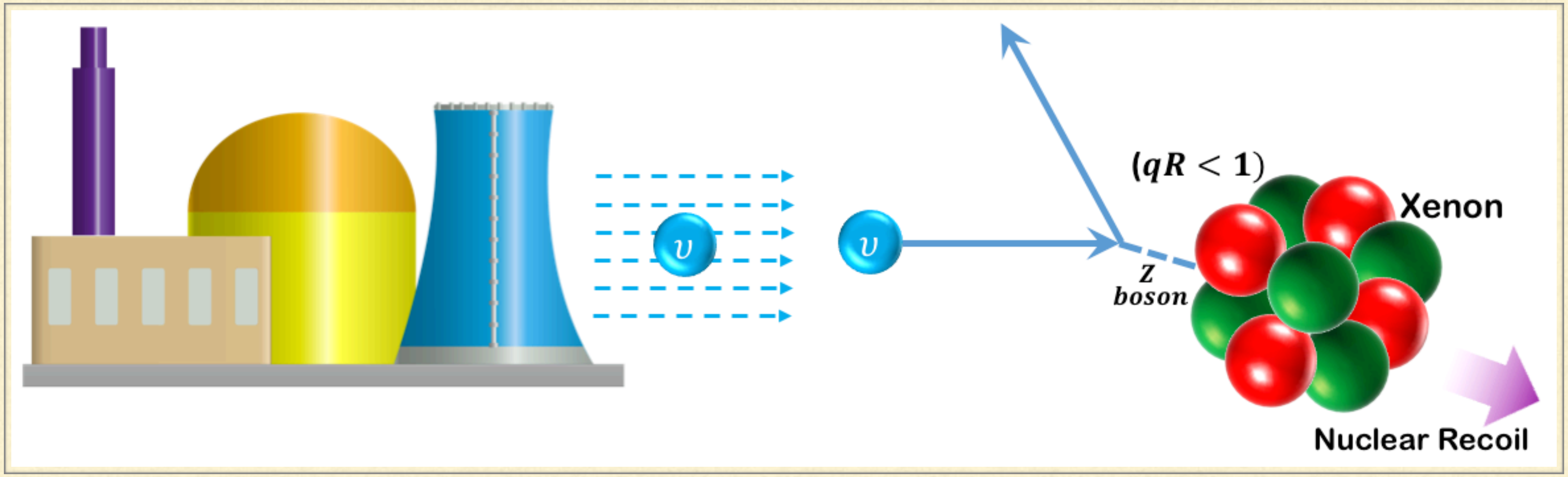
RELICS

REactor neutrino LIquid xenon Coherent Scattering experiment



中微子-原子核相干性散射

RELICS 反应堆中微子实验

魏月环

中山大学 2022/07/24

第三届粒子物理前沿研讨会

OUTLINE

- I：中微子-原子核相干散射

  (Coherent Elastic Neutrino Nucleus Scattering, CEvNS)

- II：研究意义及现状

- III：RELICS 实验计划及预期

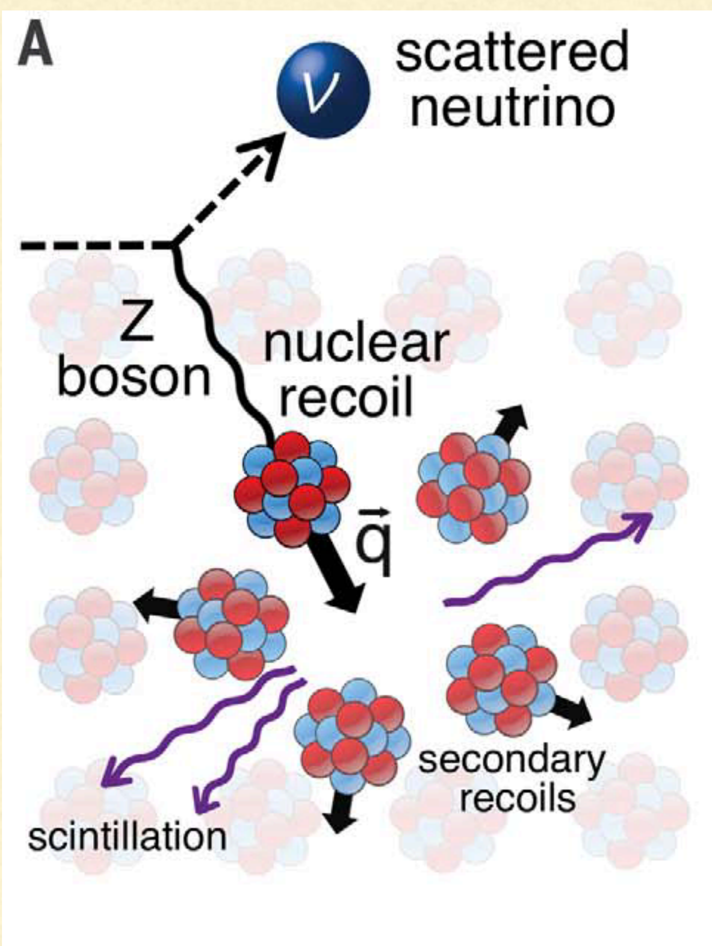
I：中微子-原子核相干散射

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

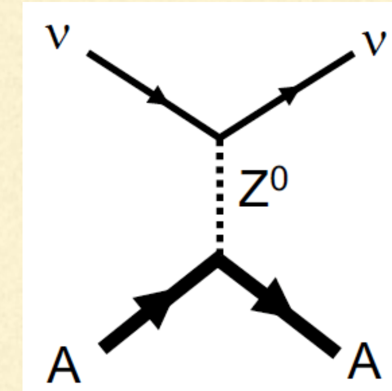
(Received 15 October 1973; revised manuscript received 19 November 1973)



Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

这个要求是有点傲慢无理，它受到事例率、分辨和本底等造成严重的实验困难，但是意义重大！

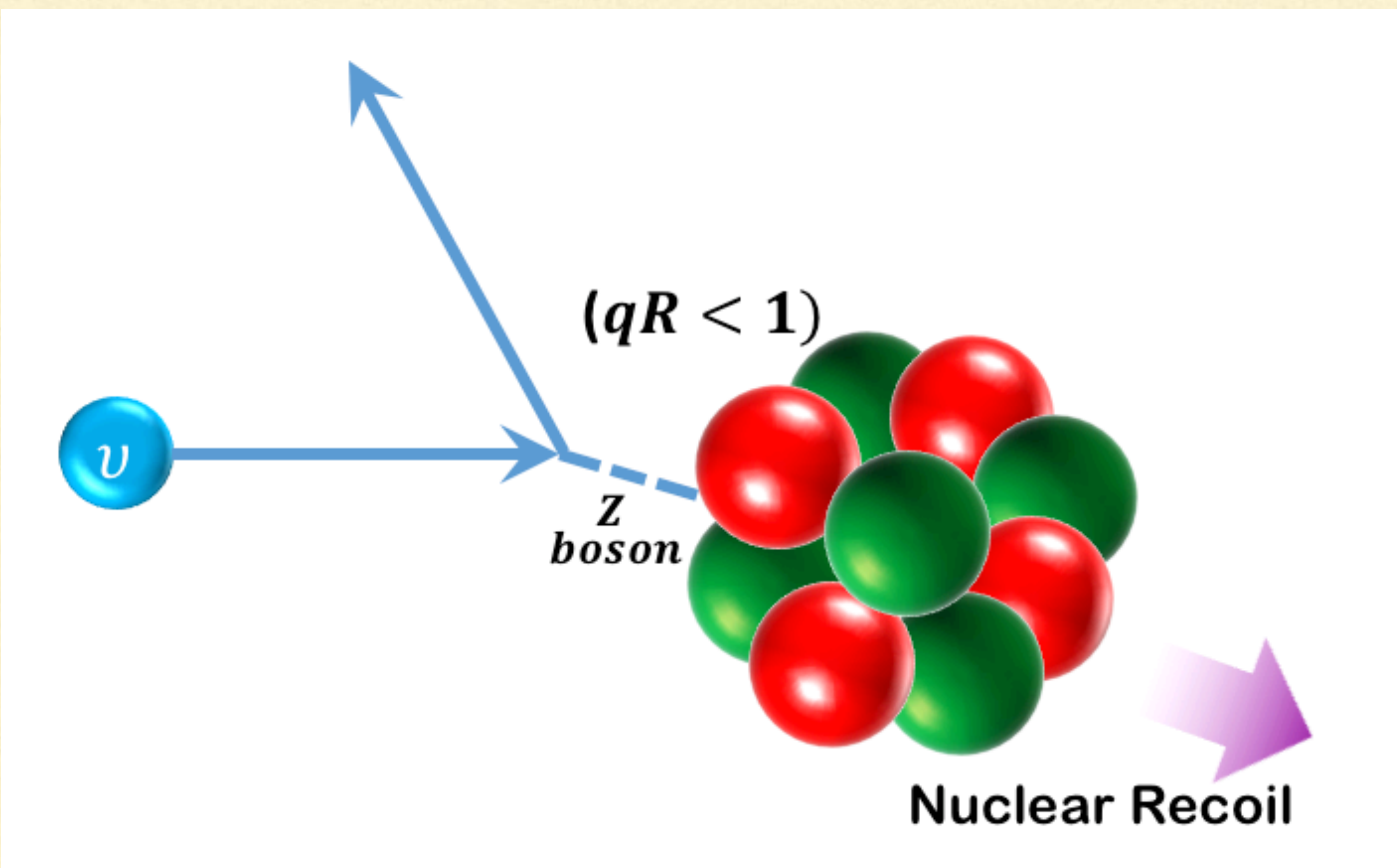
I：中微子-原子核相干散射



Z-exchange of a neutrino with nucleus

➔ **nucleus recoils as a whole**

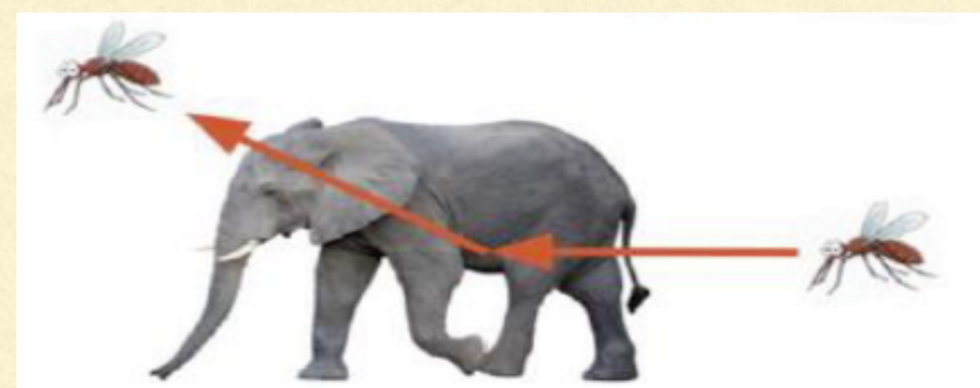
➔ **coherent up to $E_\nu \sim 50$ MeV**



Neutrino wavelength larger than size of nucleus: $qR<1$

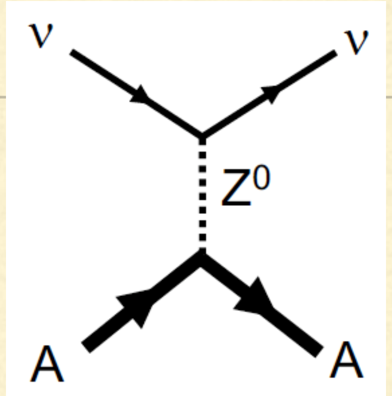
q： momentum transfer

R: nucleus size



Very low recoil energy!

I：中微子-原子核相干散射



Standard Model prediction for CEvNS differential cross section

Fermi constant

Form factor

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

Weak nuclear charge

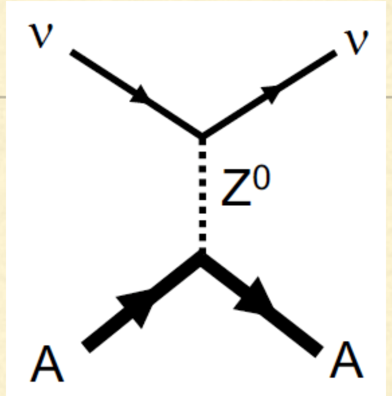
$$Q_W = N - (1 - 4\sin^2\theta_W) Z$$

$$\frac{d\sigma}{dT} \propto N^2$$

$$\sin^2\theta_W = 0.23$$

$$\Longrightarrow \quad Q_W \propto N$$

I：中微子-原子核相干散射

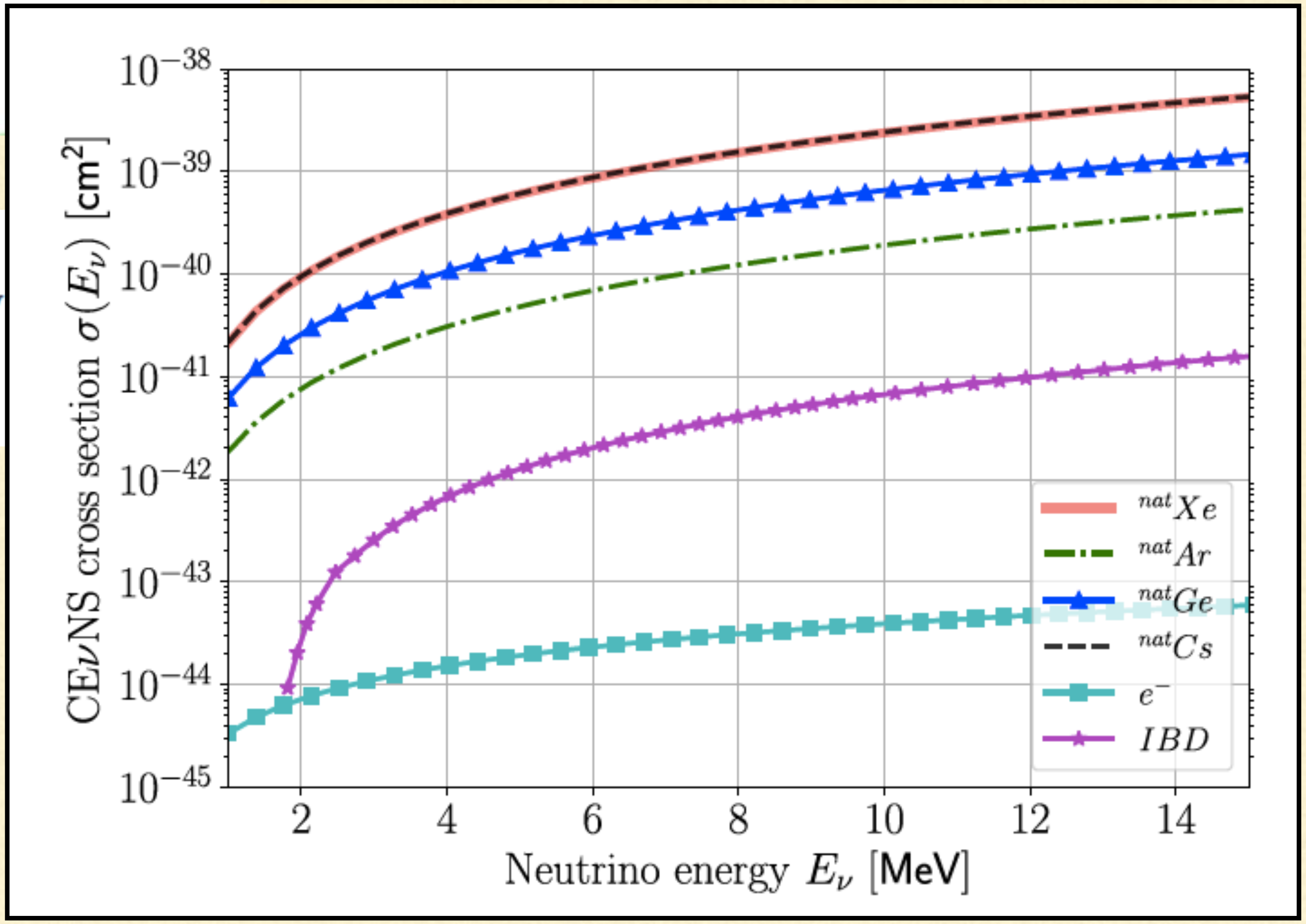


Standard Model prediction for CEvNS differential cross section

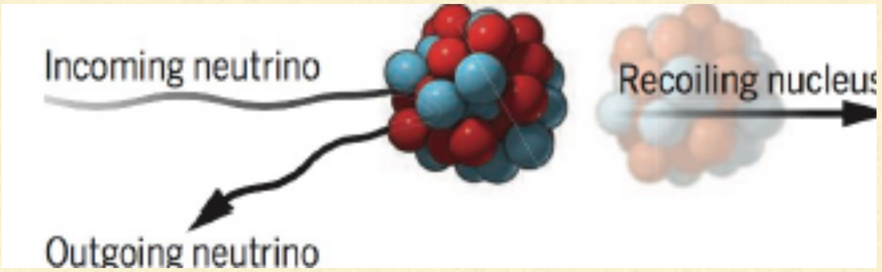
$$\sigma \propto Q_W^2 \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

$$\Longrightarrow \boxed{\sigma \propto N^2}$$

Recoil energy: $T_R \approx \frac{E_\nu^{\,2}(\mathrm{MeV})}{A}$ keV



Trade off between high/low A-nuclei !



II：研究意义

✦粒子物理：

- 低动量转移下的弱混合角
- 中微子超标准有效作用
- 反常中微子磁矩
- 惰性中微子等

✦天体物理：

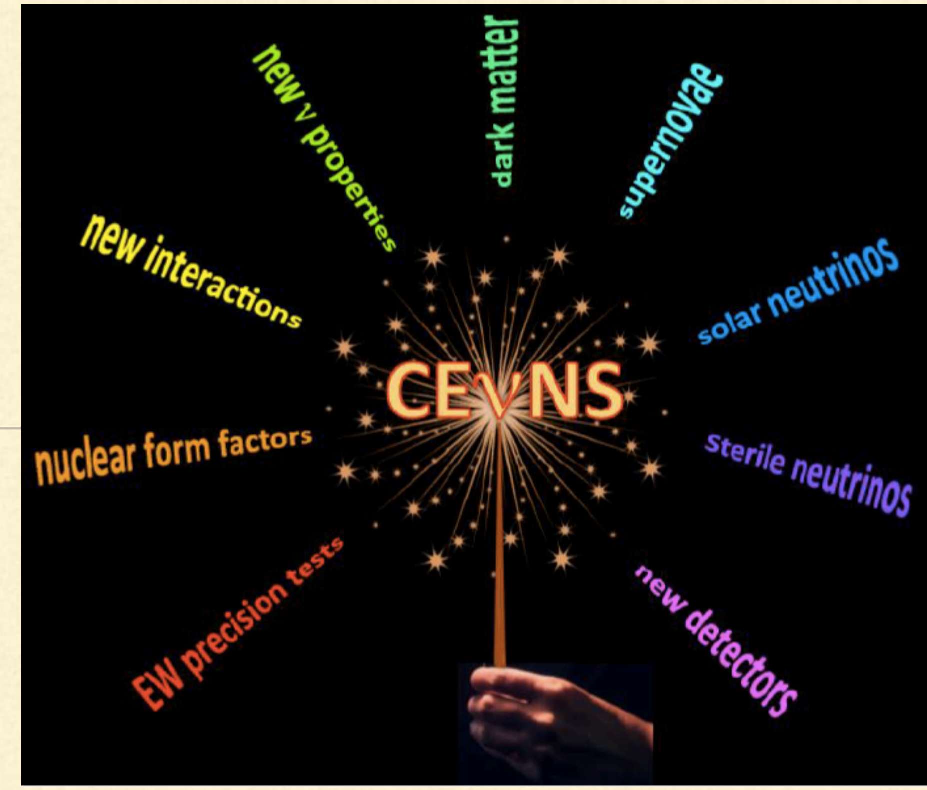
- 探测太阳中微子、超新星中微子的新手段
- 暗物质探测的重要本底

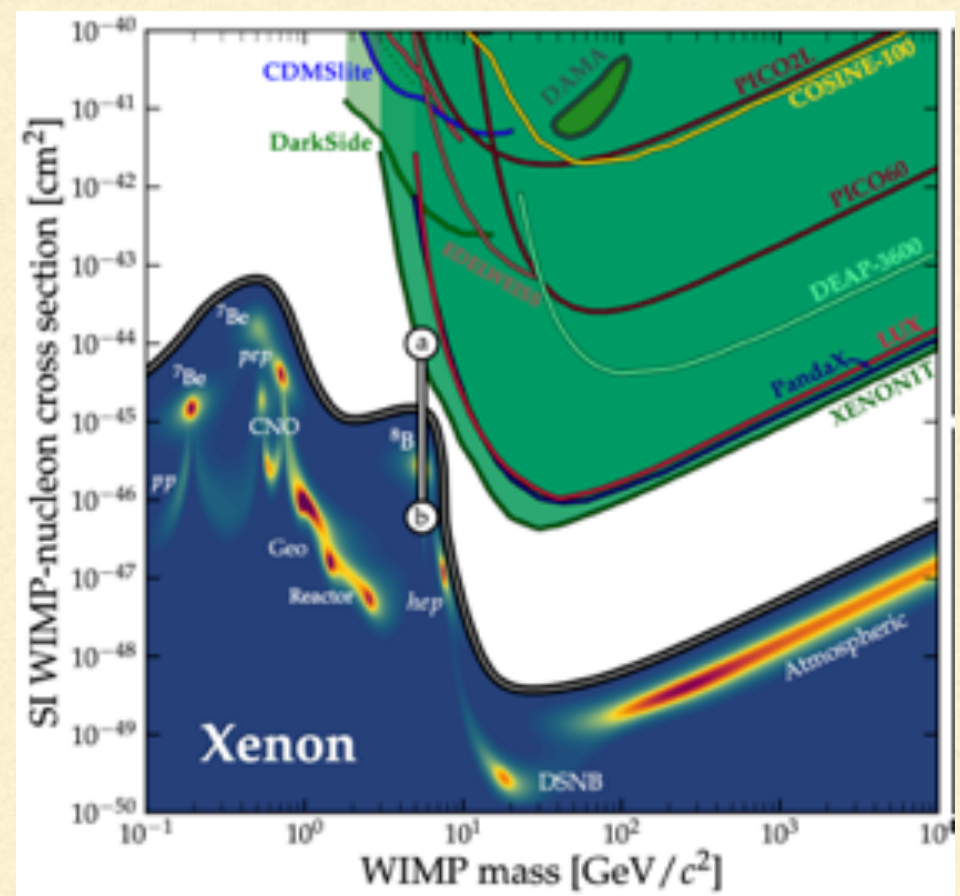
✦核物理：

- 原子核的形状因子

✦反应堆物理：

- 中微子探测器小型化，反应堆监测

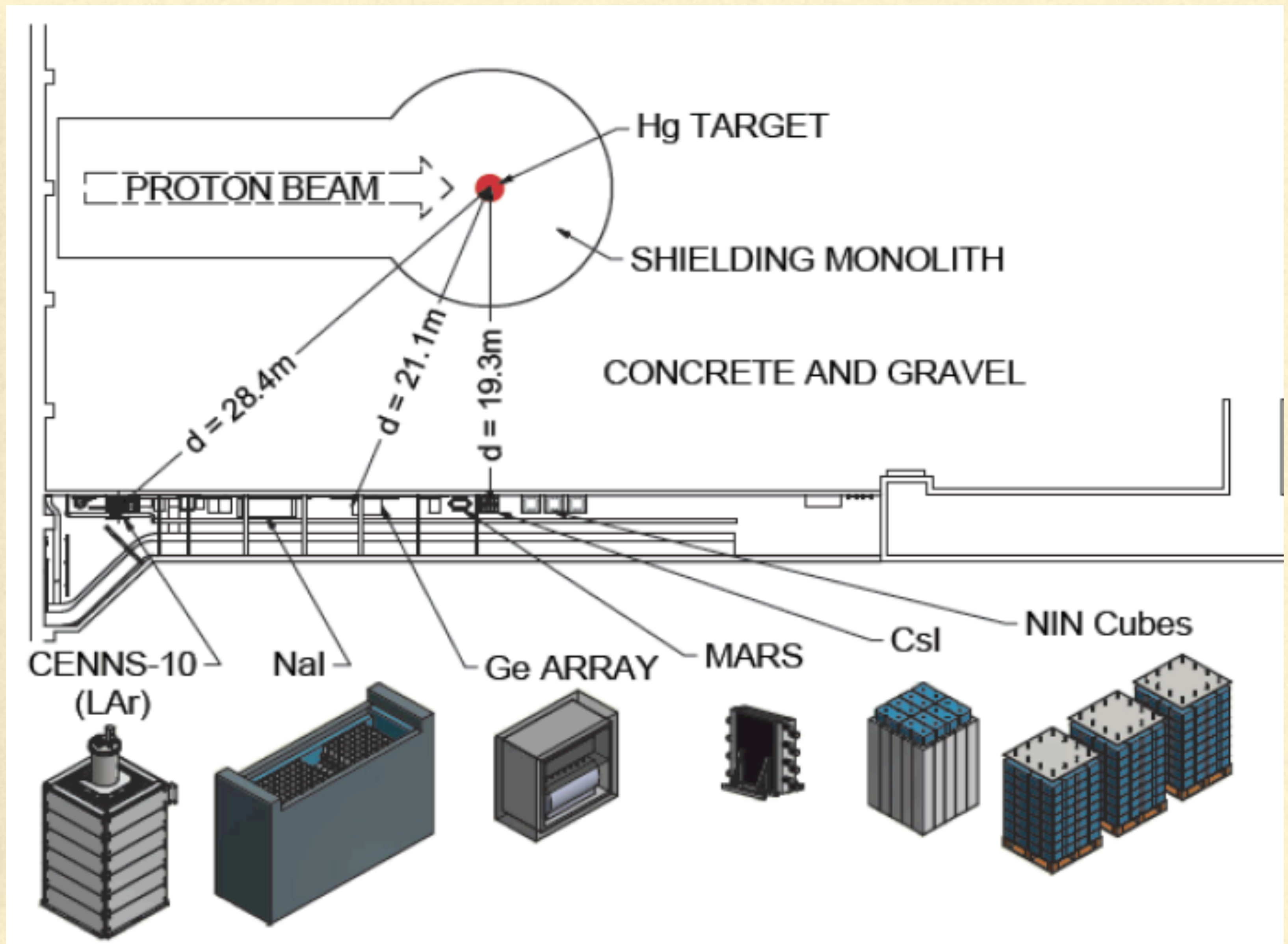




II：研究意义及现状

★ 理论预言 - 1974

★ 实验验证 - 2017 （入选《科学》杂志年度十大科技进展）

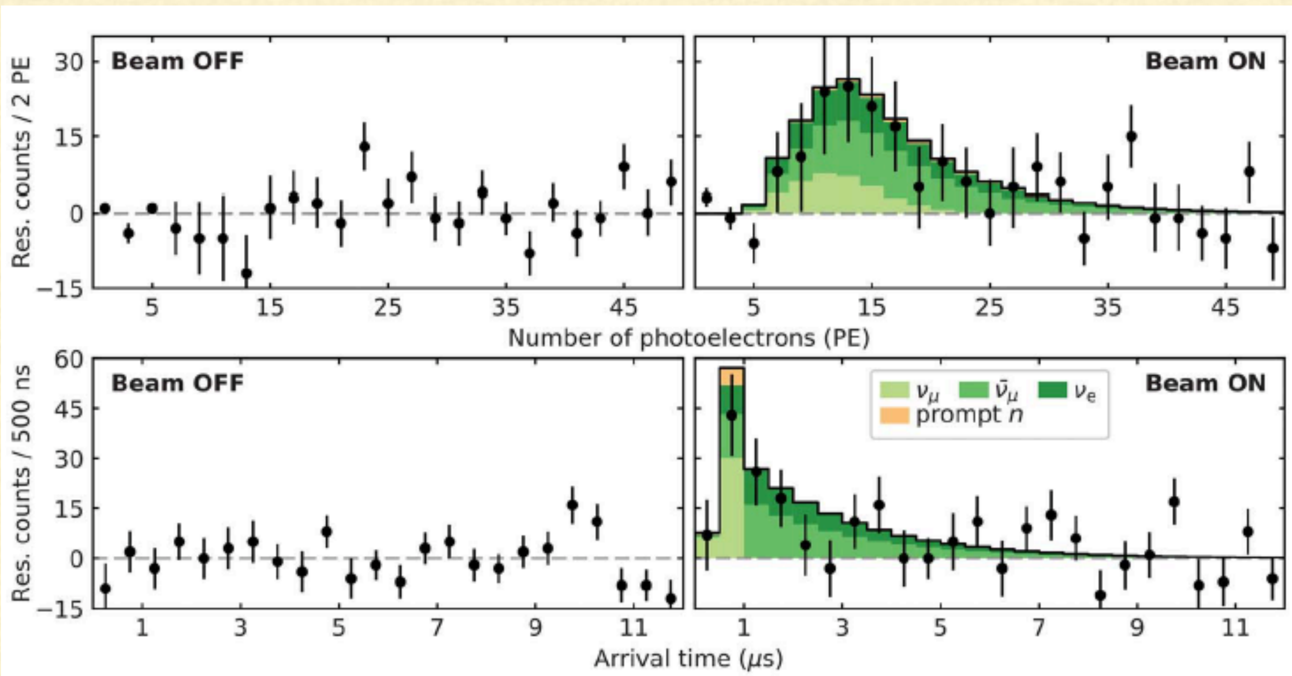


II：研究意义及现状

2017, CsI detector

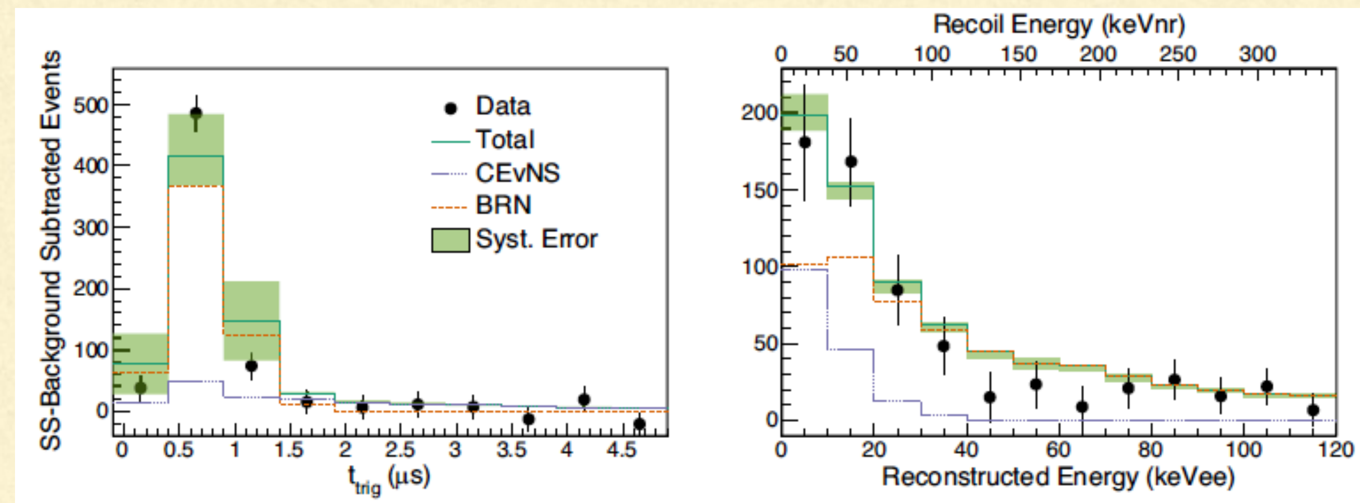
Science 357, 1123–1126 (2017)

No CEvNS rejection 6.7σ, consistent w/ SM within 1σ



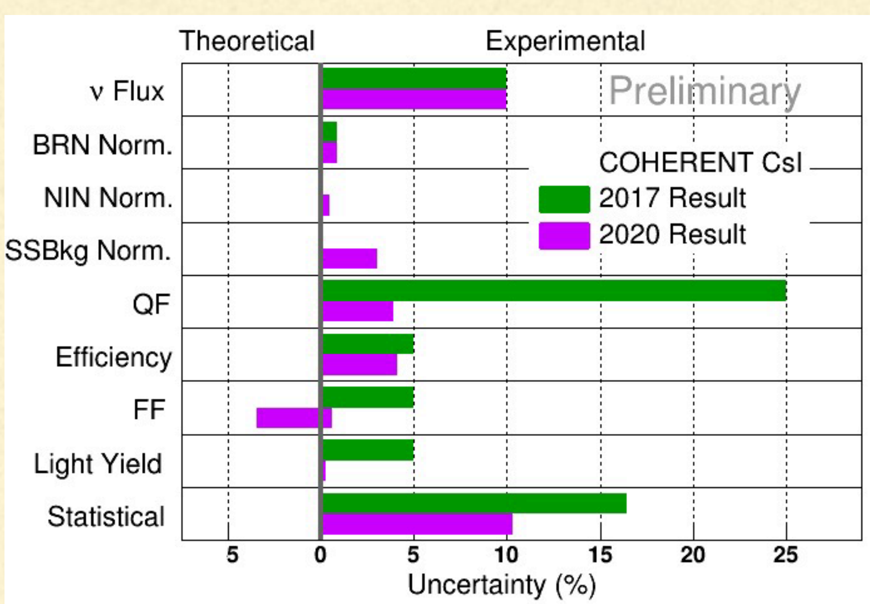
2020 Ar detector > on 3σ

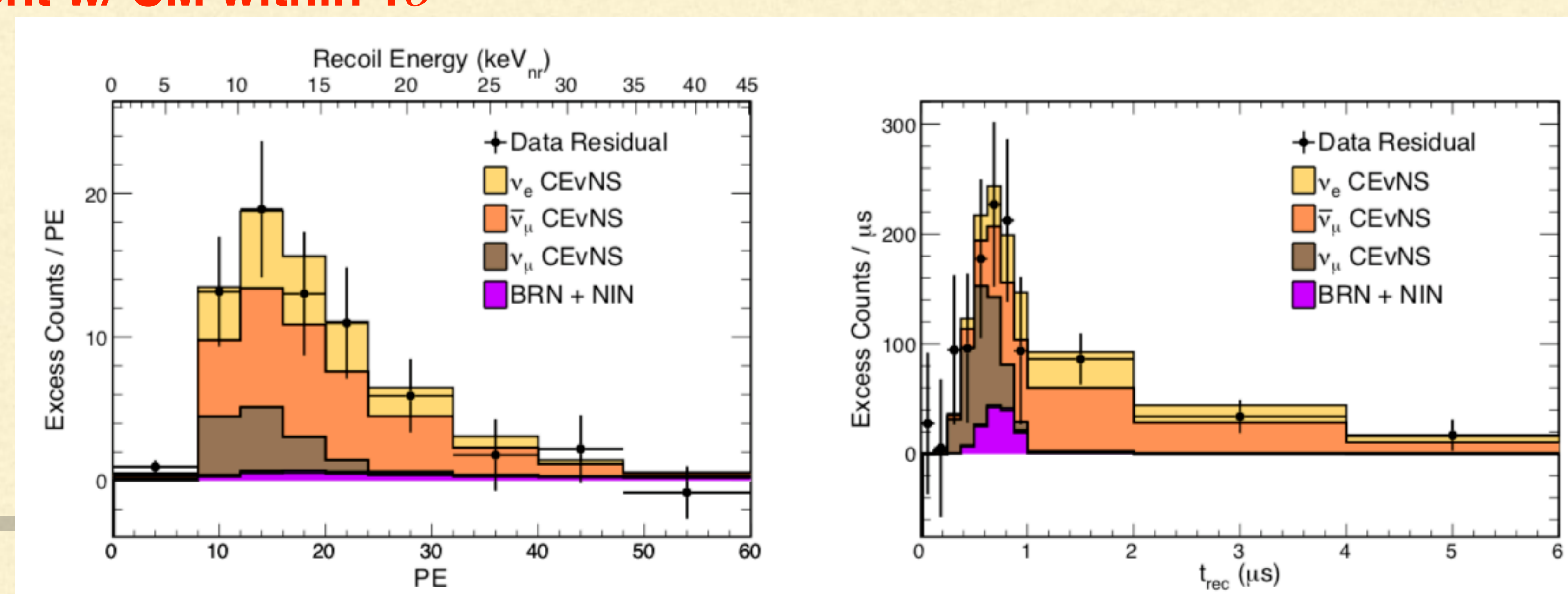
PRL 126, 012002 (2021)



2020, CsI detector, ArXiv: 2110.07730

No CEvNS rejection 11.6σ, consistent w/ SM within 1σ

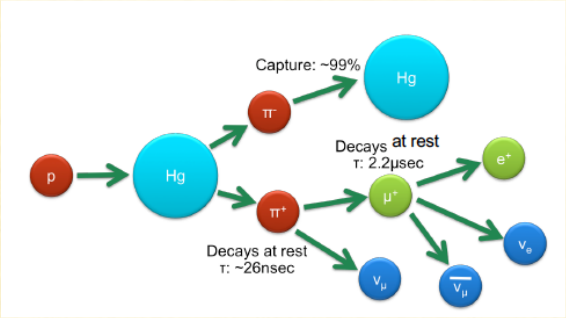


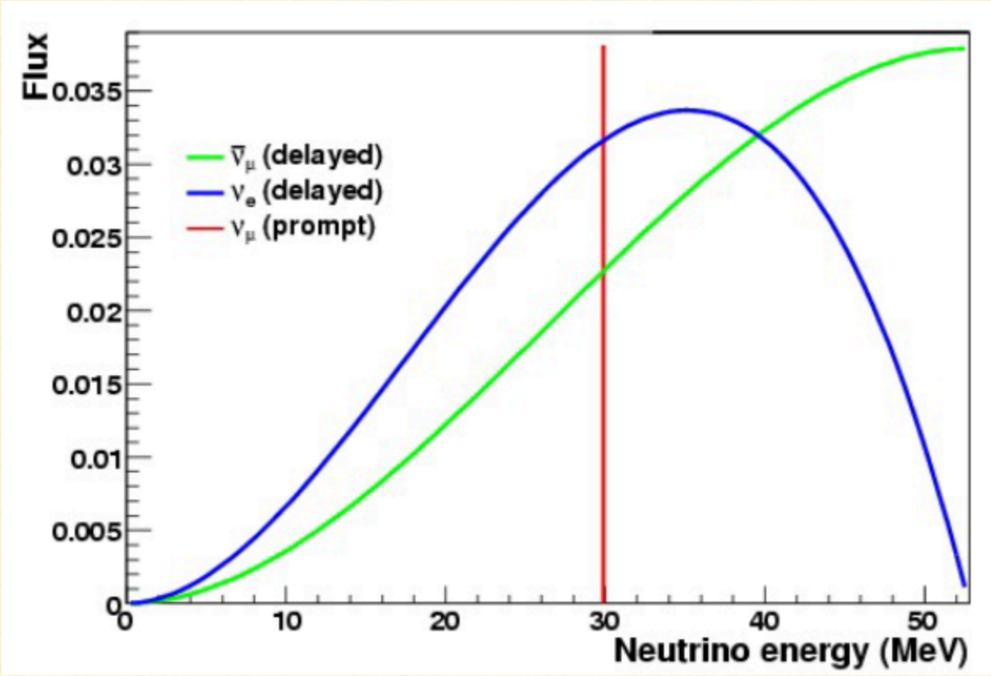


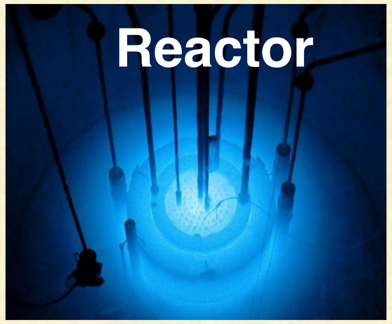
II：研究意义及现状

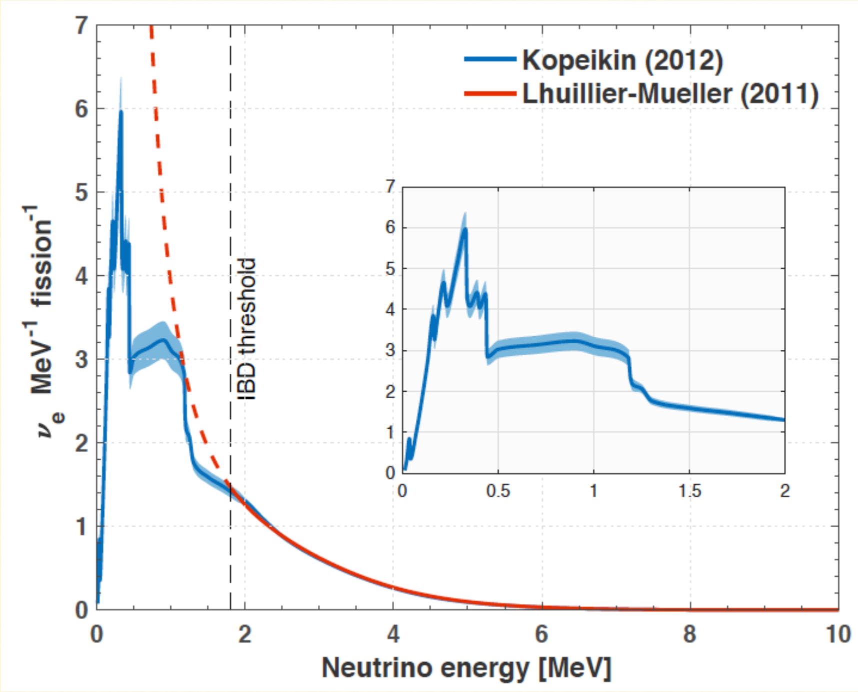
Artificial low-energy neutrinos sources

散裂中子源 (SNS) & 核反应堆 (Reactor): large neutrino flux!









★ Pion-decay-at-rest (DAR) sources: e&μ flavors

★ E < 50 MeV: close to decoherence

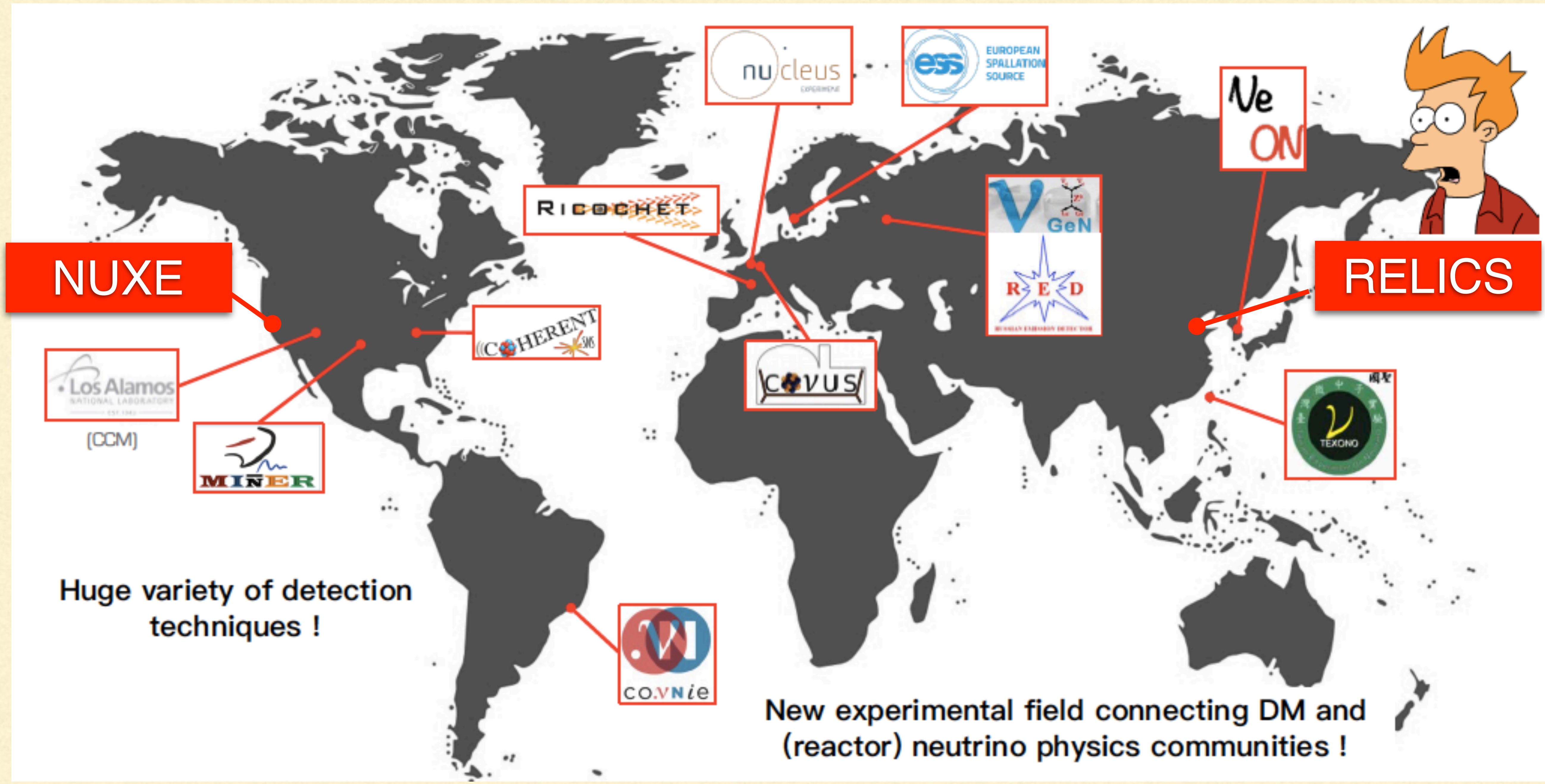
★ First observation of CEvNS by COHERENT in 2017!

★ Nuclear fission: single-e flavor

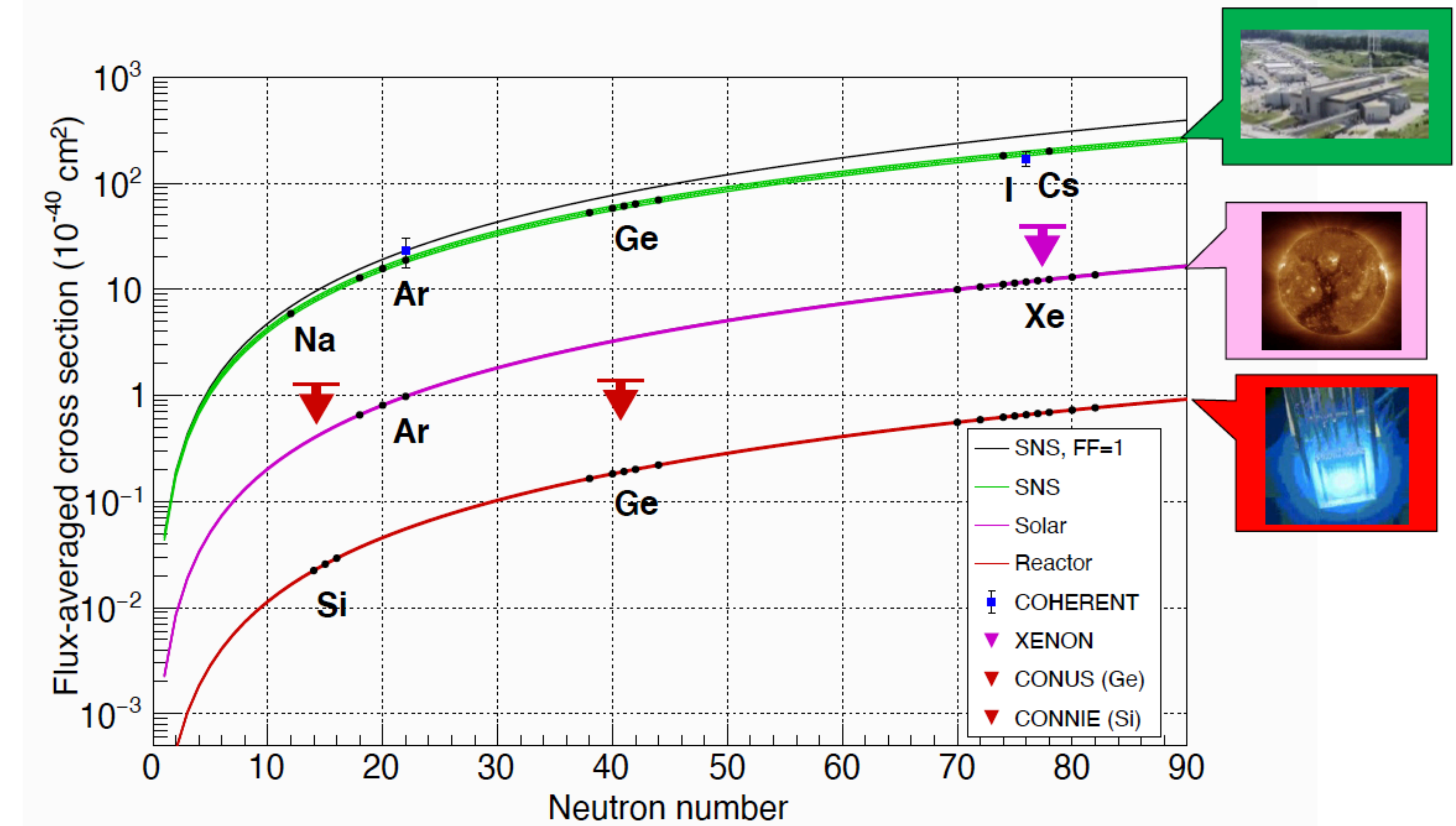
★ E<10 MeV: full coherence

★ Never observed so far!

II：研究意义及现状

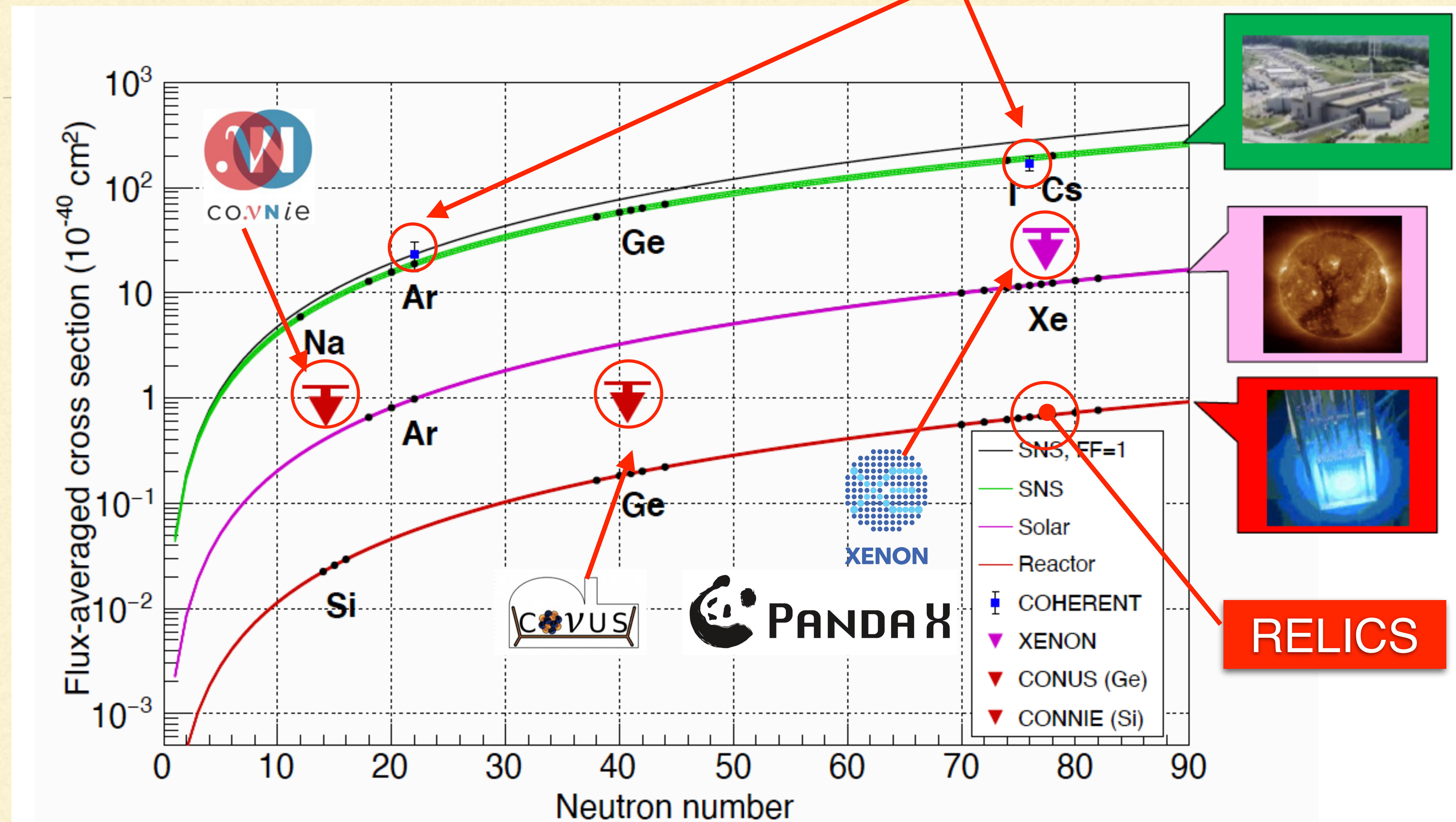

nucleus
EUROPEAN SPALLATION SOURCE
Ne ON
RICOCHET
GeN
RED
NUXE
RELICS
COHERENT
Los Alamos NATIONAL LABORATORY
(CCM)
MINER
CONUS
TEXONO
CONNIE
Huge variety of detection techniques !
New experimental field connecting DM and (reactor) neutrino physics communities !

II：研究意义及现状



Flux-averaged cross section (10^{-40} cm^2)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
0
10
20
30
40
50
60
70
80
90
Neutron number
Na
Ar
Ge
I
Cs
Xe
Ar
Ge
Si
SNS, FF=1
SNS
Solar
Reactor
COHERENT
XENON
CONUS (Ge)
CONNIE (Si)

II：研究意义及现状


Flux-averaged cross section (10^{-40} cm^2)
10^3
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80
90
Neutron number
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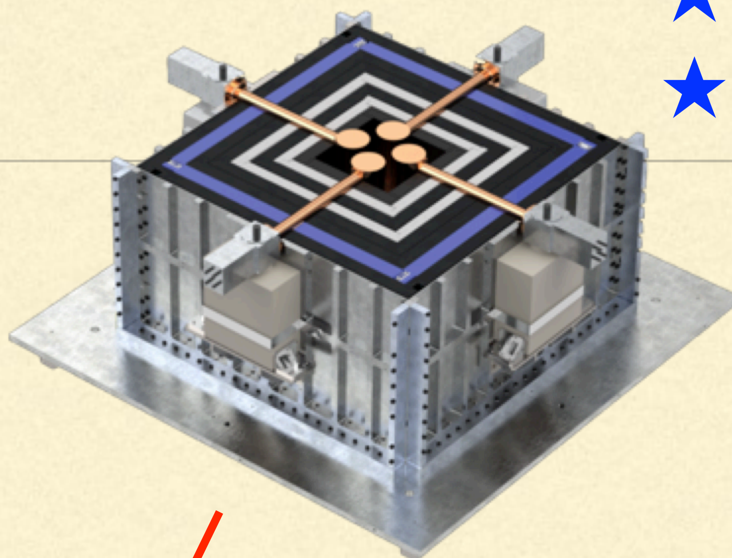
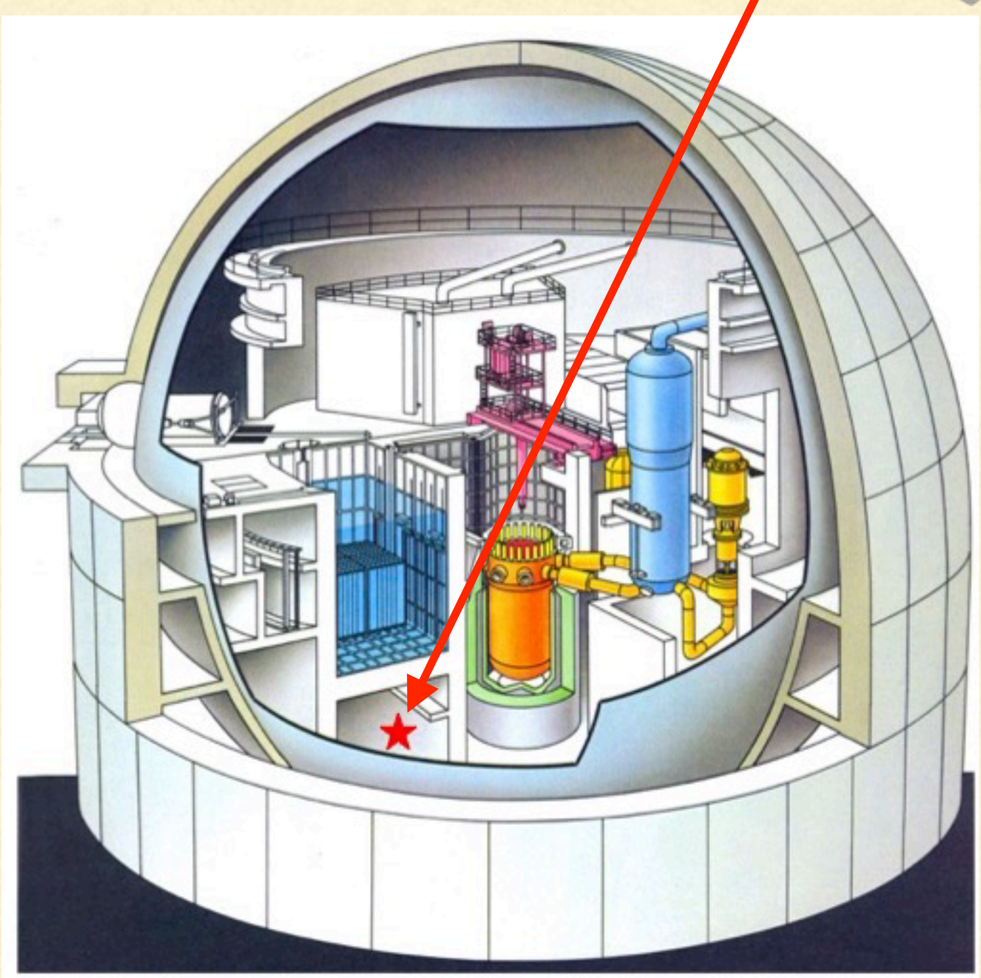
Ar
Ge
Cs
Xe
Ar
Ge
Si
SNS, FF=1
SNS
Solar
Reactor
COHERENT
XENON
CONUS (Ge)
CONNIE (Si)
RELICS

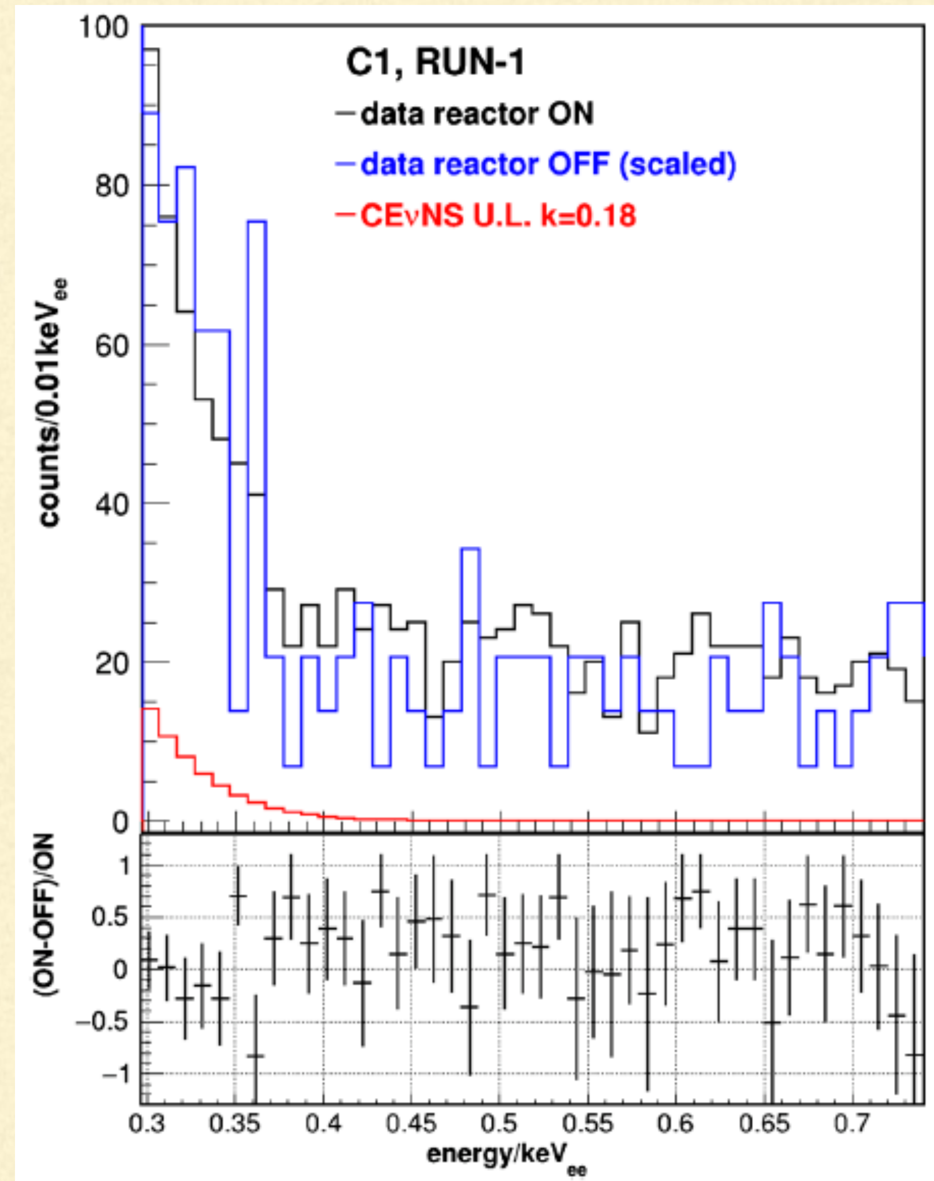
II：研究意义及现状

CONUS

- ★Brokdorf 3.9 GWth reactor, Germany
- ★17 m from core
- ★4 kg Ge
- ★~300 eVee threshold







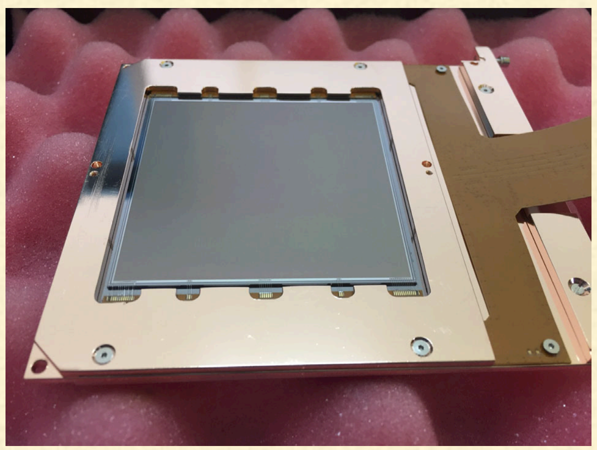
85 event in ROI set upper limit at 90% CL

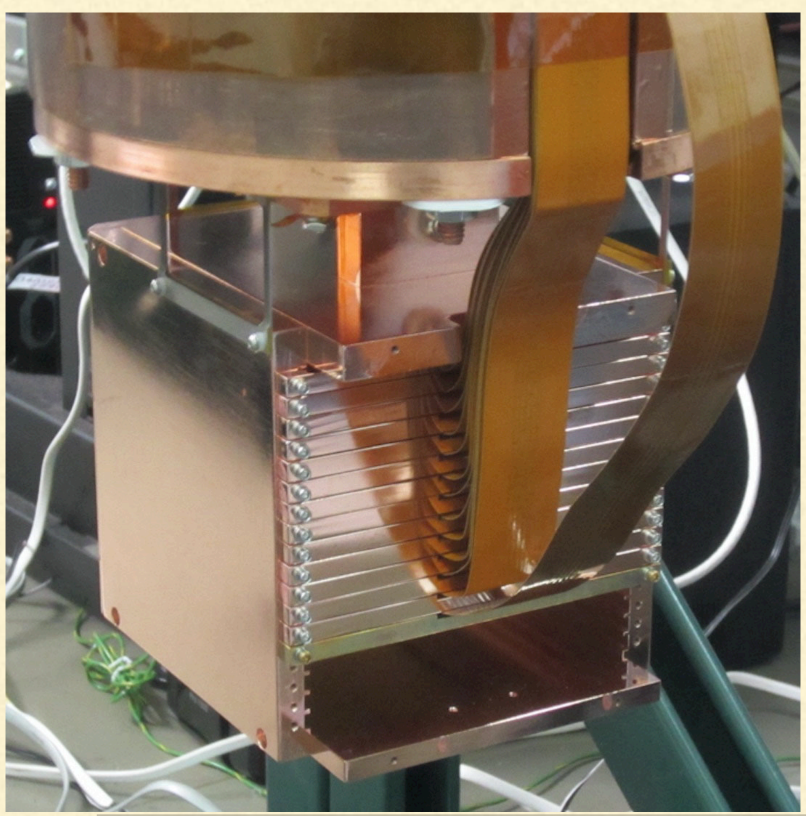
PHYSICAL REVIEW LETTERS 126, 041804 (2021)

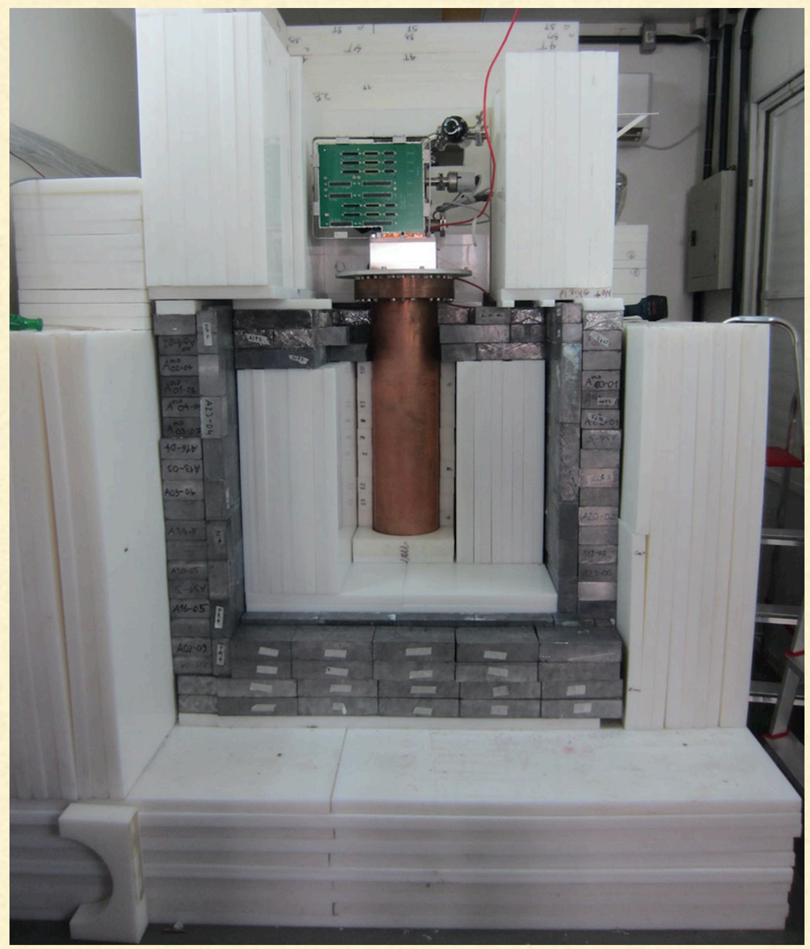
II：研究意义及现状

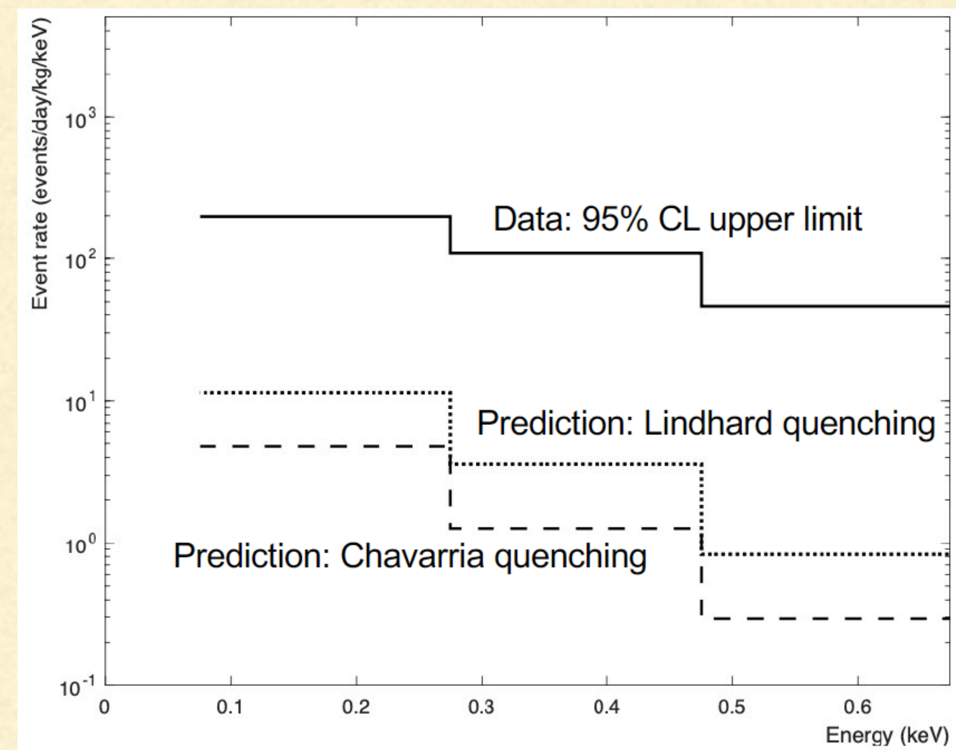
CONNIE

★3.8 GWth nuclear reactor, Brazil
★32 m from core
★47.6 g Si CCDs
★~0.1 keVee threshold







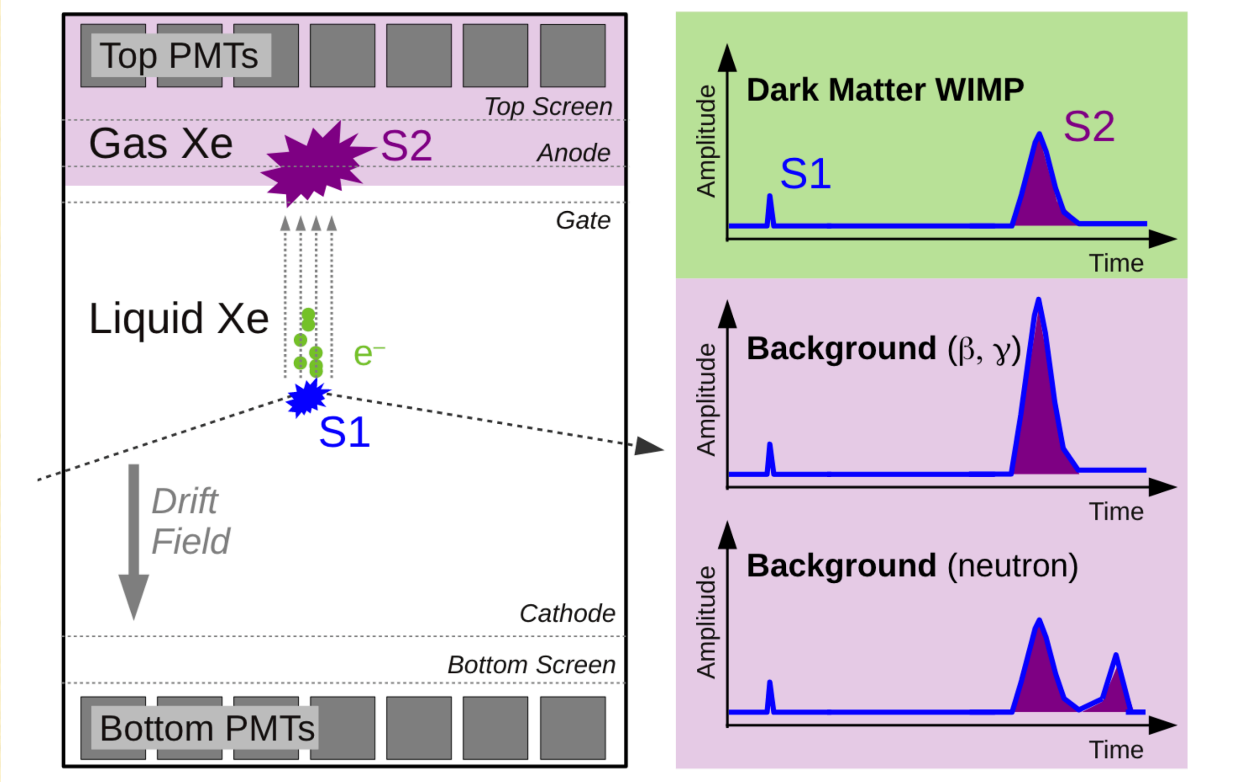


PHYS. REV. D 100, 092005 (2019)

III：RELICS实验计划及预期

RELICS 实验：　　　　两相型氙探测技术

Liquid Xenon Time Projection Chamber (LXeTPC)



研究目标：发展可在地面运行的、大质量的**极低阈值、极低本底**液氙时间投影室探测技术，精确测量CEvNS信号。

III：RELICS实验计划及预期

RELICS 合作组：

★ 清华大学：高飞

★ 中国科学技术大学：林箐

★ 中山大学：肖翔、魏月环

项目组成员：～20人，教师、博士生、本科生

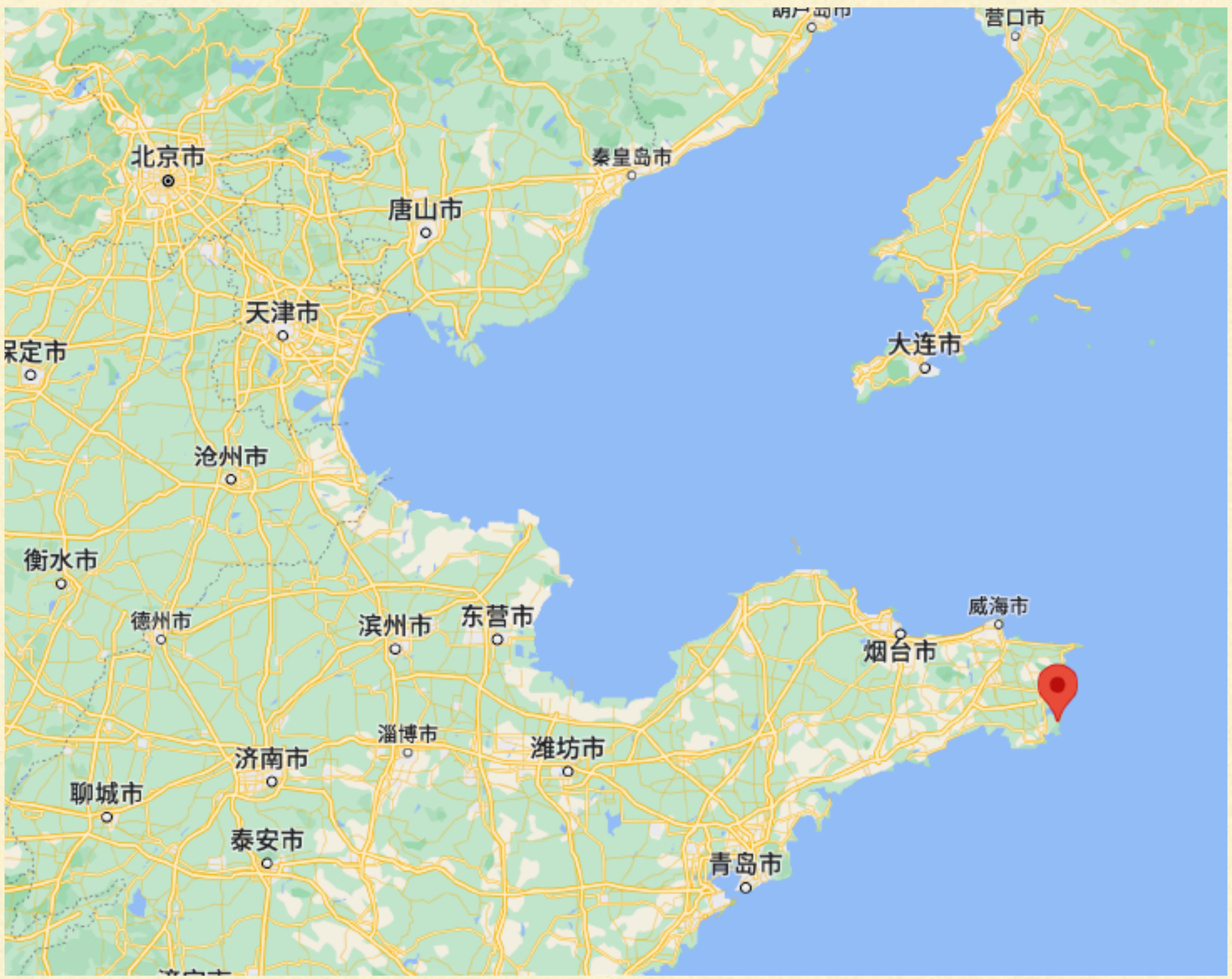
科技部“大科学装置前沿研究”国家重点研发计划

青年科学家项目支持！

III：RELICS实验计划及预期

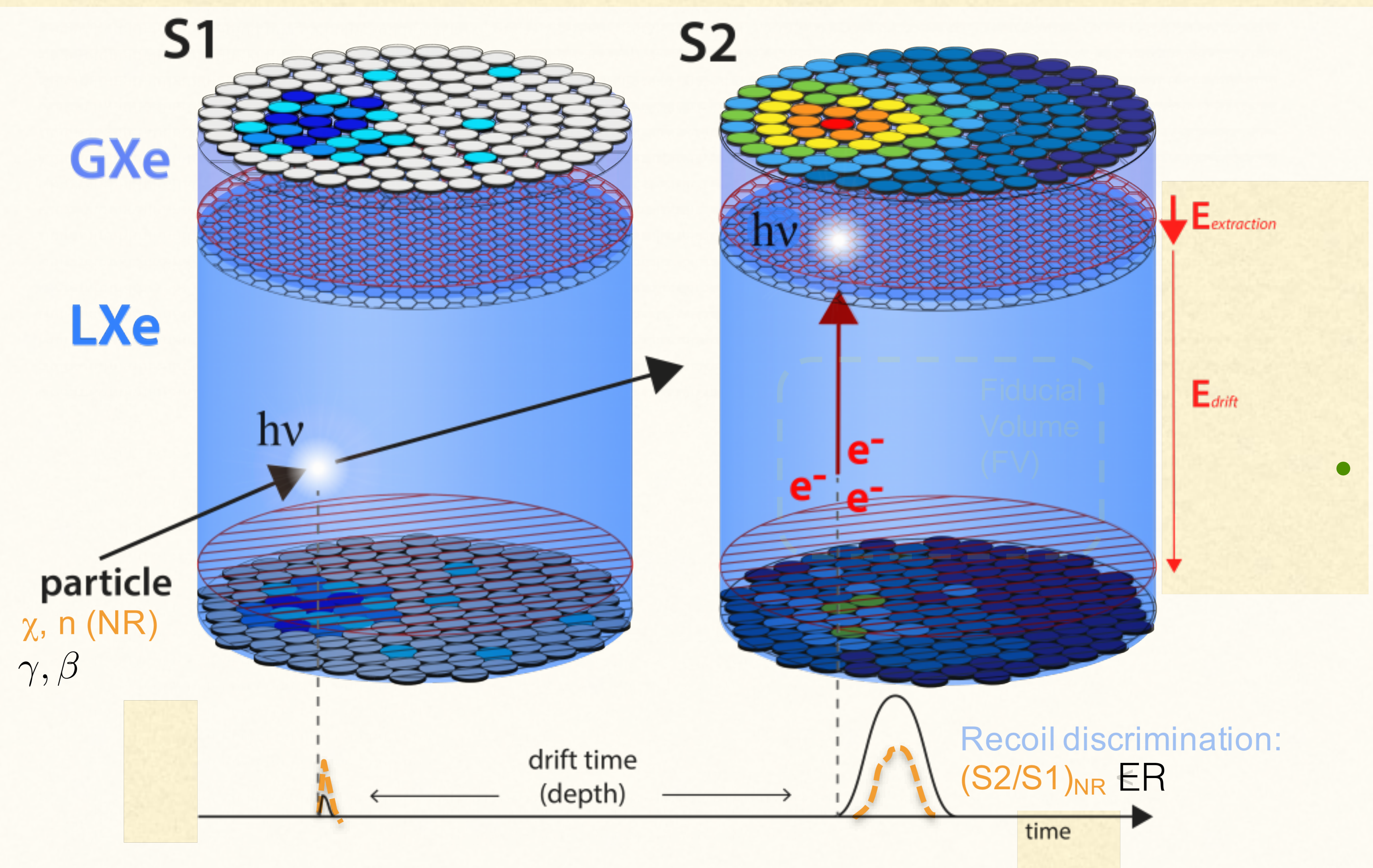
拟选址：山东石岛湾核电站，高温气冷堆

250 MW，距堆芯12米，中微子通量 2.5×10^{12} $cm^{-2}s^{-1}$

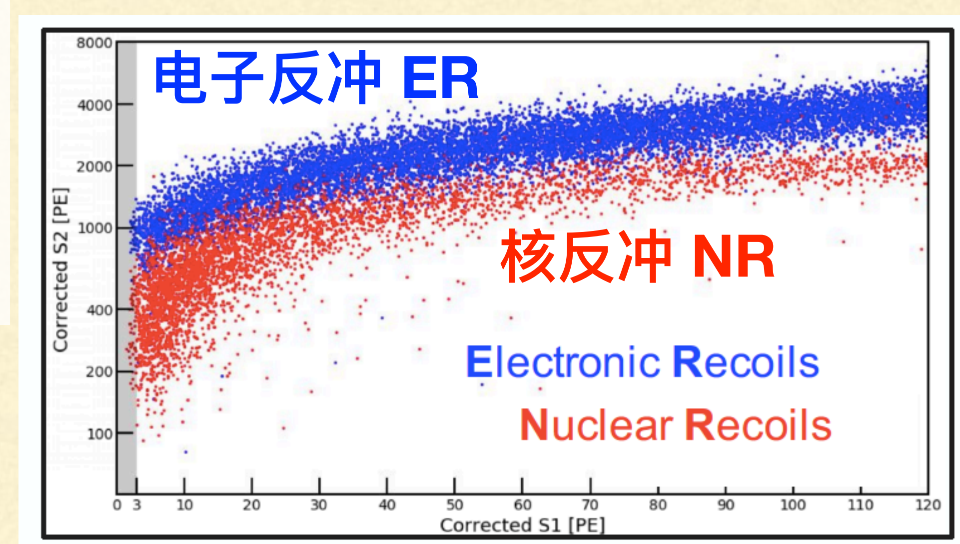


III：RELICS实验计划及预期

- **Scintillation light - S1**
- **Ionization electron -S2**



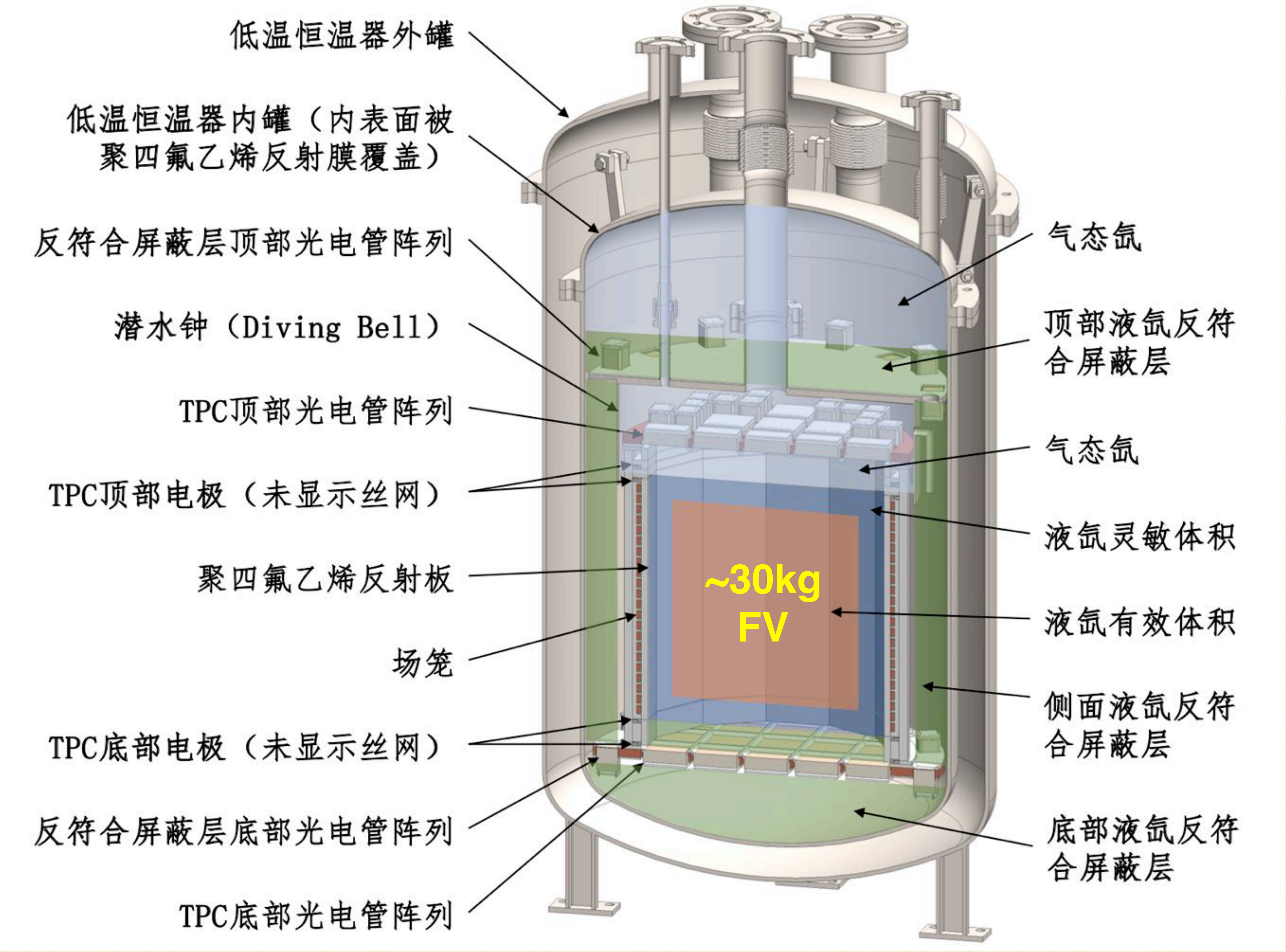
- two signals for each event:
  - Energy from S1 and S2 area
  - 3D event imaging: x-y (S2) and z (drift time)
  - self-shielding, surface event rejection, single vs multiple scatter events
- Recoil type discrimination from ratio of charge (S2) to light (S1)



PandaX, XENON, LZ Dark Matter Experiments… …

III：RELICS实验计划及预期

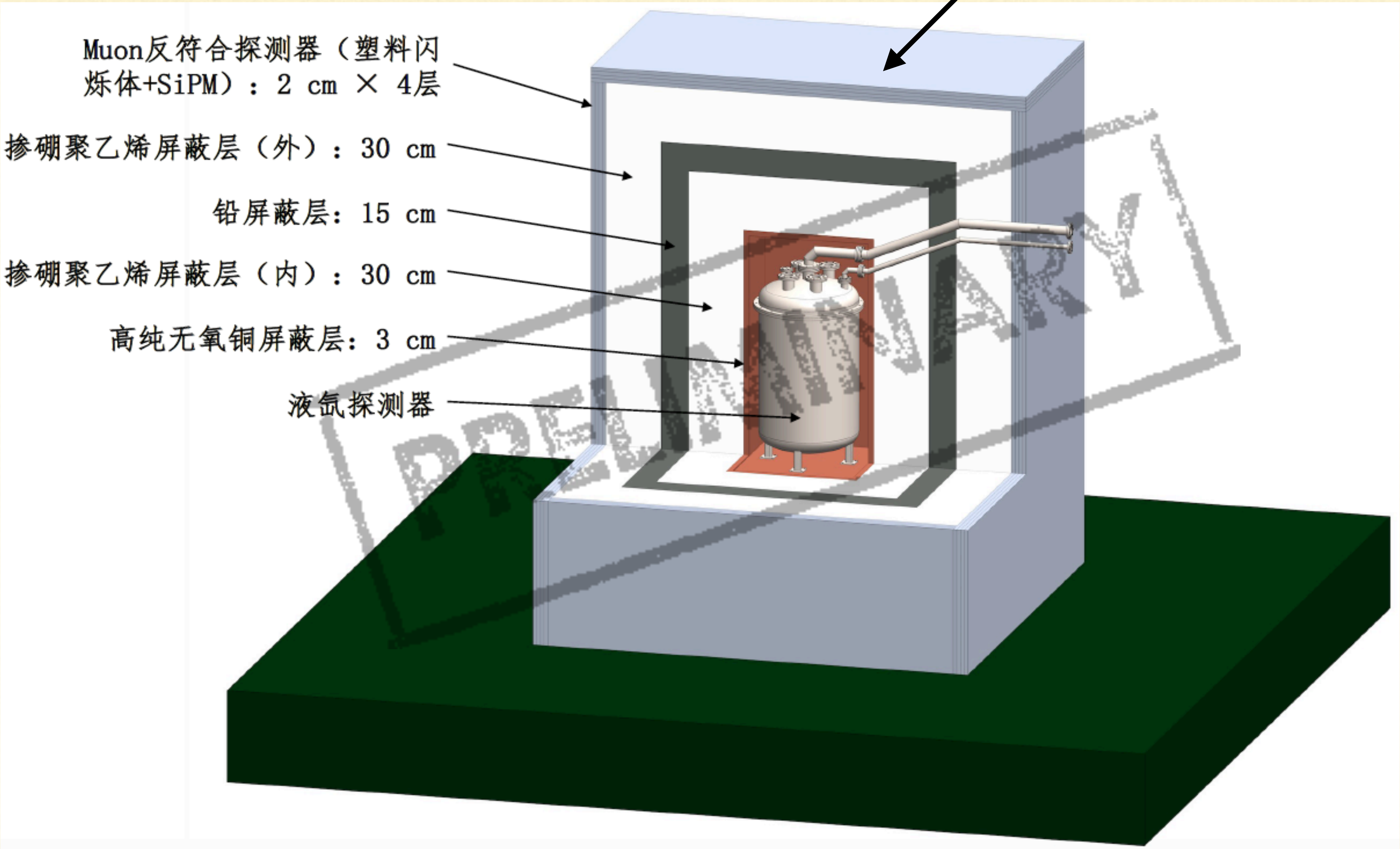
探测器初步设计：



III：RELICS实验计划及预期

屏蔽系统初步设计：

反符合效率 > 99%



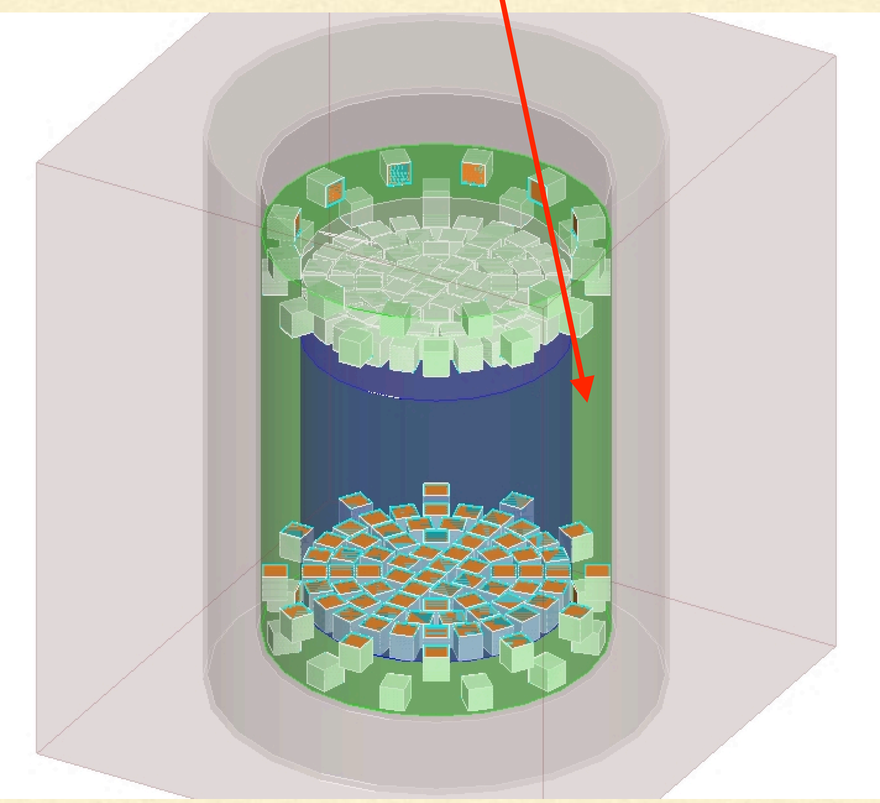
III：RELICS实验计划及预期

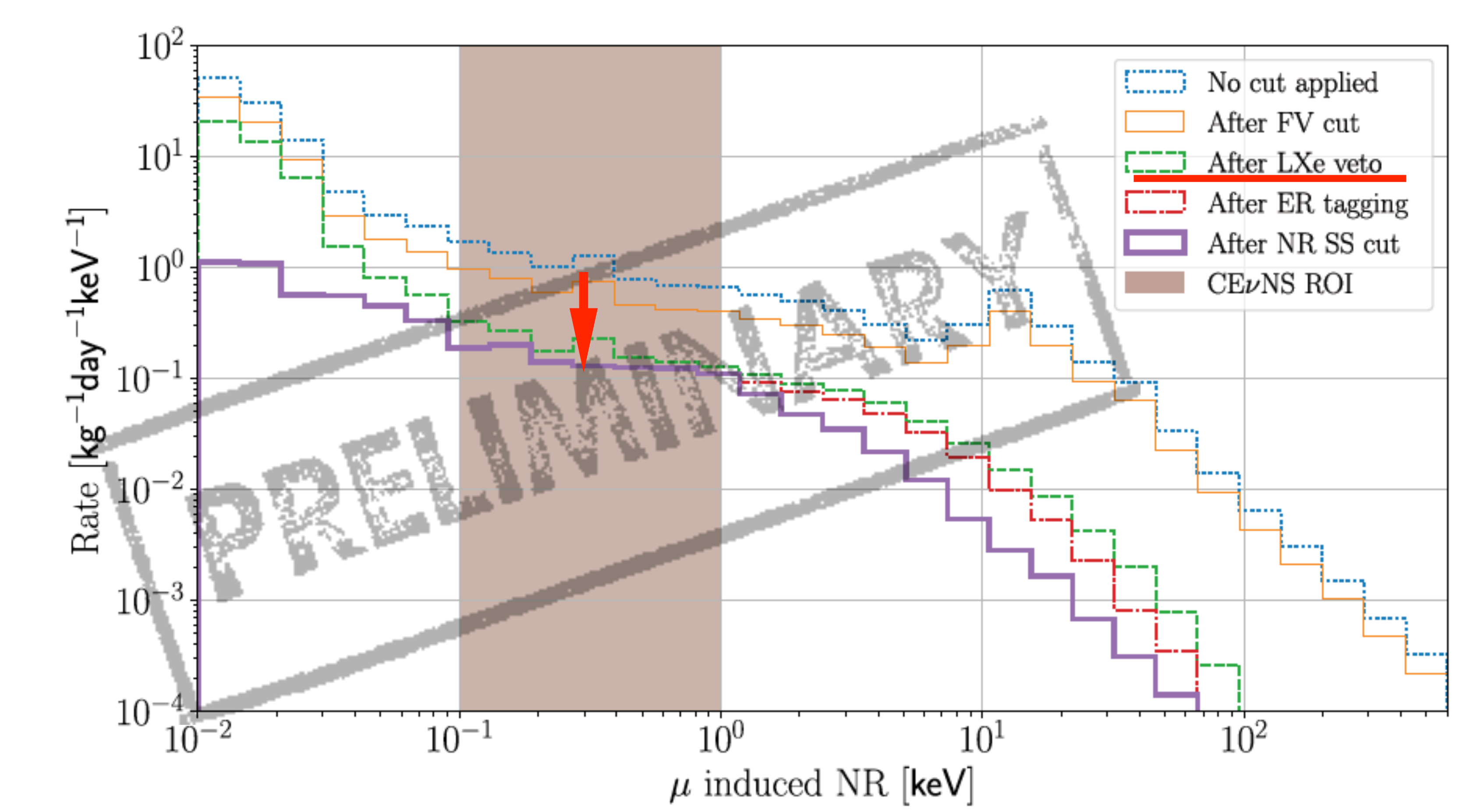
缪子引起本底

μ 子引起的 [0.1, 1]keV 内核反冲和 [0, 100]keV 内电子反冲的本底剩余事例率

NR ～0.23 /kg/day　　ER ～0.005 /kg/day/keV

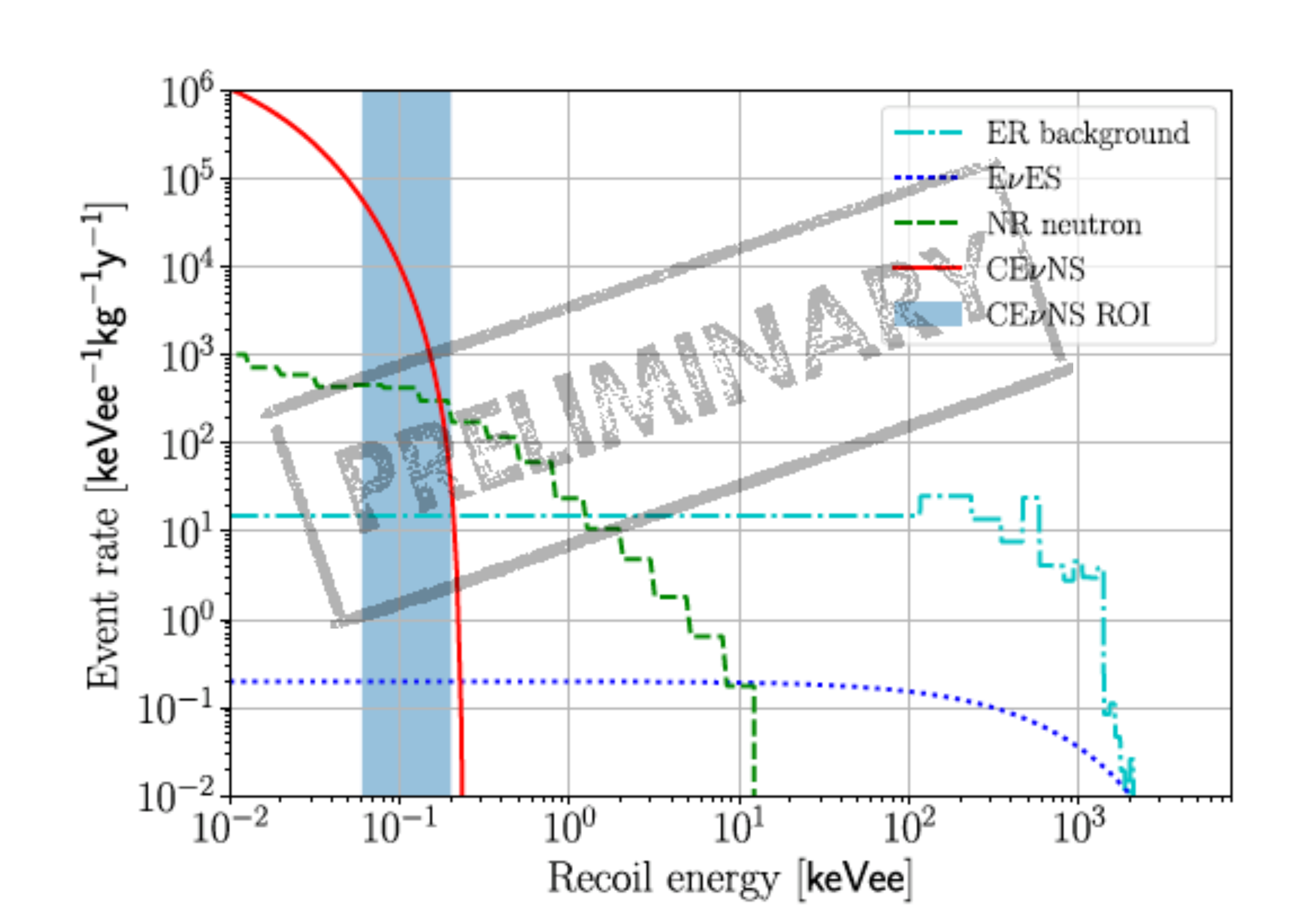
4π 液氙反符合层



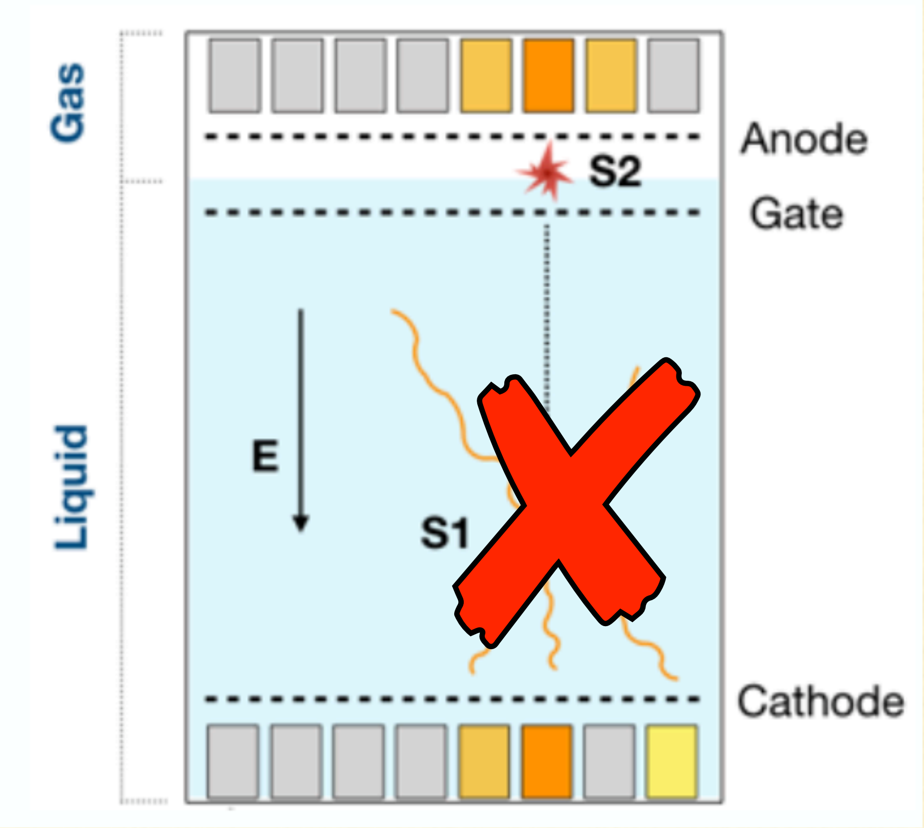


III：RELICS实验计划及预期

总体本底： ER < 0.05 /kg/day/keV NR < 0.3 /kg/day



III：RELICS实验计划及预期

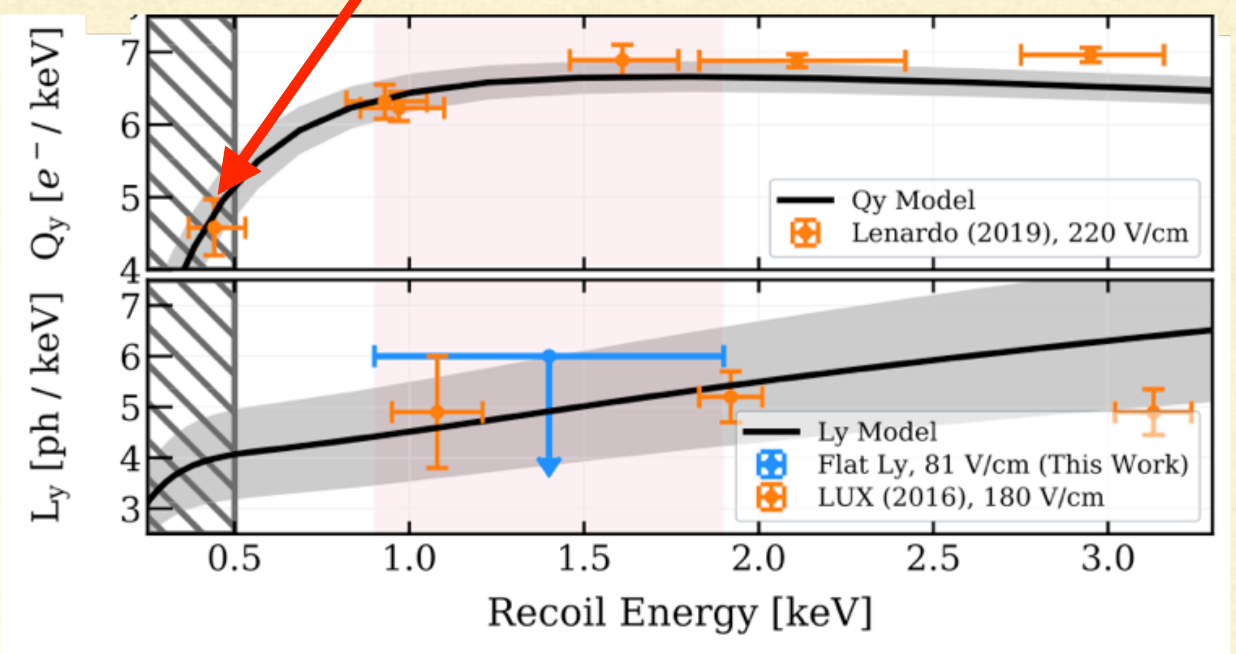


极低能量阈值：S2-Only

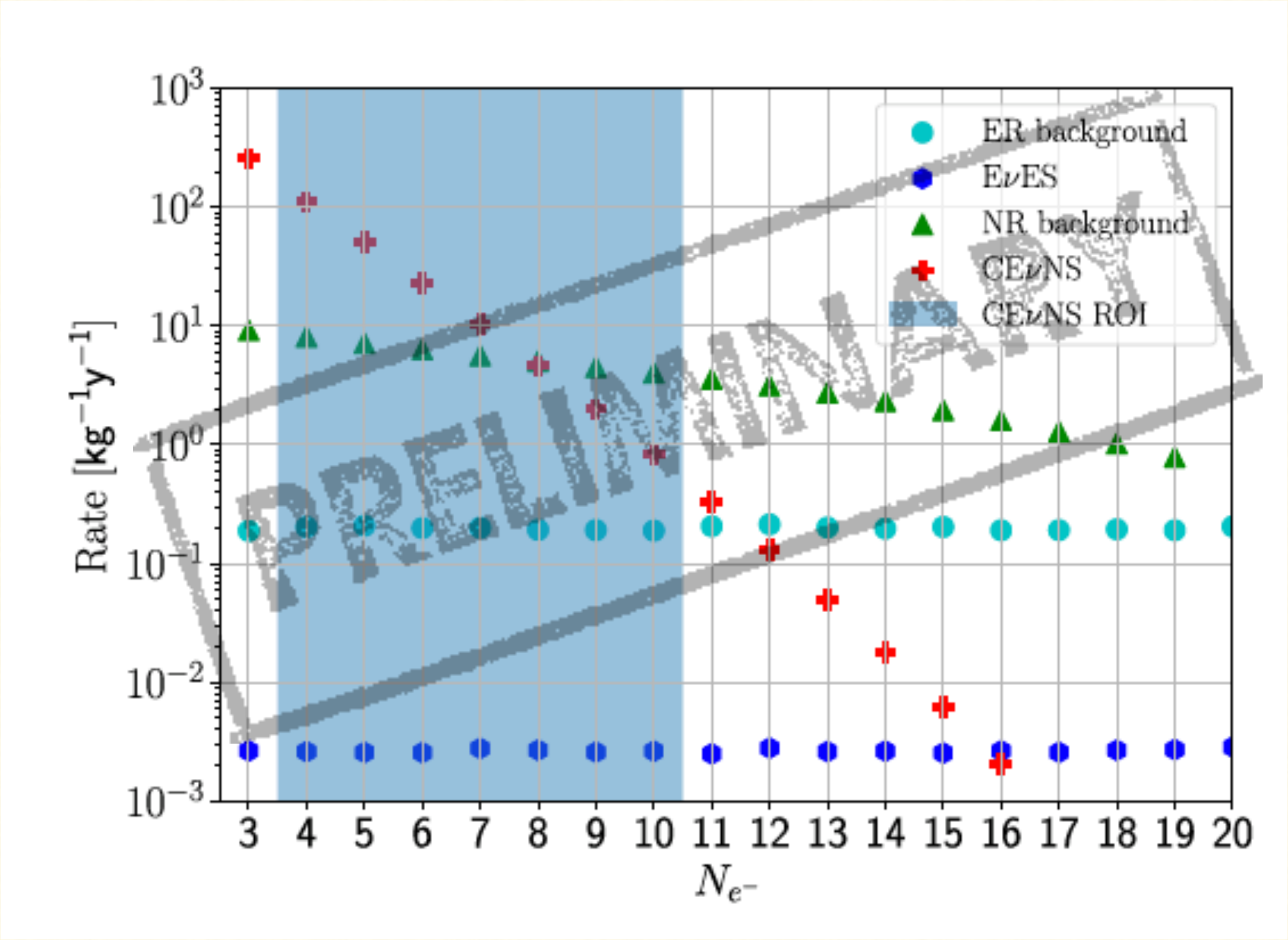
4个以上电子探测效率 100%

液氙探测器直接测量了

1keV之下的核反冲信号



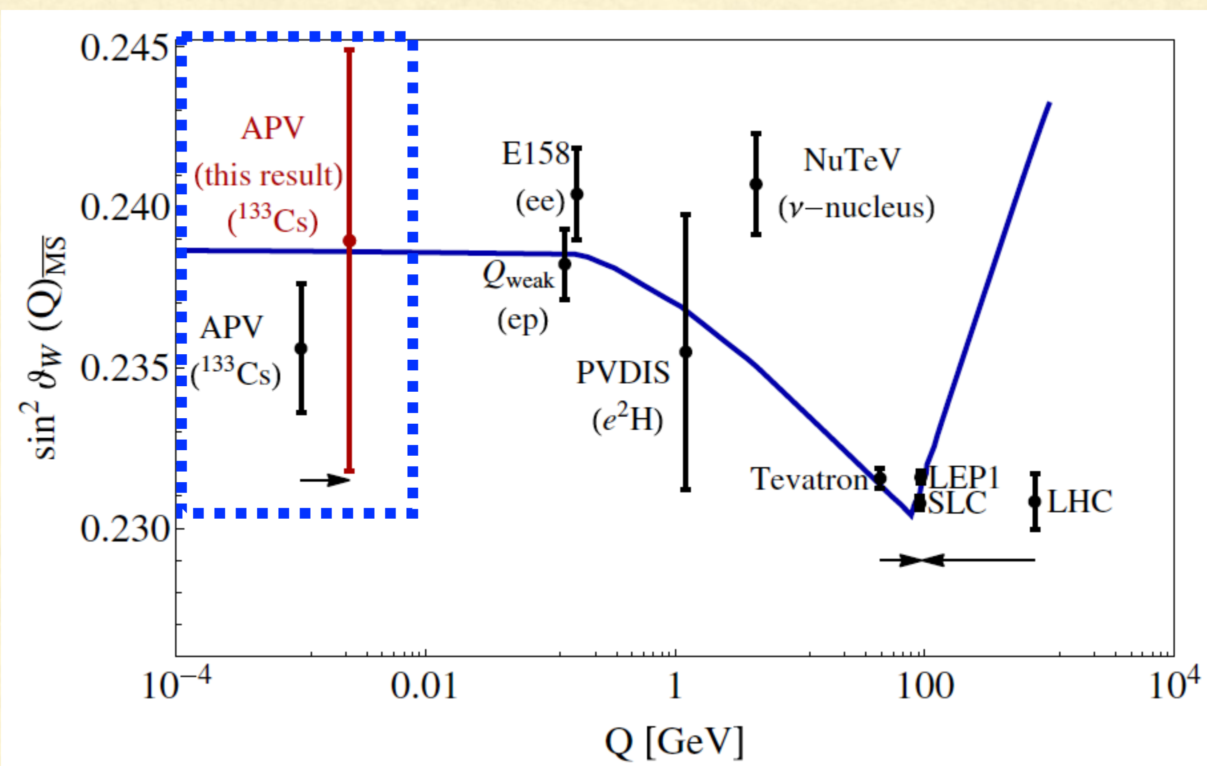
XENON1T, B8, PRL 126, 091301 (2021)



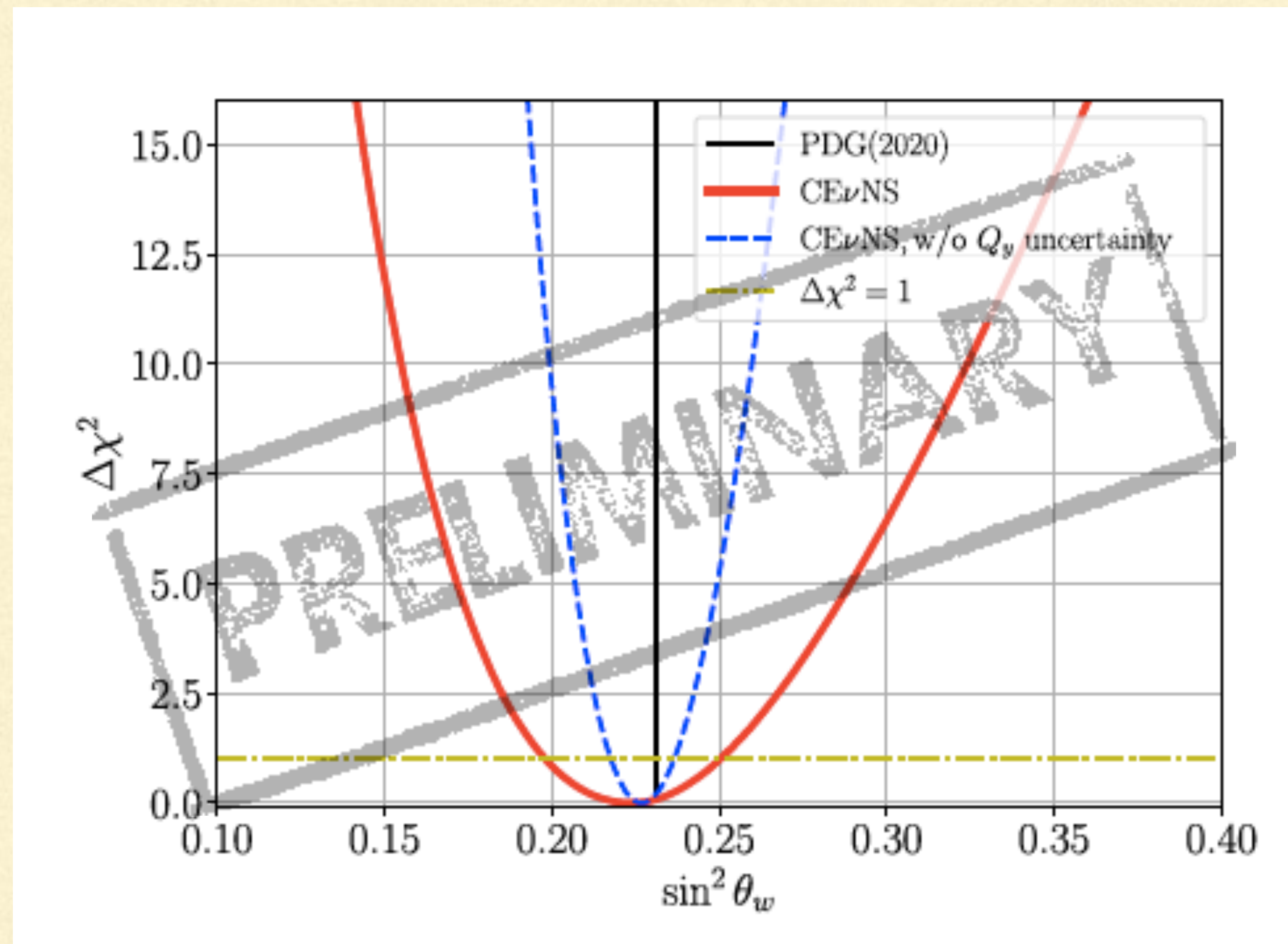
III：RELICS实验计划及预期

低动量转移下的弱混合角测量（30 kg·year）

Using the neutron radius estimate from **COHERENT** data, APV(atomic parity violation) result on^{133}Cs can be reconciled with SM prediction:

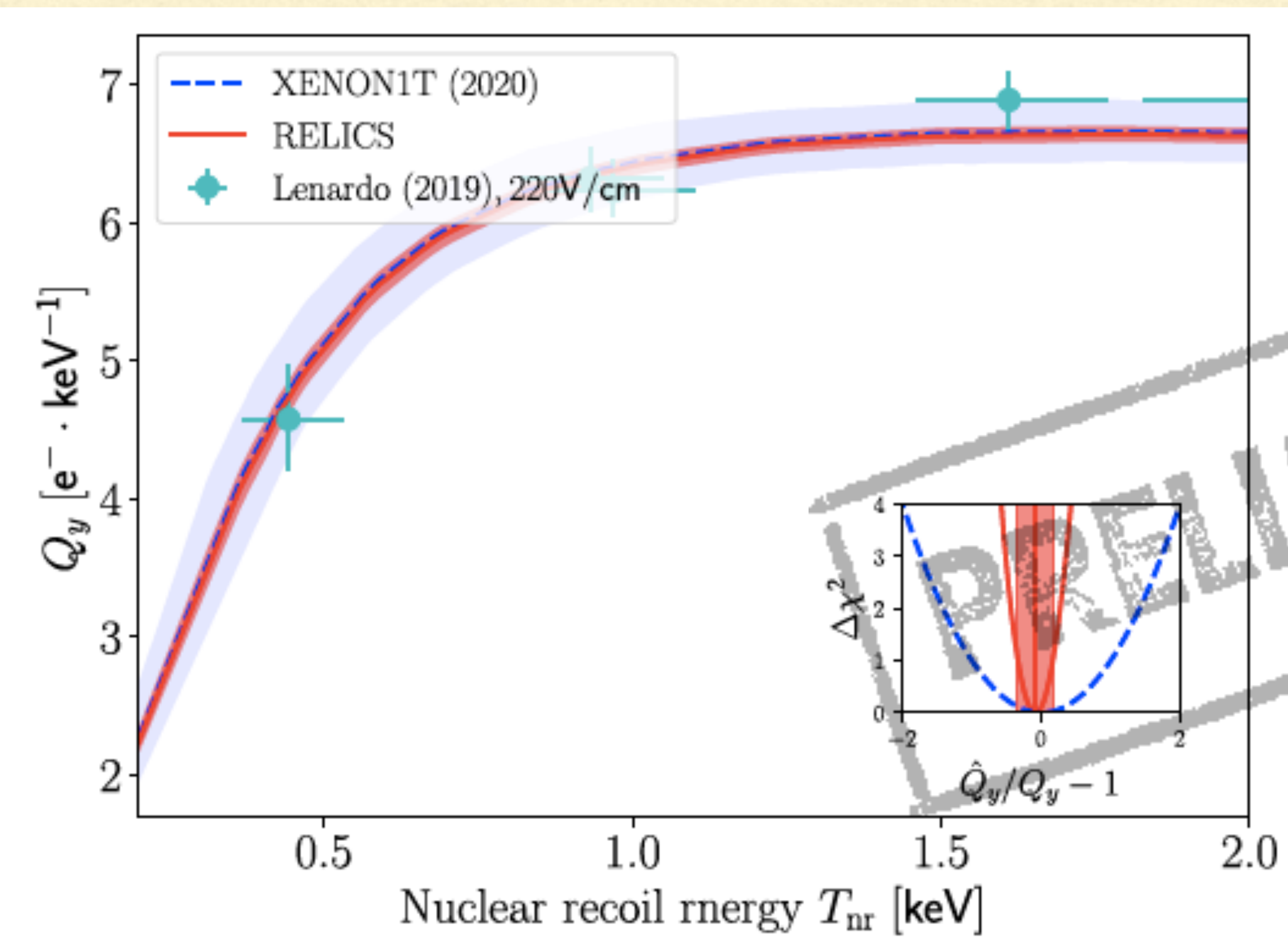


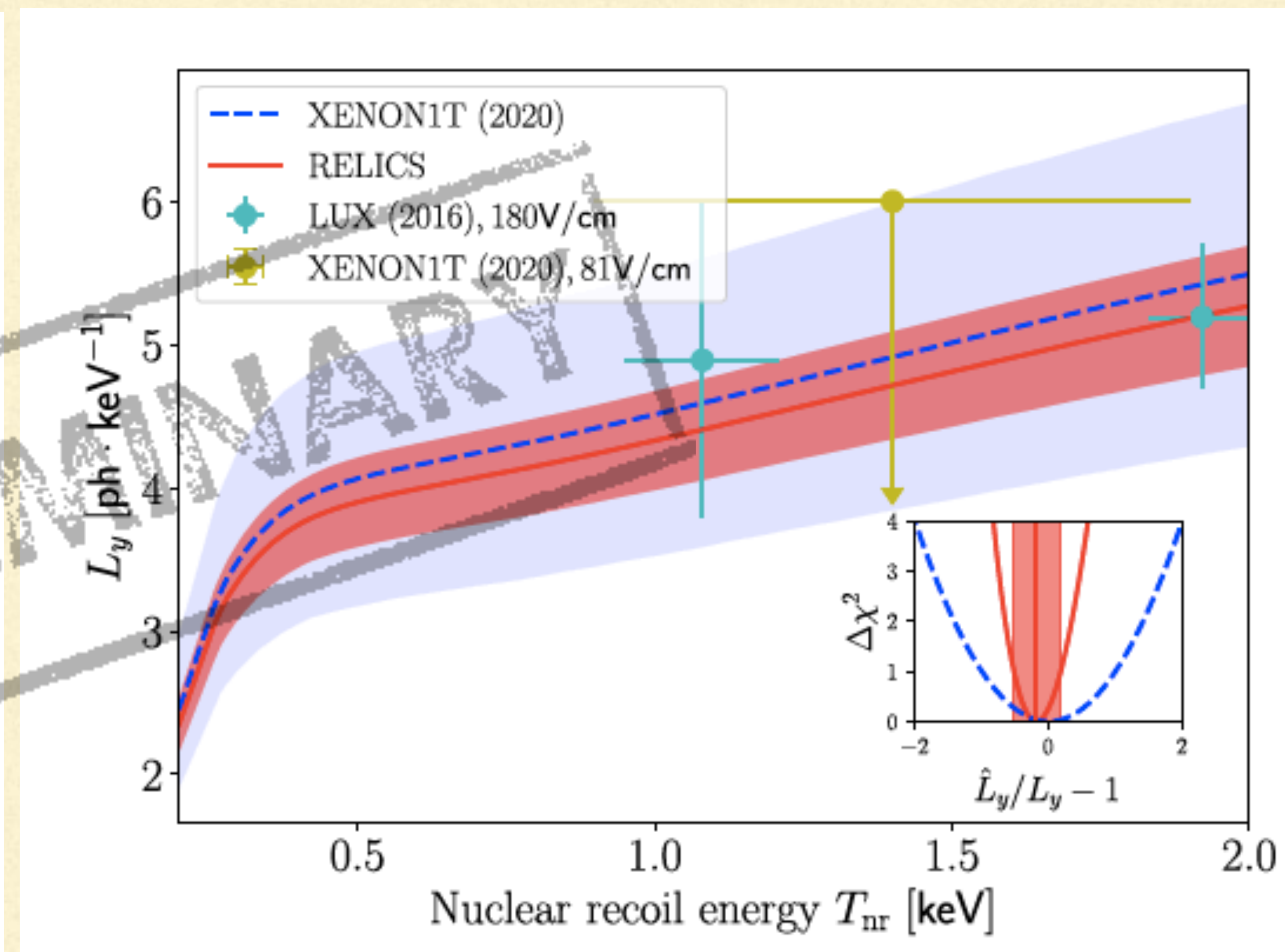
PHYS. REV. D 99, 033010 (2019)



III：RELICS实验计划及预期

低能核反冲的液氙光电产额测量（30 kg·year）





III：RELICS实验计划及预期

细节解释！

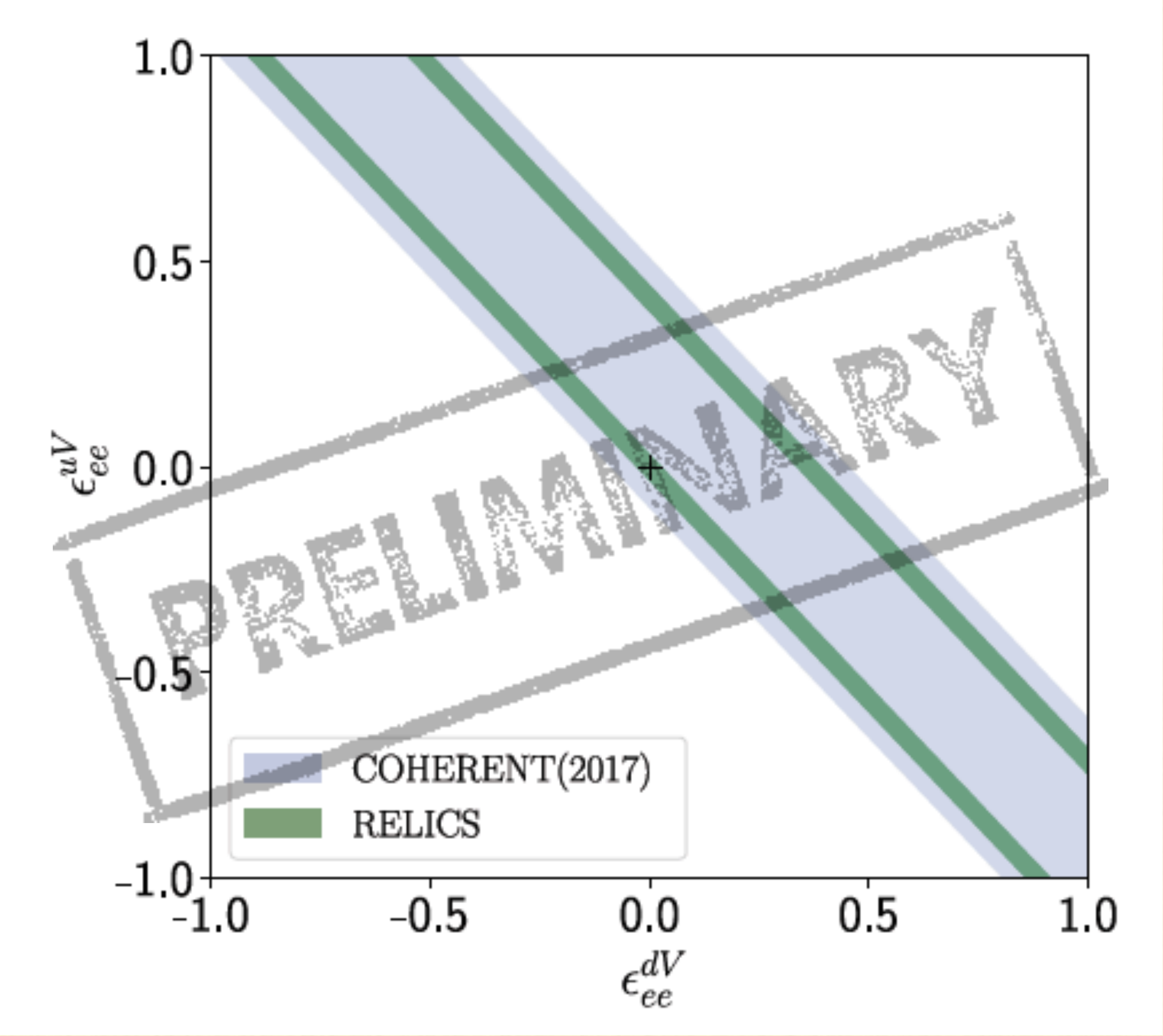
中微子超标准模型有效相互作用测量（30 kg·year）

$$\frac{d\sigma(E_\nu)}{dT} = \frac{G_F^2 M}{2\pi} G_V^2 \left[1 + (1 - \frac{T}{E_\nu})^2 - \frac{MT}{E_\nu^2}\right]$$

$$G_V = ((g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})Z + (g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})N)F^V(Q^2)$$

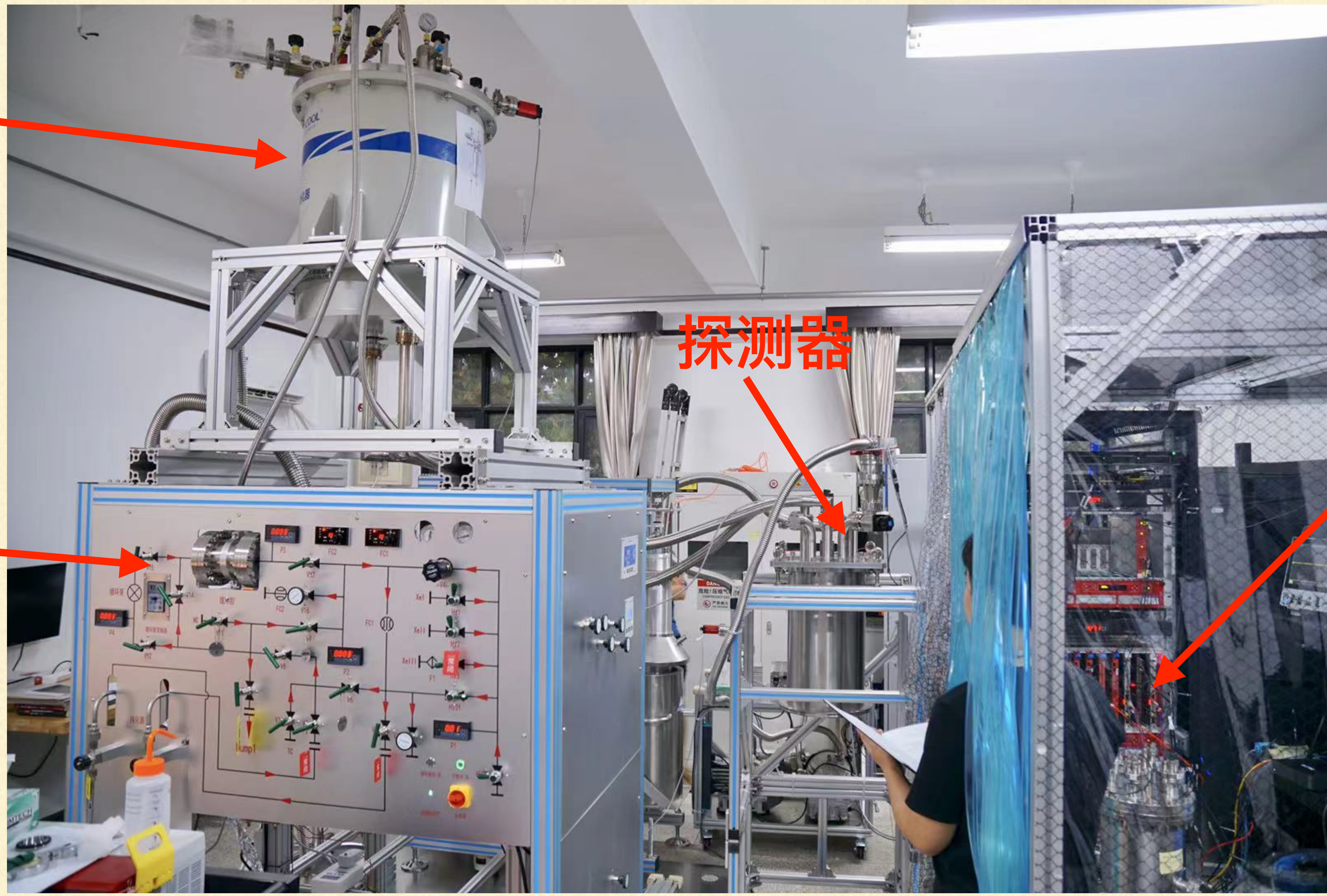
标准模型中：

$$\epsilon_{ee}^{uV} = \epsilon_{ee}^{dV} = 0$$



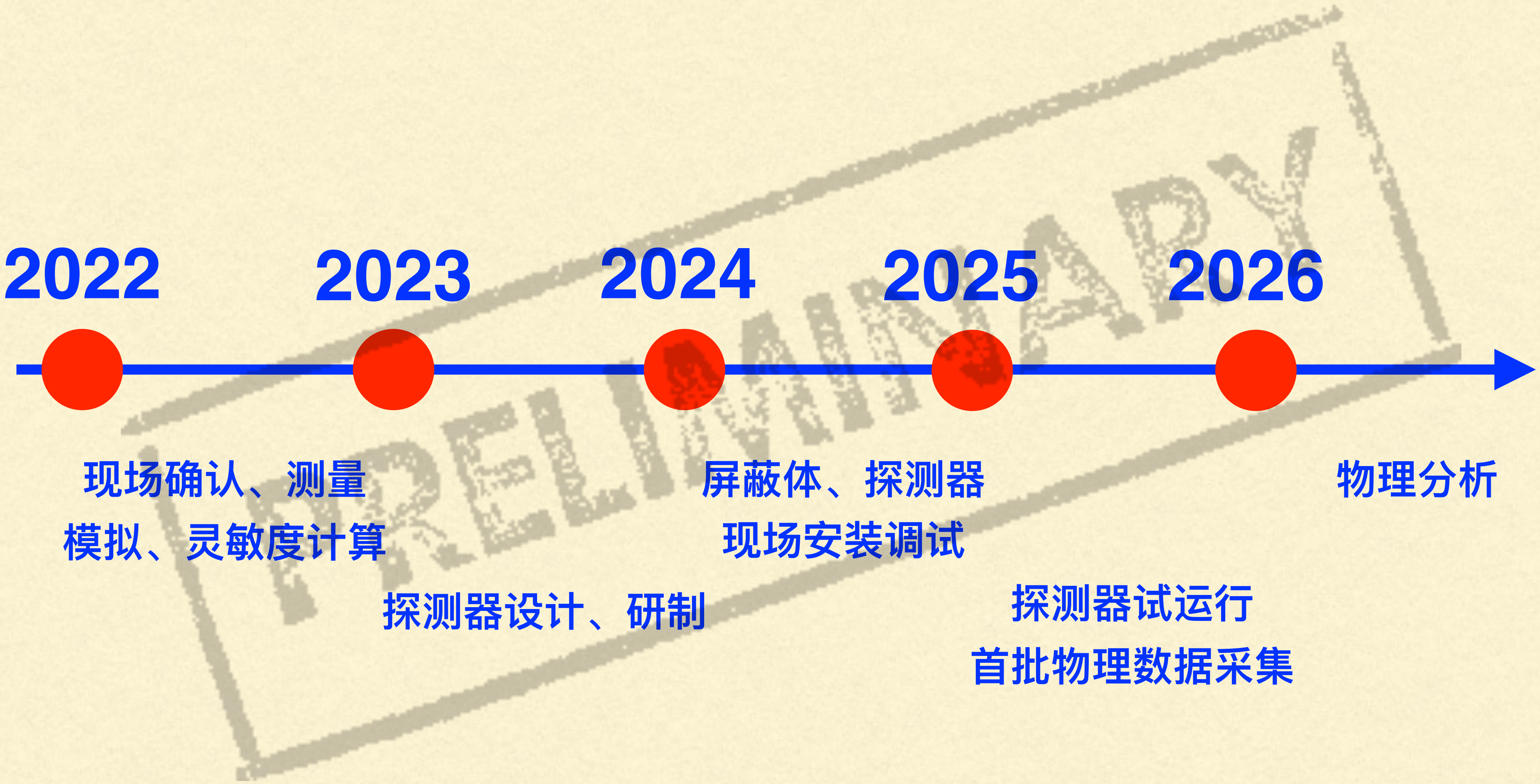
III：RELICS实验计划及预期

R&D efforts



III：RELICS实验计划及预期

RELICS 时间线 ...

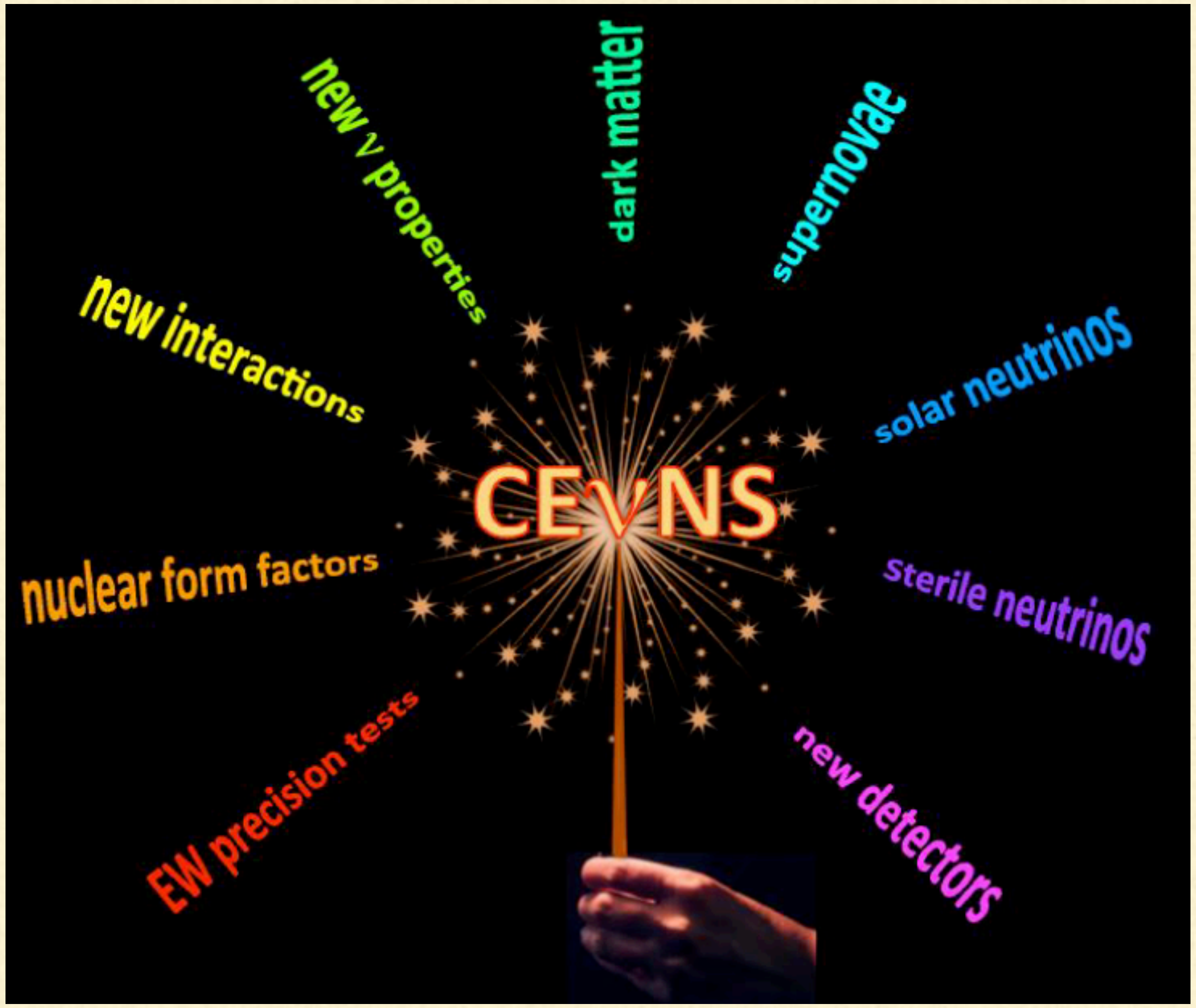


SUMMARY

✦ RELICS 是一个极低本底、极低能量阈值、用于核反应堆中微子 CEvNS 探测液氩实验。

✦ RELICS 具有丰富的物理目标，和很高的核反应堆监测应用价值。

✦ 期待实现对反应堆中微子 CEvNS 物理过程的精确测量！



期待与实验、理论同行深度合作！

Thanks