无中微子双贝塔衰变的探索

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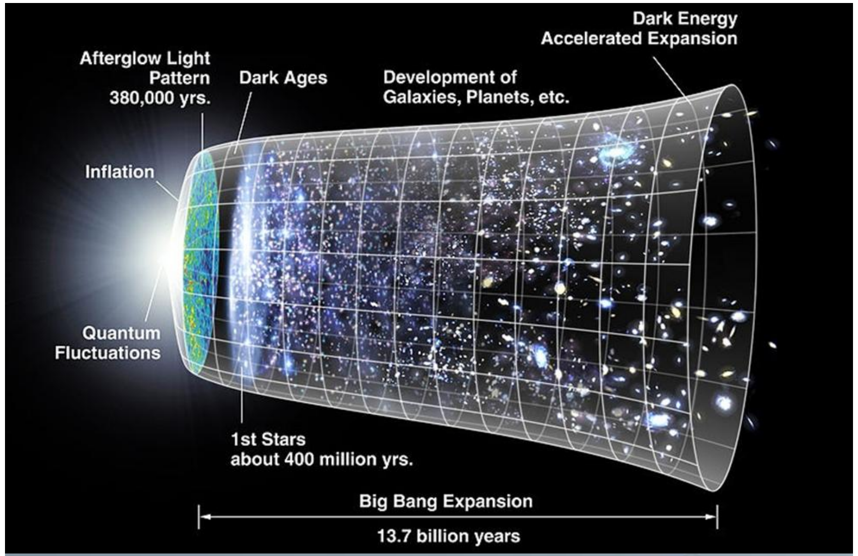
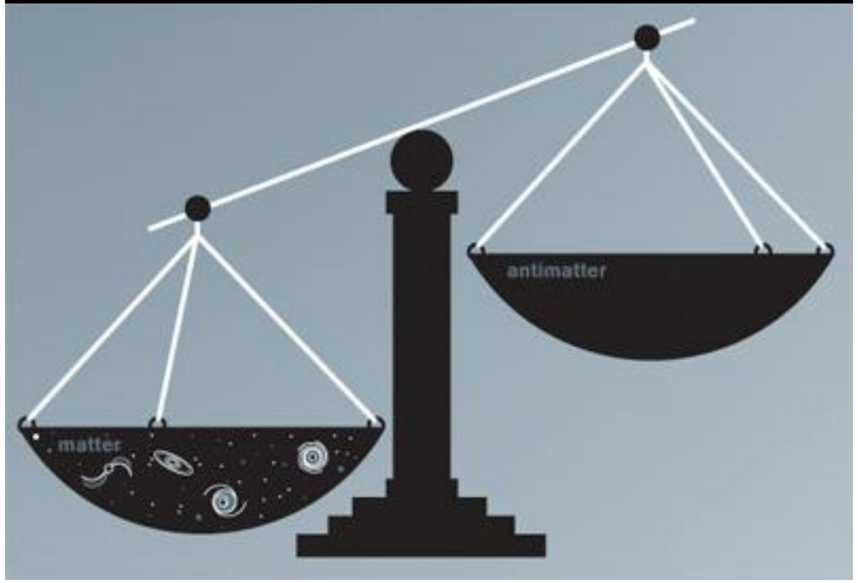
第二十届全国中高能核物理大会暨
第十四届全国中高能核物理专题研讨会
上海，2025年4月28日

问题1：正反物质的不对称性





大爆炸

↓

当前宇宙

↕ ?

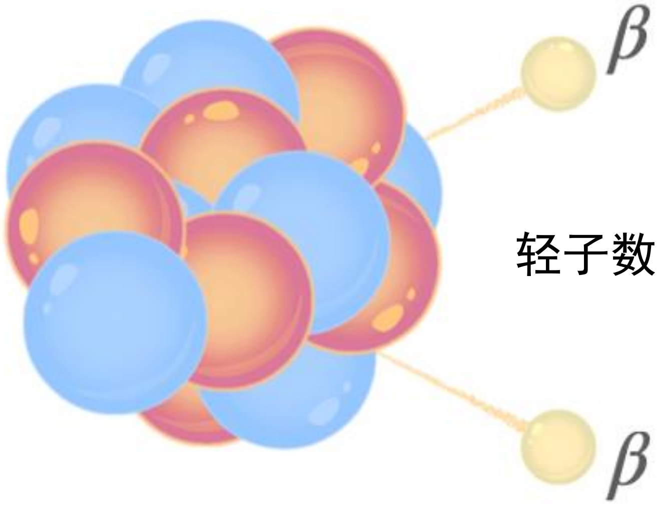
正物质

>>

反物质

无中微子双贝塔衰变：

产生正物质而无反物质伴生的过程



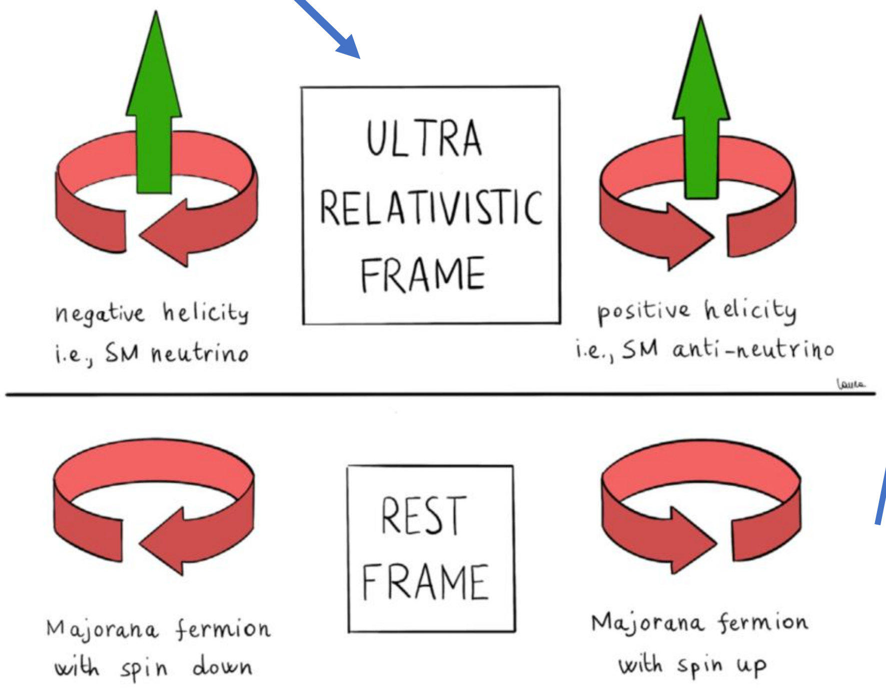
轻子数守恒被打破

$$(A, Z) \rightarrow (A, Z+2) + 2\beta^-$$

问题2：中微子的反粒子是其本身吗？

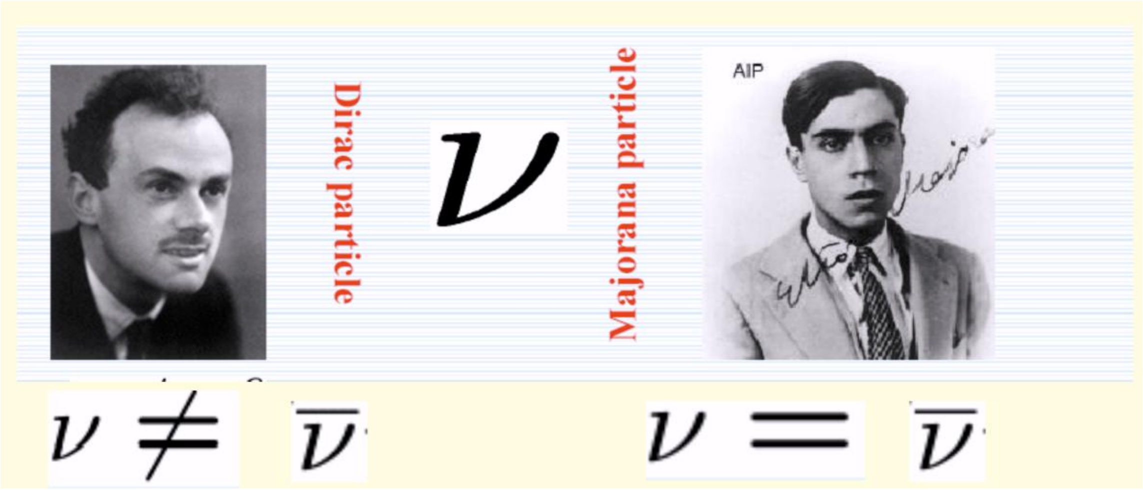
区分ν与 $\bar{\nu}$:

- 衰变伴生的带电轻子种类
- helicity



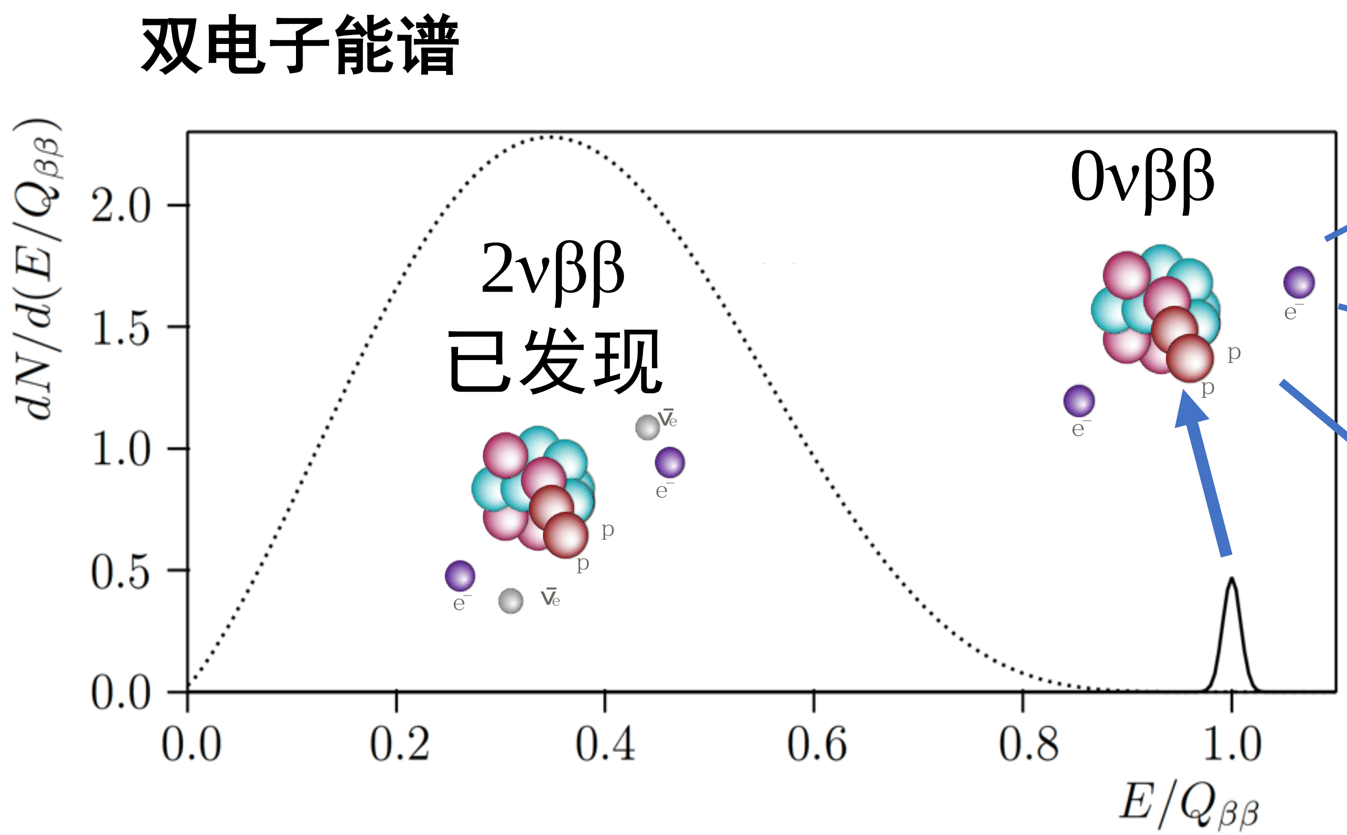
REVIEWS OF MODERN PHYSICS, VOLUME 95, APRIL–JUNE 2023

在假想的静止参考系中，区分ν与 $\bar{\nu}$ 需要一个专为这一目的而设置的量子数，如轻子数—**也许**不够自然



中微子做为马约拉纳费米子**也许**更自然

无中微子双贝塔衰变探测



非常明确的实验观测目标 ＋ 丰富而重要的物理意义

一点点历史

1935： Goeppert-Mayer提出2νββ，并预测其半衰期 >10^{17}年

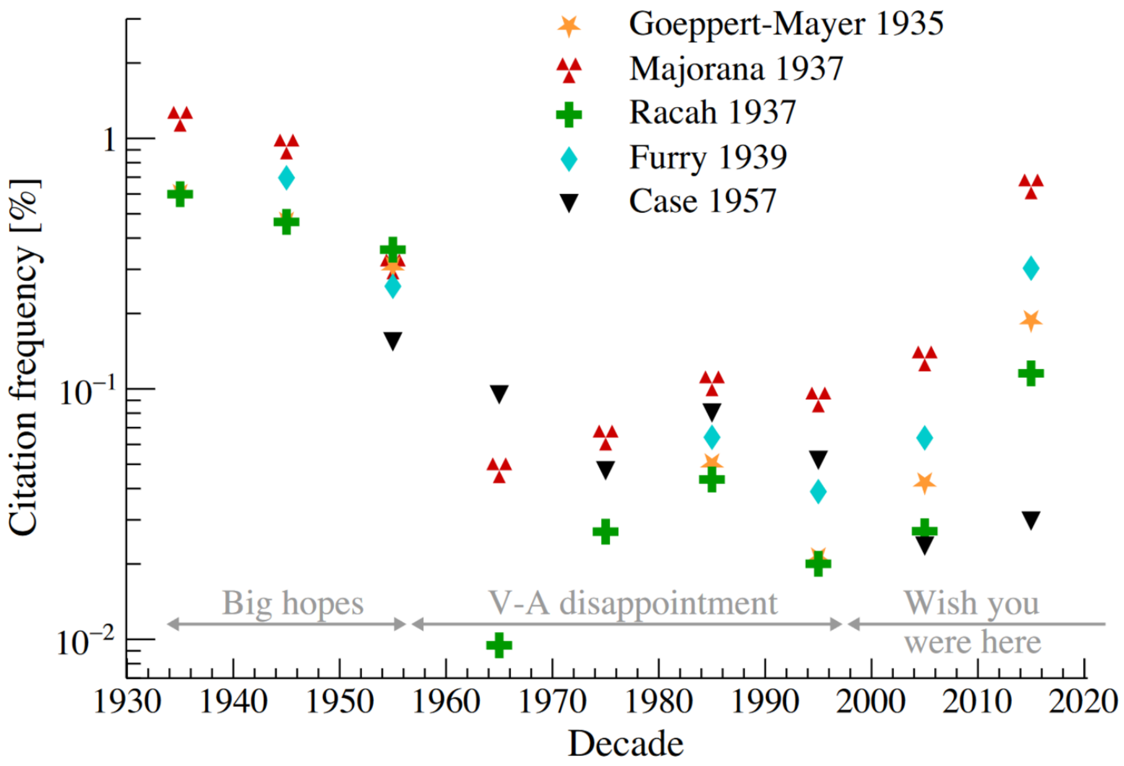
1937： Majorana提出Majorana费米子假设，并指出中微子可能是Majorana费米子

1939： Furry提出0νββ，当时计算出的半衰期可低至10^{15}年

49s-50s: 诸多探测实验进行了探测，在未发现-发现-未发现中徘徊

1957： Case, Touschek and Radicati结合V-A理论指出零质量中微子→no 0νββ

2016: 中微子振荡→中微子质量不为零



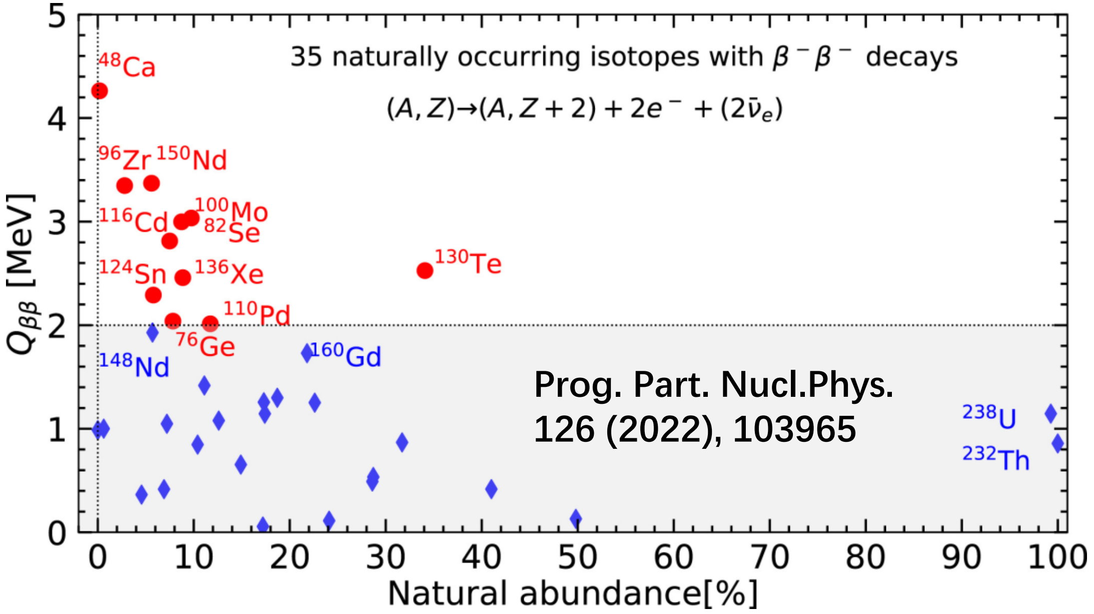
REVIEWS OF MODERN PHYSICS, VOLUME 95, APRIL–JUNE 2023

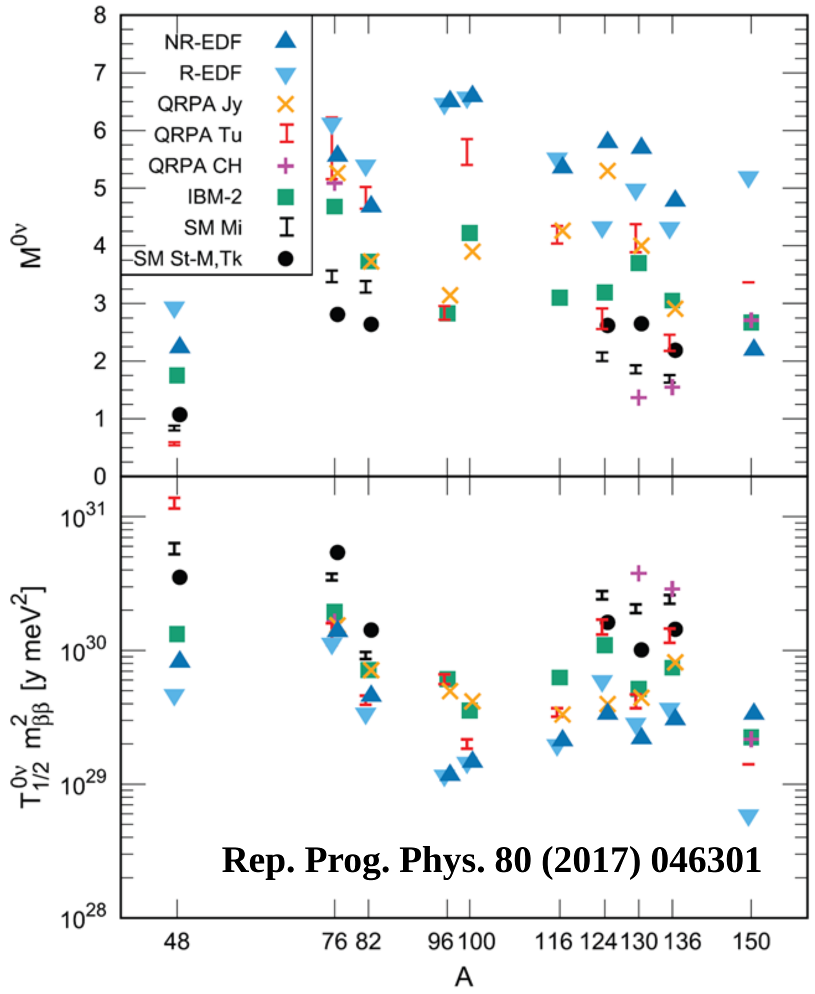
有关0νββ的主要论文的引用次数变化

0νββ探测实验的核素选择

在light-neutrino exchange model中，0νββ的半衰期与phase space factor和nuclear matrix element有关

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





高Q值：半衰期更短，避开自然本底

有合适的探测器技术可用

经济性：自然丰度，有商业用途

0νββ探测实验发展的方向

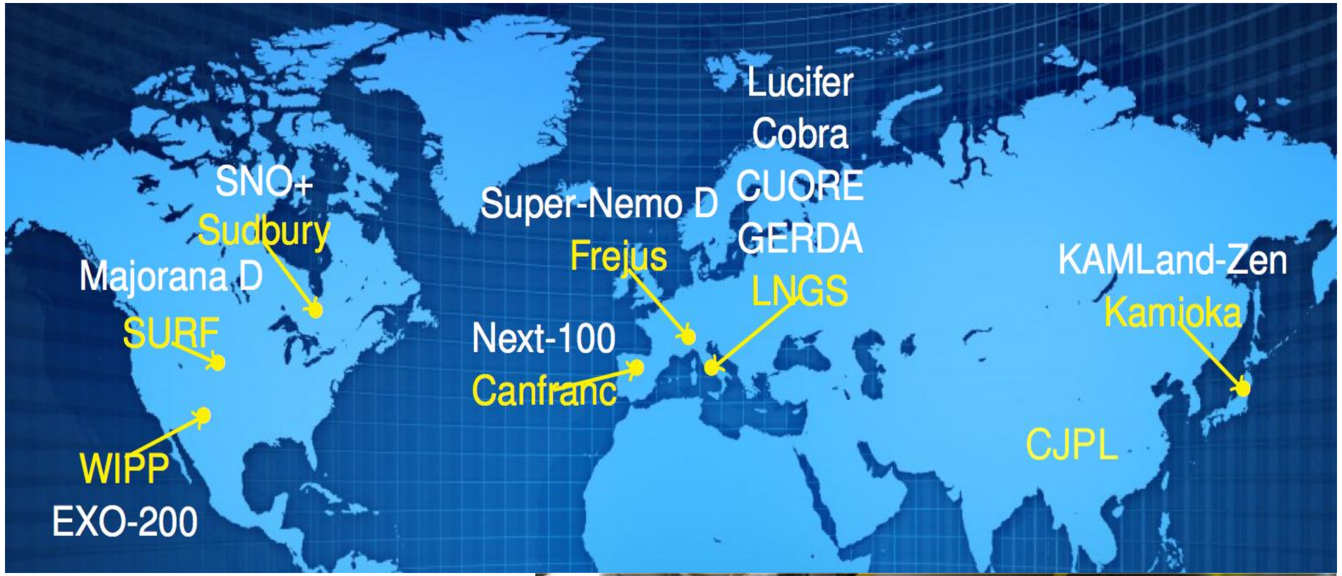
探测实验的灵敏度可以表示为

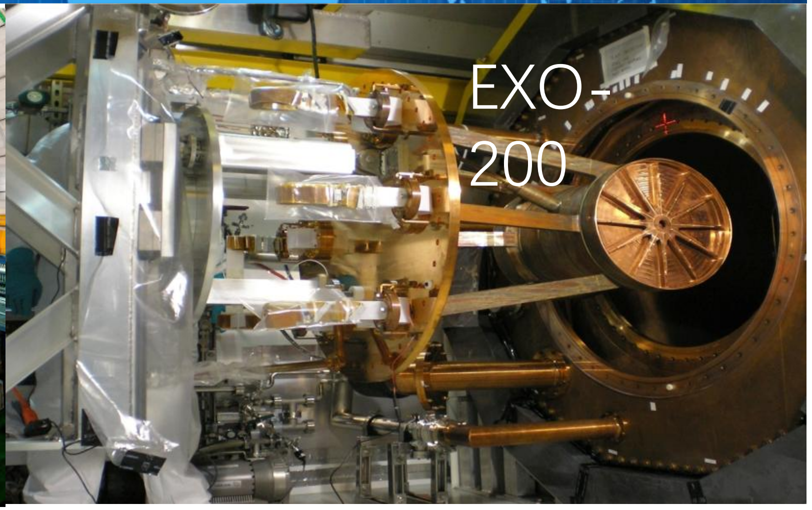
$T_{1/2}^{0\nu}\ sensitivity\ \propto a\epsilon Mt$　　无本底

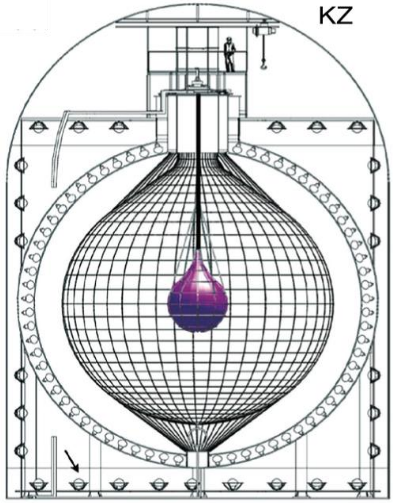
$T_{1/2}^{0\nu}\ sensitivity\ \propto a\epsilon\sqrt{\frac{Mt}{B\Delta E}}$　有本底

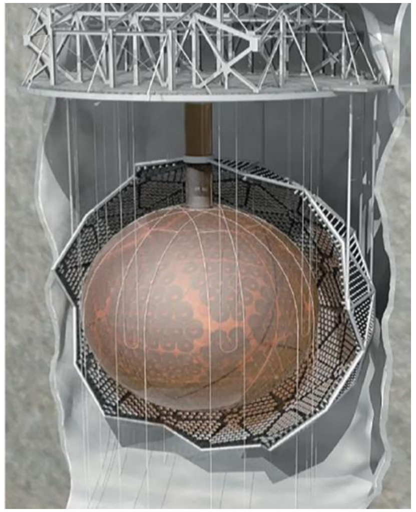
a = 目标核素质量占比	**同位素富集**
ϵ = 探测效率	0νββ源=探测器
M = 总质量	**Scale-up**
t = 实验有效运行时间	探测器稳定性
B = 本底指数　@ Q值	**降本底—深地**
ΔE = 能量分辨率 @ Q值	提高能量分辨率

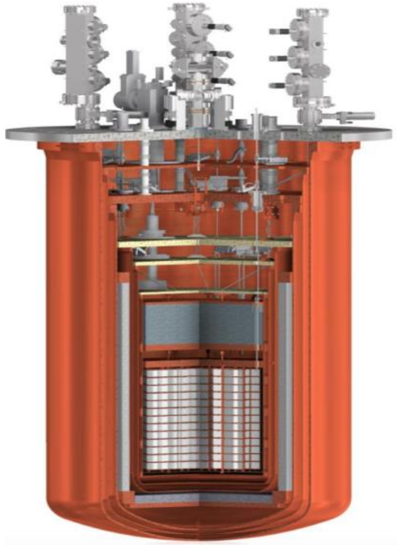
0νββ探测—深地实验





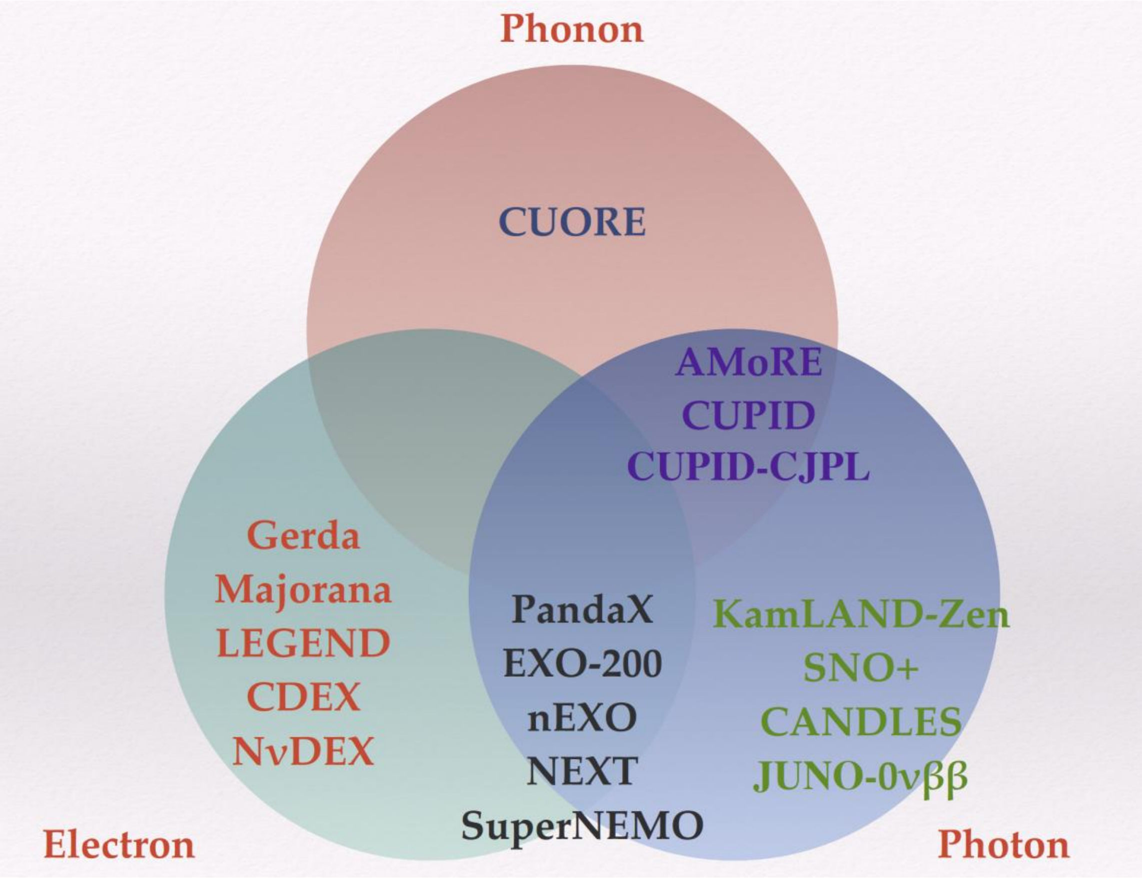






0νββ半衰期至少>10^{22}年，必须在深地实验室进行

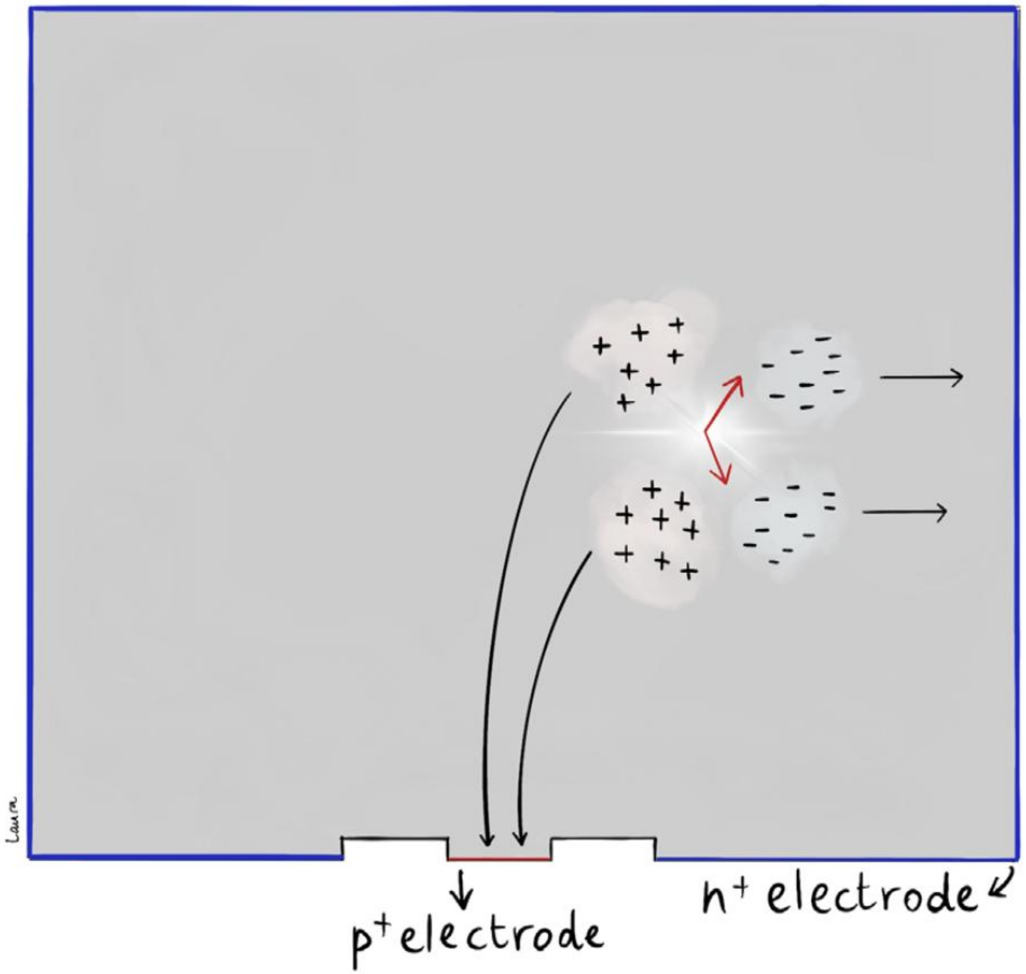
主要的探测实验

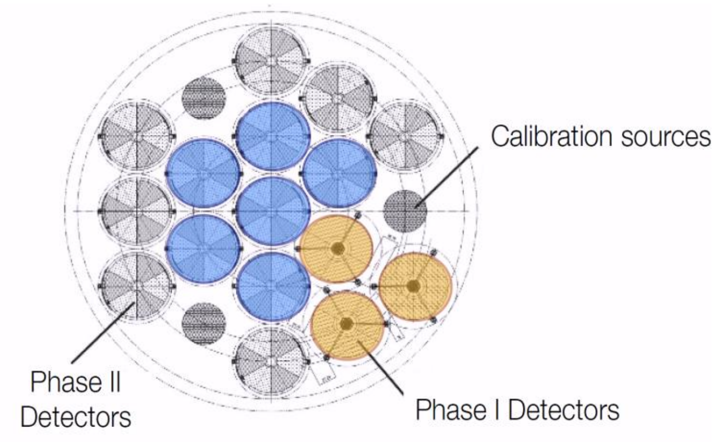


韩柯，COUSP2024

固态	液态	气态
高纯锗	EXO/nEXO	NEXT
晶体量热器	PandaX, LZ, Xenon	PandaIII
	掺杂液体闪烁体	NvDEx

高纯锗探测器—^{76}Ge





能量分辨率最高

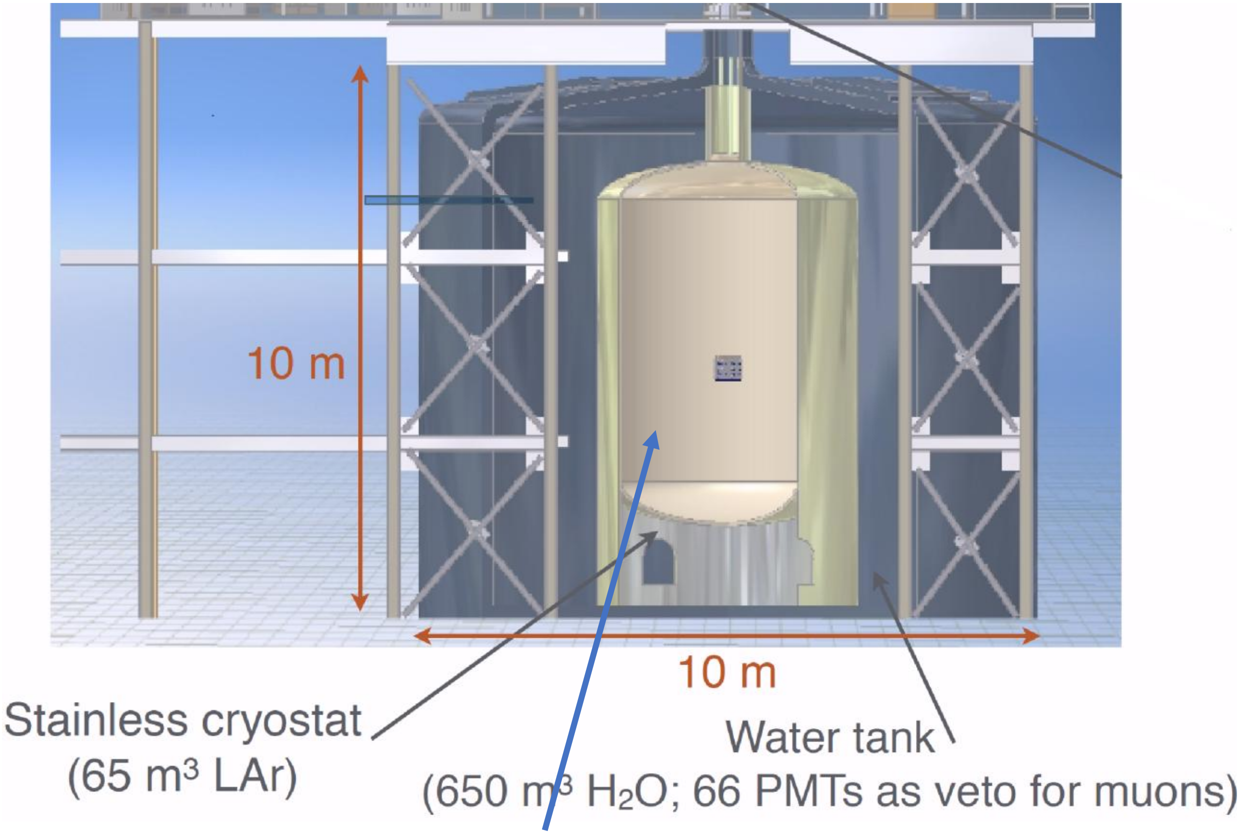
0νββ源=探测器

纯度高 → 本底少

富集^{76}Ge

可分阶段扩大规模

^{76}Ge—GERDA和MAJORANA DEMONSTRATOR



GERDA：位于意大利LNGS
39 kg富集Ge-76的锗晶体

液氩：

Phase I: passive shielding
Phase II: active veto

本底水平更低 5.2×10^{-4} cts/keV/kg/yr

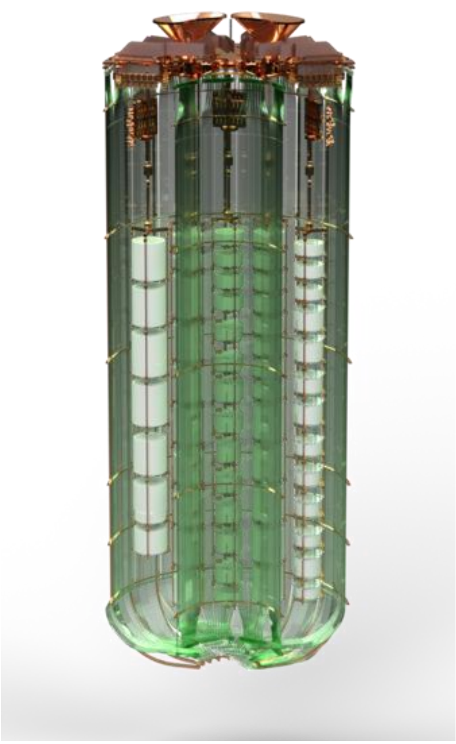
MJD: 美国SURF, 20 kg富集Ge-76的锗晶体

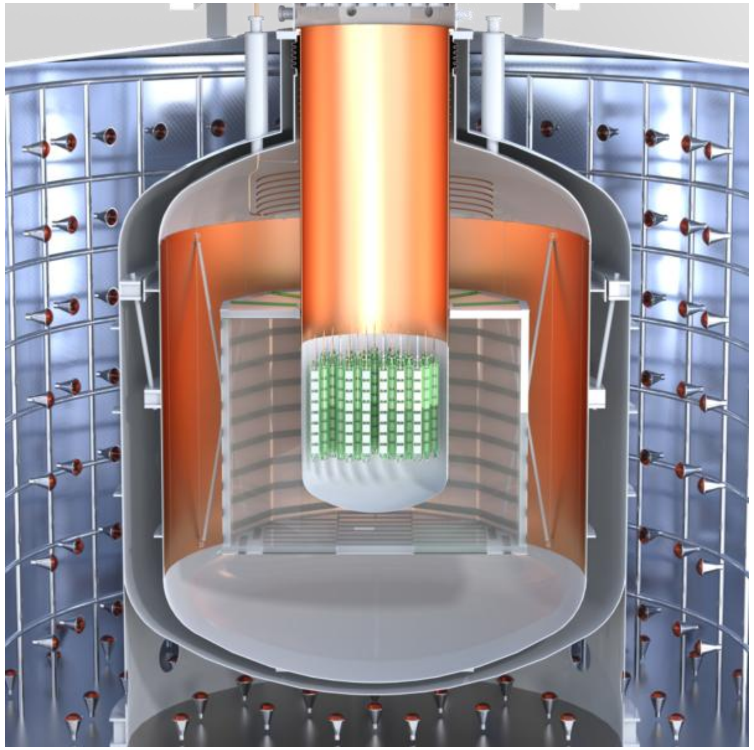
Point-like p+电极：更好的能量分辨率
1.1 keV @ Q值
underground-electroformed copper

^{76}Ge—LEGEND

GERDA

MJD





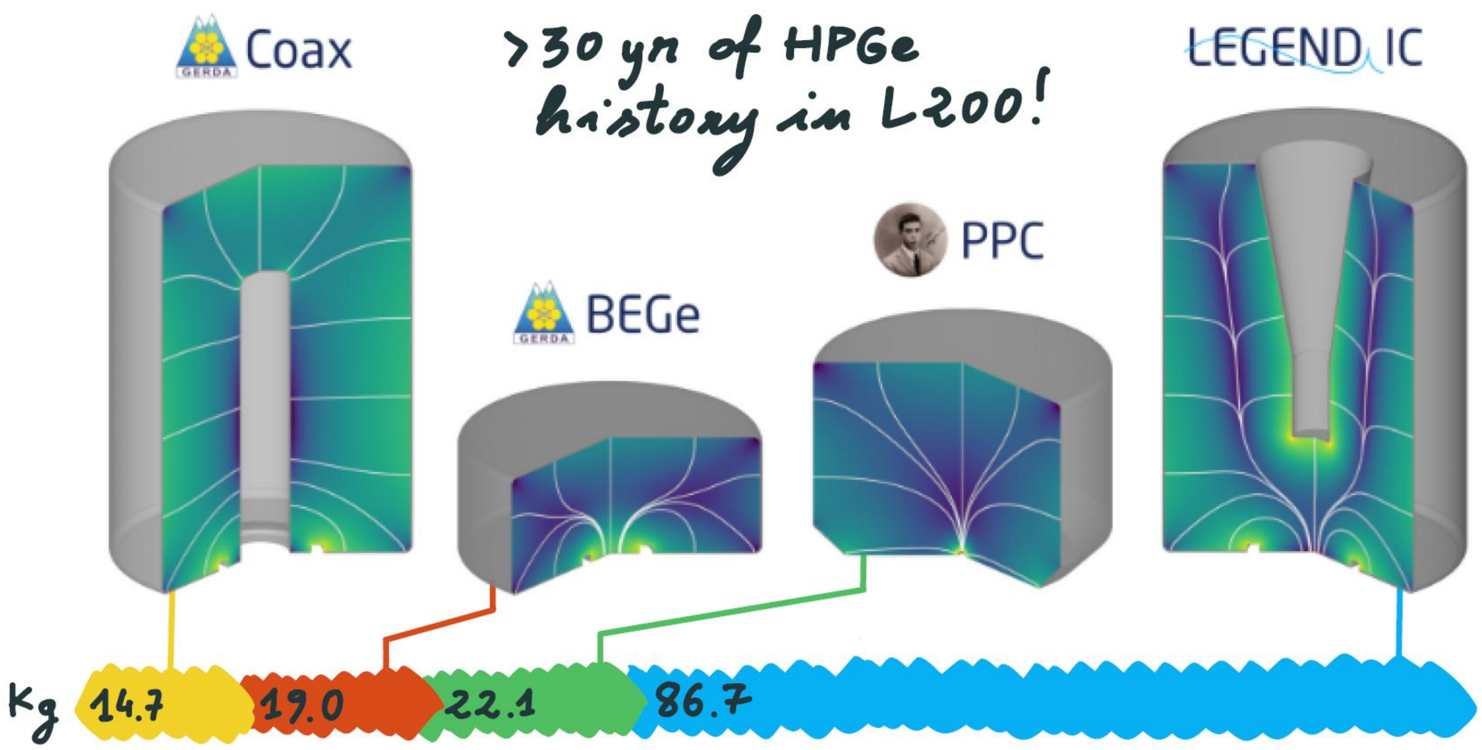
LEGEND-200

- **200 kg** of ^{enr}Ge (×5 yr), in GERDA cryostat
- Taking physics data since March 2023 with 142 kg
- $B \sim \mathbf{2 \cdot 10^{-4}}$ cts / (keV kg yr) $\longmapsto T^{0\nu}_{1/2} > \mathbf{10^{27}}$ **yr**

LEGEND-1000 arXiv 2107.11462 "pre-Conceptual Design Report"

- **1 ton** of ^{enr}Ge (×10 yr), pending funding approval
- $B < \mathbf{10^{-5}}$ cts / (keV kg yr) $\longmapsto T^{0\nu}_{1/2} > \mathbf{10^{28}}$ **yr**
- Fully cover $m_{\beta\beta}$ inverted ordering region

^{76}Ge—LEGEND strategy



LEGEND-200 phase I 的晶体来源

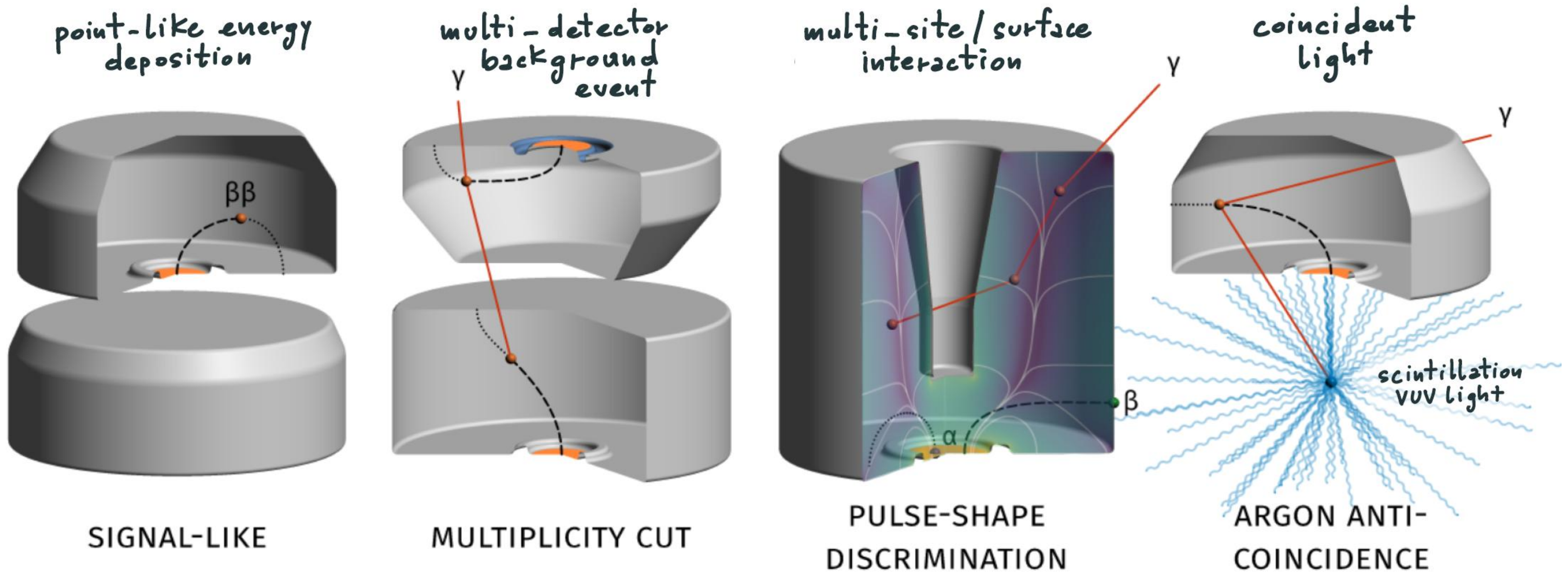
Argon veto

electroformed copper

更大的晶体

更低的本底水平

LEGEND的本底甄别技术



BI = 5.3 ± 2.2 · 10^{-4} cts / (keV kg yr)

PRELIMINARY!

From: Neutrino2025 conference

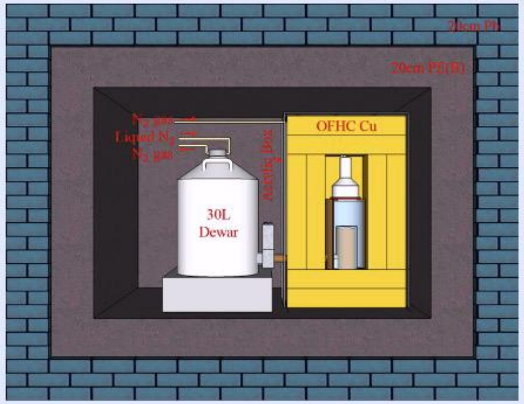
^{76}Ge—CDEX: 暗物质与0νββ

2009-2016	2016-2020	2021-	Planed

CDEX-1

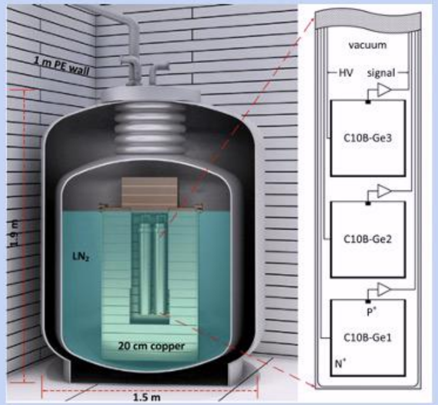
CDEX-1A
- DM: χ-N (SI/SD)
- Axion & Axion-like DM
- CDEX first 0νββ result

CDEX-1B
- DM: χ-N (SI/SD)
- DM: χ-N (Migdal Effect)
- DM: χ-N (AM)
- Axion & Axion-like DM



CDEX-10

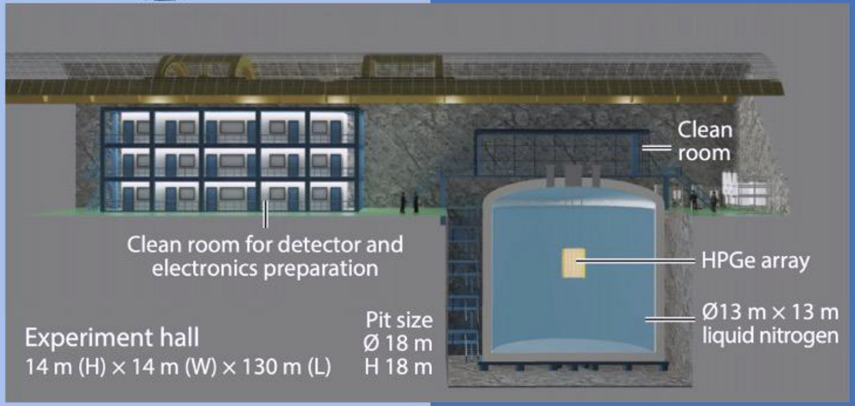
- DM: χ-N (SI/SD)
- DM: χ-N (EFT)
- Solar dark photon
- Dark photon DM
- DM: CR boosted DM
- DM: Exotic DM
- DM: χ-e
- DM: Evaporating PBHs



CDEX-50 (DM)

CDEX-300 (0νββ)

CDEX-1T (0νββ, DM...)



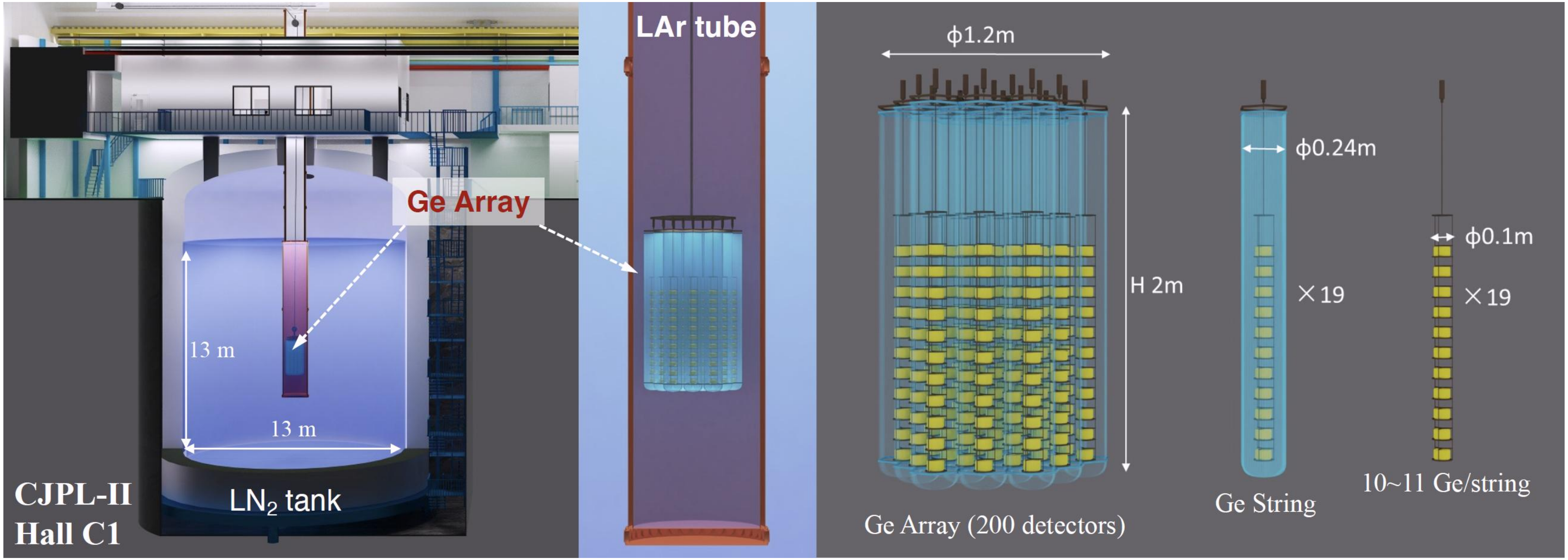
CJPL-I

CJPL-II

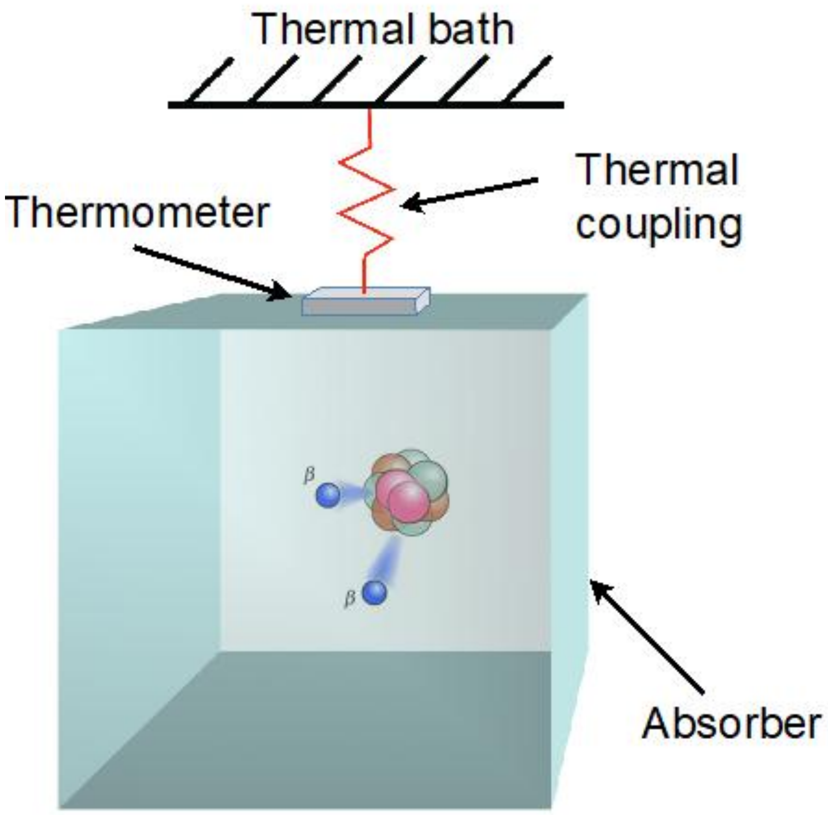
^{76}Ge—CDEX300ν

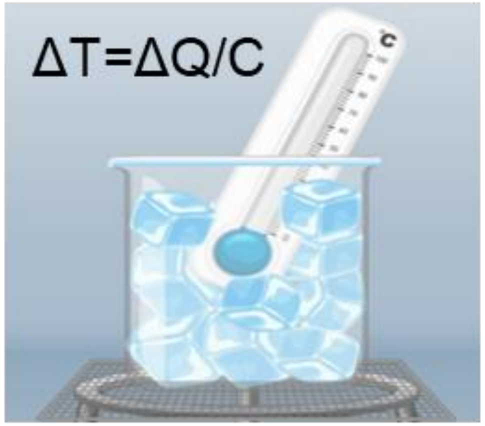
- 225 kg富集的^{76}Ge
- 液氮既为冷却剂，也是被动屏蔽
- LAr+SiPM进行主动屏蔽

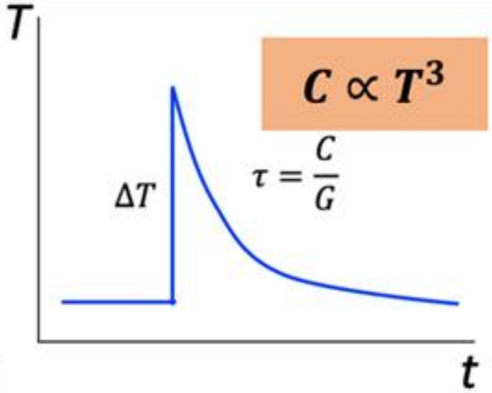
Physics goal:	**$T_{1/2} > 10^{27}$ yr**	**$<m_{\beta\beta}>$: 30-70 meV**
Key parameters:	**0.5~1 ton-yr exposure**	**1E-4 cpkky BG in ROI**



低温晶体量热器







工作温度：10-20 mK

稀释制冷机

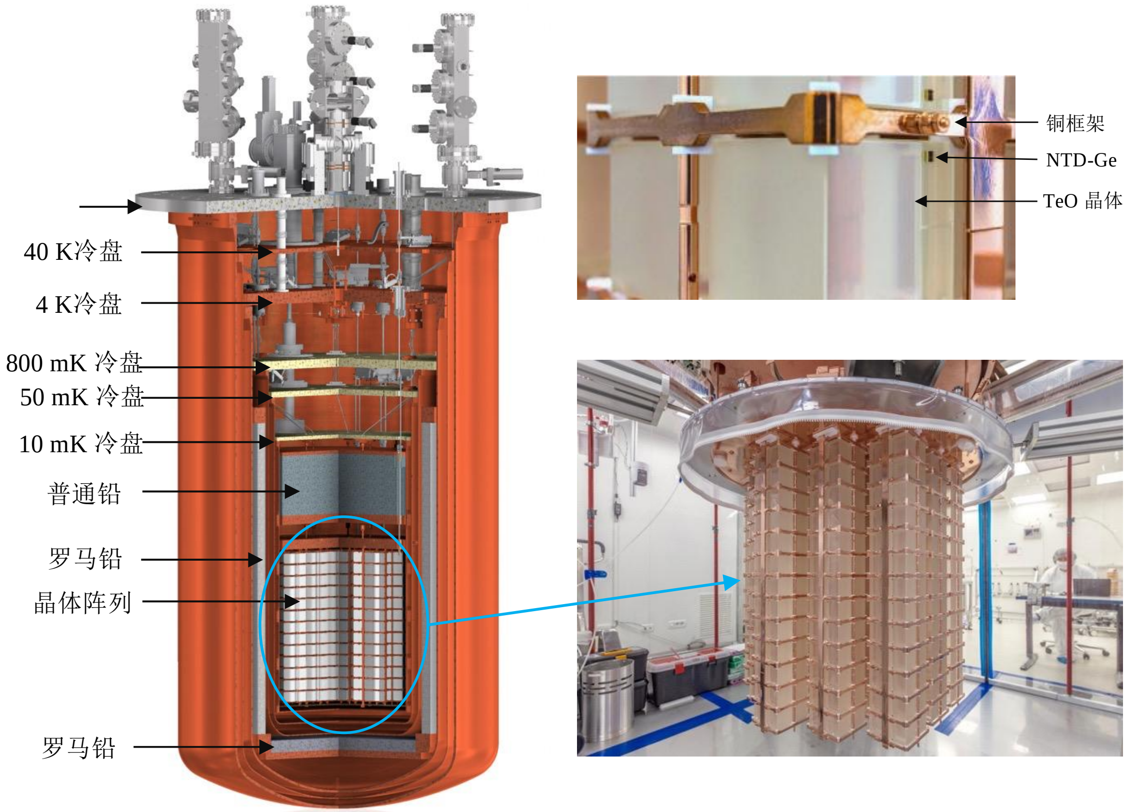
低温--能量分辨率较高

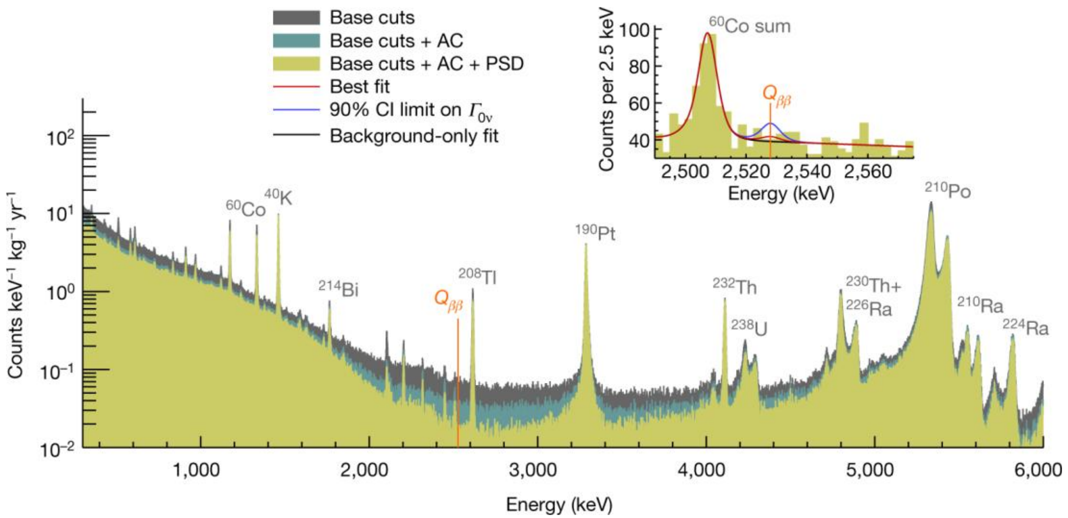
0νββ源=探测器

可适用多种核素→ 选择Q值高的核素

可分阶段扩大规模

低温晶体量热器实验CUORE—运行中



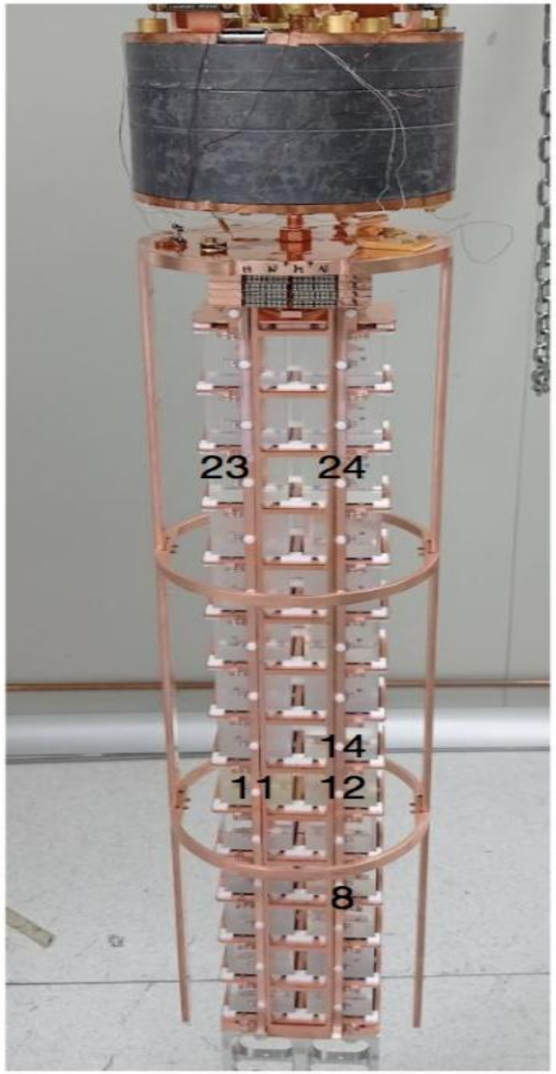


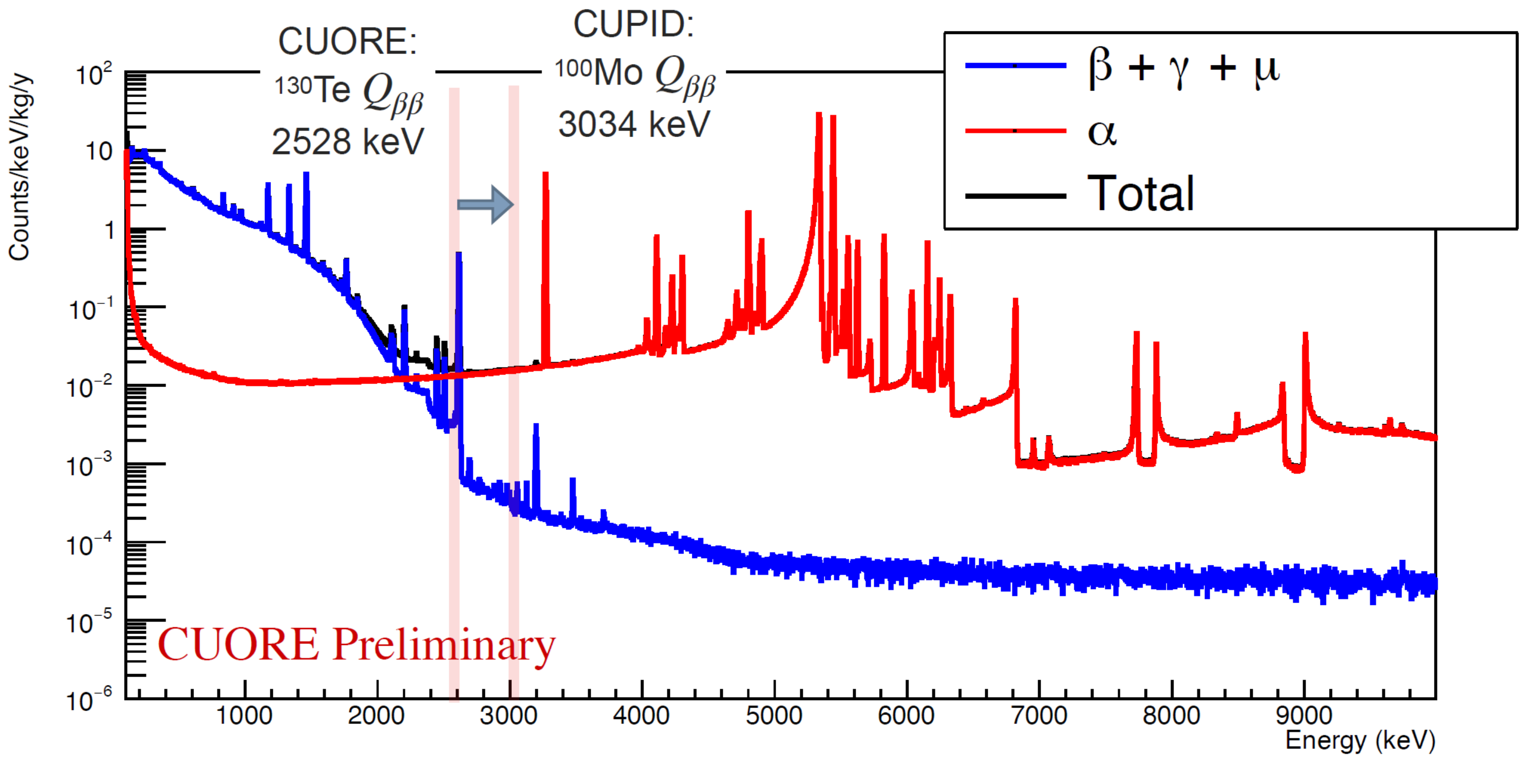
优势：~10 mK → 高能量分辨率~0.3% (FWHM)
衰变源=探测器→ 探测效率高(>85%) :

复旦大学，上海硅酸盐所，上海交大是CUORE合作组成员

目前结果：没有发现0νββ，$T_{1/2} > 2.8 \times 10^{25}$ yr，$m_{\beta\beta} <$ 90-305 meV， Best limit on ^{130}Te，*Nature 604,53 (2022)*

CUPID：更低本底—^{100}Mo





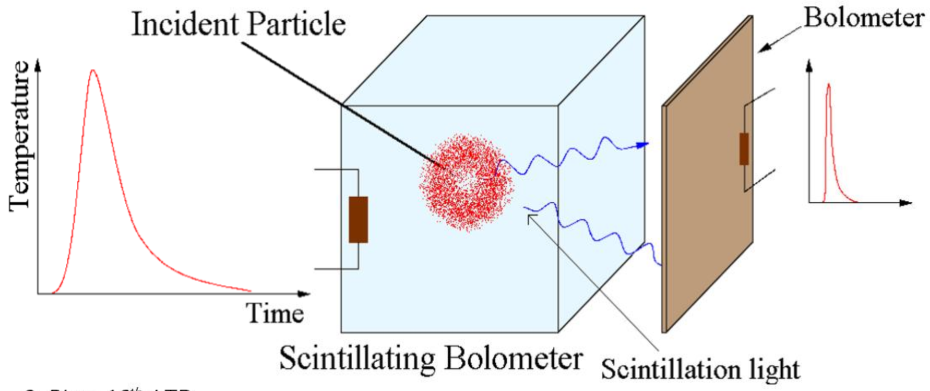
^{100}Mo高$Q_{\beta\beta}$ (~3.034 MeV)

避开自然界中大多Gamma本底

富集^{100}Mo在技术和经济性上可以接受

CUPID：更低本底—光热双信号读出

钼酸锂晶体产生光信号

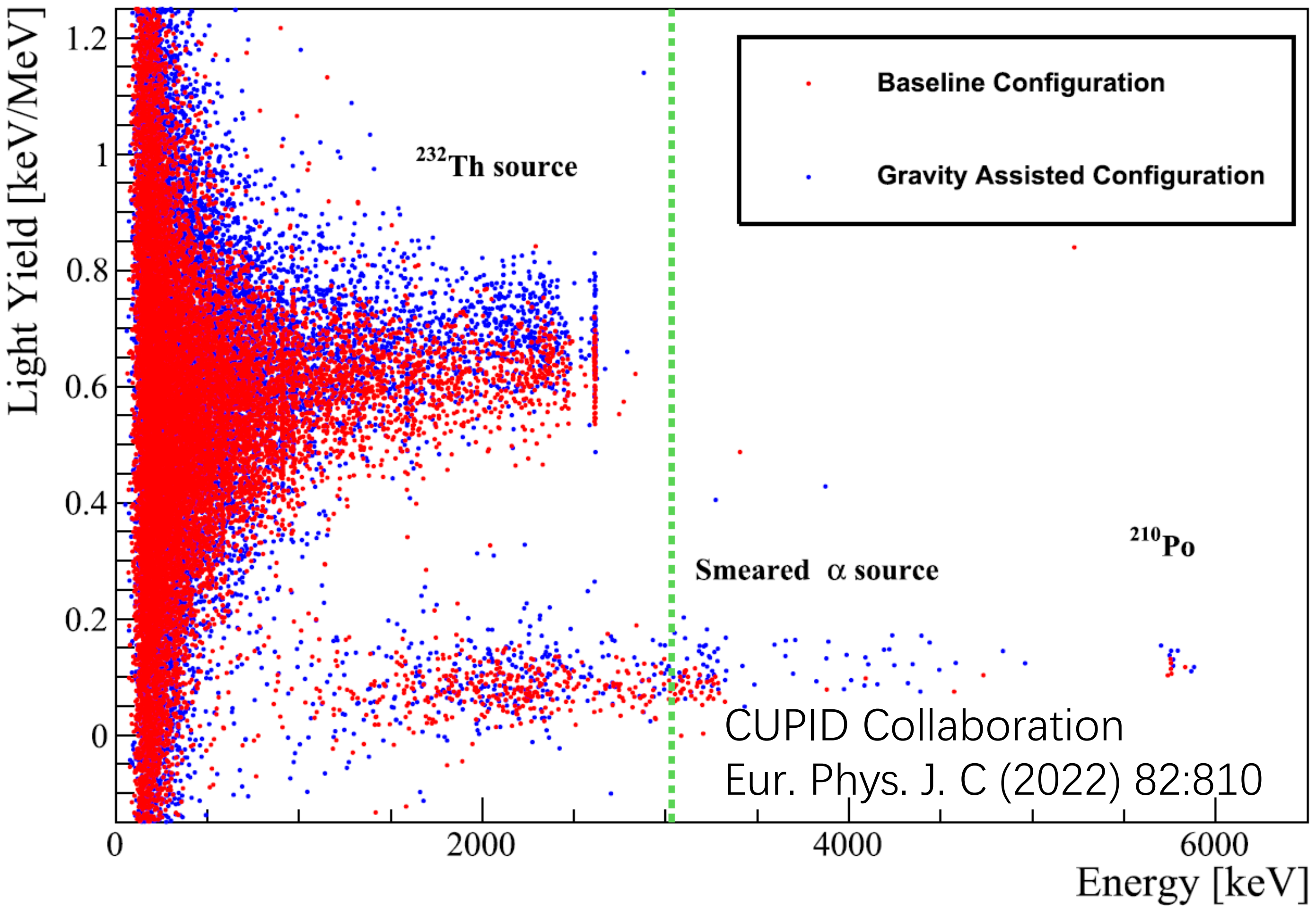


S. Pirro 18th LTD

同时读出光信号和热信号

↓

去除α本底



ROI内排除>99.9% 的α 本底 (超过CUORE灵敏度，实现CUPID目标)

CUPID合作组

International Collaboration
CUPID – Italy
CUPID – US
CUPID – France
CUPID – China
~ 30 institutes, >150 collaborators

CUPID-China

- Beijing Normal University*
- Fudan University*
- Ningbo University
- Shanghai Jiao Tong University*
- Shanghai Institute of Applied Physics
- Shanghai Institute of Ceramics
- Tsinghua University
- University of Science and Technology of China*

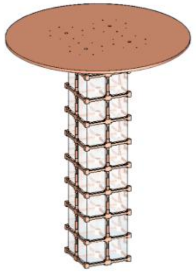
*(*Officially in the international CUPID collaboration)*

~ 8 institutes, > 40 collaborators

CUPID-CJPL发展路线

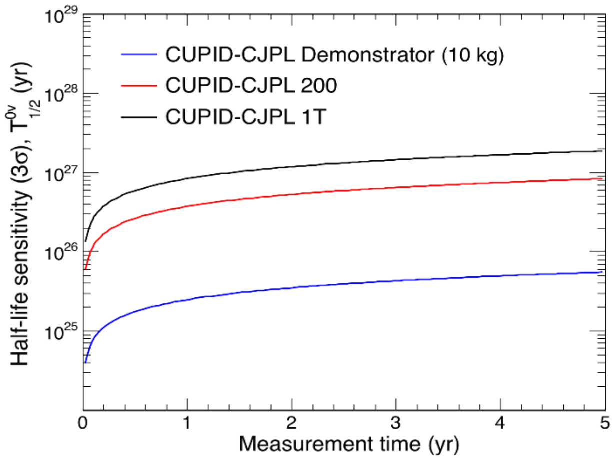
模块测试

6-12 natural crystals
(2025-2026)
CUPID LNGS QA



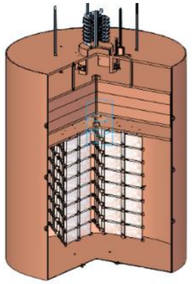
10 kg enriched crystals
(2026-2029)

CUPID-CJPL Demo



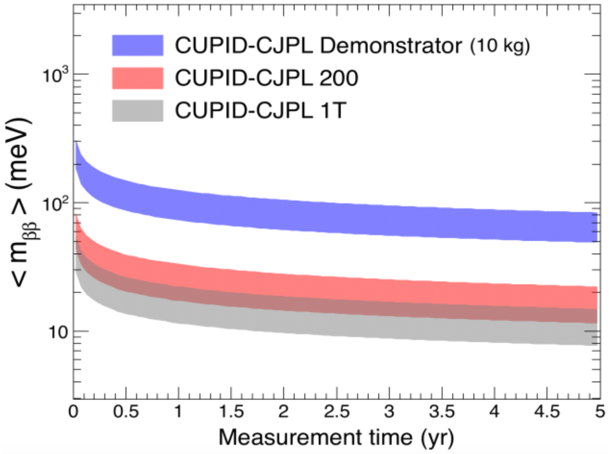
CUPID-CJPL 200

200 kg enriched
crystals
(2028+)

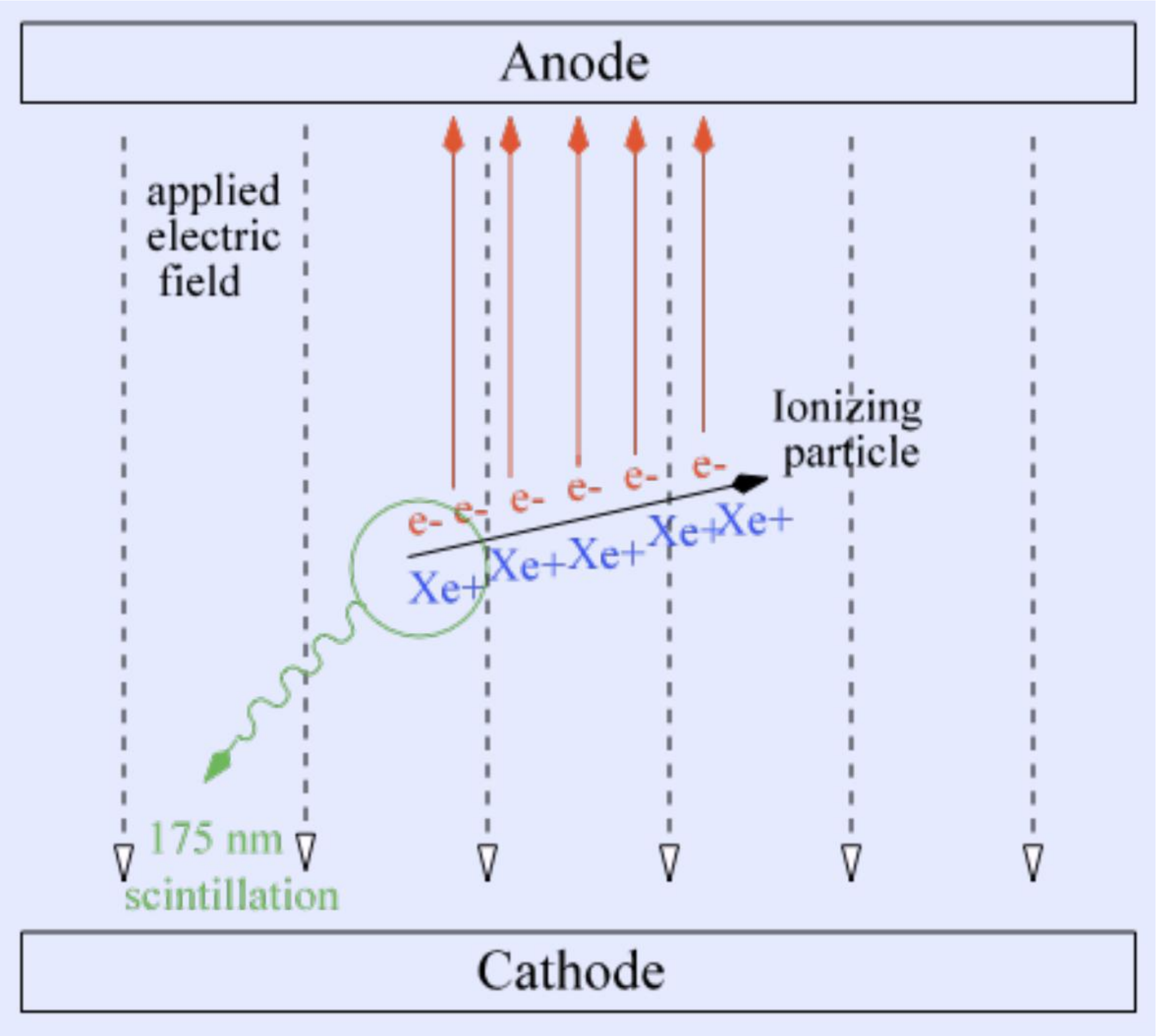


ton-scale experiment

CUPID-CJPL 1T



时间投影室(TPC)



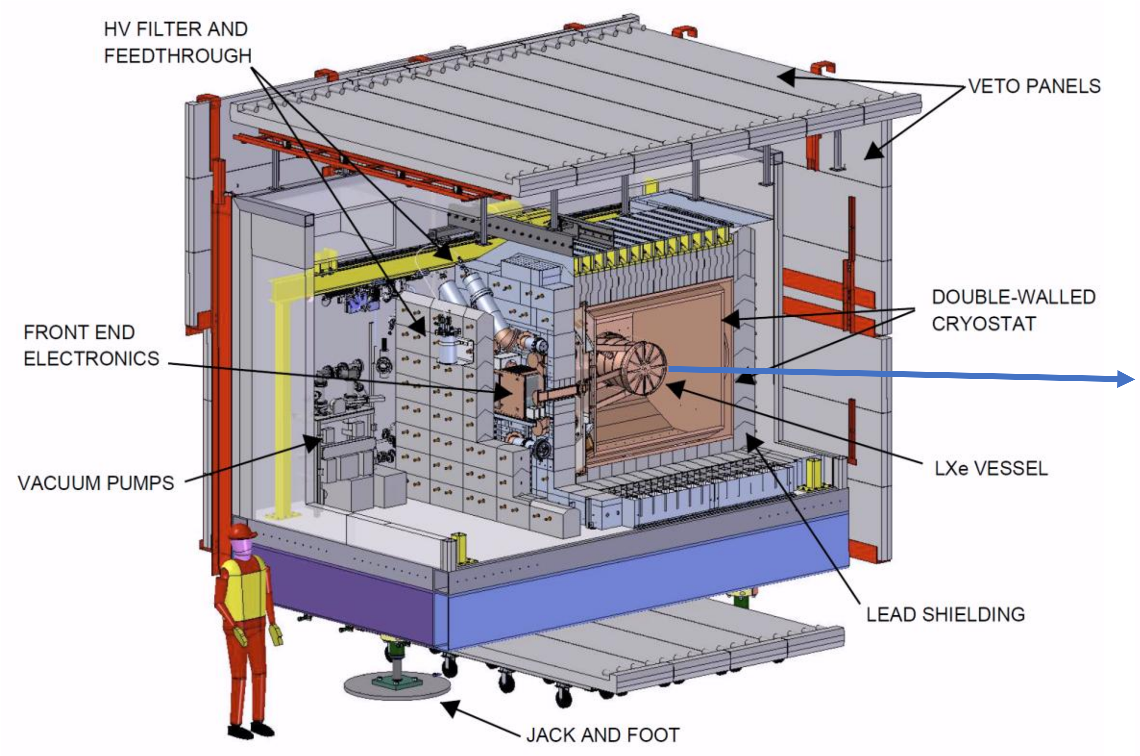
能量信息

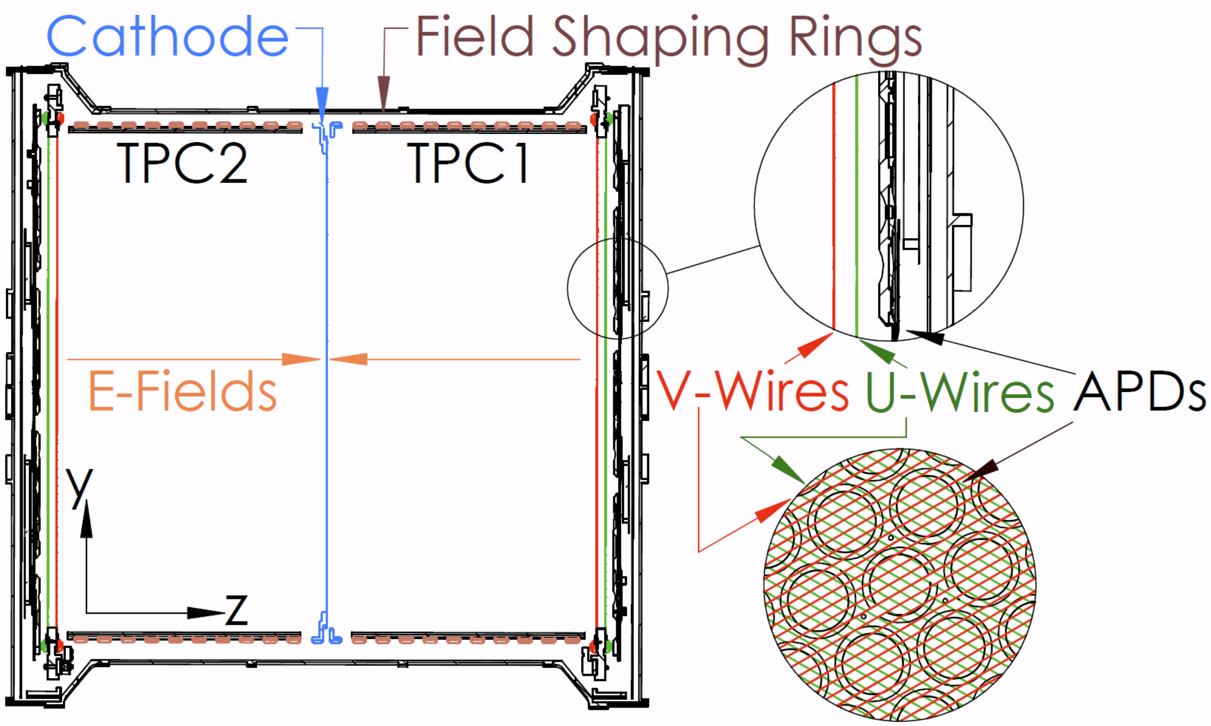
荧光信号　　电离信号

位置信息

避开本底高的探测器边缘部分
或分辨出两个电子运动的轨迹

Enriched Xenon Observatory（EXO）





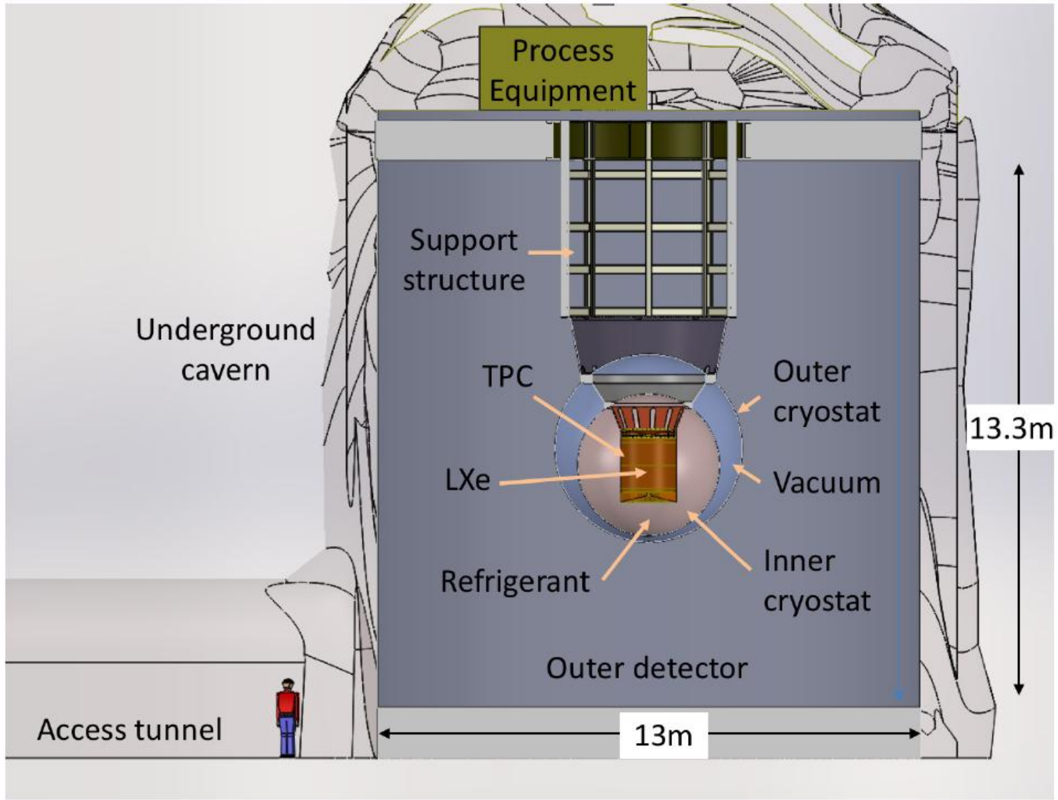
位于美国的WIPP：只有655米深，但周围的盐提供了额外的屏蔽

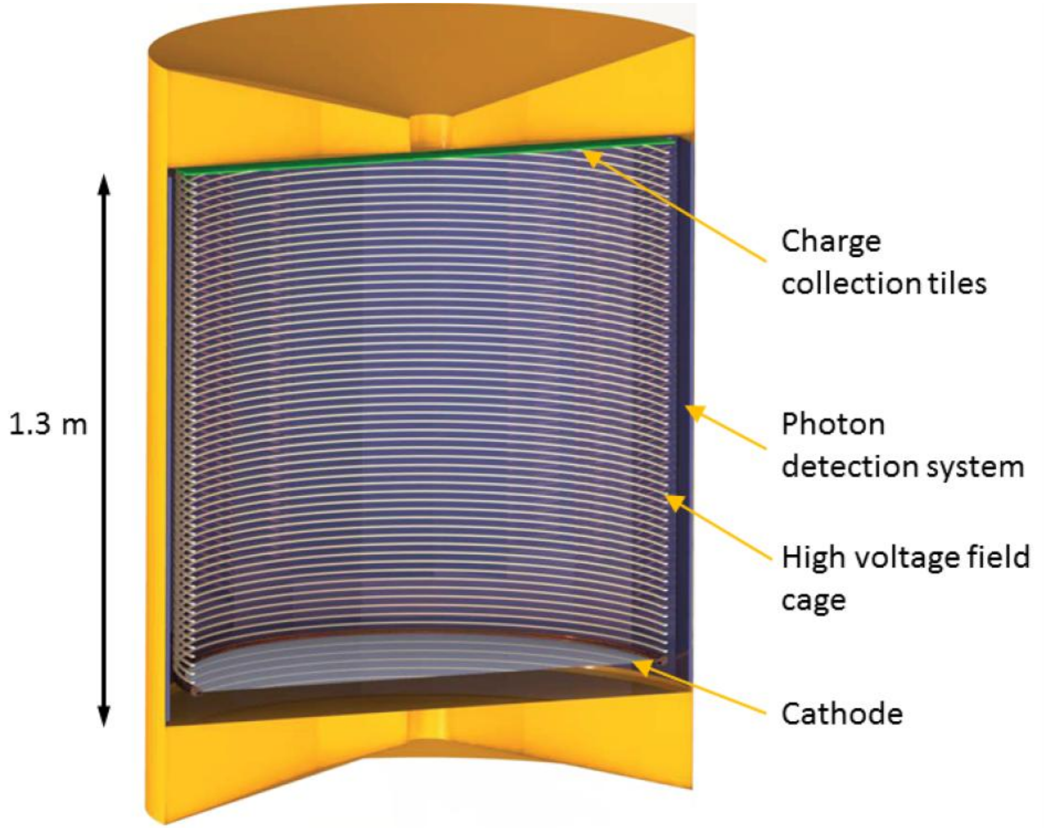
161千克的富集^{136}Xe (81%) – 75 千克有效质量

能量分辨率：28 keV @ Q值=2458 keV.

给出 limit: $T_{1/2} > 2.8 \times 10^{25}$ yr

EXO → nEXO





主要改变：

5吨的富集^{136}Xe

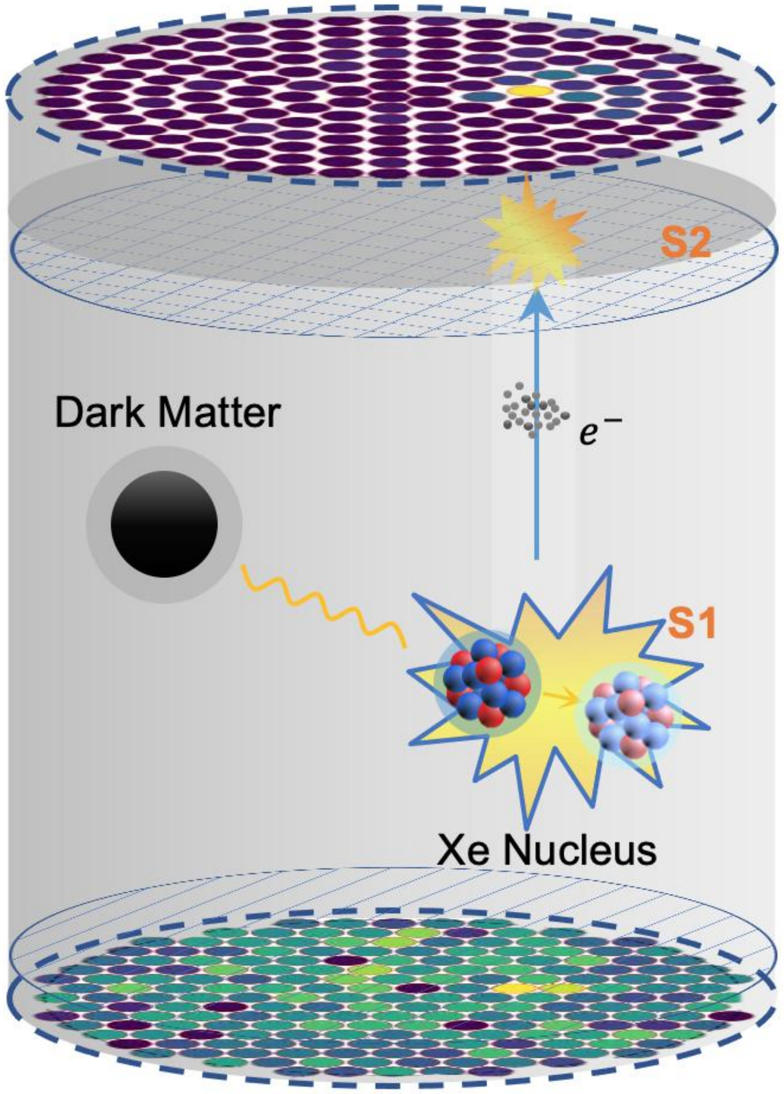
电子读出用silica tiles取代wires

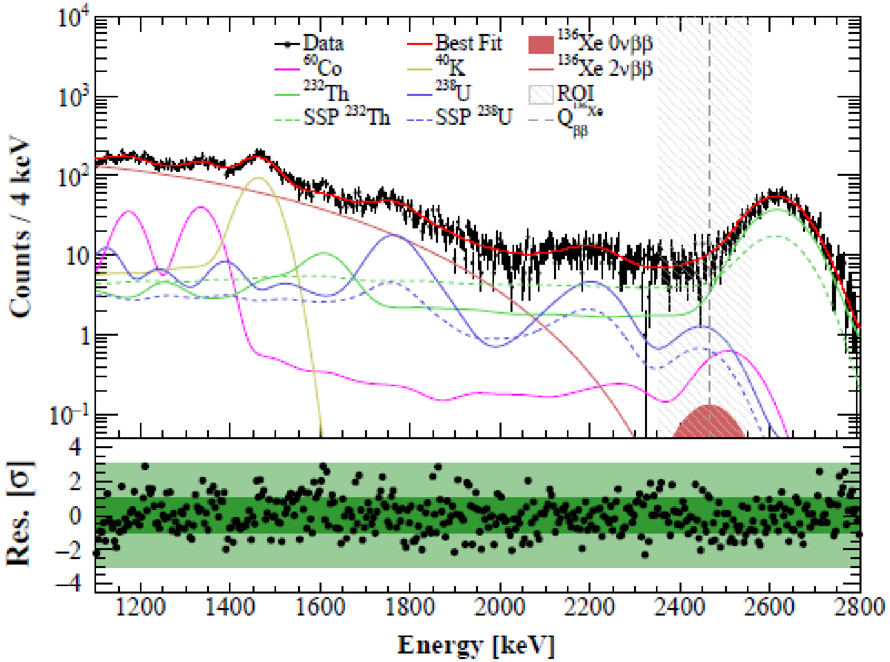
荧光读出用SiPMs取代APDs

TPC单一空间

预期灵敏度： $T_{1/2} = 7.4 \times 10^{27}$ yr

双相氙时间投影室





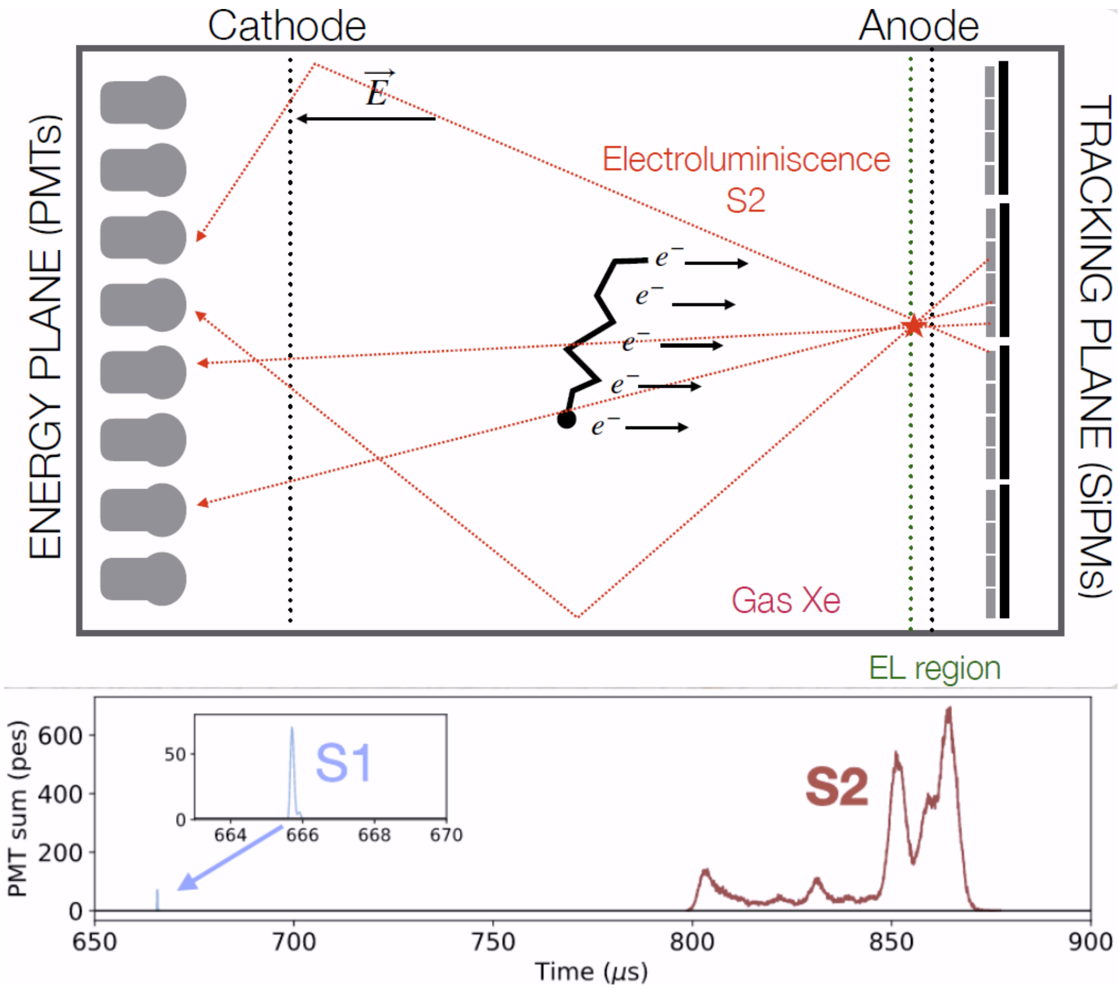
暗物质实验虽然使用未富集的氙，但总质量大，也能给出有意义的0νββ限制

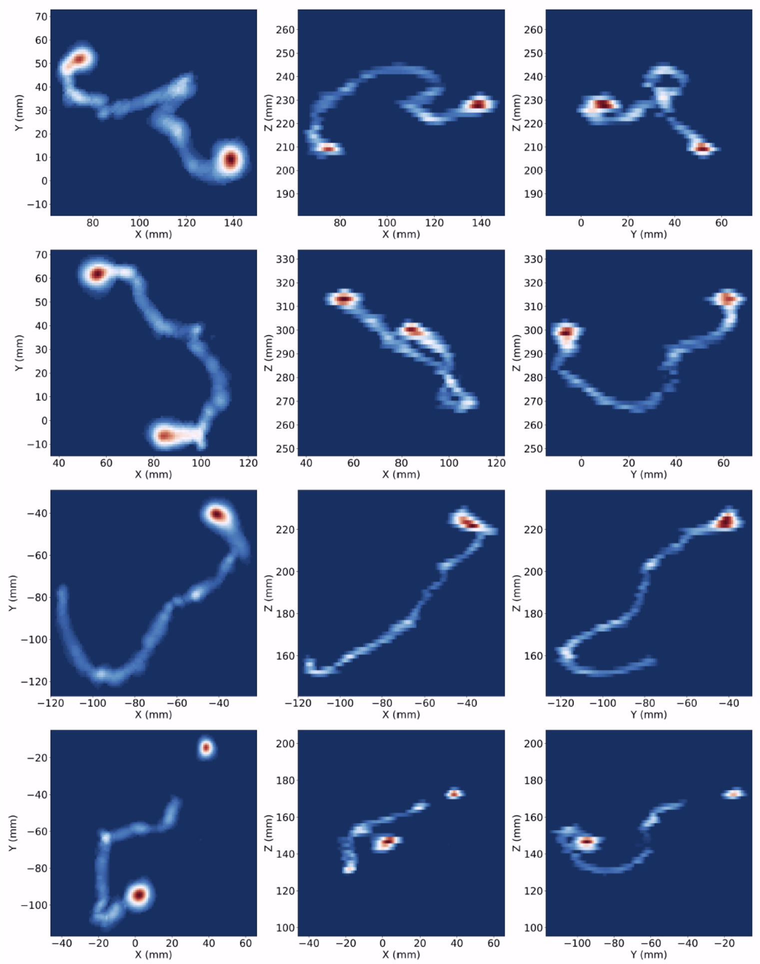
PandaX-4T给出了**自然氙**实验最灵敏的半衰期限制

（Run0+Run1）： $T_{1/2}^{0\nu\beta\beta} > 2.1\times 10^{24}$ yr (90% CL)

未来质量更大的PandaX-20T将会给出更好的结果

气体TPC--NEXT

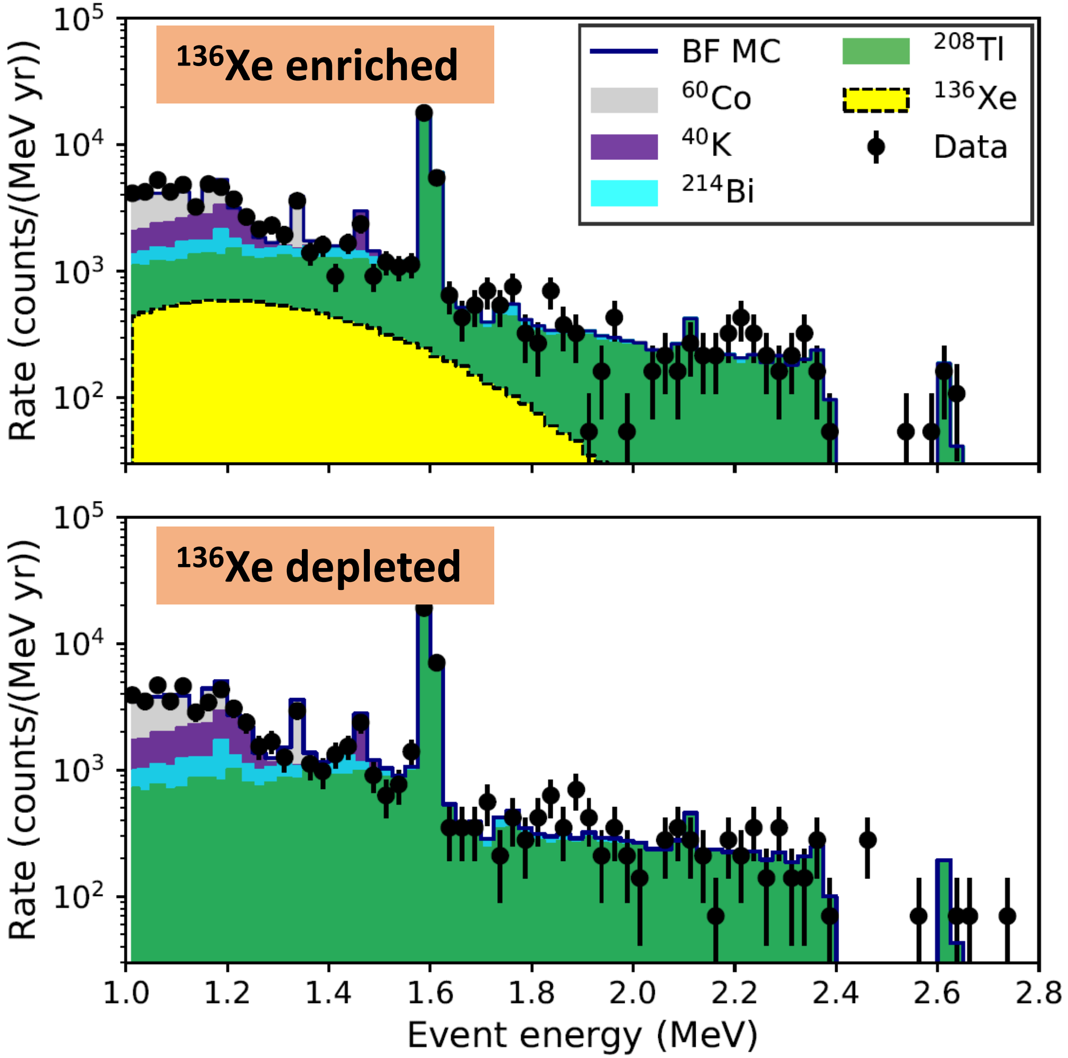


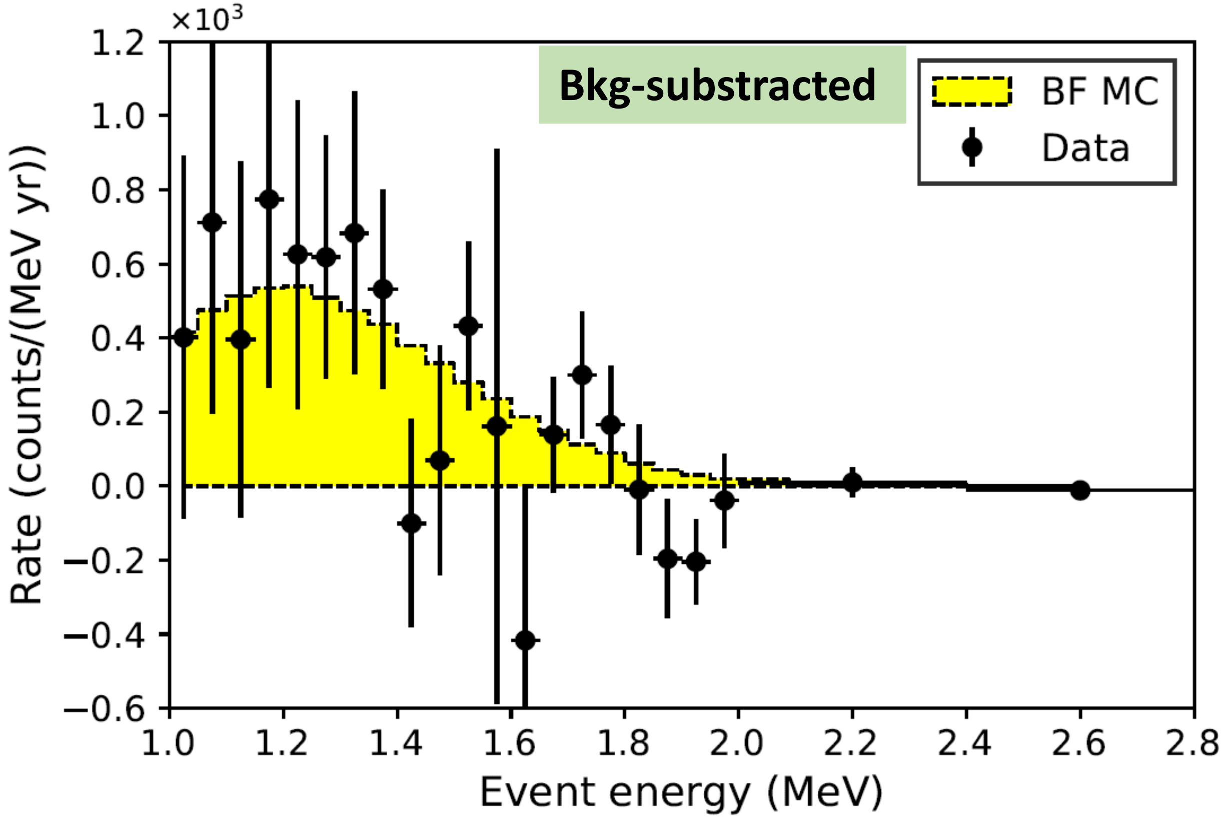


NEXT-White: 5kg， 10 bar

能量分辨率优于液态 10 keV @ Q值

NEXT—background substraction

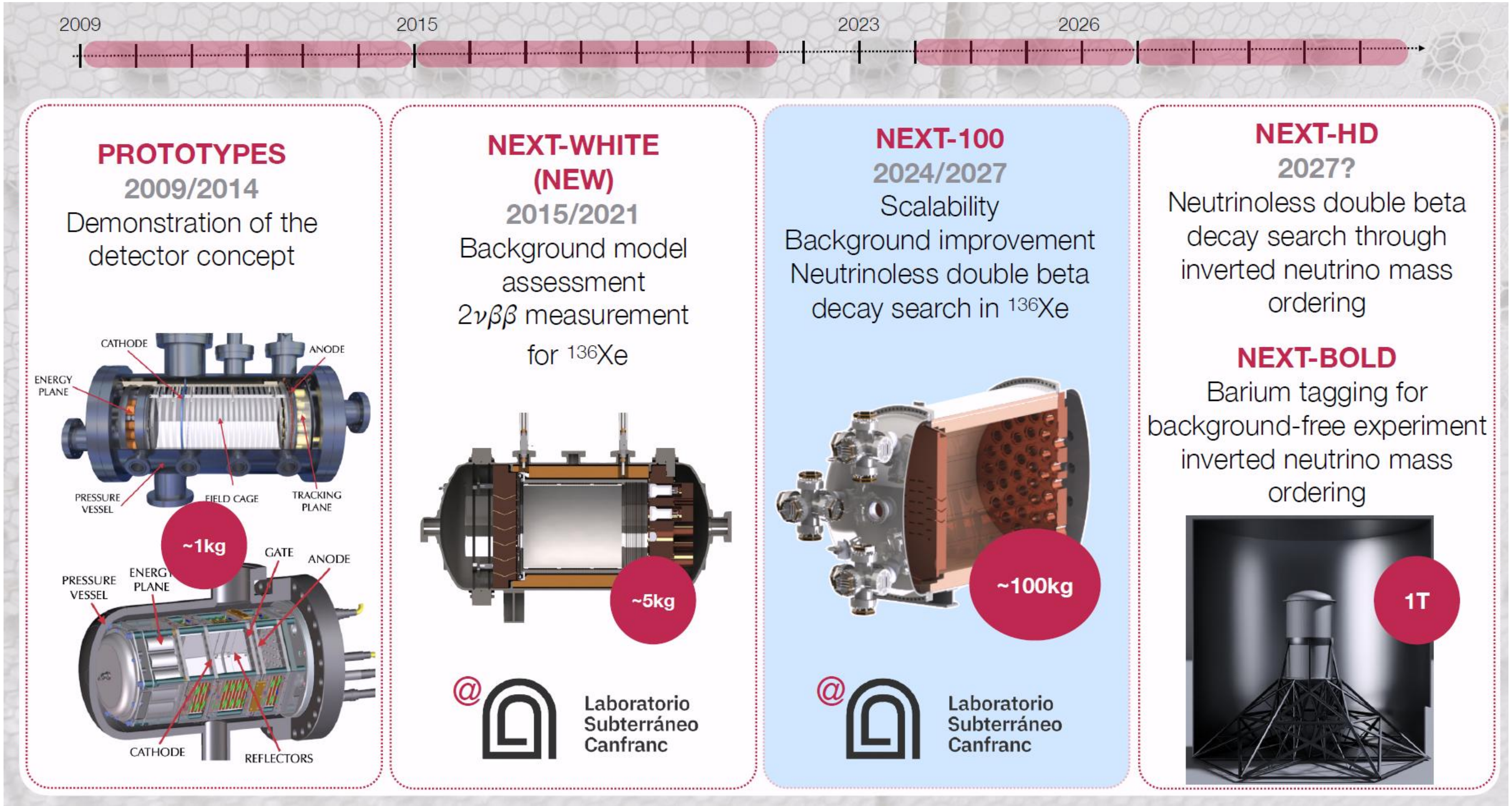




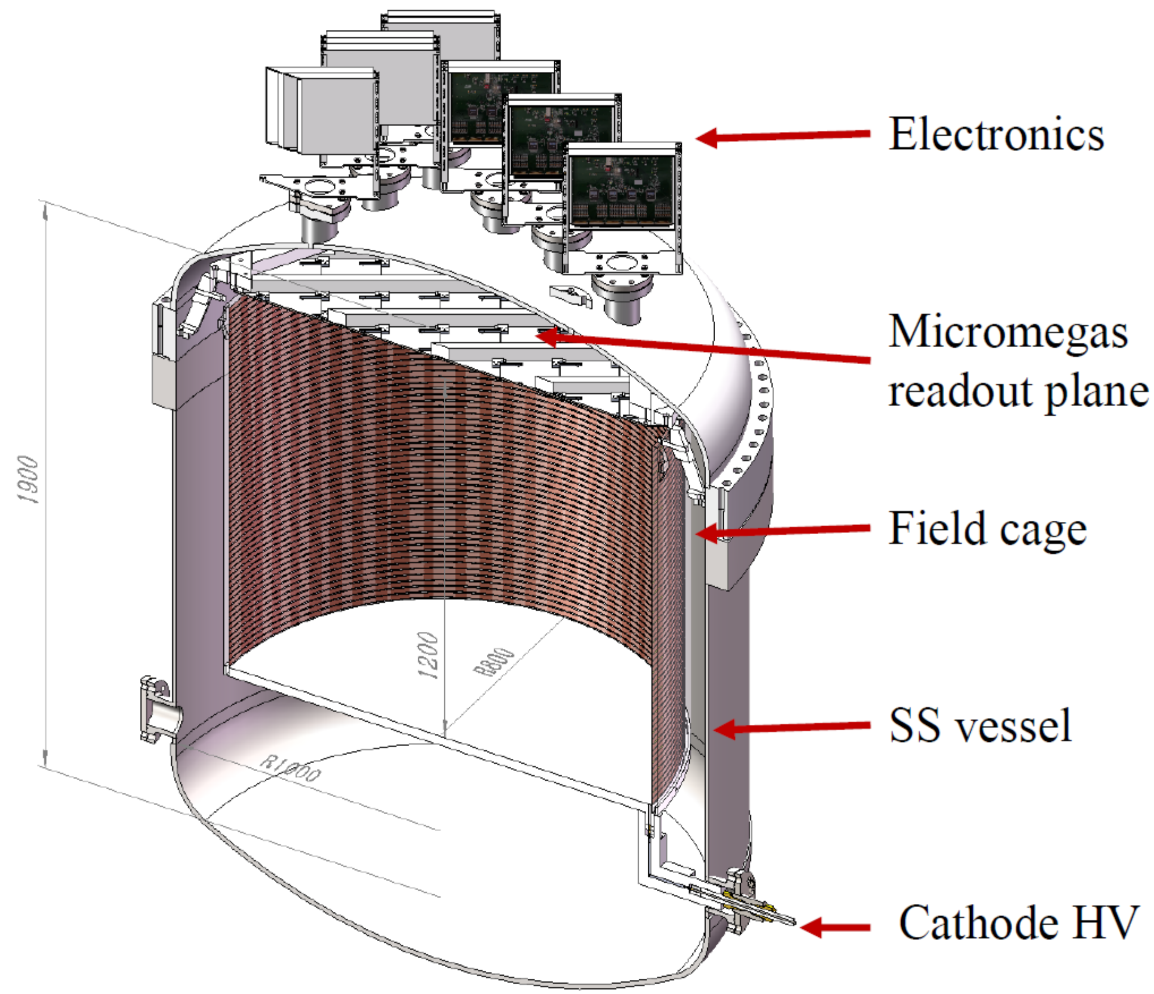
给出的半衰期限制

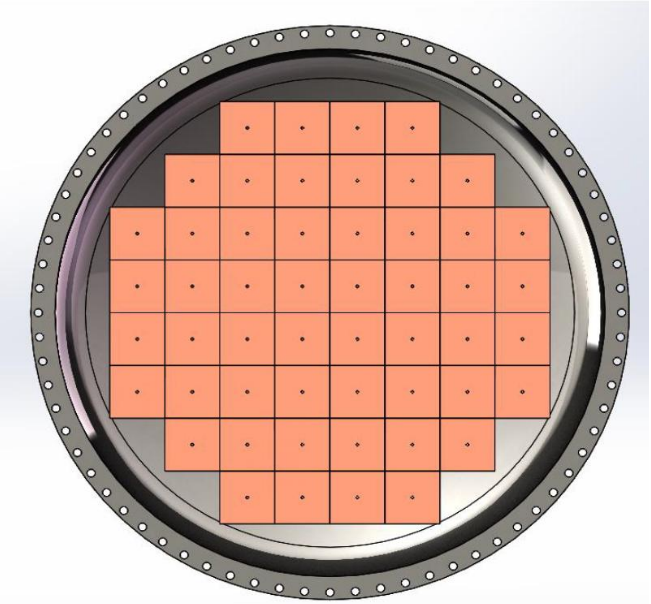
$> 1.3 \cdot 10^{24}$ yr(90% CL)

NEXT时间规划


2009
2015
2023
2026
PROTOTYPES
2009/2014
Demonstration of the detector concept
CATHODE
ANODE
ENERGY PLANE
PRESSURE VESSEL
FIELD CAGE
TRACKING PLANE
~1kg
GATE
ANODE
PRESSURE VESSEL
ENERGY PLANE
CATHODE
REFLECTORS
NEXT-WHITE (NEW)
2015/2021
Background model assessment
2νββ measurement for 136Xe
~5kg
@ Laboratorio Subterráneo Canfranc
NEXT-100
2024/2027
Scalability
Background improvement
Neutrinoless double beta decay search in 136Xe
~100kg
@ Laboratorio Subterráneo Canfranc
NEXT-HD
2027?
Neutrinoless double beta decay search through inverted neutrino mass ordering
NEXT-BOLD
Barium tagging for background-free experiment inverted neutrino mass ordering
1T

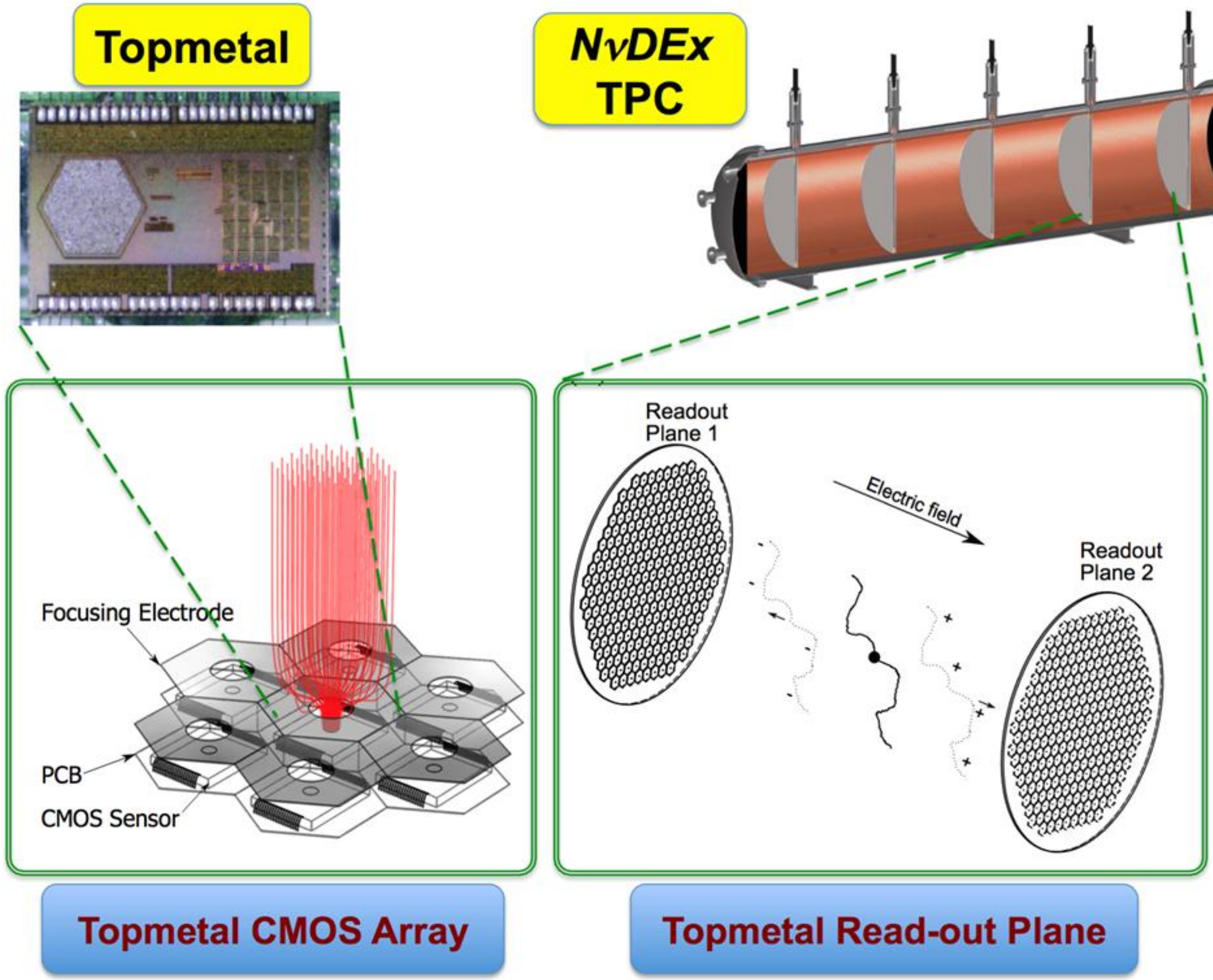
PandaX-III





与NEXT不同PandaX-III读出电子信号

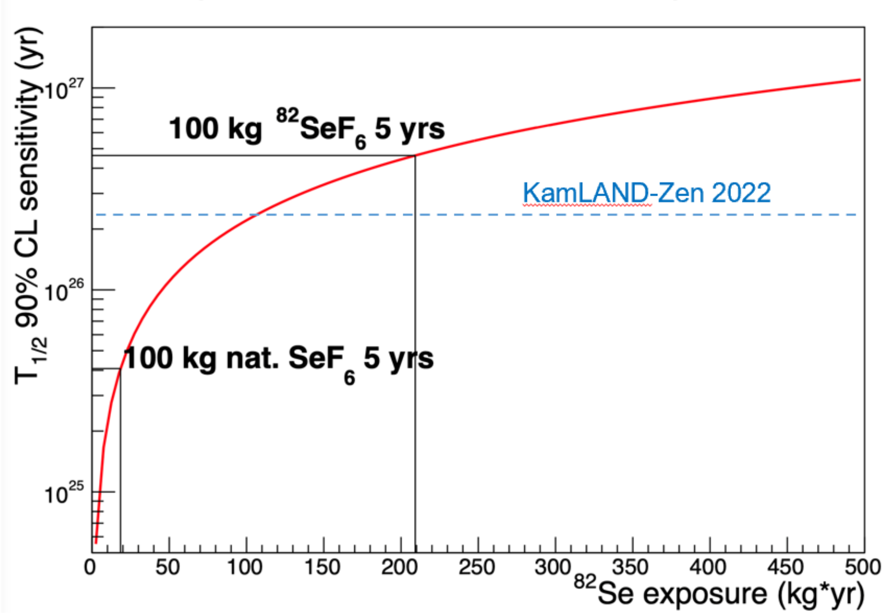
非xenon的TPC-- NνDEx



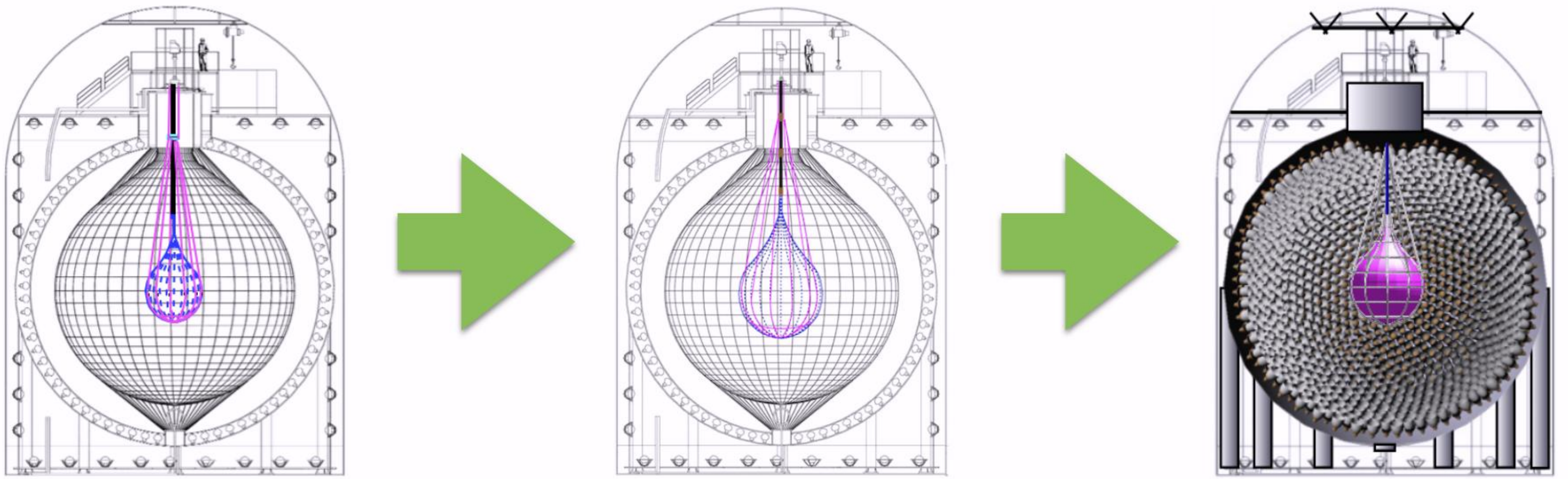
高压气体：$^{82}SeF_6$

电信号经电场聚焦后由CMOS sensors读出

^{82}Se高Q值(2.996 MeV)
电子径迹去除本底
较好的能量分辨率 ~1%



掺杂液体闪烁体—KamLAND-Zen

Past	Present	Future
		
KamLAND-Zen 400	**KamLAND-Zen 800**	**KamLAND2-Zen**
Nylon balloon R 1.54 m	Nylon balloon R 1.90 m	
Xenon 320 – 380 kg	Xenon 745 kg	Xenon 1 ton
world top performance	target ⟨$m_{\beta\beta}$⟩ ~ **40 meV**	target ⟨$m_{\beta\beta}$⟩ ~ **20 meV**

$0\nu\beta\beta$源≠探测器

但是

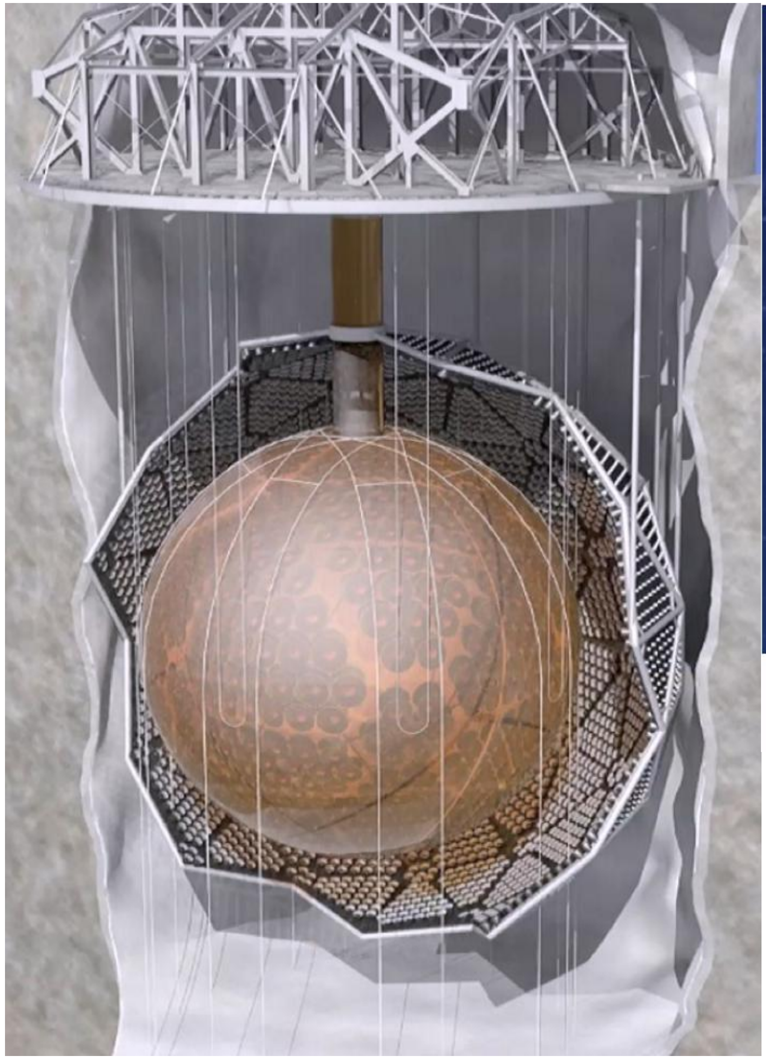
Self-shielding

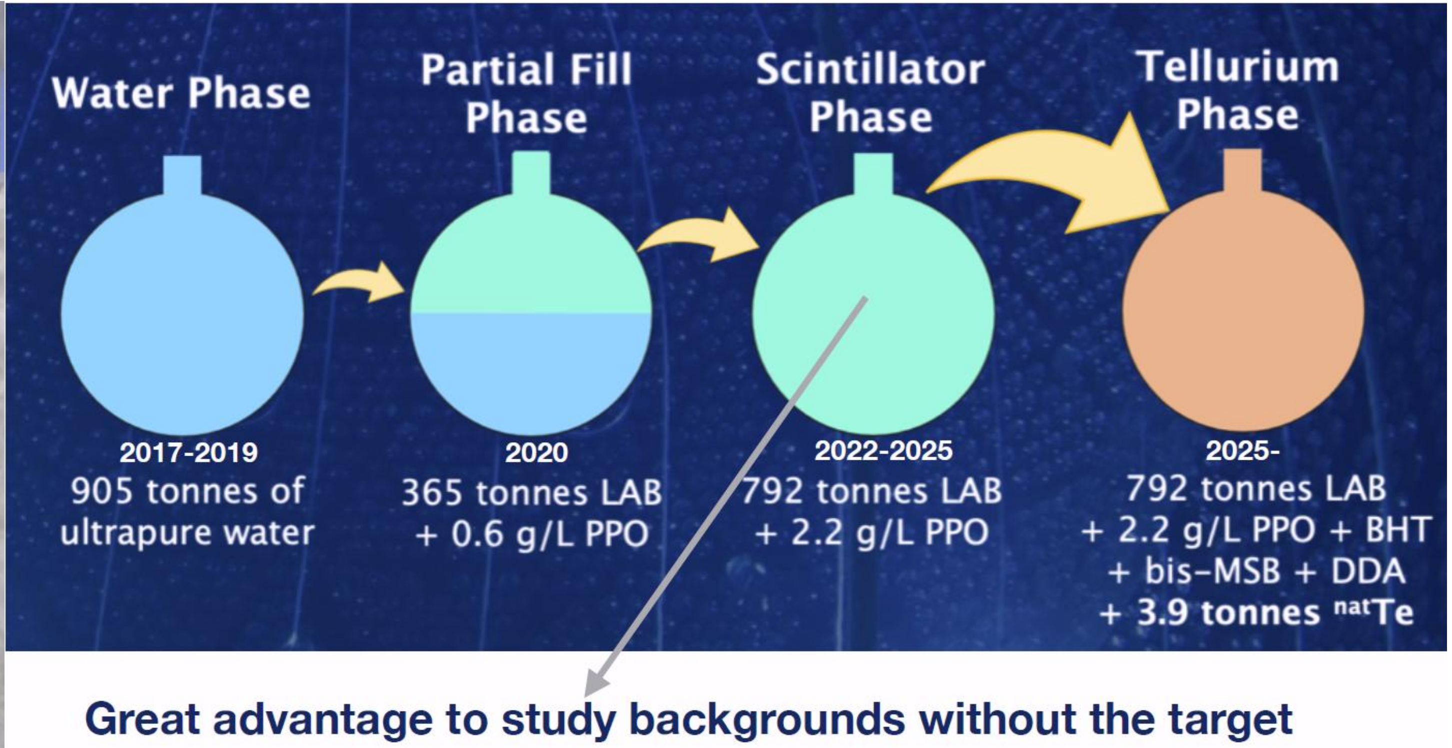
容易scale-up

^{136}Xe最好的半衰期限制

$T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26}$ yr (90% CL)

SNO+

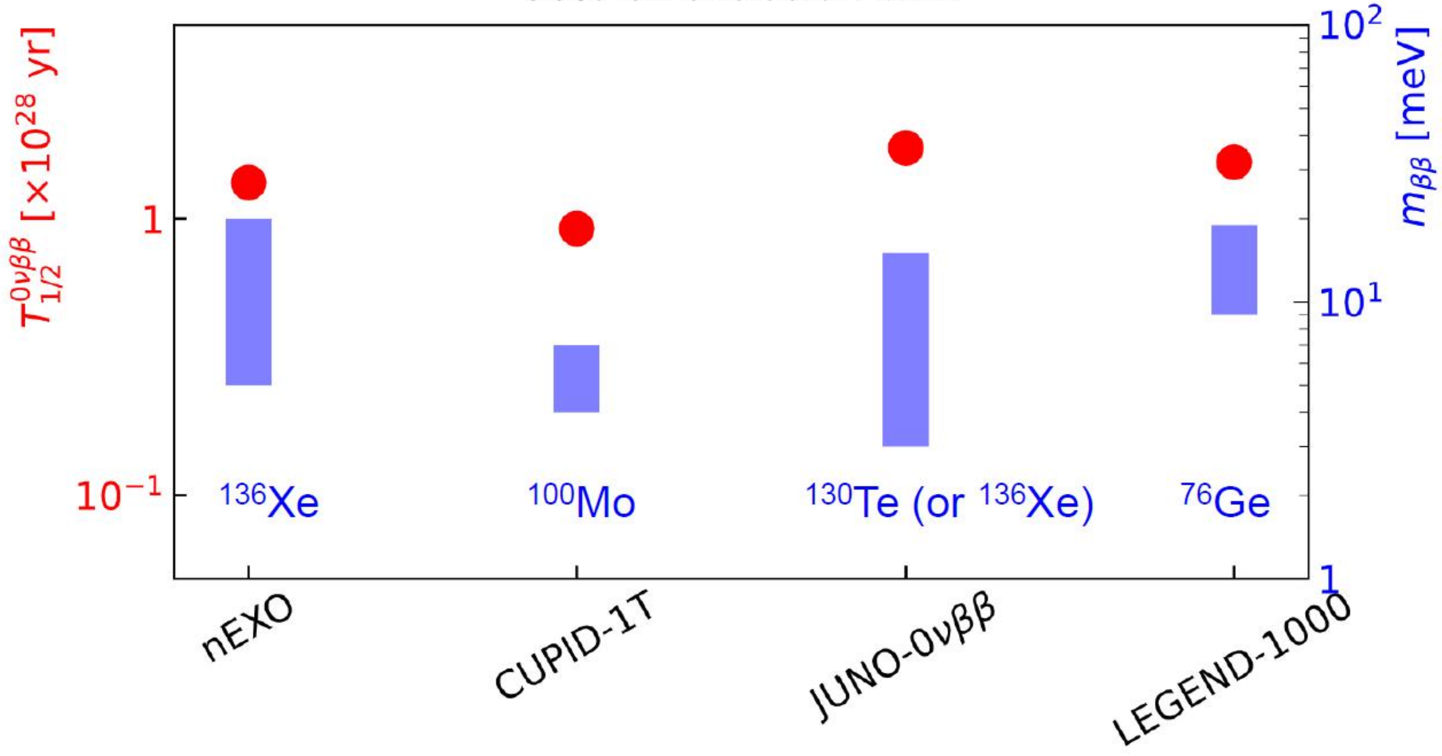




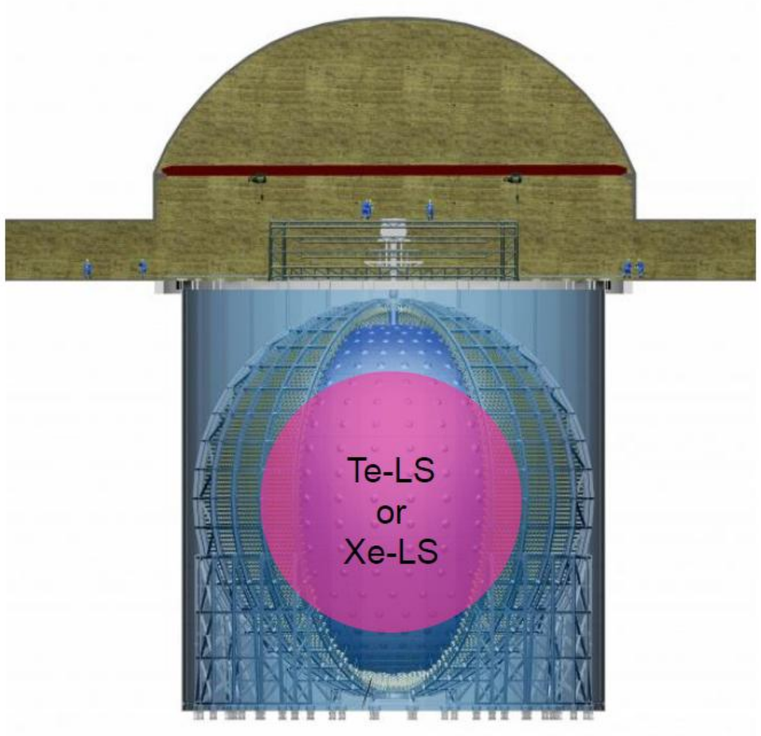
预计的半衰期限制（3年运行后）

$$T_{1/2}^{0\nu\beta\beta} > 2\times 10^{26}\ \text{yr (90\% CL)}$$

JUNO-0$\nu\beta\beta$实验



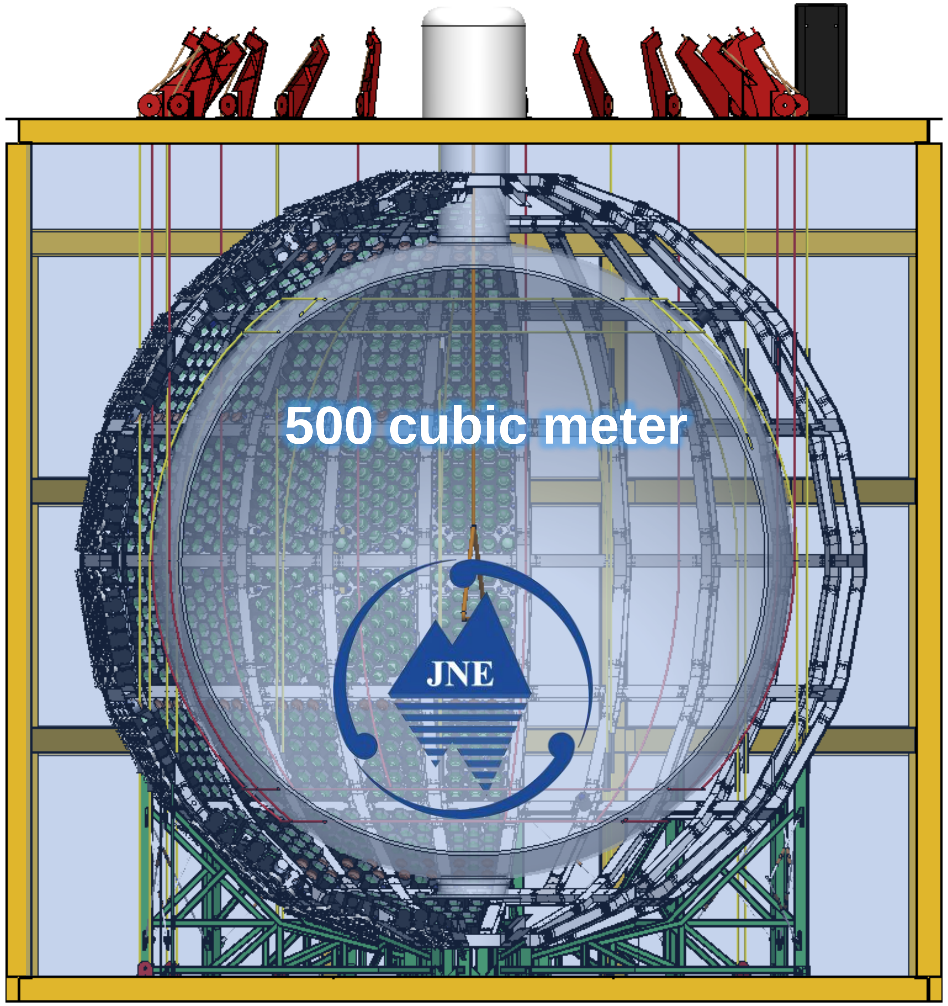
* Numbers are quoted from results shown in Neutrino2022 Conf. and the North America – Europe workshop on future 0νββ experiments in 2021.

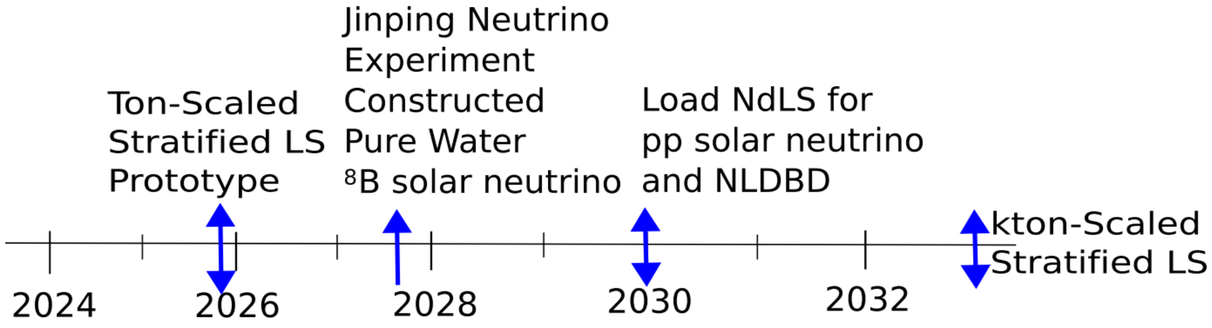


Concept of the experiment

20 kton液闪 →100 ton ^{130}Te或者^{136}Xe

锦屏中微子实验





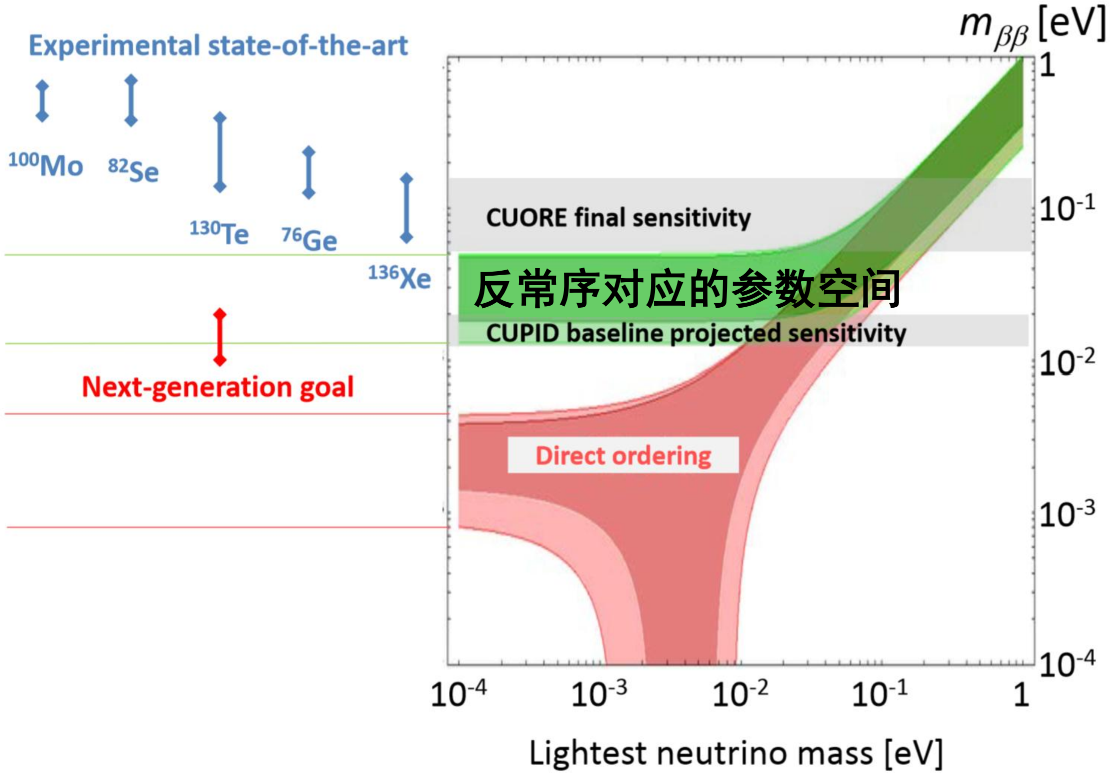
R&D for NdLS

- Nd-150的Q值高（3.37 MeV）
- 实现双贝塔核素的多核素测量，对核矩阵元进行约束
- 未来有望利用切伦科夫光闪烁光分离技术，实现双电子鉴别，大幅降低单电子本底
- 在1%天然Nd的掺杂比例、能量分辨3%@1 MeV、Nd-150曝光量为1.46 ton-year下，Nd-150的半衰期下限估计为

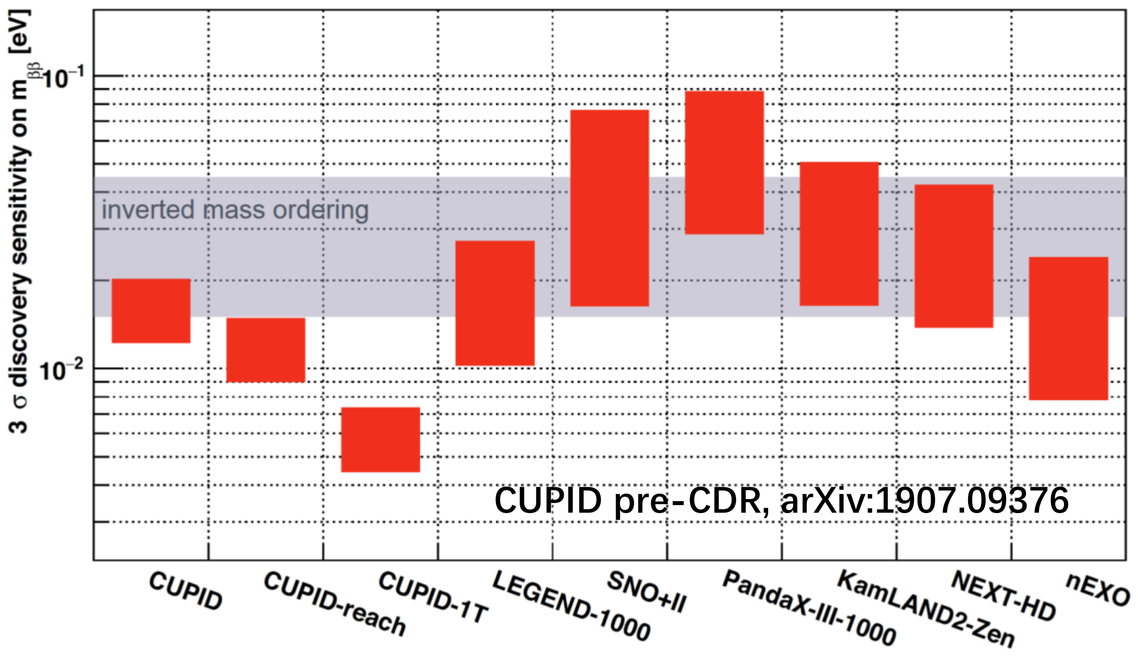
  Nd-150: **6.45×10^{25} yr(90% C.L.)**

下一代 0νββ 实验目标

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



部分下一代实验预期的探测灵敏度

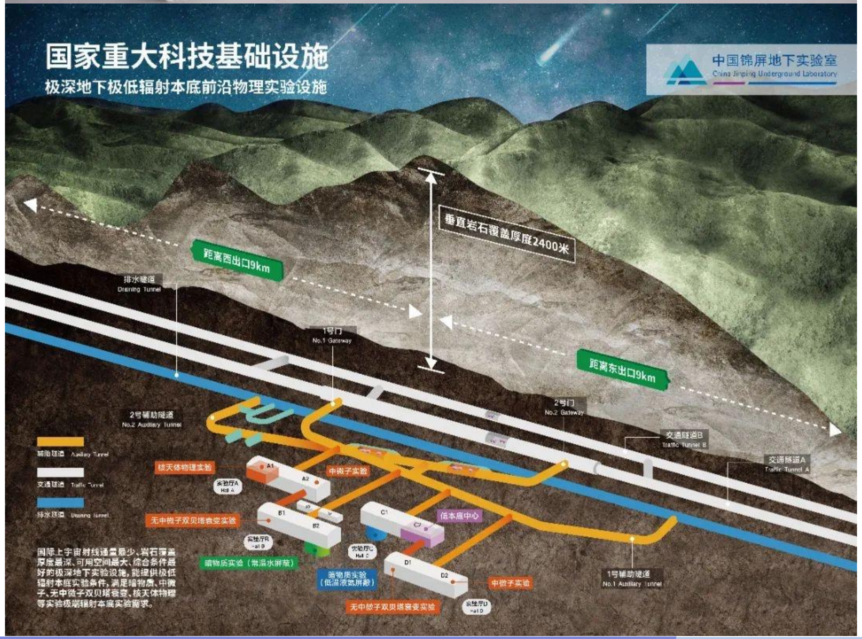


下一代实验目标：覆盖中微子质量反常排序对应的参数空间

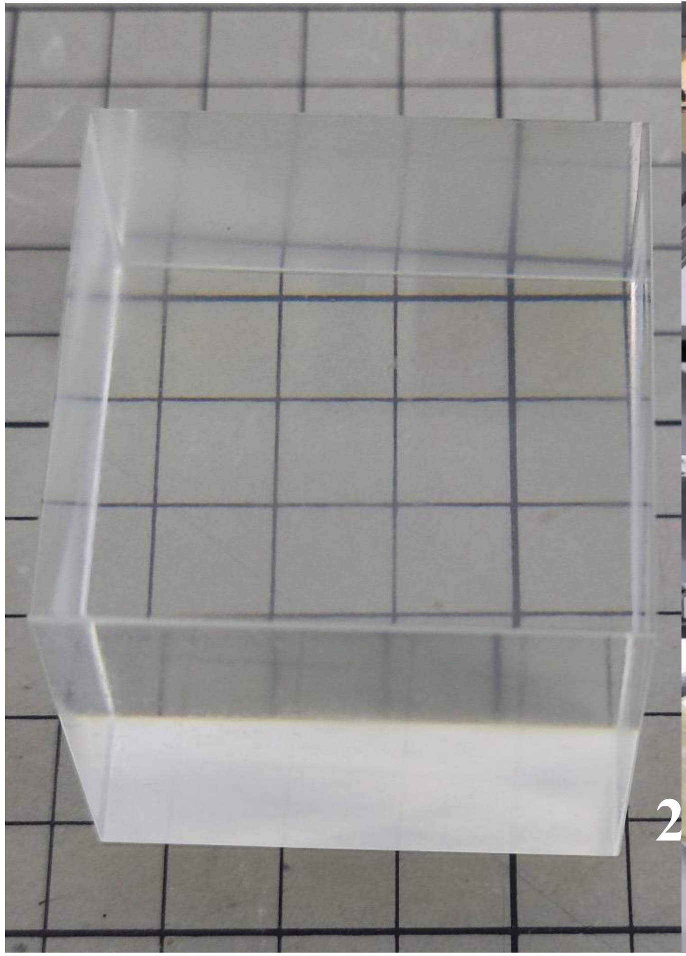
使用不同探测技术，不同核素的多个实验进行交叉验证是必要的。

国内发展机遇

成熟的同位素富集技术



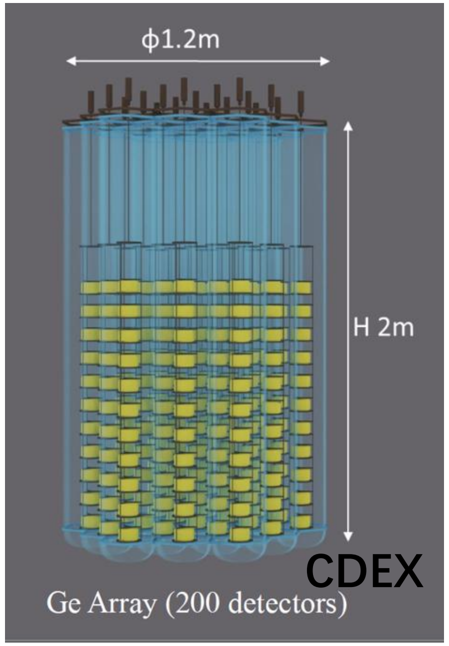
极佳的深地低本底条件—锦屏

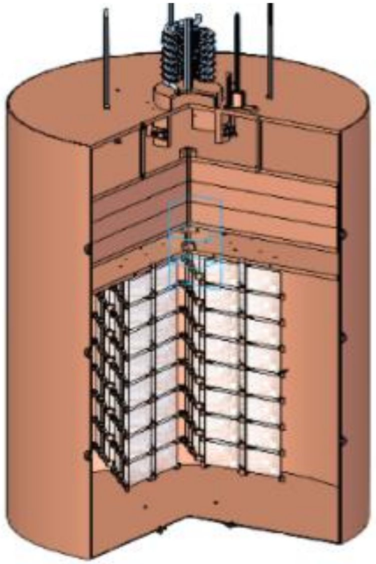


探测器材料制备工艺领先

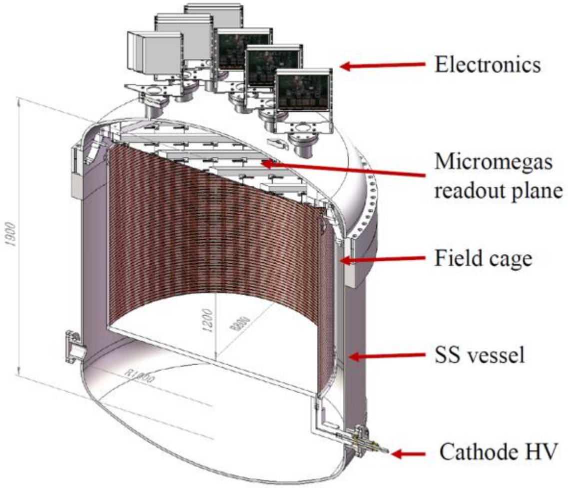
完善的工业体系

部分国内0νββ实验

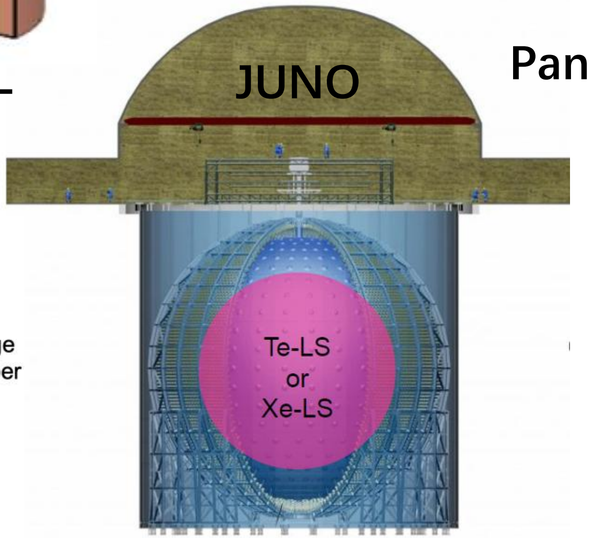


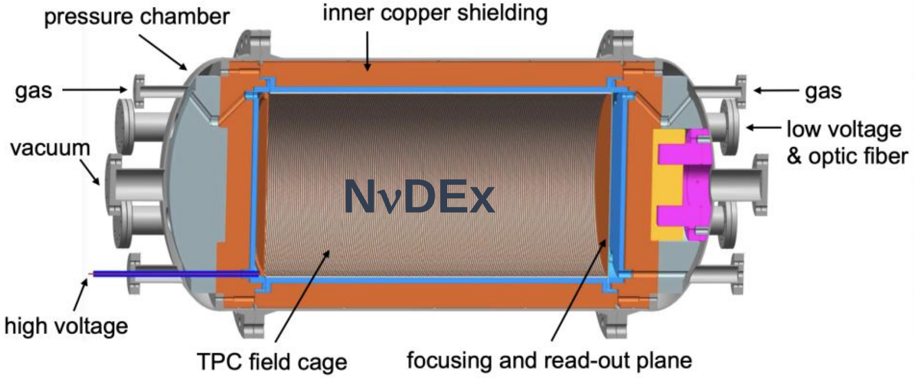


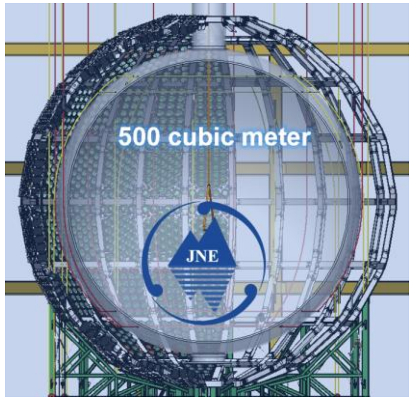
CUPID-CJPL



PandaIII&PandaX







锦屏中微子

总结

- 无中微子双贝塔衰变有重要的物理意义，实验的发展在曲折中前进。
- 无中微子双贝塔衰变的探测现状是多种核素，多种探测技术并进，拥有非常多元化的实验方法。
- 目前实验的发展已经到了一个节点，机遇与挑战并存，希望在未来十年能有所突破。