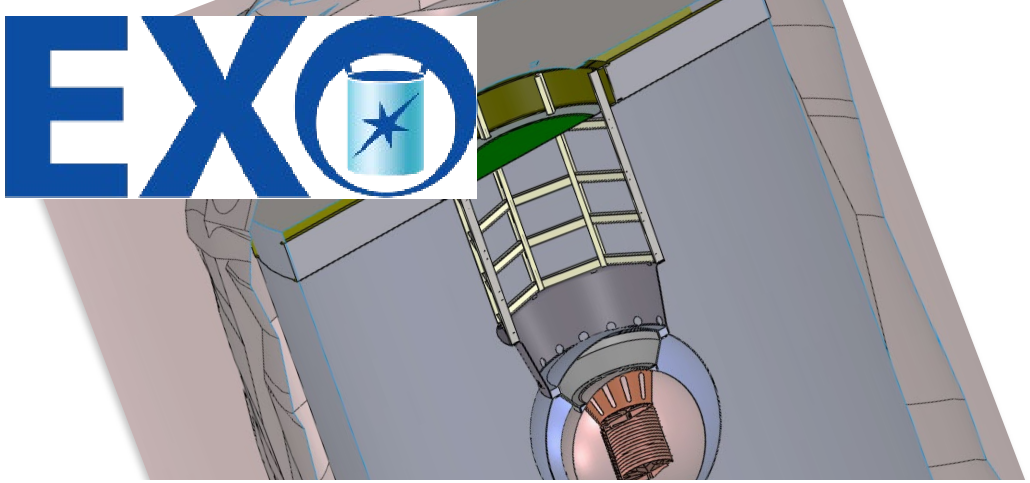
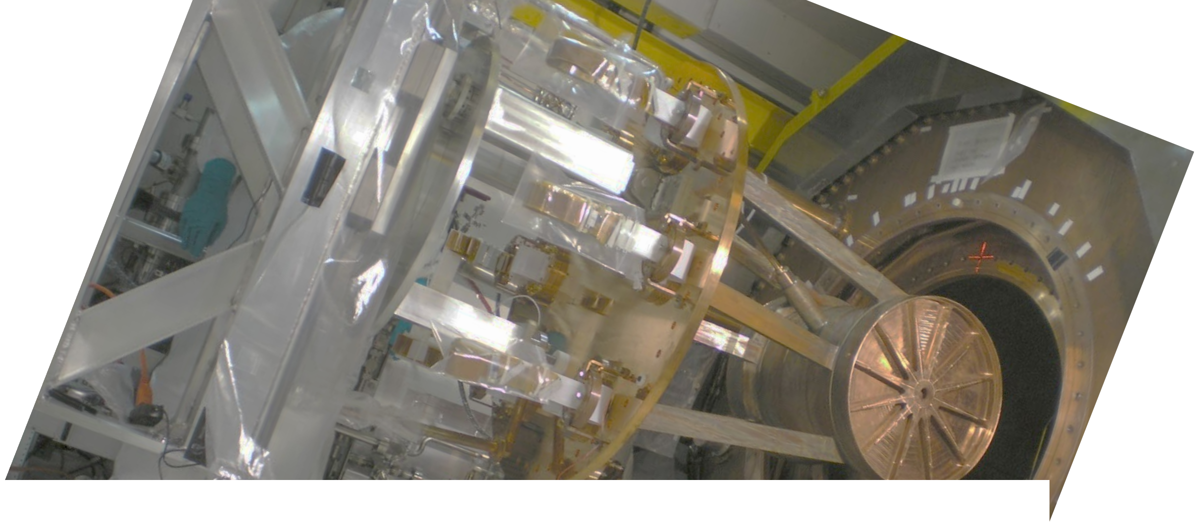
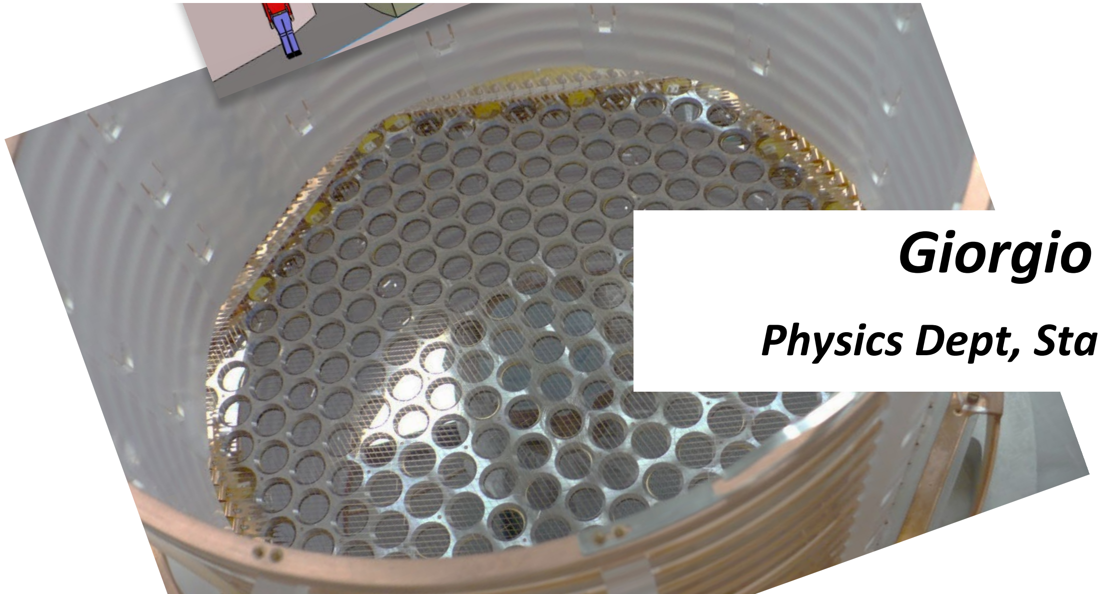
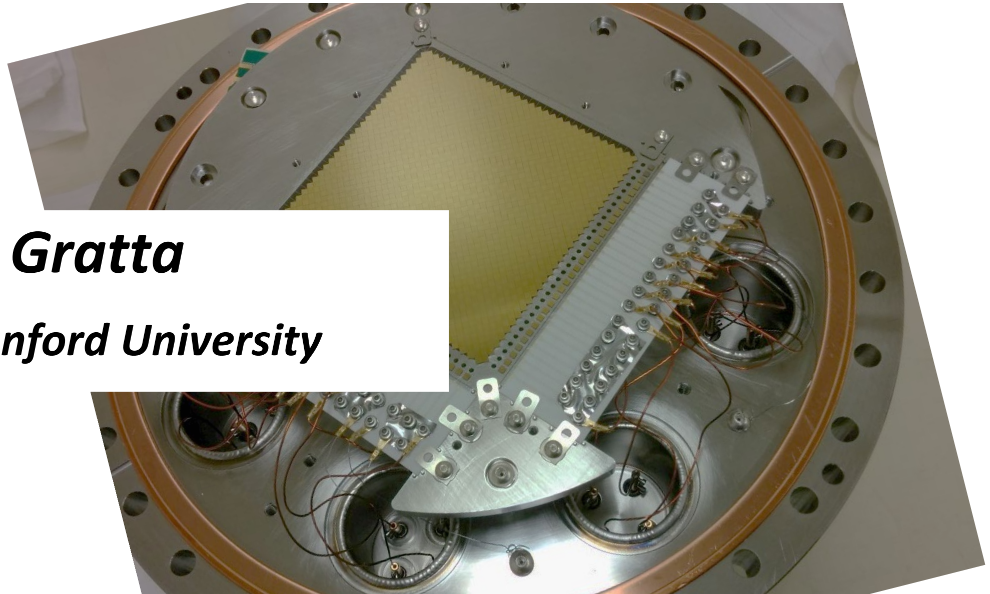




The hunt for Neutrinoless Double-Beta decay with nEXO

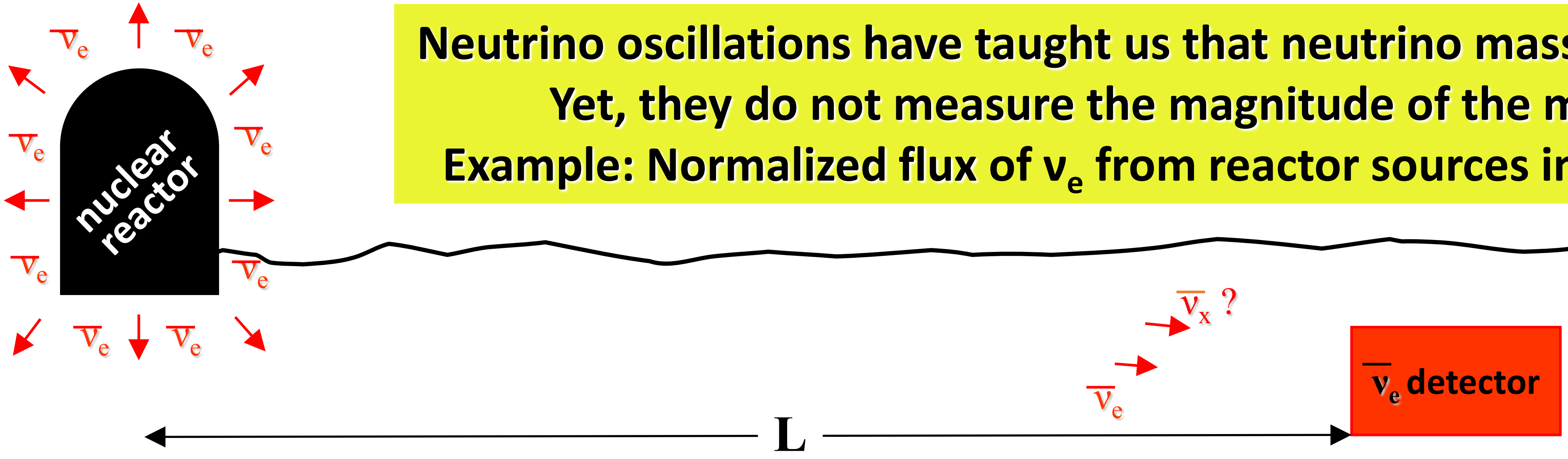


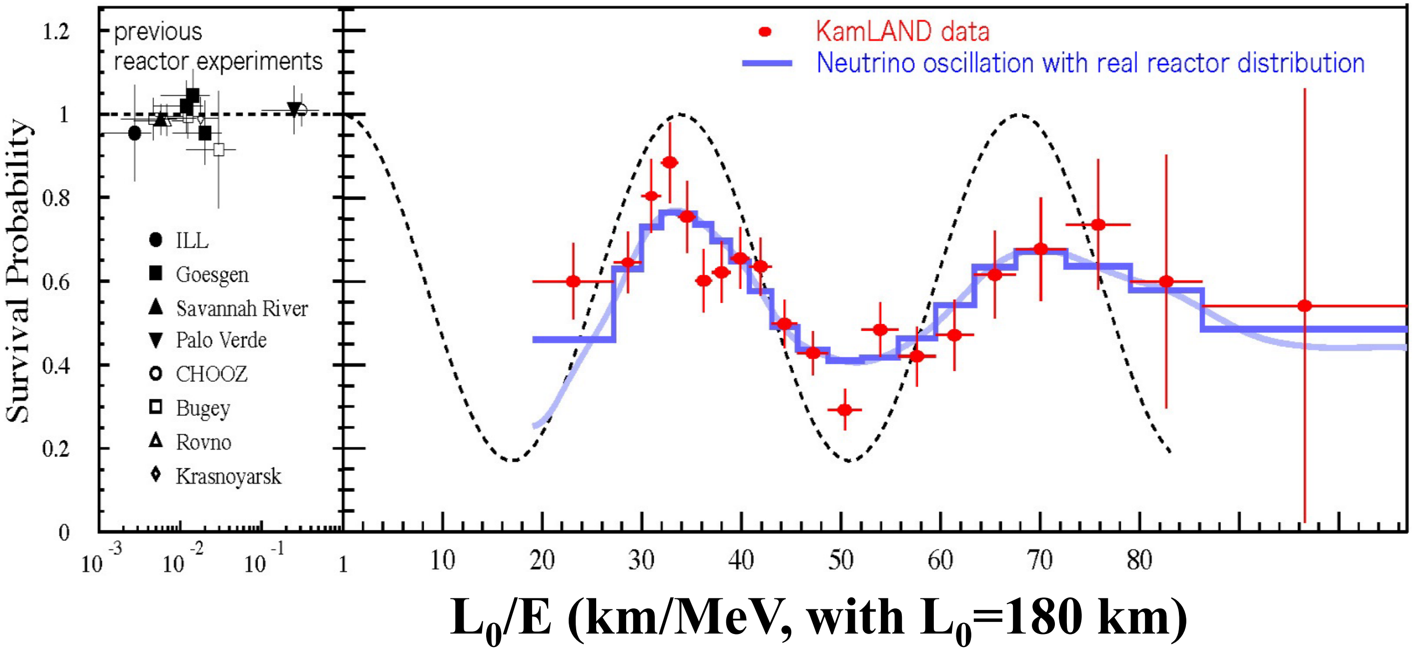


Giorgio Gratta

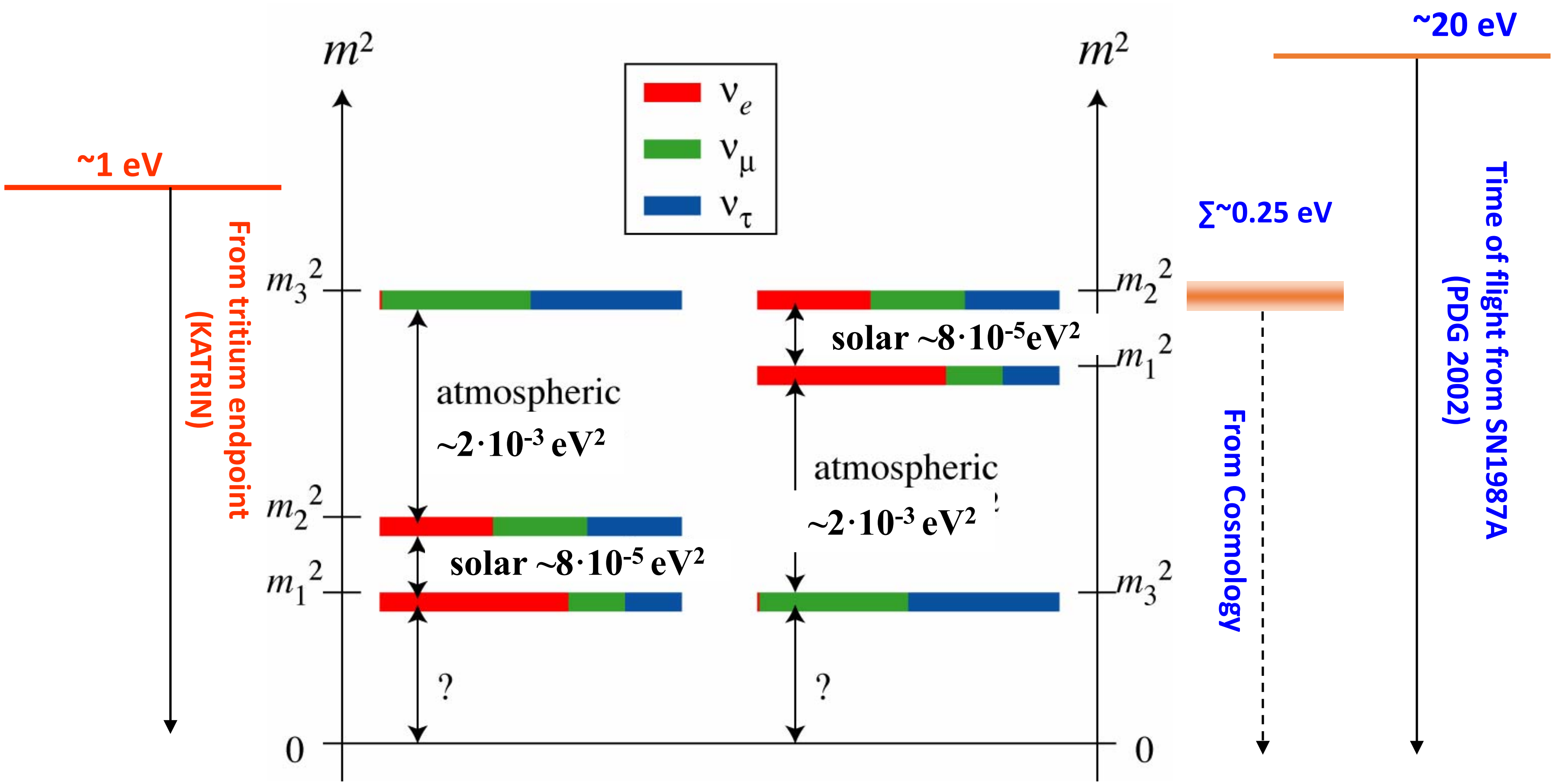
Physics Dept, Stanford University

Neutrino oscillations have taught us that neutrino masses are finite
Yet, they do not measure the magnitude of the masses
Example: Normalized flux of ν_e from reactor sources in KamLAND

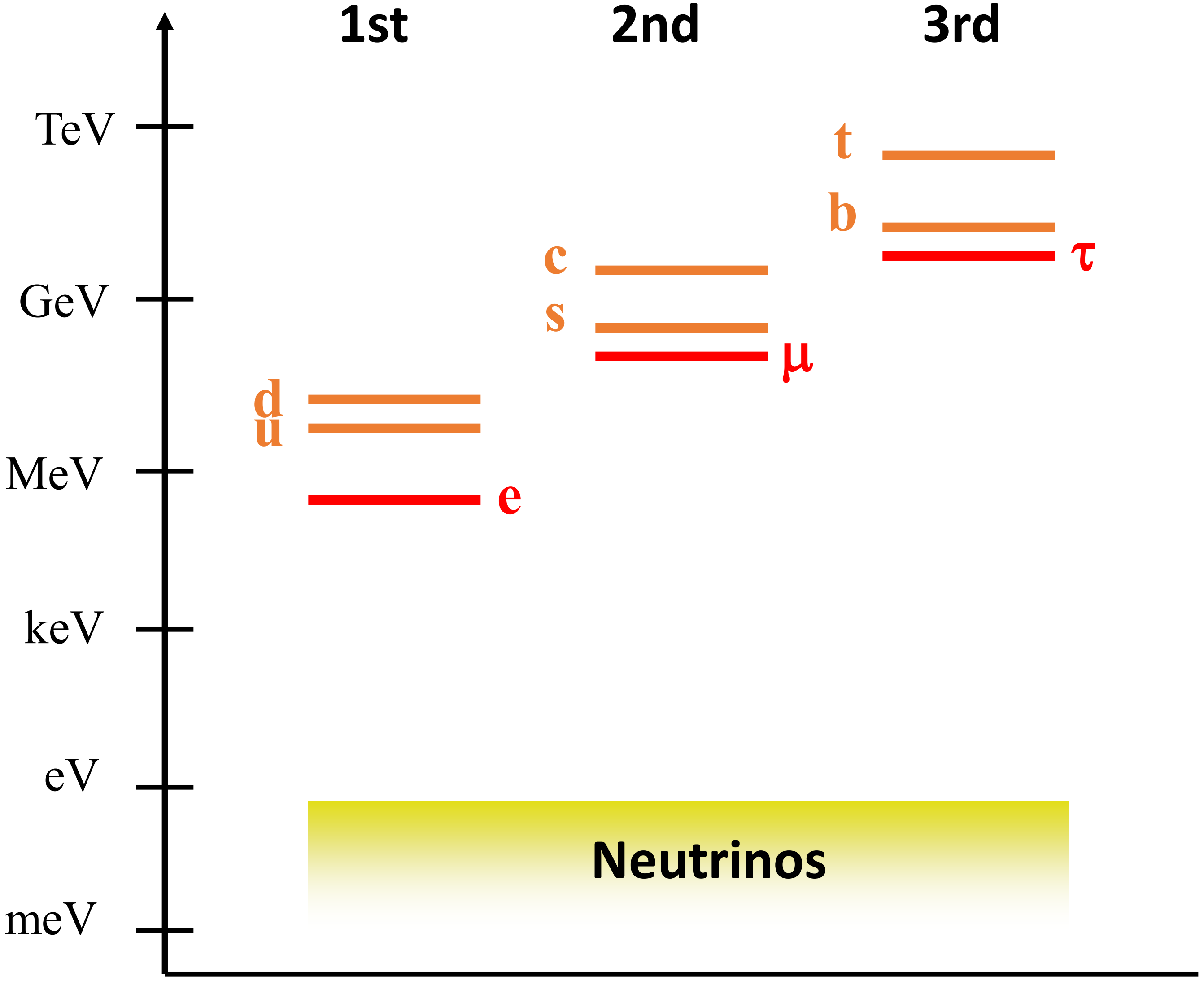




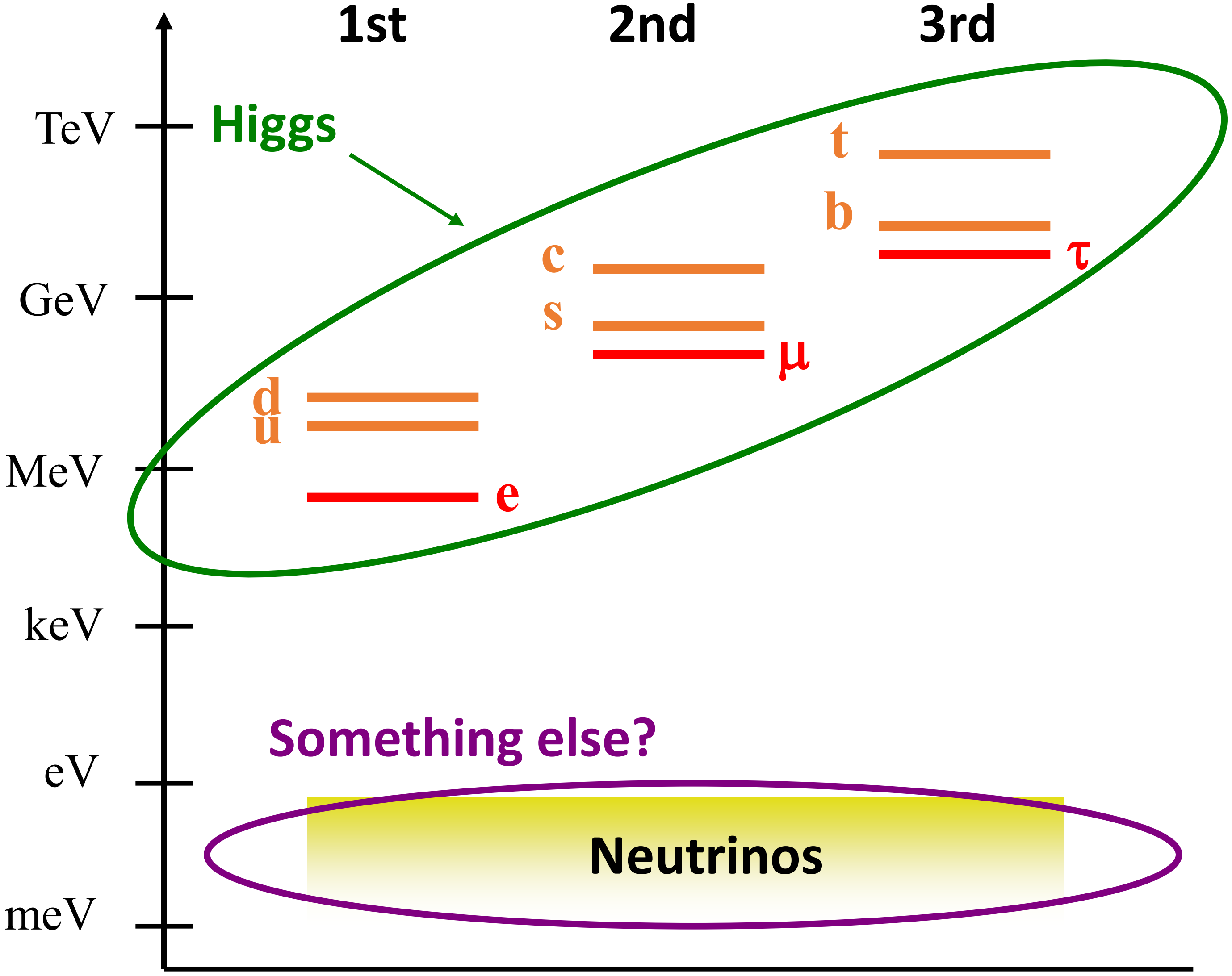
Our knowledge of the ν mass pattern



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.

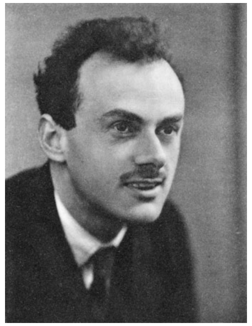
Basically lepton number is conserved "because", experimentally, $\bar{\nu} \neq \nu$.
But, in the neutral case, the distinction may derive from the different helicity states.

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…)

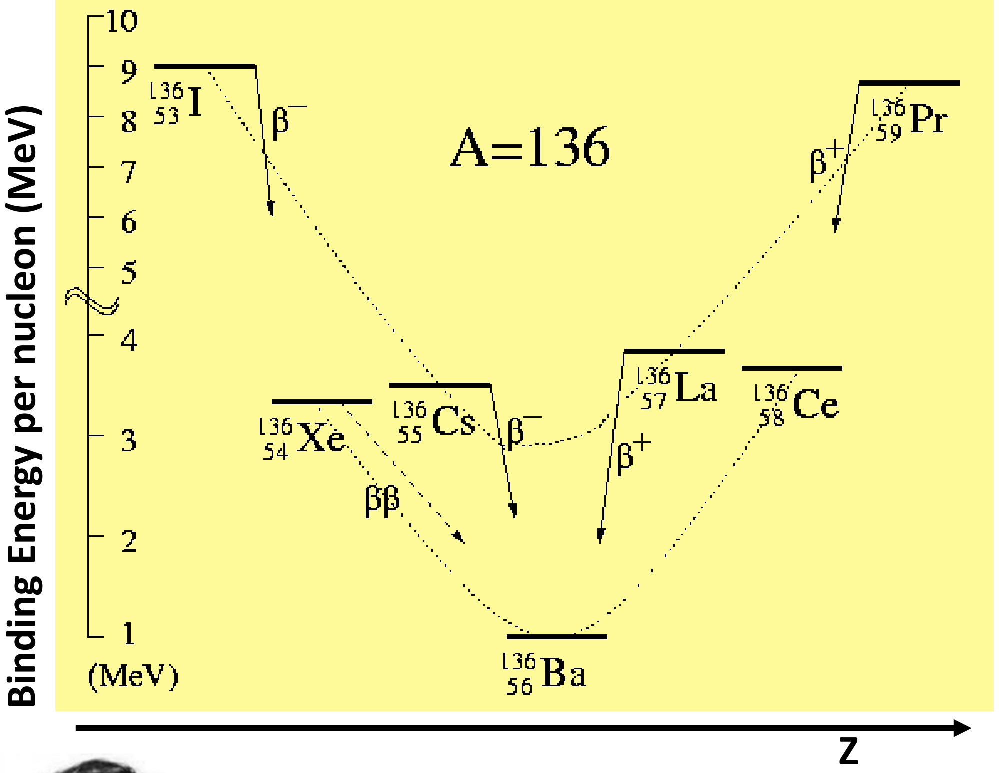
$$\nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

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)

The most sensitive probe for the Majorana or Dirac nature of neutrinos is the half-life of a nuclear state for which the regular β decay is forbidden




Amedeo Avogadro
1776-1856

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

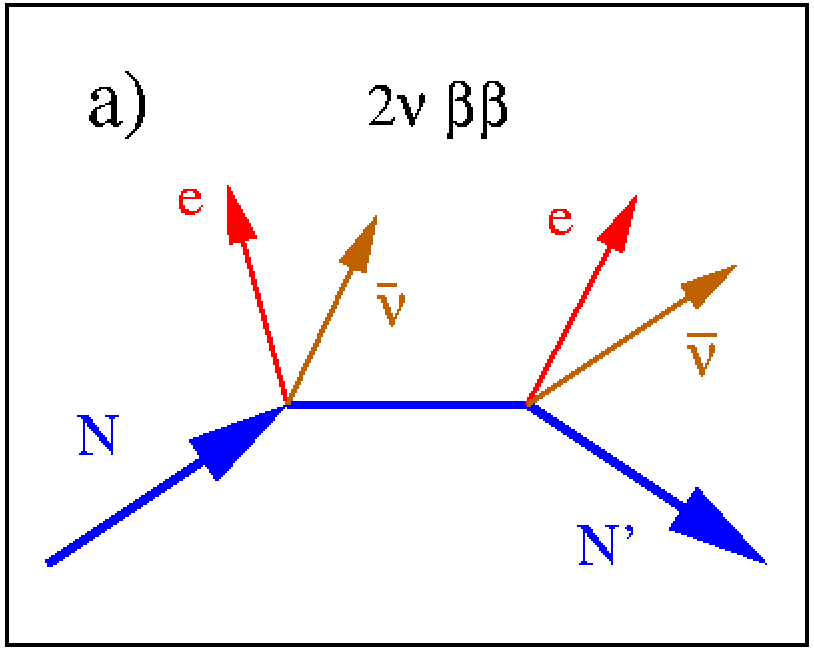
Examples with Q>2MeV

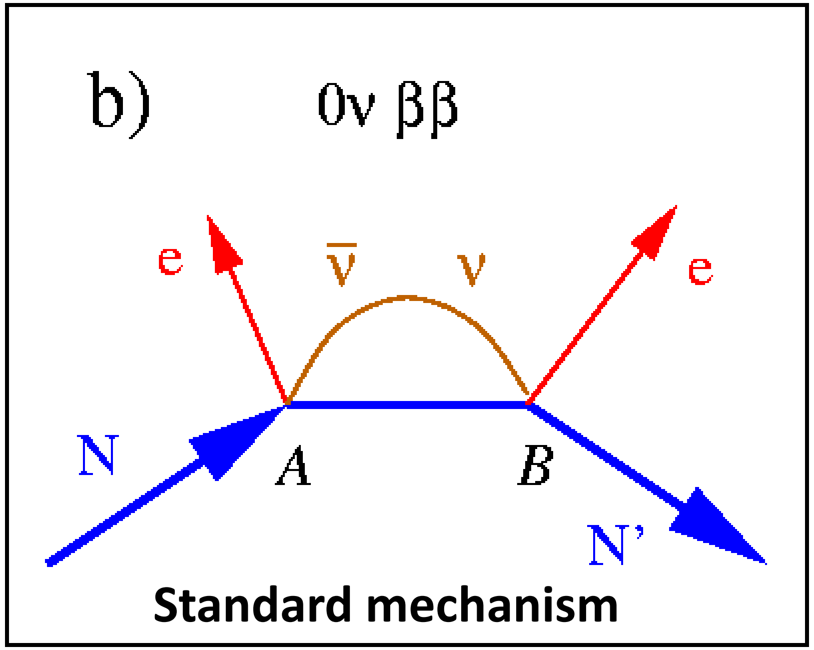
Candidate	Q (MeV)	Abundance
^{48}Ca→^{48}Ti	4.271	0.187
^{76}Ge→^{76}Se	2.040	7.8
^{82}Se→^{82}Kr	2.995	9.2
^{96}Zr→^{96}Mo	3.350	2.8
^{100}Mo→^{100}Ru	3.034	9.6
^{110}Pd→^{110}Cd	2.013	11.8
^{116}Cd→^{116}Sn	2.802	7.5
^{124}Sn→^{124}Te	2.228	5.64
^{130}Te→^{130}Xe	2.533	34.5
^{136}Xe→^{136}Ba	2.458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

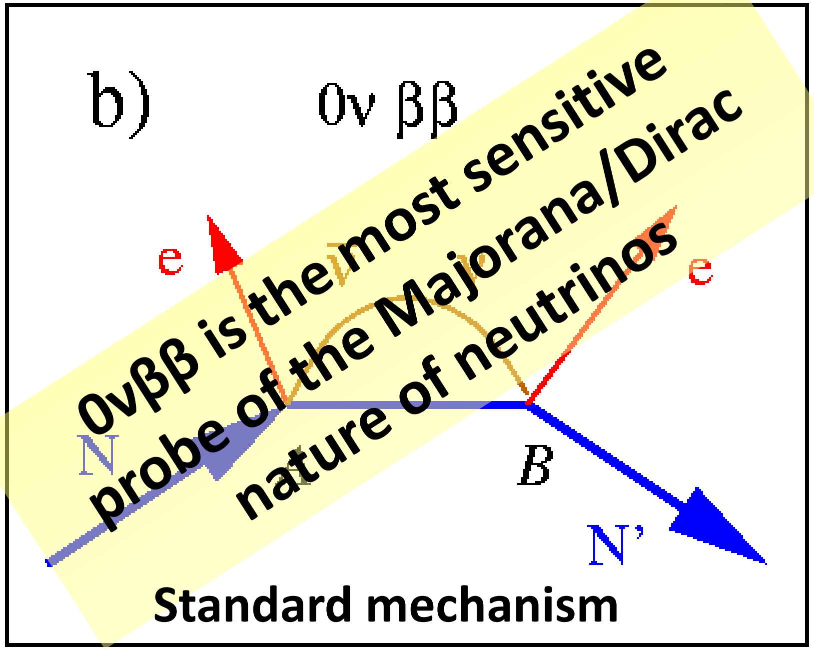
0ν mode: a hypothetical process can happen

only if: $M_\nu \neq 0$

$\nu = \bar{\nu}$

$|\Delta L|=2$

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

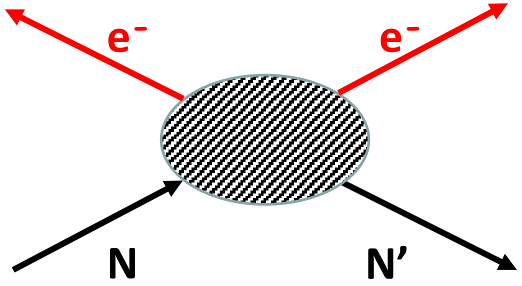


0νββ is the most sensitive probe of the Majorana/Dirac nature of neutrinos

Standard mechanism

“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 √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**

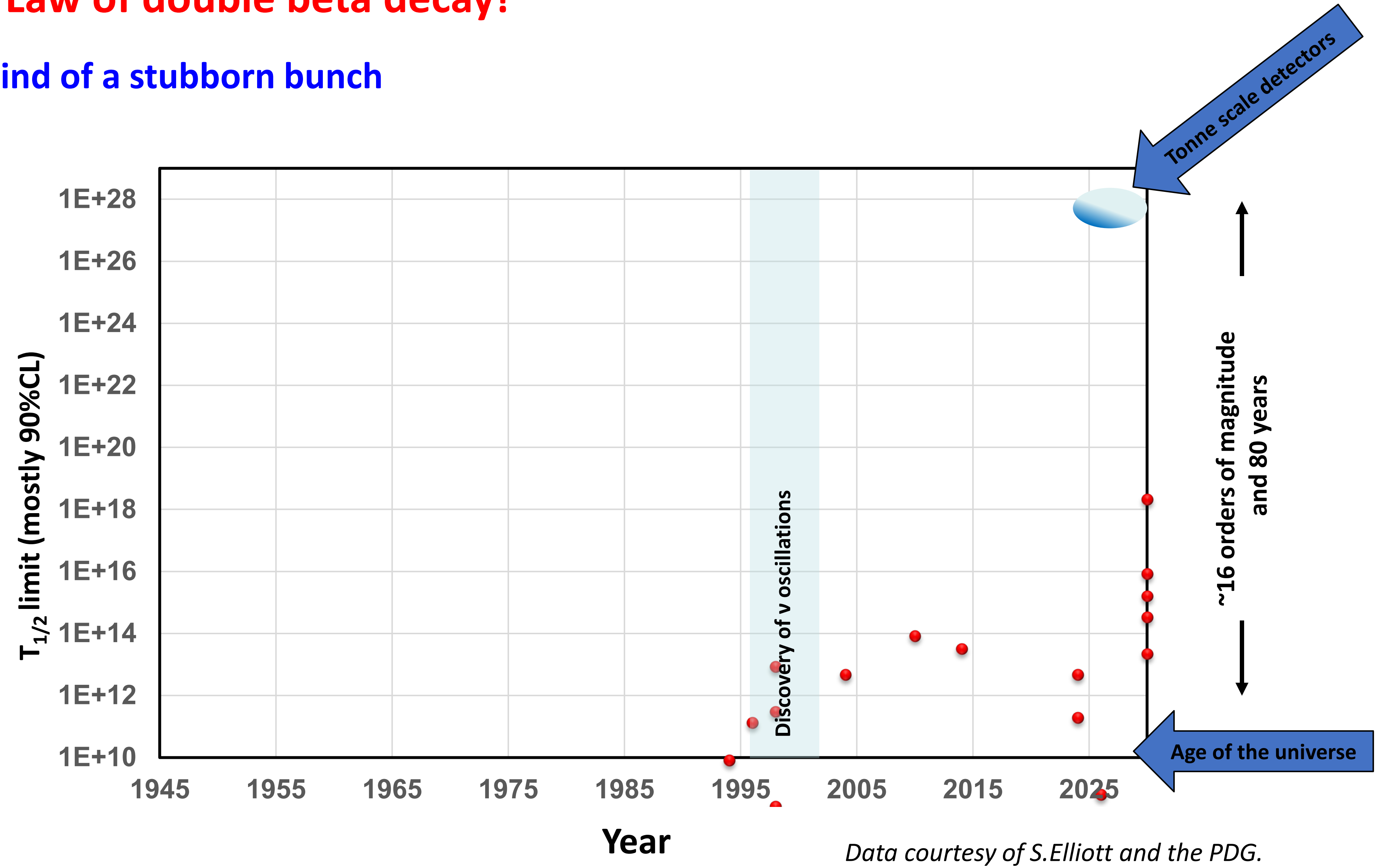
This is of course an important bonus, but these uncertainties *do not affect the discovery potential of tonne-scale experiments.*

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

➔ ***We'll come back to this later***

Moore's Law of double beta decay!

…we are kind of a stubborn bunch



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

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

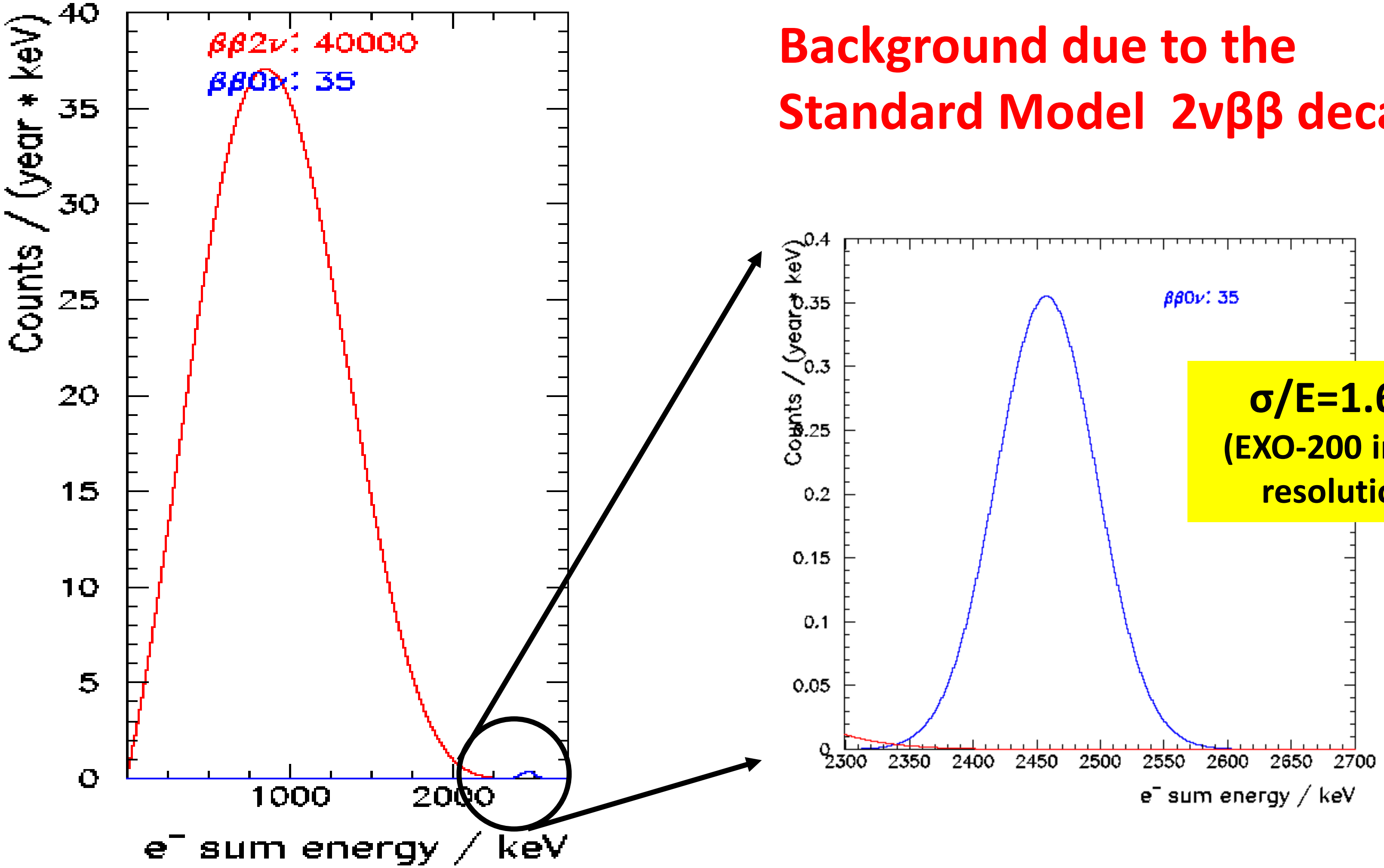
$${}^{A}_{Z}N \rightarrow {}^{A}_{Z-2}N' + e^+ + e^+$$

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

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

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

Background due to the Standard Model 2νββ decay



σ/E=1.6%
(EXO-200 initial resolution)

The neutrinoless and 2-neutrino versions of the double beta decay can be separated in a detector with sufficiently good energy resolution

But other background are generally way more important

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***

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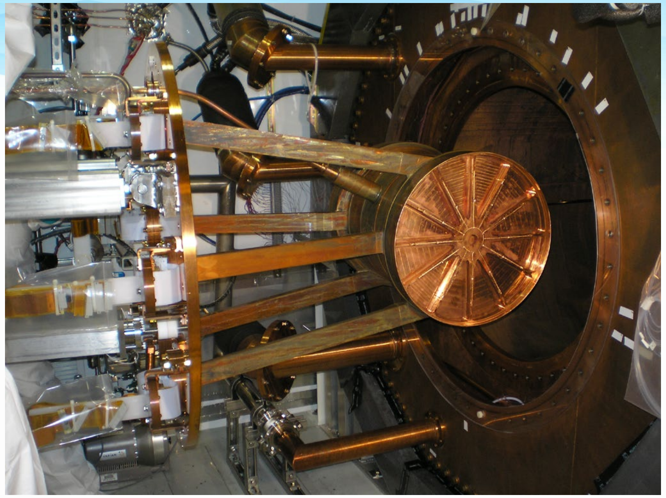
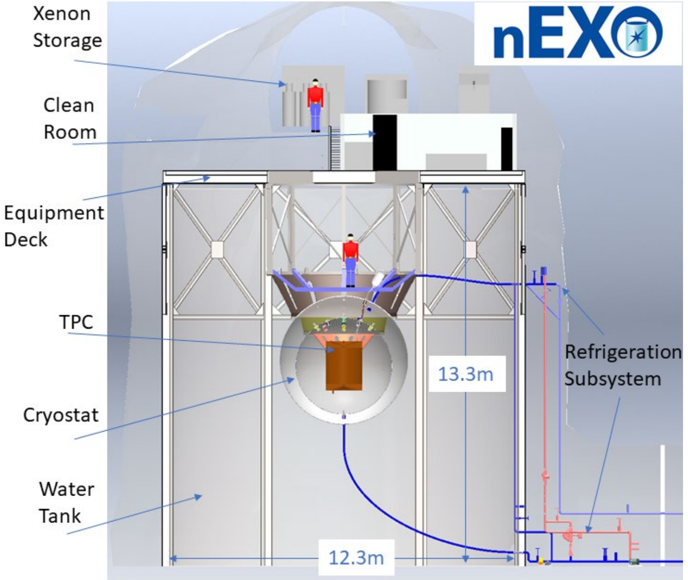
- ***The elucidation of the mechanism producing the decay requires the analysis of more than one isotope***

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 (circa 20M$), 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

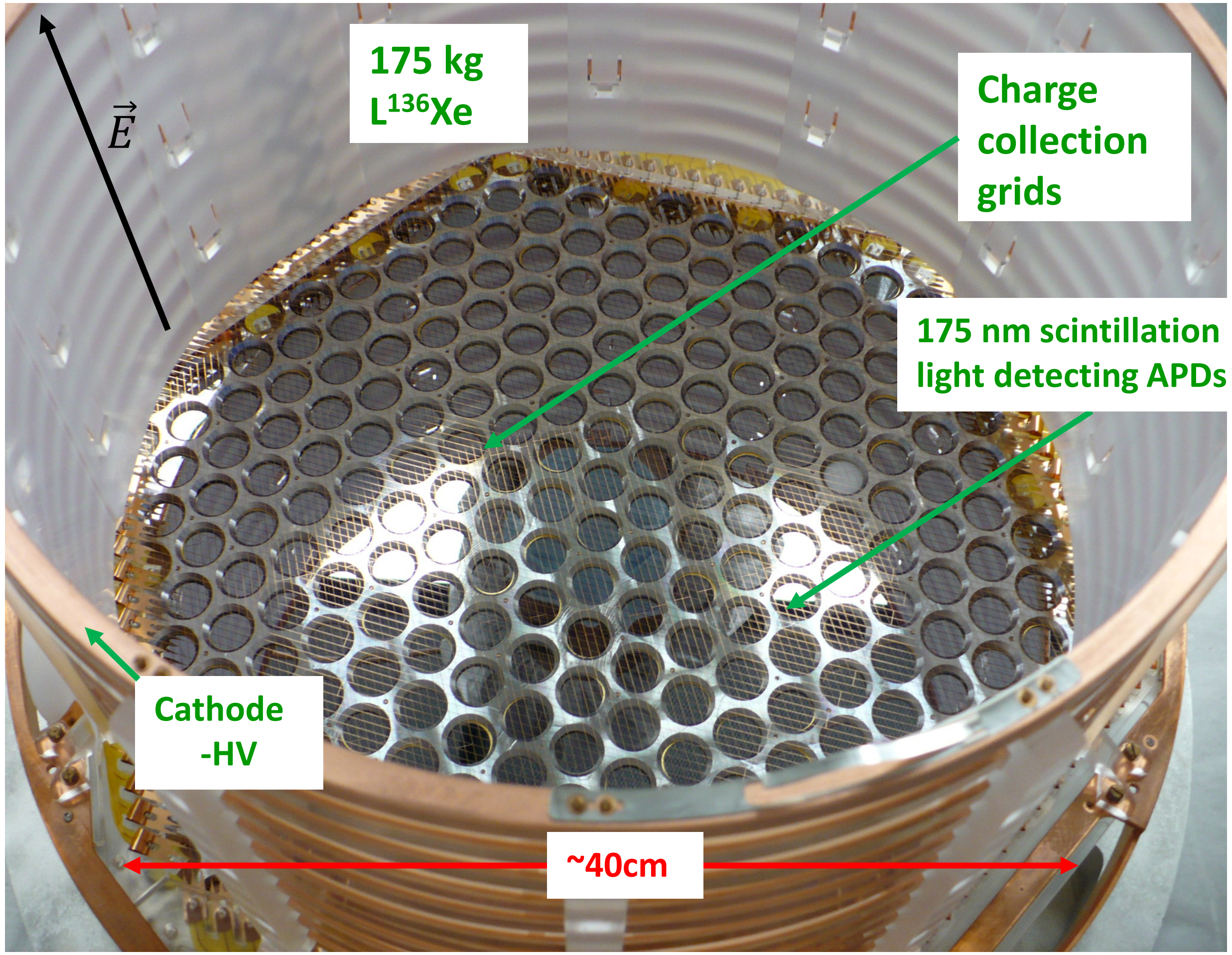


EXO-200

nEXO follows a safe and scalable technique, pioneered by EXO-200

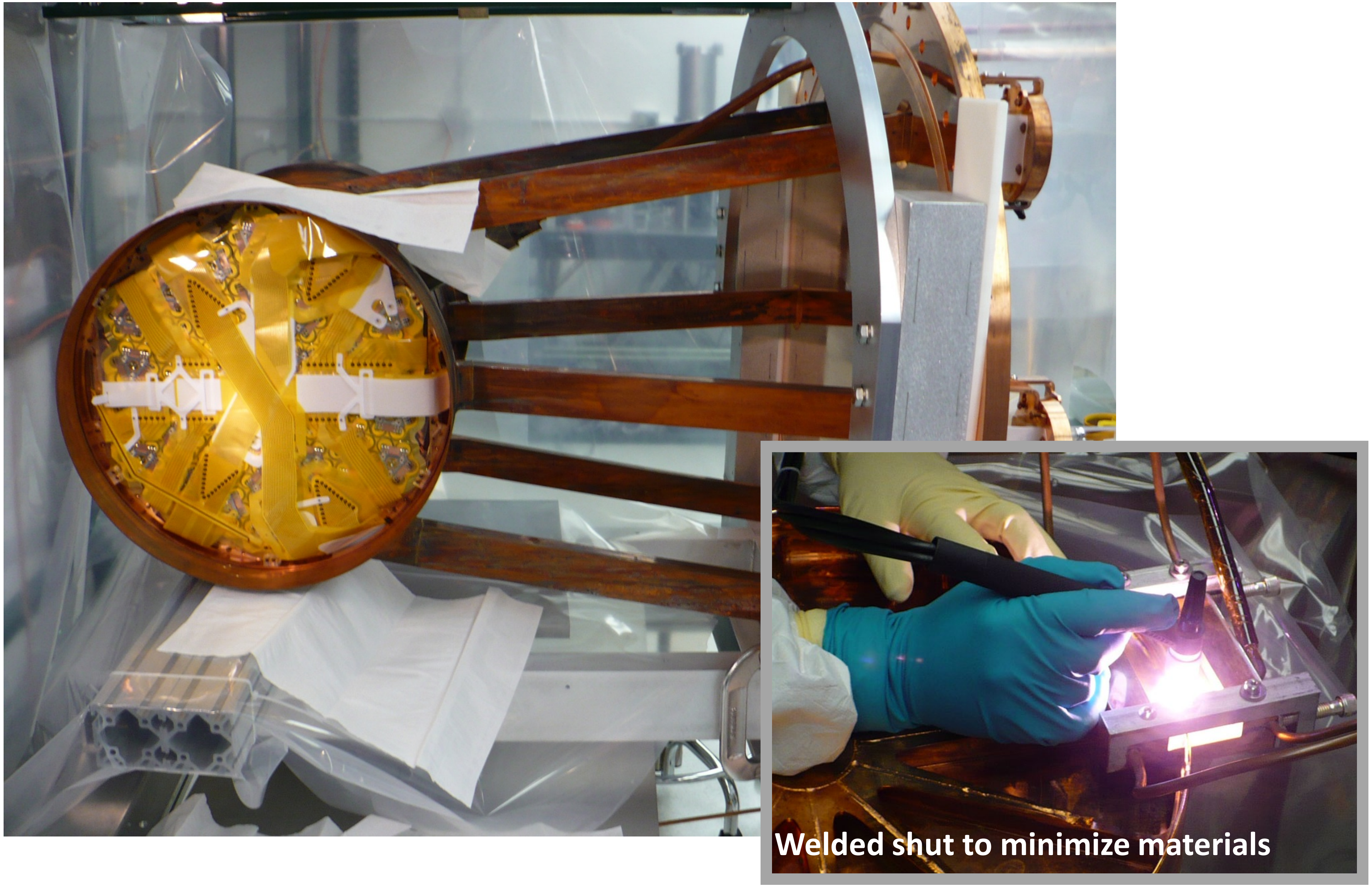
The EXO-200 LXe TPC pioneered the use of topology, position, energy, and scintillation/ionization to independently ***measure*** signal and background(s) for the expected MeV-scale energy deposits.

➔ Substantially more powerful than a simple energy measurement.



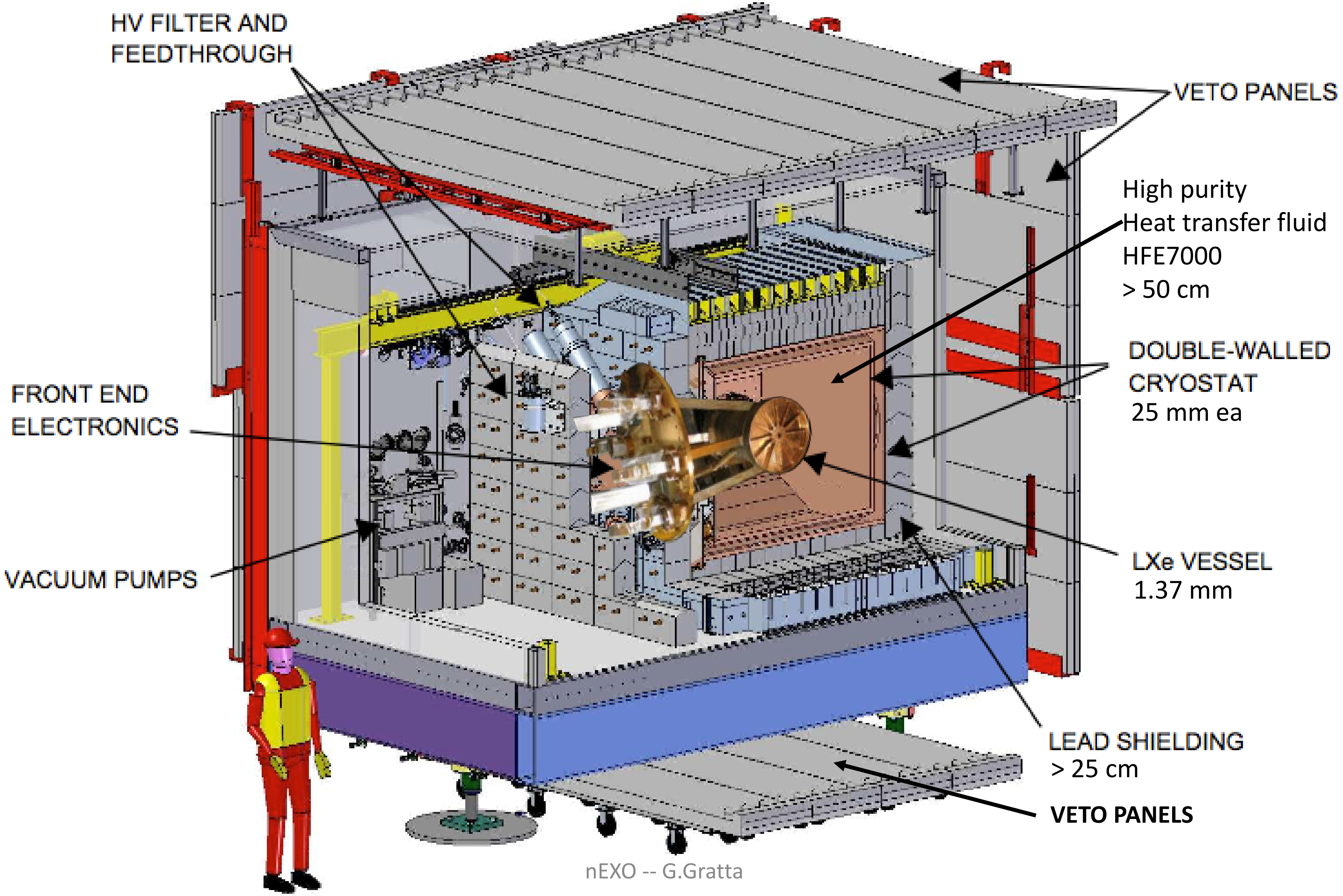
The same principle is used in nEXO

EXO-200 TPC Assembled

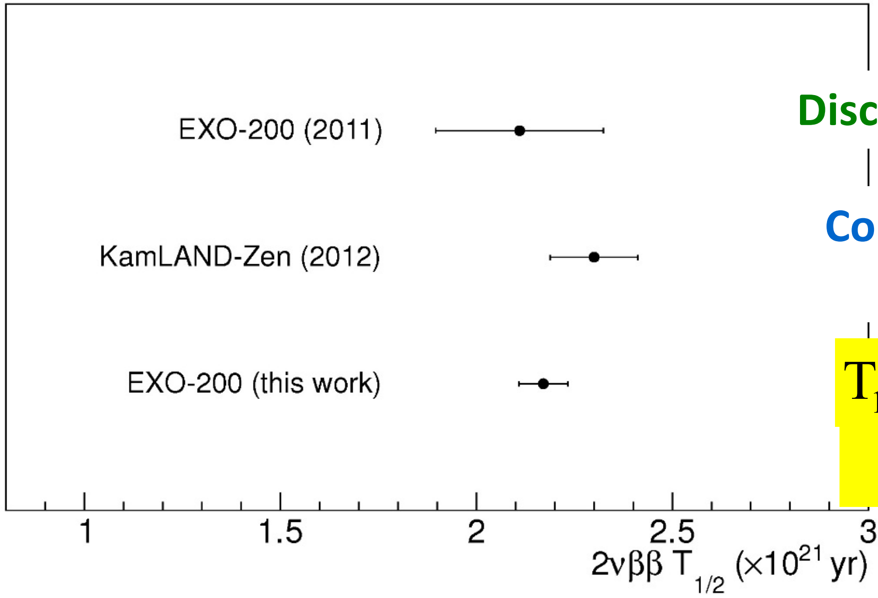


Welded shut to minimize materials

25cm-thick Pb shield, in a cleanroom, surrounded by a cosmic-ray veto, 655m underground



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)]*

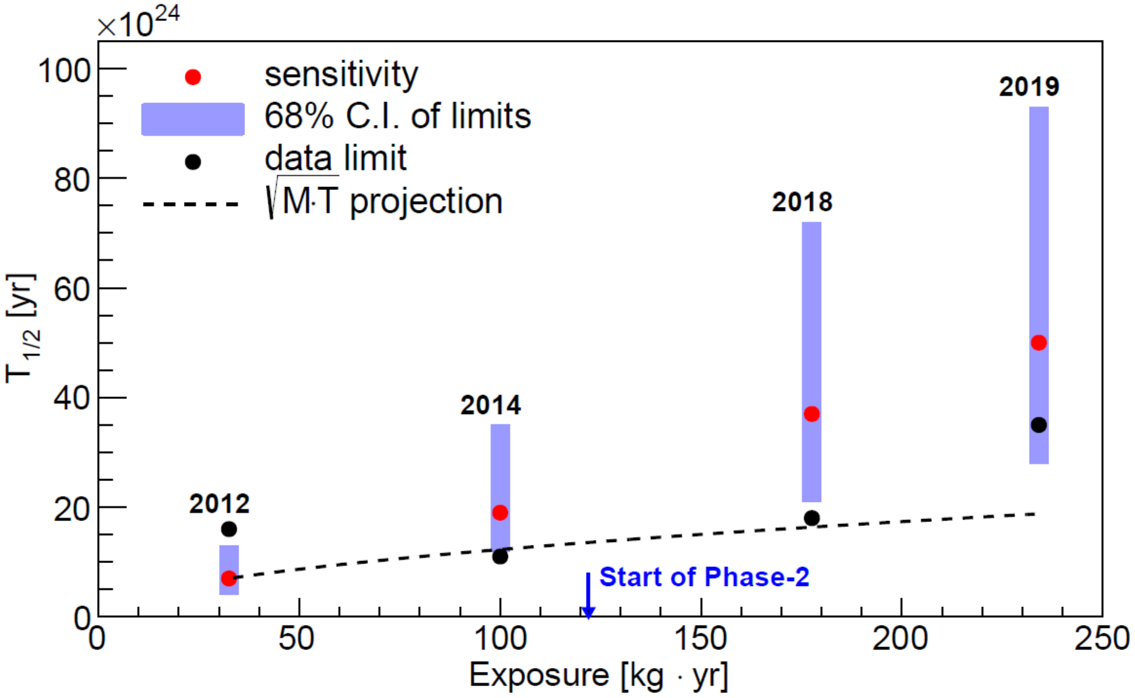
$$T_{1/2}^{2\nu\beta\beta} = \left(2.165 \pm 0.016^{\text{stat}} \pm 0.059^{\text{syst}}\right) \cdot 10^{21}\ \text{yr}$$

[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: $T_{1/2}^{0\nu\beta\beta} > 3.5\times10^{25}$ yr (90% CL)

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

Sensitivity: 5.0×10^{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:

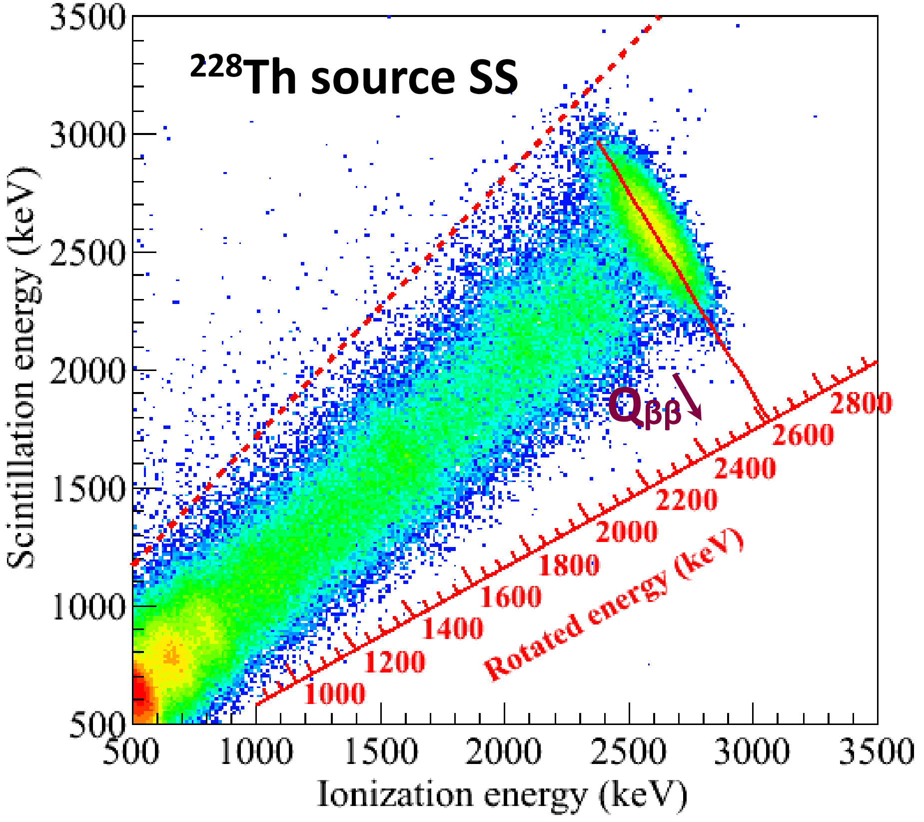
J.B. Albert et al. Phys. Rev. C 92 (2015) 015503.

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		

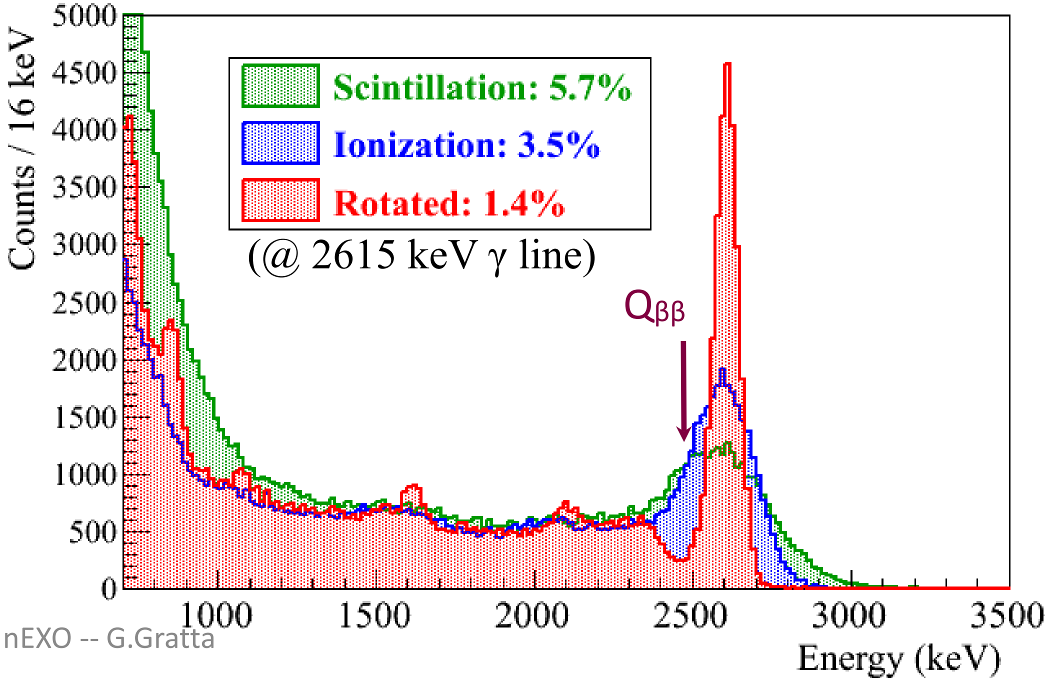
Combining Ionization and Scintillation



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

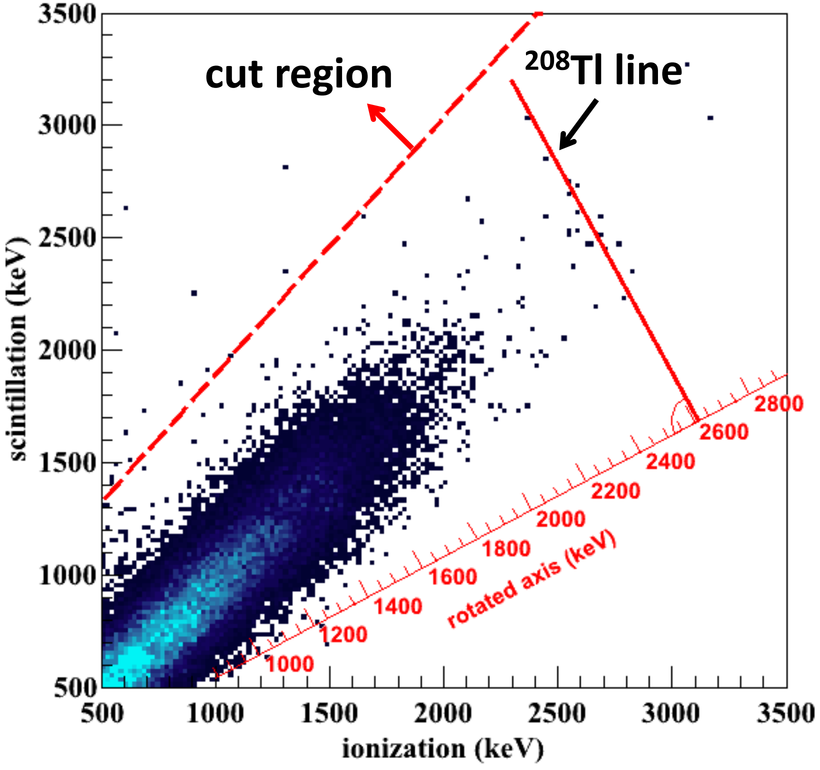
E.Conti et al. Phys Rev B 68 (2003) 054201

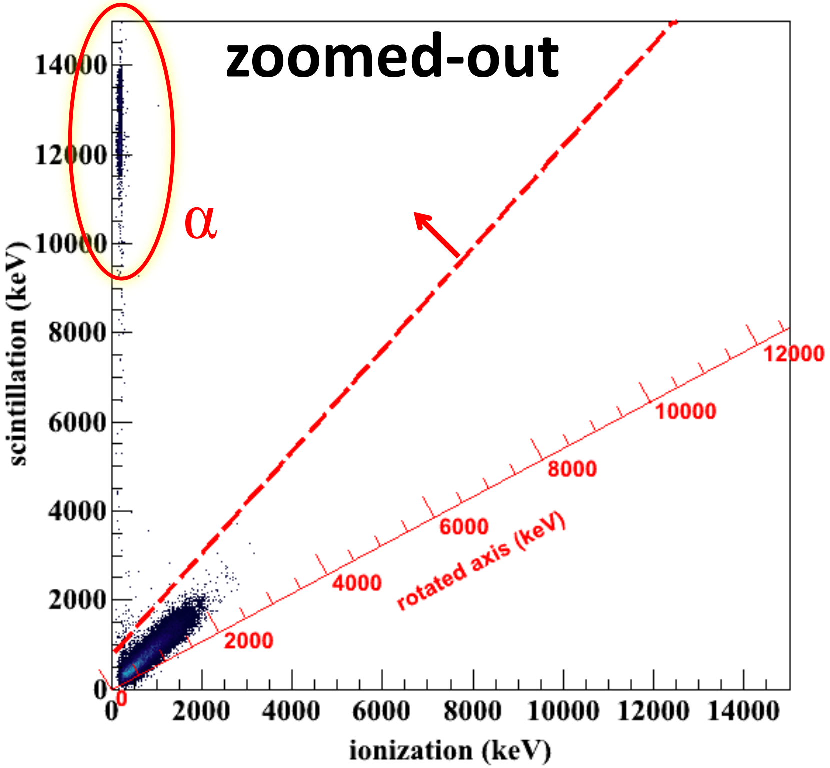
By now this is a common technique in LXe



Rotation angle chosen to optimize energy resolution at 2615 keV

Low Background 2D SS Spectrum





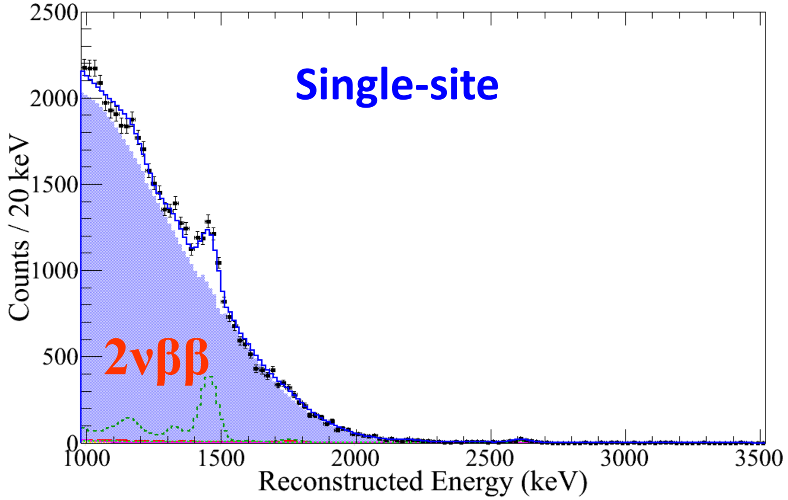
Events removed by diagonal cut:

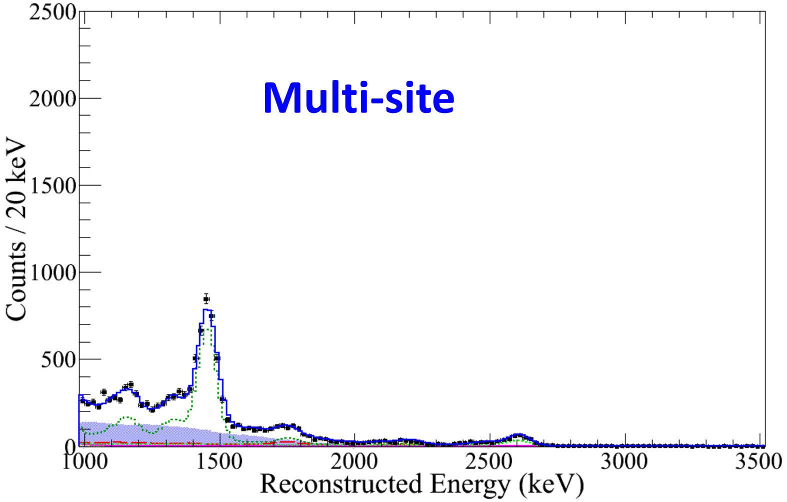
- α (larger ionization density → more recombination → more scintillation light)
- events near detector edge → not all charge is collected

Using event multiplicity to recognize backgrounds

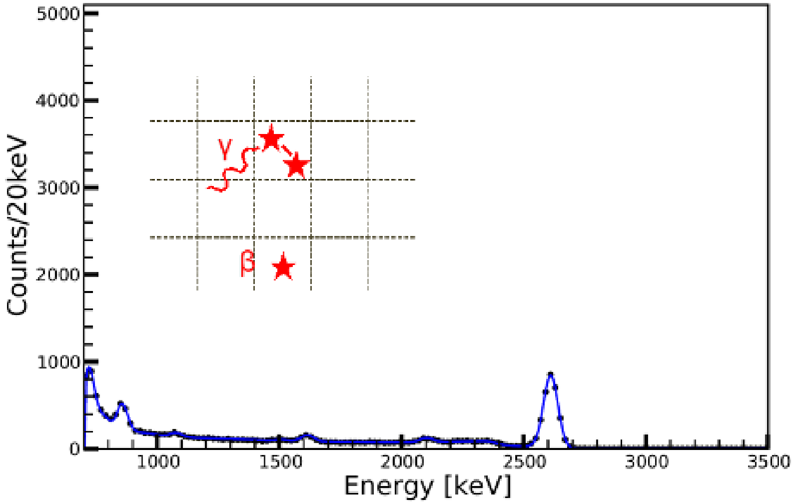
EXO-200 data

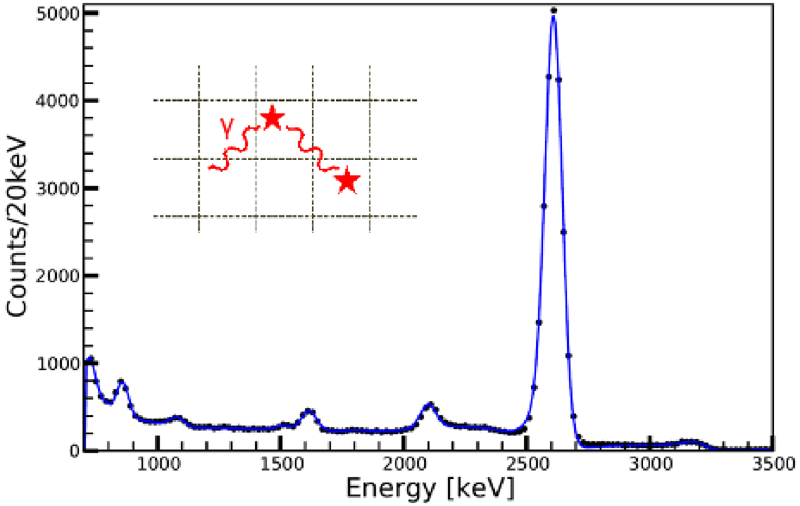
Low background data



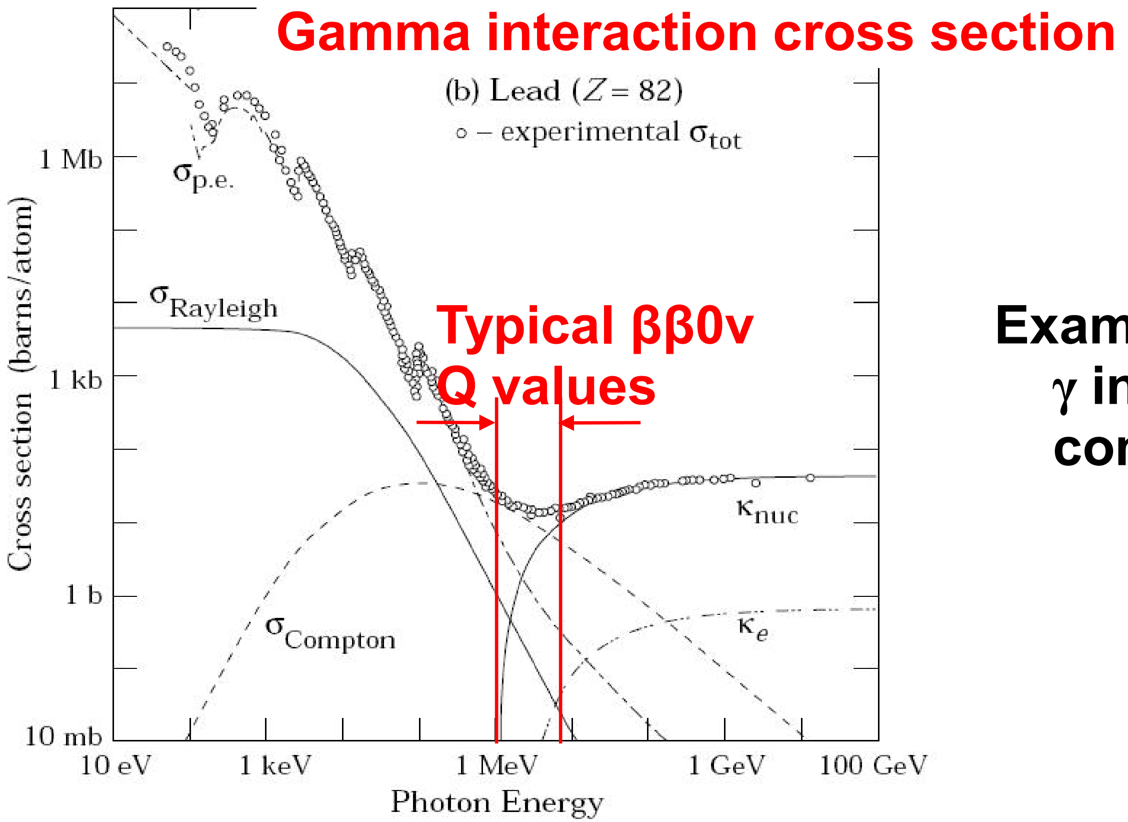


^{228}Th calibration source





Shielding a detector from gammas is difficult!



Example:

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

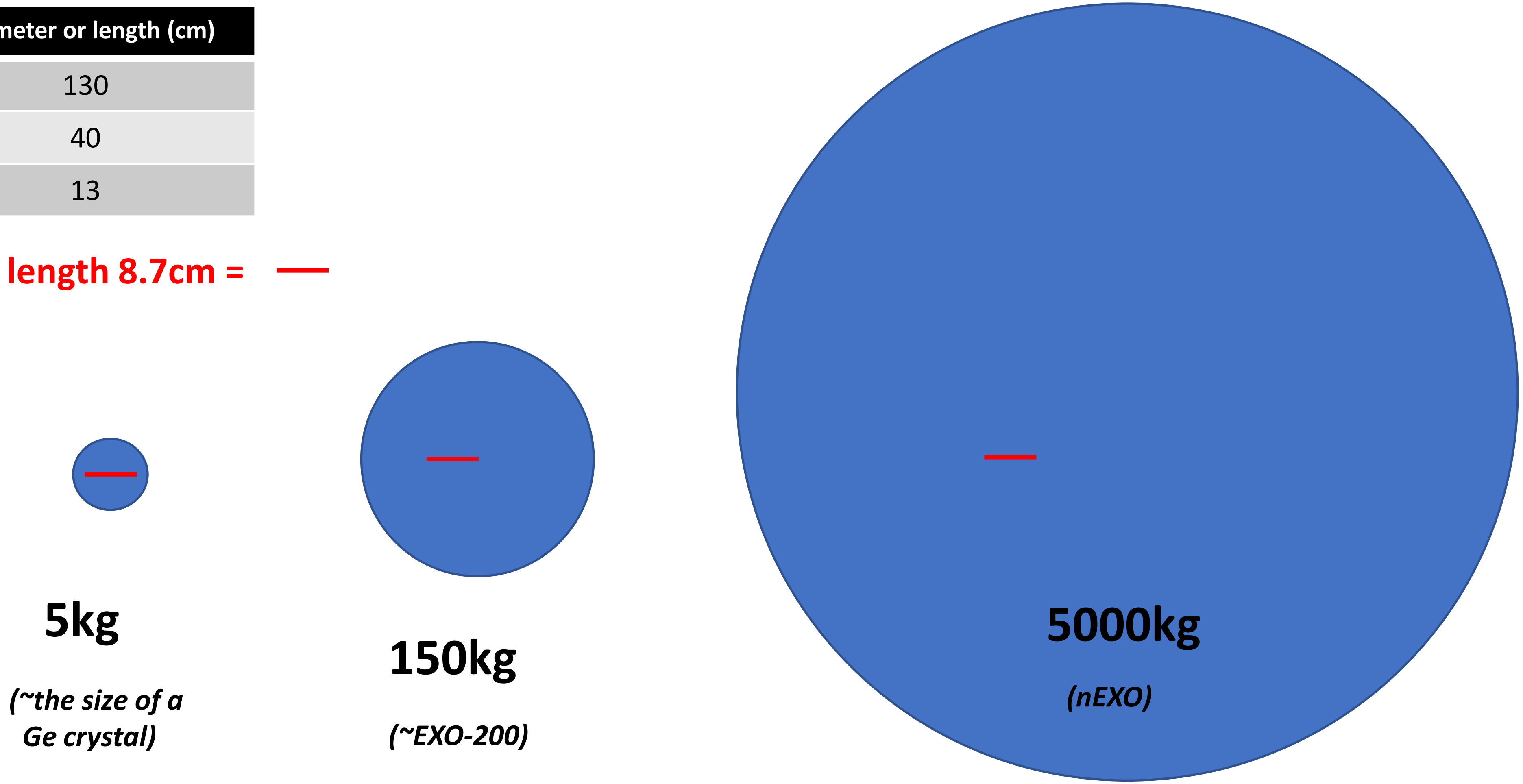
Shielding ββ decay detectors is much harder than shielding Dark Matter ones

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

Monolithic/Homogeneous is key

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

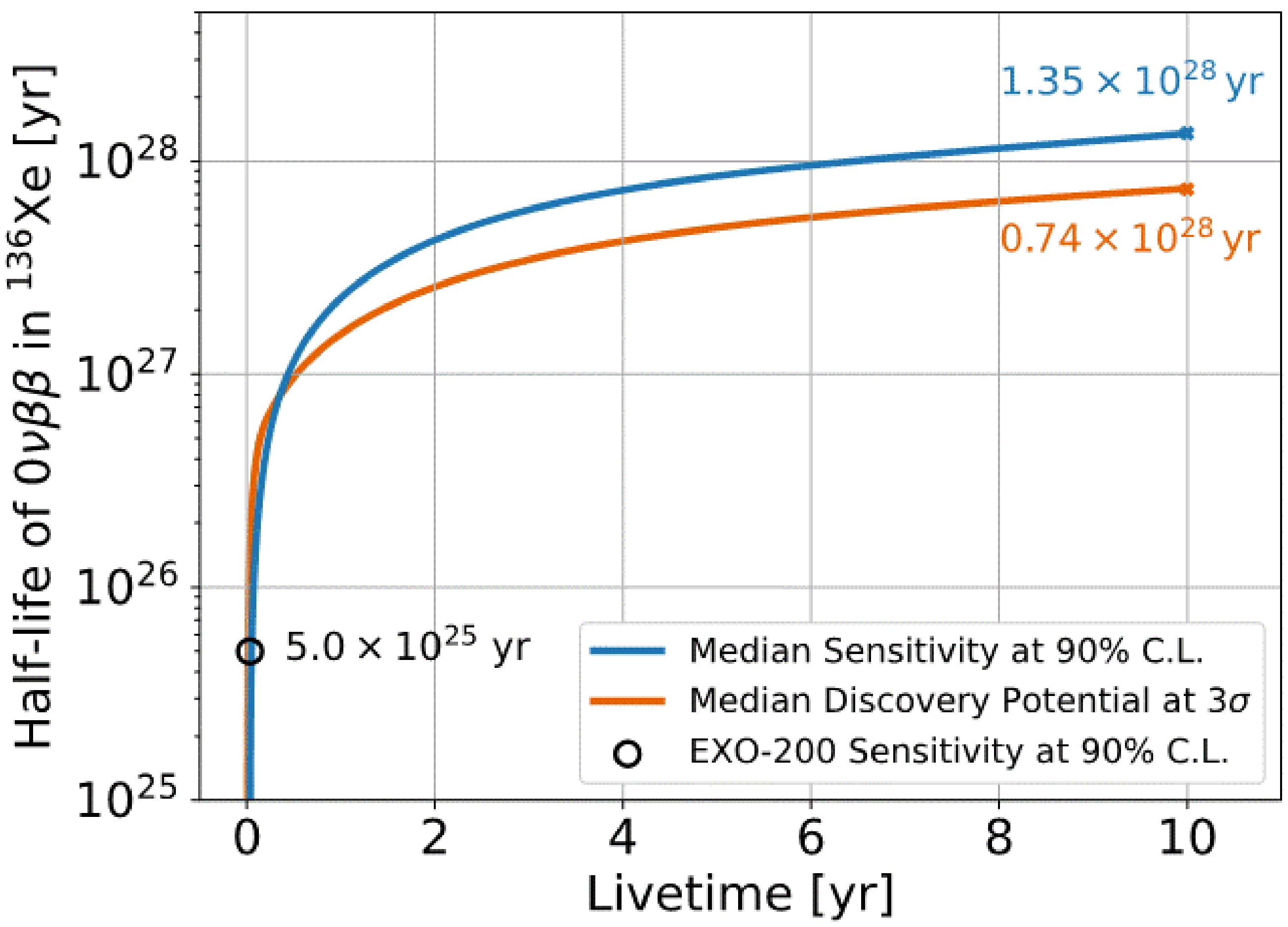
2.5 MeV γ attenuation length 8.7cm = —



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

nEXO

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

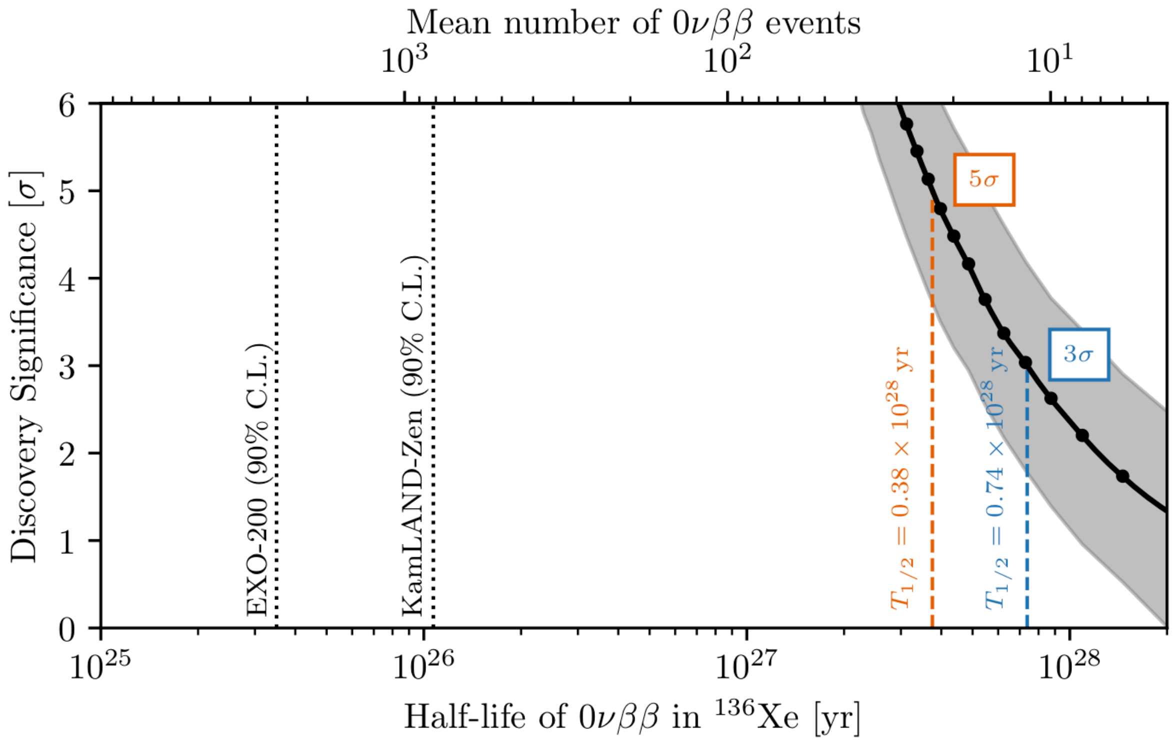


nEXO sensitivity reaches 10^{28} yr in 6.5 yr data taking

Sensitivity and Discovery Potential

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

- **10^{27} - 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

The new physics reach can be parameterized in the effective Majorana mass.

This is also useful to compare different experiments.

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

Phase space factor

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

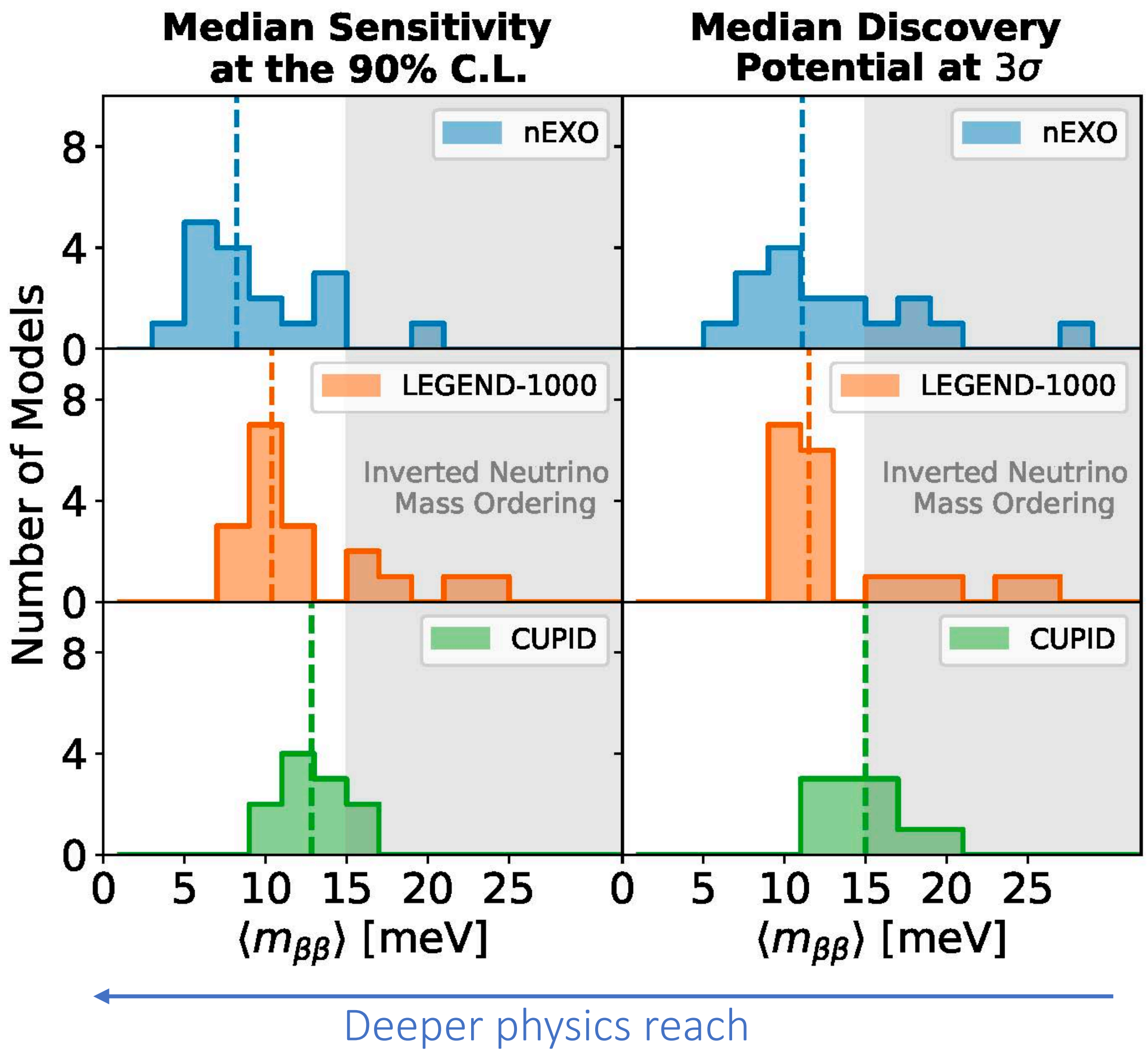
Axial coupling, $g_A = 1.27$

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

- **^{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**

Comparison with other experiments

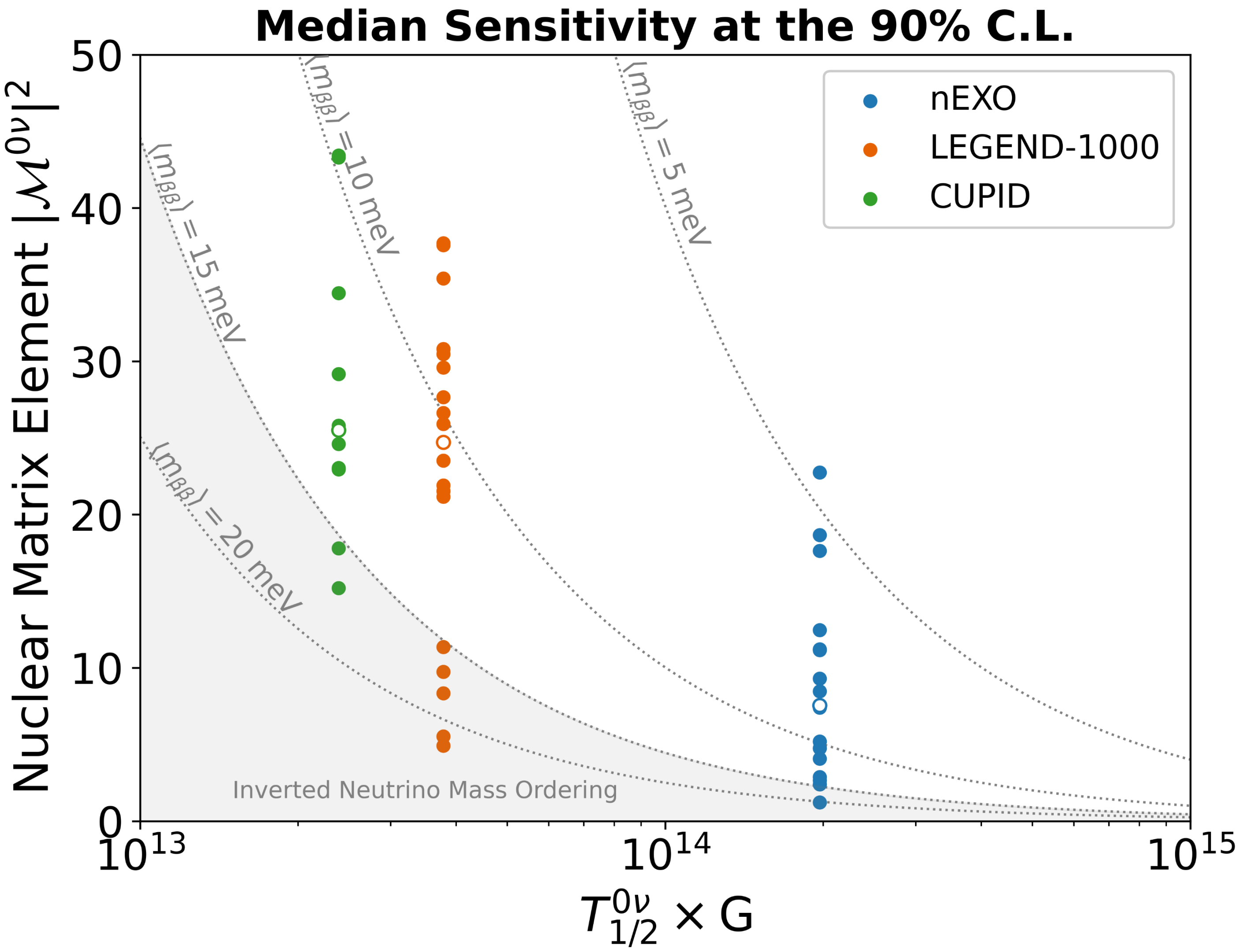


	$m_{\beta\beta}$ [meV], (*median NME*)	
	90% excl. sens.	3σ discov. potential
nEXO	8.2	11.1
LEGEND	10.4	11.5
CUPID	12.9	15.0

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

nEXO: 1.35 (90% sens.), 0.74 (3σ discov.)
LEGEND: 1.6 (90% sens.), 1.3 (3σ discov.)
CUPID: 0.15 (90% sens.), 0.11 (3σ discov.)

Comparison with other experiments

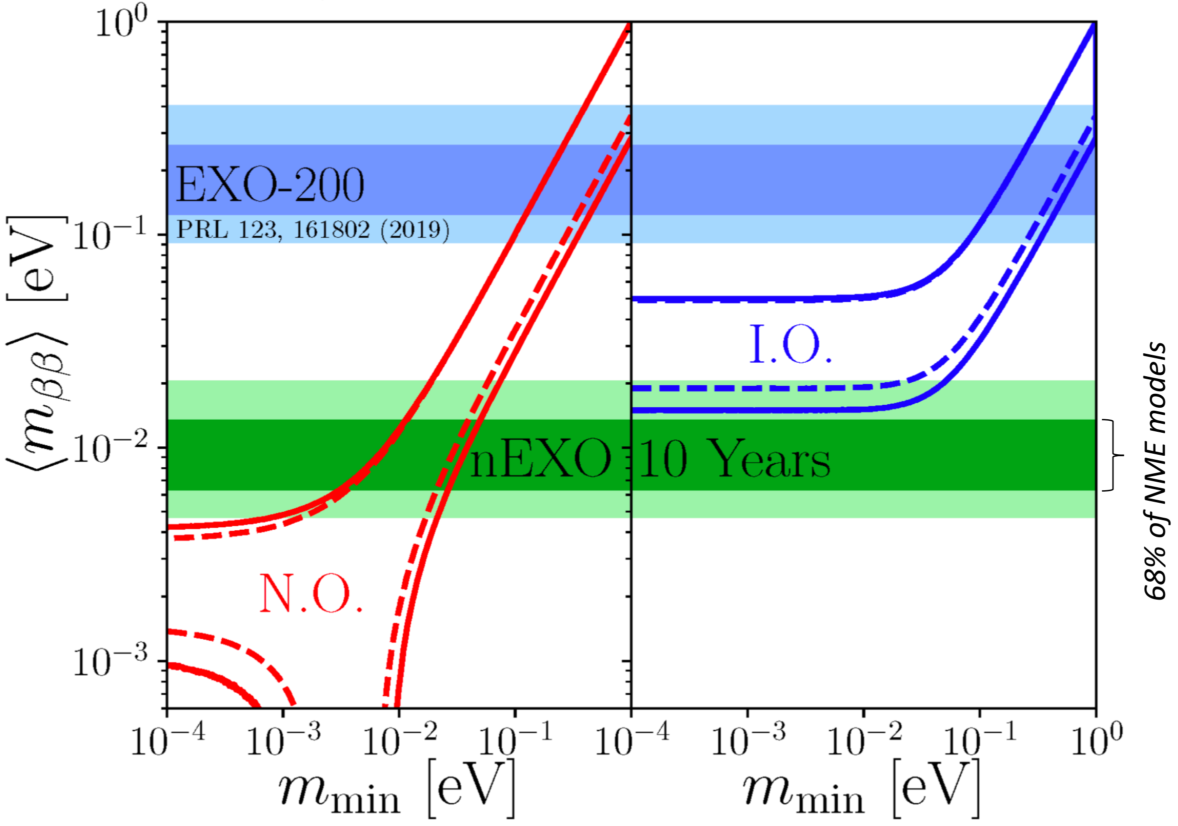


$T_{1/2}$ values used [x10^{28} yr]:

nEXO: 1.35 (90% sens.), 0.74 (3σ discov.)
LEGEND: 1.6 (90% sens.), 1.3 (3σ discov.)
CUPID: 0.15 (90% sens.), 0.11 (3σ discov.)

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:

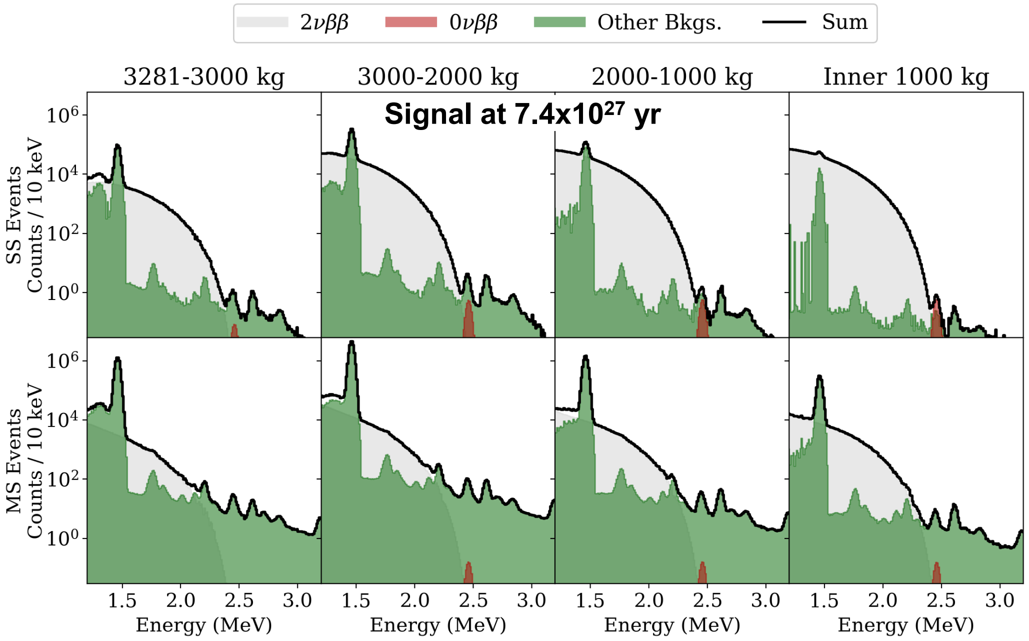
- **nEXO extends the reach into new physics by ~2 orders of magnitude, with substantial chance to make a discovery.**
- **Nominally, nEXO has a slightly better physics reach with respect to other experiments, but the NME uncertainty is large.**
- **The most important conclusion is that nEXO's sensitivity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

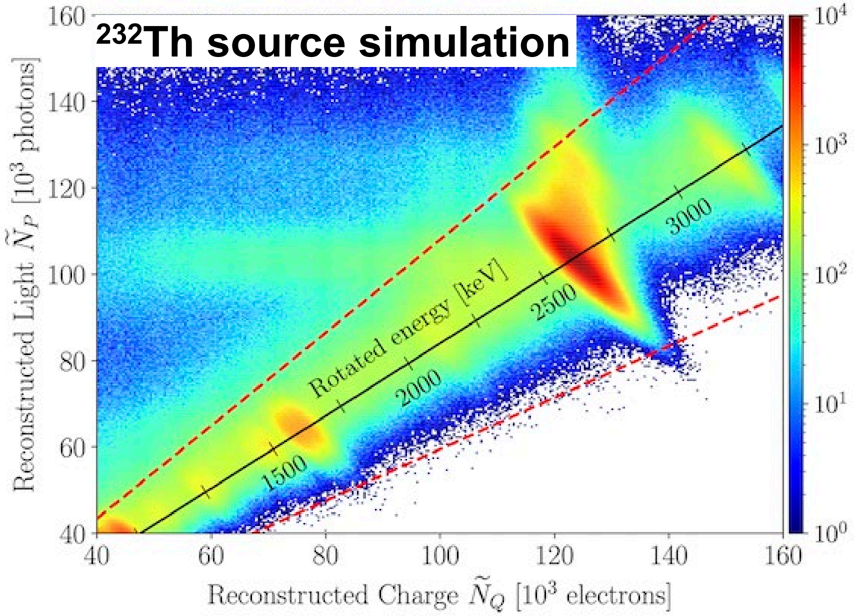
nEXO is the best option for a very large detector

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 also with 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 (western) options. All options have been extensively investigated and we have carried out site visits for three of them.**

© Cartoonbank.com

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

THE NEW YORKER

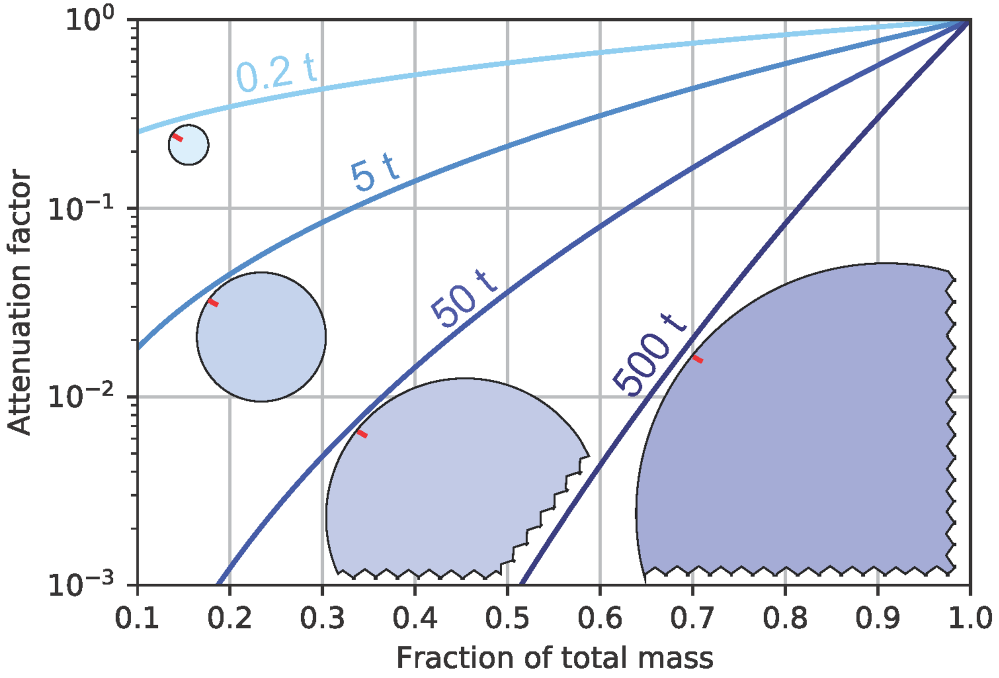
nEXO is the best option for a very large detector
beyond nEXO

7. If nEXO discovers 0νββ decay:

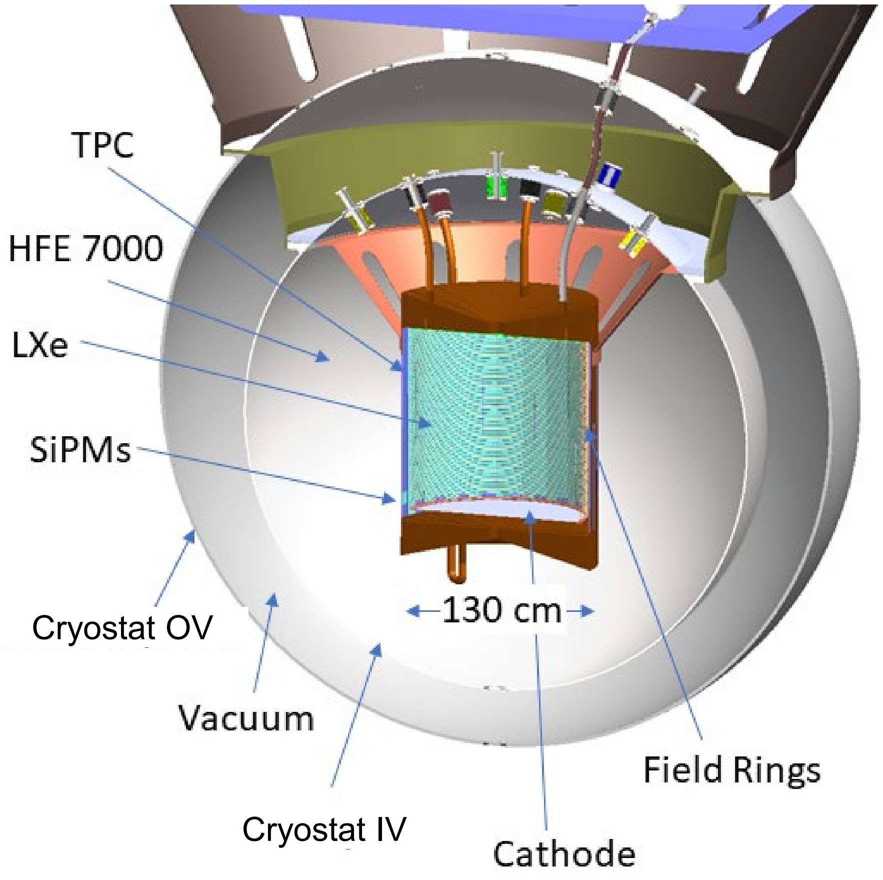
The enriched xenon is NOT "frozen" in a particular detector. Should 0νββ decay be discovered by nEXO, the xenon could be re-used in a different experimental configuration to investigate the underlying physics. ***This is particularly important at the tonne scale, given the cost of the material.***

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 is essential.***



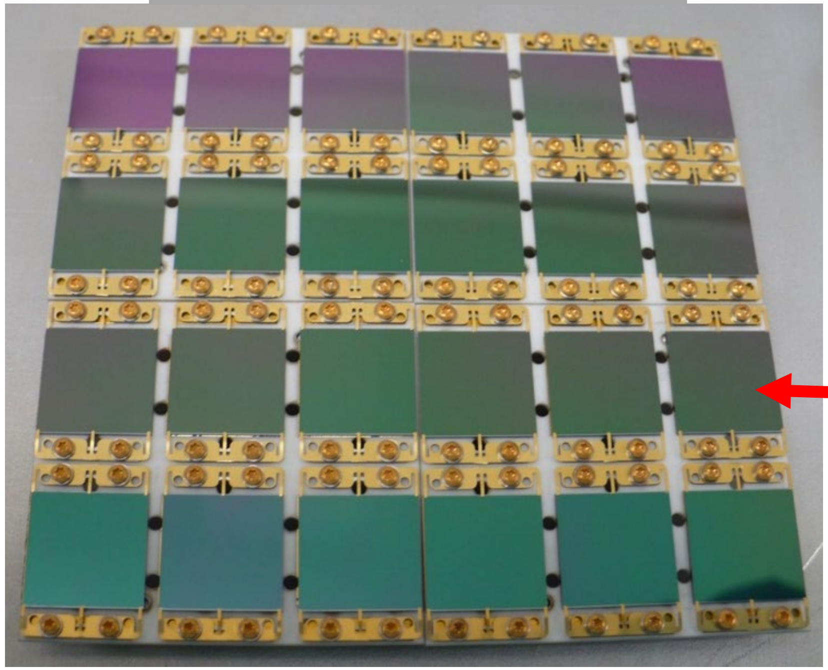
The nEXO detector is an evolution from EXO-200, yet using very advanced instrumentation



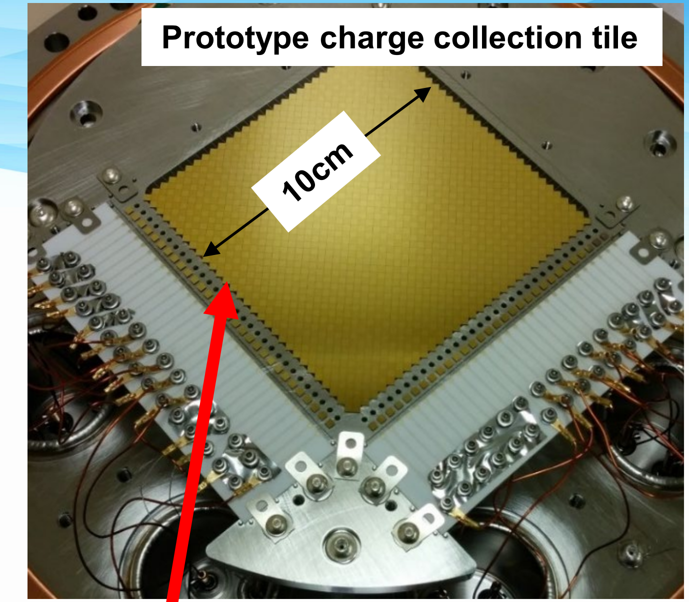
	EXO-200:	***nEXO:***	**Improvements:**
Vessel and cryostat	Thin-walled commercial Cu w/HFE	*Thin-walled electroformed Cu w/HFE*	Lower background
High voltage	Max voltage: 25 kV (end-of-run)	*Operating voltage: 50 kV*	Full scale parts tested in LXe prior to installation to minimize risk
Cables	Cu clad 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

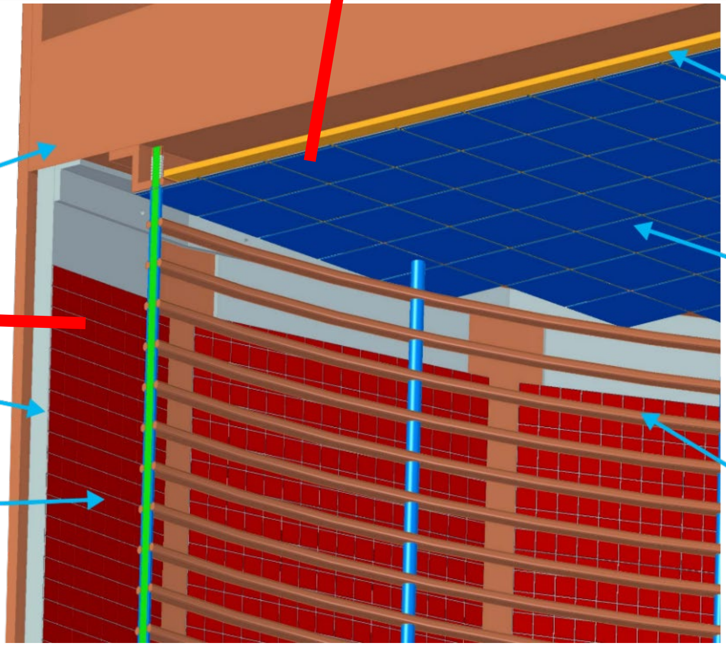
At the core of the TPC are light and Charge collection devices

Prototype VUV SiPM array (FBK)



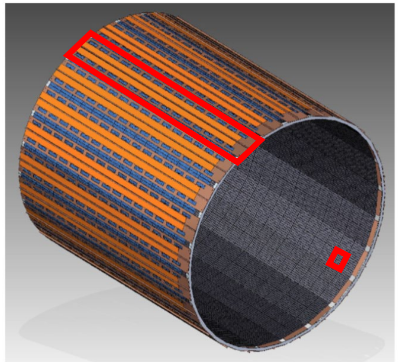
Prototype charge collection tile

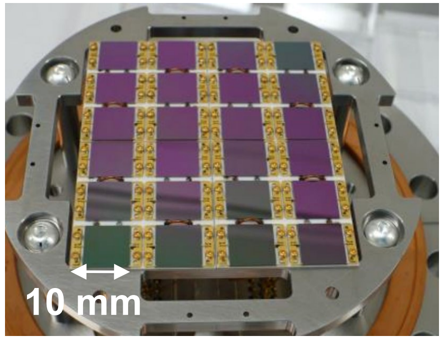




R&D – SiPMs

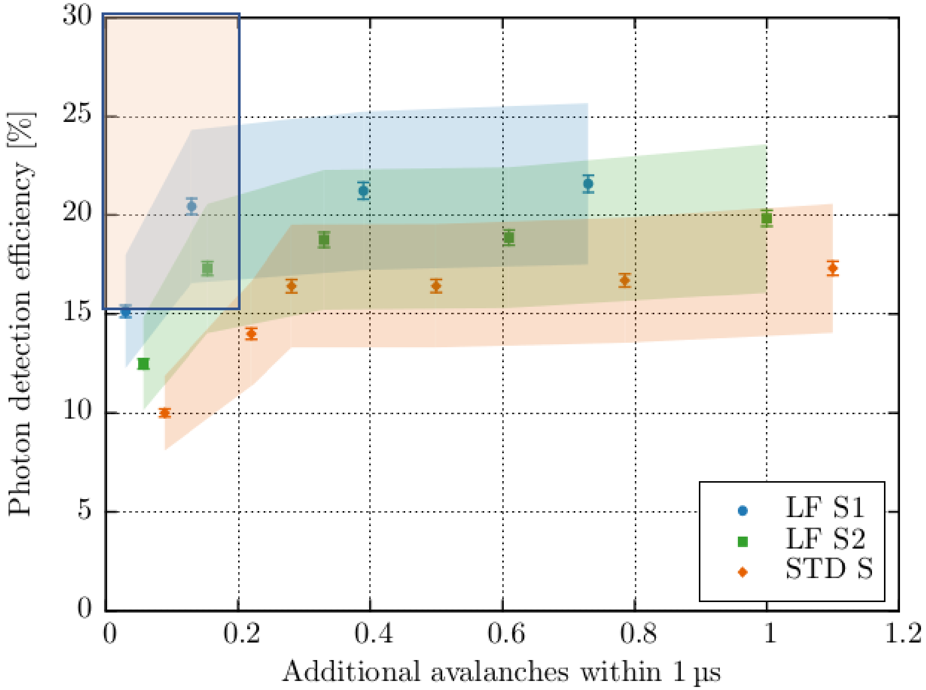
Preferred light detectors: low voltage, low background





FBK 1 cm2 VUV-sensitive SiPM

Before the nEXO R&D, no devices met the specs



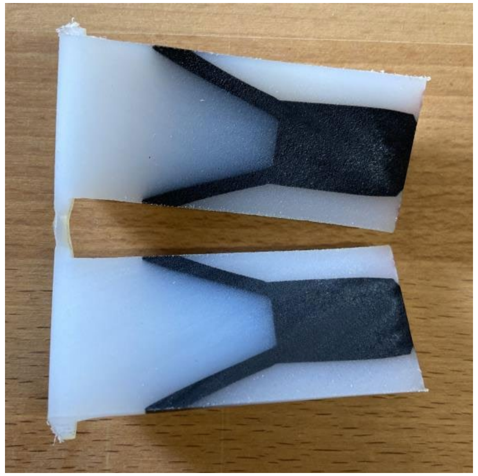
R&D focus:

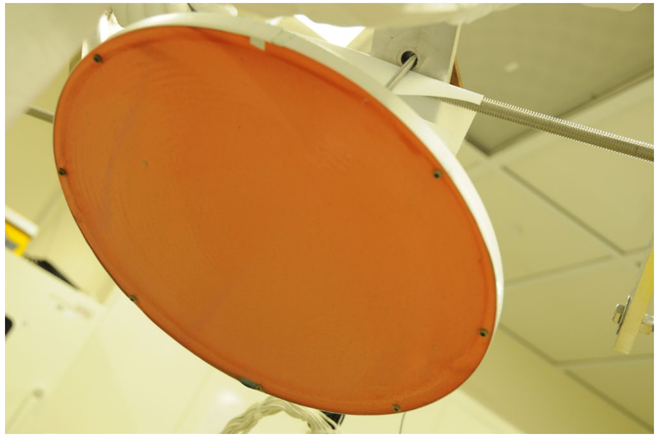
- SiPM vendor (FBK and Hamamatsu both make viable devices)
- Mounting, TSV/wirebond
- Interposer technology
- Testing requirements and assembly schedule and throughput
- Identification of minor components meeting radiopurity and outgassing requirements
- Mounting of staves within the vessel and cable routing to feedthroughs

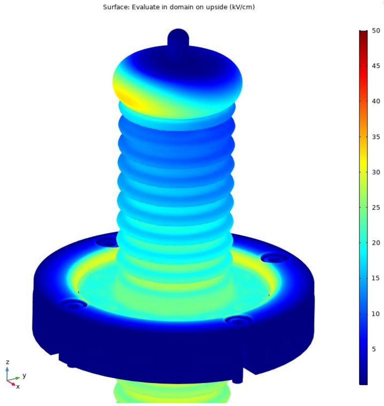
R&D – High Voltage

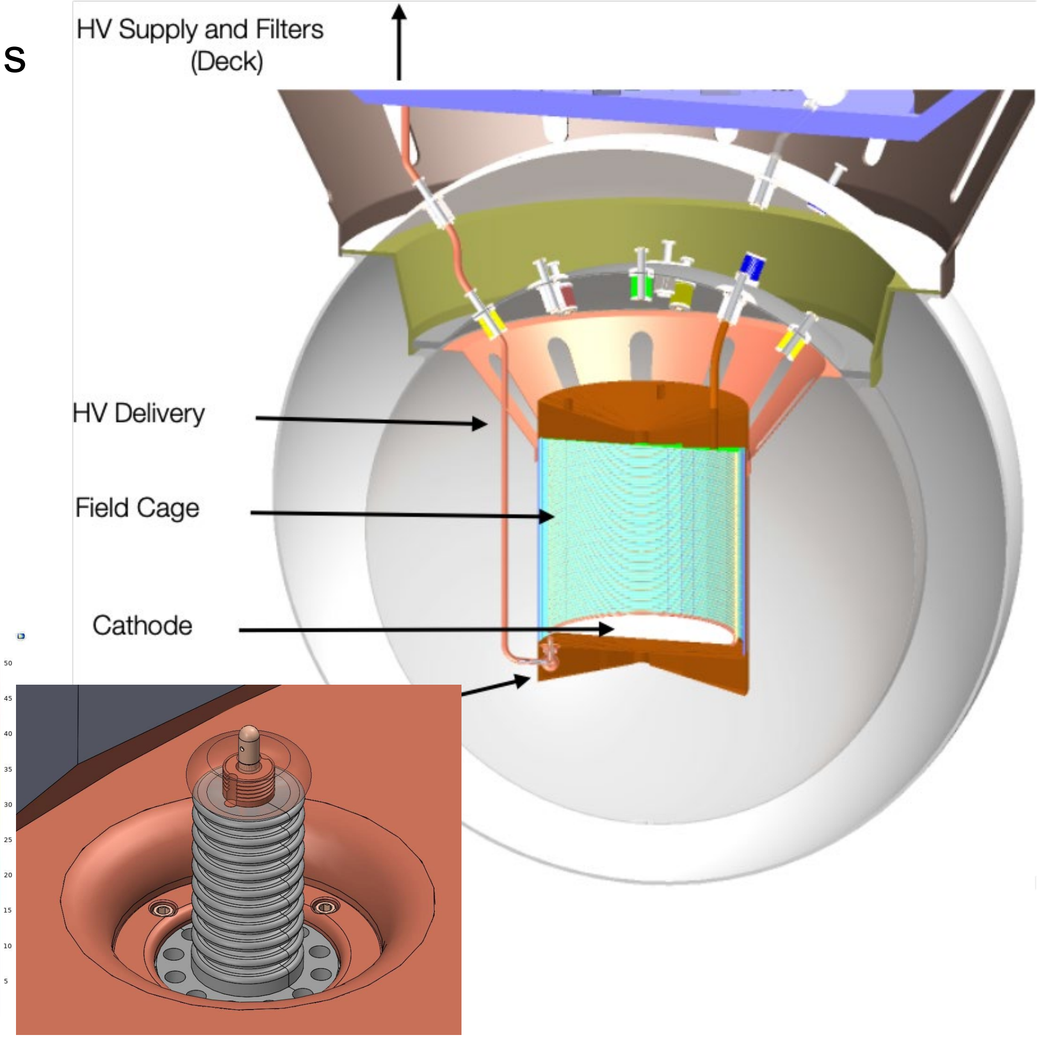
50 kV cathode voltage is required to drift electrons

R&D focus:
- Cathode Production
- HV feed
- Reflective coating
- Full scale testing









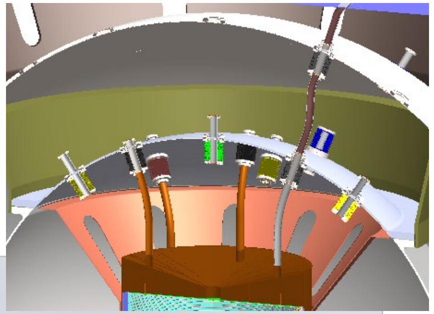
R&D – Cryostat

4 m diameter carbon fiber vessels fabricated in the mine

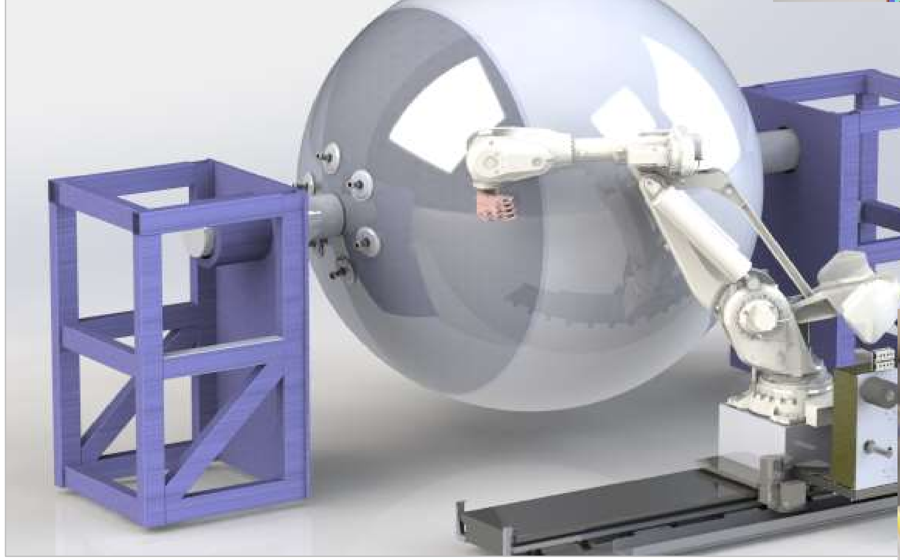
R&D focus:

- Materials radioassay
- Vendor communication/visits
  - Fiber production
  - Winders
- Liner Nickel, titanium
- Feedthroughs

Feedthroughs



Commercial Winder



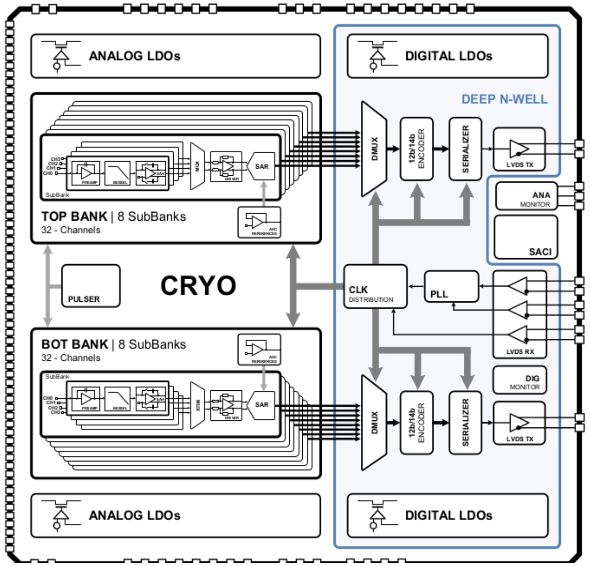
Example 3x times larger ~12m

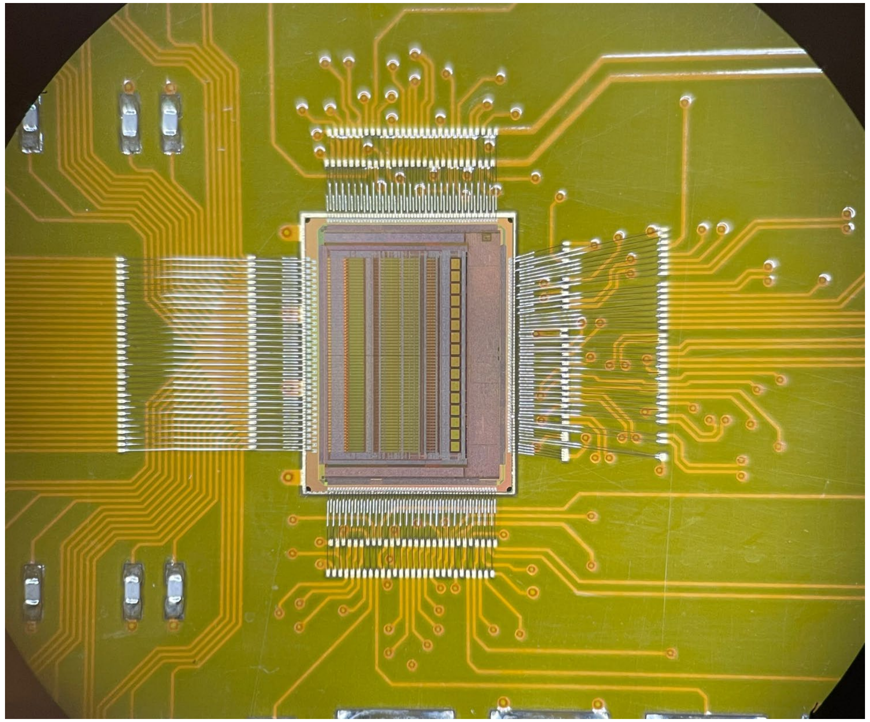
R&D – ASICs and Integration

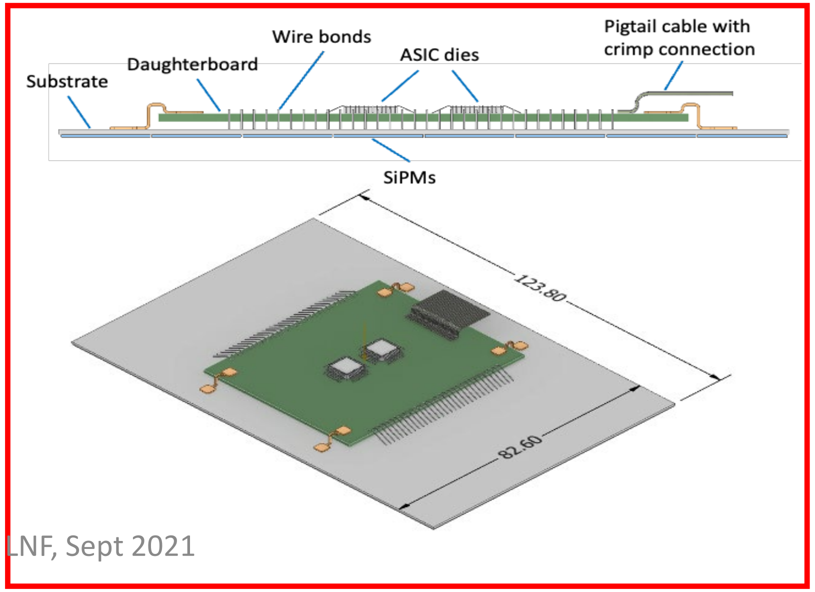
Cold electronics are needed because of the size of the detector

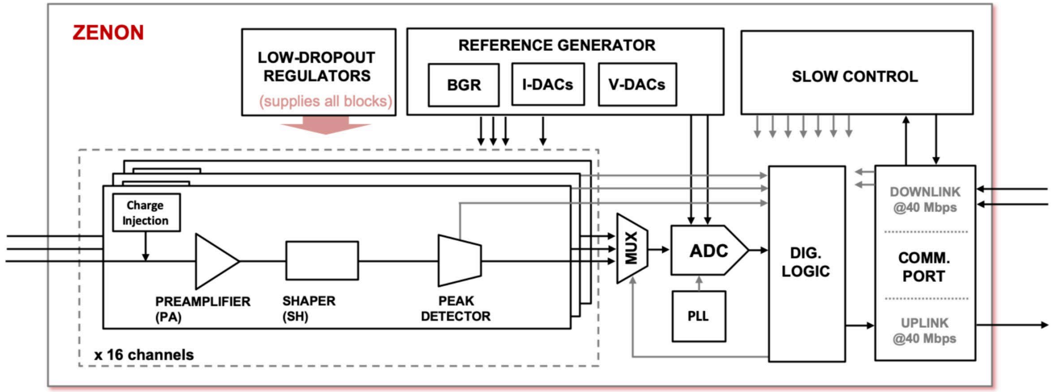
R&D focus:

- Cold design (in LXe)
- Minimal discrete components
- Integration (daughter boards, bonding)
- Long development time









The design of nEXO is mature:

Basic elements contained in the pre-CDR:

“nEXO pCDR” arXiv:1805.11142 (May 2018)

Initial sensitivity estimate:

"Sensitivity and Discovery Potential of nEXO to $0\nu\beta\beta$ decay"
Phys. Rev. C 97 (2018) 065503.

Updated sensitivity estimate:

“nEXO: Neutrinoless double beta decay search beyond
10^{28} year half-life sensitivity”, arXiv:2106.16243 (Jul 2021)

Several instrumentation papers published in the last few years.

nEXO Pre-Conceptual Design Report

nEXO

Abstract

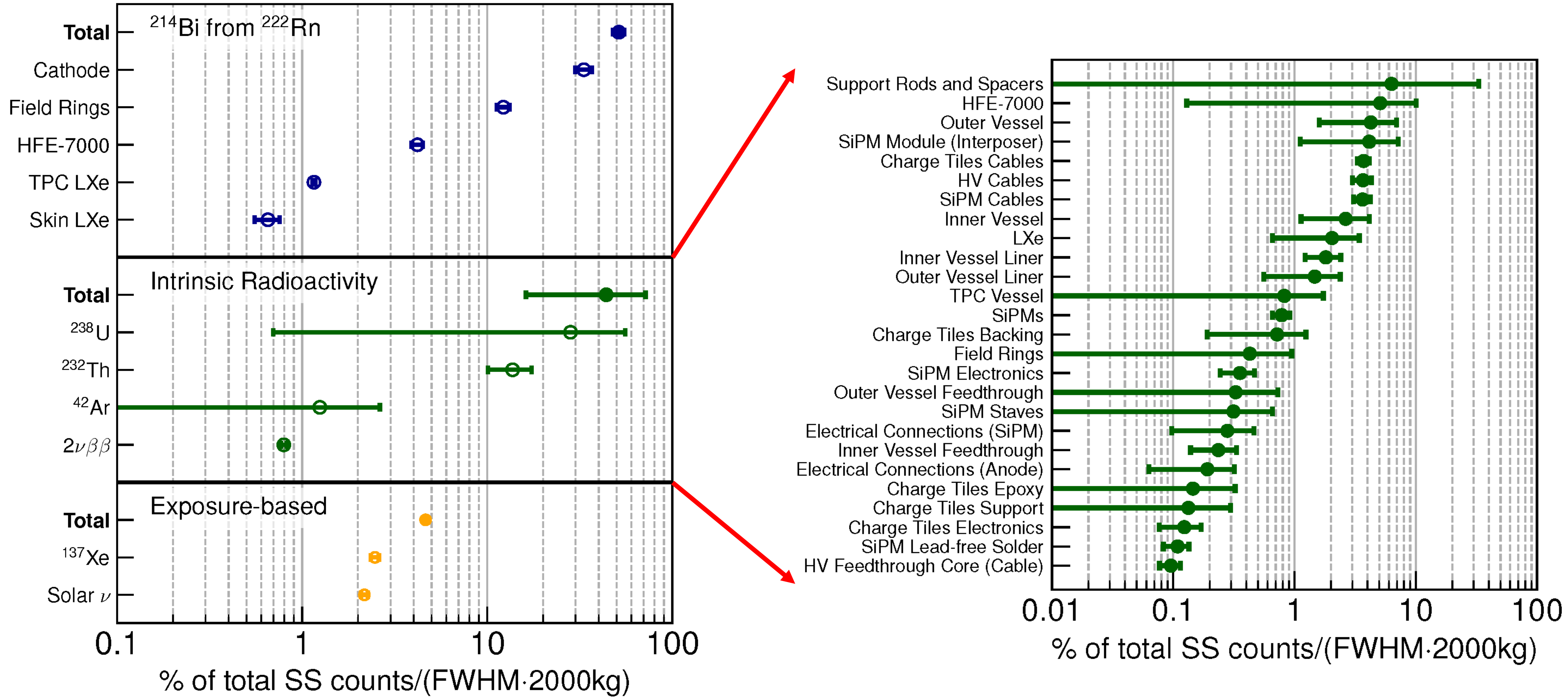
The projected performance and detector configuration of nEXO are described in this pre-Conceptual Design Report (pCDR). nEXO is a tonne-scale neutrinoless double beta ($0\nu\beta\beta$) decay search in ^{136}Xe, based on the ultra-low background liquid xenon technology validated by EXO-200. With ~ 5000 kg of xenon enriched to 90% in the isotope 136, nEXO has a projected half-life sensitivity of approximately 10^{28} years. This represents an improvement in sensitivity of about two orders of magnitude with respect to current results. Based on the experience gained from EXO-200 and the effectiveness of xenon purification techniques, we expect the background to be dominated by external sources of radiation. The sensitivity increase is, therefore, entirely derived from the increase of active mass in a monolithic and homogeneous detector, along with some technical advances perfected in the course of a dedicated R&D program. Hence the risk which is inherent to the construction of a large, ultra-low background detector is reduced, as the intrinsic radioactive contamination requirements are generally not beyond those demonstrated with the present generation $0\nu\beta\beta$ decay experiments. Indeed, most of the required materials have been already assayed or reasonable estimates of their properties are at hand. The details described herein represent the base design of the detector configuration as of early 2018. Where potential design improvements are possible, alternatives are discussed.

This design for nEXO presents a compelling path towards a next generation search for $0\nu\beta\beta$, with a substantial possibility to discover physics beyond the Standard Model.

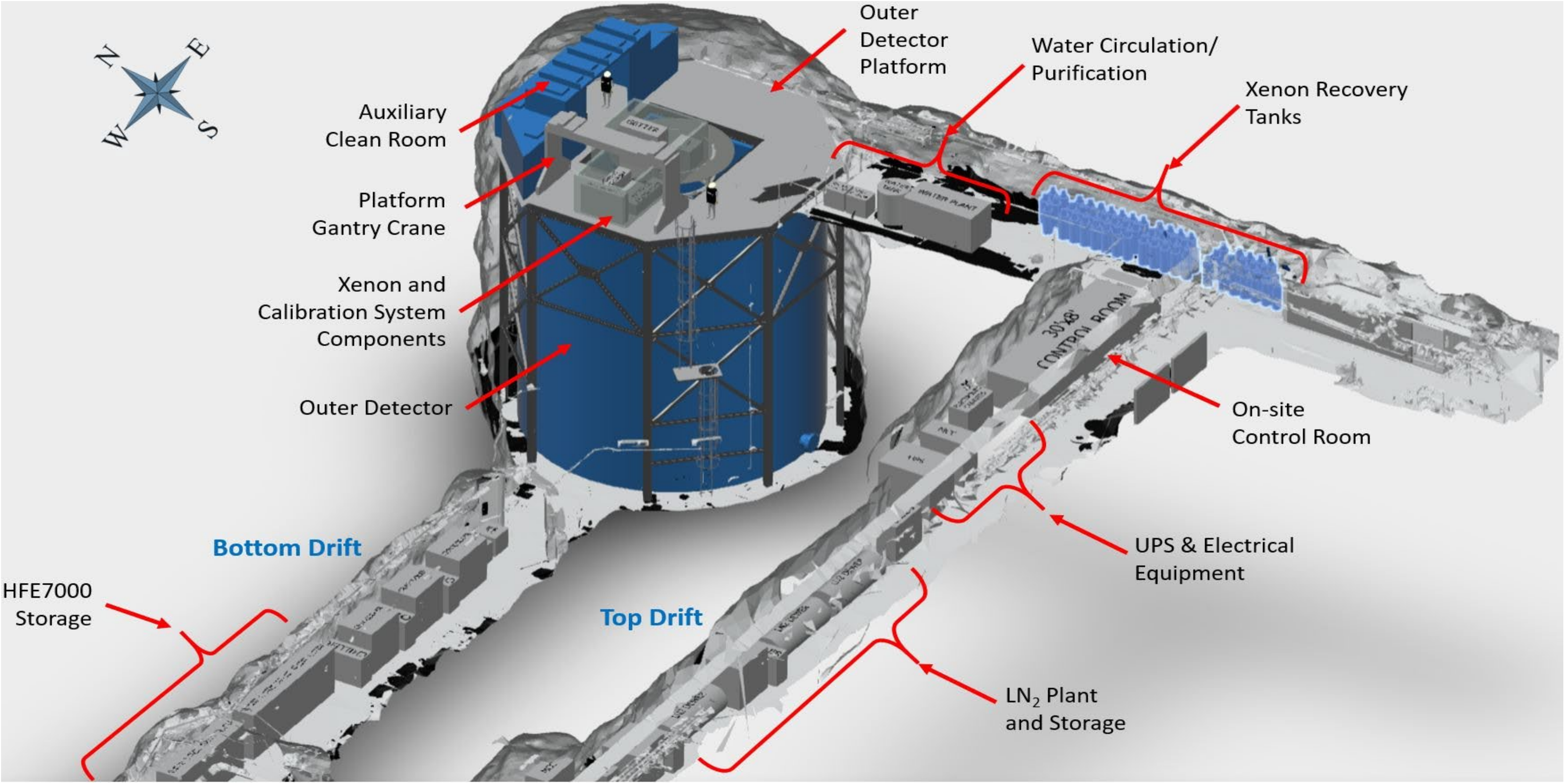
May 28, 2018

nEXO is well optimized

No detector component dominates the background.



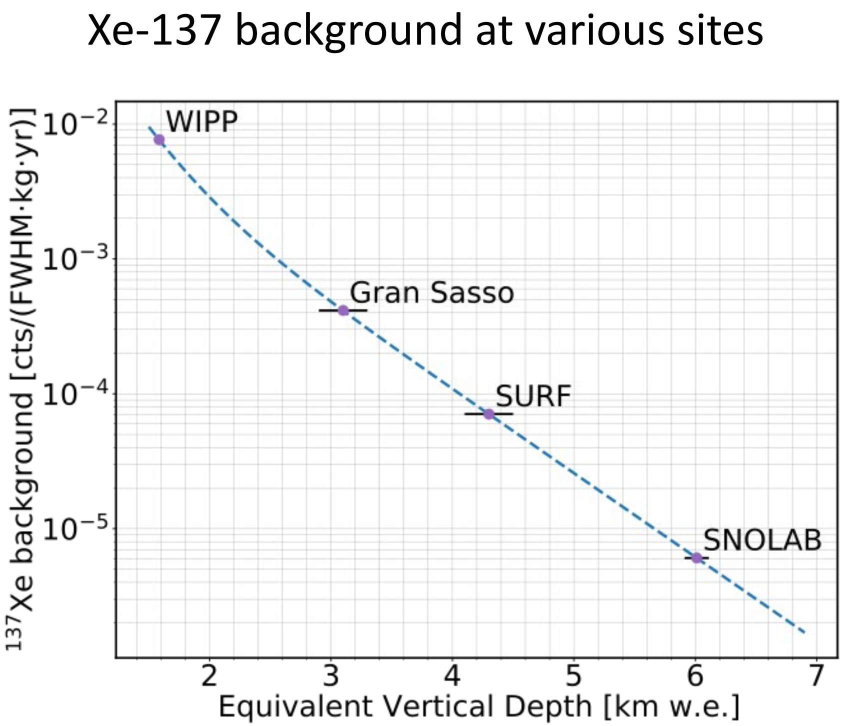
The SNOLAB Cryopit is the favourite location for nEXO and plenty of site engineering for us has been already carried out by SNOLAB

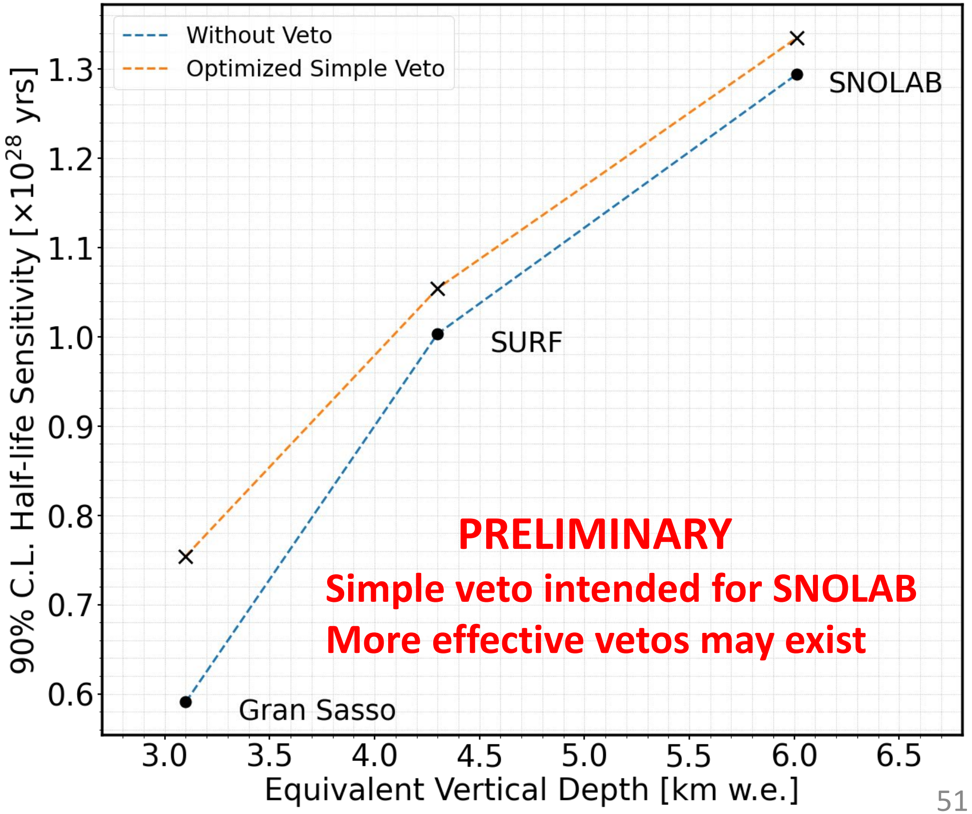


^{137}Xe background vs Underground Site

Production rate of cosmogenic ^{137}Xe is directly tied to the muon flux and spectrum at the different underground laboratories

Simulation of muons used to evaluate ^{137}Xe backgrounds at each site


Xe-137 background at various sites



PRELIMINARY

Simple veto intended for SNOLAB

More effective vetos may exist

Fully developed the project structure (last two years)

One to one mapping of subsystem to WBS
(+Management, systems engineering, integration)

Charge Readout Electronics (SLAC)
Subsystem Scientist:
L. Yang (UCSD)
Subsystem Manager:
A. Dragone (SLAC)

Photon Readout Electronics (BNL)
Subsystem Scientist:
M. Chiu (BNL)
Subsystem Manager:
L. DeMino (BNL)

TPC (PNNL)
Subsystem Scientist:
J. Orrell (PNNL)
Subsystem Manager:
A. Gorham (PNNL)

Photon Detector (BNL)
Subsystem Scientist:
D. Moore (Yale)
Subsystem Manager:
M. Worcester (BNL)

Computing, Control and Software (LLNL)
Subsystem Scientist:
S. Sangiorgio (LLNL)
Subsystem Manager:
TBD

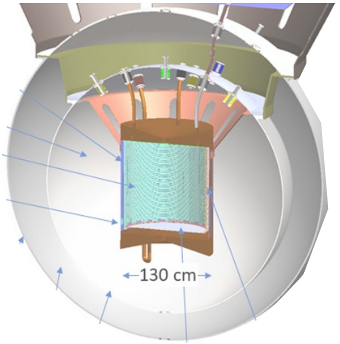
Radioactive Background Control (SLAC)
Subsystem Scientist:
A. Piepke (UA)
Subsystem Manager:
TBD

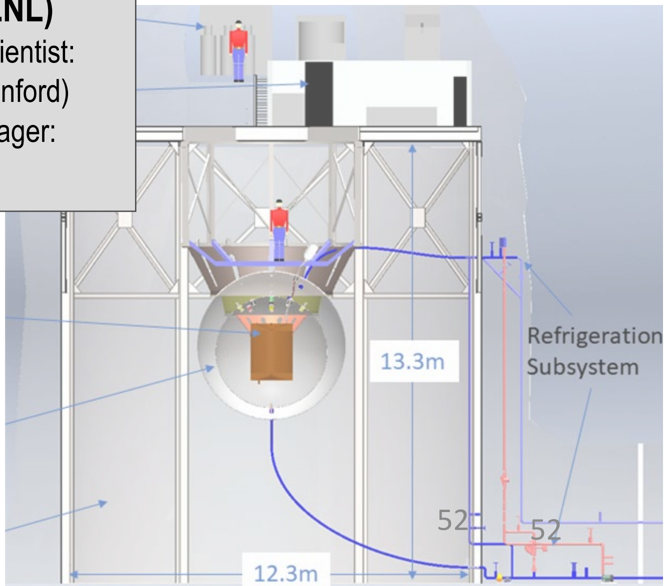
TPC Support Systems (LLNL)
Subsystem Scientist:
A. Pocar (Umass)
Subsystem Manager:
A. House (LLNL)

Xenon (LLNL)
Subsystem Scientist:
G. Gratta (Stanford)
System Manager:
TBD

Facility (SNOLAB)
Subsystem Scientist:
E. Caden
Subsystem Manager:
D. Hawkins

Outer Detector (SNOLAB)
Subsystem Scientist:
T. Brunner
Subsystem Manager:
D. Hawkins





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The WBS is Detailed, Full Dictionary

L2		L3	L4	Scope	CAM
1.01	Management	1.01.01		Management	Riot
		1.01.02		Project control	Riot
		1.01.03		QA and Safety	Riot
1.02	System engineering, Integration and commissioning	1.02.01		Systems Engineering	Hunt
		1.02.02	1.02.02.01	Integration and Commissioning Management	Nordby
			1.02.02.02	TPC Integration	Nordby
			1.02.02.03	Cryostat Integration	Nordby
			1.02.02.04	Facilities Operations and Management	Nordby
			1.02.02.05	nEXO Commissioning	Nordby
1.03	Time Projection Chamber	1.03.01		TPC Management	Gorham
		1.03.02		TPC Vessel	Gorham
		1.03.03		High Voltage and Field Cage	Gorham
		1.03.04		Charge Detector and Anode	Gorham
		1.03.05		TPC Cables and Interconnects	Gorham
		1.03.06		Calibration Systems	Gorham
1.04	Photon Detector	1.04.01		Photon Detector Management	Worcester
		1.04.02		SiPM Procurement	Worcester
		1.04.03		SiPM Test Facility	Worcester
		1.04.04		SiPM Tile Modules	Worcester
		1.04.05		Stave Assemblies	Worcester
1.05	TPC Support Systems	1.05.01		TPC Support Systems Management	House
		1.05.02		TPC Support Systems Cryostat	House
		1.05.03		Xenon Handling and Purification	House
		1.05.04		HFE Process and Refrigeration	House
1.06	Electronics	1.06.01	1.06.01.01	Charge Readout Electronics Management	Dragone
			1.06.01.02	Charge Readout ASIC	Dragone
			1.06.01.03	Charge Readout Daughter Board	Dragone
			1.06.01.04	Charge System Support Boards	Dragone
		1.06.02	1.06.02.01	Photon Readout Electronics Management	DeMino
			1.06.02.02	Photon Readout ASIC	DeMino
			1.06.02.03	Photon System Transition Board	DeMino
			1.06.02.04	Photon System Controller/Receiver Board	DeMino

L2		L3	L4	Scope	CAM
1.07	Radioactive Background Control	1.07.01		Radioactive Background Control Management	Acting - Piepke
		1.07.02		Radioactivity in Materials	Acting - Piepke
		1.07.03		Radon Outgassing	Acting - Piepke
		1.07.04		Exposure Based backgrounds	Acting - Piepke
		1.07.05		Surface Cleaning and Testing	Acting - Piepke
		1.07.06		Materials Synthesis and Industry Survey	Acting - Piepke
1.08	Computing, Controls and Software	1.08.01		CCS Management	Acting - Sangiorgio
		1.08.02		Slow Control	Acting - Sangiorgio
		1.08.03		DAQ	Acting - Sangiorgio
		1.08.04		Analysis Software	Acting - Sangiorgio
		1.08.05		Simulations Software	Acting - Sangiorgio
		1.08.06		Infrastructure Software	Acting - Sangiorgio
		1.08.07		Data and Computing Facilities	Acting - Sangiorgio
		1.08.08		Sensitivity and Science Readiness	Acting - Sangiorgio
1.09	Xenon	1.09.01		Management for Xenon sub-system	Acting - Riot
		1.09.02		Enriched Xenon procurement	Acting - Riot
		1.09.03		Xenon Assaying Systems	Acting - Riot
		1.09.04		Xenon Transfer Vessels	Acting - Riot
1.10	Outer Detector	1.10.01		Outer Detector Management	Hawkins
		1.10.02		Water Tank	Hawkins
		1.10.03		Muon Veto	Hawkins
		1.10.04		Water Circulation System	Hawkins
		1.10.05		Outer Detector Test Facility	Hawkins
1.11	Facilities	1.11.01		SNOLAB Facility Management	Hawkins
		1.11.02		SNOLAB Cryopit Infrastructure	Hawkins
		1.11.03		SNOLAB Clean Rooms	Hawkins
		1.11.04		SNOLAB LN2 Plant	Hawkins

nEXO

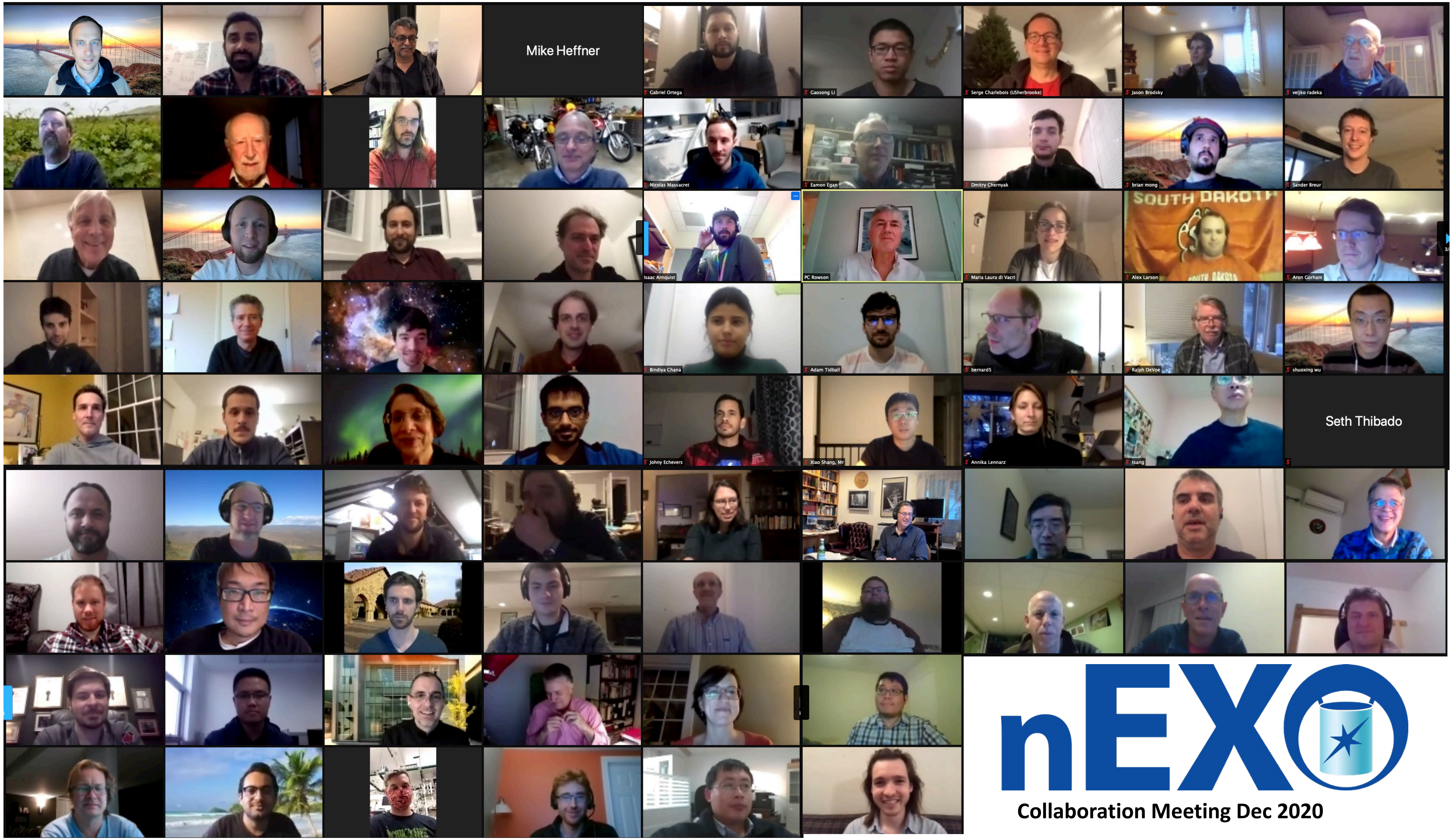
- University of Munster (Germany)
- Skyline (USA)
- Subatech (France)
- U of Western Cape (South Africa)

all joined the collaboration in the last year

nEXO is a world-wide effort, including, for the time being, 9 Countries, 33 institutions, 186 collaborators

More colleagues with interests in the science, the detector technology (or both) are encouraged to discuss possible collaboration.

(Part ot) The nEXO Collaboration



nEXO

Collaboration Meeting Dec 2020