

第十四届“晨光杯”青年优秀论文评选答辩

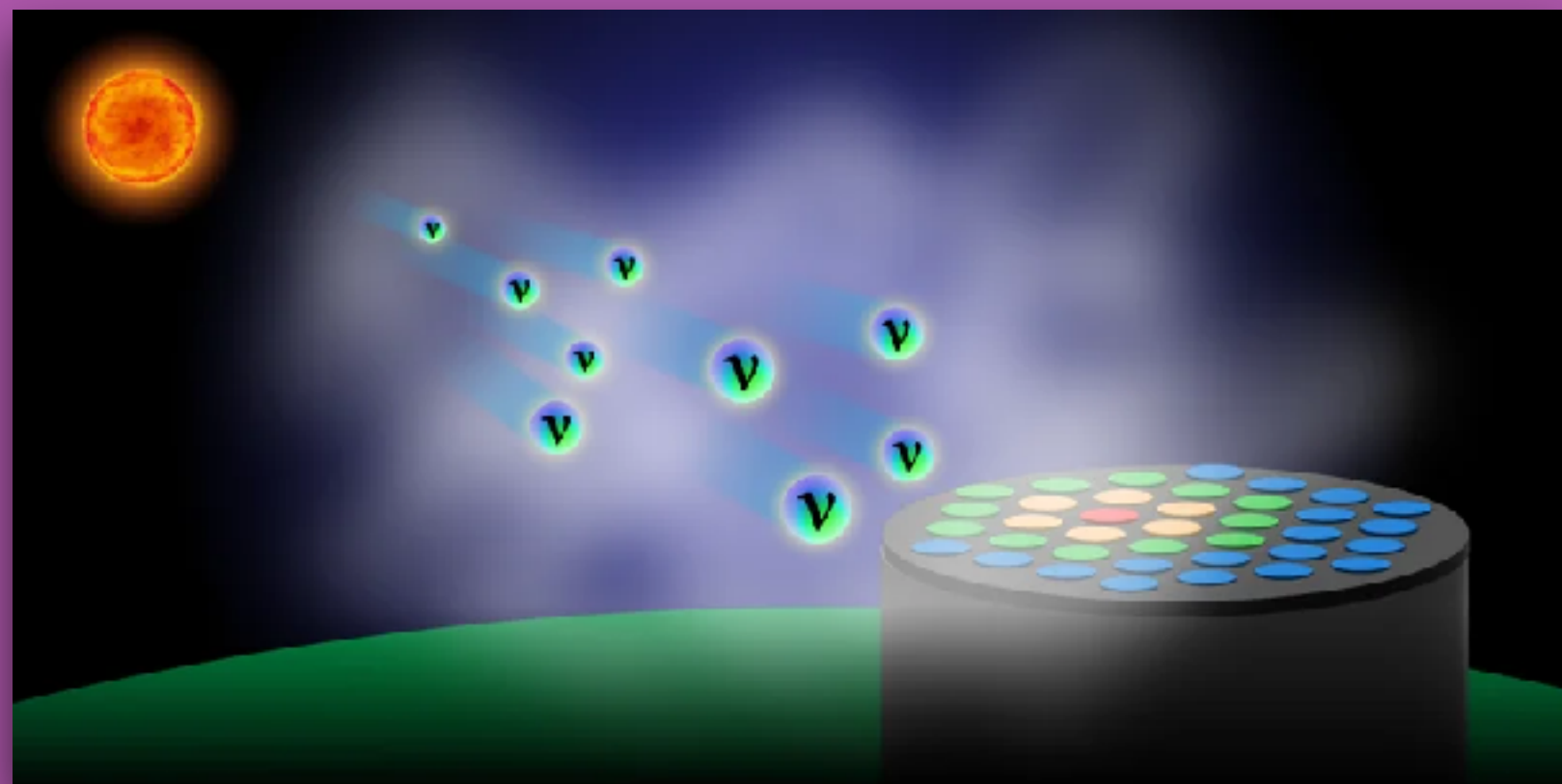
First Indication of Solar ^8B Neutrinos via
Coherent Elastic Neutrino-Nucleus Scattering with XENONnT

利用XENONnT实验首次通过中微子-原子核
相干弹性散射测量太阳 ^8B 中微子

[Phys. Rev. Lett. 133, 191002 \(2024\)](#)

刘可欣 清华大学物理系

XENON合作组



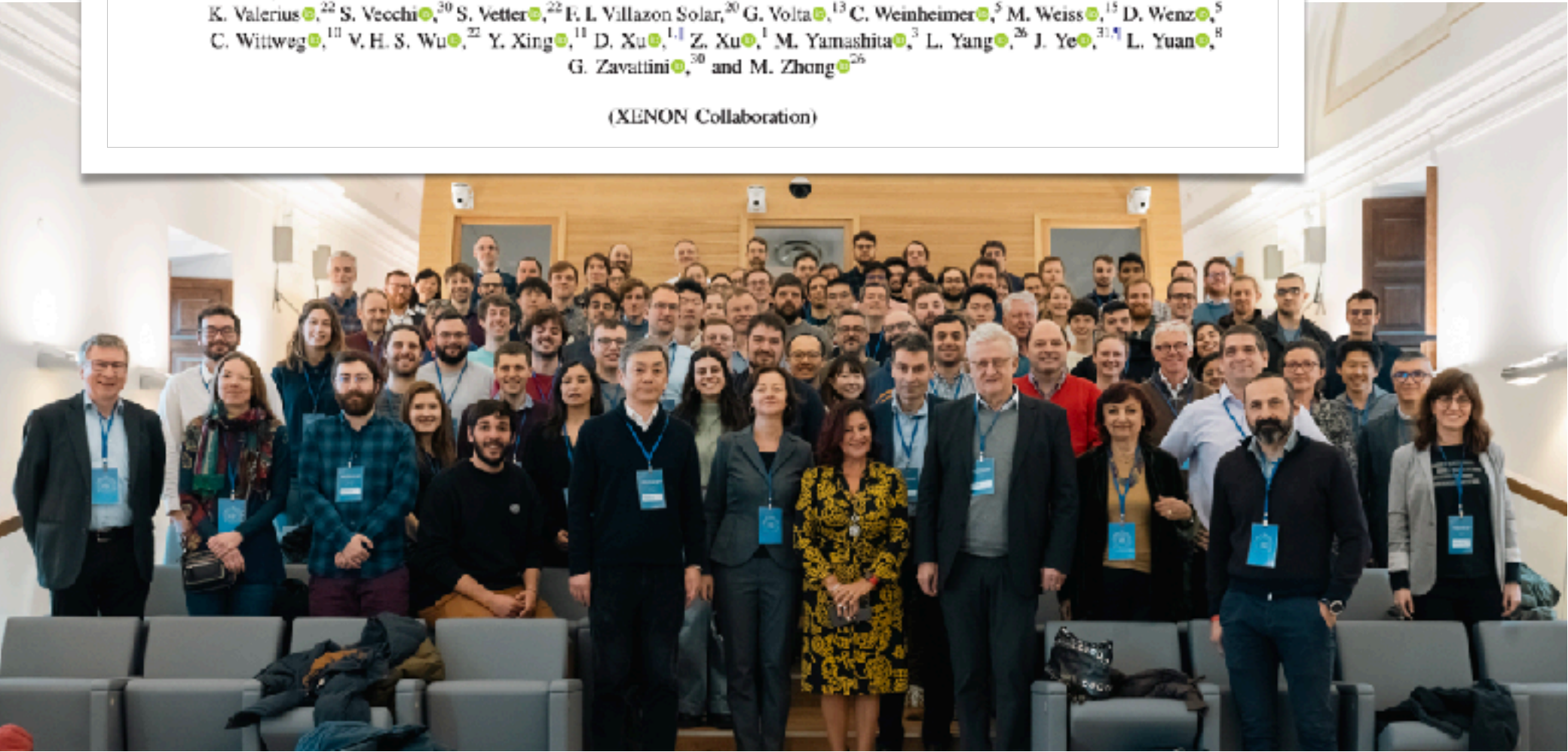
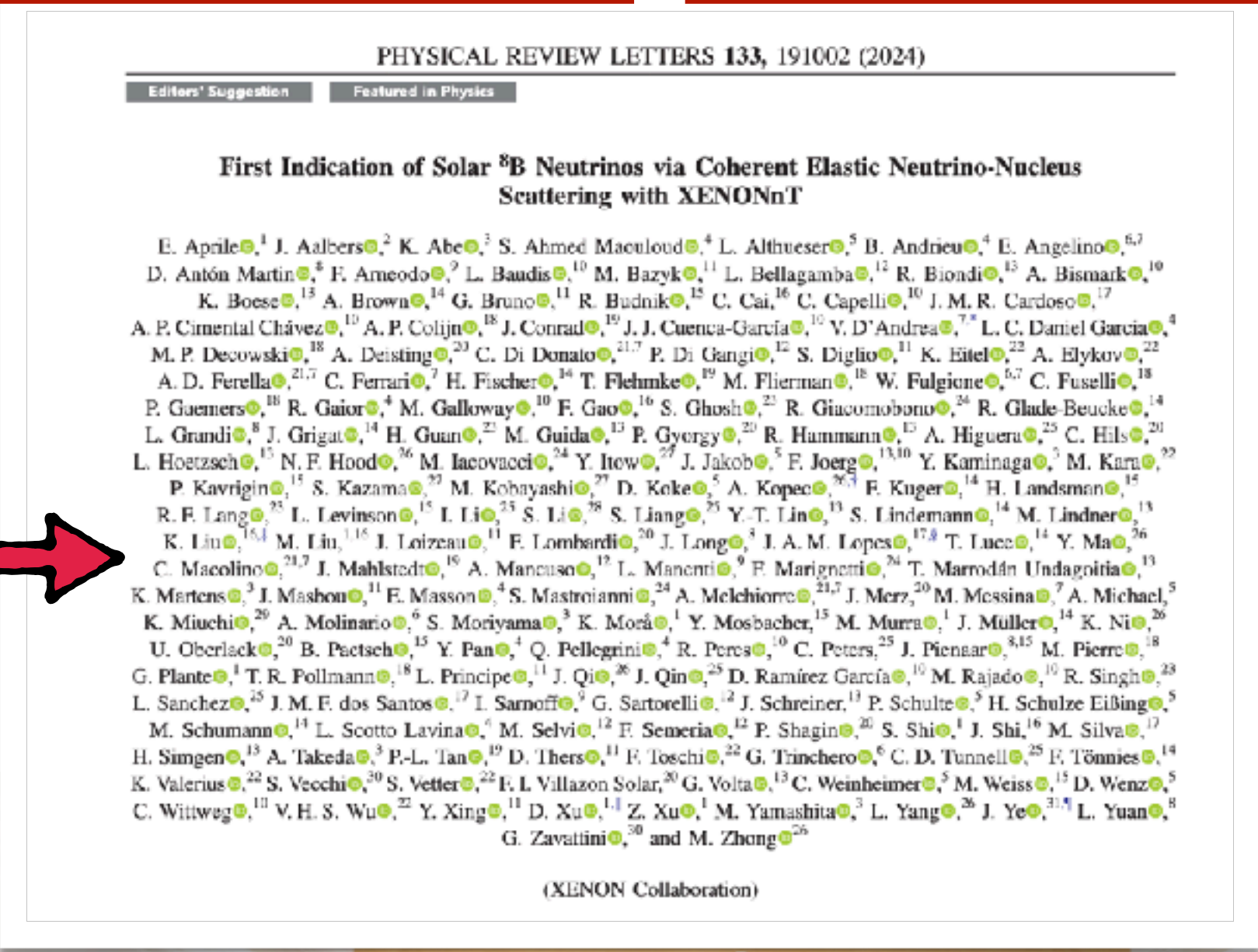
参评论文简况



清华大学
Tsinghua University

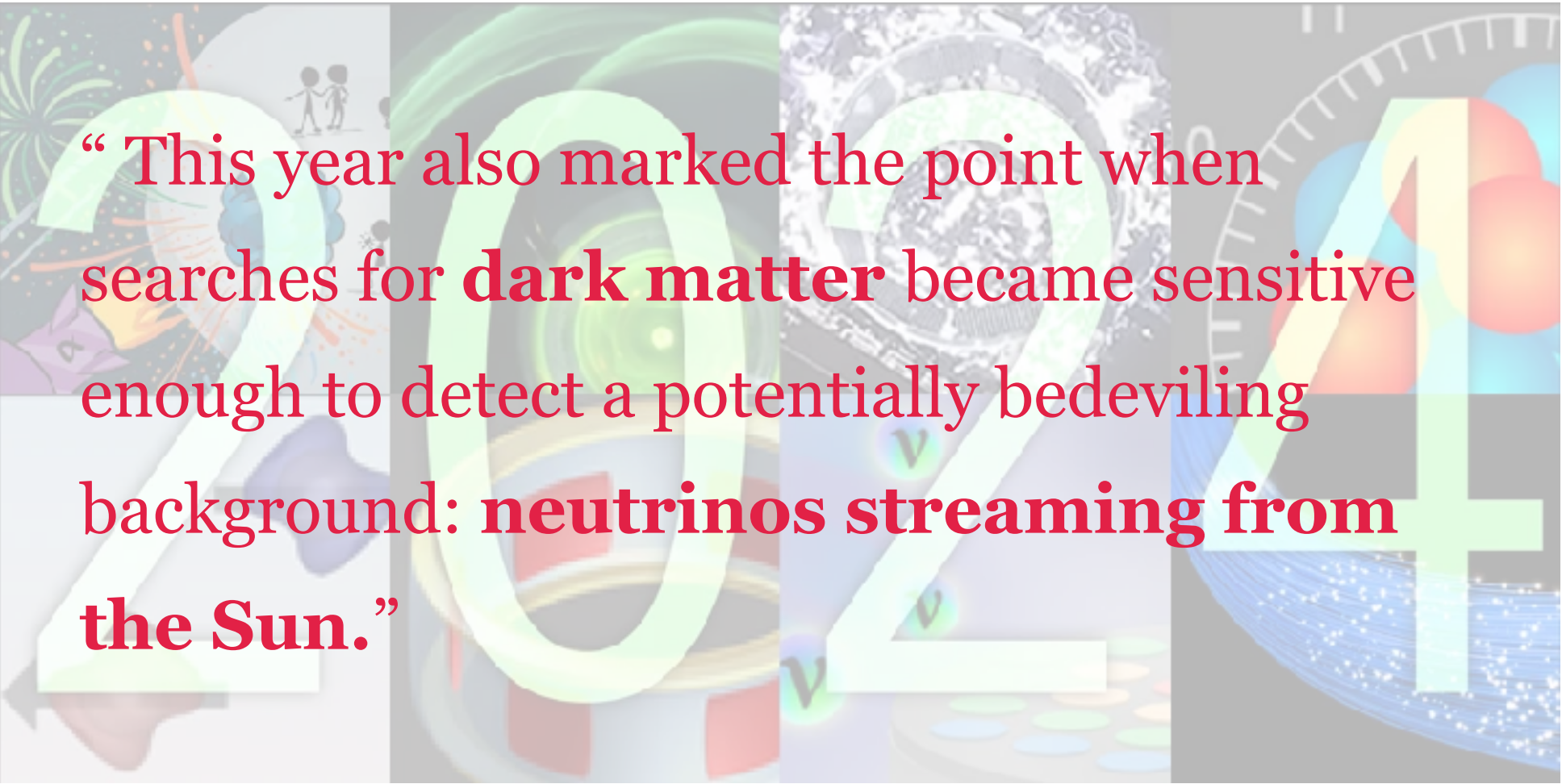
Editor's Suggestion

Featured in Physics



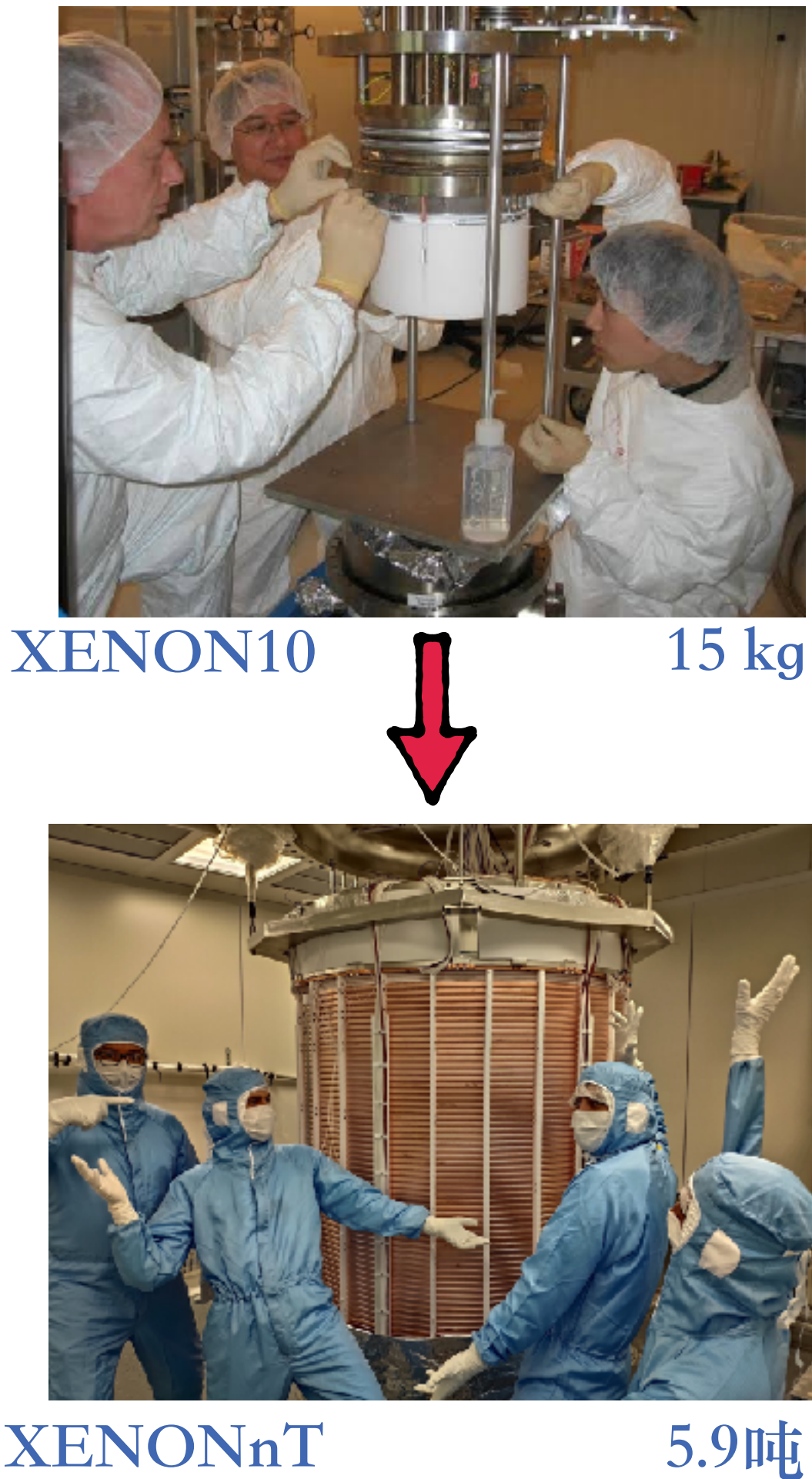
XENON合作组

- Phys. Rev. Lett. 133, 191002
- 本人为共同通讯作者
- 2024年发表至今累计引用量 195
- 入选 PRL “2024年度特辑”
- 入选APS “Highlights of the year”



研究背景 挑战与创新 结果与影响

液氙暗物质实验：XENON合作组

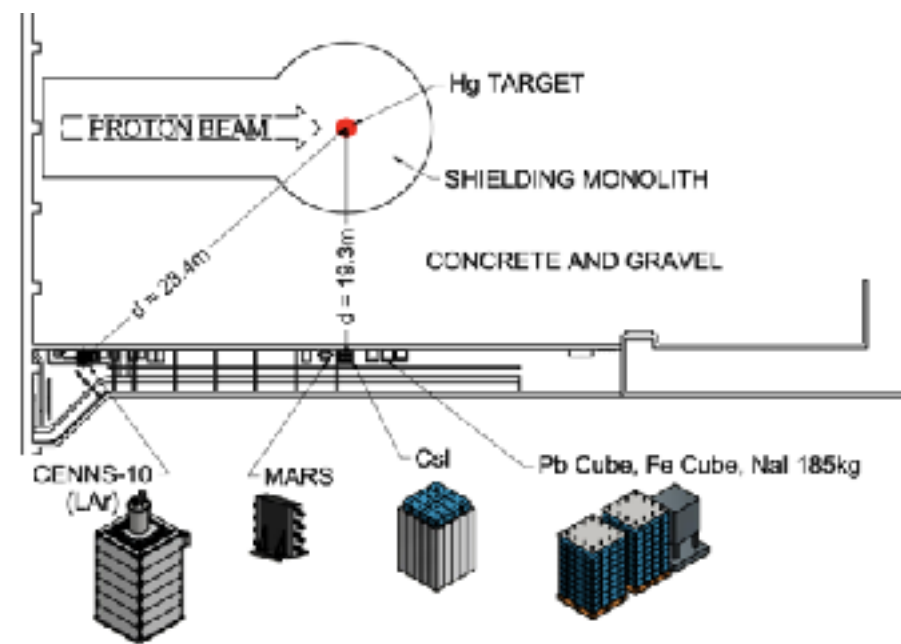
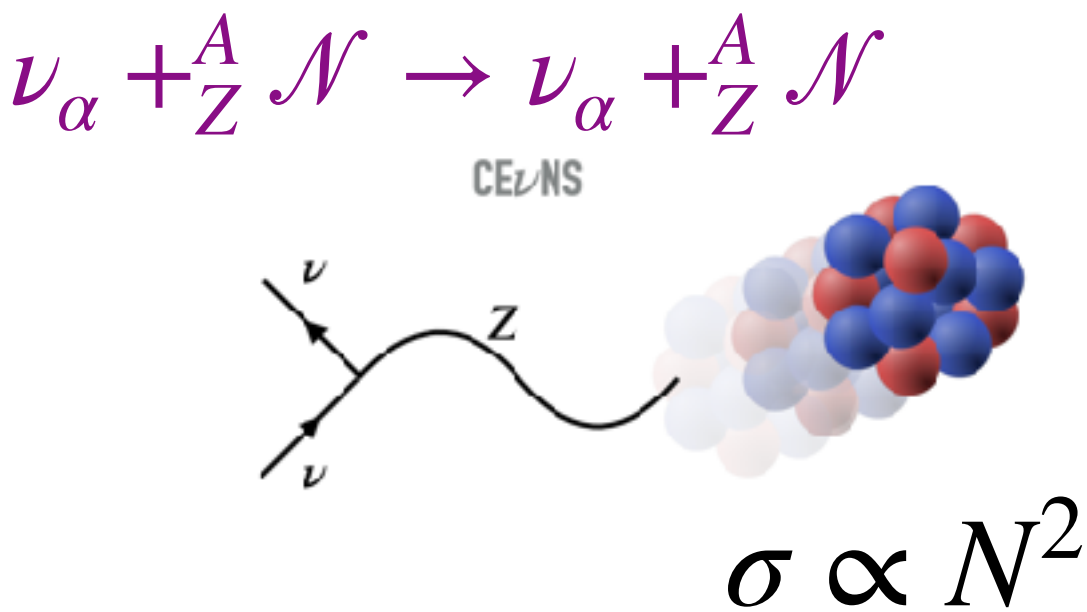


- 2020年清华大学加入合作组（PI：高飞），为首家中国单位
- 2021年XENONnT探测器正式采集科学数据，同年本人参与其物理分析

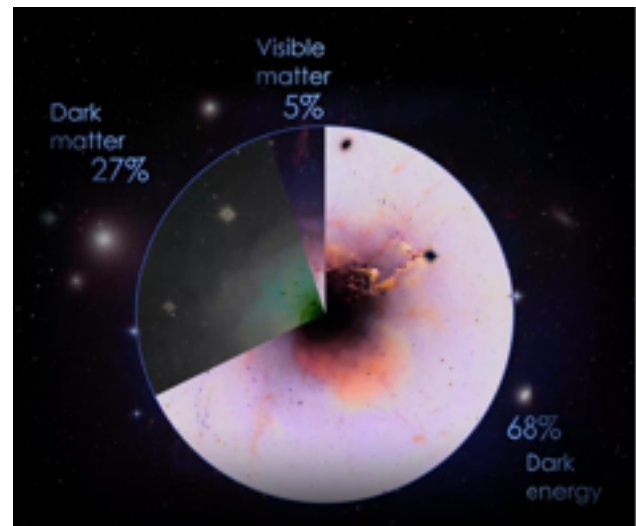
研究背景：CE ν NS探测与暗物质探测的深厚渊源



Freedman, 1974



暗物质问题提出

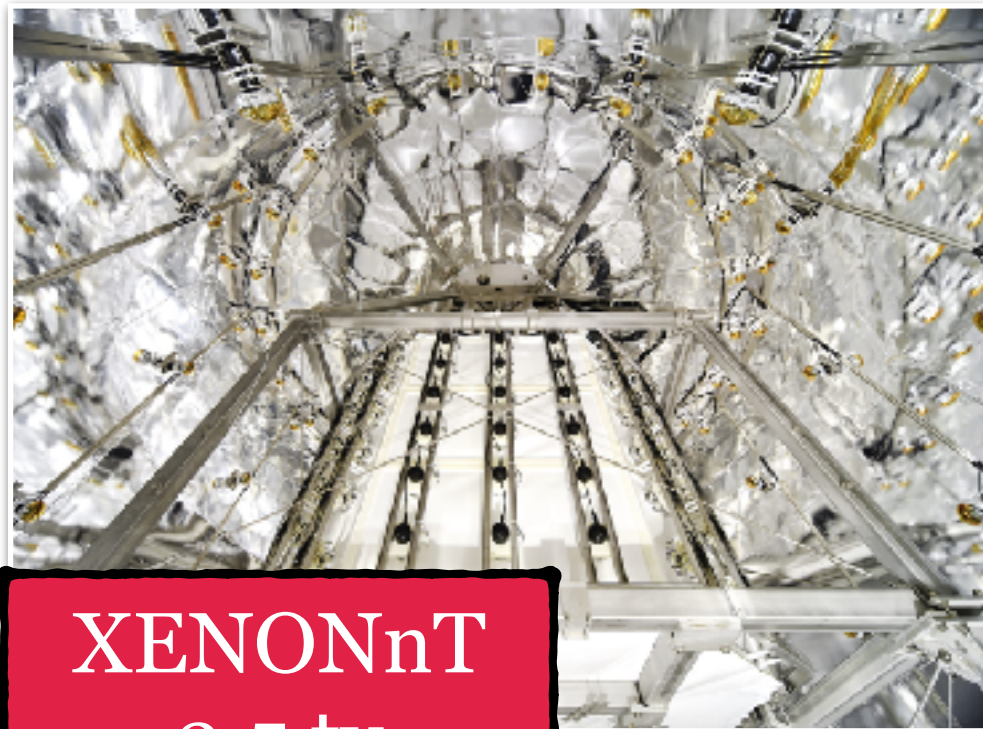
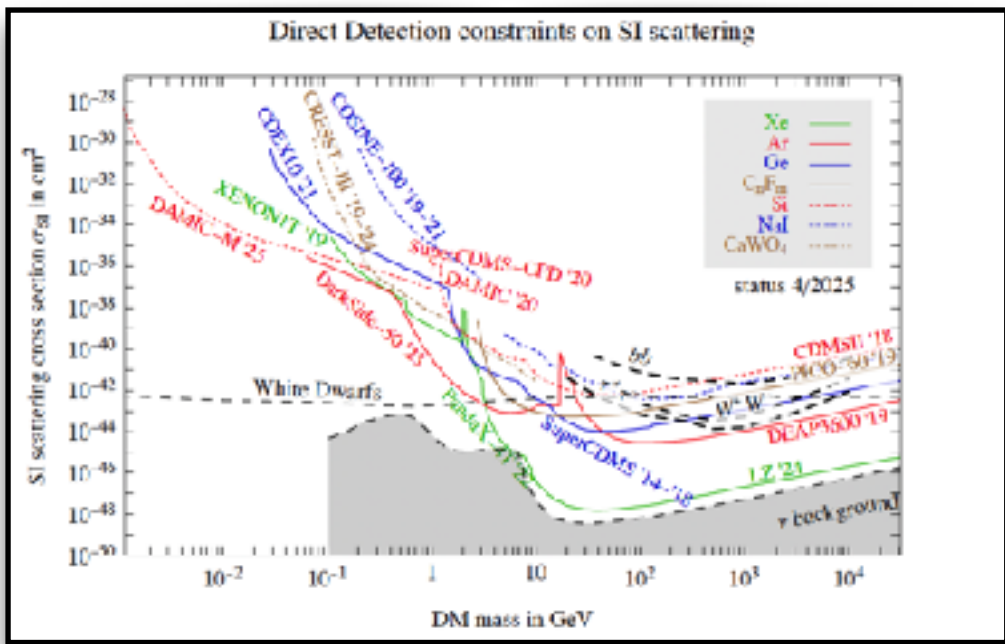
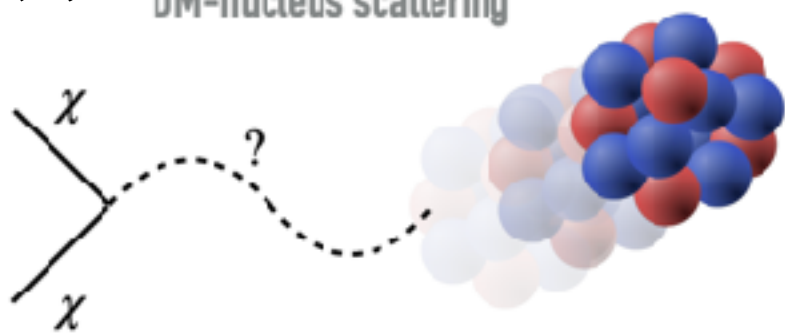


可应用于WIMPs探测!



Goodman & Witten, 1985

DM-nucleus scattering



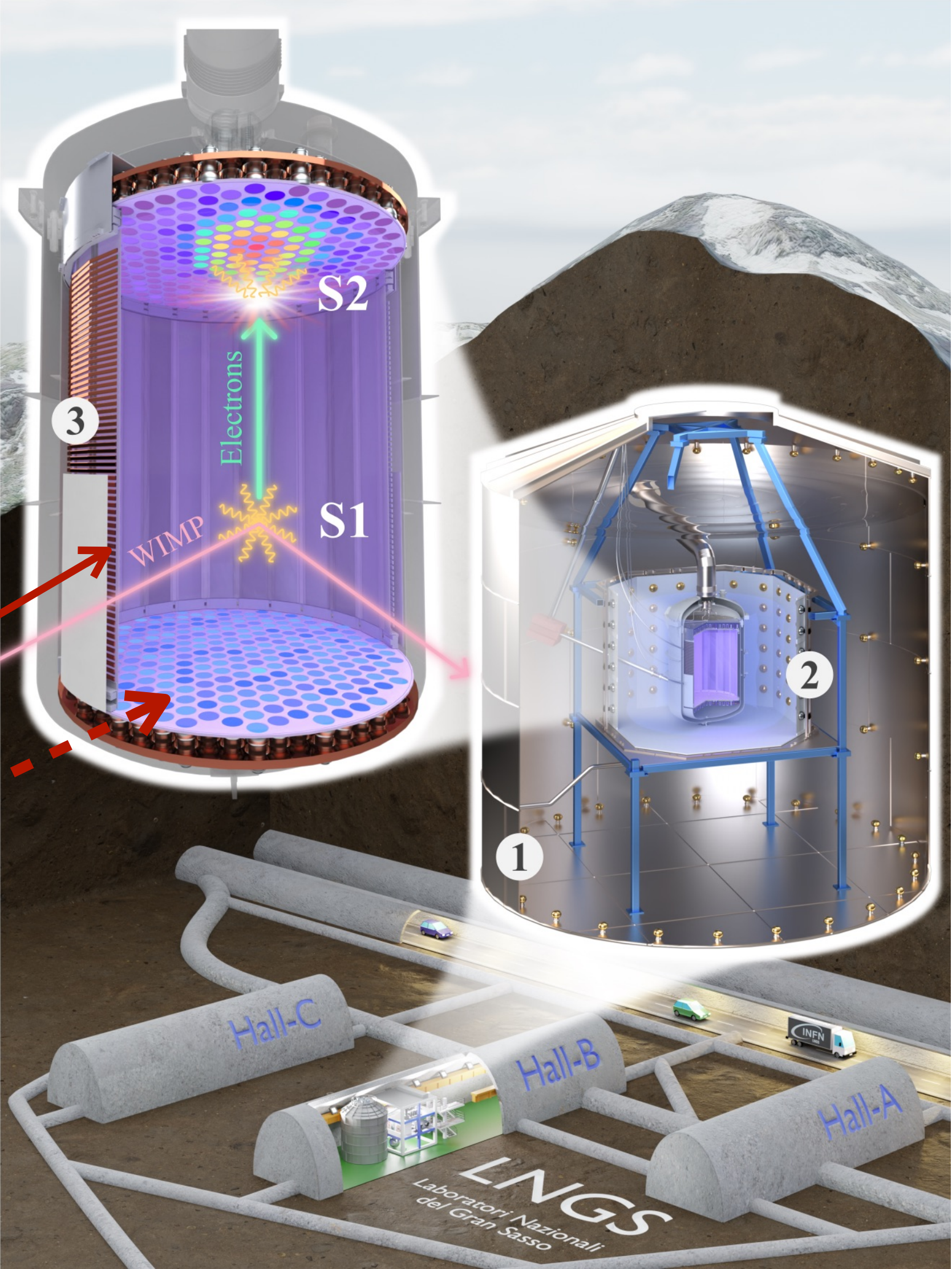
XENONnT
3.5 ty
2.73 σ



PandaX-4T
1.20(1.04) ty
paired(US2)
2.64 σ

研究目标：用暗物质实验探测太阳中微子CE ν NS

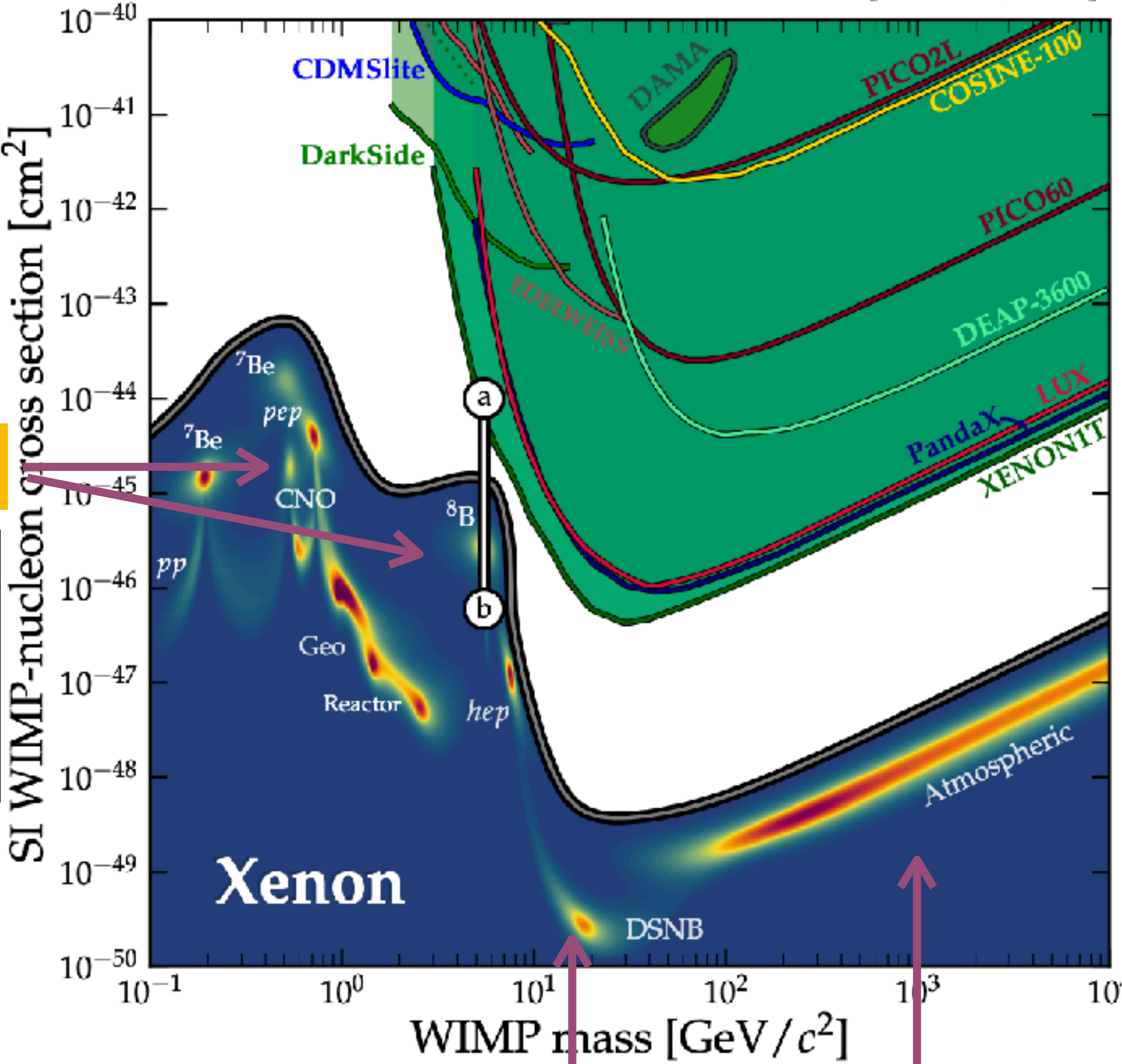
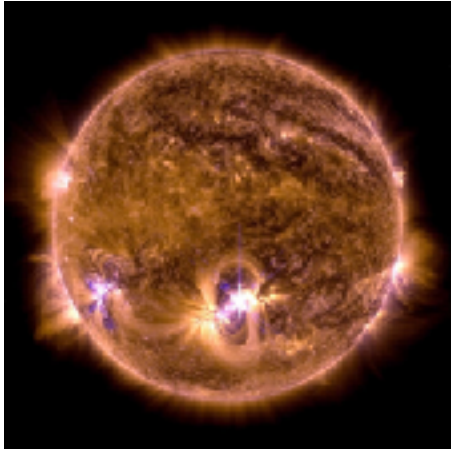
[O'Hare, 2021]



ν_e

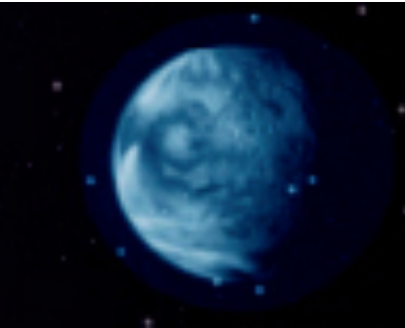
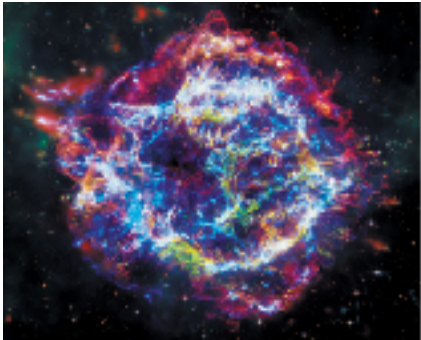
χ

太阳中微子

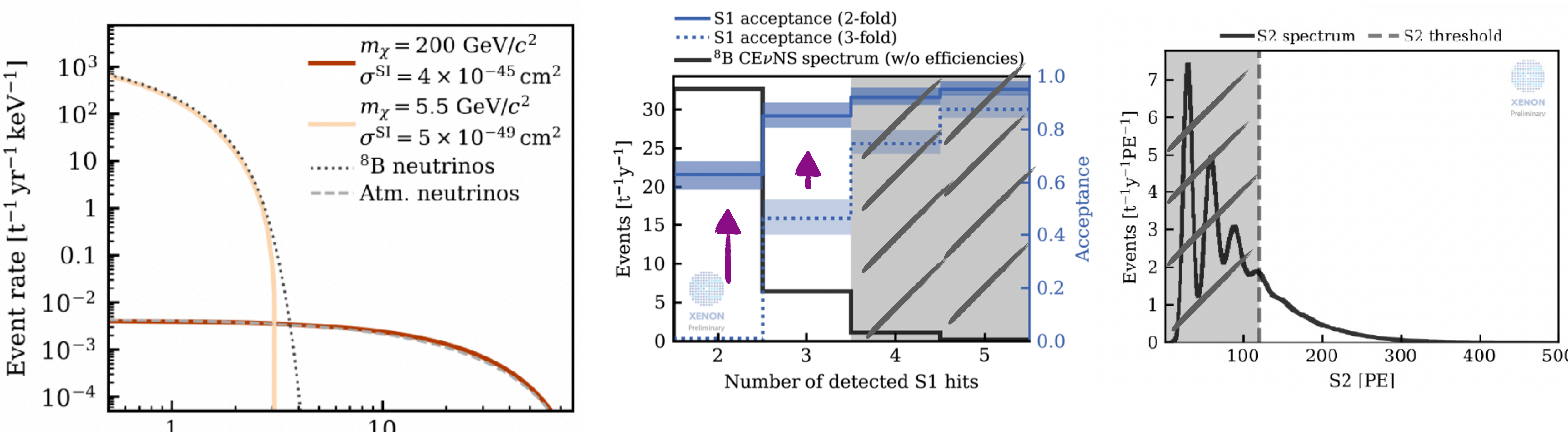


弥散超新星中微子

大气中微子



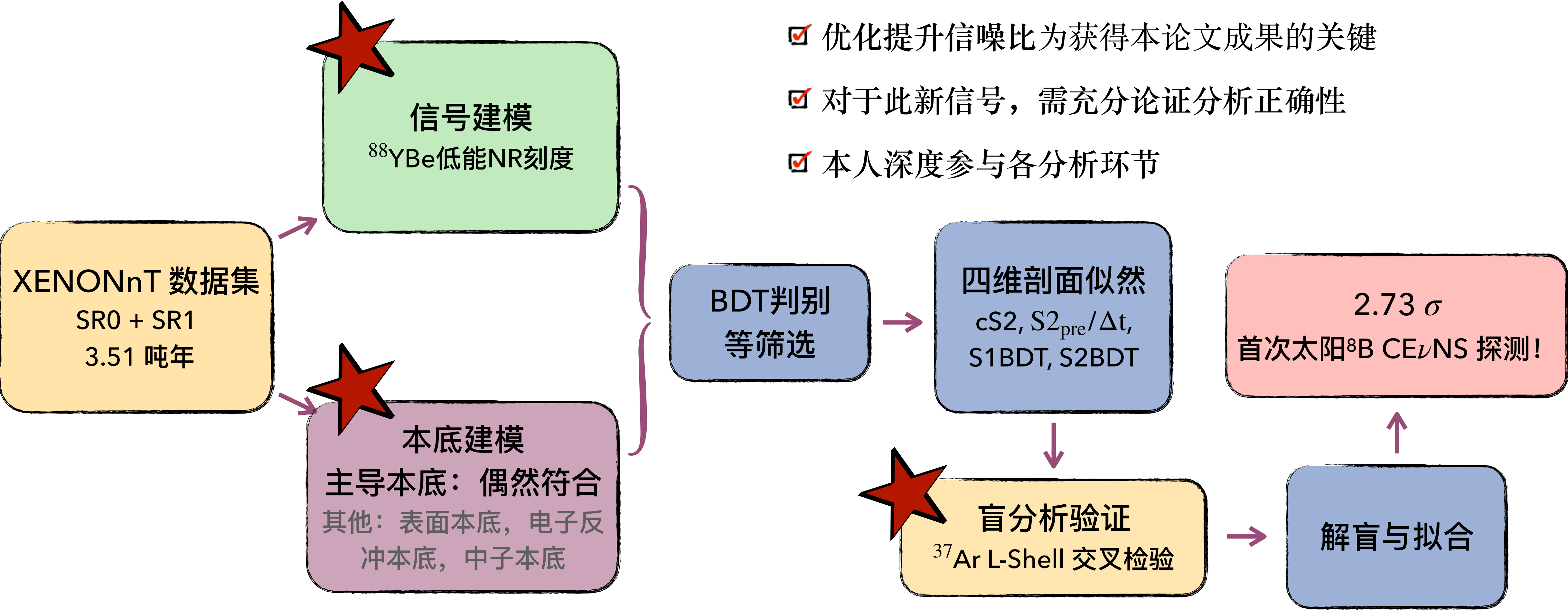
研究挑战：寻找能量极低的核反冲信号



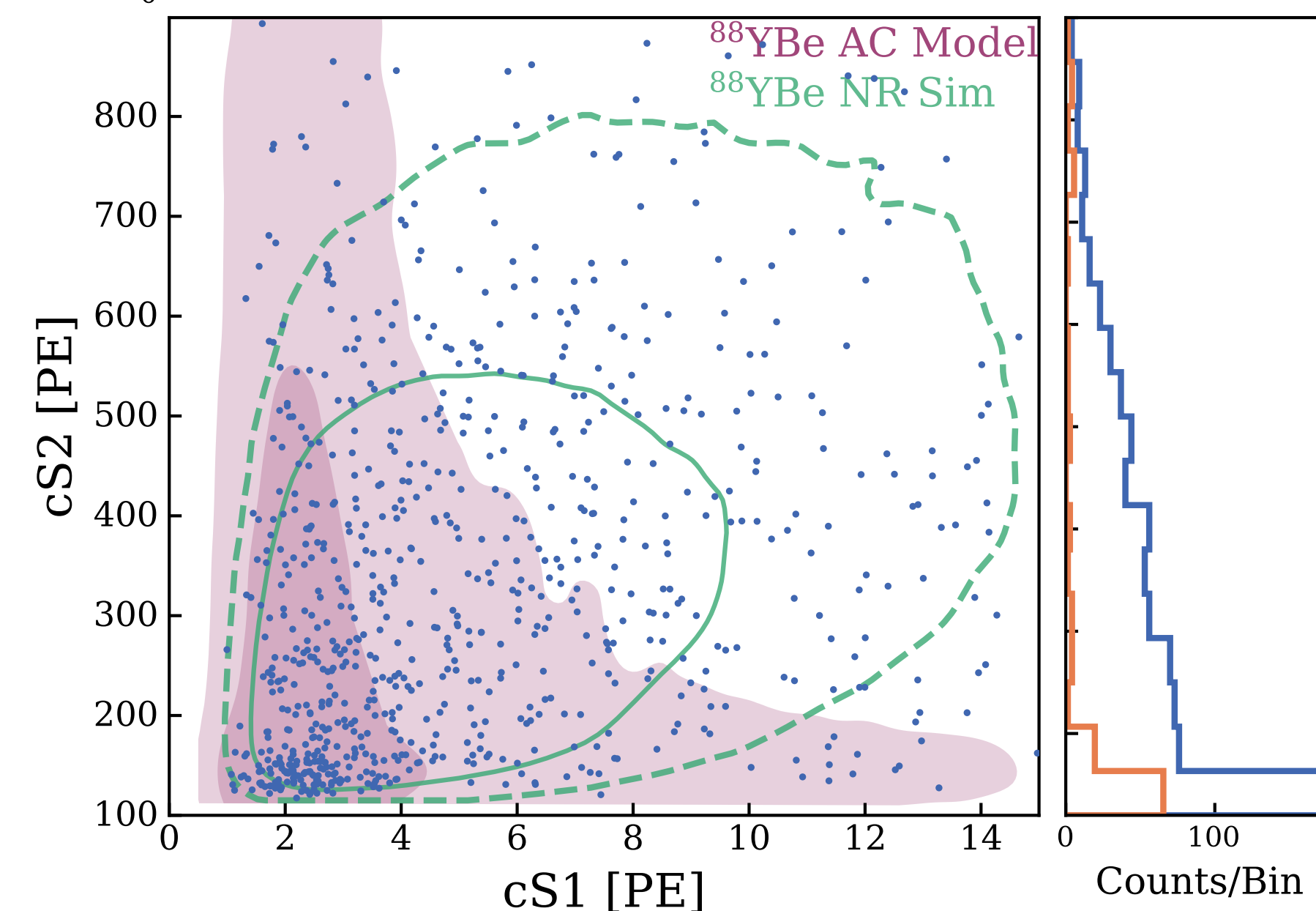
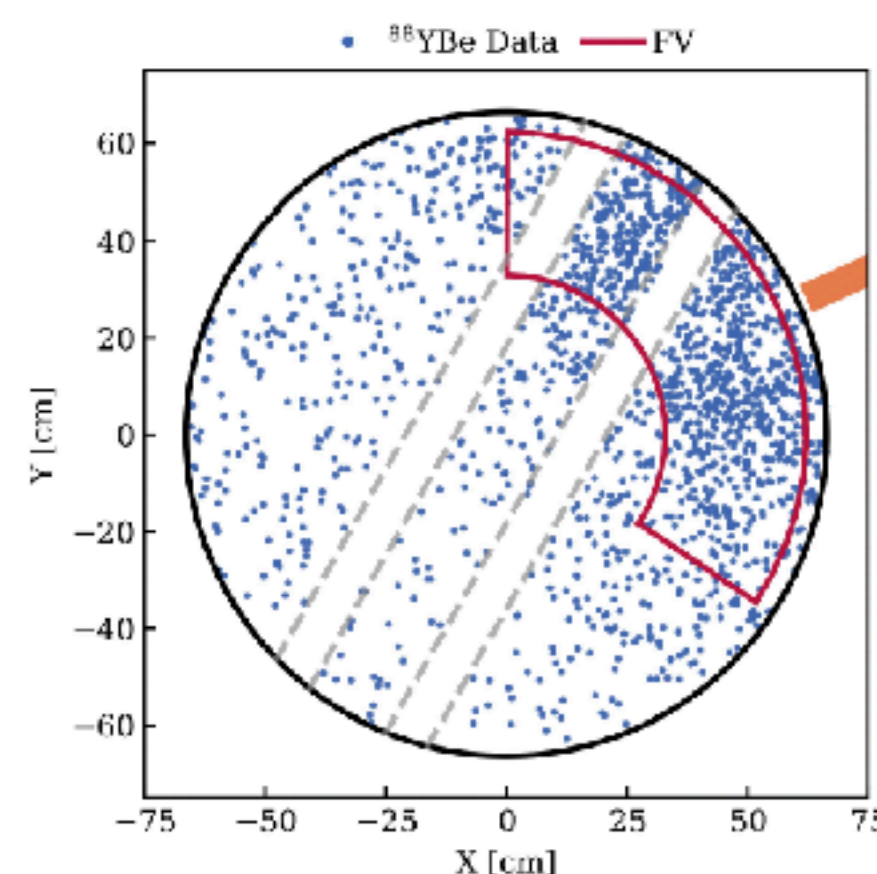
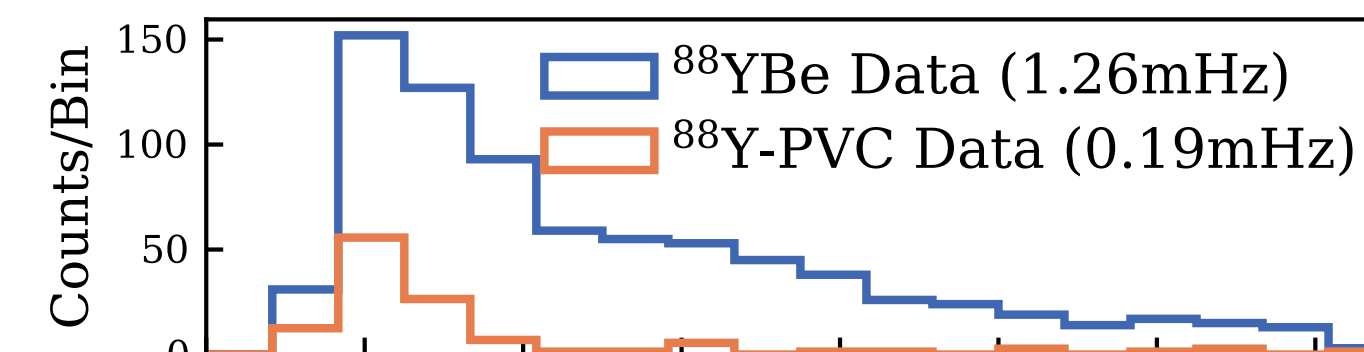
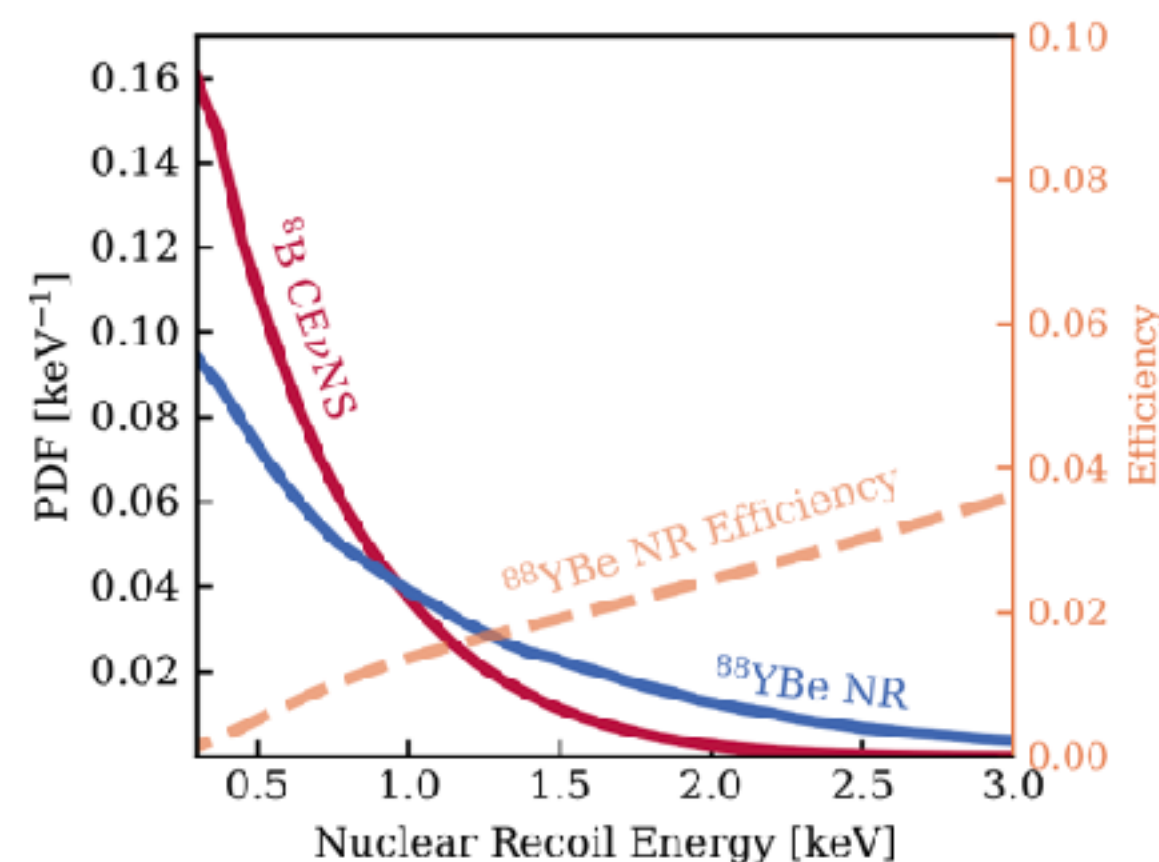
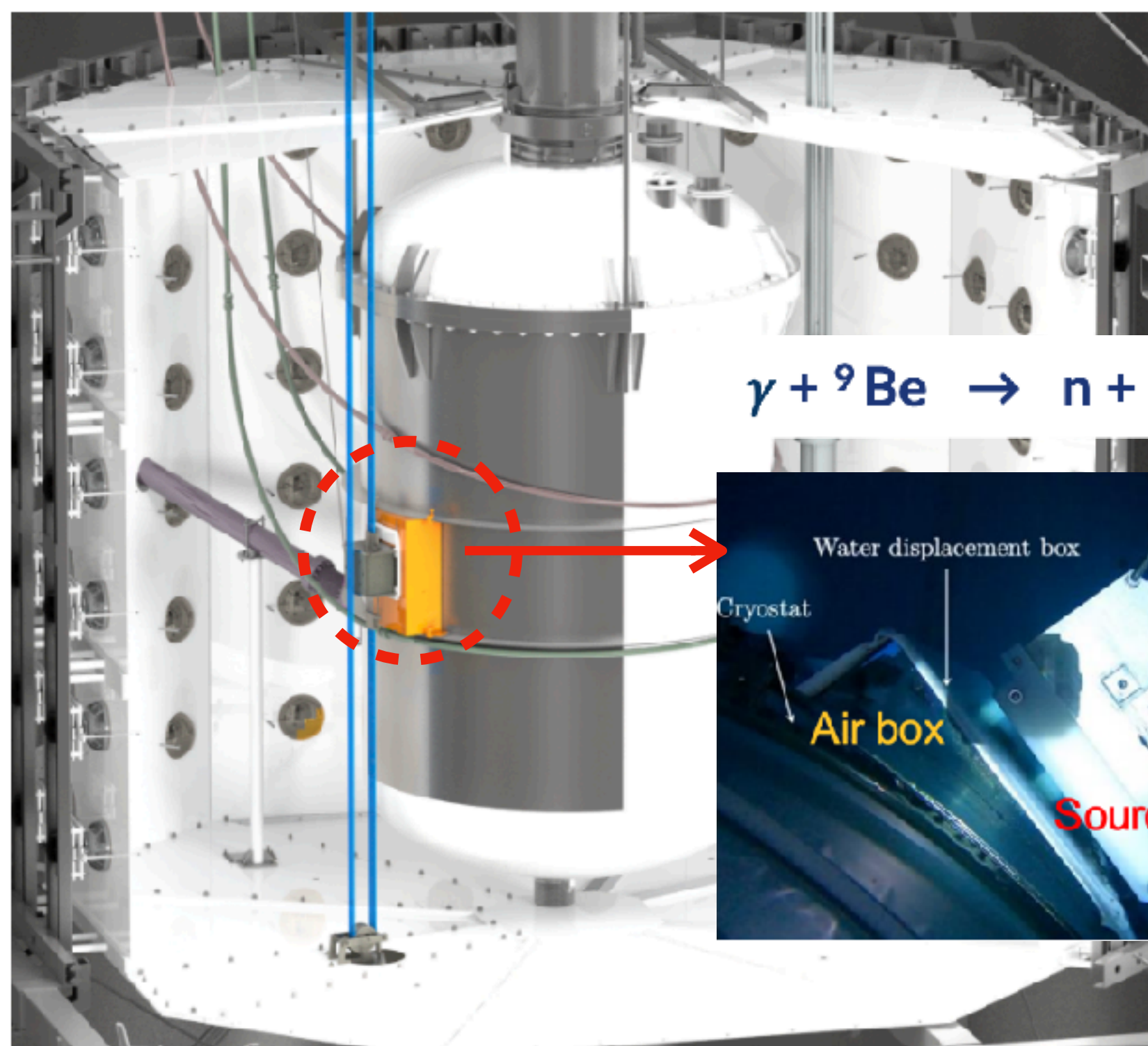
闪烁光信号（S1）：2 或3 个光子 + 电离信号（S2）：4 - 17 电子

- ☑ 散射事例率600次/吨年， $\mathcal{O}(1) \text{ keV}$ 核反冲信号
- ☑ 为提升信号探测效率，需要降低分析能量阈值，同时控制低能区本底！

研究方法：针对 ^8B $\text{CE}\nu\text{NS}$ 优化信噪比盲分析方法



^{88}YBe 中子源刻度检验低能核反冲信号探测能力



曝光约200小时

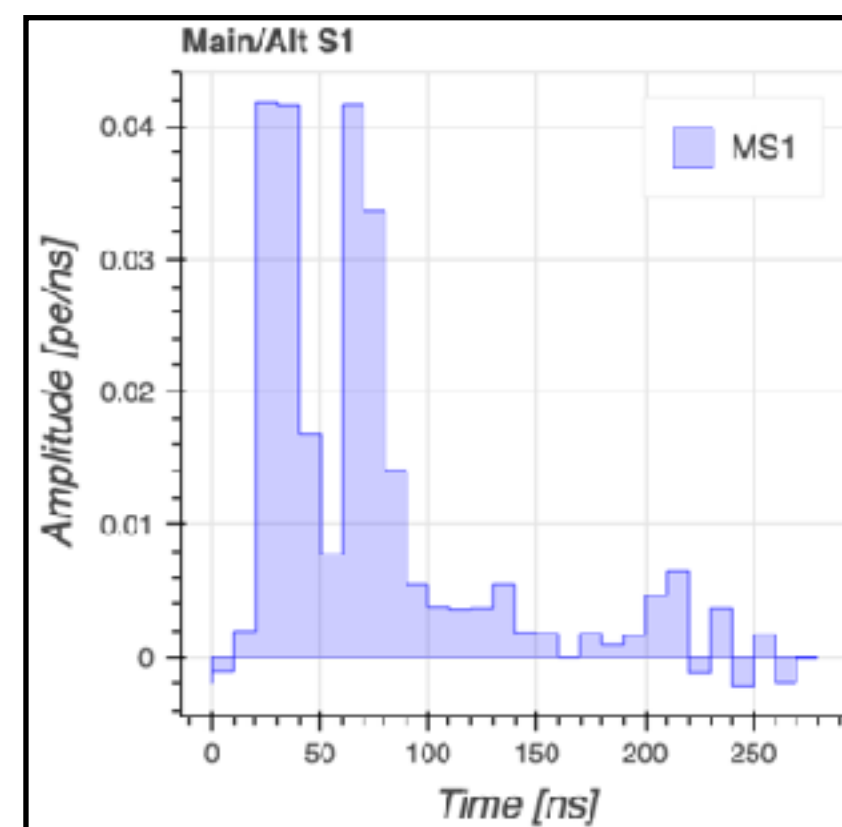
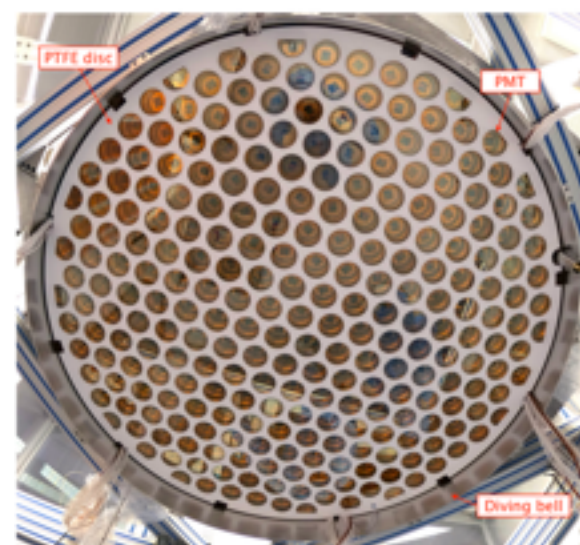
筛选后约400核反冲事例

☑ 利用 ^{88}YBe 源(154 keV单能中子)验证可测量 $\mathcal{O}(1)$ keV核反冲事件

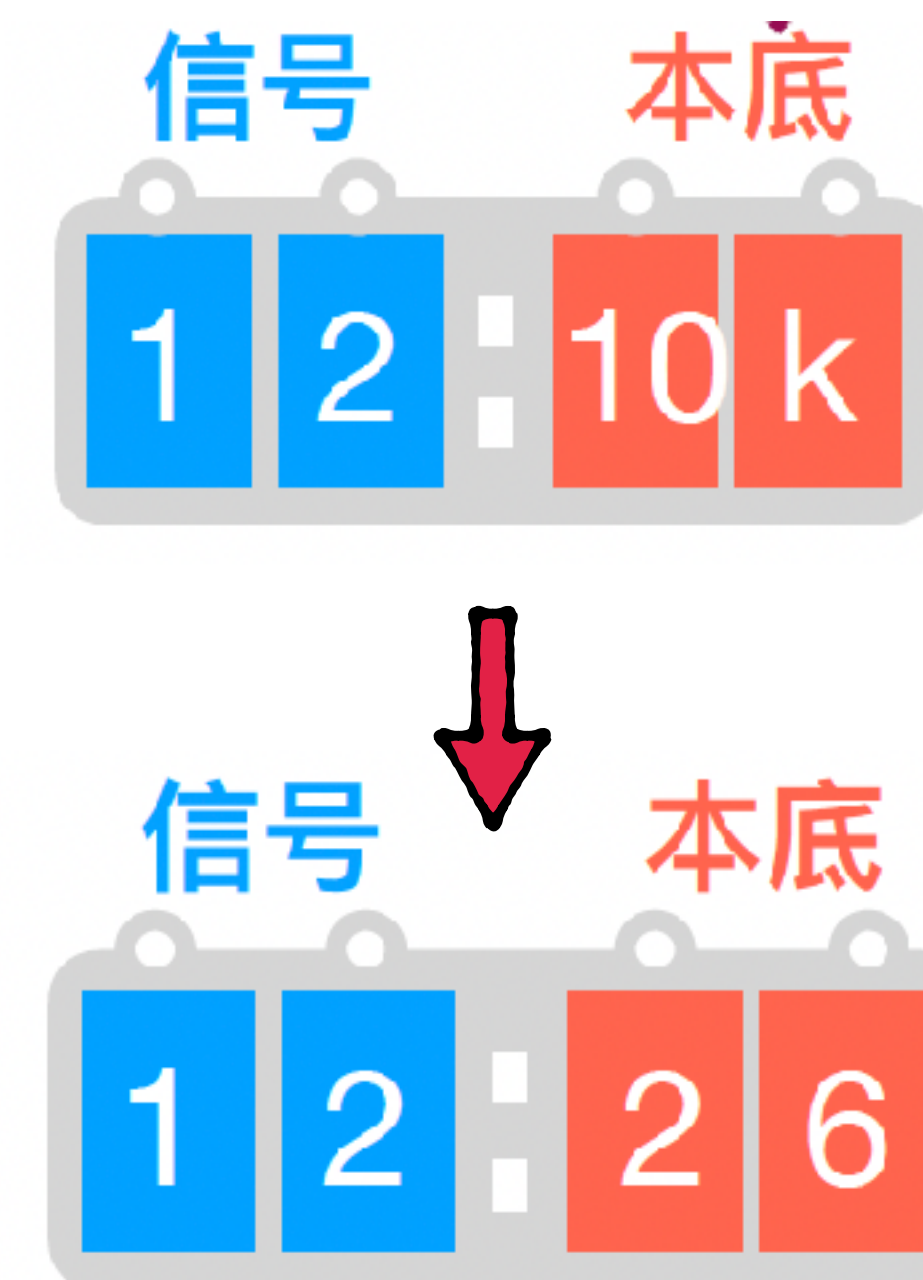
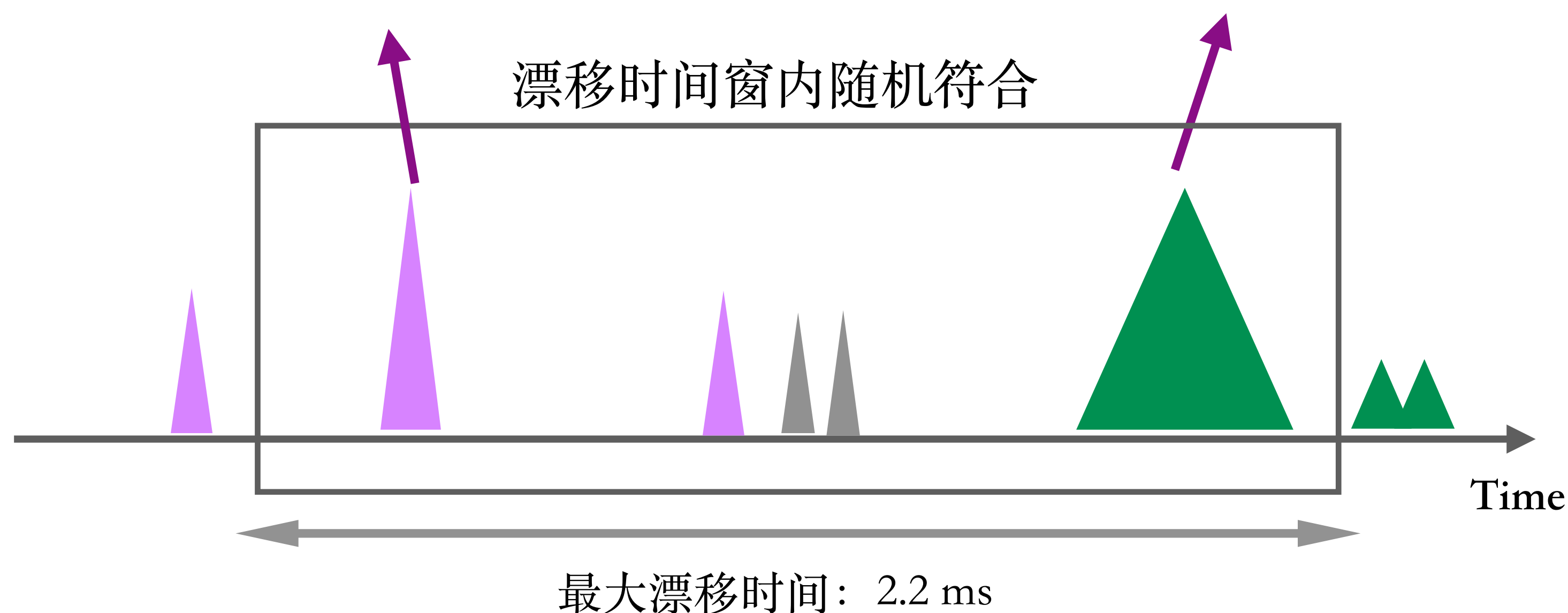
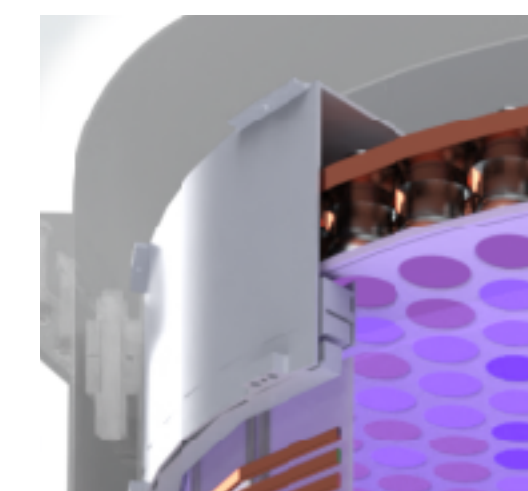
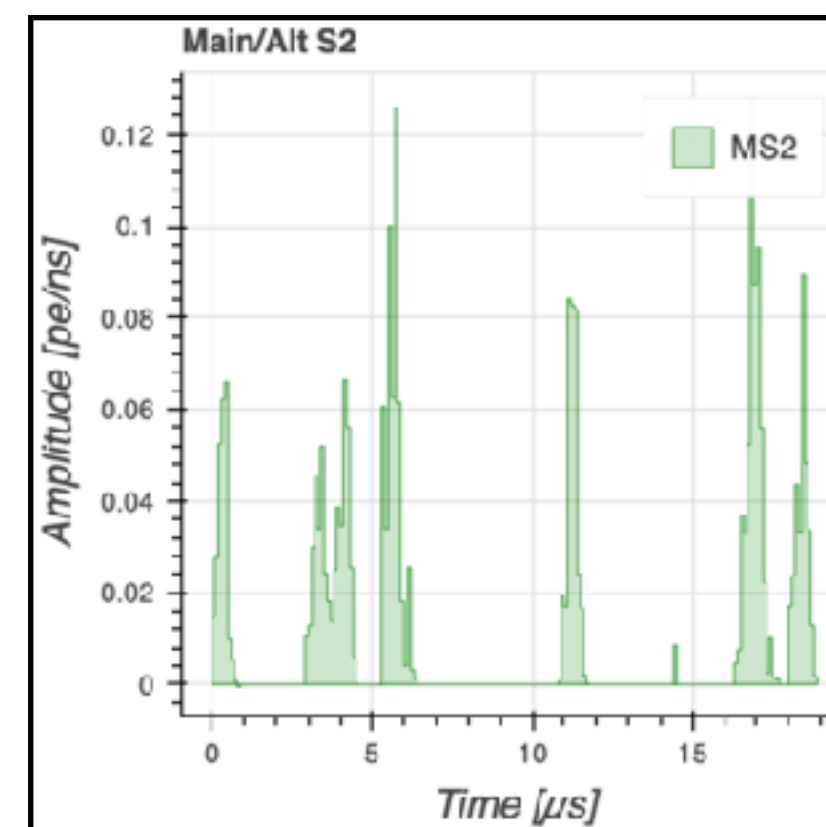
☑ 标定XENONnT电场(23V/cm)下液氙光电产生模型, 用于构建信号模型

^8B CEvNS 中的主导本底：偶然符合本底 (AC)

孤立 S1 (来自PMT lone-hit符合)



孤立 S2 (来自单电子符合、电极事件等)



AC建模与抑制：利用时空关联信息，构建新分析维度



清华大学
Tsinghua University

数据驱动模拟方法

选取孤立S1/S2信号

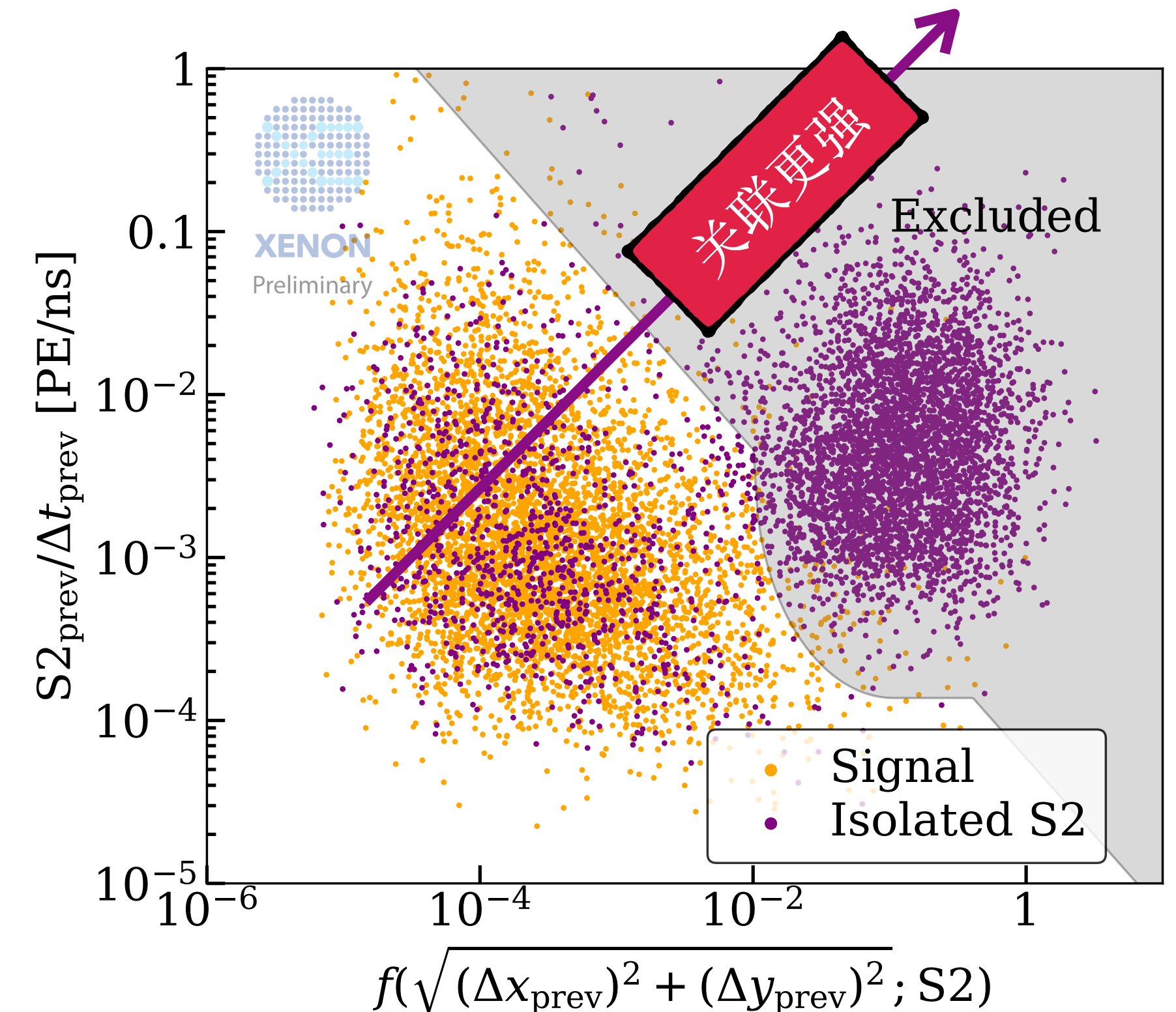
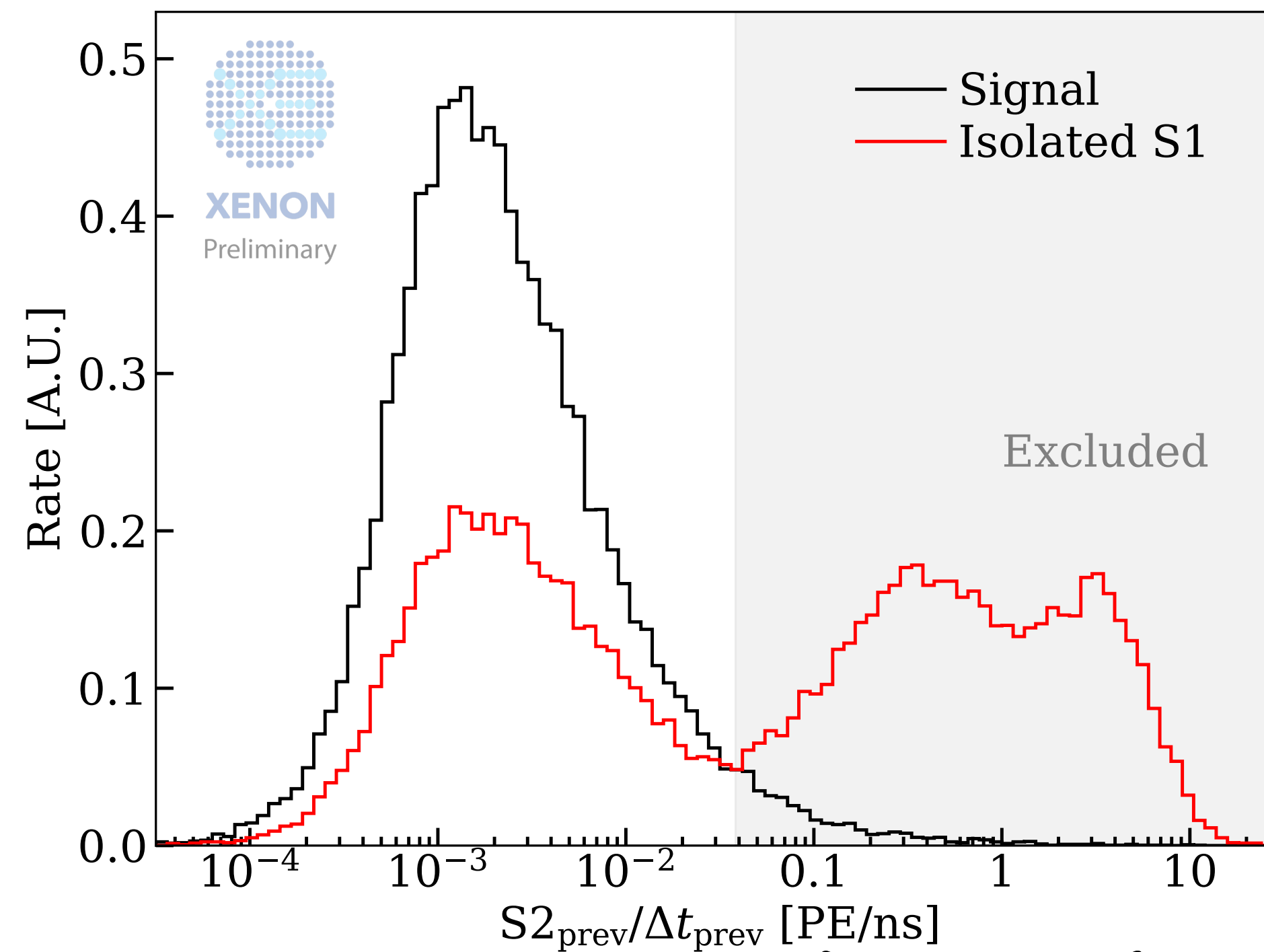
组合并重建AC事件

根据特征压低事例率

与高能事件时空关联

S1/S2波形信息

模型检验与误差评估



关联更强

- ☑ 利用与高能事件的时空关联，通过移除 20% 关联最强的事例，可将 AC 本底压低两个量级

AC建模与抑制：利用波形信息，开发机器学习方法

数据驱动模拟方法

选取孤立S1/S2信号

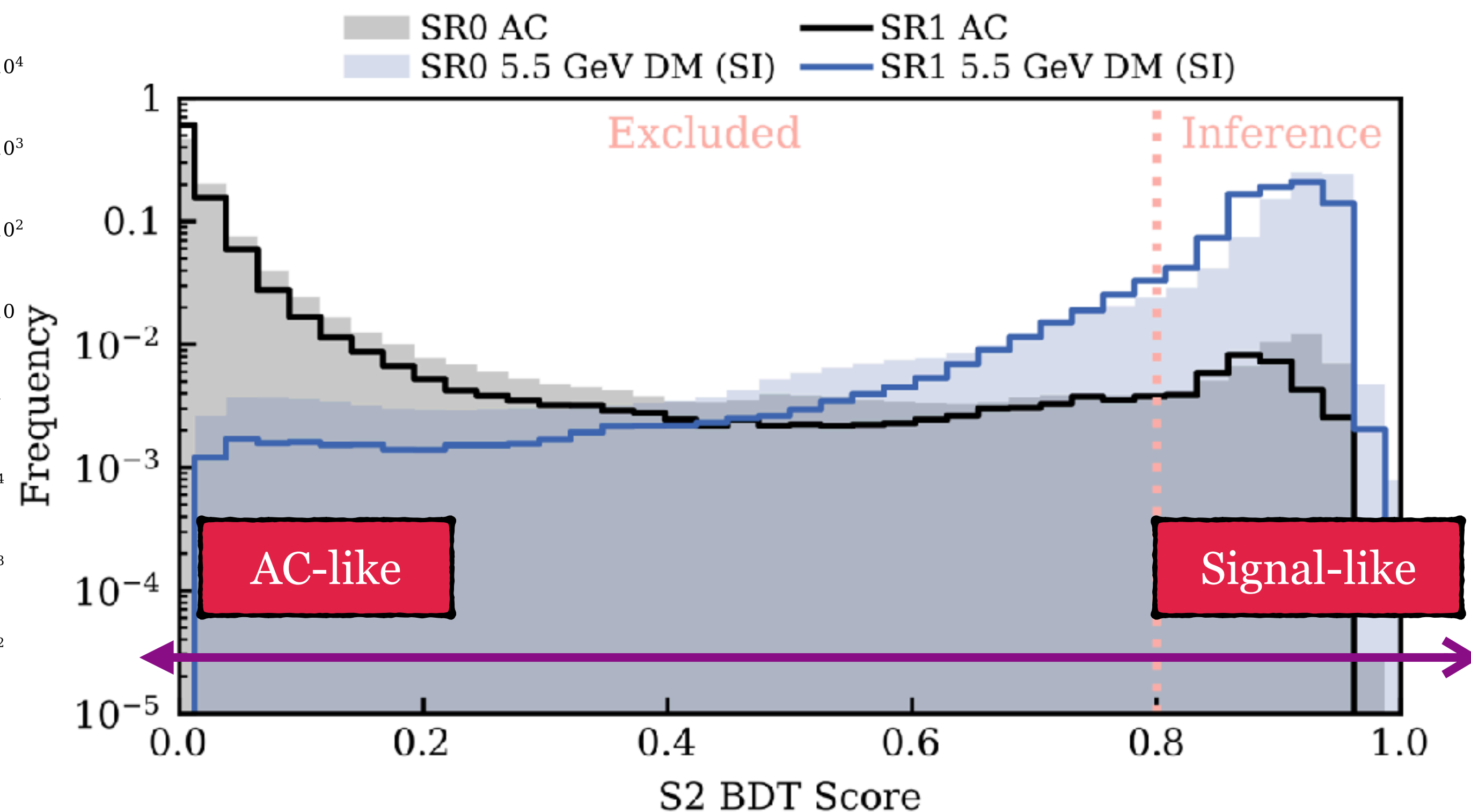
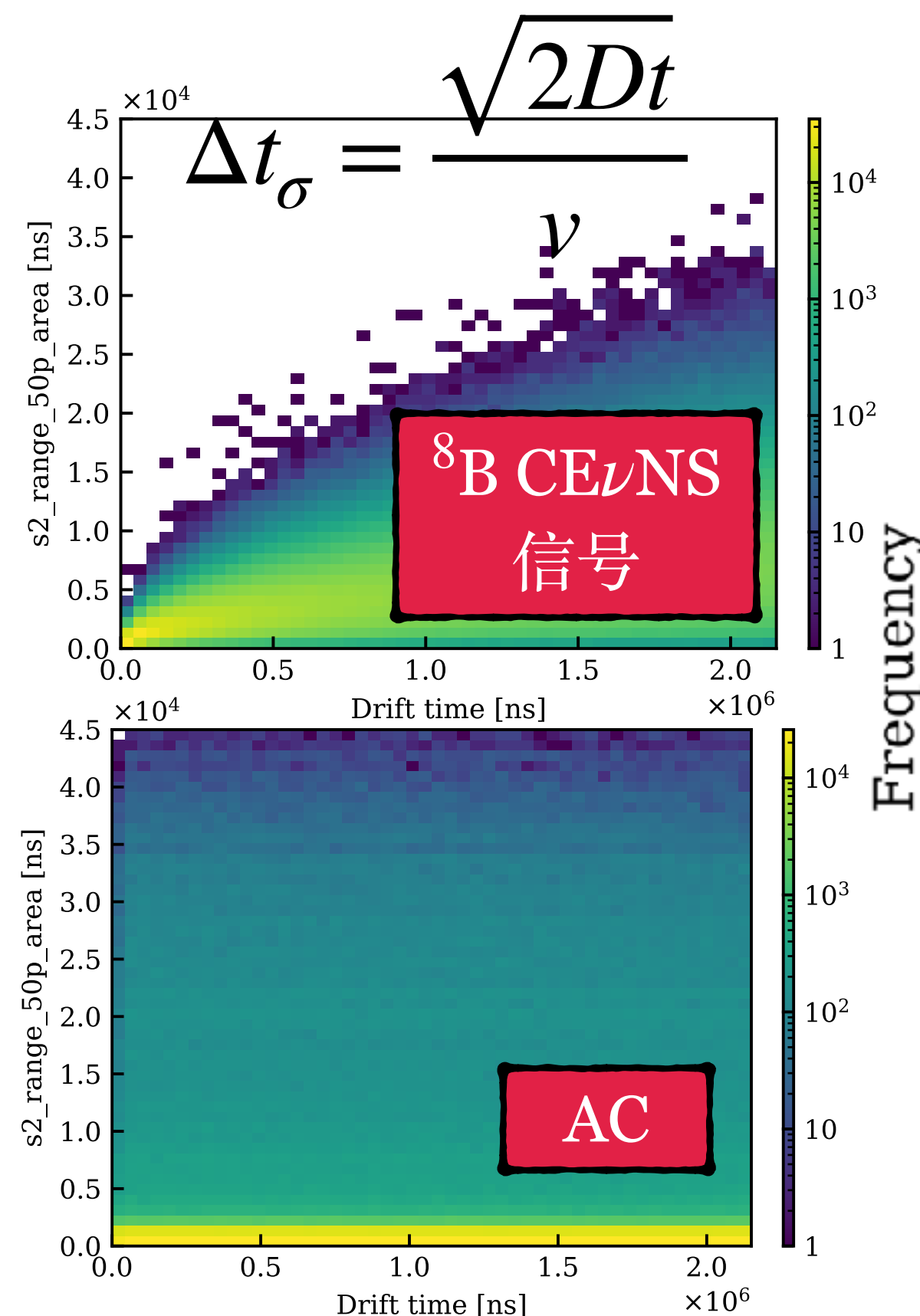
组合并重建AC事件

根据特征压低事例率

与高能事件时空关联

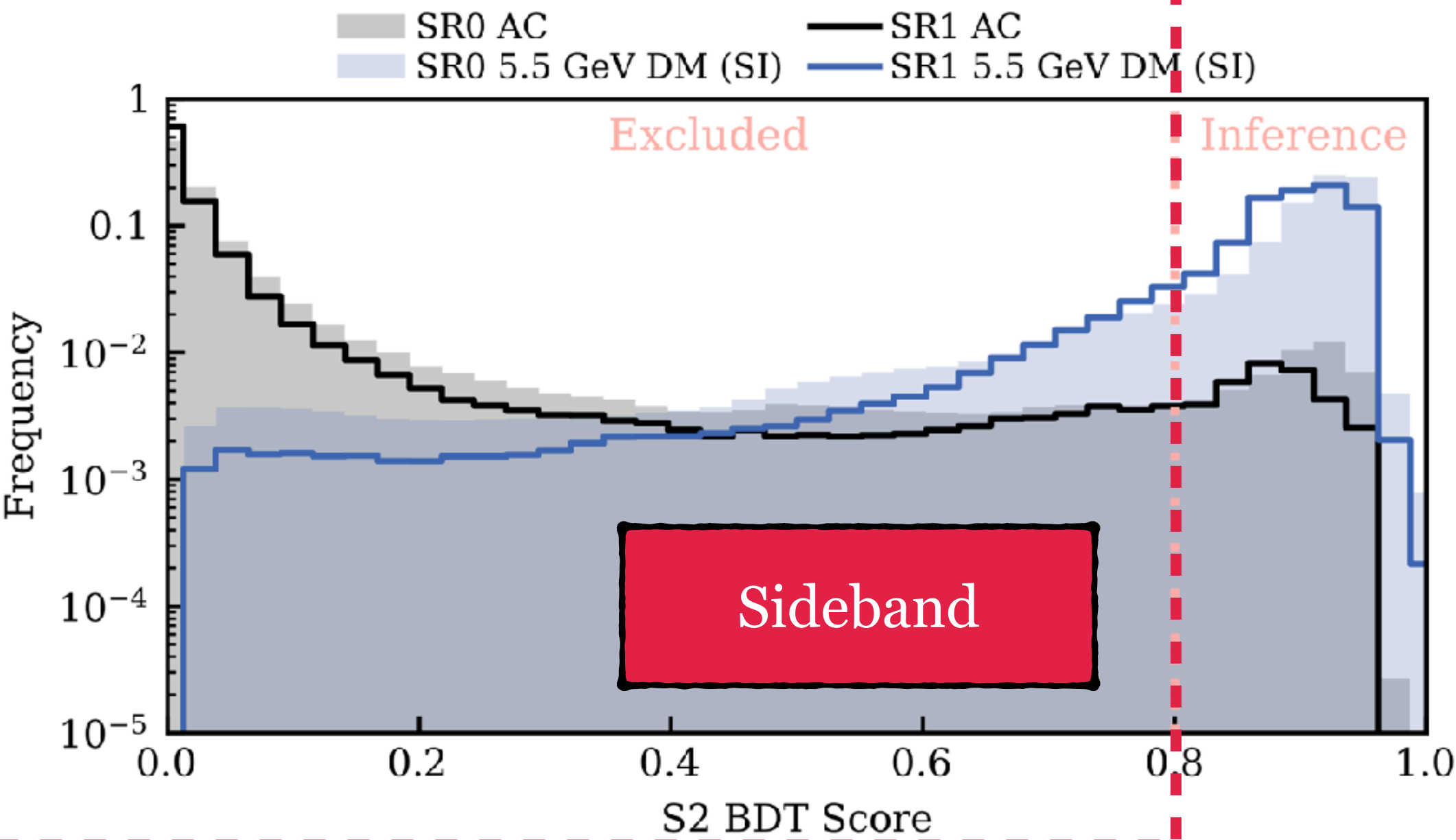
S1/S2波形信息

模型检验与误差评估

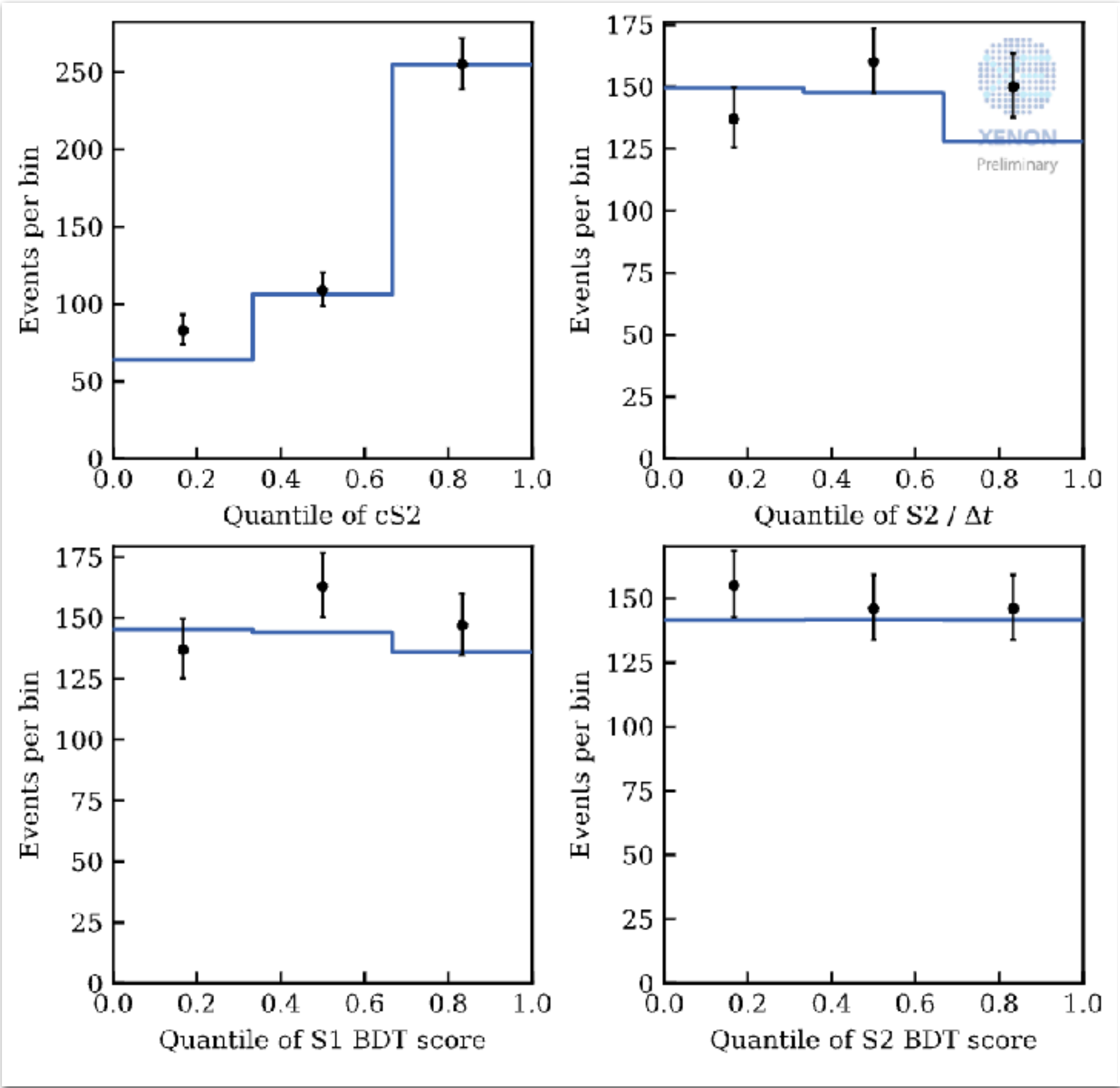


- ☑ S1/S2波形与漂移时间关联可区分信号与AC
- ☑ 利用信号与AC模拟数据集训练梯度提升决策树(GBDT) 对信号与AC进行分类；以80%信号接收率去除95%AC事件

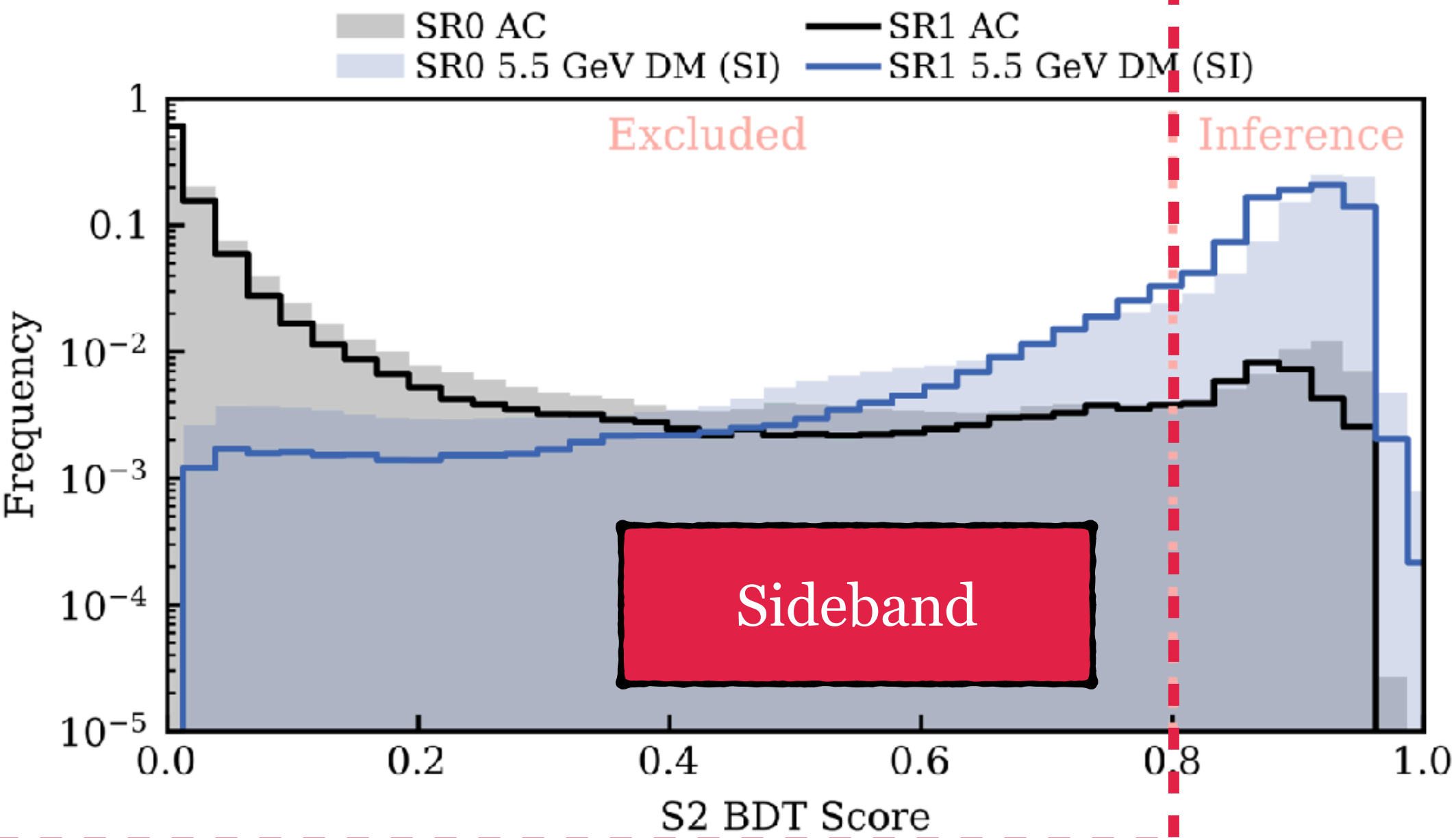
通过真实数据集检验AC模型，实现领域最好精度



	预测	观测	P-value (4D)	相对 不确定度
SR0	122.7	121	0.33	9.0%
SR1	302.5	326	0.25	5.8%

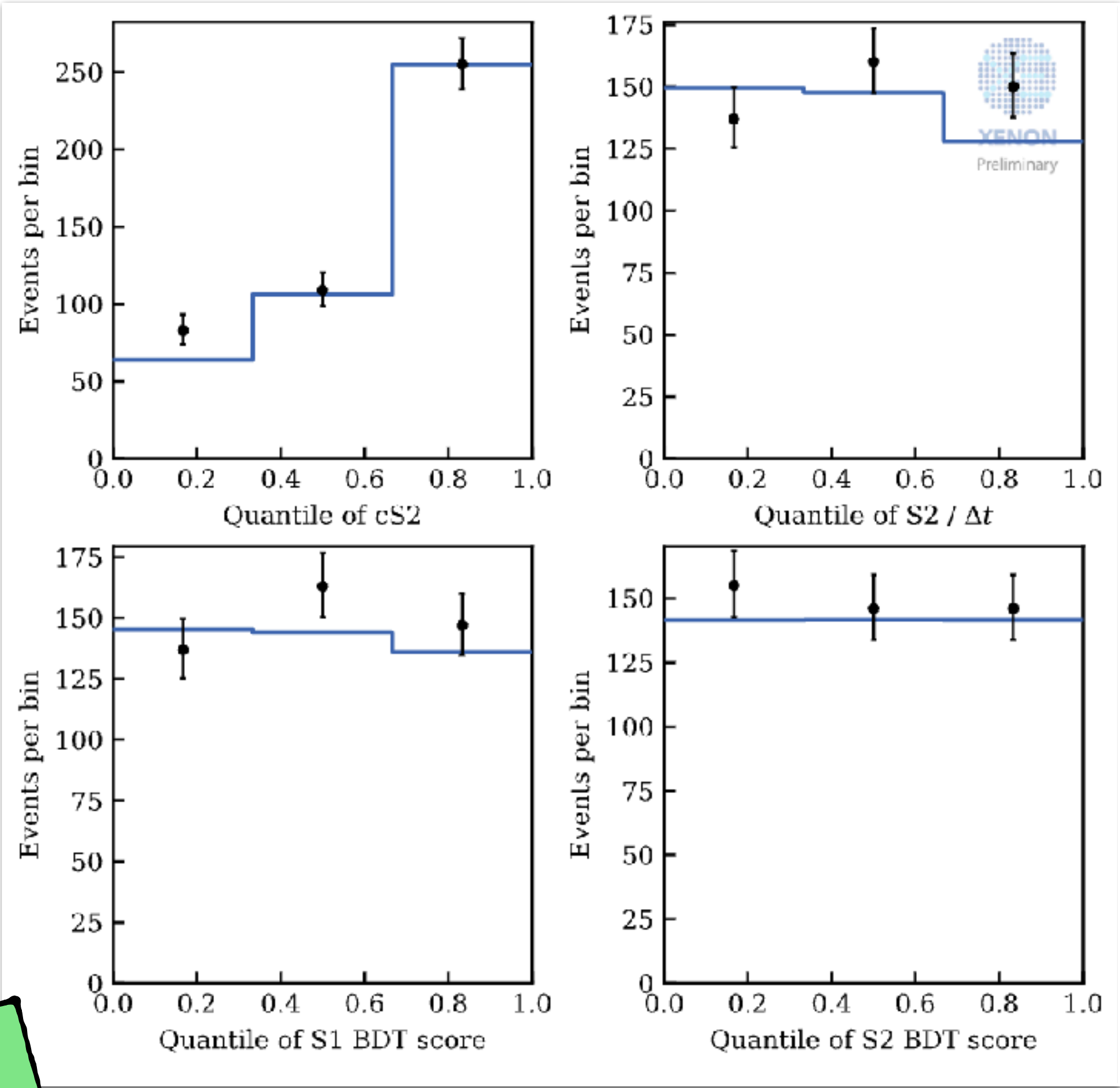


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	预测	观测	P-value (4D)	相对 不确定度
SR0	122.7	121	0.33	9.0%
SR1	302.5	326	0.25	5.8%

PASS



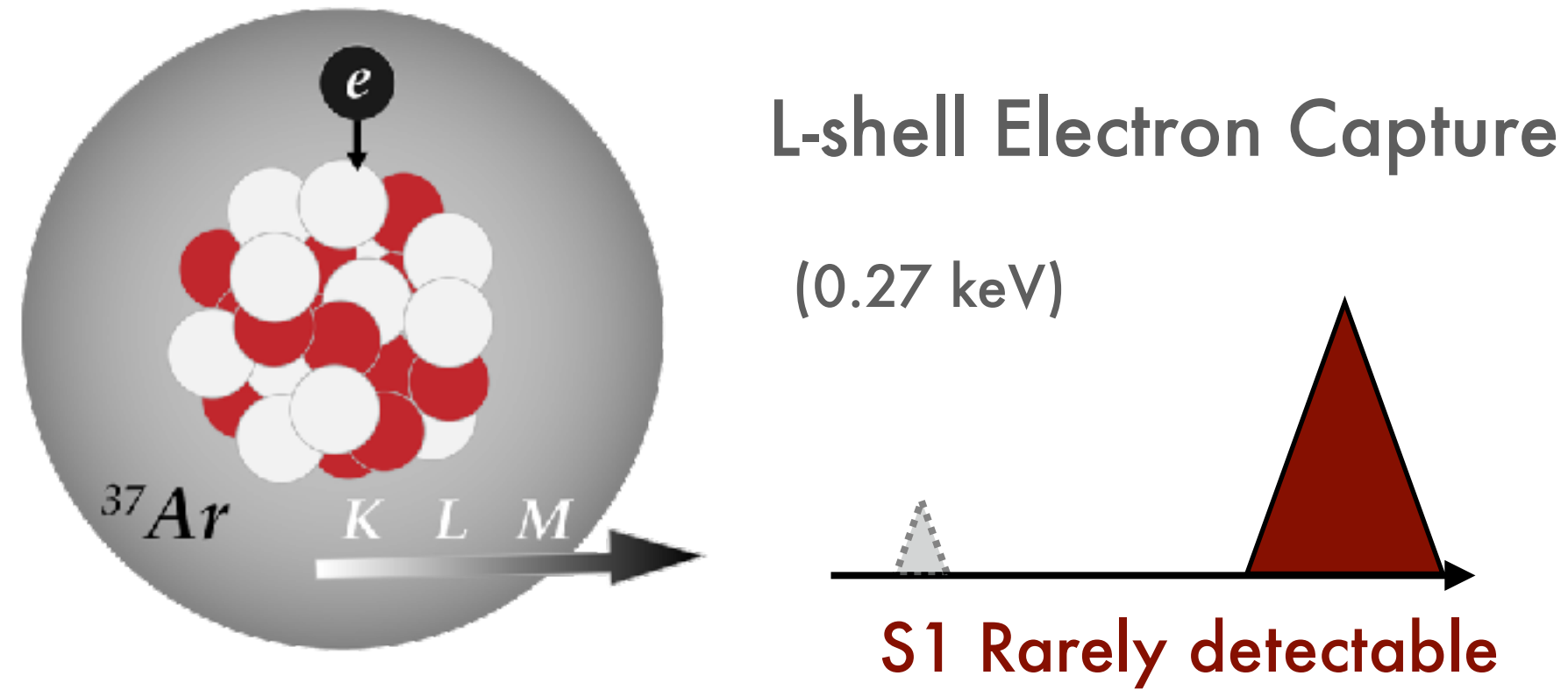
- ☑ ³⁷Ar PureAC: 预测1522.7 vs 观测 1459
- ☑ ³⁷Ar in-ROI: 预测 731.6 vs 观测 733

☑ AC模型实现液氩暗物质实验(包括 PandaX-4T, LZ)中最好精度

全链分析验证：首次探测 ^{37}Ar L-shell 电子俘获事件

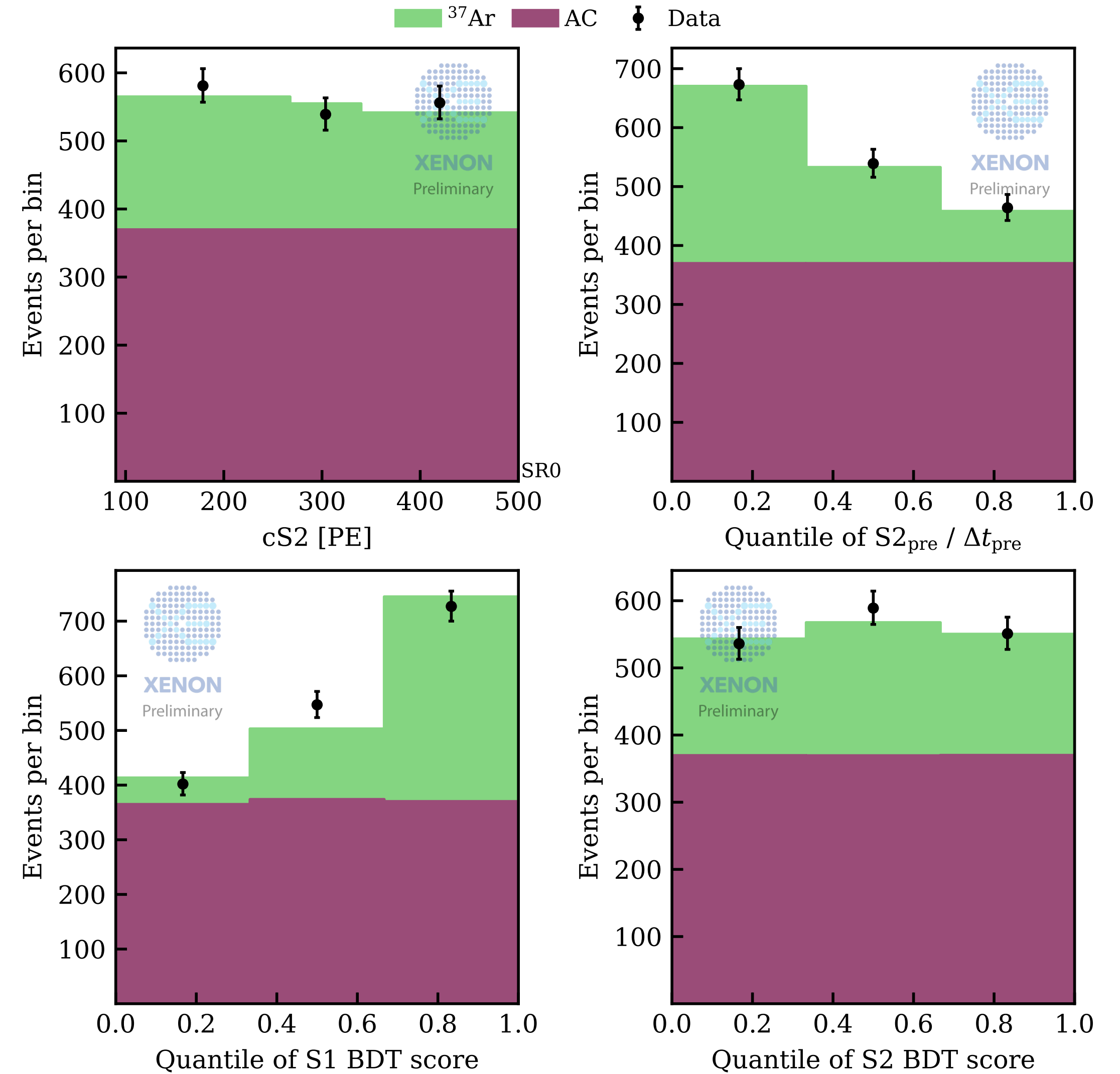


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- ☑ 从未测量的极低能ER (0.27 keV) 信号
- ☑ ^8B CE ν NS分析揭盲前的重要检验
- ☑ 预测AC 1062 ± 53 ，观测1676事件，四维拟合优度检验 p-值: 0.92

○ 论文准备中（本人为共同通讯作者）

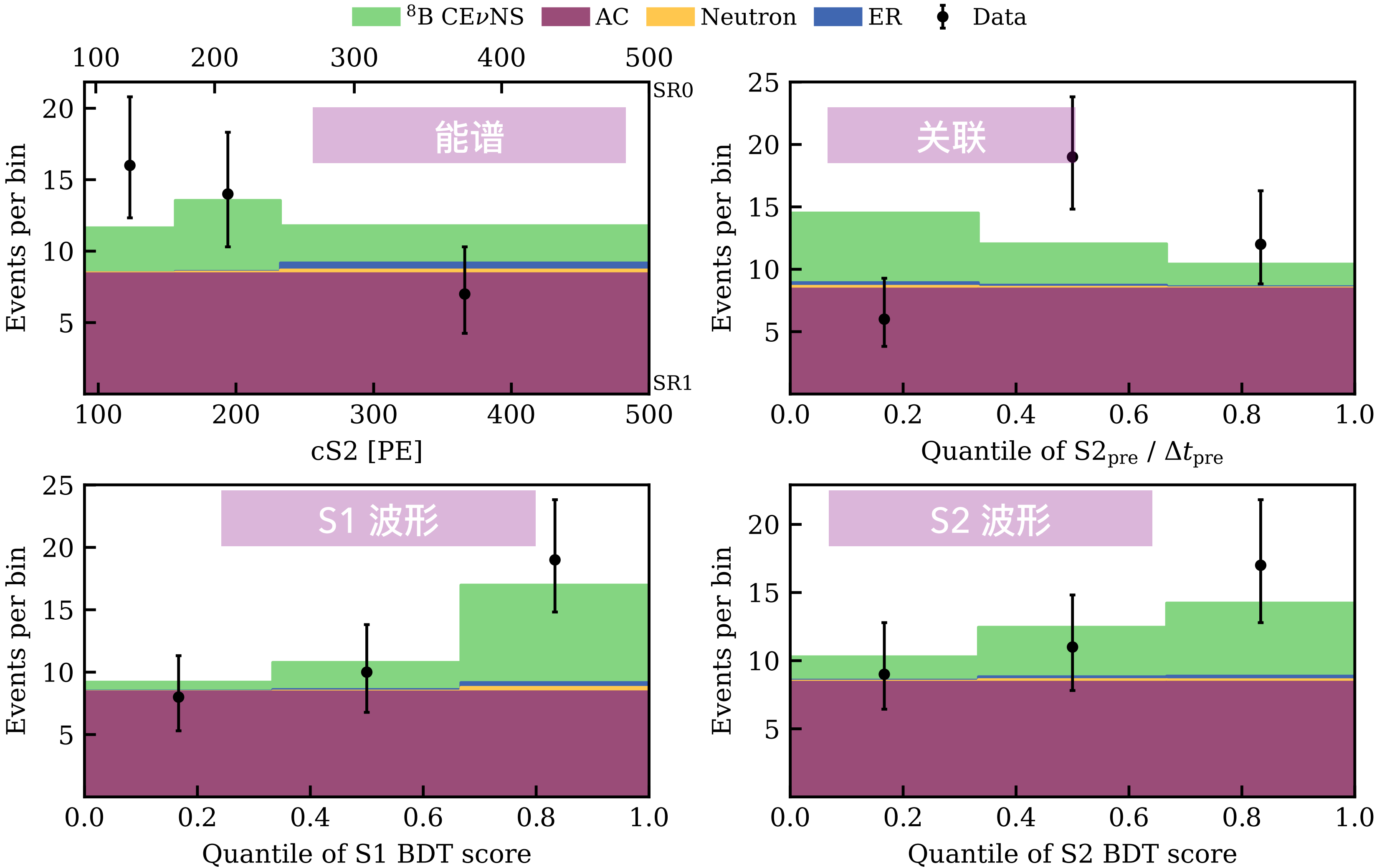


最终揭盲：3.51吨·年，37个事件，2.73 σ 显著度

成分	预期事例数
AC - SR0	7.5 ± 0.7
AC - SR1	17.8 ± 1.0
ER	0.7 ± 0.7
NR	0.5 ± 0.3
Total Background	26.4 ± 1.4
^8B	11.9 ± 4.5

☑统计显著度 **2.73 σ**

☑ ^8B 信号强度最佳拟合值
 $10.7^{+3.7}_{-4.2}$



XENONnT: The Smallest

Solar Neutrino Detector

Super-Kamiokande
(50 kt)

KamLAND
(1000 t)

SNO
(1000 t)

Borexino
(270 t)

XENONnT: The Smallest

Solar Neutrino Detector

Super-Kamiokande
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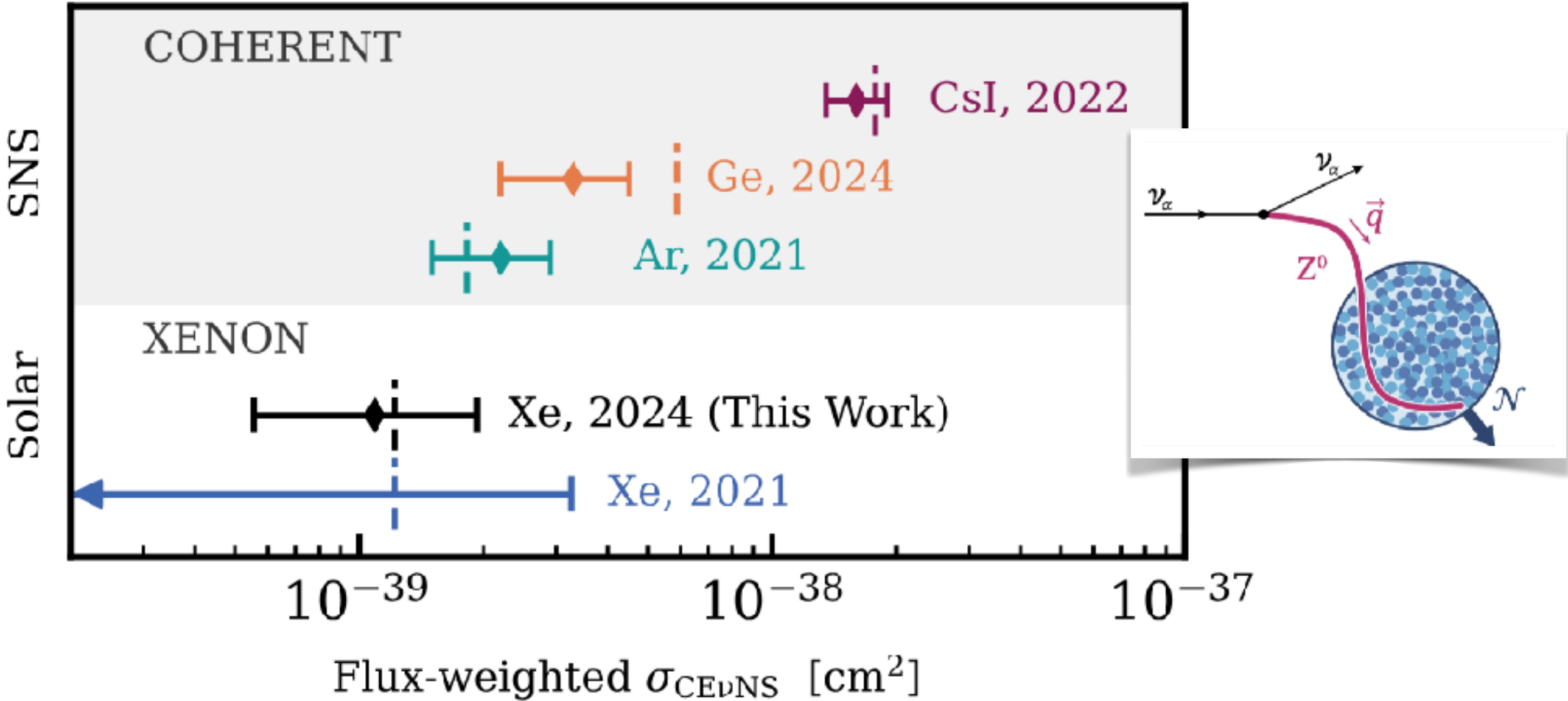
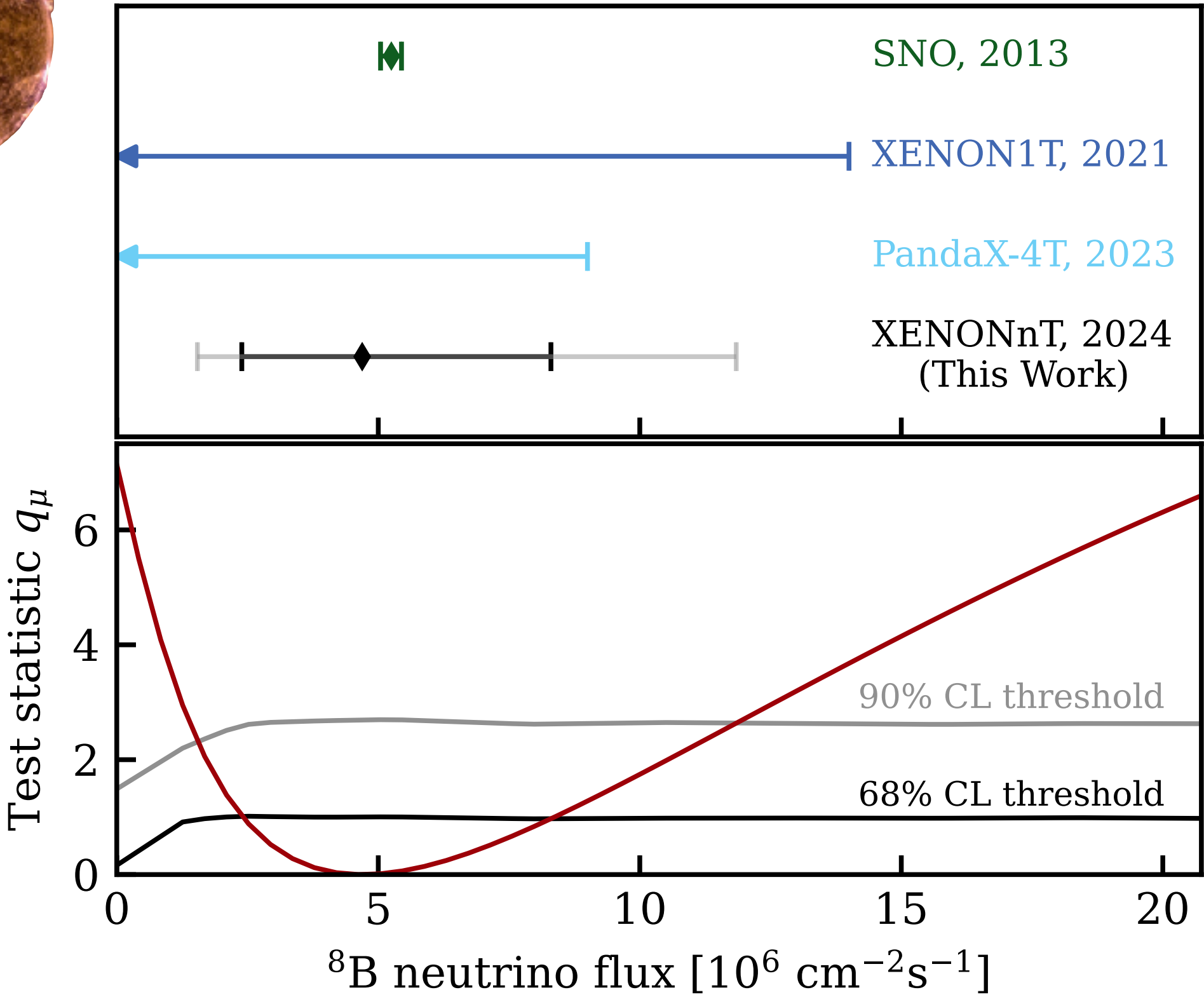
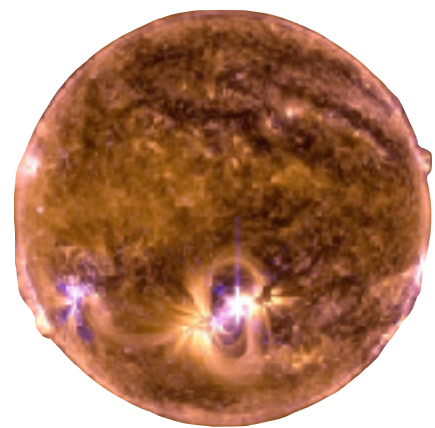
Borexino
(270 t)

XENONnT
(5.9 t)



测量⁸B中微子流强与CE ν NS过程截面

信号强度 $\propto \Phi_B, \propto \frac{d\sigma}{dE_R}$



- 首次 在暗物质实验中探测到 ^8B CE ν NS
- 首次 通过弹性核反冲测量天体中微子
- 首次 测量氙原子核 CE ν NS 过程

Physics

ABOUTBROWSEPRESSCOLLECTIONS

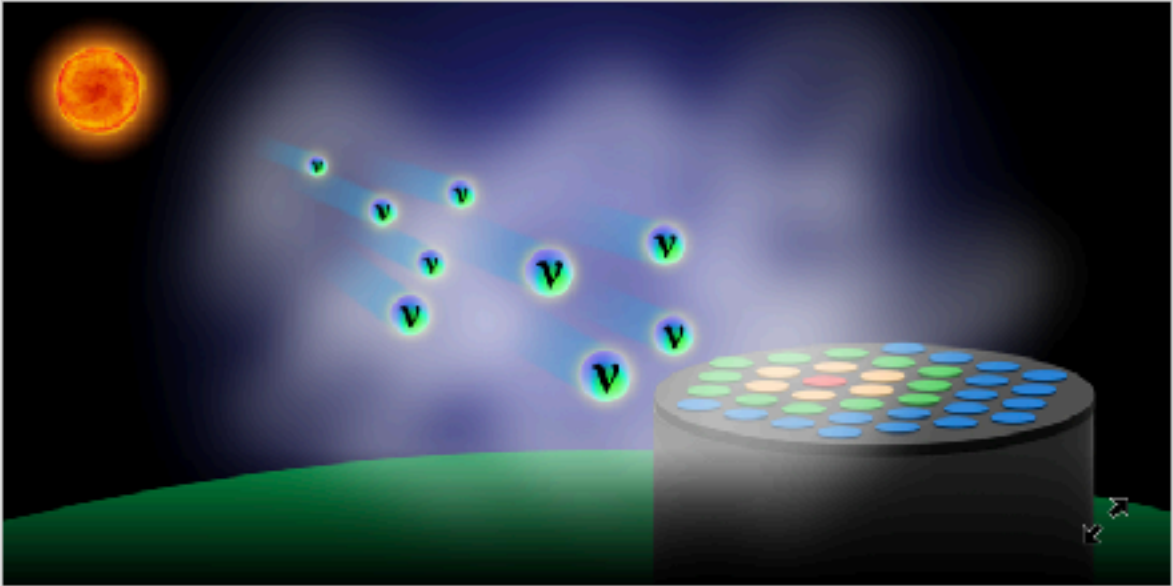
Search articles

RESEARCH NEWS

First Glimpses of the Neutrino Fog

November 7, 2024 • Physics 17, 161

Two dark matter searches report that their detectors have likely recorded neutrinos coming from the Sun—spotting the “neutrino fog” that could imperil future dark matter searches.



NPS/Alan Stonebraker

1.

Z. Bo *et al.* (PandaX Collaboration), “First indication of solar ^8B neutrinos through coherent elastic neutrino-nucleus scattering in PandaX-4T,” *Phys. Rev. Lett.* **133**, 191001 (2024).
2.

E. Aprile *et al.* (XENON Collaboration), “First indication of solar ^8B neutrinos via coherent elastic neutrino-nucleus scattering with XENONnT,” *Phys. Rev. Lett.* **133**, 191002 (2024).

☑ Physics Magazine等科学传媒专访

“这一发现验证了暗物质实验难以置信的灵敏度。”



Dan Hooper
威斯康星大学粒子天体中心主任
费米国家实验室天体物理理论部主任

“非常确信这是对中微子雾的成功探测。”

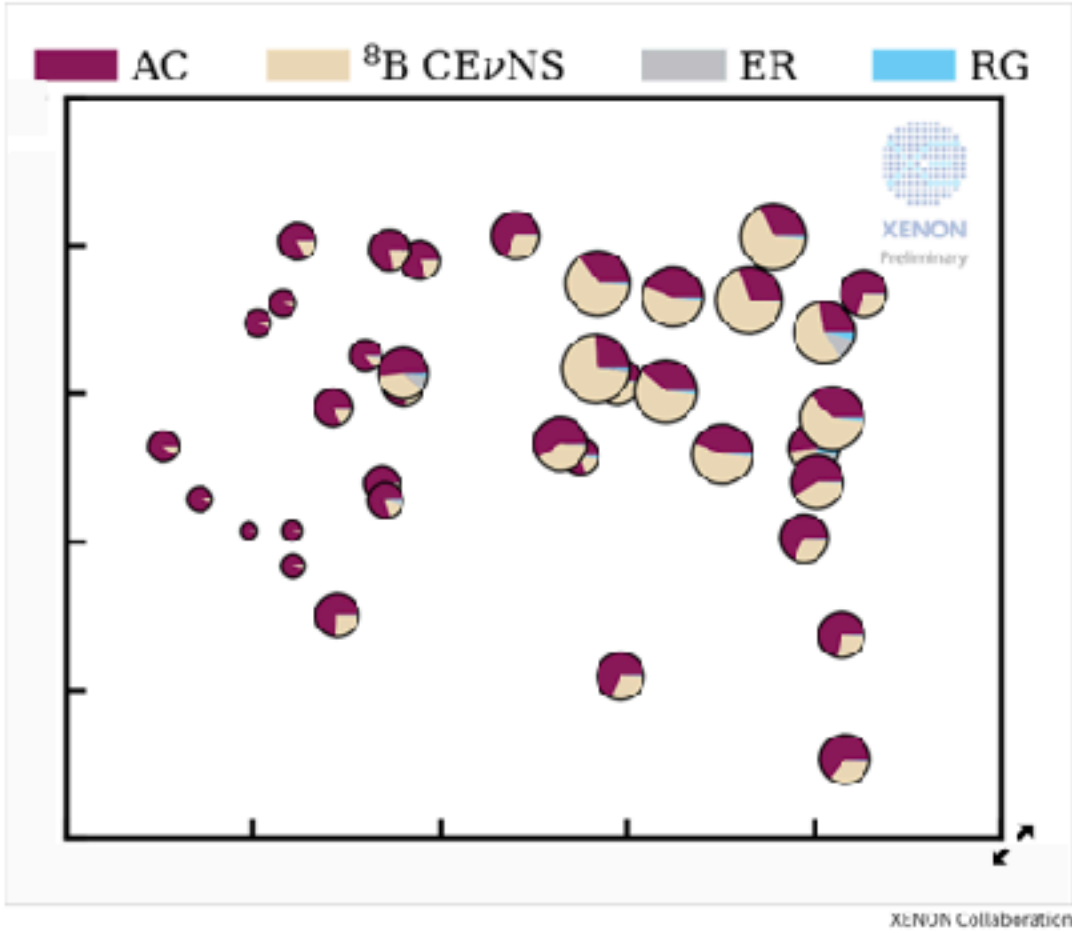


Kate Scholberg
杜克大学物理系教授
COHERENT实验发言人

“一项里程碑式的成就；开启了中微子测量新领域。”



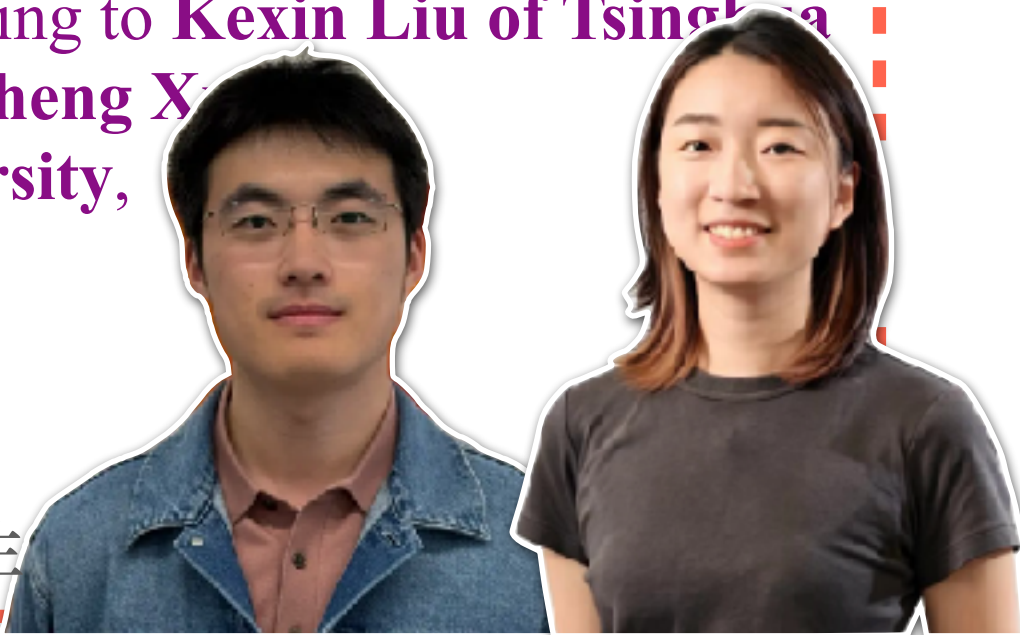
Elisabetta Barberio
墨尔本大学物理系教授
澳大利亚暗物质粒子物理卓越中心主任



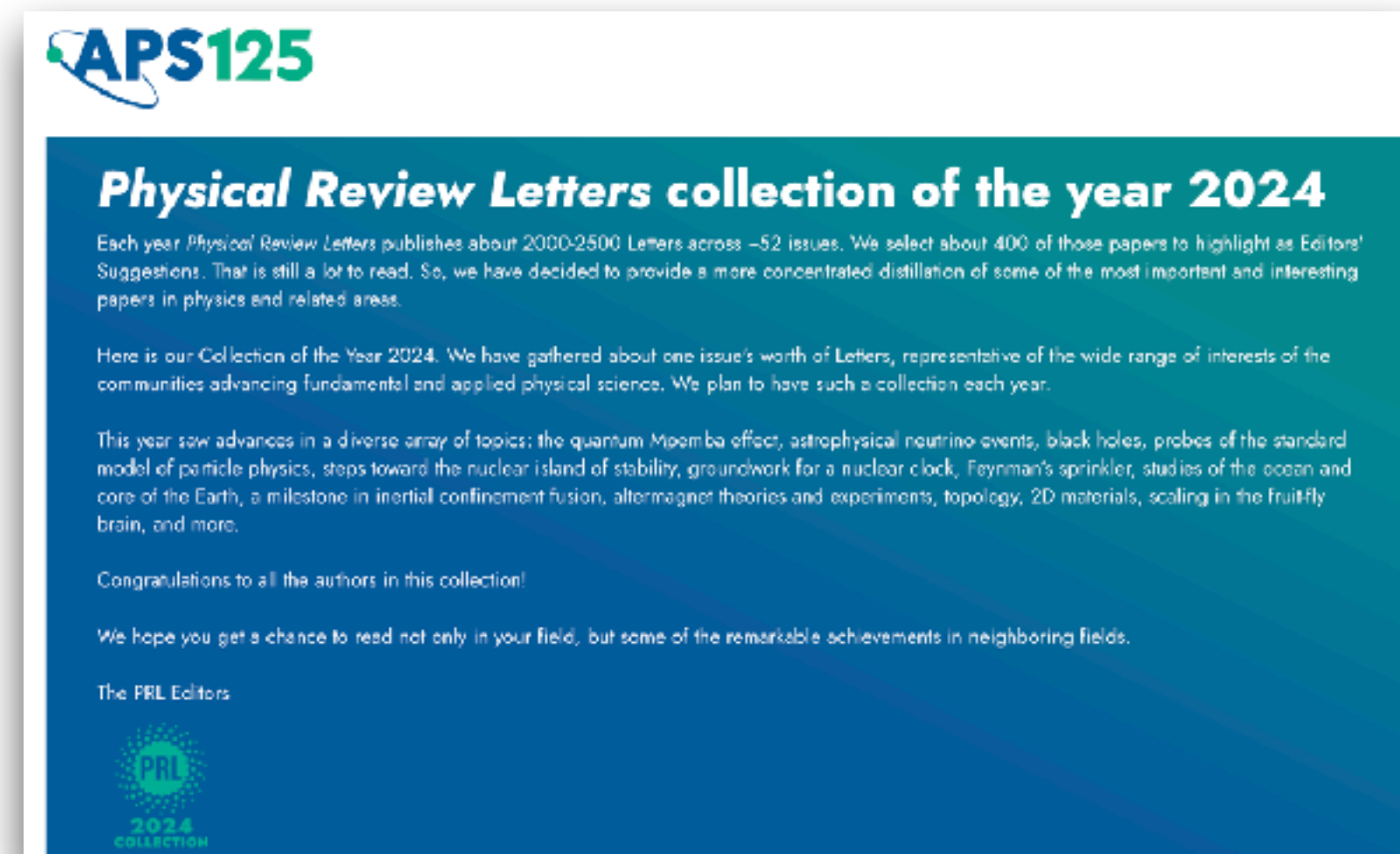
Through a machine-learning data-analysis approach, XENONnT determined the likely origin of 37 observed events, assigning 26 events to background sources and 11 events to CEvNS. Each event is represented by a pie chart where the different slices signify the relative statistical contributions of boron-8 CEvNS (beige) and several backgrounds (purple, gray, and blue).

“XENONnT deployed an extensive machine-learning-based data analysis that allowed the team to isolate about 11 CEvNS signals from different types of backgrounds even without full knowledge of the physical origin of such backgrounds, according to Kexin Liu of Tsinghua University and Dacheng Xu of Columbia University, who worked on such analysis.”

徐大成
哥伦比亚大学博士生

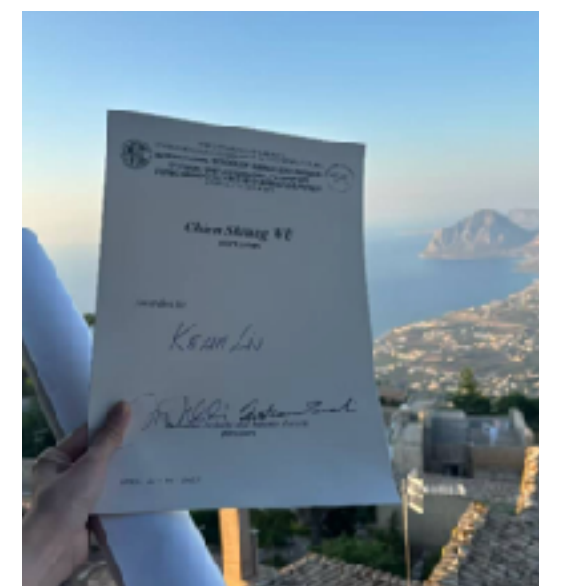
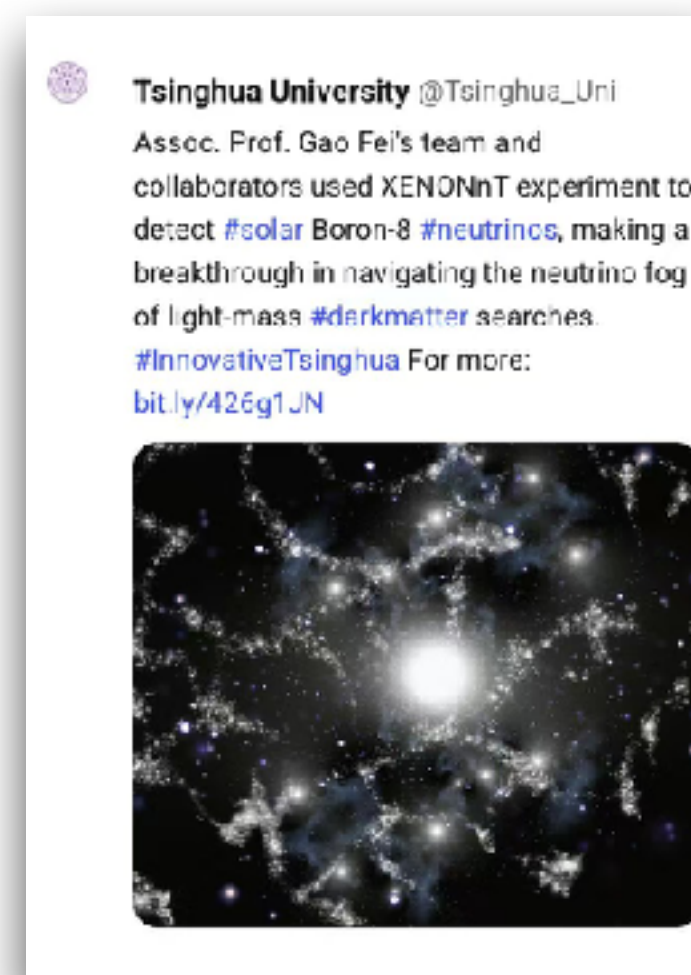


2024: “Highlights of the year”



- APS “Highlights of the year”
- PRL “2024年度特辑”

部分本人于国内外交流中获得奖项：



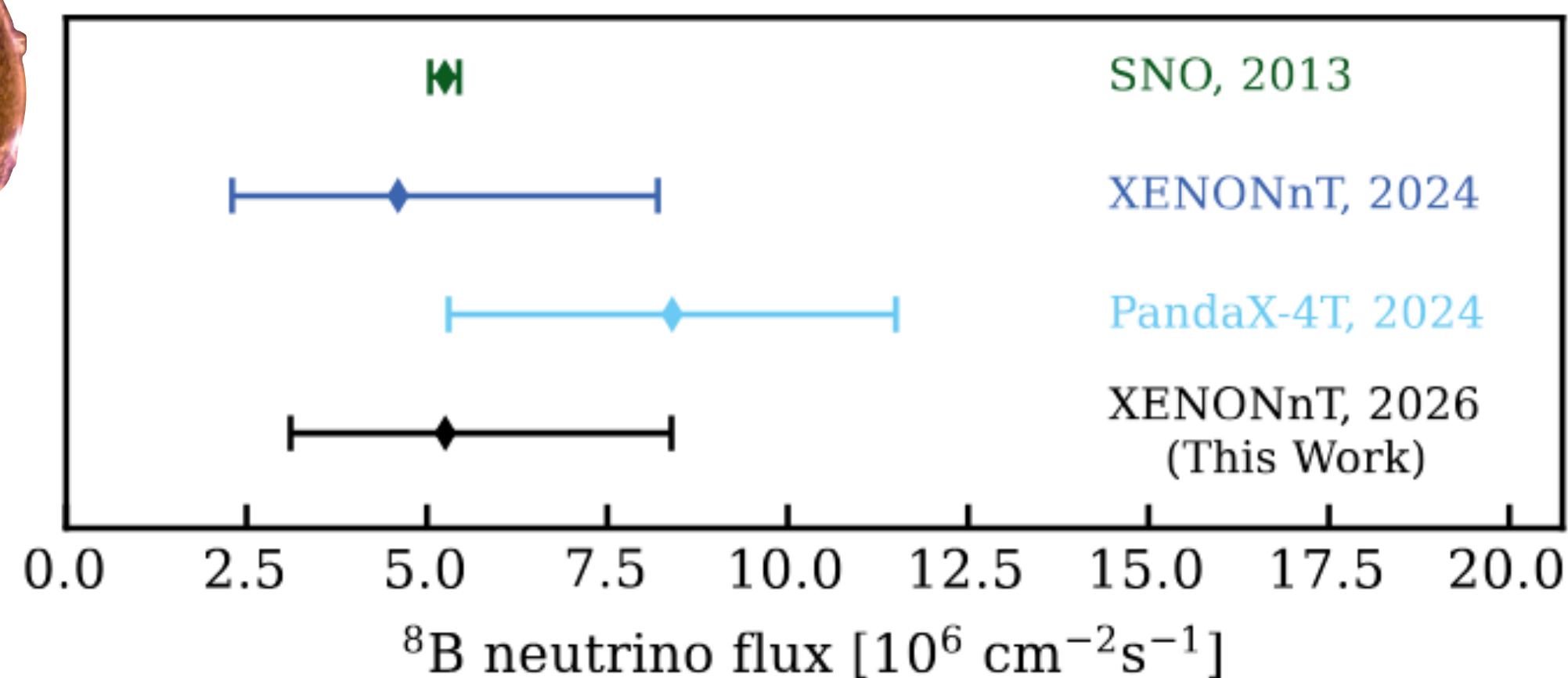
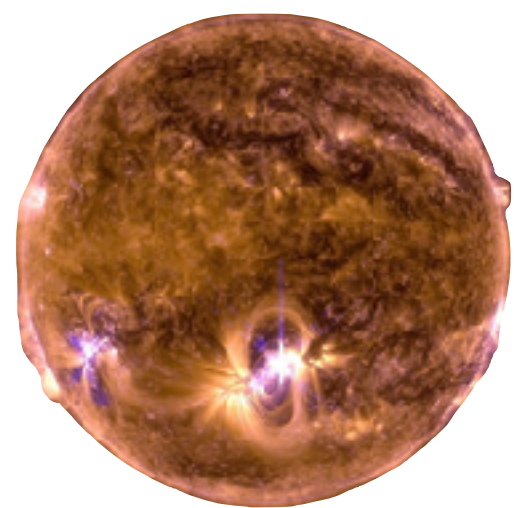
- 清华大学新闻网和国际传媒报道

- 2024年博士生国家奖学金
- 2024年“五校联盟”博士生论坛“口头报告一等奖”、“墙报展示最佳人气奖”等
- 2025年国际亚原子暑期学校“吴健雄文凭”

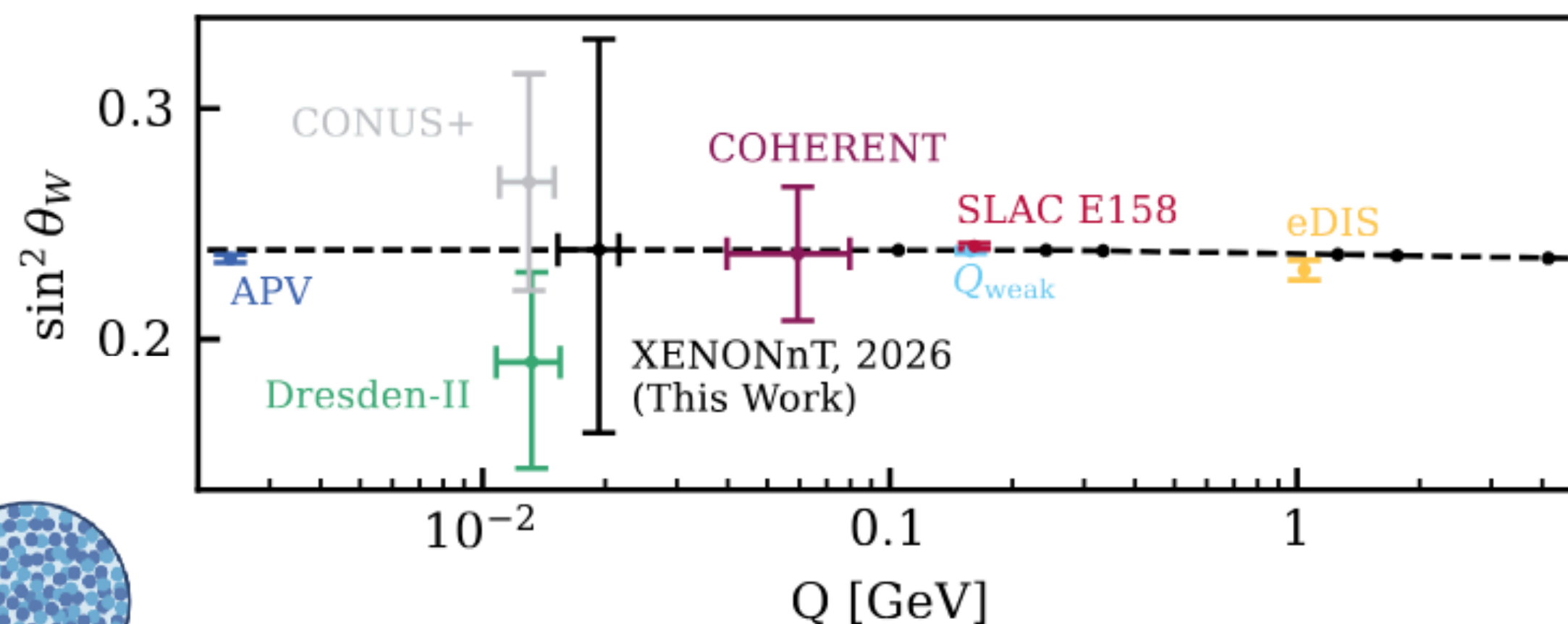
工作延续1：大曝光量（ $3.5+3.2=6.71$ 吨年）升级测量



清华大学
Tsinghua University



- 预期本底42，观测62 → 3.3σ
- 太阳中微子测量结果与SNO实验一致
- 约束 $\mathcal{O}(10)$ MeV 动量转移弱混合角

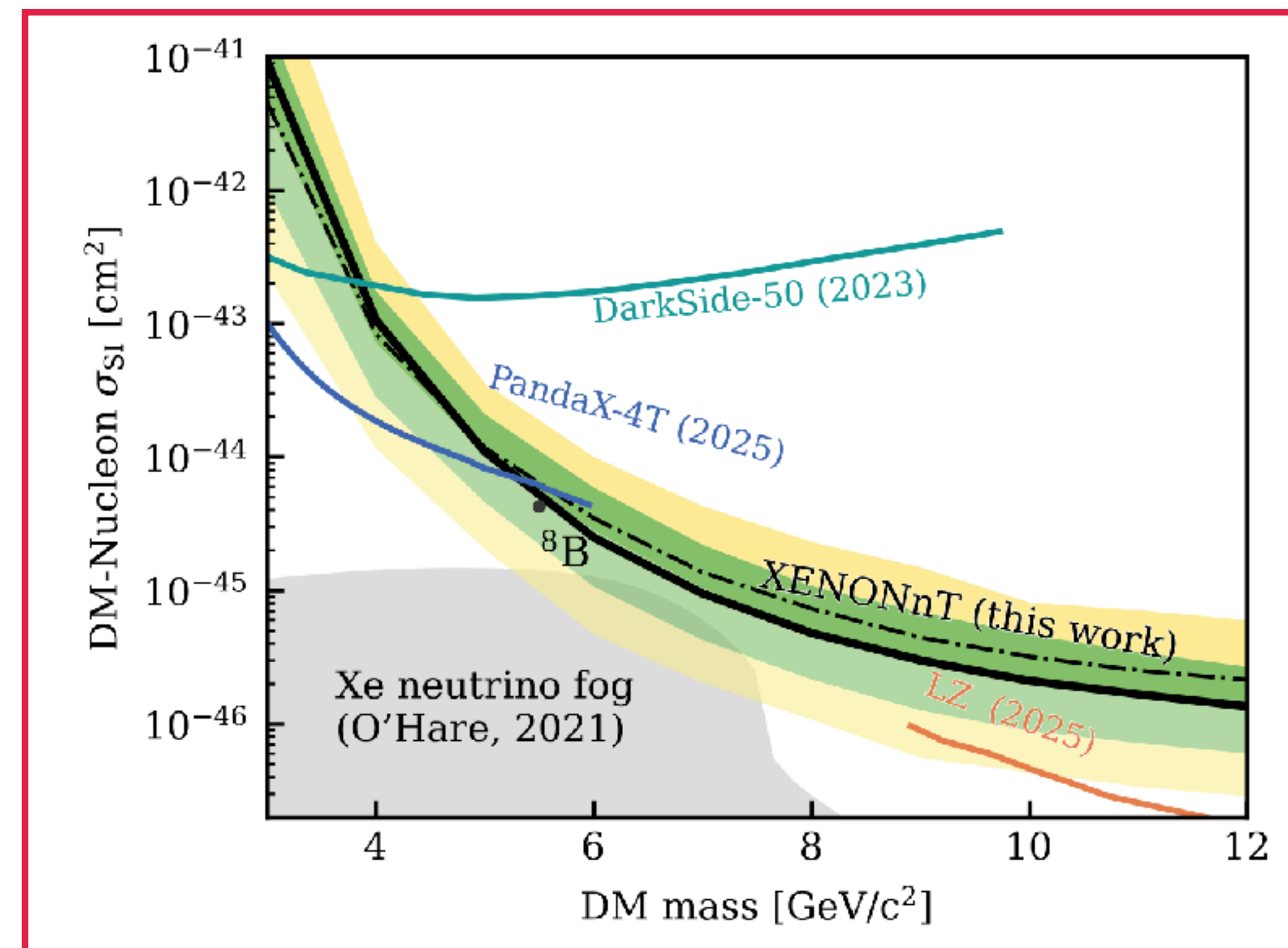
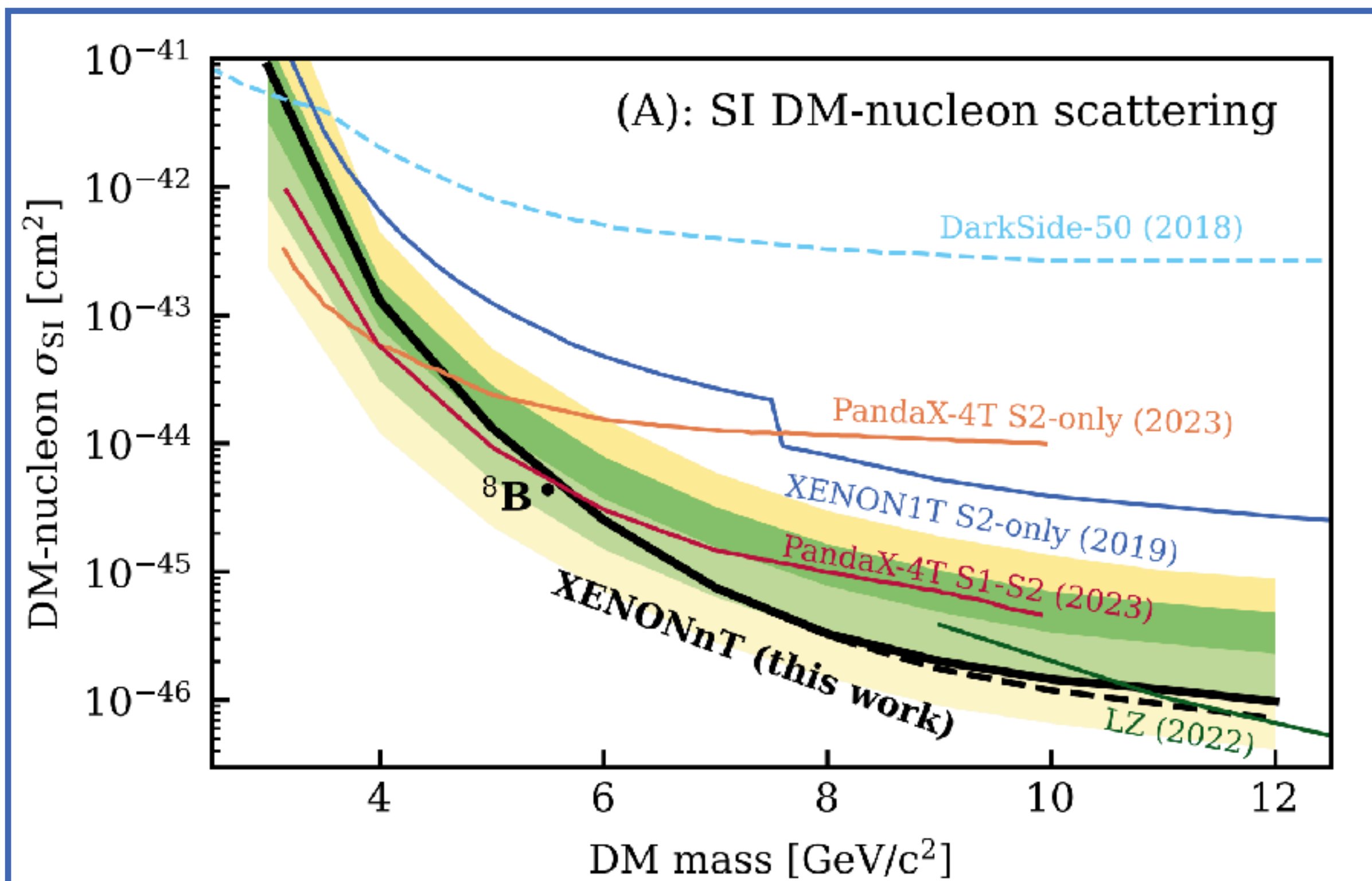


○ arXiv 2604.06002 (本人为共同通讯作者)

○ PRL已接收

○ “中微子物理、粒子天体”分会报告
(7月17日10:47)

工作延续2：在“中微子雾”中探测轻质量暗物质

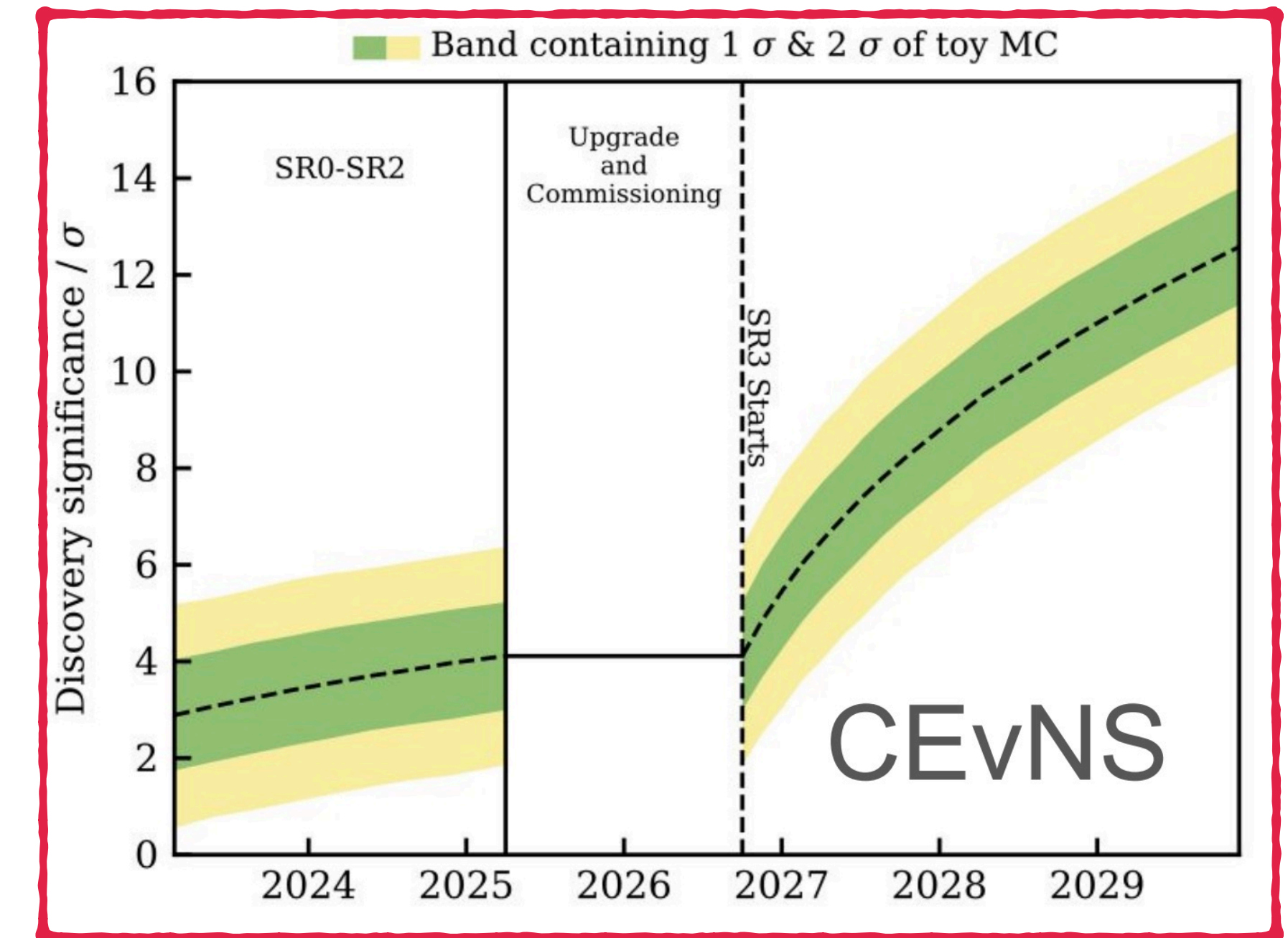
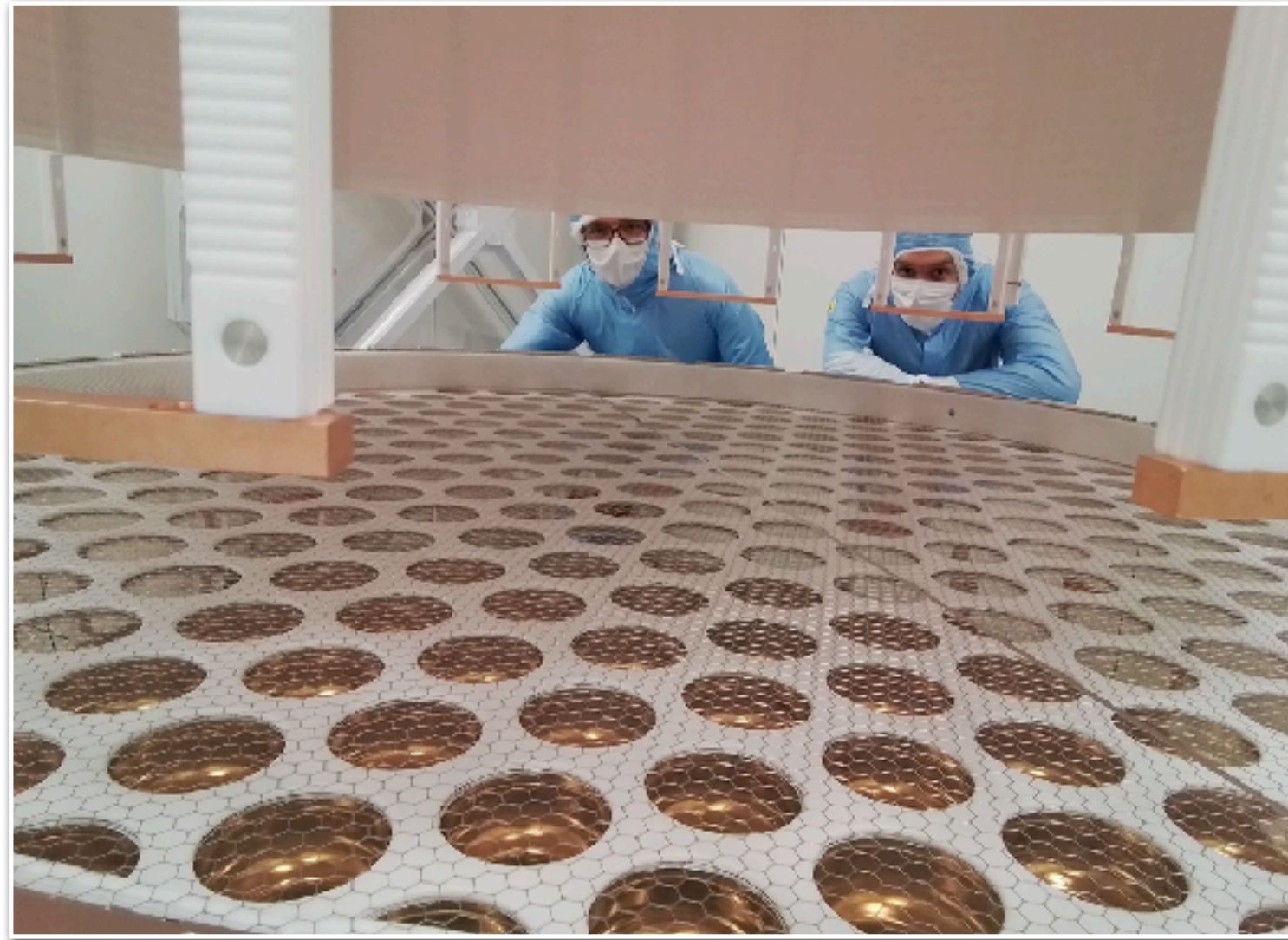


○ Phys. Rev. Lett. 134, 111802 (入选“PRL 2025年度特辑”)

○ arXiv 2604.06002 (PRL已接收，本人为共同通讯作者)

☑ 同一数据集、同一分析框架， ^8B CE ν NS 作为本底，寻找轻质量暗物质

展望：XENONnT 2.0预期大幅提升 ^8B $\text{CE}\nu\text{NS}$ 灵敏度



☑ 探测器升级 (2025年3月-2026年1月) ☑ 首批数据显示探测器电场提升，采数后预期快速实现对 $\text{CE}\nu\text{NS}$ 5σ 测量

- 本人于26年6月博士毕业，同题毕业论文获评清华大学2026年“优秀博士论文”
- 当选XENON合作组分析协调人 (Analysis Coordinator)，负责统筹探测器升级后首个科学数据集采集与分析
- 将赴哥伦比亚大学Elena Aprile教授 (XENON合作组发言人) 组开展博士后研究

- 基于 XENONnT 实验 3.51 吨 · 年曝光量数据，**首次测量太阳 ^8B 中微子与氙原子核的相干弹性散射 ($\text{CE}\nu\text{NS}$)** [1]，为暗物质直接探测领域里程碑事件。

[1] Phys. Rev. Lett. 133,191002 (2024) (本参评论文)

- 利用 6.71 吨 · 年曝光量数据，以 3.3σ **测量 ^8B $\text{CE}\nu\text{NS}$ 过程** [2] (本人为共同通讯作者)

[2] arXiv 2604.06002 (2026) (PRL 已接收，本人为共同通讯作者)

- 将 ^8B $\text{CE}\nu\text{NS}$ 作为本底，开展**对轻暗物质的测量** [2][3]，给出 4 - 7 GeV 自旋无关 WIMPs 散射截面**最灵敏上限**，证明“中微子雾”对轻质量暗物质探测的影响

[3] Phys. Rev. Lett. 134,111802 (2025) (编辑推荐，入选 PRL2025 “年度特辑”)



谢谢大家！ 敬请各位老师批评指正！

