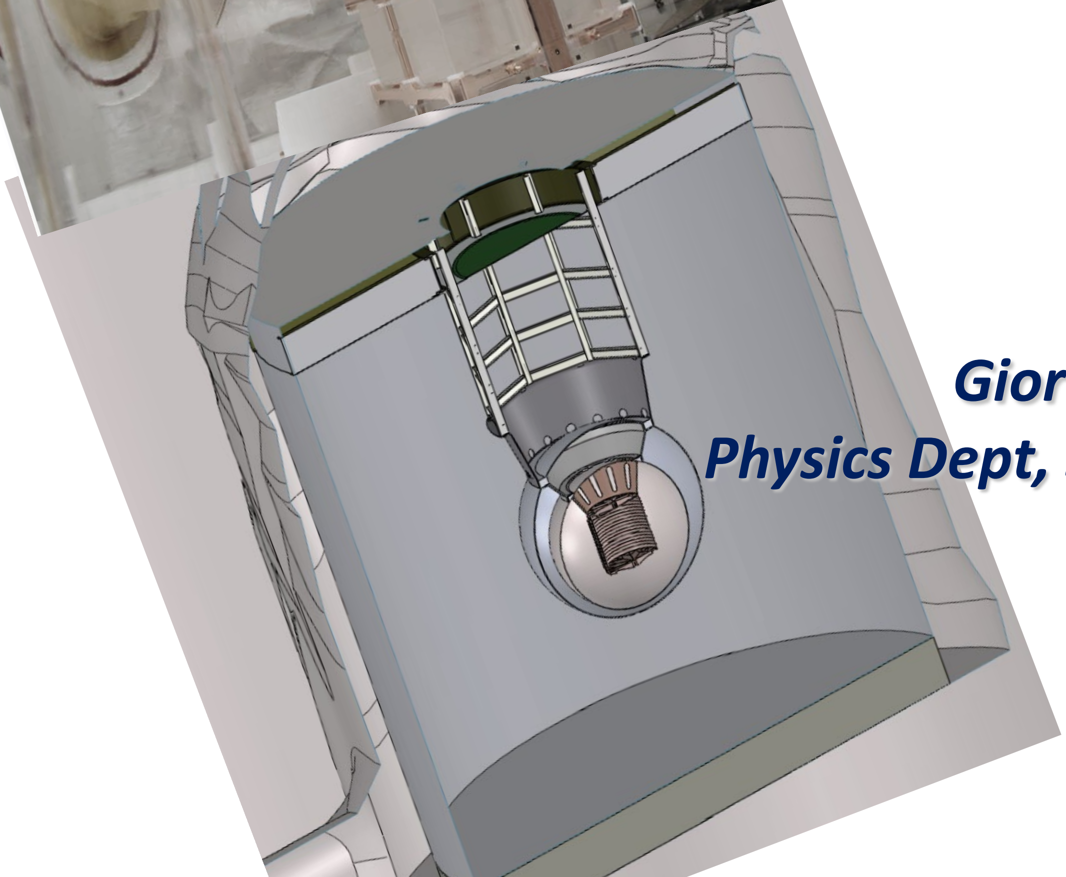
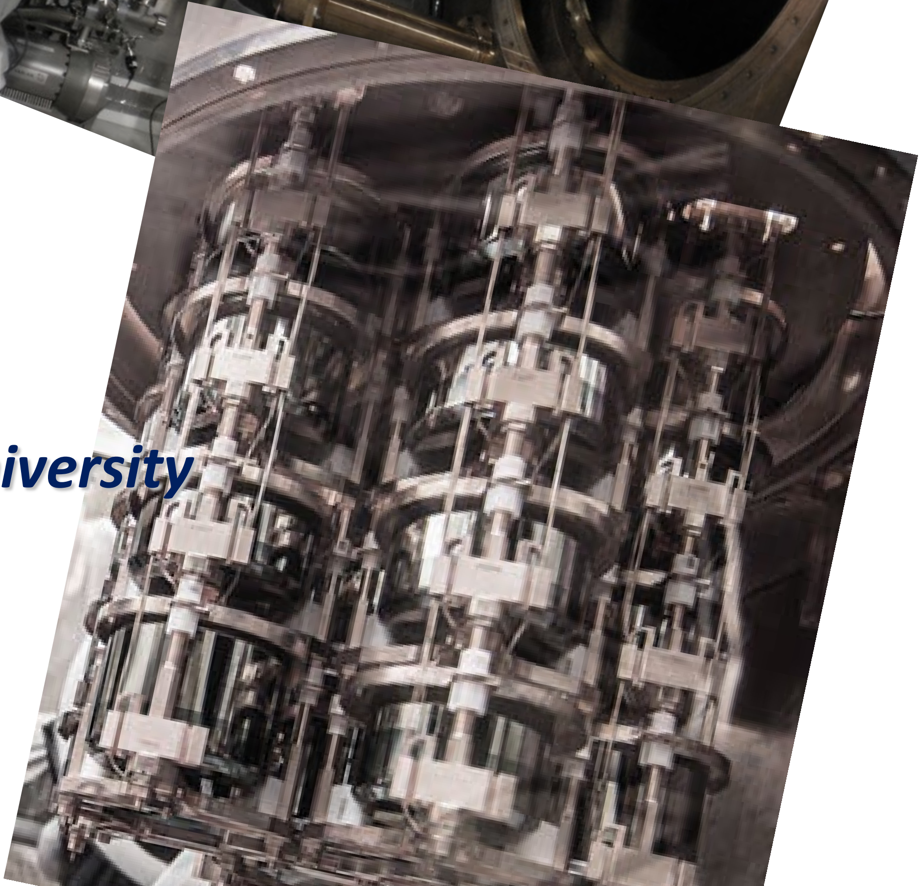
The quest for Neutrinoless double-beta decay





Giorgio Gratta
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Last 20 yrs: the age of ν physics

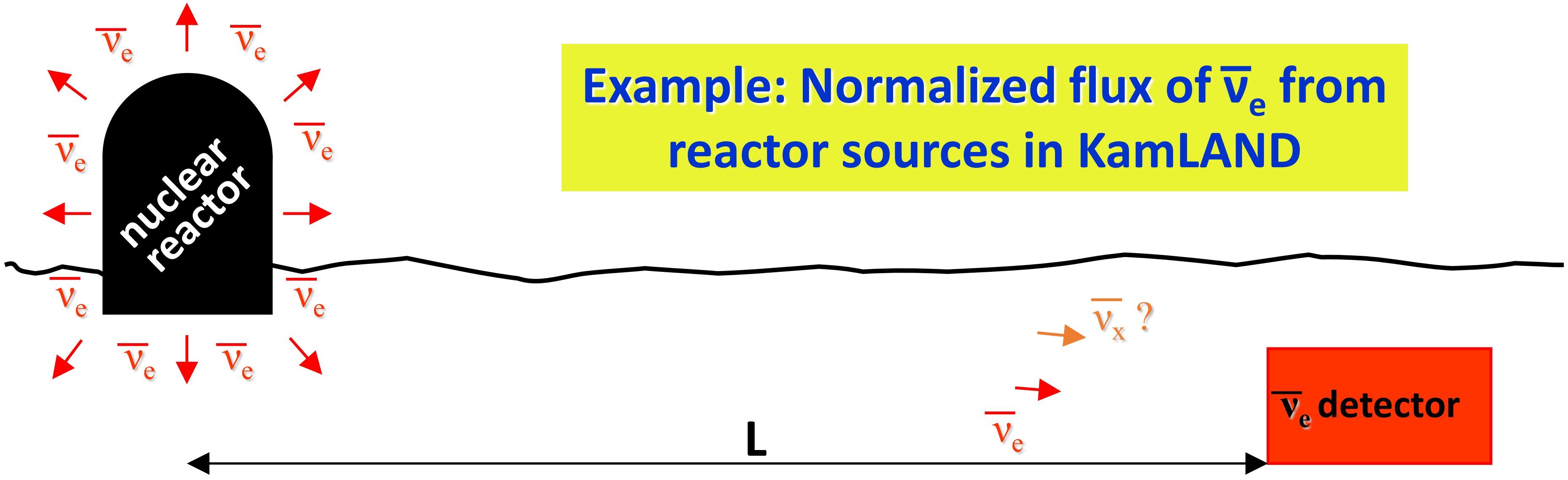
Discovery of ν flavor change

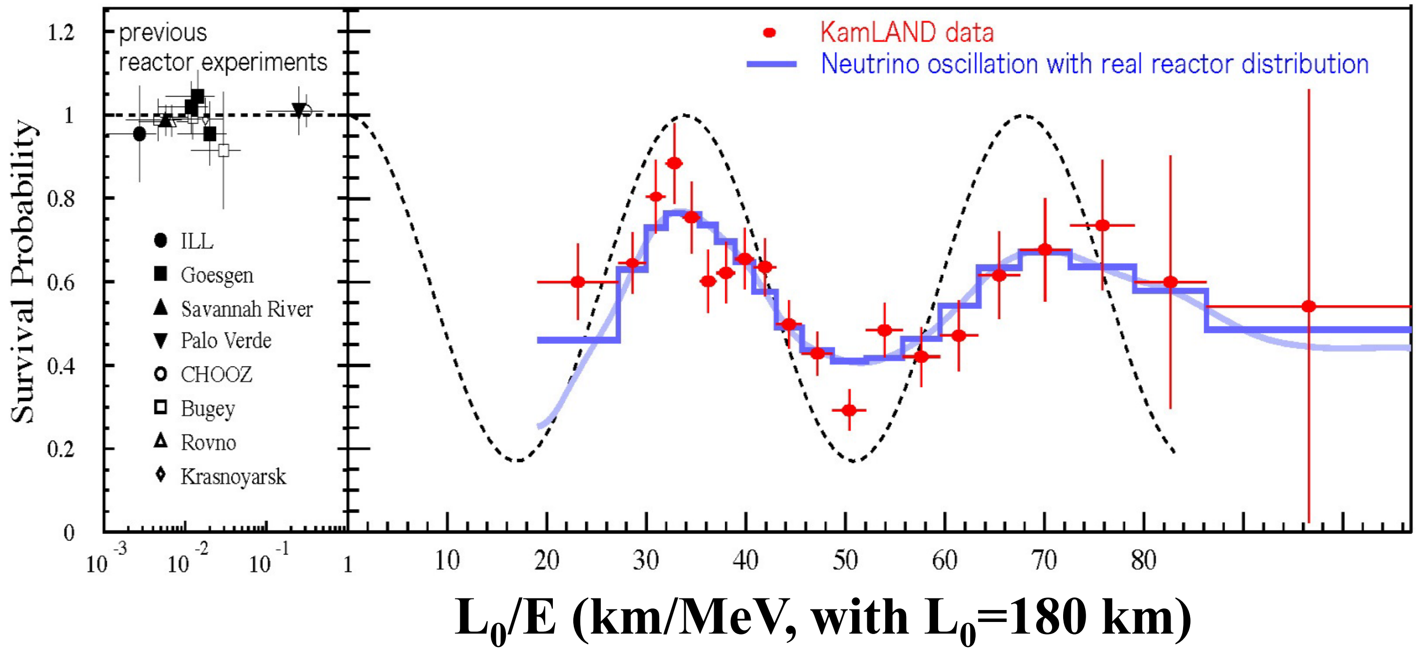
- *Solar neutrinos (MSW effect)*
- *Reactor neutrinos (vacuum oscillation)*
- *Atmospheric neutrinos (vacuum oscillation)*
- *Accelerator neutrinos (vacuum oscillation)*

We also found that:

- **ν masses are non-zero**
- **there are 2.981±0.008 ν (Z lineshape)**
- **3 ν flavors were active in Big Bang Nucleosynthesis**
- **The Sun emits neutrinos as expected**
- **Supernovae emit neutrinos**

Example: Normalized flux of $\bar{\nu}_e$ from reactor sources in KamLAND





If $m_\nu \neq 0$ neutrinos show a different image depending on our vantage point:

- "Weak interaction eigenstate"

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

this is the state of definite flavor: interactions couple to this state

- "Mass eigenstate"

$$\begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$

this is the state of definite energy: propagation happens in this state

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$

A source produces –say- ν_e
always via weak interactions

$$\nu_e$$

To see what propagates to the detector
I have to project this flavor state onto the mass state using the matrix inverse of U

$$\nu_m = U^{-1} \nu_e$$

Now each of the ν_m will evolve in time as prescribed by the wave functions

$$\nu_{m1}(t) = e^{-i(E_1 t - p_1 L)}\nu_{m1}$$
$$\nu_{m2}(t) = e^{-i(E_2 t - p_2 L)}\nu_{m2}$$
$$\nu_{m3}(t) = e^{-i(E_3 t - p_3 L)}\nu_{m3}$$

note that the periodic term contains the neutrino mass via $E_i=m_ic^2$

So at the end of their flight -at the detector- the mix of $\nu_{m1}, \nu_{m2}, \nu_{m3}$ will not necessarily be the one that makes "exactly" ν_e !

The neutrinos are then detected via weak interactions and so we need to find again the composition in terms of ν_e, ν_μ, ν_τ

Formally

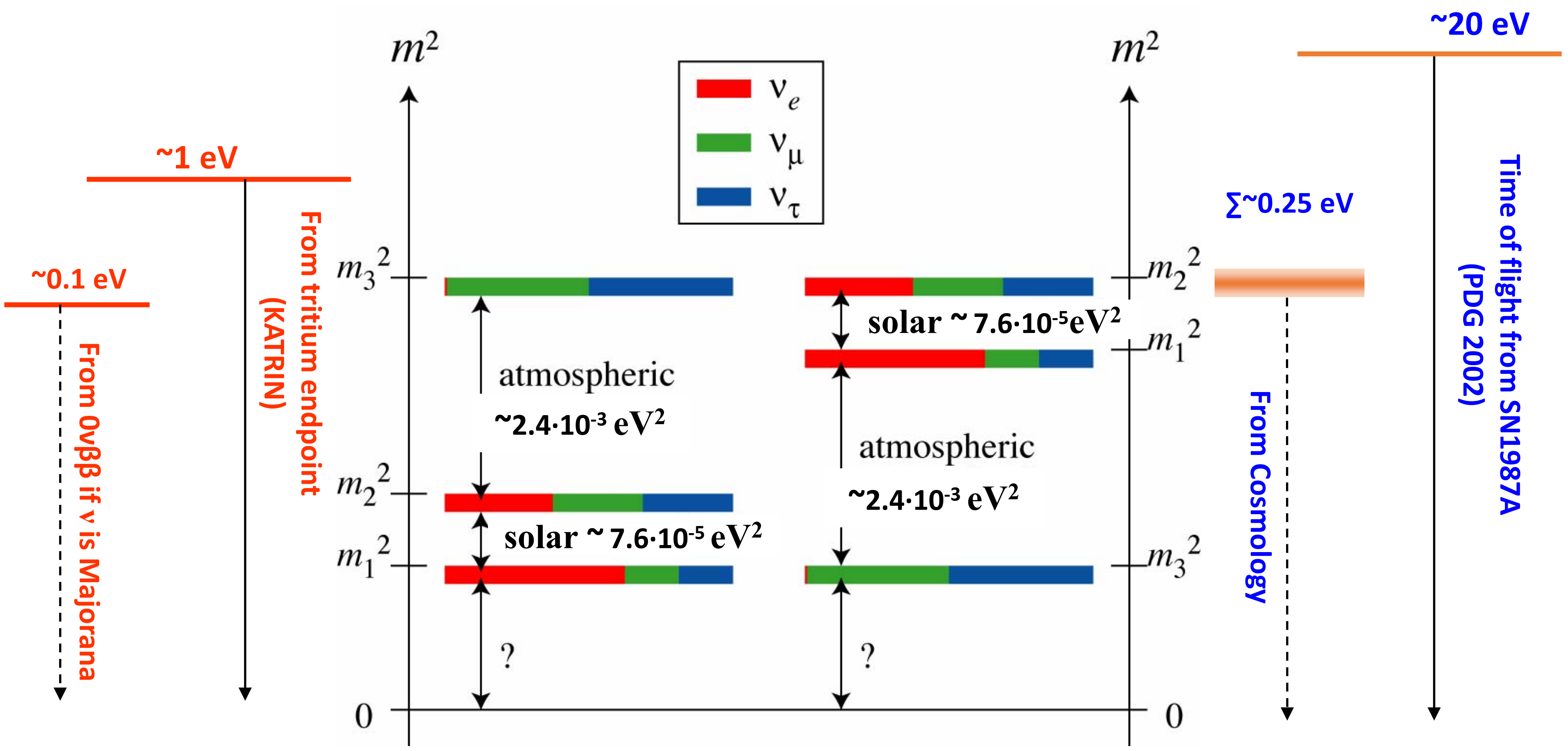
$$\left|\nu_j\right\rangle = \sum_{j'}\sum_{l} U_{lj} e^{-i(E_j t - p_j L)} U^*_{j'l} \left|\nu_{j'}\right\rangle$$

So, after some propagation one can "find" a neutrino of a flavor that was not originally present

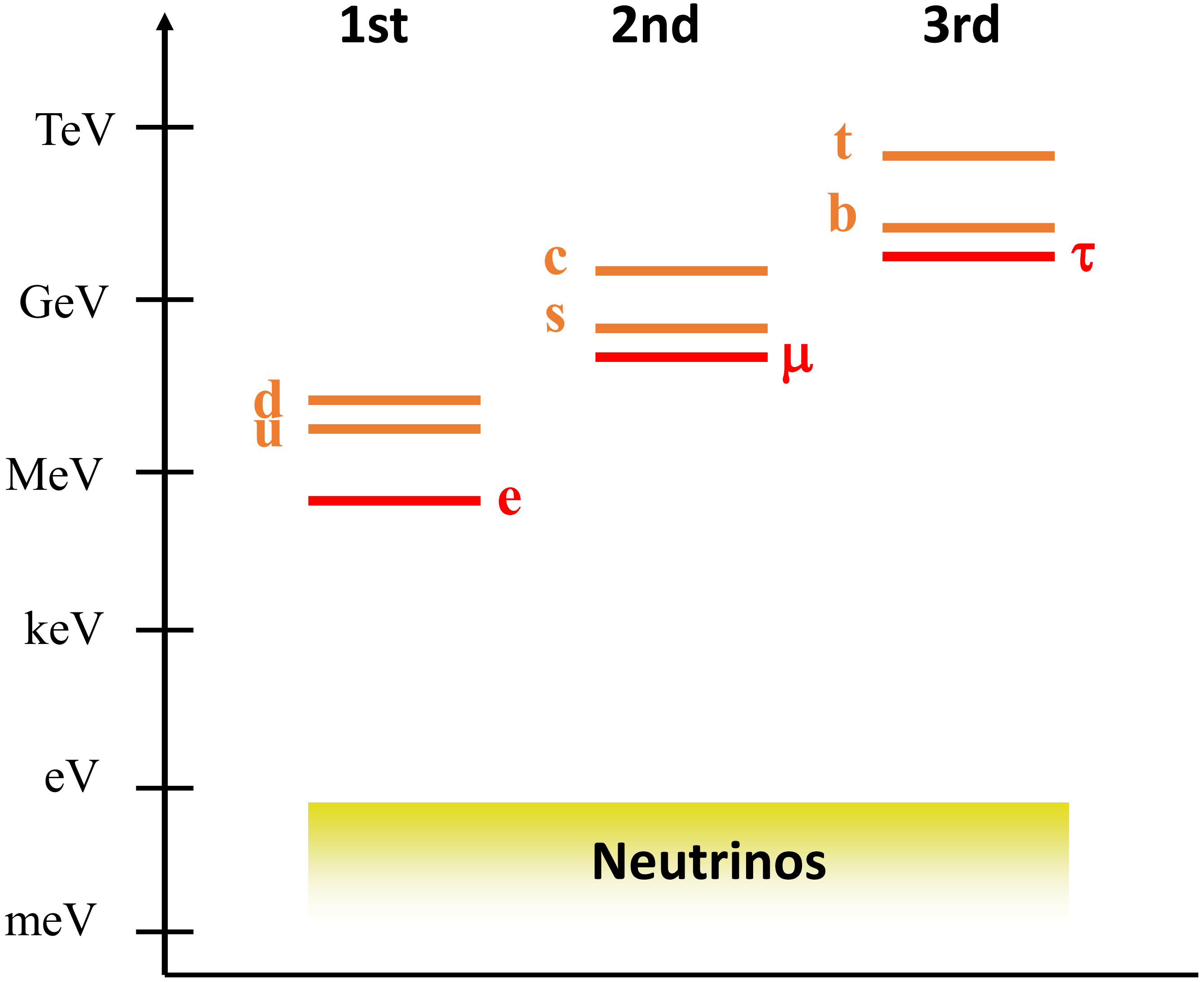
This is a pure quantum-mechanical effect, there is no classical interpretation of it

It can ONLY happen if the mass is non-0

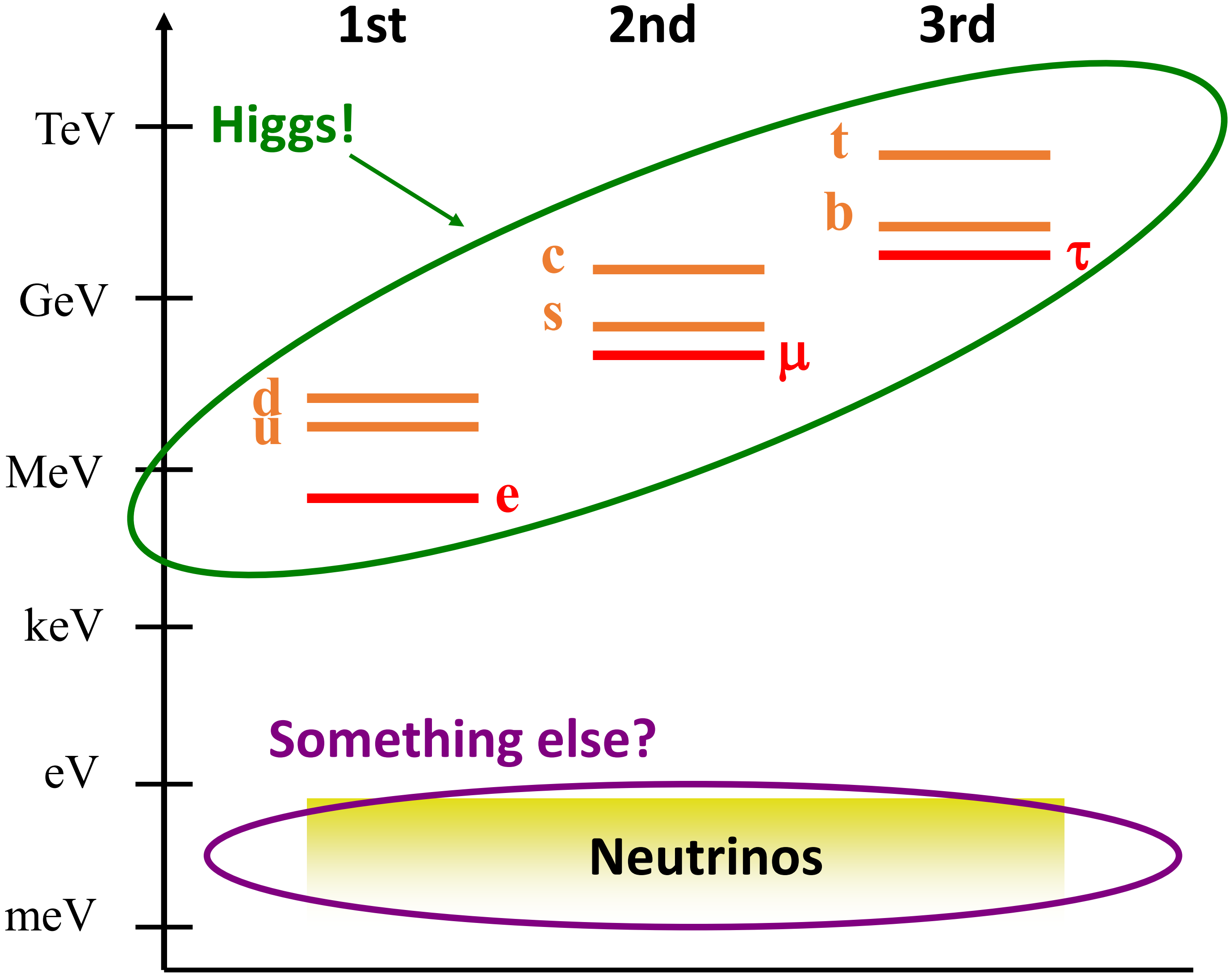
Our knowledge of the ν mass pattern



Fermion mass spectrum



Fermion mass spectrum



Neutrinos have other peculiarities:
They are the only electrically neutral fermions

Generation

Charge	1st	2nd	3rd
1	e^+	μ^+	τ^+
2/3	u	c	t
1/3	$\bar{d}$	$\bar{s}$	$\bar{b}$
0	ν_e	ν_μ	ν_τ
-1/3	d	s	b
-2/3	$\bar{u}$	$\bar{c}$	$\bar{t}$
-1	e^-	μ^-	τ^-

Neutrinos do not carry charge
What about lepton number?

Could it be that the mass and charge peculiarities are somehow related?

Say that for neutrinos $\bar{\nu} = \nu$, since they have no charge…

But… isn't there a lepton number to conserve?

No worries: lepton number conservation is not as "serious" as –say- energy conservation

Lepton number conservation is just an empirical notion.

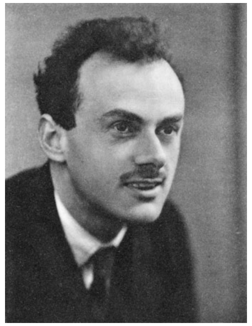
Basically, lepton number is conserved "because", experimentally, $\bar{\nu} \neq \nu$
In the neutral case, the distinction could derive from the different helicity states.

We have two possible ways to describe neutrinos:

"Dirac" neutrinos

(some "redundant" information but the "good feeling" of things we know…)

$$\nu^D = \begin{pmatrix} \nu_L \\ \overline{\nu}_L \\ \nu_R \\ \overline{\nu}_R \end{pmatrix}$$



"Majorana" neutrinos

(more efficient description, no total lepton number conservation, new paradigm…)

$$\nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

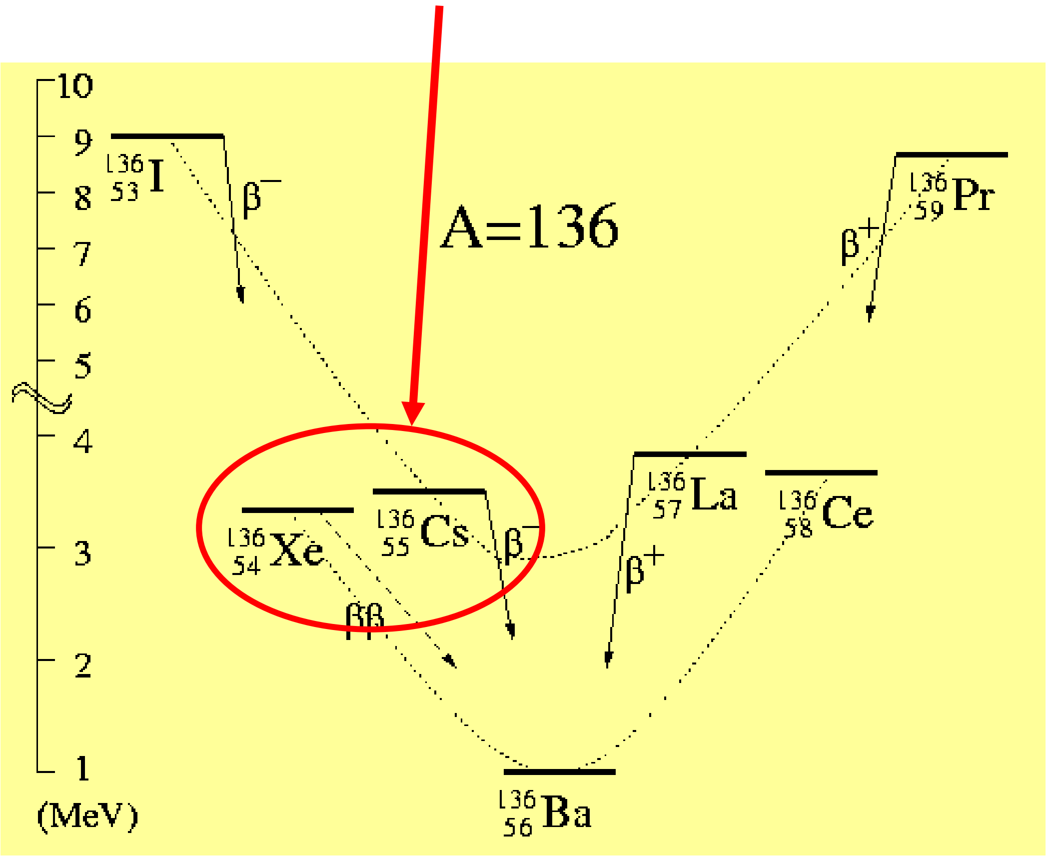
Which way Nature has chosen to proceed is an experimental question

But the two descriptions are distinguishable only if $m_\nu \neq 0$

(and the observable difference → 0 for m_ν → 0)

Enters Nuclear Physics:
Double-beta decay

a second-order process only detectable if first order β-decay Is energetically forbidden



Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

There are two varieties of ββ decay

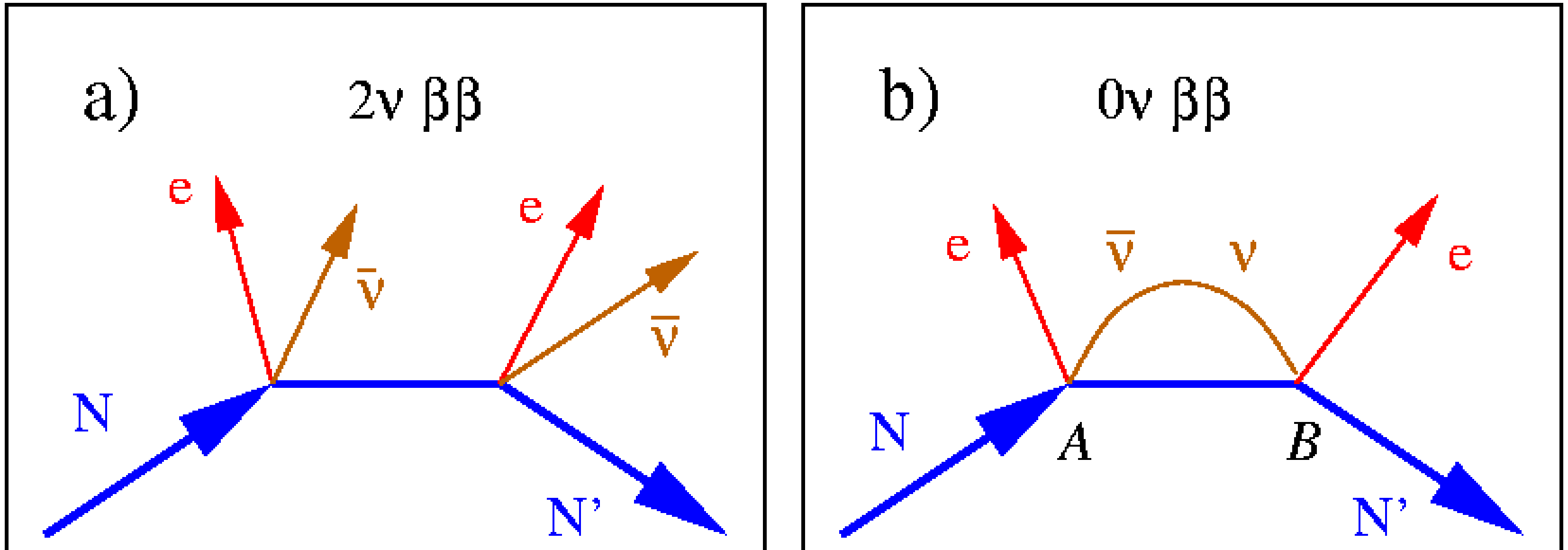
2ν mode:
a conventional
2^{nd} order process
in nuclear physics

0ν mode: a hypothetical process can happen only if: $M_\nu \neq 0$

$\nu = \bar{\nu}$

$|\Delta L|=2$

$|\Delta(B-L)|=2$

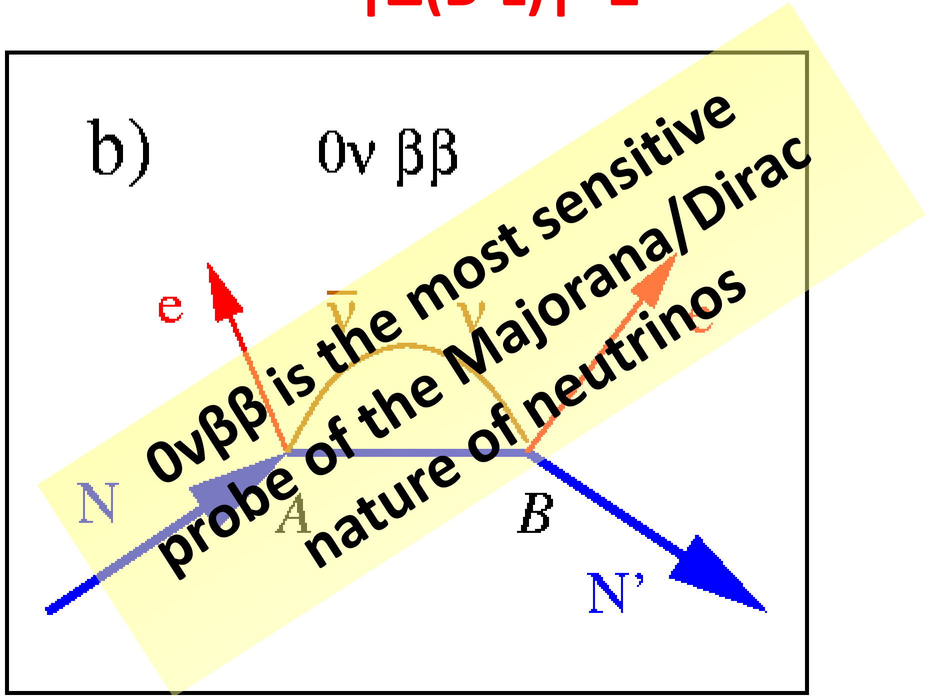


"Standard mechanism"

There are two varieties of ββ decay

0ν mode: a hypothetical process can happen only if:

- $M_\nu \neq 0$
- $\nu = \bar{\nu}$
- $|\Delta L| = 2$
- $|\Delta(B-L)| = 2$



Note that along with the double β⁻ decay

$$ {}^{A}_{Z}N \rightarrow {}^{A}_{Z+2}N' + e^{-} + e^{-} $$

there is also a β⁺ mode that in practice would also appear as a single or double electron capture

$$ {}^{A}_{Z}N \rightarrow {}^{A}_{Z-2}N' + e^{+} + e^{+} $$

$$ {}^{A}_{Z}N + e^{-} \rightarrow {}^{A}_{Z-2}N' + e^{+} $$

$$ {}^{A}_{Z}N + e^{-} + e^{-} \rightarrow {}^{A}_{Z-2}N' $$

All these processes are phase-space suppressed with respect to the β⁻ case and isotope fractions low in natural mix: usually not considered

The idea of double-beta decay is almost as old as neutrinos themselves:

The possibility of neutrinos-less decay
was first discussed in 1937:

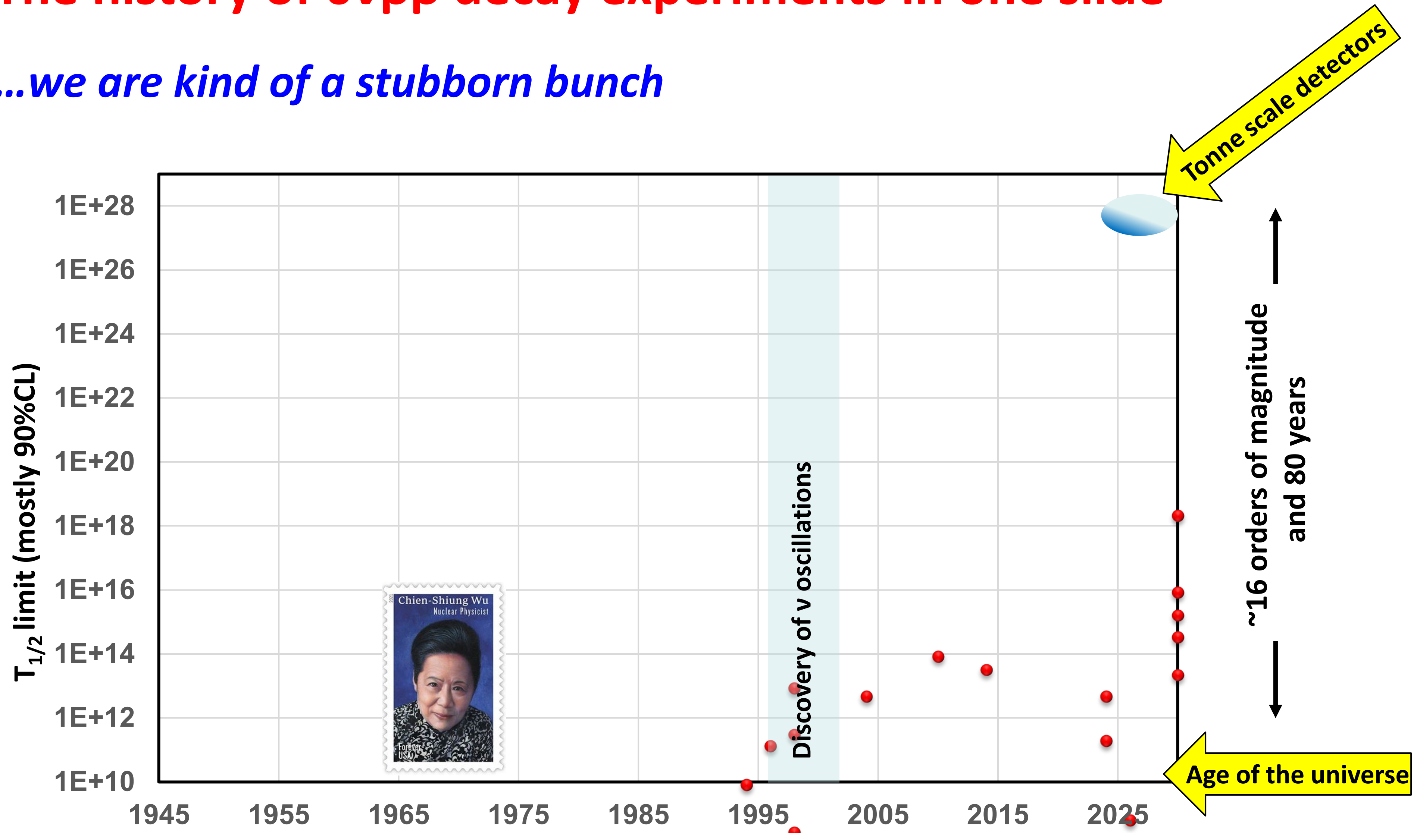
E. Majorana, Nuovo Cimento 14 (1937) 171
G. Racah, Nuovo Cimento 14 (1937) 322

Even earlier the study of nuclear structure led to the conclusion that the 2 neutrino mode would have half lives in excess of 10^{20} years

M. Goeppert-Mayer, Phys. Rev. 48 (1935) 512

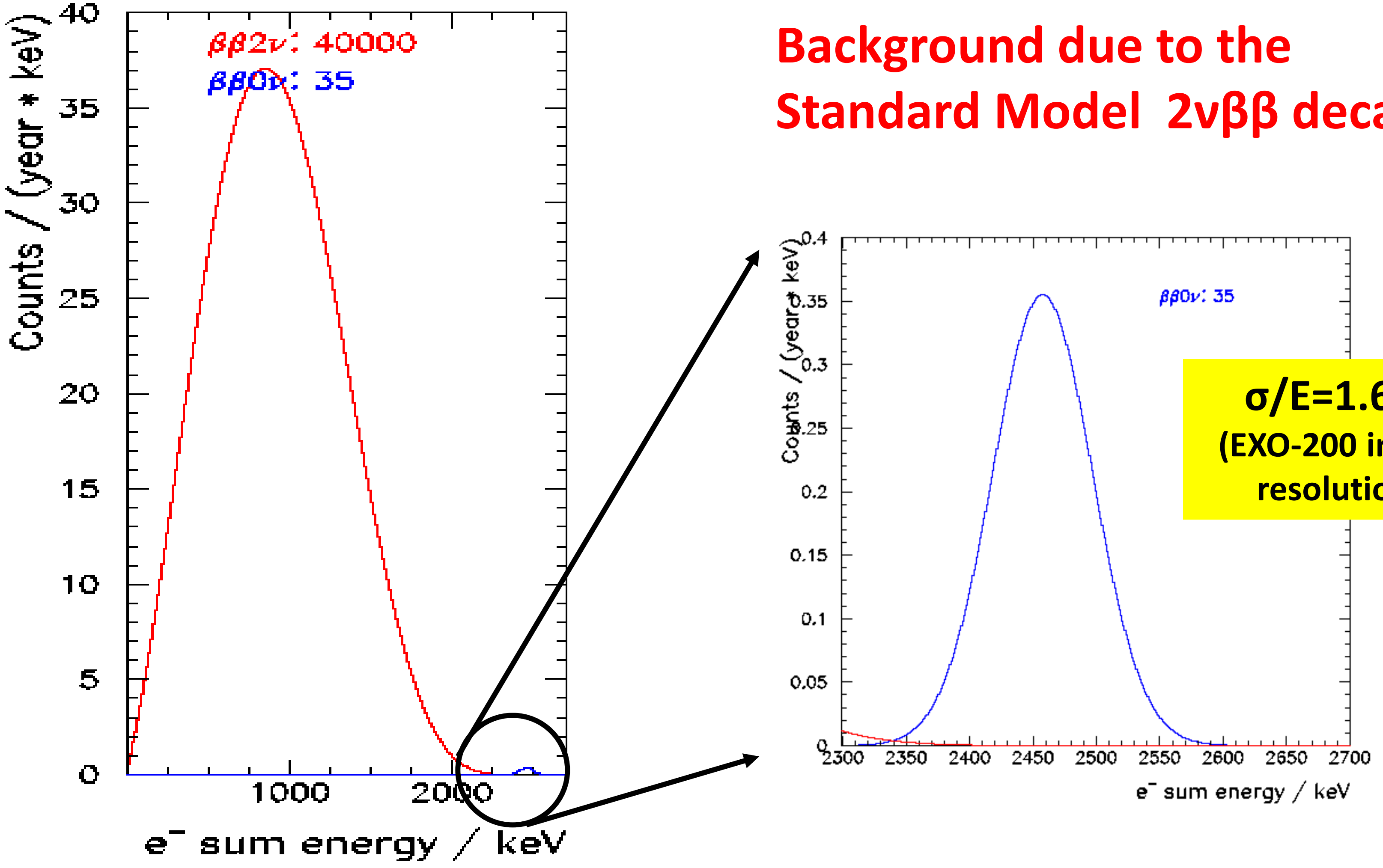
The history of 0νββ decay experiments in one slide

…we are kind of a stubborn bunch



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

Background due to the Standard Model 2νββ decay



σ/E=1.6%
(EXO-200 initial resolution)

The two can be separated in a detector with sufficiently good energy resolution

Topology and particle ID are also important to recognize backgrounds

If $0\nu\beta\beta$ is due to the "standard mechanism"

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \, G^{0\nu\beta\beta}(E_0, Z) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models

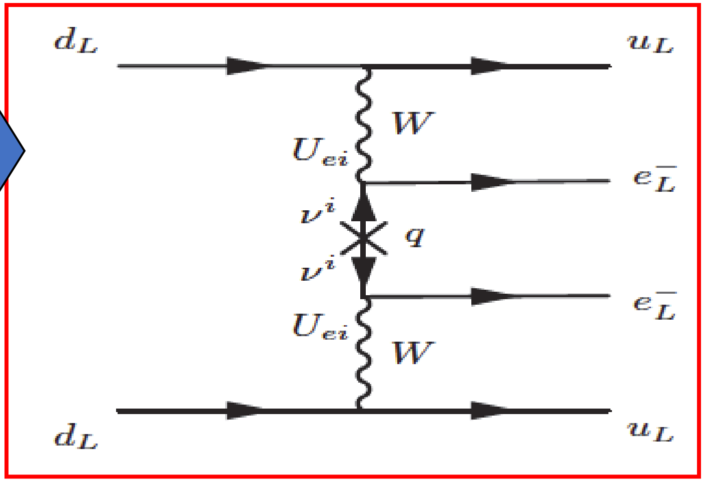
$G^{0\nu\beta\beta}$ a known phasespace factor

$T_{1/2}^{0\nu\beta\beta}$ is the quantity to be measured

$$\langle m_\nu \rangle = \sum_{i=1}^{3} \left| U_{e,i} \right|^2 m_i \, \varepsilon_i$$

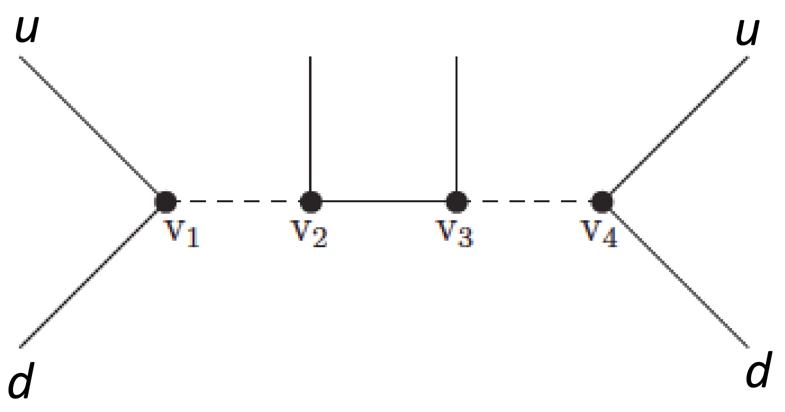
is the effective Majorana ν mass (ε_i = ±1 if CP is conserved)

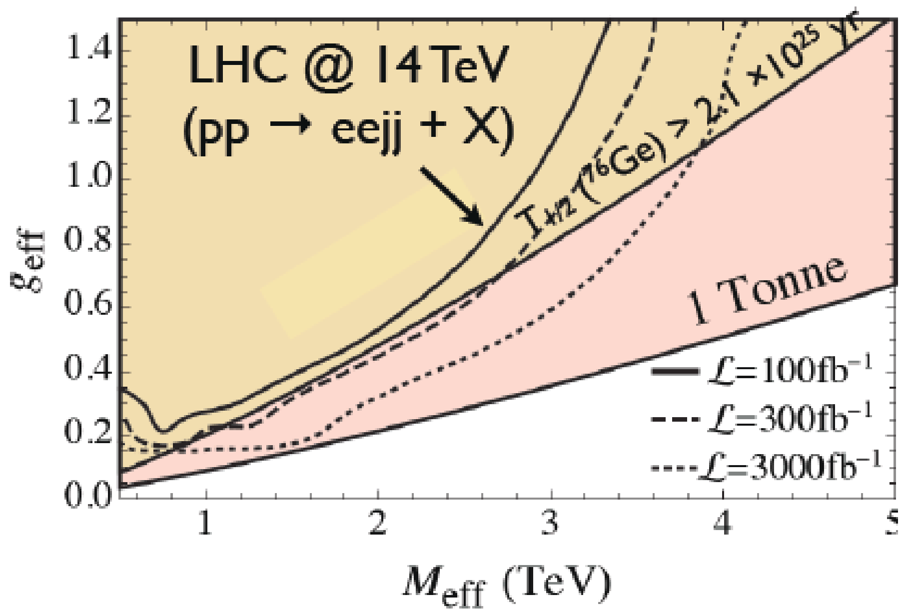
While it is convenient to think in terms of the standard mechanism



other mechanisms can produce the lepton number violation

SUSY-inspired example:





Peng, Ramsey-Musolf, Winslow, 2015

Note that even in this case the decay implies Majorana masses, except the relationship to the half-life is now a different one.

In fact, there is a *theorem*:
"$0\nu\beta\beta$ decay always implies new physics"

There is no scenario in which observing

$0\nu\beta\beta$ 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

→ The absolute sensitivity to new physics is cleanly expressed by the half-life sensitivity

→ Comparisons among experiments require knowledge of the nuclear matrix elements

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
- **Counting experiments with gram quantities of candidate isotopes.**

"Previous generation" experiments:

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

State of the art data:

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

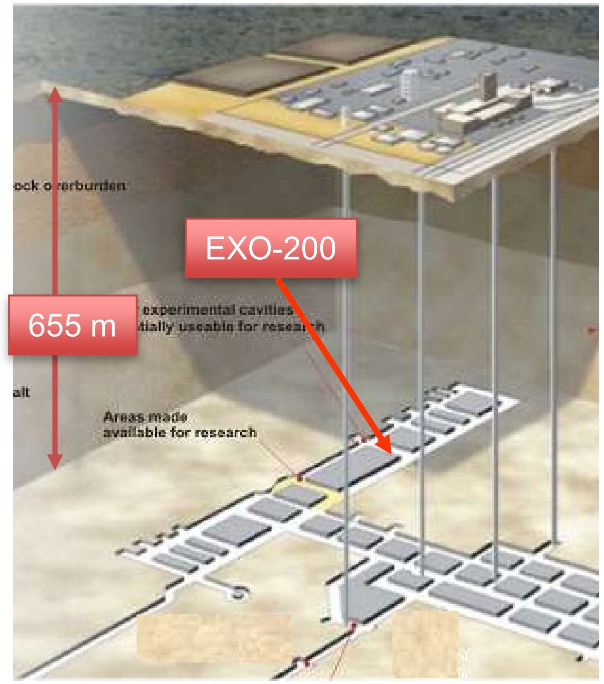
Four fundamental requirements for modern experiments:

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

100kg – class experiment running or completed.
Ton – class experiments coming!

2) Underground location to shield cosmic-ray induced background

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



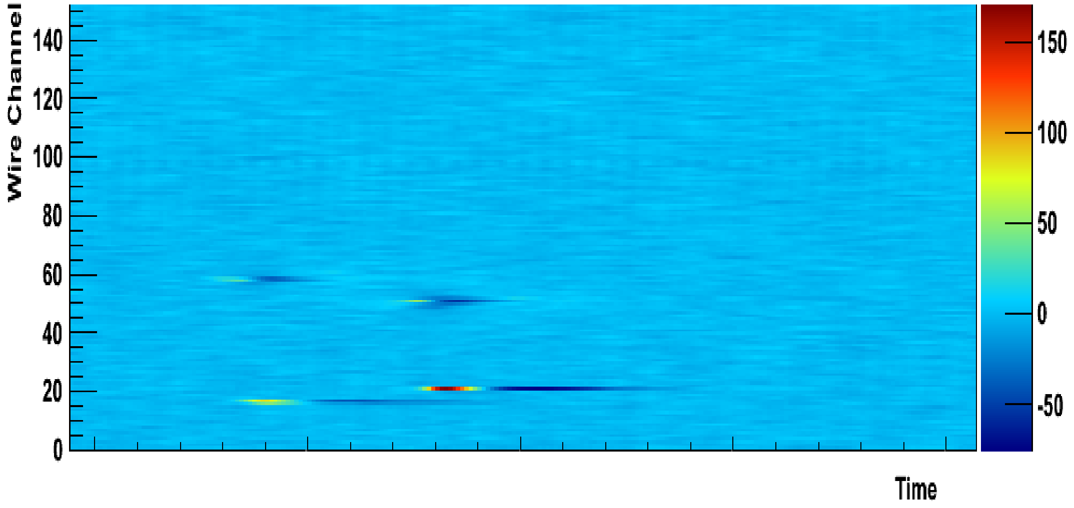
Four fundamental requirements for modern experiments:

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

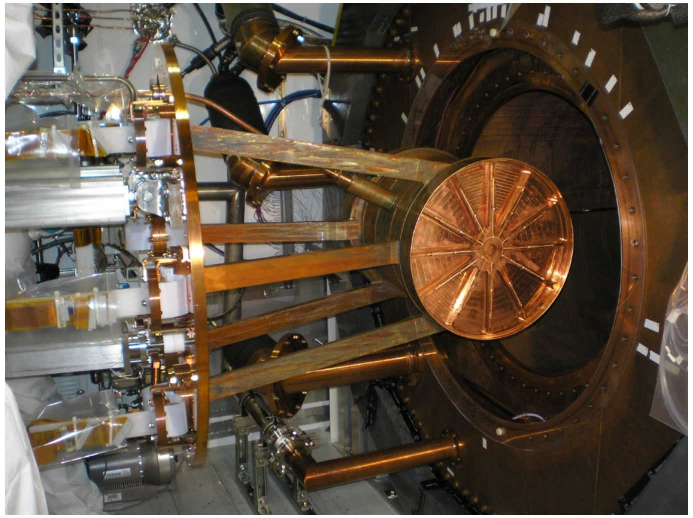
Non trivial for E~1MeV.
- Signal (2e$^-$) more localized than most background.
- Good E resolution helps.
- Low density shows the two e$^-$ tracks but hard for large fiducial masses.
- Final state ID may be possible.

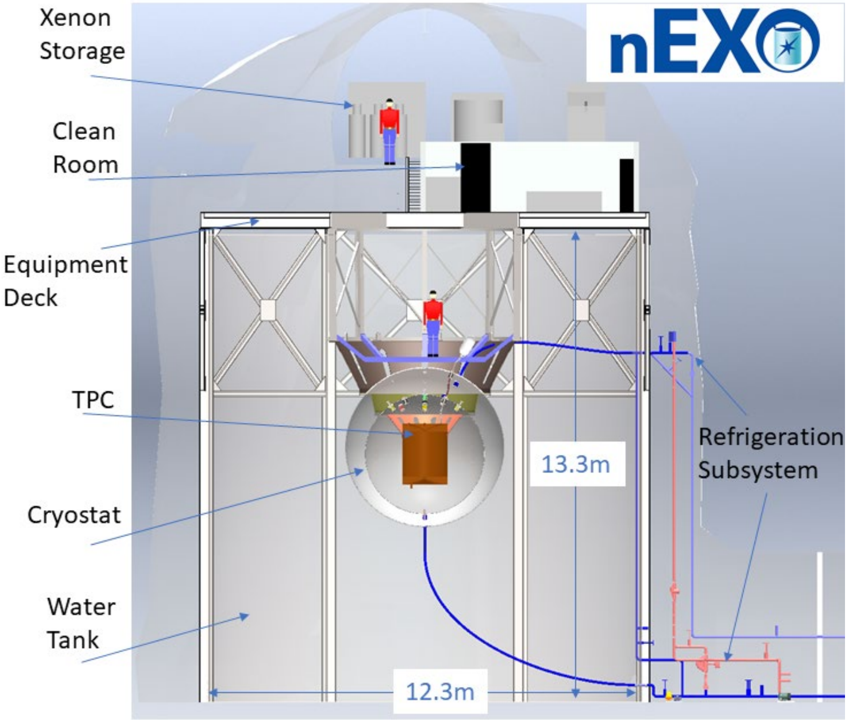


Milestones in the EXO program

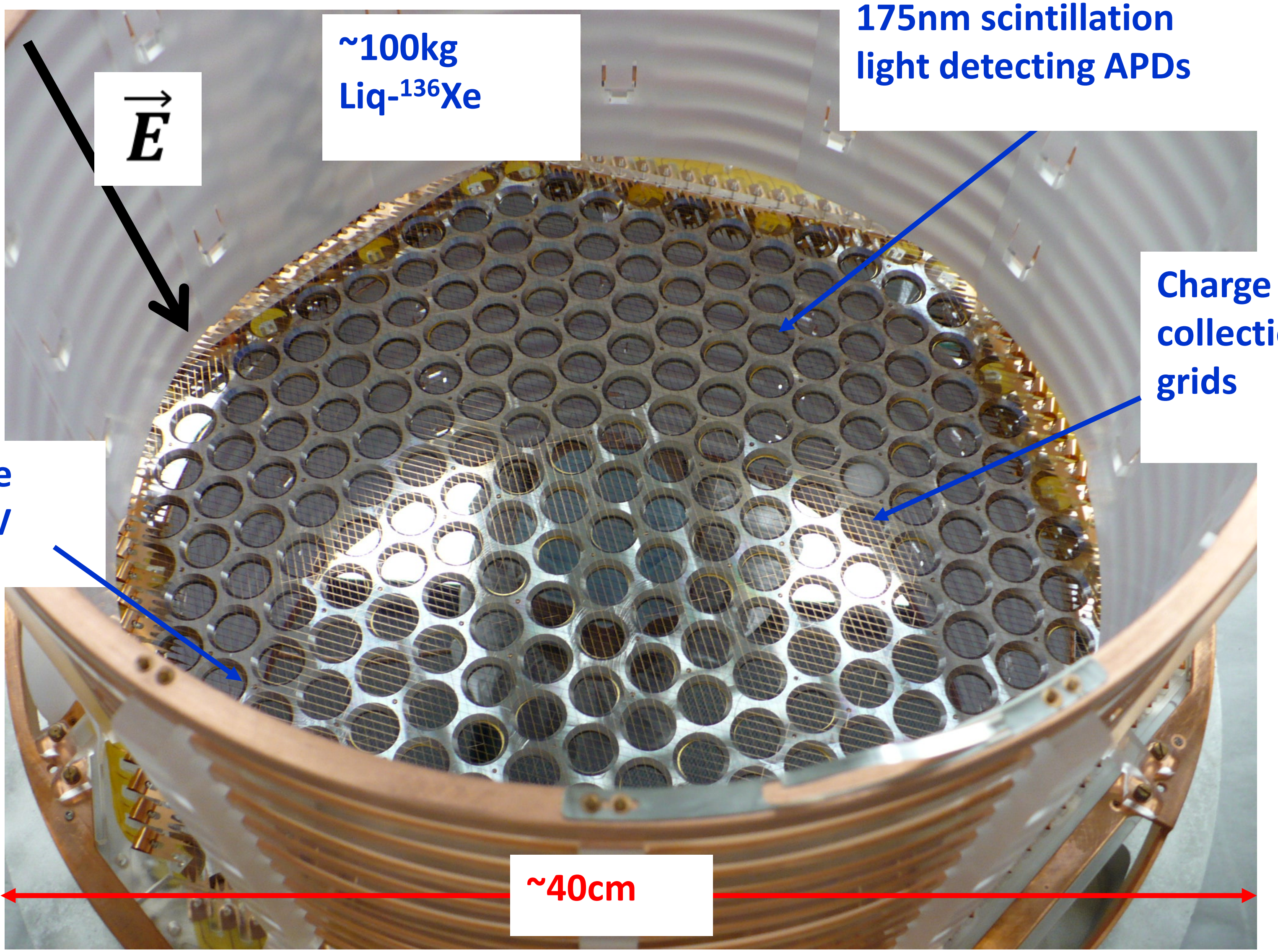
Since 2001

- 2001: "EXO" started as an R&D towards a ^{136}Xe ββ decay experiment.
- 2002: The improved energy resolution in LXe using the correlation between scintillation and ionization is discovered.
- Circa 2005: Settled on a LXe TPC design for a "prototype" 200 kg detector.
- 2007-2010: The EXO-200 detector is designed and built, with major contributions from Canada, Russia and Switzerland.
- 2012-2016: After EXO-200 started taking data, showing excellent performance, the idea of a 5000 kg was further developed.
- 2014: The "nEXO collaboration" was formed.
- 2014-2016: Five US Nat'l Labs join the collaboration.
- May 2018: nEXO pre-CDR posted on the arXiv
- Nov 2018: CD-0 for tonne-scale ββ decay
- Dec 2018: End of EXO-200 run
- 2019-now: nEXO project developed; substantial nEXO engineering at SNOLAB
- Feb 2020: nEXO MAC review
- Feb 2021: nEXO budget review
- Jul 2021: DoE portfolio review
- Sept 2021: Europe – North America Summit at LNGS

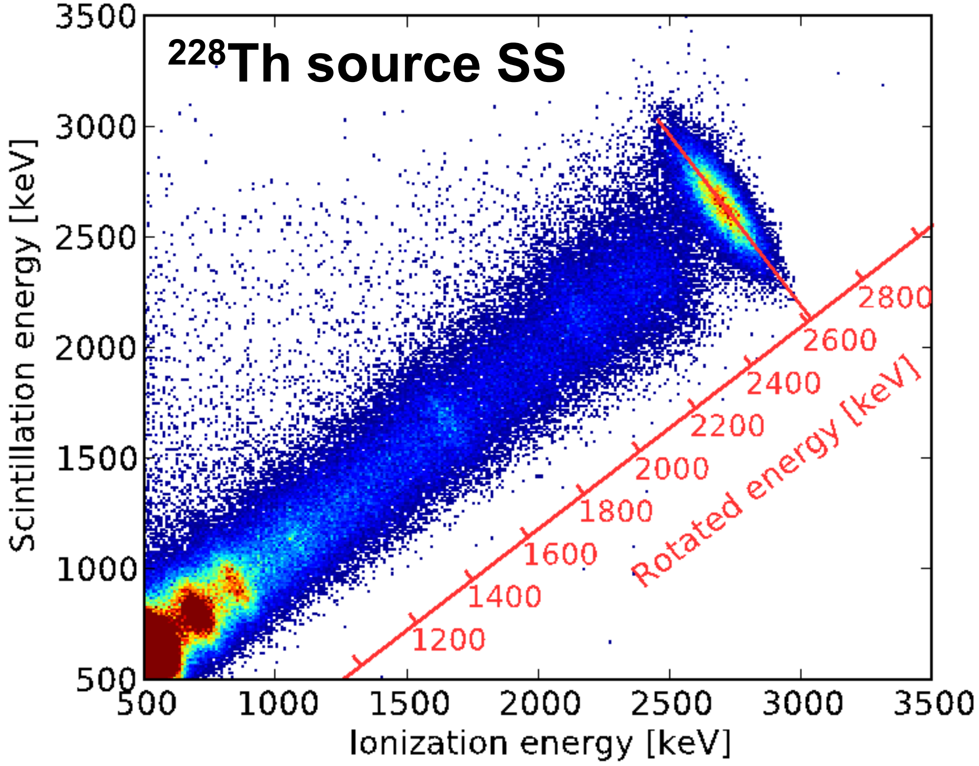




The EXO-200 liquid ^{136}Xe Time Projection Chamber



Combining Ionization and Scintillation

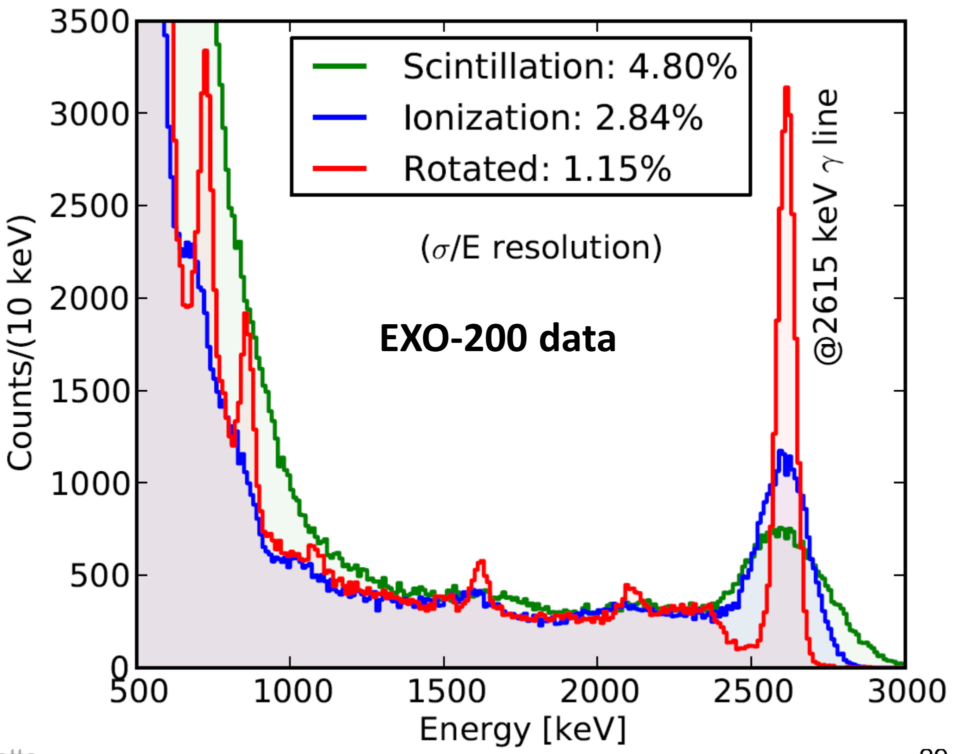


Rotation angle chosen to optimize energy resolution at 2615 keV

Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

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

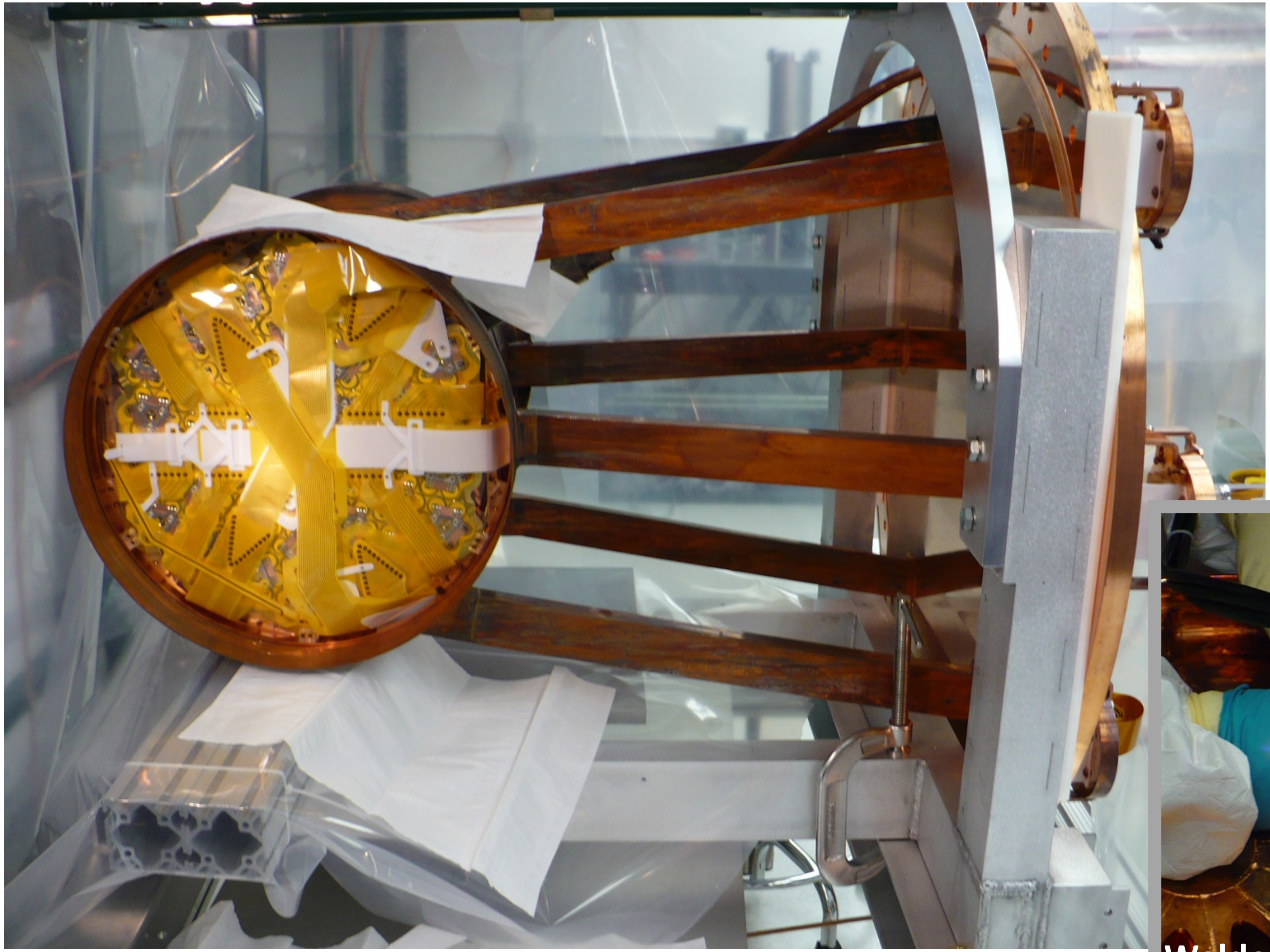
By now this is
a common technique in LXe

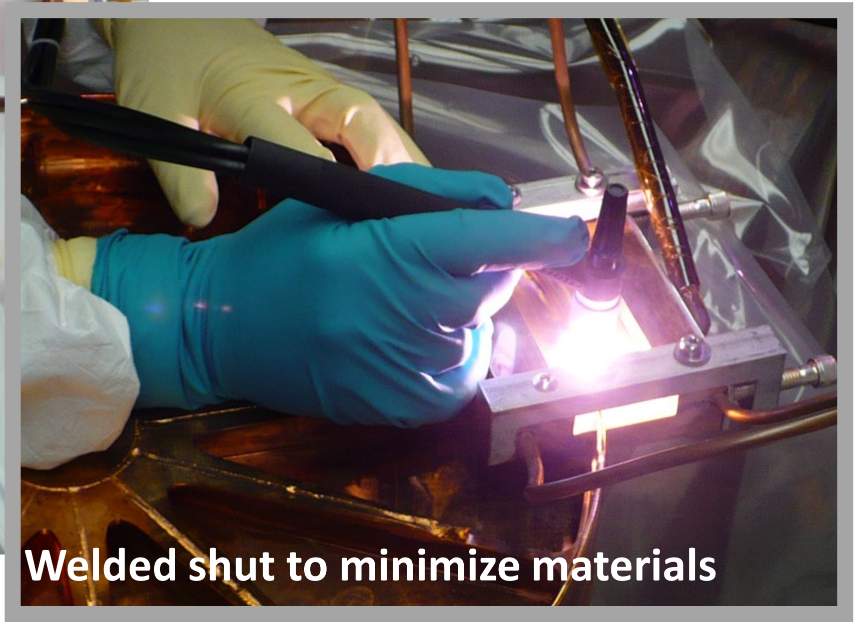


Ultra-low activity Cu vessel

- Very light (~1.5mm thin, ~15kg) to minimize materials
- Different parts e-beam welded together
- Field TIG weld(s) to seal the vessel after assembly (TIG technology tested for radioactivity)
- All machining done under shallow shielding to reduce cosmogenic activation

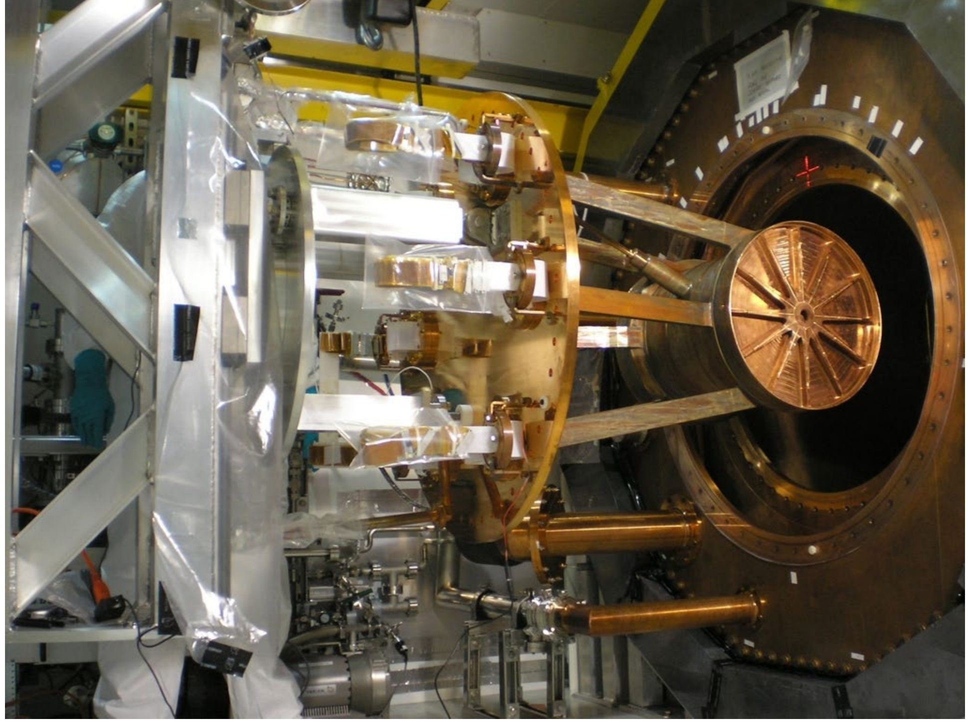
EXO-200 TPC Assembled

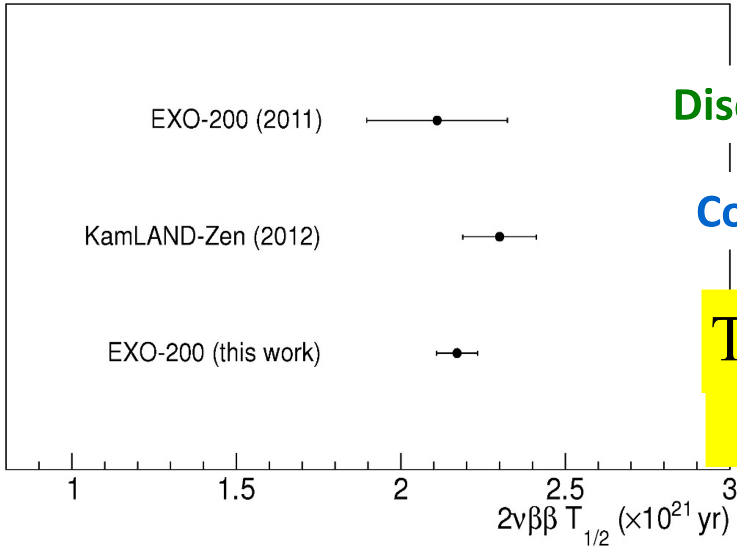




Welded shut to minimize materials

The 2νββ decay in ^{136}Xe was discovered in the first week of EXO-200 data





Discovery of 2ν mode *[PRL 107, 212501 (2011)]*

Confirmation by KamLAND-Zen *[PRC 85, 045504 (2012)]*

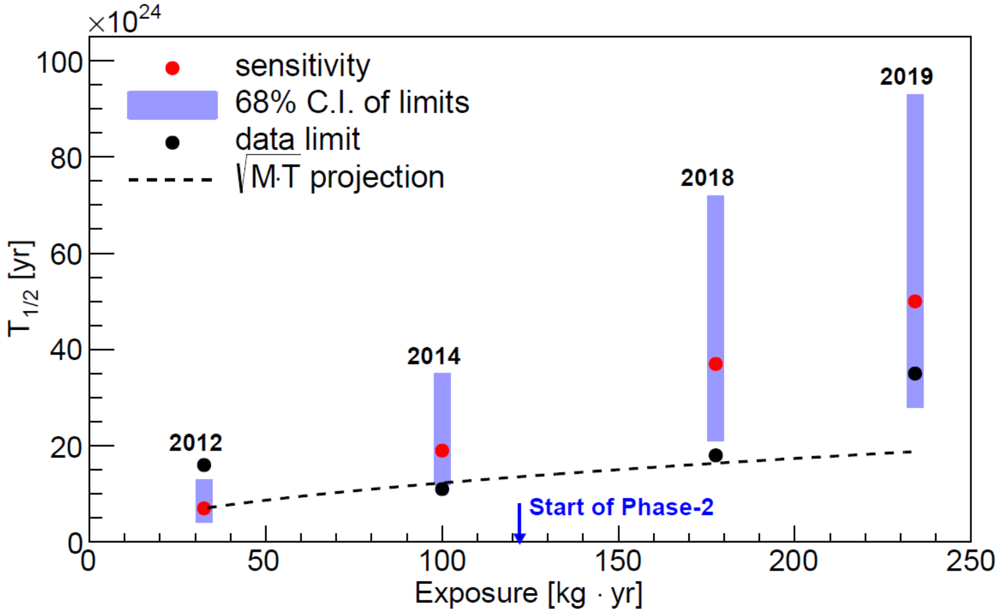
$$T_{1/2}^{2\nu\beta\beta} = \left(2.165 \pm 0.016^{\mathrm{stat}} \pm 0.059^{\mathrm{syst}}\right) \cdot 10^{21}\ \mathrm{yr}$$

[Phys. Rev. C 89 (2014) 015502]

For a while, this was the most accurately measured 2ν decay.

EXO-200 results for 0νββ

- **First 100 kg-class experiment to take data.**
- **Excellent background, very well predicted by the massive material characterization program (and the simulation).** ***This is essential for nEXO design.***
- **Sensitivity increased linearly with exposure.**
- **More papers on non-ββ decay physics.**



2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: Phys. Rev. Lett. 123 (2019) 161802

Final result

Phase I+II: 234.1 kg yr of ^{136}Xe exposure

Limit: $T_{1/2}^{0\nu\beta\beta}$ > 3.5x10^{25} yr (90% CL)

$\langle m_{\beta\beta} \rangle$ < (93 -286) meV

Sensitivity: 5.0x10^{25} yr

Radioactivity in EXO-200 was successfully predicted ***before*** turning on the detector

→Massive effort on material radioactive qualification, using:

- **NAA**
- **Low background γ-spectroscopy**
- **α-counting**
- **Radon counting**
- **High performance GD-MS and ICP-MS**

The materials database includes >300 entries

D.S. Leonard et al., Nucl. Ins. Meth. A 591 (2008) 490
D.S. Leonard et al., Nucl. Inst. Meth. A 871 (2017) 169
M. Auger et al., J. Inst. 7 (2012) P05010.

The background can then be directly measured in the data:

J.B. Albert et al. Phys. Rev. C 92 (2015) 015503.

Cosmogenic backgrounds:

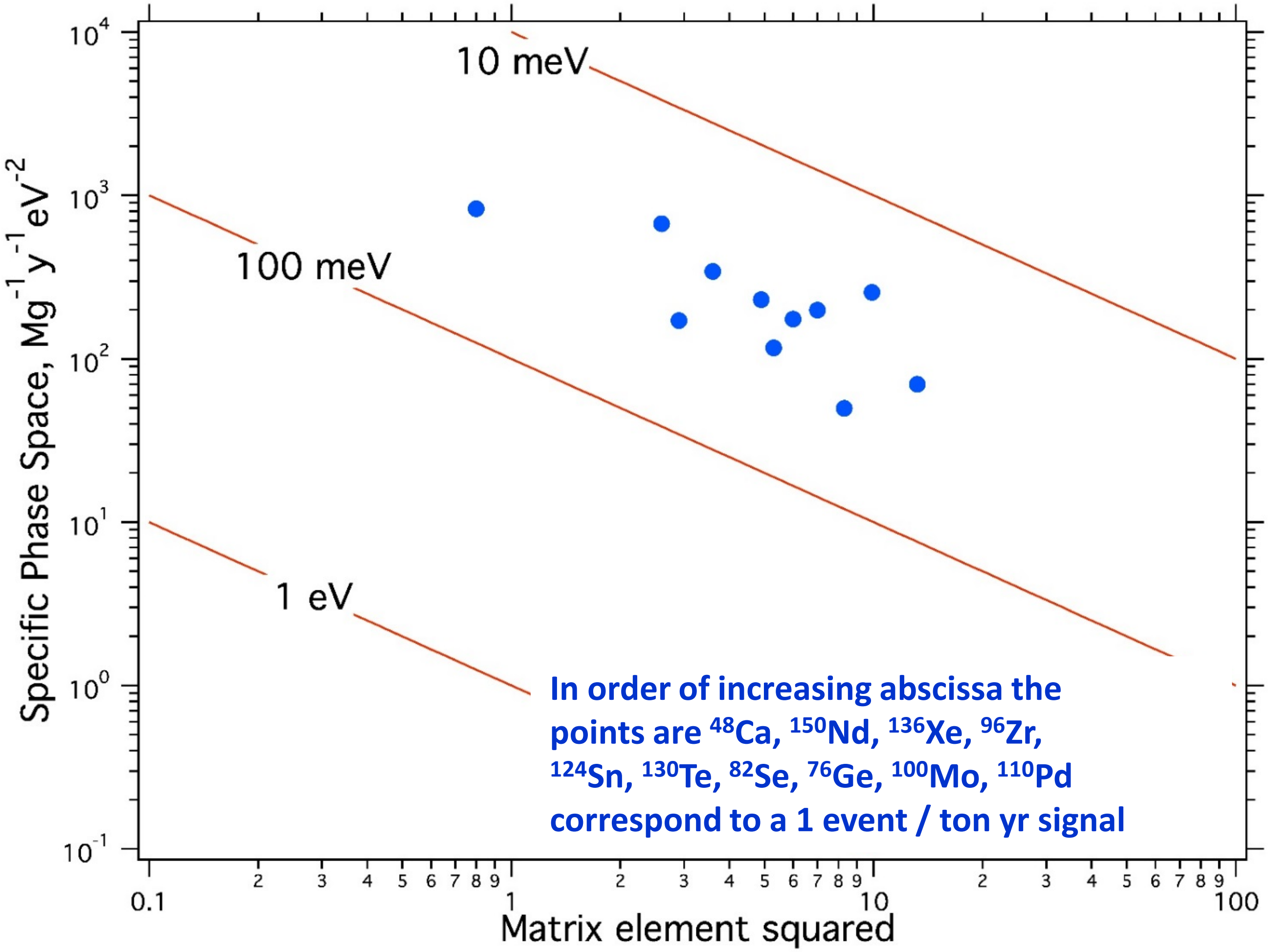
J.B. Albert et al., JCAP 04 (2016) 029.

Events in ±2σ around Q	Radioactive bkgd prediction using certification data and G4 Monte Carlo	^{137}Xe bkgd	Background from 0ν analysis fit
90%CL Upper	56	18	63.2 ± 4.7 (65 events observed)
90%CL Lower	8.2		

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

Testing lepton number violation with 100x the current sensitivity

Many isotopes have comparable sensitivities (at least in terms of rate per unit neutrino mass)



In order of increasing abscissa the points are ^{48}Ca, ^{150}Nd, ^{136}Xe, ^{96}Zr, ^{124}Sn, ^{130}Te, ^{82}Se, ^{76}Ge, ^{100}Mo, ^{110}Pd 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.

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

This is because:

- ***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***

Note that this is more than two experiments confirming each other!

The experimental basis for the announcement of discovery of the W in UA1 and UA2. (stolen from Tim Hallman, DOE)

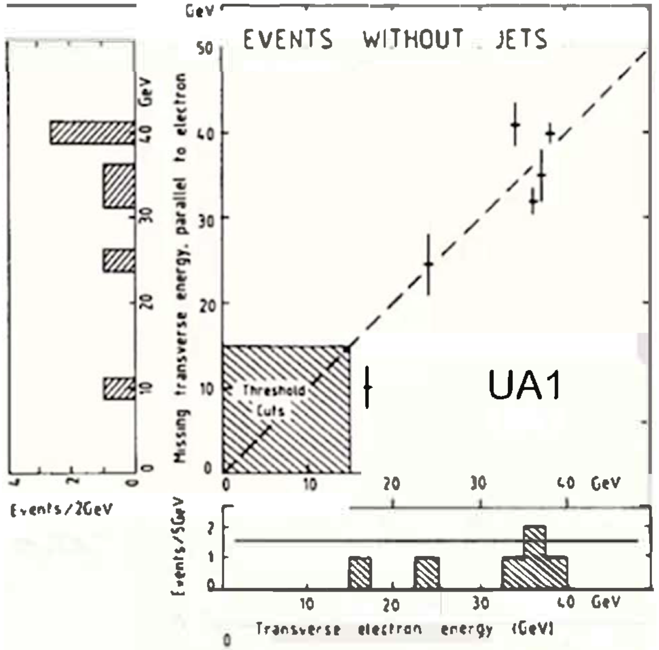


Fig. 11. UA1 scatter plot of all the events from the 1982 data which contain a high-pT electron and large $|\vec{p}_T^{miss}|$. The abscissa is the electron $|\vec{p}_T|$ and the ordinate is the $\vec{p}_T^{miss}$ component antiparallel to the electron $\vec{p}_T$.

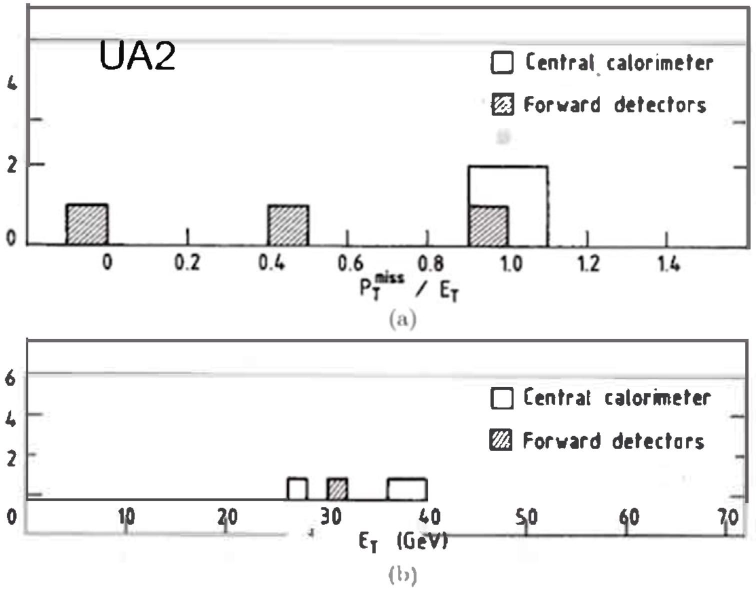


Fig. 13. (a) Display of the ratio between $|\vec{p}_T^{miss}|$ and the electron transverse momentum (called E_T in this plot) for six UA2 events containing an electron with $E_T > 15$ GeV; (b) Electron distribution for the four events with the highest $|\vec{p}_T^{miss}|/E_T$ ratio.

One (my own) possible classification of technologies

Low density trackers

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

Pros: Superb topological information

Cons: Very large size

Liquid (organic) scintillators

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

Pros: "simple", large detectors exist

Cons: Not very specific, hard to claim discovery

Crystals

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

Pros: Superb energy resolution, possibly 2-parameter measurement

Cons: Intrinsically fragmented

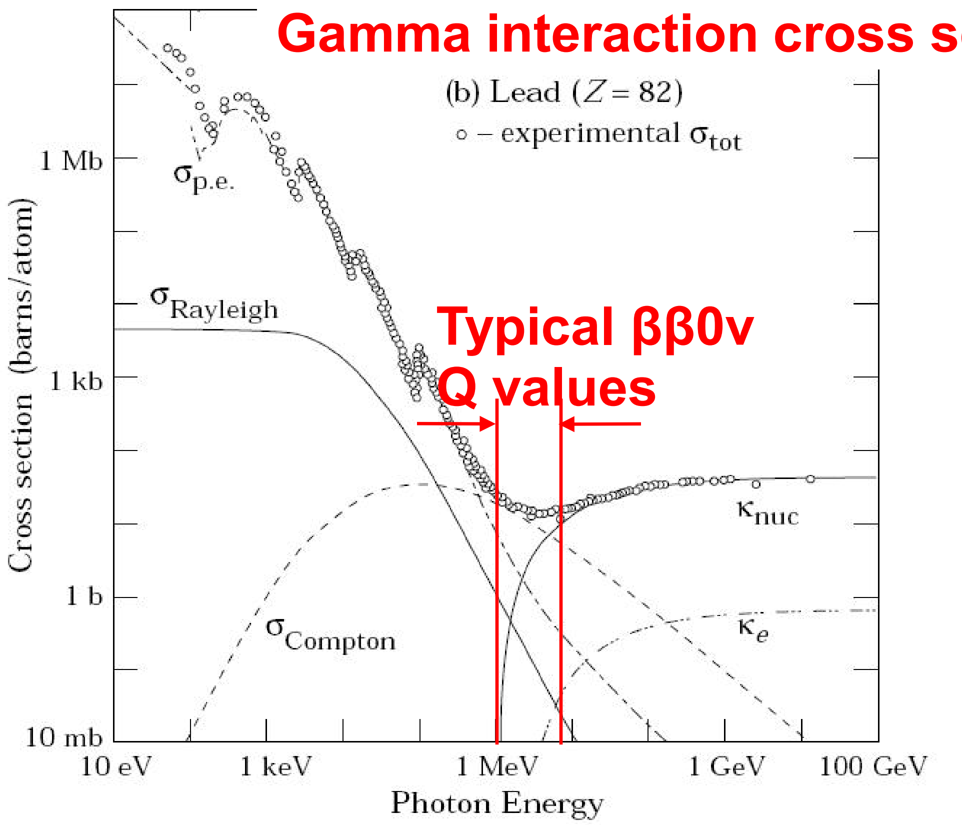
Liquid TPC

- nEXO (^{136}Xe)

Pros: Homogeneous with good E resolution and topology

Cons: Does not excel in any single parameter

Shielding a detector from gammas is difficult!



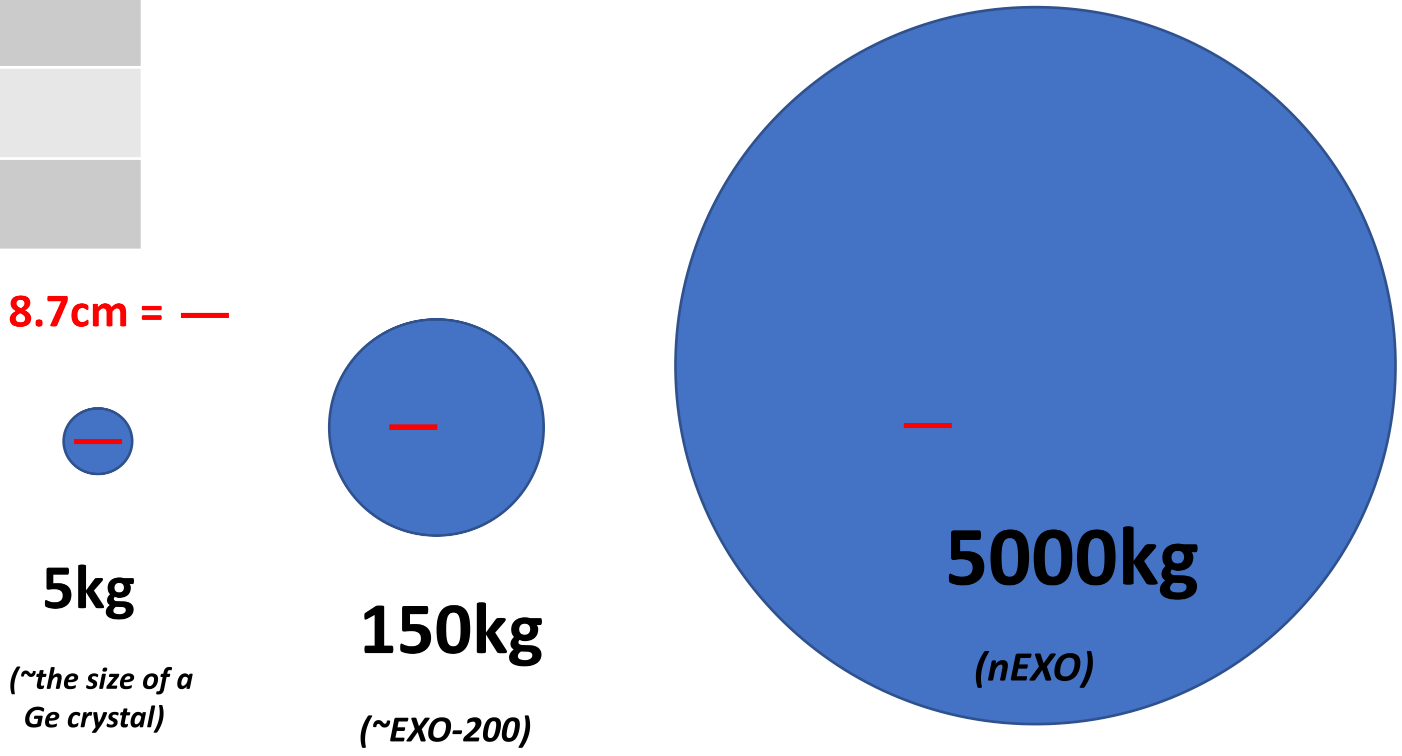
Shielding ββ decay detectors is much harder than shielding Dark Matter ones

We are entering the "golden era" of ββ decay experiments as detector sizes exceed interaction length

Monolithic/Homogeneous is key

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

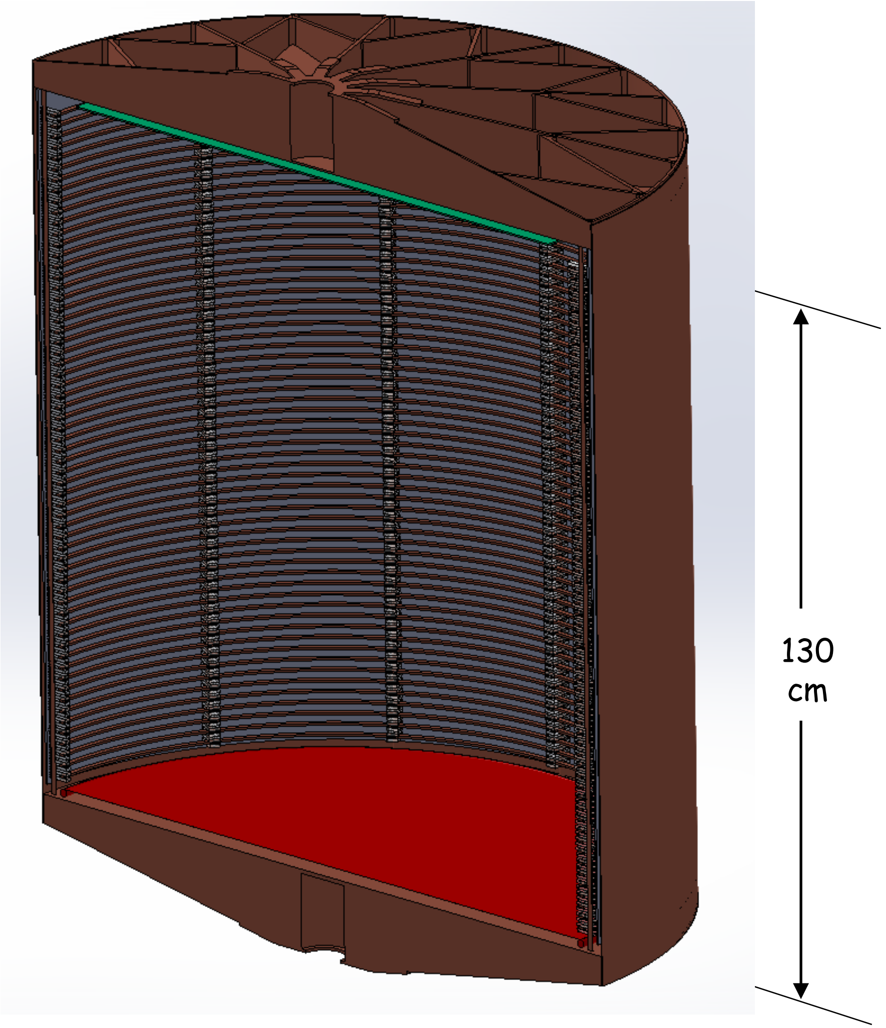
2.5 MeV γ attenuation length 8.7cm = —

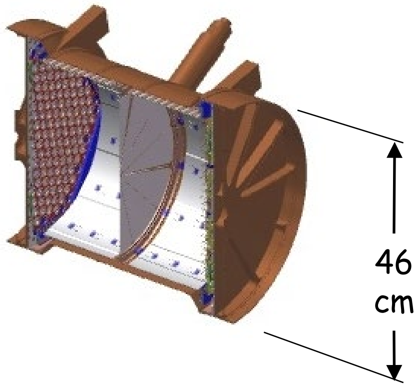


Important: The estimate of the nEXO sensitivity relies only on materials already tested for radioactivity (except for the intrinsic contamination of the LXe which can be/is repurified during running)

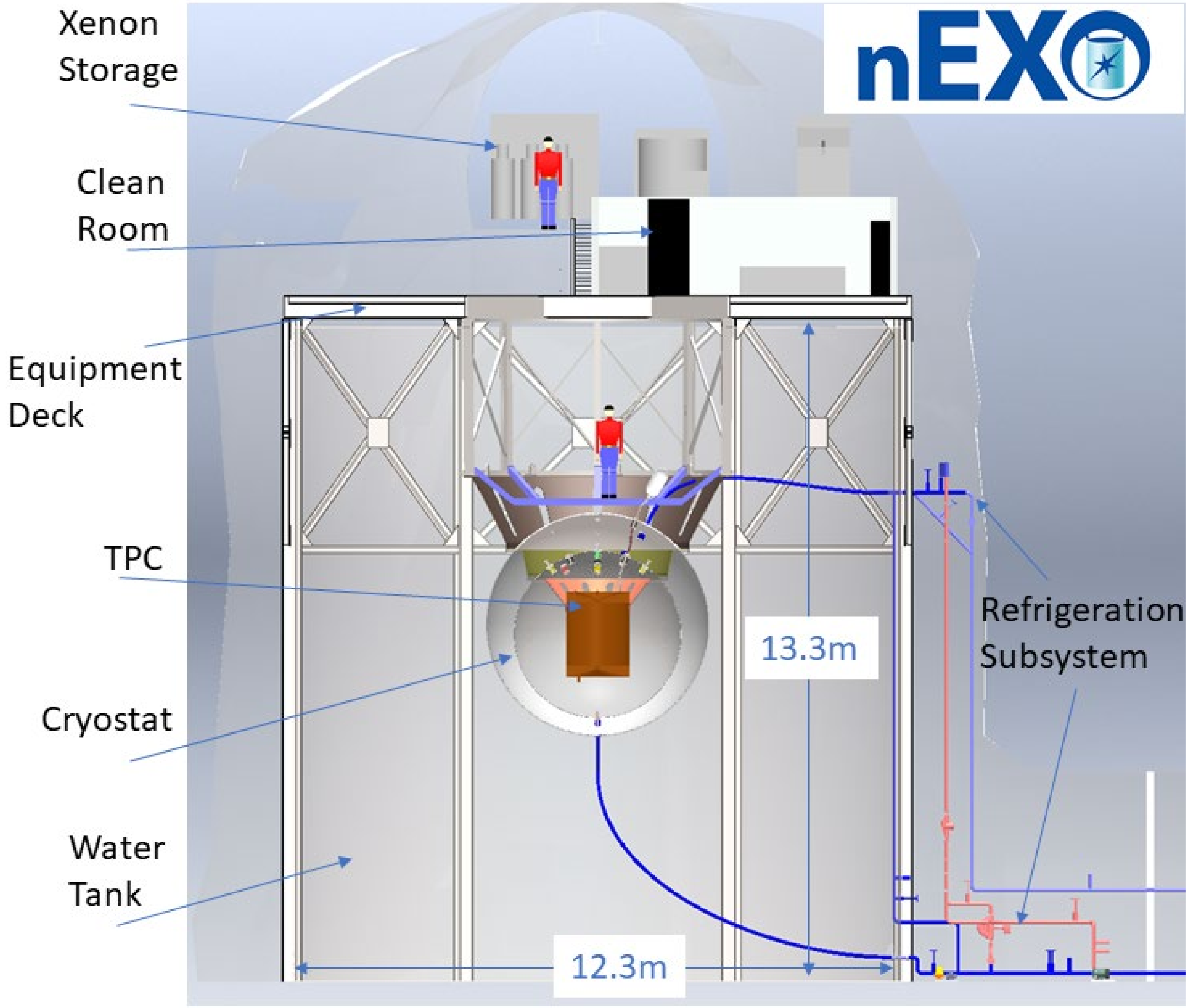
The nEXO detector

A 5000 kg enriched LXe TPC,
***directly extrapolated from* EXO-200**





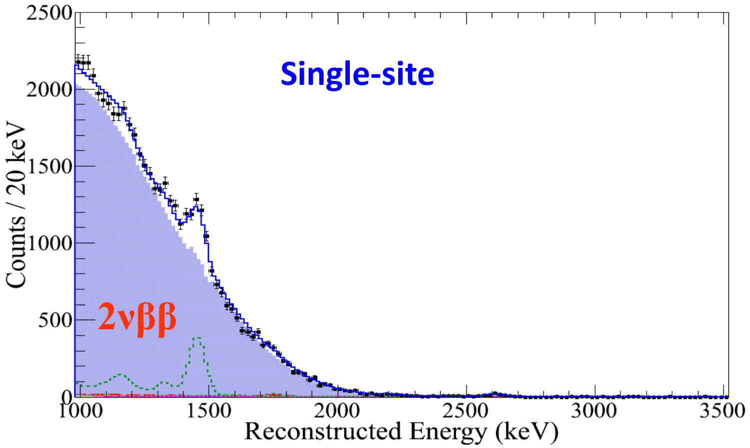
The entire nEXO detector in the SNOLAB Cryopit (more equipment in various drifts)

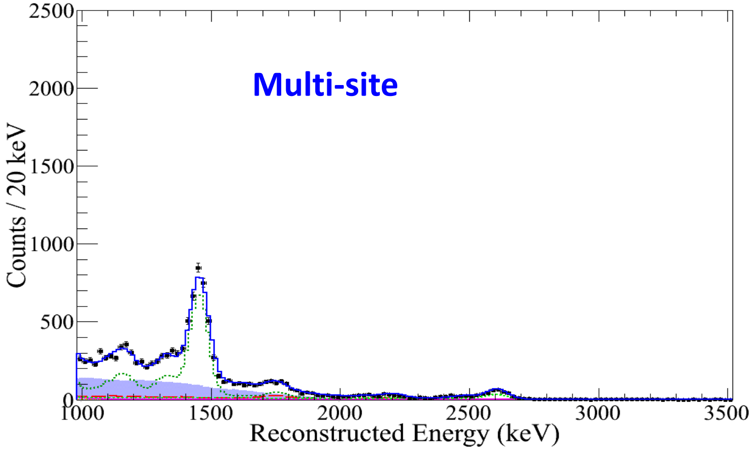


Using event multiplicity to recognize backgrounds

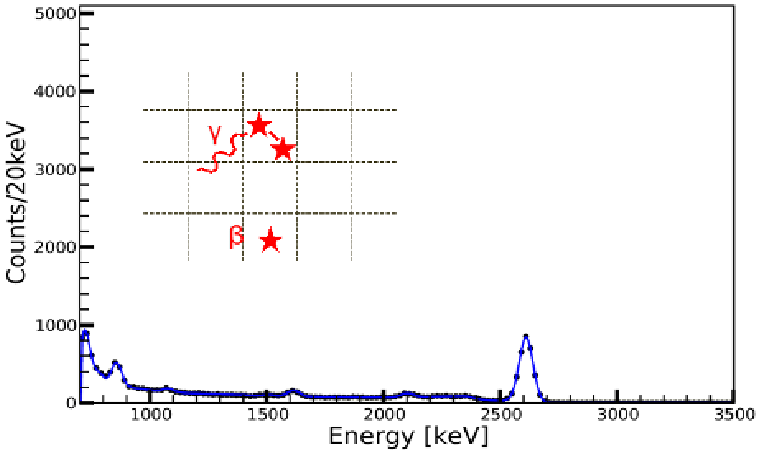
EXO-200 data

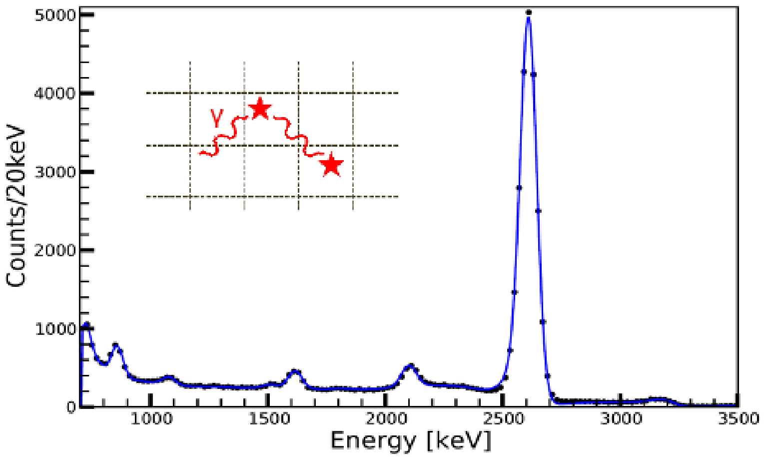
Low background data





^{228}Th calibration source



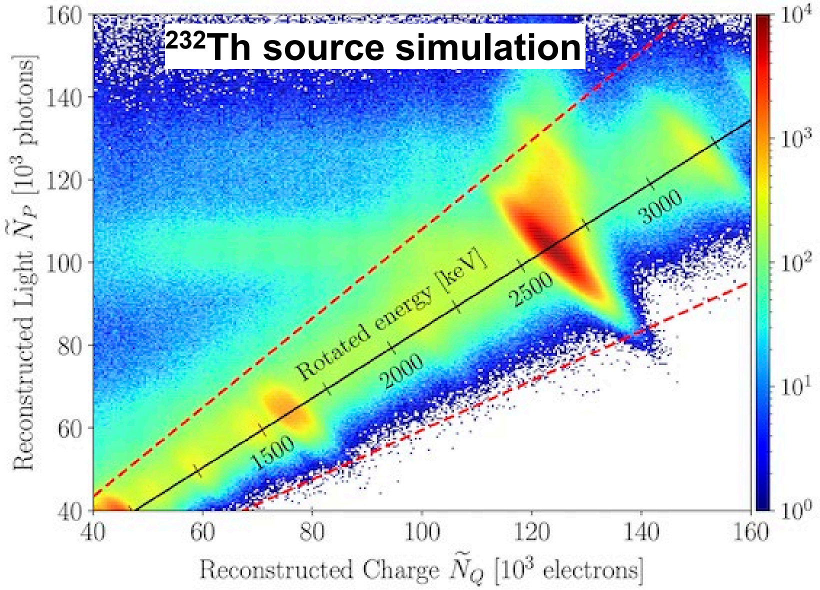


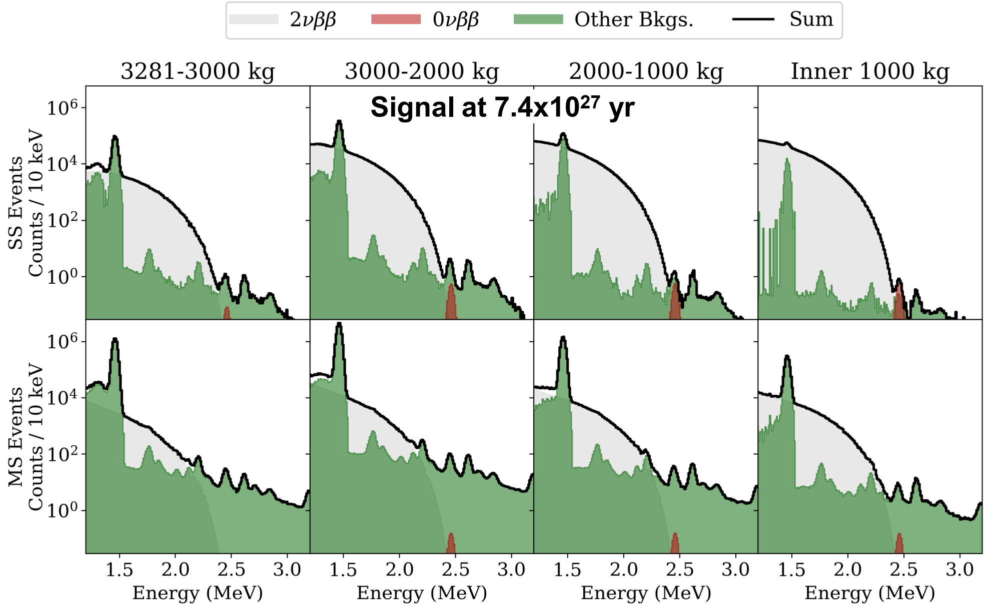
nEXO is the best option for a very large detector

Multi-parameter analysis: much more information than just energy

1. **The homogeneous detector with advanced topological reconstruction has a proven track record for γ background <u>identification</u> and <u>rejection.</u>**

   Multi-parameter analysis also makes the measurement robust even for currently unknown backgrounds.





2. **The energy resolution, still important, is quite good, once the scintillation and ionization are used in tandem. nEXO will have a resolution <1% at the Q-value.**

3. **The ratio of scintillation to ionization entirely removes α backgrounds.**

nEXO is the best option for a very large detector

Using xenon results in reliability and cost effectiveness

4. nEXO can make a discovery by itself, by repeating the experiment with non-enriched Xenon to confirm that a signal goes away (see “Standard of proof” in the 2014 NSAC ββ NSAC subcommittee report)

5. Recirculating Xenon reduces risk, as the purification system can be upgraded if unexpected backgrounds are discovered and/or if new technology becomes available.
Note that xenon has no long-lived, unstable isotopes.

6. Xenon enrichment is well understood and cost effective.

- **EXO-200 used 200 kg of Xe enriched to 80% in 136, at the time a pioneering production.**
- **KamLAND-ZEN more recently purchased ~800 kg of xenon enriched to 90% in 136.**
- **The nEXO need is only 5x of what already available.**
- **nEXO has identified at least two western suppliers each with enough enrichment capacity for the entire production at competitive price. We also have two backup options.**

“And then I thought, What better hedge than a ~~uranium~~ centrifuge?”
xenon

nEXO is the best option for a very large detector

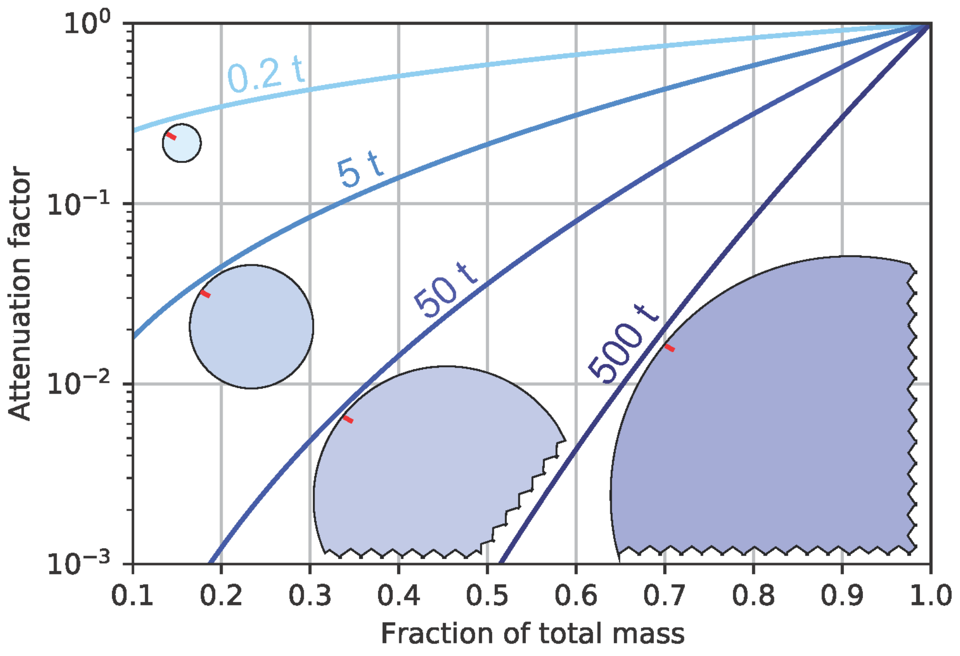
beyond nEXO

7. If nEXO discovers 0νββ decay:

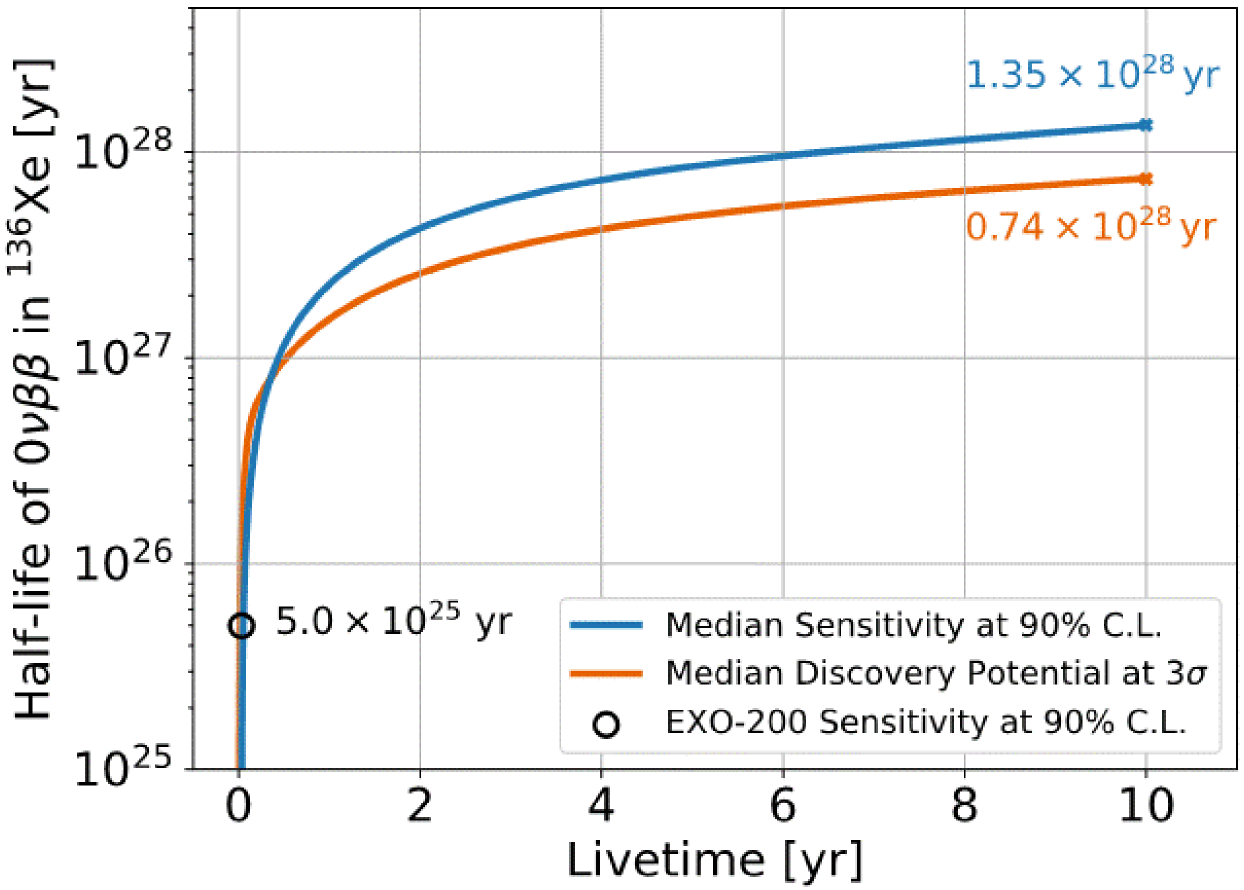
The enriched xenon is NOT "frozen" in a particular detector. Should 0νββ decay be discovered by nEXO, the xenon could be re-used in a different experimental configuration to investigate the underlying physics.
This is particularly important at the tonne scale, given the cost of the material.

8. If nEXO does not discover 0νββ decay:

The advantages of the homogeneous detector keep improving with size. Should 0νββ decay not be discovered by nEXO, larger detectors using the same technology are plausible. There is enrichment capacity for this, although the feed stock will need to be directly extracted from air; again, this is plausible.
A clear avenue for the future.



nEXO: In the land of large, scalable double-beta decay experiments



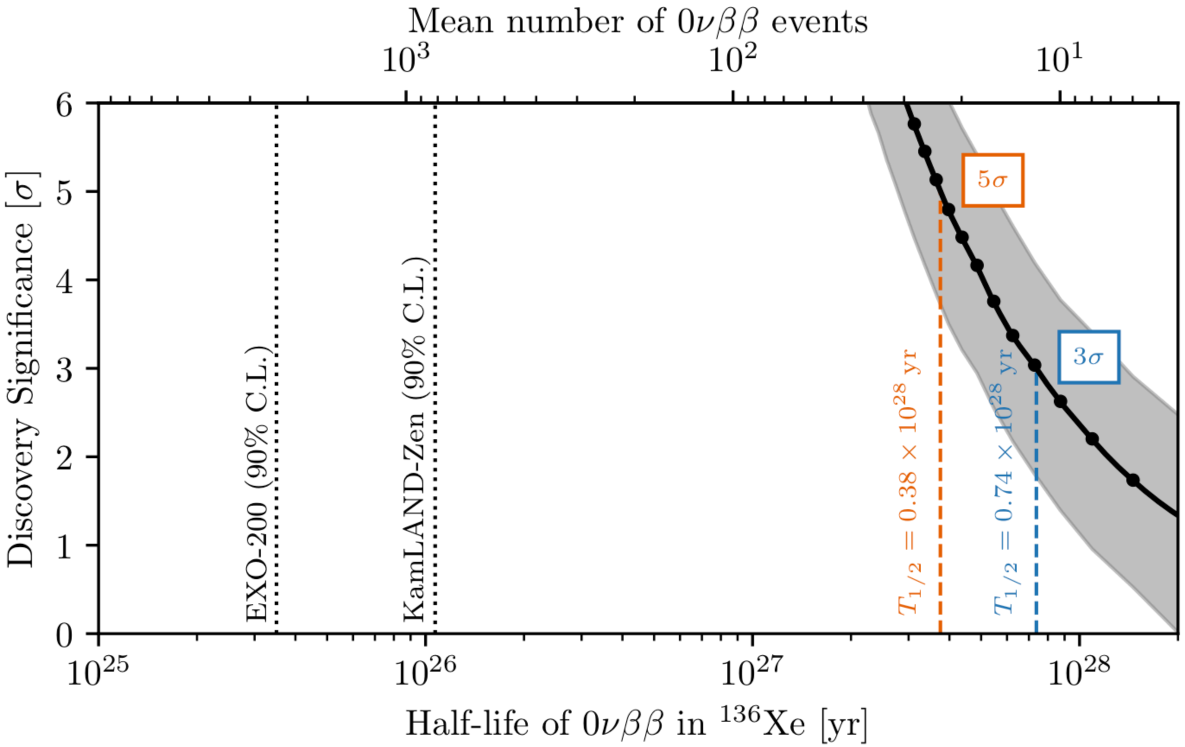
nEXO sensitivity reaches 10^{28} yr in 6.5 yr data taking

Sensitivity and Discovery Potential

nEXO is a discovery experiment that will search for lepton number violation over a large, unexplored parameter space

- **>10^{28} yr $T_{1/2}$ sensitivity**
- **Can provide compelling evidence of discovery without other experiments**
- **Probes effective Majorana neutrino masses, $m_{\beta\beta}$, down to 15 meV**

	Limit / Discovery Sensitivity	**Reference:**
EXO-200	3.5×10^{25} yr (90% CL)	PRL 123, 161802 (2019)
KamLAND-Zen	1.07×10^{26} yr (90% CL)	PRL 117, 082503 (2016)
nEXO	0.38×10^{28} (5σ) 0.74×10^{28} (3σ)	arXiv:2106.16243



Physics reach in terms of effective Majorana mass.
This is also useful to compare different experiments.

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} g_A^4 |M^{0\nu}|^2$$

Phase space factor
J. Kotila and F. Iachello, Phys Rev C 85, 034316 (2012)

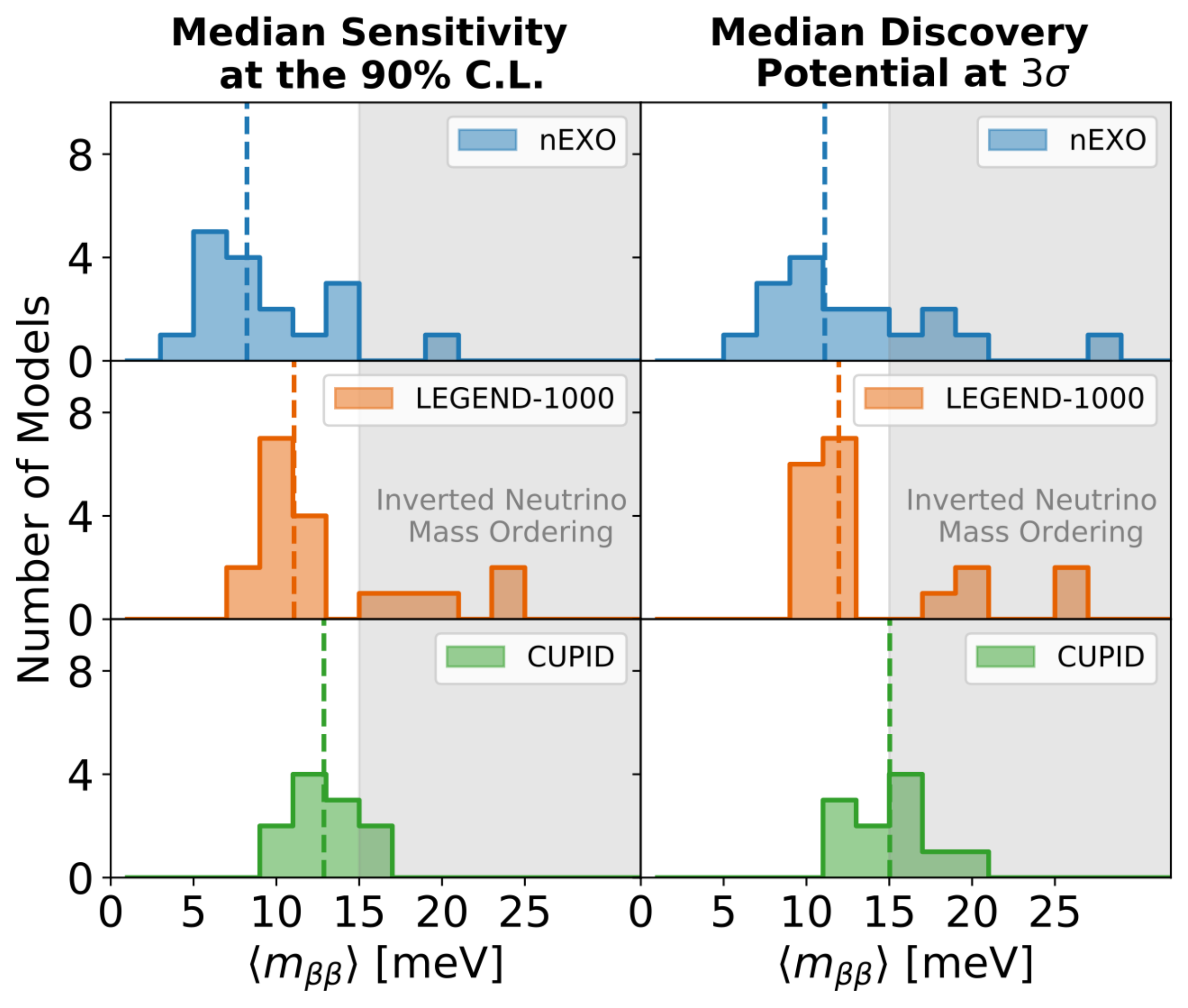
Axial coupling, $g_A = 1.27$

- ^{136}Xe benefits from larger $G^{0\nu}$ than lighter isotopes ($G^{0\nu}$ is known precisely)
- Significant theoretical uncertainty in NMEs
  - Adopt agnostic approach considering all published NMEs not directly superseded by later publications
  - Conclusions not qualitatively changed if *all* published NMEs are considered

References for the NMEs used

Method	Year	Citation
IBM	2015	PRC 91 034304 (2015)
NSM	2008	PRL 100, 052503 (2008)
IBM	2020	PRD 102, 095016 (2020)
QRPA	2014	PRC 89, 064308 (2014)
NSM	2016	PRC 93, 024308 (2016)
QRPA	2015	PRC 91, 024613 (2015)
QRPA	2018	PRC 98, 024608 (2018)
NSM	2018	JPS Conf. Proc. 23, 012036 (2018)
QRPA	2013	J. High Energ. Phys. 2013, 25 (2013)
QRPA	2013	PRC 87, 064302 (2013)
QRPA	2013	PRC 87, 045501 (2013)
QRPA	2018	PRC 97, 034315 (2018)
QRPA	2010	Nucl.Phys.A 847 (2010) 207
EDF	2013	PRL 111, 142501 (2013)
EDF	2015	PRC 91, 024316 (2015)
QRPA	2018	PRC 97, 045503 (2018)
EDF	2017	PRC 96, 054310 (2017)
QRPA	2015	PRC 91, 024613 (2015)
EDF	2010	Prog.Part.Nucl.Phys. 66 (2011) 436

Comparison with other experiments



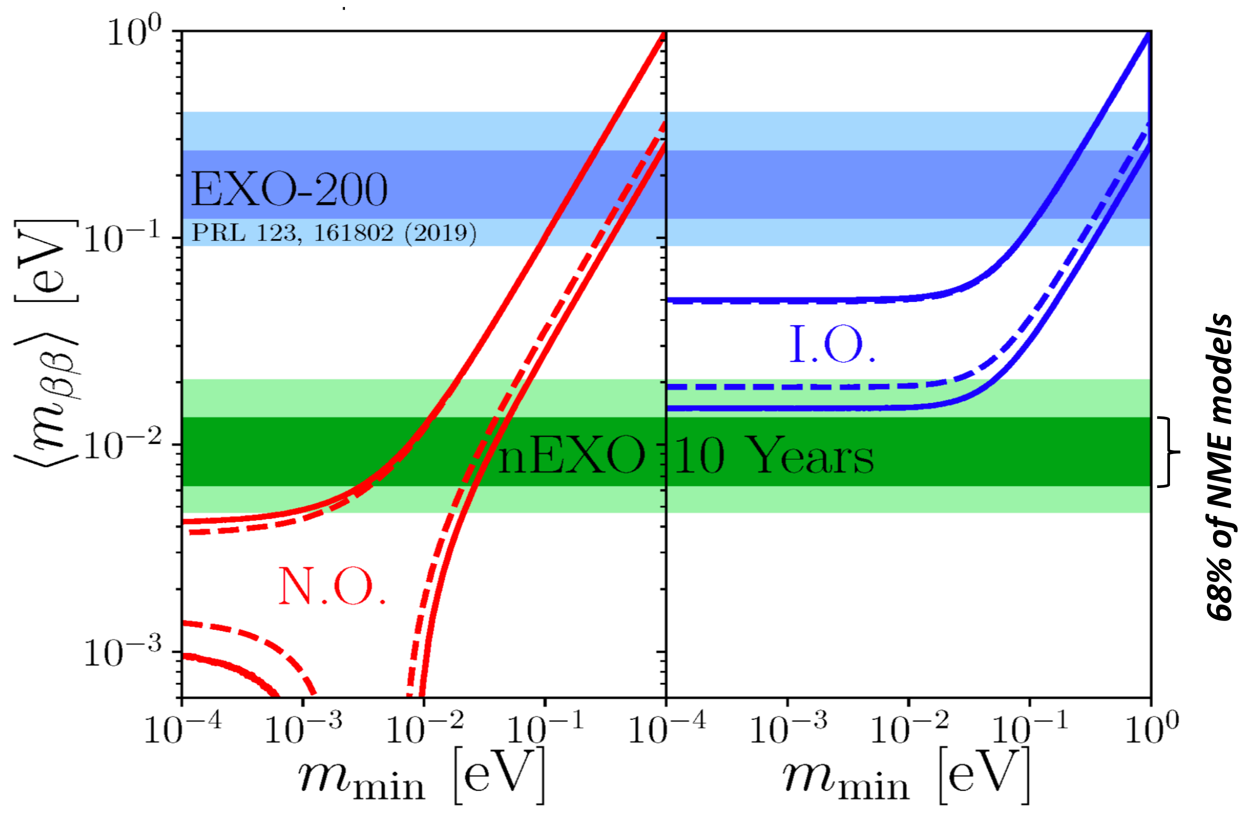
	$m_{\beta\beta}$ [meV], (*median NME*)	
	90% excl. sens.	3σ discov. potential
nEXO	**8.2**	**11.1**
LEGEND	**11.1**	**12.0**
CUPID	**12.9**	**15.0**

***$T_{1/2}$ values used [x10^{28} yr]:**

nEXO: 1.35 (90% sens.), 0.74 (3σ discov.) [1]
LEGEND: 1.4 (90% sens.), 1.2 (3σ discov.) [2]
CUPID: 0.15 (90% sens.), 0.11 (3σ discov.) [3]

Majorana Mass Reach

Allowed parameter space and nEXO exclusion sensitivity (90% CL):

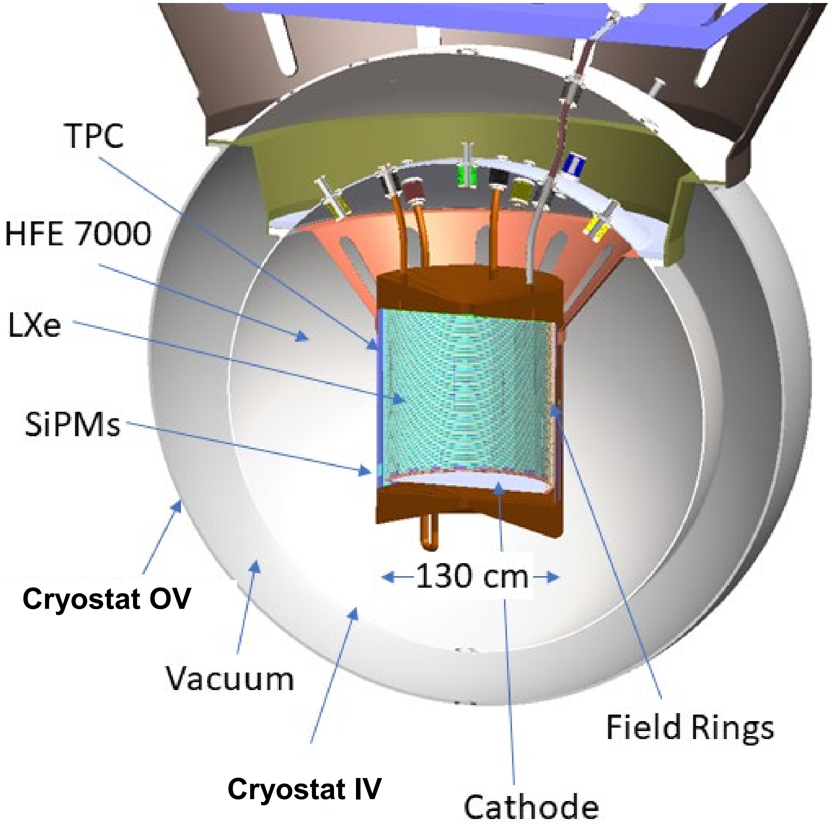


nEXO 3σ discovery sensitivity for the median NME model considered is 11.1 meV, reaching beyond IO further into NO

Conclusions:

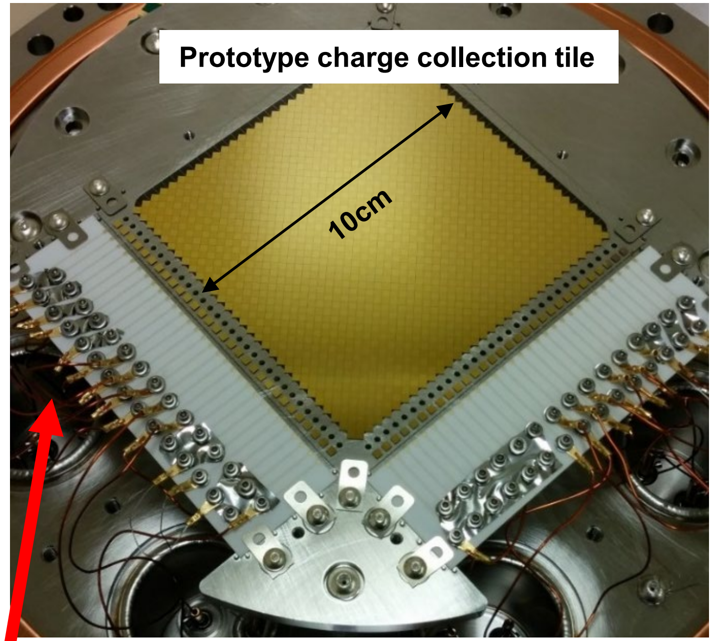
- **nEXO extends the reach into new physics by ~2 orders of magnitude, with substantial chance to make a discovery.**
- **Nominally, nEXO has a slightly better physics reach with respect to other experiments, but the NME uncertainty is large.**
- **The most important conclusion is that nEXO's sensitivity estimates are robust and built from a bottom-up approach based on measured data.**

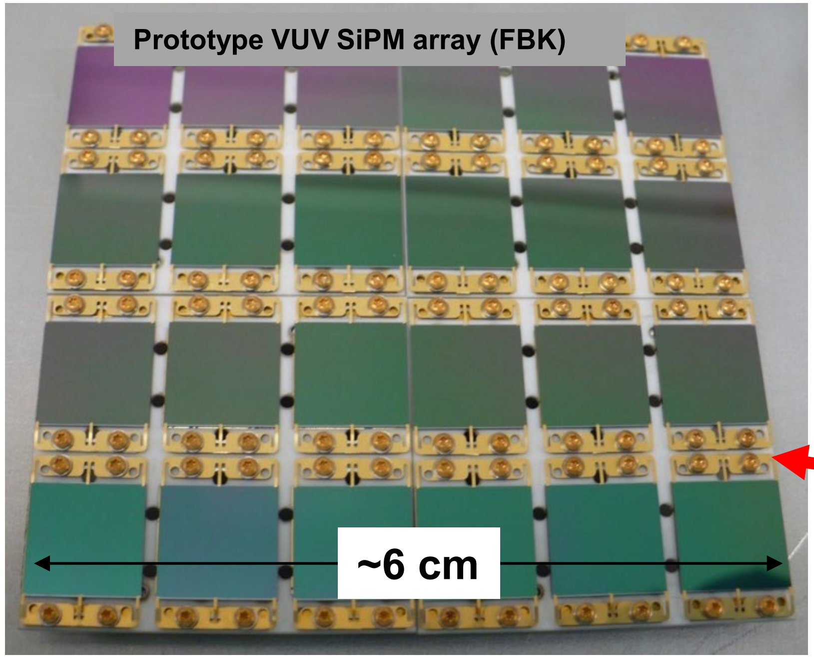
The nEXO detector is an evolution from EXO-200

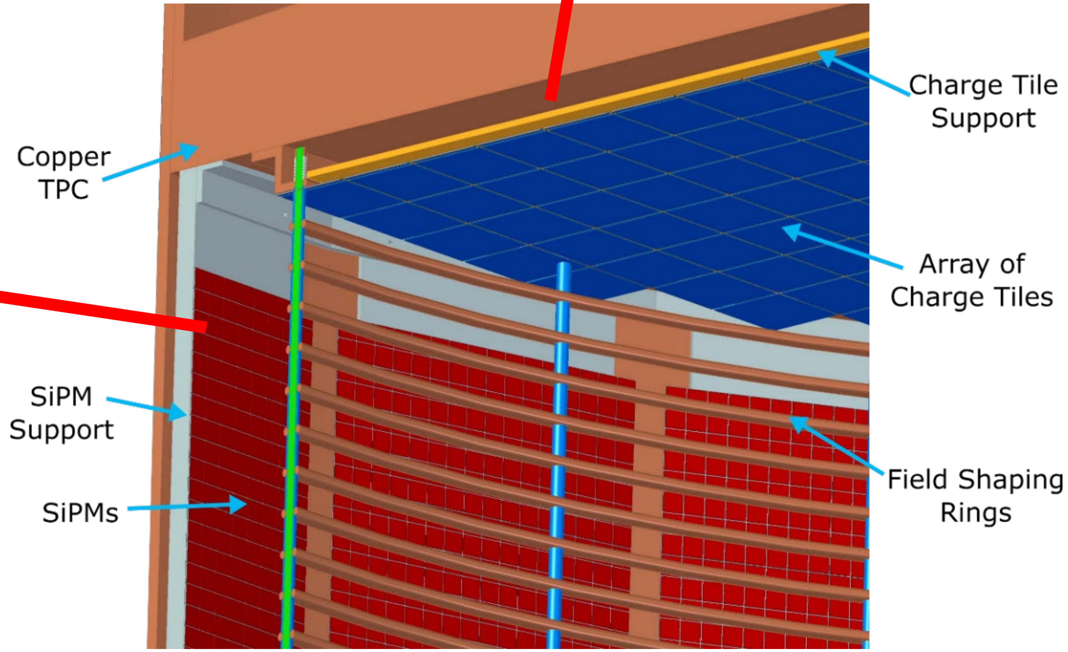


	EXO-200:	*nEXO:*	Improvements:
Vessel and cryostat	Thin-walled commercia Cu w/HFE	*Thin-walled electroformed Cu w/HFE*	Lower background
High voltage	Max voltage: 25 kV (end-of-run)	*Operating voltage: 50 kV*	Full scale parts tested in LXe prior to installation to minimize risk
Cables	Cu clad polyimide (analog)	*Cu clad polyimide (digital)*	Same cable/feedthrough technology, R&D identified 10x lower bkg substrate and demonstrated digital signal transmission
e^- lifetime	3-5 ms	*5 ms (req.), 10 ms (goal)*	Minimal plastics (no PTFE reflector), lower surface to volume ratio, detailed materials screening program
Charge collection	Crossed wires	*Gridless modular tiles*	R&D performed to demonstrate charge collection with tiles in LXe, detailed simulation developed
Light collection	APDs + PTFE reflector	*SiPMs around TPC barrel*	SiPMs avoid readout noise, R&D demonstrated prototypes from two vendors
Energy resolution	1.2%	*1.2% (req.), 0.8% (goal)*	Improved resolution due to SiPMs (negligible readout noise in light channels)
Electronics	Conventional room temp.	*In LXe ASIC-based design*	Minimize readout noise for light and charge channels, nEXO prototypes demonstrated in R&D and follow from LAr TPC lineage
Background control	Measurement of all materials	*Measurement of all materials*	RBC program follows successful strategy demonstrated in EXO-200
Larger size	>2 atten. length at center	*>7 atten. length at center*	Exponential attenuation of external gammas and more fully contained Comptons

At the core of the TPC are light and Charge collection devices

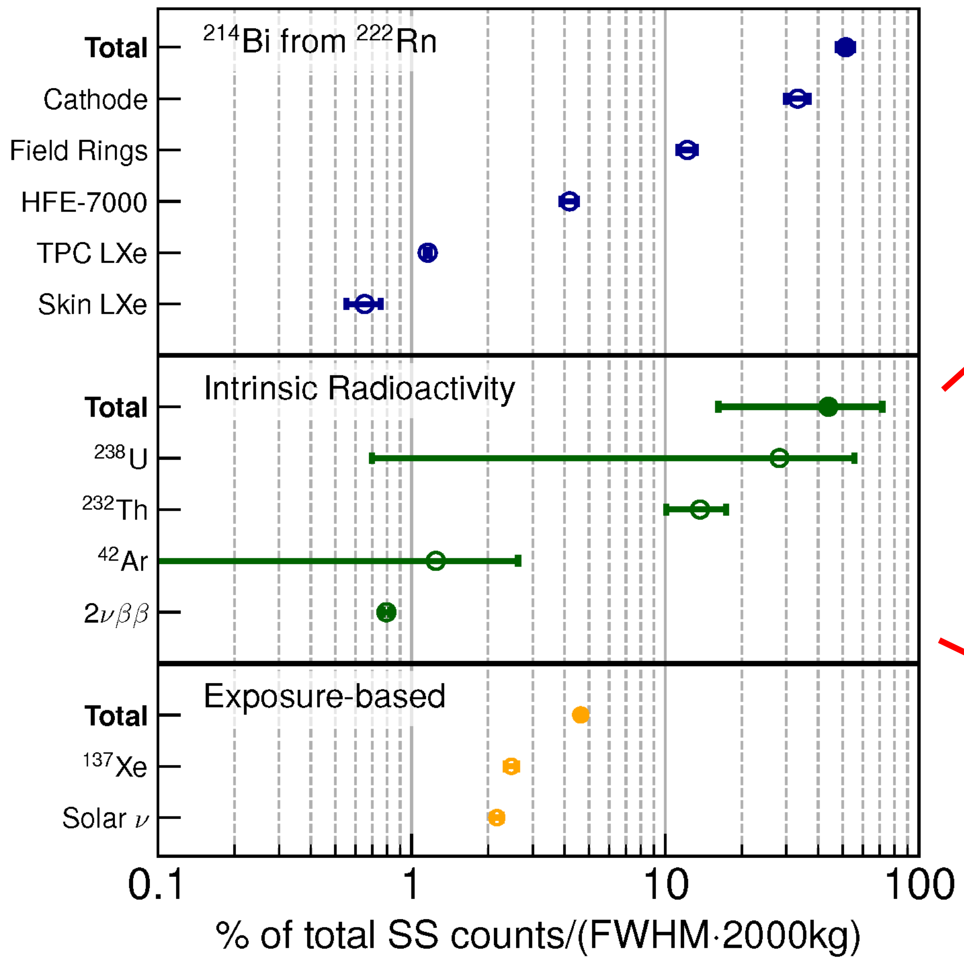


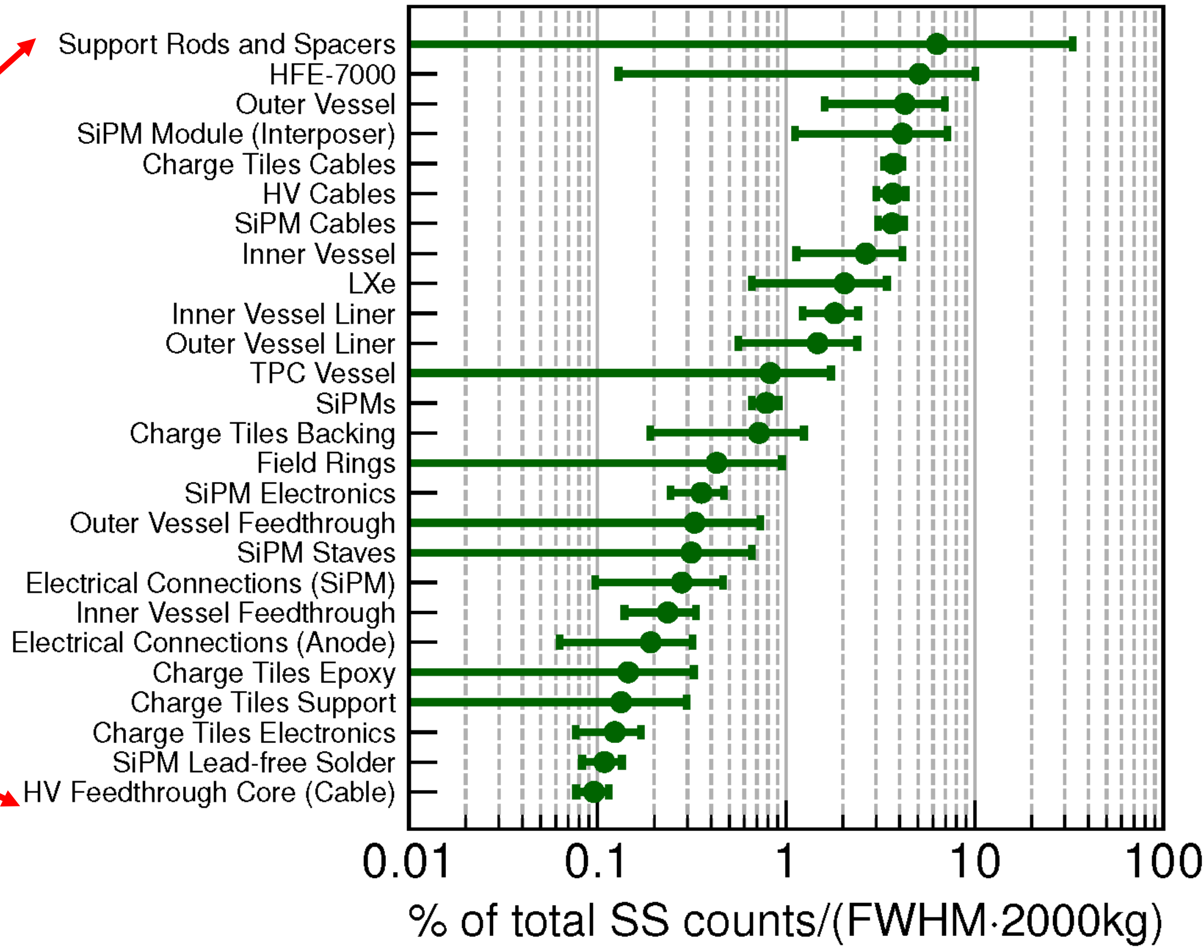




nEXO is well optimized

No detector component dominates the background.





Summary

- $0\nu\beta\beta$ searches are discovery physics, with connections to many areas of modern physics
- No discovery yet, with sensitivities $>10^{25}$ yr
- Looking at more than one isotope is important
- The global community is gearing up for the construction of two tonne-scale experiments, with sensitivity exceeding 10^{28} yrs

nEXO

nEXO is a world-wide effort, including, for the time being, 9 Countries, 33 institutions, ~200 collaborators