CJPL, Jinping, China

Neutrinoless double beta decay

无双实验（无中微子双贝塔衰变）

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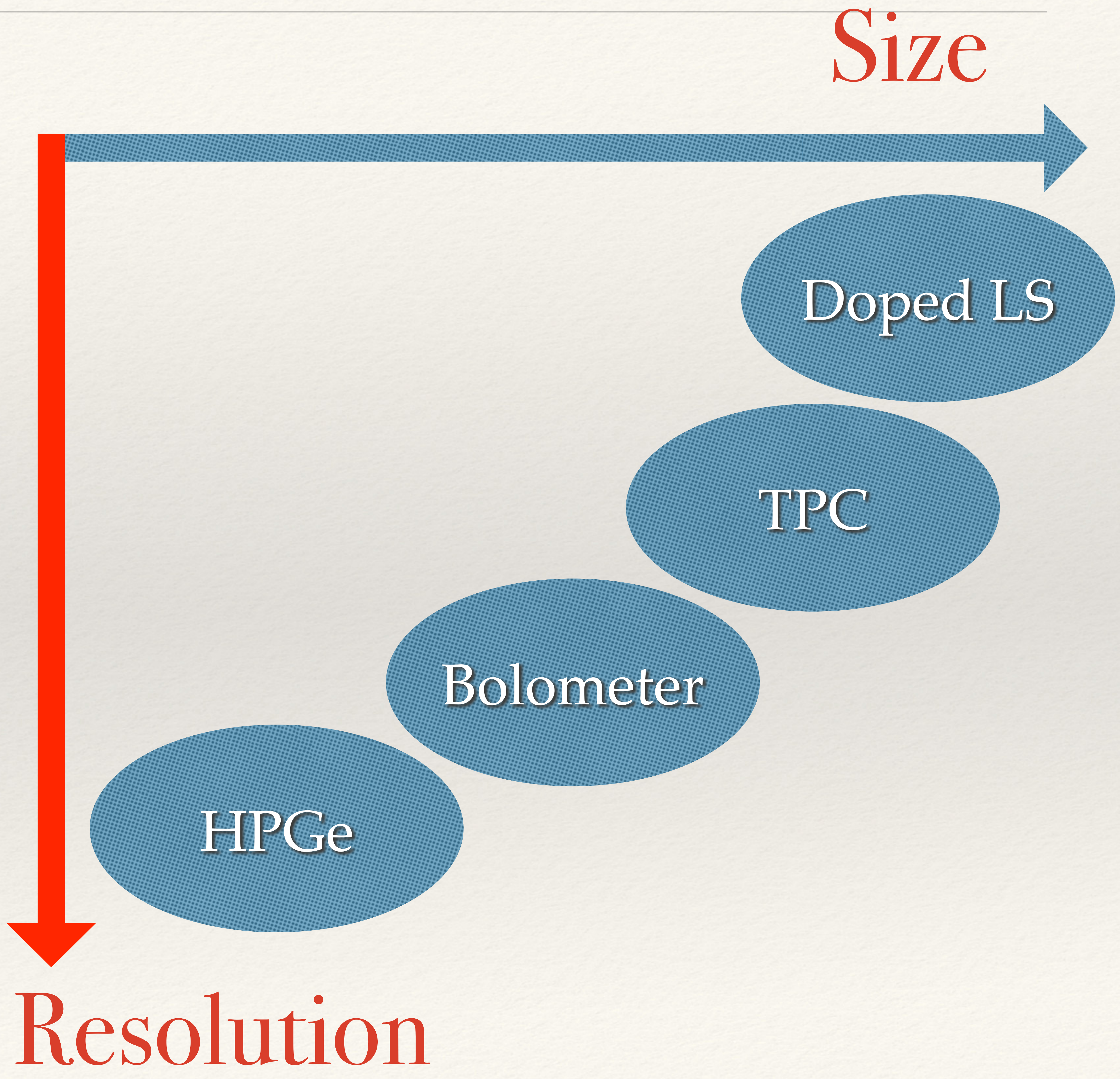
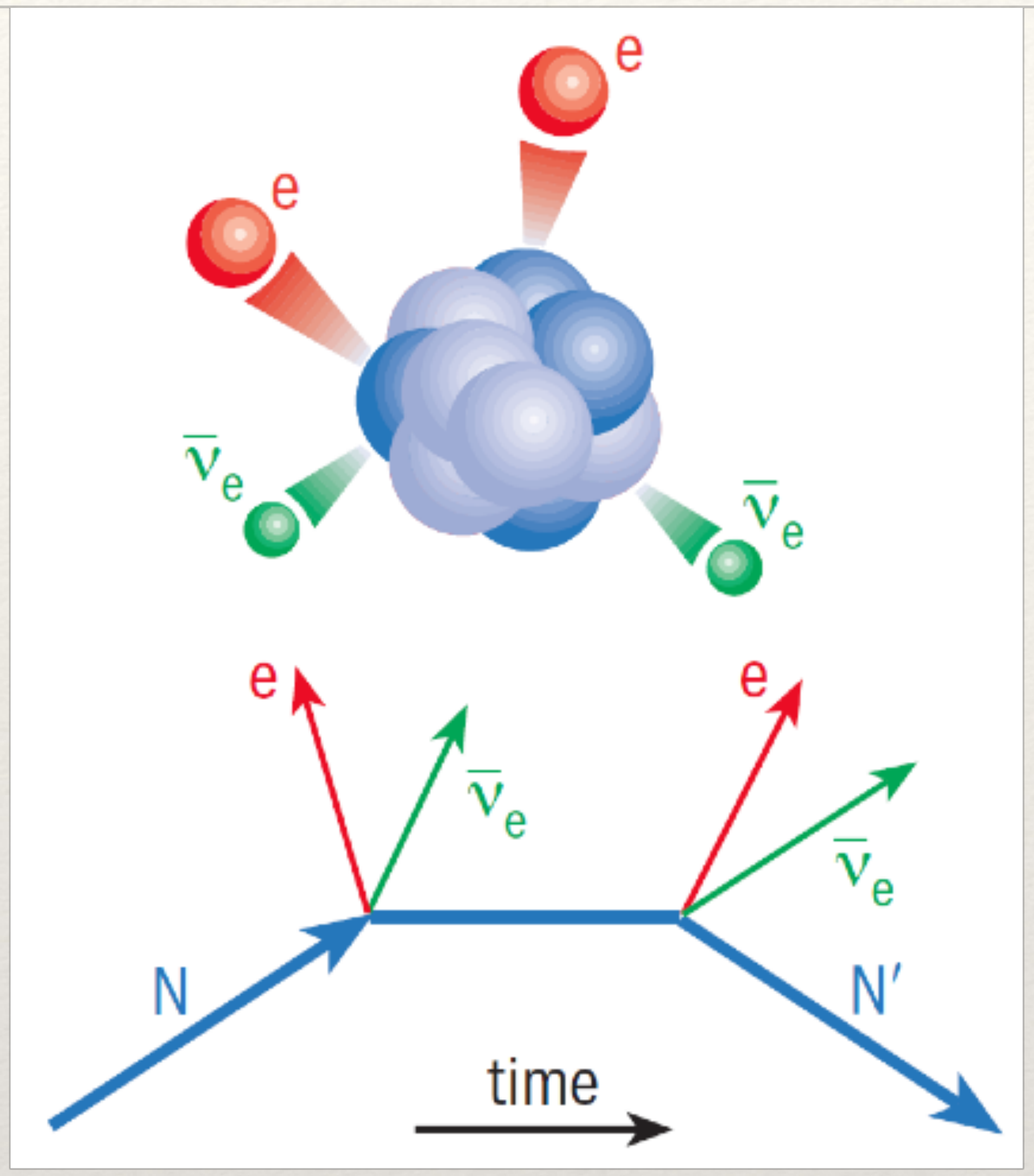
Shanghai Jiao Tong University
December 17, 2023

Outline

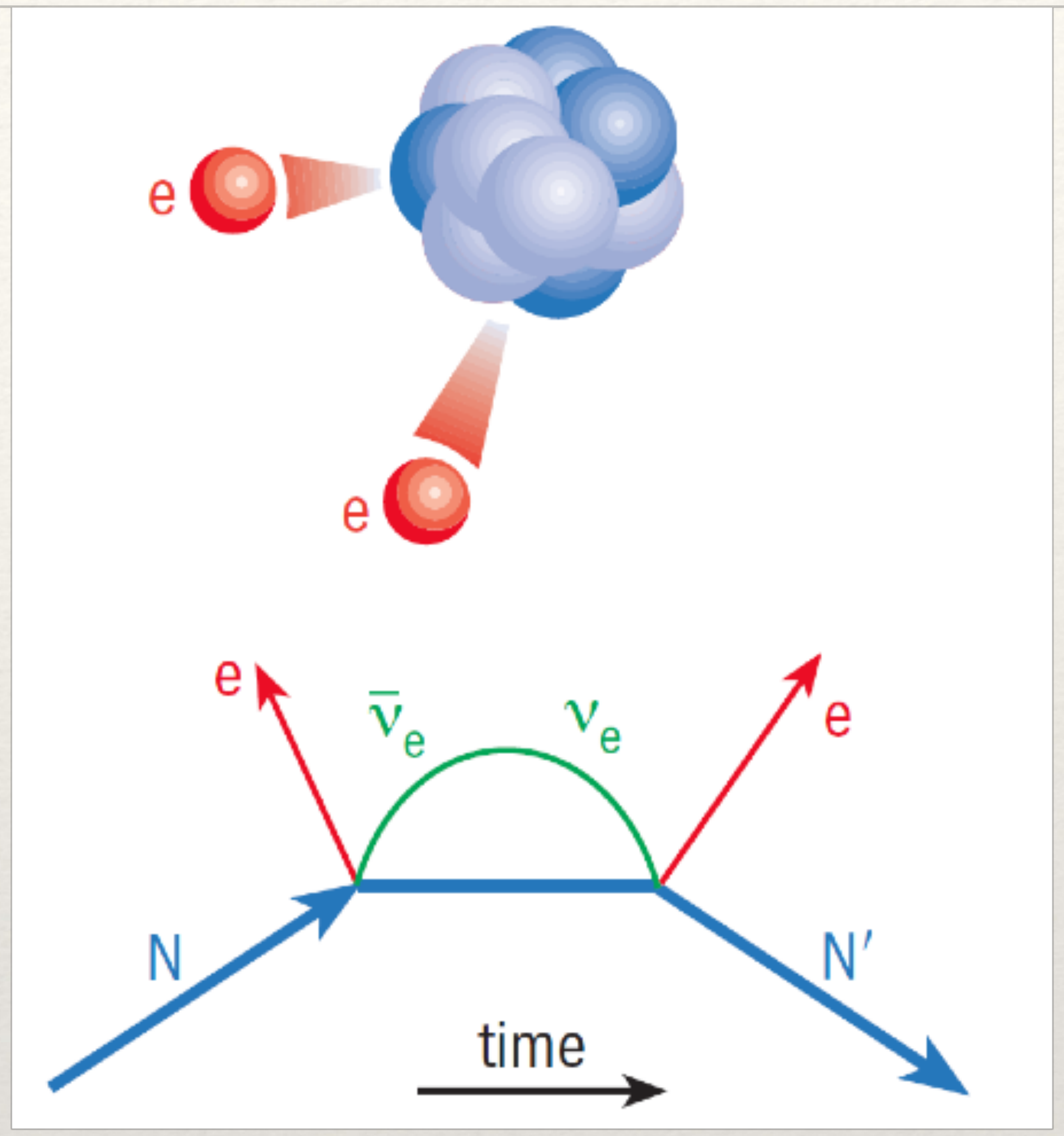
- Physics of Neutrinoless double beta decay
- Experimental searches and challenges
- Different techniques:
  - Bolometers: CUORE/CUPID, CUPID-CJPL
  - HPGe: LEGEND, CDEX
  - Doped LS: KamLAND-ZEN, JUNO-0νββ
  - TPC: nEXO, NνDEX, **PandaX**



Majorana neutrino and NLDBD



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



From Physics World

1935, Goeppert-Mayer
Two-Neutrino double beta decay

1937, Majorana
Majorana Neutrino

1939, Furry
Neutrinoless double beta decay 0νββ

1930, Pauli
Idea of neutrino

1933, Fermi
Beta decay theory

$$^{136}_{54}Xe \rightarrow {}^{136}_{56}Ba + 2e^- + (2\bar{\upsilon})$$

First round of experiments

- Initial calculation showed half-life of 2νββ of 10^{21} year, and 0νββ of 10^{15} year
- Triggered a large number of experiments
- Detect electrons and/or daughter nuclei

1948, First experiment

- 25 g of enriched ^{124}Sn

  $^{124}Sn \rightarrow {}^{124}Te + 2e^- + (2\bar{\nu}_e)$
- Geiger counters to measure the emitted electrons
- $0\nu\beta\beta$ half-life estimation: 3×10^{15} year

1950, First evidence of $2\nu\beta\beta$

- Geochemical experiment

  $^{130}Te \rightarrow {}^{130}Xe + 2e^- + (2\bar{\nu}_e)$
- Count relative abundance of ^{130}Xe in a 1.5 billion year old Tellurium ore.

1956, Lee and Yang

Parity non-conservation

1957, Lee and Yang, and others

Two-component theory of neutrino

1967

Ge detector

10^{21}y half-life limit

Physics Letters B

Volume 26, Issue 2, 25 December 1967, Pages 112-116

Double beta decay in ^{48}Ca and the conservation of leptons ☆

R.K. Bardin, D.J. Gollon, J.D. Ullman, C.S. Wu

1984, Fiorini and Niinikoski

Low temperature detector

1987, Elliott, Hahn, Moe

First direct observation of $2\nu\beta\beta$(^{82}Se); used a TPC

Minghan Ye et al

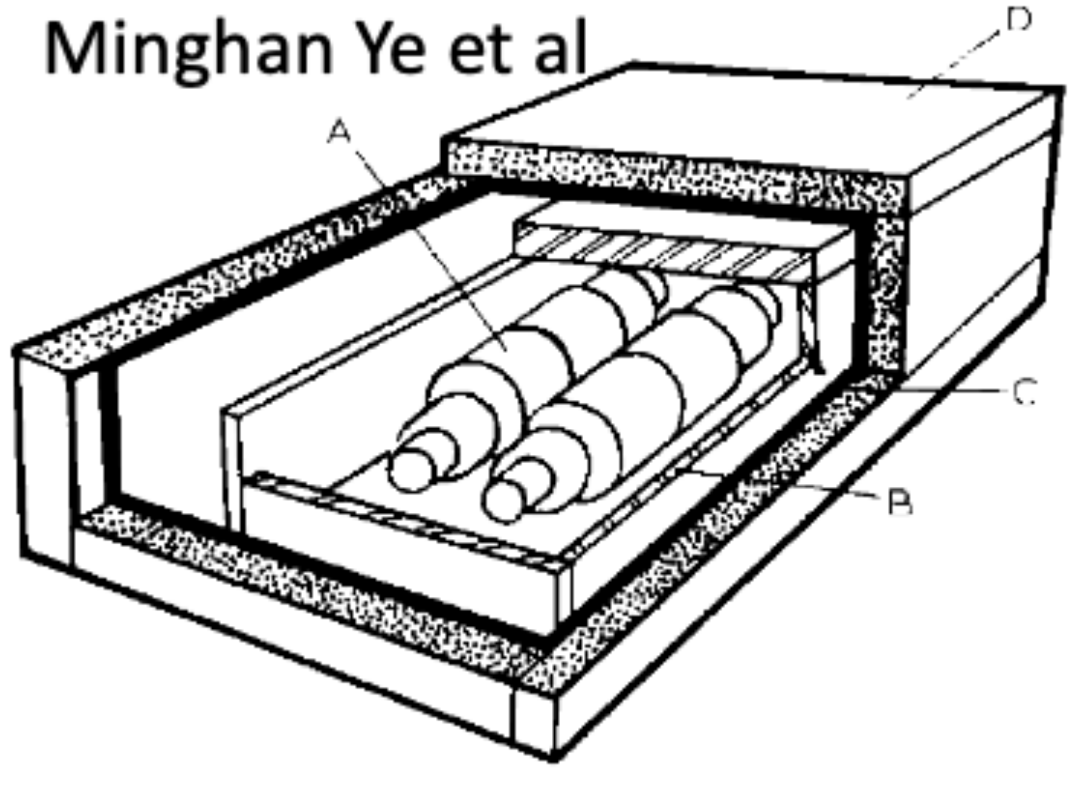


Fig. 1. Schematic drawing of detector assembly. A: CaF_2 crystal, B: plastic scintillator, C: steel shielding, D: lead shielding.

1982, Schechter and Valle

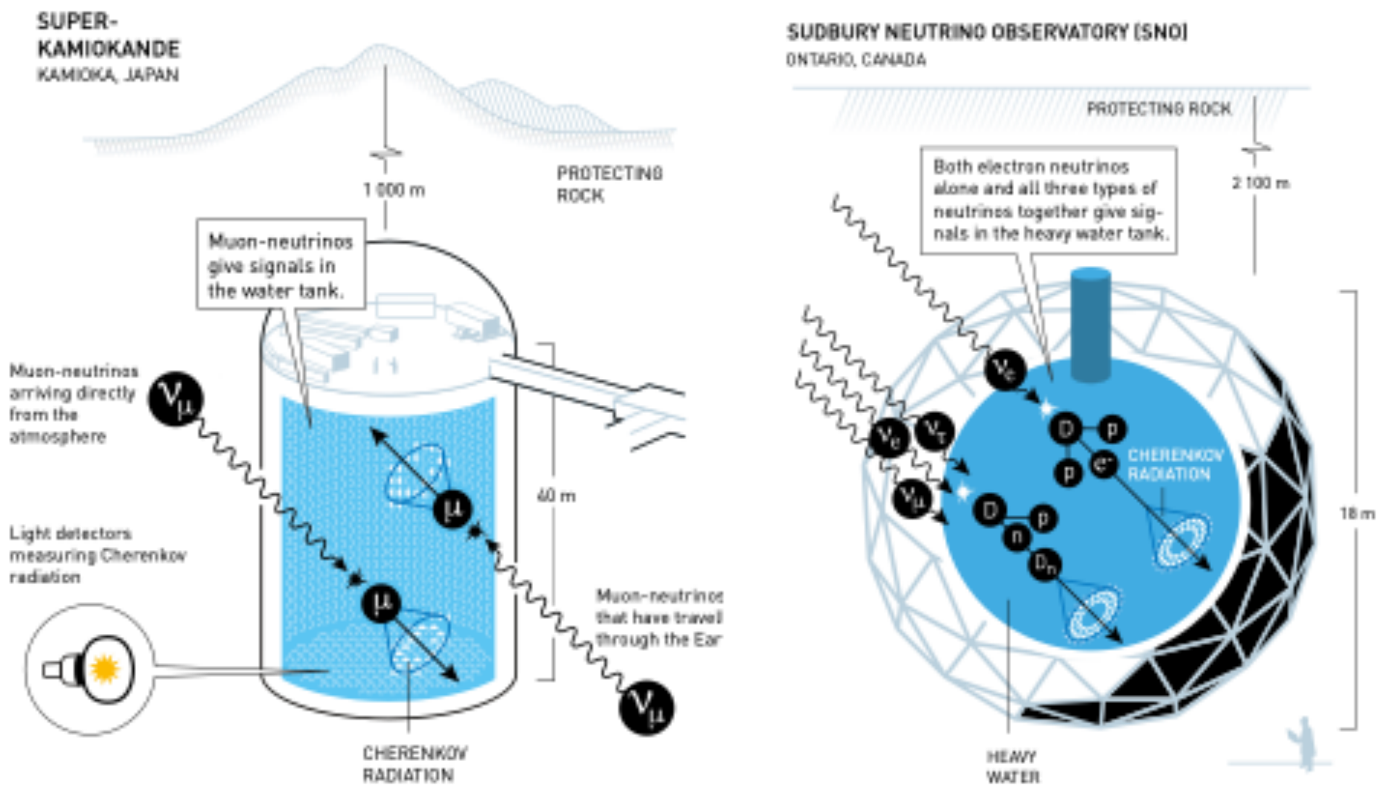
$0\nu\beta\beta$ → Majorana neutrinos

~2000, SK and SNO

Tiny but finite neutrino mass

Physics beyond the SM

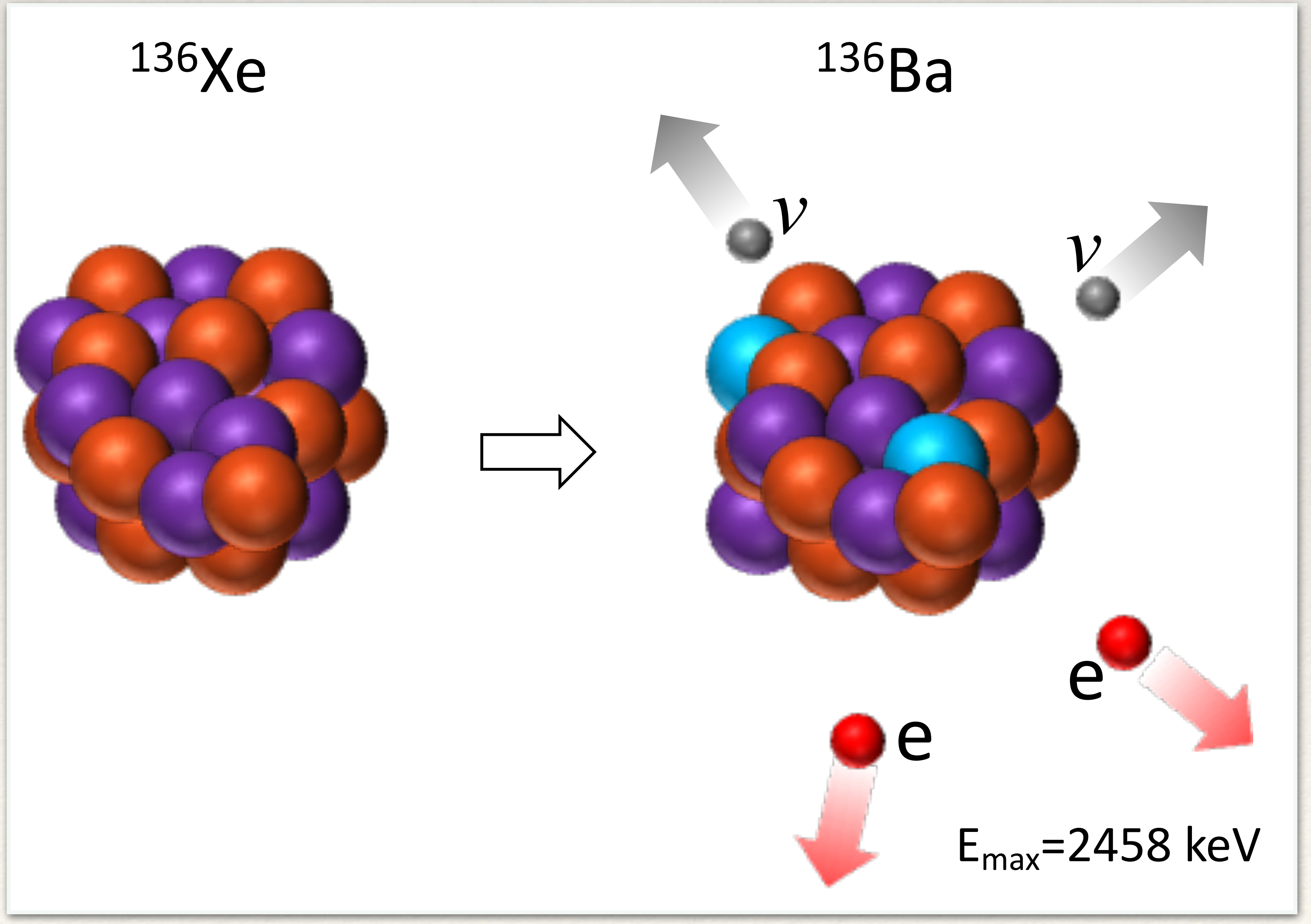
Helicity flipping possible at $0\nu\beta\beta$

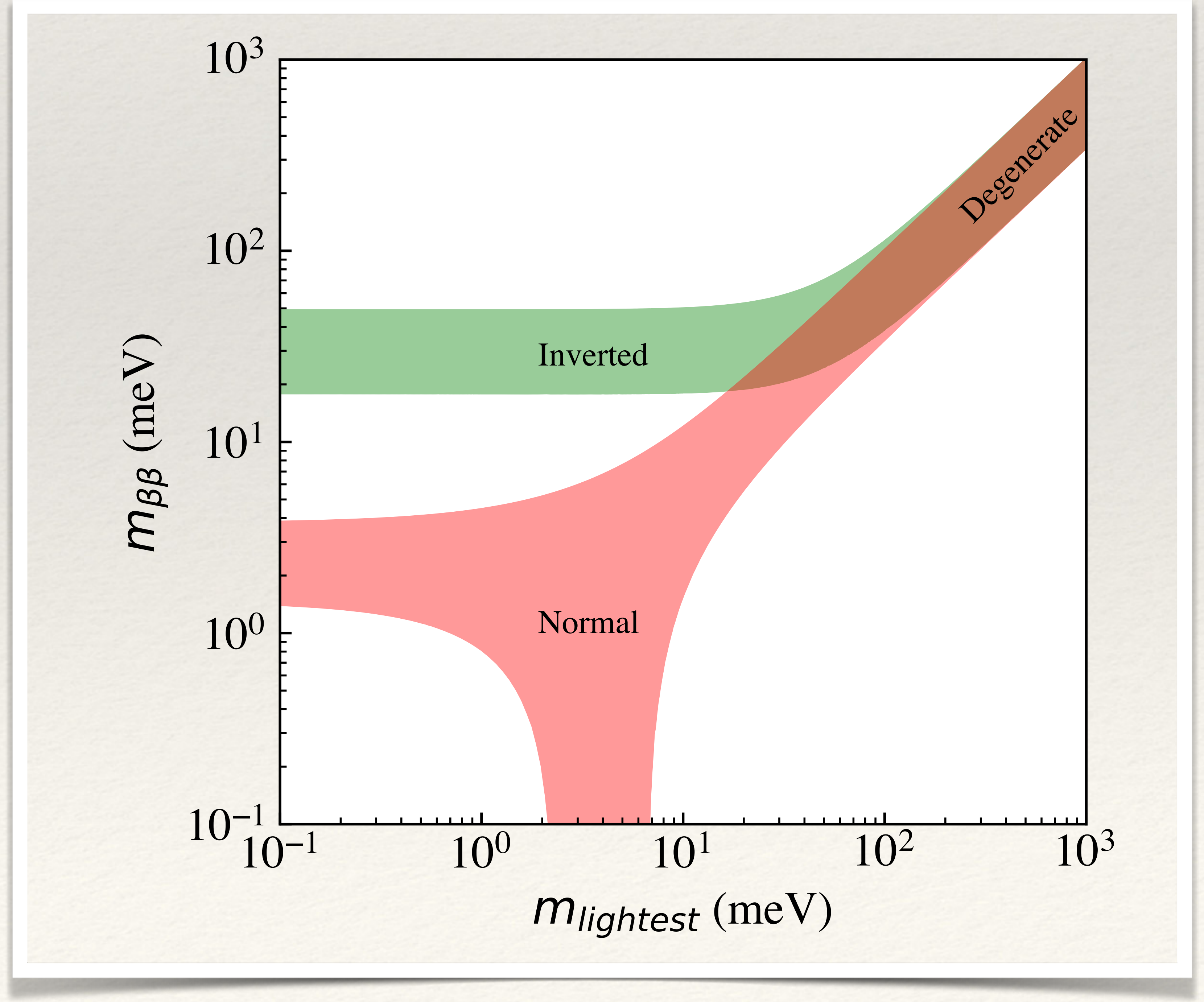


Neutrinoless Double beta decay (NLDBD)

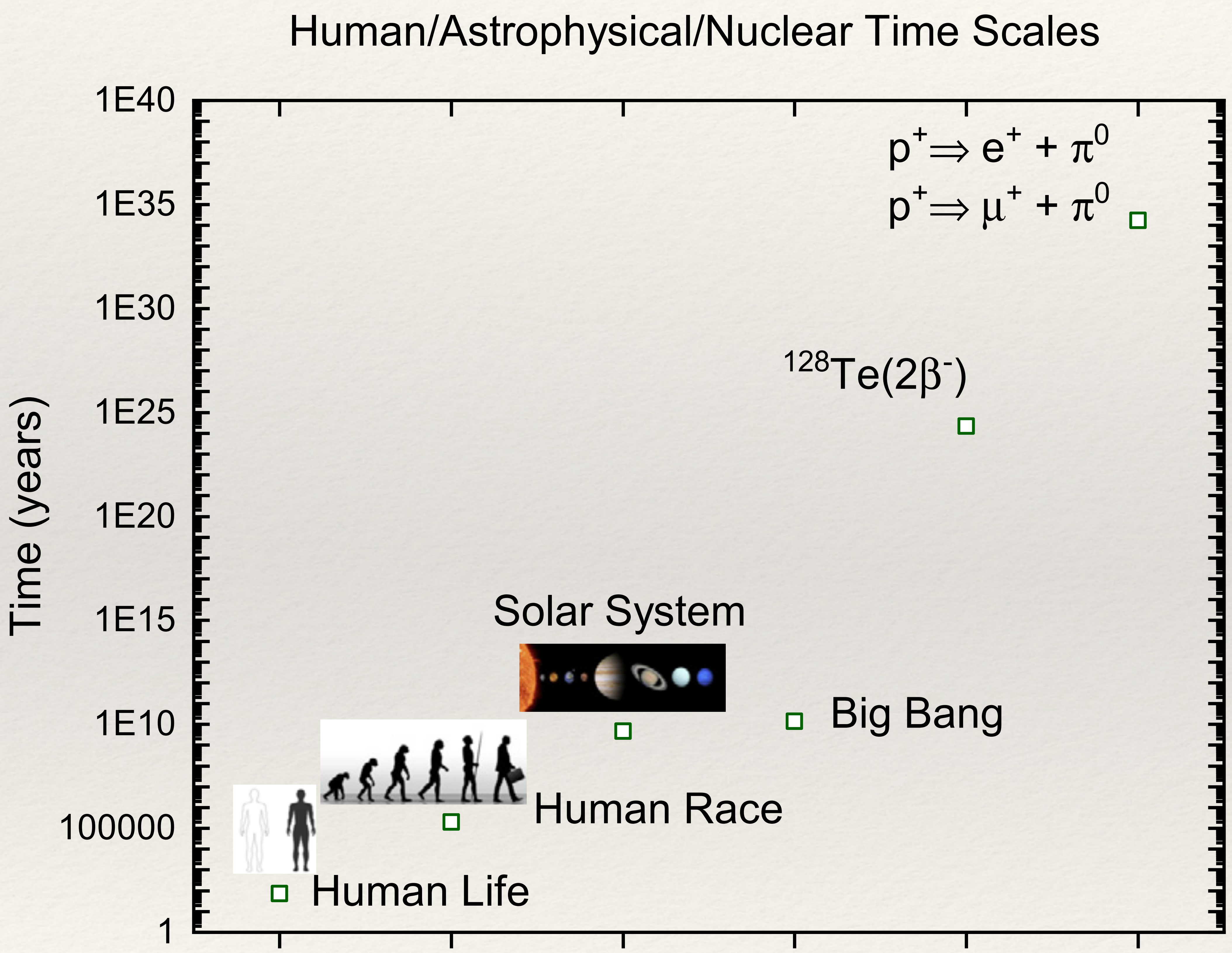
- Majorana or Dirac nature of neutrinos
- Lepton number violating process: beyond neutrino physics
- Measures effective Majorana mass: relate 0νββ to the neutrino oscillation

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





Extremely rare events



Nuclear Physics A 1033 (2023) 122628

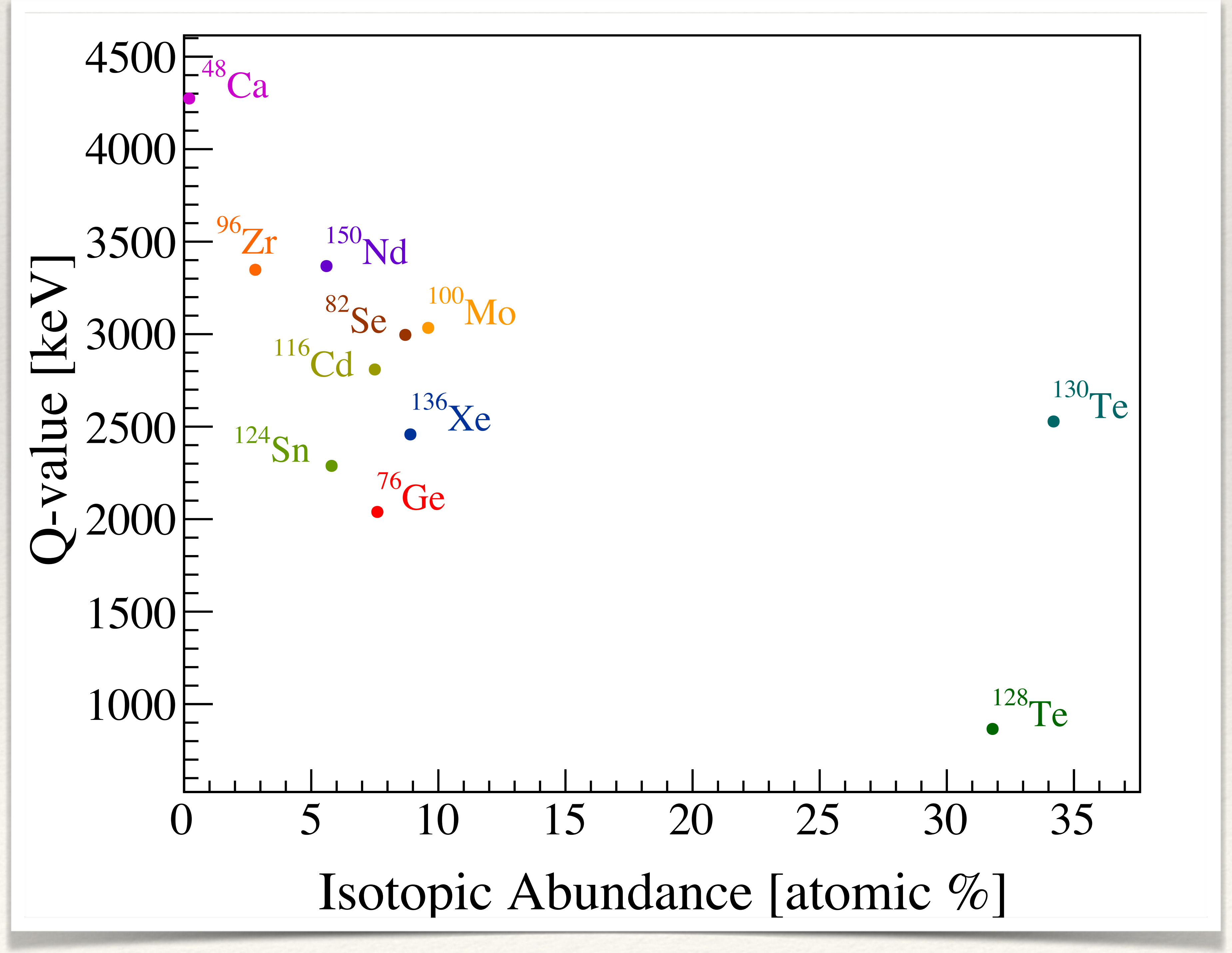
Nucleus	$Q_{2\beta}$-value (MeV)	$T_{1/2}^{2\nu,eval.}$(y)
^{48}Ca	4.26808	$(4.39\pm0.58)\times10^{19}$
^{76}Ge	2.03906	$(1.43\pm0.53)\times10^{21}$
^{82}Se	2.9979	$(9.19\pm0.76)\times10^{19}$
^{96}Zr	3.35603	$(2.16\pm0.26)\times10^{19}$
^{100}Mo	3.03436	$(6.98\pm0.44)\times10^{18}$
^{116}Cd	2.81349	$(2.89\pm0.25)\times10^{19}$
^{128}Te	0.8667	$(3.49\pm1.99)\times10^{24}$
^{130}Te	2.52751	$(7.14\pm1.04)\times10^{20}$
^{136}Xe	2.45791	$(2.34\pm0.13)\times10^{21}$
^{150}Nd	3.37138	$(8.37\pm0.45)\times10^{18}$
^{238}U	1.1446	$(2.00\pm0.60)\times10^{21}$

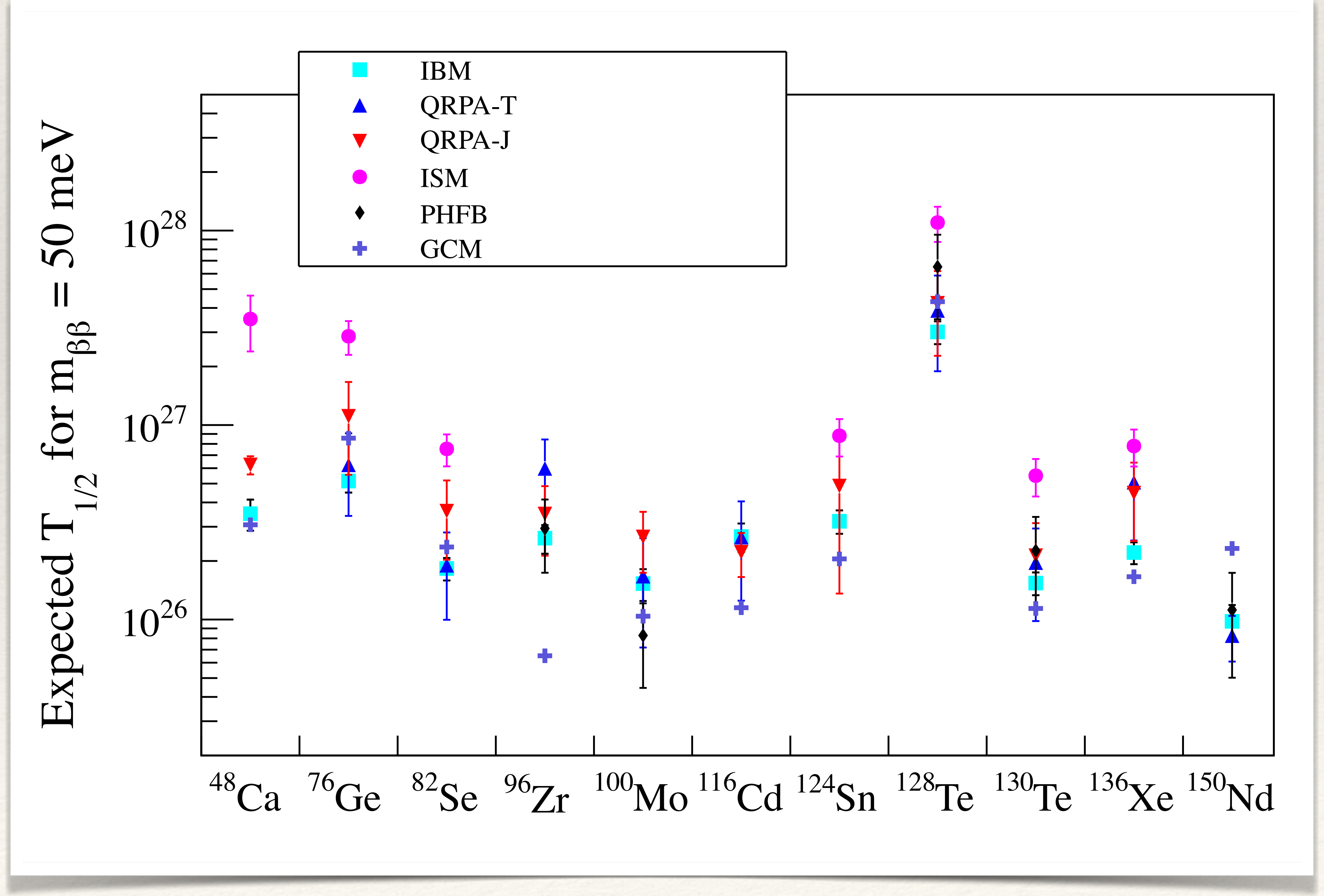
No magic isotopes

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

Phase space factor **Nuclear matrix element**

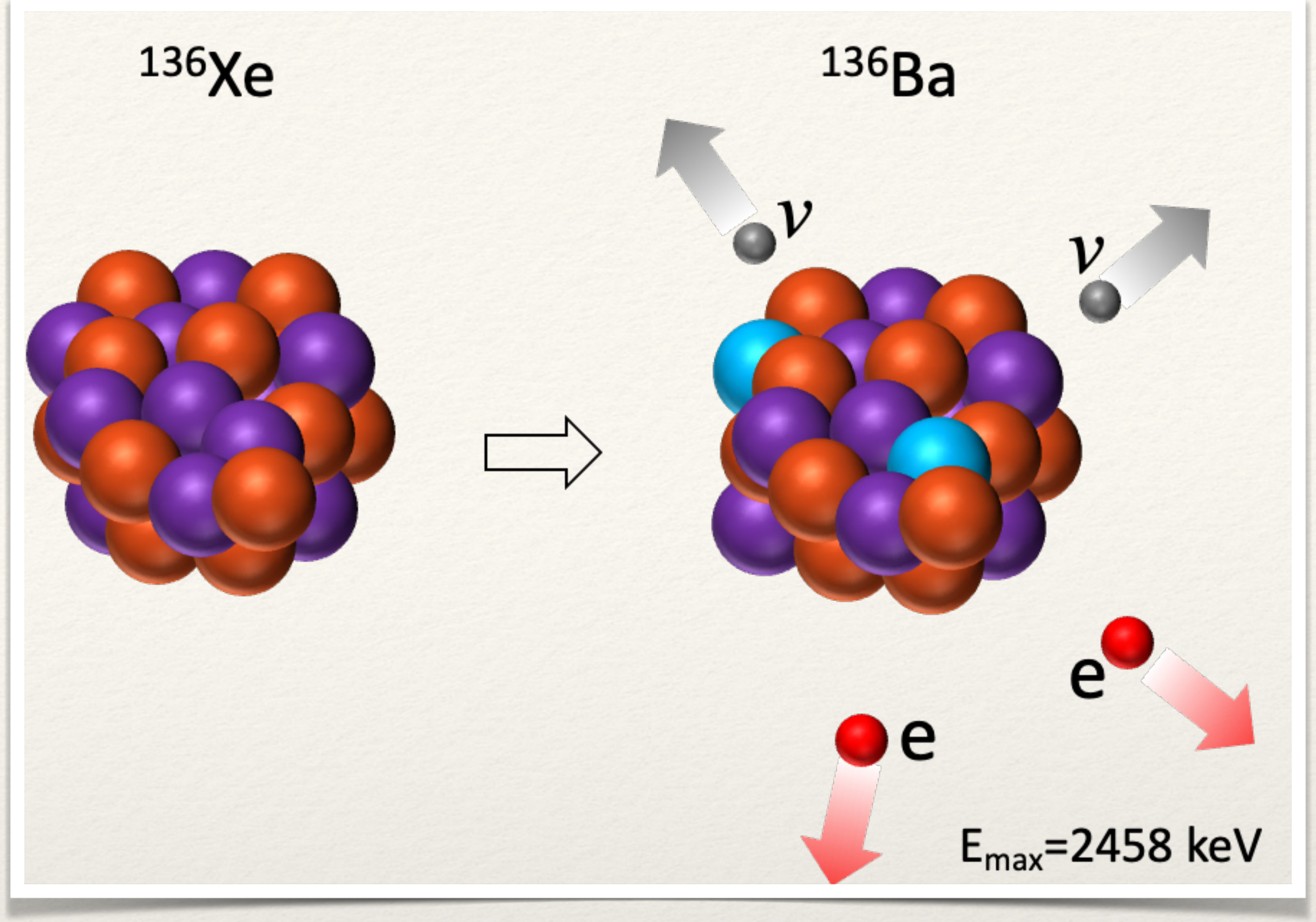
$$G^{0\nu} \propto Q^5$$

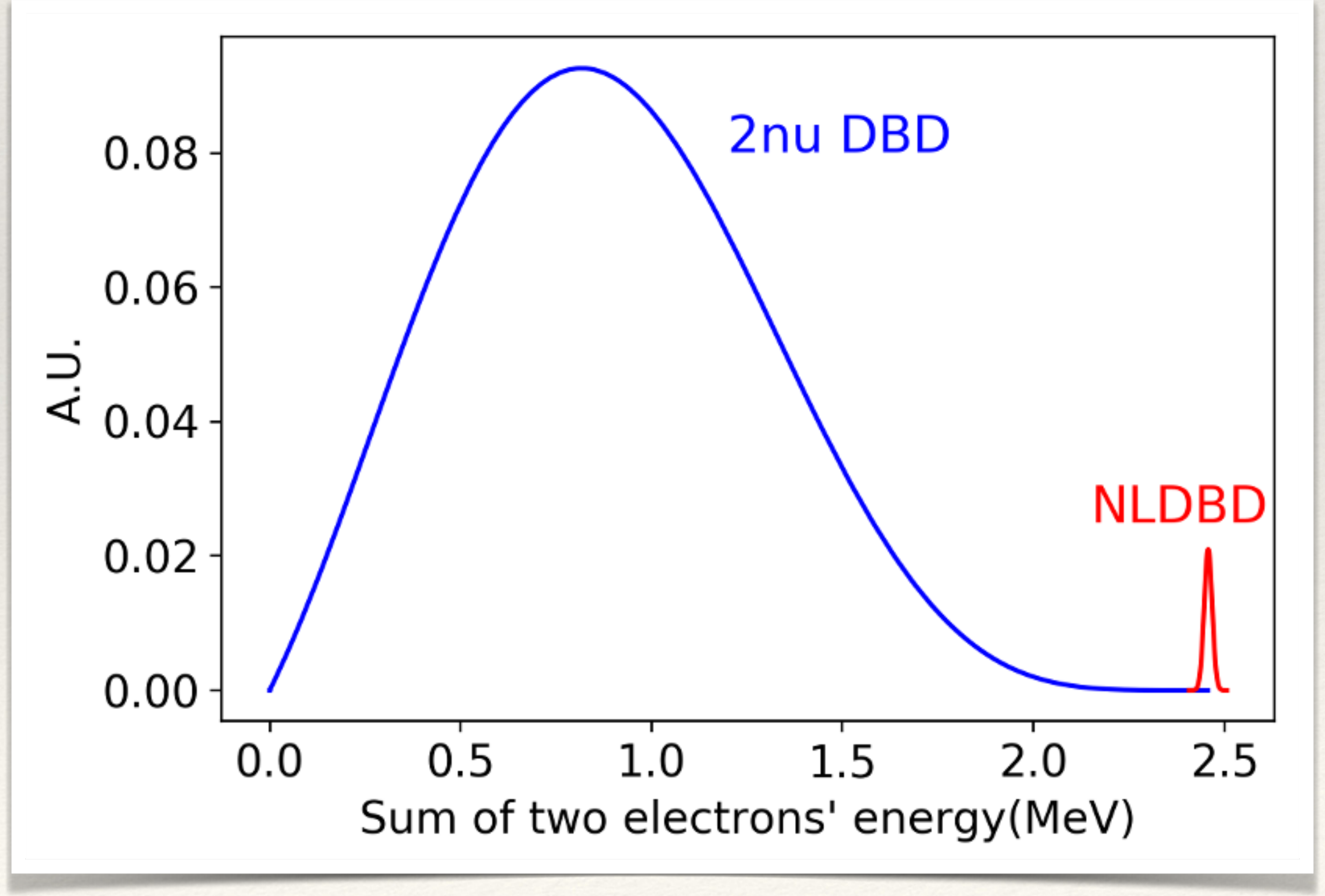




Experimental Searches

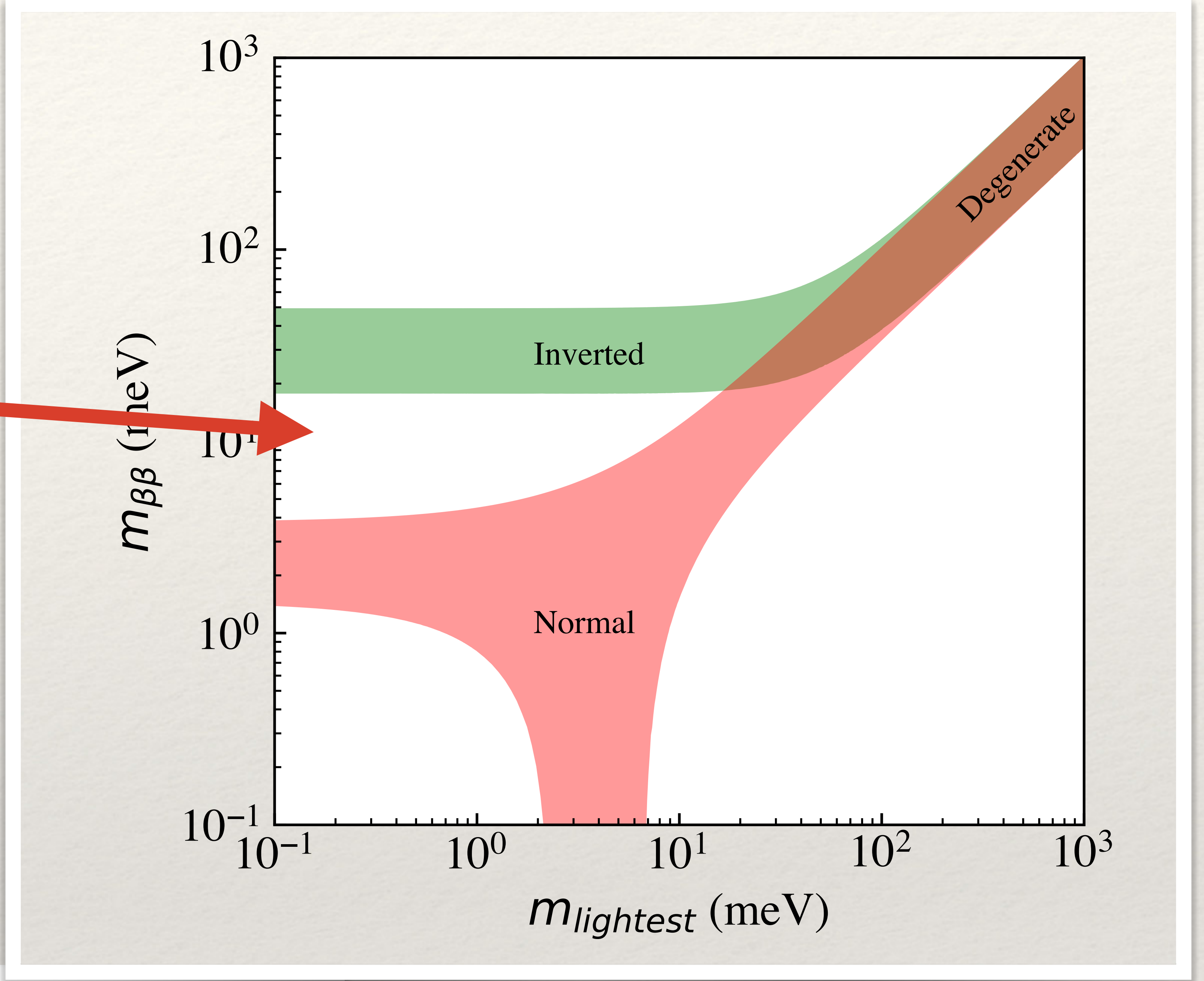
- Detect the electrons
  - Energy
  - Trajectories
- Detect the daughter nuclei
  - Geochemical and radiochemical
  - Imaging

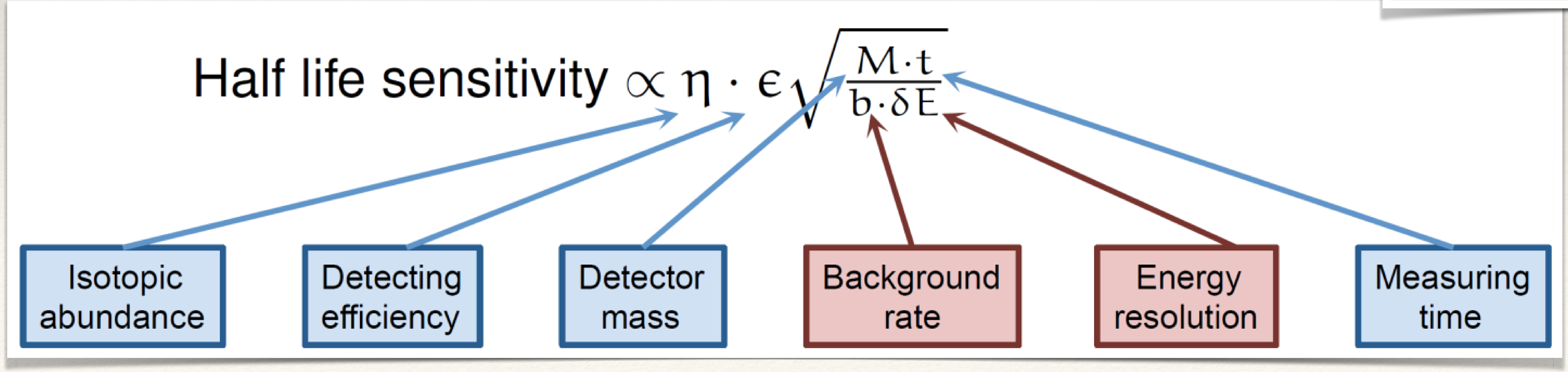




Half-life sensitivity from experiments

- Small signals: Fewer than 1 event/year for ton-scale experiments
- Number of signals over fluctuation of background for possible observation
- Extreme requirements for detector performance and background control






Canfranc
Modane
LNGS
CJPL
Y2L
Kamioka
SURF
SNOLAB
WIPP


CJPL
PandaX, CDEX
CUPID-CJPL, NvDEx
Y2L
AMoRE
Kamioka
KamLAND-Zen
CANDLES
SURF
Majorana
Canfranc
NEXT
Modane
SuperNEMO
LNGS
CUORE
CUPID
LEGEND
WIPP
EXO-200
SNOLAB
SNO+
Major players

美国核科学长期规划

- 2015

RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

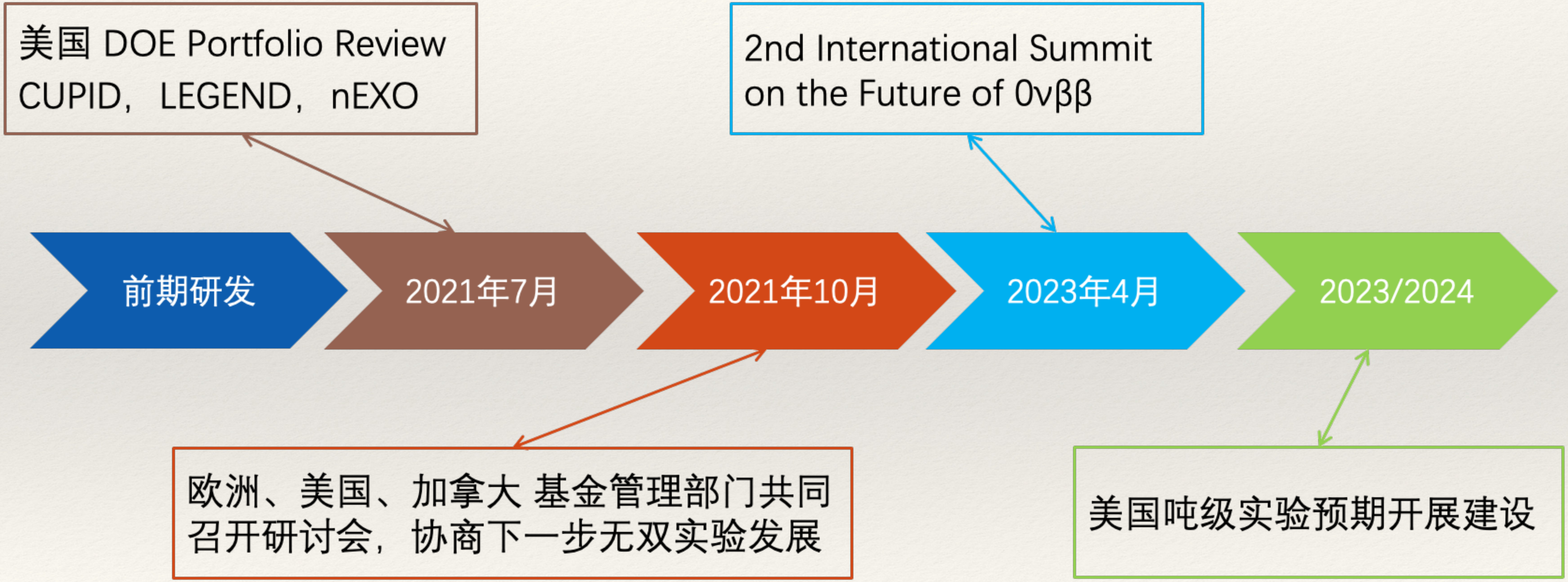
We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

- 2023

RECOMMENDATION 2

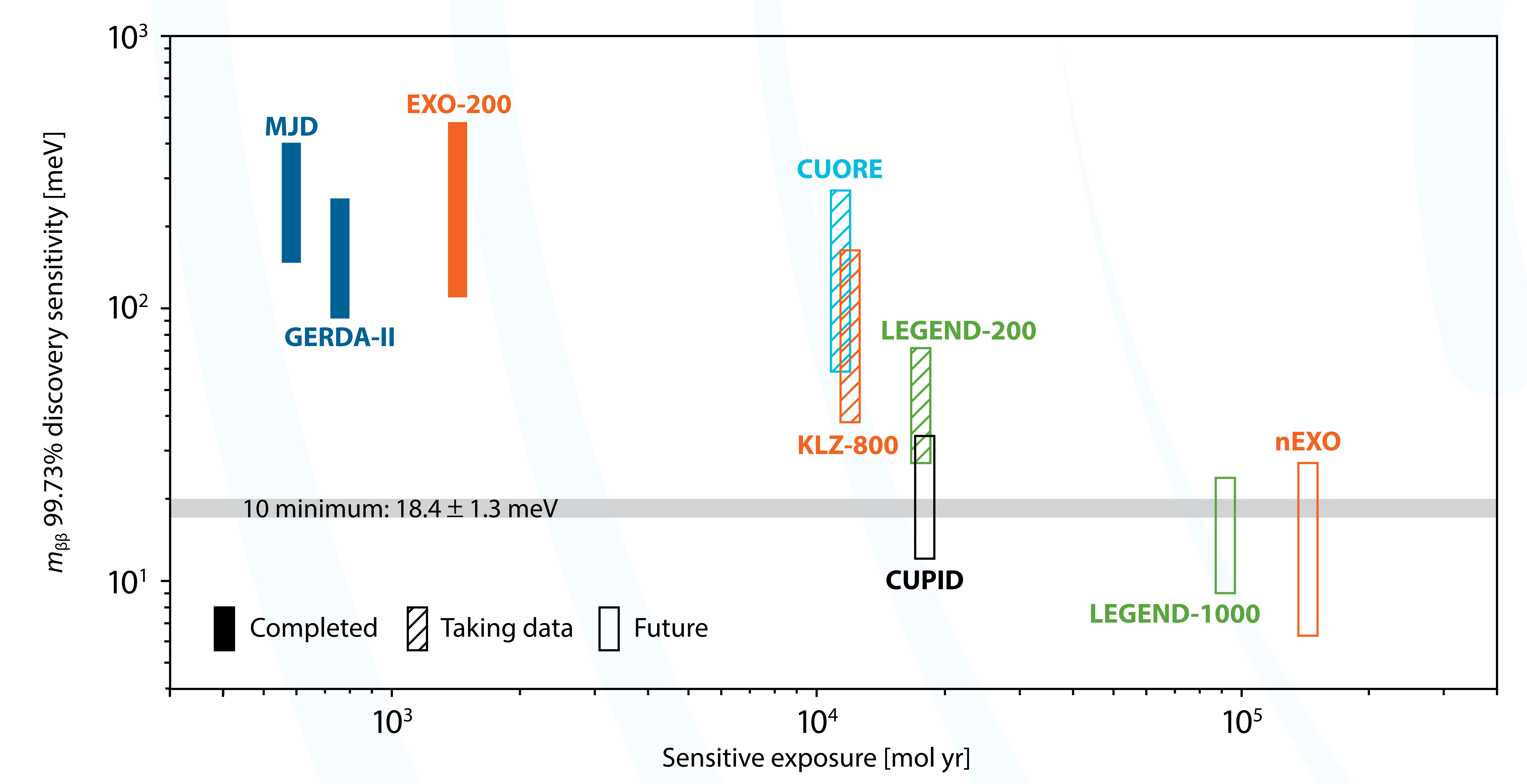
As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

Joint NA-EU effort

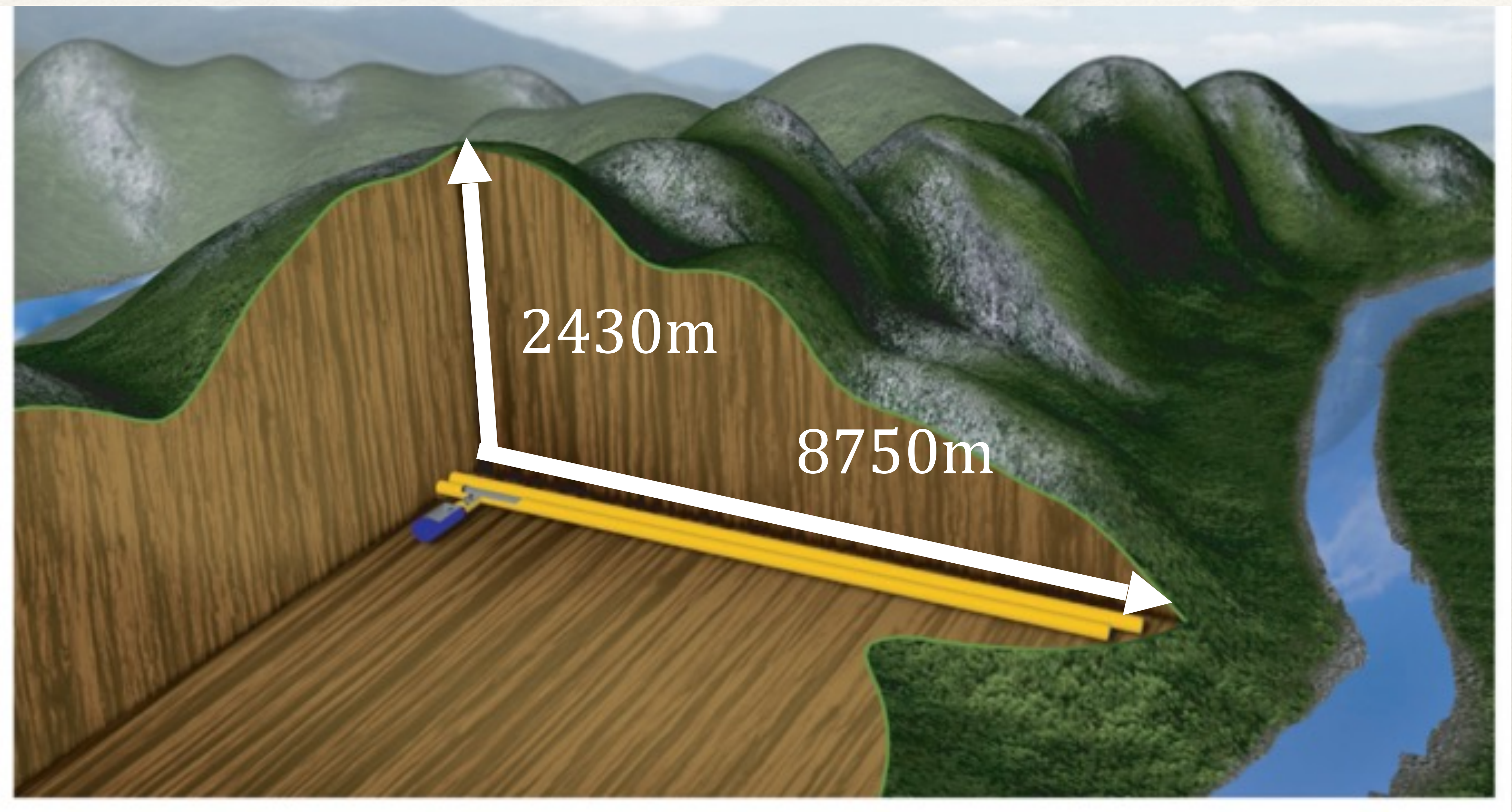


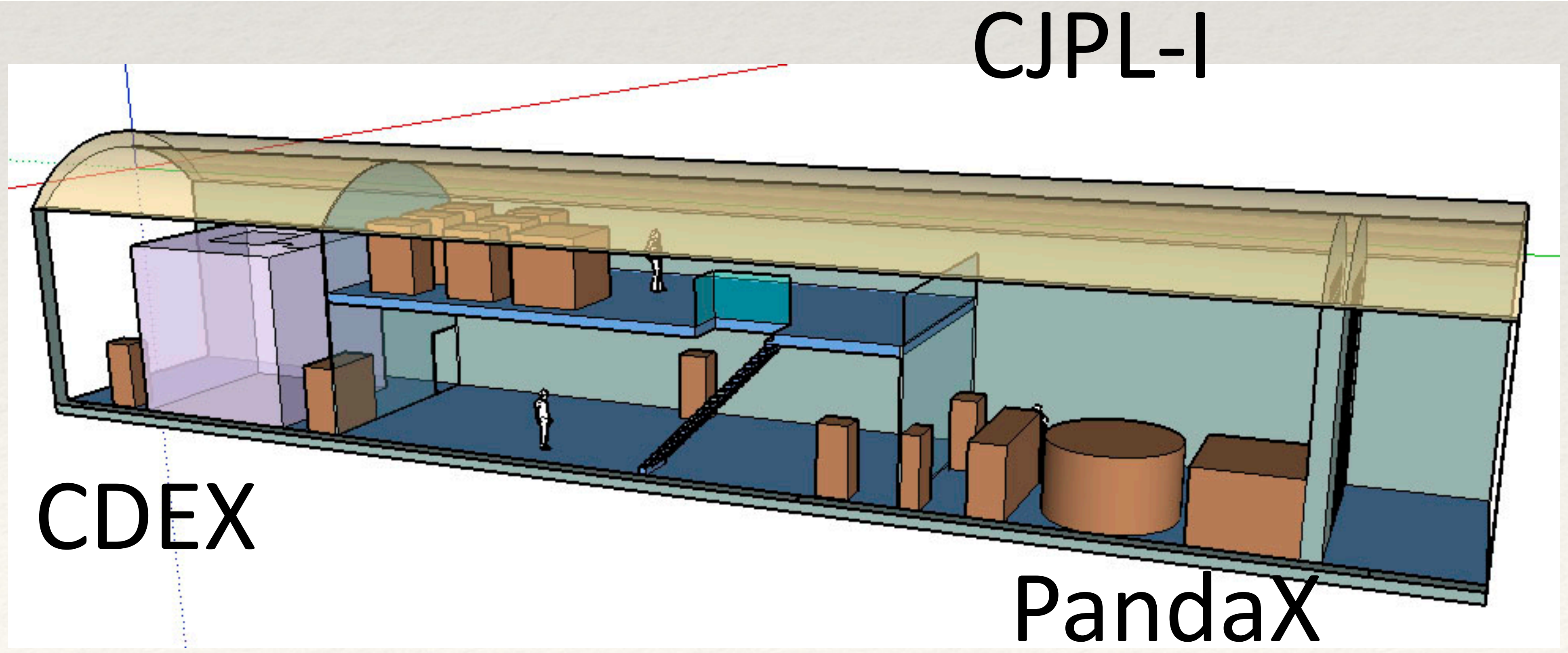
https://agenda.infn.it/e/double-beta-2021

Sensitivity comparison

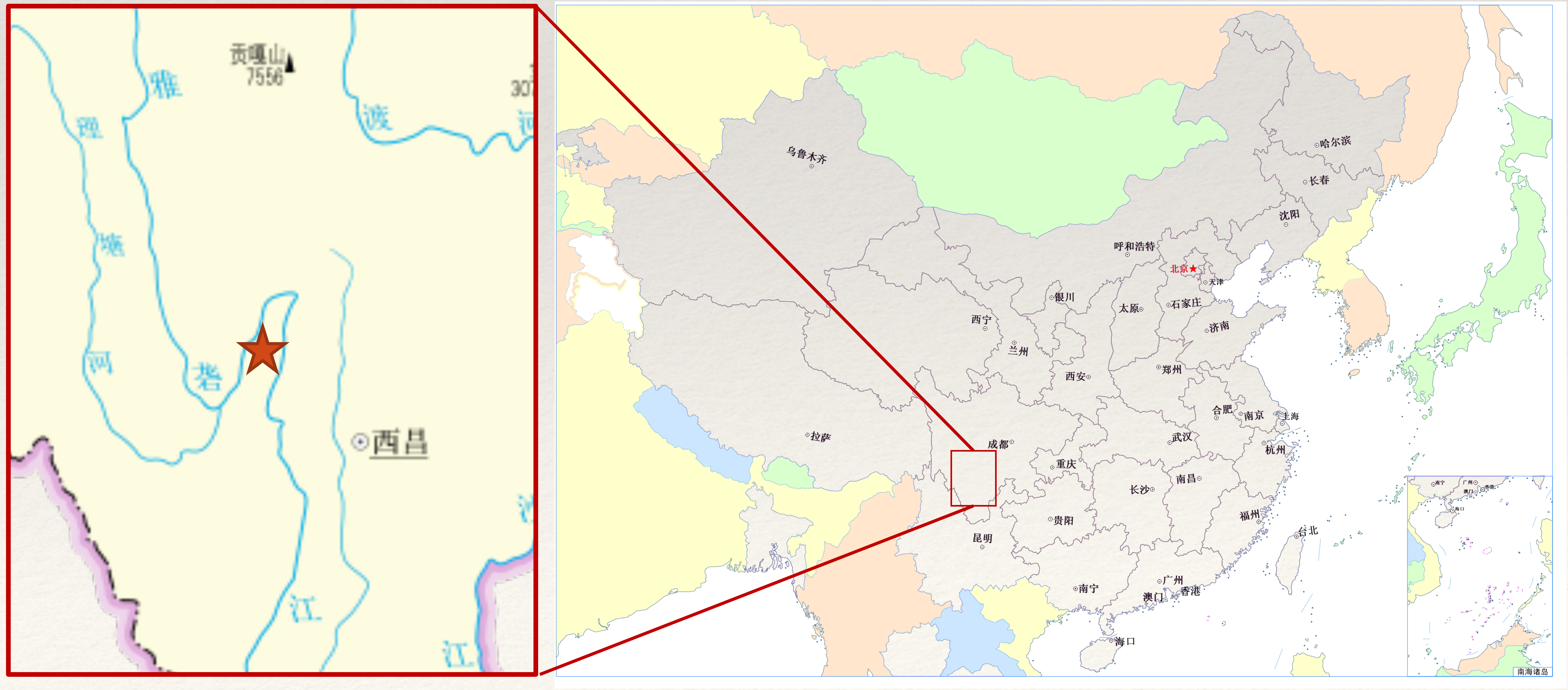


CJPL: Deepest underground lab

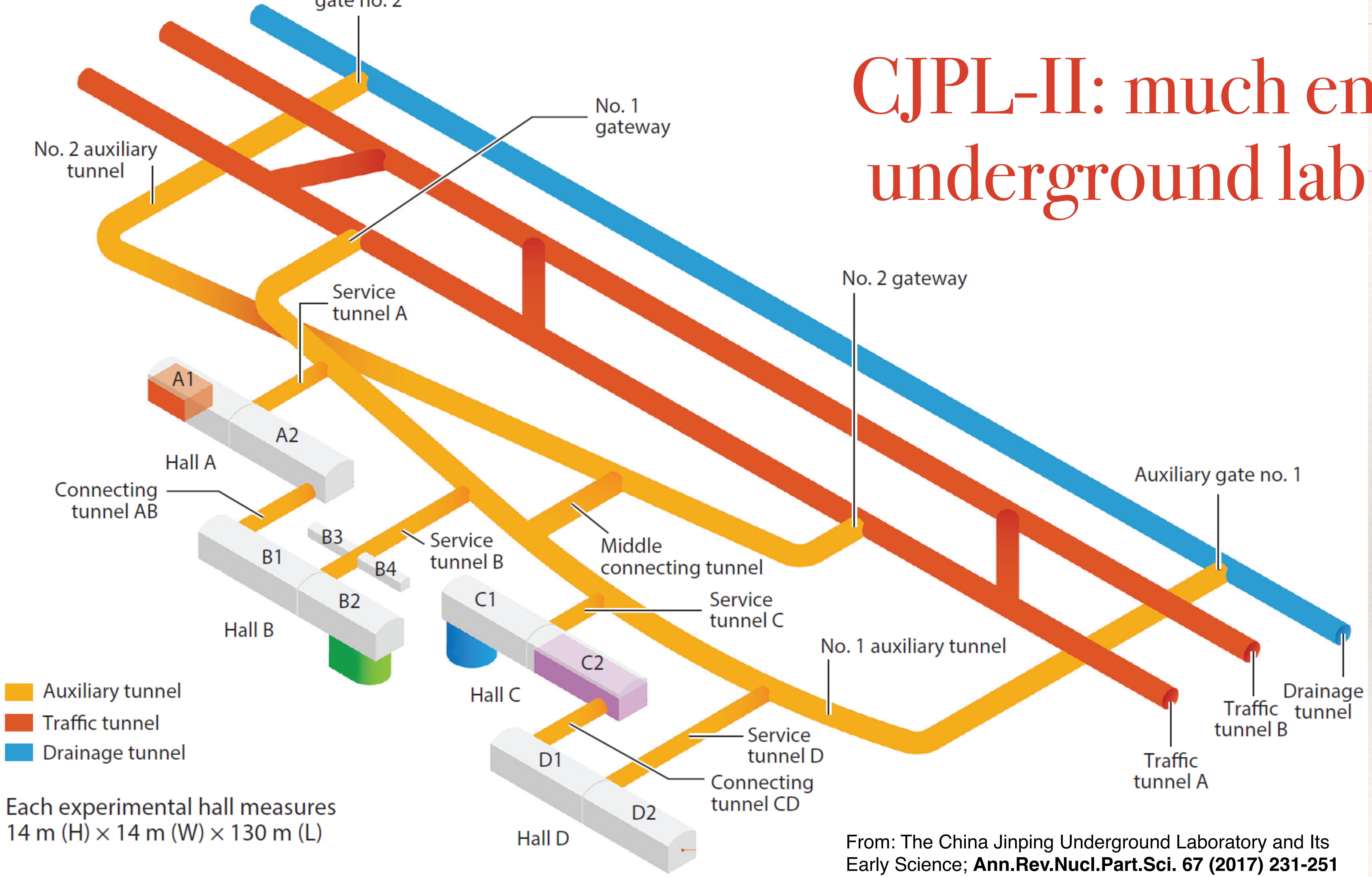




- Deepest (6800 m.w.e): < 0.2 muons/m^2/day
- Horizontal access with ~9 km long tunnel: large truck can drive in.
- Dark matter searches, neutrino physics, and astroparticle physics, etc.



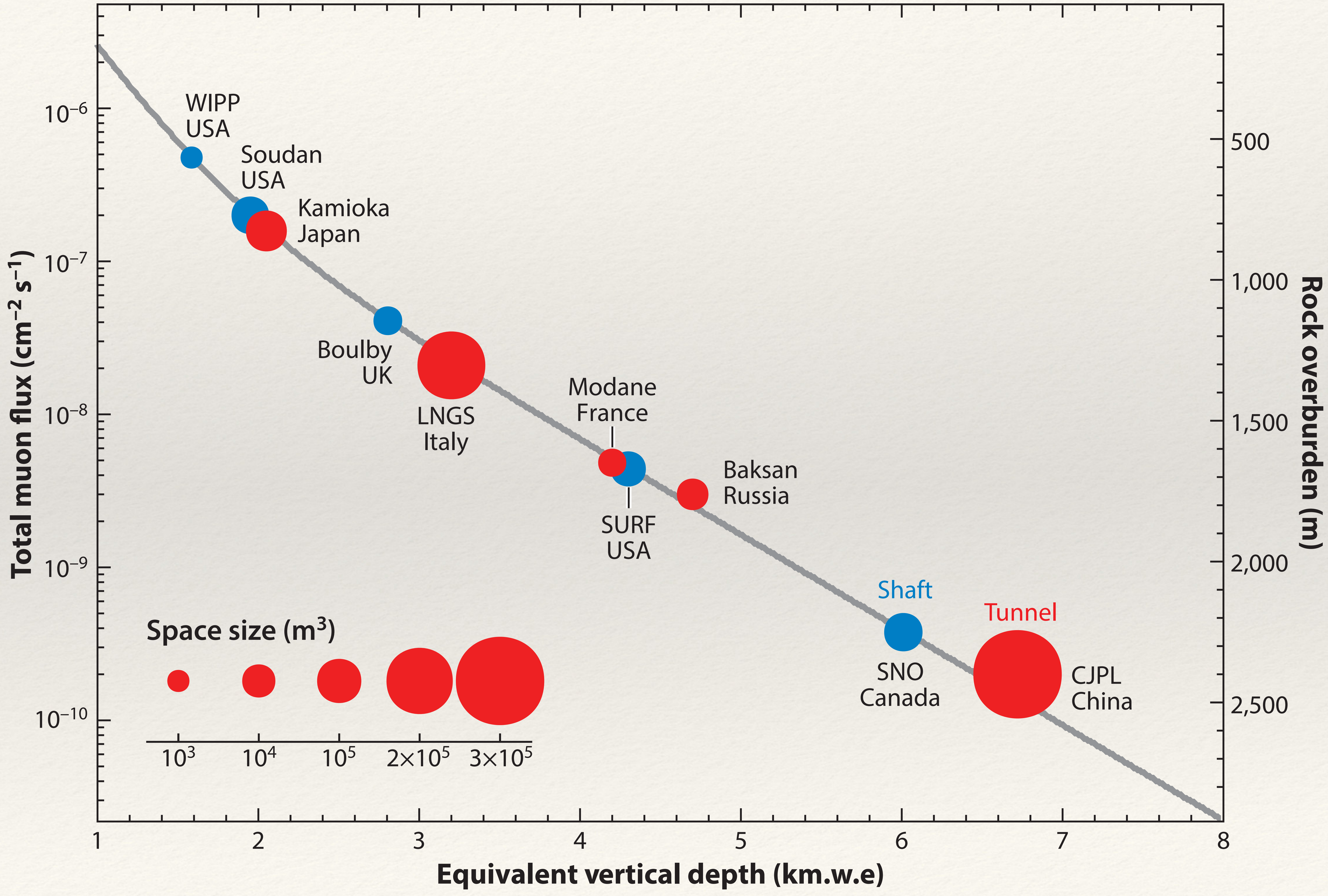
CJPL-II: much enlarged underground lab space



From: The China Jinping Underground Laboratory and Its Early Science; **Ann.Rev.Nucl.Part.Sci. 67 (2017) 231-251**

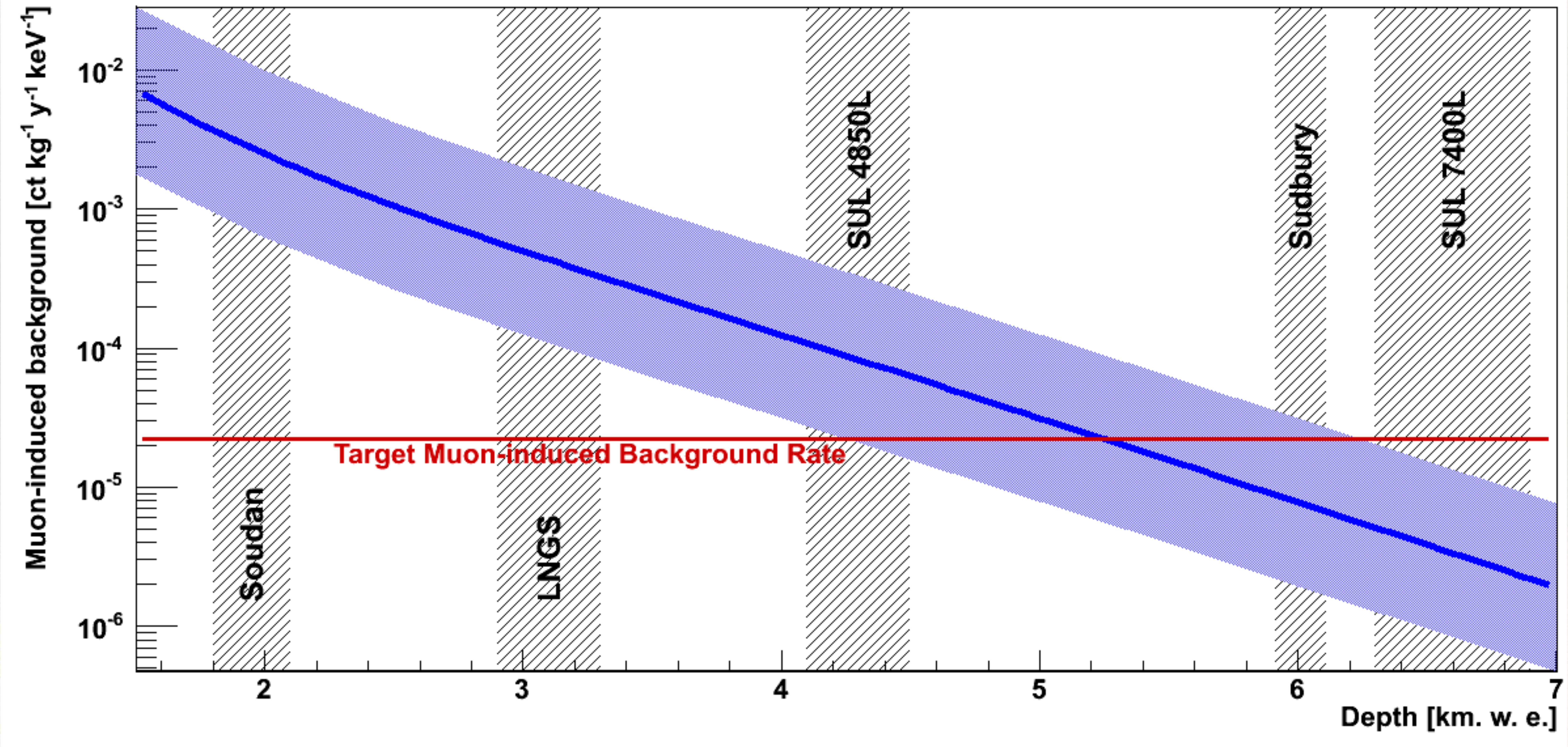
锦屏：埋深与便利性的结合

- 2400m岩石埋深：muon 通量仅为 LNGS 的1/100
- 水平隧道开车进出：与 SNOLab 相比感觉“更安全”，仪器设备尺寸受限小



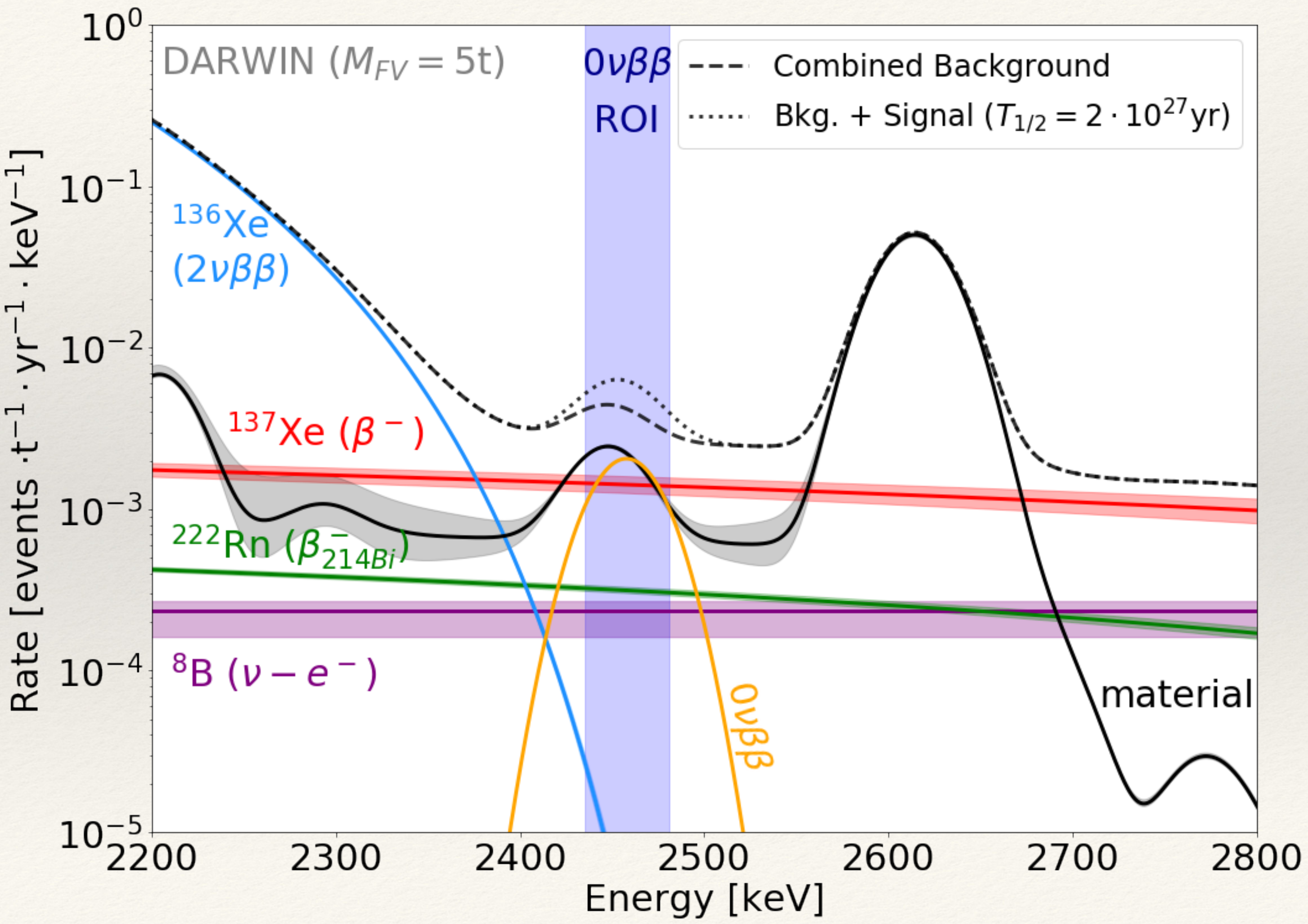
Muon-induced 环境本底

- 抑制Muon-induced 本底：更深的实验室或者更强力的主动屏蔽体（大型探测器）

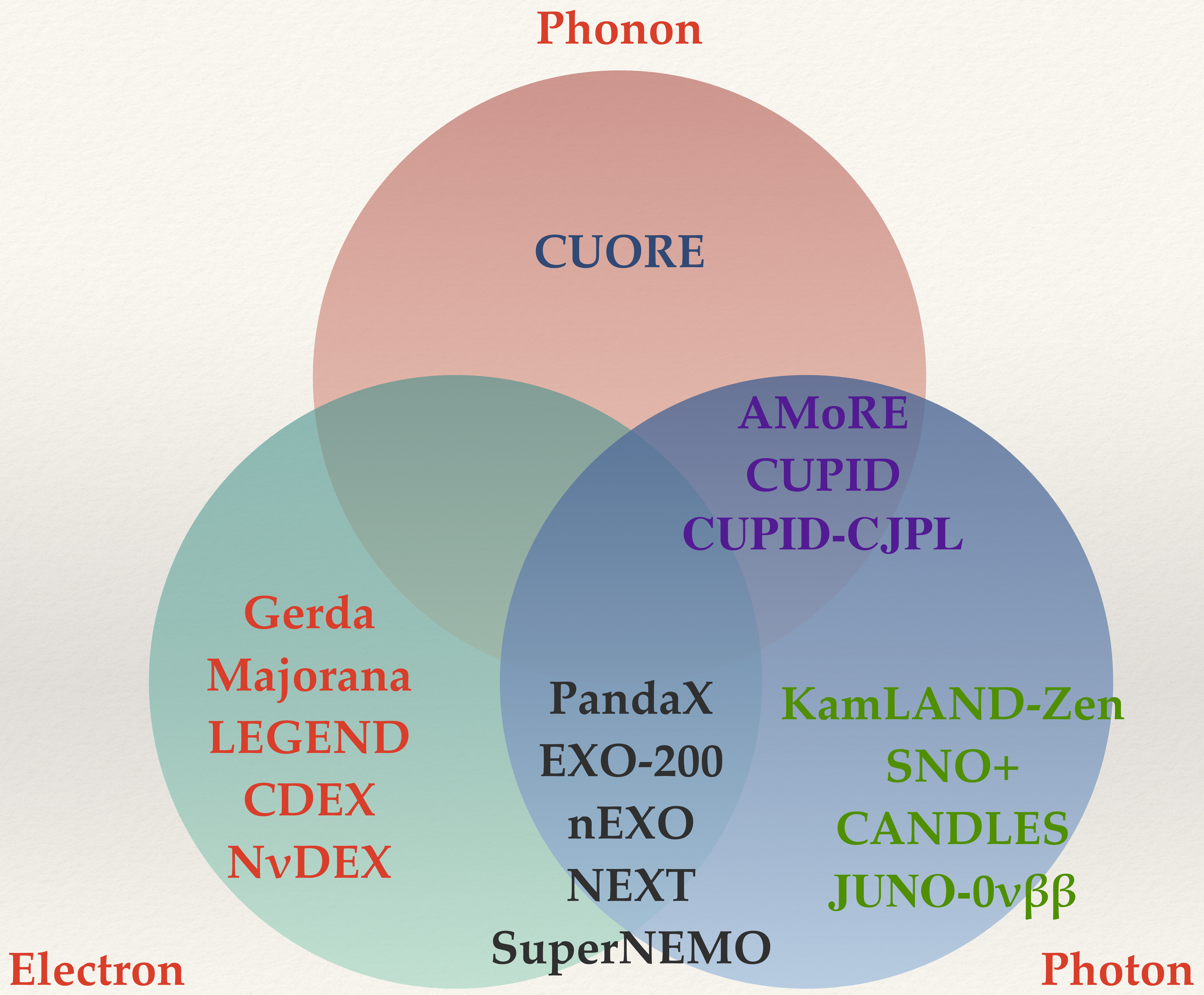


Muon-induced 探测器本底

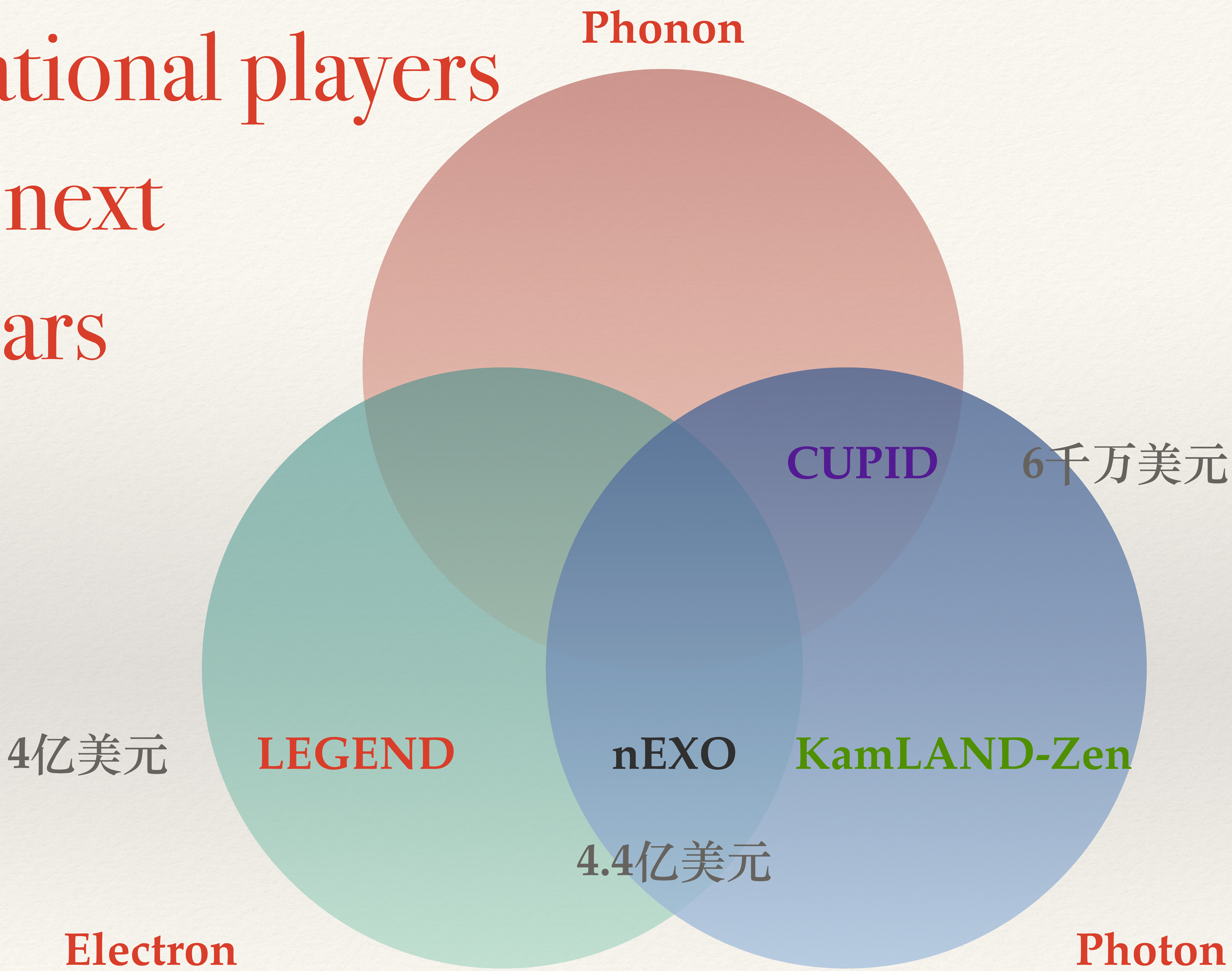
- Muon激活探测器材料带来不可避免的本底
- DARWIN@LNGS：^{137}Xe beta能谱为^{136}Xe 0νββ ROI主要本底
- 相应本底在锦屏低100倍，优势明显




国家重大科技基础设施
极深地下极低辐射本底前沿物理实验设施
实验项目组正式入驻仪式
中国 四川 锦屏 2023.12
项目组正式入驻！
热烈庆祝锦屏大设施


Phonon
CUORE
AMoRE
CUPID
CUPID-CJPL
Gerda
Majorana
LEGEND
CDEX
NνDEX
PandaX
EXO-200
nEXO
NEXT
SuperNEMO
KamLAND-Zen
SNO+
CANDLES
JUNO-0νββ
Electron
Photon

International players for the next 20+ years

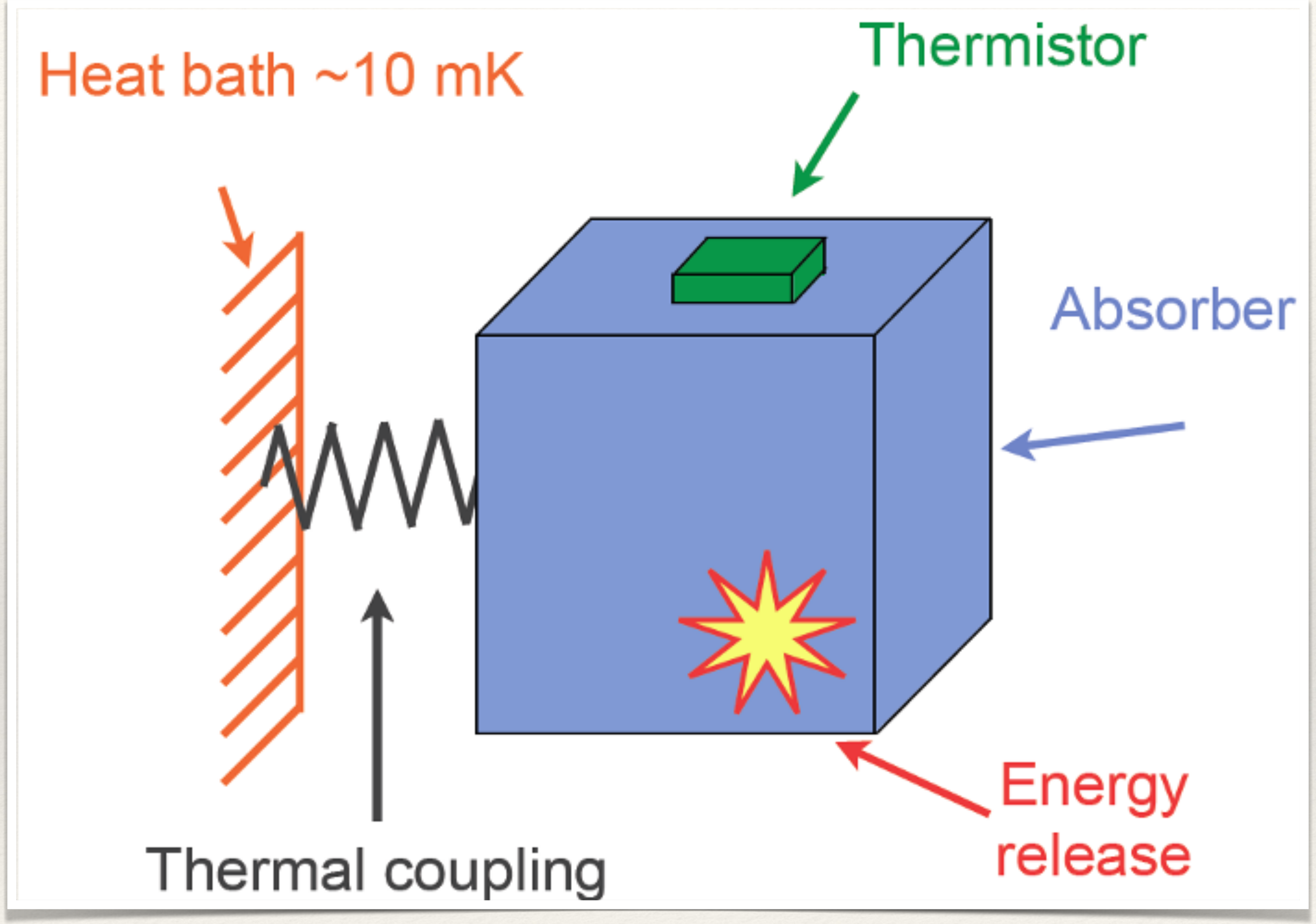


Bolometer
低温量能器

CUORE

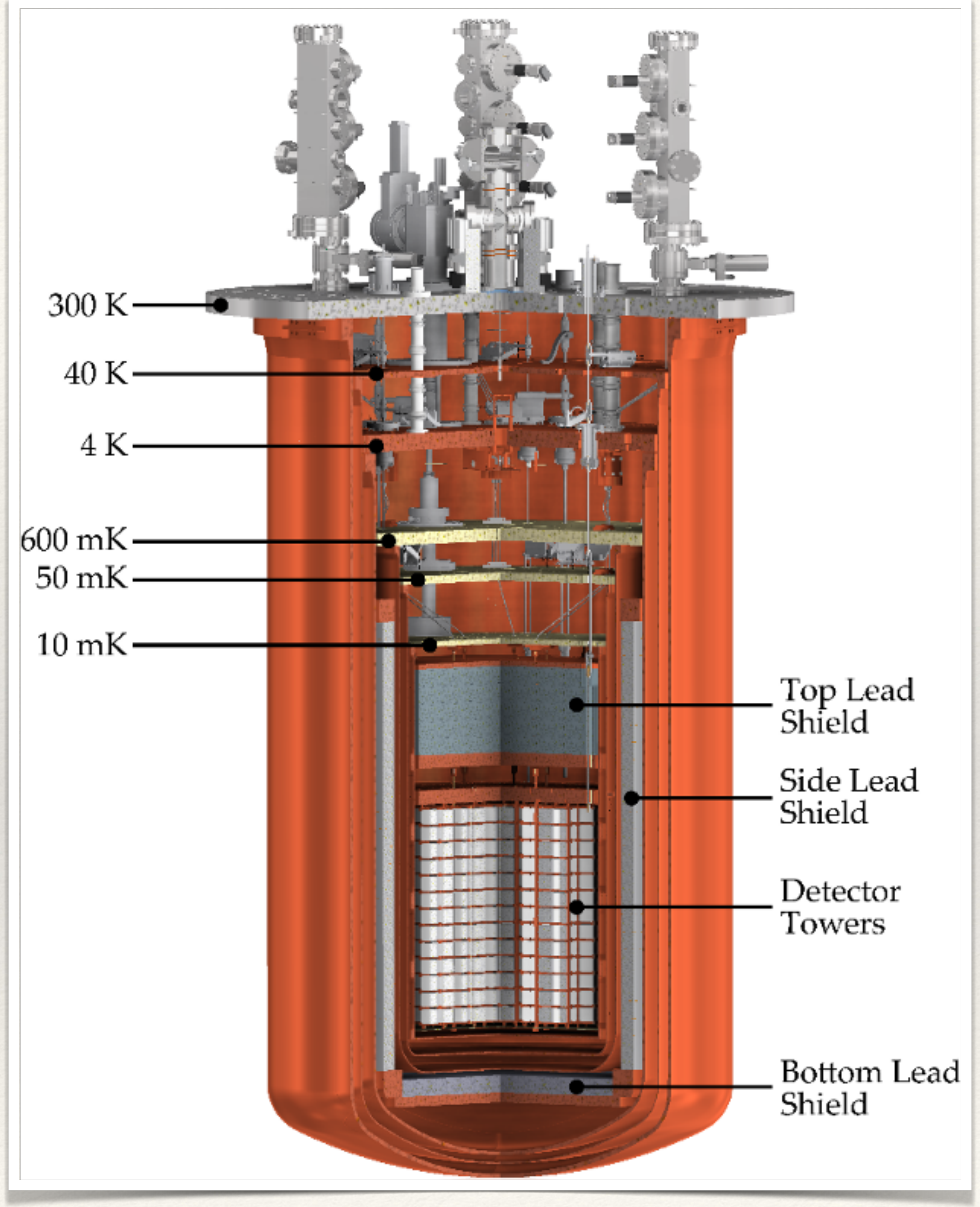
CUPID

CUPID-CJPL



CUORE bolometer array

- Search for *0νββ* of ^{130}Te and other rare events
- 988 TeO_2 crystals run as a bolometer array
  - 19 Towers
  - 13 floors
  - 4 modules per floor
- 10 mK in a custom dilution refrigerator



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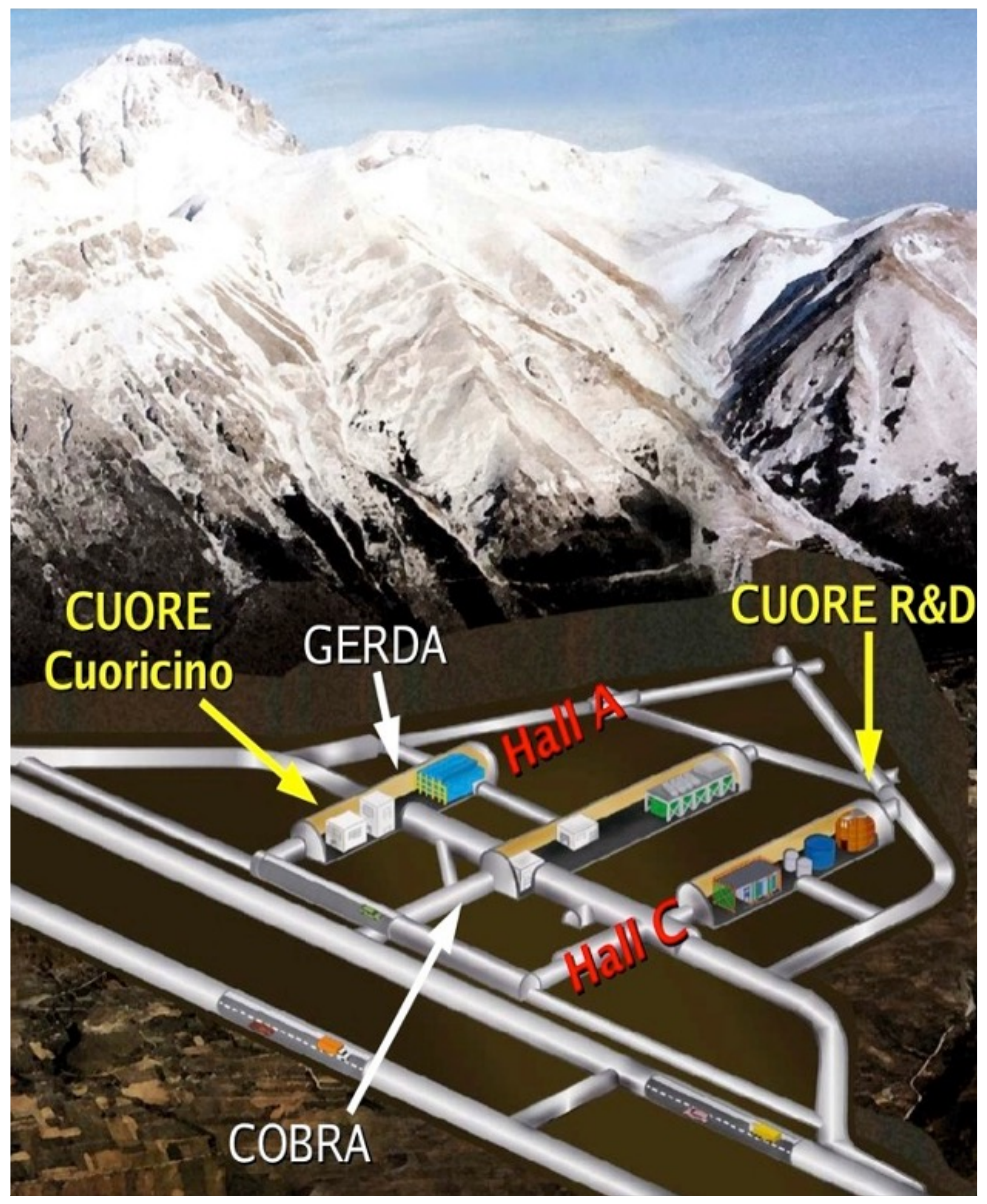
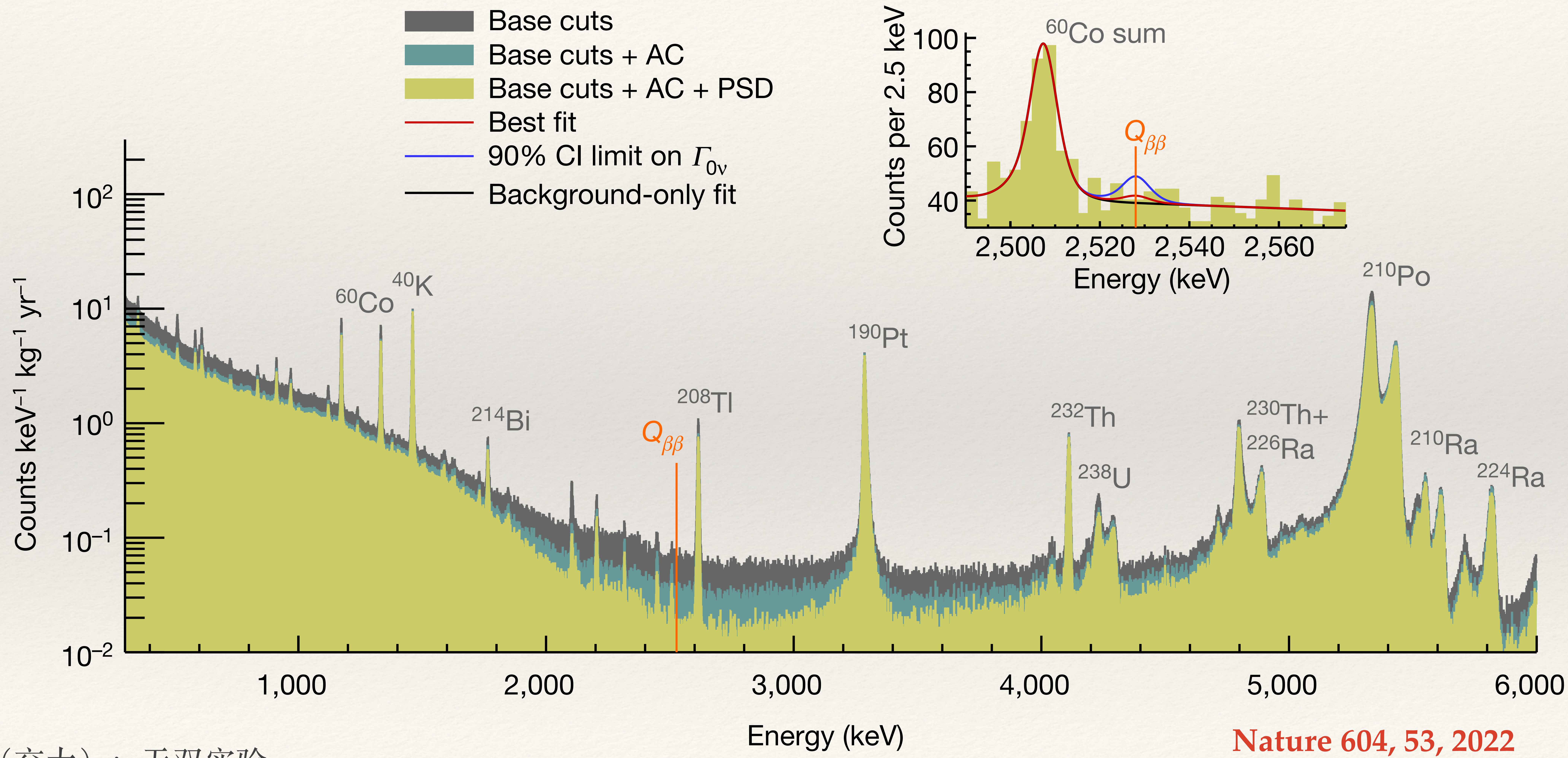
  - 4 modules per floor
- 10 mK in a custom dilution refrigerator
- Gran Sasso underground lab (LNGS), Italy



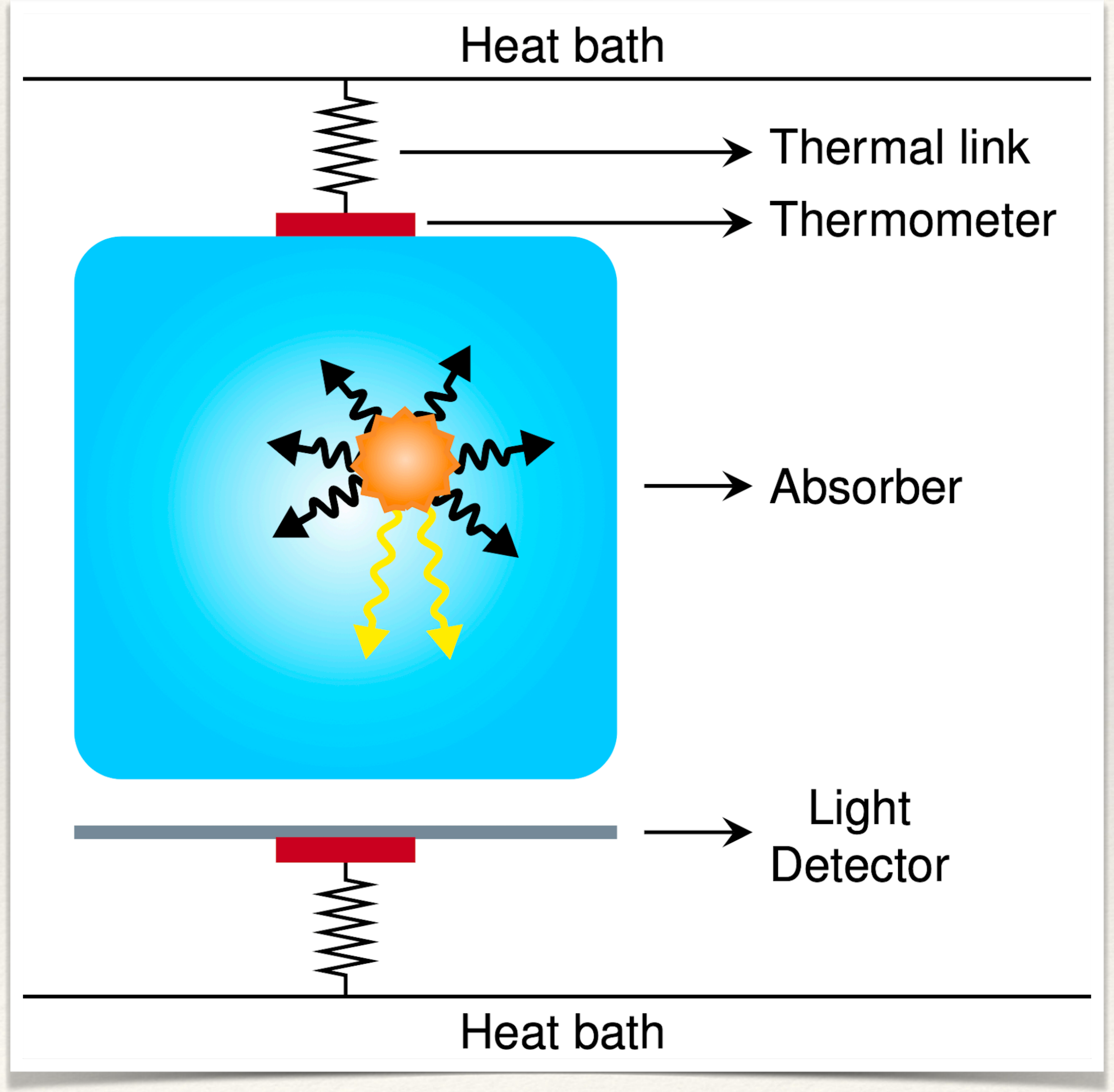
CUORE 1 ton-year data

1. Stable data taking since 2017
2. Excellent energy resolution



Nature 604, 53, 2022

CUPID: Li_2MoO_4 (LMO) scintillating bolometer



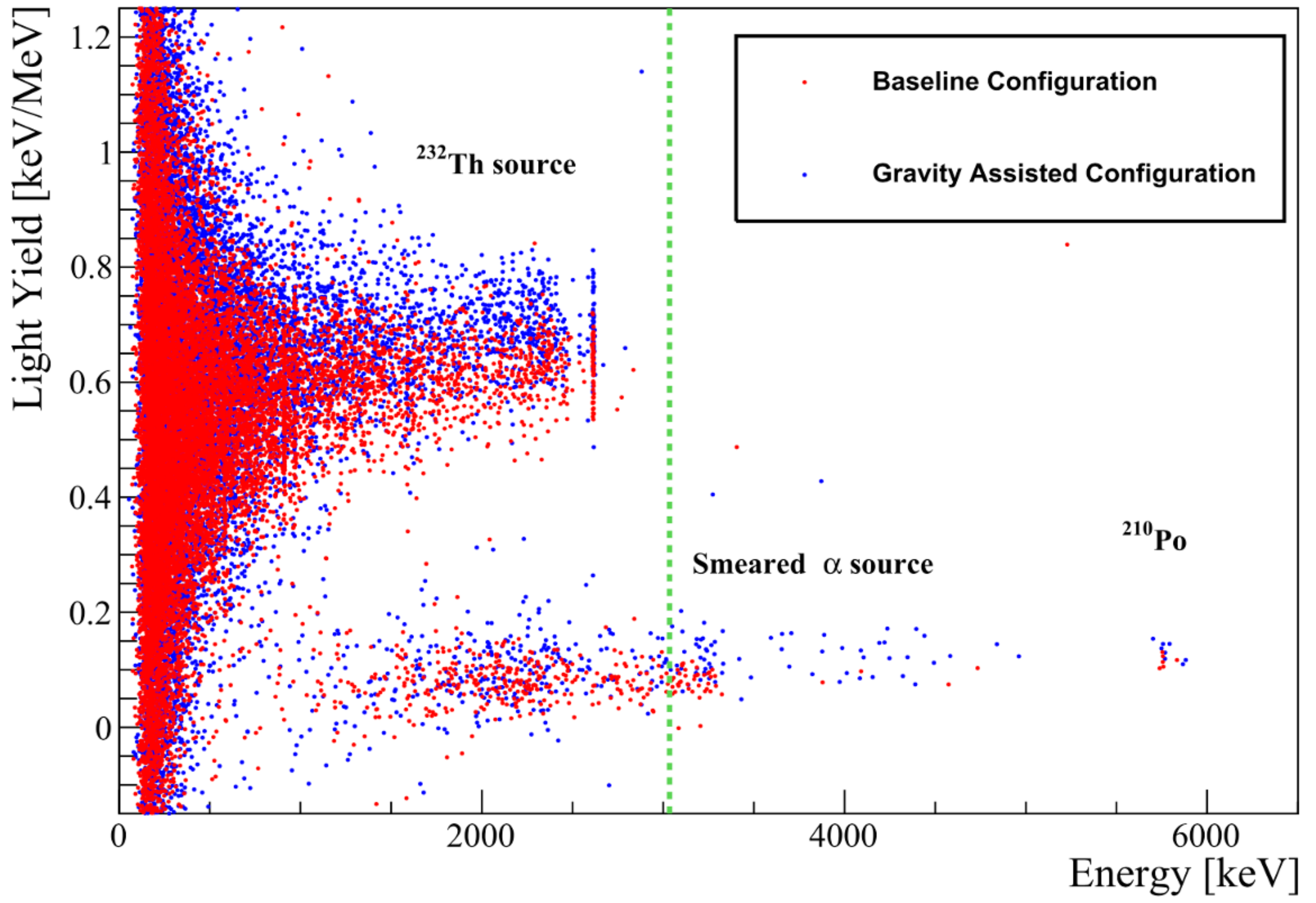
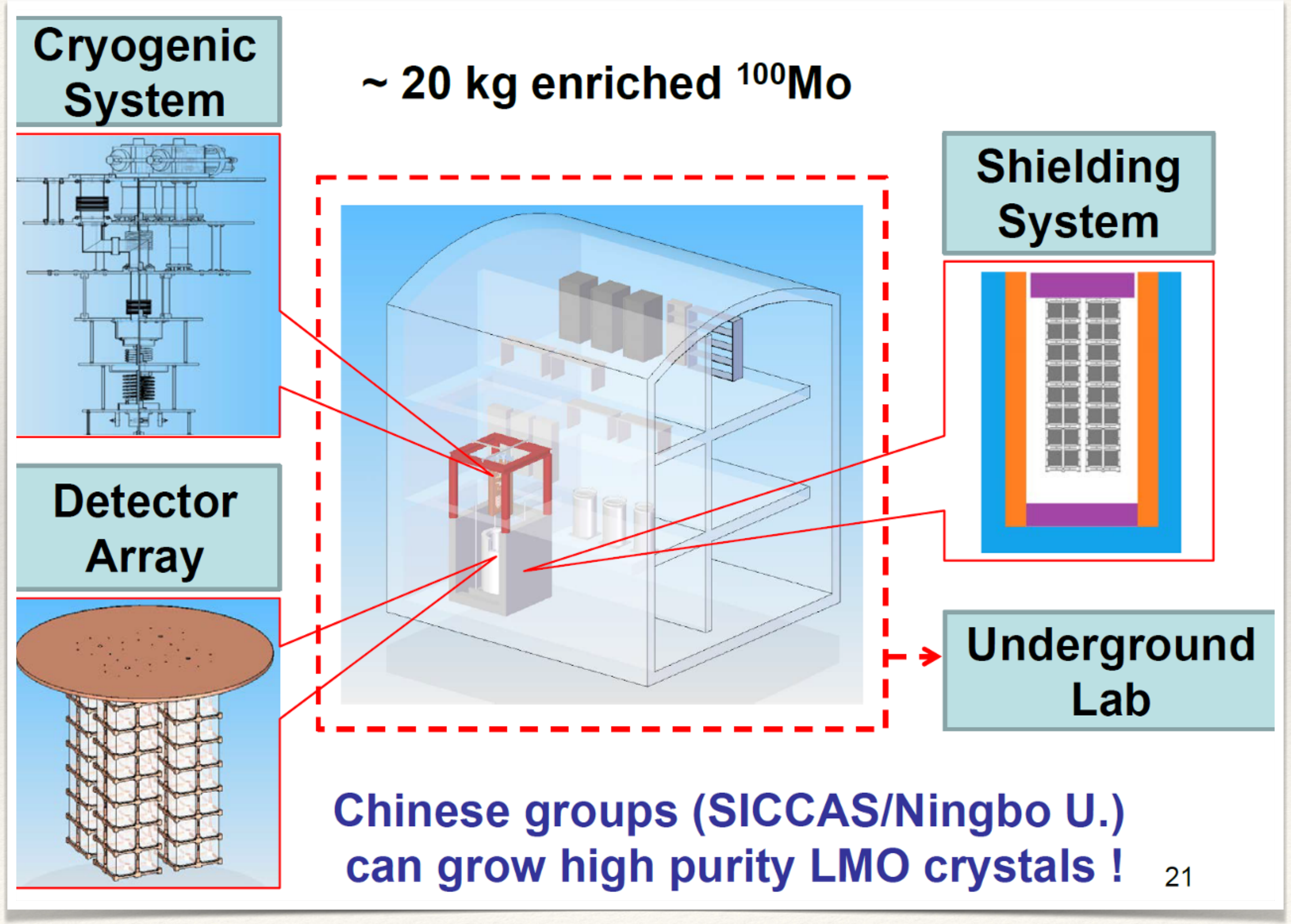


Fig. 5 Light Yield as a function of the energy deposited in the LMO crystal. Red: baseline configuration; blue: gravity-assisted configuration. Green vertical line: Q-value of ^{100}Mo

Eur. Phys. J. C (2022) 82:810

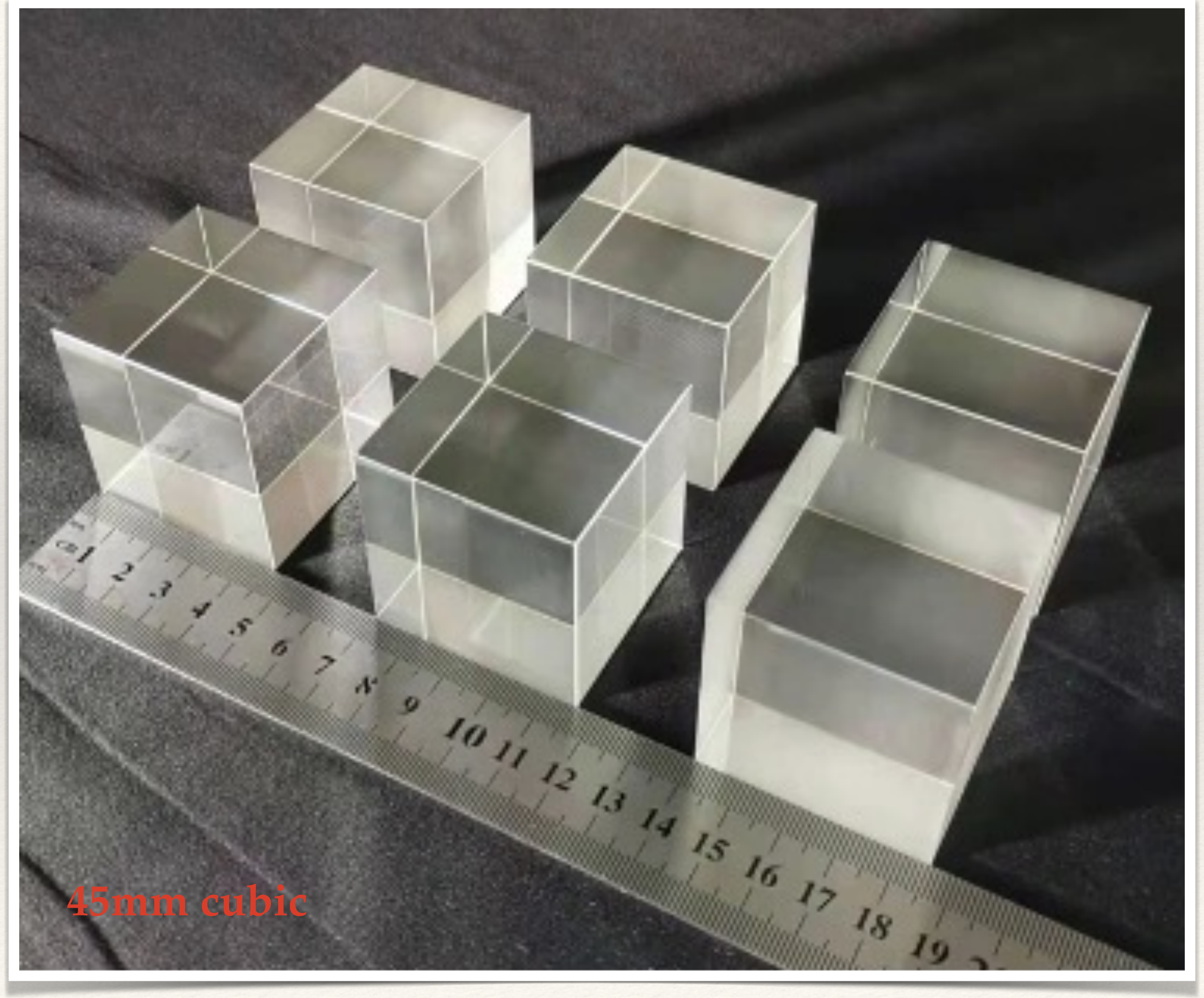
CUPID-CJPL

- Li_2MoO_4 scintillating bolometer arrays
- Particle ID to reject alpha background
- High Q-value (3.0 MeV) for low gamma background
- Build the first demonstrator array in the next 3-5 years



Current status

- Large high-quality LMO crystals can be produced
- Starting to produce crystals with enriched materials
  - Bkg control: U/Th<10 μBq/kg
- Fabricating NTD-Ge thermistor and readout electronics
- R&D detector assembly and tests ongoing



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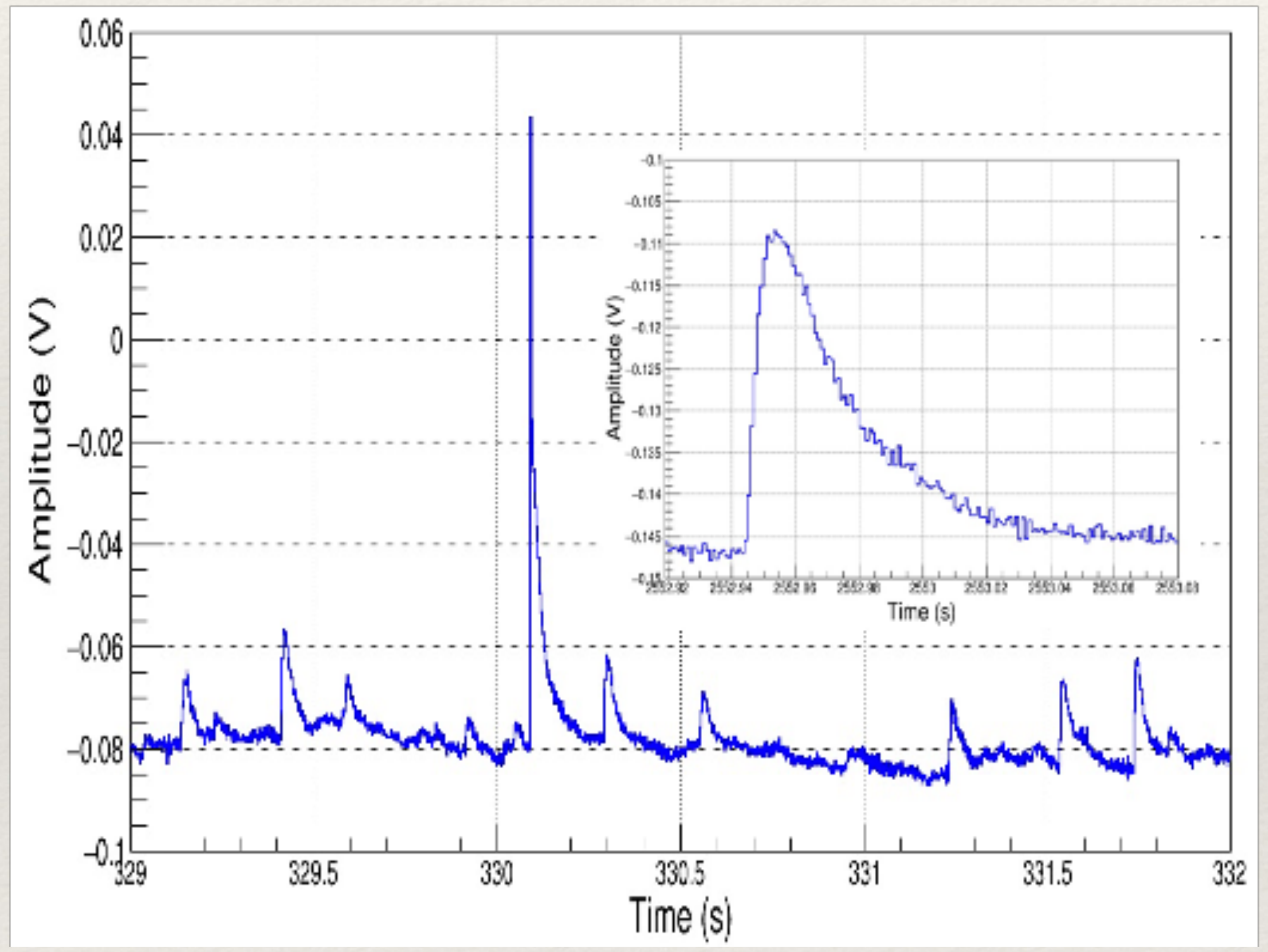
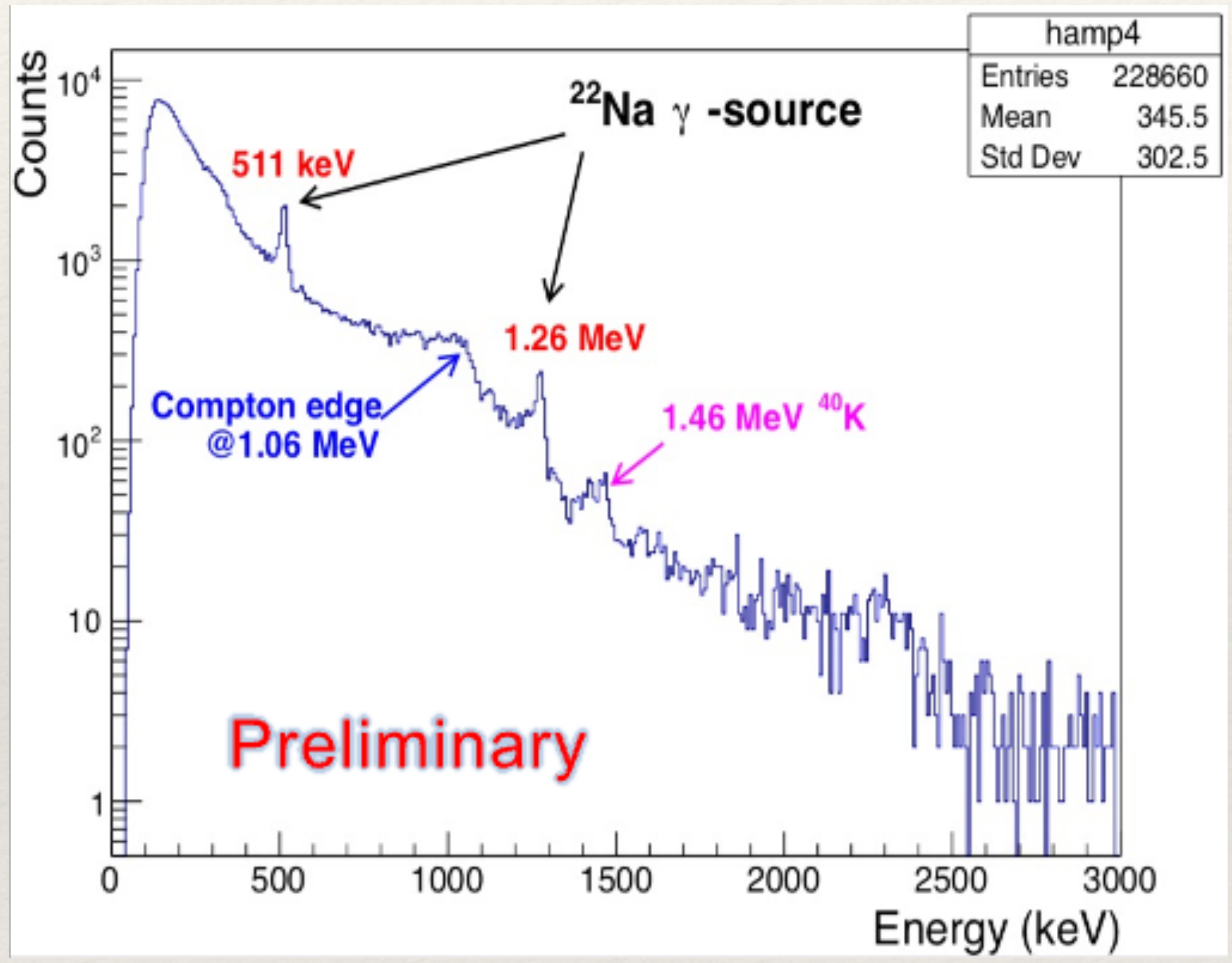
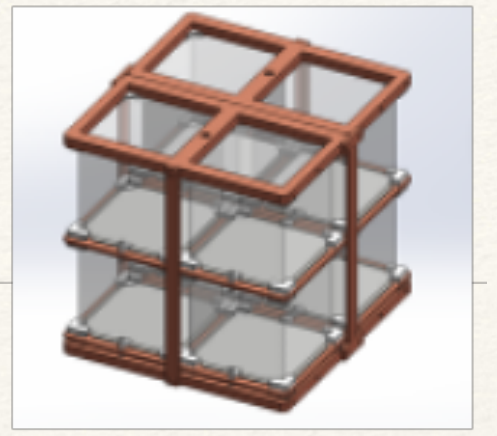
- Fabricating NTD-Ge thermistor and readout electronics
- R&D detector assembly and tests ongoing

First Spectrum

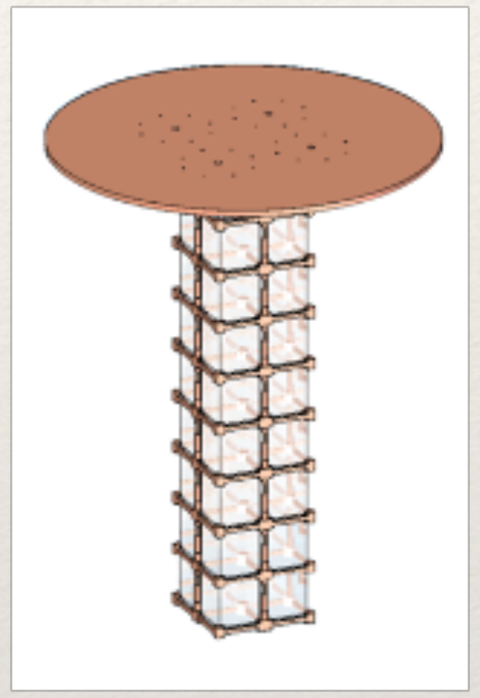




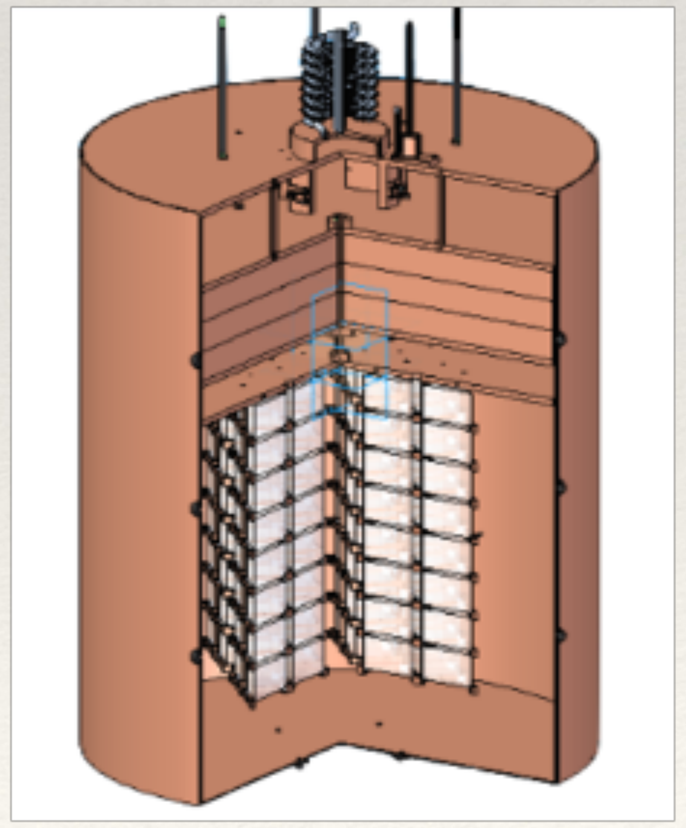
Crystal testing (2023-2025)
6-12 natural crystals



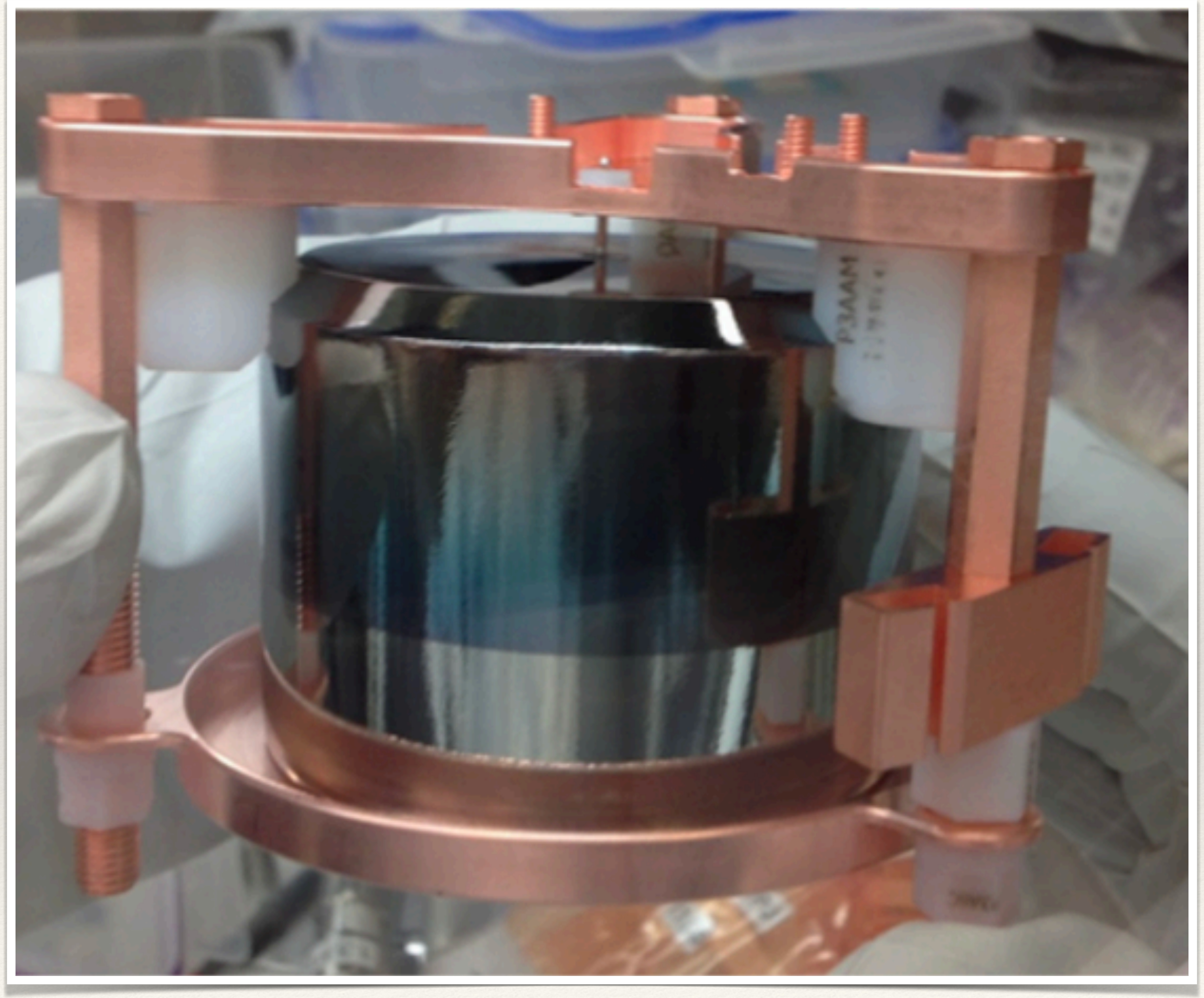
CUPID-CJPL Demo (2025-2028)
10 kg enriched crystals



CUPID-CJPL-200/1T (2028+)
> 200 kg enriched crystals



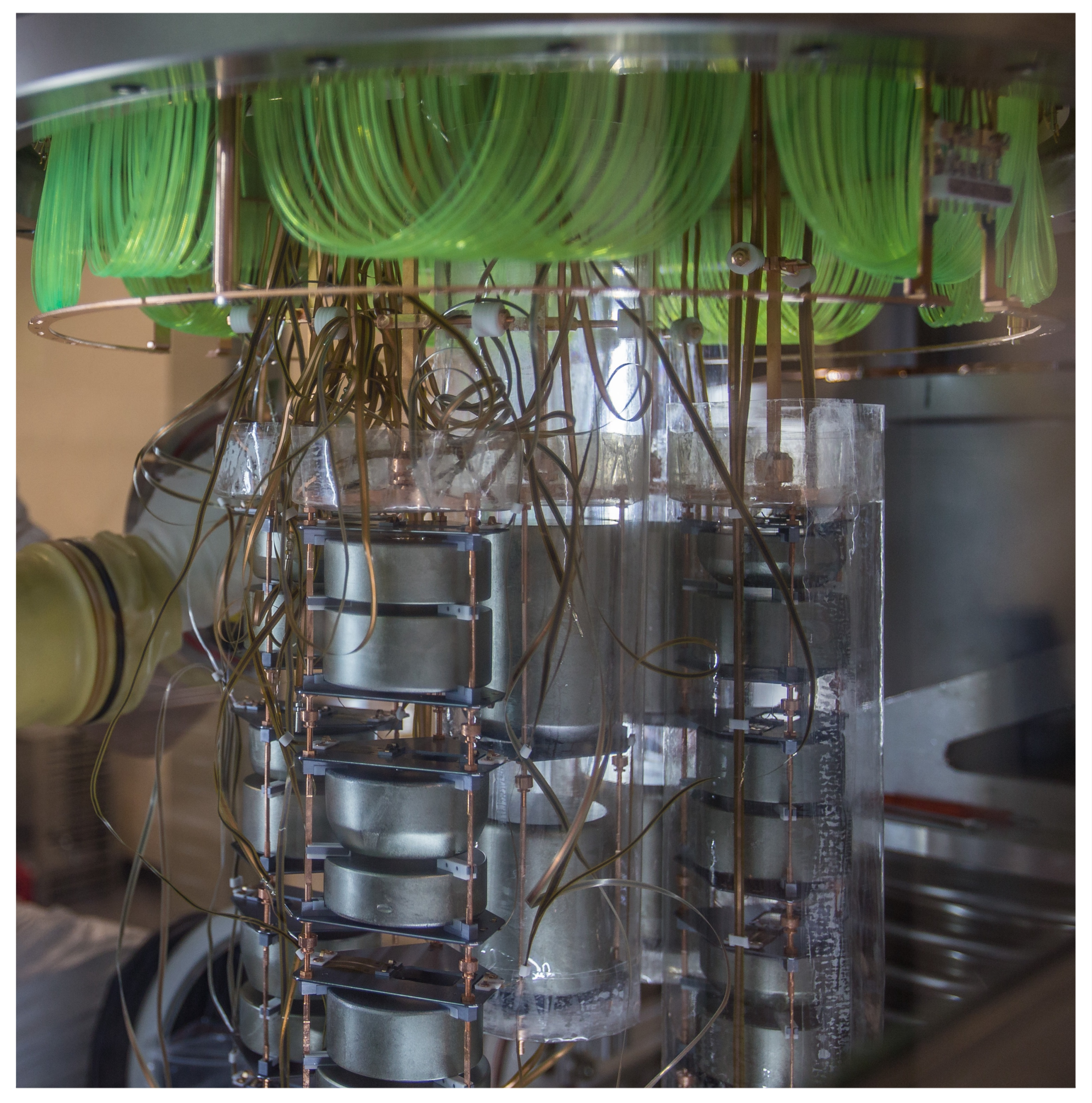
HPGe
高纯锗



LEGEND

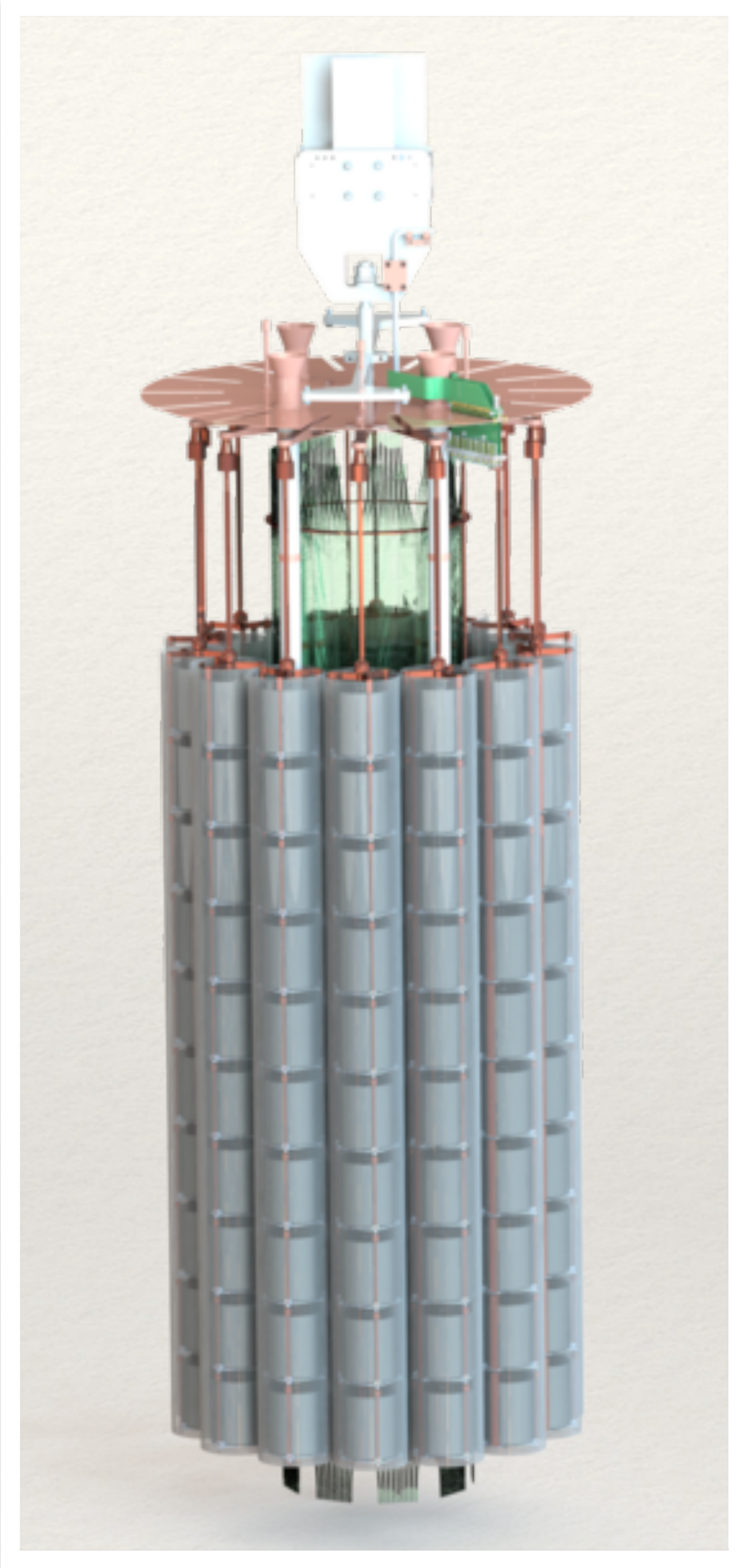
CDEX

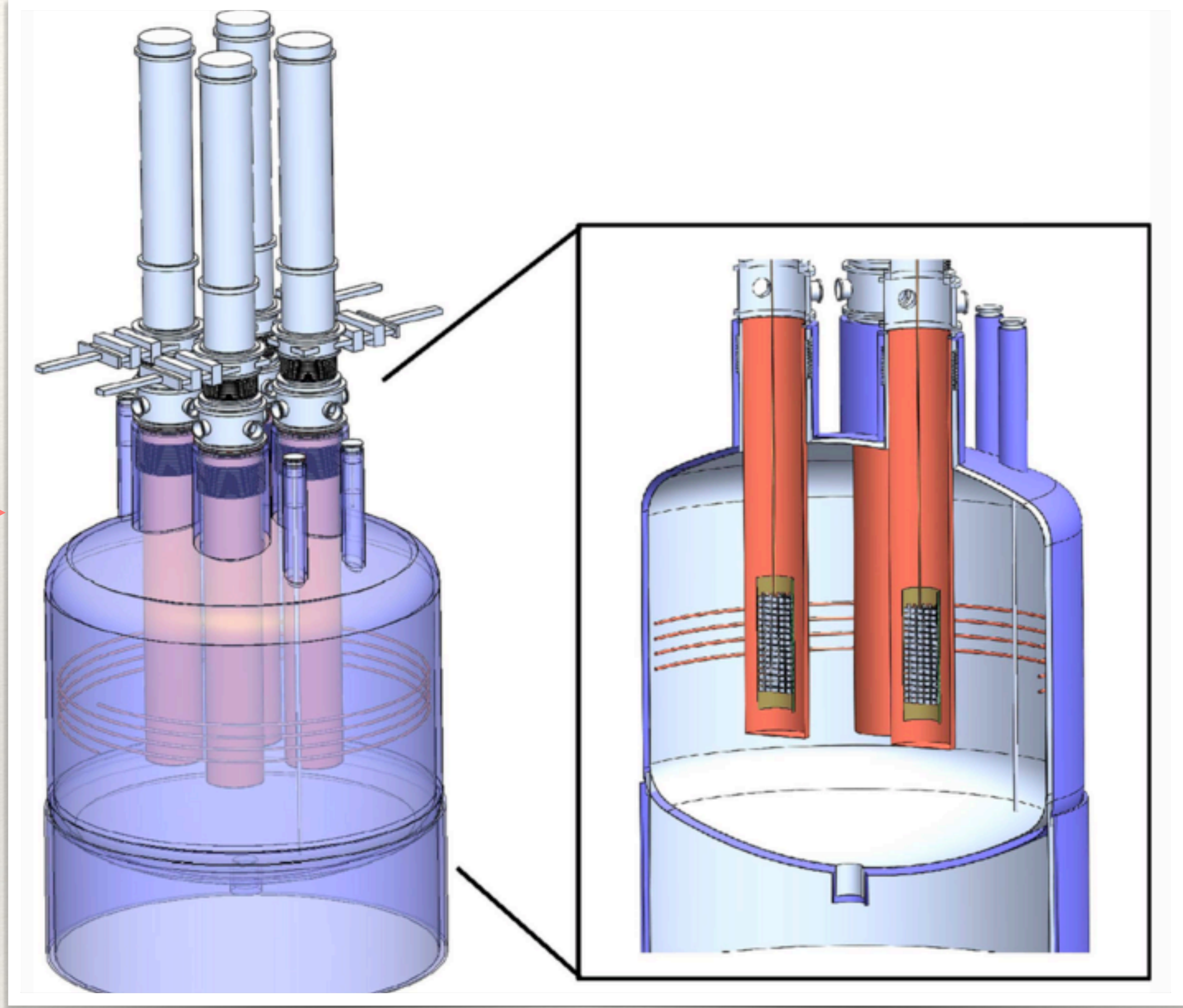
LEGEND: HPGe for ^{76}Ge $0\nu\beta\beta$

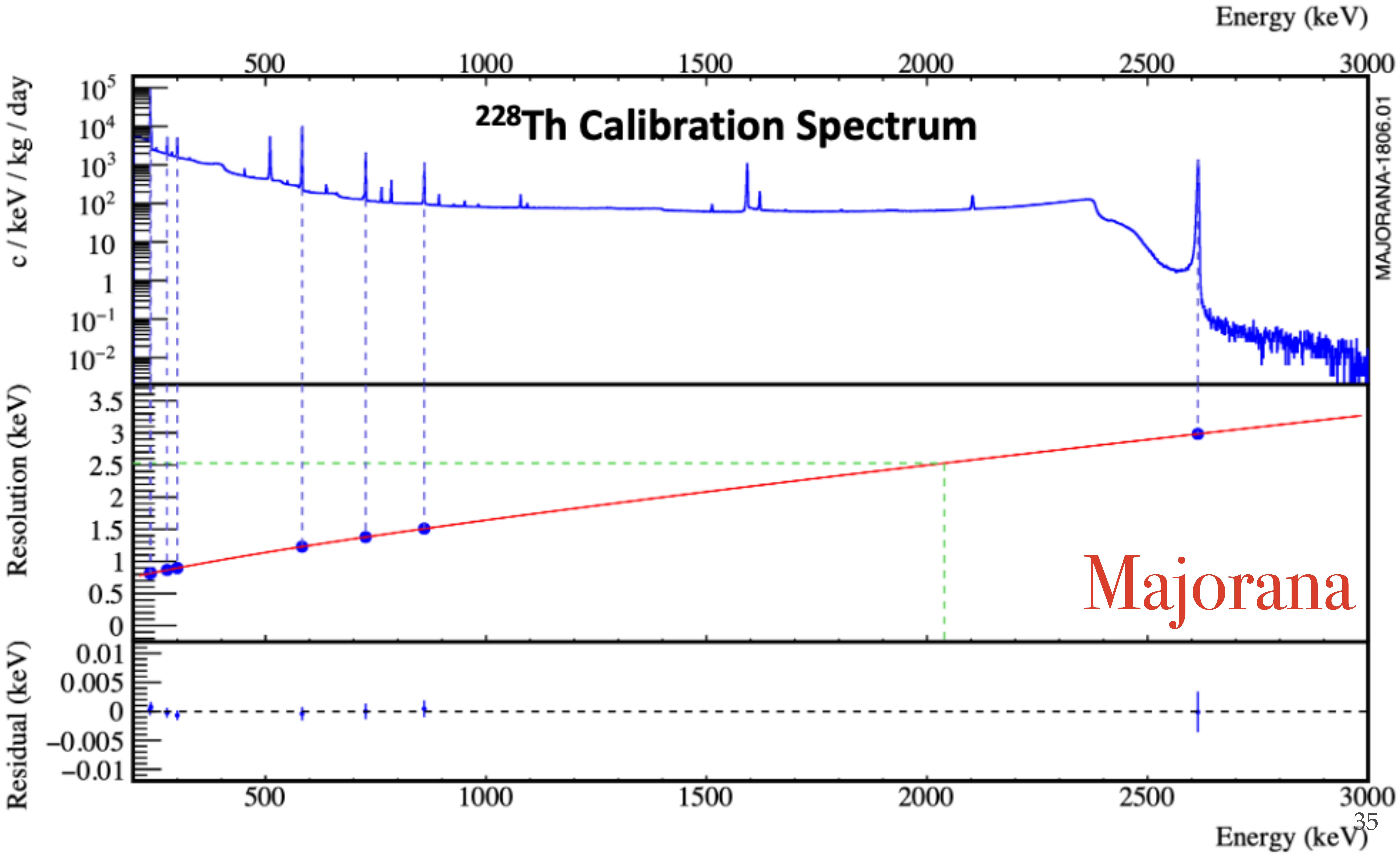


Gerda

Majorana



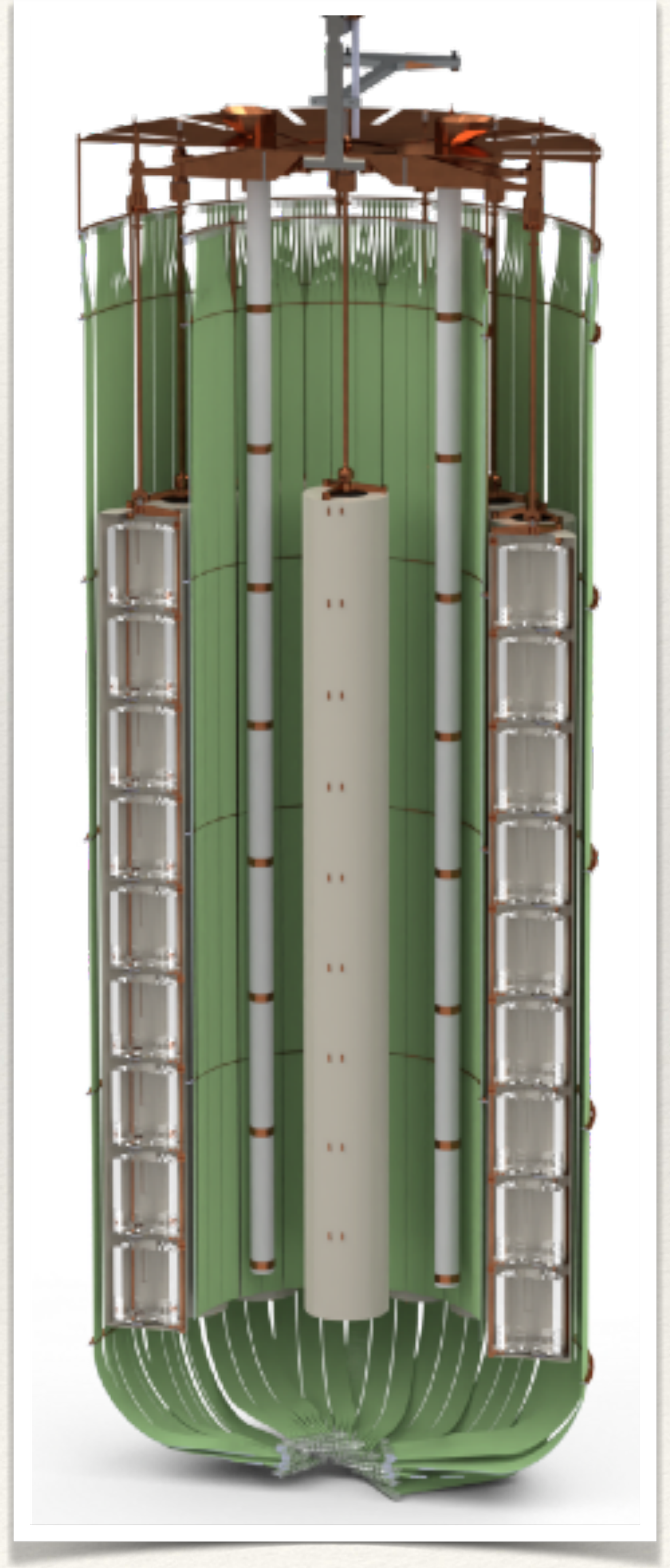


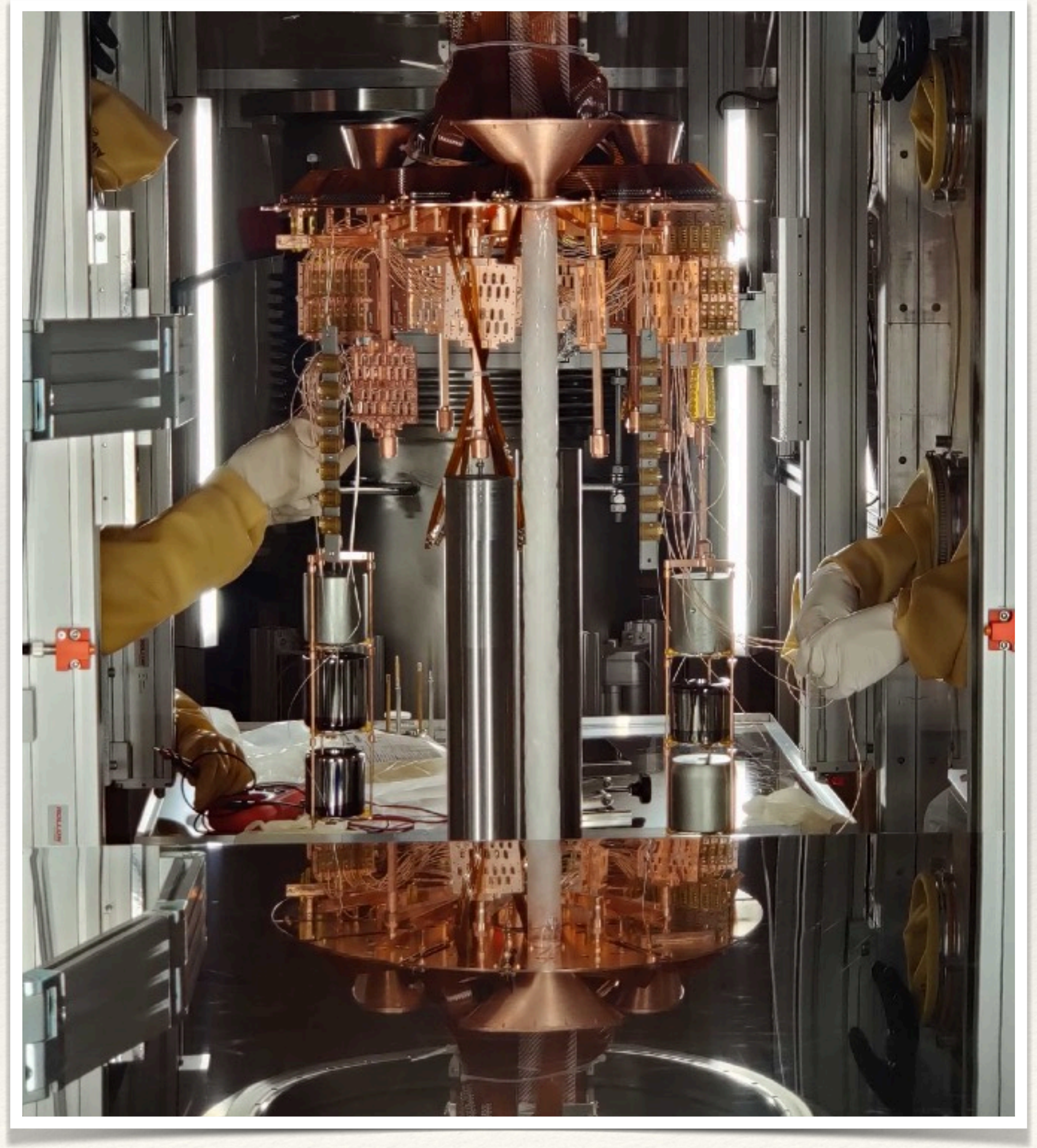


Energy (keV)
228Th Calibration Spectrum
c / keV / kg / day
Resolution (keV)
Residual (keV)
MAJORANA-1806.01
Majorana

LEGEND-200: Commissioning now at LNGS

- 200 kg of HPGe in the upgraded Gerda infrastructure at LNGS
  - LAr active veto
  - inside water tank
- Targeting 2.5 keV FWHM resolution
- Background goal: <0.6 cts/(FWHM t yr)
- Discovery sensitivity up to 10^{27} yrs

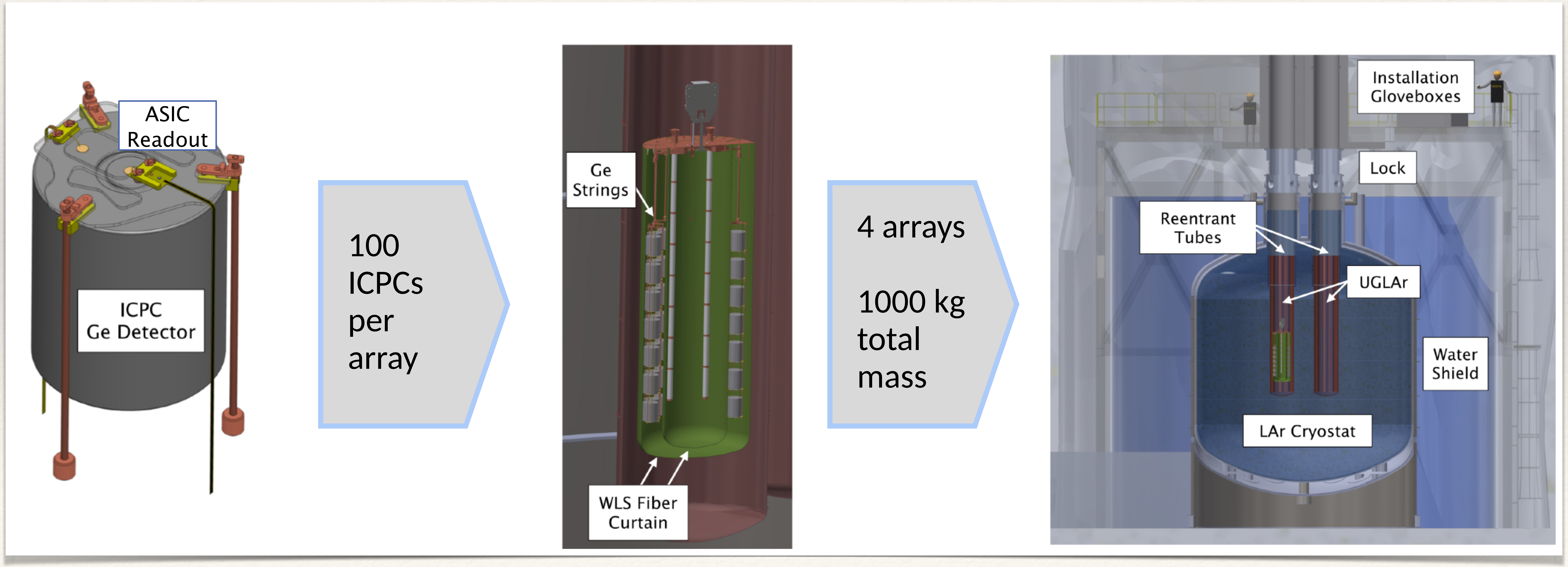




LEGEND-1000

LEGEND-1000 aims for unambiguous discovery of 0νββ with 10^{28} years of sensitivity

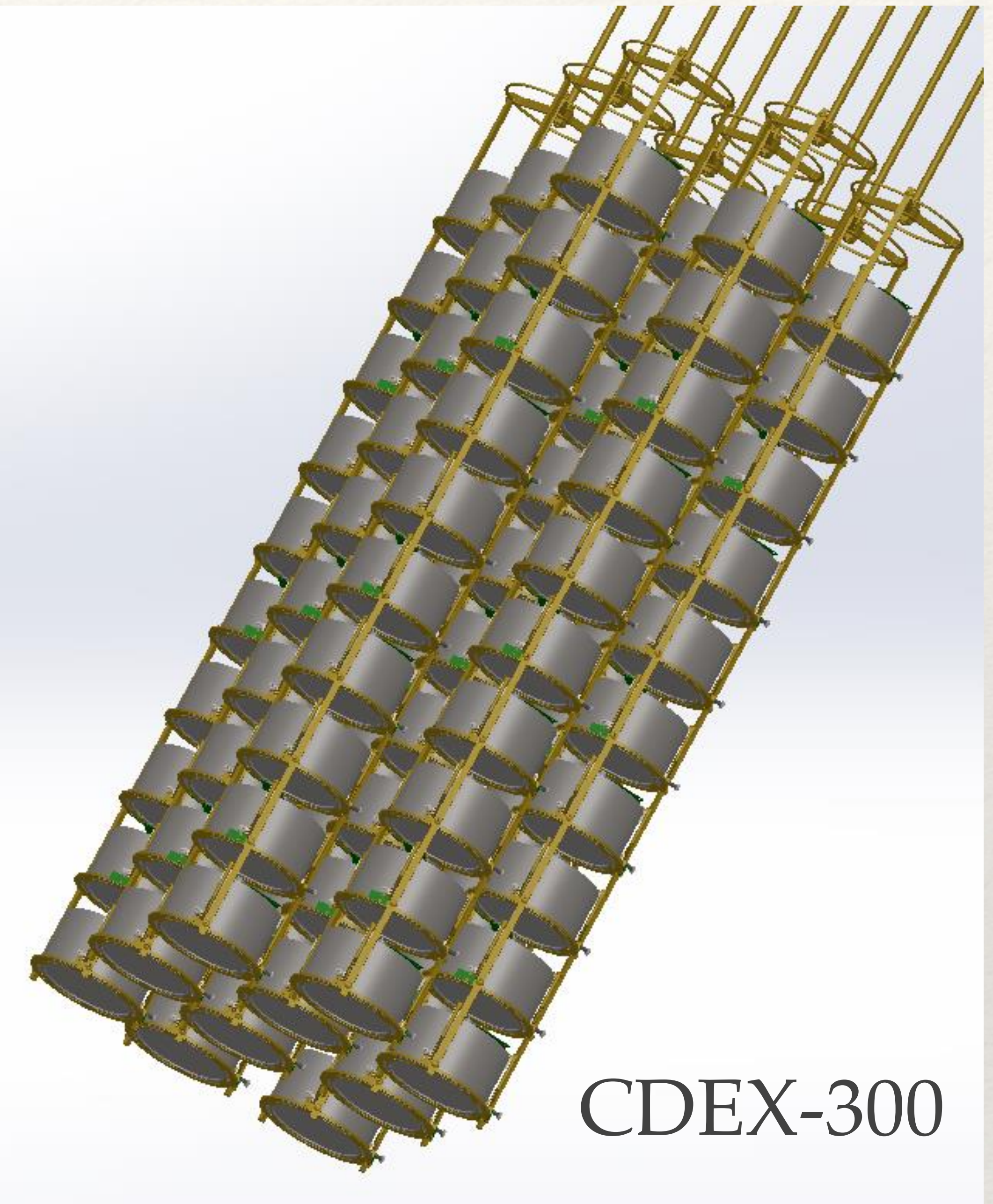
Targeting 10 ton-years exposure: 1000 kg mass, 10 year run plan

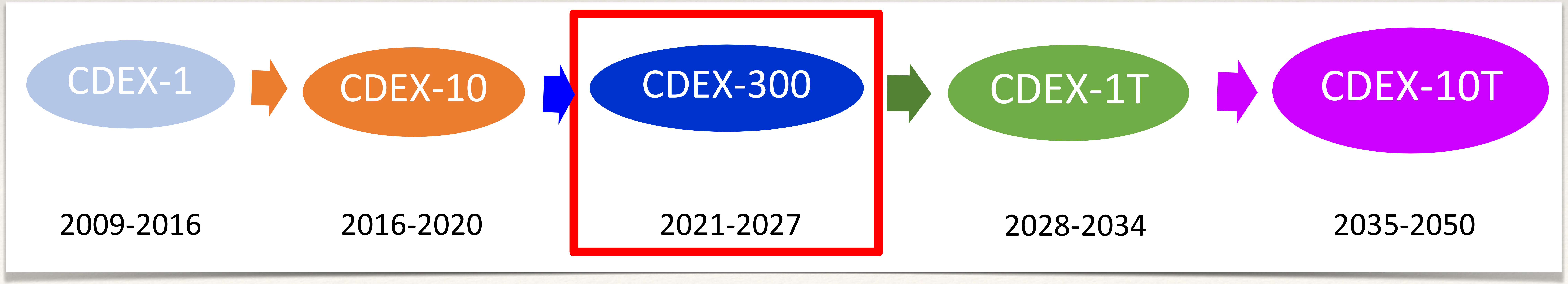


CDEX dark matter and DBD experiment

Established in 2009; over 100 collaborators from 11 institutions

- CDEX-300*ν*: 225 kg enriched HPGe, 200 units, 1.12 kg each
- BEGe + ASIC + Silicon Substrate
- 20T LAr active veto shielding
- 1725m^3 LN2 passive shielding





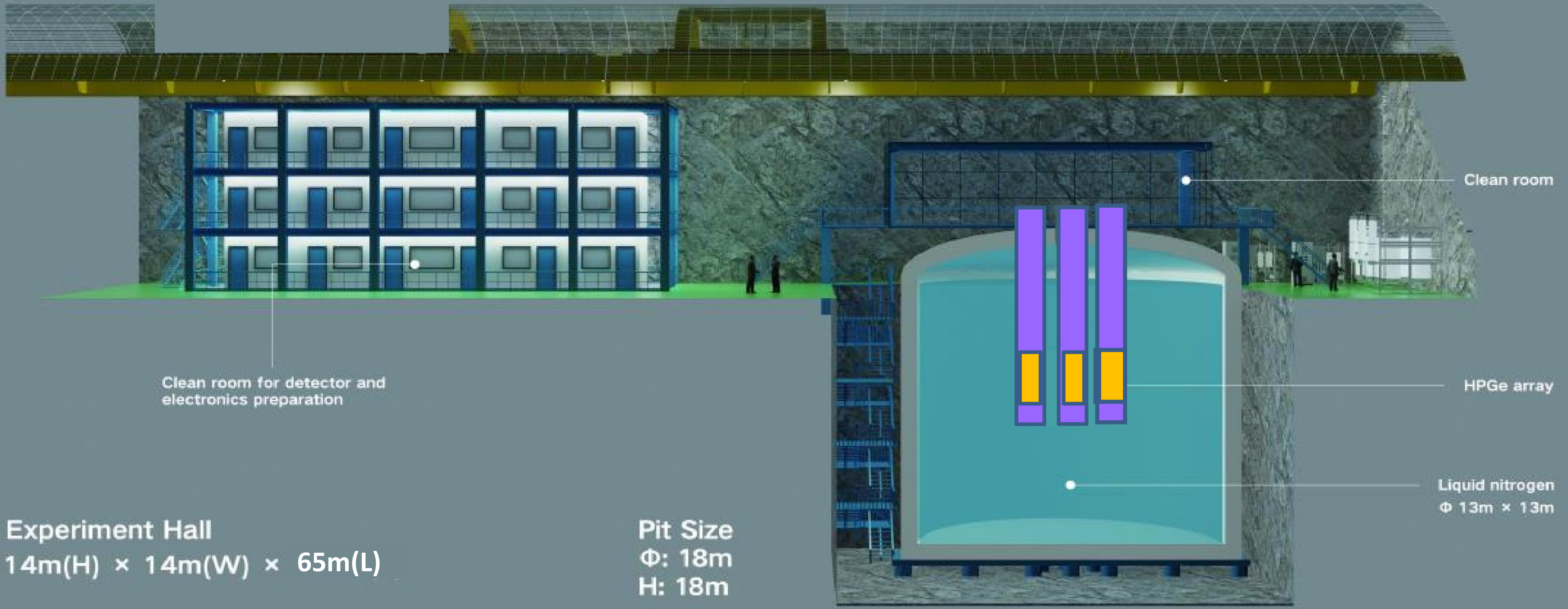
CDEX-300ν status

- 200kg ^{76}Ge (>86%) arrived, half from Russia and half from China: an important: an contribution to international Ge 0νββ experiment community
- Physics goal : $T_{1/2}>10^{27}$ yr; $m_{\beta\beta}$: 28.5-68.0 meV
- First batch of Enriched Ge detectors deployed in 2024

CDEX-1T and CDEX-10T Conceptual Layout

中国暗物质实验
China Dark matter EXperiment

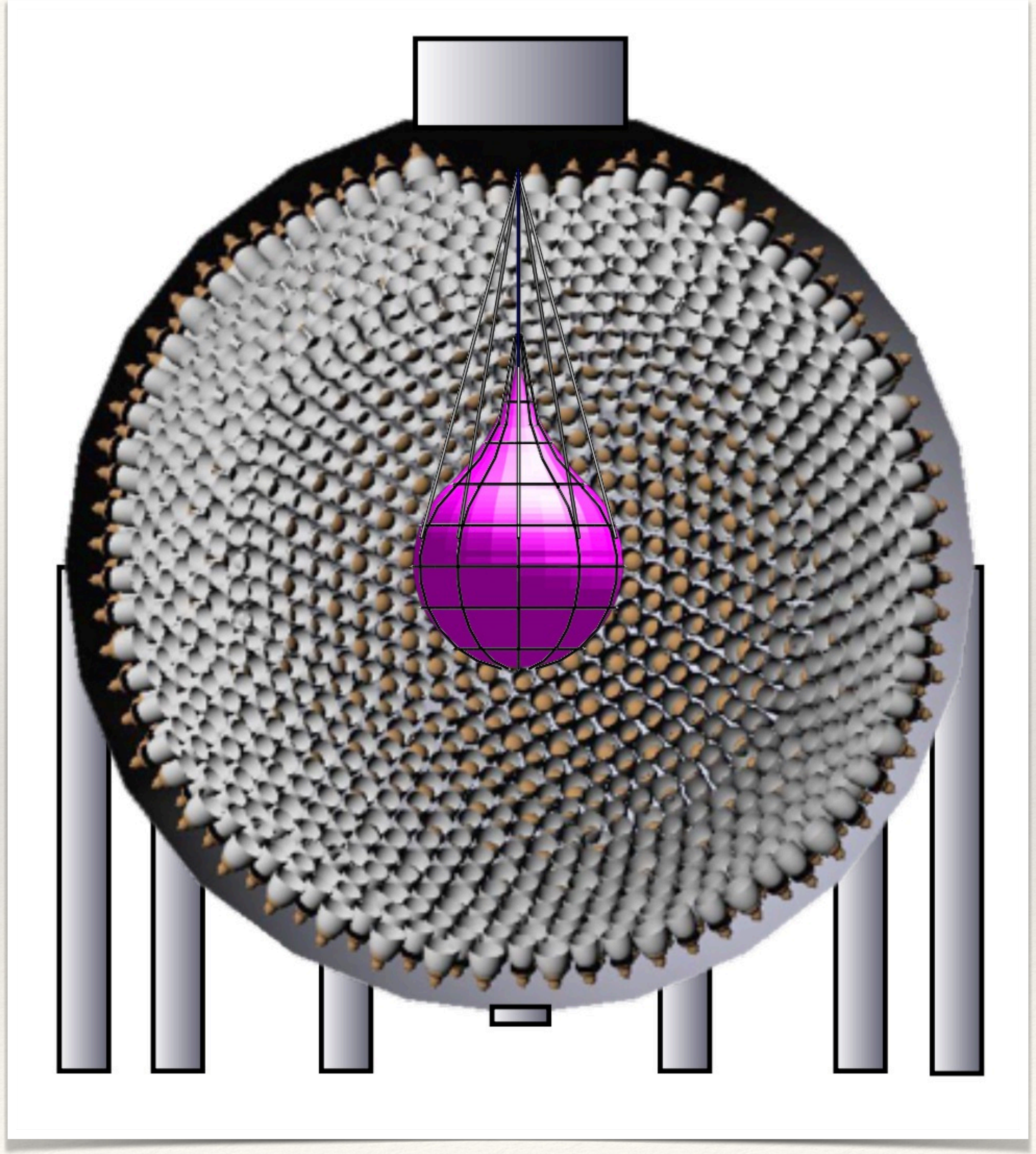
中国锦屏地下实验室
China Jinping Underground Laboratory
CJPL
清华大学 · 雅砻江流域水电开发有限公司



Doped LS
掺杂液体闪烁体

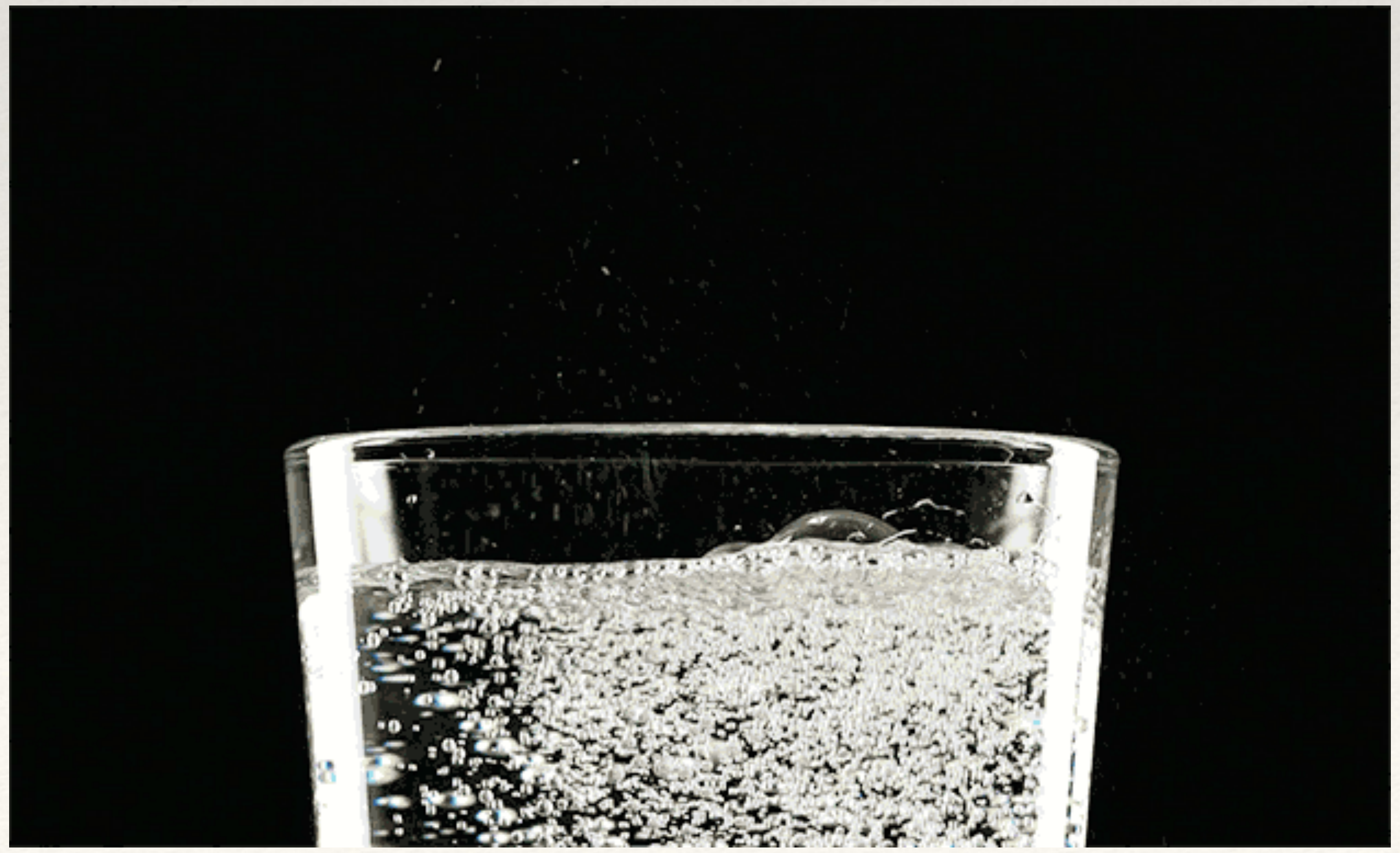
KamLAND-Zen

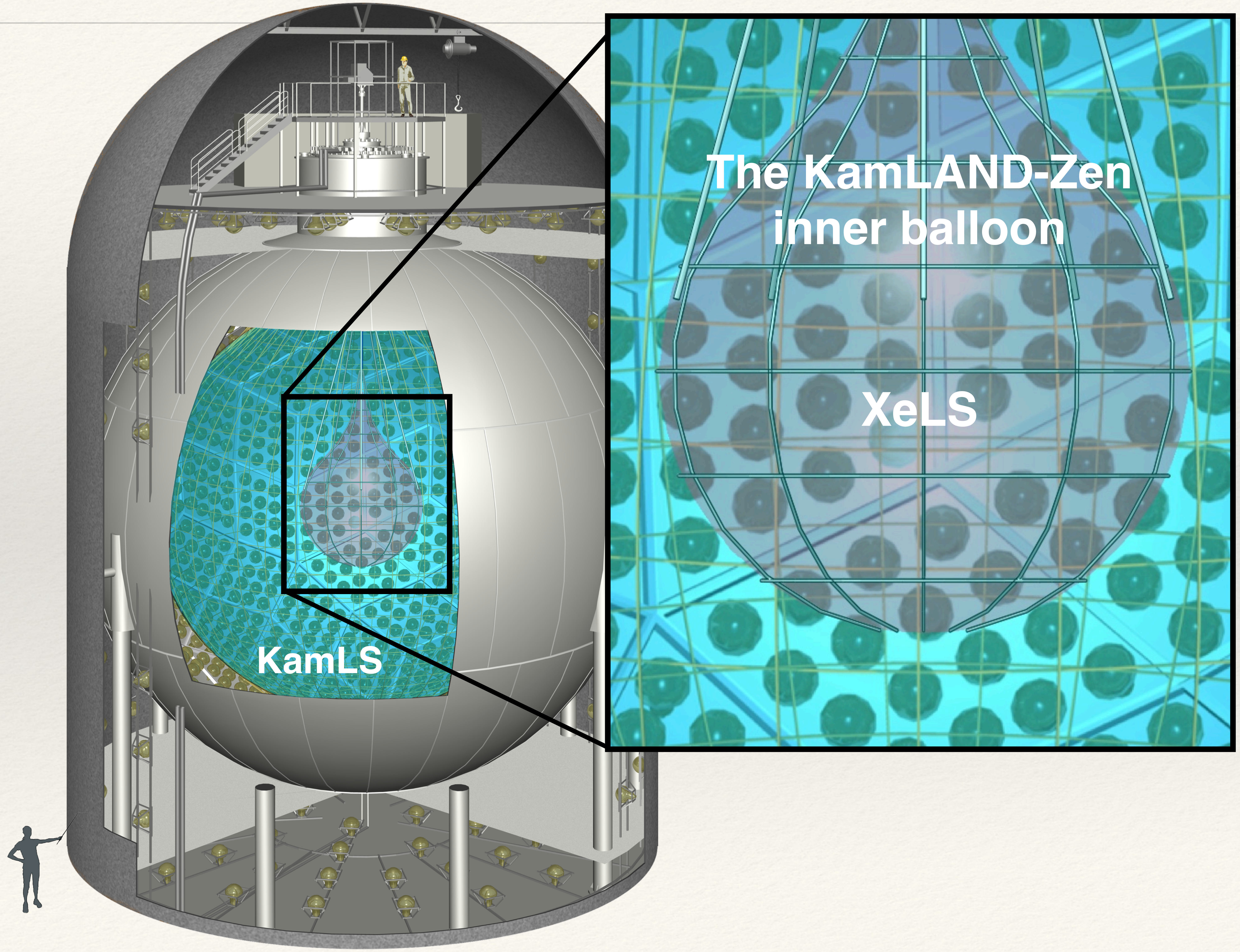
JUNO-0νββ



KamLAND-ZEN: Xe-loaded LS

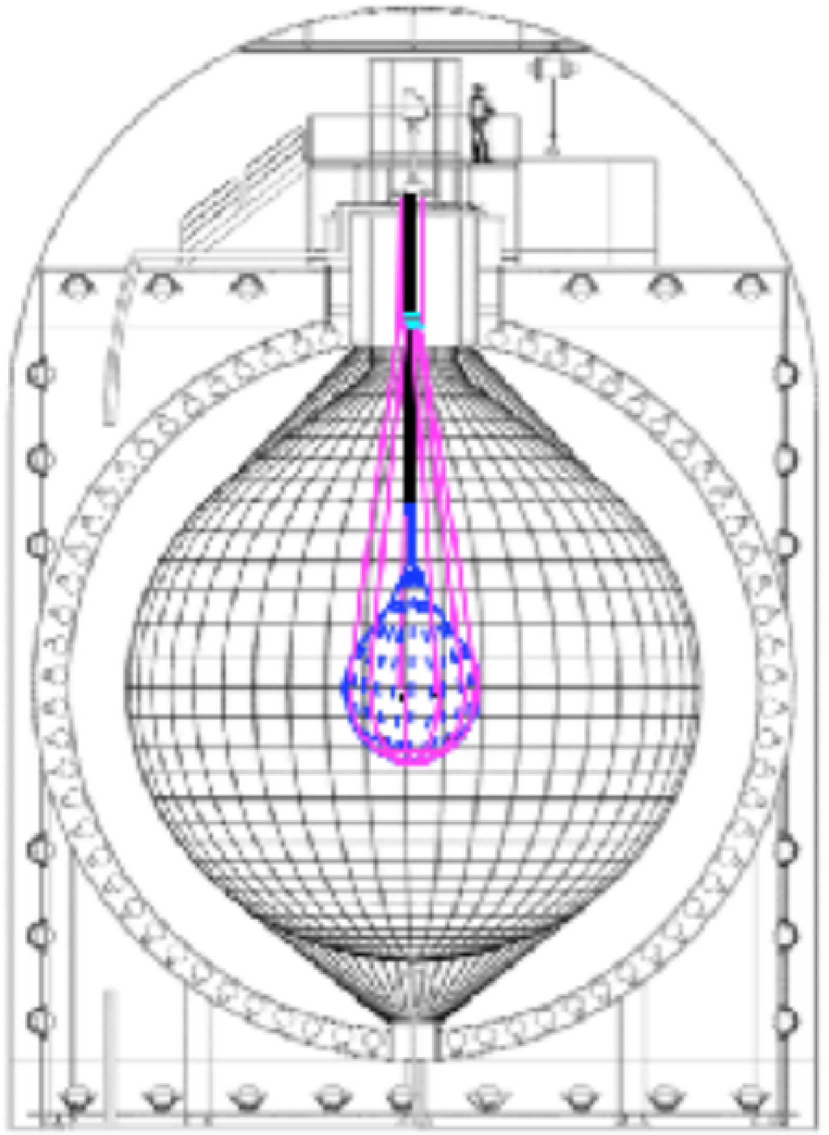
- KamLAND: 1 kiloton of ultra-low radioactivity liquid scintillator (LS)
- 3% wt xenon soluble in Liquid Scintillator (XeLS)





KamLAND-ZEN upgrade path

Past



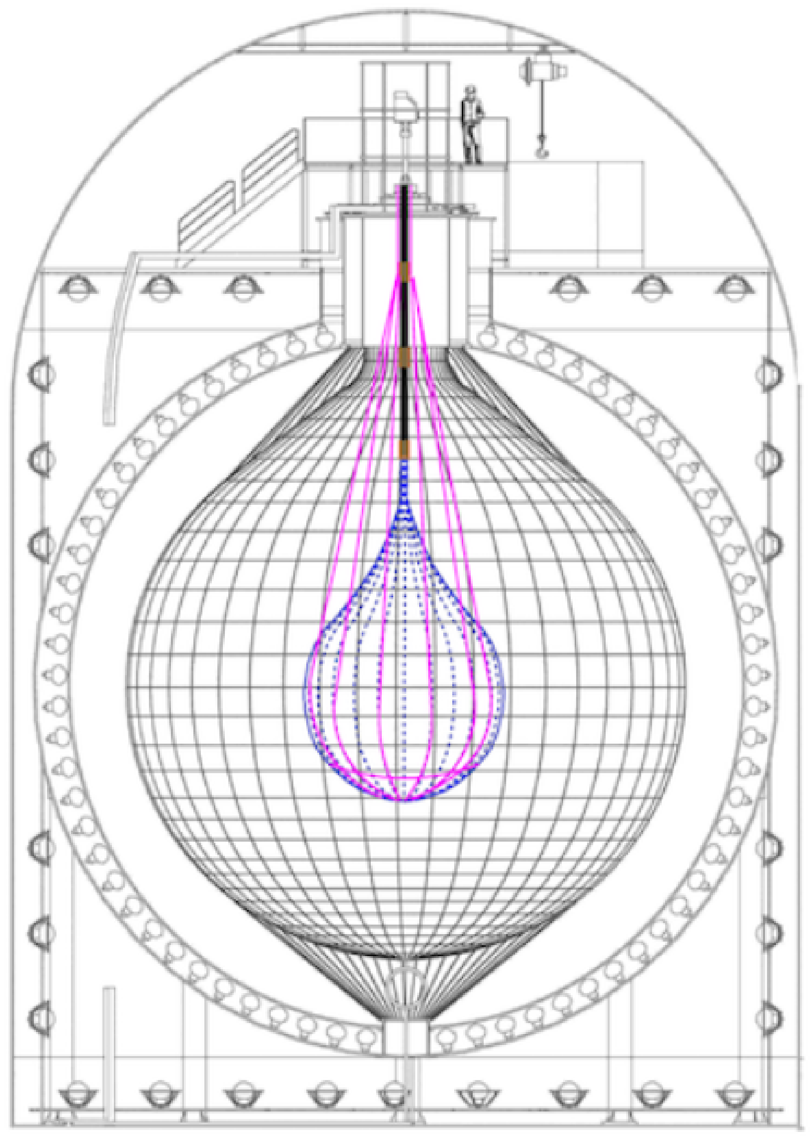
KamLAND-Zen 400

R = 1.54m mini-balloon

Xenon 320 ~ 380 kg

2011 ~ 2015

Ongoing



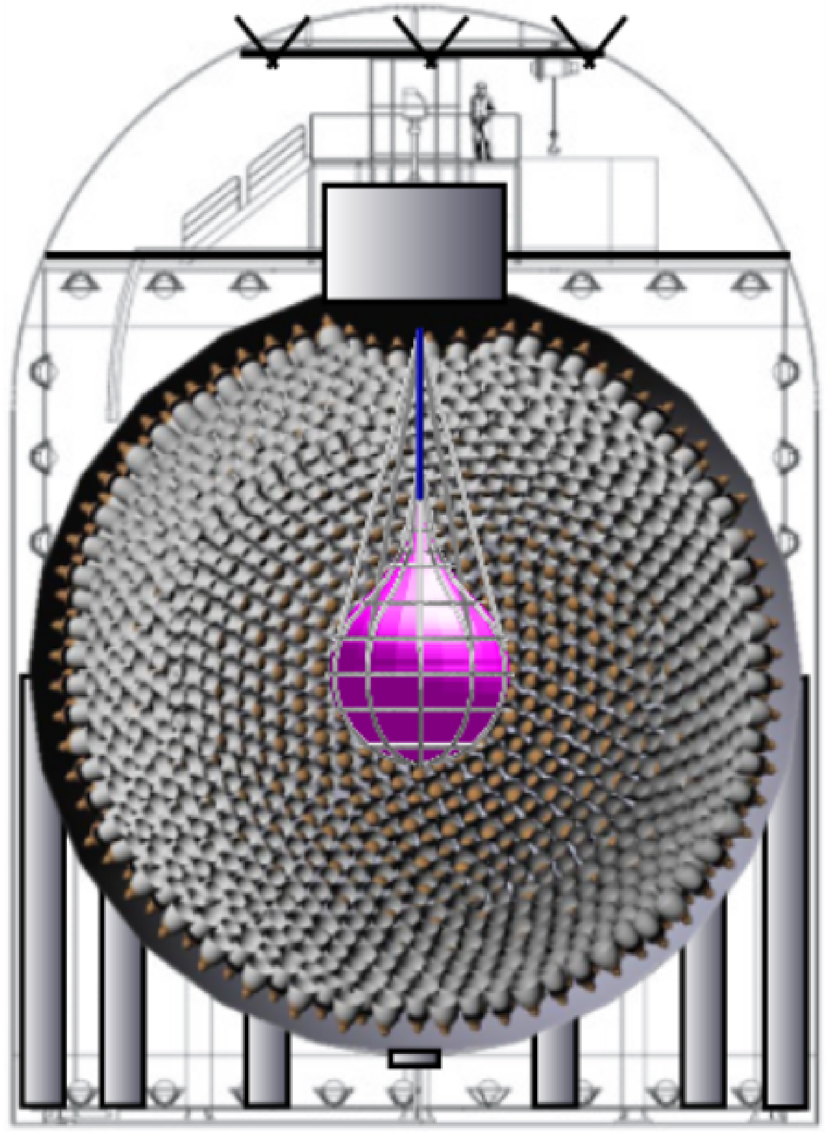
KamLAND-Zen 800

R = 1.90m mini-balloon

Xenon 745 kg

Jan. 22, 2019 ~

Future



KamLAND2-Zen

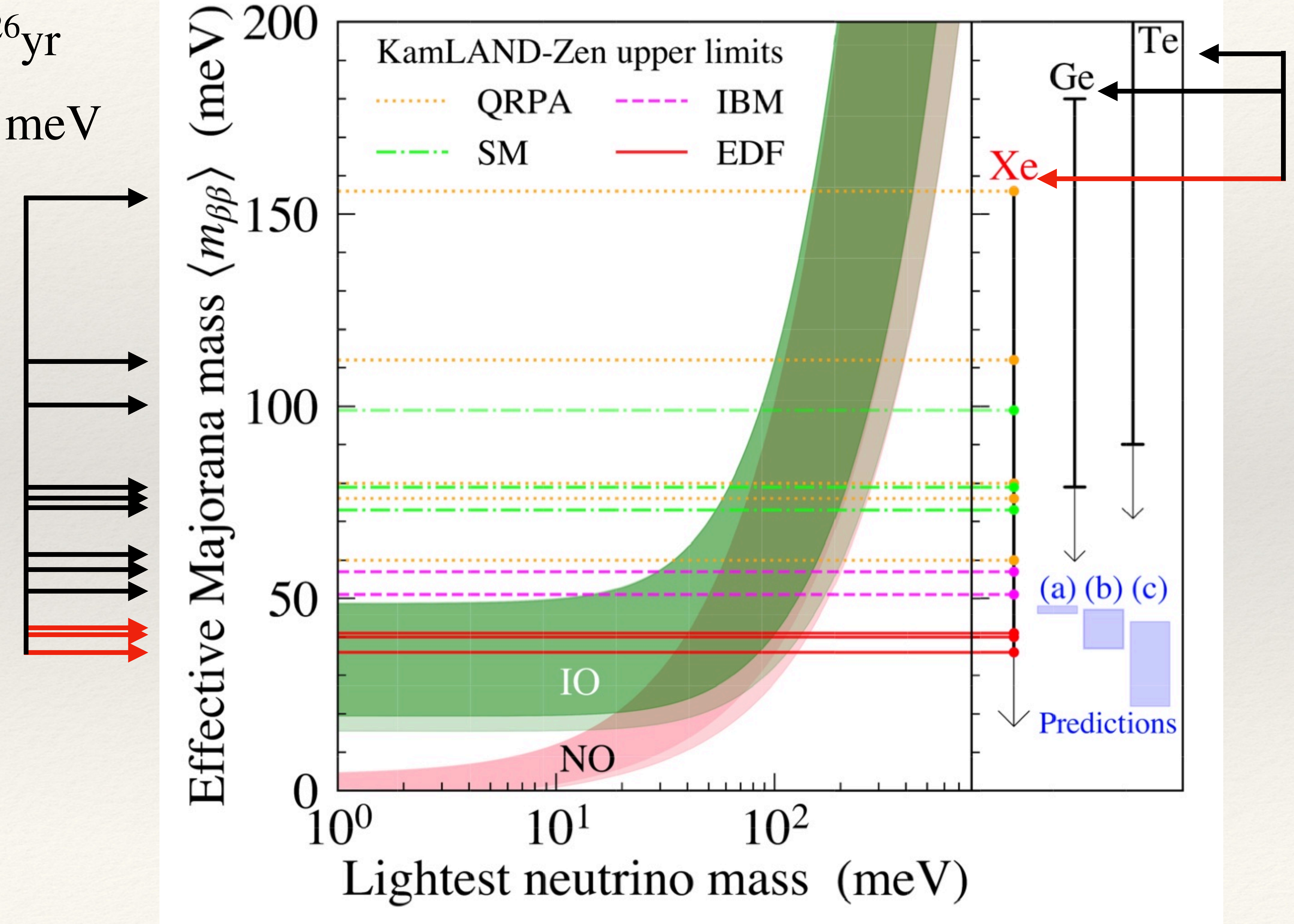
Xenon ~ 1 ton

KamLAND-ZEN 800 results

$T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26}$yr

$\langle m_{\beta\beta} \rangle < 36 - 156\,$meV

Result dependent on individual NMEs

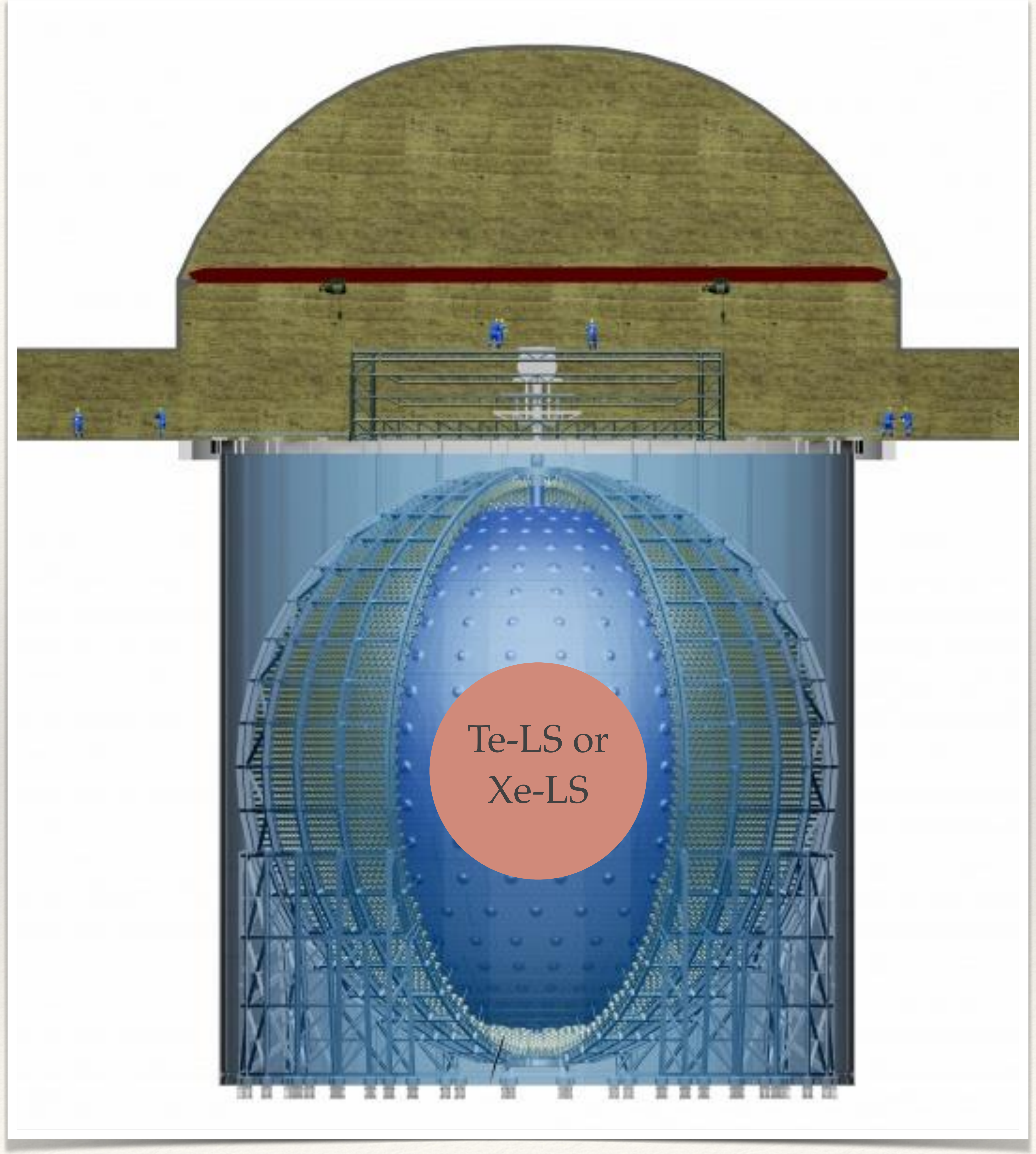


This Xe $0\nu\beta\beta$ search represents the **worlds most stringent limit** on the effective Majorana mass.

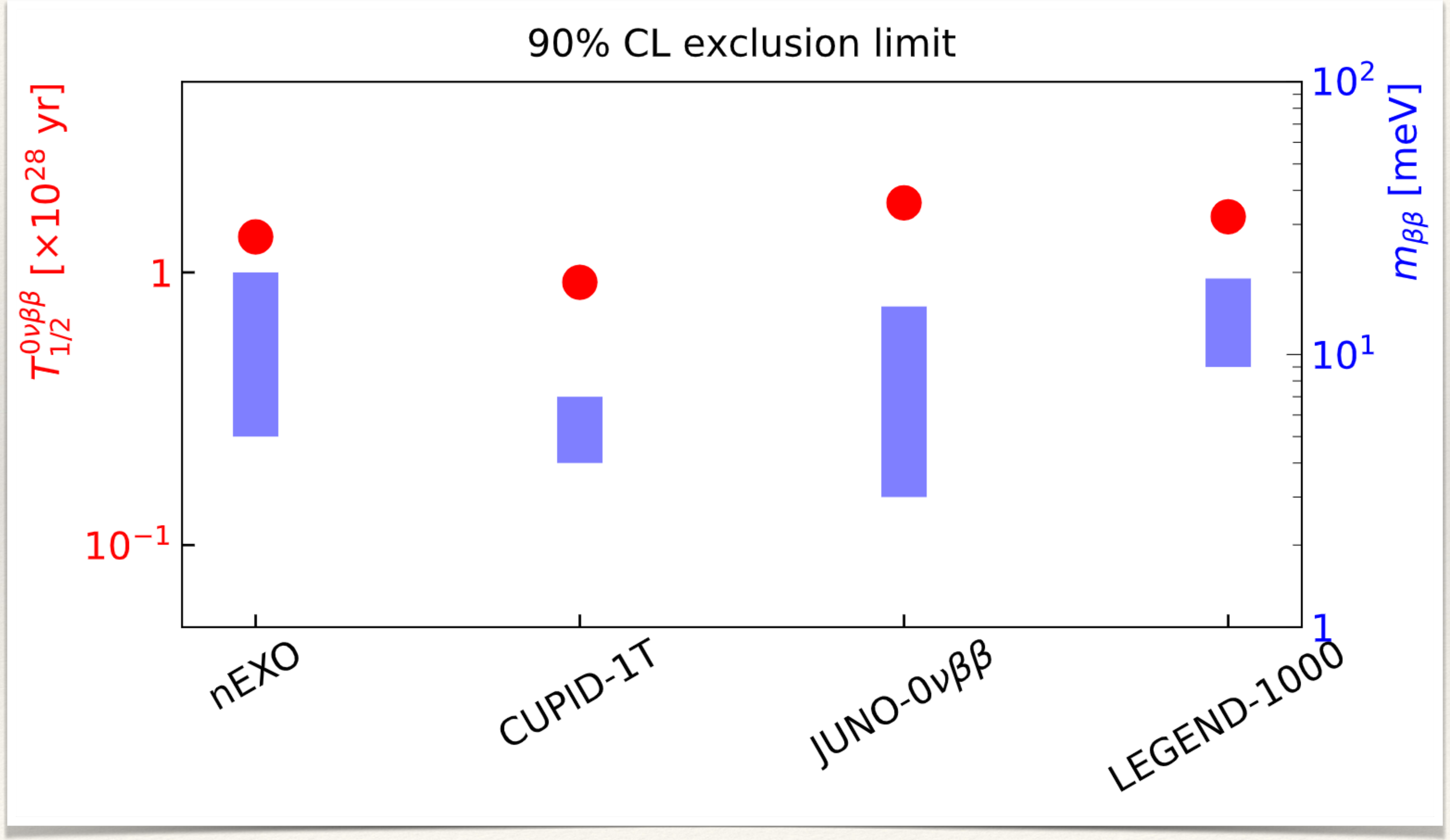
(Ge) GERDA: Phys.Lett. **125** 252502
(Te) CUORE: Nature 604, 53 (2022)

JUNO-0νββ

- Aims to start right after current mass hierarchy programs
- Half life sensitivity at 10^{28} year
- Energy resolution < 3% @ 1 MeV → 2.4x better than KamLAND-Zen
- Xe or Te loading: 100 ton of Te of 20 kton LS possible



JUNO-0νββ physics potential

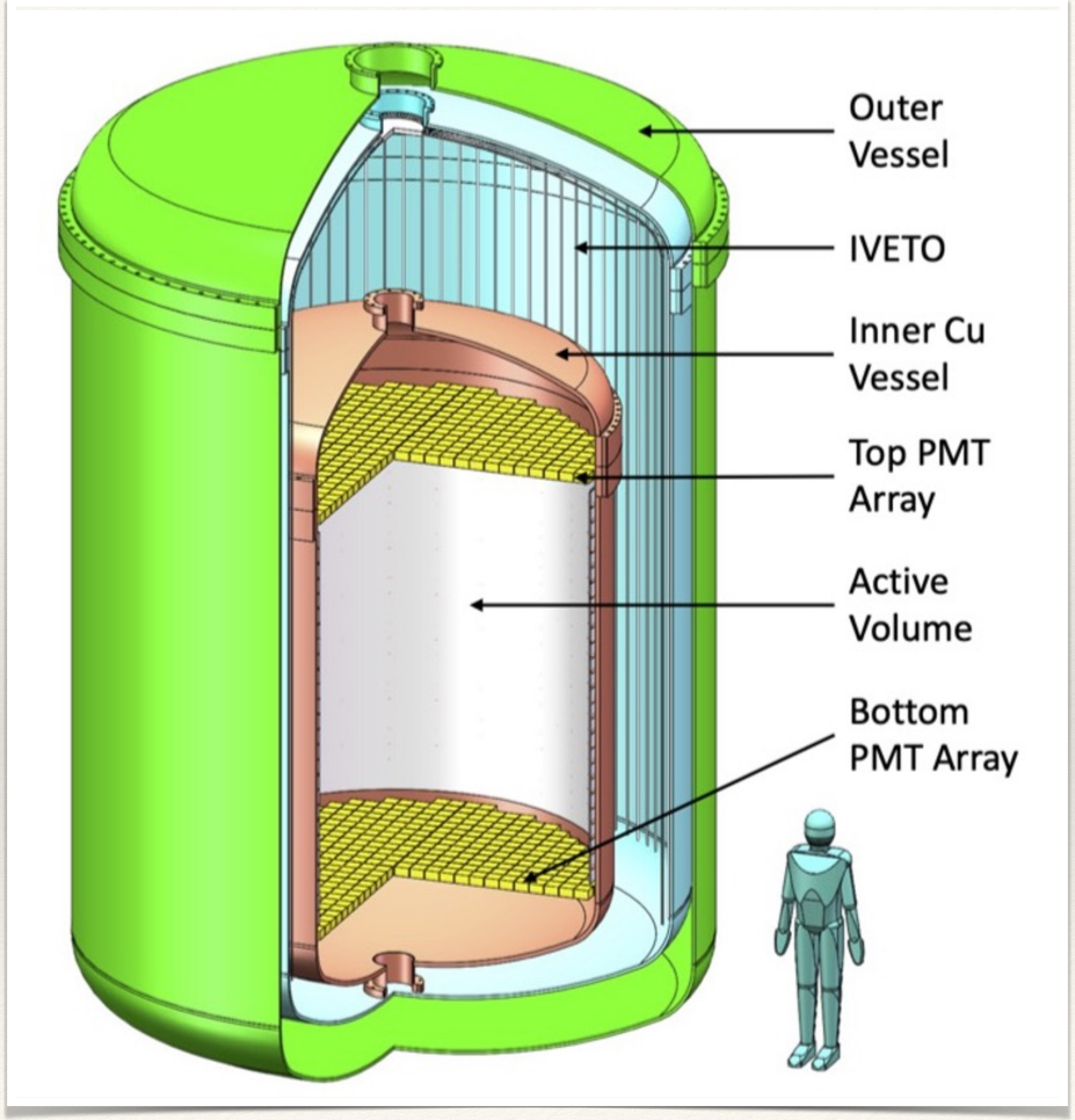


TPC
时间投影室

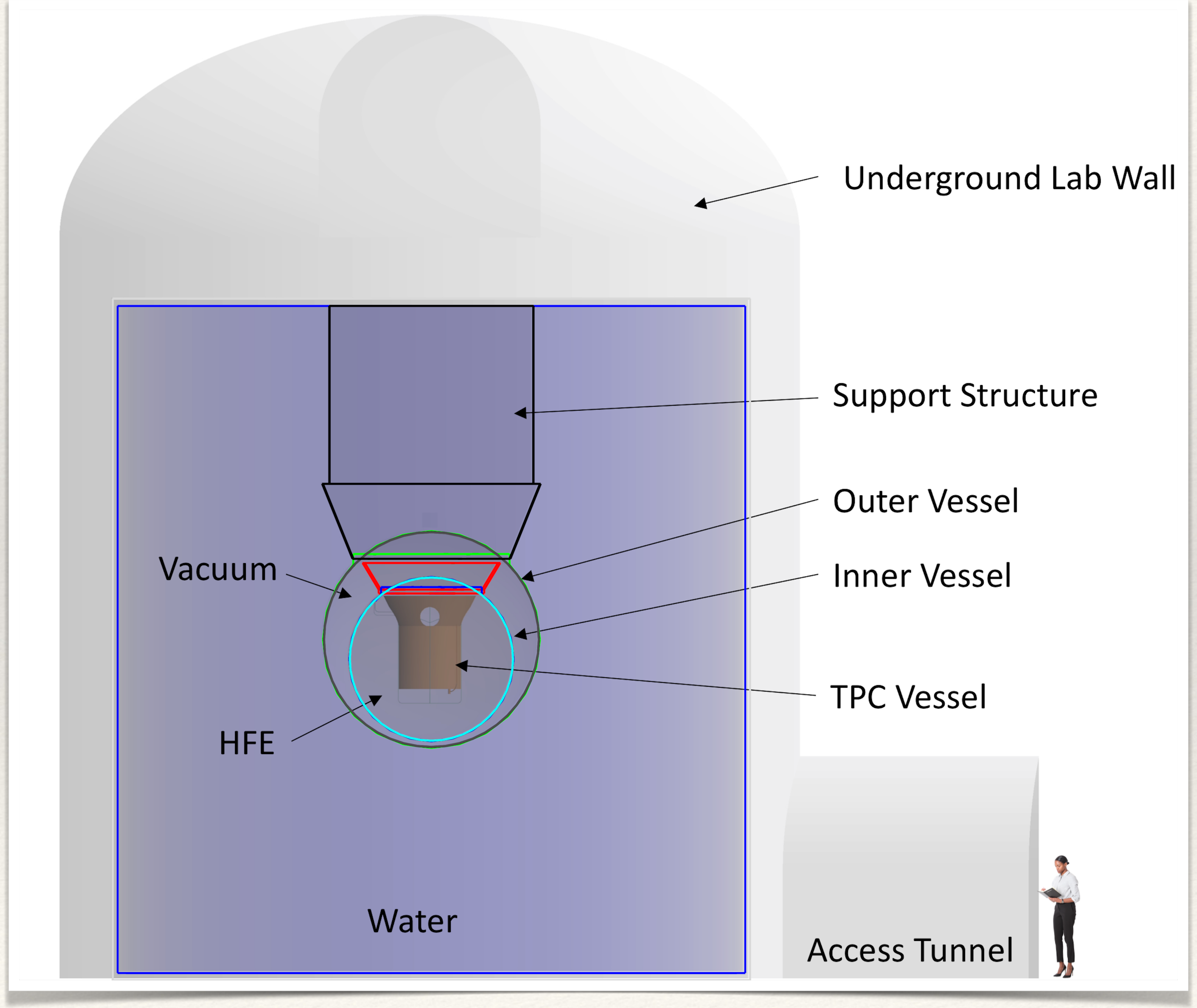
nEXO

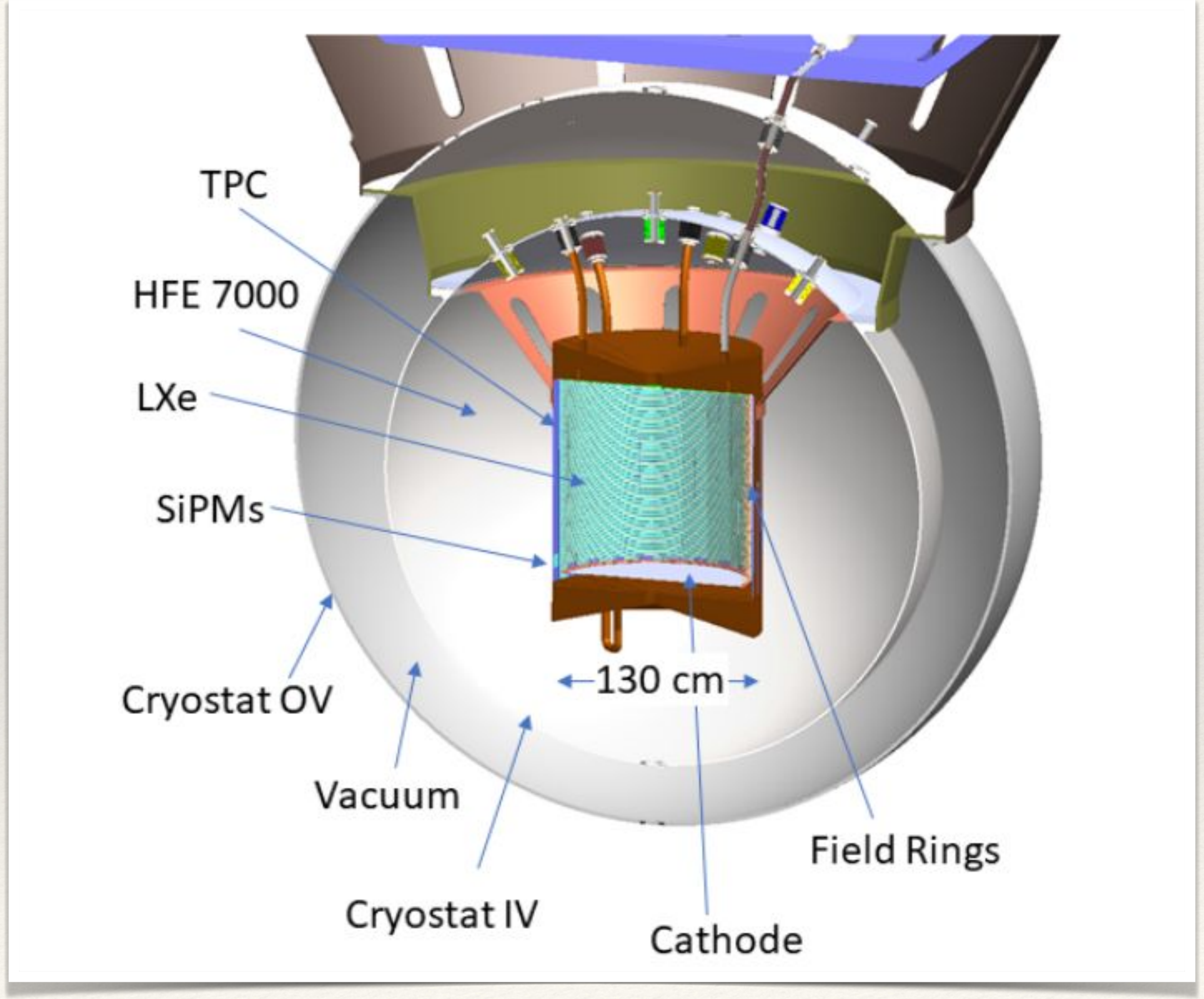
NνDEX

PandaX



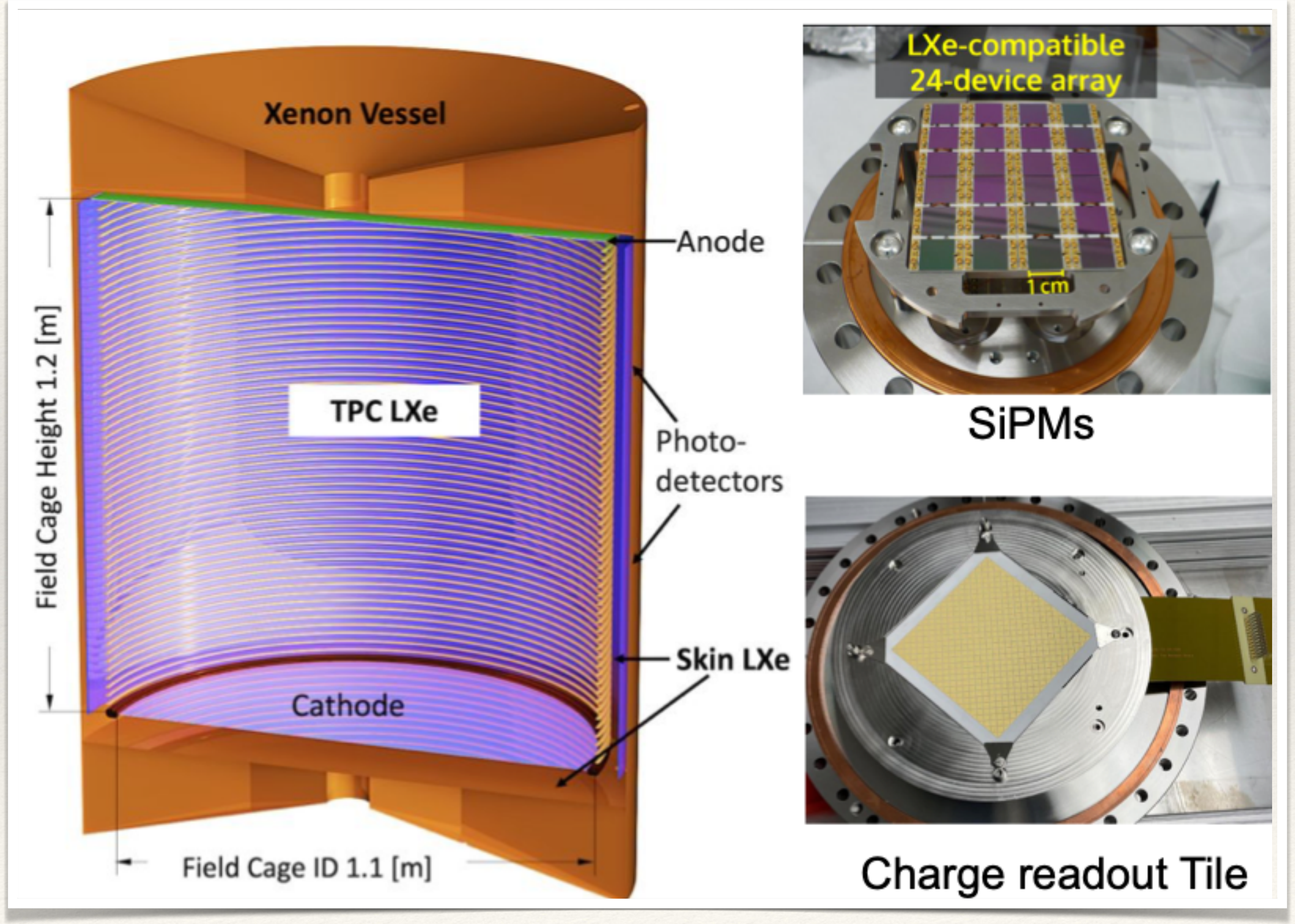
nEXO: liquid xenon TPC



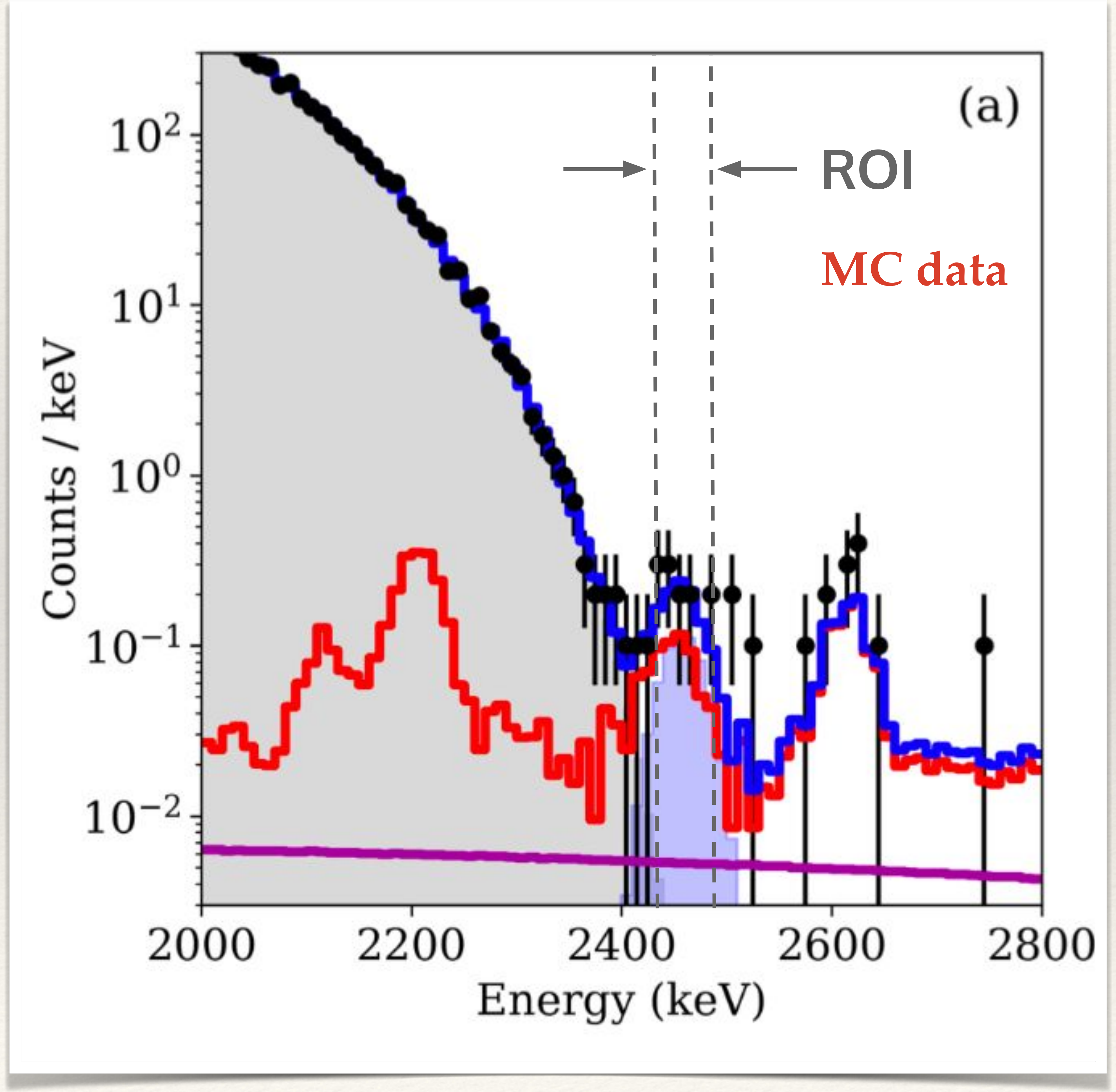


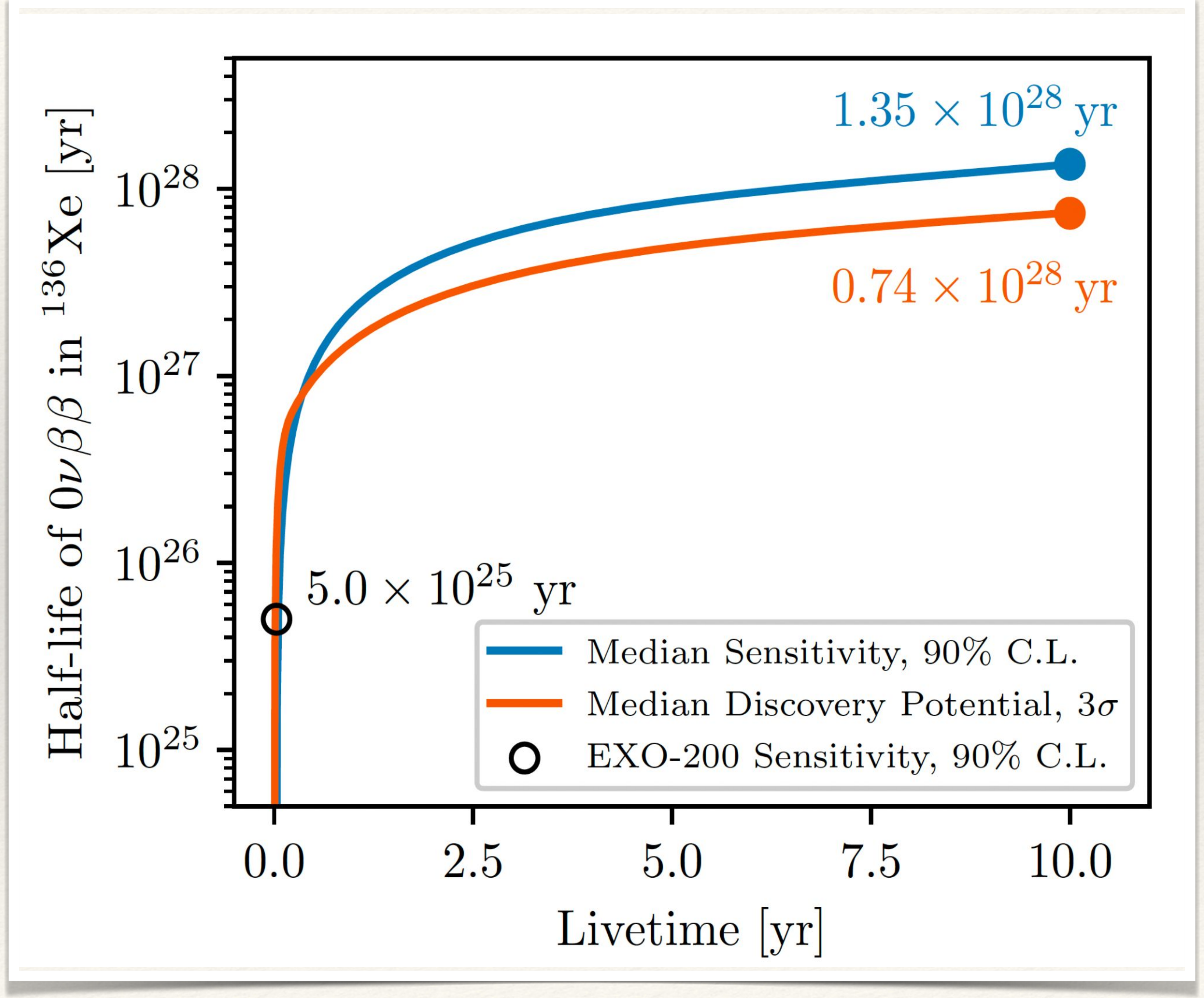
nEXO Time projection chamber

- Light detection: 4.5 m² silicon photomultipliers with ASIC readout in LXe.
- Charge collection: Anode plane filled with charge readout strips (10 cm long and 6 mm pitch)
- Field strength: 400 V / cm
- Electron lifetime: 10 ms



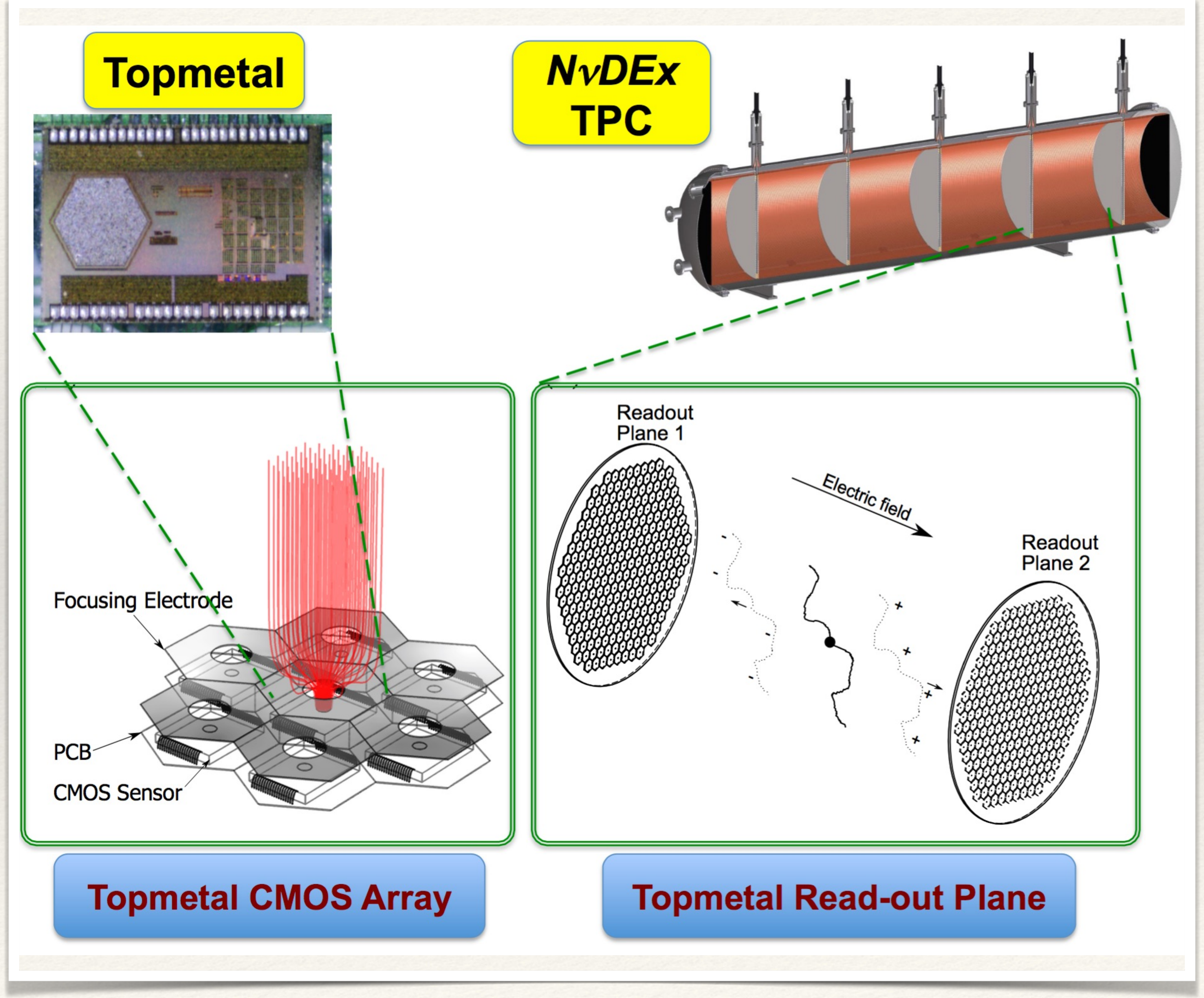
nEXO Physics potential





NvDEx: high pressure ion TPC

- High pressure $^{82}SeF_6$ TPC with Topmetal CMOS readout
- Ions drift, not electrons in SeF_6
- expected 1% FWHM resolution based on low noise Topmetal readout
- Gases TPC has unique tracking capability for background suppression



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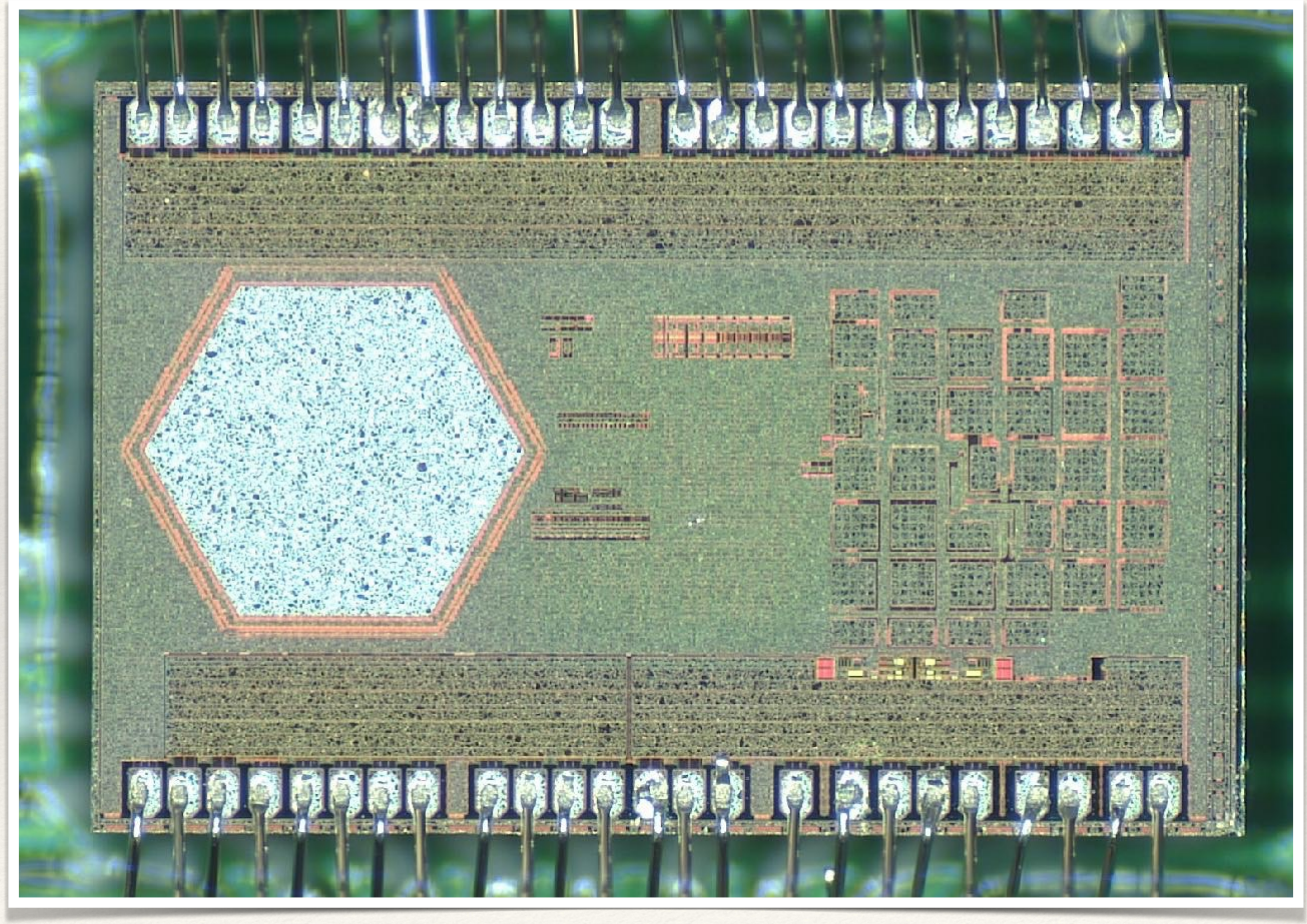
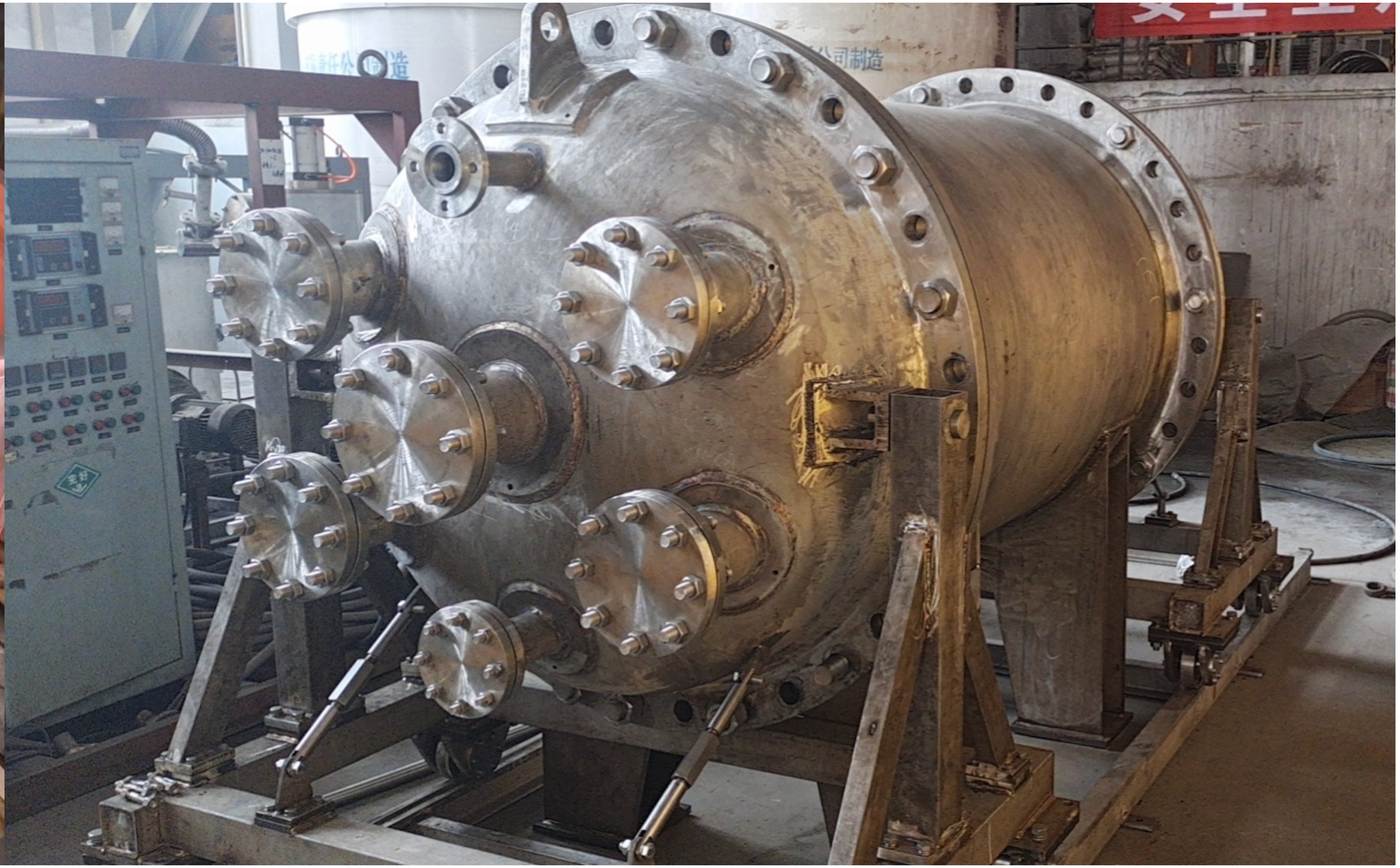
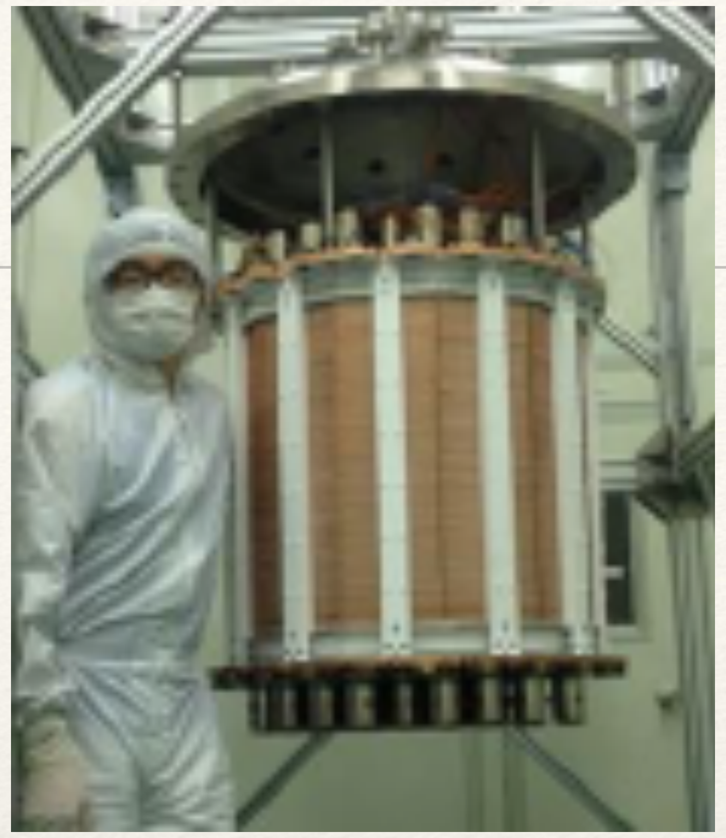
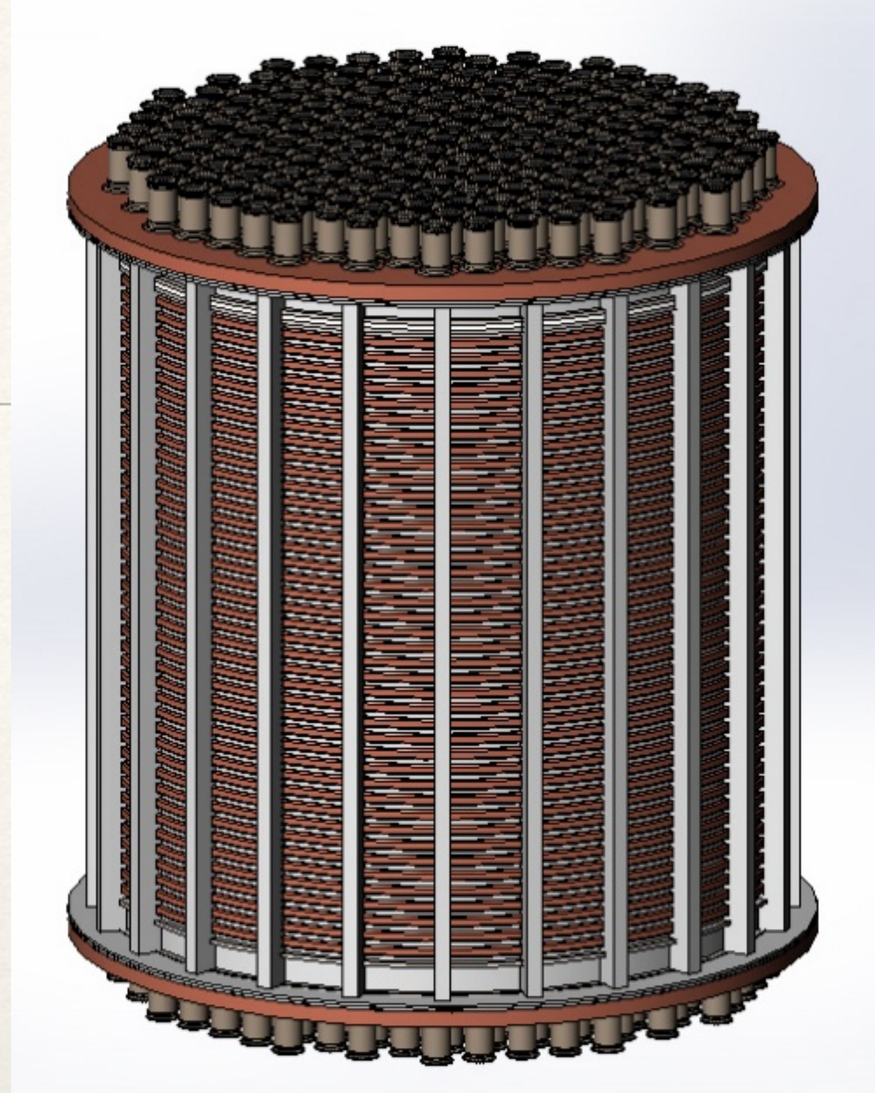


NνDEx-100

PandaX Detectors





WIMP searches
(0νββ as well)

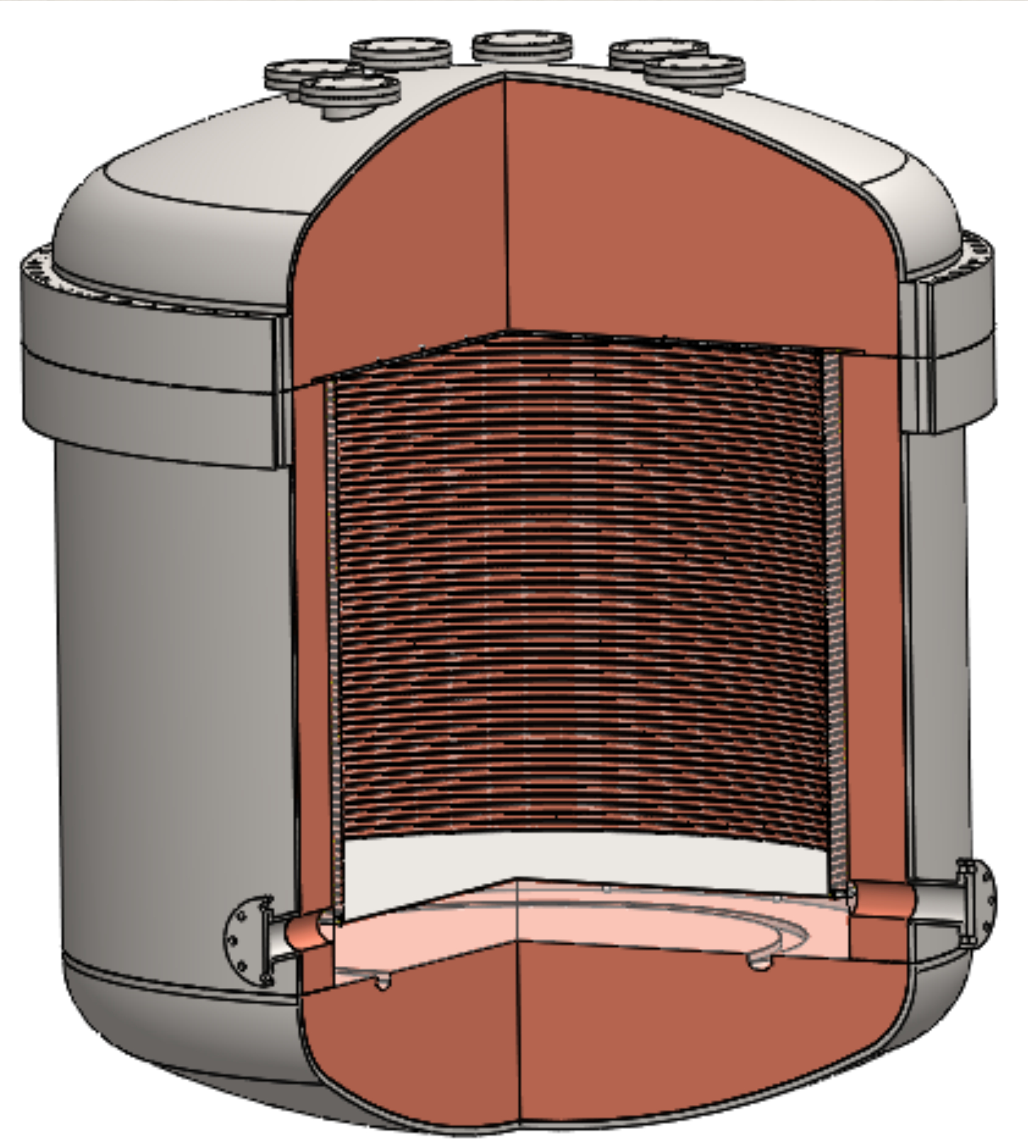
PandaX-I: 120kg LXe
(2009 – 2014)

PandaX-II: 500kg LXe
(2014 – 2018)

PandaX-xT LXe
(future)

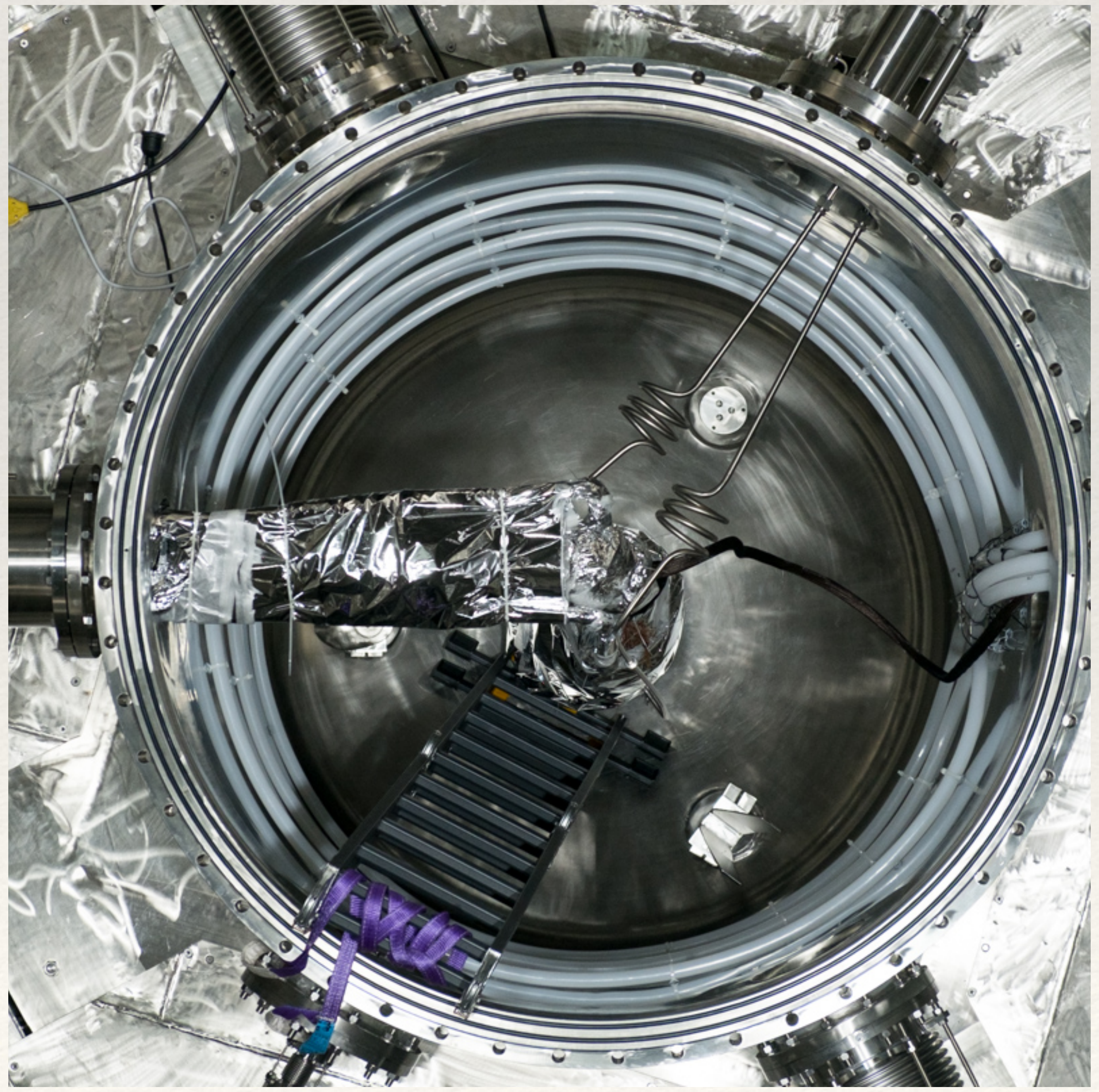
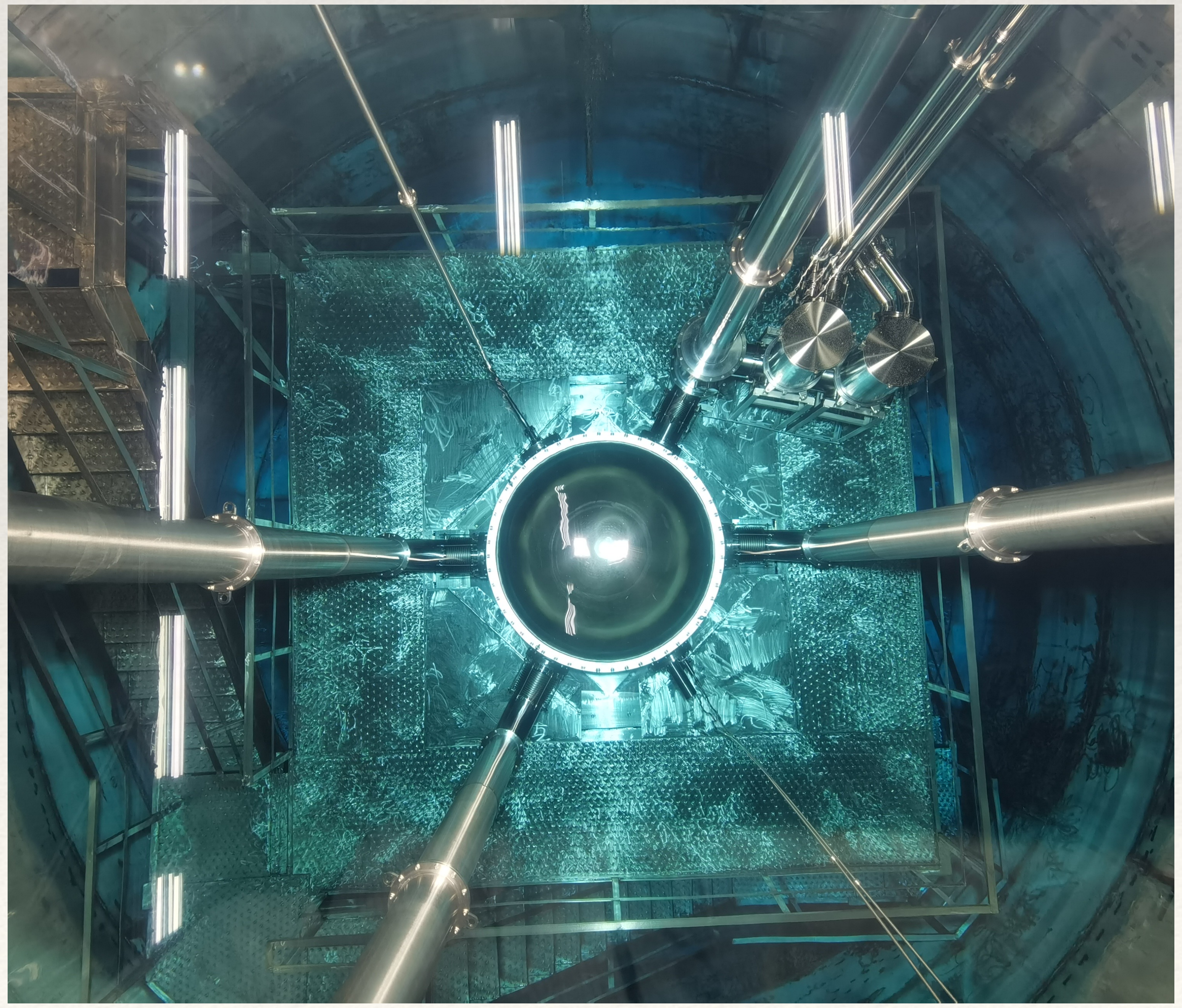
PRL 117, 121303 (2016)

PandaX-III: 100kg - 1 ton
HPXe for 0νββ (future)



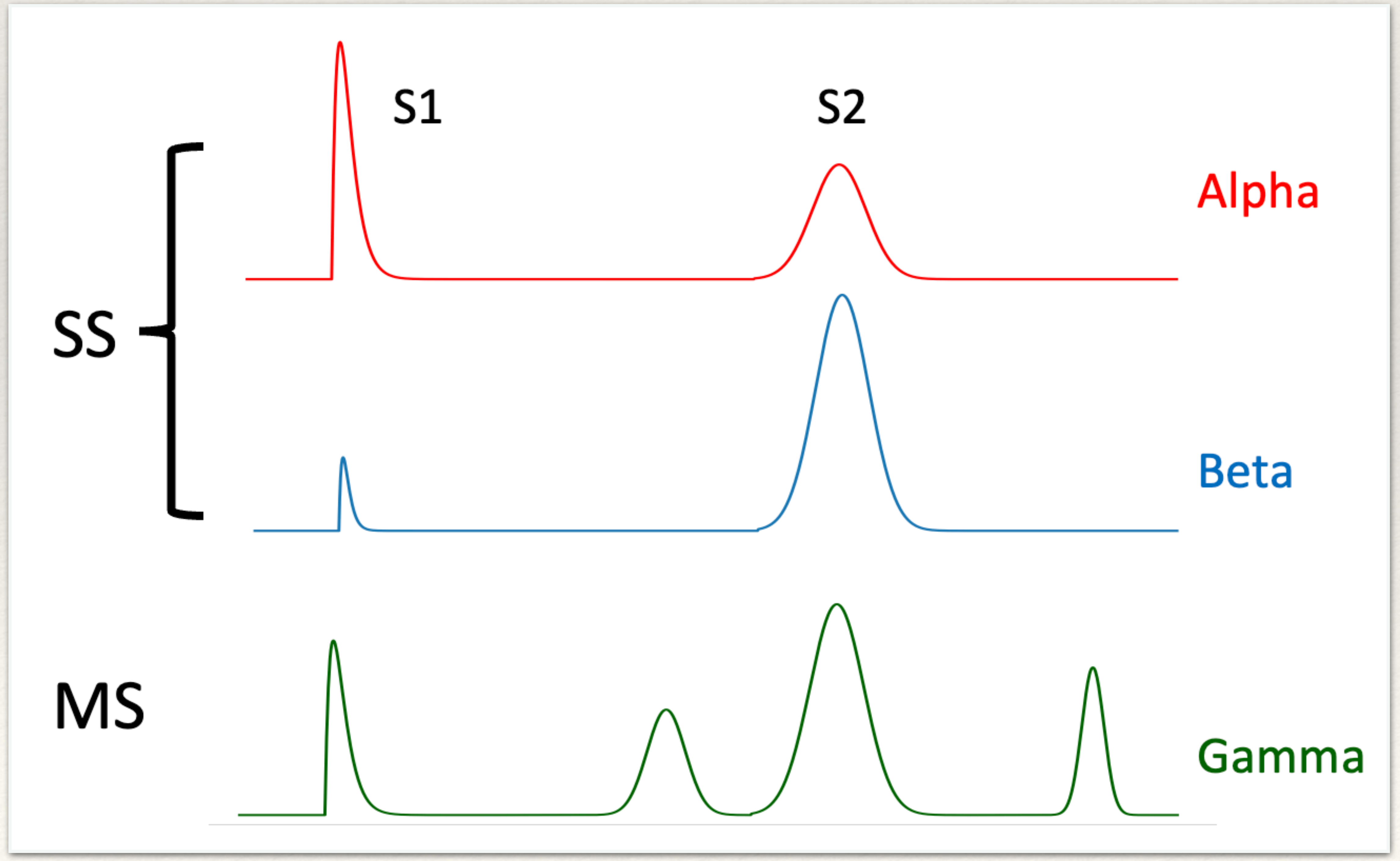
PandaX-4T currently with ~250 days' data

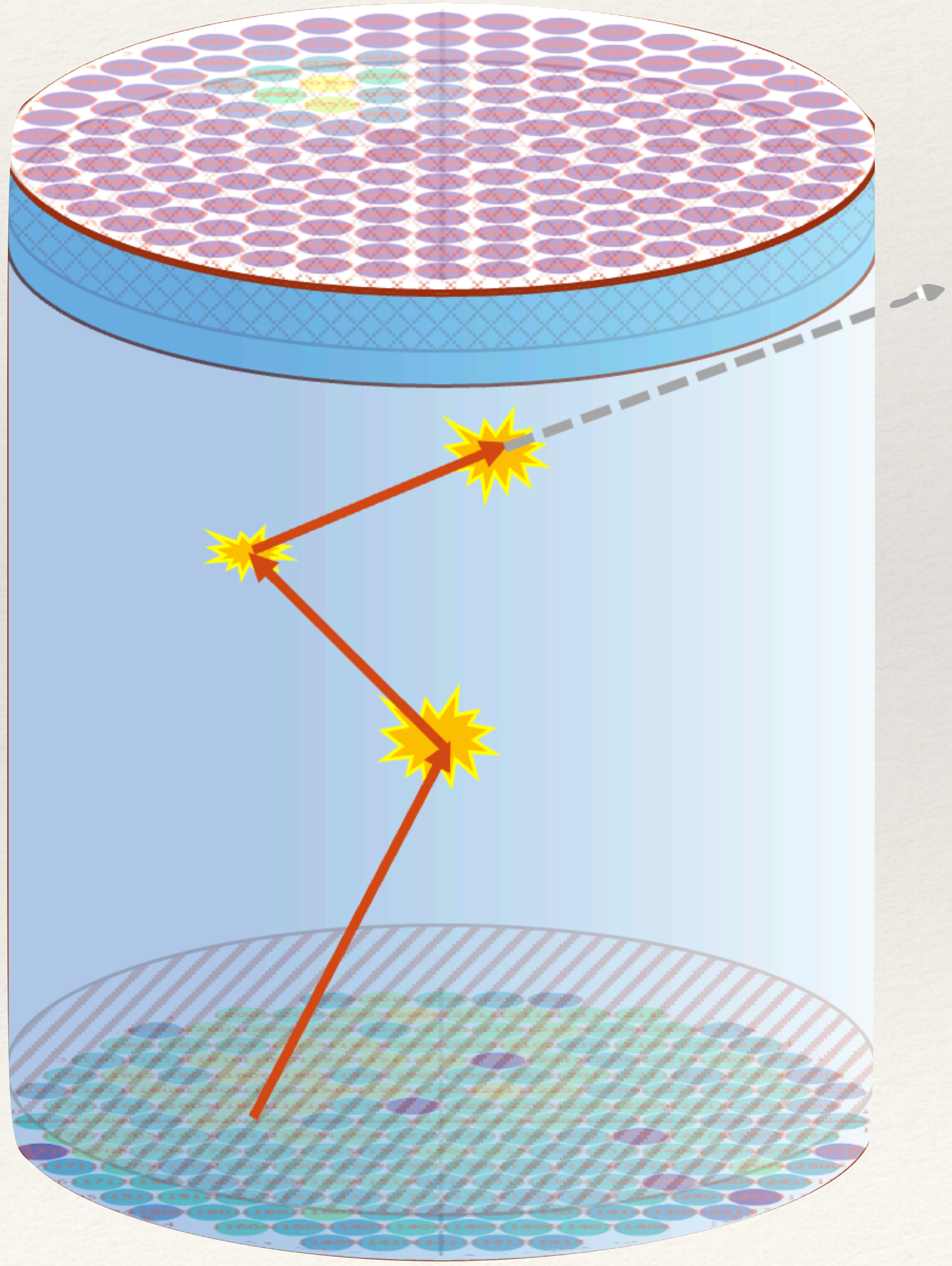
- A multi-ton dual phase xenon TPC at CJPL
- Commissioned since late 2020
  - commissioning Run 0 (~ 95 d); physics Run 1 (~ 154 d)

PandaX LXe TPC: Total-Absorption 5D Calorimeter

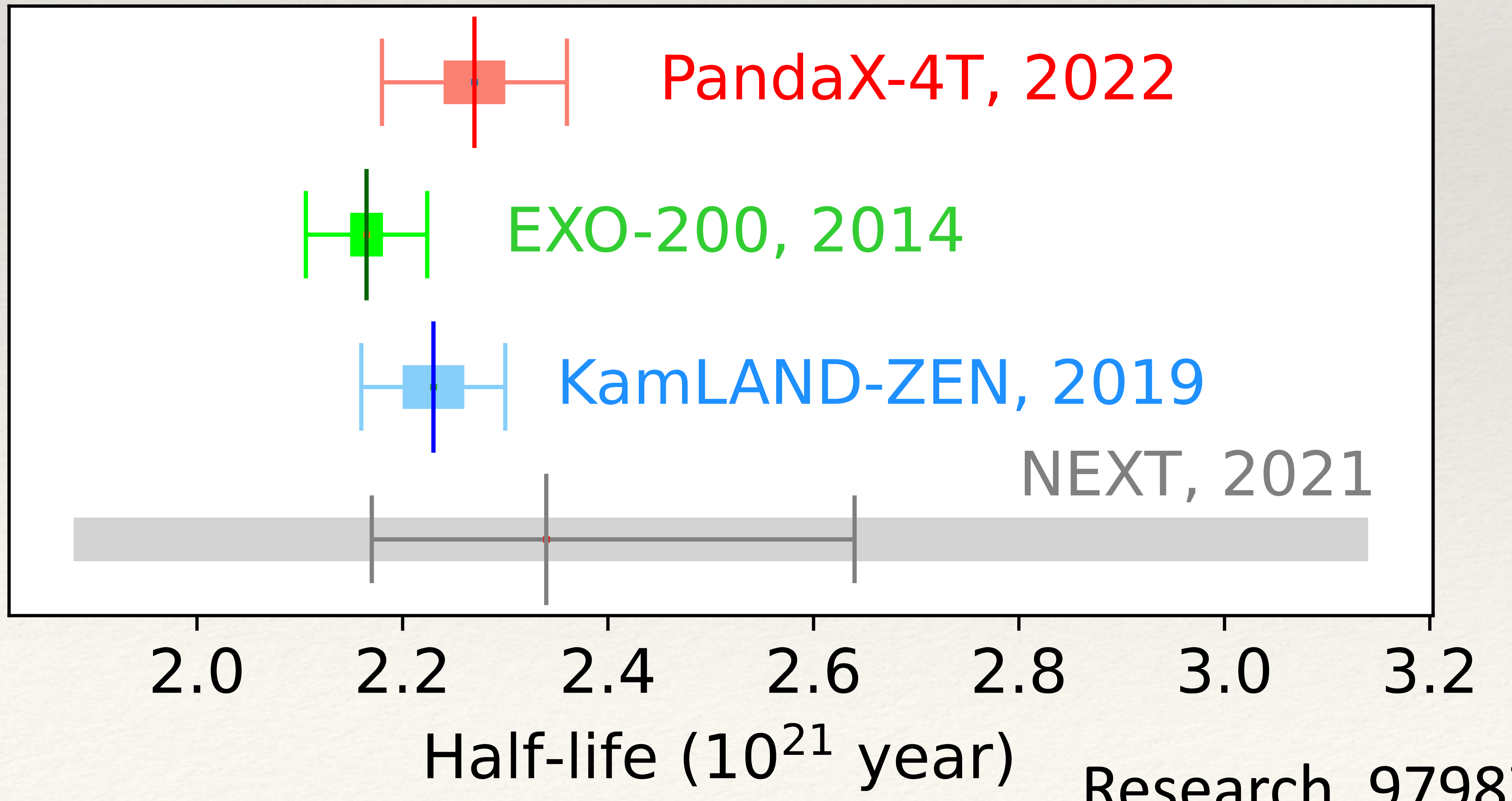
- Precisely measure 3D position, energy, and timing information in the energy range from sub-keV to 10MeV
- Large monolithic volume: total absorption; ~20 x MeV ɣ attenuation length
- Single-site (SS) and multi-site (MS) event for event topology and particle ID

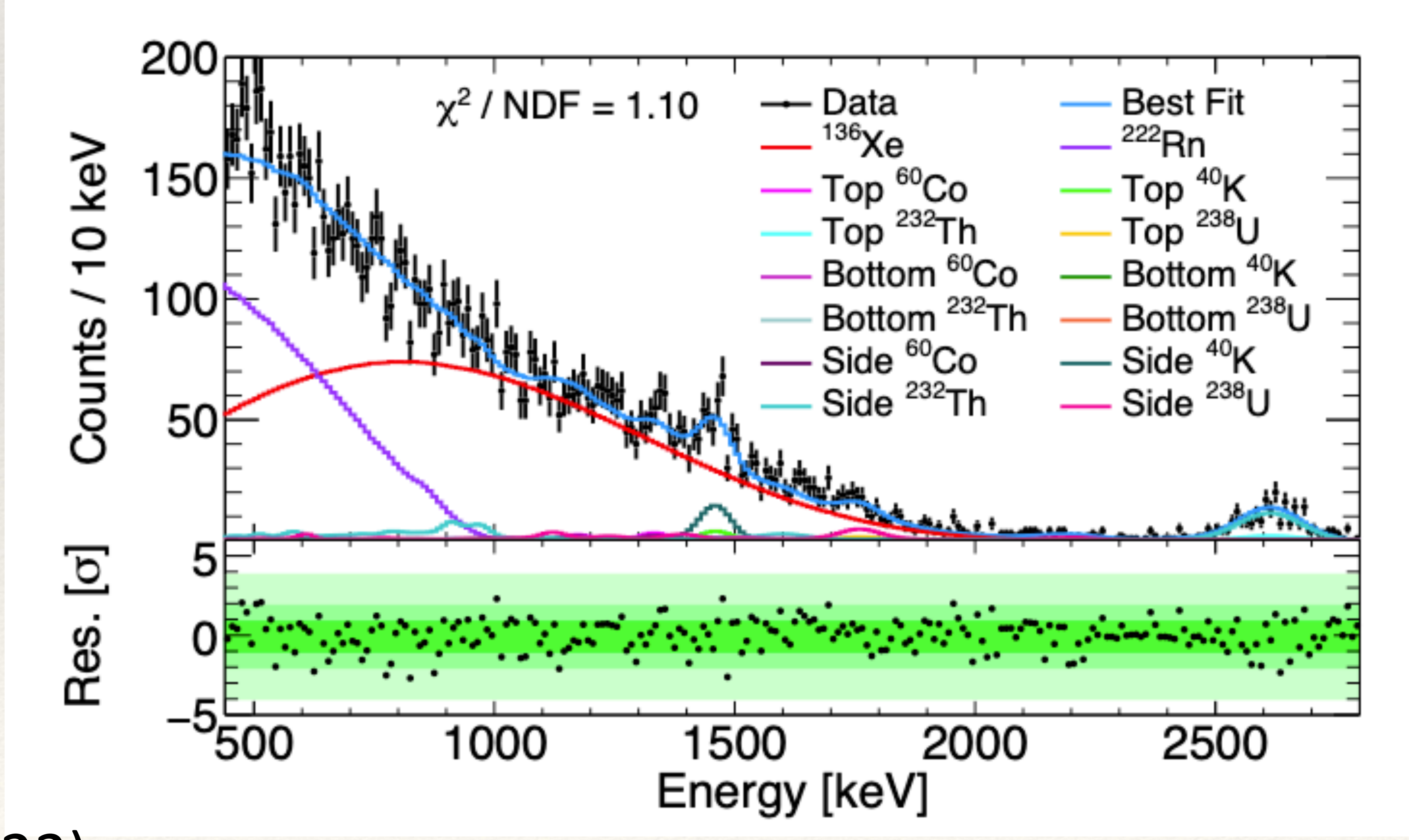




^{136}Xe DBD half-life measurement

- ^{136}Xe DBD half-life measured by PandaX-4T: 2.27 ± 0.03(stat.) ± 0.09(syst.) × 10^{21} year
- 440 keV – 2800 keV range is the widest ROI
- Comparable precision with leading results
- First such measurement from a natural xenon TPC

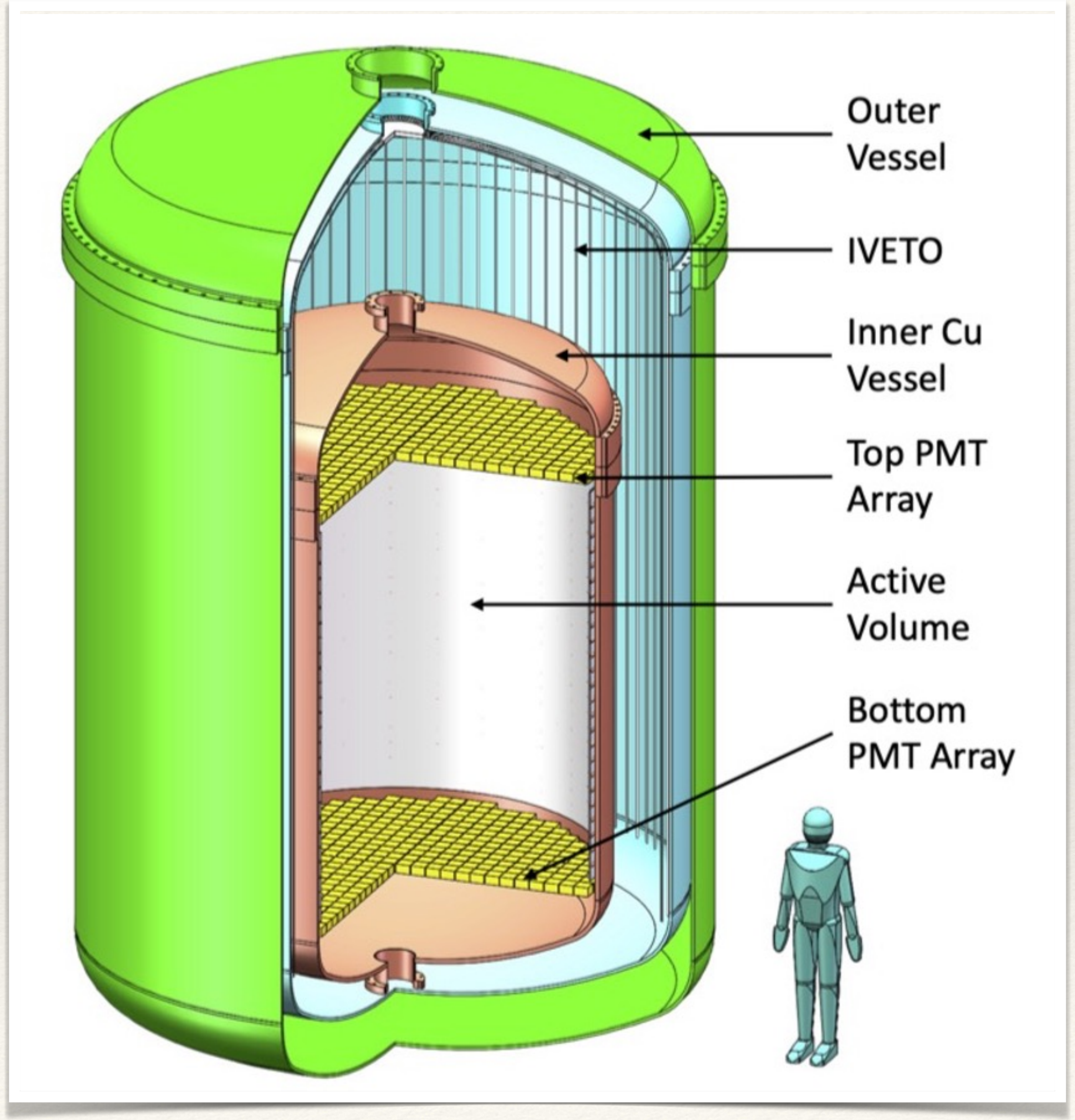




Research, 9798721 (2022)

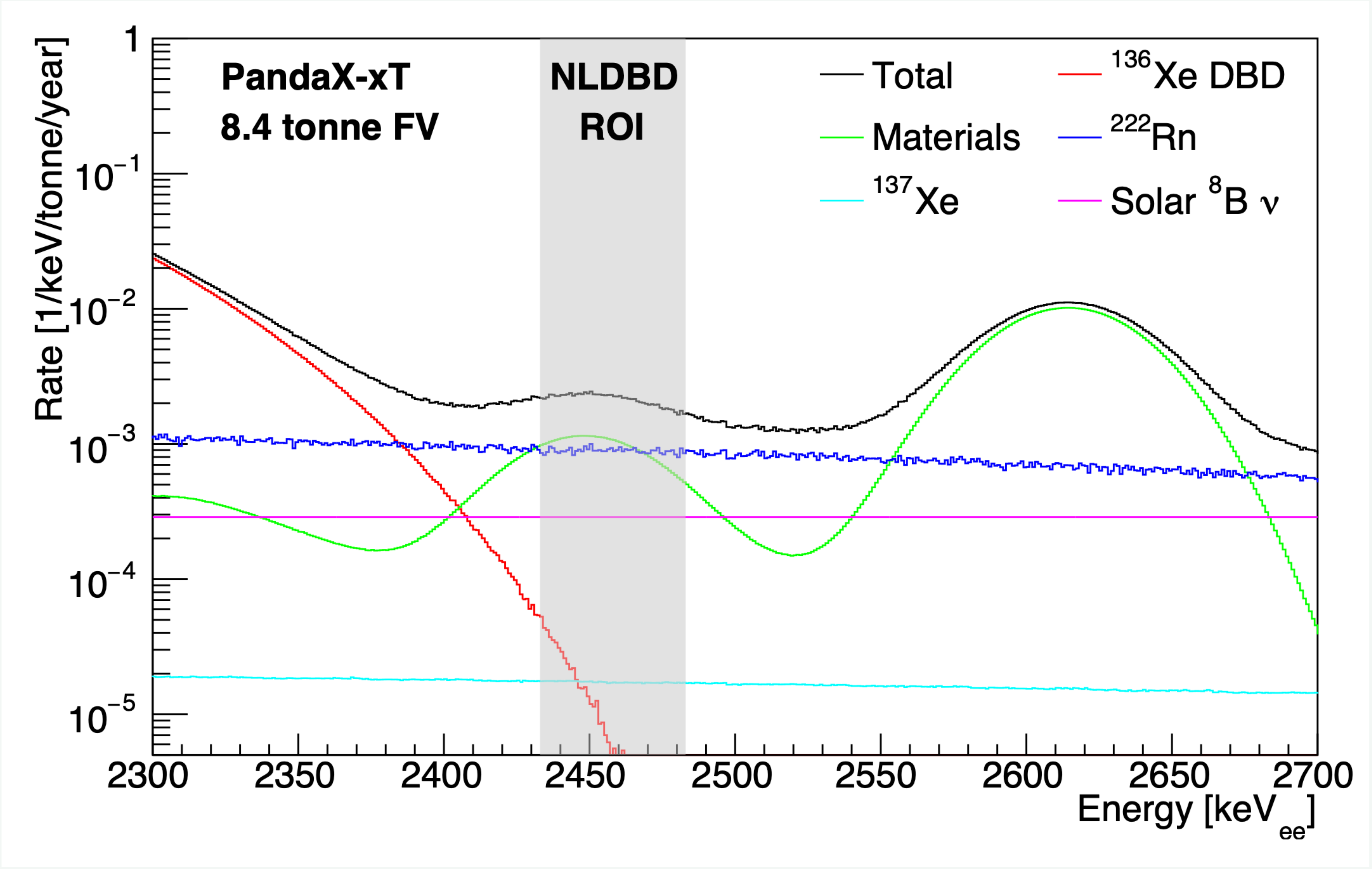
PandaX-xT: Multi-ten-tonne Liquid Xenon Observatory

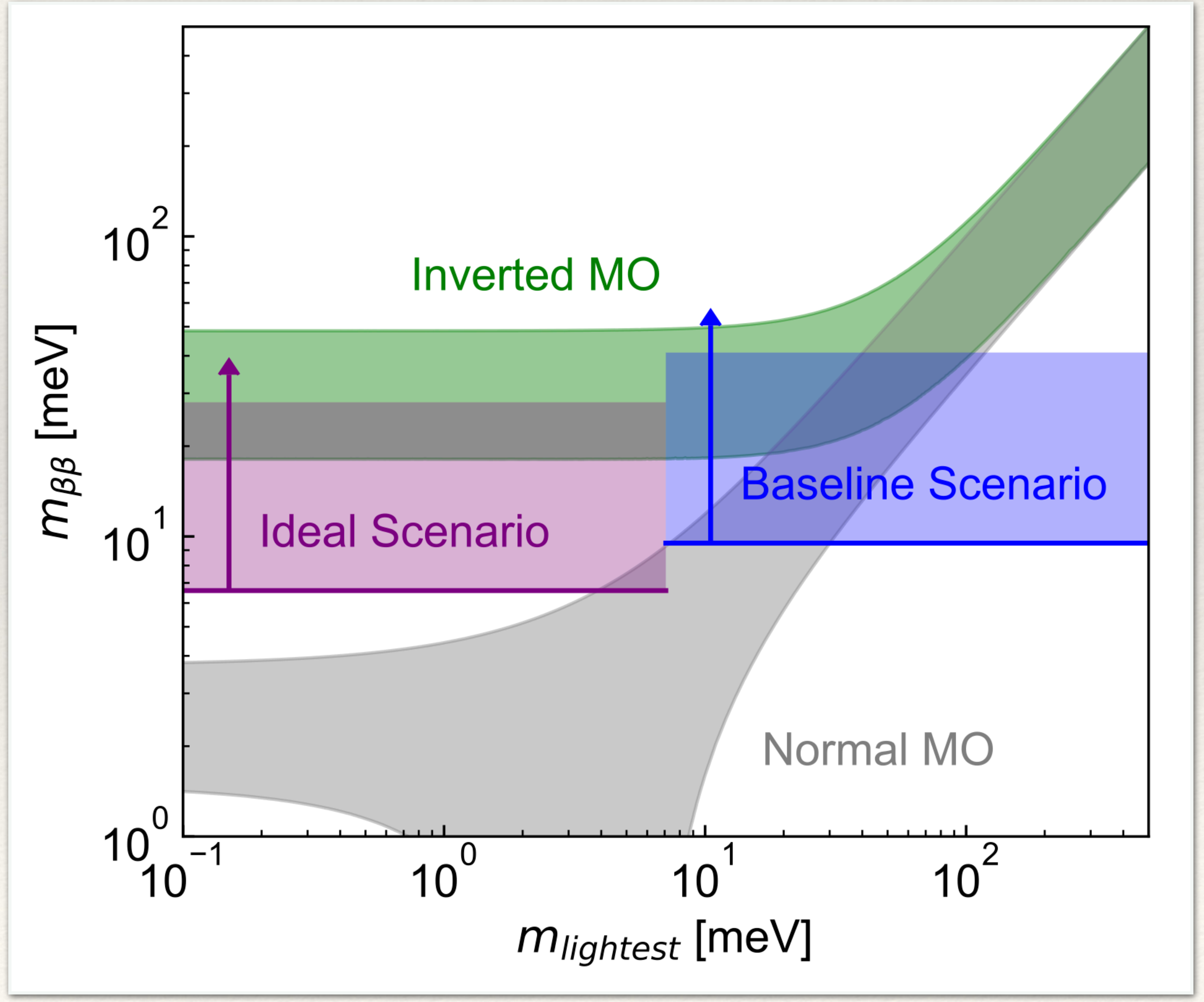
- Active target: 43 ton of Xenon
  - Decisive test to the WIMP paradigm
  - Explore the Dirac/Majorana nature of neutrino
  - Search for astrophysical or terrestrial neutrinos and other ultra-rare interactions
- Improved PMT, veto, vessel radiopurity, etc
- Staged upgrade utilizing isotopic separation on natural xenon.



PandaX-xT for NLDBD

- 4 ton of ^{136}Xe: one of the largest DBD experiments
- Effective self-shielding: Xenon-related background dominates





Neutrinoless double beta decay

- Exciting physics to probe the fundamental nature of neutrino
- International efforts to search for the rare signal in multiple isotopes with various techniques
- Ambitious R&D program in China
- PandaX is developing multi-purpose physics program, with DBD as one of the main objectives.