清华大学 Tsinghua University

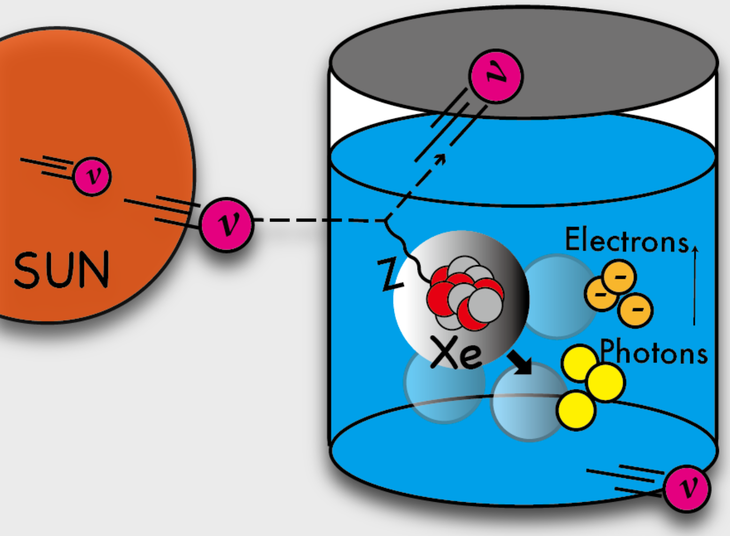
XENON

RELICS

第七届粒子物理天问论坛

2025年9月18-22日，武汉

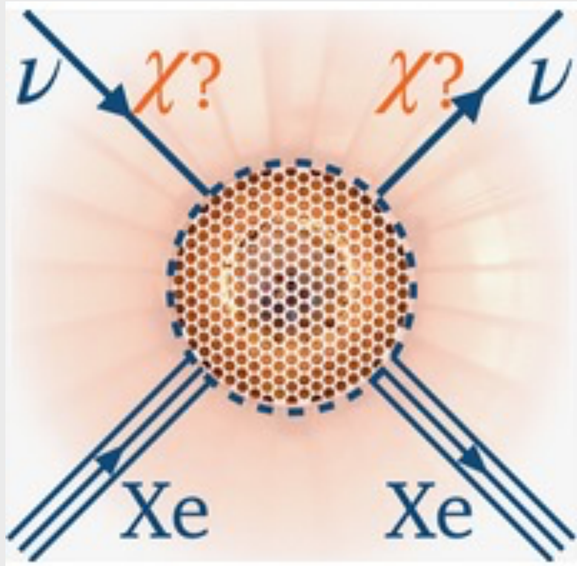
基于液氙的暗物质和中微子实验



高飞 feigao@tsinghua.edu.cn

清华大学 物理系

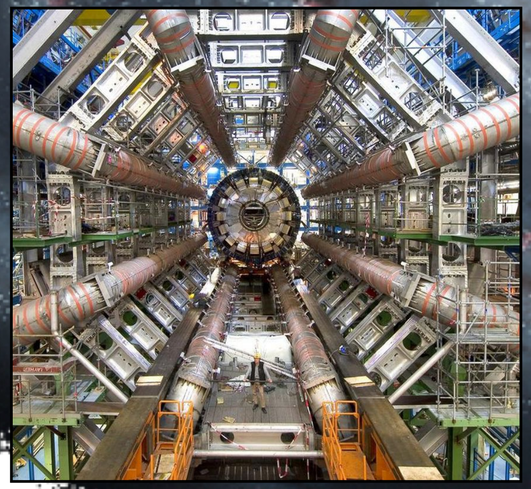
2025.09.19

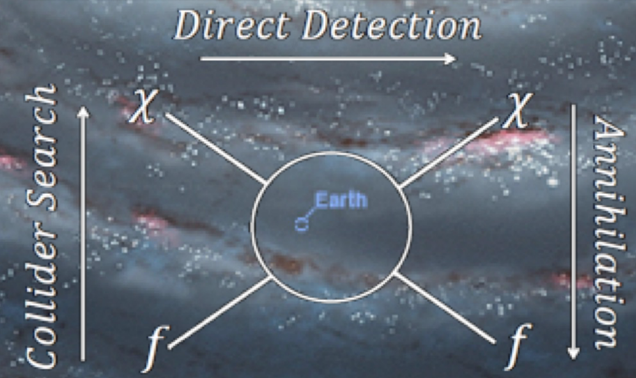


暗物质的探测方法—上天、入地和造加速器

CDEX、PandaX、
XENON

LHC





FERMI、悟空

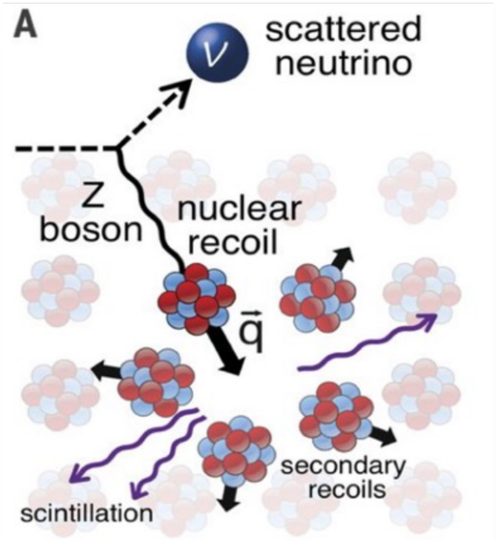
暗物质的直接探测

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 $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ 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} cm^2 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 $\nu + A \to \nu + A^*$ 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.



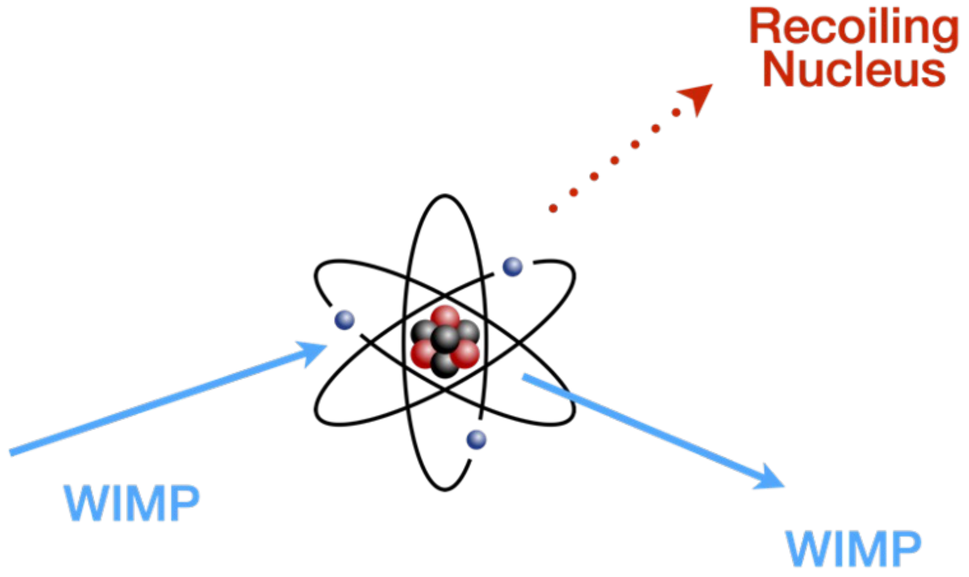
D. Akimov et al, Science 357 (2017)

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

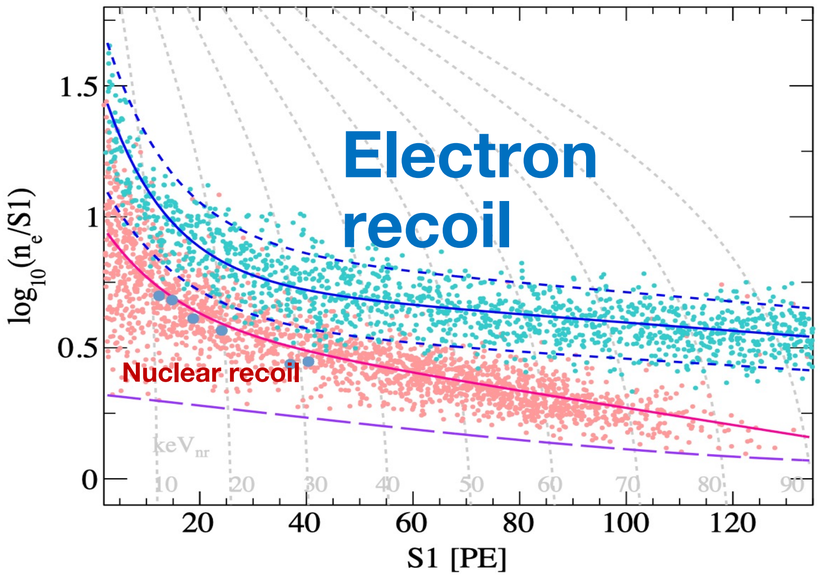
Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

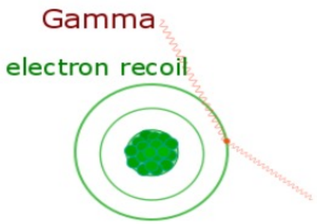
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and 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.

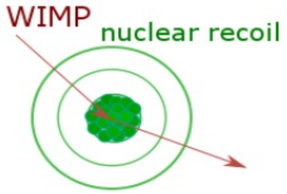


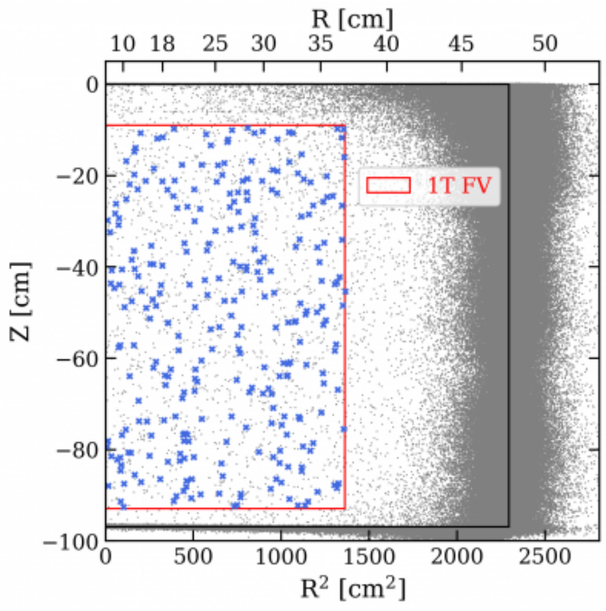
Local density ~ 0.3 GeV/cm^3

用液氙探测暗物质





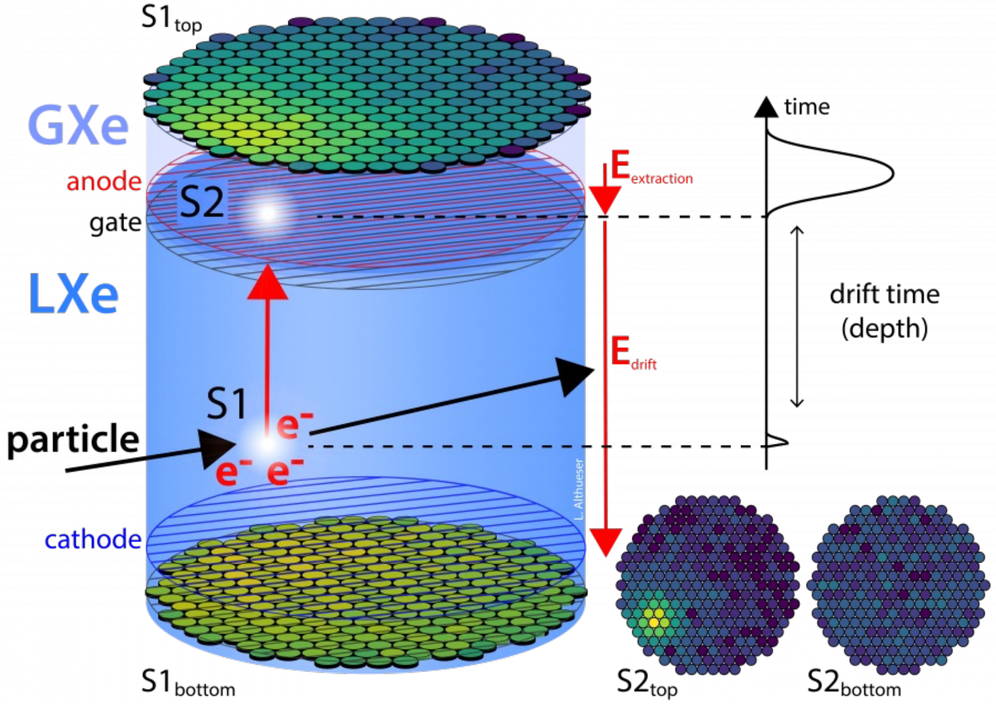




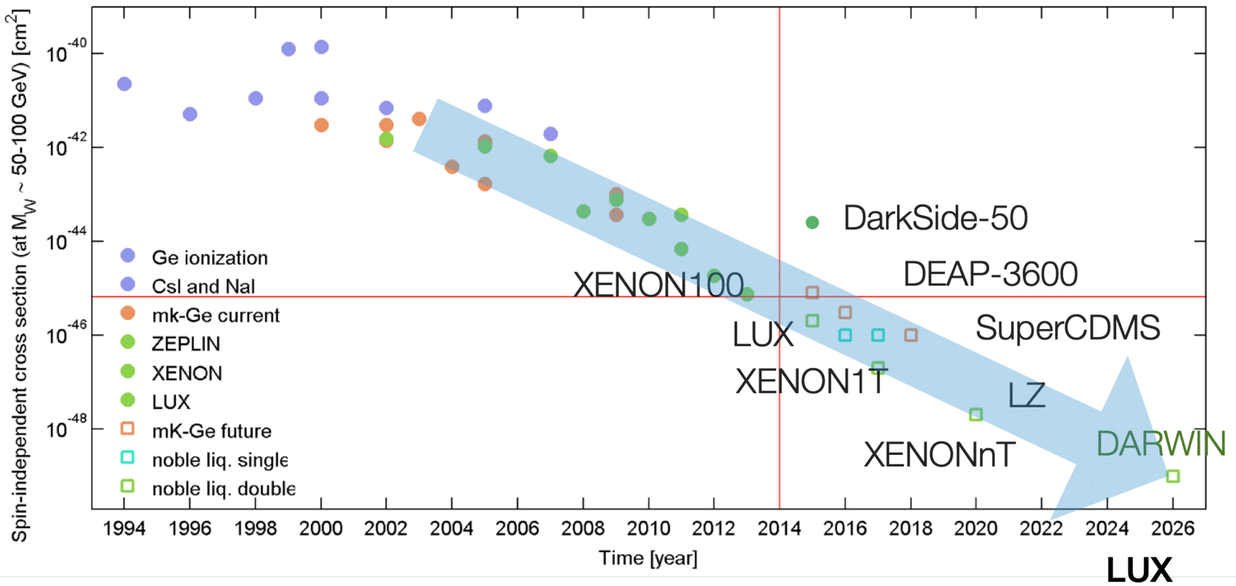
two signals for each event:

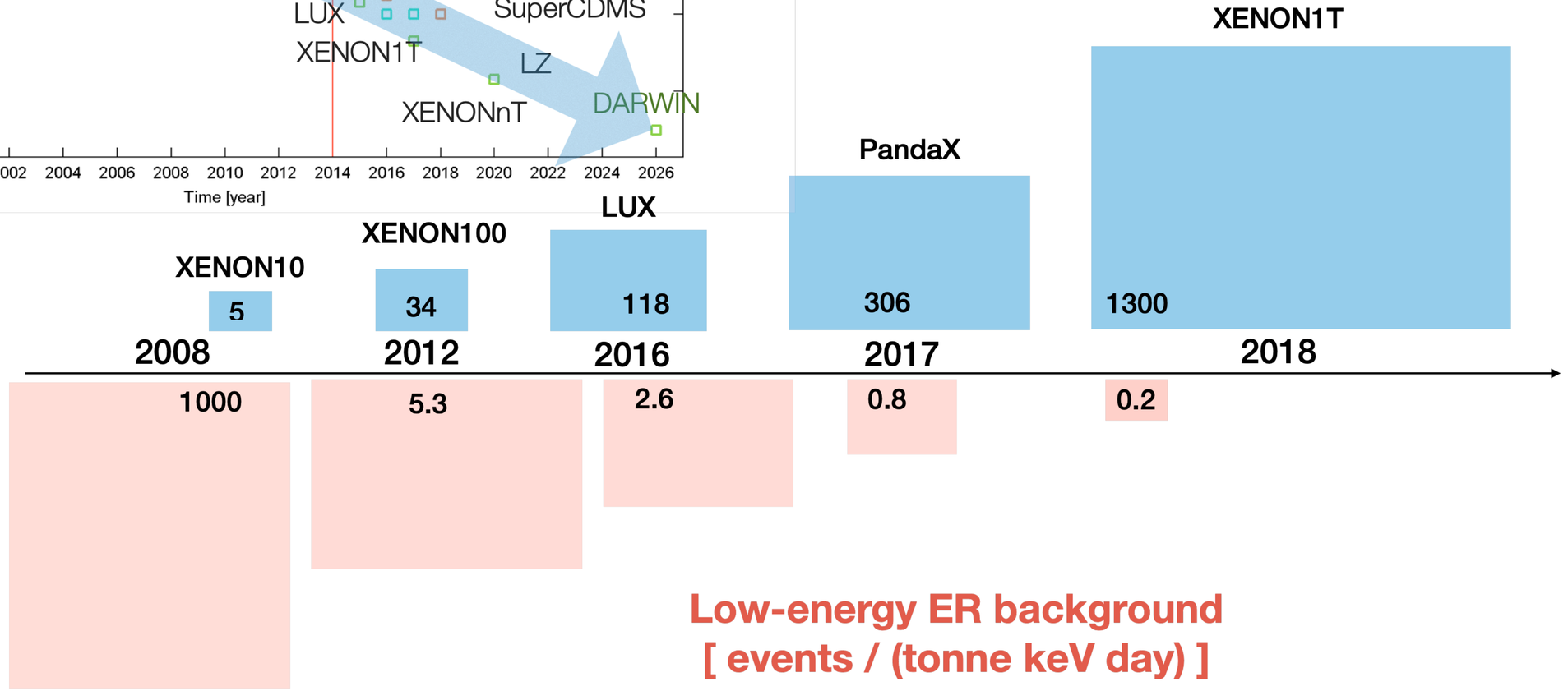
3D event imaging: x-y (S2) and z (drift time)

Recoil type discrimination from ratio of charge (S2) to light (S1)



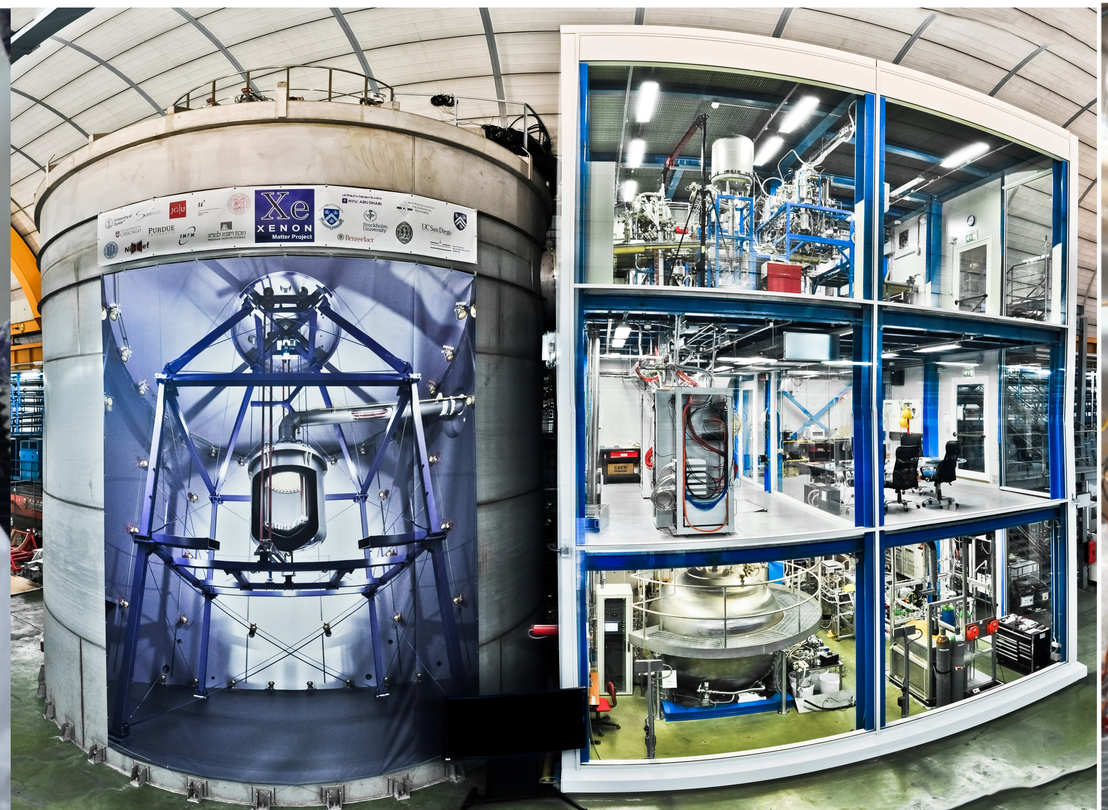
暗物质探测实验的灵敏度





液氙暗物质探测实验的国际竞争与合作

Experiments	Location	Sensitive Mass [t]	Fiducial mass [t]	Radon reduction	Neutron veto	Data taking	First Results
PandaX-4T	CJPL (China)	4.0	2.8	Y	N	2021	2021
XENONnT	LNGS (Italy)	5.9	4.0	Y	Y	2021	2023
LZ	SURF (US)	7.0	5.6	Y	Y	2022	2022



PandaX合作组

XENON合作组

~170 SCIENTISTS, 29 INSTITUTIONS, 12 COUNTRIES

AMERICA

- UC San Diego — San Diego
- Houston
- The University of Chicago — Chicago
- Columbia University in the City of New York — New York City
- Purdue University — Lafayette

EUROPE

- Zurich
- KIT Karlsruhe Institute of Technology — Karlsruhe
- WWU Münster — Münster
- Uni Freiburg — Freiburg
- JGU — Mainz
- Max-Planck-Institut für Kernphysik — Heidelberg
- Nikhef — Amsterdam
- Stockholm University — Stockholm
- University of Coimbra — Coimbra
- Subatech — Nantes
- LPNHE Paris — Paris
- INFN Torino — Torino
- Alma Mater Studiorum Università di Bologna — Bologna
- Università degli Studi dell'Aquila — L'Aquila
- INFN LNGS — Assergi
- Università degli Studi di Napoli Federico II — Napoli

EAST

- Weizmann Institute of Science — Rehovot
- NYU Abu Dhabi — Abu Dhabi

ASIA

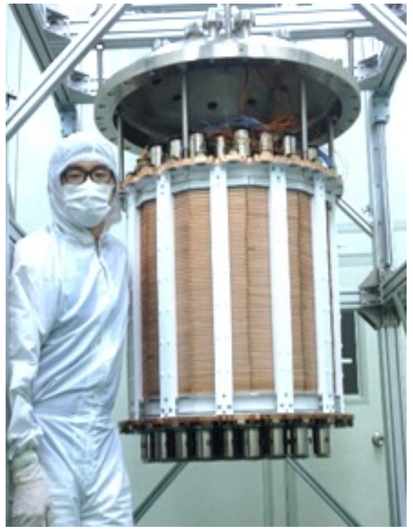
- 清華大學 Tsinghua University — Beijing
- 西湖大學 Westlake University — Hangzhou
- The Chinese University of Hong Kong, Shenzhen — Shenzhen
- 東京大学 The University of Tokyo — Tokyo
- Nagoya University — Nagoya
- Kobe University — Kobe

PandaX实验的演化路线

PandaX Start

PandaX-I 120kg

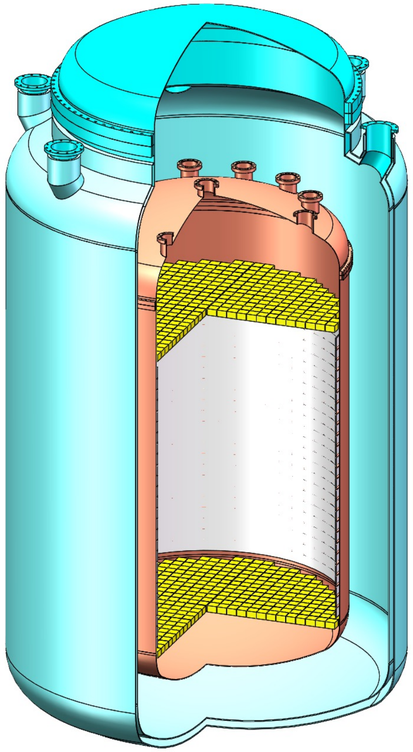
PandaX-II 580kg



PandaX-4T

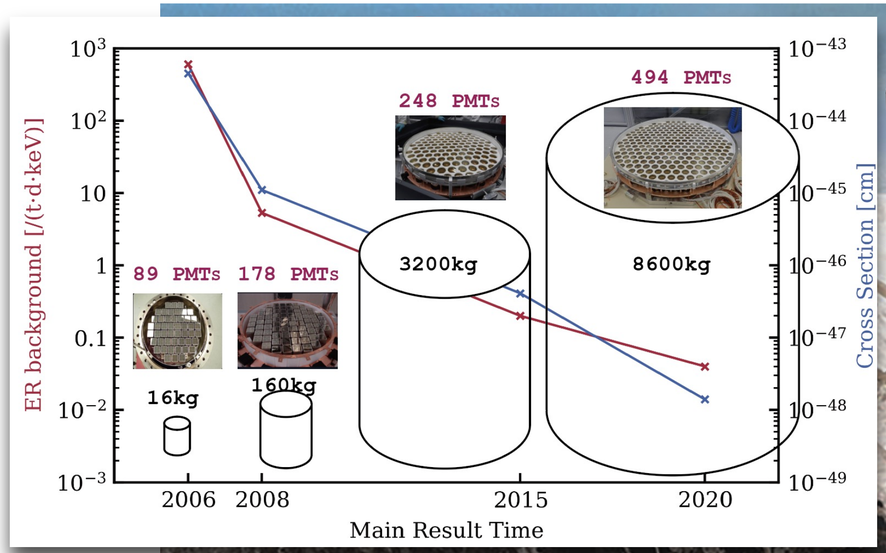
(3.7 tonne)

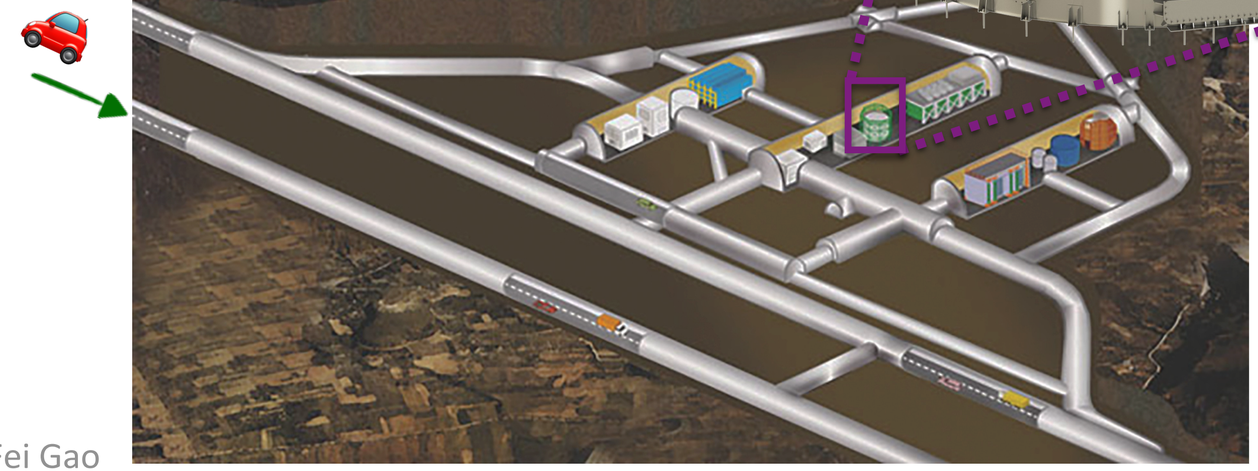
PandaX-20T

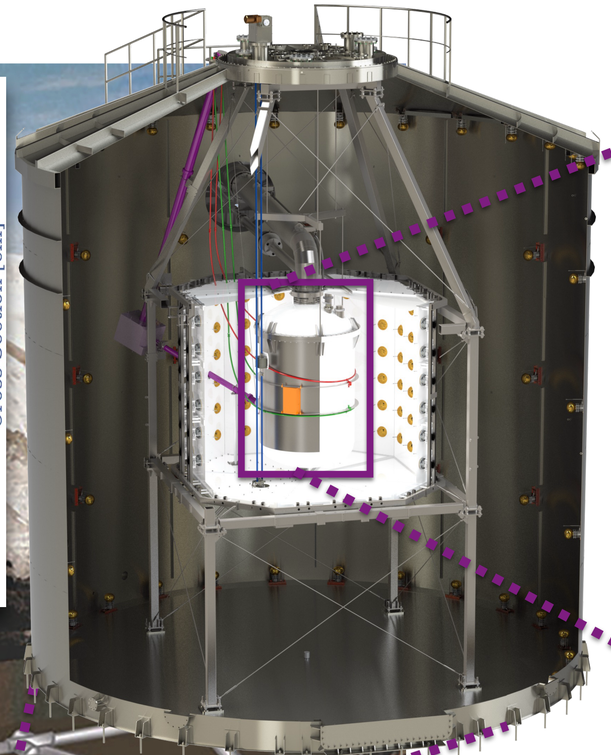


2009 | 2010-2014 | 2015-2019 | 2021- | 2027-

XENONnT实验：地下实验室与探测器





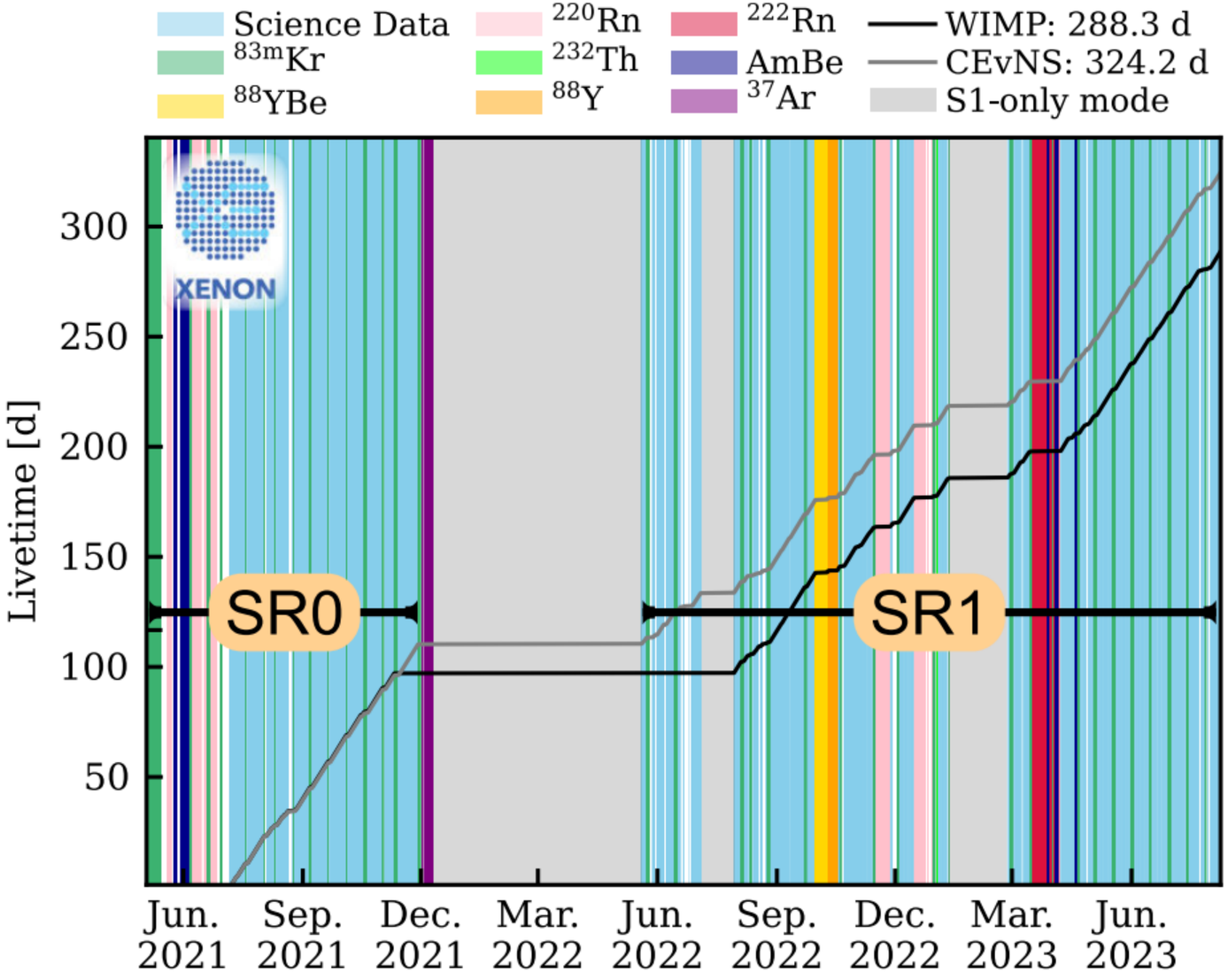


- 主探测器参数

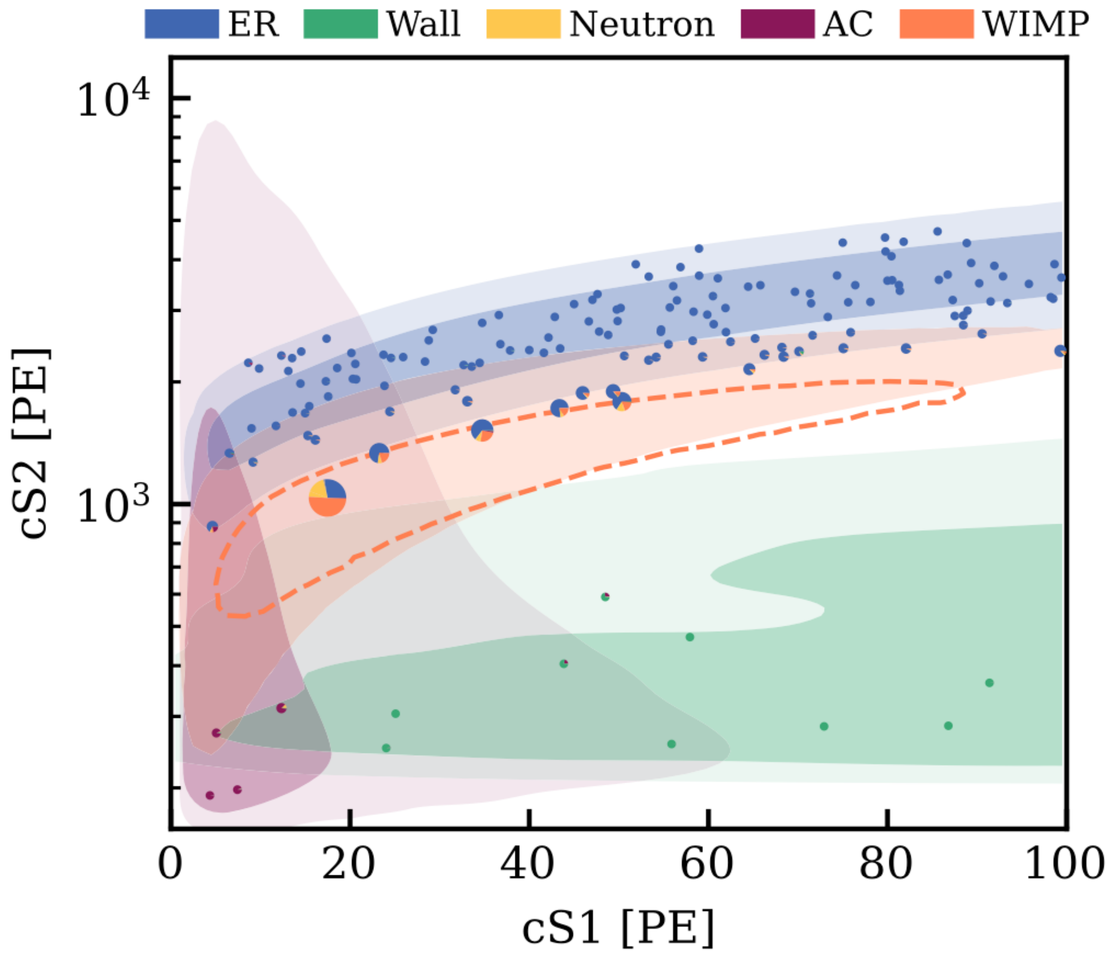
漂移长度	直径	灵敏区液氙质量	漂移电场
1.5 米	1.32 米	5.9 吨	23 V/cm

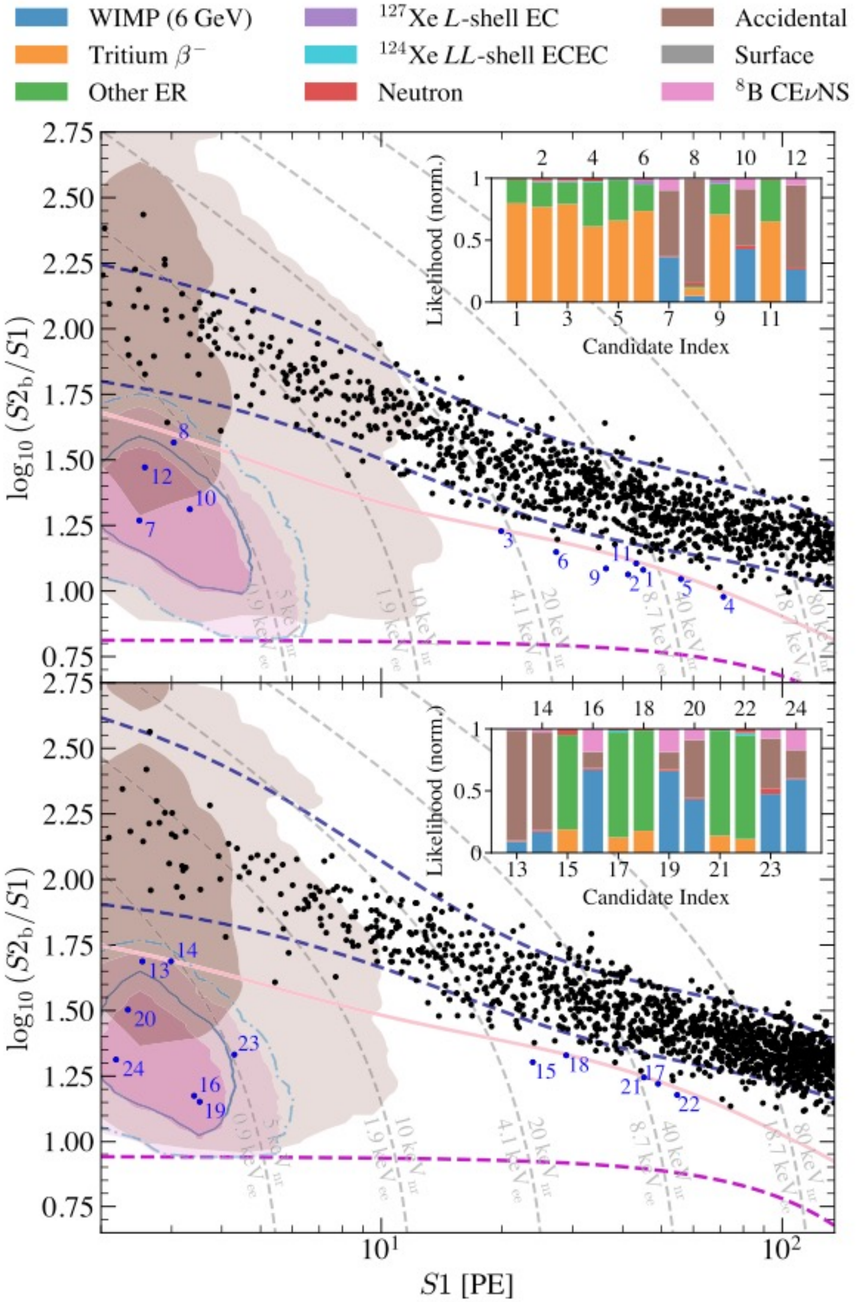
Eur.Phys.J.C 84 (2024) 8, 784

数据采集与物理分析：盲分析 (blind analysis)

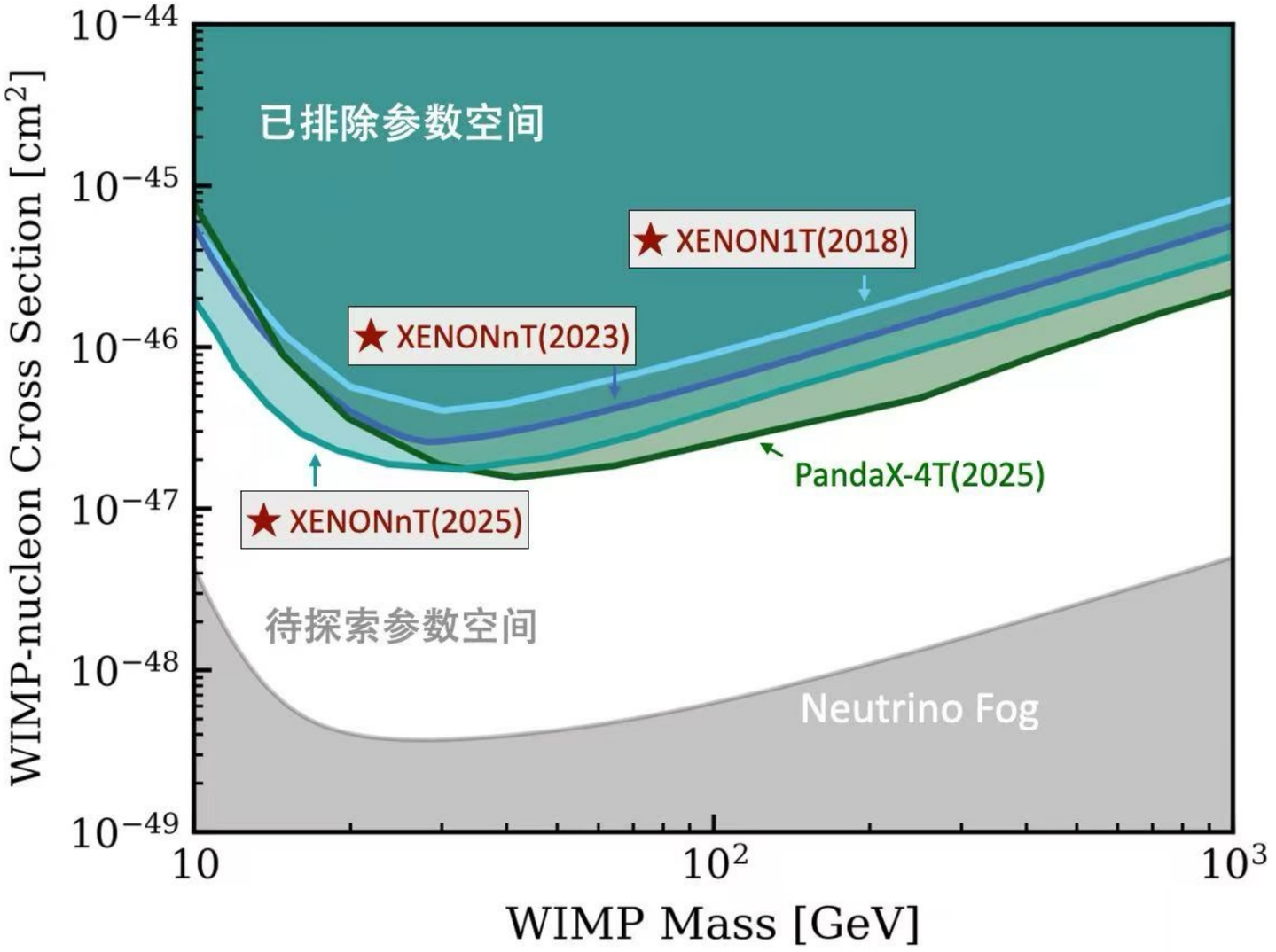


暗物质探测结果

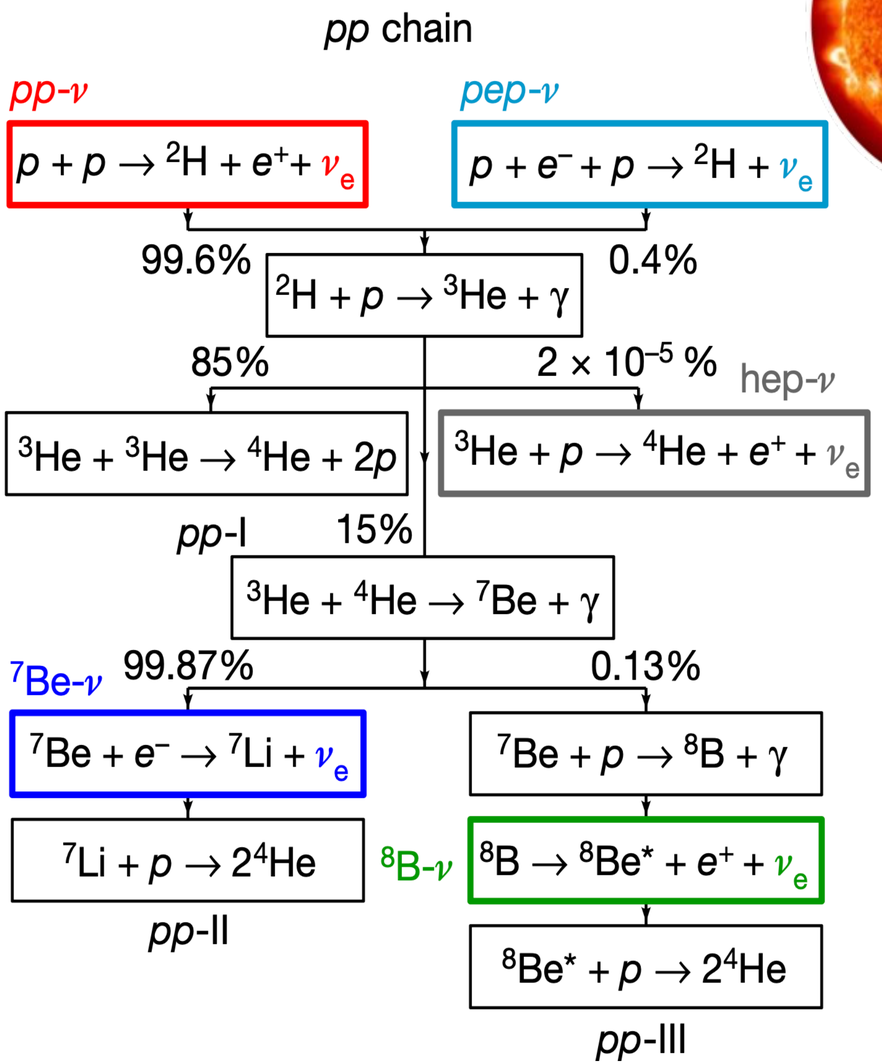

ER
Wall
Neutron
AC
WIMP
10^4
10^3
cS2 [PE]
0
20
40
60
80
100
cS1 [PE]

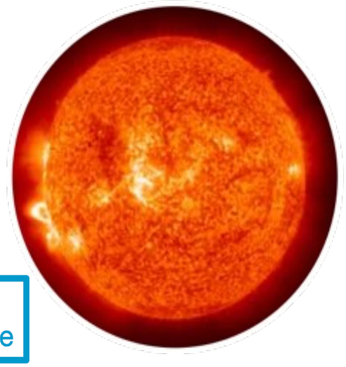

WIMP (6 GeV)
Tritium β^-
Other ER
^{127}Xe L-shell EC
^{124}Xe LL-shell ECEC
Neutron
Accidental
Surface
^{8}B CEνNS
$\log_{10}(S2_b/S1)$
Likelihood (norm.)
Candidate Index
$S1$ [PE]
10^1
10^2

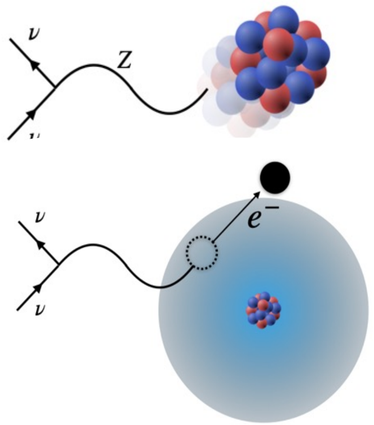
暗物质探测结果

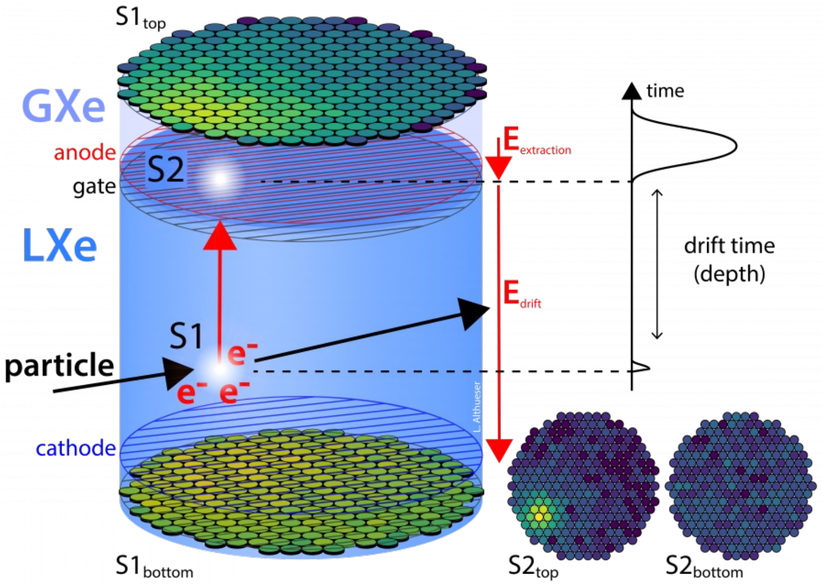

已排除参数空间
XENON1T(2018)
XENONnT(2023)
PandaX-4T(2025)
XENONnT(2025)
待探索参数空间
Neutrino Fog
WIMP-nucleon Cross Section [cm^2]
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10
10^2
10^3
WIMP Mass [GeV]

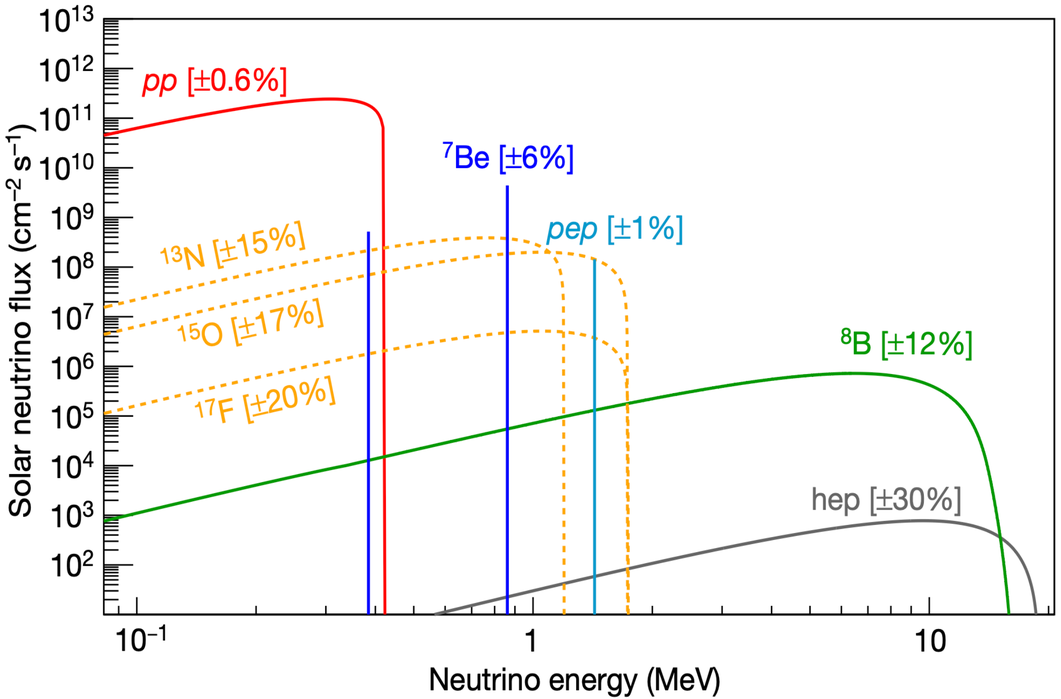
太阳中微子的探测


pp chain
pp-ν
pep-ν
p + p → ²H + e⁺ + νe
p + e⁻ + p → ²H + νe
99.6%
0.4%
²H + p → ³He + γ
85%
2 × 10⁻⁵ %
hep-ν
³He + ³He → ⁴He + 2p
³He + p → ⁴He + e⁺ + νe
pp-I
15%
³He + ⁴He → ⁷Be + γ
⁷Be-ν
99.87%
0.13%
⁷Be + e⁻ → ⁷Li + νe
⁷Be + p → ⁸B + γ
⁷Li + p → 2⁴He
⁸B-ν
⁸B → ⁸Be* + e⁺ + νe
pp-II
⁸Be* + p → 2⁴He
pp-III

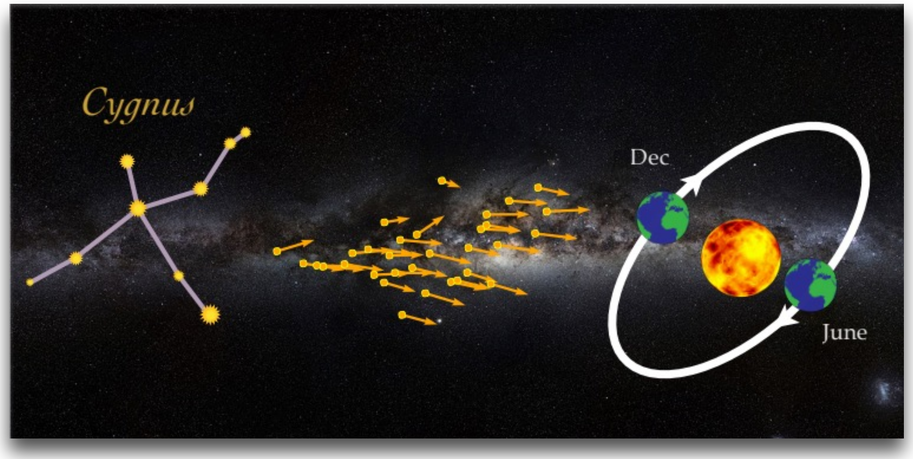


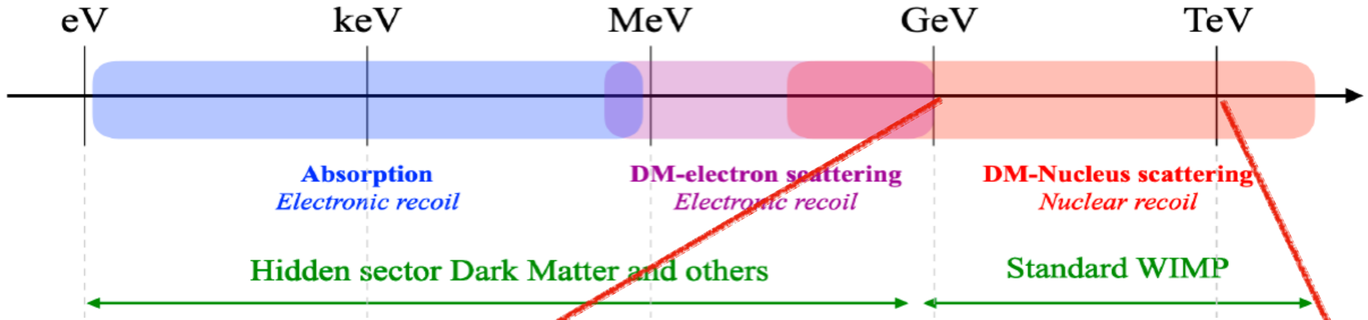

ν
Z
ν
ν
e⁻
ν

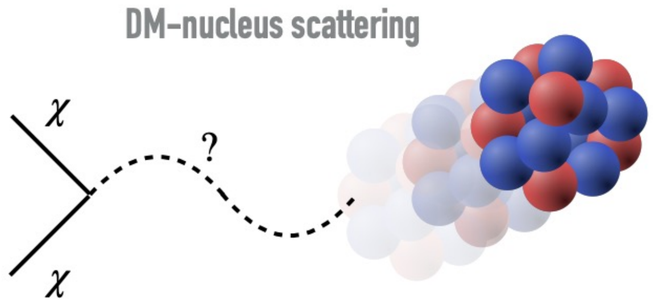

S1top
GXe
anode
gate
S2
LXe
particle
S1
e⁻
e⁻ e⁻
cathode
S1bottom
E extraction
E drift
time
drift time
(depth)
S2top
S2bottom

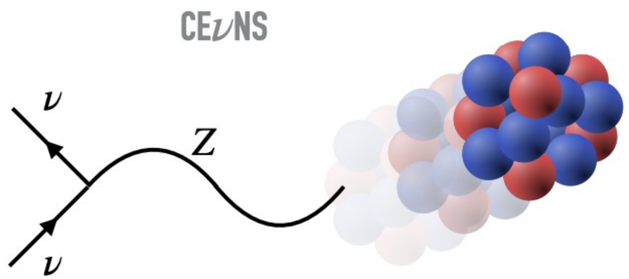

pp [±0.6%]
⁷Be [±6%]
pep [±1%]
¹³N [±15%]
¹⁵O [±17%]
¹⁷F [±20%]
⁸B [±12%]
hep [±30%]
Solar neutrino flux (cm⁻² s⁻¹)
Neutrino energy (MeV)

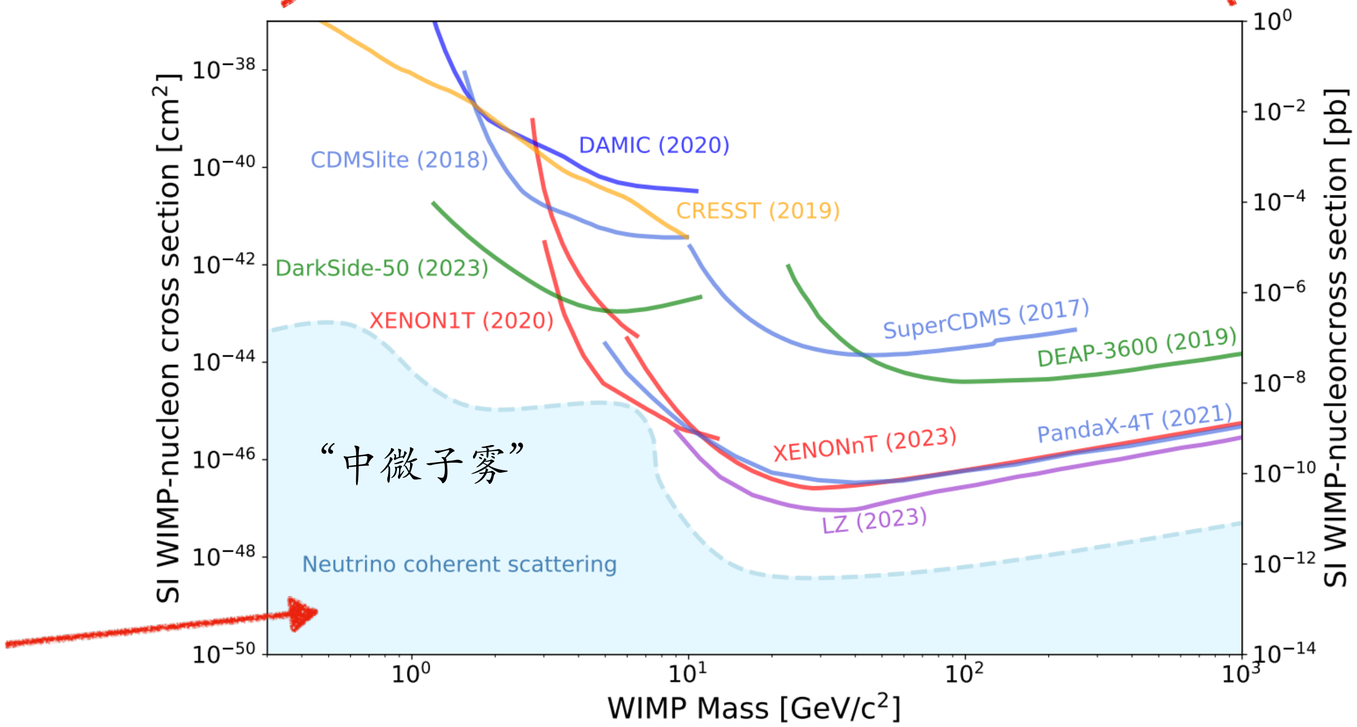
暗物质直接探测的“中微子雾”?











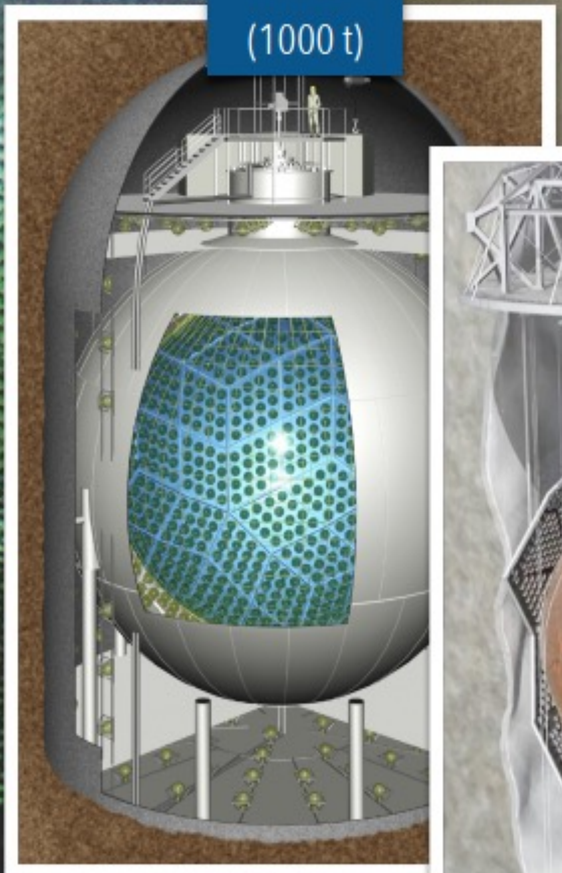
R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update

XENONnT: The Smallest Solar Neutrino Detector

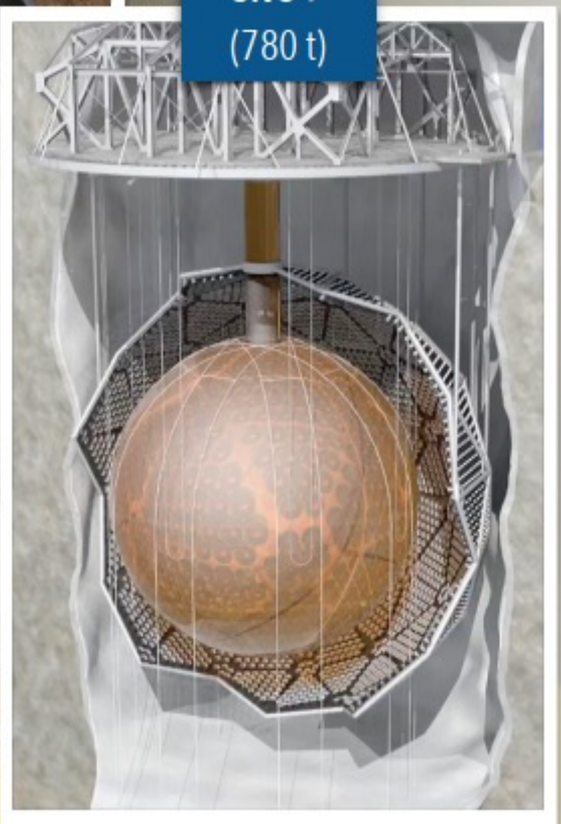
XENON

Super-Kamiokande
(50 kT)

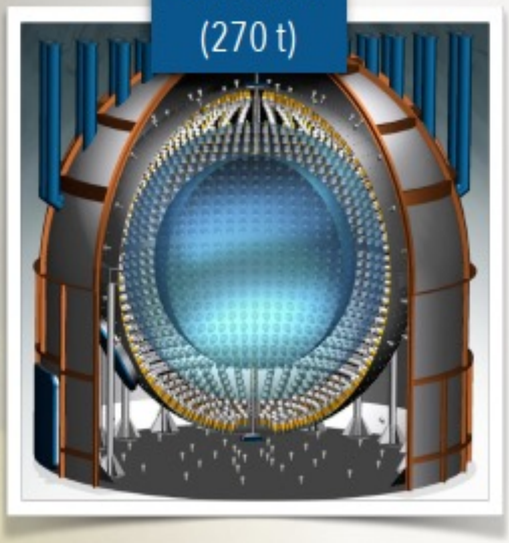
KamLAND
(1000 t)



SNO+
(780 t)



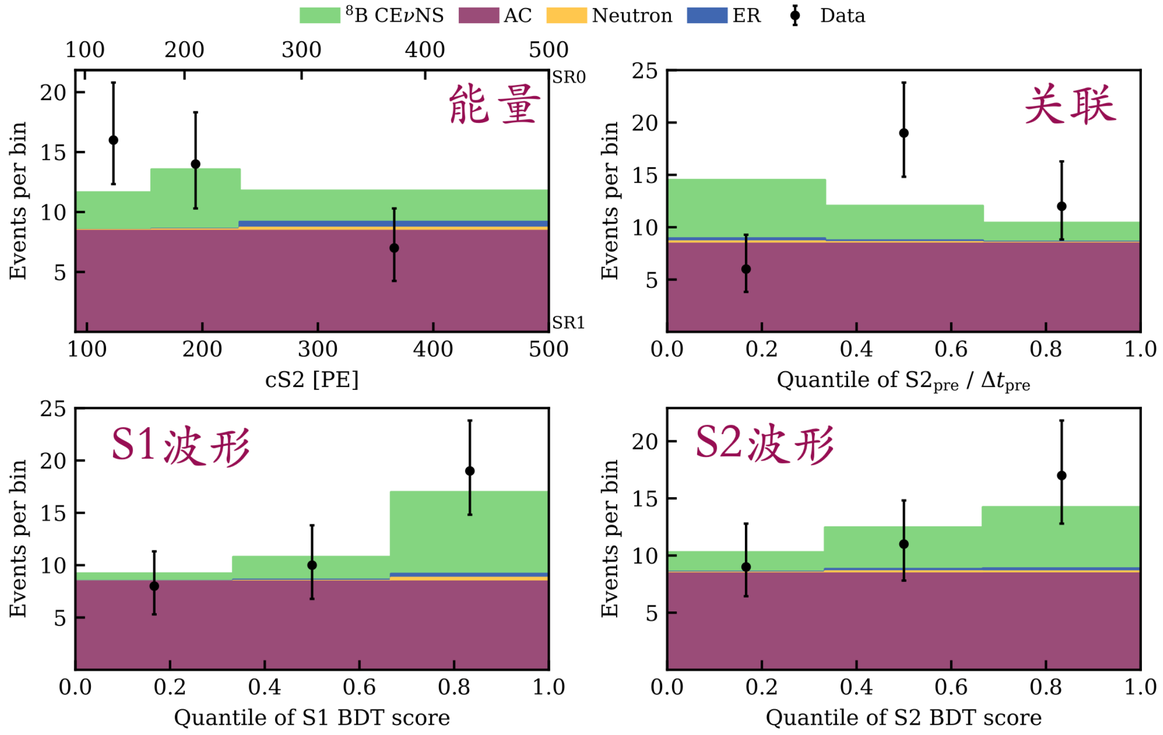
Borexino
(270 t)

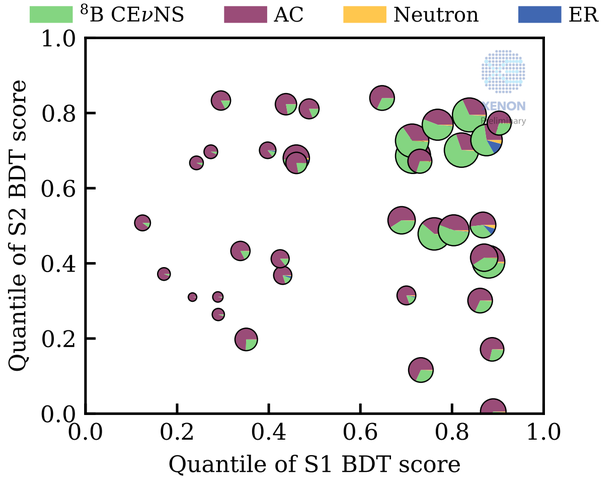


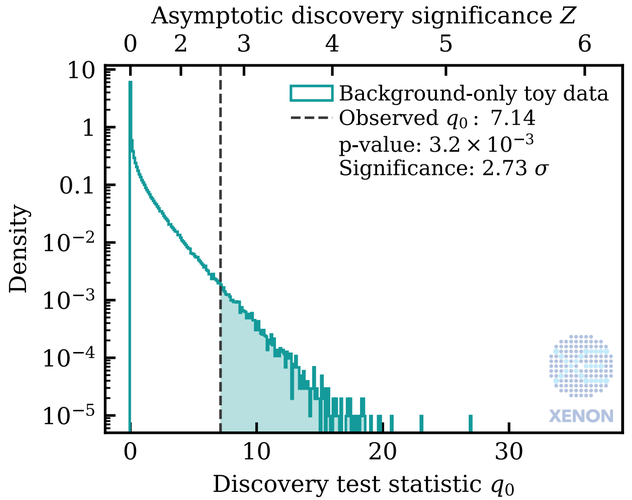
XENONnT
(5.9 t)

测量结果：XENONnT

成分	预测	本底 + ^{8}B best fit
AC - SR0	7.5 ± 0.7	7.4
AC - SR1	17.8 ± 1.0	17.9
ER	0.7 ± 0.7	0.5
NR	0.5 ± 0.3	0.5
总本底	26.4 ± 1.4	26.3
^{8}B	11.9 ± 4.5	10.7
观测	37	







测量结果：PandaX-4T

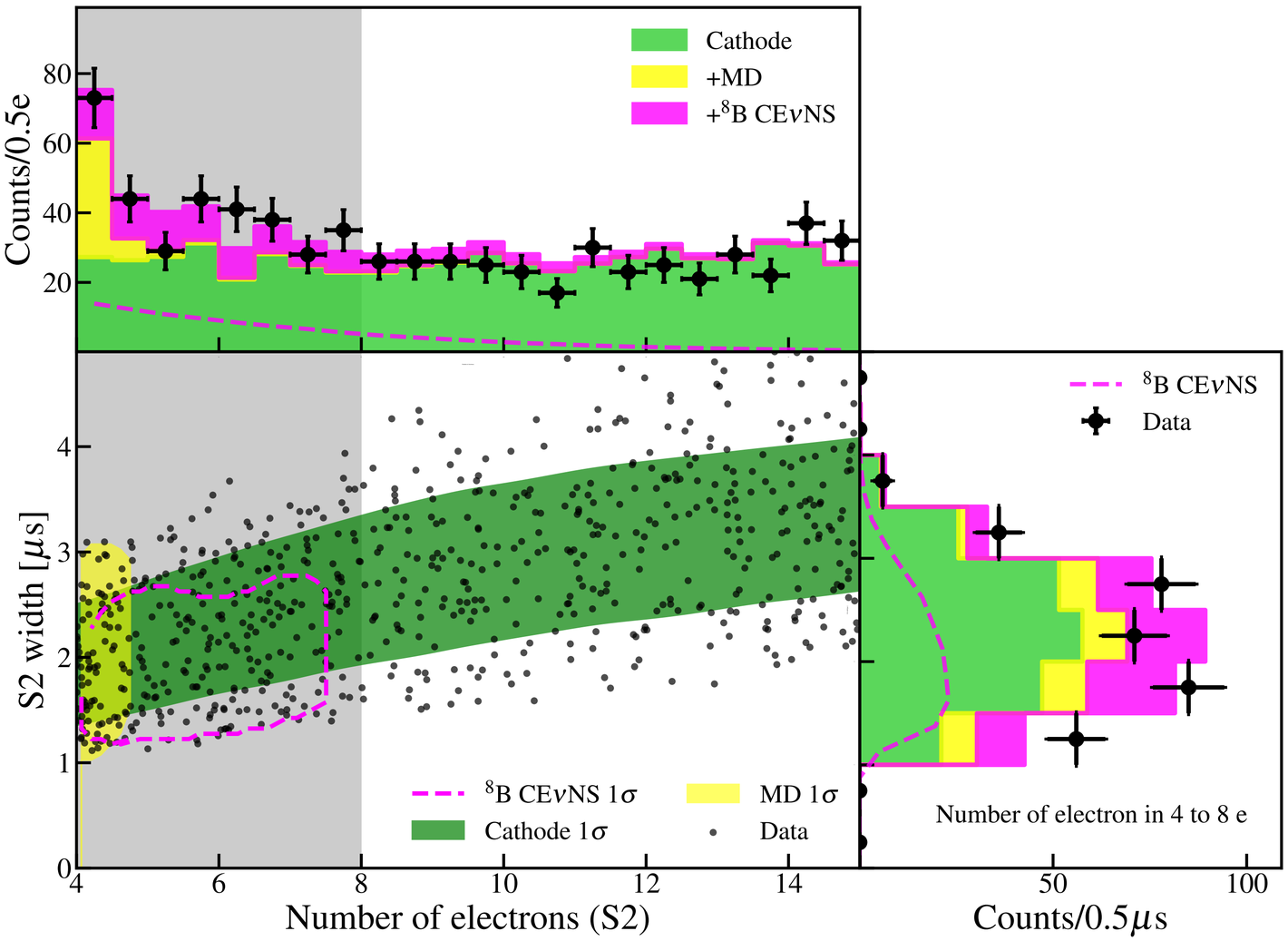
US2 ROI	Run0	Run1
Cathode	100 ± 24	104 ± 21
MD	25 ± 3	20 ± 4
ERs	1.3 ± 0.1	0.9 ± 0.2
Total bkg.	126 ± 24	125 ± 21
^{8}B CEνNS	18 ± 4	25 ± 6
Observed	158	174

Best-fit ^{8}B yield

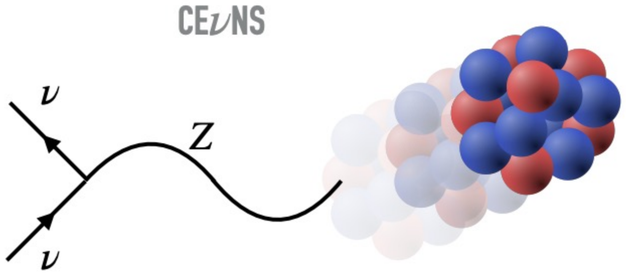
Paired: 3.5 ± 1.3 evts

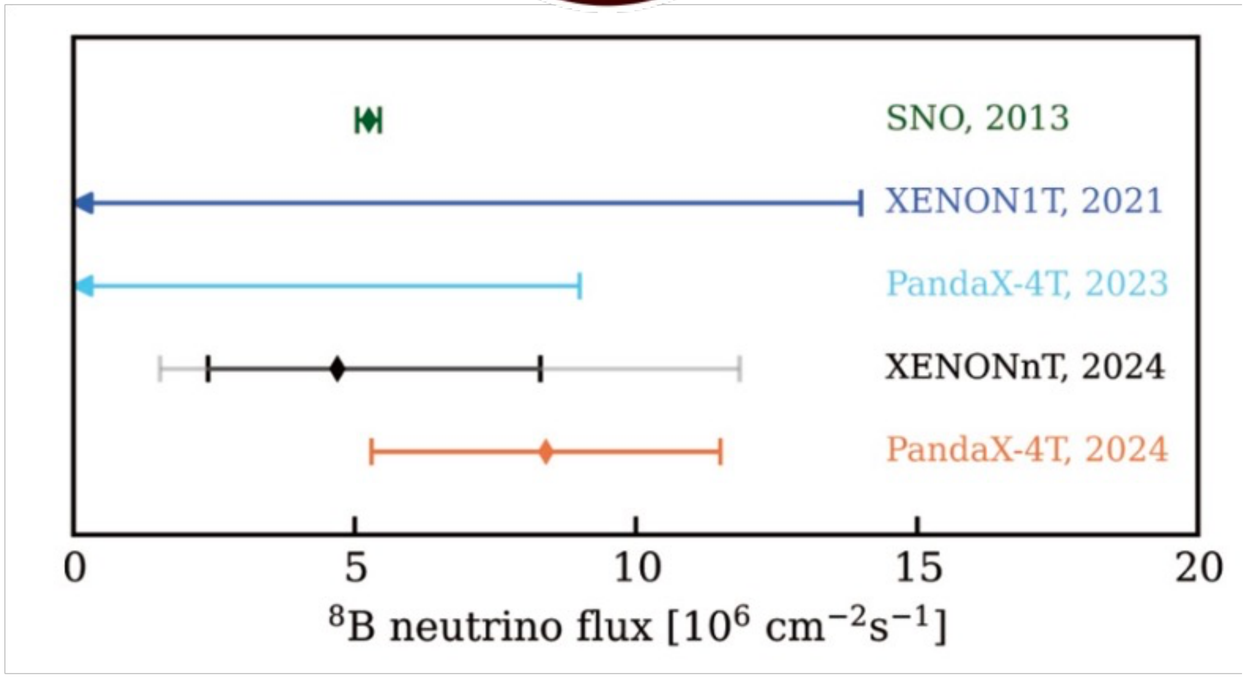
S2only: 75 ± 28 evts

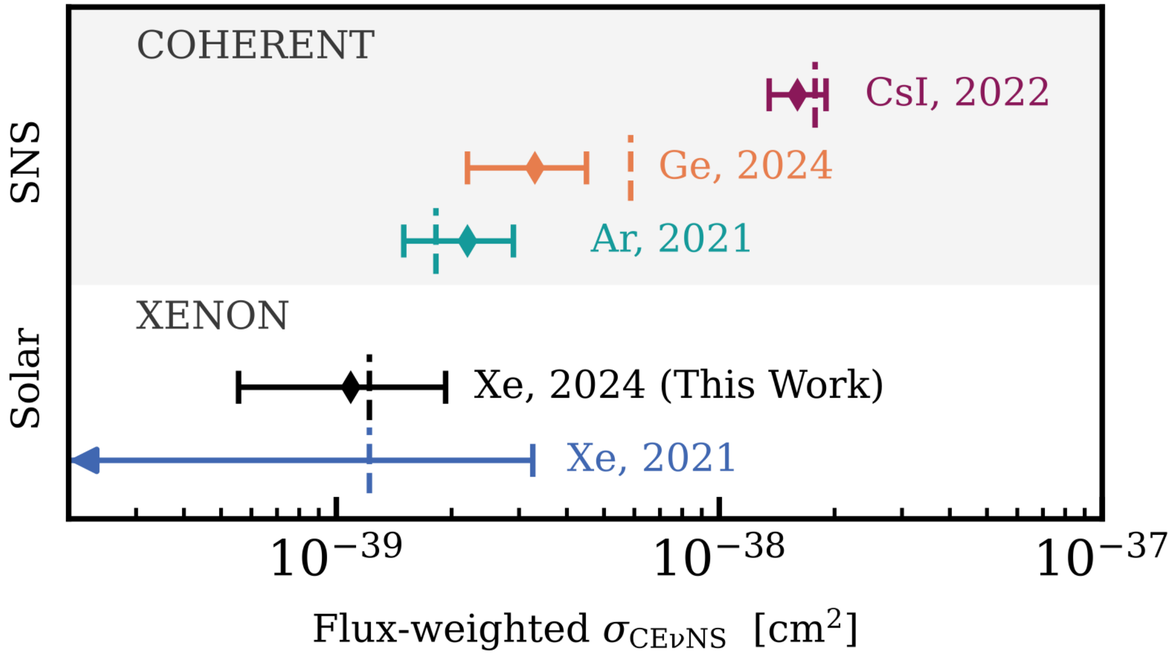
统计显著度：2.6-sigma



测量结果







$\phi_{B8} = (4.7^{+3.6}_{-2.3}) \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$

$\sigma_{CE\nu NS} = (1.1^{+0.8}_{-0.5}) \times 10^{-39} \mathrm{cm}^2$

太阳“中微子雾”实验迹象之路

PHYSICAL REVIEW LETTERS **130,** 021802 (2023)

Search for Solar ^{8}B Neutrinos in the PandaX-4T Experiment Using Neutrino-Nucleus Coherent Scattering

➢2023年，PandaX 首次尝试，未测到

PHYSICAL REVIEW LETTERS **133,** 191001 (2024)

Editors' Suggestion | Featured in Physics

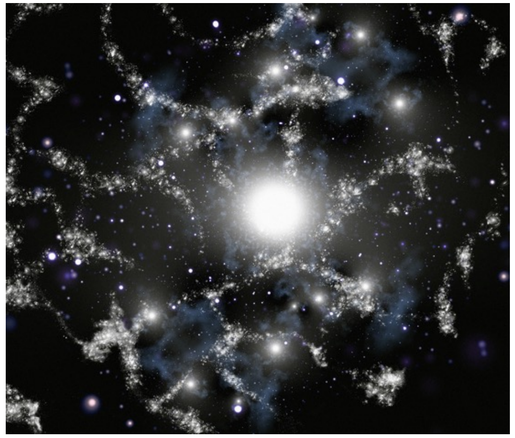
First Indication of Solar ^{8}B Neutrinos through Coherent Elastic Neutrino-Nucleus Scattering in PandaX-4T

PHYSICAL REVIEW LETTERS **126,** 091301 (2021)

Editors' Suggestion

Search for Coherent Elastic Scattering of Solar ^{8}B Neutrinos in the XENON1T Dark Matter Experiment

➢2021年，XENON 首次尝试，未测到



PHYSICAL REVIEW LETTERS **133,** 191002 (2024)

Editors' Suggestion | Featured in Physics

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

➢2024年，XENON 和 PandaX 测到太阳“中微子雾”迹象

工作评价：走进“中微子雾”

PHYSICAL REVIEW LETTERS **133,** 191002 (2024)

Editors' Suggestion | Featured in Physics

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

APS125

PRL 2024年度特辑

Physical Review Letters collection of the year 2024

Each year *Physical Review Letters* publishes about 2000-2500 Letters across ~52 issues. We select about 400 of those papers to highlight as Editors' Suggestions. That is still a lot to read. So, we have decided to provide a more concentrated distillation of some of the most important and interesting papers in physics and related areas.

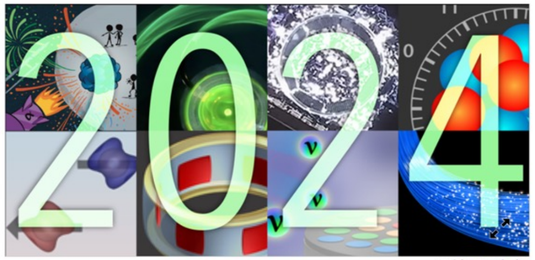
Physics ABOUT BROWSE PRESS COLLECTIONS Search articles

SPECIAL FEATURE

Highlights of the Year

December 16, 2024 • *Physics* 17, 181

Physics Magazine Editors pick their favorite stories from 2024.



APS/Alan Stonebraker

美国物理学会“年度十大亮点”

Quantamagazine Physics Mathematics Biology Computer Science Topics Archive

SERIES 2024 IN REVIEW

The Year in Physics

3

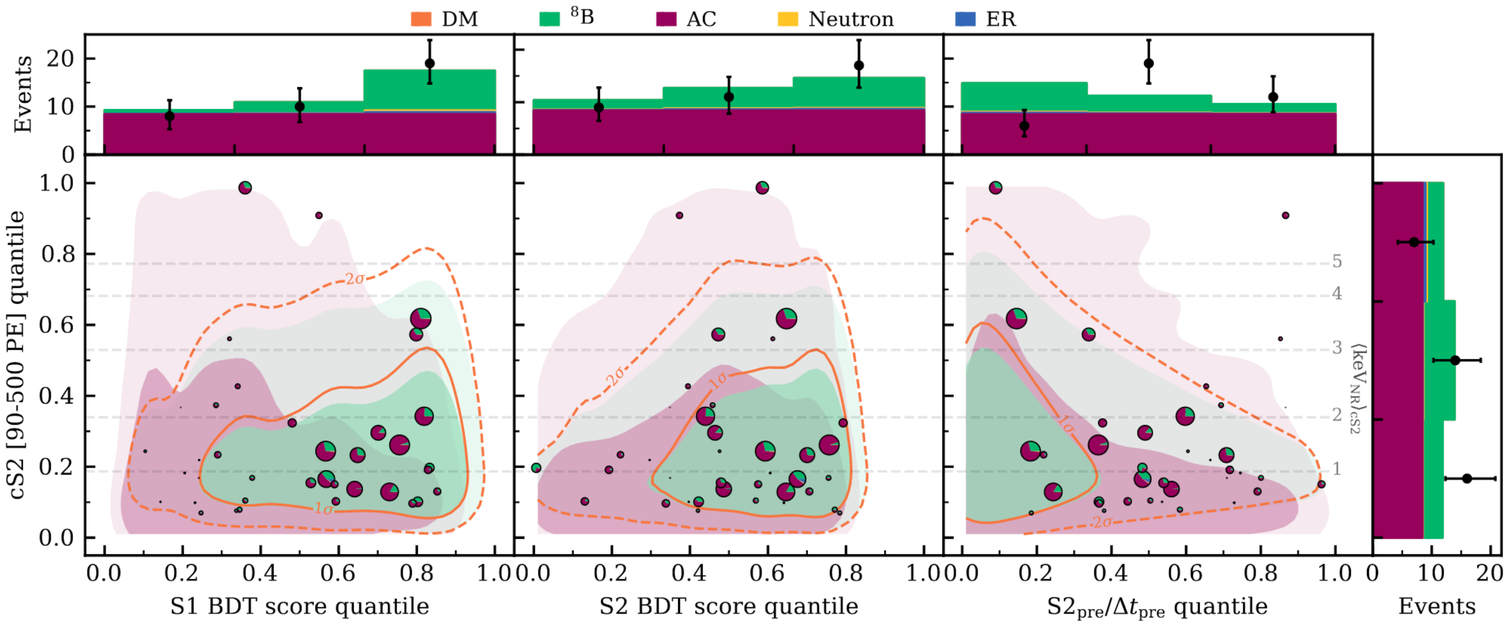
Physicists discovered strange supersolids, constructed new kinds of superconductors, and continued to make the case that the cosmos is far weirder than anyone suspected.

《Quanta magzine》“年度物理三大关注方向”

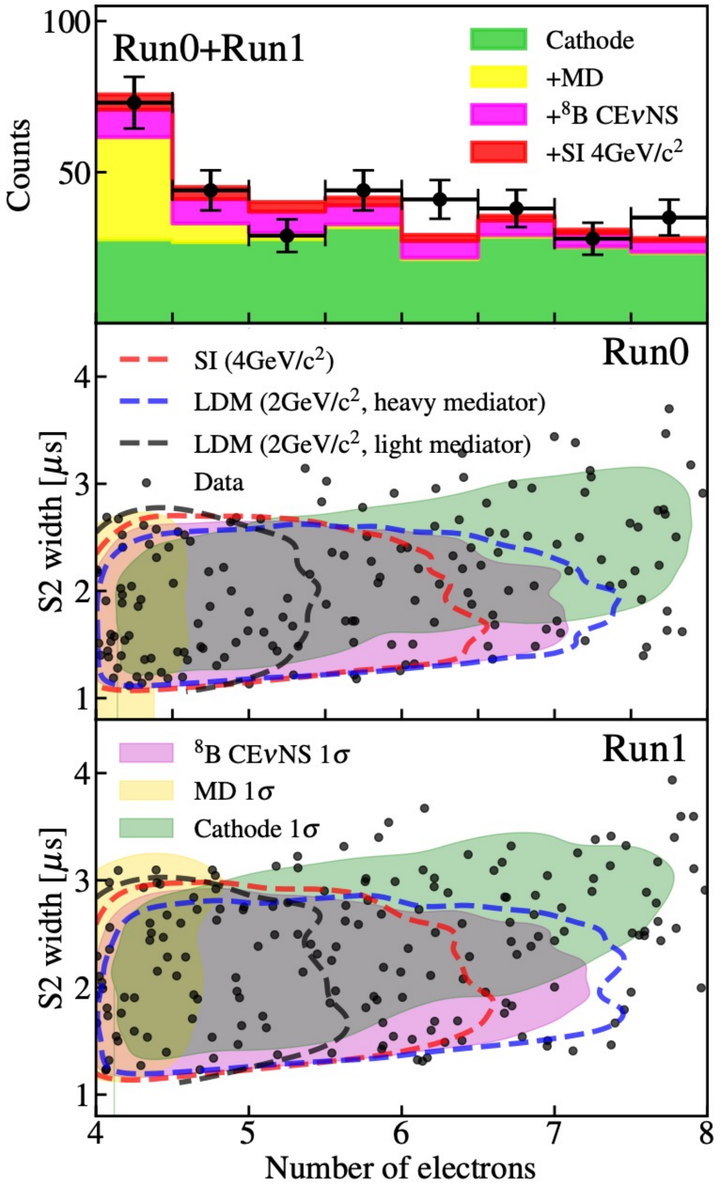
Dark Matter Is Dead, Long Live Dark Matter

In the search for the invisible components of the universe, dark matter reached a discouraging milestone. (Fuzzy on the difference between dark energy and dark matter? Read our *Fundamentals* newsletter from May.) Experimenters hunting for hypothesized dark matter particles known as WIMPs — heavy, inert particles that were long considered the top candidate for the nonreflective stuff floating in and around galaxies — hit a limit. Detectors have become so sensitive that they're now picking up the glow of neutrinos from the sun, which blinds them to any subtler signals. "So that's kind of the end of the WIMP detection era," the Stanford University physicist Natalia Toro told us.

在“中微子雾”中寻找暗物质

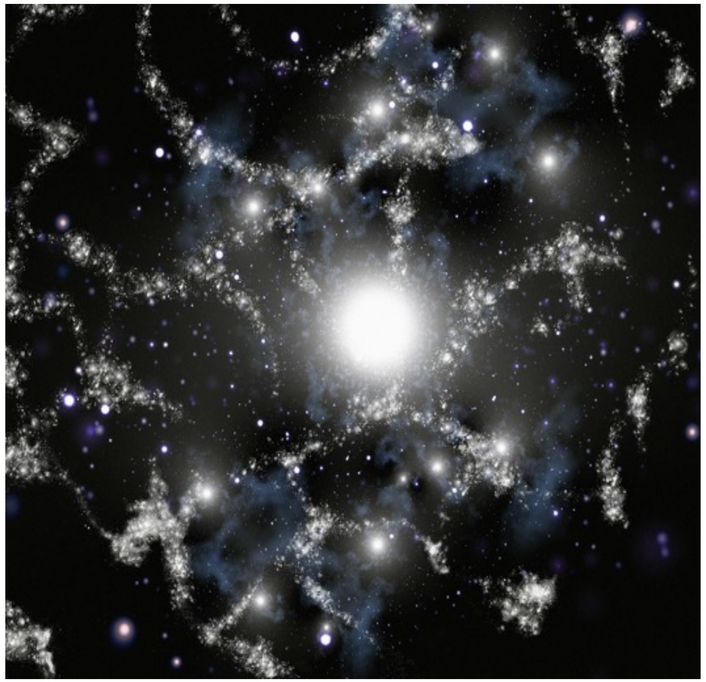


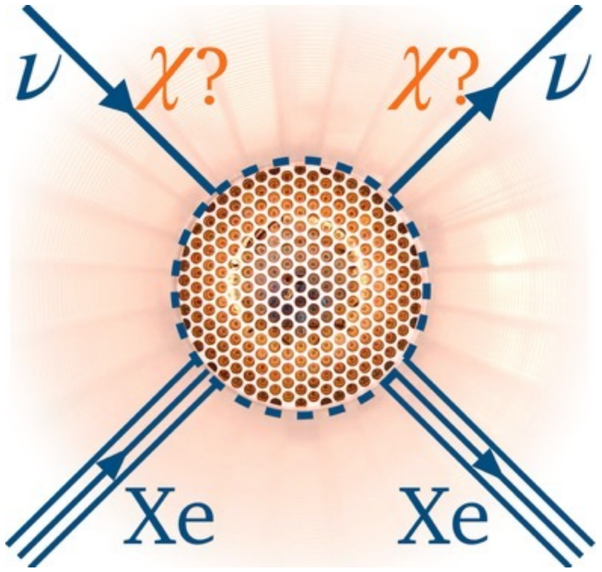
XENON: PRL 134, 111802, 2025

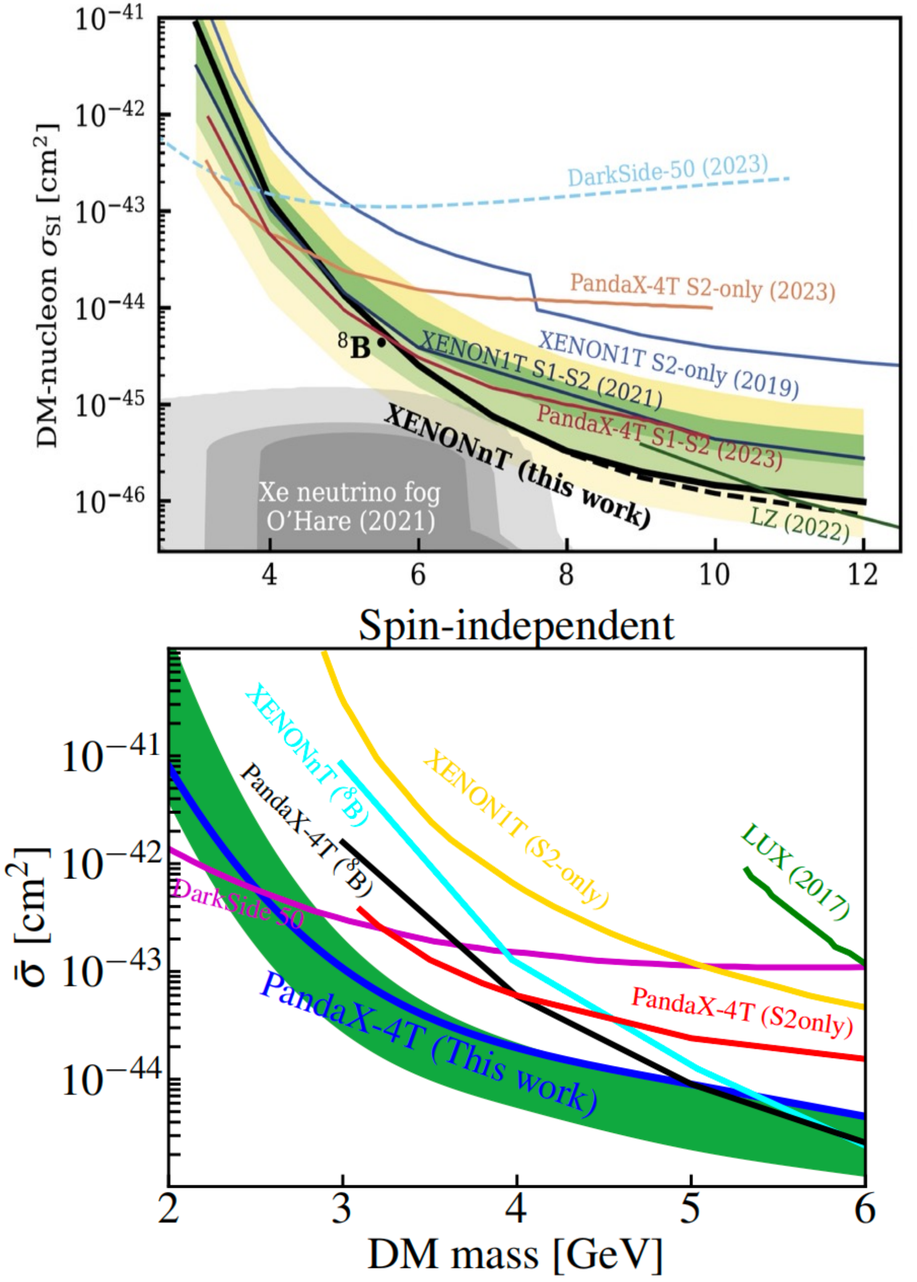


PandaX: arXiv 2507.11930

在“中微子雾”中寻找暗物质

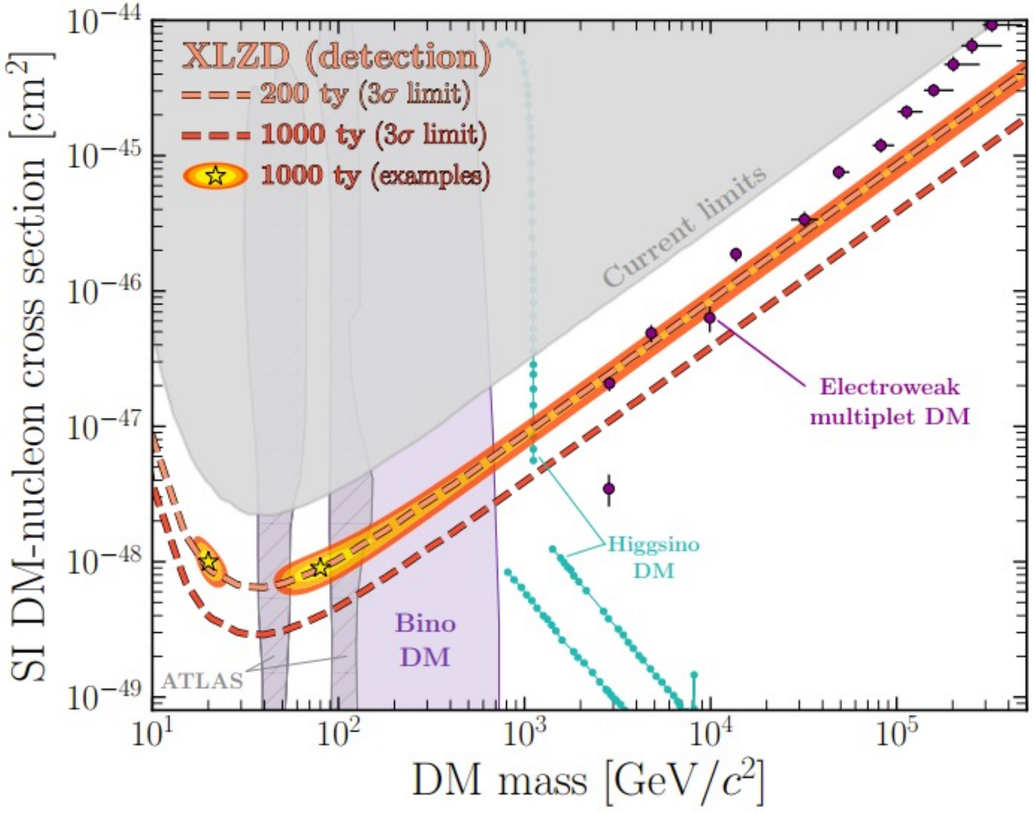




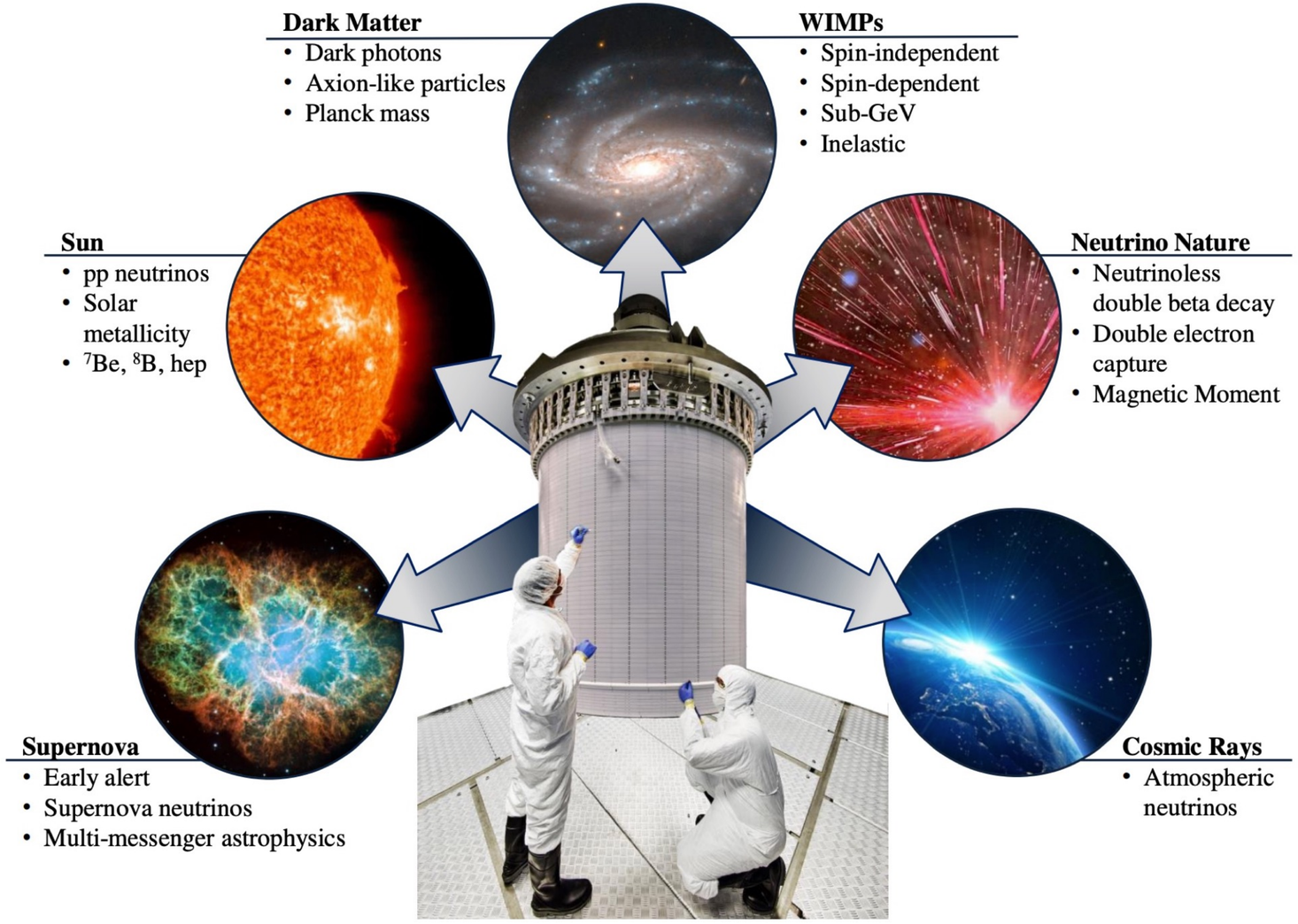


已触及“中微子雾”

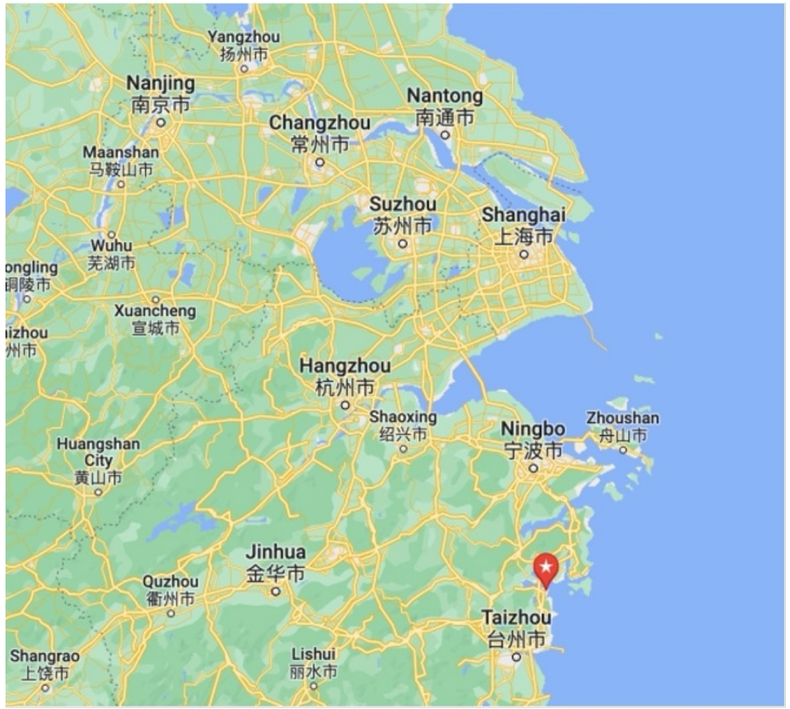
展望：建设更灵敏的暗物质探测器

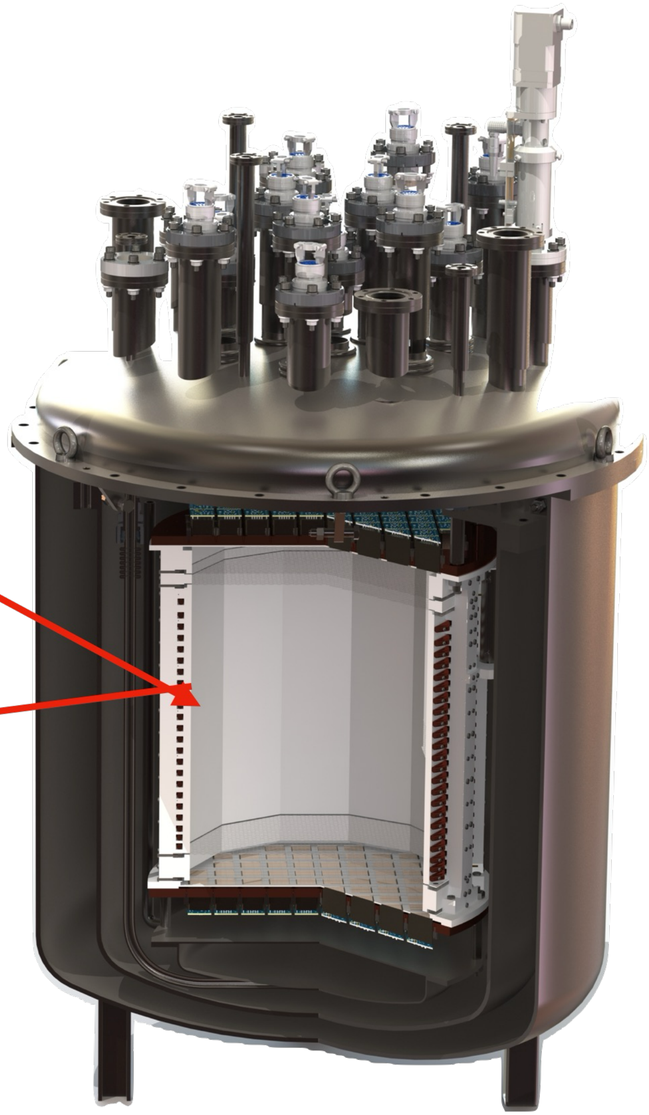


未来100吨级探测器有望测量到主流模型预言的暗物质信号



RELICS 反应堆中微子实验

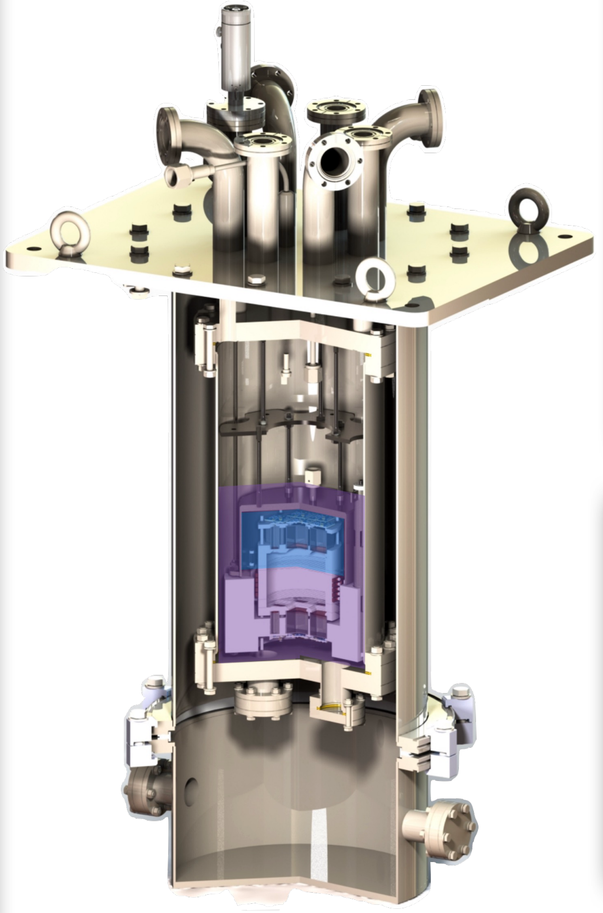


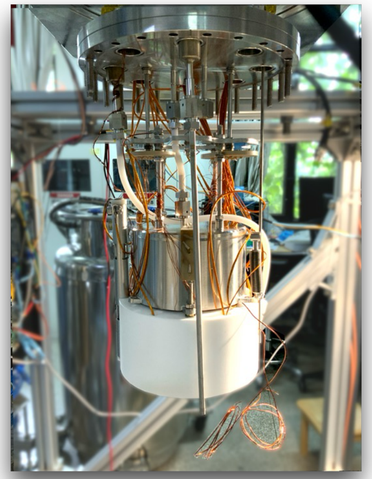


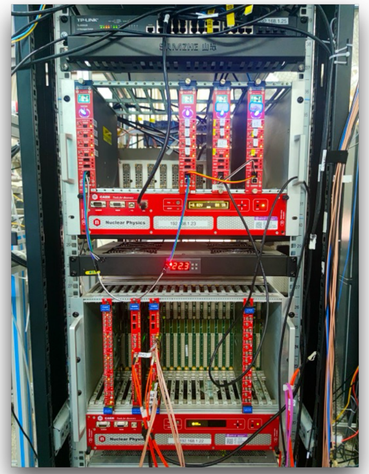
- Reactor power ~3.4GW， baseline ~25m
- Expected neutrino flux ~$10^{13}\upsilon/cm^2/s$

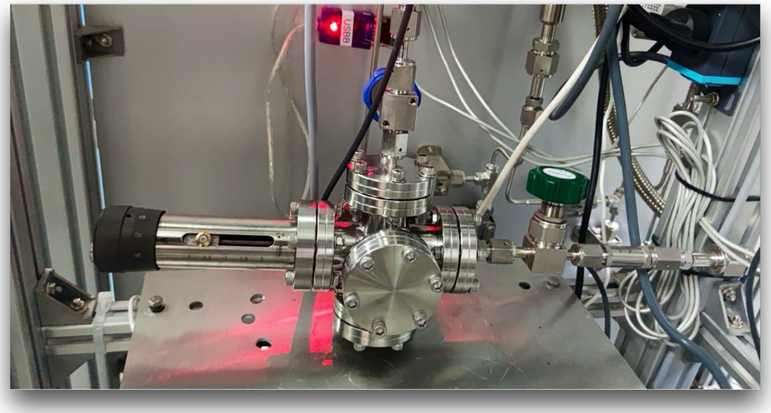
RELICS合作组

RELICS - 公斤级探测器研发进展

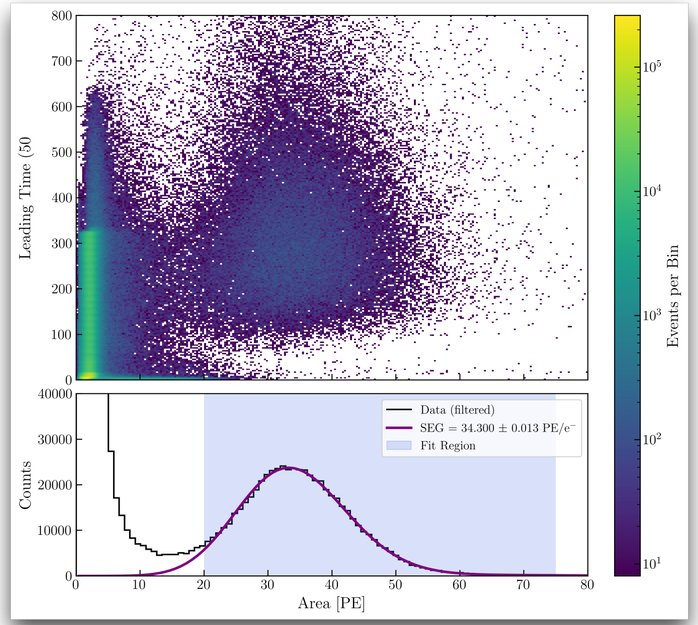


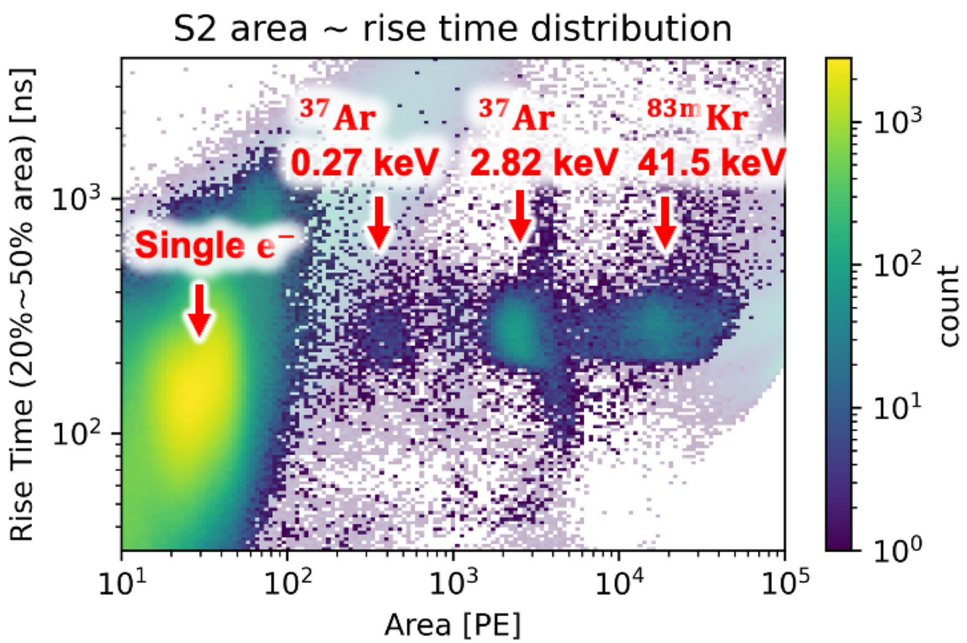


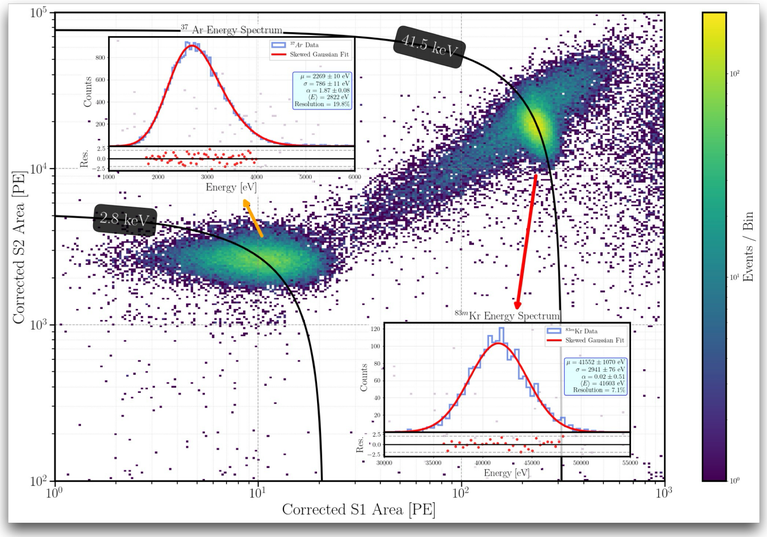


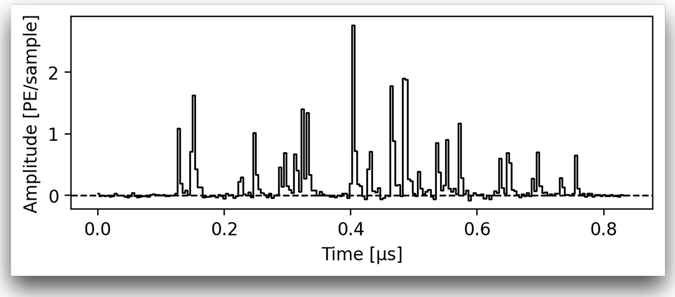


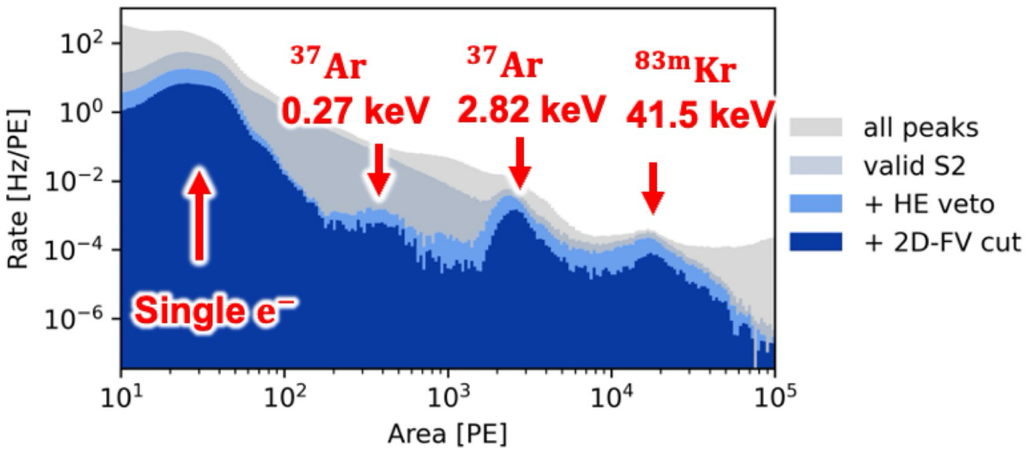
RELICS - 公斤级探测器研发进展



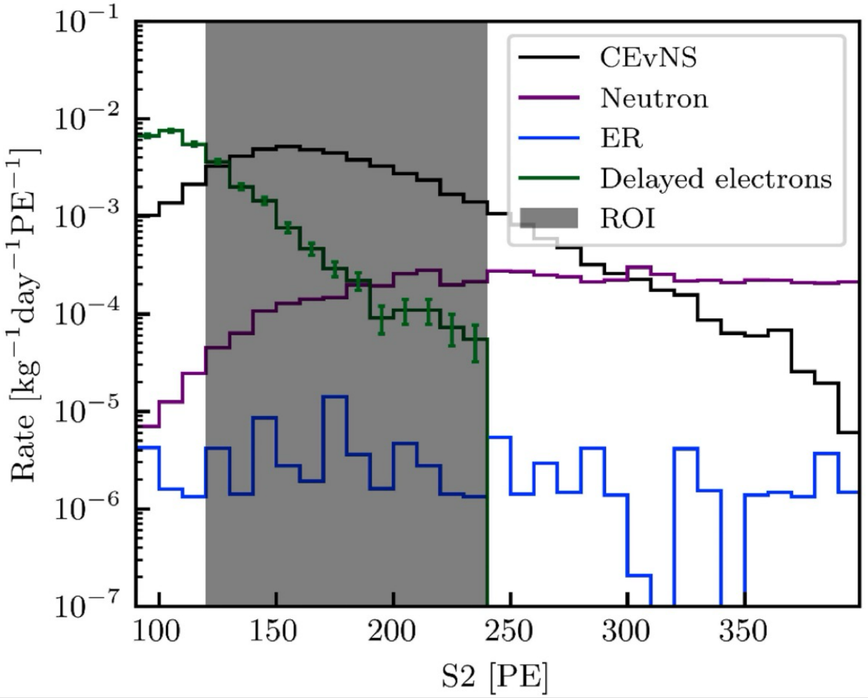




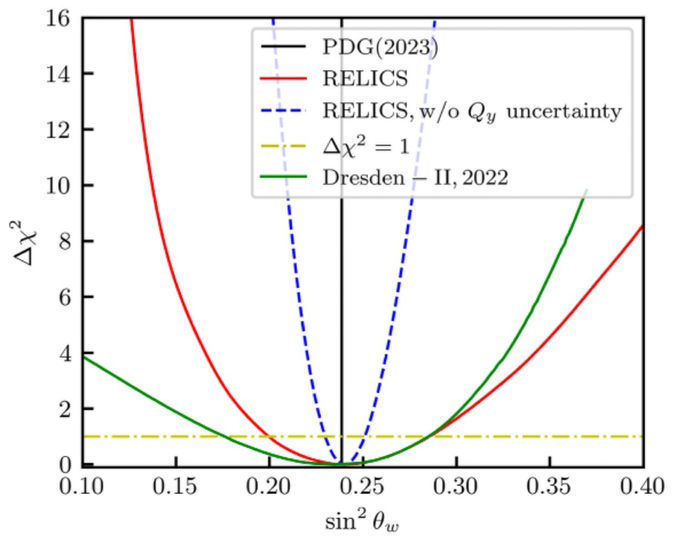




利用 RELICS 探测中微子



	Events/(32kg·year)
CEvNS	4902.4
Cosmic Ray n	229.4
μ induced n	1.5
Electronic Recoil	5.7
Pile-up DE	1429

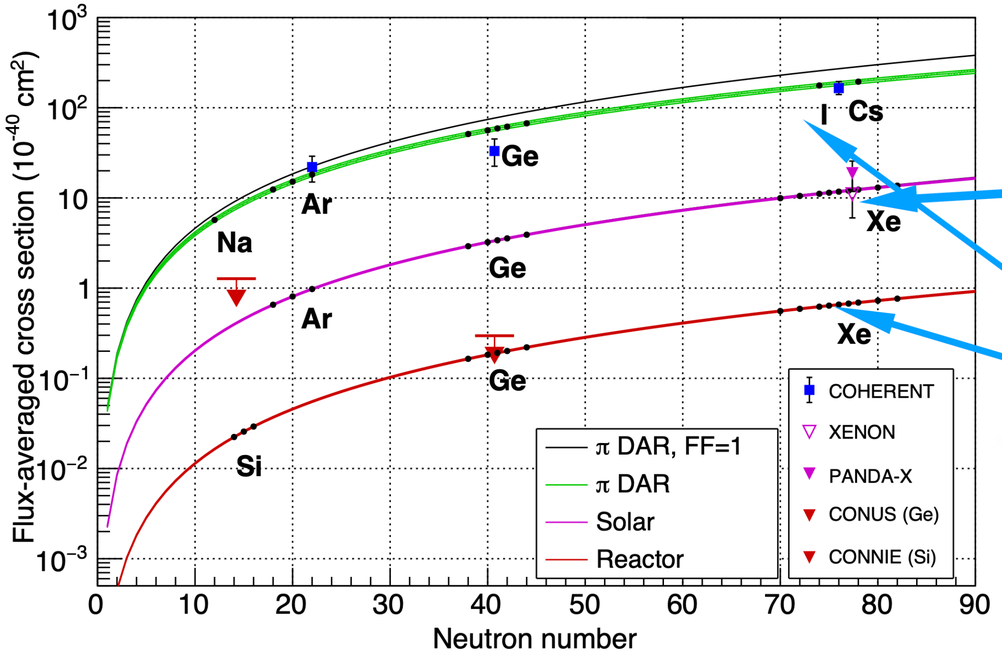


PHYSICAL REVIEW D **110,** 072011 (2024)

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,‡] Gaojun Jin,[2] Yipin Jing,[1,¶] Gaojun Ju,[2] Yang Lei,[1] Jiayi Li,[1] Kaihang Li,[1] Meng Li,[2] Minhua Li,[2] Shengchao Li,[8] Siyin Li,[8] Tao Li,[2] Qing Lin,[5,6] Jiajun Liu,[9] Minghao Liu,[1] Sheng Lv,[2] Guang Luo,[9] Jian Ma,[1] Chuanping Shen,[2] Mingzhuo Song,[1] Lijun Tong,[5,6] Xiaoyu Wang,[8] Wei Wang,[3,9] Xiaoping Wang,[4,10] Zihu Wang,[2] Yuehuan Wei,[3,†] Liming Weng,[2] Xiang Xiao,[9] Lingfeng Xie,[1] Dacheng Xu,[1,§] Jijun Yang,[8] Litao Yang,[11] Long Yang,[2] Jingqiang Ye,[7] Jiachen Yu,[5,6] Qian Yue,[11] Yuyong Yue,[3] Bingwei Zhang,[2] Shuhao Zhang,[1] Yifei Zhao,[1] and Chenhui Zhu[6]

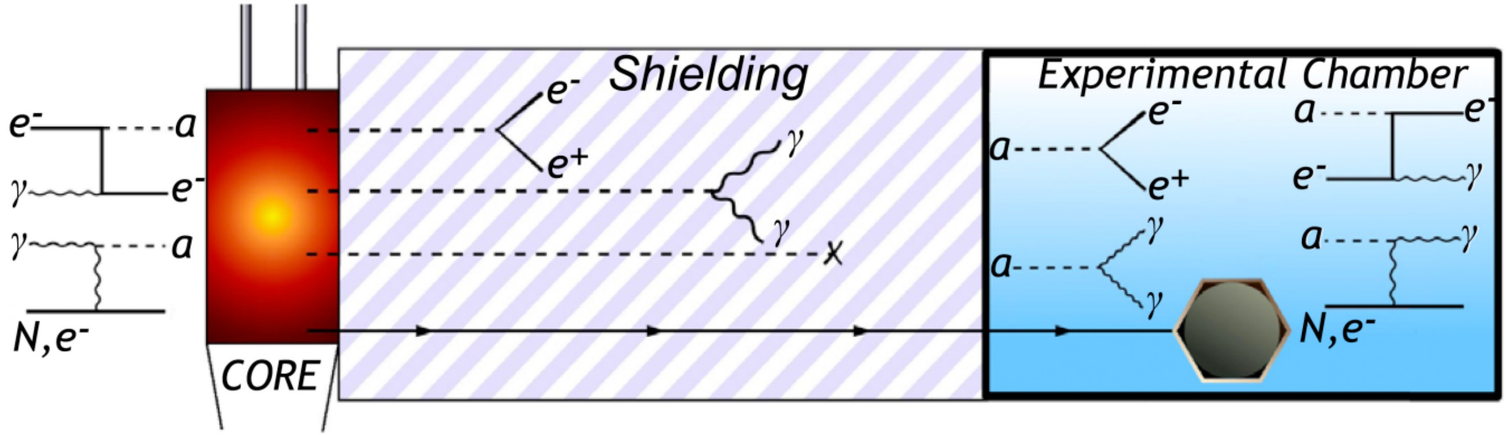
(RELICS Collaboration)



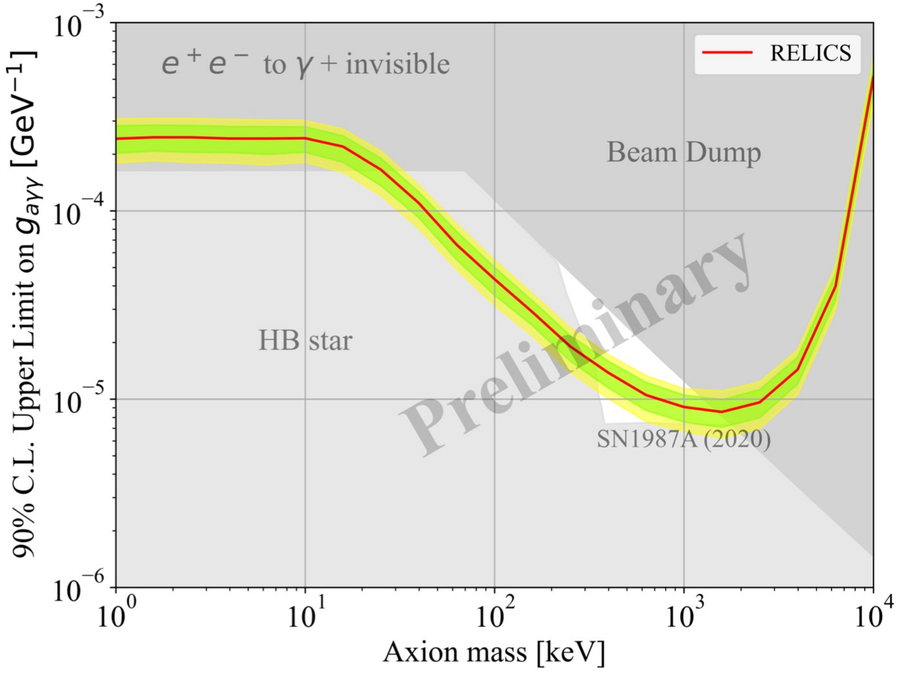
XENON

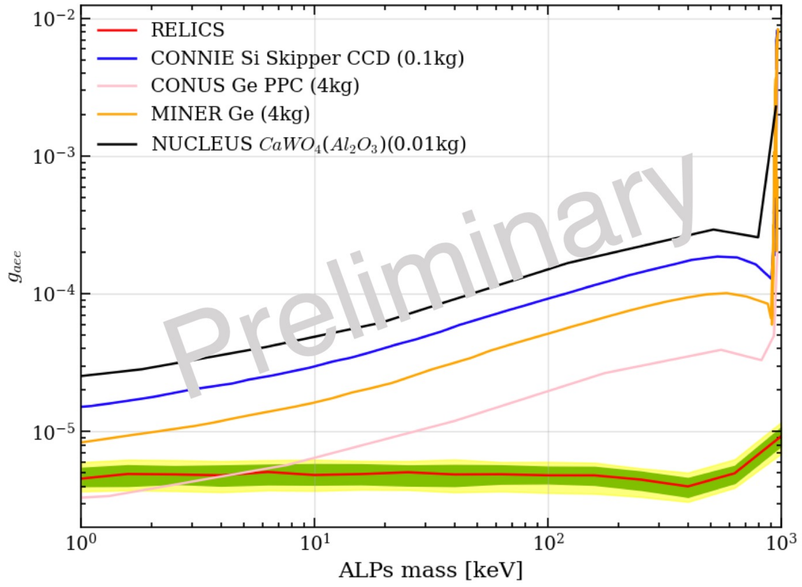
RELICS

利用 RELICS 探测轴子

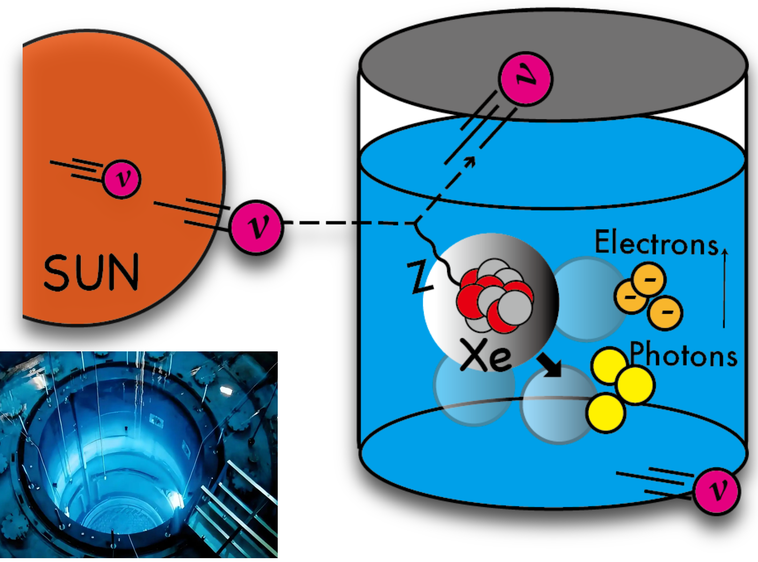


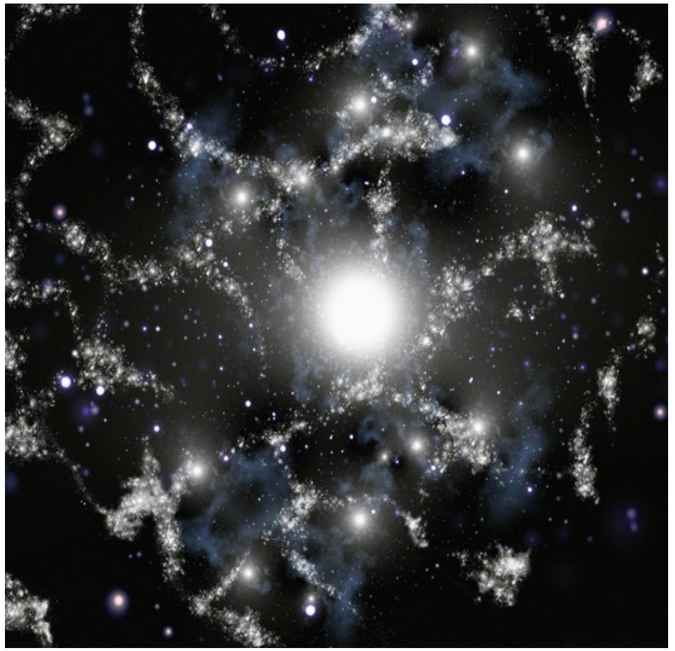
Dent et al., PRL 124, 211804 (2020)

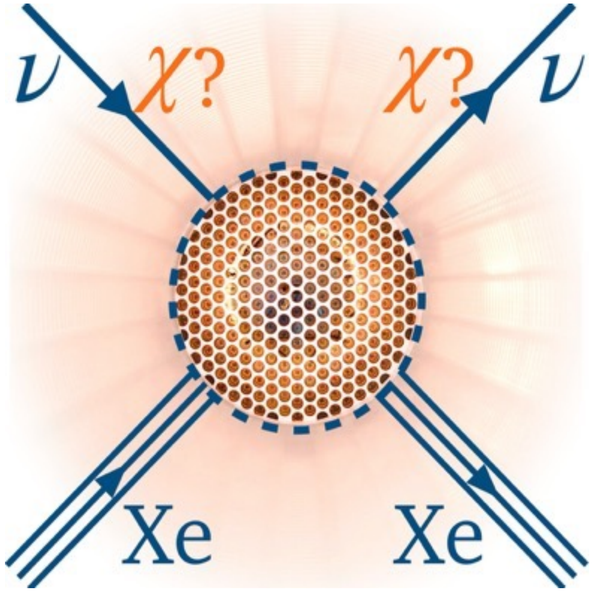


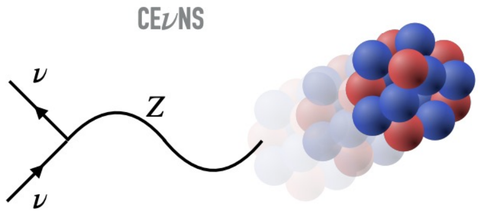


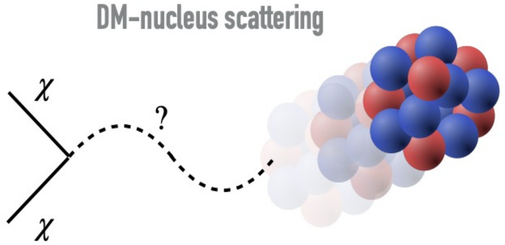
总结


SUN
Electrons
Photons
Xe




Xe
Xe

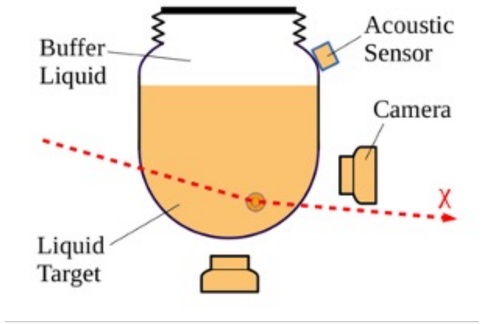

CEνNS
Z

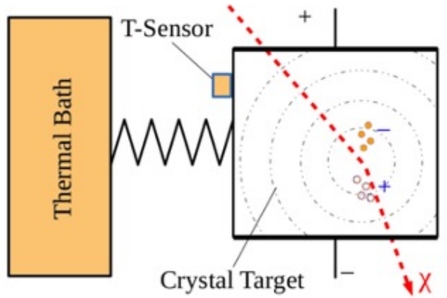

DM-nucleus scattering

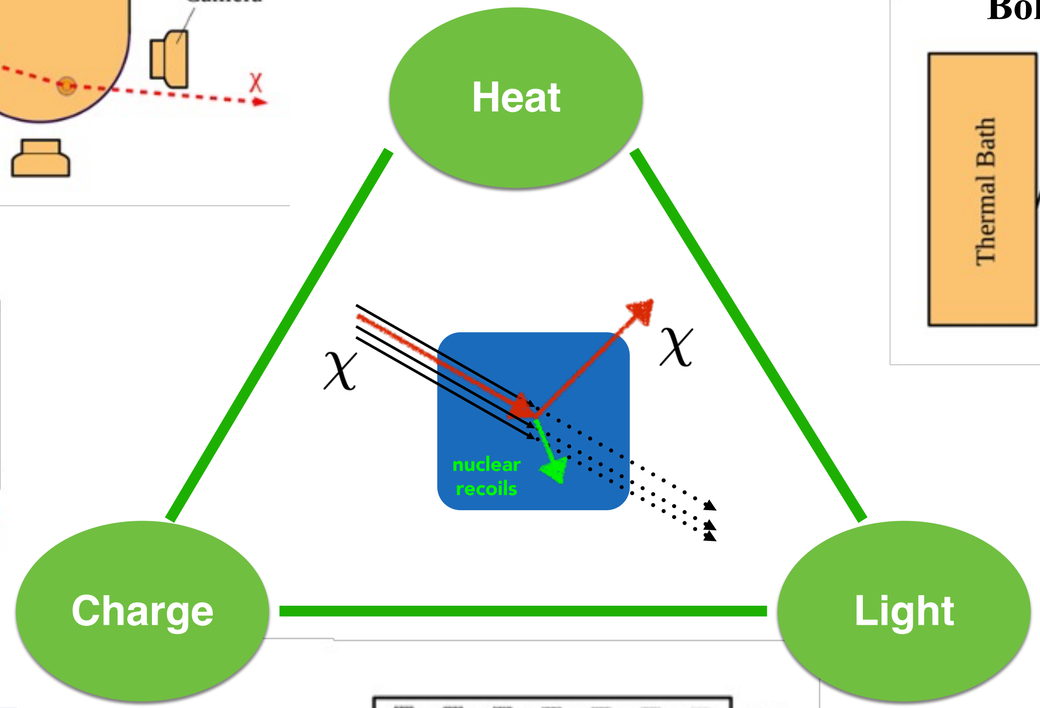
谢谢！


暗物质探测器原理

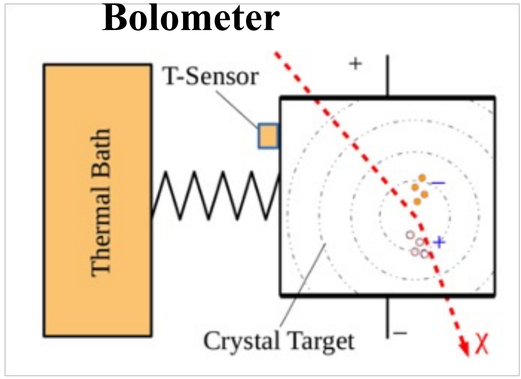
Bubble Chamber

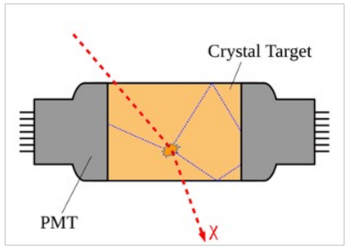




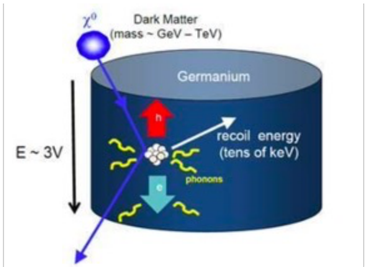


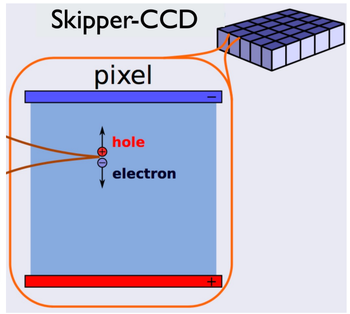
Bolometer

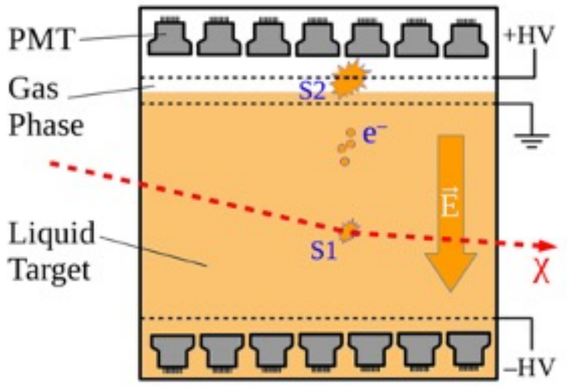




Point Contact Ge







Scintillator