# Searches for Neutrinoless Double-Beta Decay

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Nuclear Science Division

# Outline

- Physics motivation - $0\nu\beta\beta$ decay
- Current and future experiments
- Summary

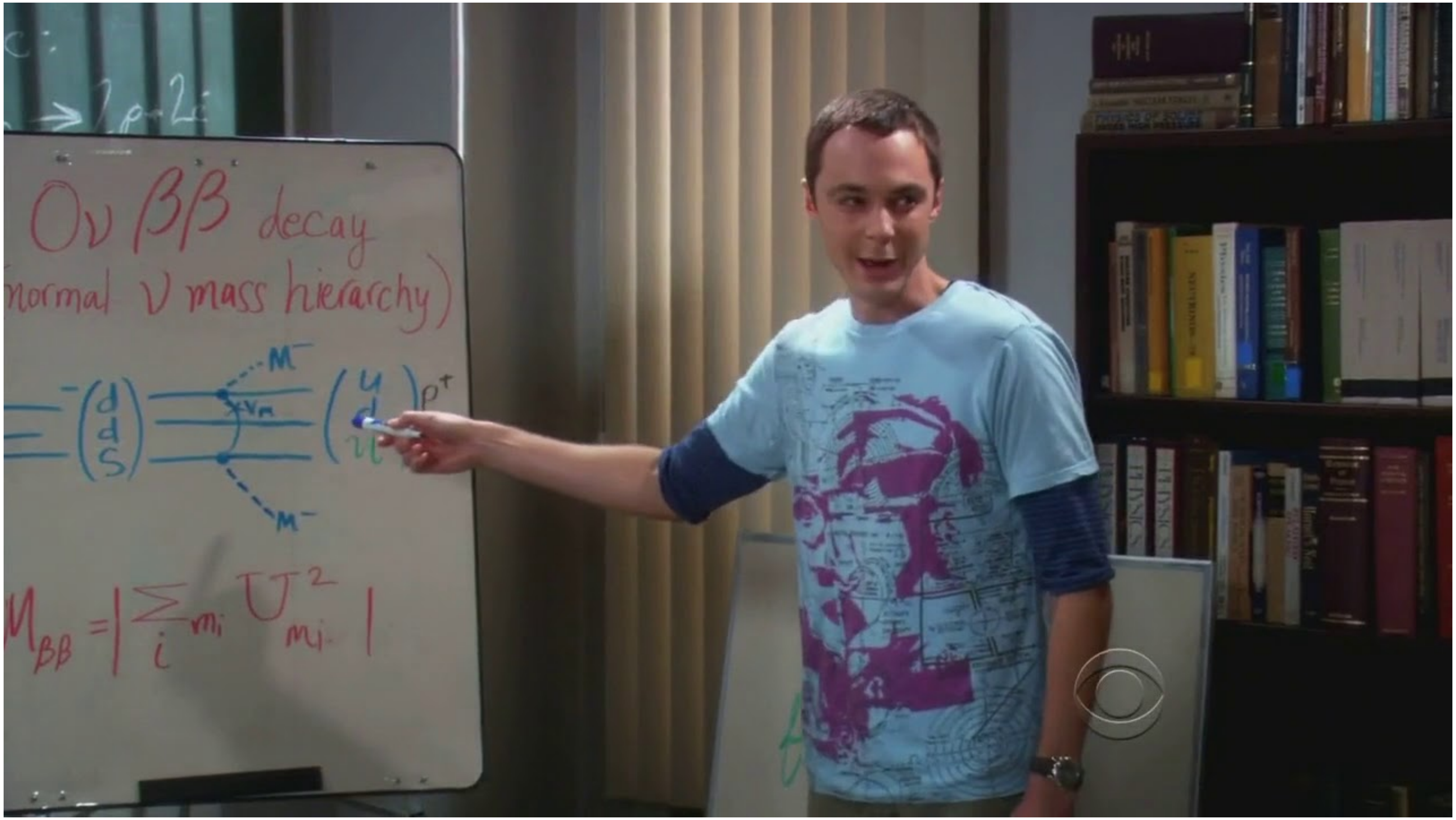
# The Big Bang Theory - CMB meets Neutrinos

Nobel Laureate George Smoot (Berkeley & IAS HKUST)

Nobel Laureate Art McDonald (Queen's)

When it is on
the Big Bang Theory,
it is important science.

# 0νββ decay

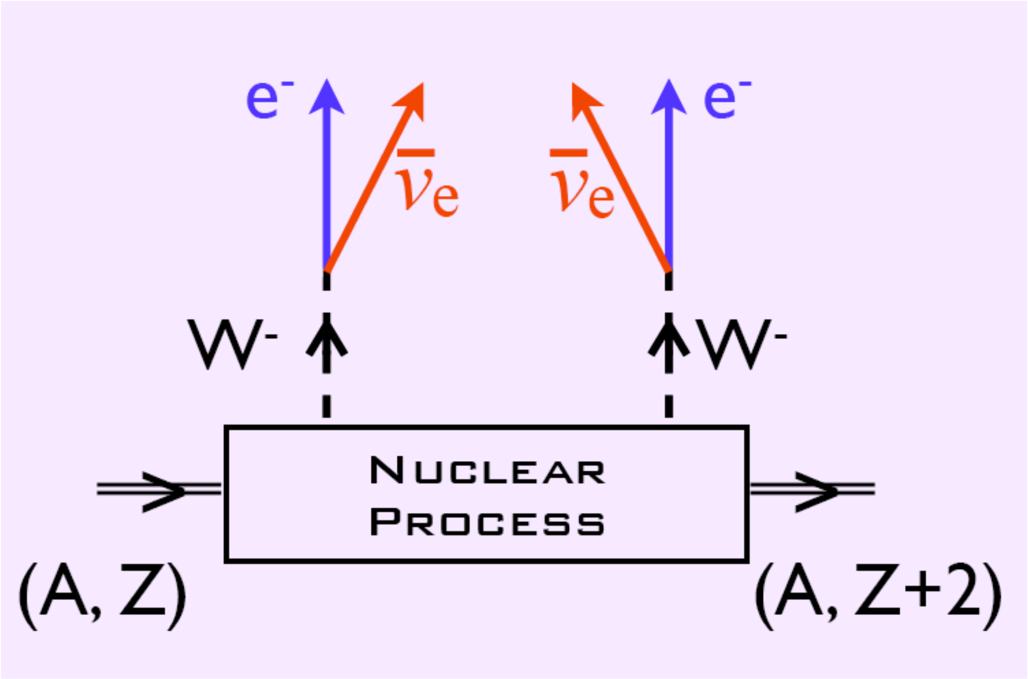


**What is 0νββ decay?**

# Double-Beta (ββ) Decay

## Two-neutrino mode

$$(A, Z) \rightarrow (A, Z+2) + 2\,e^{-} + 2\,\bar{\nu}_e + Q_{\beta\beta}$$



- Standard Model process
- Directly observed

R. Saakyan, Ann. Rev. Nucl. Part. Sci. 2013)

$$T_{1/2}^{2\nu} \sim 10^{18-24}\ \mathrm{y}$$

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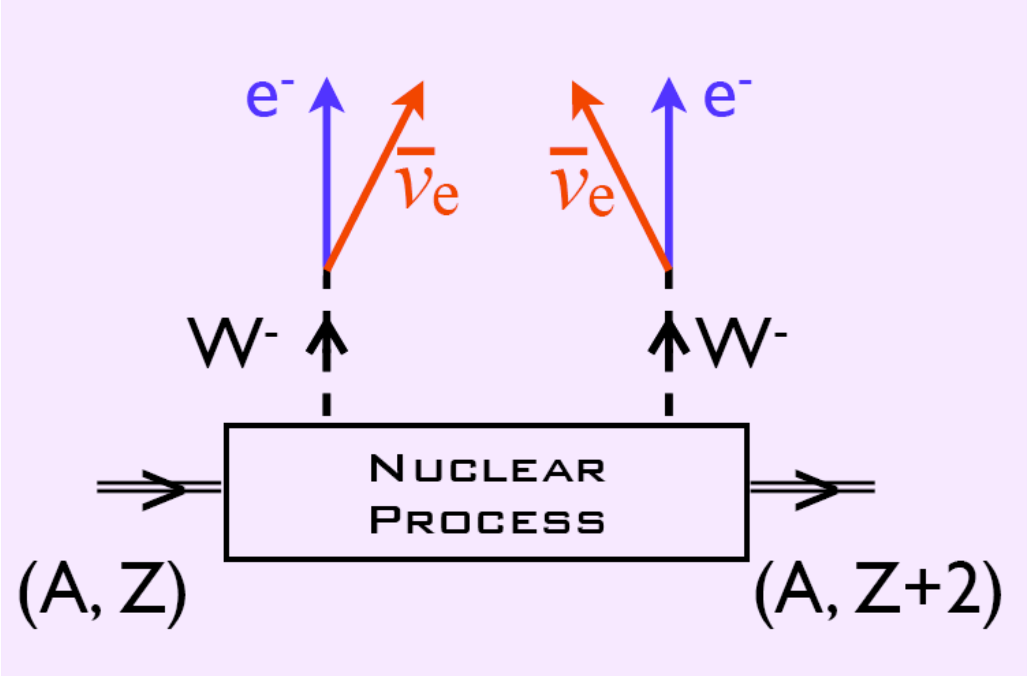

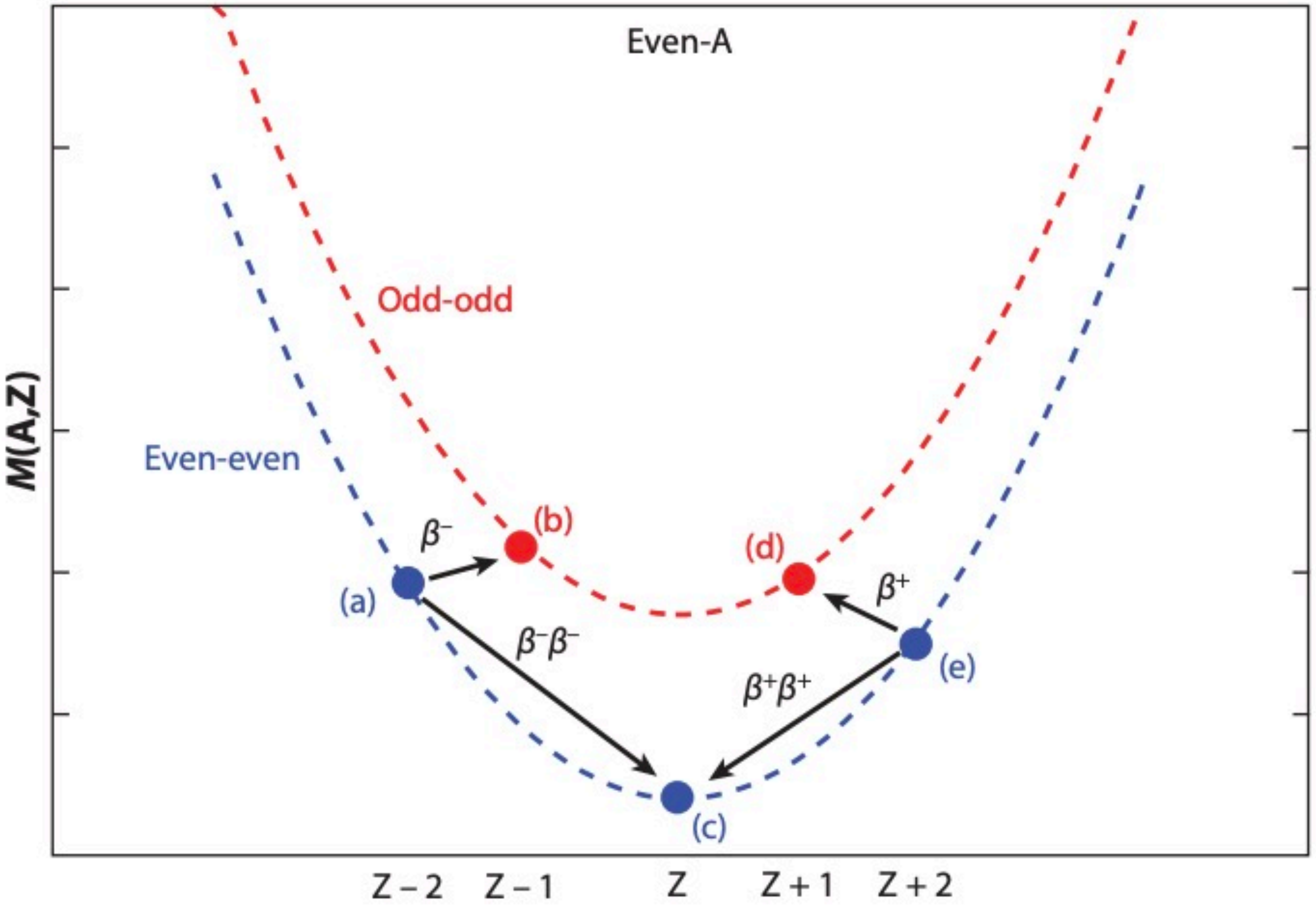

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R. Saakyan, Ann. Rev. Nucl. Part. Sci. 2013)

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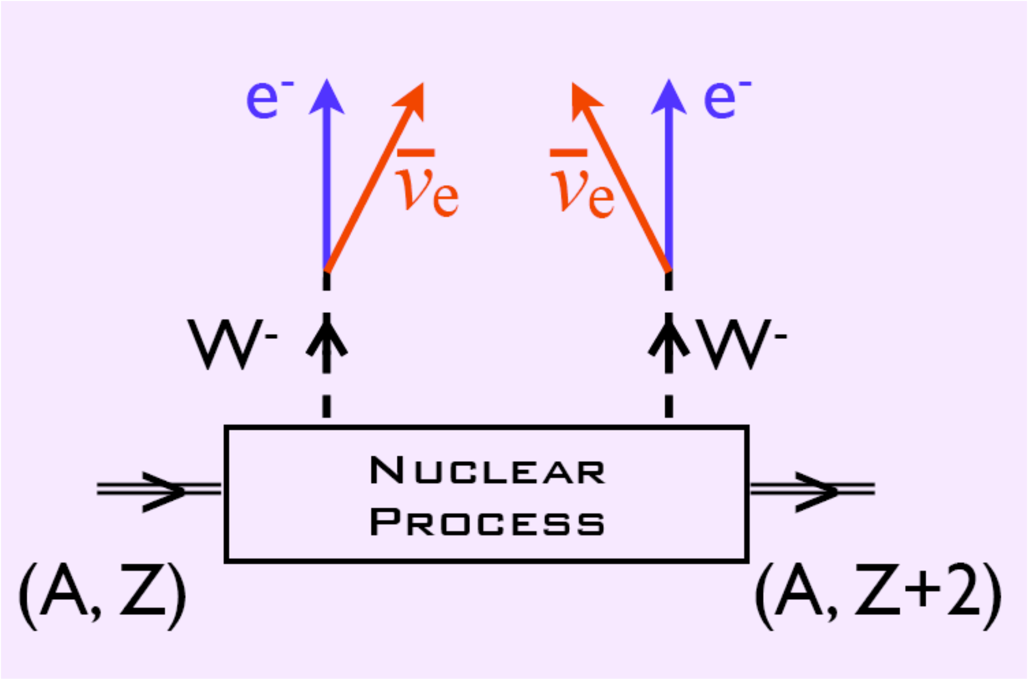

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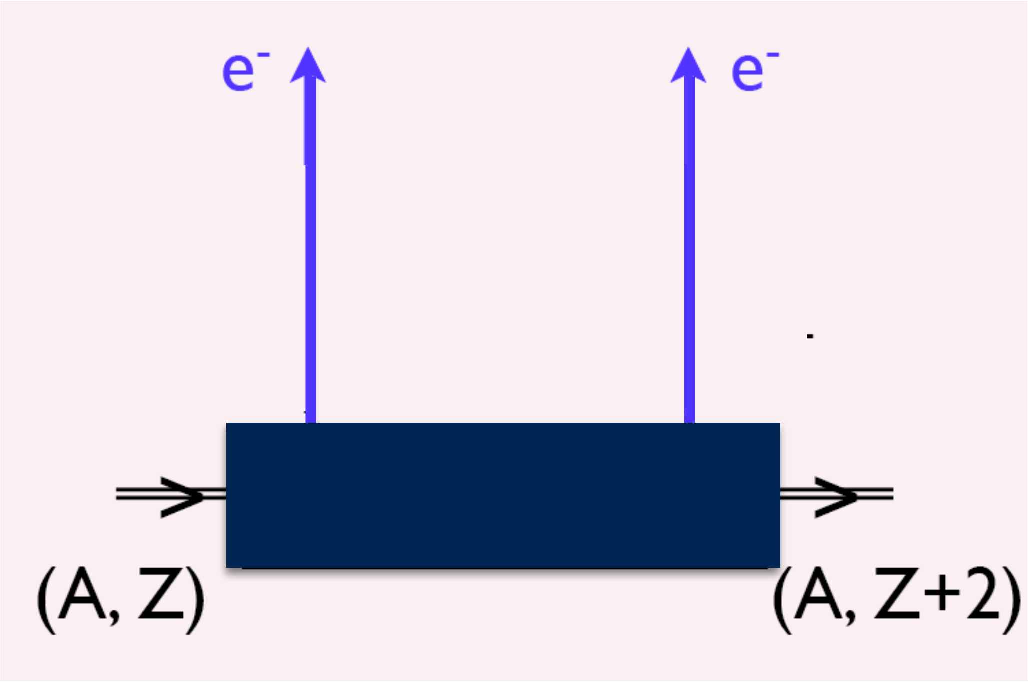
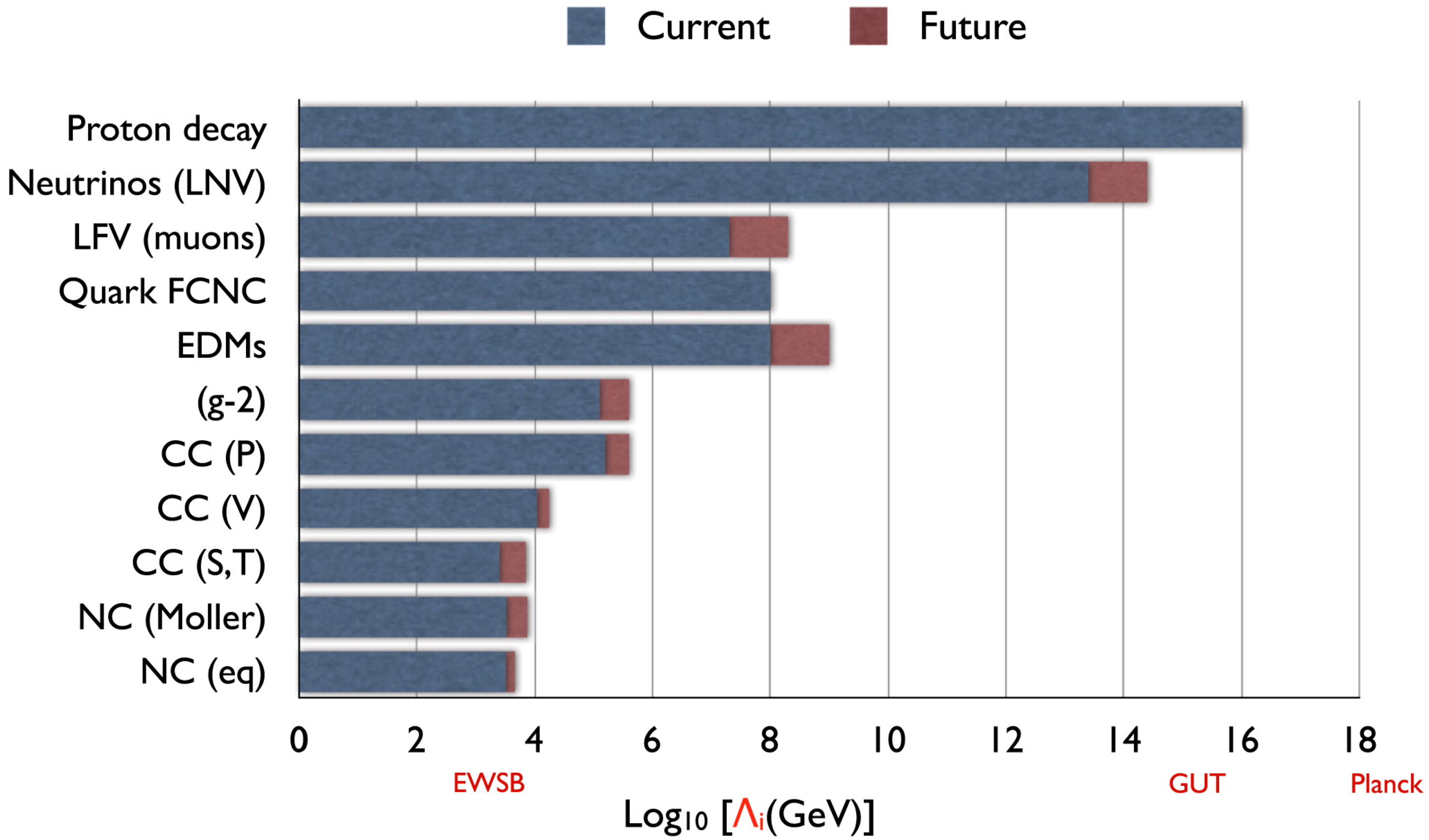


- ΔL=2 process
- ∃ Majorana mass term

Schechter &Valle, Phys. Rev. D 25 (1982) 2951

$$T^{0\nu}_{1/2} > \sim 10^{26}\ \mathrm{y}$$

# Low energy probes of BSM physics



Λ: effective new physics scale

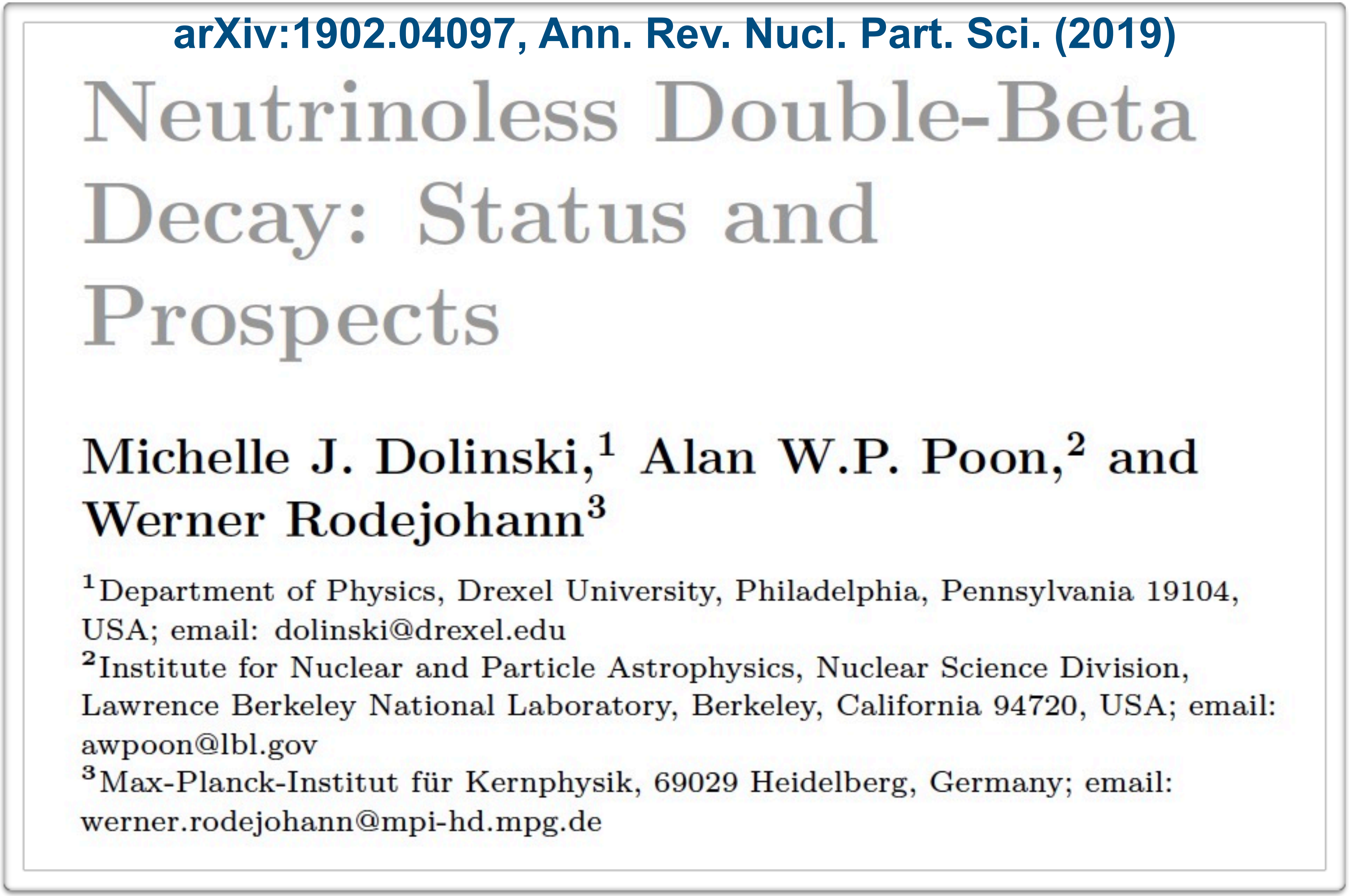
V. Cirigliano and M. Ramsey-Musolf, Prog. Part. Nucl. Phys, 71 (2013) 2-20

WE INTERRUPT THIS PROGRAM FOR A

# COMMERCIAL BREAK

# Neutrinoless Double-Beta $(0\nu\beta\beta)$ Decay

arXiv:1902.04097, Ann. Rev. Nucl. Part. Sci. (2019)



## Neutrinoless Double-Beta Decay: Status and Prospects

Michelle J. Dolinski,[1] Alan W.P. Poon,[2] and Werner Rodejohann[3]

[1] Department of Physics, Drexel University, Philadelphia, Pennsylvania 19104, USA; email: dolinski@drexel.edu
[2] Institute for Nuclear and Particle Astrophysics, Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA; email: awpoon@lbl.gov
[3] Max-Planck-Institut für Kernphysik, 69029 Heidelberg, Germany; email: werner.rodejohann@mpi-hd.mpg.de

# Neutrinoless Double-Beta (0νββ) Decay

$$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + Q_{\beta\beta}$$

Measure half-life $T^{0\nu}_{1/2}$ :

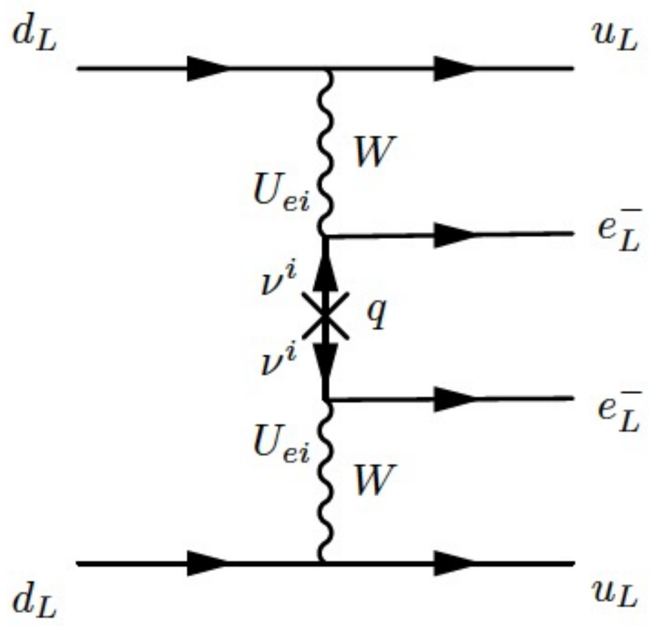
$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_x(Q_{\beta\beta},Z)\,|\mathcal{M}_x(A,Z)\eta_x|^2$$

$G_x(Q_{\beta\beta},Z)$ ➡ Calculable phase-space factor.

$\mathcal{M}_x(A,Z)$ ➡ Hard-to-calculate nuclear matrix elements (NME).

$\eta_x$ ➡ Particle physics parameter.

# “Vanilla” mechanism

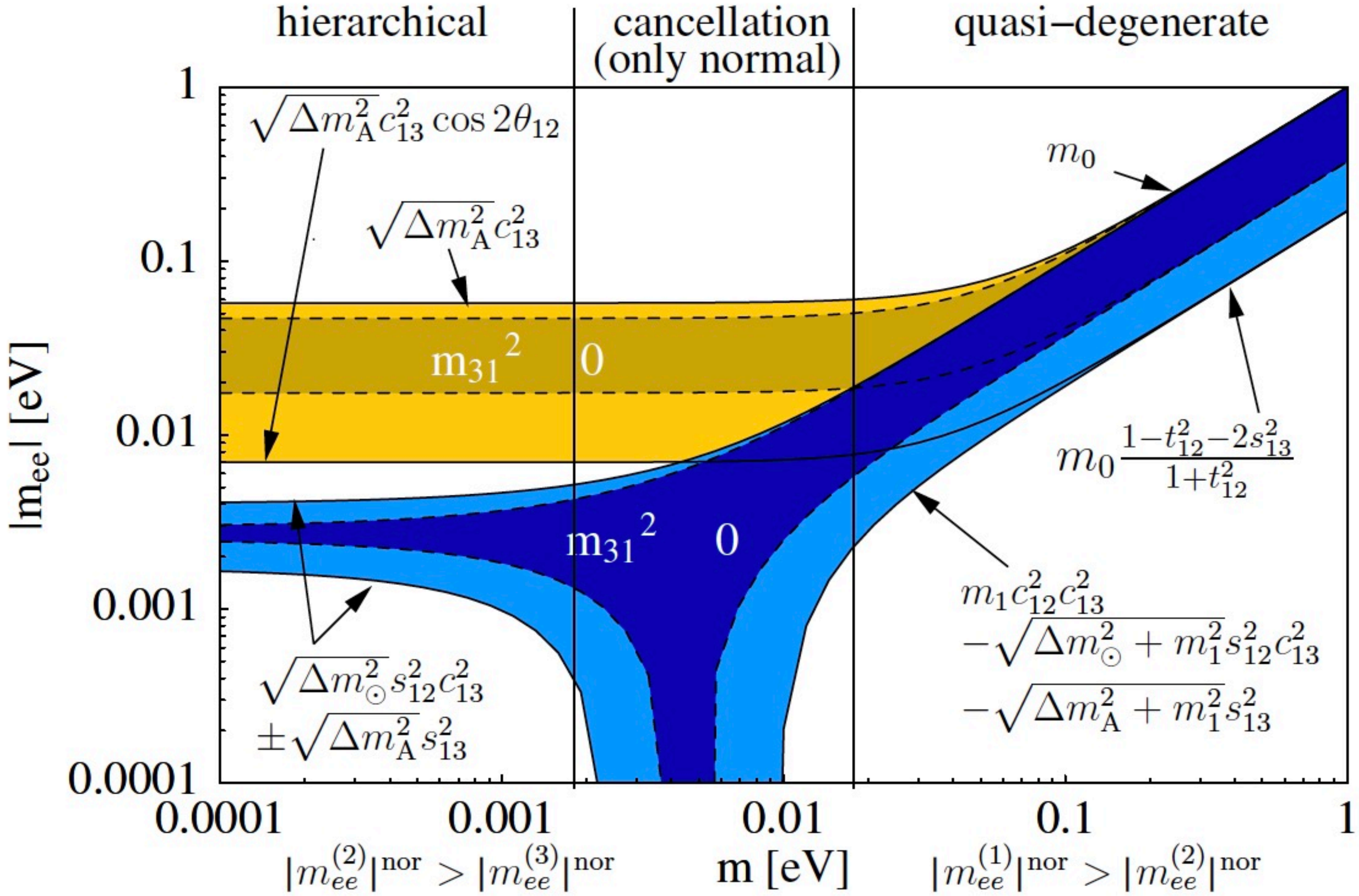


- $0\nu\beta\beta$ is mediated by light Majorana neutrinos;
- other ΔL≠ 0 mechanisms are negligible.

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\,|\mathcal{M}_{0\nu}(A,Z)|^2\,\langle m_{\beta\beta}\rangle^2$$

$$\langle m_{\beta\beta}\rangle = \left|U^2_{ei} m_i\right| = f(\theta_{12}, m_i, \mathrm{sign}(\Delta m^2_A), \alpha, \beta)$$

PMNS matrix: $U$



M. Lindner et al,
PRD 73 (2006) 053005

# Measuring the “mass” $m_i$

Cosmology:

$$\sum m = \sum_{i=1}^{3} m_i = m_1 + m_2 + m_3$$

β decays:

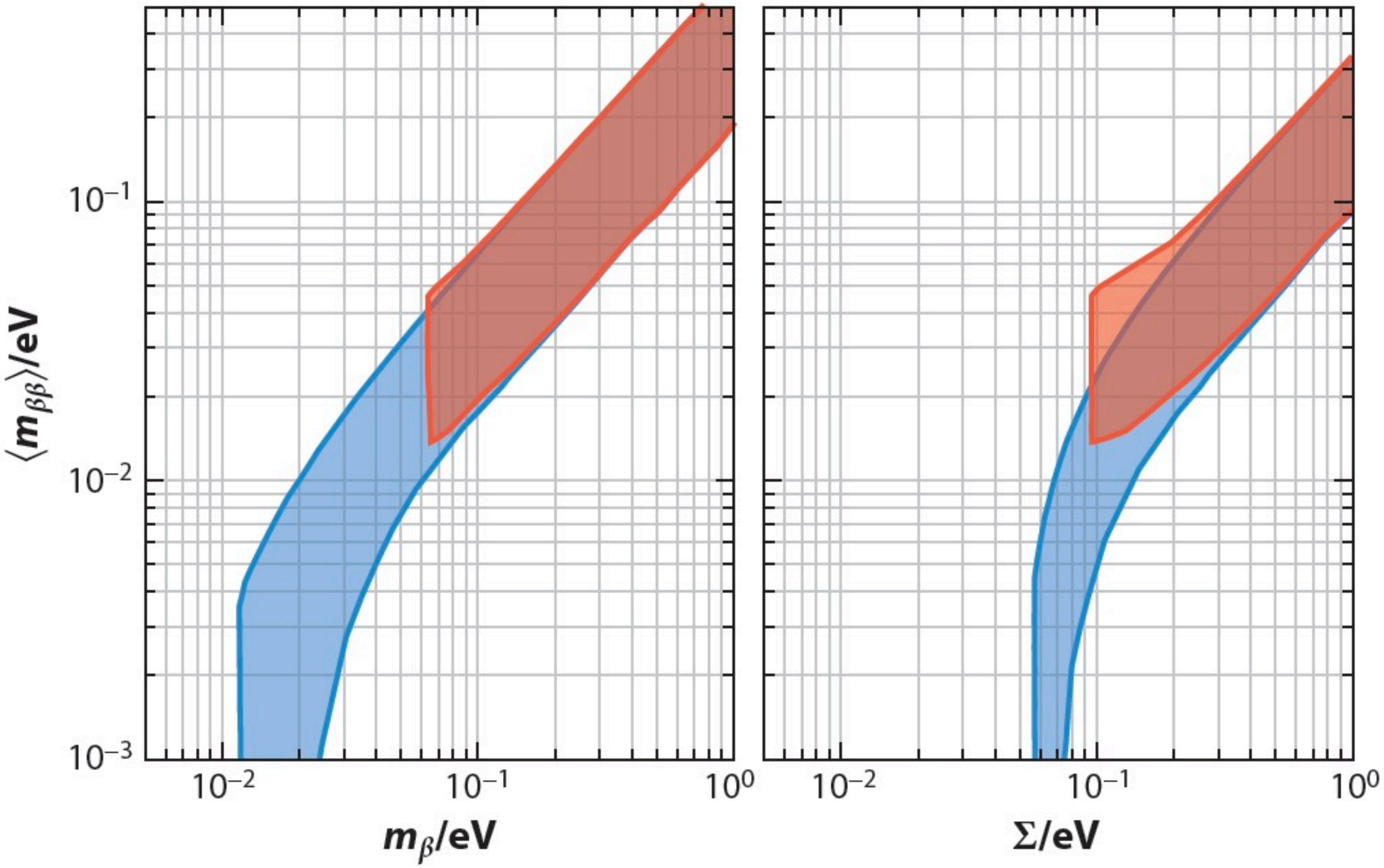
$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

ββ decays:

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

Oscillations:

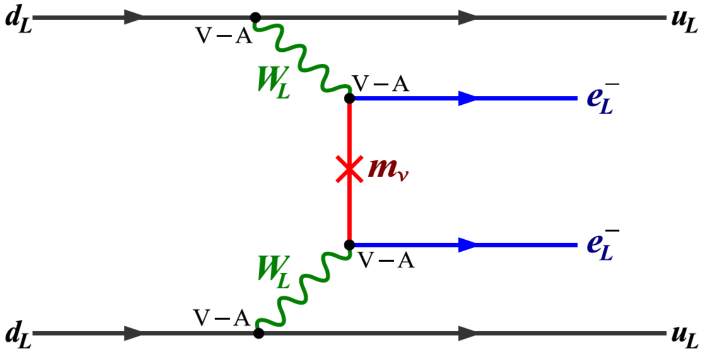
$$\Delta m_{ij}^2 = m_j^2 - m_i^2$$



# Do other mechanisms tell us anything about (light) m(ν)?

### "Vanilla" mass mechanism

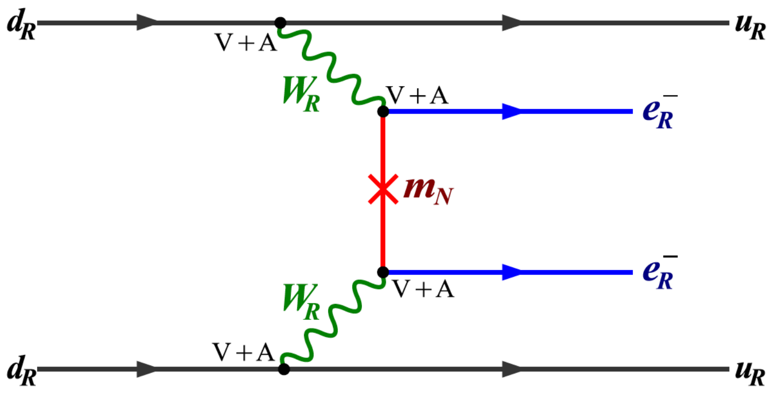
$$\langle m_{\beta\beta}\rangle = \sum_{i=1}^{3}\left|U_{ei}^2 m_i\right|$$



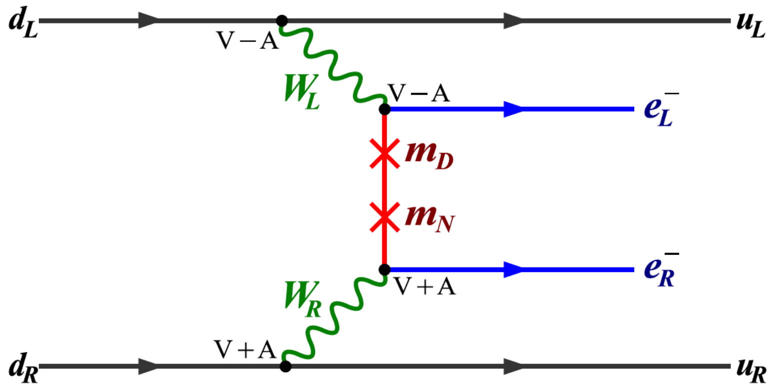
0νββ half-life may not yield any direct information about the neutrino mass.

### L-R symmetric model

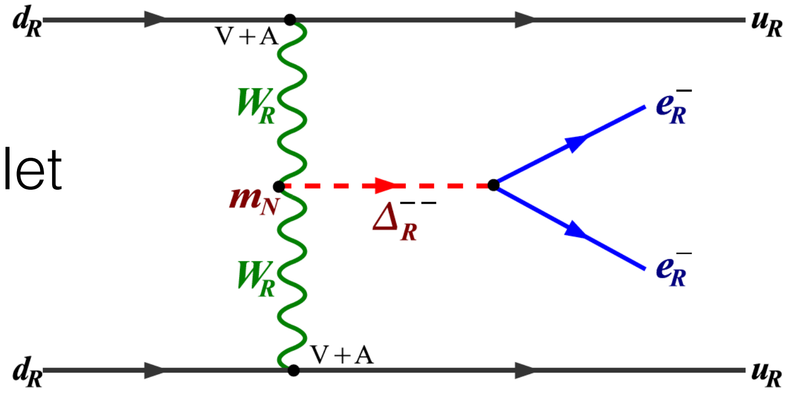
Heavy neutrino exchange



L-R mixing



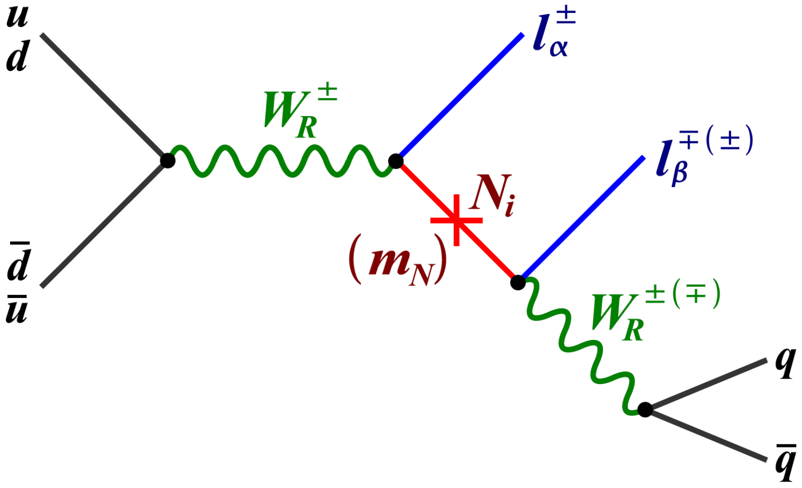
Doubly-charged Higgs triplet exchange



Hirsch 2016

# Complementarity to LHC / heavy flavor physics

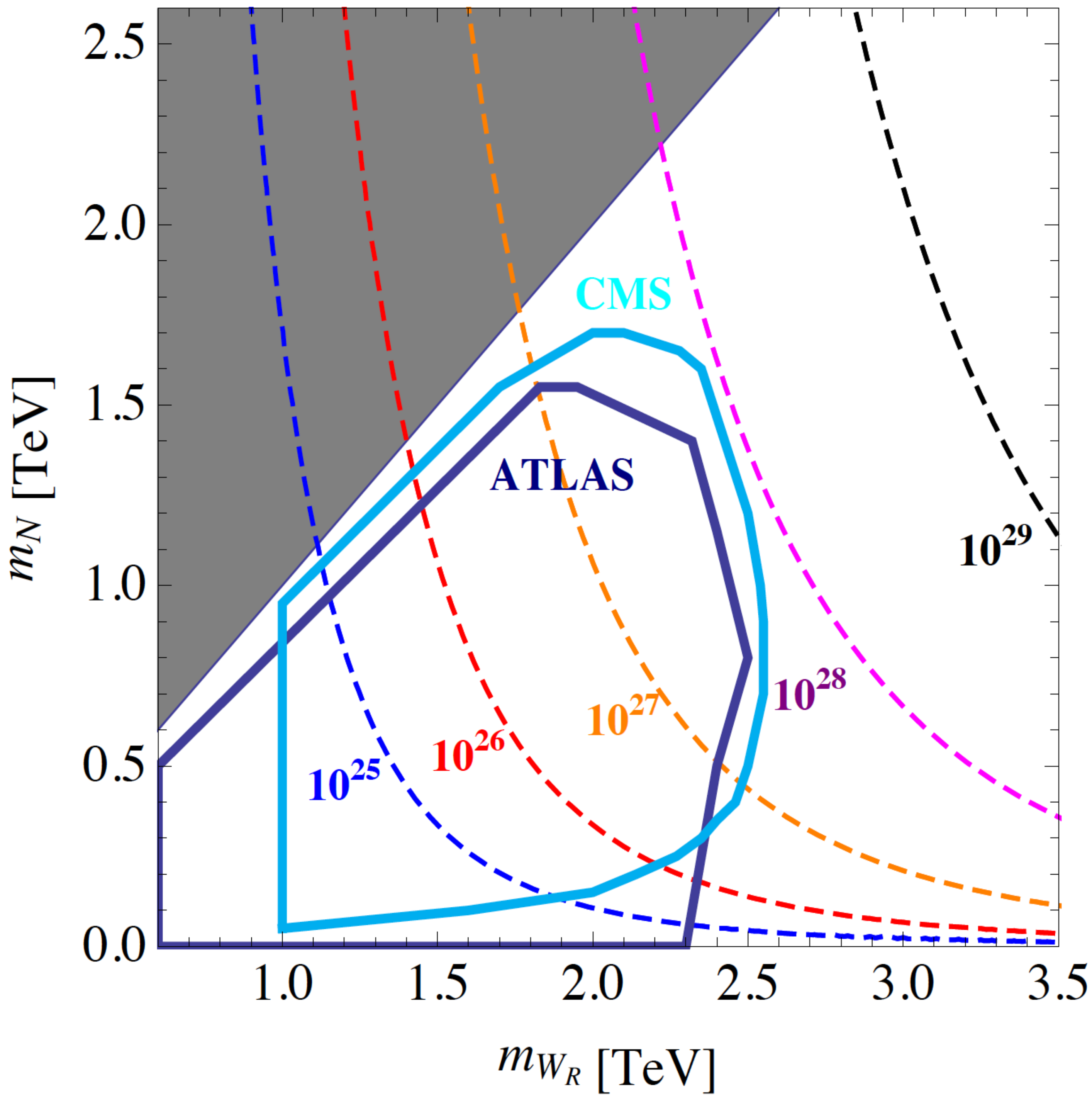
- LNV via heavy right-handed neutrino exchange can be probed via $l^\pm l^\pm + 2j$



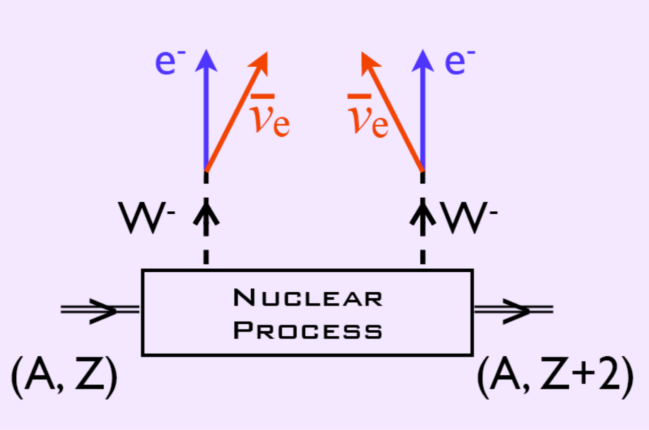
Same sign: $l^\pm l^\pm + 2j$

Non-observation gives stringent limits on short-range $W_R$ mechanisms

Hirsch 2016



# Experimental signal

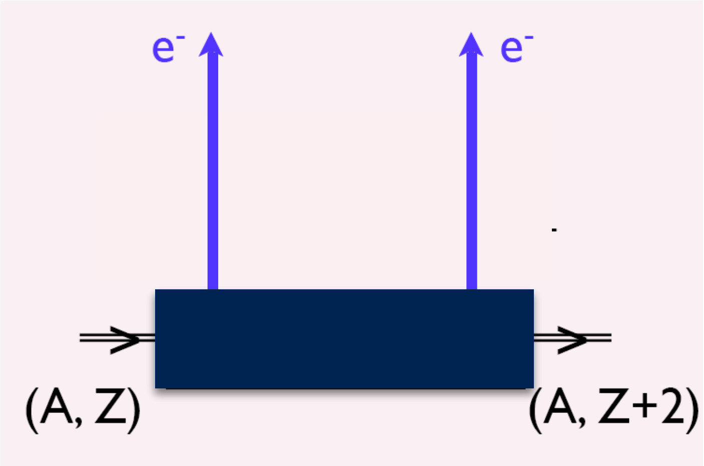


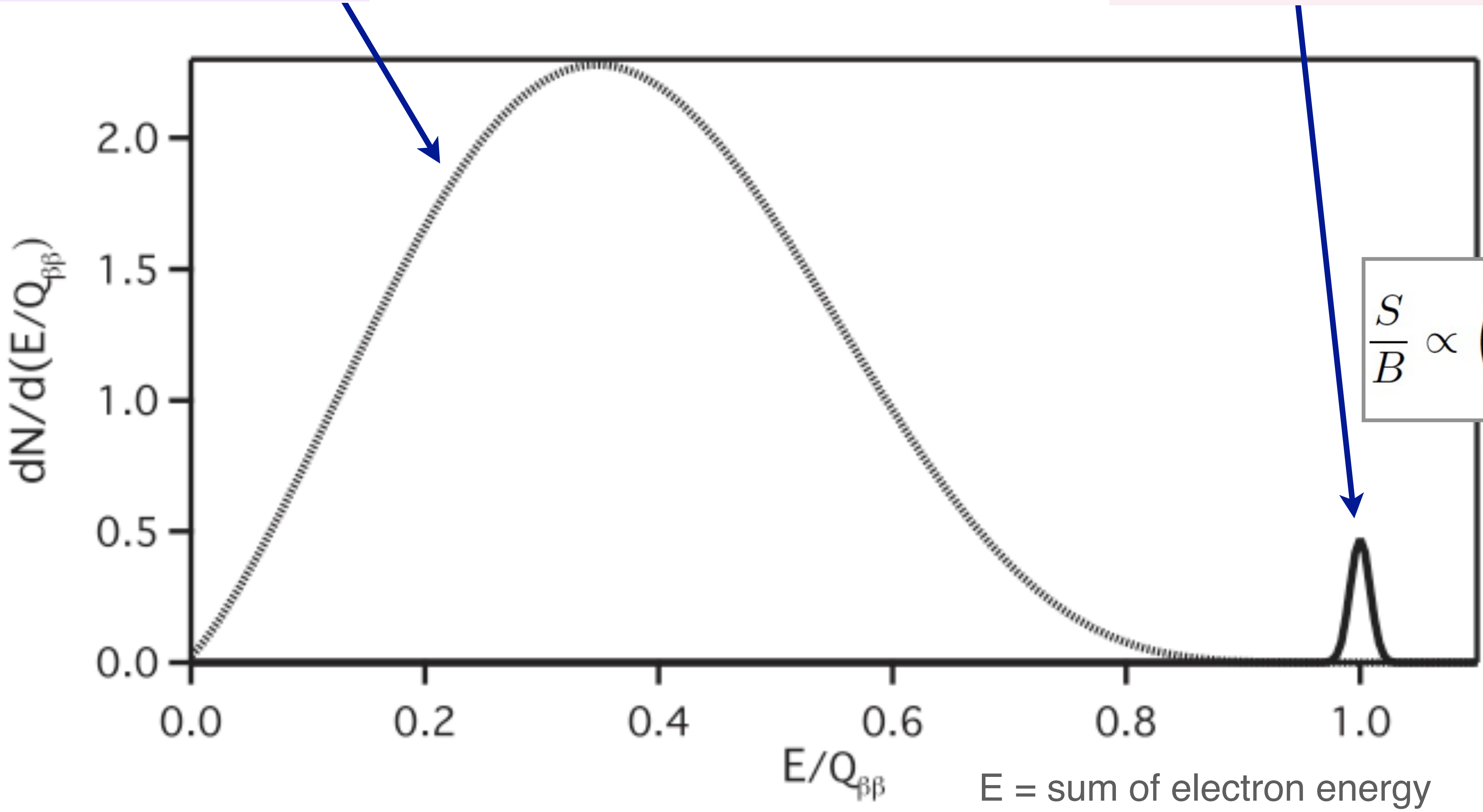
**Background (B)**

$T_{1/2}^{2\nu} \sim 10^{18-24}$ y

**Signal (S)**

$T_{1/2}^{0\nu} > 10^{26}$ y





$$\frac{S}{B} \propto \left(\frac{Q_{\beta\beta}}{\Delta E}\right)^6 \frac{T_{1/2}^{2\nu}}{T_{1/2}^{0\nu}}$$

E = sum of electron energy

# Experimental considerations

$$T^{0\nu}_{1/2}(\mathrm{FOM}) \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

- Preferably:
  - high isotopic abundance
  - high efficiency
  - large mass
  - long exposure (counting time)
  - good energy resolution
  - low background: $2\nu\beta\beta$, U/Th, cosmogenic

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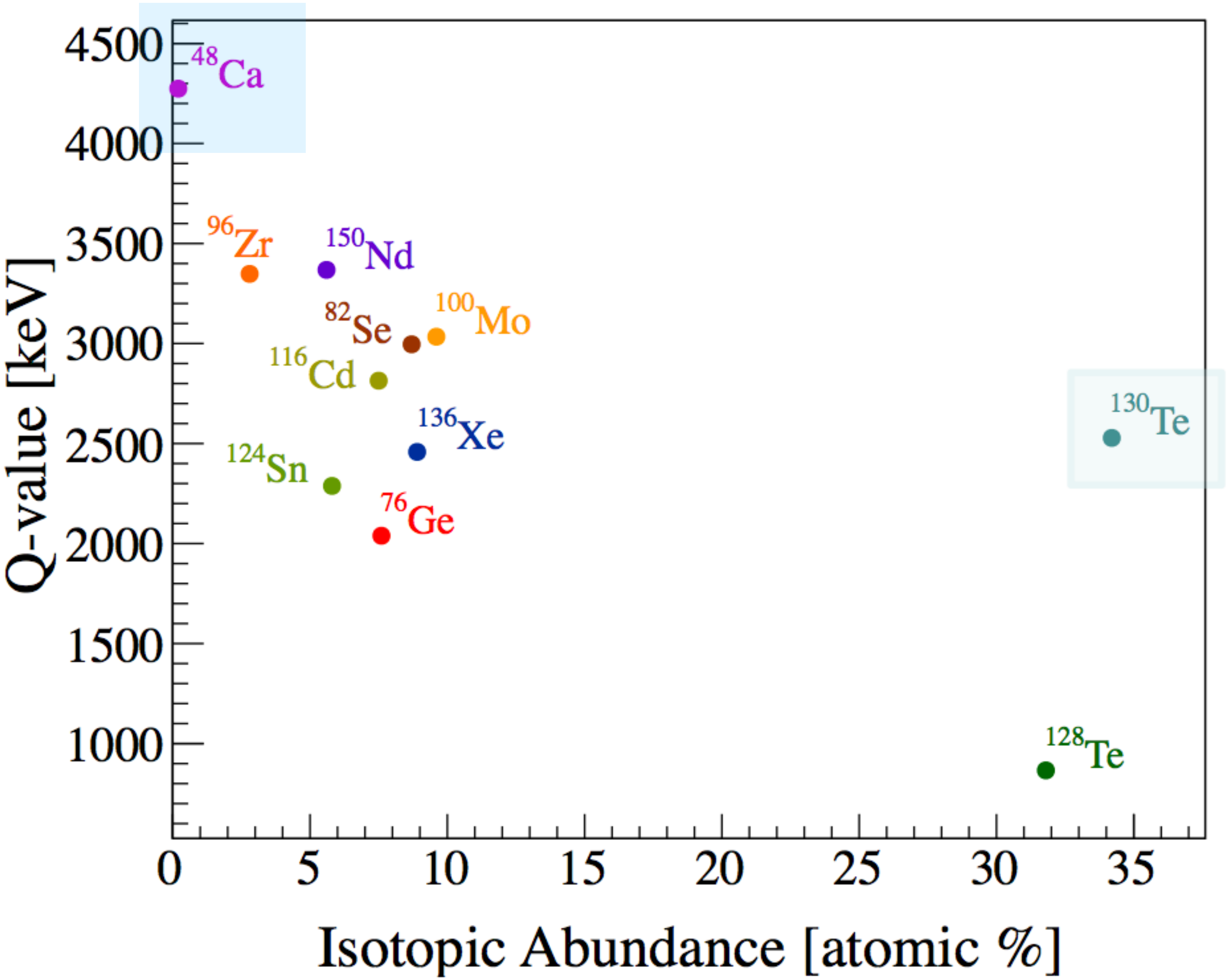
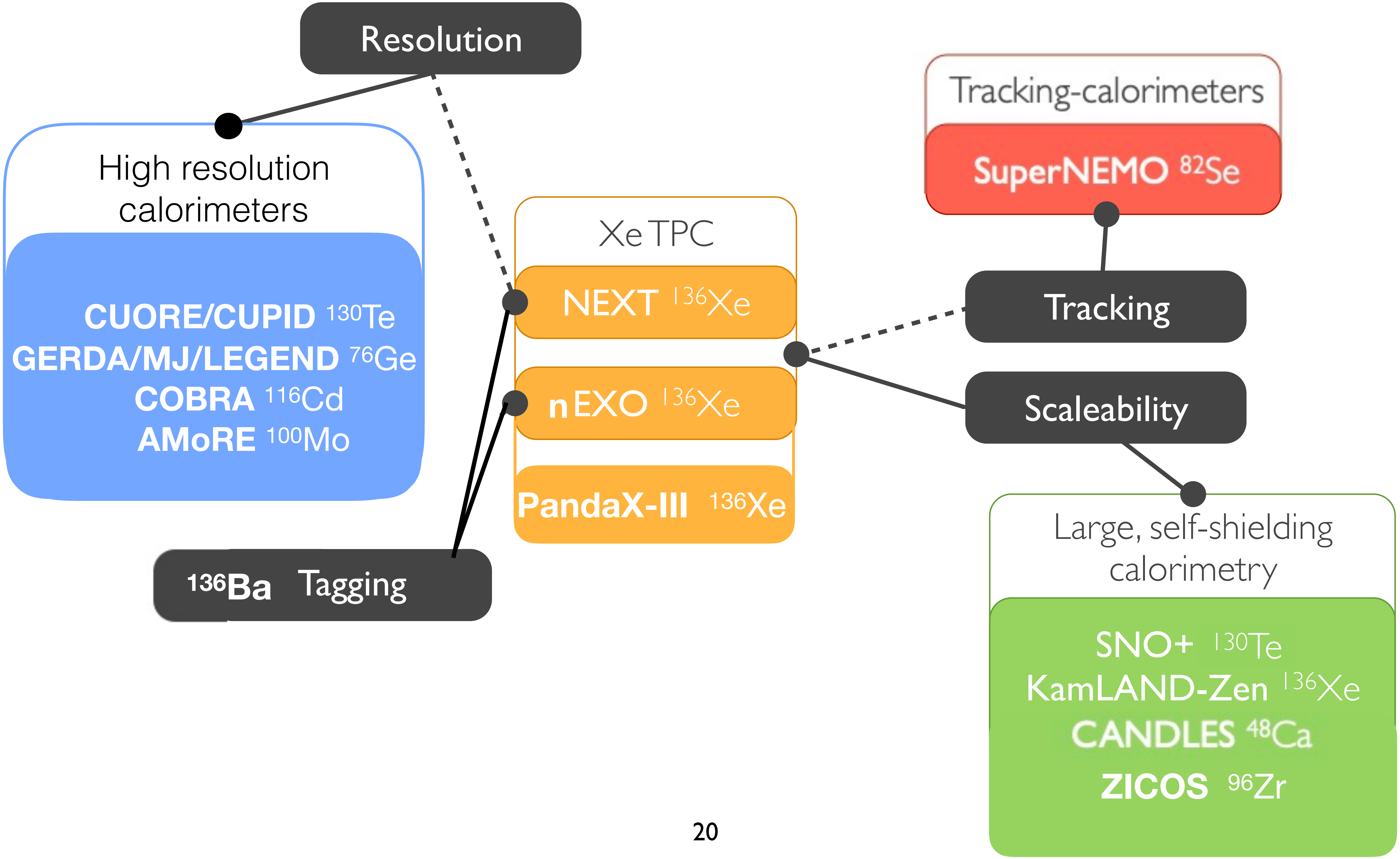
**There is not an obvious choice of isotope or detector technology**

# Experimental consideration: Target



# Detector Technology



Resolution

High resolution calorimeters

**CUORE/CUPID** $^{130}$Te
**GERDA/MJ/LEGEND** $^{76}$Ge
**COBRA** $^{116}$Cd
**AMoRE** $^{100}$Mo

Xe TPC

NEXT $^{136}$Xe
nEXO $^{136}$Xe
**PandaX-III** $^{136}$Xe

$^{136}$**Ba** Tagging

Tracking-calorimeters

SuperNEMO $^{82}$Se

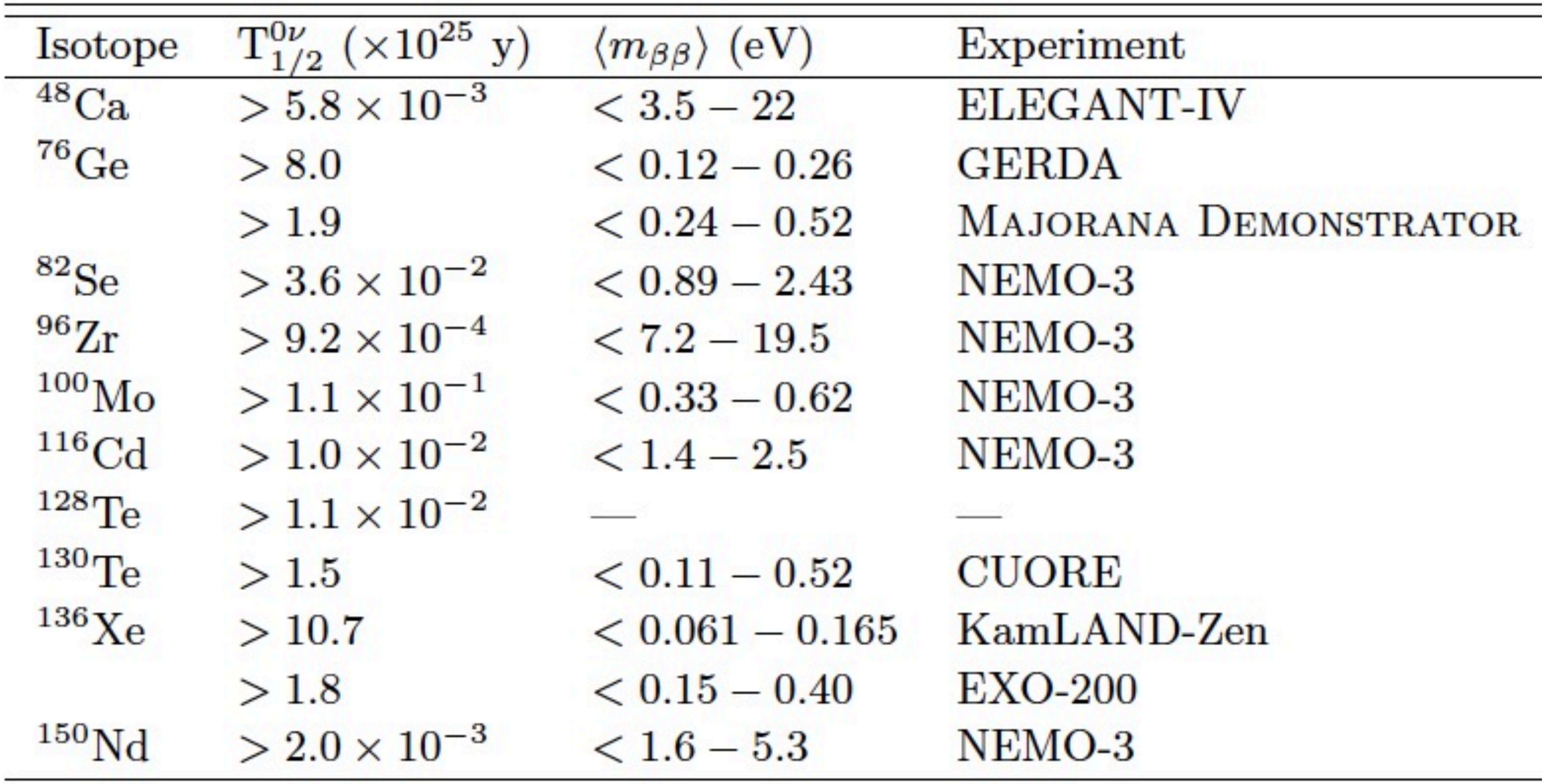
Tracking

Scaleability

Large, self-shielding calorimetry

SNO+ $^{130}$Te
KamLAND-Zen $^{136}$Xe
CANDLES $^{48}$Ca
**ZICOS** $^{96}$Zr

# Current 0νββ decay half-life limit



| Isotope | $T^{0\nu}_{1/2}$ ($\times 10^{25}$ y) | $\langle m_{\beta\beta} \rangle$ (eV) | Experiment |
|---|---|---|---|
| $^{48}$Ca | $> 5.8 \times 10^{-3}$ | $< 3.5 - 22$ | ELEGANT-IV |
| $^{76}$Ge | $> 8.0$ | $< 0.12 - 0.26$ | GERDA |
|  | $> 1.9$ | $< 0.24 - 0.52$ | MAJORANA DEMONSTRATOR |
| $^{82}$Se | $> 3.6 \times 10^{-2}$ | $< 0.89 - 2.43$ | NEMO-3 |
| $^{96}$Zr | $> 9.2 \times 10^{-4}$ | $< 7.2 - 19.5$ | NEMO-3 |
| $^{100}$Mo | $> 1.1 \times 10^{-1}$ | $< 0.33 - 0.62$ | NEMO-3 |
| $^{116}$Cd | $> 1.0 \times 10^{-2}$ | $< 1.4 - 2.5$ | NEMO-3 |
| $^{128}$Te | $> 1.1 \times 10^{-2}$ | — | — |
| $^{130}$Te | $> 1.5$ | $< 0.11 - 0.52$ | CUORE |
| $^{136}$Xe | $> 10.7$ | $< 0.061 - 0.165$ | KamLAND-Zen |
|  | $> 1.8$ | $< 0.15 - 0.40$ | EXO-200 |
| $^{150}$Nd | $> 2.0 \times 10^{-3}$ | $< 1.6 - 5.3$ | NEMO-3 |

Goal for the next generation of experiments

$$T^{0\nu}_{1/2} > \sim 10^{28} \text{ y}$$

# Next-Generation 0νββ Experiments

| $T_{1/2}$ (0ν) | Signal rate<br>[cts/(ton-Ge y)] |
|---|---|
| $10^{25}$ y | 500 |
| $5 \times 10^{26}$ | 10 |
| $5 \times 10^{27}$ | 1 |
| $> 10^{29}$ | < 0.05 |

Need a “large-scale” experiment

&

Background index < ~ O(0.1) count/(ton-Ge yr) in ROI

# How crazy is 0.1 count/(ton yr)?

## 500 MΩ SMD resistor used by GERDA

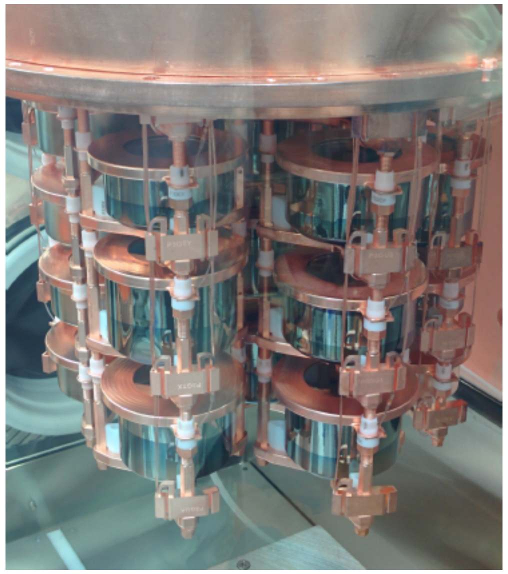
| Size | Th-234 [uBq/pc] | Ra-226 [uBq/pc] | Th-228 [uBq/pc] | K-40 [uBq/pc] | Pb-210 [uBq/pc] |
|---|---|---|---|---|---|
| 0603<br>0.48 mm$^3$/pc<br>1.33 mg | 4 ± 2 | 1.9 ± 0.3 | 0.6 ± 0.2 | 10 ± 4 | 46 ±5 |
| 0402<br>0.153 mm$^3$/pc<br>0.6 mg/pc | 2 ± 1 | 0.7 ± 0.1 | 0.2 ± 0.1 | < 2.6 | 32 ± 3 |

Cattadori, LRT 2015

1 μBq ≈ 0.1 / day

# $^{76}$Ge HPGe: GERDA, MAJORANA, LEGEND

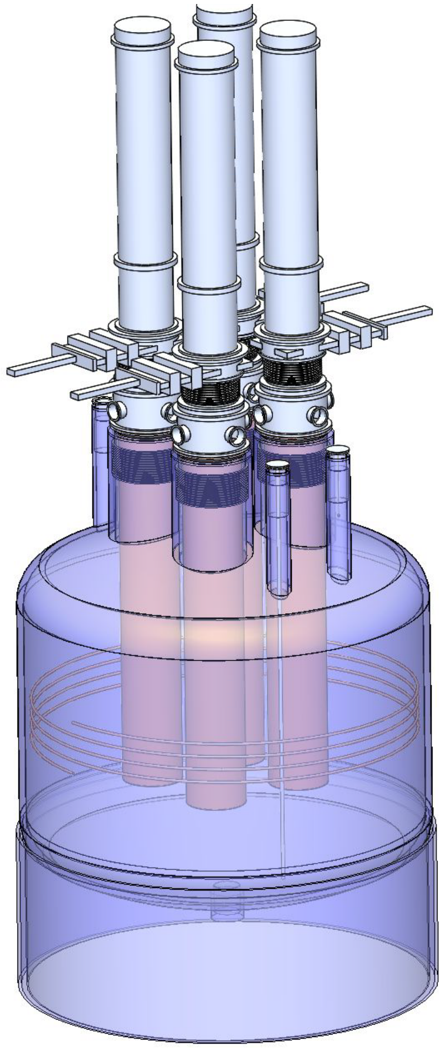
**MAJORANA DEMONSTRATOR**



**GERDA**

## LEGEND-200

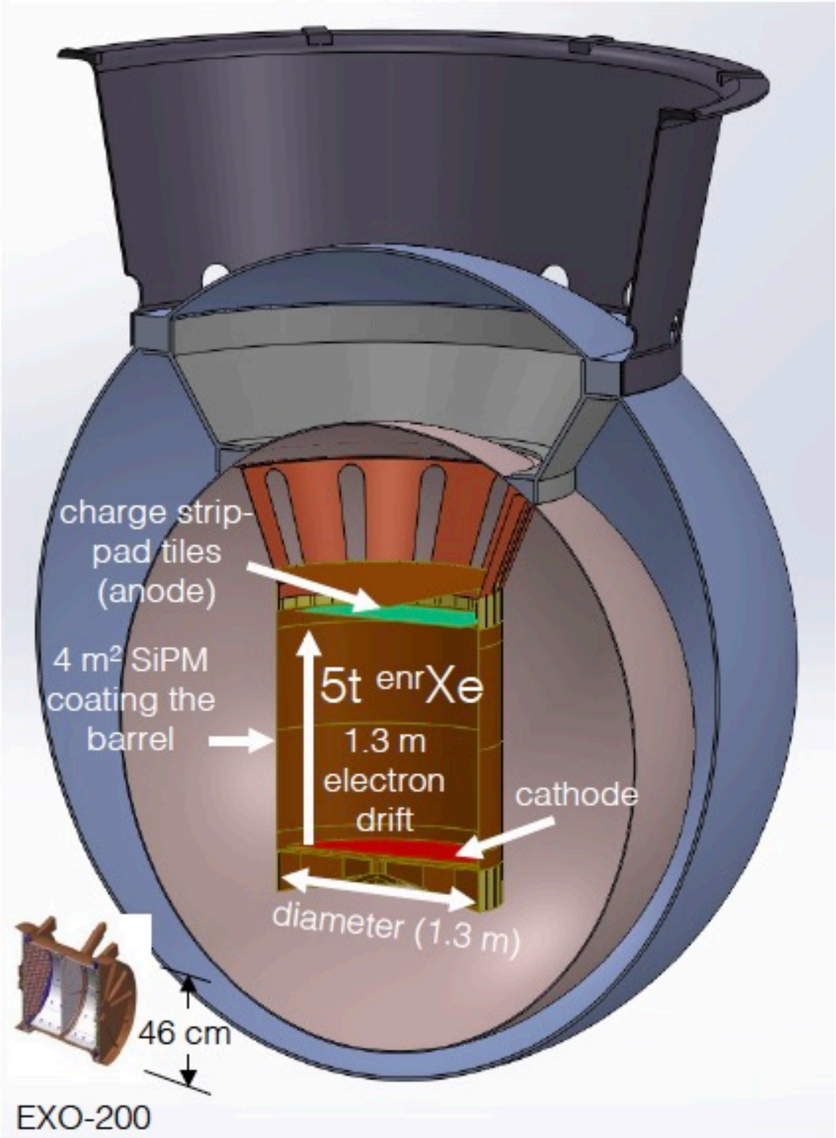
- Use existing GERDA infrastructure at LNGS
- Up to 200 kg
- BG goal: 1/5 of existing
- Start by 2021

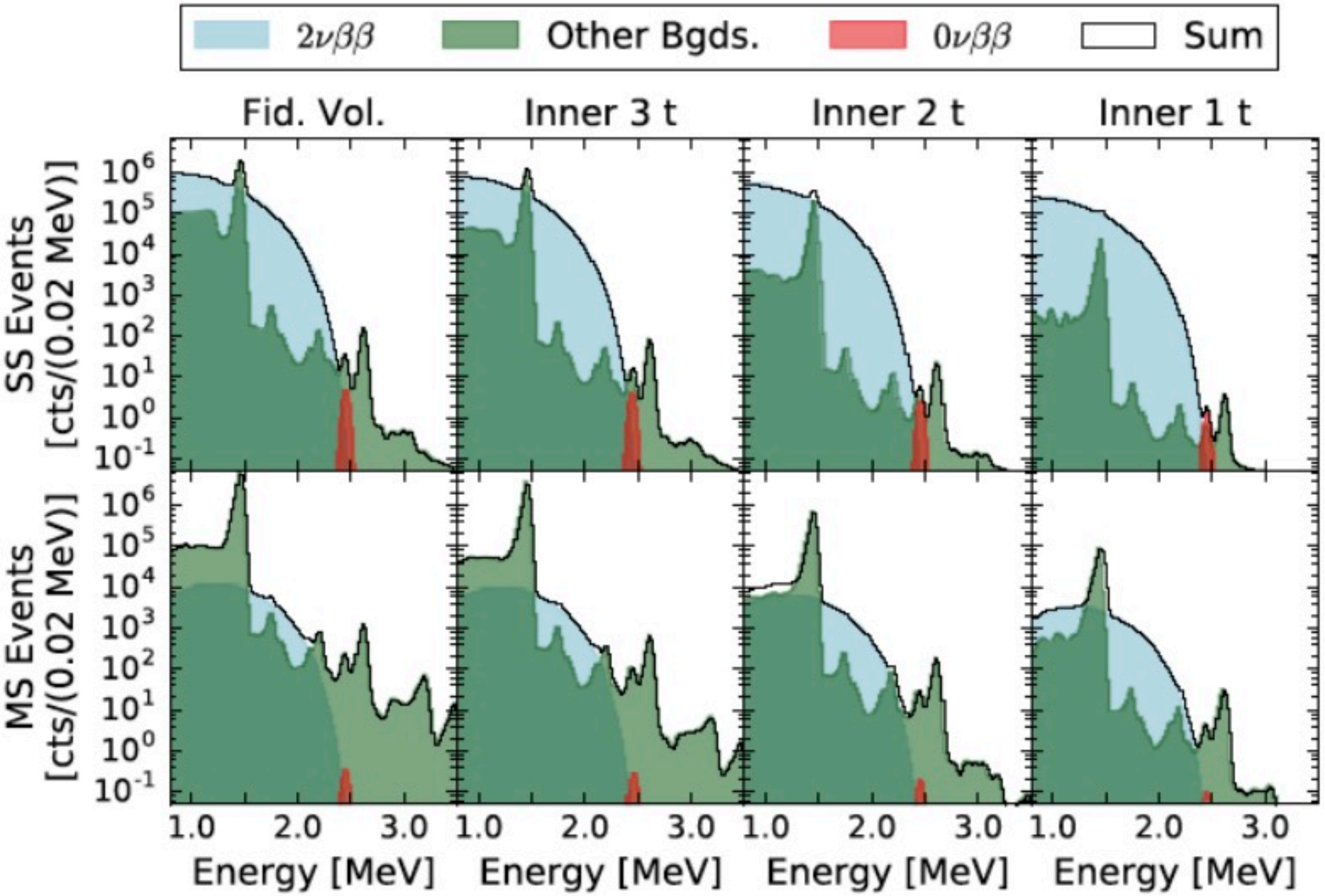


## LEGEND-1000

- Deep underground
- UG LAr
- Phased implementation
- BG goal: 1/30 of existing (0.1 c/FWHM t y)

# $^{136}$Xe TPC: EXO-200 & nEXO





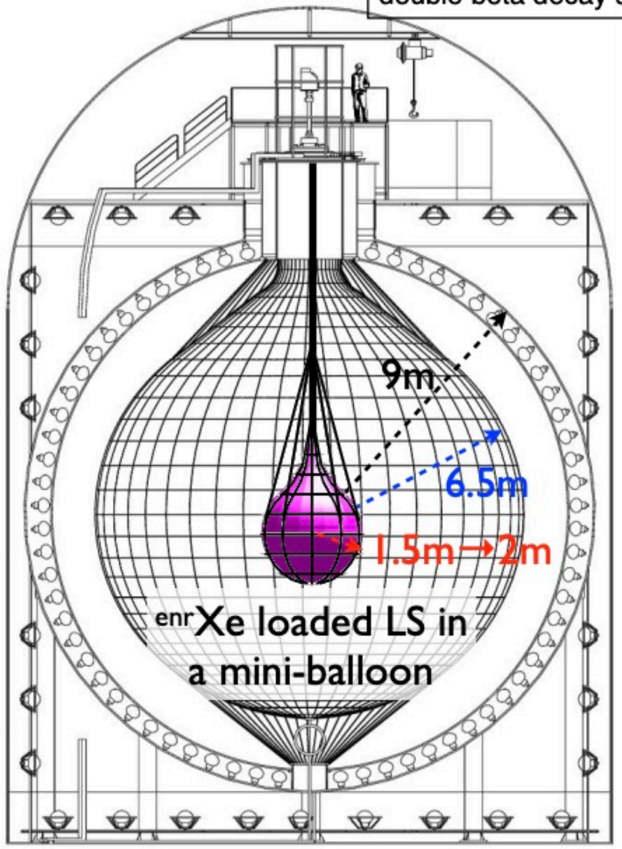
Discovery sensitivity (3σ, 50%) after 10 yr
$T_{1/2}^{0\nu\beta\beta} = 5.5\times10^{27}$ yr

If $^{136}$Ba-tagging can be implemented:
$T_{1/2}^{0\nu\beta\beta} = 1.6\times10^{28}$ yr

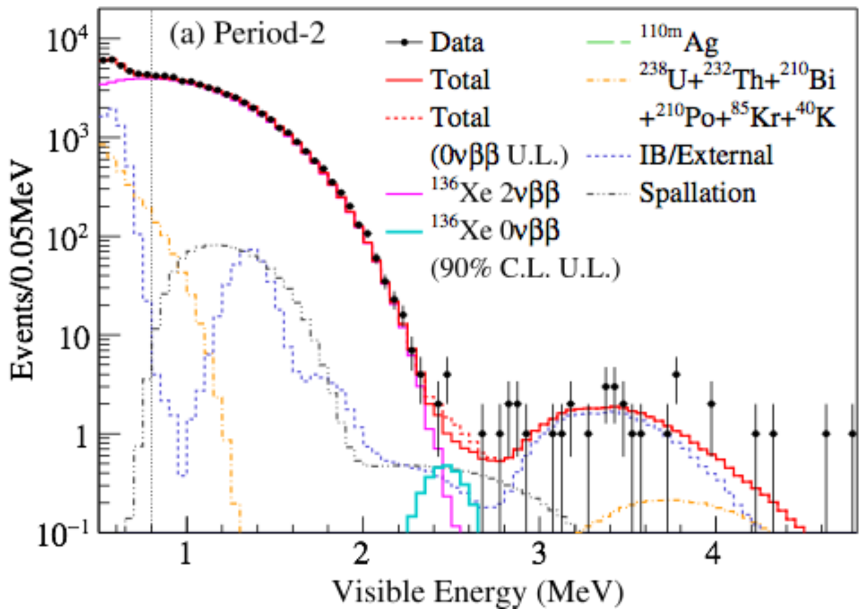
# $^{136}$Xe Liquid Scintillator: KamLAND-ZEN

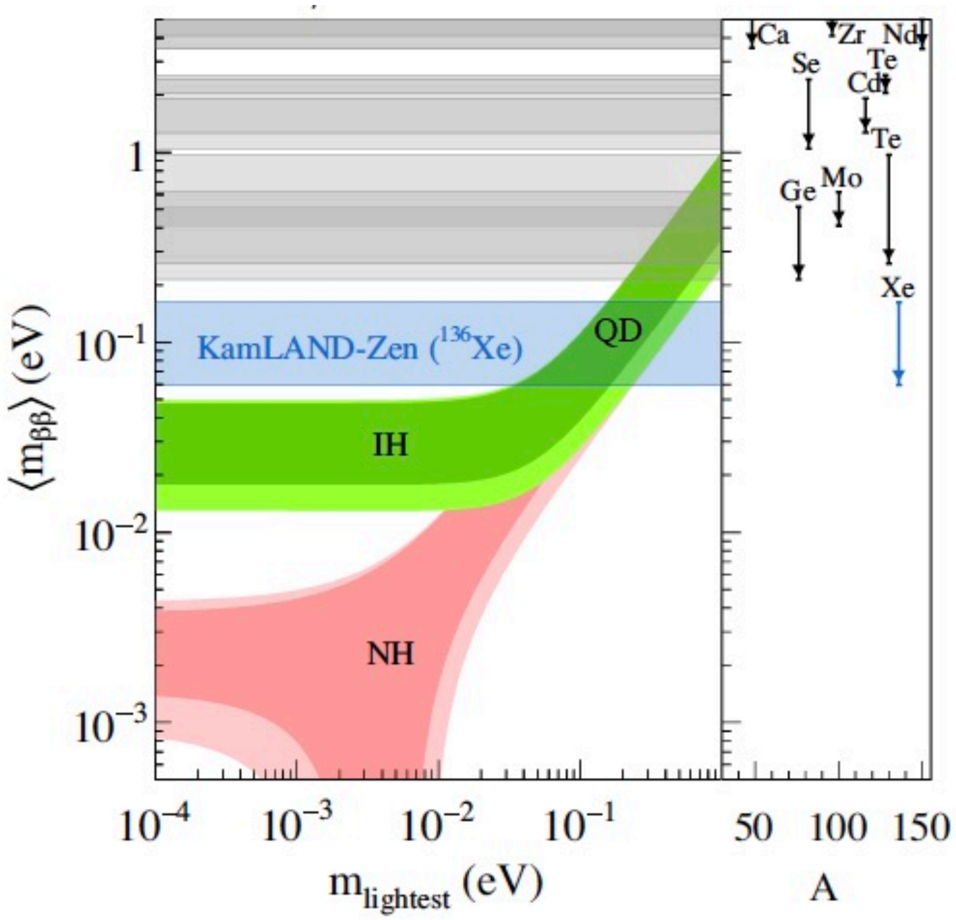
**KamLAND-Zen**

Zero Neutrino double beta decay search



**KL-Z 400** $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ y





**KL-Z 400:**

- Phase 1- 320 kg ($^{110m}$Ag background)
- Phase 2 - 380 kg (after purification)

**KL-Z 800:**

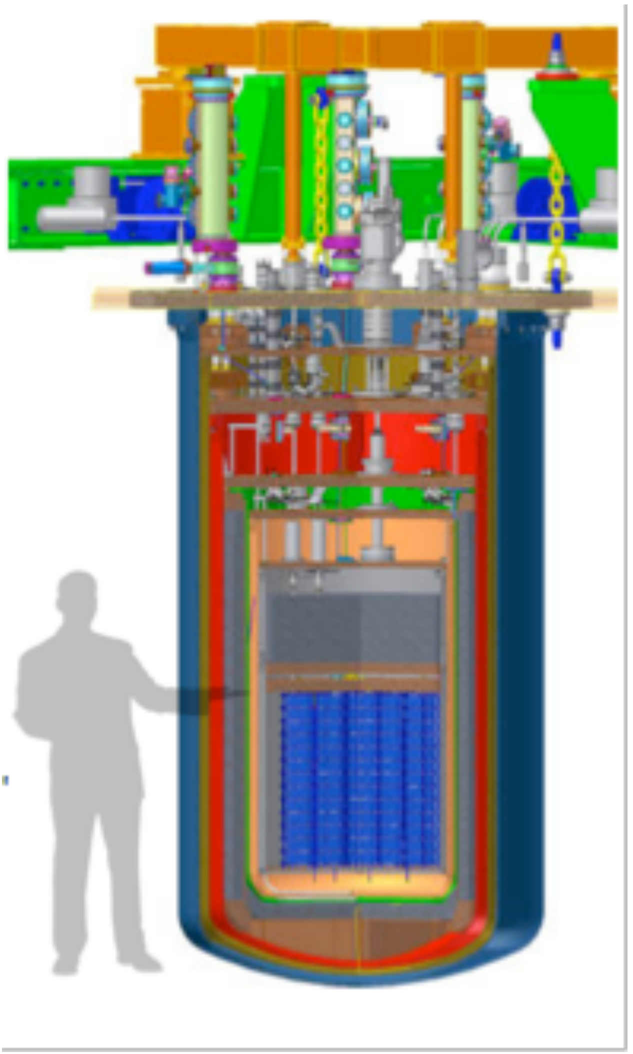
- 745 kg $^{enr}$Xe started in 2019.01

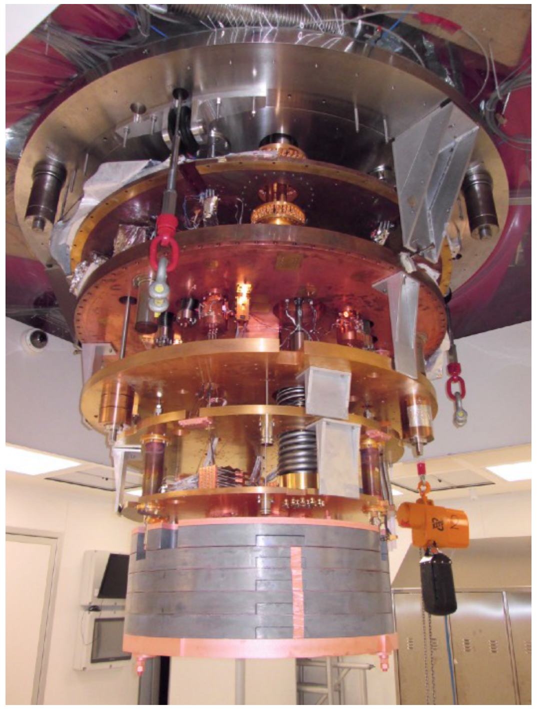
**KL2-Z:**

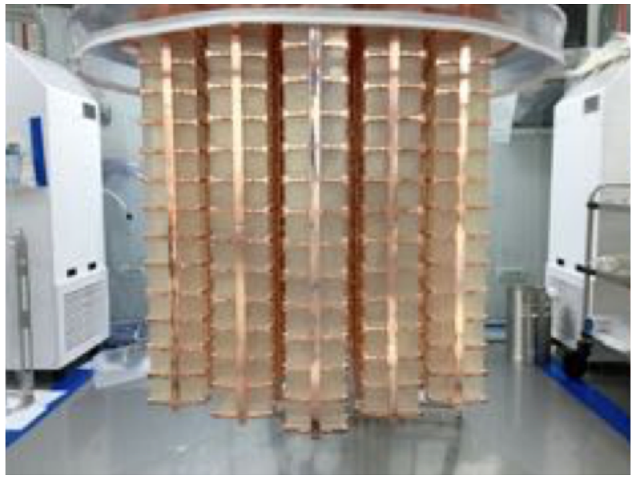
- 1000 kg+; Y2026?

K. Inoue (2019)

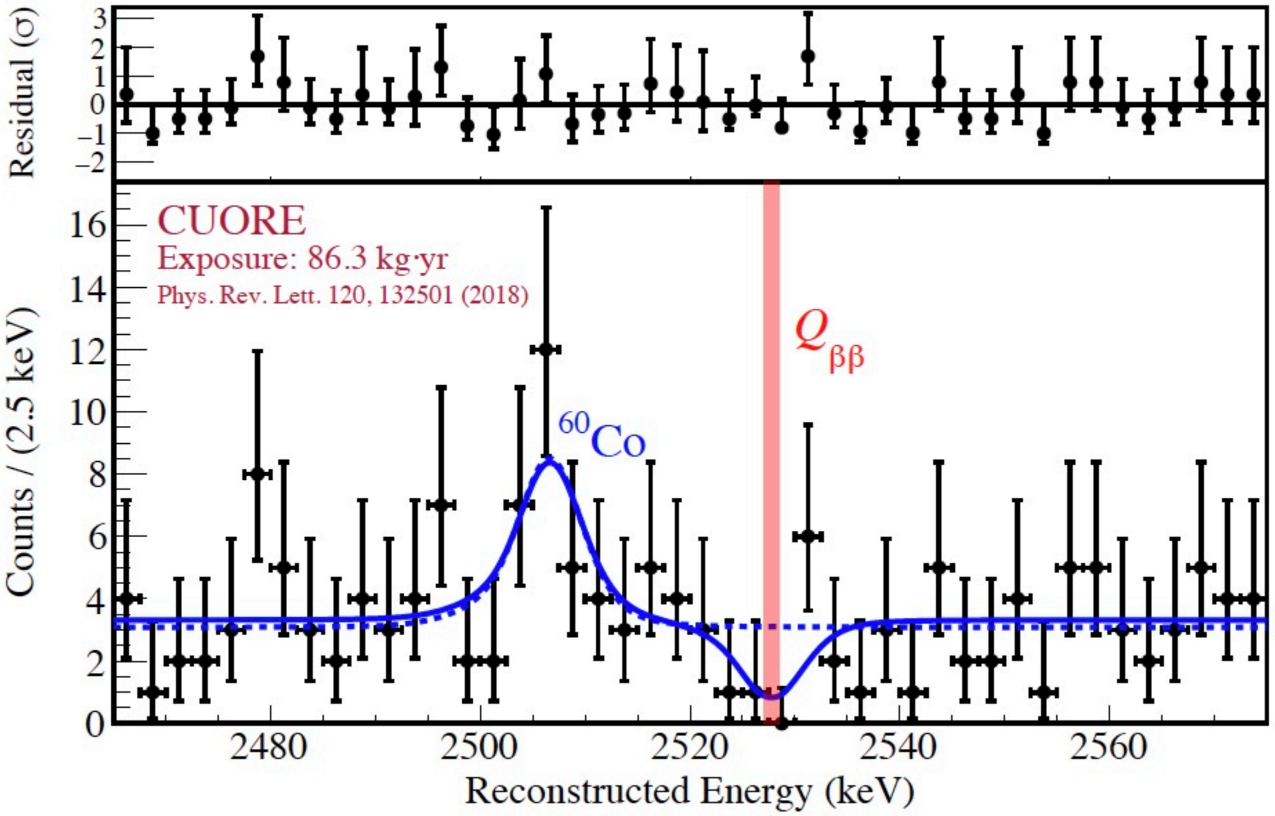
# $^{130}$Te / $^{100}$Mo Bolometers: CUORE / CUPID



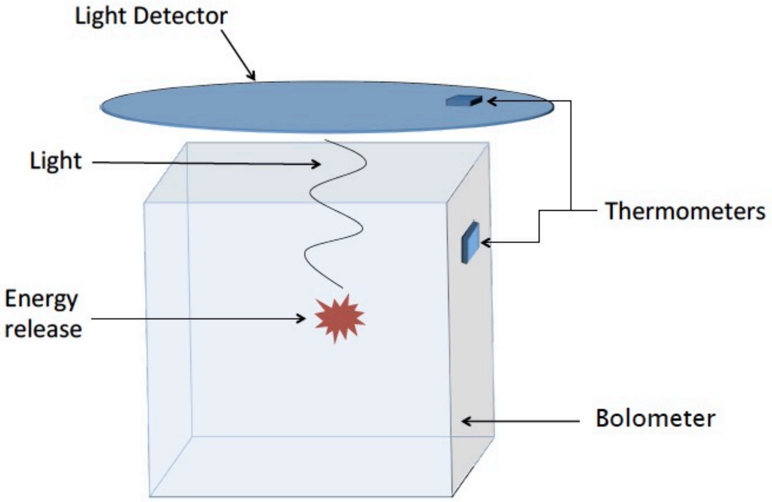




## CUORE ($^{130}TeO_2$)

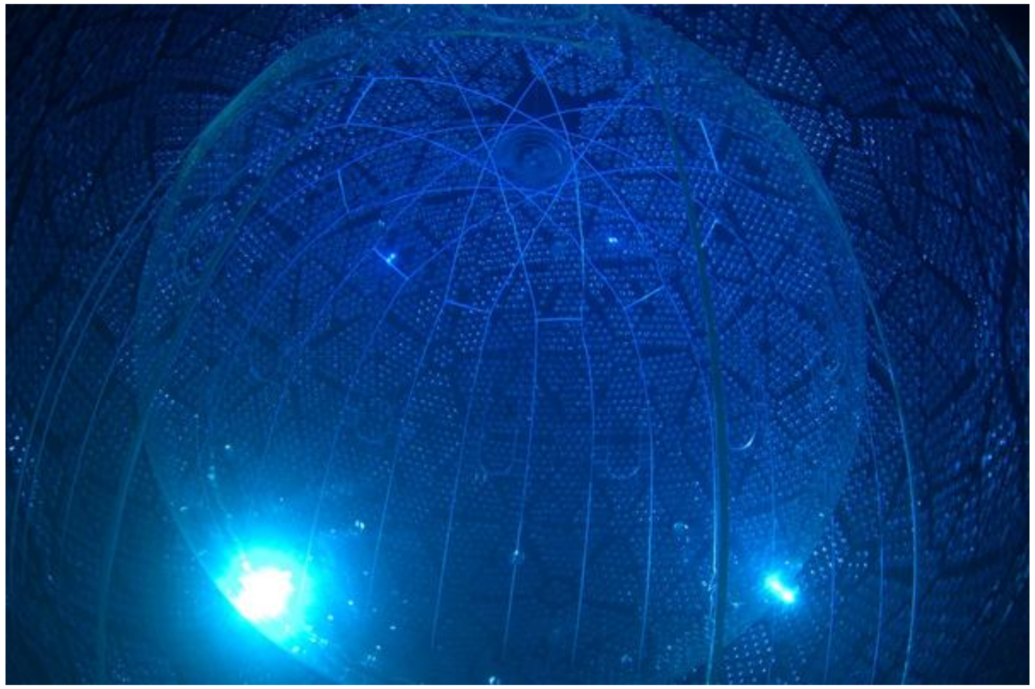


## CUPID ($Li_2{}^{100}MoO_4$)



V. Singh (WIN 2019)

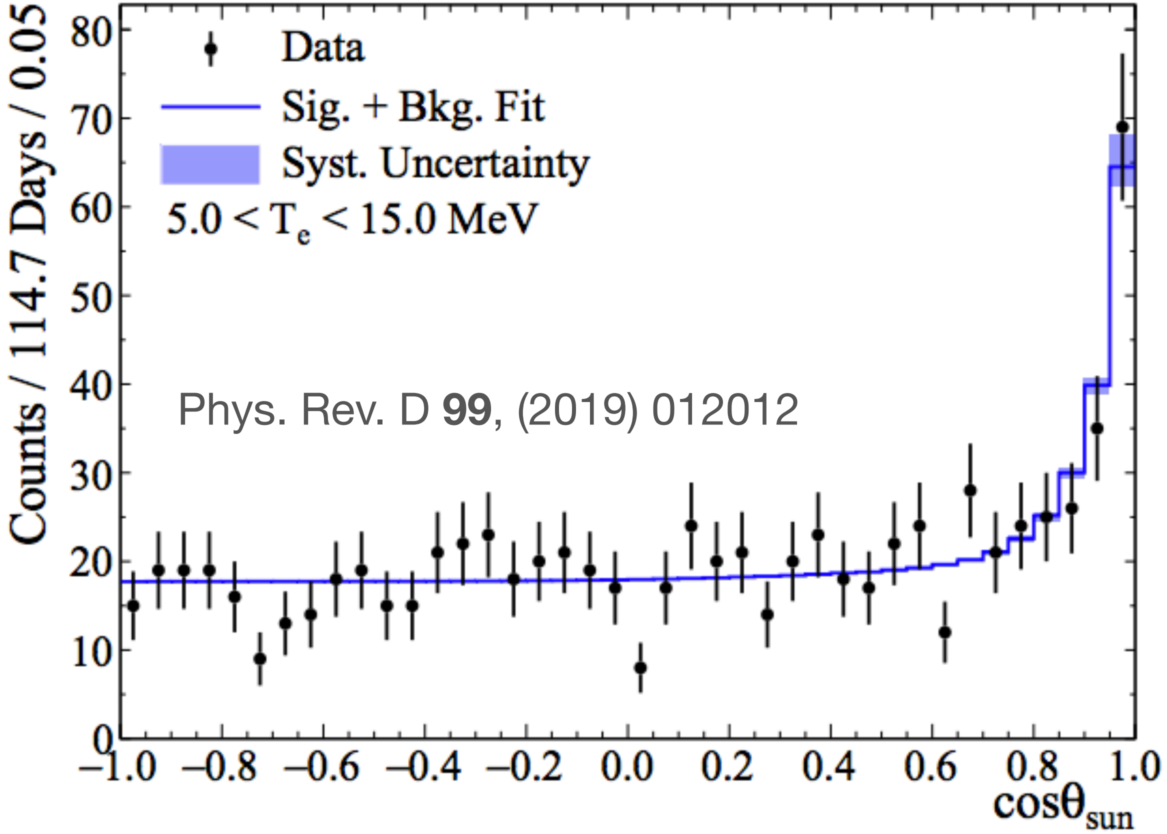
# $^{130}$Te Liquid Scintillator: SNO+



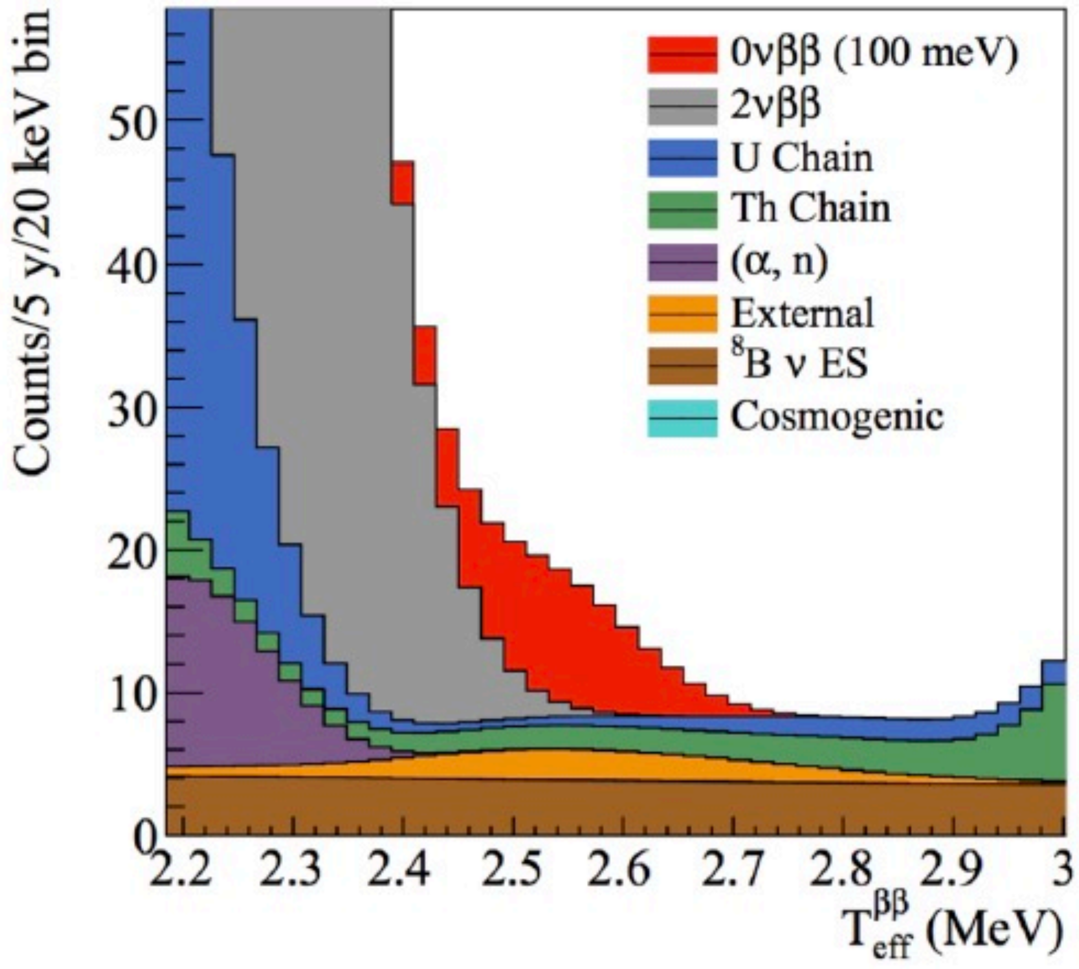
**Liquid scintillator being filled**

- 3.9 t Te
- 780 t LAB(+PPO+Te-ButaneDiol)
- 0.5% loading → 1300 kg $^{130}$Te

**Pure $H_2O$ running**

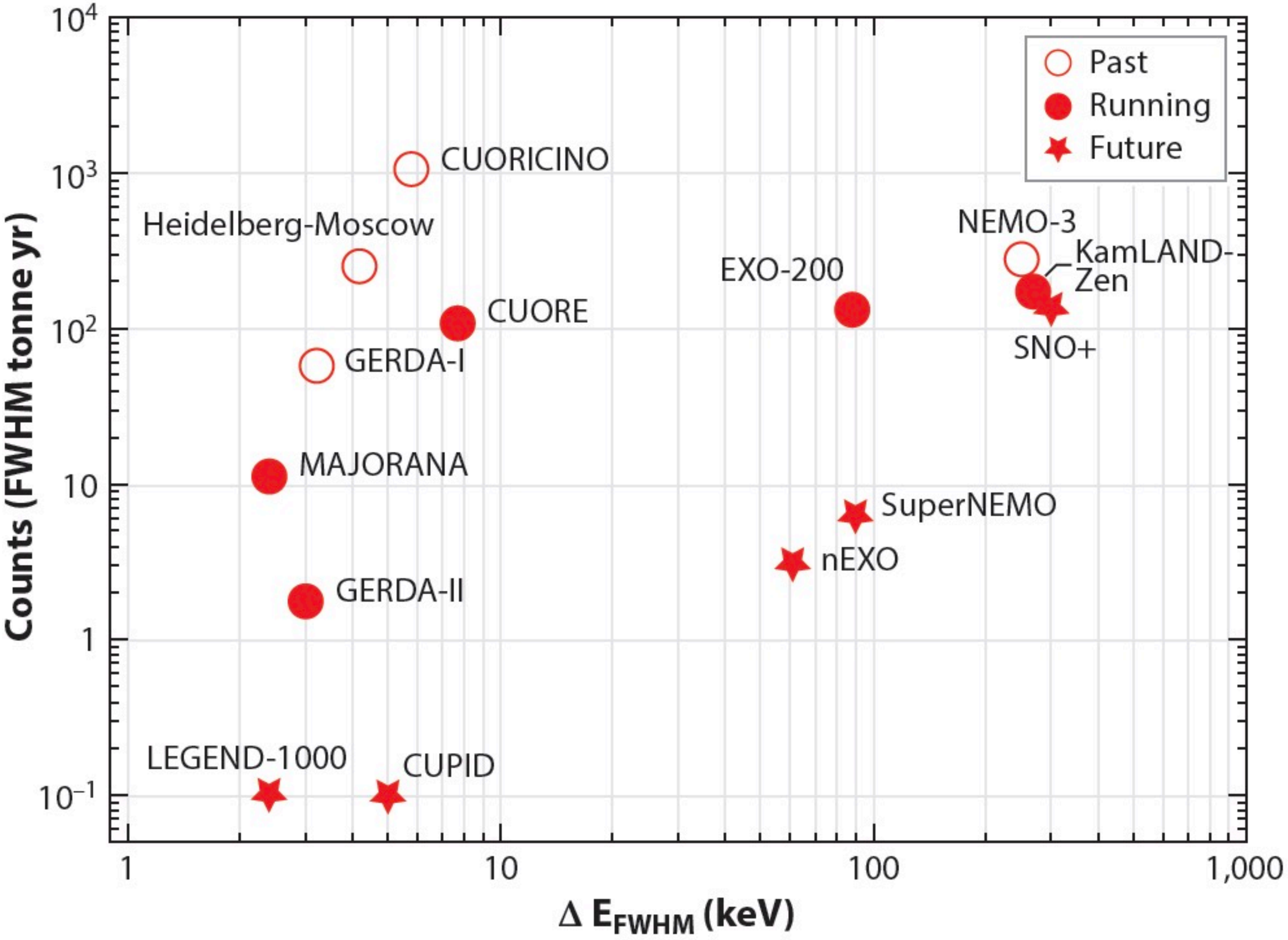


Phys. Rev. D **99**, (2019) 012012



# Comparing the experiments

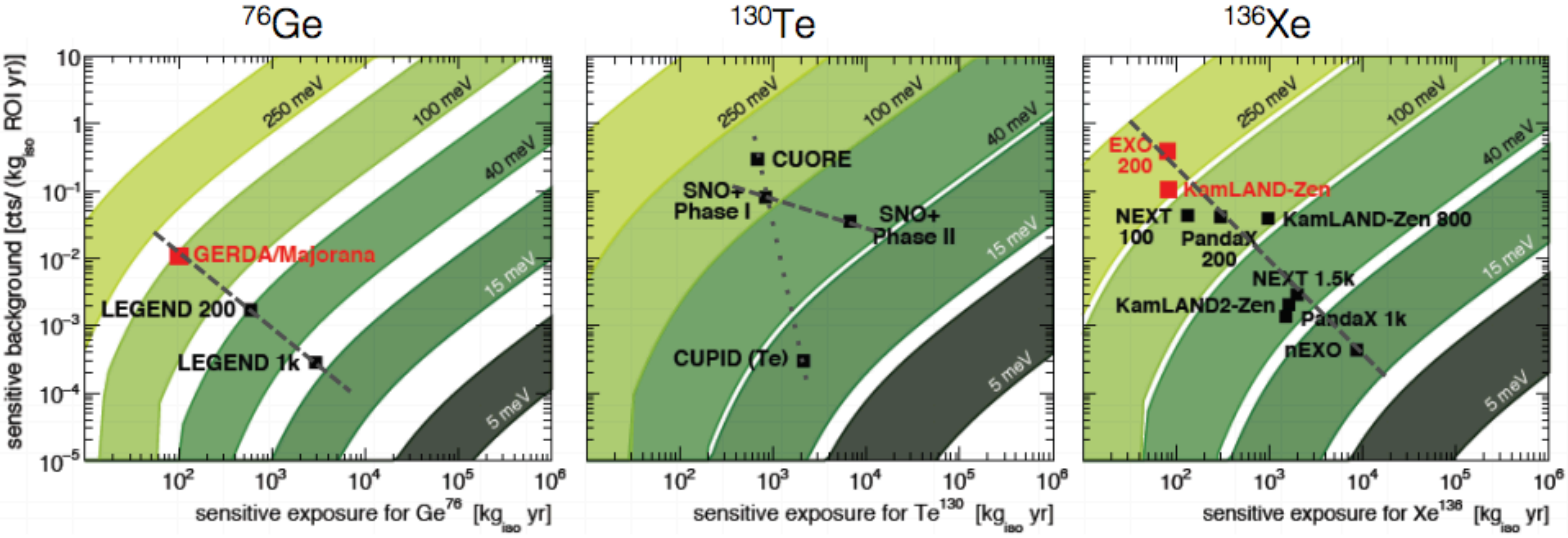
$$T_{1/2}^{0\nu}(\mathrm{FOM}) \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$



M. Dolinski, AP, W. Rodejohann (2019)

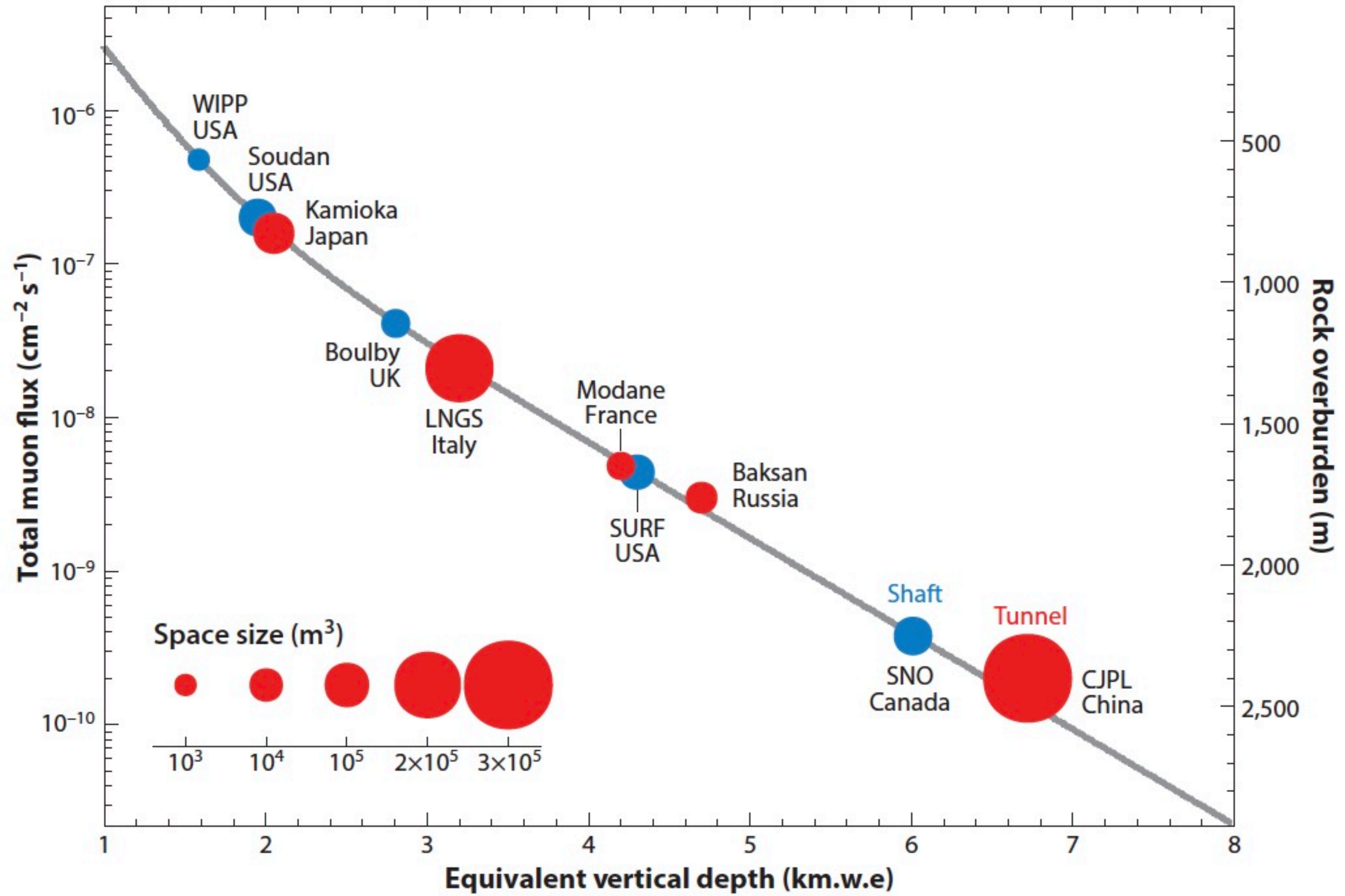
# Discovery sensitivity ("vanilla")

**Discovery sensitivity: >50% chance of seeing a 3σ signal**



Agostini, Benato & Detwiler, Phys. Rev. D **96**, 053001 (2017)

# Underground facilities



J.P. Cheng et al, Ann. Rev. Nucl. Part. Sci. (2017)

# Summary

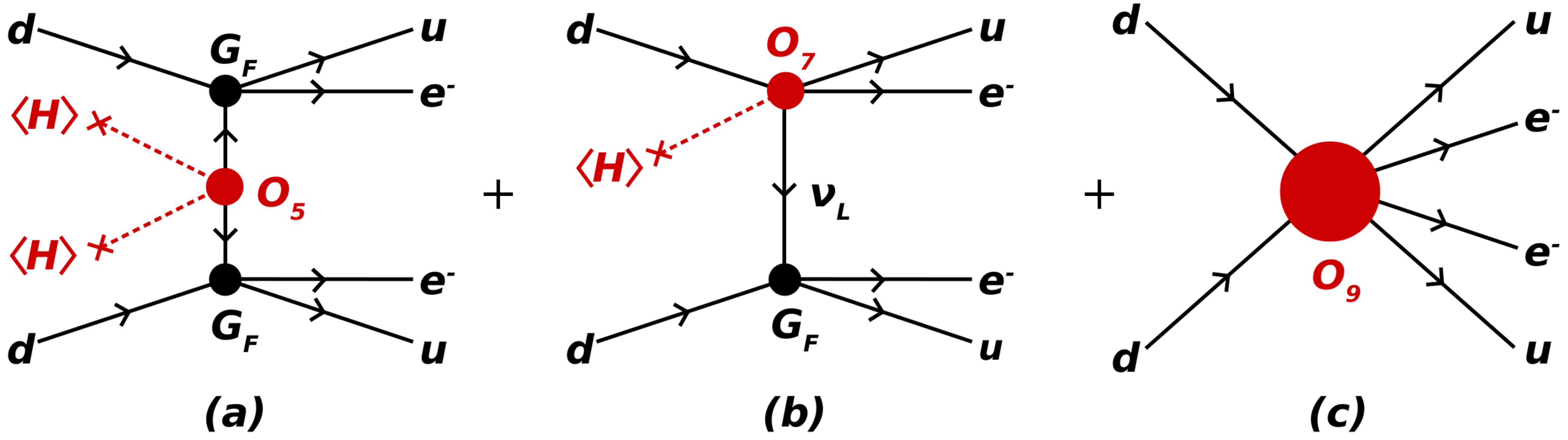
- Neutrinoless double-beta ($0\nu\beta\beta$) decay experiments are the most "practical" way to search for lepton-number violation.
- There are strengths and weaknesses in each of candidate detector technology for the ton-scale $0\nu\beta\beta$ decay experiment(s).
- The current generation of $0\nu\beta\beta$ experiments have already reached a half-life limit > ~$10^{26}$ years; the next generation of experiments target a discovery potential with half-life > ~$10^{28}$ years.

# What are the possibilities inside the black box?

$$\boxed{\Delta L = 2}$$

GUT scale / seesaw

LHC energy



Mass mechanism

“Long-range”

“Short-range”

Graphics from Hirsch 2016

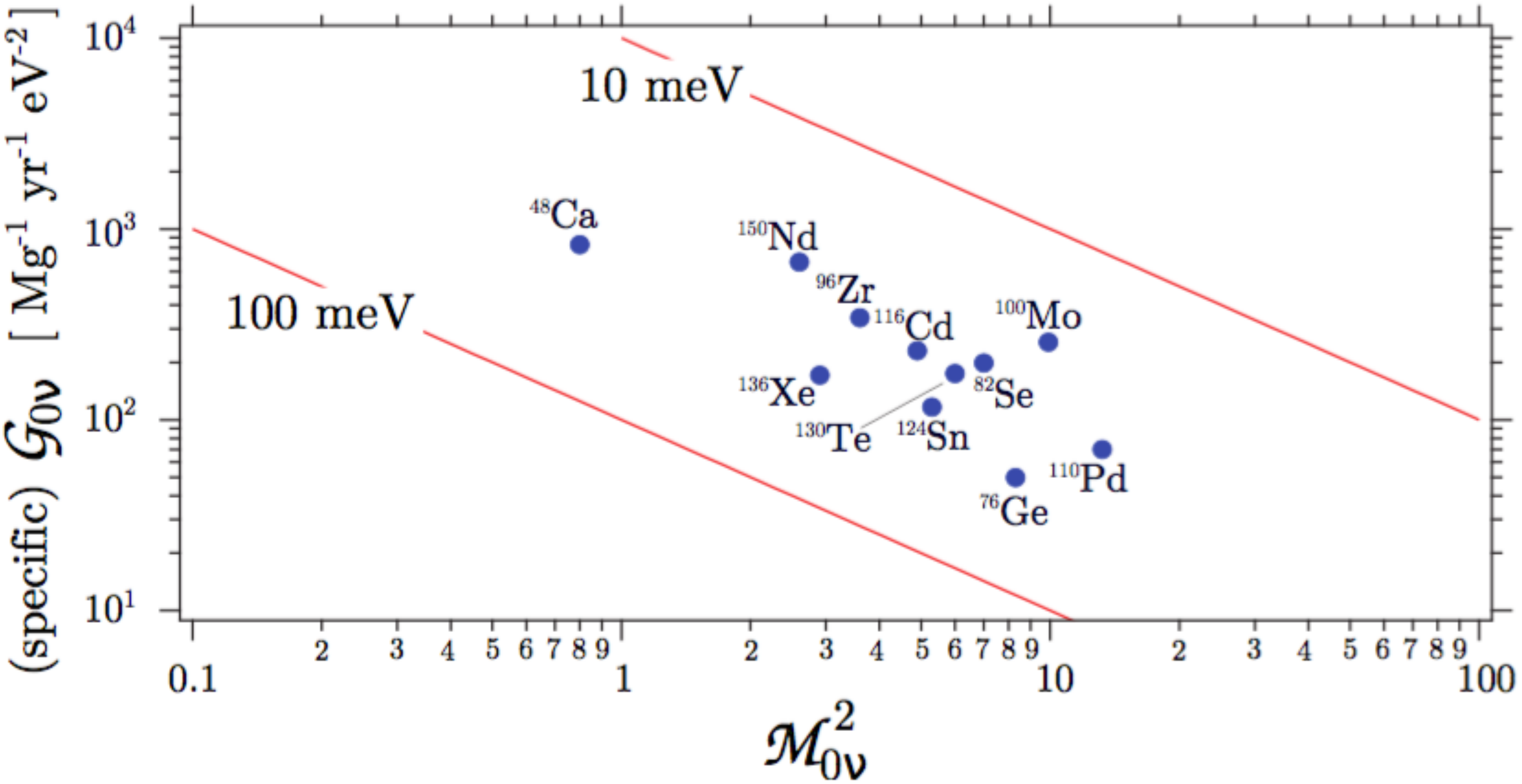
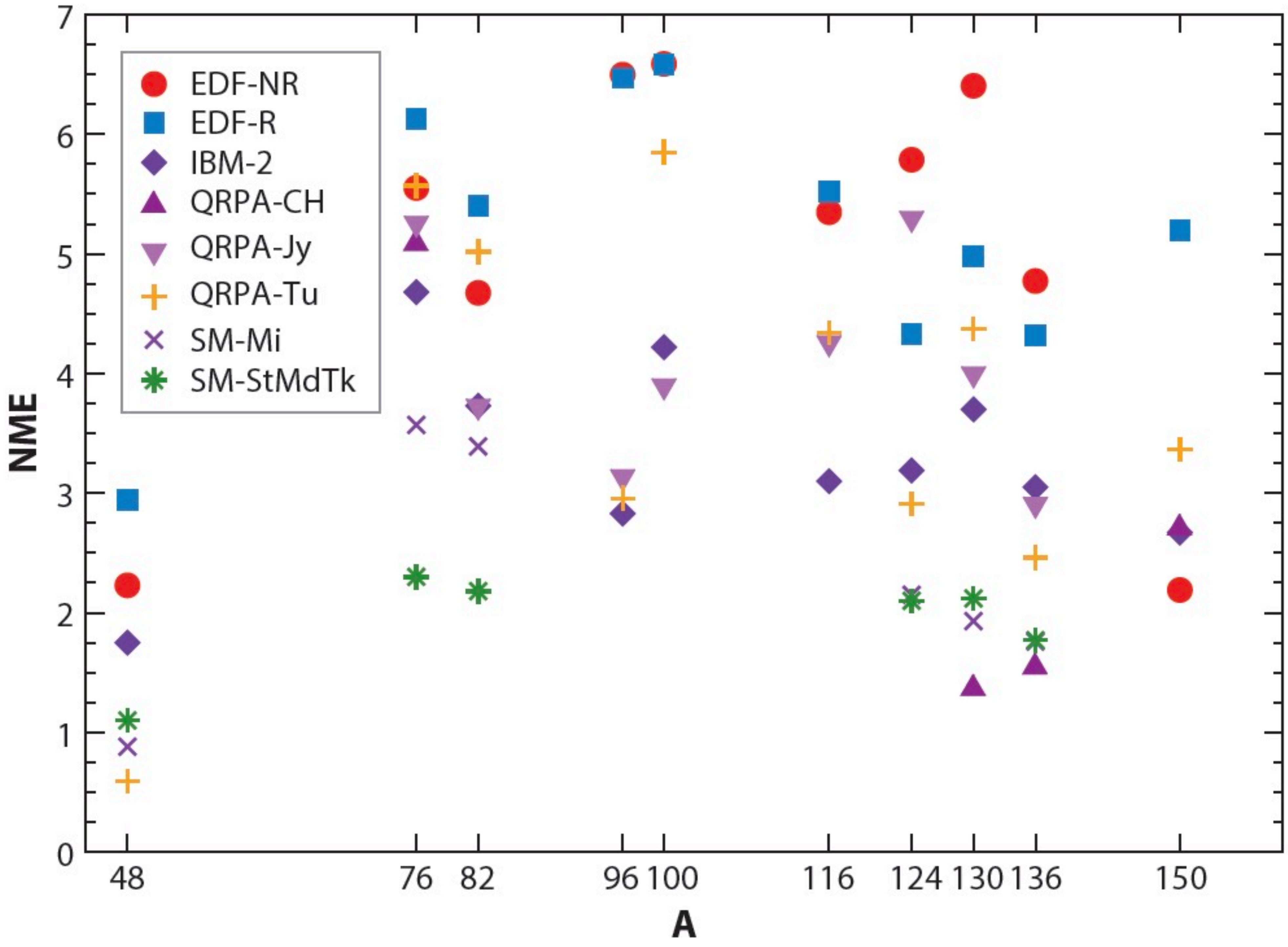


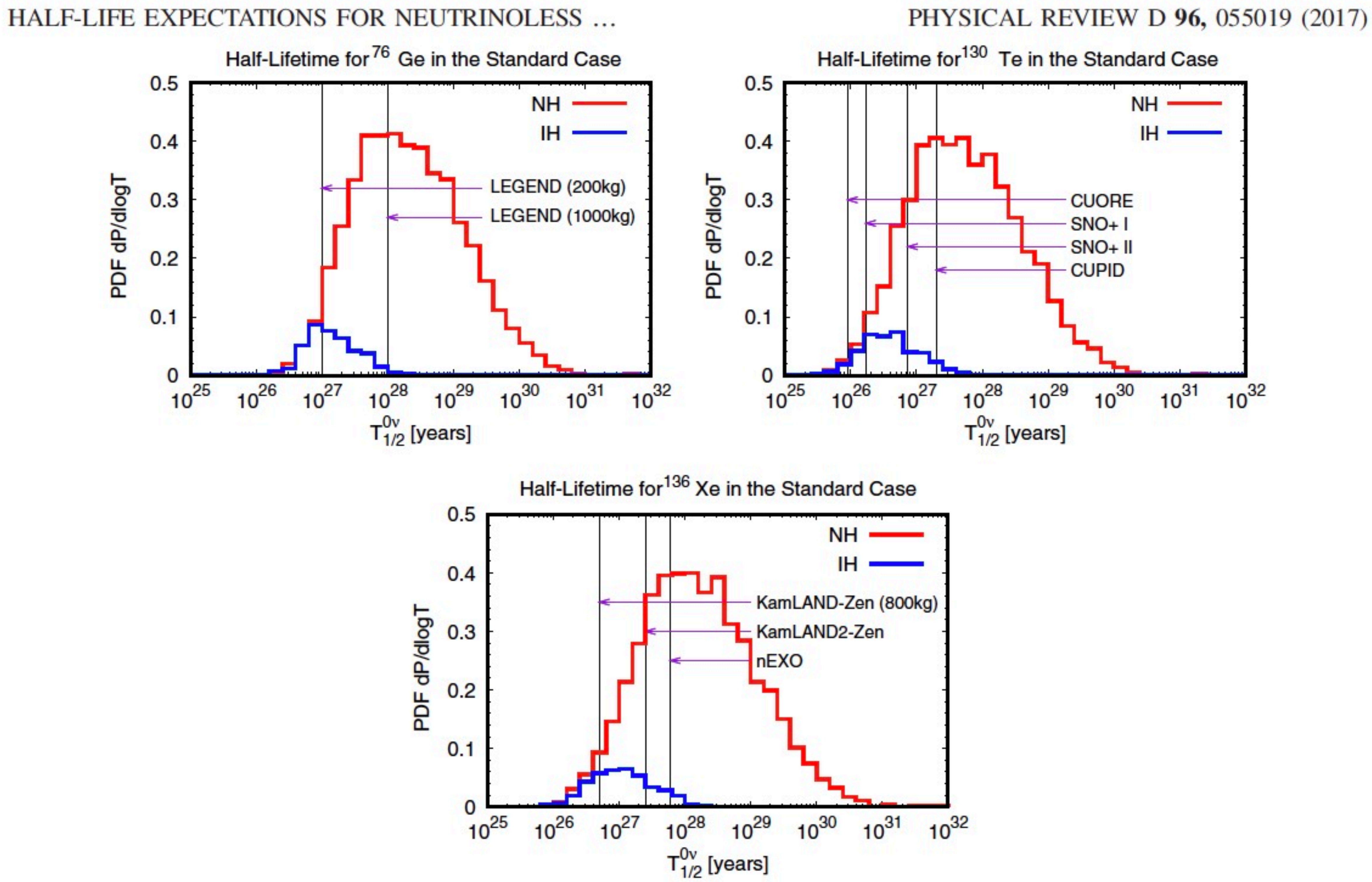
FIG. 14. Geometric mean of the squared $\mathcal{M}_{0\nu}$ considered in Ref. [174] vs. the specific $G_{0\nu}$. The case $g_A = g_{\text{quark}}$ is assumed. Adapted from Ref. [174].

Dell'Oro 2016

# Nuclear Matrix Elements



# IH vs NH

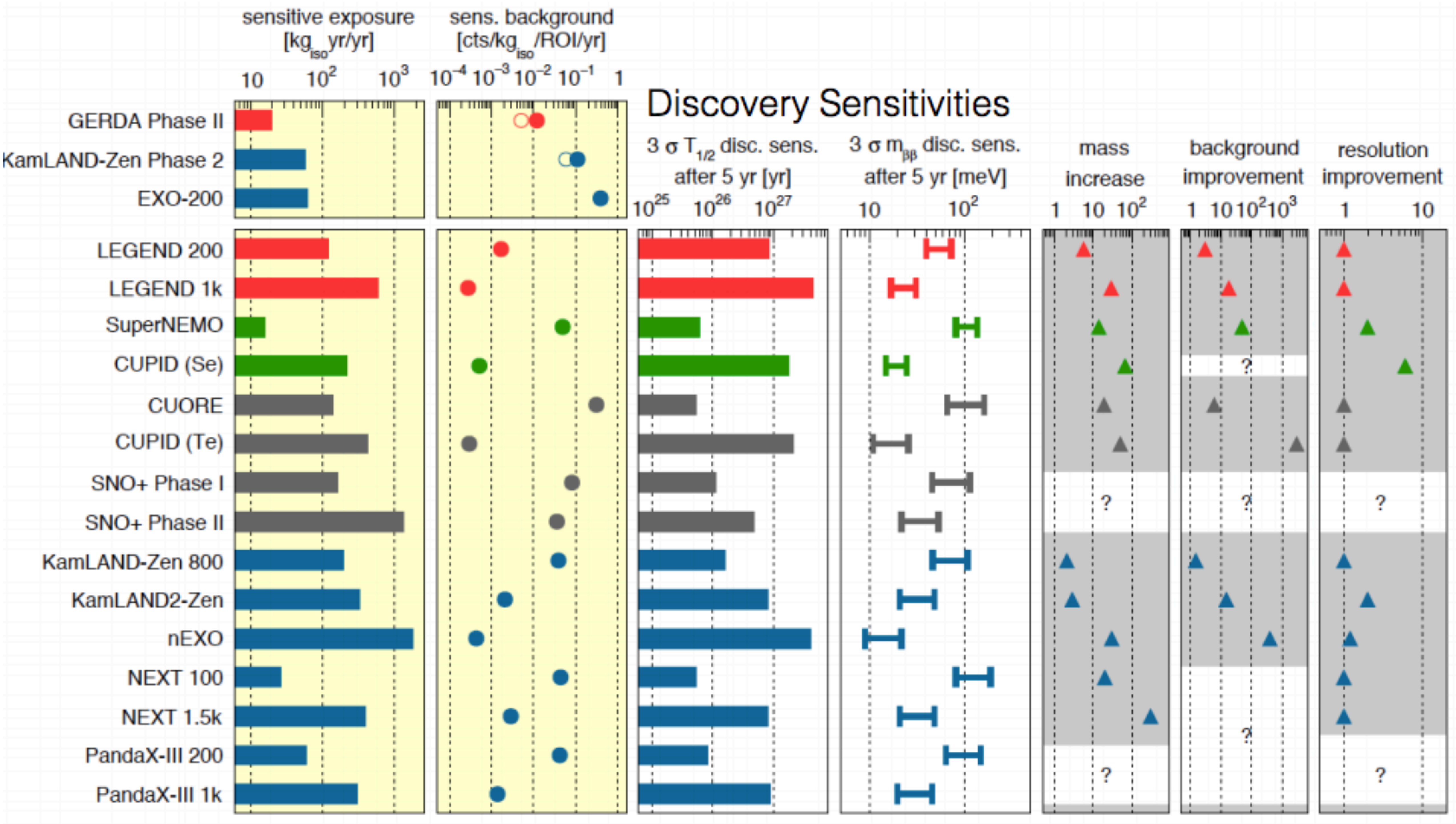


HALF-LIFE EXPECTATIONS FOR NEUTRINOLESS …

PHYSICAL REVIEW D **96,** 055019 (2017)

Ge, Rodejohann, Zuber (2017)

# Comparison of 0νββ experiments



**No clear winner! Experiments are complementary to each other.**

Schönert @TAUP2017