Double beta decay experiments-I

Or how to build a rare events experiment

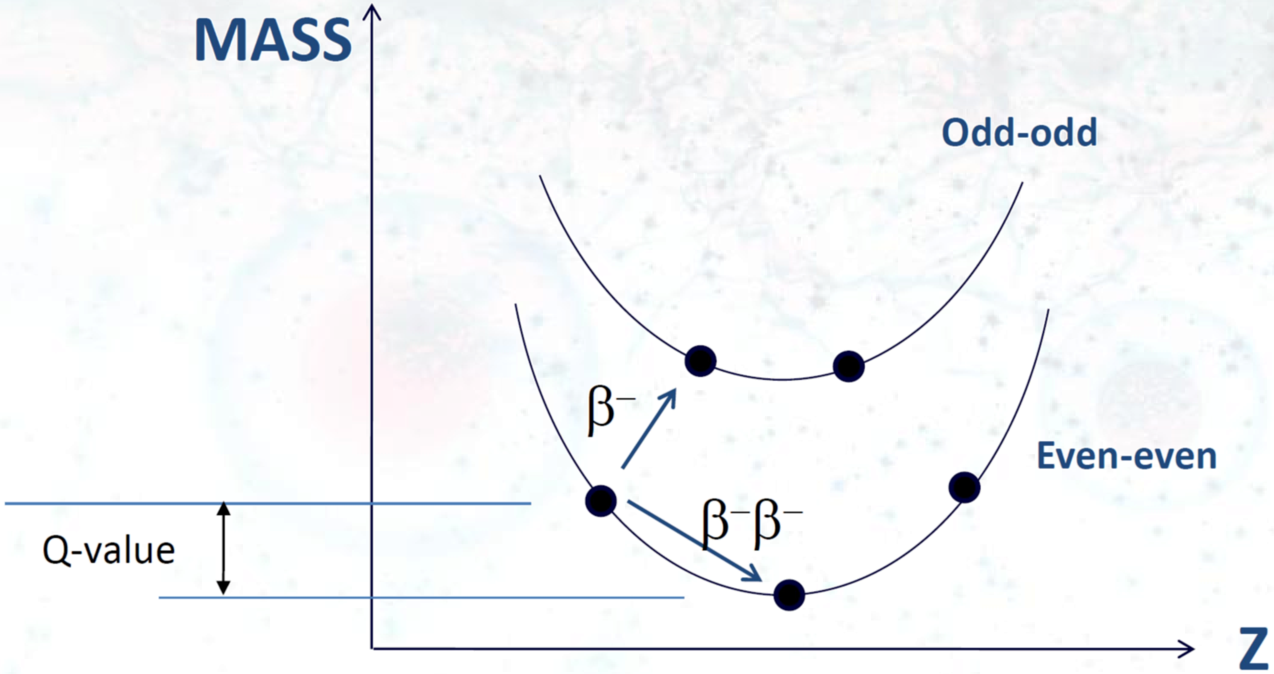
Double beta decay

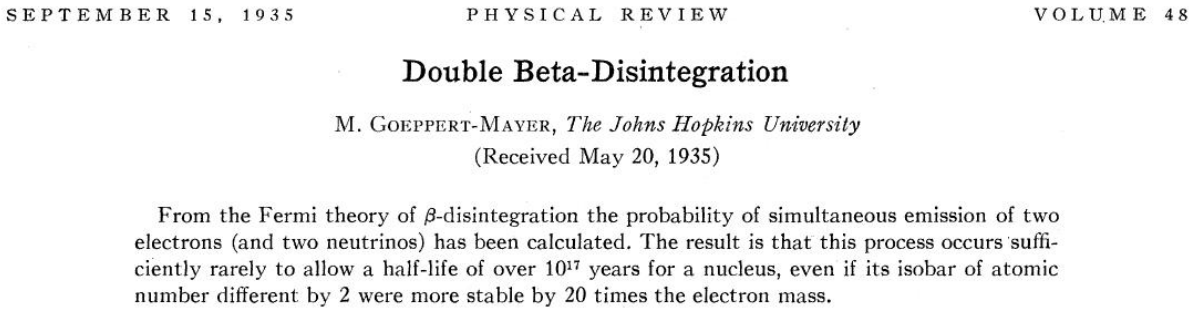
Theoretical prediction on 2ν2β: 1935

Weiszaecker's formula for the binding energy of a nucleus

$$E_B(\mathrm{MeV}) = a_v A - a_a (N - Z)^2/A - a_c Z^2/A^{1/3} - a_s A^{2/3} \overset{\text{Even-even}}{\underset{\text{Odd-odd}}{\pm}} a_\delta/A^{3/4}$$

Nuclear mass as a function of Z, **with fixed A (even)**





SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Double Beta-Disintegration

M. Goeppert-Mayer, *The Johns Hopkins University*

(Received May 20, 1935)

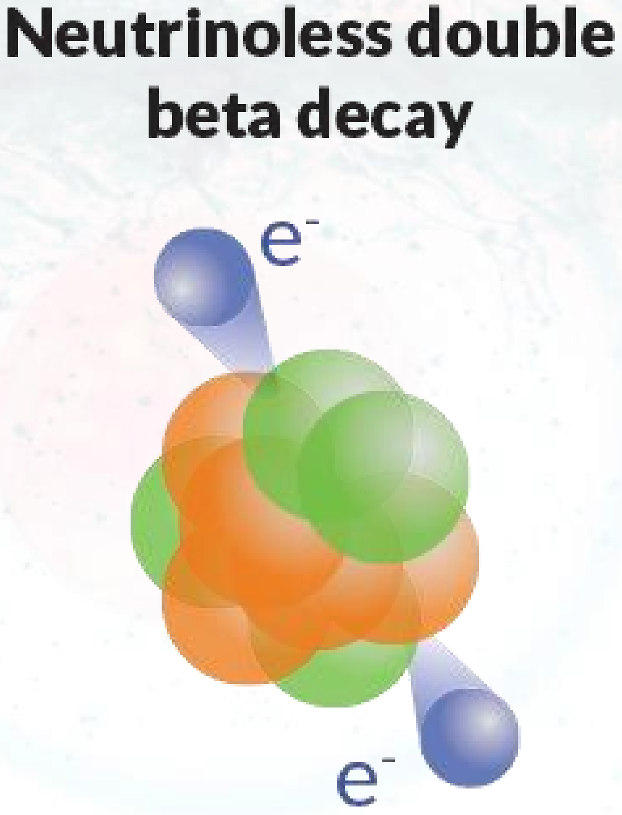
From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

Allowed in SM

Well described and understood

Physics beyond the SM

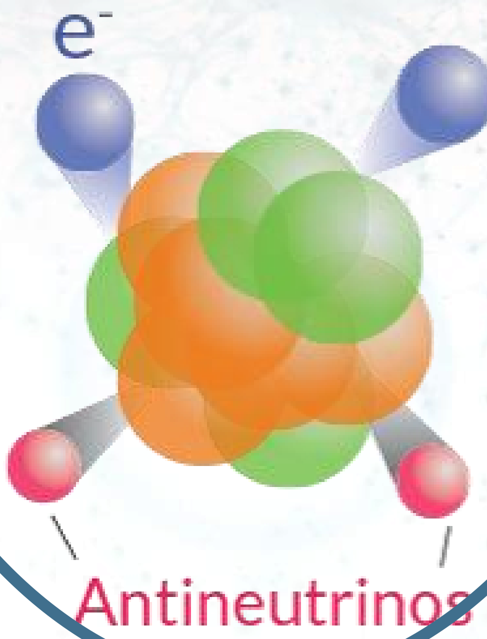
Several possible mechanisms of the process



Allowed in SM

Well described and understood

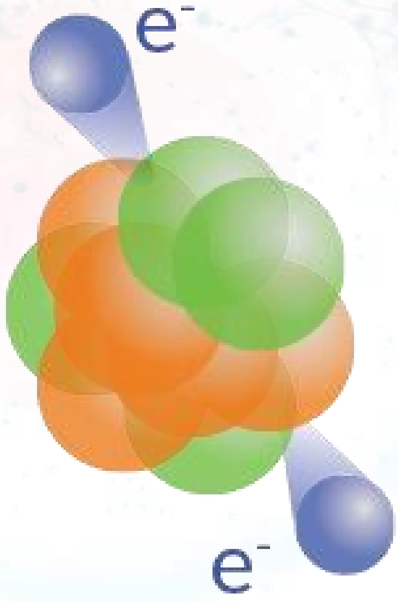
Double beta decay



Physics beyond the SM

Several possible mechanisms of the process

Neutrinoless double beta decay



Allowed by SM double decay modes

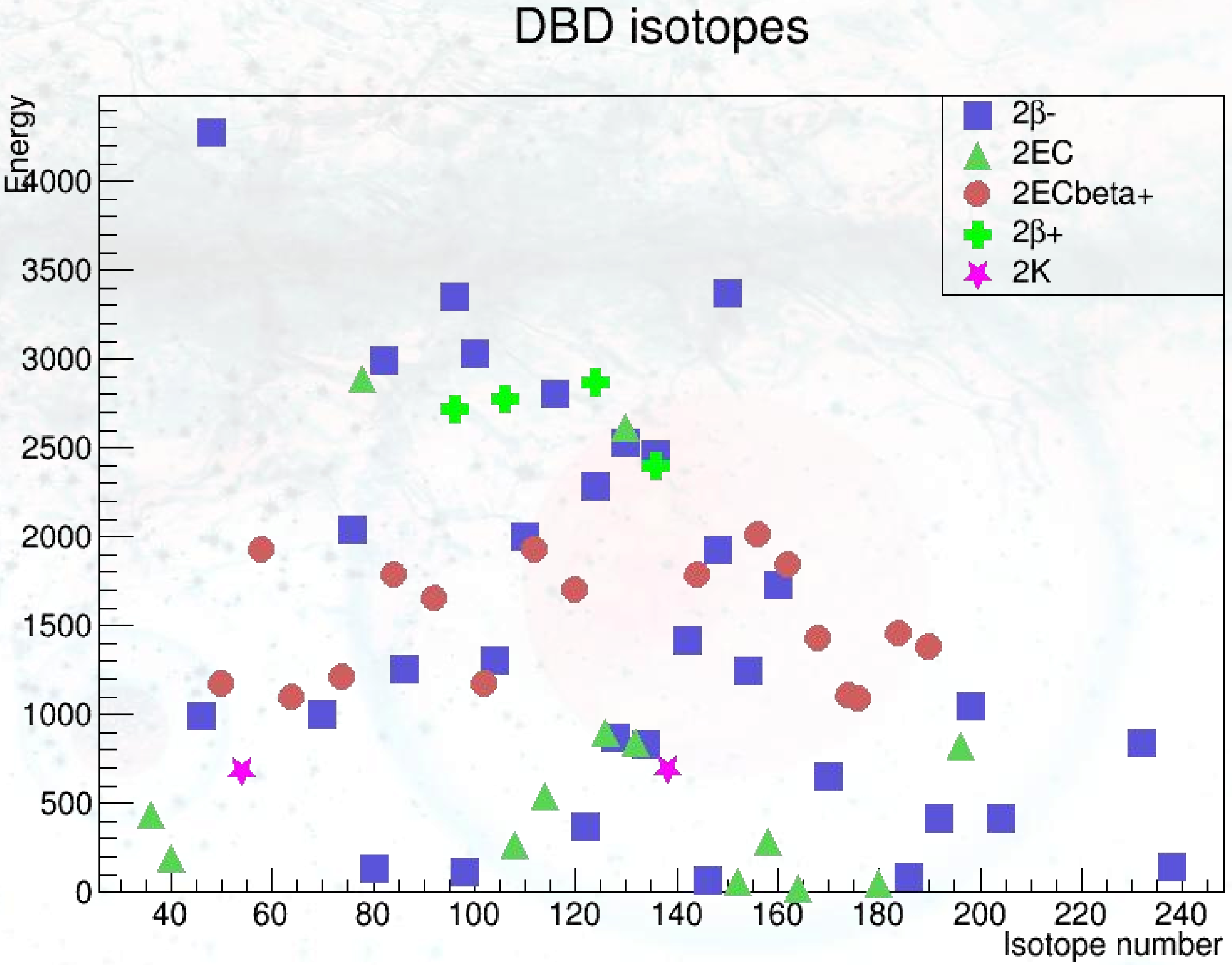
- Allowed when single beta decay is forbidden energetically or suppressed
- Requires even-even nuclei

$$\beta^-\beta^- : (\mathrm{A}, \mathrm{Z}) \rightarrow (\mathrm{A}, \mathrm{Z}+2) + 2e^- + 2\bar{\nu}_e\,, \qquad \text{Very rare}$$

$$\left.\begin{array}{r} \beta^+\beta^+ : (\mathrm{A}, \mathrm{Z}) \rightarrow (\mathrm{A}, \mathrm{Z}-2) + 2e^+ + 2\nu_e\,, \\ \mathrm{ECEC} : 2e^- + (\mathrm{A}, \mathrm{Z}) \rightarrow (\mathrm{A}, \mathrm{Z}-2) + 2\nu_e\,, \\ \mathrm{EC}\beta^+ : e^- + (\mathrm{A}, \mathrm{Z}) \rightarrow (\mathrm{A}, \mathrm{Z}-2) + e^+ + 2\nu_e \end{array}\right\} \text{Even more rare}$$

Double beta decay landscape

- More than 70 isotopes can undergo sertain mode of 2b decay…



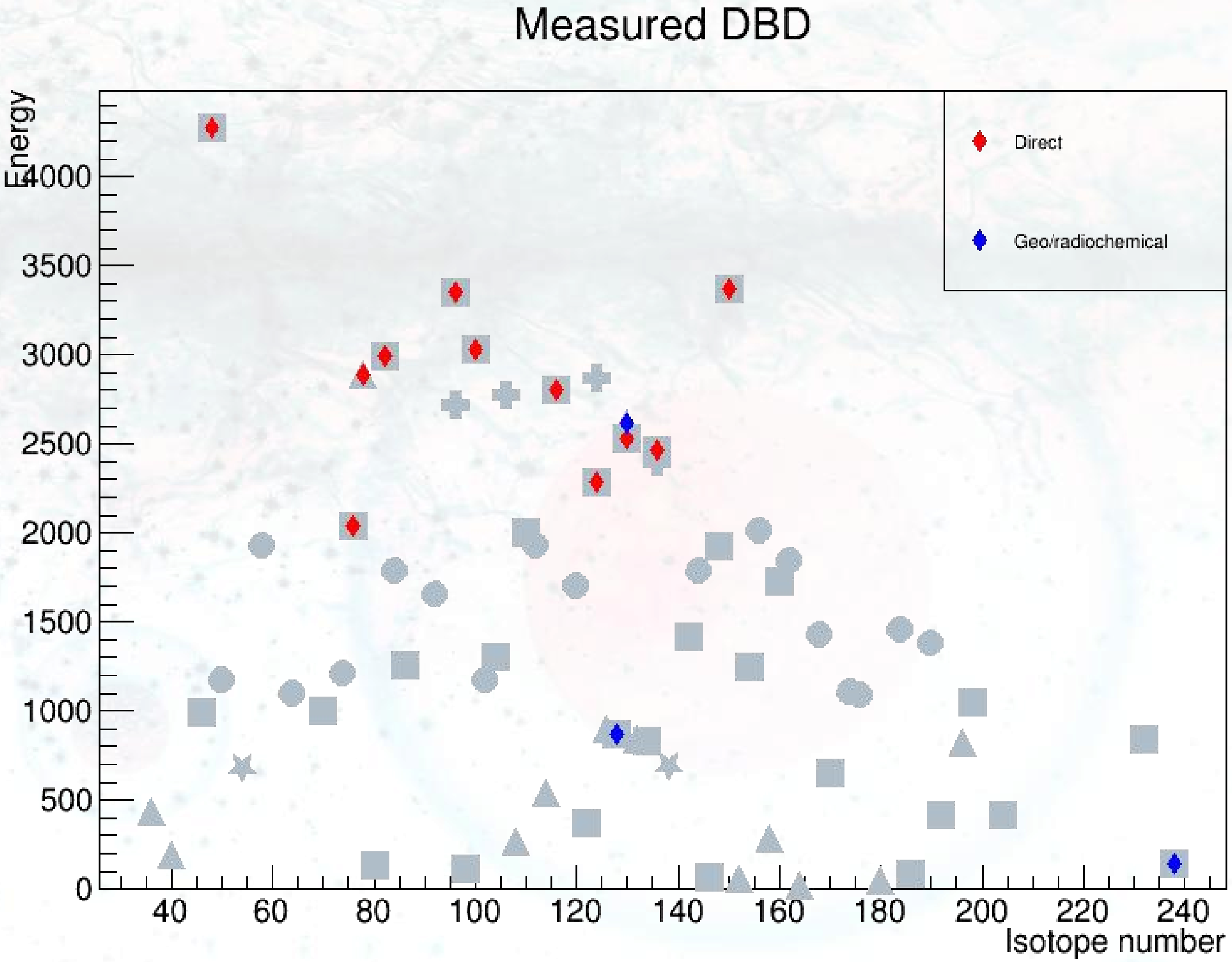
Tables of double beta decay data: An update
V.I. Tretyak (Kiev, INR), Yuri G. Zdesenko (Kiev, INR)
DOI: 10.1006/adnd.2001.0873
Atom.Data Nucl.Data Tabl. 80 (2002), 83-116

Double beta decay landscape

- More than 70 isotopes can undergo sertain mode of 2b decay...

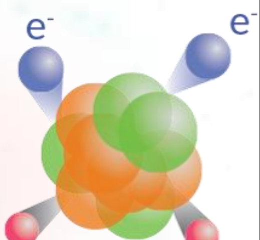
- But so far only small fraction is used in experiments

- Very complicated for measurements due to rarity and backgrounds

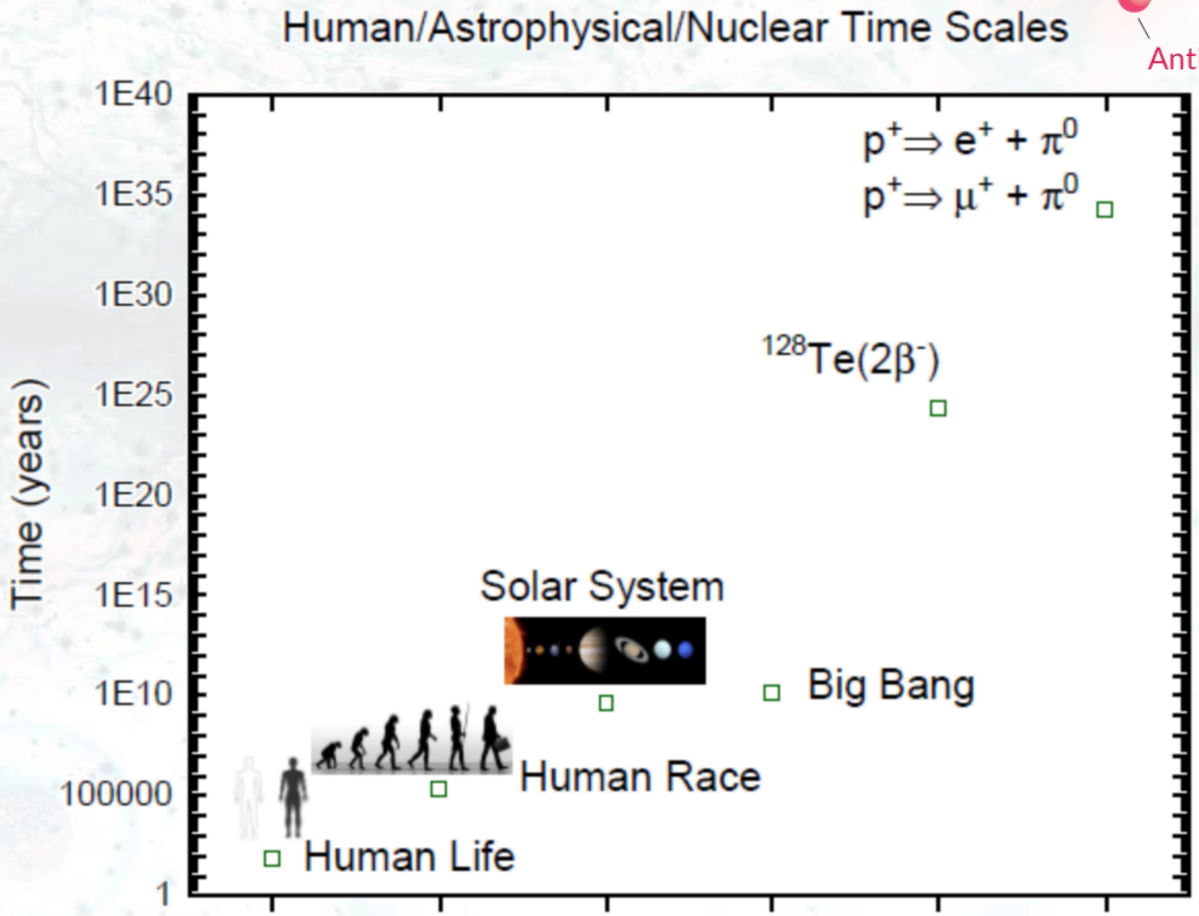


[Tables of double beta decay data: An update](https://doi.org/10.1006/adnd.2001.0873)
V.I. Tretyak (Kiev, INR), Yuri G. Zdesenko (Kiev, INR)
DOI: 10.1006/adnd.2001.0873
Atom.Data Nucl.Data Tabl. 80 (2002), 83-116

Two-neutrino mode of double beta decay



- Second-order process -> strongly supressed, very long half-lifes
- First direct observation in 1987
- Half-lifes 10^{19}-10^{24} yrs

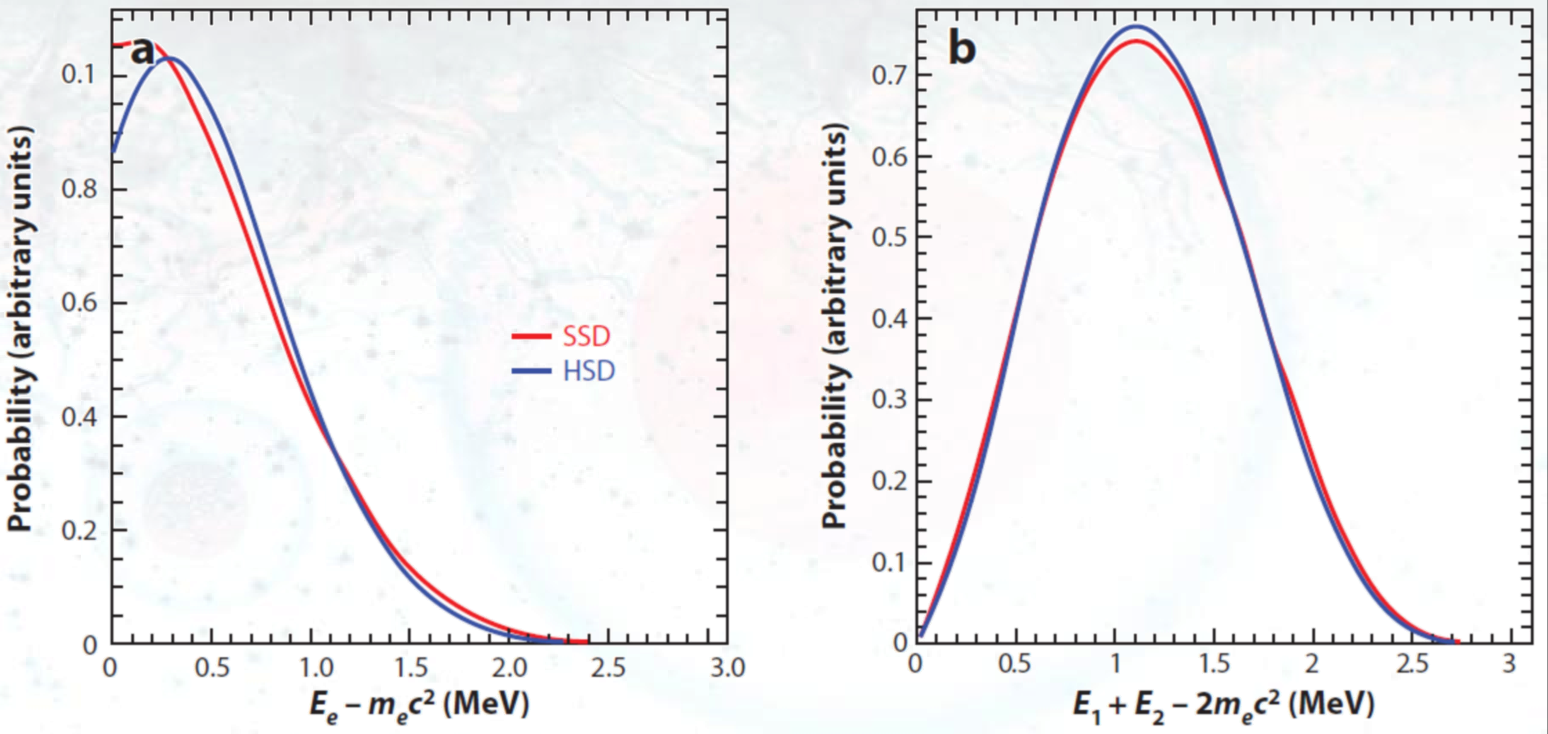


B. Pritychenko, Nucl. Phys. A 1033 (2023) 122628

Why it is interesting anyway?

Nuclear models: $2\nu2\beta$ decay is described by two virtual β decay transitions:

- Single state dominance:
  1. the ground state of the initial nucleus to 1^+_1 intermediate state
  2. from the 1^+_1 state to the final ground state
- Higher state dominance:
  - Same idea, but higher intermediate states
- Important for detailing the nuclear structure models



R. Saakyan, Two-Neutrino Double-Beta Decay, Ann. Rev. of Nuclear and Particle Science 2013 63:1, 503-529

Why it is interesting anyway?

- Insights for the nuclear structure models
- Information for nuclear matrix elements evaluation

$$\Gamma^{2\nu} = \frac{1}{T^{2\nu}_{1/2}} = G^{2\nu}(Q_{\beta\beta}, \mathrm{Z})|M^{2\nu}|^2$$

Phase space, calculated exactly:

$$G^{2\nu} \propto \int_{m_e}^{E_0-m_e} F(\mathrm{Z}, E_{e1}) p_{e1} E_{e1} \mathrm{d}E_{e1} \times \int_{m_e}^{E_0-E_{e1}} F(\mathrm{Z}, E_{e2}) p_{e2} E_{e2} \mathrm{d}E_{e2} \\ \times \int_{0}^{E_0-E_{e1}-E_{e2}} p_{\nu1}^2 (E_0 - E_{e1} - E_{e2} - p_{\nu1})^2 \mathrm{d}p_{\nu1},$$

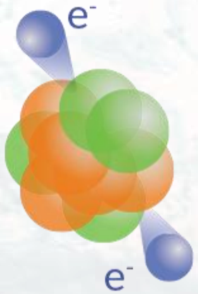
$$G^{2\nu} \propto Q_{\beta\beta}^{11}$$

Nuclear matrix elements, difficult to evaluate

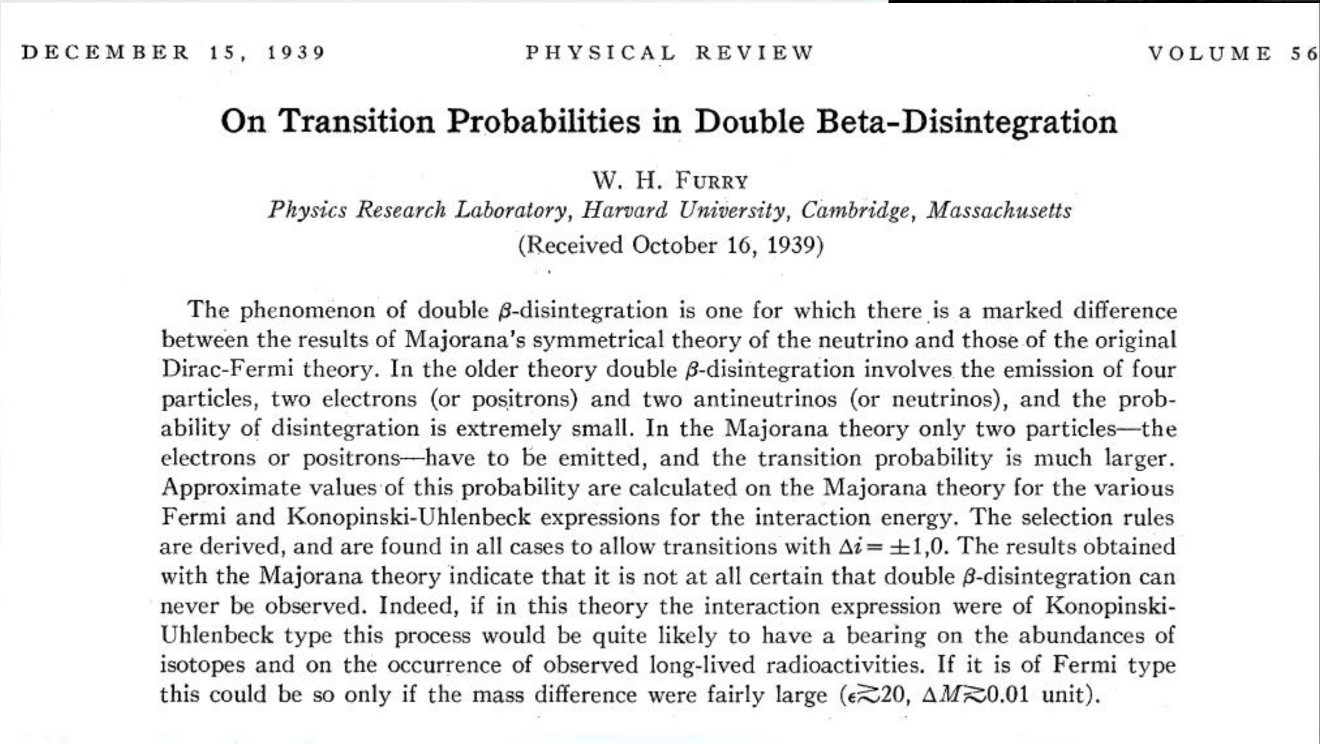
$$M^{2\nu}_{\mathrm{GT}} = \sum_{m} \frac{\langle 0_f^+ || \tau^+ \sigma || 1_m^+ \rangle \langle 1_m^+ || \tau^+ \sigma || 0_i^+ \rangle}{E_m - (M_i + M_f)/2}$$

Neutrinoless double beta decay

- Proposed by Furry in 1939 following Majorana theory on truly neutral particles (particle=antiparticle)



- Gained larger interest after neutrino oscillations discovery



DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

On Transition Probabilities in Double Beta-Disintegration

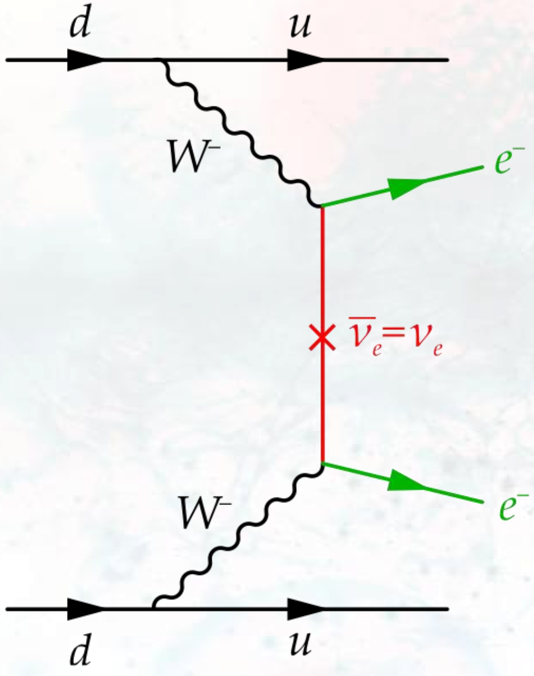
W. H. Furry
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts

(Received October 16, 1939)

The phenomenon of double β-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double β-disintegration involves the emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability of disintegration is extremely small. In the Majorana theory only two particles—the electrons or positrons—have to be emitted, and the transition probability is much larger. Approximate values of this probability are calculated on the Majorana theory for the various Fermi and Konopinski-Uhlenbeck expressions for the interaction energy. The selection rules are derived, and are found in all cases to allow transitions with $\Delta i = \pm 1, 0$. The results obtained with the Majorana theory indicate that it is not at all certain that double β-disintegration can never be observed. Indeed, if in this theory the interaction expression were of Konopinski-Uhlenbeck type this process would be quite likely to have a bearing on the abundances of isotopes and on the occurrence of observed long-lived radioactivities. If it is of Fermi type this could be so only if the mass difference were fairly large ($\epsilon \gtrsim 20$, $\Delta M \gtrsim 0.01$ unit).

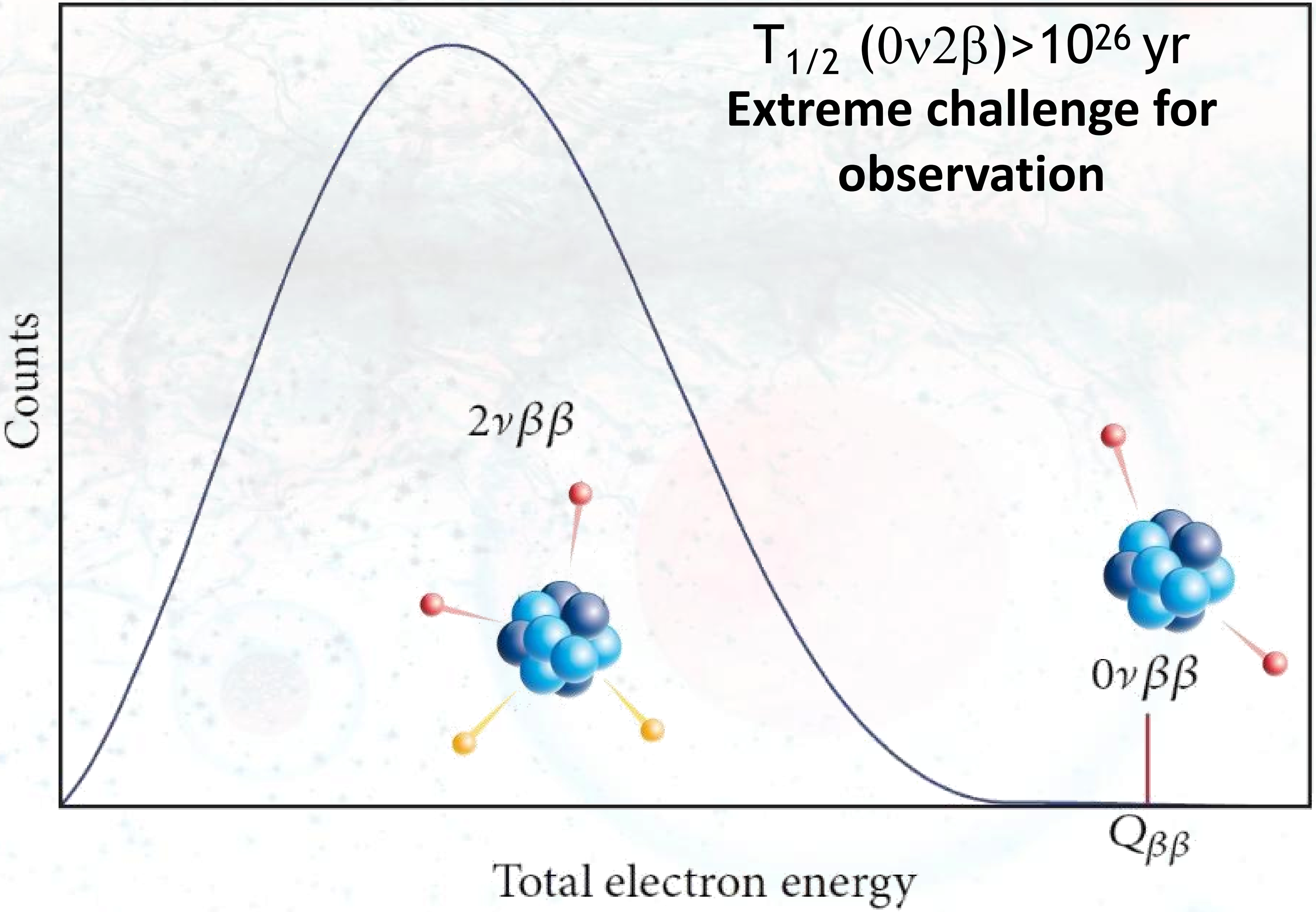
Neutrinoless double beta decay

$(A,Z) \rightarrow (A,Z+2) + 2e^-$



Total lepton number violation →
new physics beyond SM

$T_{1/2}$ $(0\nu2\beta)$>10^{26} yr
Extreme challenge for observation

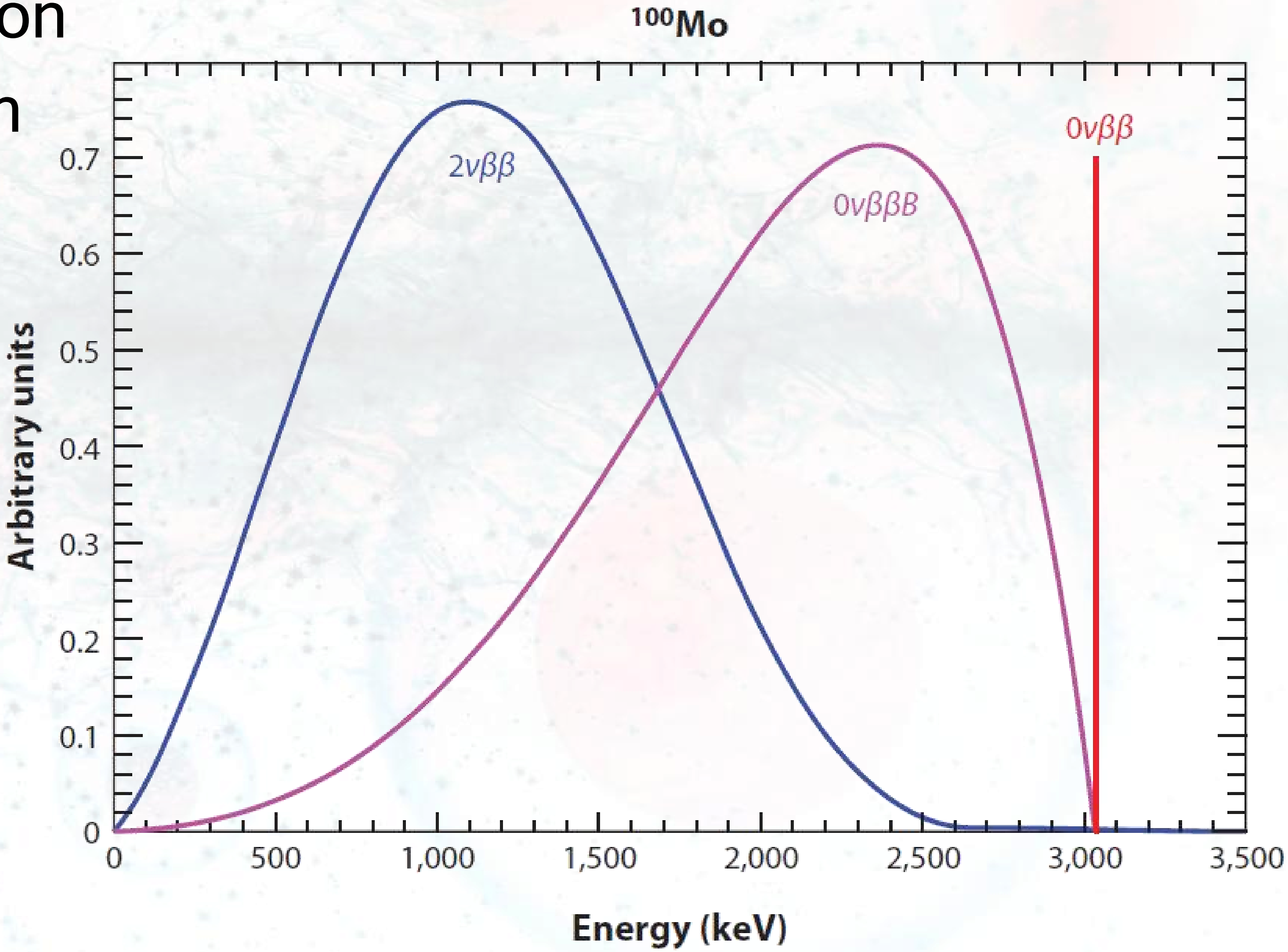


Neutrinoless double beta decay: exotic modes

- Hypothetical Goldstone boson
- Introduced to mediate lepton number violation

$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + \chi^{0}(+\chi^{0})$$

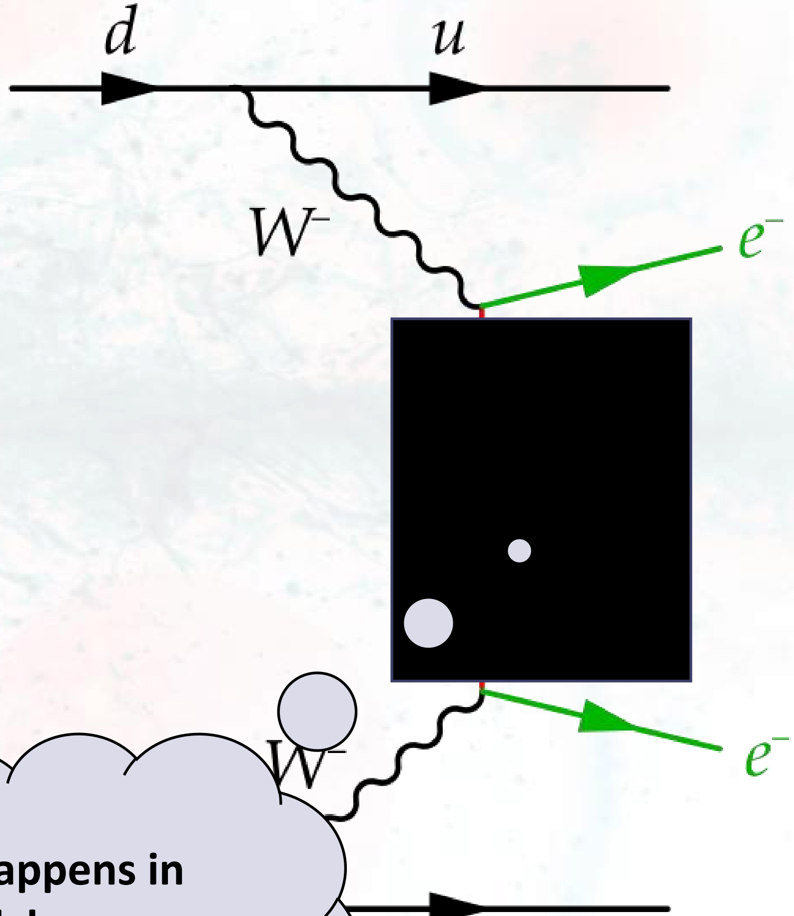
$$[T_{1/2}(0\nu\chi^{0})]^{-1} = G_{0\nu\chi^{0}} g_{A}^{4} \langle g_{ee} \rangle^{2} \mid M_{0\nu} \mid^{2}$$



Neutrino properties in abcence of neutrinos

What do we learn in case of observation?

- Neutrinos are Majorana particles, not Dirac
- Fix the neutrino mass scale
- Confirm lepton number violation - new physics beyond the Standard Model



Whatever happens in the black box, neutrinos are Majorana particles!

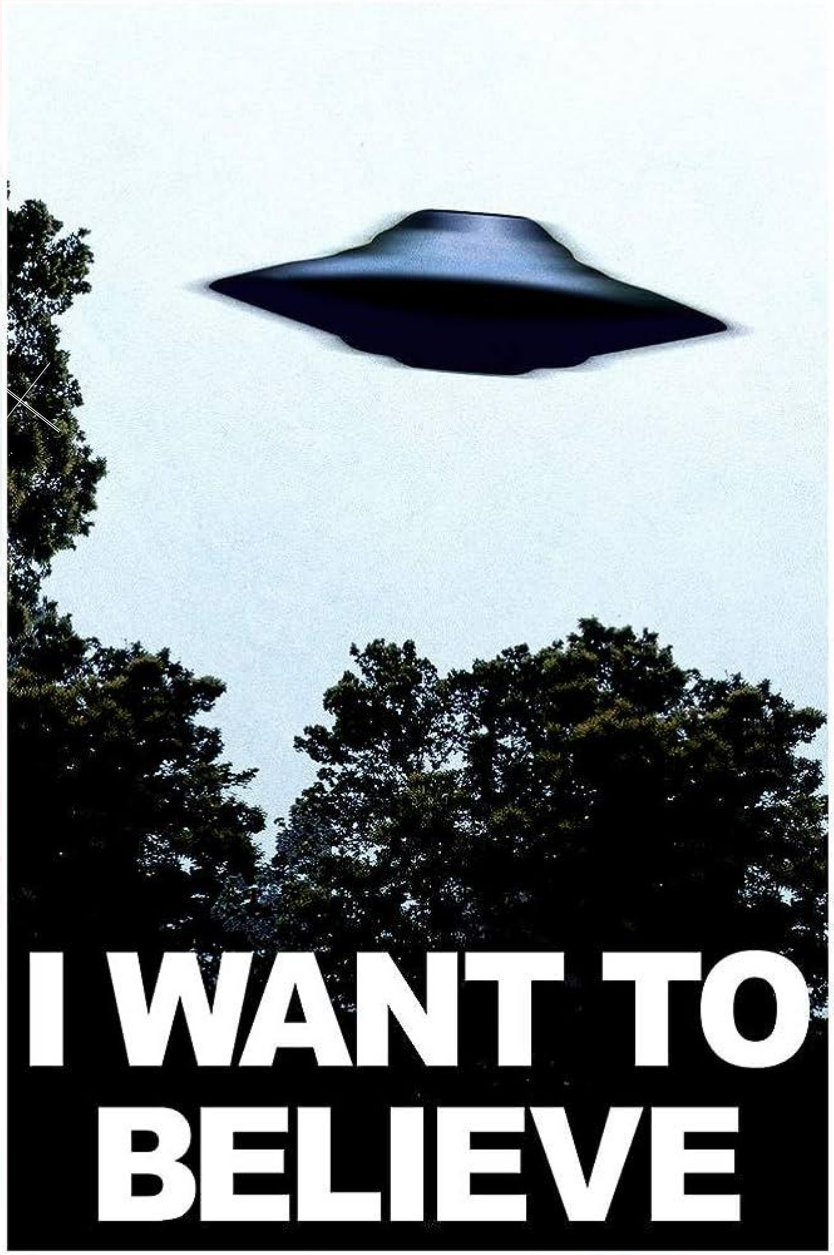
Why we think neutrinoless mode should exist?

- Natural extension of Standard Model, with Majorana mass term (in addition to Higgs mechanism)

- Two-component field -the most economical

- Explain smallness of neutrino masses (See-saw mechanism)

- Can explain matter / antimatter asymmetry in the Universe (Leptogenesis, Sakharov conditions)



Neutrinoless double beta decay rate

$$(T^{0\nu2\beta}_{1/2})^{-1} = \boxed{G(Q,Z)}\boxed{g_A^4}\boxed{|NME|^2}\left(\frac{\boxed{m_{\beta\beta}}}{m_e}\right)^2$$

Effective Majorana mass, the unknown

Phase space factor

Nuclear matrix elements

- Represent the distortion of the electronplane waves in the Coulomb field of the nucleus
- Can be calculated with high precision

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

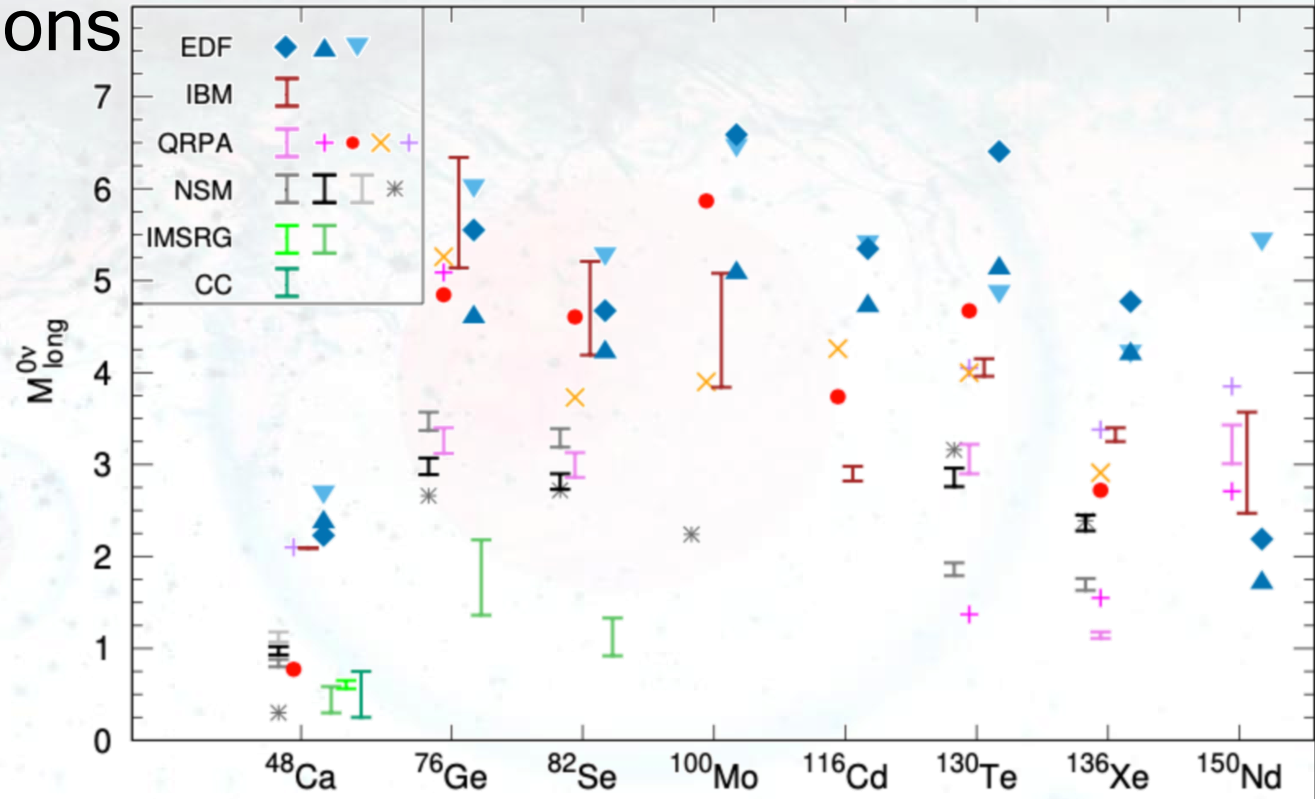
g_A is the coupling to the nucleon
hard to compute (lattice QCD) but can be measured in other decays: quenching is not defined well

- Represent nuclear structure of the initial and final nuclei
- To calculate it exactly we need the full wavefunction of the nucleus before and after the decay: $M \propto \langle N_f | J_1 J_2 | N_i \rangle$
- Main source of unsertanties for $0\nu2\beta$ experiments sensitivity

Nuclear matrix elements calculations

- Historically, phenomenological models give 2-3x scatter
- This is a complex theory problem, but a lot of new developments are underway:

- Ab initio nuclear structure calculations to solve the many-body problem
- Develop reliable uncertainty estimates for computed NMEs
- Quantify the form of the relevant decay operators in EFT
- Lattice QCD and modeling to constrain coefficients



Effective majorana mass, neutrino mass and 0n2b

$$(T^{0\nu 2\beta}_{1/2})^{-1} = G(Q,Z) g_A^4 |NME|^2 \left\langle \frac{m_{\beta\beta}}{m_e} \right\rangle^2$$

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

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} \boxed{e^{i\alpha_1/2}} & 0 & 0 \\ 0 & \boxed{e^{i\alpha_2/2}} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$|m_{\beta\beta}| = \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i\beta} \right|$$

the 0ν2β rate depends on:

- neutrino mixing angles
- neutrino masses
- mass hierarchy
- 2 totally unknown phases (in case of light Majorana neutrino exchange)

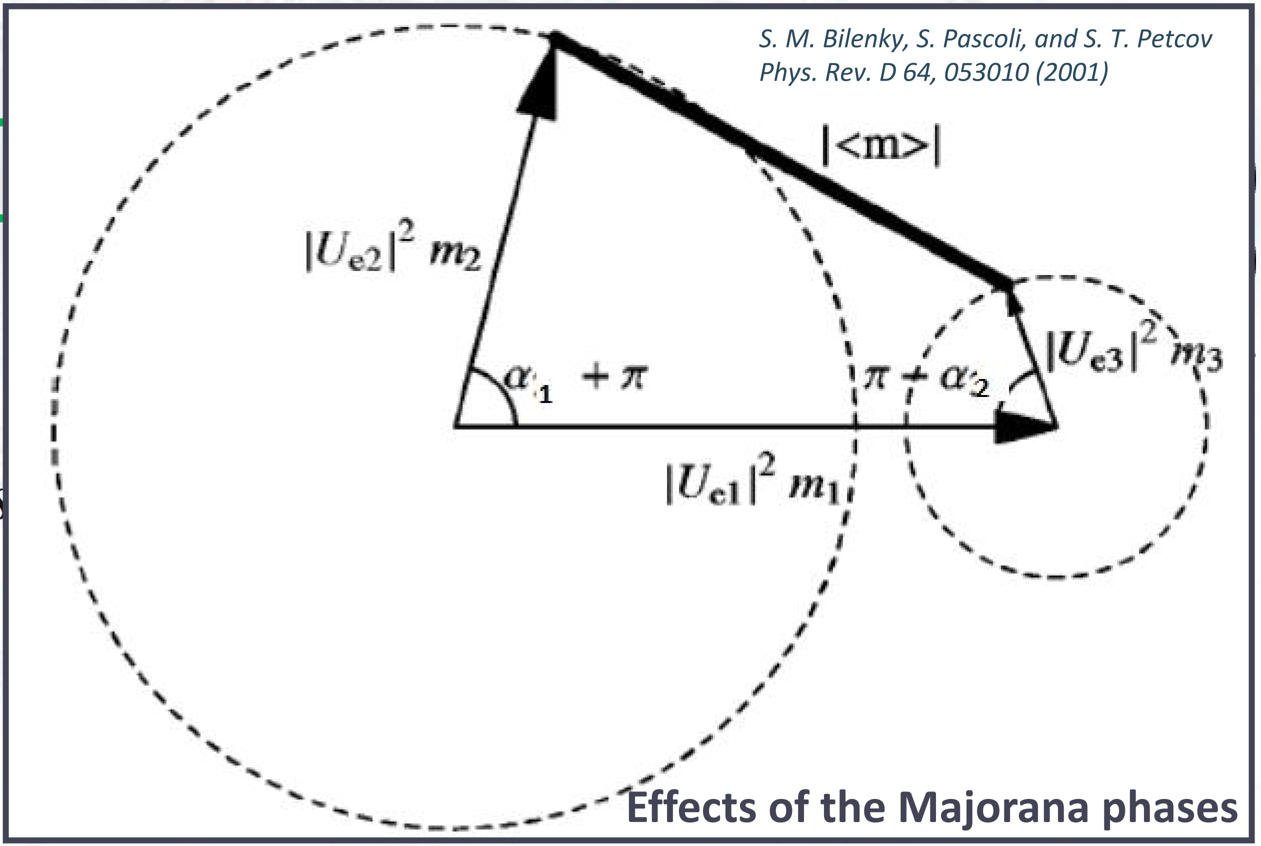
Effective majorana mass, neutrino mass and 0n2b

$$(T^{0\upsilon 2\beta}_{1/2})^{-1} = G(Q,Z)\, g_A^4 |NME|^2 \left\langle\frac{m_{\beta\beta}}{m_e}\right\rangle^2$$

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

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} \boxed{c_{12}c_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} \end{bmatrix}$$

$$|m_{\beta\beta}| = \left|c_{12}^2 c_{13}^2 m_1 + \right.$$



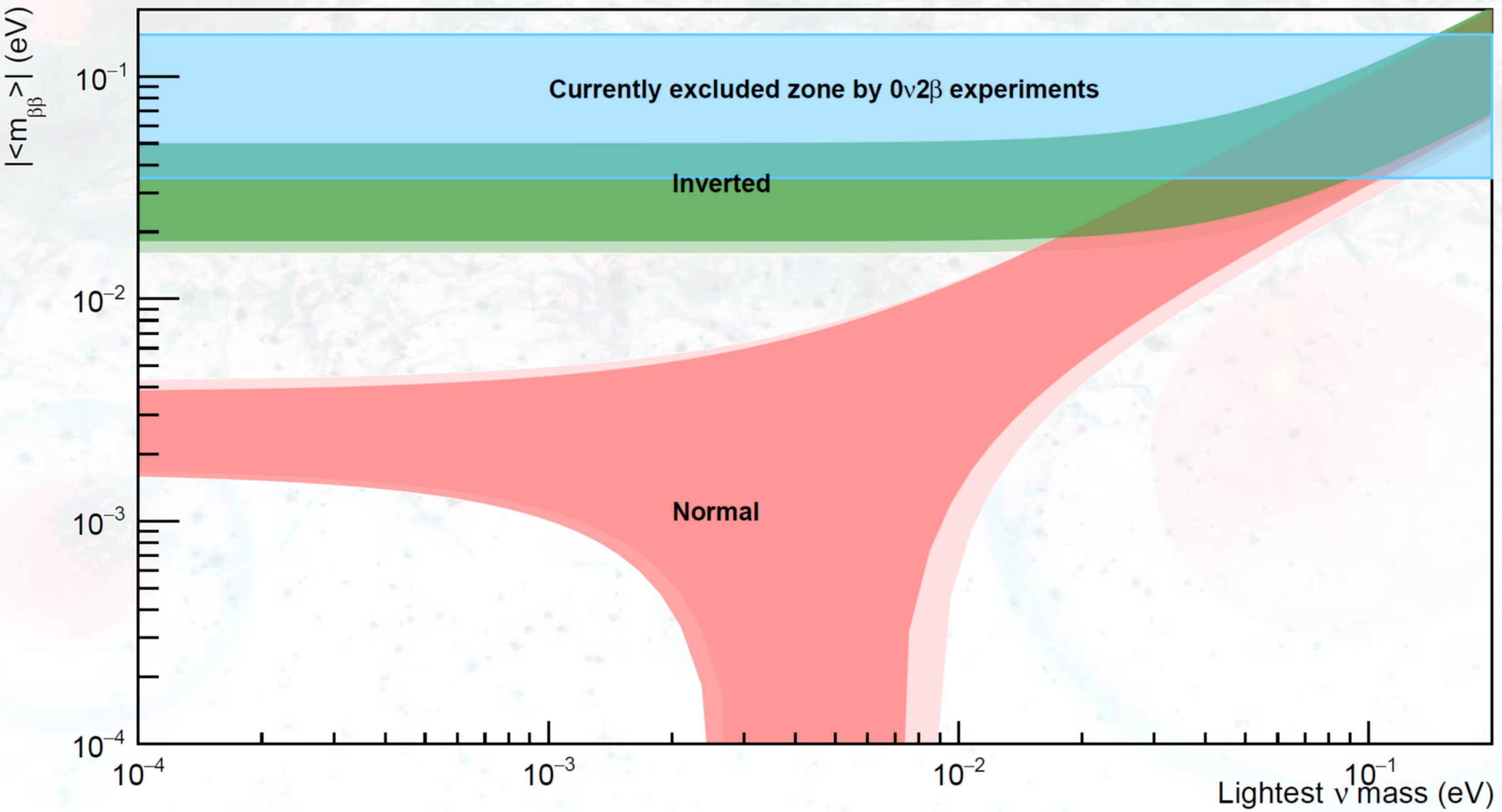
S. M. Bilenky, S. Pascoli, and S. T. Petcov
Phys. Rev. D 64, 053010 (2001)

Effects of the Majorana phases

the 0ν2β rate depends on:
- neutrino mixing angles
- neutrino masses
- mass hierarchy
- 2 totally unknown phases (in case of light Majorana neutrino exchange)

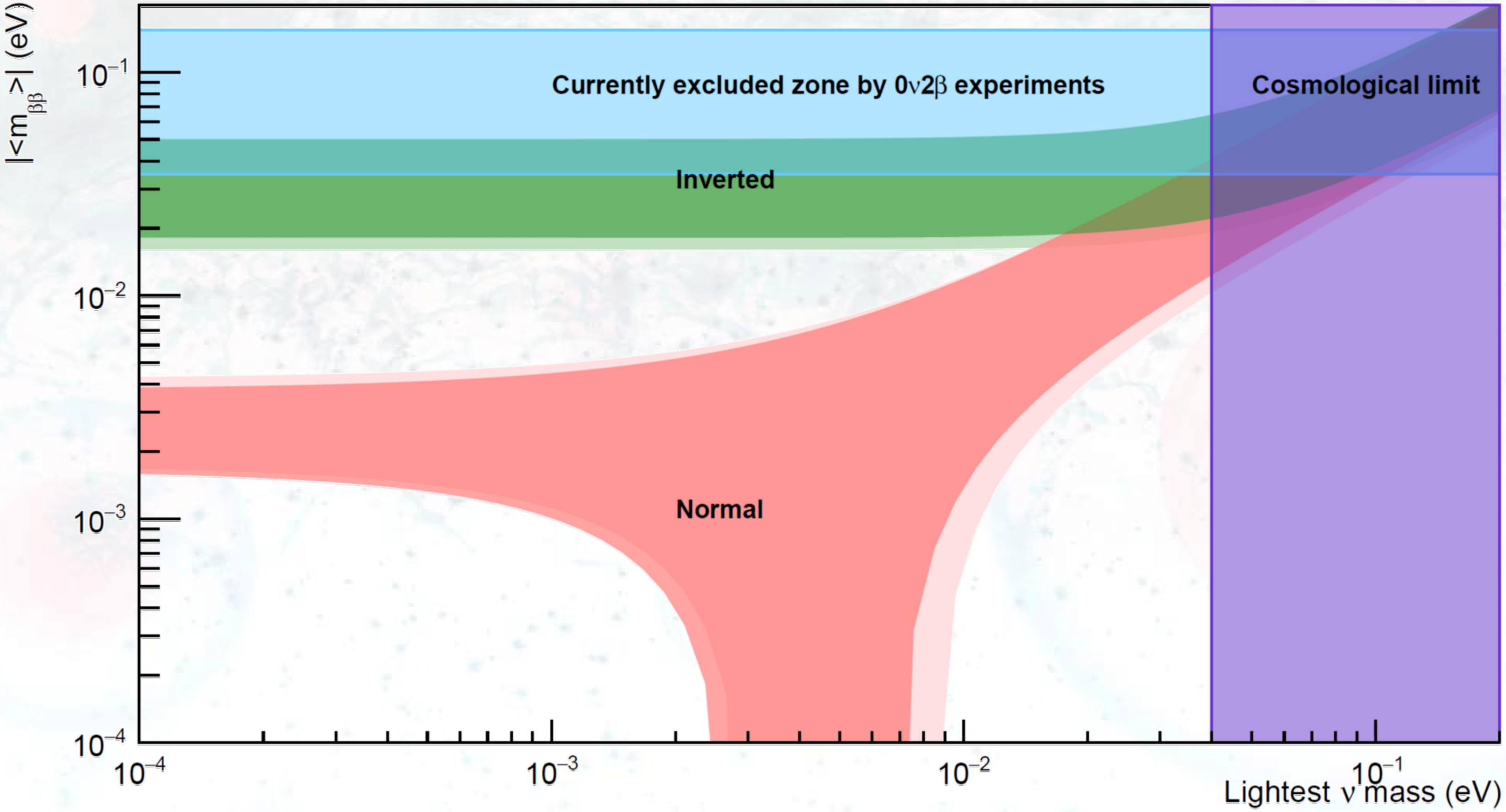
0ν2β decay and neutrino masses

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



0ν2β decay and neutrino masses

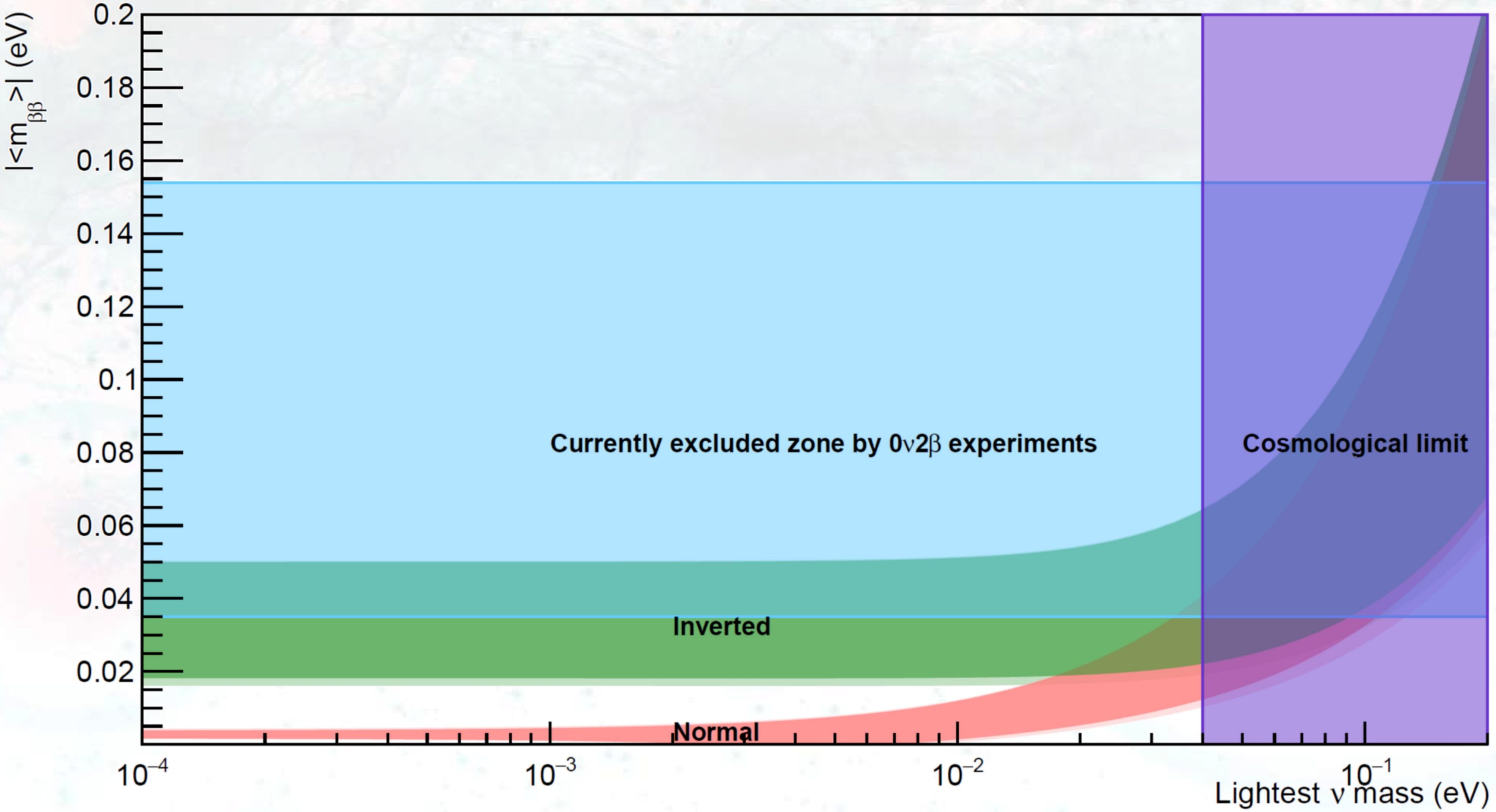
$$\left(T_{1/2}^{0\upsilon 2\beta}\right)^{-1} = G^{0\upsilon}(Q,Z)\,|M^{0\upsilon}|^2 \frac{m_{\beta\beta}^2}{m_e^2}$$



Doesn't seem like a lot, right?

0ν2β decay and neutrino masses

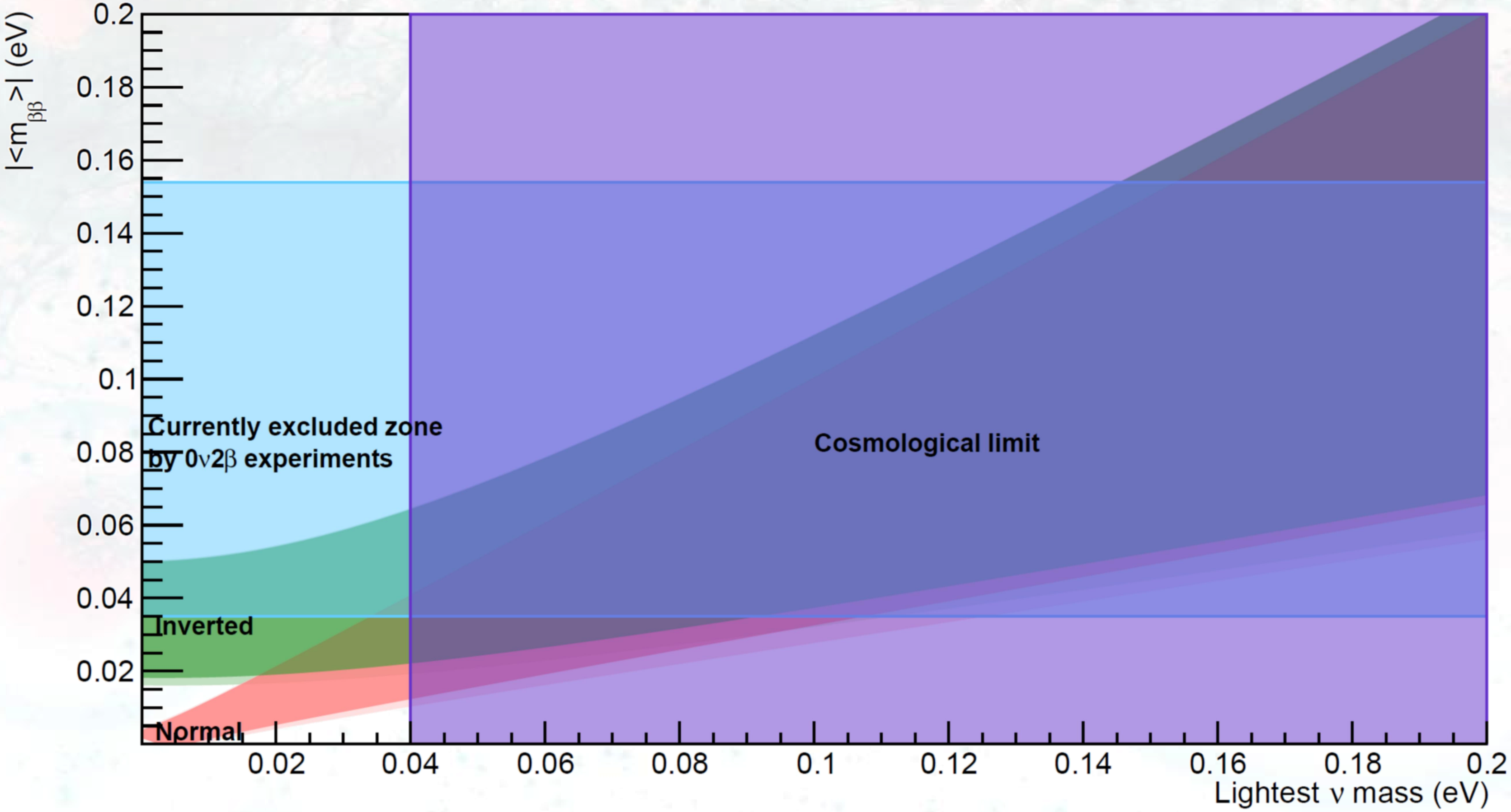
$$(T_{1/2}^{0\upsilon 2\beta})^{-1} = G^{0\upsilon}(Q,Z)\,|M^{0\upsilon}|^2\,\frac{m_{\beta\beta}^2}{m_e^2}$$



Log scales are dangerous...

0ν2β decay and neutrino masses

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



Not that bad progress!

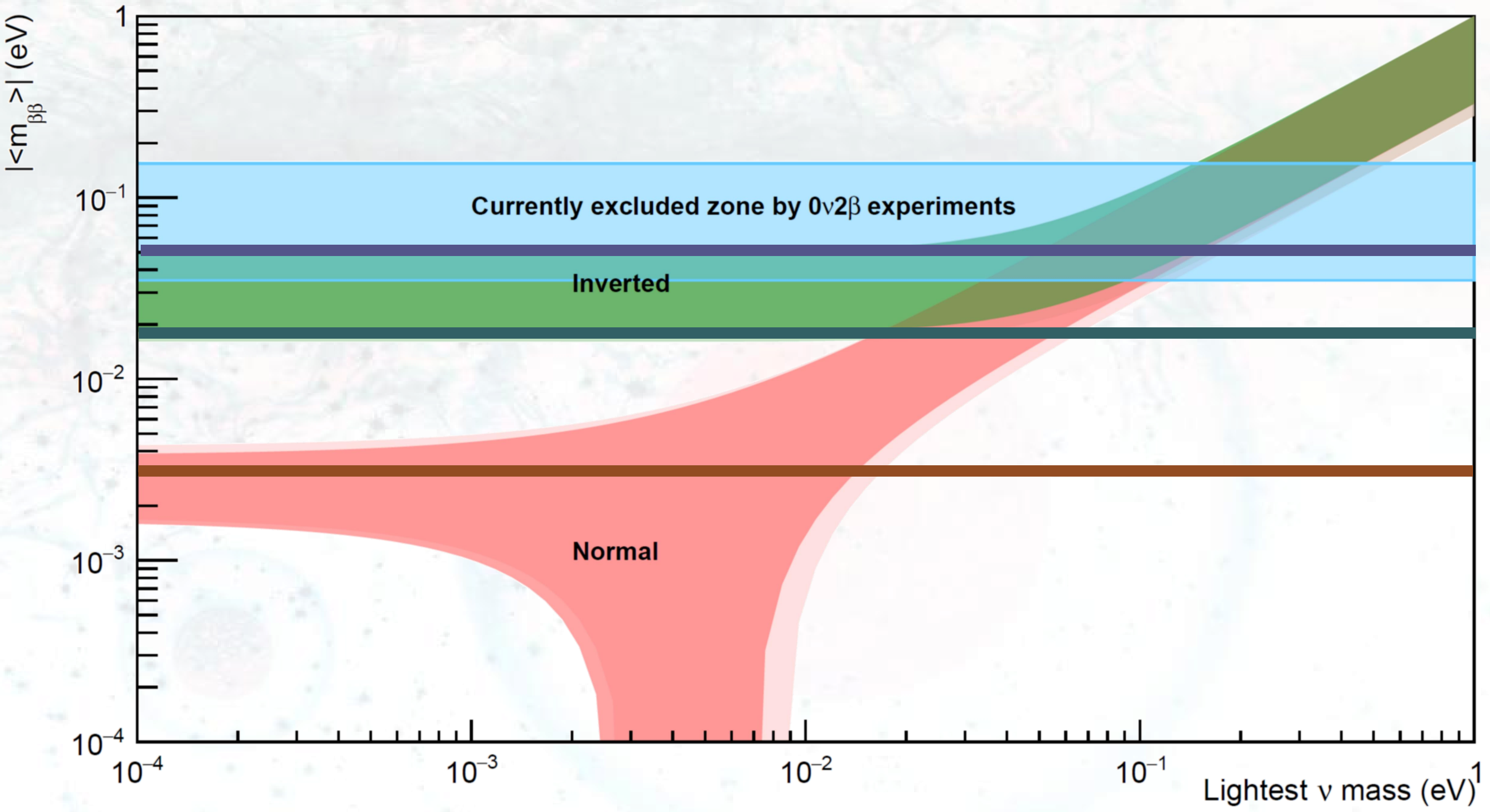
Experimental sensitivity for 0ν2β decay

$$(T_{1/2}^{0v2\beta})^{-1} = G^{0v}(Q,Z)\,|M^{0v}|^2\,\frac{m_{\beta\beta}^2}{m_e^2}$$

$$N = \log 2 \cdot \frac{N_A}{W} \cdot \varepsilon \cdot \frac{M \cdot t}{T_{1/2}^{0\nu}}$$

$T_{1/2}$:	**Signal:**
~10^{26} yr	**~10 counts/keV/ton**
~10^{27} yr	**~1 count/keV/ton**
~10^{29} yr	**~1 count/keV/10ton**

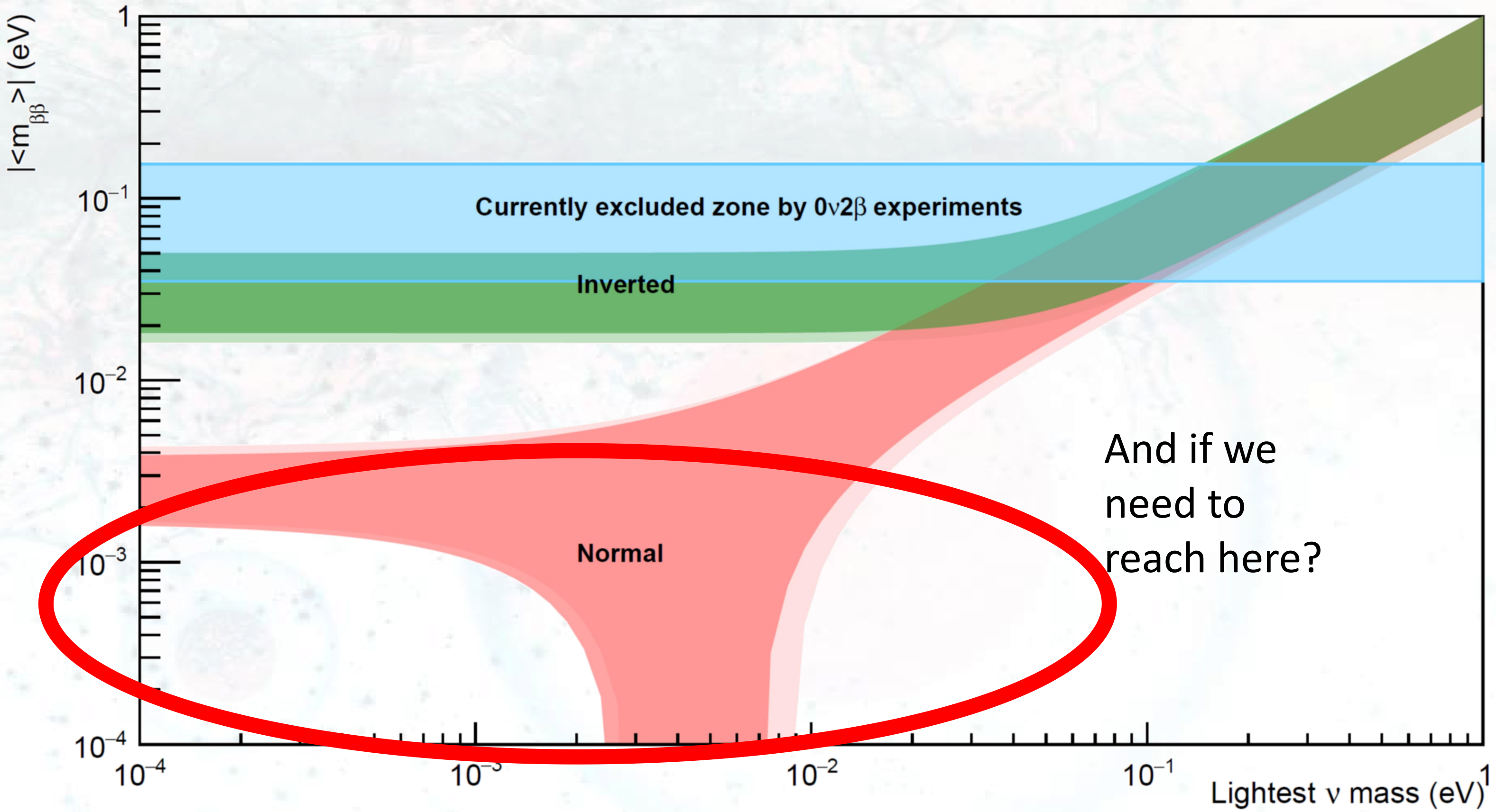
$$\boldsymbol{T_{1/2}^{0v2\beta} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \delta E}}}$$



Experimental sensitivity for 0n2b decay

$$(T_{1/2}^{0v2\beta})^{-1} = G^{0v}(Q,Z)\,|M^{0v}|^2\,\frac{m_{\beta\beta}^2}{m_e^2}$$

$$T_{1/2}^{0v2\beta} \propto \mathbf{a}\cdot\epsilon\cdot\sqrt{\frac{\mathbf{M}\cdot t}{\mathbf{b}\cdot\delta E}}$$



And if we need to reach here?

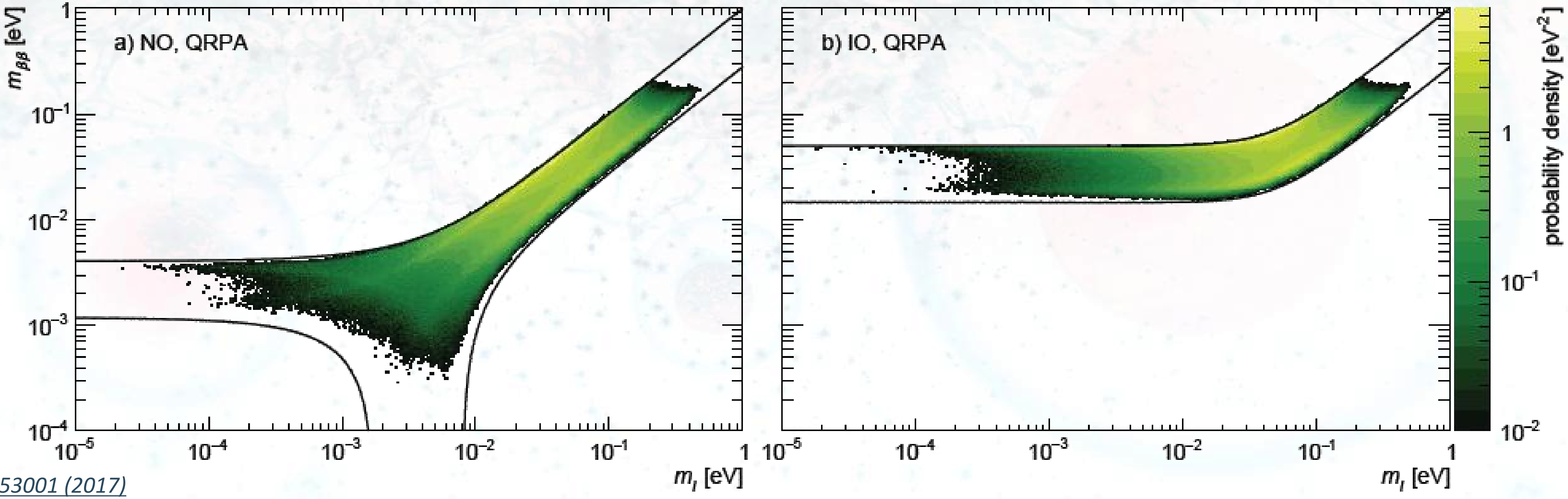
Probability of discovery: evaluation

- **Global Bayesan analysis** including neutrino oscillations, tritium, double beta decay, cosmology
- Ignorance of the scale of the parameters → **Scale-invariant prior distributions**

➢ $\Sigma = m_1+m_2+m_3$, Δm_{ij}^2: **logarithmic**

➢ Angles and phases in PMNS matrix: **flat**

Marginalized posterior distributions of $m_{\beta\beta}$

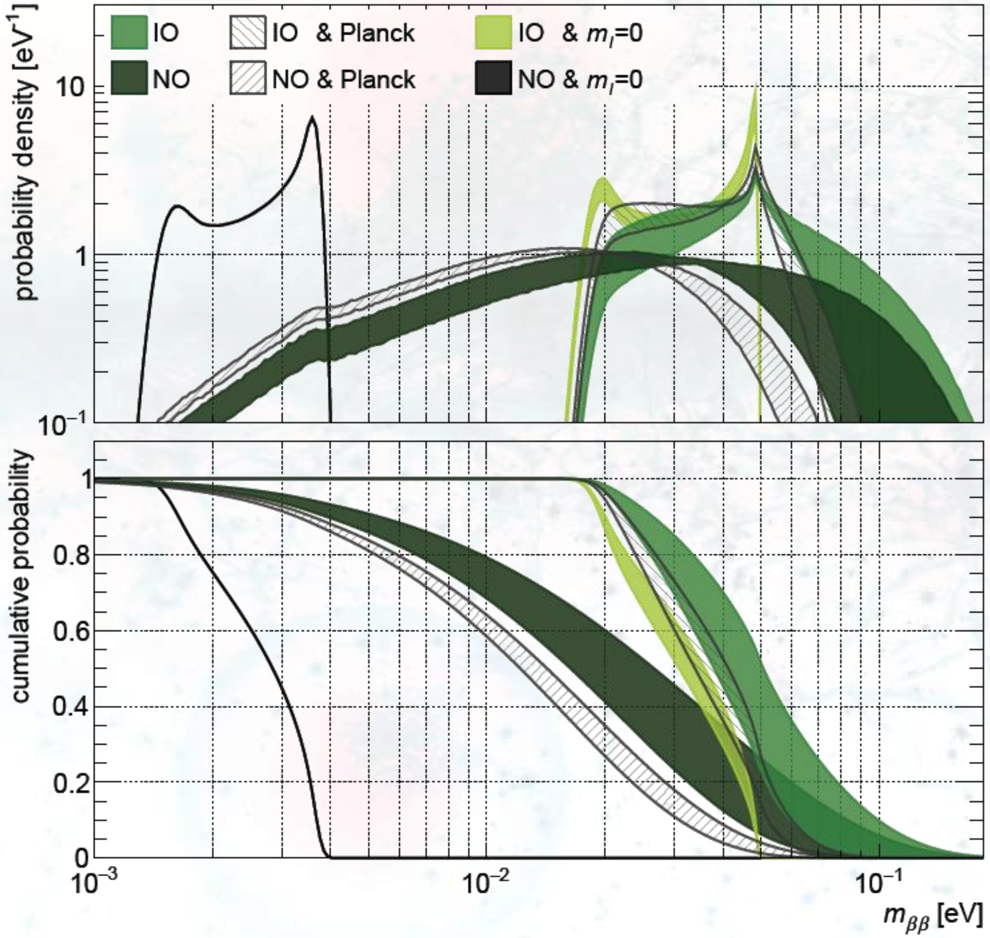


Phys. Rev. D 96, 053001 (2017)

$m_{\beta\beta}$ distribution in the parameter space

Phys. Rev. D 96, 053001 (2017)

Probability densities and cumulative probabilities for m_{ee}



Next-generation most promising experiments have a **high discovery potential**:
The **cumulative probability** for $m_{\beta\beta}$ to be higher than **20 meV** is

- **1** for Inverted Ordering
- ~ **0.5** for Normal Ordering

g_A quenching has an important effect but not dramatic

30% g_A quenching reduces the discover potential by

- ~ **15%** for Inverted Ordering
- ~ **25%** for Normal Ordering

How to build a succesfull experiment?

Background

zero bkg “boosts” the sensitivity

Isotope selection for experiment is very important

$$T_{1/2}^{0\nu2\beta} \propto \mathbf{a}\cdot\epsilon\cdot\sqrt{\frac{\mathbf{M}\cdot t}{\mathbf{b}\cdot\delta E}}$$

In case of $\mathbf{b}\cdot\Delta\mathbf{E}\cdot\mathbf{M}\cdot\mathbf{t} \ll 1$:

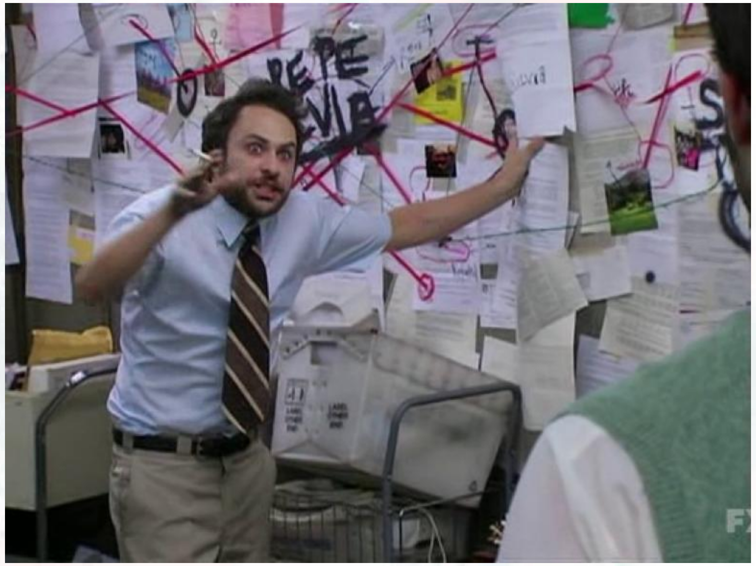
$$\lim T_{1/2}^{0\nu2\beta} \propto \mathbf{a}\cdot\epsilon\cdot M\cdot t$$

Energy resolution

Better resolution -> narrower region of interest

Exposure

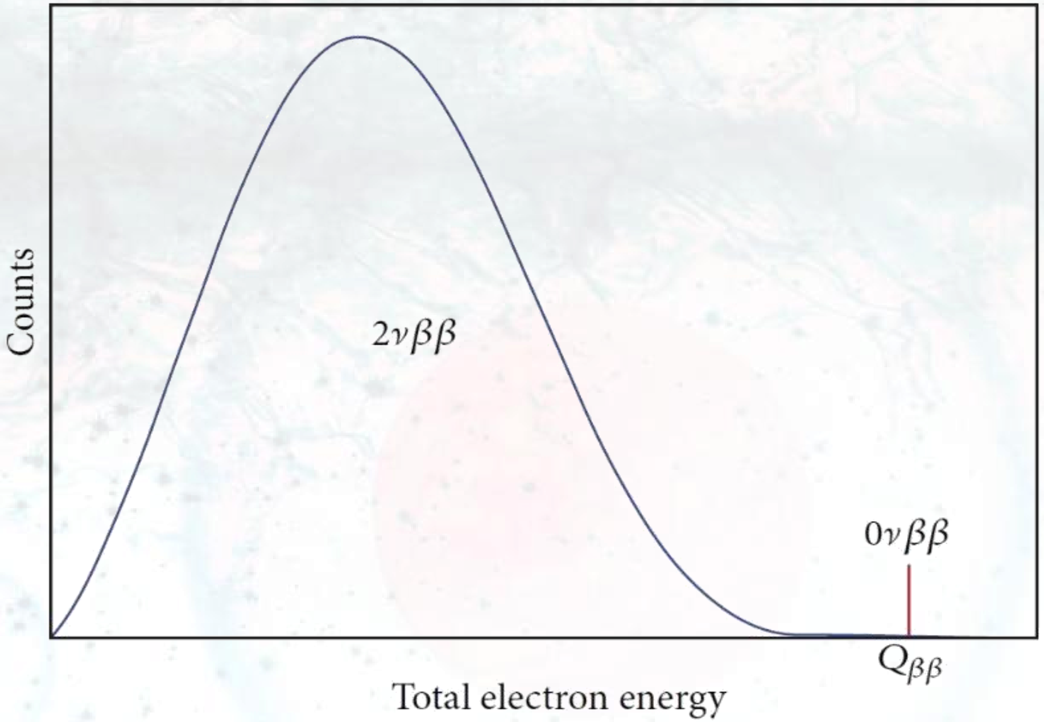
Large masses and a lot of patience



Background sources for 0v2β experiments

$$T_{1/2}^{0\upsilon 2\beta} \propto \mathbf{a} \cdot \epsilon \cdot \sqrt{\frac{\mathbf{M} \cdot t}{\boxed{\mathbf{b}} \cdot \delta E}}$$

This is around 0.1 Bq/g



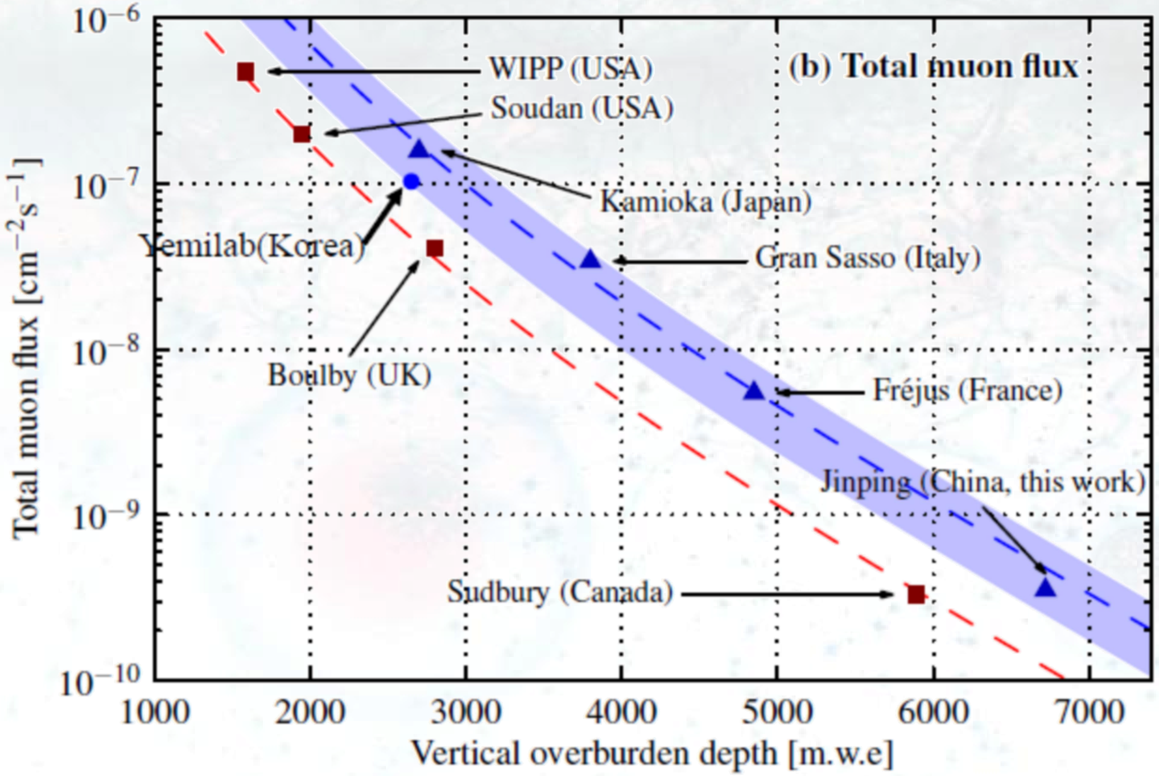
Here we look for 3×10^{-14} Bq/g

Background sources for 0ν2β experiments

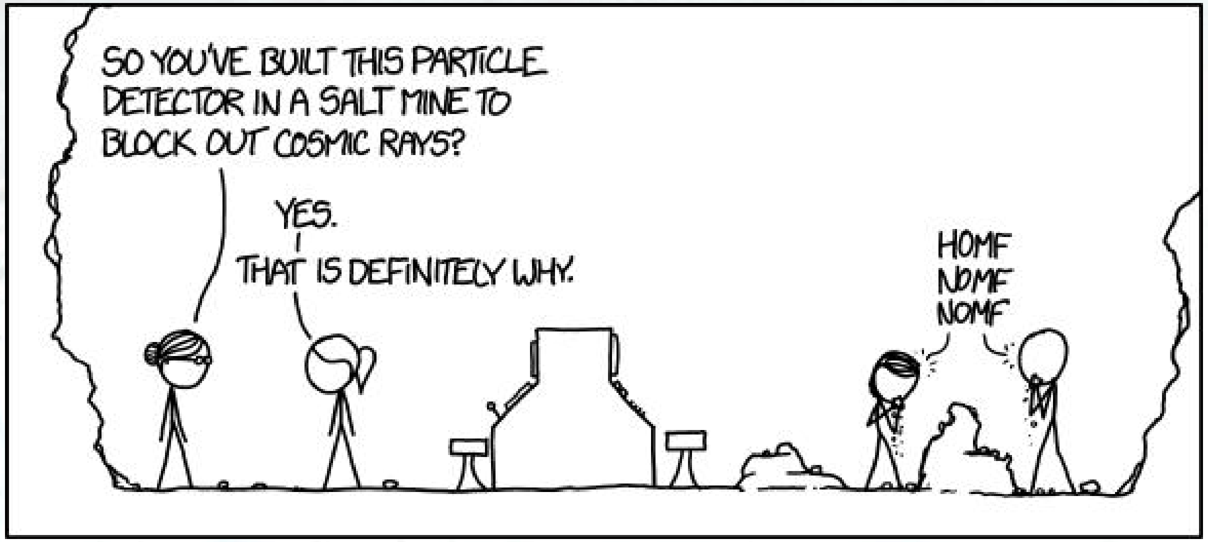
Cosmic muons, neutrons and cosmogenic activation

- Going underground is not enough - active 4π vetos are mandatory

$$T_{1/2}^{0\nu2\beta} \propto \mathbf{a} \cdot \epsilon \cdot \sqrt{\frac{\mathbf{M} \cdot t}{\boxed{\mathbf{b}} \cdot \delta E}}$$



arXiv:2007.15925

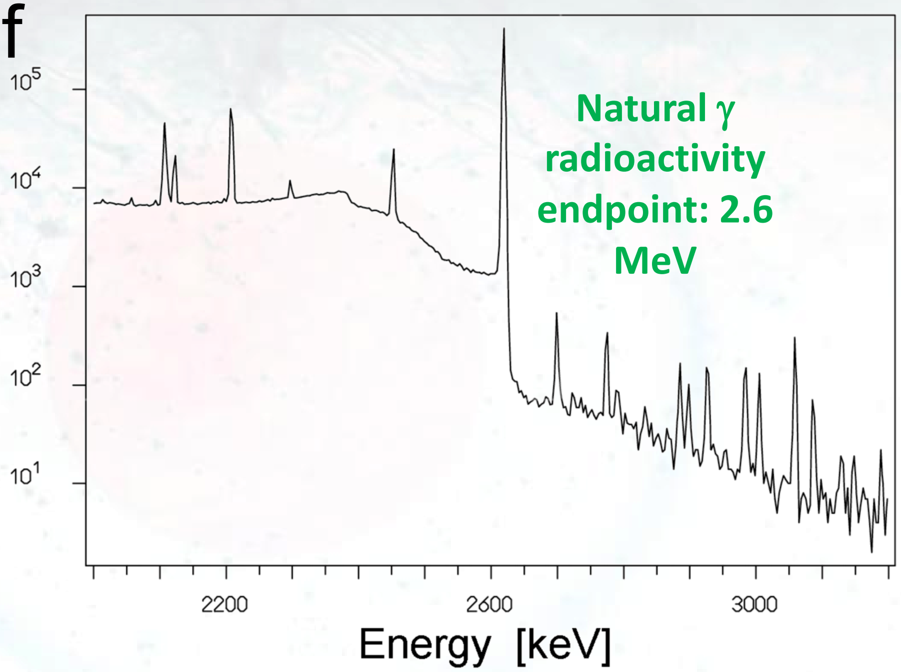


Background sources for 0ν2β experiments

$$T_{1/2}^{0\nu2\beta} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{\boxed{b} \cdot \delta E}}$$

Environmental γ’s, α’s and β’s

- Passive and active shielding
- Material screeing, radiopurity: levels of < 1 mBq / kg are required (ordinary materials - 1-100 Bq/kg)
- γ’s: select high Q-value isotopes, end-point of natural γ radioactivity is 2615 keV



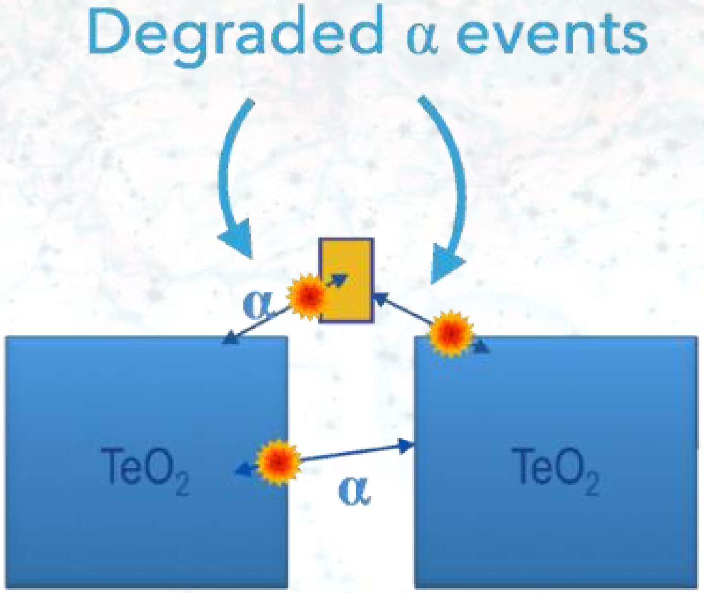
Natural γ radioactivity endpoint: 2.6 MeV

Background sources for 0v2β experiments

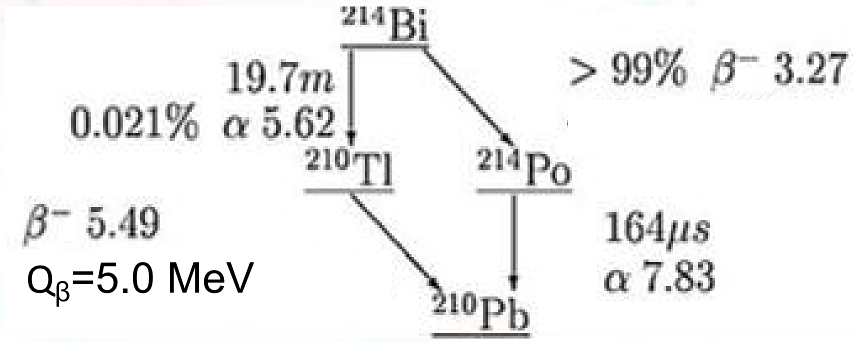
Environmental γ’s, α’s and β’s

$$T_{1/2}^{0v2\beta} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{\boxed{b} \cdot \delta E}}$$

- **α’s and β’s**: Develop advanced detectors with particle or/and impact-point identification
- Double read-out, events tagging: work on detector technology


Degraded α events

High energy β decays



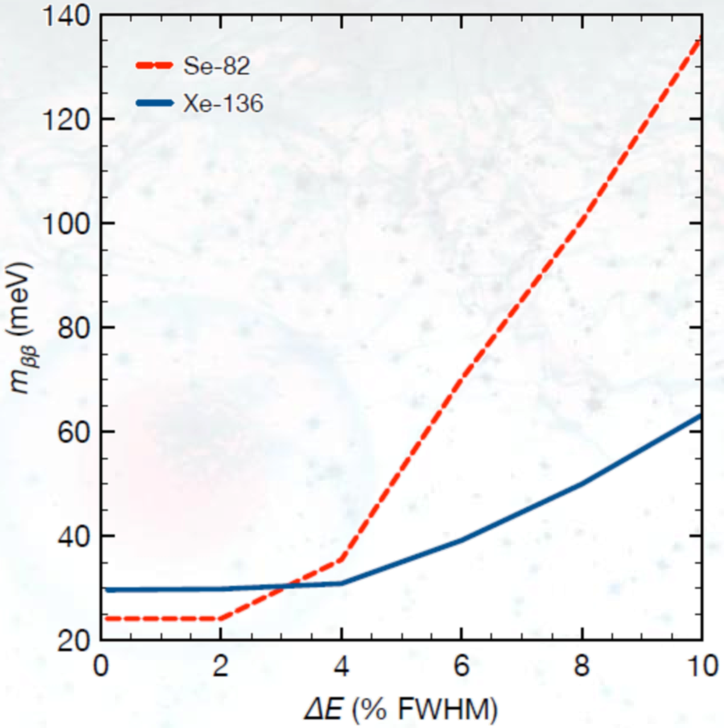
Q_β=5.0 MeV

Background sources for 0ν2β experiments

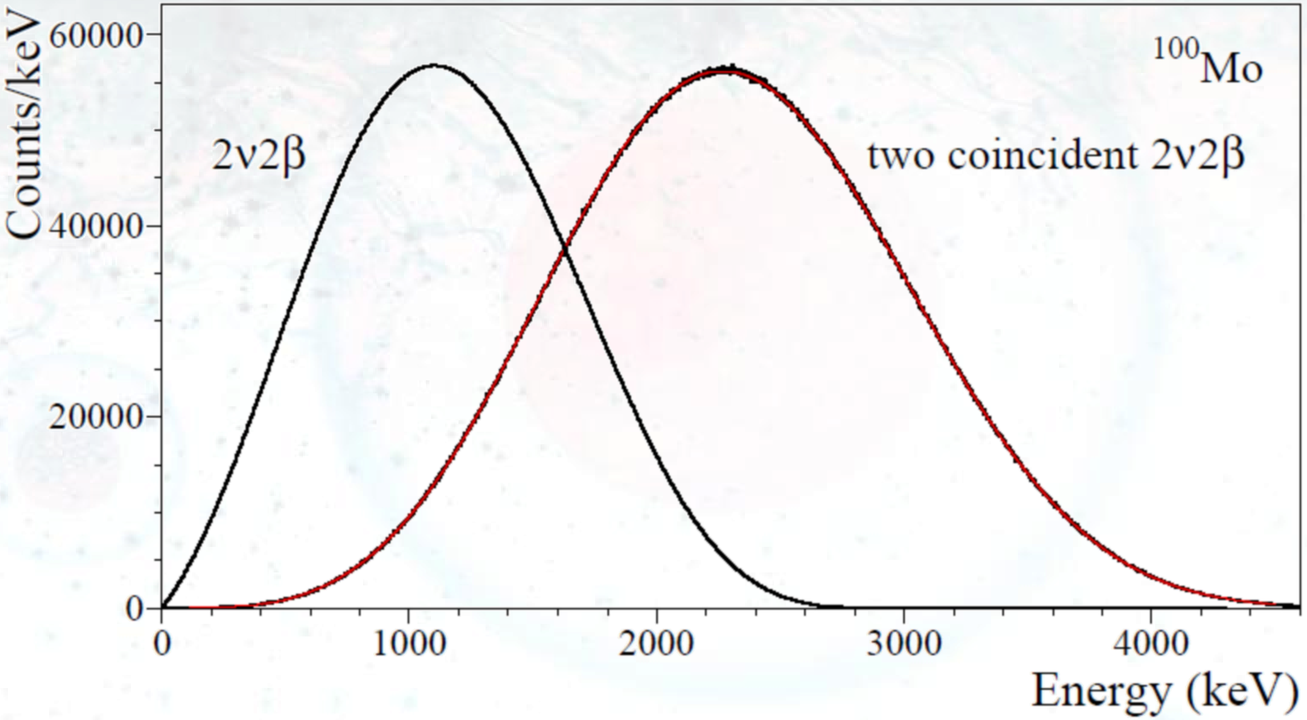
$$T_{1/2}^{0\nu2\beta} \propto \mathbf{a} \cdot \epsilon \cdot \sqrt{\frac{\mathbf{M} \cdot t}{\boxed{\mathbf{b} \cdot \delta E}}}$$

2ν2β decay: tail and pile-ups

- The only background that will be always present
- High energy and time resolution of the detectors helps to reduce it



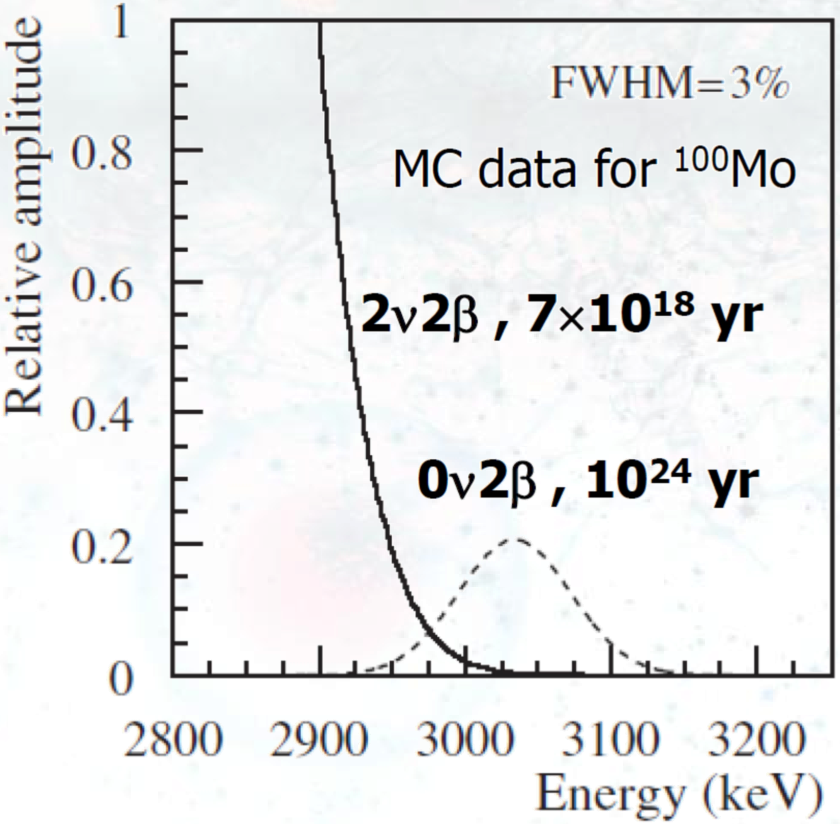
https://doi.org/10.48550/arXiv.1502.00581

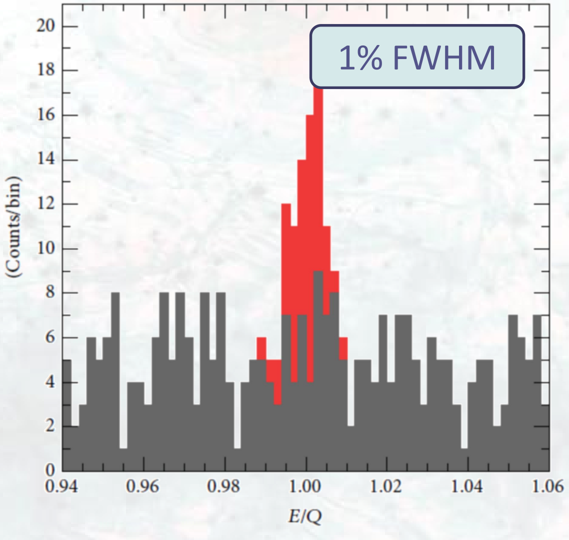


Resolution impact on sensitivity

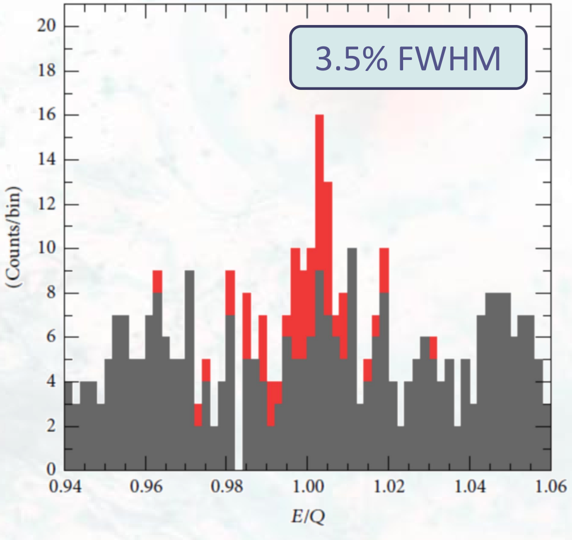
$$T^{0\nu2\beta}_{1/2} \propto a\cdot\epsilon\cdot\sqrt{\frac{M\cdot t}{b\cdot\boxed{\delta E}}}$$

- Defines the region of interest



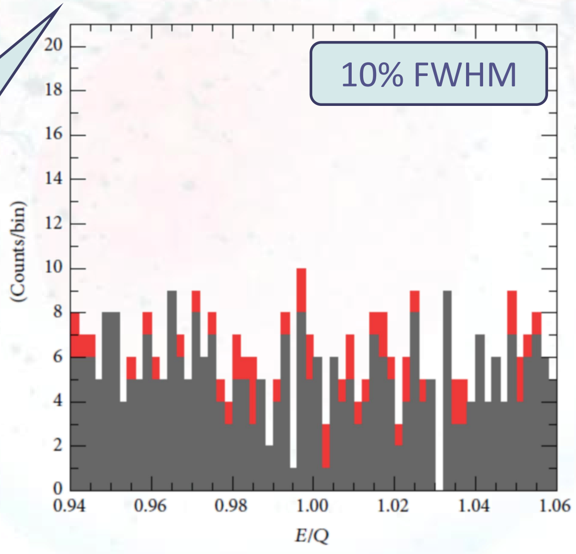


(a)



(b)

Simulation with 50 counts for signal and bkg of 1 count/keV. In reality, numbers will be much lower



(c)

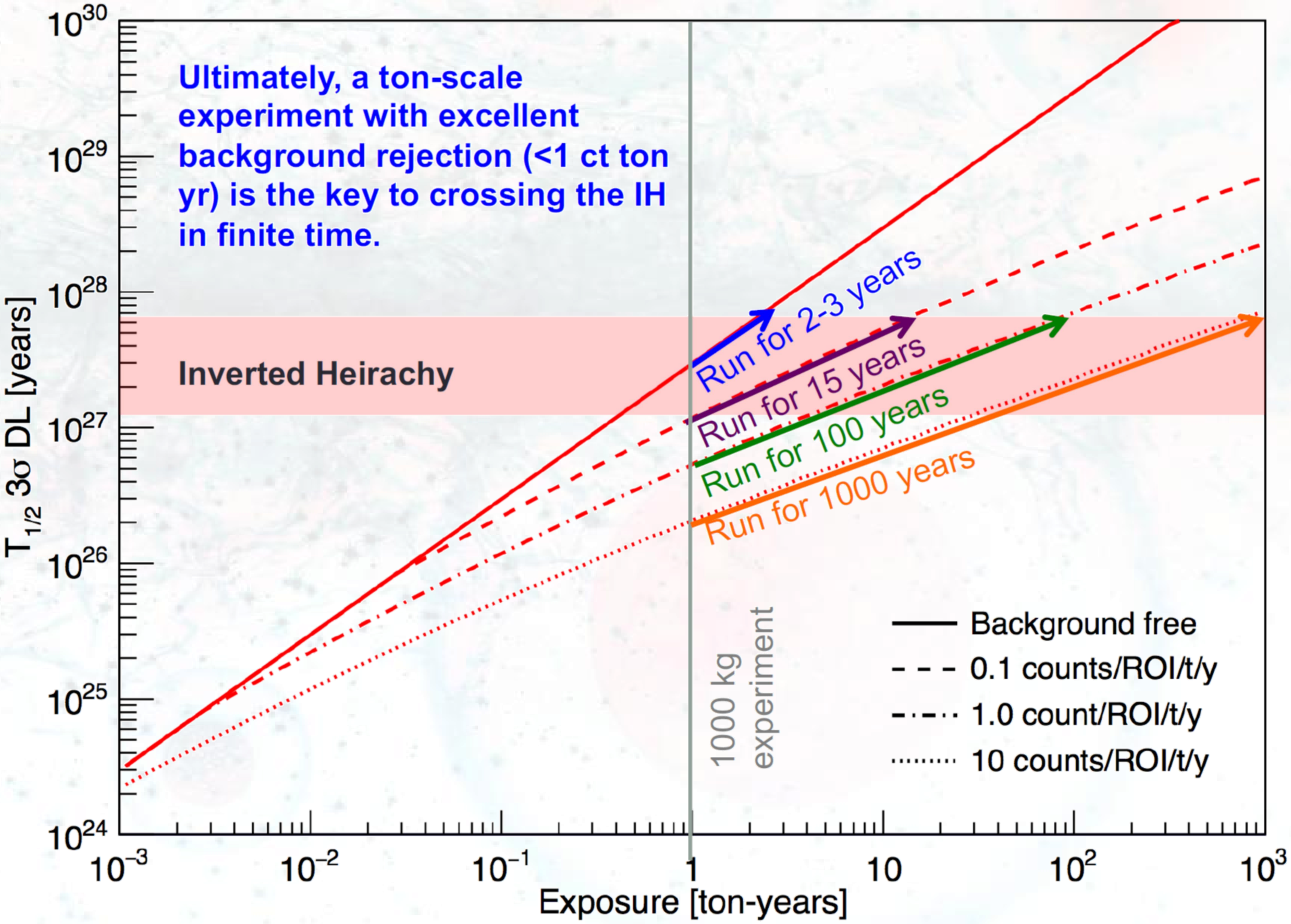
https://doi.org/10.48550/arXiv.1502.00581

Background impact on sensitivity

Long half-lives mean very big exposures

To see 3-4 counts of 0v2β at given $T_{1/2}$:

- 10^{26} years: 100 kg/yr
- 10^{27} years: 1 ton/yr
- 10^{28} years: 10 ton/yr

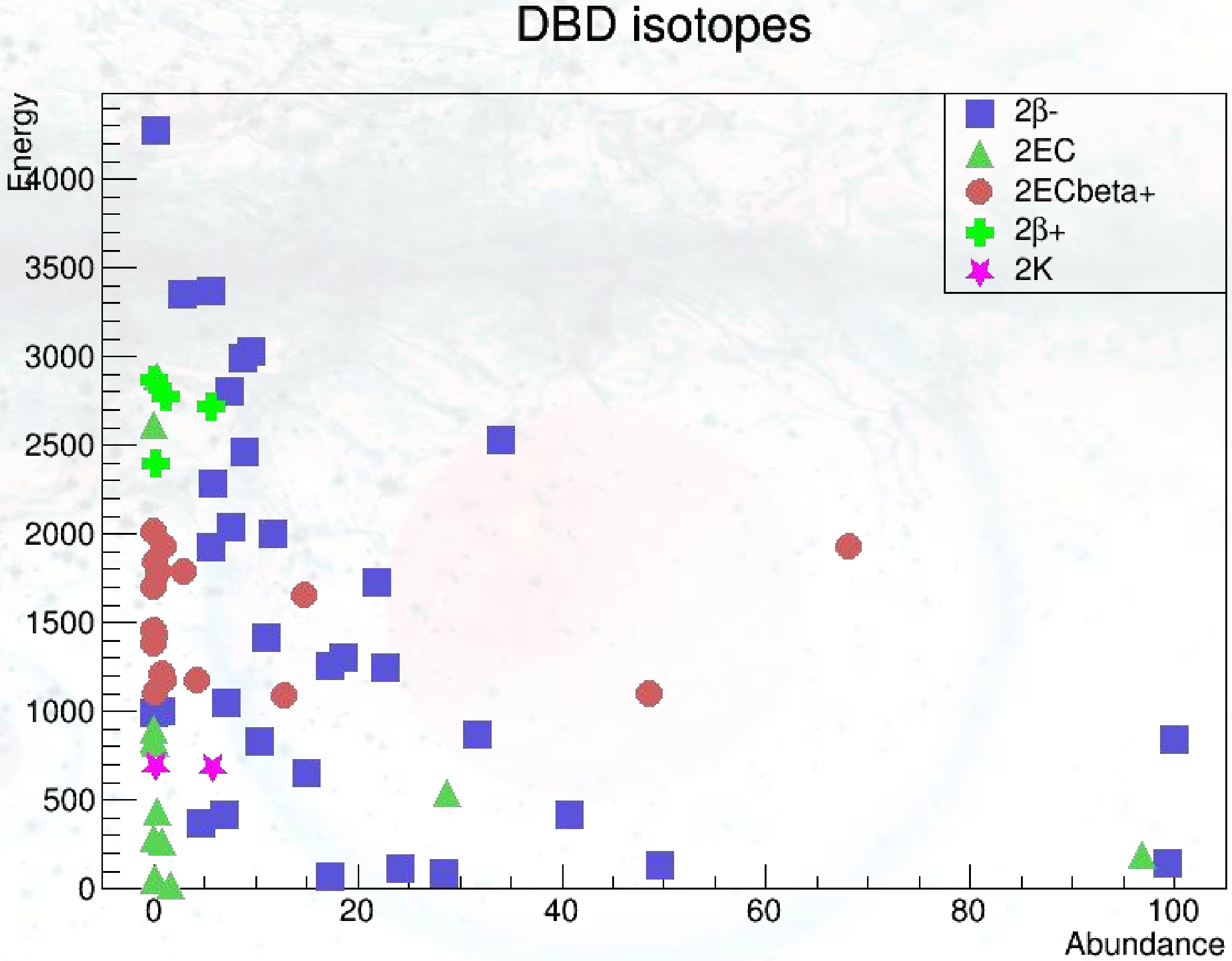


[The Physics of Neutrinoless Double Beta Decay: A Primer, B.J.P. Jones](#)

Practical considerations: isotopes

$$T_{1/2}^{0\nu2\beta} \propto \mathbf{a} \cdot \epsilon \cdot \sqrt{\frac{\mathbf{M} \cdot t}{\boxed{\mathbf{b}} \cdot \delta E}}$$

- 2β- mode is most suitable to search for observation of neutrinoless mode

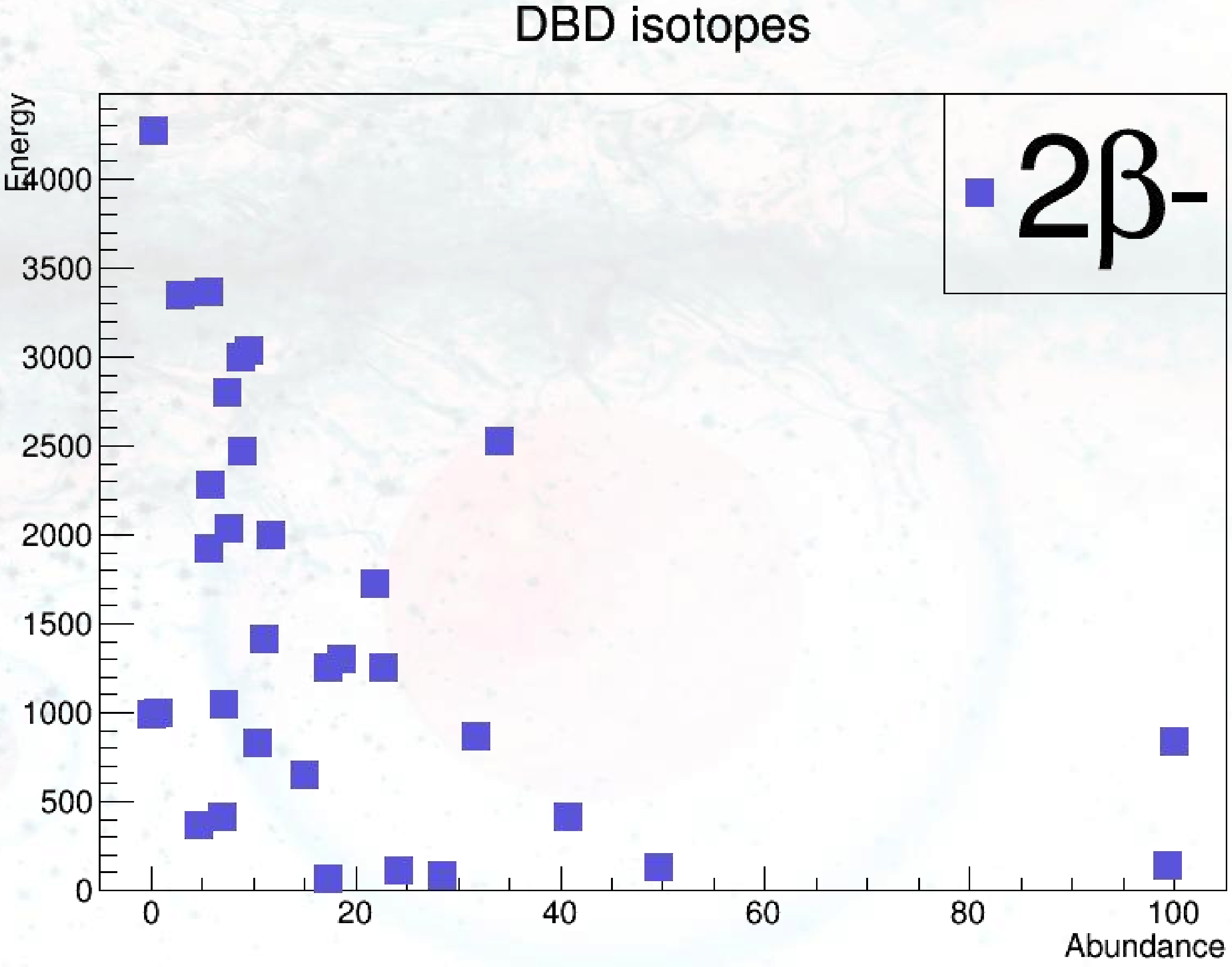


Practical considerations: isotopes

$$T_{1/2}^{0\nu2\beta} \propto \mathbf{a}\cdot\epsilon\cdot\sqrt{\frac{\mathbf{M}\cdot t}{\boxed{\mathbf{b}}\cdot\delta E}}$$

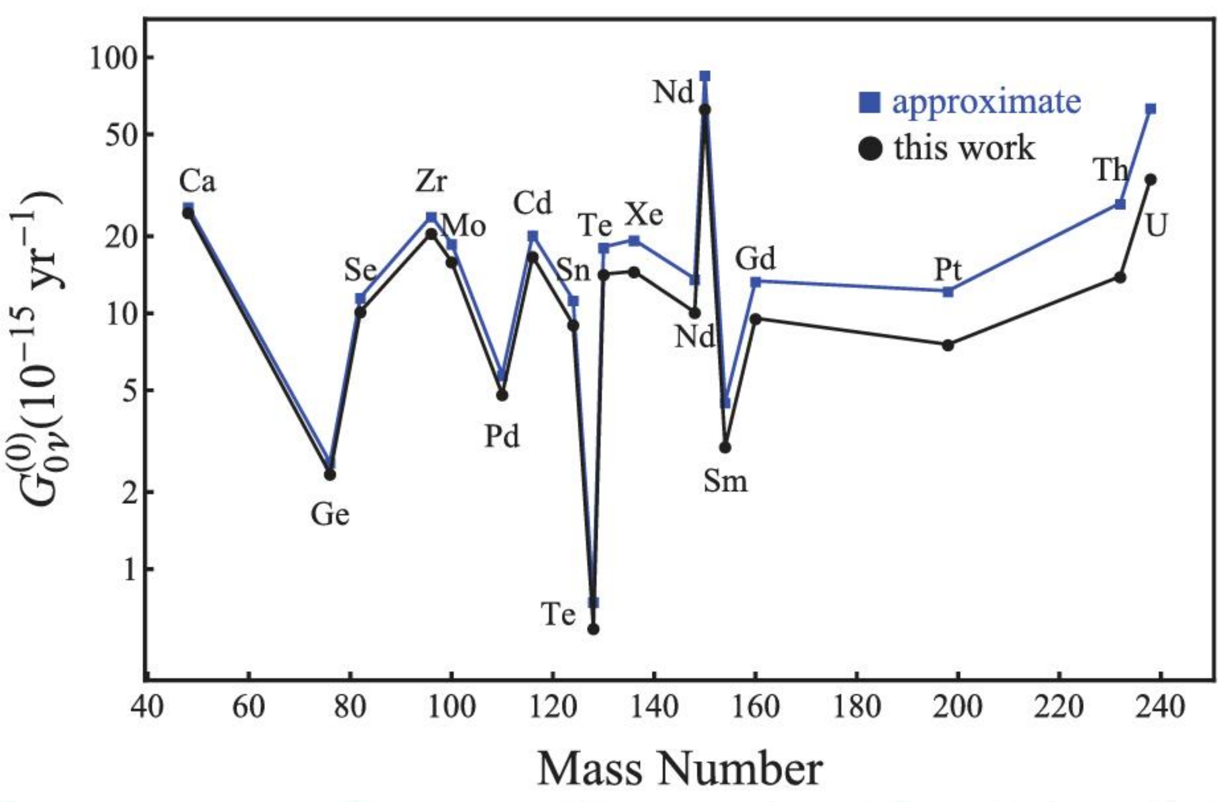
- 2β- mode is most suitable to search for observation of neutrinoless mode
- High $Q_{\beta\beta}$ → lower background level in ROI and higher $0\nu2\beta$ decay rate

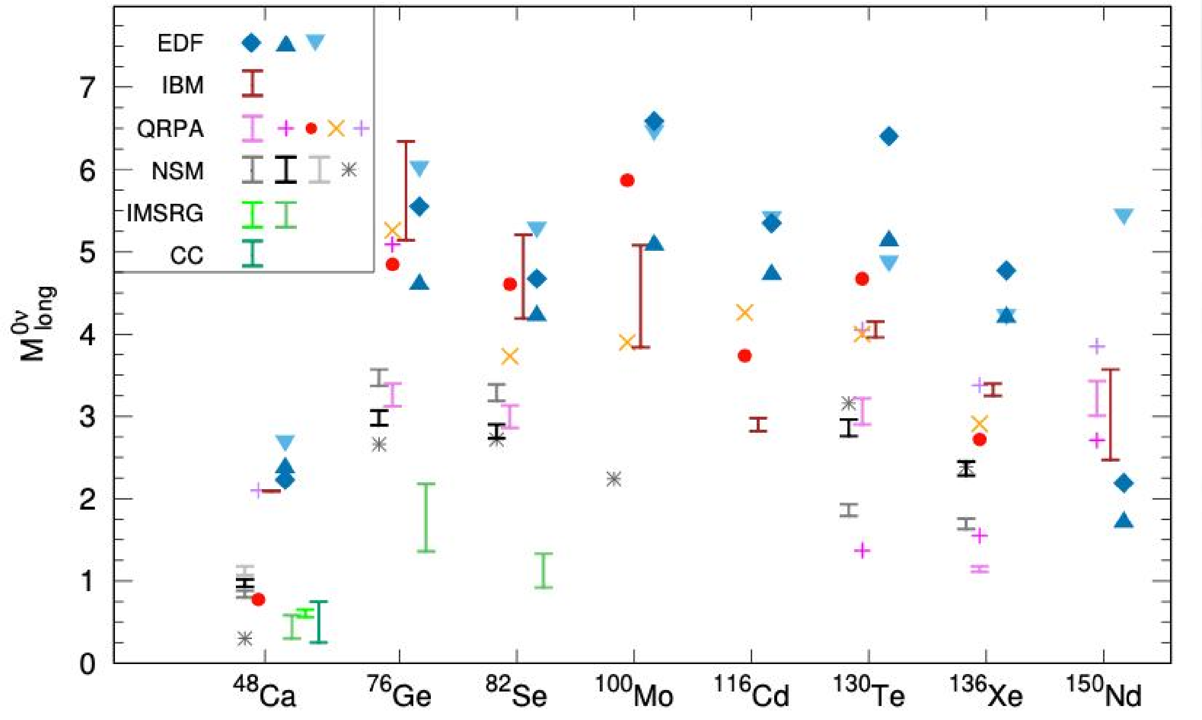
$$G^{0\nu} \propto Q_{\beta\beta}^{5}$$



Decay rate predictions

- Let’s come back to this formula: $(T^{0\nu 2\beta}_{1/2})^{-1} = \boxed{G(Q,Z) g_A^4 |NME|^2} \left\langle \frac{m_{\beta\beta}}{m_e} \right\rangle^2$
- The higher the better
- But NMEs are featuring huge uncertainties in calculations





Rev. Mod. Phys. 95, 025002 (2023)
https://doi.org/10.1103/RevModPhys.95.025002

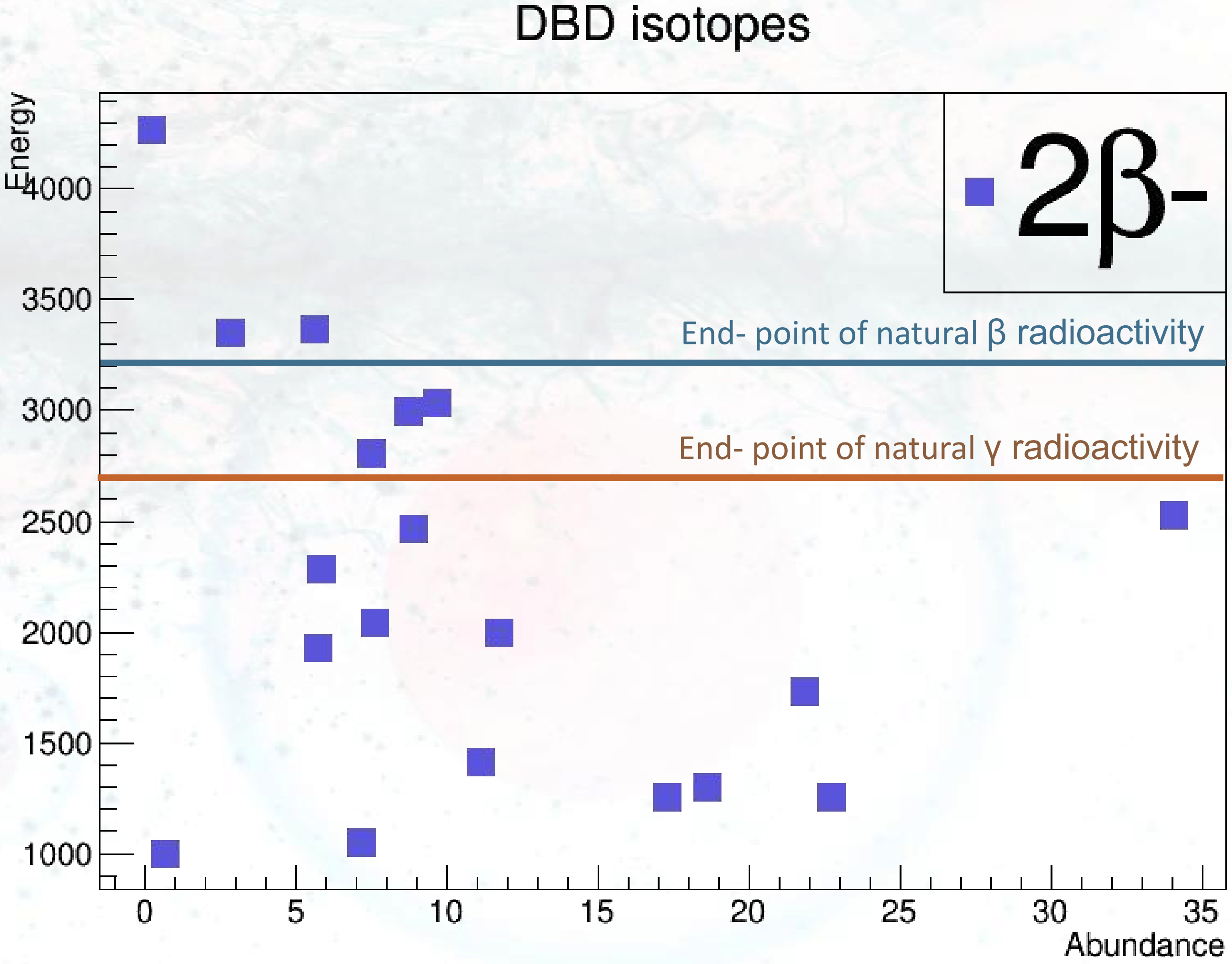
Practical considerations: isotopes

$$T_{1/2}^{0\nu 2\beta} \propto \boxed{a \cdot \epsilon \cdot \sqrt{\frac{M}{b \cdot \delta E}}} \cdot t$$

- 2β- mode is most suitable to search for observation of neutrinoless mode
- High $Q_{\beta\beta}$ → lower background level in ROI and higher $0\nu 2\beta$ decay rate

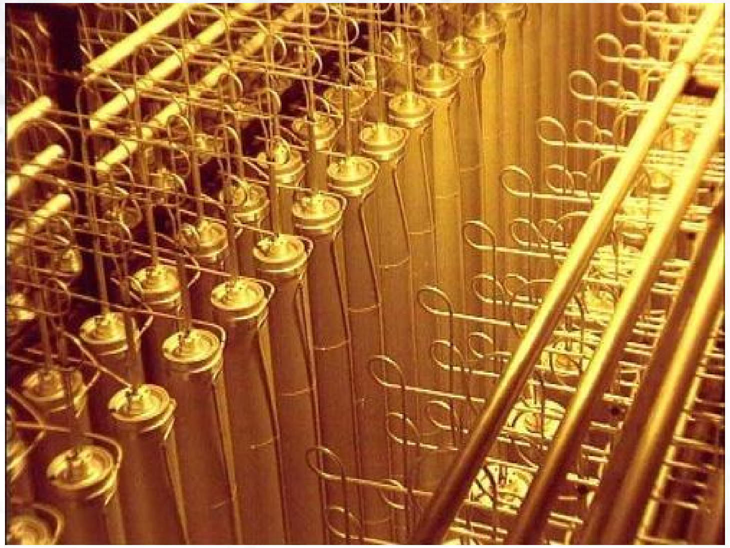
$$G^{0\nu} \propto Q_{\beta\beta}^5$$

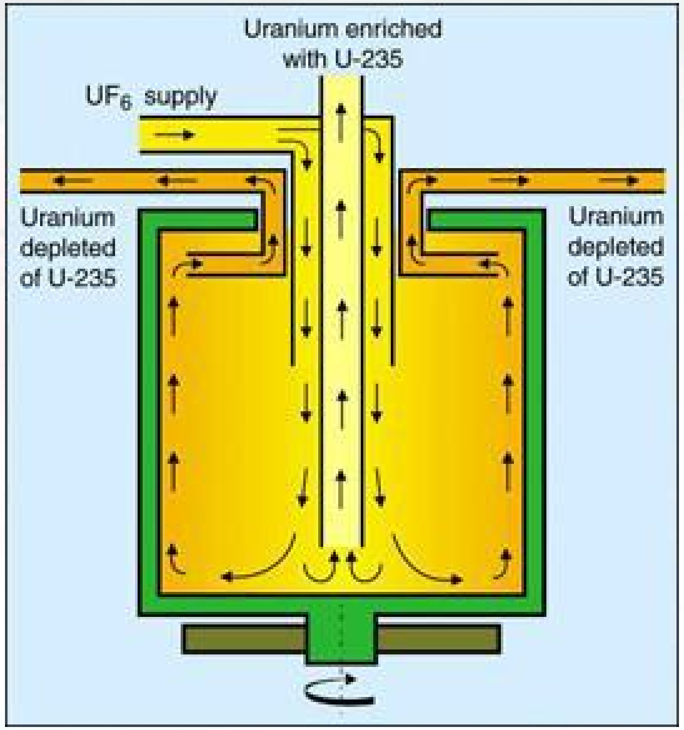
- Large exposure - big mass: natural abundance and possibility of enrichment is important



Enrichment capability

- Isotopic enrichmentby centrifugation - currently, the only viable large scale method
- Costs: 10-80 eur/g - big fraction of the total cost of the experiment
- Market of stable isotopes for medical applications
- Geopolitics impacts access to production: Russian agression in Ukraine impacts some DBD experiments directly





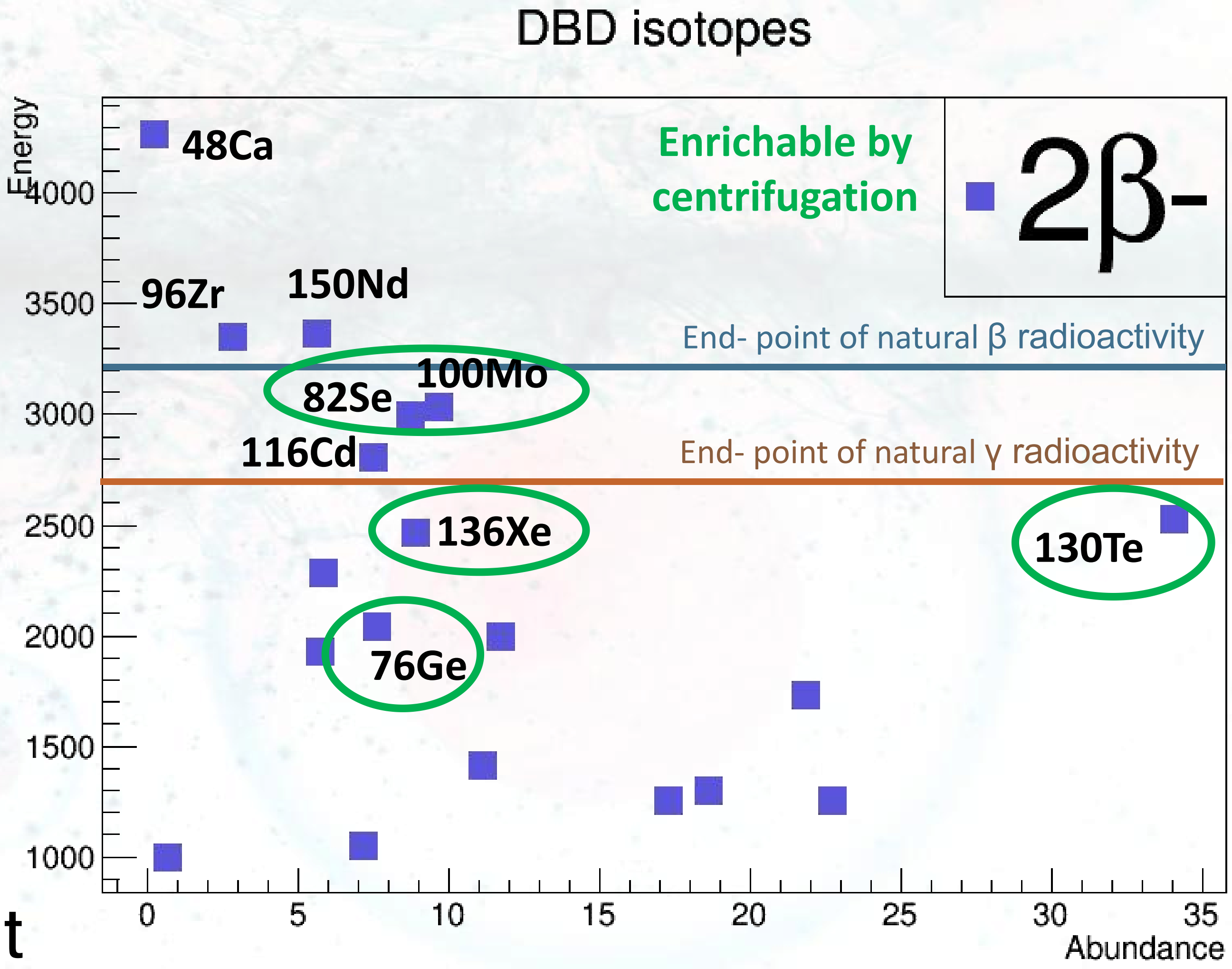
Practical considerations: isotopes

$$T^{0\nu2\beta}_{1/2} \propto a\cdot\epsilon\cdot\sqrt{\frac{M\cdot t}{b\cdot\boxed{\delta E}}}$$

- 2β- mode is most suitable to search for observation of neutrinoless mode
- High $Q_{\beta\beta}$ → lower background level in ROI and higher $0\nu2\beta$ decay rate

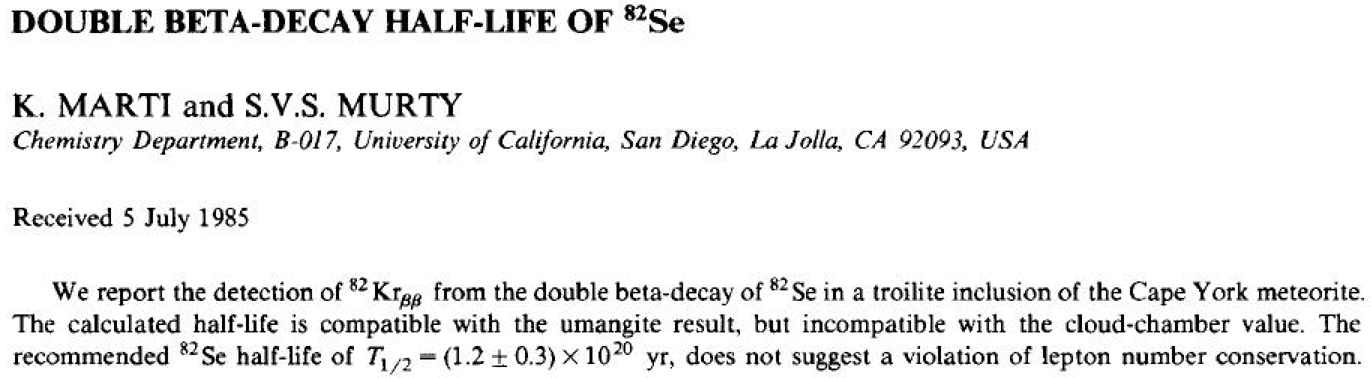
$$G^{0\nu} \propto Q^5_{\beta\beta}$$

- Large exposure - big mass: natural abundance and possibility of enrichment is important
- Finally, detector technology for the most efficient measurement



Indirect searches for 2β decay

- Identification and counting an excess of daughter nuclei
- No distinguishing betwen 2v and 0v modes
- Were used for first confirmations of double beta decay excistence, not so interesting for neutrino physics



DOUBLE BETA-DECAY HALF-LIFE OF ^{82}Se

K. MARTI and S.V.S. MURTY
Chemistry Department, B-017, University of California, San Diego, La Jolla, CA 92093, USA

Received 5 July 1985

We report the detection of $^{82}\mathrm{Kr}_{\beta\beta}$ from the double beta-decay of ^{82}Se in a troilite inclusion of the Cape York meteorite. The calculated half-life is compatible with the umangite result, but incompatible with the cloud-chamber value. The recommended ^{82}Se half-life of $T_{1/2} = (1.2 \pm 0.3) \times 10^{20}$ yr, does not suggest a violation of lepton number conservation.

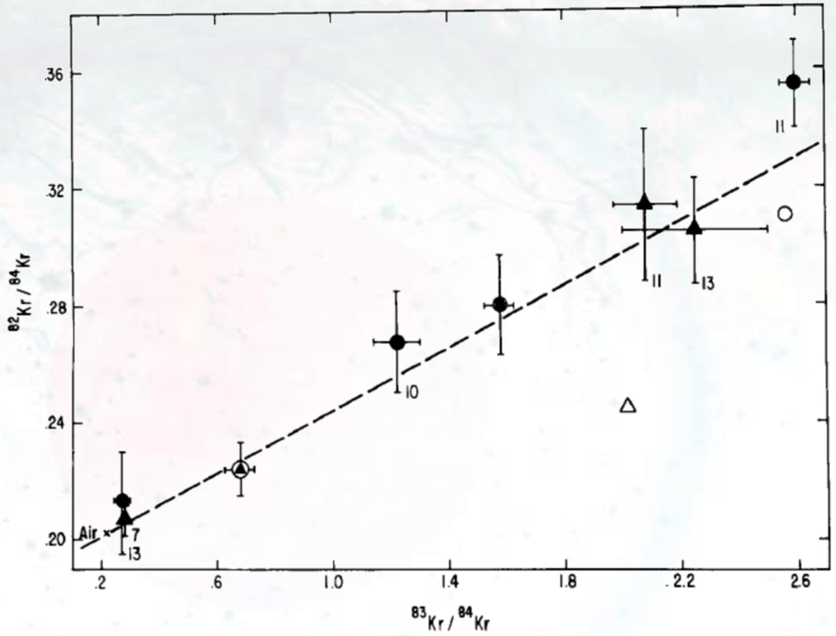


Fig. 1. The filled symbols in the figure show the measured ratios ^{82}Kr/^{84}Kr versus ^{83}Kr/^{84}Kr; totals are also given as circled data points. The digits refer to the temperature (hundreds of °C) steps in the stepwise release experiment. Open symbols are explained in the text.

Direct searches for DBD

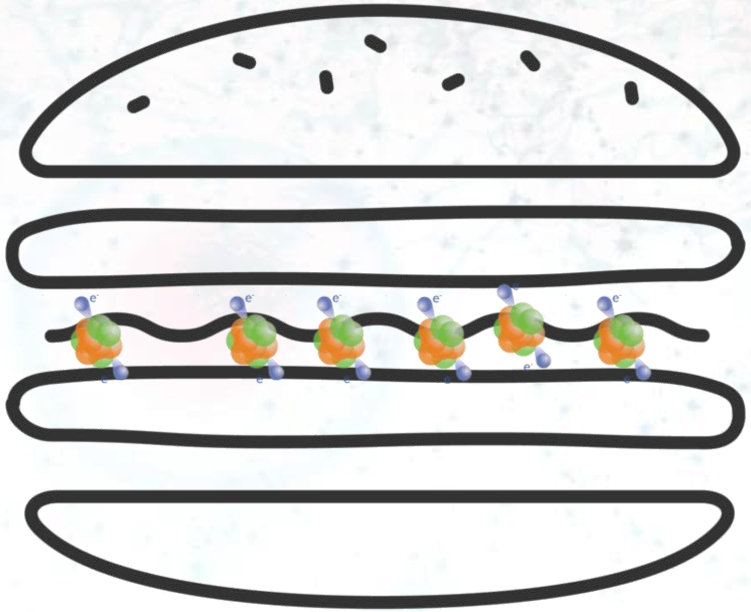
- Two approaches:

Source≠detector

☺ neat **reconstruction of event topology**: individual electron track recognition!

☺ **several candidates** can be studied with the same detector: isotope in the form of thin foil

× BUT: very hard to get large mass

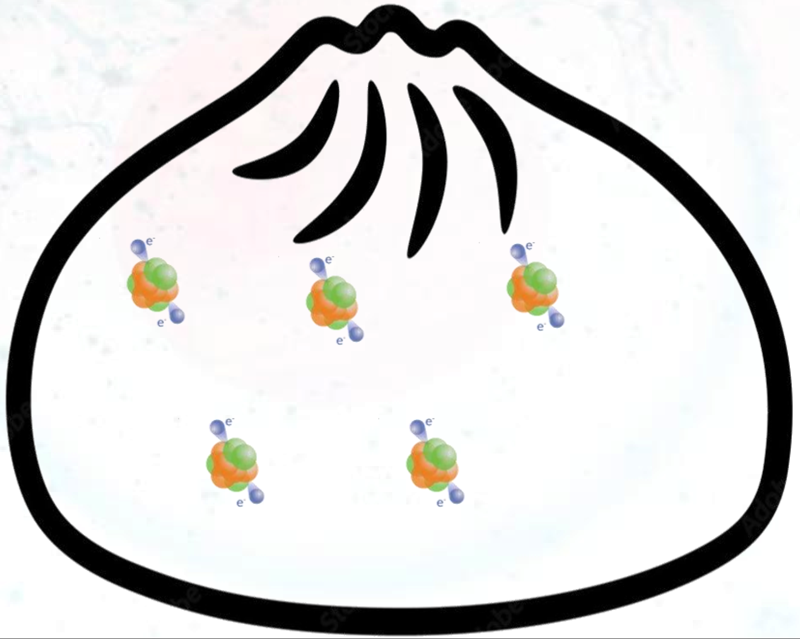


Source=detector

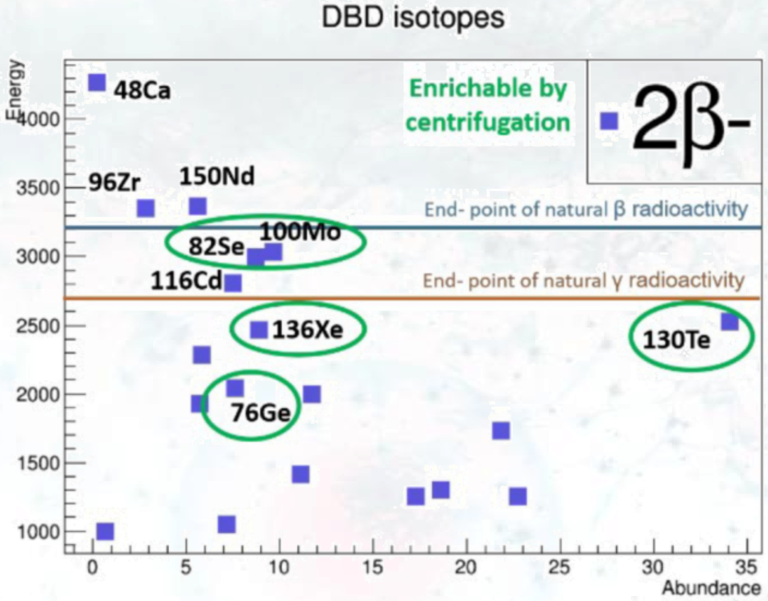
× main constraint: detector material - has to contain the isotope of interest

☺ Ton-scale masses are possible

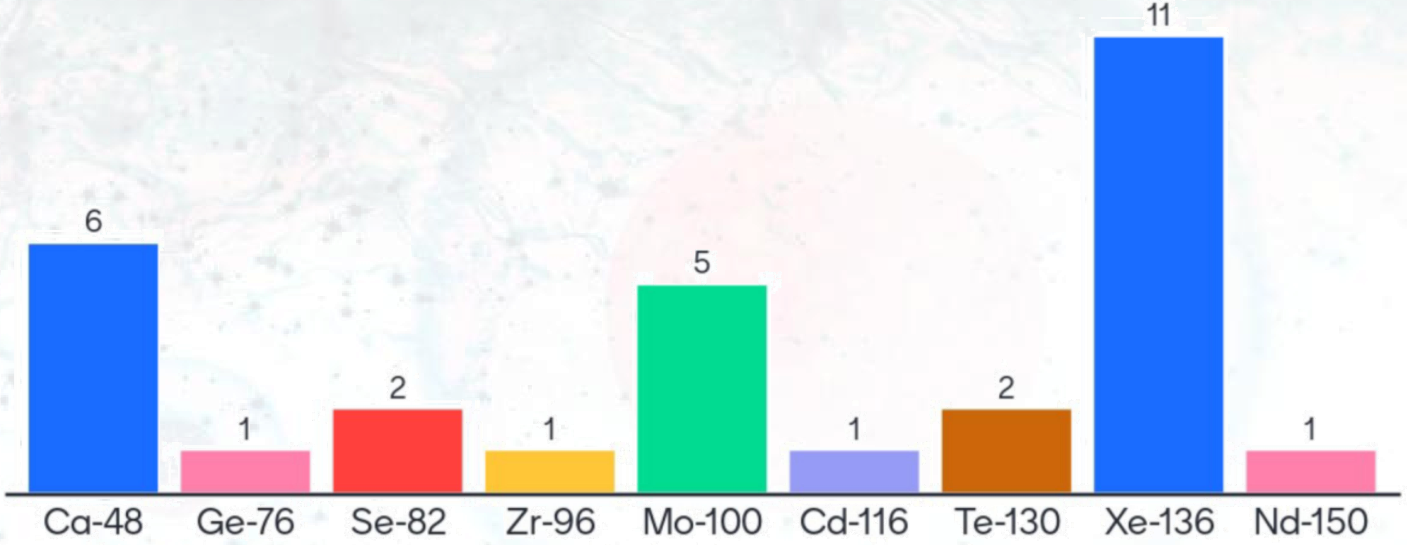
☺ Several detection techniques proposed with high resolution and particle identification capability



So, imagine you get a grant:



Imagine you get 10 Meuro today. Which isotope whould you choose to build an experiment?



Status of current searches

This is the scope of lecture II

This is the scope of lecture III