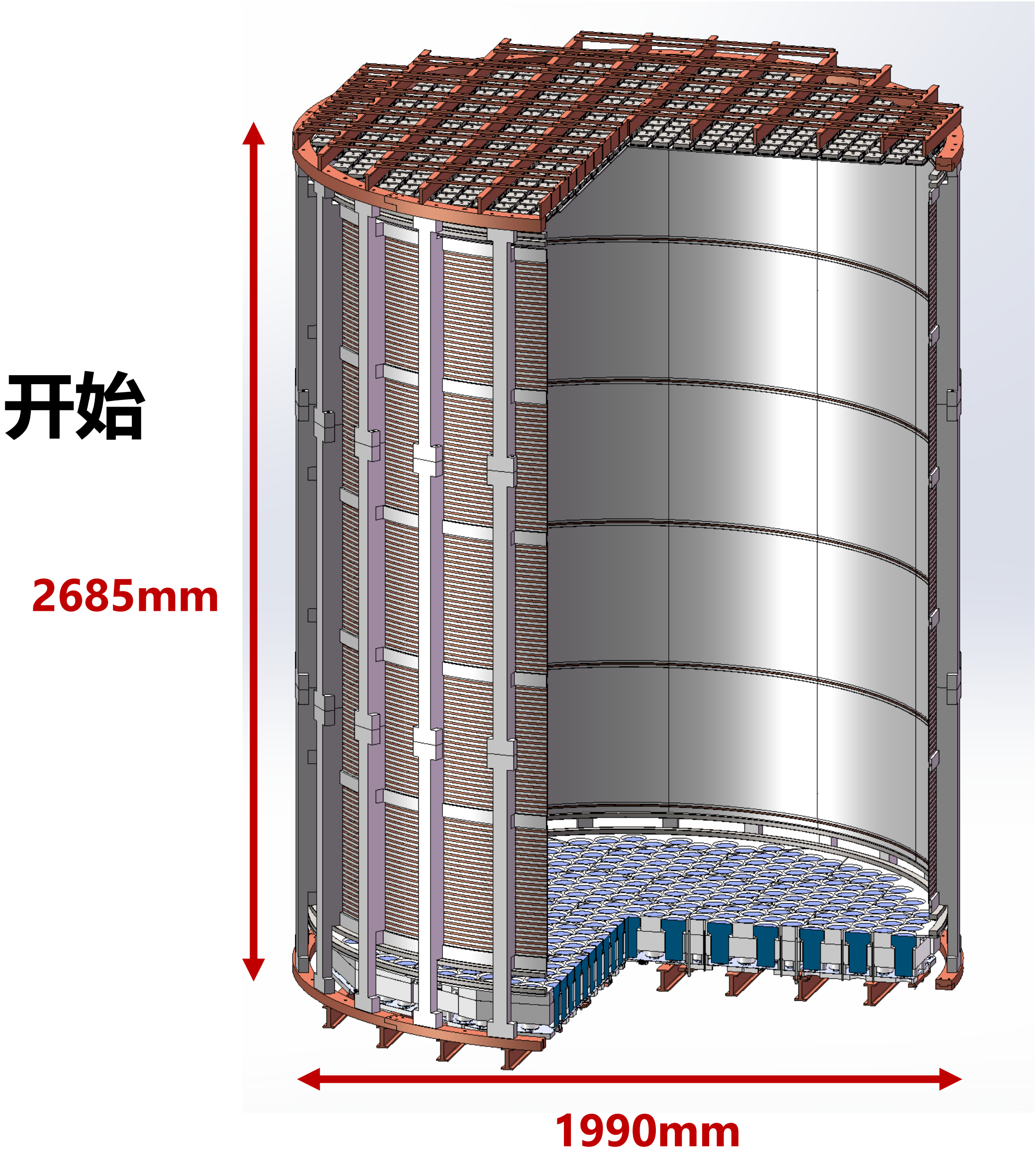


总结和展望

- 通过单独电离信号将能量阈值降低到 0.33keV，同时优化筛选条件，大幅提高了信号效率
- 对本底成分的进一步研究优化了本底估计方法，显著降低了误差
- 以 2.64σ 显著度首次观测到太阳 ^{8}B中微子相干弹性散射信号的迹象
  - 标志着暗物质探测实验达到了中微子地板的里程碑灵敏度
  - 预示了中微子探测的新途径
  - 获得PRL编辑推荐 PRL 133, 191001 (2024)
  - 入选2024年美国物理学会亮点工作

总结和展望

- **PandaX-20T**
  - 共约22吨氙，**17.32吨**灵敏体积
- **2027年完成安装，开始试运行**
- **这将标志着对 ^{8}B CEνNS 信号的探测开始进入精确测量阶段**
  - 在低能量下测量弱混合角
  - 中微子磁矩
  - 中微子非标准相互作用
  - 验证太阳模型
  - 暗物质探测中的中微子本底测量



PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

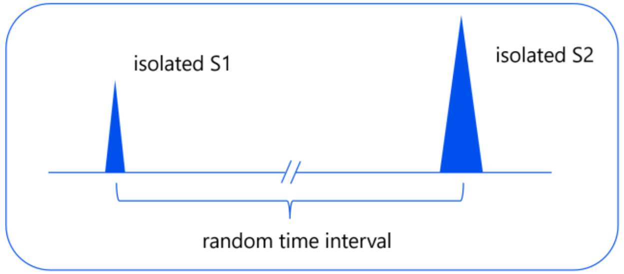
谢谢！

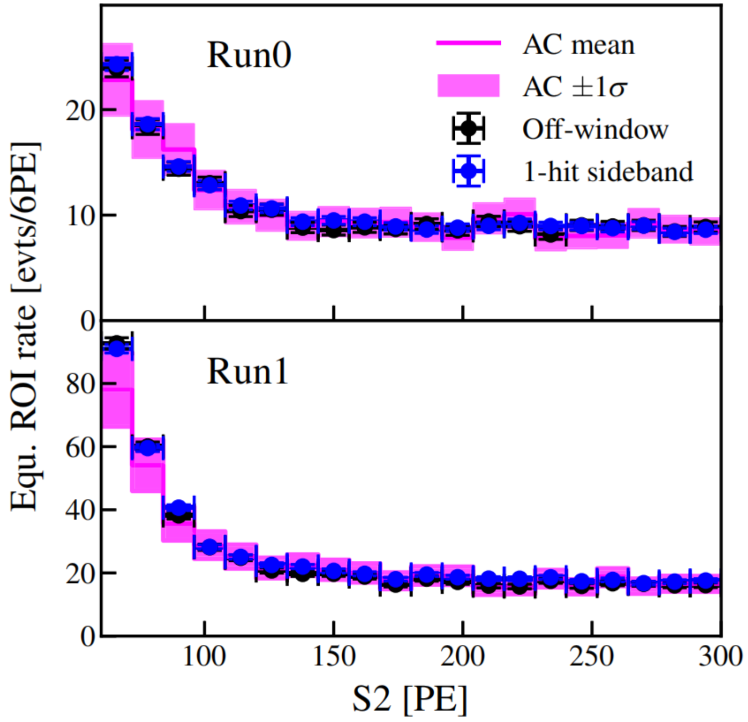
Paired channel

- Accidental coincidence(AC) background
  - Model: Select isolated S1 and S2, randomly pair them together
  - Sideband to test:
    - Off-window: the interval between isolated S1 and S2 is larger than maximum drift time window
    - 1-hit: events with S1 only containing 1 hit
- Boosted decision tree (BDT)
  - Remove most AC backgrounds based on 23 variables related to waveform shape and position reconstruction

		Run0 W/O BDT	Run0 W/ BDT	Run1 W/O BDT	Run1 W/ BDT
Off-window	Prediction	180±27	0.9±0.2	417±63	1.2±0.4
	Data	205	1	404	0
10% data	Prediction	26±6	0.12±0.04	34±7	0.06±0.02
	Data	18	0	29	0
1-hit side-band	Prediction	17095±2564	14±4	27567±4135	15±5
	Data	17374	9	29359	17

- AC: Isolated S1 and S2 accidentally paired



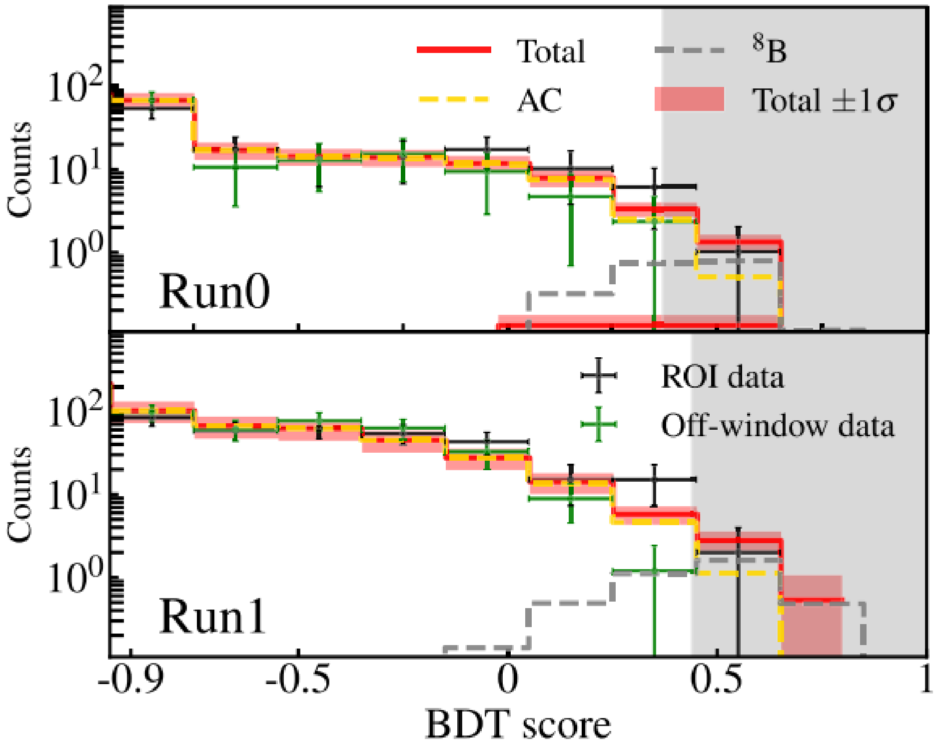


Paired channel

Candidate events

- Total exposure: 1.20 tonne·year
- Some downward fluctuation

paired ROI	Run0 2-hit	Run0 3-hit	Run1 2-hit	Run1 3-hit
Surface	0.06±0.01	0.06±0.01	0.01±0.01	0.02±0.02
ER	0.01±0.00	0.00±0.00	0.01±0.01	0.01±0.01
Neutron	0.02±0.01	0.02±0.01	0.03±0.01	0.03±0.01
AC	1.08±0.28	0.07±0.02	1.15±0.35	0.24±0.08
Total bkg.	1.16±0.28	0.15±0.02	1.21±0.35	0.30±0.08
^{8}B CEνNS	1.00±0.24	0.24±0.09	1.76±0.50	0.40±0.18
Observed	1	0	2	0

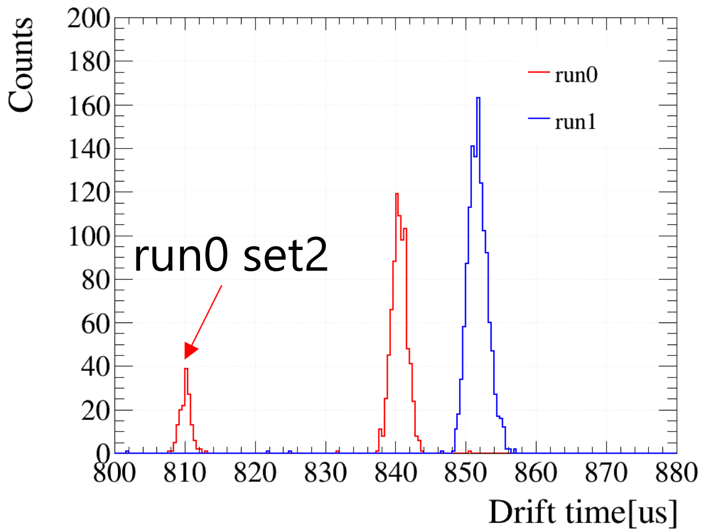


Cathode estimation

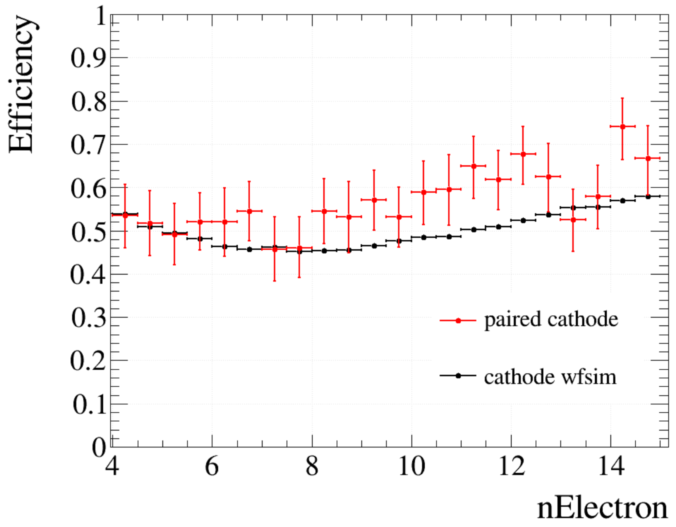
Cathode sample

Efficiency: $\dfrac{selection\ cut}{selection\ cut\ with\ loose\ width\ cut}$

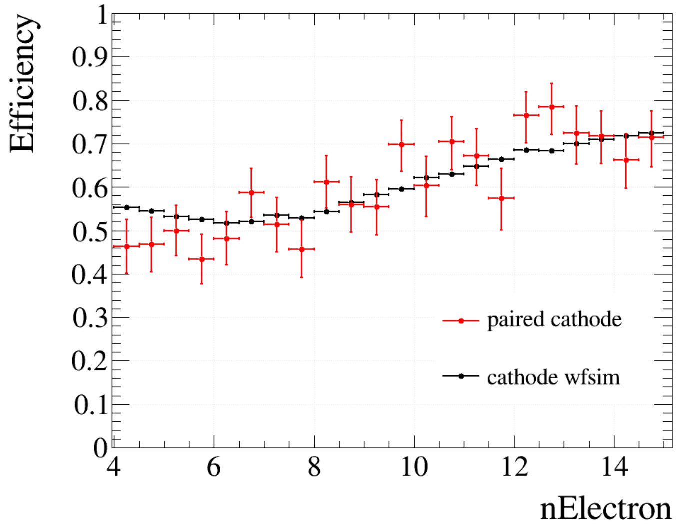
Cathode drift time distribution



Run0 efficiency



Run1 efficiency



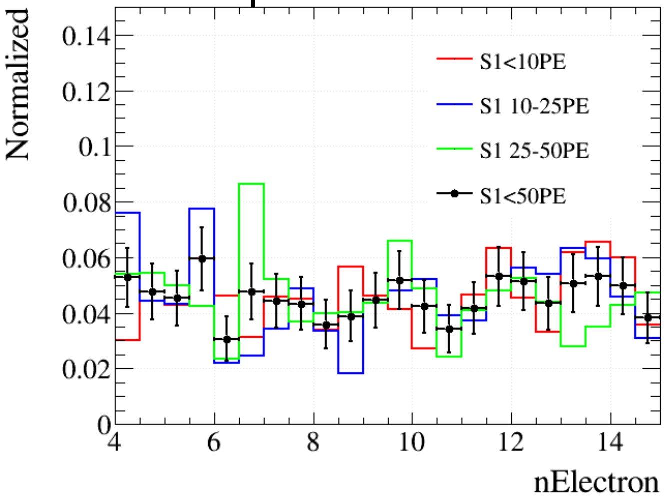
- Use paired cathode events as background sample
- Simulate events at the bottom of detector, these samples are consistent with paired cathode events
- To reduce spectrum statistical fluctuation, use the spectrum under a loose width cut, and then apply corresponding efficiency from waveform simulation to it

Cathode estimation

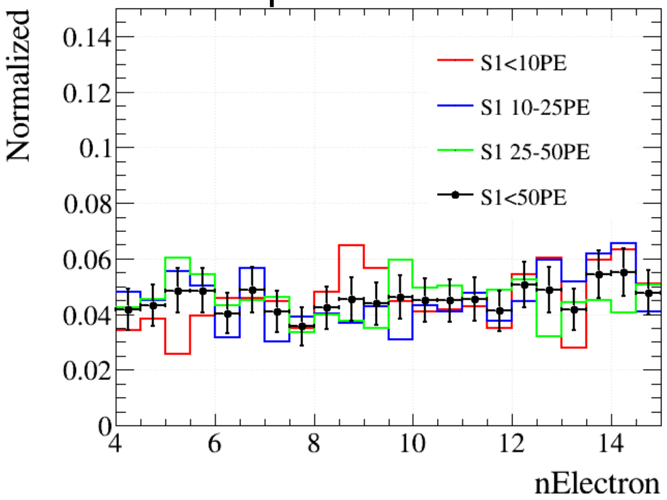
$$nominal = \frac{num\_sample\_in\_roi}{num\_sample\_in\_cr} \cdot num\_data\_in\_cr$$

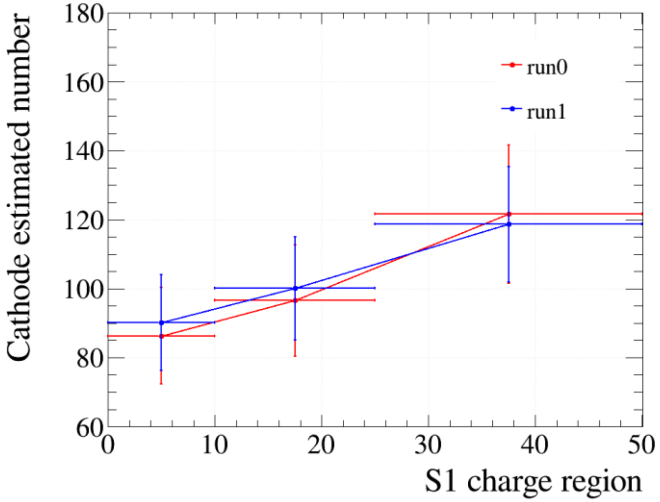
roi : 4-8nE cr : 11-15nE

Run0 spectrum



Run1 spectrum





- Spectrum with different S1 range give systematic error
- Spectrum with total statistic give the nominal value and statistical error
- Difference of results given by efficiency from data and simulation give efficiency error

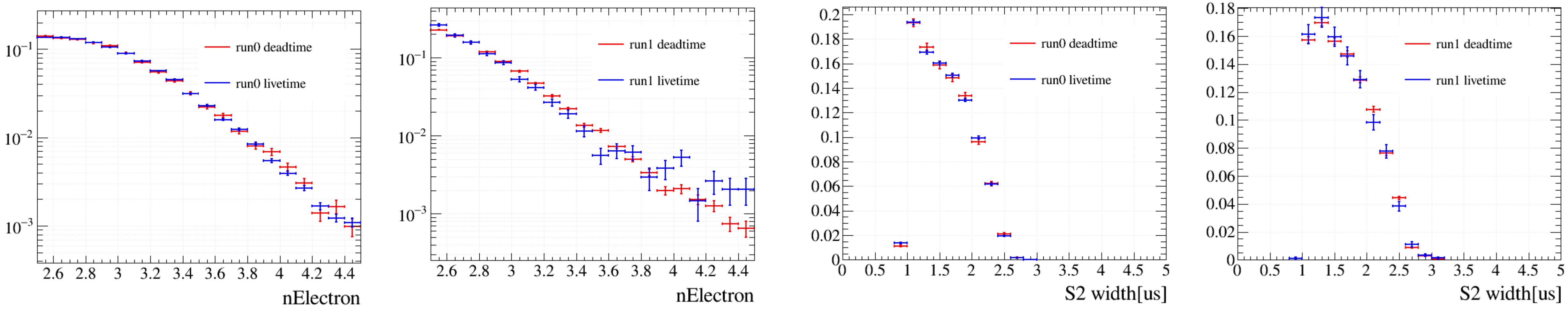
Estimation	run0	Run1
Result	100±24	104±21
Statistical error	12.4%	11.4%
Systematic error	18.1%	13.9%
Efficiency error	10.6%	9.4%

MD Estimation

MD sample

Charge distribution

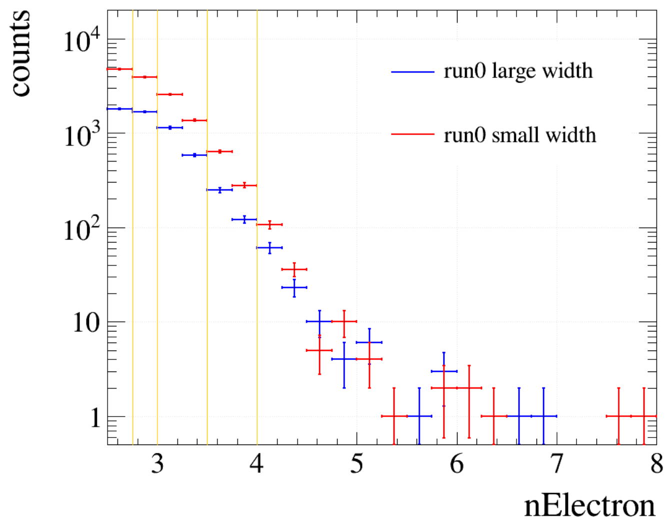
Width distribution

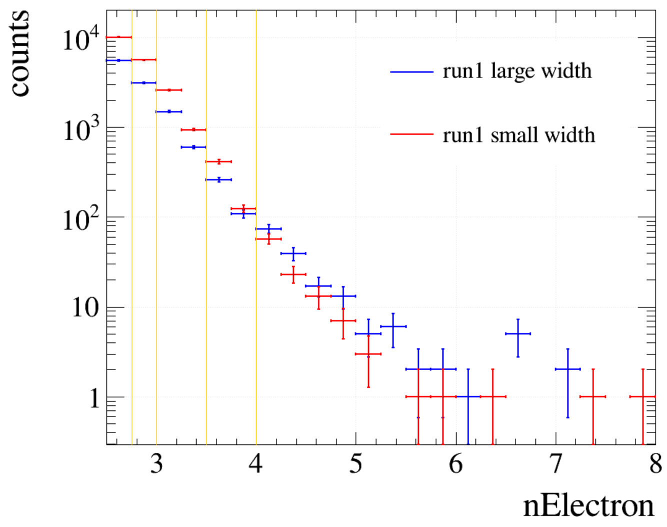


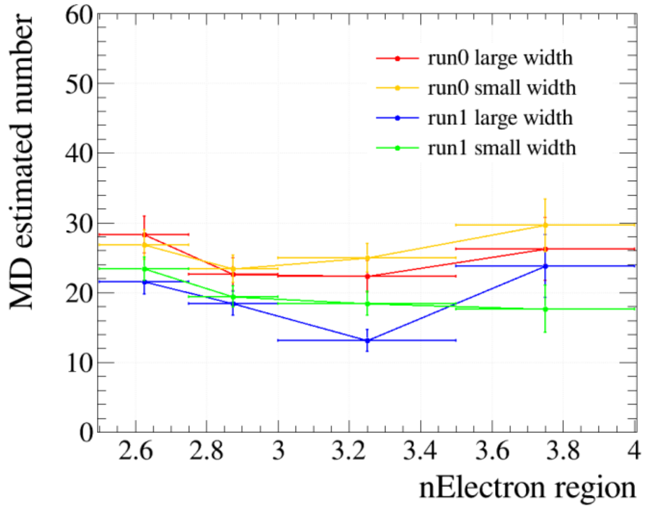
- We find that MD rate is related with single electron(SE) rate, so we get MD samples from deadtime region where SE rate is very high
- The sample in deadtime is consistent with the MD events in livetime
- MD events in livetime are from high US2(2.5-3nE) rate runs

MD Estimation

$$nominal = \frac{num\_sample\_in\_roi}{num\_sample\_in\_cr} \cdot num\_data\_in\_cr \qquad roi: \text{4-8nE} \; cr: \text{2.5-4nE}$$





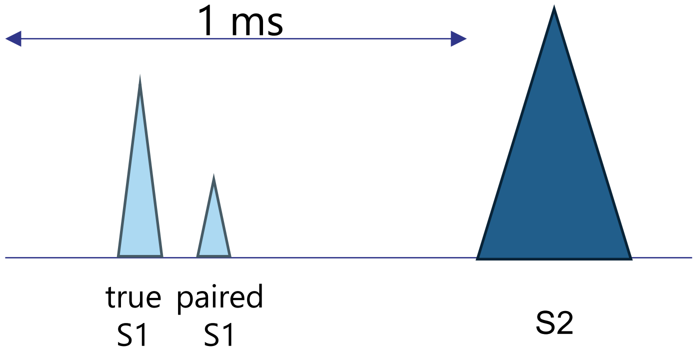


- Different small control regions divided by S2 charge and width give systematic error
- Spectrum with total statistic give the nominal value and statistical error

Estimation	Run0	Run1
Result	25±3	20±4
Statistical error	6.5%	6.4%
Systematic error	10.6%	16.9%

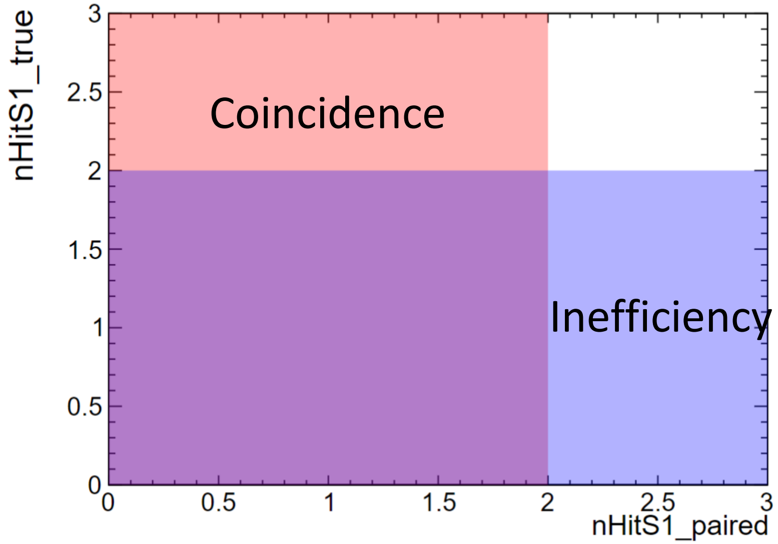
Signal inefficiency

Run0
- Inefficiency: SS1 rate × window
  61.08 [Hz] × 1 [ms] = 6.11%
- Coincidence: tag ineff (wf-simu) × (SS1 rate × window)
  18.23% × 362.60 [Hz] × 1 [ms] = 6.61%



Run1:
- Inefficiency: 72.86 [Hz] × 1 [ms] = 7.29%
- Coincidence: 20.01% × 389.07 [Hz] × 1 [ms] = 7.79%

Case: mispair




```
SS1 Cuts:
TCut cut = "iS1_max!=-
1&&qS1_max<50&&qS2_max<50 &&
nHitS1_max>1 && nHitS1_max>=2 "; //
inefficiency SS1 cut

TCut cut = "iS1_max!=-
1&&qS1_max<50&&qS2_max<50 &&
nHitS1_max<2 "; // coincidence SS1 cut
```