10^{27}

10^{28} years

10^{29}

The future of neutrino-less double beta decay

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The origin

TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

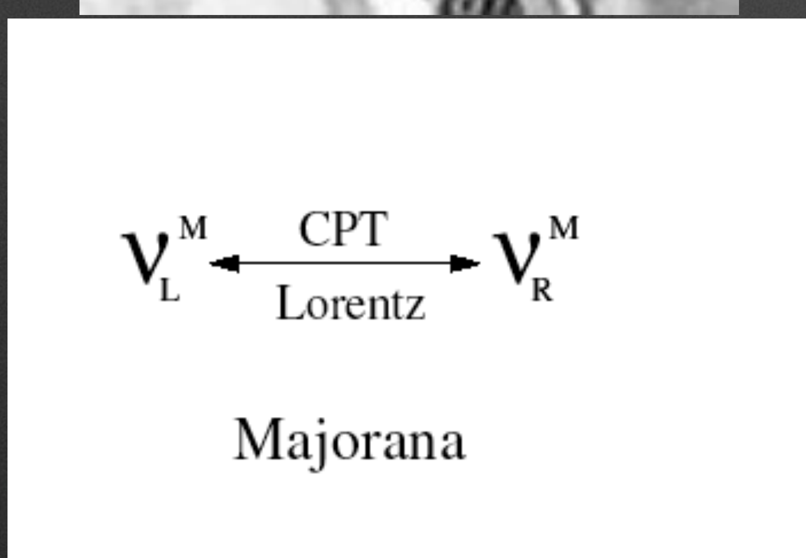
Nota di ETTORE MAJORANA

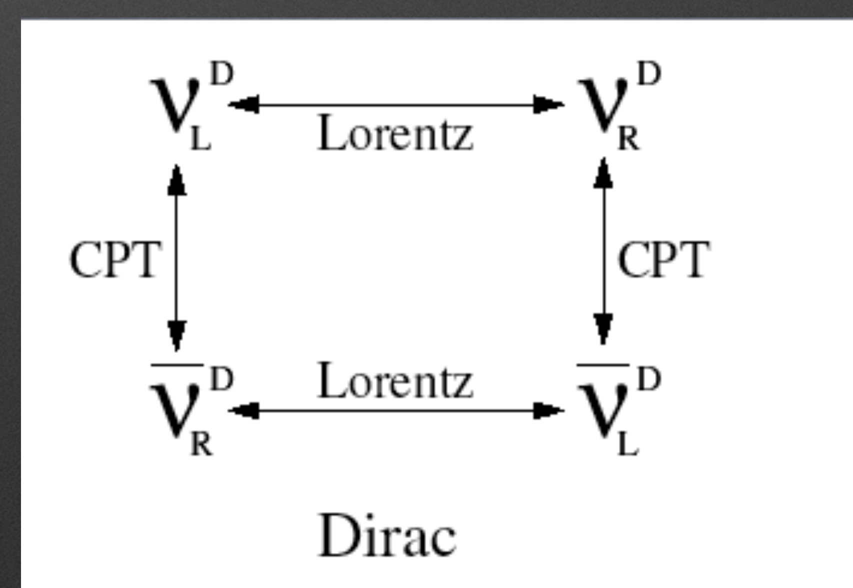
In the case of electrons and positrons, we may anticipate only a formal progress; but we consider it important, for possible extensions by analogy, that the very notion of negative energy states can be avoided. We shall see, in fact, that it is perfectly, and most naturally, possible to formulate a theory 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

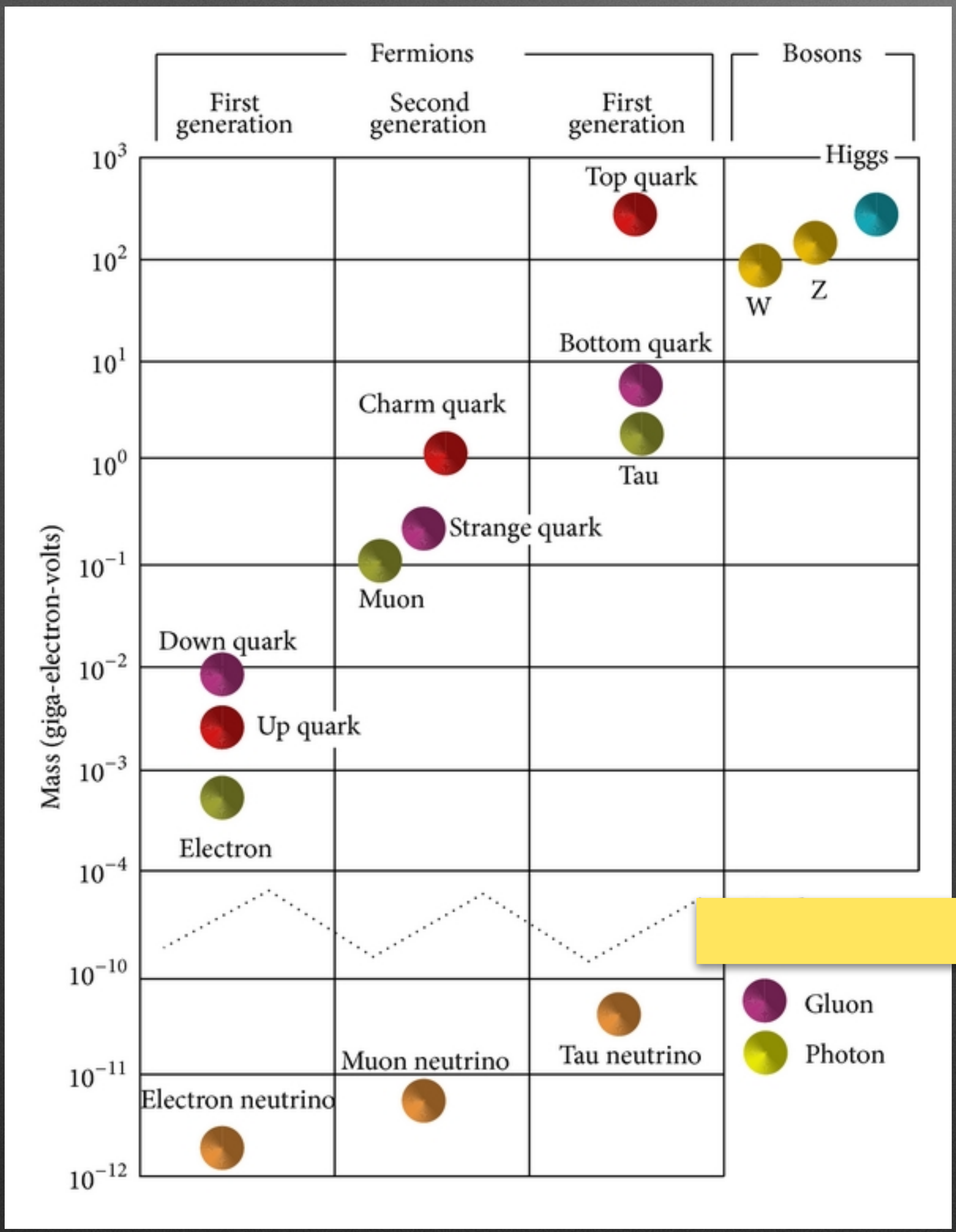
"The advantage. . . is that there is no reason now to infer the existence of antineutrons or antineutrinos. The latter particles are introduced in the theory of positive β-ray emission; the theory, however, can be obviously modified so that the β-emission, both positive and negative, is always accompanied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

Quest for Majorana particles





lepton mass spectrum
neutrinos are far from every other



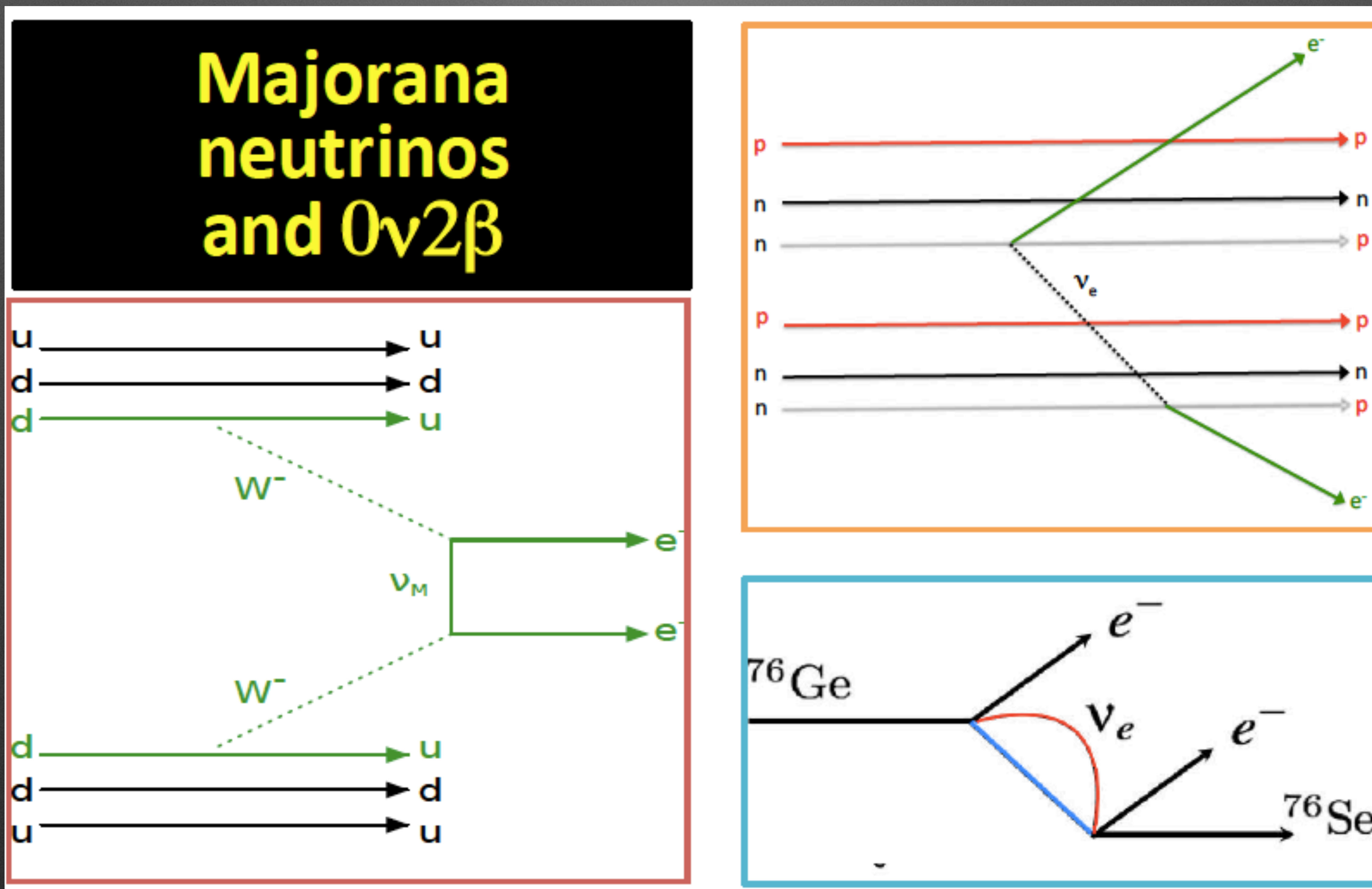
in reality we do not know the mass ordering of each neutrino. What we know is the squared mass difference

a really impressive gap

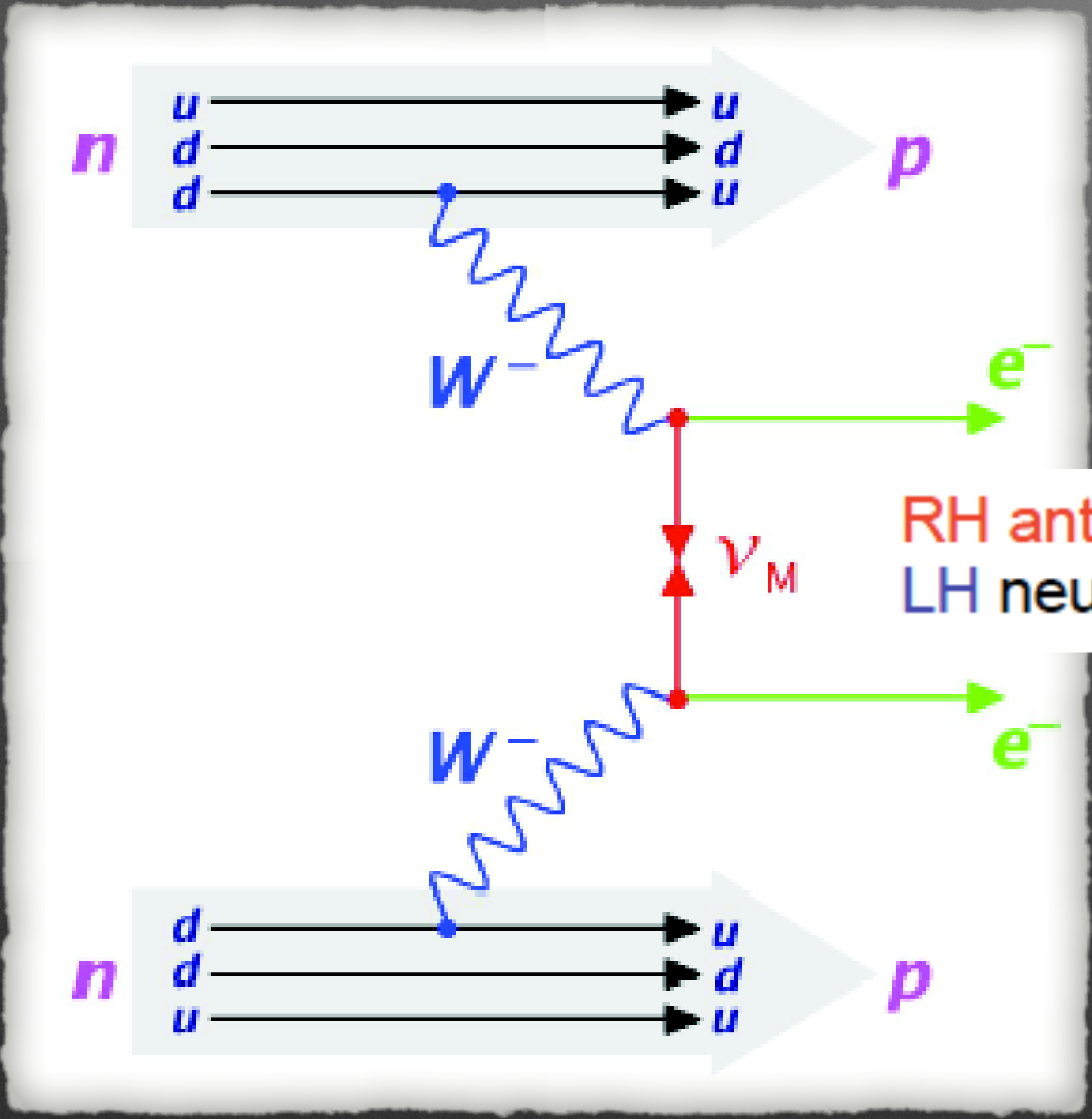
General consideration

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

The process as seen by a particle, nuclear, atomic physicist !



as simple as such !



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

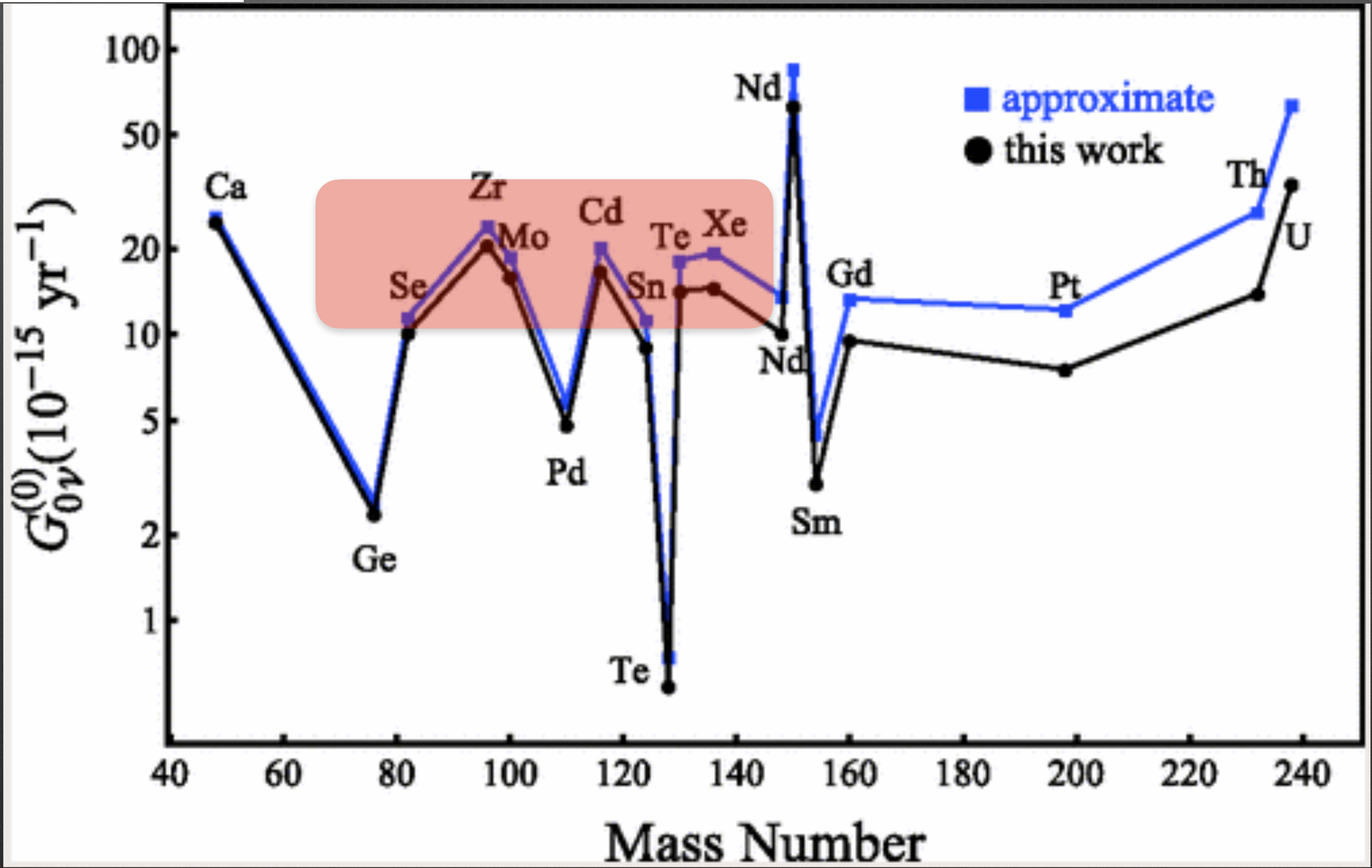
Half life

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

G (Q,Z)

for the neutrino less case

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



Nuclear Matrix Elements (NME)

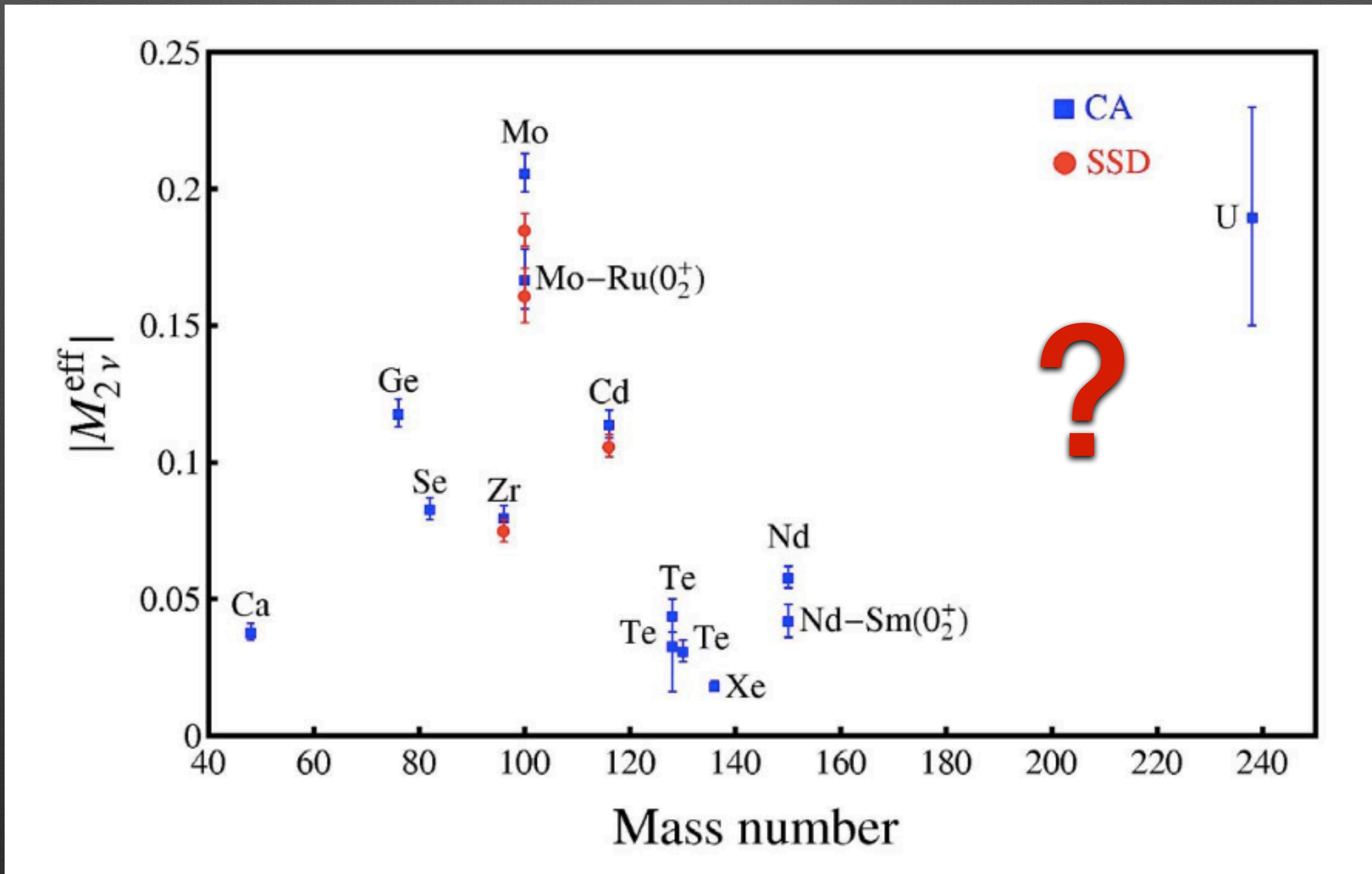
Nuclear Matrix Elements

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

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

$g_{nucleon} = 1.269$

compare to measured half-lives



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

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

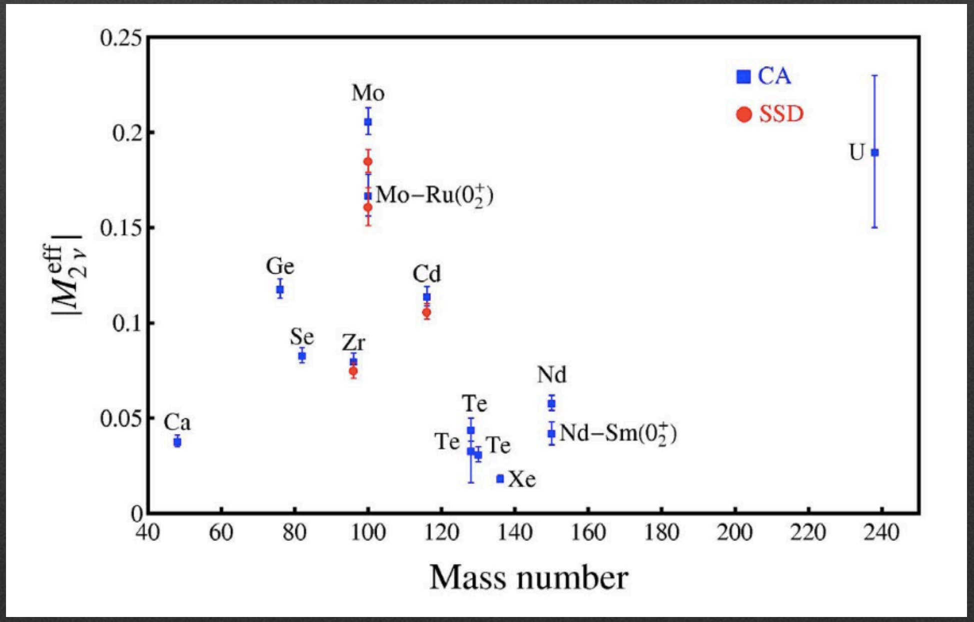
would be great

we could we live with

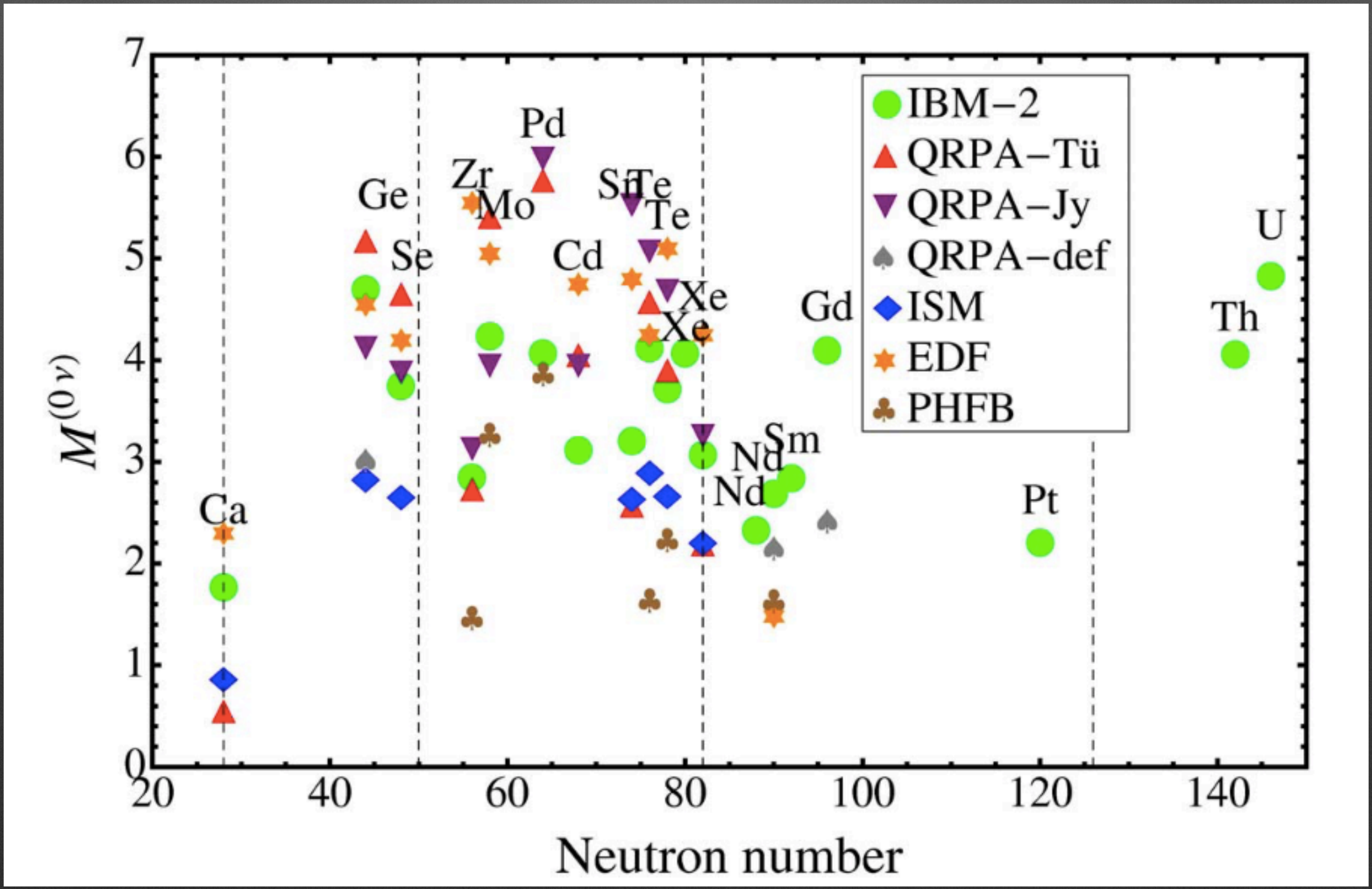
very bad

So this is the meaning of the plot you have seen

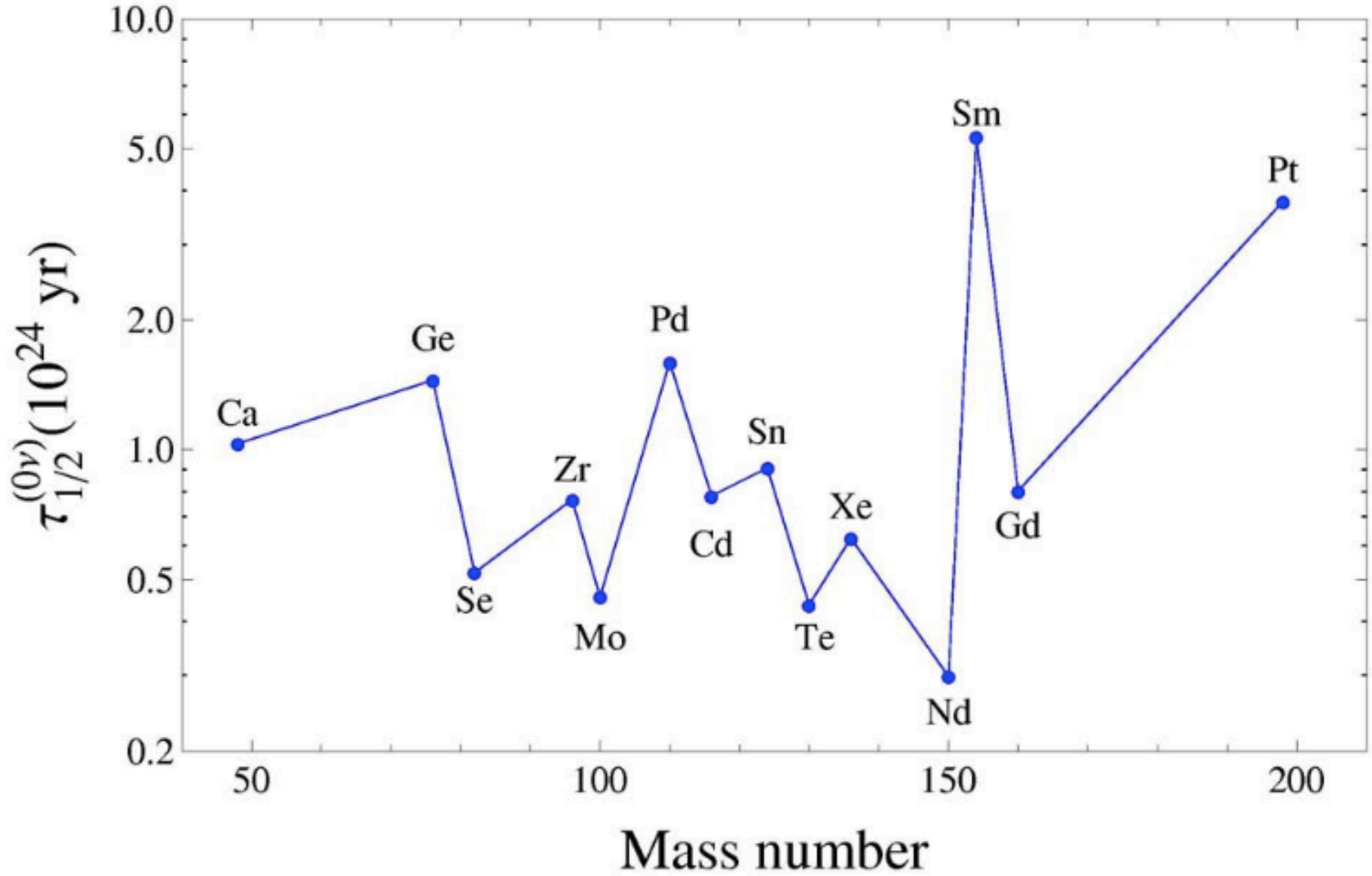
The problem for us is what the value of g_A in 0νββ will be.



here the calculations of $M^{0\nu}$



bringing to some prediction for half lives



m_ν= 1 eV
g_A=1.269

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

The effective neutrino mass that enters the 0νββ

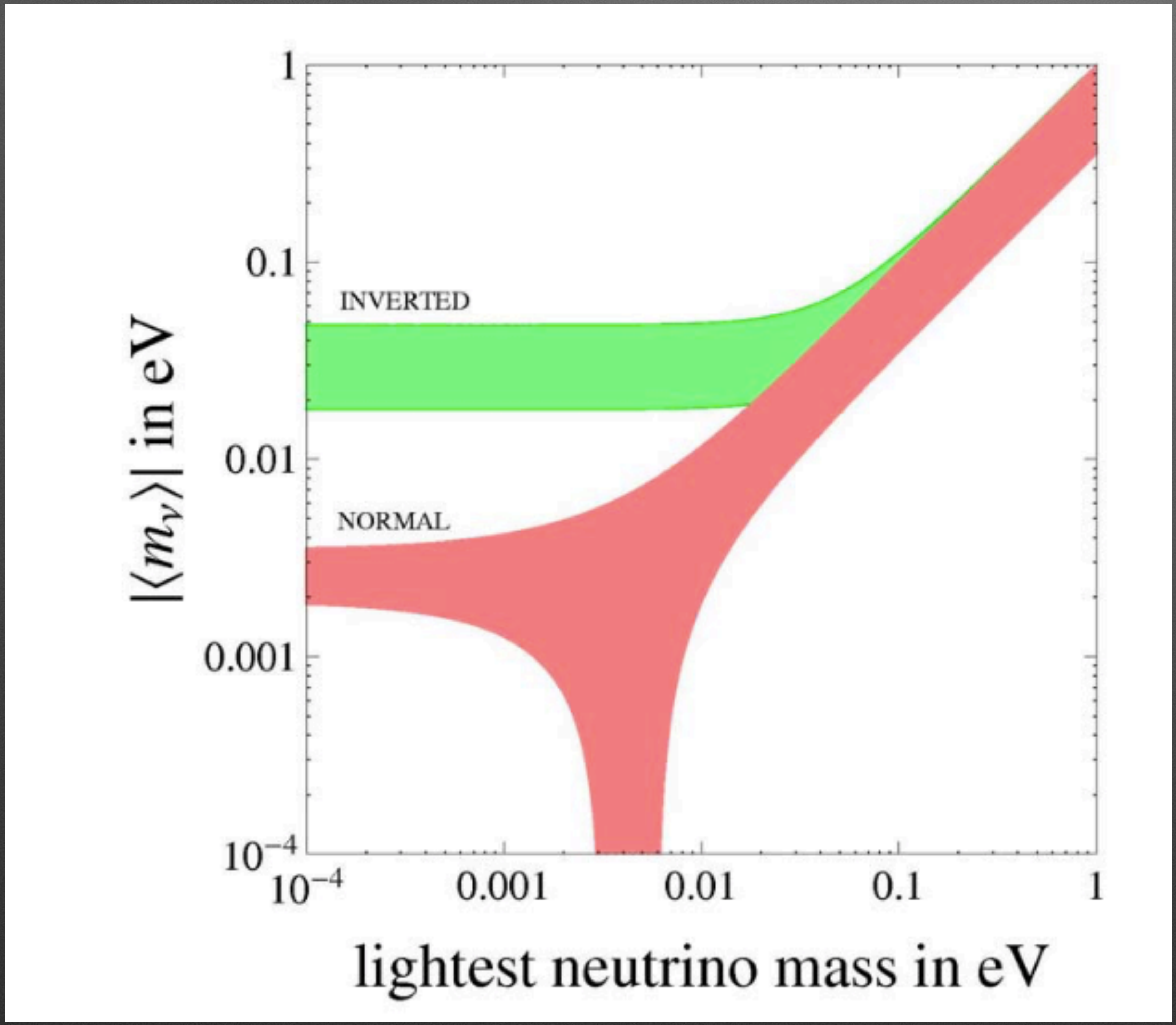
$$m_{\beta\beta} \equiv \left| \sum_{i=1,2,3} U_{ei}^2 \, m_i \right|$$

called : effective Majorana mass

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

with the complication of the unknown phases

the famous exclusion plot

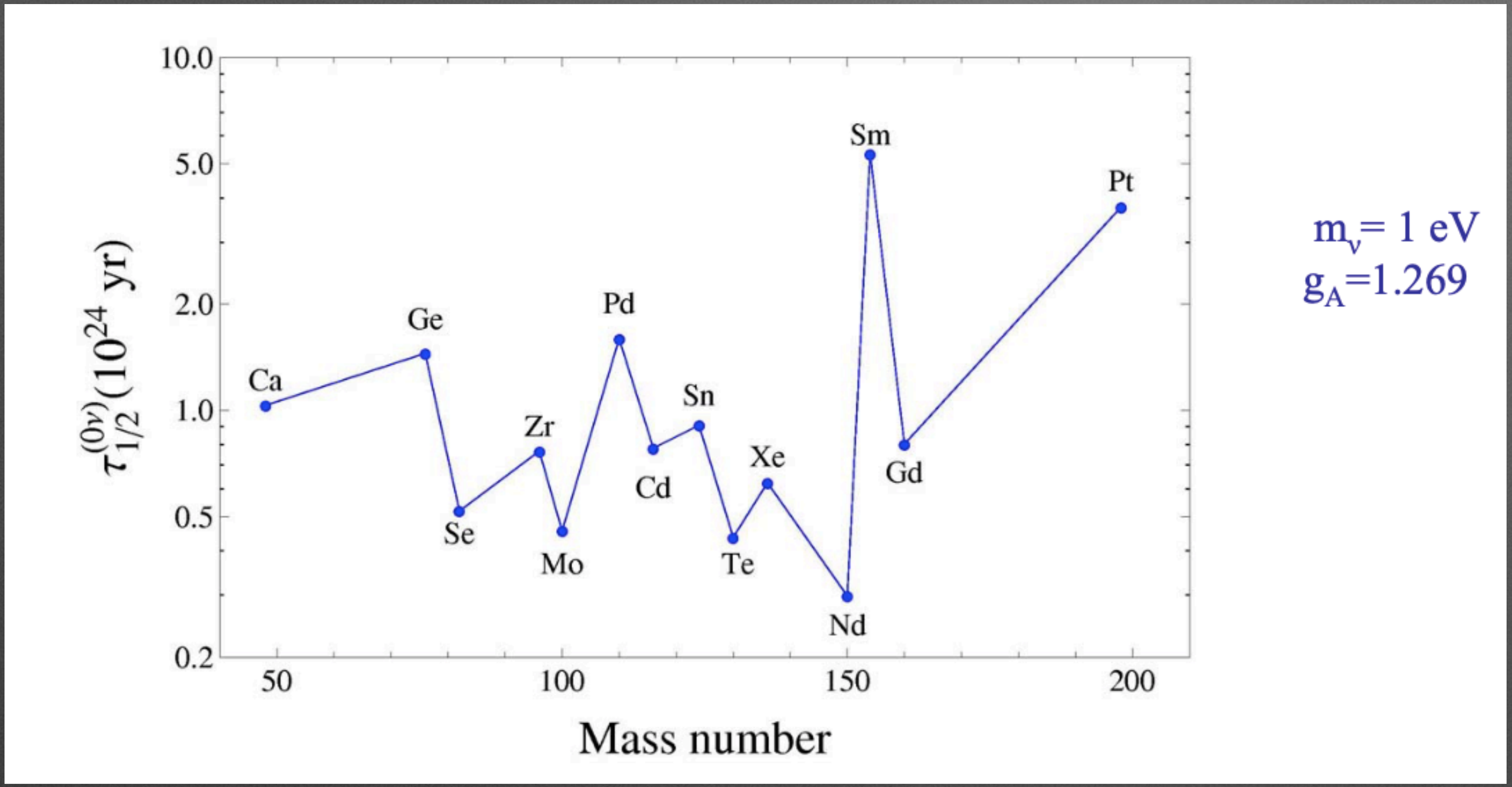


realistic predictions say:

20 meV for IH
2 meV for NH

now you can design your new generation experiment !

the Wall to break



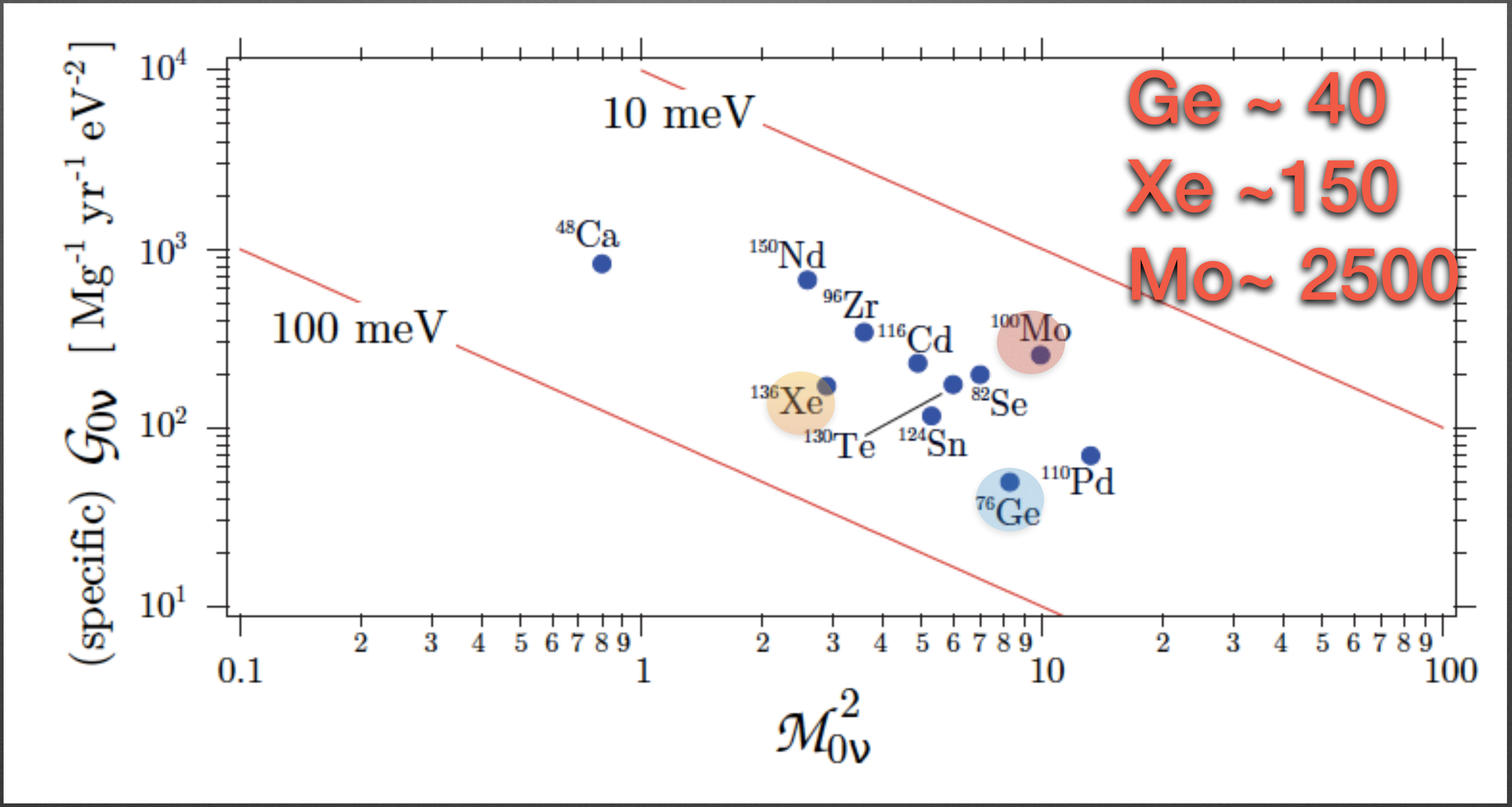
Take ^{100}Mo

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

for IH 20 meV it requires to measure $\tau_{1/2}$ ~ 10^{27} yr
for NH 2 meV it requires to measure $\tau_{1/2}$ ~ 10^{29} yr

Daring or scaring

en passant….



a uniform inverse correlation between the PSF and the square of the NME emerges in all nuclei. This happens to be more a coincidence than something physically motivated and, as a consequence, no isotope is either favored or disfavored for the search of $0\nu\beta\beta$. It turns out in fact that all isotopes have qualitatively the same decay rate per unit mass for any given value of $m_{\beta\beta}$ (inside a factor 5)

.

how to compare exp's

1) compare just half-life neglecting NME and phase space: pure experimental approach (wrong)

2) consider half-life and phase space neglecting NME (more correct but neglects apparent NME-phase space anti correlation)

3) consider everything without assuming a specific NME (most conservative and common approach, source of large bands, hinders the comparison)

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}\; g_A^4 \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

4) consider everything comparing NME model-by-model (is there a NME calculation correct for all isotopes?)

No matter what , half life sensitivity measures the quality of the experiment

so it comes as

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

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

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 desired experiment

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

example

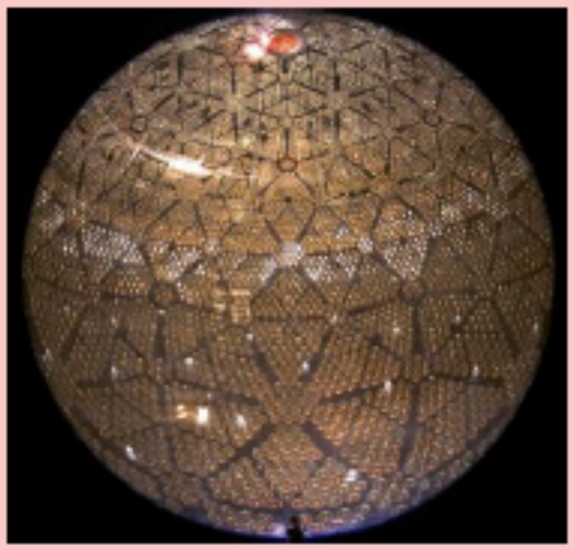
- M = 100 Kg (1 Ton)
- t = 1 y
- Q value = 3 MeV
- ΔE = 1% (0.1 %)
- what you need is $n_B = 3.3 \times 10^{-4}$

Tough game, we knew it !

Detector options

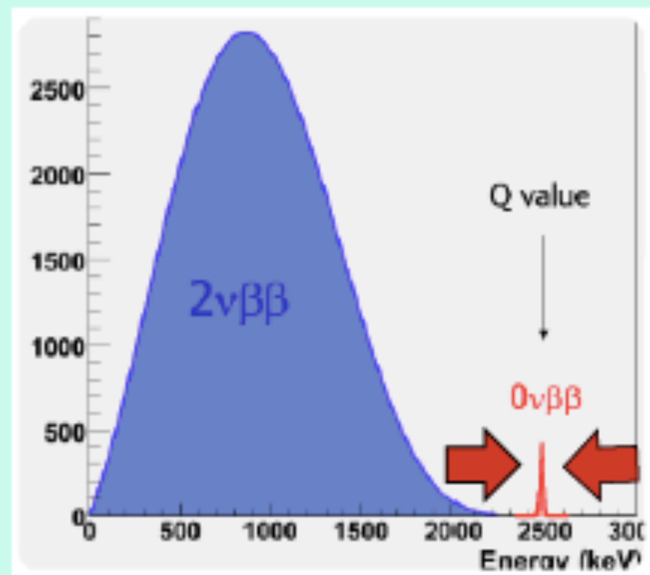
Three main options

The "Brute Force" Approach



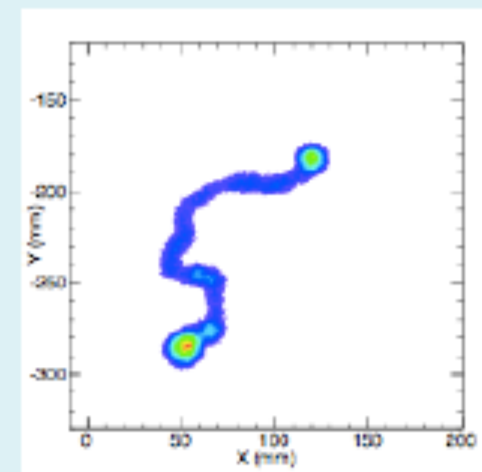
focus on the numerator with **a huge amount of material**
(often sacrificing resolution)

The "Peak-Squeezer" Approach



focus on the denominator by **squeezing down ΔE**
(various technologies)

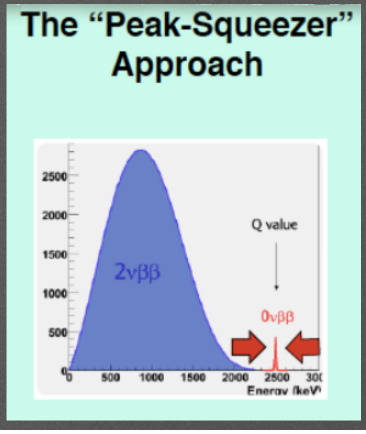
The "Final-State Judgement" Approach

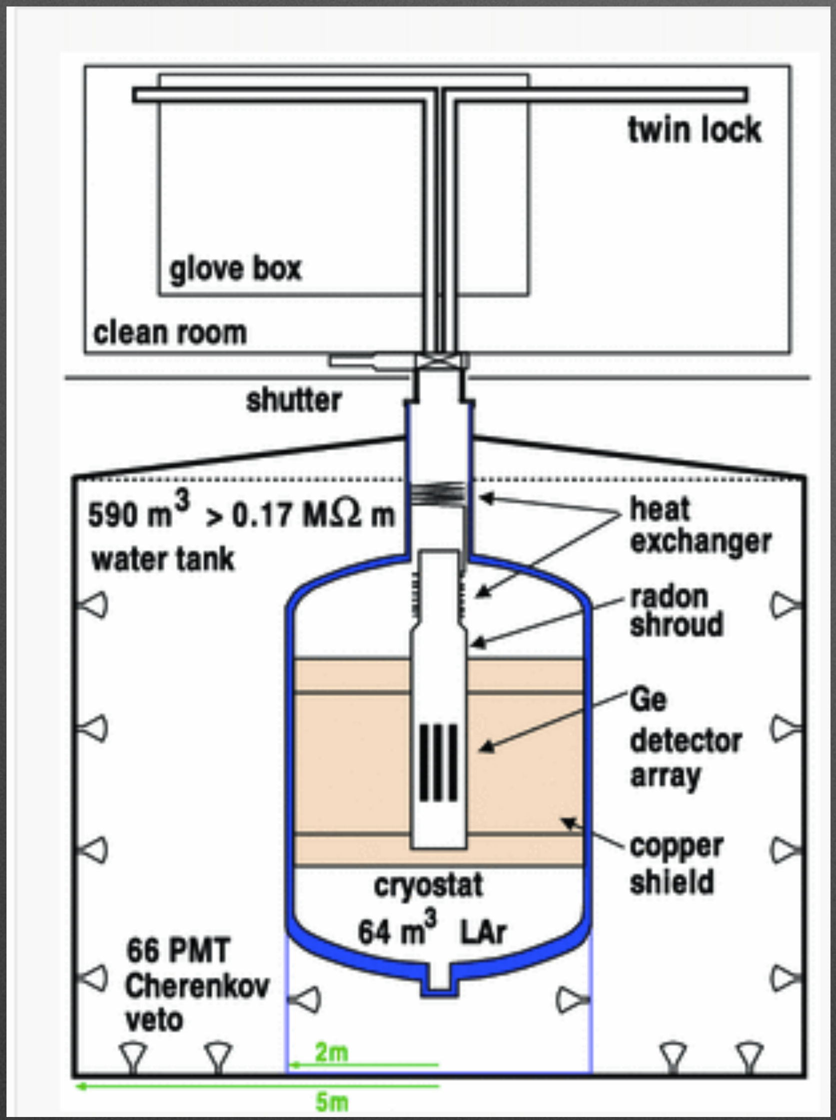


try to make the background zero by **tracking or tagging**

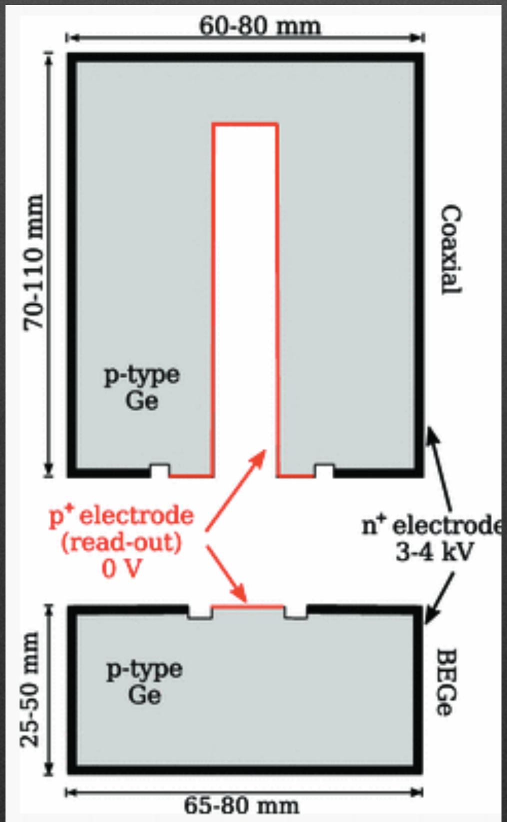
or any suitable combination !

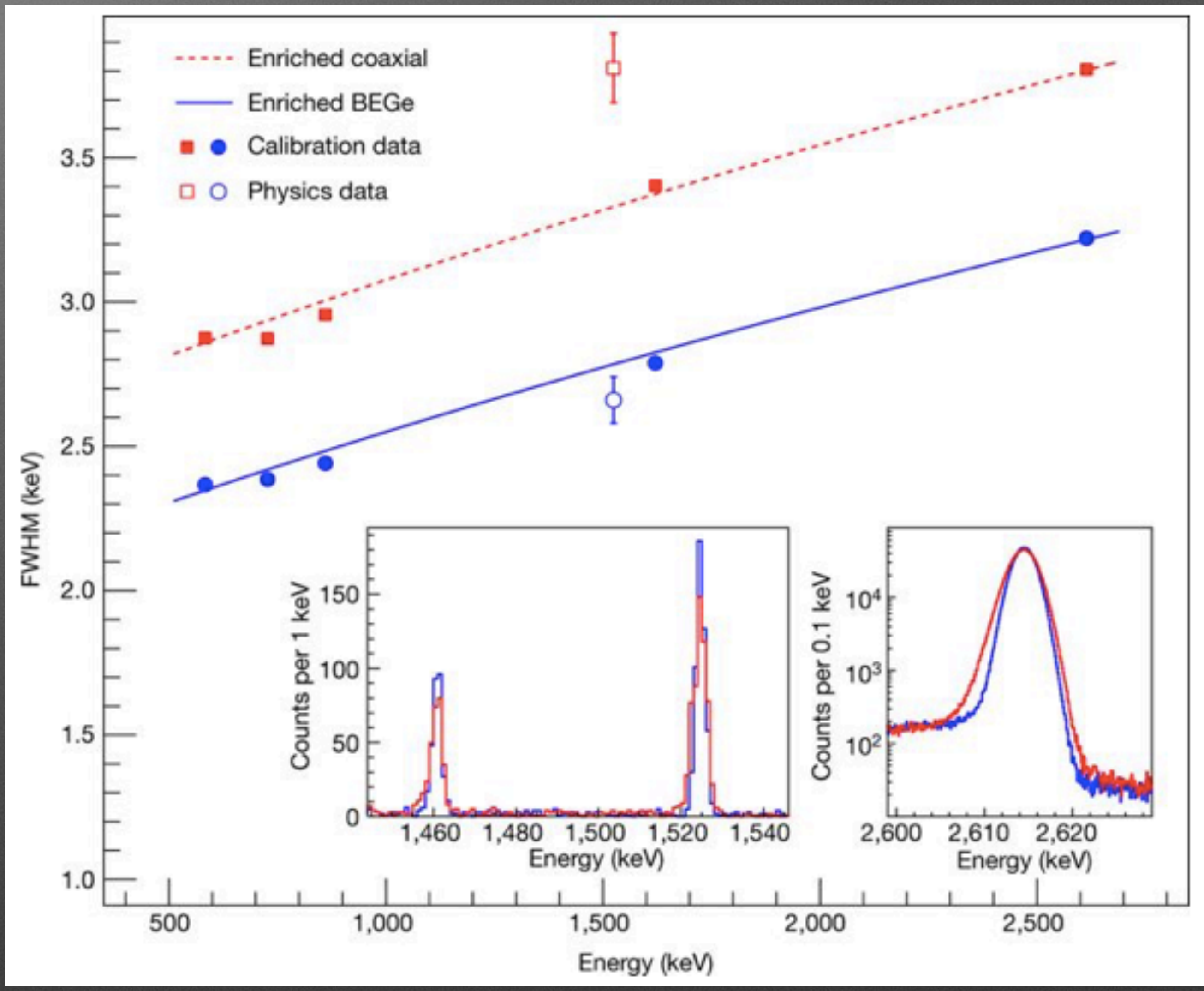
A Germanium calorimeter





G
E
R
D
A





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

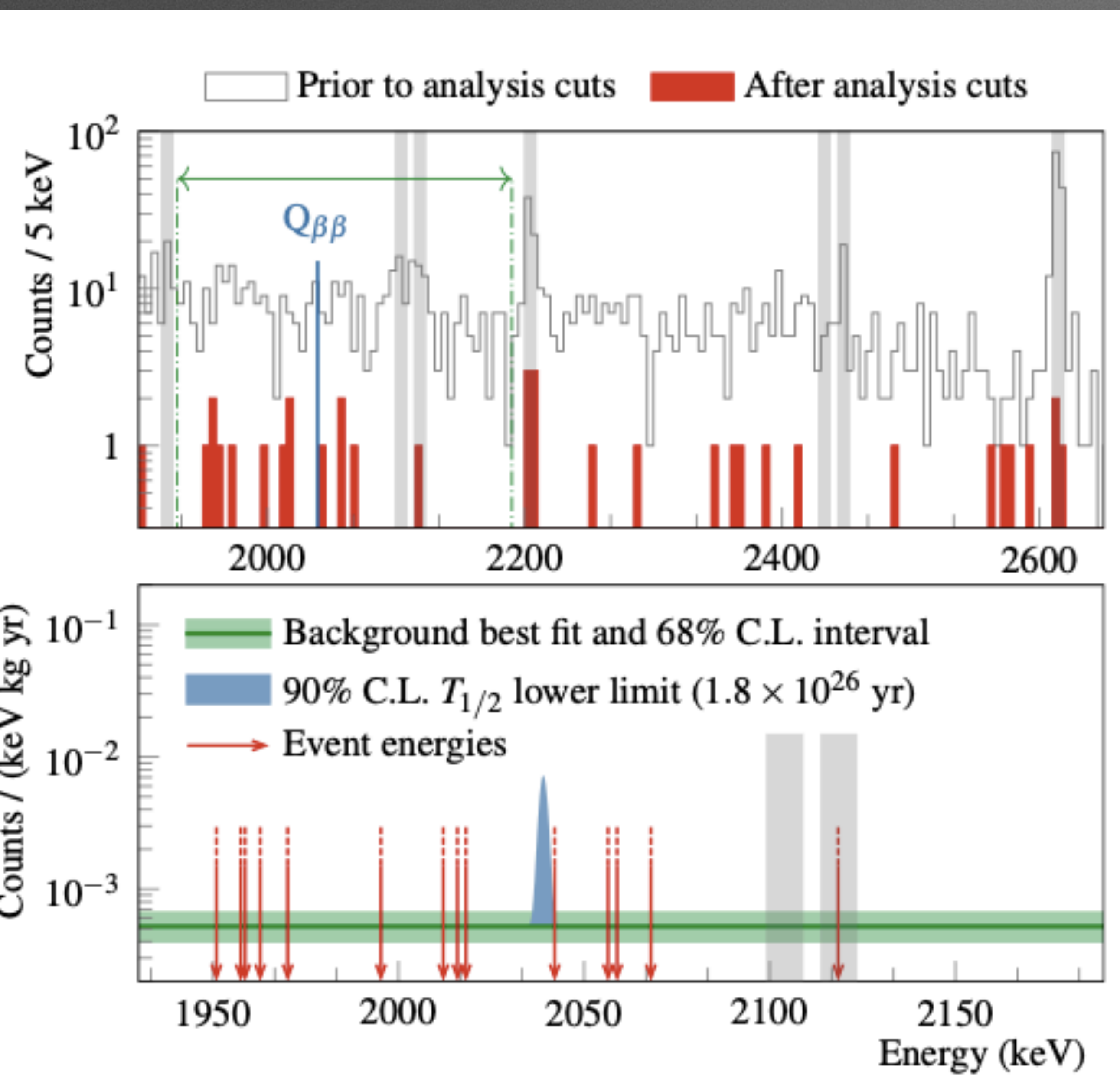
GERDA results to-date

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

$T_{1/2} > 1.8 \times 10^{26}$ yr at 90% C.L.

$N_B = 5.2 \times 10^{-4}$

	pre-upgrade	post-upgrade
	[10^{-3} cts/(keV·kg·yr)]	
coaxial	$0.6^{+0.4}_{-0.3}$	$0.7^{+1.0}_{-0.5}$
BEGe	$0.6^{+0.3}_{-0.2}$	$0.4^{+0.6}_{-0.3}$
inverted-coaxial	-	< 2.6 (90%)



you could run 500 Kg of isotope for 1 year at this bckg bringing the limit close to 10^{27} y

(still you would not cover the entire inverted hierarchy even with the most optimistic NME)

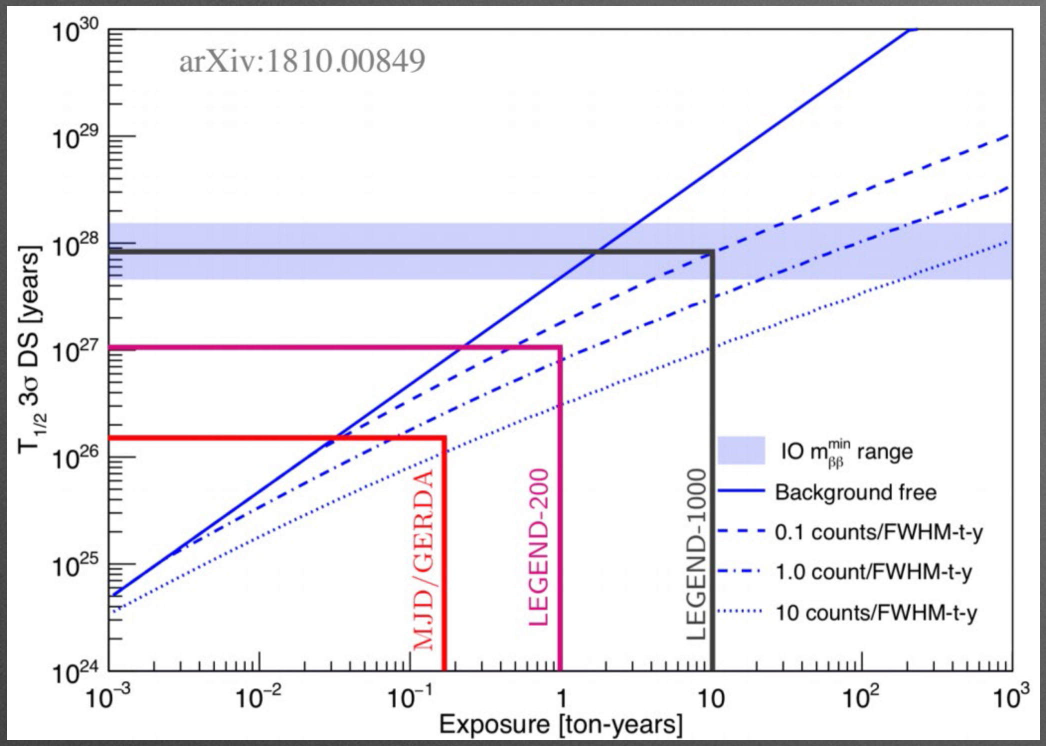
what really counts is

- $n_B \times \Delta E$
- 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 $Kg \cdot y$

turning to LEGEND@LNGS



BI x FWHM/ε

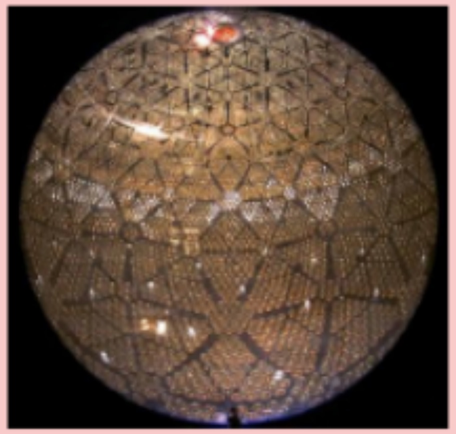
based on N_B~6 x 10^{-4}
and FWHM~ 3keV

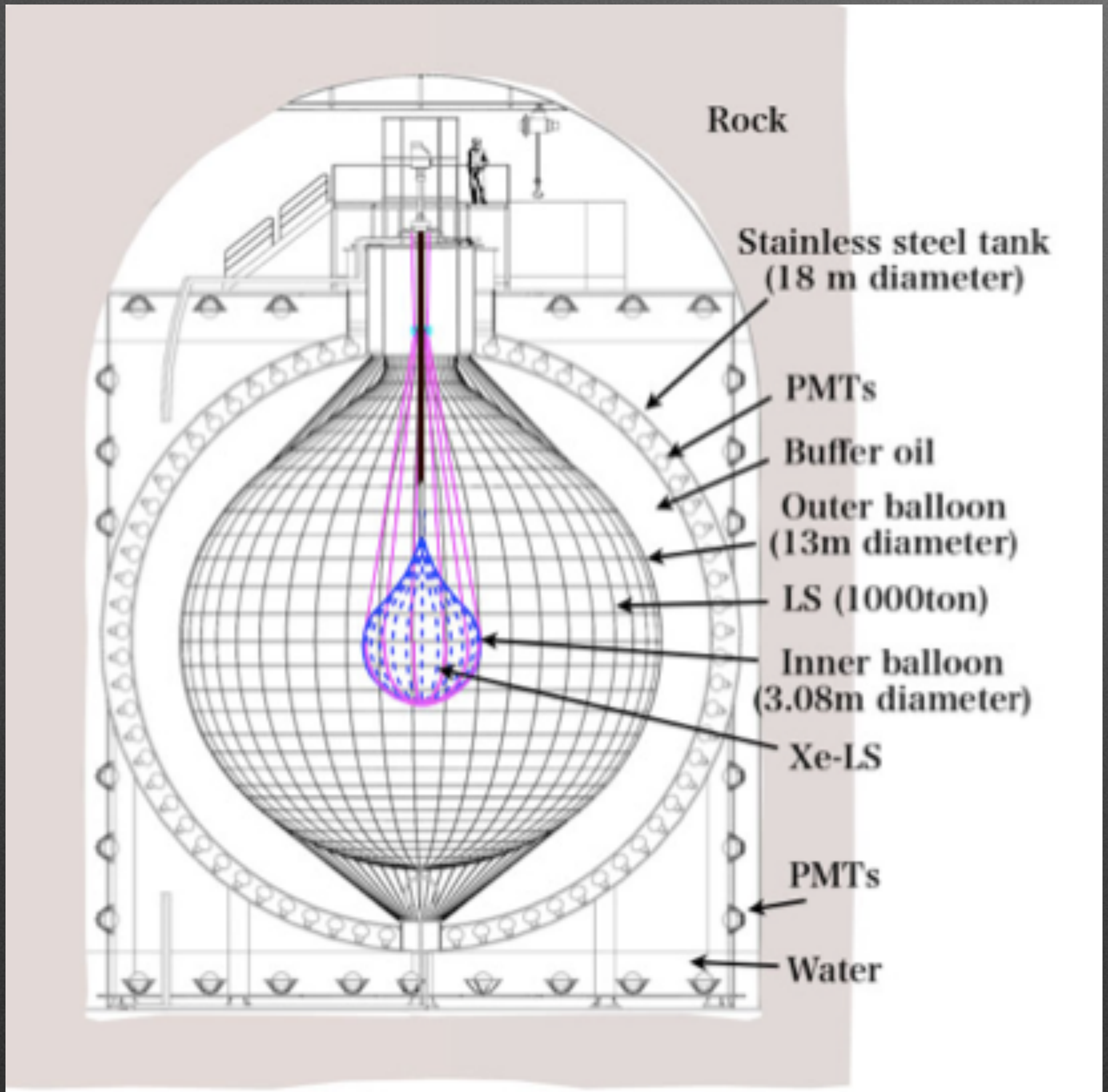
The reach can be 10^{27}
with LEGEND 200

and with a factor 5 improvement in Background
LEGEND 1000 could be in the game for 10^{28}

Kamland-ZEN

The "Brute Force" Approach

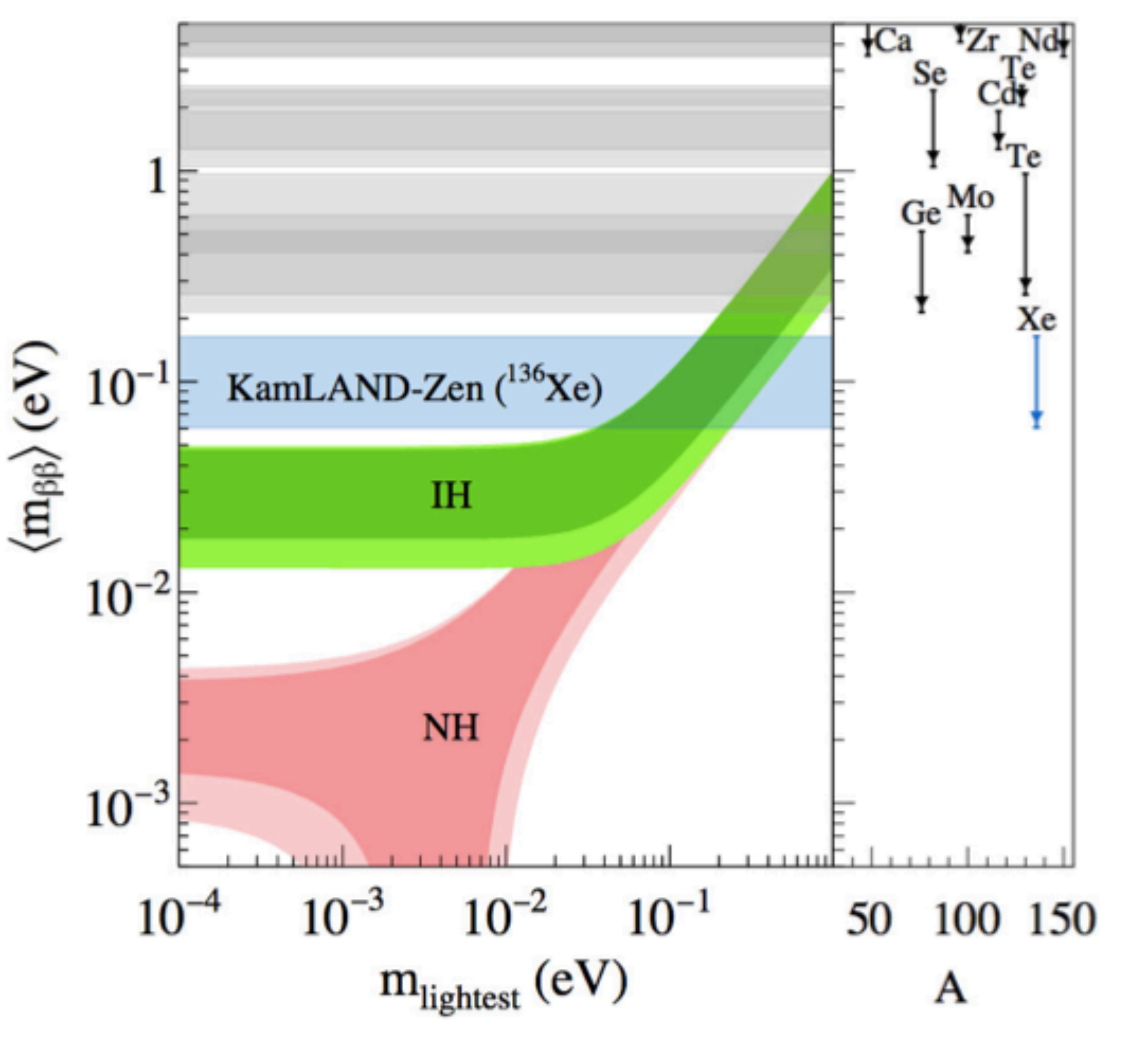




The inner balloon is filled with ^{136}Xe dissolved in liquid scintillator

Result

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



another comparison

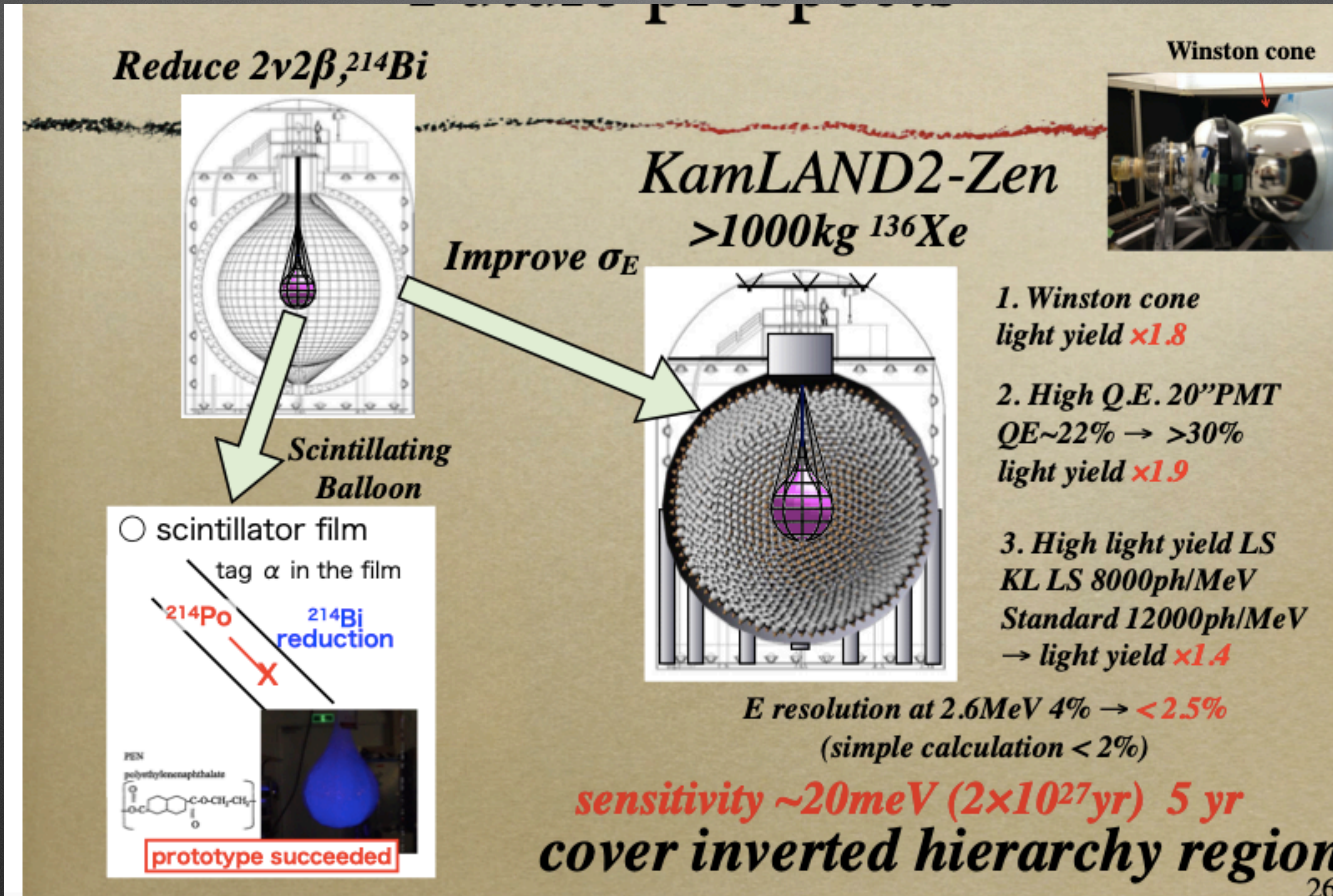
it is written in a way that is extremely difficult to know !

- $n_B \times \Delta E$
- 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 :

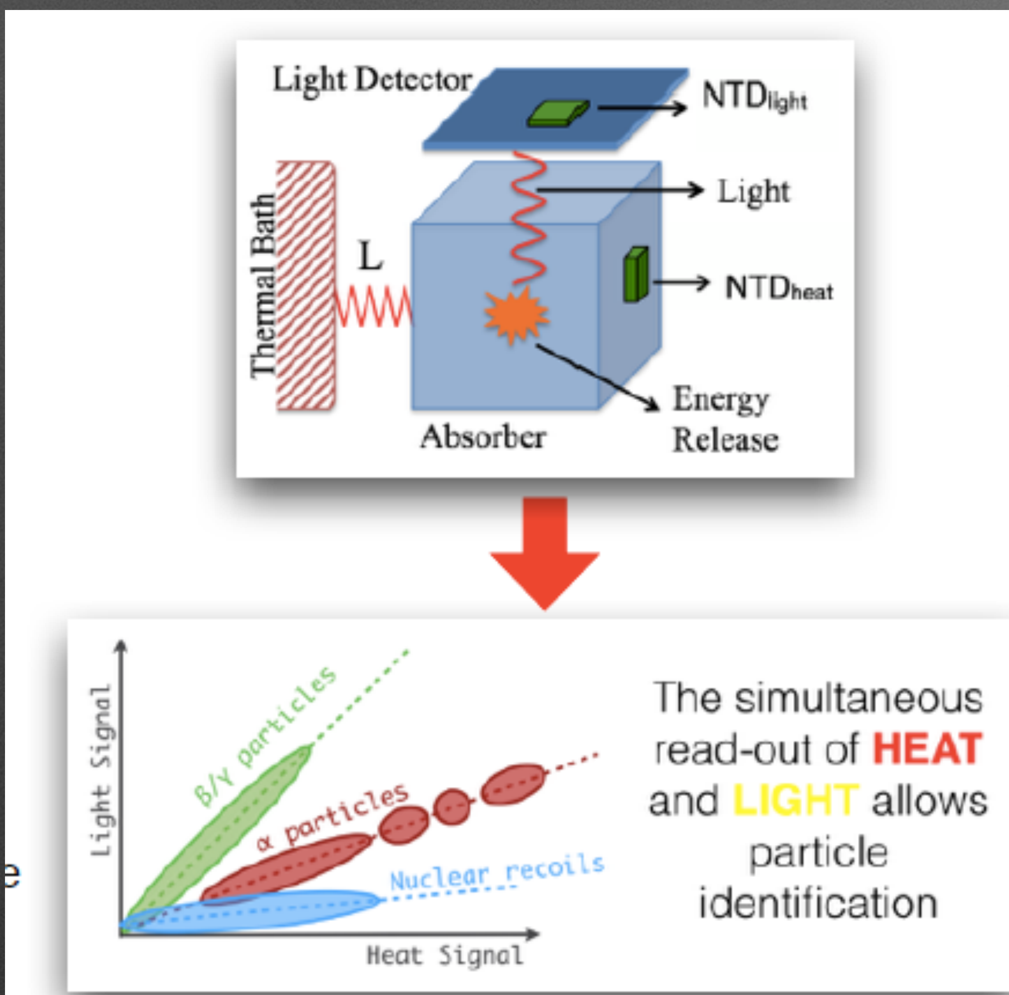
$$1 \cdot 10^{-5} \frac{1}{(kg \cdot KeV \cdot y)} \times 400 KeV \sim 4 \cdot 10^{-3}$$

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

Kamland ZEN improved

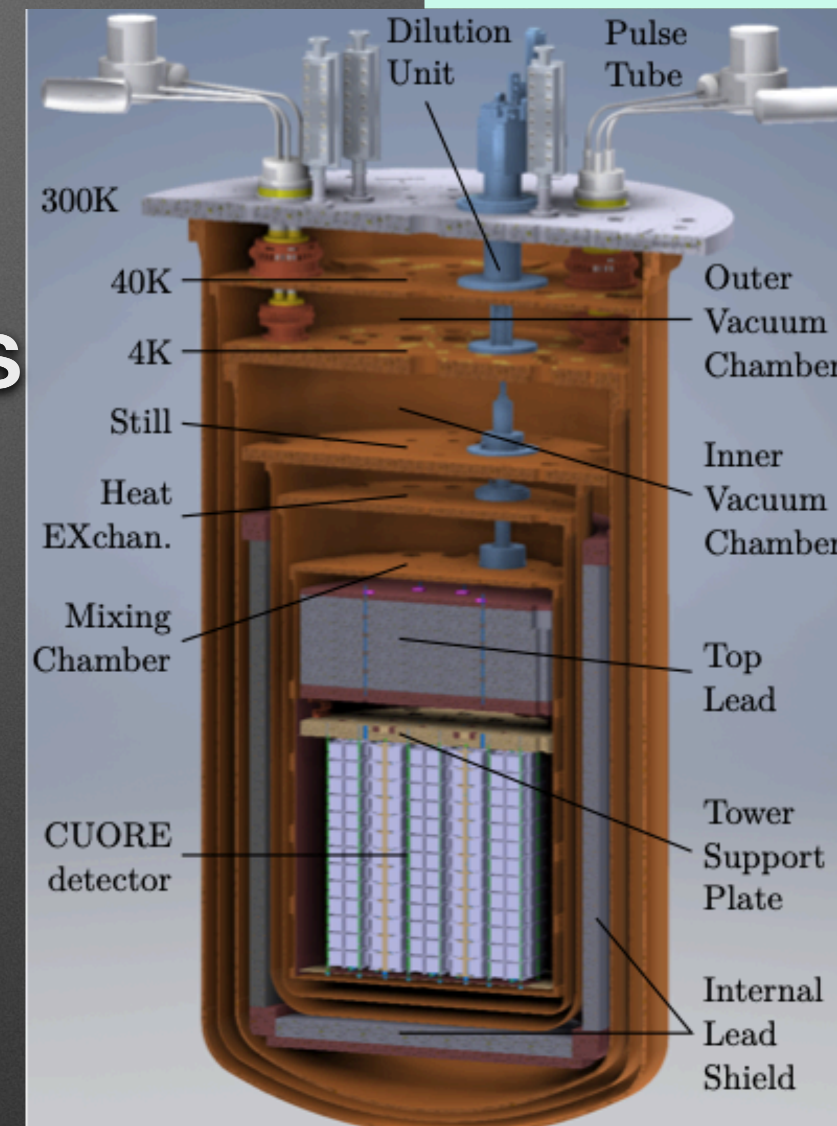


The evolution of the bolometer technique: CUPID



$Li_2{}^{100}MoO_4$ scintillating x-tals

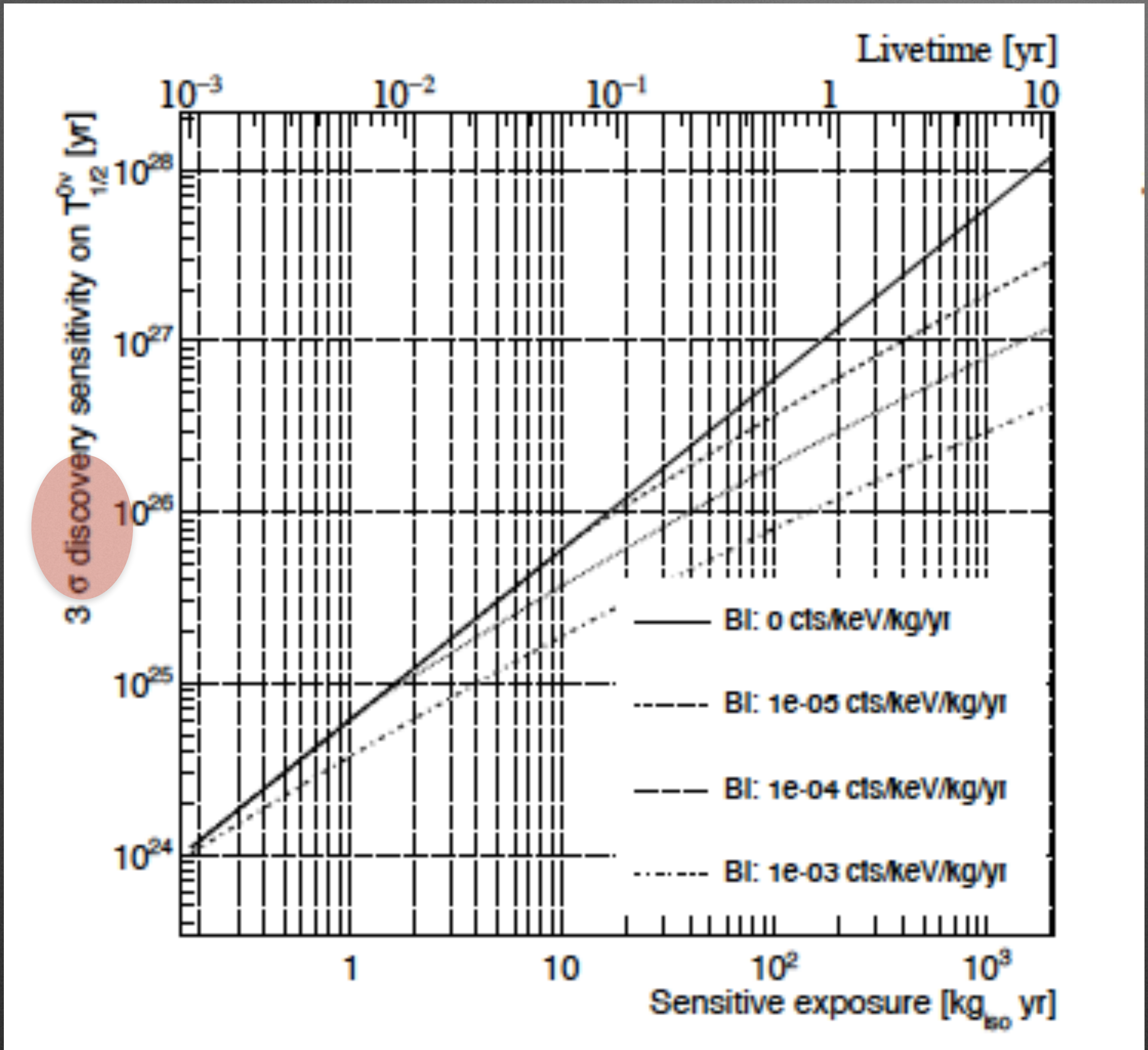
Read Heat and Light



Use CUORE cryostat

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

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

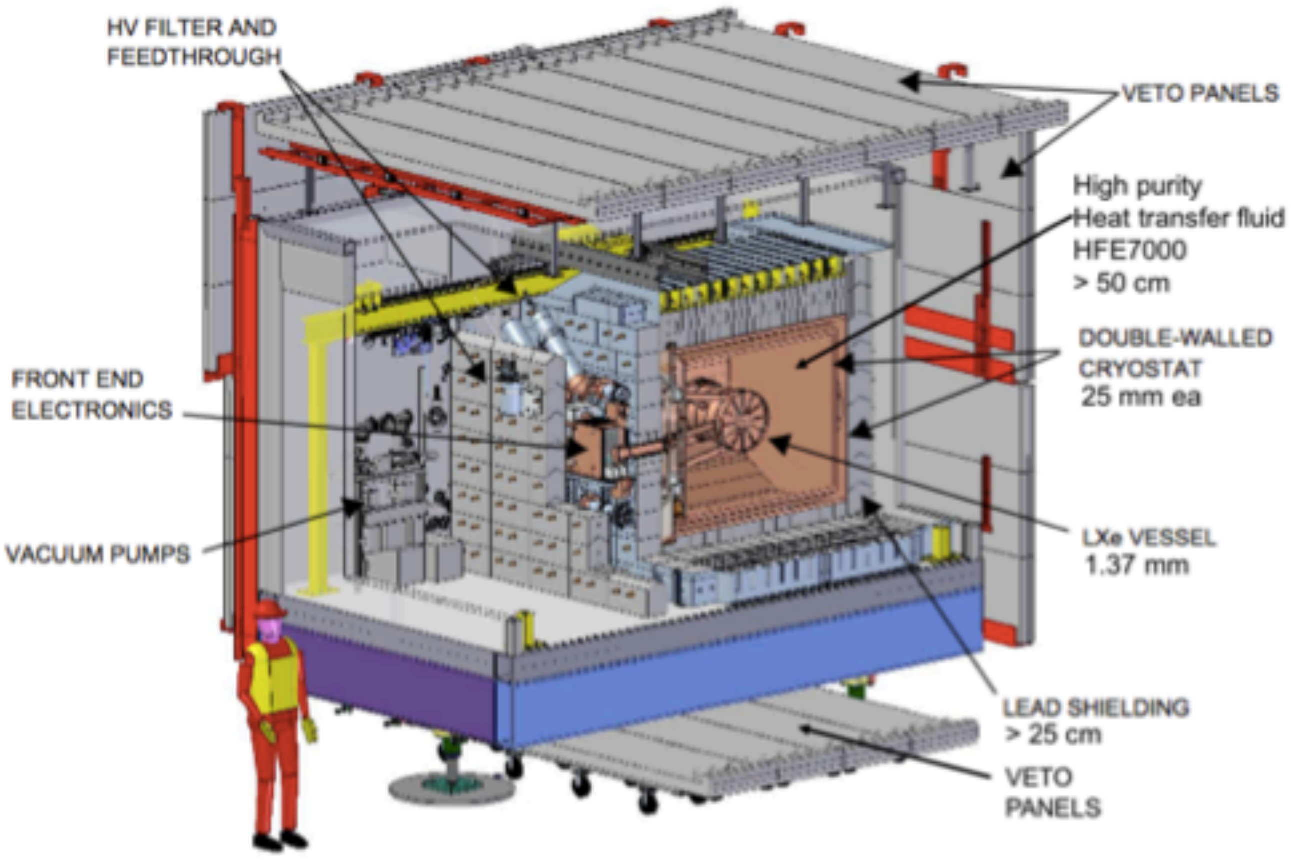
10^{27} y reachable and perhaps……

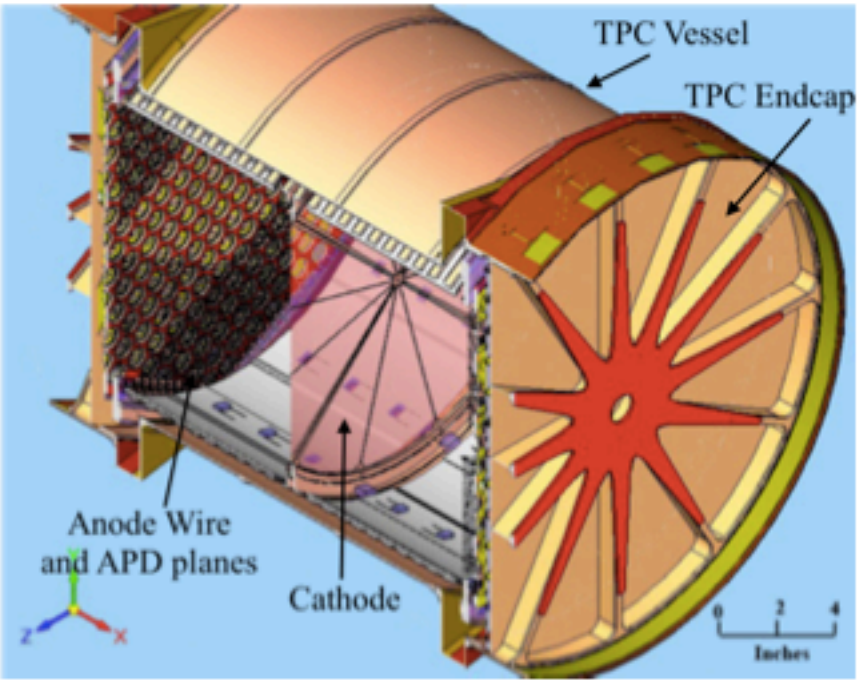
* 2000Kg producing background but only 1120 Kg of isotope for signal

so……10^{27} ‘easy’

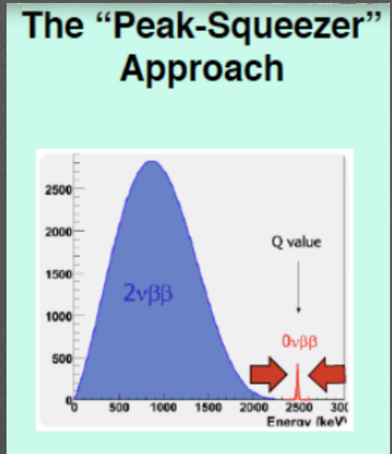
10^{28} ?

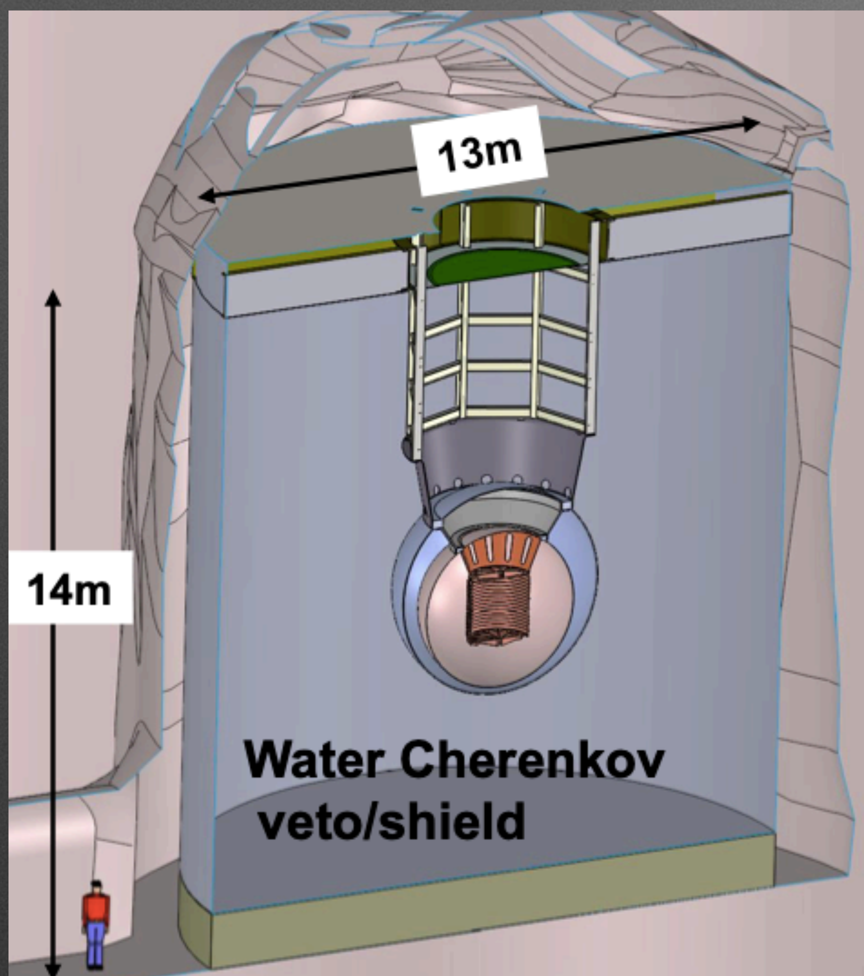
The chances of LXe from EXO to nEXO

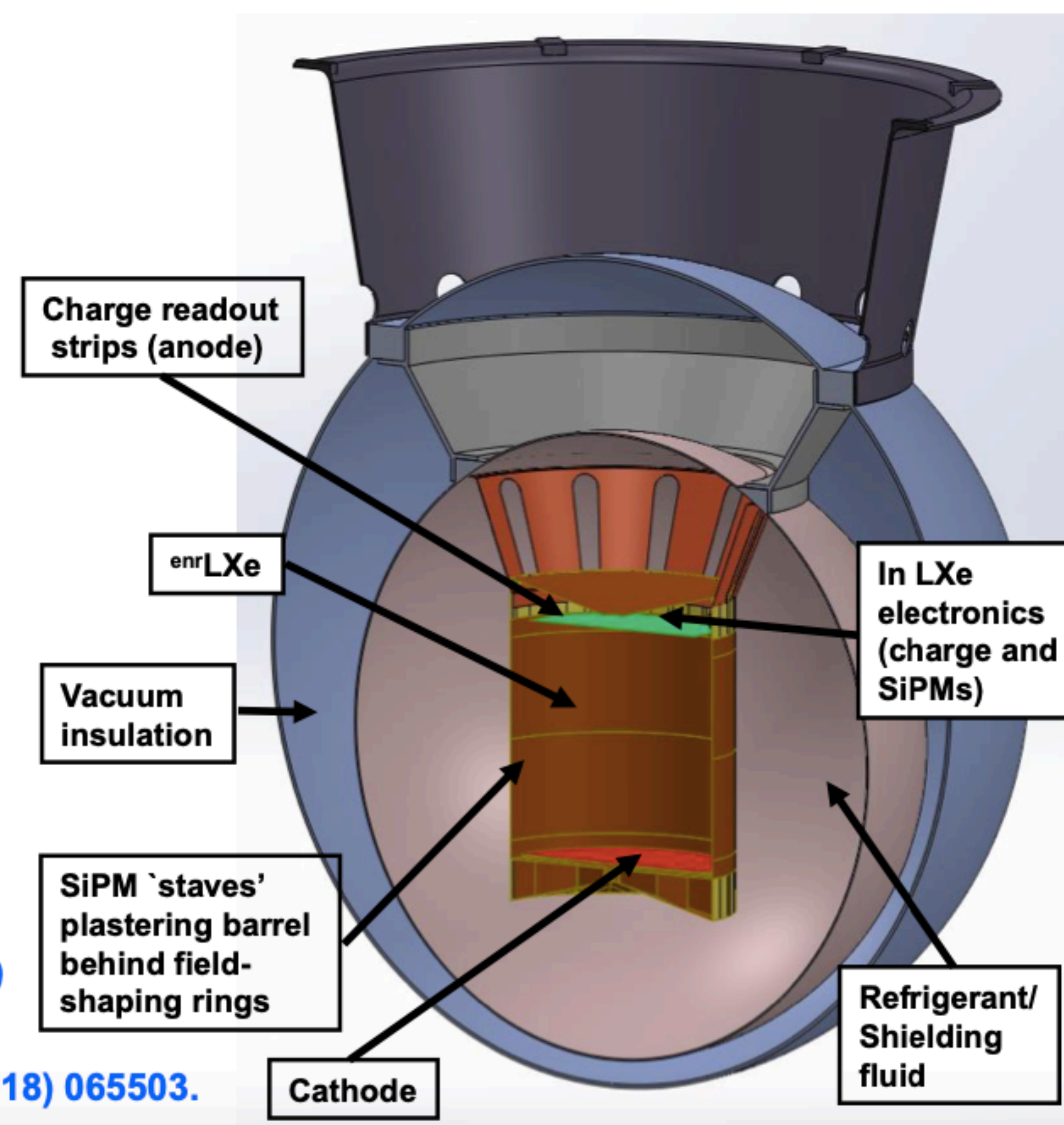




nEXO project



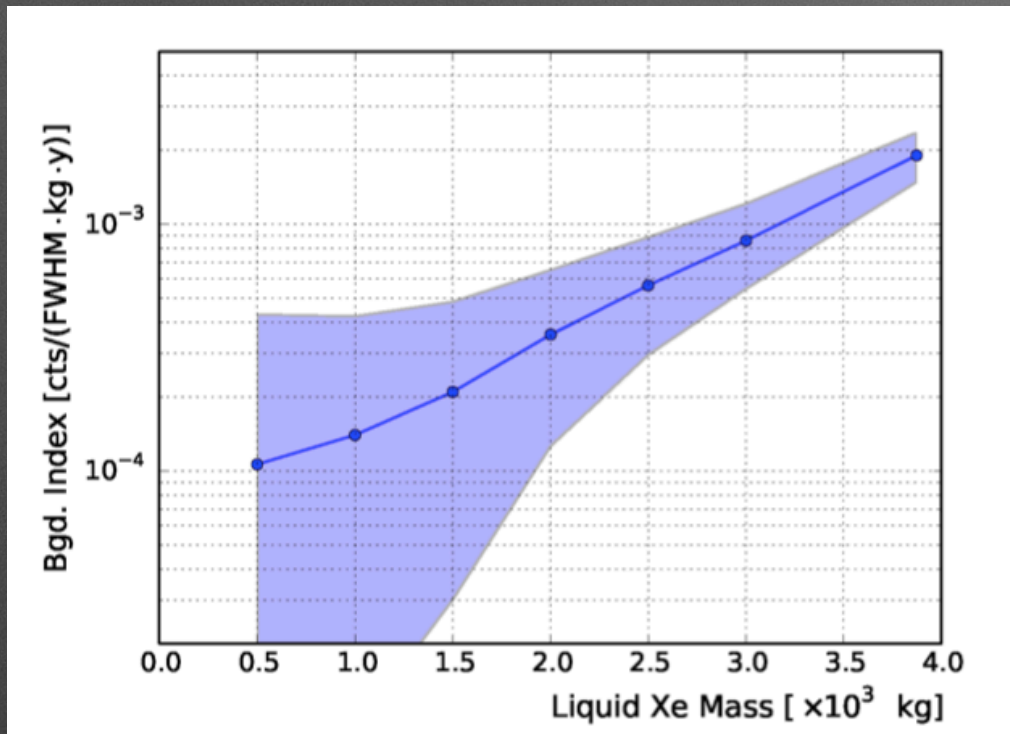




- "nEXO pCDR" arXiv:1805.11142 (May 2018)
- "Sensitivity and Discovery Potential of nEXO to 0νββ decay" Phys. Rev. C 97 (2018) 065503.

5 Tons ^{enr}LXe

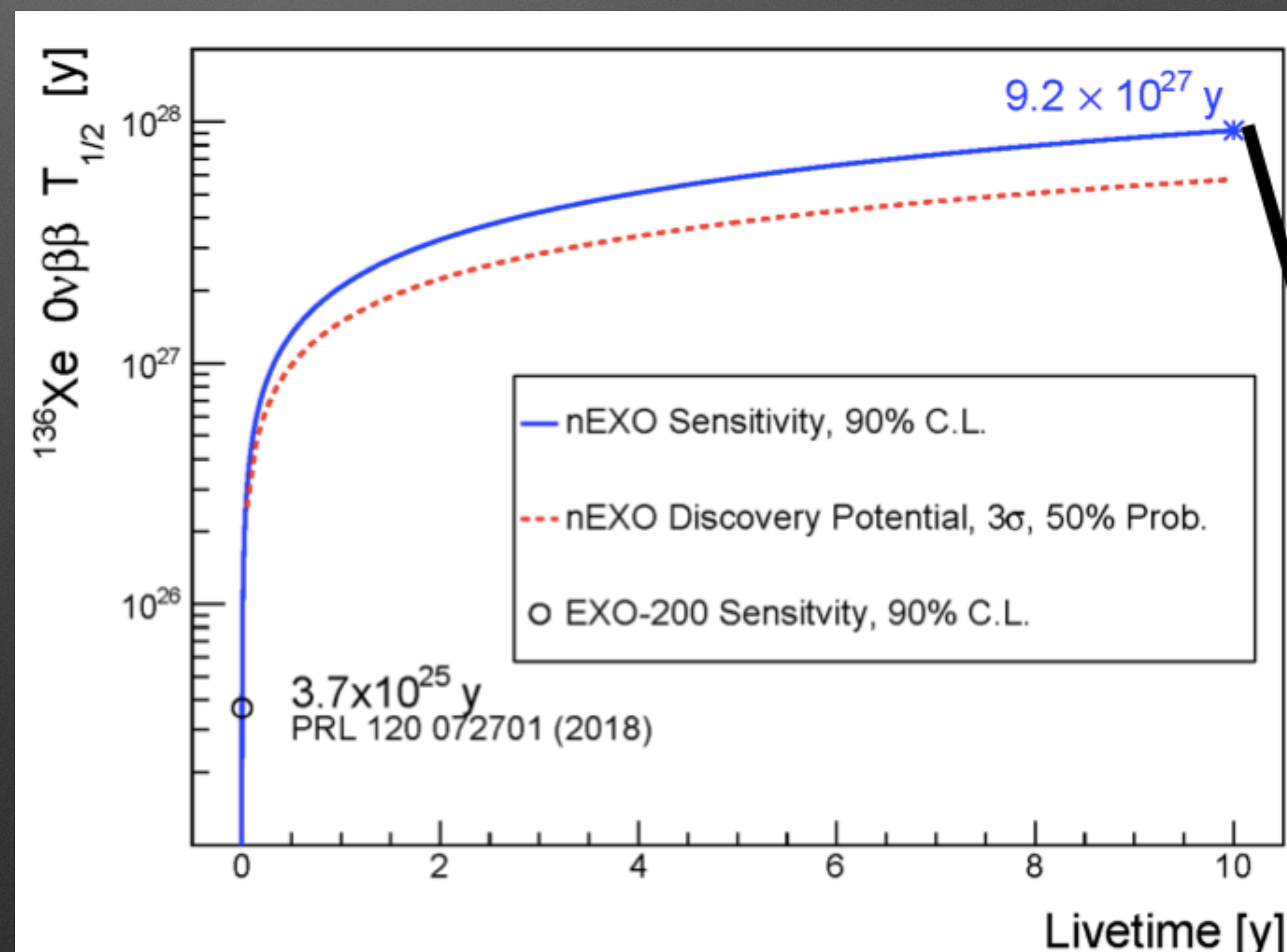
potentiality



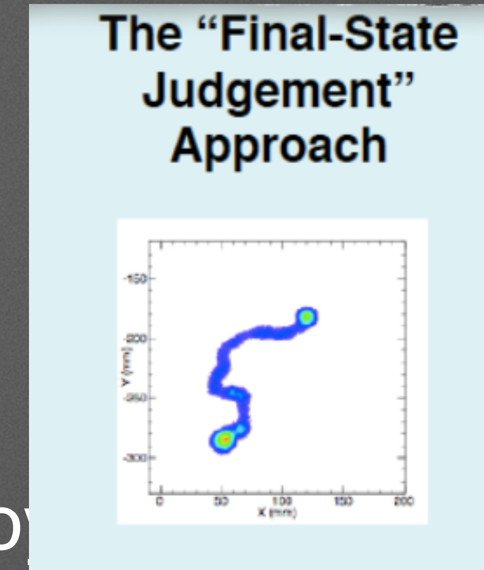
merit factor ~ 10^{-4}

10000 Kg y !

going from outside to inside



The NEXT family



1) Demonstration of the HPXe technology with prototypes deplo f natural xenon in the range of 1 kg
2) Characterisation of the backgrounds to the 0vββ signal and measurement of the 2vββ signal with the NEW detector, deploying 10 kg of enriched xenon
3) Search for 0vββ decays with the NEXT-100 detector, which deploys 100 kg of enriched xenon
4) Search for 0vββ decays with the NEXT-1Ton* detector (Xe at 15 bars), capable to reach 10^{27} years half life sensitivity (needs R&D on photodetectors)

5) an additional, although very difficult to implement, feature would be the barium tagging (BaTa)** only possible in a HPXe. If successful it could open the way toward 10^{28} sensitivity

*https://arxiv.org/pdf/2005.06467.pdf

**Nature 583 (2020) 7814, 48-54

so.....10^{28} ‘pretty difficult’

10^{29} ?

The problem at 10^{29} is rather the signal than the background !!!!

Probing Majorana neutrinos in the regime of the normal mass hierarchy

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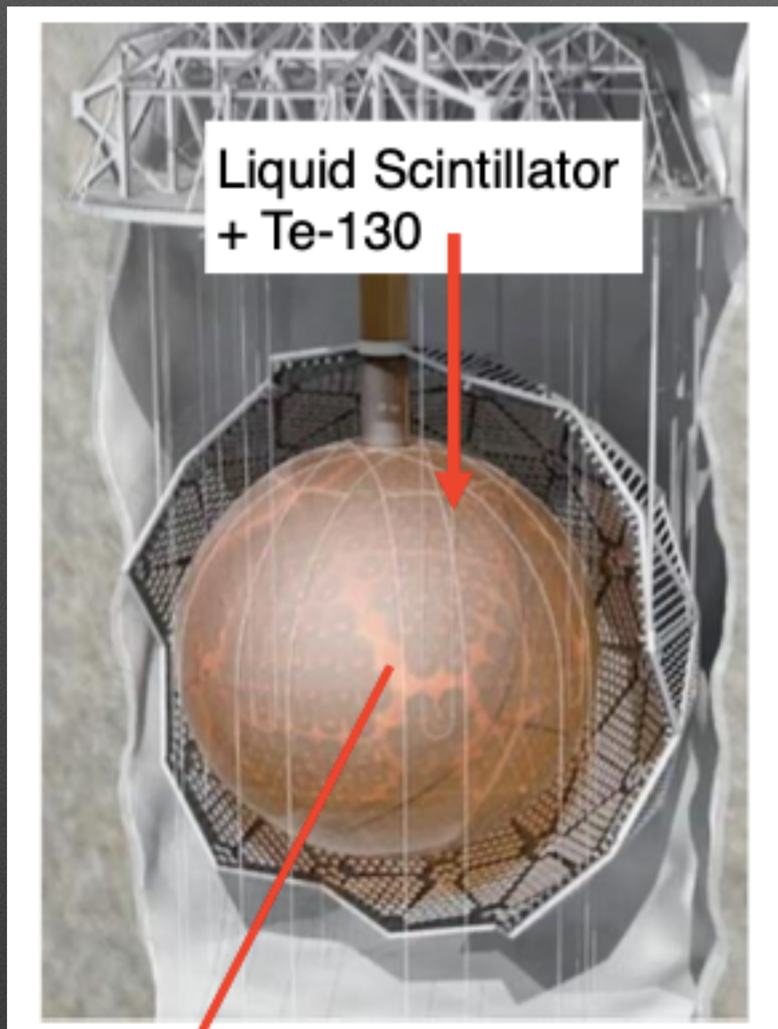
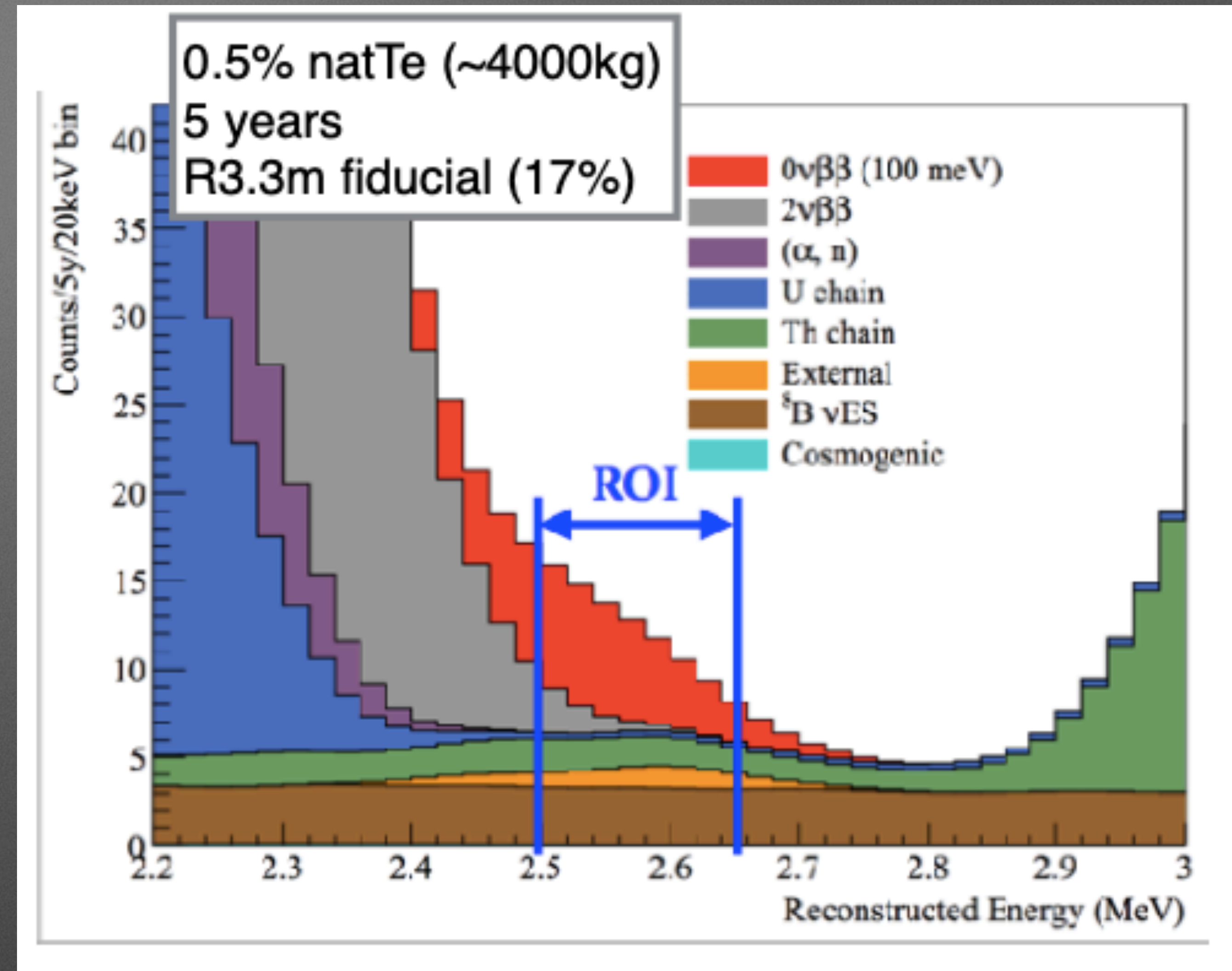
Isotope	Q (MeV)	percent natural abund.	element cost [5] ($/kg)	$G^{0\nu}$ (10^{-14}/yr) [6]	$M^{0\nu}$ (avg) [7]	$T^{0\nu}_{1/2}$ for 2.5meV (10^{29}yrs)	tons of isotope for 1 ev/yr	equivalent natural tons	annual world production [5] (tons/yr)	natural elem. cost ($M)	enriched at $20/g ($M)	$0\nu/2\nu$ 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	622	0.016
^{76}Ge	2.04	7.8	1650	0.57	4.8	3.18	58.2	746	118	1221	1164	0.55
^{82}Se	3.00	9.2	174	2.48	4.0	1.05	20.8	225	2000	39	416	0.092
^{96}Zr	3.35	2.8	36	5.02	3.0	0.93	21.4	763	1.4×10^{6}	27	427	0.025
^{100}Mo	3.04	9.6	35	3.89	4.6	0.51	12.2	127	2.5×10^{5}	4.4	244	0.014
^{110}Pd	2.00	11.8	23000	1.18	6.0	0.98	26.0	221	207	5078	521	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	441	0.035
^{124}Sn	2.29	5.6	30	2.21	3.7	1.38	41.2	736	2.5×10^{5}	22	825	0.072
^{130}Te	2.53	34.5	360	3.47	4.0	0.75	23.6	68	$\sim$150	24	471	0.92
^{136}Xe	2.46	8.9	1000	3.56	2.9	1.40	45.7	513	50	513	914	1.51
^{150}Nd	3.37	5.6	42	15.4	2.7	0.37	13.4	240	$\sim 10^{4}$	11	269	0.024

The only choice that does not call for an impossible cost for the enrichment points to natTe

the small scale concept: SNO+





ROI : -0.5 ~ 1.5 σ (2.49 ~ 2.65 MeV)
Predict : 12.4 counts/yr (in yr 1)

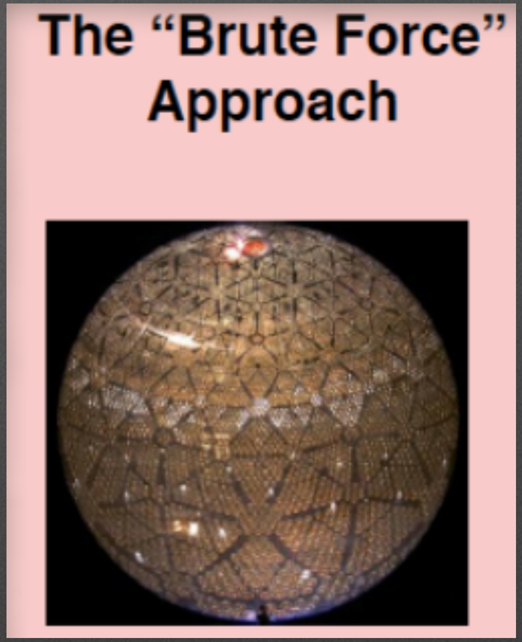
Unlike in the Xe case, here chemistry is needed! Tellurium will be dissolved in LS in the form of a Te-butanediol complex

It might be the idea for a future giant project

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

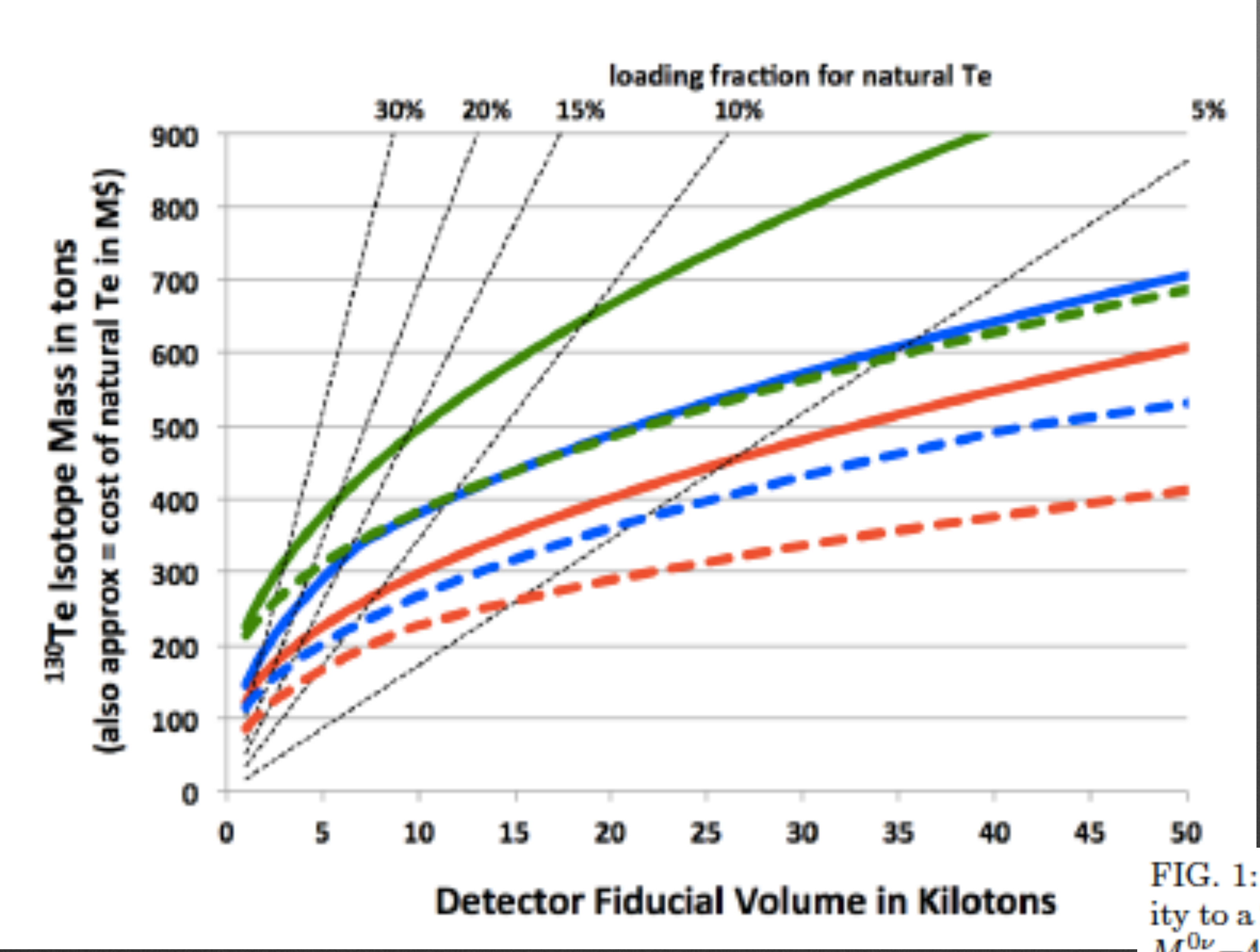
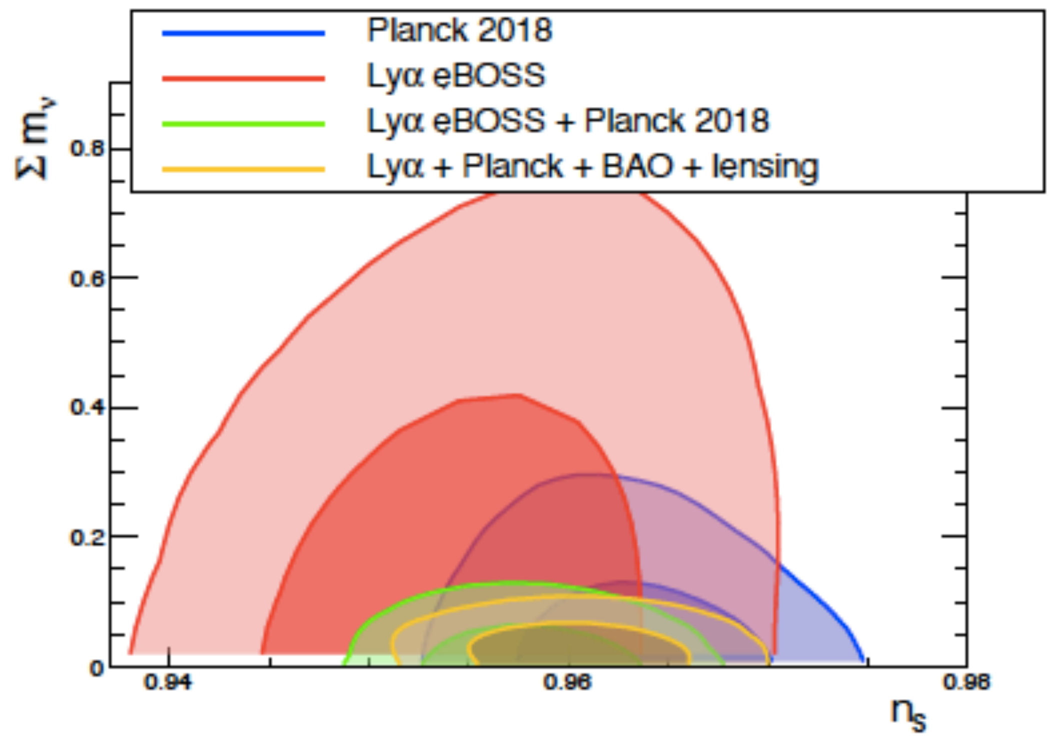


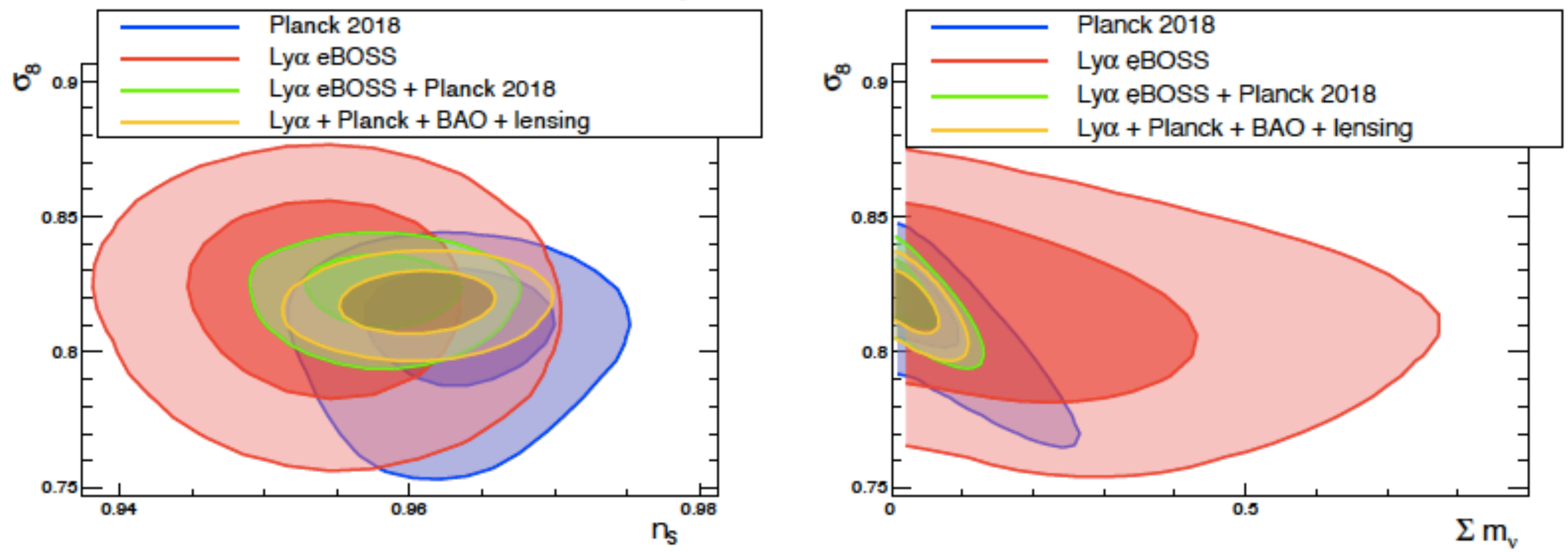
FIG. 1: Required mass of ^{130}Te to achieve a 90%CL sensitivity to a 2.5meV Majorana mass after 5 years of data, assuming $M^{0\nu}$=4. Solid curves are for full ^{8}B background, whereas long dashes correspond to a 90% "forward-backward" directional discrimination of these. Upper curves (green) correspond 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.

Finally, if you buy the indication from cosmology



Hints, neutrino bounds, and WDM constraints from SDSS DR14 Lyman-α and Planck full-survey data

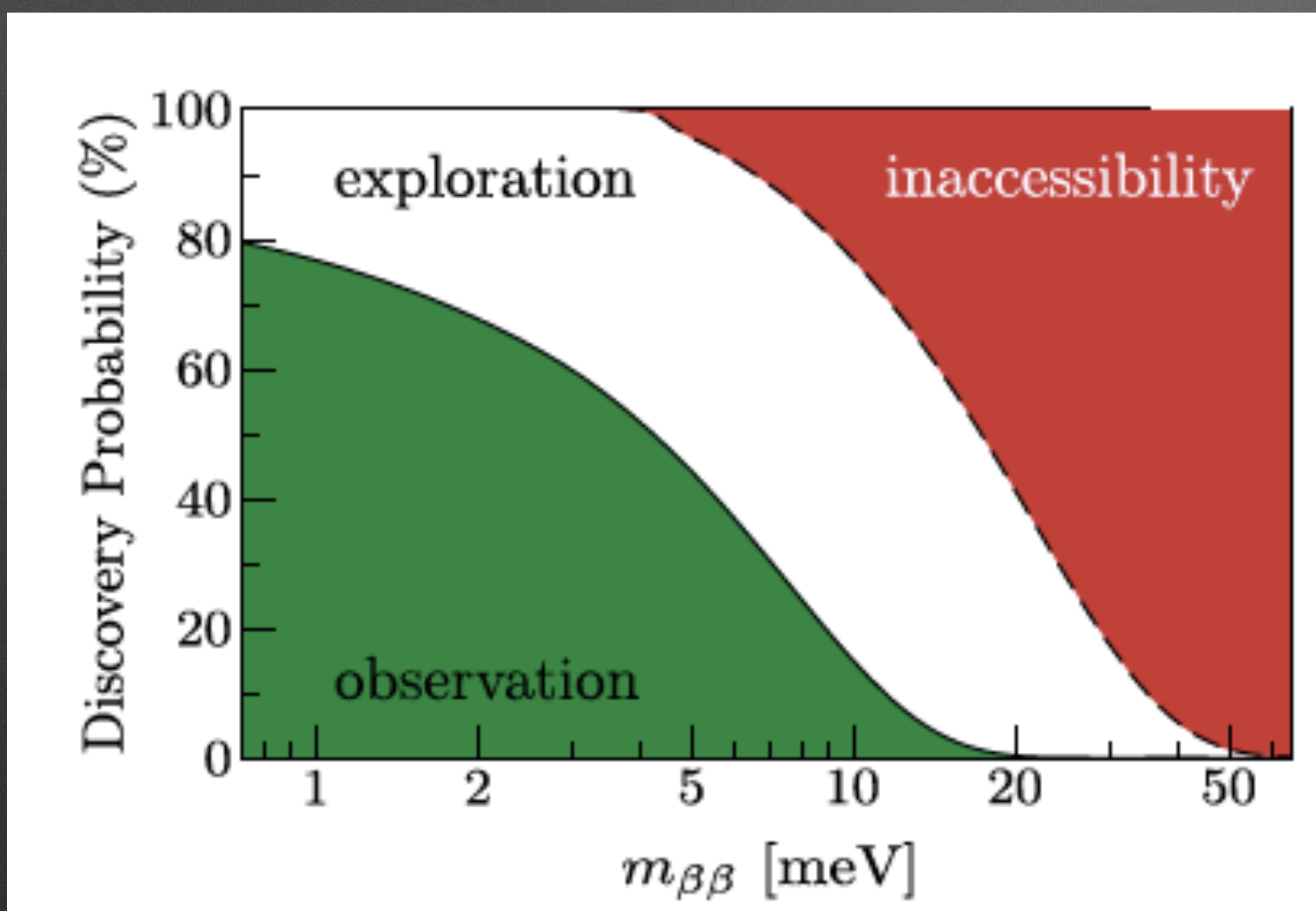
Nathalie Palanque-Delabrouille,[a] Christophe Yèche,[a] Nils Schöneberg,[b] Julien Lesgourgues,[b] Michael Walther,[a] Solène Chabanier,[a] Eric Armengaud[a]



This is the phase space to explore

Constraints on the mass of Majorana neutrinos from Cosmology

M. Agostini,[1,2] G. Benato,[3] S. Dell'Oro,[4,5] S. Pirro,[3] and F. Vissani[3,6]



Observation does not depend from Majorana phases.
Exploration region is bound by the most favourable assumption on Majorana phases.

$m^*_{\beta\beta}$ [meV]	inaccess.	exploration	observation
50	98.7 %	1.3 %	0.0 %
20	58.6 %	41.1 %	0.3 %
15	41.9 %	55.1 %	3.0 %
10	23.1 %	62.0 %	14.9 %
5	4.4 %	51.4 %	44.2 %
2	0.0 %	32.3 %	67.7 %
0	0.0 %	12.4 %	87.6 %

Conclusion

- 10^{27} reachable by LEGEND-200, Kamland-ZEN, CUPID, NEXT (?)
- 10^{28} is a difficult task for LEGEND-1000, NEXO, NEXT+ BaTa(?)
- 10^{29} is half a way between a dream and a long and tortuous way without certainty of success

Additional material

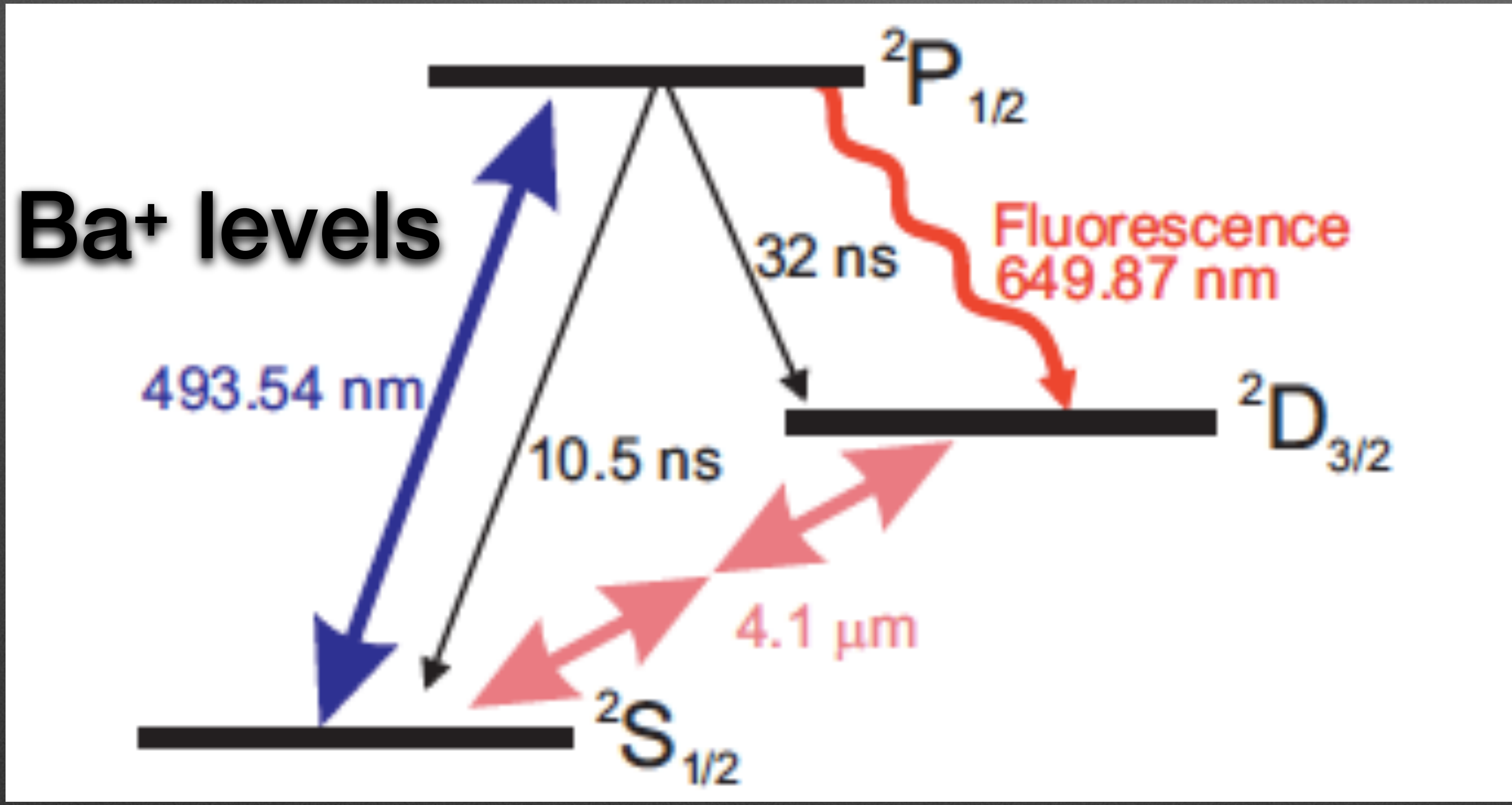
comparison IBM-2 / QRPA

	$M^{(0\nu)}$ IBM-2[§]	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

conceptual idea of Barium Tag

$$Xe \rightarrow Ba^{++} + 2e^{-}$$



a laser that induce the S-P transition

D state is metastable

a laser that induces tha transition D-S (deshelving) producing a lot of photons