Double beta decay - an experimental review

无中微子双贝塔衰变实验

韩柯

上海交通大学

物理意义　　技术挑战　　群雄逐鹿　　中国方案

Kamioka

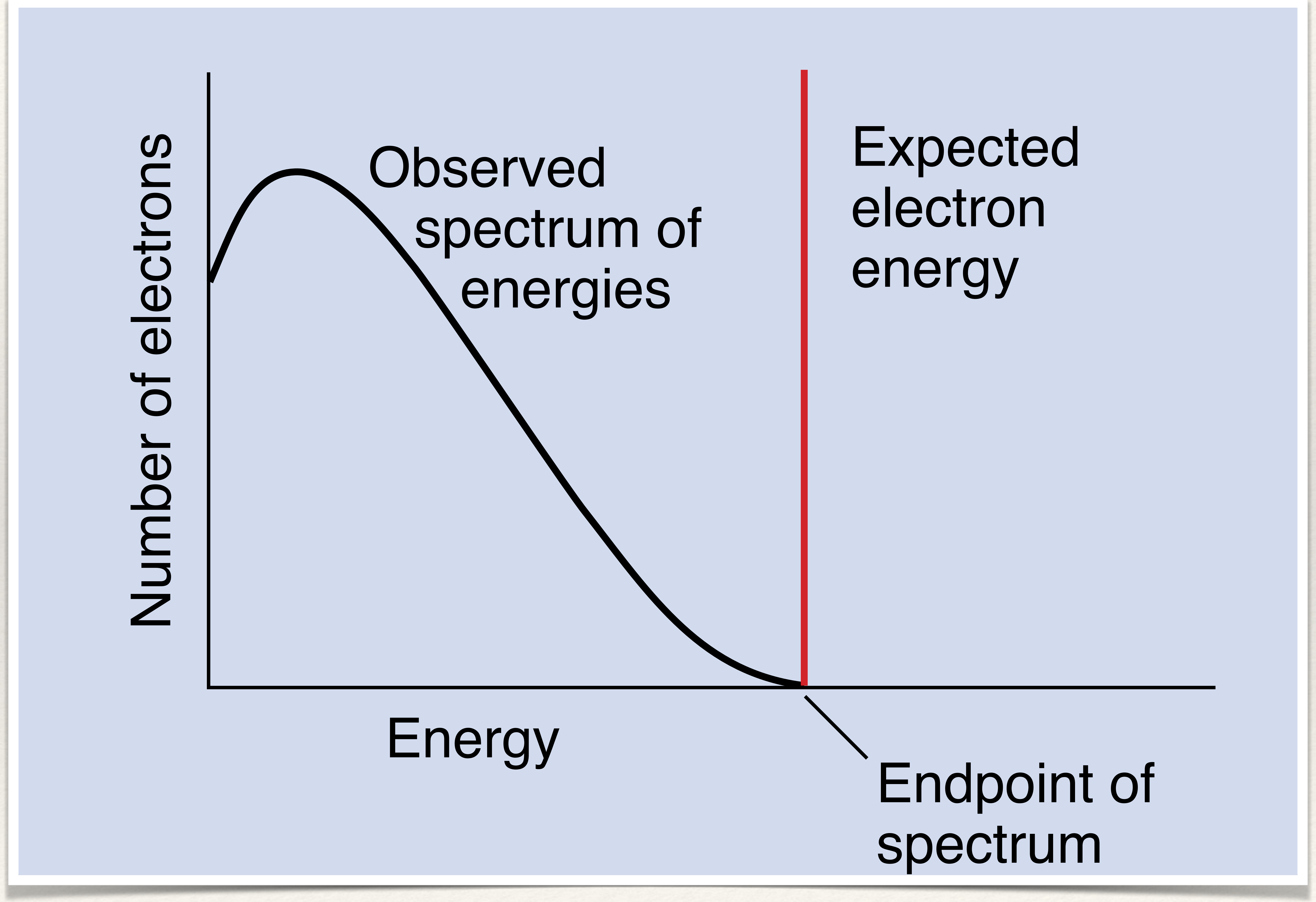
无双实验：物理意义

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

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



Beta decay

- Beta spectra, continuous or mono-energetic? → Neutrinos
- 1930, Pauli: Idea of neutrino
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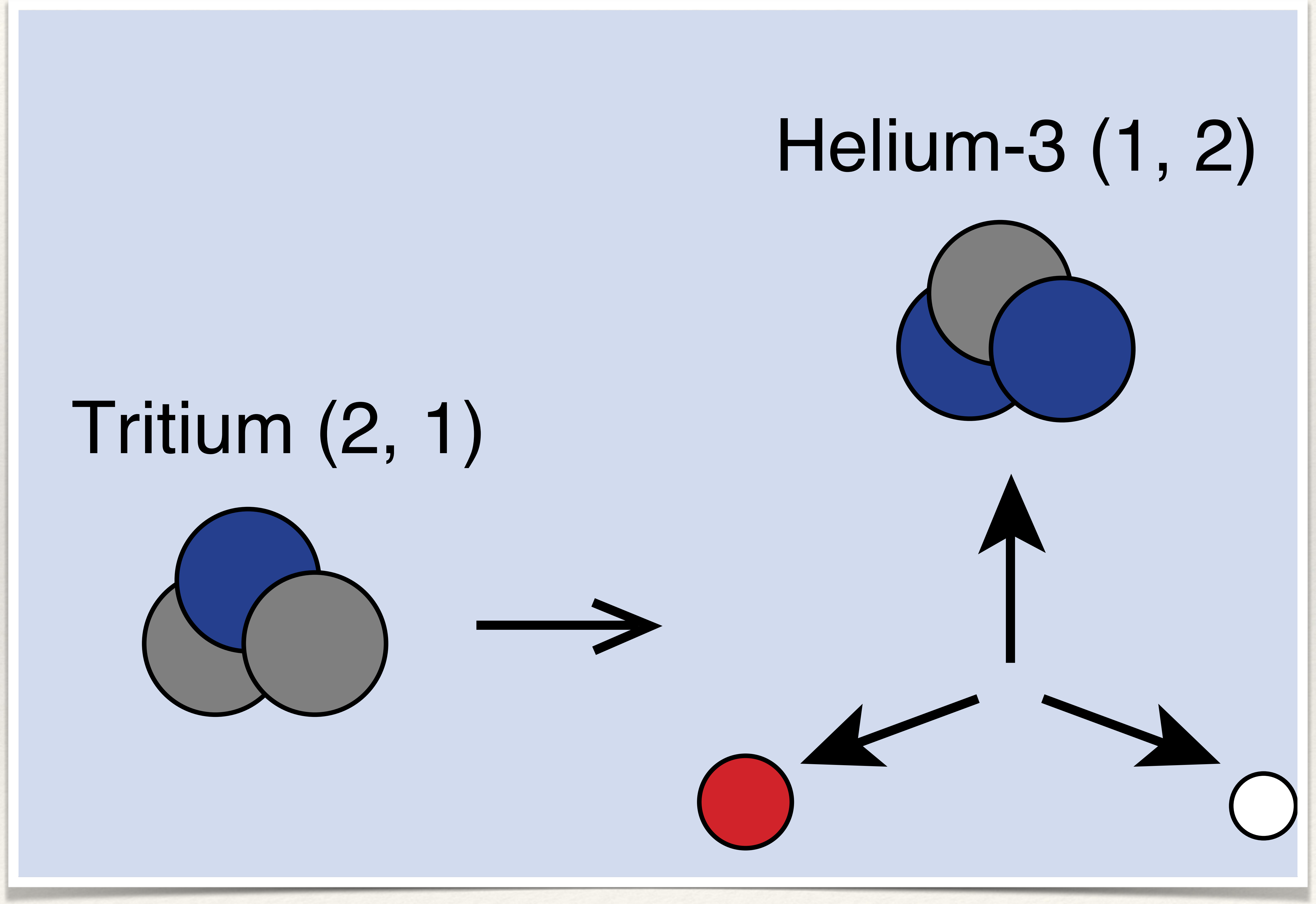
$$n \to p + e^- + \bar{\nu}_e$$

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

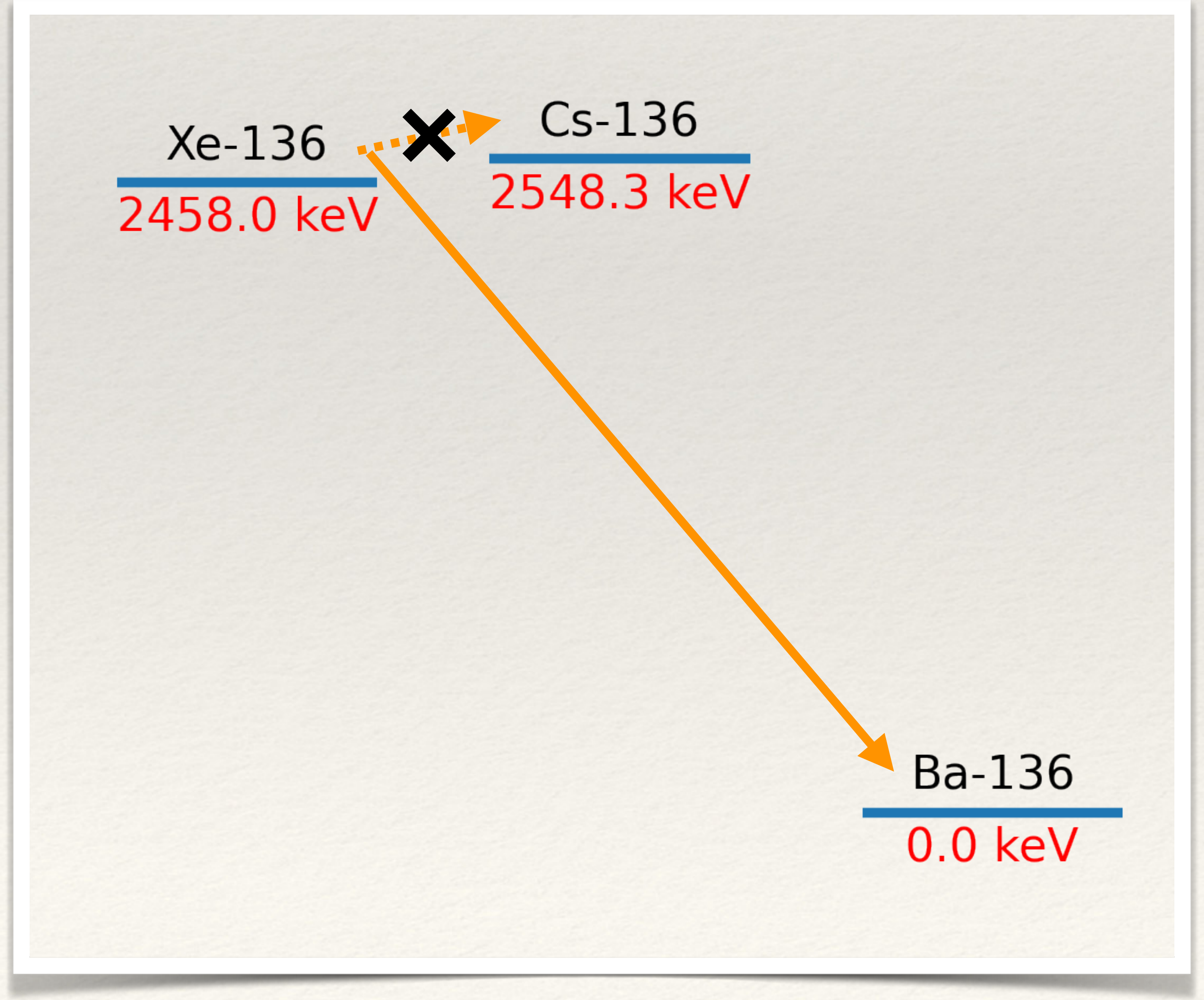


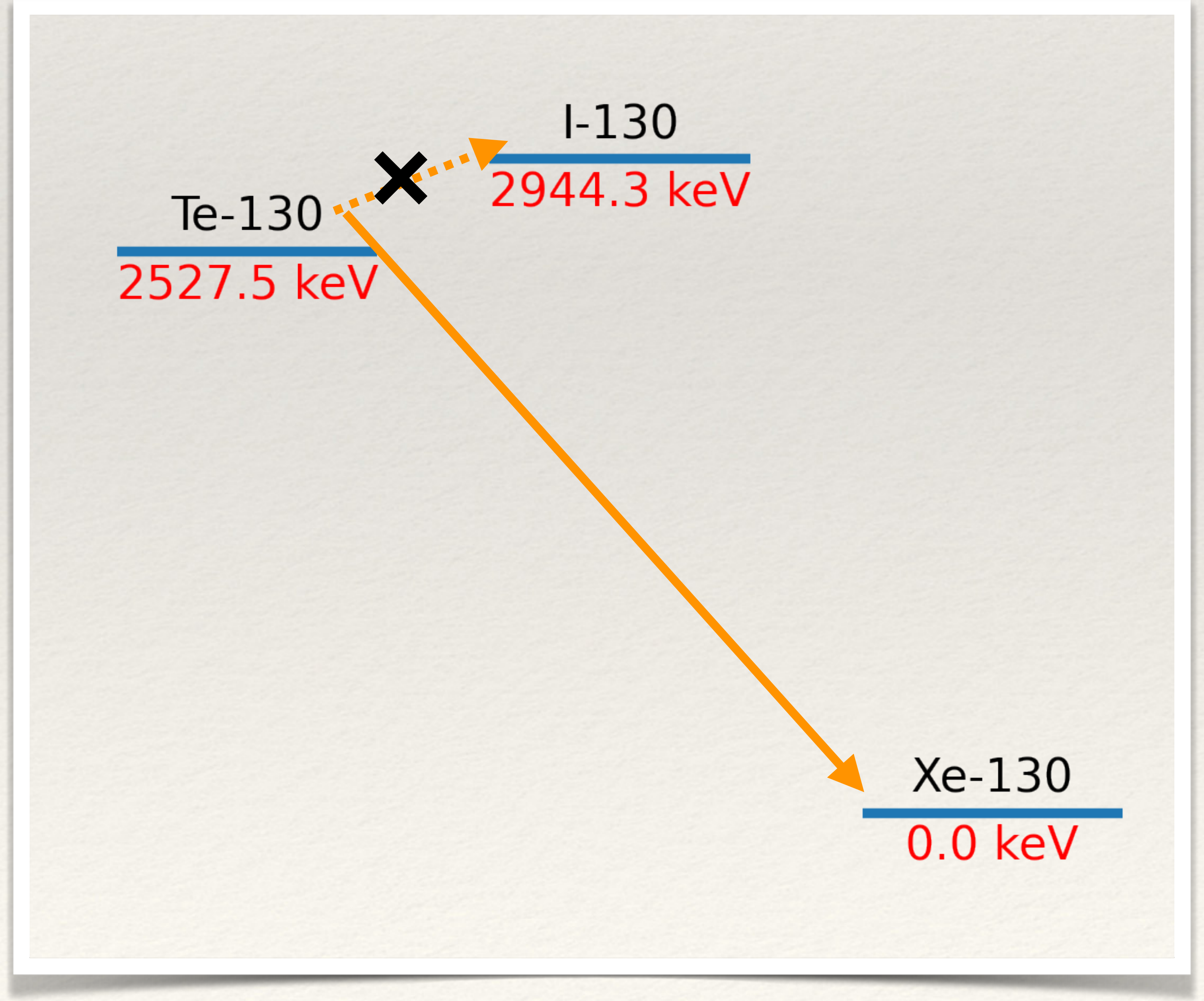

^{40}Ti β+
^{41}Ti β+
^{42}Ti β+
^{43}Ti β+
^{44}Ti e- capture
^{45}Ti β+
^{46}Ti Stable
^{47}Ti Stable
^{48}Ti Stable
^{49}Ti Stable
^{50}Ti Stable
^{51}Ti β-
^{39}Sc p
^{40}Sc β+
^{41}Sc β+
^{42}Sc β+
^{43}Sc β+
^{44}Sc β+
^{45}Sc Stable
^{46}Sc β-
^{47}Sc β-
^{48}Sc β-
^{49}Sc β-
^{50}Sc β-
^{38}Ca β+
^{39}Ca β+
^{40}Ca 2β+
^{41}Ca e- capture
^{42}Ca Stable
^{43}Ca Stable
^{44}Ca Stable
^{45}Ca β-
^{46}Ca 2β-
^{47}Ca β-
^{48}Ca 2β-
^{49}Ca β-
^{37}K β+
^{38}K β+
^{39}K Stable
^{40}K β-
^{41}K Stable
^{42}K β-
^{43}K β-
^{44}K β-
^{45}K β-
^{46}K β-
^{47}K β-
^{48}K β-
^{36}Ar 2β+
^{37}Ar e- capture
^{38}Ar Stable
^{39}Ar β-
^{40}Ar Stable
^{41}Ar β-
^{42}Ar β-
^{43}Ar β-
^{44}Ar β-
^{45}Ar β-
^{46}Ar β-
^{47}Ar β-
^{35}Cl Stable
^{36}Cl β-
^{37}Cl Stable
^{38}Cl β-
^{39}Cl β-
^{40}Cl β-
^{41}Cl β-
^{42}Cl β-
^{43}Cl β-
^{34}S Stable
^{35}S β-
^{36}S Stable
^{37}S β-
^{38}S β-
^{39}S β-
^{40}S β-
^{41}S β-
^{42}S β-
Primary Decay Mode
Stable
Fission
α
β-
2β-
n
2n
β+
2β+
e+
p
2p
3p

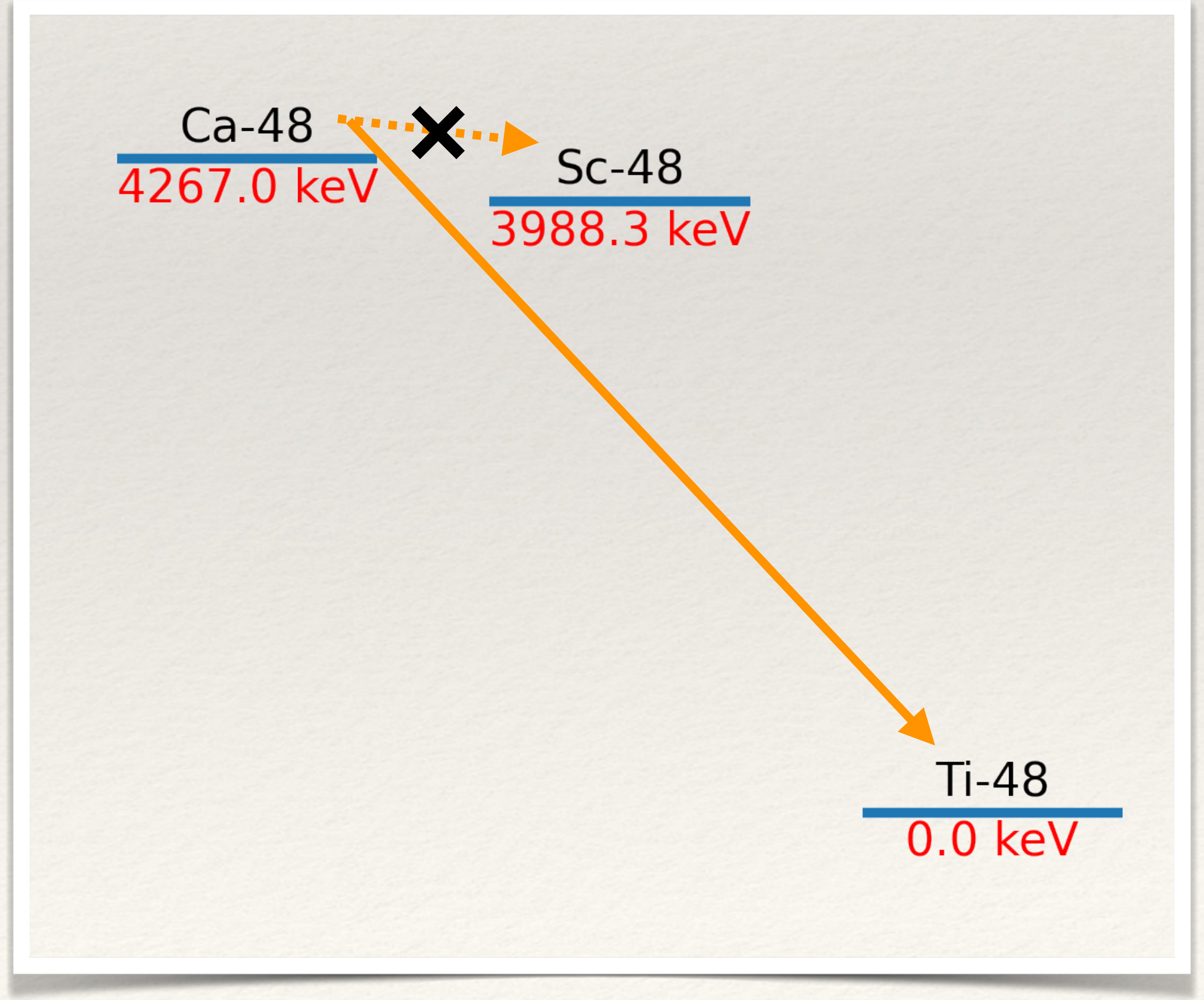
Double beta decay

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

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

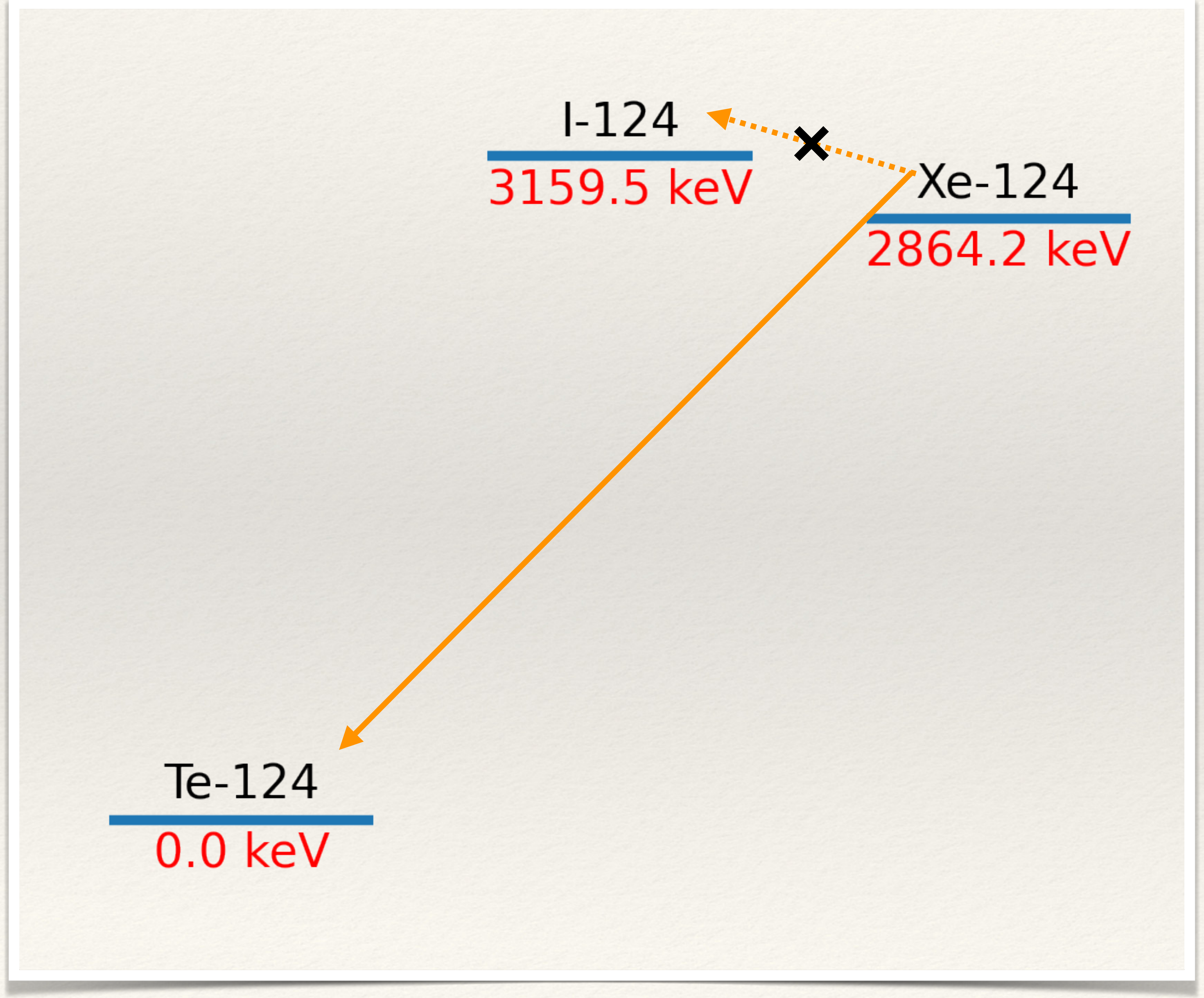


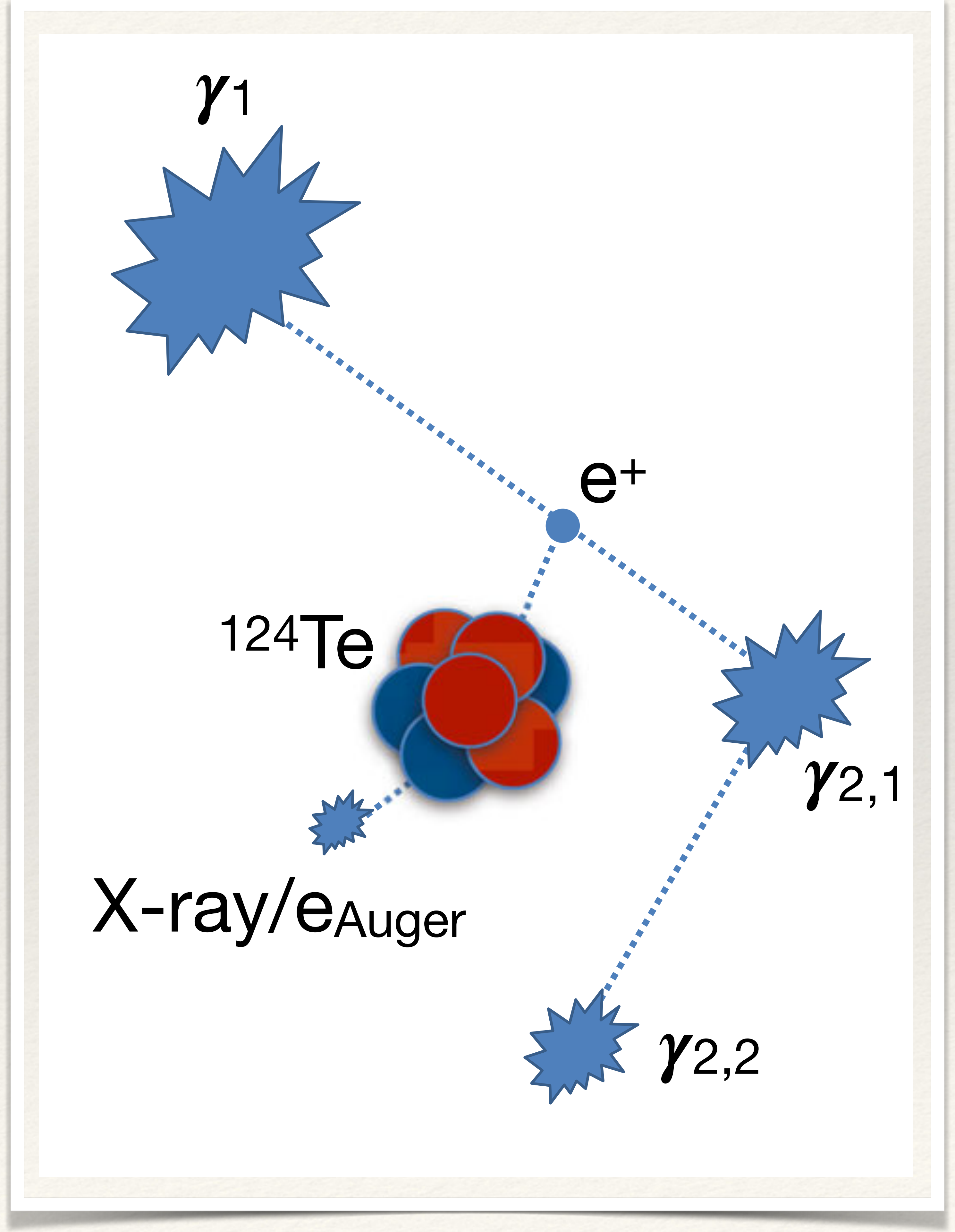




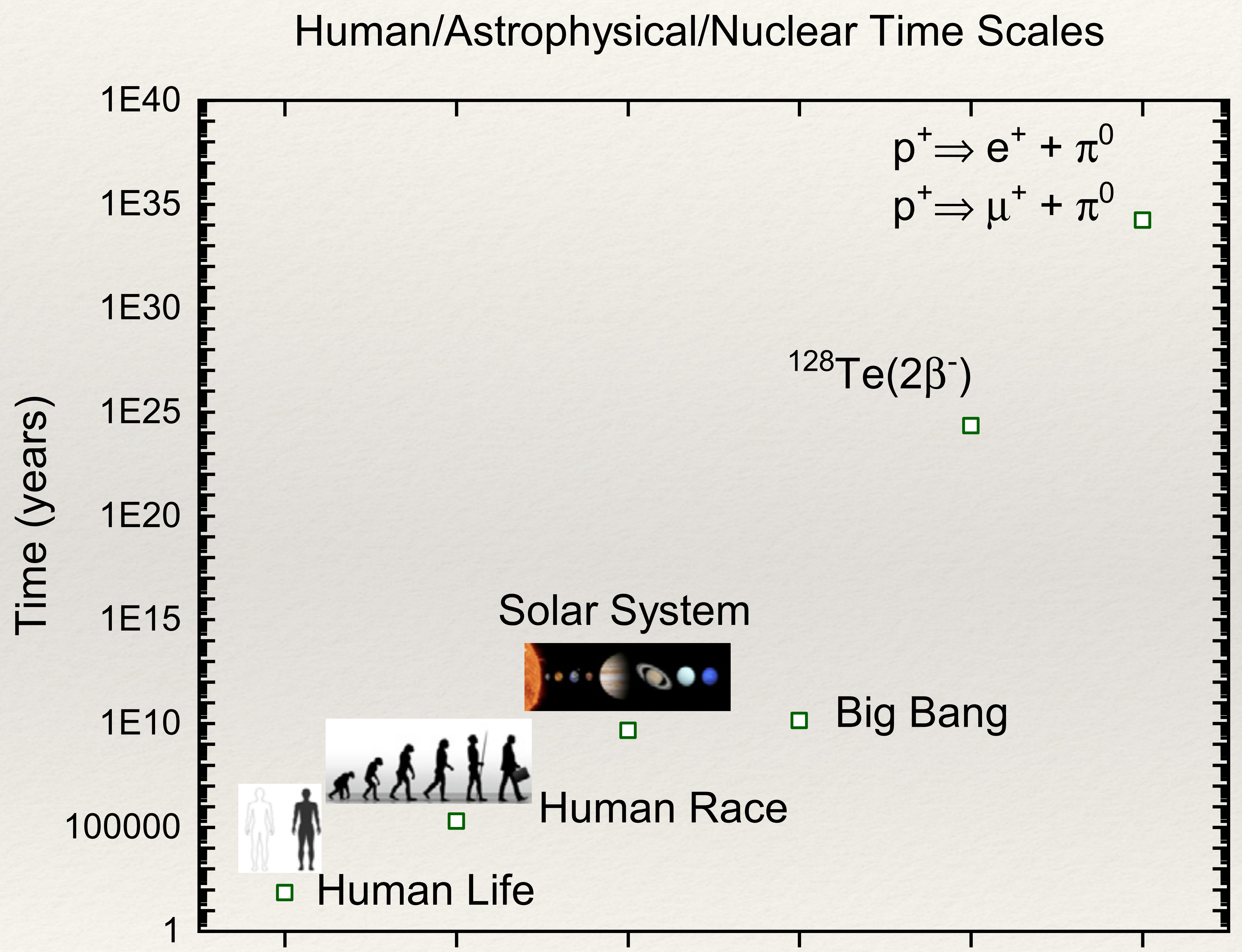
123Ba β+
124Ba β+
125Ba β+
126Ba β+
127Ba β+
128Ba e- capture
129Ba β+
130Ba 2β+
131Ba β+
132Ba 2β+
133Ba e- capture
134Ba Stable
122Cs β+
123Cs β+
124Cs β+
125Cs β+
126Cs β+
127Cs β+
128Cs β+
129Cs β+
130Cs β+
131Cs e- capture
132Cs β+
133Cs Stable
121Xe β+
122Xe e- capture
123Xe β+
124Xe 2β+
125Xe β+
126Xe 2β+
127Xe e- capture
128Xe Stable
129Xe Stable
130Xe Stable
131Xe Stable
132Xe Stable
120I β+
121I β+
122I β+
123I β+
124I β+
125I e- capture
126I β+
127I Stable
128I β-
129I β-
130I β-
131I β-
119Te β+
120Te 2β+
121Te β+
122Te Stable
123Te e- capture
124Te Stable
125Te Stable
126Te Stable
127Te β-
128Te 2β-
129Te β-
130Te 2β-
118Sb β+
119Sb e- capture
120Sb β+
121Sb Stable
122Sb β-
123Sb Stable
124Sb β-
125Sb β-
126Sb β-
117Sn Stable
118Sn Stable
119Sn Stable
120Sn Stable
121Sn β-
122Sn 2β-
123Sn β-
124Sn 2β-
125Sn β-
Primary Decay Mode
Stable
Fission
α
β-
2β-
n
2n
β+
2β+
e+
p
2p
3p

Double β^+, double EC, and β^+EC





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	$(2.00\pm0.60)\times10^{21}$

A bit history

- 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 0νββ

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

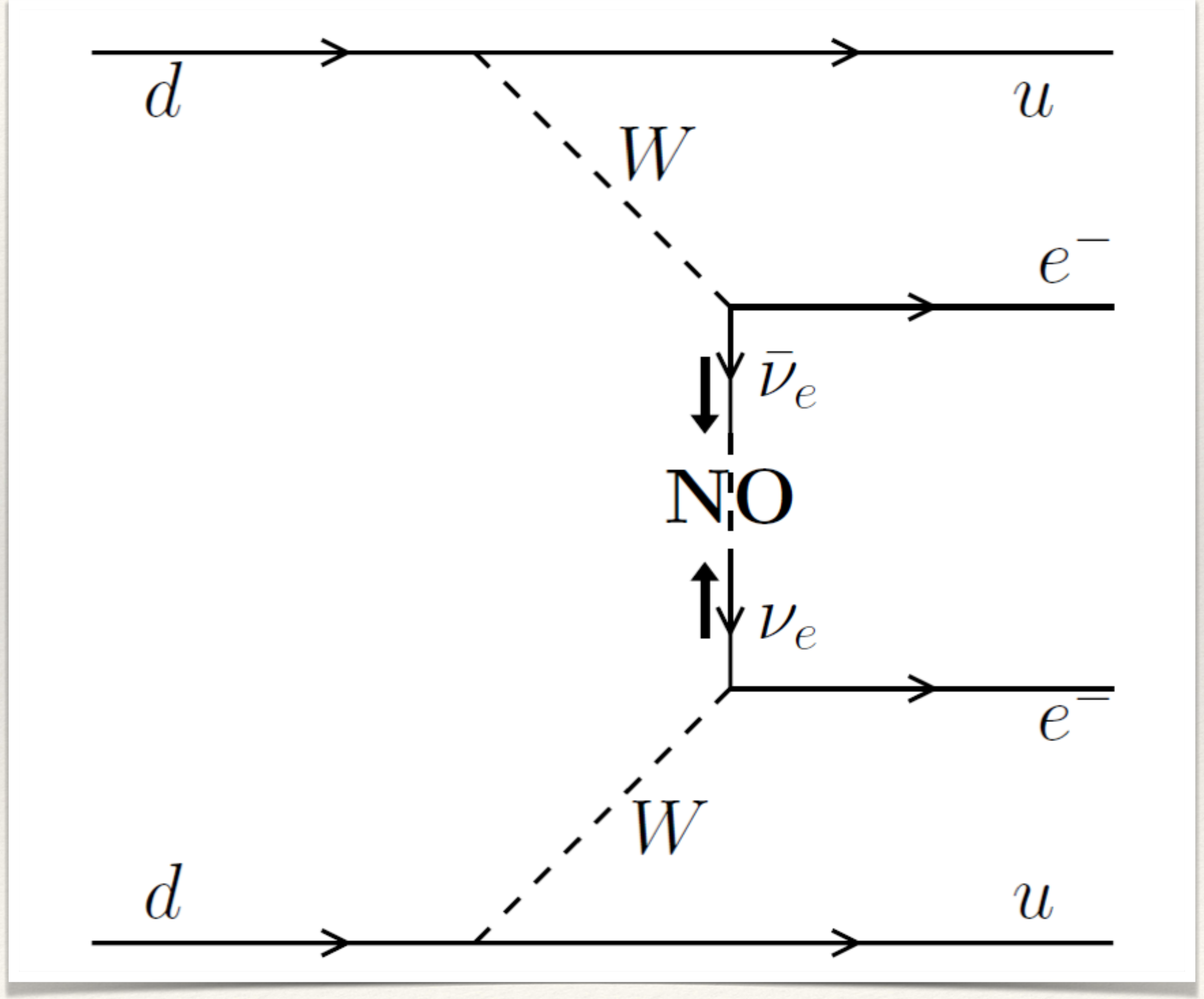
0νββ is forbidden in the SM

SM two-component theory of neutrino

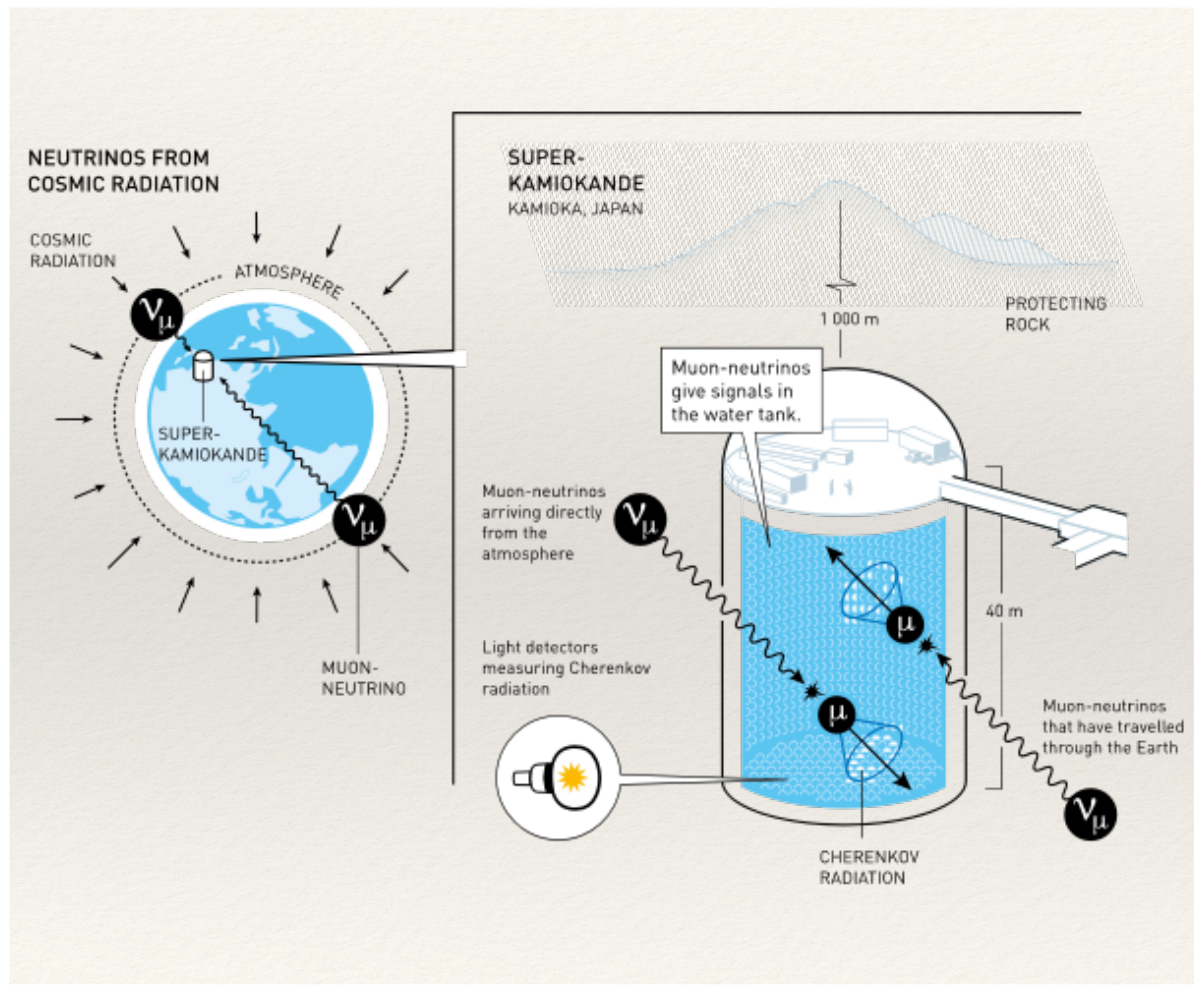
- Neutrinos are left-handed and antineutrinos are right-handed (helicity)

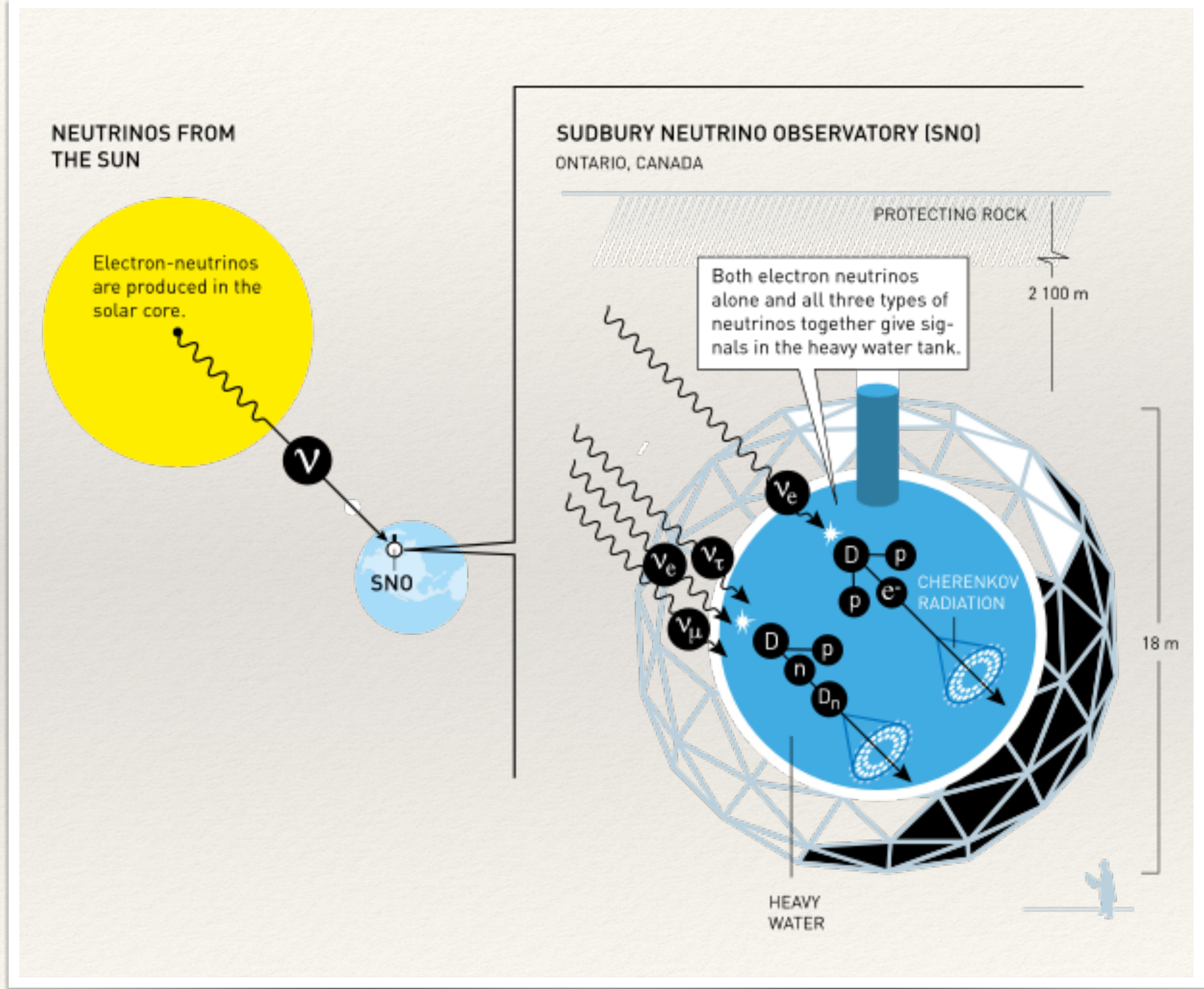
0νββ is forbidden in the SM

- Neutrino-antineutrino distinction
- Helicity mis-match

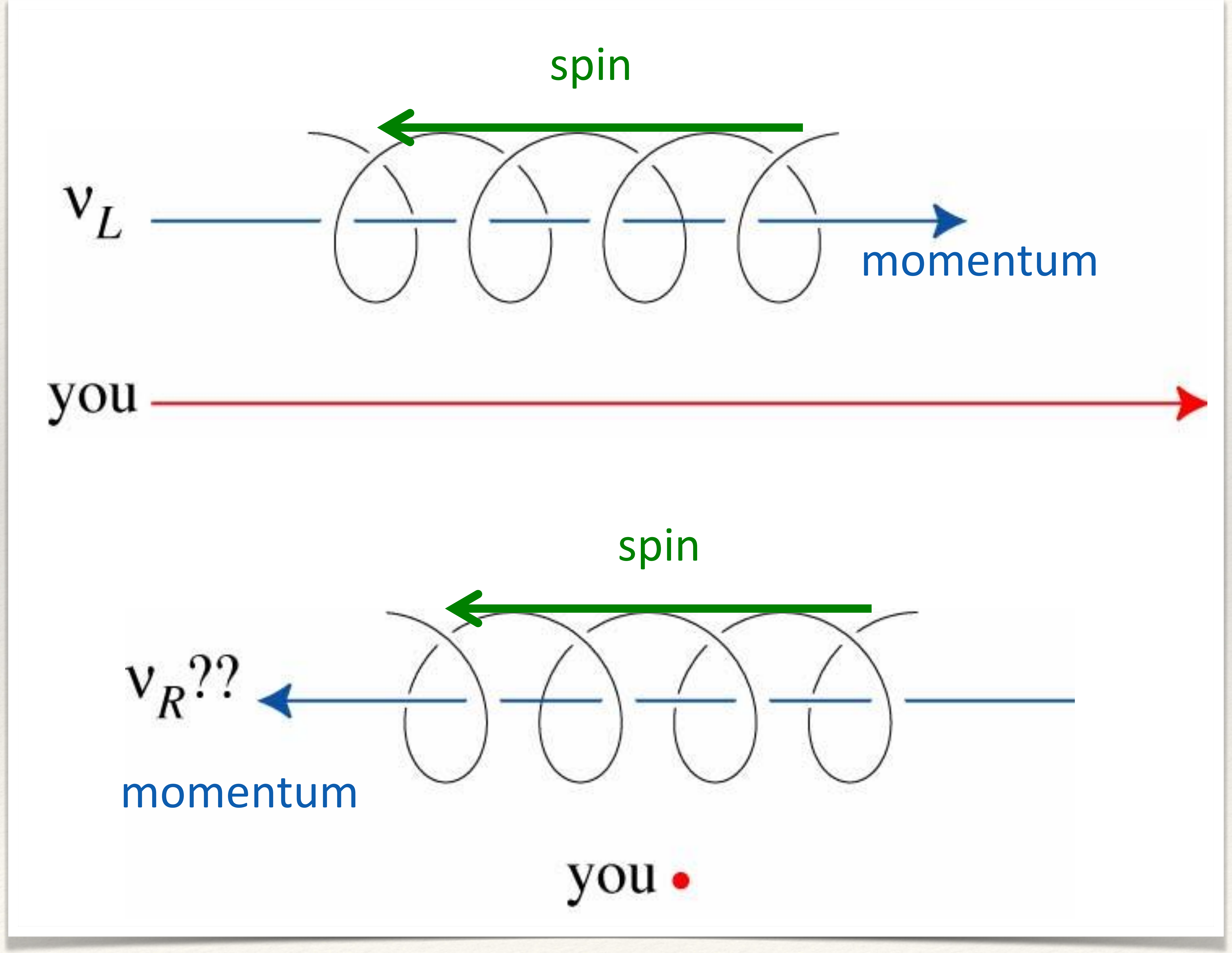


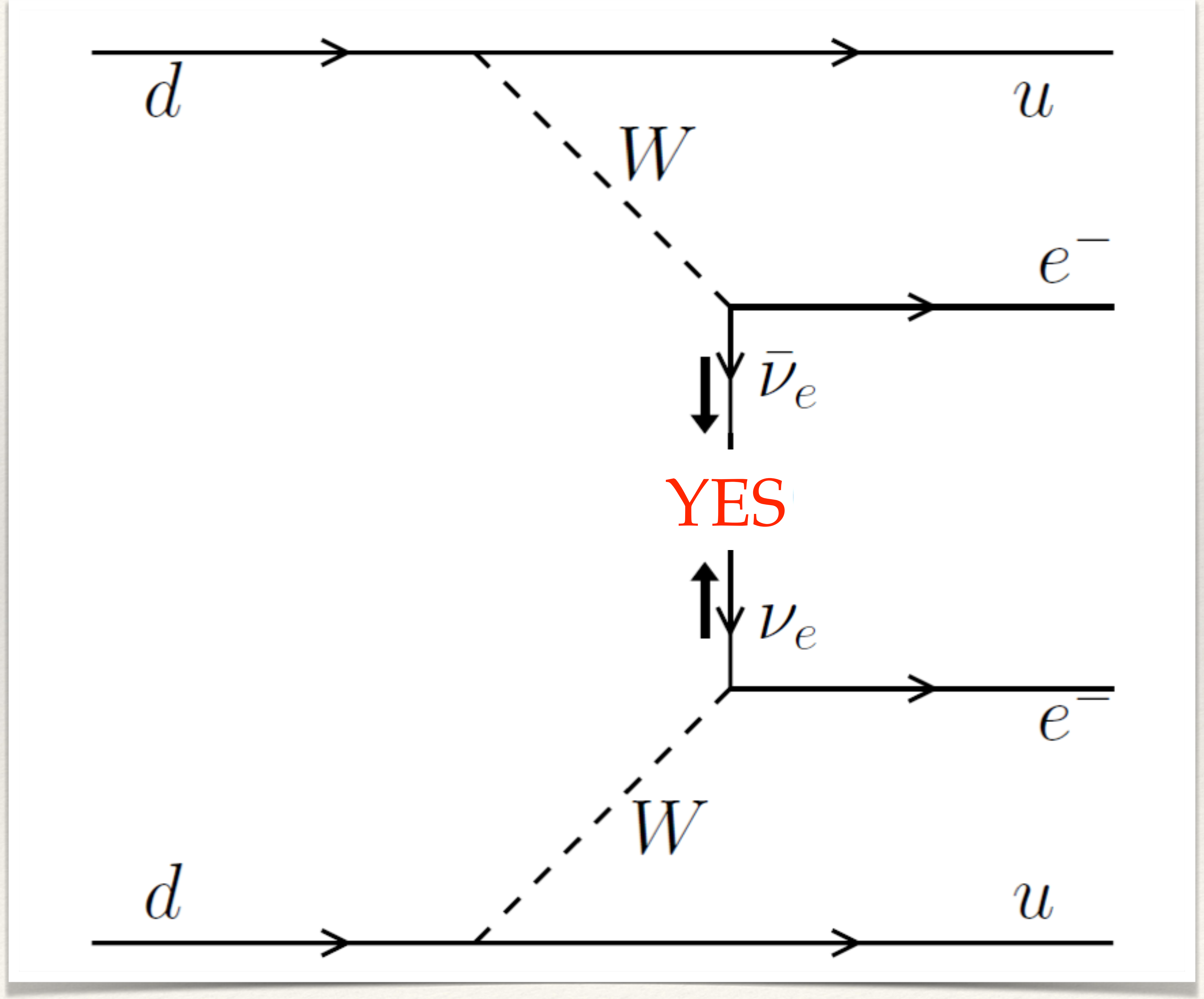
Tiny but finite neutrino mass





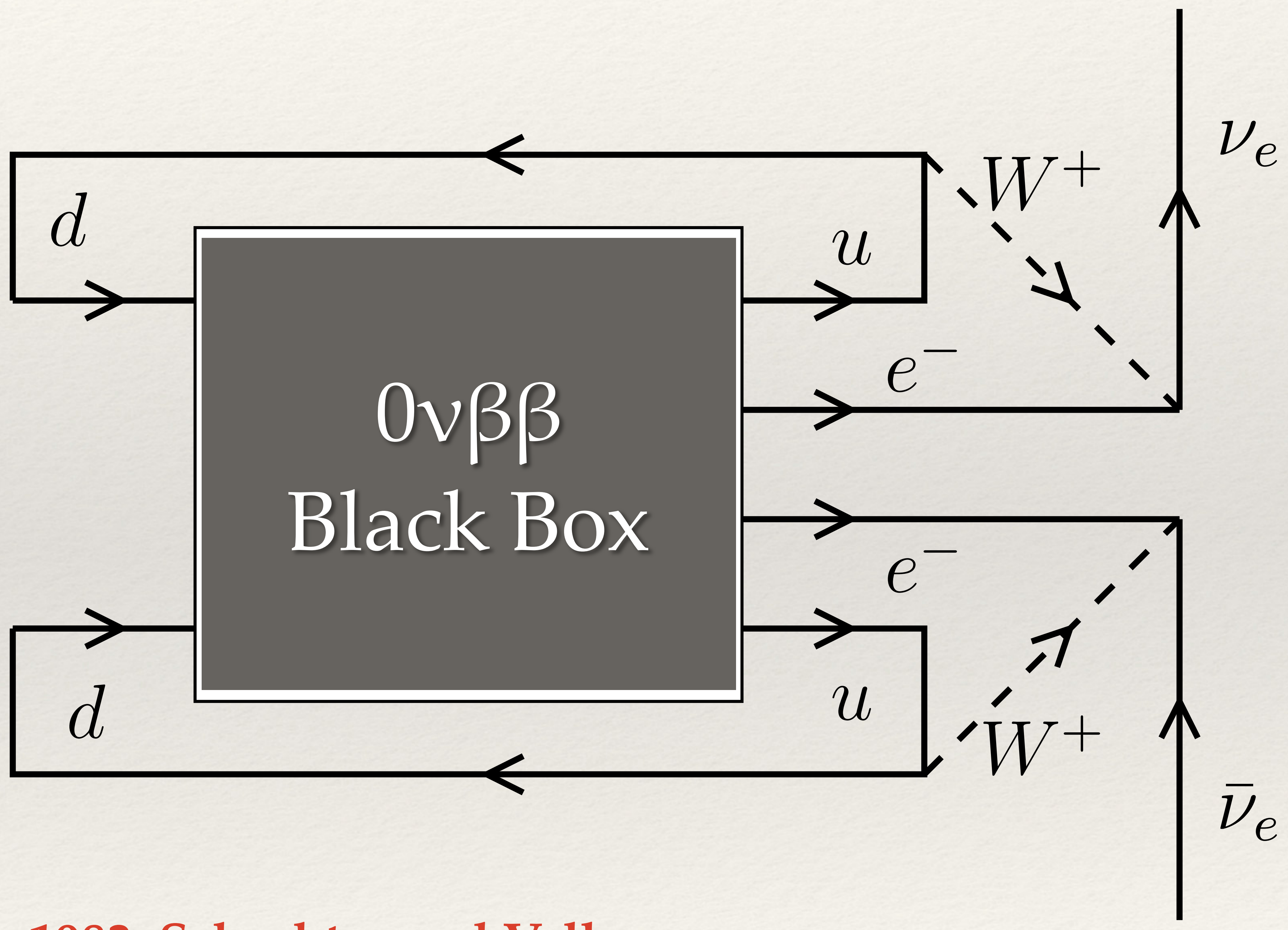
Helicity flipping is possible





Black-box Theorem: 0νββ→Majorana neutrinos

- “Minima” mechanism for 0νββ: exchange of a light Majorana neutrino
- However, many models exist
- 0νββ Black Box may include any models, but it always leads to an effective $\bar{\nu}_e \leftrightarrow \nu_e$



1982, Schechter and Valle

$0\nu\beta\beta \leftrightarrow$ Majorana neutrinos

0νββ Decay rate

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

Phase space factor **Nuclear matrix element**

Effective Majorana Mass:

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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Phase space factor **Nuclear matrix element**

Effective Majorana Mass:

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

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & e^{i\alpha_3} \end{pmatrix}$$

Effective Majorana Mass

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

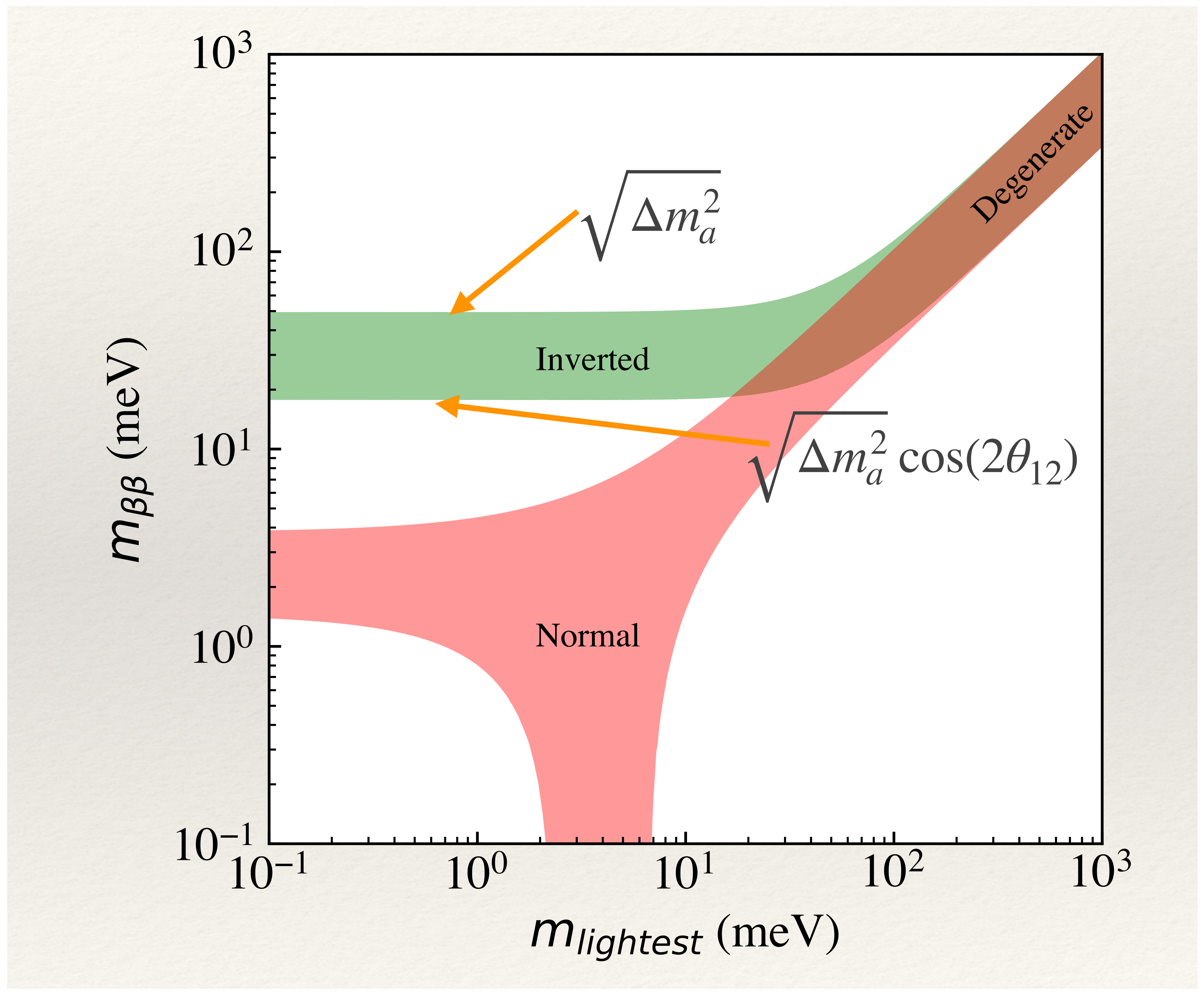
Inverted mass ordering:

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

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

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

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

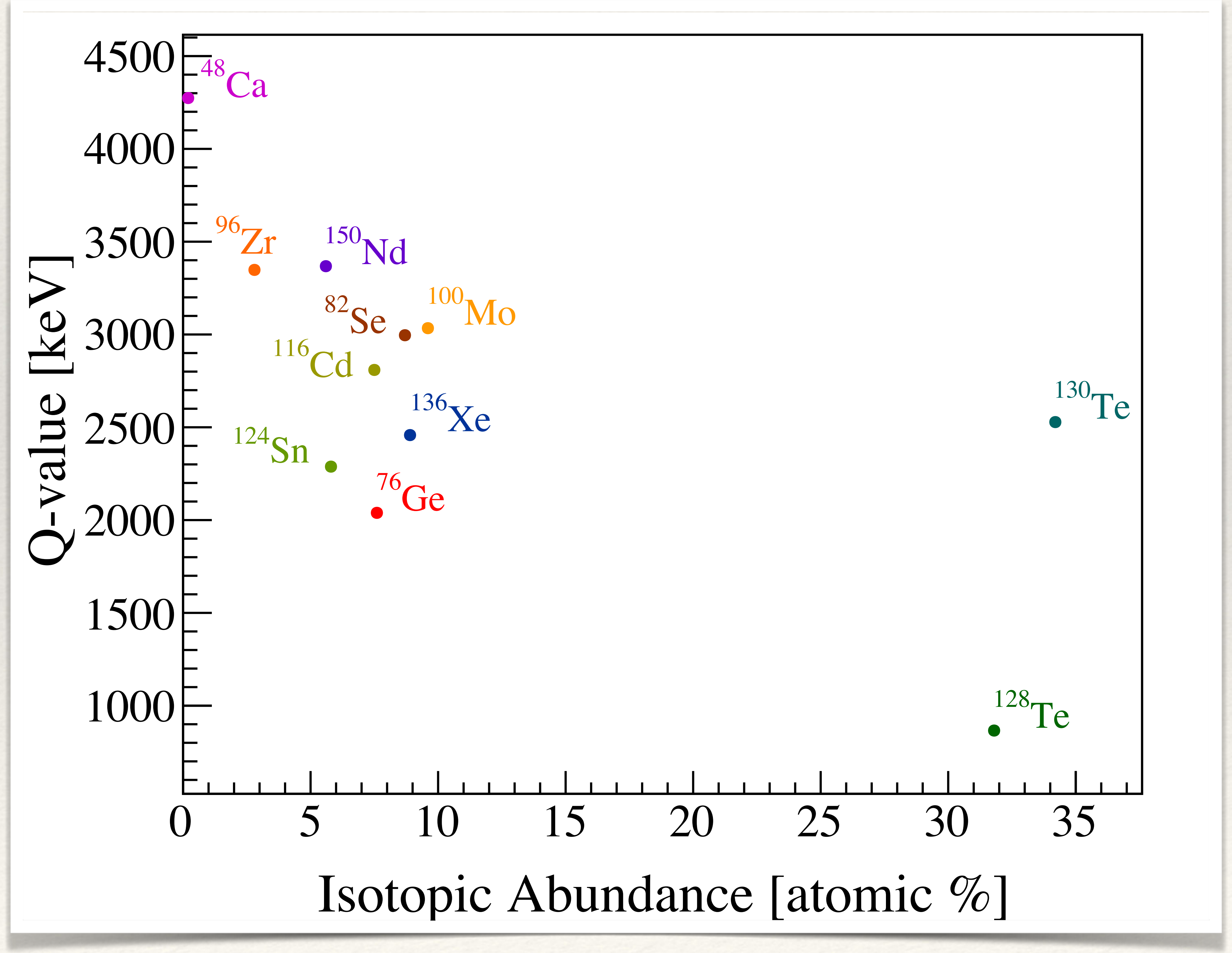


Importance of nuclear physics

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

Phase space factor **Nuclear matrix element**

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



- $G^{0\nu} \propto Q^5$
- $M^{0\nu} \in [1,10]$ depending on isotopes, models
- See more from Prof. Yao's talk

No magic isotopes

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

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

Phase space factor **Nuclear matrix element**

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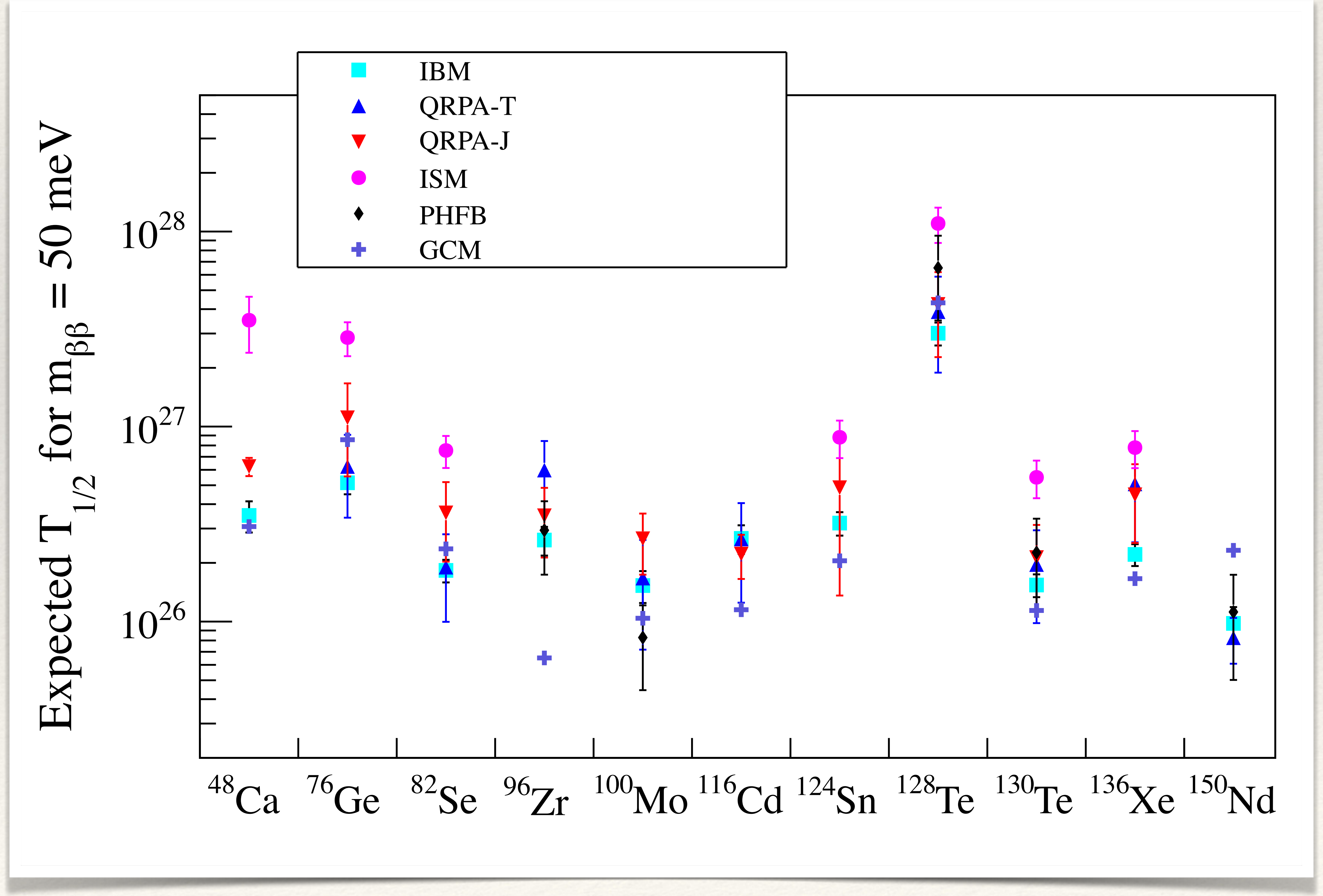

The importance of $0\nu\beta\beta$

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

SNOLab

无双实验：技术挑战

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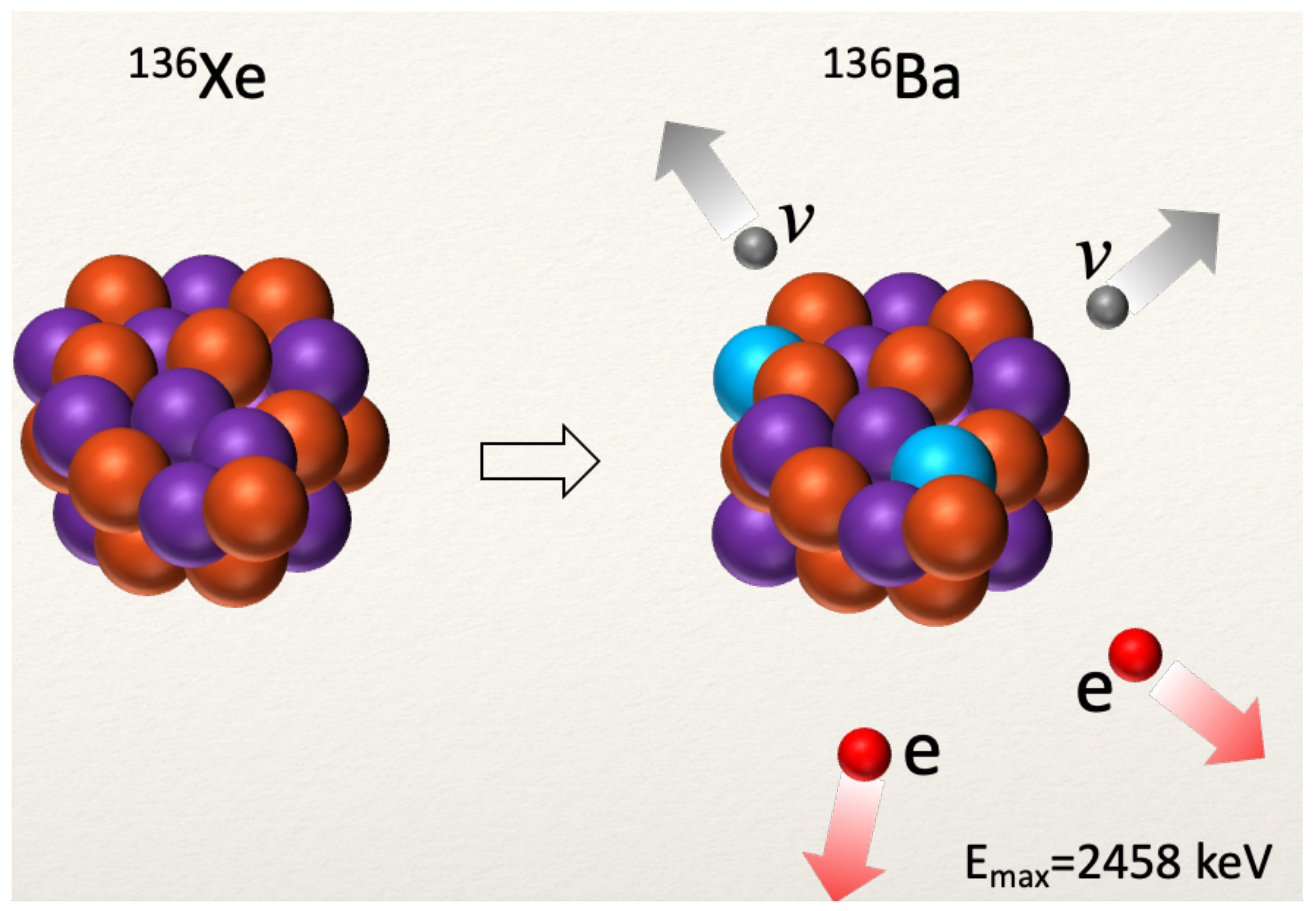
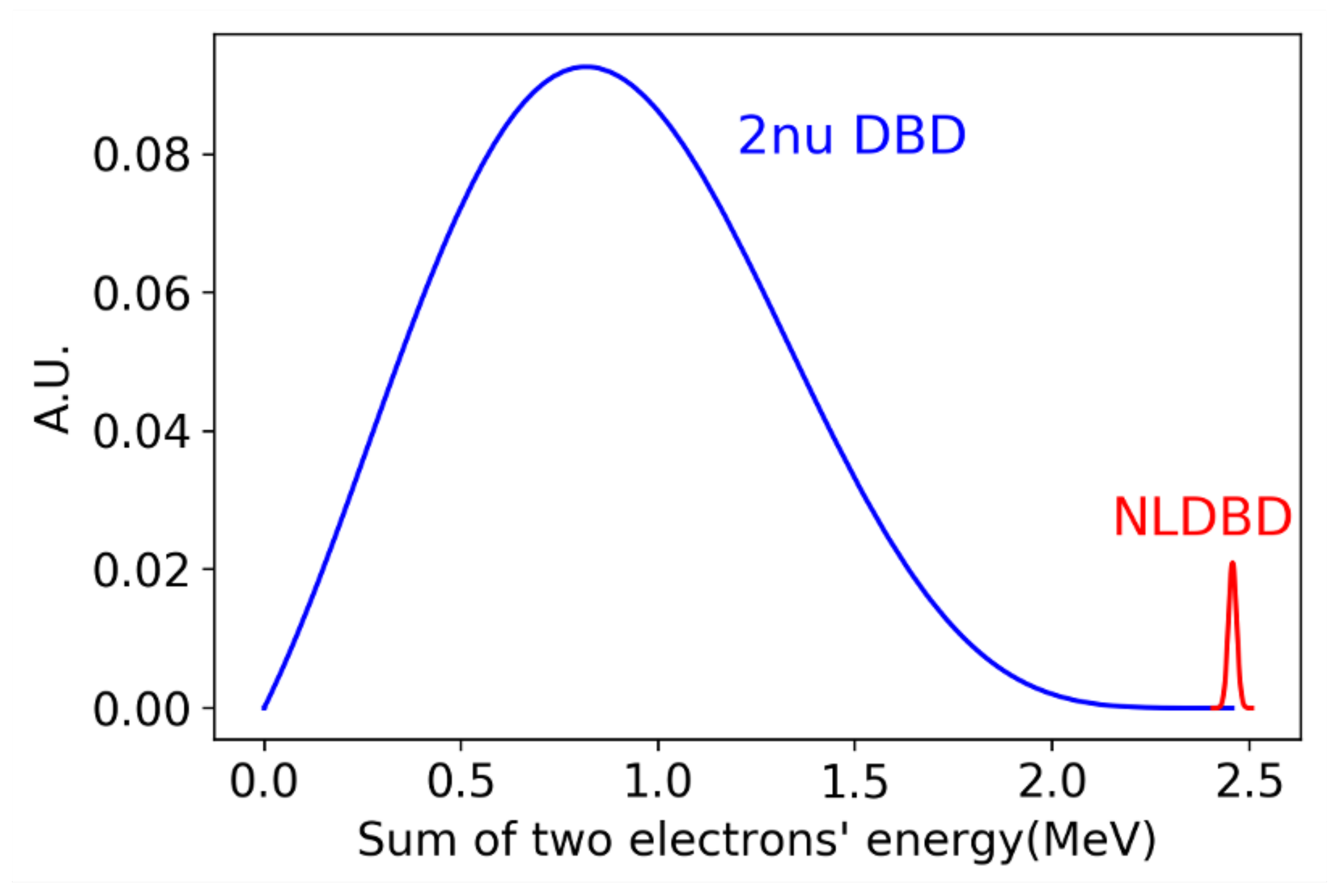
Experimental Searches

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





Geochemical and radiochemical

TABLE I. Isotopic composition of xenon extracted from 371 g of a 1.5×10^9 year old mineral containing 70 percent Bi_2Te_3. The total xenon content was 2.6×10^{-7} cc S.T.P.

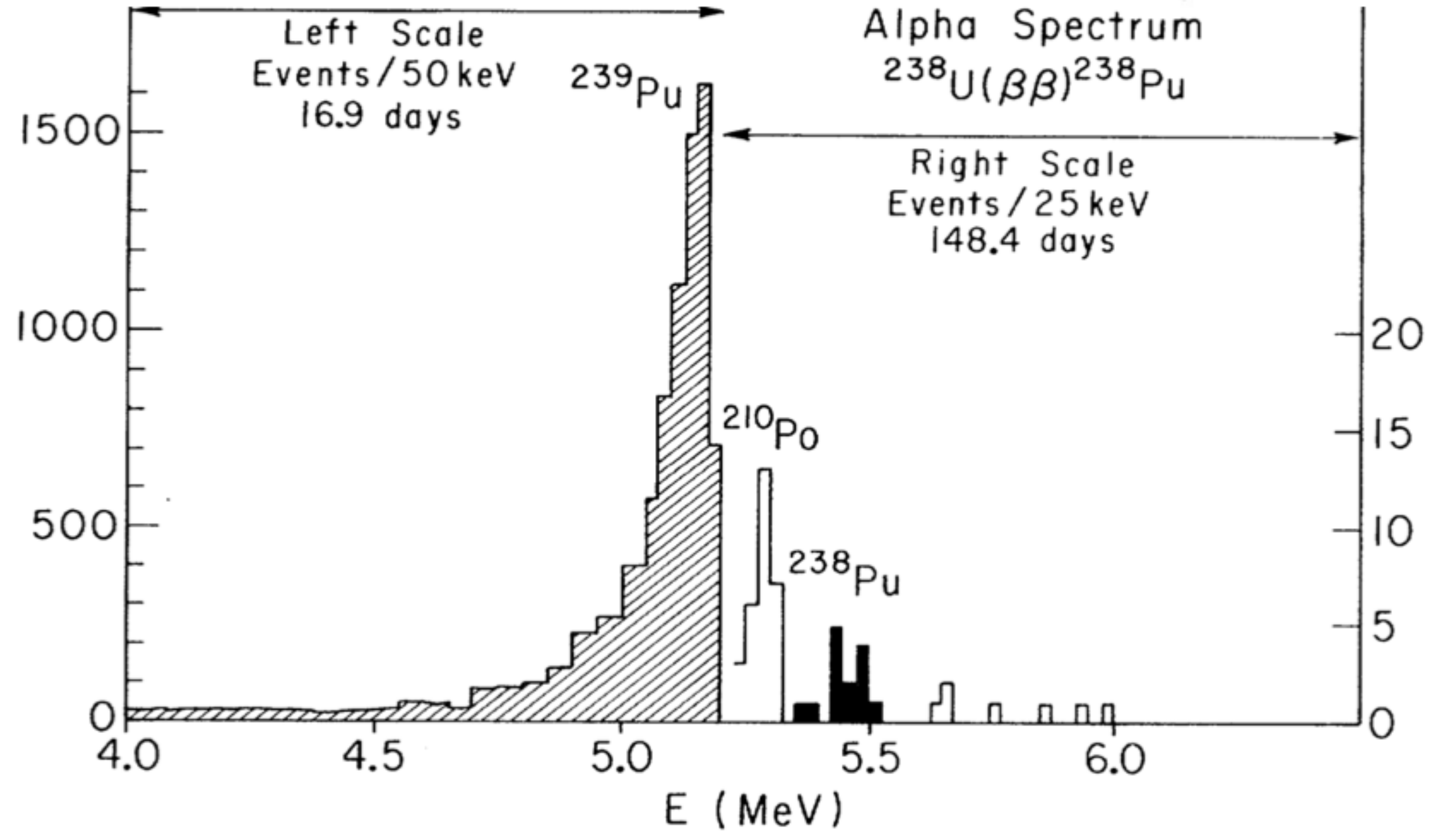
Mass	Bi_2Te No. 4	Normal	Diff.	Difference normalized	
124	<0.004	0.0005	<0.0035	<0.29	—
126	<0.005	0.0005	<0.0045	<0.38	—
128	<0.014	0.011	<0.003	<0.25	—
129	≡1.000	0.1525	0.8475	71.66±0.7	
130	0.0652	0.0236	0.0416	3.52±0.17	

The excess Xe^{130} is attributed to double beta-decay of Te^{130}. There appears to be no other explanation for its formation. Assuming an age of 1.5×10^9 years for the Bi_2Te_3, the excess Xe^{130} present corresponds to double beta-decay of Te^{130} with a half-life of 1.4×10^{21} years. This result is to be compared with theoretical half-lives of 6×10^{14} years and 10^{24} years, the former computed from the Majorana theory of the neutrino, and the latter from the Dirac theory. Both calculations are for allowed transitions with 1.6 Mev of available energy.

[1] M. G. Inghram and J. H. Reynolds, Phys. Rev. **76**, 1265 (1949).
[2] Seren, Friedlander, and Turkel, Phys. Rev. **72**, 888 (1947).

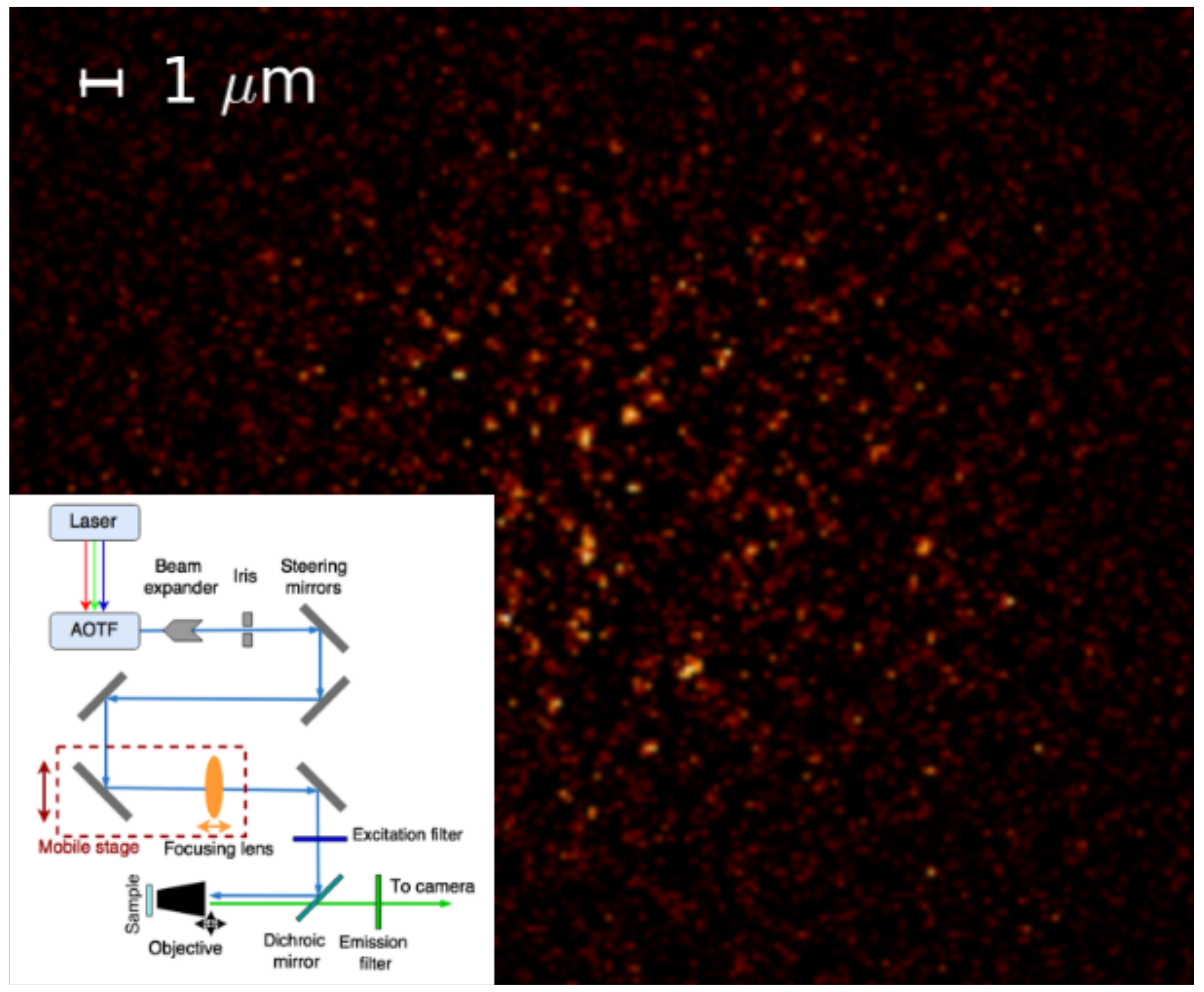
Phys. Rev. **78**, 822 (1950)

Haxton, Cowan, and Goldhaber [15] revived interest in the ^{238}U system and the present work was started as a result of their publication. The experiment involves the extraction of the accumulated plutonium from uranium salt that had been purified and isolated from fallout for 33 yr. This amount of uranyl nitrate (1.02×10^{25} atoms of ^{238}U) produces 2.3×10^5 atoms of ^{238}Pu in 33 yr if the half-life for double beta decay is 10^{21} yr. The chemically

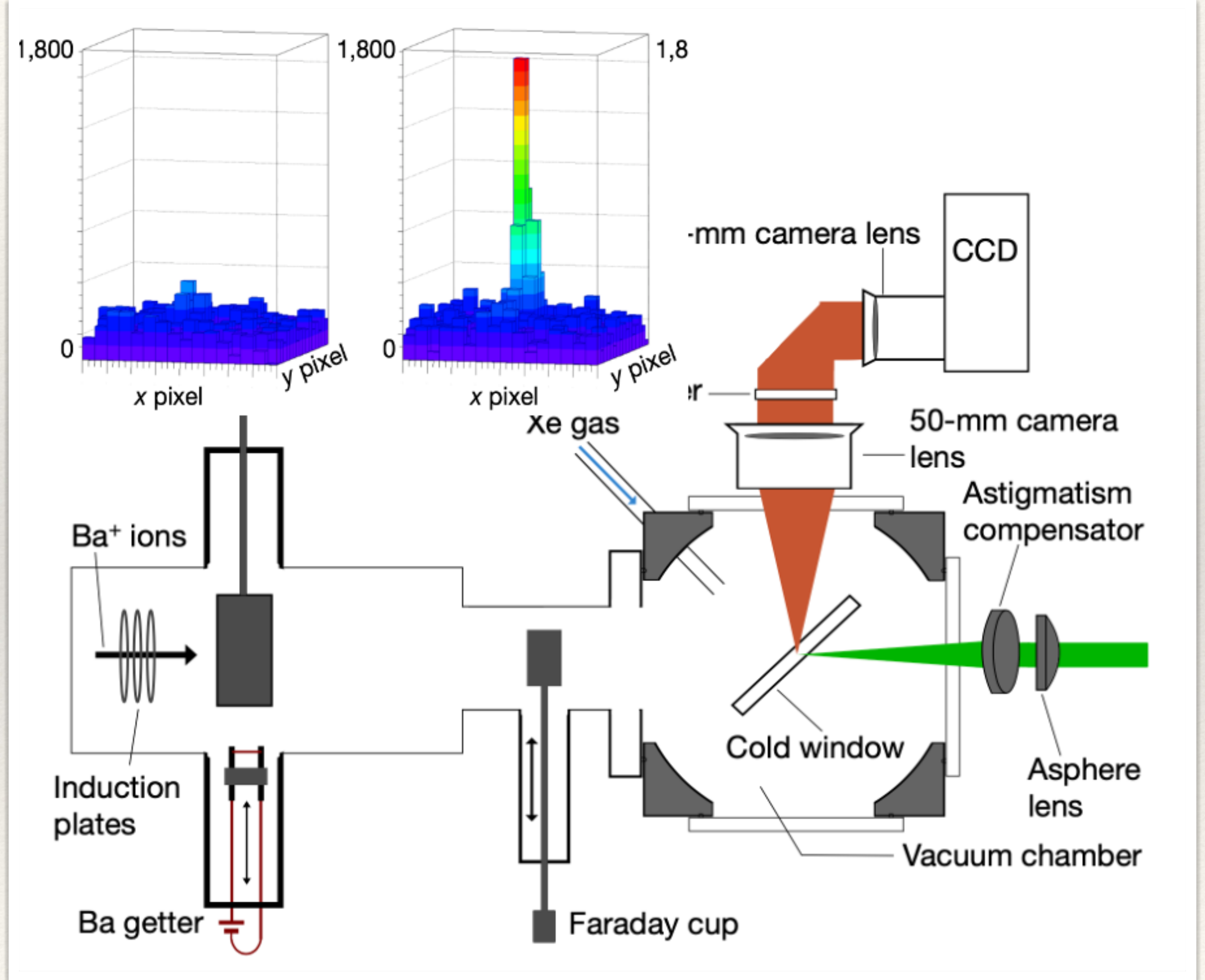


Phys. Rev. Lett. **67**, 3211 (1991)

Imaging daughter nuclei



NEXT, Phys. Rev. Lett. **120**, 132504 (2018)



nEXO, Nature. **569**, 203 (2019)

Experimental Searches

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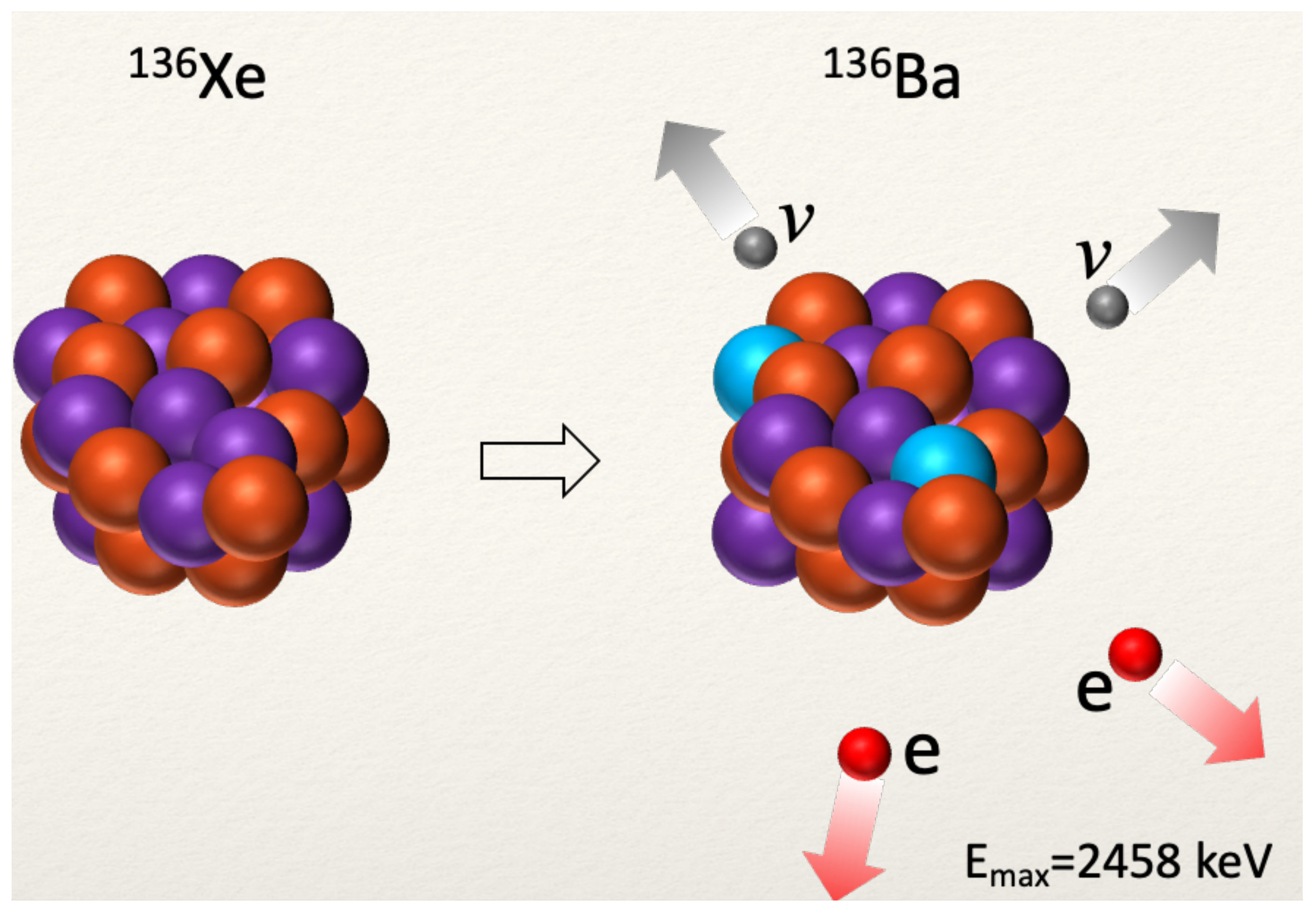
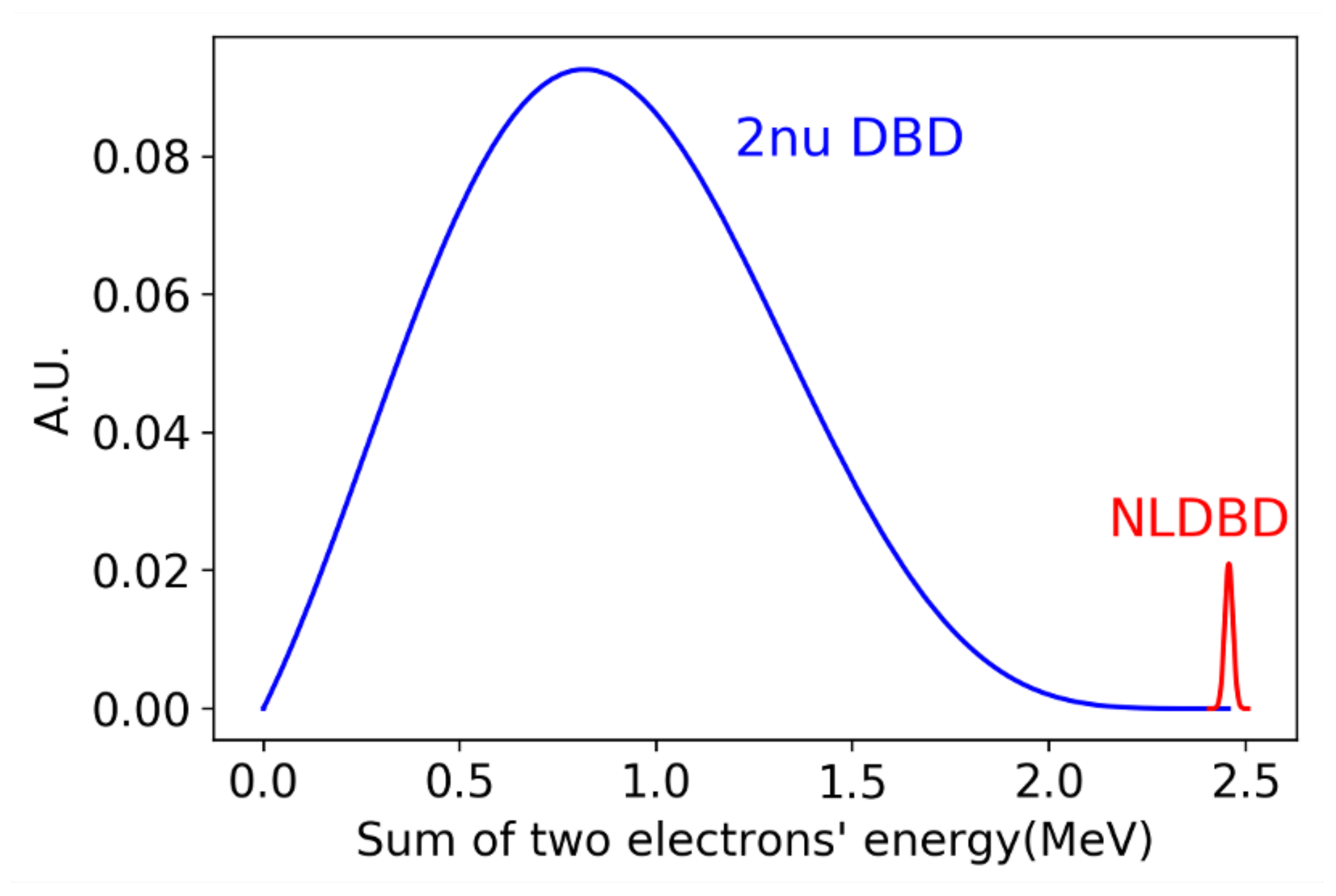
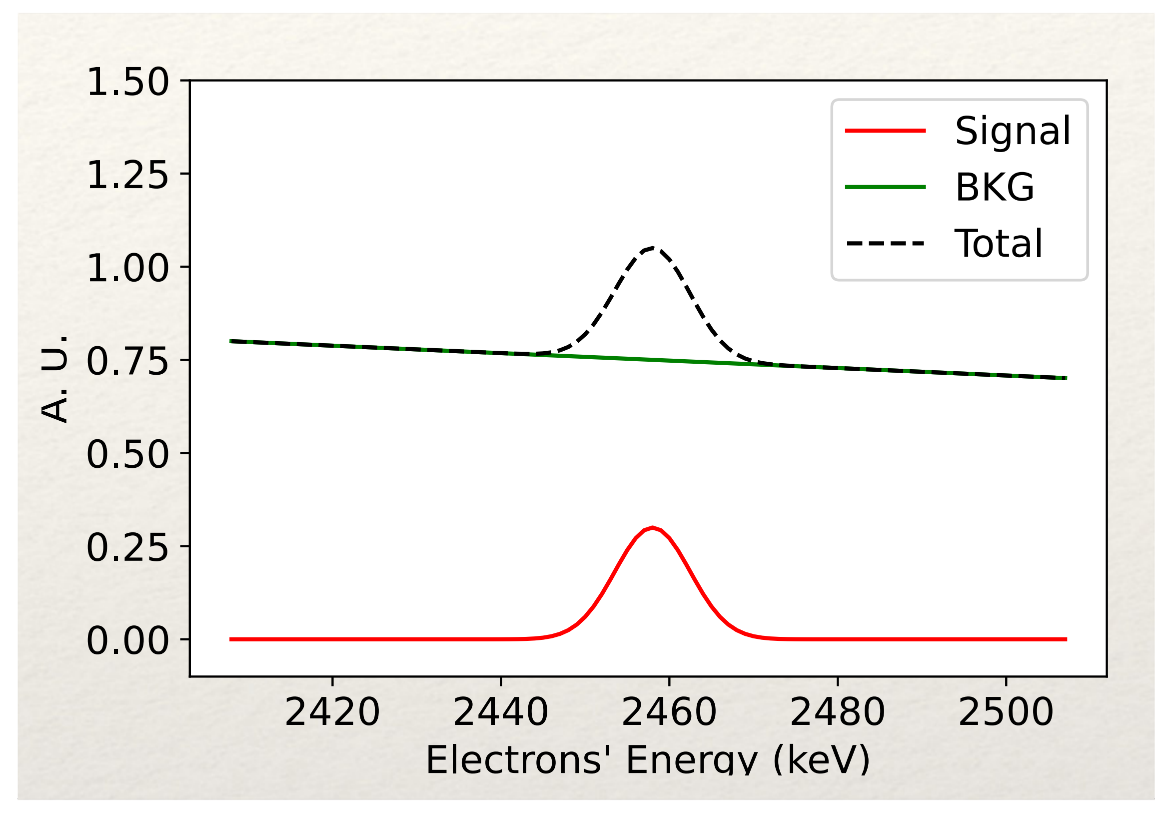
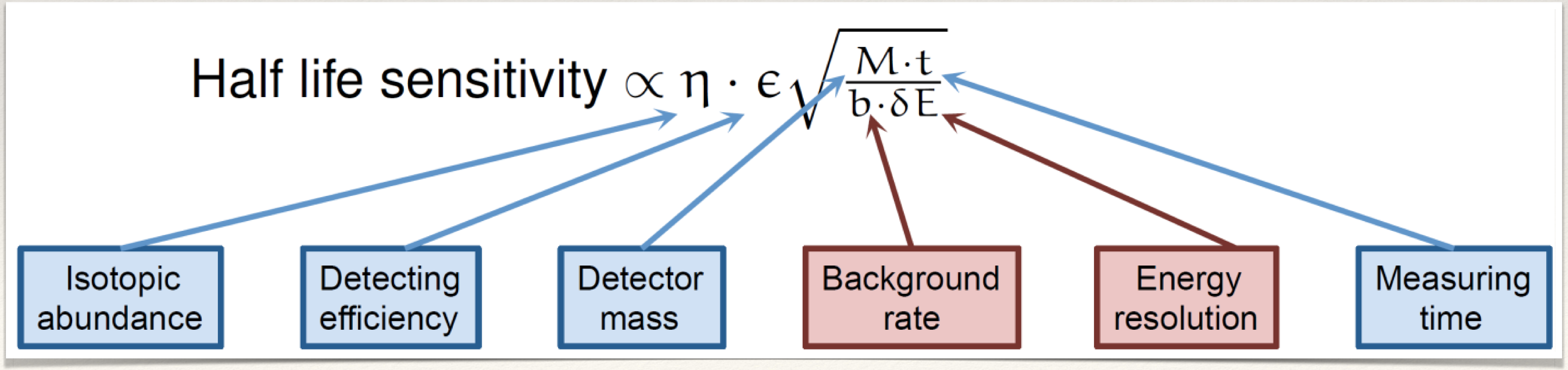




Half-life sensitivity from experiments

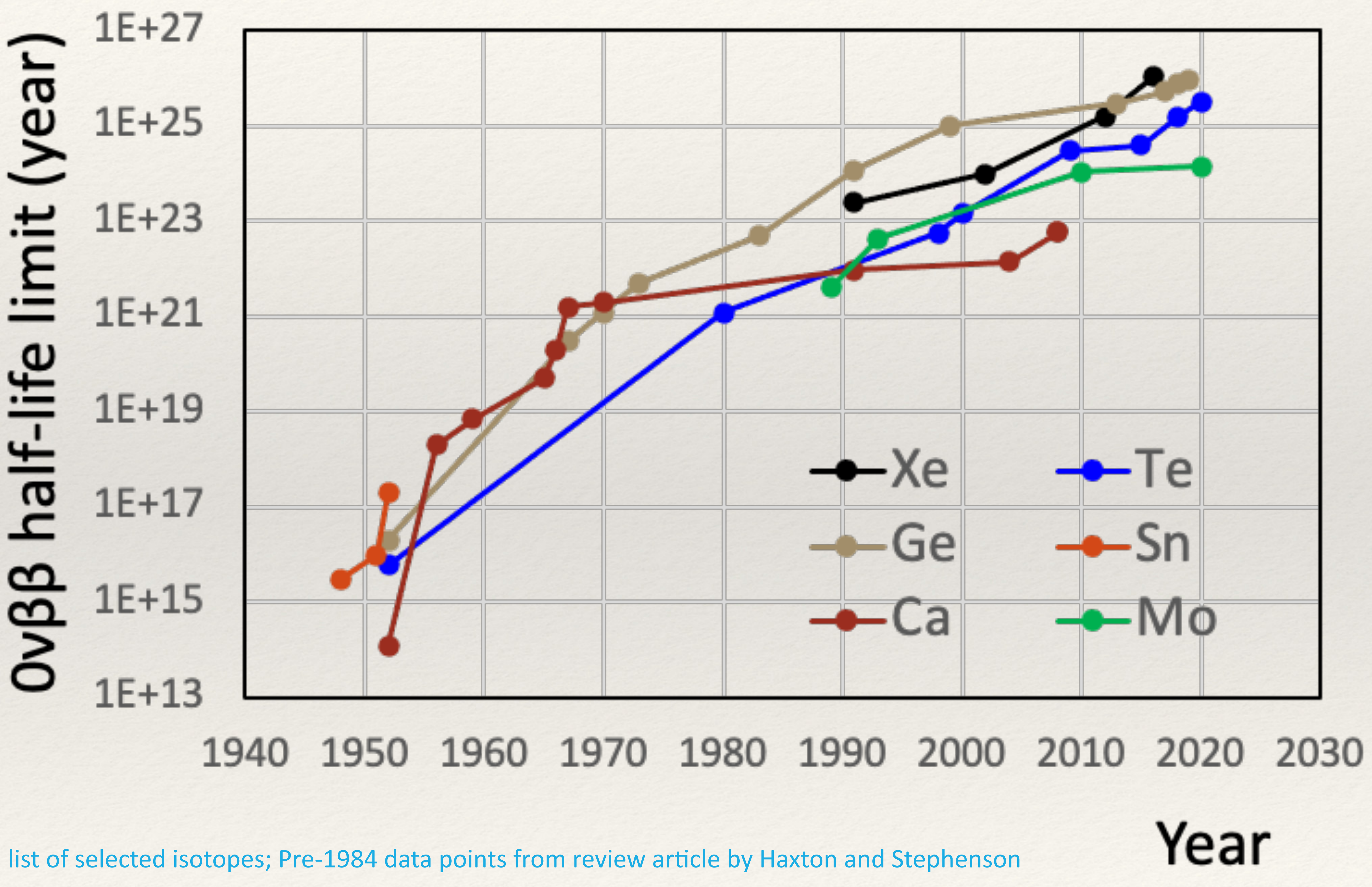
- Number of signals over fluctuation of background for possible observation
- Extreme requirements for detector performance and background control





Impressive experimental progress

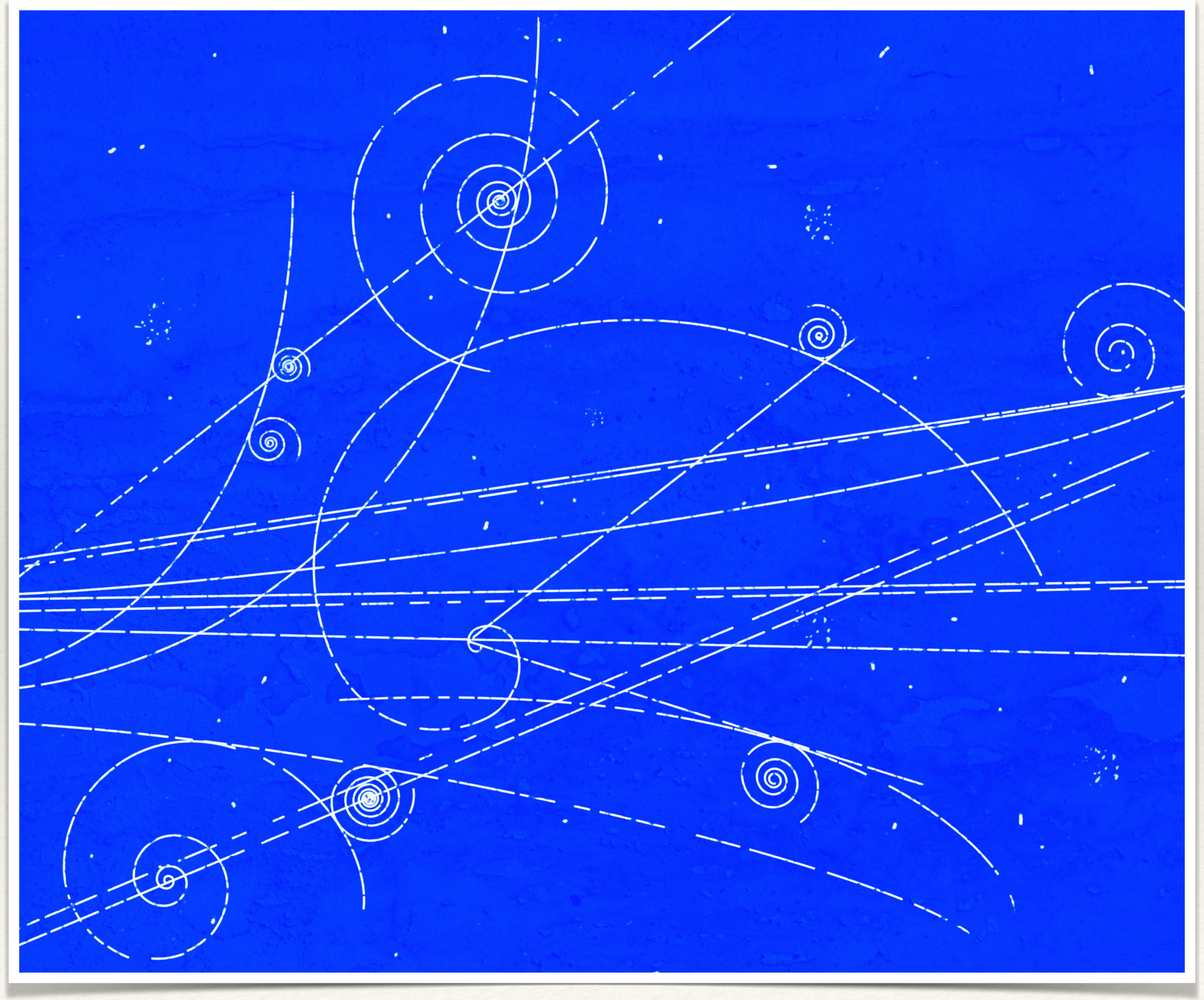
- Still no discovery but half-life limits improved significantly
- MeV electron measurement is relatively straightforward
- From above-ground table-top experiments with grams of isotopes
- To underground ton-scale detectors, done by hundreds of collaborators



Partial list of selected isotopes; Pre-1984 data points from review article by Haxton and Stephenson

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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- 各显神通: Cowan and Reines, C.S. Wu, etc
- 1967: Fiorini et al., Ge detector

1933-2023

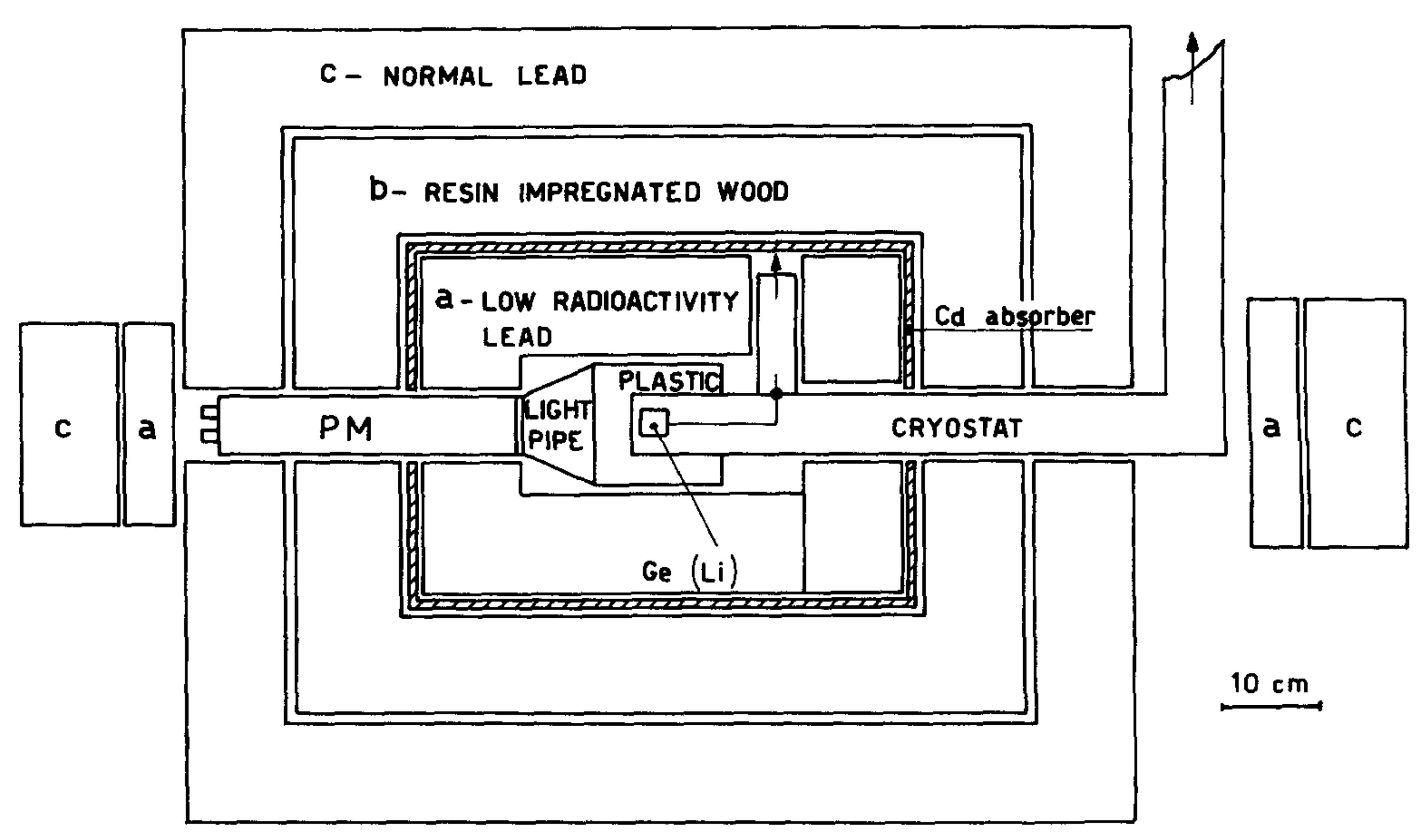

Fig. 1. Experimental setup.

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- 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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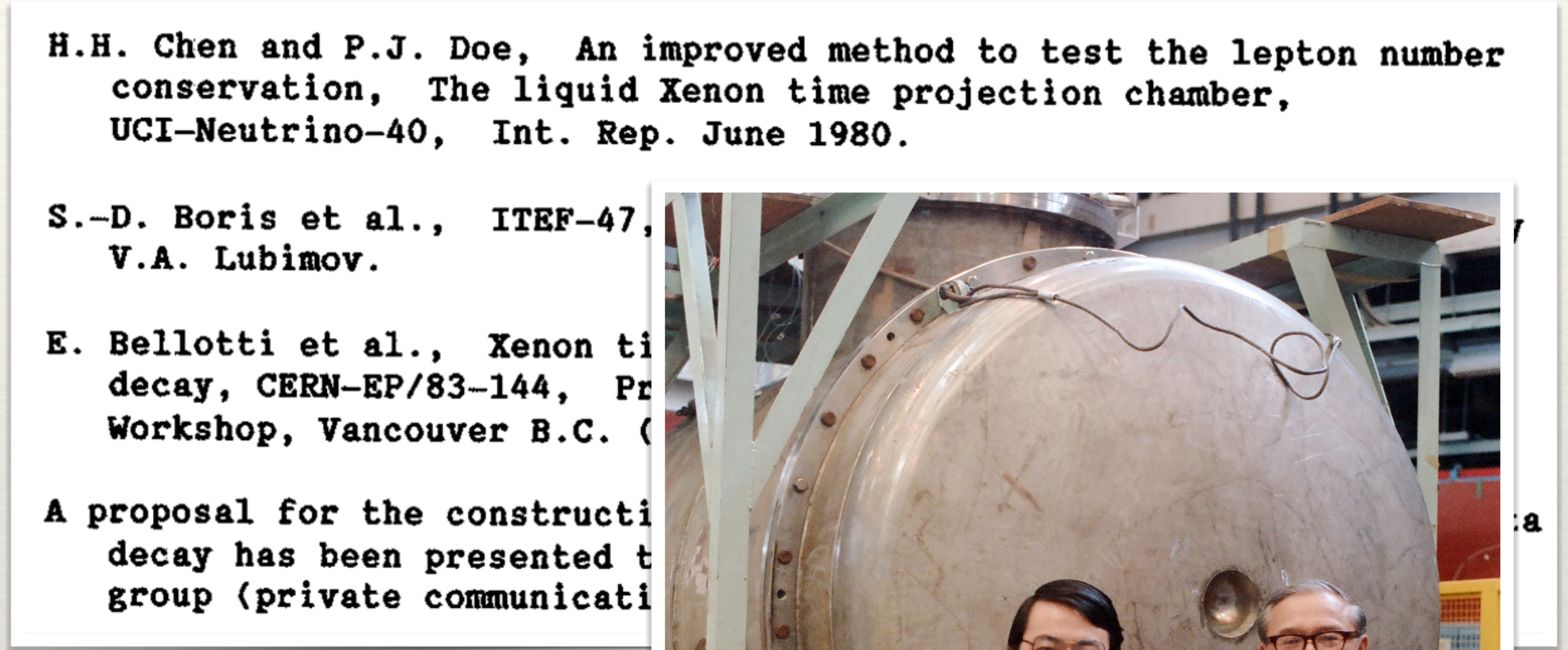
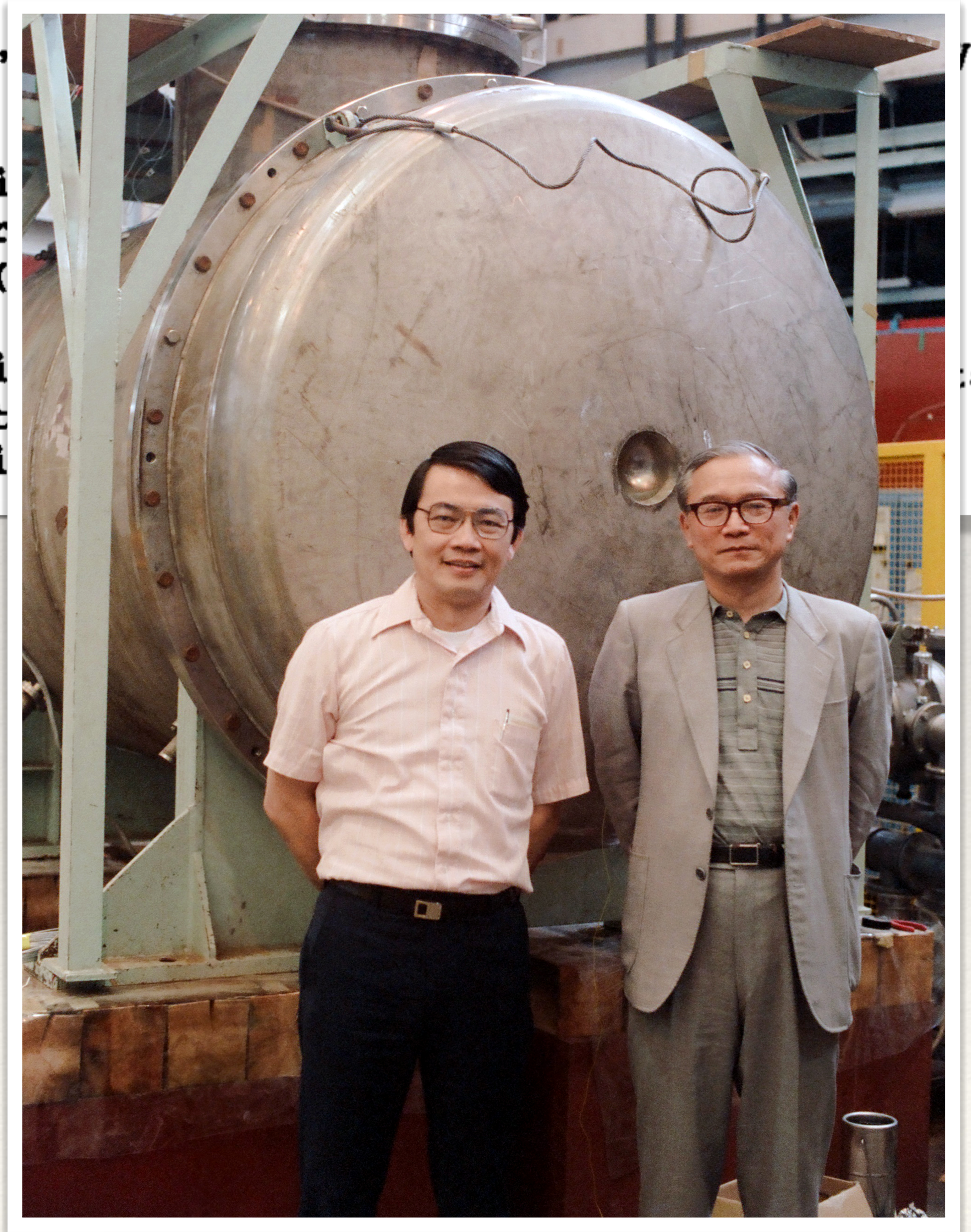


H.H. Chen and P.J. Doe, An improved method to test the lepton number conservation, The liquid Xenon time projection chamber, UCI-Neutrino-40, Int. Rep. June 1980.

S.-D. Boris et al., ITEF-47,
V.A. Lubimov.

E. Bellotti et al., Xenon ti
decay, CERN-EP/83-144, Pr
Workshop, Vancouver B.C. (

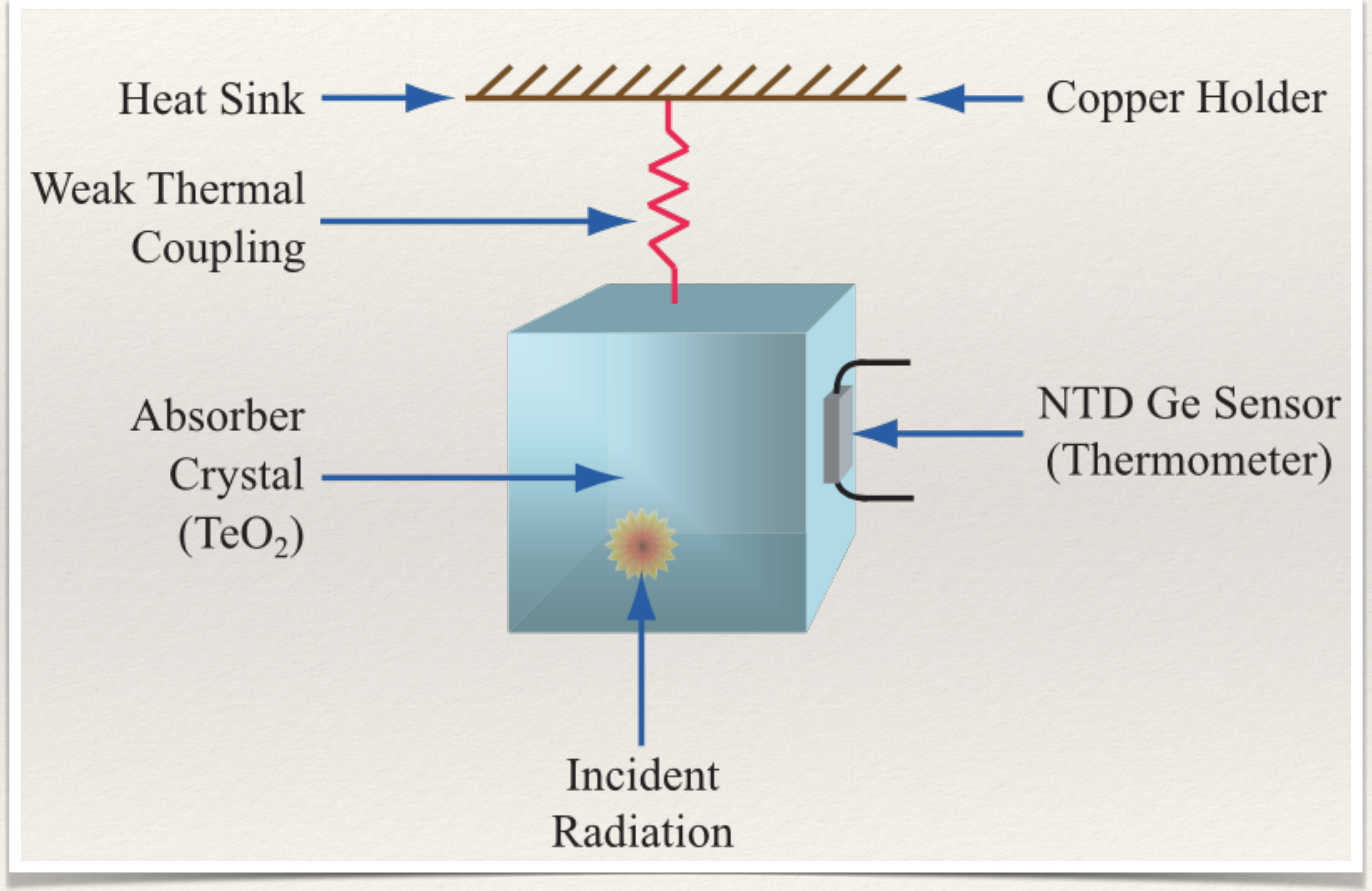
A proposal for the constructi
decay has been presented t
group (private communicati



陈华生
1942-1987

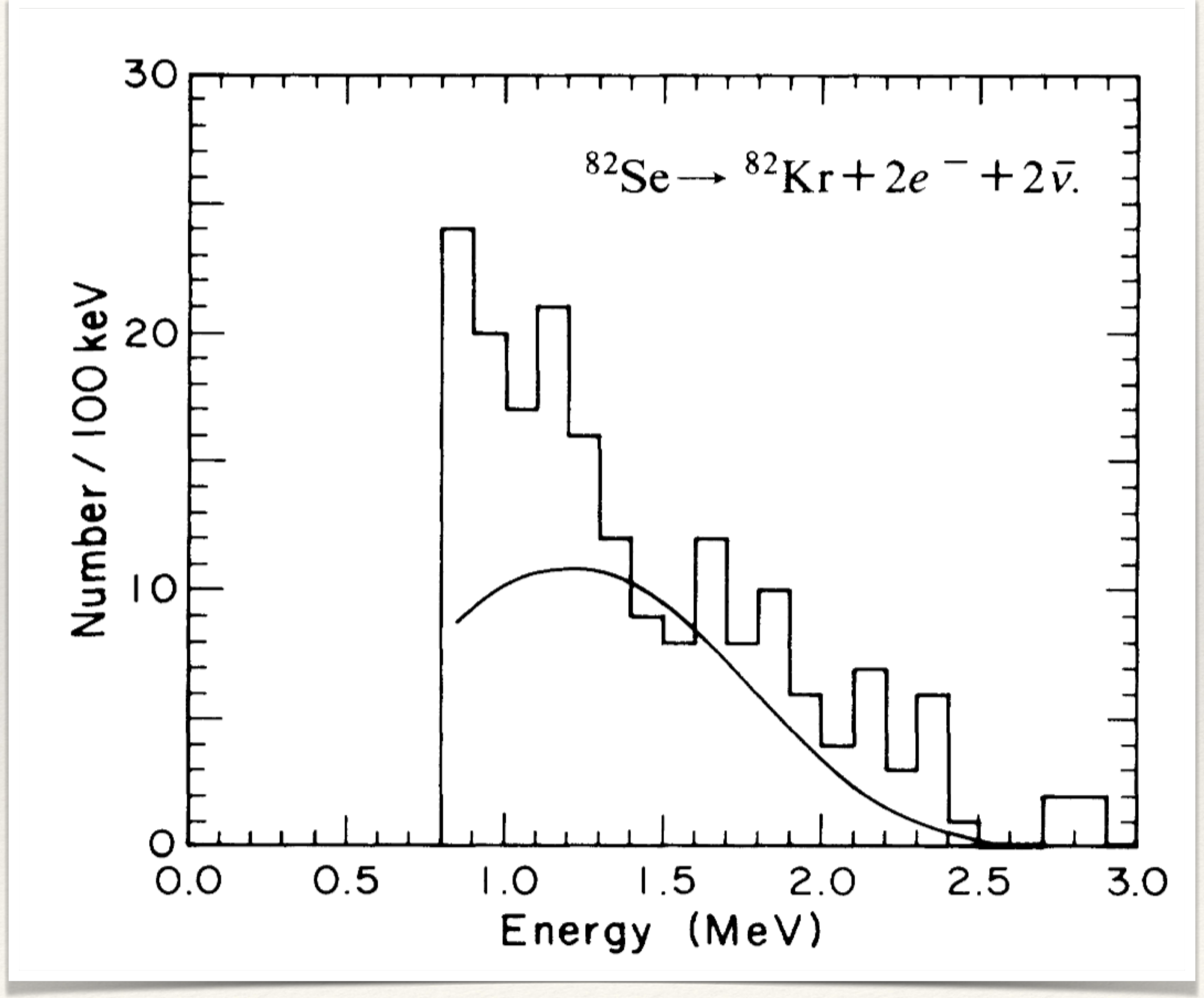
A bit history

- 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
- 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."

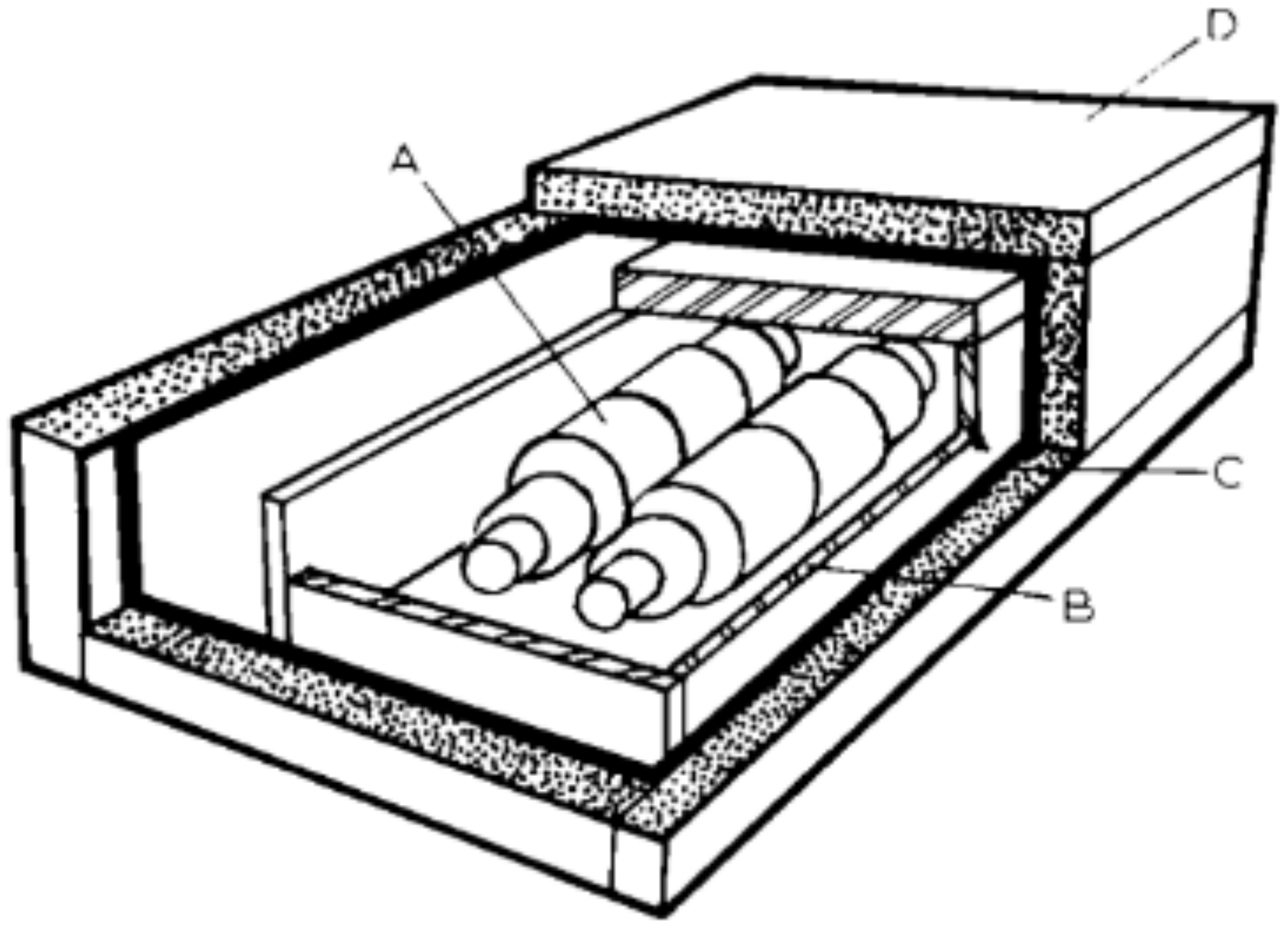


First experiment in China

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*

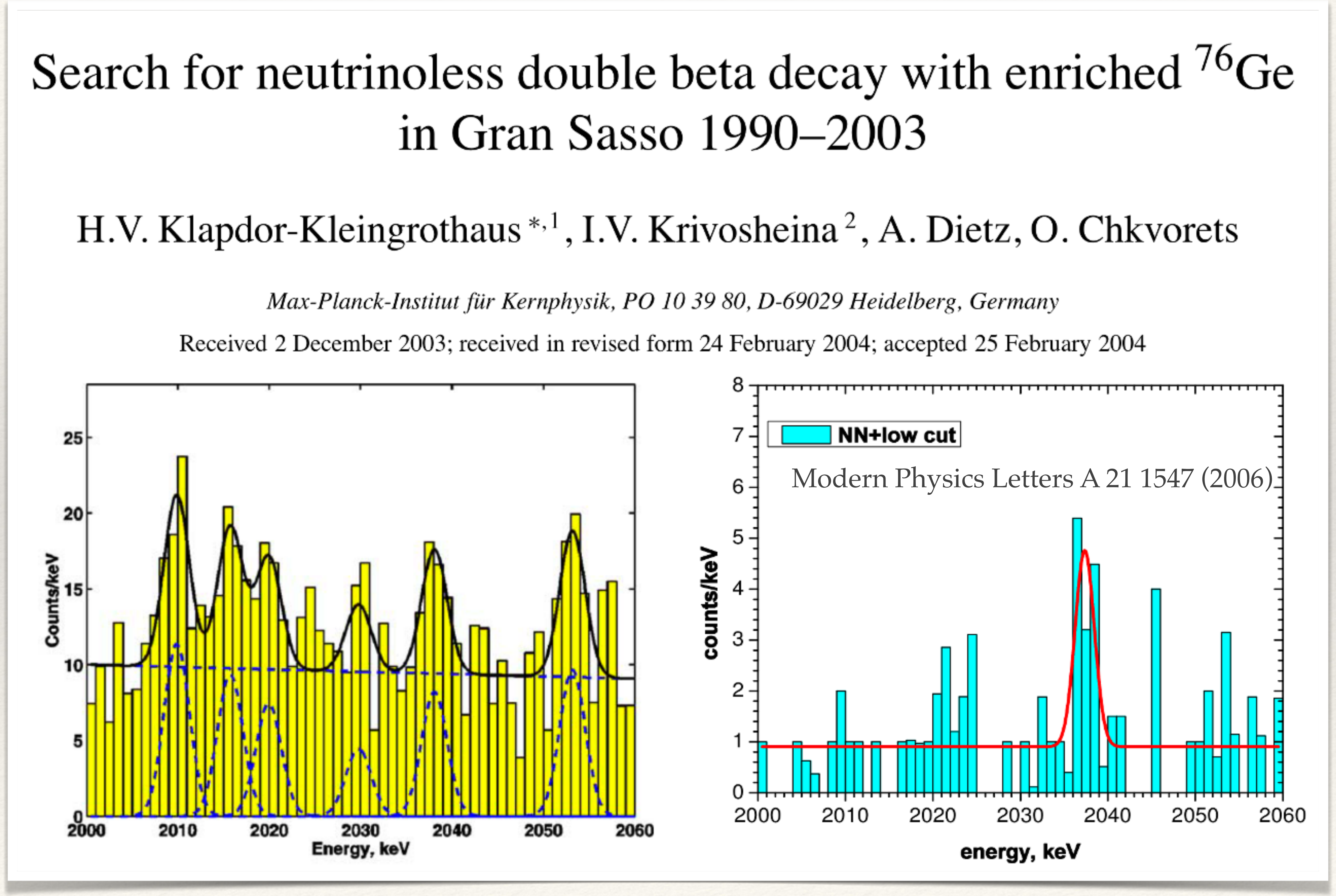


Received 10 December 1990; revised manuscript received 5 June 1991

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.

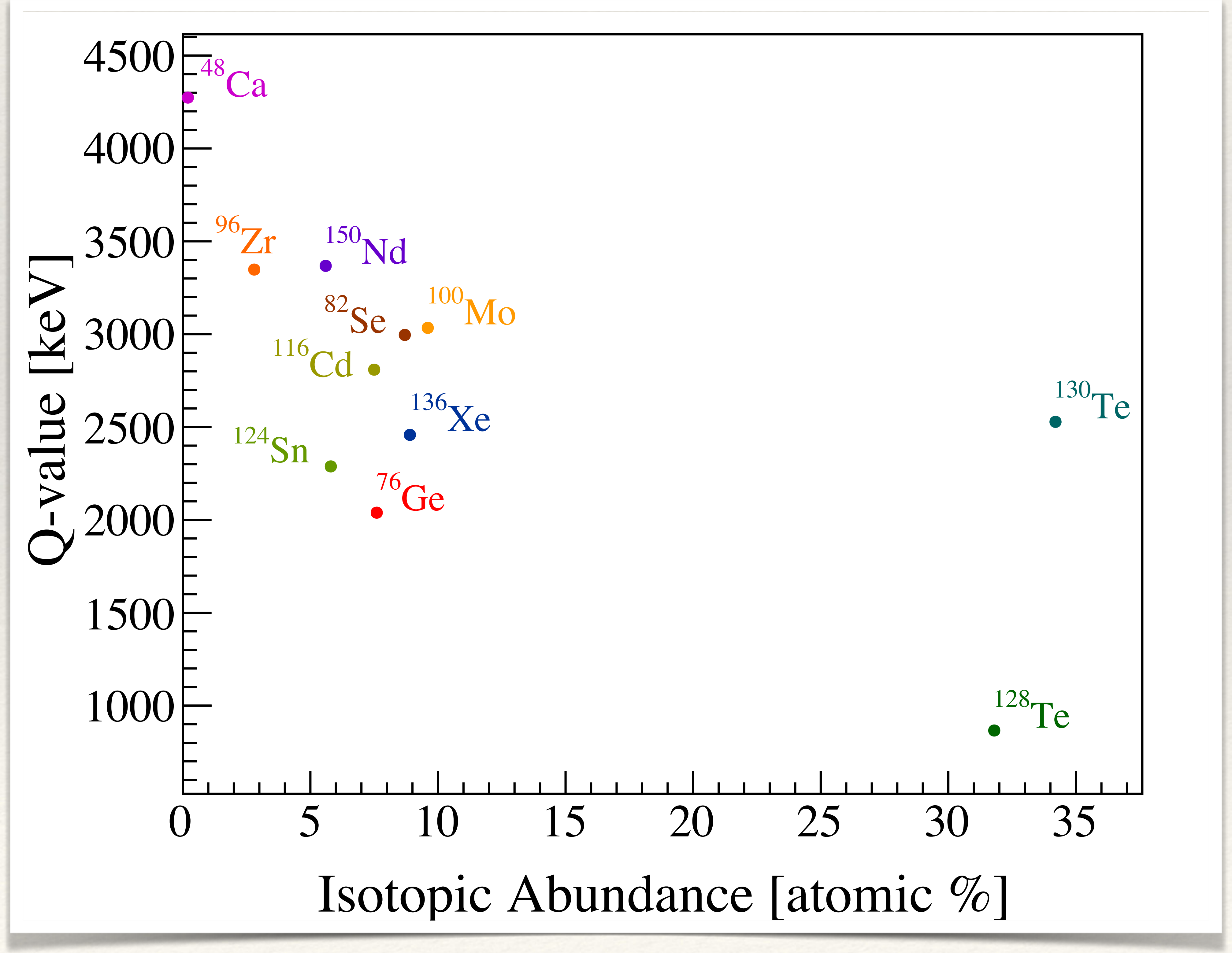
A false discovery claim in early 2000

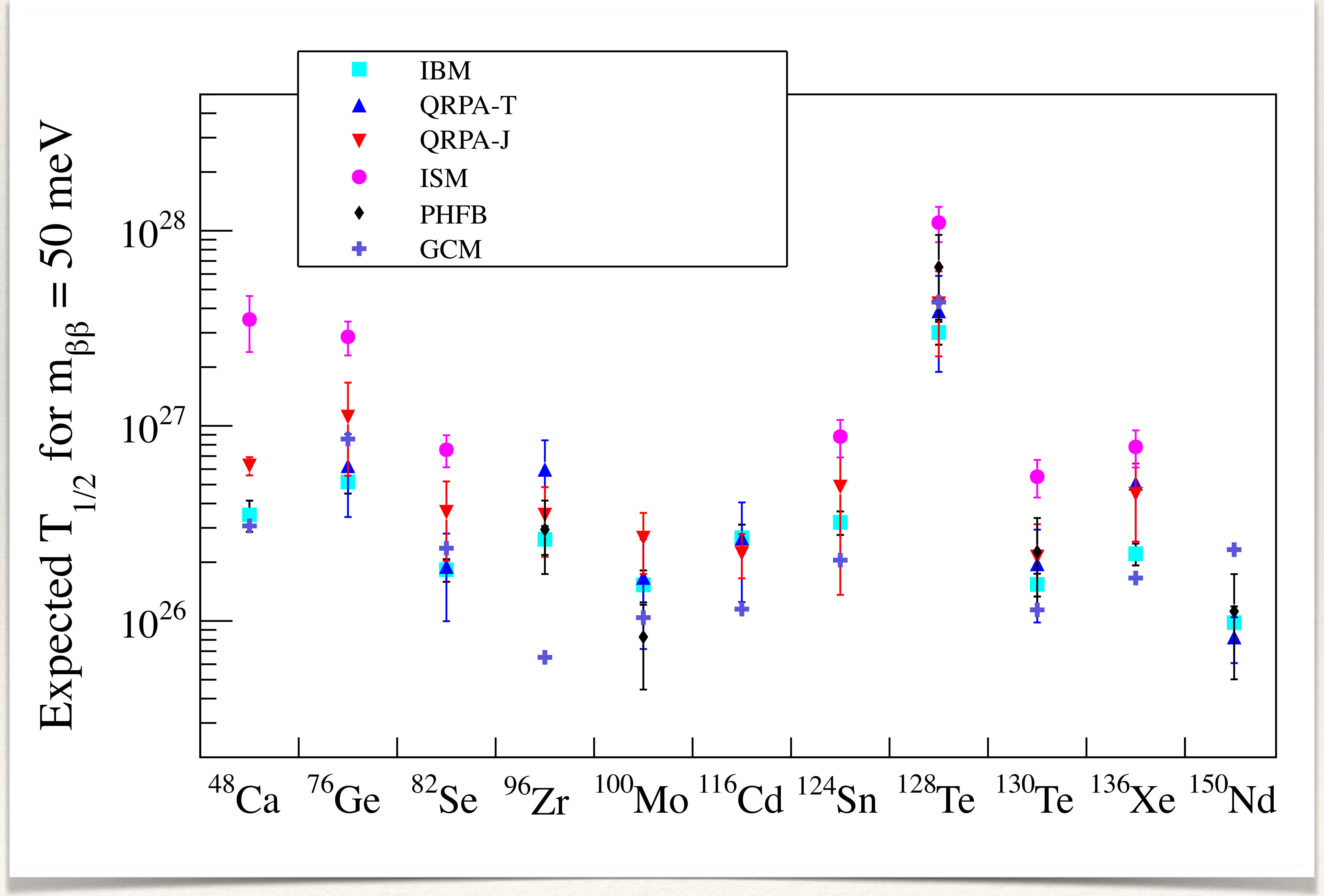
- Subset of Heidelberg-Moscow collaboration claims a signal from HM data
- Strong motivation for verification in early 2000
- Falsified by Gerda and other experiments subsequently
- Can we learn something?



No magic isotopes

- No isotopes with high Q, high natural isotopic abundance, and large NME
- Choice of isotope depends on detector technology (generally speaking)



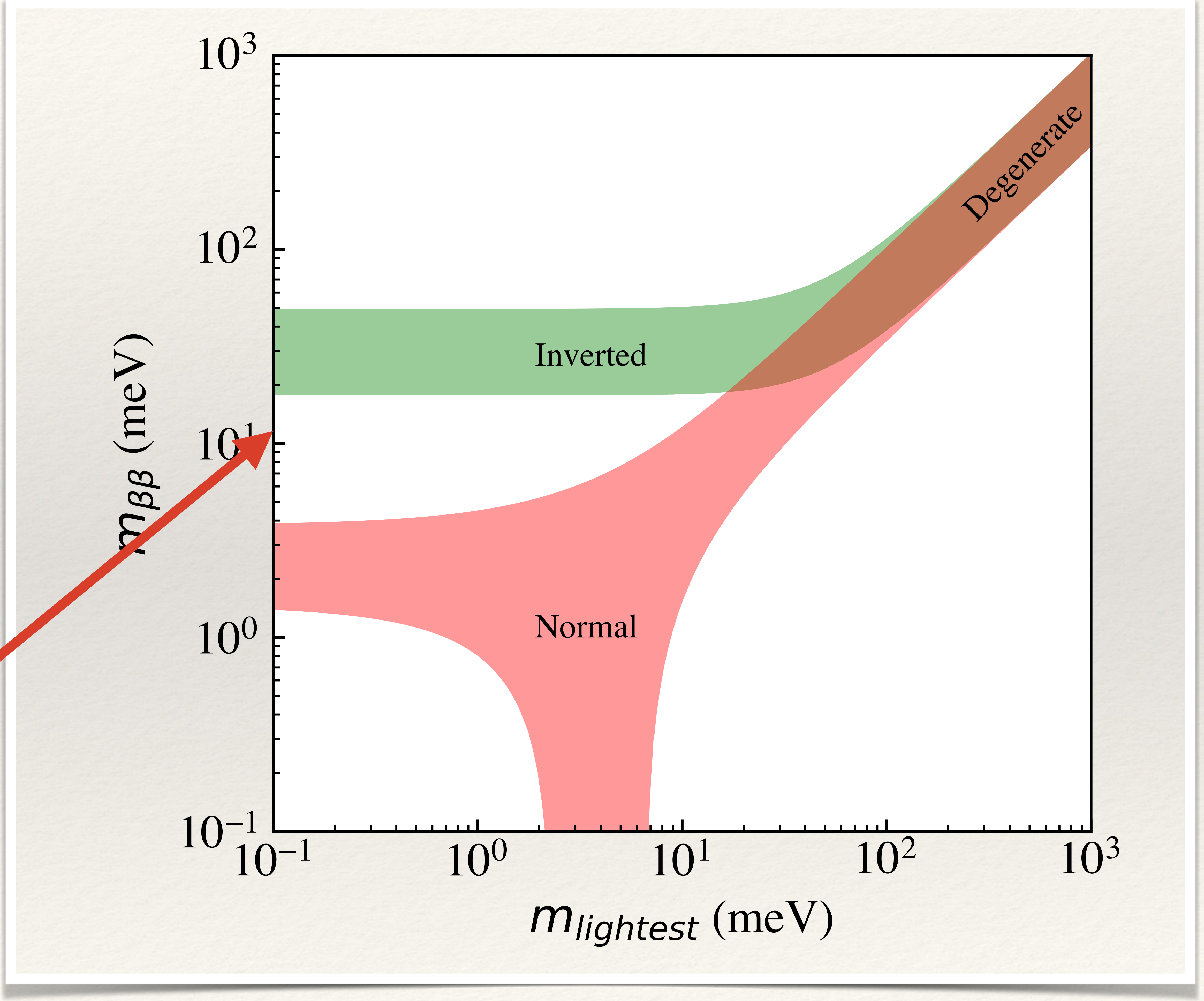


Small signals

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

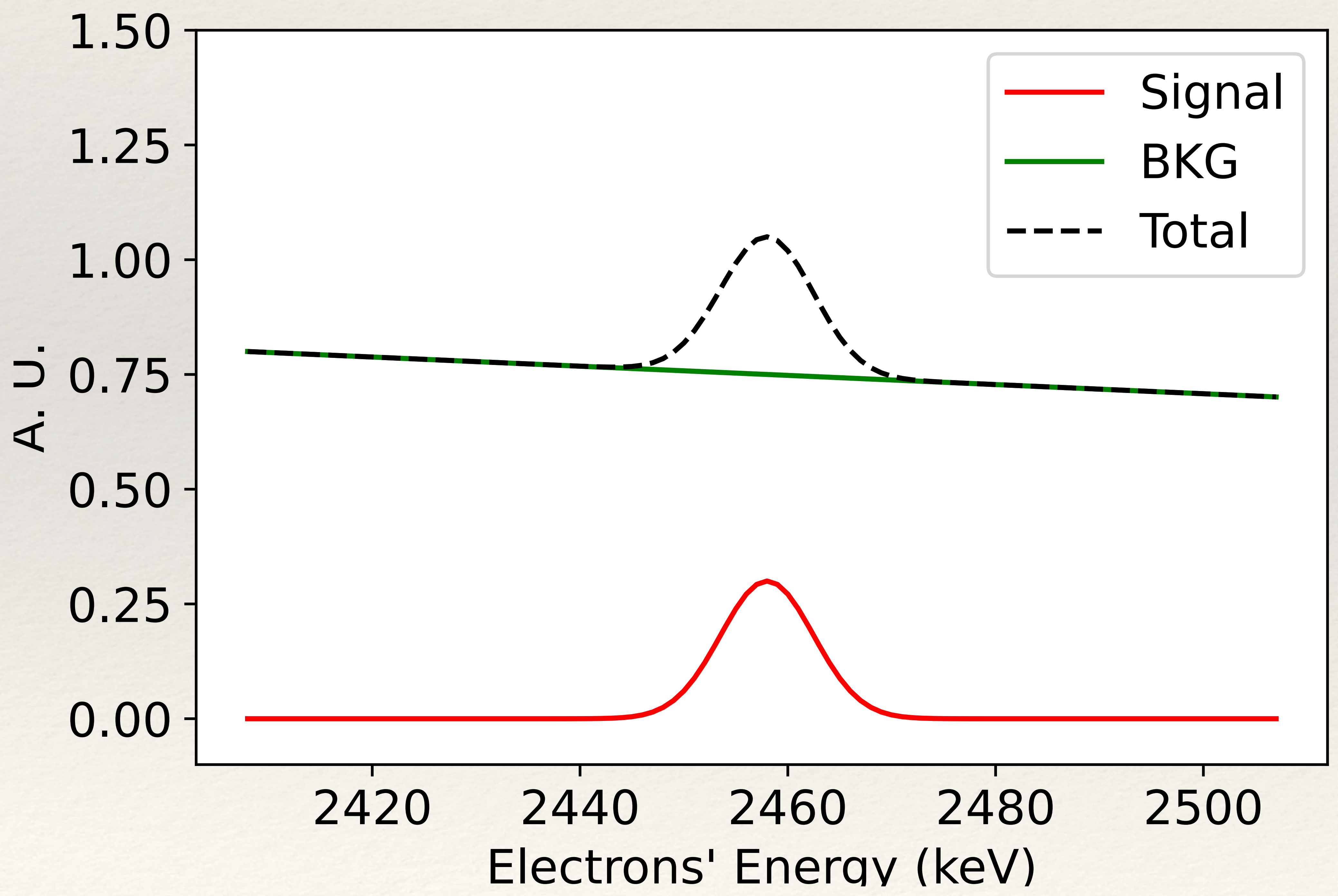
M	Mass	ε	Efficiency
N_A	6.02×10^{23}	W	Molar mass
a	Abundance	t	Detection time

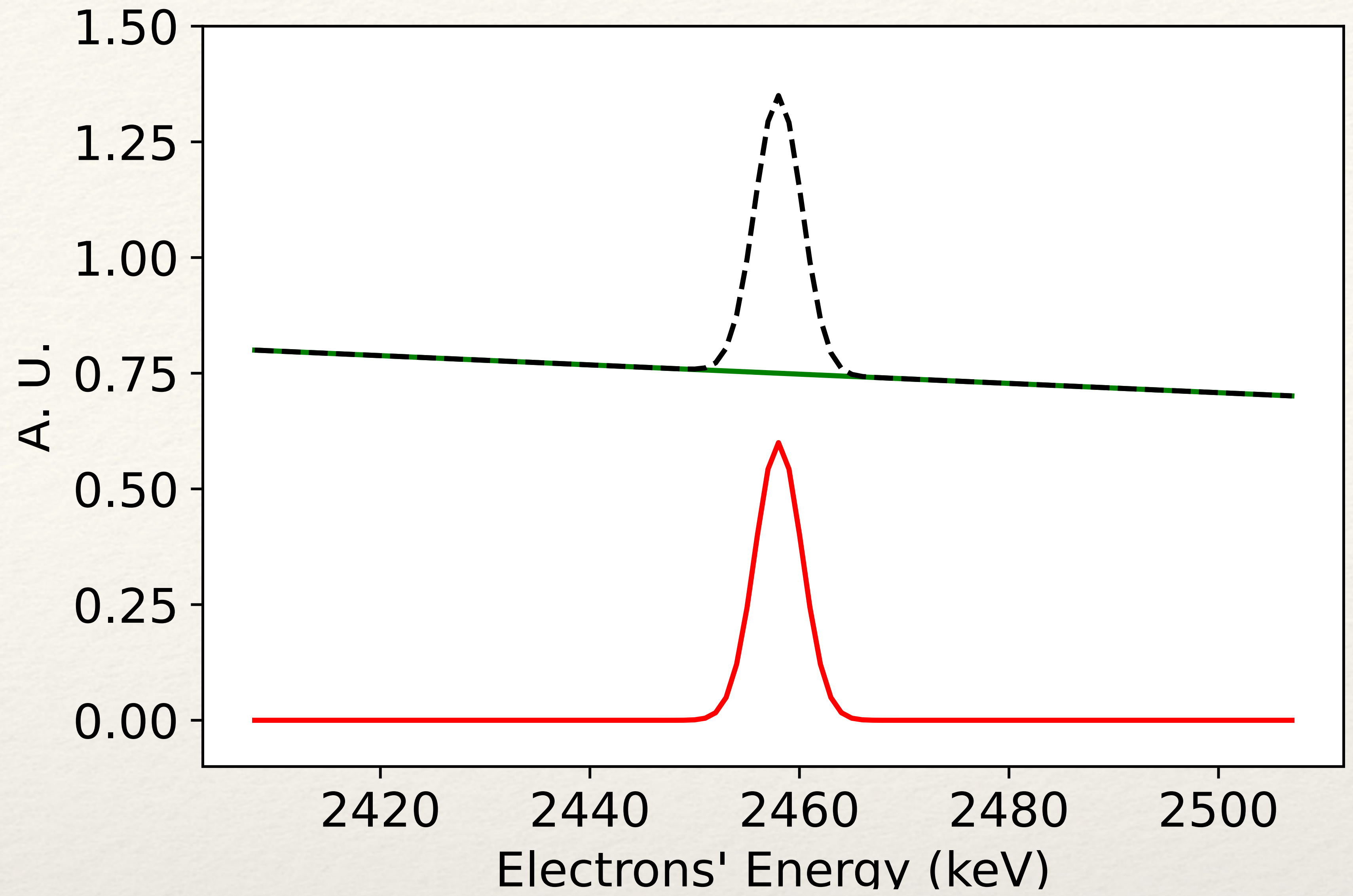
- Current half-life limits >10^{26} year
  - 100 kg 90% enriched ^{136}Xe: fewer than three signals per year
- Sensitivity of ton-scale experiments: 10^{27} to 10^{28} year
  - Fewer than 1 event/year

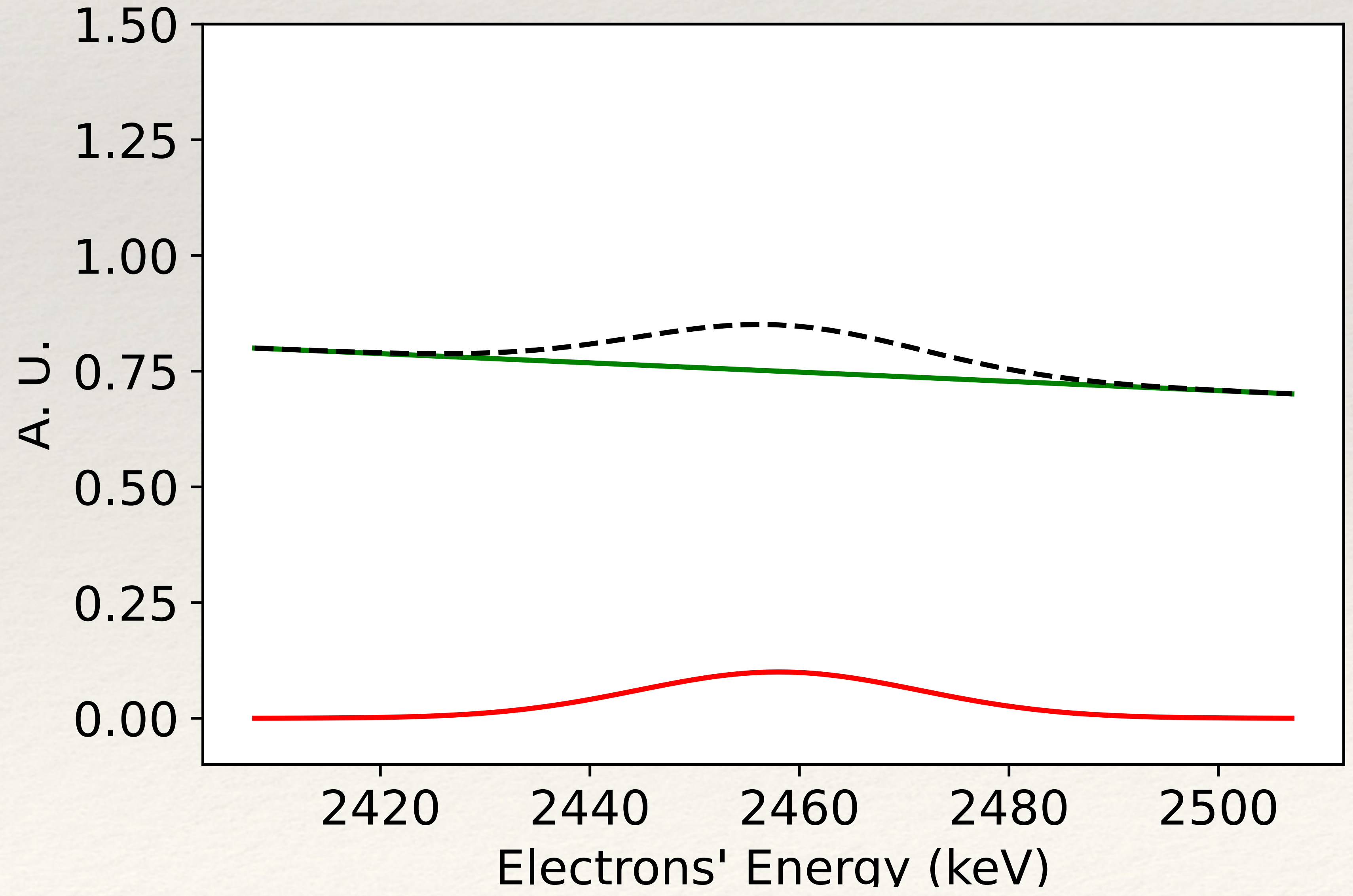


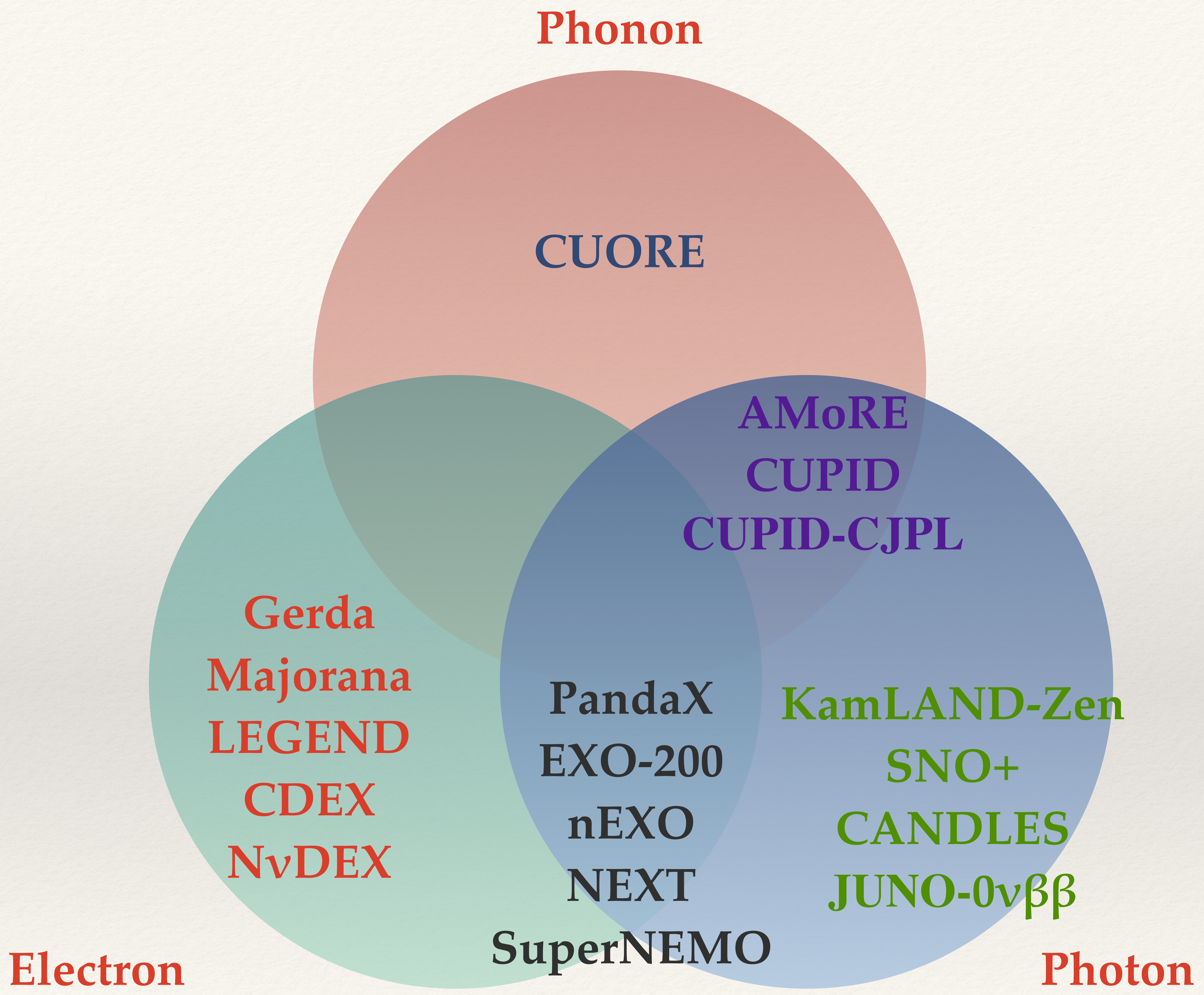
极致探测器技术挑战

- 极低本底
- 极高性能（效率、分辨率）

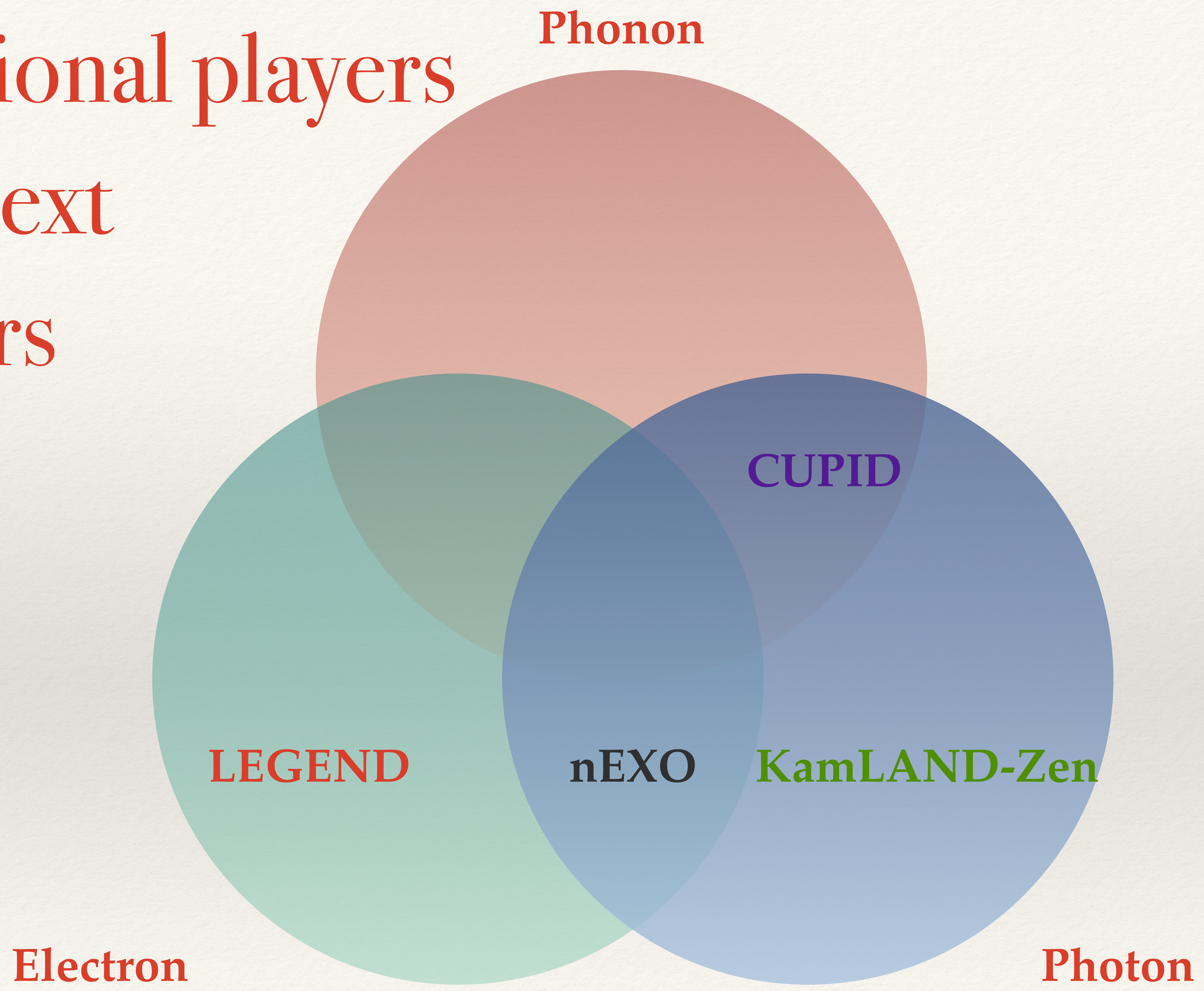




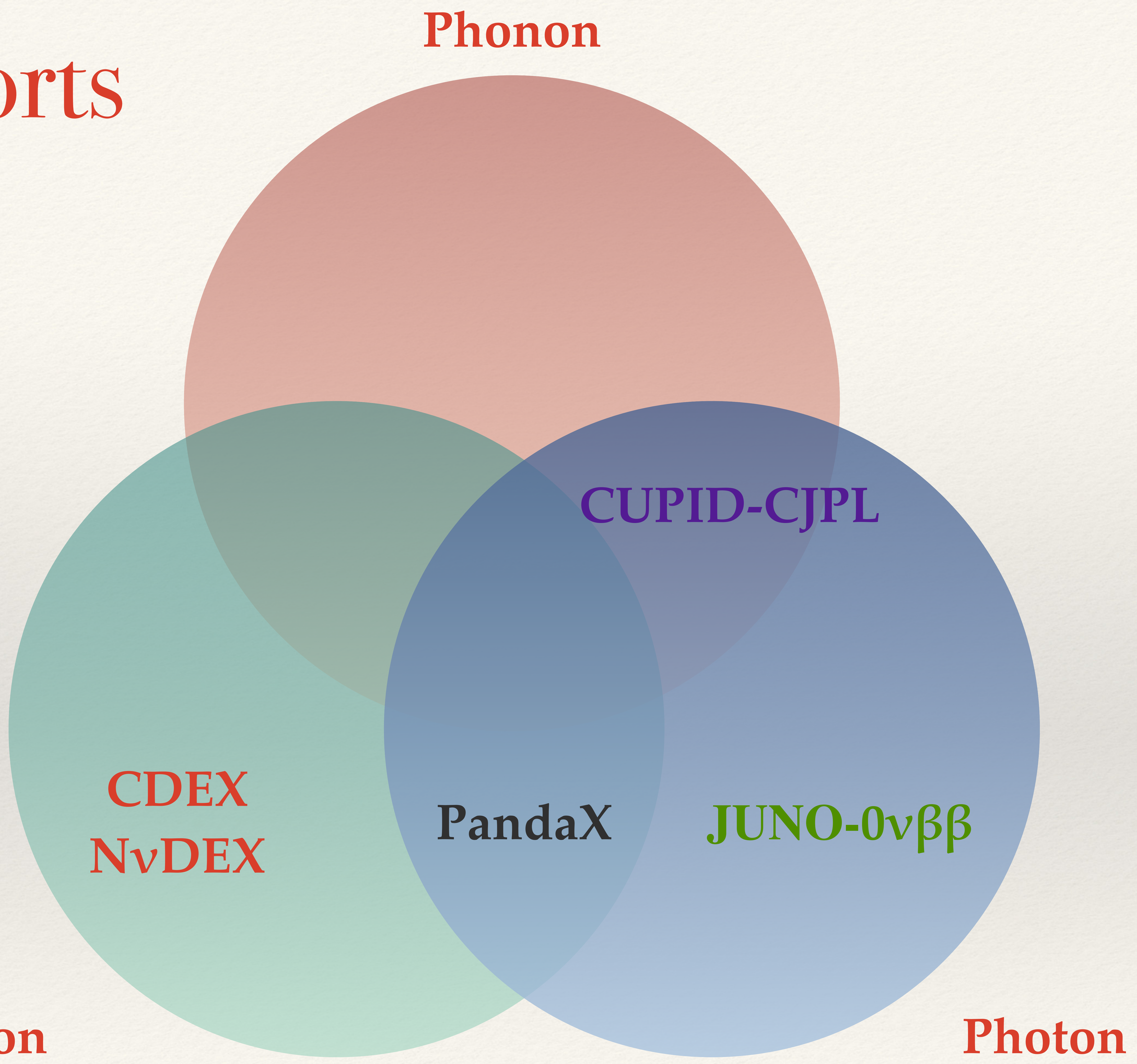



Phonon
CUORE
AMoRE
CUPID
CUPID-CJPL
Gerda
Majorana
LEGEND
CDEX
NνDEX
PandaX
EXO-200
nEXO
NEXT
SuperNEMO
KamLAND-Zen
SNO+
CANDLES
JUNO-0νββ
Electron
Photon

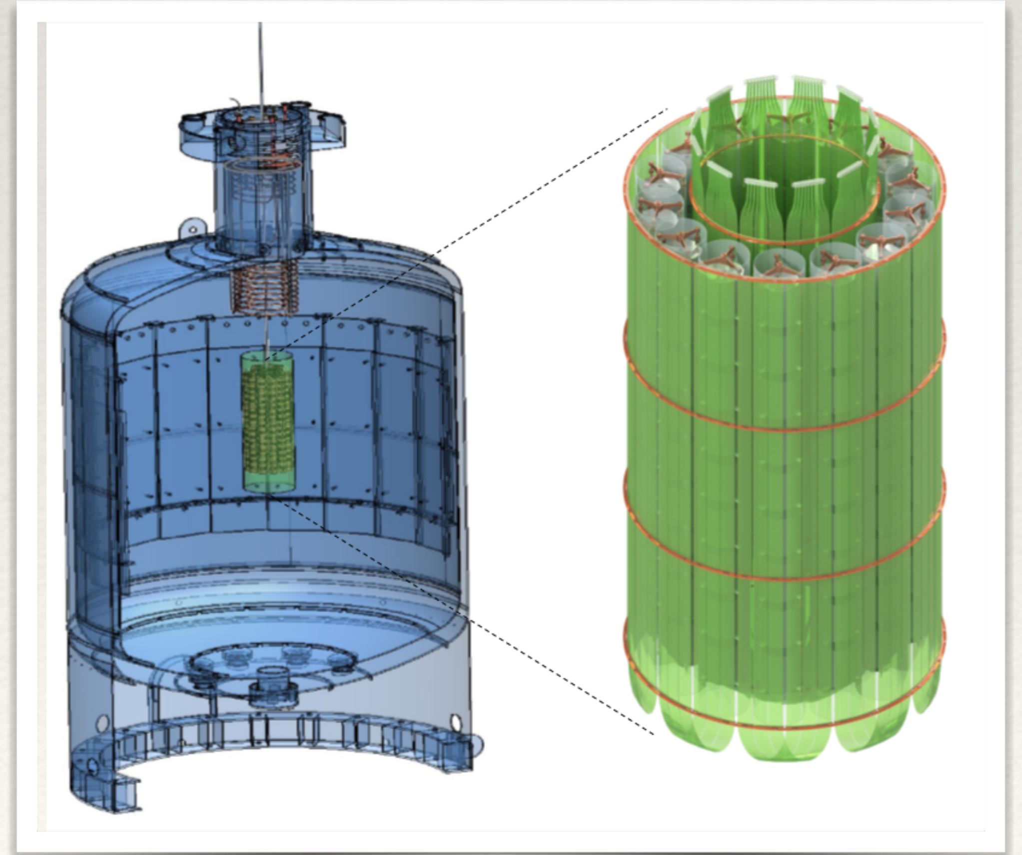
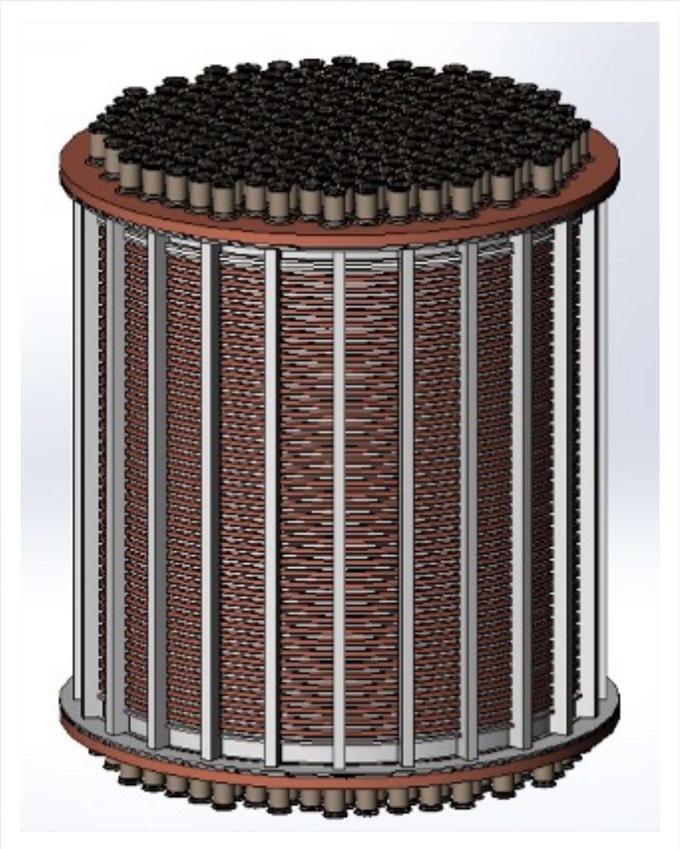
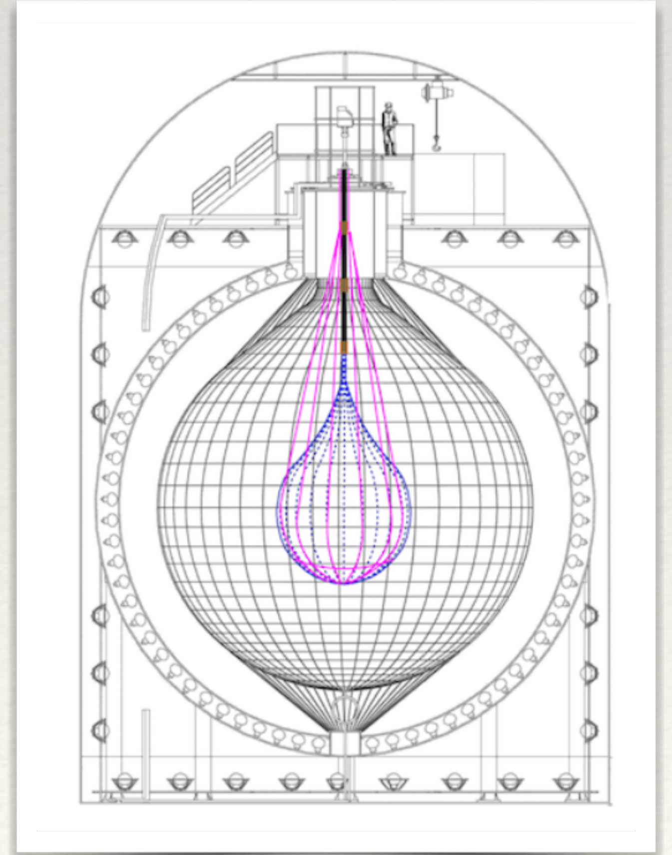
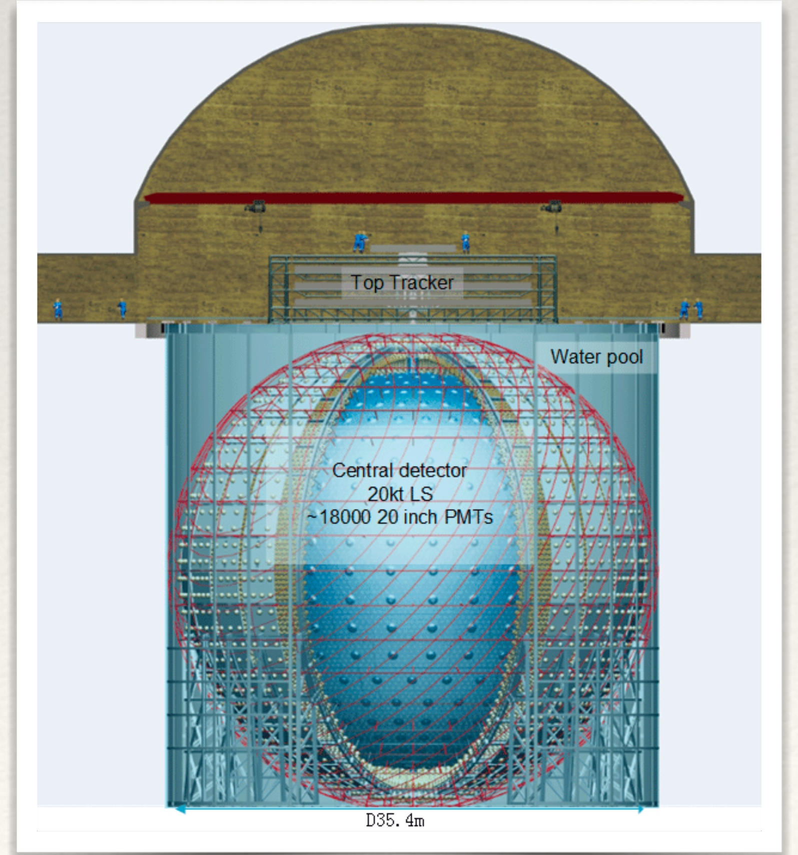
International players for the next 20+ years



Chinese efforts

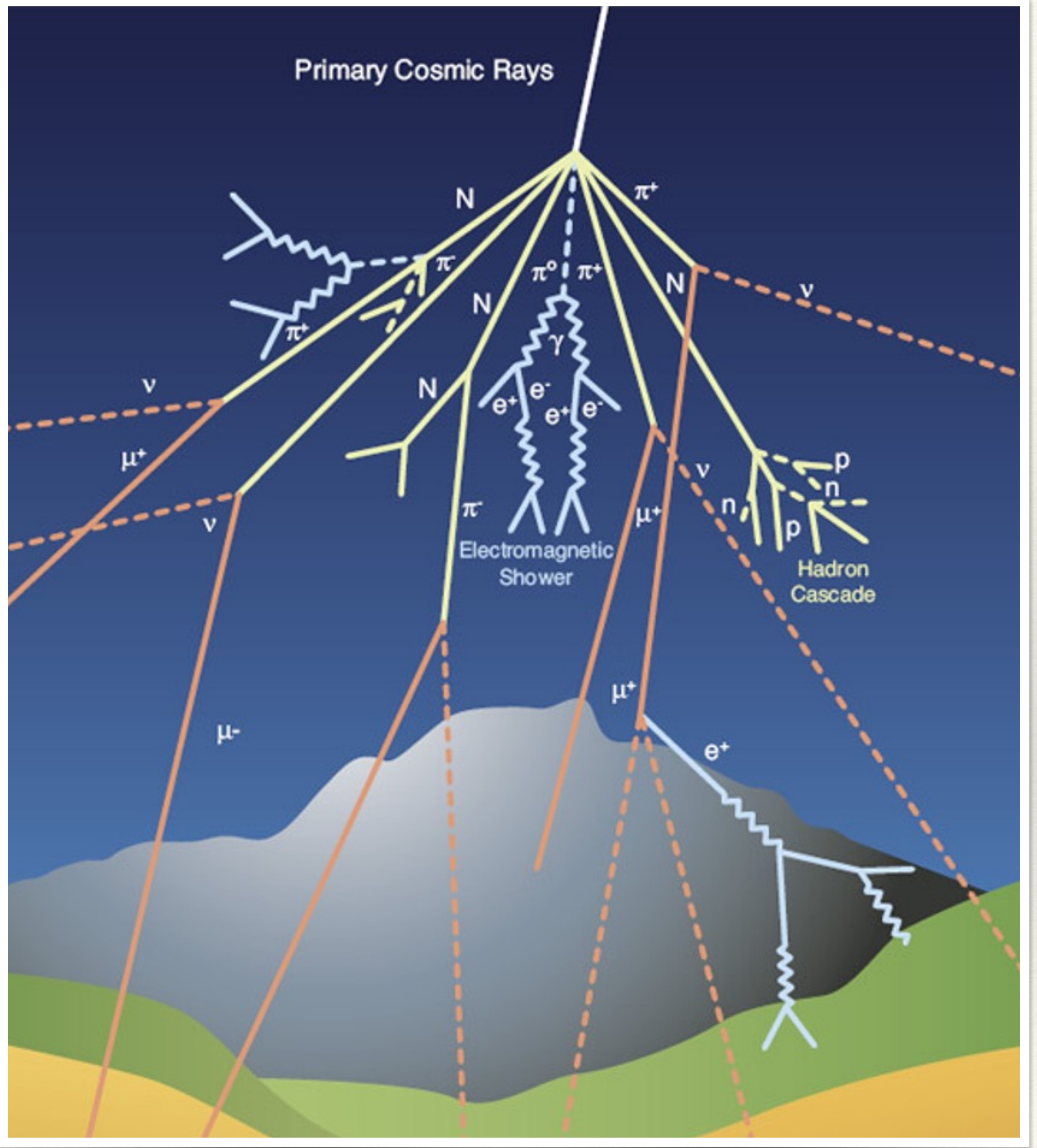


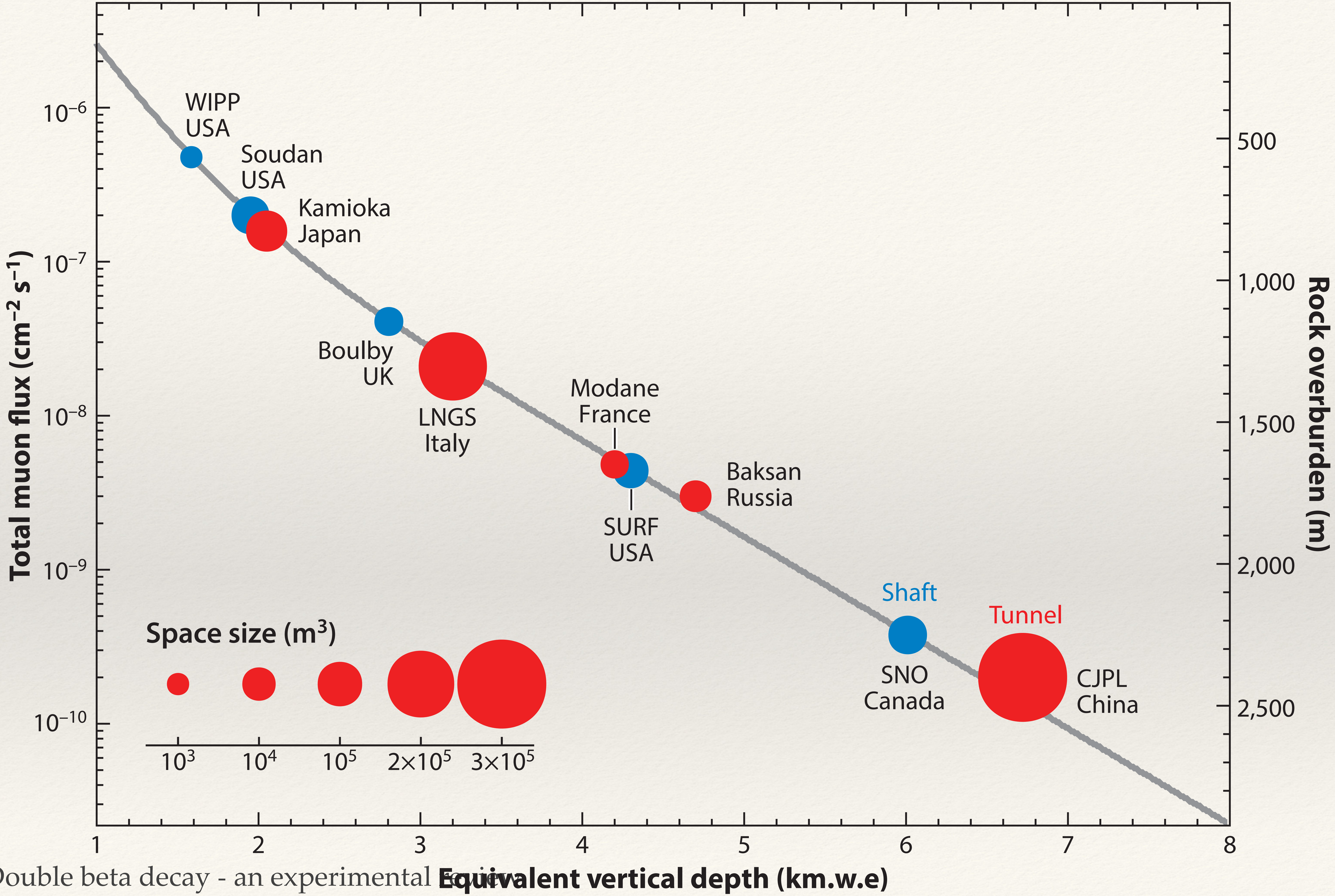
固体探测器阵列	气液探测器
CUPID	KamLAND-ZEN
LEGEND	nEXO
CDEX	PandaX
CUPID-CJPL	NνDEX
	JUNO-0νββ

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.





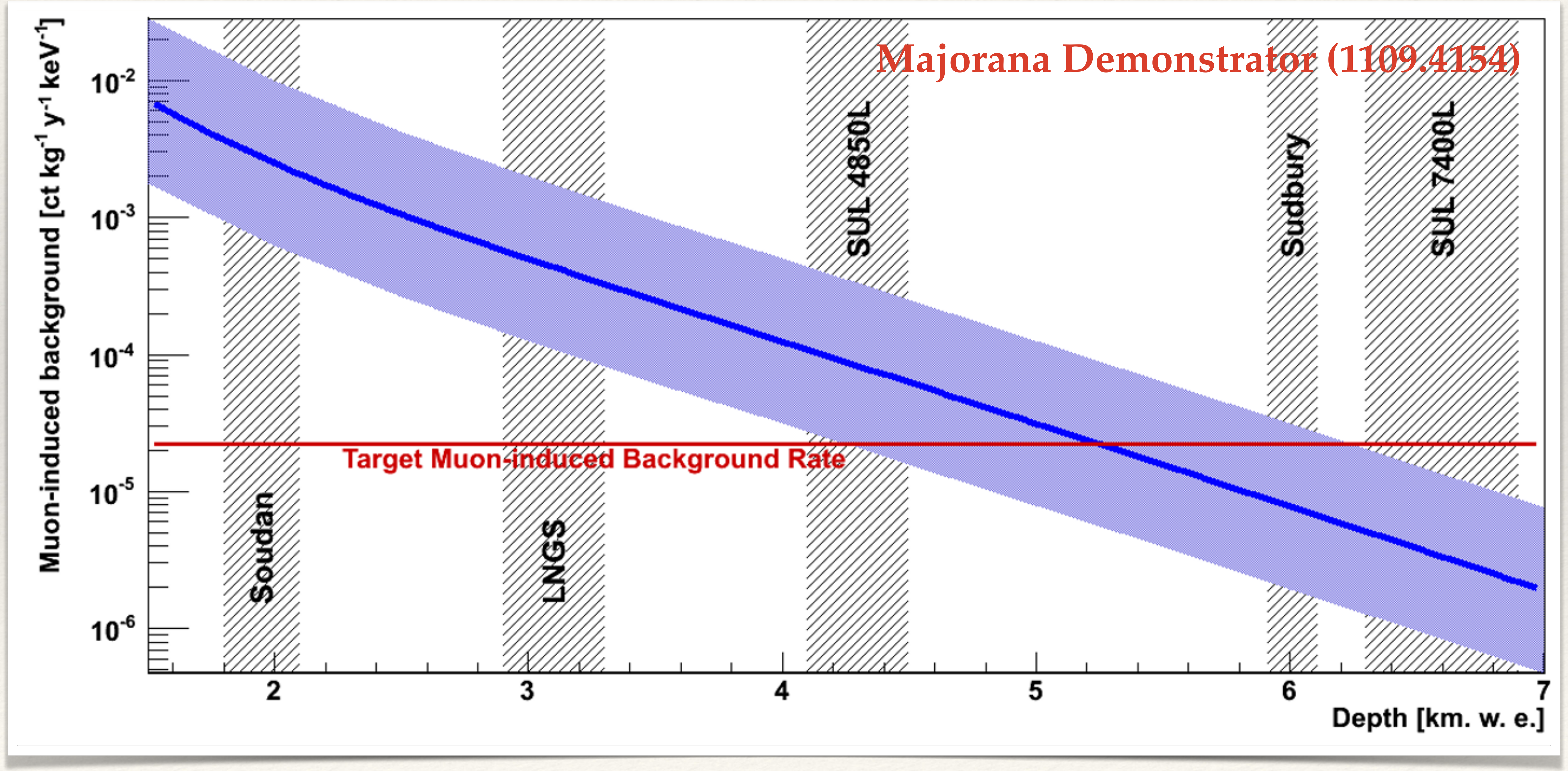
Total muon flux (cm^{-2} s^{-1})
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
Rock overburden (m)
500
1,000
1,500
2,000
2,500
WIPP USA
Soudan USA
Kamioka Japan
Boulby UK
LNGS Italy
Modane France
SURF USA
Baksan Russia
Shaft
Tunnel
SNO Canada
CJPL China
Space size (m^3)
10^3
10^4
10^5
2×10^5
3×10^5
1
2
3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


Canfranc
Modane
LNGS
CJPL
Y2L
Kamioka
SURF
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

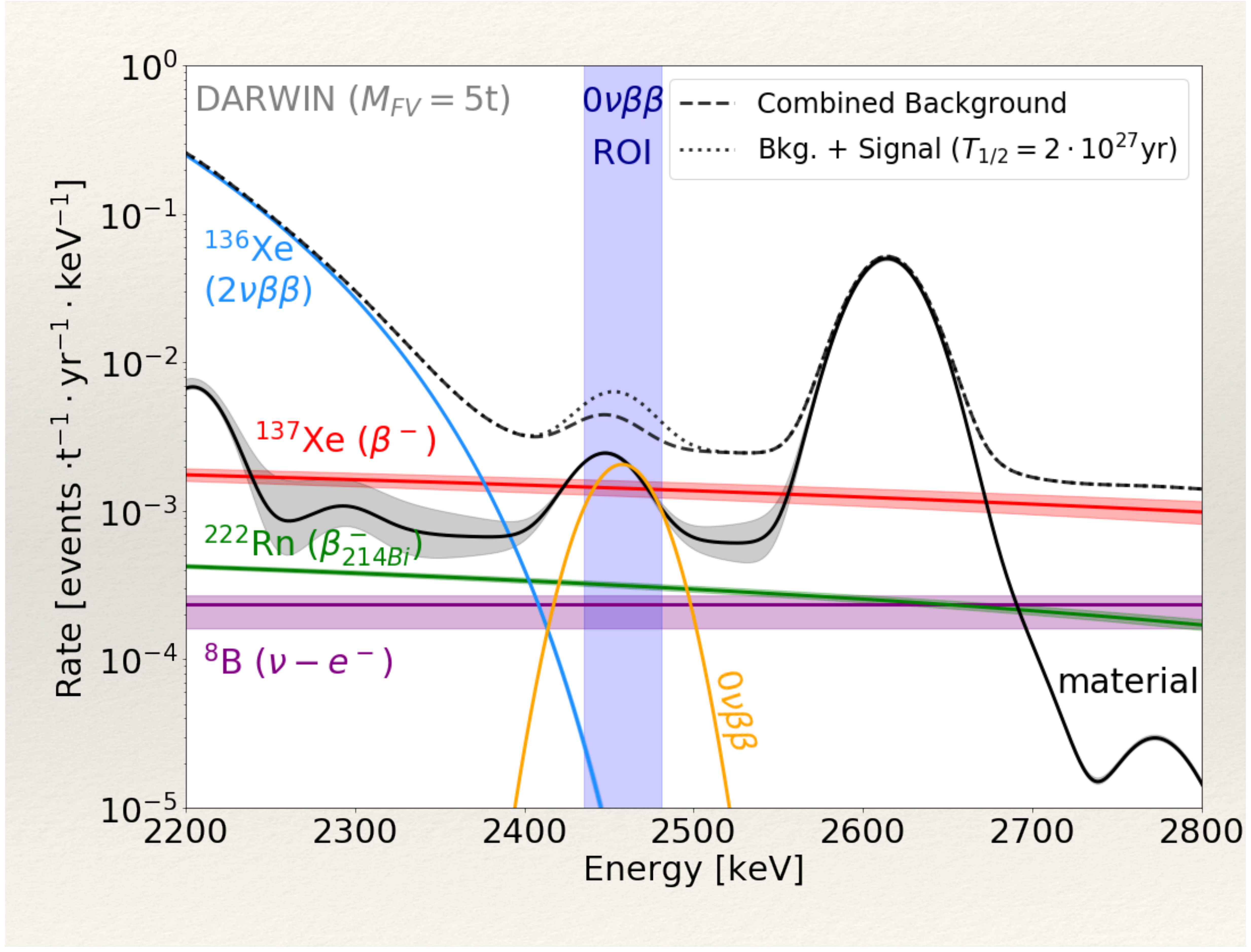
Mitigate muon-induced background

- Deeper lab or more powerful active veto



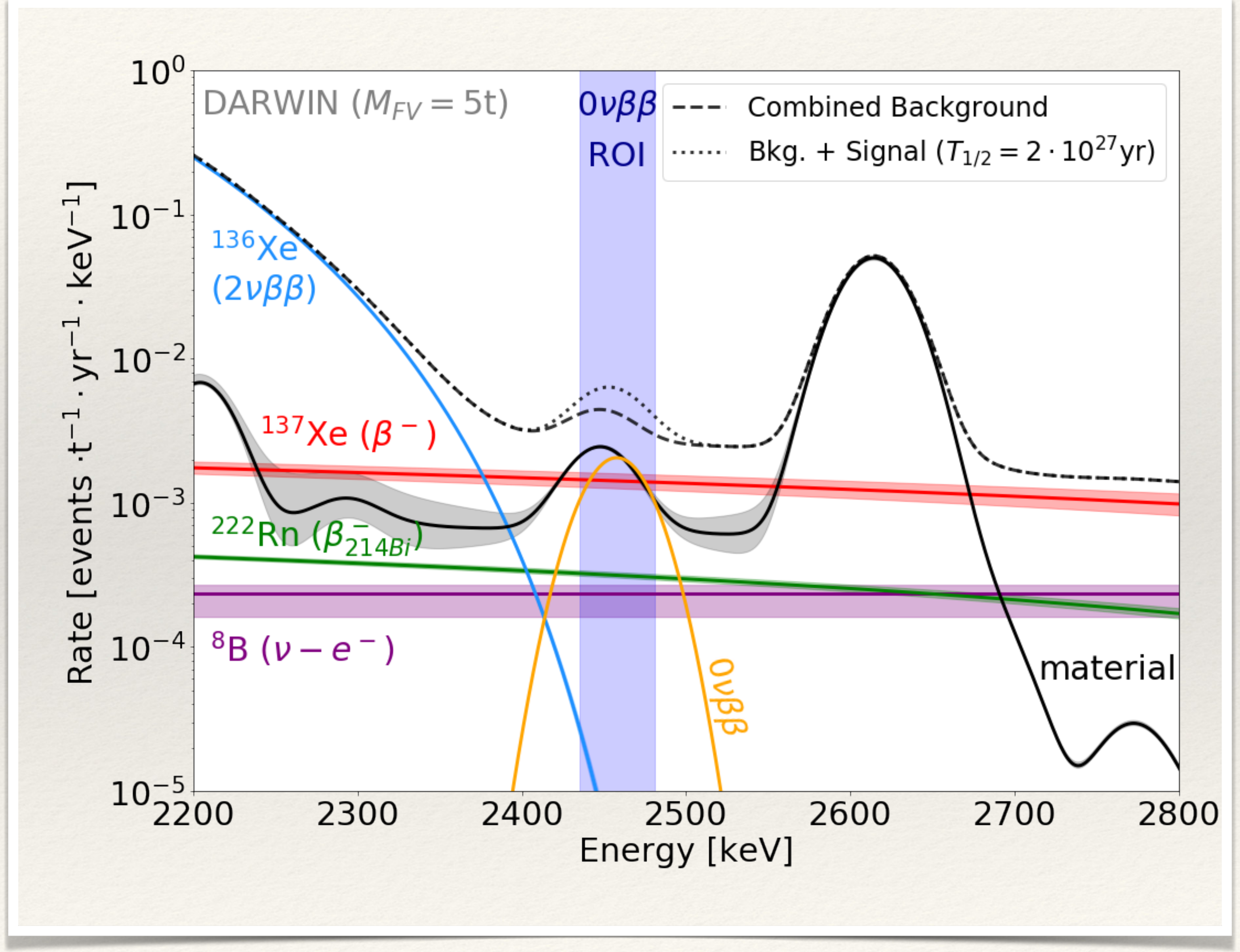
Mitigate muon-induced background

- Muon activated ^{136}Xe to ^{137}Xe, which is the main background in the ROI for 0νββ searches with DARWIN@LNGS
- Can not be vetoed in a large liquid xenon detector
- This background is 100 times smaller at CJPL



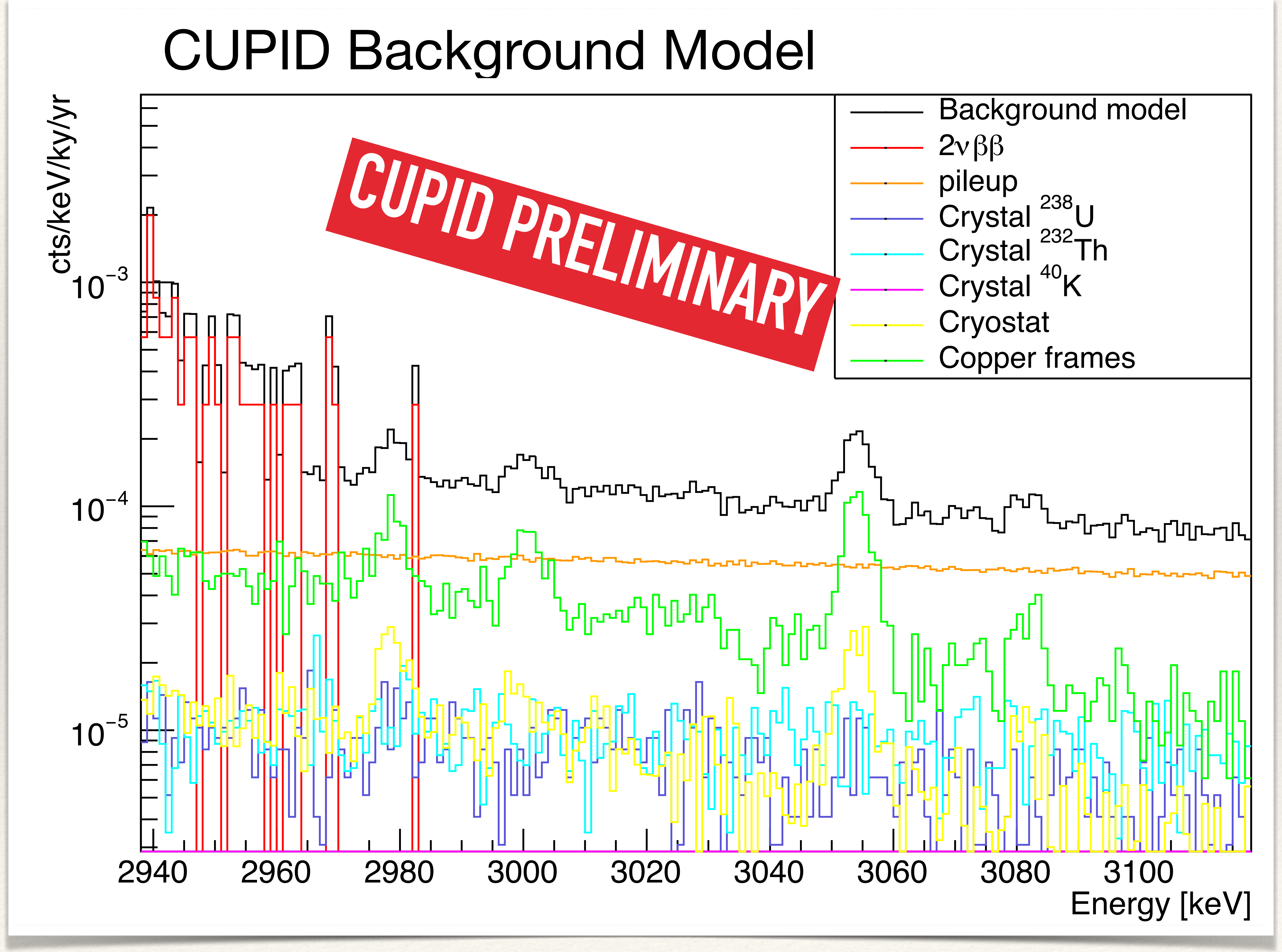
Intrinsic 2νββ background

- 2νββ may be a problem if the half-life is short and energy resolution is VERY bad



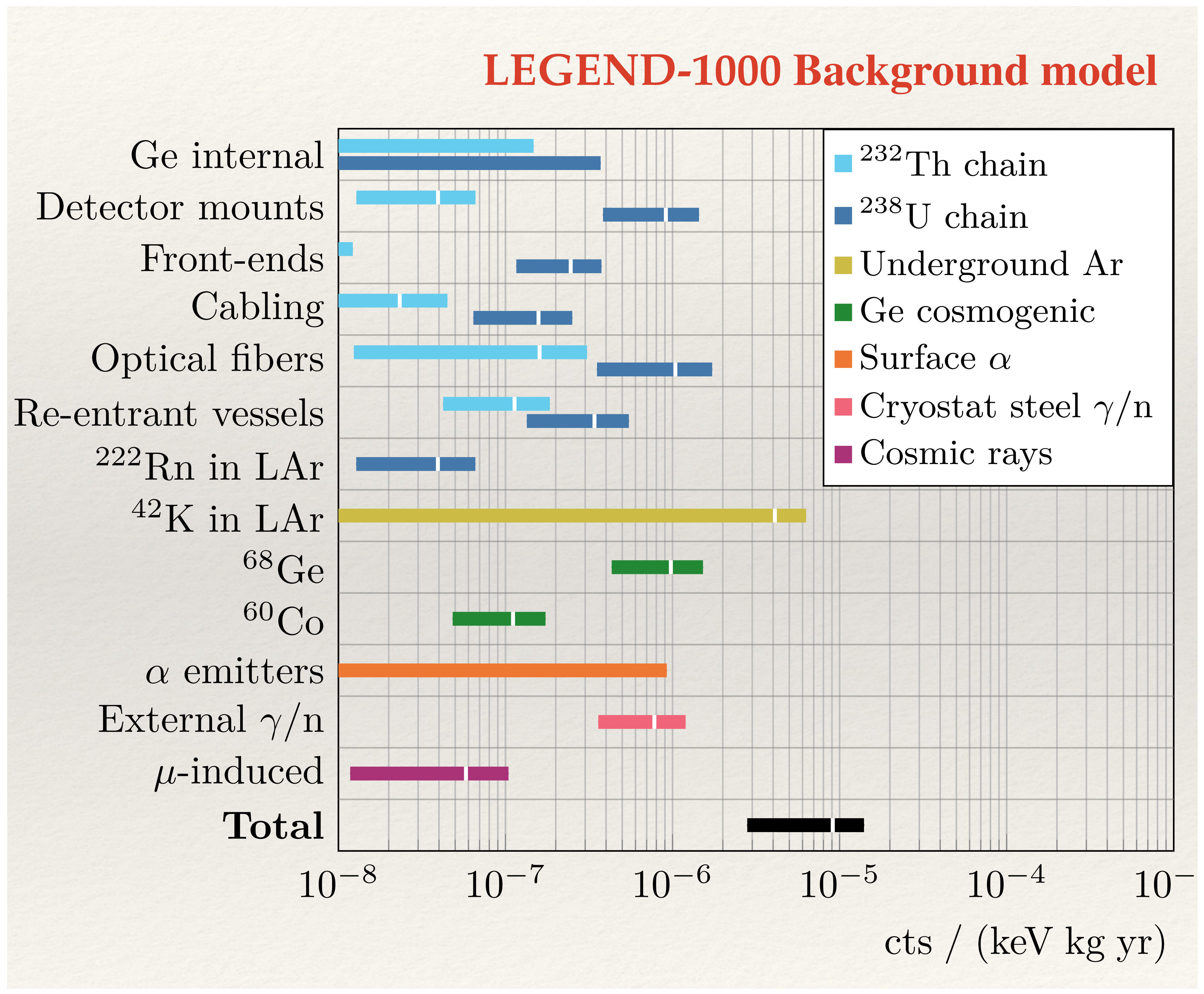
Intrinsic 2νββ background

- 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

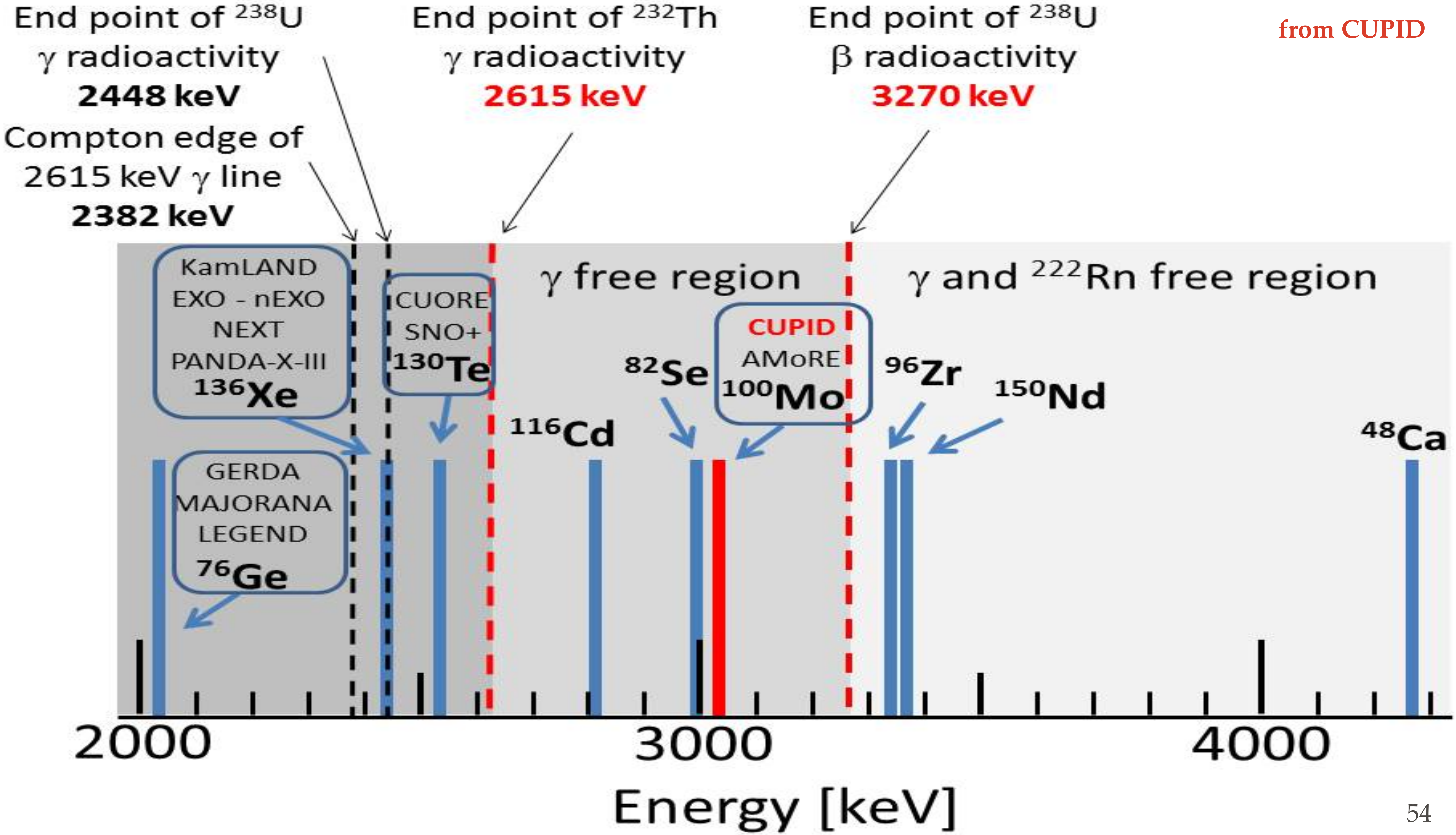


Background from detector material/shielding

- 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



from CUPID


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

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, Dupon	
72	FEP, Dupon	

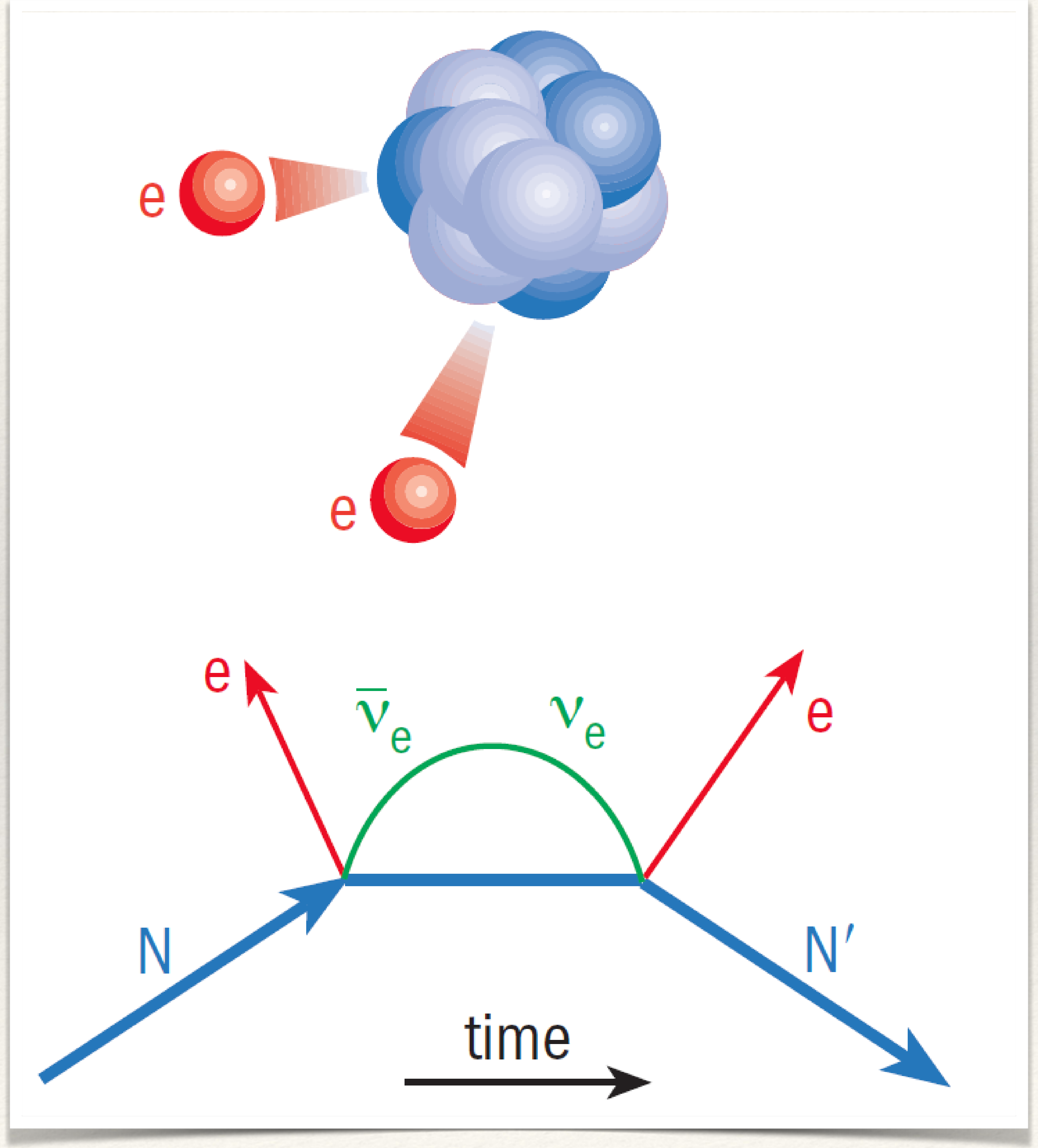
#	Material	Method
73	Picocoax®,	
74	Picocoax®,	
75	Cu wire, bar	
76	Cu wire, bar	
77	Mini Coax ca	
78	Mini Coax ca	
79	Parylene coa	
80	Picocoax®,	
81	Picocoax®,	
82	Picocoax®,	
83	Picocoax®,	
84	Picocoax®,	
85	Axon’ HV ca	
86	Axon’ HV (f	
87	Axon’ Signal	
	Connectors	
88	Silver epoxy	
89	Silver epoxy	
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	
109	Pins without	
110	Pins with Be	
111	Vespel®, in-	
112	Vespel®, in-	
113	Vespel®, in-	
114	Sapphire C-	
115	JFET dies,	
116	Full LMFE	
117	Full LMFE	
	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

总结与思考

- 什么是无双实验；为什么要做无双实验？
    - 有效中微子质量计算
- 无双实验的挑战：信号大小与本底来源
    - 如何测量材料放射性？



无双实验题目

习题1：双中微子双贝塔衰变（DBD）目标核素众多，但是发现DBD的核素仅有10种左右，热门核素仅仅有数个。调研3个尚未实验确认DBD的目标核素，给出实验观测的实际困难，提出相应的可能解决方案。

习题2：无中微子双贝塔衰变实验的技术核心是测量MeV能量电子。除了课堂讲授的常见测量手段，思考一种新颖的电子测量方法，论证其可能的优点和挑战。

Thank You

All plots are from corresponding collaborations