In search for Matter Creation©

The landscape of double beta decay

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Thanks for material:
- Chiara Brofferio
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- Steve Elliott
- Kunio Inoue
- Yuri Kolomenski
- Suzanne Mertens
- John Wilkerson

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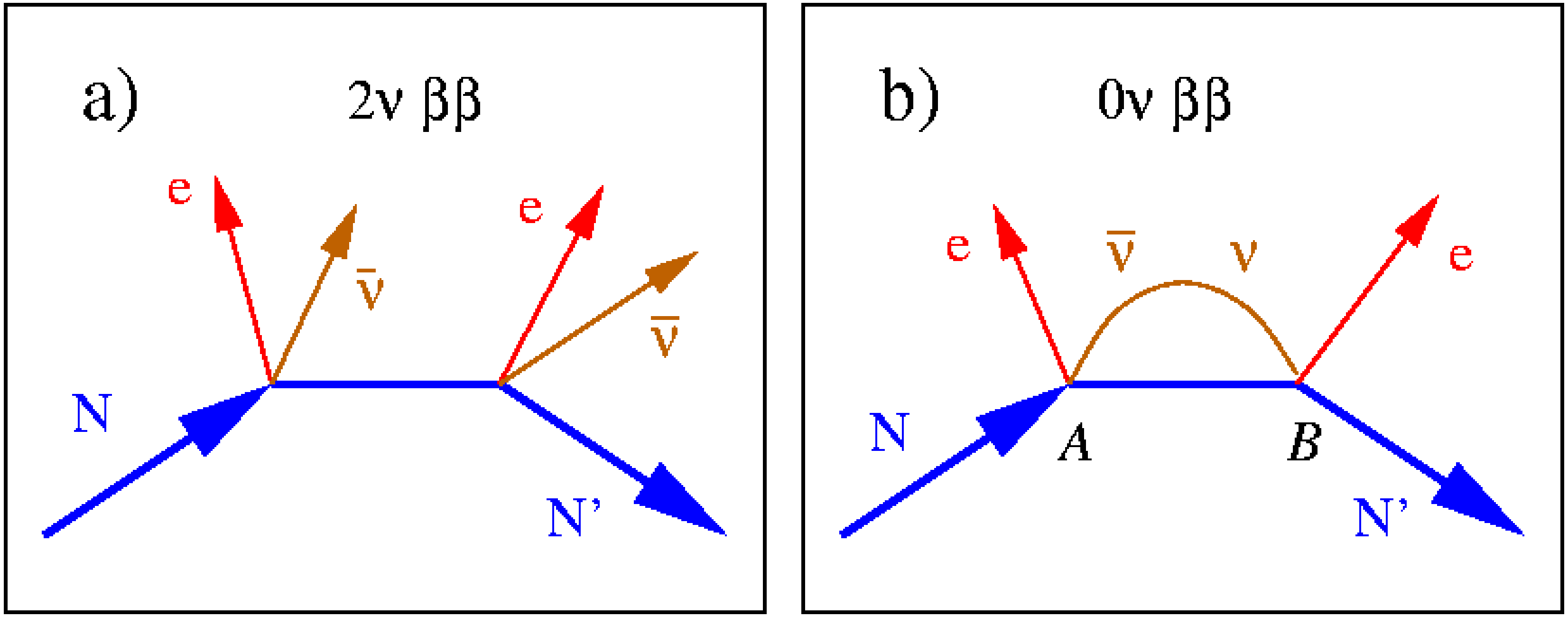
There are two varieties of ββ decay

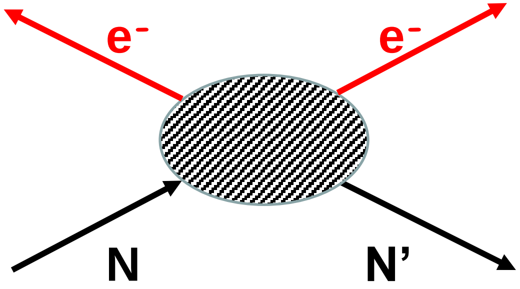
2ν mode:
a conventional
2nd order process
in nuclear physics

0ν mode: a hypothetical
process can happen
only if: $M_\nu \neq 0$
$\bar{\nu} = \nu$
$|\Delta L|=2$
$|\Delta(B-L)|=2$



“Black box” theorem*: “0νββ decay always implies new physics”

There is no scenario in which observing 0νββ decay would not be a great discovery



- ➔ Majorana neutrinos
- ➔ Lepton number violation
- ➔ Probe new mass mechanism up to the GUT scale
- ➔ Probe key ingredient in generating cosmic baryon asymmetry

Neutrino masses have to be non-zero for 0νββ to be possible.
➔ **Because the distinction between Dirac and Majorana particles is only observable for particles of non-zero mass.**

Strictly speaking, this is the ONLY connection with neutrino masses relevant to discover new physics.

Hence it is appropriate to think of the sensitivity to new physics as scaling with $T_{1/2}$, irrespective of the neutrino mass scenarios. A $T_{1/2}$ sensitivity increase from ~10^{26} to ~10^{28} yr (~100x), should be compared, e.g., to the $\sqrt{s}$ increase from Tevatron to LHC (~20), although, admittedly, with a smaller array of channels for new physics.

*** J. Schechter, and J. W. F. Valle, Phys. Rev. D25, 2951 (1982).**

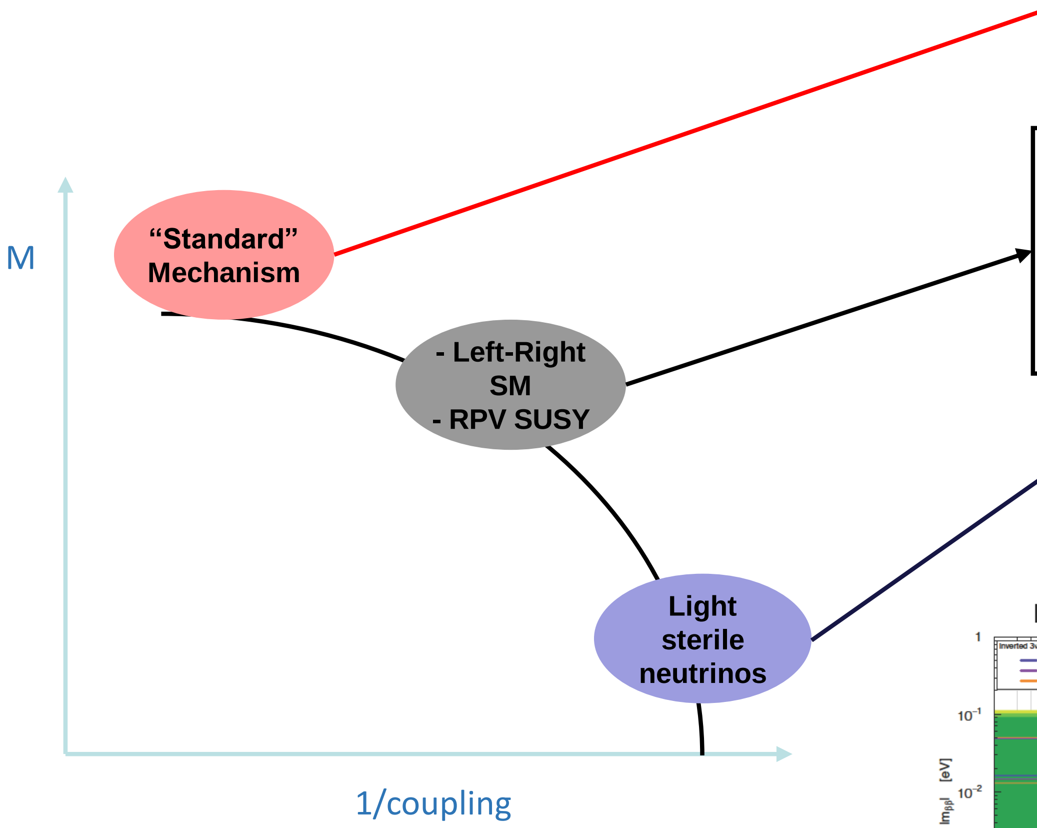
The connection with the ν mass also means that the observation of 0νββ decay can provide information on the ν mass scale, <u>provided that</u>:

- **The mechanism producing the decay is understood**
- **The nuclear matrix element is calculated with sufficiently small uncertainty**
- **The appropriate value of g_A to be used is clarified**

This is of course an important bonus, but these uncertainties *do not affect the discovery potential of tonne-scale experiments.*

It is also a convenient, although imperfect, metric to compare isotopes and experiments.

Different physics can contribute to the decay

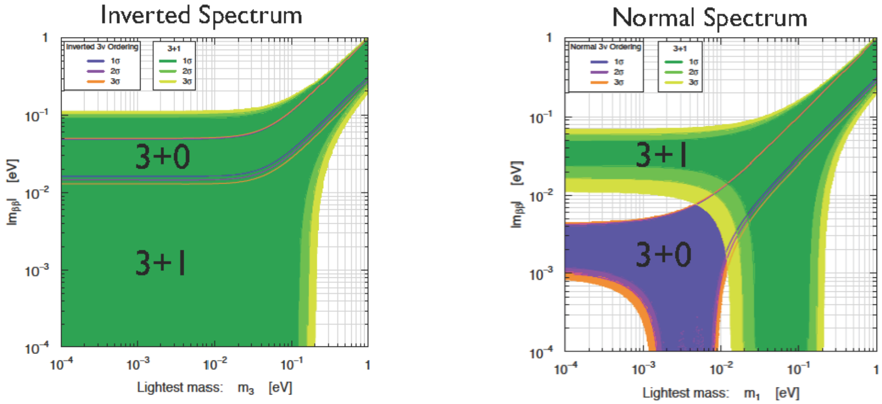


LNV dynamics at M>>TeV
Only low energy manifestation are the three light neutrino flavors

LNV dynamics at M~TeV
- Contribution to 0νββ decay not related to light neutrino masses
- Related to pp→ eejj at LHC

LNV dynamics at M_R
Additional Majorana states

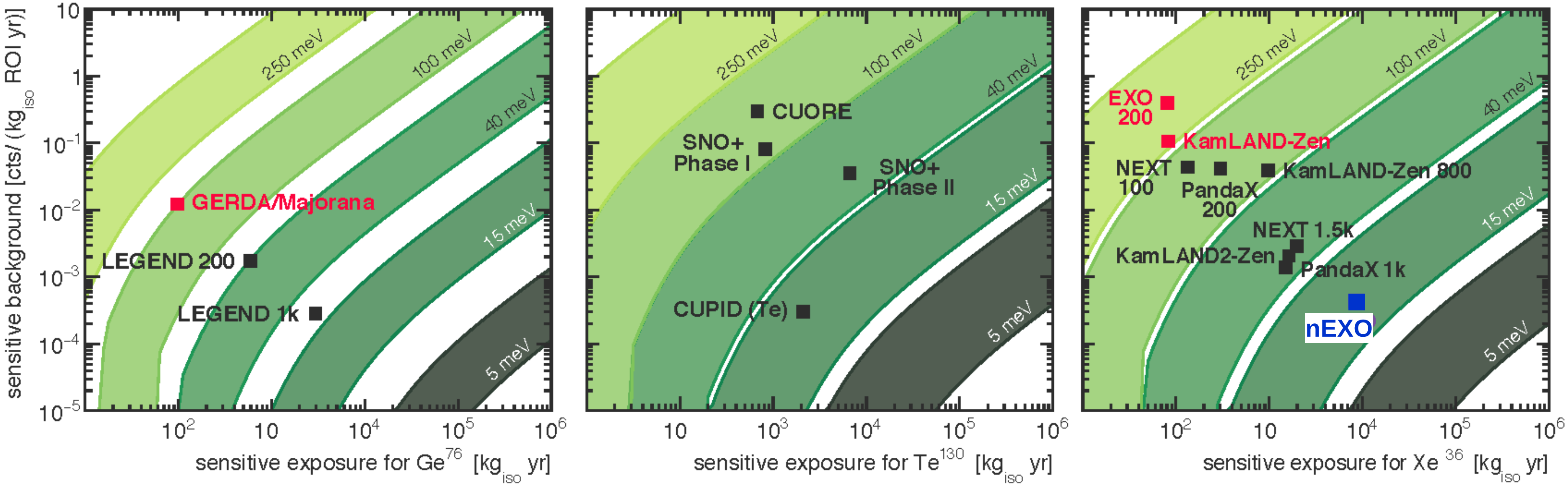
After V. Cirigliano



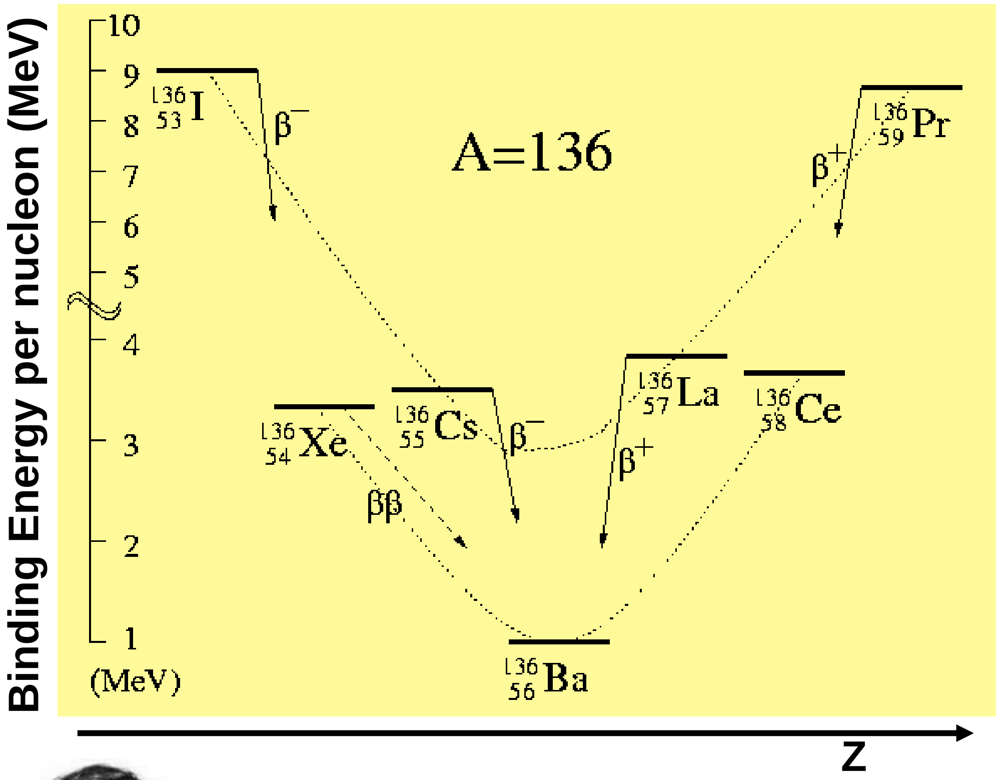
Giunti-Zavanin 1505.00978, JHEP07(2015)171

The discovery potential was recently estimated for various proposals, assuming Type I seesaw, the free value of g_A and using a Bayesian analysis with flatly distributed priors

(Agostini, Benato, Detwiler, PRD 96 (2017) 053001
also A. Caldwell et al., PRD 96 (2017) 073001)



The observable is the half-life of a nuclear state for which the regular β decay is forbidden



Examples with Q>2MeV

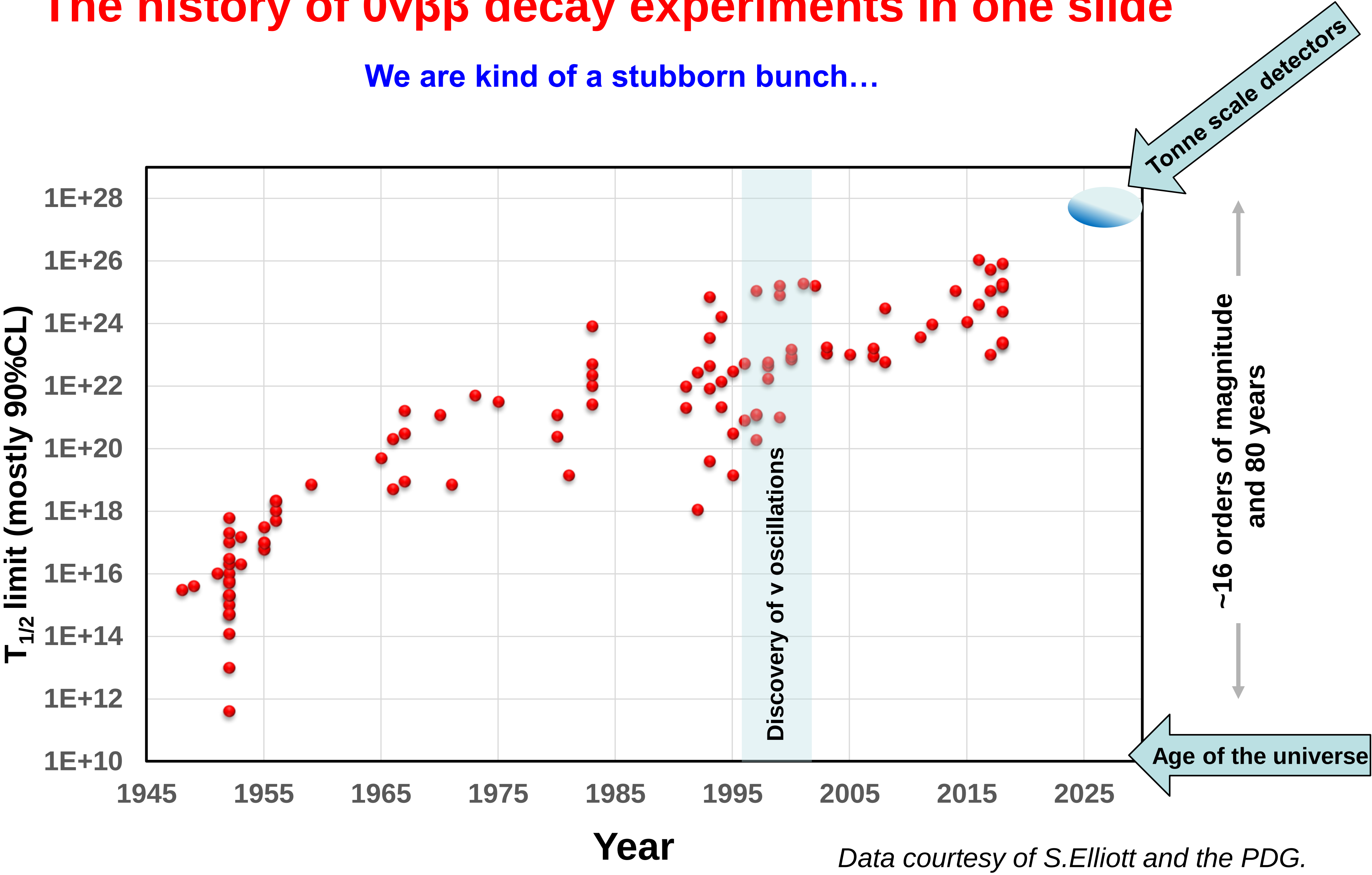
Candidate	Q (MeV)	Abundance
$^{48}\text{Ca}\rightarrow{}^{48}\text{Ti}$	4.271	0.187
$^{76}\text{Ge}\rightarrow{}^{76}\text{Se}$	2.040	7.8
$^{82}\text{Se}\rightarrow{}^{82}\text{Kr}$	2.995	9.2
$^{96}\text{Zr}\rightarrow{}^{96}\text{Mo}$	3.350	2.8
$^{100}\text{Mo}\rightarrow{}^{100}\text{Ru}$	3.034	9.6
$^{110}\text{Pd}\rightarrow{}^{110}\text{Cd}$	2.013	11.8
$^{116}\text{Cd}\rightarrow{}^{116}\text{Sn}$	2.802	7.5
$^{124}\text{Sn}\rightarrow{}^{124}\text{Te}$	2.228	5.64
$^{130}\text{Te}\rightarrow{}^{130}\text{Xe}$	2.533	34.5
$^{136}\text{Xe}\rightarrow{}^{136}\text{Ba}$	2.458	8.9
$^{150}\text{Nd}\rightarrow{}^{150}\text{Sm}$	3.367	5.6

Amedeo Avogadro
1776-1856

…and we owe the remarkable $T_{1/2}$ sensitivity to the magnitude of Avogadro's number!

The history of 0vββ decay experiments in one slide

We are kind of a stubborn bunch…



Tonne scale detectors

~16 orders of magnitude and 80 years

Age of the universe

Data courtesy of S.Elliott and the PDG.
Not all results are necessarily shown.

A historical note

Early experiments:

- **Geochemical or Radiochemical experiments**

  (search for trace amounts of element A in a large amount of B after a long time).

  ➔ Can't discriminate between 0ν and 2ν decays

  But may see a renaissance in combination with real-time counting
- **Counting experiments with gram quantities of candidate isotopes.**

"Previous generation" experiments:

- **Counting experiments with kg quantities of enriched material**

Running and future experiments:

- **>100kg-class counting experiments (mainly enriched)**

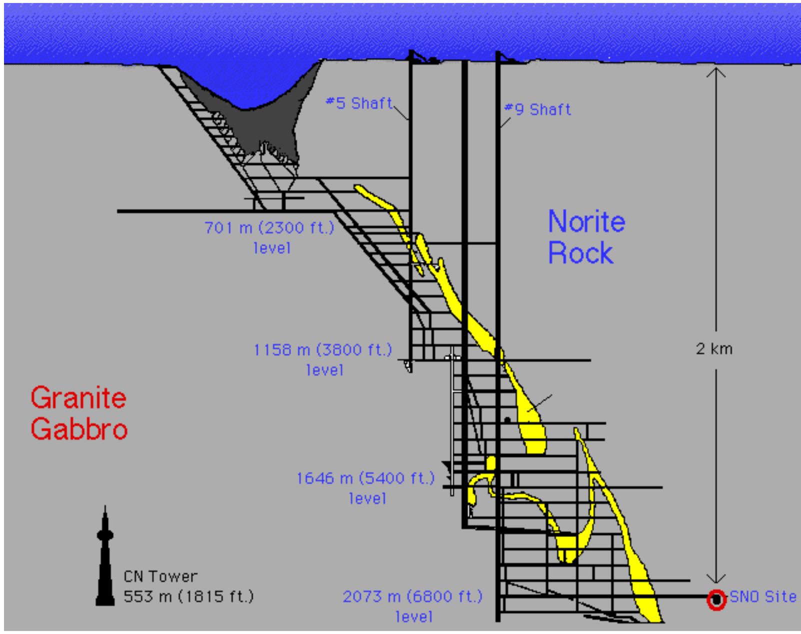
Four fundamental requirements for modern experiments:

1) Isotopic enrichment of the source material (that is generally also the detector)

100kg – class experiment running or completed.
Ton – class experiments under planning.

2) Underground location to shield cosmic-ray induced background

Several underground labs around the world,
Next round of experiments 1-2 km deep.



Four fundamental requirements for modern experiments:

3) Ultra-low radioactive contamination for detector construction components

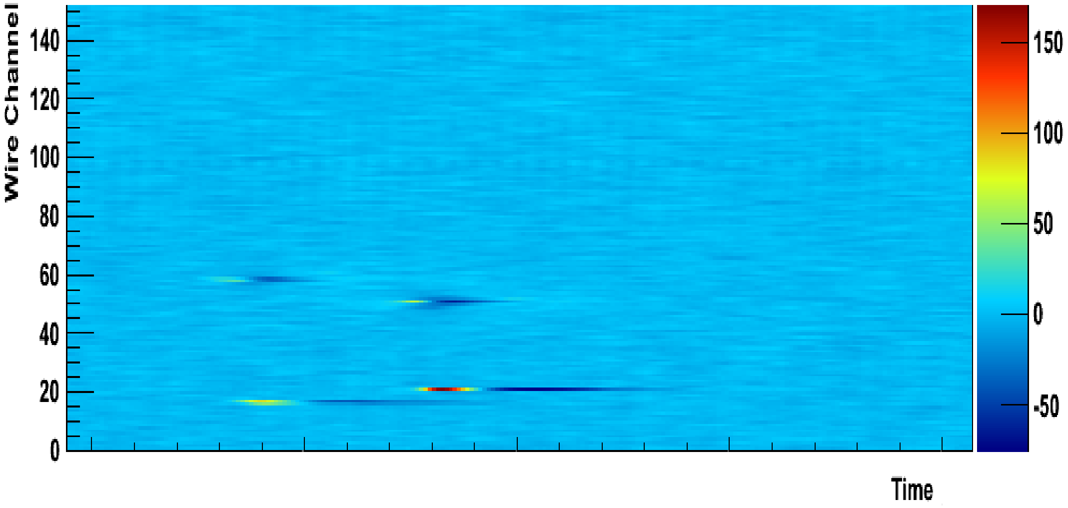
Materials used ≈<10^{-15} in U, Th
(U, Th in the earth crust ~ppm)

4) New techniques to discriminate signal from background

Non trivial for E~1MeV

Modern detectors have a number of handles.

This gets easier in larger detectors.



The last point deserves more discussion,
particularly as the size of detectors grows…

Modern detectors use a combination of four parameters/measurements:

1. **Energy measurement (for small detectors this is ~all there is).**
2. **Event multiplicity (γ's Compton scatter depositing energy in more than one site in large detectors).**
3. **Depth in the detector (or distance from the walls) is (for large monolithic detectors) a powerful parameter for discriminating between signal and (external) backgrounds.**
4. **αs can be distinguished from electrons in many detectors.**

Powerful detectors use most (possibly all) these parameters in combination, providing the best possible background rejection and simultaneously fitting for signal and background.

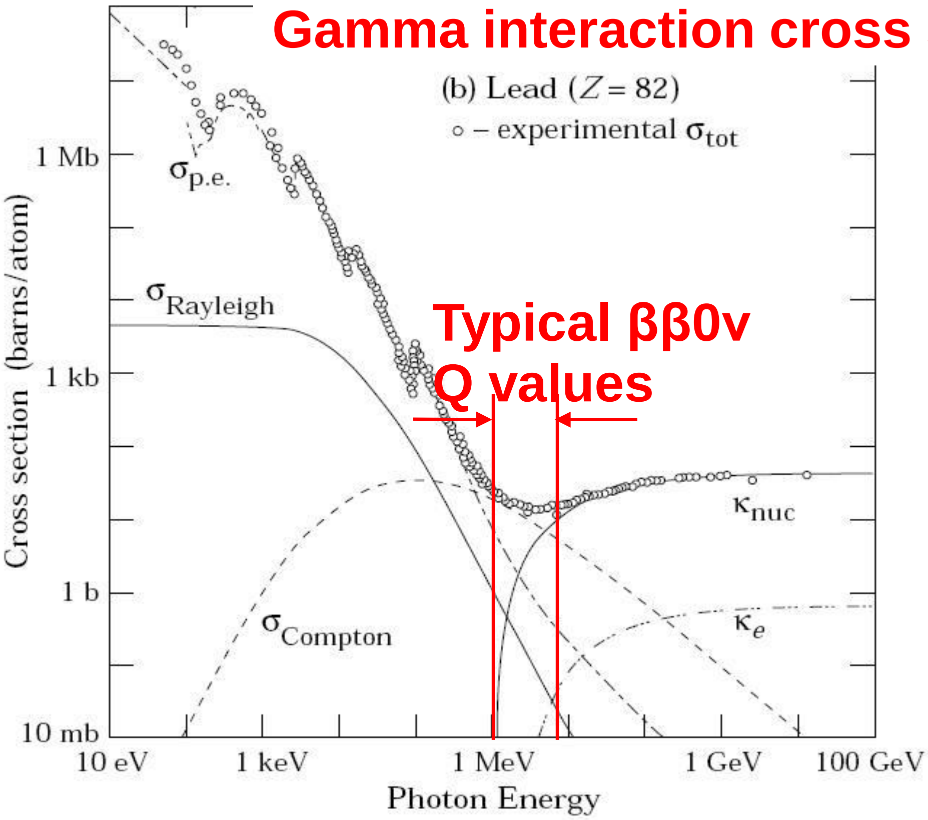
The optimal combination of parameters does depend on the size of the detector and on new techniques constantly being developed.

0νββ searches are quite different from Dark Matter ones

0νββ decay searches	Dark Matter searches
Optimize for energy resolution at O(2MeV)	Optimize for <100keV threshold
Gamma ray shielding essential	Neutron shielding essential
Signal is electron-like	Signal is nuclear recoil-like
Isotopic enrichment	2νββ is a background
Self shielding starts being useful at 100kg scale	Infinite self shielding, external backgrounds generally not important

But there is synergy in the detector development for some of the technologies

Shielding a detector from ~MeV γs is difficult!



Gamma interaction cross section

Typical ββ0v Q values

Example:

γ interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

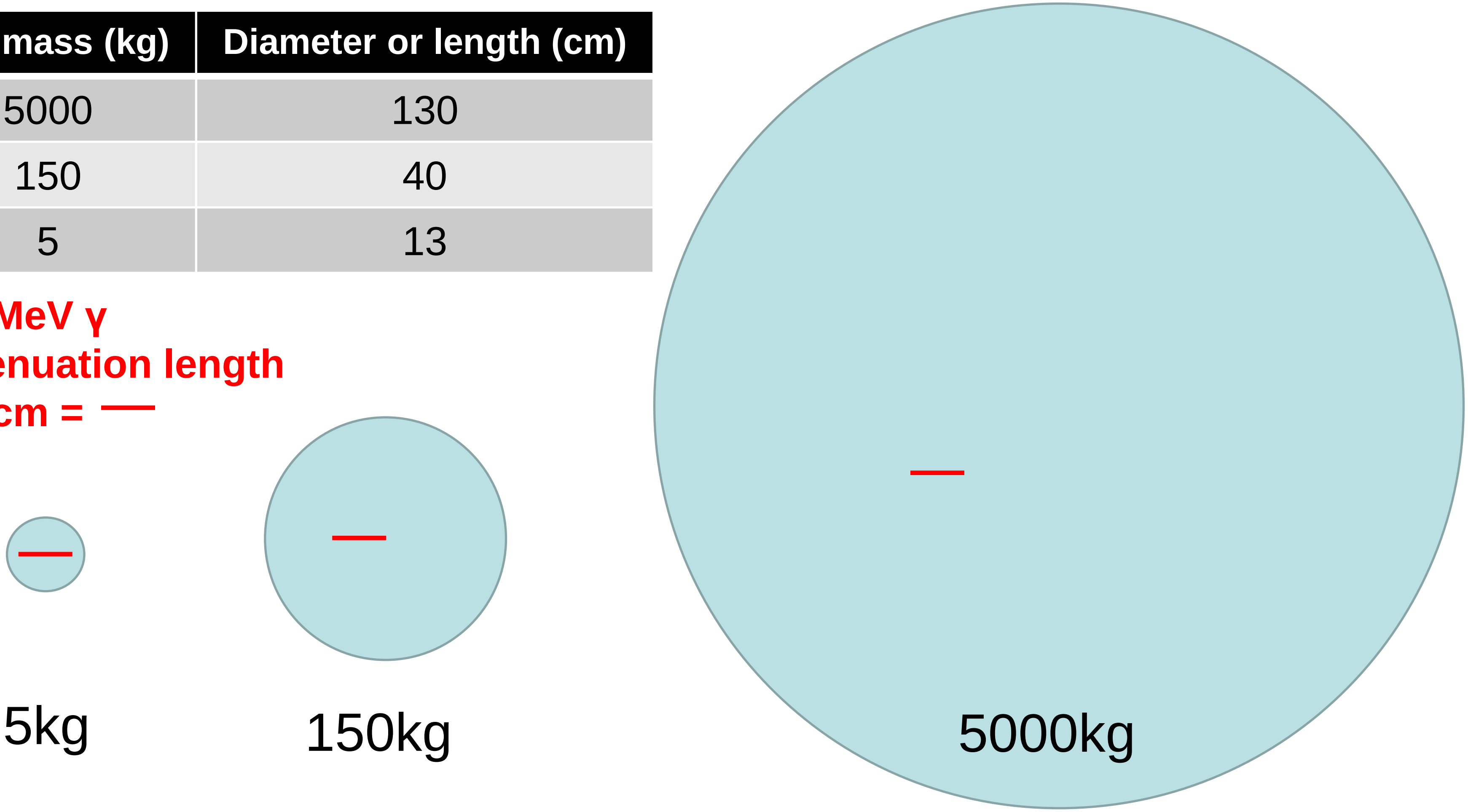
Shielding ββ decay detectors is much harder than shielding Dark Matter ones

We are entering the “golden era” of ββ decay experiments as detector sizes exceed int lengths

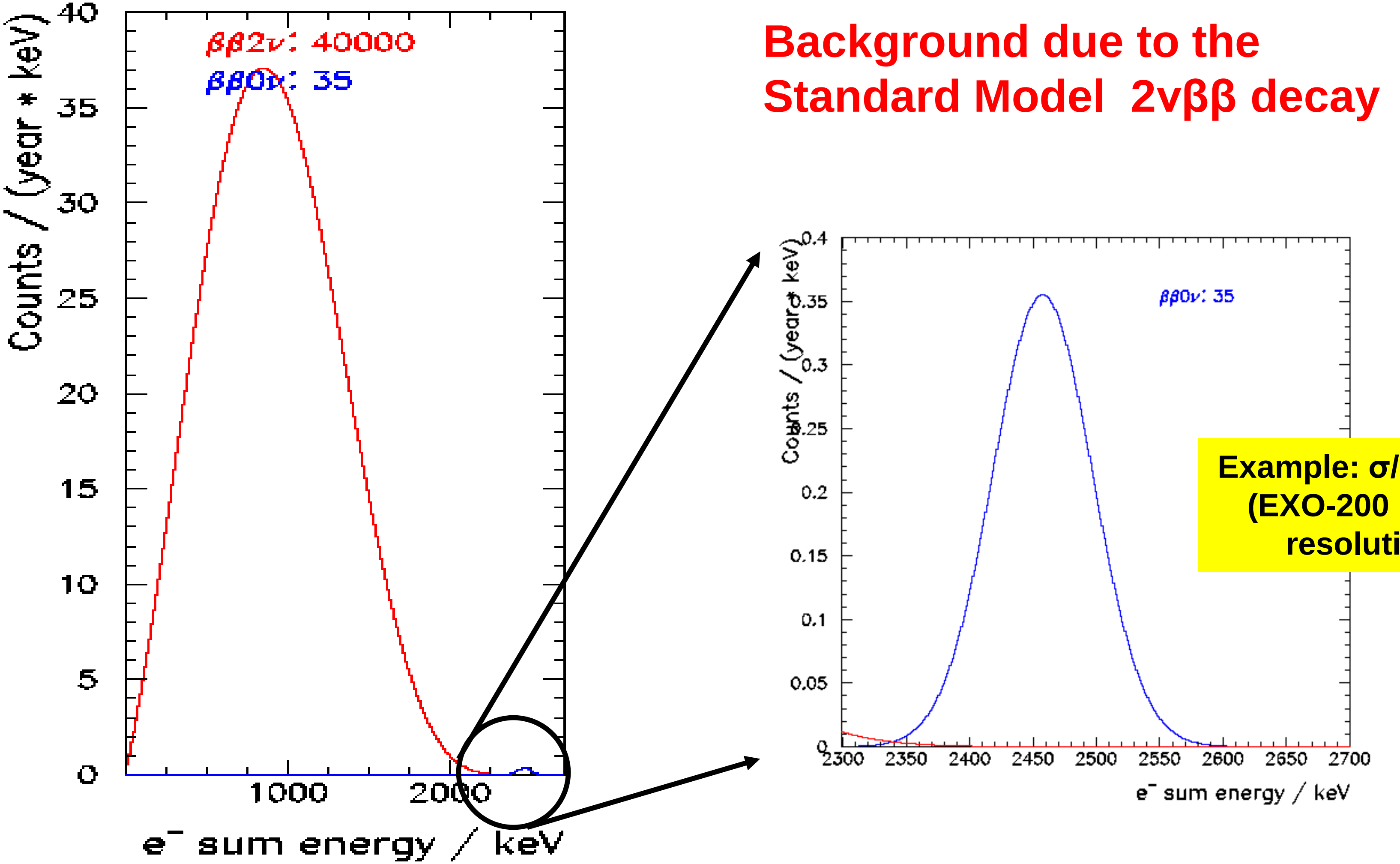
Moving forward, monolithic is very attractive

LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

2.5MeV γ attenuation length 8.5cm = —



Background due to the Standard Model 2νββ decay



Example: σ/E=1.6%
(EXO-200 initial
resolution)

Subtracting the tail under the 0νββ peak is tricky and, irrespective of other background considerations, sufficient energy resolution is required.

Of course goal of 0νββ experiments is to make a discovery

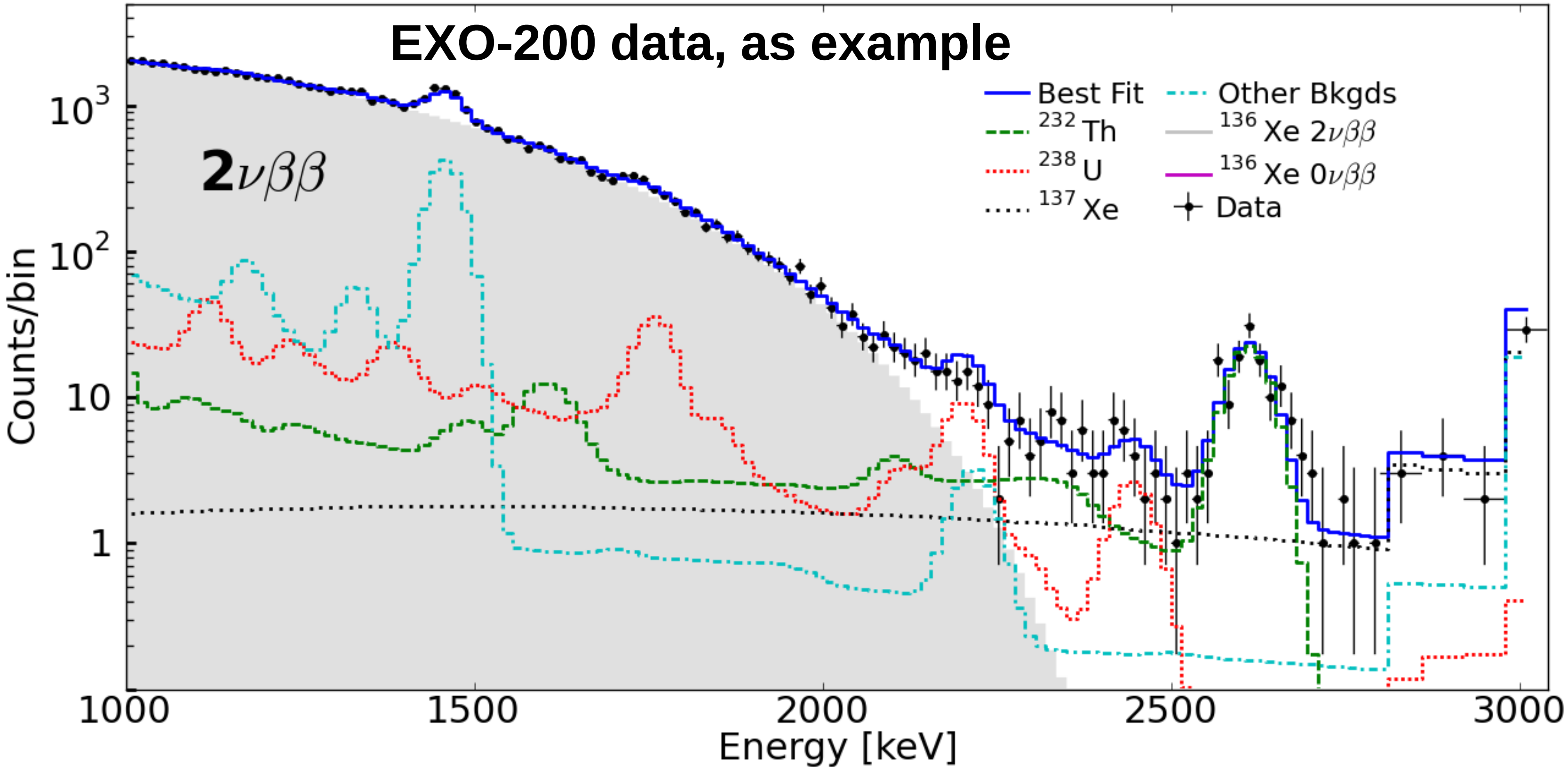
--setting a limit is the fall back position!

So, making sure that experiments have sensitivity is also very important

One can think of the 2νββ in a more positive way,

as Nature's "blind injection"

–these events look like 0νββ events, extending in energy just below the Q-value.



EXO-200 data, as example

A healthy neutrinoless double-beta decay program requires more than one isotope.

This is because:

- ***There could be unknown γ transitions and a line observed at the "end point" in one isotope does not necessarily imply the 0νββ decay discovery***
- ***Nuclear matrix elements are not very well known and any given isotope could come with unknown liabilities***
- ***Different isotopes correspond to vastly different experimental techniques***
- ***2 neutrino background is different for various isotopes***
- ***The elucidation of the mechanism producing the decay requires the analysis of more than one isotope***

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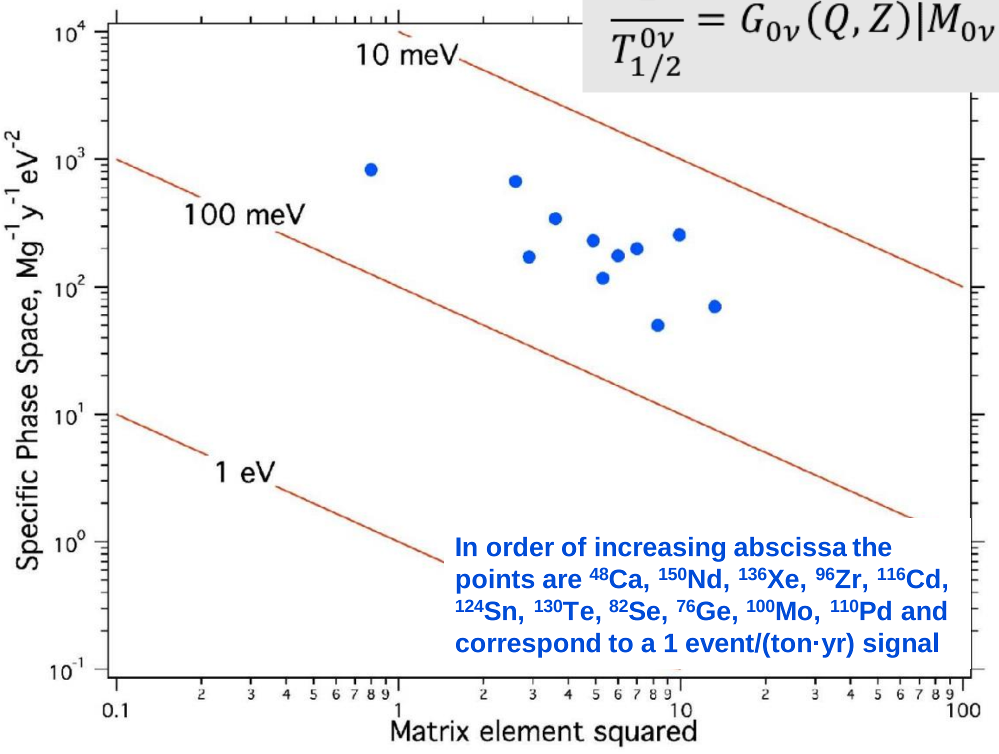
Can we just concentrate on the best isotope?

Many isotopes have comparable sensitivities

(at least in terms of rate per unit neutrino mass using the standard SeeSaw)

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q,Z)|M_{0\nu}|^2\langle M_{0\nu}\rangle$$



In order of increasing abscissa the points are ^{48}Ca, ^{150}Nd, ^{136}Xe, ^{96}Zr, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{82}Se, ^{76}Ge, ^{100}Mo, ^{110}Pd and correspond to a 1 event/(ton·yr) signal

R.G.H. Robertson, MPL A 28 (2013) 1350021

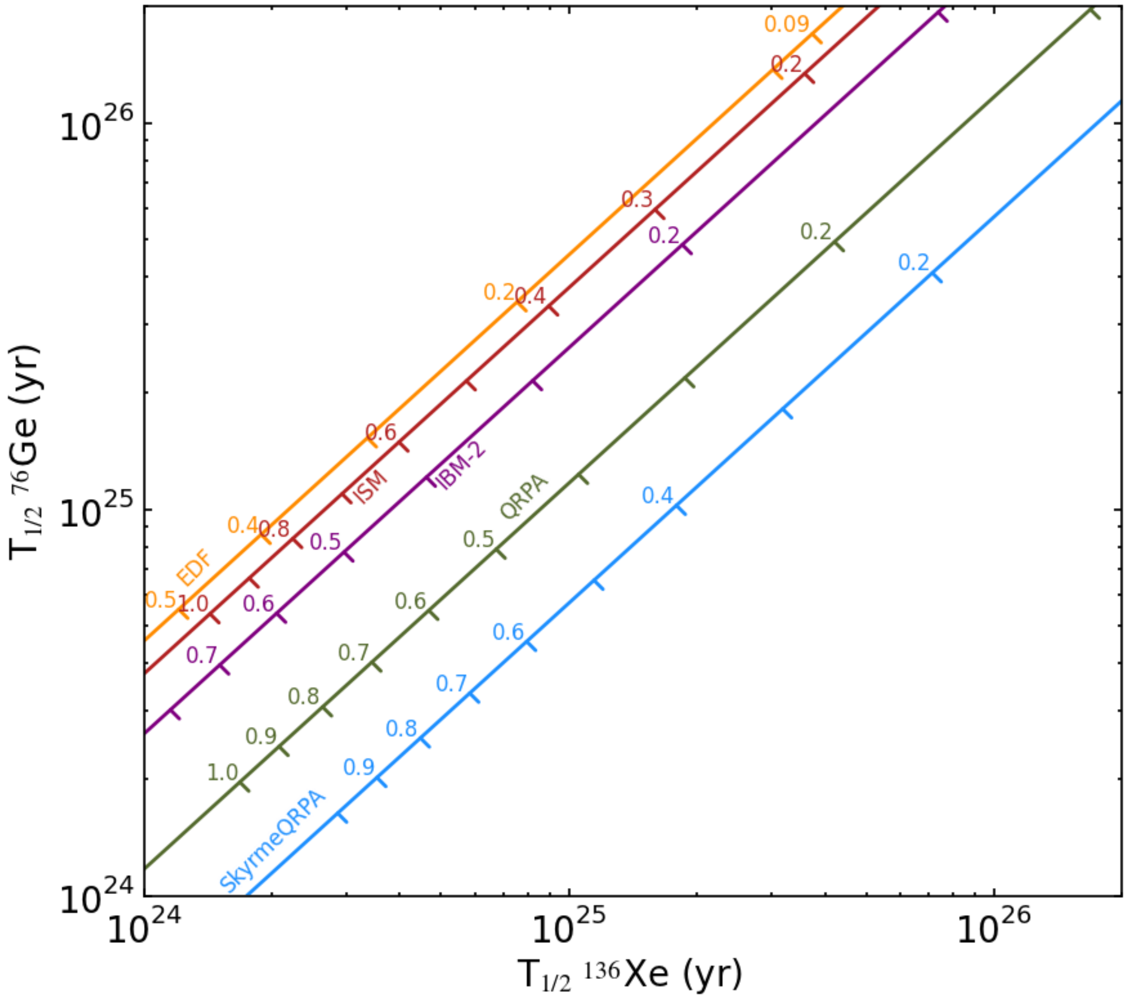
There is an "empirical" anticorrelation between phasespace and NME.

The choice between isotopes is more a choice between different techniques and the performance they have achieved *in actually running* detectors.

This is essential for the tonne scale, where we are talking about ~100M$ investments.

Because of the uncertainties in the $0\nu\beta\beta$ decay mechanism and the NME, accurate comparisons between different isotopes are non-trivial.

Example using ^{136}Xe and ^{76}Ge (and assuming standard SeeSaw)



EDF: Vaquero et al, PRL 111, 142501 (2013)
ISM: Menendez et al, Nucl. Phys. A818, 139 (2009)
IBM-2: Barea et al, PRC 91, 034304 (2015)
QRPA: Engel et al, PRC 89, 064308 (2014)
SkyrmeQRPA: Mustonen et al, PRC 87, 064302 (2013)

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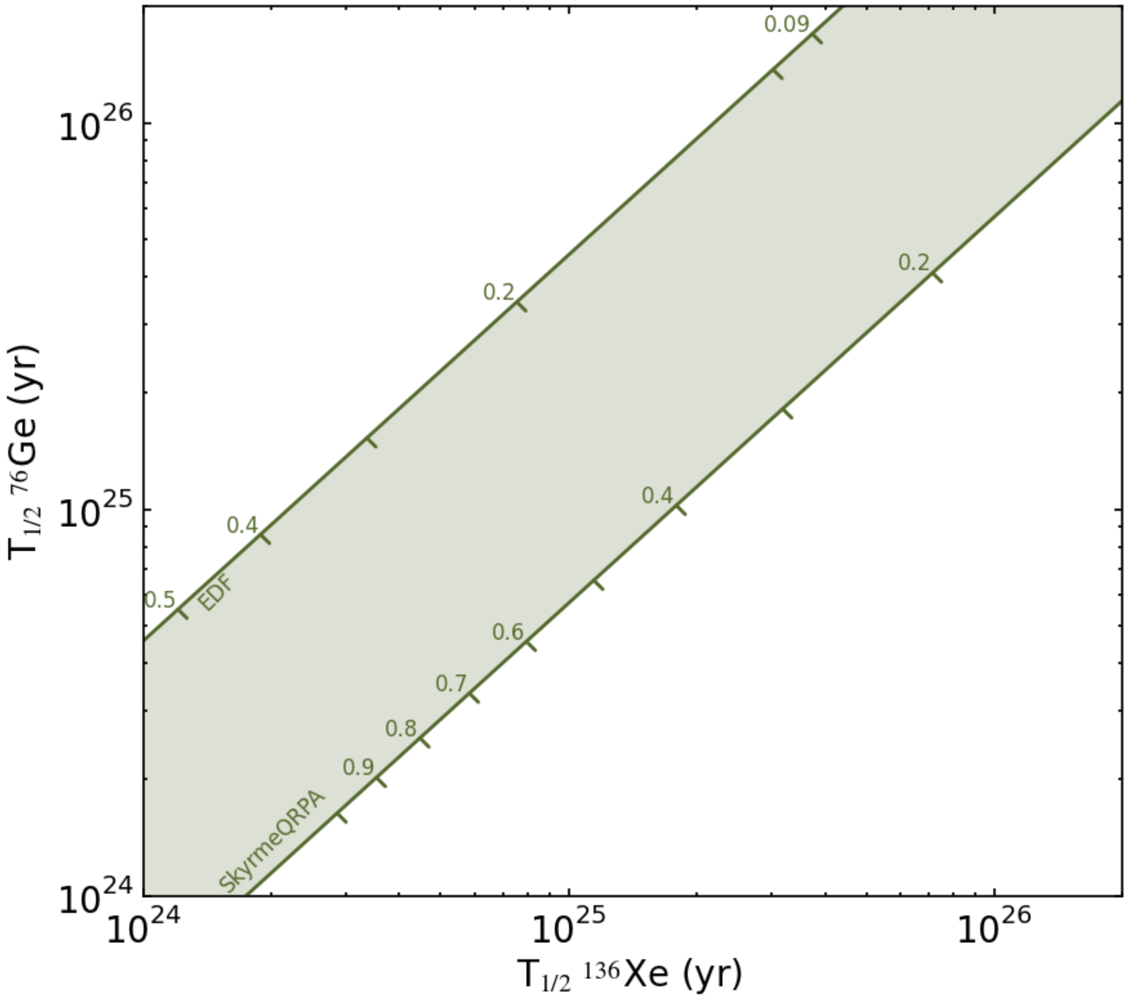

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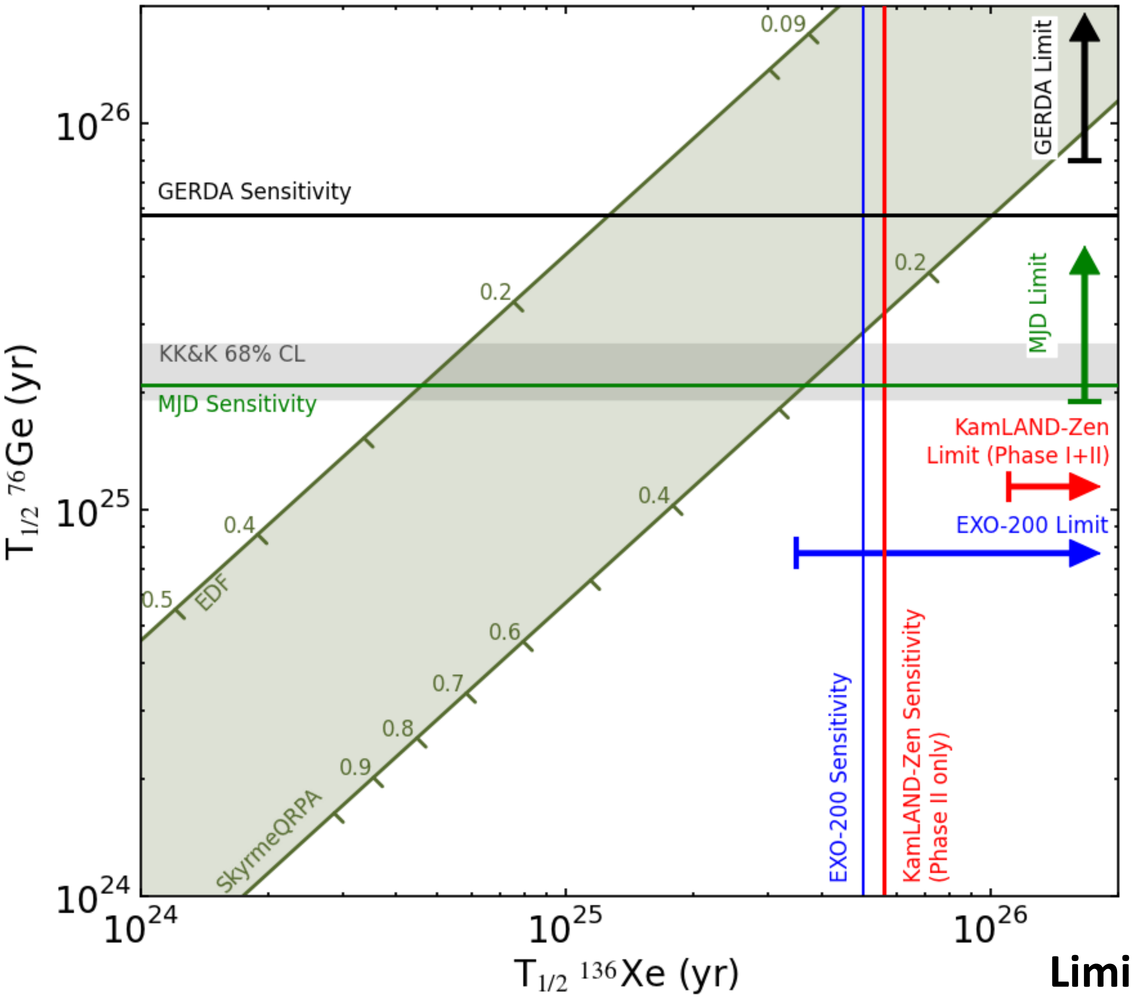


Limits are 90% CL

GERDA: M. Agostini et al., Phys. Rev. Lett. 120(2018) 132503
KLZ: A. Gando et al., Phys. Rev. Lett. 117(2016) 082503
MJD: C.E. Aalseth et al., Phys. Rev. Lett. 120 (2018) 132502
New EXO-200: G.Anton et al., arXiv:1906.02723 (2019)

One (my own) possible classification of technologies

(keeping in mind that real things are always more complex than classifications!)

Crystals

- **GERDA, Majorana (^{76}Ge)**
- **CUORE, CUPID (^{130}Te, ^{100}Mo)**

Pros: Superb energy resolution, 2-parameter measurement

Cons: Intrinsically fragmented

Liquid (organic) scintillators

- **KamLAND-ZEN (^{136}Xe)**
- **SNO+ (^{130}Te)**

Pros: “simple”, large detectors exist, self-shielding

Cons: Not very specific, 2ν background

Low density trackers

- **NEXT, PandaX (^{136}Xe gas TPC)**
- **SuperNEMO (foils and gas tracking, ^{82}Se)**

Pros: Superb topological information

Cons: Very large size → expensive

Liquid TPC

- **nEXO (^{136}Xe)**

Pros: Homogeneous with good E resolution and topology

Cons: Does not excel in any single parameter

Recent results (>10^{25} yr half life)

Isotope	Experiment	Isotope exposure (kg yr)	$T^{0\nu\beta\beta}_{1/2}$ average sensitivity (10^{25} yr)	$T^{0\nu\beta\beta}_{1/2}$ limit 90CL (10^{25} yr)	$T^{0\nu\beta\beta}_{1/2}$ limit 90CL (13.8 Gyr)	$\langle m_\nu \rangle$ range from NME * (meV)	Reference
^{76}Ge	Gerda	82	5.8	>8	$>5.8\cdot10^{15}$	<120-260	Agostini et al., PRL 120 (2018) 132503
	Majorana	26	4.8	>2.7	$>1.9\cdot10^{15}$	<200-433	Alvis et al., arXiv:1902.02299 (2019)
^{130}Te	CUORE	24	0.7	>1.3	$>9.4\cdot10^{14}$	<110-520	Alduino et al., PRL 120 (2018) 132501
^{136}Xe	EXO-200 New	341	5.0	>3.5	$>2.5\cdot10^{15}$	<93-286	Anton et al. arXiv:1906.02723 (2019)
	KamLAND-ZEN	504	5.6	>10.7	$>7.7\cdot10^{15}$	<61-165	Gando et al., PRL 117 (2016) 082503

* Note that the range of "viable" NME is chosen by the experiments and uncertainties related to g_A are not included

I will concentrate on these proven techniques in the rest, while just mentioning (or omitting --apologies) many other concepts and ideas.

I will omit discussing bolometers since there is a dedicated talk by F.Bellini (Cuore/Cupid)

The next step:
ton-scale detectors entirely covering the inverted hierarchy

Testing lepton number violation
with >100x the current $T_{1/2}$ sensitivity.

Modern 0νββ detectors are truly beautiful machines, with every component carefully optimized to work in harmony with everything else.

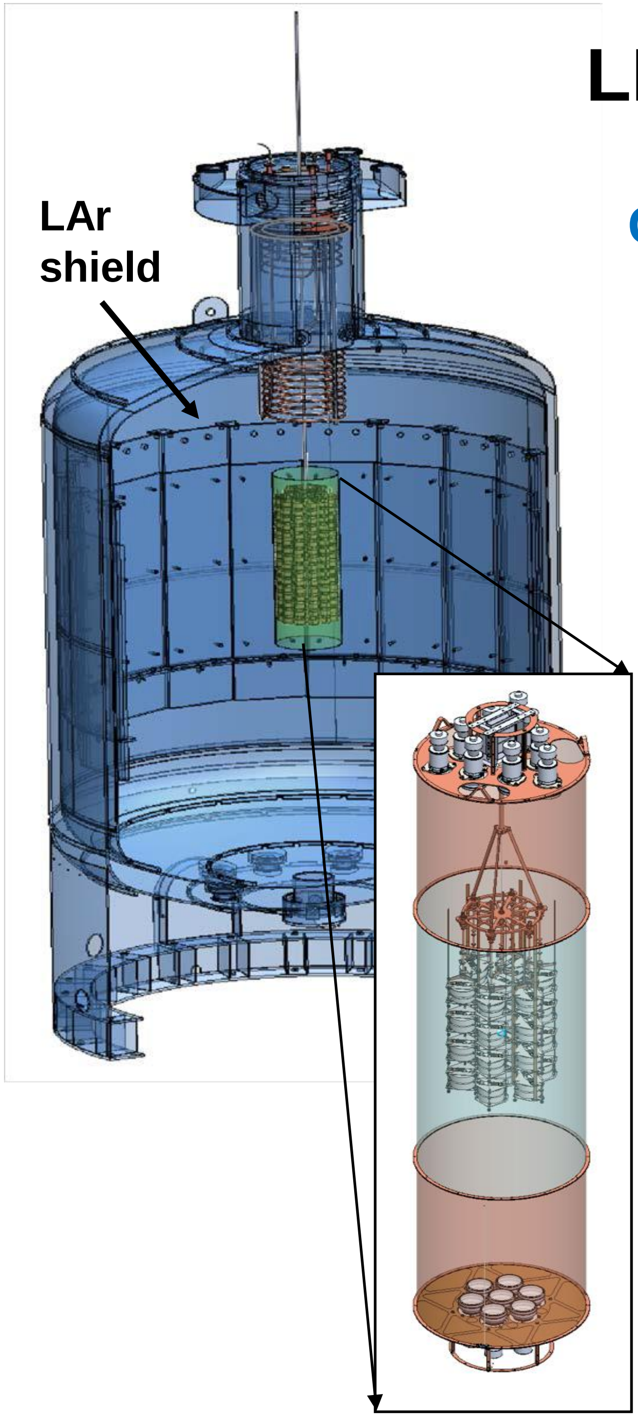
A tour of the proposed techniques.

A (possibly controversial) rambling on scalability and unbiased measurements

- Much has been said about the appropriateness of performing blind analyses to obtain unbiased experiments. "With moderation" this is, of course, very good.
- Much has been said about the convenience (particularly when seeking funding!) of scalable detectors, whereby the active mass can be increased gradually.

But, these two laudable ideas are not entirely compatible with each other! In some extreme every increase of detector mass is guaranteed not to be able to make a discovery and the discovery occurs adiabatically by means of a never-improving limit and liability to biases.

LEGEND: ^{76}Ge detectors



Ge counters played an essential role in the early developments on the field.

E.Fiorini et al. Phys Lett 25B (1967) 602

Merging of Gerda and Majorana programs

- ***Infrastructure***
- ***LAr active veto***
- ***low-A shield***

- *Electroformed Cu*
- *Low-E threshold*
- *Radio-pure low-noise electronics*

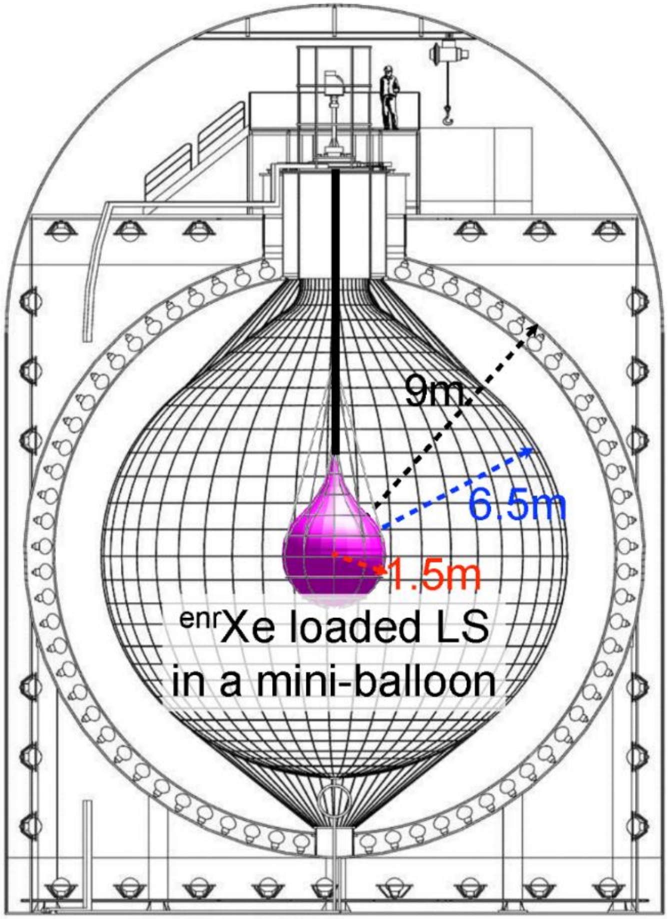
First stage: (Legend-200)

- **(up to) 200 kg by upgrading the existing infrastructure at LNGS**
- **Background goal 0.6 cts/(FWHM t yr)**
- **Data start ~2021**

Subsequent stages:

- **1000 kg, staged via individual payloads**
- **Background goal <0.1 cts/(FWHM t yr)**
- **Required depth (Ge-77m) under investigation**

Isotope dissolved in a large liquid scintillation detector
More advanced detector KamLAND-ZEN, using ^{136}Xe



In many ways this is the "extreme opposite" to the Ge and bolometric detectors (poor energy resolution, not very specific, "low tech" but huge and homogeneous)

KamLAND detector:

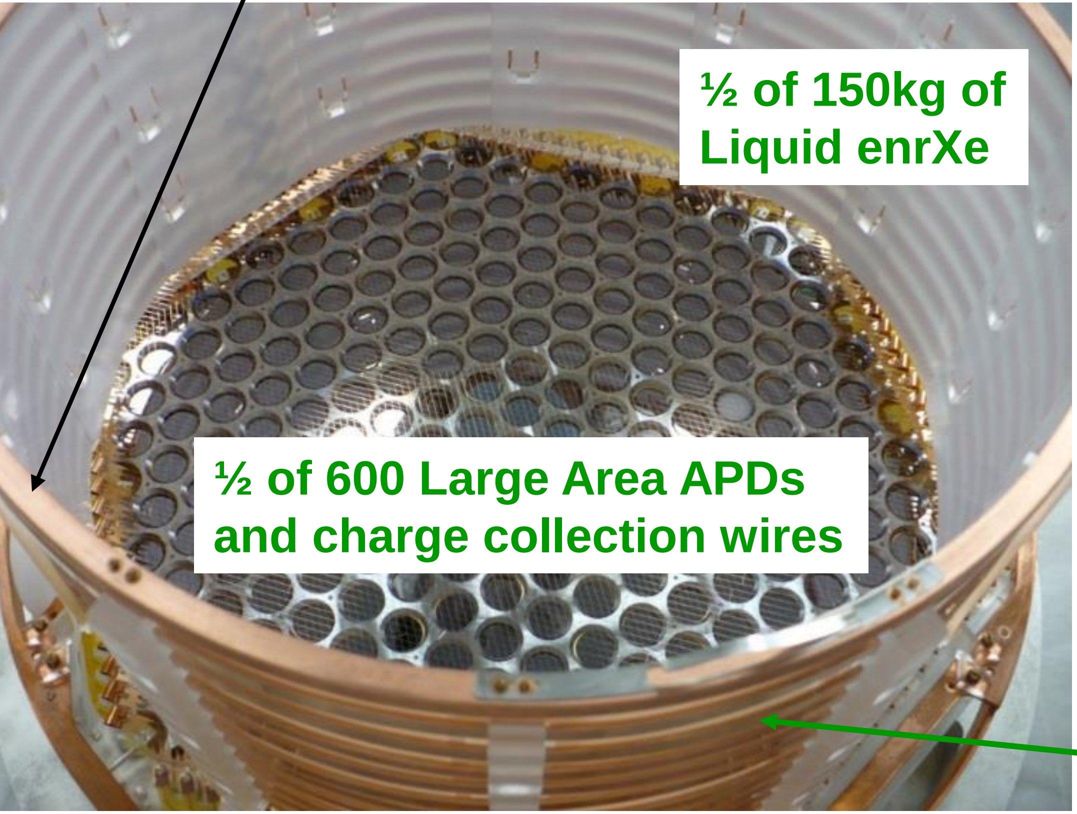
- **1kton of isoparaffine-pseudocumene liquid scintillator**
- **~2000 20"/17" PMTs**
- **~2.5m-thick paraffine buffer to shield active volume from PMT activity**
- **External, active water Cherenkov veto**
- **"Ballon" separates active (scintillating) volume from non-scintillating buffer**
- **Taking data since 2002, with glorious contributions to neutrino oscillation (reactors) and geo-neutrino measurements**

- **Added "miniballoon" to contain the ^{136}Xe-doped scintillator**

Liquid Xe Time Projection Chambers:
EXO-200 and nEXO

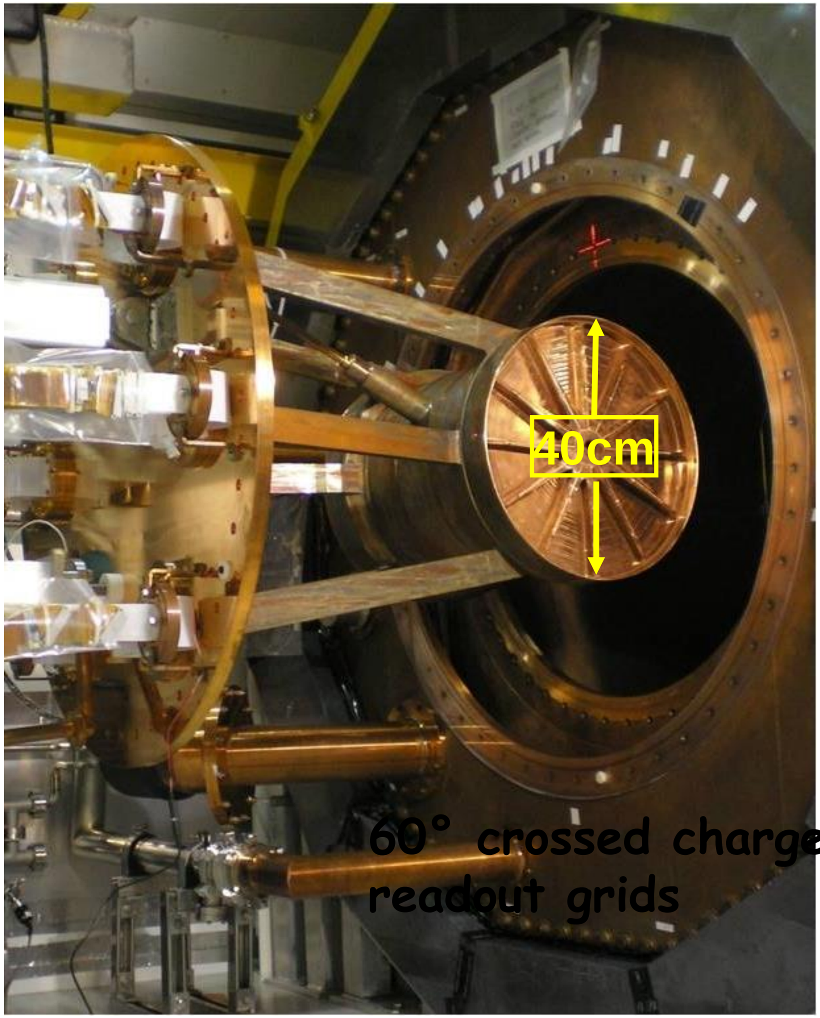
Example:
the EXO-200 detector

Cathode (not shown)



½ of 150kg of Liquid enrXe

½ of 600 Large Area APDs and charge collection wires



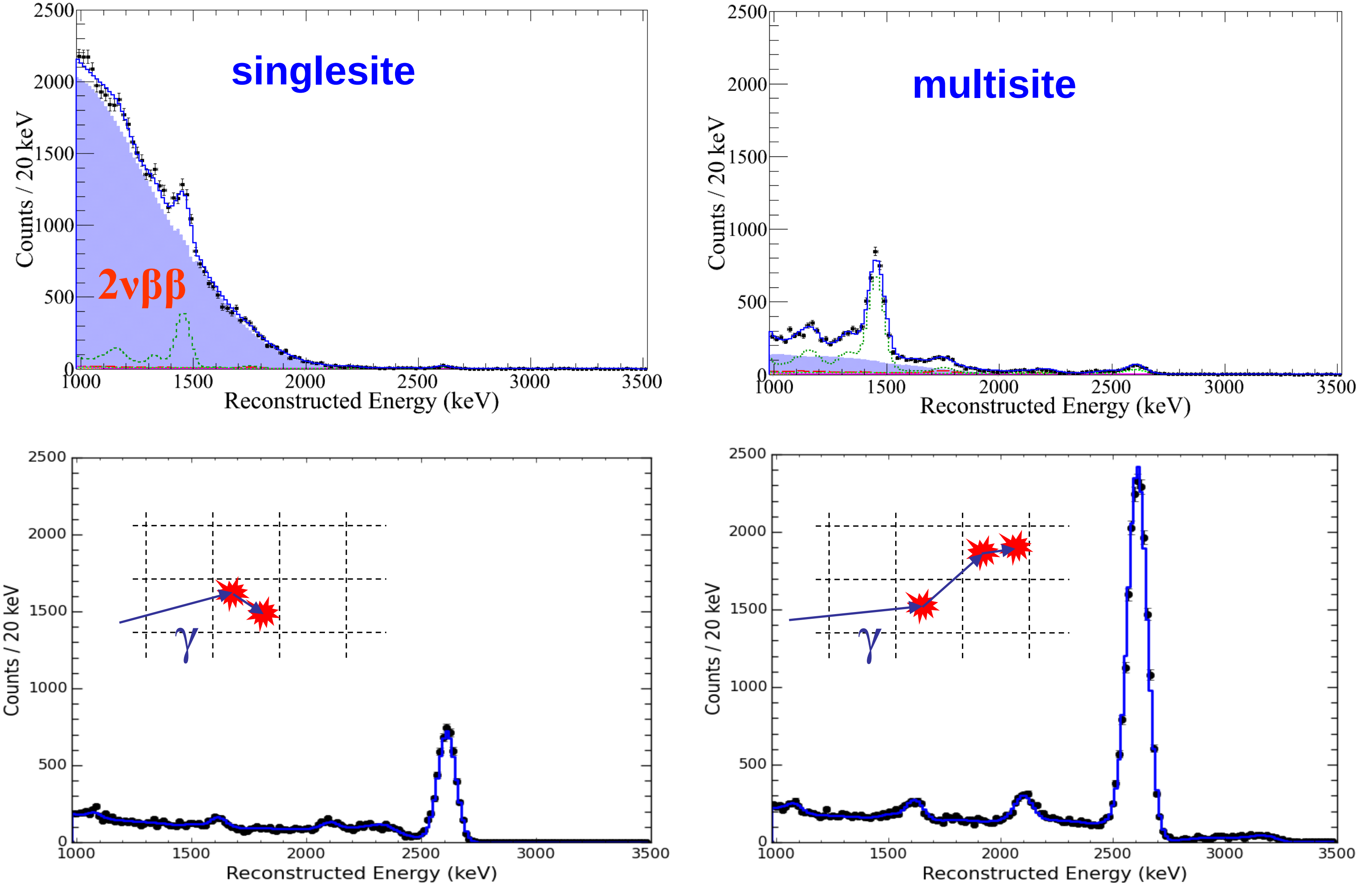
60° crossed charge readout grids

Field-shaping rings

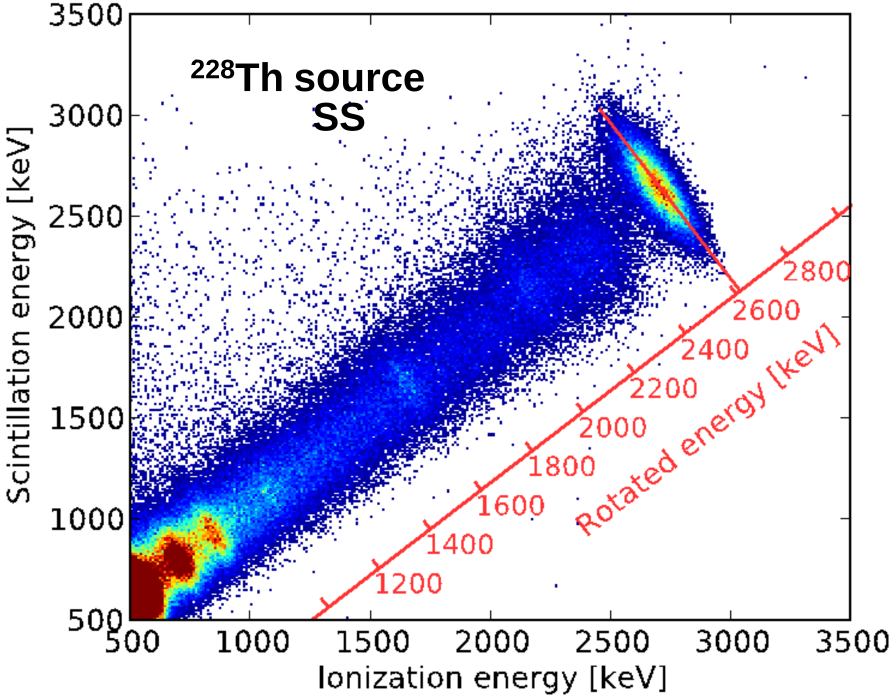
Using event multiplicity to recognize the dominant γ backgrounds

Low background data

^{228}Th calibration source



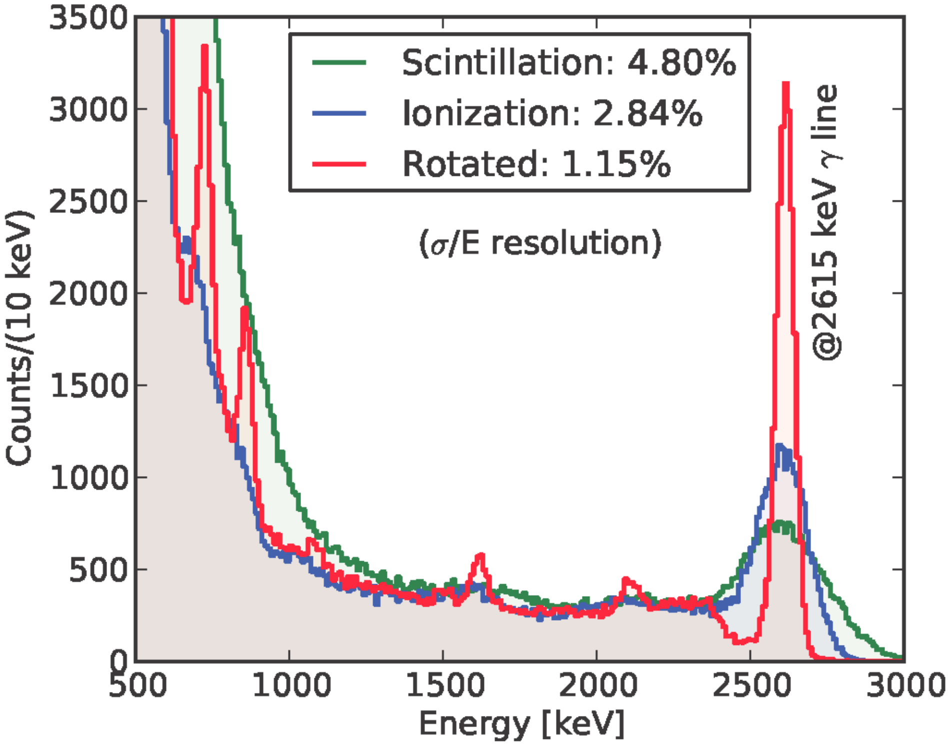
Combining Ionization and Scintillation to obtain the best energy resolution



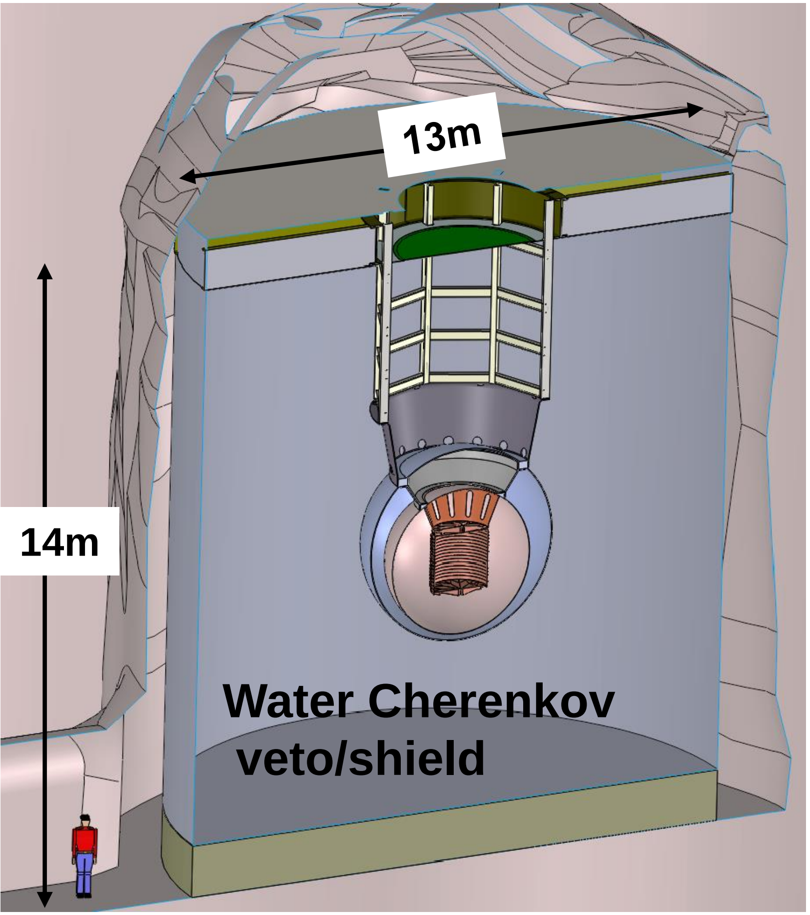
While no one really understands the energy resolution in LXe, scintillation and ionization are anticorrelated and this can be exploited to improve the energy resolution

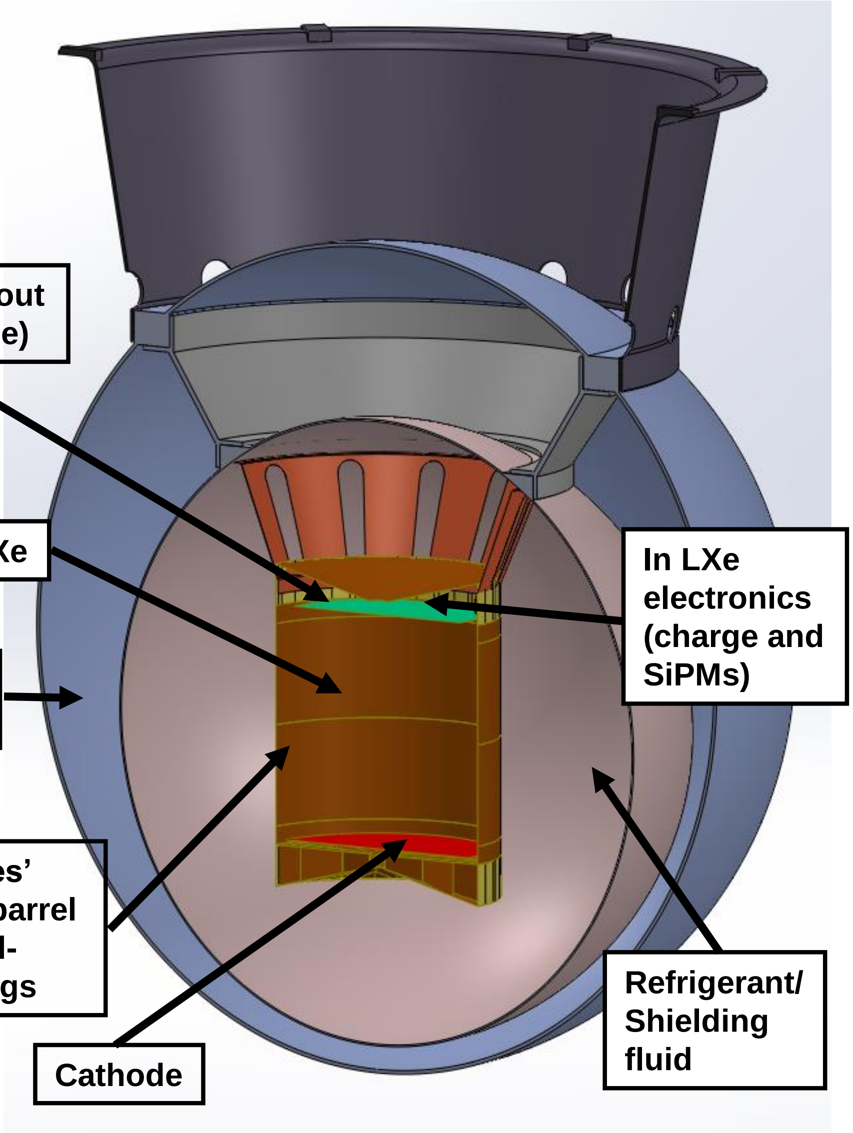
E.Conti et al. Phys Rev B 68 (2003) 054201

"Rotation angle" chosen to optimize energy resolution at 2615 keV



Moving towards the tonne scale: the 5000kg ^{enr}Xe nEXO detector




Charge readout strips (anode)

^{enr}LXe

Vacuum insulation

SiPM `staves' plastering barrel behind field-shaping rings

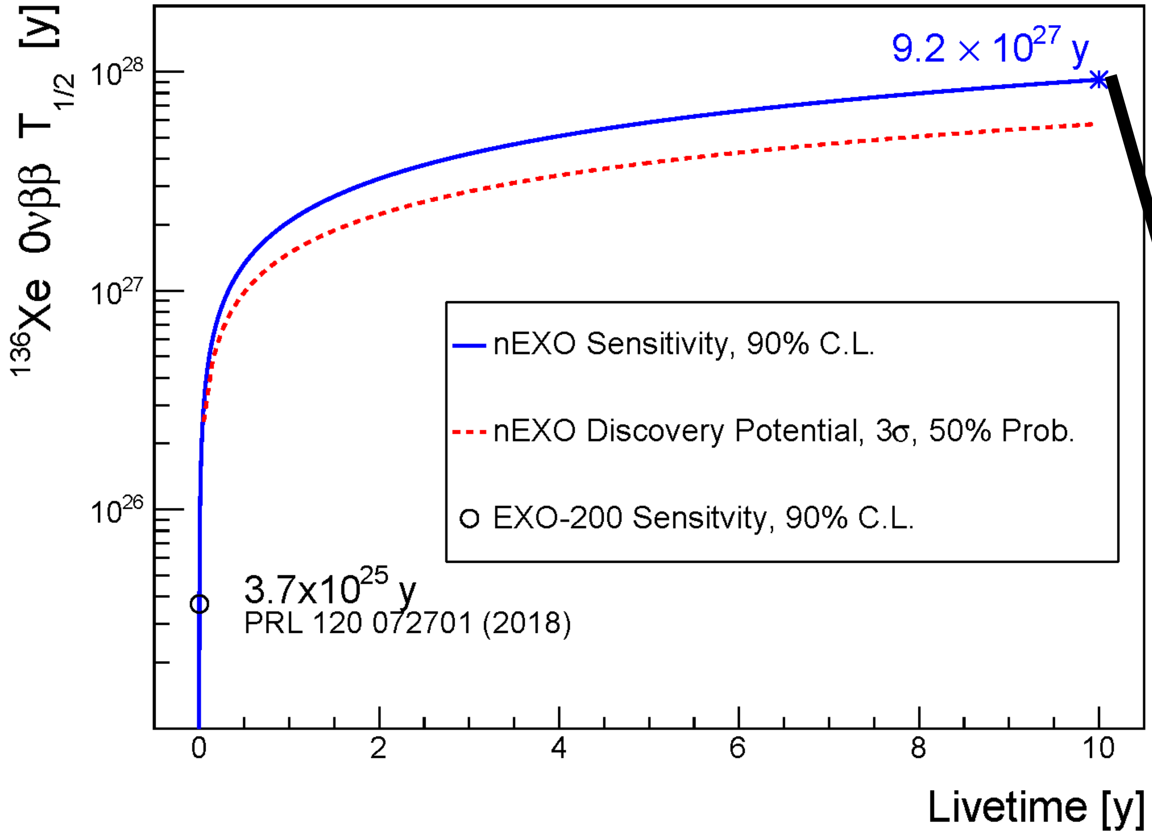
Cathode

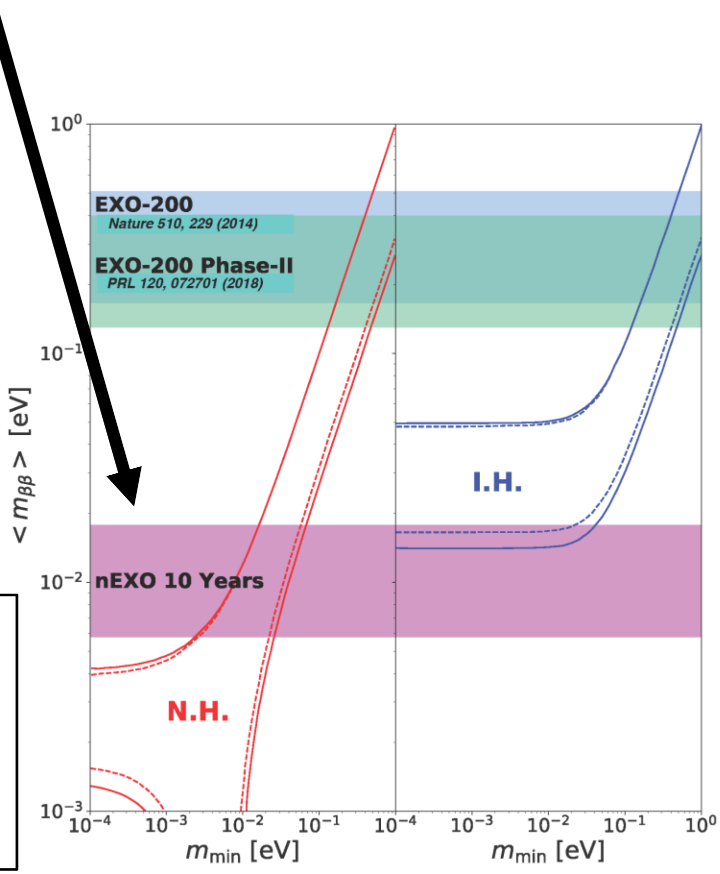
In LXe electronics (charge and SiPMs)

Refrigerant/ Shielding fluid

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

nEXO sensitivity as a function of time for the baseline design

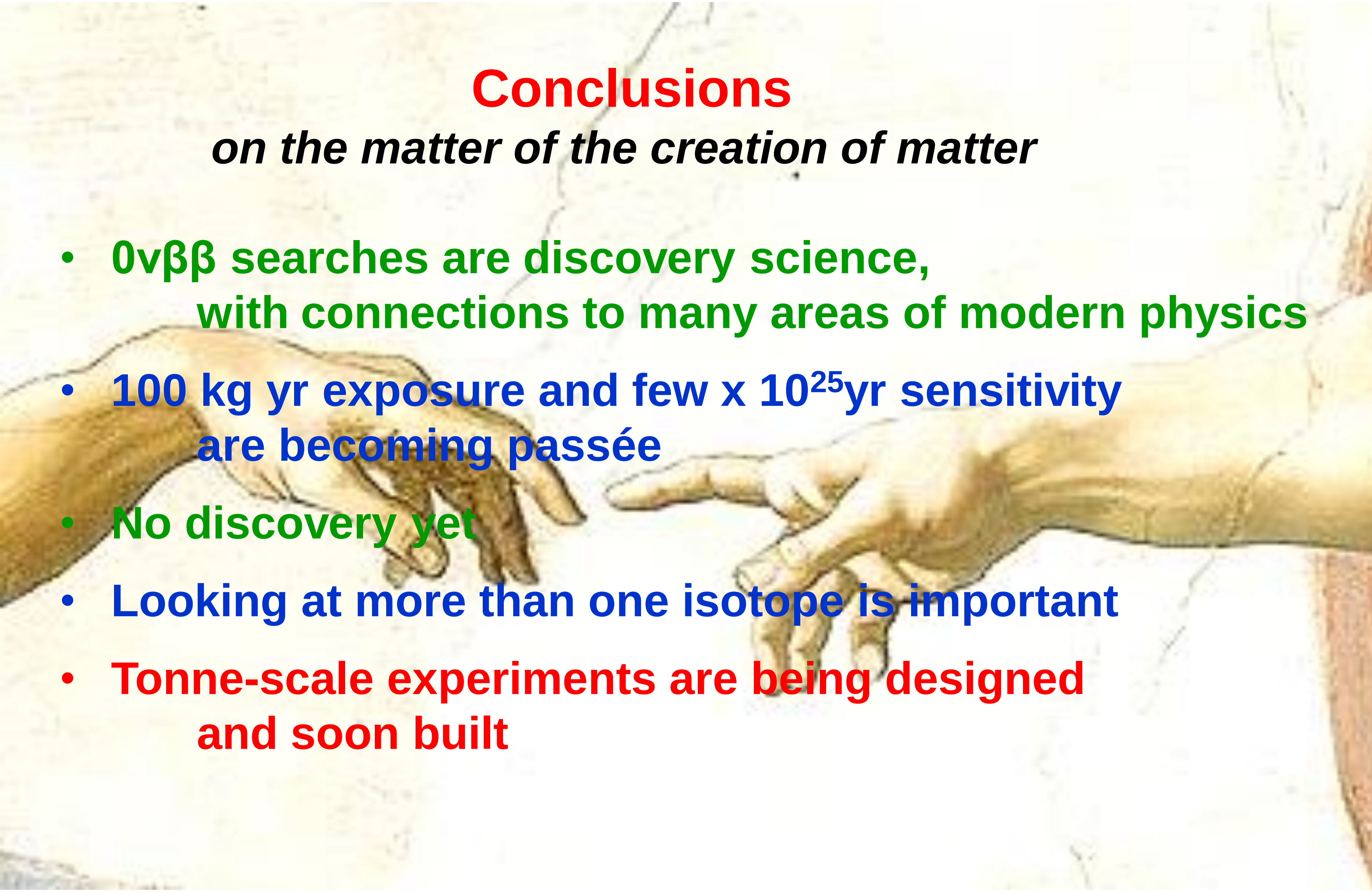




- $g_A = g_A^{free} = -1.2723$

- Band is the envelope of NME:

EDF: T.R. Rodríguez and G. Martínez-Pinedo, PRL 105, 252503 (2010)
ISM: J. Menendez et al., Nucl Phys A 818, 139 (2009)
IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)
QRPA: F. Šimkovic et al., PRC 87 045501 (2013)
SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)



Conclusions

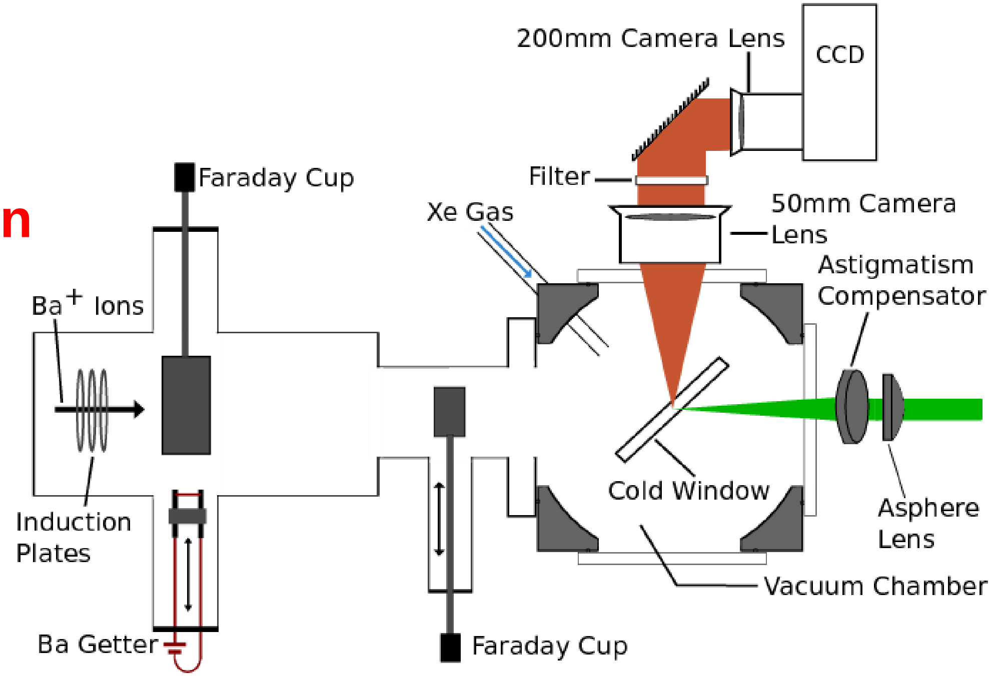
on the matter of the creation of matter

- 0νββ searches are discovery science, with connections to many areas of modern physics
- 100 kg yr exposure and few x 10^{25}yr sensitivity are becoming passée
- No discovery yet
- Looking at more than one isotope is important
- Tonne-scale experiments are being designed and soon built

In fact, ^{136}Xe offers the possibility to confirm a ββ decay by retrieving and tagging spectroscopically the Ba atom in the final state.

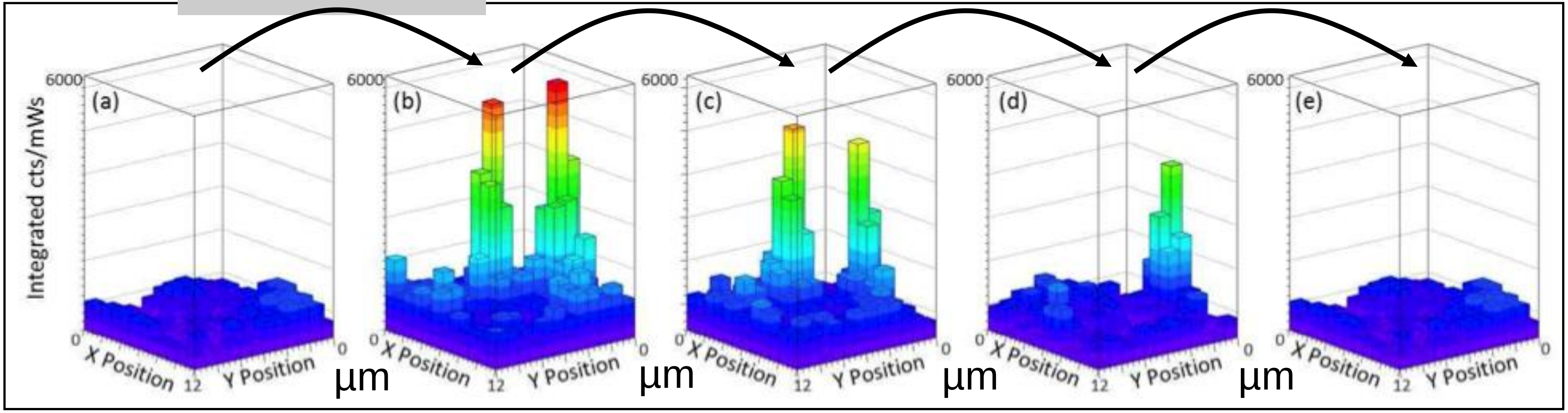
This is not necessary for nEXO to reach its design sensitivity and, indeed, it is not part of the design presented in the pre-CDR.

Nevertheless the "physics component" of the technique was recently demonstrated, including the ability to delete "old" Ba atoms (i.e. there is no "memory effect").



This work only addresses the physics feasibility, while the engineering of its implementation has not been explored yet.

Possibly Ba tagging could become a long term upgrade patch, extending the sensitivity of the experiment after a 5 to 10yr run in the baseline configuration.



Accelerator deposits a few atoms in the SXe matrix

Wait a little

Wait some more

Warm up

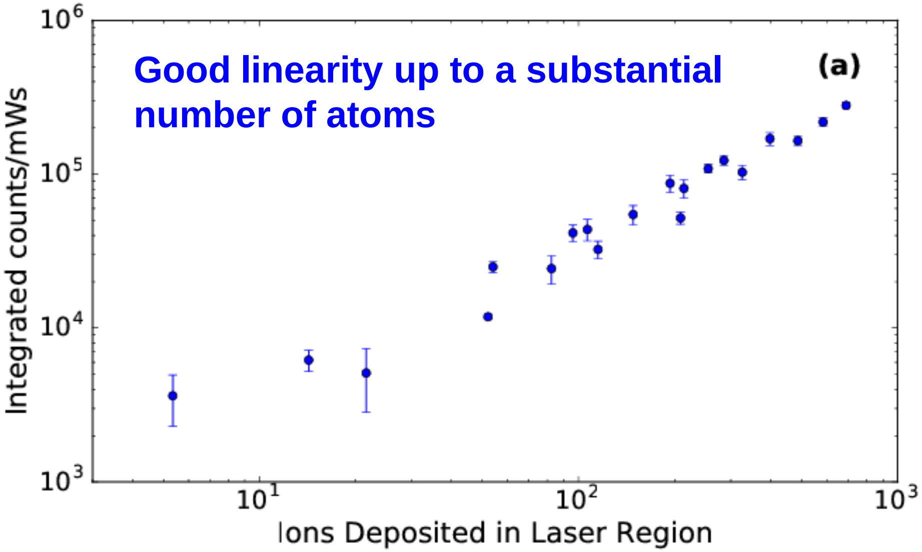
SXe but no Ba

Oh, there are two atoms!

The Ba signal is still present

One of the Ba signals is no longer present

Signal is erased, back to pre-Ba signals



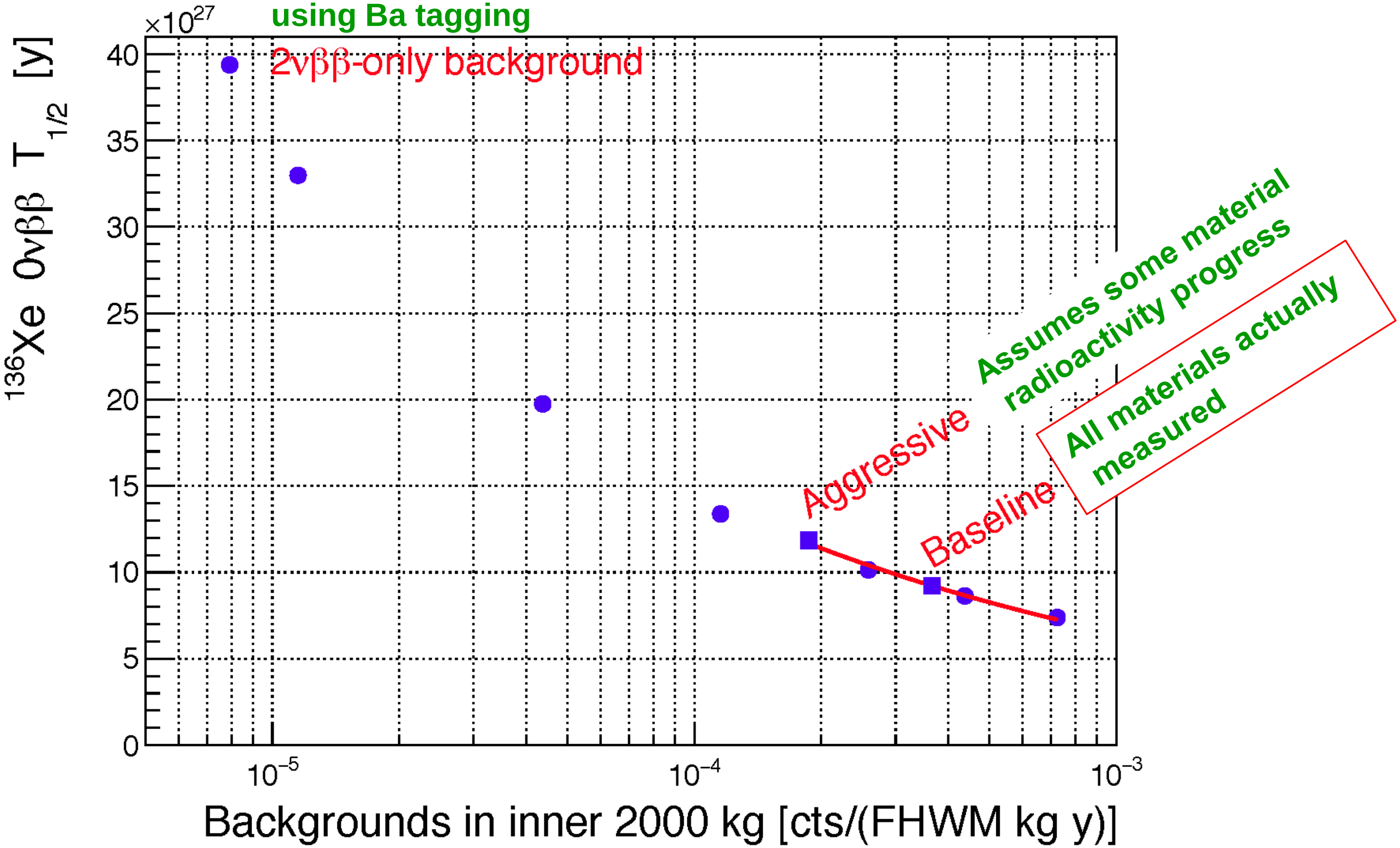
Good linearity up to a substantial number of atoms

C.Chambers et al. Nature 569 (2019) 203

see also similar result in
A.D. McDonald et al., Phys Rev Lett 120 (2018) 132504.

How does the sensitivity scale with background assumptions?

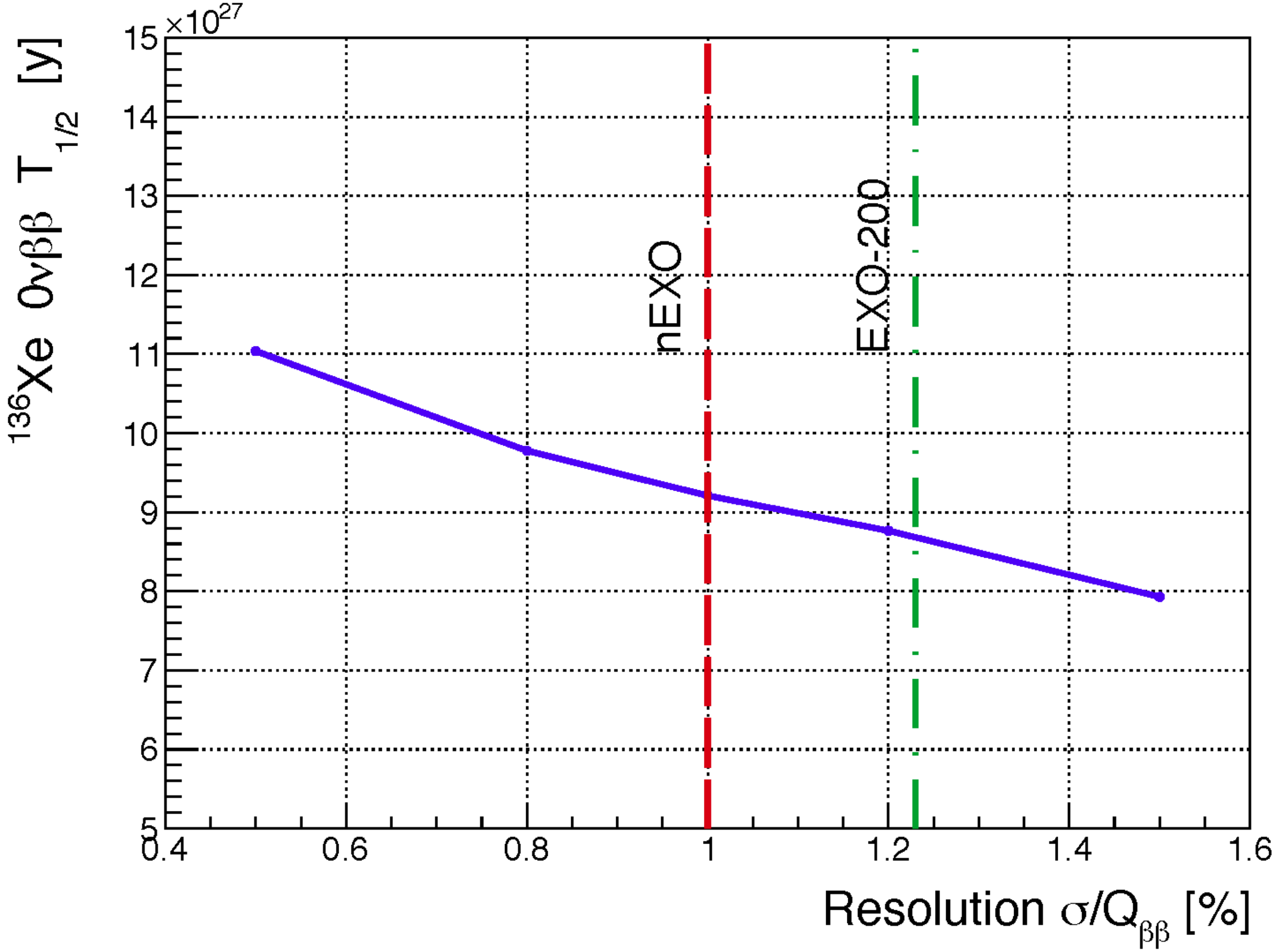
Asymptotic sensitivity
for a hypothetical upgrade
using Ba tagging



Assumes some material
radioactivity progress

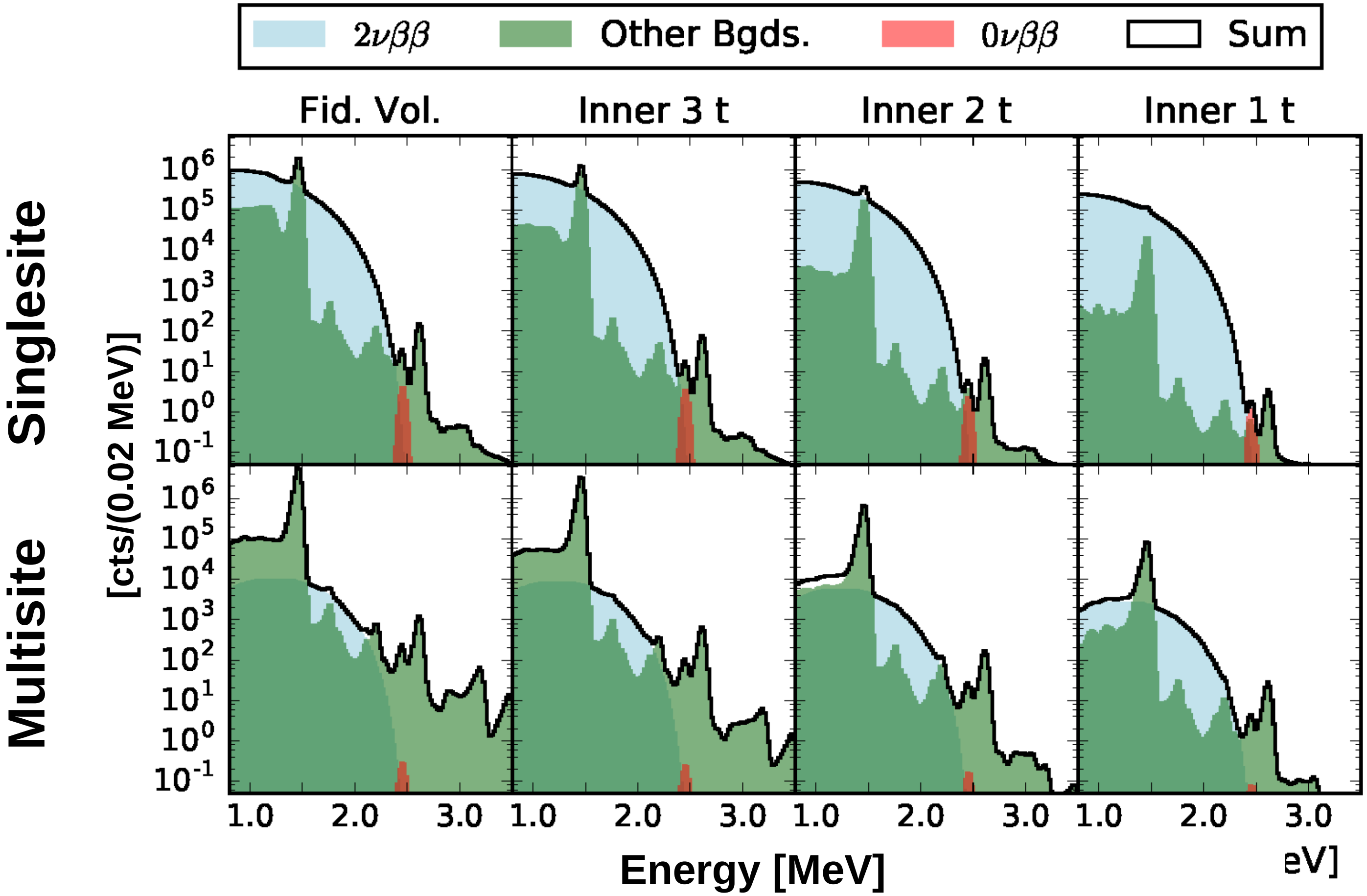
All materials actually
measured

…and with energy resolution



Particularly in the larger nEXO, background identification and rejection fully use a fit considering simultaneously energy, e-γ and α-β discrimination and event position.

➔ ***The power of the homogeneous detector, this is not just a calorimetric measurement!***



Corresponding to 10 yr data, with 0νββ $T^{1/2}=5.7\times10^{27}$ yr

So, a simple “background index” is not the entire story.

- ***The innermost LXe mostly measures signal***
- ***The outermost LXe mostly measures background***
- ***The overall fit knows all this (and more) very well and uses all the information available to obtain the best sensitivity***

Nevertheless, for the aficionados of “background index”, here it is, as a function of depth in the TPC. For the inner 3000 kg this is better than 10^{-3} (kg yr FWHM)$^{-1}$