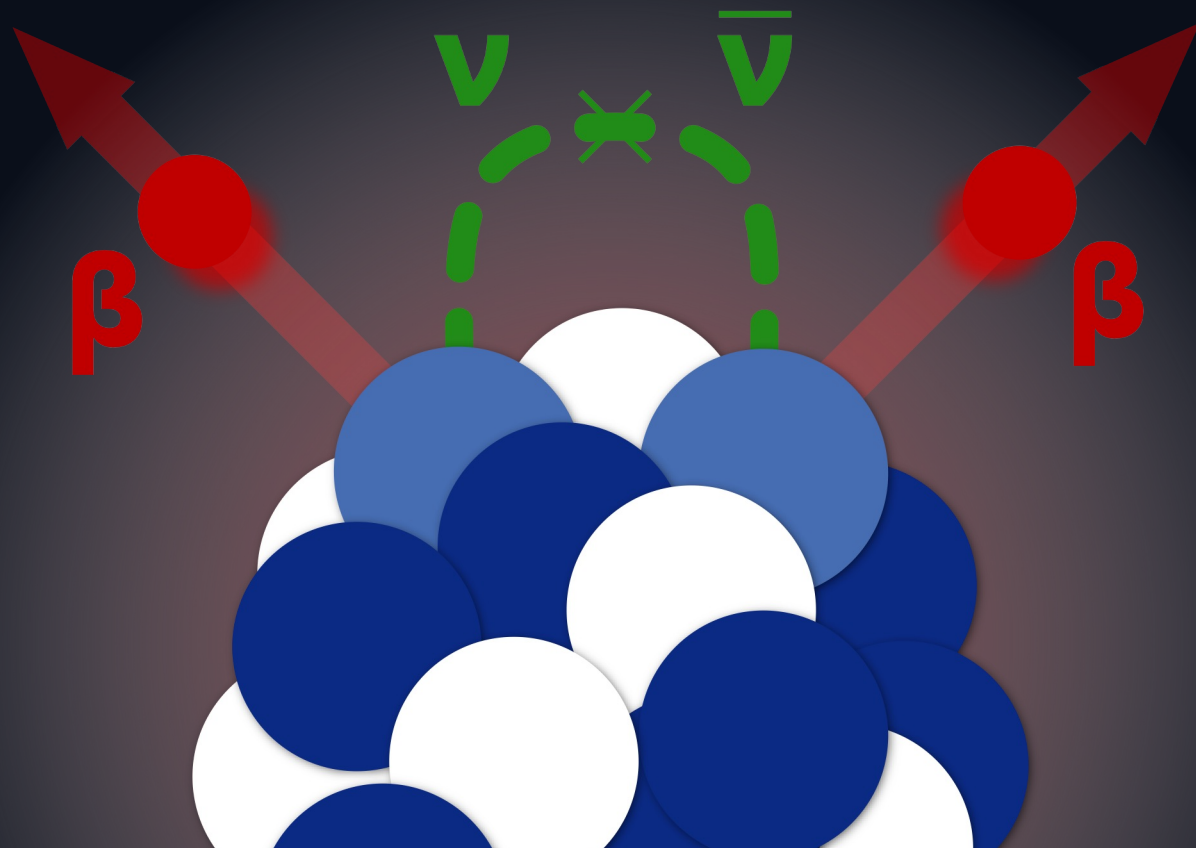


Double Beta Decay

Experiments

Ke Han (SJTU)

韩柯 (上海交通大学)



Outline

1

Introduction

2

**Experimental
searches**

3

**Chinese
efforts**

Outline

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PandaX

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1

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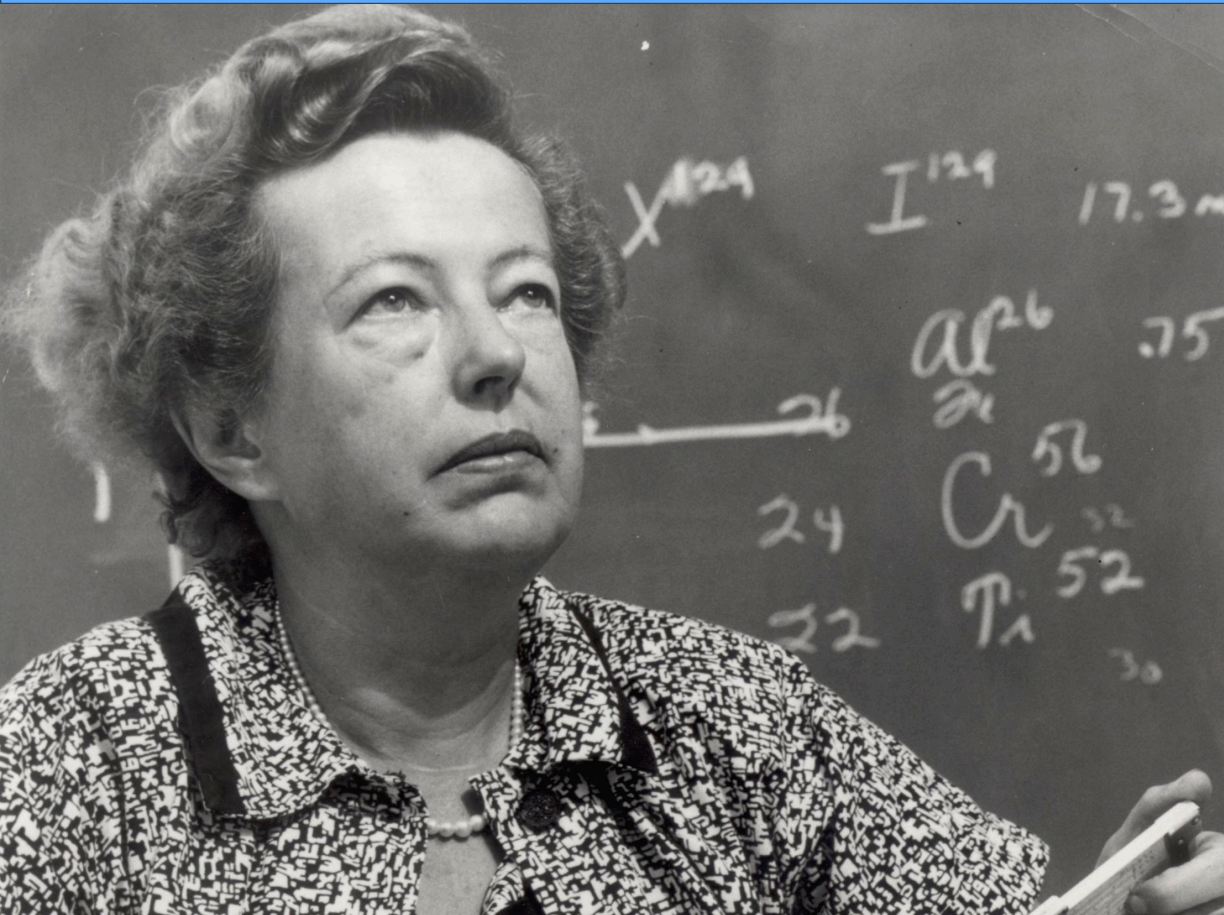
3

**Chinese
efforts**

PandaX

Goeppert-Mayer (1935): double beta decay $2\nu\beta\beta$

Example: $^{136}\text{Xe} \rightarrow ^{136}\text{Ba} + 2e^- + 2\bar{\nu}$



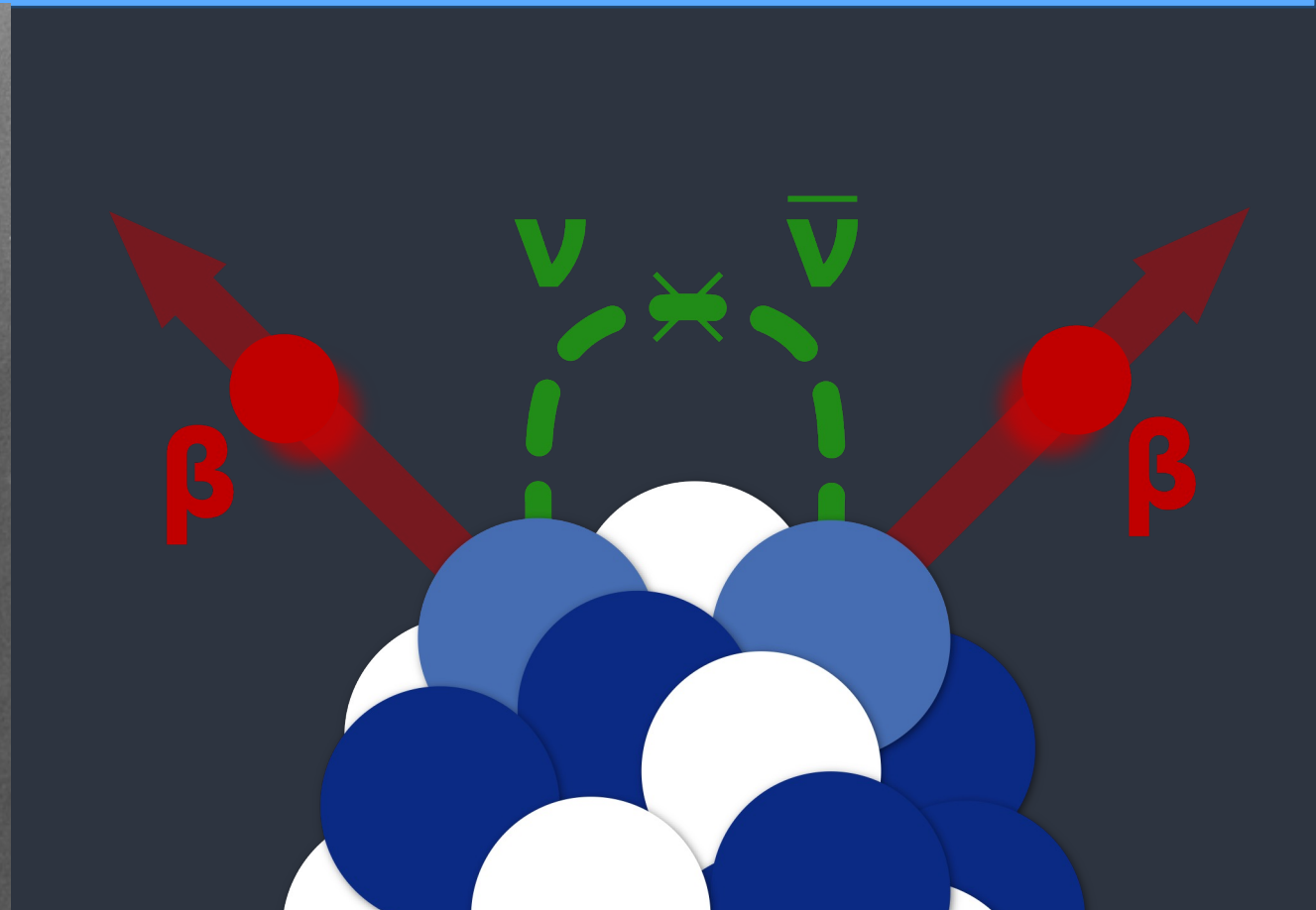
Majorana (1937): Fermions as Their **Own Antiparticles?**



$$\bar{\nu} \stackrel{?}{=} \nu$$

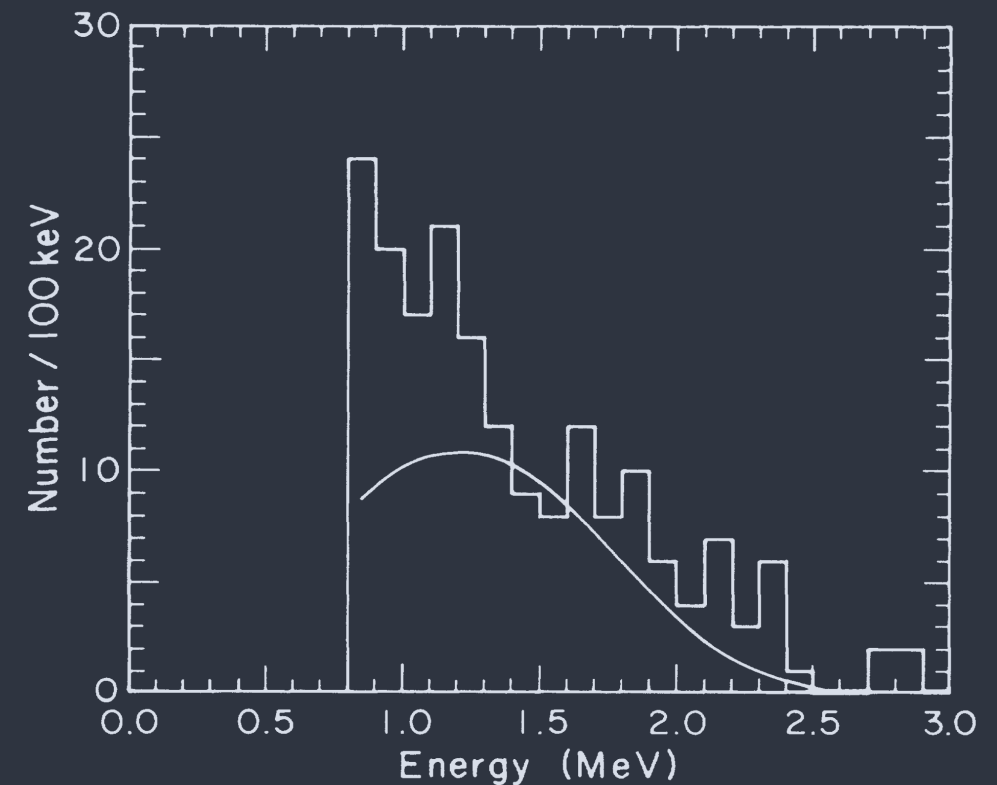
Furry (1939): **neutrinoless** double beta decay $0\nu\beta\beta$

Example: $^{136}\text{Xe} \rightarrow ^{136}\text{Ba} + 2e^{-}$

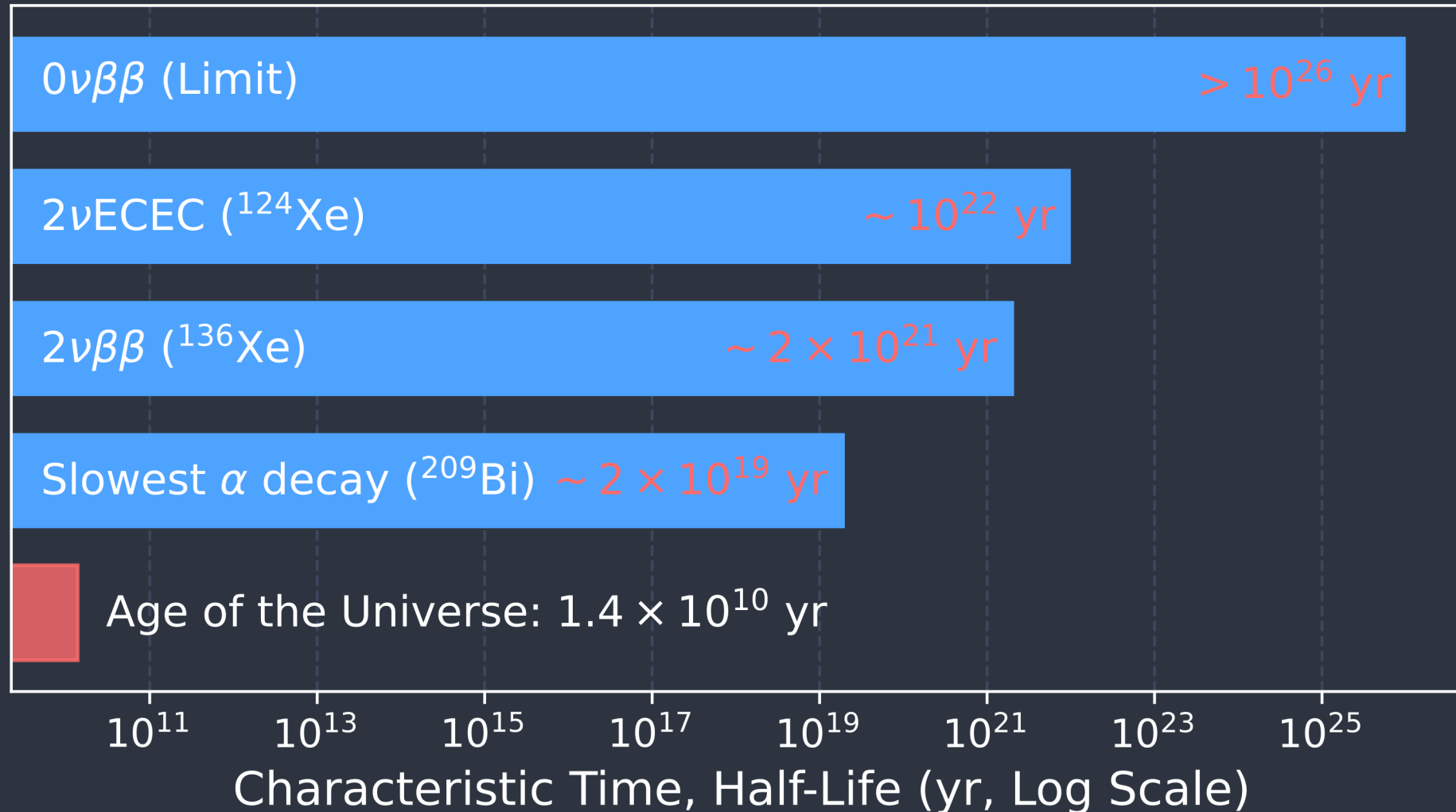


Elliott, Hahn, Moe (1987): First **observation** of $2\nu\beta\beta$

Gas Time Projection chamber, ^{82}Se $2\nu\beta\beta$, 10^{20} year half-life



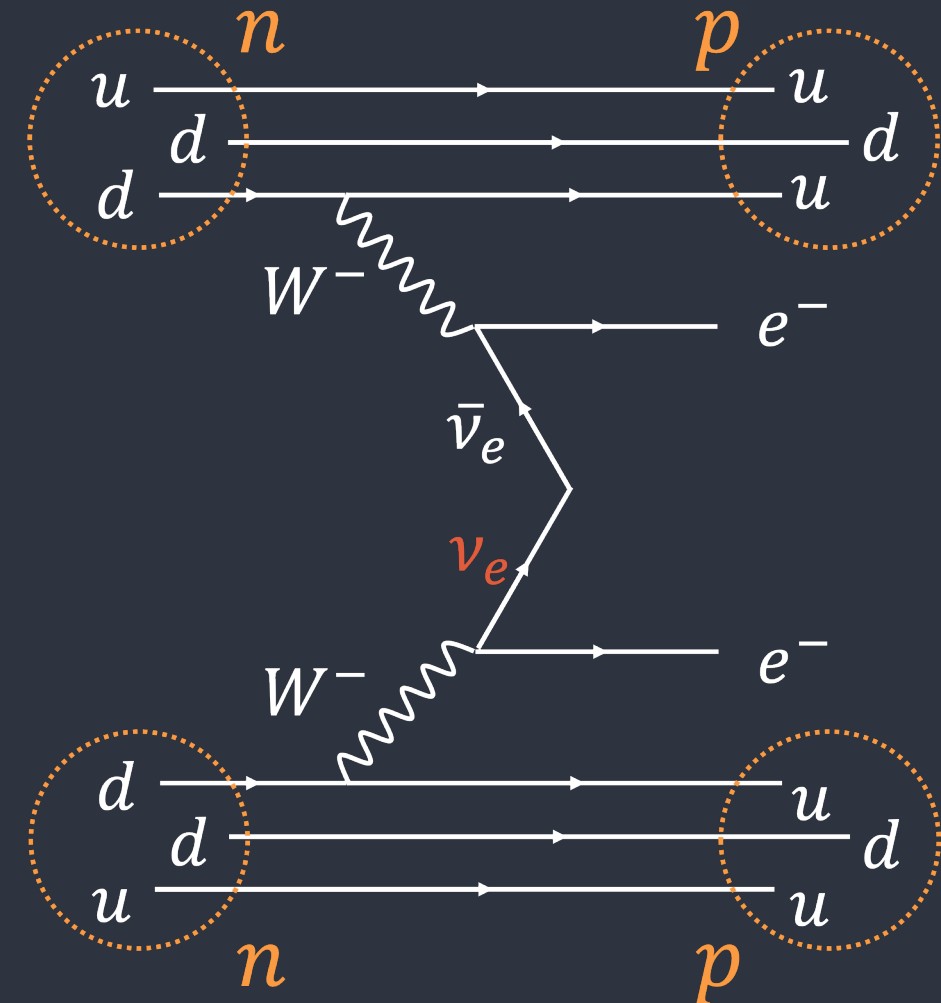
Slowest measured process



$0\nu\beta\beta$ and neutrino physics

- Majorana or Dirac nature of neutrinos
- Lepton number violating process: beyond neutrino physics
- Measures effective Majorana mass: relate $0\nu\beta\beta$ to the neutrino oscillation

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

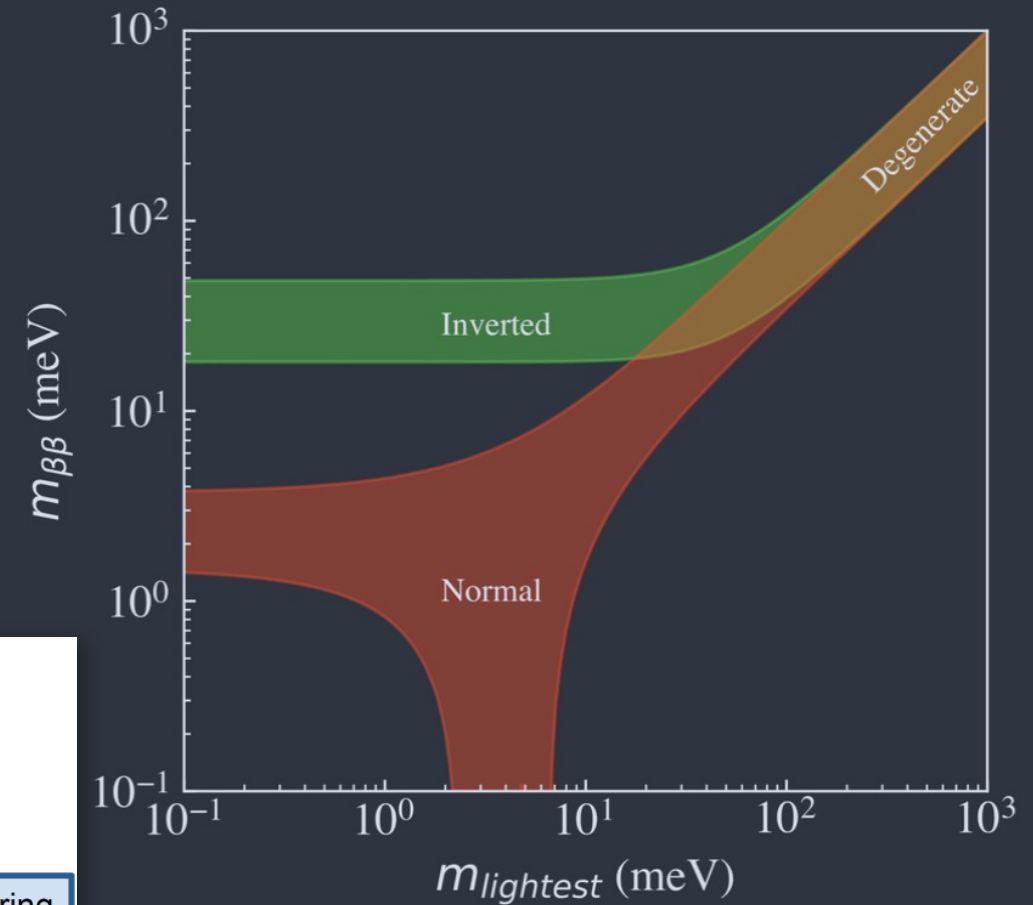


$0\nu\beta\beta$ experiments and $m_{\beta\beta}$

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

$G^{0\nu}(Q, Z)$: Phase space factor

$|M^{0\nu}|$: Nuclear Matrix Elements



$$\text{Half life sensitivity} \propto \eta \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

Isotopic abundance

Detecting efficiency

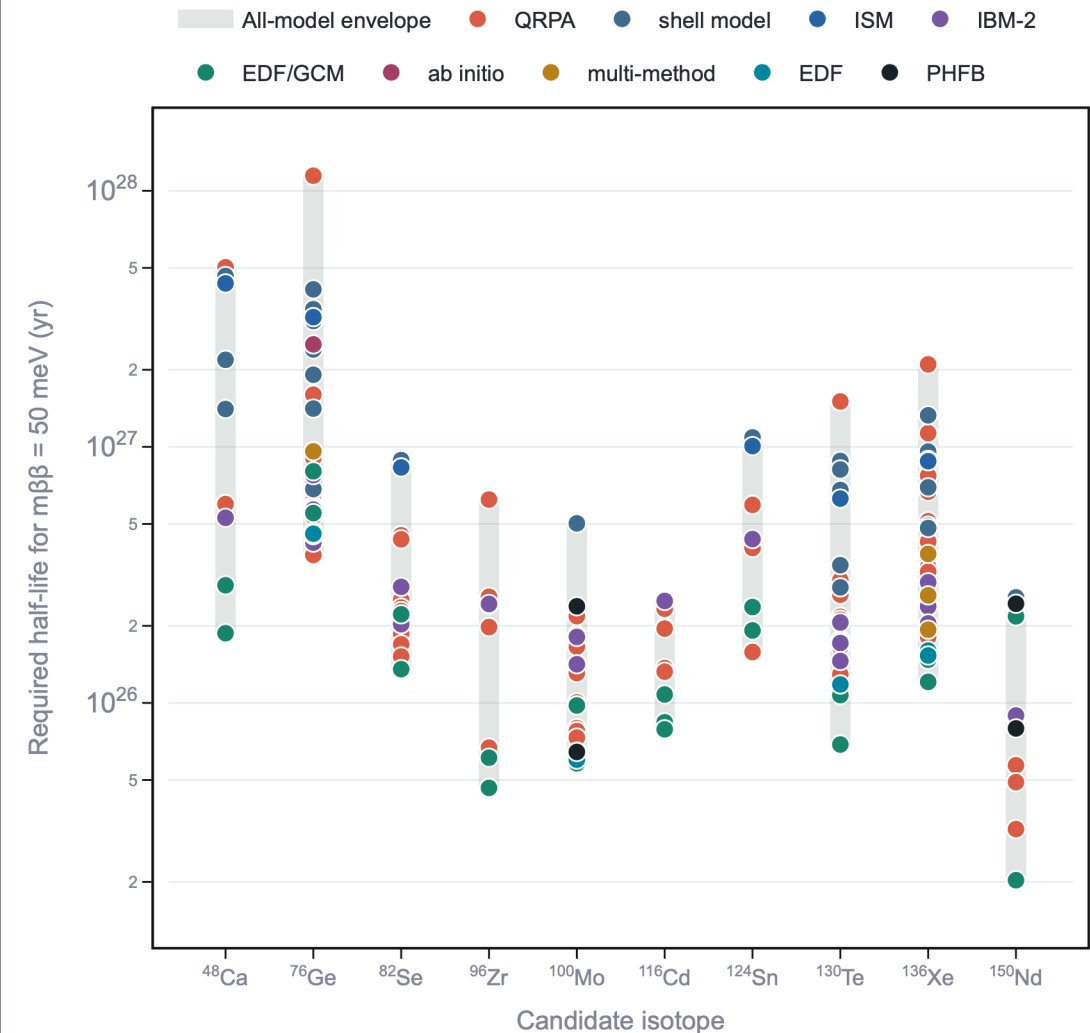
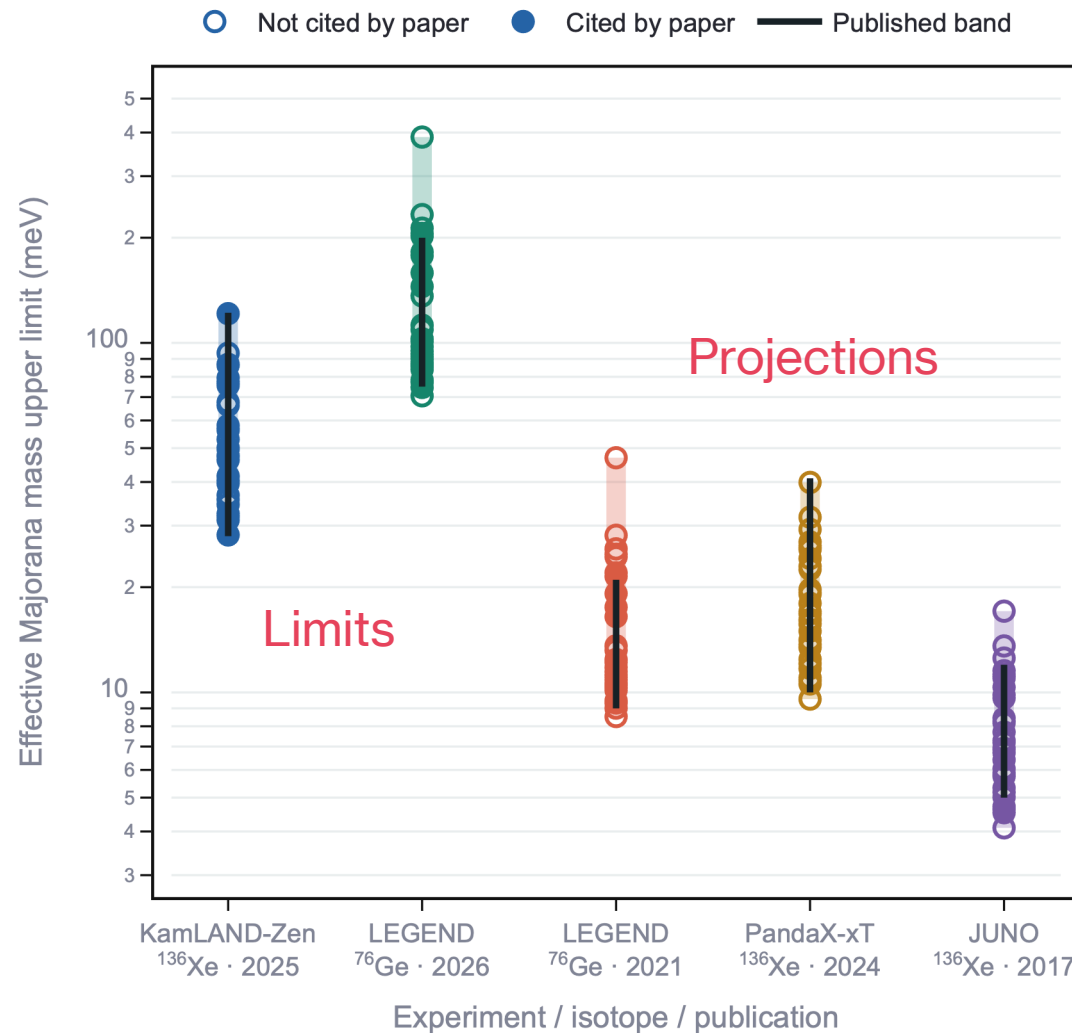
Detector mass

Background rate

Energy resolution

Measuring time

Importance of NMEs



Smaller NMEs get fewer citations?

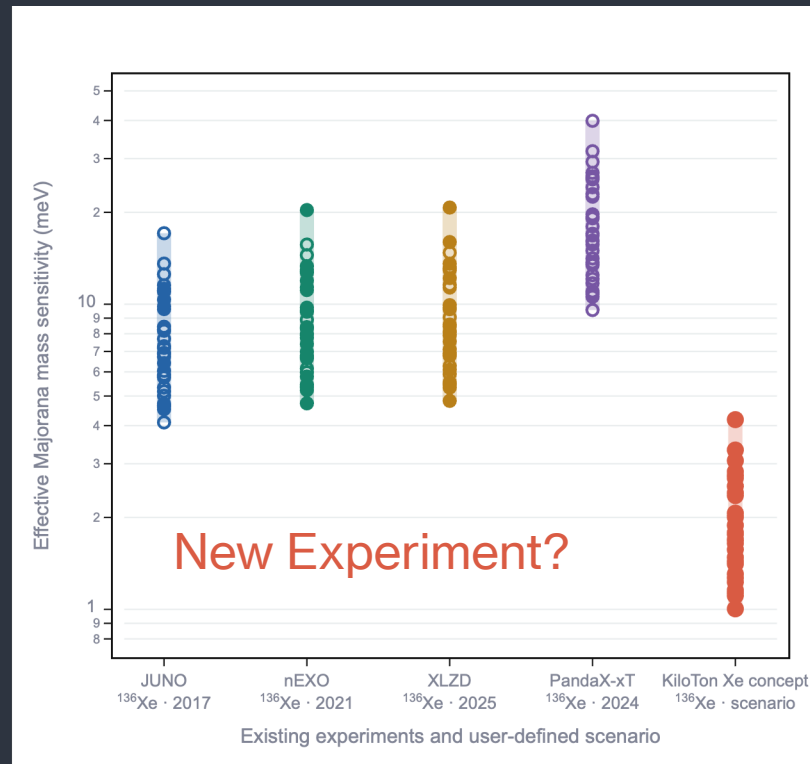
Smaller NMEs get fewer citations?

Samples	Large NME	Small NME	Difference
Ge/Xe results	67.4% (29/43)	62.5% (35/56)	+4.9 %
Ge/Xe results+projections	51.2% (43/84)	50.0% (55/110)	+1.2 %
All-isotope results	65.9% (56/85)	66.7% (74/111)	-0.8 %
All-isotope results+projections	48.0% (72/150)	50.3% (98/195)	-2.3 %
Projections only	24.6% (16/65)	28.6% (24/84)	-4.0 %

- The answer is No!

$m_{\beta\beta}$ Atlas

- Compiled the list of experimental and NME papers
- More transparent citation pairs
- <https://mbbatlas.streamlit.app>



mbb Atlas

Experimental limits, nuclear matrix elements and effective Majorana mass interpretations

Paper detail

Mass bands

Head to head

Isotopes

New Experiment?

Selected paper

CUPID · 100Mo · 2026 — Sensitivity of the CUPID experiment to $0\nu\beta\beta$ decay of ^{100}Mo

Sensitivity of the CUPID experiment to $0\nu\beta\beta$ decay of ^{100}Mo

Design

100Mo

Target sensitivity

Half-life

1.6×10^{27} yr

Confidence

90% CI

Direct NME sources

7

Publication

CUPID · 2026

Bayesian exclusion sensitivity for the ten-live-year baseline

Open source article

Published band

10 meV – 28 meV

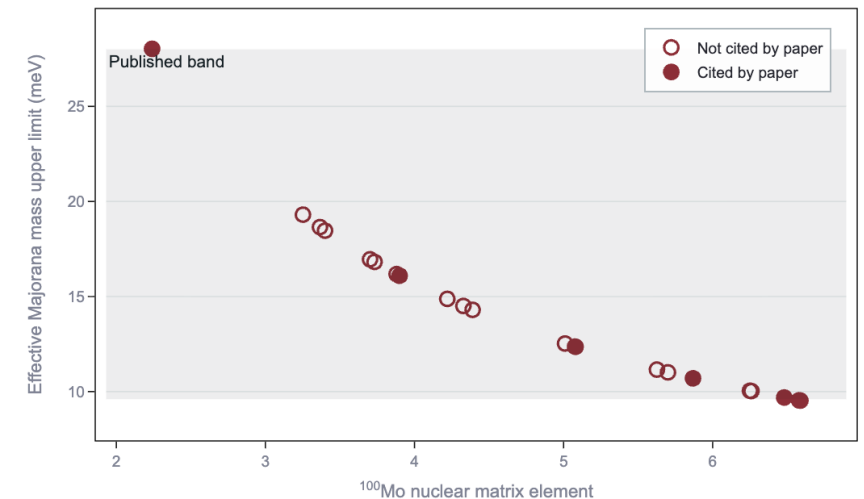
Recomputed cited band

10 meV – 28 meV

All-model envelope

10 meV – 28 meV

Published band source: article abstract. It is shown as reported and is not rescaled when gA changes.



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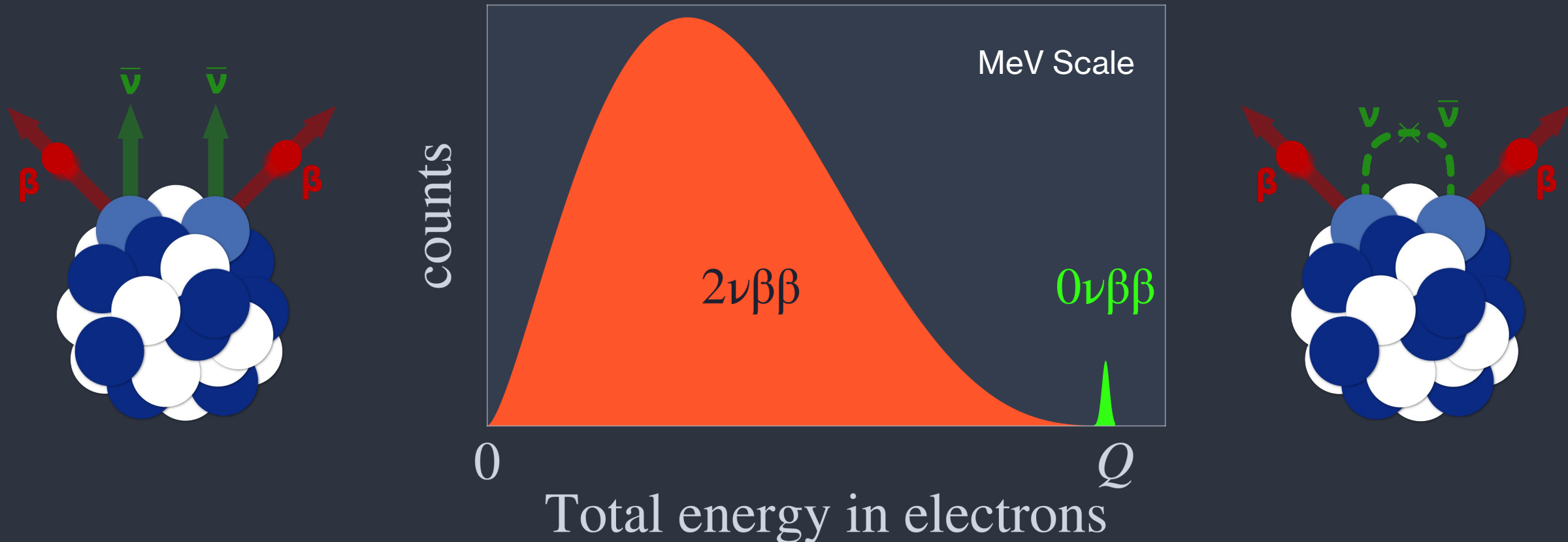
3

**Chinese
efforts**

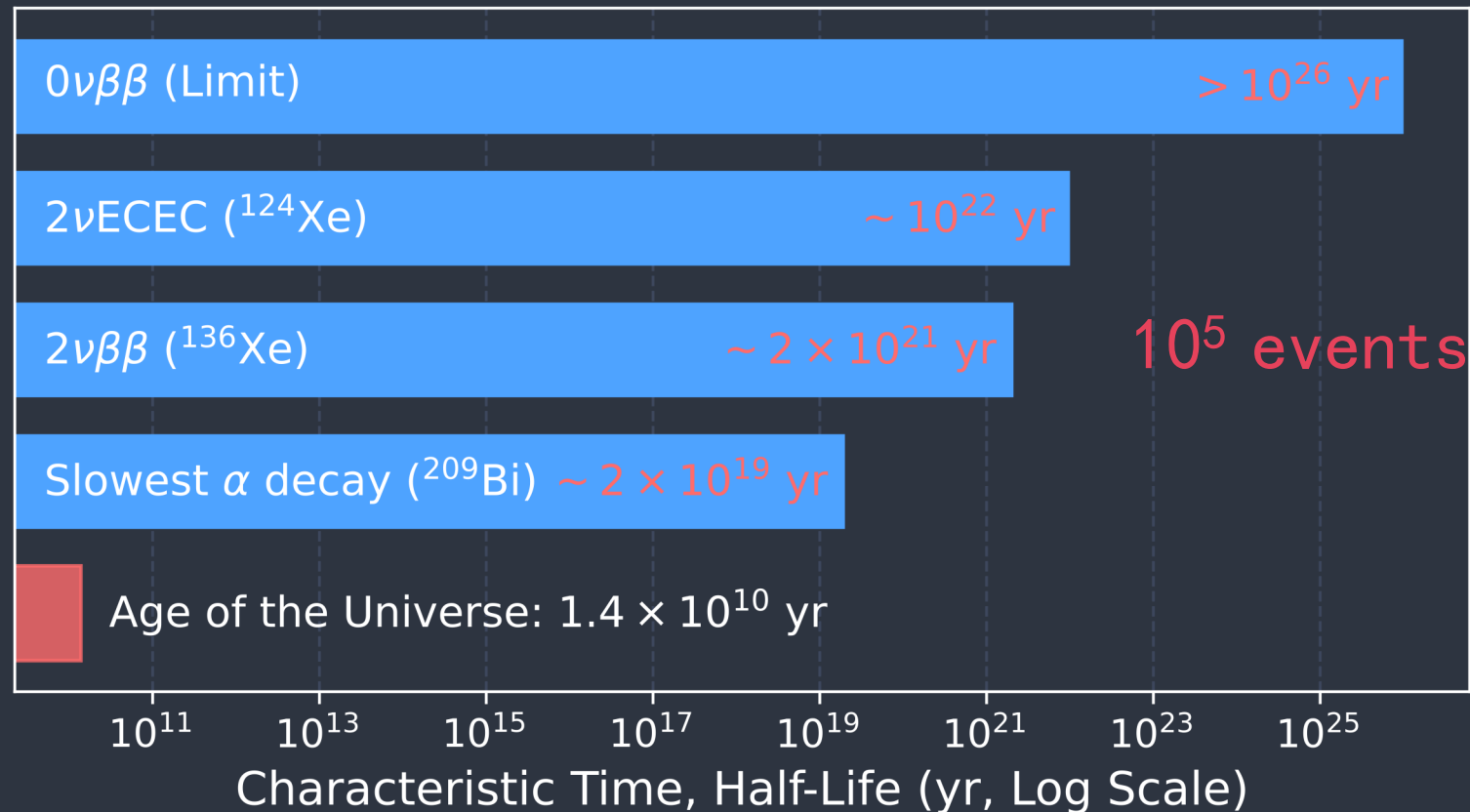
PandaX

Experimental searches

Measure the electrons' energy, searching for possible peak at Q-value

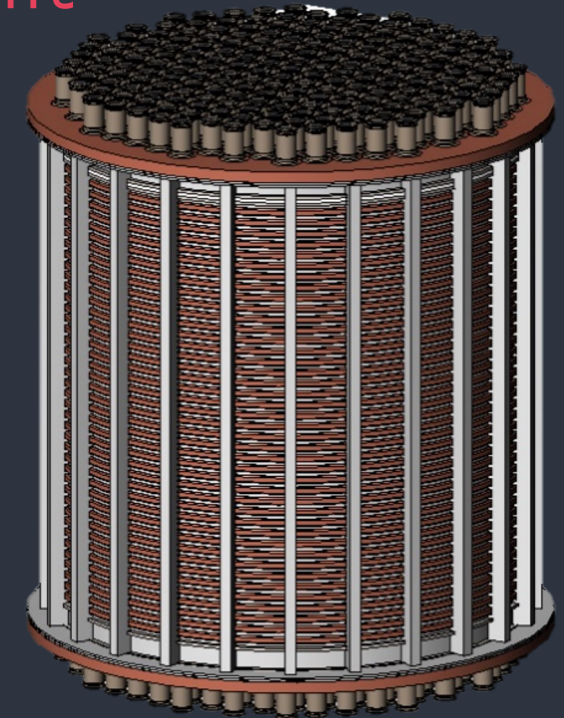


The main challenge: extremely rare event



< 1 event

10^5 events



PandaX-4T

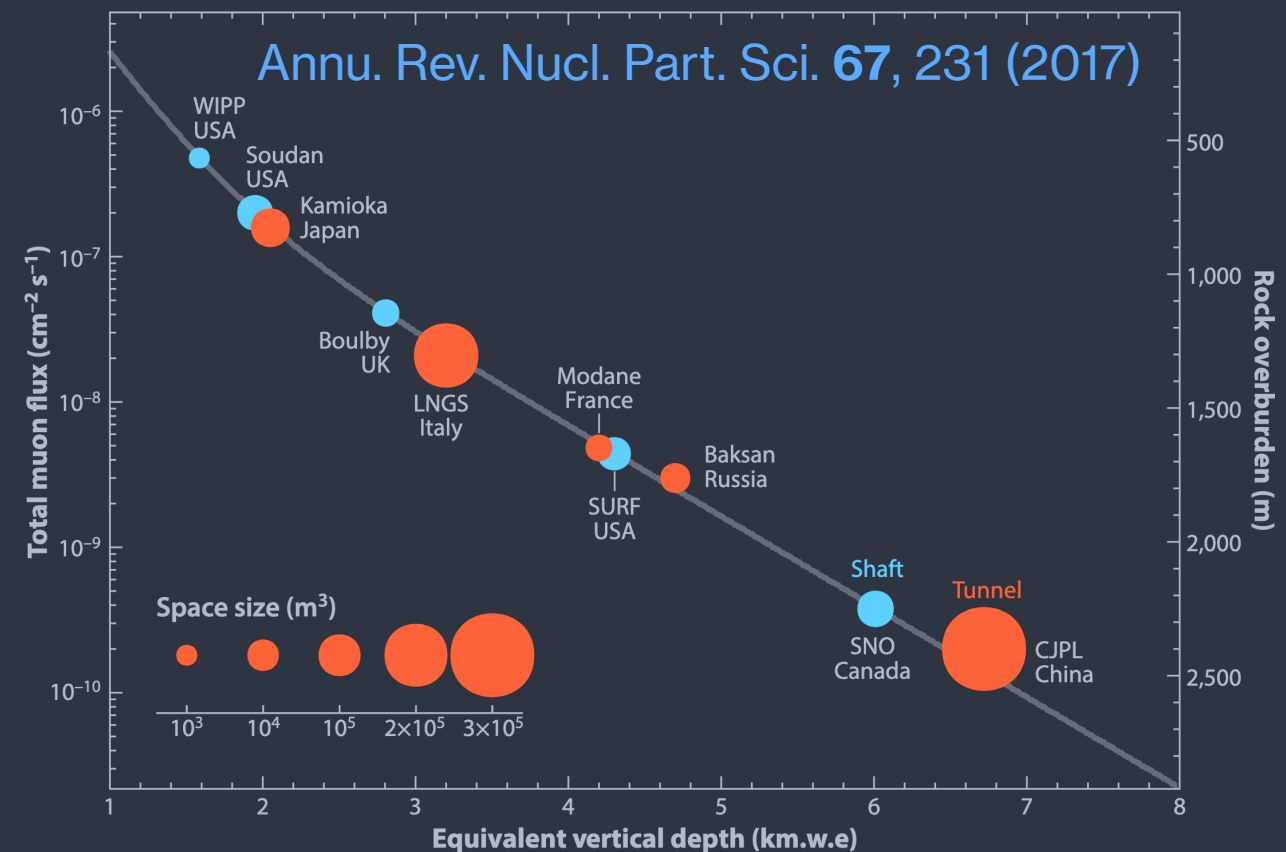
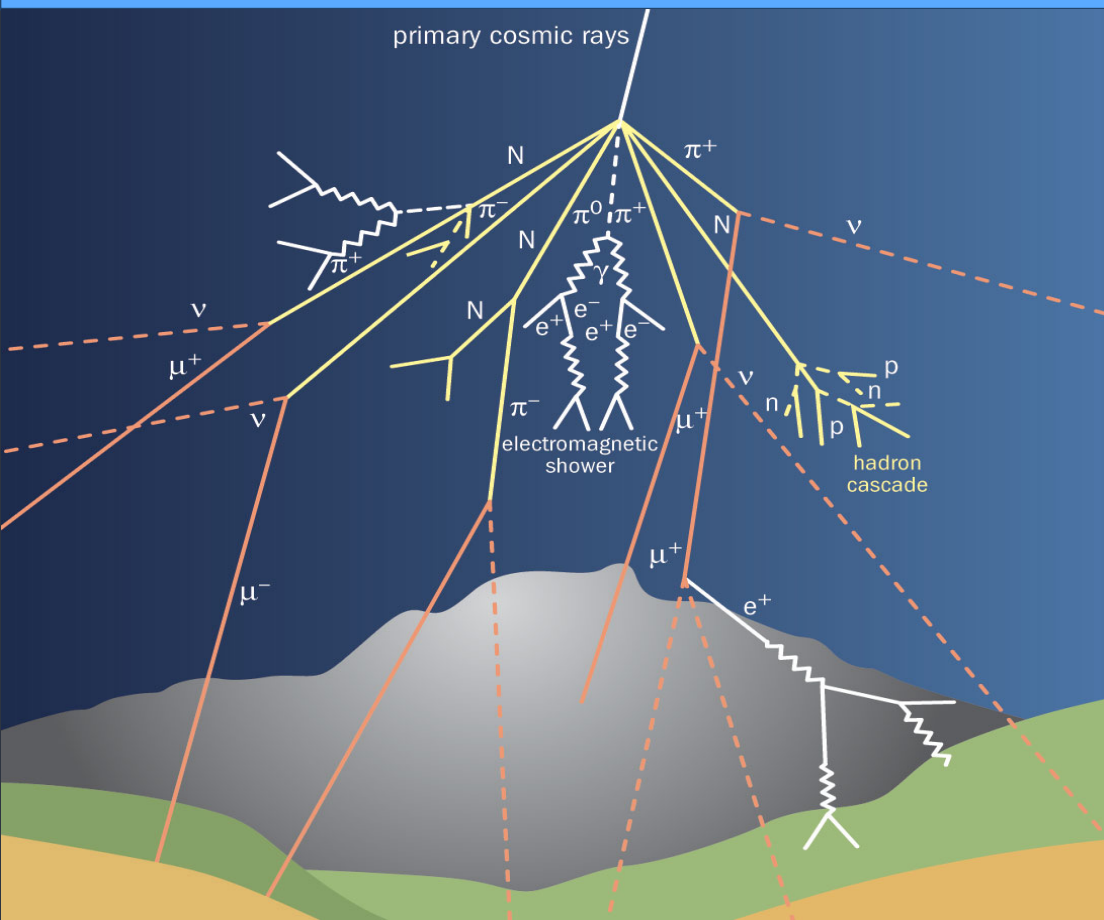
Background control

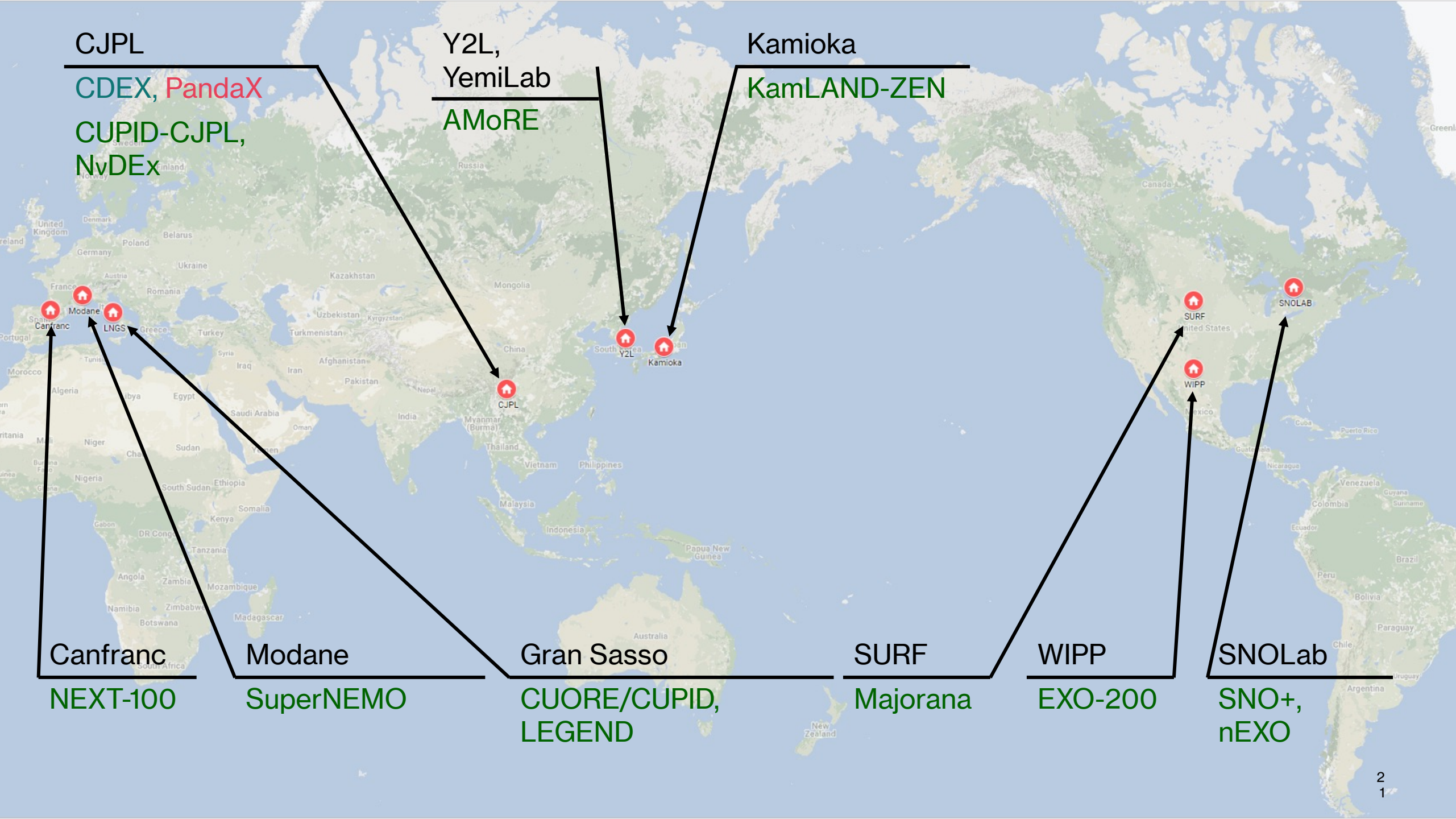
- Intrinsic radioactivity in materials
 - Normally 1-100 Bq/kg
 - Experimental target: < 1 mBq/kg
- Surface radioactivity of detector
 - Surface treatment protocols
 - Radon suppression
- Laboratory environment
 - Additional low-background shielding



Background Control: going Underground

- Direct muon hits in the detector
- Cosmogenic radioactivity

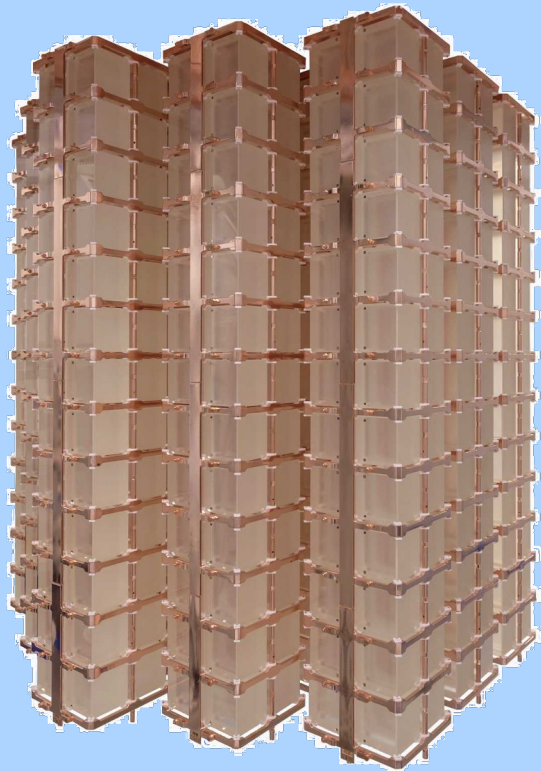




Major International Collaborations

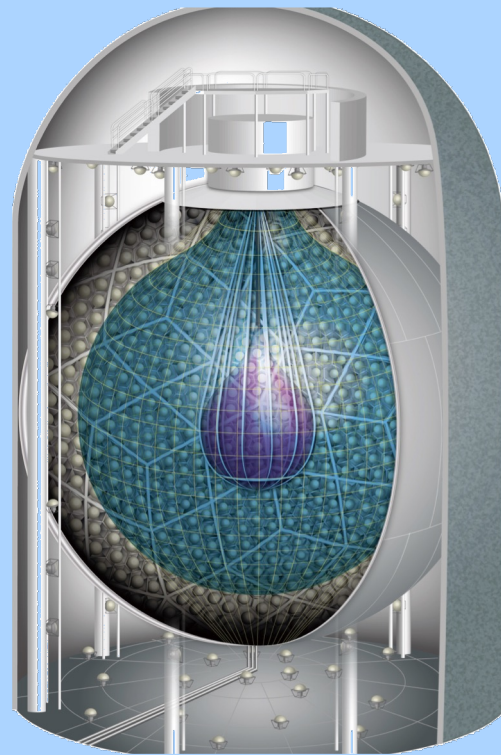
CUORE/CUPID

Bolometers



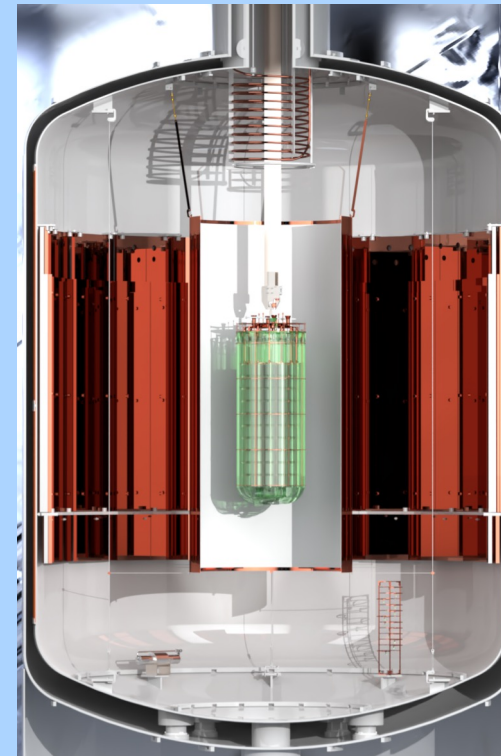
KamLAND-Zen

Liquid scintillator



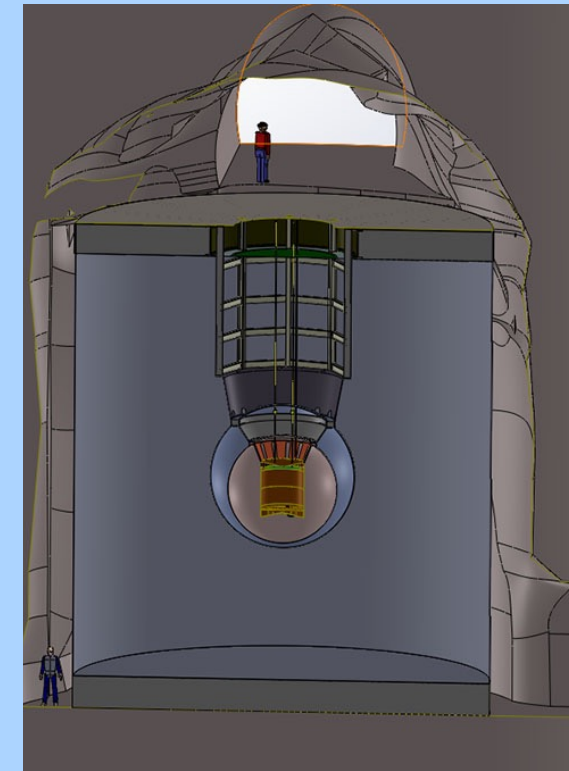
LEGEND family

HPGe



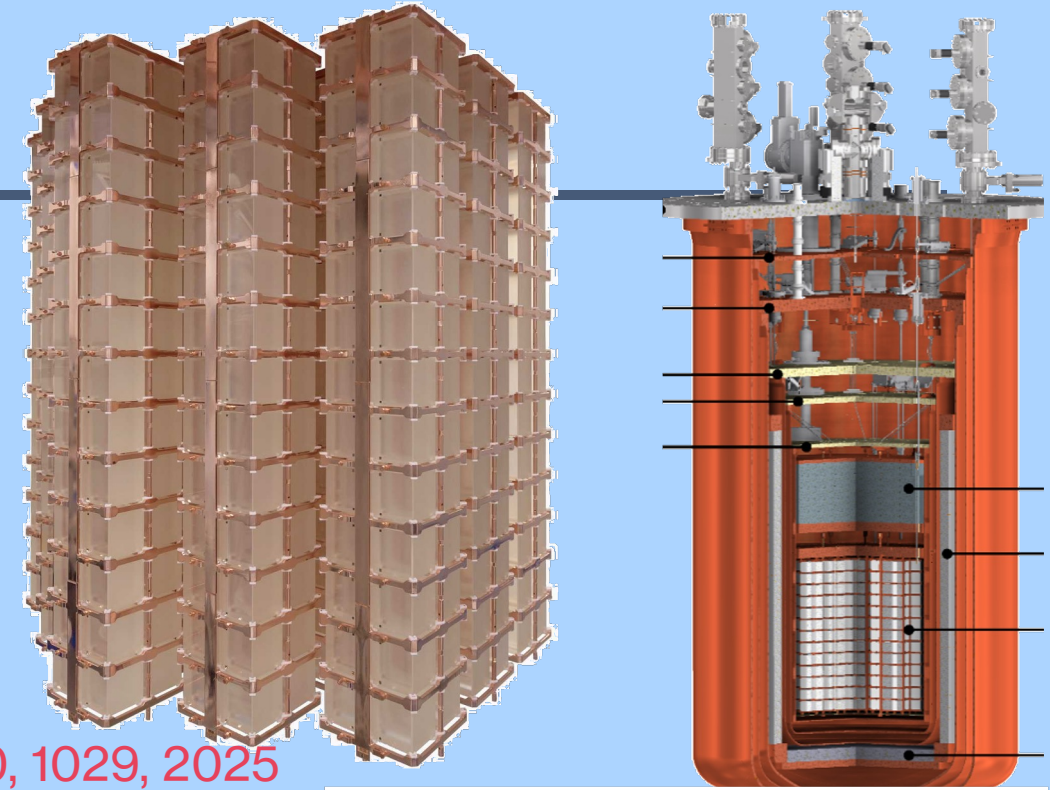
nEXO/XLZD

Xe TPC

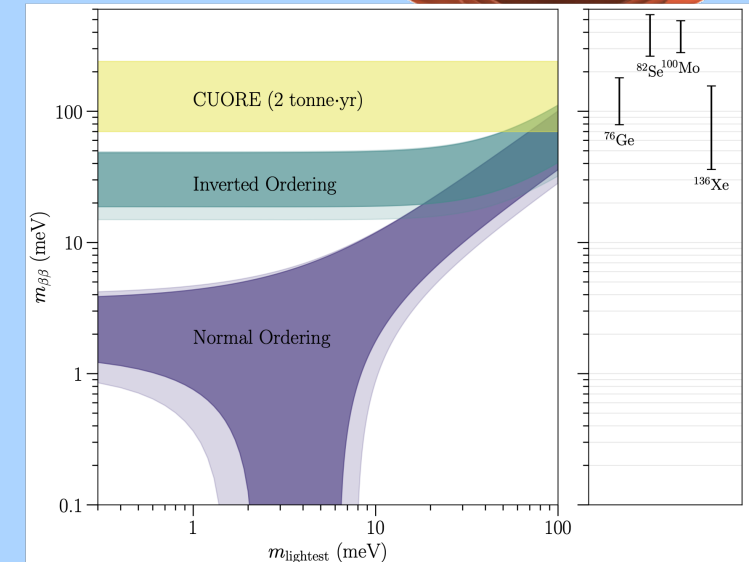
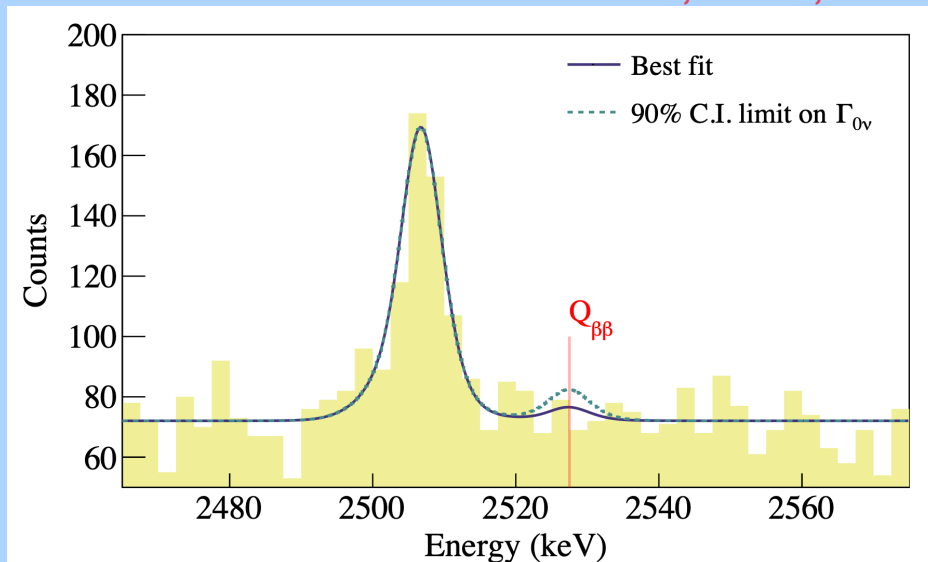
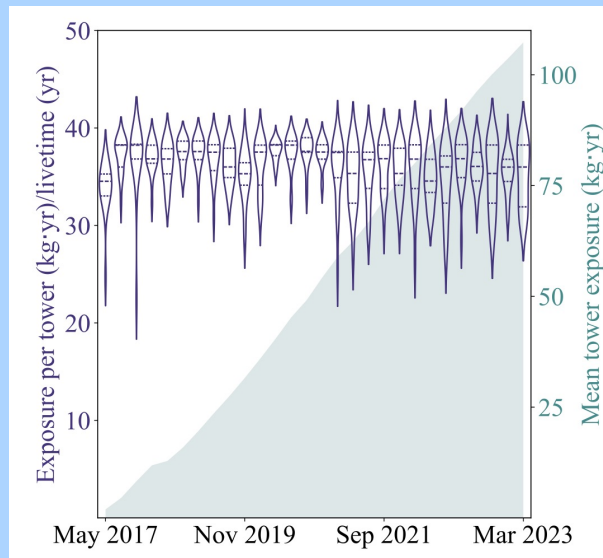


CUORE bolometers

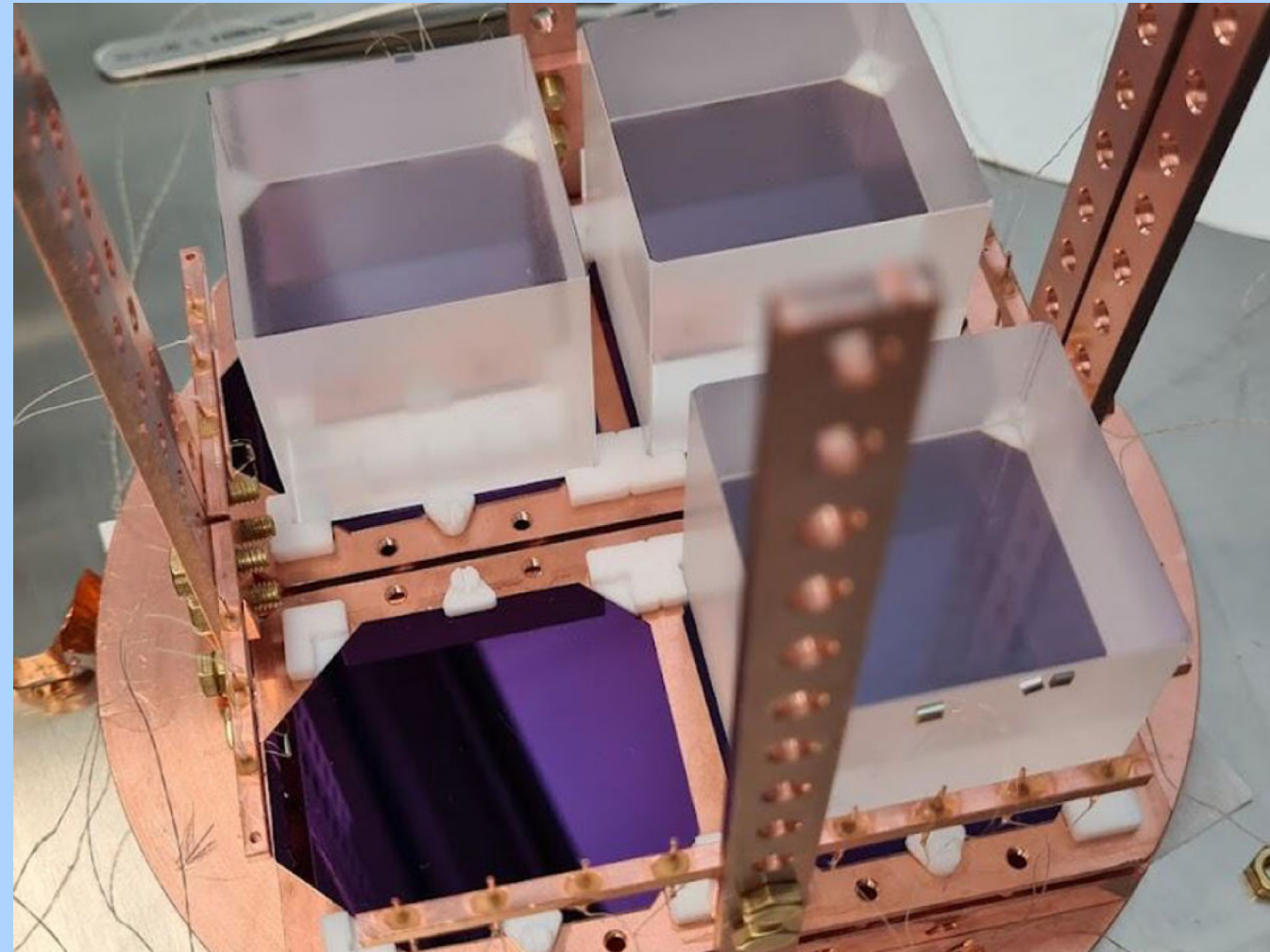
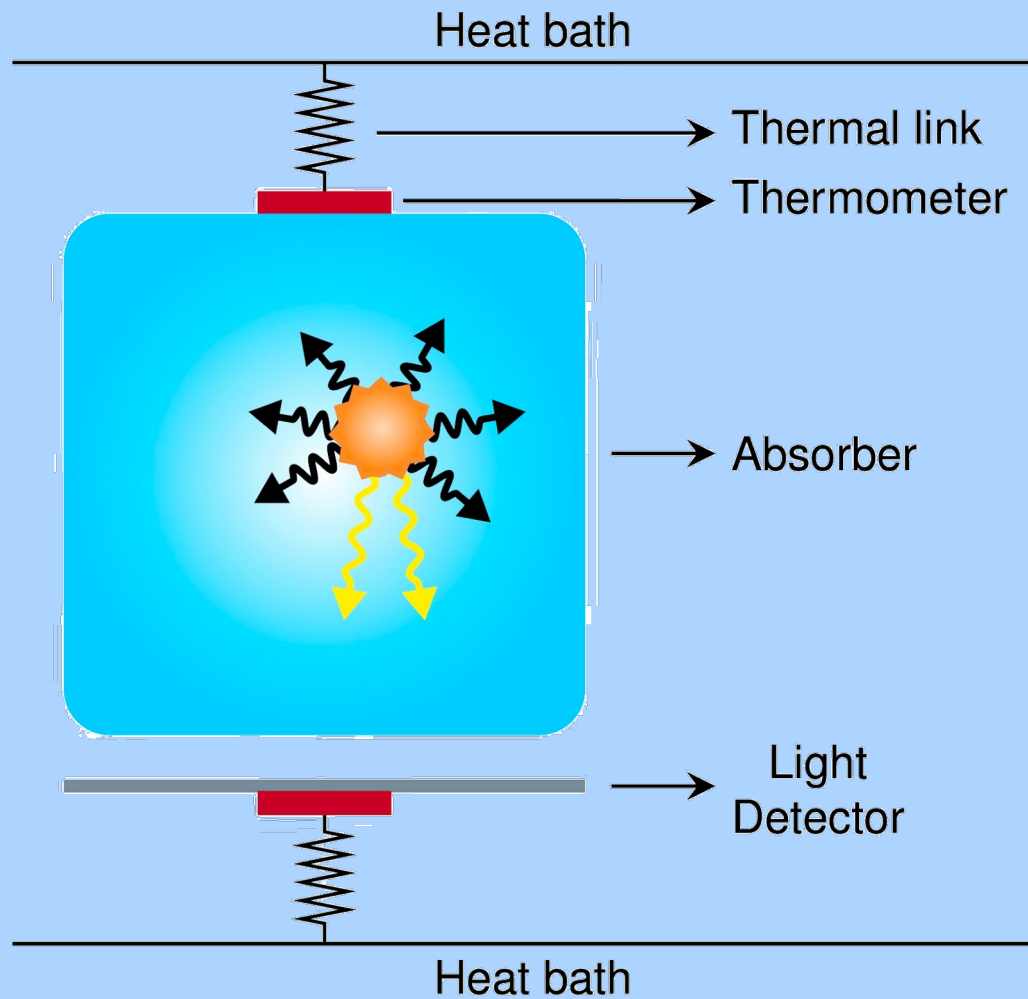
- 988 TeO_2 crystals for $0\nu\beta\beta$ of ^{130}Te
- 10 mK in a custom dilution refrigerator
- Energy resolution: 7.3 keV @ 2.5 MeV
- Background index: 1.4 cts/keV/kg/yr



Science 390, 1029, 2025

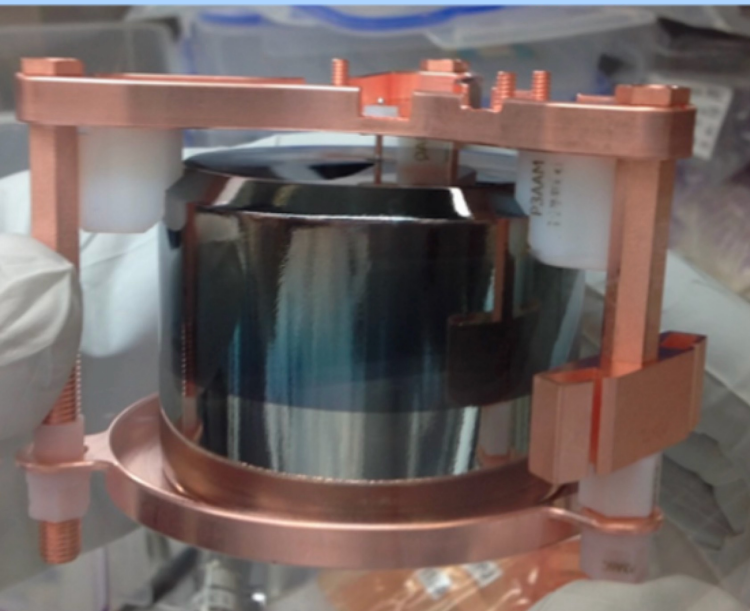


CUPID: CUORE Upgrade with Particle ID

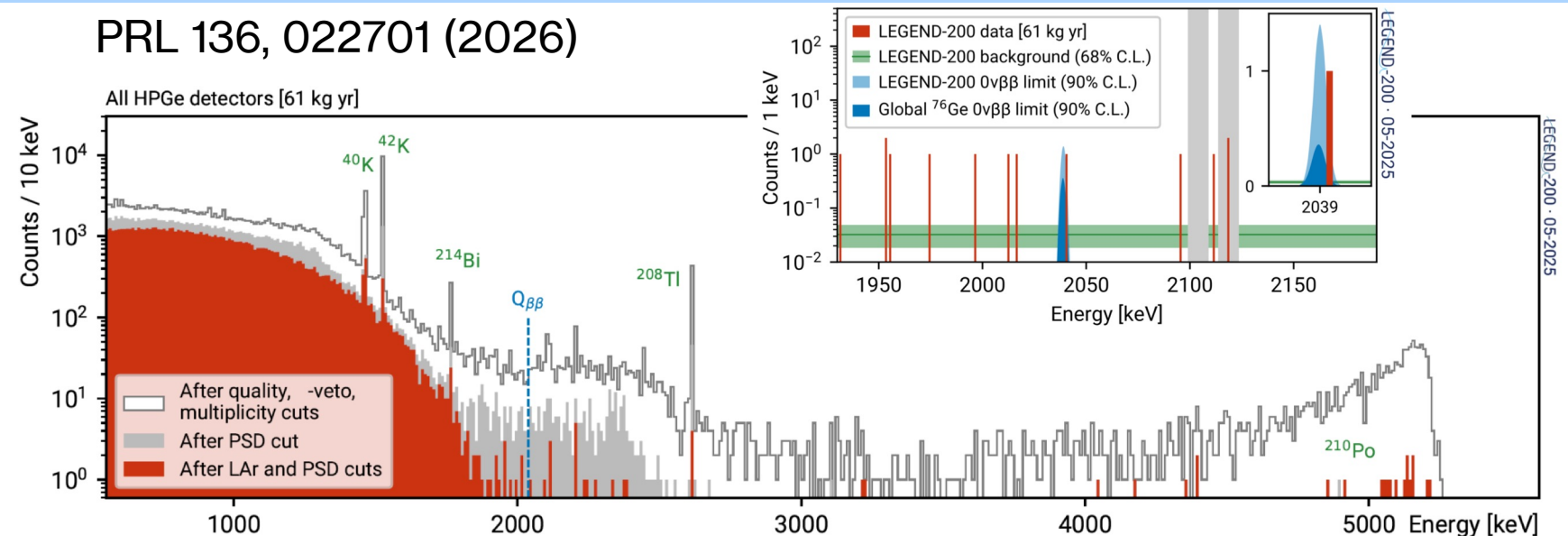


LEGEND: HPGe array for ^{76}Ge $0\nu\beta\beta$

- LEGEND-200: Stable data taking with 138 kg of enriched Ge detectors
- $\sim 0.1\%$ resolution at $Q_{\beta\beta}$
- First results in 2026; more detectors/lower background expected



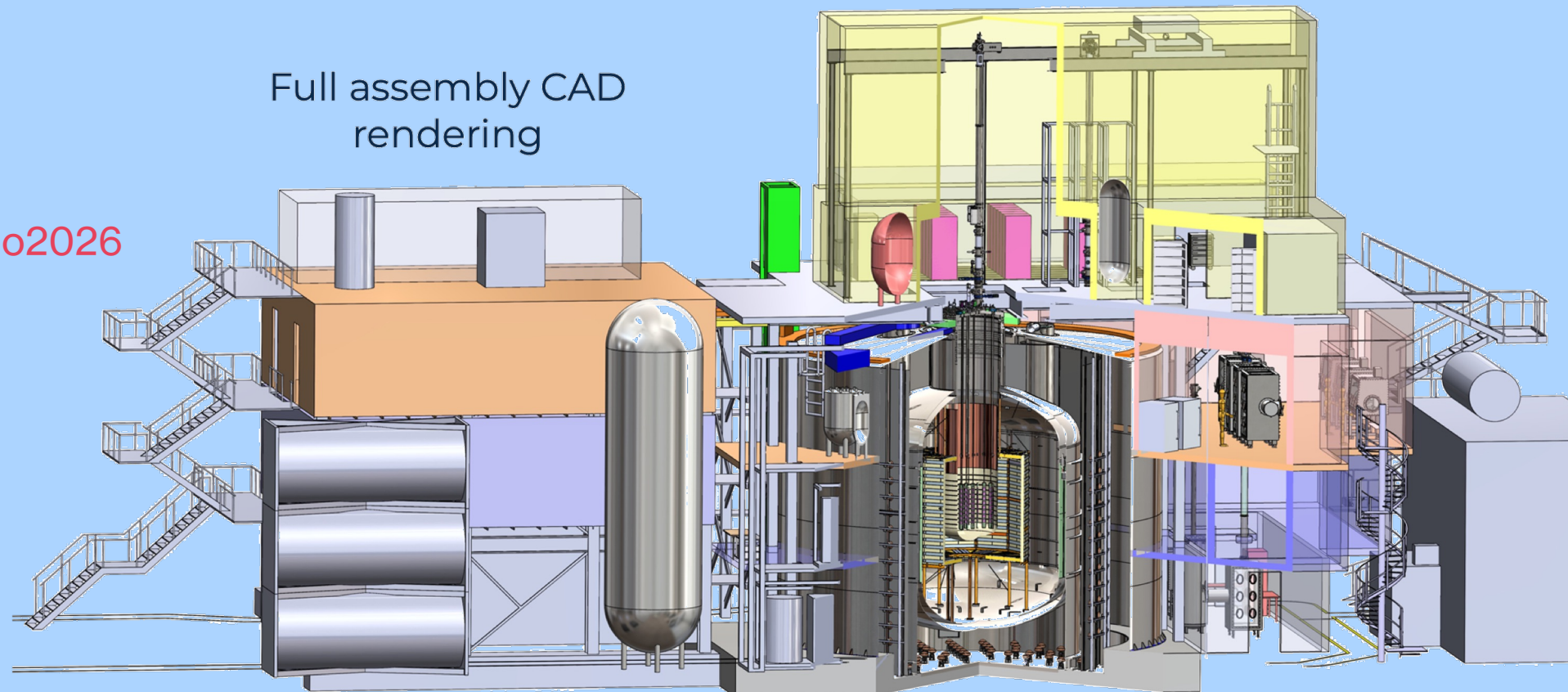
PRL 136, 022701 (2026)



LEGEND-1000 tonne scale experiment

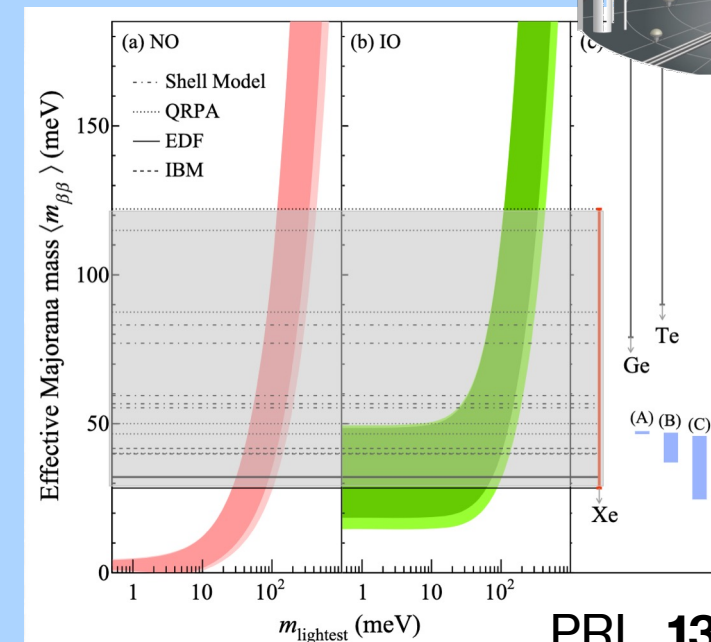
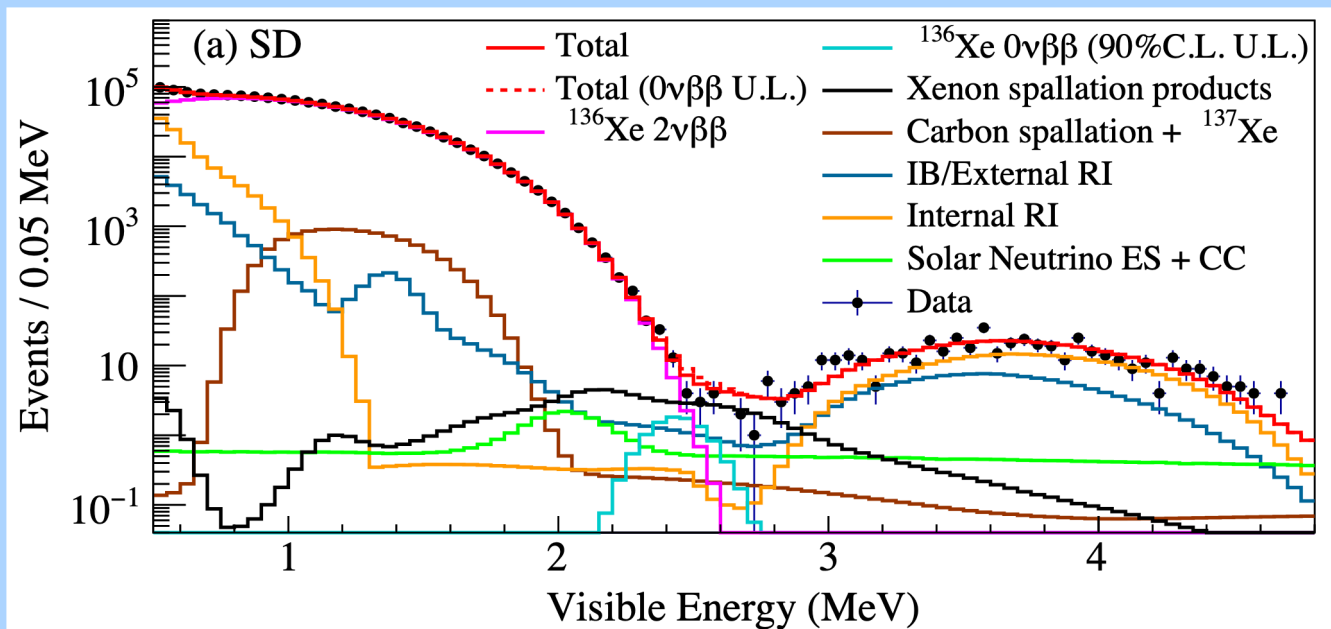
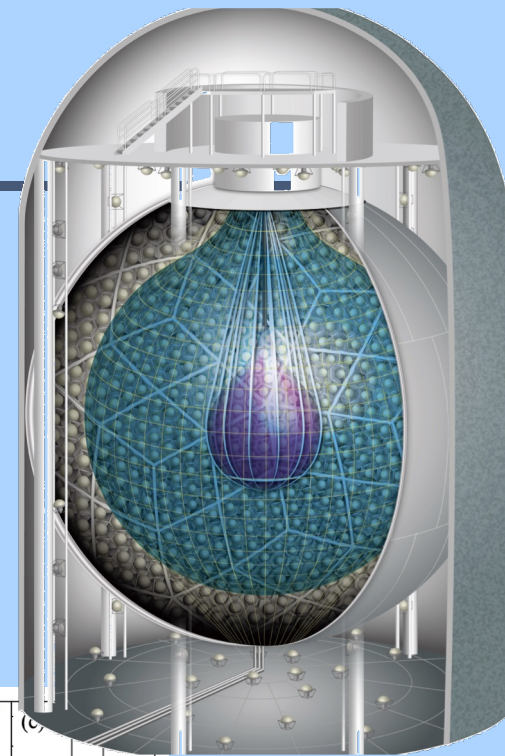
- $0\nu\beta\beta$ discovery sensitivity $> 10^{28}$ yr
- Background goal of 10^{-5} cts/(keV kg yr) and 10 t yr exposure.

Neutrino2026

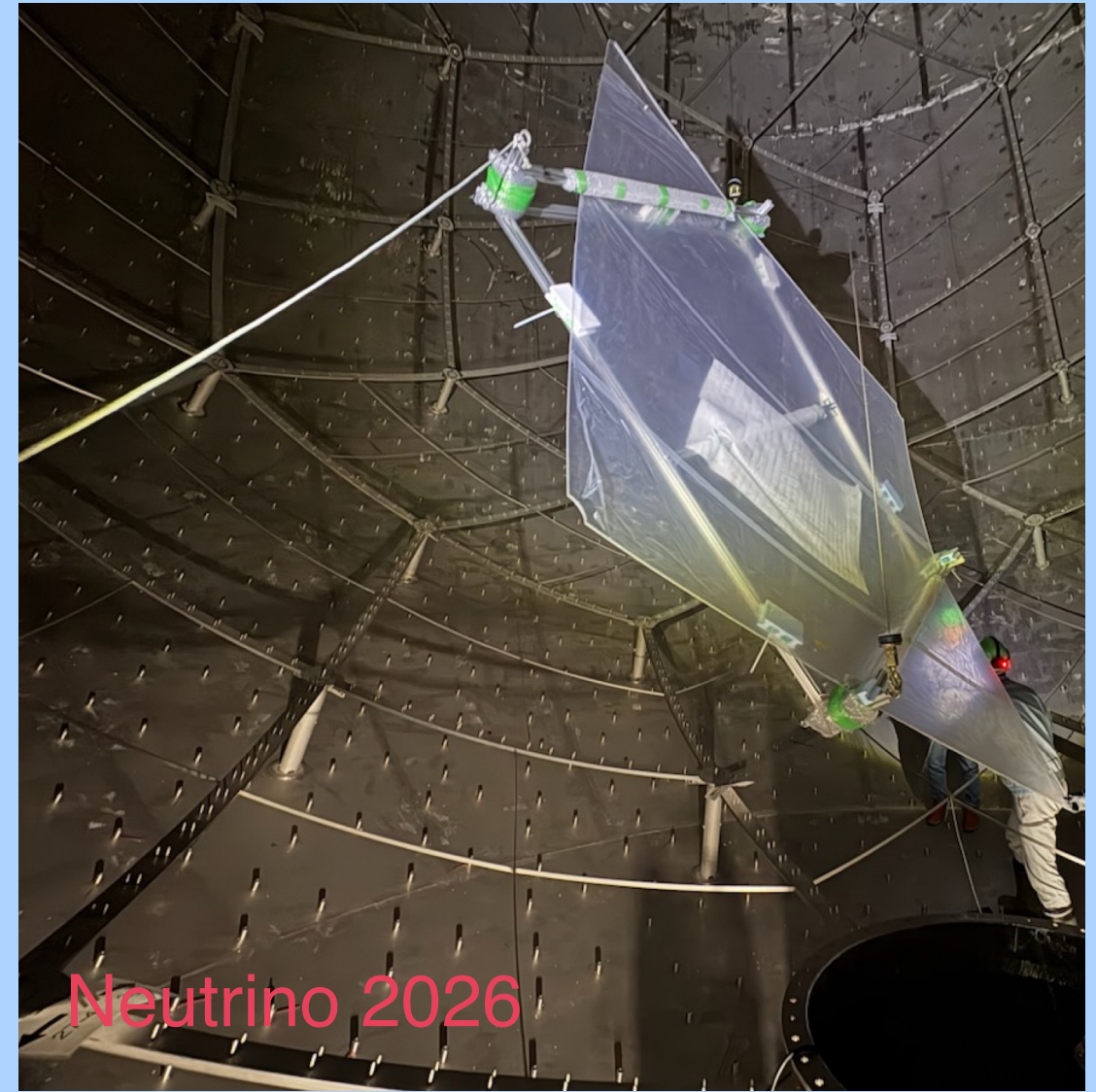
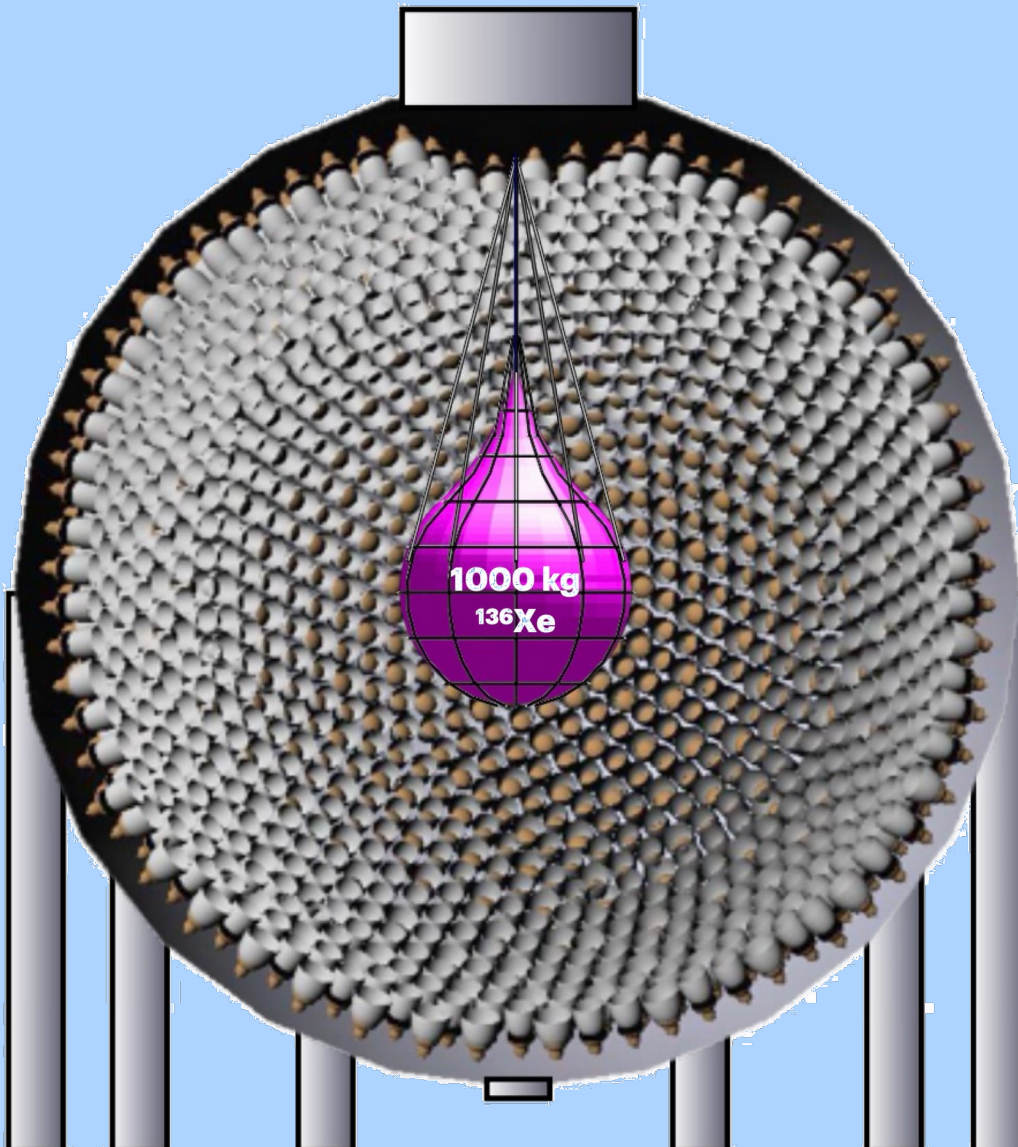


KamLAND-Zen: Xe-loaded LS for ^{136}Xe

- 1 kiloton of ultra-low radioactivity liquid scintillator (LS)
- 745 kg enriched xenon gas loaded in a mini-balloon
- 4% resolution (σ); 2.097 ton yr of ^{136}Xe result (2025)

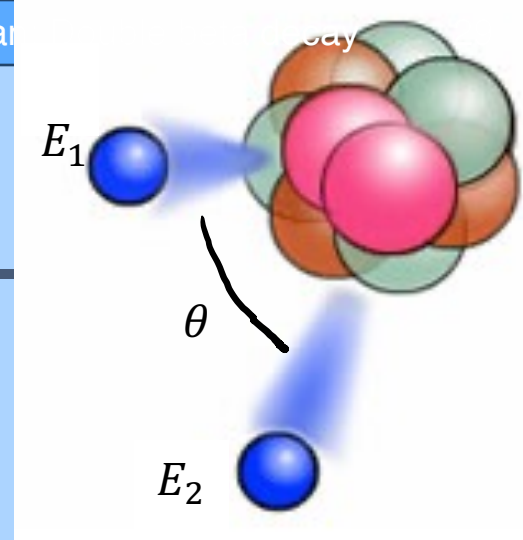


KamLAND2-Zen under construction



How many events needed?

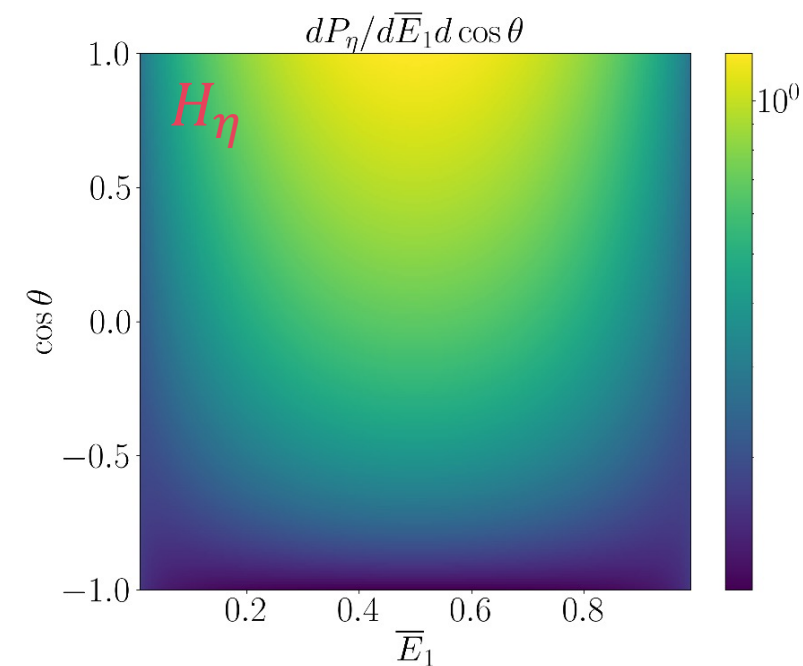
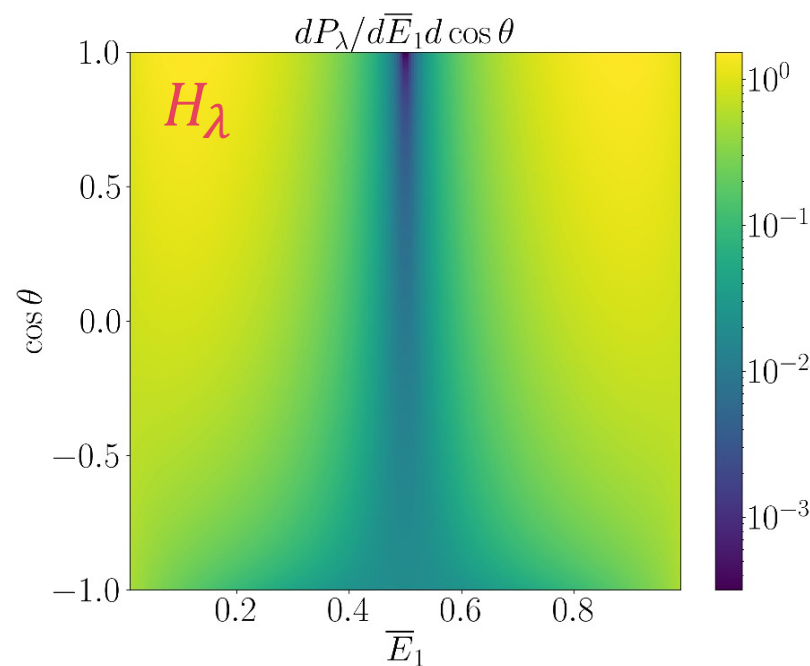
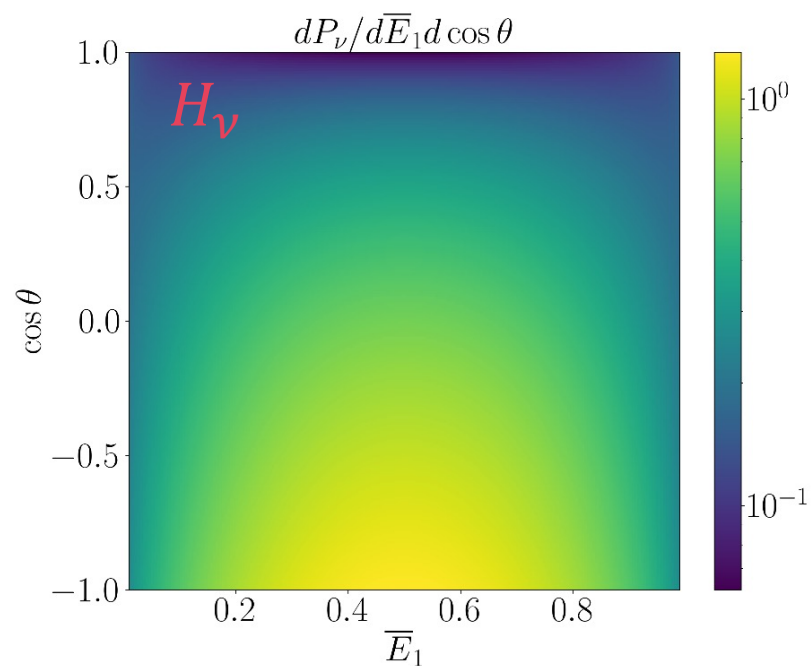
- to distinguish different $0\nu\beta\beta$ mechanism?



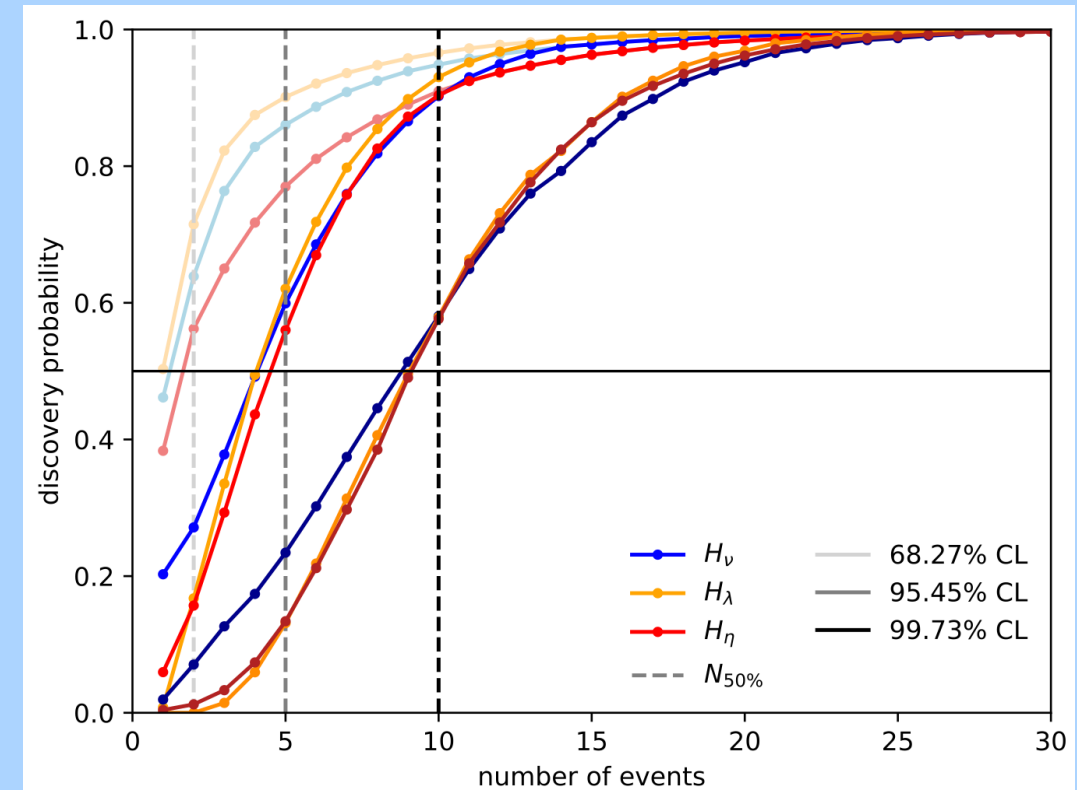
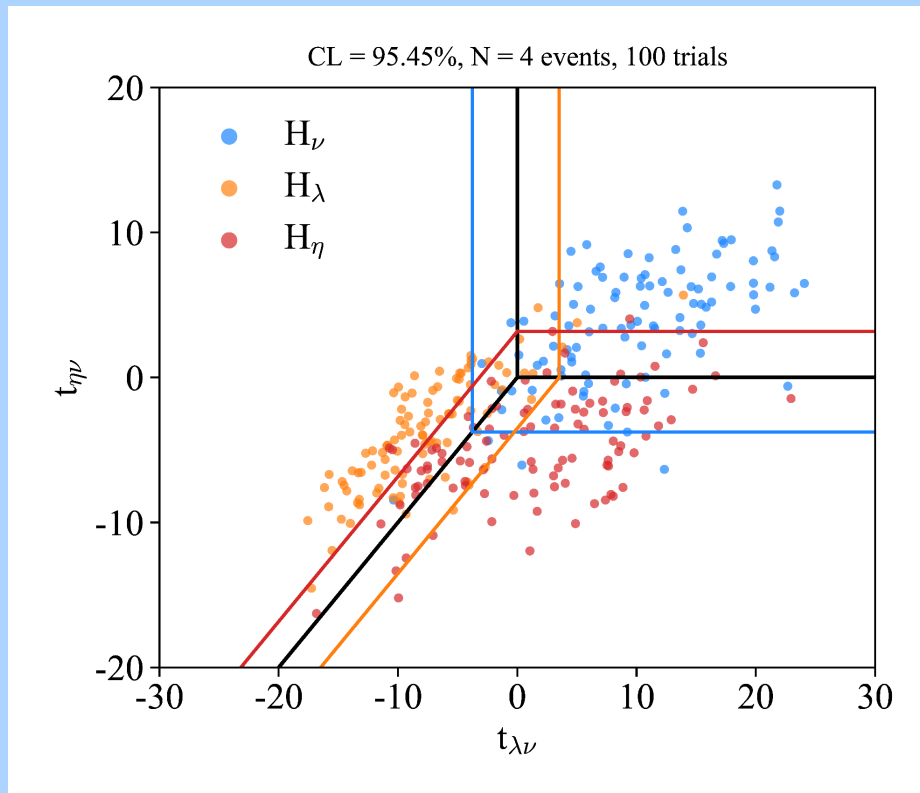
E_1 : near $Q_{\beta\beta}/2$
 β s: back-to-back

E_1 : far from $Q_{\beta\beta}/2$
 β s: the same direction

E_1 : near $Q_{\beta\beta}/2$
 β s: the same direction



Ideal discrimination

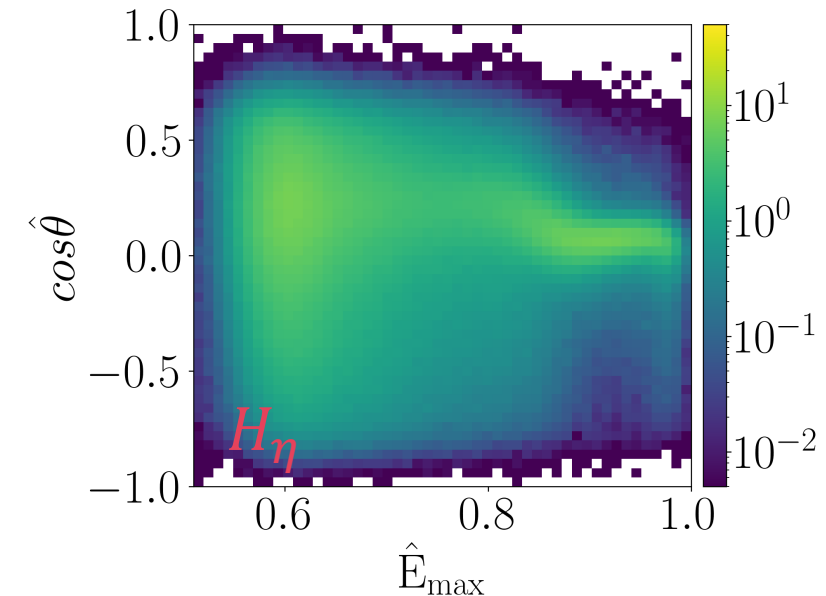
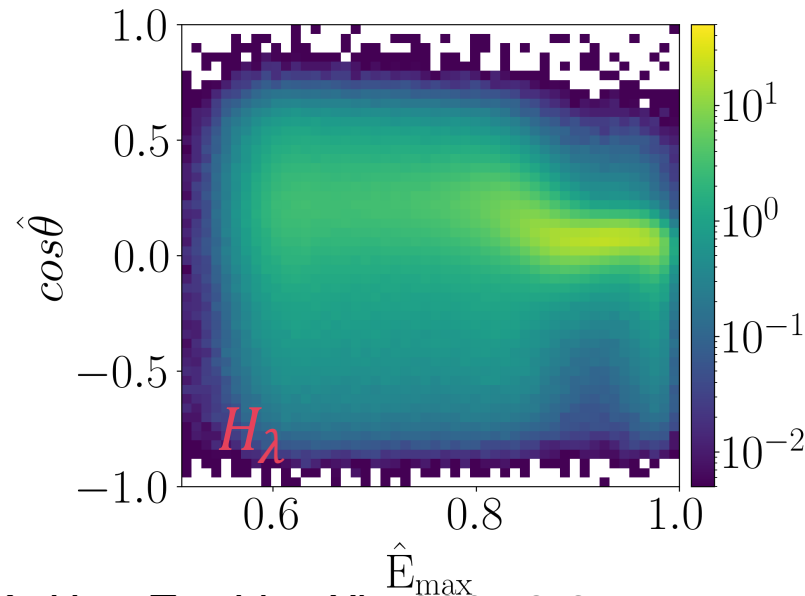
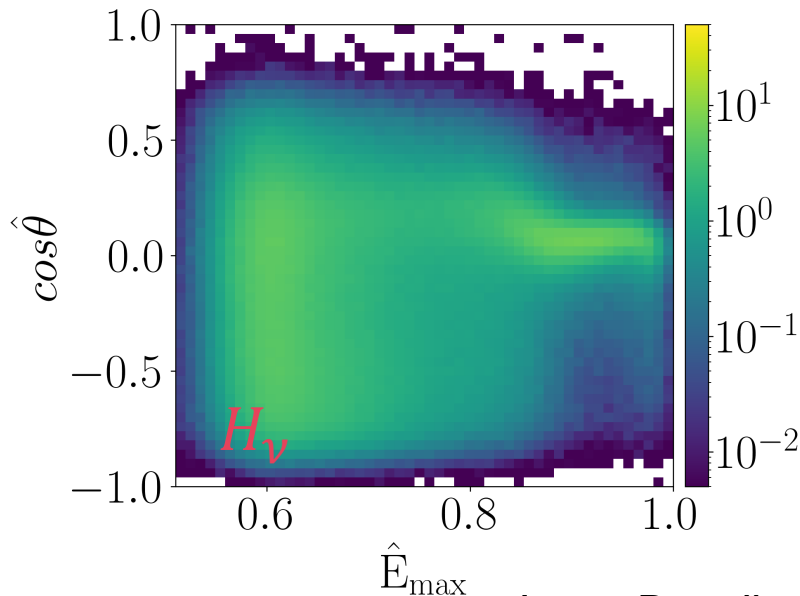
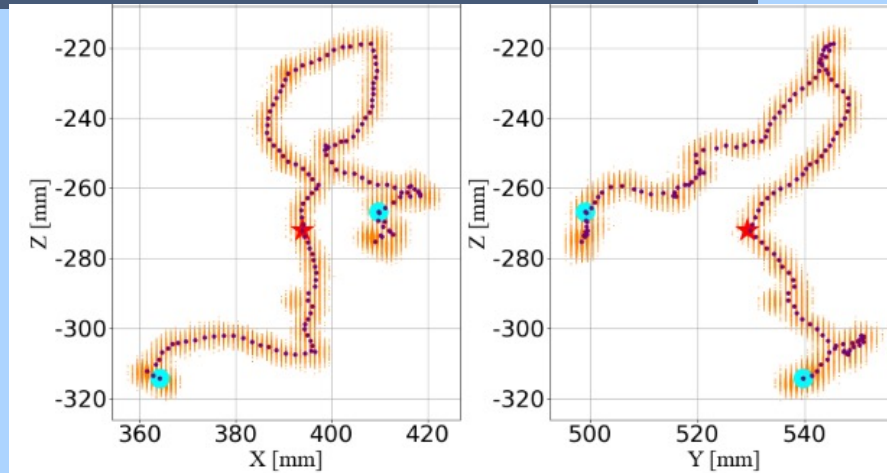


1σ , 2σ , 3σ discrimination with just 2, 5, 10 events!

Jason Detwiler, Ke Han, Tao Li, arXiv: 2605.21315

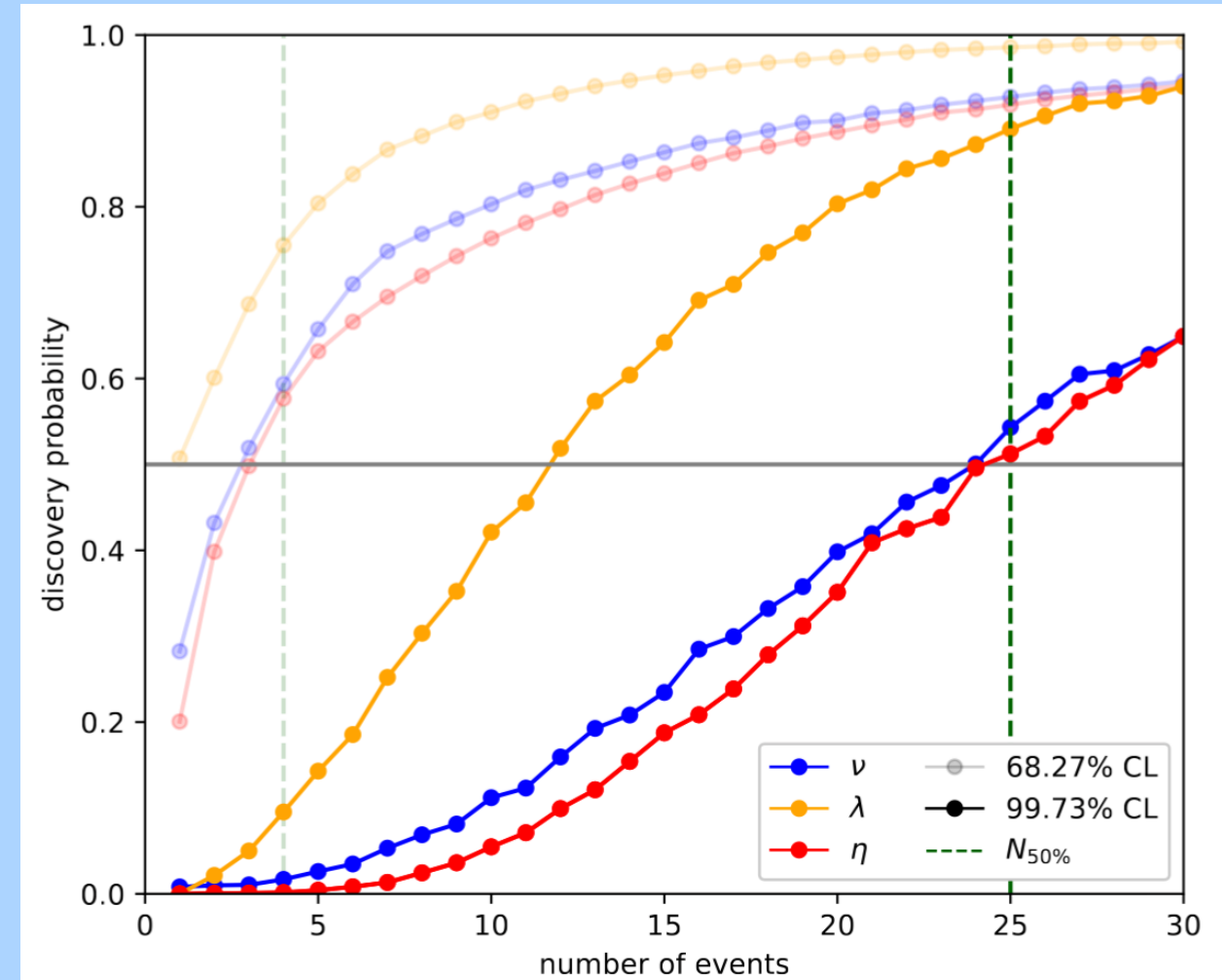
Realistic Kinematic Reconstruction

- Simulation of gas-TPC tracks with AI-based reconstruction
 - Based on PandaX-III R&D: 1% E resolution, 1 mm pixels, 70% detection efficiency



Kinematic exchange mechanism probes

- ~ 25 events for 3σ discrimination of a mechanism (assuming no mixing)
- Surprisingly small number
- Free of NME uncertainties



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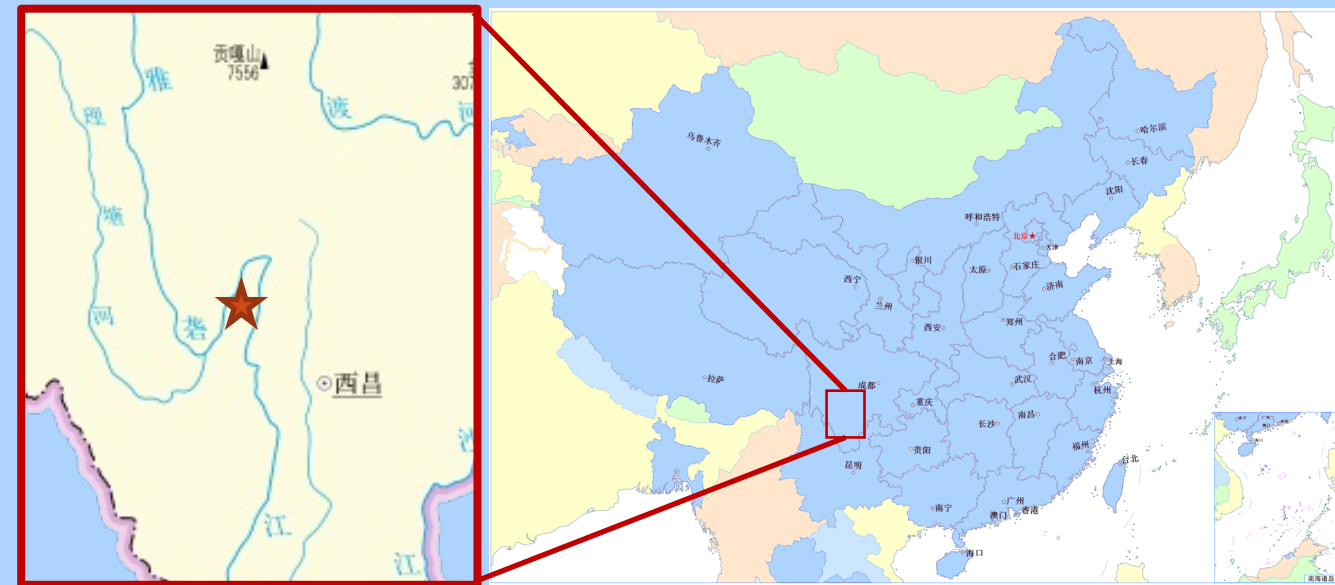
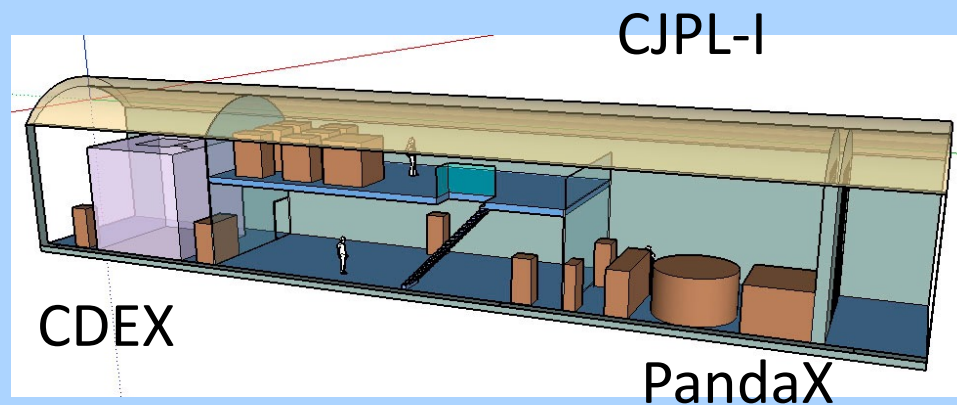
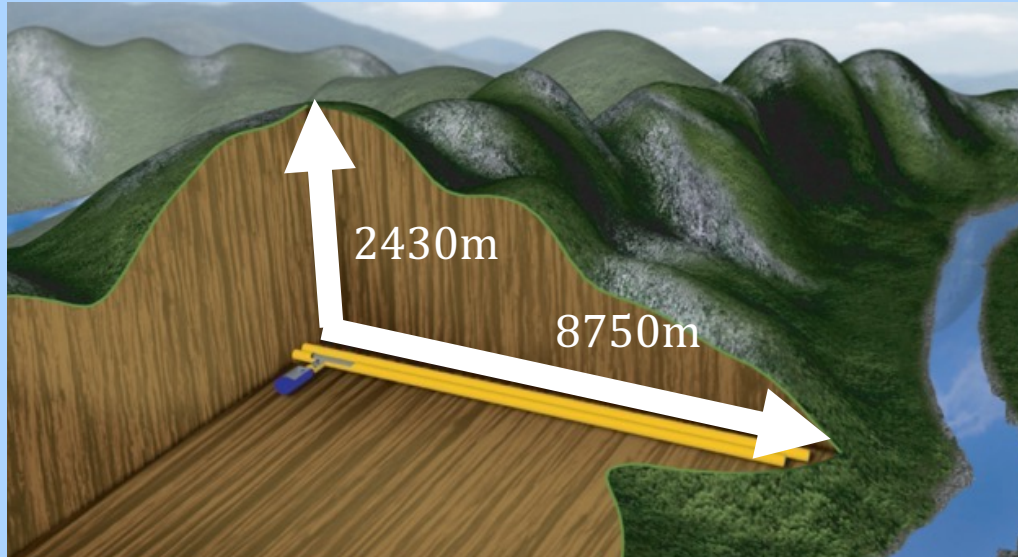
3

**Chinese
efforts**

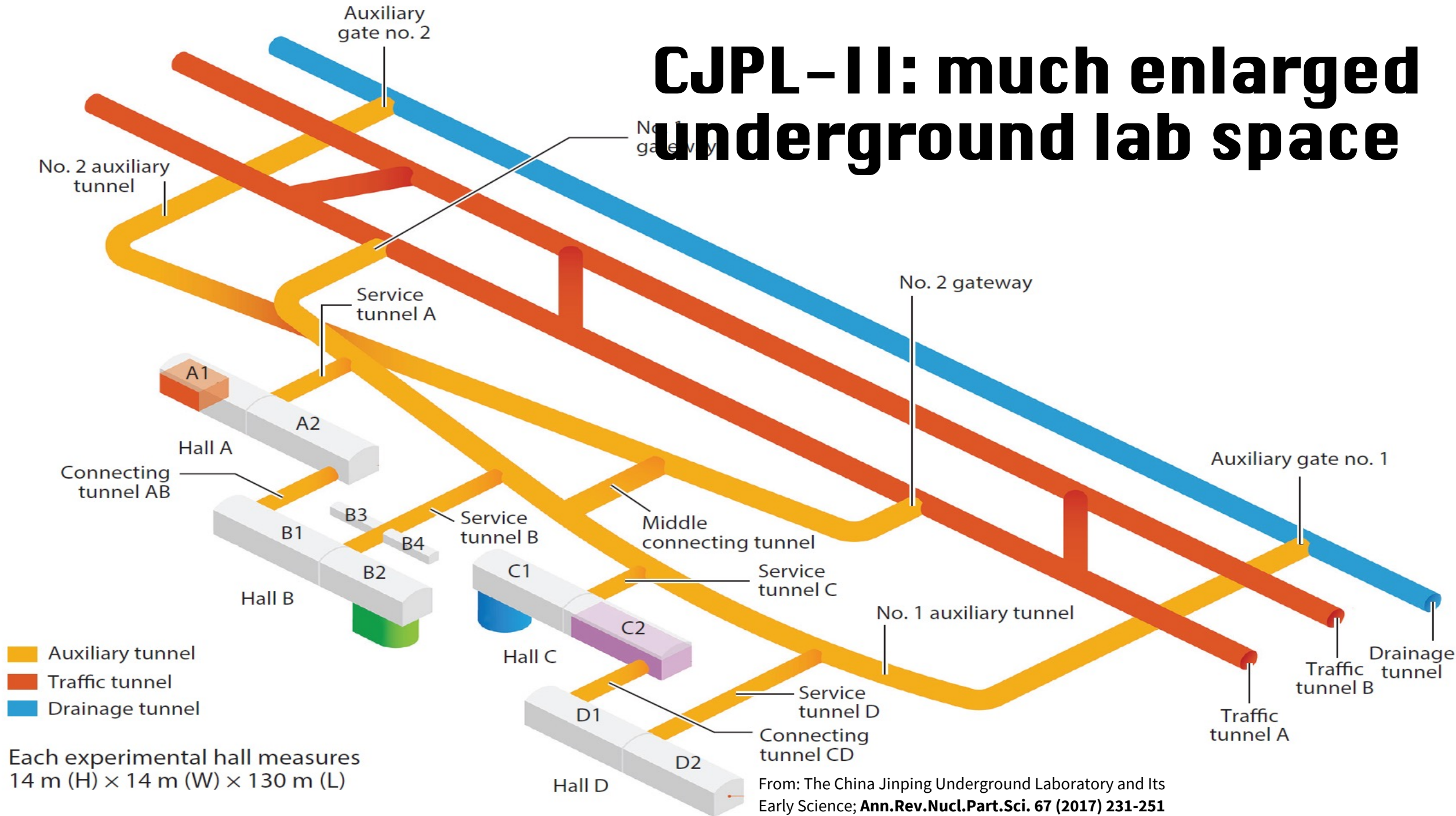
PandaX

CJPL: China JinPing underground Lab

- 6800 m.w.e overburden: $< 0.2 \mu\text{m}^2/\text{day}$
- Horizontal access with $\sim 9 \text{ km}$ long tunnel
- Dark matter, neutrino physics, and astroparticle physics, etc.



CJPL-II: much enlarged underground lab space





Ke Han: Double beta decay

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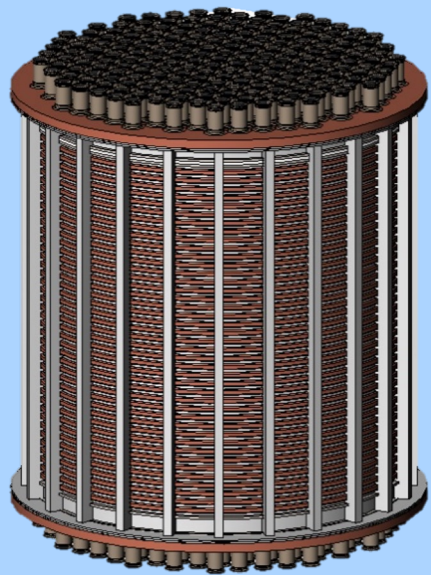


>Welcome!
CJPL 2015

Chinese efforts

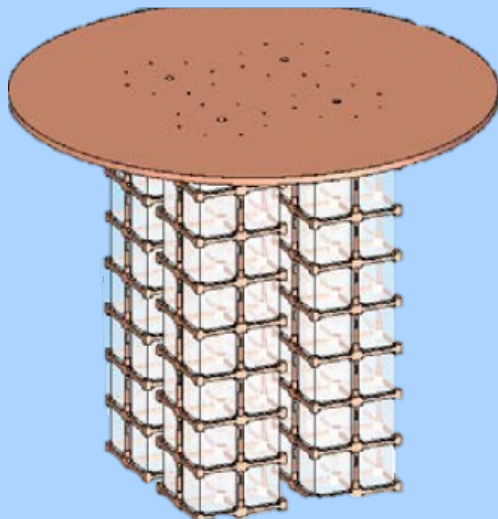
PandaX

Xe TPC



CUPID-China

Bolometer



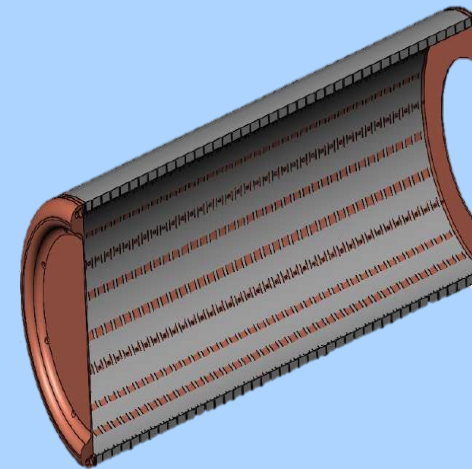
CDEX

HPGe



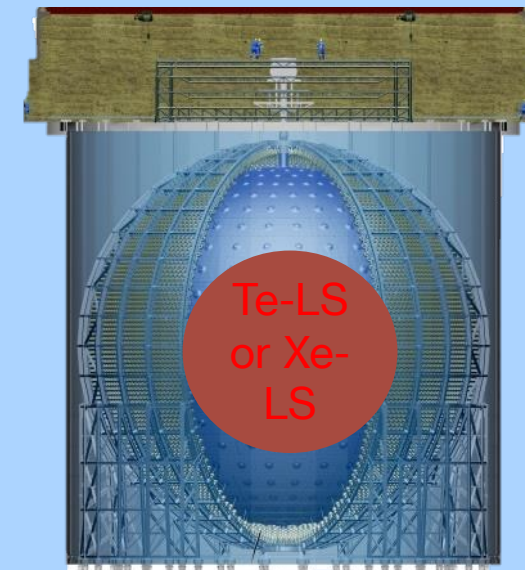
NvDEX

Gas TPC



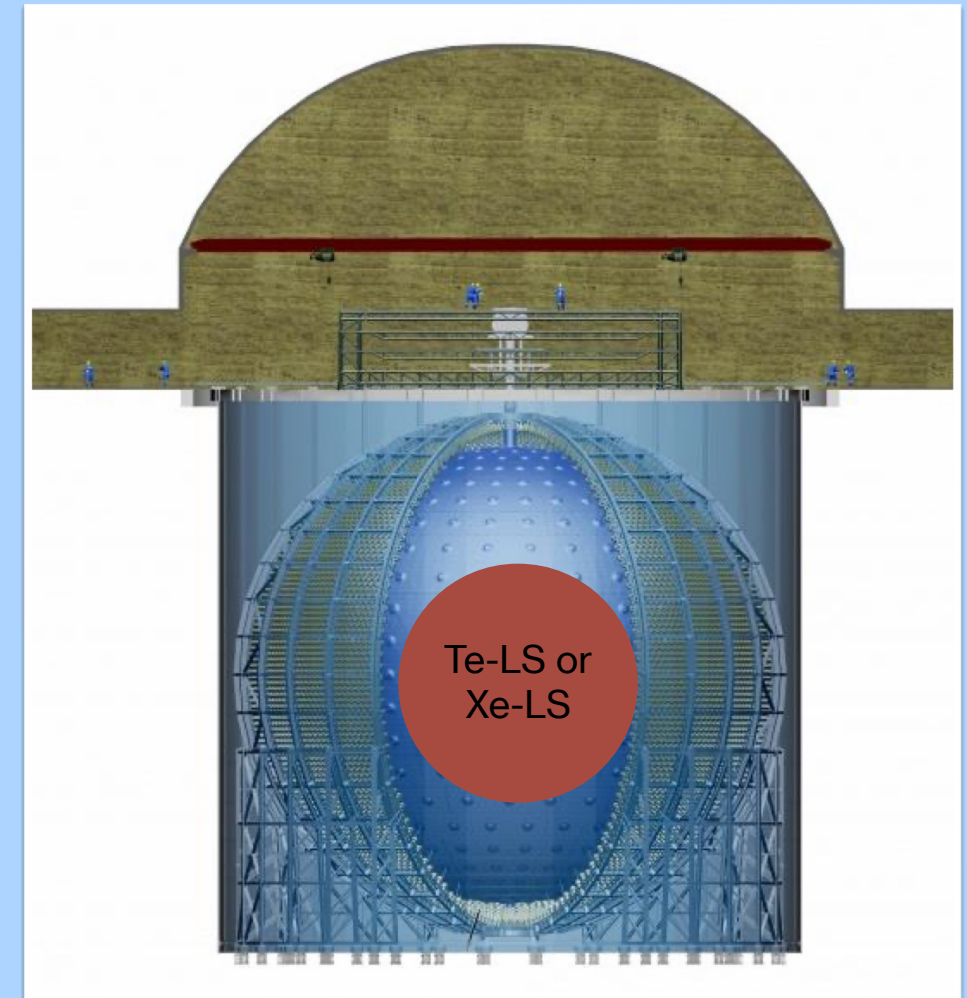
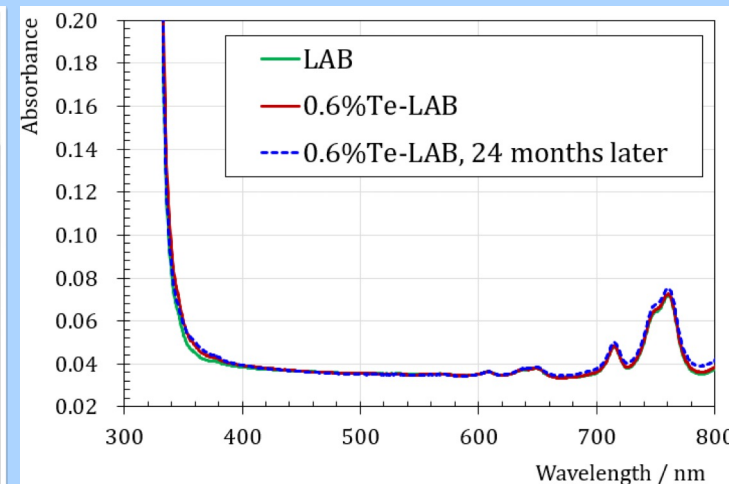
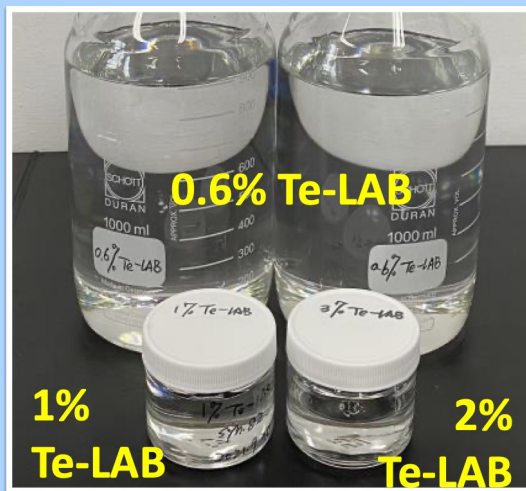
JUNO- $0\nu\beta\beta$

Loaded LS

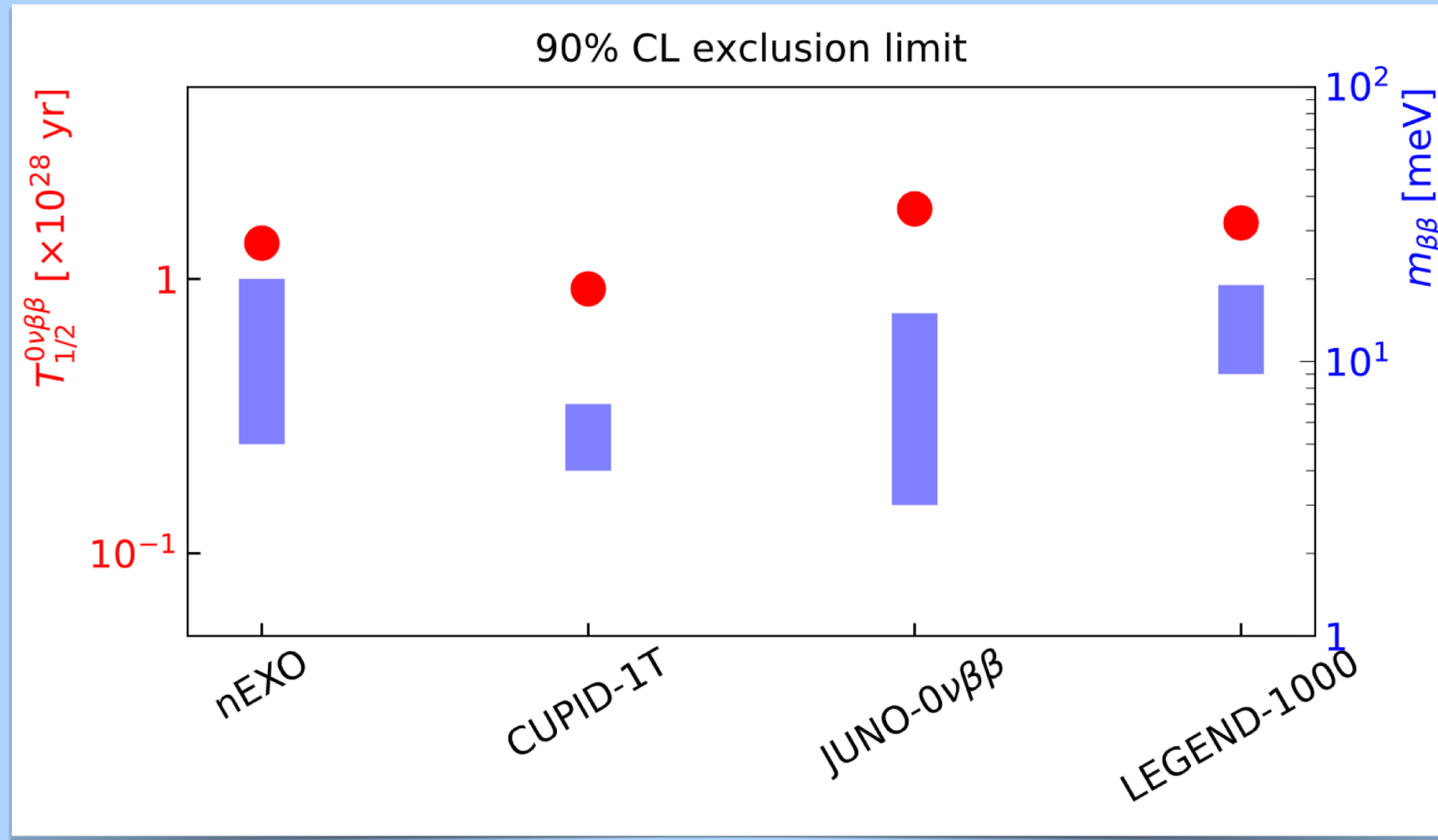


JUNO- $0\nu\beta\beta$

- Aims to start right after current mass hierarchy programs
- Half life sensitivity at 10^{28} year
- Energy resolution $< 3\%$ @ 1 MeV
- **Xe or Te** loading: 100 ton of Te of 20 kton LS possible

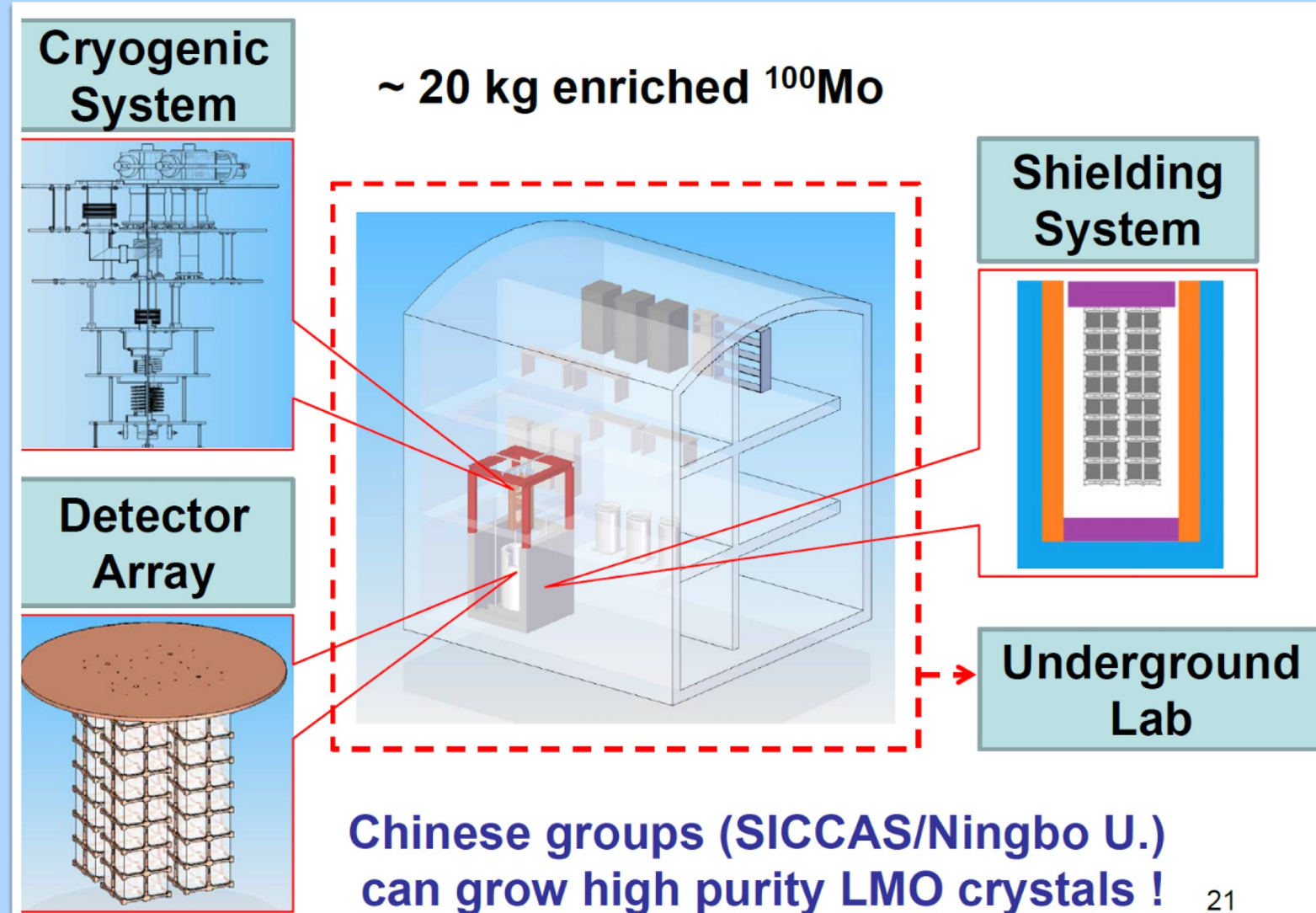


JUNO- $0\nu\beta\beta$ physics potential



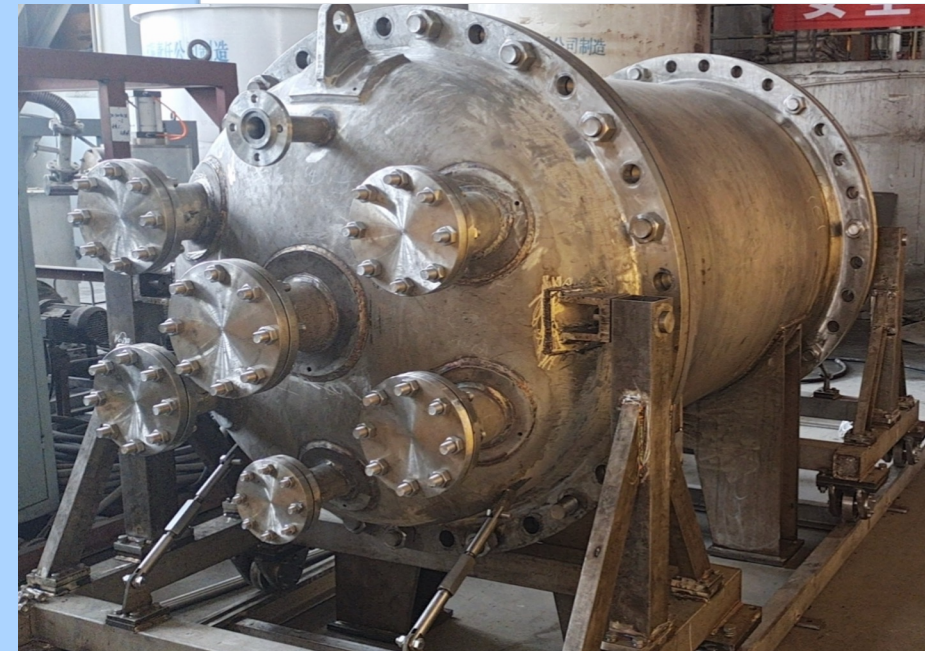
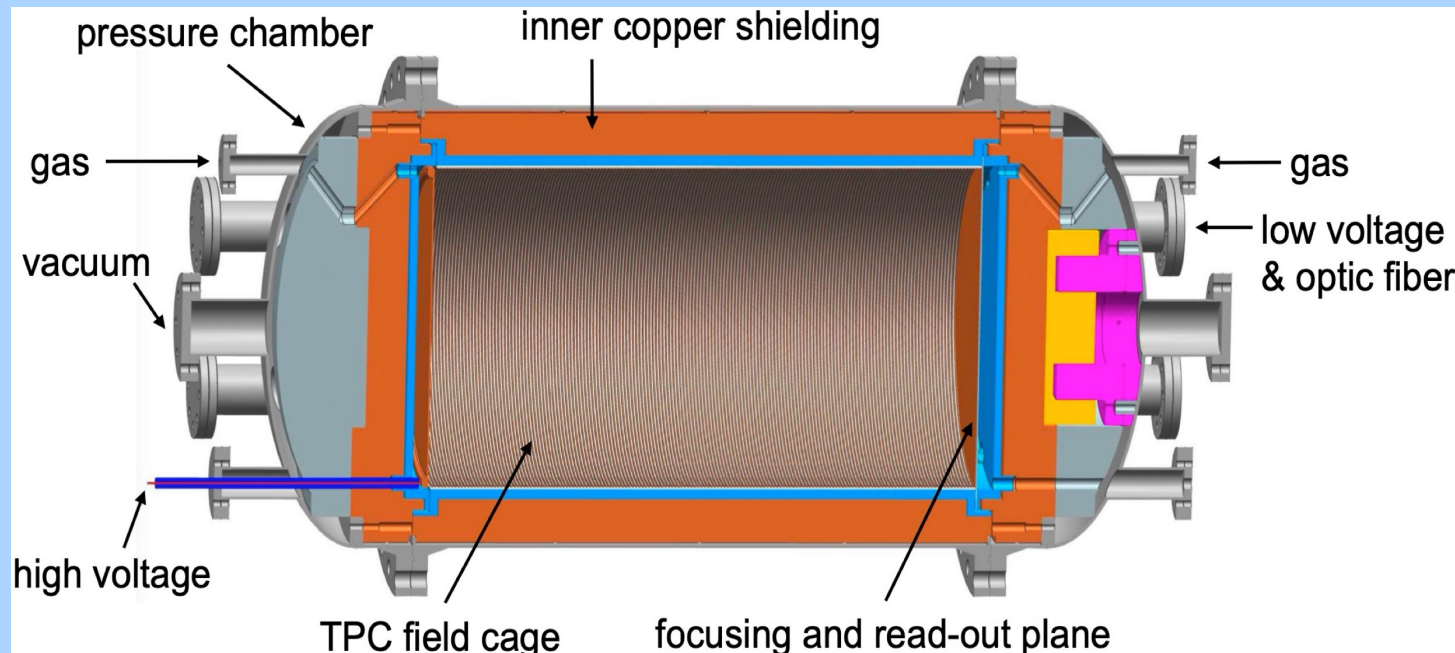
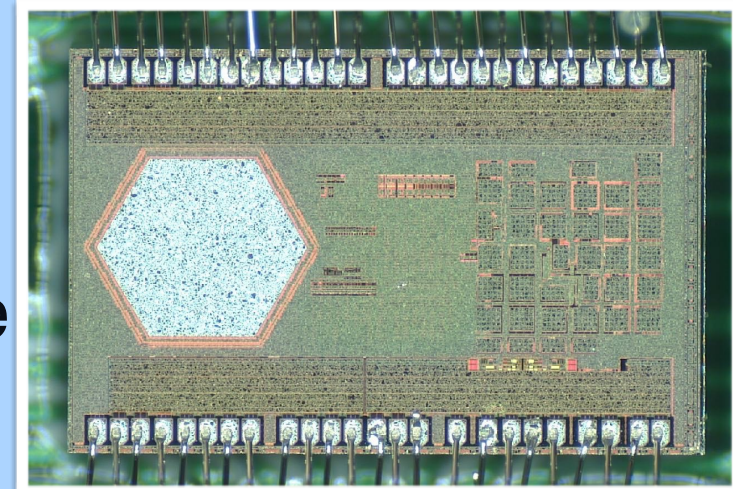
CUPID-CJPL

- $\text{Li}_2^{100}\text{MoO}_4$ scintillating bolometers at CJPL in the next 3-5 years
- Synergy with CUPID:
 - LMO crystal production radioactivity control and QA
 - Electronics
 - Data analysis



NvDEx: high pressure ion TPC

- High-pressure ion-drifting $^{82}\text{SeF}_6$ TPC with Topmetal readout
- 100 kg prototype in design and production phase

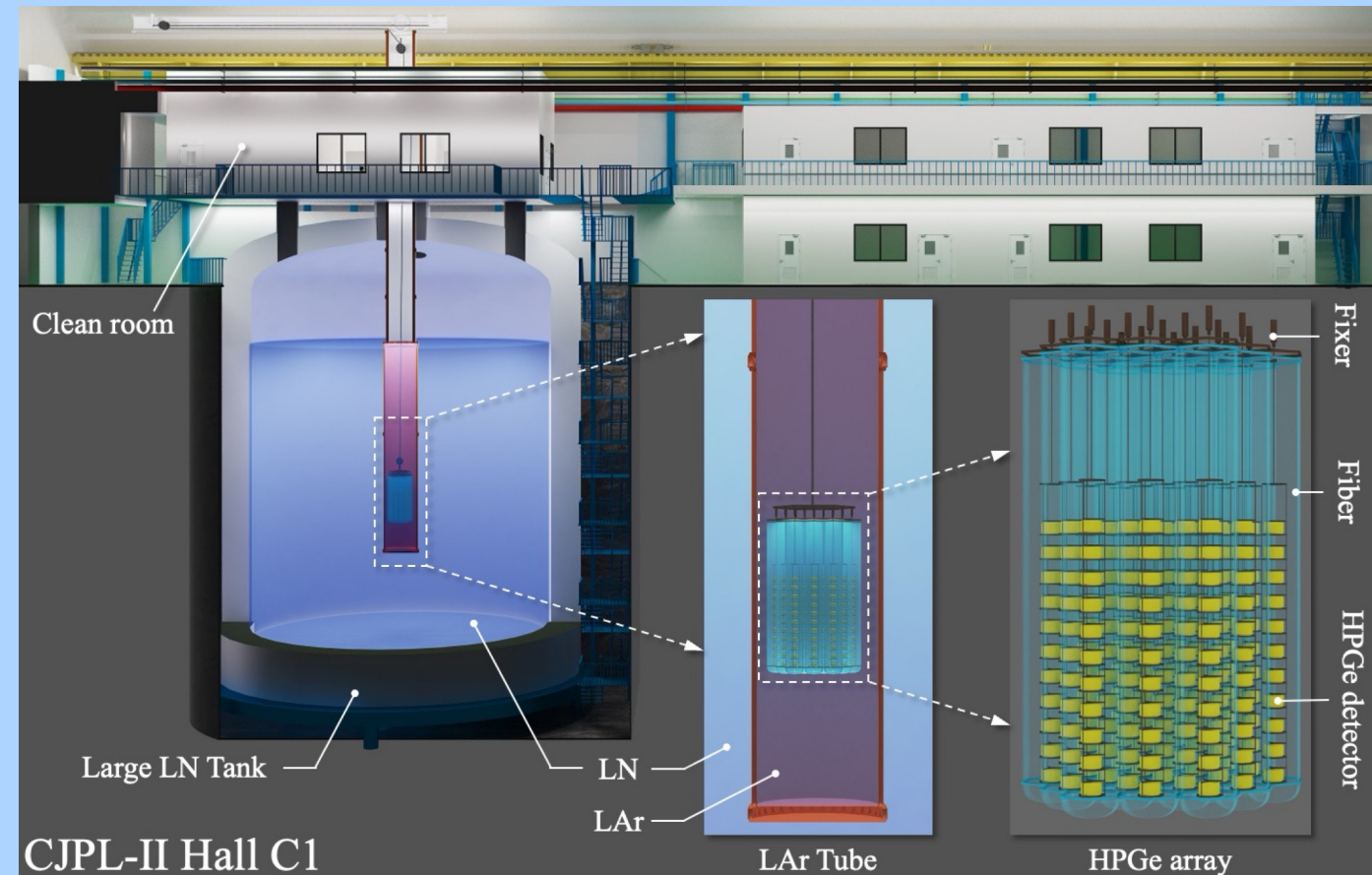


CDEX dark matter and $0\nu\beta\beta$ program

Established in 2009; over 100 collaborators from 11 institutions

CDEX-300v:

- 200 enriched HPGe detectors
- 20T LAr active veto shielding
- 1725 m³ LN2 passive shielding



CDEX-300 ν status

Total ~190 kg enriched GeO₂ for detector production

- 90 kg from Russia
- 100 kg from CNNC @China
- Ge-76 enrichment: 86%-92%



Top of the commissioned LN₂ tank



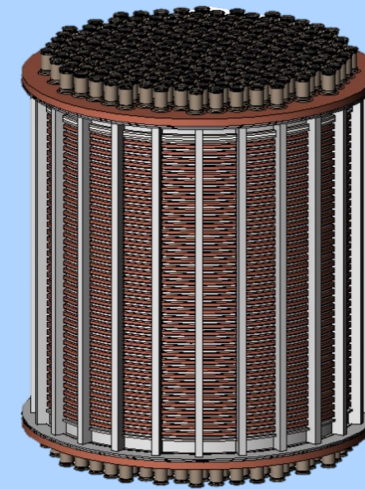
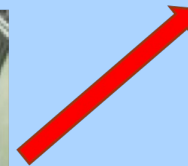
PandaX detectors



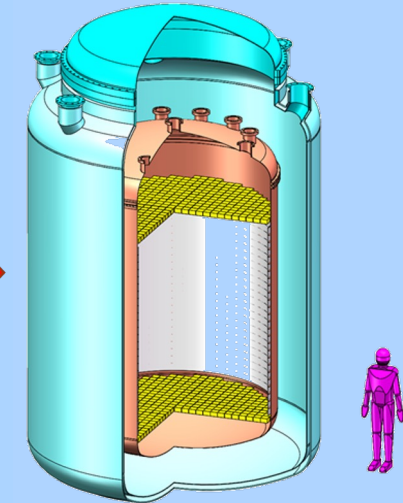
PandaX-I: 120kg
LXe (2009 – 2014)



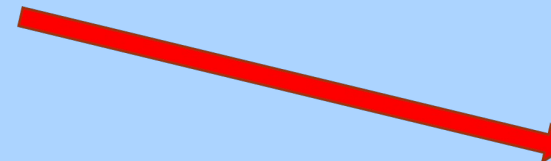
PandaX-II: 500kg
LXe (2014 – 2018)



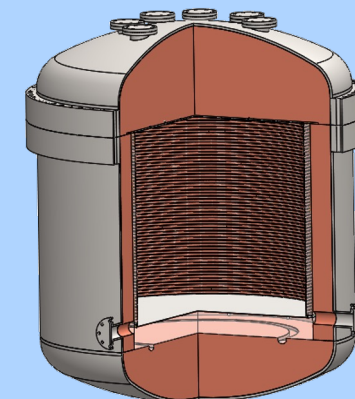
PandaX-4T LXe
(2020-)



PandaX-xT LXe
(future)



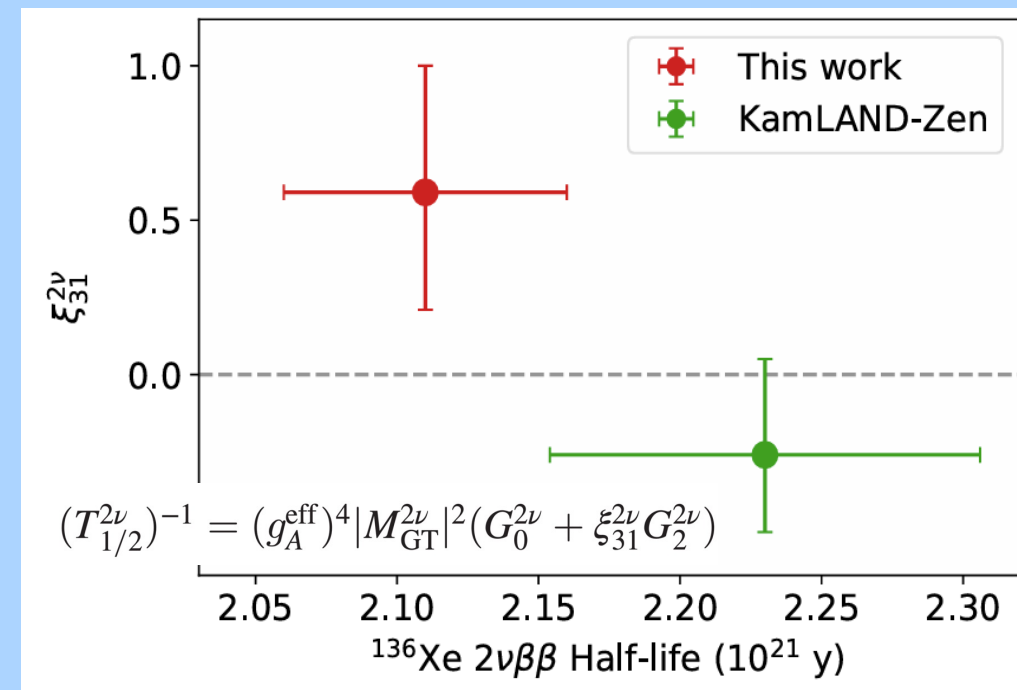
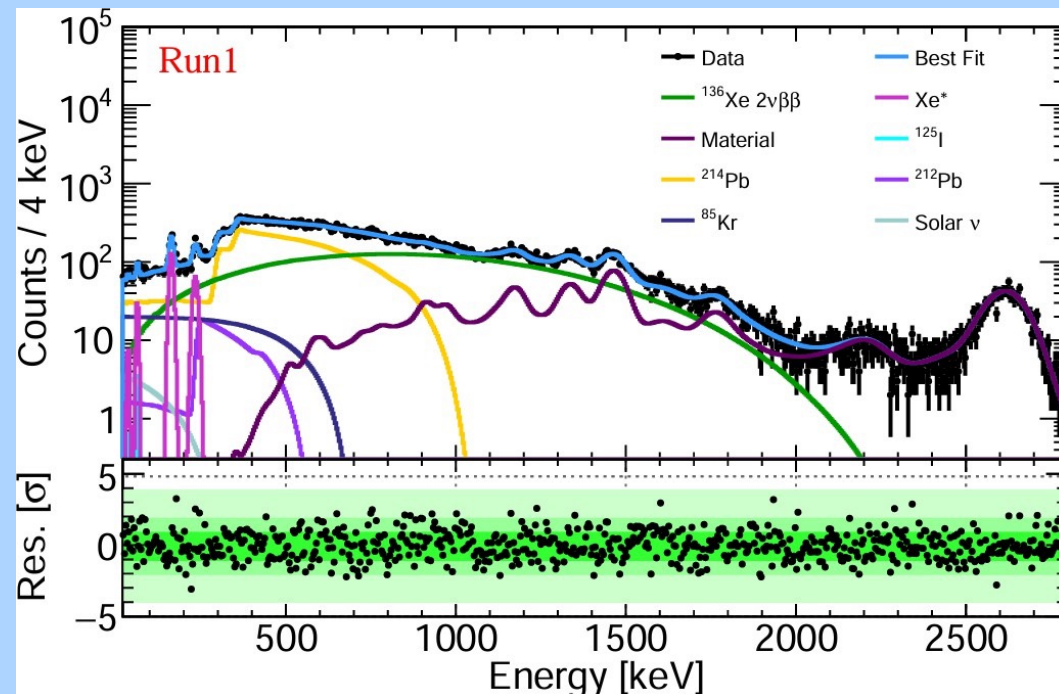
PandaX-III: 100kg - 1 ton
HPXe for $0\nu\beta\beta$ (future)



^{136}Xe $2\nu\beta\beta$ half-life measurement

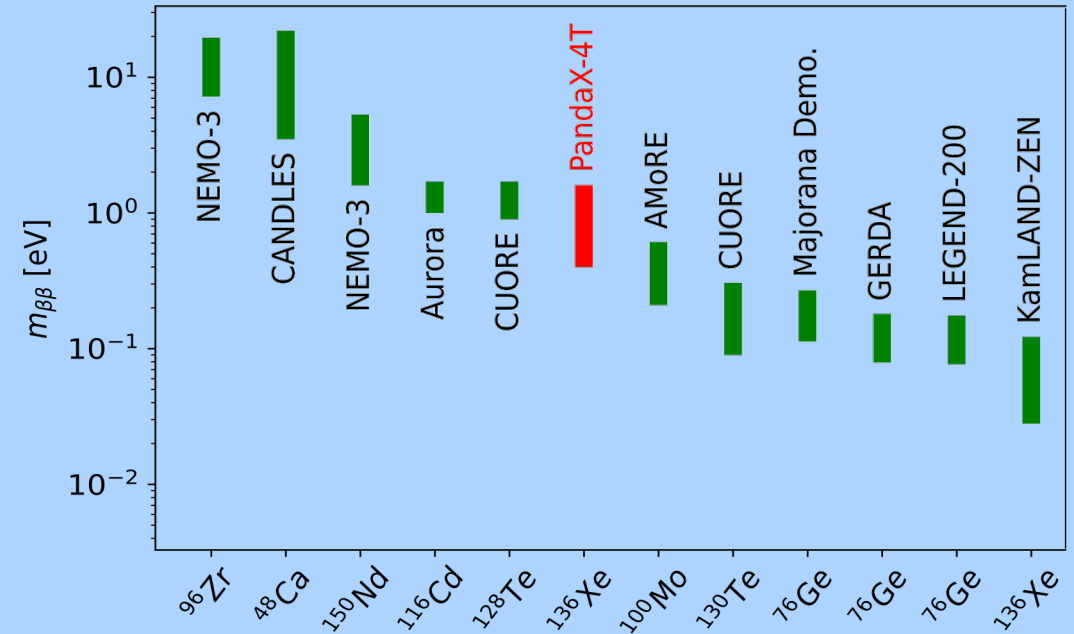
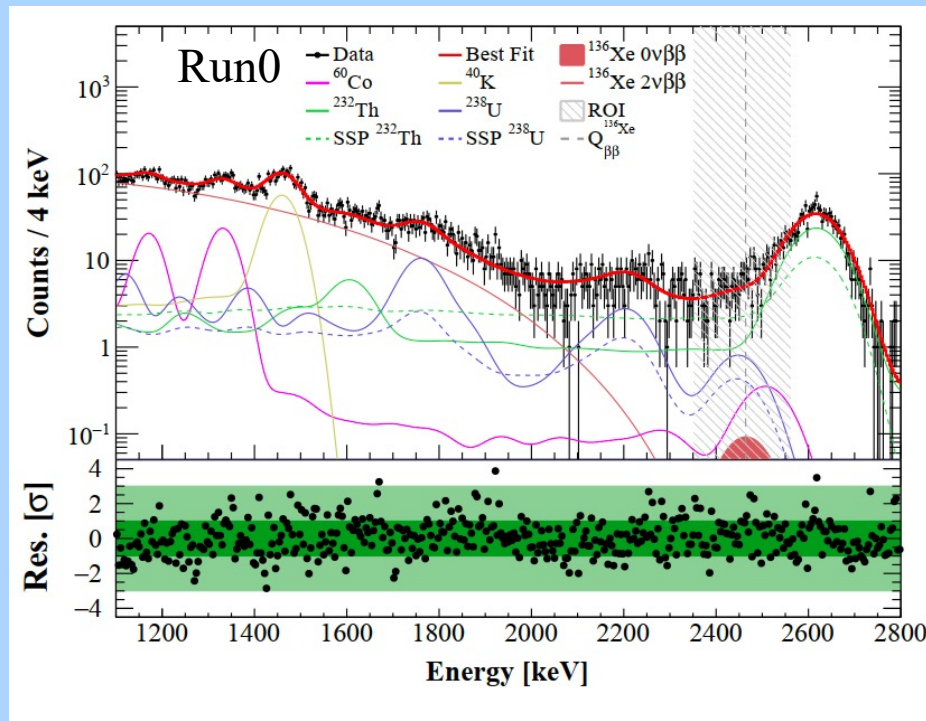
- A **near-complete** ^{136}Xe $2\nu\beta\beta$ spectrum from 20 keV to endpoint
- The **most precise** half-life measurement: $(2.14 \pm 0.05) \times 10^{21}$ yr
- Constrains higher-order matrix elements contribution $\xi_{31}^{2\nu}$ and Majoron emissions

PRL 136, 162501 (2026)



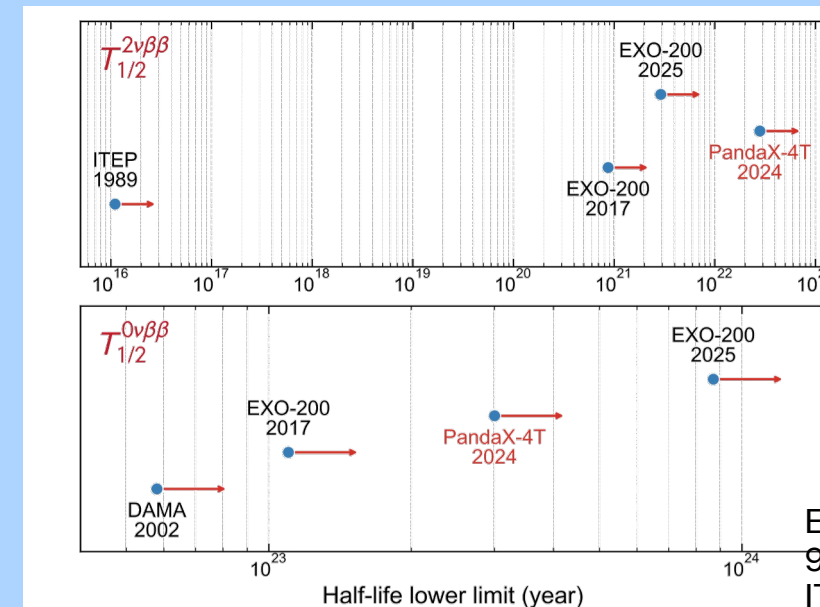
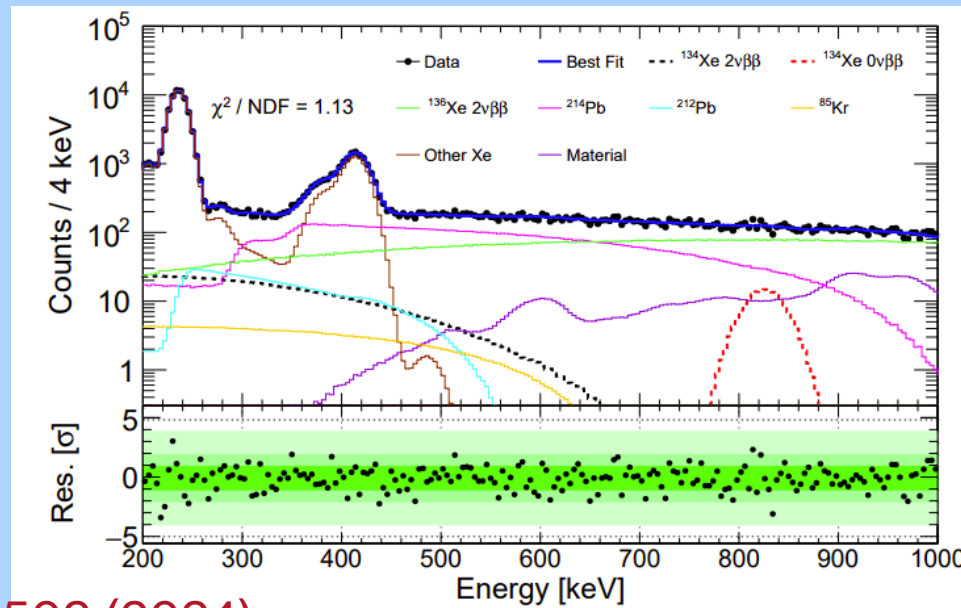
^{136}Xe $0\nu\beta\beta$ limit

- 44.6 kg · yr isotope exposure
- Stringent half-life limit from **a natural xenon detector**: 2.1×10^{24} yr (90% C.L.)
- The effective Majorana mass constraint: $< (0.4\text{-}1.6)$ eV



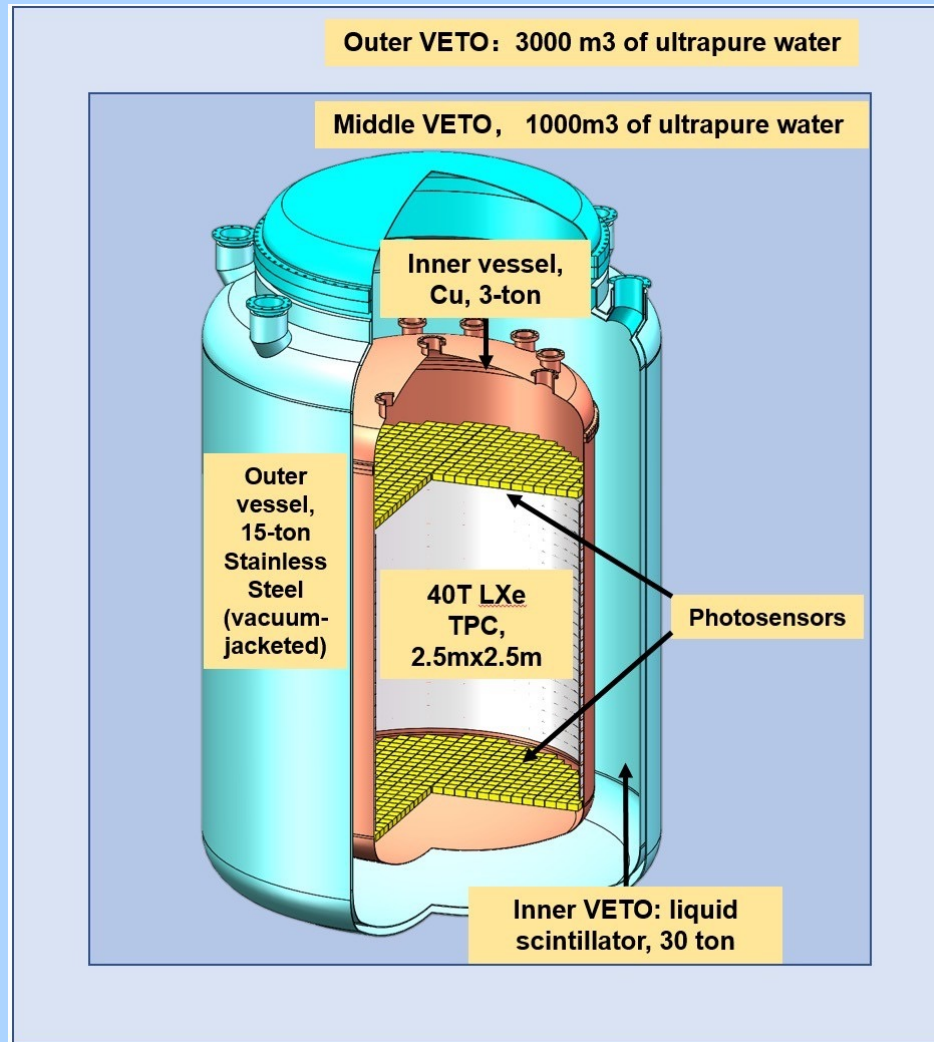
$^{134}\text{Xe} (0)2\nu\beta\beta$ searches

- $Q=826$ keV; Half-life from theoretical predictions: $10^{24} - 10^{25}$ yr; Never been observed
- PandaX-4T: more ^{134}Xe ; much less ^{136}Xe ; wider energy range
- limits on the half-life: $T_{1/2}^{2\nu\beta\beta} > 2.8 \cdot 10^{22}$ yr and $T_{1/2}^{0\nu\beta\beta} > 3.0 \cdot 10^{23}$ yr



EXO-200: 2511.13990, PRD
96, 092001 (2017)
ITEP: PLB 223, 273 (1989);
DAMA: PLB 527, 182 (2002)

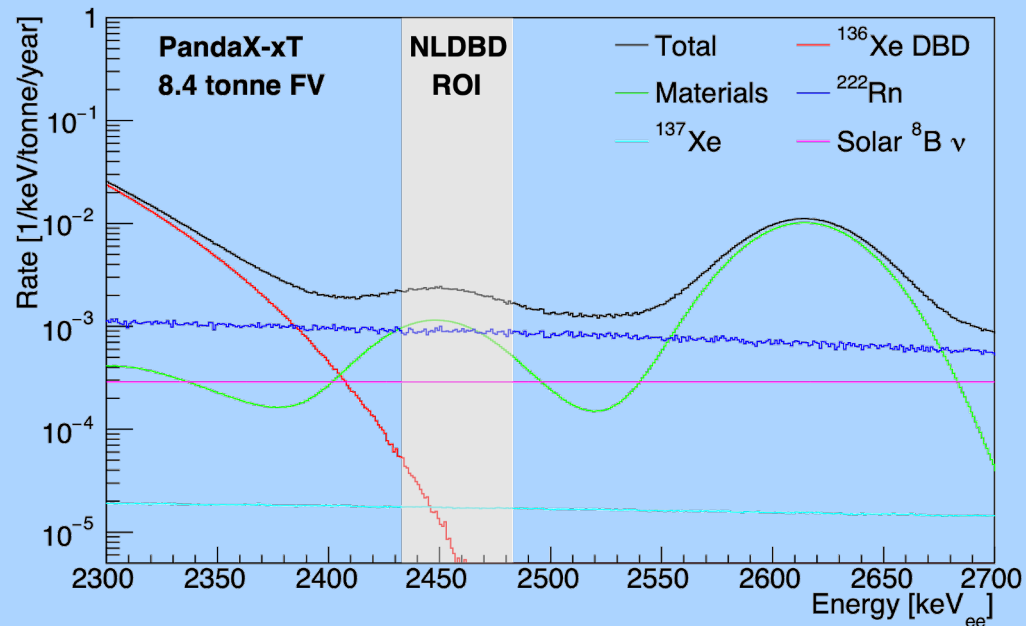
Future experiment: PandaX-xT



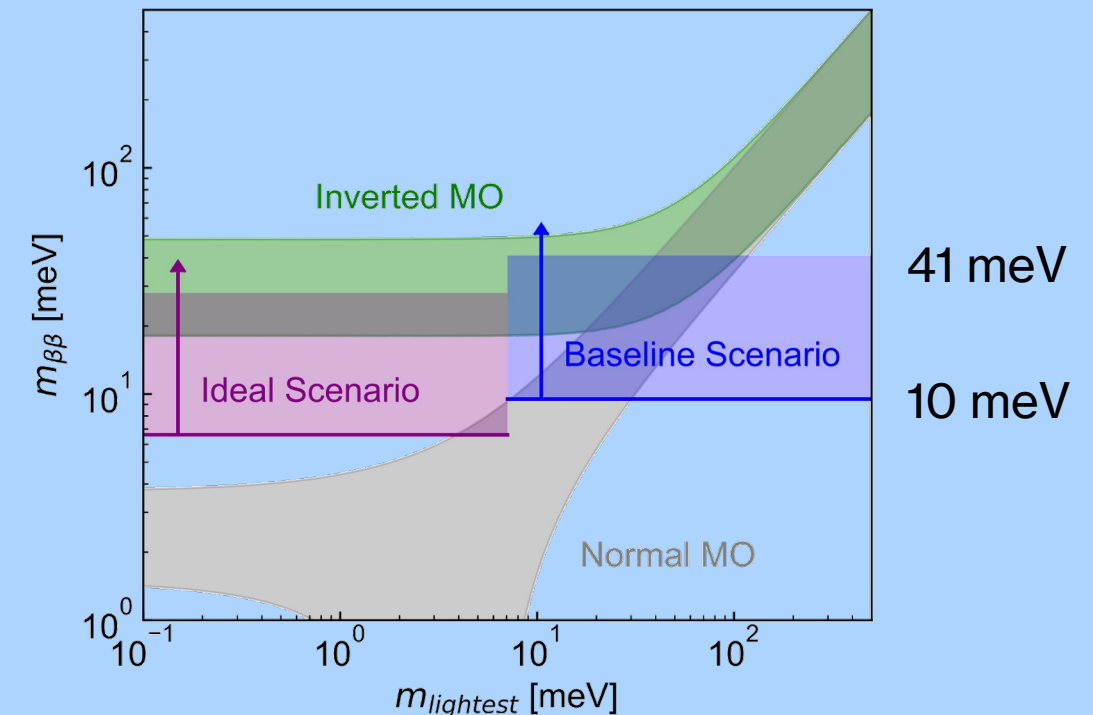
- 47-ton xenon, 40-ton sensitive volume
 - TPC 2.5m in diameter and 3m in height
 - High-granularity, low-background 2-in PMT array
 - Cold LS veto outside of Cu inner vessel
 - Staged and upgradable
- First stage is PandaX-20T

PandaX-xT for $0\nu\beta\beta$

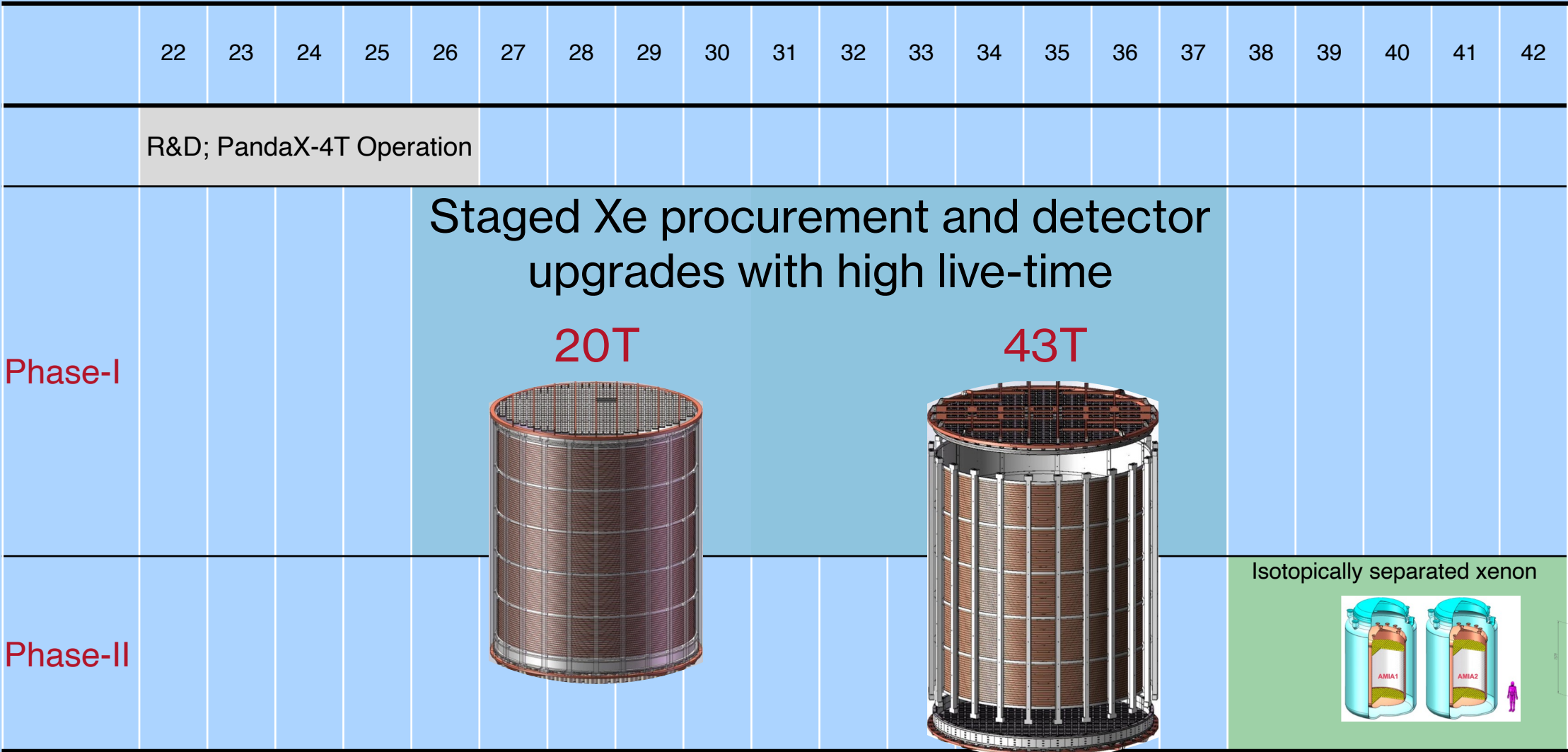
- 4 ton of ^{136}Xe for $0\nu\beta\beta$
- Effective self-shielding: Xenon-related background dominates in the 8.4-tonne center FV



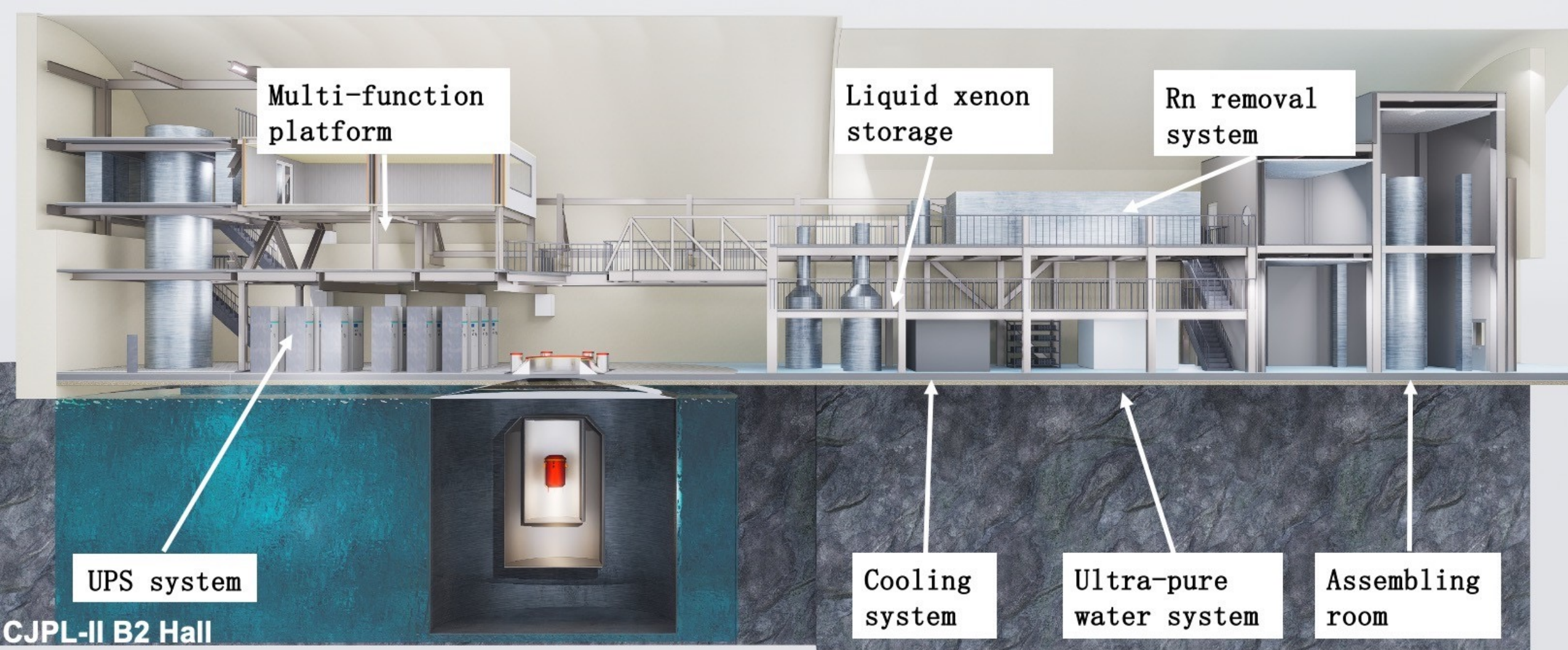
	Baseline (1/tonne/year)	Ideal (1/tonne/year)
Photosensors	1.4×10^{-2}	2.8×10^{-3}
Copper vessel	3.2×10^{-2}	6.3×10^{-3}
^{222}Rn	4.5×10^{-2}	-
^{136}Xe DBD	5.2×10^{-4}	5.2×10^{-4}
^{137}Xe	8.7×10^{-4}	8.7×10^{-4}
Solar ^8B ν	1.4×10^{-2}	1.4×10^{-2}
Total	1.1×10^{-1}	2.4×10^{-2}



PandaX-xT Project Timeline



PandaX-xT infrastructure

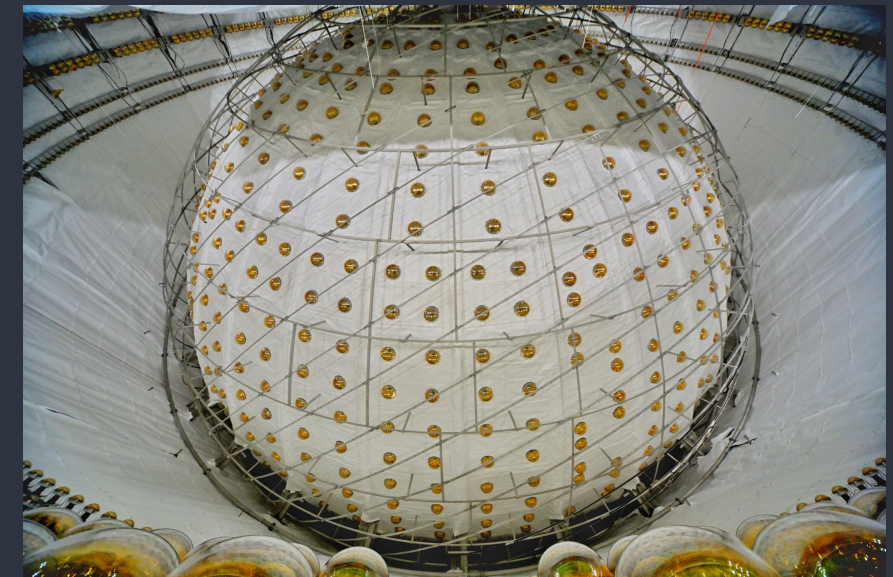
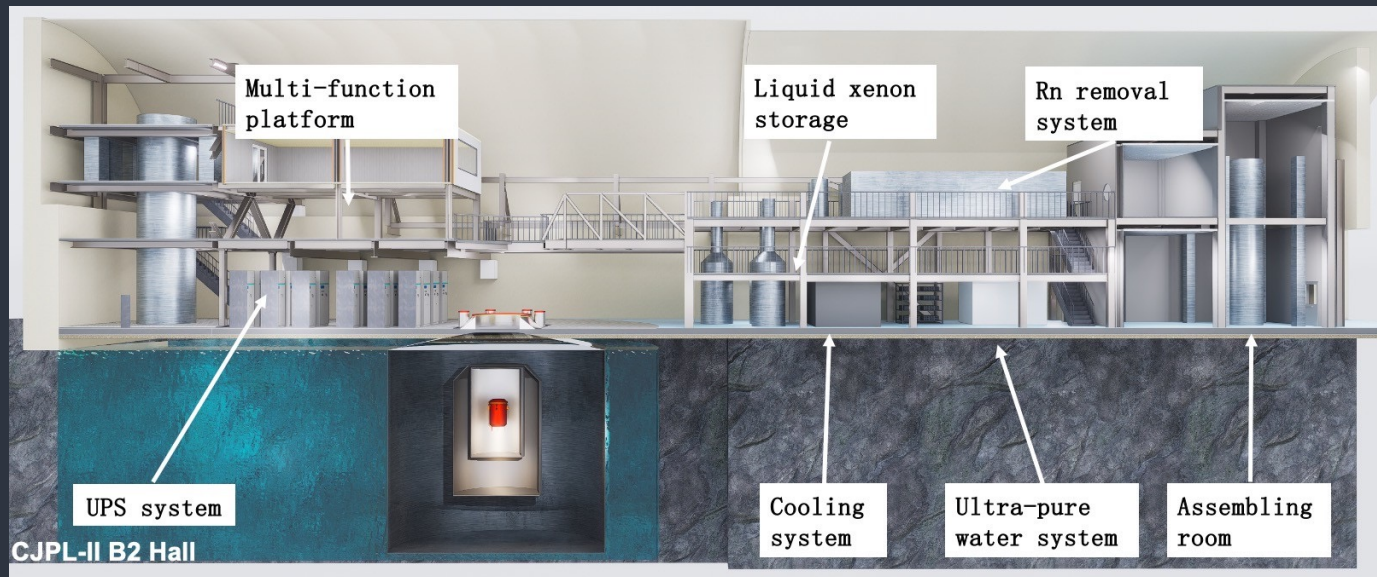


Transporting xenon to CJPL



Summary

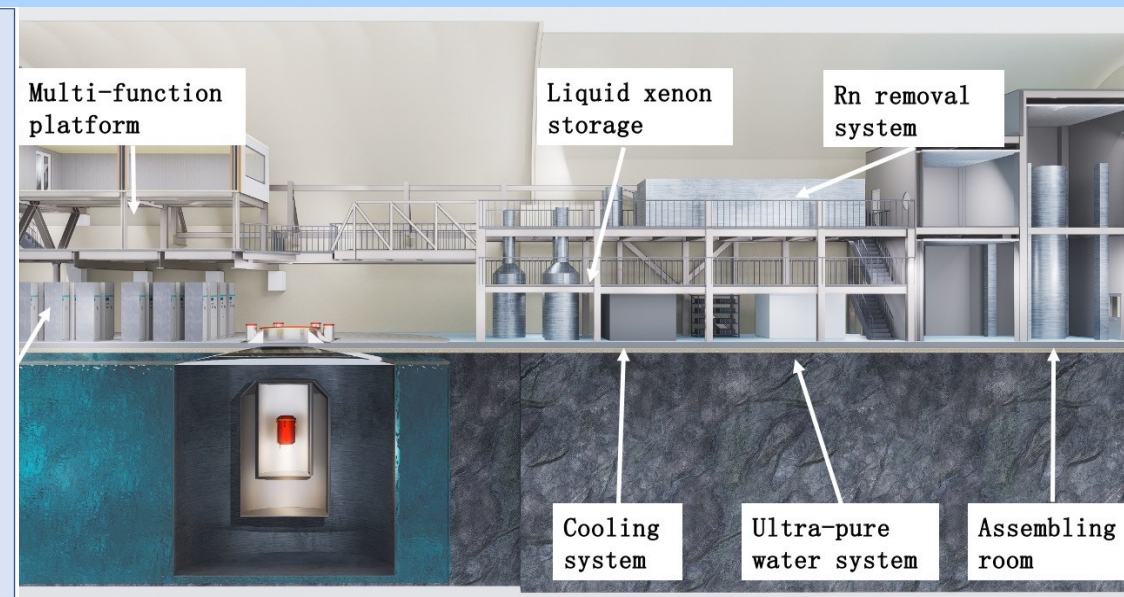
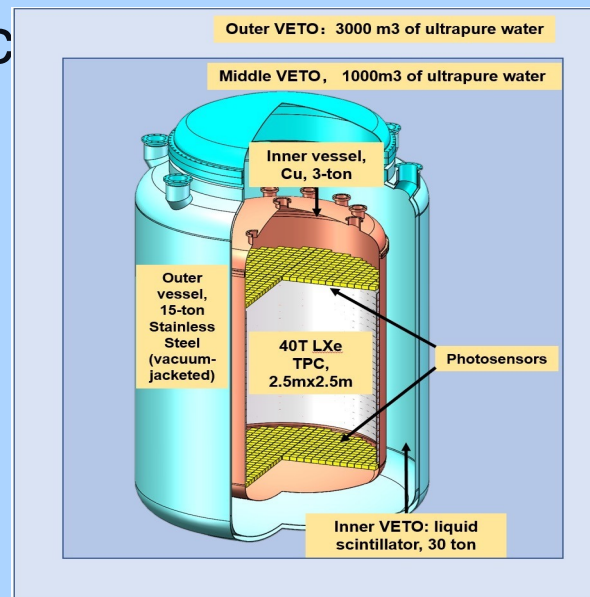
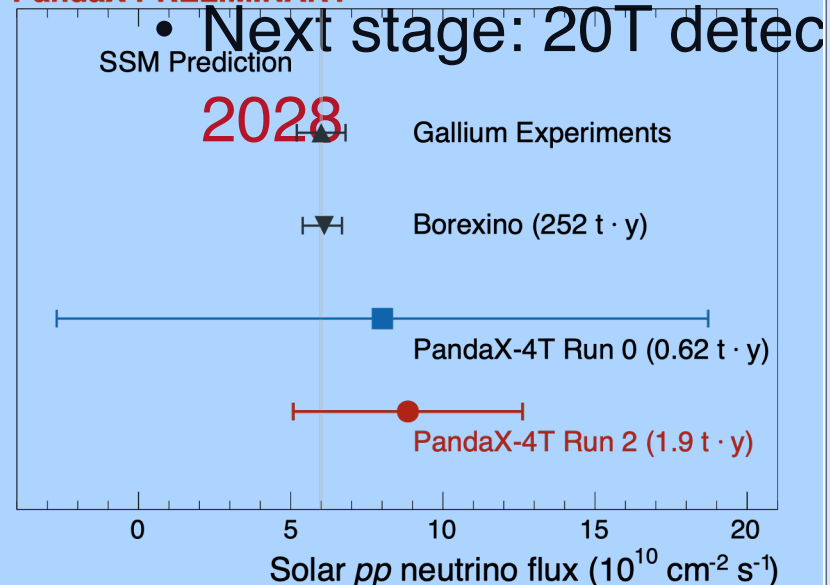
- Exciting $0\nu\beta\beta$ physics program worldwide, aiming for discovery
 - $m_{\beta\beta}$ **Atlas**: a repository to track the impact of NMEs on $m_{\beta\beta}$
 - Dozens of identified signals to distinguish kinematic exchange **mechanisms**
- Rapid progress in China; stay tuned for **PandaX-xT, JUNO- $0\nu\beta\beta$** , etc



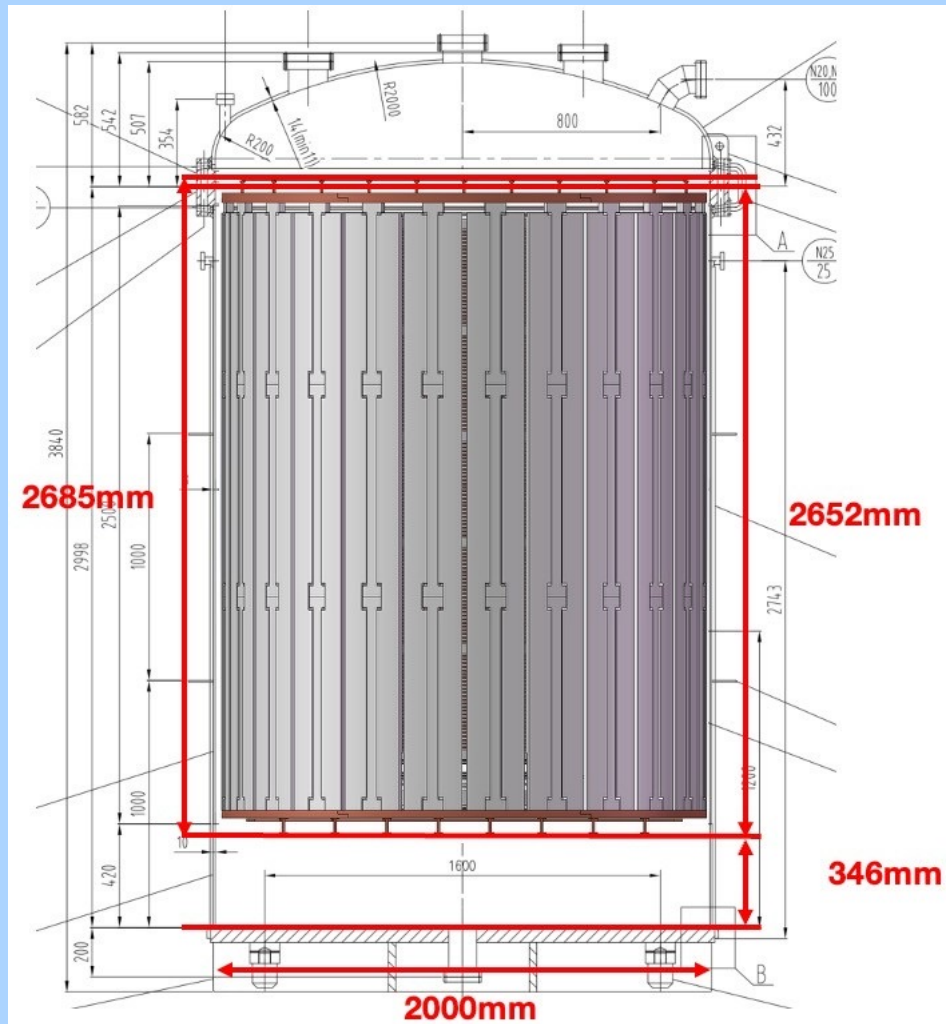
Summary

- Multi-physics goals in PandaX with an active **neutrino program**
- **Solar pp neutrino** measured with PandaX-4T electron scattering data
- **PandaX-xT** with competitive $0\nu\beta\beta$ and solar neutrino detection capabilities

PandaX PRELIMINARY



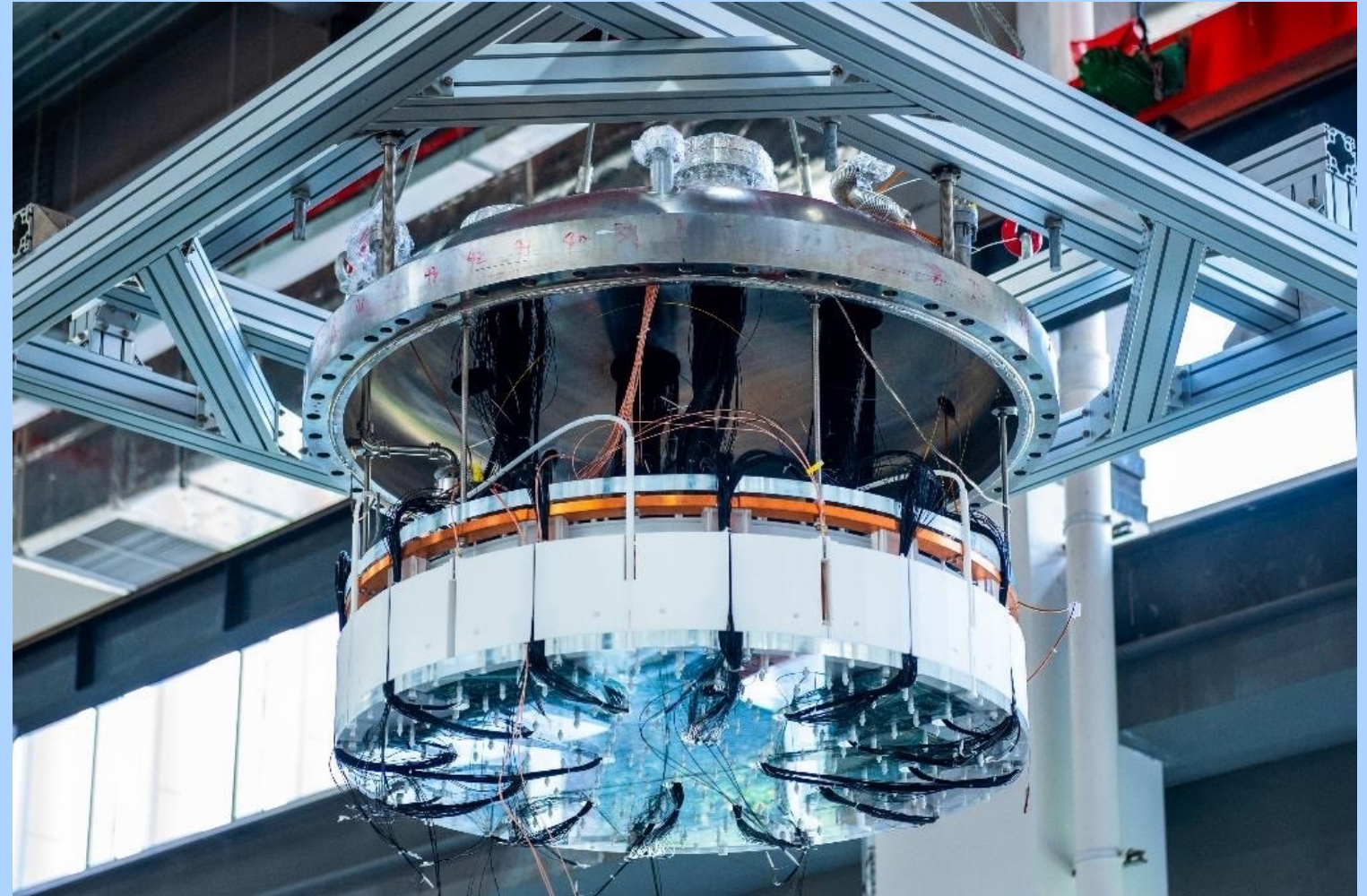
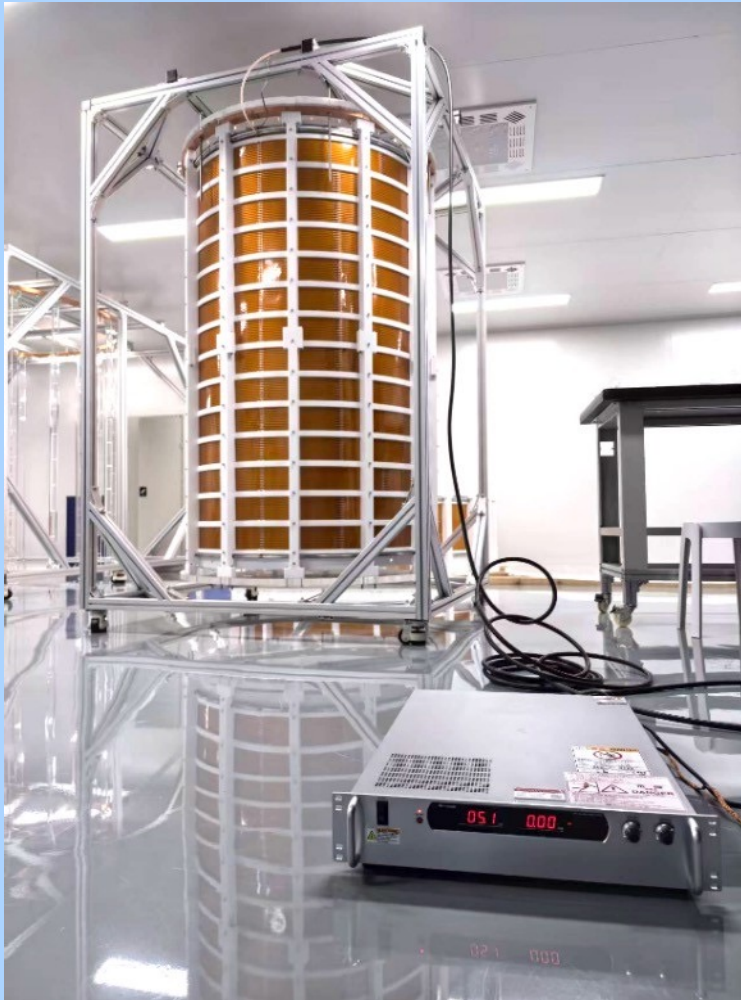
PandaX-20T TPC



17 ton sensitive mass

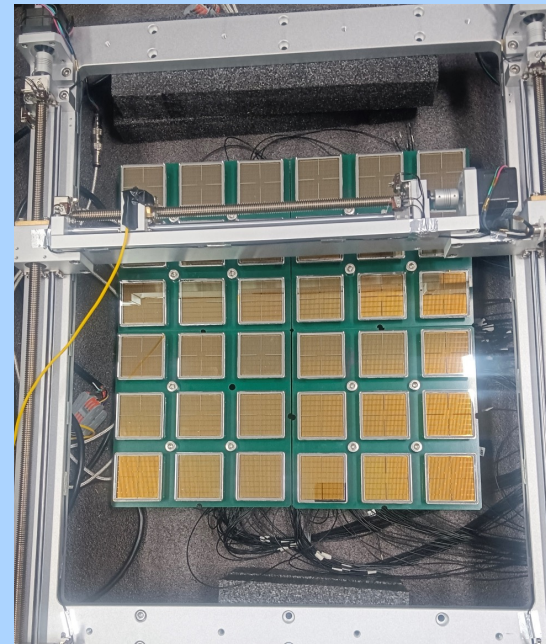
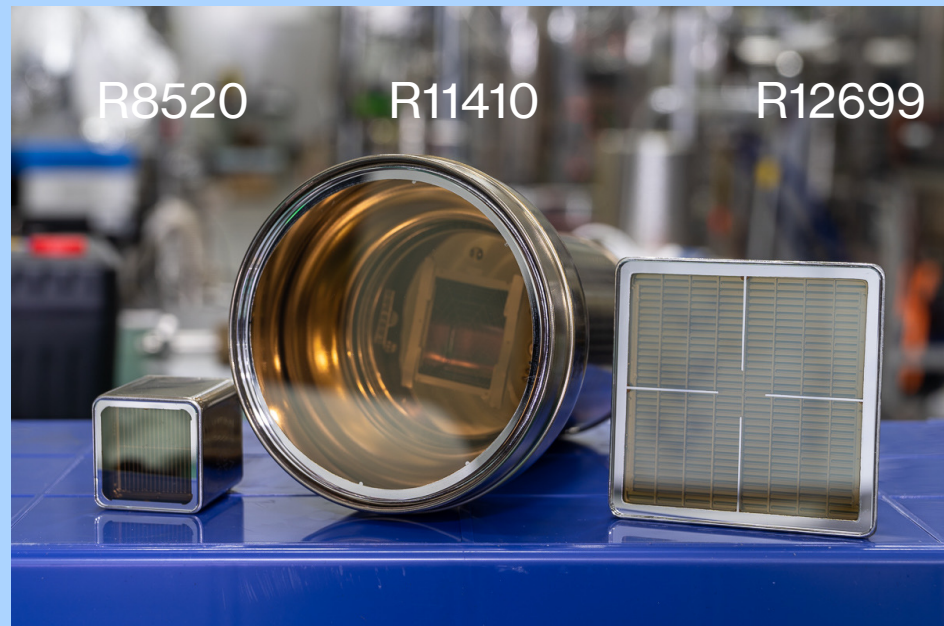


Field cage and prototype tests

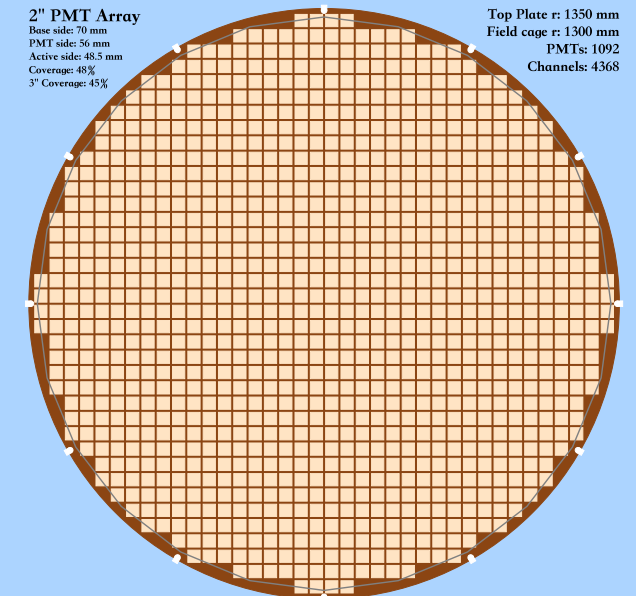


New 2" multi-anode R12699 PMT for LXe TPC

- Higher granularity while maintaining low dark noise: best of both large PMT and SiPM
 - Improved position reconstruction for better event topology
 - 2" array has an effectively wider dynamic range for DM and DBD simultaneously
- Collaboration between PandaX and Hamamatsu for a low-radioactivity version of R12699



2" PMT Array
Base side: 70 mm
PMT side: 56 mm
Active side: 48.5 mm
Coverage: 48%
3" Coverage: 45%



Top Plate r: 1350 mm
Field cage r: 1300 mm
PMTs: 1092
Channels: 4368

Conceptual array for a PandaX-xT

PMT system

- Top PMT array
 - 616 2inch multi-anode PMTs (R12699)
 - Low-radioactivity version to be delivered in 2026
 - Flexible-Rigid PCB (FRP) boards for integrated HV/signal readout lines with base
- Bottom PMT array
 - 433 3inch PMTs (PandaX-II and PandaX-4T)
 - Flexible PCB bases
- Assembly and system-level testing in progress

