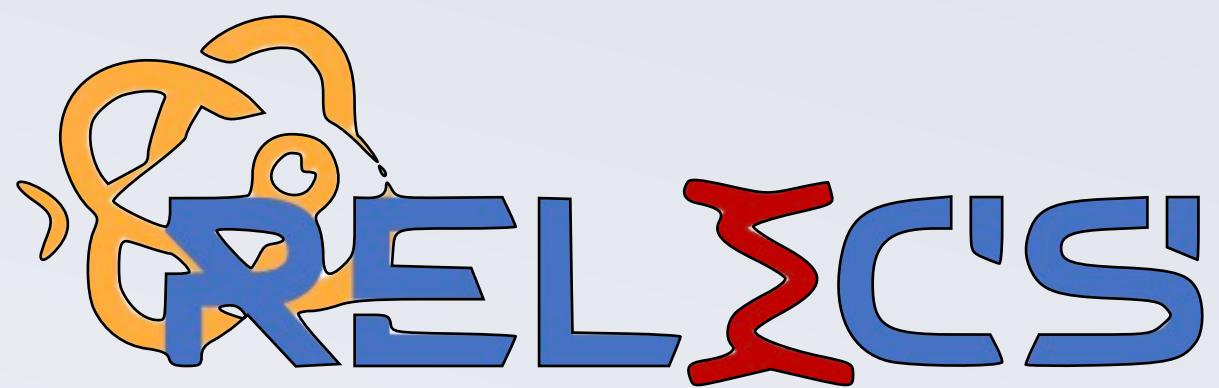




清华大学
Tsinghua University

RELICS 反应堆 CEvNS 实验：进展与展望

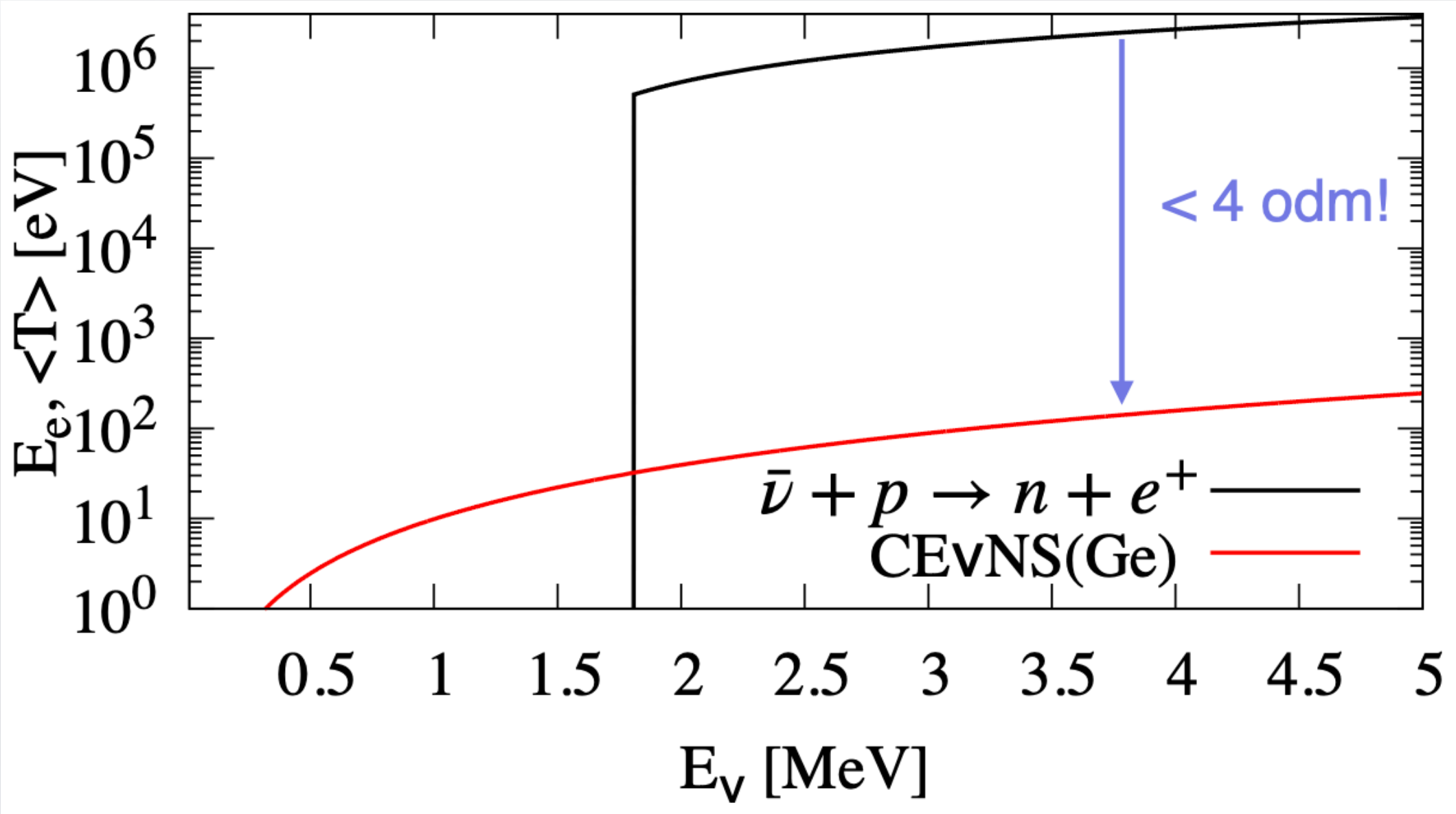
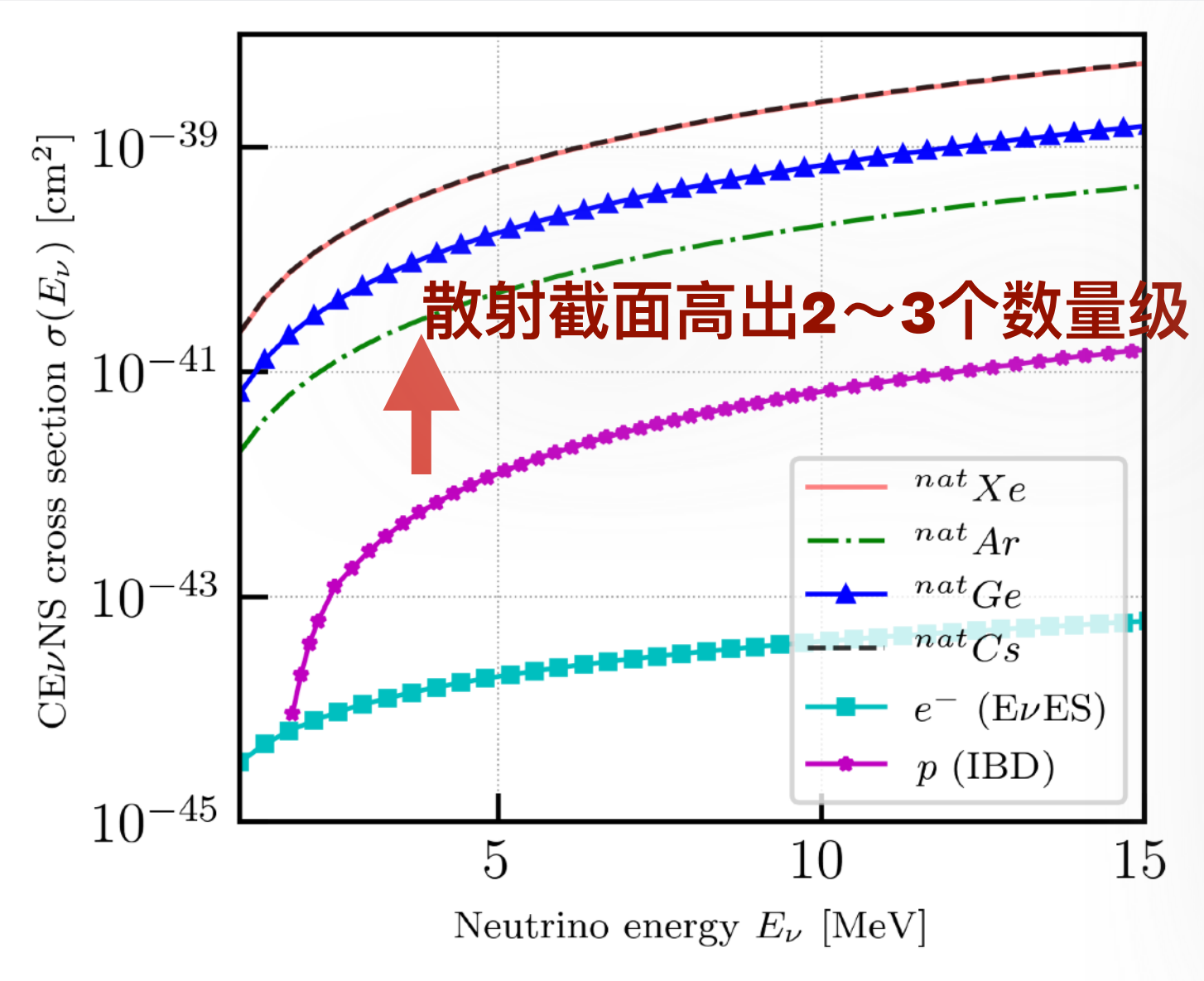
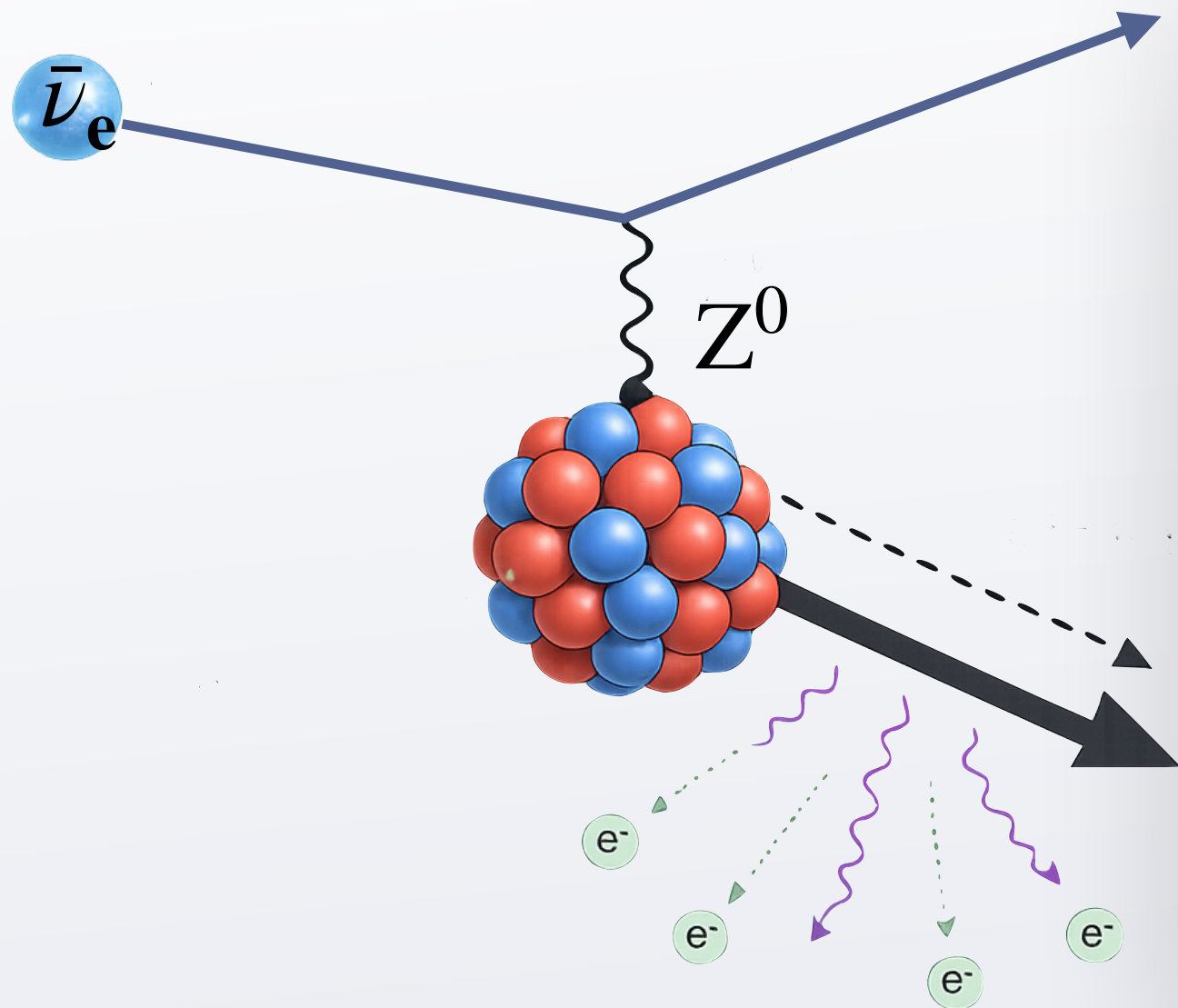
RELICS 合作组

谢凌峰 | 清华大学 物理系

中国物理学会高能物理分会第十二届全国会员代表大会暨学术年会

2026.07.16 | 广州

CE ν NS (Coherent Elastic Neutrino-Nucleus Scattering) 中微子-原子核相干弹性散射



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)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm² on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \rightarrow \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

- $$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi} \left(1 - \frac{MT}{2E_\nu^2} \right) Q_W^2 F_W^2(q^2)$$

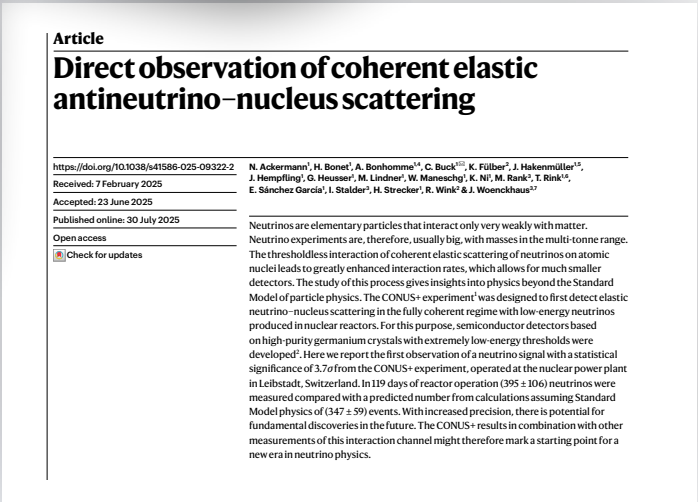
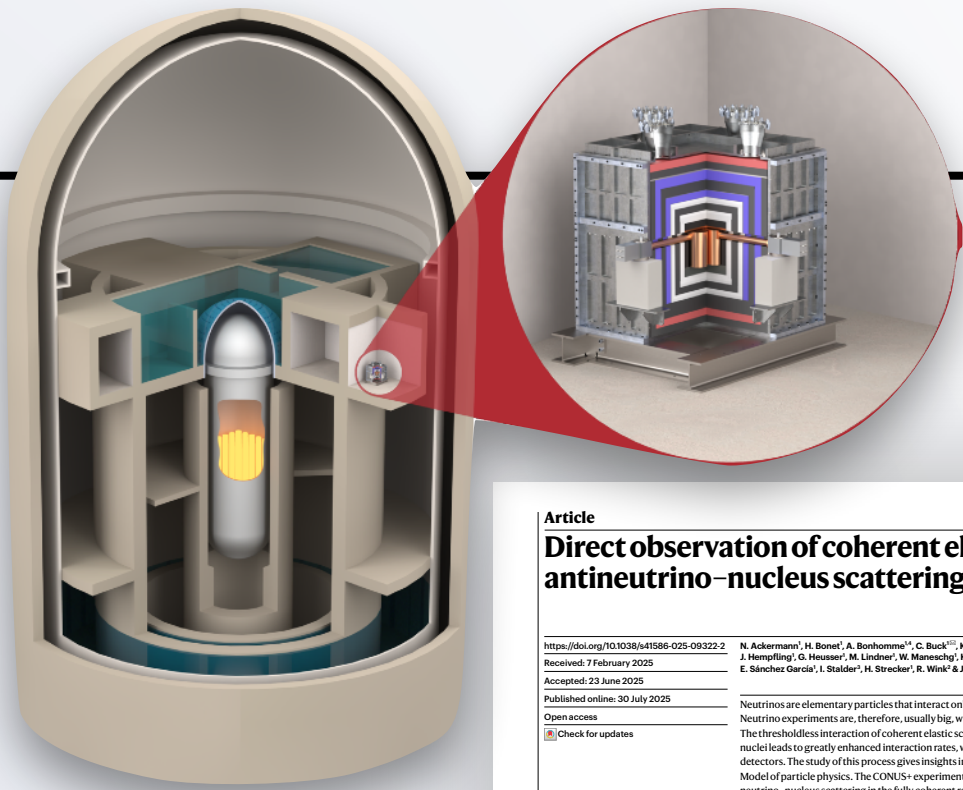
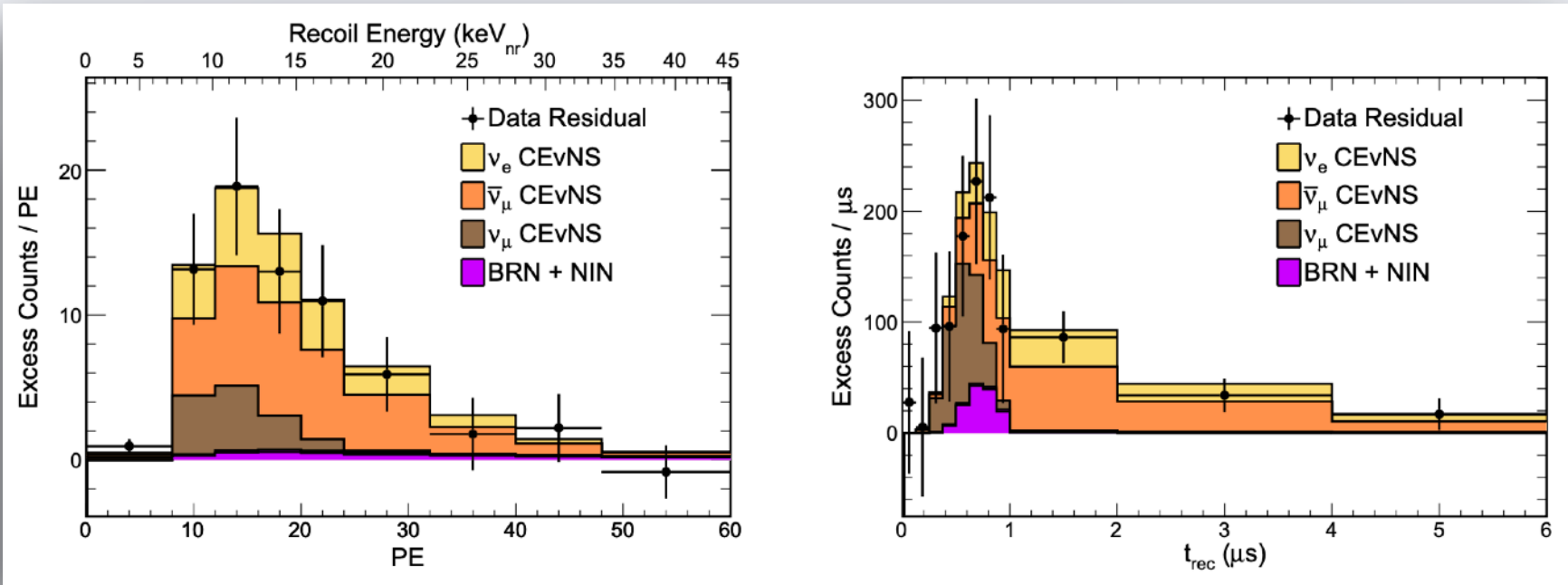
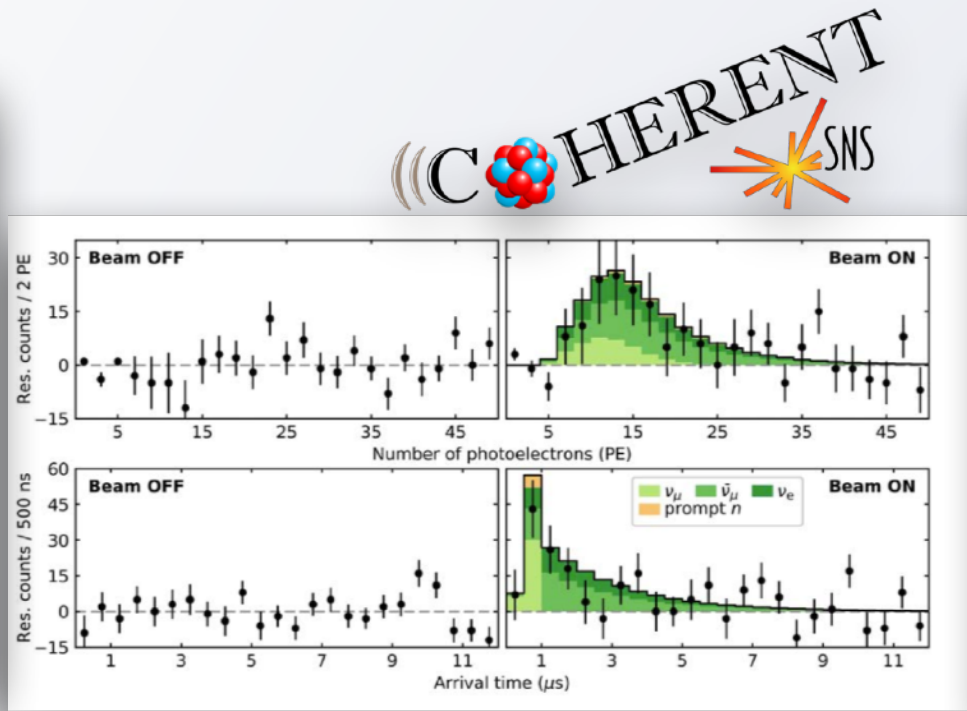
- $$Q_W = N - (1 - 4 \sin^2 \theta_W) Z \approx N$$

- $$\sigma_{\text{CE}\nu\text{NS}} \propto Q_W^2 \approx N^2$$

- 相干性: $q R \lesssim 1$

- 相干条件: $E_\nu < 10 \text{ MeV} \rightarrow F_W^2(q^2) \approx 1$

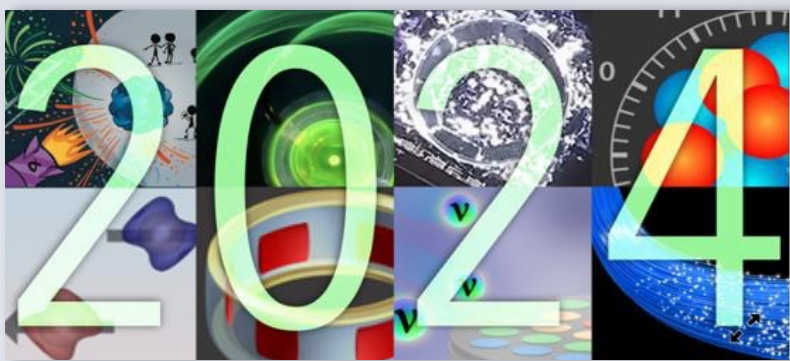
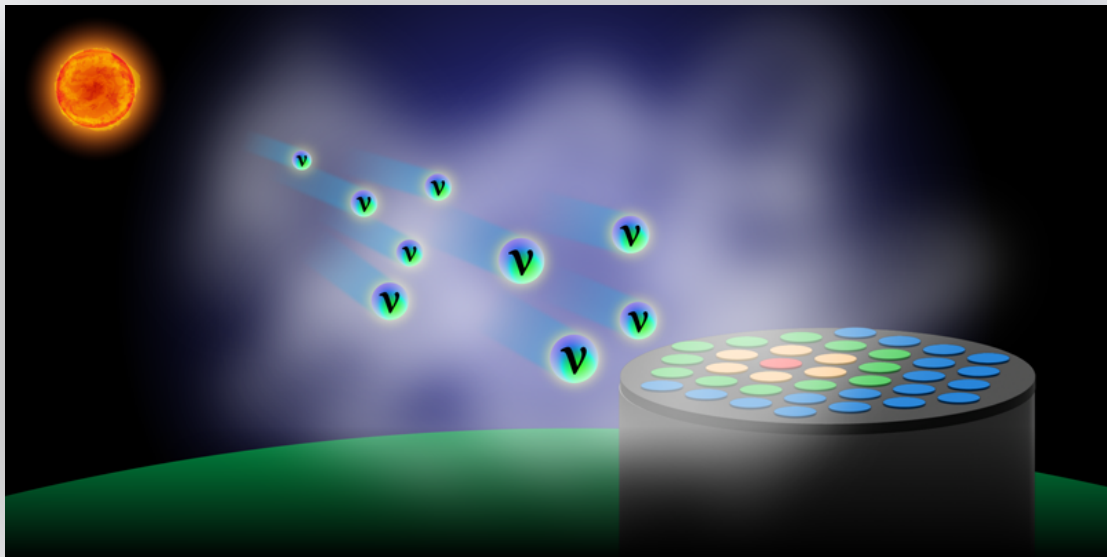
CEvNS 实验探测进展



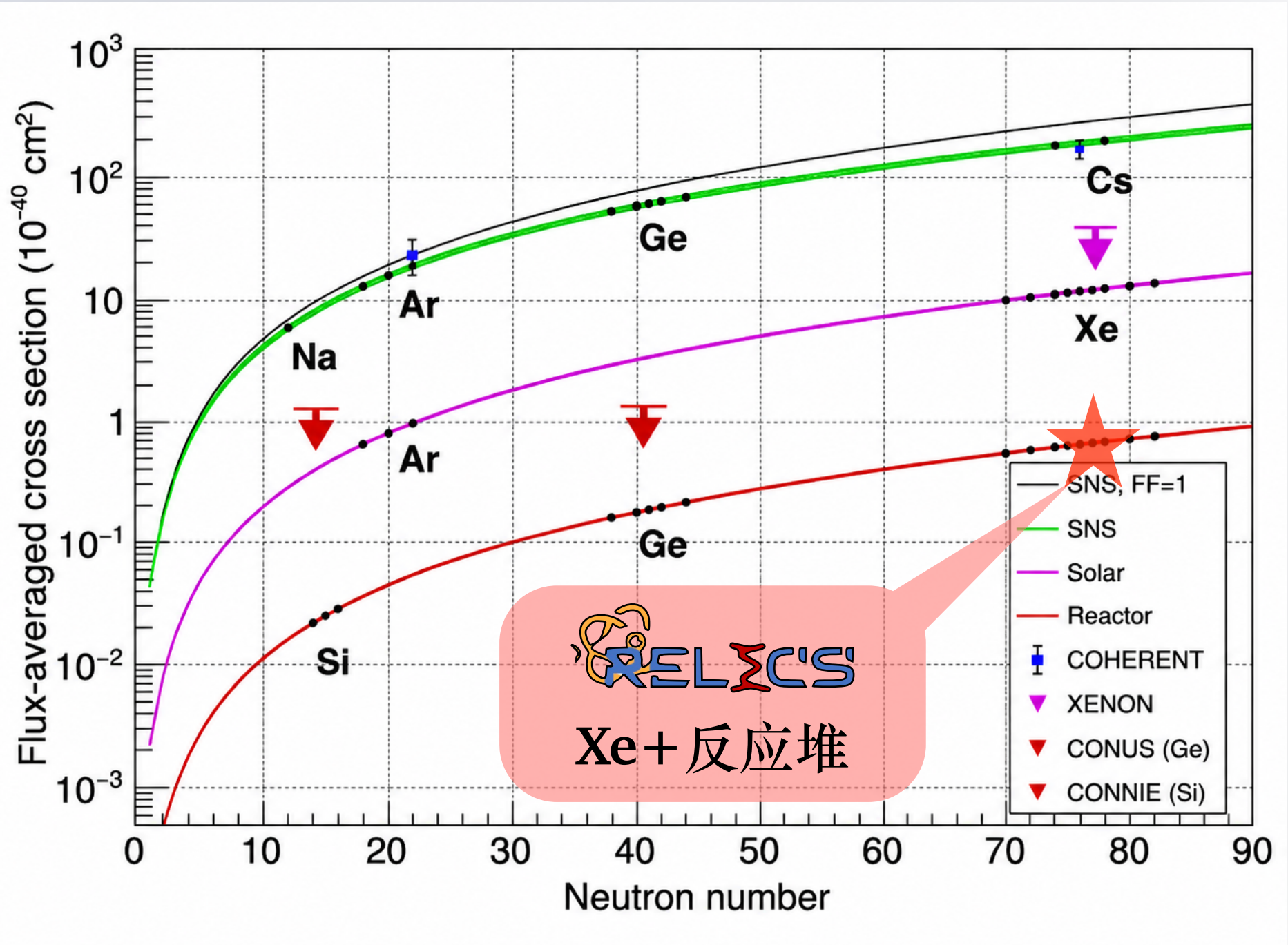
Science 357, 1123 (2017) | COHERENT 首次实验观测
SNS 中微子源 + CsI[Na] 探测器 | 显著度: 6.7σ

PRL 129 081801 (2022) | 优化本底模型与统计分析 | 显著度: 11.6σ

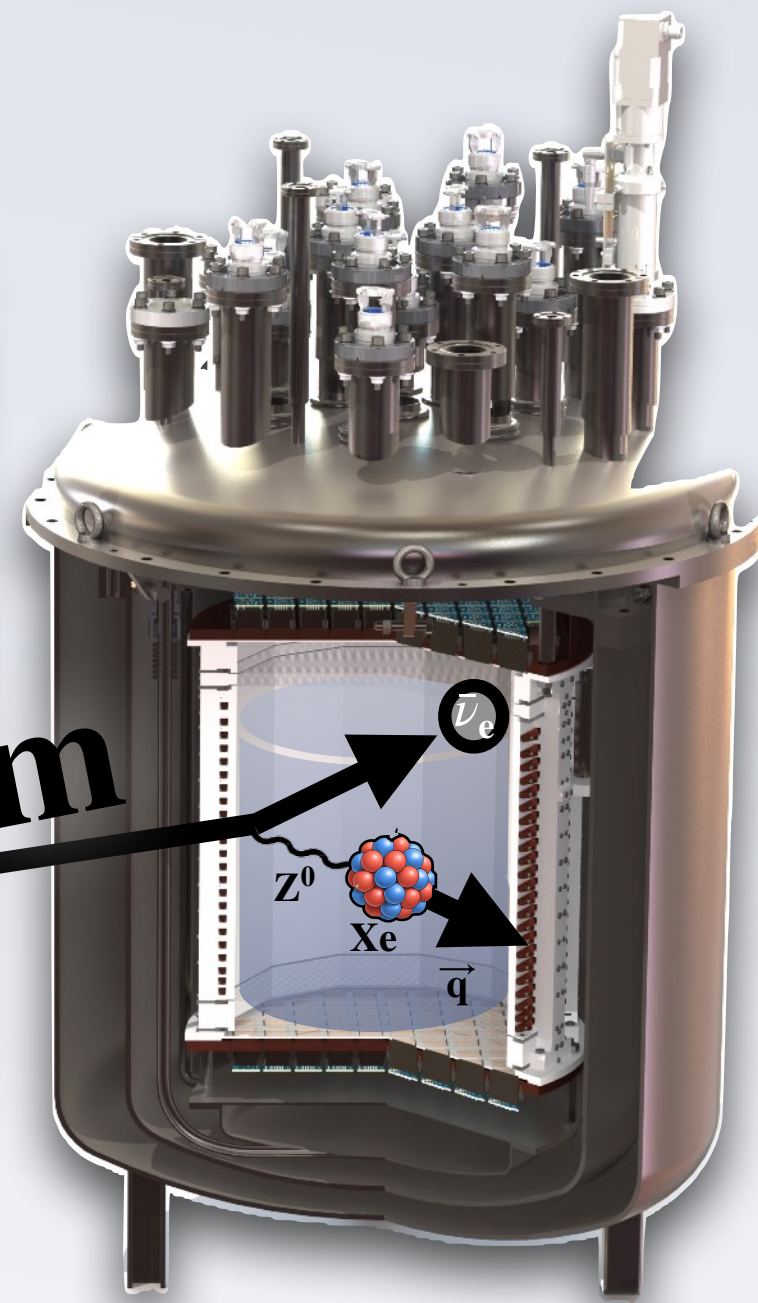
2025 | CONUS+: 反应堆 CEvNS 直接观测
HPGe 探测器, reactor-ON/OFF 信号 | 3.7σ
N. Ackermann et al., Nature 643, 1229 (2025)



2024 | 暗物质液氙探测器 太阳 ^8B 中微子 CEvNS 迹象
XENONnT PRL 133, 191002 (2024) 2.73σ
PandaX-4T PRL 133, 191001 (2024) 2.64σ
2025 | LZ arXiv:2512.08065 ^8B CEvNS 迹象 4.5σ
2026 | XENONnT: 高统计量 CEvNS 进一步测量 3.3σ



RELICS实验：反应堆源 + 双相型氙时间投影室



AP1000反应堆
热功率 $\sim 3 \text{ GW}_{\text{th}}$

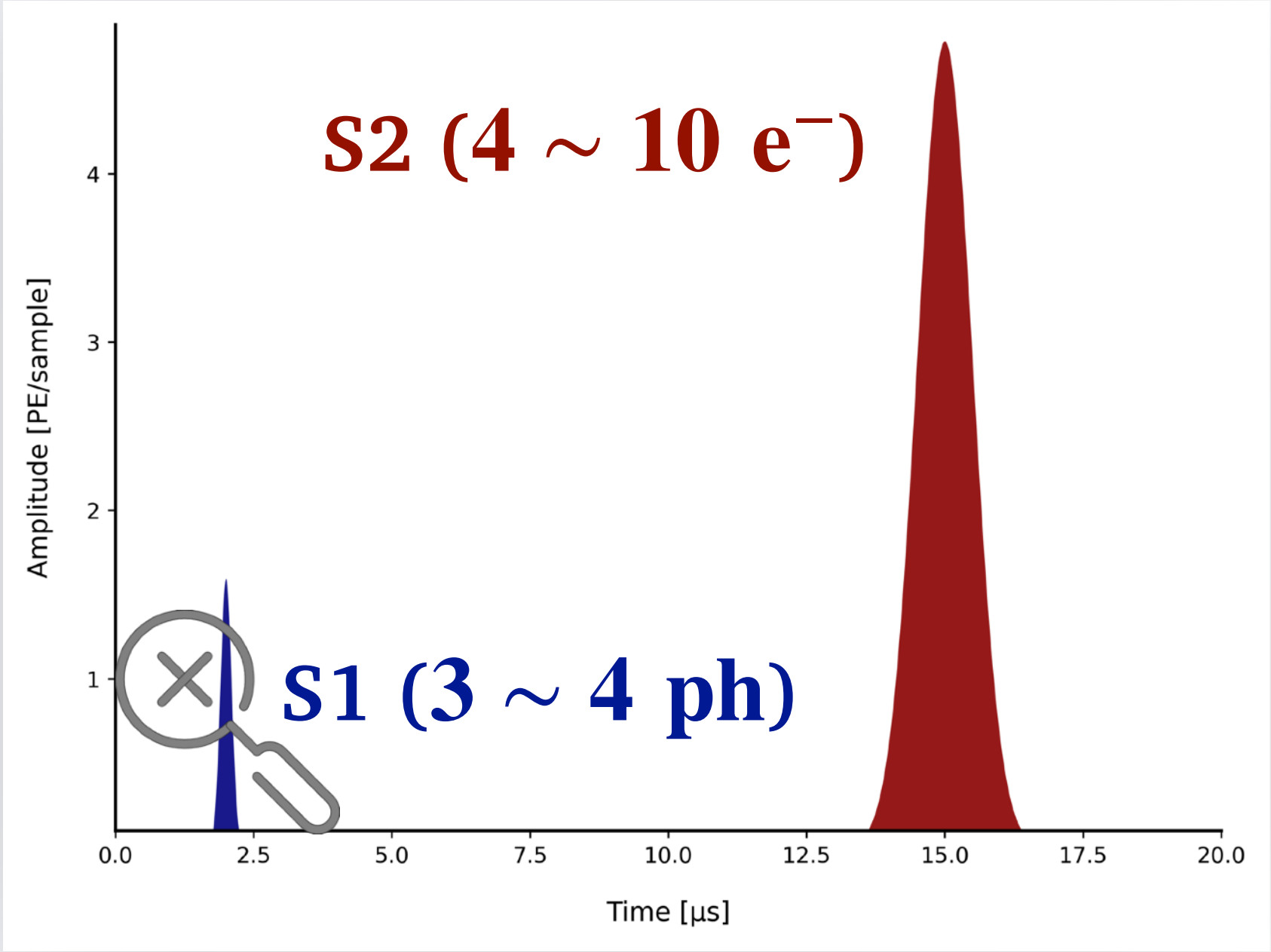
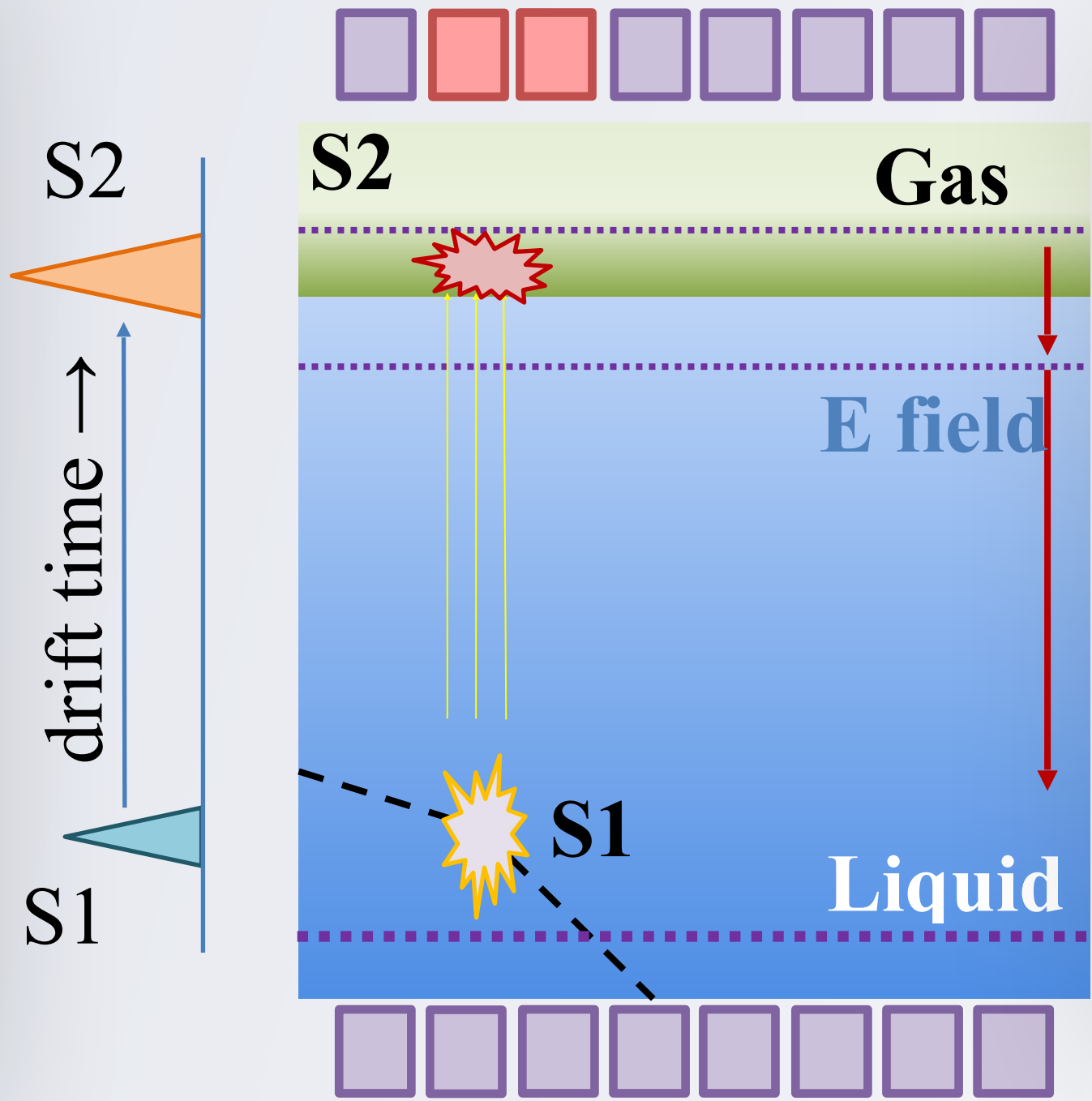
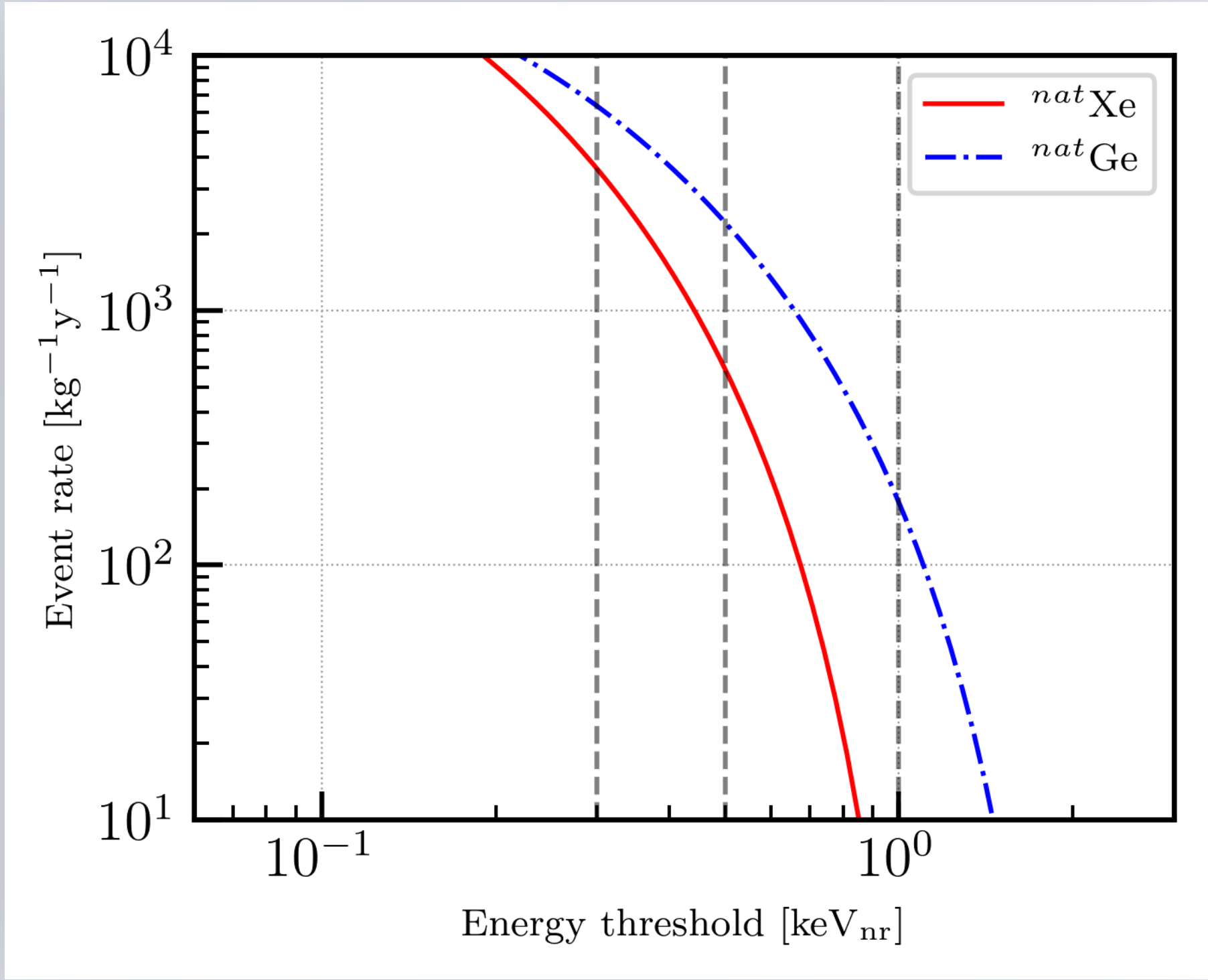
► 中微子通量： $\Phi_{\bar{\nu}_e} \sim 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$

成功探测关键：

- 亚-keV 低阈值探测
- 实验本底控制



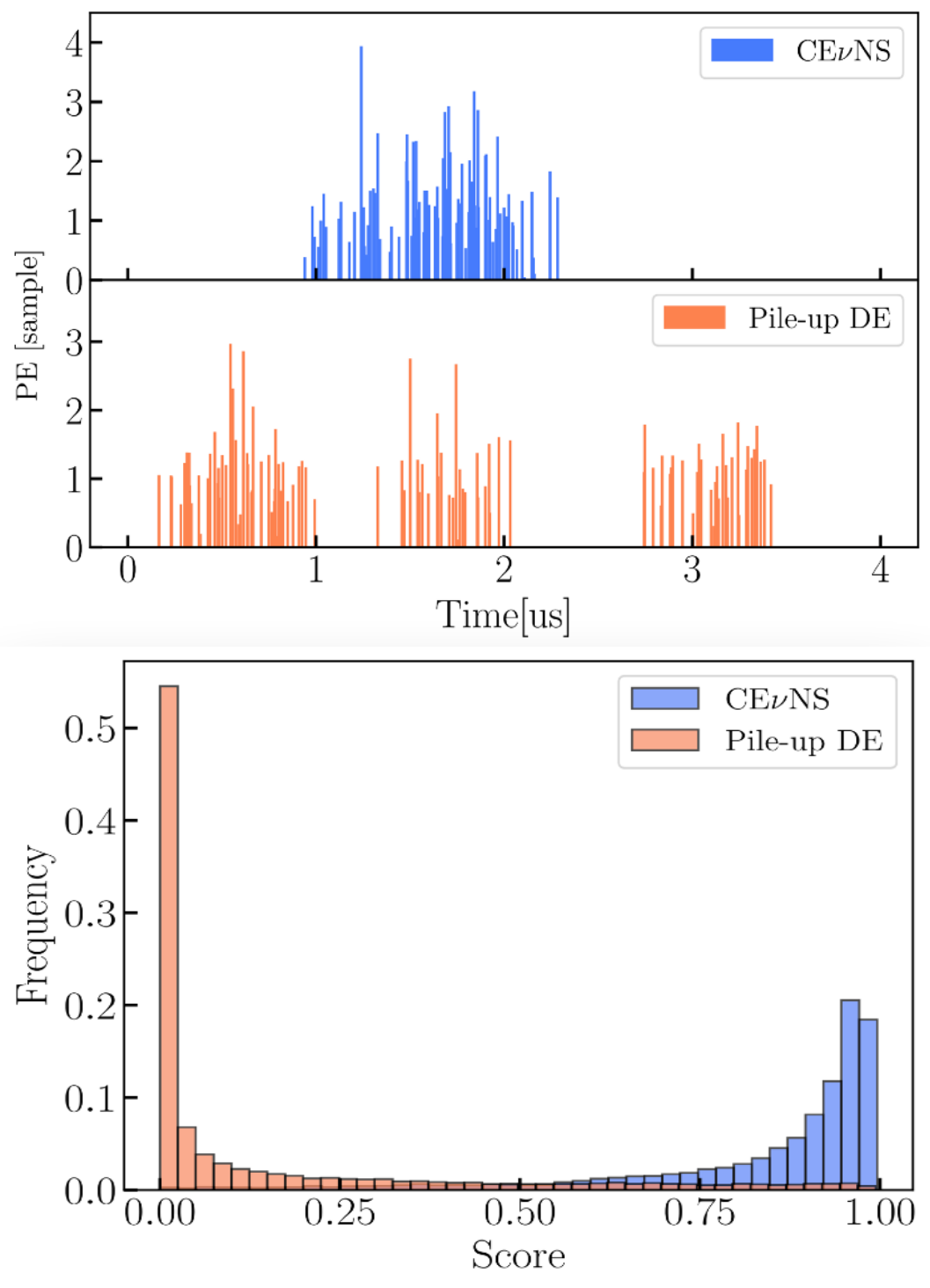
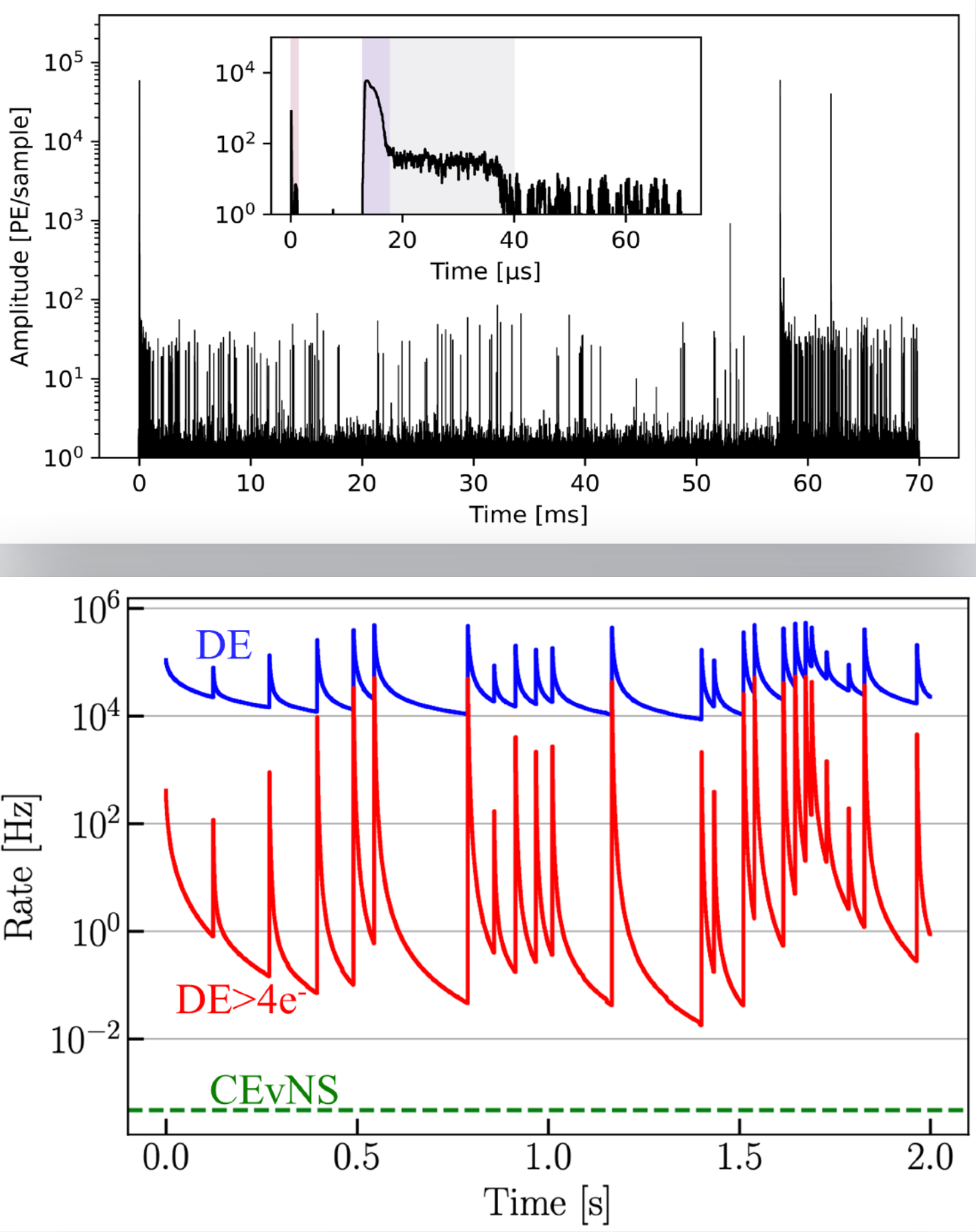
低閾值探测策略：S2-only 分析



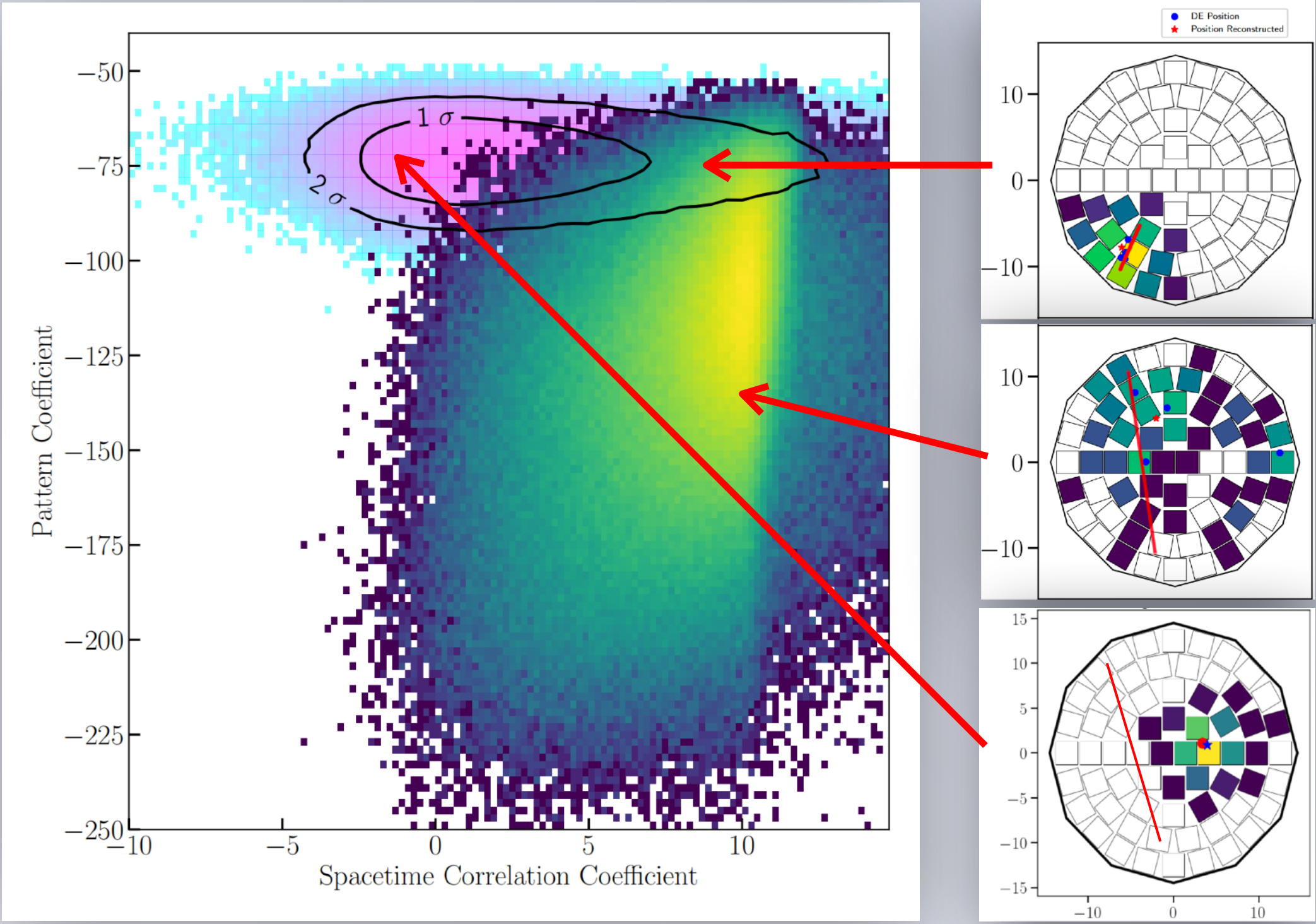
閾值升高， $\text{CE}_{\nu\text{NS}}$ 事例率迅速下降

◎ 采用 S2-only 分析实现 sub-keV 探测閾值

延迟电子(DE)本底与抑制



波形形状

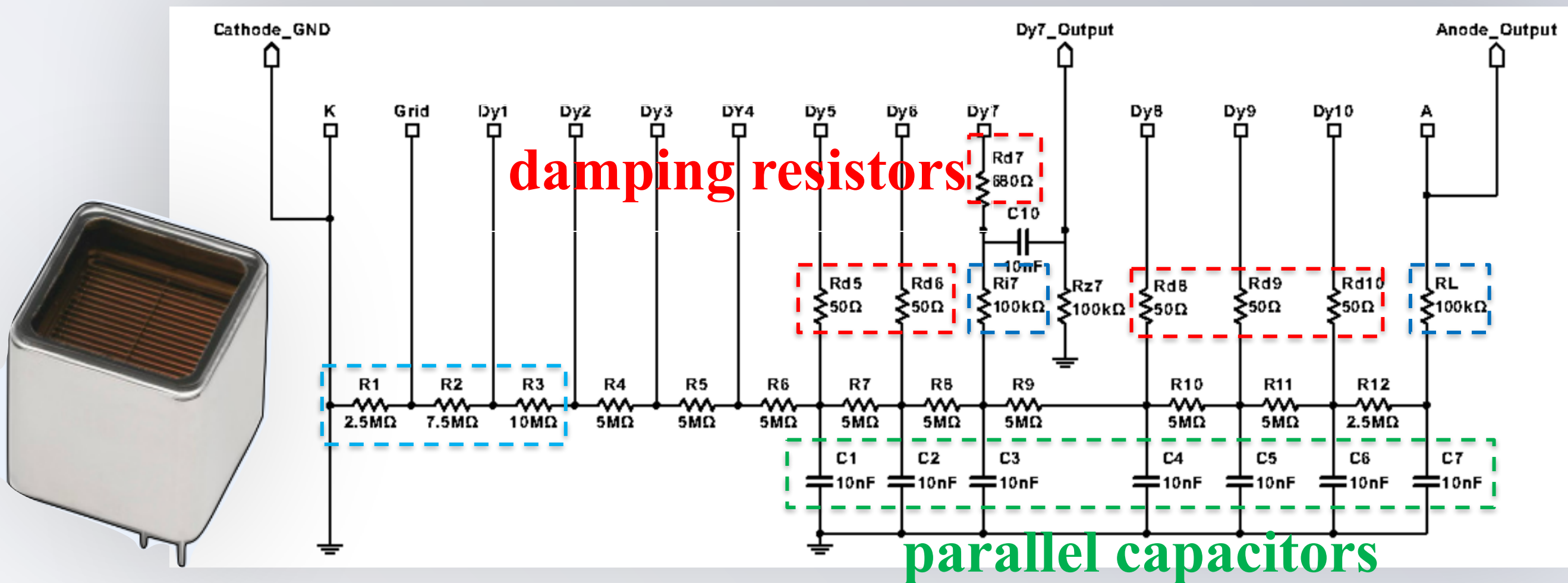


PMT响应分布+高能事件时空关联

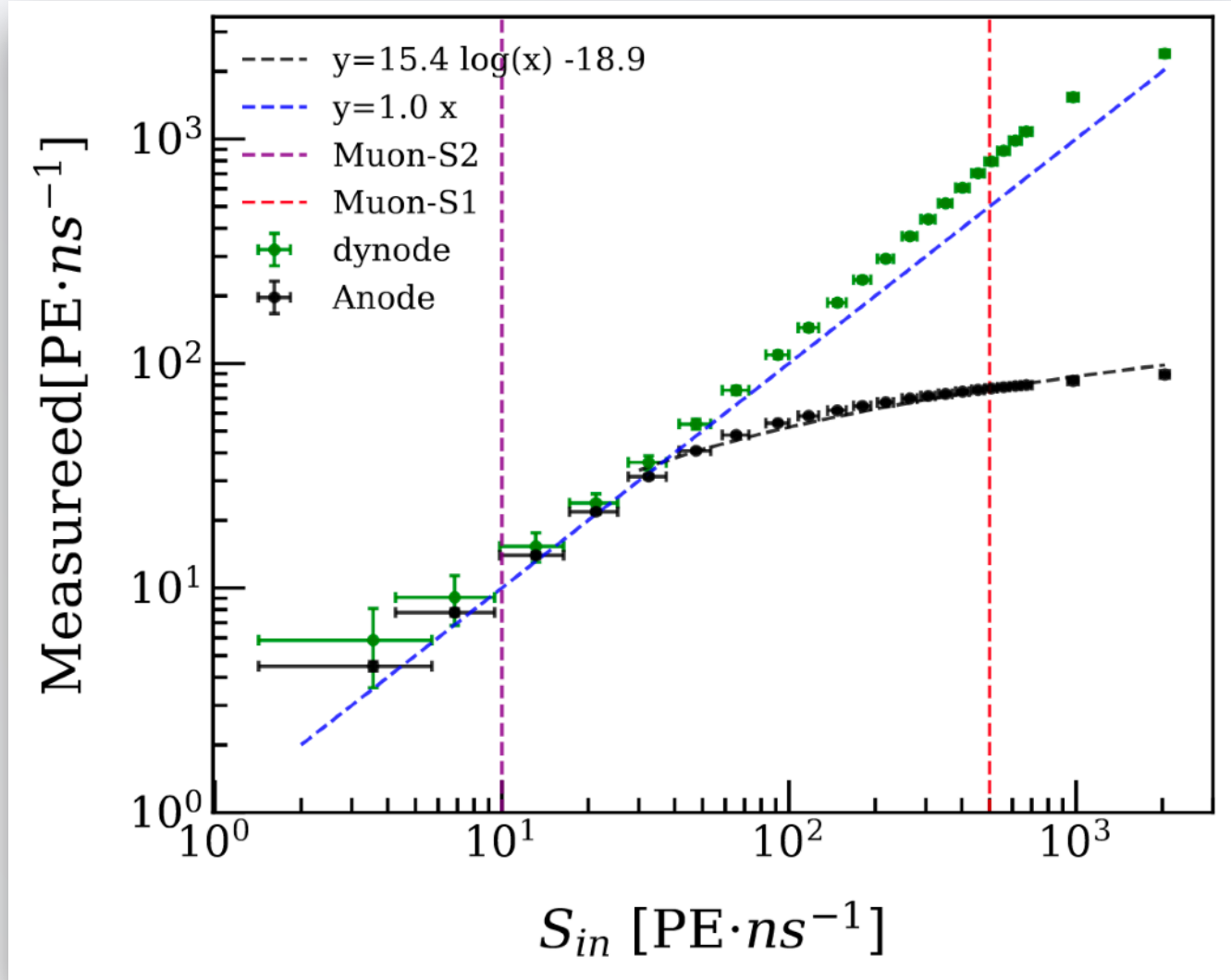
- 高能 S2 / μ 子事件后产生
- 持续时间数百毫秒，呈幂律分布
- 地表 μ 事例率约 10 Hz，延迟电子堆叠事例率高于 CEvNS 信号

	信号接受率	本底剩余率
波形判别	~ 80%	~ 10%
响应分布 + 时空关联	~ 52%	~ 0.01%

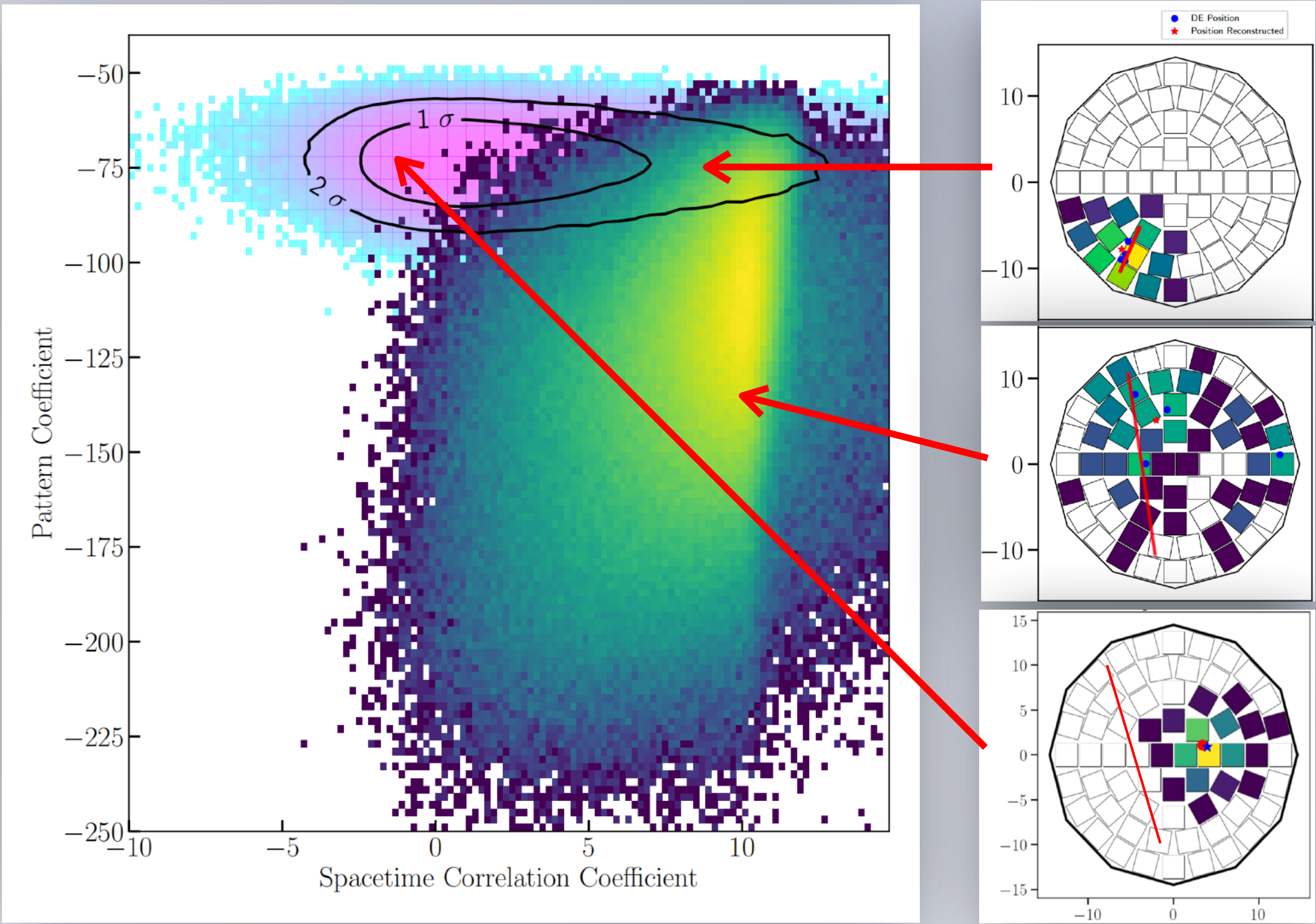
延迟电子(DE)本底与抑制



- ◆阳极通道：单电子、CE_LNS 低能 S2
- ◆打拿极通道： μ 子与高能 S2
- ◆双通道同步记录：为高能事件时空关联提供信息



- 阳极饱和拐点 **~40 PE/ns**
- 扩展后读出范围 **~1000 PE/ns**



PMT响应分布+高能事件时空关联

杨继军 | 分会快速报告
7月17日 09:10–09:20 | 分会场 V

◆ *Phys. Rev. D* **110**, 072011 (2024)

◆ *JINST* **21**, P02039 (2026)

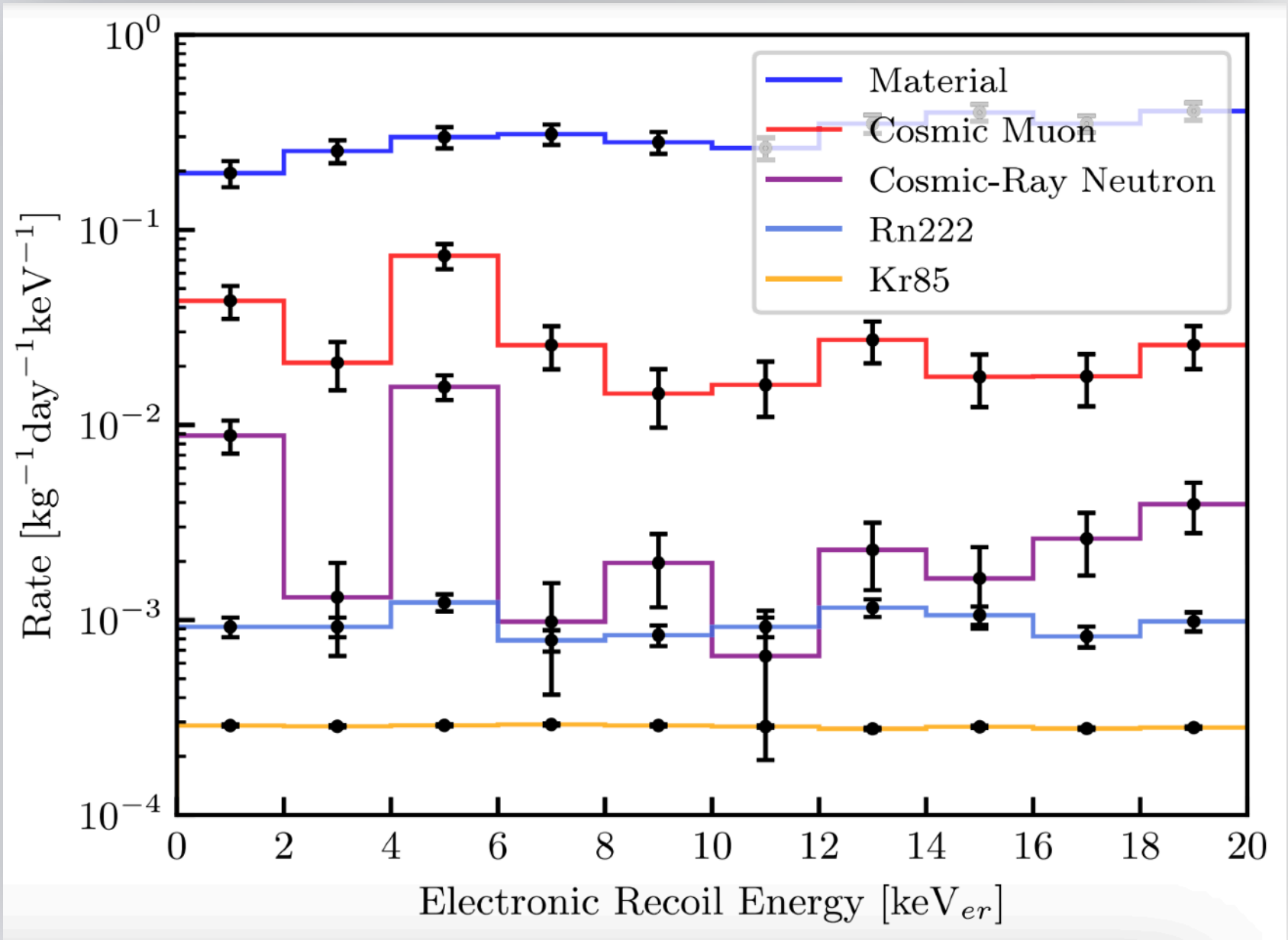
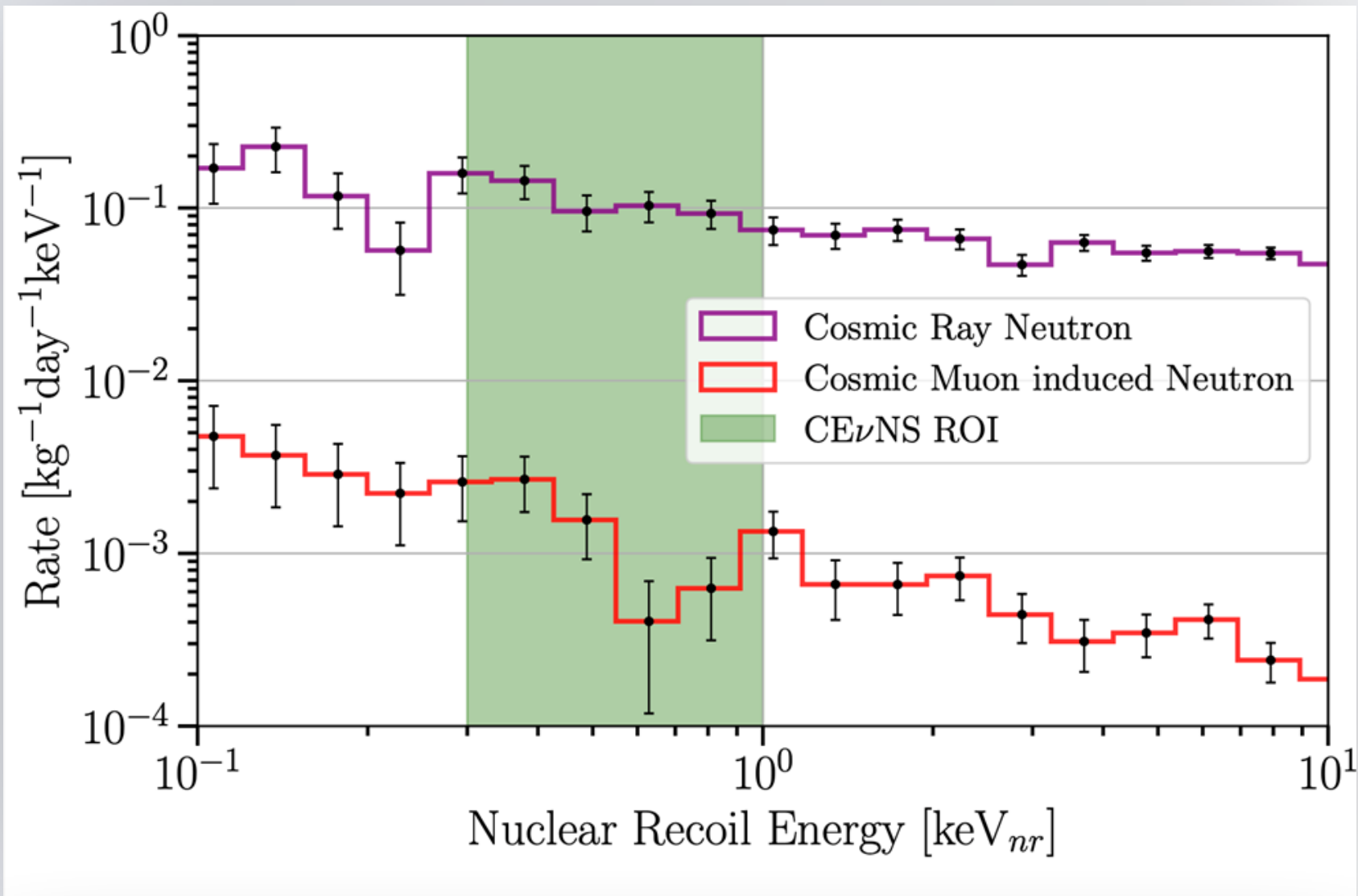
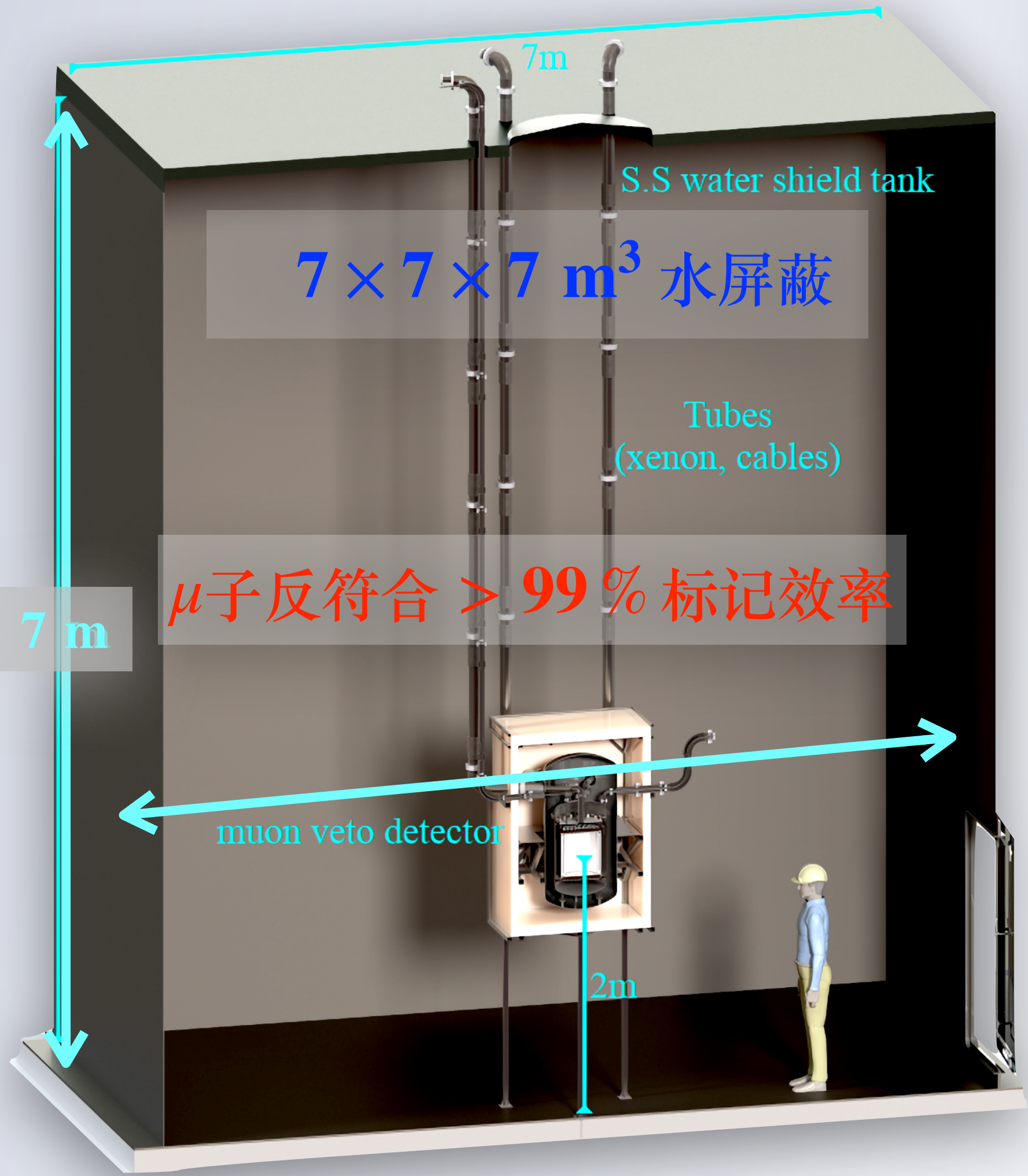
电子反冲(ER)与核反冲(NR)本底的来源及抑制

NR本底主要来源:

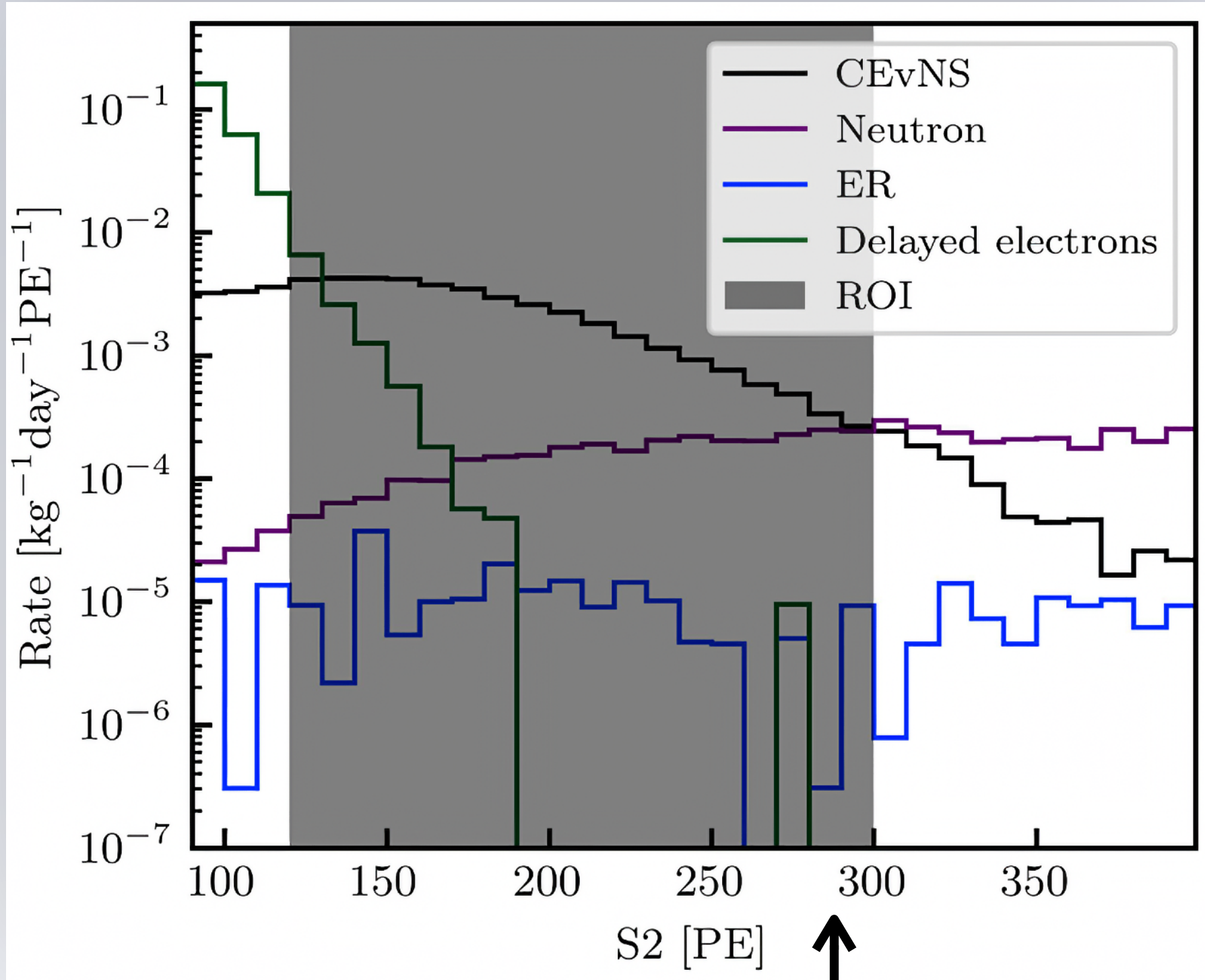
- 反应堆/环境中子
- 宇宙线中子
- μ 子诱导中子

ER本底主要来源:

- 材料放射性
- 宇宙线 μ 子
- 宇宙线中子
- 液氙内部 ^{222}Rn 、 ^{85}Kr

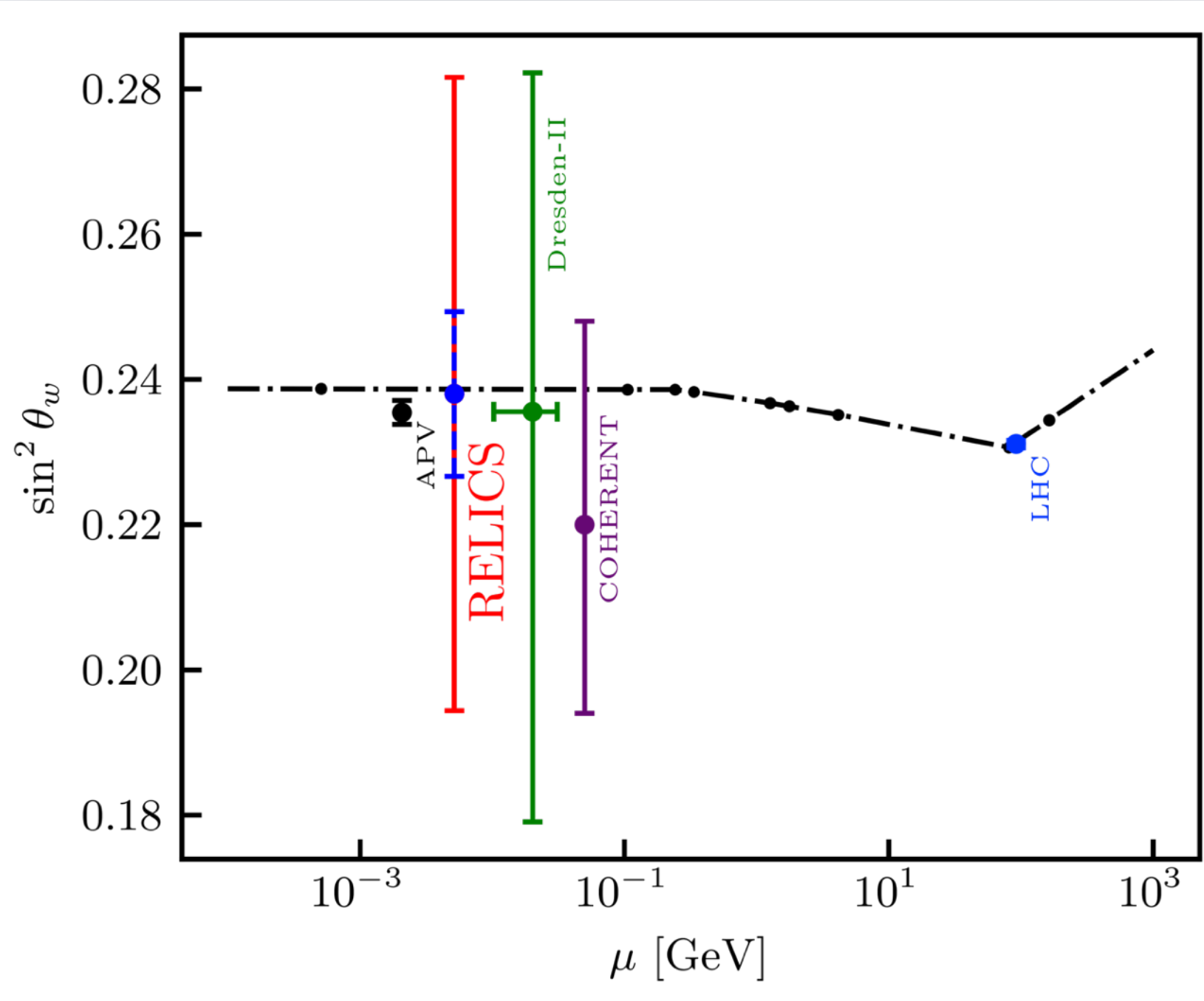


实验预期结果



单电子增益假设: 30 PE/e⁻

	事例数/(32kg·year)
总背景数	1687.8
NR 宇宙中子本底	339.9
NR 缪子诱导中子本底	1.7
ER: β, γ放射性本底	21.1
延迟电子本底	1325.1
CEvNS	4639.7



OPEN ACCESS

Reactor neutrino liquid xenon coherent elastic scattering experiment

[Chang Cai](#)¹, [Guocai Chen](#)², [Jiangyu Chen](#)³, [Rundong Fang](#)⁴, [Fei Gao](#)^{1,*}, [Xiaoran Guo](#)^{5,6}, [Jiheng Guo](#)⁴, [Tingyi He](#)^{7,†}, [Chengjie Jia](#)^{1,‡} *et al.* (RELICS Collaboration)

Show more

Phys. Rev. D **110**, 072011 – Published 18 October, 2024

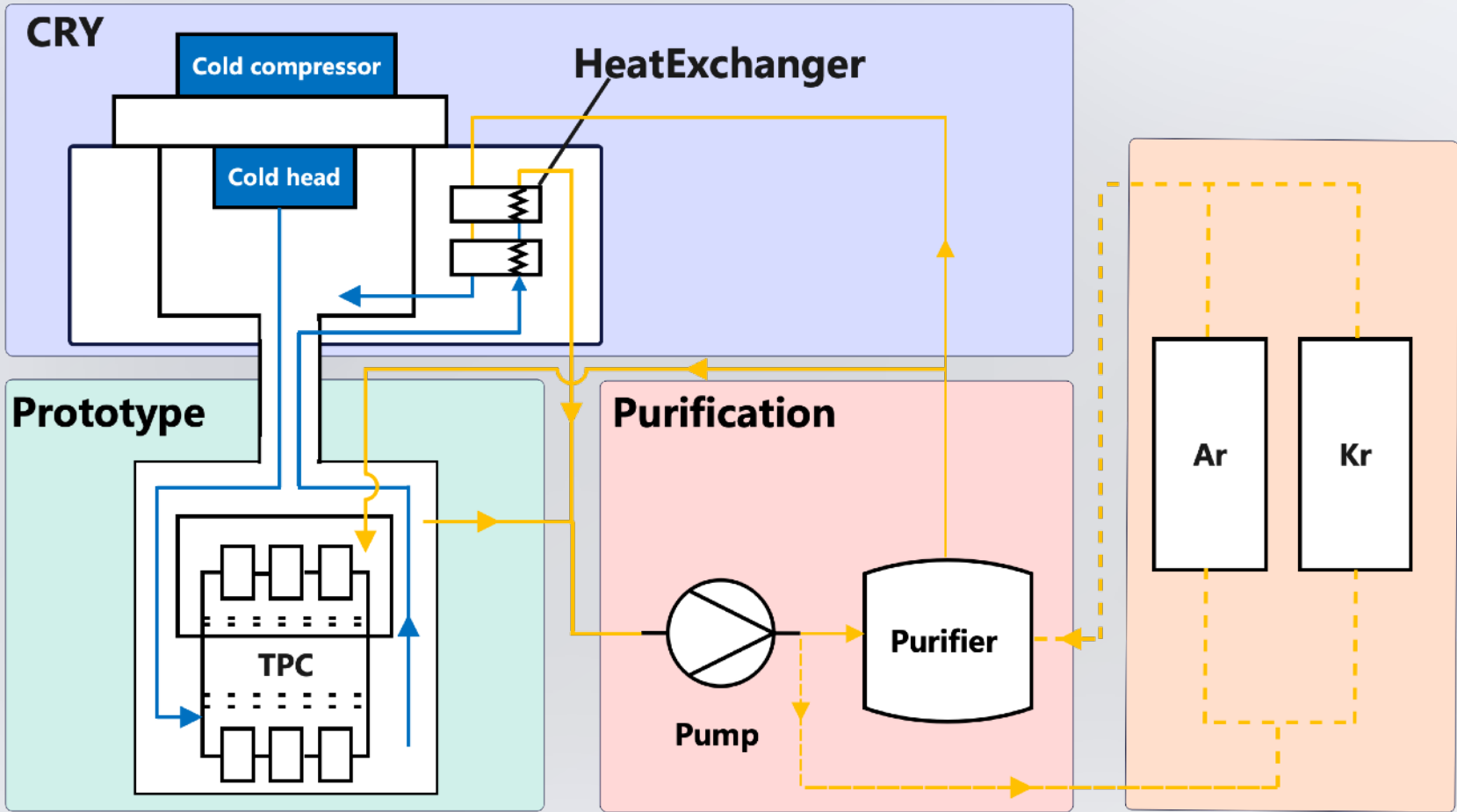
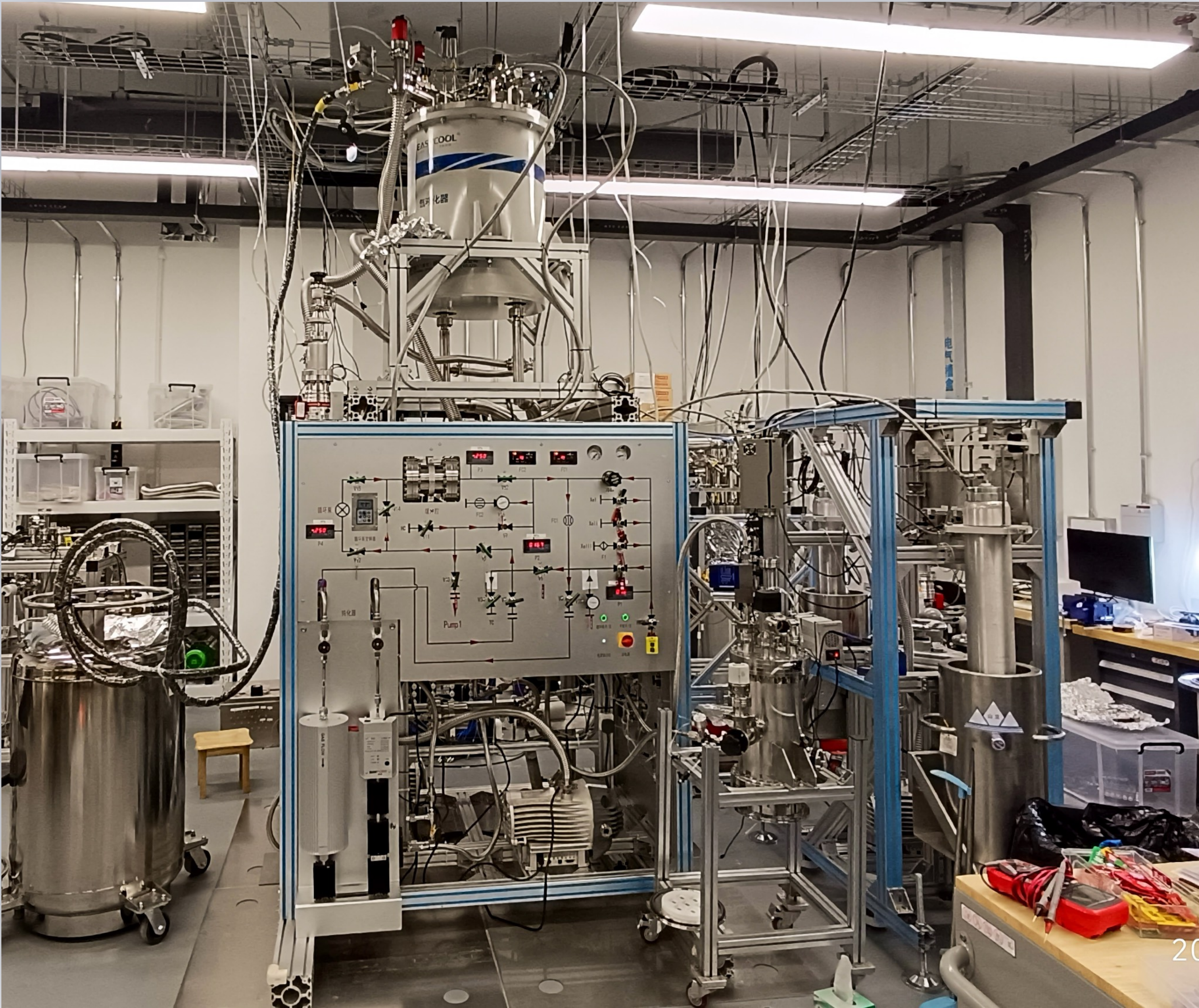
DOI: <https://doi.org/10.1103/PhysRevD.110.072011>

PDF

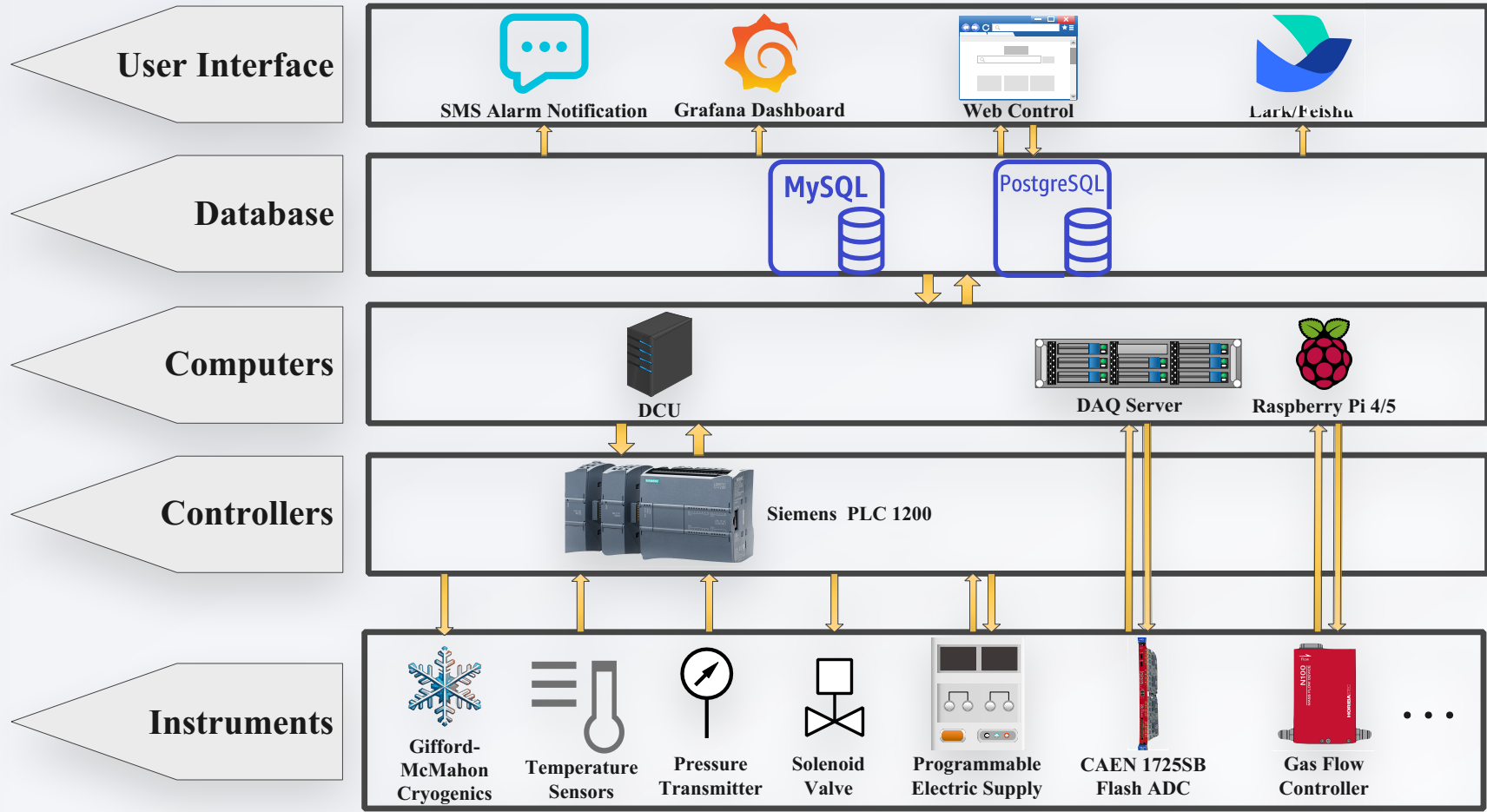
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RELICS 原型机：完整系统集成与运行验证

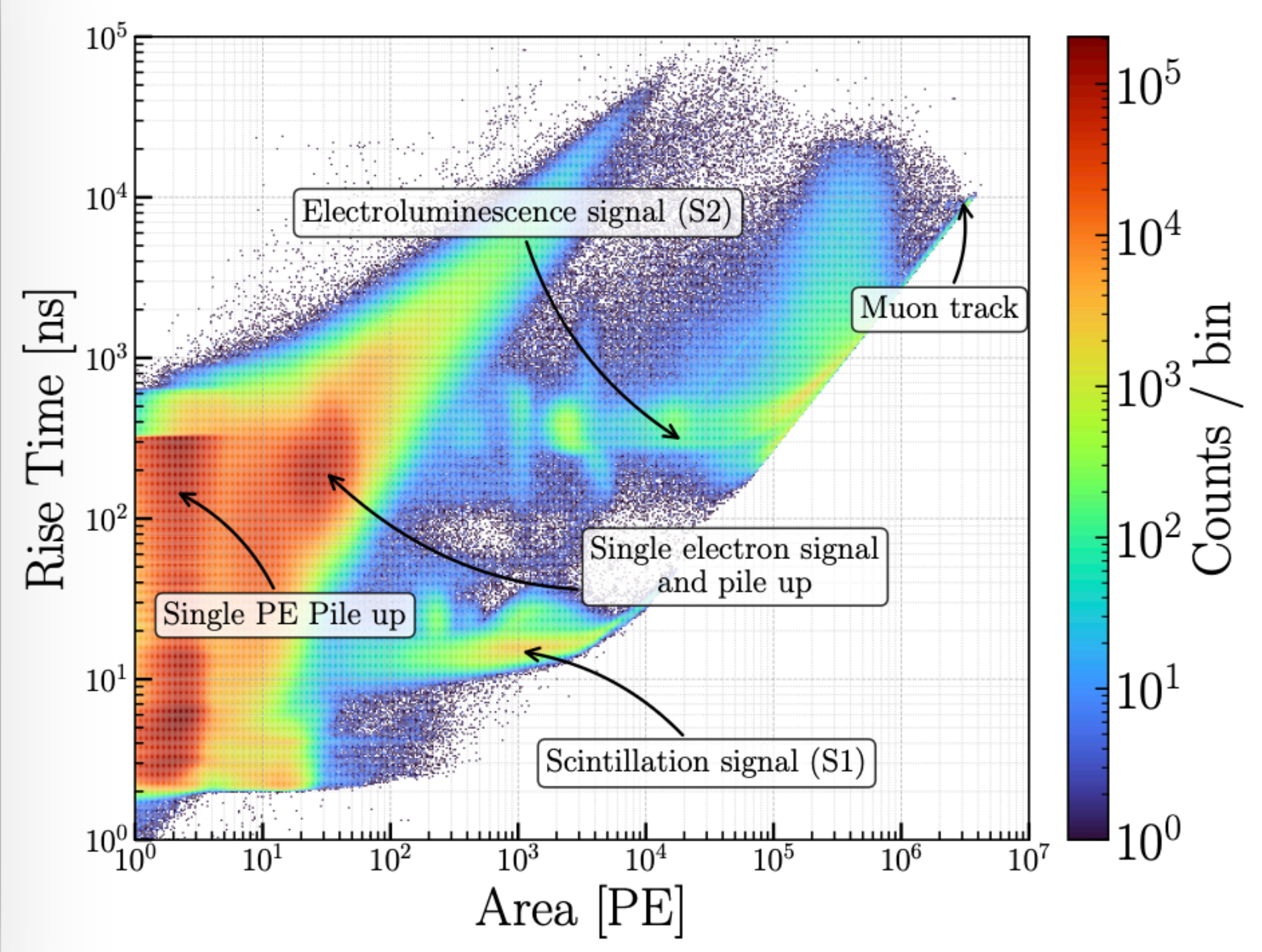
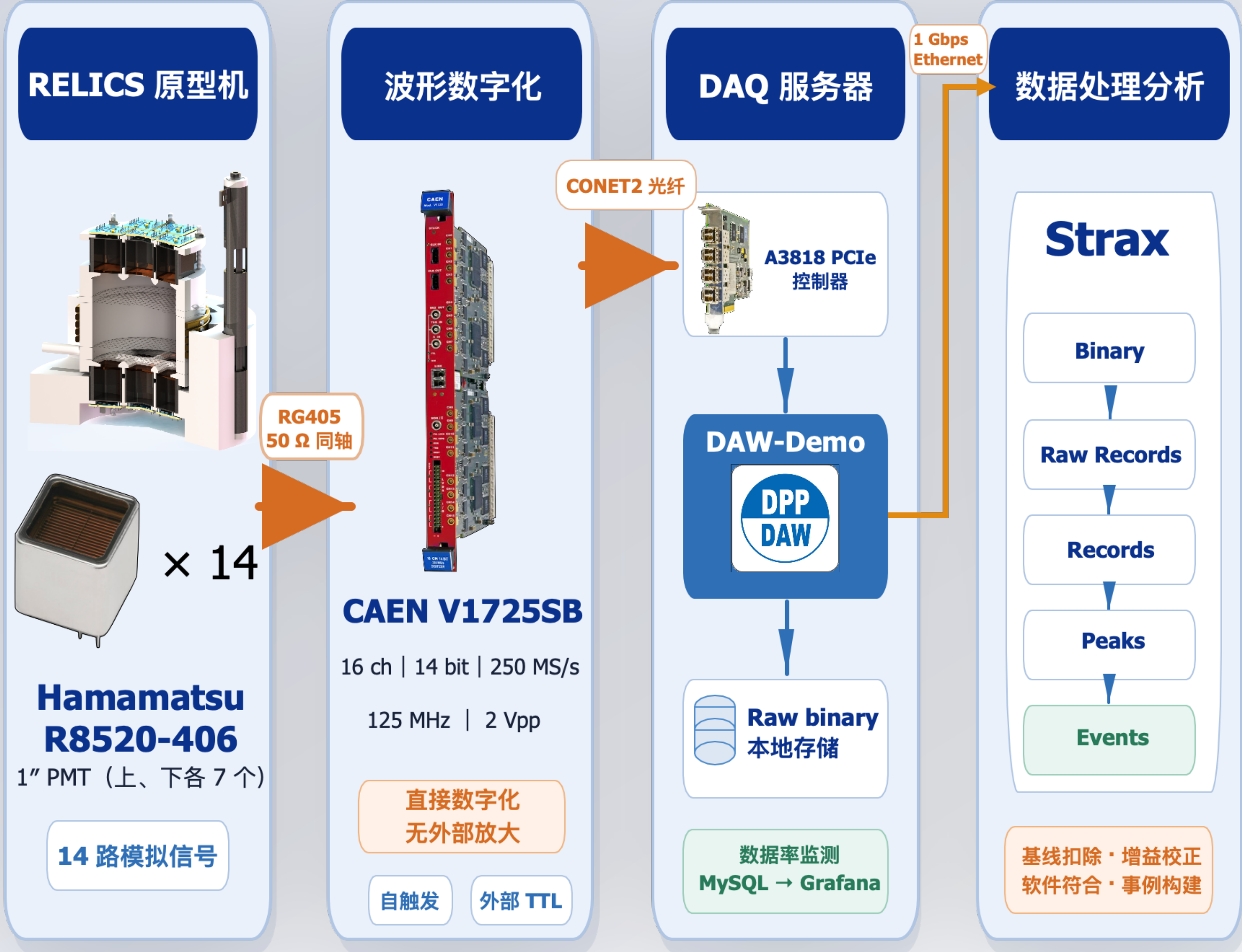


维持稳定的液氩运行状态
持续去除电负性杂质，并注入内部刻度源

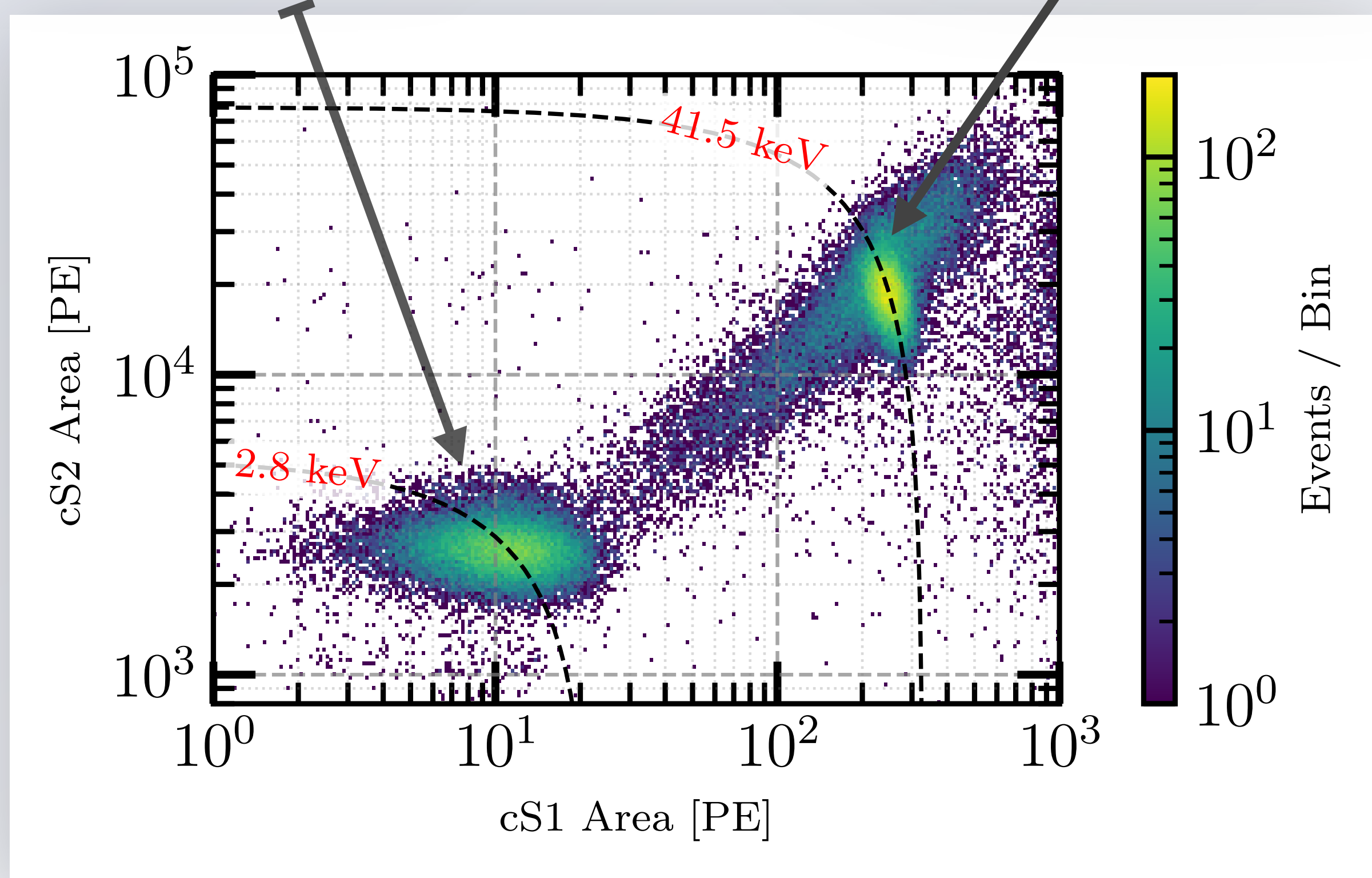
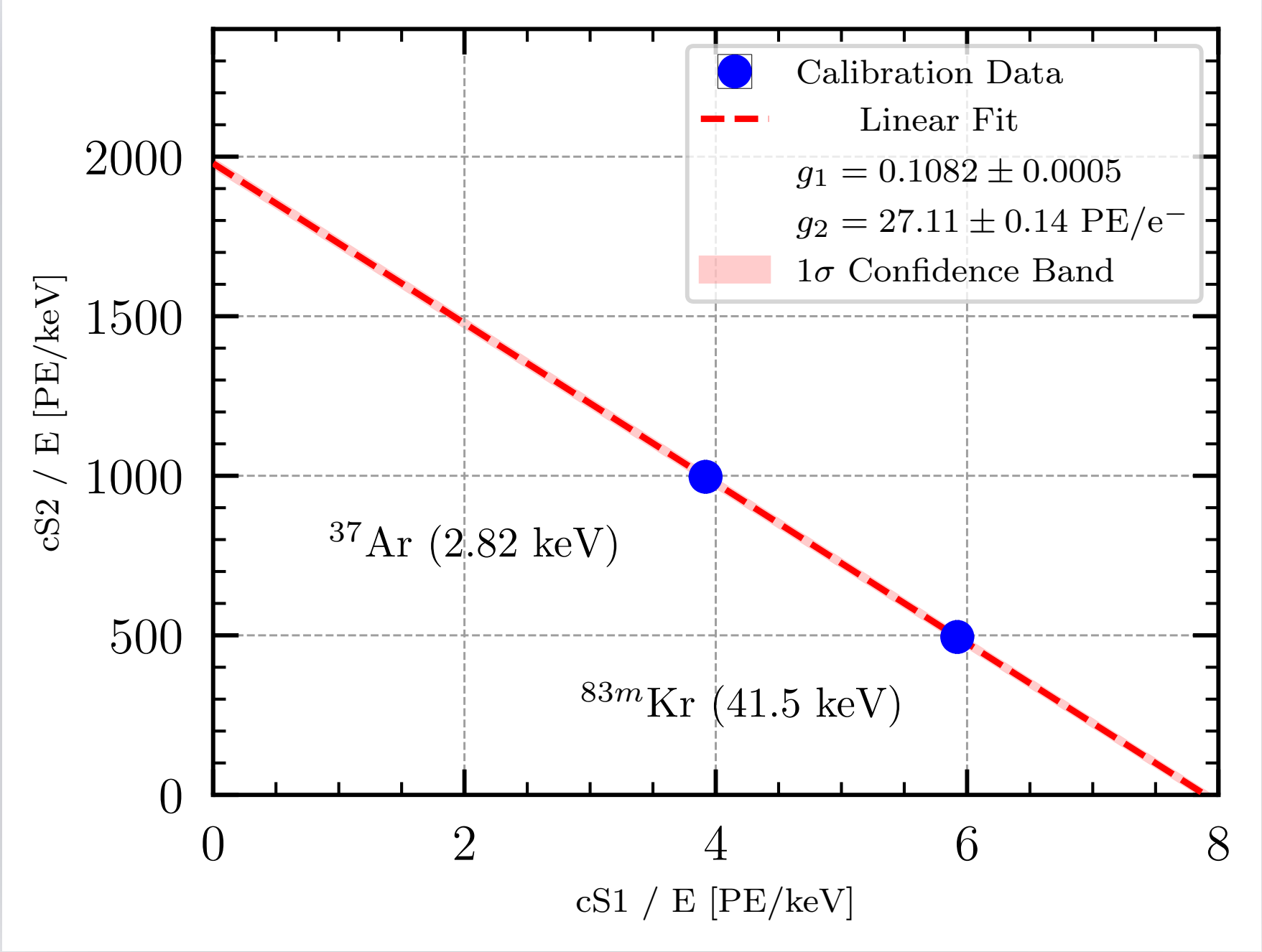
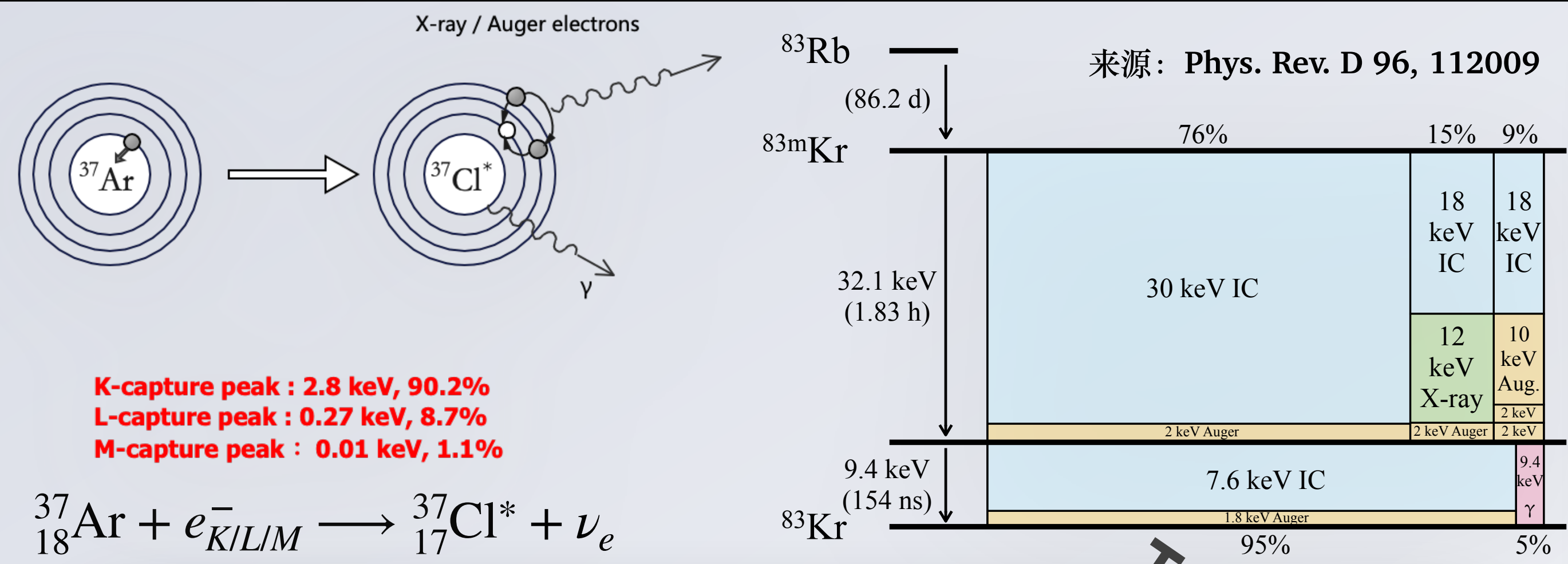


温度、压力、液位和流量实时监测，自
动报警与应急控制

RELICS 原型机：数据采集与数据分析

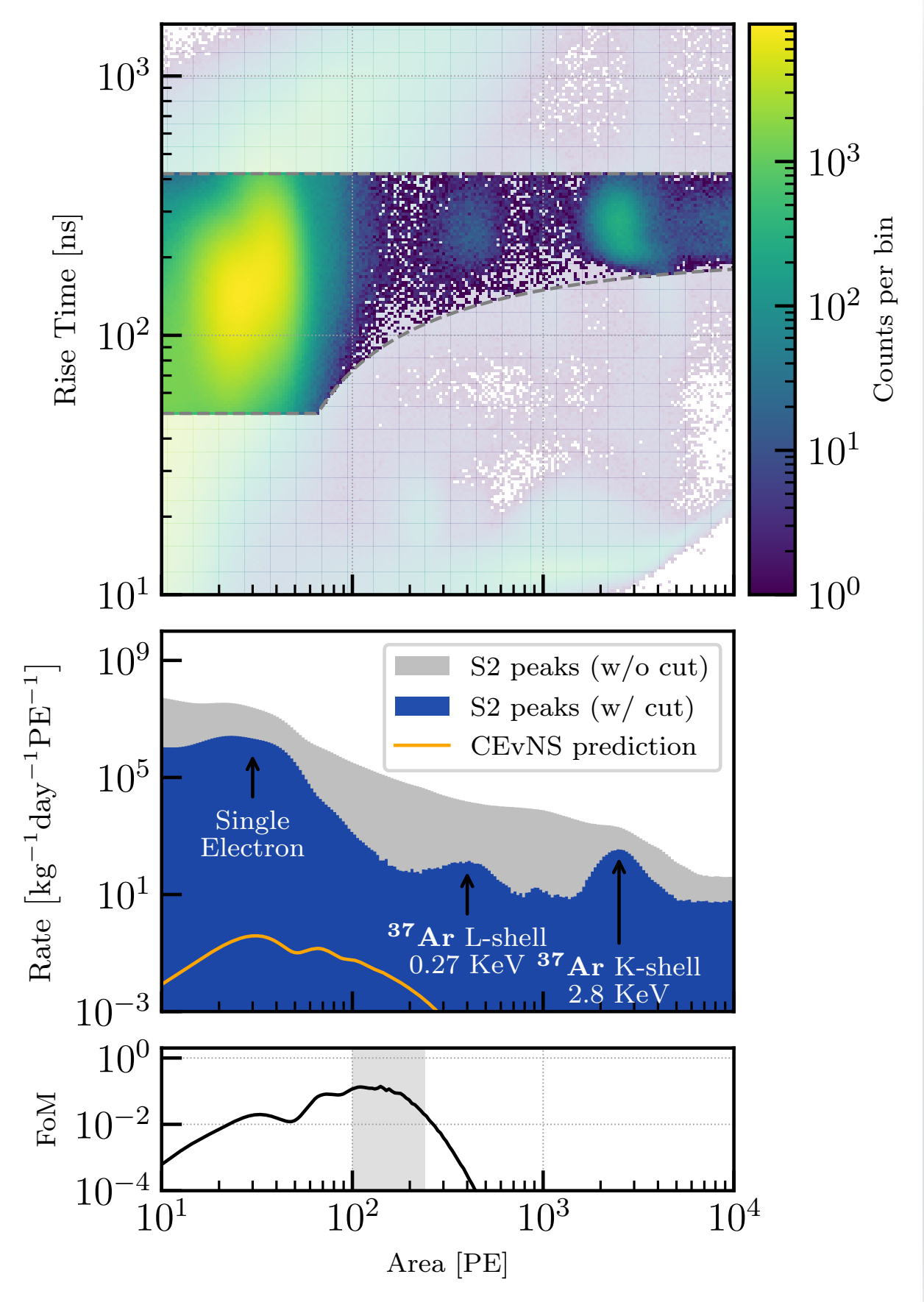
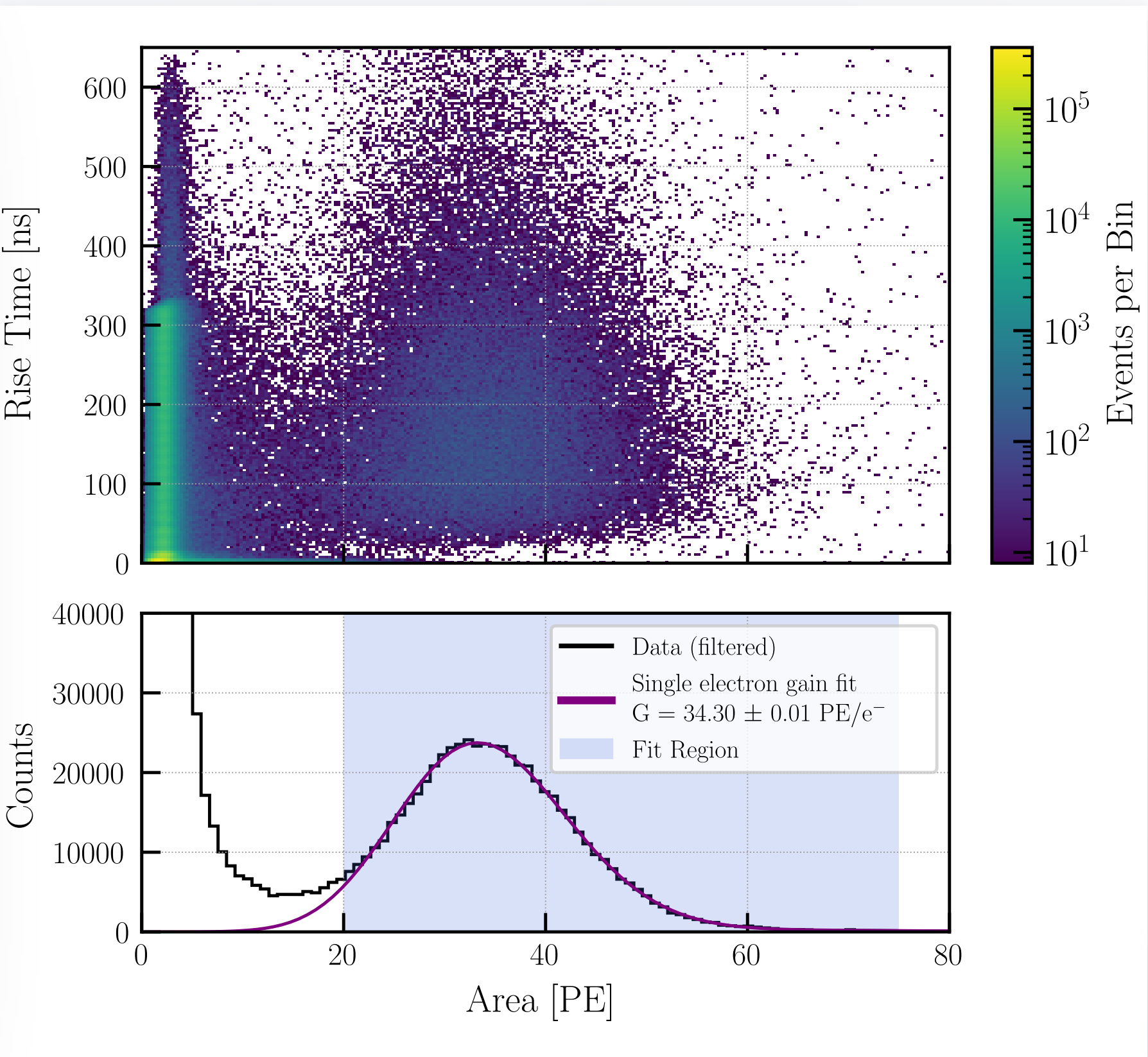
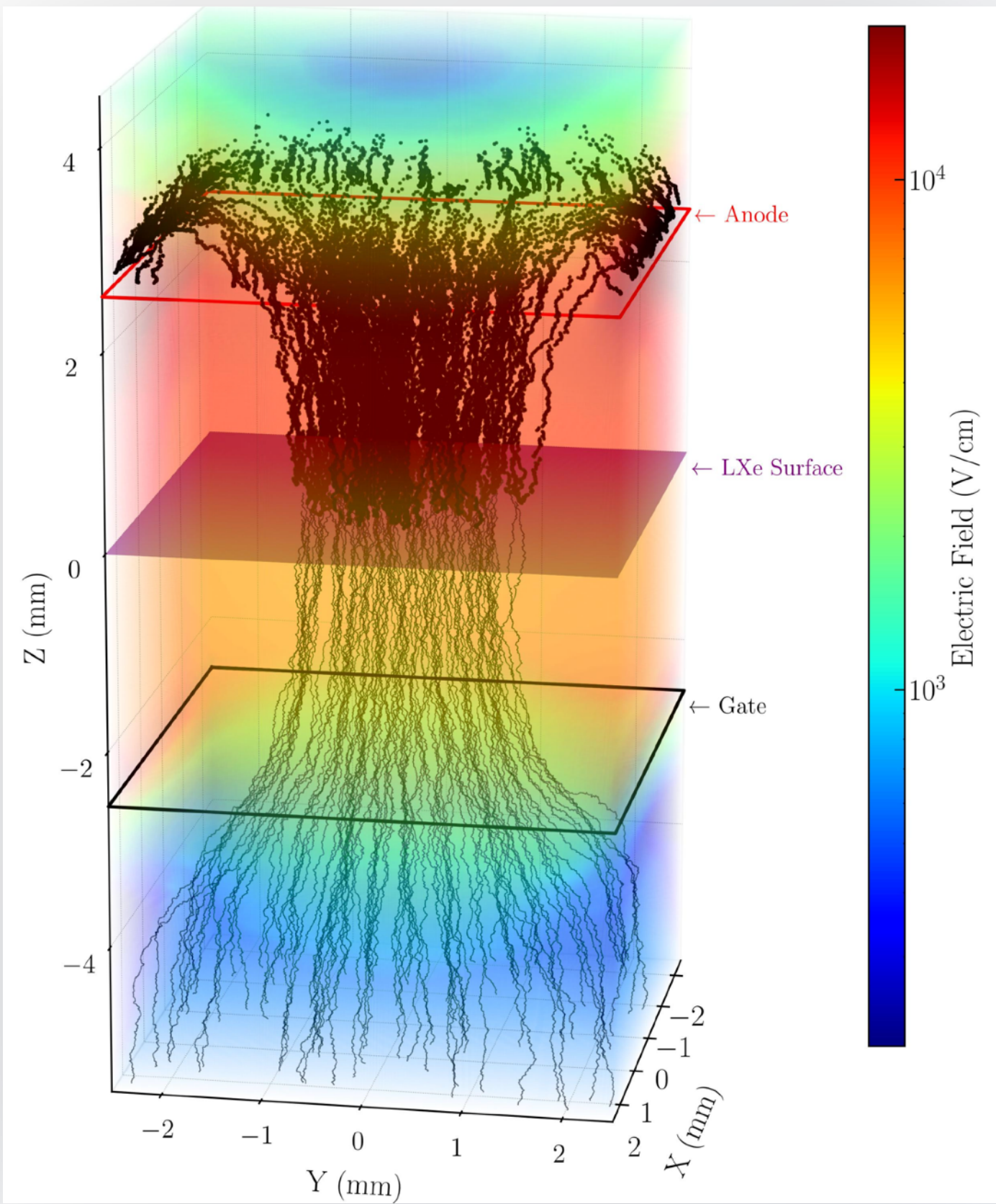


RELICS 原型机：内部刻度源标定



- $E = W \left(\frac{S1}{g_1} + \frac{S2}{g_2} \right)$
- g_1 : 液氙内闪烁光子探测效率 0.1082 PE/ph
- g_2 : 电离电子经过拉出液面与电致发光的放大能力 27.11 PE/e⁻

RELICS 原型机：单电子信号与亚 keV 低阈值验证



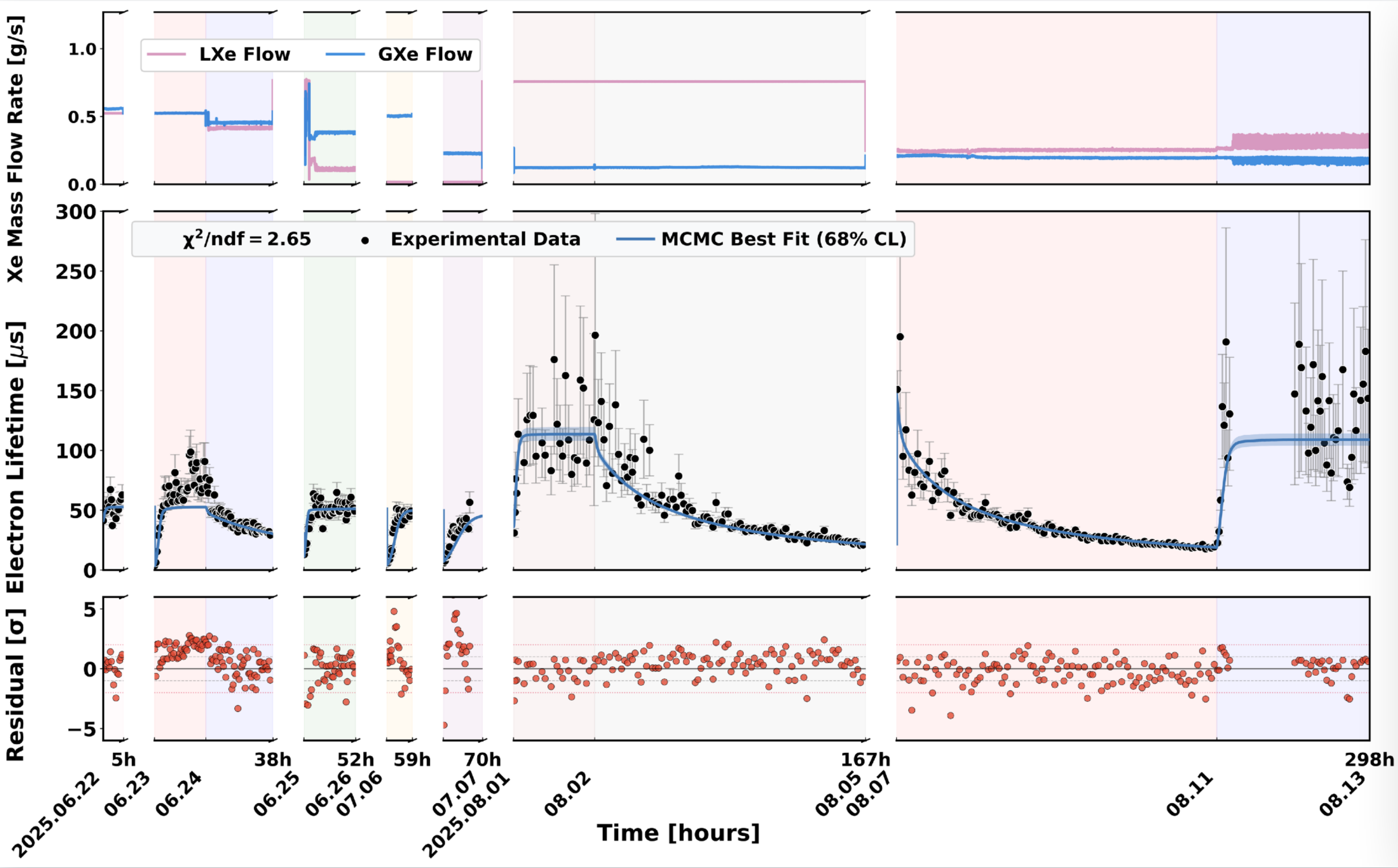
电致发光过程示意图

上图：单电子信号波形面积、上升时间分布
下图：单电子波形面积分布直方图

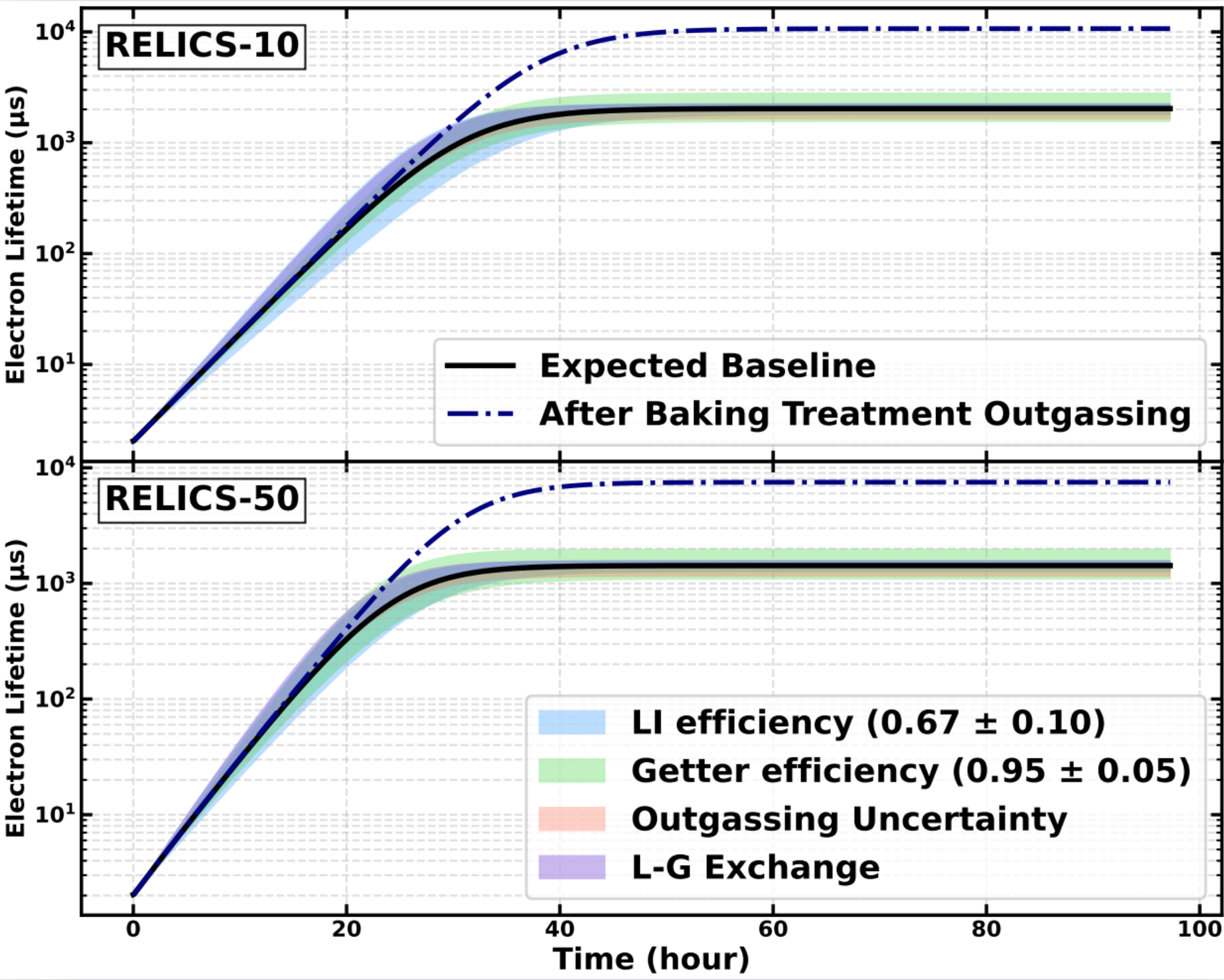
成功分辨 ^{37}Ar L-俘获 0.27 keV 信号，验证 S2-only 的 sub-keV 信号探测能力。

- 单电子增益： 气氙中电致发光的放大能力 $34.30 \pm 0.01 \text{ PE/e}^-$

RELICS 原型机：纯化模型建立



纯化模型在原型机数据验证



模型预测正式实验电子漂移寿命演化
2天时间内达到 $\sim \text{ms}$ 量级

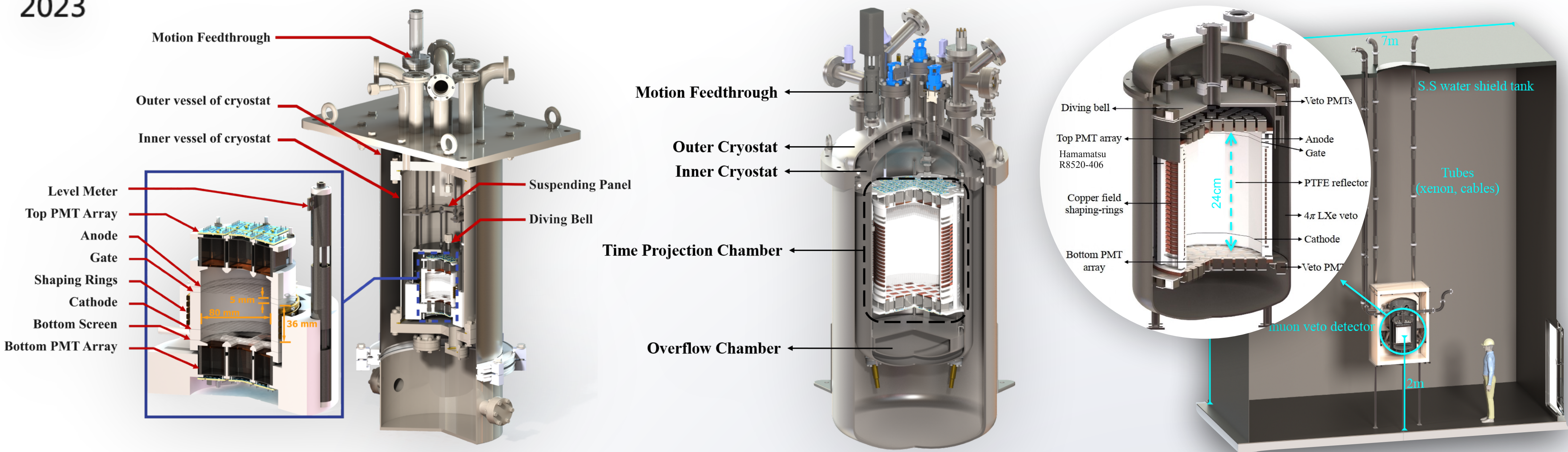
RELICS 实验规划

2023 - 2025
RELICS 原型机

2026 - 2028
RELICS-10

2029 -
RELICS-50

2023



陈江宇 | 墙报 5-06 | 粒子物理实验技术
王俊 | flash 报告 | 7月17日 11:26 | 分会场 IV

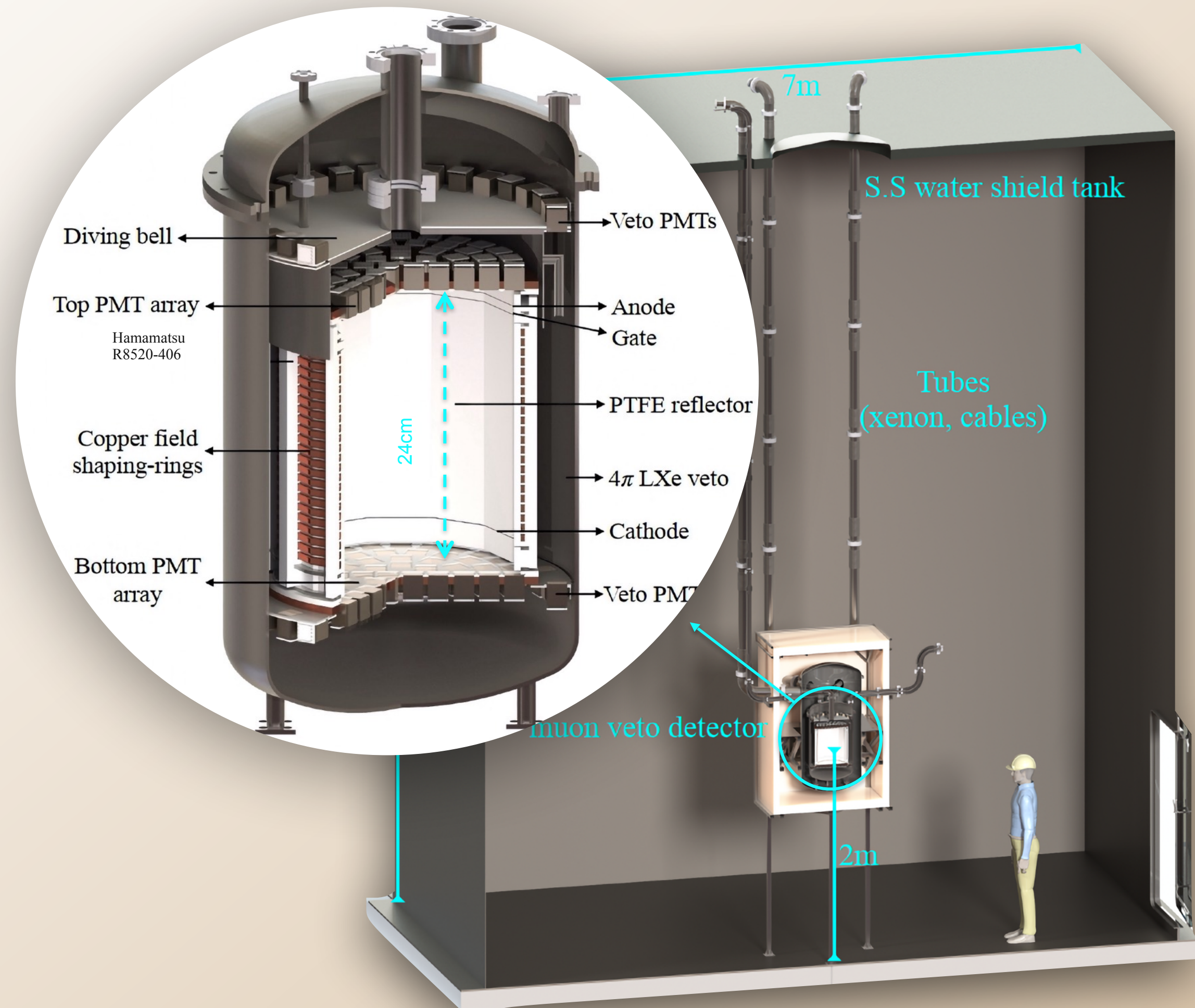
总结

- **实验目标：** 在三门核电站利用双相氙时间投影室测量反应堆 **CEvNS**。
- **技术进展：** 原型机已完成系统集成与稳定运行，验证单电子读出和亚 **keV S2-only** 探测能力。
- **近期计划：** 2026 年于西湖大学完成 **RELICS-10** 建设与测试运行，2027 年开展反应堆现场数据采集，后续推进 **RELICS-50**。

总结

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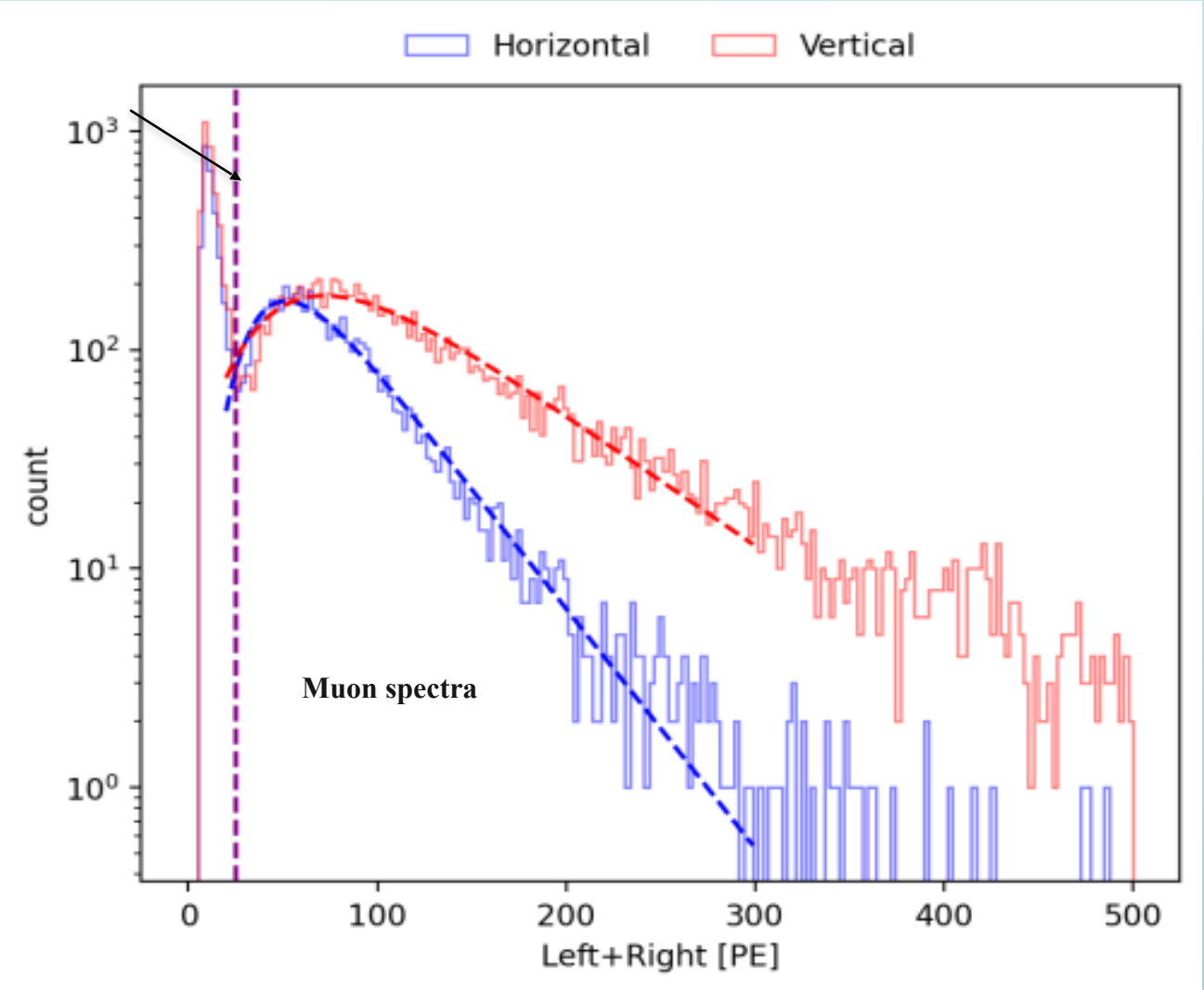
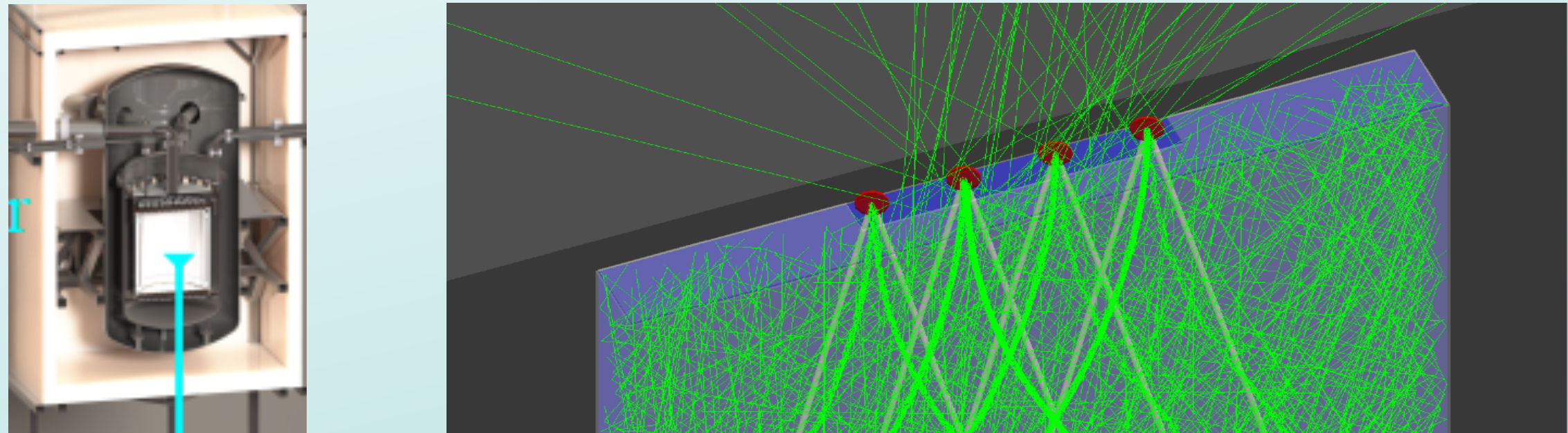
Backup1: RELICS-50 探测器设计



- **32 kg** 液氙有效质量
- 上下各 **64** 个 1 英寸光电倍增管阵列
- 高电场设计，提高电荷产额与提取效率
- **$7 \times 7 \times 7 \text{ m}^3$** 被动**水屏蔽**
- 低本底材料选型
- 塑料闪烁体 μ 子反符合系统

Backup2: 宇宙线缪子反符合

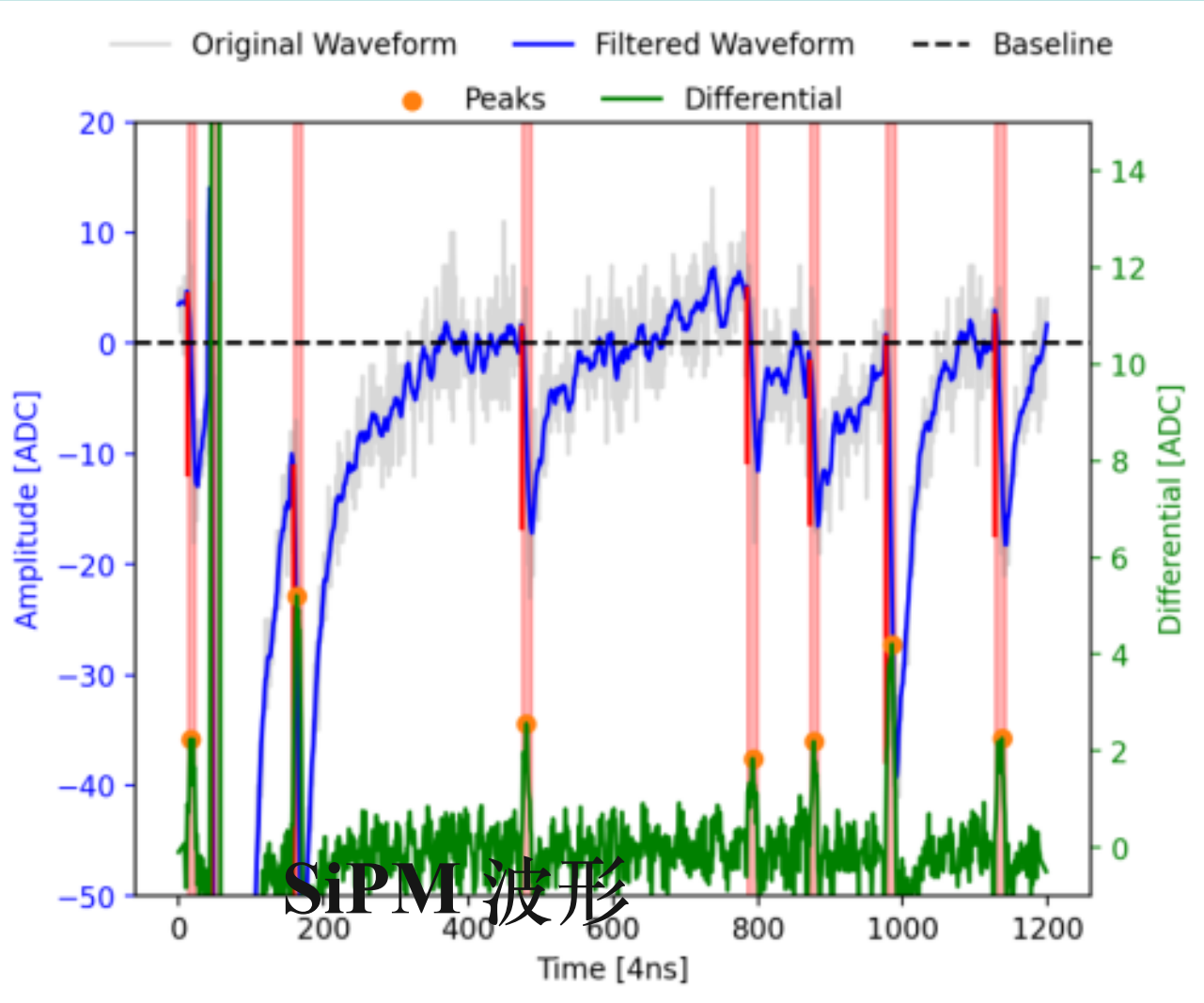
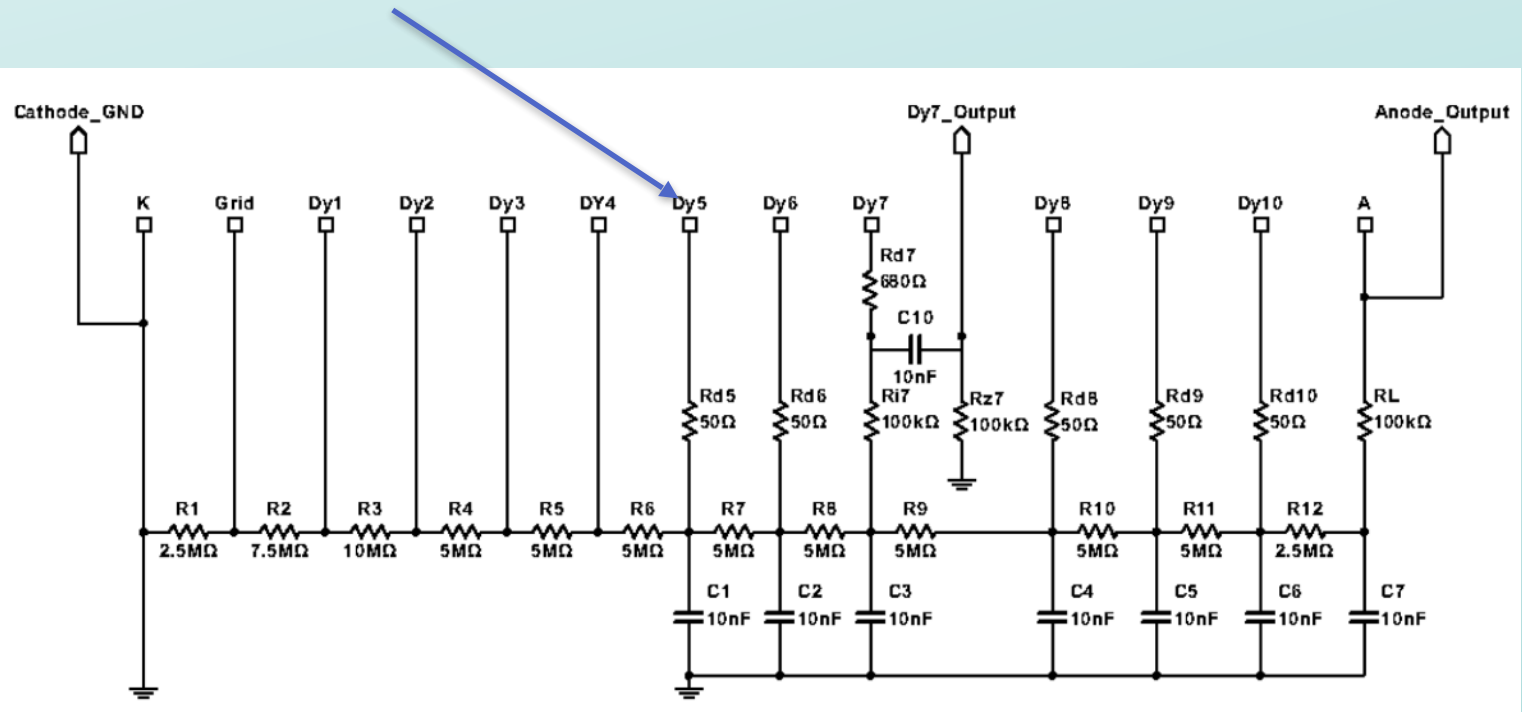
Path 1: Muon **Active Veto** Boards



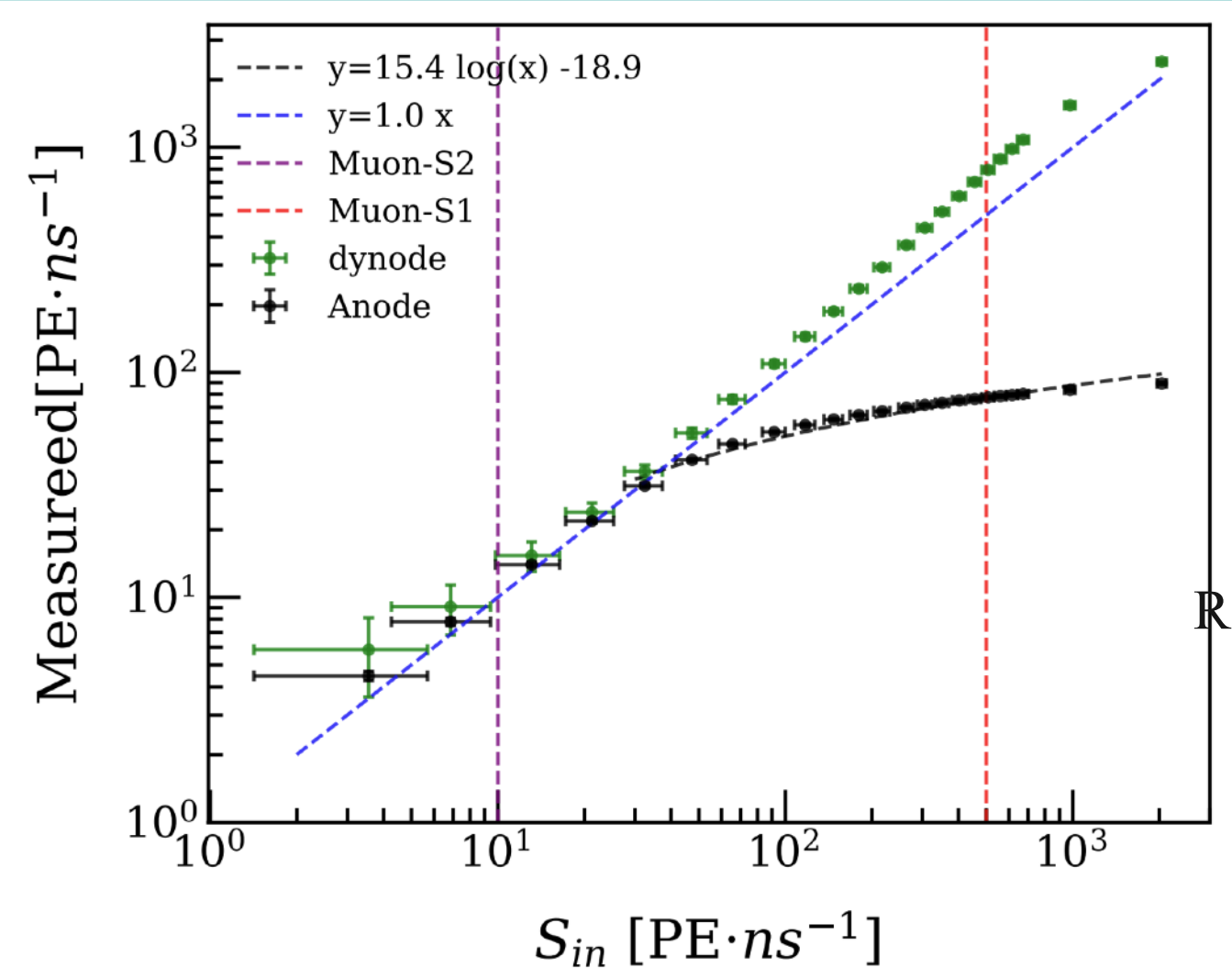
Plastic scintillator bars w/ SiPM to tag muons

Path 2: TPC PMT **Dynode** Readout

arXiv: 2510.24196



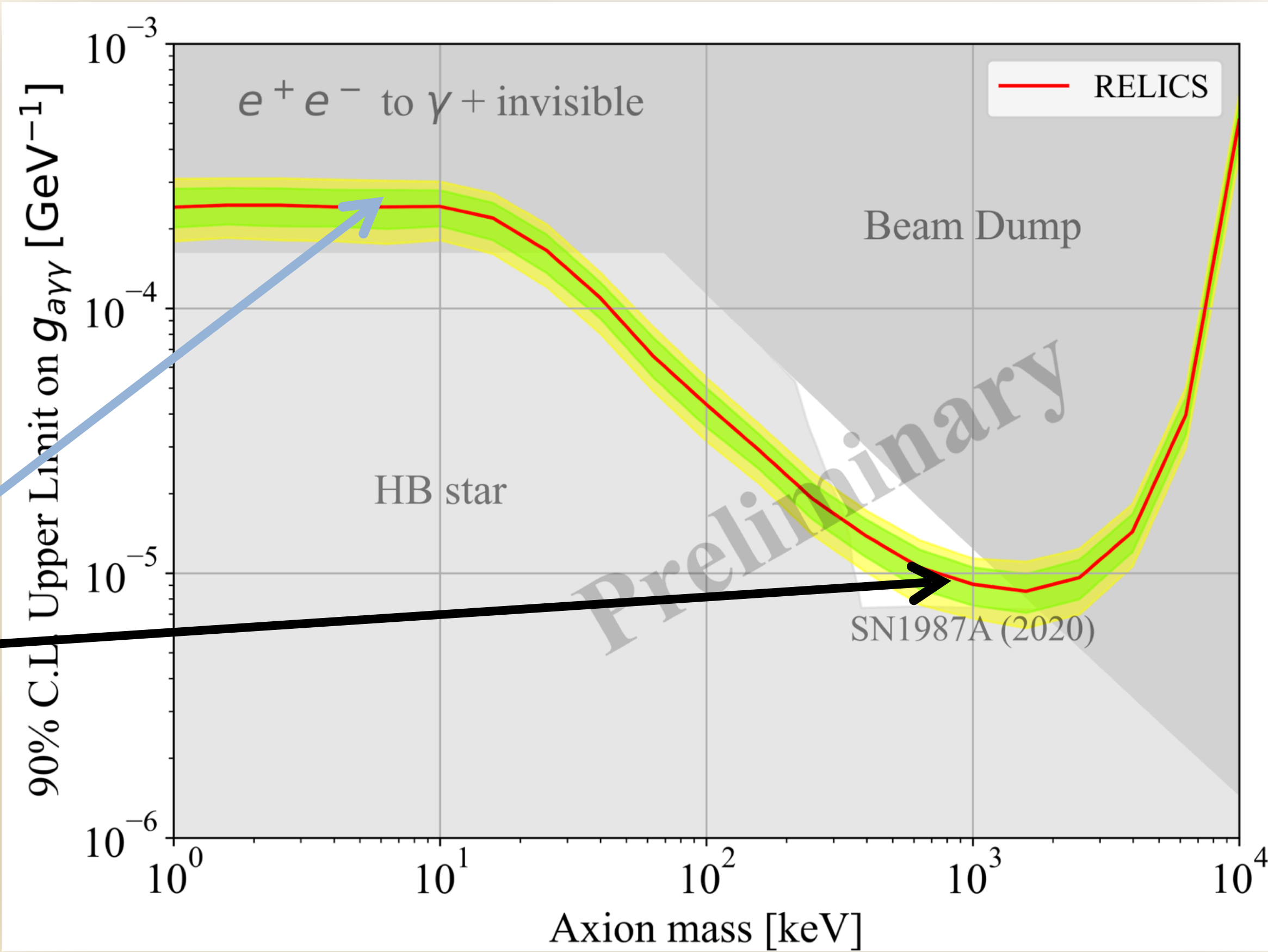
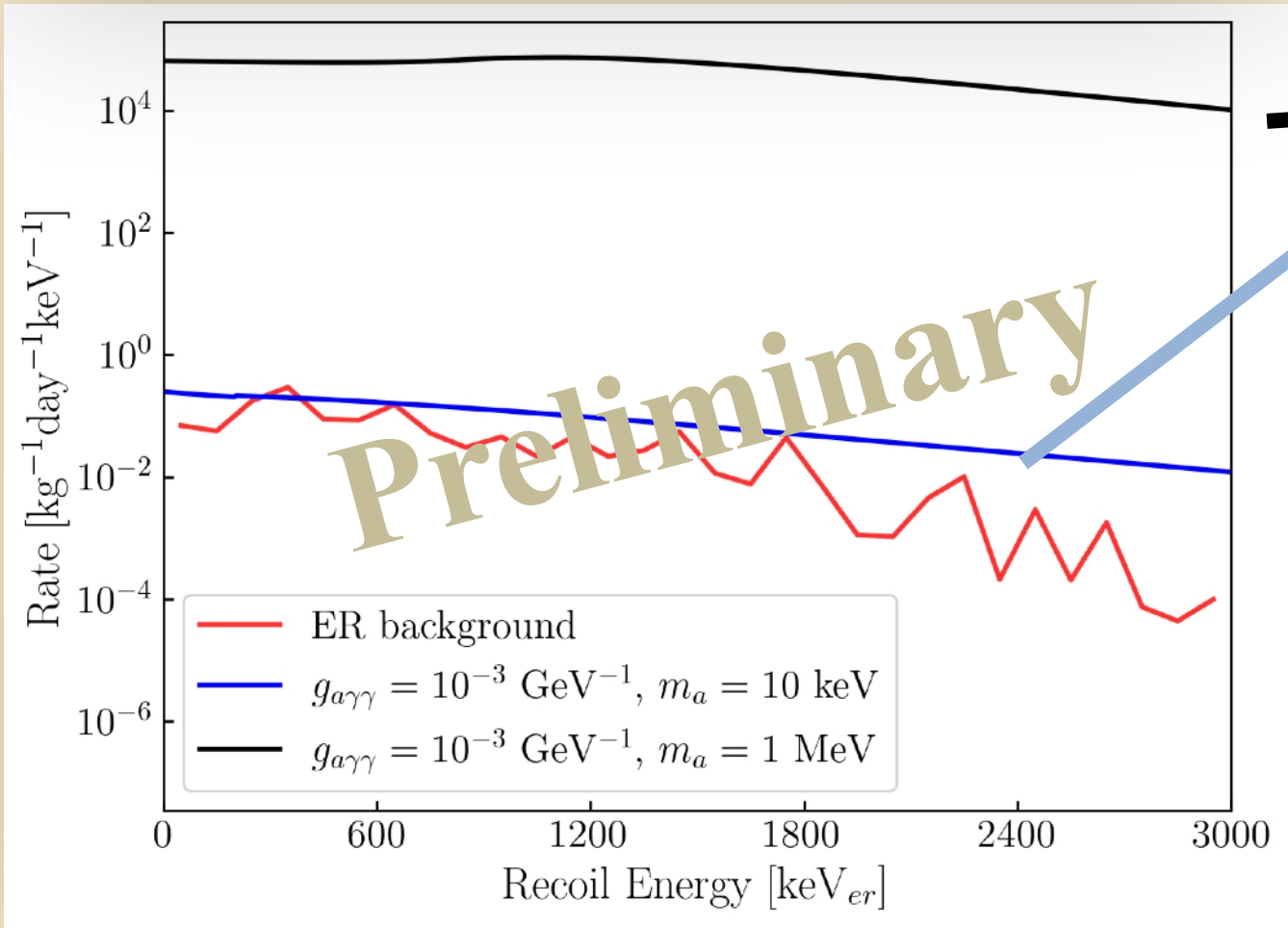
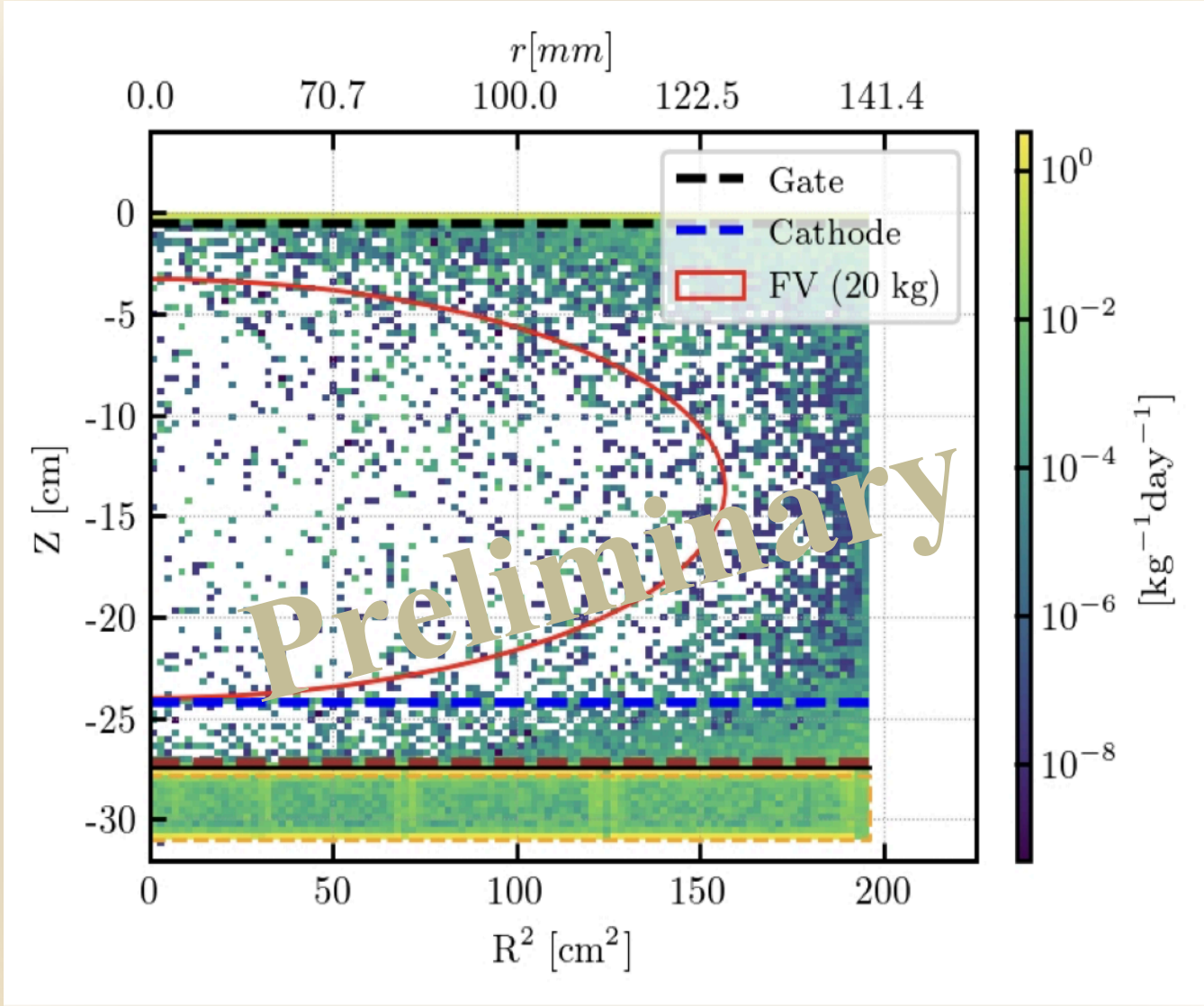
SiPM 波形



Range: keV $\rightarrow$ MeV

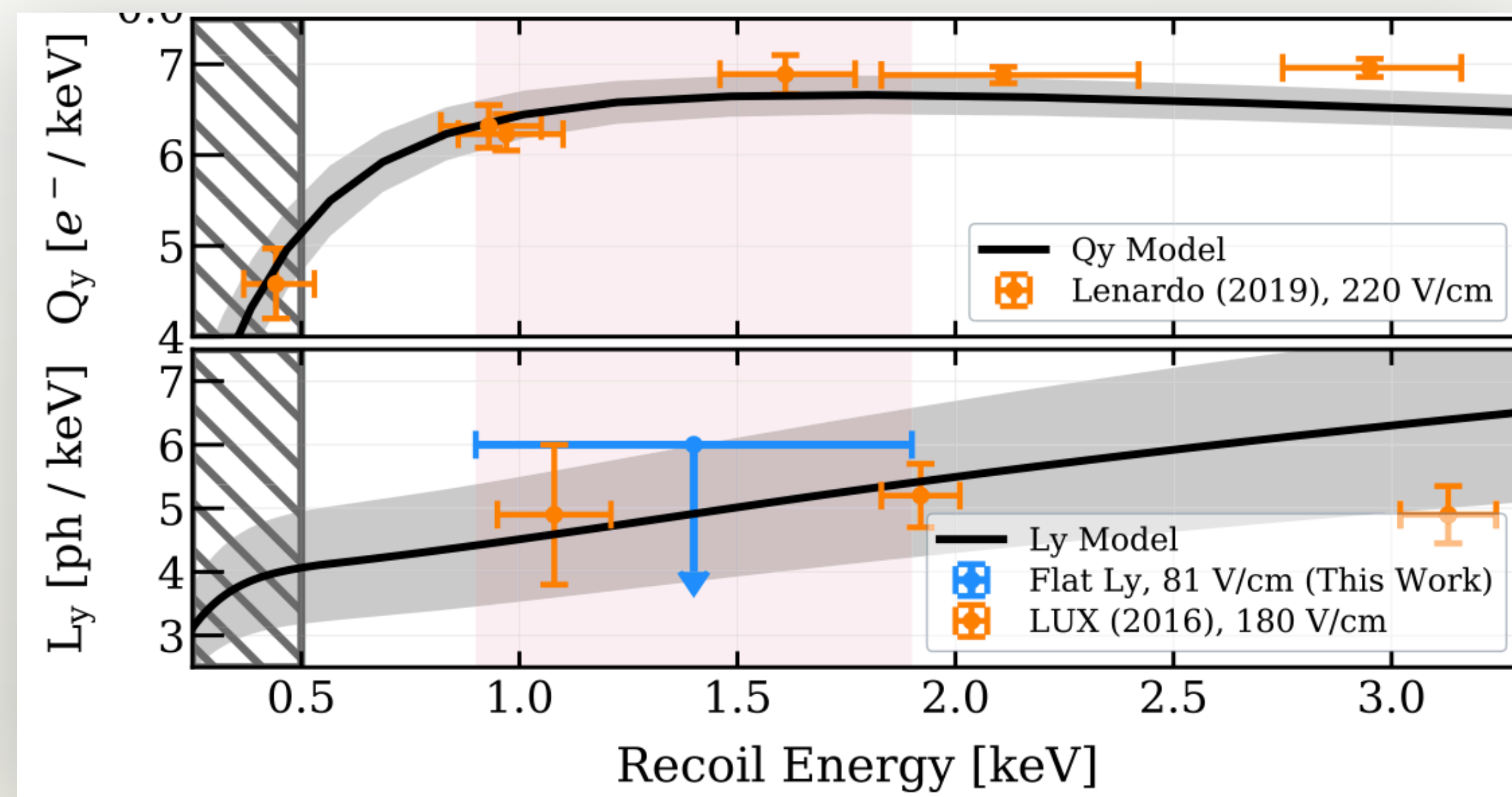
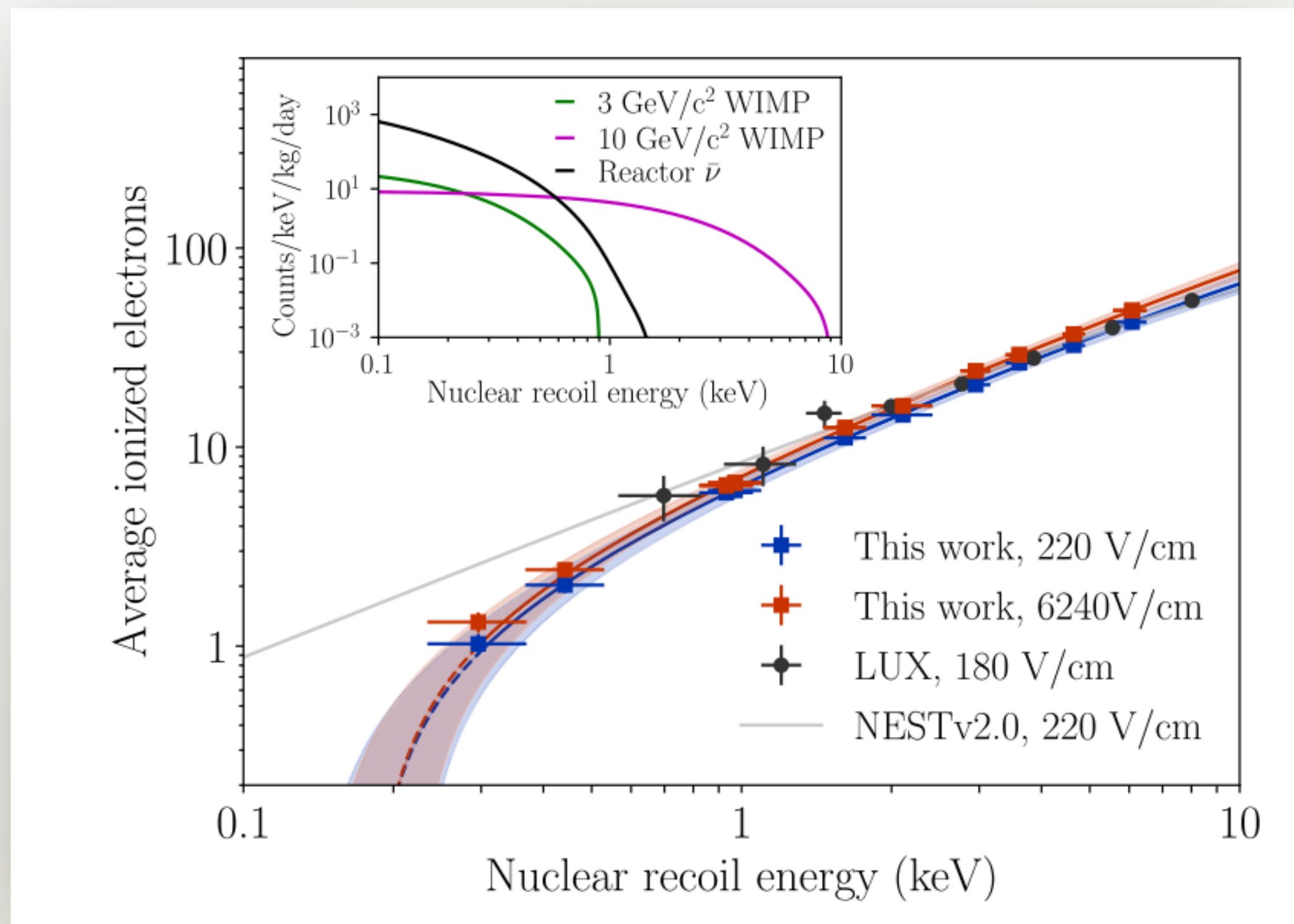
Dynode recovers otherwise **saturated** anode signal

Backup3: 轴子物理探测



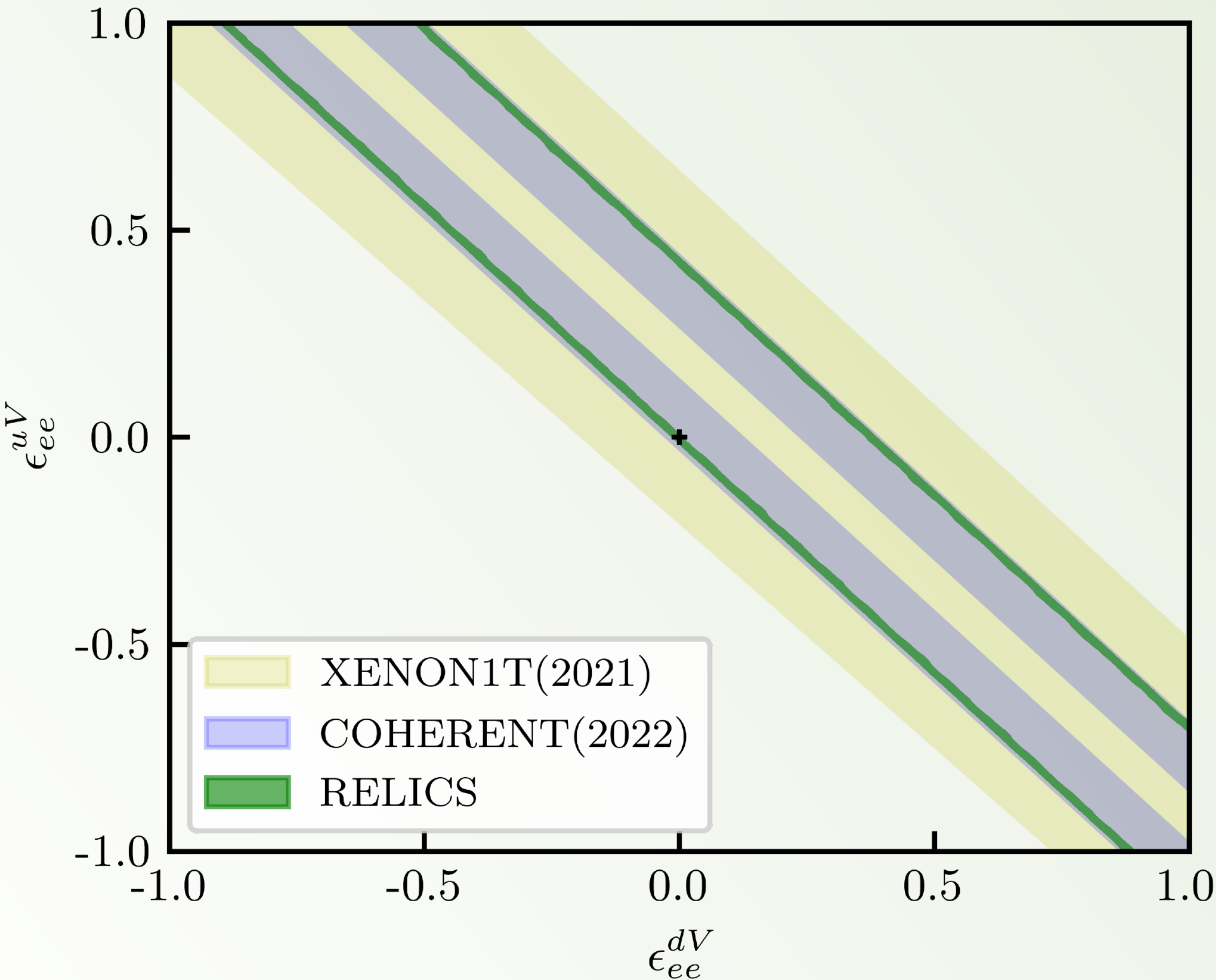
- 20 kg-年曝光量
- 探测反应堆 ALPs

Backup4: 核反冲电子产额



- 电场依赖项: $\zeta(\mathcal{E}, \rho) = \gamma \mathcal{E}^\delta \left(\frac{\rho}{\rho_0} \right)^\nu$
- 电子数产额: $Q_y(E, \mathcal{E}, \rho) = \frac{1}{\zeta(\mathcal{E}, \rho)(E + \epsilon)^p} \left(1 - \frac{1}{1 + (E/\zeta)^\eta} \right)$

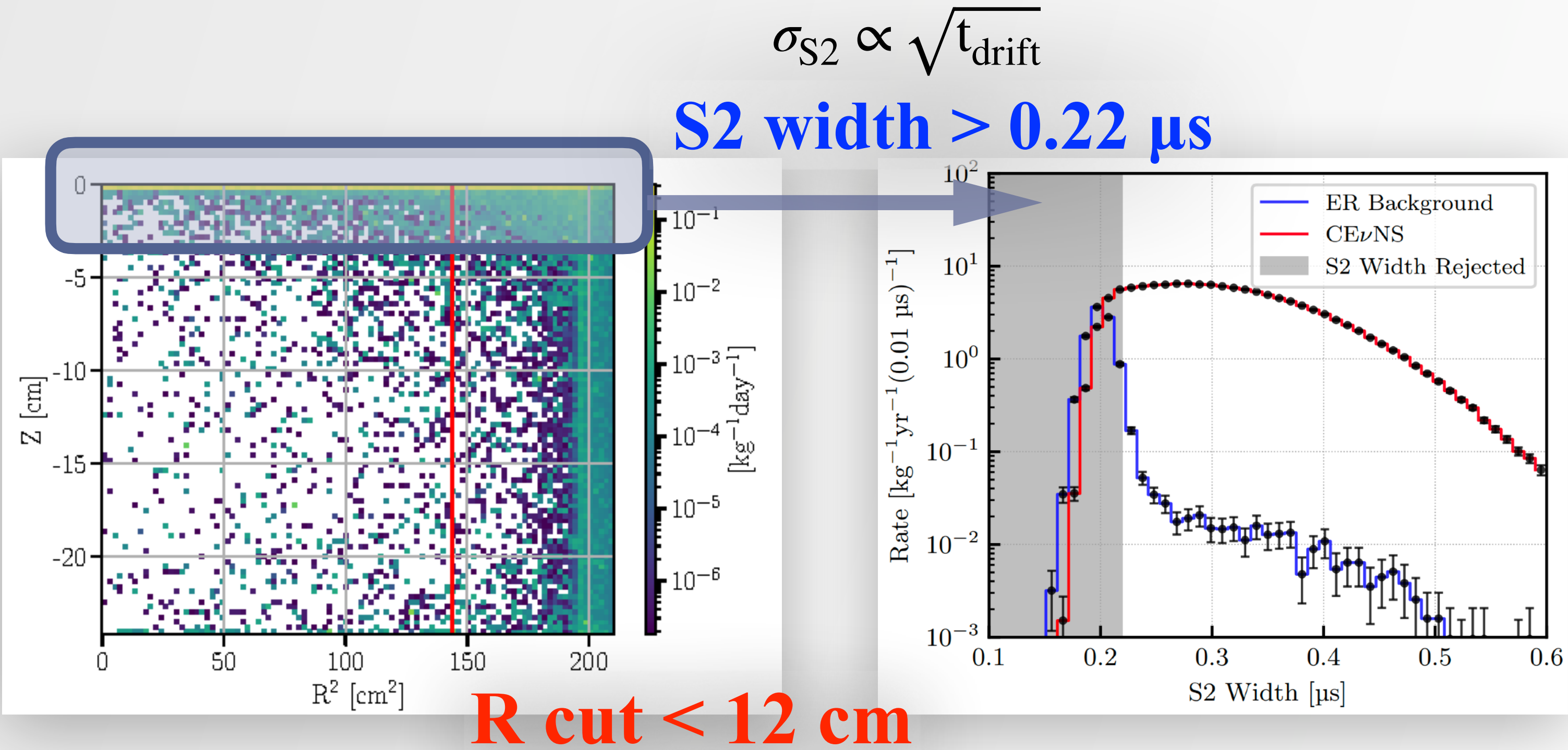
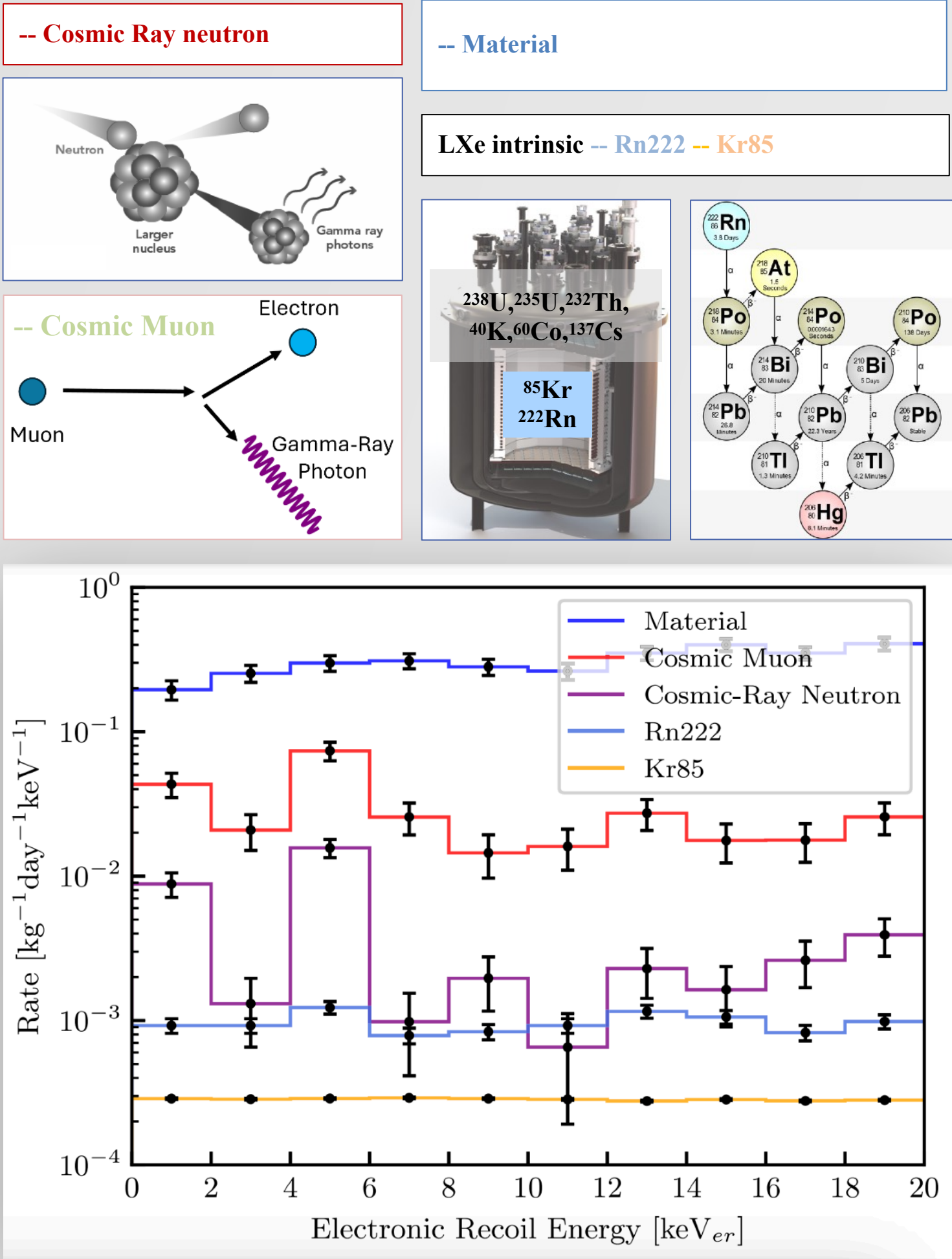
Backup5: 非标准相互作用(NSI)测量



非标准中微子相互作用(NSI)参数的限制，
描述中微子与上下夸克的非轴矢量相互作用的强度

$$Q_{\text{eff}} \simeq Q_W + (2Z + N)\epsilon_{ee}^{uV} + (Z + 2N)\epsilon_{ee}^{dV}$$

Bakcup6: 电子反冲(ER) 本底与抑制



ER 拒绝效率 $\approx 94\%$ CEvNS 接受效率 $\approx 86\%$

R位置筛选后、S2时间宽度筛选前的ER本底平均事例率:

$$(3.1 \pm 0.1) \times 10^{-1} \text{ kg}^{-1} \cdot \text{day}^{-1} \cdot \text{keV}_{\text{ER}} @ [0,20] \text{ keV}_{\text{er}}$$