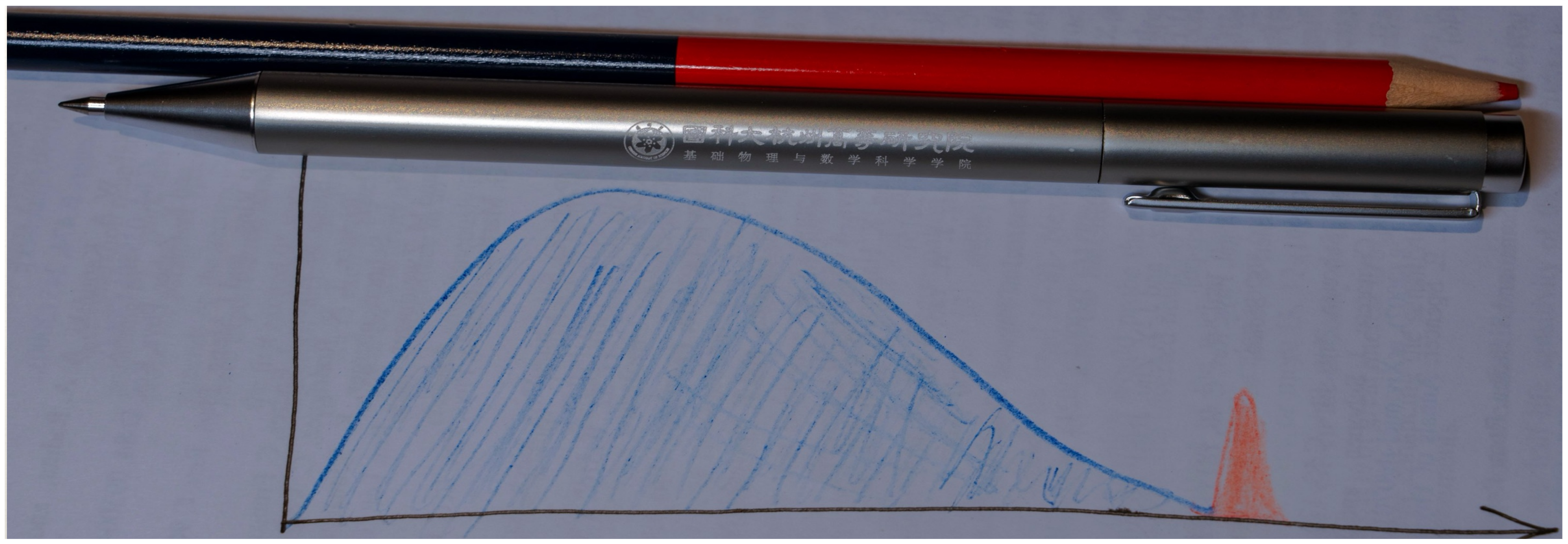


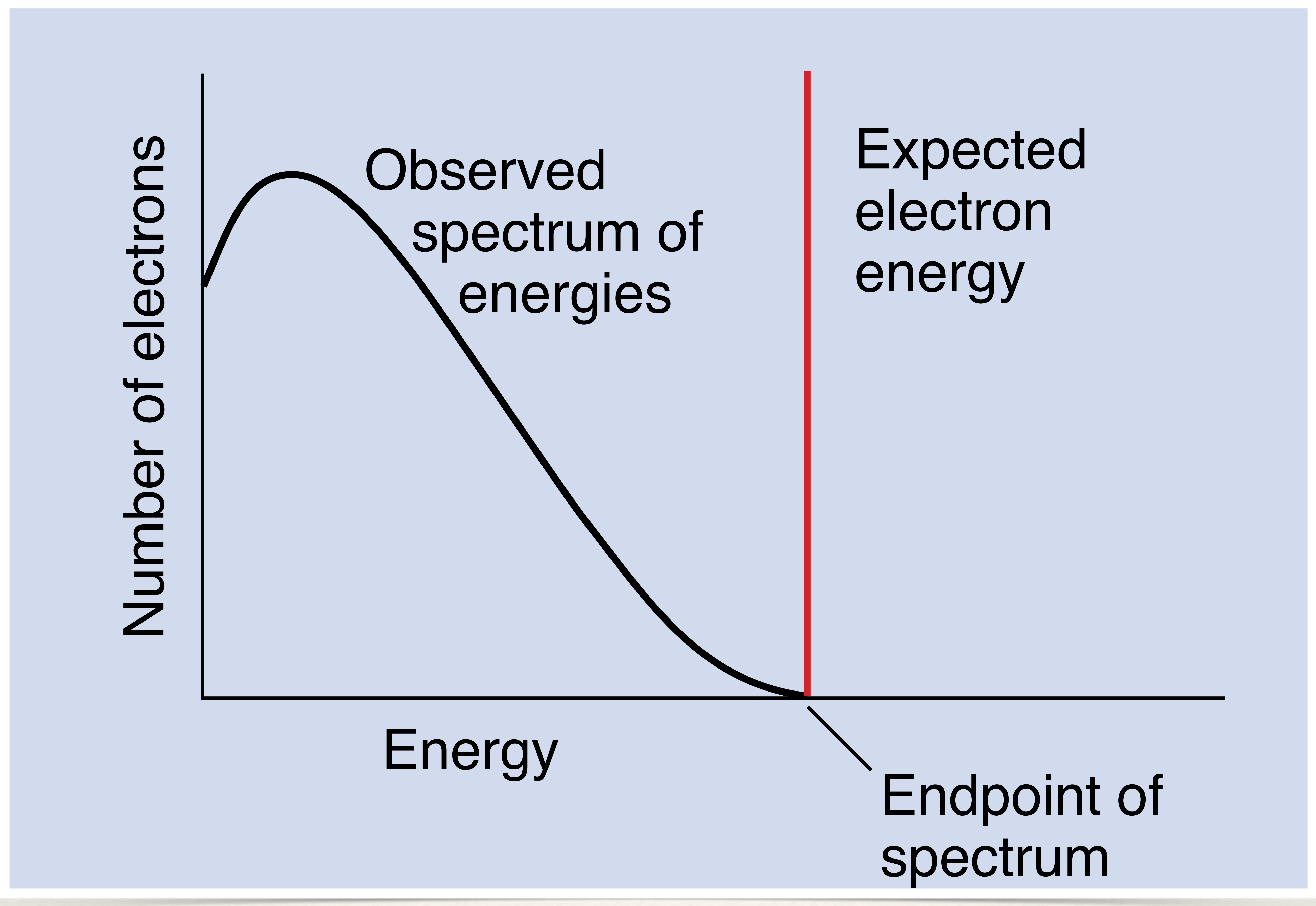
无中微子双贝塔衰变实验

韩柯
上海交通大学

Beta decay

- Beta spectra, continuous or mono-energetic? → Neutrinos
- 1930, Pauli: Idea of neutrino
- 1933, Fermi: Beta decay theory

$$n \to p + e^- + \bar{\nu}_e$$

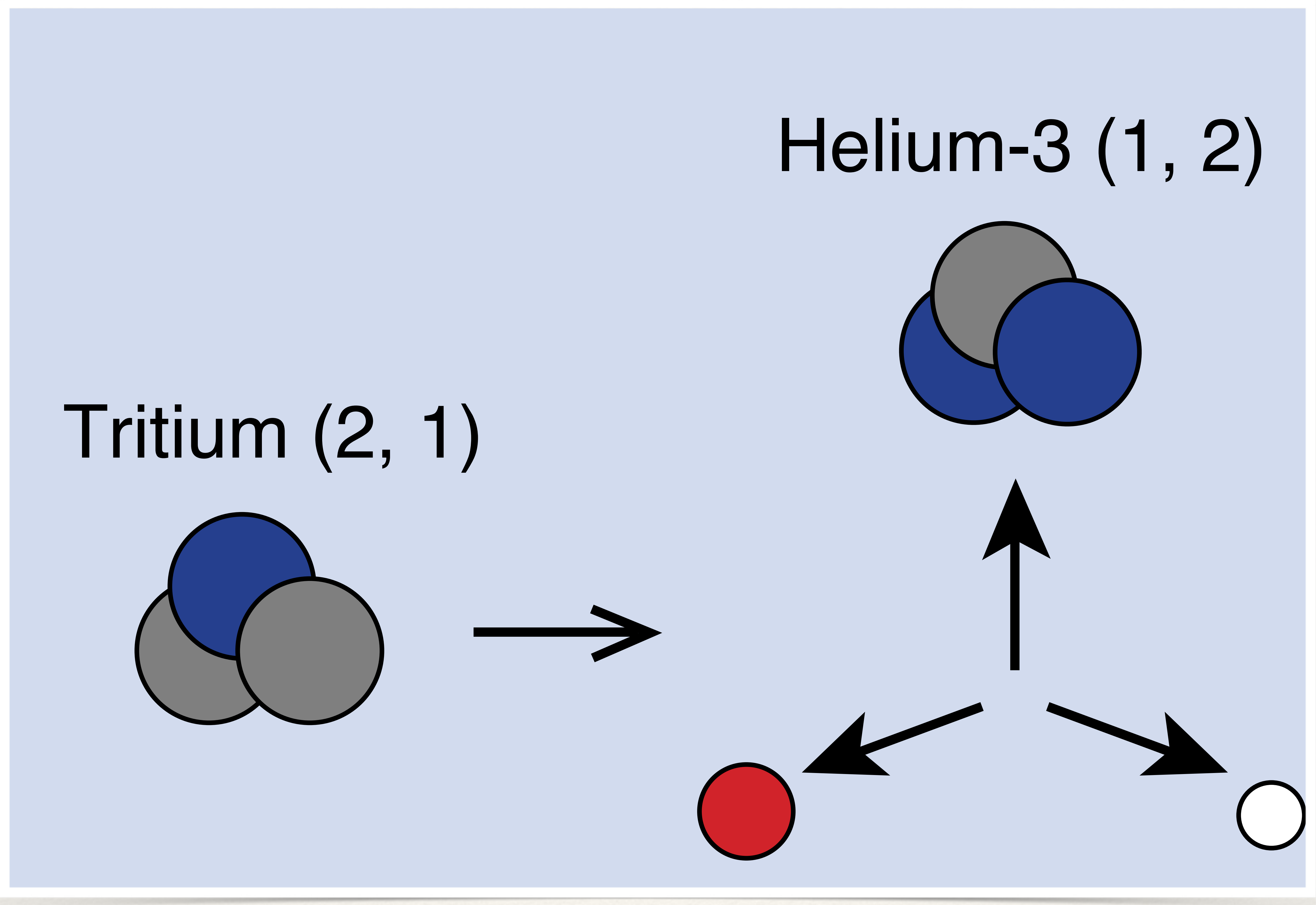


Beta decay

- Beta spectra, continuous or mono-energetic? → Neutrinos
- 1930, Pauli: Idea of neutrino
- 1933, Fermi: Beta decay theory

$$n \to p + e^- + \bar{\nu}_e$$

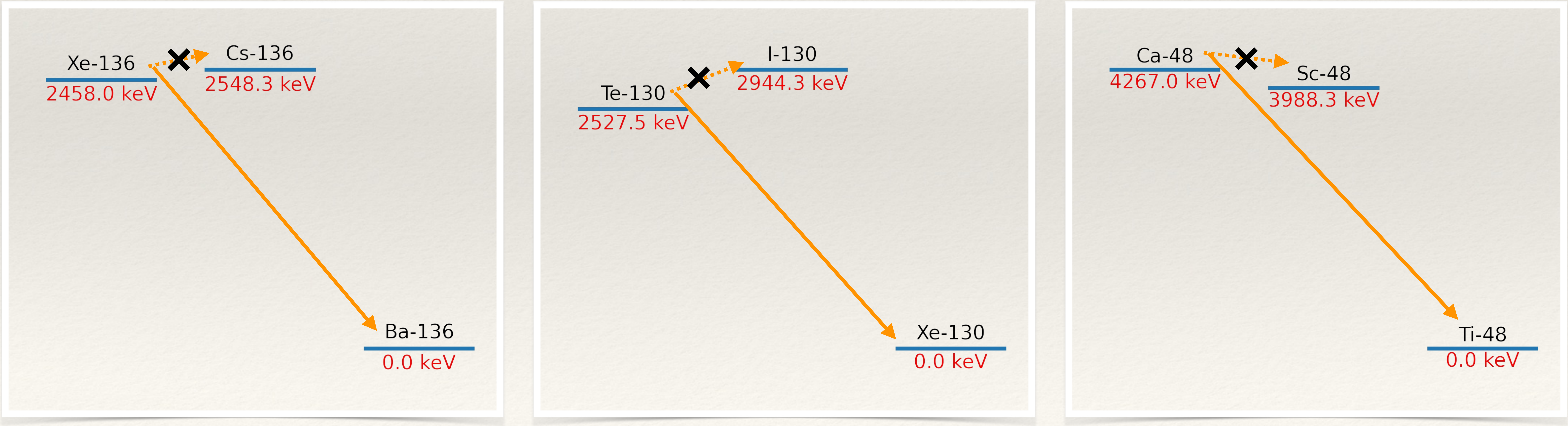
$$^3H \to {}^3He^+ + e^- + \bar{\nu}_e$$



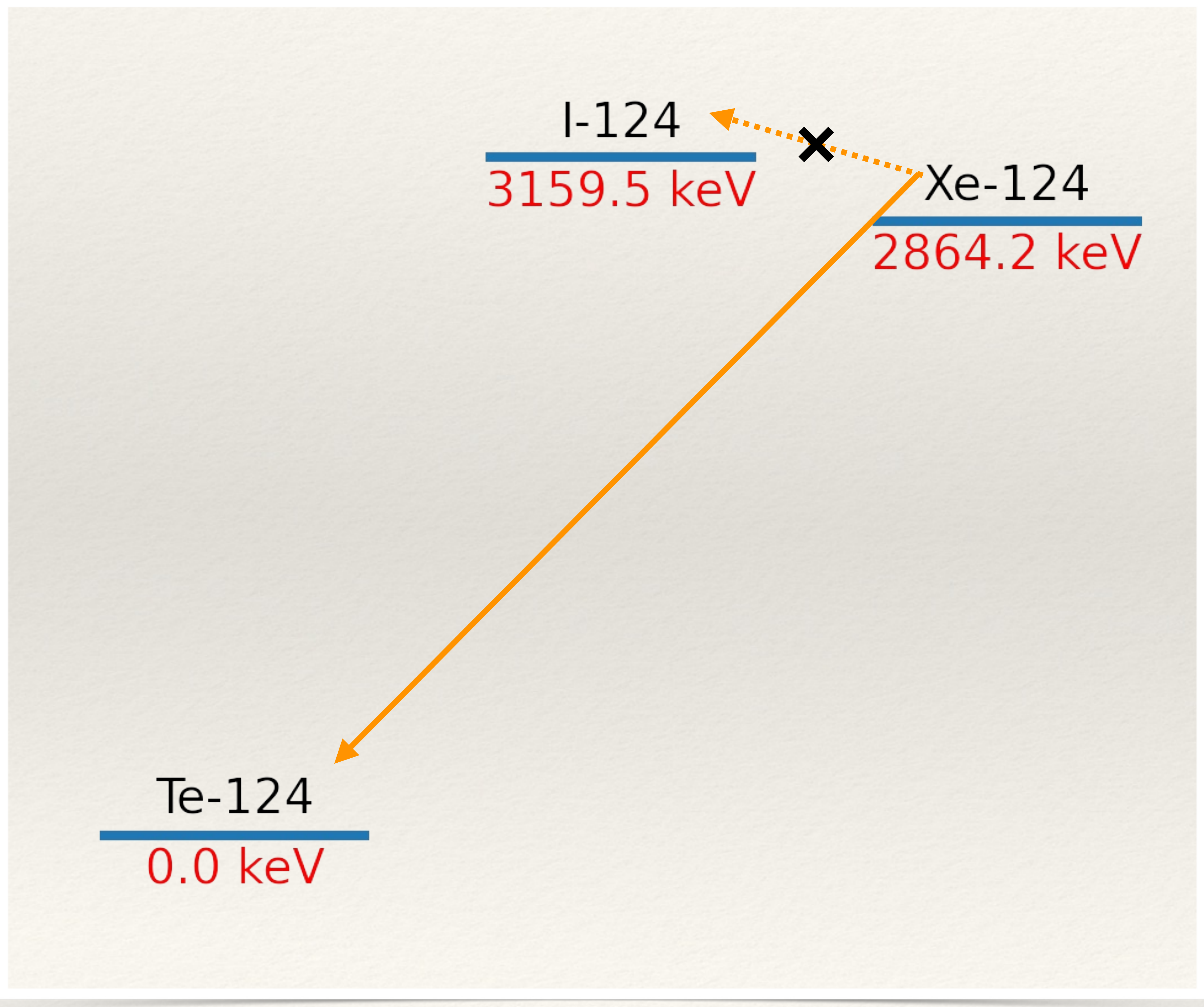
Double beta decay

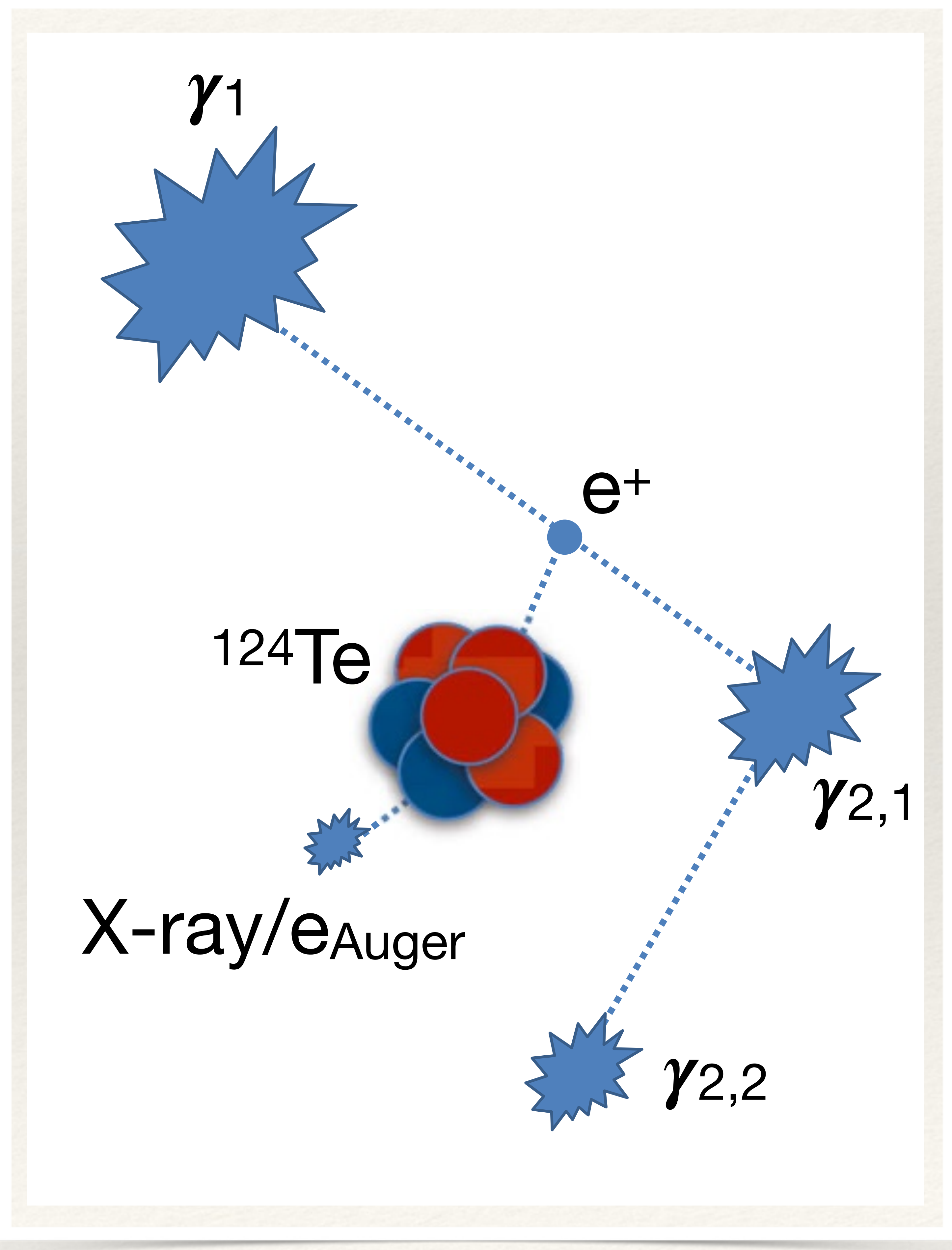
$$^{48}Ca \rightarrow {}^{48}Ti^{++} + 2e^- + 2\bar{\nu}_e$$

$$2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$$

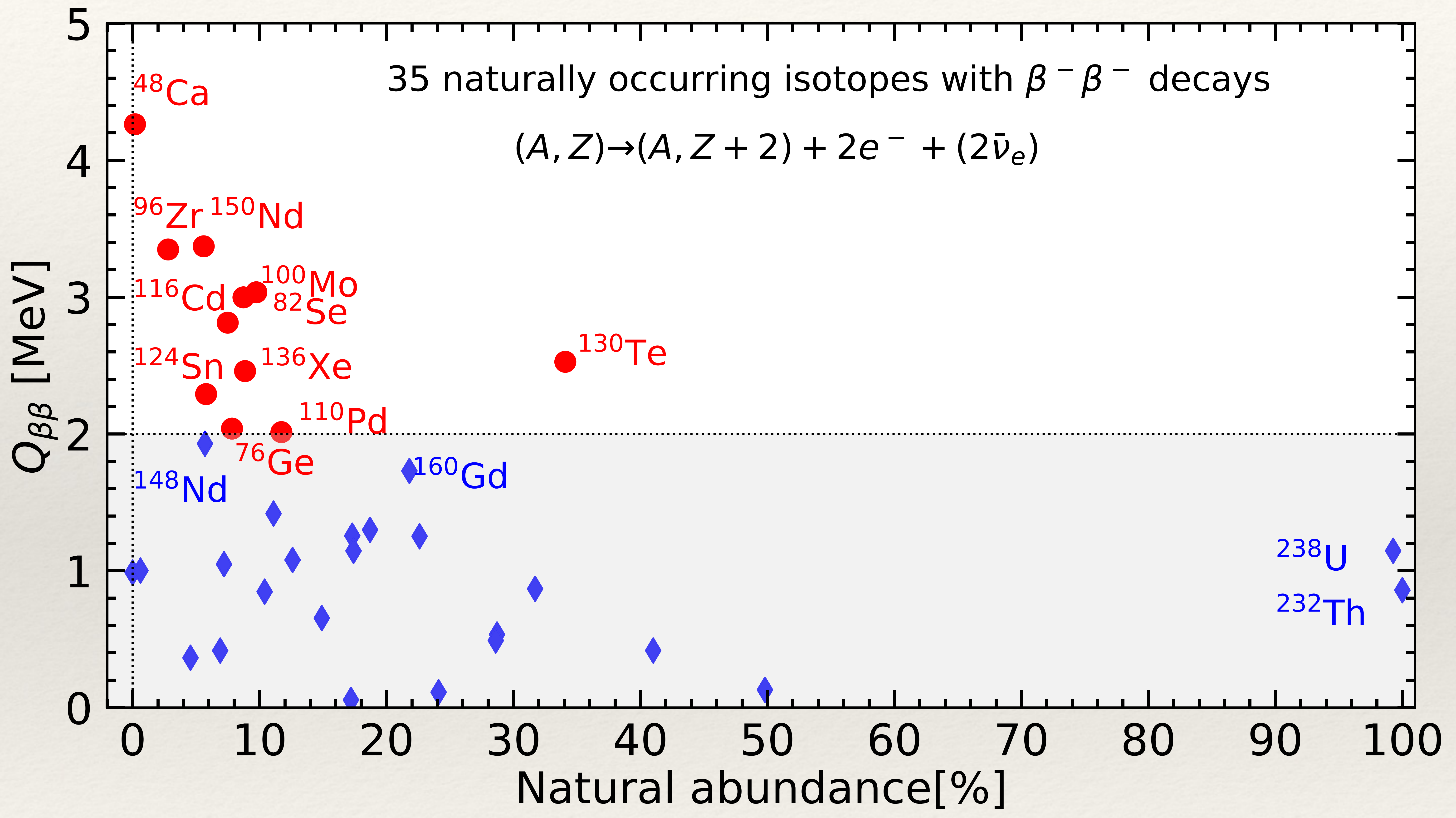


Double β⁺, double EC, and β⁺EC



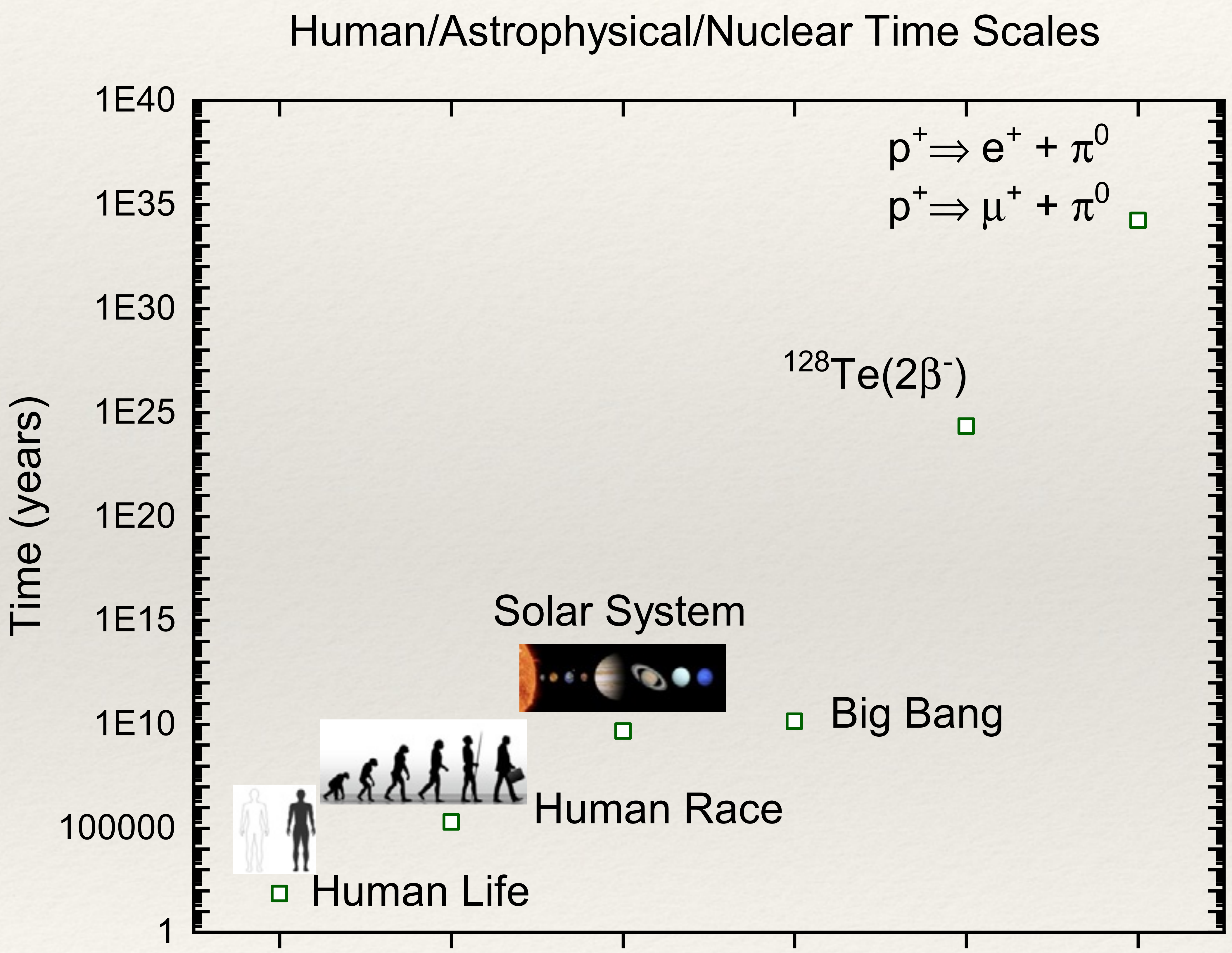


Candidate isotopes



- J.M. Yao, J. Meng, Y.F. Niu, P. Ring, Prog.Part.Nucl.Phys. 126 (2022), 103965

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±0.58)x10^{19}
^{76}Ge	2.03906	(1.43±0.53)x10^{21}
^{82}Se	2.9979	(9.19±0.76)x10^{19}
^{96}Zr	3.35603	(2.16±0.26)x10^{19}
^{100}Mo	3.03436	(6.98±0.44)x10^{18}
^{116}Cd	2.81349	(2.89±0.25)x10^{19}
^{128}Te	0.8667	(3.49±1.99)x10^{24}
^{130}Te	2.52751	(7.14±1.04)x10^{20}
^{136}Xe	2.45791	(2.34±0.13)x10^{21}
^{150}Nd	3.37138	(8.37±0.45)x10^{18}
^{238}U	1.1446	(2.00±0.60)x10^{21}

0νββ Decay rate

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

Phase space factor　Nuclear matrix element

Effective Majorana Mass:

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Effective Majorana Mass

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

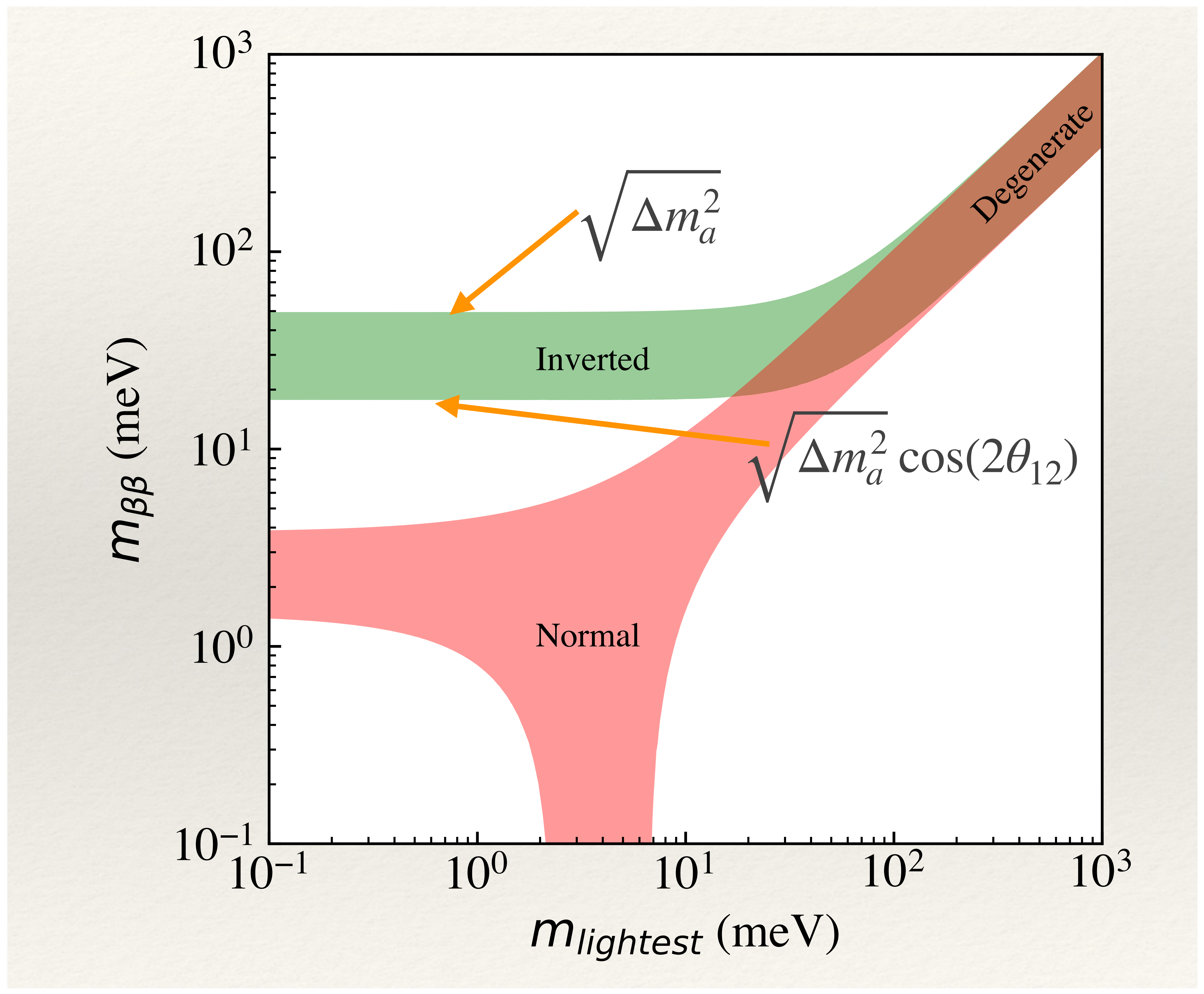
Inverted mass ordering:

$$m_3 \approx 0, m_1 \approx m_2 \approx \sqrt{\Delta m_a^2}$$

$$m_{\beta\beta} = |U_{e1}^2 + U_{e2}^2|\sqrt{\Delta m_a^2}$$

$$= |c_{12}^2 + s_{12}^2 e^{i2\alpha_2}|\sqrt{\Delta m_a^2}, (s_{13} \approx 0, c_{13} \approx 1)$$

$$\sqrt{\Delta m_a^2} \approx 50 \text{ meV}$$



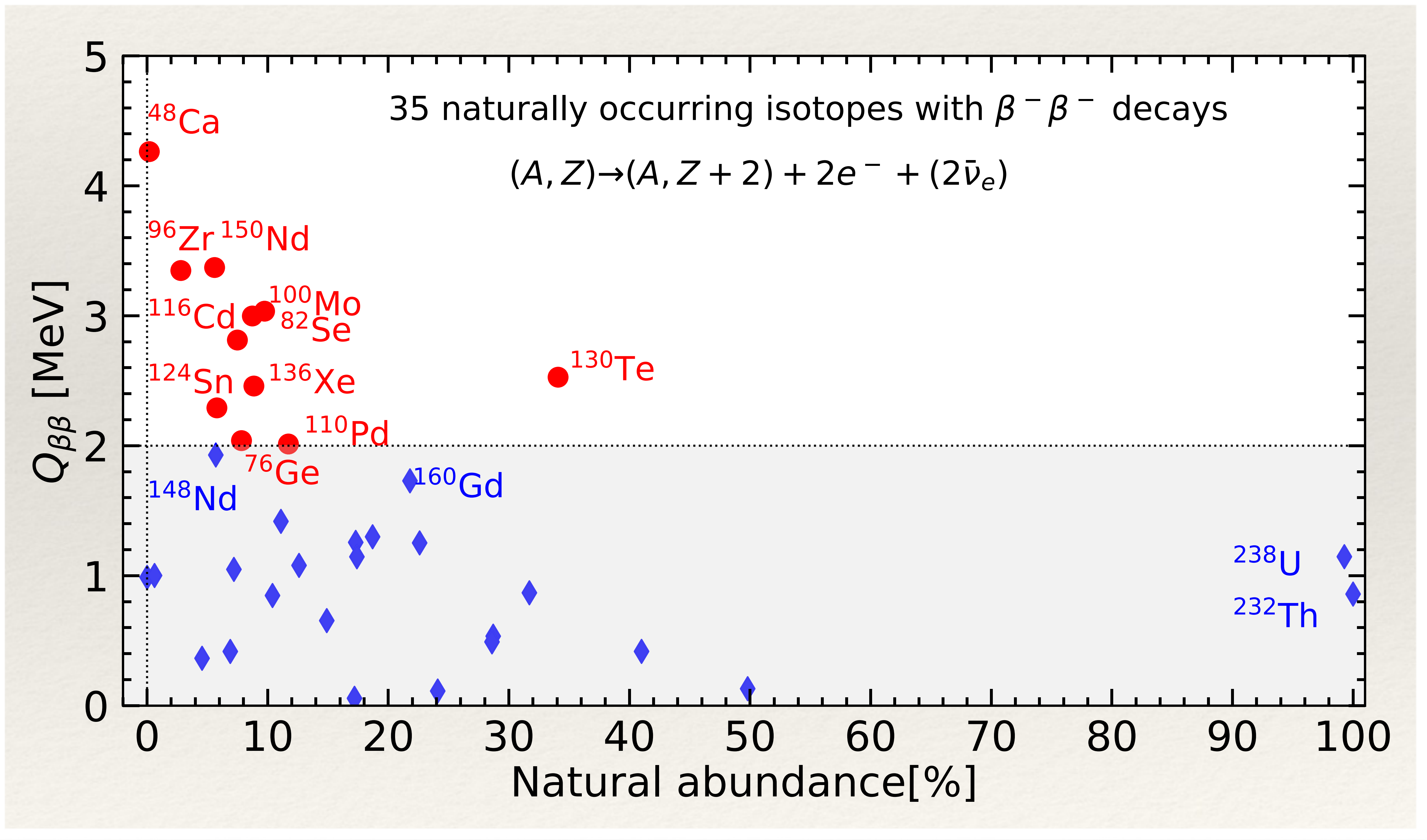
Importance of nuclear physics

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

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^- + Q(2458\,keV)$$

Phase space factor **Nuclear matrix element**

- $G^{0\nu} \propto Q^5$
- $M^{0\nu} \in [1,10]$ depending on isotopes, models

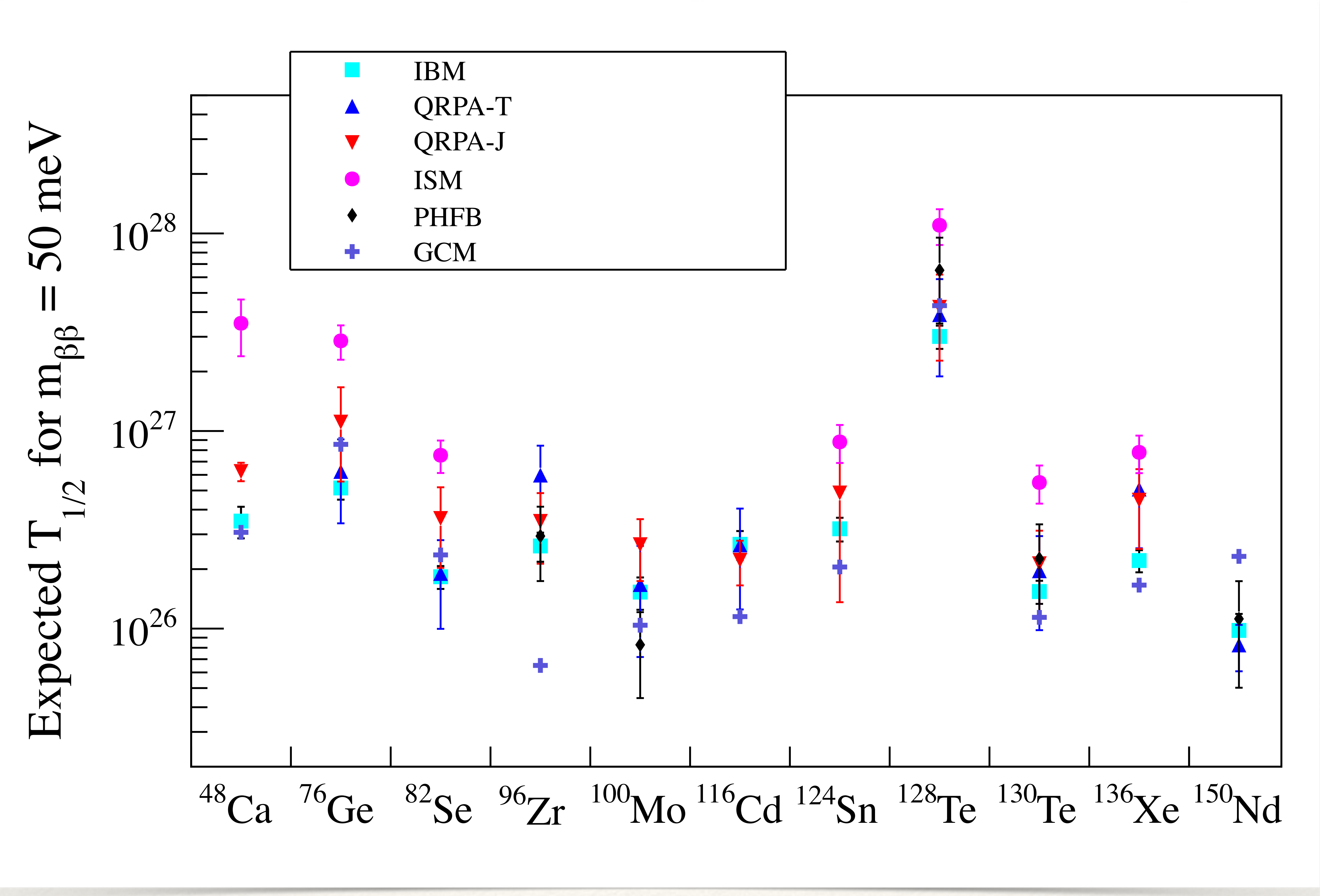


No magic isotopes

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

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^- + Q(2458\,keV)$$

Phase space factor **Nuclear matrix element**



- $G^{0\nu} \propto Q^5$
- $M^{0\nu} \in [1,10]$ depending on isotopes, models

The importance of 0νββ

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

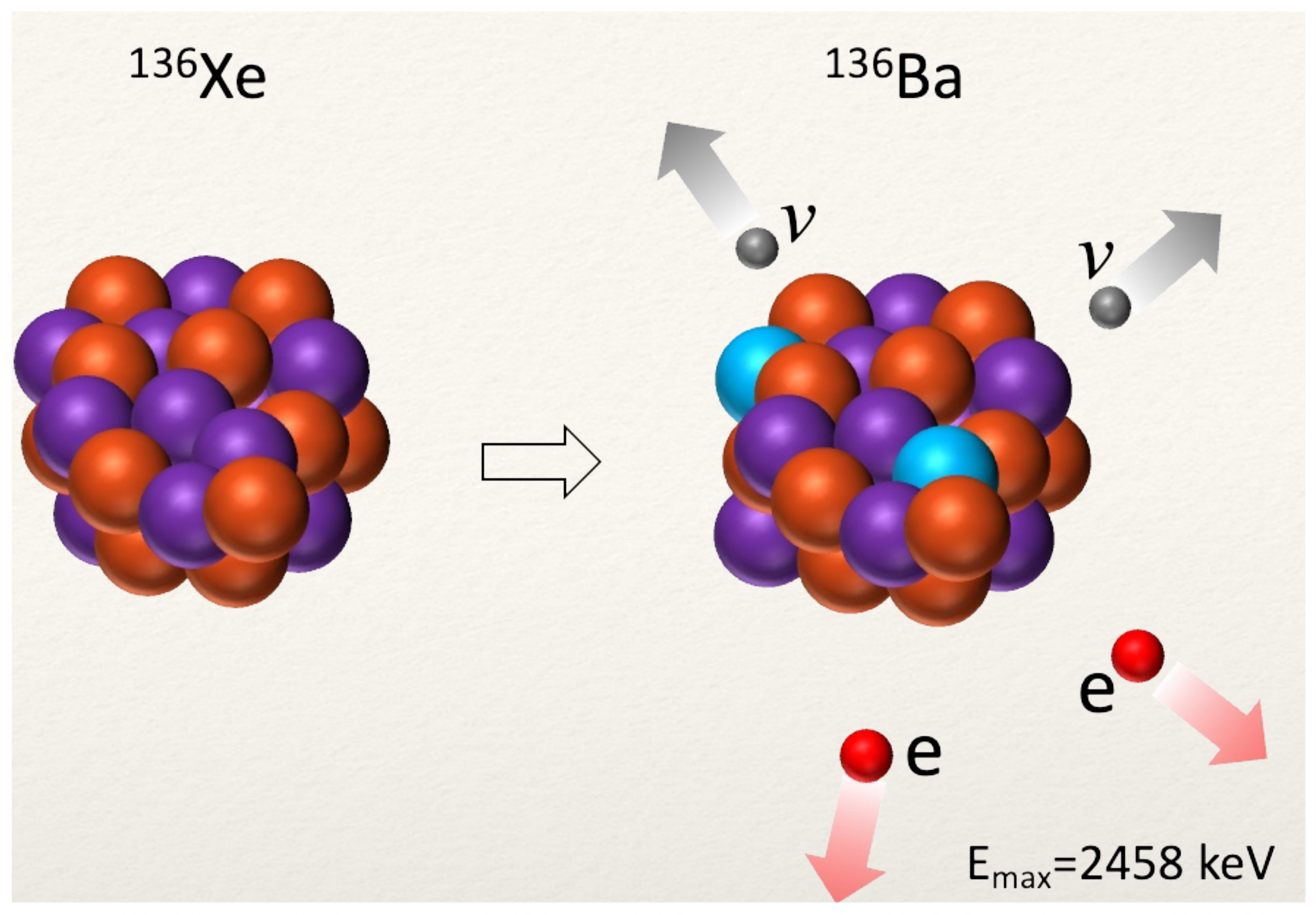
SNOLab

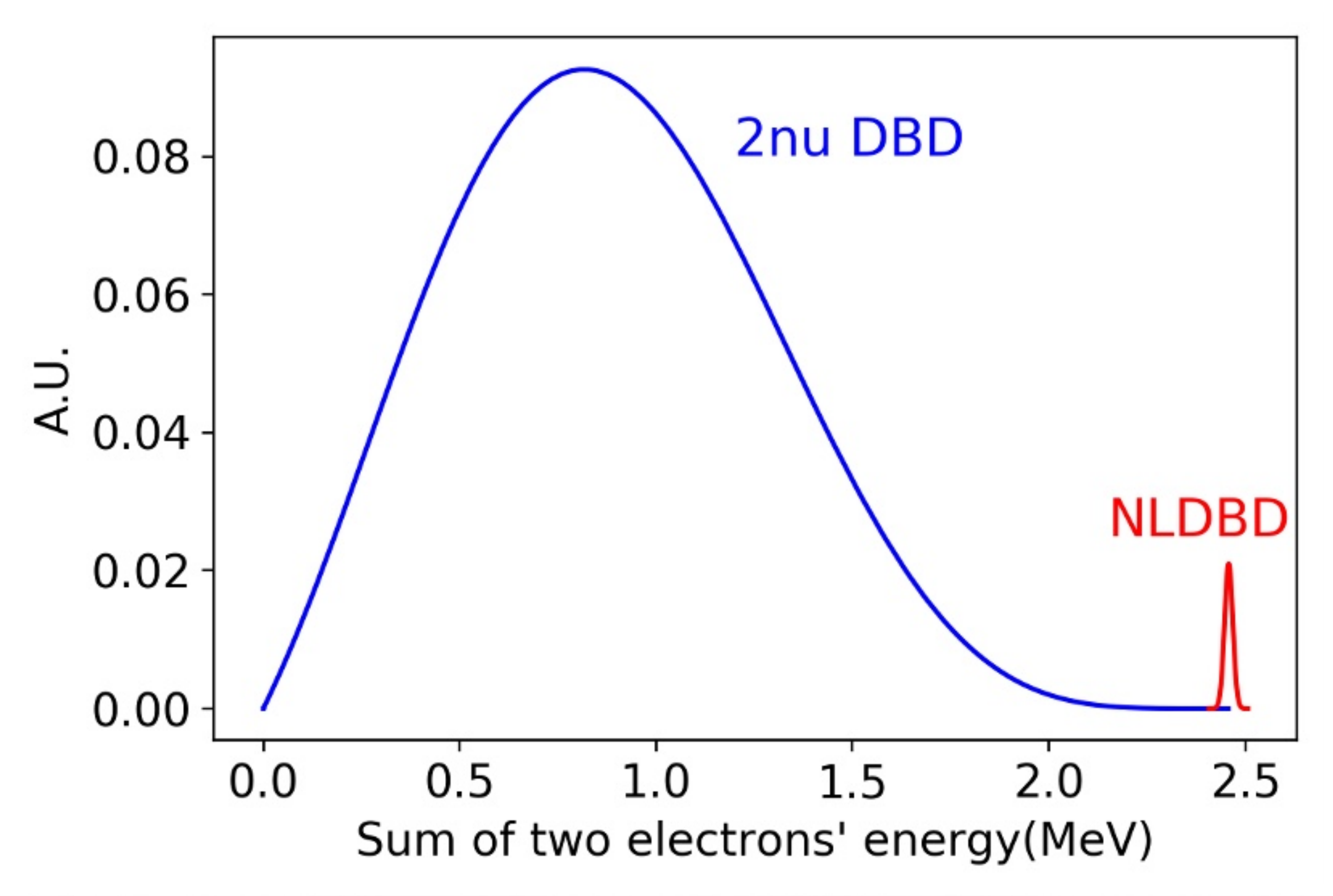
无双实验：技术挑战

韩柯
上海交通大学

Experimental Searches

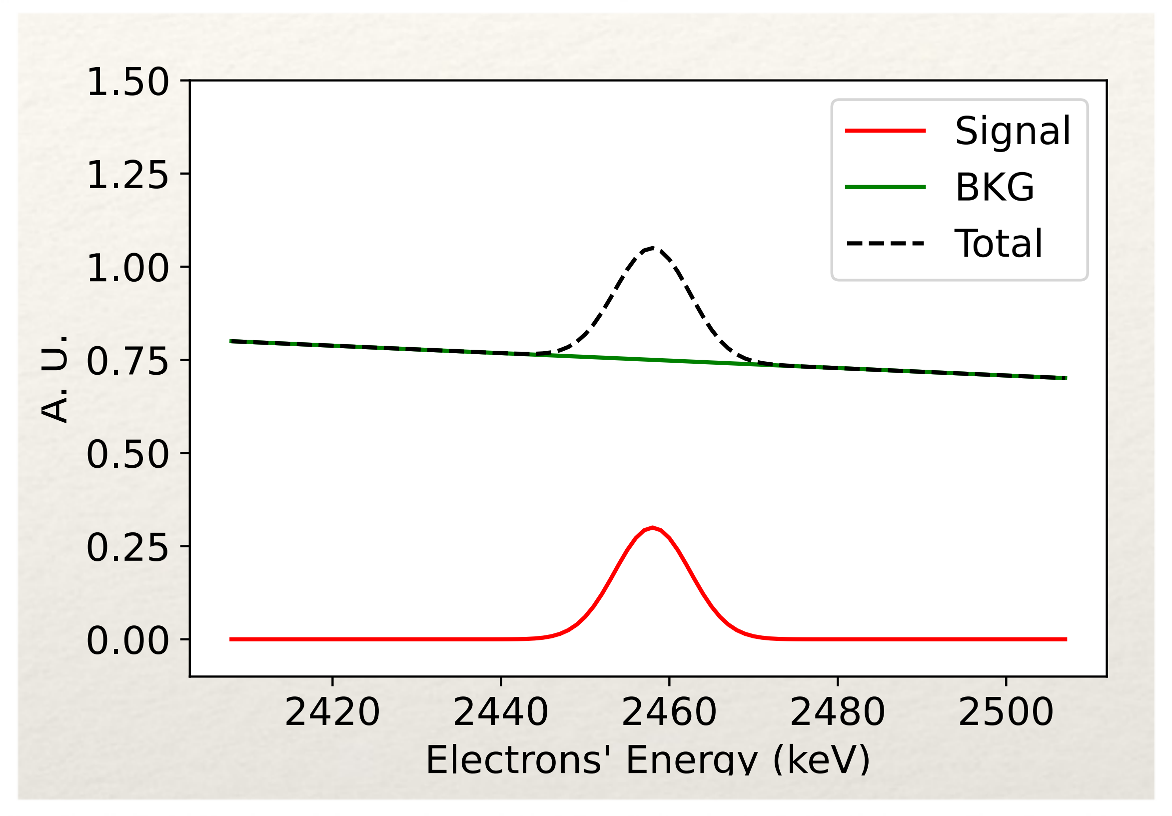
- Detect the electrons
  - Energy
  - Trajectories
- Detect the daughter nuclei
  - Geochemical and radiochemical
  - Imaging

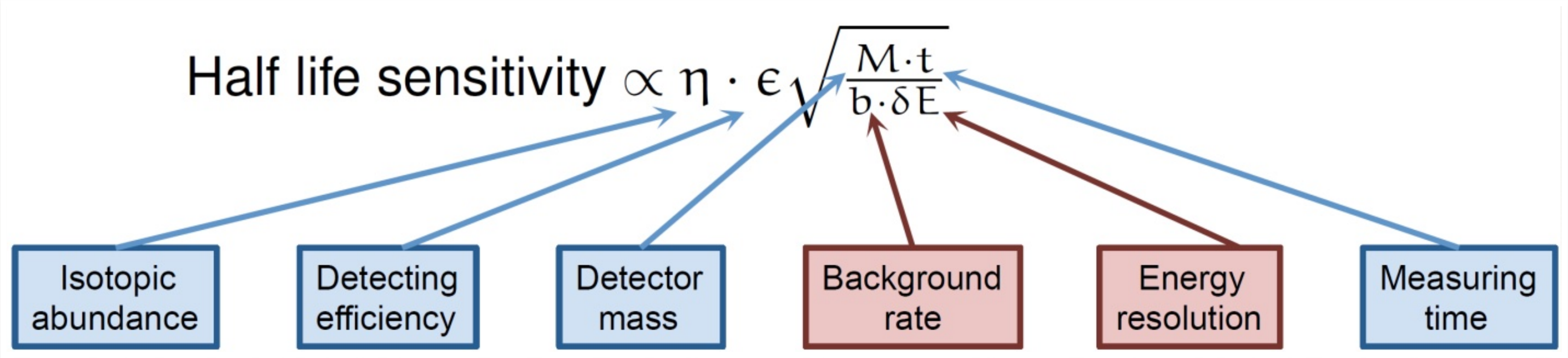




Half-life sensitivity from experiments

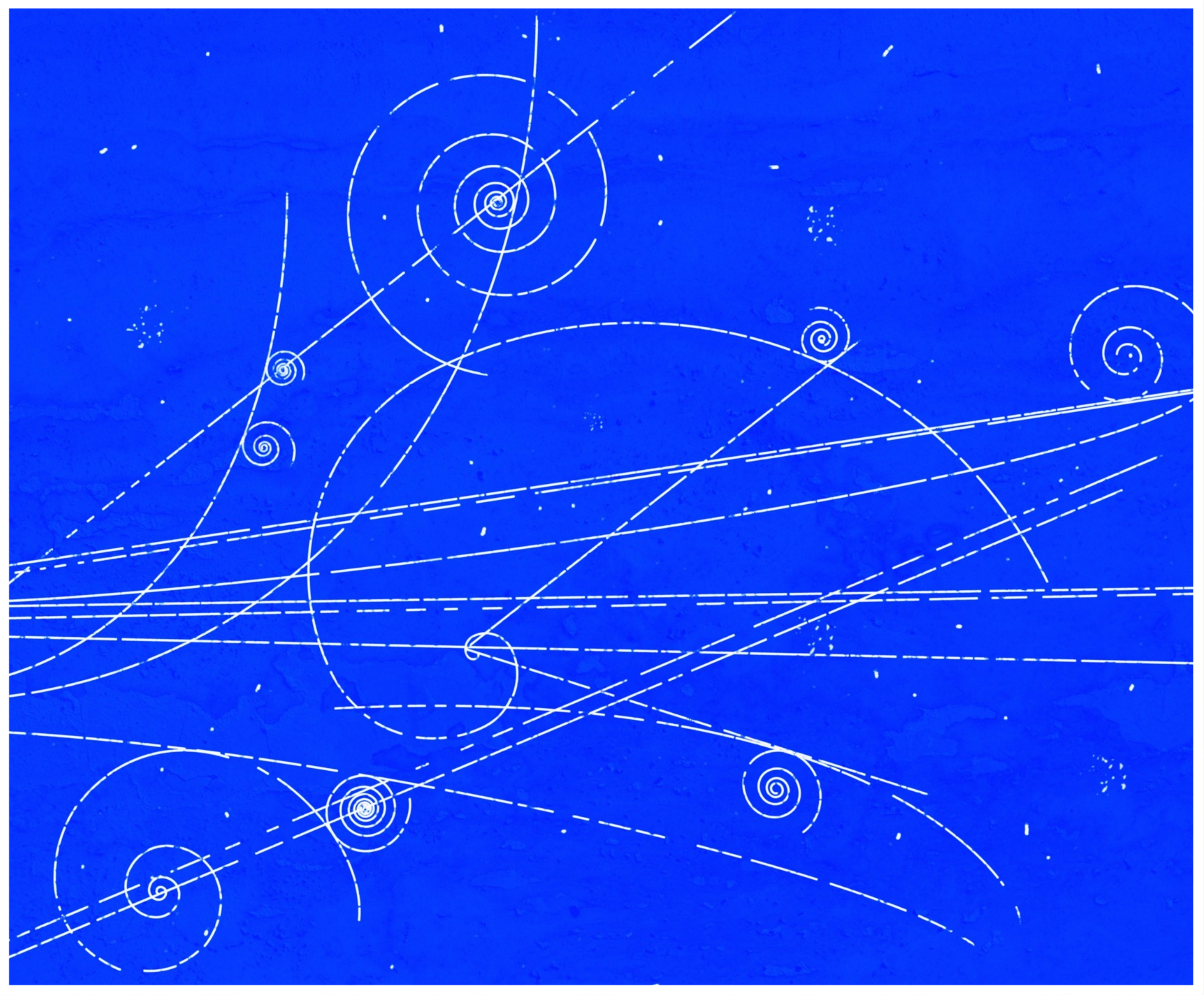
- Number of signals over fluctuation of background for possible observation
- Extreme requirements for detector performance and background control





A bit history

- 1948: Coincidence counting with Geiger counter for $^{124}Sn \rightarrow {}^{124}Te$
- 百花齐放: cloud chamber, etc



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- 各显神通: Cowan and Reines, C.S. Wu, etc

Test of Neutrino—Antineutrino Identity

Clyde L. Cowan, Jr. and Frederick Reines

Phys. Rev. **106**, 825 – Published 15 May 1957

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

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

Phys. Lett. B 26 (1967) 112

RESEARCH ARTICLE | MARCH 20 1983

Double beta decay-an experimental review

Chien-Shiung Wu

Check for updates

AIP Conference Proceedings 96, 374–395 (1983)

https://doi.org/10.1063/1.33918

A bit history

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- 1967: Fiorini et al., Ge detector

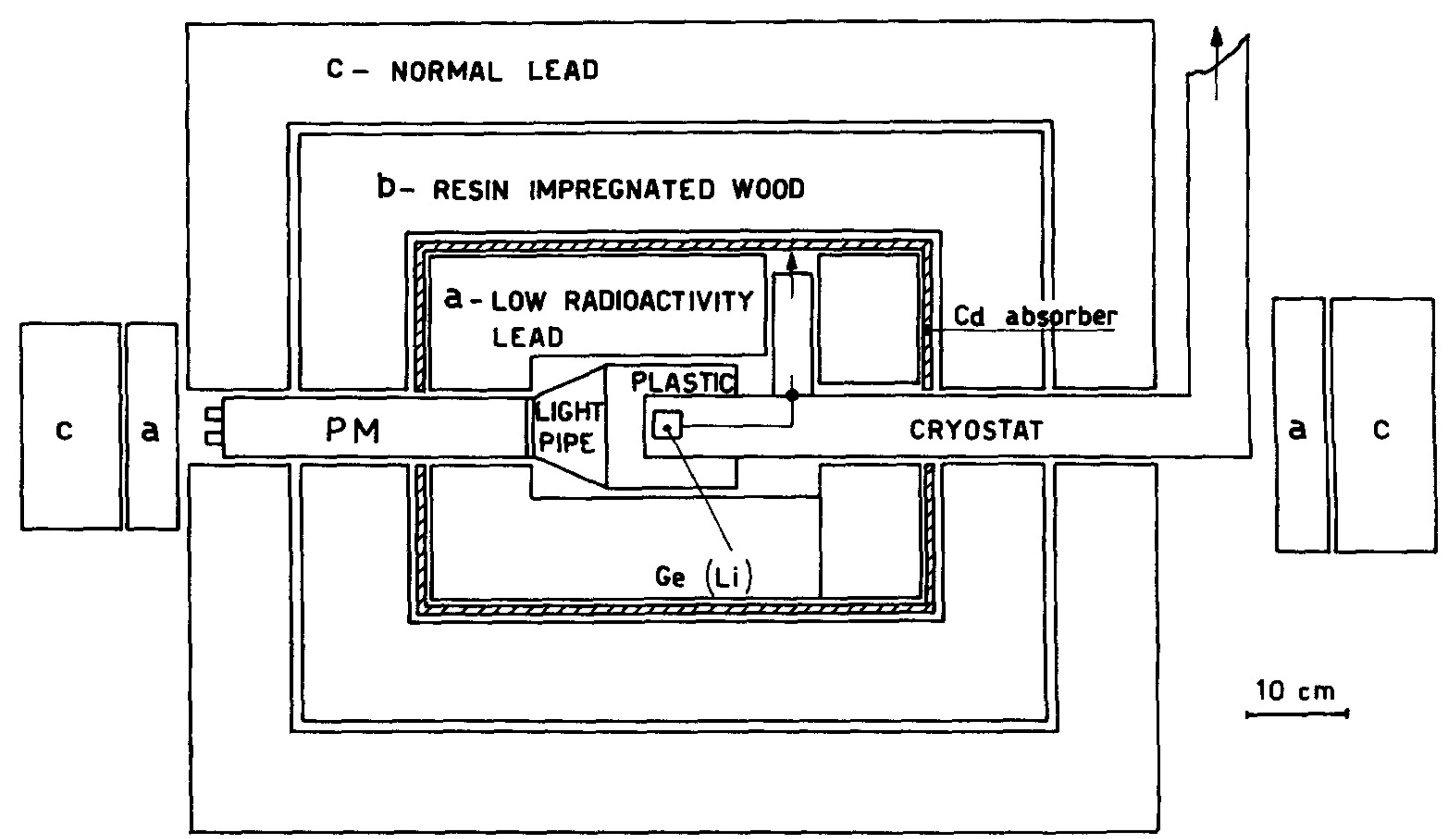

Fig. 1. Experimental setup.

A bit history

- 1948: Coincidence counting with Geiger counter for $^{124}Sn \rightarrow {}^{124}Te$
- 百花齐放: cloud chamber, etc
- 各显神通: Cowan and Reines, C.S. Wu, etc
- 1967: Fiorini et al., Ge detector
- 1980~: H.H. Chen et al., Xe TPC

H.H. Chen and P.J. Doe, An improved method to test the lepton number conservation, The liquid Xenon time projection chamber, UCI-Neutrino-40, Int. Rep. June 1980.

S.-D. Boris et al., ITEF-47, Moscow 1982 and private communication by V.A. Lubimov.

E. Bellotti et al., Xenon time projection chamber for double-beta decay, CERN-EP/83-144, Presented at the Time Projection Chamber Workshop, Vancouver B.C. (Canada) 1983.

A proposal for the construction of a TPC for the search for double-beta decay has been presented to the funding authorities by the Caltech group (private communication by F. Boehm).

A bit history

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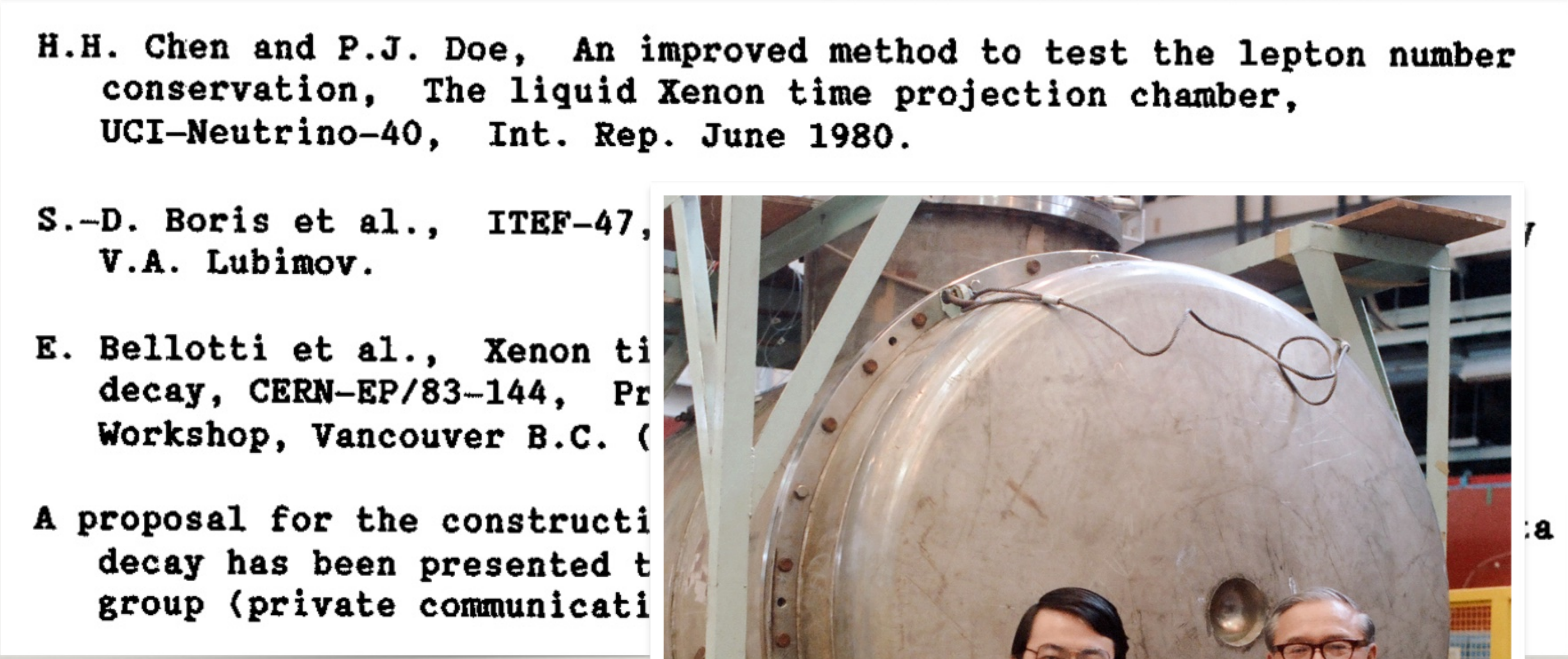
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decay, CERN-EP/83-144, Pr
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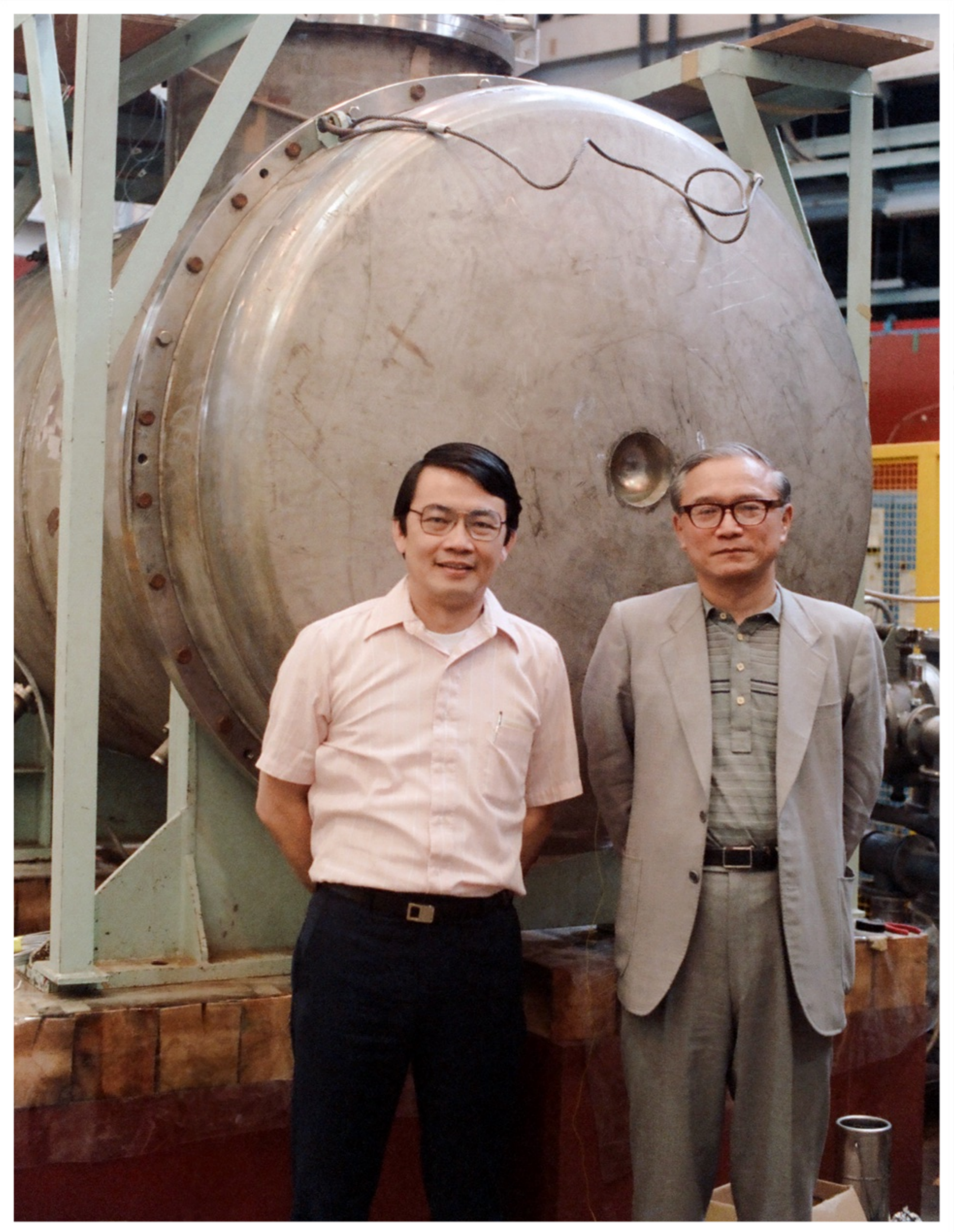
group (private communicati



陈华生
1942-1987

A bit history

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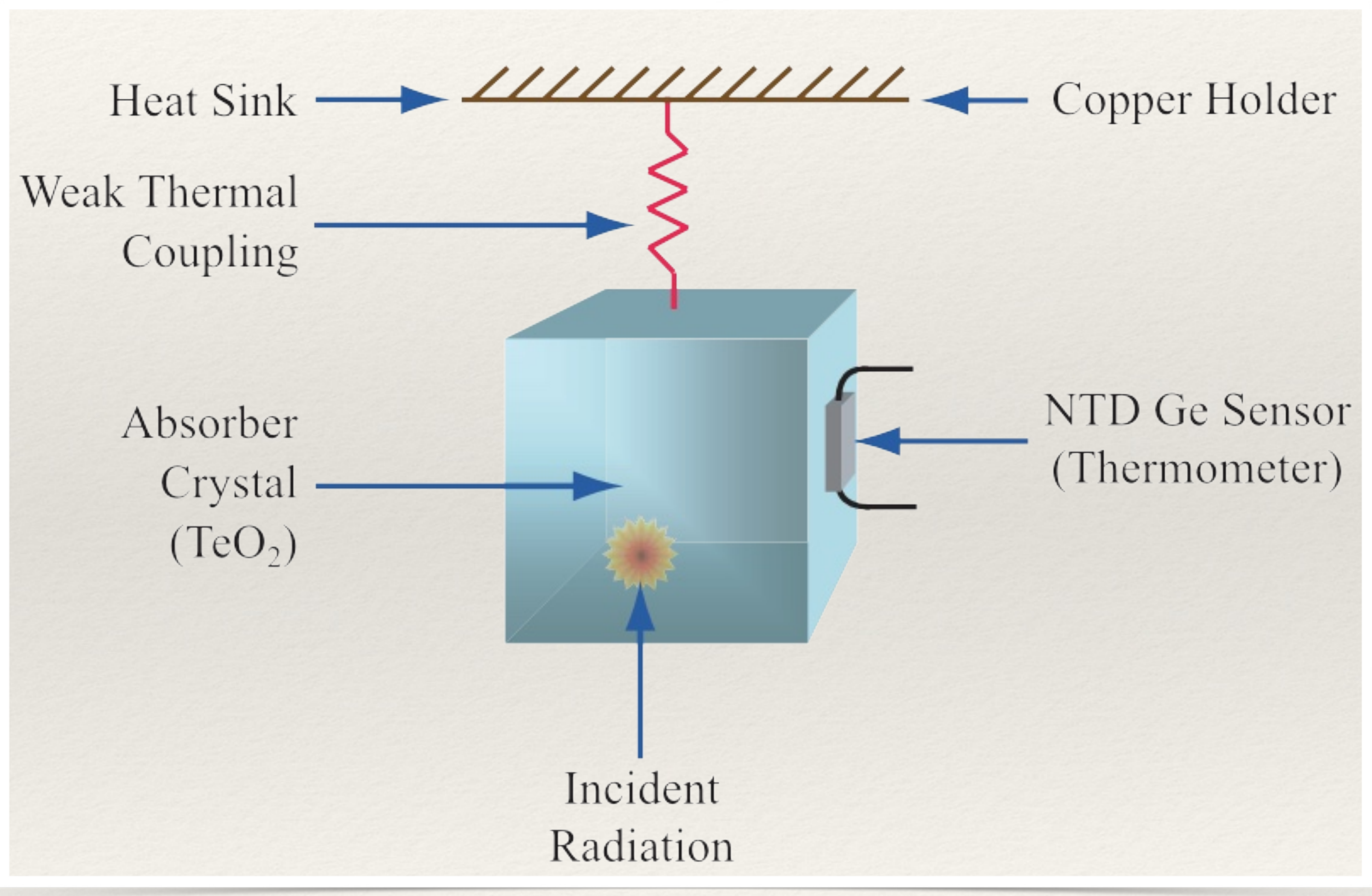
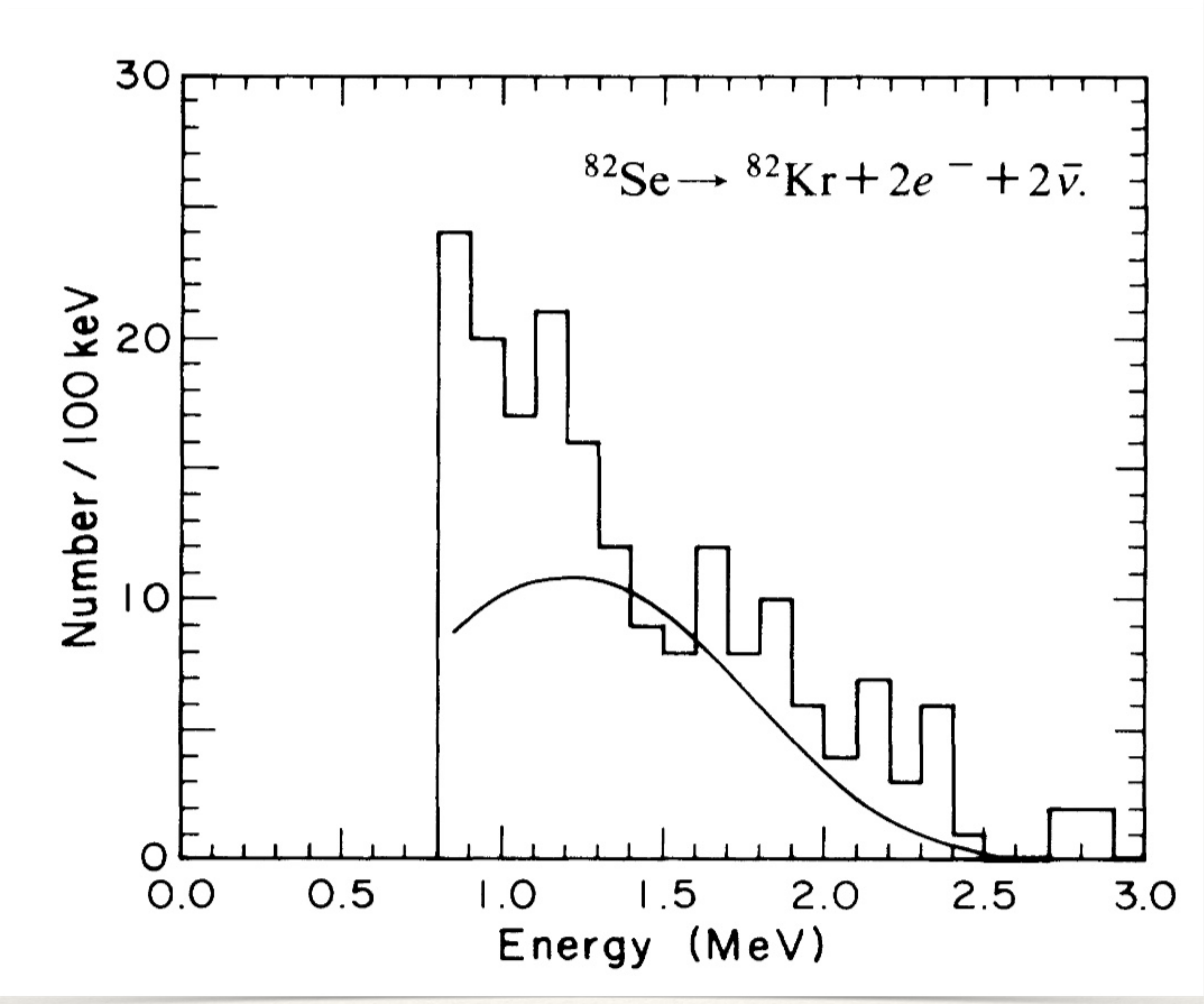
- 1967: Fiorini et al., Ge detector
- 1980~: H.H. Chen et al., Xe TPC
- 1984: Fiorini and Niinikoski, Low temperature detector



Discovery of 2νββ

- Elliott, Hahn, Moe, Direct evidence for two-neutrino double-beta decay in ^{82}Se. Phys. Rev. Lett. 59, 2020 (1987)
- UC Irvine (Reines)
- "The two-neutrino mode of double-beta decay ^{82}Se in has been observed in a time-projection chamber at a half-life of $(1.1^{+0.8}_{-0.3}) \times 10^{20}$ yr (68% confidence level). … It is the rarest natural decay process ever observed directly in the laboratory."

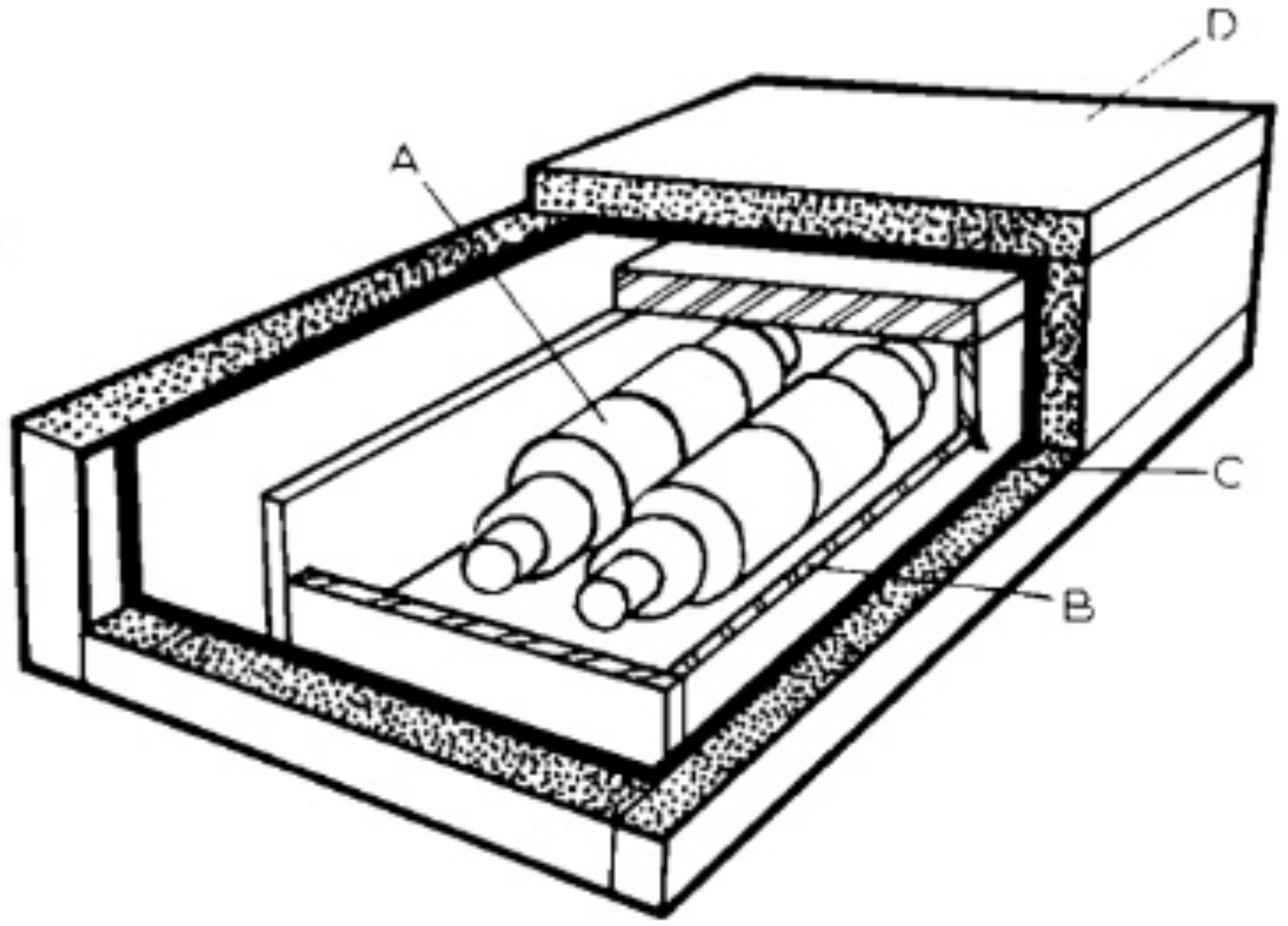


First experiment in China

A search for neutrinoless double β decay of ^{48}Ca ☆

Ke You [a], Yucan Zhu [a], Junguang Lu [a], Hanseng Sun [a], Weihua Tian [a], Wenheng Zhao [a], Zhipeng Zheng [a,b], Minghan Ye [a,b], Chengrui Ching [b,c], Tsohsiu Ho [b,c], Fengzhu Cui [d], Changjiang Yu [d] and Guojing Jiang [d]

[a] *Institute of High Energy Physics, Academia Sinica, P.O. Box 918, Beijing 100039, China*
[b] *China Center of Advanced Science and Technology (World Laboratory), P.O. Box 8730, B*
[c] *Institute of Theoretical Physics, Academia Sinica, P.O. Box 2735, Beijing 100080, China*
[d] *Institute of Optics and Fine Mechanics, Academia Sinica, Changchun, China*



Received 10 December 1990; revised manuscript received 5 June 1991

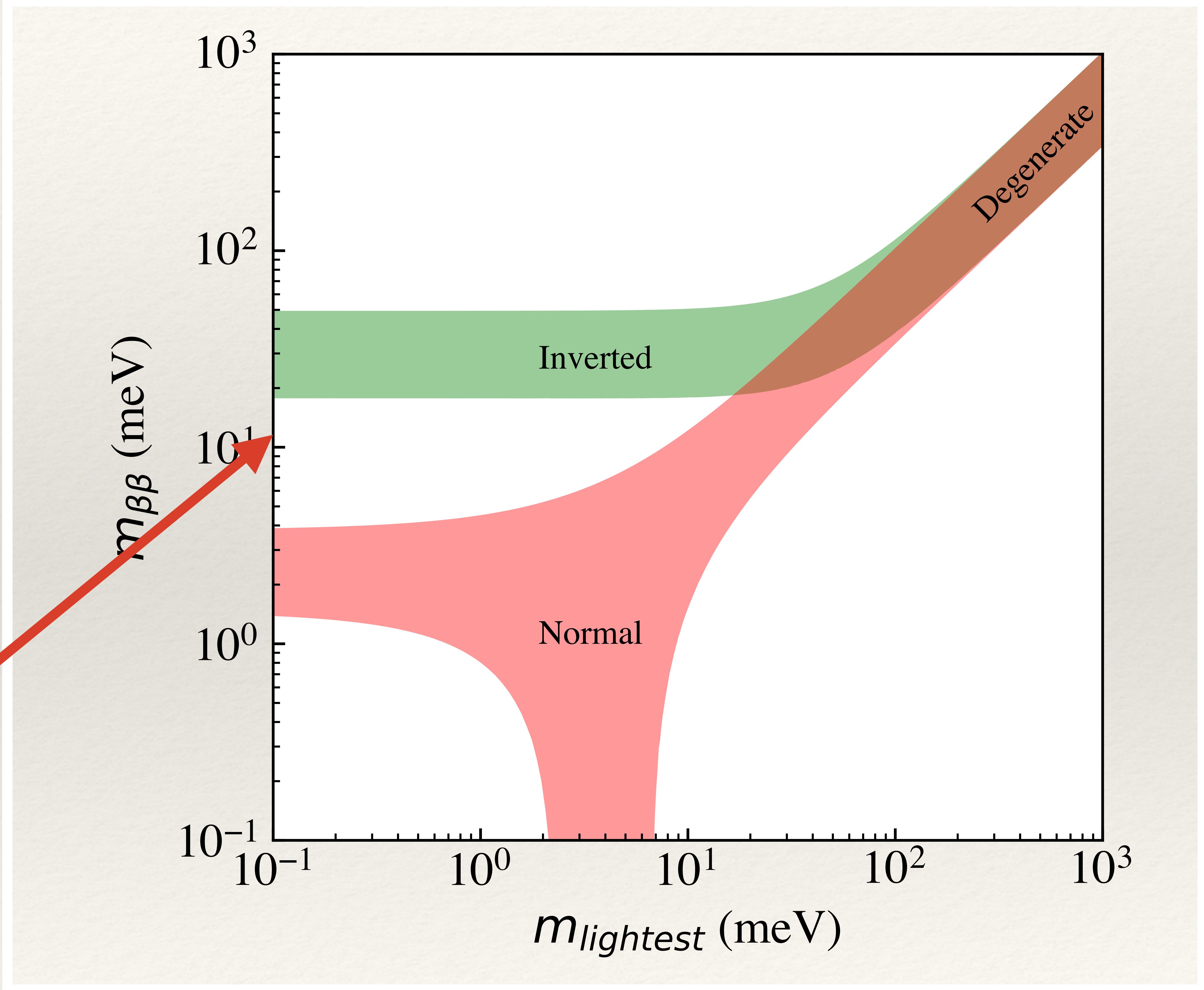
A search for the neutrinoless double β decay of ^{48}Ca is carried out in a coal mine near Beijing. Large scintillation crystals of natural CaF_2 were used as both detector and β source. Results obtained after a total of 7588.5 h of data taking give 9.5×10^{21} yr (76% confidence level) as the lower limit of the half-life of neutrinoless double β decay of ^{48}Ca.

Small signals

$$S = \ln(2)\frac{M \cdot N_A \cdot a \cdot \varepsilon}{W}\frac{t}{T_{0\nu}}$$

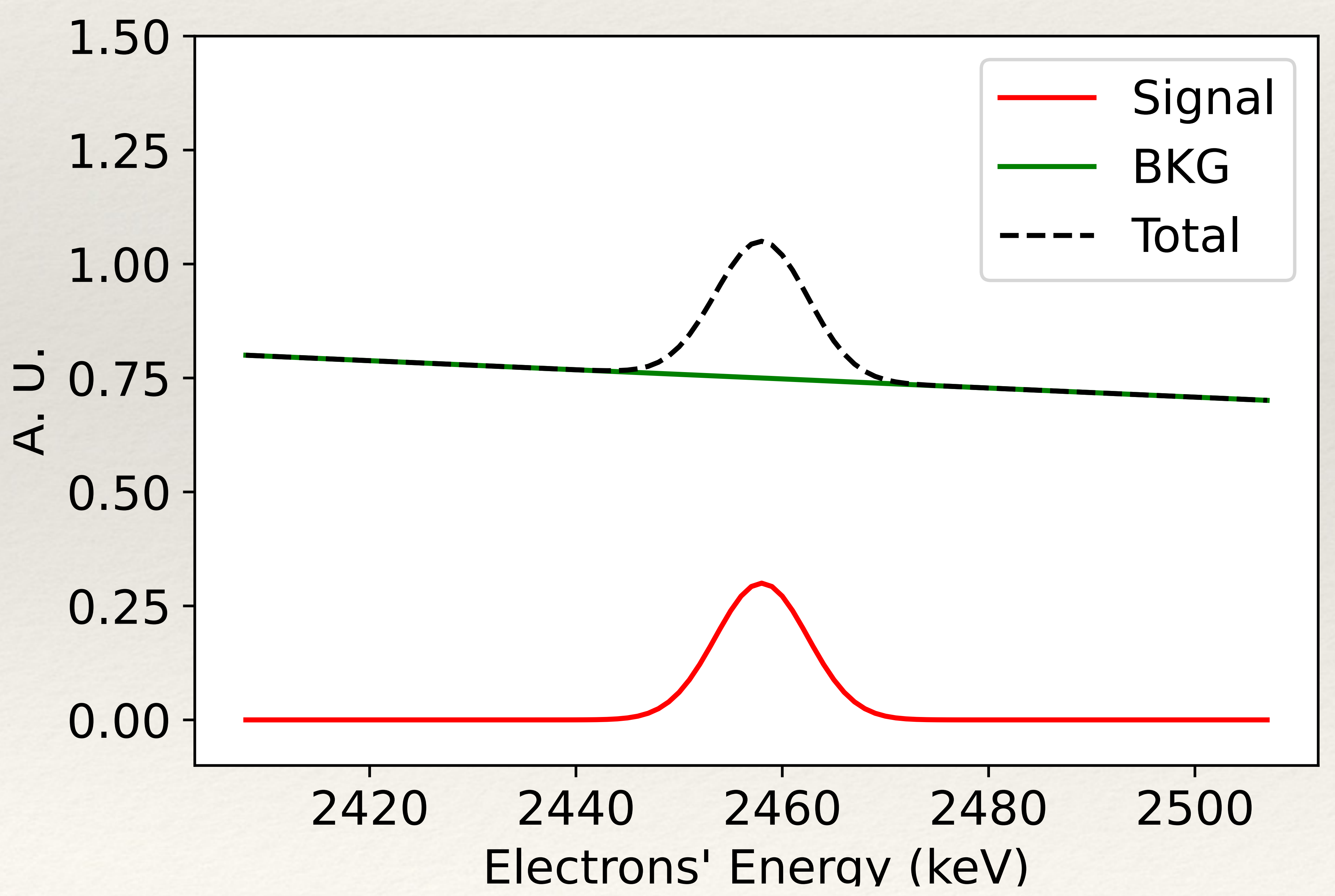
M	Mass	ε	Efficiency
N_A	6.02×10^{23}	W	Molar mass
a	Abundance	t	Detection time

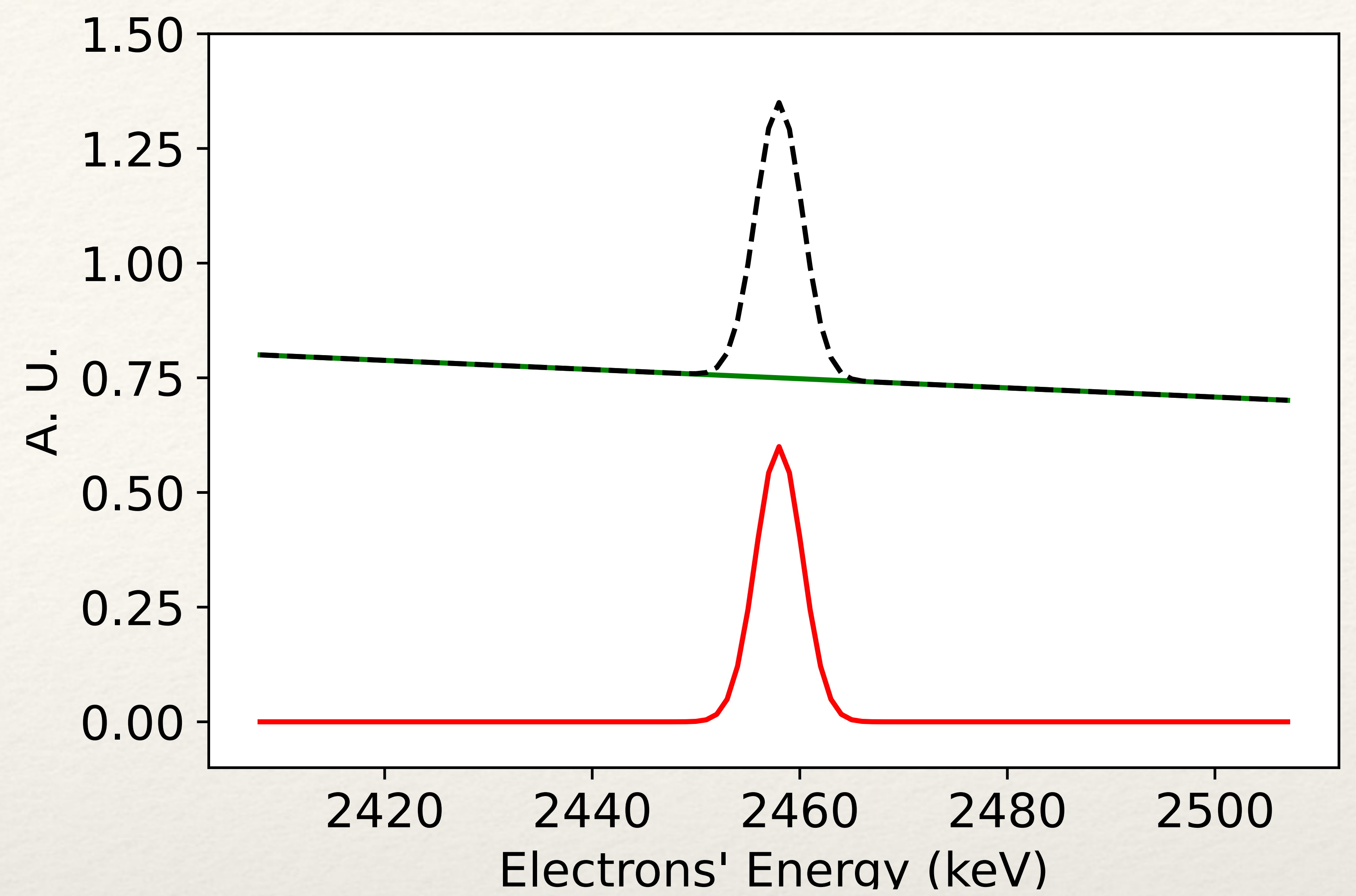
- Current half-life limits $>10^{26}$ year
  - 100 kg 90% enriched ^{136}Xe: fewer than three signals per year
- Sensitivity of ton-scale experiments: 10^{27} to 10^{28} year
  - Fewer than 1 event/year

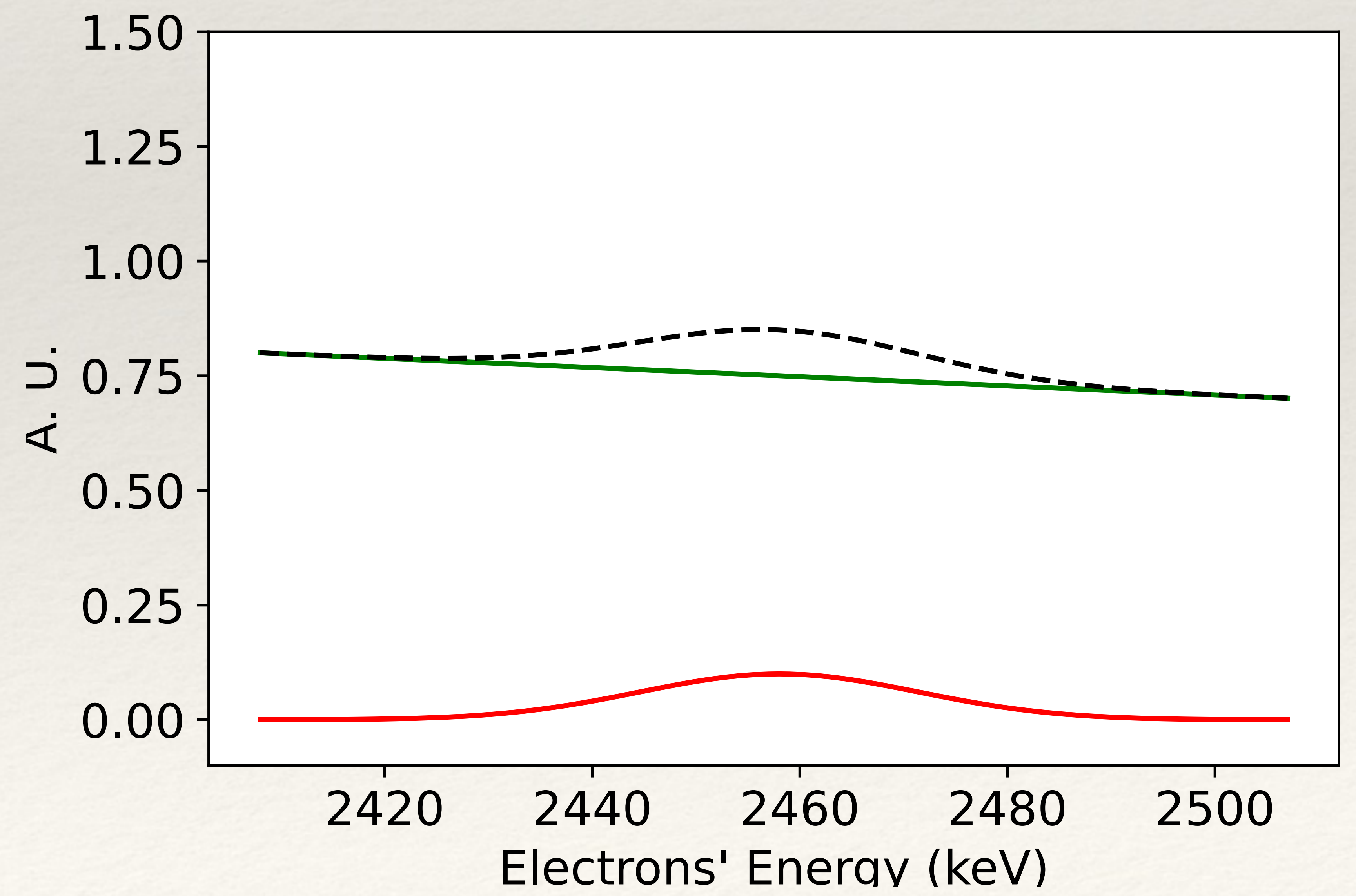


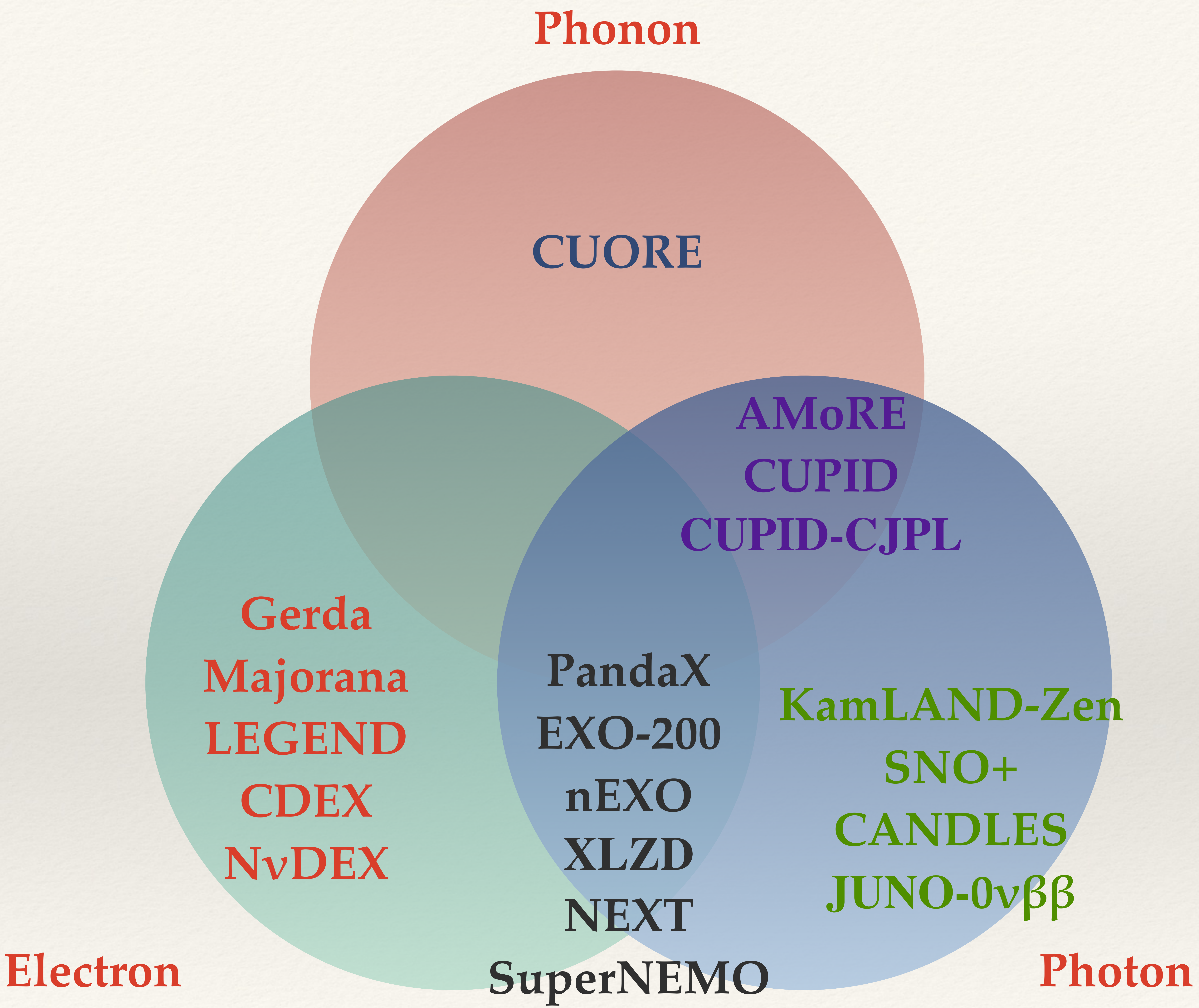
Extreme Detector requirements

- Background
- Performance (Efficiency, Resolution)

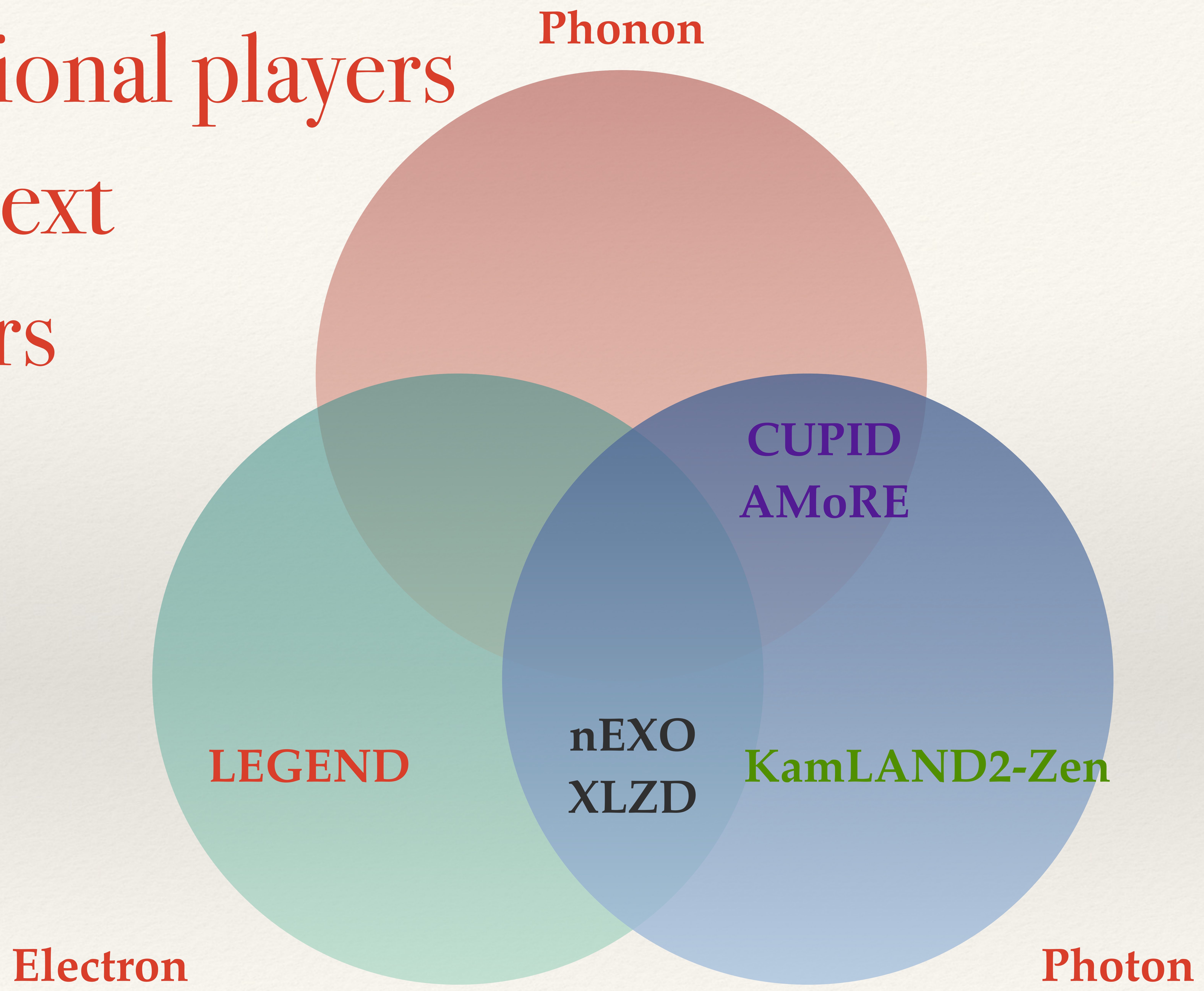




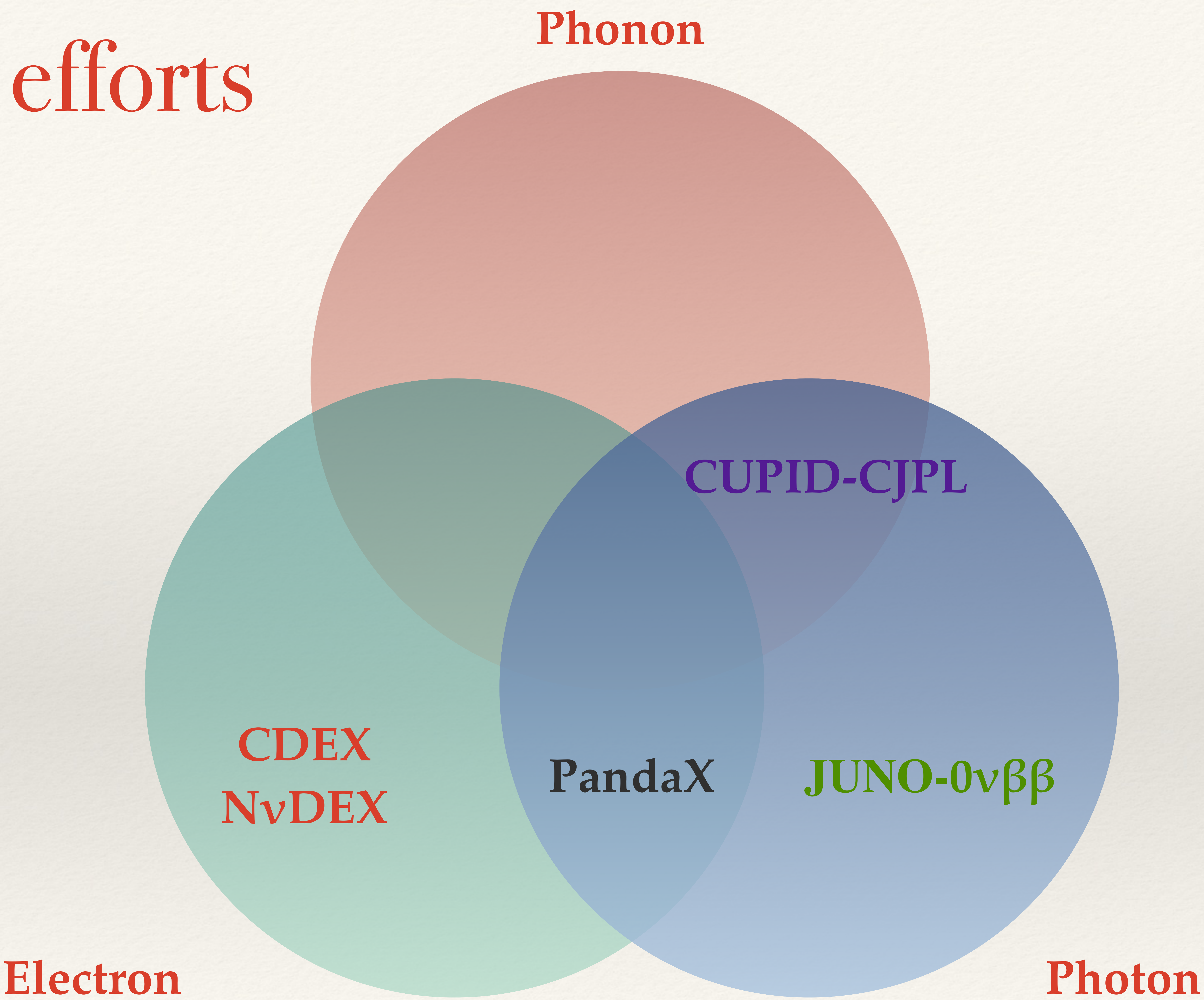



Phonon
CUORE
AMoRE
CUPID
CUPID-CJPL
Gerda
Majorana
LEGEND
CDEX
NνDEX
PandaX
EXO-200
nEXO
XLZD
NEXT
SuperNEMO
KamLAND-Zen
SNO+
CANDLES
JUNO-0νββ
Electron
Photon

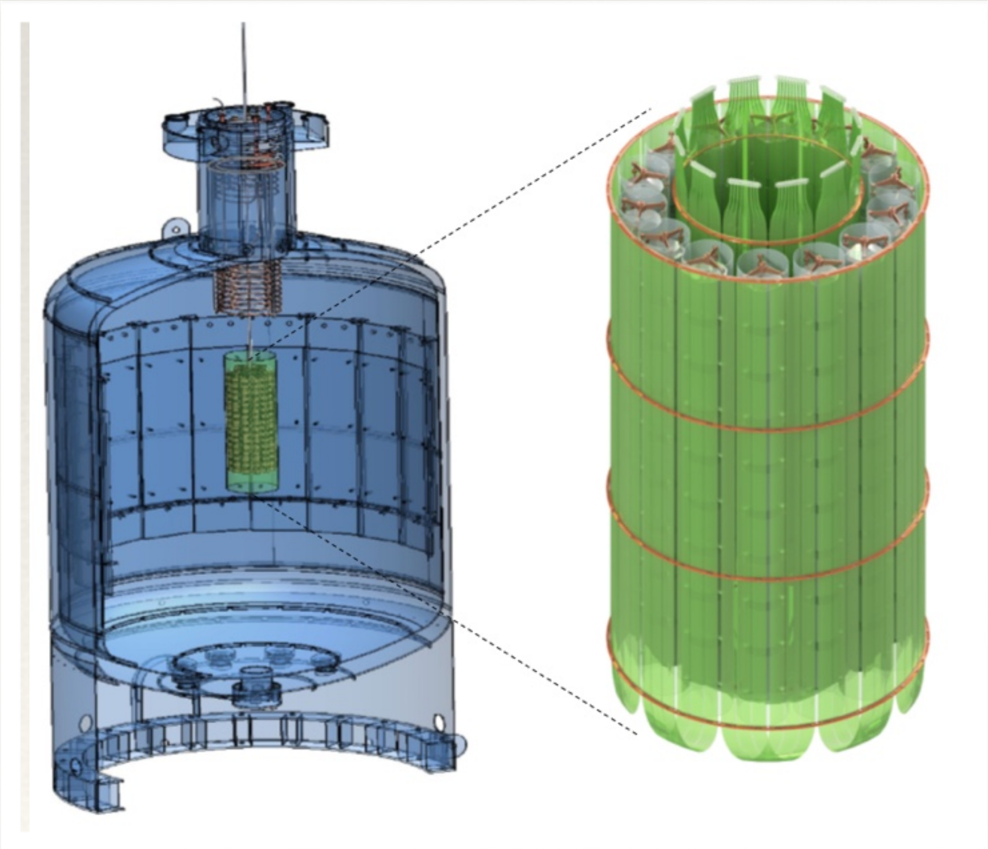
International players for the next 20+ years

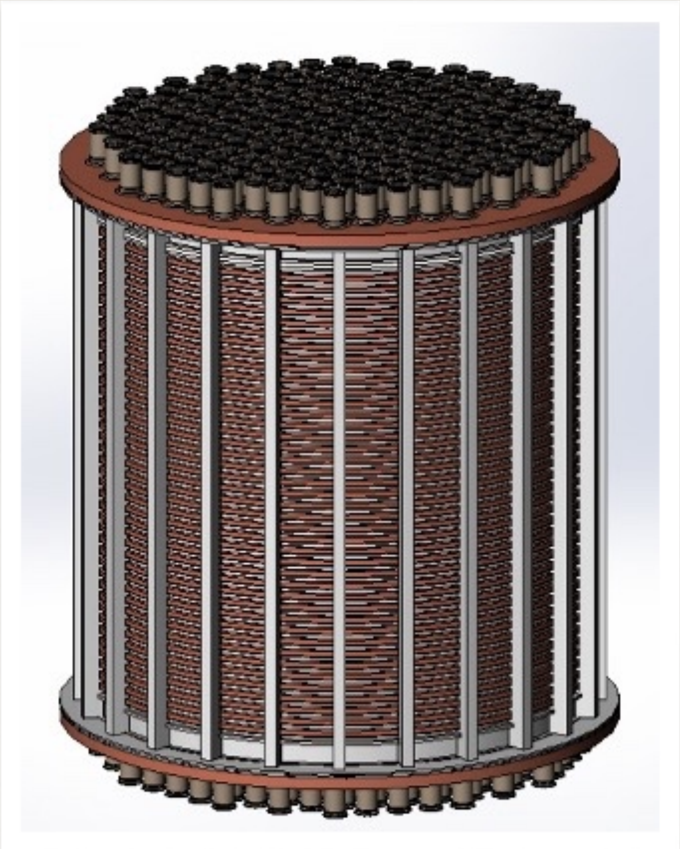


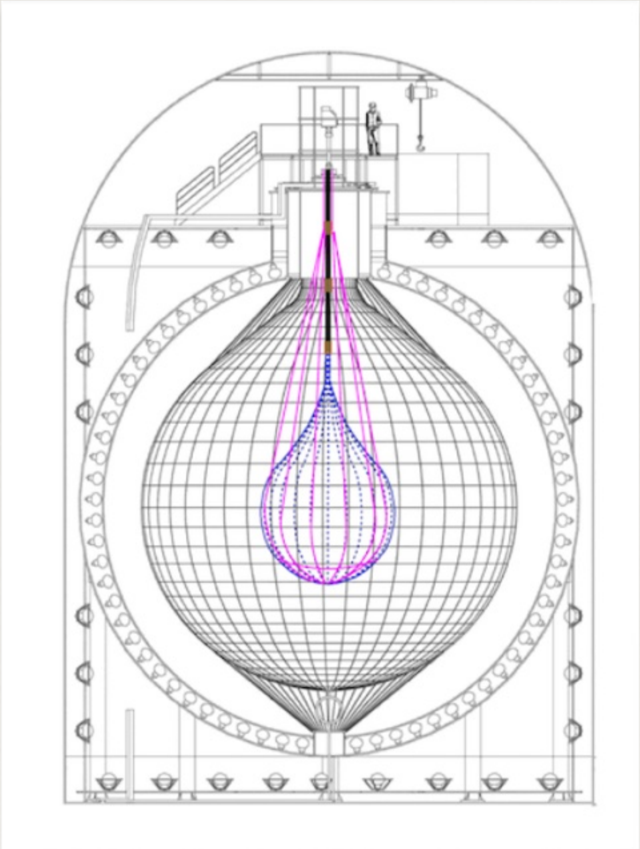
Chinese efforts

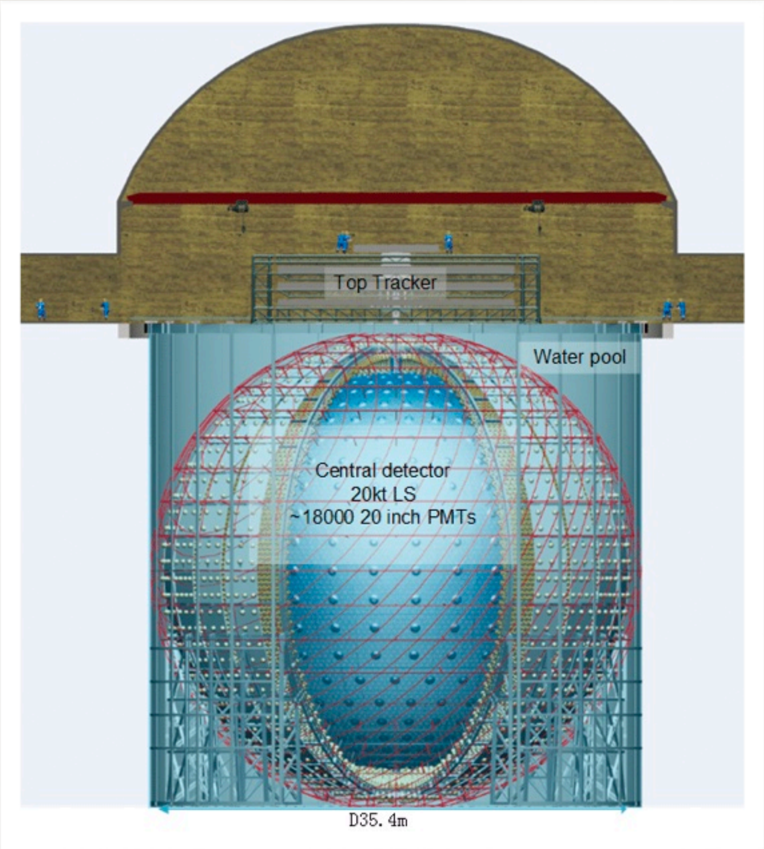


固体探测器阵列	气液探测器
CUPID, AMoRE	KamLAND-ZEN
LEGEND	nEXO, XLZD
CDEX	PandaX
CUPID-CJPL	NνDEX
	JUNO-0νββ



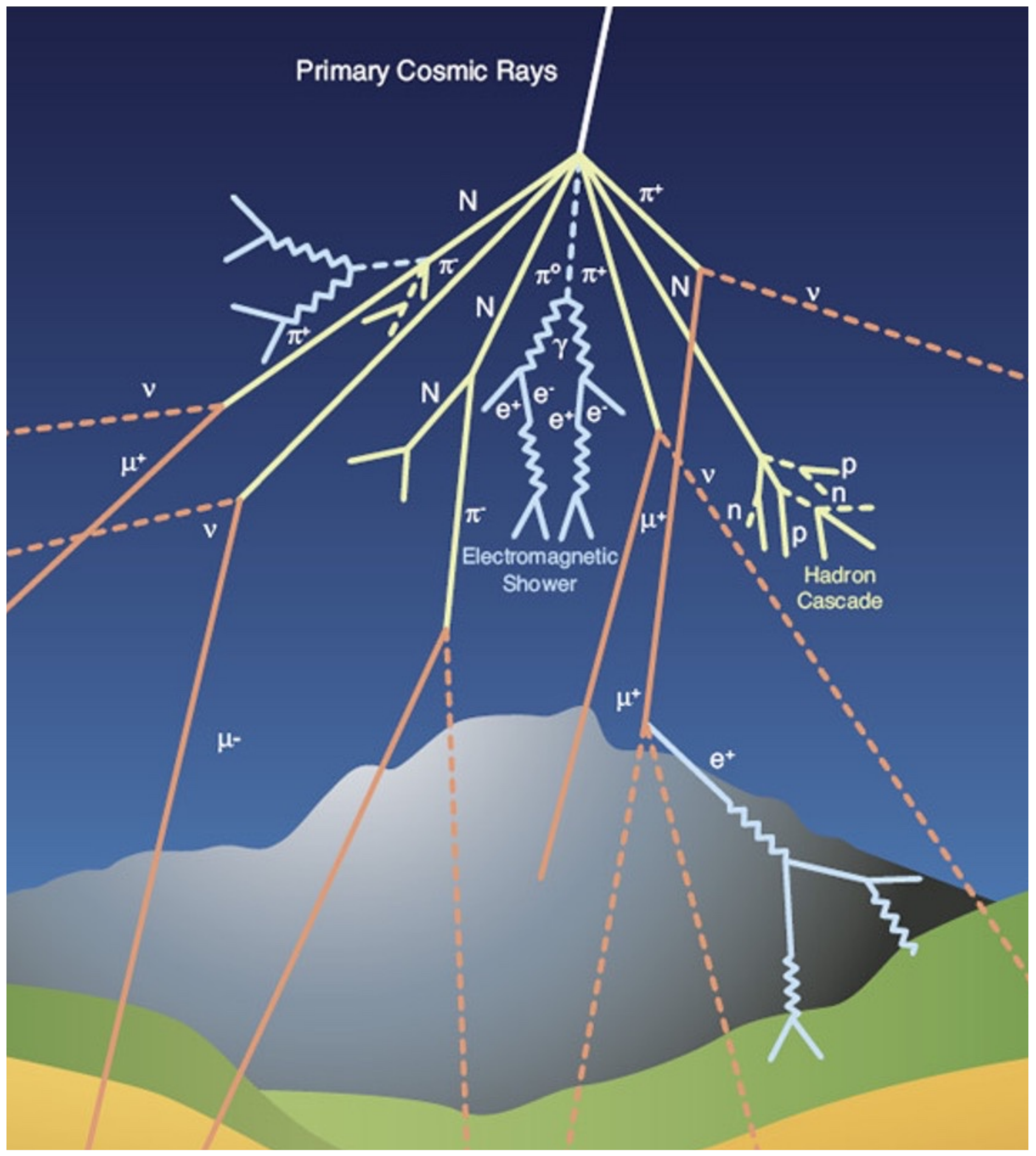


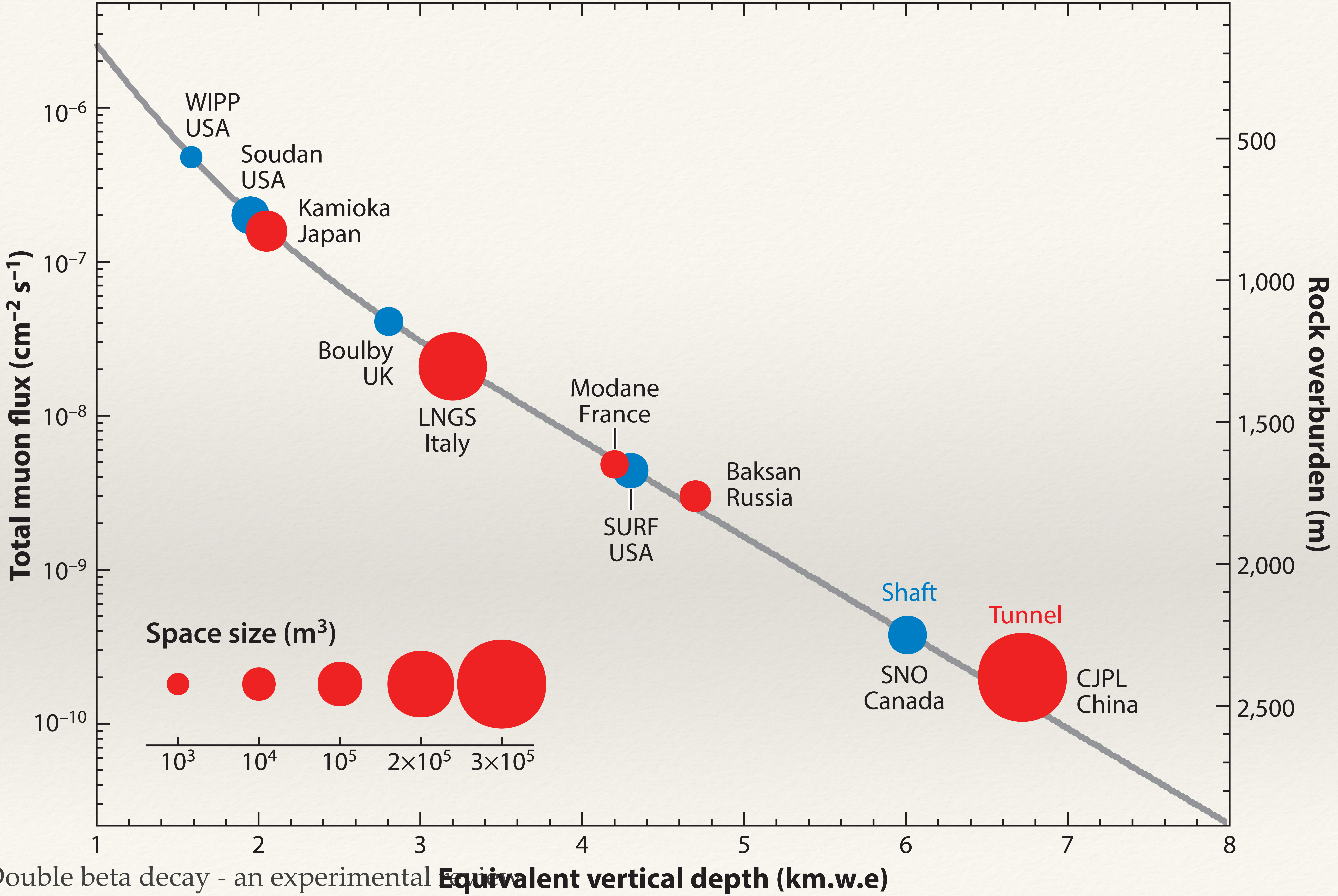




Cosmic rays

- Muons and muon-induced (e.g. neutrons) background
- Cosmogenic radioactivity (^{60}Co, ^{68}Ge, etc)
- Challenges even for R&D aboveground
- Mitigated by going underground: muon flux is reduced by a factor of 10 per 1500 m.w.e.





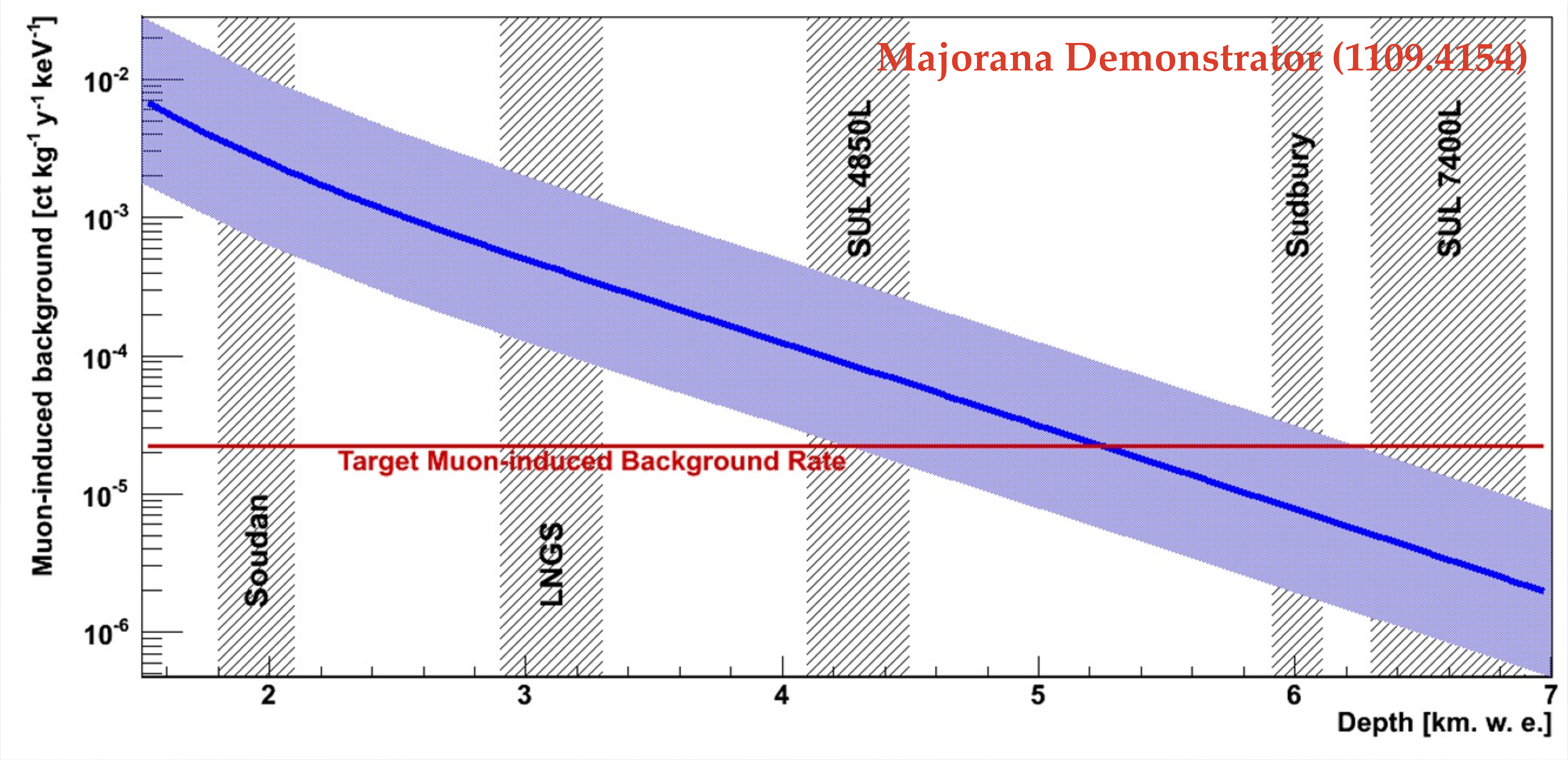
Total muon flux (cm⁻² s⁻¹)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
Rock overburden (m)
500
1,000
1,500
2,000
2,500
WIPP
USA
Soudan
USA
Kamioka
Japan
Boulby
UK
LNGS
Italy
Modane
France
SURF
USA
Baksan
Russia
Shaft
Tunnel
SNO
Canada
CJPL
China
Space size (m³)
10^3
10^4
10^5
2×10^5
3×10^5
1
2
3
4
5
6
7
8
Equivalent vertical depth (km.w.e)


Canfranc
Modane
LNGS
CJPL
Y2L
Kamioka
SURF
WIPP
SNOLAB

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

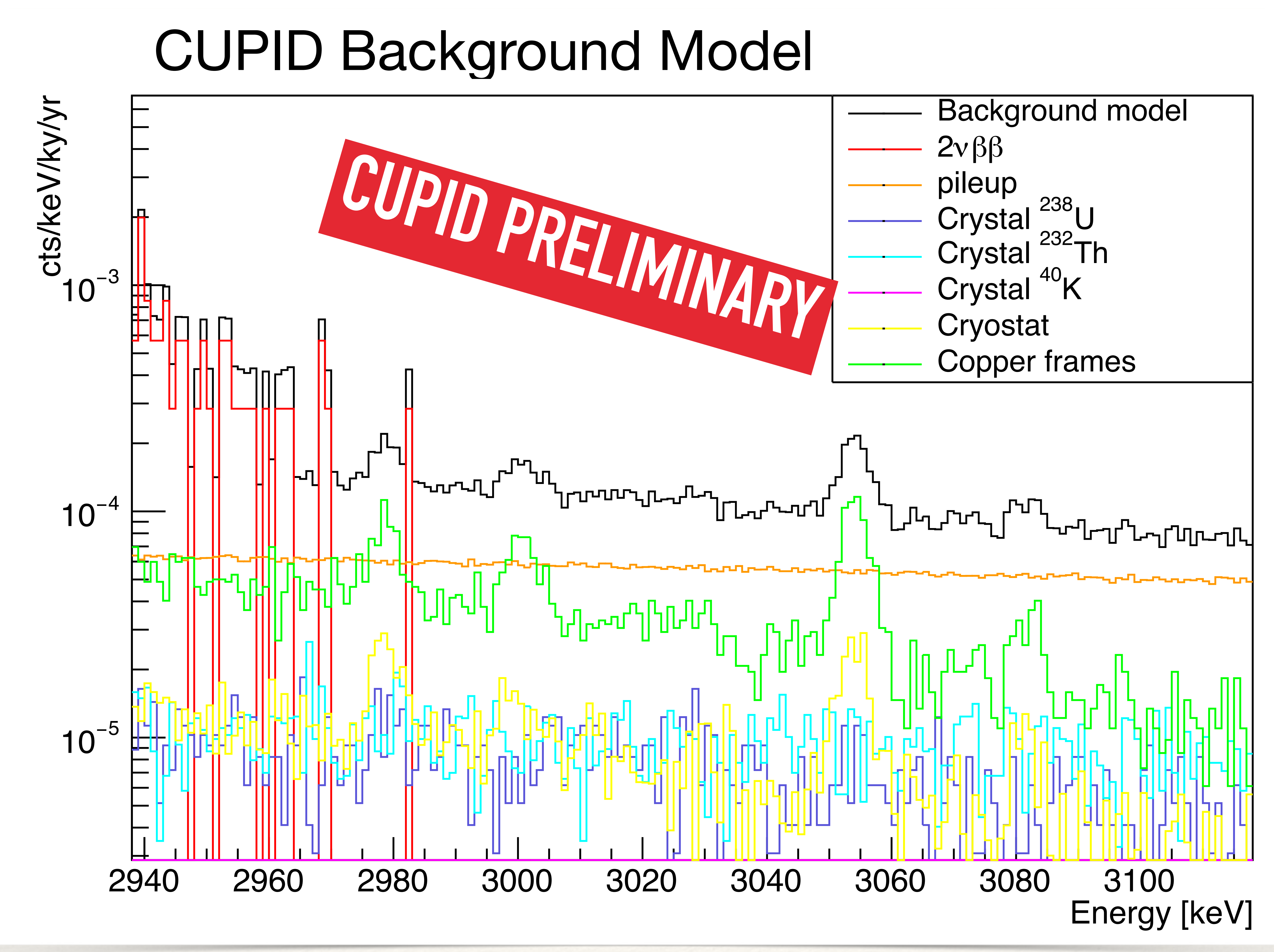
Mitigate muon-induced background

- Deeper lab or more powerful active veto



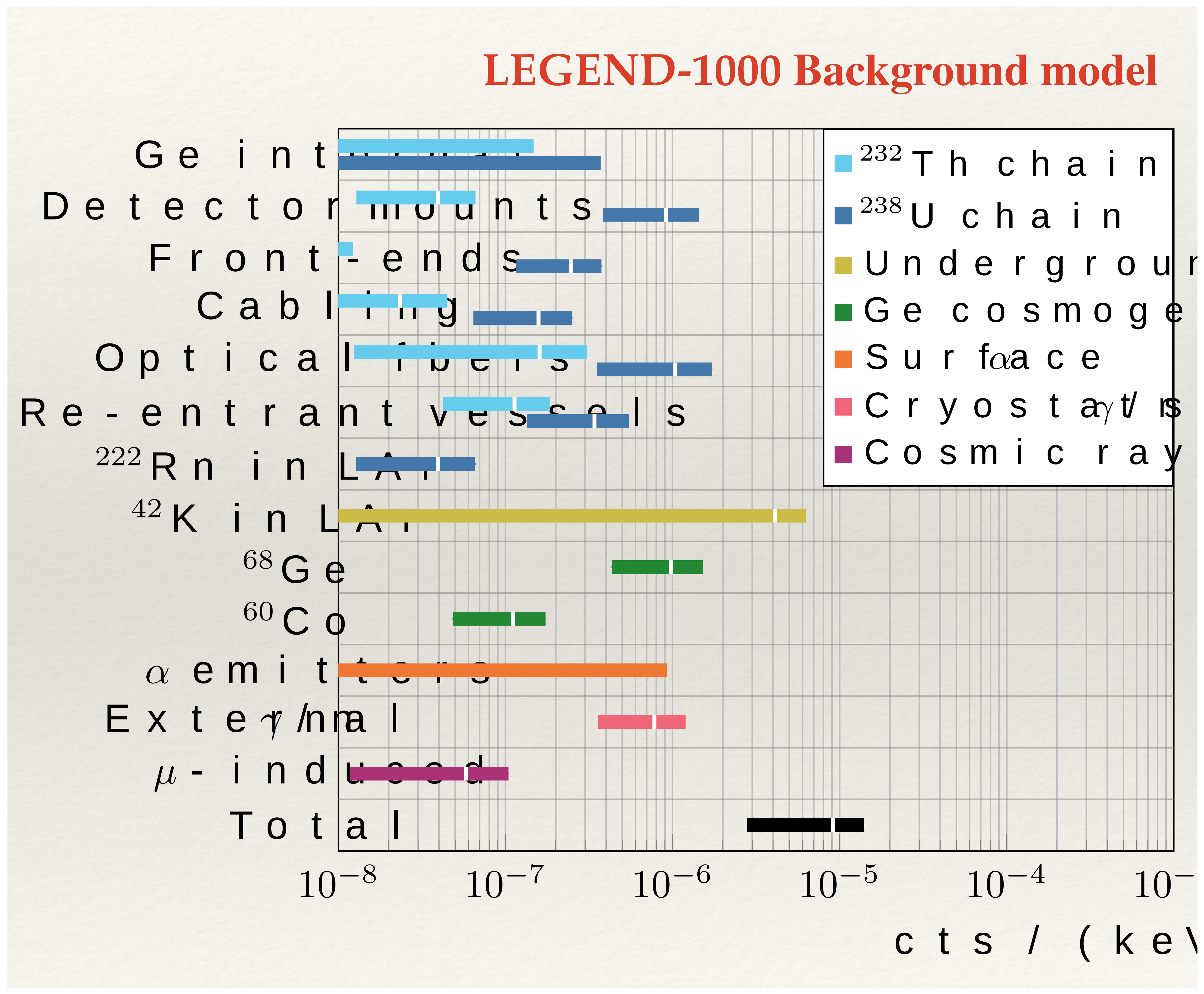
Intrinsic 2νββ background

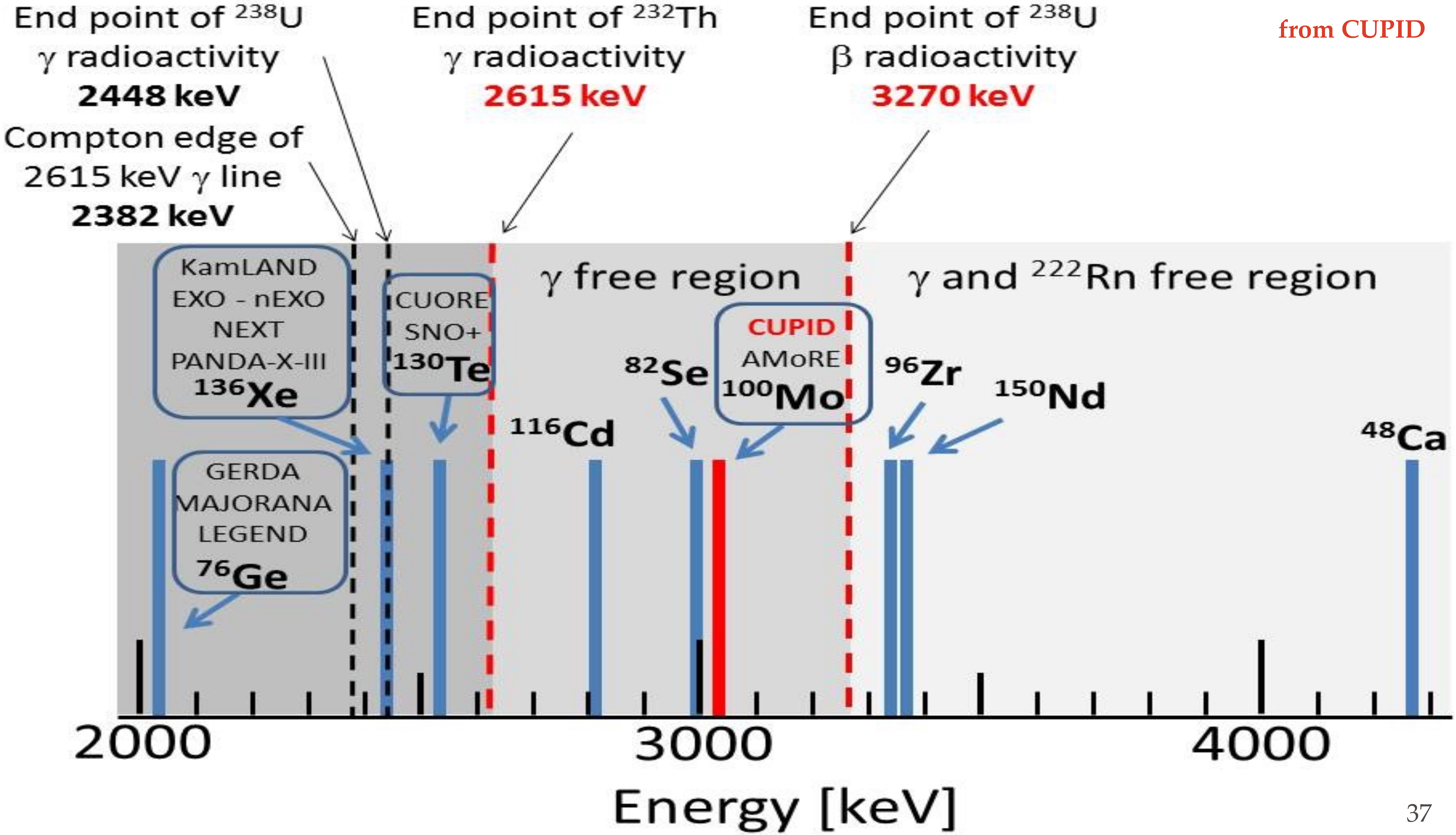
- 2νββ may be a problem if the half-life is short and energy resolution is VERY bad
- ^{100}Mo has a relatively short half-life (10^{18} year, fastest 2νββ) and pileup of two ^{100}Mo 2νββ decay is a major concern for CUPID



Background from detector material/shielding

- Shielding is mandatory to stop gamma background from underground lab environment
- Detector/shielding material screening is a major task for 0νββ experiments
  - Natural radioactivity: 1-100 Bq/kg
  - 0νββ requirement: < 1 mBq/kg
- High Q of 0νββ helps since most natural gamma is less than 2.6 MeV




End point of ²³⁸U γ radioactivity 2448 keV
Compton edge of 2615 keV γ line 2382 keV
End point of ²³²Th γ radioactivity 2615 keV
End point of ²³⁸U β radioactivity 3270 keV
γ free region
γ and ²²²Rn free region
KamLAND
EXO - nEXO
NEXT
PANDA-X-III
136Xe
CUORE
SNO+
130Te
CUPID
AMoRE
100Mo
82Se
116Cd
96Zr
150Nd
48Ca
GERDA
MAJORANA
LEGEND
76Ge
2000
3000
4000
Energy [keV]

from CUPID

Majorana Demonstrator

#	Material	Method
	Metals	
1	Cu Electrofo	
2	Cu Electrofo	
3	Cu Electrofo	
4	Cu Electrofo	
5	Cu Electrofo	
6	Cu Electrofo	
7	Cu Electrofo	
8	Cu Electrofo	
9	Cu Electrofo	
10	Cu Electrofo	
11	Cu Electrofo	
12	Cu Electrofo	
13	Cu Electrofo	
14	Cu Electrofo	
15	Cu Electrofo	
16	Cu Electrofo	
17	Cu, C101 cal	
18	Cu, C101 2.5	
19	Cu, C101 2.5	
20	Cu, C101 1”	
21	Cu, C101 1”	
22	Cu, C101 1”	
23	Cu, C101 1”	
24	Cu, C101 2.5	
25	Cu, C101 2.5	

#	Material	Method
26	Cu, C101 0.5”	
27	Cu wire, Cal	
28	Pb, smelted	
29	Pb, UW	
30	Pb, UW	
31	Pb, smelted	
32	Pb, smelted	
33	Pb, UW	
34	Pb, UW	
35	Pb, archeolog	
36	Pb, archeolog	
37	Pb (Average	
38	Sn, sample o	
39	Sn, sample o	
40	Sn, sample s	
41	6-way SS cor	
42	TIG-Ce weld	
43	TIG-Zr weld	
44	Cr, stock use	
45	Au, sputterin	
46	Al, sputtered	
47	Al, sputtered	
48	Ge, sputtered	
49	Ge, sputtered	
	Plastics	

#	Material	Method
50	Teflon® TE-	
51	Peek®, Vict	
52	Vespel®, Du	
53	Vespel®, Du	
54	Vespel®, Du	
55	Parylene N c	
56	Parylene, Sp	
57	Parylene C,	
58	Parylene C,	
59	Parylene C,	
60	Parylene C,	
61	Parylene C,	
62	Poly, 5% bor	
63	Poly, Denset	
64	PTFE, 0.5”	
65	Kalrez®, Du	
66	Kalrez®, Du	
67	FEP shrink t	
68	FEP shrink t	
69	FEP tubing	
70	PTFE 0.002-	
	Cables and p	
71	FEP, Dupont	
72	FEP, Dupont	

#	Material	Method
73	Picocoax®,	
74	Picocoax®,	
75	Cu wire, bar	
76	Cu wire, bar	
77	Mini Coax ca	
78	Mini Coax ca	
79	Parylene coa	
80	Picocoax®,	
81	Picocoax®,	
82	Picocoax®,	
83	Picocoax®,	
84	Picocoax®,	
85	Axon' HV ca	
86	Axon' HV (f	
87	Axon' Signal	
	Connectors	
88	Silver epoxy	
89	Silver epoxy	
90	Silver epoxy	
91	Silver epoxy	
92	Silver epoxy,	
93	Silver epoxy	
94	Silver epoxy,	
95	Silver epoxy	

#	Material	Method
96	Silver epoxy,	
97	Silver Epoxy	
98	SnAg Solder	
99	Abietic acid,	
100	Abietic acid,	
101	Soap solution	
102	Soap solution	
103	Fused silica,	
104	Fused silica,	
105	Fused silica,	
106	Fused silica,	
107	Fused silica,	
108	CFW Al-Si b	
109	Pins without	
110	Pins with Be	
111	Vespel®, in-	
112	Vespel®, in-	
113	Vespel®, in-	
114	Sapphire C-P	
115	JFET dies, M	
116	Full LMFE b	
117	Full LMFE b	
	Miscellaneou	
118	Precision Ur	

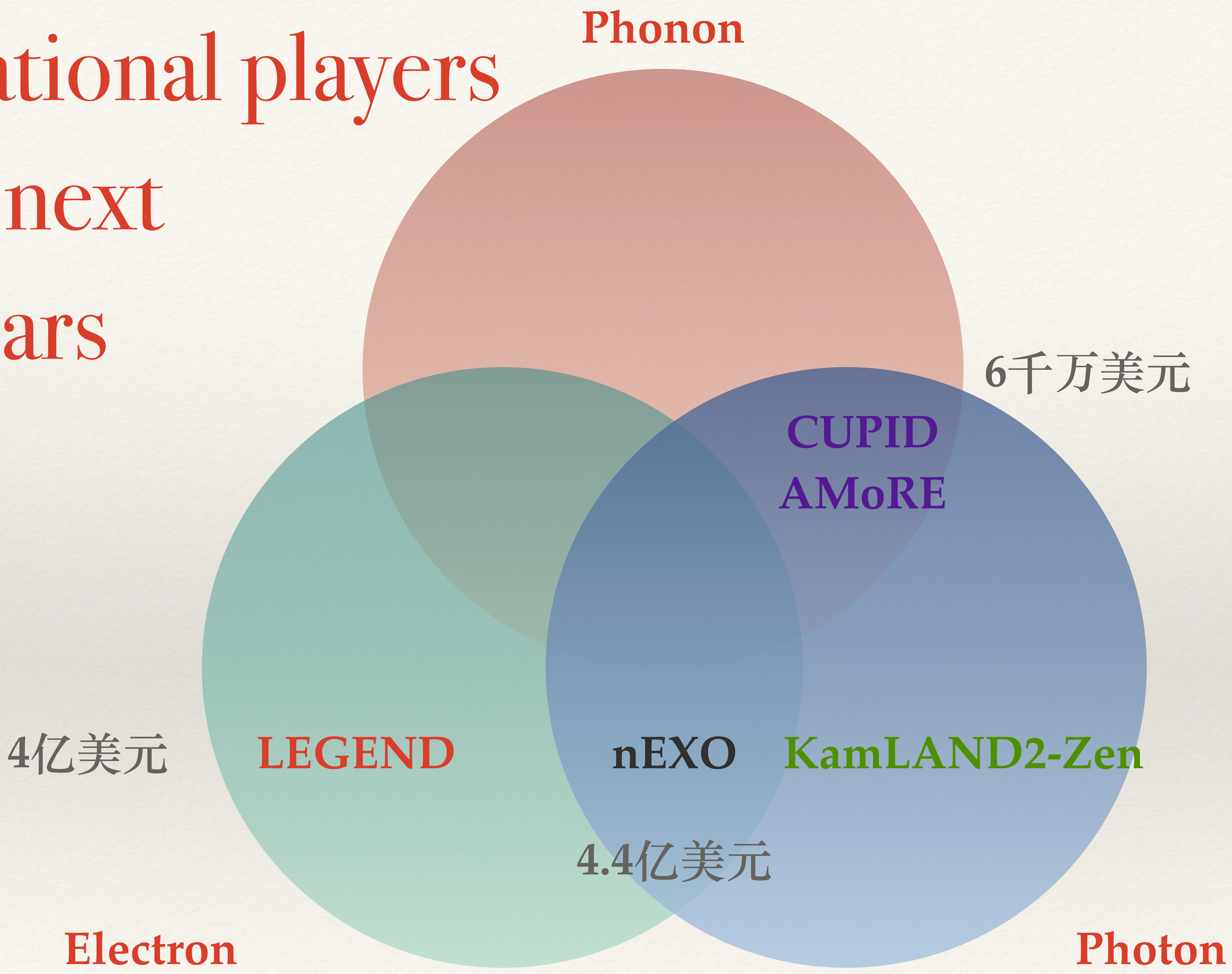
#	Material	Method
119	Wipes, KIMTECH PURE® W4, Kimberly-Clark Prof.®	γ count
120	Charcoal, 102022, finer size grain, Blücher	ICPMS
121	Charcoal, 101135 Saratoga, 0.47 mm, Blücher	ICPMS
122	Charcoal, 101135 Saratoga, 0.47 mm, Blücher	γ count
123	Charcoal, UHP granules, Carbo-Act Int.	ICPMS
124	Charcoal, sample from MPI, Heidelberg	ICPMS
125	Charcoal, K48, Silcarbon	ICPMS
126	Charcoal, Calgon Carbon	γ count
127	Charcoal, source from Canberra	γ count
128	Hysol® 0151™ resin, McMaster-Carr	ICPMS
129	Hysol® 0151™ hardener, McMaster-Carr	ICPMS
130	Hysol® 1C™ resin, McMaster-Carr	ICPMS
131	Hysol® 1C™ hardener, McMaster-Carr	ICPMS
132	Torr Seal® Base, McMaster-Carr A	ICPMS
133	Torr Seal® Hardener B, McMaster-Carr	ICPMS
134	Silicone Rubber, P-4, Silicones Inc.	γ count
135	2-propanol, A461-500, Fischer Scientific	ICPMS
136	Mix colored beads, 100780, Accu-Glass Prod. Inc.	ICPMS
137	White beads, 100780, Accu-Glass Products Inc.	ICPMS
138	Green beads, 100780, Accu-Glass Products Inc.	ICPMS
139	Black bead leachate	ICPMS
140	Blue bead leachate	ICPMS
141	Brown bead leachate	ICPMS
142	Green bead leachate	ICPMS
143	Grey bead leachate	ICPMS

Assergi

无双实验：国际竞争

韩柯
上海交通大学

International players for the next 20+ years



CUPID: scintillating bolometer array for ^{100}Mo

CUPID: CUORE Upgrade with Particle IDentification

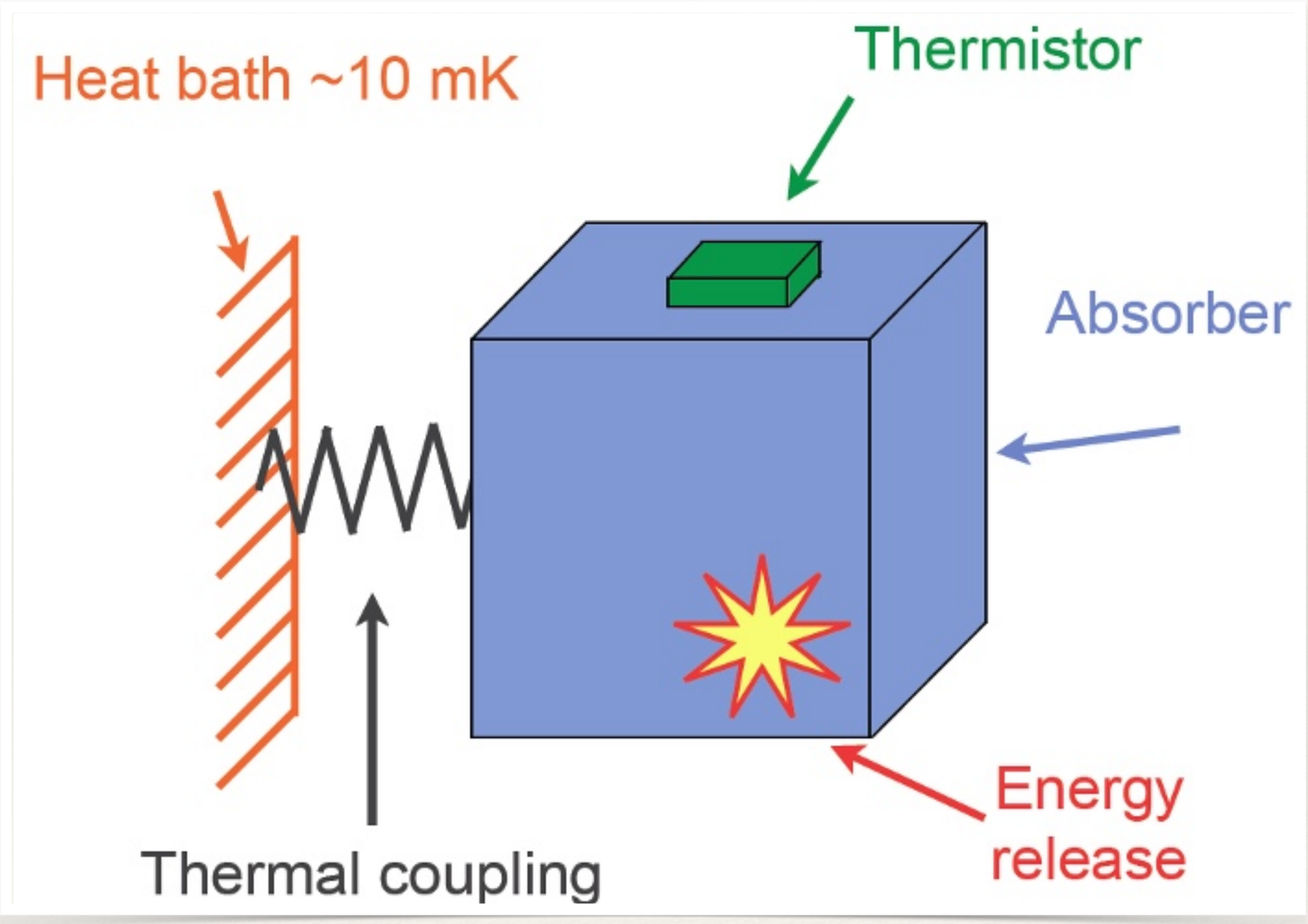
CUORE: Cryogenic Underground Observatory for Rare Events

Bolometers (calirometers)

- Bolometer: measure the energy via temperature change

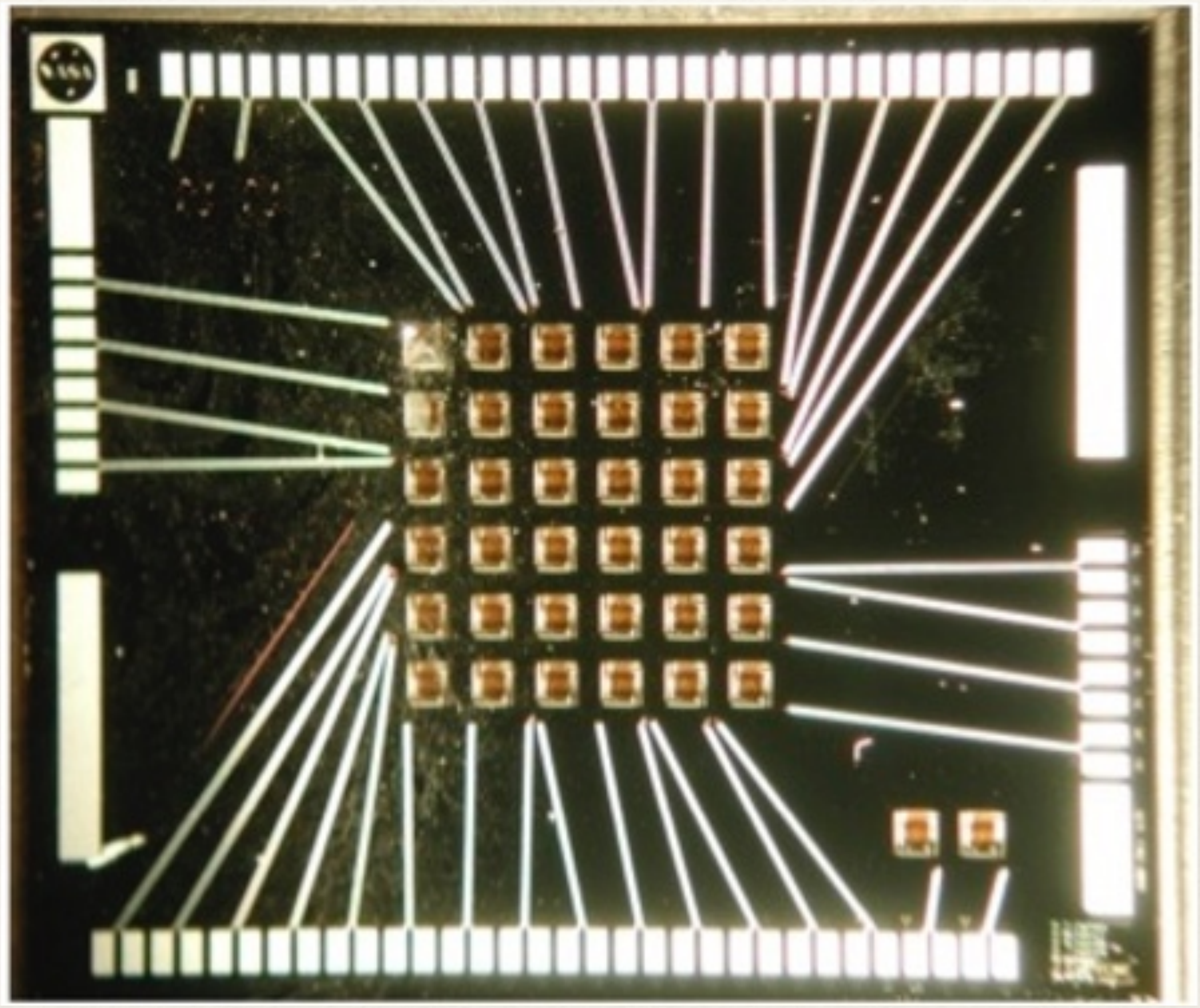
$$\Delta T = \frac{E}{C}$$

- Phonons carry energy quanta: very high intrinsic energy resolution
- Smart absorber choice: small heat capacity C
- Sensitive thermistor

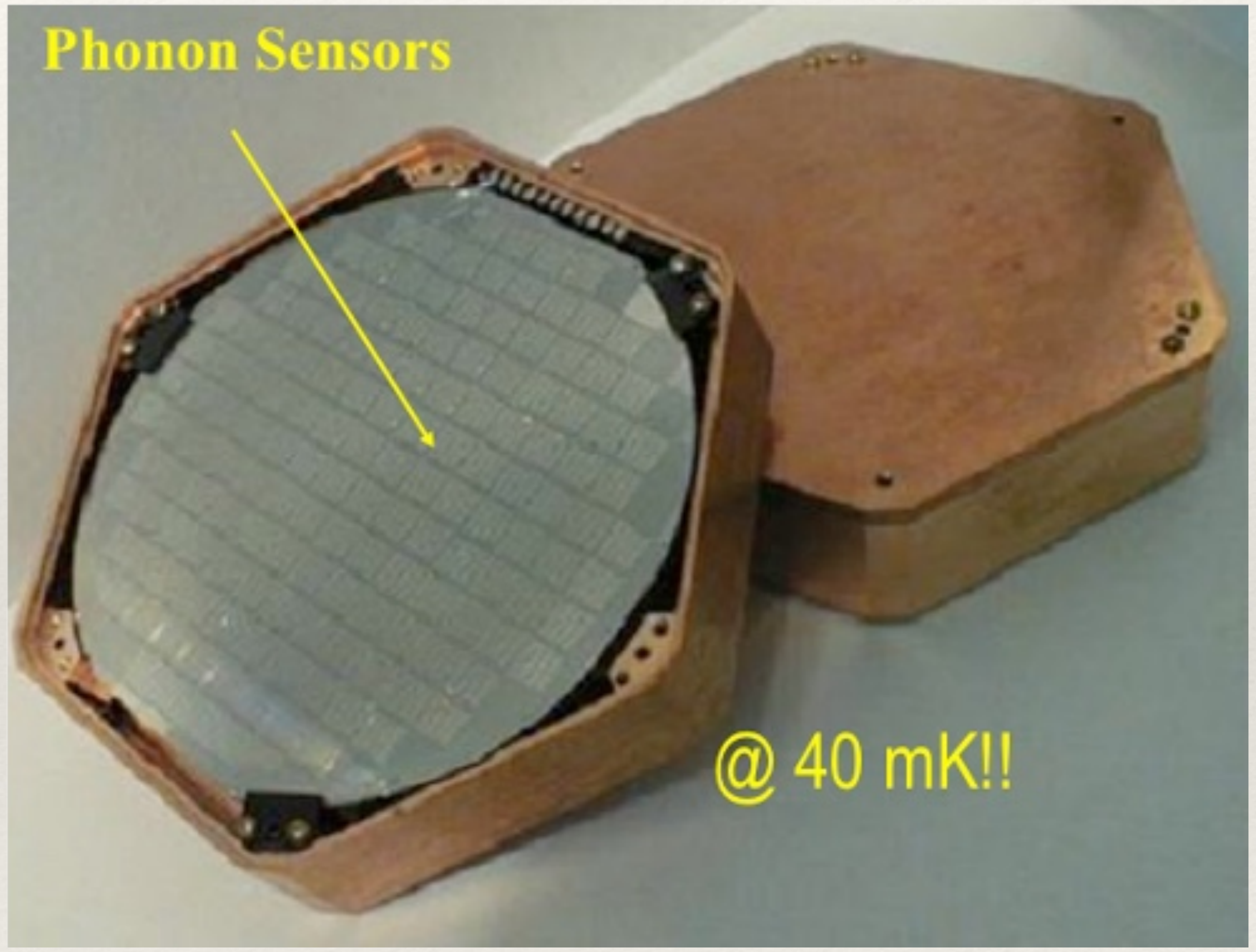


Wide applications in particle/astro/cosmology

Spider Web



MARE

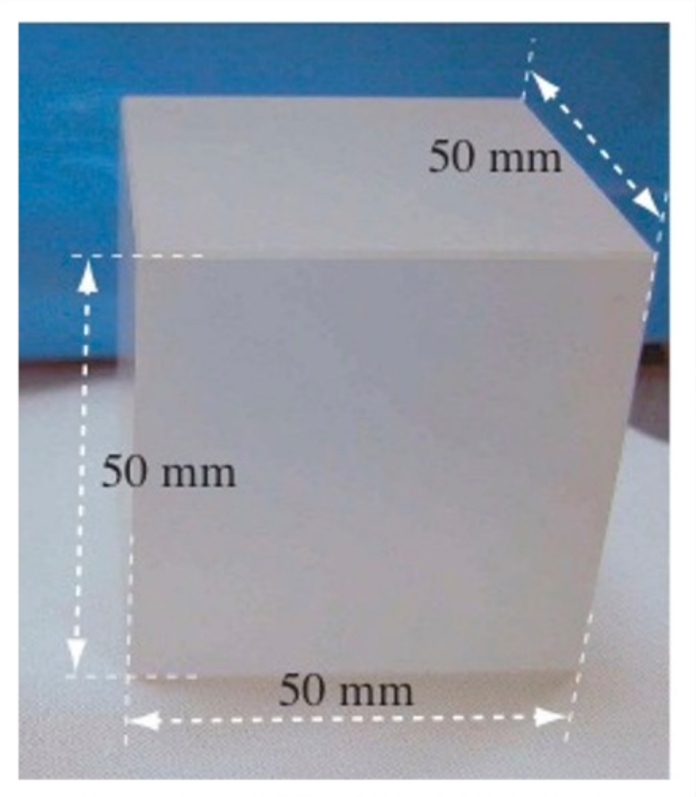


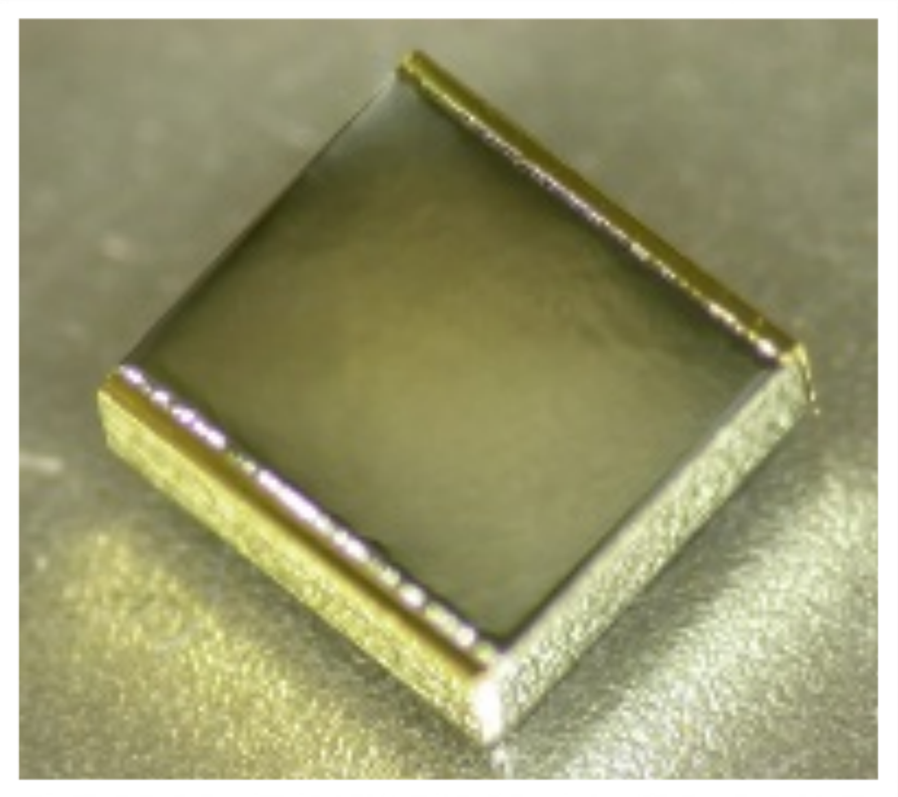
SuperCDMS

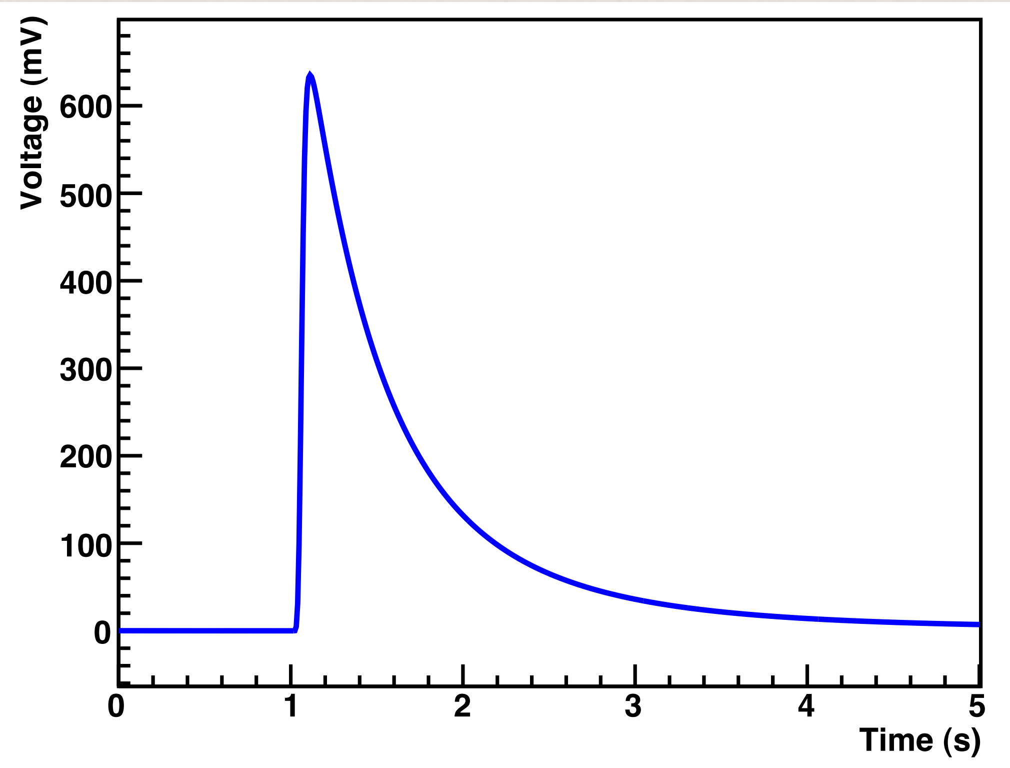
CUORE bolometer array

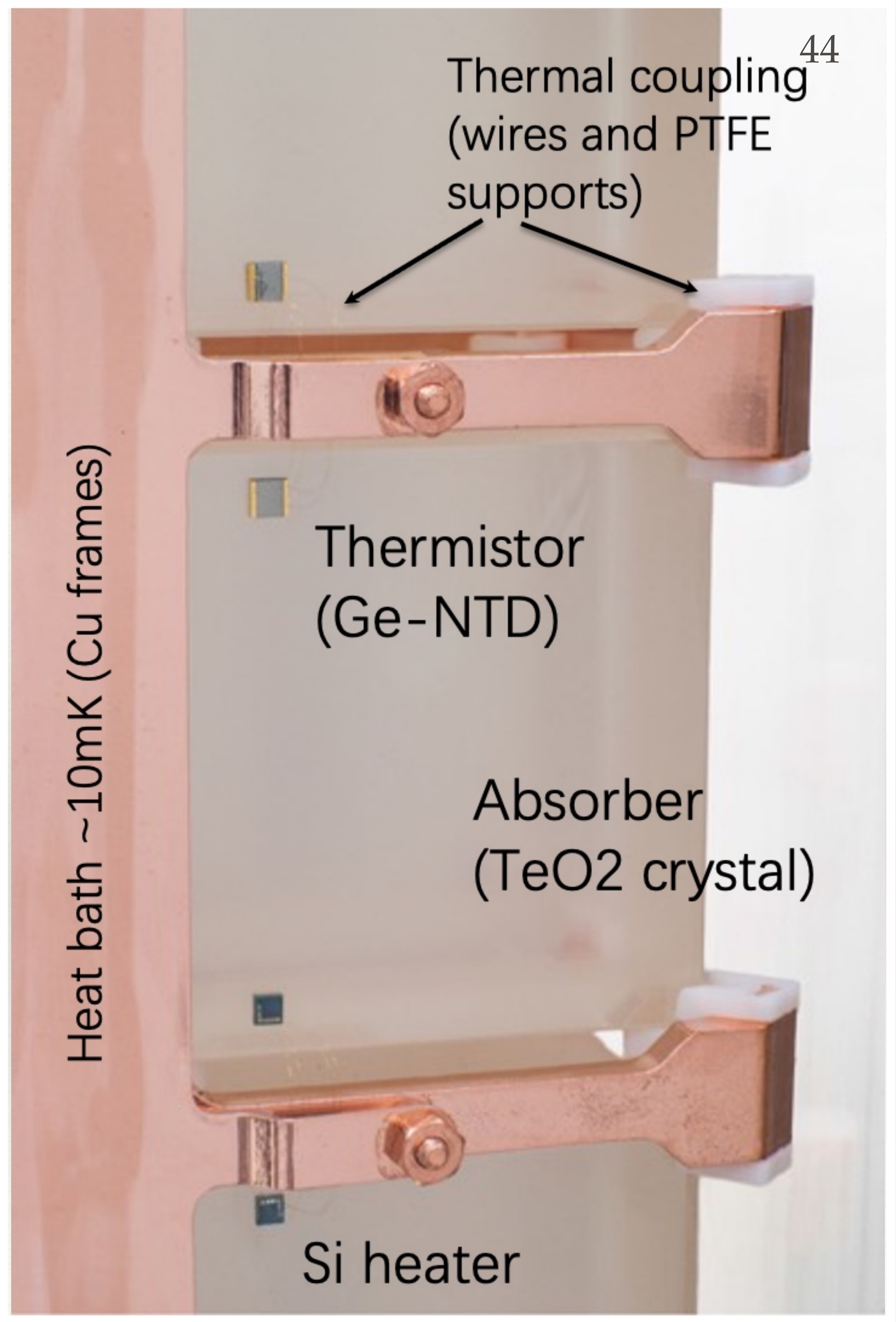
- Search for $0\nu\beta\beta$ of ^{130}Te and other rare events
- 988 TeO_2 crystals run as a bolometer array

所有晶体购于上海硅酸盐所



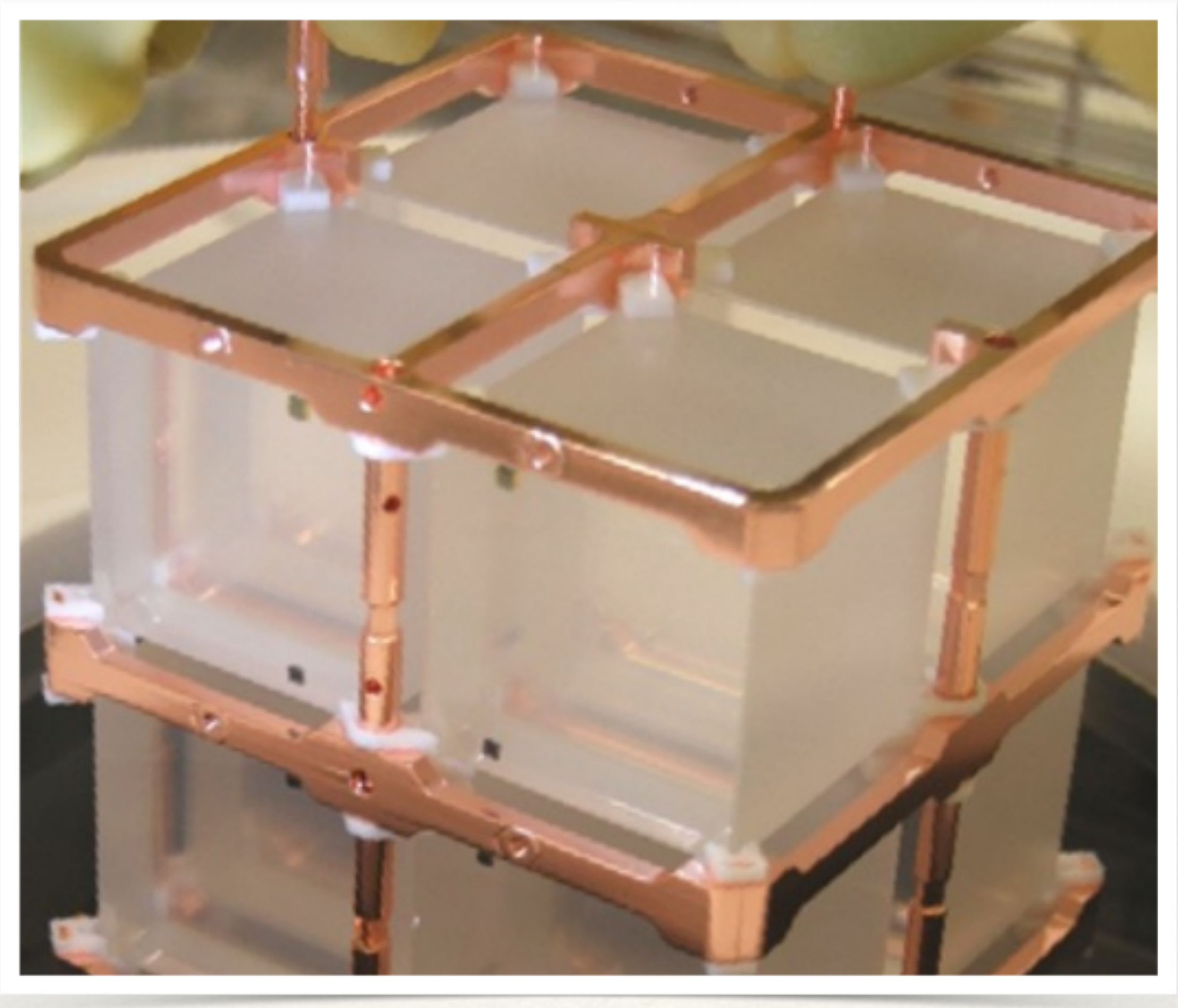


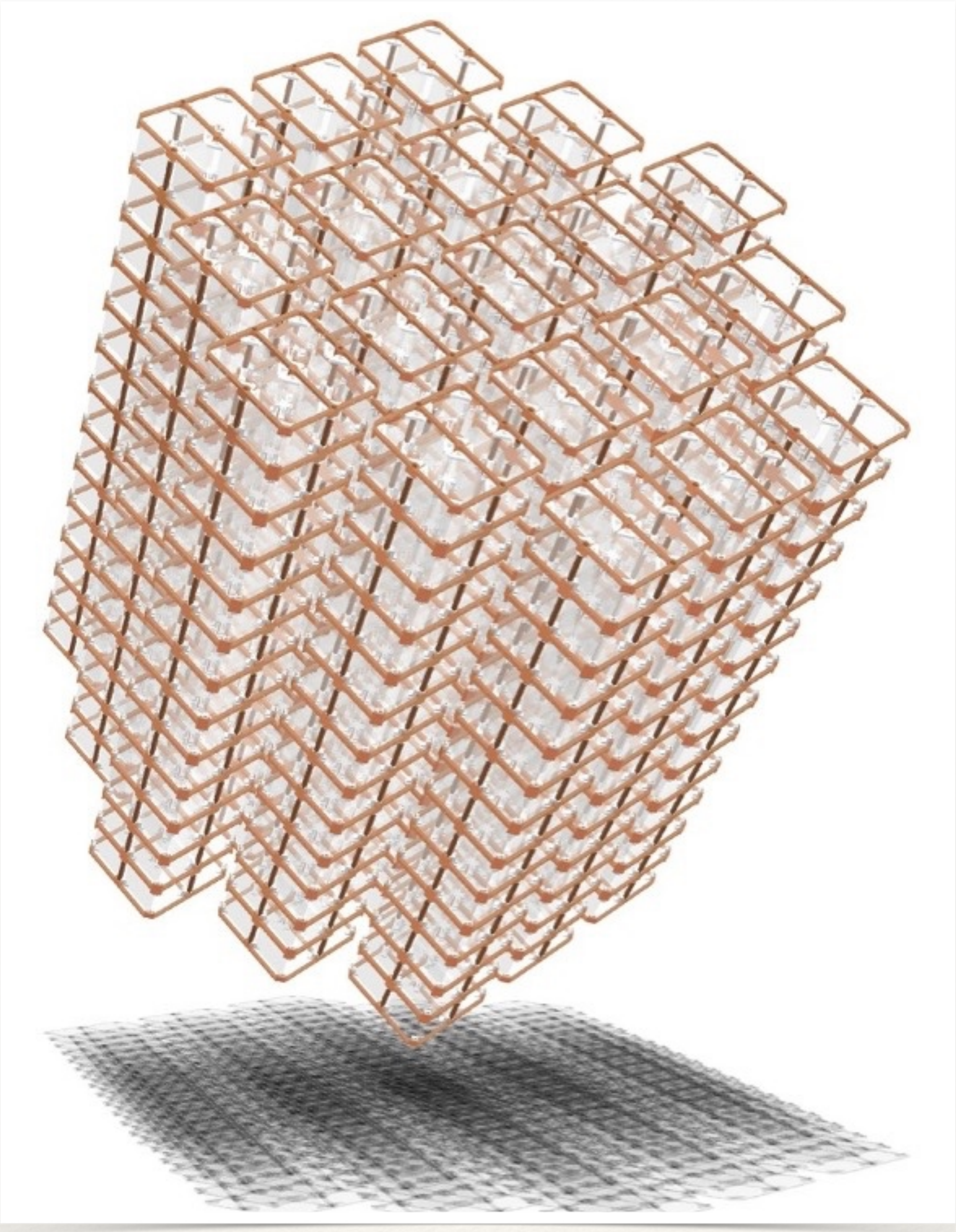




CUORE bolometer array

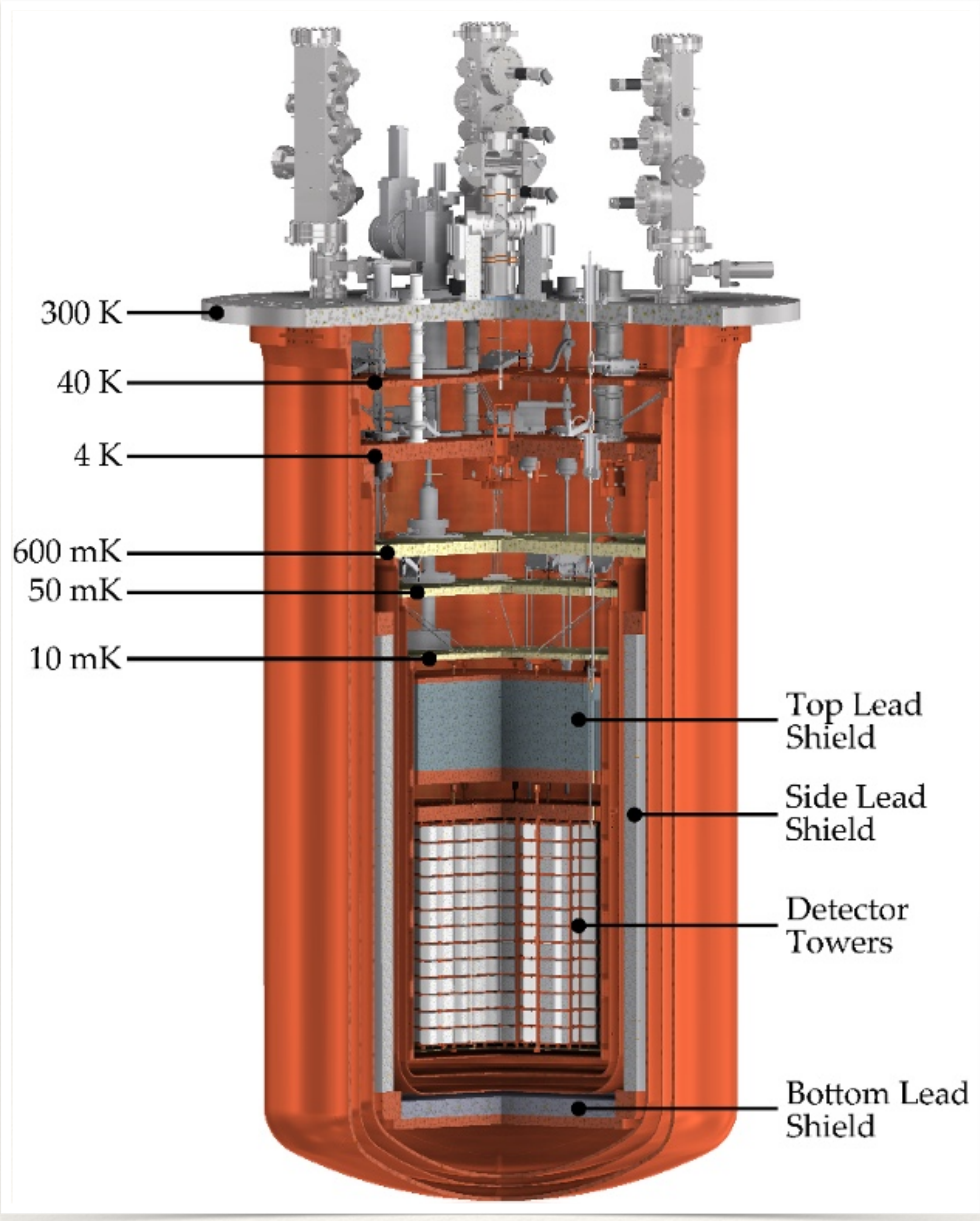
- Search for $0\nu\beta\beta$ of ^{130}Te and other rare events
- 988 TeO_2 crystals run as a bolometer array
  - 19 Towers
  - 13 floors
  - 4 modules per floor





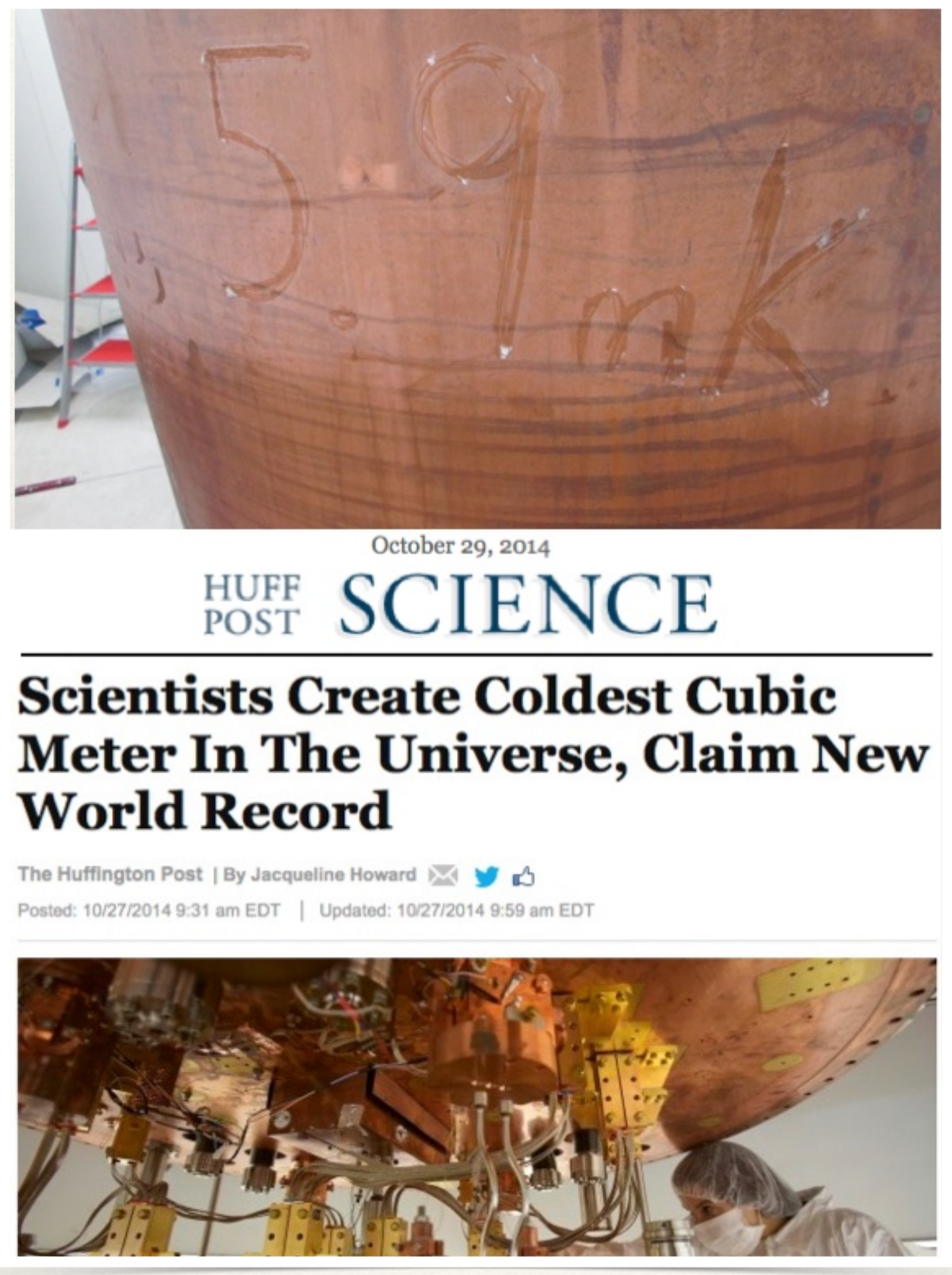
CUORE bolometer array

- Search for $0\nu\beta\beta$ 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



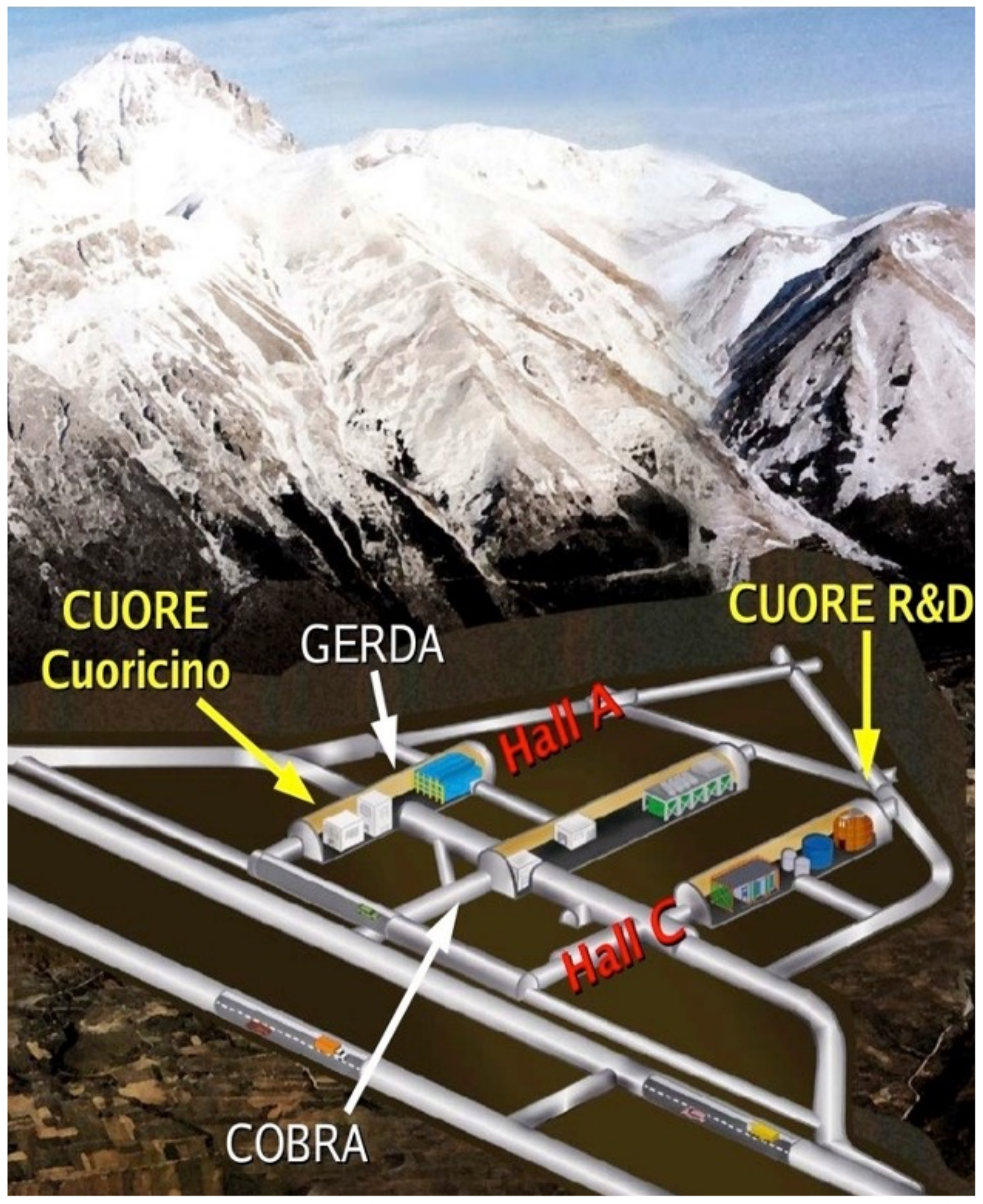
CUORE bolometer array

- 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



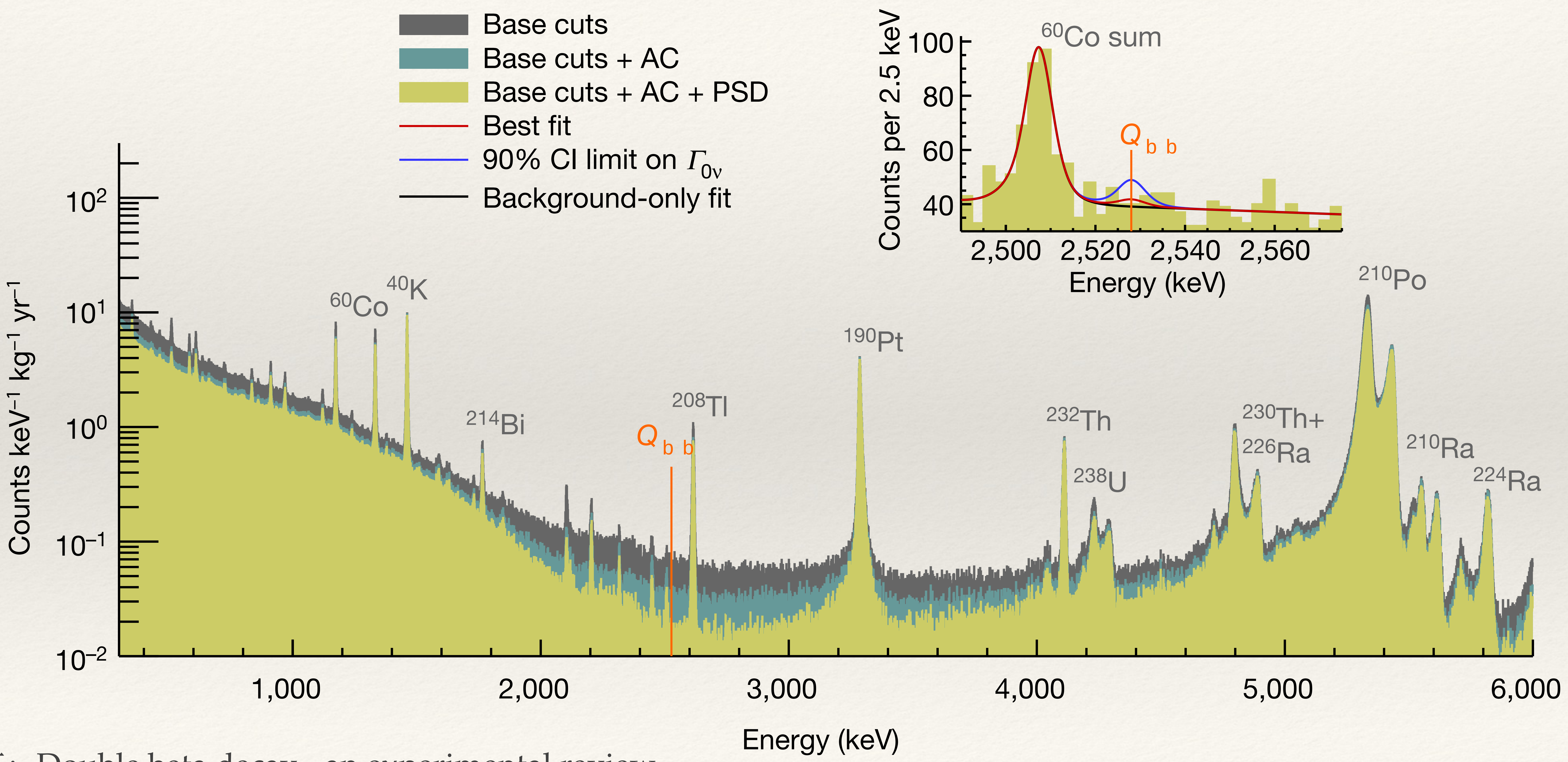
CUORE bolometer array

- 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
- Gran Sasso underground lab (LNGS), Italy

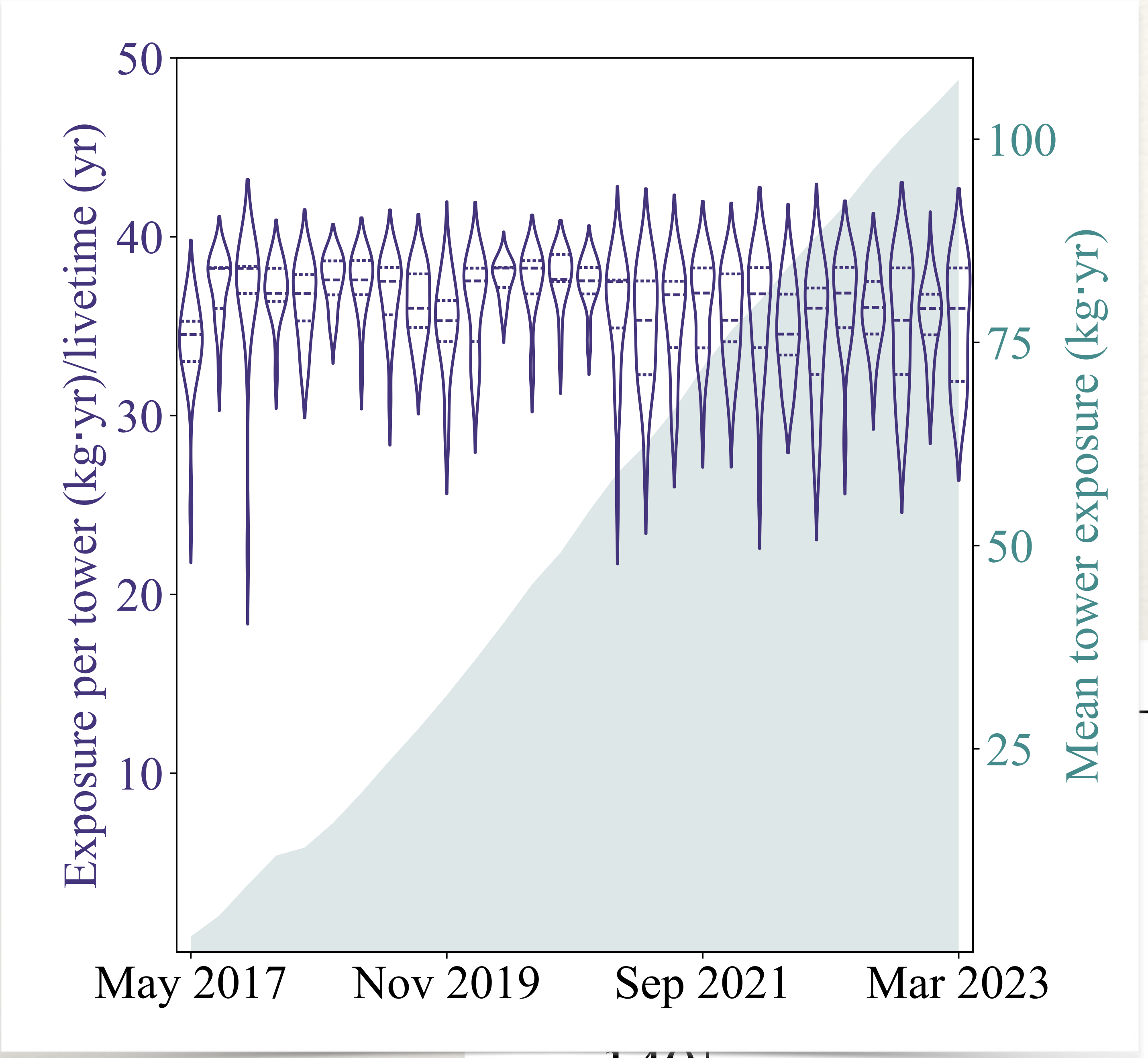


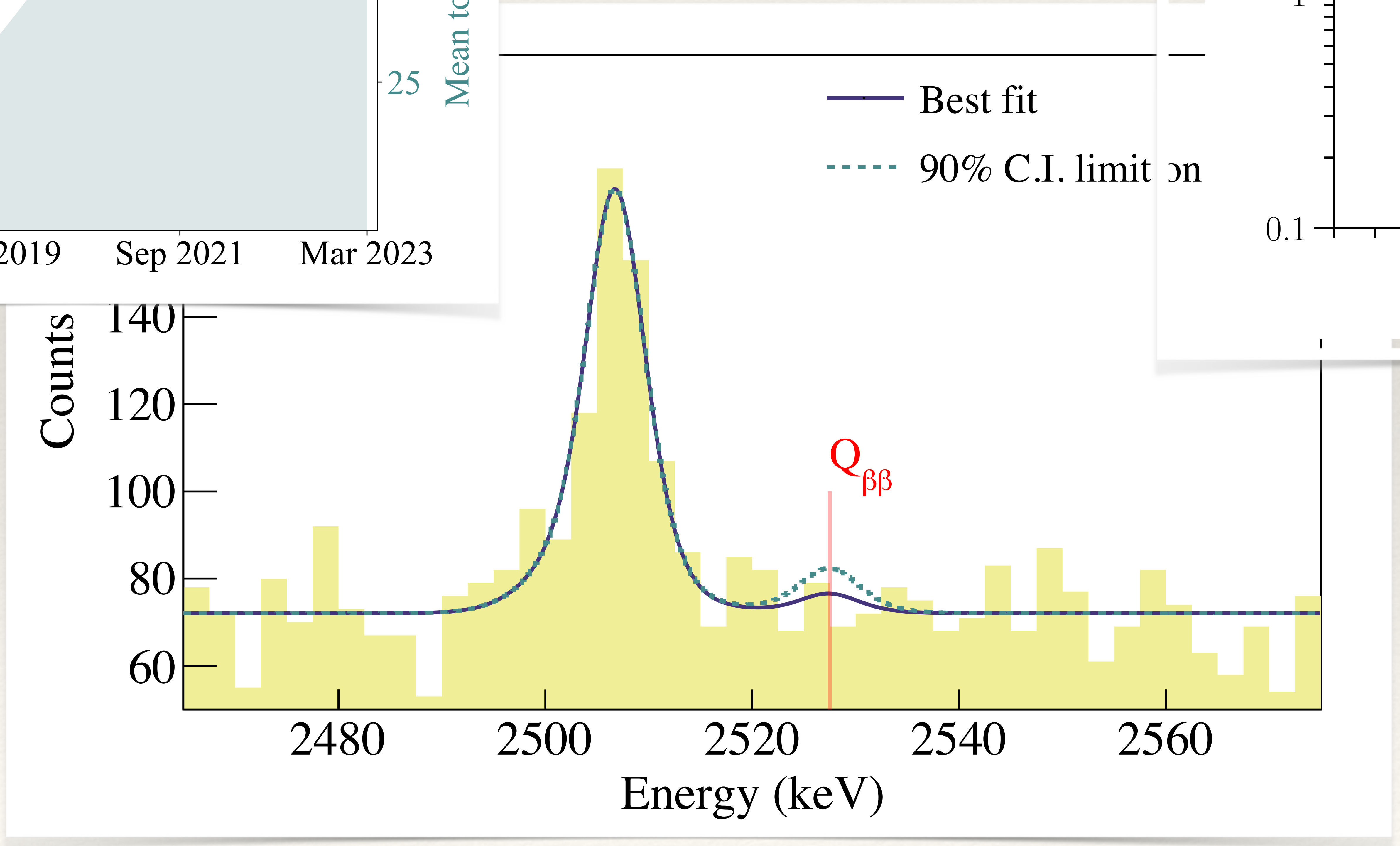
CUORE 1 ton-year data

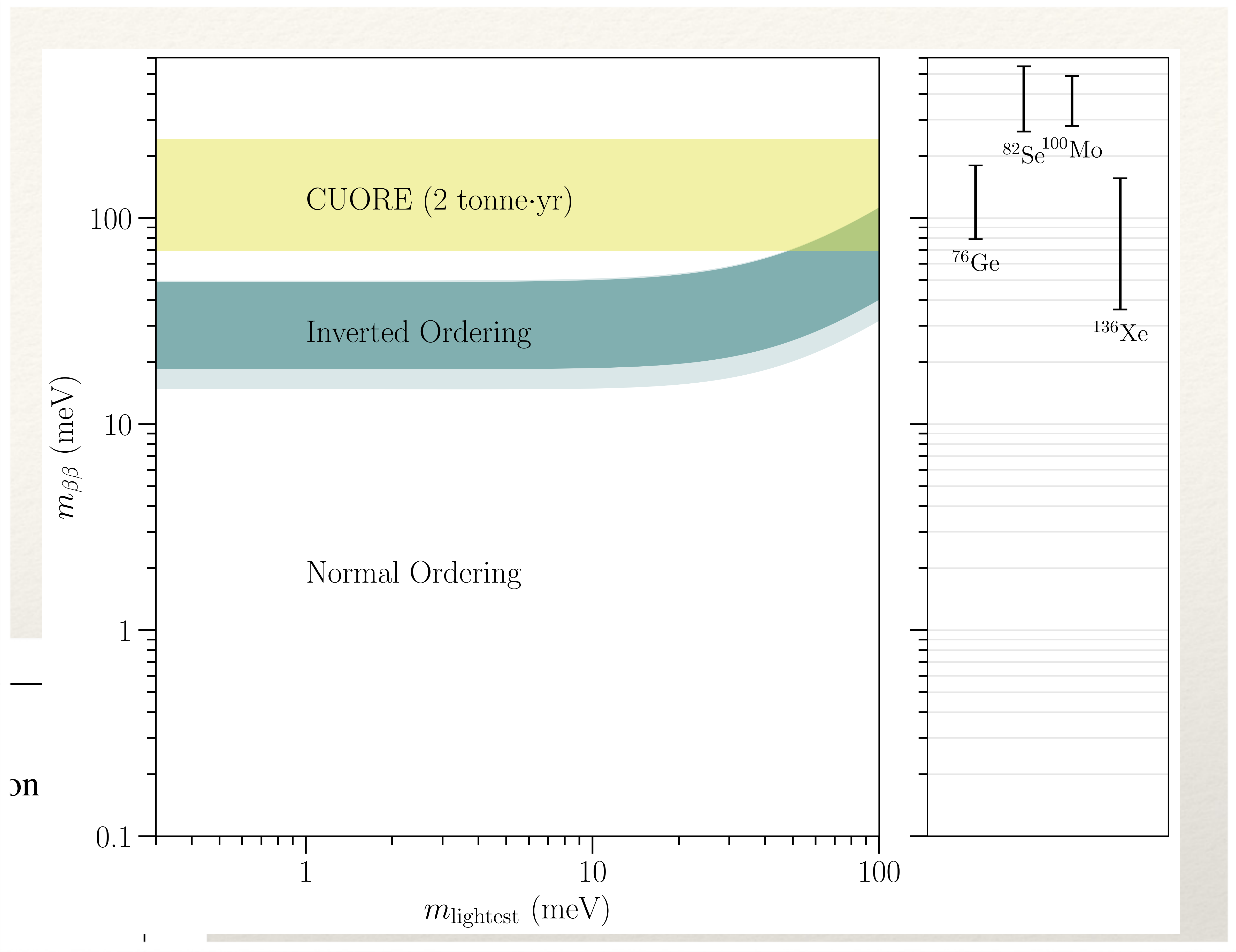
1. Stable data taking since 2017
2. Excellent energy resolution



CUORE 2 ton-year data







arXiv:2404.04453

FWHM: 7.3 keV

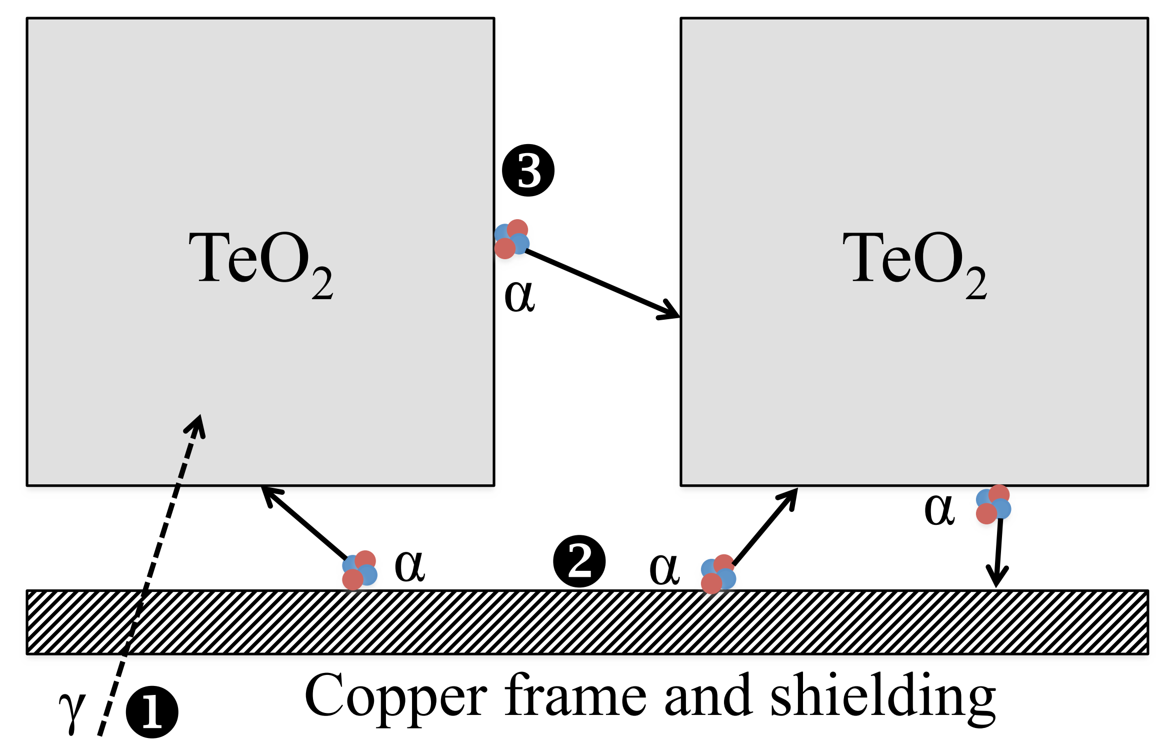
Background index: 1.4 cts/keV/kg/yr

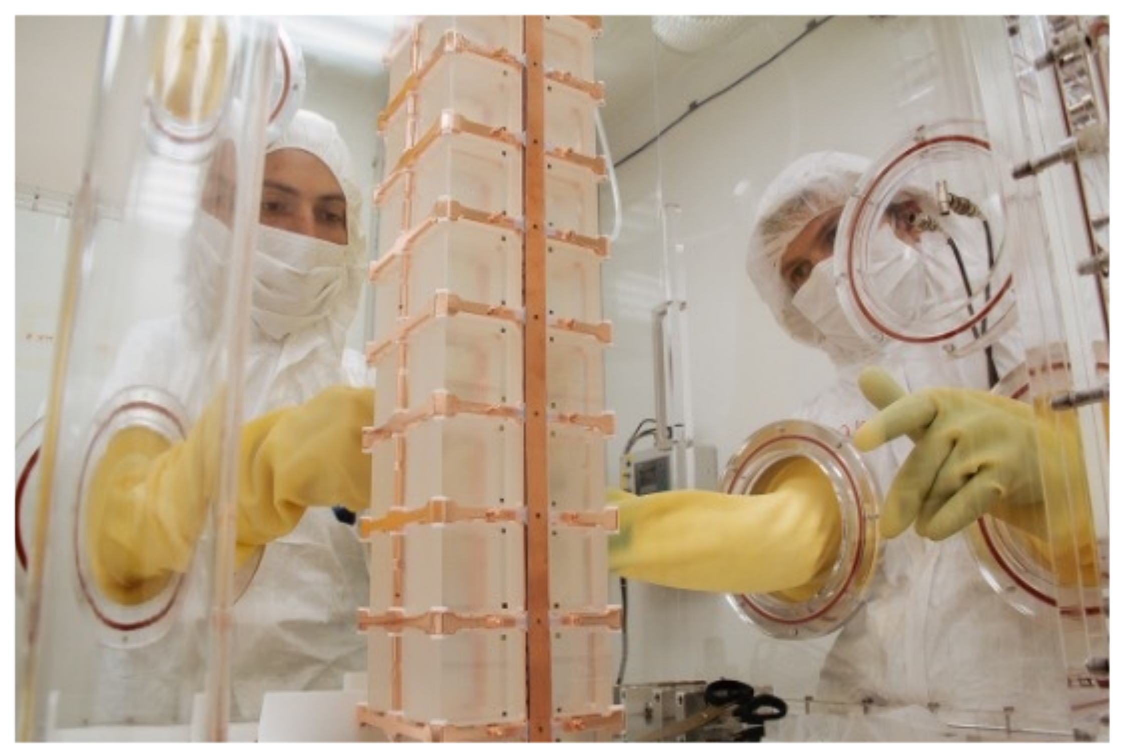
$T_{1/2} > 3.8 \times 10^{25}$ yr (90% C.L.)

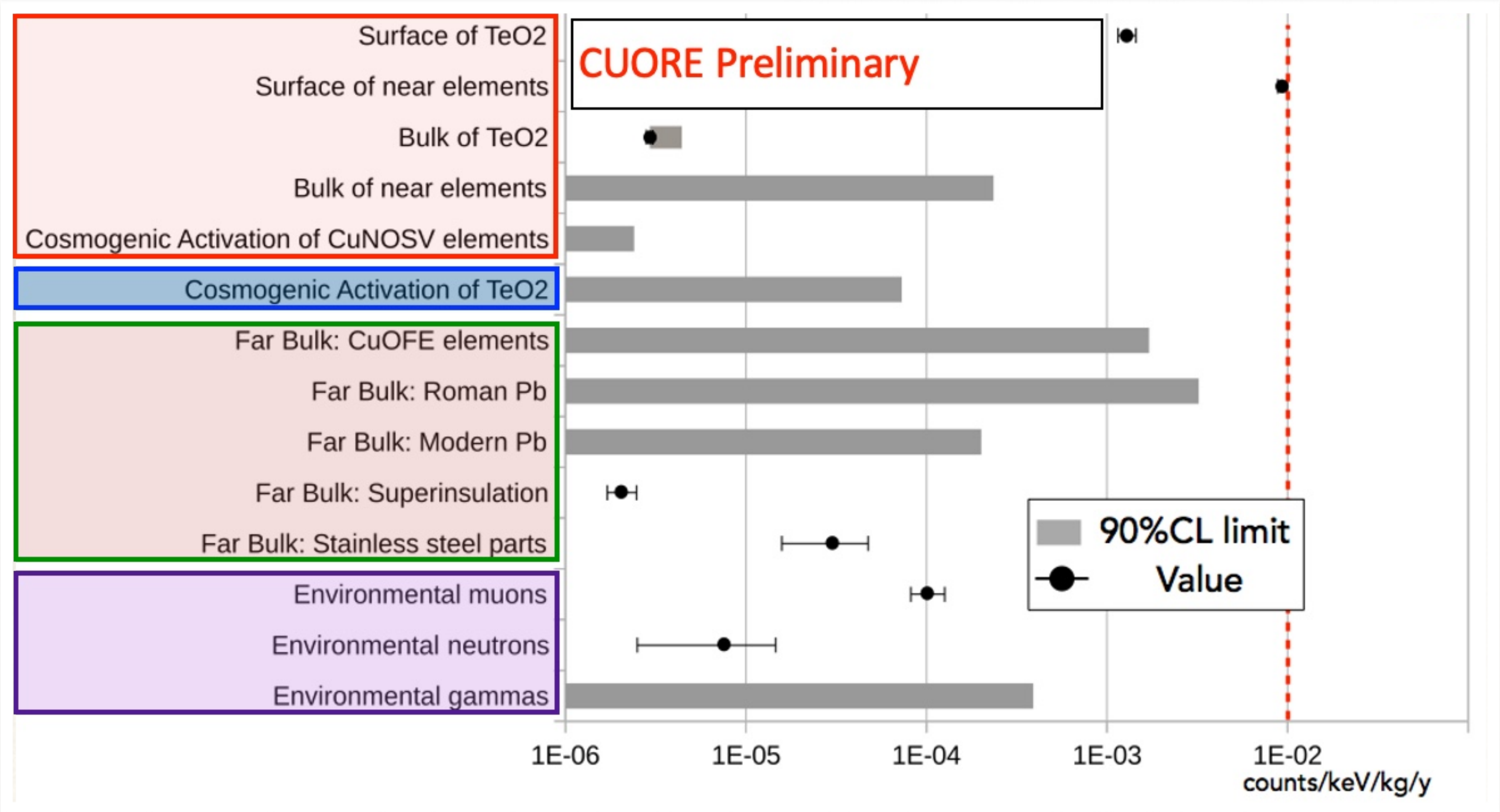
$m_{\beta\beta} < (70 - 240)$ meV

CUORE challenge: surface α background

- Surface background a common challenge for solid-state detector modules
- CUORE cannot distinguish $\alpha/\beta/\gamma$ particles
  - A heat pulse is a heat pulse for TeO_2
- Extremely careful treatment of copper/crystal surfaces
  - Coating/etching copper surface
  - Lapping crystal surface







CUPID: scintillating bolometer

- Li_2MoO_4 (LMO) scintillating crystals
- ^{100}Mo enrichment > 95%
- 45×45×45 mm^3 crystals
- ~1500 crystals → ~250 kg of 100Mo
- Goal FWHM: 5 keV at $Q_{\beta\beta}$
- α rejection via particle identification on light detector
  - Li_2MoO_4 (LMO) crystals scintillates and light yield is particle dependent
- Goal background: 10^{-4} counts/keV/kg/yr
- New challenge: detect tiny scintillation light
  - Another bolometer

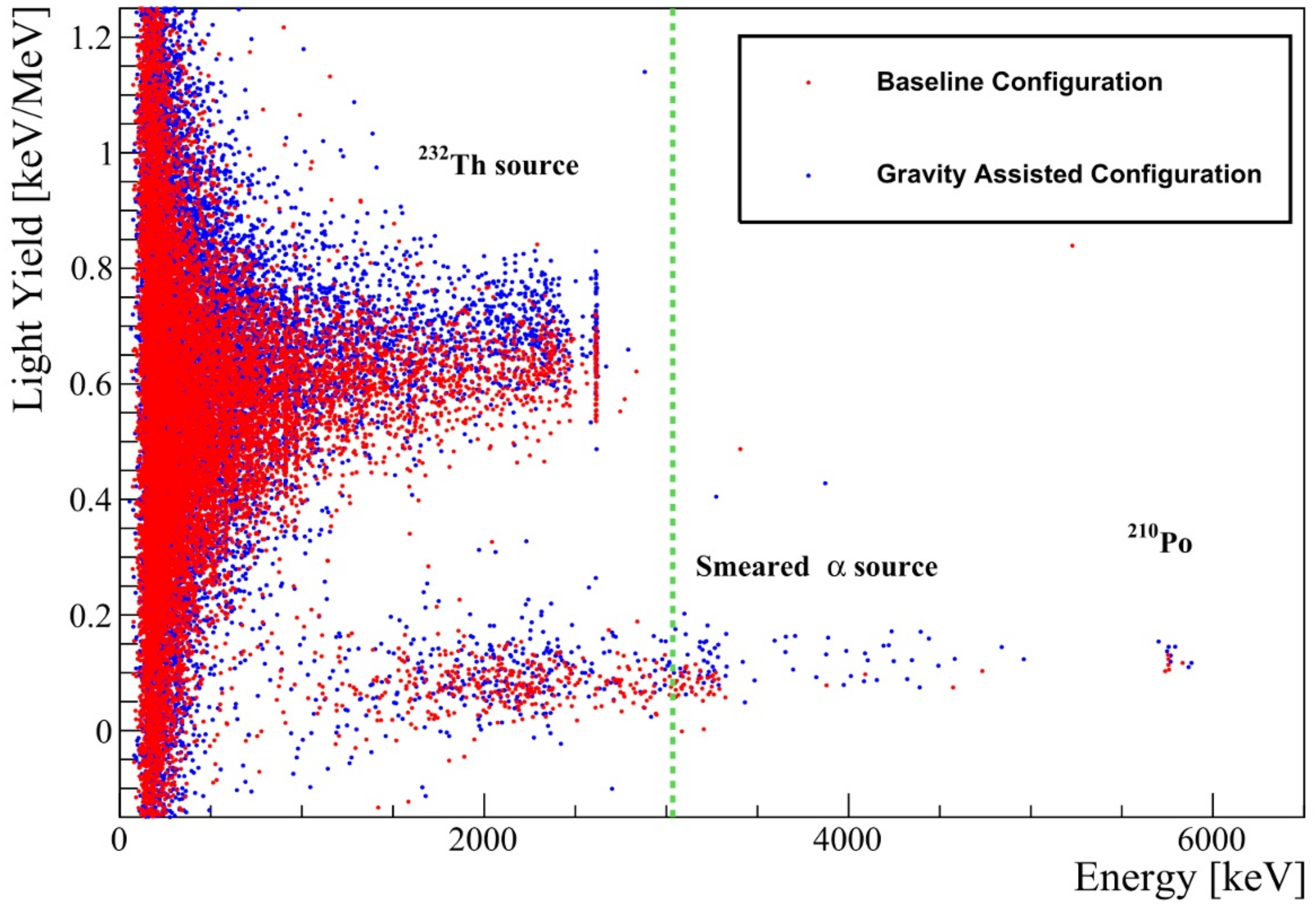
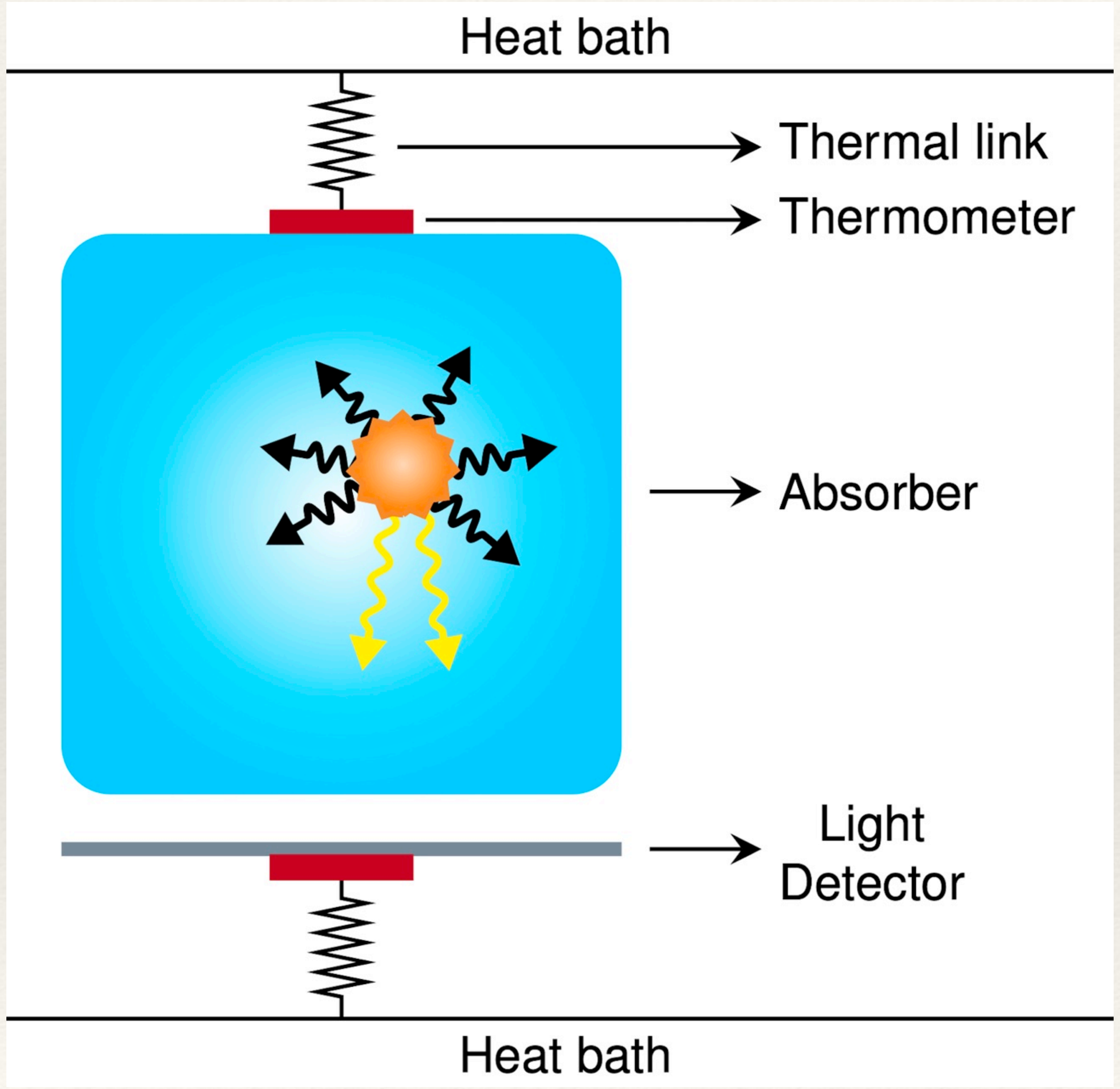
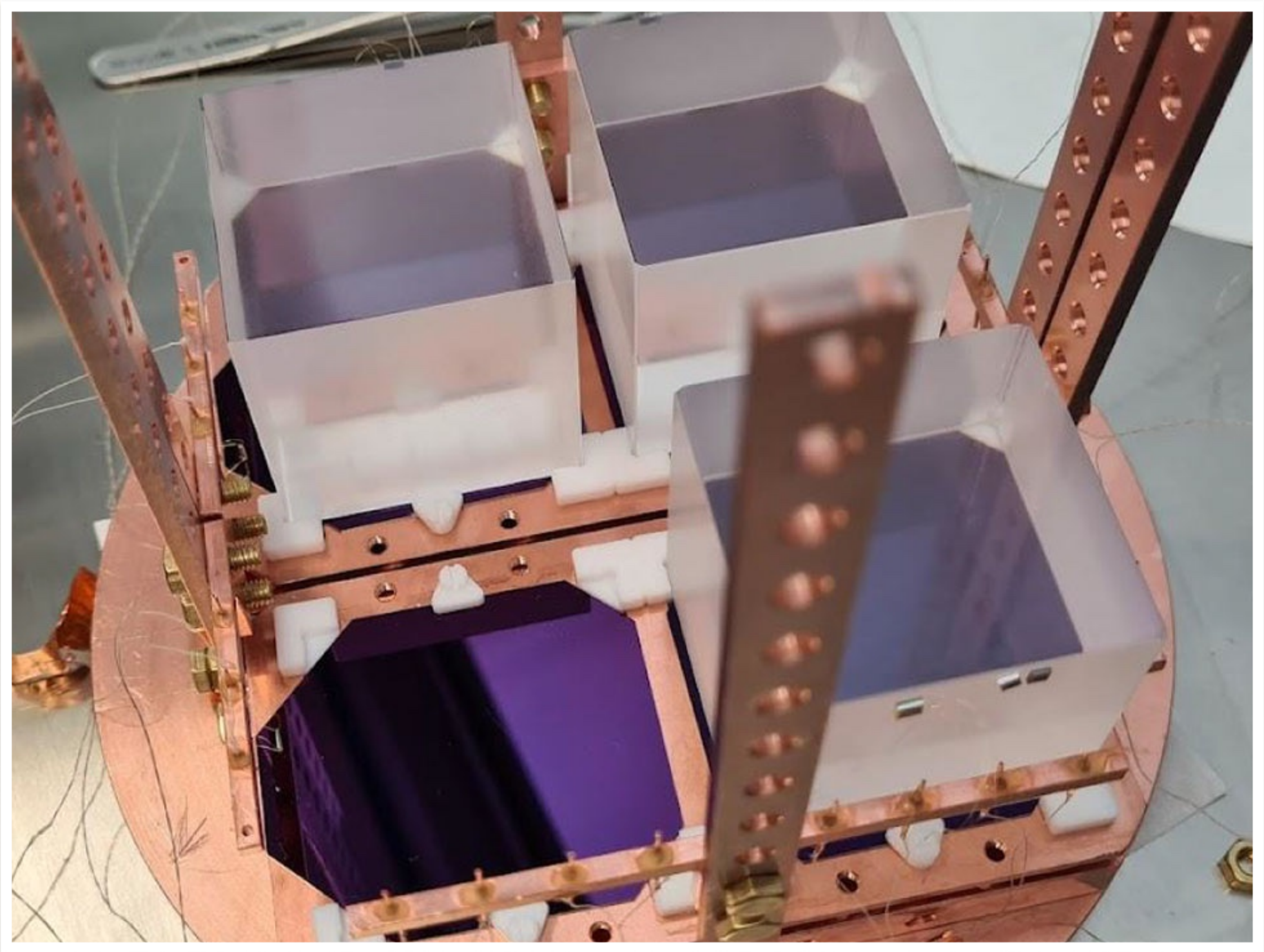


Fig. 5 Light Yield as a function of the energy deposited in the LMO crystal. Red: baseline configuration; blue: gravity-assisted configuration. Green vertical line: Q-value of ^{100}Mo

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

CUPID: scintillating bolometer

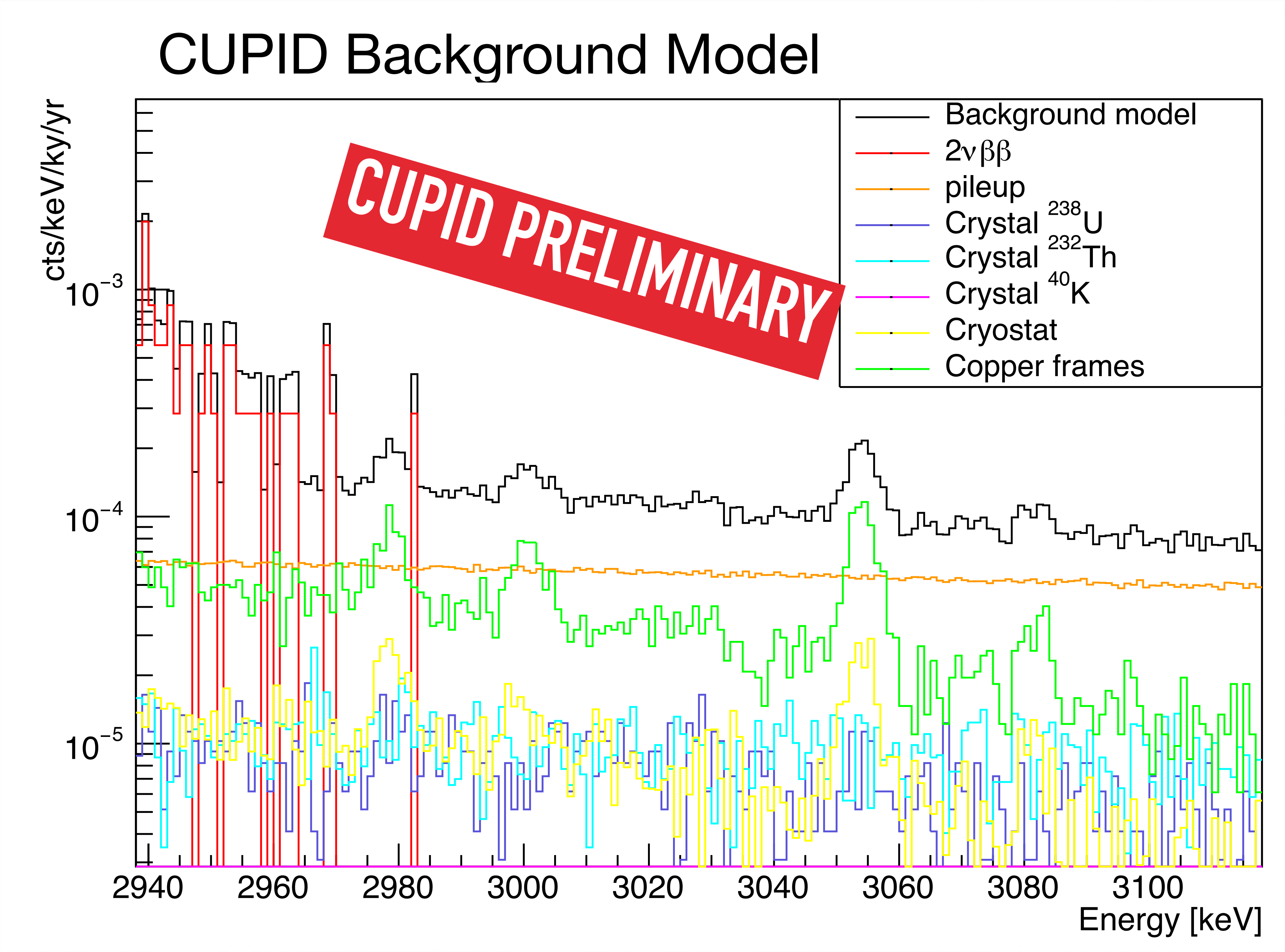


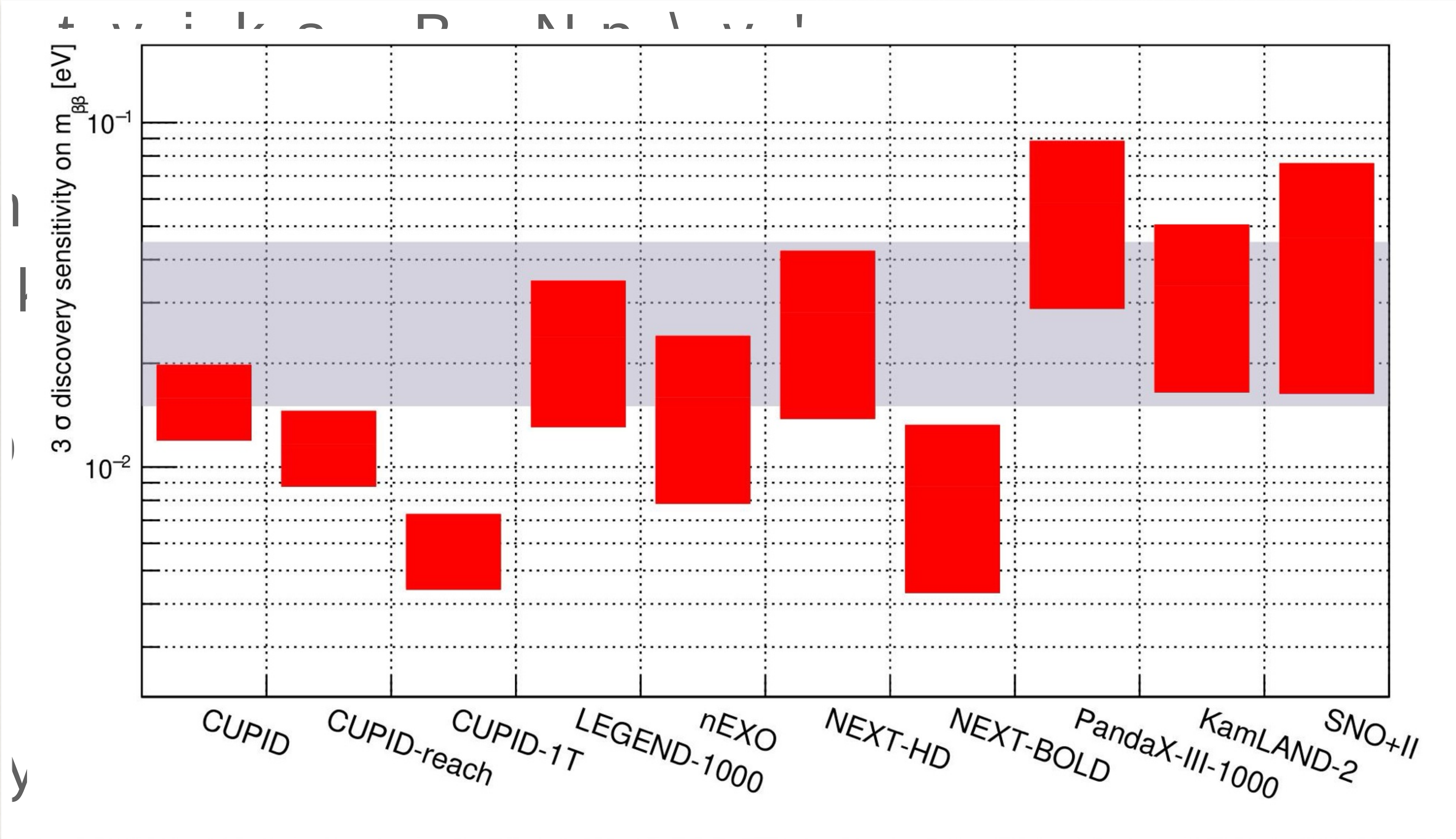


Eur. Phys. J. C (2022) 82:810

CUPID physics potential

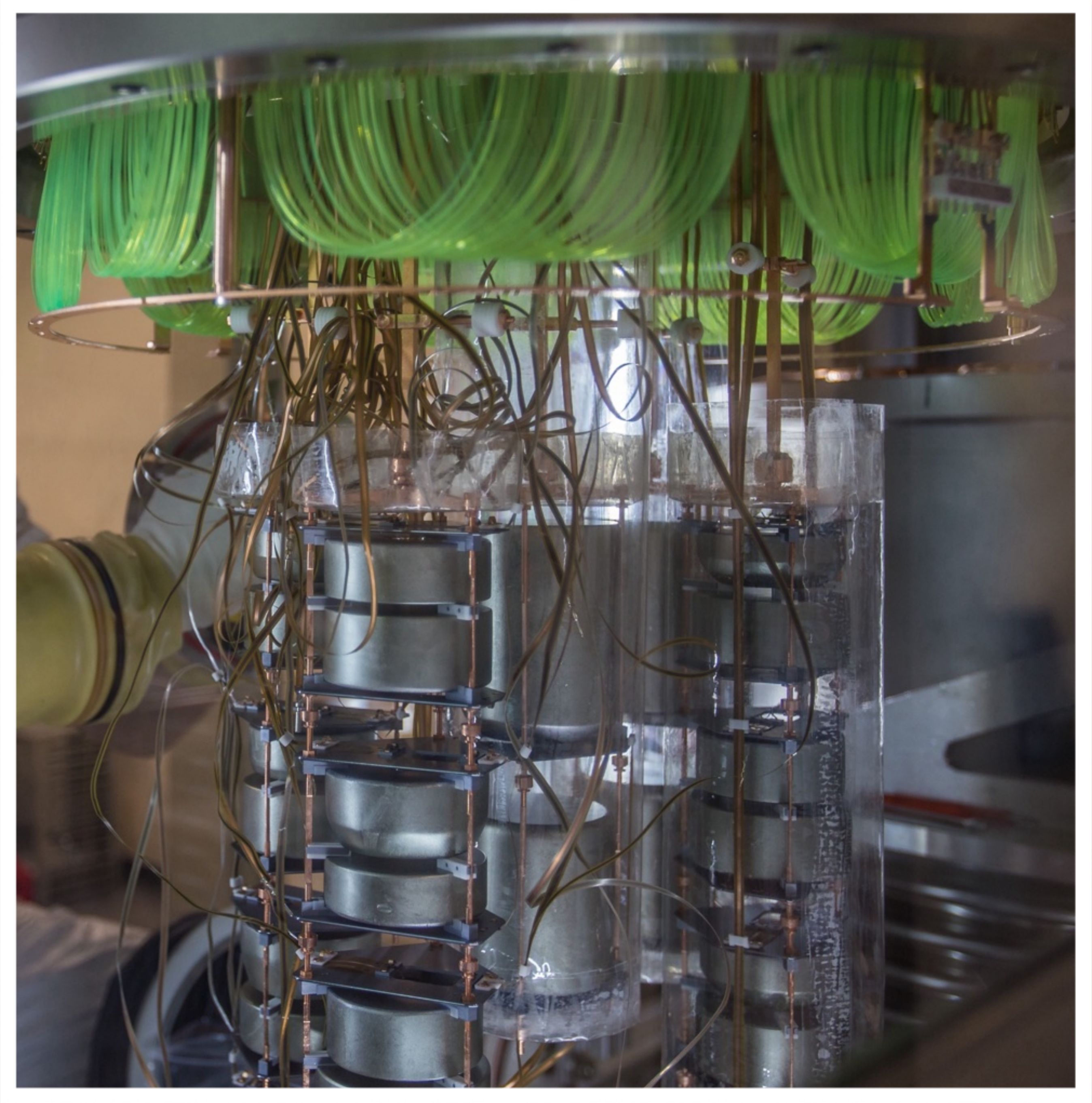
- $T^{0\nu}_{1/2} = 10^{27}$ year; $m_{\beta\beta} = 12 - 20$ meV; fully cover the inverted mass region

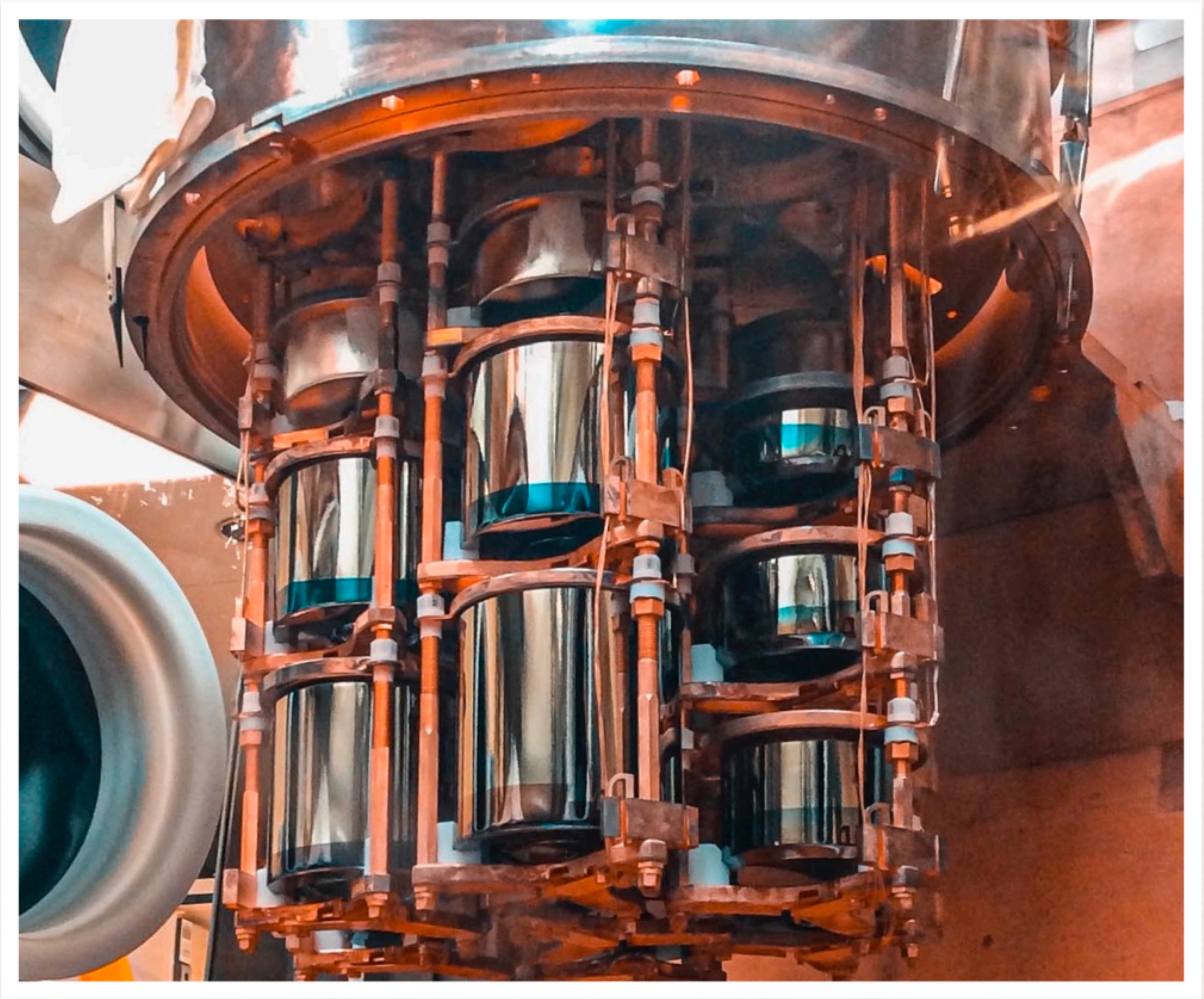


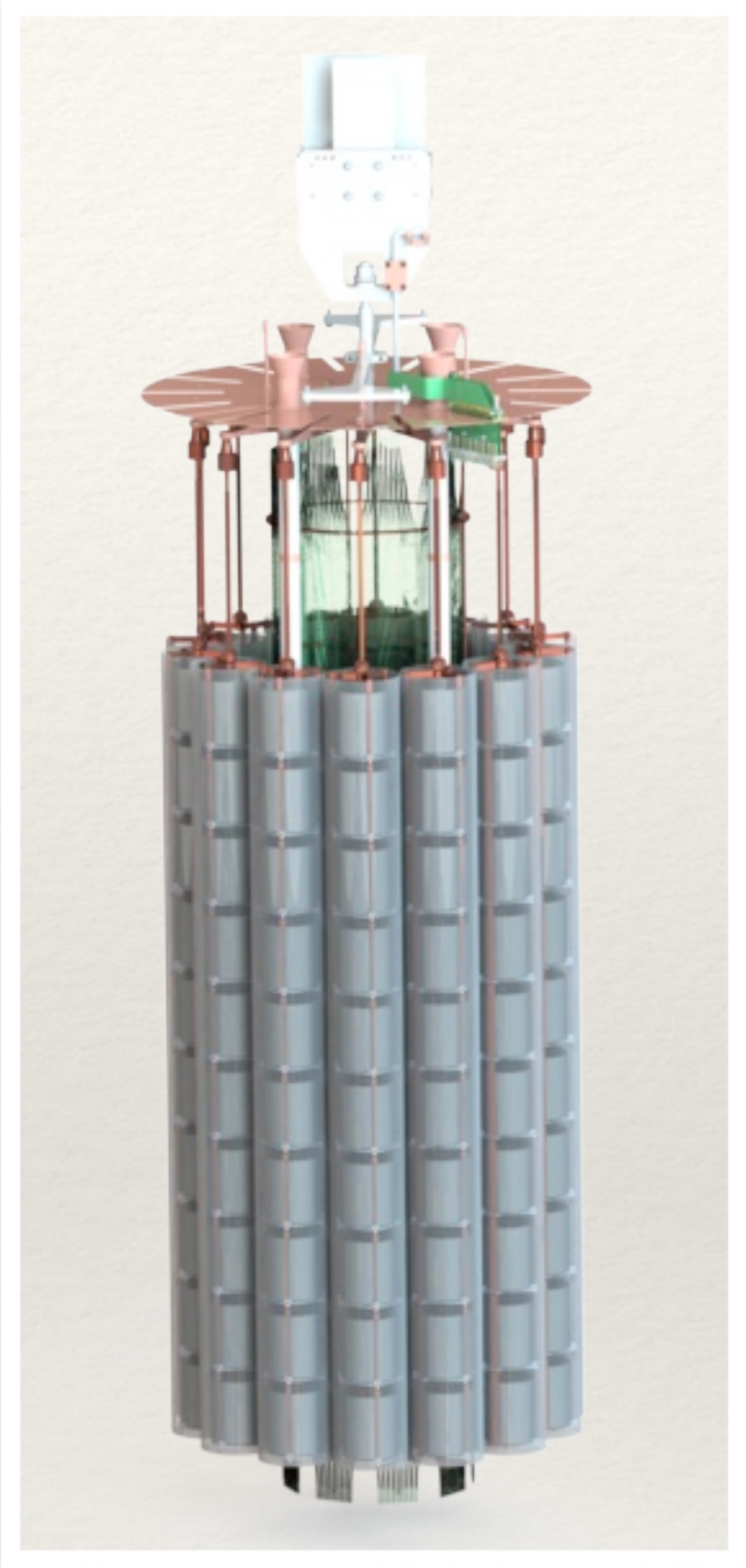


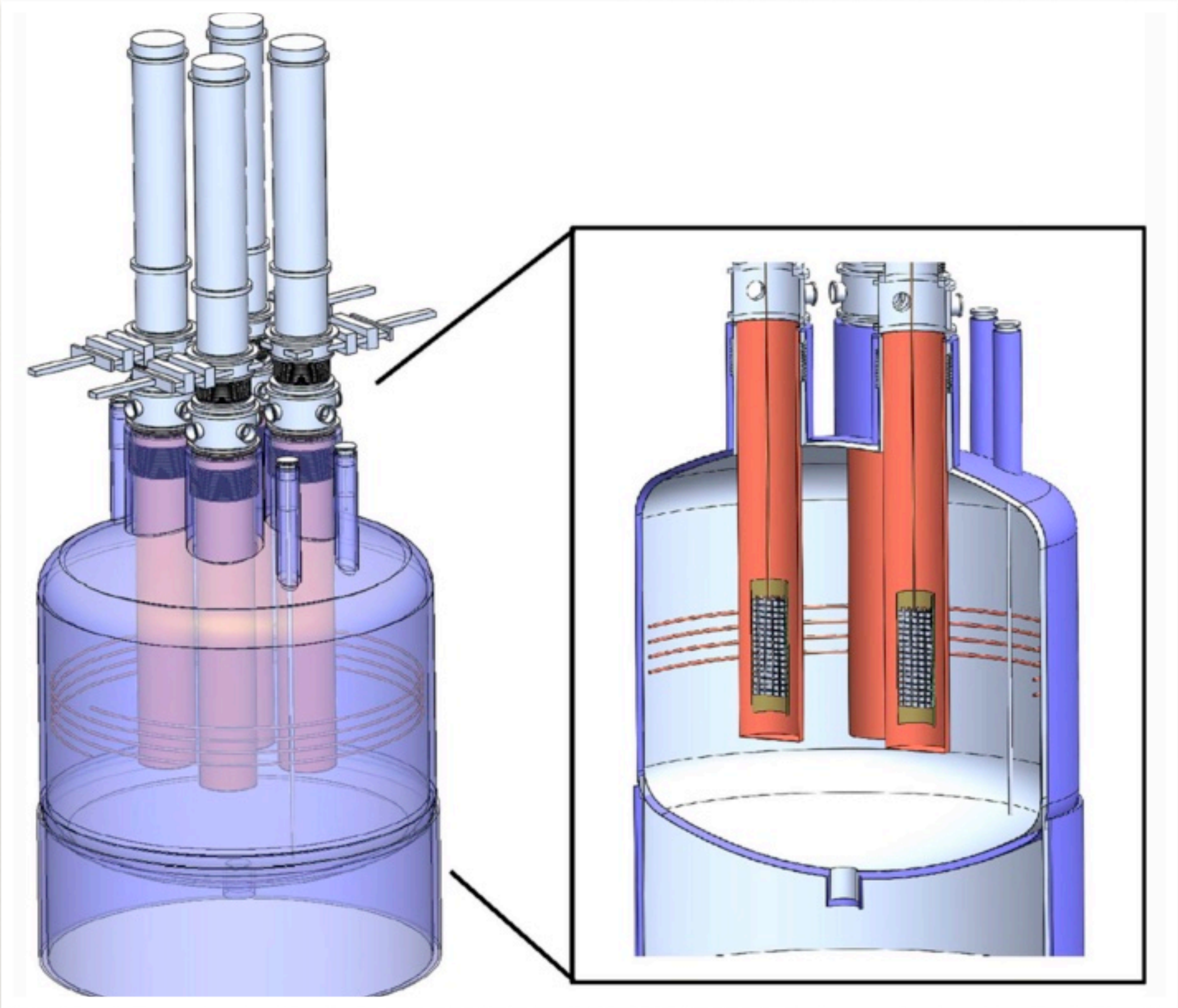
LEGEND
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

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









HPGe technology for double beta decay

- Mature technology chain with wide industrial applications
- Little detector R&D except background control
- Superb energy resolution (FWHM/Q ~ 0.1%)
- Solid basis for unambiguous discovery

HPGe technology for double beta decay

- Mature technology chain with wide industrial applications
- Little detector R&D except background control
- Superb energy resolution (FWHM / Q ~ 0.1%)
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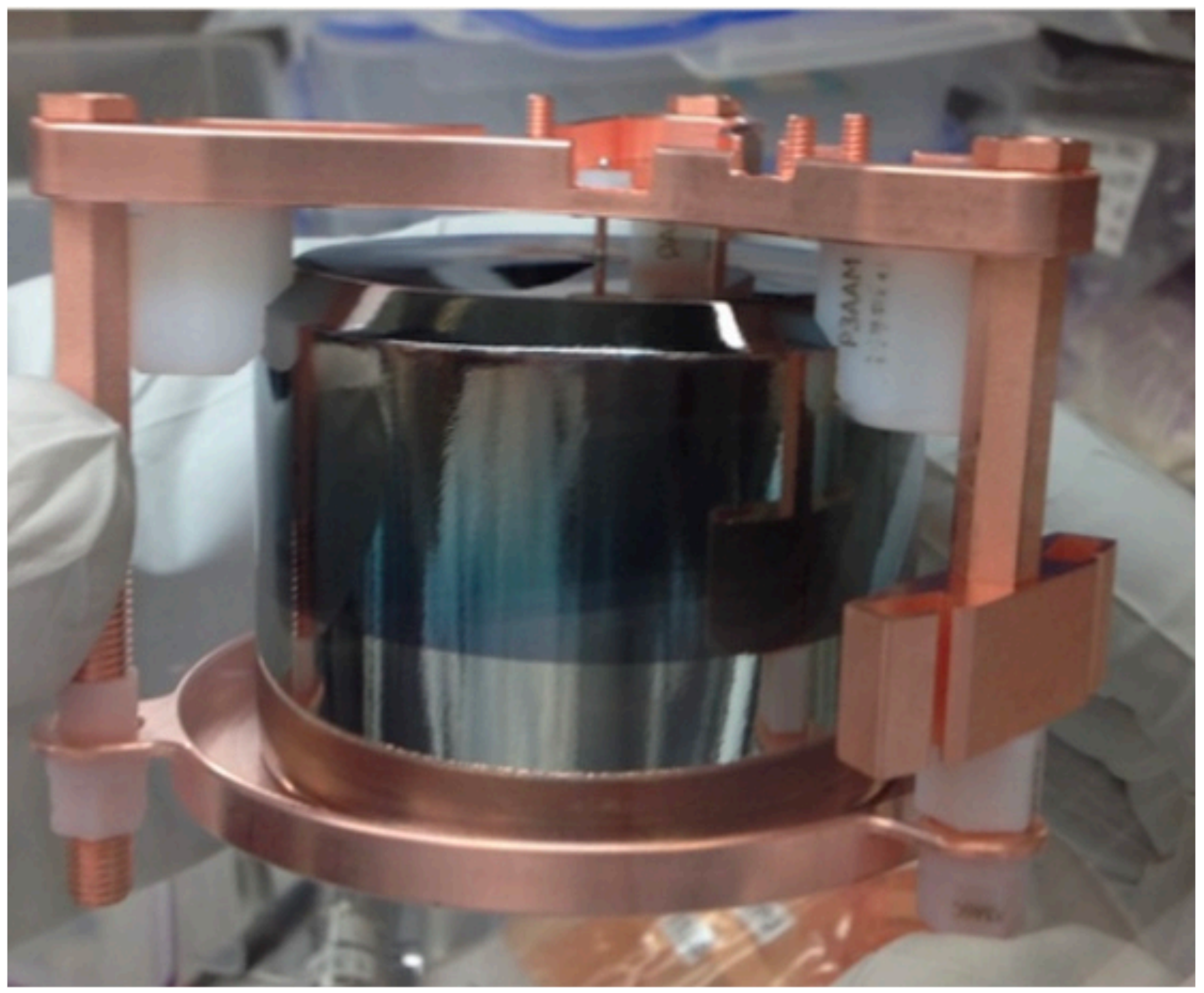
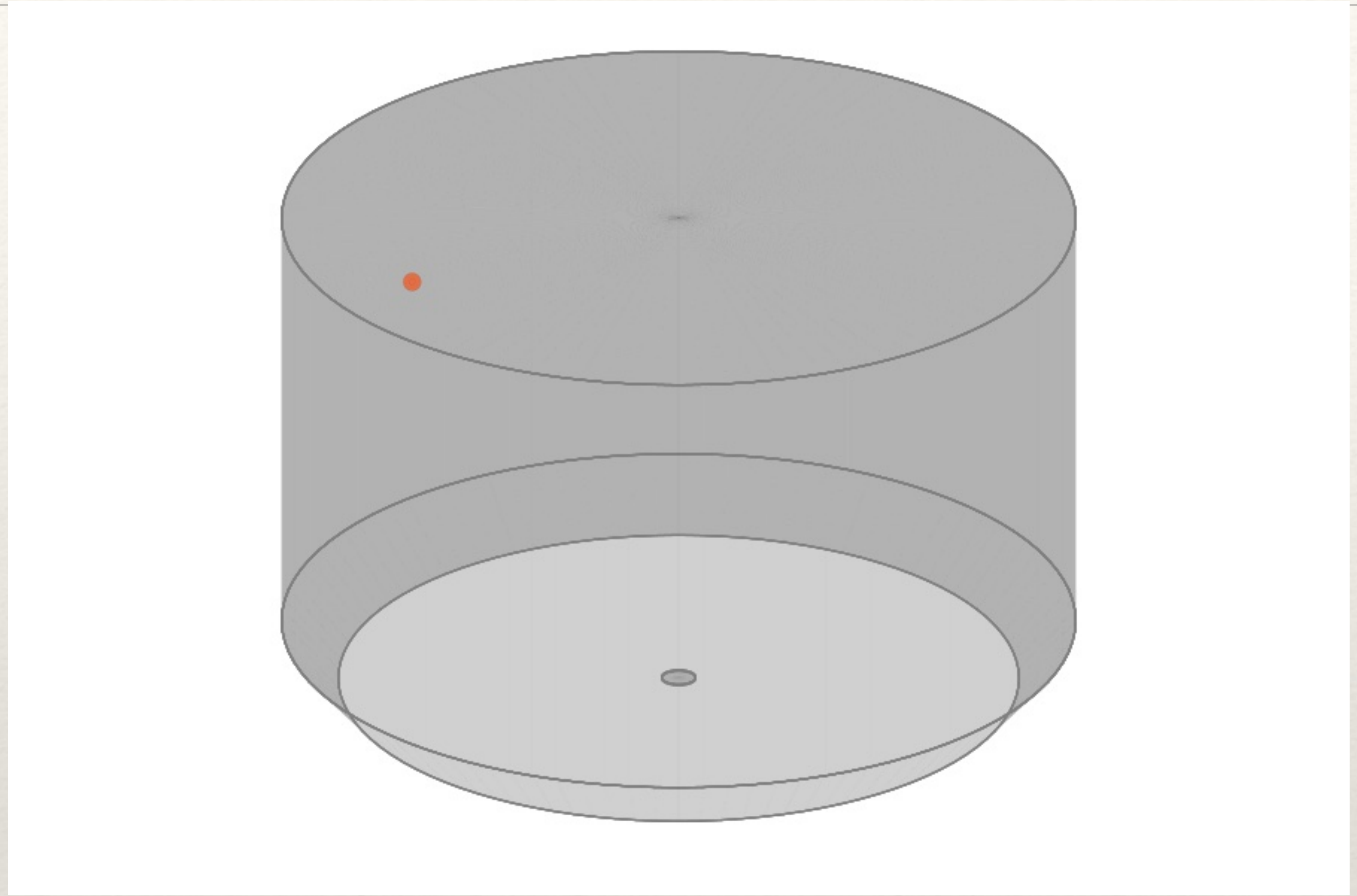
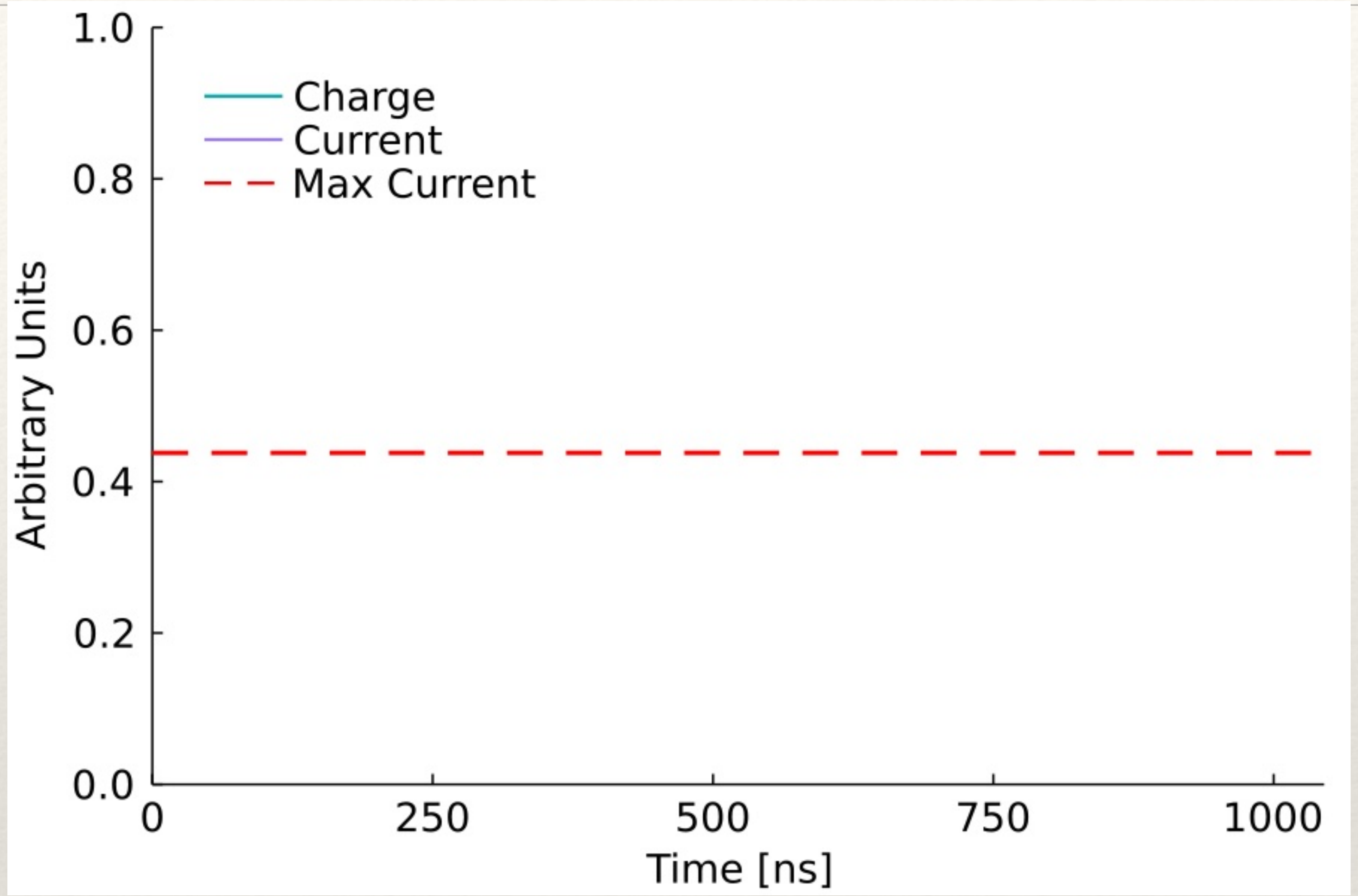
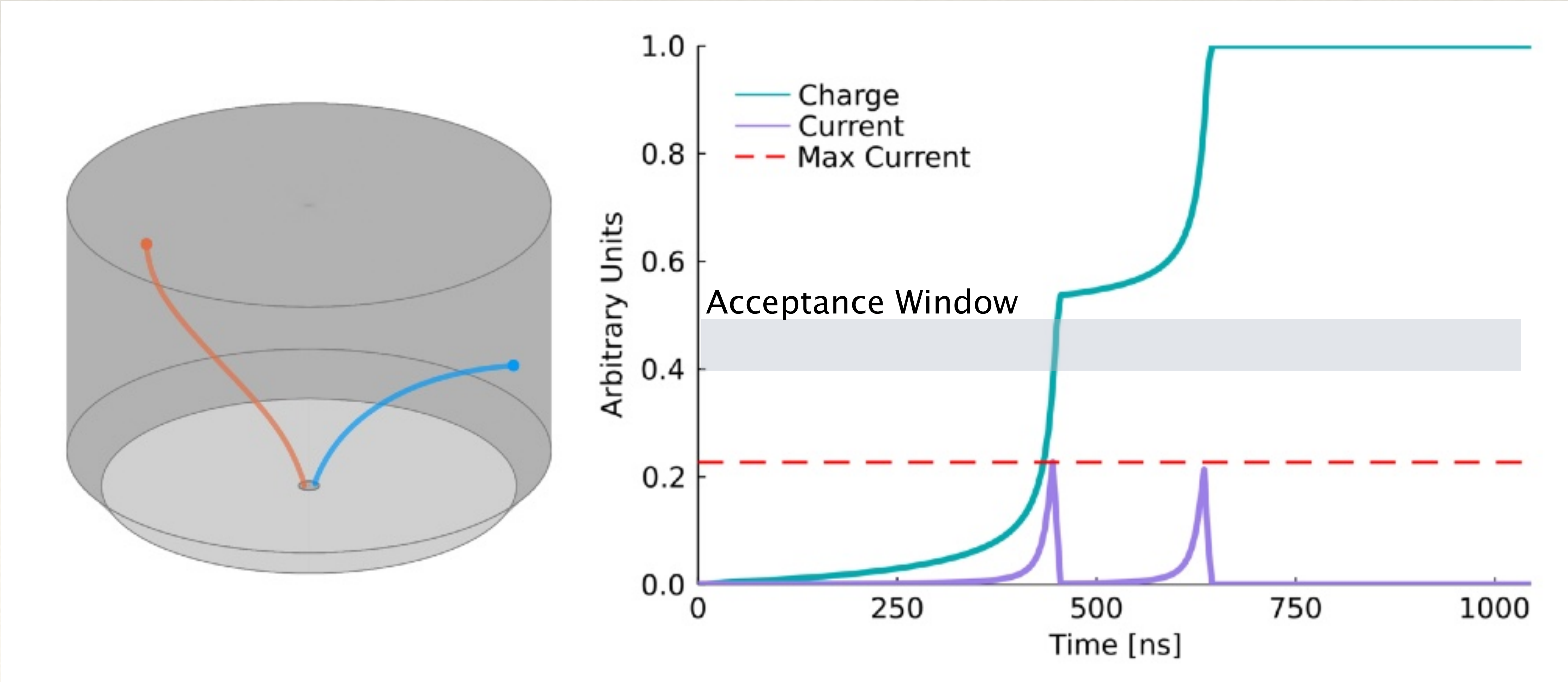


Signals from HPGe



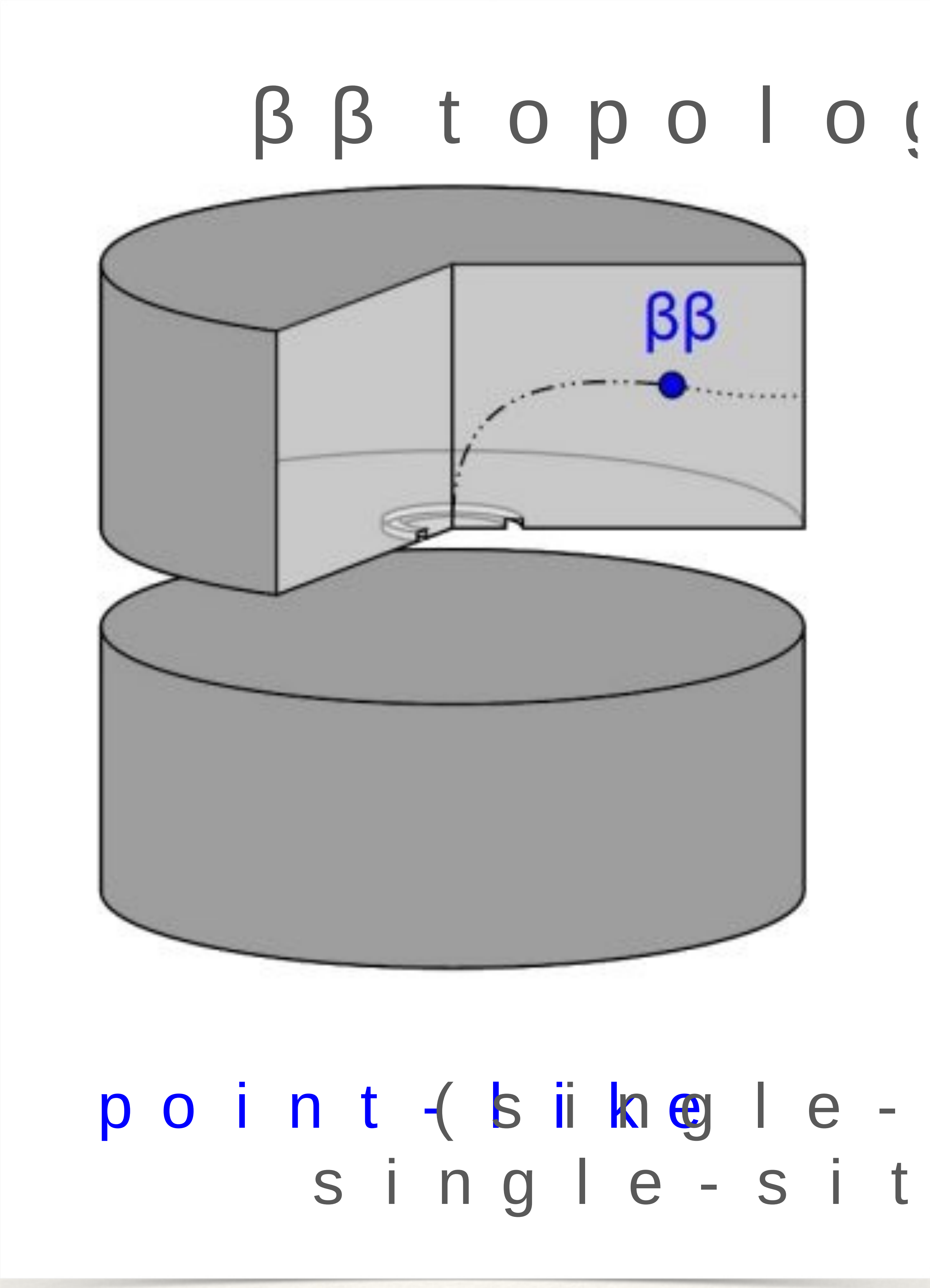


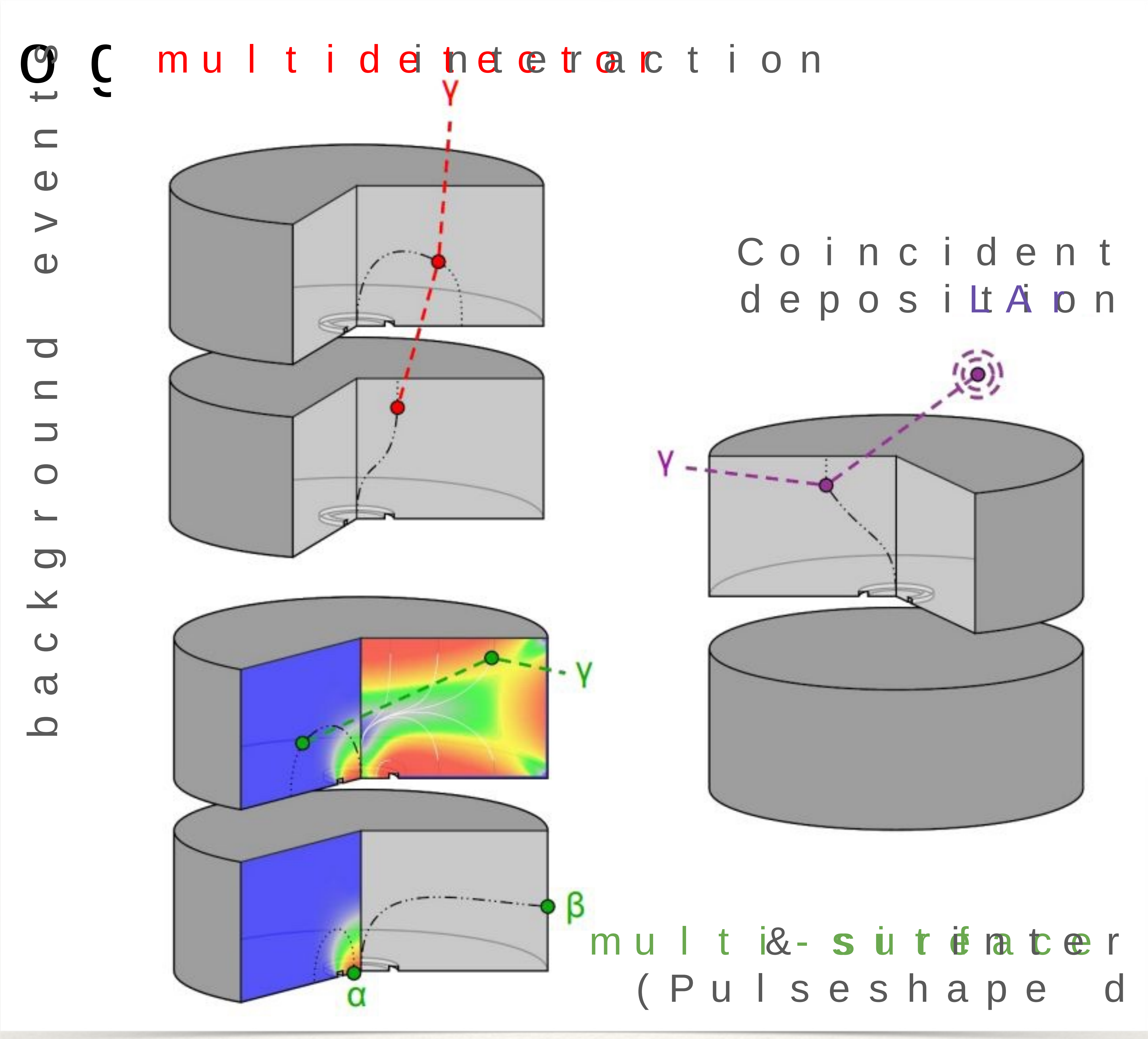


Pulse Shape Discrimination (PSD)

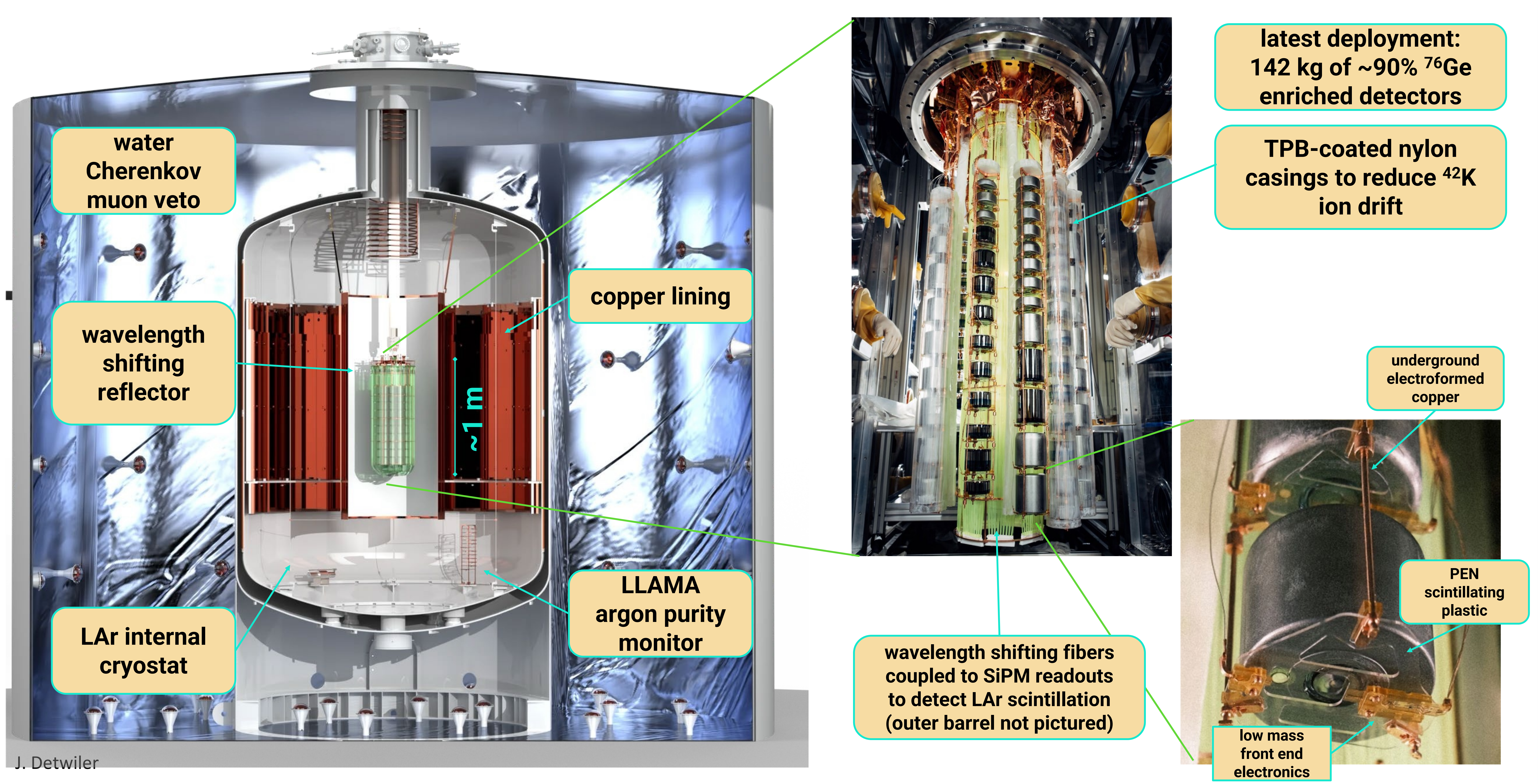
courtesy of David Hervas

Background rejection with HPGe array analysis



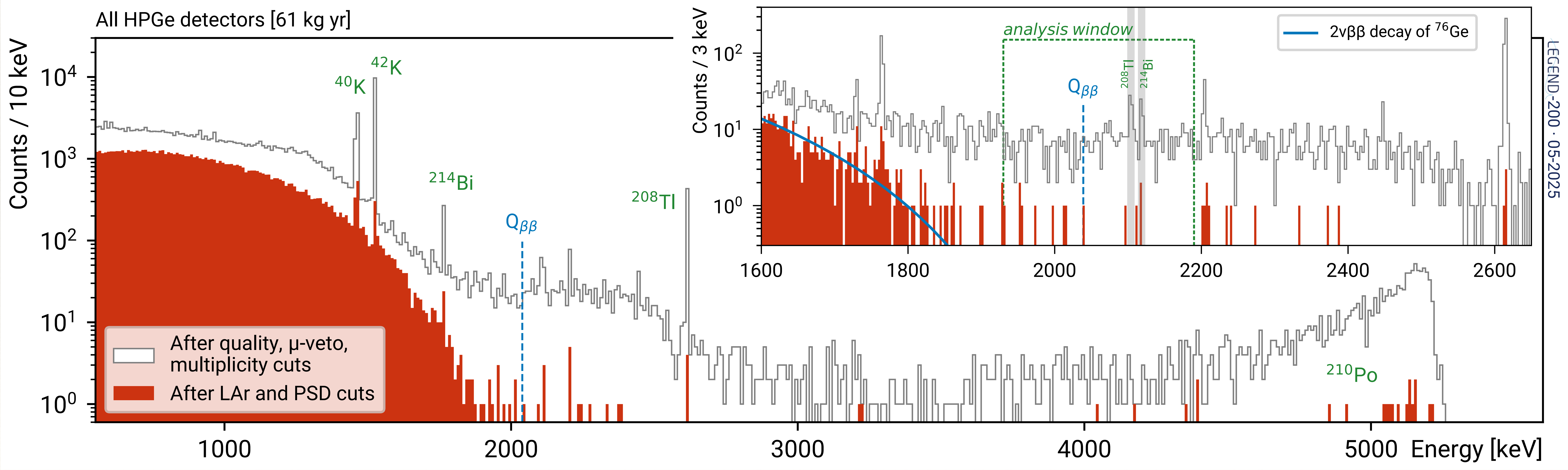


LEGEND-200: HPGe for ^{76}Ge $0\nu\beta\beta$



LEGEND-200 first results

- Background index: 0.5 cts / (keV ton yr); resolution 2.1-4.4 keV (FWHM)
- $T_{1/2} > 1.9 \times 10^{26}$ yr (90% C.L.); $m_{\beta\beta} < (75 - 200)$ meV

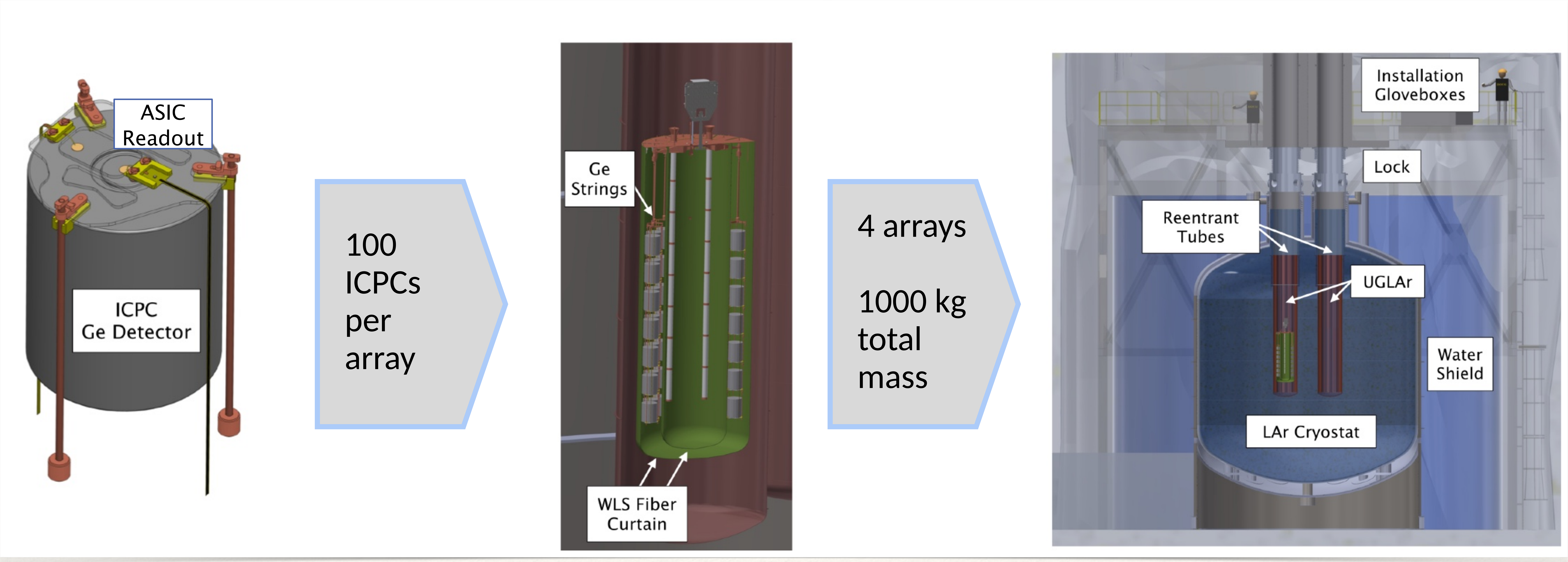


ArXiv:2505.10440

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



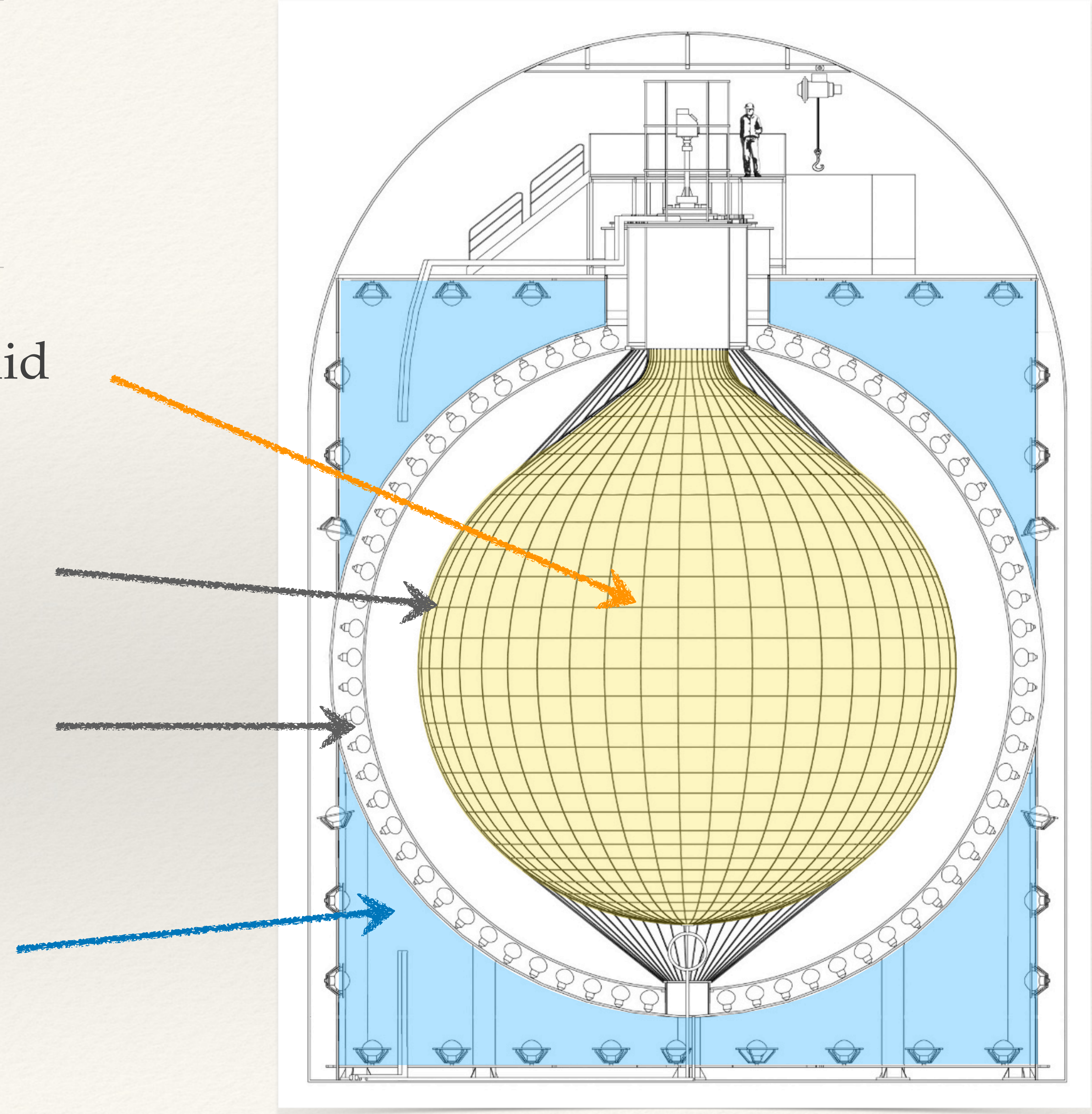
KamLAND-ZEN: Xe-loaded LS

Kamioka Liquid Scintillator Anti-neutrino Detector – Zero Neutrino Double β-Decay

π+/-
p
n
e+/-
...
1 km
μ+/-
The Kamioka Observatory
Sea of Japan
Kamioka Observatory, Space Particle Research...
Nagoya
名古屋
Osaka
大阪
Tokyo
東京

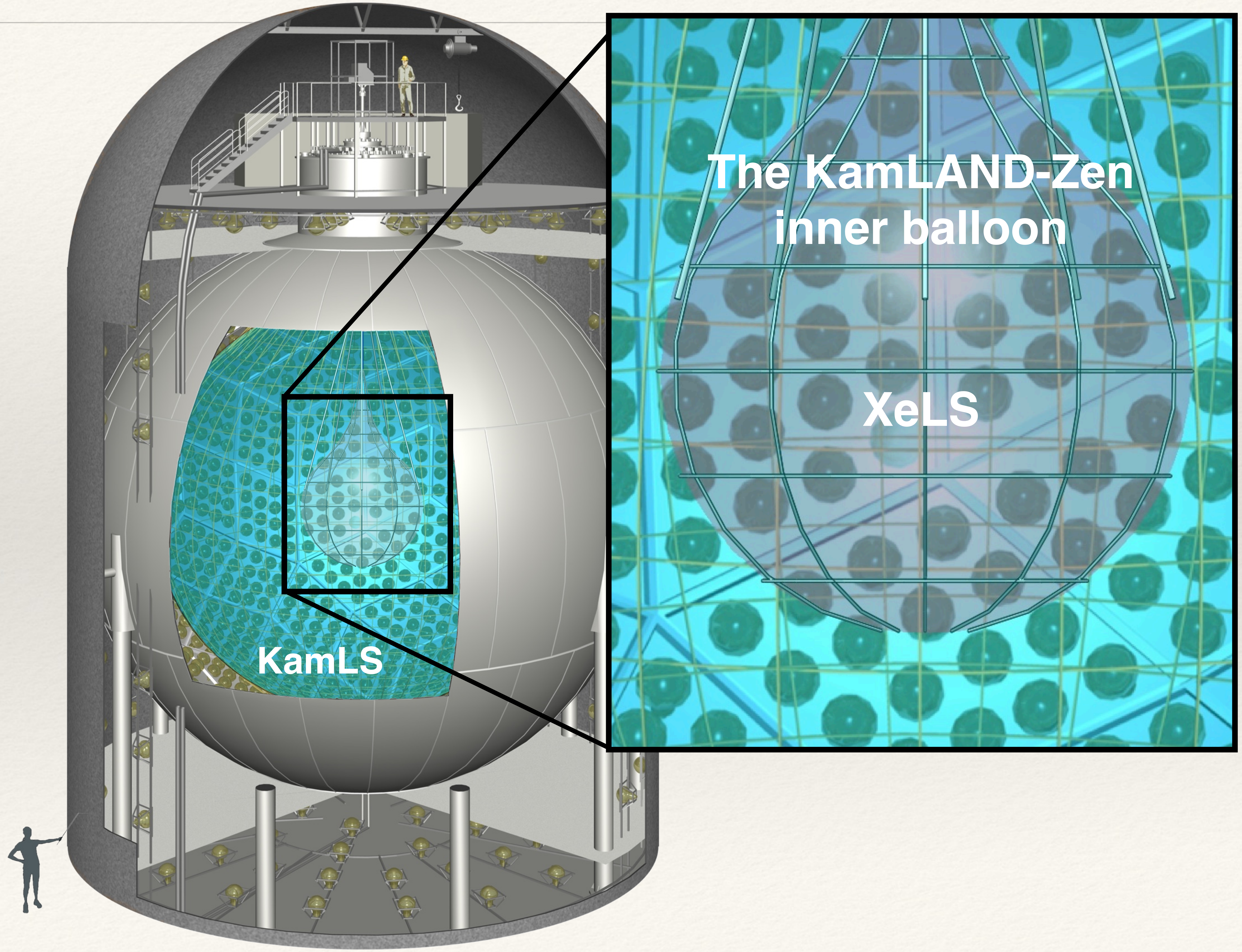
KamLAND Detector

- 1 kiloton of ultra-low radioactivity liquid scintillator (LS)
- 13-meter-diameter transparent balloon surrounded by a mineral oil buffer
- LS is viewed by 1,879 photomultiplier tubes (PMTs) providing ~34% photo-coverage
- Water Cherenkov outer detector (for tagging muons)



Xenon loading

- ^{136}Xe: Isotopic enrichment = 90.86%
- 3% wt soluble in Liquid Scintillator (XeLS)

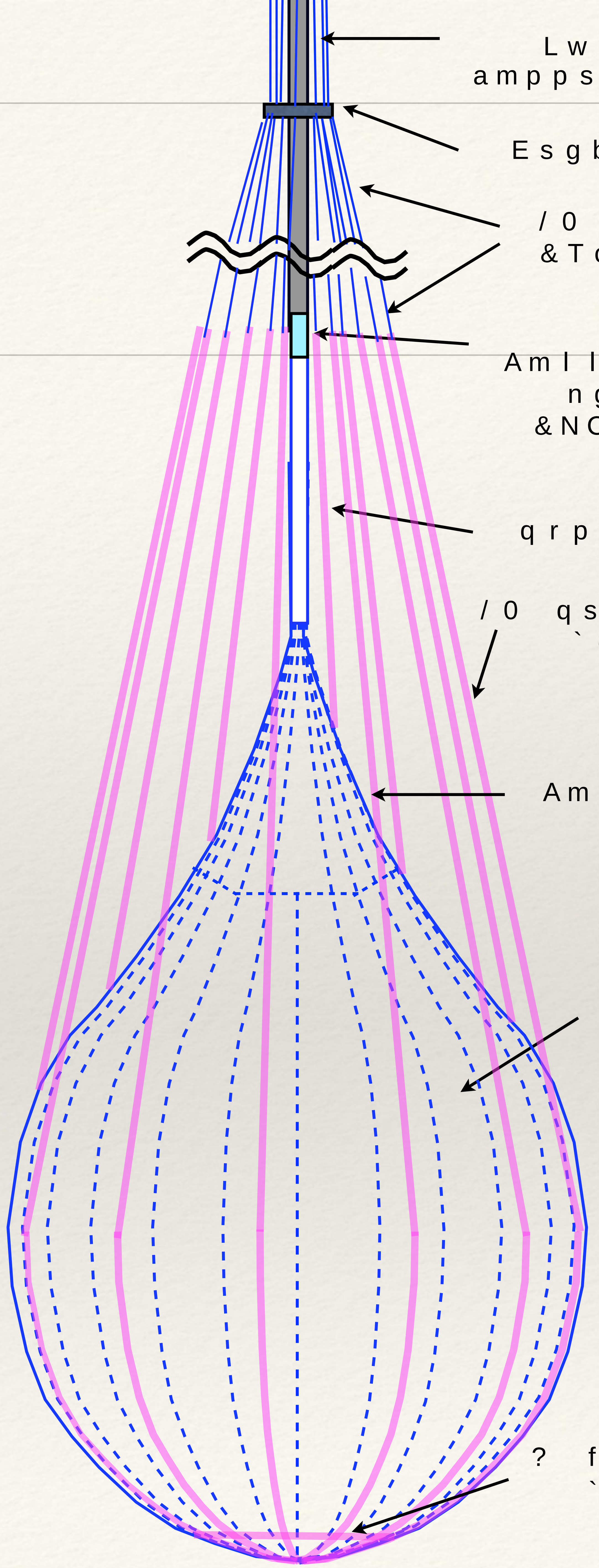


Inner Balloon

Welded with 25 μm nylon film in a Class 1 cleanroom

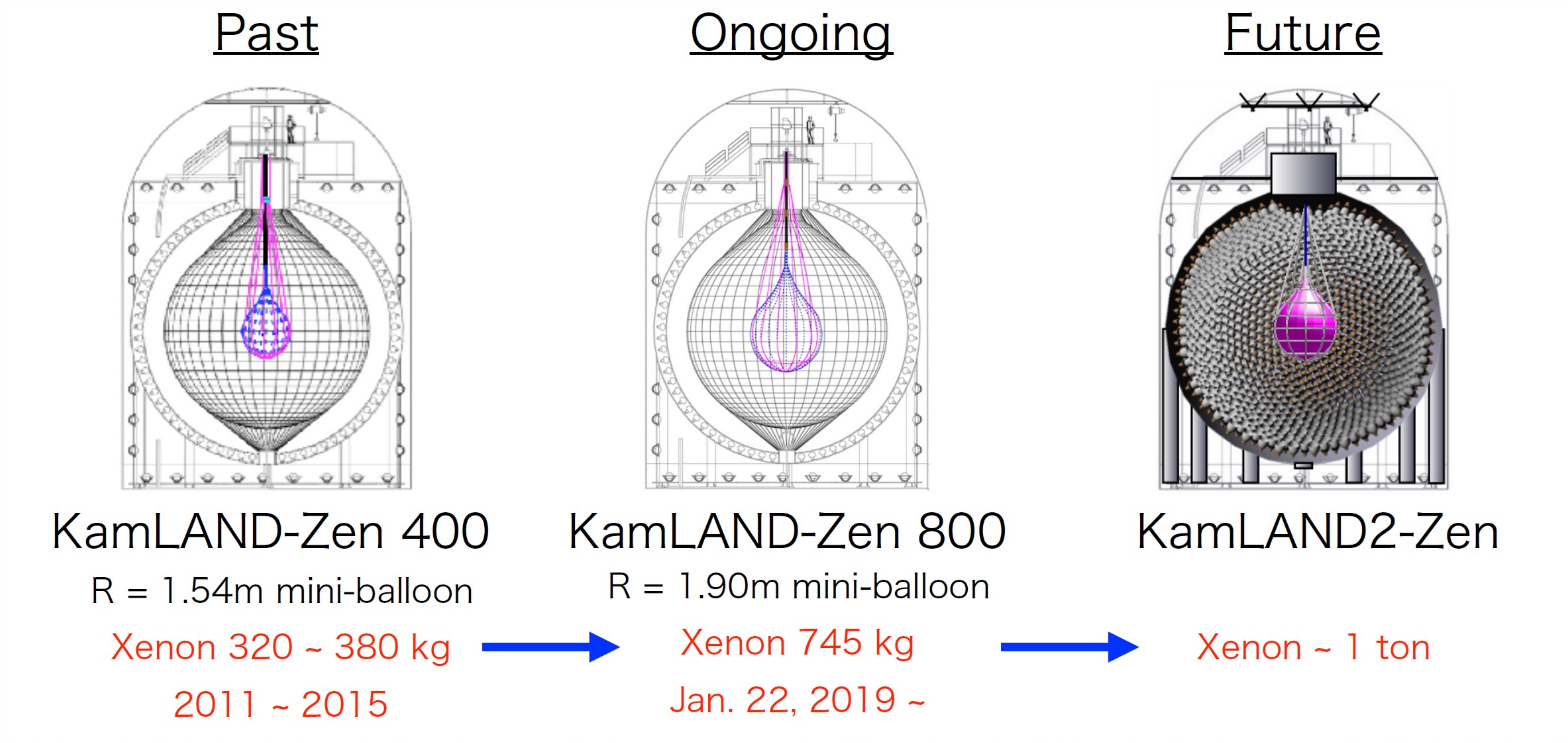
	KamLAND-Zen 400	KamLAND-Zen 800
Radius [m]	1.54	1.90
^{238}U [g/g]	4.6×10^{-11}	3×10^{-12}
^{232}Th [g/g]	3.4×10^{-10}	3.8×10^{-11}

1/10



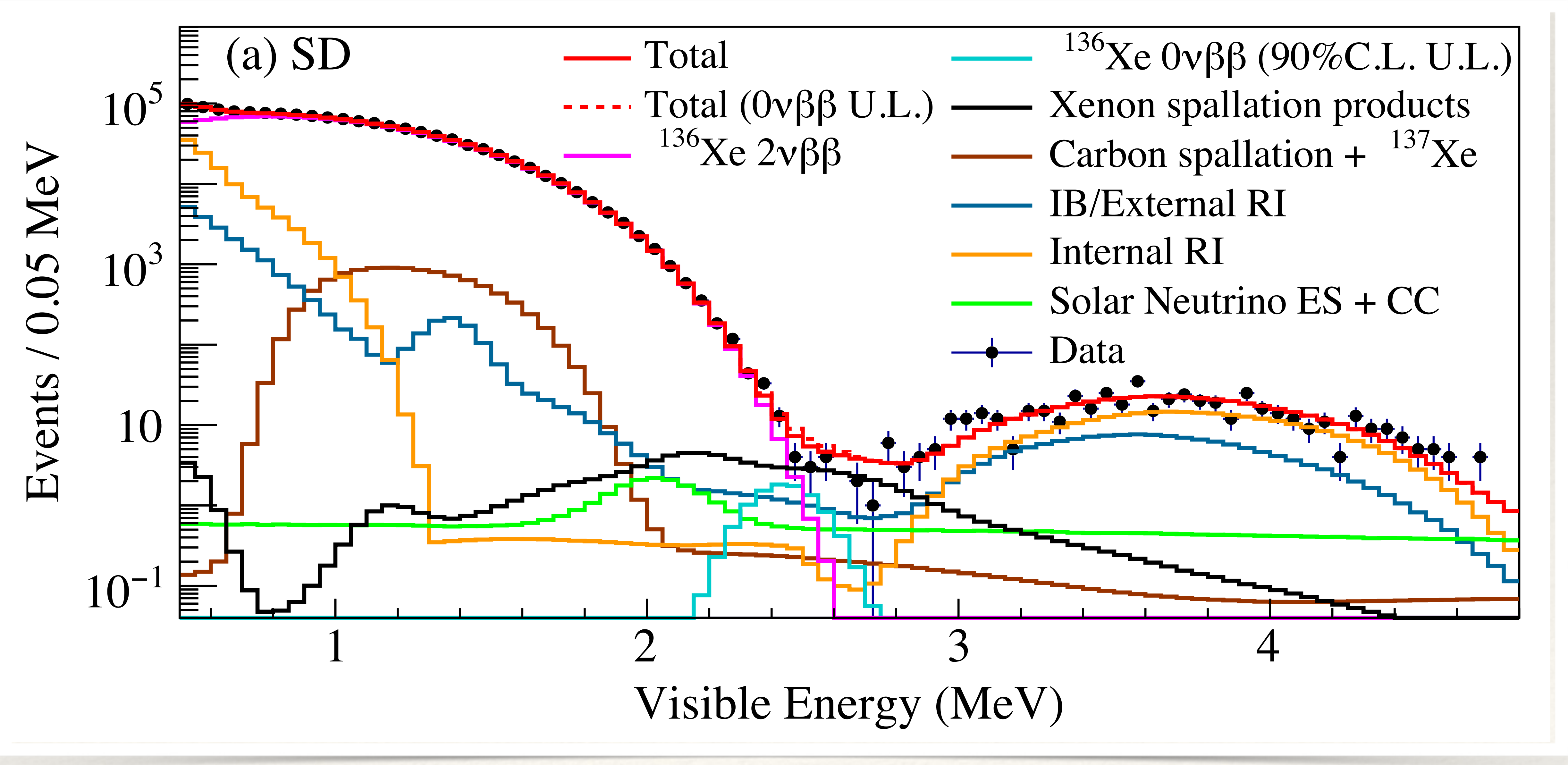

Taking physics data
since January 2019.

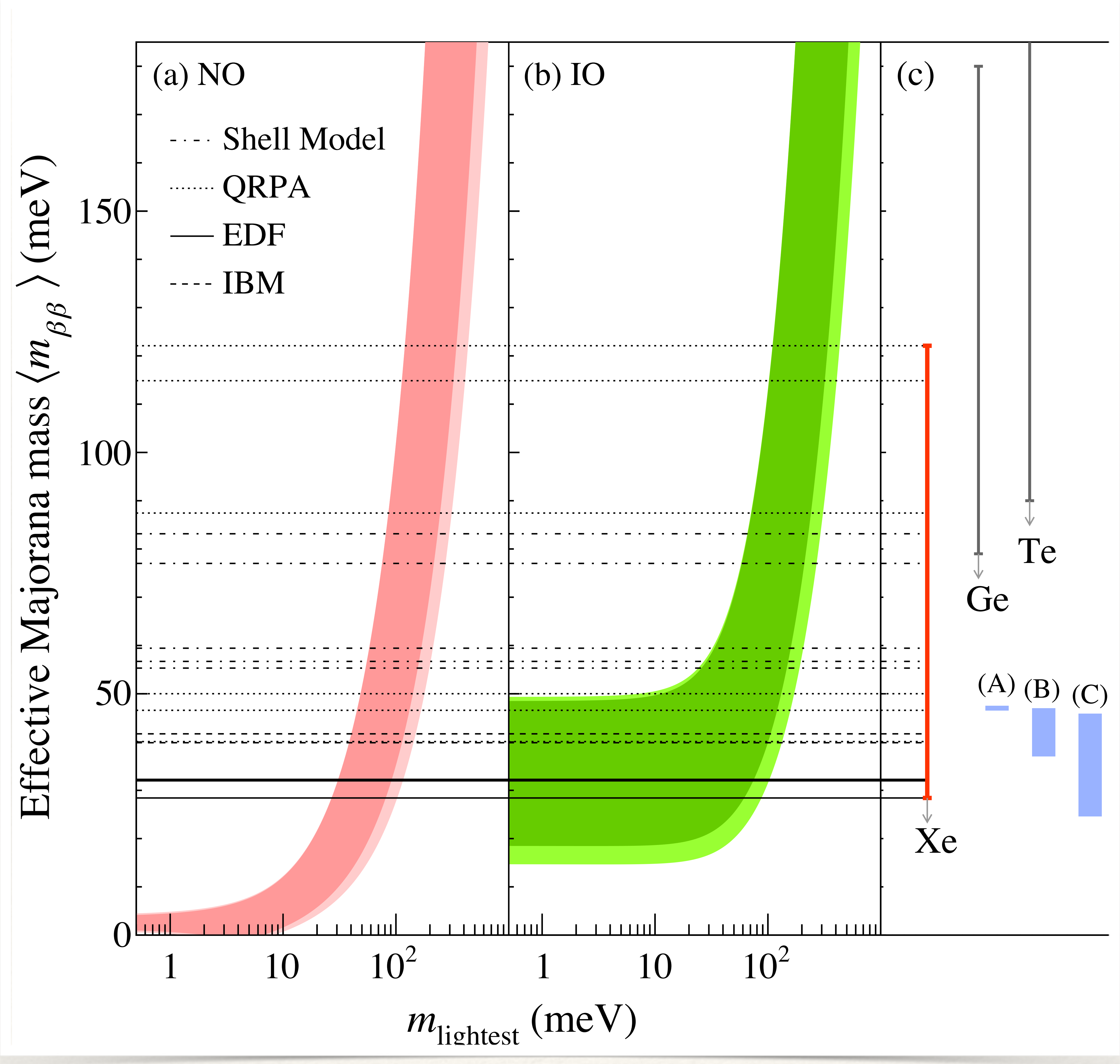
KamLAND-ZEN upgrade path



Results from complete KamLAND-Zen 800 dataset

- 2.097 ton yr of ^{136}Xe
- $T_{1/2} > 3.8 \times 10^{26}$ yr (90% C.L.)
- $m_{\beta\beta} < (28 - 122)$ meV
- World-leading limit on $m_{\beta\beta}$.

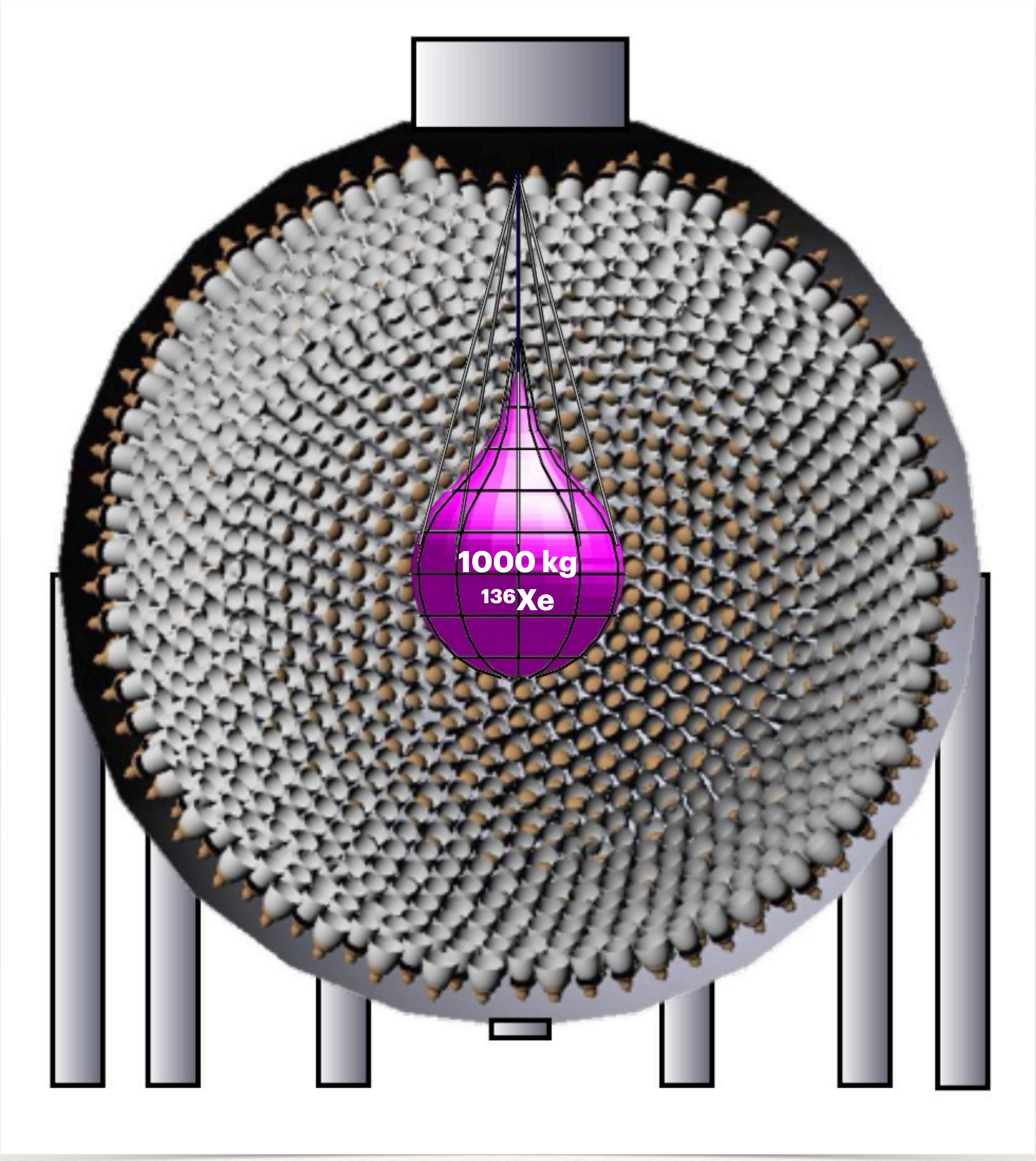




ArXiv: 2406.11438

KamLAND2-ZEN

- Improve energy resolution 4% → 2%:
  - Light collection with Winston Cones (x1.8)
  - High light yield scintillator (x1.4)
  - High QE 20" PMTs (x1.9)
- Scintillating inner balloon
- New electronics to reject cosmic ray spallation background



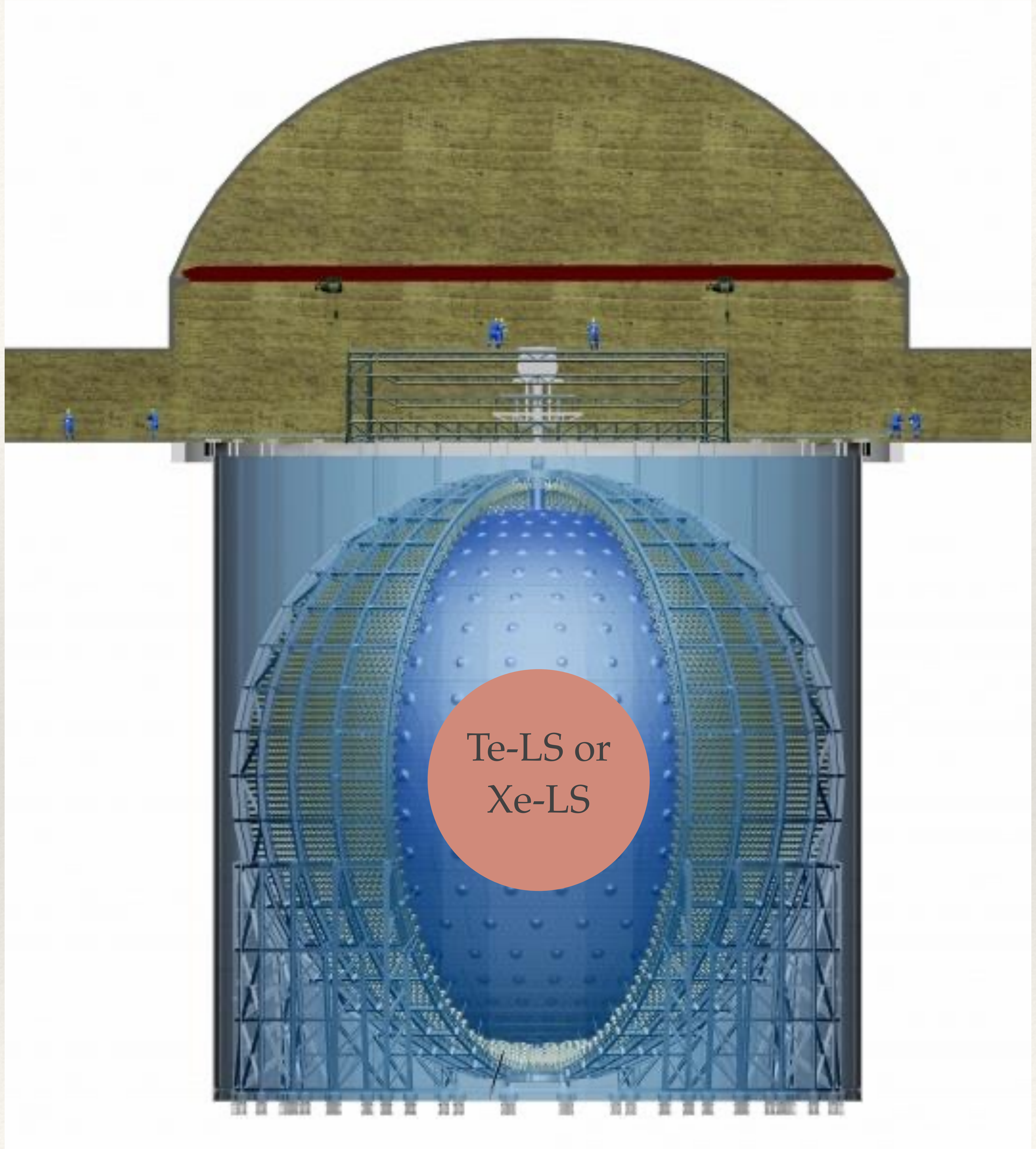
Jinping

无双实验：中国方案

韩柯
上海交通大学

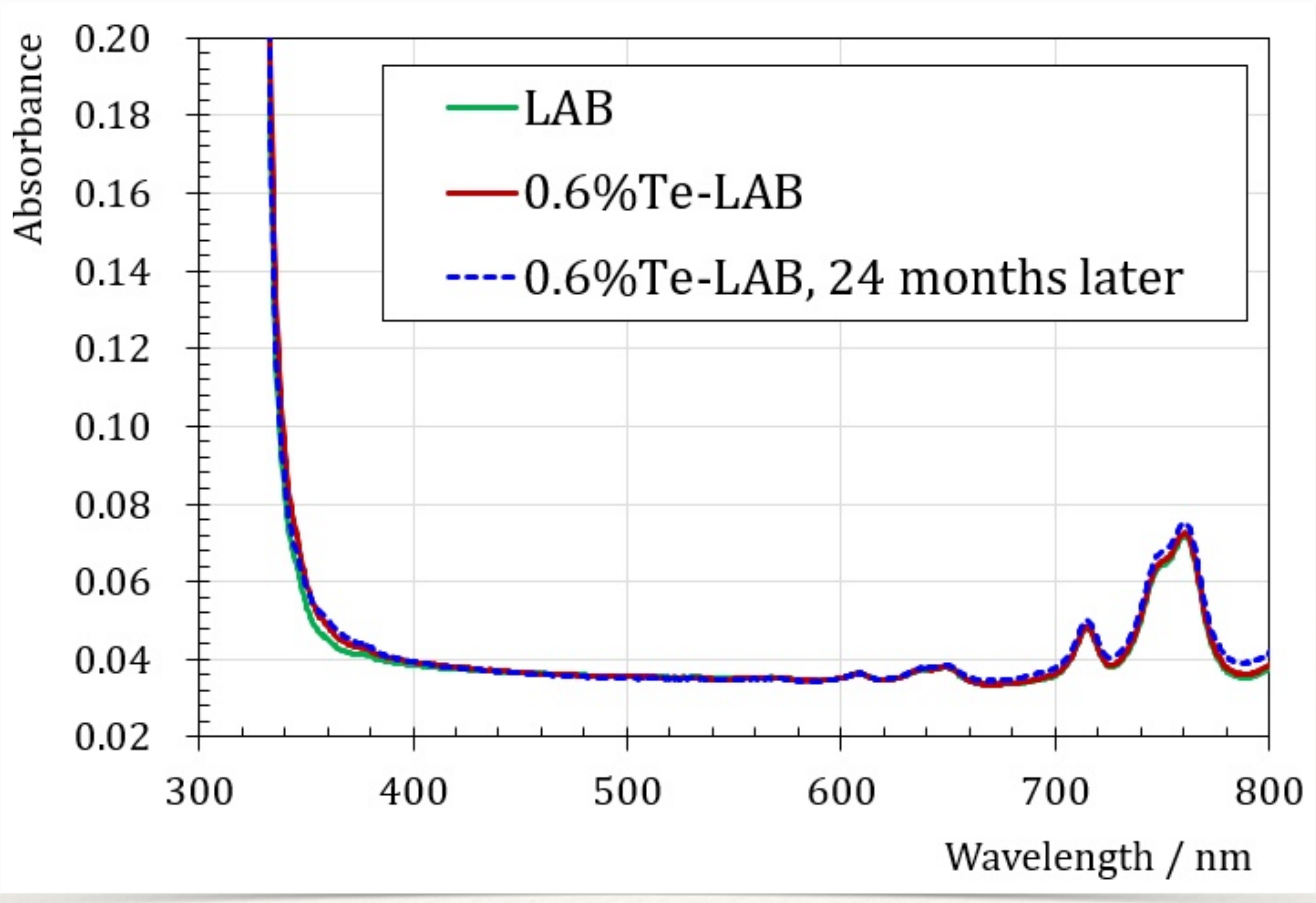
JUNO-0νββ

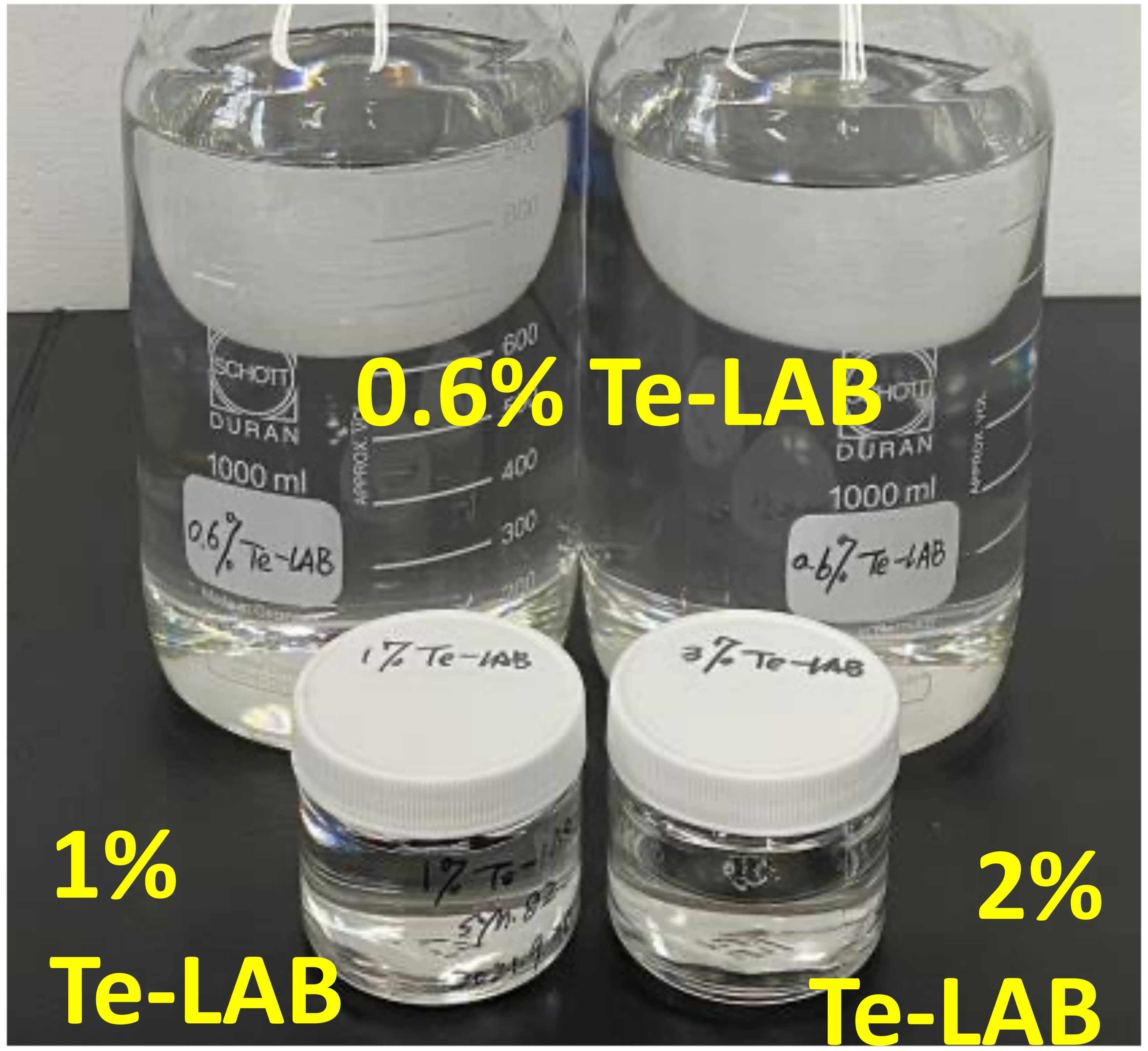
- 现有物理目标完成后下一阶段重点
- 10^{28}年量级的半衰期灵敏度
- 20 kton LS 可以掺杂约100吨量级同位素（Te）
- 极低本底
- 高能量分辨率< 3% @ 1 MeV → **2.4x better than KamLAND-Zen**



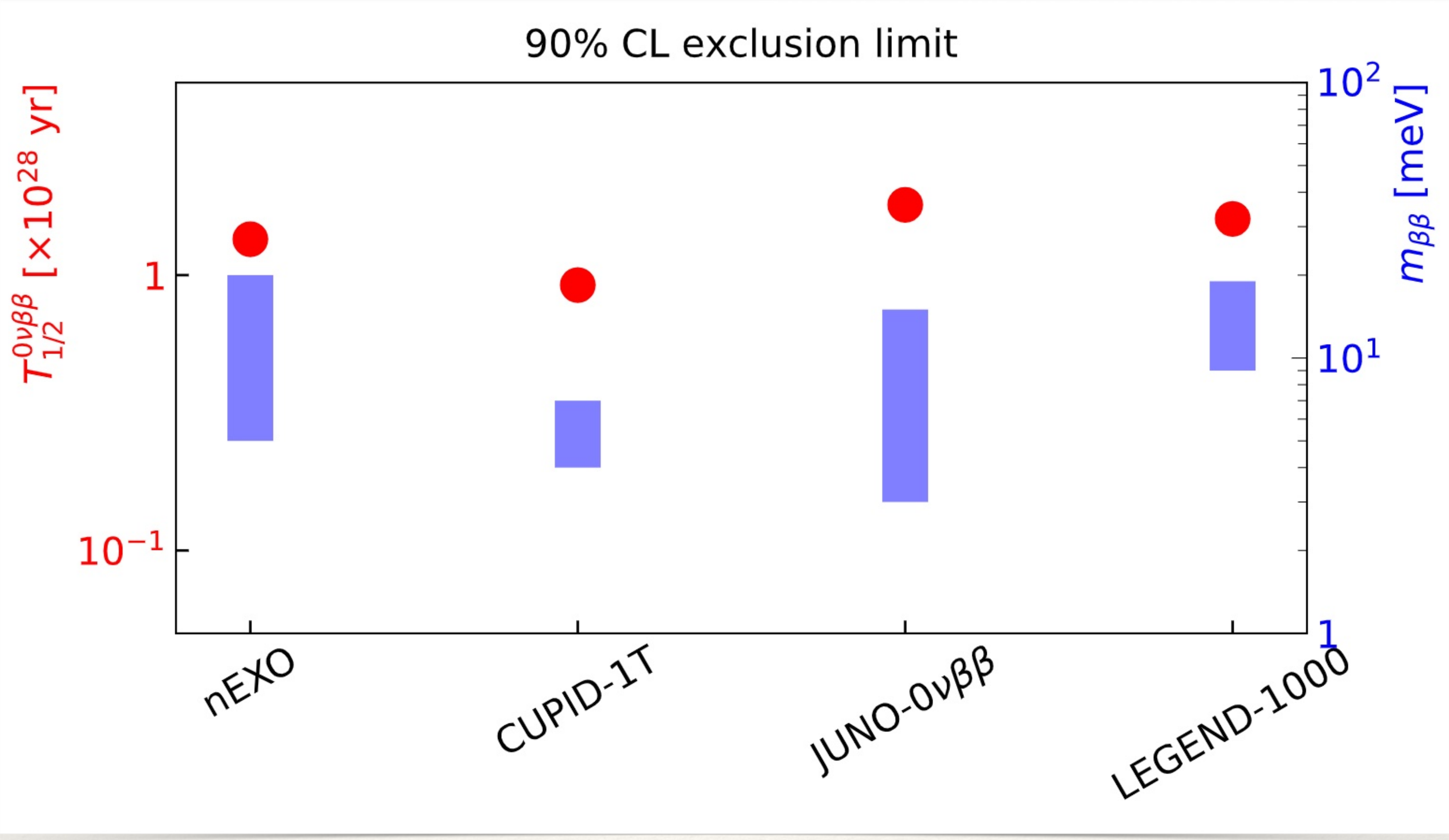
Te 掺杂

- 实现3%Te掺入LS，需要长期测量光产额、稳定性
- 目前测量0.6% Te 掺杂结果良好

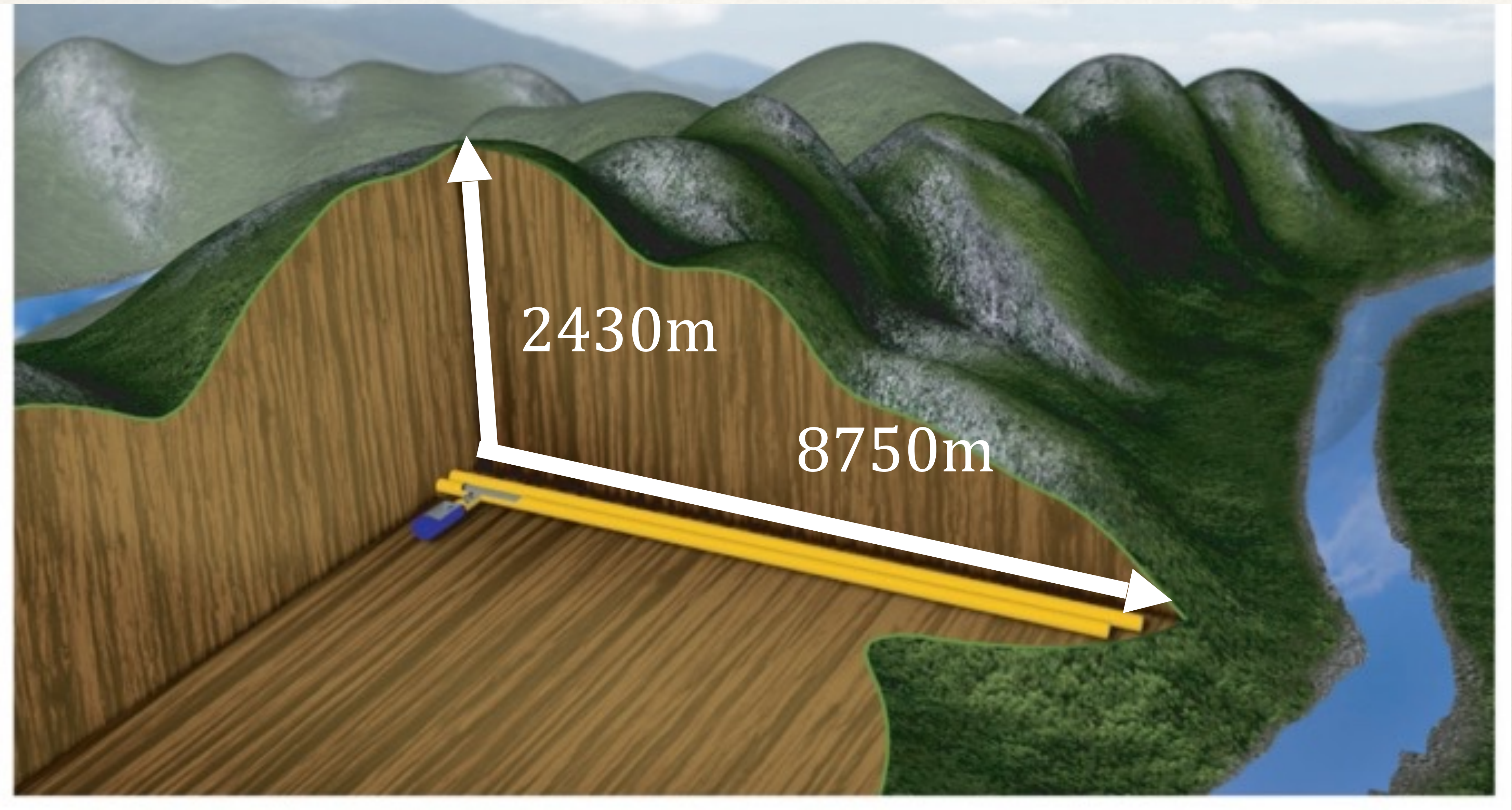


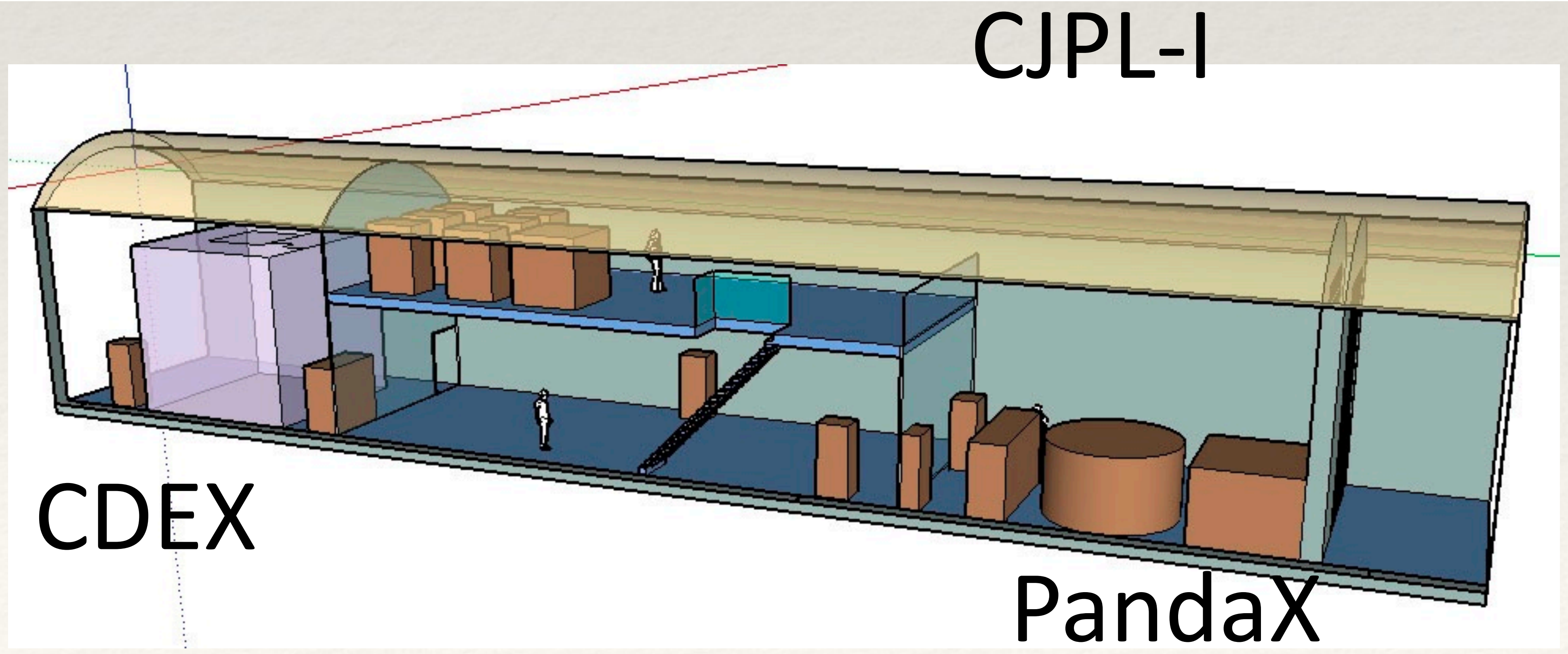


JUNO-0νββ 物理潜力（Xe）

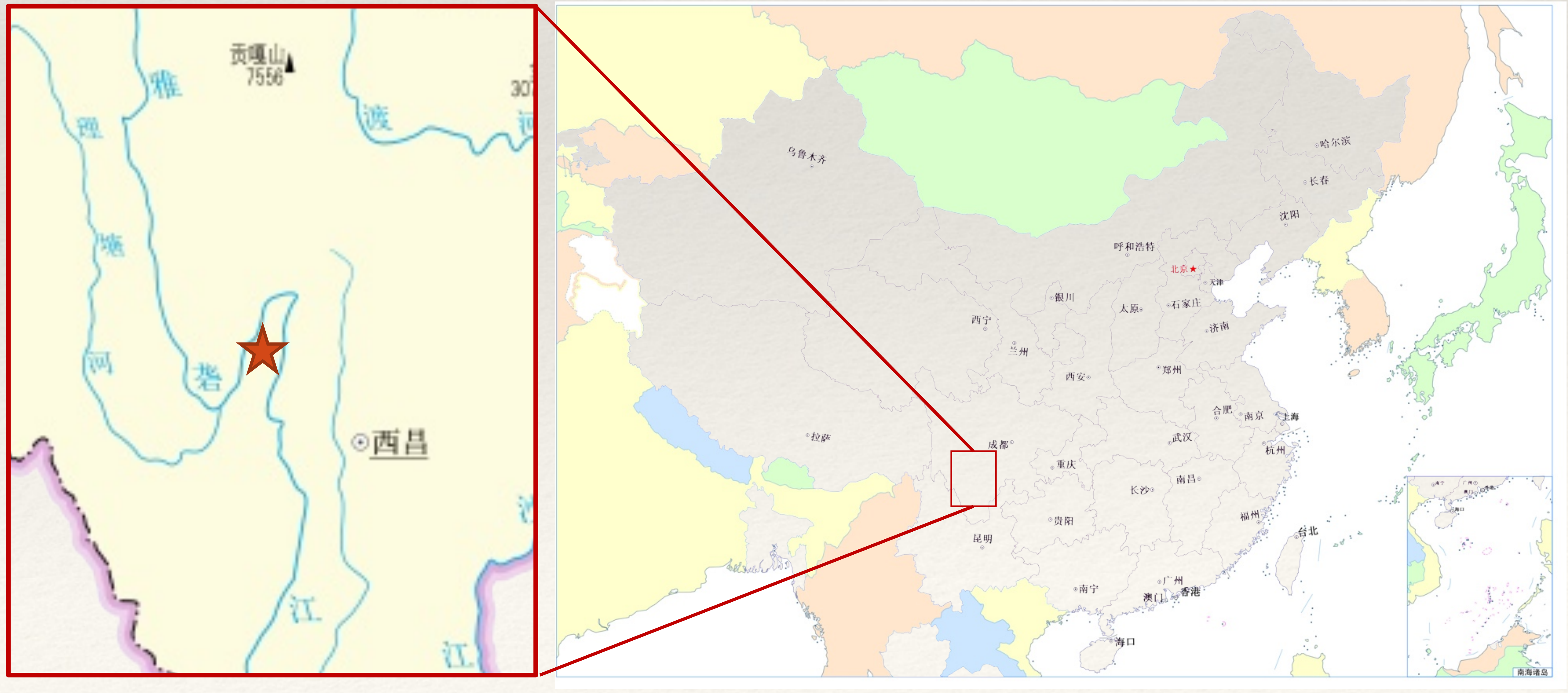


CJPL: China JinPing underground Lab

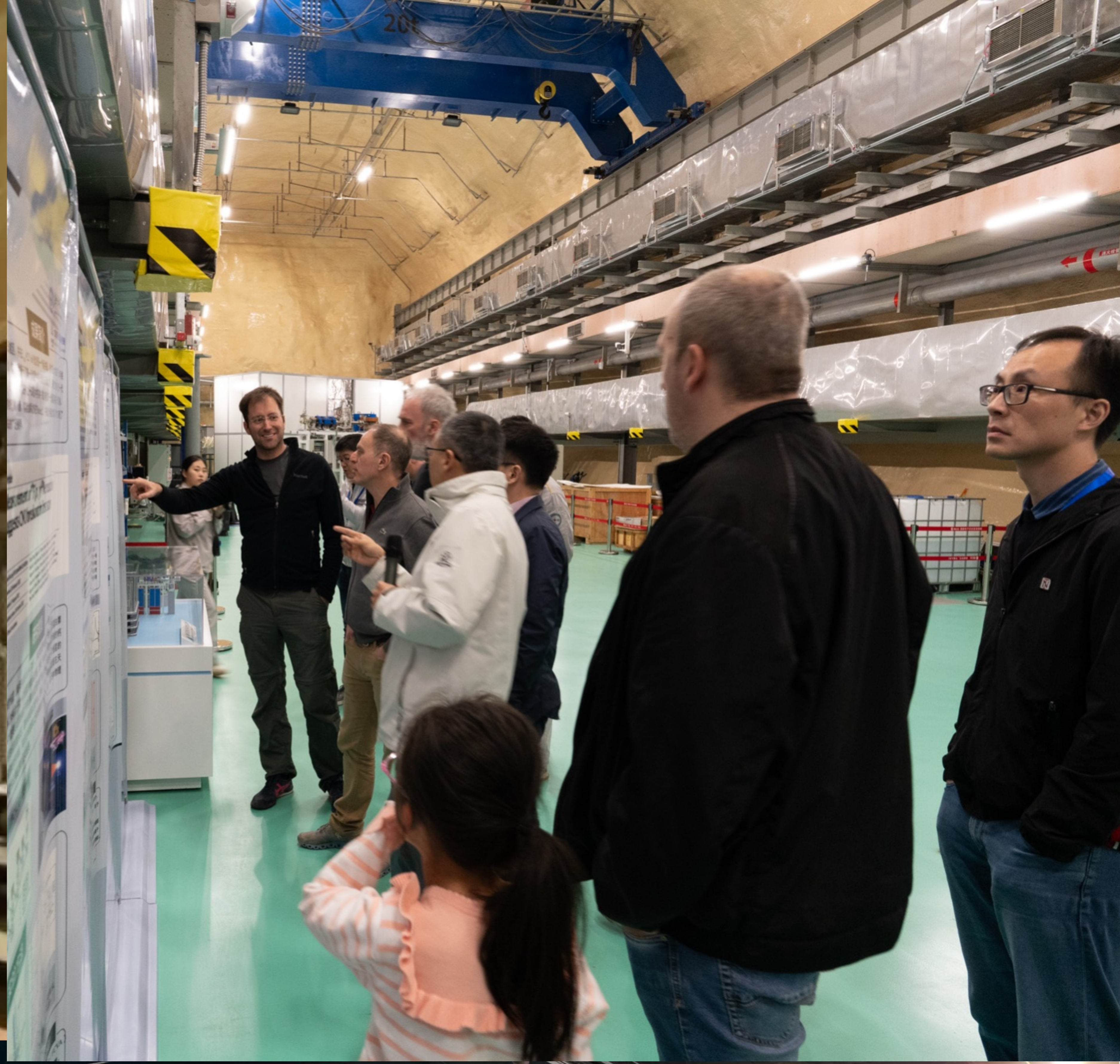




- 6800 m.w.e overburden: < 0.2 muons / m^2 / day
- Horizontal access with ~9 km long tunnel: large truck can drive in.
- Dark matter searches, neutrino physics, and astroparticle physics, etc.



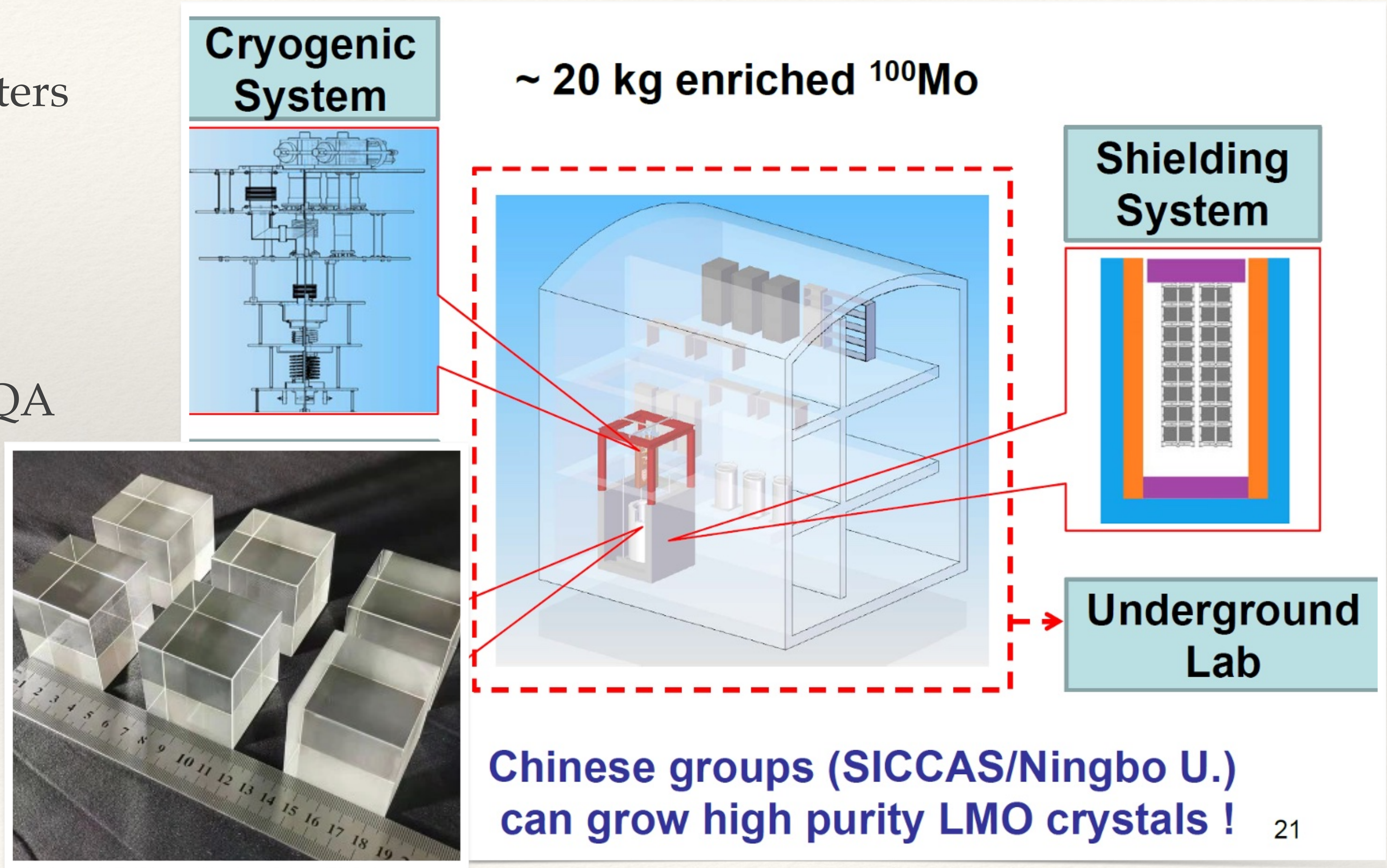

垂直岩石覆盖厚度2400米
距离西出口9km
距离东出口9km
排水隧道
华西医院
辅引2#堵头实验室
1号门
2号门
华西医院
6#横通道实验室
2号辅助隧道
辅助隧道
交通隧道
排水隧道
核天体物理实验
A1
A2
实验厅A
中微子实验
B1
B2
B3
B4
无中微子双贝塔衰变实验
实验厅B
暗物质实验（常温水屏蔽）
C1
C2
实验厅C
低本底中心
暗物质实验
（低温液氮屏蔽）
D1
D2
中微子实验
无中微子双贝塔衰变实验
实验厅D
1号辅助隧道
实验室一期
交通隧道B
交通隧道A
华西医院
44#横通道实验




CJPL
中国锦屏地下实验室
China Jinping Underground Laboratory
CJPL-I entrance

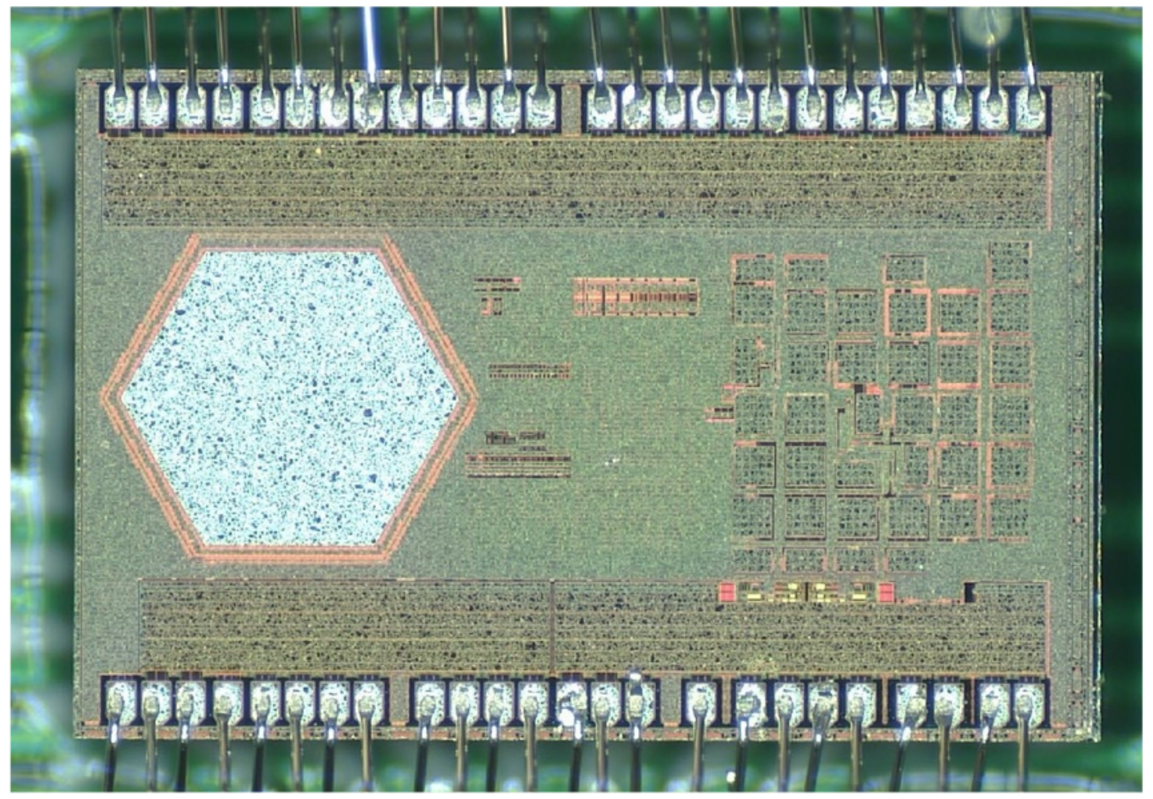
CUPID-CJPL

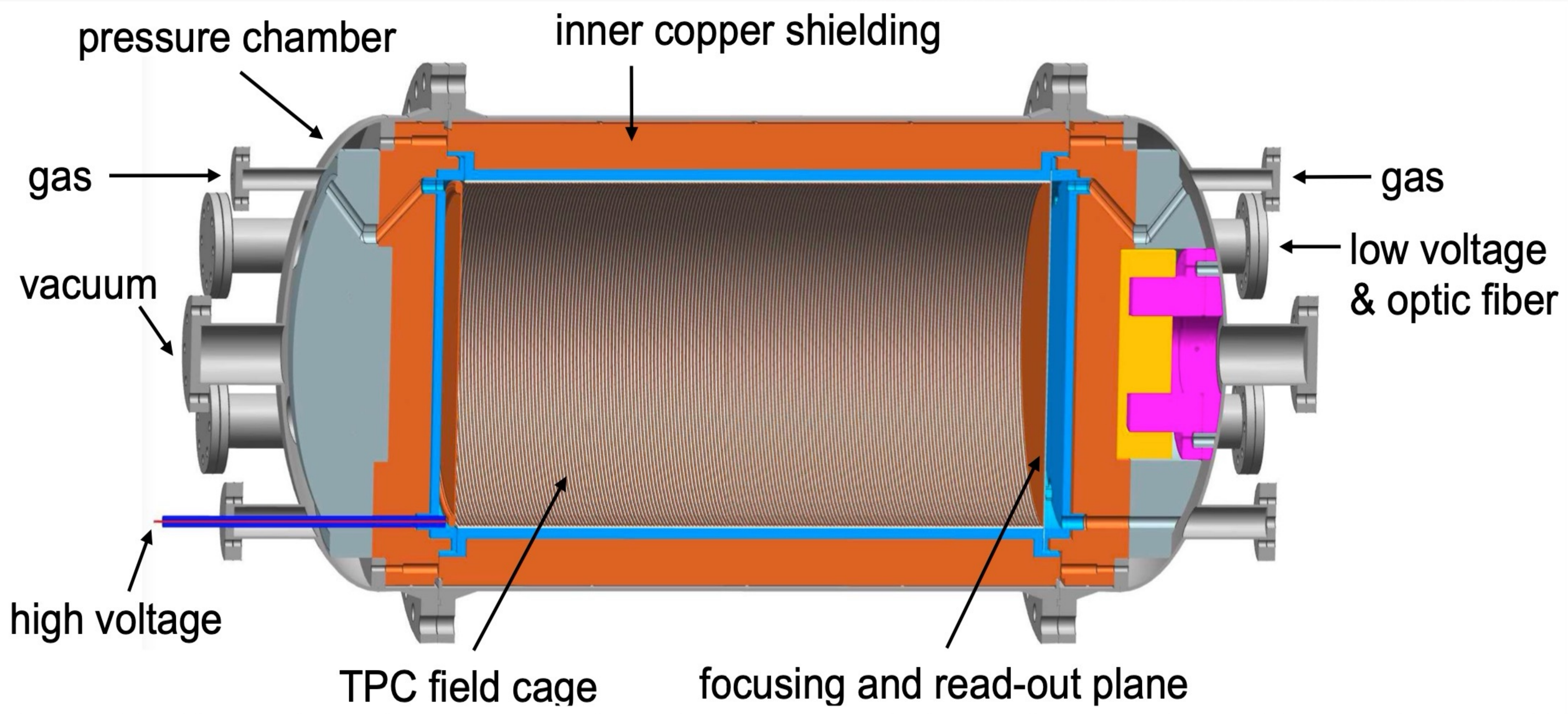
- Li_2MoO_4 scintillating bolometers at CJPL in the next 3-5 years
- Synergy with CUPID:
  - LMO crystal production radioactivity control and QA
  - Electronics
  - Data analysis

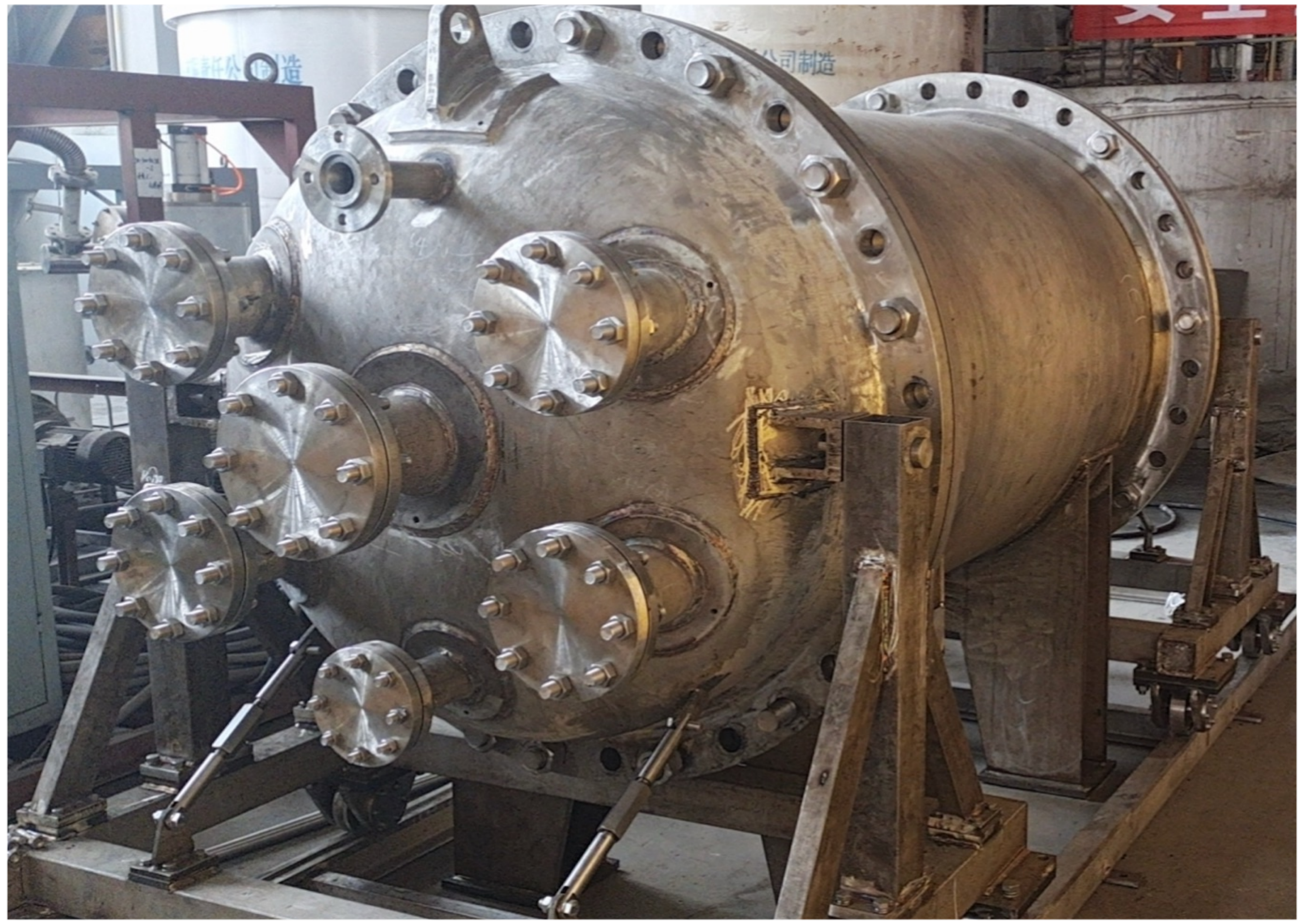


NvDEx: high pressure ion TPC

- High-pressure ion-drifting $^{82}SeF_6$ TPC with Topmetal readout
- 100 kg prototype in design and production phase





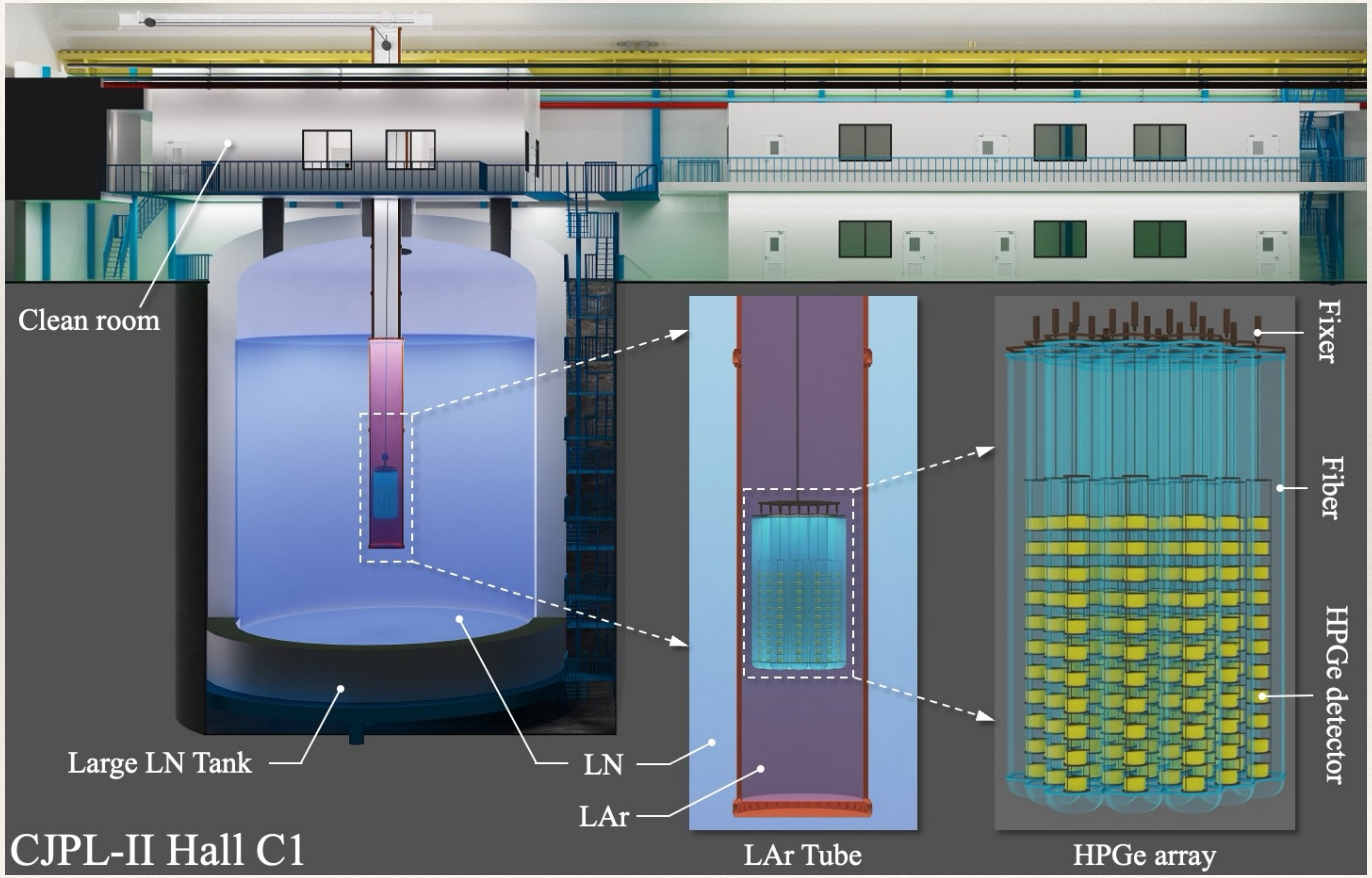


CDEX dark matter and 0νββ program

Established in 2009; over 100 collaborators from 11 institutions

CDEX-300ν:

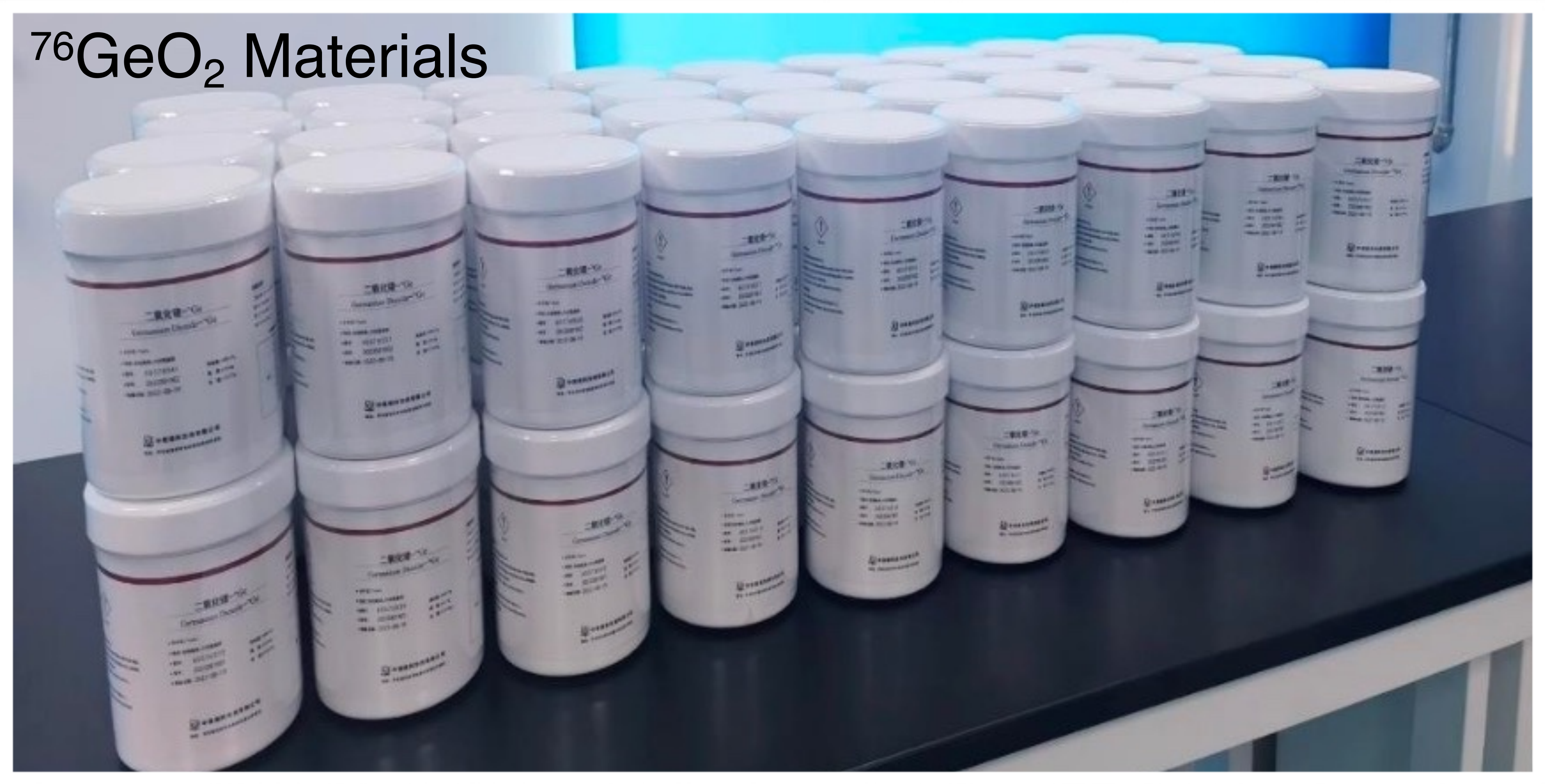
- 200 enriched HPGe detectors
- 20T LAr active veto shielding
- 1725 m^3 LN2 passive shielding



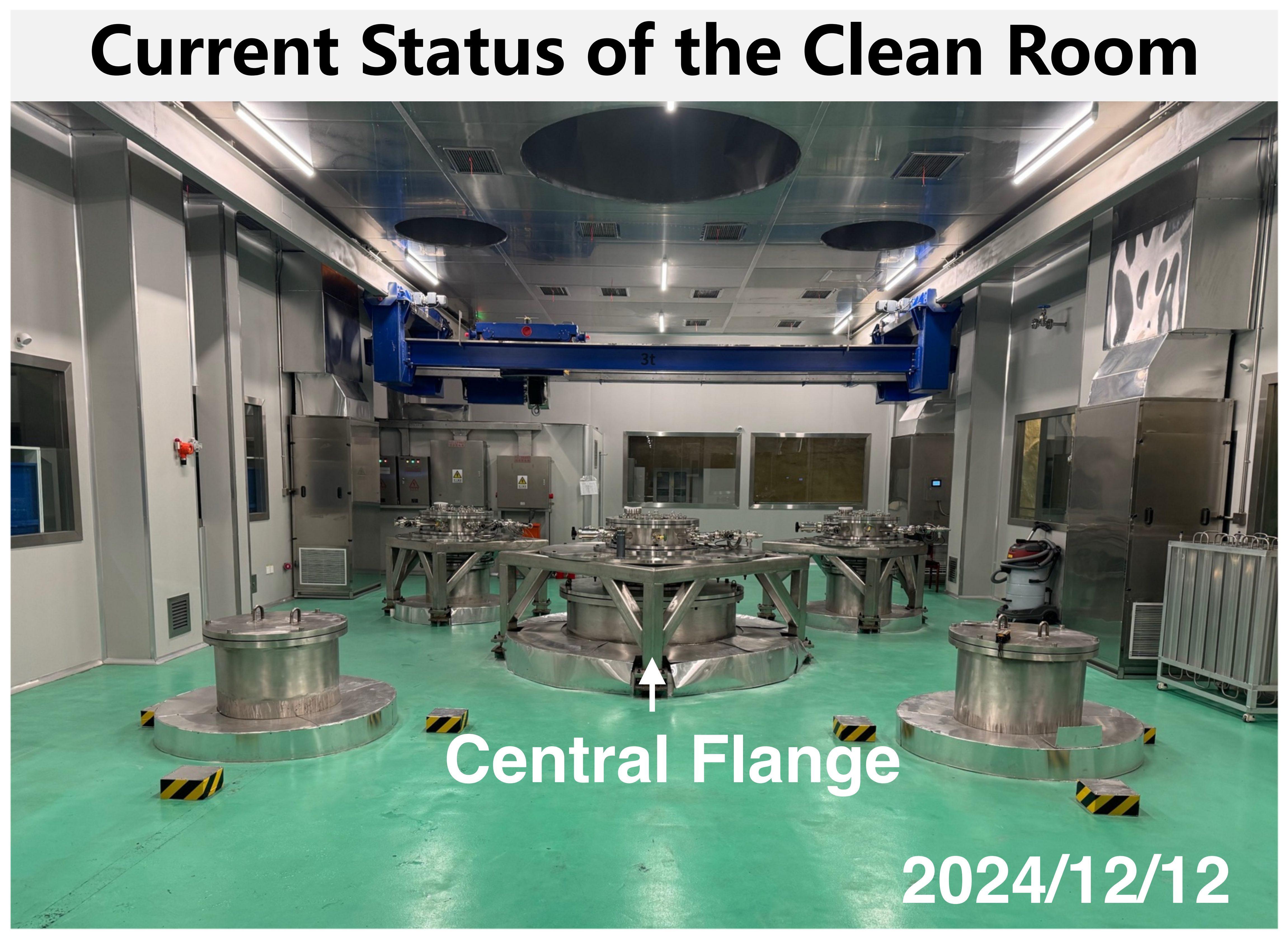
CDEX-300ν status

Total ~190 kg enriched GeO_2 in hand

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



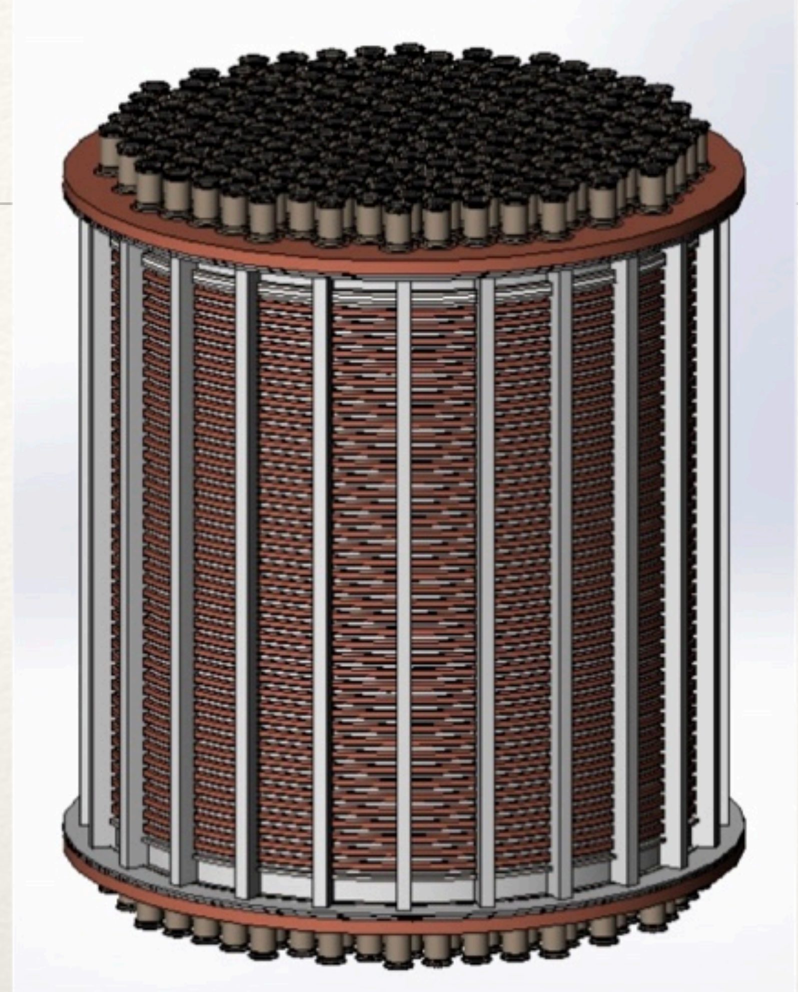
LN2 filling in progress



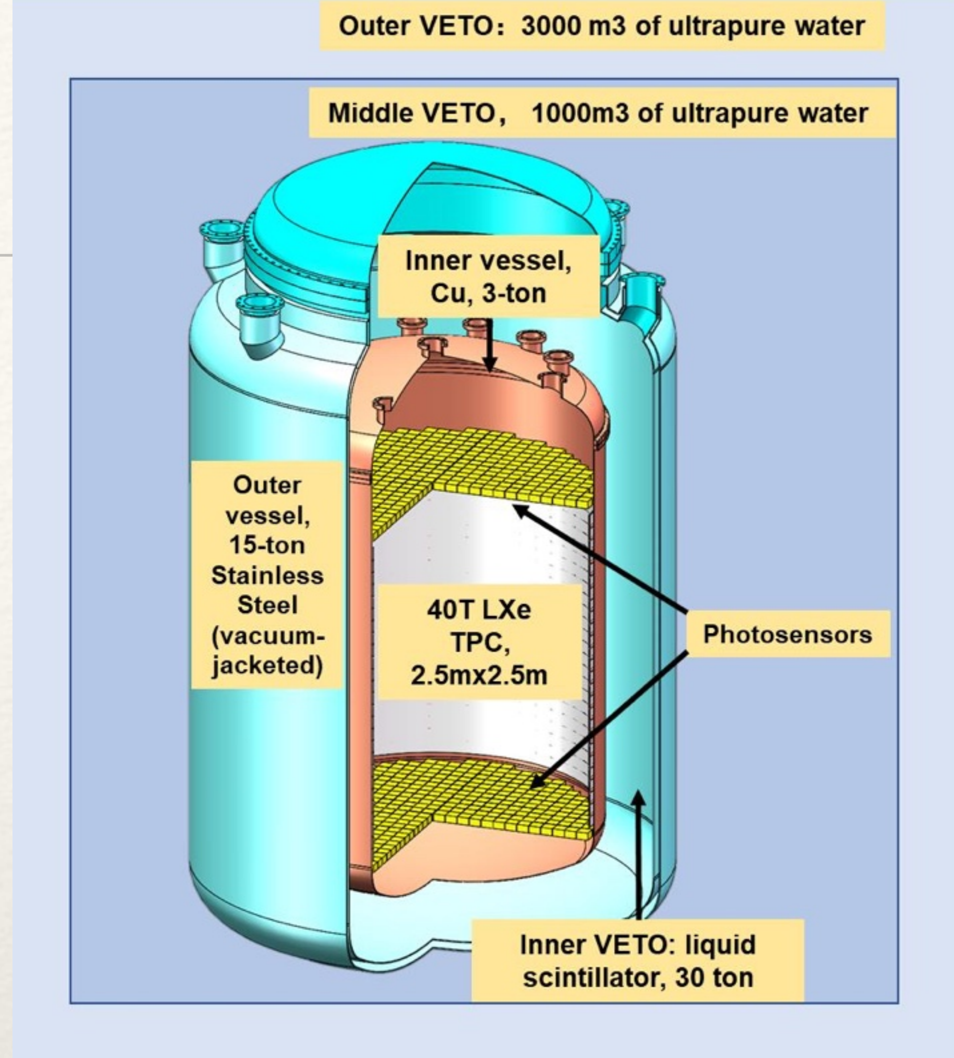
PandaX detectors

PandaX-I: 120kg
LXe (2009 – 2014)

PandaX-II: 500kg
LXe (2014 – 2018)

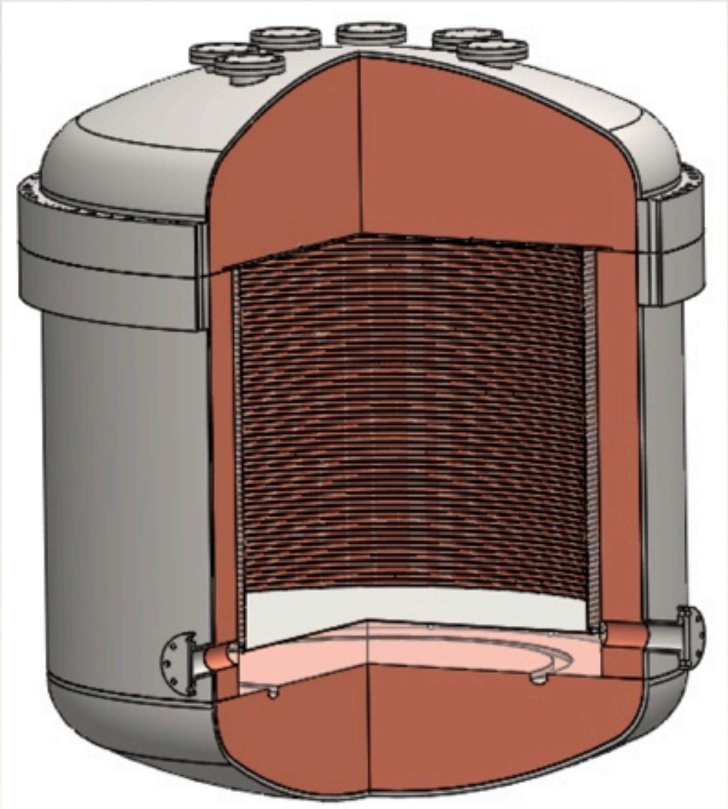


PandaX-4T LXe
(2020-)



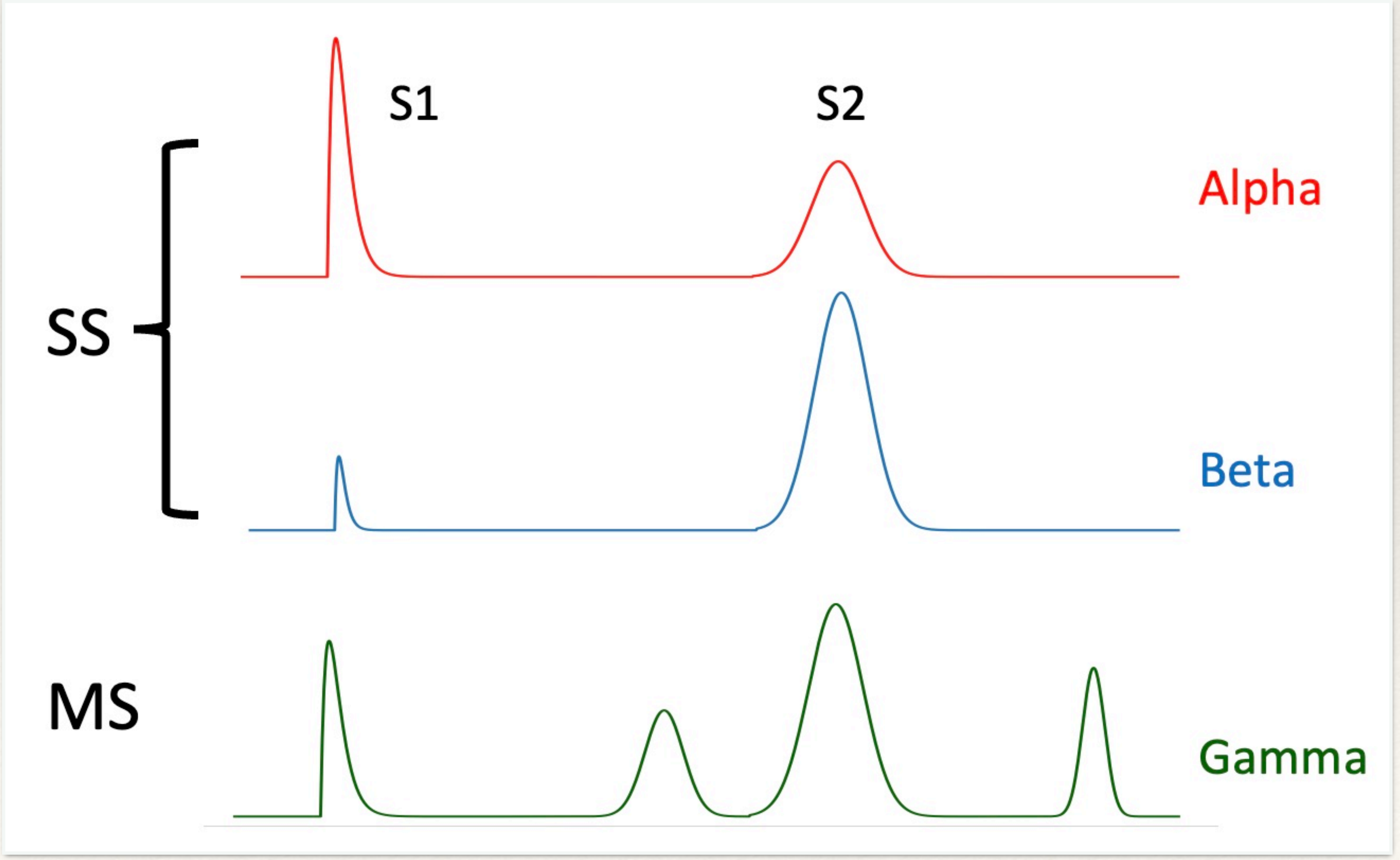
PandaX-xT LXe
(future)

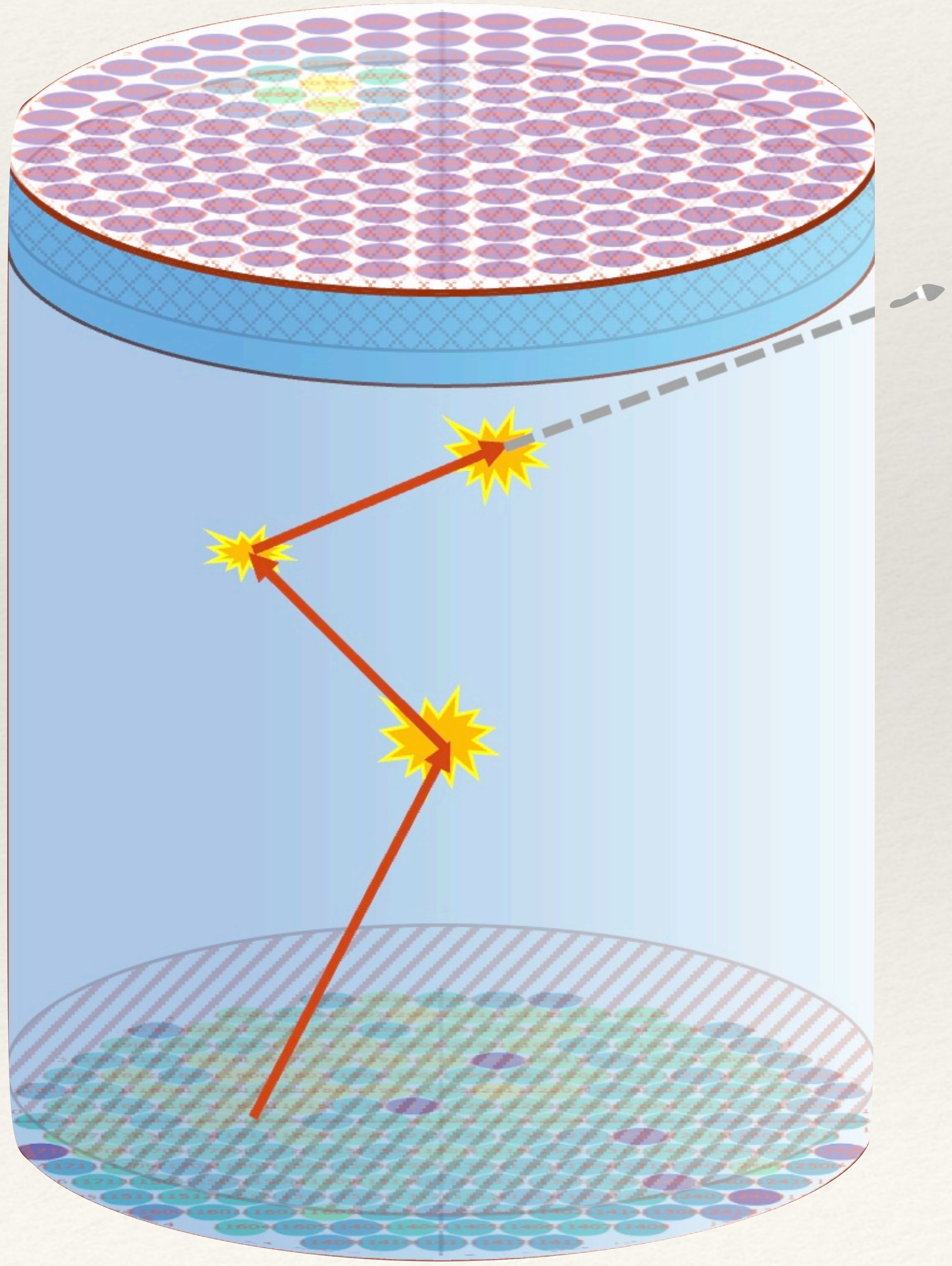
PandaX-III: 100kg - 1 ton
HPXe for 0νββ (future)



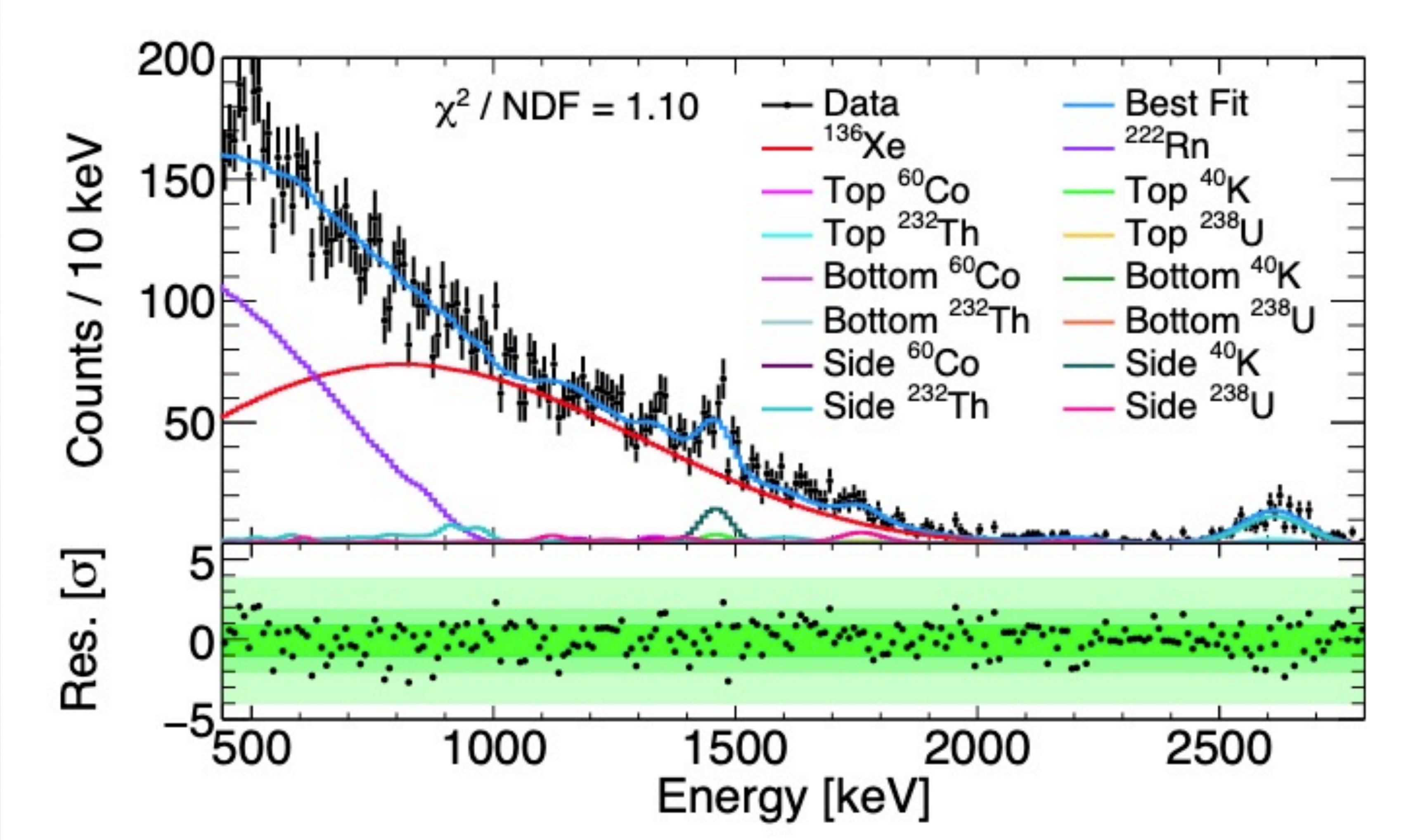
PandaX LXe TPC: Total-Absorption 5D Calorimeter

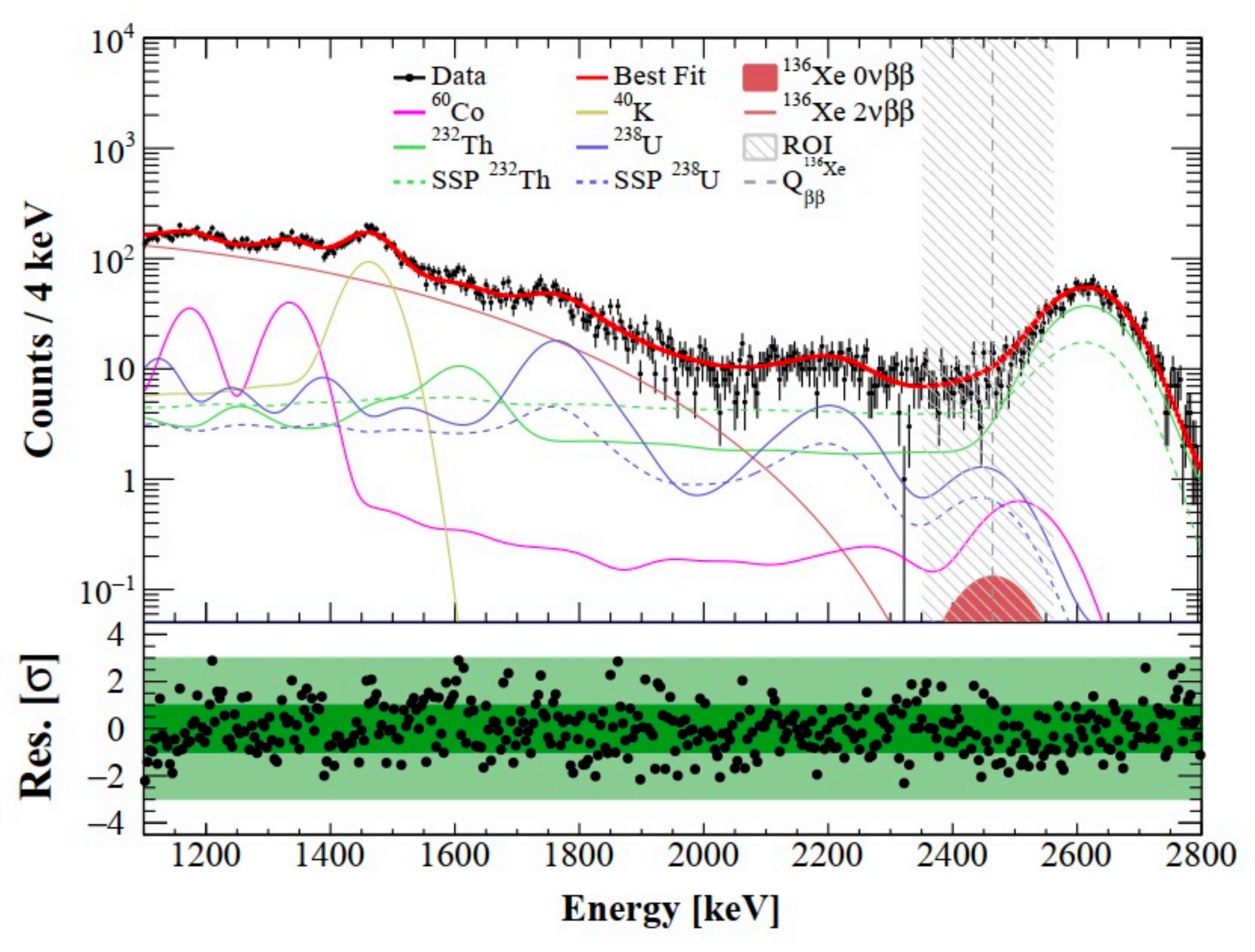
- Precisely measure 3D position, energy, and timing information in the energy range from sub-keV to 10MeV
- Large monolithic volume: total absorption; ~20 x MeV γ attenuation length
- Single-site (SS) and multi-site (MS) event for event topology and particle ID

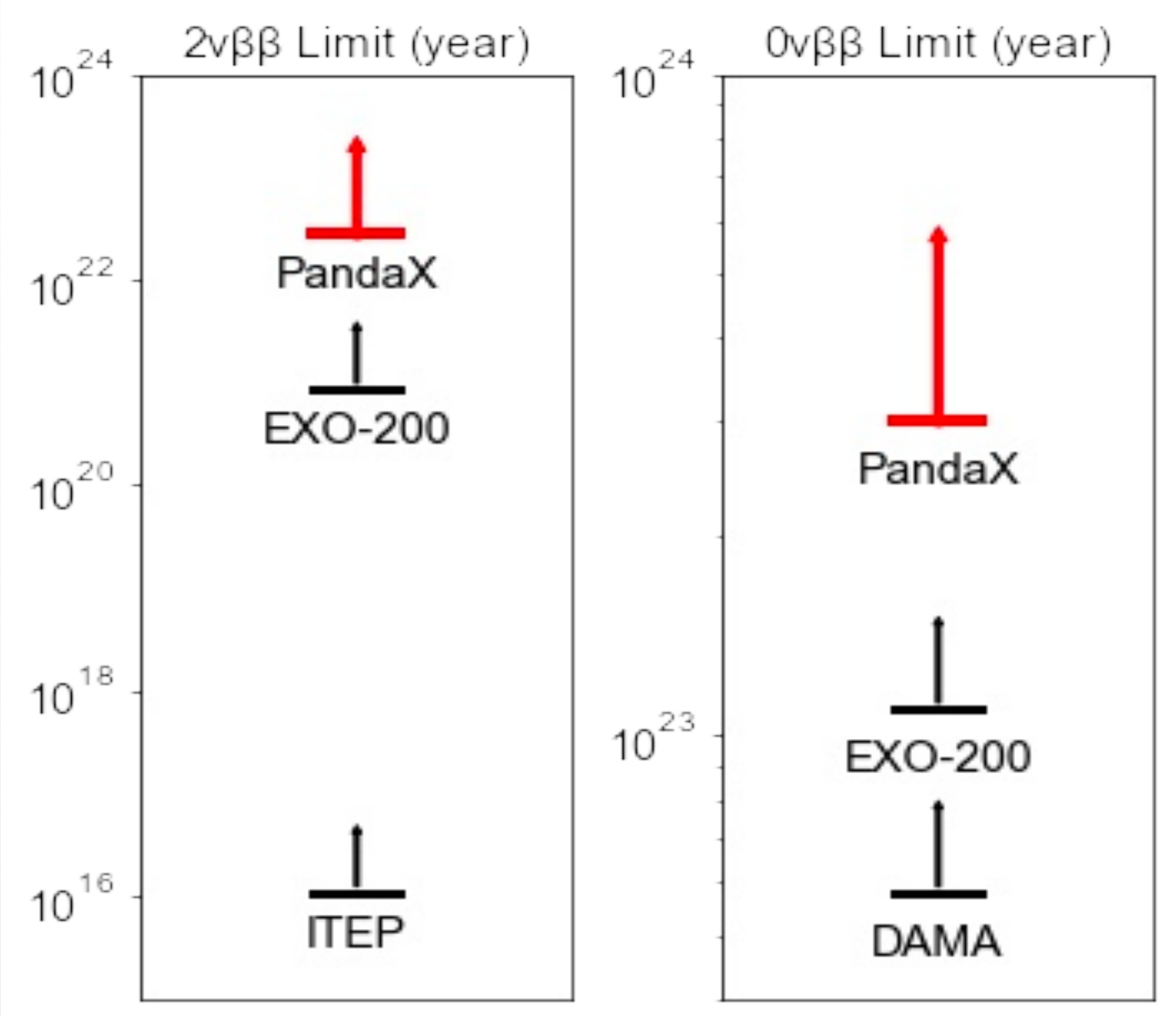




Recent PandaX-4T DBD results







^{136}Xe $2\nu\beta\beta$ half-life: 2.27 ± 0.03(stat.) ± 0.09(syst.) × 10^{21} yr

Research, 9798721 (2022)

^{136}Xe $0\nu\beta\beta$ half-life $> 2.1 \times 10^{24}$ yr (90% C.L.)

$m_{\beta\beta} < (0.4 - 1.6)$ eV

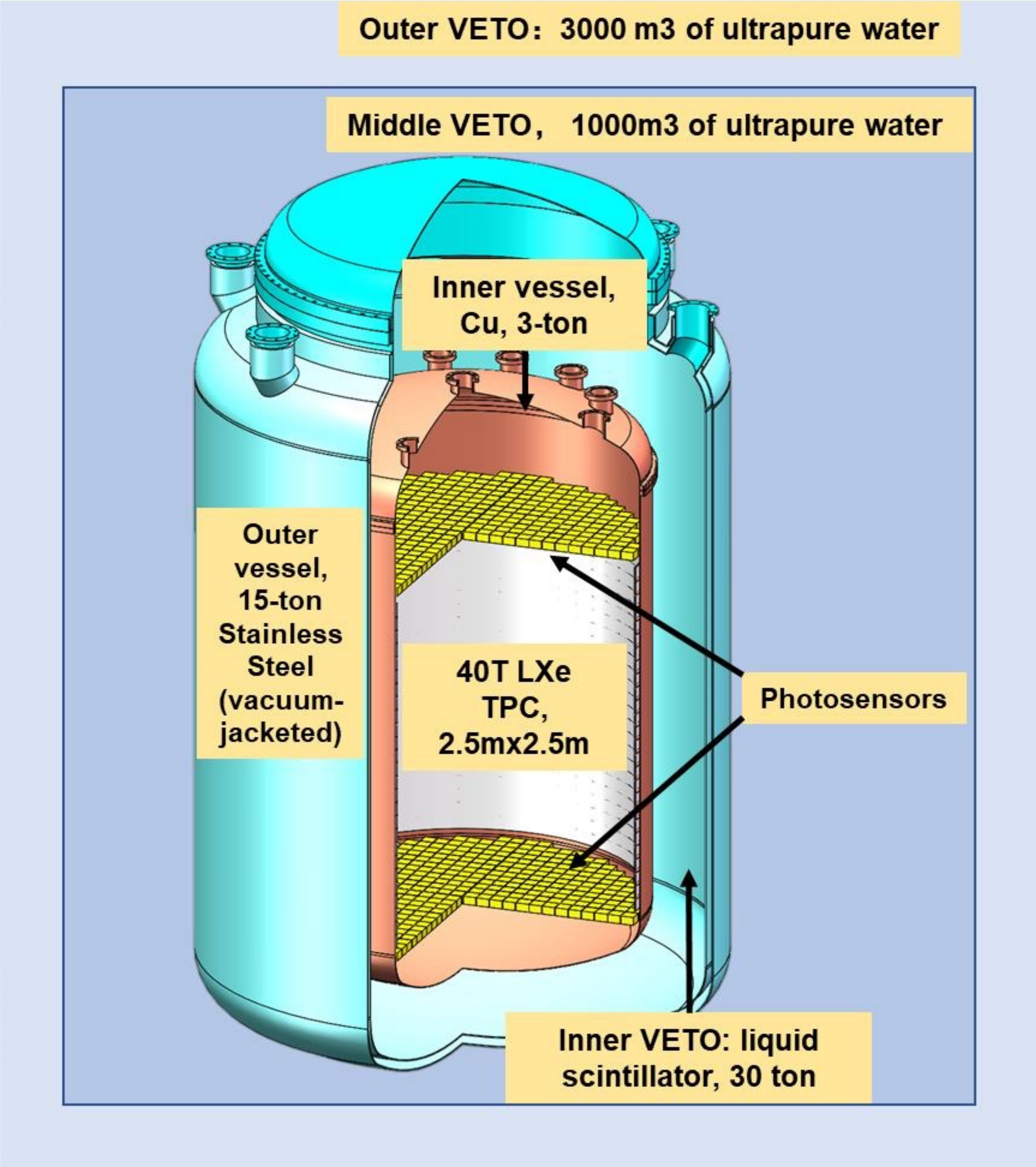
Science Bulletin 70, 1779 (2025)

The most stringent ^{134}Xe $2\nu\beta\beta$ and $0\nu\beta\beta$ half-life limits

PRL 132, 152502 (2024)

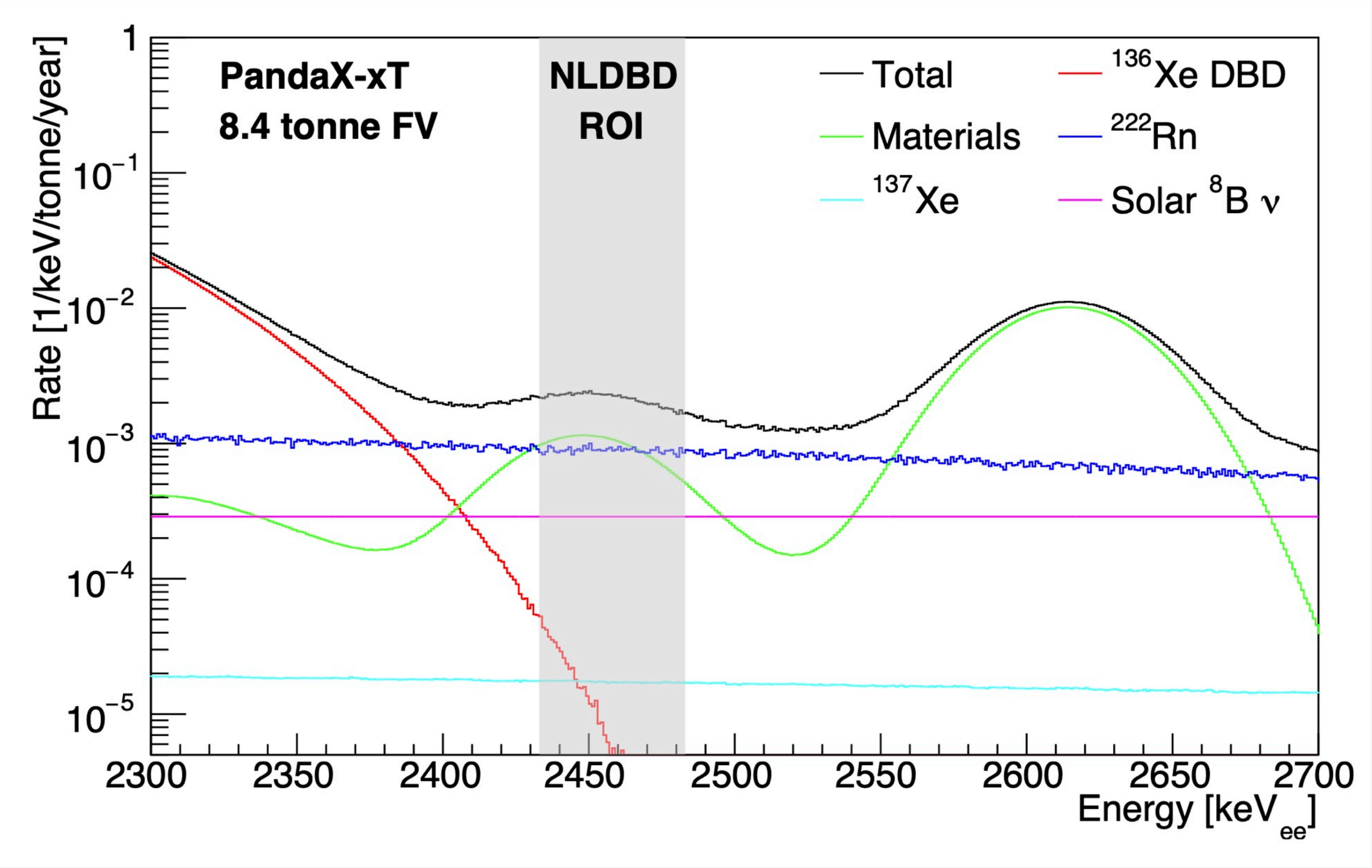
PandaX-xT: Multi-ten-tonne Liquid Xenon Observatory

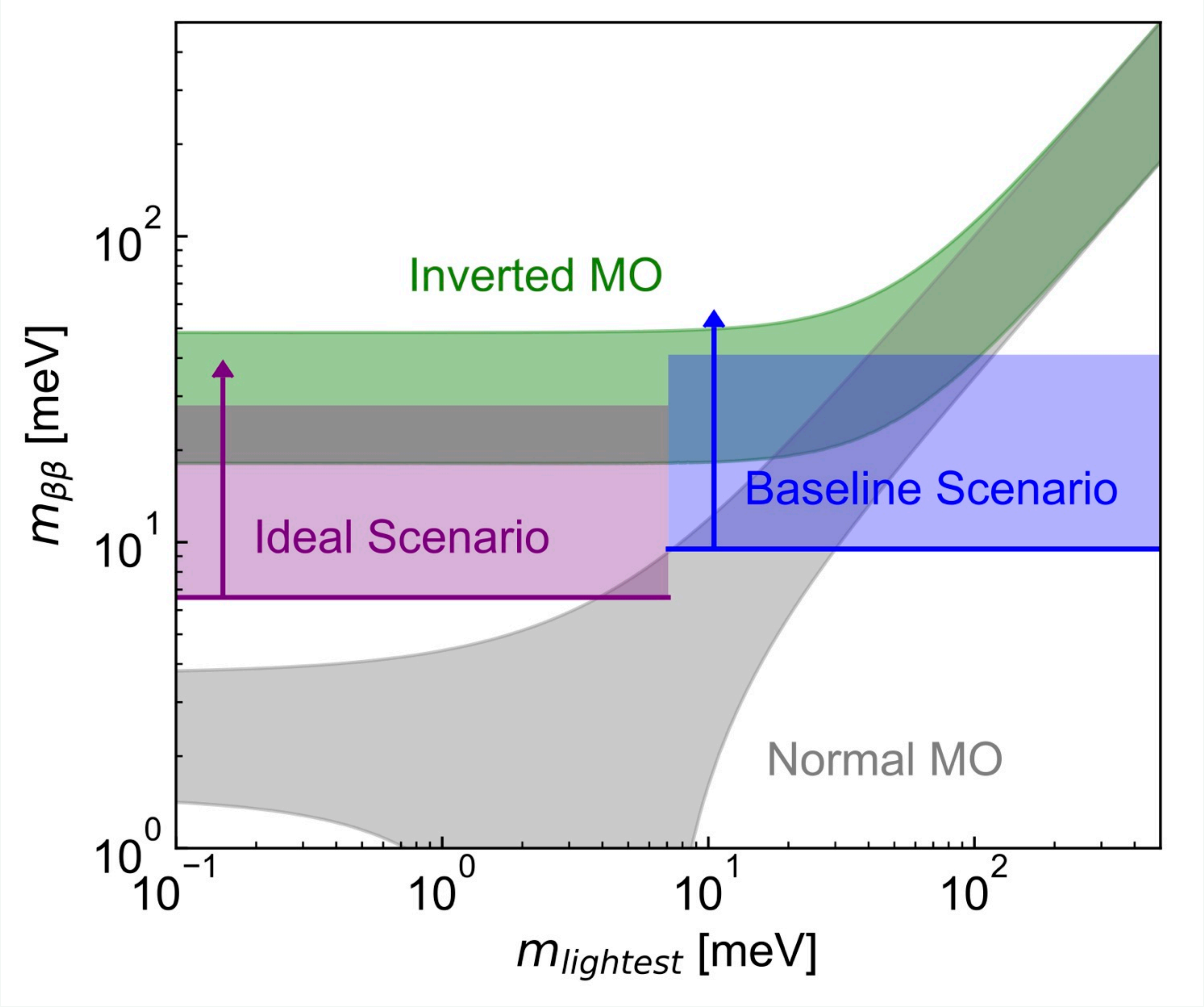
- Active target: 43 ton of Xenon
  - Decisive test to the WIMP paradigm
  - Explore the Dirac/Majorana nature of neutrino
  - Search for astrophysical or terrestrial neutrinos and other ultra-rare interactions
- Improved PMT, veto, vessel radiopurity, etc
- Staged upgrade utilizing isotopic separation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



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

- 4 ton of ^{136}Xe: one of the largest $0\nu\beta\beta$ experiments
- Effective self-shielding: Xenon-related background dominates

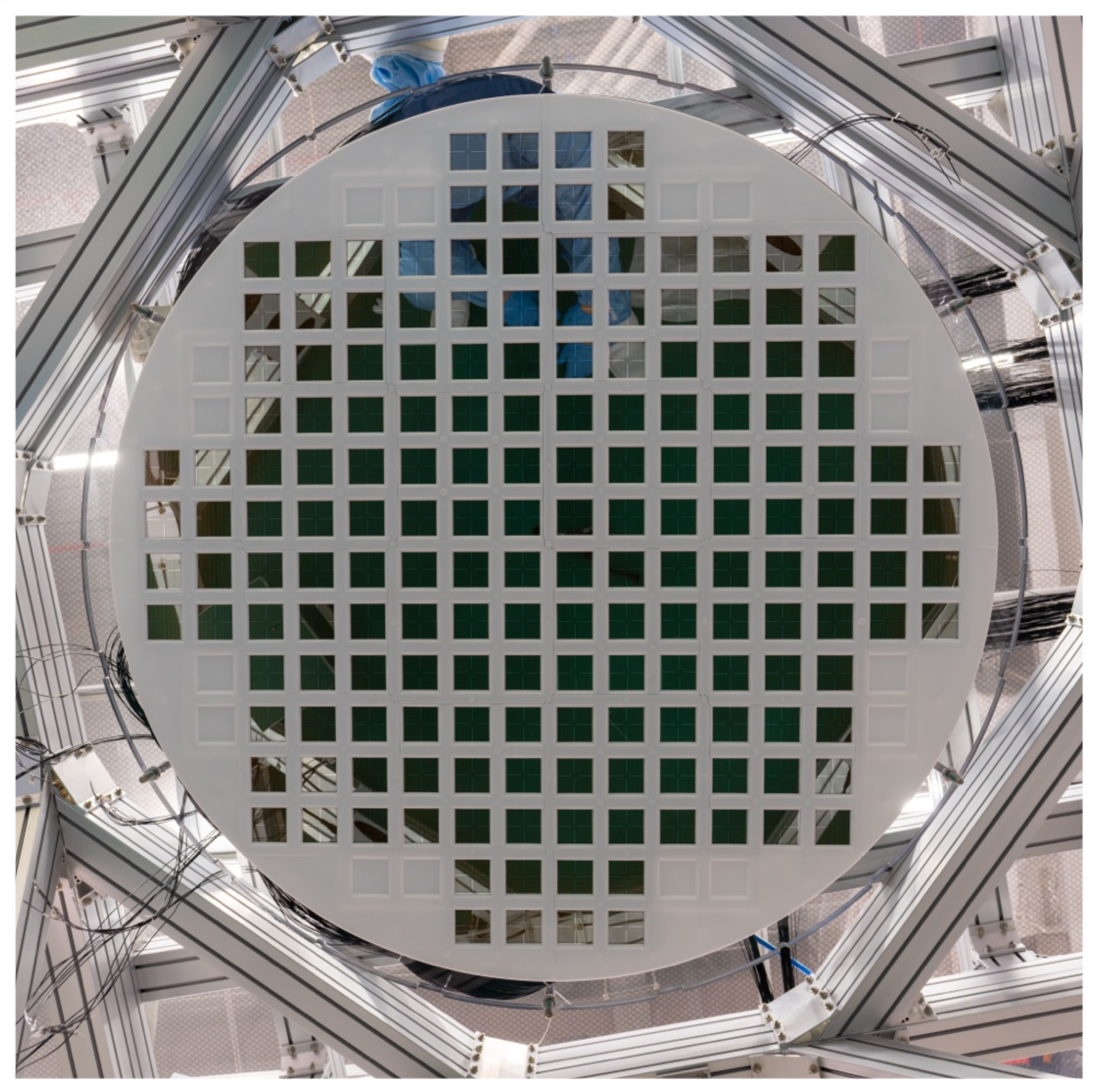


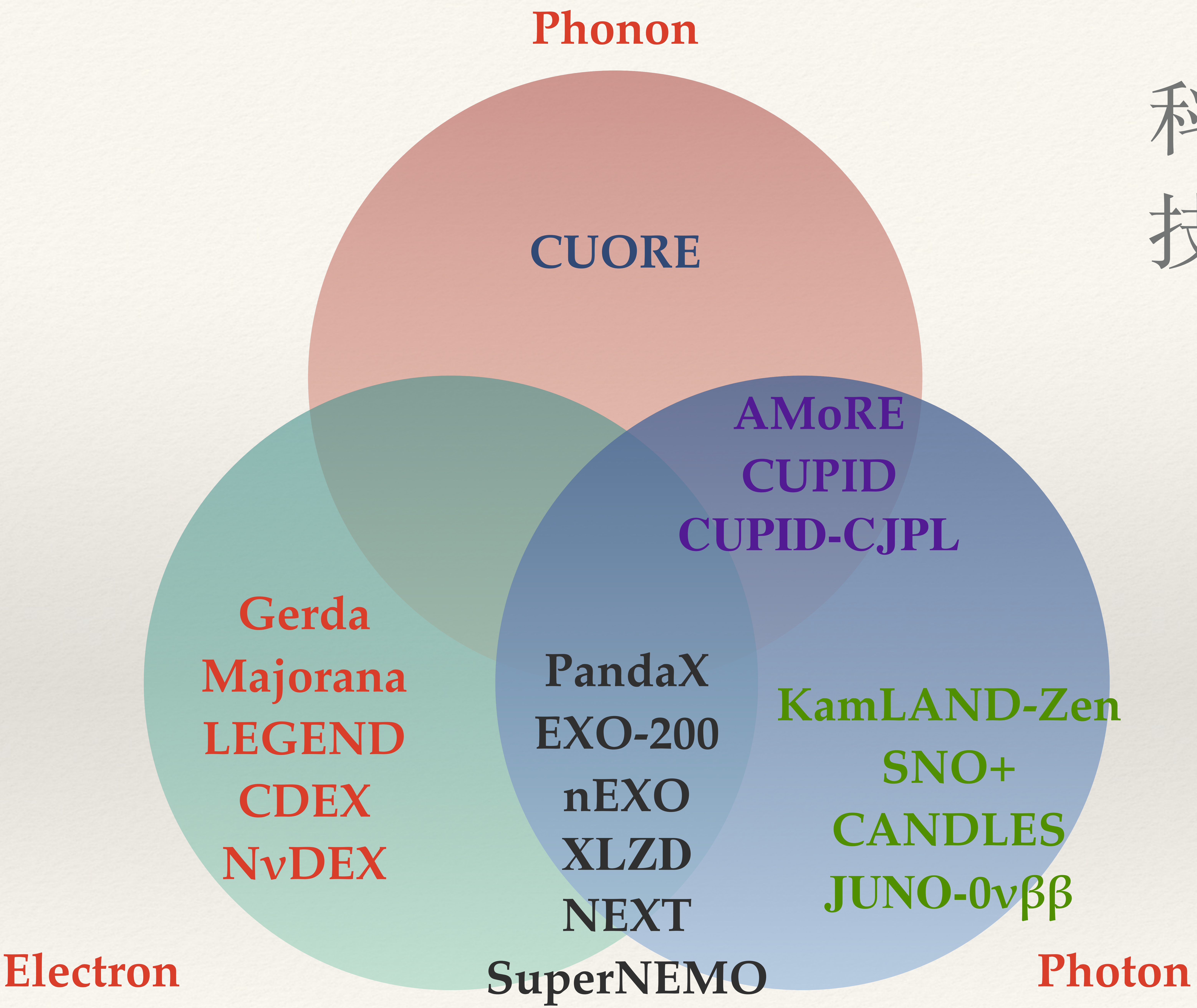


PandaX-xT 20T stage

- Mostly funded
- Detector prototyping and construction in progress

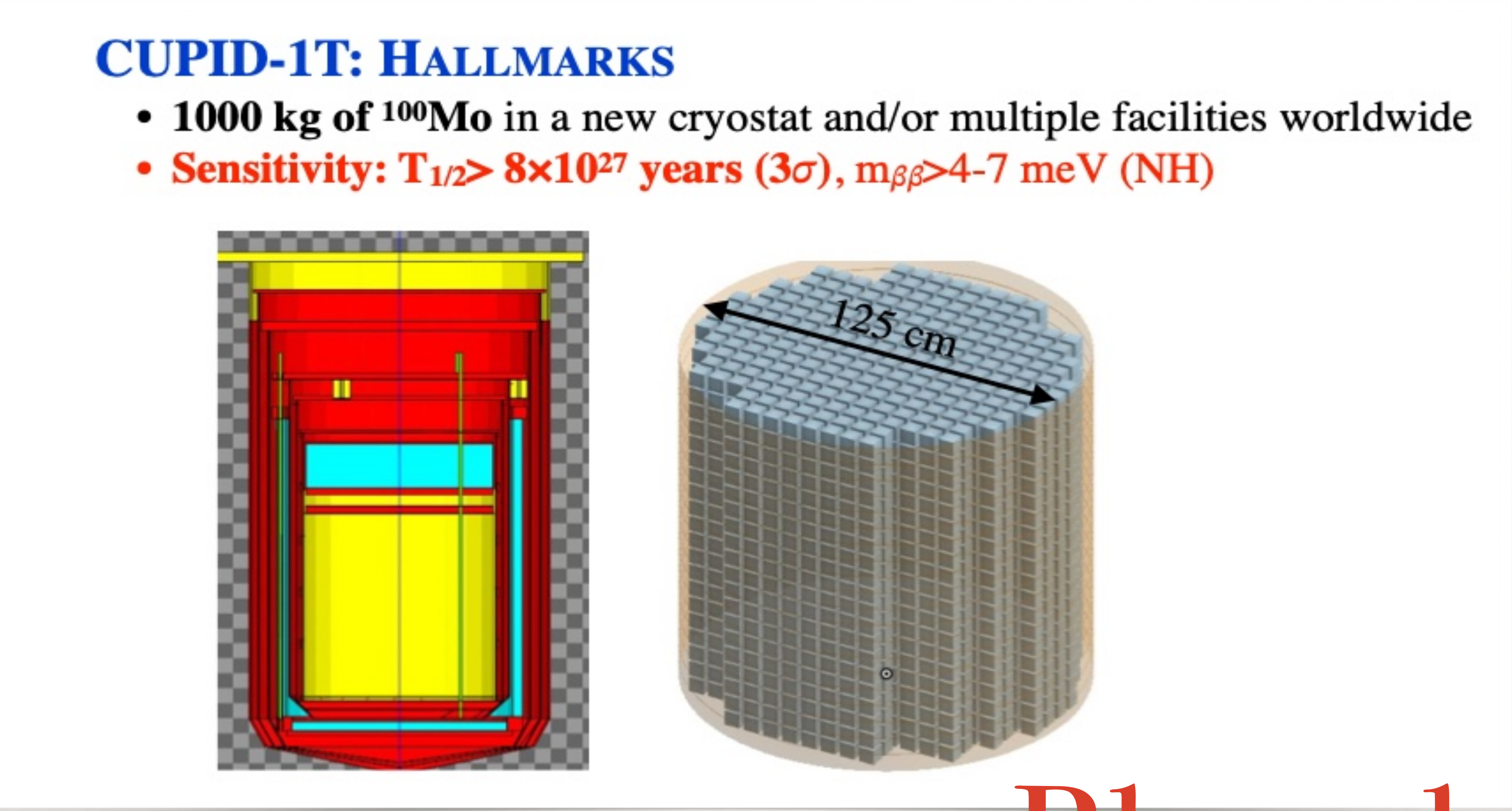
More at PandaX-xT Open Meeting
https://indico-tdli.sjtu.edu.cn/event/2934

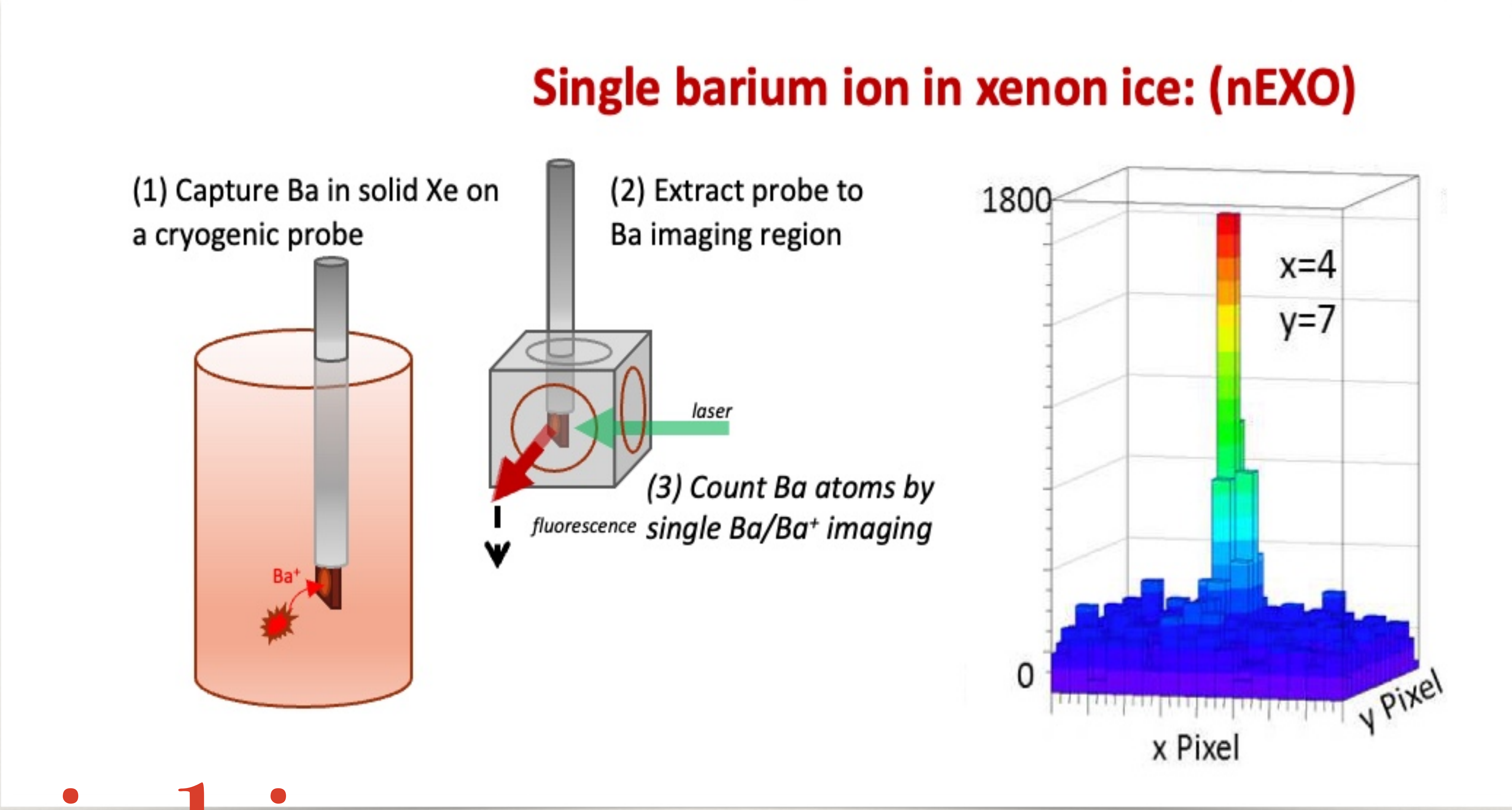


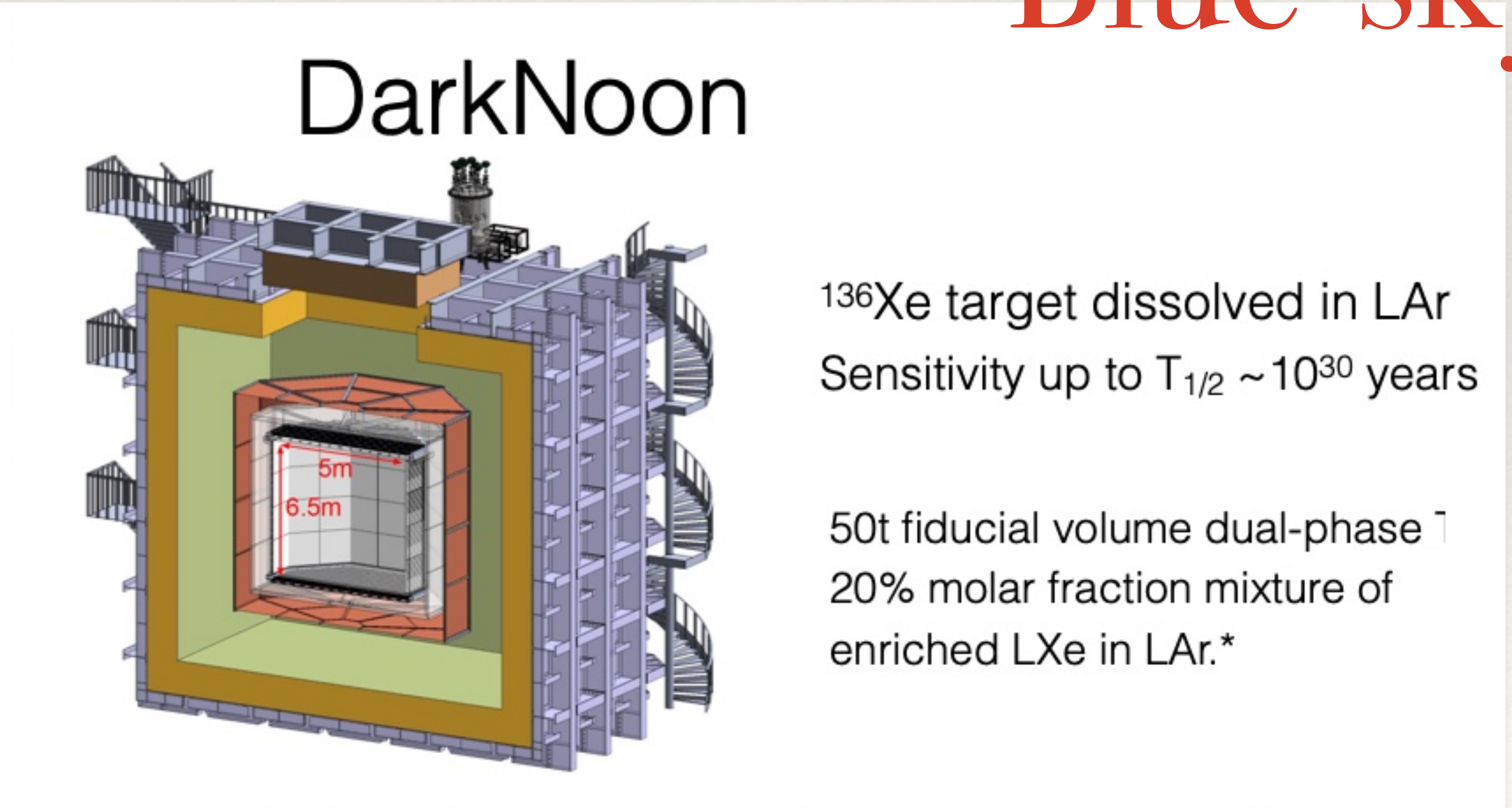

Phonon
CUORE
AMoRE
CUPID
CUPID-CJPL
Gerda
Majorana
LEGEND
CDEX
NvDEX
PandaX
EXO-200
nEXO
XLZD
NEXT
SuperNEMO
KamLAND-Zen
SNO+
CANDLES
JUNO-0νββ
Electron
Photon

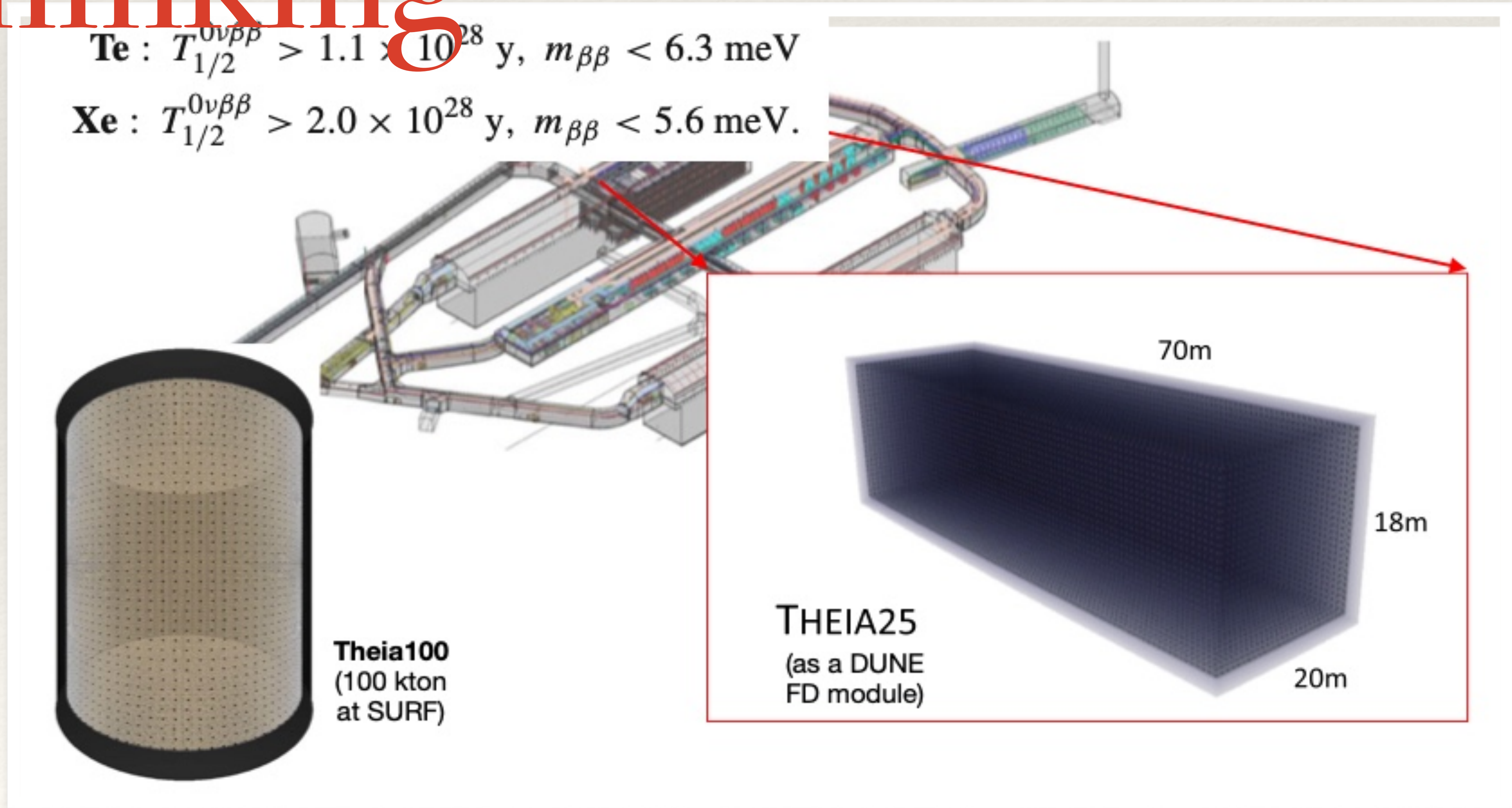
科学技术化
技术科学化

Blue-sky thinking









History and future landmark dates?

- 1930, Pauli: Idea of neutrino
- 1933, Fermi: Beta decay theory
- 1935, Goeppert-Mayer: Two-Neutrino double beta decay
- 1937, Majorana: Majorana Neutrino
- 1939, Furry: Neutrinoless double beta decay $0\nu\beta\beta$

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