

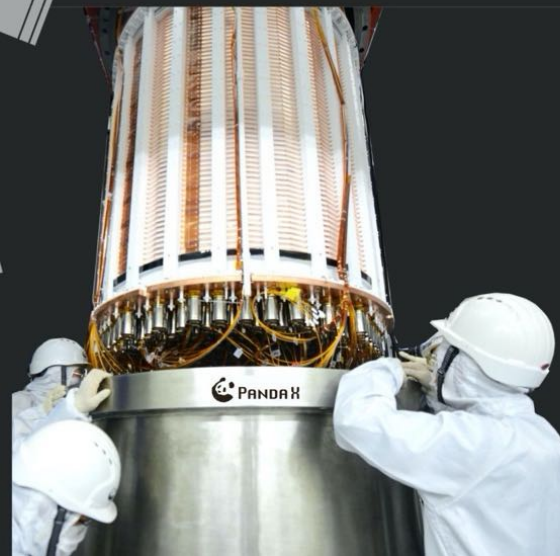
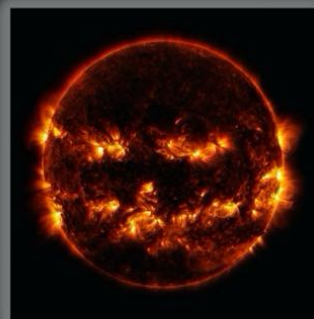
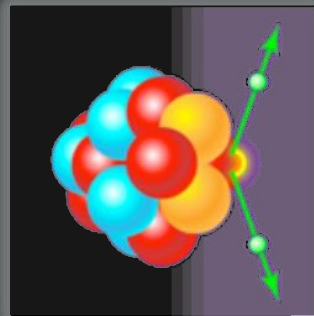
PandaX实验介绍

— 探索宇宙中的神秘物质

周宁

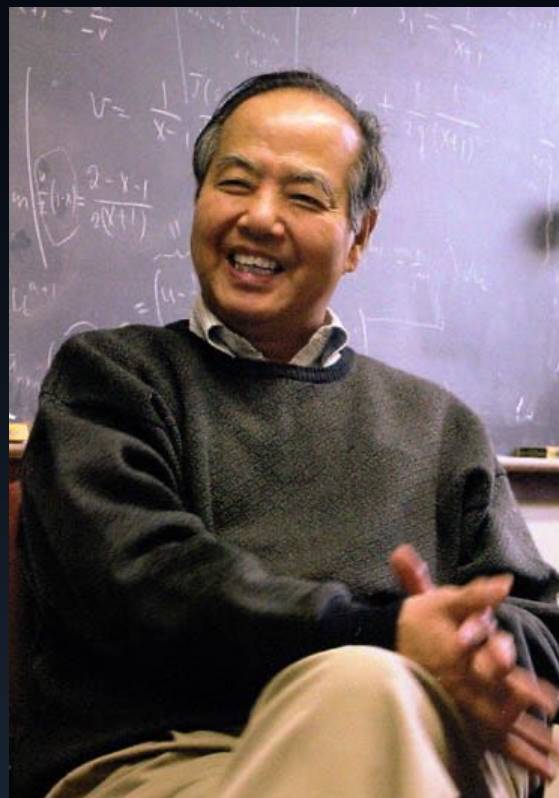
上海交通大学

南山清北暑期学校 2026/07/18



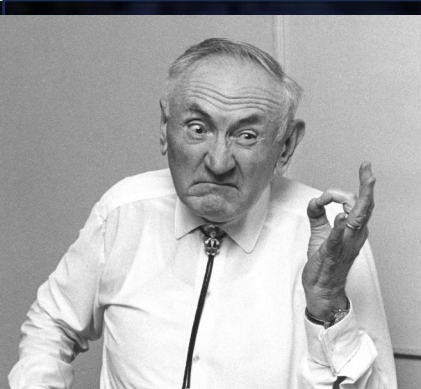
暗物质是笼罩20世纪末
和21世纪初现代物理学的最大
乌云，它将预示着物理学的
又一次革命。

—— 李政道



关于李政道先生引言的参考文献：

秦波，精确宇宙学时代的暗物质问题，《现代物理知识》2007 Vol19 (5):17-24



Fritz Zwicky
1933



James Peebles
2019

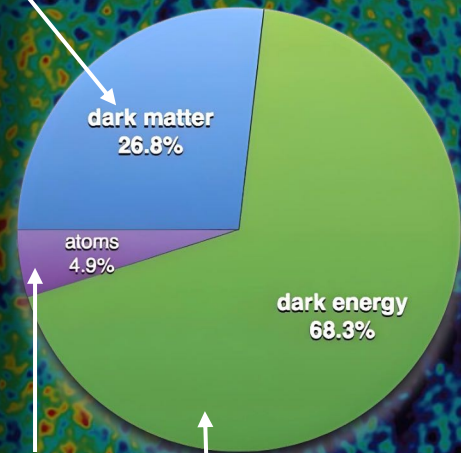


暗物质占比: 26.8%

暗物质之谜

暗物质的本质是什么?

和普通物质发生怎样的相互作用?



可见物质占比: 4.9%

暗能量占比: 68.3%

星系中的“雾霾”

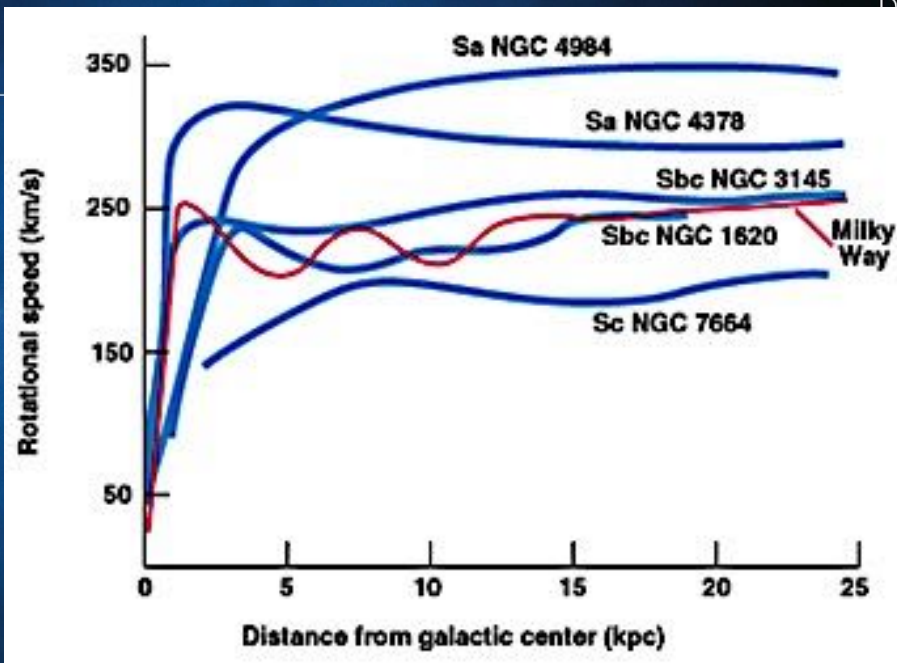
Extent of Survey
around the Sun

Dark Matter Halo

Milky Way

星系中的“雾霾”

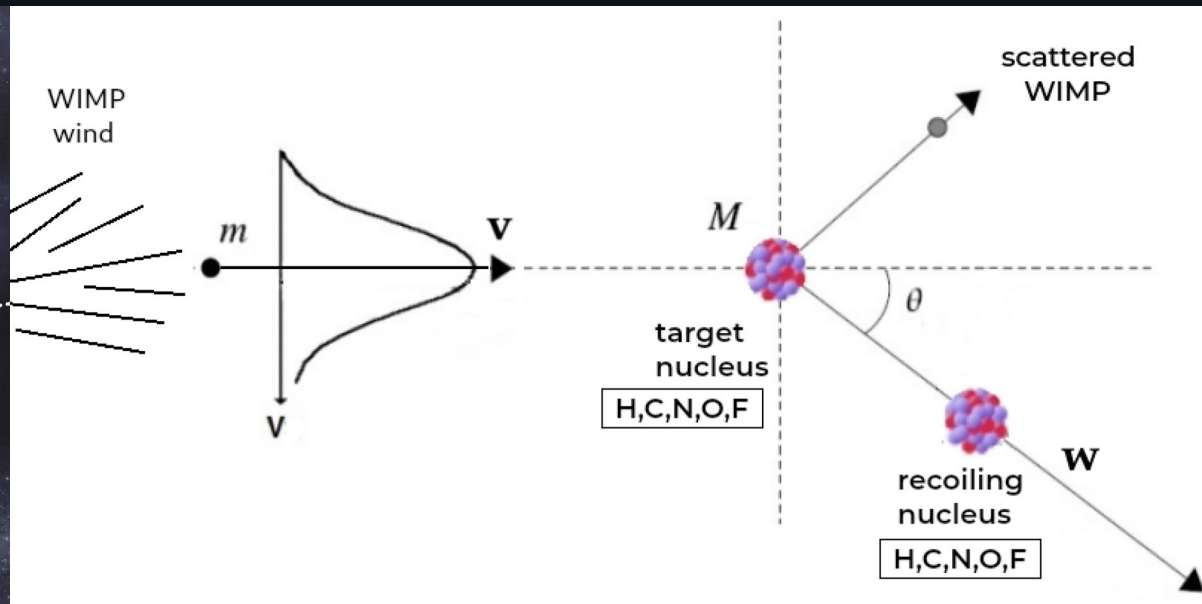
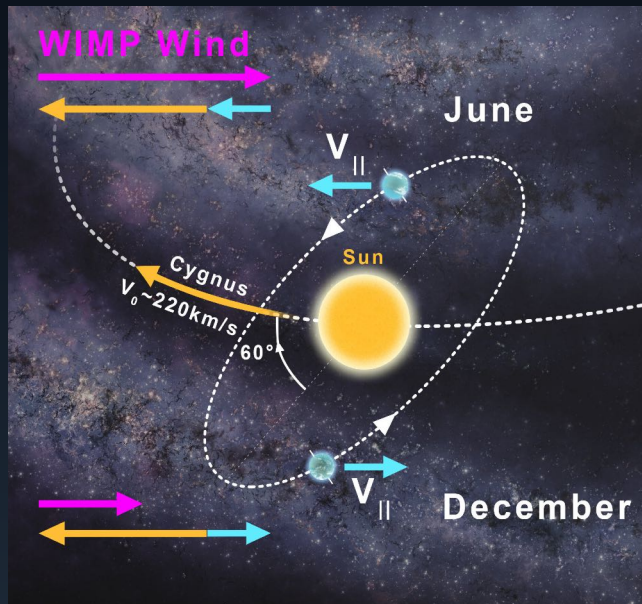
Extent of Survey
around the Sun



- 太阳系附近
- 每立方厘米有1/3质子重量的暗物质

暗物质直接探测

- 测量暗物质和**靶物质碰撞**后原子核**反冲**的信号
 - 1985年提出，40年以来探测灵敏度推进7个数量级



直接探测的挑战

of Survey
the Sun

信号弱

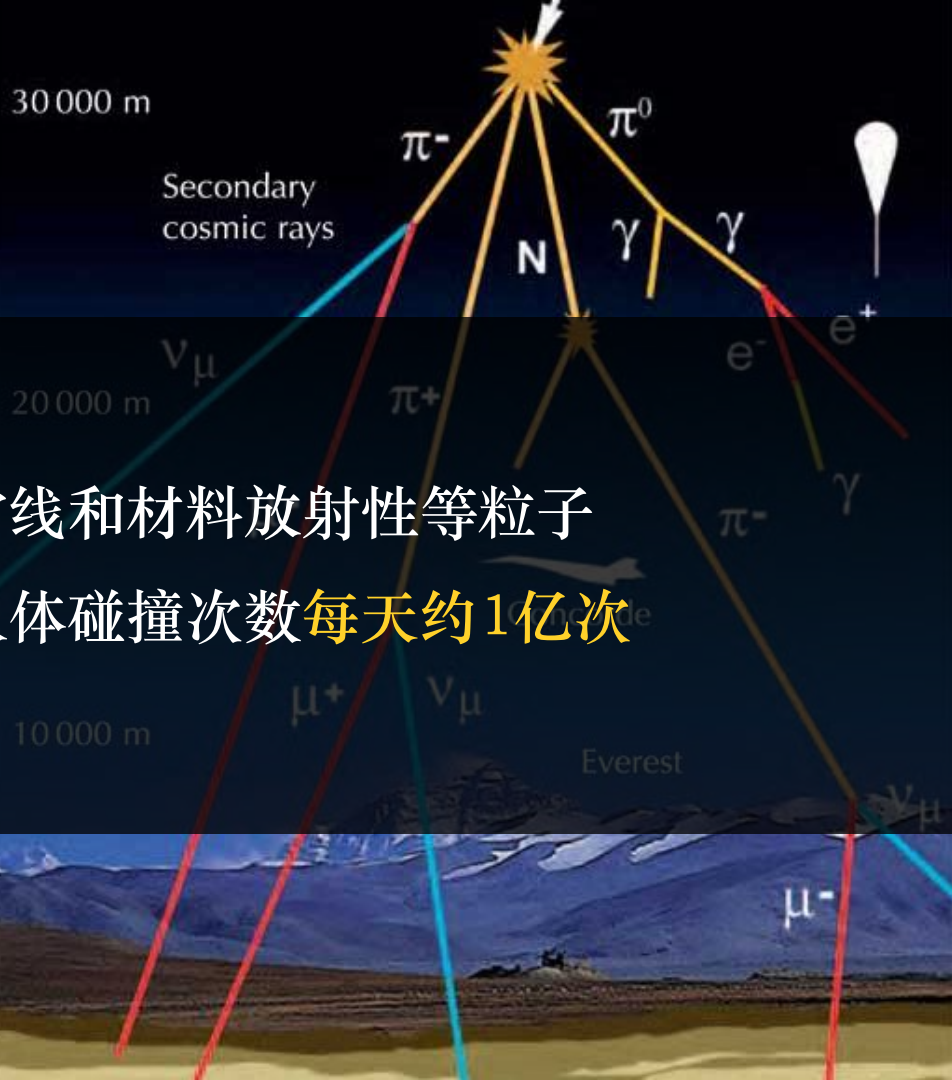
- 每秒有1亿个暗物质粒子穿过
- 每个人身上有 10^{29} 个靶原子
- 可是每年暗物质和每个人碰撞次数 < 1 次！

Milky Way

直接探测的挑战

噪声高

- 宇宙线和材料放射性等粒子
- 和人体碰撞次数每天约1亿次



世界各国在深地实验室开展研究

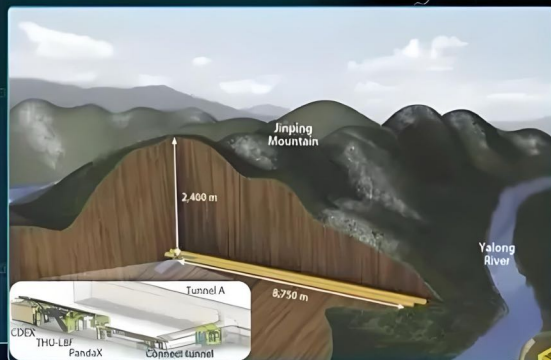




2008年8月8日，连接两座世界级水电站——锦屏一级水电站、锦屏二级水电站的锦屏山隧道贯通。隧道长达17.5公里，最大埋深2525米，垂直岩石覆盖2400米，是国际上岩石覆盖最厚的地下隧道。

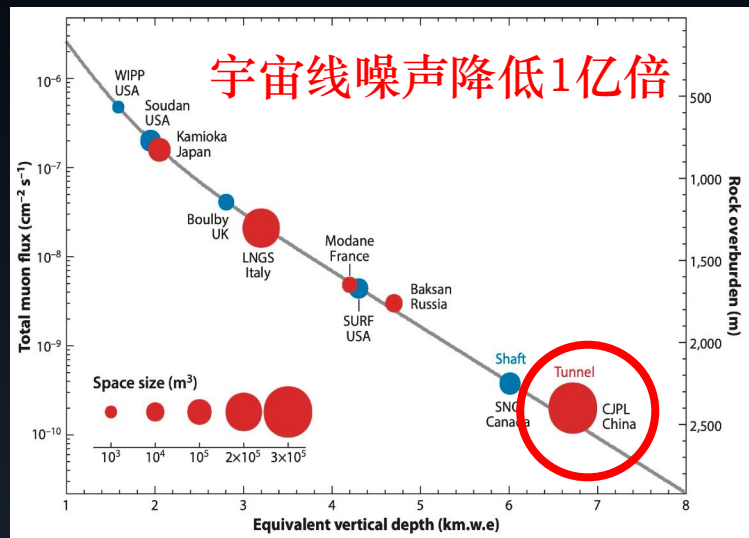
四川省凉山州

中国锦屏地下实验室

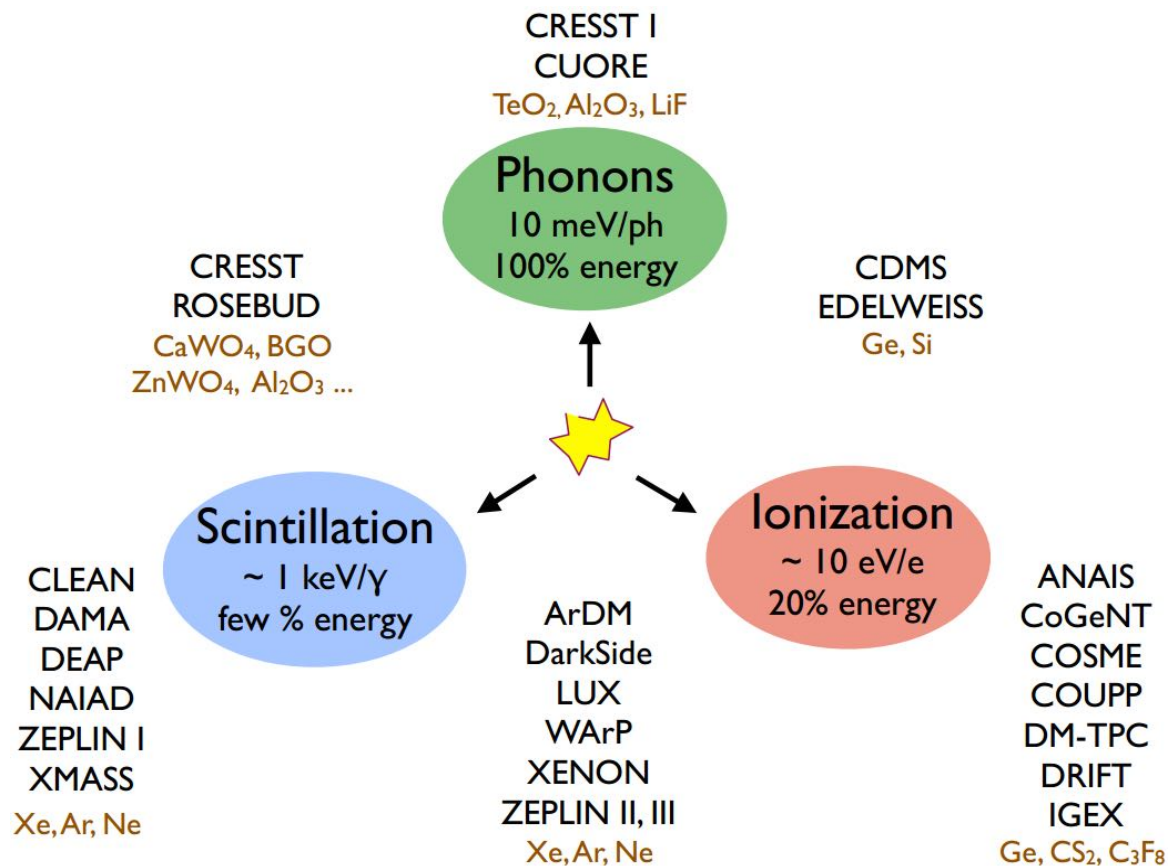




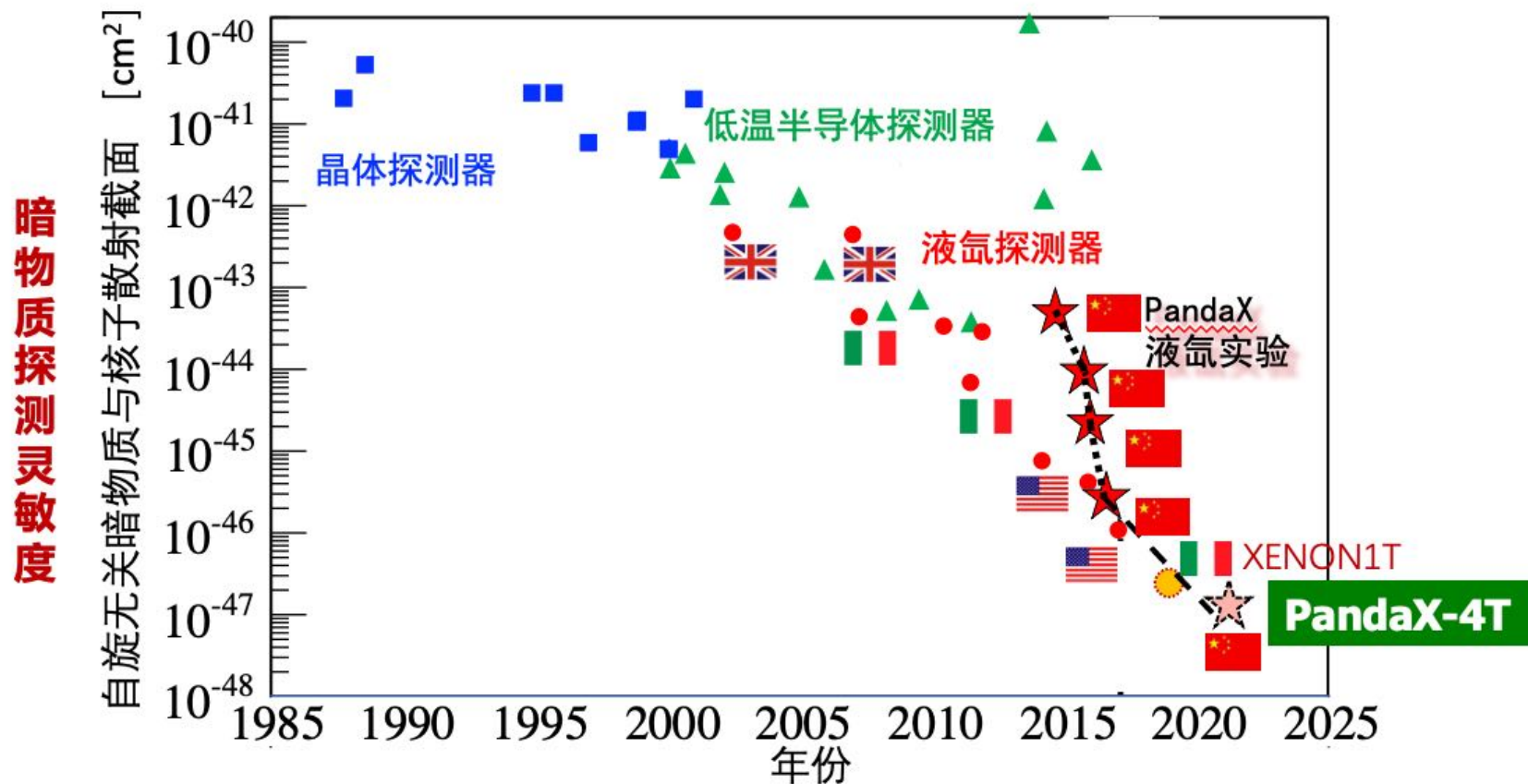
- 世界最深（2400米岩石覆盖）
- 空间容积最大（33万立方米）
- 水平隧道进出，有利大型实验设施
- 四季恒温、冬暖夏凉



Detection Strategy



Direct Detection





Particle and Astrophysical Xenon TPC

粒子和天体物理氙探测器

氙：暗物质探测最优材料之一

- 惰性元素，**敏感度高**
- 原子序数大，**反应概率高**
- 具有优异的**光电特性**
- 液氙密度大，**屏蔽噪声效果好**
- 液态靶，**探测体量易于扩大**
- 氙**三相点高**（173K），容易液化



54
Xe
Xenon
131.293

计算暗物质信号特征



- **暗物质假设**

- 暗物质质量 100GeV
- 暗物质和氦核散射截面 $1\text{E-}38\text{ cm}^2$
- 暗物质相对速度 200km/s
- 地球附近暗物质密度 0.3 GeV/cm^3

- **请估算暗物质和原子核散射产生的核反冲能量**

暗物质和原子核散射



- 暗物质粒子和靶原子核发生弹性散射

- 原子核获得的反冲能量 $E_R = \frac{4m_\chi m_N}{(m_\chi + m_N)^2} E_\chi^{kin}$

- $E_\chi^{kin} \sim \frac{1}{2} m_\chi v^2 \sim 50 \text{ keV} \frac{m_\chi}{100 \text{ GeV}}$

- 单位质量靶物质和暗物质散射的事例率

- $\frac{dR}{dE_R} \propto \sigma_N \frac{\rho_{DM}}{m_{DM}} \int_{v_{min}}^{v_{esc}} \frac{dv}{v} f(v)$

- 核自旋无关散射 $\sigma_N^{SI}(E_R) \propto A^2 F^2(E_R) \sigma_n$

- 核自旋相关散射 $\sigma_N^{SD}(E_R) \propto \frac{1}{2J+1} S(E_R) \sigma_n$

需要极低的探测阈值

需要大质量数靶核

需要有自旋靶核

Dark Matter Signals



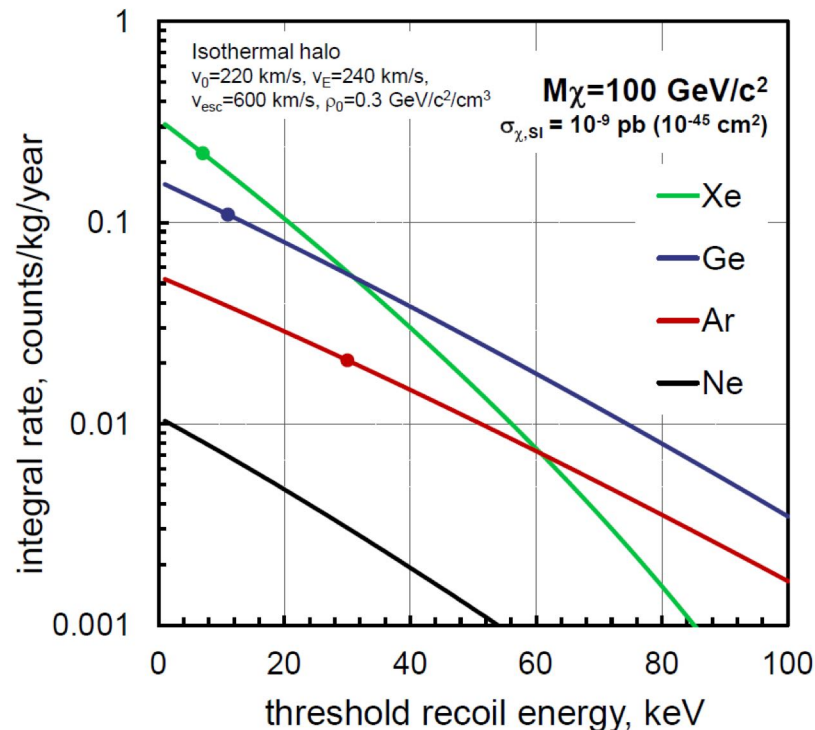
- **Scattering cross section on nuclei**

- Spin-independent, $\propto A^2$, Form factor
- Spin-dependent, spin structure factor

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} \frac{d\sigma_{\chi N}}{dE_R}(v, E_R) v f(v) dv$$

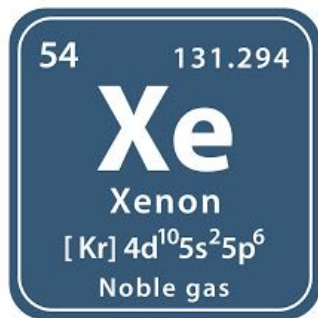
$$\frac{d\sigma_{\chi N}}{dE_R} = \frac{m_N}{2\mu_N^2 v^2} (\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R))$$

Recoil energy spectrum



氙: xenon

- 惰性气体
- 空气中0.0087%
- 无色无味
- 密度(液):3g/ml
- 沸点: -100°C
- 全世界年产量: 60吨



元素周期表

周期	I A	II A	III A	IV A	V A	VI A	VII A	0	18	电子层	0 族									
1	1 H 氢 1.008	2 He 氦 4.003								1s	K									
2	3 Li 锂 6.941	4 Be 铍 9.012								2s	L									
3	11 Na 钠 22.99	12 Mg 镁 24.31								3s	M									
	19 K 钾 39.098	20 Ca 钙 40.078	21 Sc 钪 44.956	22 Ti 钛 47.867	23 V 钒 50.942	24 Cr 铬 51.996	25 Mn 锰 54.938	26 Fe 铁 55.845	27 Co 钴 58.933	28 Ni 镍 58.693	29 Cu 铜 63.546	30 Zn 锌 65.38	31 Ga 镓 69.723	32 Ge 锗 72.64	33 As 砷 74.922	34 Se 硒 78.96	35 Br 溴 79.904	36 Kr 氪 83.80	8	N
	37 Rb 铷 85.468	38 Sr 锶 87.62	39 Y 钇 88.906	40 Zr 锆 91.224	41 Nb 铌 92.906	42 Mo 钼 95.94	43 Tc 锝 98	44 Ru 钌 101.07	45 Rh 铑 102.91	46 Pd 钯 106.36	47 Ag 银 107.868	48 Cd 镉 112.411	49 In 铟 114.818	50 Sn 锡 118.710	51 Sb 锑 121.757	52 Te 碲 127.6	53 I 碘 126.905	54 Xe 氙 131.29	8	N
	55 Cs 铯 132.905	56 Ba 钡 137.327	57 La 镧 138.905	58 Ce 铈 140.12	59 Pr 镨 140.908	60 Nd 钕 144.242	61 Pm 钷 145	62 Sm 钐 150.36	63 Eu 铕 151.964	64 Gd 钆 157.25	65 Tb 铽 158.925	66 Dy 镝 162.50	67 Ho 钬 164.930	68 Er 铒 167.259	69 Tm 铥 168.930	70 Yb 镱 173.054	71 Lu 镥 174.967	8	N	
	87 Fr 钫 223	88 Ra 镭 226	89 Ac 锕 227	90 Th 钍 232.037	91 Pa 镤 231.036	92 U 铀 238.029	93 Np 镎 237	94 Pu 钚 244	95 Am 镅 243	96 Cm 锔 247	97 Bk 锫 247	98 Cf 锿 251	99 Es 镅 252	100 Fm 镆 257	101 Md 镎 258	102 No 镎 259	103 Lr 镎 262	8	N	

原子序数 元素名称 注*的是人造元素

元素符号, 红色指放射性元素

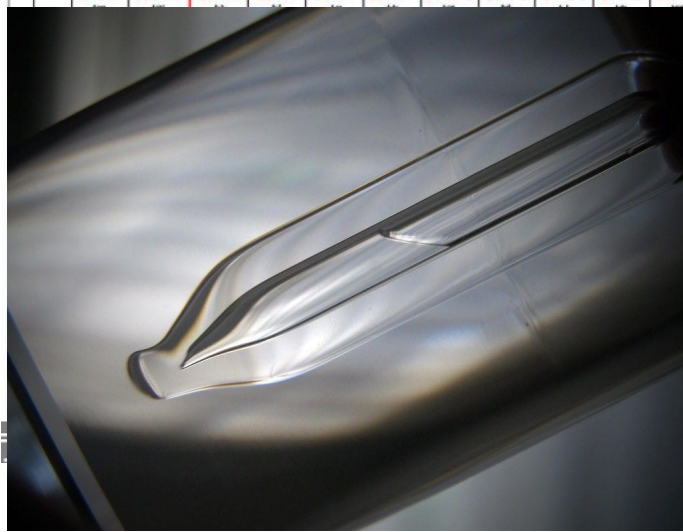
非金属 金属

过渡元素

外围电子层排布, 括号指可能的电子层排布

相对原子质量(加括号的数据为该放射性元素半衰期最长同位素的质量数)

注: 相对原子质量来自2001年国际原子量表, 并全部取4位有效数字。



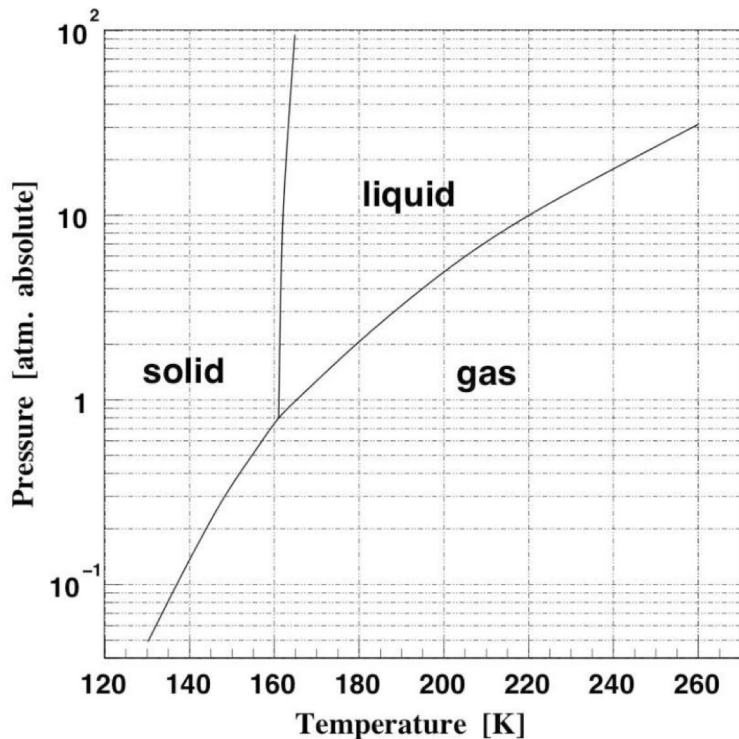
液氙性质



- 大气中含量低 - 成本相对其他惰性气体高
- 高沸点 - 易于液化

性质	氦 (He)	氖 (Ne)	氩 (Ar)	氙 (Kr)	氙 (Xe)	氙 (Rn)
原子序数 (Z)	2	10	18	36	54	86
平均摩尔质量	4.0	20.2	39.9	83.8	131.3	222
熔点 (T_m , 标准大气压)	-	24.5 K	83.4 K	115.6 K	161.4 K	202 K
沸点 (T_b , 标准大气压)	4.2 K	27.2 K	87.2 K	121.2 K	165.2 K	211.3 K
三相点温度 (T_t)	2.2 K	24. 6 K	83.8 K	115.8 K	161.3 K	202 K
三相点压强 (P_t)	0.05 atm	0.43 atm	0.68 atm	0.72 atm	0.78 atm	0.69 atm
气体密度 (标况)	0.18	0.90	1.78	3.71	5.85	9.97
液体密度, g/cm^3	1.25	1.21	1.39	2.42	3.06	4.40
附体密度, g/cm^3	-	1.44	1.62	2.83	3.54	-
相对介电常数 ϵ_r	1.06	1.53	1.50	1.66	1.95	-
大气中丰度 (ppm, 体积)	5.2	18.2	9340	1.1	0.09	-
市场价格, 美元/立方米	22.3-44.9	2.7-8.5	60-120	400-500	4000-5000	-

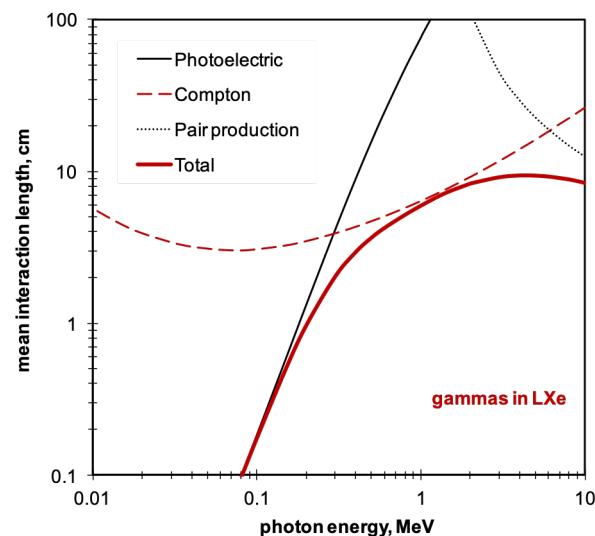
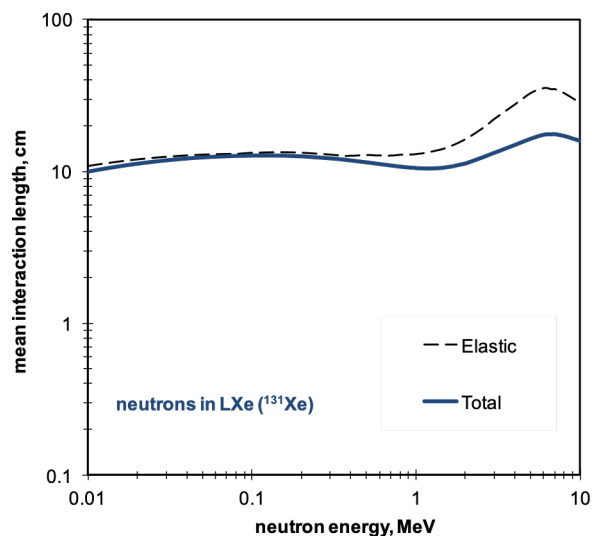
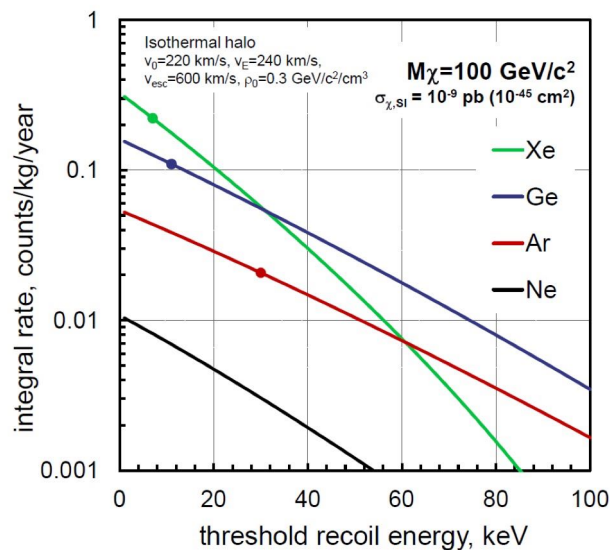
气体密度是指 0 °C, 标准大气压的条件下



液氙性质



- 大原子序数，较高密度，高事例率
- 自屏蔽效应



液氙性质



- 不同自旋稳定同位素

- Xe-129: 1/2

- Xe-131: 3/2

氙 (Xenon)	^{124}Xe (0.09%), ^{126}Xe (0.09%), ^{128}Xe (1.92%) ^{129}Xe (26.44%), ^{130}Xe (4.08%), ^{131}Xe (21.18%) ^{132}Xe (26.89%), ^{134}Xe (10.44%), ^{136}Xe (8.87%)
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- 既能探测自旋无关暗物质散射，又能探测自旋相关

氙光和电的效应



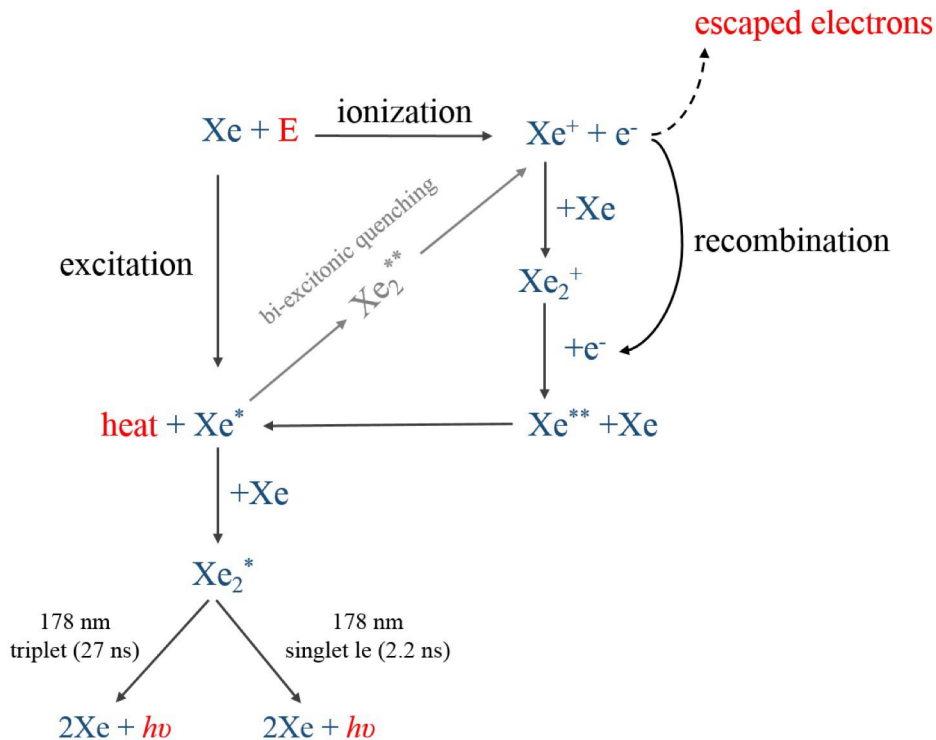
• 液氙中能量沉积

- 暗物质信号, 中子, X射线

• 受激发原子, 电子 - 离子对

- 178nm 真空紫外光
- 电离电子

$$E_{dep} = W \times (N_i + N_{ex})$$



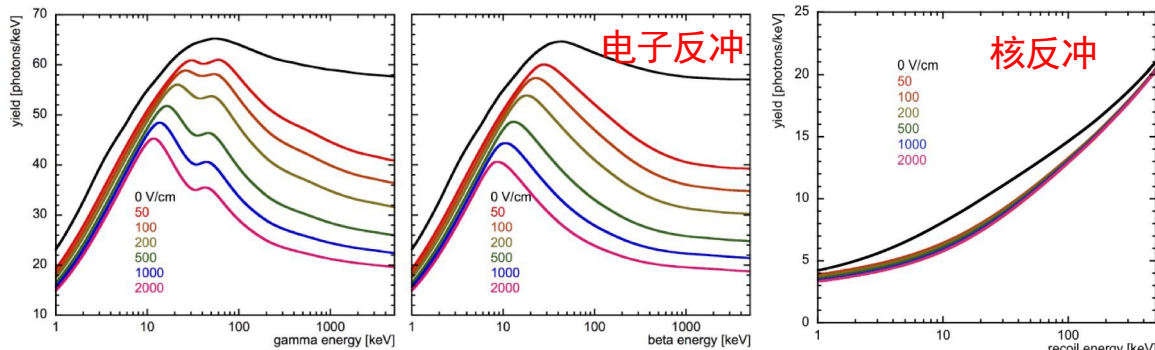
氙光和电的效应



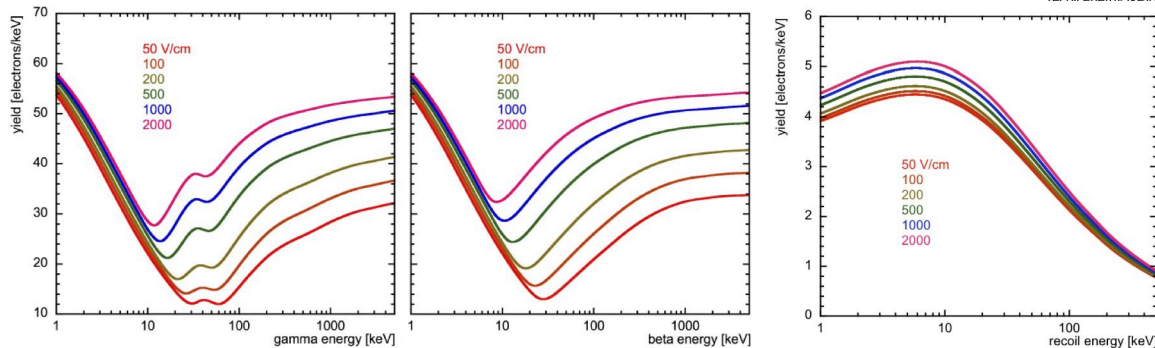
- 闪烁光和电离电子产额 (NEST模拟)

- 核反冲和电子反冲不同的相对产额

闪烁光信号



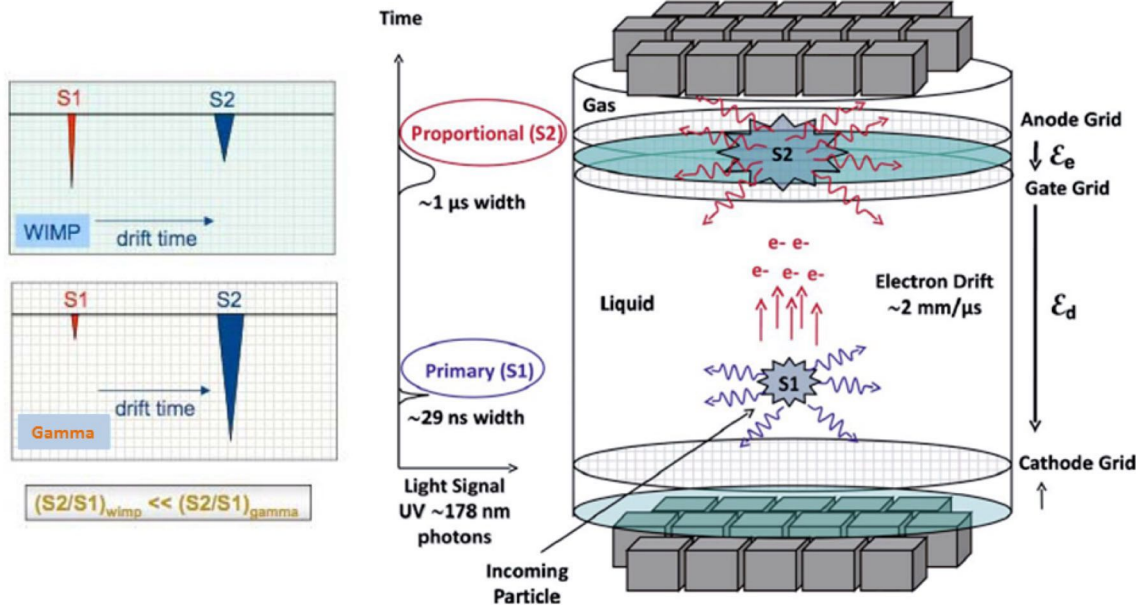
电离电子信号



光电信号探测



- 光信号：光探测装置
- 电信号：外加电场
 - 抑制电子离子重结合
 - 电子在外场中漂移
- 完整采集反冲能量
- 提供散射位置信息
- 提供信号背景鉴别
- 由于电荷传感器噪音，很难直接读取电离电子



光电信号探测

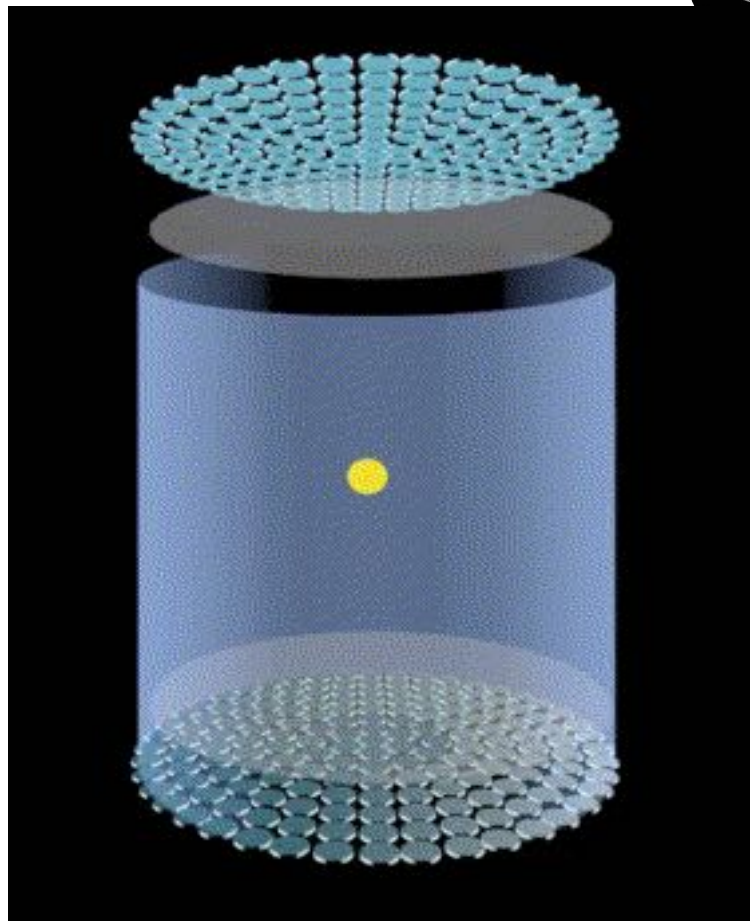
- 电子漂移到气氙区（更高电场）
- 通过非弹性散射引起惰性气体原子激发，进而退激发释放闪烁光

- 放大电场 - 正比闪烁光

$\alpha = 70 \text{ photon/kV}$
 $\beta = 1 \text{ kV / cm / atm}$

$$\frac{dN_{\text{ph}}}{dx} = \alpha \left(\frac{E_g}{p} - \beta \right) p$$

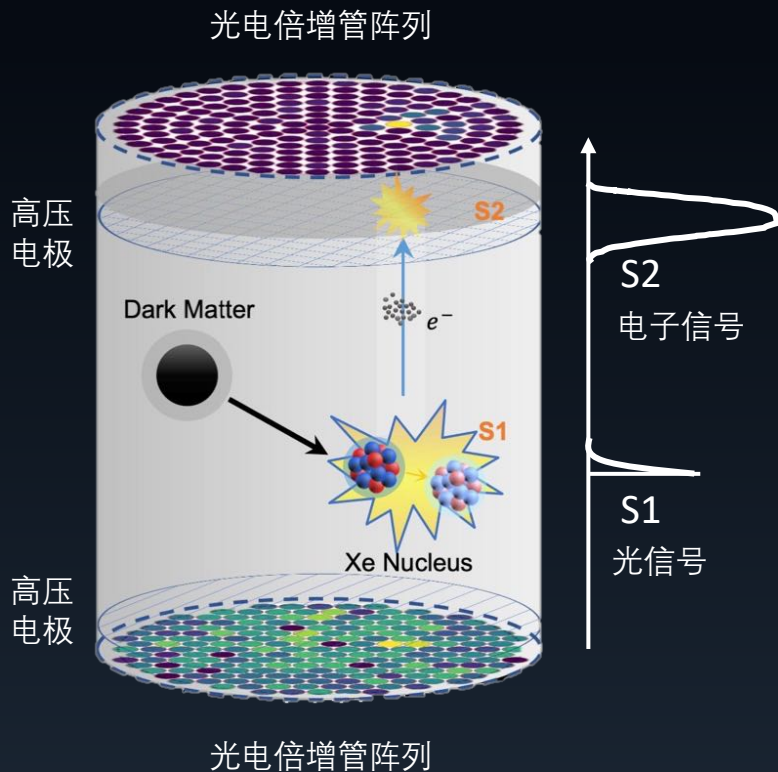
- 放大电离电子信号



PandaX 双相氙探测器



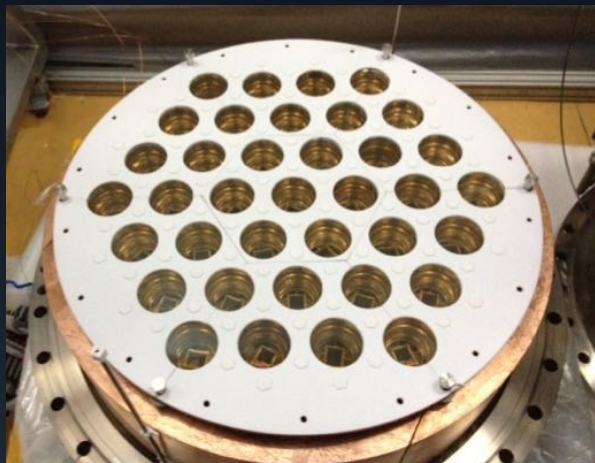
气液两相氙时间投影室探测技术

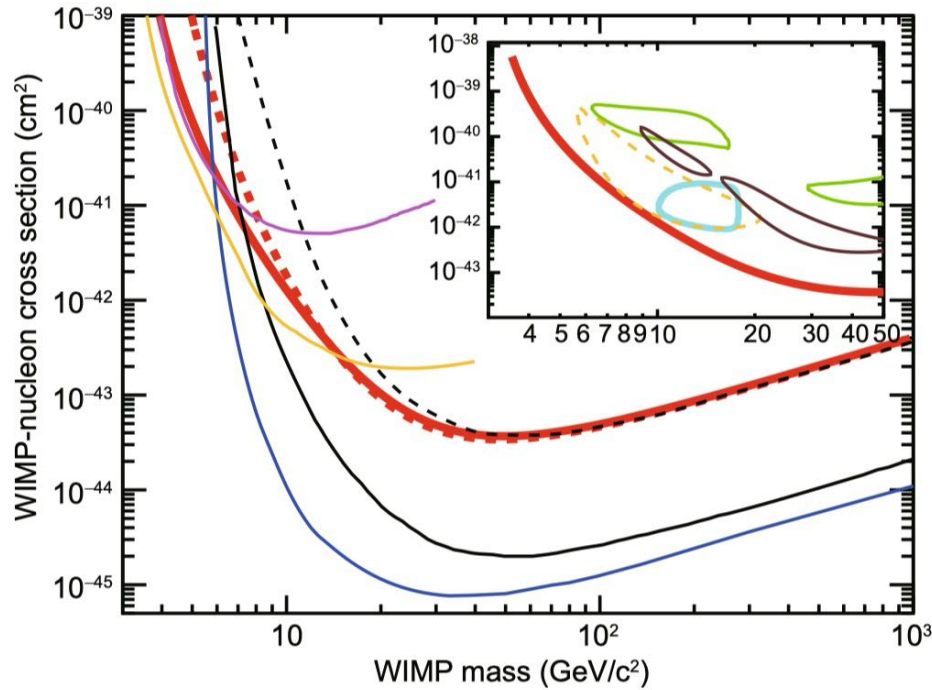


- 高精度重建信号3维位置 (亚厘米级)
- 高灵敏探测极小信号能量 (keV阈值)
- 高效率甄别暗物质信号和探测器噪声
(99.5%的噪声抑制)

2009-2014： PandaX首期实验

- 用了5年时间，建成了第一个
120公斤的液氙“蛋糕”





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f t y in

Researchers will quadruple the amount of liquid xenon in the PandaX detector just by making it taller and pouring in more liquid.

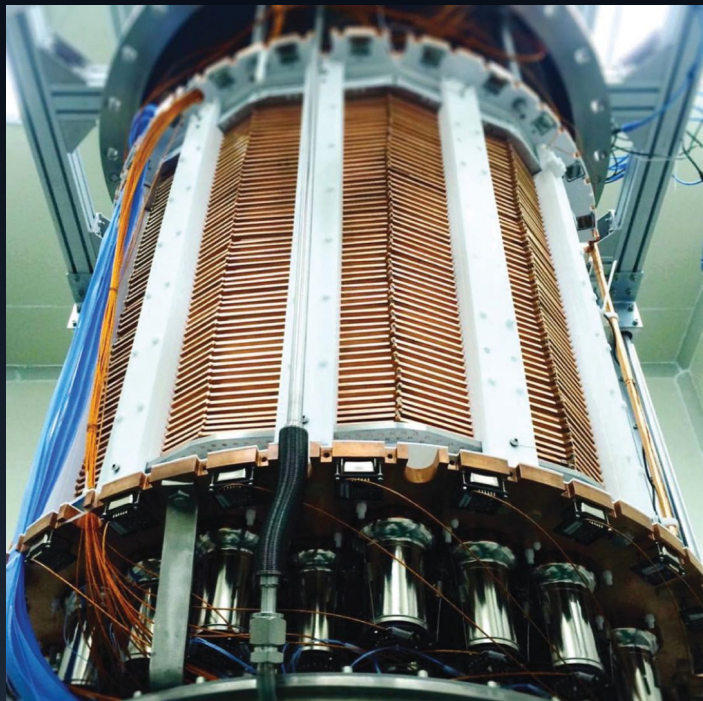
Mengao Xiao/Shanghai Jiao Tong University

Chinese team is catching up in hunt for dark matter

By Adrian Cho | Aug. 26, 2014, 6:00 PM

2015-2019: PandaX二期实验

- “蛋糕”升级成了一个580公斤的“冰激凌桶”



2016年中国重大科学、技术和工程进展

陈广仁, 刘志远, 田恬, 祝叶华

《科技导报》编辑部, 北京 100081

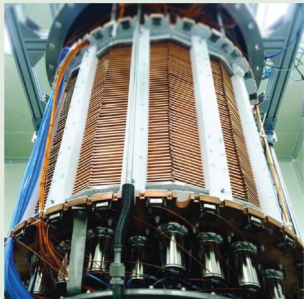
摘要 本着分门别类、本刊推荐、专家遴选、宁缺毋滥、叙述事实的原则, 从国内外重要科技期刊和科技新闻媒体所报道的中国科技成果中, 按科学、技术、工程3个类别, 由《科技导报》编辑部遴选、推荐候选条目, 经《科技导报》编委、审稿人等专家通信评选,

推出2016年度中国重大科学、技术、工程进展30项。1) 2016年中国重大科学进展: 性性状跨代遗传; 构建出世界上首个非人类灵长类自闭症模型; 提出基于胆固醇代谢调节度揭示水的核量子效应; 实验证实马约拉纳费米子的存在; 揭示RNA剪接的关键分子并给出迄今最强的限制; 揭示水稻产量性状杂种优势的分子遗传机制; 在玻色-爱因斯坦凝聚胚胎发育过程中关键信号通路的表现遗传调控机理。2) 2016年中国重大技术进展10项

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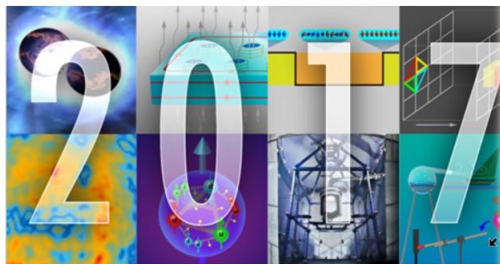
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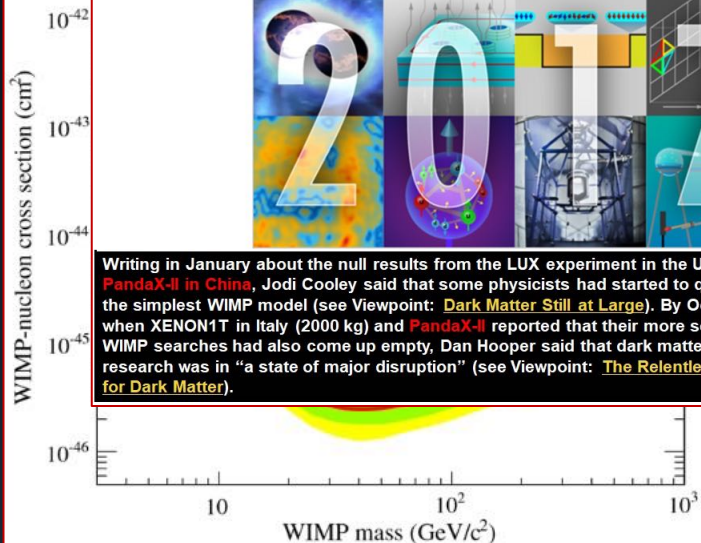
Volume 117, Number 12

Physics A APS《物理》2017年度八大亮点

Highlights of the Year



Writing in January about the null results from the LUX experiment in the US and PandaX-II in China, Jodi Cooley said that some physicists had started to question the simplest WIMP model (see Viewpoint: [Dark Matter Still at Large](#)). By October, when XENON1T in Italy (2000 kg) and PandaX-II reported that their more sensitive WIMP searches had also come up empty, Dan Hooper said that dark matter research was in "a state of major disruption" (see Viewpoint: [The Relentless Hunt for Dark Matter](#)).

高等学校科学研究优秀成果奖
(科学技术)

证书

项目名称: 液氦暗物质探测研究

奖励类别: 自然科学奖

奖励等级: 一等奖

获 奖 者: 上海交通大学



2022年教育部自然科学一等奖

证书编号: 2022-050-D01

实验物理学者的真实生活

- 2015年漫长的调试，解决了无数预期不到的问题
 - 《五年青春，我成为了一名山底洞人》（作者：谈安迪）

可惜事与愿违，探测器经过包括2015年春节在内的三个月紧张的安装后进入调试运行，发现有漏，氙气以不可接受的速率泄漏到外真空层并造成损失。

修复了这个压力容器泄漏的问题，又过了一个多月，我们发现了探测器出现了奇怪的信号，紧接着经过了两个月的研究，我们推断它来自于电极加工的不完美，这种奇怪的信

又过了两个月，第三次失败，谁还没经历过一些失败呢，过一过二不过.....过一过二过三不过四嘛.....

又过了两个月，出现了一种新的干扰信号，第四次失败.....

- 最终我们在11月22日准备完成，**开始数据采集！！！！**
- 19天后，我们发现了一种新的内部本底氦85... **停止采集数据！！！！**

放射性气体：氪气

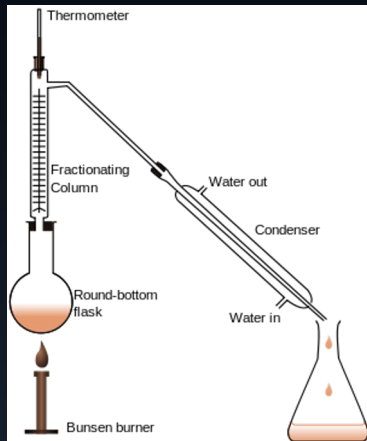
- 空气中有0.000001的**氪气**
- ^{85}Kr （贝塔衰变，半衰期10年）是核时代的产物，大约占天然氪的0.000000000002 (2×10^{-11})
- 但是，即使是稀少的氪气混入探测，也会产生讨厌的本底噪声信号！



氙精馏系统

- 通过不同沸点分离不同气体

■ Helium:	-269°C
■ Neon:	-246°C
■ Argon:	-186°C
■ Krypton:	-152°C
■ Xenon:	-108°C
■ radon	-62°C



- PandaX实验建了一个10米高精馏塔，要求氙气含量降到 10^{-12} 量级！

- 1公斤氙中仅100个氙-85原子



我们完整掌握了氙探测技术，但是……

PandaX 启动



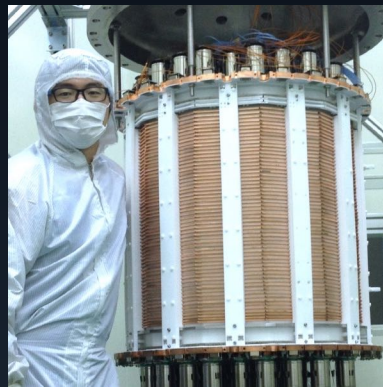
2009

第一代 (120公斤氙)



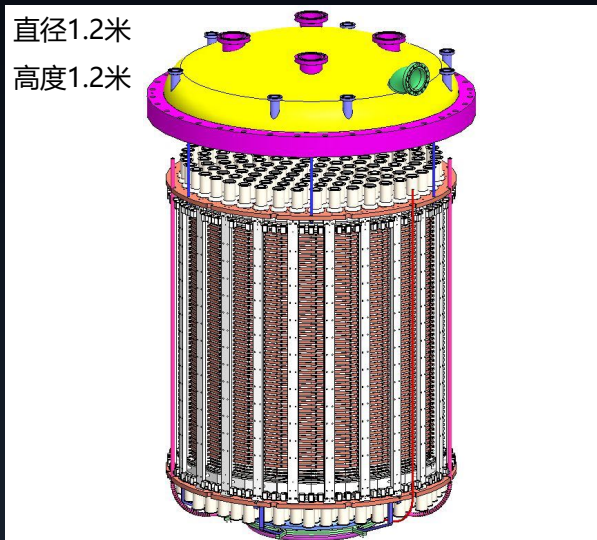
2010-2014

第二代 (580公斤)



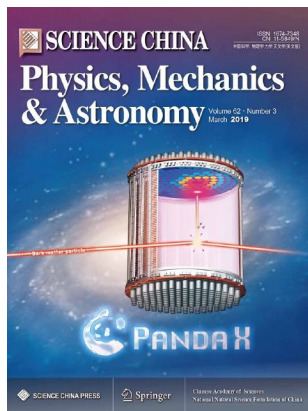
2015-2019

2016年初，决心建设国际新一代4吨级液氙实验



目标：引领国际暗物质探测灵敏度

领先国际，探测灵敏度需要达到多少？



ESI高被引论文

- 对几十个GeV质量的暗物质与核子碰撞截面的探测灵敏度达到 10^{-47}cm^2
- 指标：在暗物质信号区，放射性杂质引入的噪声事例 $< 1\text{个/吨/天}$

设计绘制上百个零件图纸，和加工厂反复迭代



全国范围调研和筛选探测器所需超纯材料

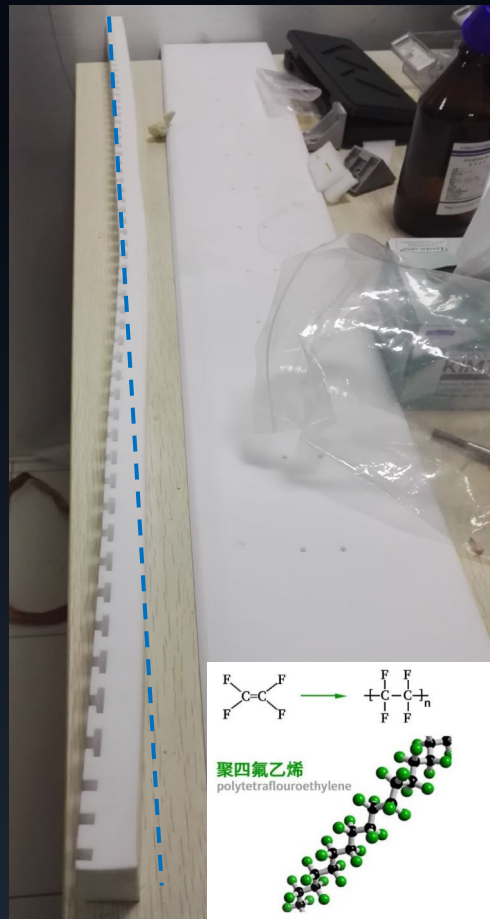


聚四氟乙烯 (PTFE) 特氟龙，用于投影室壁和底材

聚四氟乙烯 (PTFE) 特氟龙

- 具有高度的化学稳定性和卓越的耐化学腐蚀能力，有突出的耐热、耐寒及耐磨性，长期使用温度范围为-200-+250℃
- 优异的电绝缘性，且不受温度与频率影响
- 对氙产生的178nm紫外光反射率>95%
- 无掺杂，纯度高，放射性杂质含量低

但是，加工难度大...



聚四氟乙烯
polytetrafluoroethylene

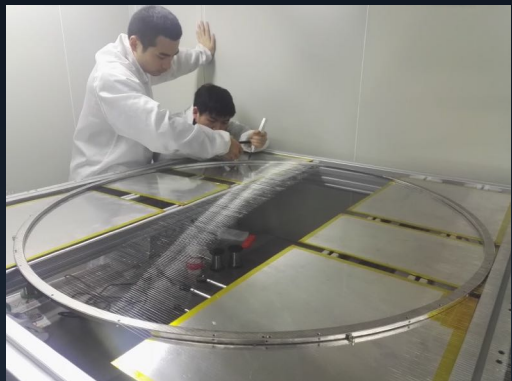




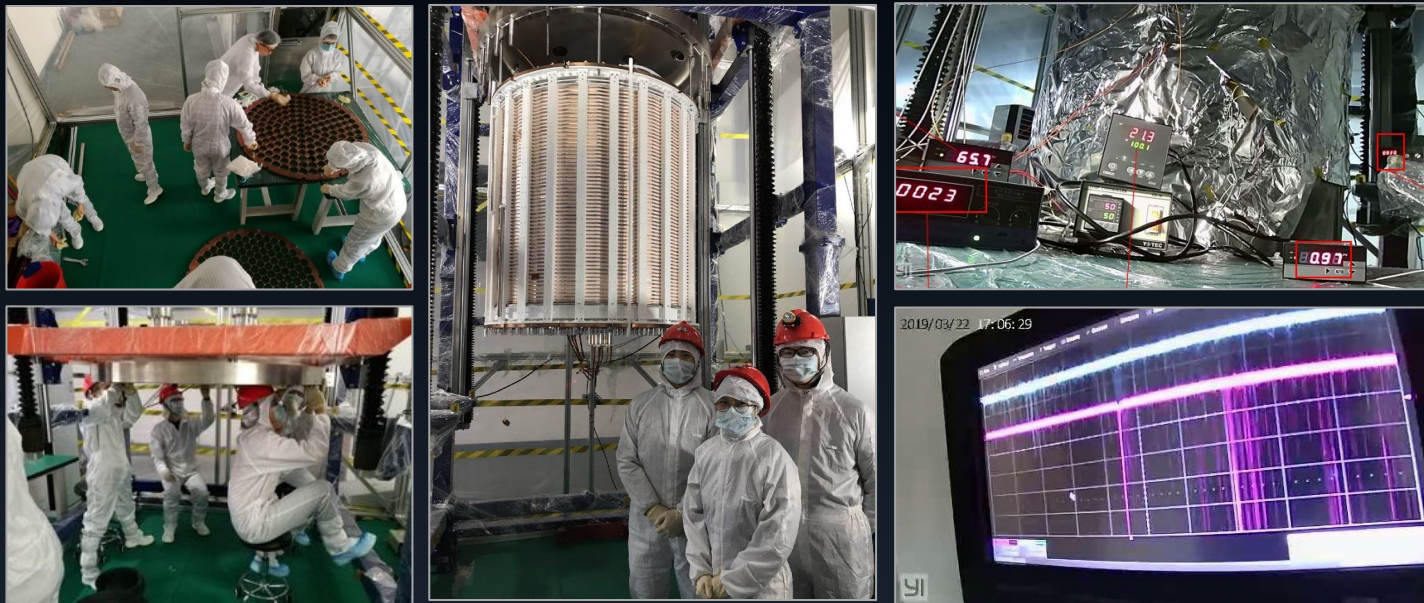
和加工车间反复调整工艺流程，最终解决了1.4米长PTFE零件的形变问题

部件加工

2016年9月—2018年8月，中心探测器各部件用低本底材料建造完成



完成四吨级探测器初次联合调试

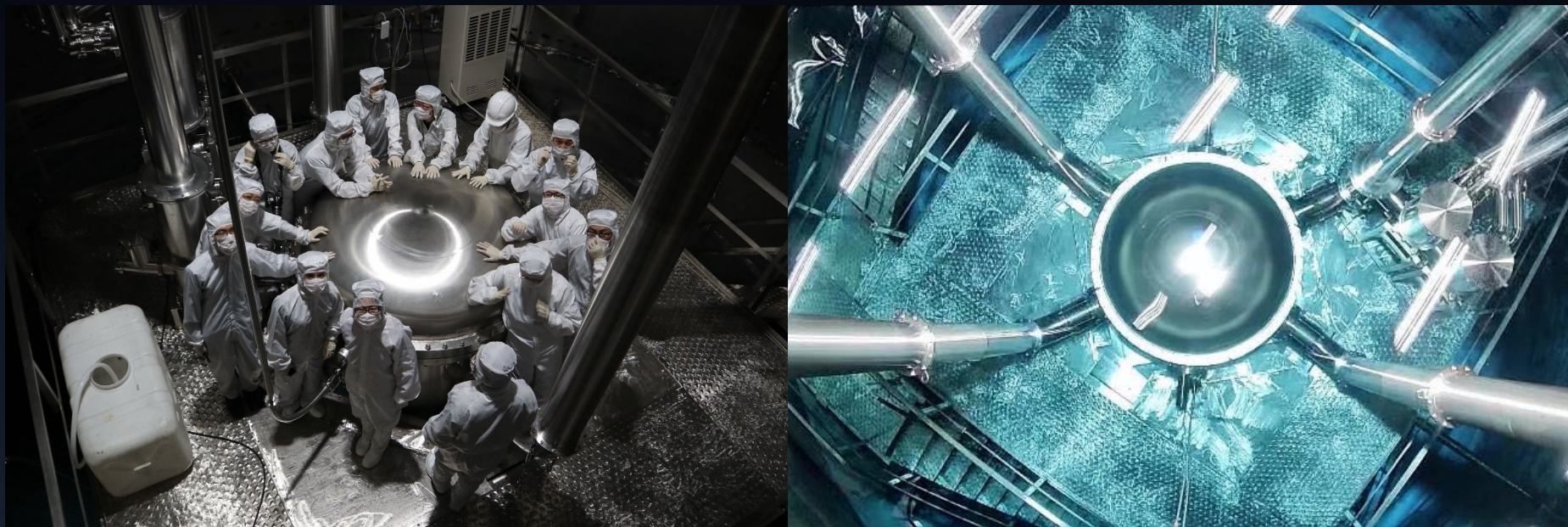


- 2018年8月，探测器各部件逐次进入万级洁净挑高空间，试组装
- 2019年5月，在交大实验室，完成探测器和其他系统初次联合调试

2019年8月，进驻锦屏地下实验室正式安装调试

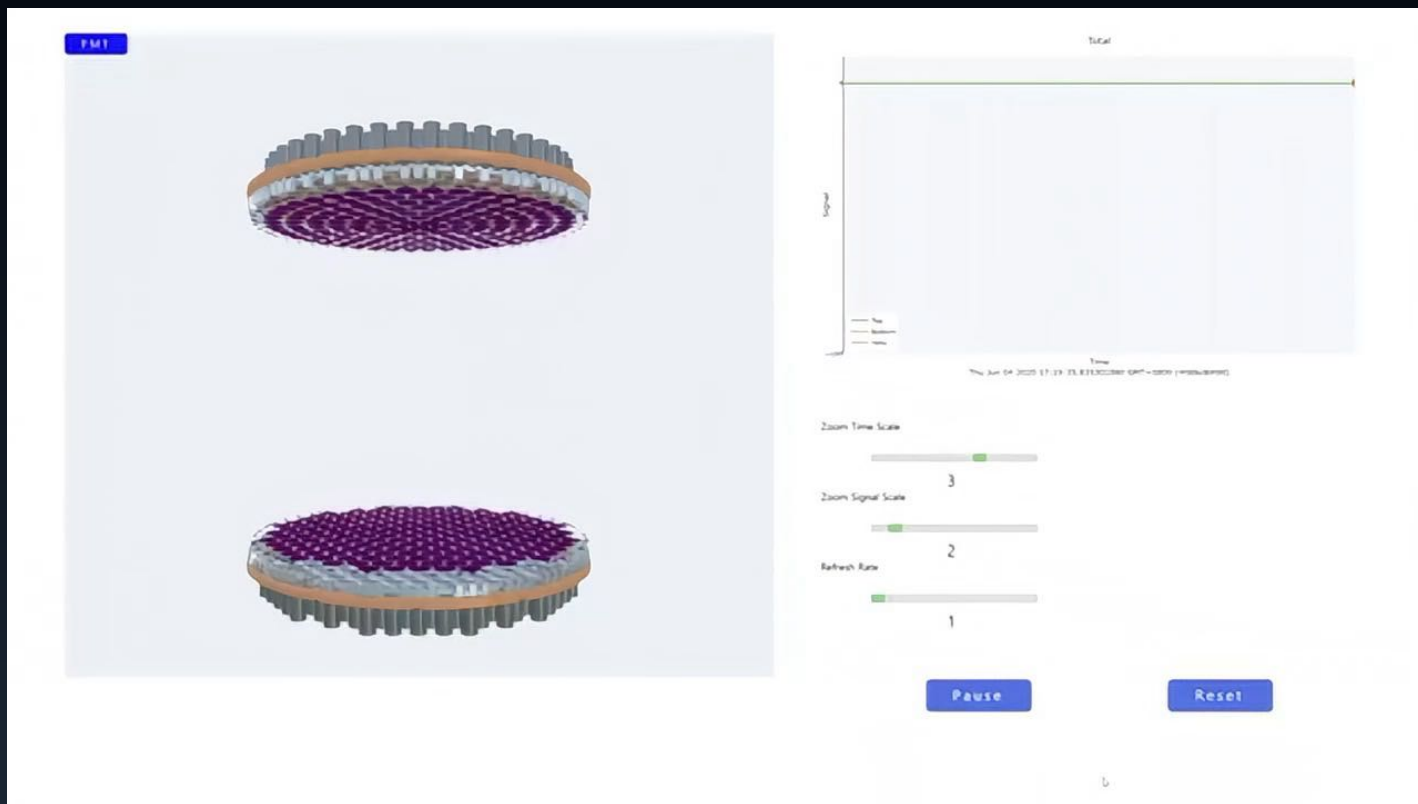


2016年2月 - 2020年11月，历经5年完成建设



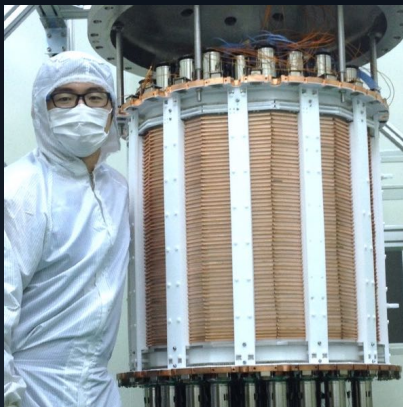
- 2020年5月20日，液氦灌注，开始取数测试
- 2020年11月28日-2021年04月16日，试运行物理取数

PandaX-4T探测器首个物理事例 (2020/6/3 17:19:35)



PandaX-4T性能比上一代大幅提升

- 探测体量提升6倍，达到3.7吨
- 探测能量范围大幅扩大
跨越4个数量级0.1keV - ~MeV
- 放射性杂质噪声显著下降
 ^{85}Kr 降低20倍，达到0.3ppt (mol/mol)
 ^{222}Rn 降低6倍，达到3mBq/kg



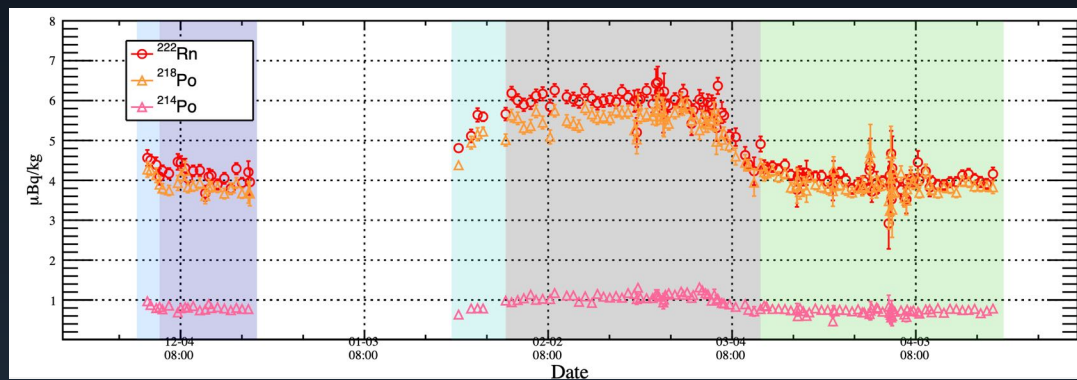
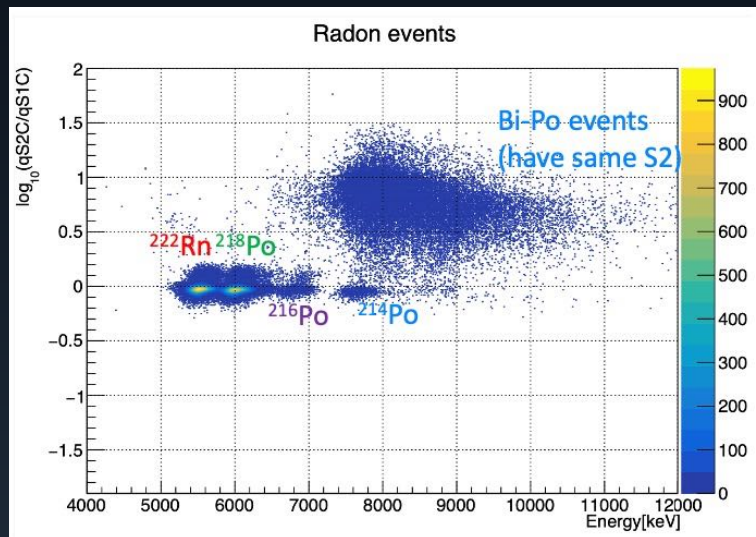
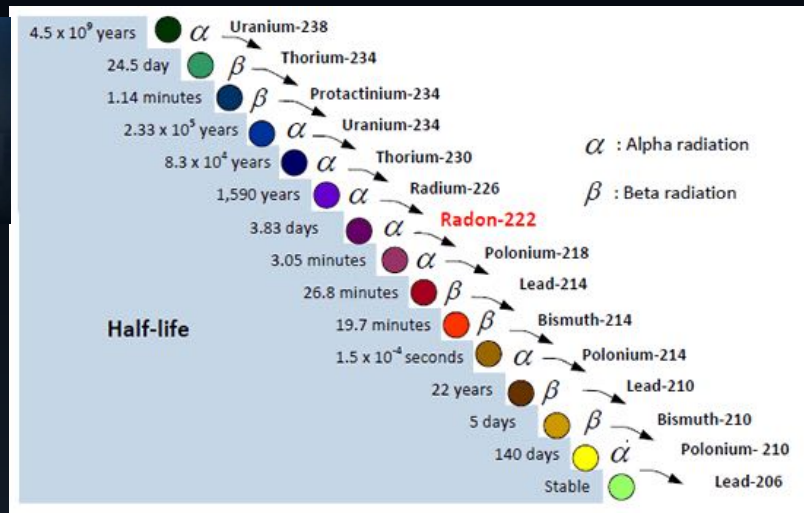
PandaX-II



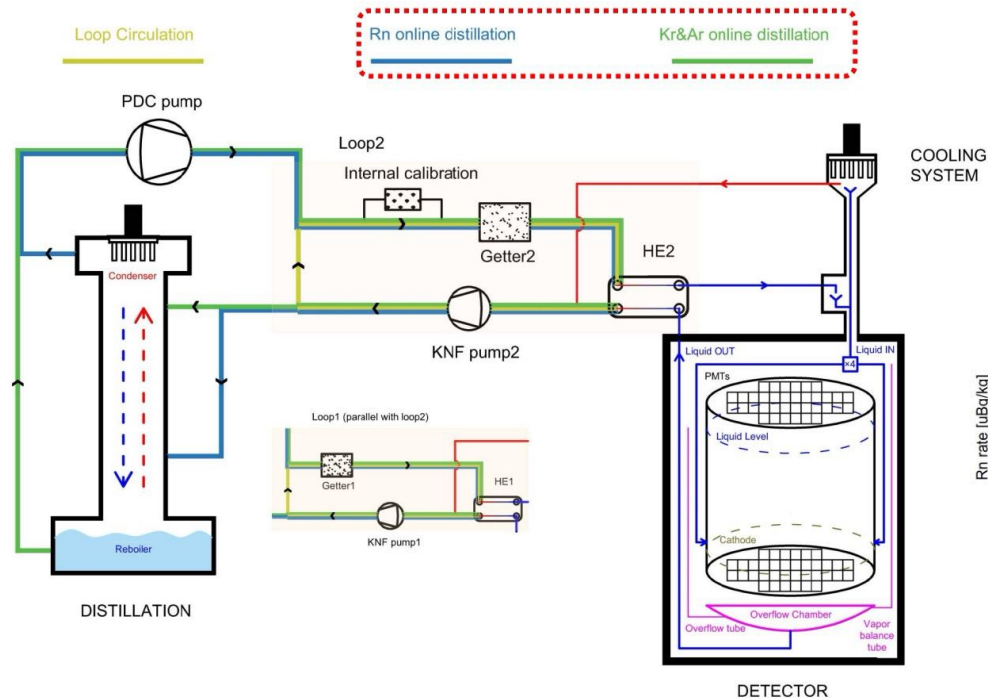
PandaX-4T

Radioactive Rn

- ^{222}Rn
- long-lived daughter

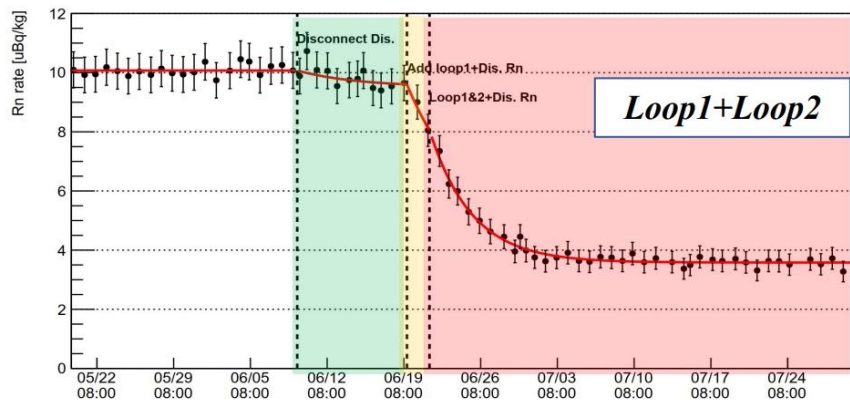


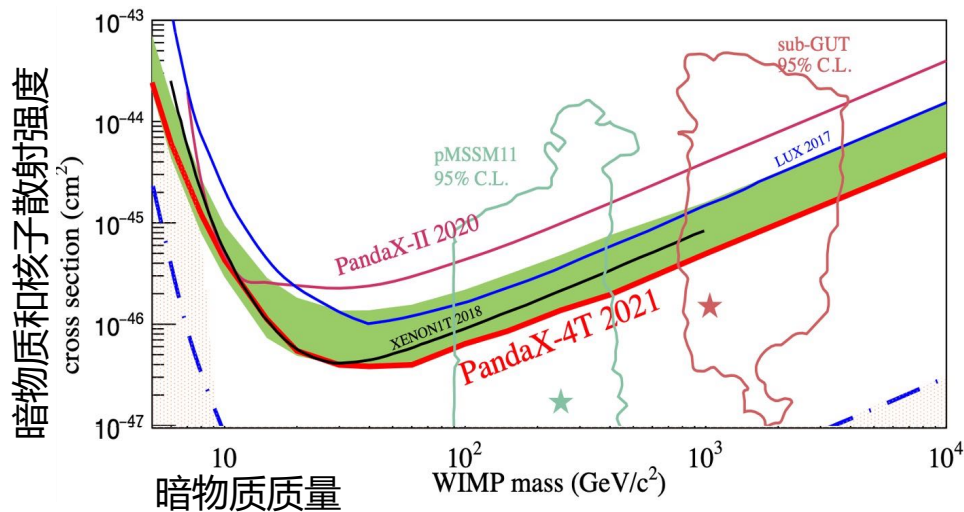
精馏除氦



Boiling points and masses of noble gases

Helium:	-269°C	4.00 g/mol
Neon:	-246°C	20.18 g/mol
Argon:	-186°C	39.95 g/mol
Krypton:	-152°C	83.80 g/mol
Xenon:	-108°C	131.3 g/mol
radon	-62°C	~222 g/mol





PandaX-4T实验 95天试运行结果公布

2021年8月发布对暗物质散射强度最强的实验限制，再次领先世界。

PRL(2021) 编辑推荐 ESI 高被引



进驻锦屏国家重大科技基础设施的PandaX-4T实验发布首个暗物质搜寻结果

发布时间: 2021/09/17 来源: 高技术司 打印

PandaX-4T 实验发布首个暗物质搜寻结果

本报讯 近日,上海交通大学教授、中国锦屏地下实验室 PandaX 实验(“熊猫”实验)发言人刘江来在三年一度的马塞尔·格罗斯曼国际广义相对论大会上公布了 PandaX-4T 实验的首个暗物质搜寻结果。这次结果基于 PandaX-4T 试运行 95 天的数据,用 0.63 吨·年的曝光量,再次刷新了暗物质性质的边界值。

近百年的天文学和宇宙研究表明,宇宙中“看不见”的暗物质比人们已知的普通物质多了 5 倍多。科学家普遍认为,暗物质与普通物质之间极可能存在一种新的微弱的相互作用,可以在极深地下,利用超高灵敏度的探测器寻找它们。

PandaX 实验由上海交通大学教授李向东于 2009 年发起,目前合作单位包括山东大学、北京大学、中国科学技术大学等多位科研工作者参与。PandaX 实验位于凉山州的中国锦屏地下实验室,上方深达 2400 米,是世界上最大埋深、守底最低的地下实验室。PandaX 采用液氙为暗物质靶和探测器。弥散在银河系物质粒子可能碰撞到氙原子核,而

的反冲将在探测器中发光或产生其他氙原子的电离,从而被位于探测器上下部的灵敏的光电倍增管记录下来。在过去的 10 余年中,PandaX 合作组已经完成了两代暗物质实验。

为了提升暗物质探测的灵敏度,2019 年起 PandaX 团队在锦屏二期的 B2 实验厅开展新一代的 4 吨级实验(PandaX-4T)。2020 年 11 月 28 日,探测器调试完成,进入试运行,至 2021 年 4 月 15 日结束运行,其中稳定取数共 95 天。

在 95 天的运行中,PandaX-4T 探测器记录了约 13.7 亿次的事件,其中仅有 1058 个事例通过筛选进入了最终的暗物质分析数据集。这些事例中有 6 个事例落在了信号区域内,通过分析,它们和本底预期吻合,未出现暗物质事例超出的迹象。由于出众的灵敏度,

中国科学报

CHINA SCIENCE DAILY

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第 7815 期 2021 年 7 月 13 日 星期二 今日 8 版



发言人公布了首个暗物质搜寻的边界值



Examining the results of searches by the PandaX-4T collaborations

16 February 2022, by Ingrid Fadelli



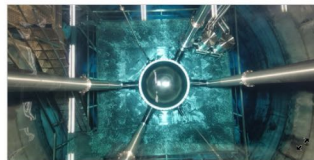
The ADMX apparatus right after extracting from the magnet bore. It was cooled by Liquid Nitrogen, so it makes cold mist. The left big black bag and right big reservoir are the parts of liquid Helium recycling system. Credit: ADMX Collaboration.



Tightening the Net on Two Kinds of Dark Matter

December 23, 2021 • Physics 14, s164

New dark matter results strengthen constraints on axions and WIMPs.



have very **weak interactions** with matter, allowing them to be searched for in laboratory experiments.*

The primary objective of the recent work by the PandaX-4T Collaboration was to search for the energy deposition resulting from a direct interaction between WIMP particles and target nuclei. To do this, they used a detector located deep

Sanford Lab, LZ, 7 ton

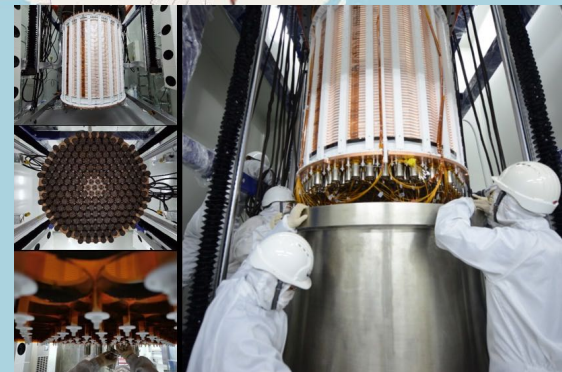
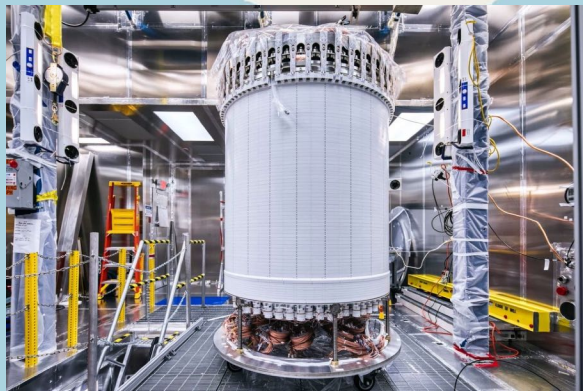


United States

LNGS, XENONnT, 6.5 ton



CJPL, PandaX-4T, 3.7 ton



PandaX-4T是国际首个投入运行的新一代多吨级液氙探测实验

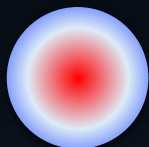
How dark is dark matter?



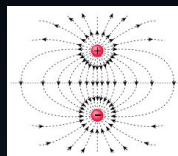
- 类比已知中性粒子，暗物质也可能存在一些**极其微弱的电磁属性**



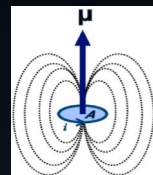
微弱电荷
millicharge



电荷半径
charge radius



电偶极矩
electric dipole



磁偶极矩
magnetic dipole



零极矩
anapole

$$\mathcal{L} = \underbrace{Qe\bar{\chi}\gamma^\mu\chi A_\mu}_{\text{millicharge}} + \underbrace{\frac{\mu_\chi}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}}_{\text{magnetic dipole}} + \underbrace{i\frac{d_\chi}{2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}}_{\text{electric dipole}} + \underbrace{b_\chi\bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}}_{\text{charge radius}} + \underbrace{a_\chi\bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu}}_{\text{anapole}}$$

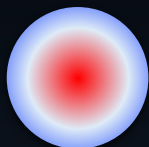
tree-level

higher-order loop-level

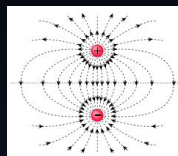
- 类比已知中性粒子，暗物质也可能存在**一些极其微弱的电磁属性**



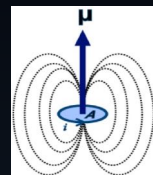
微弱电荷
millicharge



电荷半径
charge radius



电偶极矩
electric dipole



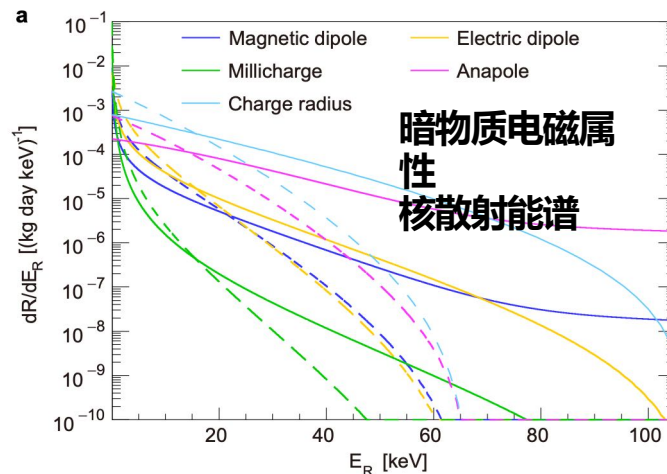
磁偶极矩
magnetic dipole



零极矩
anapole

➤ 不同电磁属性产生的原子核散射能谱有**显著差异**

- 分析PandaX-4T高灵敏数据，**针对性研究**暗物质可能的电磁属性



• 暗物质电荷半径的首个实验结果

- 40GeV/c²暗物质：电荷均方半径上限比中微子小4个数量级，换算成尺寸比质子半径小10万倍

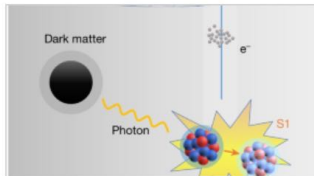
• 其他电磁属性限制提升3至10倍

Limits on the luminance of dark matter from xenon recoil data

A direct search for effective electromagnetic interactions between dark matter and xenon nuclei that produce a recoil of the latter is carried out and the first constraint on charge radius of dark matter is derived.

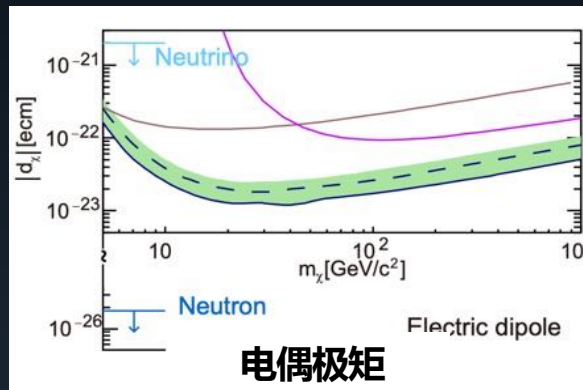
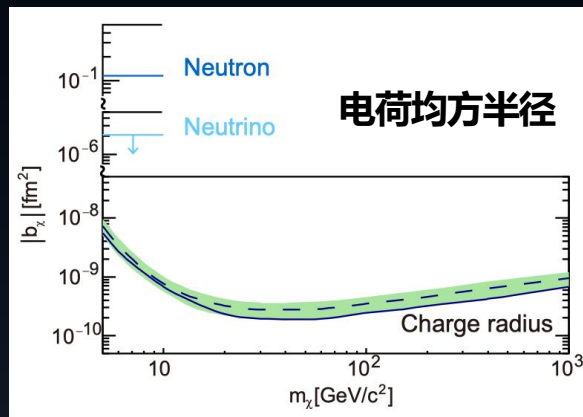
Xuyang Ning, Abdusalam Abdukerim ... Yubo Zhou

Article | 17 May 2023



Nature 618, 47-50 (2023)

通过**最灵敏**的数据对“暗物质有多暗”这个问题给出**系统定量**的实验回答

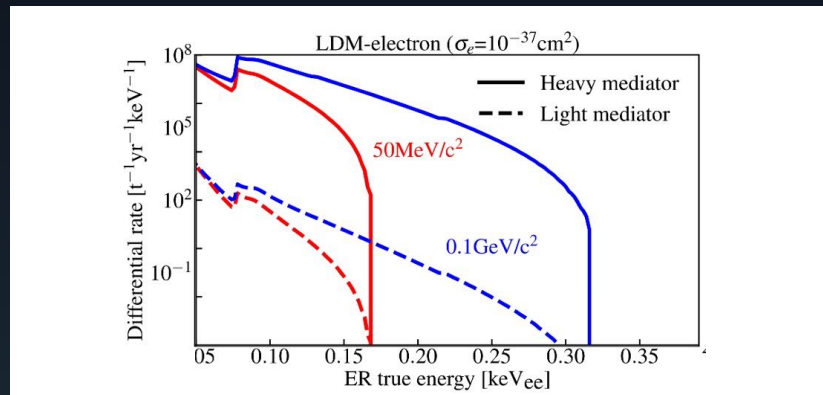


轻质量暗物质探测

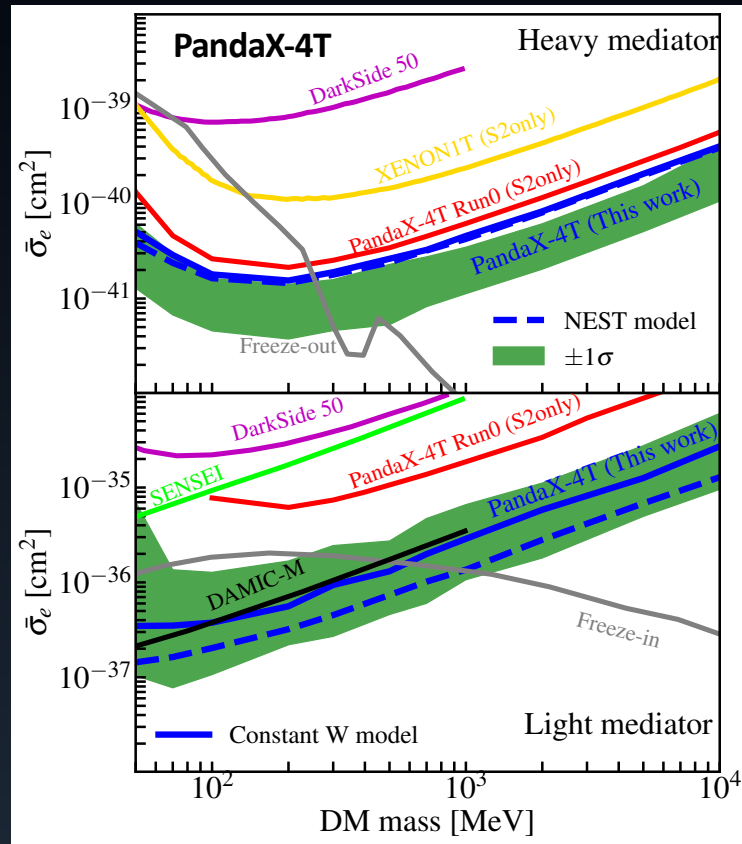
- WIMP-electron coupling
 - Heavy mediaor or light mediator

$$\frac{dR}{d \ln E_{\text{er}}} = N_T \frac{\rho_\chi}{m_\chi} \sum_{nl} \frac{d\langle \sigma_{\text{ion}}^{nl} v \rangle}{d \ln E_{\text{er}}}$$

$$\frac{d\langle \sigma_{\text{ion}}^{nl} v \rangle}{d \ln E_{\text{er}}} = \frac{\bar{\sigma}_e}{8 \mu_{\chi e}^2} \int dq q |f_{\text{ion}}^{nl}(k', q)|^2 |F_{\text{DM}}(q)|^2 \eta(v_{\text{min}})$$



- Probing DM mass $\sim 100 \text{MeV}$ in LXe



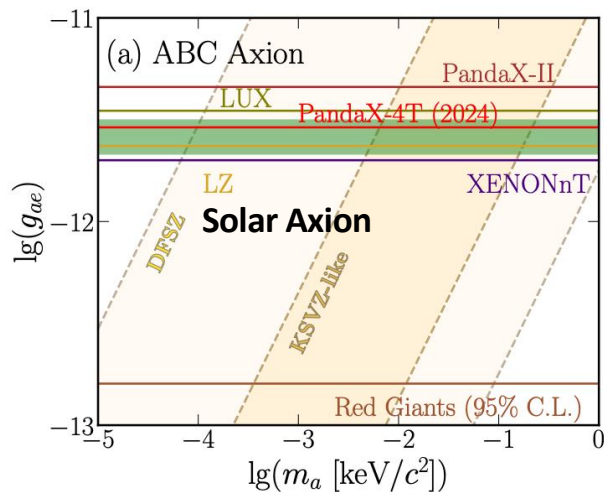
Accelerated Low Mass DM

- The Universe is a big accelerator
- Accelerating light DM based on the same interaction

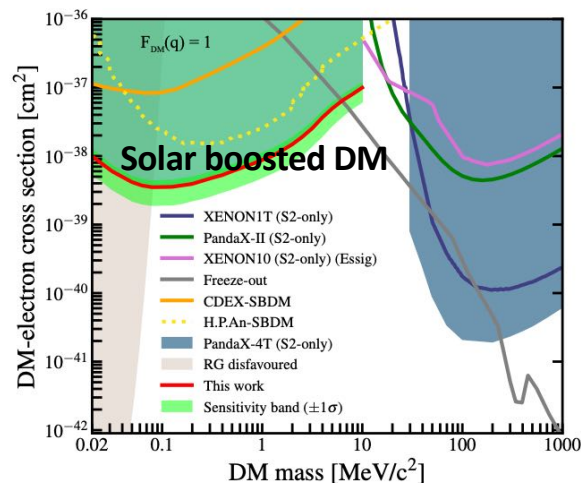


Accelerated Low Mass DM

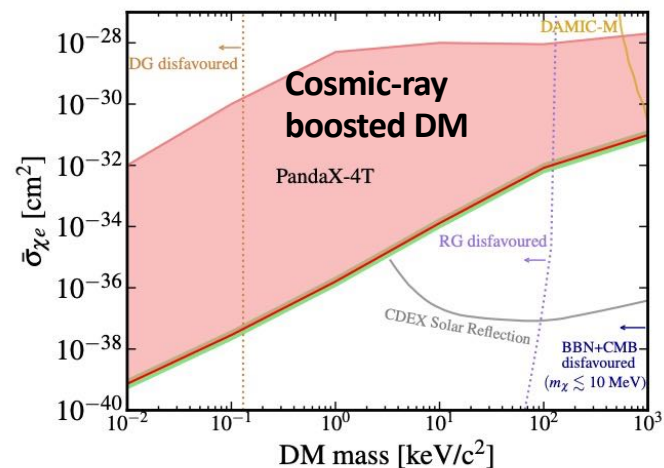
- The Universe is a big accelerator
- Accelerating light DM based on the same interaction
- Covering DM mass $\sim 0.1 \text{ keV}/c^2$



arXiv:2408.07641

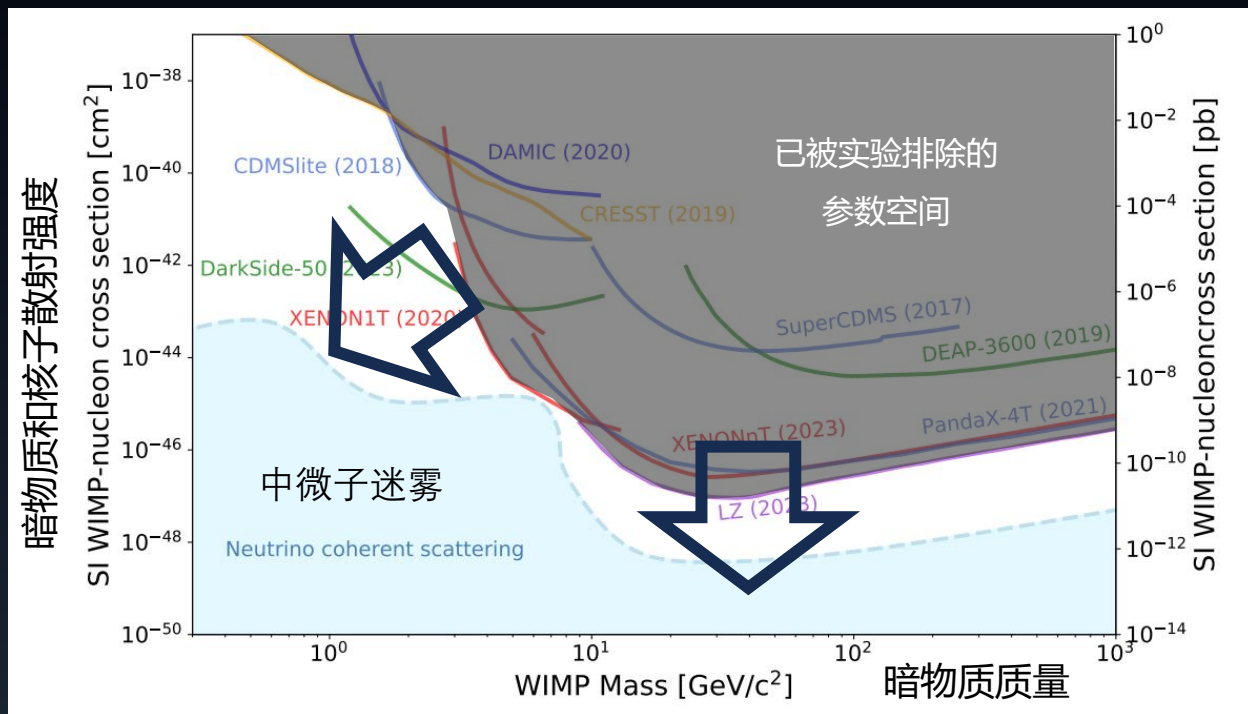


arXiv:2412.19970



Arxiv:2403.08361

探测灵敏度不断拓展



发掘探测器潜力

大幅提升对更弱信号的探测灵敏度

传统探测模式

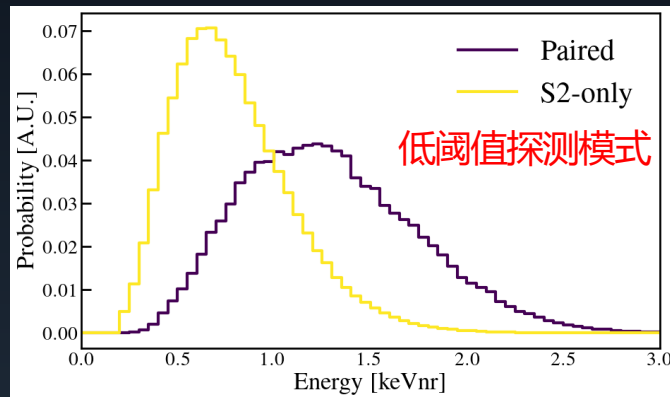
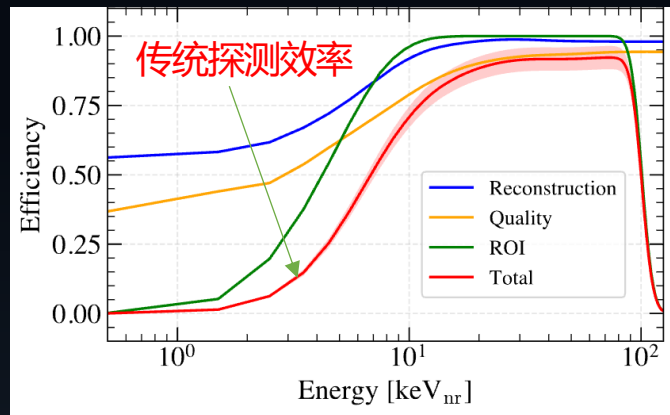
- 光信号+电子信号
- 探测阈值 $\sim 2\text{keV}$

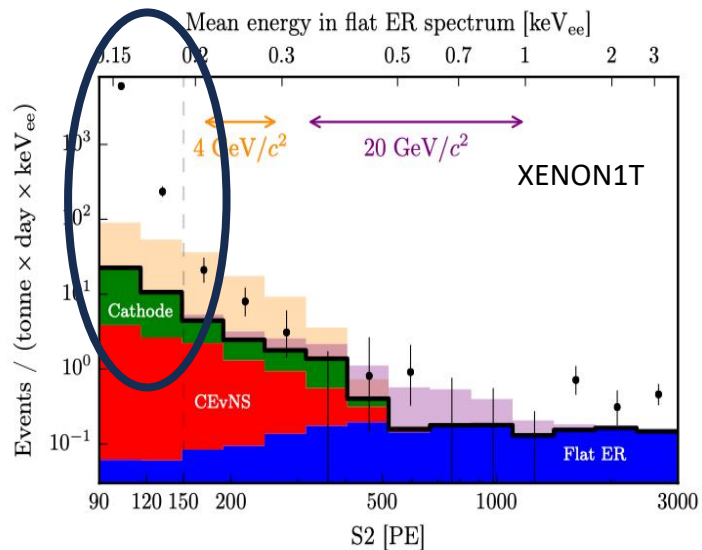
低阈值探测模式

- 电子信号
- 探测阈值 $\sim 0.5\text{keV}$

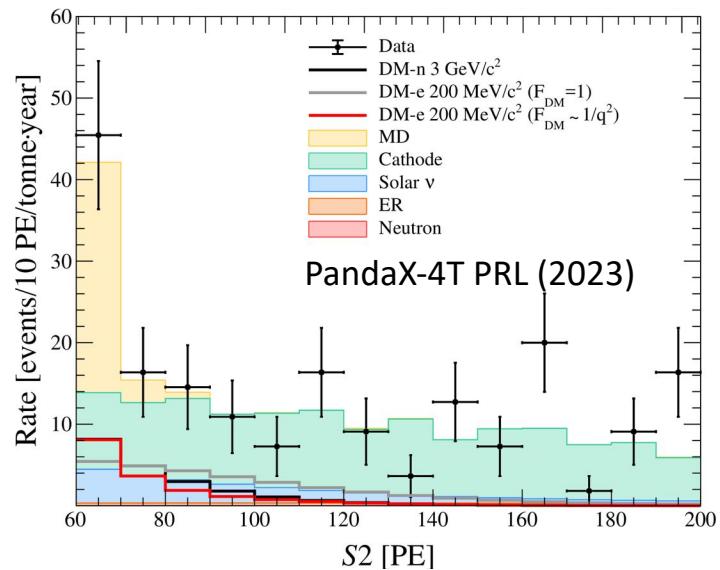
液氙低阈值探测模式

- 通过单独电离信号事例，将探测阈值从3keV降低至0.3keV
 - 低阈值S1-S2配对事例
 - 单独电离信号事例 (S2-only)
- 技术挑战
 - 低能信号响应模型
 - 非物理噪声控制



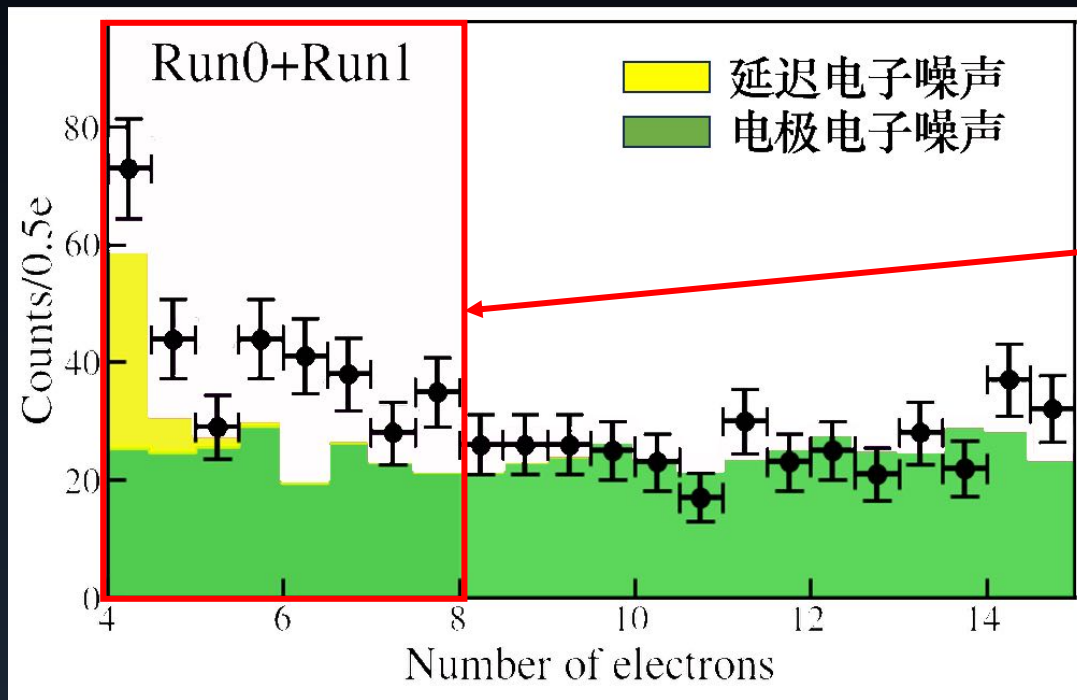


但是，低阈值探测模式存在大量难以理解的
低能量噪声



经过一年多的研究，我们在2023年首次完整评估了液
氙实验低能量噪声，铺平了低阈值探测暗物质的道路

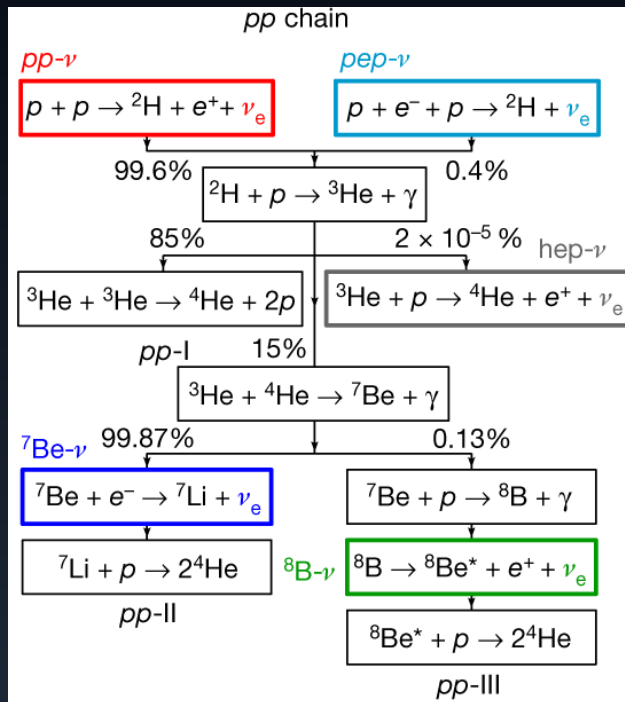
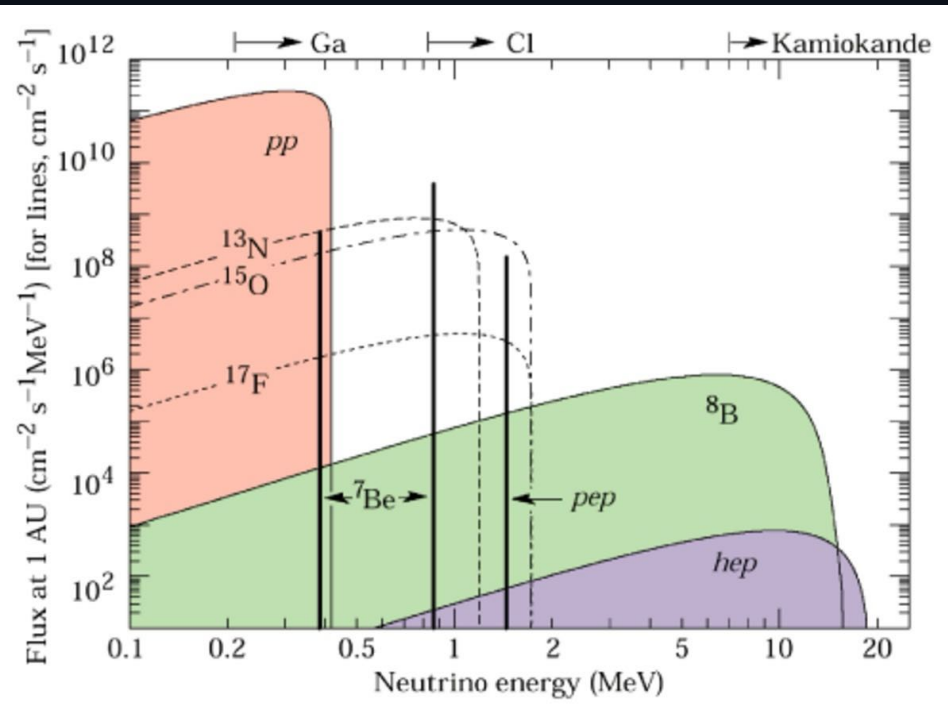
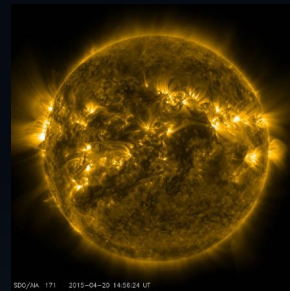
低能量区域数据出现明显超出



是暗物质信号么! ?

太阳中微子

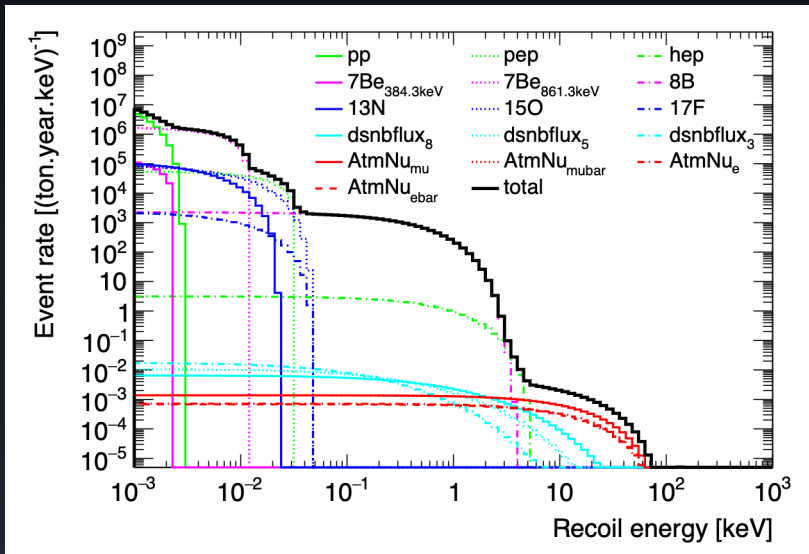
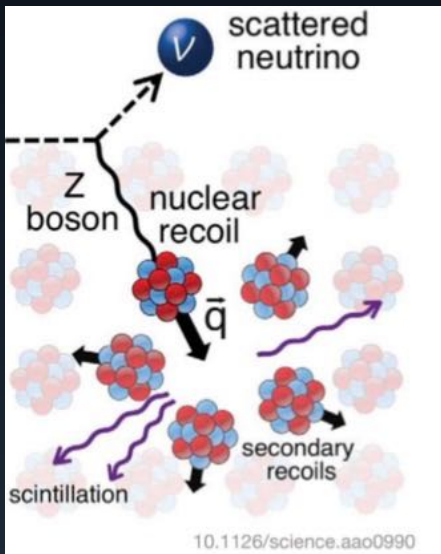
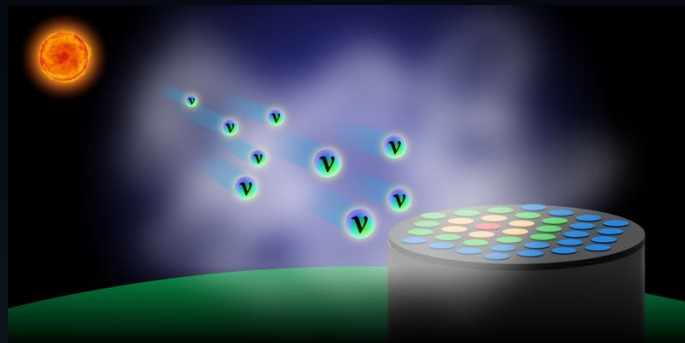
- ^8B neutrino ~ 10 MeV



太阳中微子CEvNS信号

- Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- 中微子与原子核弹性相干散射





Coherent effects of a weak neutral current

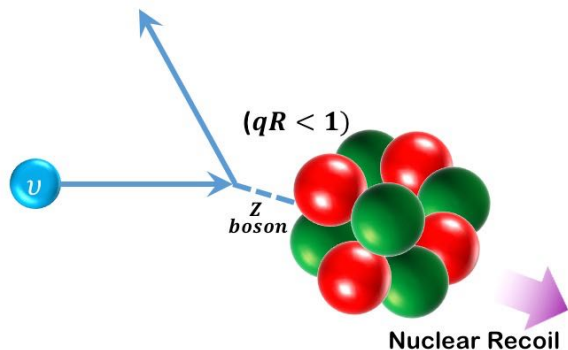
Daniel Z. Freedman†

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)

- $qR < 1$
- Z-exchange between neutrino and nucleus
- Nucleus recoils as a whole
- Coherent up to $E_\nu \sim 50$ MeV

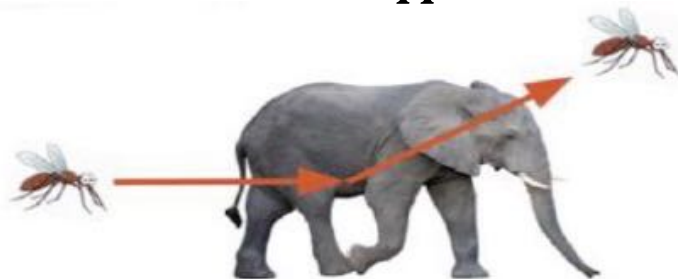


$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F(Q^2)^2$$

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

$$\Rightarrow \sigma \propto N^2$$

$$T_R \approx \frac{E_\nu^2 (\text{MeV})}{A} \text{ keV}$$

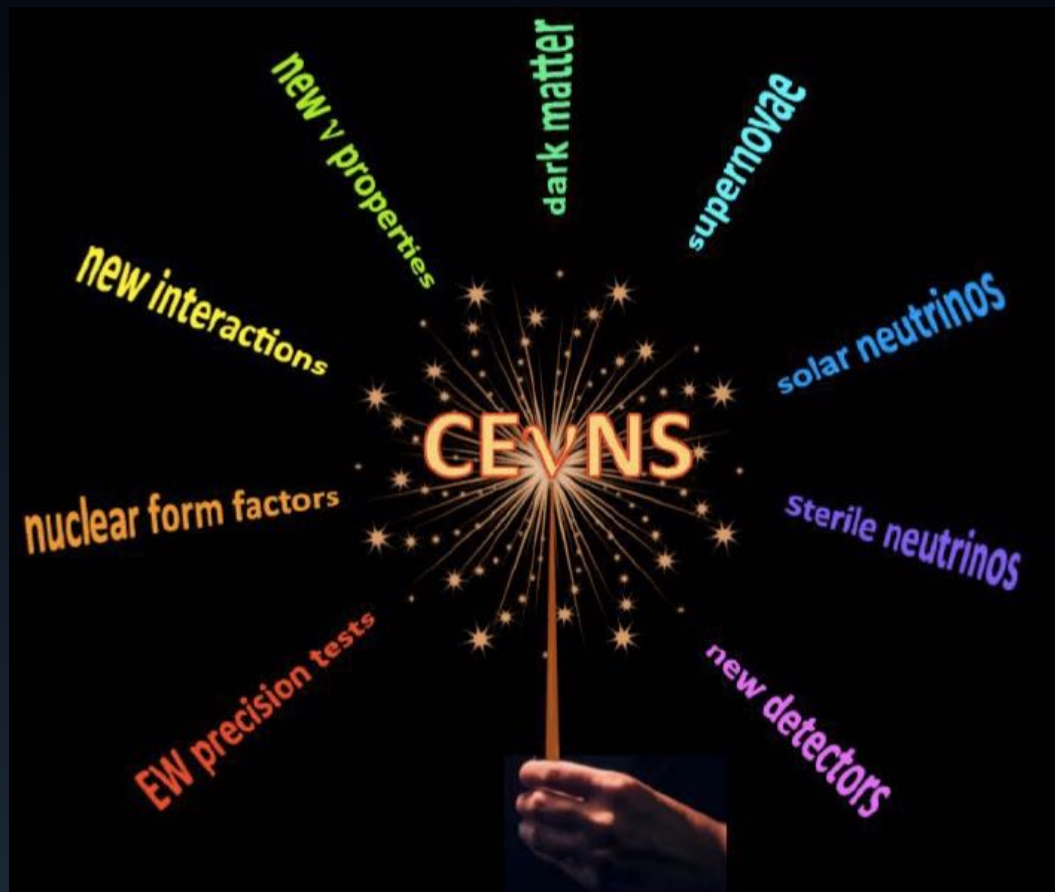


CEvNS as a new probe

First observation by COHERENT in 2017

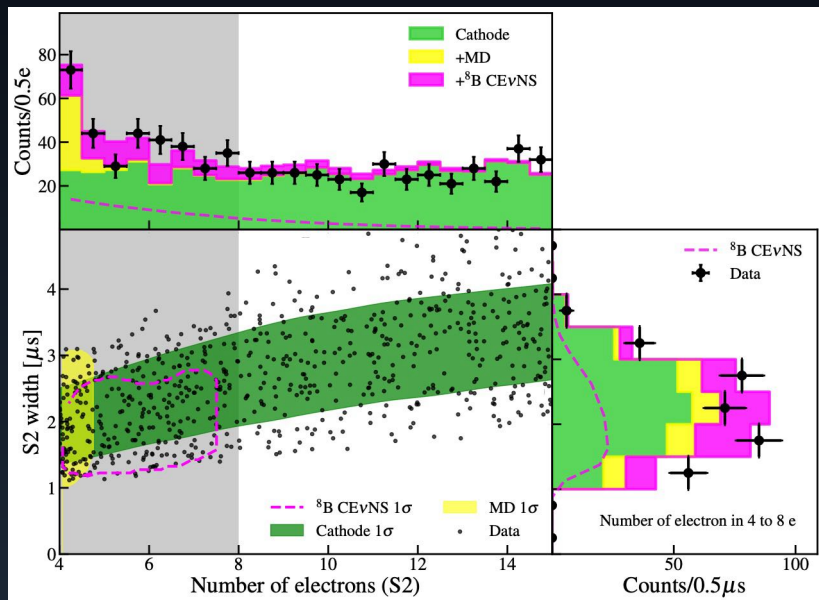


SCIENCE 357, no. 6356,
1123-1126 (2017)

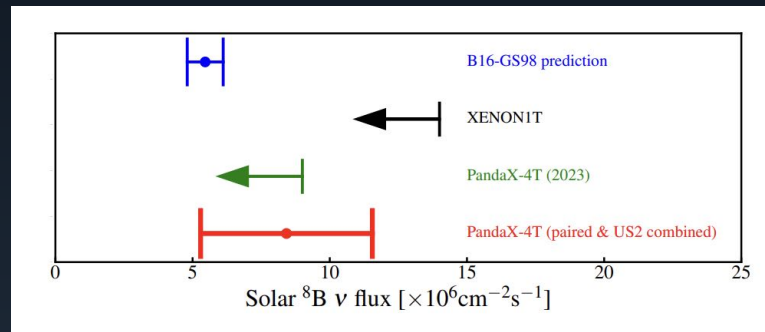


首次观测太阳硼-8中微子相干散射信号

- 首次测量到**太阳硼-8中微子相干散射**过程，达到里程碑级探测灵敏度
- 发现由太阳硼-8中微子造成的信号超出，统计显著度达到 2.64σ



Best-fit	paired	s2only
B8 number	3.5 ± 1.3	75 ± 28
P-value	0.004	
significance	2.64σ	



太阳中微子探测

首次测量到太阳中微子和原子核相干散射过程，
标志实验达到里程碑级探测灵敏度

成果入选美国物理学会2024年度十大亮点

Phys. Rev. Lett. **133**, 191001, Editors' Suggestion

低能量中微子探测的新途径、核反应监控

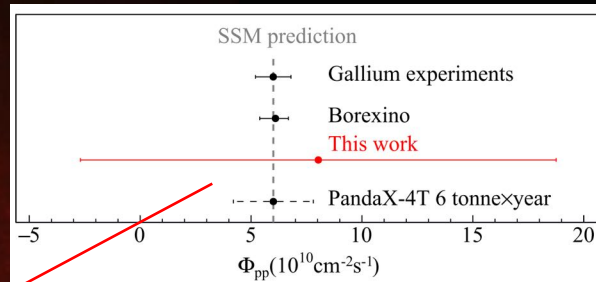
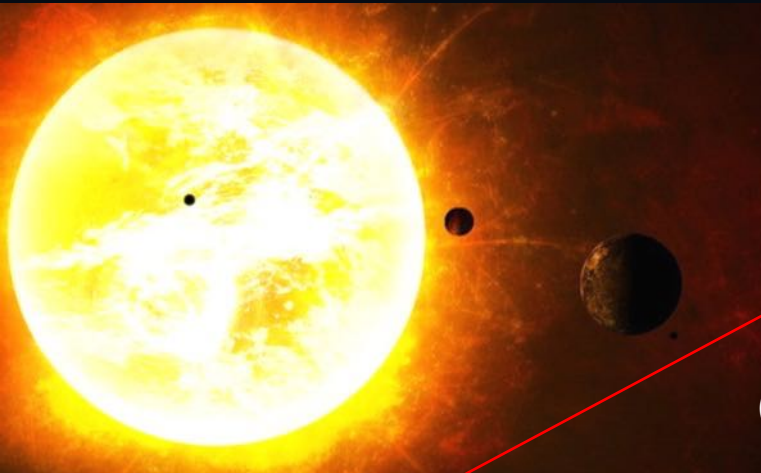


超新星爆发产生中微子



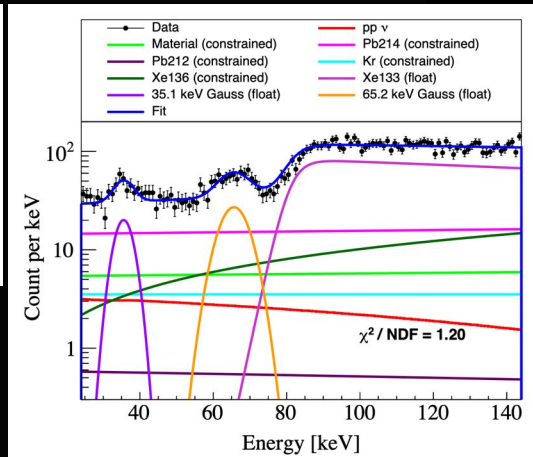
核反应产生中微子

Solar Neutrinos

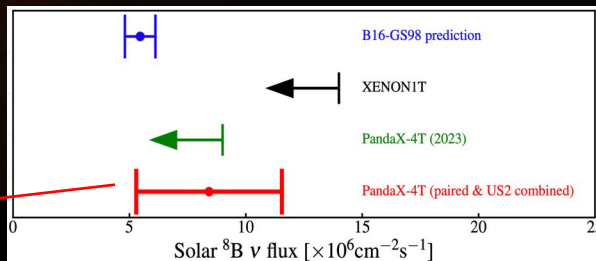
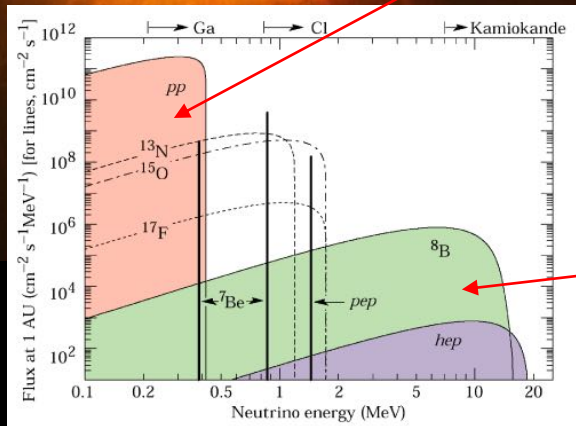


CPC 48, 091001 (2024)

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



24 -144 keV, Run0 Data



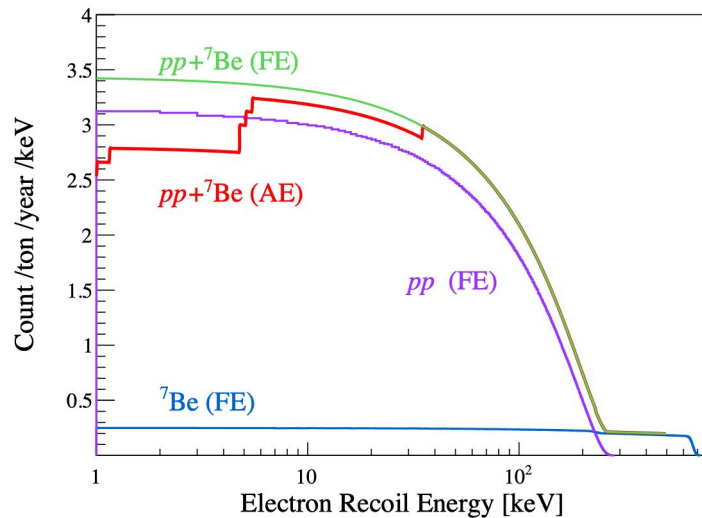
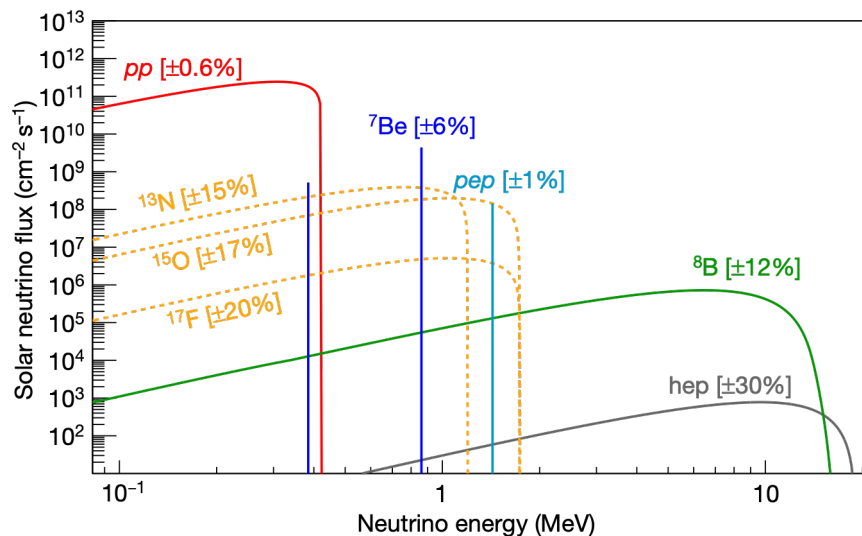
$$(8.4 \pm 3.1) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

PRL 133, 191001 (2024)

Solar pp neutrino scattering on electrons



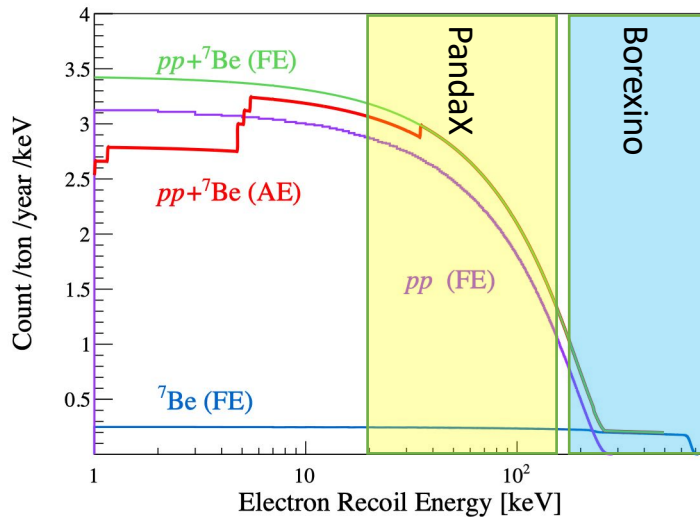
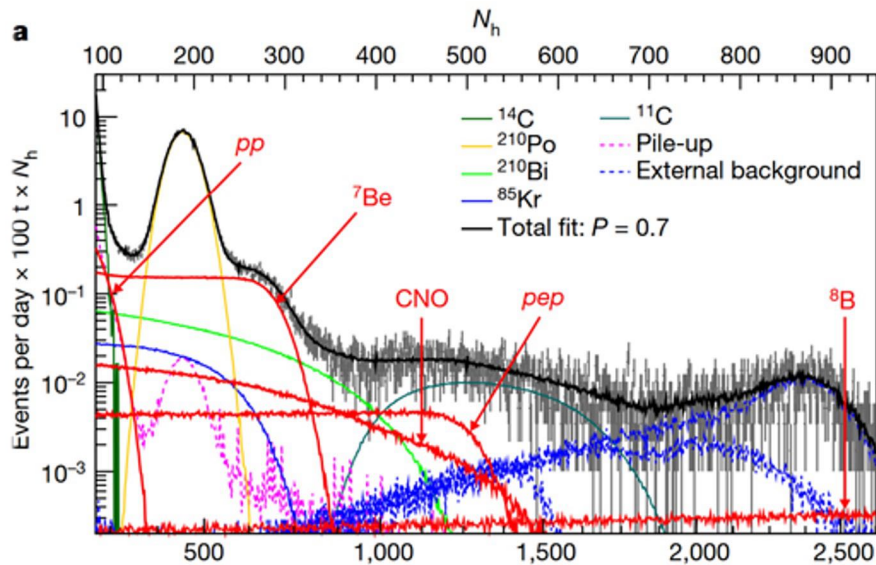
- Leading result from Borexino with a recoil energy of >165 keV
- PandaX-4T: traditionally a DM detector, i.e. **low energy threshold**



Solar pp neutrino scattering on electrons



- Leading result from Borexino with a recoil energy of >165 keV
- PandaX-4T: traditionally a DM detector, i.e. **low energy threshold**



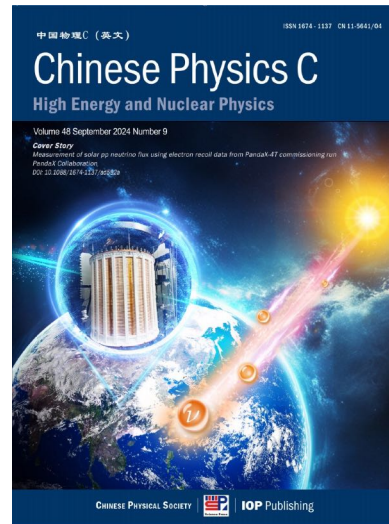
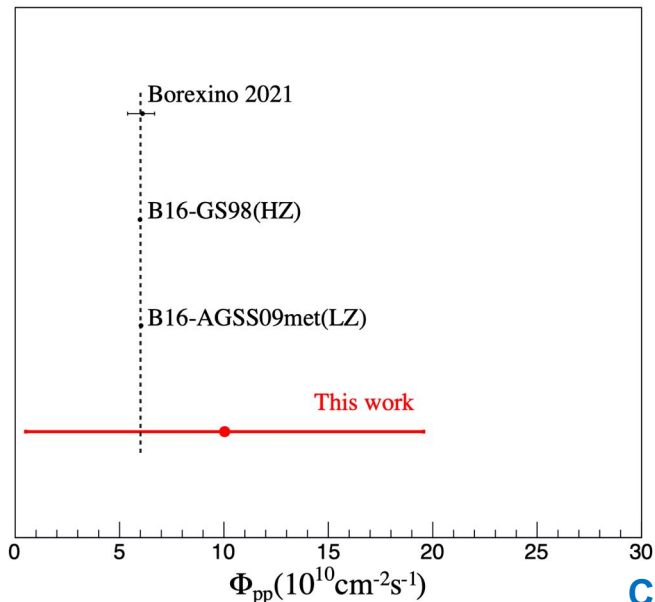
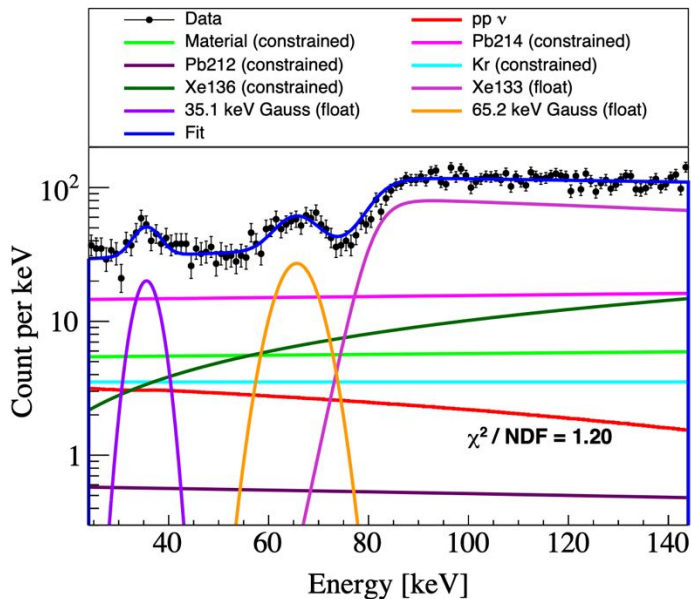
Borexino, Nature 562, 505–510 (2018)

Solar pp neutrinos



- **Run0 data: ER signals**

- The 1st solar pp neutrino measurement in recoil energy from 24 to 144keV

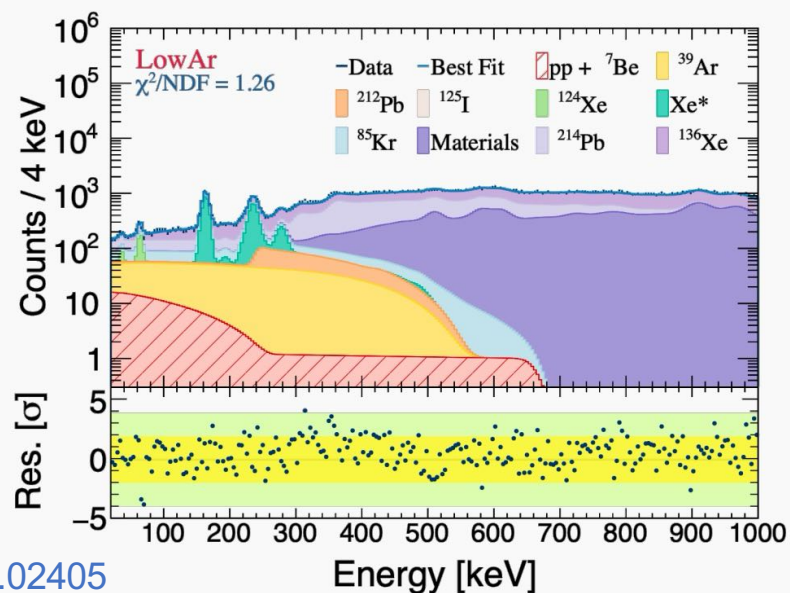
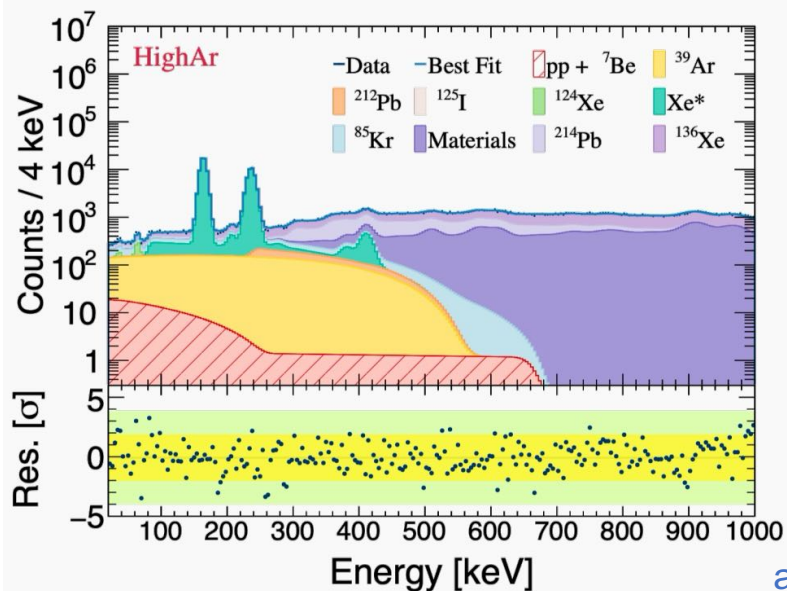


Solar pp neutrino scattering on electrons



- PandaX first Run2 data release
- Blind analysis for solar pp neutrino
- 2.2 sigma over background, **first positive indication of solar pp ν -e**

scattering in the ER energy < 165 keV region



[arxiv:2607.02405](https://arxiv.org/abs/2607.02405)

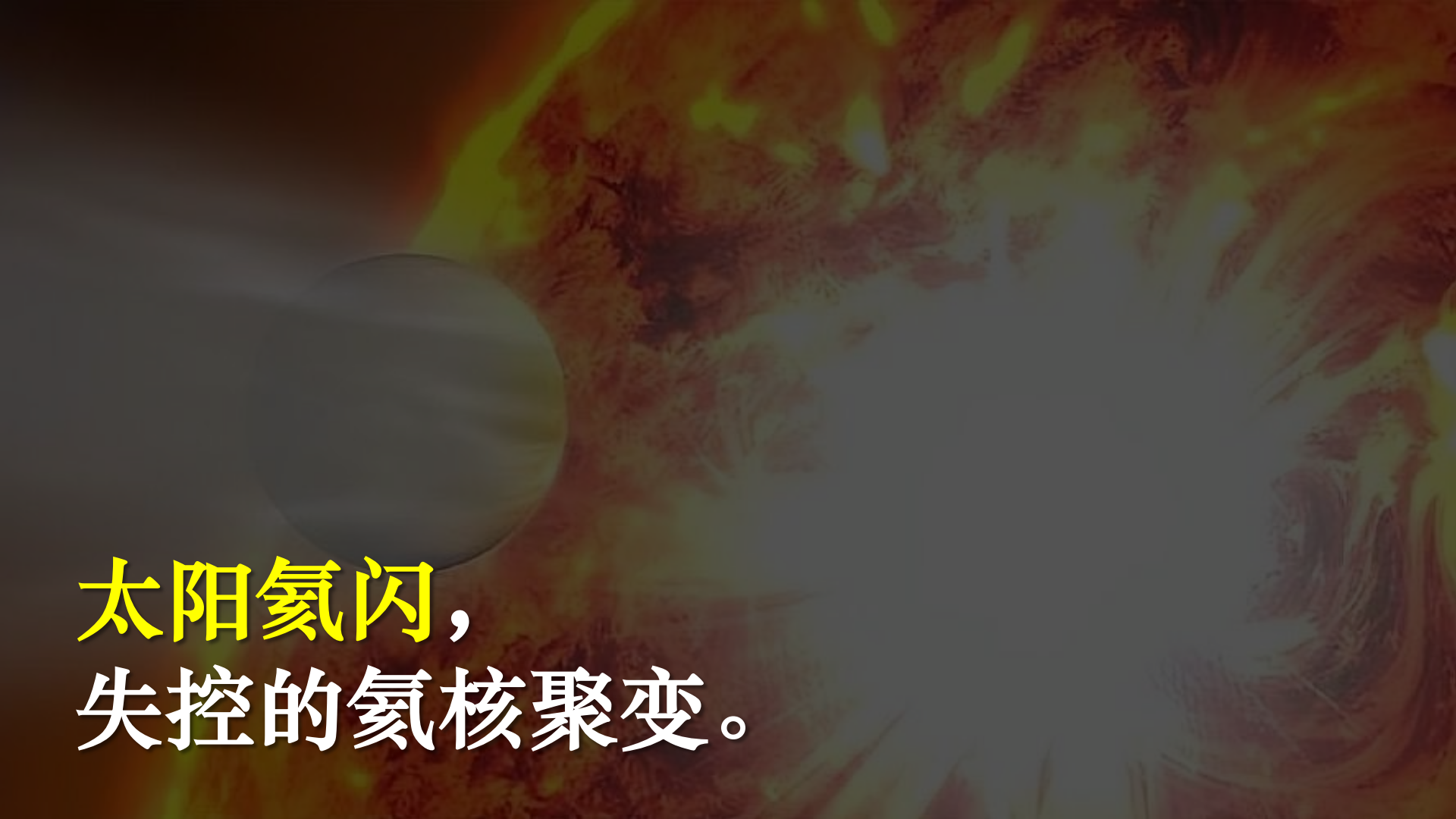
刘慈欣参观PandaX实验室
2024年4月 《东方新科幻》

The background of the image is a movie poster for 'The Wandering Earth'. It depicts a massive, ancient-looking mechanical structure, possibly a giant engine or a massive ship, with a large, circular, metallic component on the left. A massive, swirling plume of dust and debris is being ejected from the structure, creating a large, dark, and turbulent cloud that fills much of the frame. In the upper right corner, a small, blue and white Earth is visible, appearing to be part of the debris or a separate celestial body. The overall scene is set against a dark, starry background, suggesting a space environment. The title '流浪地球' is written in large, stylized red characters on the right side, with 'THE WANDERING EARTH' in English below it. The text 'A FRANTZ GWO FILM' and 'DARK MATTER' are also visible at the bottom right.

地球，
为什么要流浪？

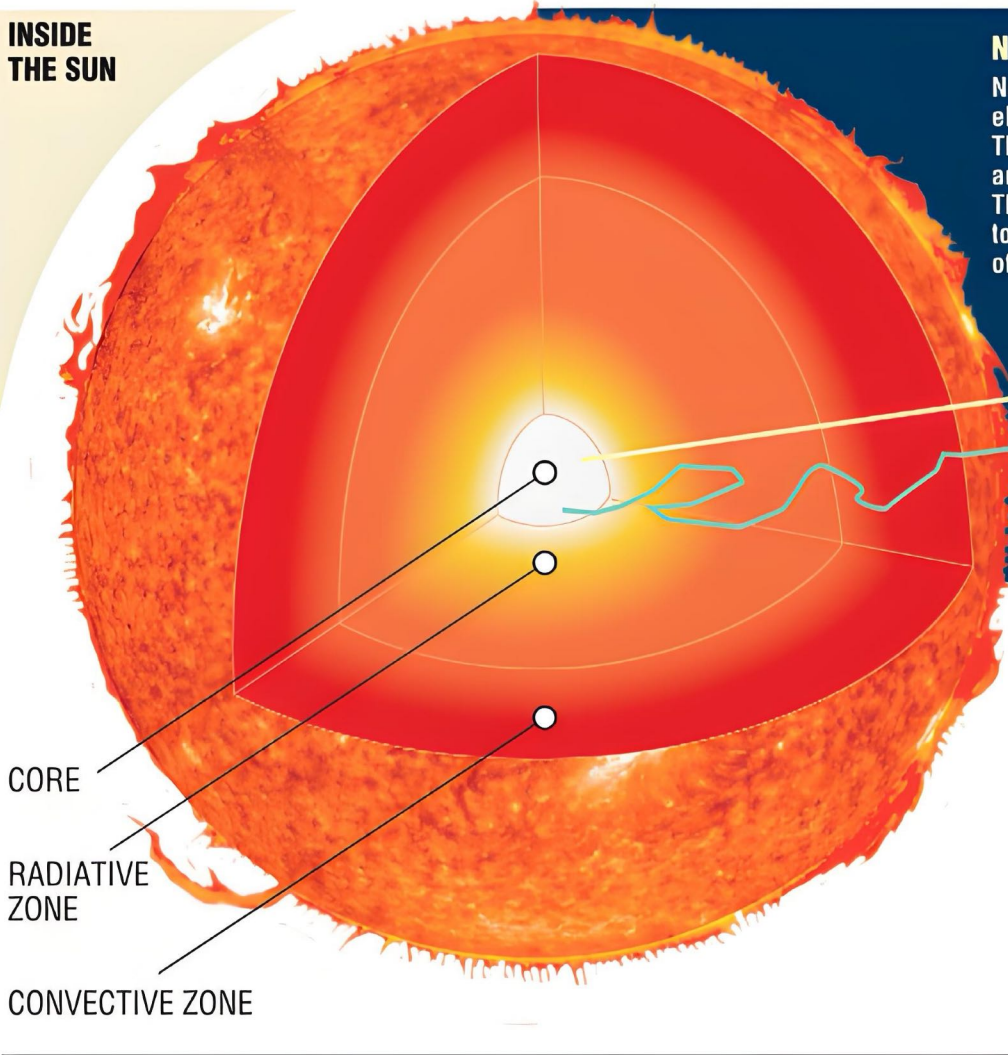
流浪地球

A FRANTZ GWO FILM
THE WANDERING
EARTH
DARK MATTER



太阳氢闪，
失控的氢核聚变。

INSIDE THE SUN



NEUTRINOS

Neutrinos are particles with no electric charge and a tiny mass. They rarely interact with matter and may cross it undisturbed. That's why they take 8 minutes to get there from the core of the Sun to the Earth.

8 minutes

100,000
years

PHOTONS

The radiation studied so far is made up of photons, which interact with solar matter. It takes about 100,000 years for it to reach the Sun's surface and reach Earth.



中微子

中微子是一种不带电，质量极小的粒子。中微子和普通物质相互作用极弱，具有极强的穿透能力

光子

太阳辐射的主要构成是光子，光子和太阳物质发生相互作用

太阳中微子探测器

日本超级神冈实验

5万吨 纯水

直径40米/高40米圆柱

加拿大SNO实验

1千吨重水

直径12米球体

意大利Brexino实验

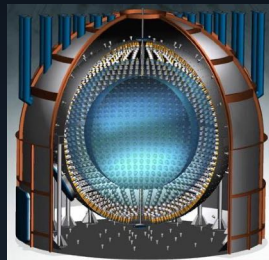
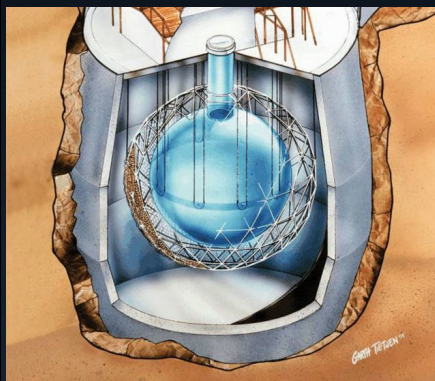
300吨液闪

直径8.5米球体

中国PandaX实验

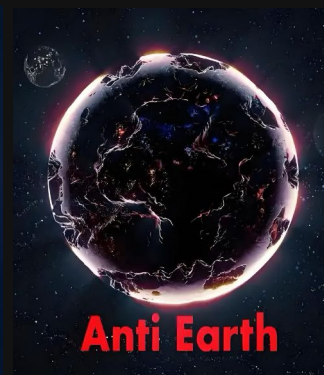
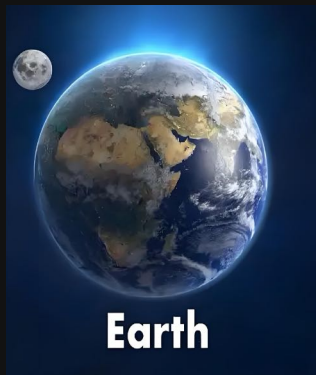
4吨液氙，直径1.2米/高

1.2米圆柱

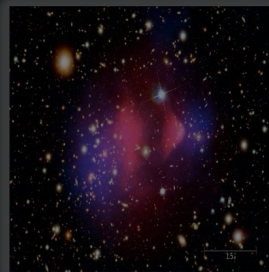


世界最小的太阳
中微子探测器

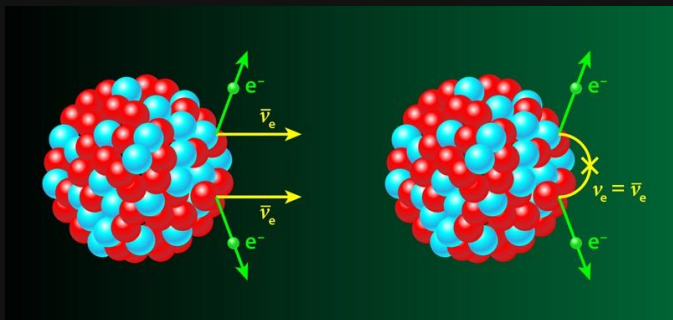
马约拉纳中微子探测



暗物质
信号区 1keV - 10keV



马约拉纳中微子
信号区 > 2MeV



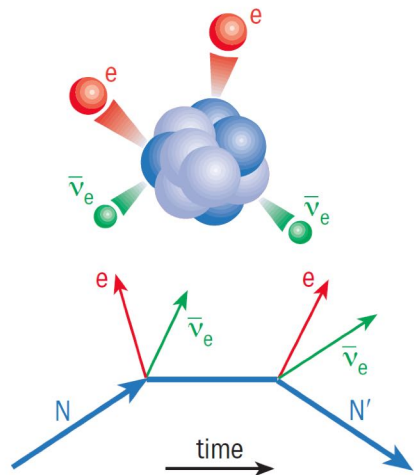
无中微子双贝塔衰变信号



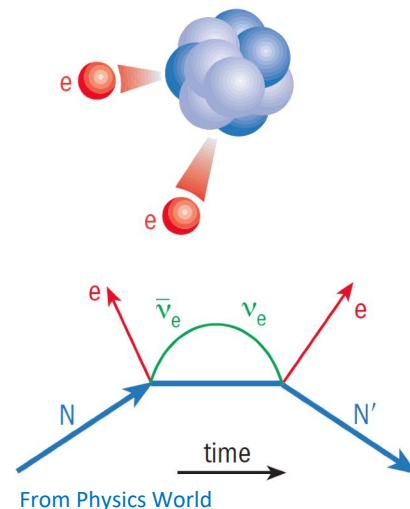
天体中微子
信号区 < 200keV



Majorana neutrino



$$\bar{\nu} = \nu$$



1935, Goeppert-Mayer

Two-Neutrino double beta decay ($2\nu\beta\beta$)

1937, Majorana

Majorana Neutrino

1939, Furry

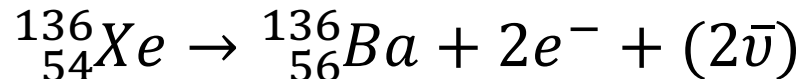
Neutrinoless double beta decay ($0\nu\beta\beta$)

1930, Pauli

Idea of neutrino

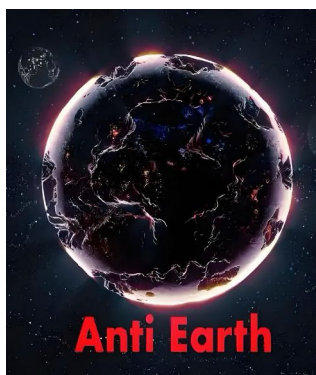
1933, Fermi

Beta decay theory

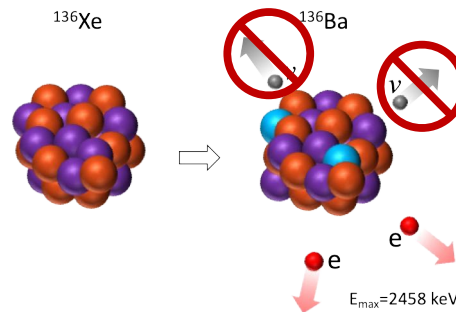


Majorana neutrino

- Lepton number violation
- Matter-antimatter asymmetry of the Universe



- Neutrinoless double-beta decay
 - Effective Majorana neutrino mass



$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \frac{|\langle m_{\beta\beta} \rangle|^2}{m_e^2}$$

Phase space factor

Nuclear matrix element

**Effective Majorana
neutrino mass:**

$$|\langle m_{\beta\beta} \rangle| = \left| \sum_{i=1}^3 U_{ei}^2 m_i \right|$$

Current limit: $T_{1/2} > 10^{26}$ year
(age of the universe: 1.4×10^{10} year)

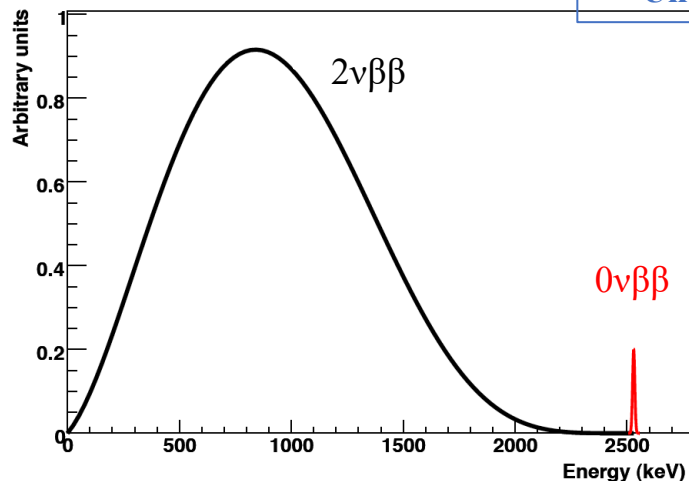


Detection of $0\nu\beta\beta$

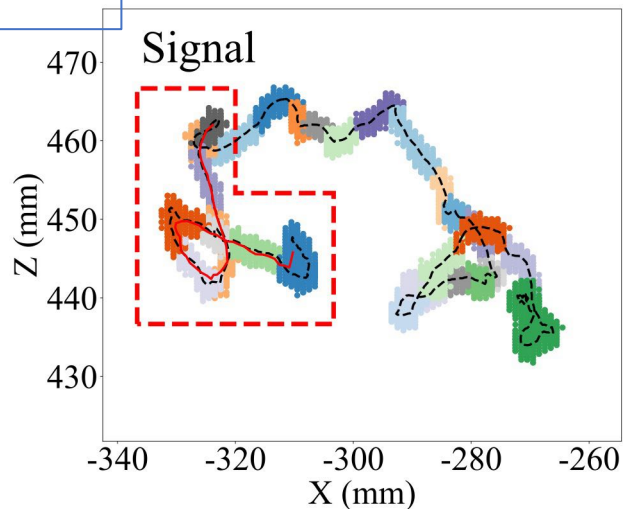
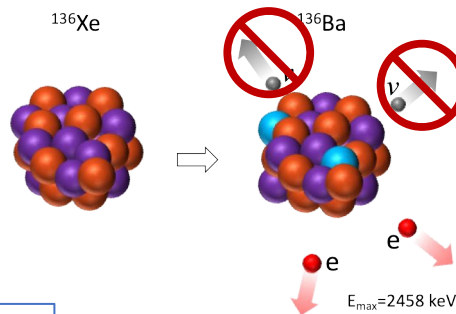
- Measure energies of emitted electrons
- Electron tracks are a huge plus
- Daughter nuclei identification

Background matters!

- Low-radioactive detector
- Shielding
- Underground



Sum of two electrons energy (not in scale)



Simulated track of $0\nu\beta\beta$ in high pressure Xe

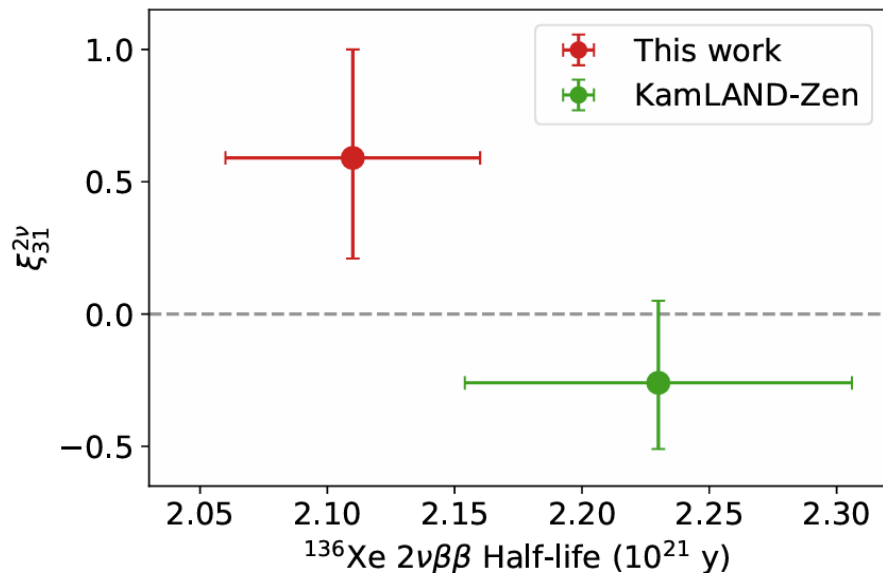
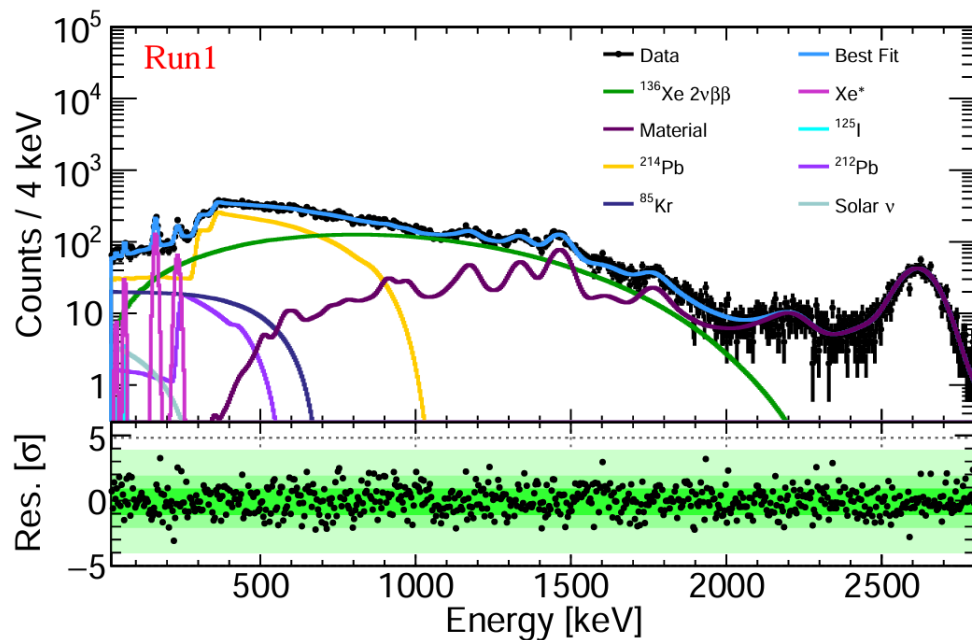


Most accurate ^{136}Xe $2\nu\beta\beta$ (rate/spec)!



- 39.1 kg×year of ^{136}Xe , best fit: 54k events!
- Providing info of nuclear matrix element

PRL 136, 162501 (2026)

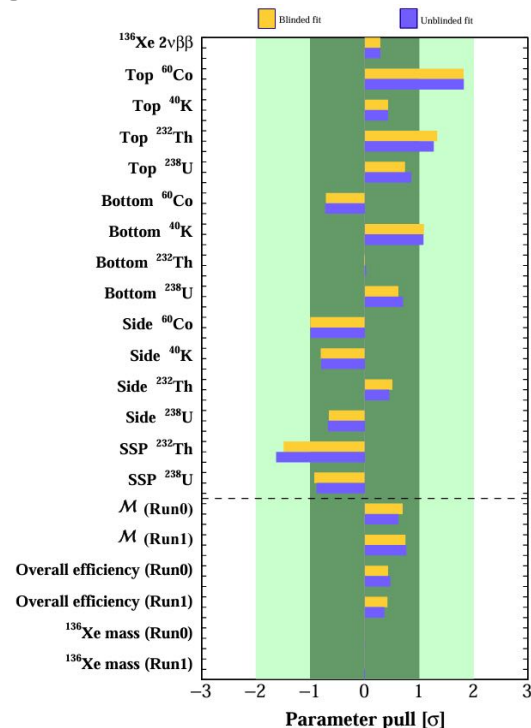
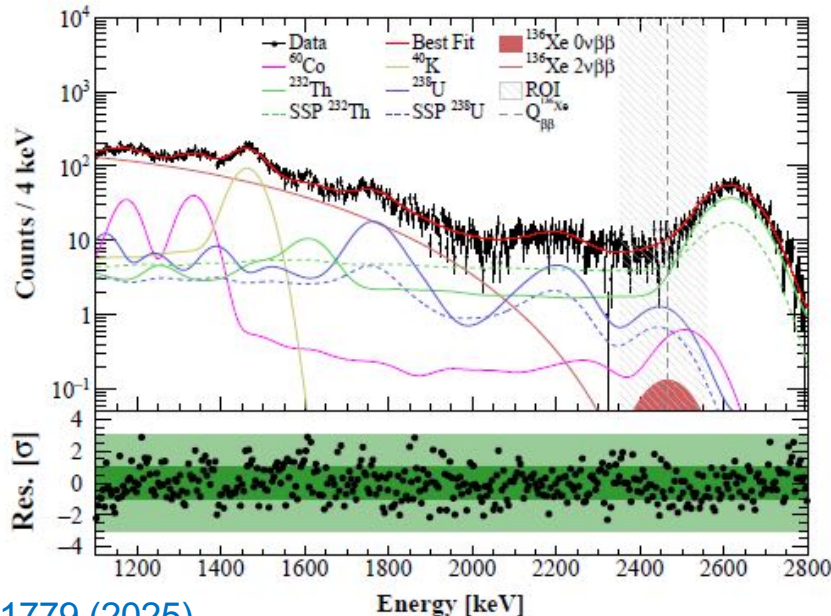


Search for $^{136}\text{Xe } 0\nu\beta\beta$

Run0 + Run1 Data



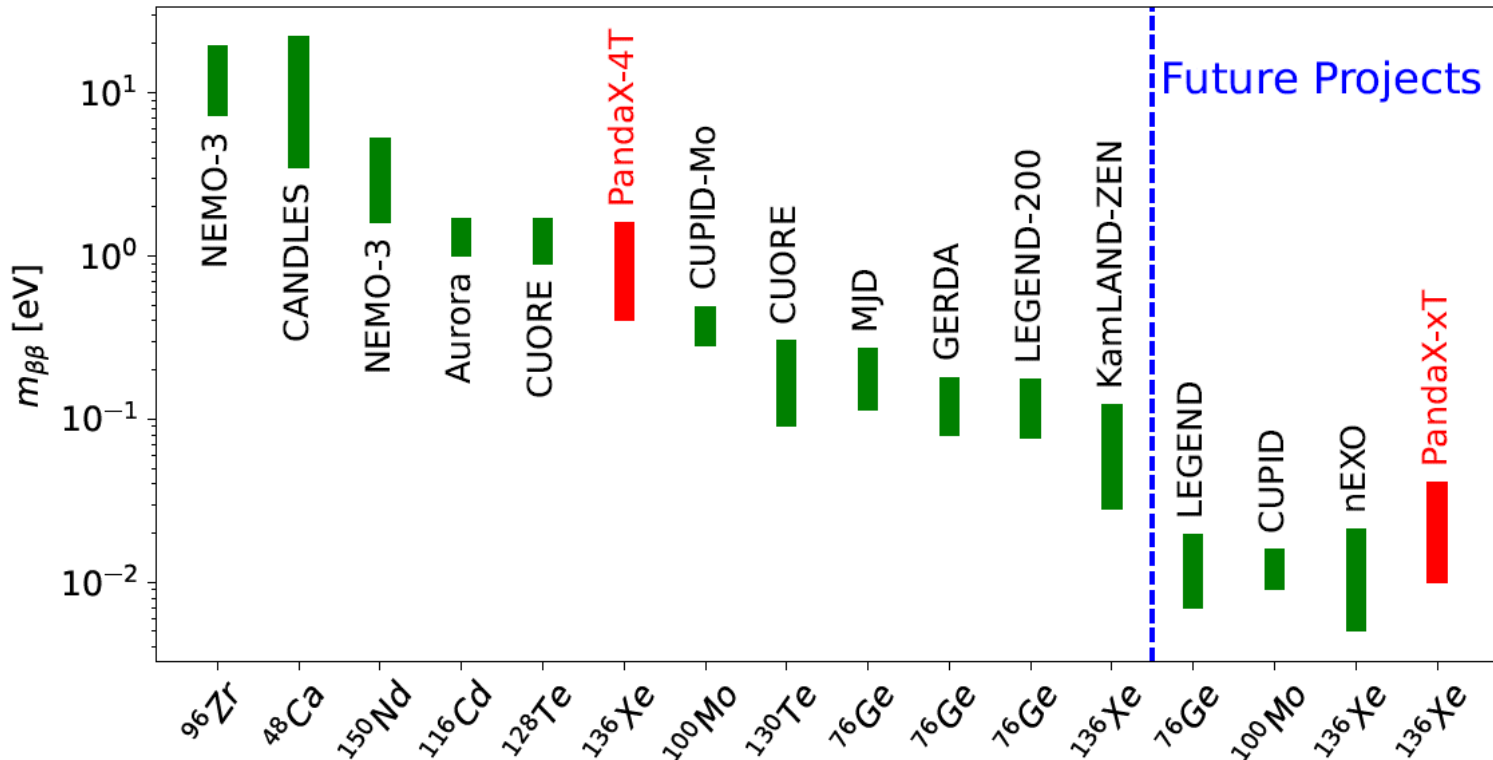
- In-situ fit of material radioactivity
- Best constraints from natural xenon detector
 - $T_{1/2} > 2 \times 10^{24} \text{ yr}$



Race of Majorana neutrino mass



- Getting into world-wide effort



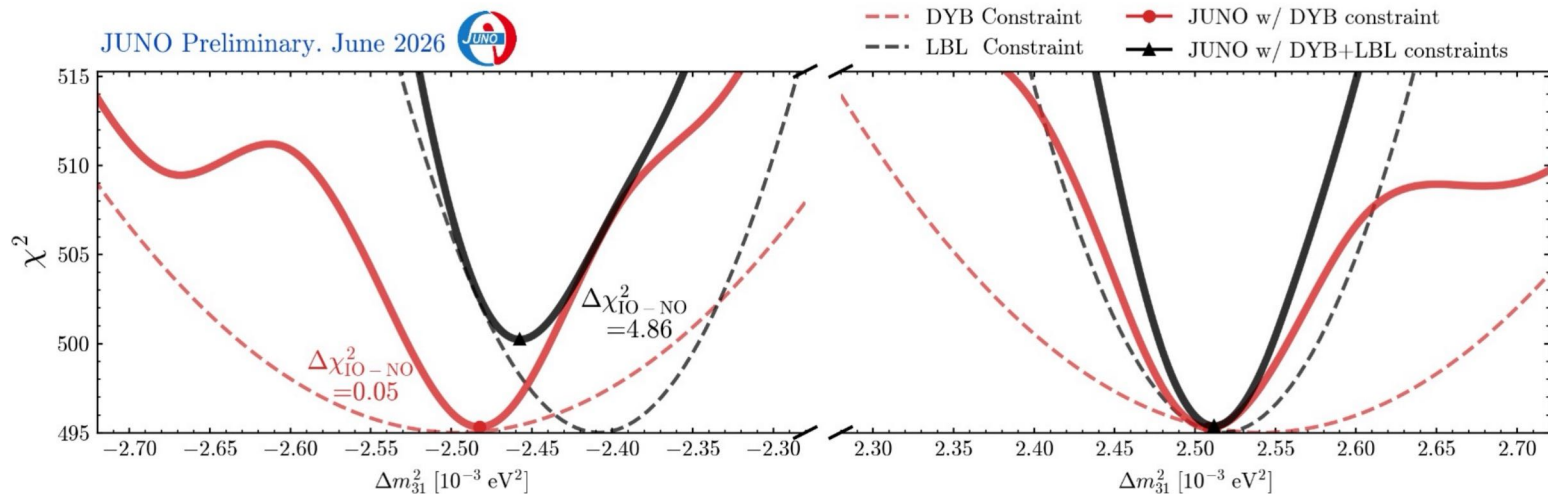
Neutrino mass ordering



Adding Constraint from NuFit-LBL



- ◆ 在正确的中微子质量排序下，由反应堆中微子实验和加速器中微子实验测得的 Δm_{31}^2 应该是一致的[1]
- ◆ 采用文献 [2] 中的 NuFit-LBL 结果作为外部约束后: $\Delta\chi^2 = 4.86$ 倾向于正序.



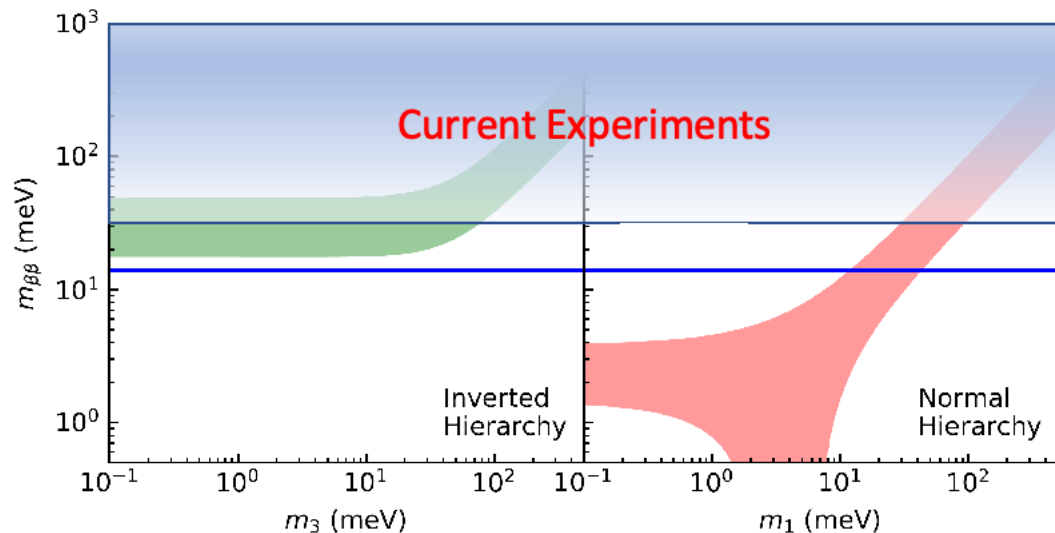
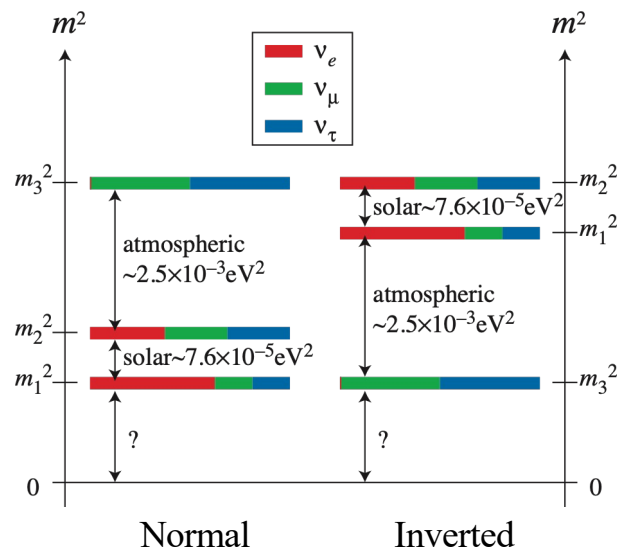
- [1] H. Nunokawa, S. Parke and R.Z. Funchal, Phys. Rev. D 72 (2005) 013009; Y. F. Li et al., Phys. Rev. D 88, 013008 (2013)
[2] NuFIT 6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380]), www.nu-fit.org and M. Maltoni private communication

Neutrino mass ordering



**Effective Majorana
neutrino mass:**

$$|\langle m_{\beta\beta} \rangle| = \left| \sum_{i=1}^3 U_{ei}^2 m_i \right|$$

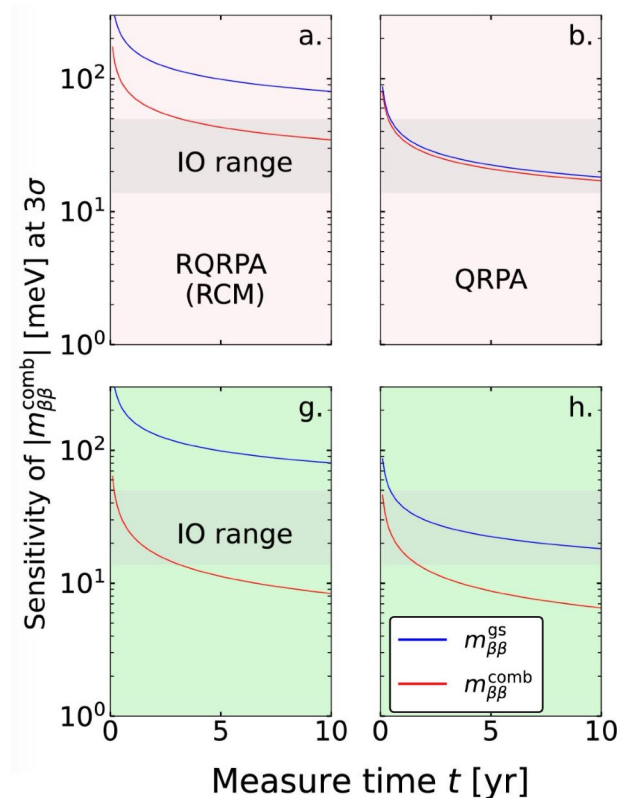
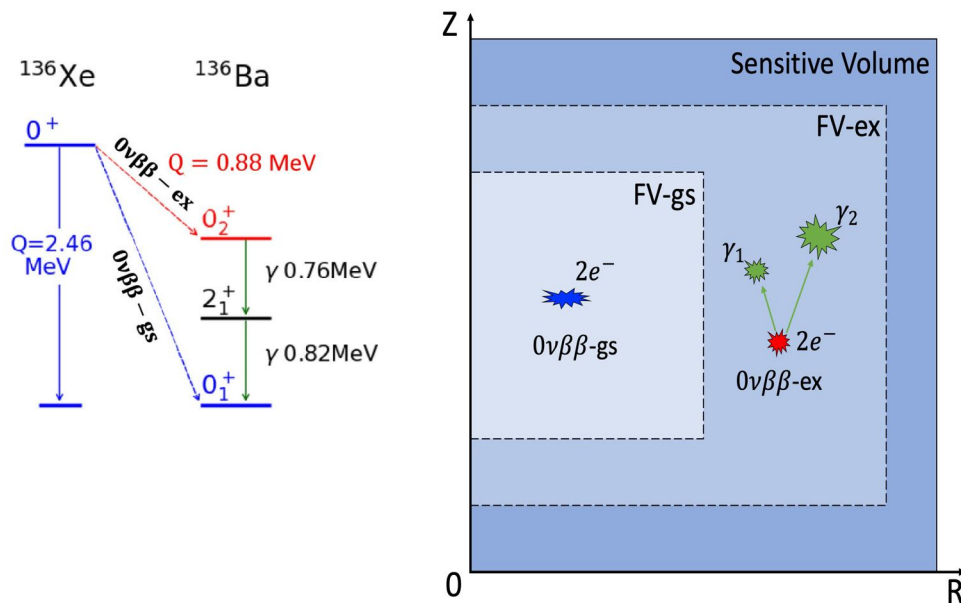


^{136}Xe 0vDBD to $^{136}\text{Ba}^*$



• Multi-site events

- unique advantage of natural xenon



^{134}Xe 2 ν DBD and 0 ν DBD

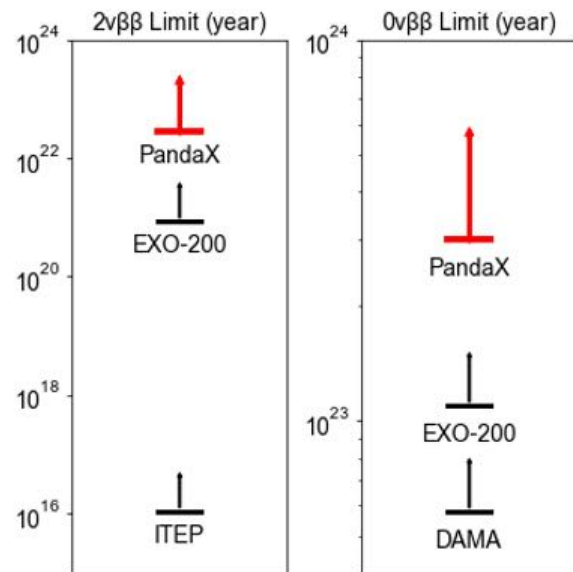
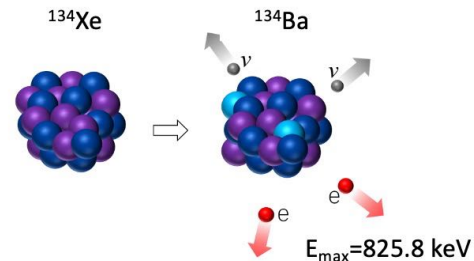
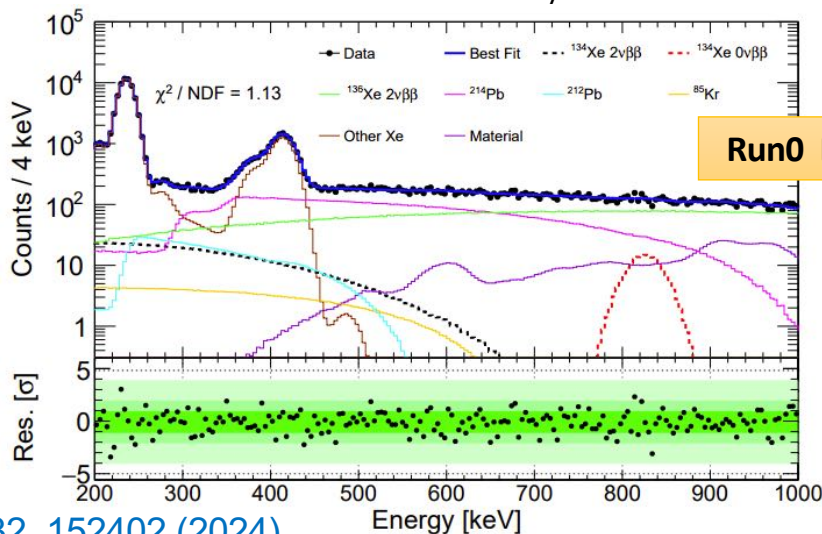


- Next promising discovery of 2 ν DBD decay

- natural abundance 10.4%, $Q_{\beta\beta}$ 0.83 MeV

- 95 live-days with 656 kg natural xenon

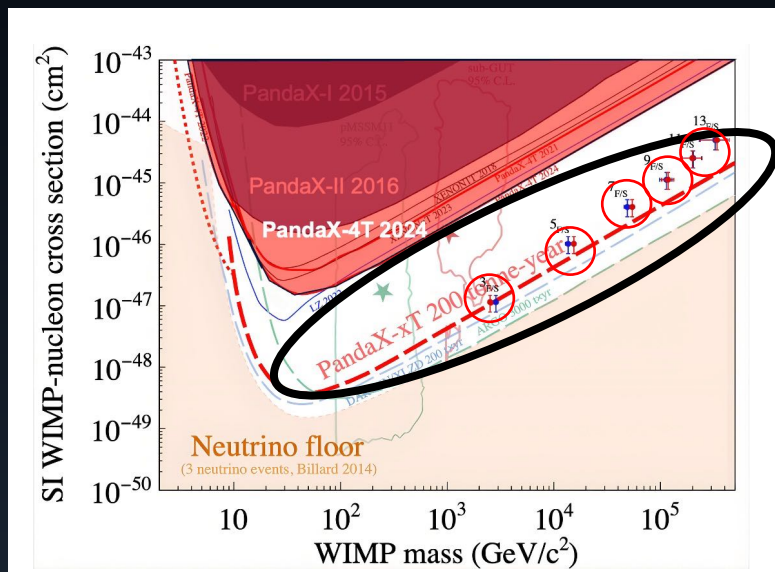
- 90%CL limits on half-life $T_{1/2}^{2\nu\beta\beta} > 2.8 \times 10^{22}$ yr



The public needs answers



“终极”目标：对主流暗物质理论给出关键性检验



需求：200吨-年的数据曝光量

PandaX-4T：4吨探测器运行50年

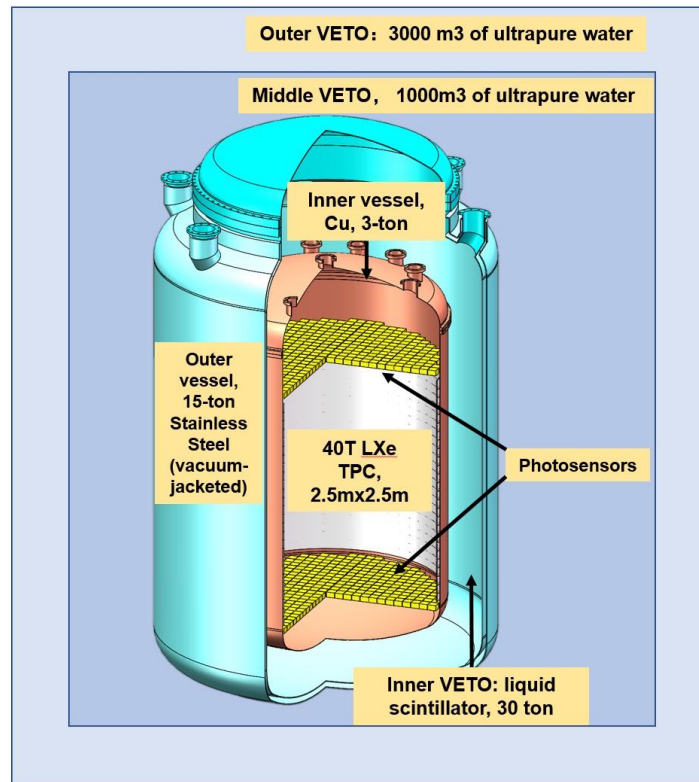
“体量”换“时间”

PandaX-xT：40吨探测器运行5年

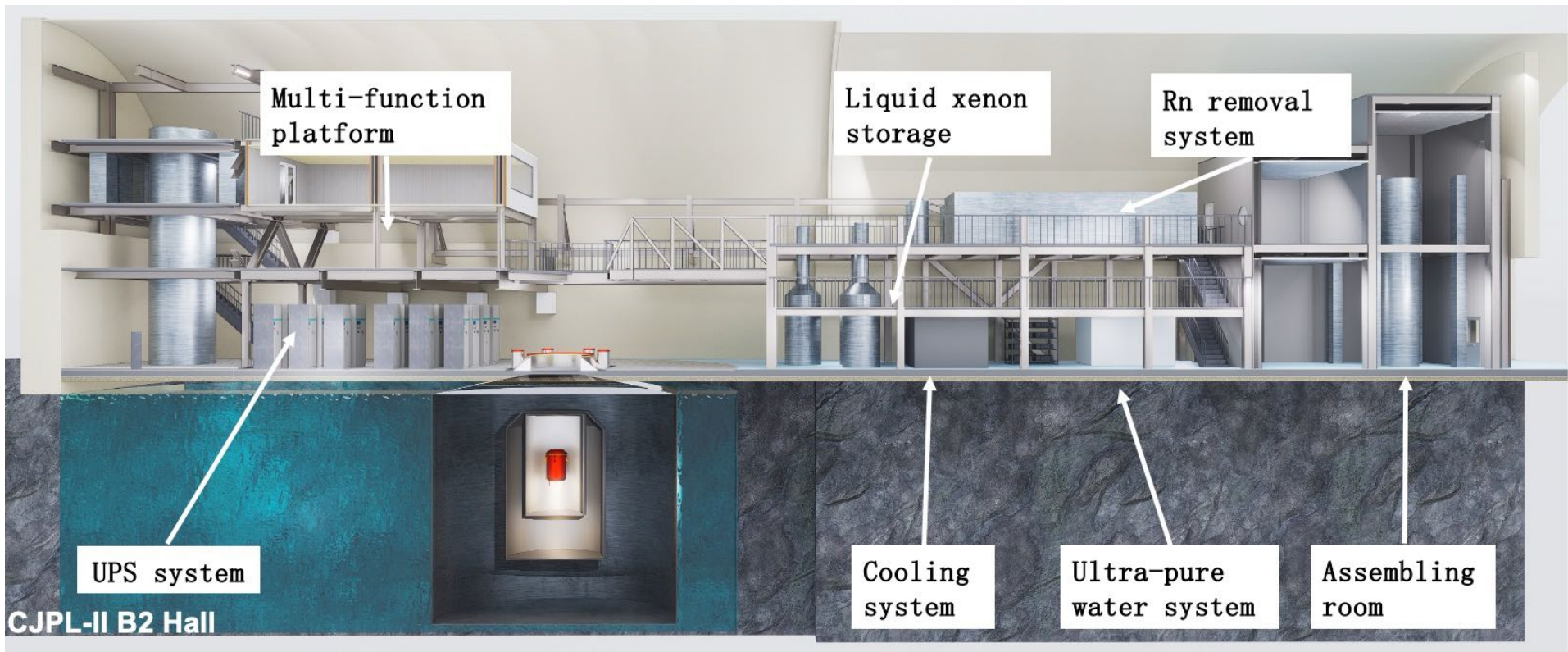
Future experiment: PandaX-xT



- Eventually, 47-ton xenon, including 40-ton sensitive volume
 - TPC 2.5m in diameter and 3m in height
 - Cold LS veto right outside Cu cryostat
 - Staged and upgradable
 - Dual-phase or single-phase options
- **First stage is PandaX-20T**



PandaX-xT Infrastructure



Transporting xenon to CJPL



Titanium cryostat



- **Inner vessel**

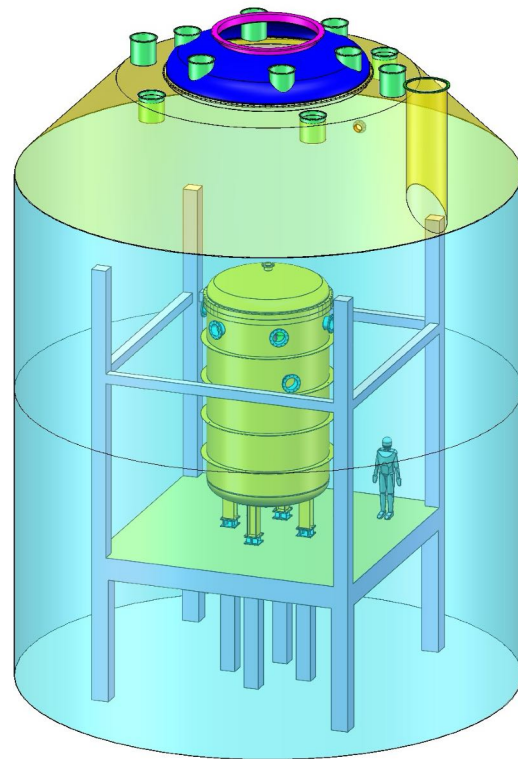
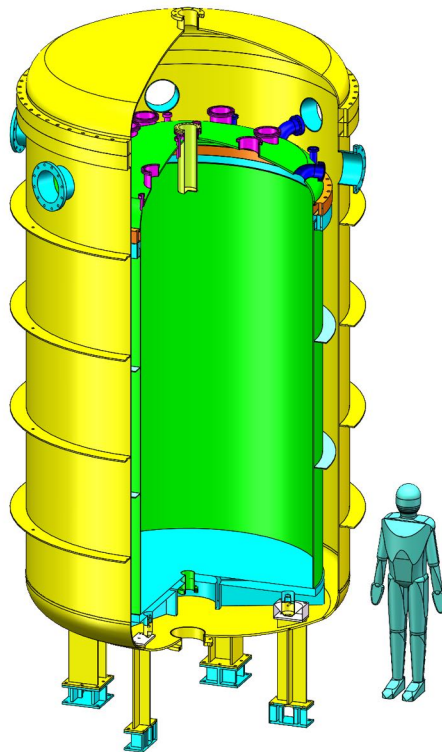
- ID 2000mm, height 3000mm
- Barrel thickness 8mm
- 0.1~0.45MPa

- **Outer vessel**

- ID 2400mm
- Barrel thickness 10 mm

- **Water shield**

- 10m diameter and 13m height



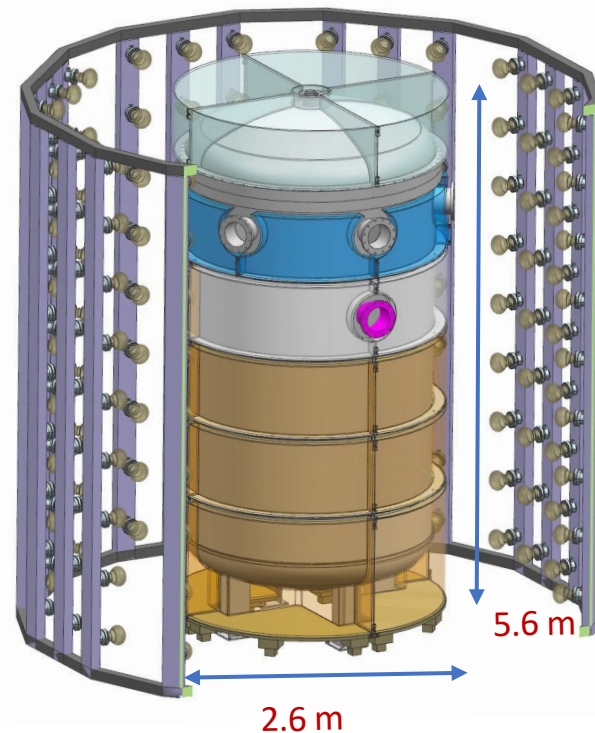
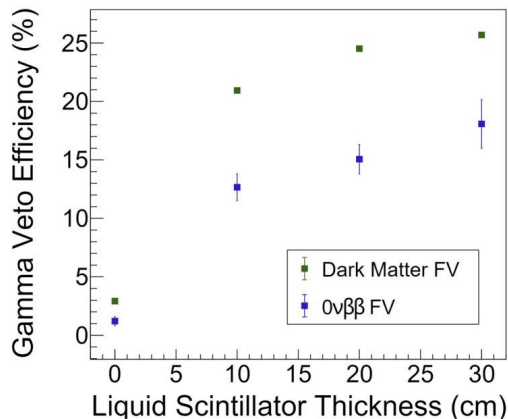
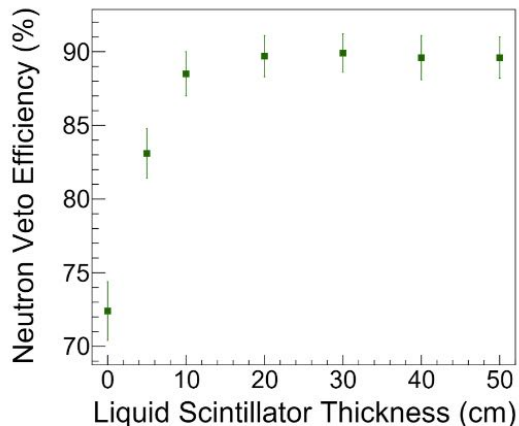
Cryostat in fabrication



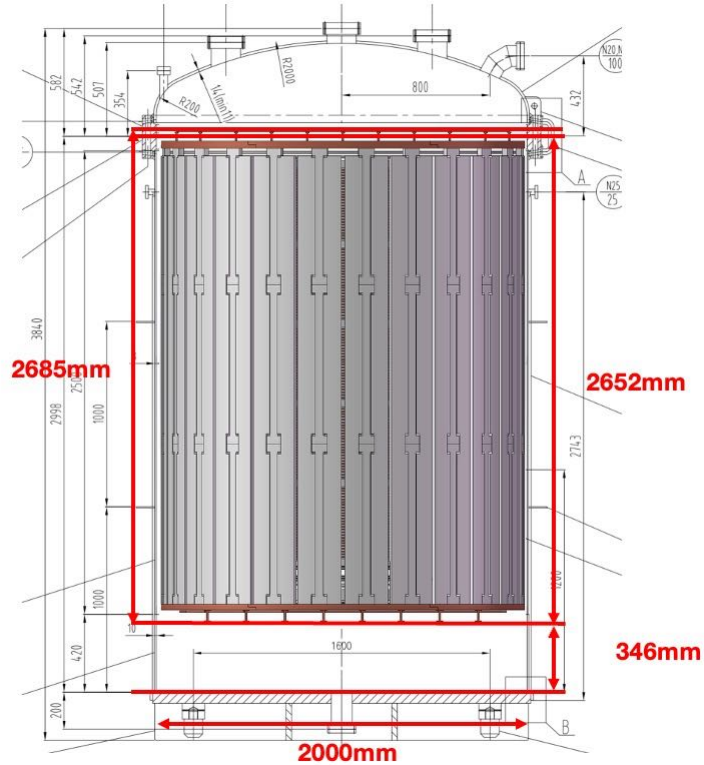
Veto upgrade



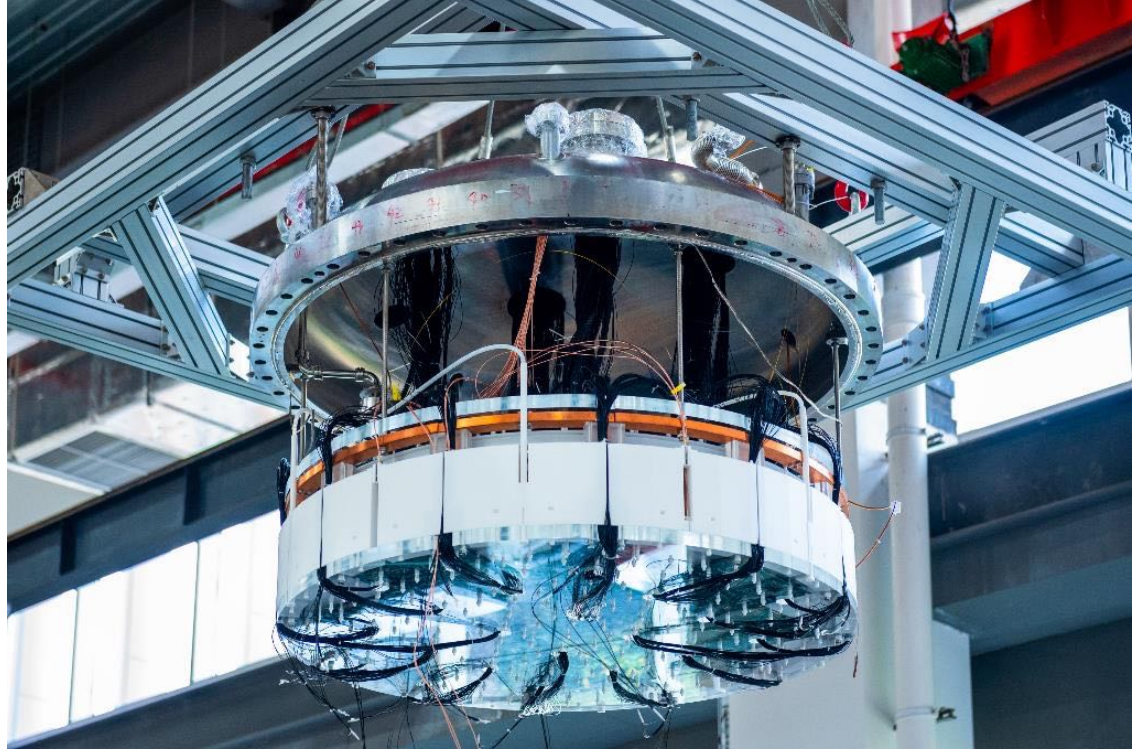
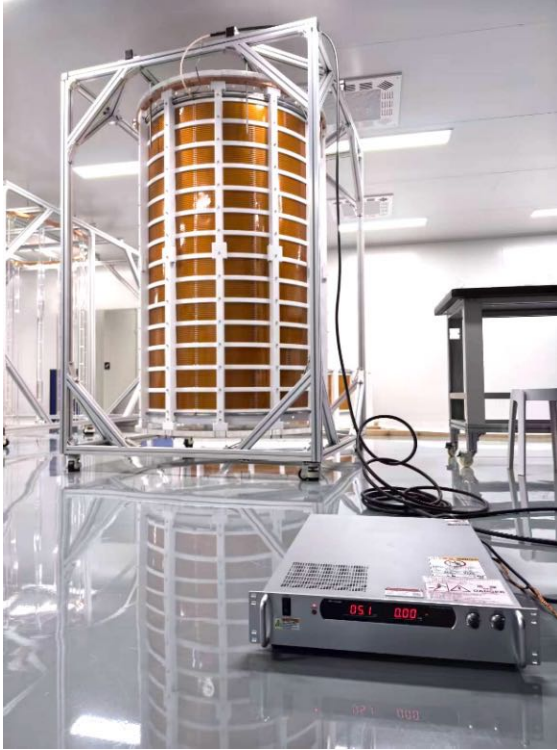
- 10cm thickness JUNO liquid scintillator in acrylic containers
- Optical simulation
 - close to 90% neutron veto efficiency
 - about 20% gamma veto efficiency



- 17 tonne sensitive mass



Field cage and prototype tests

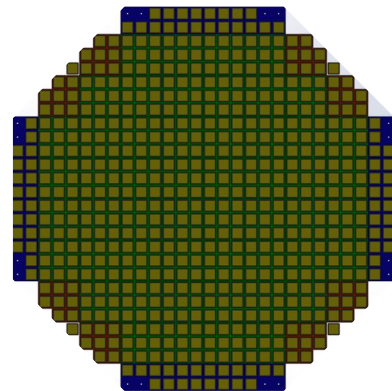


PMT system



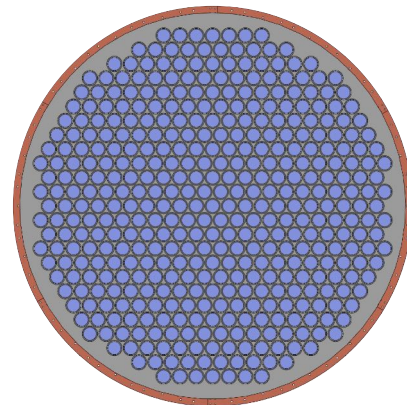
- **Top PMT array**

- 616 2inch multi-anode PMTs (R12699)
- Mainly 3×3 PMT array tiles
- Flexible-Rigid PCB (FRP) boards for integrated HV/signal readout lines with base



- **Bottom PMT array**

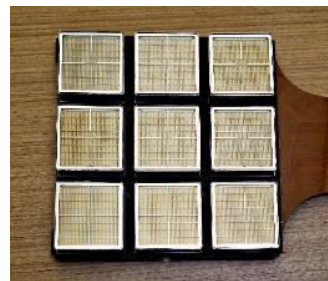
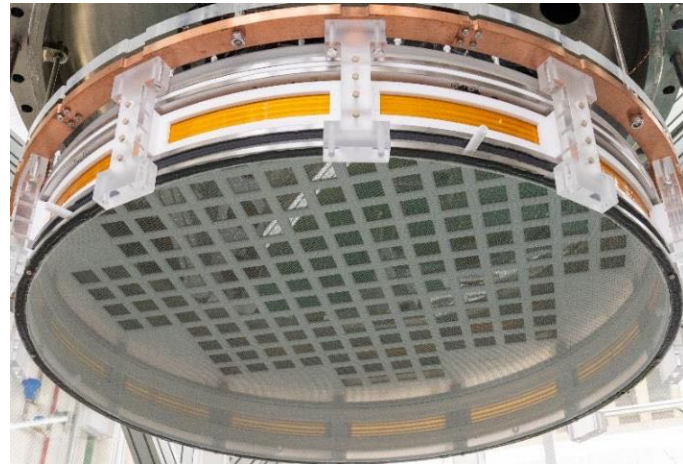
- 433 3inch PMTs (PandaX-II and PandaX-4T)
- Mainly 19 PMT array tiles
- Flexible PCB bases



PMT array tests



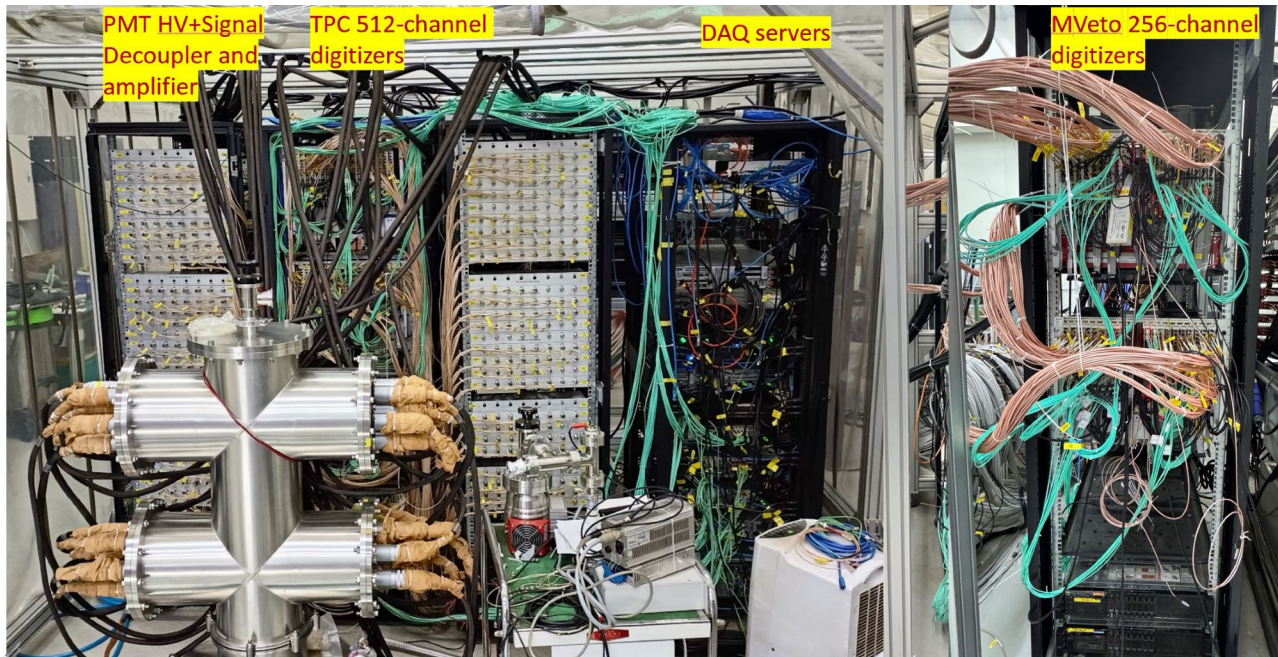
- **Low-radioactivity R12699 PMTs under production**
 - Delivery scheduled for 2026
- **Assembly and system-level testing in progress**



500 MS/s digitizers



- Inherited from PandaX-4T



768-channel in PandaX-4T CJPL



3000-channel in TDLI

Liquid xenon storage and handling



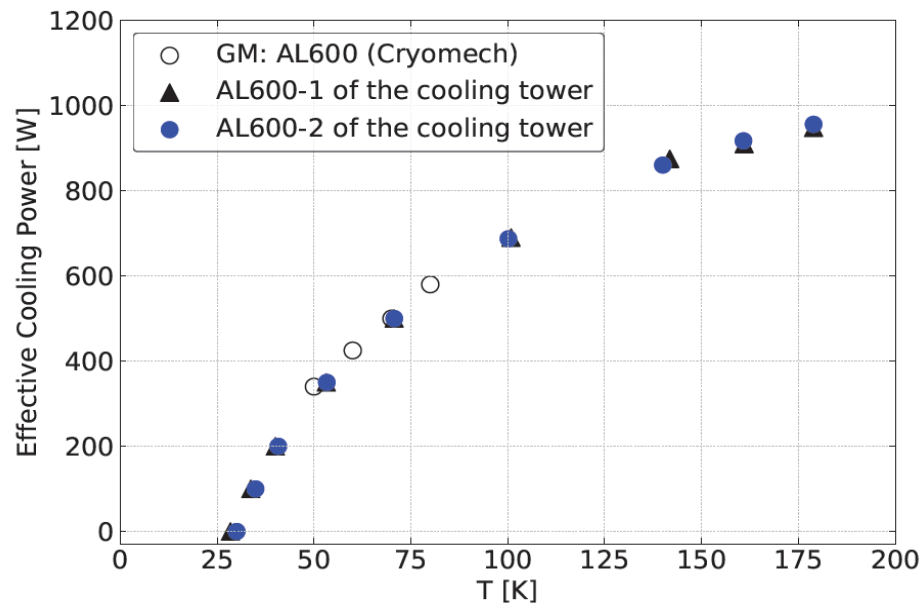
- Each storage tank: **6m³ (maximum 18 ton)** of LXe
- Cryogenic pump: filling/emptying detector @ 1.5 ton/hour.



Cryogenics and recirculation



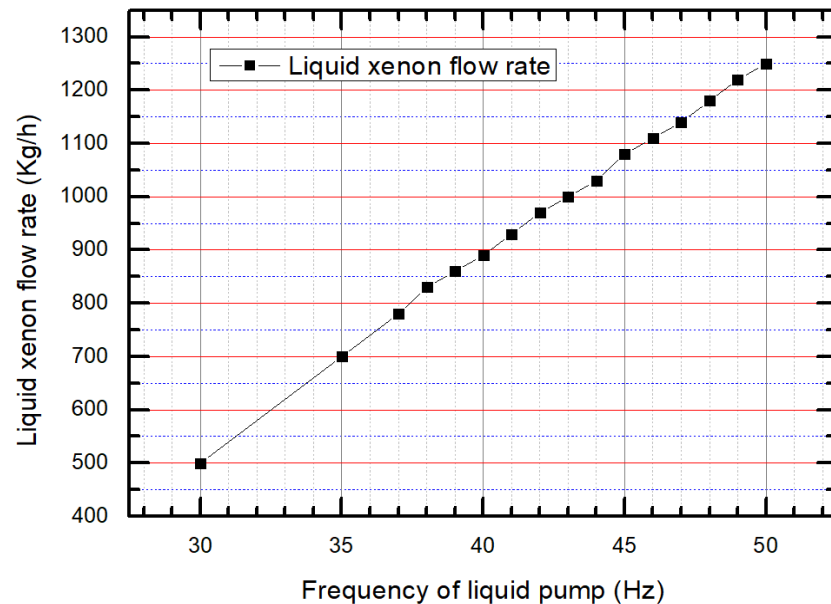
- **Cooling Power (tested at TDLI)**
 - 1900W@178K (2*GM Cryocoolers)



Cryogenics and recirculation

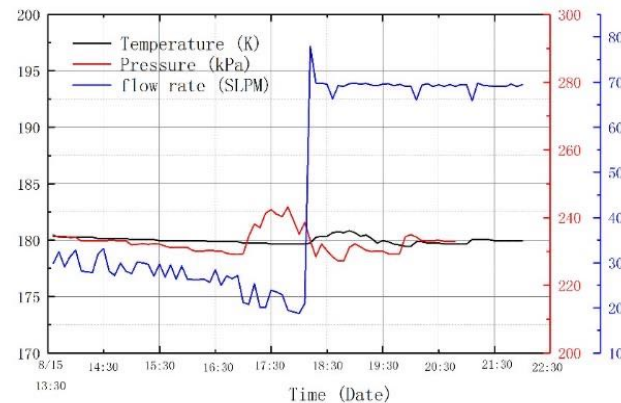
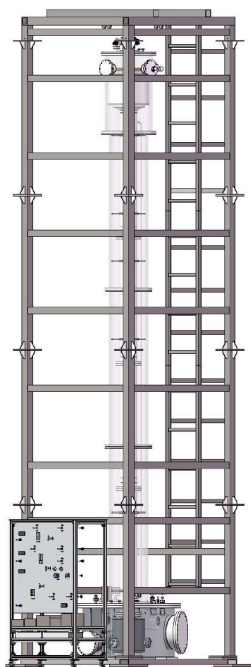


- **Online purification speed (tested at TDLI)**
 - ~3.1 tonne/day for gas (2*LOOPS)
 - ~16 tonne/day for liquid

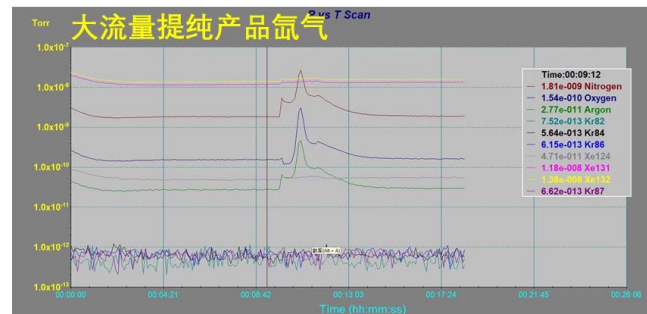


Distillation towers

- Kr distillation tower : 30 kg/hour
- Target Kr concentration in Xe: 0.1 ppt



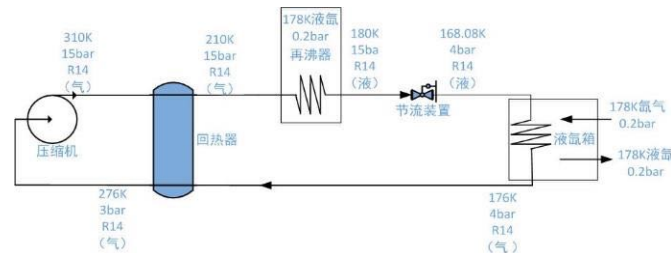
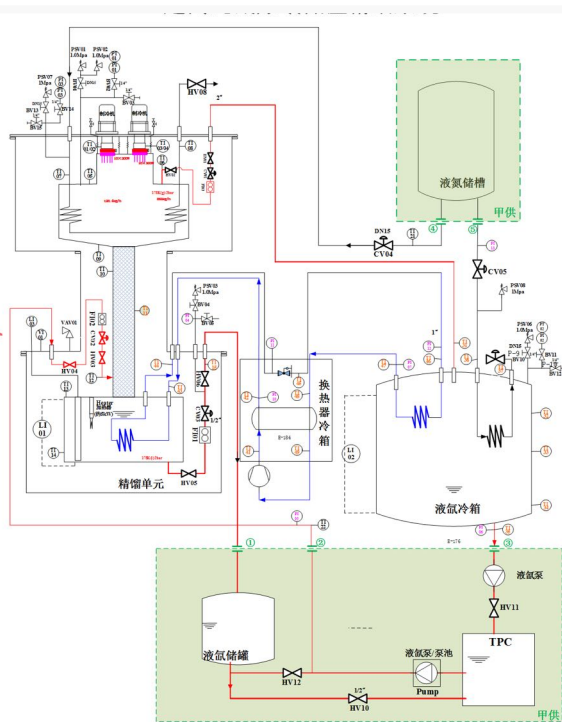
Temperature, pressure and flow rate during stable distillation



RGA spectrum of the product Xe measurement

Distillation towers

- Rn distillation tower : 850 kg/hour
- Target: $0.5 \mu\text{Bq/kg}$



High-power cooling recovery R&D System
Target: 20kW cooling power for 850kg/h circulation

Background sources of 20T

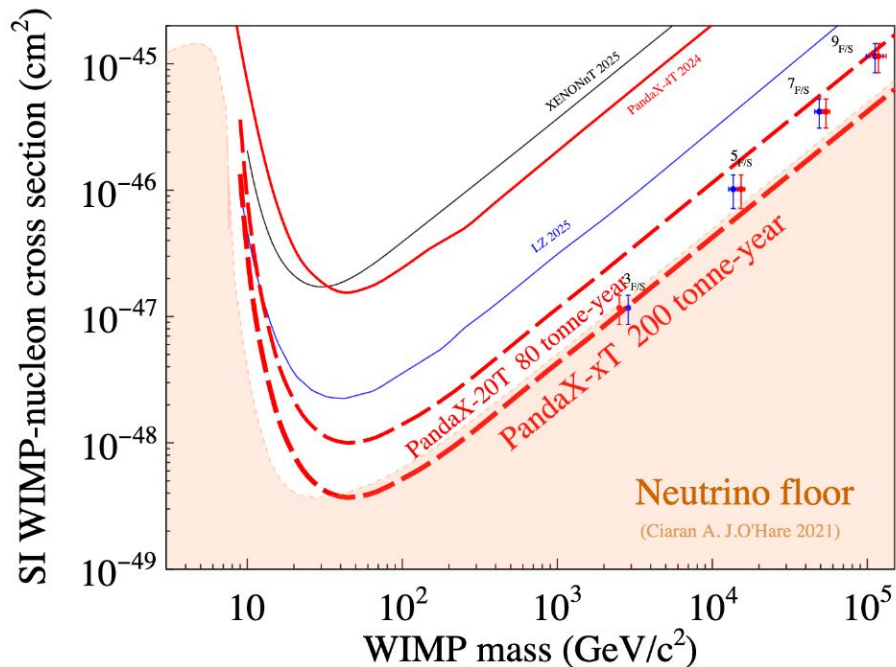


Component		Background assumption
1	Photosensors	U/Th/K = 0.002/0.003/1.4 mBq/cm ² Hamamatsu R12699 v2
2	Inner/Outer Ti vessel	U _{early} /U _{late} /Th 1200/22/200 ppt (g/g)
3	Kr	0.1 ppt (mol/mol)
4	Rn-222	0.5 μBq/kg

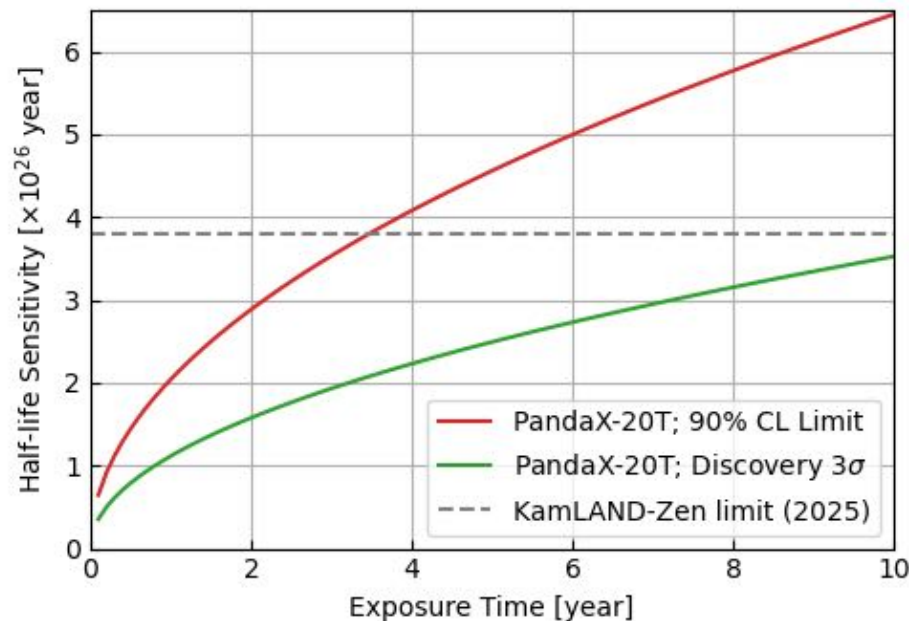
Baseline scientific potential of 20T



- WIMP and Xe-136 $0\nu\beta\beta$



FV 13 ton, ROI 1-10 keVee, 99.7% ER rejection



FV 2.4 ton natural, 1% resolution

PandaX-20T schedule



- **2026.6-2026.12**
 - Infrastructure construction
- **2027.1-2027.6**
 - PandaX-20T installation
- **2027.7-2027.12**
 - PandaX-20T commissioning
- **2028.1-**
 - Physics operation

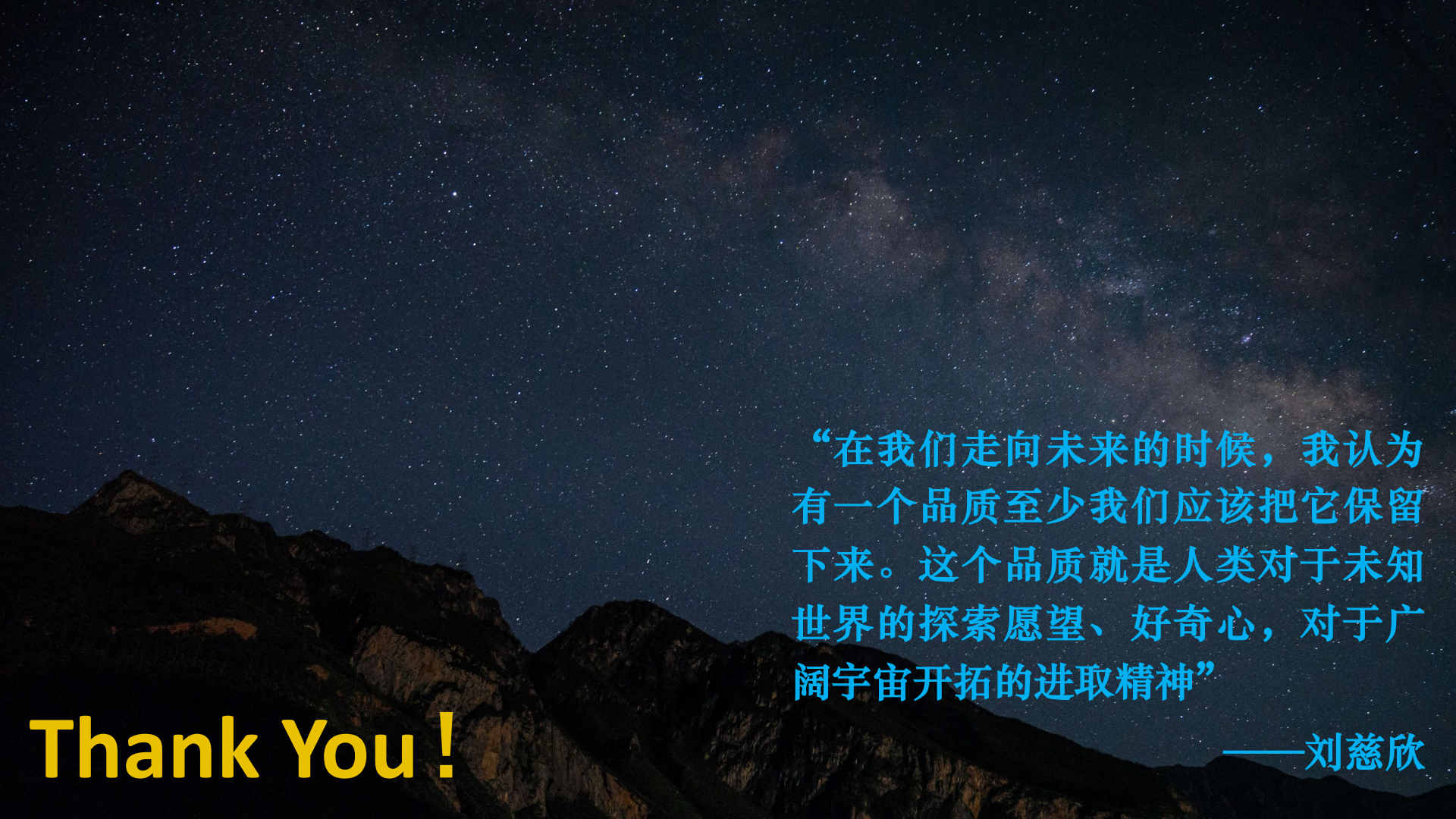




1933 – 2033
破解暗物质百年谜团

Summary

- The detection of dark matter is a crucial component in the exploration of new physics
- Experiments are developing rapidly, presenting significant opportunities for important discoveries
- Further develop flagship experiments and unlock their new potential
- Actively expand new detection methods to cover a broader parameter space



“在我们走向未来的时候，我认为有一个品质至少我们应该把它保留下来。这个品质就是人类对于未知世界的探索愿望、好奇心，对于广阔宇宙开拓的进取精神”

——刘慈欣

Thank You !