Status of Double Beta Decay Research

"The quest for Majorana Neutrinos"

Fernando Ferroni
Gran Sasso Science Institute & INFN

Outline

- What is it ?
- Why should be studied
- How difficult it is
- Experimental history
- Today's status
- Perspectives

What is it ?

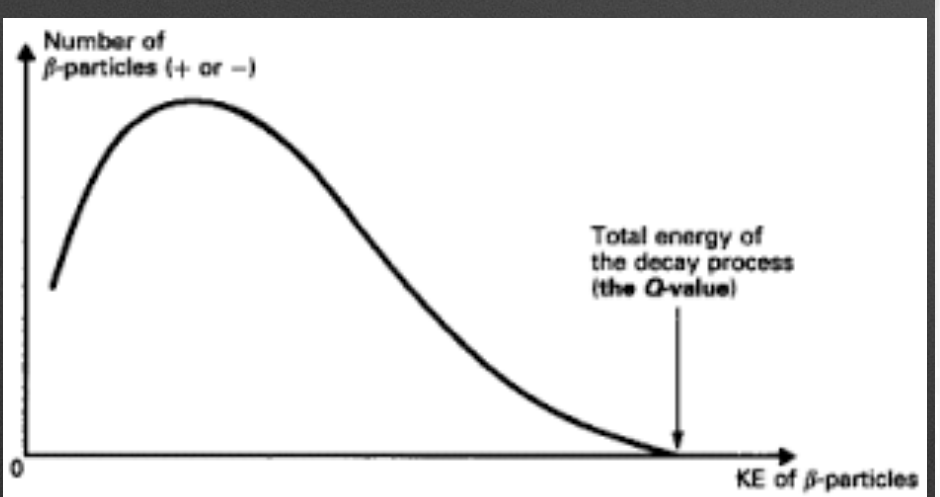
if one decay why not two ? (in the same nucleus) [1935]

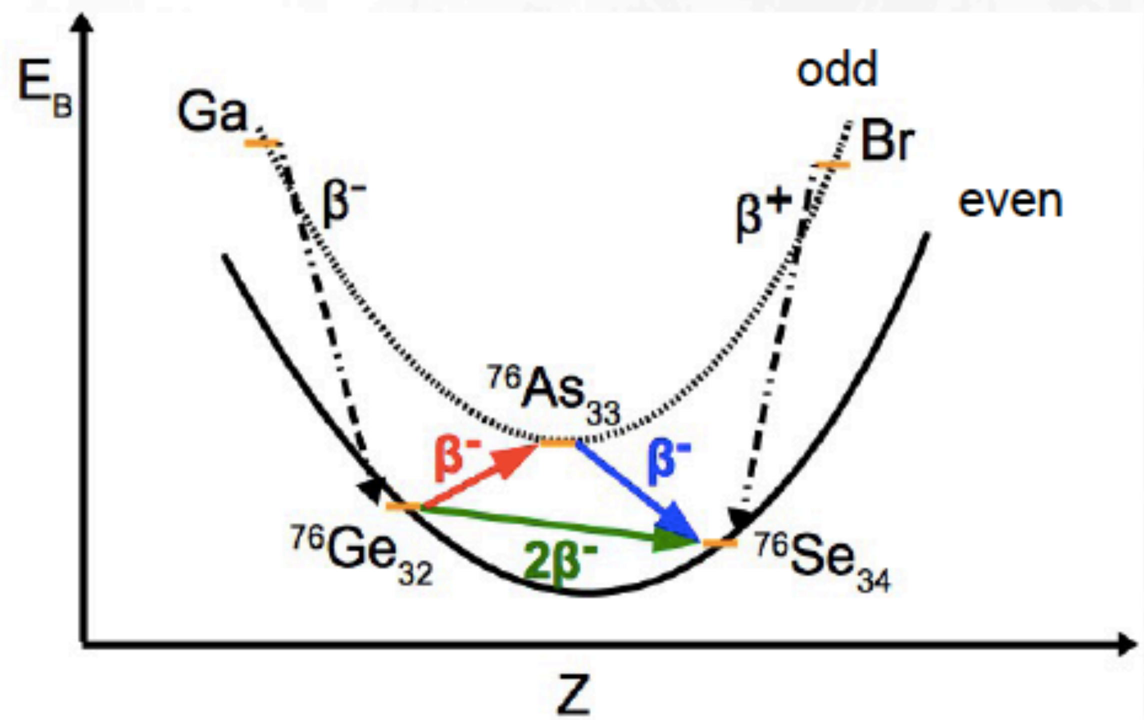
SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

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
ciently rarely to allow a half-life of over 10^{17} years for a nucl
number different by 2 were more stable by 20 times the electr





2vββ possible in 35 isotopes

Measured in Ca^{48}, Ge^{76}, Xe^{136}, …

$T_{1/2}$ (2vββ) = (10^{18} – 10^{21}) year

Age of the Universe: ~10^{10} years !

Avogadro number ~ 6 10^{23} !!

even more explicit

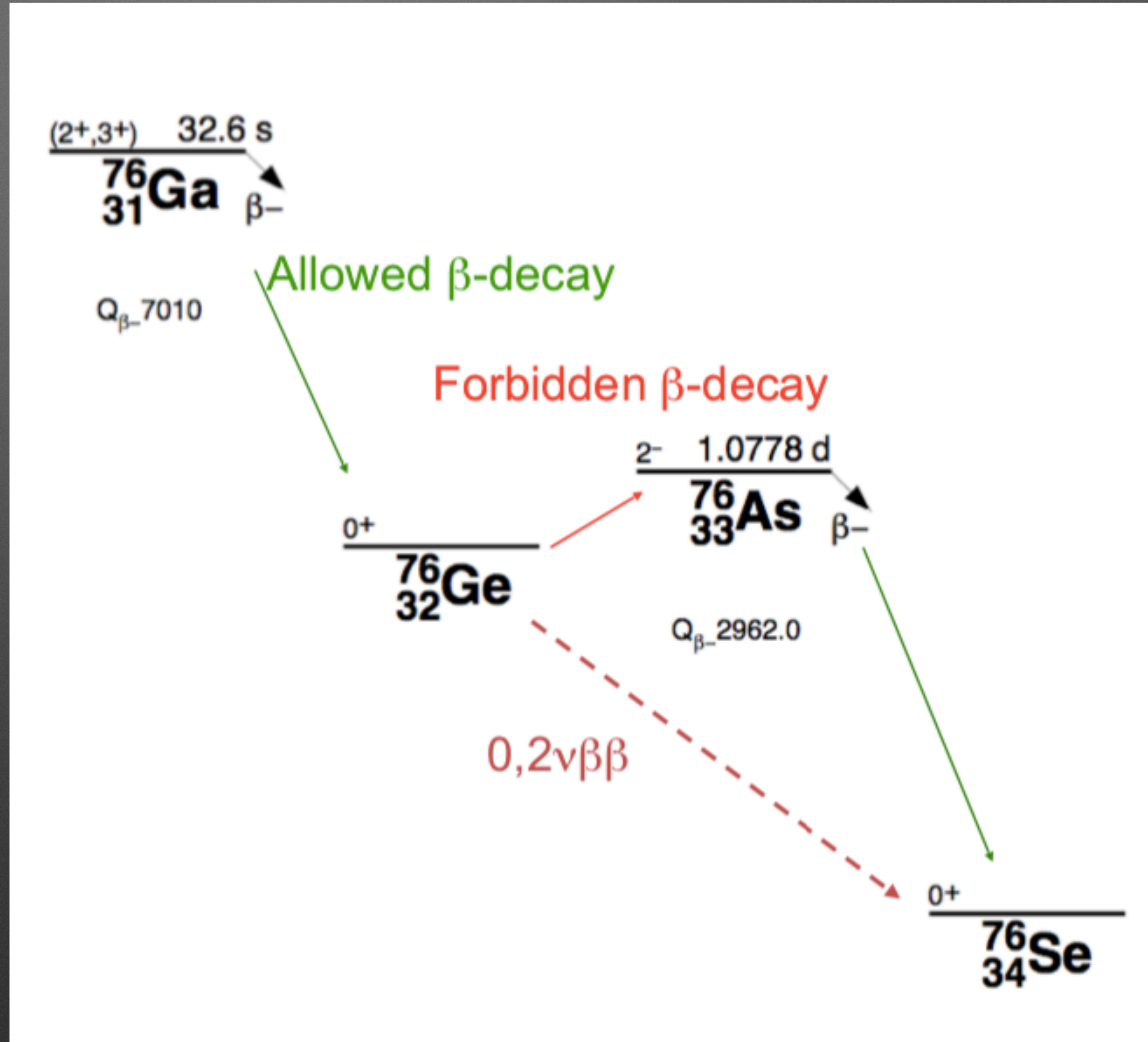
$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^-$$

Energetically allowed in many nuclei.

Prefer nuclei stable against β-decay (about 30)

2υββ: Observed 2nd order weak process.

$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^- + 2\bar{\nu}_e$$



a new, fundamental step

TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di ETTORE MAJORANA

In the case of electrons and positrons, we may anticipate only a formal progress; but we consider it important, for possible extensions by analogy, that the very notion of negative energy states can be avoided. We shall see, in fact, that it is perfectly, and most naturally, possible to formulate a theory of elementary neutral particles which do not have negative (energy) states.

it is perhaps not yet possible to ask experiments to decide between the new theory and a simple extension of the Dirac equations to neutral particles

“The advantage. . . is that there is no reason now to infer the existence of antineutrons or antineutrinos. The latter particles are introduced in the theory of positive β-ray emission; the theory, however, can be obviously modified so that the β-emission, both positive and negative, is always accompanied by the emission of a neutrino. ”

and indeed in 1939 …W. Furry

DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

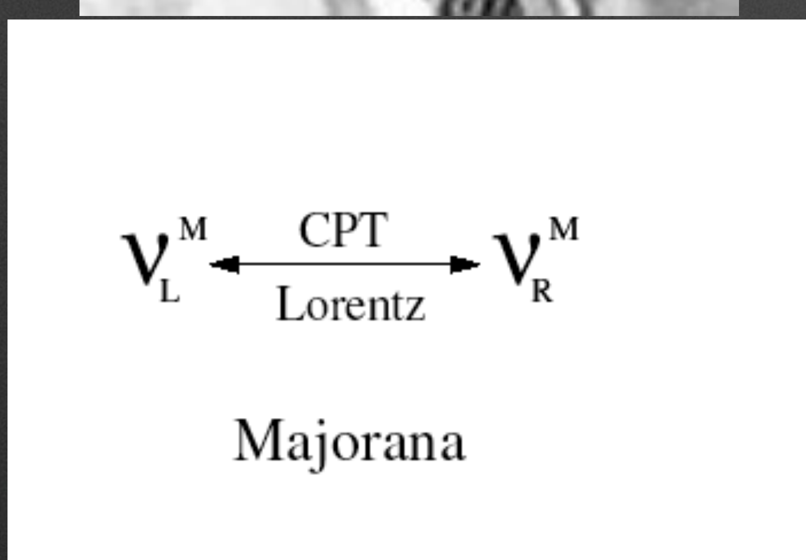
On Transition Probabilities in Double Beta-Disintegration

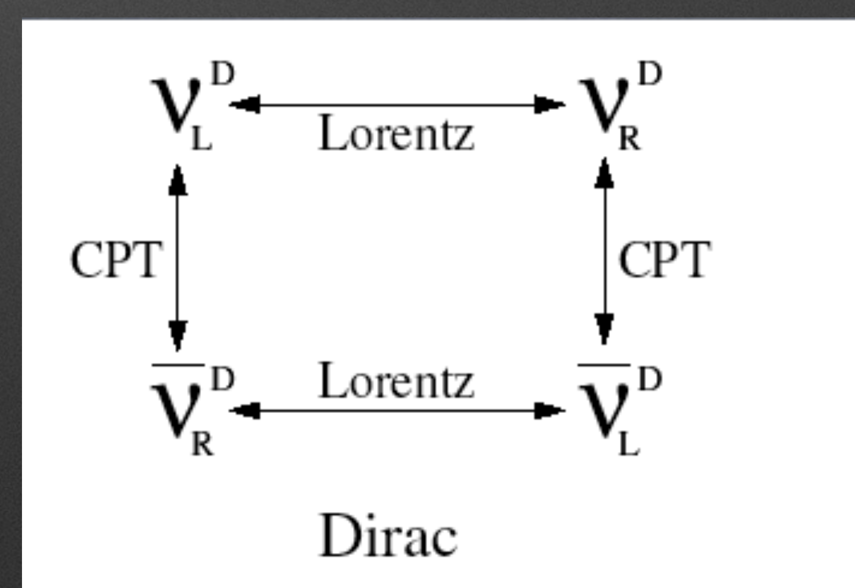
W. H. Furry
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts

(Received October 16, 1939)

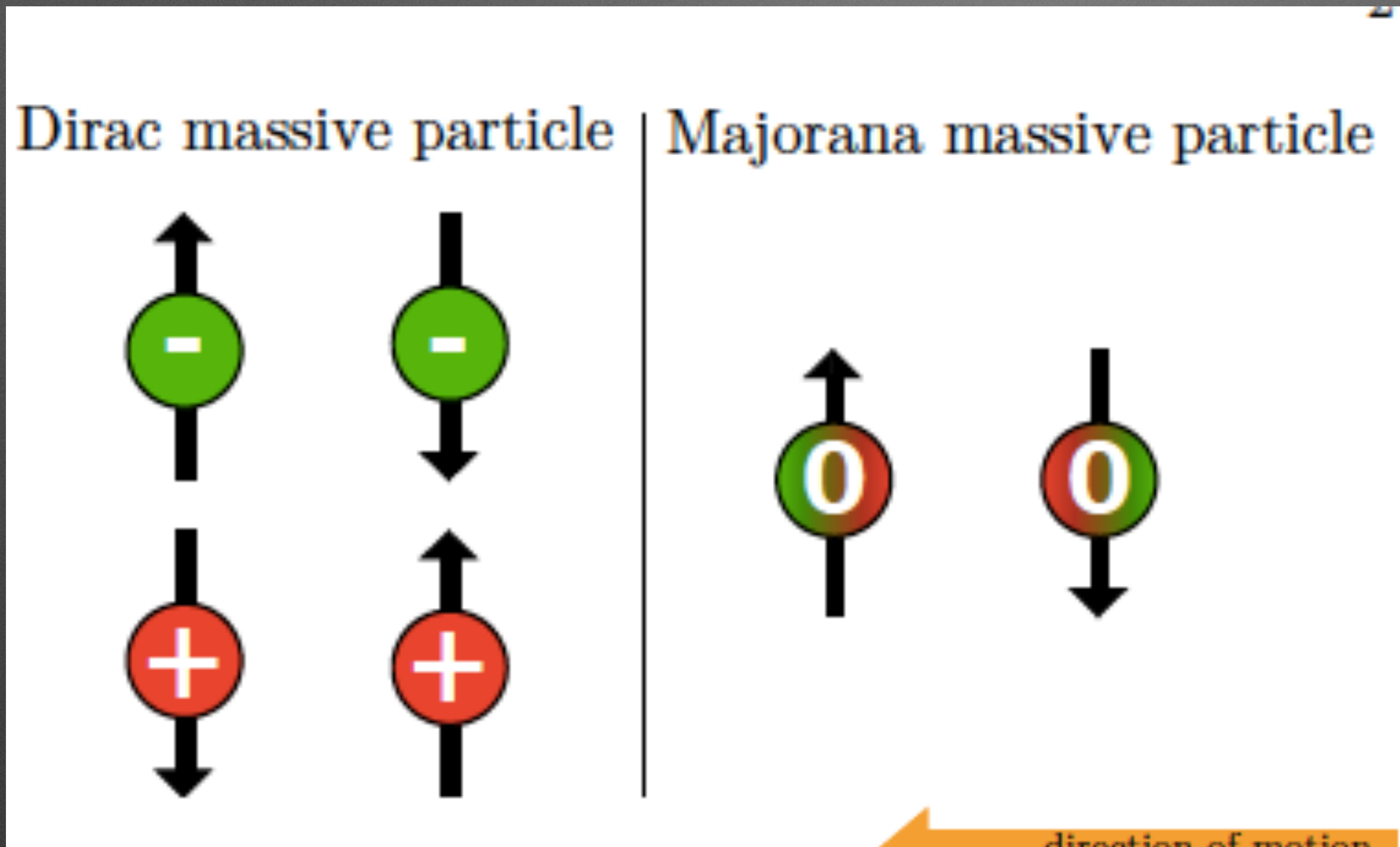
It can be shown that the use of the Majorana form of neutrino theory instead of the usual theory makes no difference in the case of ordinaryβ-decay. For the double β-disintegration, however, there is a marked qualitative difference between the results of the two theories. In the ordinary form of the theory four particles must be emitted in such a process: two neutrinos (or antineutrinos) must accompany the emission of two positrons (or electrons). In the Majorana theory there can occur not only these four particle disintegrations, but also disintegrations in which only the two charged particles -electrons or positrons- are emitted, unaccompanied by neutrinos. In these two-particle disintegrations the neutrino plays only a transitory or virtual part, such as is played by electron-positron pairs in certain hypothetical radiative processes.

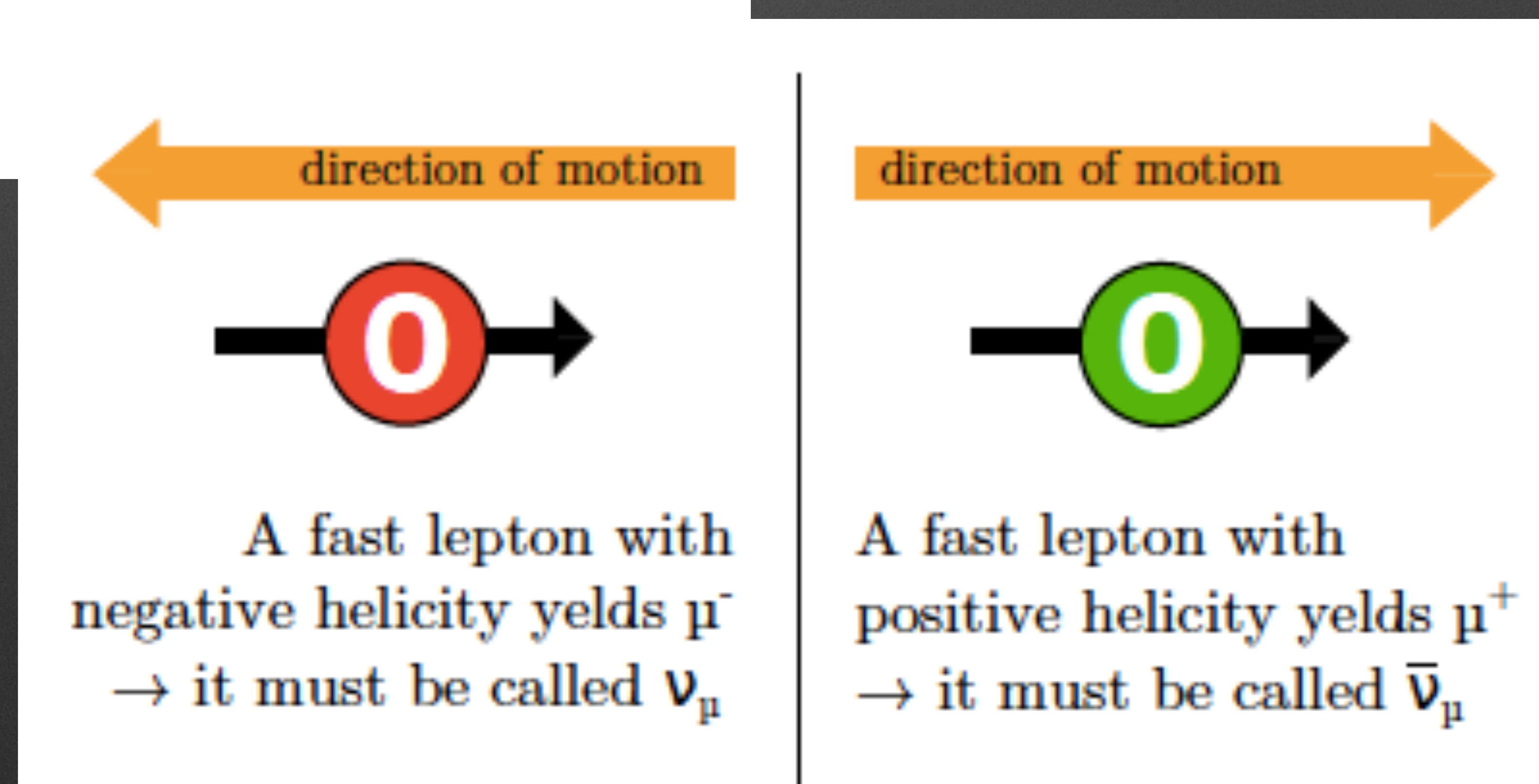
Quest for Majorana particles





or in a pictorial way





Now , the story freezes in 1939 and start to thaw in the ’90’s

- why so ?

- At the time of Furry the idea of measuring something with an half life larger than 10^{20} years was unconceivable even for the most daring experimentalists

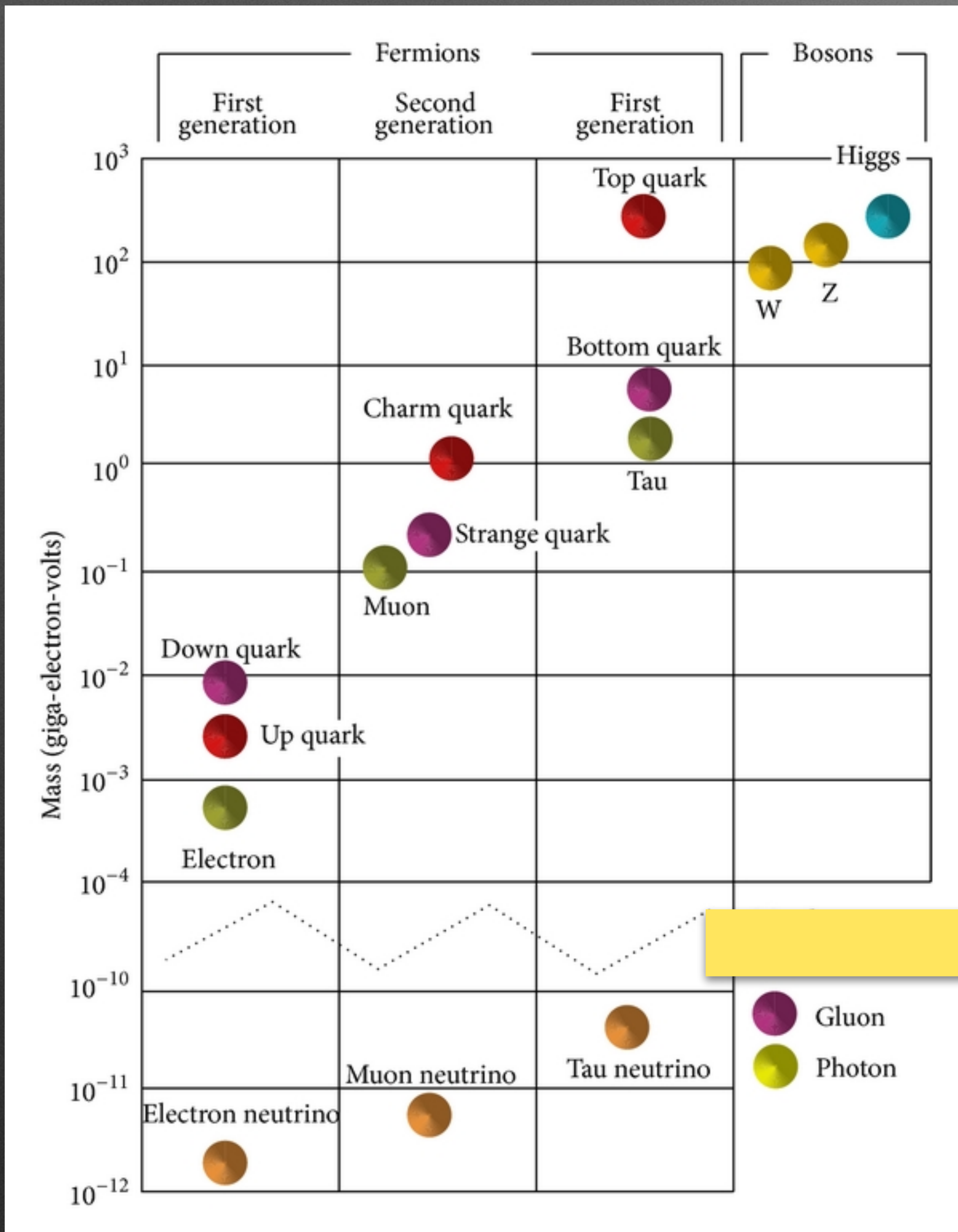
- Later the success of Standard Model of Electroweak Interactions (Glashow-Weinberg- Salam) with its built-in massless neutrino made all the efforts pretentious (yes , experimentalists are listening too much to theorists !)

- A massless particle cannot flip its helicity (no reference frame can be faster than light !). End of Majorana-Dirac story.

But , slow and unrelenting, the truth emerges

- Neutrinos are massive
- Their mass (not yet measured) is however very tiny compared to that of the other leptons
- Standard Model has a serious problem in accommodating this fact

lepton mass spectrum
neutrinos are far from every other



in reality we do not know the mass ordering of each neutrino. What we know is the squared mass difference

a really impressive gap

Dirac Mass terms for neutrinos

- if you want a Dirac mass you need a right handed neutrino and a Yukawa coupling (anomaly smaller than all the others)

$$\nu_{\mathrm{L}} = \begin{pmatrix} \nu_{e\mathrm{L}} \\ \nu_{\mu\mathrm{L}} \\ \nu_{\tau\mathrm{L}} \end{pmatrix} , \quad N_{\mathrm{R}} = \begin{pmatrix} N_{1\mathrm{R}} \\ N_{2\mathrm{R}} \\ N_{3\mathrm{R}} \end{pmatrix}$$

$$-\mathcal{L}'_{\mathrm{Dirac}} = \overline{\nu_{\mathrm{L}}} M_{\mathrm{D}} N_{\mathrm{R}} + \mathrm{h.c.} \, ,$$

- M_D is the <H> v.e.v
- All the terms (mass, kinetics, interaction) are invariant under a global phase transformation
- Hence, L is conserved (lepton number conservation)

Majorana mass term

- The left-handed field and its charge conjugate can form a mass term $-\mathcal{L}'_{\text{Majorana}} = \frac{1}{2}\overline{\nu_{\text{L}}} M_{\text{L}} (\nu_{\text{L}})^c + \text{h.c.}$
- The difference with Dirac is that here there is no lepton number conservation as the mass term is not invariant under a phase transformation
- Here we are out of Standard Model

Hybrid mass term

$$-\mathcal{L}'_{\rm hybrid} = \overline{\nu_{\rm L}} M_{\rm D} N_{\rm R} + \frac{1}{2}\overline{\nu_{\rm L}} M_{\rm L} (\nu_{\rm L})^c + \frac{1}{2}\overline{(N_{\rm R})^c} M_{\rm R} N_{\rm R} + {\rm h.c.}$$
$$= \frac{1}{2}\begin{bmatrix}\overline{\nu_{\rm L}} & \overline{(N_{\rm R})^c}\end{bmatrix}\begin{pmatrix} M_{\rm L} & M_{\rm D} \\ M_{\rm D}^T & M_{\rm R}\end{pmatrix}\begin{bmatrix}(\nu_{\rm L})^c \\ N_{\rm R}\end{bmatrix} + {\rm h.c.}\,,$$

- Now you have a Dirac mass term and a Majorana one
- Three scales of mass (M_D, M_L, M_R)
- See-saw mechanism allowed and the smallness of neutrino mass could be due to existence of a very large Majorana mass (M_D/M_R)

See-Saw in a nutshell

as both Dirac and Majorana mass terms are allowed the smallness of neutrino mass can find a reasonable explanation

- M_D is at electroweak scale (Higgs v.e.v)
- M_L is ~ 0 (2νββ process)
- M_R is determined by the actual value of m_ν !

$$\begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \Rightarrow m_\nu^{\text{light}} \sim m_D \left(\frac{m_D}{m_R}\right)$$

- i.e. m_ν~ 50meV, M_D~ 200 GeV…… → …… $M_R \sim 10^{15}$ GeV

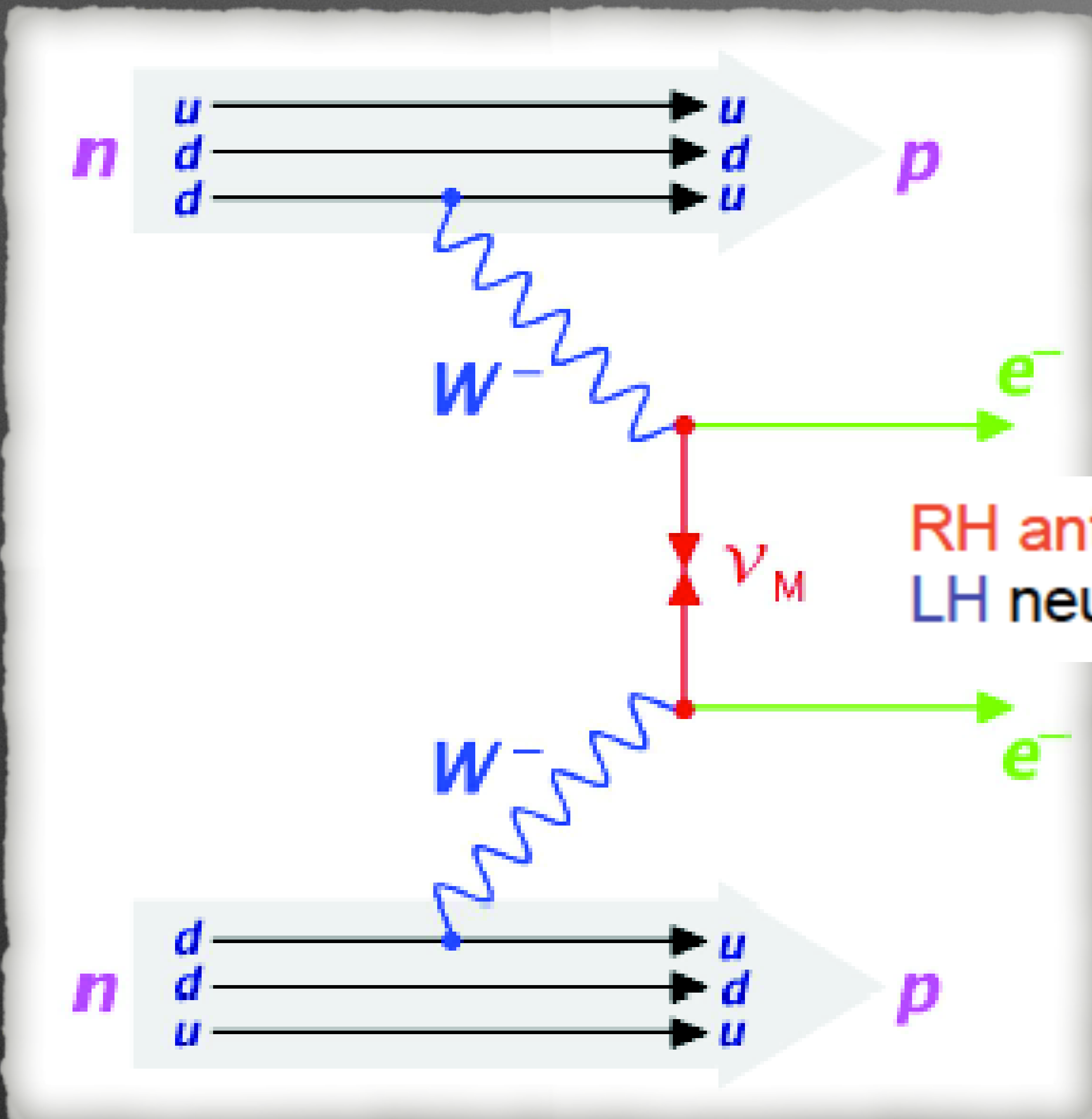
General consideration

for very small neutrino masses,
distinguish Dirac from Majorana
is
horribly difficult
whatever you do

so we have to study in detail Neutrinoless Double Beta Decay

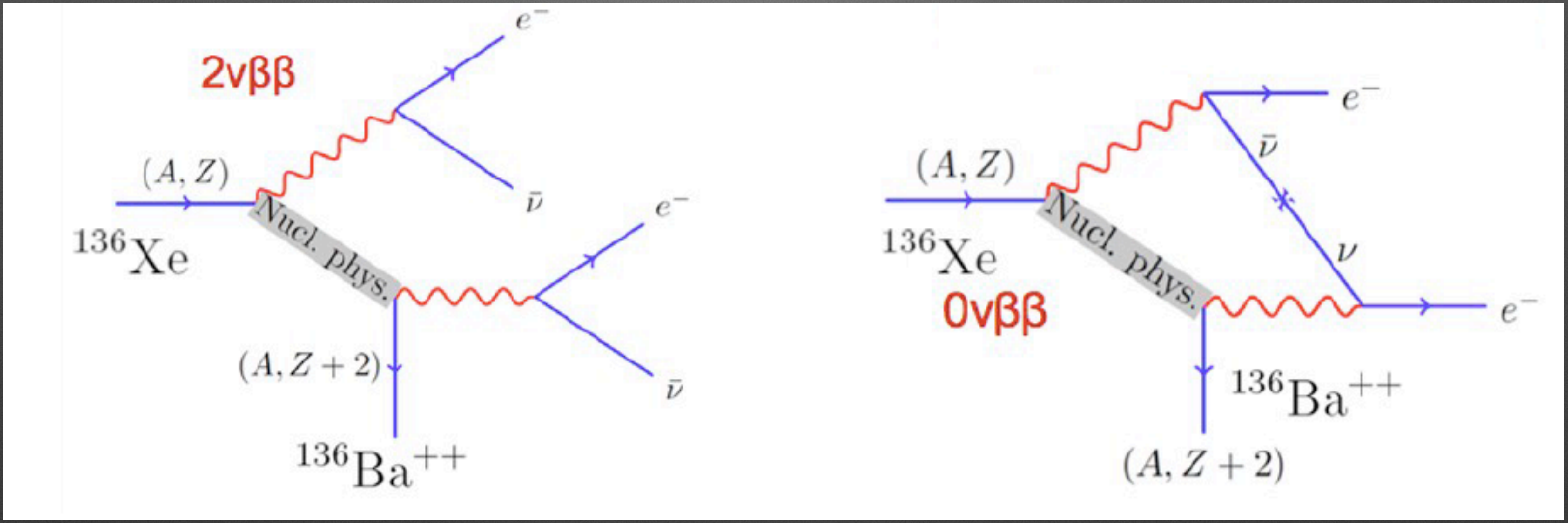
- what should we expect in term of lifetime ?
- how worse can it be with respect to the process with the emission of two neutrinos (Dirac allowed)

The process



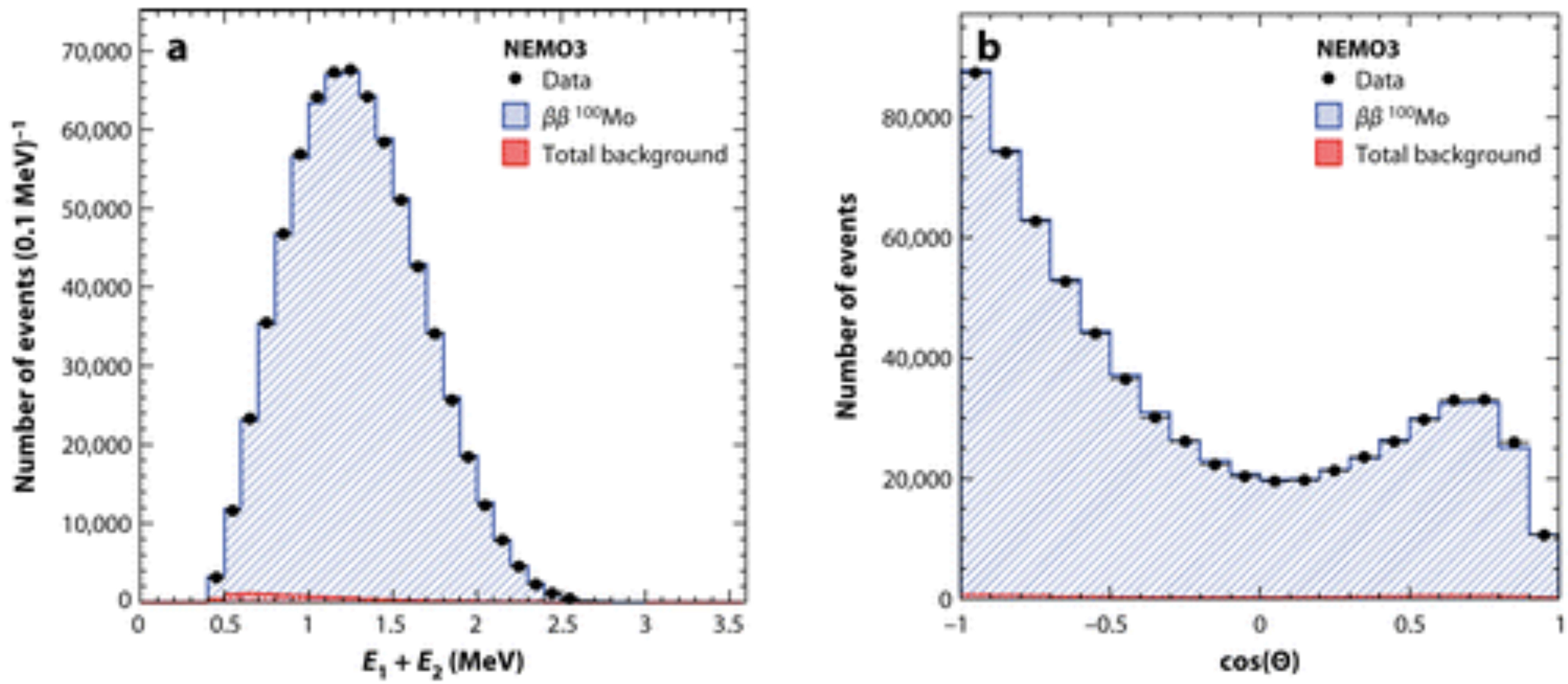
RH antineutrino (L=1) is emitted at one vertex
LH neutrino (L=-1) is absorbed at the other vertex

how much we learn from 2νββ



2νββ is observed and well measured in many cases
which part of the decay rate is in common ?
if any !

just to show you that 2νββ is precisely measured



Saakyan R . 2013.
Annu. Rev. Nucl. Part. Sci. 63:503–29

2νββ in ^{100}Mo

all in excess of 10^{18} y

some longer than 10^{21} y

Half-life measurements of the two-neutrino double-β decay

The measured half-life values for the transitions (Z,A) $\rightarrow$ (Z+2,A) + $2e^-$ + $2\overline{\nu}_e$ to the 0^+ ground state of the final nucleus are listed. We also list the transitions to an excited state of the final nucleus (0^+_i, etc.). We report only the measuremetnts with the smallest (or comparable) uncertainty for each transition.

$t_{1/2}(10^{21}$ yr)			ISOTOPE	TRANSITION	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 0.87			^{134}Xe		EXO-200	[1] ALBERT	17C
0.82	±0.02	±0.06	^{130}Te		CUORE-0	[2] ALDUINO	17
0.00690	±0.00015	±0.00037	^{100}Mo		CUPID	[3] ARMENGAUD	17
0.0274	±0.0004	±0.0018	^{116}Cd		NEMO-3	[4] ARNOLD	17
0.064	$^{+0.007}_{-0.006}$	$^{+0.012}_{-0.009}$	^{48}Ca		NEMO-3	[5] ARNOLD	16
0.00934	±0.00022	$^{+0.00062}_{-0.00060}$	^{150}Nd		NEMO-3	[6] ARNOLD	16A
1.926	±0.094		^{76}Ge		GERDA	[7] AGOSTINI	15A
0.00693	±0.00004		^{100}Mo		NEMO-3	[8] ARNOLD	15
2.165	±0.016	±0.059	^{136}Xe		EXO-200	[9] ALBERT	14
9.2	$^{+5.5}_{-2.6}$	±1.3	^{78}Kr		BAKSAN	[10] GAVRILYAK	13
2.38	±0.02	±0.14	^{136}Xe		KamLAND-Zen	[11] GANDO	12A
0.7	±0.09	±0.11	^{130}Te		NEMO-3	[12] ARNOLD	11
0.0235	±0.0014	±0.0016	^{96}Zr		NEMO-3	[13] ARGYRIADES	10
0.69	$^{+0.10}_{-0.08}$	±0.07	^{100}Mo	$0^+ \rightarrow 0^+_1$	Ge coinc.	[14] BELLI	10
0.57	$^{+0.13}_{-0.09}$	±0.08	^{100}Mo	$0^+ \rightarrow 0^+_1$	NEMO-3	[15] ARNOLD	07
0.096	±0.003	±0.010	^{82}Se		NEMO-3	[16] ARNOLD	05A
0.029	$^{+0.004}_{-0.003}$		^{116}Cd		$^{116}CdWO_4$ scint.	[17] DANEVICH	03

Lifetime side-by-side

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

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

technically the term depending on neutrino mass applies only in the case where the 2vββ happens because neutrino is a Majorana particle

There are diagrams of some kind of New Physics that might induce the same decay

common (!!???) elements of decay rates

- G (Q, Z) Kinematic term (Phase space)
- M Nuclear Matrix Elements (NME)

in a good approximation the two parts are independent (factorization !)

G (Q,Z)

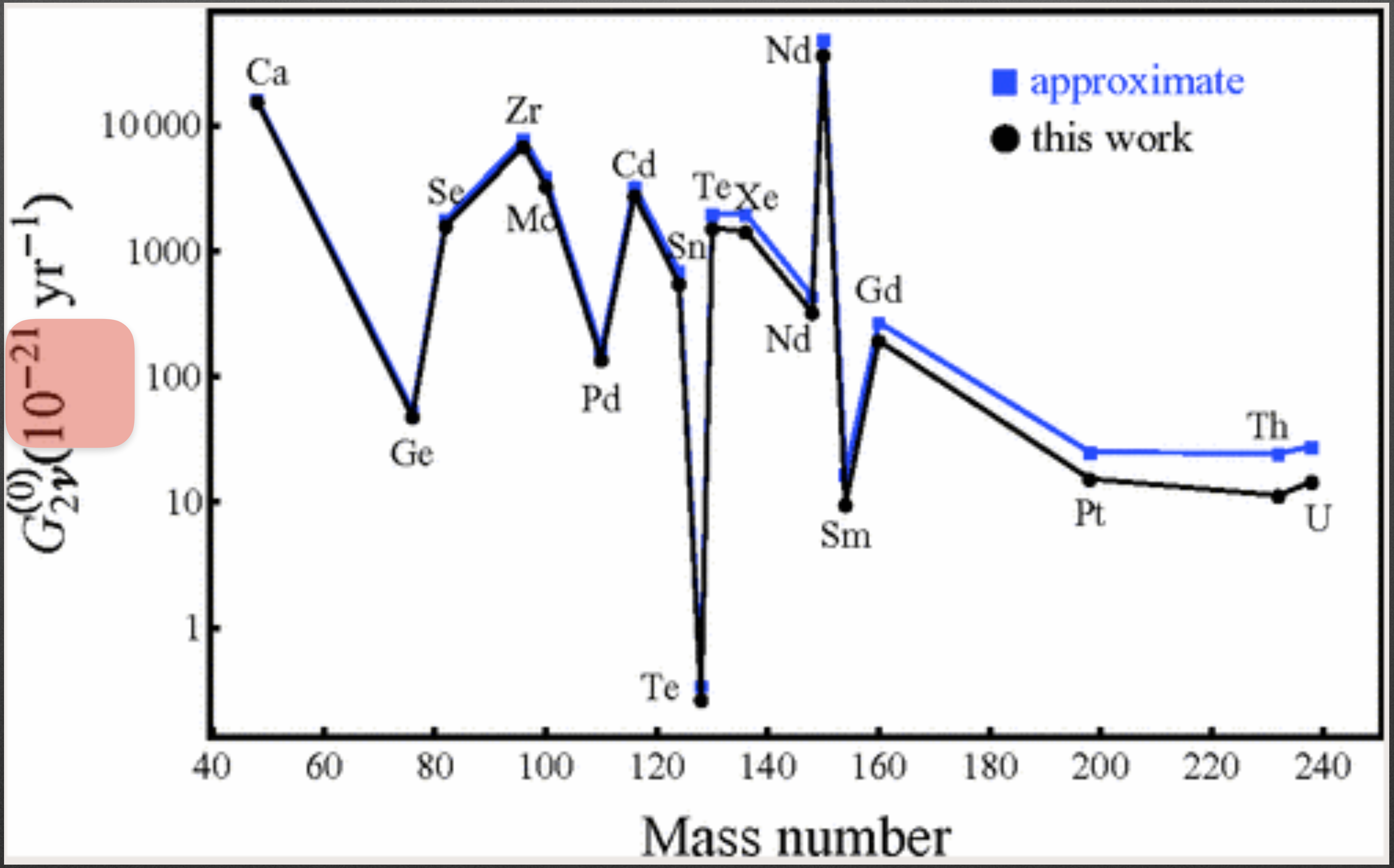
Phase space (calculable)

$$G^{2\nu} \propto \int_{m_e}^{E_0-m_e} F(Z, E_{e1}) p_{e1} E_{e1} \mathrm{d}E_{e1} \times \int_{m_e}^{E_0-E_{e1}} F(Z, E_{e2}) p_{e2} E_{e2} \mathrm{d}E_{e2} \times \int_0^{E_0-E_{e1}-E_{e2}} p_{\nu 1}^2 (E_0 - E_{e1} - E_{e2} - p_{\nu 1})^2 \mathrm{d}p_{\nu 1},$$

integration over all possible energies and angles of the leptons emitted in the decay process.

For the two neutrino mode , two electrons and two neutrinos

look at huge variations !



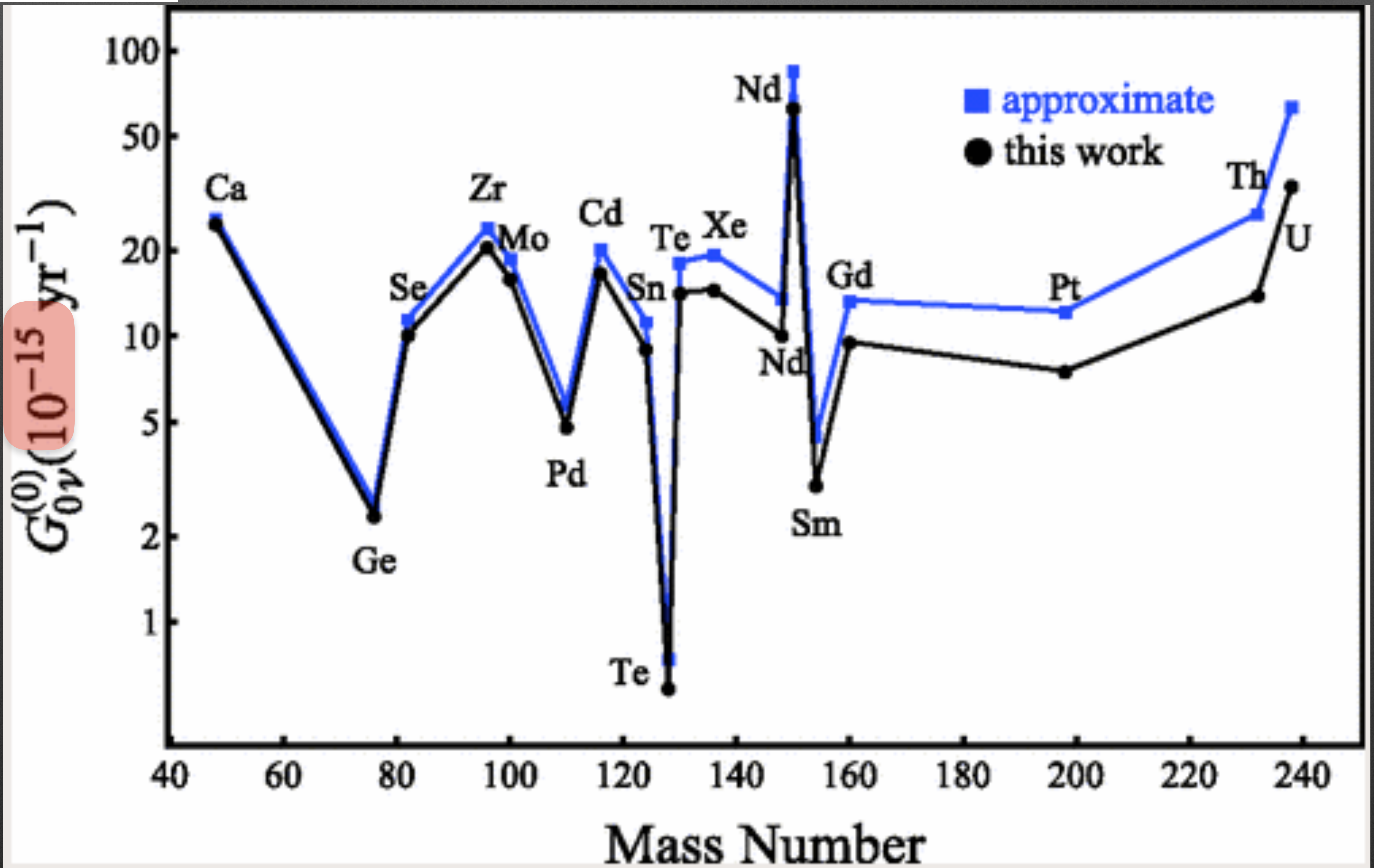
there is a reason for it (0th order)

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

it will have an important implication when this rare process will become a background to the one we would like to measure

for the neutrino less case

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

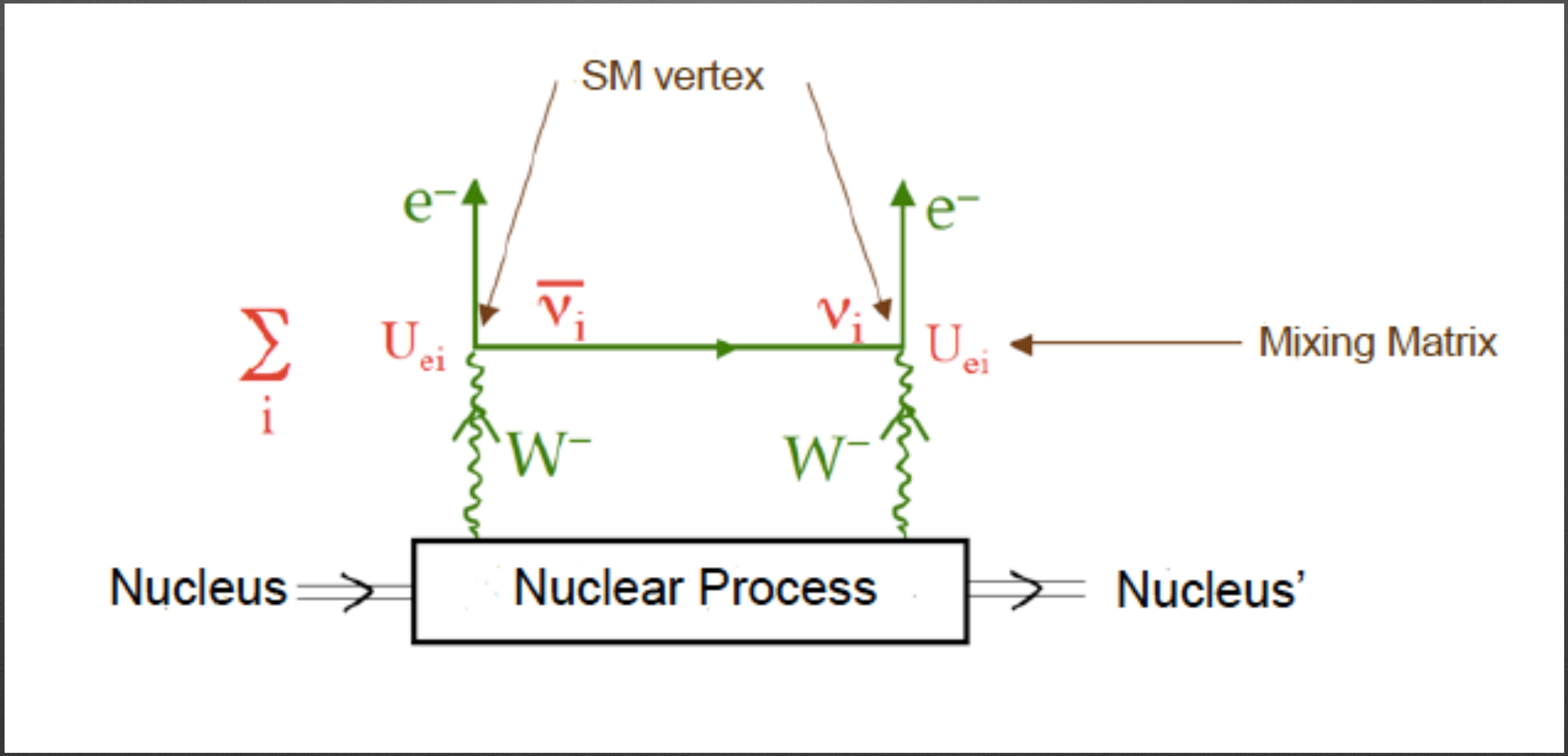


it already brings bad news

- take one case ....Germanium
- $G^{2\nu} \sim 2.4\ 10^{-15}\ y^{-1}$
- $G^{0\nu} \sim 48\ 10^{-21}\ y^{-1}$
- The ratio of half lives will start with a kinematic suppression larger than 10^5
- The 2v measured is ~2 10^{21} y therefore be prepared to be sensitive to half lives larger than 10^{26}

although NMEs could work in your favour !!!!

the nasty term (NME)



and next the SM part (the neutrino mixing matrix)

Nuclear Matrix Elements (NME)

what is a NME

NMEs define the nuclear-structural part of the probability for the double-β transition between the parent and daughter nuclei.

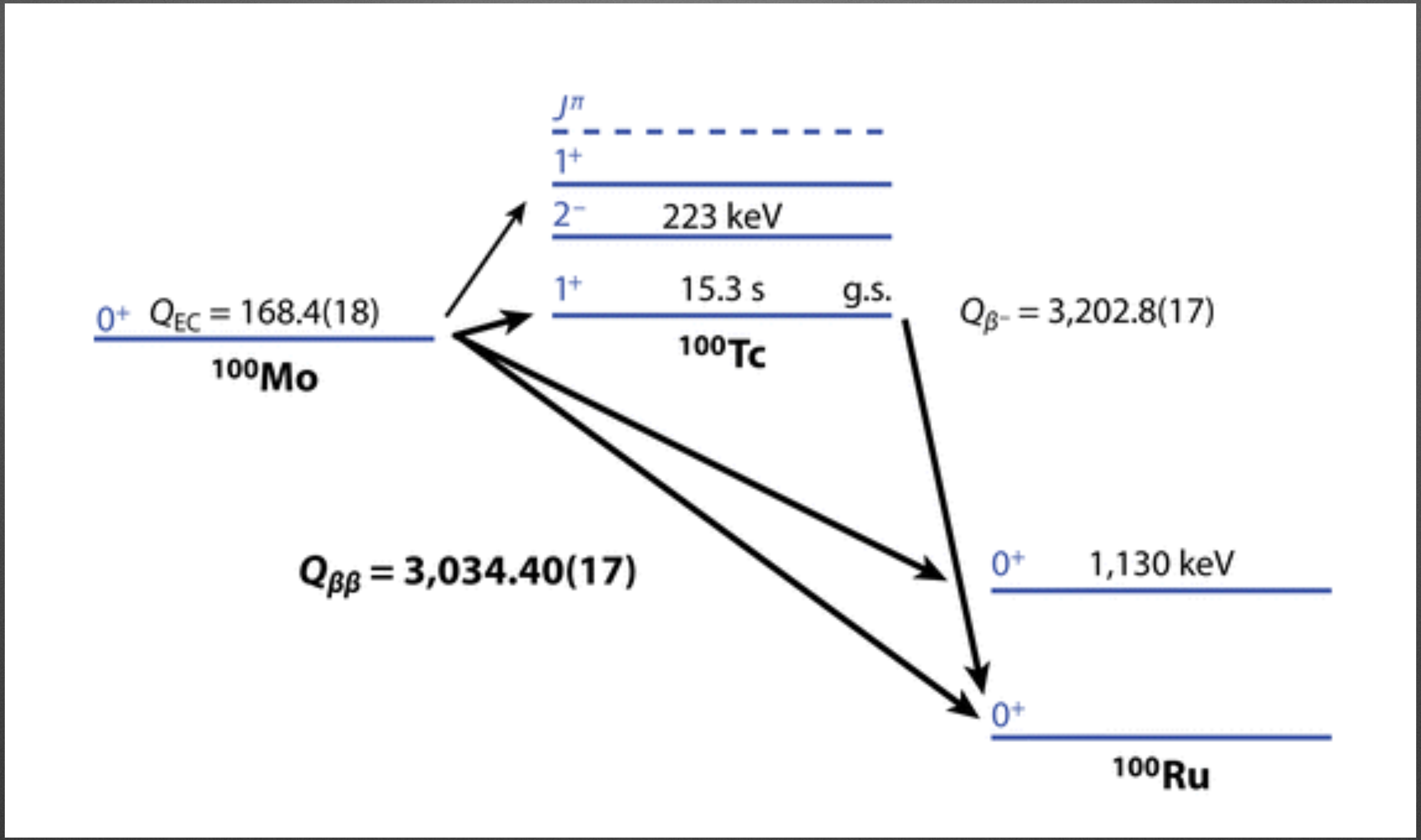
making such a calculation involves mapping out all possible transitions between the two complex multibody systems (initial and final nuclei)

this is a difficult task

learning by 2$\nu\beta\beta$

- The 2$\nu\beta\beta$ and 0$\nu\beta\beta$ have different NME
- however if you are able to calculate the 2$\nu\beta\beta$ NME and successfully check wrt. experimental data you gain confidence

the nuclear-level diagram



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

The models

- Nuclear Shell Model (NSM)
- Quasiparticle random phase approximation (QRPA)
- Microscopic interacting boson model (IBM-2)
- others (interacting shell model [ISM]…….)

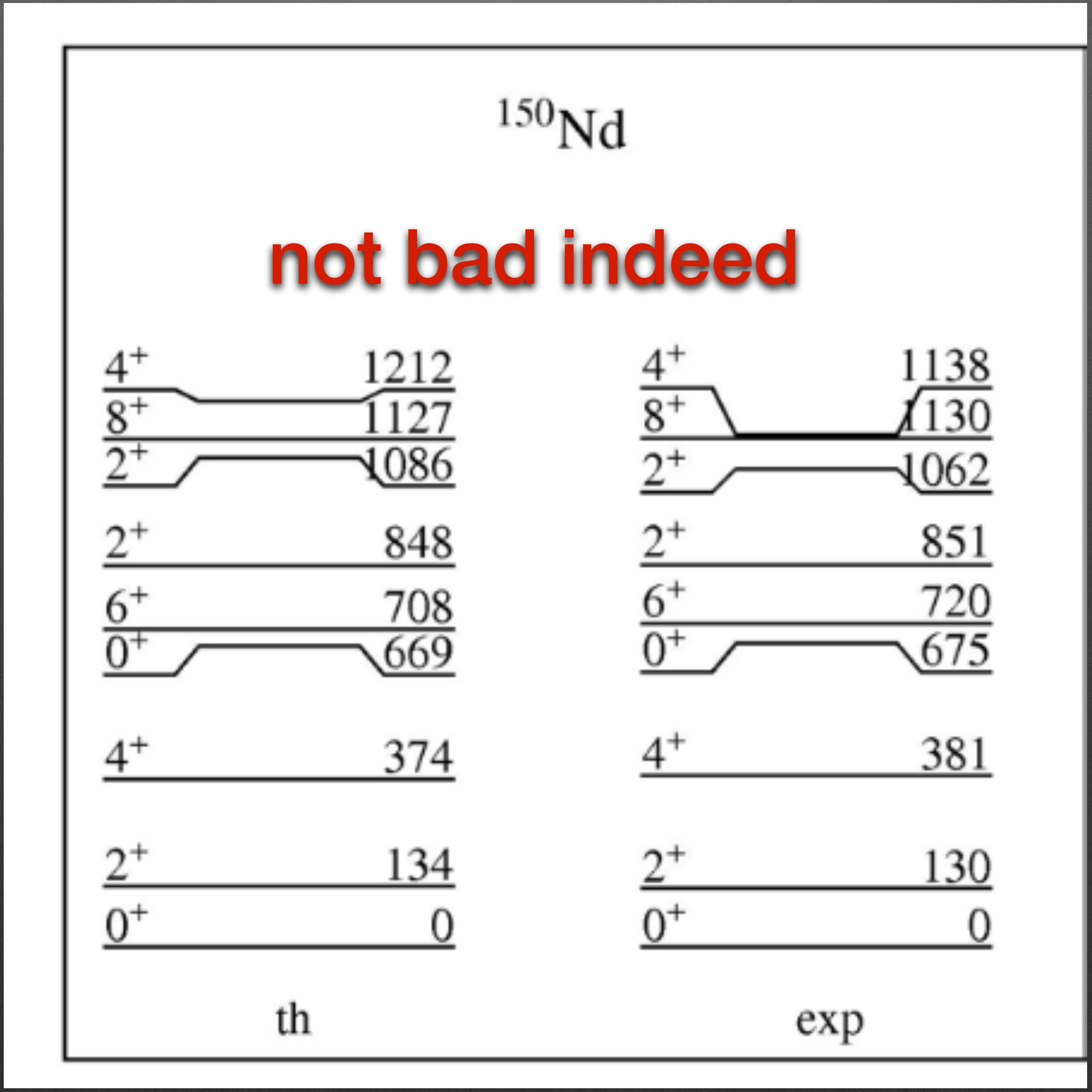
at the end of the day does it predict or does not ?

- you need some approximation before checking models wrt. experiments
- Single state dominance (SSD) , which in most cases is reasonable

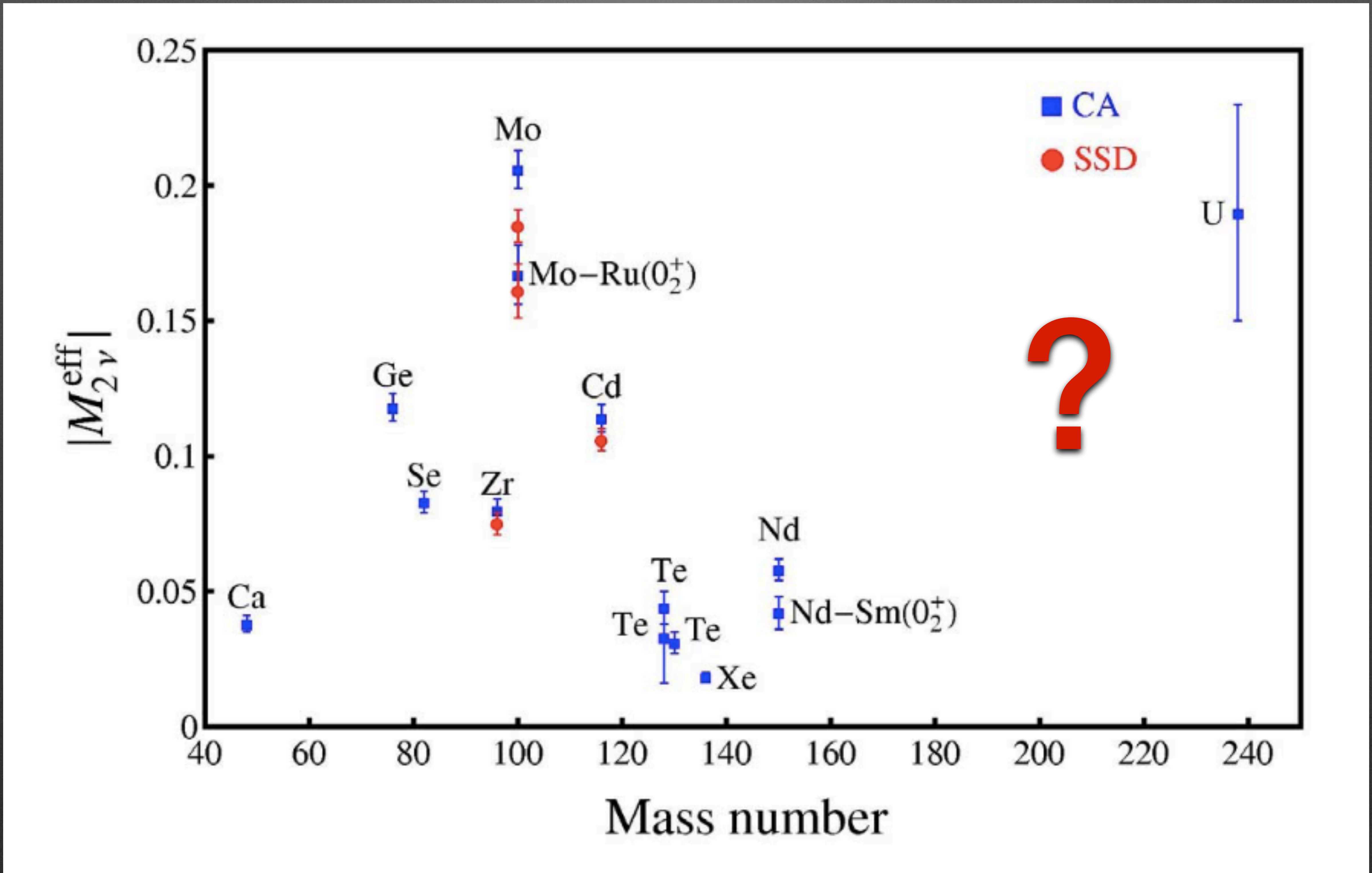
OR

- Closure approximation (CA), which is to give an average energy for all the intermediate states (doable if neutrino momentum is larger than excitation energies…..not very good in $2\nu\beta\beta$ case as $E\nu \sim 1$ MeV)

check IBM-2:
first ability in predicting levels



now the moment of truth: compare to measured half-lives



wait a moment !!!
we have forgot one thing

$$M_{2\nu} = g_A^2 M^{(2\nu)}$$

so what ? Isn't g_A well known from neutron decay ?

$$g_{nucleon} = 1.269$$

so the idea is :
(2vββ is two times a β decay)

$$g_A = \begin{cases} g_{\text{nucleon}} & = 1.269 \\ g_{\text{quark}} & = 1 \\ g_{\text{phen.}} & = g_{\text{nucleon}} \cdot A^{-0.18} \end{cases}$$

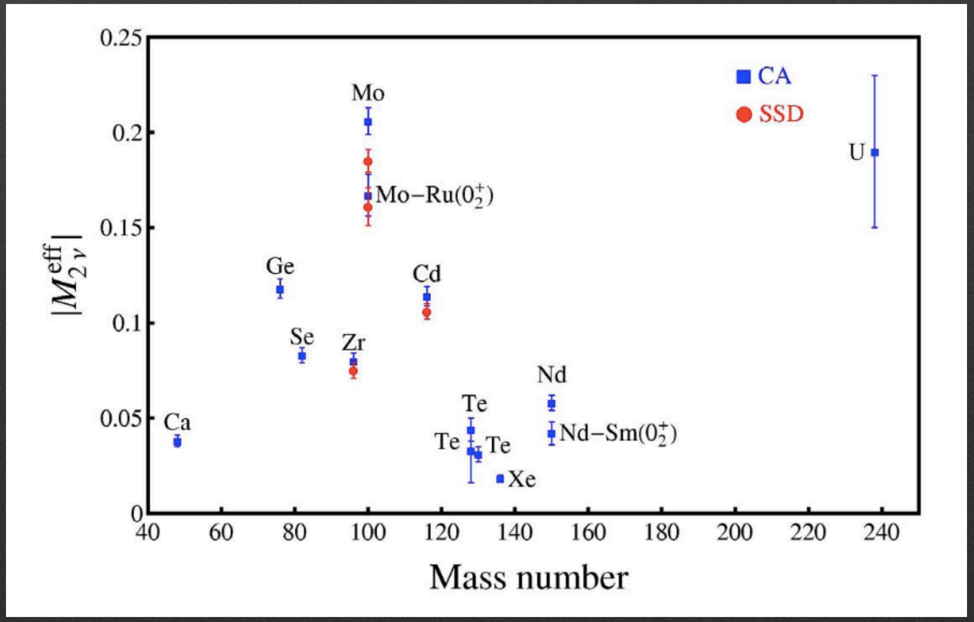
would be great

we could we live with

very bad

So this is the meaning of the plot you have seen

The problem for us is what will the value of g_A in 0vββ will be.

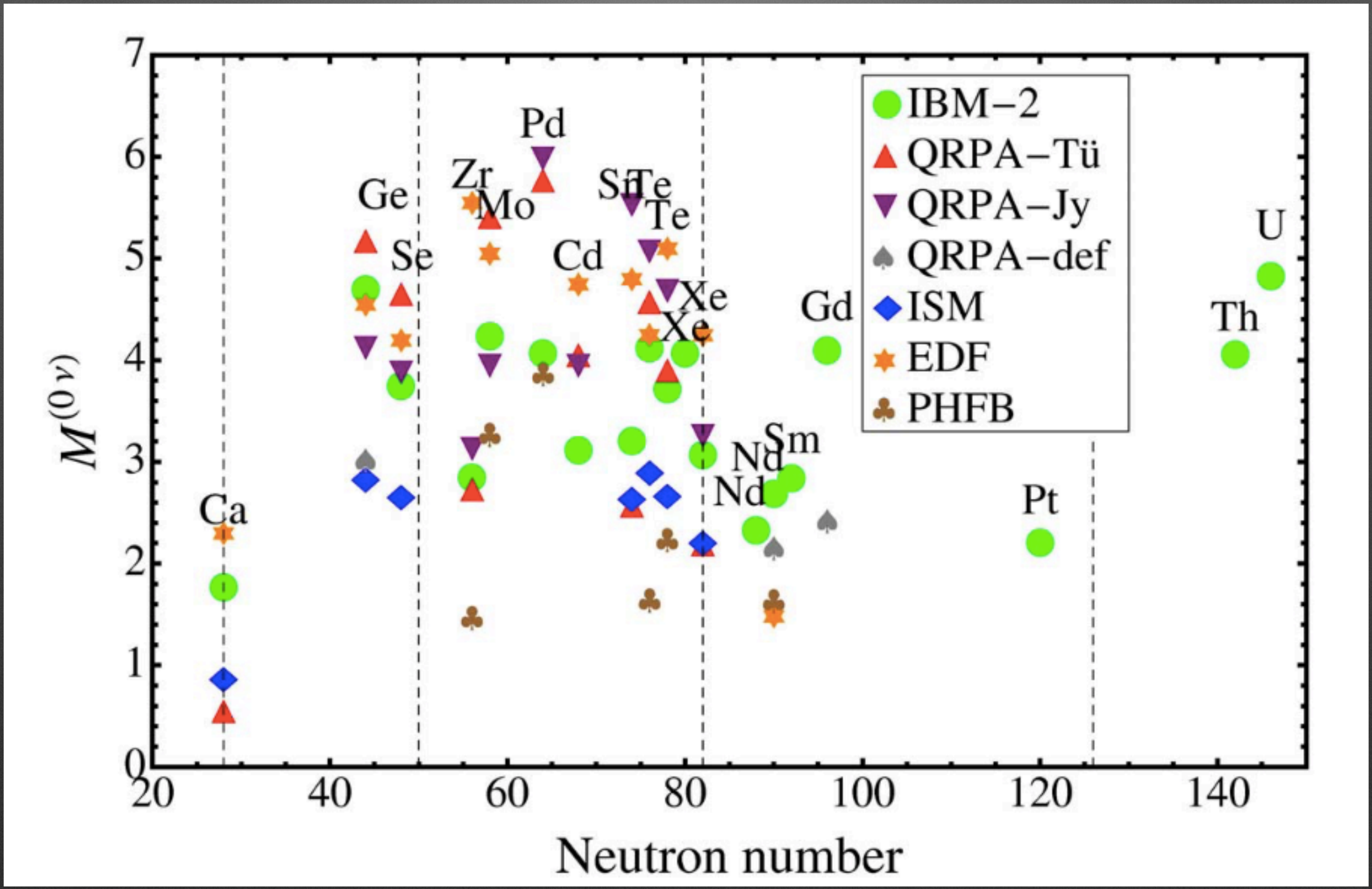


Now we go to 0νββ

$$\mathcal{M} \equiv g_A^2\,\mathcal{M}_{0\nu} = g_A^2 \left(M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_F^{(0\nu)} + M_T^{(0\nu)} \right)$$

- unlike the 2νββ where only GT (axial) transition can happen here you have also the Fermi (vector) one, and even Tensor
- a big difference is in the momentum transfer of the neutrino. Here the virtual process happens at the scale of nuclear size, a few 100 MeV (the closure approximation works very well)
- there are nuclei where the process only happens under SSD hypothesis (^{100}Mo amongst them)

what the calculations of $M^{0\nu}$ say

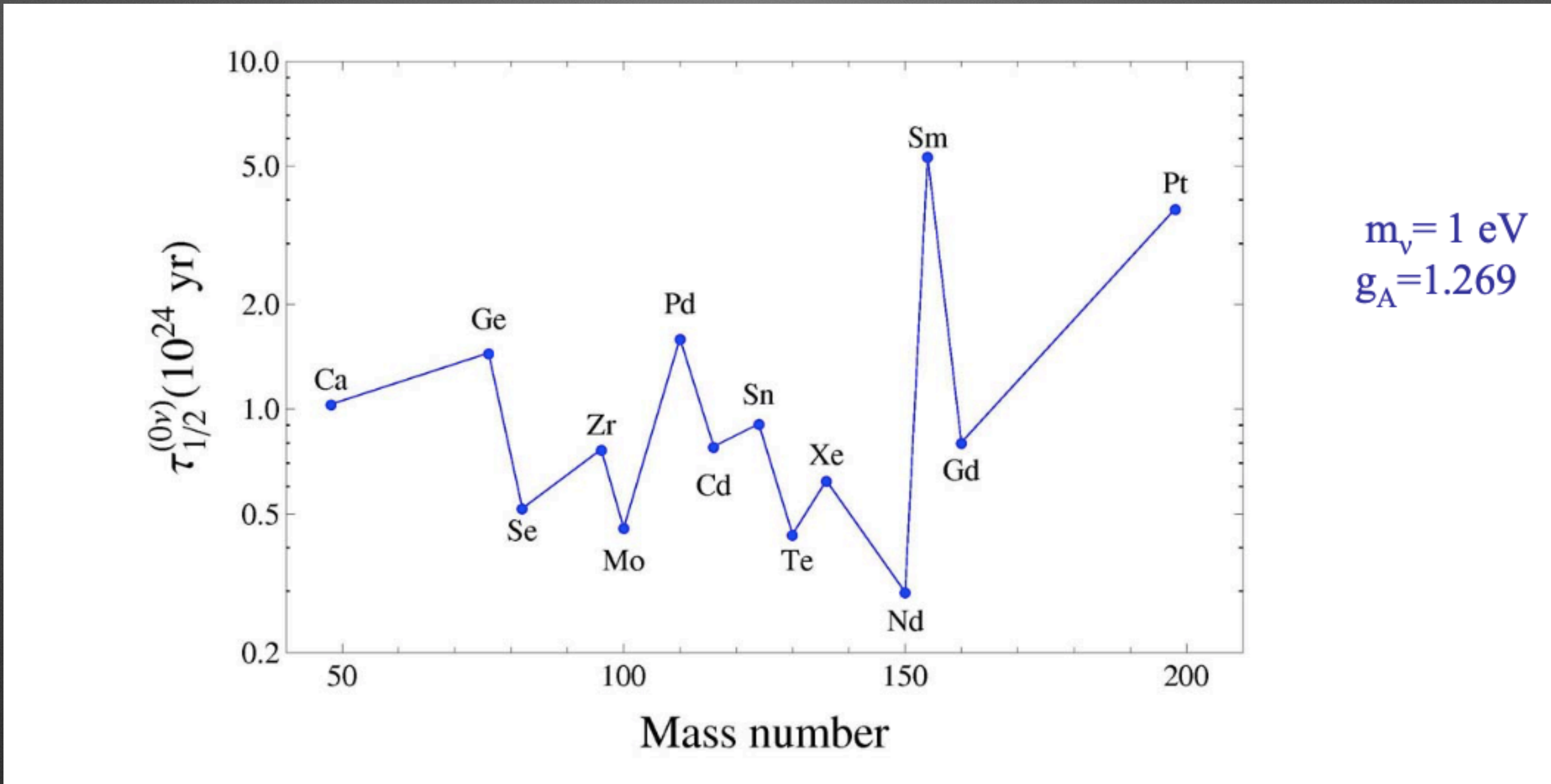


comparison IBM-2 / QRPA

	$M^{(0\nu)}$ IBM-2§	$M^{(0\nu)}$ QRPA¶
$^{48}Ca \rightarrow ^{48}Ti$	1.98	
$^{76}Ge \rightarrow ^{76}Se$	5.42	4.68
$^{82}Se \rightarrow ^{82}Kr$	4.37	4.17
$^{96}Zr \rightarrow ^{96}Mo$	2.53	1.34
$^{100}Mo \rightarrow ^{100}Ru$	3.73	3.53
$^{110}Pd \rightarrow ^{110}Cd$	3.62	
$^{116}Cd \rightarrow ^{116}Sn$	2.78	2.93
$^{124}Sn \rightarrow ^{124}Te$	3.50	
$^{128}Te \rightarrow ^{128}Xe$	4.48	3.77
$^{130}Te \rightarrow ^{130}Xe$	4.03	3.38
$^{136}Xe \rightarrow ^{136}Ba$	3.33	2.22

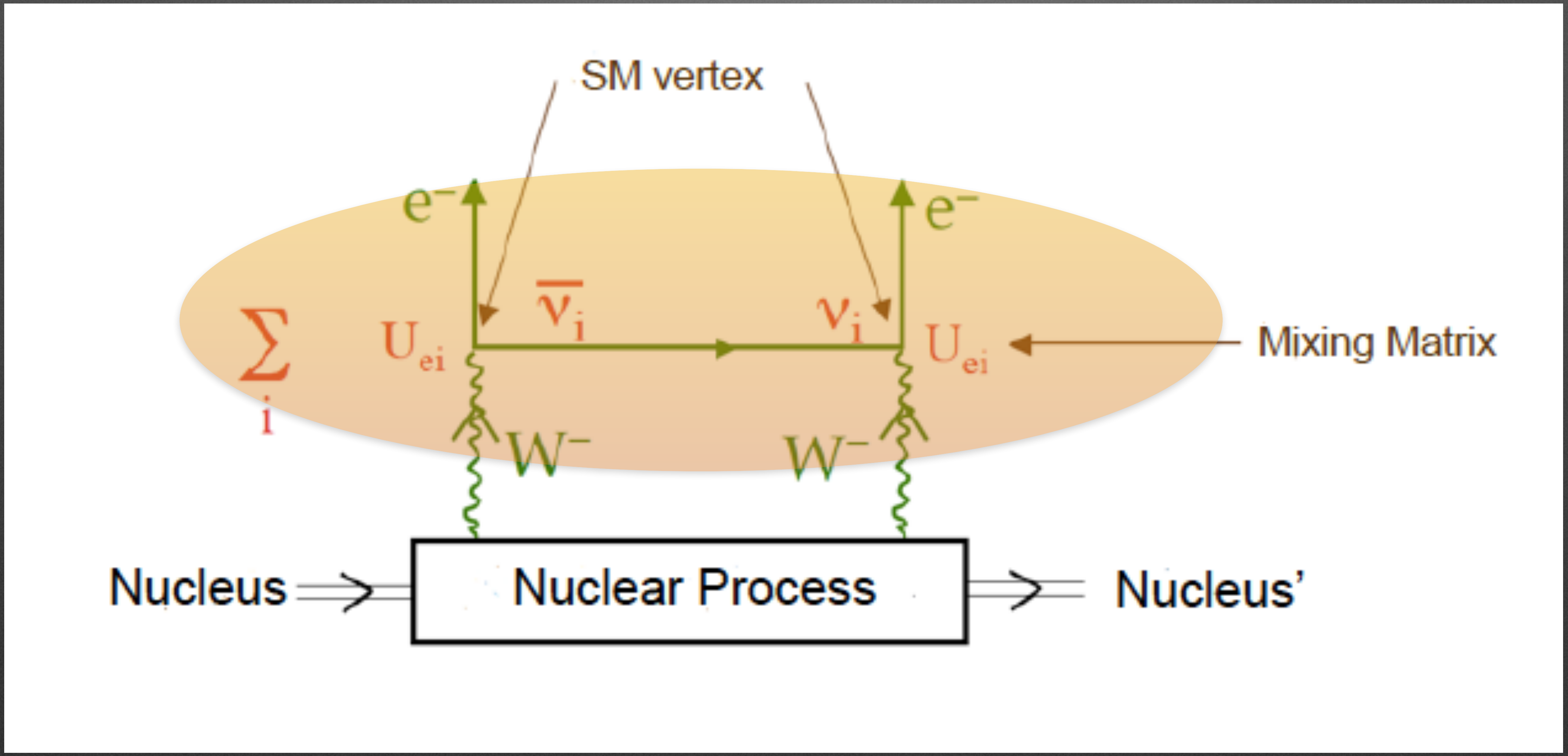
In most cases differences are well below a factor 2

bringing to some prediction for half lives



useful to make your choice of isotope….look only at the ratios. Time to despair has yet to come.

the last element : weak interactions



The weak knowledge

- Neutrinos are massive fermions
- There are 3 different flavours (e, μ, τ)
- The weak eigenstates are not the mass eigenstates
- So, each flavour is a combination of the (1,2,3) mass states

$$\nu_\ell = \sum_{i=1}^{N} U_{\ell i}\ \nu_i \quad \text{with} \quad \begin{cases} \ell = \mathrm{e}, \mu, \tau & \text{[flavor]} \\ i = 1, 2, 3 & \text{[mass]} \end{cases}$$

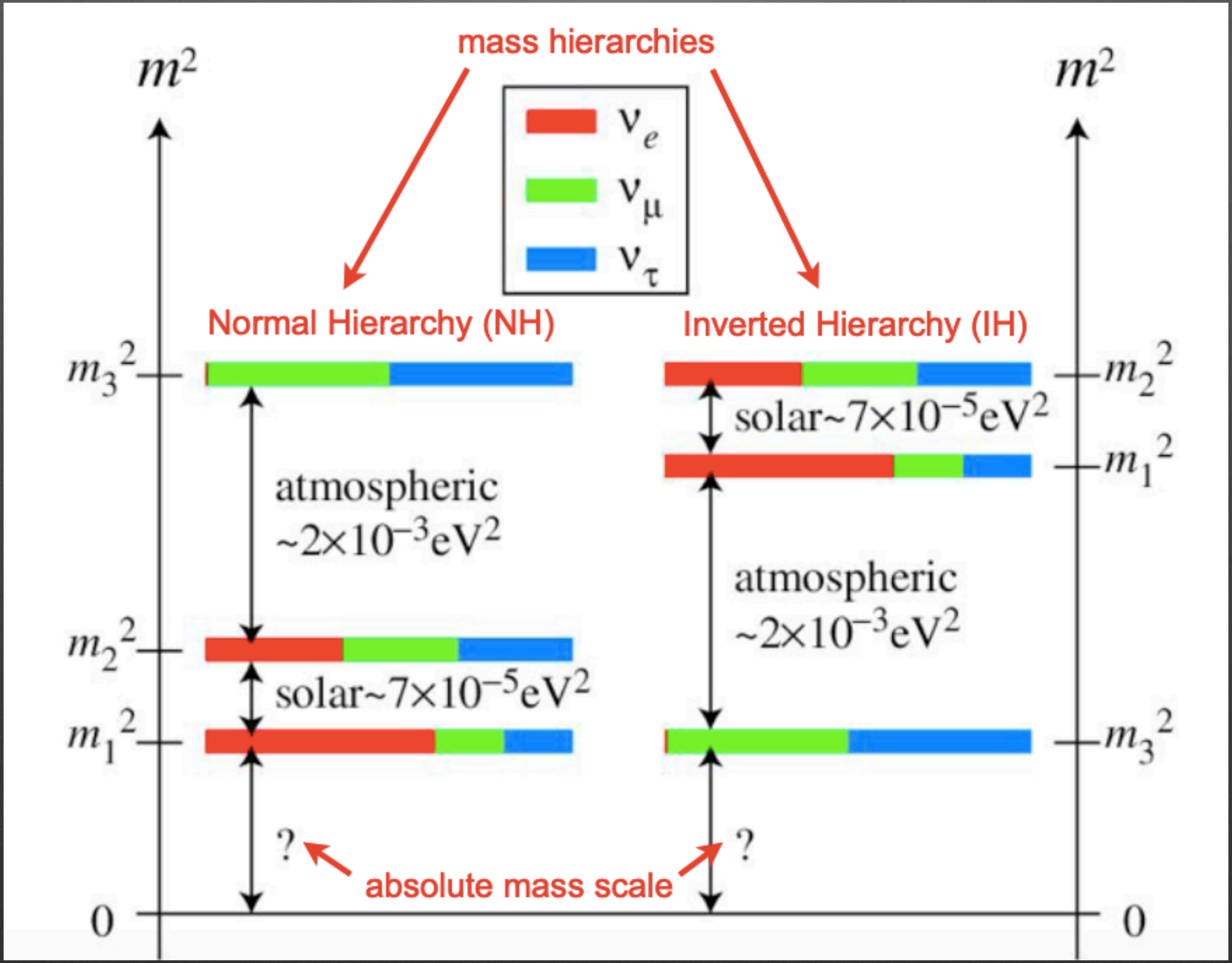
The mass-flavour matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

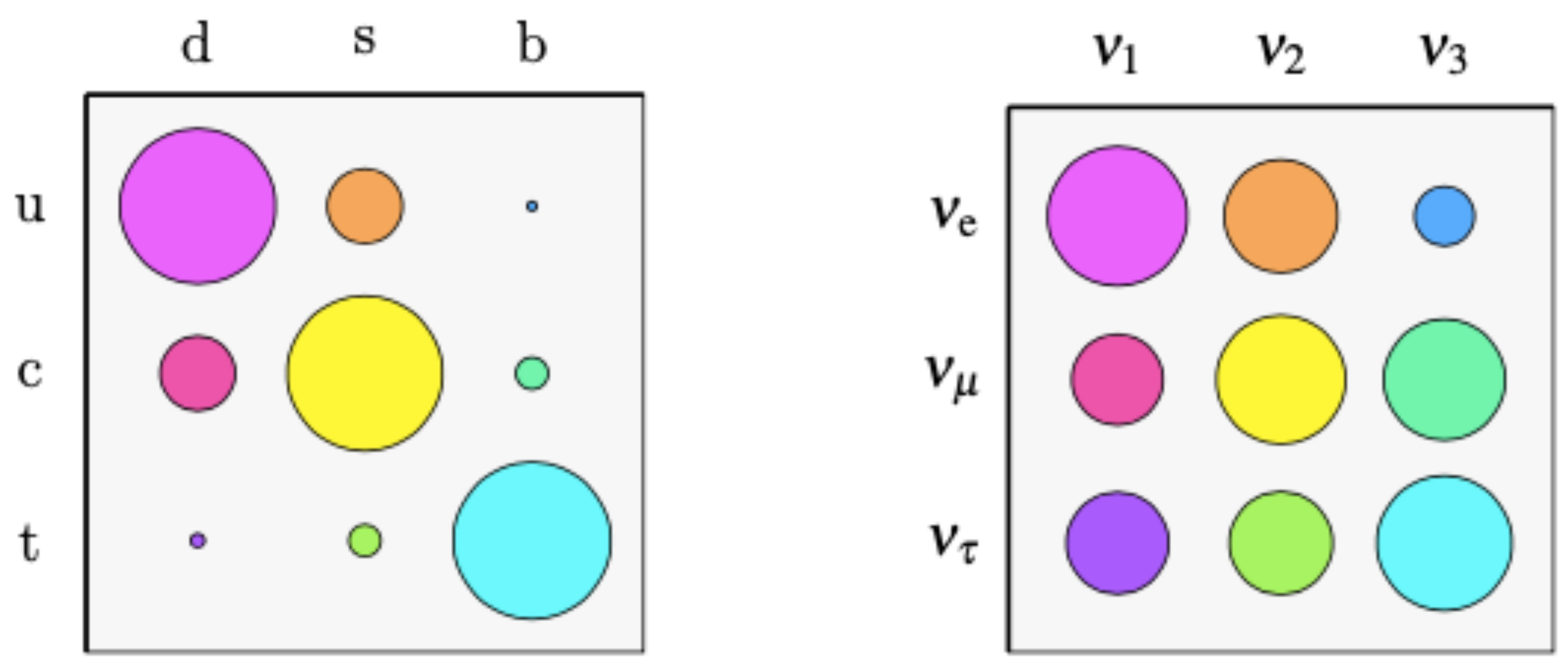
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric / Accelerator	Reactor / Accelerator	Solar / Reactor

pictorially



and just as a comparison with quarks



(a) Quark Mixing Elements.

(b) Lepton Mixing Elements.

Neutrinos are quite democratic

The effective neutrino mass that enters the 0νββ

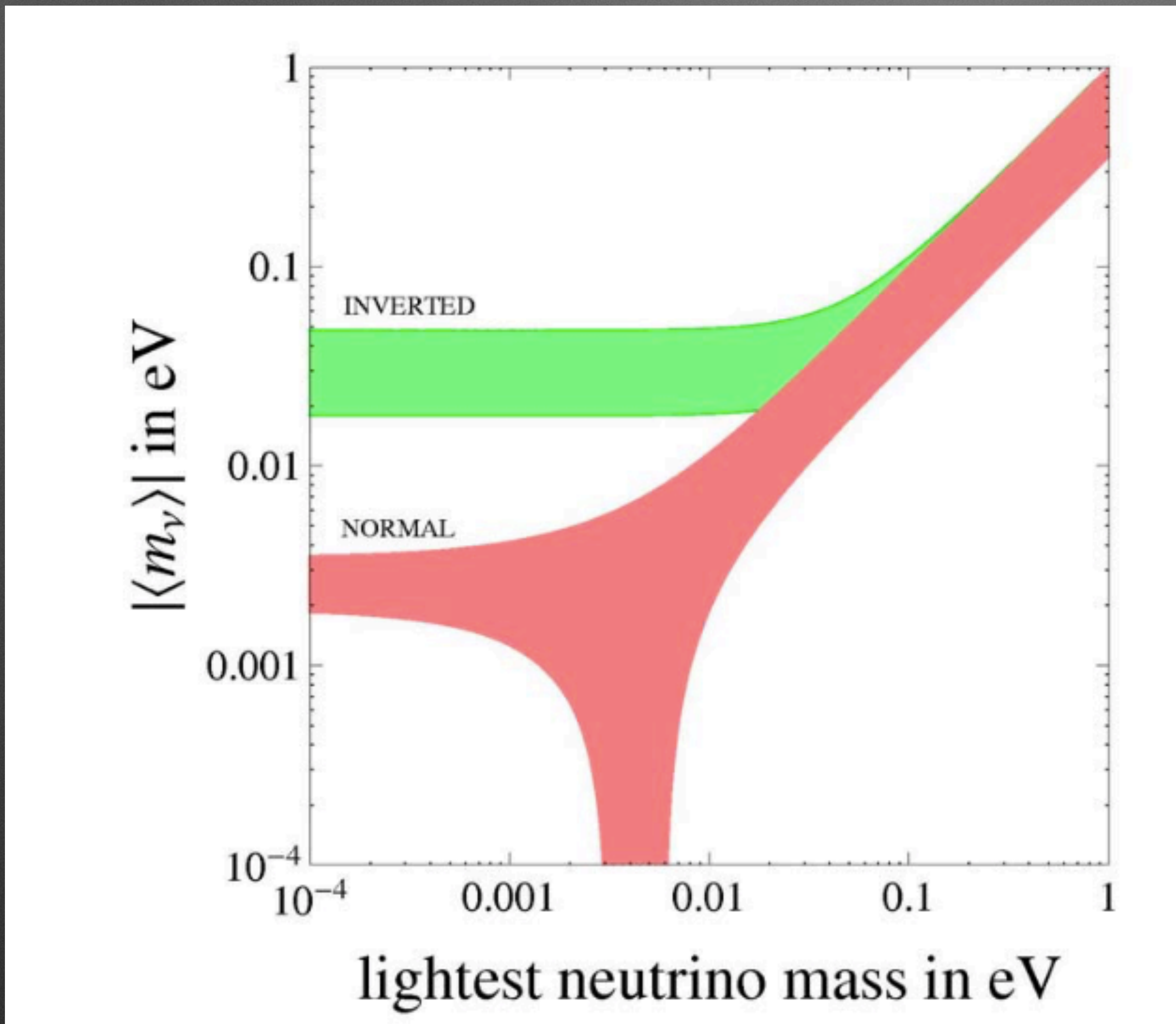
$$m_{\beta\beta} \equiv \left| \sum_{i=1,2,3} U_{\mathrm{e}i}^2 \, m_i \right|$$

called : effective Majorana mass

$$|m_{ee}| \equiv |\sum U_{ei}^2 m_i| = ||U_{e1}|^2 m_1| + ||U_{e2}|^2 m_2| e^{2i\alpha} + ||U_{e3}|^2 m_3| e^{2i\beta}$$

thanks to existence of phases cancellations can occur !

the famous exclusion plot

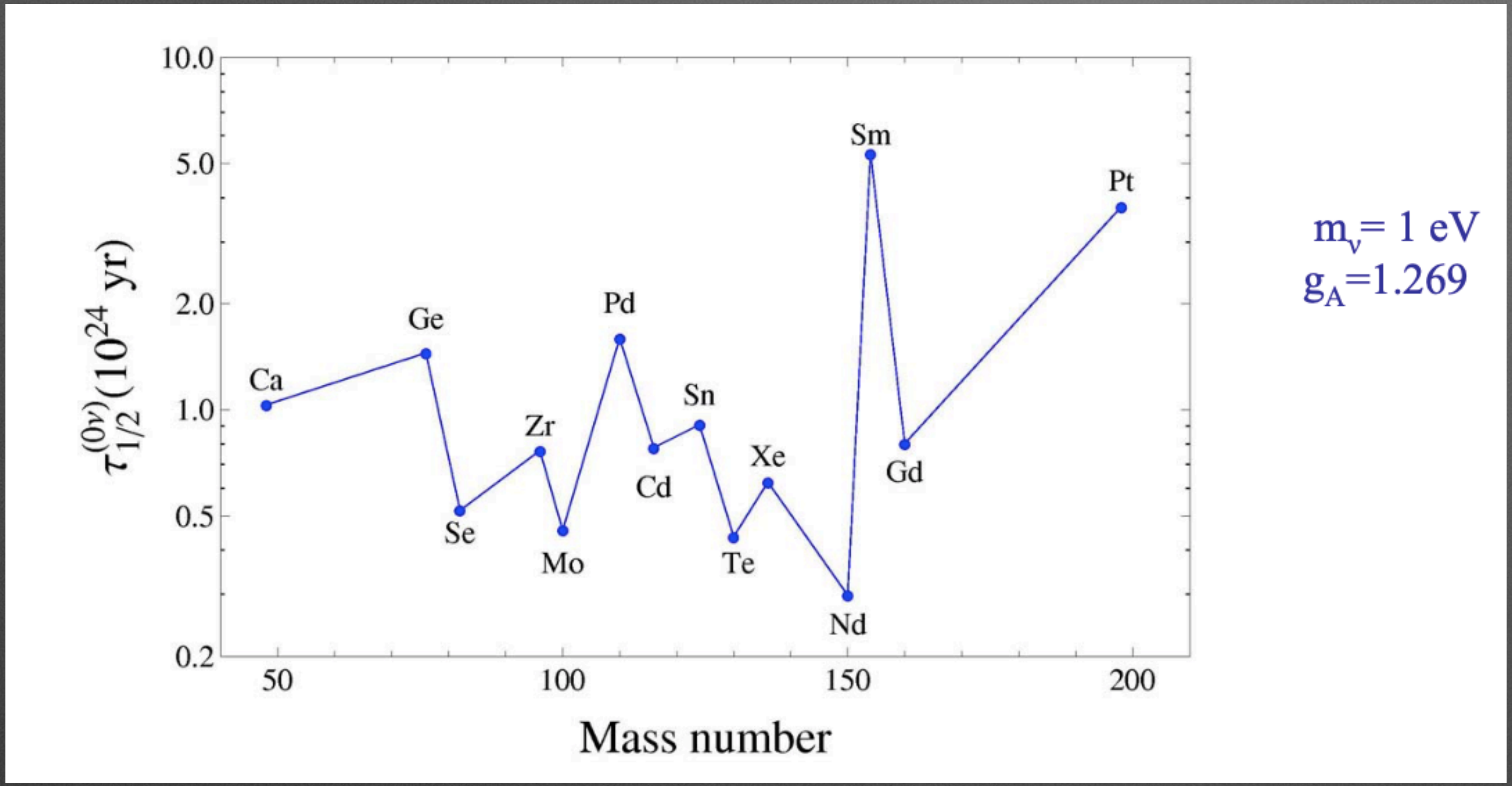


the worst thoughts just materialised

say:

20 meV for IH
2 meV for NH

the Wall



Take ^{100}Mo

Normalized half-life
$\tau_{1/2}$ ~4 x 10^{23} yr

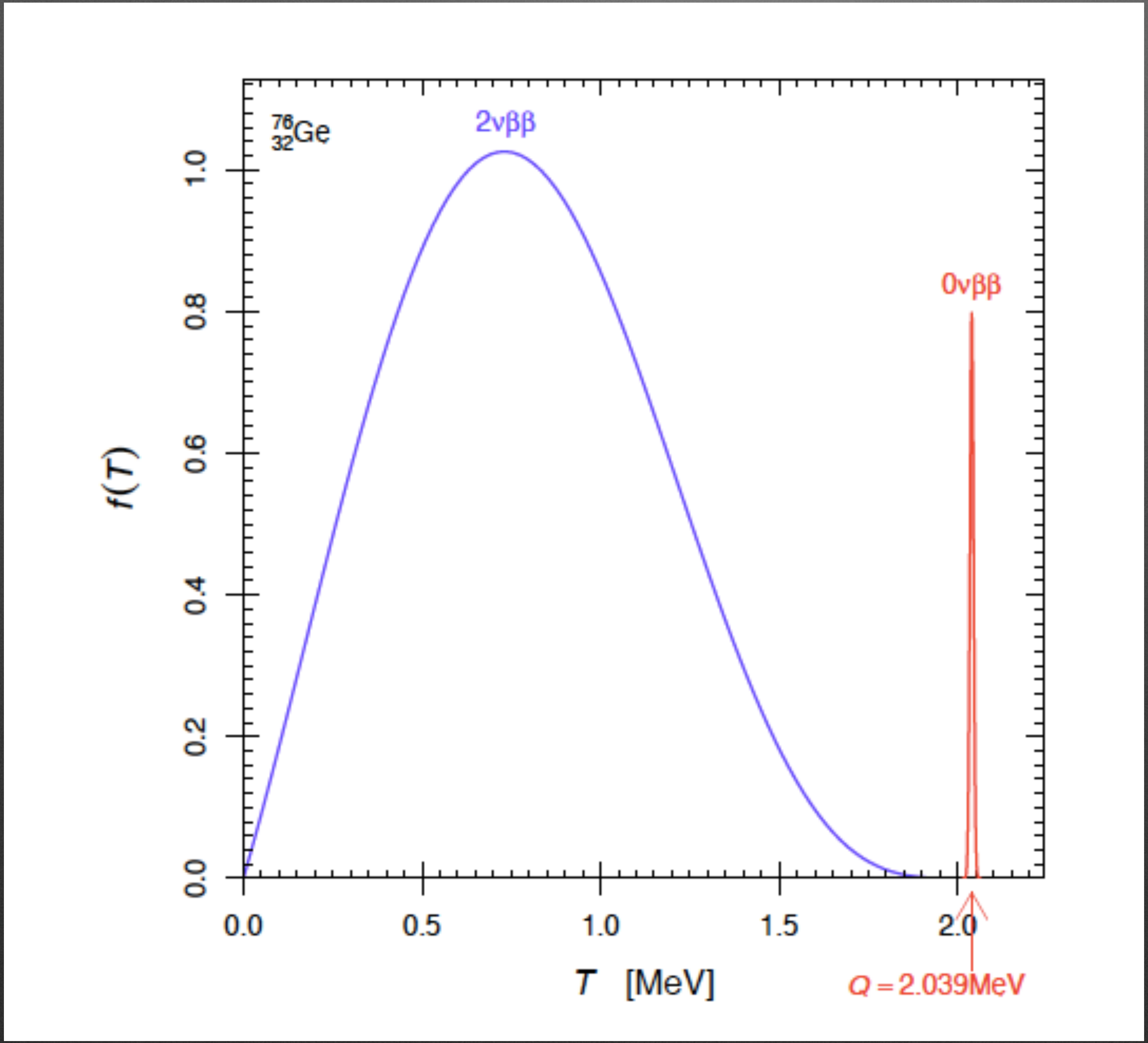
for IH 40 meV it requires to measure $\tau_{1/2}$ ~ 2.5 x10^{26} yr
for NH 4 meV it requires to measure $\tau_{1/2}$ ~ 2.5 x10^{28} yr

Daring or scaring

The most relevant parameter

Sensitivity

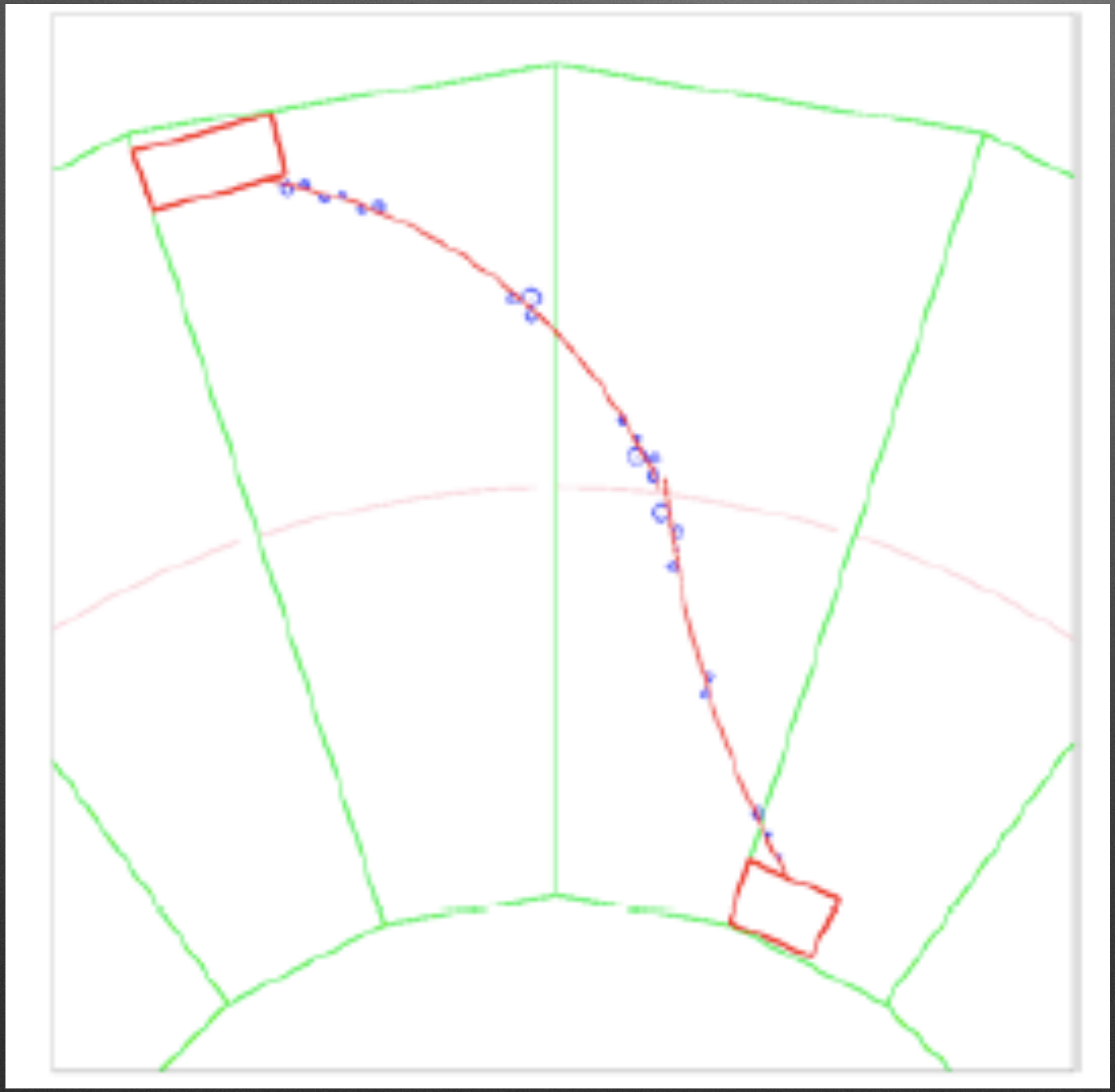
Signal
(a calorimetric point of view)



a peak at Q

width determined by Energy resolution

Signal
(a tracking point of view)



a pair of same sign particles coming from a common vertex

Signal count

- depends on half-life $(T^{0\nu}_{1/2})$
- depends on number of nuclei that could decay (N_{nuclei})
- dependes on your patience (time of the experiment, t)
- depends on the efficiency of your detector (ε)

so it comes as

- $N_{\beta\beta} = ln2 \times N \times t \times \varepsilon \frac{1}{T_{1/2}^{0\nu}}$

- we can assume that N $\propto M$

- however there is something to discuss about it !

which mass ?

- if you could do an experiment with a single isotope there would be no problem
- except that chemical elements are a collection of different isotopes !
- take Germanium
- Atomic number 32, Atomic mass 72,64
- isotope that could undergo 2v/0vββ is ^{76}Ge

Germanium

Main isotopes of germanium				
Isotope	Abundance	Half-life ($t_{1/2}$)	Decay mode	Product
^{68}Ge	syn	270.95 d	ε	^{68}Ga
^{70}Ge	20.52%	stable		
^{71}Ge	syn	11.3 d	ε	^{71}Ga
^{72}Ge	27.45%	stable		
^{73}Ge	7.76%	stable		
^{74}Ge	36.7%	stable		
^{76}Ge	7.75%	1.78×10^{21} y	$\beta^-\beta^-$	^{76}Se

even in this simple case (single element)

the 'useful' mass is only a fraction of the detector

for each 72 kg (1000 moles) of Ge you have

$N_{\beta\beta} = N_A \times N_m \times$ i.a.

~ 5×10^{25} atoms of ^{76}Ge

the solution

- isotopic enrichment !!
- we will be back to this (for now assume that you can get 95%)
- the clear advantage is that if you want to have , say , 10^{27} atoms of ^{76}Ge in your detector this would correspond to ($N_m = 10^{27}/N_A/0.95 = 1750$) which makes 125 Kg of ^{76}G instead of 1630 of Ge
- it does cost though !

not always as simple as that

- you could do the experiment with a compound (molecule)
- in this case the mass of your experiment will differ considerably from the mass of the isotope
- take TeO_2 as example for a calculation

TeO_2
tellurium dioxide or tellurite

- Te has atomic mass of 127,6
- There are two isotopes that double beta decay ^{128}Te (31,7%) and ^{130}Te (34,1%)
- TeO_2 has a molecular mass of 160
- so that for one of the isotope (130 for example) the effective mass will be (without isotopic enrichment) about (130/160)x0,34 ~ 0,28……..i.e. 10^{27} atoms of ^{130}Te that are 4900 moles of Te brings to an experiment of total mass of 780 kg

all the possible elements

$\beta^-\beta^-$ candidates	T_0 (keV)	Abundance (%)	$(G^{2\nu})^{-1}$ (y)	$(G^{0\nu})^{-1}$ (y)
$^{46}Ca \rightarrow {}^{46}Ti$	987 ±4	0.0035	8.71E21	7.16E26
$^{48}Ca \rightarrow {}^{48}Ti$[a]	4271 ±4	0.187	2.52E16	4.10E24
$^{70}Zn \rightarrow {}^{70}Ge$	1001 ±3	0.62	3.17E21	4.27E26
$^{76}Ge \rightarrow {}^{76}Se$	2039.6±0.9	7.8	7.66E18	4.09E25
$^{80}Se \rightarrow {}^{80}Kr$	130 ±9	49.8	8.20E27	2.34E28
$^{82}Se \rightarrow {}^{82}Kr$	2995 ±6	9.2	2.30E17	9.27E24
$^{86}Kr \rightarrow {}^{86}Sr$	1256 ±5	17.3	3.00E20	1.57E26
$^{94}Zr \rightarrow {}^{94}Mo$	1145.3±2.5	17.4	4.34E20	1.57E26
$^{96}Zr \rightarrow {}^{96}Mo$[a]	3350 ±3	2.8	5.19E16	4.46E24
$^{98}Mo \rightarrow {}^{98}Ru$	112 ±7	24.1	1.03E28	1.49E28
$^{100}Mo \rightarrow {}^{100}Ru$	3034 ±6	9.6	1.06E17	5.70E24
$^{104}Ru \rightarrow {}^{104}Pd$	1299 ±2	18.7	1.09E20	8.32E25
$^{110}Pd \rightarrow {}^{110}Cd$	2013 ±19	11.8	2.51E18	1.86E25
$^{114}Cd \rightarrow {}^{114}Sn$	534 ±4	28.7	6.93E22	6.10E26
$^{116}Cd \rightarrow {}^{116}Sn$	2802 ±4	7.5	1.25E17	5.28E24
$^{122}Sn \rightarrow {}^{122}Te$	364 ±4	4.56	9.55E23	1.16E27
$^{124}Sn \rightarrow {}^{124}Te$	2288.1±1.6	5.64	5.93E17	9.48E24
$^{128}Te \rightarrow {}^{128}Xe$	868 ±4	31.7	1.18E21	1.43E26
$^{130}Te \rightarrow {}^{130}Xe$	2533 ±4	34.5	2.08E17	5.89E24
$^{134}Xe \rightarrow {}^{134}Ba$	847 ±10	10.4	1.16E21	1.30E26
$^{136}Xe \rightarrow {}^{136}Ba$	2479 ±8	8.9	2.07E17	5.52E24
$^{142}Ce \rightarrow {}^{142}Nd$	1417.6±2.5	11.1	1.38E19	2.31E25
$^{146}Nd \rightarrow {}^{146}Sm$[b]	56 ±5	17.2	2.06E29	7.05E27
$^{148}Nd \rightarrow {}^{148}Sm$[b]	1928.3±1.9	5.7	9.35E17	7.84E24
$^{150}Nd \rightarrow {}^{150}Sm$	3367.1±2.2	5.6	8.41E15	1.25E24
$^{154}Sm \rightarrow {}^{154}Gd$	1251.9±1.5	22.6	2.44E19	2.38E25
$^{160}Gd \rightarrow {}^{160}Dy$	1729.5±1.4	21.8	1.51E18	7.99E24
$^{170}Er \rightarrow {}^{170}Yb$	653.9±1.6	14.9	1.82E21	6.92E25

$\beta^-\beta^-$ candidates	T_0 (keV)	Abundance (%)	$(G^{2\nu})^{-1}$ (y)	$(G^{0\nu})^{-1}$ (y)
$^{176}Yb \rightarrow {}^{176}Hf$	1078.8±2.7	12.6	3.26E19	1.75E25
$^{186}W \rightarrow {}^{186}Os$[b]	490.3±2.2	28.6	7.68E21	6.95E25
$^{192}Os \rightarrow {}^{192}Pt$	417 ±4	41.0	1.98E22	7.70E25
$^{198}Pt \rightarrow {}^{198}Hg$	1048 ±4	7.2	1.63E19	8.74E24
$^{204}Hg \rightarrow {}^{204}Pb$	416.5±1.1	6.9	1.23E22	5.06E25
$^{232}Th \rightarrow {}^{232}U$[b]	858.2±6	100	1.68E19	3.97E24
$^{238}U \rightarrow {}^{238}Pu$[b]	1145.8±1.7	99.27	1.47E18	1.68E24

$\beta^+\beta^+$ candidates	T_0 (keV)	Abundance (%)	$(G^{2\nu})^{-1}$ (y)	$(G^{0\nu})^{-1}$ (y)
$^{78}Kr \rightarrow {}^{78}Se$	838	0.35	2.56E24	1.8E29
$^{96}Ru \rightarrow {}^{96}Mo$	676	5.5	3.34E25	8.8E29
$^{106}Cd \rightarrow {}^{106}Pd$	738	1.25	1.69E25	7.4E29
$^{124}Xe \rightarrow {}^{124}Te$	822	0.10	7.57E24	5.9E29
$^{130}Ba \rightarrow {}^{130}Xe$	534	0.11	6.92E26	6.4E30
$^{136}Ce \rightarrow {}^{136}Ba$	362	0.19	5.15E28	6.1E31

EX signifies 10^x

[a] The single beta decay is kinematically allowed.

[b] The daughter nucleus is unstable against alpha decay.

it looks a wide choice !

in reality

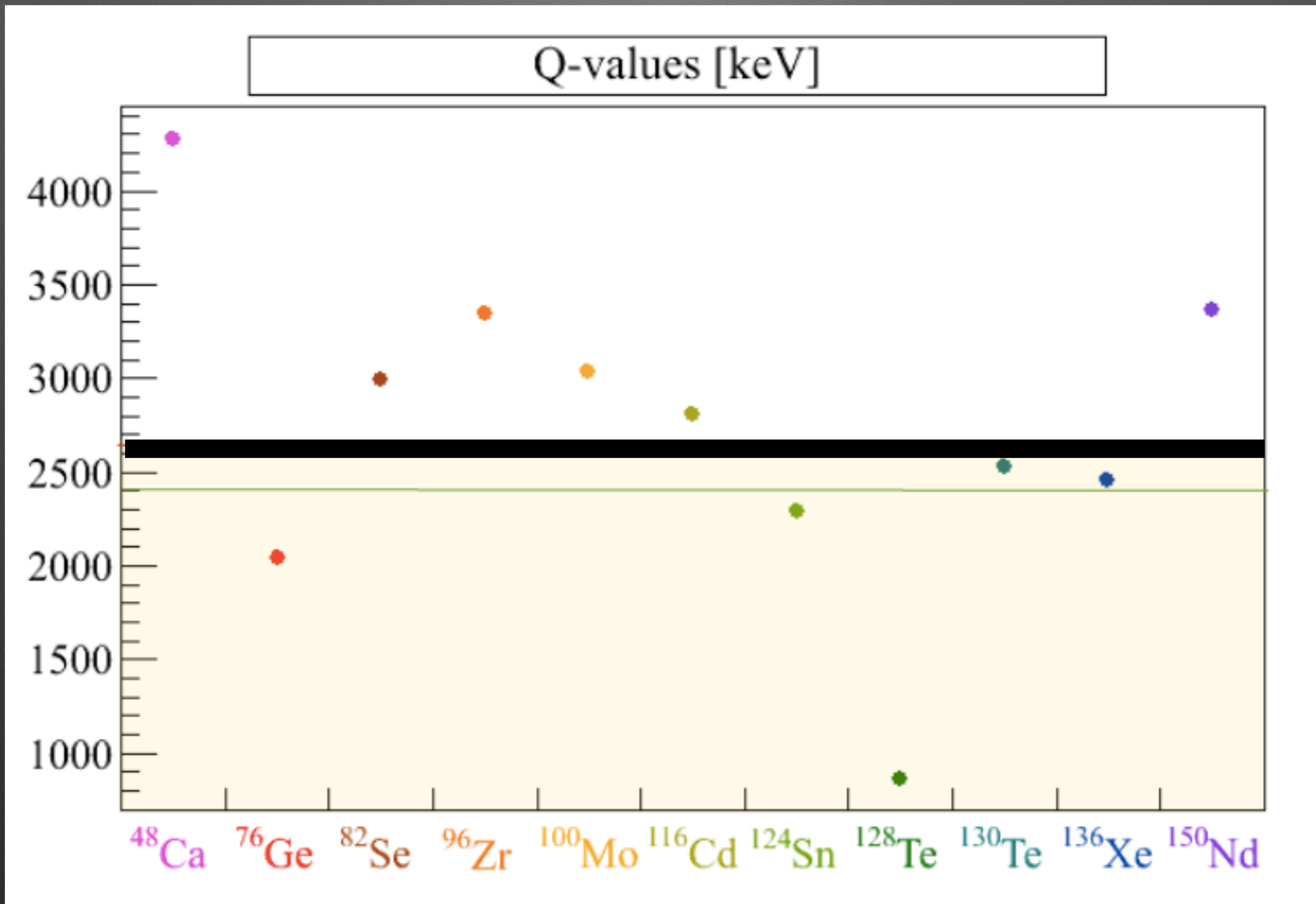
- if you do not want to wait forever and build a cathedral instead of an experiment at least the phase space should be favourable
- it goes with the advantage of a large Q-value
- that is good for background discrimination (see later)
- and the isotopic abundance should be as large as possible

the special ones

Isotope	Abundance (%)	$Q_{\beta\beta}$ (MeV)	$G^{2\nu}$ (10^{-18} year^{-1})
^{48}Ca	0.187	4.263	15.6
^{76}Ge	7.8	2.039	0.0482
^{82}Se	9.2	2.998	1.60
^{96}Zr	2.8	3.348	7.83
^{100}Mo	9.6	3.035	4.13
^{116}Cd	7.6	2.813	3.18
^{130}Te	34.08	2.527	1.53
^{136}Xe	8.9	2.459	1.43
^{150}Nd	5.6	3.371	36.4

aim to: high Q-value, high i.a., slow $2\nu\beta\beta$ decay

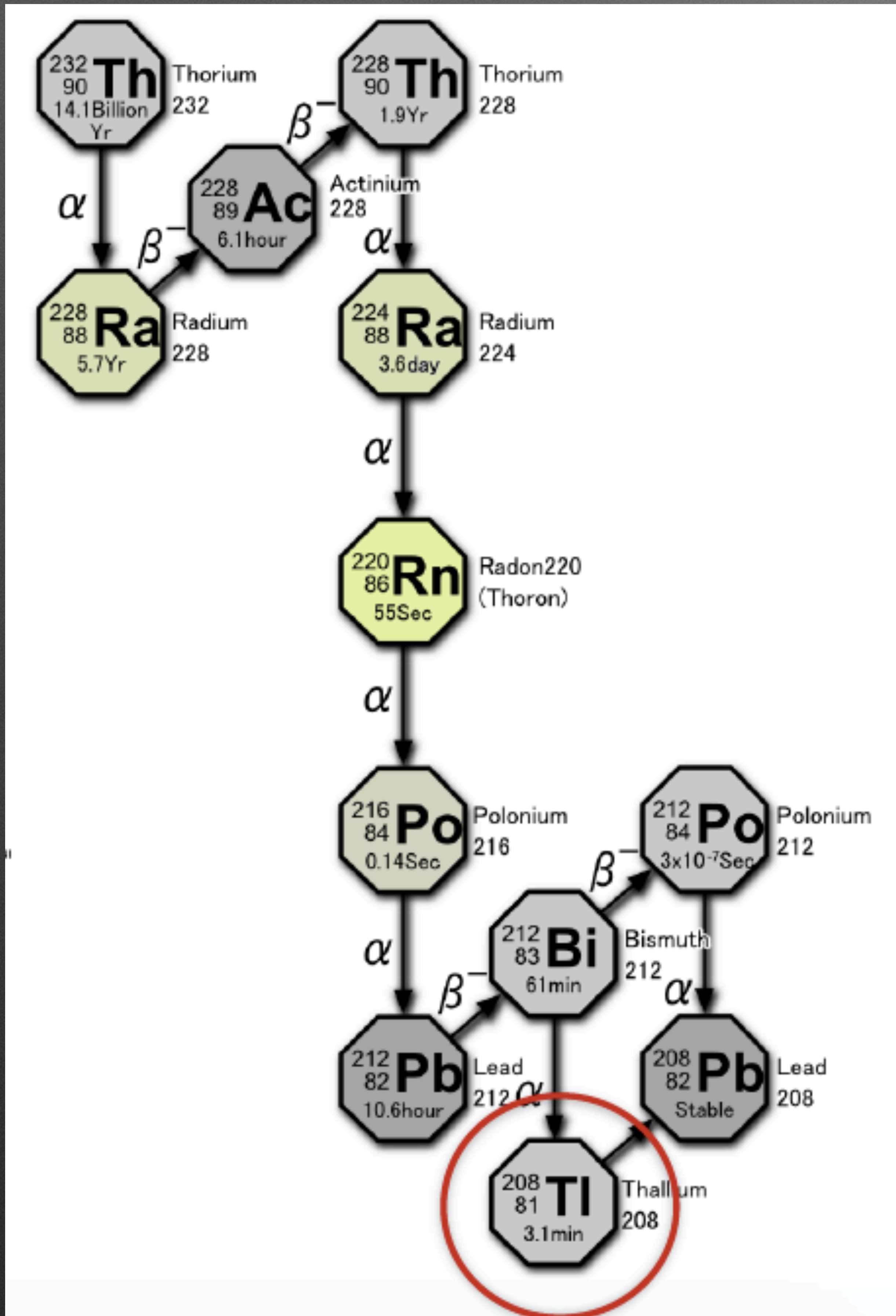
table of Q-values



something important on the black line !

- ^{208}Tl has a gamma decay line at 2.615 MeV
- it is a very important line as far as natural radioactivity is concerned

Natural radioactivity



Th contamination is unavoidable at a given level.

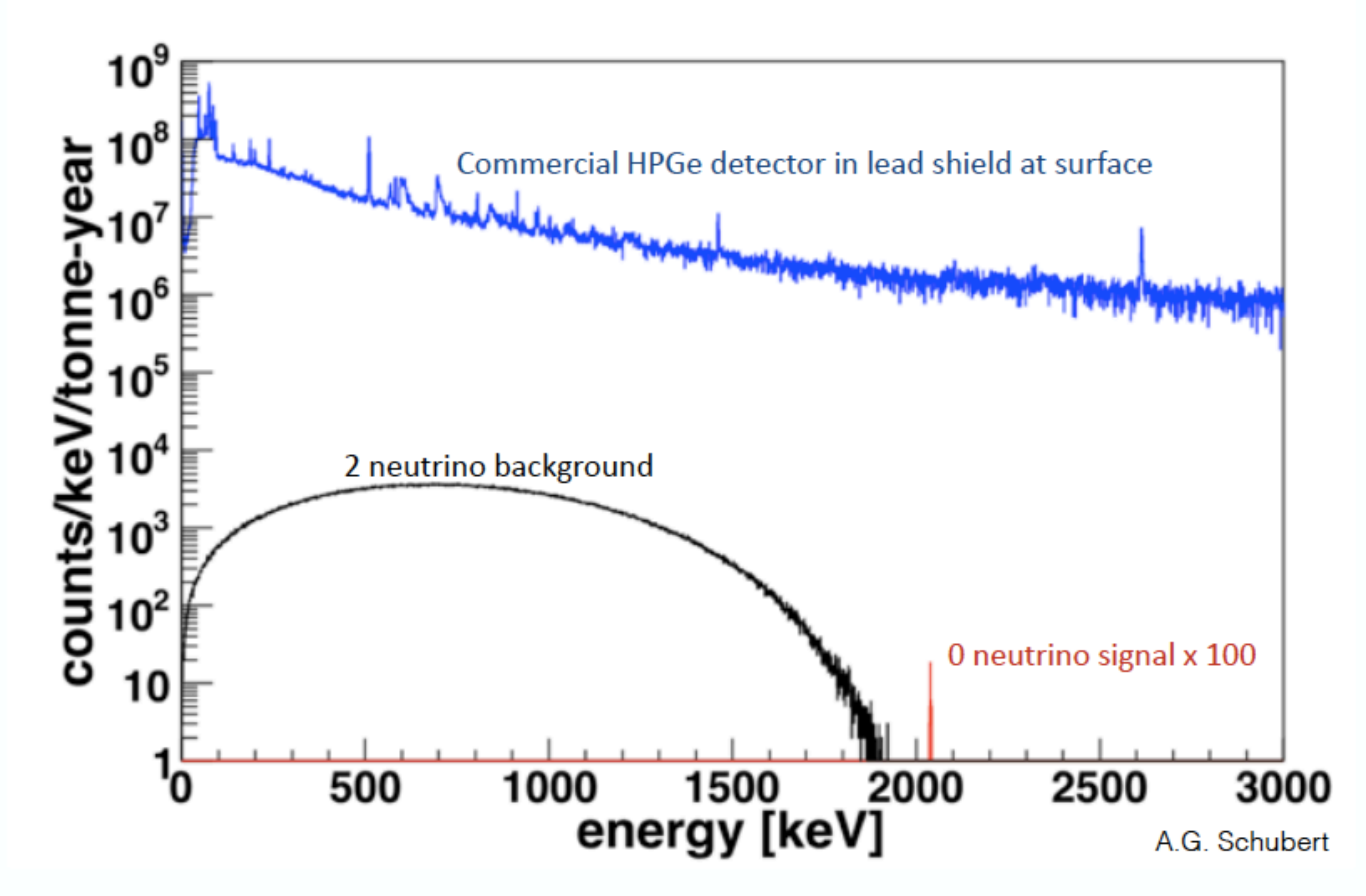
The secular equilibrium is established.

^{208}Tl is the last decaying element before ending into ^{208}Pb

and gives rise to the last of the intense lines

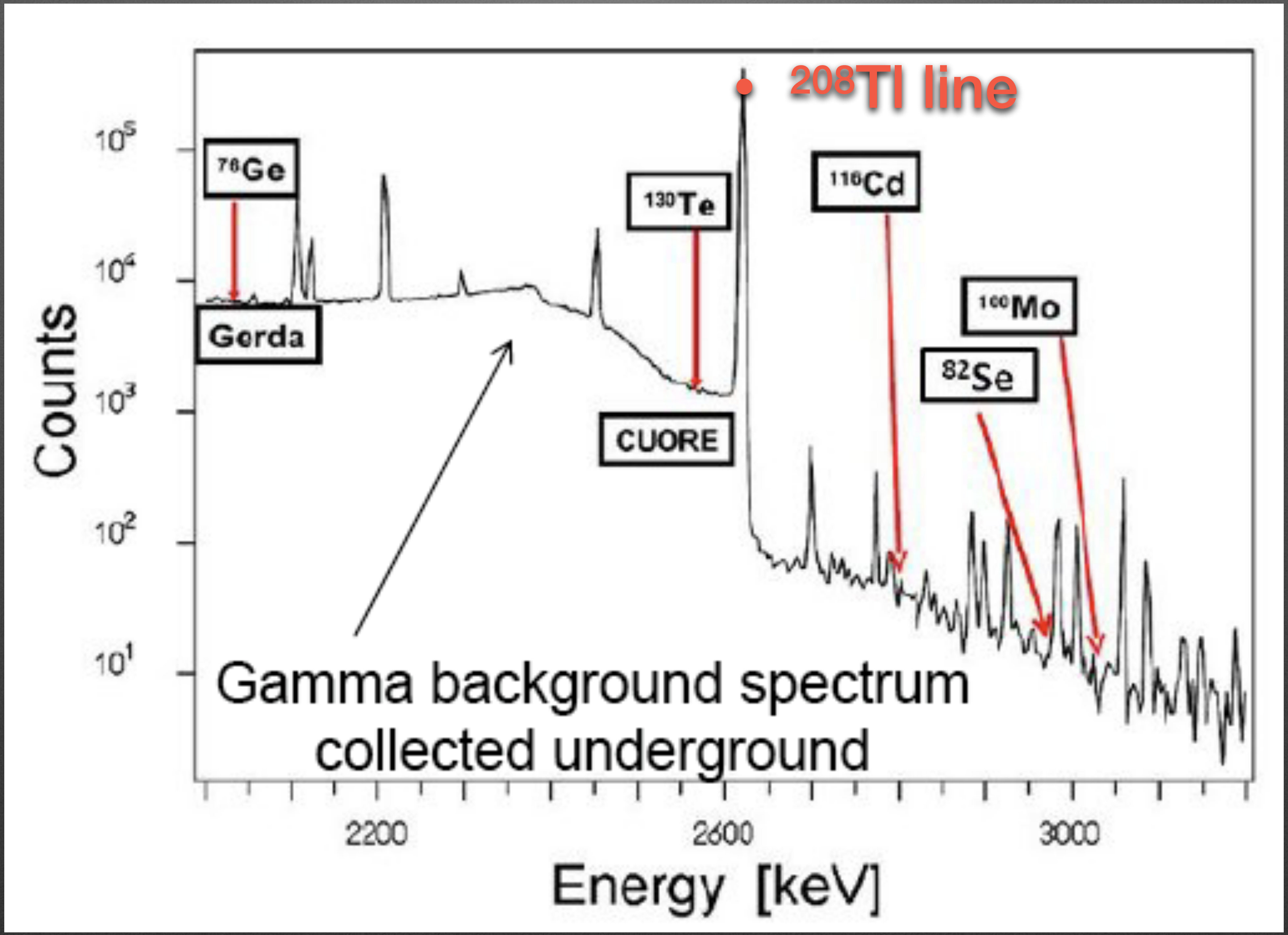
http://holbert.faculty.asu.edu/eee460/RadioactiveDecay.pdf

Measuring background at surface



why should we worry about ^{208}Tl ?

because we can go underground



we will come back to this……

dramatic effect

to be or not to be above (2615 keV)

counts from background

- $N_B = n_B \times t \times \Delta E \times M$
- provided that n_B is the number of background events (of any kind) per unit of mass , unit of energy, unit of time)
- normally the units are Kg, KeV, year

The sensitivity is given by

$$\frac{S}{\sqrt{B}} = \frac{n_{\beta\beta}}{\sqrt{N}_B}$$

$$S_{0\nu} \propto x \times \eta \times \epsilon \times \sqrt{\frac{M \times t}{n_B \times \Delta E}}$$

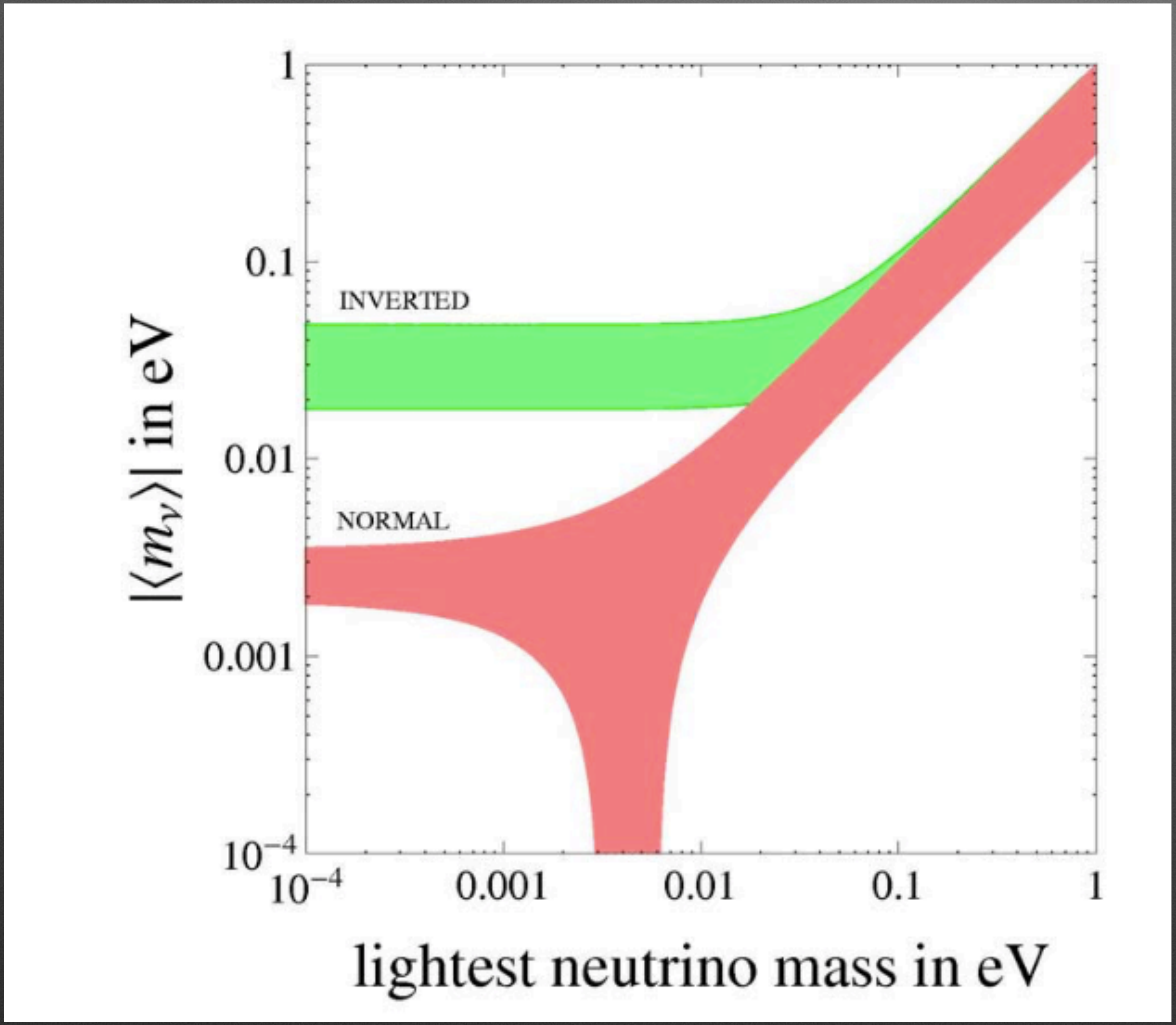
first analysis of sensitivity formula

- a square root dependance is a disgrace
- every factor 10 you want to gain in sensitivity will cost you a factor 100 in the product of parameters (except for $\eta \times \epsilon$ whose product however is limited to 1)
- even worse $$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \,\frac{|m_{\beta\beta}|^2}{m_e^2}$$
- $m_{\beta\beta} \propto \sqrt{\frac{1}{T^{0\nu}_{1/2}}}$

in brutal terms

- gaining a factor 10 in sensitivity on the ‘effective’ neutrino mass costs 4 orders of magnitude (10000) improvement in the combination of the experiment parameters (quantity and quality)

it means that



the experiments able to probe the Inverted Hierarchy are likely not being the ones that will challenge the Normal one

Something radically different will be needed

but…..

- if you are able to limit N_B to ≤ 1 for the life of your experiment
- or more realistically you can run a time t before observing your first bckg event then:

$$S_{0\nu} \propto M \times t$$

you get rid of the first square root

the so called

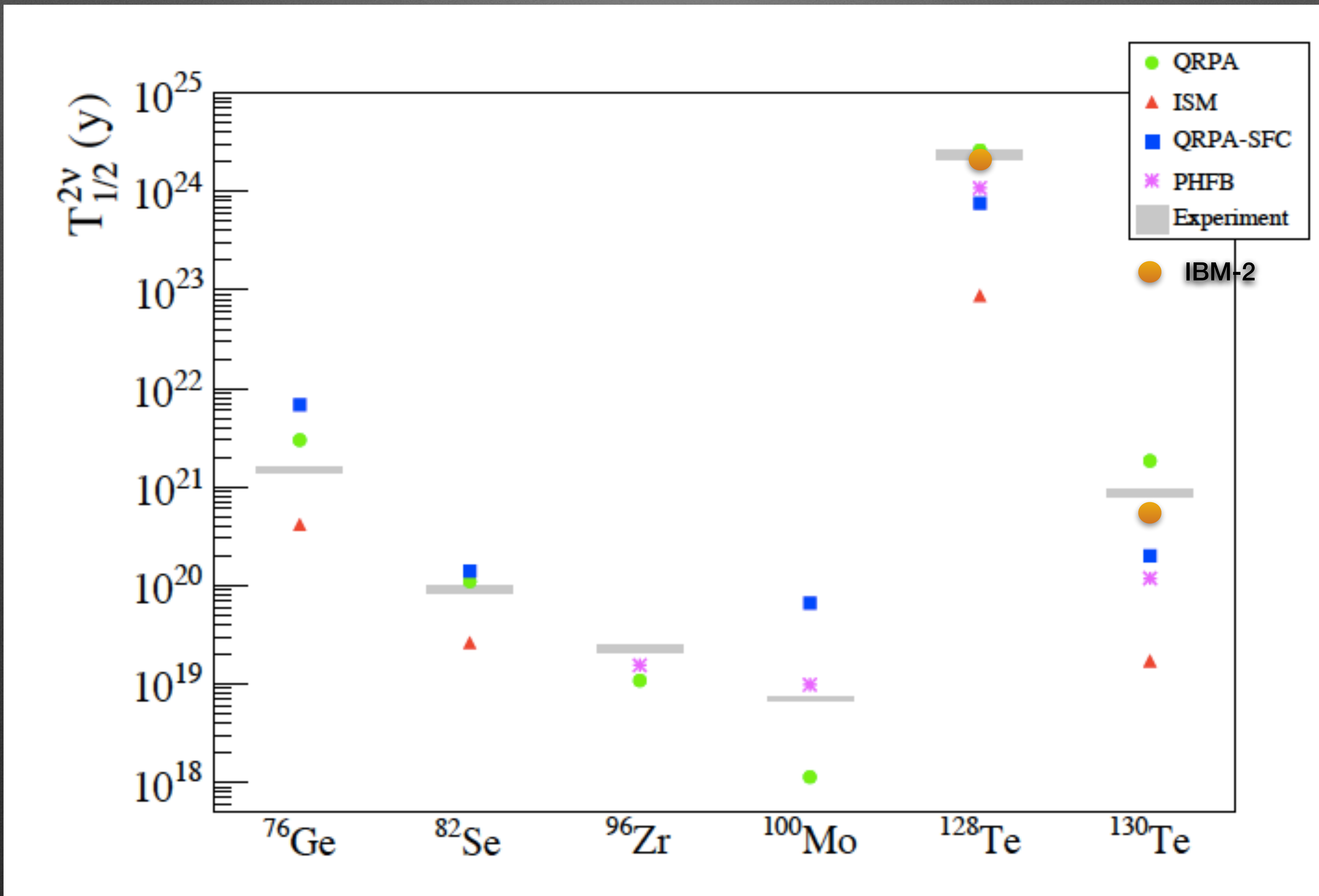
zero background approximation

the goals are clear (how to score them , less !)

- maximise the amount of Mass of the right isotopic composition
- minimise Background Index (counts per unit of energy per unit time per unit of mass)
- achieve the best Energy Resolution possible
- aim to Efficiency as close to 1 as possible

a long and tortuous story

what you expect from $2\nu\beta\beta$ is the comparison exp-th



Background analysis

how many bckg ?

- Internal

- External

External bckg

- γ from natural chains
- Rn
- cosmic muons
- neutrons

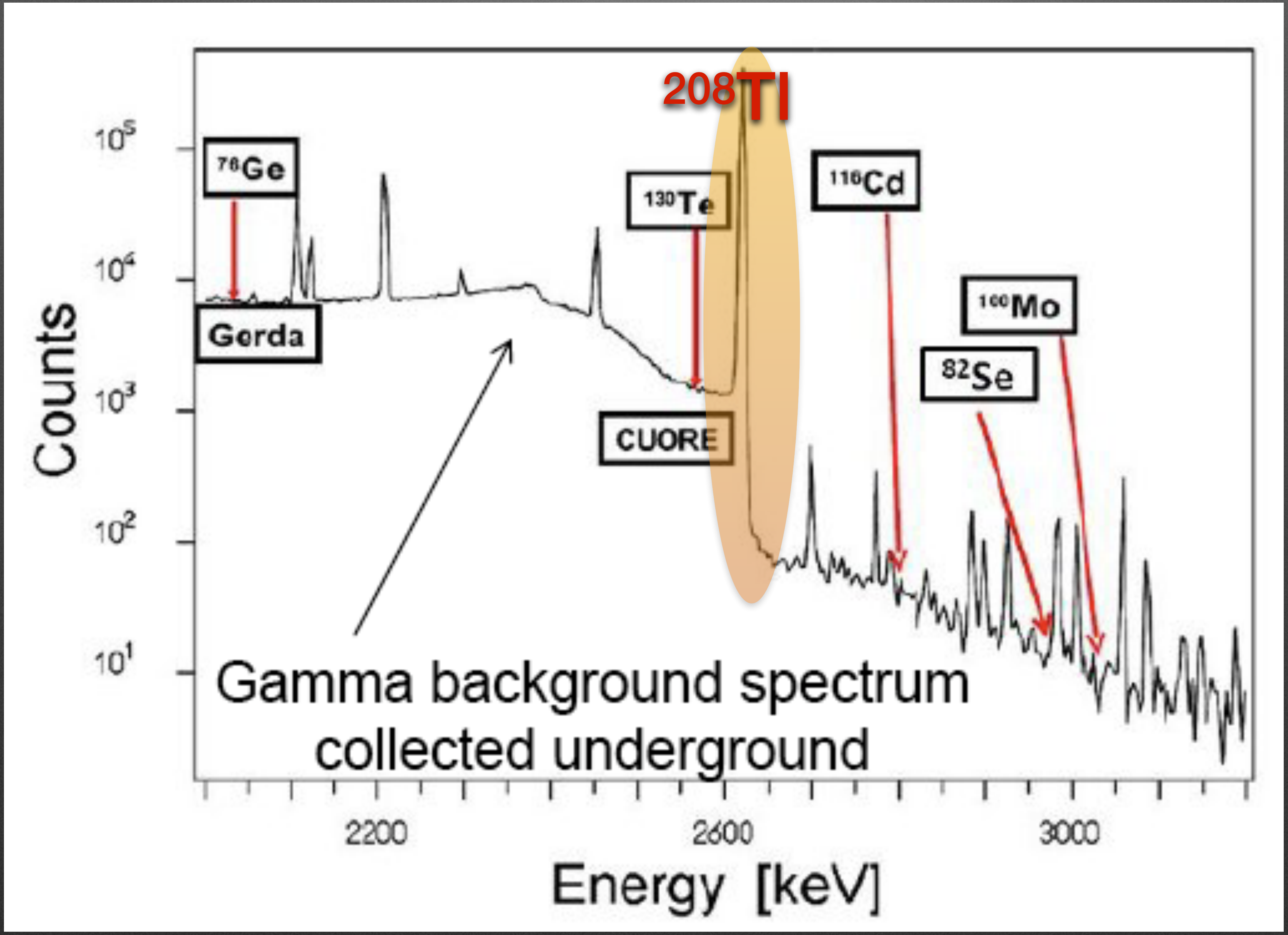
Internal background

- Cosmogenic
- Bulk & Surface material
- $2\nu\beta\beta$

Reduction strategies

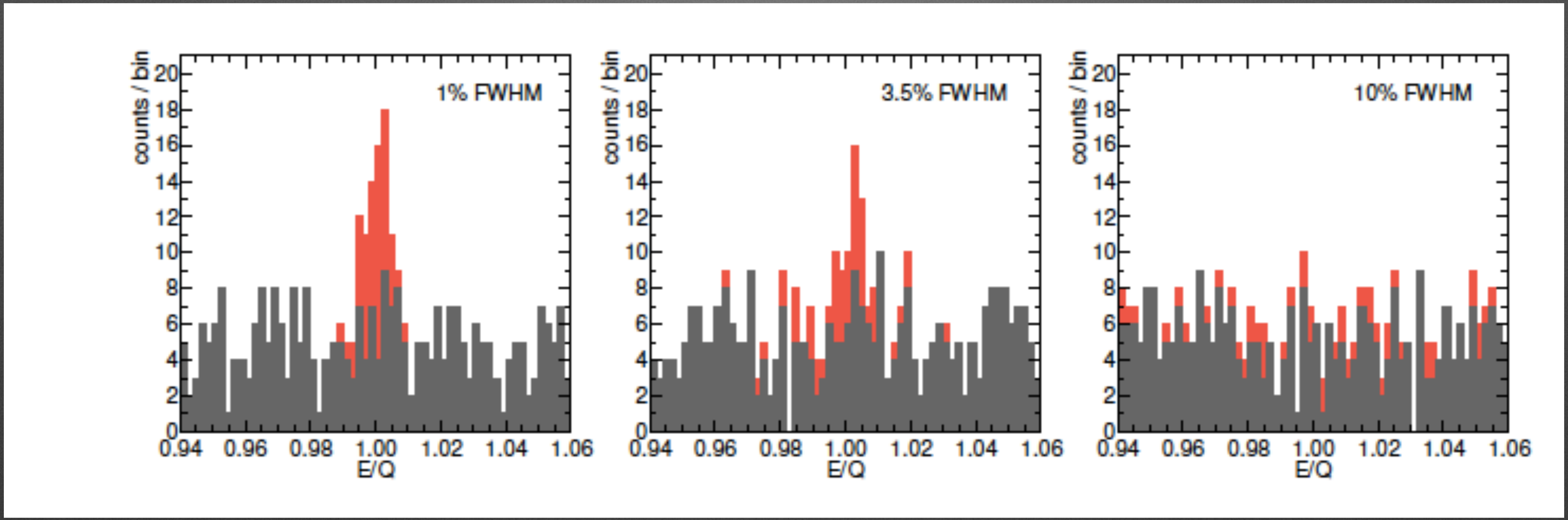
- High Q-value
- Energy resolution
- Underground operation
- Shielding
- Active veto
- Radiopure materials
- Particle Identification
- Identification of daughter nuclei
- Minimization of exposure to cosmic rays

High Q-value



208Tl
76Ge
Gerda
130Te
CUORE
116Cd
100Mo
82Se
Counts
Gamma background spectrum collected underground
2200
2600
3000
Energy [keV]

Energy resolution

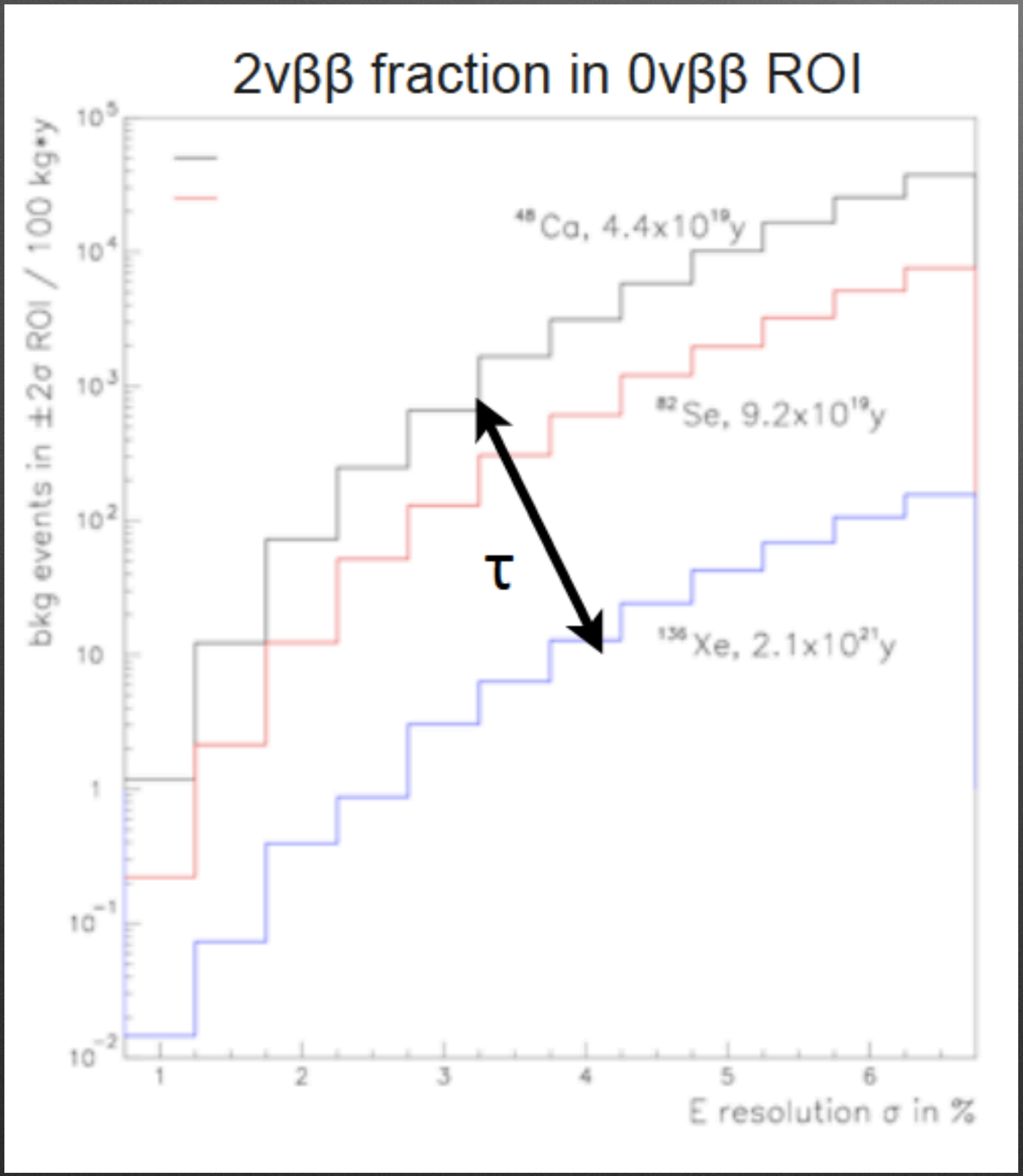


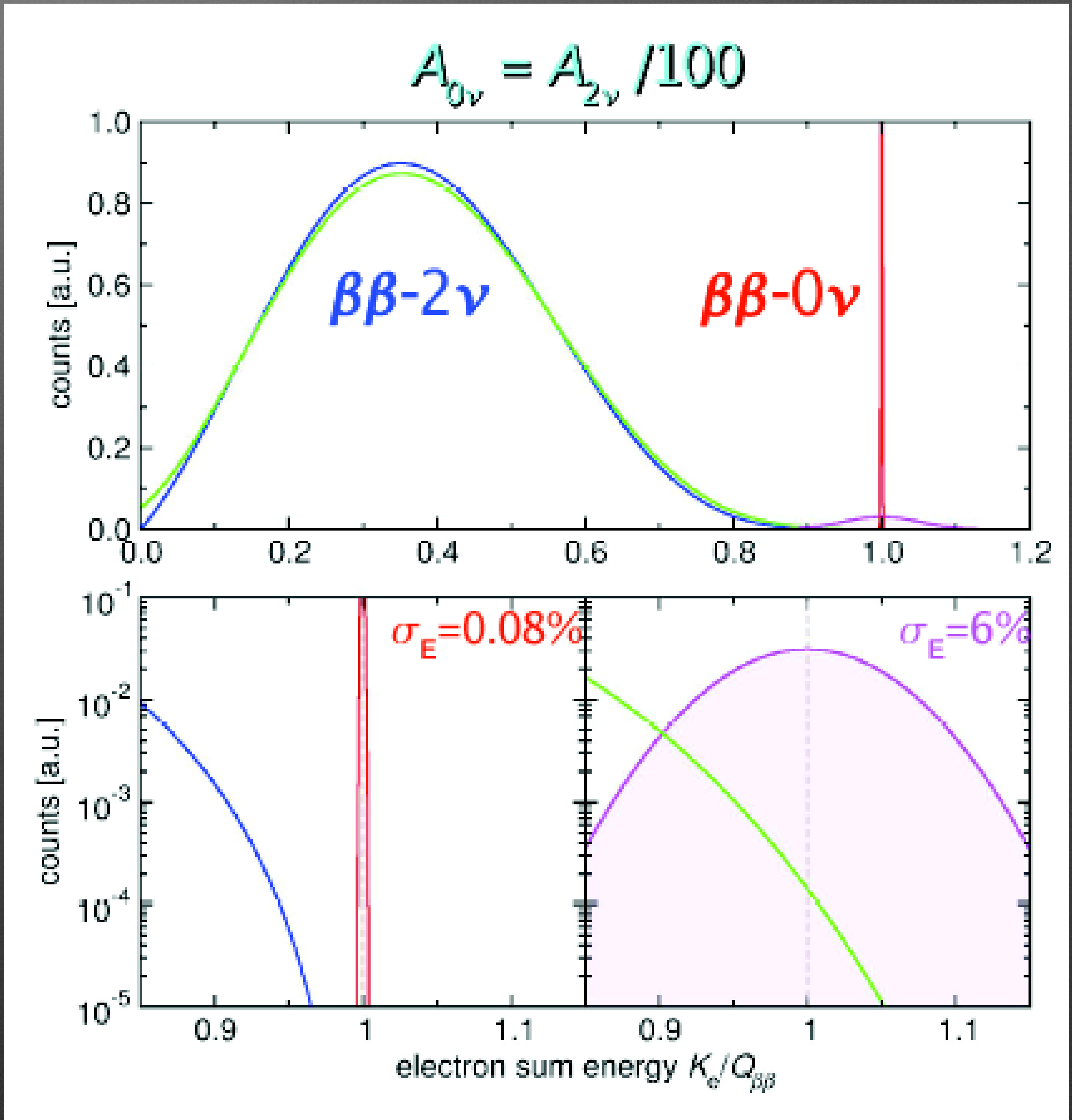
just an example

S= 50 events, B = 1 count/keV

$2\nu\beta\beta$ irreducible background

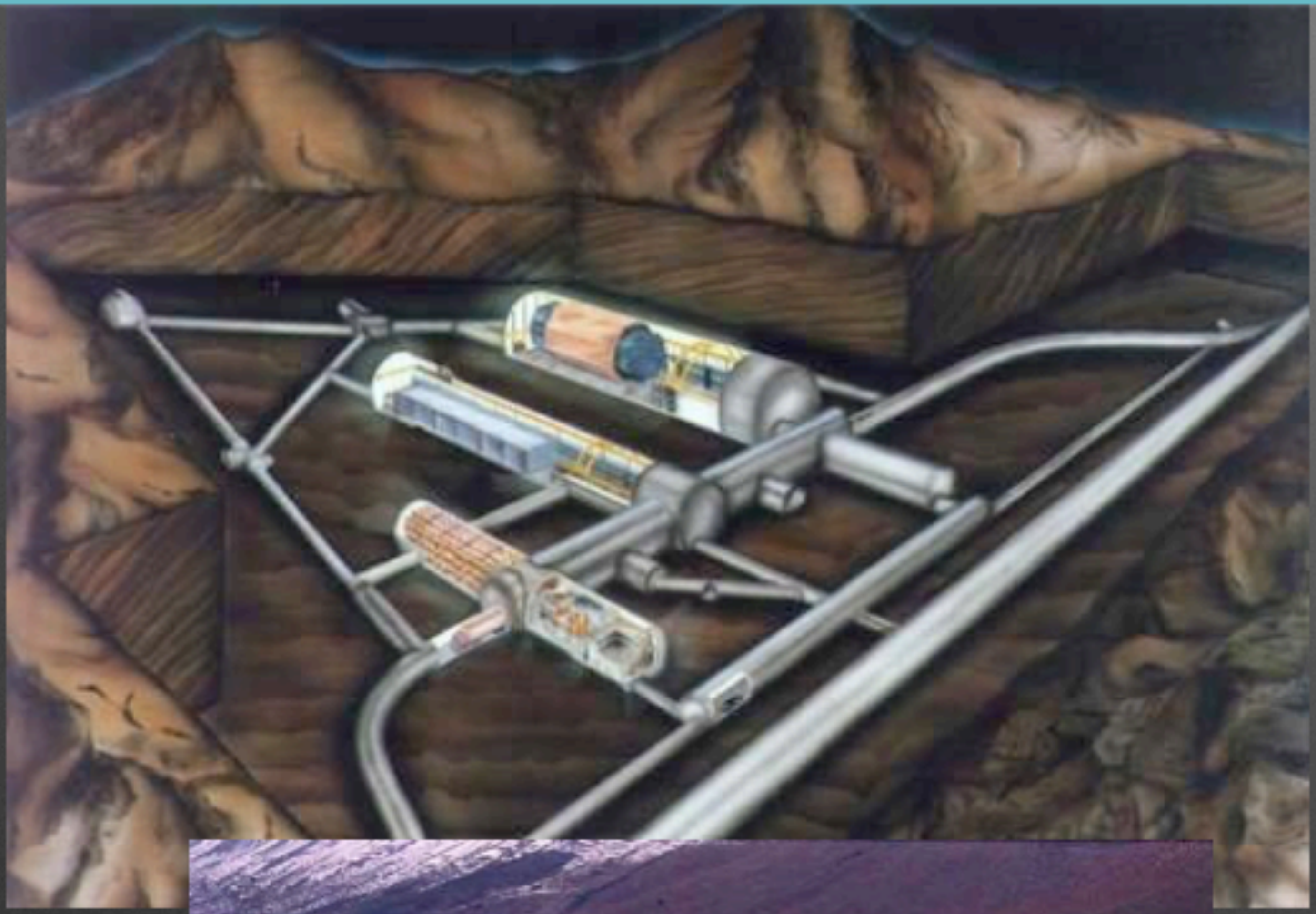
$$R_{0\nu/2\nu} \propto \left(\frac{Q_{\beta\beta}}{\Delta}\right)^6 \frac{t_{2\nu}^{1/2}}{t_{0\nu}^{1/2}}.$$





LNGS

3 main halls A B C ~100 x 20 m² (h 20 m)



Muon Flux
$3.0\ 10^{-4}\ \mu\ m^{-2}\ s^{-1}$

Neutron Flux	
$2.92\ 10^{-6}\ n\ cm^{-2}\ s^{-1}$	(0-1 keV)
$0.86\ 10^{-6}\ n\ cm^{-2}\ s^{-1}$	(> 1 keV)

Depth: 1400 m (**3800 m w.e.**)

Surface: 17800 m²

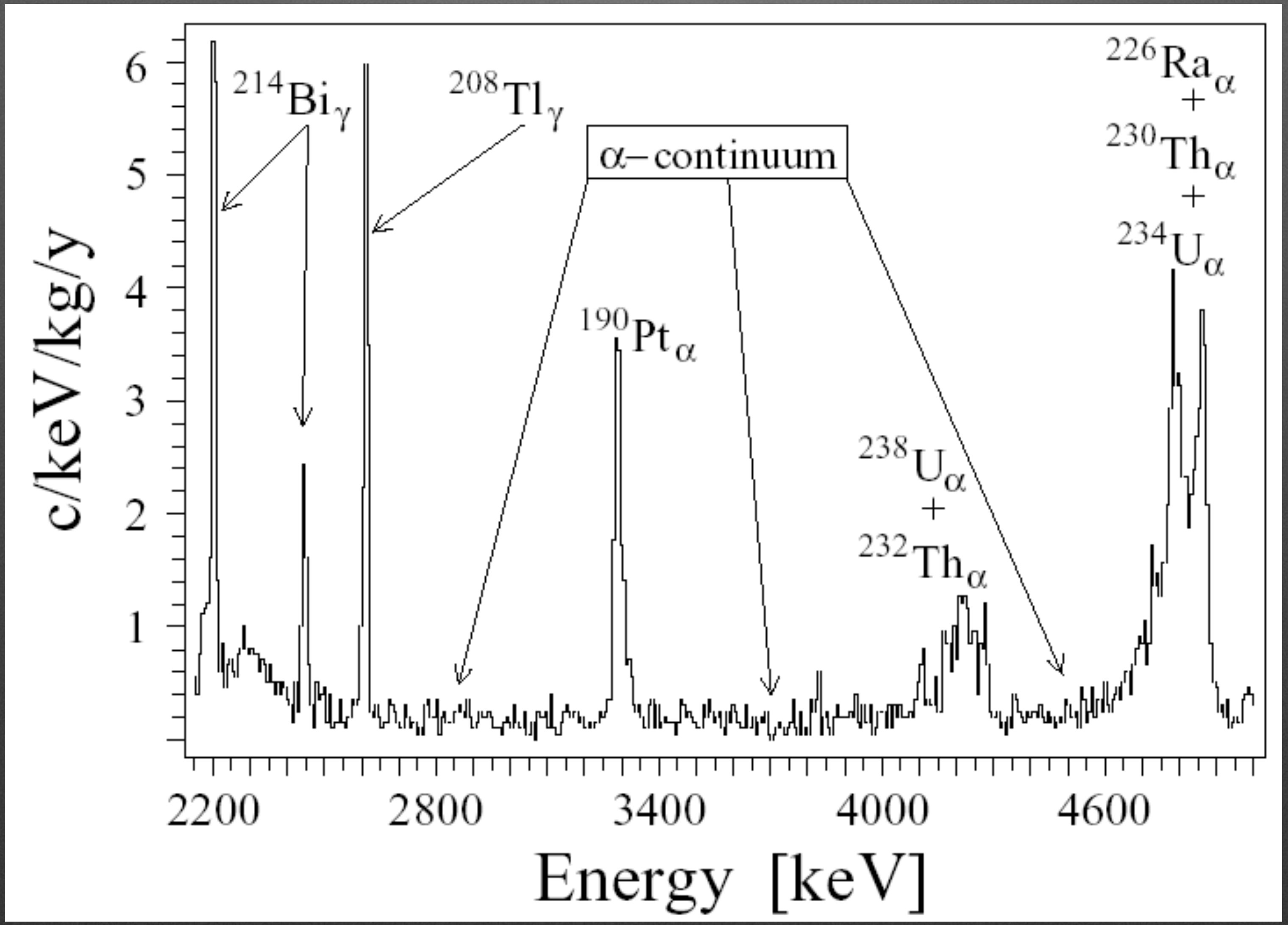
Volume: **180000** m³

Rn in air: 20-80 Bq/m³

At the end of the day

- Your signal is given by electrons
- Your background is given by natural (and induced) radioactivity
- In the few MeV's region photons and……

Alpha particles

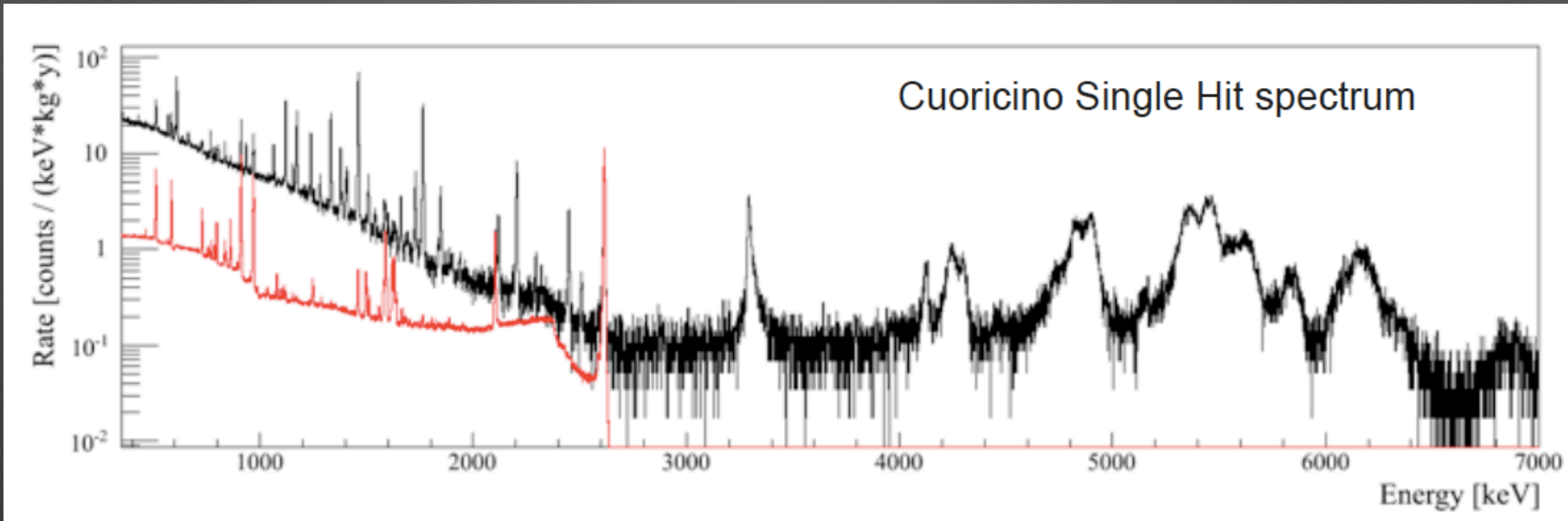


the α land

note that

- the background appears in two forms:
  - peaks (photons making photoelectric effects, alphas in the bulk of detectors)
  - continuum (external background degraded by Compton scattering, surface alpha's)

an example of real background



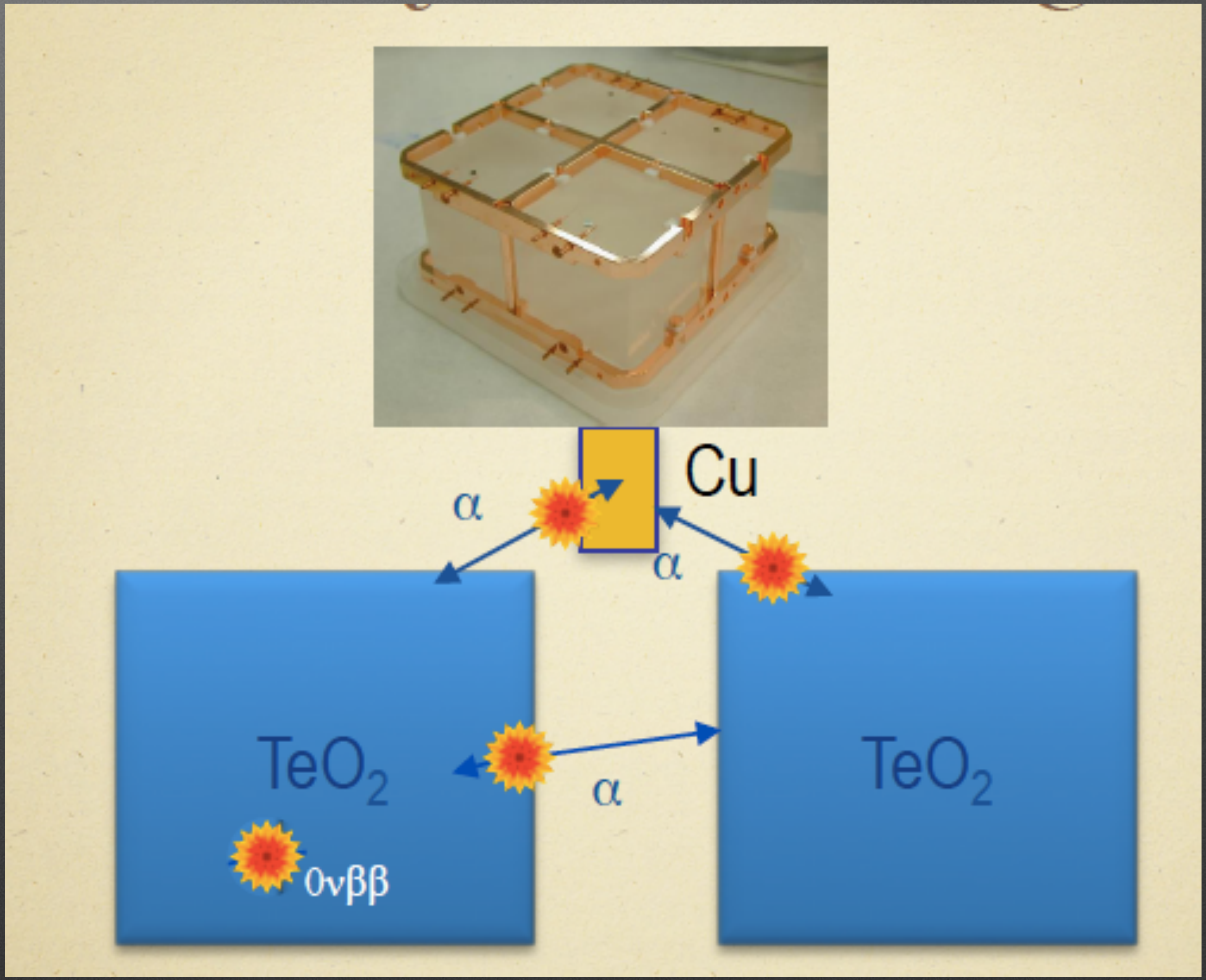
where the black line is what you measure and the red line is the simulation of pure photons background, that as said, almost disappear above the ^{208}Tl line.

The lesson

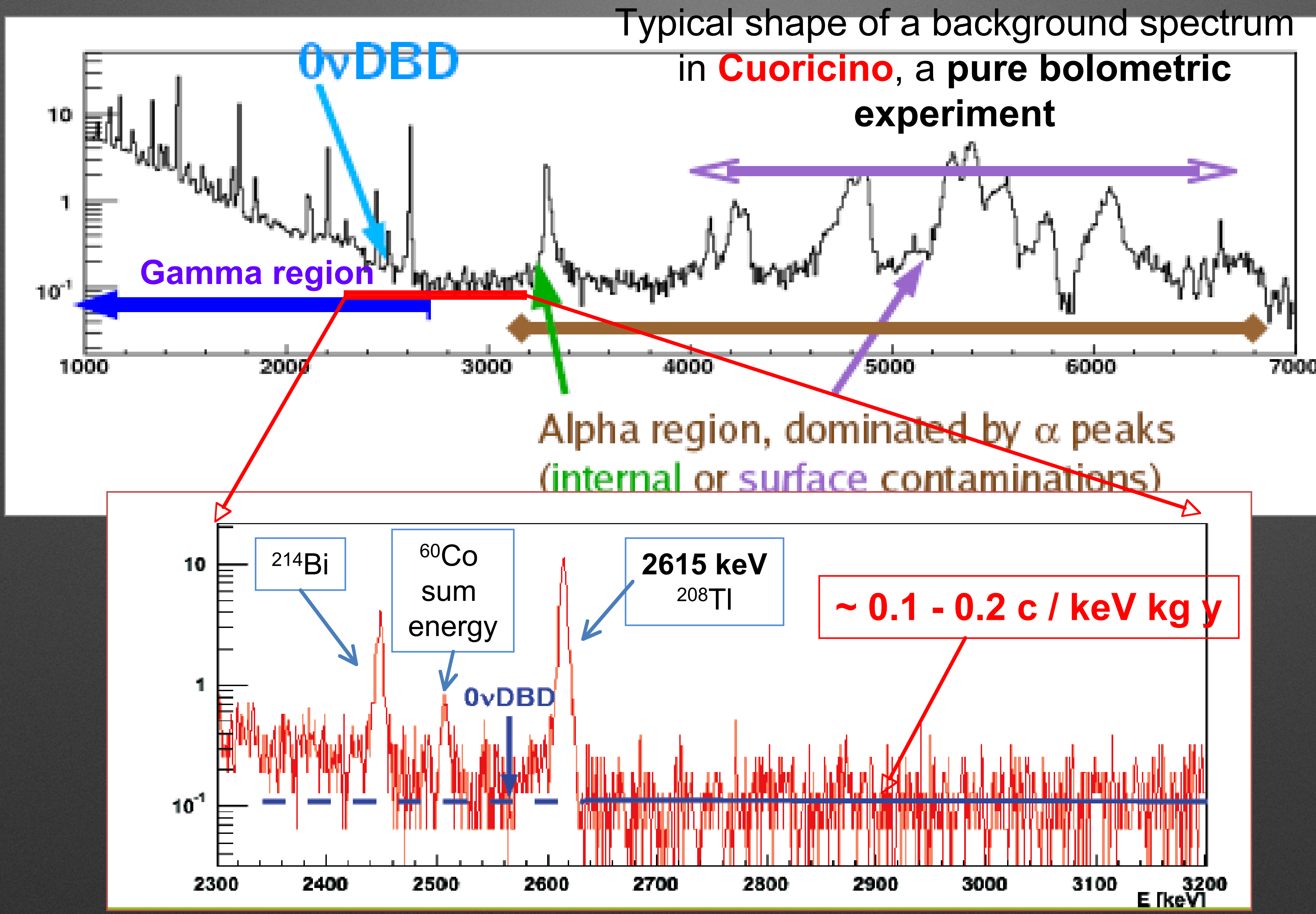
- if you do not discriminate alphas from photons/ electron you have little chances to achieve a sensible measurement of neutrino less double beta decay

The problem with alphas

- is somewhat equivalent to the one of Compton scattering of photons



indeed



Typical shape of a background spectrum in Cuoricino, a pure bolometric experiment
0νDBD
Gamma region
Alpha region, dominated by α peaks (internal or surface contaminations)
10
1
10⁻¹
1000
2000
3000
4000
5000
6000
7000
214Bi
60Co sum energy
2615 keV 208Tl
~ 0.1 - 0.2 c / keV kg y
0νDBD
2300
2400
2500
2600
2700
2800
2900
3000
3100
3200
E [keV]

The desired experiment

$$M \times t \times n_B \times \Delta E \leq 1$$

in principle you have four knobs

- in practice not
- as we said each factor 10 is a real pain
- once you have chosen a technology there is not much you can do about
  - energy resolution

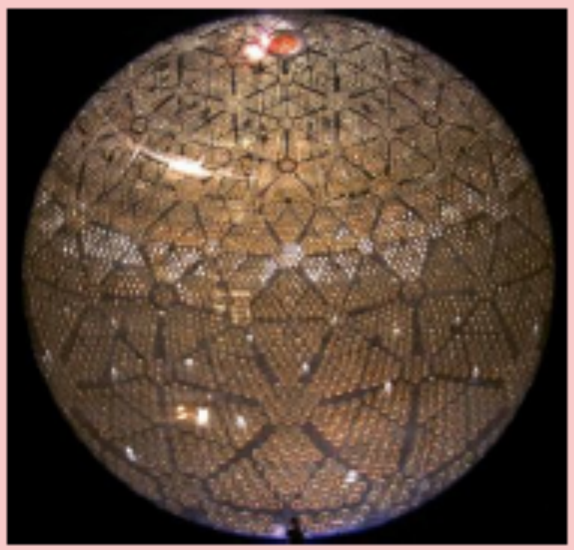
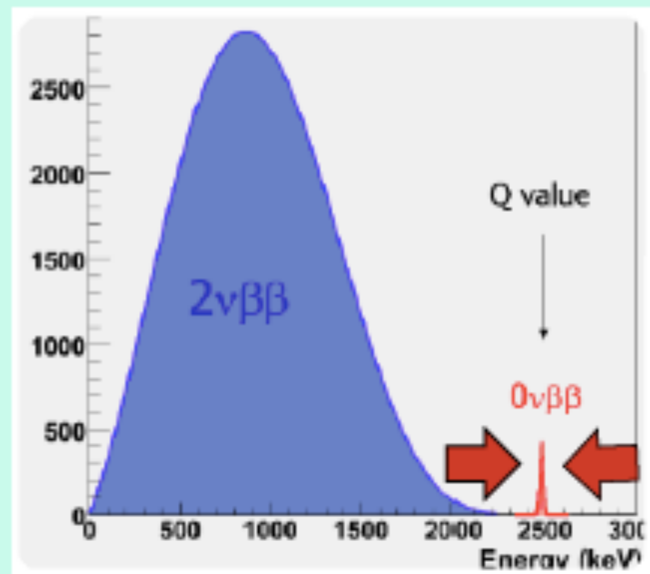
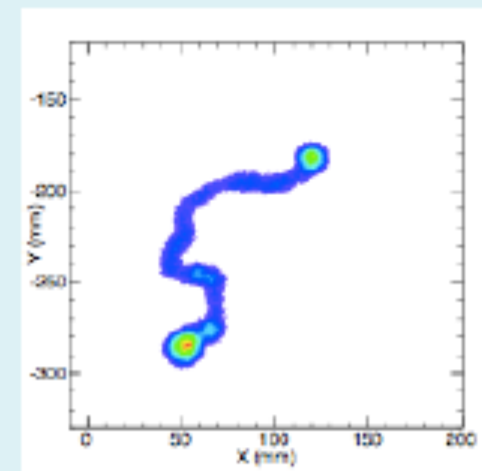
example

- M = 100 Kg (1 Ton)
- t = 1 y
- Q value = 3 MeV
- ΔE = 1% (0.1 %)
- what you need is $n_B = 3.3 \times 10^{-4}$

Tough game, we knew it !

Detector options

Way of though

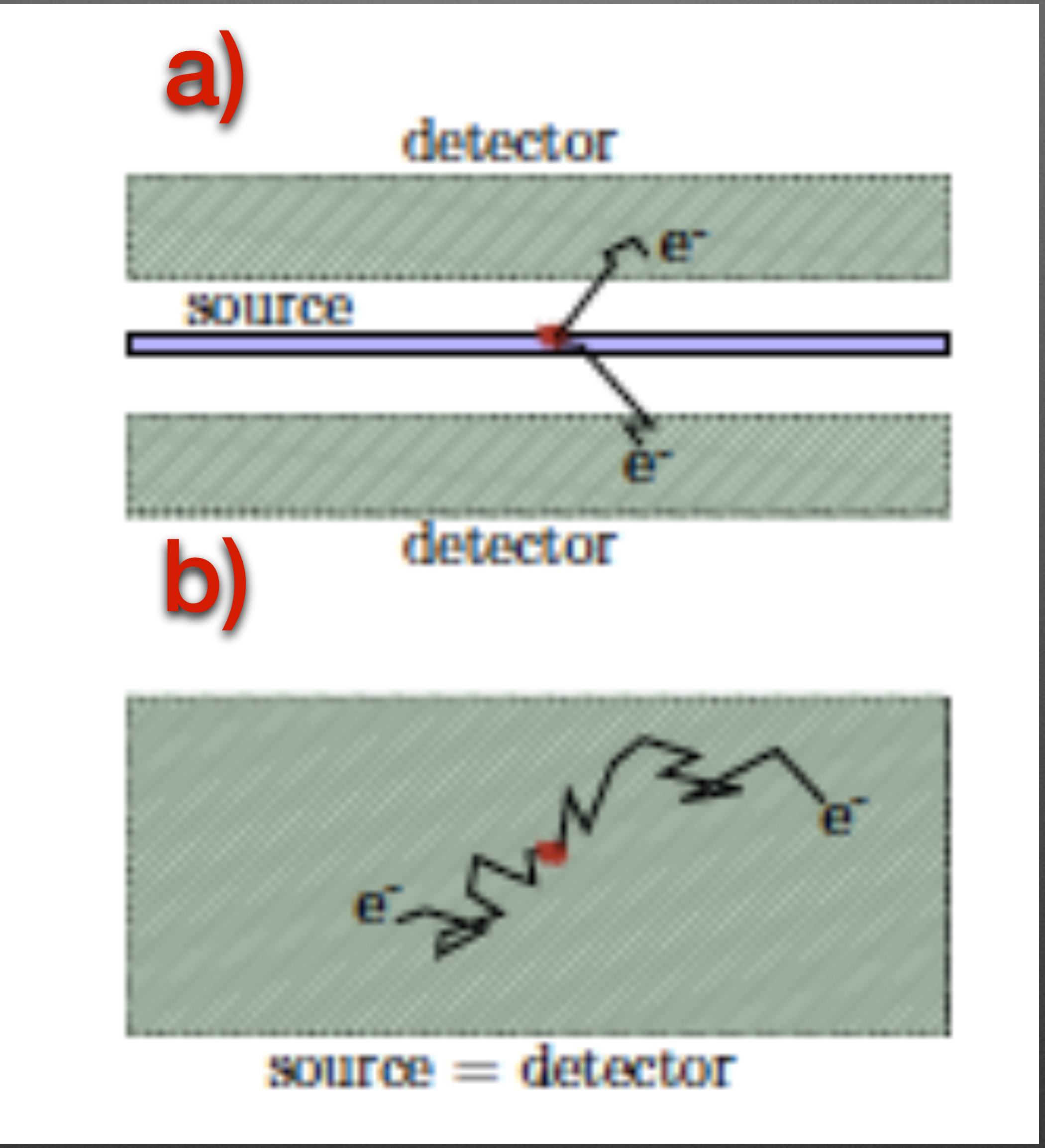
The "Brute Force" Approach	The "Peak-Squeezer" Approach	The "Final-State Judgement" Approach
		
focus on the numerator with **a huge amount of material** (often sacrificing resolution)	focus on the denominator by **squeezing down ΔE** (various technologies)	try to make the background zero by **tracking or tagging**

or any suitable combination !

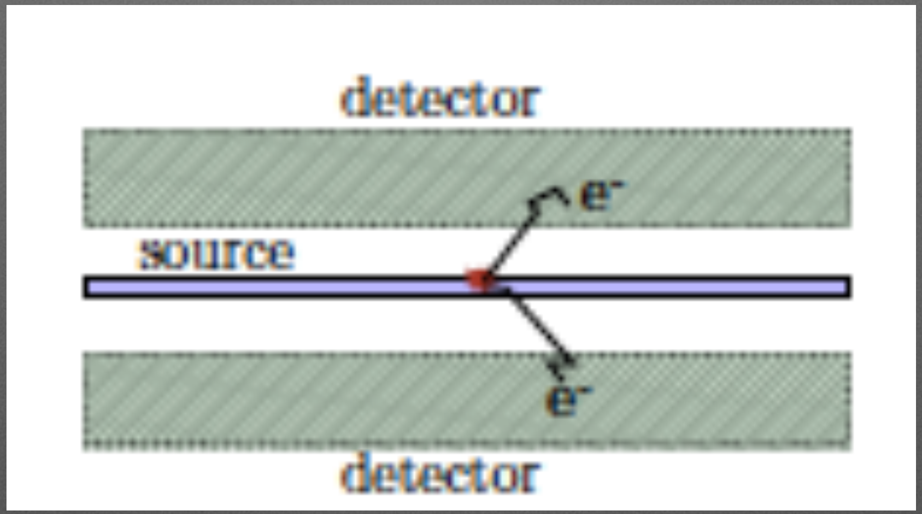
Main choice

- Calorimeter
- Tracker

pictorially

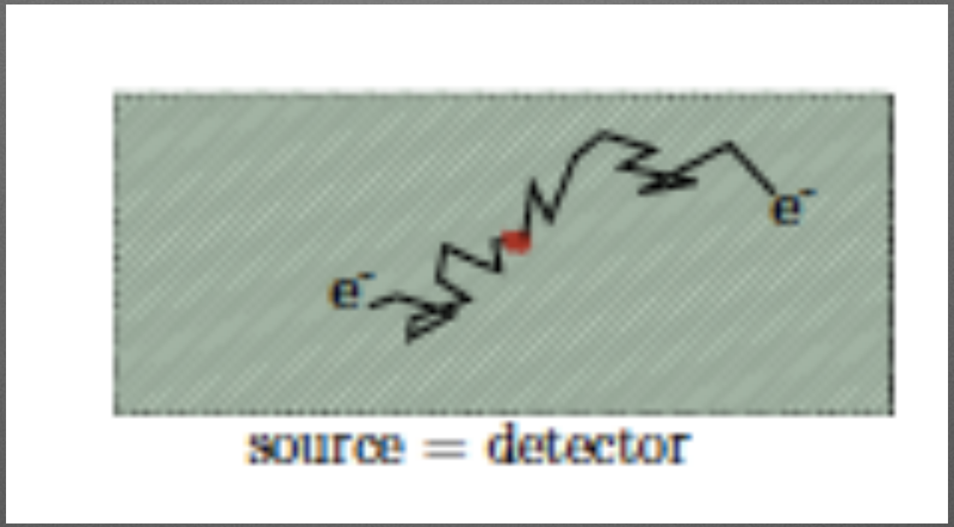


Pro and cons (tracker)



- good background rejection (topology)
- critical energy resolution
- low mass

Pro and cons (calorimeter)



- maximal efficiency
- good energy resolution
- high mass possible
- complex background reduction

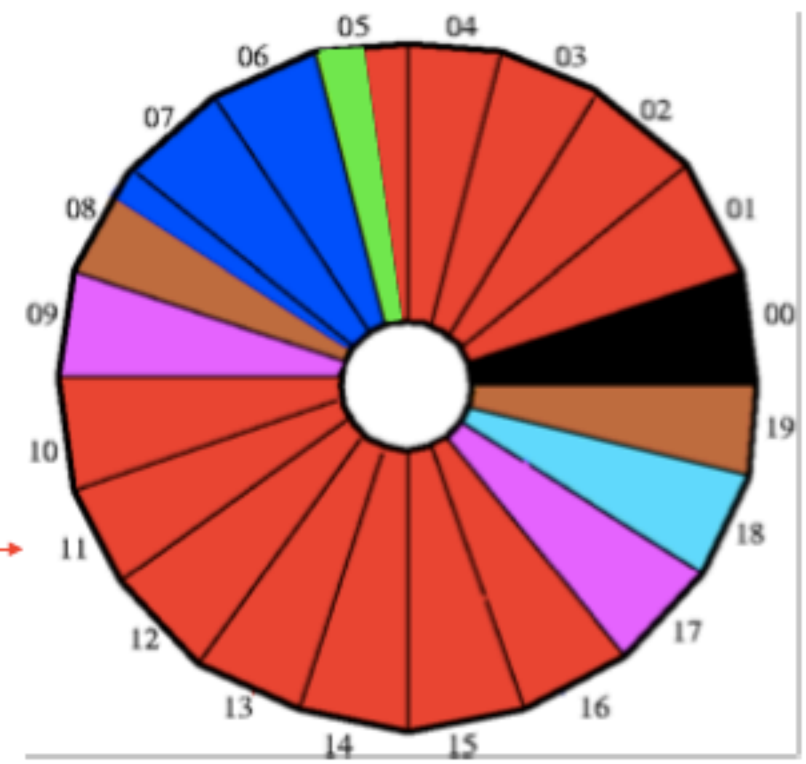
Calorimeters

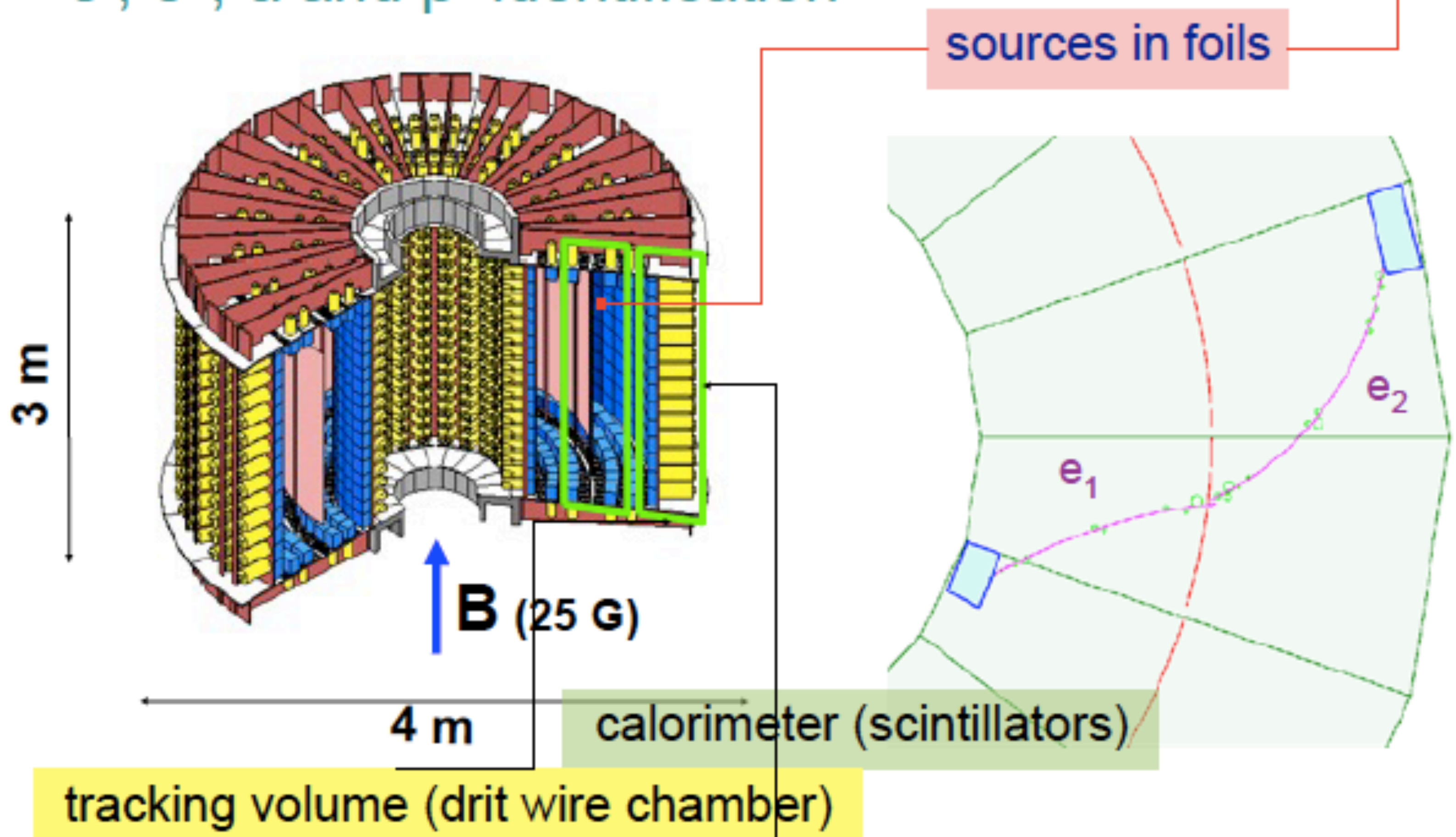
- gaseous / liquid : scintillation/ ionisation
- solid : crystals (non scintillating/scintillating)

Tracker : NEMO concept

Tracking detector for $2\nu\beta\beta$ and $0\nu\beta\beta$
at Frejus (4800 m.w.e.)

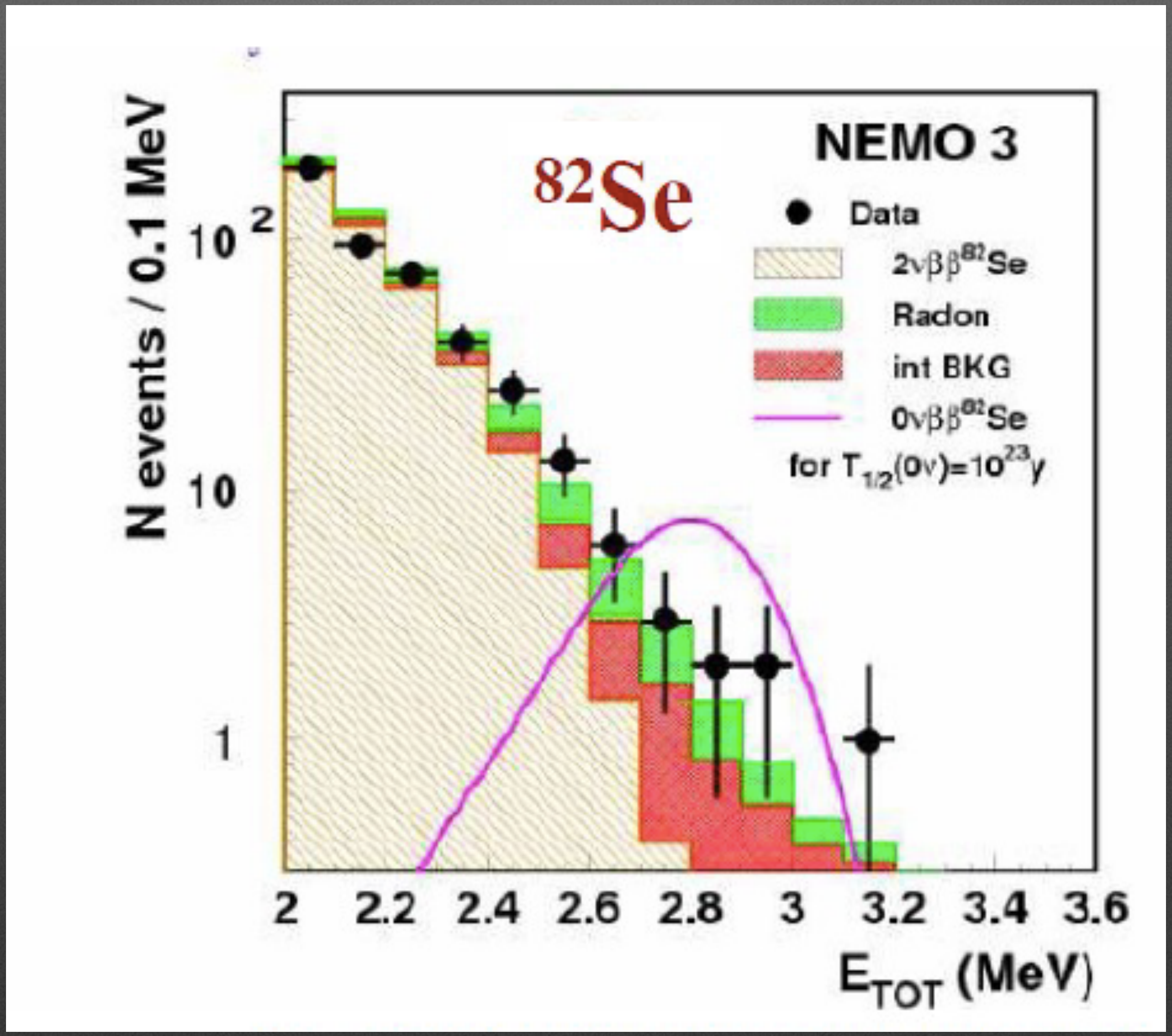
- 10 kg of enriched material in foils
- 6180 geiger cells ⇒ drift wire chamber
- 1940 plastic scintillators + PMTs
- iron (γ) + water with B (n) shielding + anti-Rn box
- e^-, e^+, α and β identification





^{100}Mo	(6.9 kg)	➡ $0\nu\beta\beta$
^{82}Se	(0.9 kg)	
^{130}Te	(0.45 kg)	
^{116}Cd	(0.4 kg)	
^{150}Nd	(37g)	
^{96}Zr	(9.4 g)	
^{48}Ca	(7.0g)	
^{nat}Te	(0.5 kg)	
Cu	(0.6 kg)	

Great detector for $2\nu\beta\beta$
Bad detector for $0\nu\beta\beta$

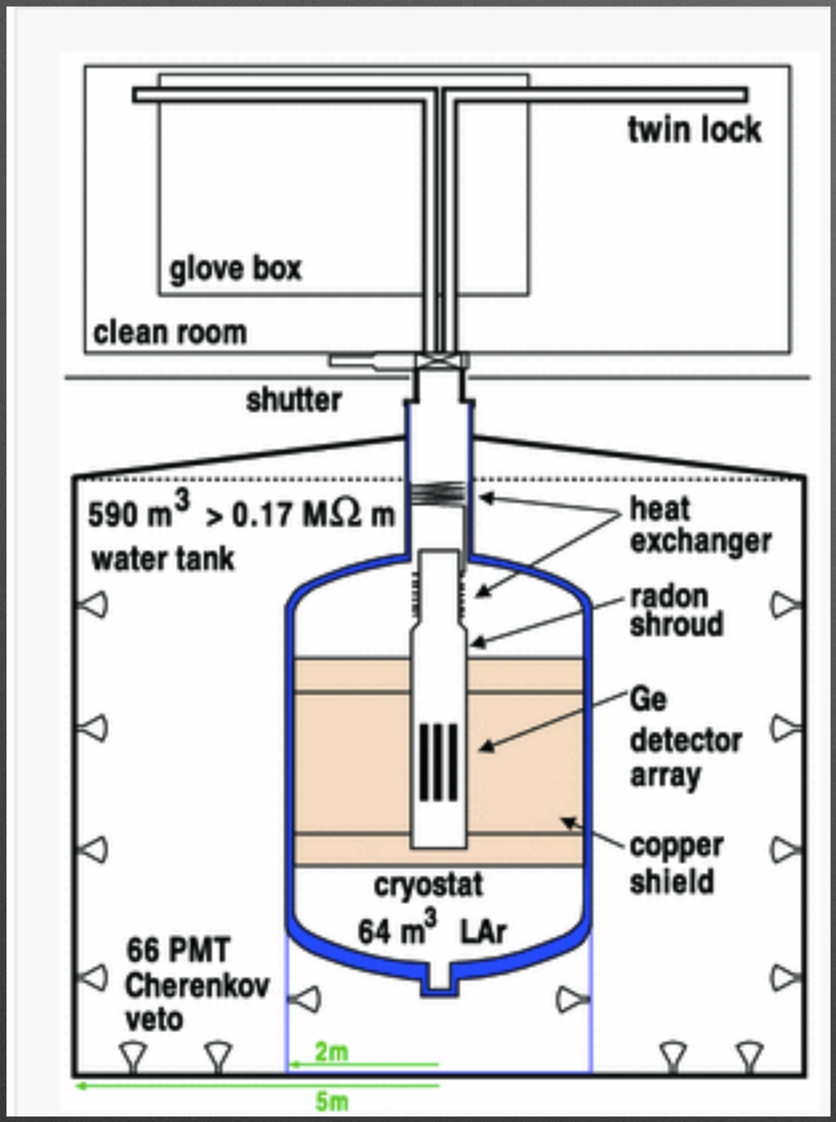


It hardly would see an half-life of 10^{23}….and the name of the game is $\geq 10^{26}$

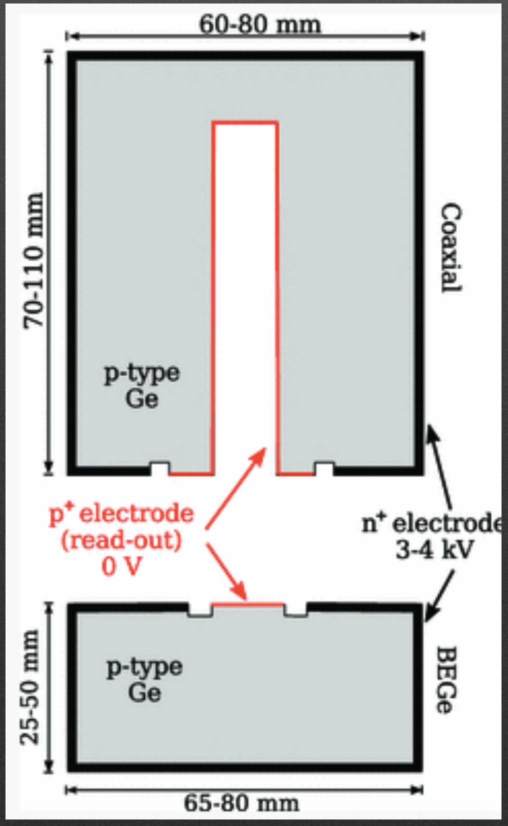
Crystal calorimeters

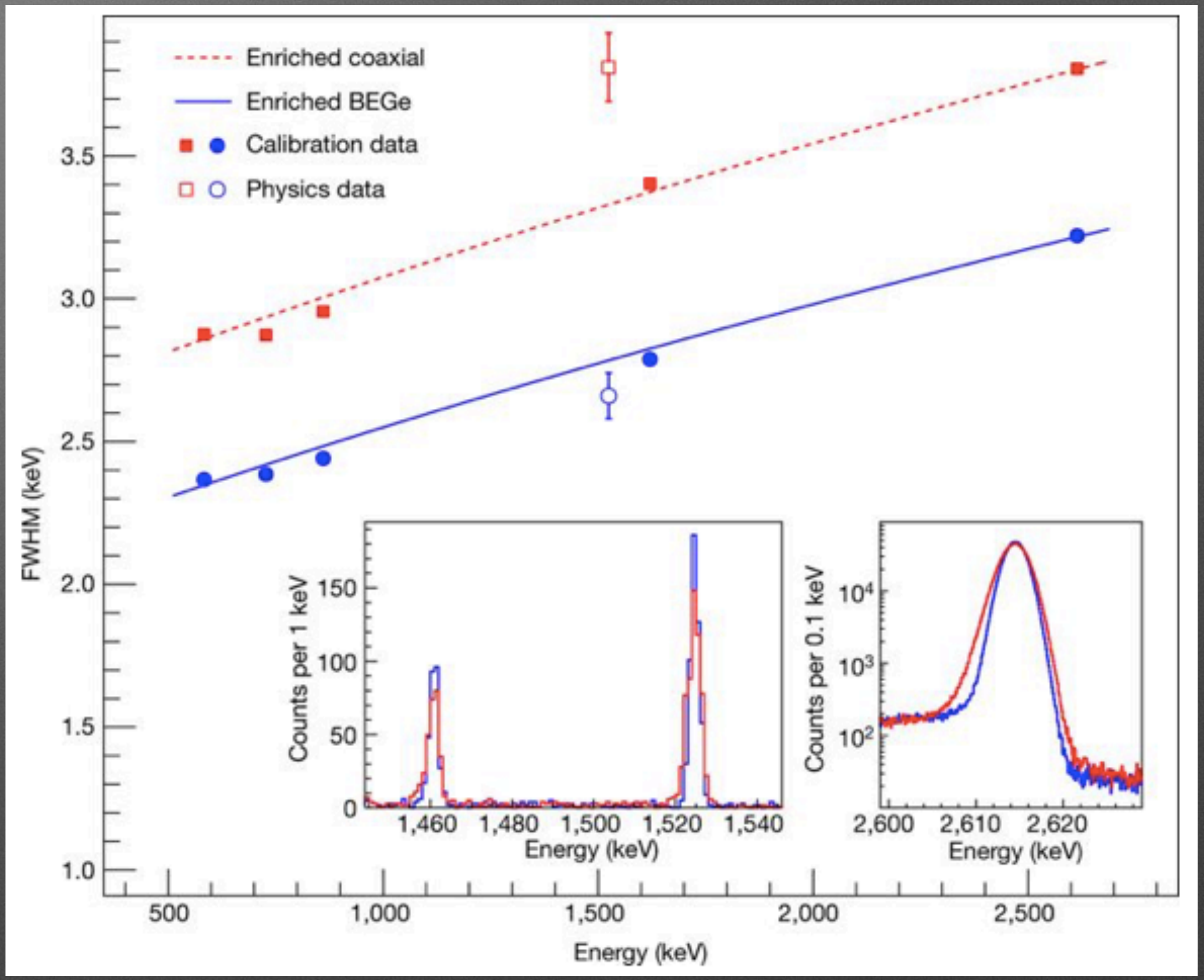
- Cryogenic at Liquid Nitrogen (Germanium diodes)
- Bolometric at 10 mK scale ($^{nat}TeO_2$, $Zn^{82}Se$, $Zn^{100}MoO_4$, $Li^{100}MoO_4$……)

A Germanium calorimeter



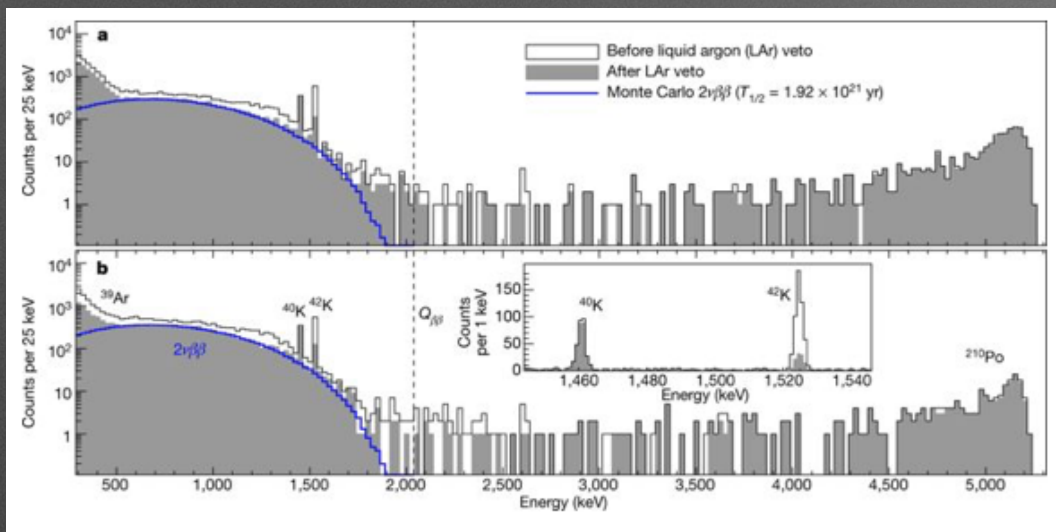
G
E
R
D
A

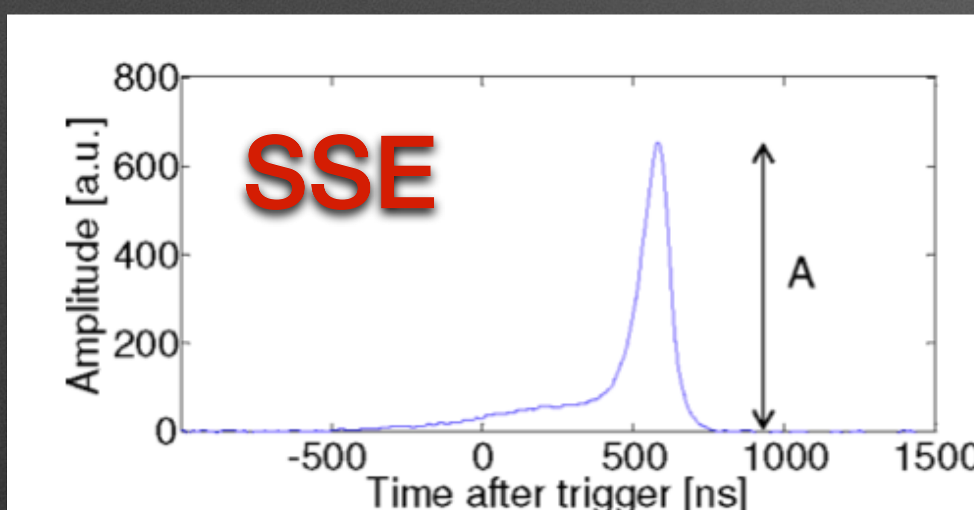


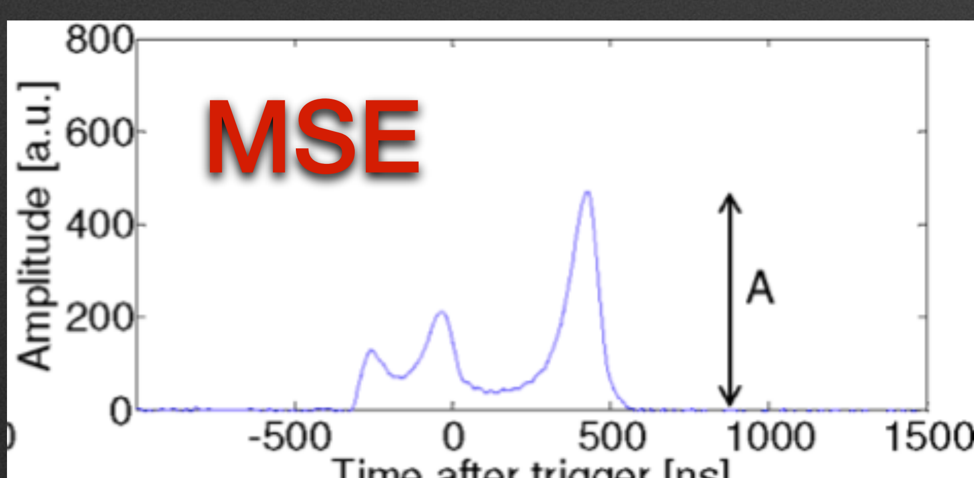


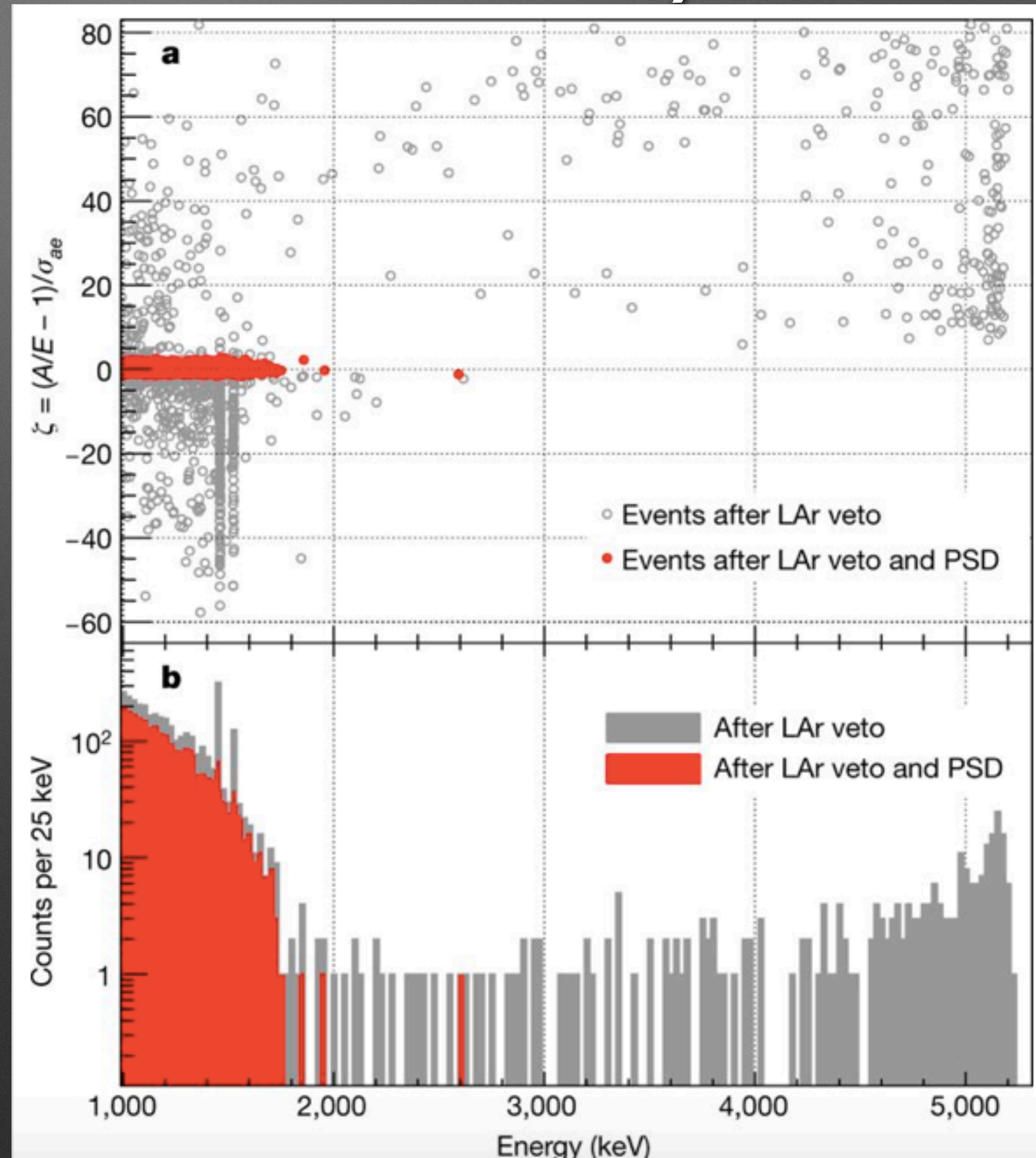
A FWHM of $0.15\ \%$
at Q-value

Pulse Shape Discrimination
(single site versus multi site)



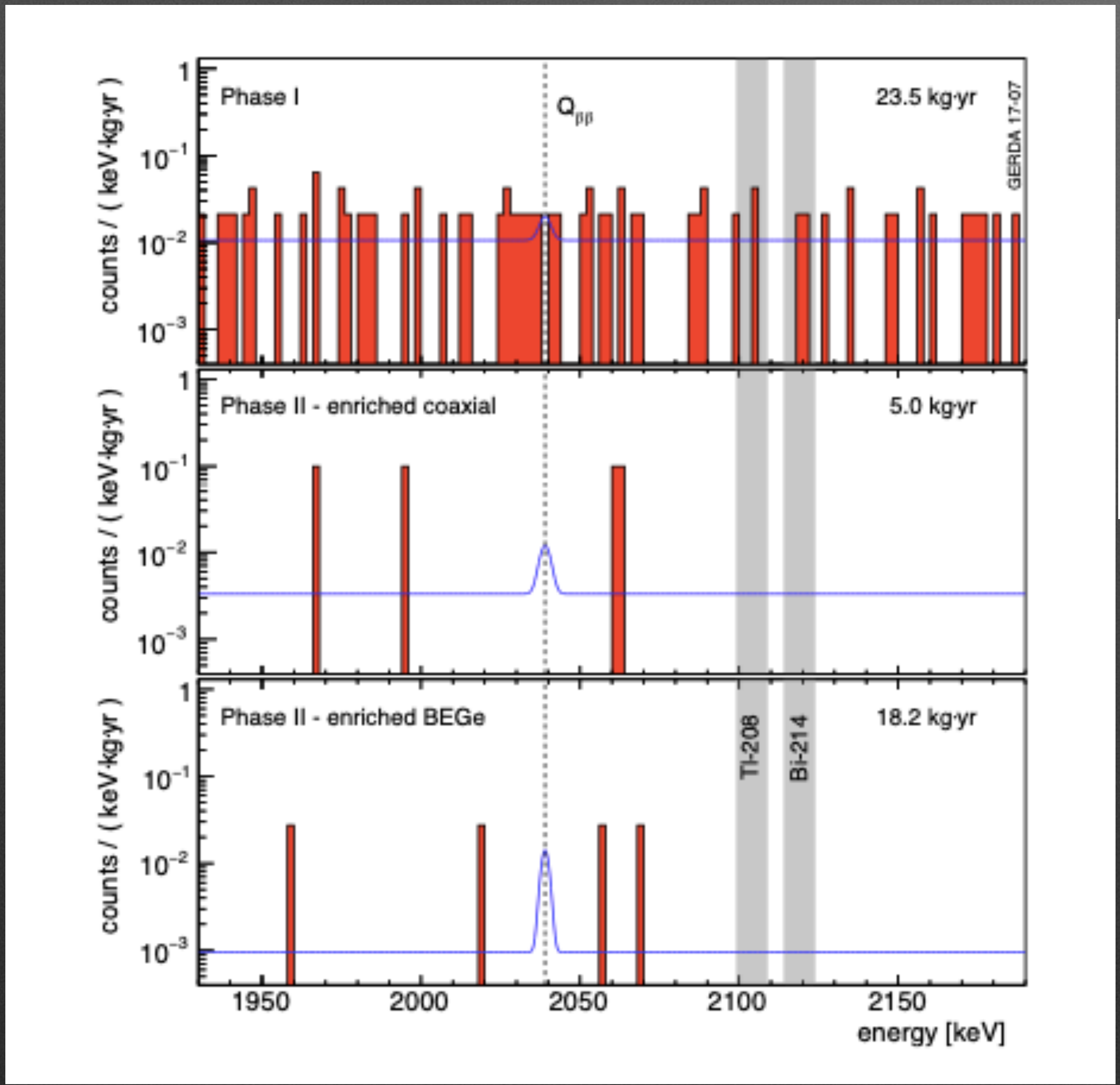






GERDA results to-date

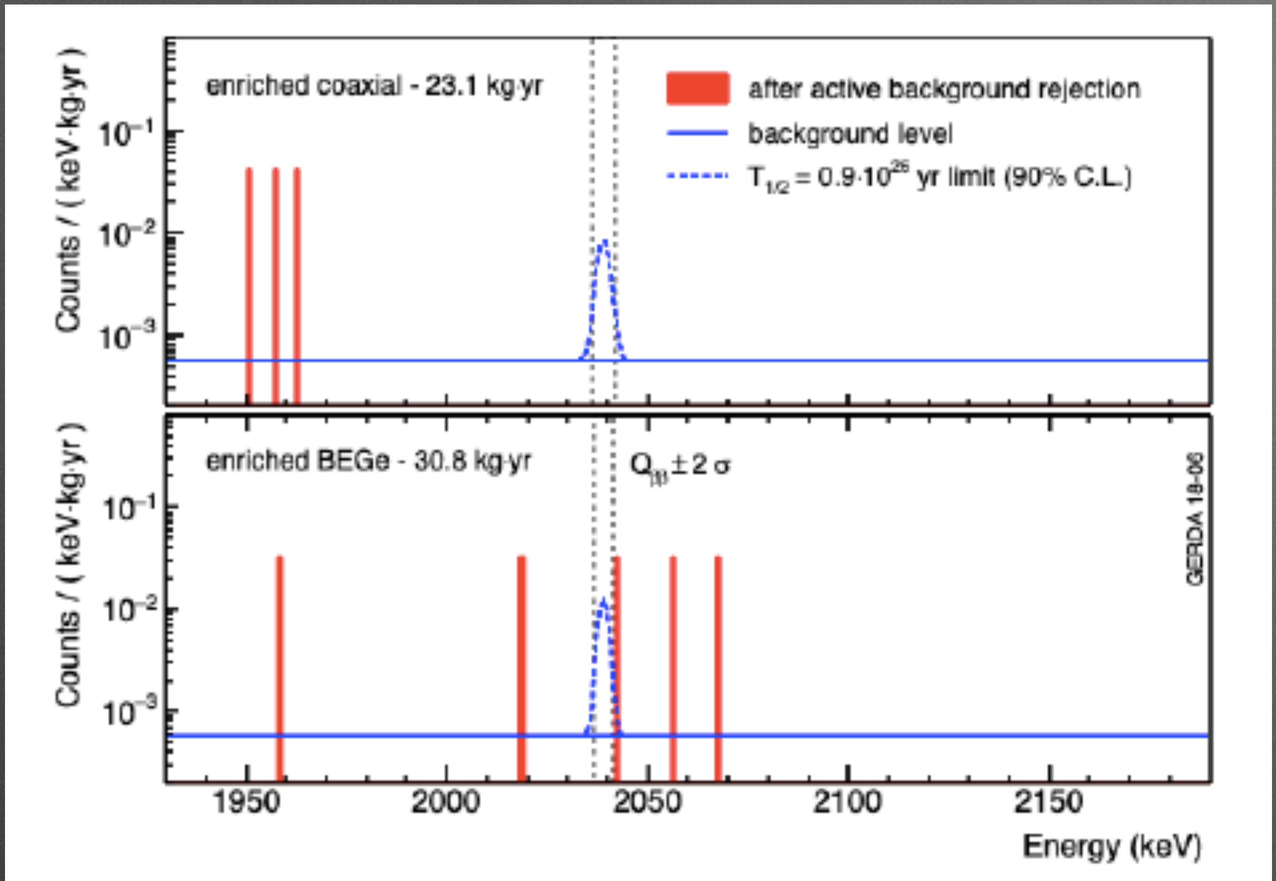
experiment	isotope	M_i [kg]	NME	sensitivity $T^{0\nu}_{1/2}$ [10^{25} yr]	sensitivity $m_{\beta\beta}$ [eV]	limit $T^{0\nu}_{1/2}$ [10^{25} yr]	limit $m_{\beta\beta}$ [eV]
GERDA	^{76}Ge	31	2.8-6.1	5.8	0.14–0.30	8.0	0.12–0.26



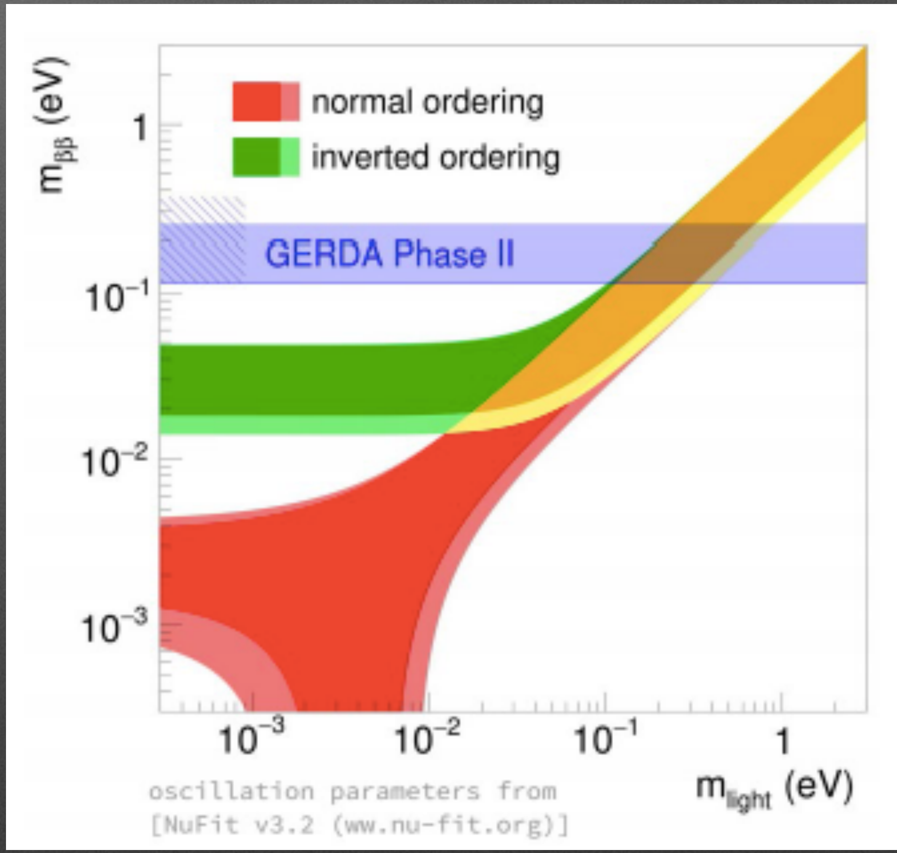
data set	$\mathcal{E}$ [kg·yr]	FWHM [keV]	ϵ	BI [10^{-3}cts/(keV·kg·yr)]
PII coaxial	5.0	4.0(2)	0.53(5)	$3.5^{+2.1}_{-1.5}$
PII BEGe	18.2	2.93(6)	0.60(2)	$1.0^{+0.6}_{-0.4}$
total PII	23.2			

you could run 300 Kg of isotope for 1 year at 10^{-3} bckg bringing the limit close to 10^{27} y
still you would not cover the entire inverted hierarchy even with the most optimistic NME

GERDA@LNGS



$T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ yr (90% C.L.)

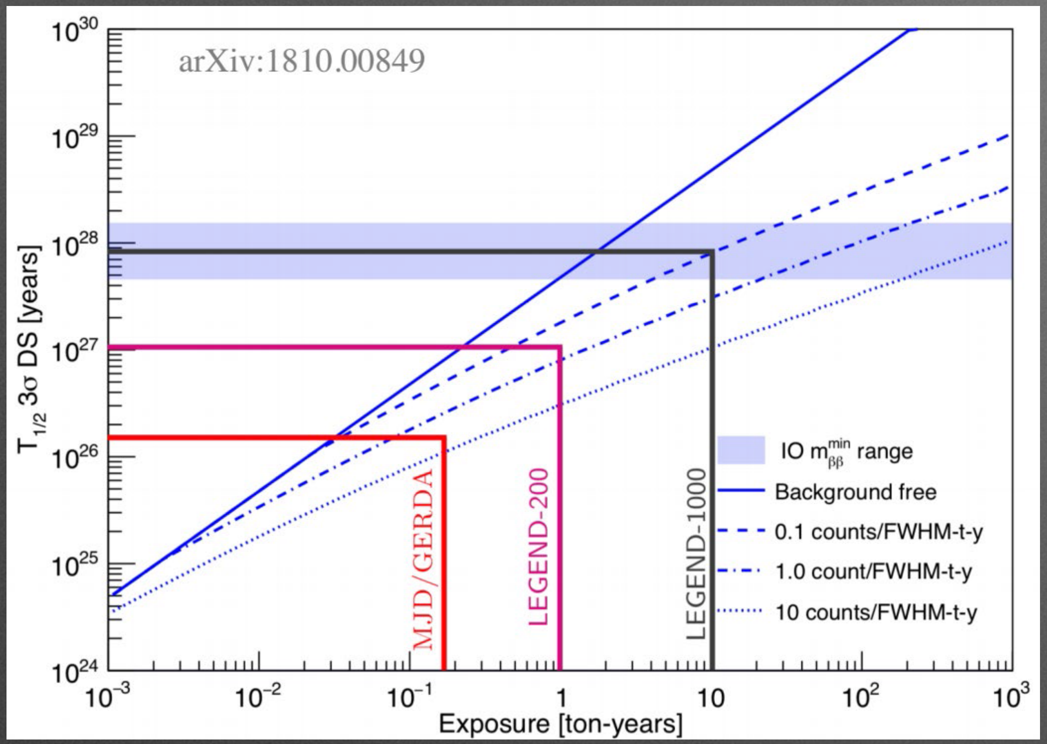


Lowest background per ROI ever achieved in $0\nu\beta\beta$ experiments. Background Index:

- for coaxial detectors: $5.7 \cdot 10^{-4}$ cts/(kg·keV·yr)
- for BEGe detectors $5.6 \cdot 10^{-4}$ cts/(kg·keV·yr)

So, for the given FWHM and the background index you expect to be able to run 2 years ‘square root free’

turning to LEGEND@LNGS



BI x FWHM/ε

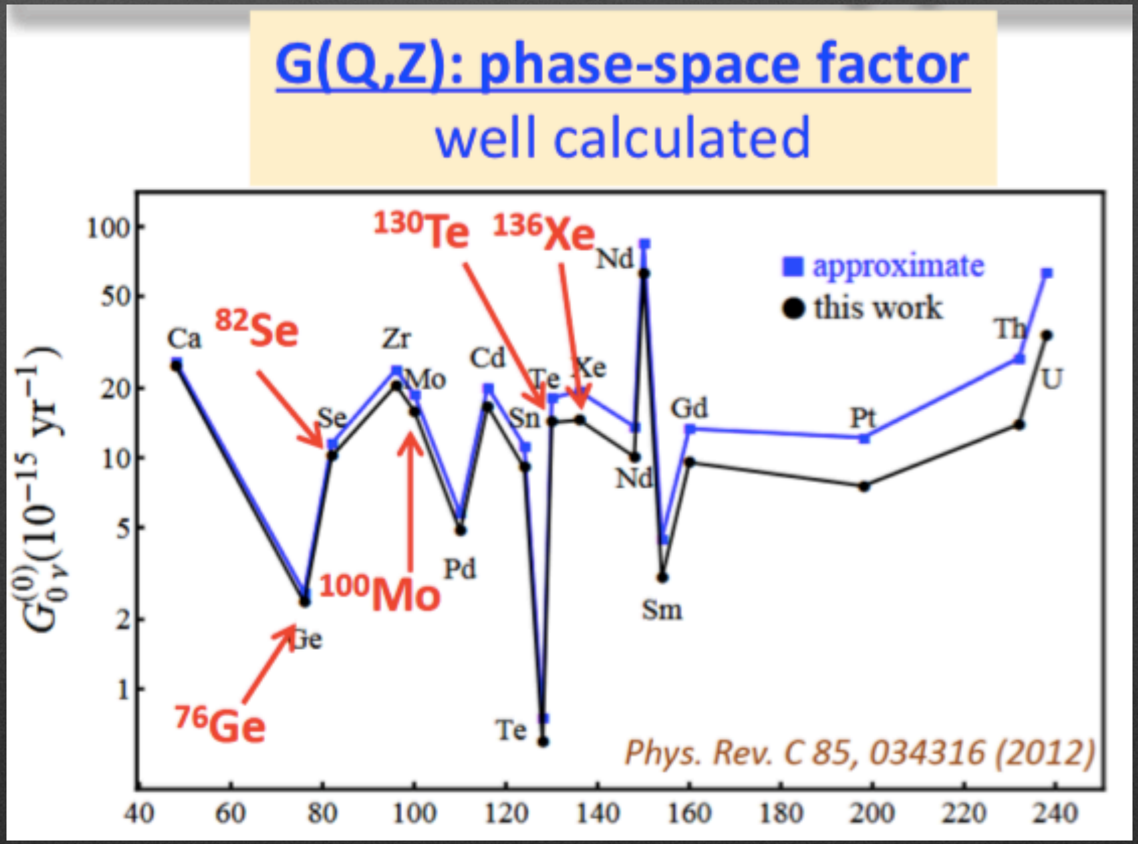
based on BI~6x10^{-4}
and FWHM~ 3keV

The reach can be
10^{27}

but

$$\left(T_{1/2}^{0\nu}\right)^{-1} \propto G^{0\nu}(Q,Z)\cdot\left|M^{0\nu}\right|^2\left\langle m_{\beta\beta}\right\rangle^2$$

heavy price to pay to phase space



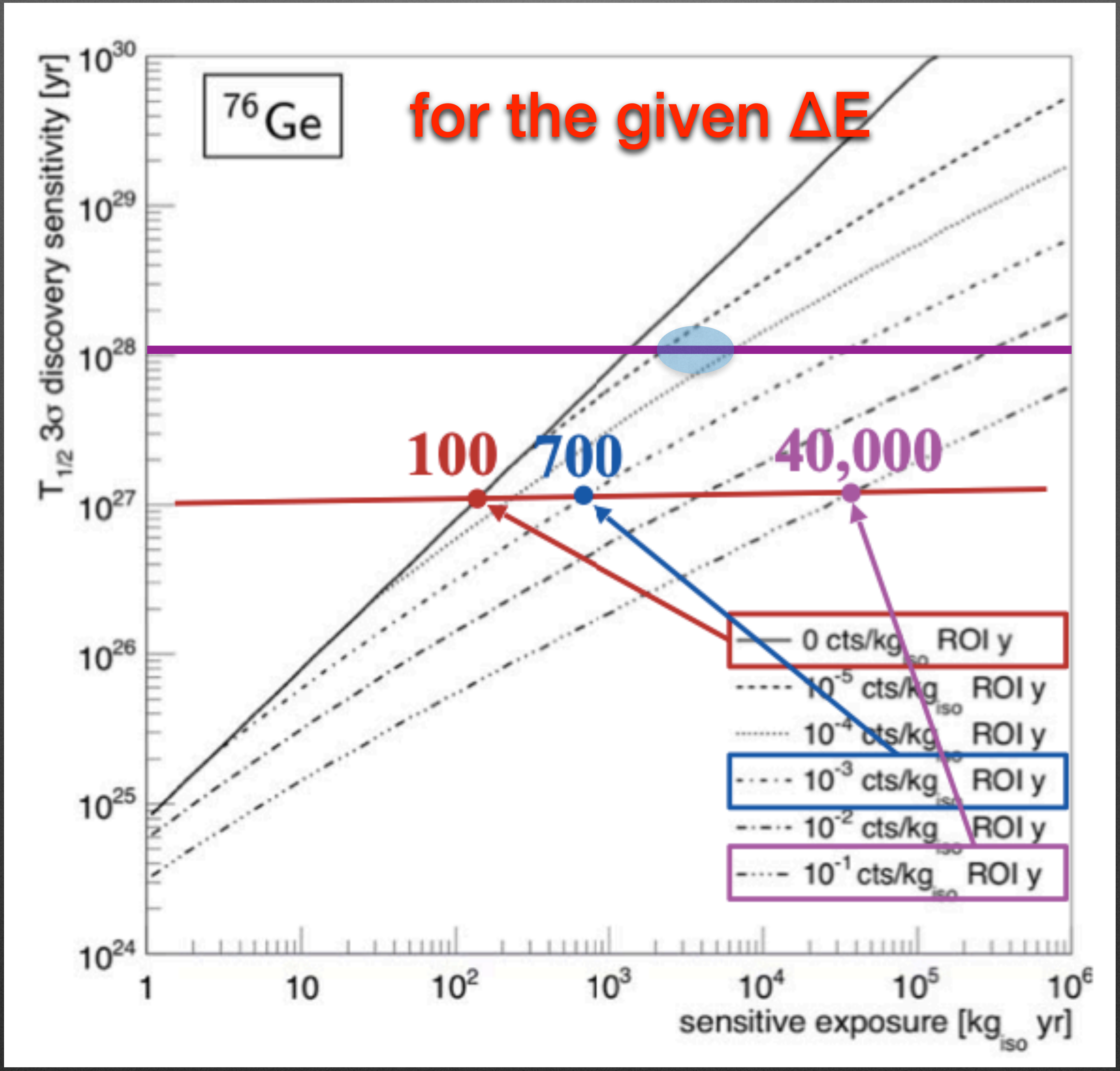
what really counts is

- $n_B \times \Delta E$
- Ge Calorimeter ~ 3 KeV
- the merit factor for Gerda today is :

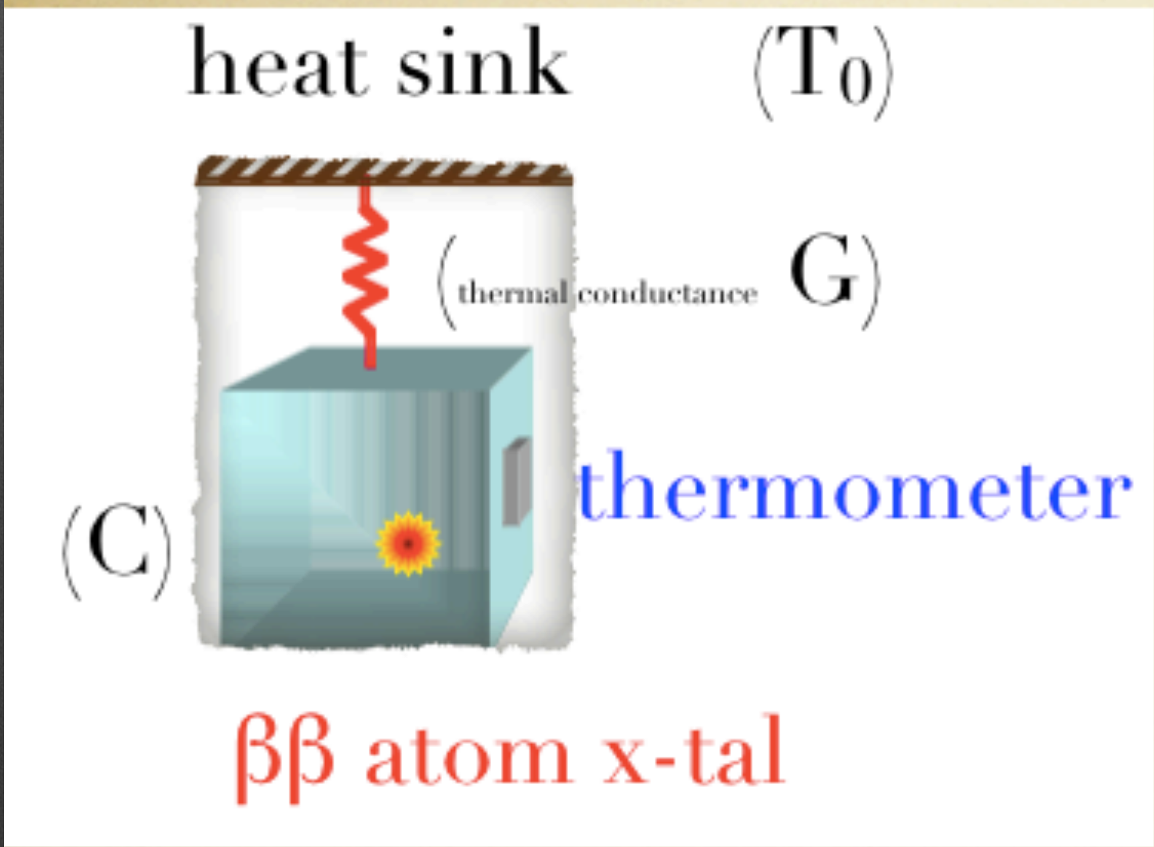
$$5.6 \cdot 10^{-4} \frac{1}{(kg \cdot KeV \cdot y)} \times 3KeV \sim 2 \cdot 10^{-3}$$

- you are background free until 500 $Kg \cdot y$

possible futures



Bolometer
(a very low temperature calorimeter)
A true calorimeter !



Basic Physics: $\Delta T = E/C$
(Energy release/ Thermal capacity)

Implication: Low C ⇒ Low T

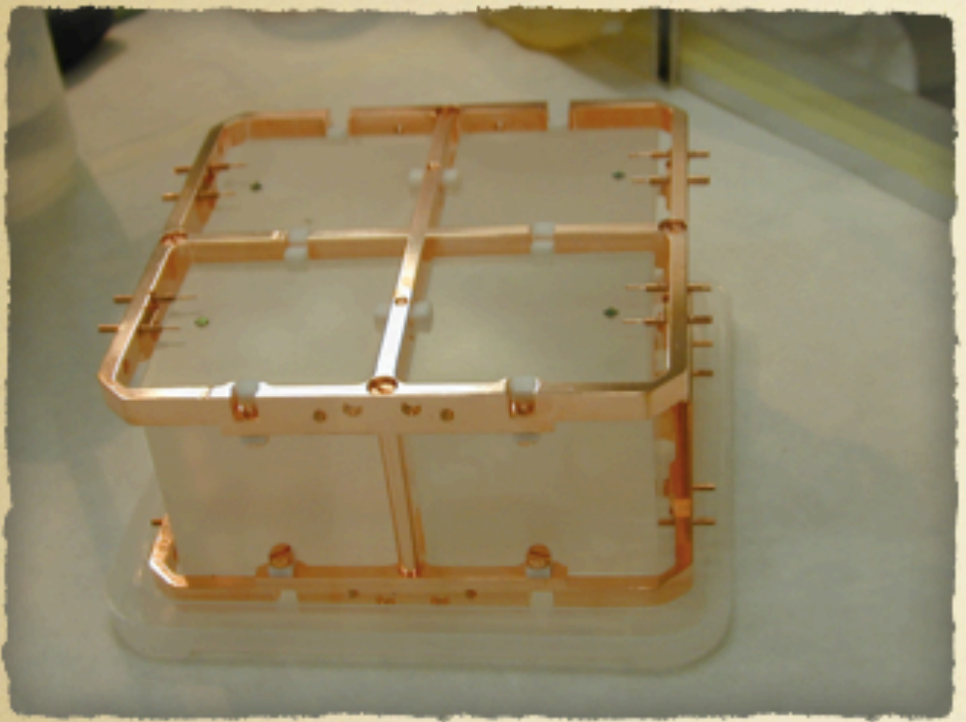
Bonus: (almost) No limit to ΔE
($k_B T^2 C$)

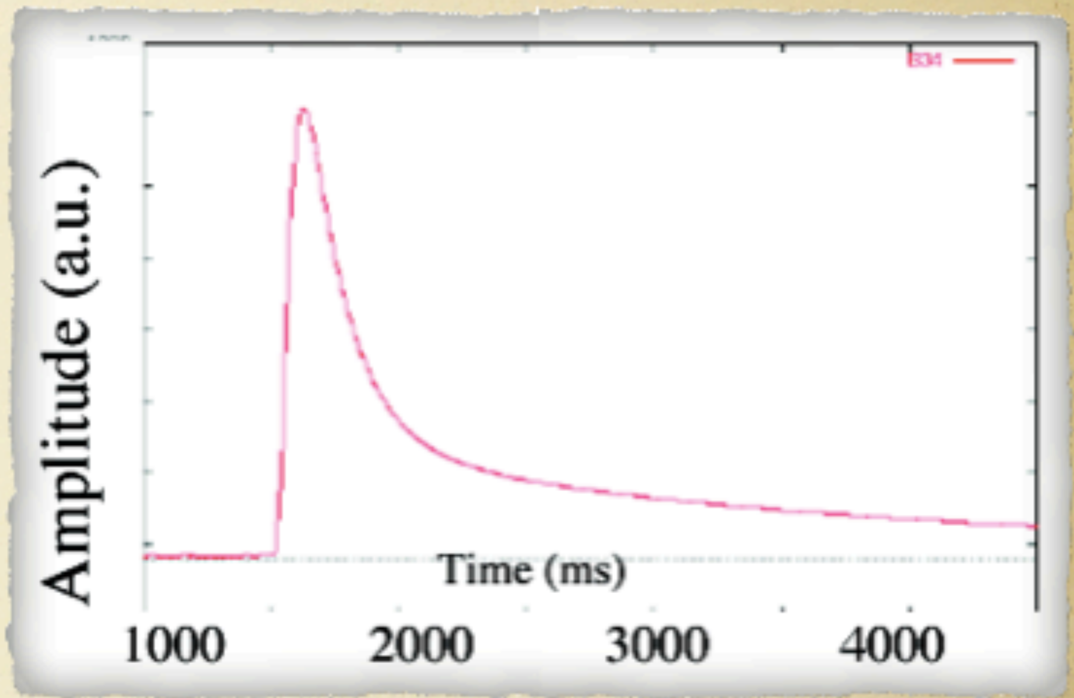
Not for all apps : $\tau = C/G \sim 1s$

$$C(T) = \beta \frac{m}{M} \left(\frac{T}{\Theta_D} \right)^3$$

$$\Delta T(t) = \frac{\Delta E}{C} \exp\left(-\frac{t}{\tau} \right)$$

TeO_2 : a show case



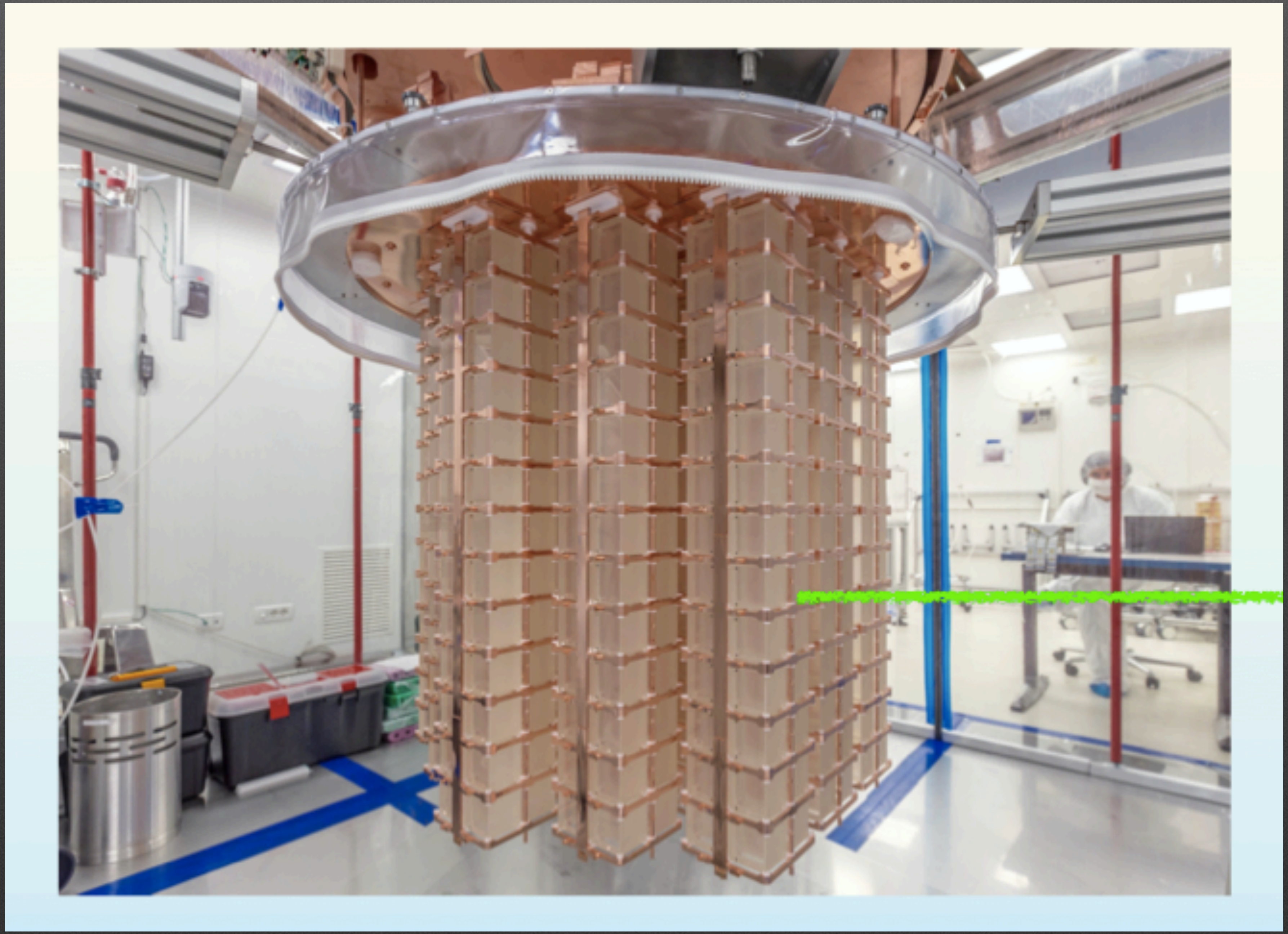


Numerology:

$T_0 \sim 10$ mK
$C \sim 2$ nJ/K ~ 1 MeV/0.1 mK
$G \sim 4$ pW/mK

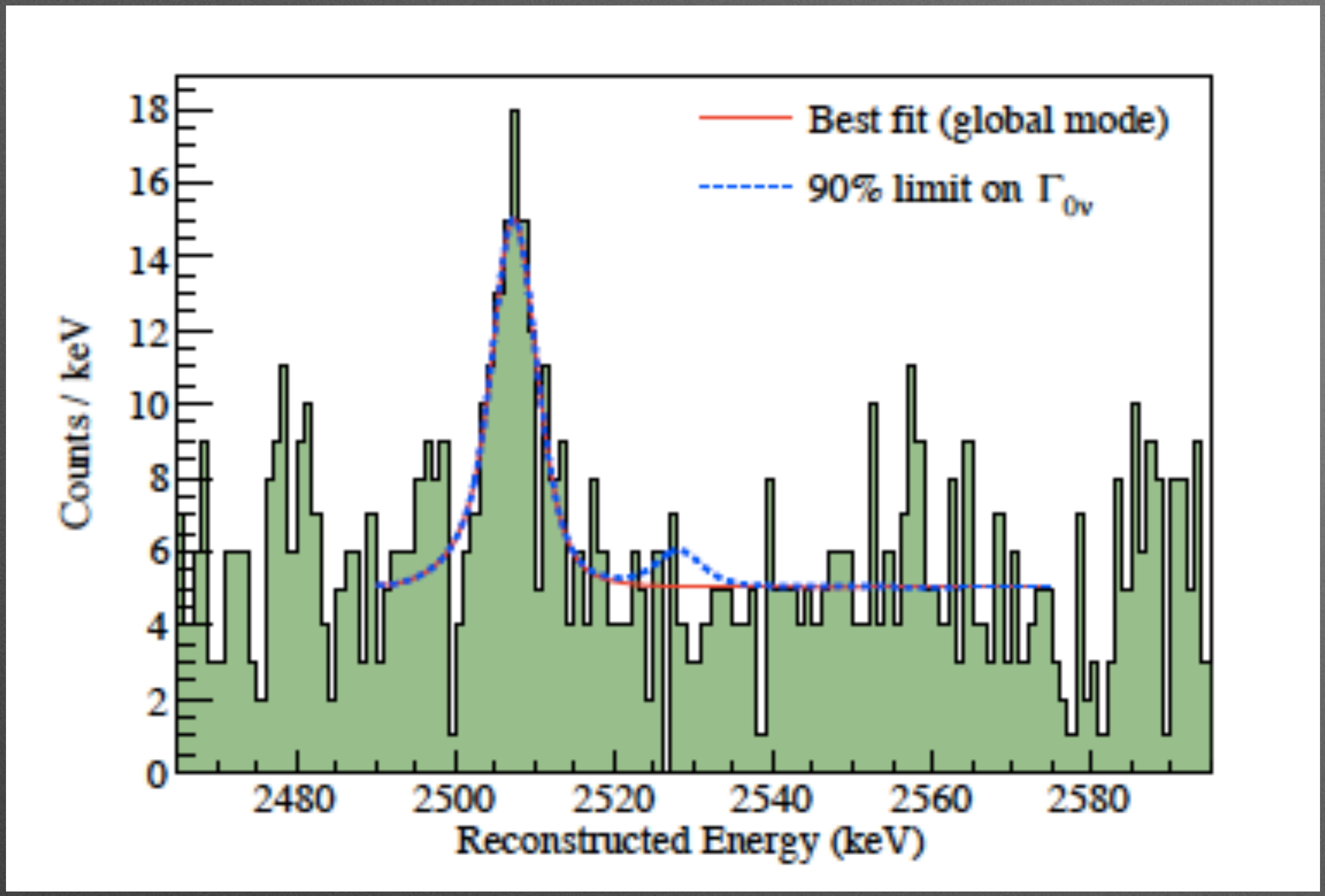
Need to be able to detect temperature jumps of a fraction of μK (per mil resolution on MeV signals)

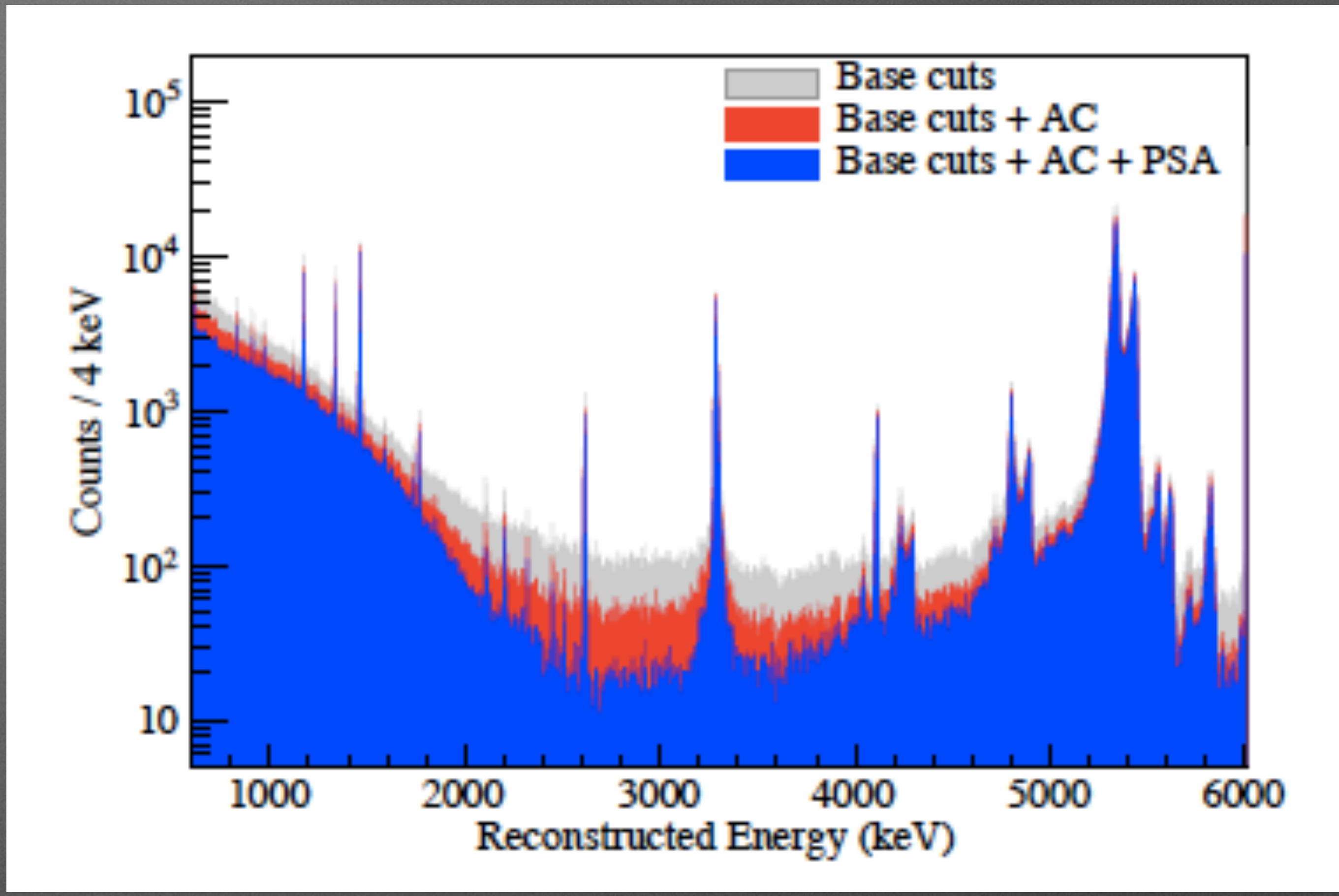
CUORE impressive array



the coldest cubic meter in the universe

Cuore so-far





Number of datasets	7
Number of valid calorimeters (min–max)	900–954
TeO_2 exposure	372.5 kg·yr
FWHM at 2615 keV in calibration data	7.73(3) keV
FWHM at $Q_{\beta\beta}$ in physics data	7.0(4) keV
Reconstruction efficiency	95.802(3) %
Anticoincidence efficiency	98.7(1) %
PSA efficiency	92.6(1) %
Total analysis efficiency	87.5(2) %
Containment efficiency	88.35(9) % [49]

$T^{0\nu}_{1/2} > 3.2 \cdot 10^{25}$ yr at 90% credibility interval (CI)

BI of $(1.38 \pm 0.07) \cdot 10^{-2}$ counts/(keV·kg·yr)

This is not a zero background experiment !

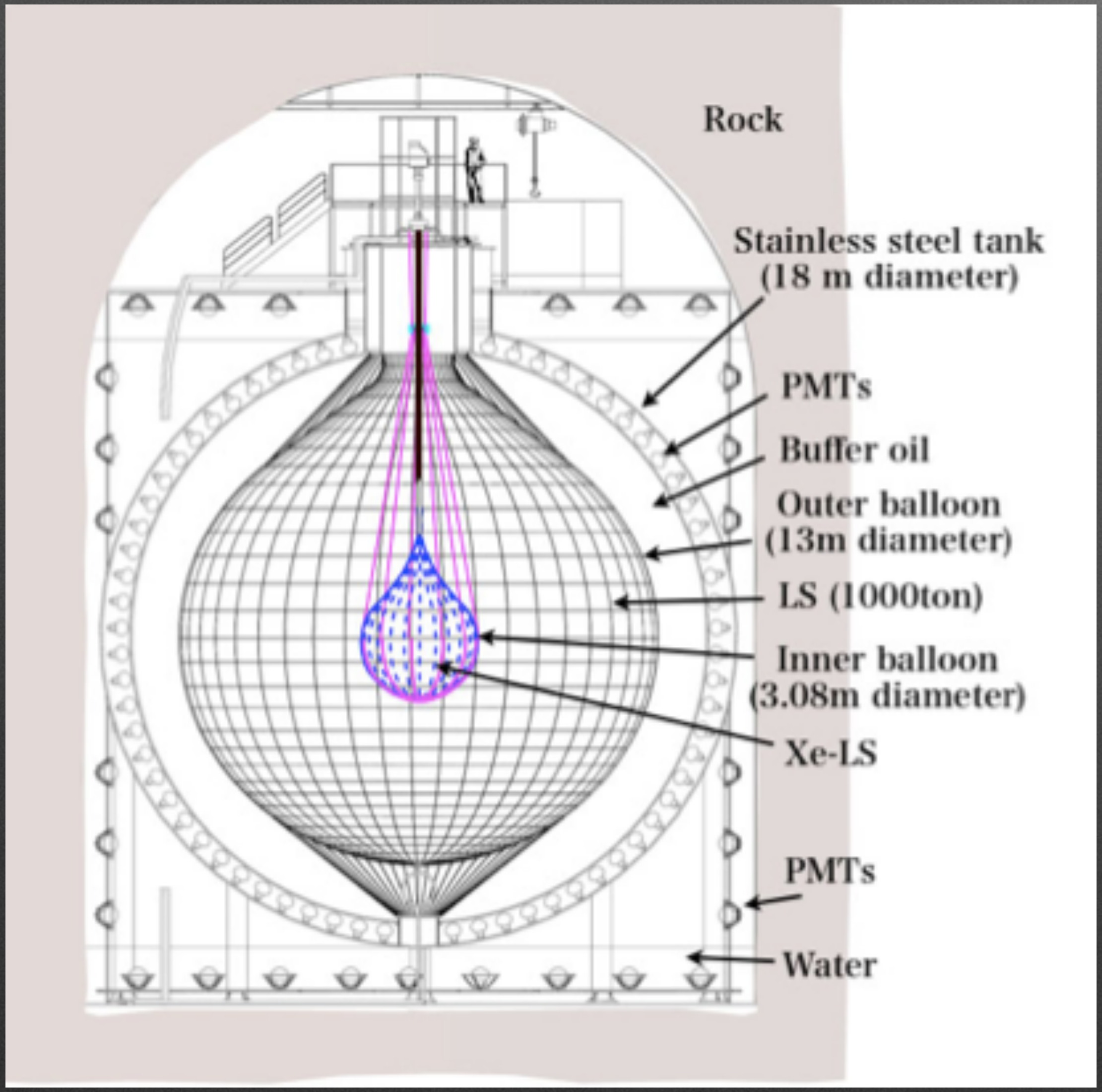
just to compare with Gerda

- $n_B \times \Delta E$
- TeO_2 bolometers have ~ 7 KeV
- the merit factor for CUORE today is :

$$1.4 \cdot 10^{-2} \frac{1}{(kg \cdot KeV \cdot y)} \times 7KeV \sim 1 \cdot 10^{-1}$$

- you are background free until 10 $Kg \cdot y$!!!!!!!!!
- $\sqrt{\ }$ is the fate !

Kamland-ZEN

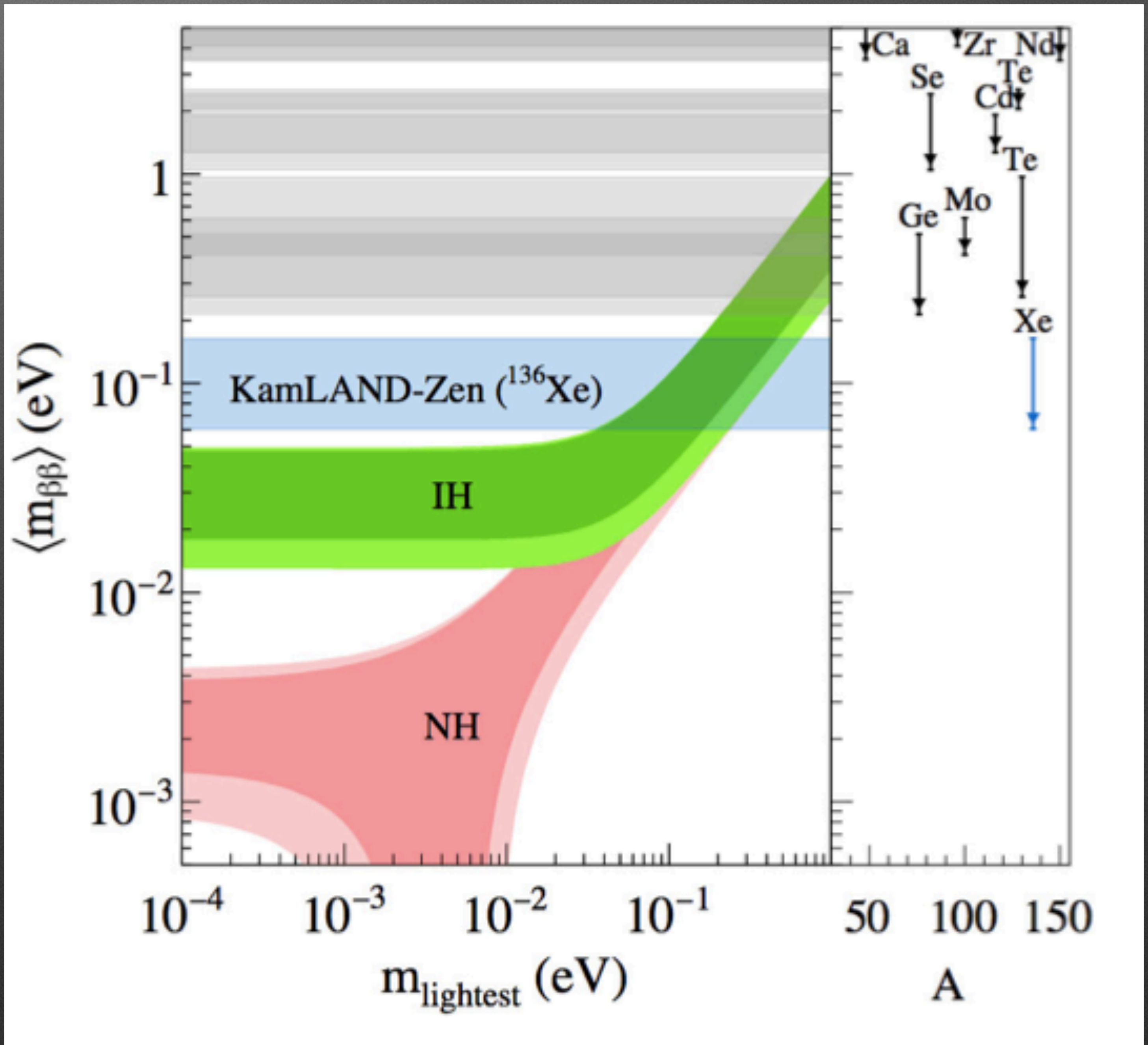


The inner balloon is filled with ^{136}Xe dissolved in liquid scintillator

Two phases so far

Result

$$T_{1/2}^{0\nu} > 1.07 \times 10^{26} \text{ yr at } 90\% \text{ C.L}$$



another comparison

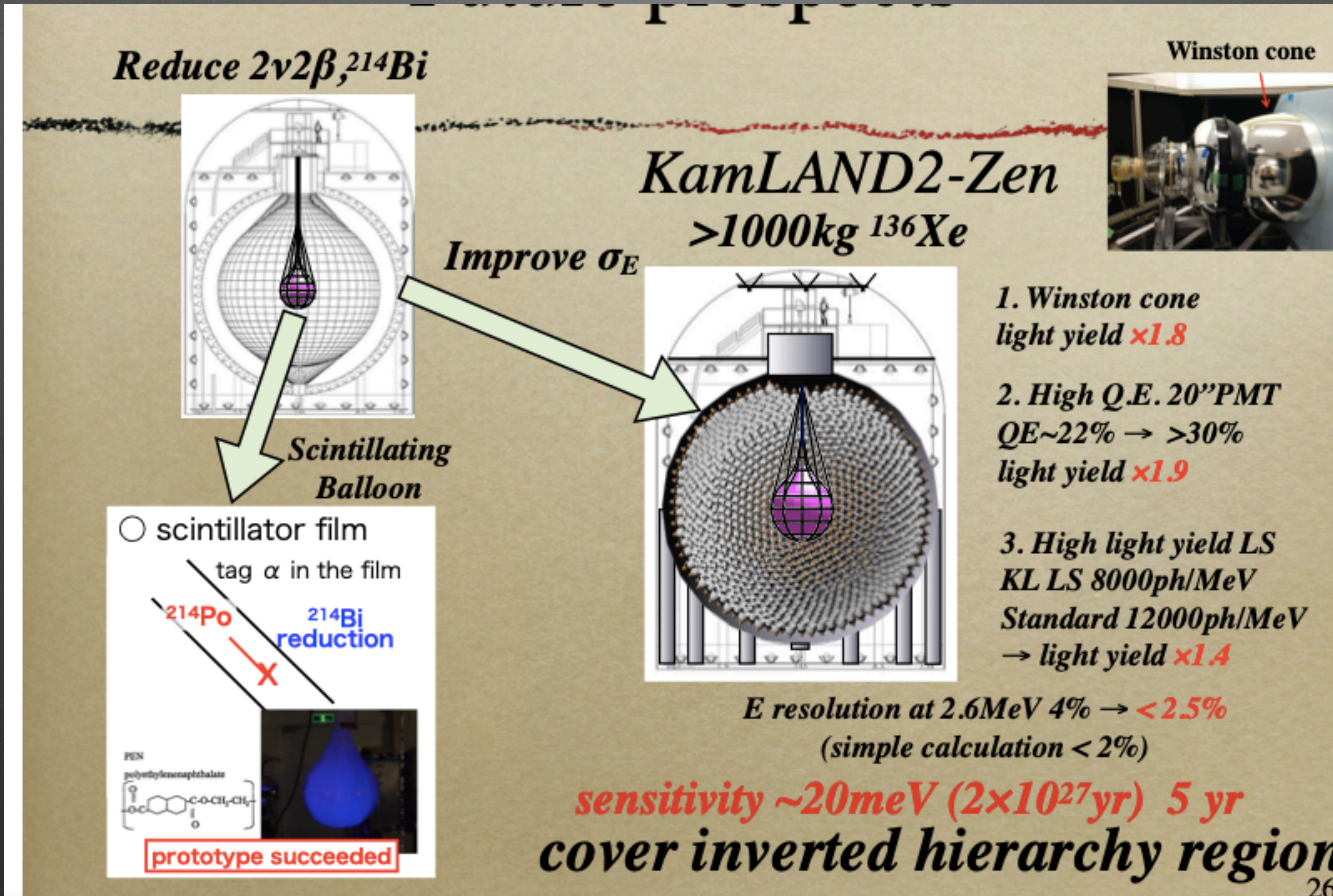
it is written in a way that is extremely difficult to know !

- $n_B \times \Delta E$
- Scintillator has a FWHM ~ 280 KeV
- n_B is derived by 11 event observed in 264 days, 400 KeV window and 3.8 ton of (scintillator +Xe) . Xe is 380 Kg.
- n_B could be : $[(11 \cdot 365)/264]/3800/400$ ~ 10^{-5}
- the merit factor for Kamland-ZEN today is :

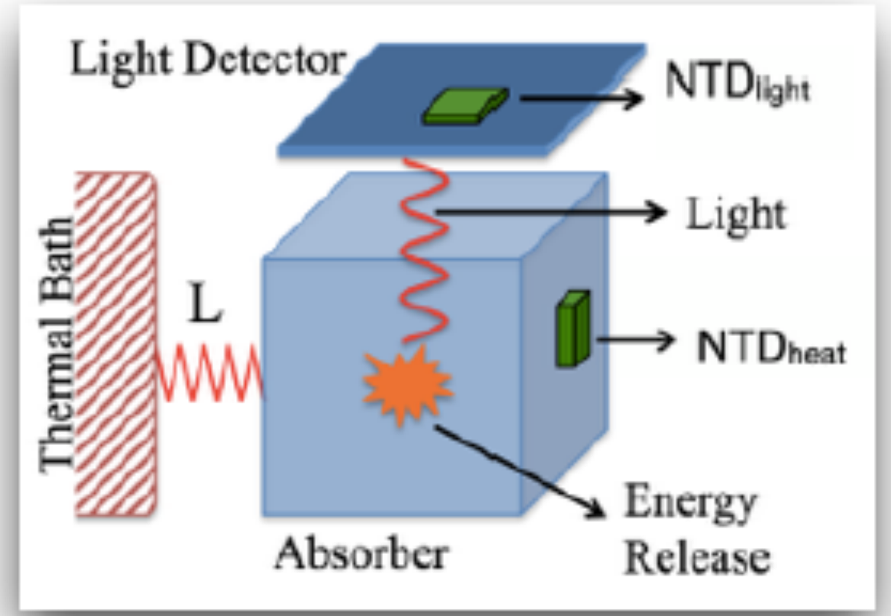
$$1 \cdot 10^{-5} \frac{1}{(kg \cdot KeV \cdot y)} \times 400 KeV \sim 4 \cdot 10^{-3}$$

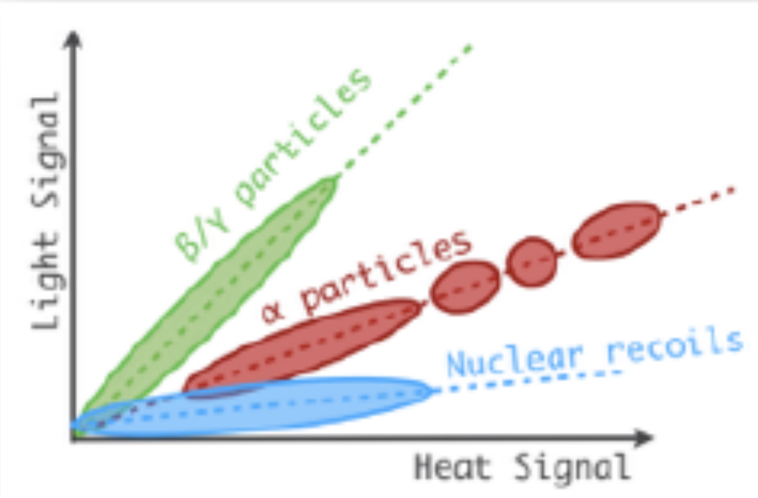
- you are background free until 250 $Kg \cdot y$
- with 380 Kg already in $\sqrt{\ }$ regime

a possible future

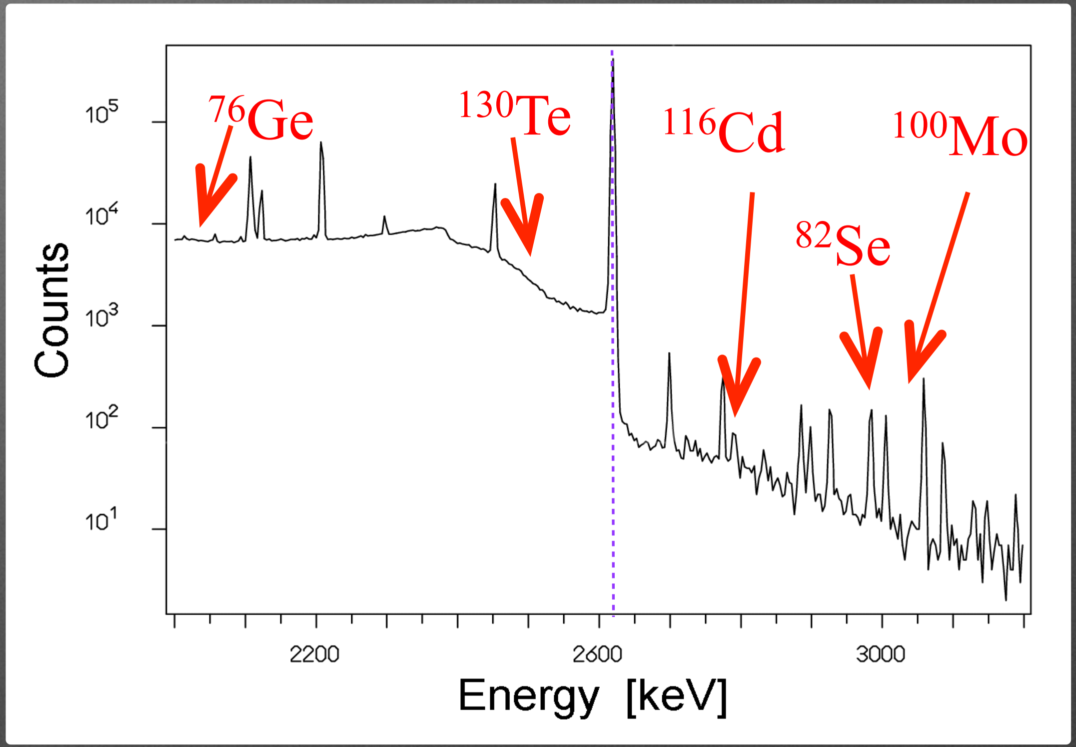


The evolution of the bolometer technique





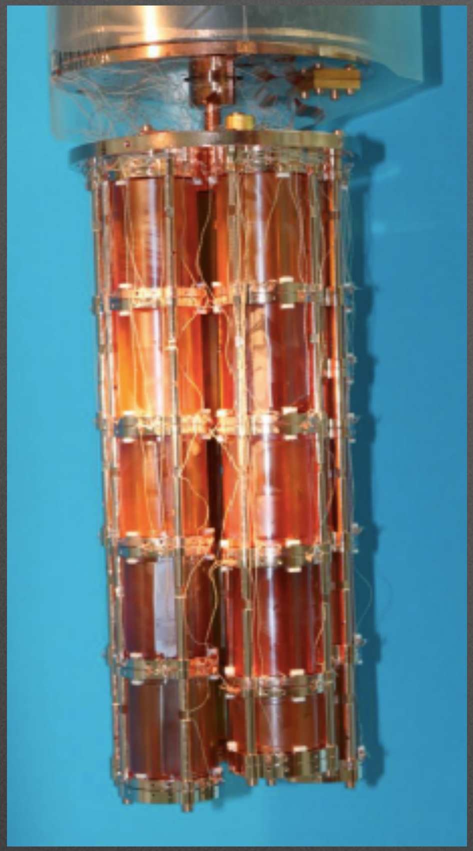
The simultaneous read-out of **HEAT** and **LIGHT** allows particle identification

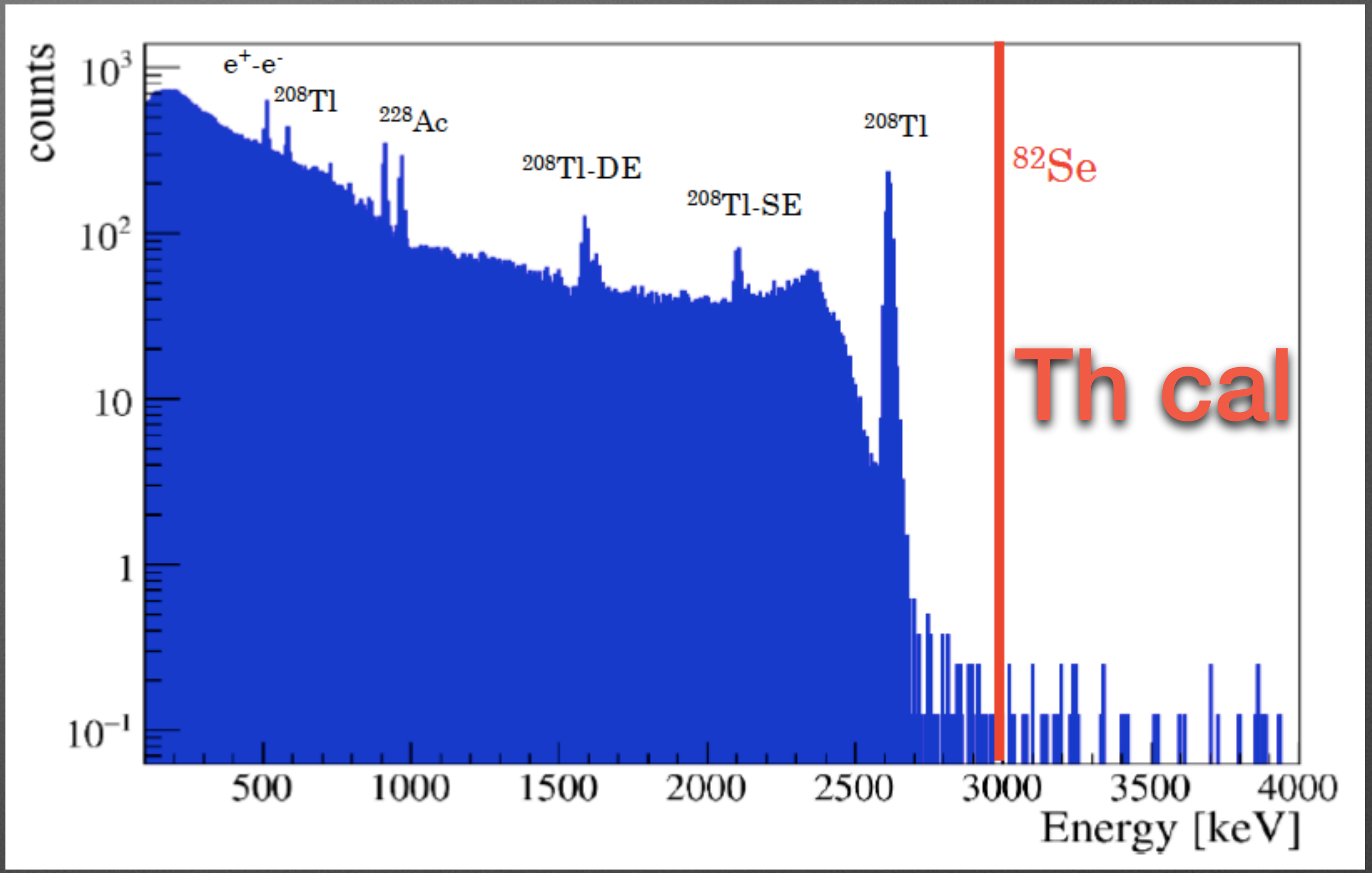


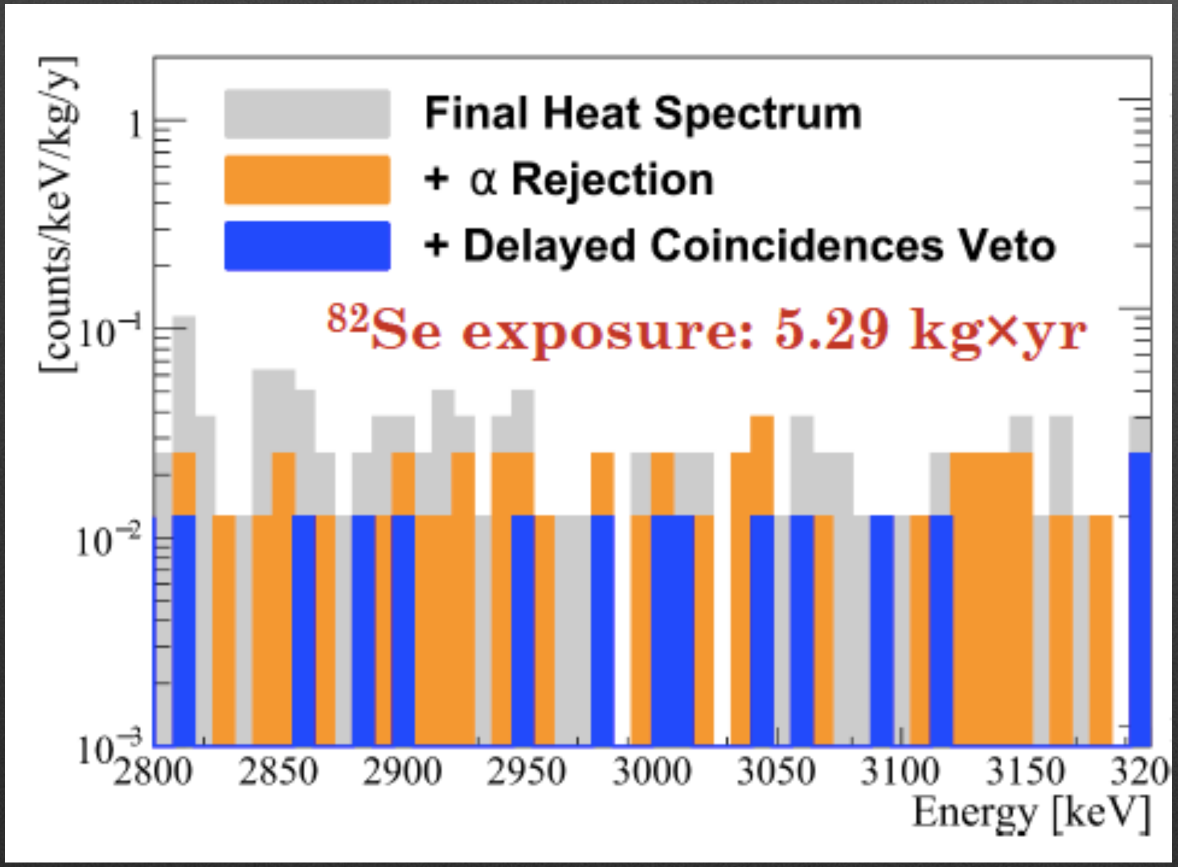
A **background-free experiment** is possible:
α-background: identification and rejection
β-background: ββ isotope with large Q-value

The application: CUPID-0

(former LUCIFER)





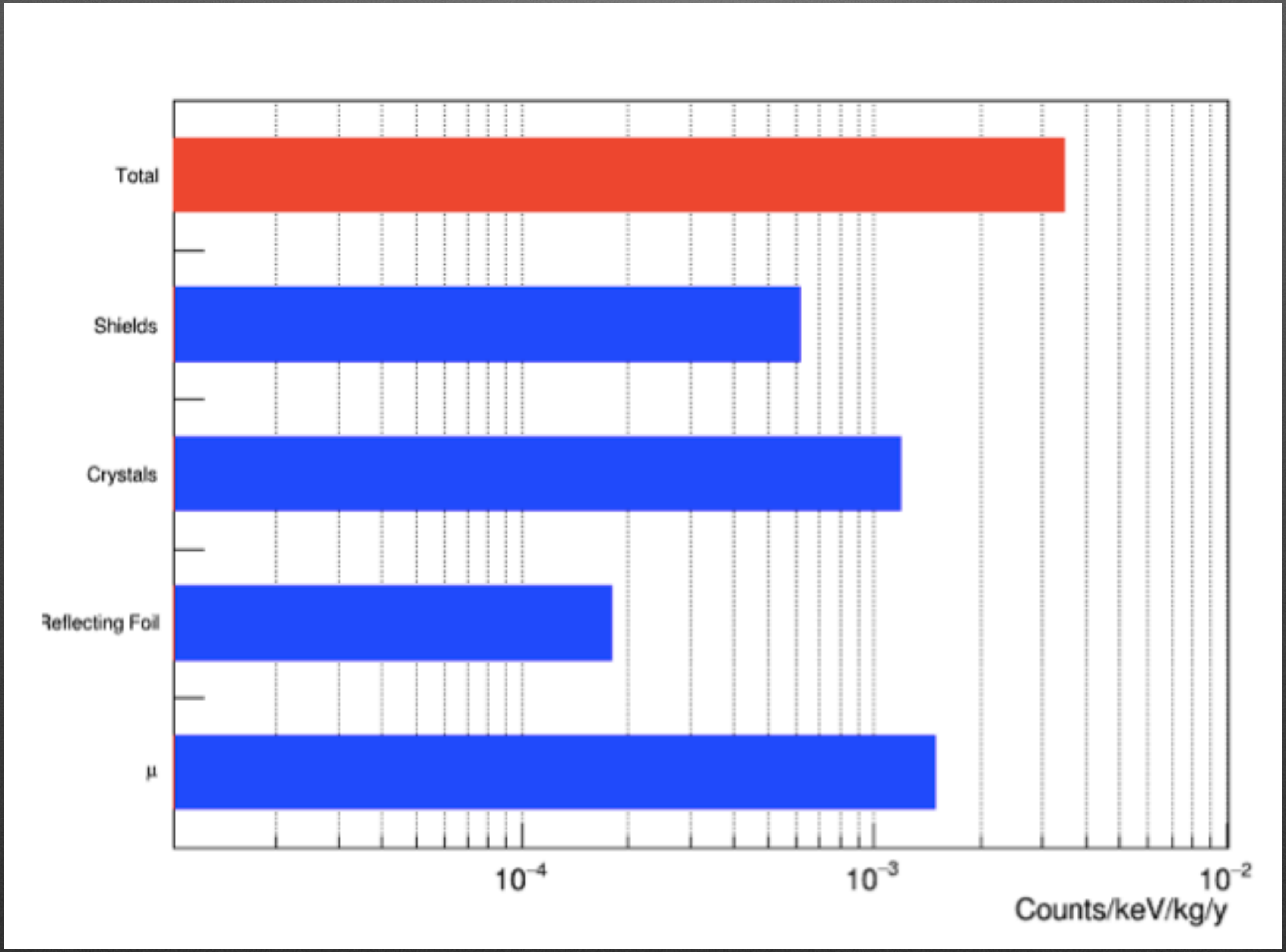


Background index in the range [2.8 – 3.2] MeV:

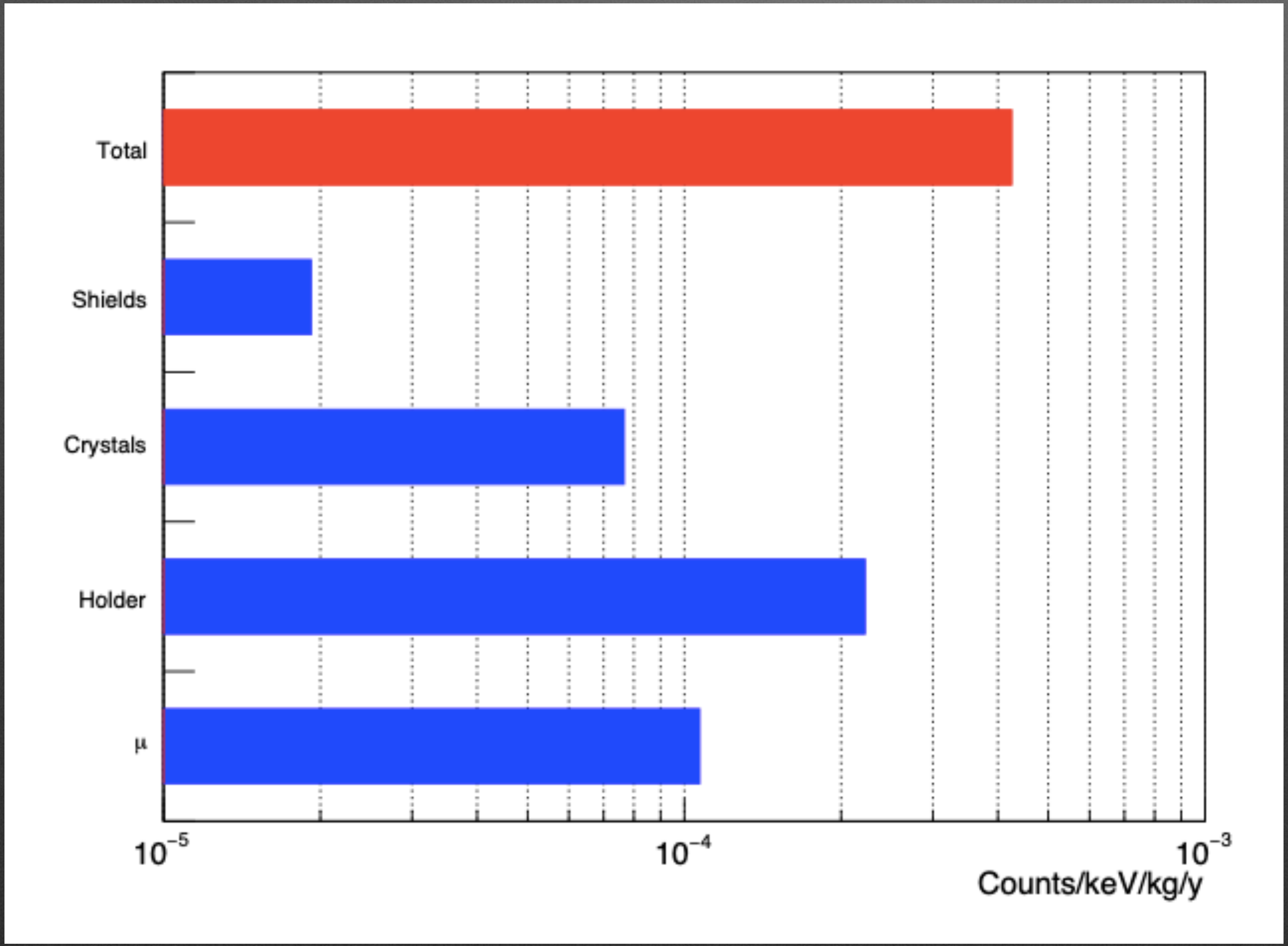
$$(3.5^{+1.0}_{-0.9}) \cdot 10^{-3}\ \mathrm{cnts/(keV \cdot kg \cdot yr)}$$

Lowest background achieved with bolometric experiments.

key issue: background simulation vs. measured



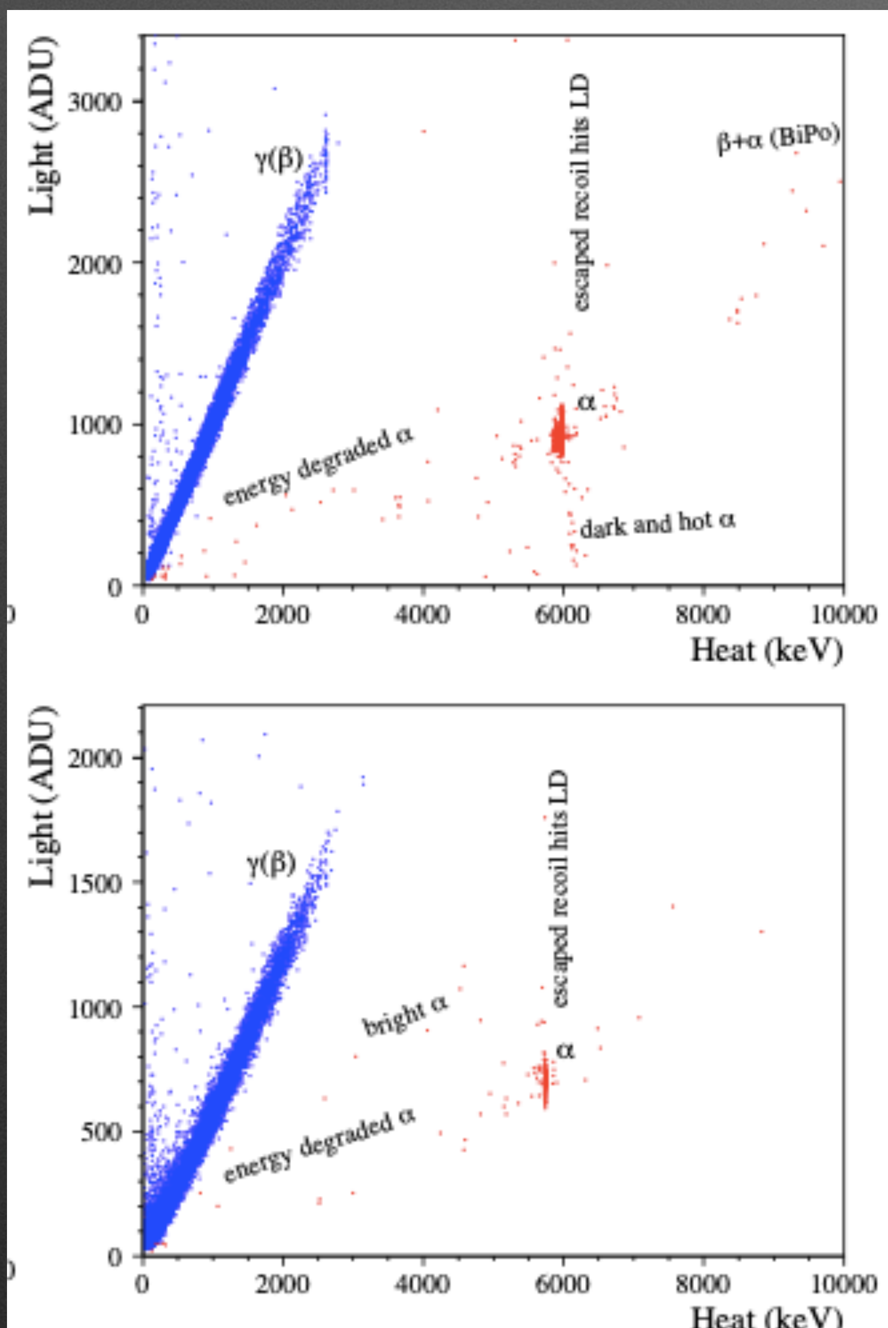
which allows to predict background in the CUORE cryostat

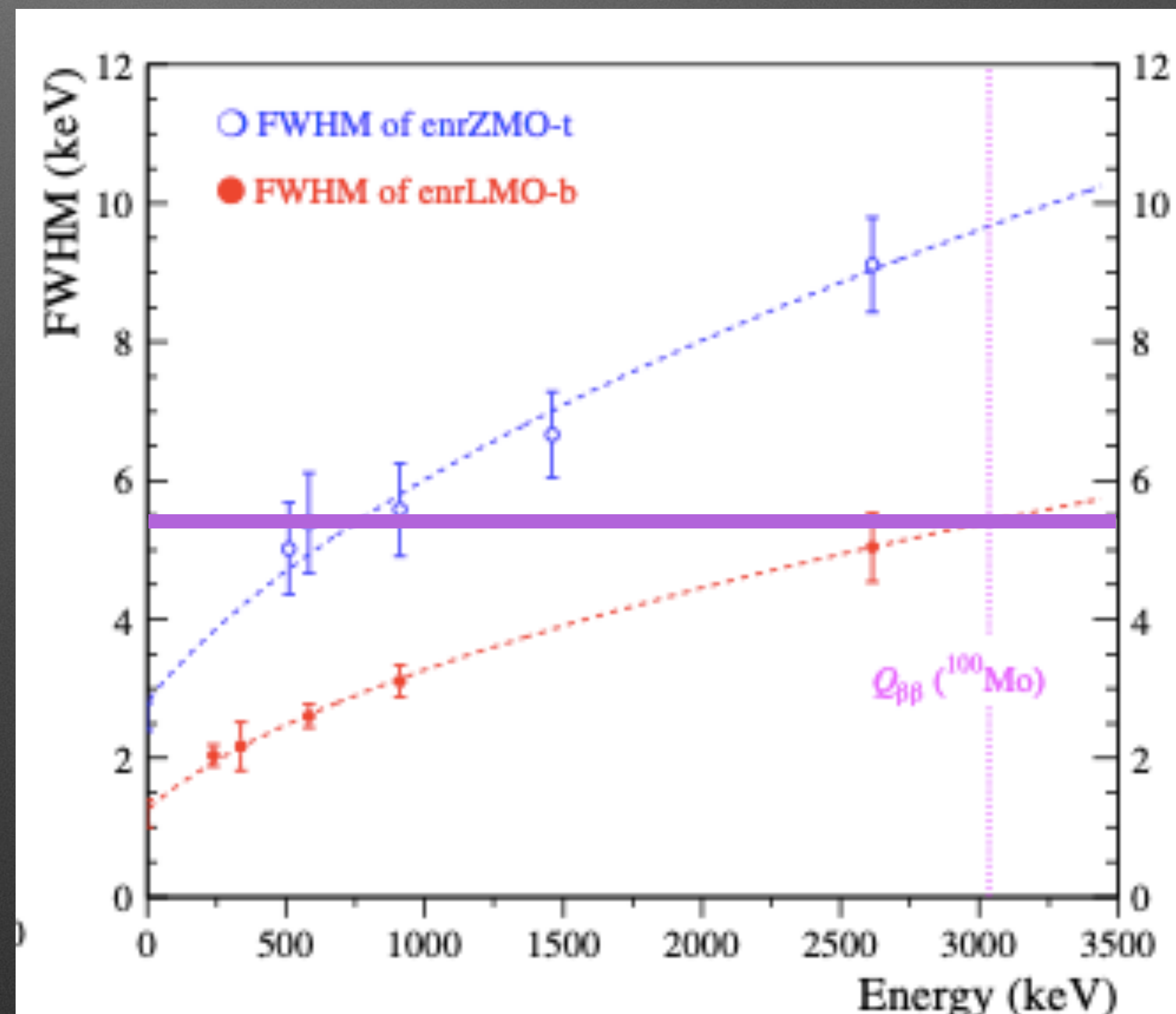


without any improvement
a factor 10
wrt.
CUPID-0
a few 10^{-4}

The final choice will be ^{100}Mo

- Mo based crystals much easier to produce
- Energy resolution 3-4 times better

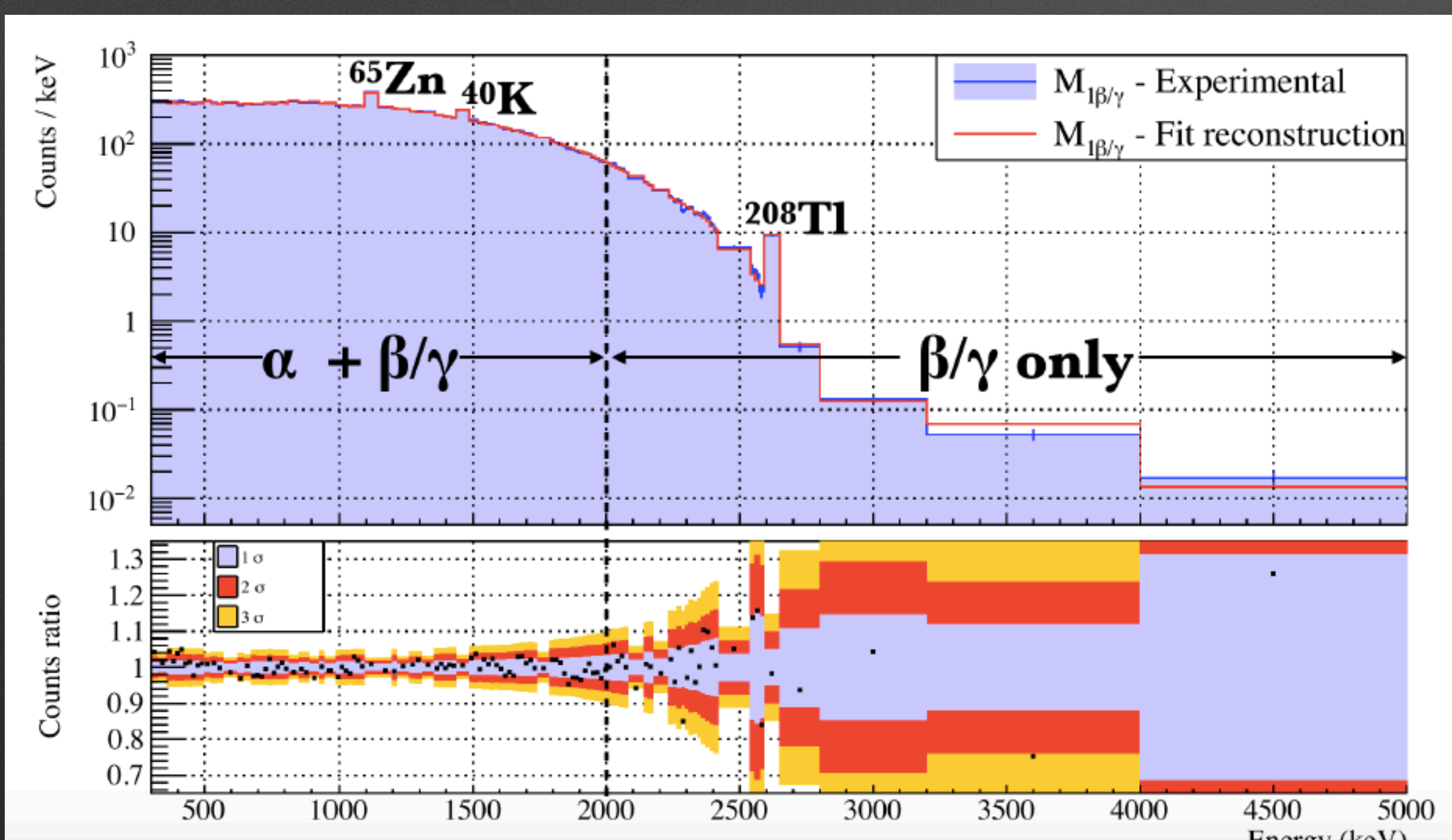




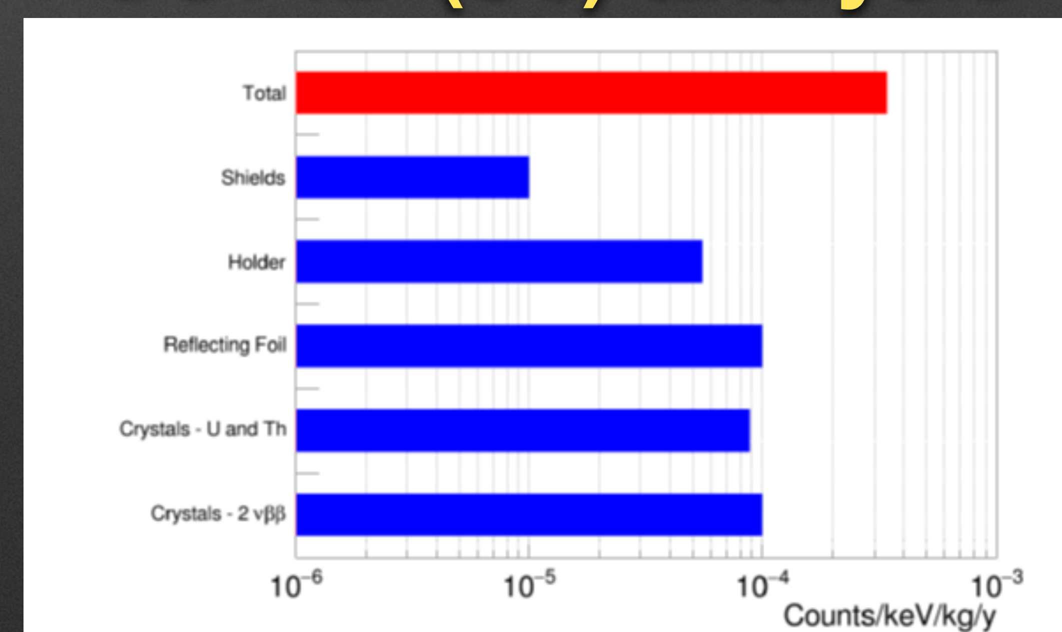
$$\Delta E \sim 5.5 keV$$

the reason for this choice

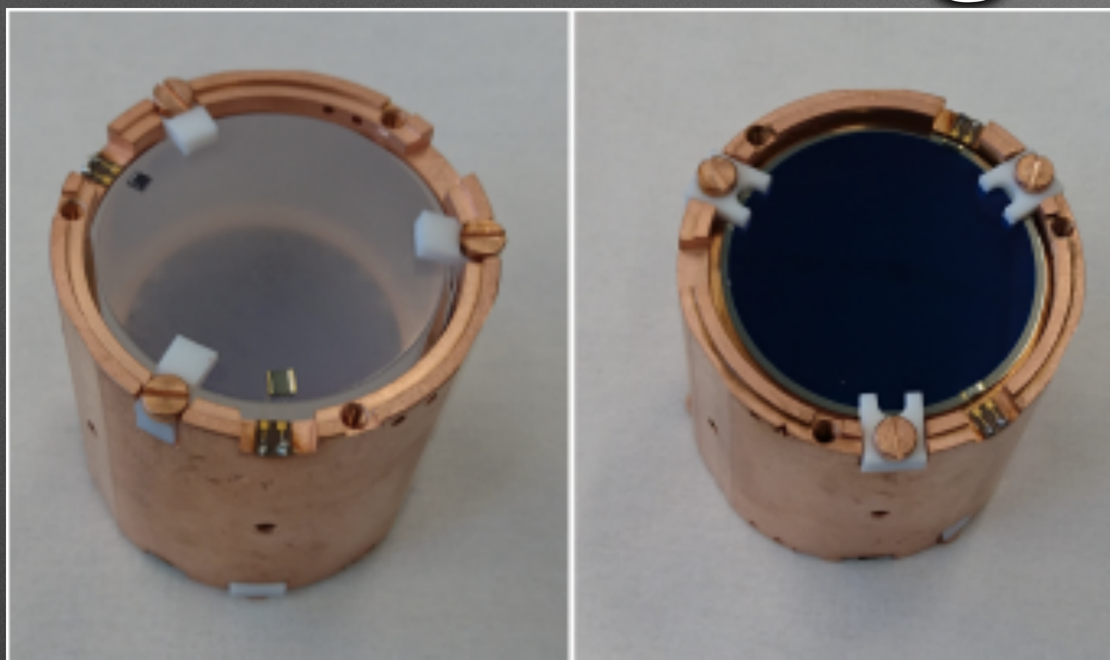
Experiment	Iso	M_{iso} [kg]	σ [keV]	ROI [σ]	ϵ_{sig} [%]	$\mathcal{E}$ $\left[\frac{kg_{iso} yr}{yr}\right]$	$\mathcal{B}_{ROI}$ $\left[\frac{cts}{kg_{iso} yr}\right]$	3σ disc. sens. $T_{1/2}$ [yr]	$m_{\beta\beta}$ [meV]
CUPID	^{100}Mo	247	2.1	−2.0, +2.0	68	168	$2 \cdot 10^{-3}$	$1.1 \cdot 10^{27}$	12–20



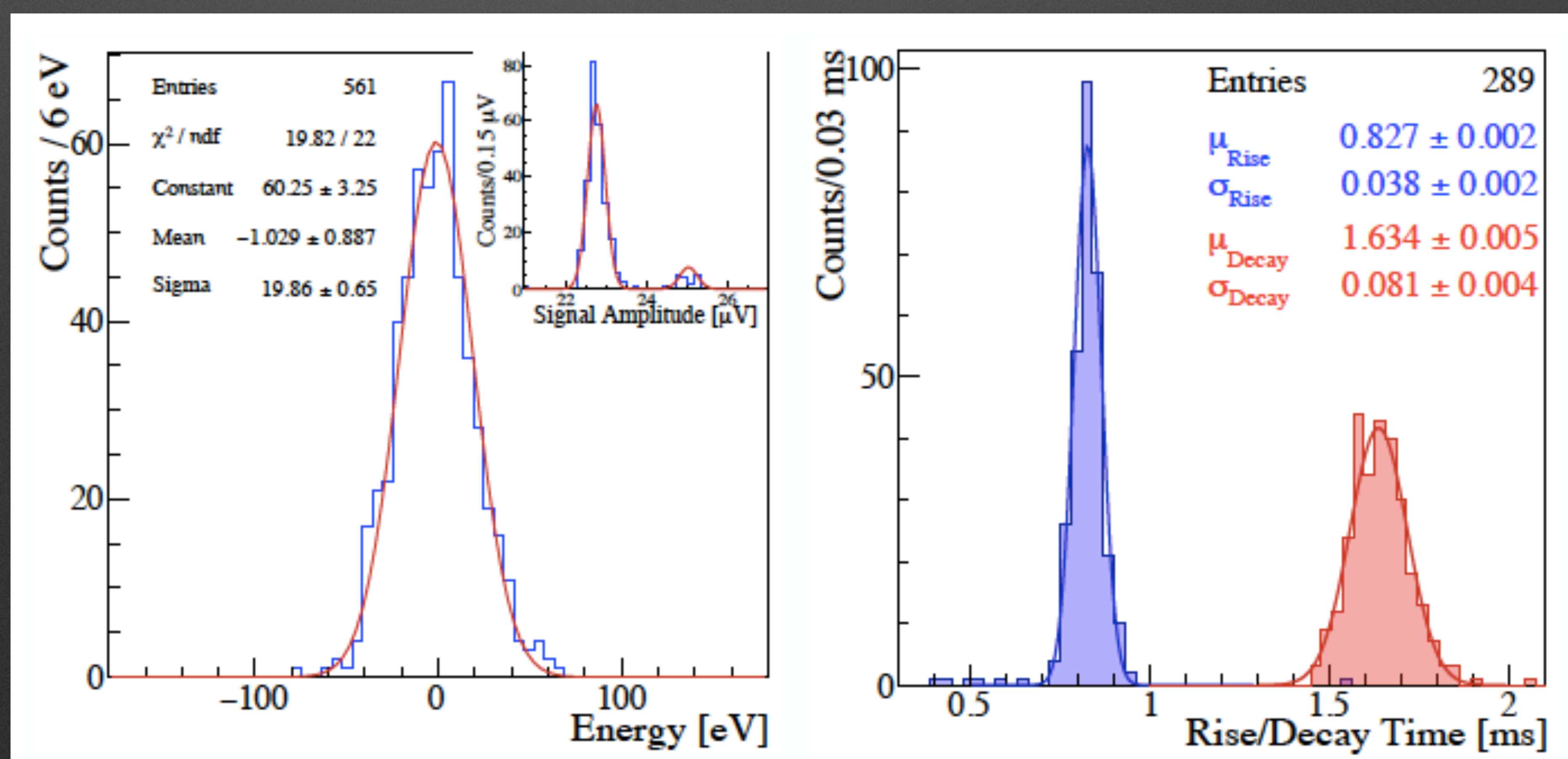
MC simulation from CUPID (Se) analysis



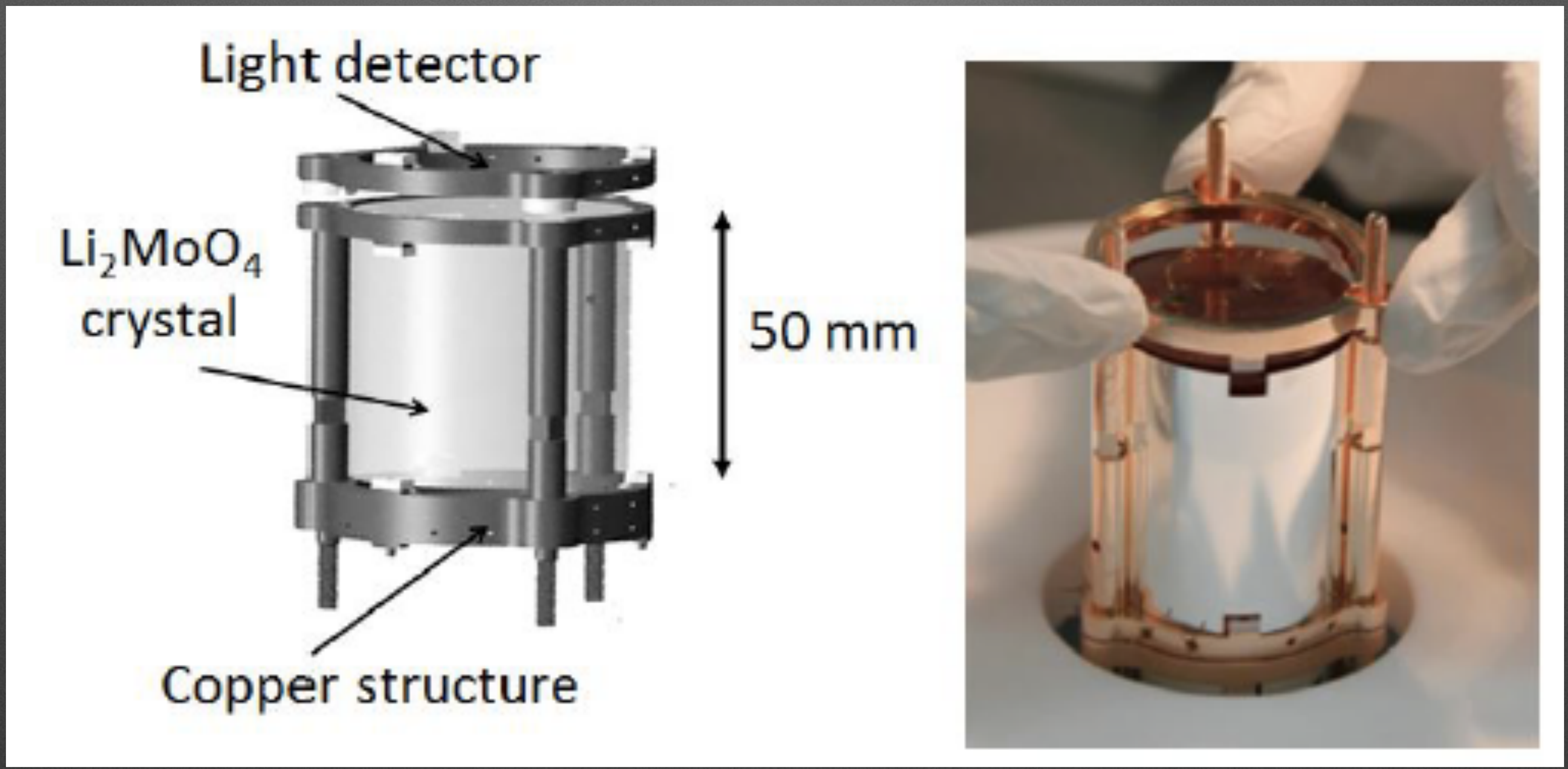
a new element is needed
a light detector



A Ge bolometer matching the size of the crystal



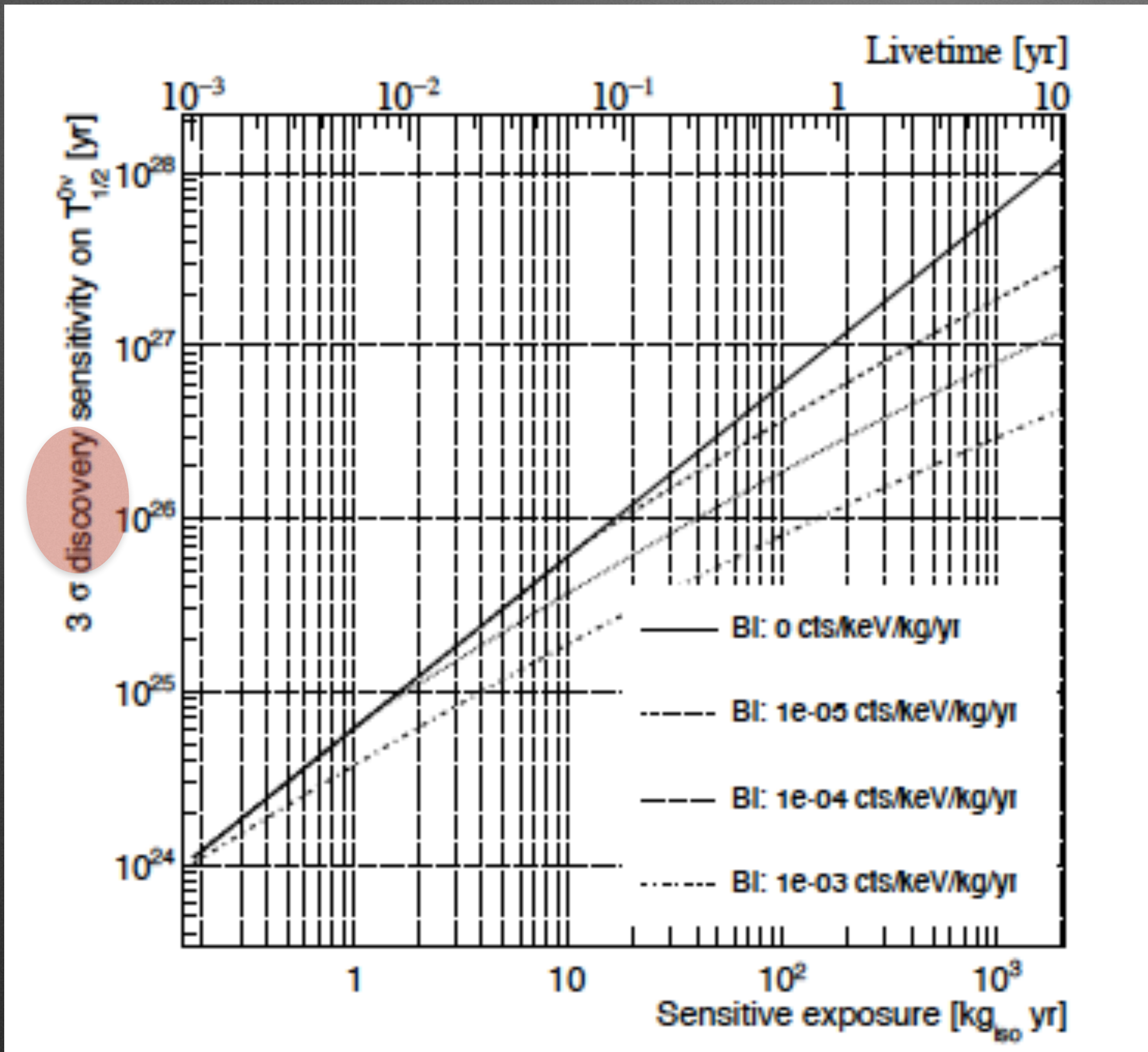
The final choice



An array of 1534 crystals of $Li_2{}^{100}MoO_4$ corresponding to 253 Kg of isotope

Using the CUORE cryostat and infrastructure

Sensitivity of CUPID



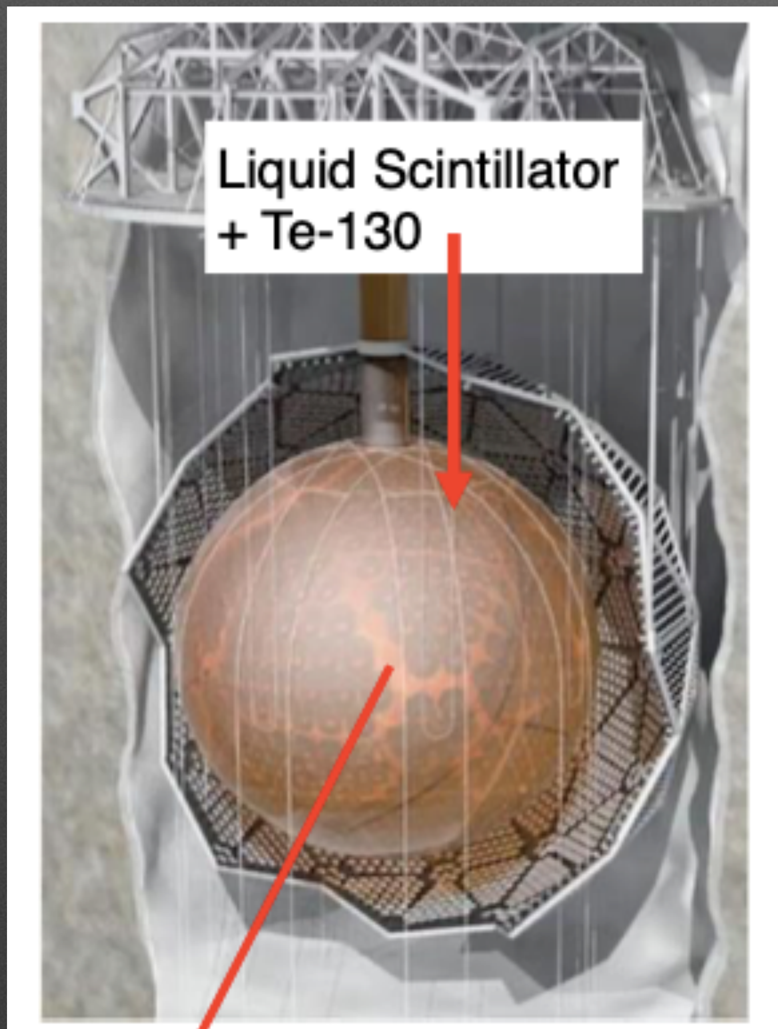
the merit factor could be

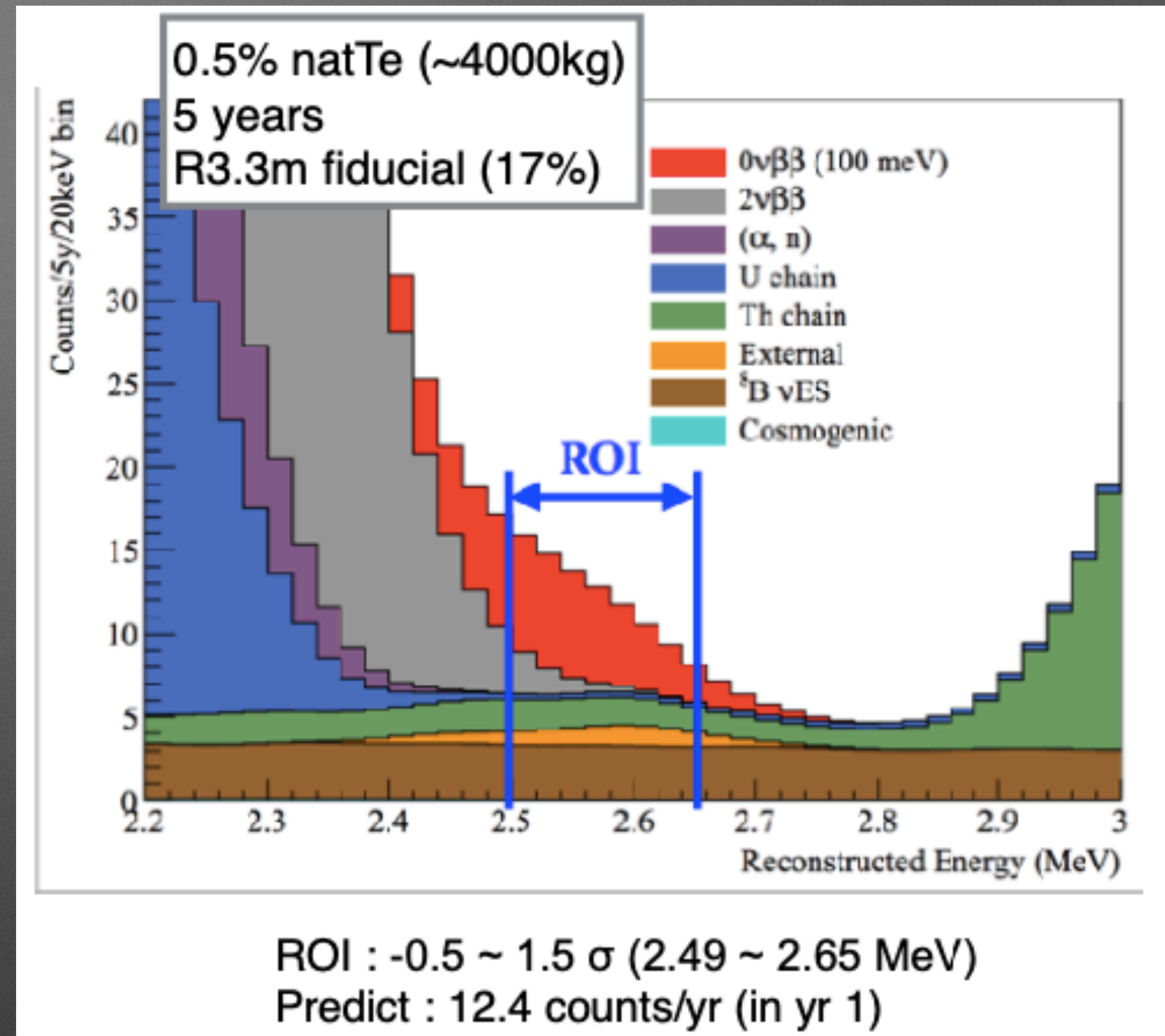
$$1 \cdot 10^{-4} \times 5 \sim 5 \cdot 10^{-4}$$

allowing to run 2000 Kg y background free

10^{27} y reachable and perhaps……

another concept: SNO+





Unlike in the Xe case, here chemistry is needed! Tellurium will be dissolved in LS in the form of a Te-butanediol complex

It might be the idea for a future giant project

an instructive table

Isotope	Q (MeV)	percent natural abund.	element cost [5] ($/kg)	$G^{0\nu}$ (10^{-14}/yr) [6]	$M^{0\nu}$ (avg) [7]	$T^{0\nu}_{1/2}$ for 2.5meV (10^{29}yrs)	tons of isotope for 1 ev/yr	equivalent natural tons	annual world production [5] (tons/yr)	natural elem. cost ($M)	enriched	$0\nu/2\nu$ rate [2][8] (10^{-8})
^{48}Ca	4.27	0.19	0.16	6.06	1.6	2.70	31.1	16380	2.4×10^8	2.6		0.016
^{76}Ge	2.04	7.8	1650	0.57	4.8	3.18	58.2	746	118	1221		0.55
^{82}Se	3.00	9.2	174	2.48	4.0	1.05	20.8	225	2000	39		0.092
^{96}Zr	3.35	2.8	36	5.02	3.0	0.93	21.4	763	1.4×10^6	27		0.025
^{100}Mo	3.04	9.6	35	3.89	4.6	0.51	12.2	127	2.5×10^5	4.4		0.014
^{110}Pd	2.00	11.8	23000	1.18	6.0	0.98	26.0	221	207	5078		0.16
^{116}Cd	2.81	7.6	2.8	4.08	3.6	0.79	22.1	290	2.2×10^4	0.81		0.035
^{124}Sn	2.29	5.6	30	2.21	3.7	1.38	41.2	736	2.5×10^5	22		0.072
^{130}Te	2.53	34.5	360	3.47	4.0	0.75	23.6	68	$\sim$150	24		0.92
^{136}Xe	2.46	8.9	1000	3.56	2.9	1.40	45.7	513	50	513		1.51
^{150}Nd	3.37	5.6	42	15.4	2.7	0.37	13.4	240	$\sim 10^4$	11		0.024

if you want to get to normal hierarchy the problem is more the number of signal events than the background

Te might strikes back

Dissolve a huge quantity of natural Te (few hundred tons) at the highest concentration allowed by the transmission of the light in a scintillator

(Juno -20000 tons)
(SuperK -50000tons)

Two backgrounds are serious: $2\nu\beta\beta$ and ^{8}B from the Sun

The neutrinos from the Sun might be tagged if some directionality could be implemented (Cherenkov !)

in the world where dreams become reality

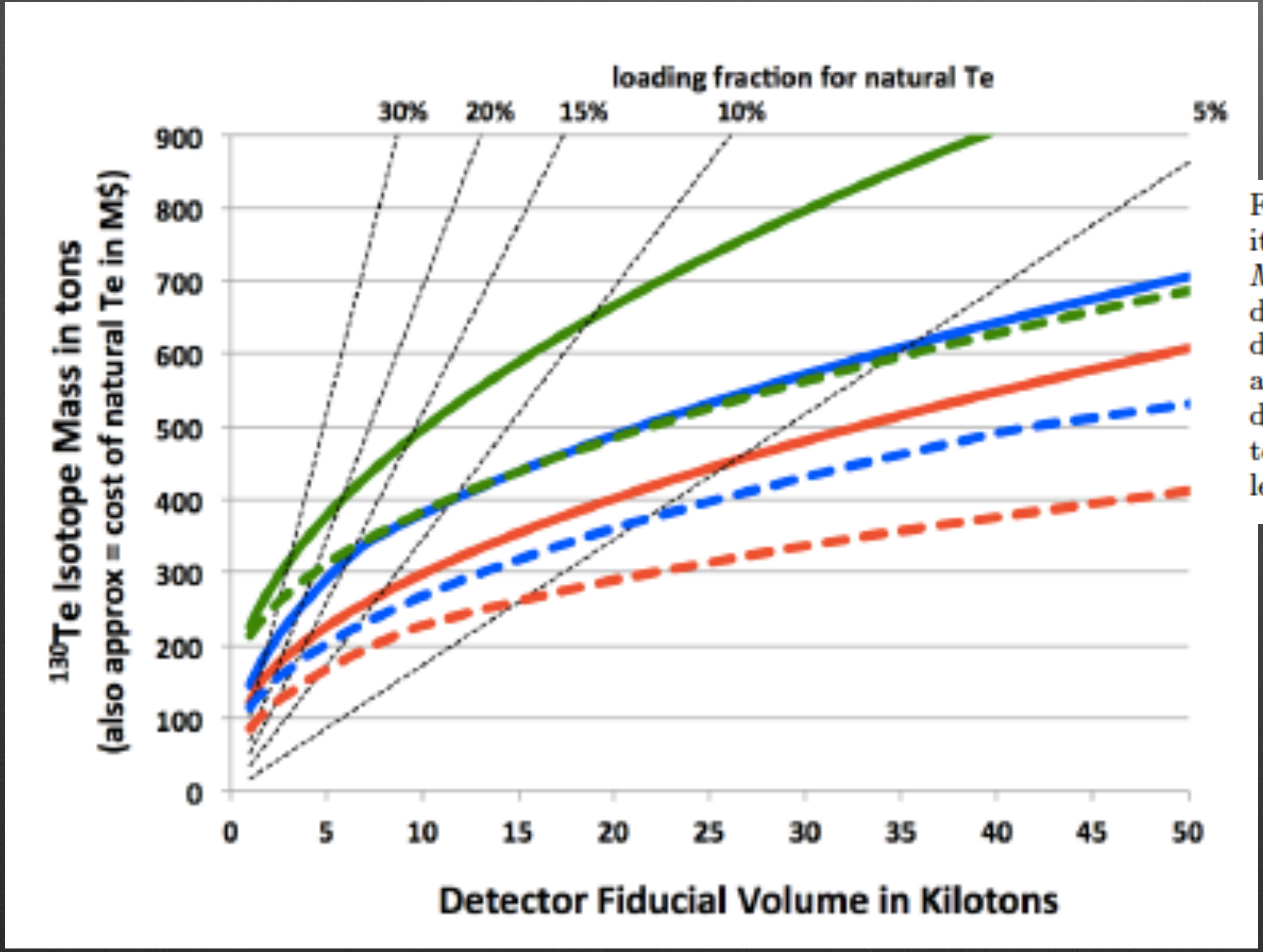


FIG. 1: Required mass of ^{130}Te to achieve a 90%CL sensitivity to a 2.5meV Majorana mass after 5 years of data, assuming $M^{0\nu}$=4. Solid curves are for full ^{8}B background, whereas long dashes correspond to a 90% "forward-backward" directional discrimination of these. Upper curves (green) correspond to a detected scintillation light level of L=1000 pe/MeV; middle curves (blue) to L=1500 pe/MeV; and lower curves (red) to L=2000 pe/MeV. Dotted curves show scintillator loading levels for natural Te.