

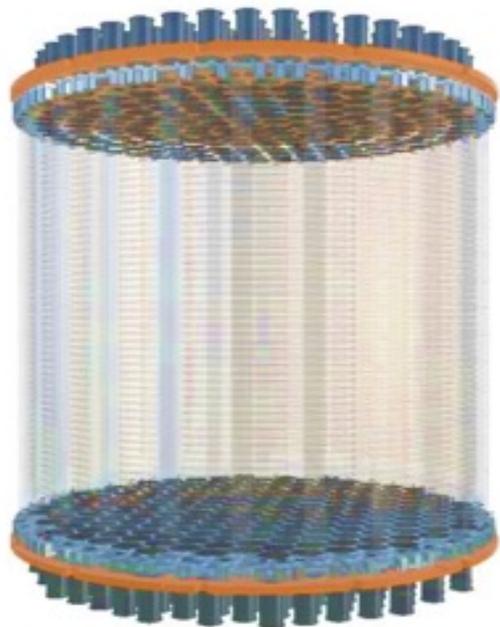
PandaX-基于氙时间投影室技术的 暗物质和中微子实验平台

李涛

代表PandaX合作组

2025年8月21日

第十三届全国先进气体探测器研讨会



PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC



上海交通大学
SHANGHAI JIAO TONG UNIVERSITY

taoli@sjtu.edu.cn

PandaX - Particle and Astrophysical Xenon



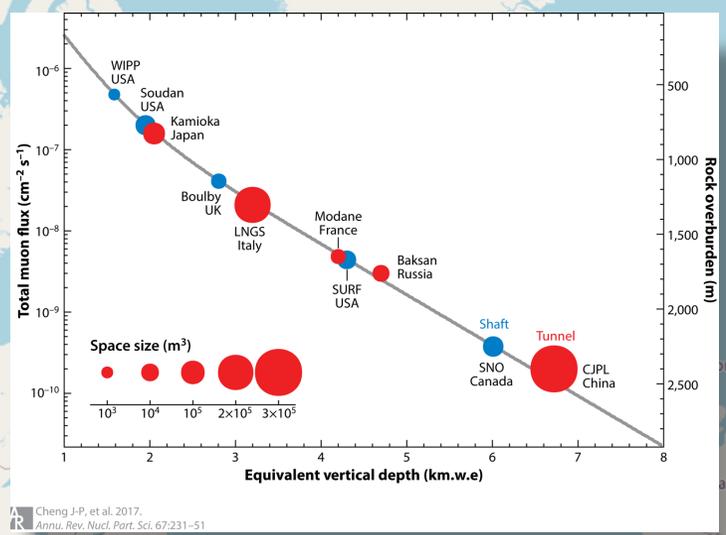
16家单位的100余名合作者

PandaX @ CJPL

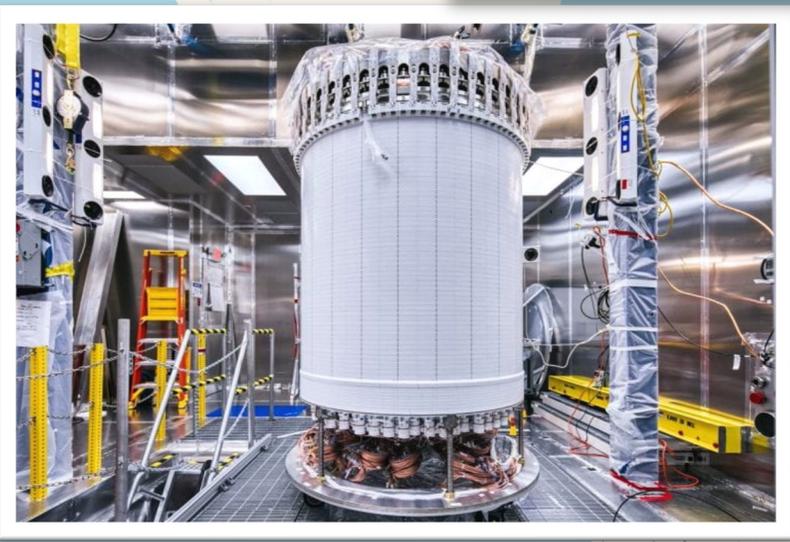
中国锦屏地下实验室



最灵敏的三大深地液氙暗物质实验



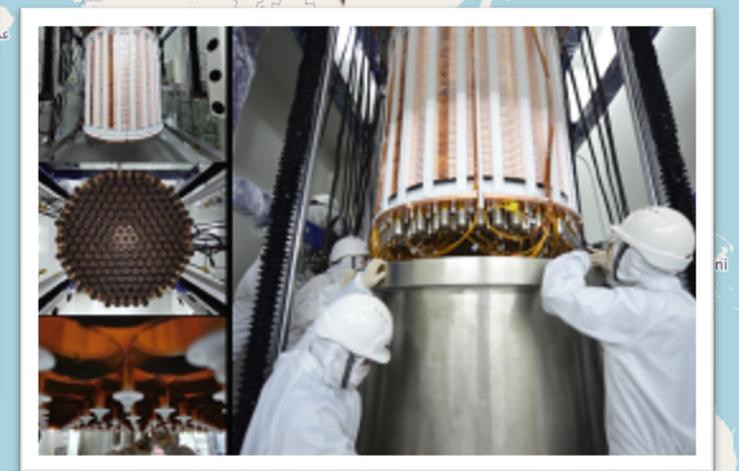
CJPL拥有世界最低的宇宙缪子通量，为搜寻暗物质、中微子的稀有信号提供了绝佳的实验环境。



Sanford Lab, LZ, 7 ton



LNGS, XENONnT, 6.5 ton



CJPL, PandaX-4T, 3.7 ton

PandaX实验发展历程

➤ 气液两相时间投影室技术

➤ 灵敏体积不断升高;

➤ 放射性本底水平不断降低;

PandaX Start



2009

PandaX-I
120 kg



2010-2014

PandaX-II
580 kg



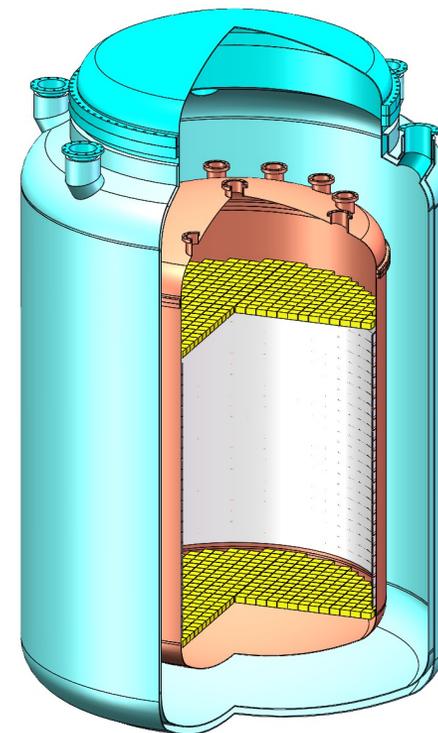
2015-2019

PandaX-4T
(3.7 tonne)



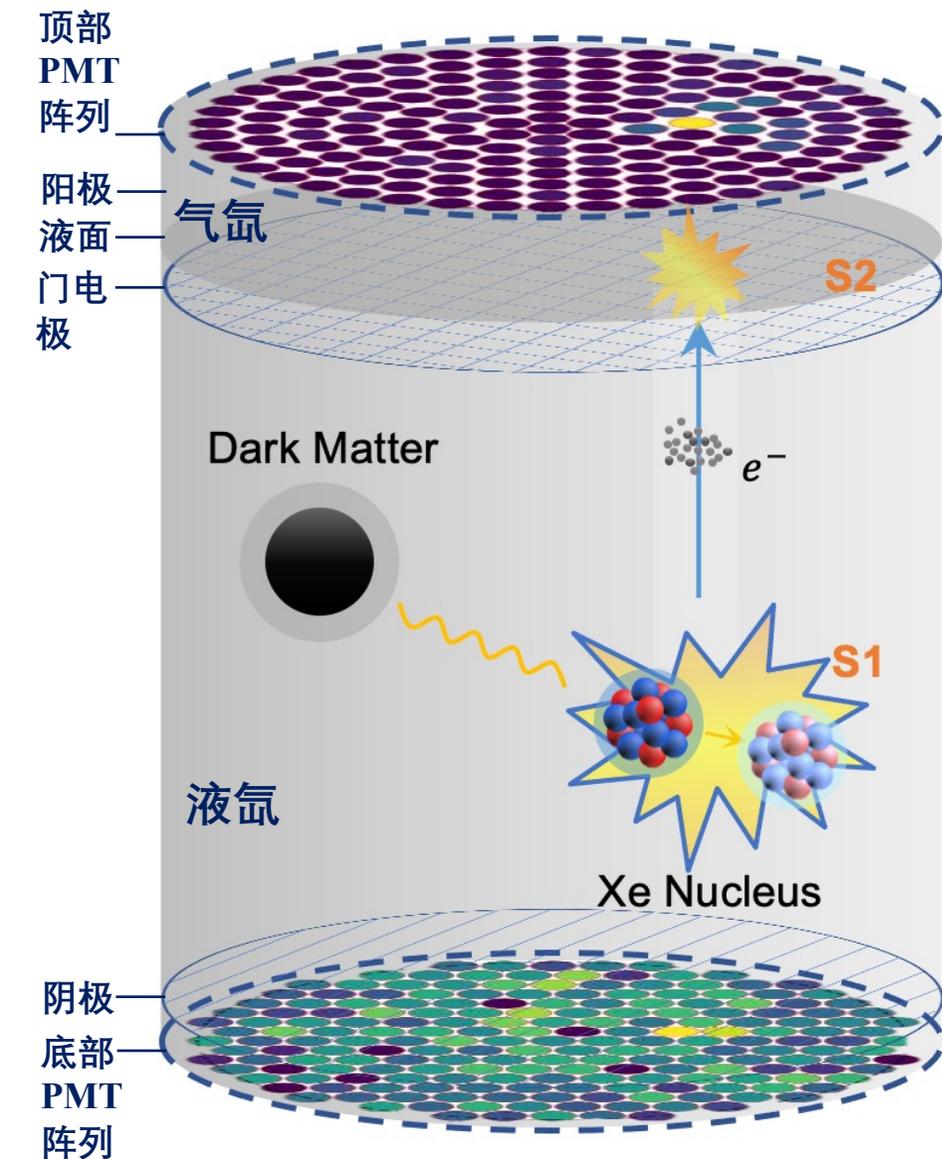
2021-

PandaX-xT



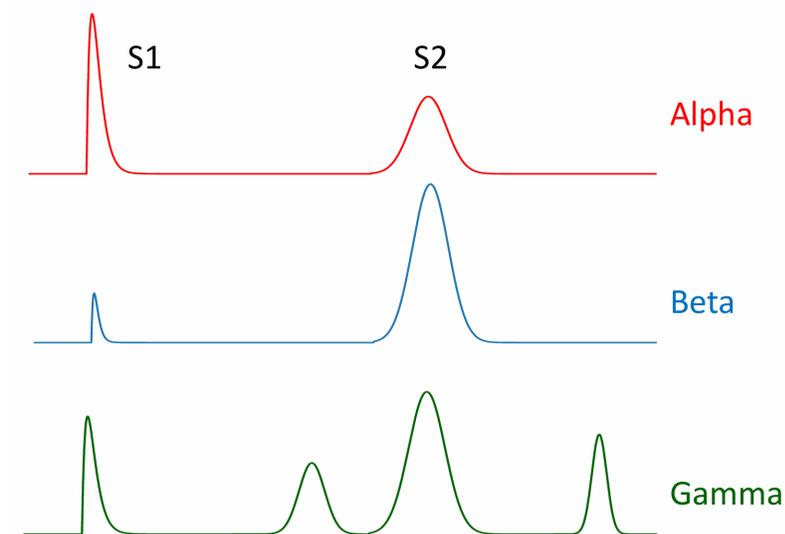
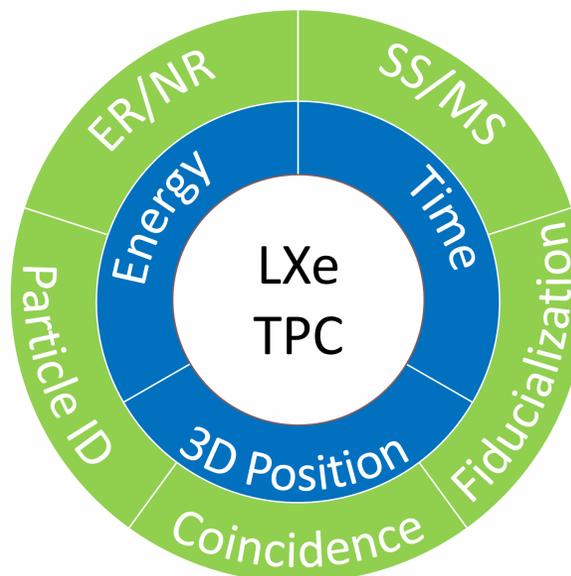
2027-

PandaX-4T探测器

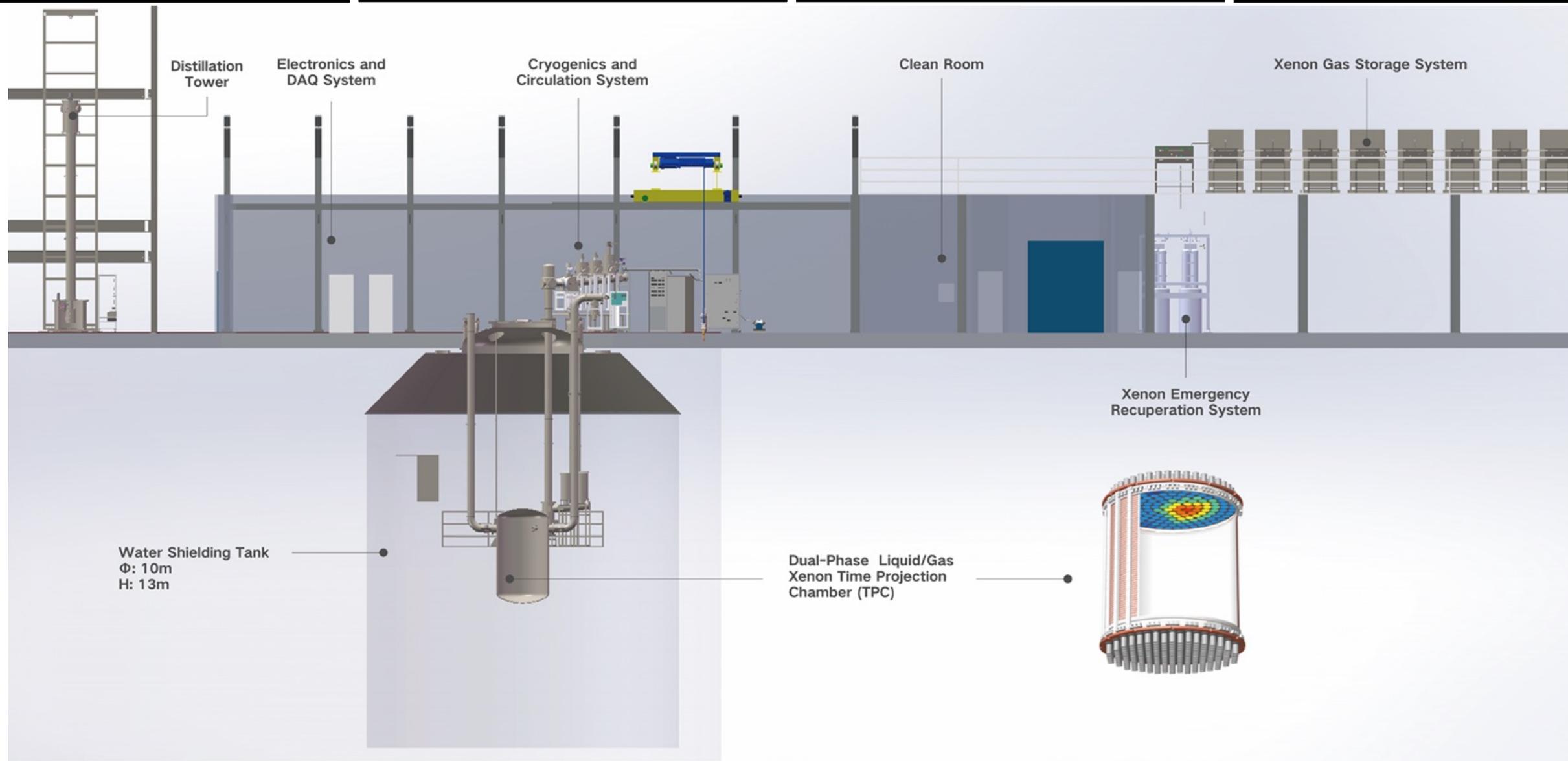


► 双相时间投影室技术:

- 大体量 (3.7吨)、低本底
- 闪烁光信号(S1) 和电离信号(S2)
- 事件3D位置、时间、能量测量: keV-MeV
- 电子/核子反冲鉴别, 粒子鉴别, 符合测量



PandaX-4T整体布局



PandaX-4T子系统



精馏塔



电子学系统



制冷系统



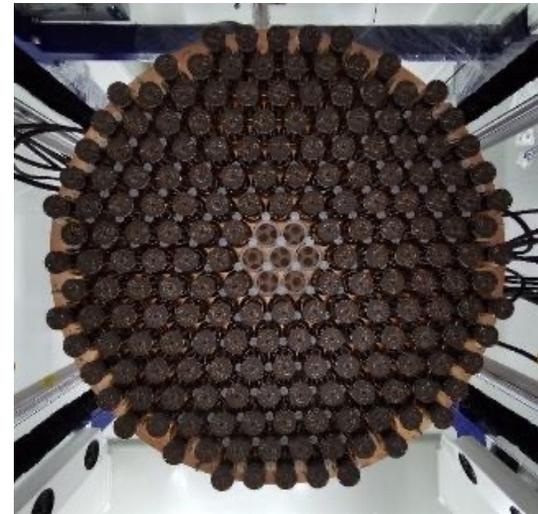
气体存储系统



水屏蔽



TPC



PMT阵列

PandaX-4T光电探测阵列

➤ 关键技术要求:

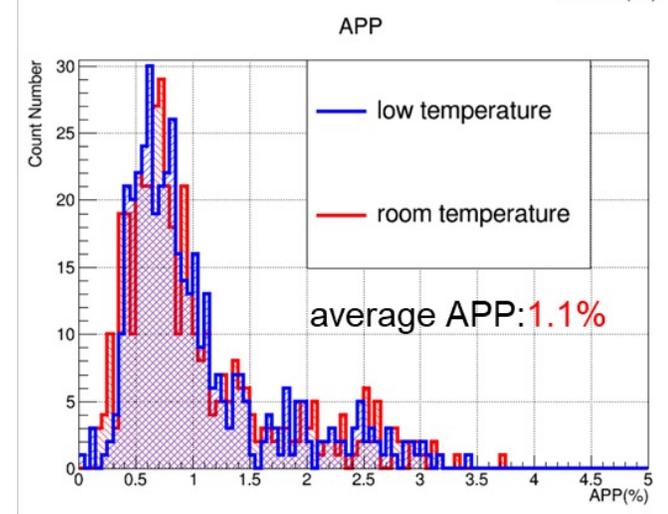
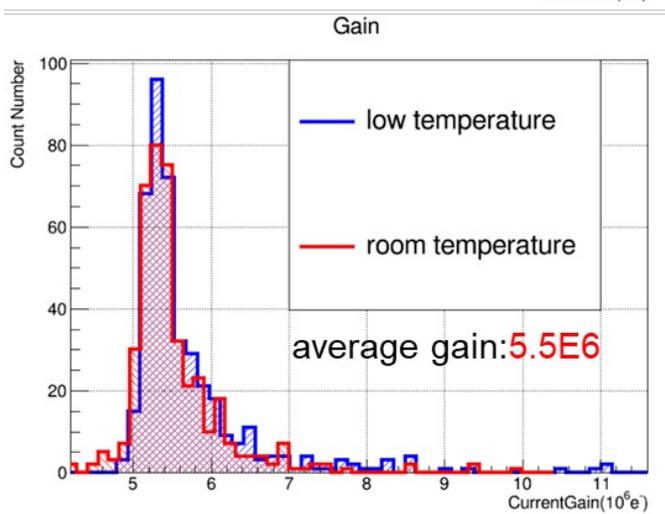
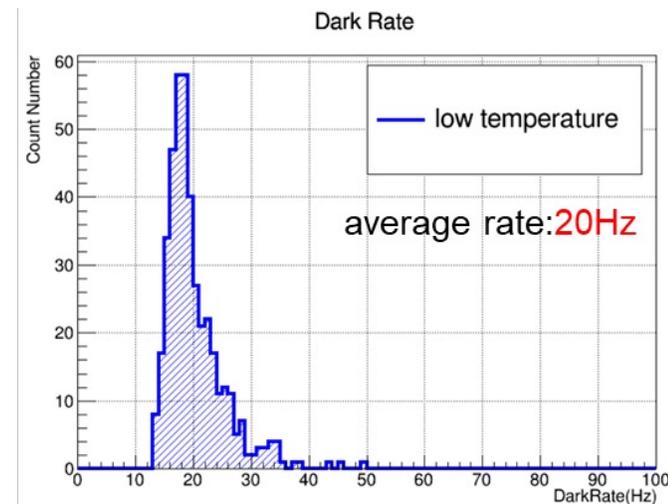
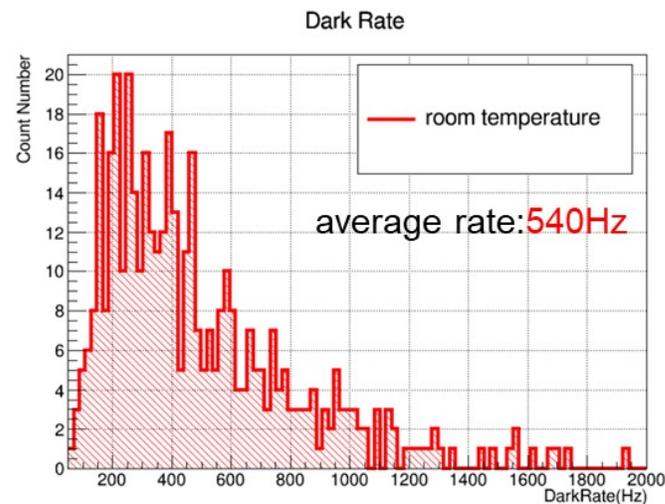
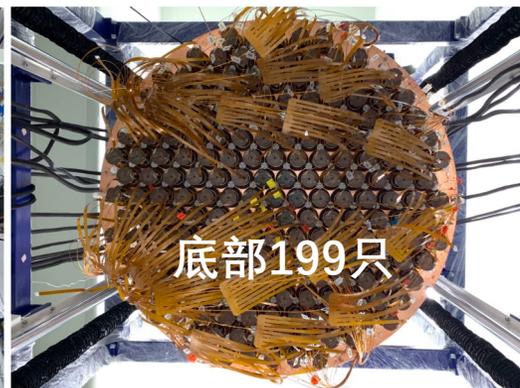
高量子效率: $\sim 34\% @ 178\text{nm}$;

高增益: $\sim 5 \times 10^6 @ 1500\text{V}$;

低后脉冲 (APP) 概率;

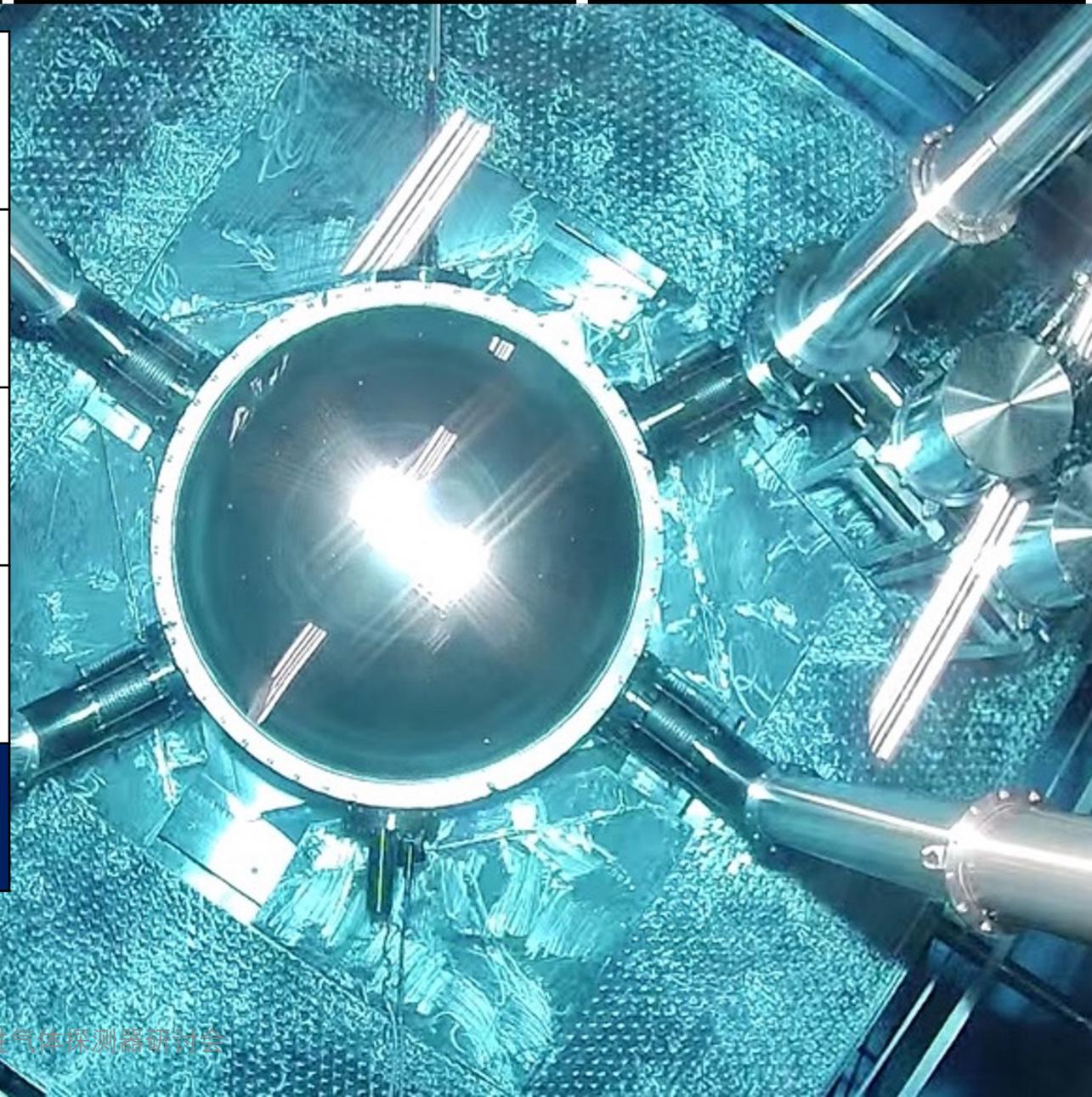
低暗技术率;

低放射性本底;



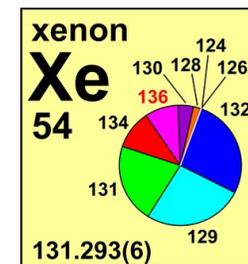
PandaX-4T物理运行

2020/11 — 2021/04	Commissioning (Run0) 95 days
2021/07 — 2021/10	Tritium removal xenon distillation, gas flushing, etc
2021/11 — 2022/05	Physics run (Run1) 164 days
2022/09 — 2023/12	CJPL B2 hall construction xenon recuperation, detector upgrade
Current Status	Physics run (Run2)



PandaX-4T科学目标

- 能区横跨sub keV 至 MeV;
- 从暗物质到双贝塔衰变;



^{136}Xe (~9%)
 ^{134}Xe (~10%)
 ^{124}Xe (~0.1%)

$2\nu\beta\beta/0\nu\beta\beta$

$2\nu\beta\beta/0\nu\beta\beta$

$2\nu\text{DEC}$

WIMPs, ALPs, DPs, boosted dark matters...

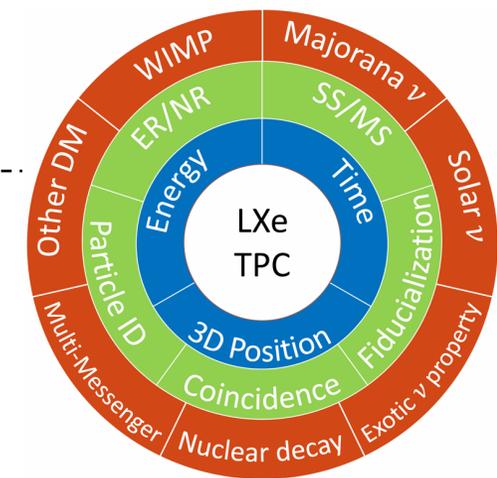
Solar Axion

Solar pp ν

➔ MeV能区

keV能区 ←

Natural Xenon



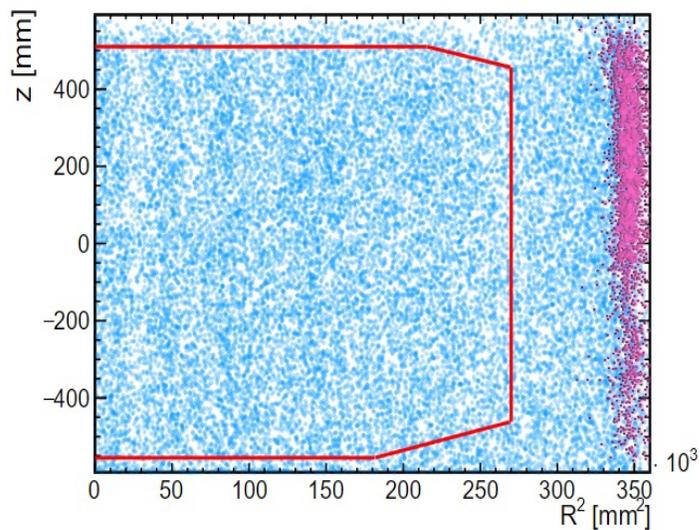
WIMP直接探测

➤ Run0 + Run1: 1.54吨年的曝光量

➤ 对自旋无关暗物质的限制:

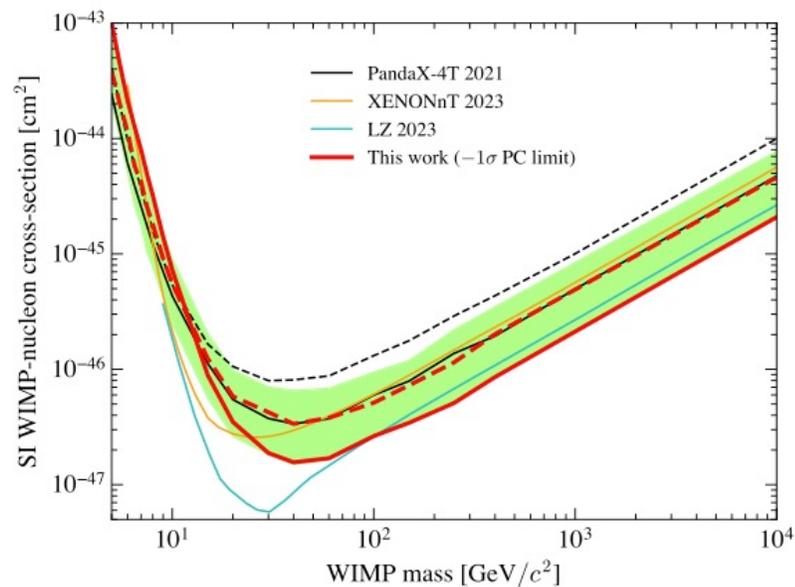
排除线最低可至 $1.6 \times 10^{-47} \text{cm}^2$;

大于100 GeV/c^2 的暗物质质量区间取得了世界最好结果。

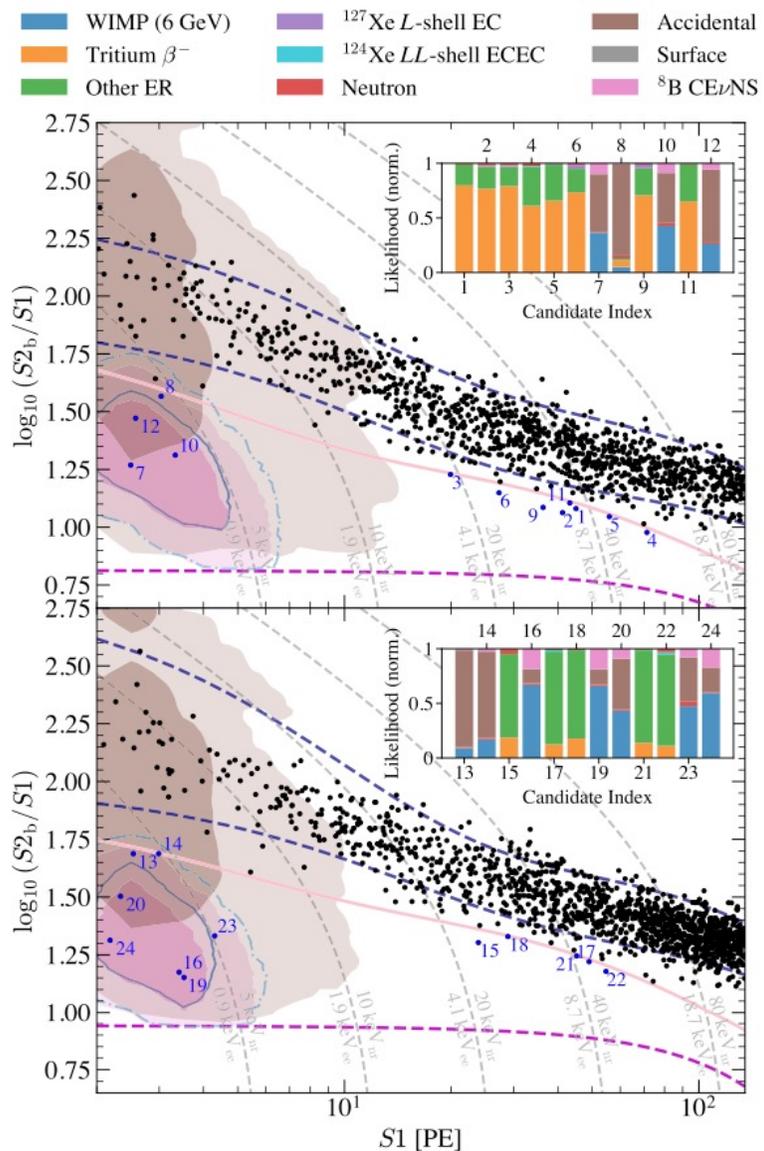


PRL 134, 011805 (2025)

2025/8/21



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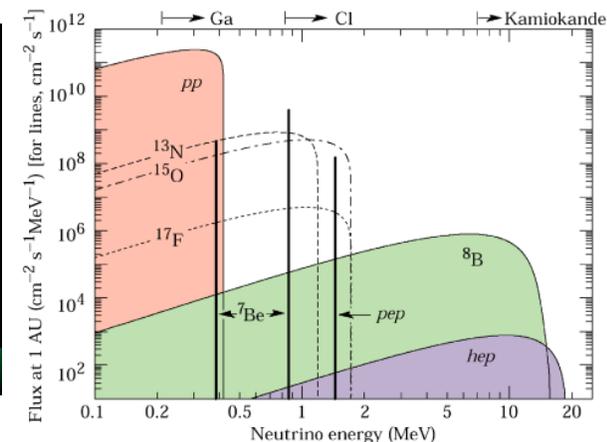
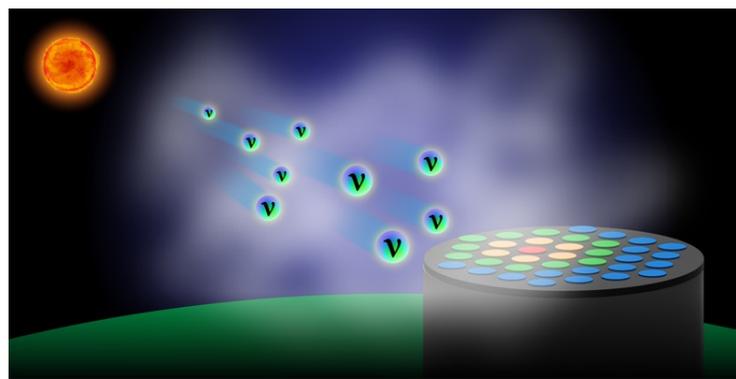
11

太阳中微子探测

➤ 探测到太阳硼-8中微子信号:

显著度达到 2.64σ ;

中微子通量为 $(8.4 \pm 3.1) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$;



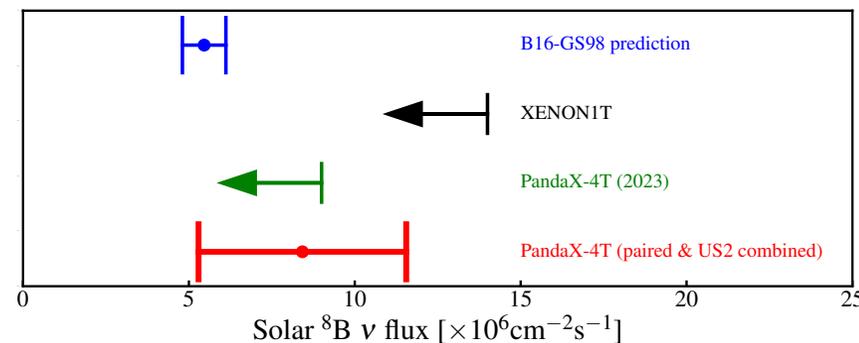
Best-fit ^8B yield:

Paired: 3.5 ± 1.3 evts

S2only: 75 ± 28 evts



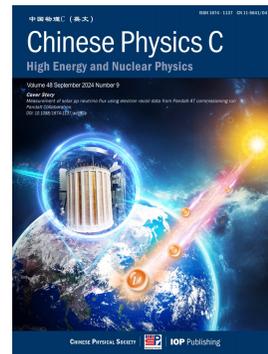
PRL 133, 191001 (2024)



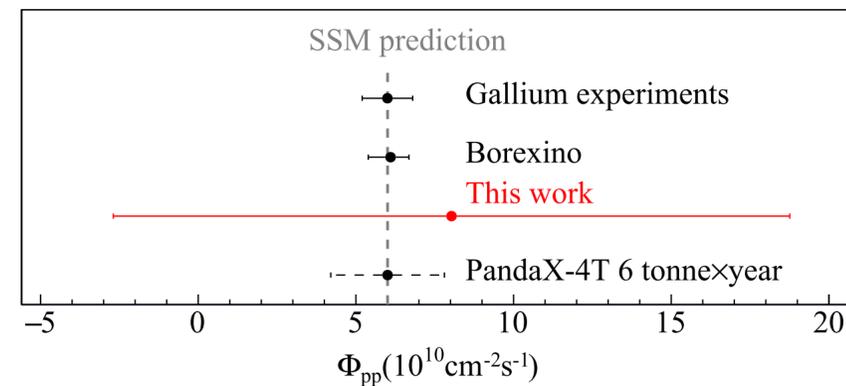
➤ pp中微子通量测量:

pp solar neutrino flux:

$(8.0 \pm 3.9(\text{stat}) \pm 10.0(\text{syst})) \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$

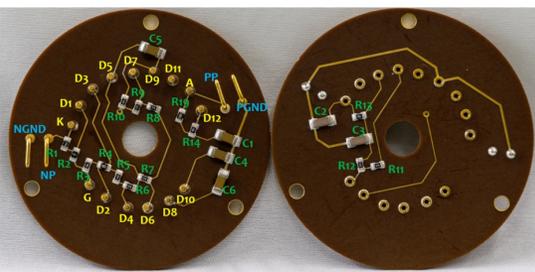
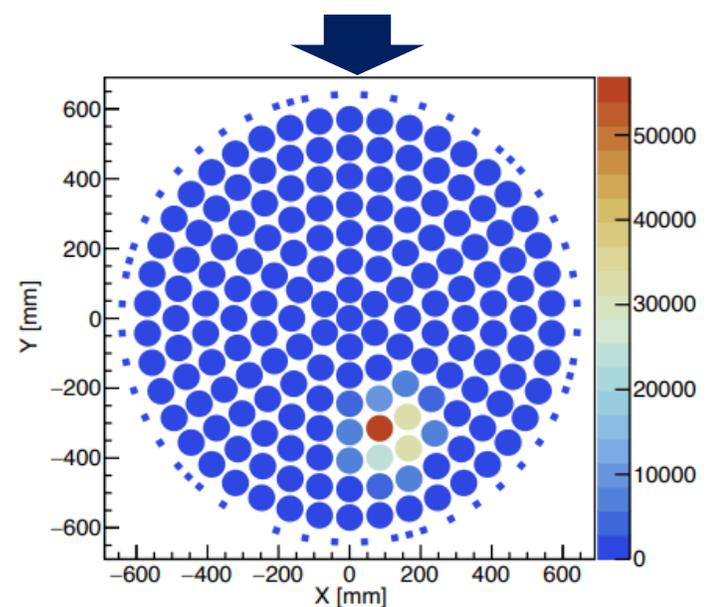
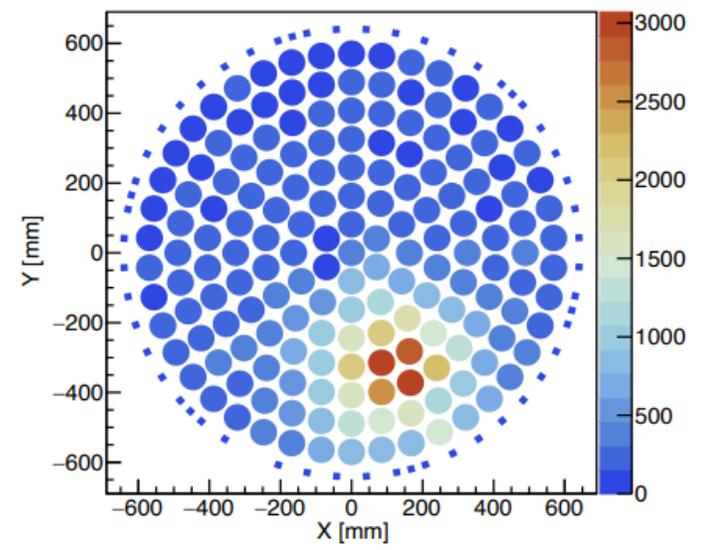
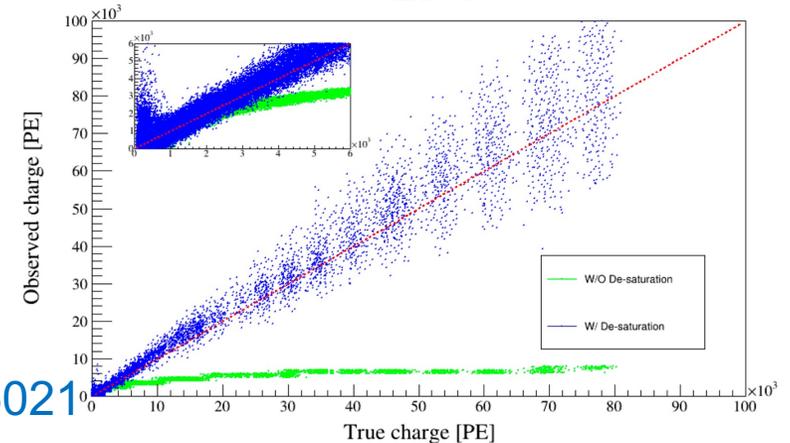
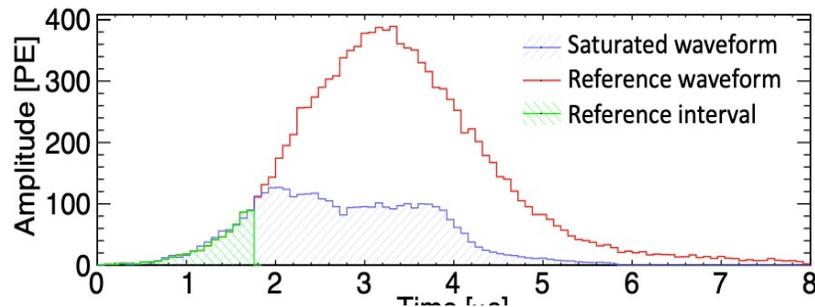
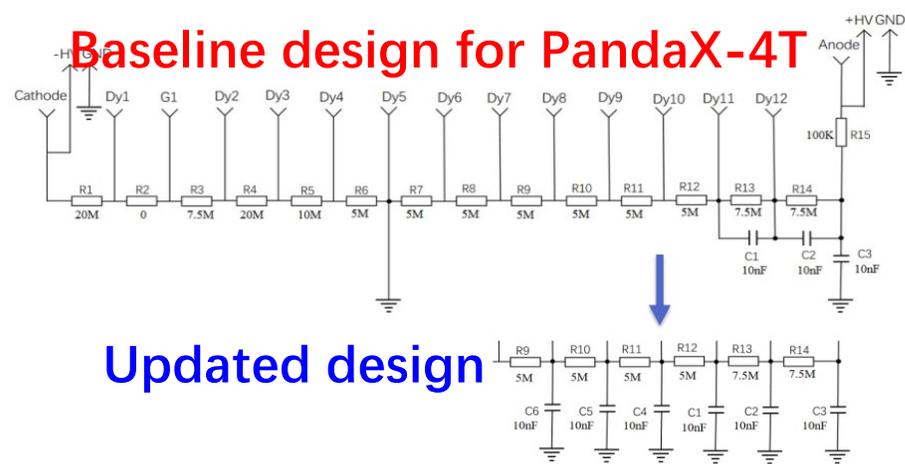


CPC 48, 091001 (2024)



高能信号重建的挑战

- 原Base设计方案主要用于低能暗物质直接探测，电容较少；
百keV以上的高能信号存在饱和和抑制效应；
- 分析开发波形匹配方法，还原信号饱和前光电探测梯度信息
- keV-MeV能量重建线性度**1%**，能量分辨率**1.9% @ 2.5 MeV**；



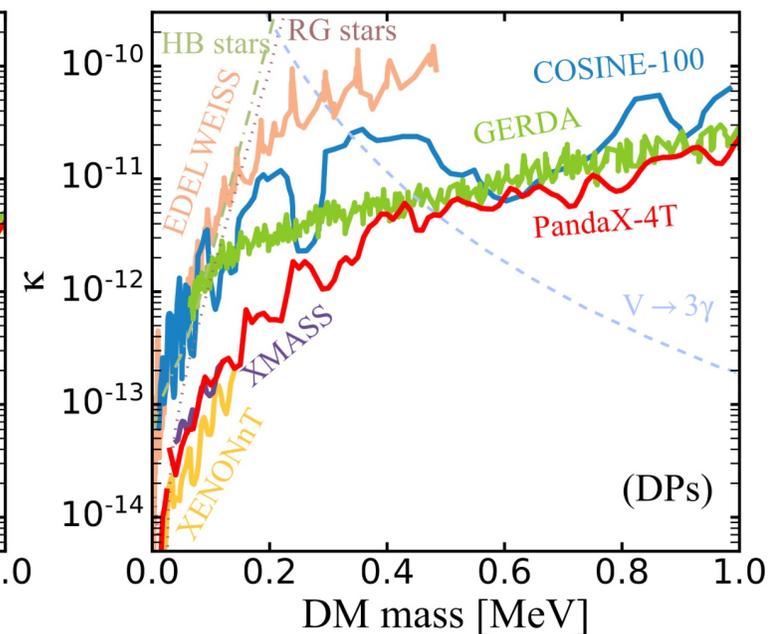
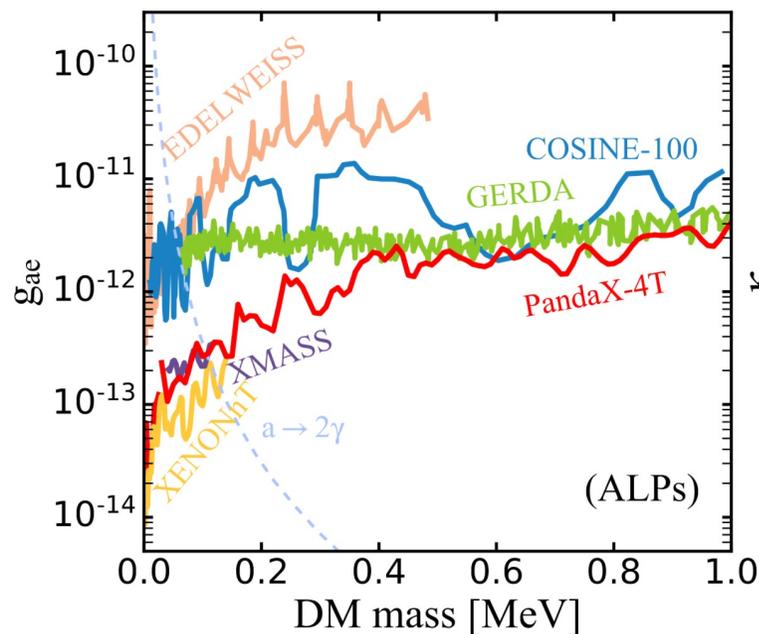
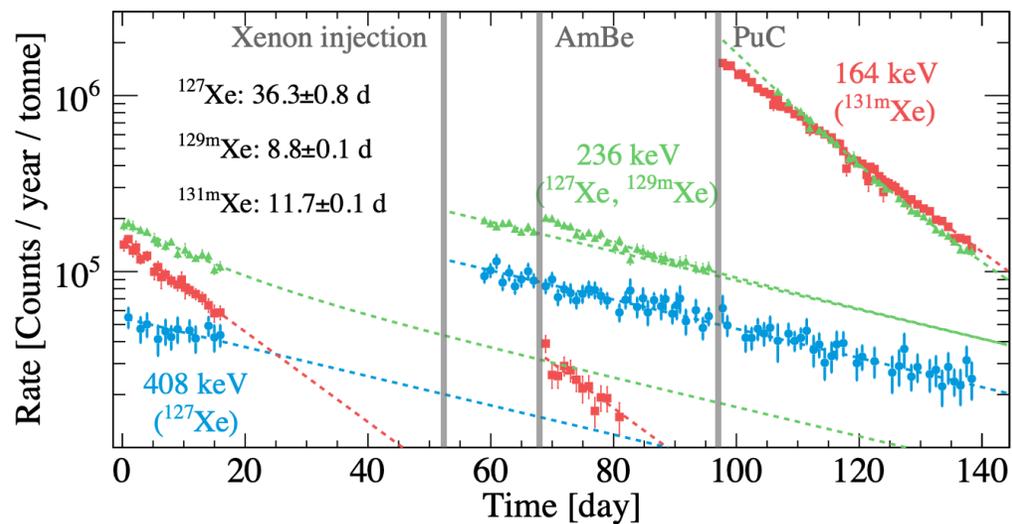
2024 JINST 19 P05021

类轴子/暗光子暗物质

- 暗物质质量 $[150 \text{ keV}/c^2, 1 \text{ MeV}/c^2]$ 内取得了世界最强限制；
- 对短寿命的氙同位素 (^{127}Xe , $^{129\text{m}}\text{Xe}$, $^{131\text{m}}\text{Xe}$) 构建时间演化模型。

$$R_{\text{ALP}} = \frac{1.47 \times 10^{19}}{A} g_{ae}^2 \cdot m_a \sigma_{pe} [\text{kg}^{-1} \text{d}^{-1}],$$

$$R_{\text{DP}} = \frac{4.7 \times 10^{23}}{A} \frac{(e\kappa)^2}{4\pi\alpha} \frac{\sigma_{pe}}{m_d} [\text{kg}^{-1} \text{d}^{-1}],$$



PRL 134, 071004 (2025)

2025/8/21

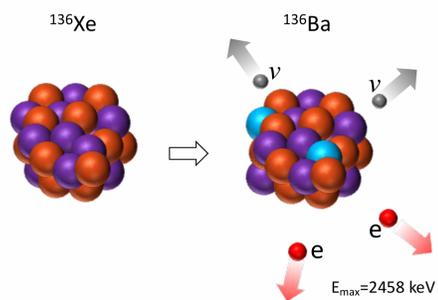
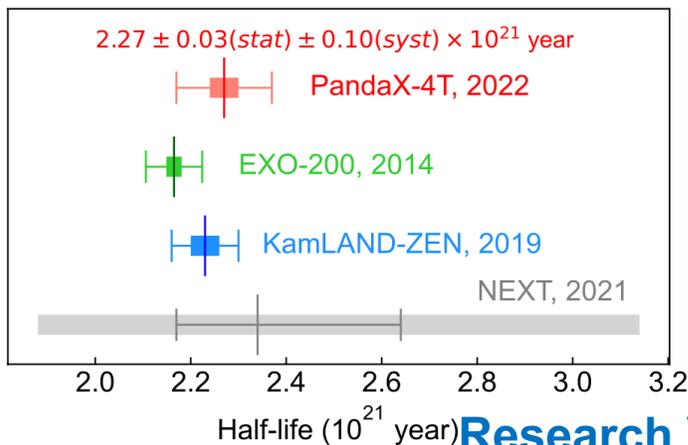
从暗物质到双贝塔衰变

➤ $^{136}\text{Xe } 2\nu\beta\beta$

半衰期测量 (Run0) :
 $2.27 \pm 0.03(\text{stat.}) \pm 0.10(\text{syst.}) \times 10^{21} \text{ yr}$

首个基于自然氙实验的测量结果;

当前最宽的衰变能谱: 440 keV-2800 keV;

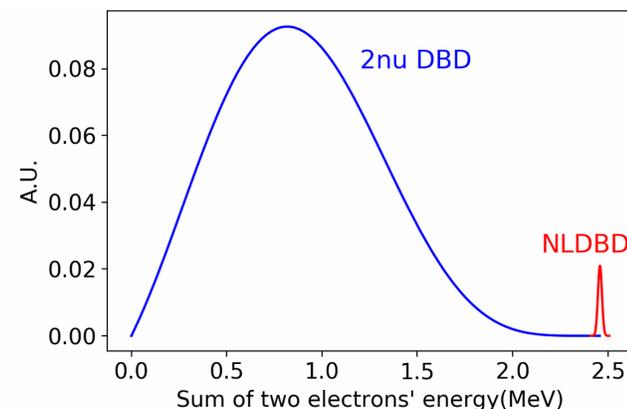
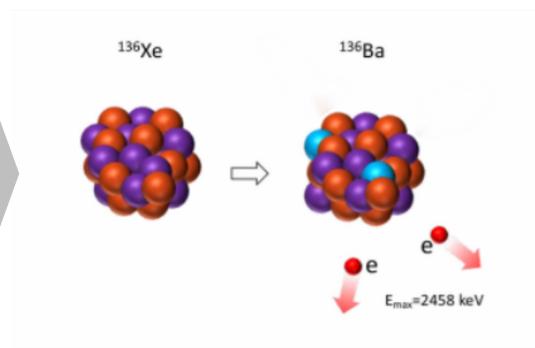


Research Vol 2022, 9798721 (2022)

➤ $^{136}\text{Xe } 0\nu\beta\beta$

半衰期限制 (Run0+Run1) :
 $T_{1/2}^{0\nu\beta\beta} > 2.1 \times 10^{24} \text{ yr (90\% CL)}$

自然氙实验最灵敏的半衰期限制;



Sci.Bull. 70 (2025) 1779-1785

➤ ^{136}Xe 奇异衰变道 $2\nu\beta\beta-0_1^+$

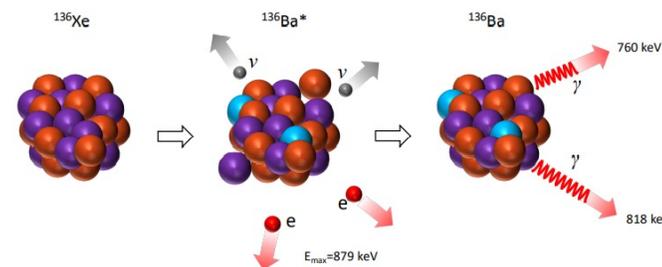
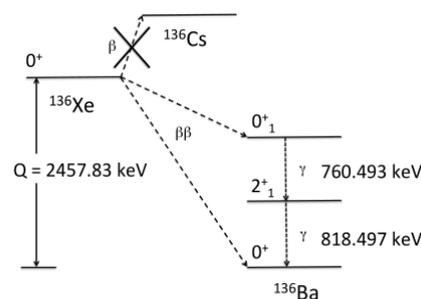
高显著度的信号本底鉴别;

实验对 0_1^+ 激发态的限制已

在被发现的边缘;

2025/8/21

半衰期限制 (Run0) :
 $T_{1/2}^{2\nu\beta\beta-0_1^+} > 7.5 \times 10^{22} \text{ yr}$

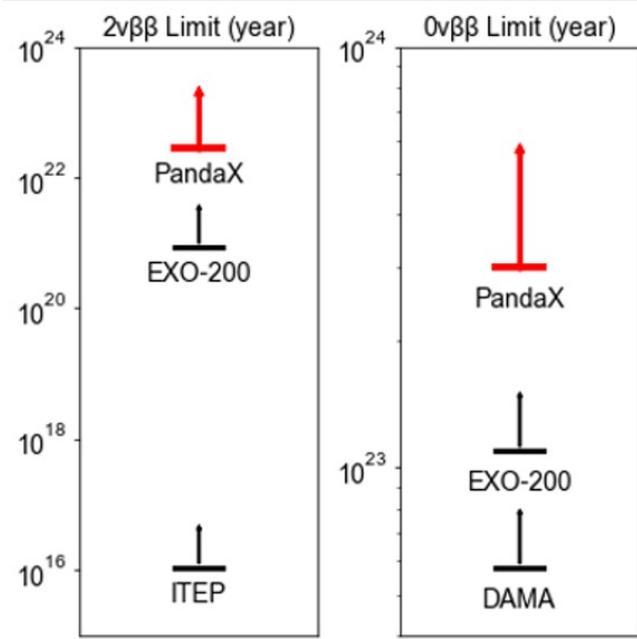
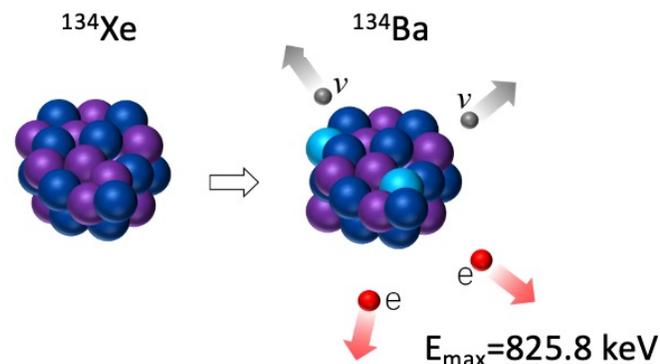


JHEP 05 (2025) 089

从暗物质到双贝塔衰变

➤ ^{134}Xe $2\nu\beta\beta$ / $0\nu\beta\beta$

下一个最有可能被发现的
双贝塔衰变核素；
世界最灵敏的半衰期结果；



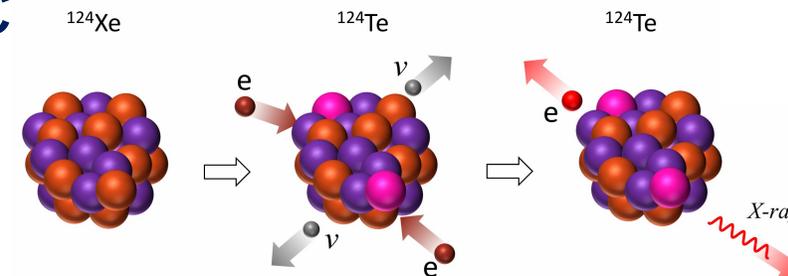
半衰期限制 (only Run0):

$$T_{1/2}^{2\nu\beta\beta} > 2.8 \times 10^{22} \text{ yr}$$

$$T_{1/2}^{0\nu\beta\beta} > 3.0 \times 10^{23} \text{ yr}$$

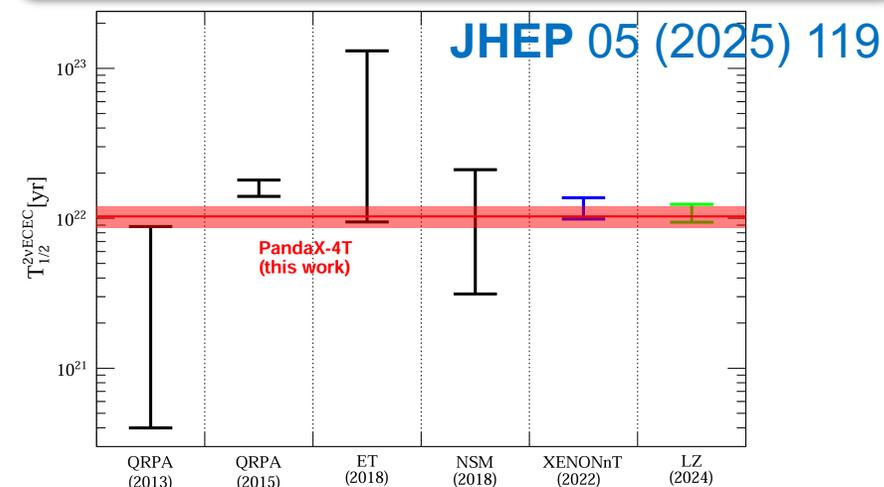
PRL 132, 152402 (2024)

➤ ^{124}Xe $2\nu\text{ECEC}$



目前测量的最长半衰期；
能量+时间演化的信号本底模型；

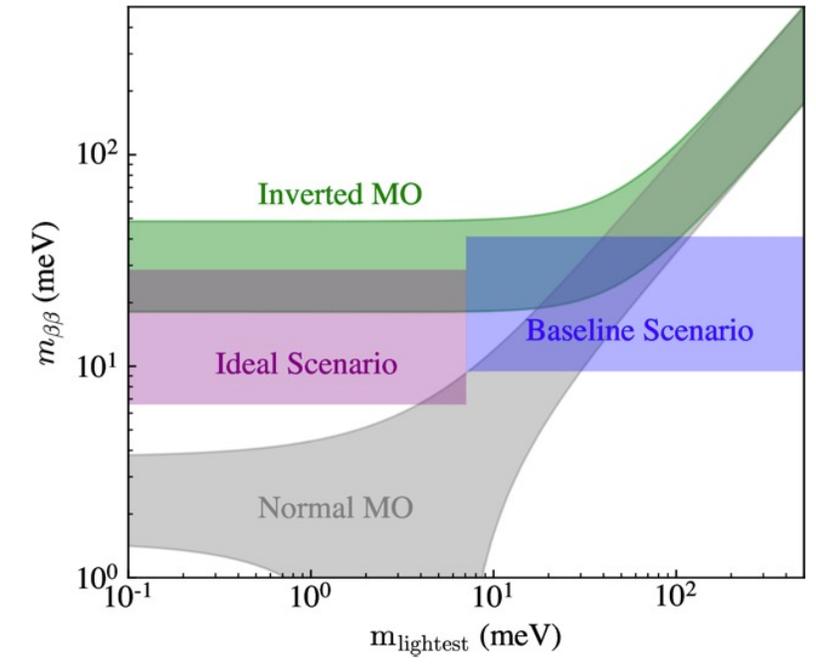
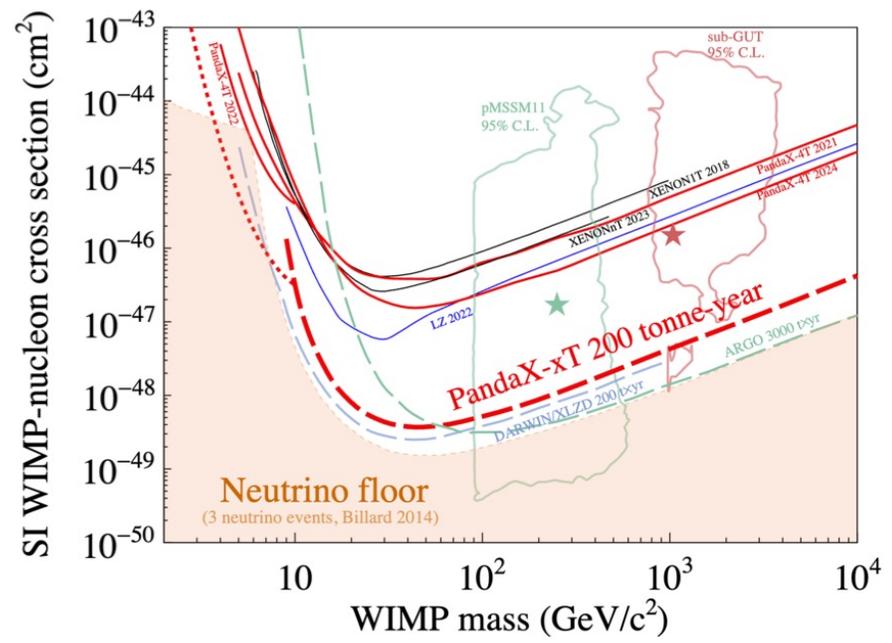
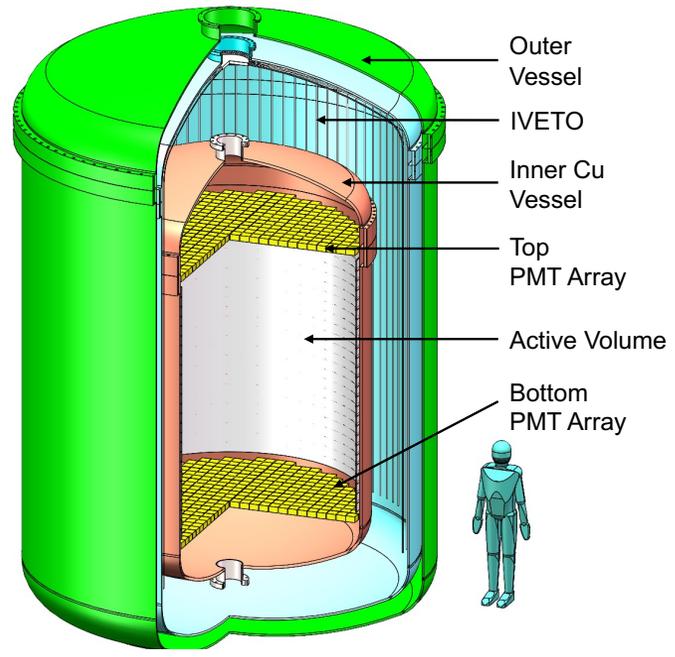
半衰期测量: $(1.03 \pm 0.15_{\text{stat}} \pm 0.08_{\text{sys}}) \times 10^{22} \text{ yr}$
KK shell 分支比: $(65 \pm 5)\%$



面向下一代实验：PandaX-xT

➤ 数十吨级、超低本底、多物理目标的实验观测平台。

1. 对暗物质-核子相互作用截面的探测灵敏度达到中微子地板，对WIMP提供关键检验；
2. 利用 ^{136}Xe 的NLDBD对中微子的马约拉纳属性进行严格检验，覆盖质量反序的参数空间；
3. 探测来自太阳和其他天体物理源的低能中微子等超稀有物理信号；



阶段性计划

➤ PandaX-4T

- 2025年底结束物理运行；

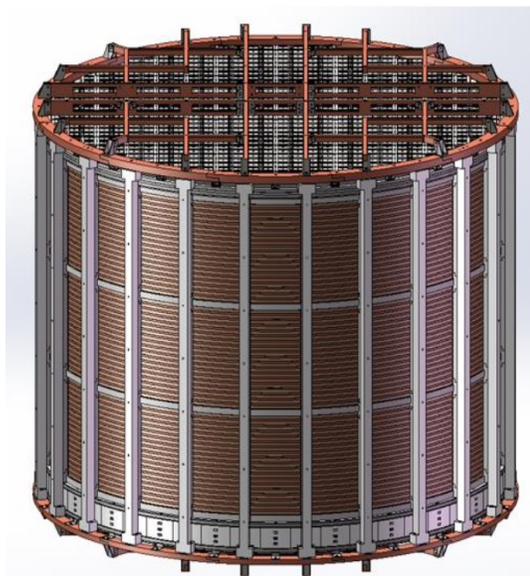
➤ PandaX-20T

- 2026年入驻锦屏开始安装
- 2027年开始运行；

➤ PandaX-xT

- TPC尺寸：2.55米直径、2.95米高度
- 47吨自然液氙，43吨灵敏体积
- 探测范围：100 eV – 10 MeV
- 分辨率：1% @ 2.5 MeV；sub-cm；

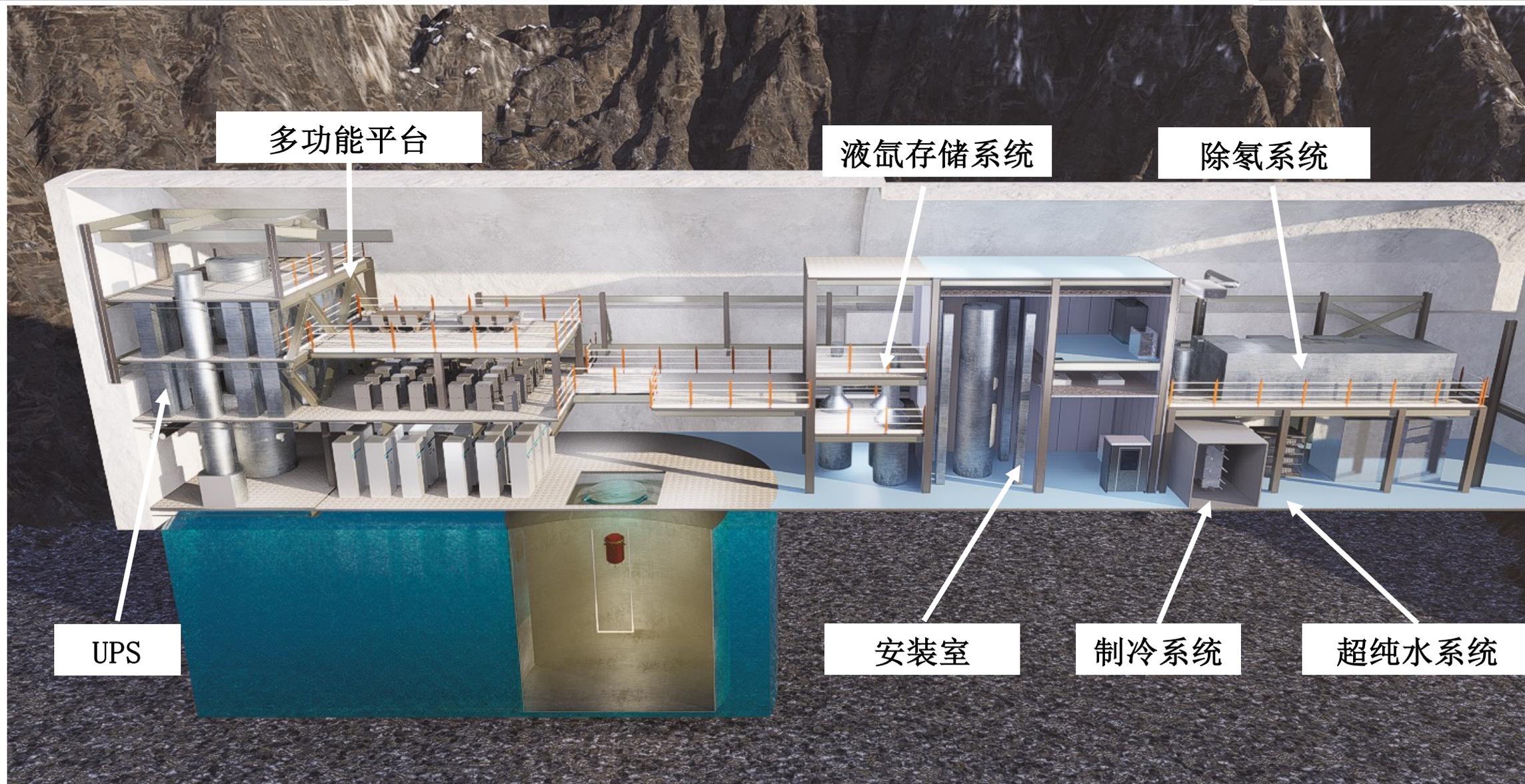
PandaX-20T



PandaX-xT



PandaX-20T实验布局



VETO系统

➤外层反符合 OVETO:

安装在900方水池内壁，两层8英寸PMT阵列；

➤内层反符合 IVETO:

安装在外罐内壁朝向探测器；10%的光阴极覆盖；氢原子的中子俘获特征2.2 MeV伽马；

4千方大水池

水屏蔽

液氙探测器

低温恒温器

内层PMT

外层PMT

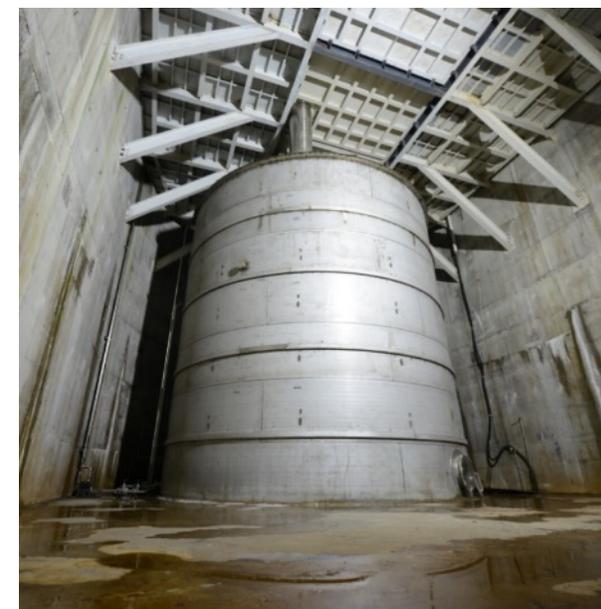
900方水池

Muon和大气中微子

中子和伽马射线

低温液闪

4.5千吨水池也可用于大气中微子探测。

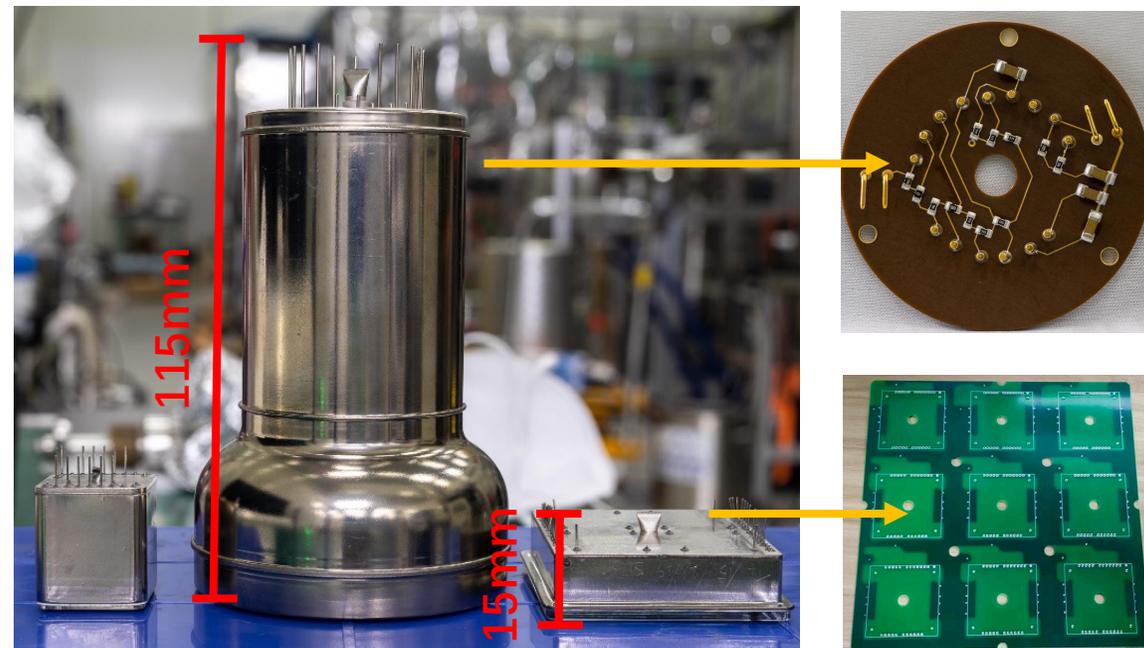


高精度光电探测阵列

- 滨松R12699 (2"x2"), 10 m²的光阴极覆盖面积;
- 暗技术率<10 Hz/通道, 量子效率> 30%@178 nm;
- 更好的时间响应性能可用于波形鉴别;

Parameter		R12699-406-M4	R11410-20	Unit
Cathode Sensitivity	Luminous (2856K)	95	90	uA/lm
	Blue Sensitivity Index	10.0	10	-
Anode Sensitivity	Luminous (2856K)	140	315	A/lm
Gain		1.5×10^6	3.5×10^6	-
Anode Dark Current (Each anode) (after 30min. storage in darkness)		1.5	10	nA
Time Response	Rise Time	1.2	5.5	ns
	Transit Time	5.9	46	ns
	Transit Time Spread (FWHM)	0.41	9	ns
Uniformity Between Each Anode		1:1.5	-	-

- 显著减少阵列空间, 节省数百公斤液氩;



- 更低的放射性本底水平

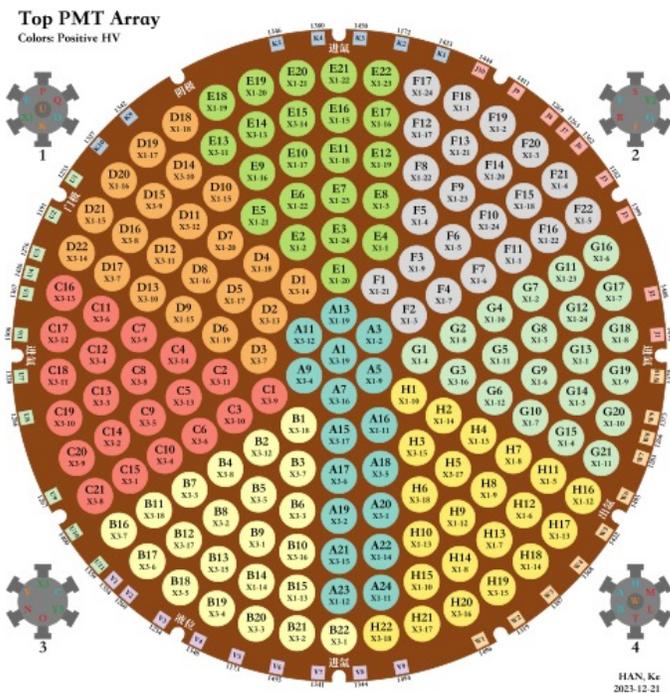
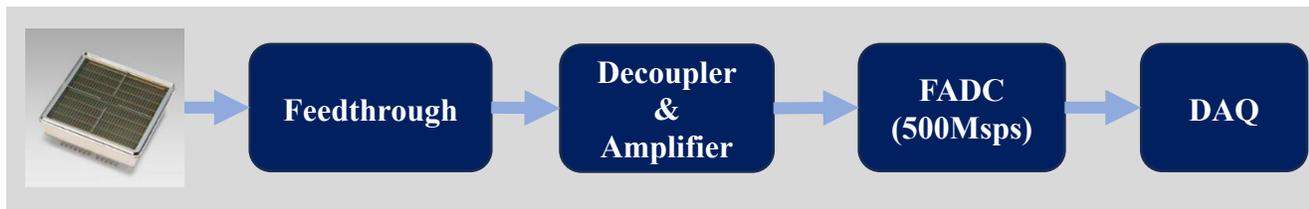
Background level		R12699	R11410
Radioactivity [mBq/pc]	Co-60	<0.07	1.16±0.72
	Th-232	<0.40	4.33±2.16
	U-238	0.47±0.11	26.29±16.90

Unit: mDRU	ER	NR
PMT	$(5.1 \pm 1.2) \times 10^{-3}$	$(2.3 \pm 0.4) \times 10^{-4}$
PTFE	$(2.1 \pm 0.3) \times 10^{-5}$	$(8.4 \pm 1.3) \times 10^{-6}$
Copper	$(1.6 \pm 0.2) \times 10^{-6}$	$(7.2 \pm 0.5) \times 10^{-8}$
Inner vessel	$(1.8 \pm 0.8) \times 10^{-3}$	$(1.4 \pm 1.2) \times 10^{-4}$
Outer vessel	$(2.6 \pm 1.3) \times 10^{-3}$	$(5.2 \pm 1.9) \times 10^{-4}$
Total Material	$(9.5 \pm 1.9) \times 10^{-3}$	$(9.1 \pm 2.2) \times 10^{-4}$

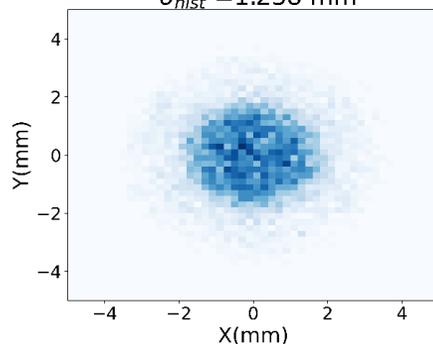
PandaX-4T中PMT+Base贡献了一半的材料放射性本底。

高精度光电探测阵列

- 高精度位置重建 -> 单点/多点事例重建;
- 约3000道电子学读出通道;
- 像素密度增加6倍, 位置重建精度提升**2倍**。

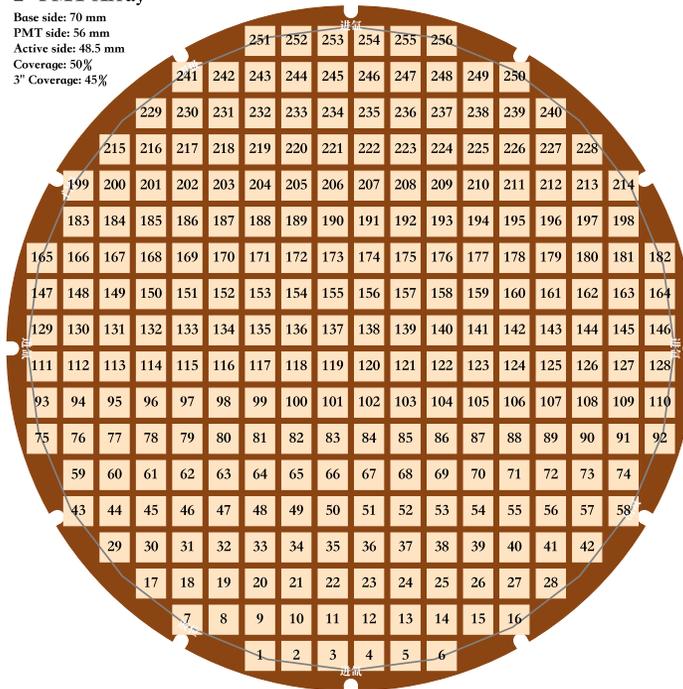


3-inch_deviation_hist_map
 $\sigma_{hist} = 1.238$ mm

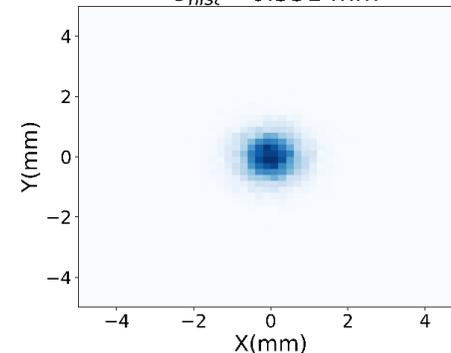


2" PMT Array

Base side: 70 mm
PMT side: 56 mm
Active side: 48.5 mm
Coverage: 50%
3" Coverage: 45%

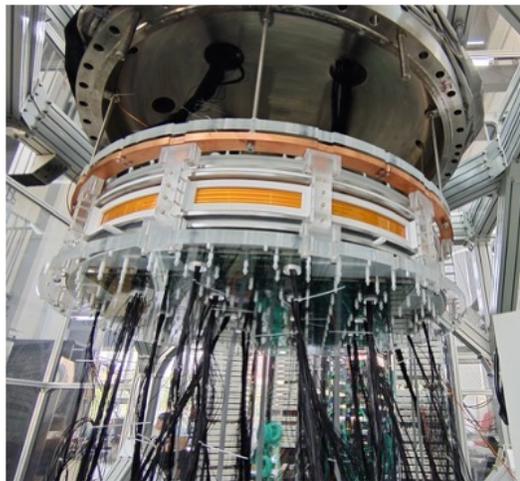


1-inch_deviation_hist_map
 $\sigma_{hist} = 0.551$ mm

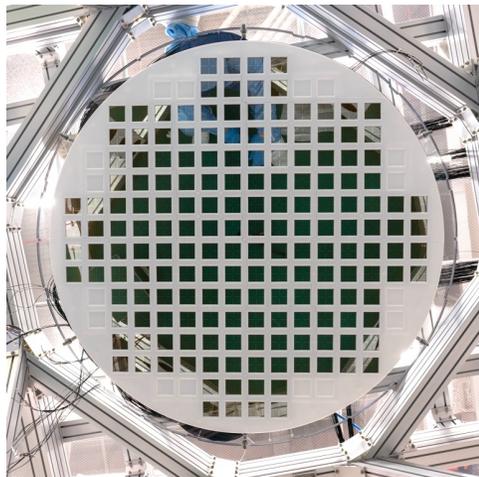


PandaX-20T研制

➤ 800公斤液氙；115 mm漂移距离；1400道2英寸PMT读出；



时间投影室



光电探测系统



光电读出电子学系统



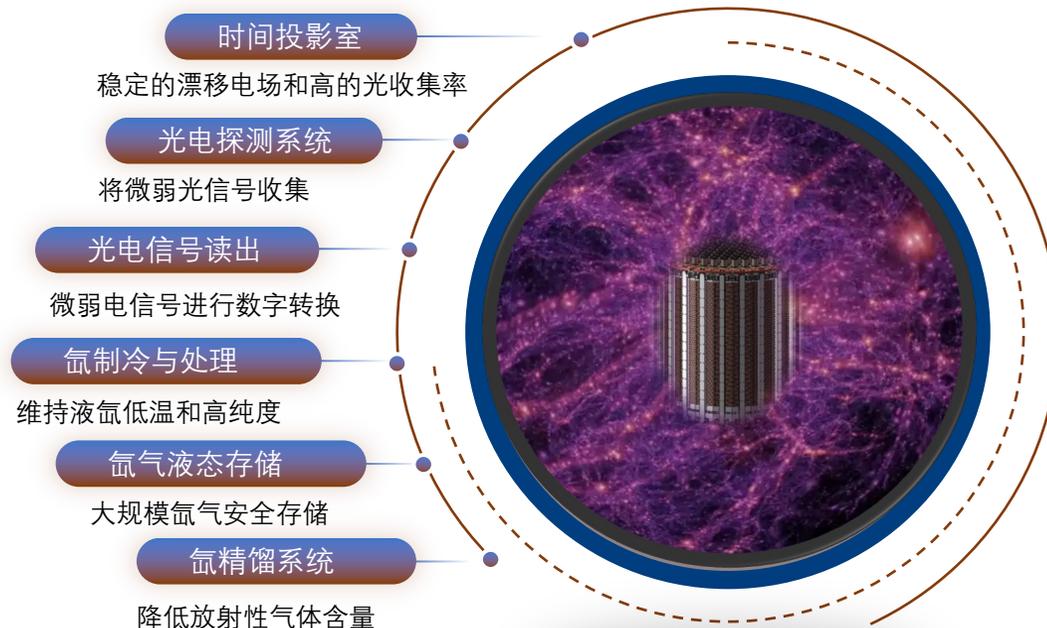
氙存储系统



氙制冷和处理系统

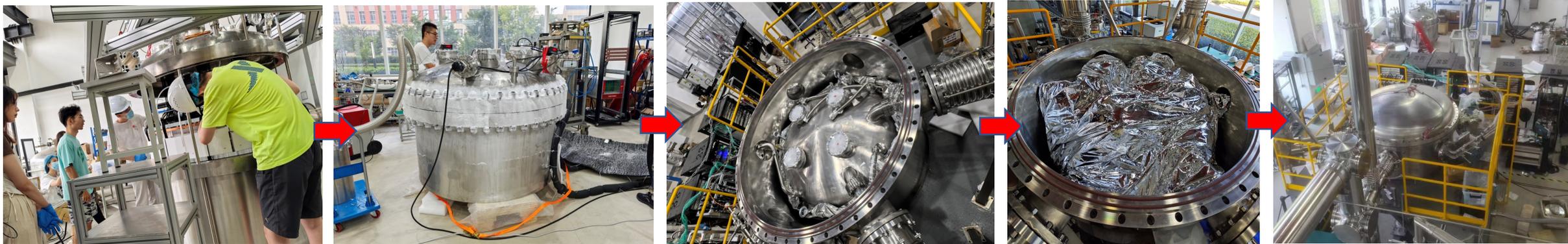


氙精馏系统



PandaX-20T研制

联合调试-安装



宇宙线缪子通量测量

与塑闪探测器
测量结果一致

探测器	缪子通量 (counts·min ⁻¹ ·cm ⁻²)
原型机	0.536±0.010
塑闪探测器	0.525

光产额测试

满足设计要求

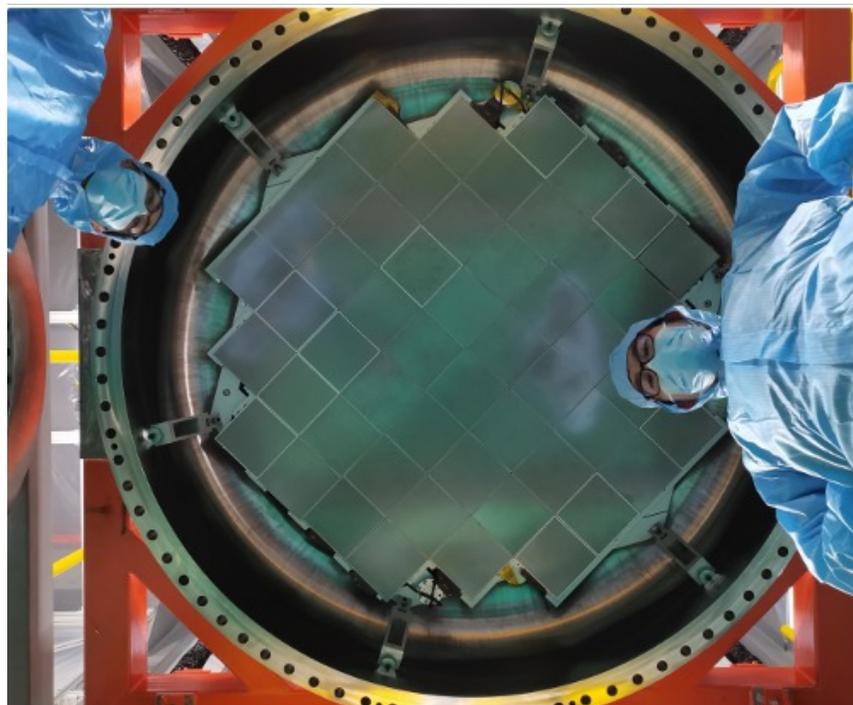
阴极电压 (kV)	漂移电场 (V/cm)	光产额 (PE/keV)
0	0	6.48
-1	87	4.49
-5	435	3.10
-10	870	2.83

PandaX-III 高压气氙实验

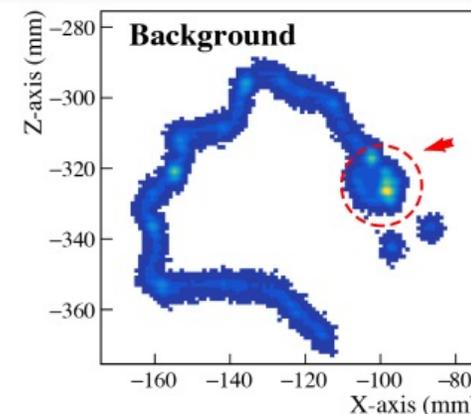
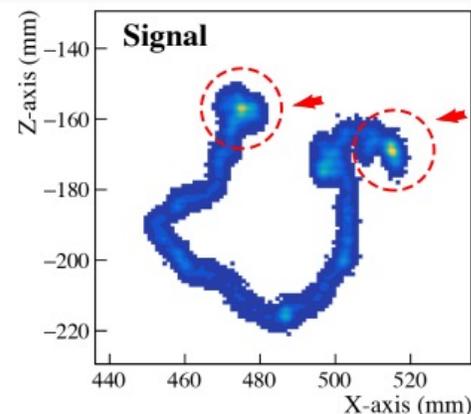
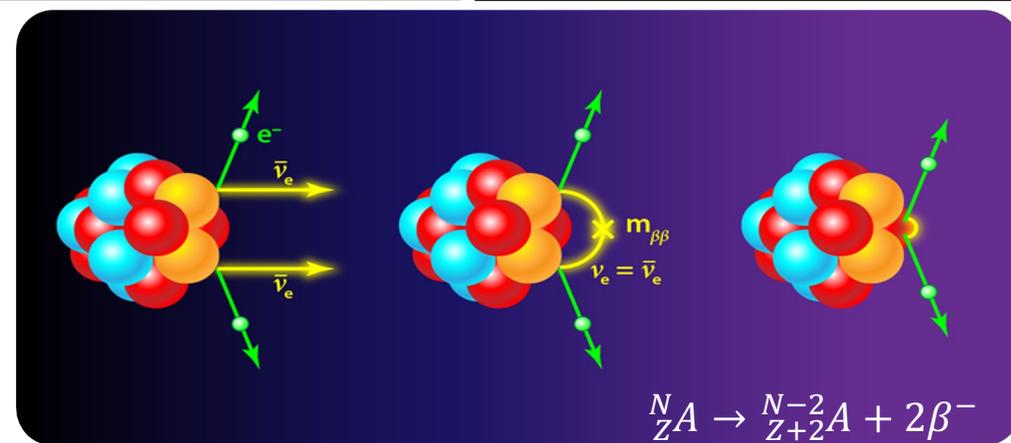
- 搜寻 ^{136}Xe 无中微子双贝塔衰变稀有信号;
- 双电子径迹特征压低实验本底;
- 140 kg, 10 bar, 90%富集 ^{136}Xe ;
- 52块Micromegas, 3mm条读出;



2025/8/21



第十三届全国先进气体探测器研讨会



气体TPC的刻度方法和径迹重建的研究

📅 2025年8月22日 08:50

🕒 20m

报告人

👤 尹鑫 刘

Micromegas在高气压下稳定性的研究与改进

📅 2025年8月22日 09:30

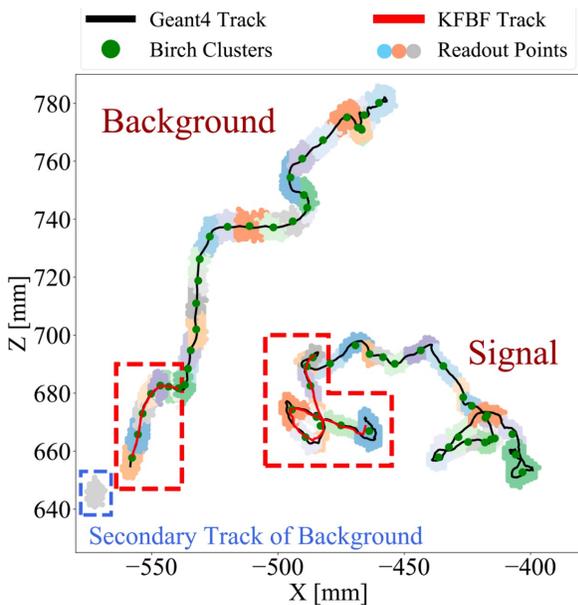
🕒 20m

报告人

👤 Yunzhi Pena (中国科学技术大学)

PandaX-III灵敏度估算

基于贝叶斯卡尔曼滤波的径迹重建算法:



6维状态向量

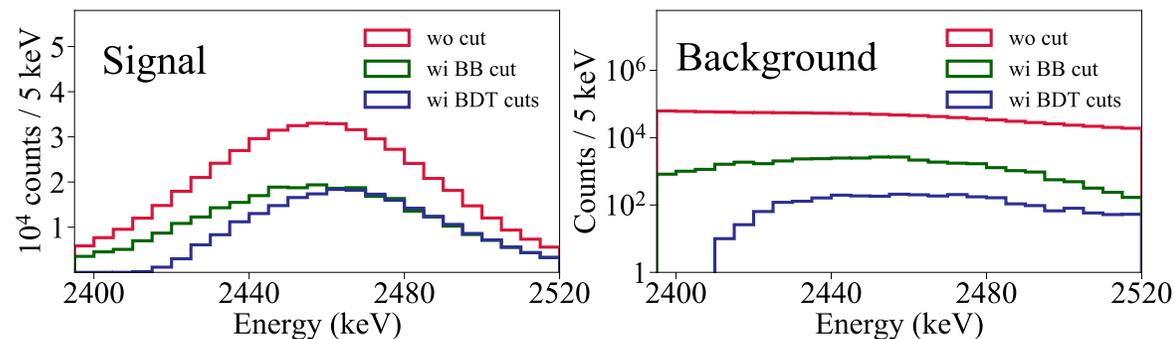
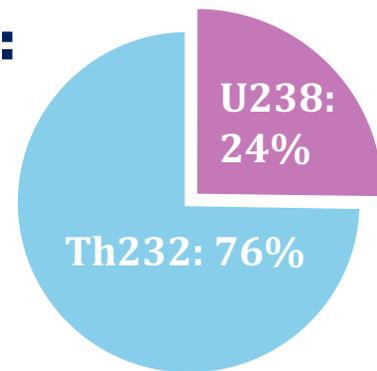
$$\begin{bmatrix} [x]_k \\ [y]_k \\ [z]_k \\ [u_x]_k \\ [u_y]_k \\ [u_z]_k \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & \lambda & 0 & 0 \\ 0 & 1 & 0 & 0 & \lambda & 0 \\ 0 & 0 & 1 & 0 & 0 & \lambda \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} [x]_{k-1} \\ [y]_{k-1} \\ [z]_{k-1} \\ [u_x]_{k-1} \\ [u_y]_{k-1} \\ [u_z]_{k-1} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ G(0, [\theta_x]_k) \\ G(0, [\theta_y]_k) \\ G(0, [\theta_z]_k) \end{bmatrix},$$

信号本底鉴别与本底估计:

本底水平预期为**152 CPY**

信号效率: 50%;

本底效率: **0.32% (0.48 CPY)**



运行5年的灵敏度估计: $T_{1/2}^{0\nu} = \frac{\ln 2}{3} \cdot \frac{N_A \epsilon a}{W} \sqrt{\frac{M \cdot t}{b \cdot dE}}$

- 排除灵敏度可达到 2.7×10^{26} y (90% C.L.);
- 压低1个数量级的本底, 灵敏度可以提升**2至3**倍。

JHEP 06. 106 (2021)

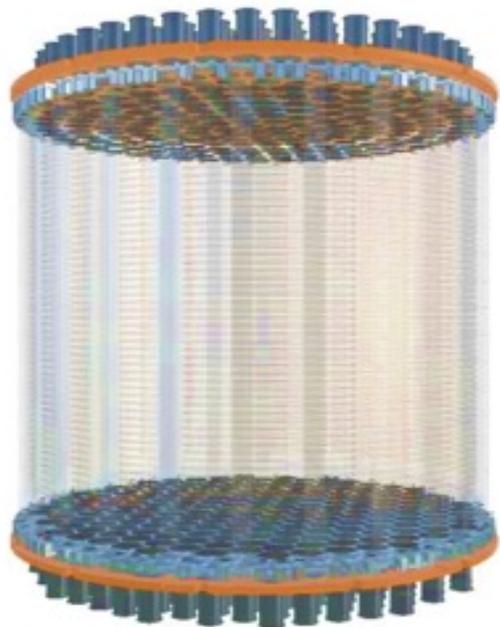
Comparison	Ξ	Overall efficiency	background counts	Sensitivity (90% C.L.)
This work	8.8	34.7%	2.4	2.7×10^{26} yr
Design target ¹	2.8	35.0%	25.3	9.8×10^{25} yr
Work by Galan ²	3.3	23.2%	7.6	1.1×10^{26} yr

总结与展望

未来在路上：PandaX-4T实验预计物理运行到2025年底，下一代第一阶段PandaX-20T实验将于2027年试运行。



Backup



李涛
代表PandaX合作组

2025年8月21日
第十三届全国先进气体探测器研讨会



PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC



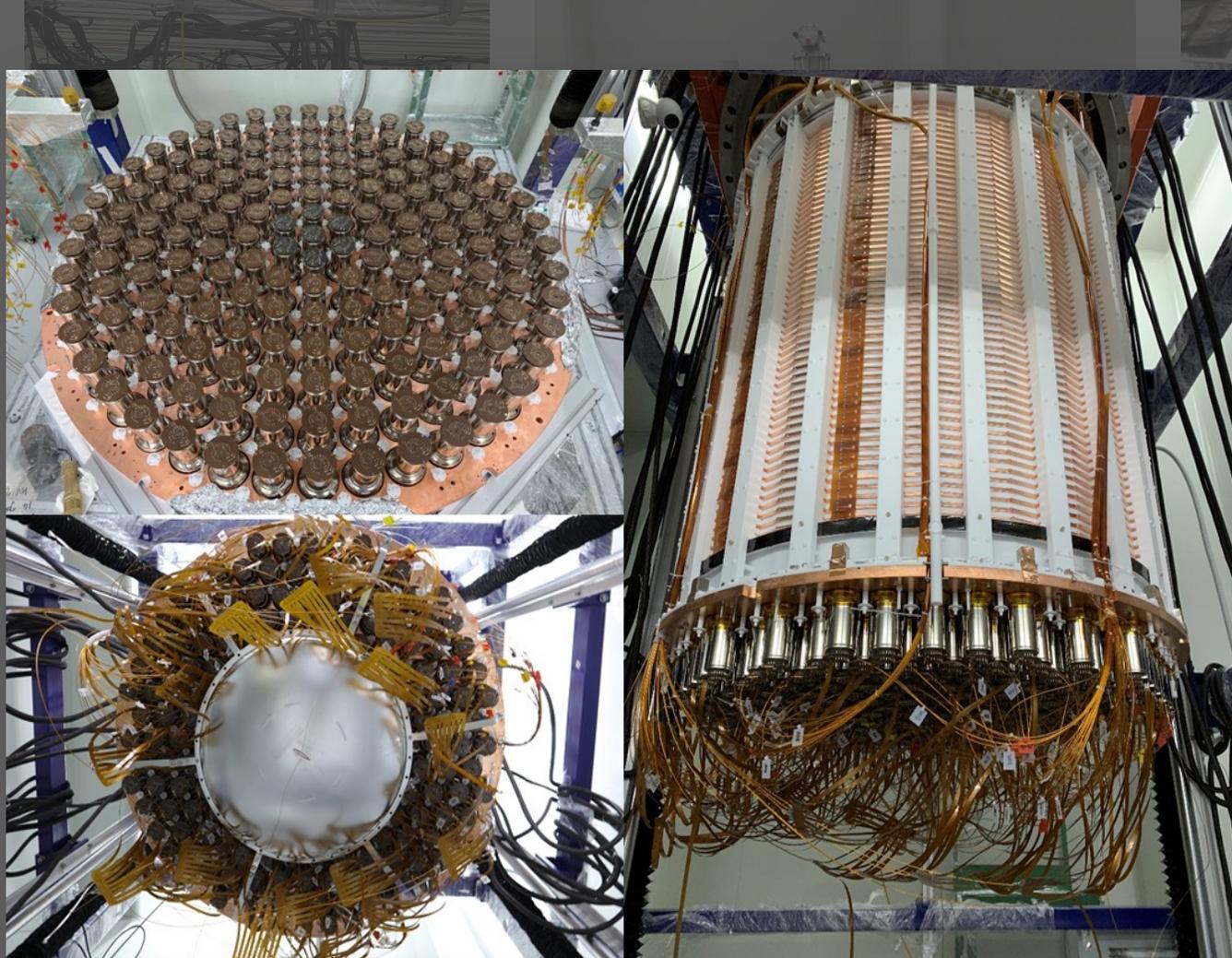
上海交通大学
SHANGHAI JIAO TONG UNIVERSITY

taoli@sjtu.edu.cn

PandaX-4T子系统

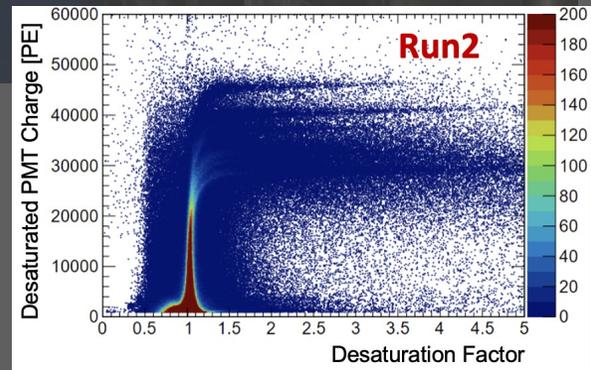


Distillation tower



Water tank

TPC

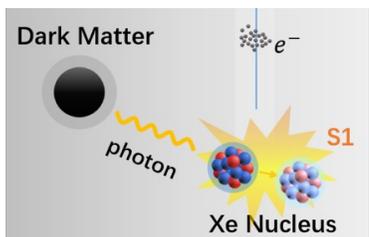


PMT

PandaX-4T 近期物理结果



Dark Matter



- **Run0+Run1 combined 1.54 tonne-year exposure**
 - Leading constraints for WIMP mass above 100 GeV
 - Leading constraints for ALP and dark photon 150keV-1MeV
 - Competitive constraints on axion, neutrino magnetic moment, etc
- **Limits on the luminance of dark matter**
 - First constraints on DM charge radius

[PRL 134, 011805 \(2025\)](#)

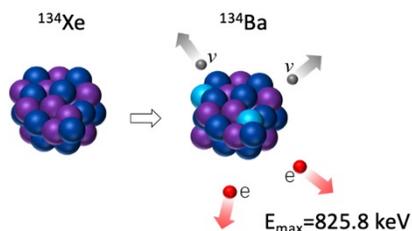
[PRL 134, 071004 \(2025\)](#)

[PRL 134, 041001 \(2025\)](#)

[Nature 618, 47-50 \(2023\)](#)



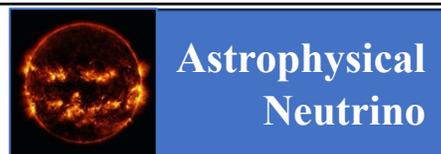
Majorana Neutrino



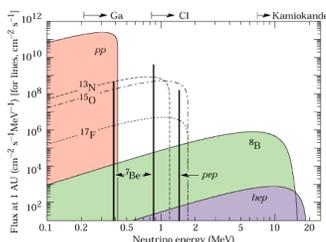
- **First ^{134}Xe $2\nu\beta\beta$ and $0\nu\beta\beta$ search from natural xenon detector**
 - ROI: 200 - 1000 keV
 - 90%CL limits on half-life $T_{1/2}^{2\nu\beta\beta} > 2.8 \cdot 10^{22}$ yr and $T_{1/2}^{0\nu\beta\beta} > 3.0 \cdot 10^{23}$ yr
- **Leading ^{136}Xe $0\nu\beta\beta$ constraints from natural xenon detector**
 - 90% CL limits on half-life $T_{1/2} > 2 \times 10^{24}$ yr

[PRL 132, 152402 \(2024\)](#)

[Sci.Bull. 70 \(2025\) 1779-1785](#)



Astrophysical Neutrino



- **First indication of solar ^8B neutrinos through CEvNS**
 - 2.64 sigma significance
 - Two ROI regions: paired (3.5 ± 1.3 events) and S2only (75 ± 28 events)
- **First search of solar pp neutrinos in xenon detector**
 - Flux: 8.0 ± 3.9 (stat) ± 10.0 (syst) $\times 10^{10}$ s $^{-1}$ cm $^{-2}$

[PRL 133, 191001 \(2024\)](#)

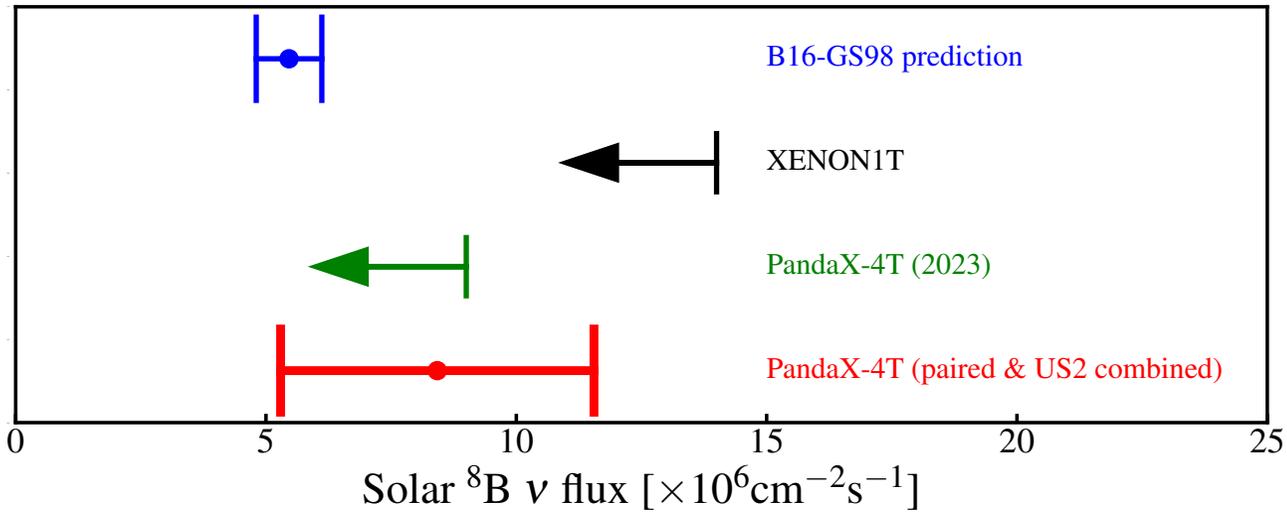
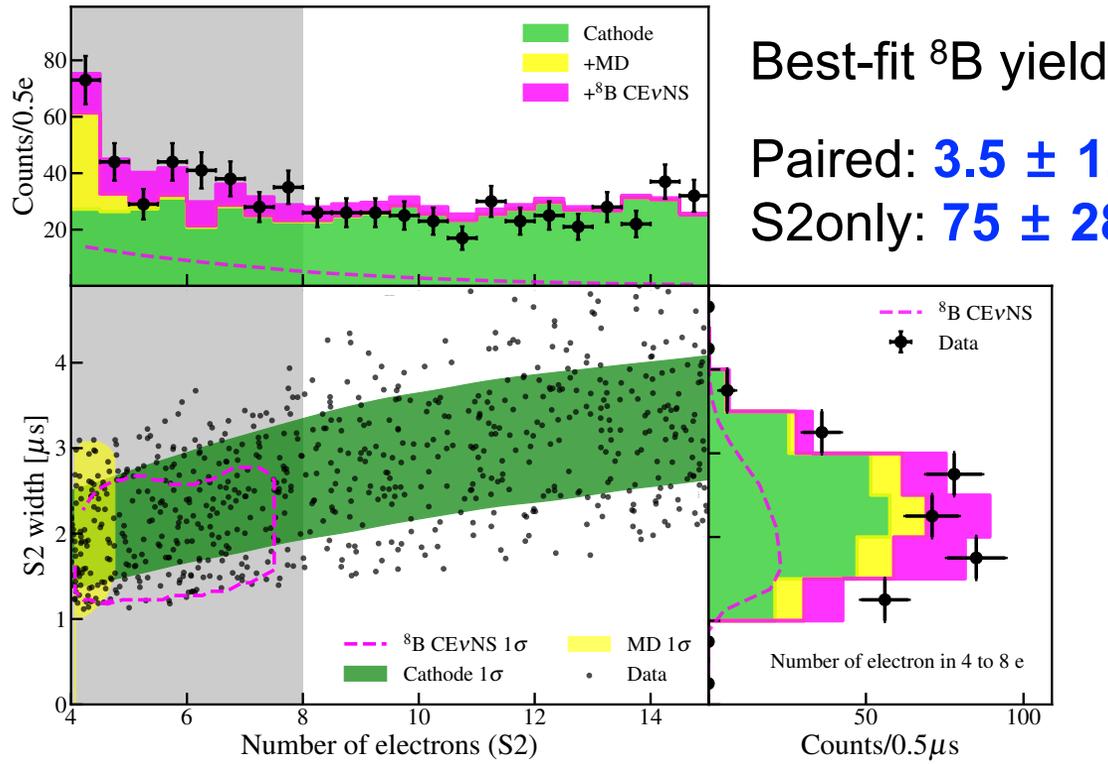
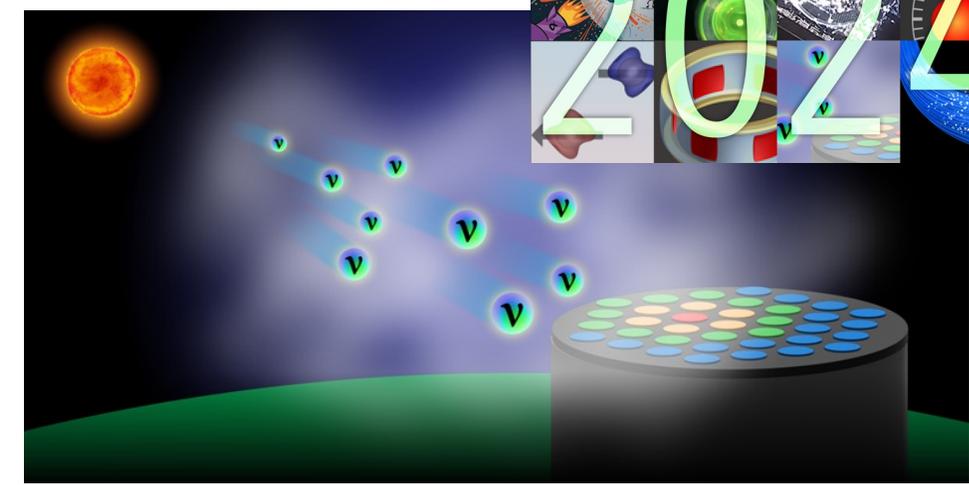
[CPC 48, 091001 \(2024\)](#)

太阳硼-8中微子探测

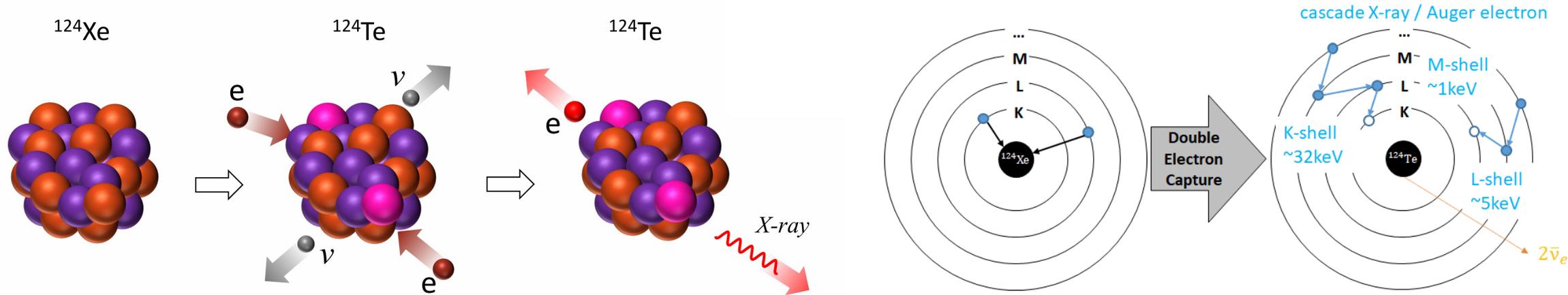
➤ 世界首次对太阳硼-8中微子的探测：

显著度达到 2.64 sigma；

中微子通量为 $(8.4 \pm 3.1) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ ；

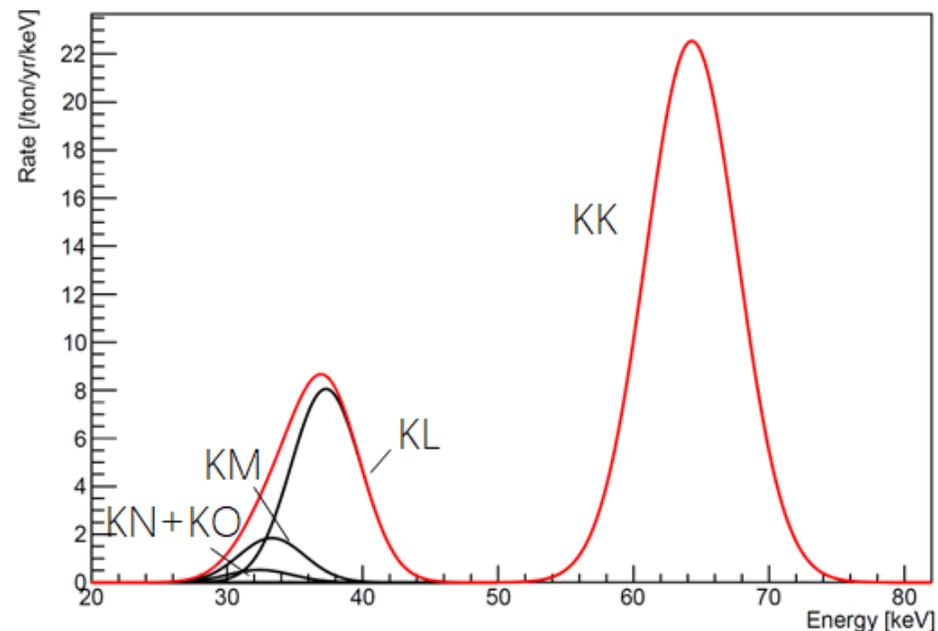


Back up



- 氙-124双电子俘获，目前测量的最长半衰期
 - $Q = 2857 \text{ keV}$
 - Auger electron & X-ray cascades
- XENONnT: $T_{1/2} = (1.18 \pm 0.13_{\text{stat}} \pm 0.14_{\text{sys}}) \times 10^{22} \text{ yr}$
- LZ: $T_{1/2} = (1.09 \pm 0.14_{\text{stat}} \pm 0.05_{\text{sys}}) \times 10^{22} \text{ yr}$

[J.Phys.G 52 (2025) 1, 015103]
 PRL 133, 191001 (2024)
 2023/9/21

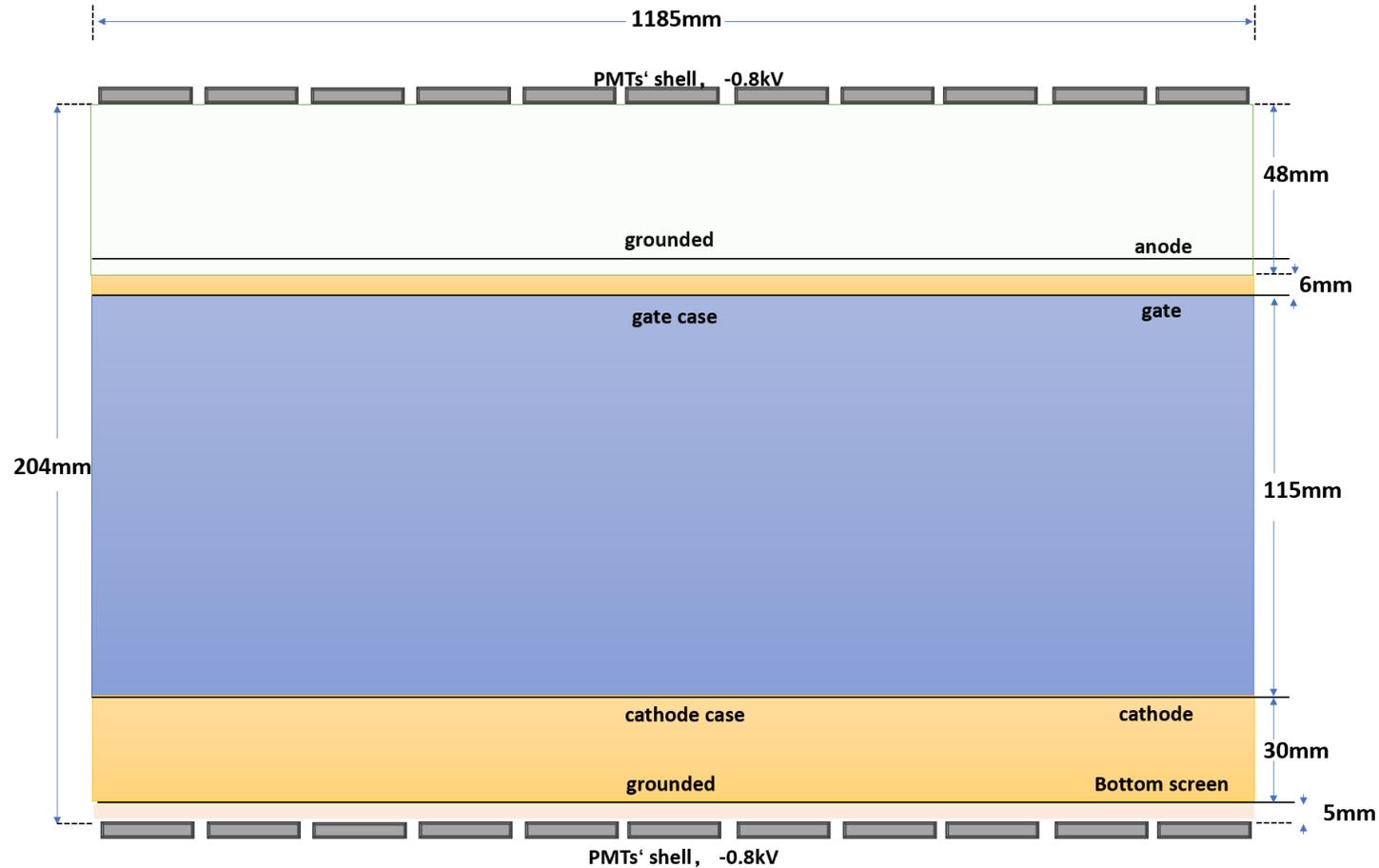


- Default: Waveform digitization with 500 Msps
 - Proved technology and solution
 - Readout channels: ~ 10000
 - A large number of coaxial cables and feedthroughs



- Under R&D:
 - Multiplexing, base linear study, and dual-gain readout
 - Pre-amplifier ASIC @LXe, allowing long flat cable option ($>10\text{m}$)
 - Digitization @ LXe, reducing coaxial cables and feedthroughs

李所平台尺寸



Electrodes style:
all mesh , size: 200 μ m gap 5mm
PMT: R12699

李所平台联调

• 联合调试-安装

- 探测器放入内罐，常温检漏，低温检漏，包绝热层，放入外罐，连接相关电缆和管道，测试和检漏，封闭外真空罩检漏，抽真空，充氦气，预冷，注入液氦，正

