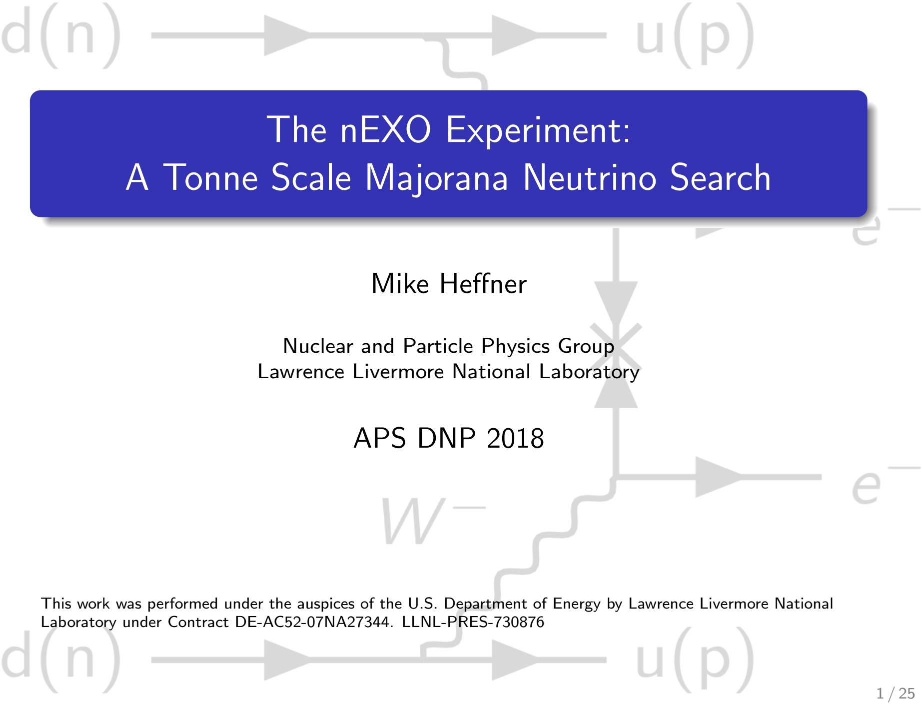

The nEXO Experiment:
A Tonne Scale Majorana Neutrino Search

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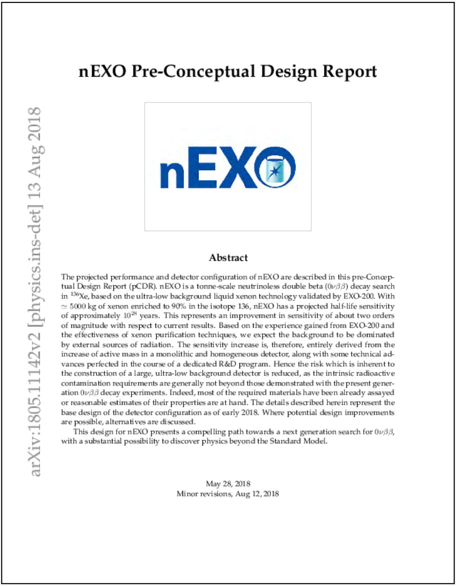
Nuclear and Particle Physics Group
Lawrence Livermore National Laboratory

APS DNP 2018

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-PRES-730876

Sensitivity Paper and pCDR – nexo.llnl.gov



nEXO Pre-Conceptual Design Report

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 $\simeq$ 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
Minor revisions, Aug 12, 2018

Sensitivity and Discovery Potential of nEXO to Neutrinoless Double Beta Decay

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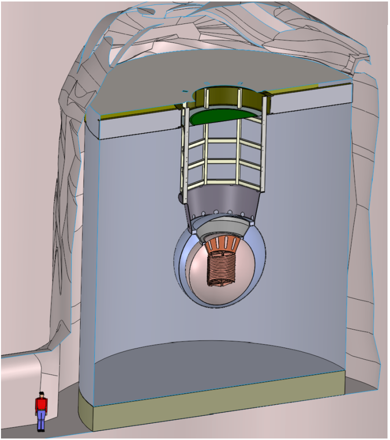
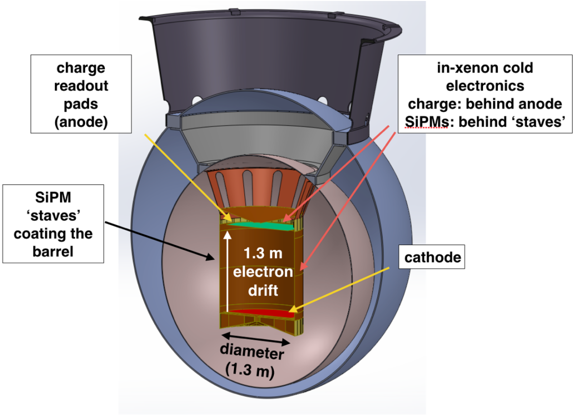
(Dated: October 17, 2017)

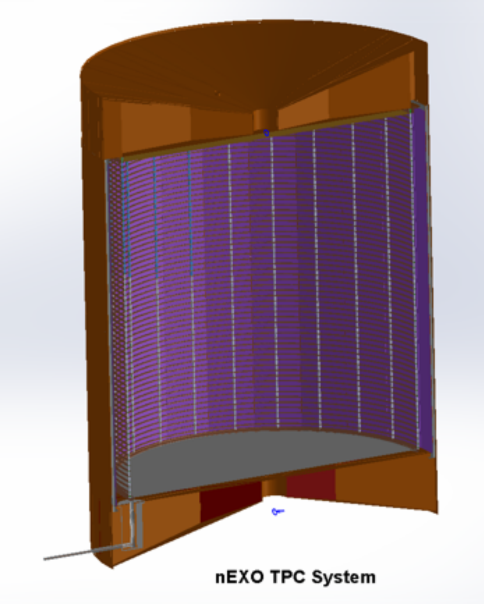
The nEXO Concept

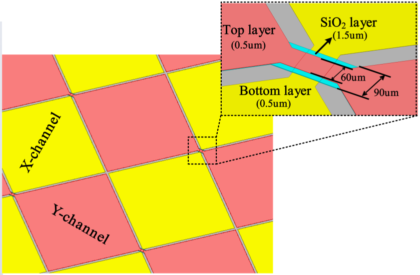
Conceptual Design for nEXO

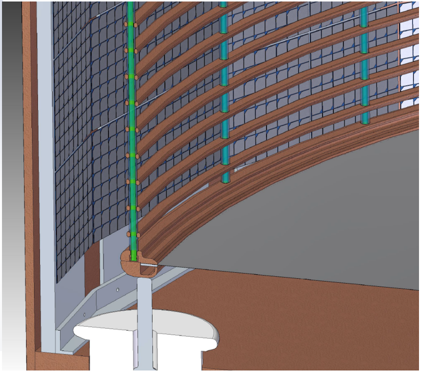




Conceptual Design for nEXO

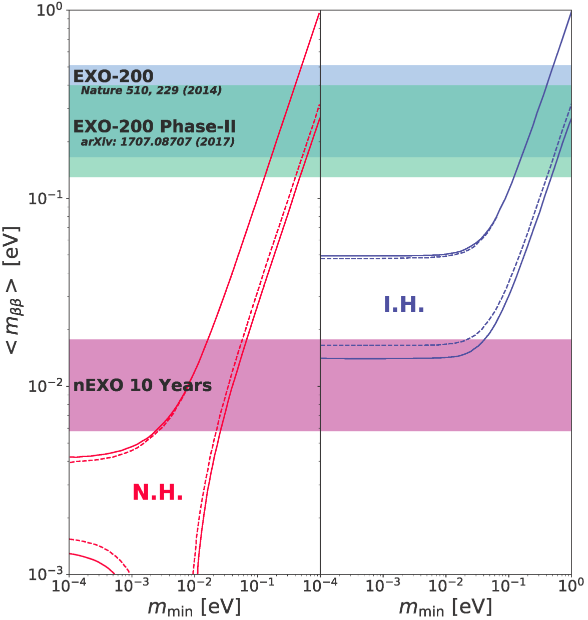

nEXO TPC System

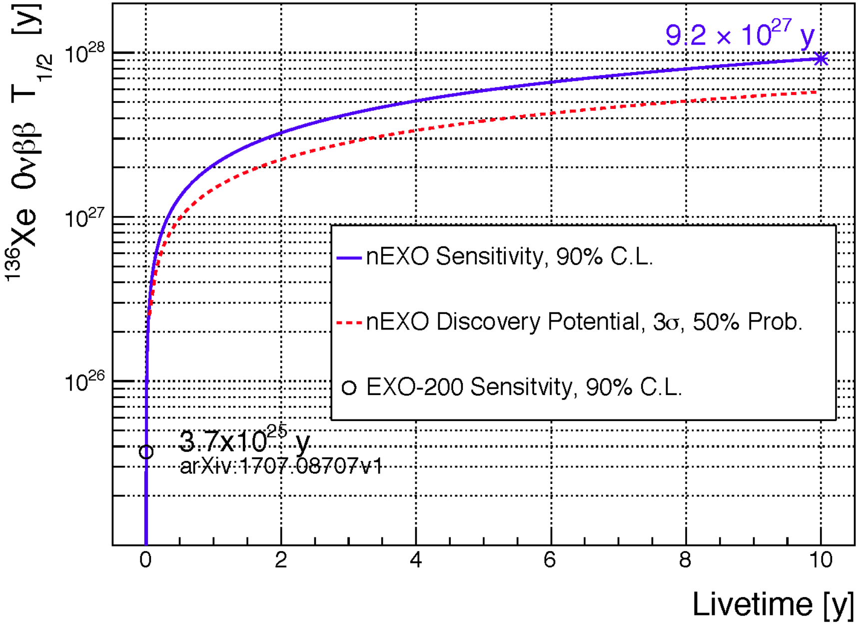


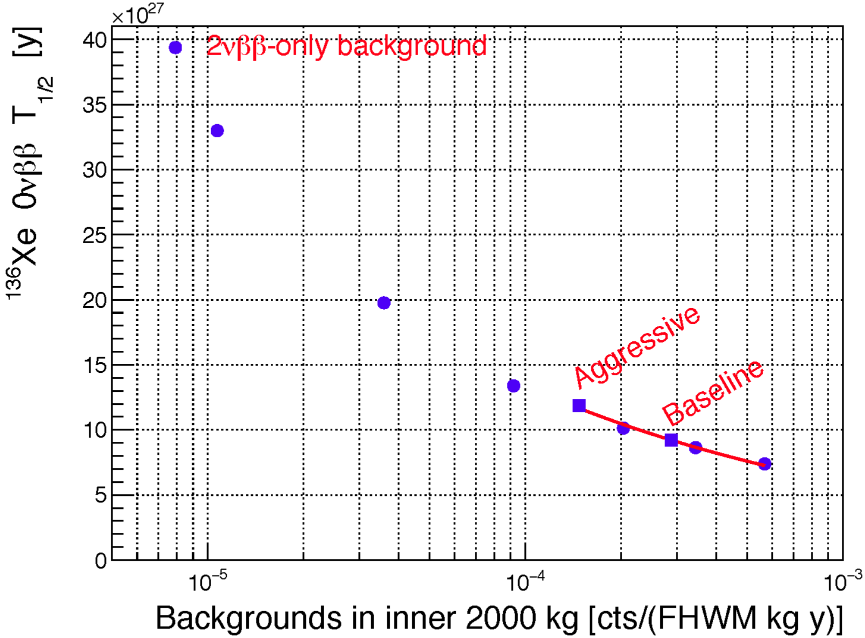


nEXO Sensitivity

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

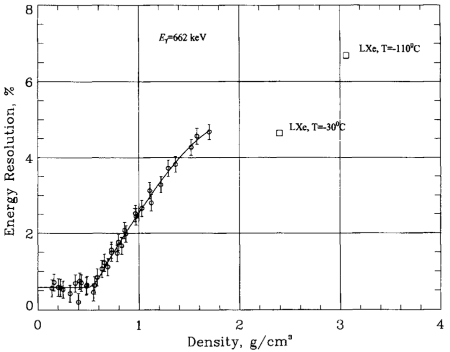



^{136}Xe 0νββ $T_{1/2}$ [y]
10^{28}
10^{27}
10^{26}
0
2
4
6
8
10
Livetime [y]
9.2×10^{27} y
3.7×10^{25} y
arXiv:1707.08707v1
nEXO Sensitivity, 90% C.L.
nEXO Discovery Potential, 3σ, 50% Prob.
EXO-200 Sensitvity, 90% C.L.

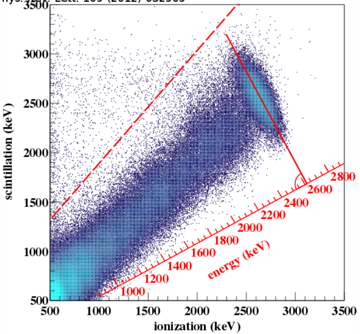

×10^27
2νββ-only background
Aggressive
Baseline
136Xe 0νββ T1/2 [y]
40
35
30
25
20
15
10
5
0
10^−5
10^−4
10^−3
Backgrounds in inner 2000 kg [cts/(FHWM kg y)]

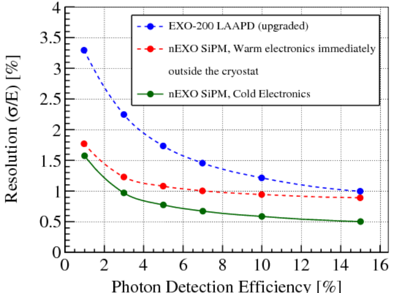
Energy resolution

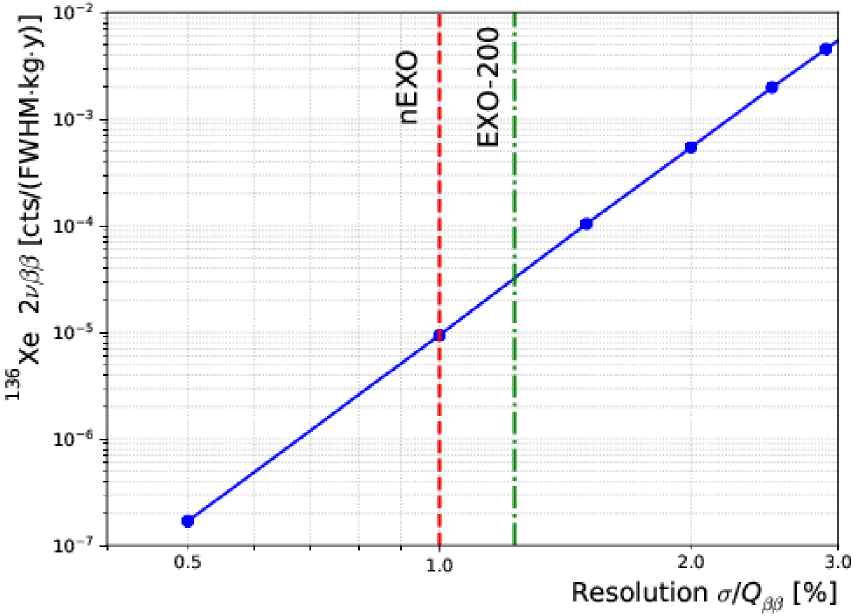
A. Bolotnikov, B. Ramsey / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 360–370

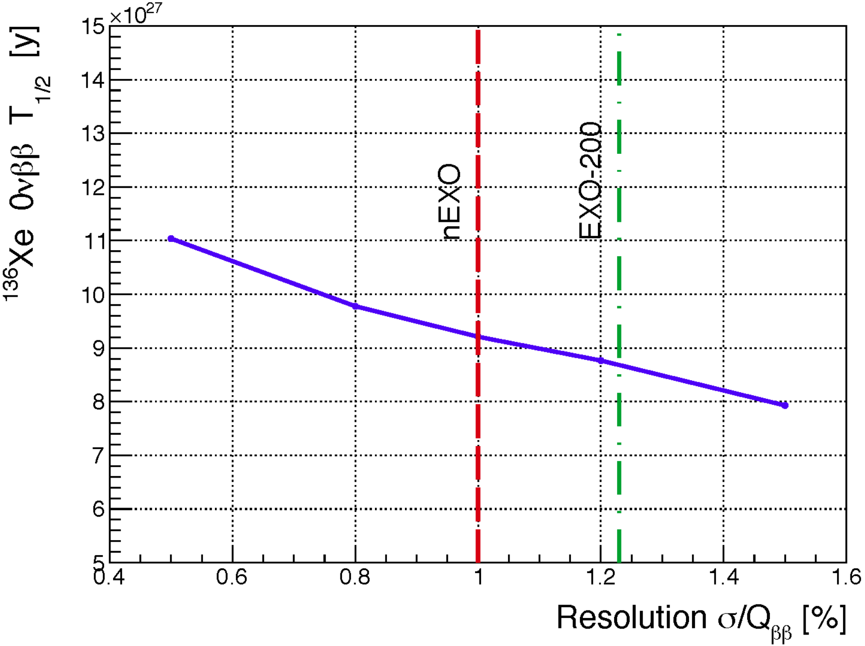


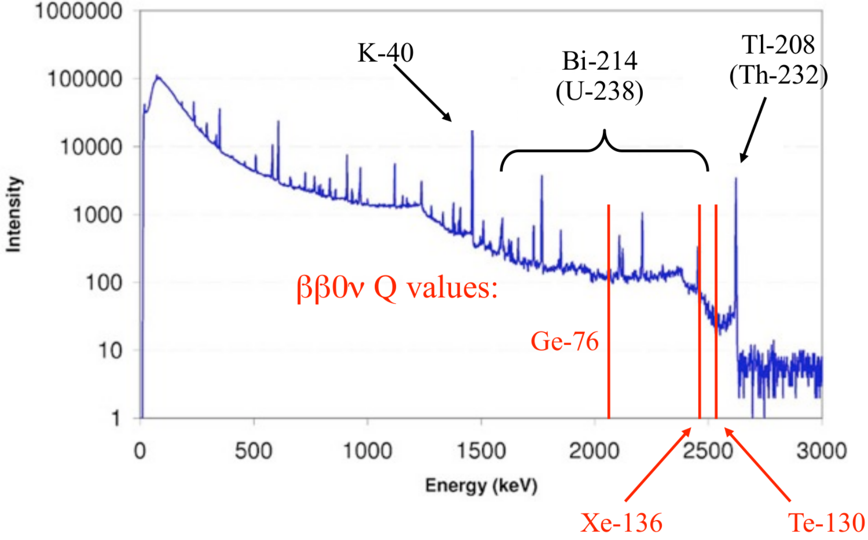
Phys. Rev. Lett. 109 (2012) 032505



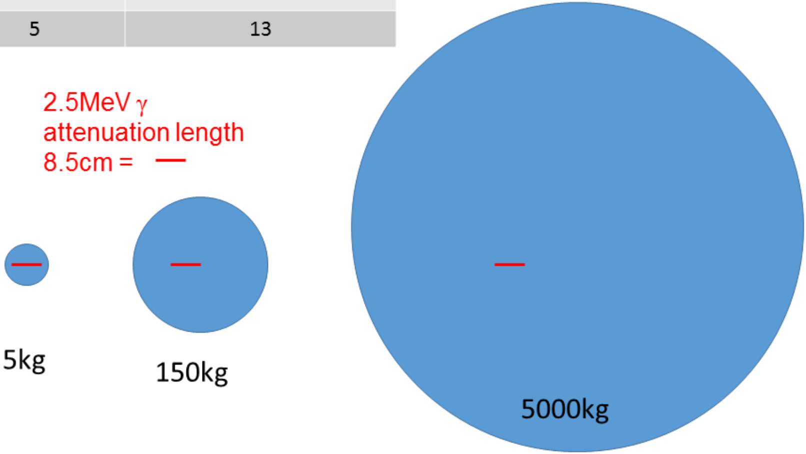


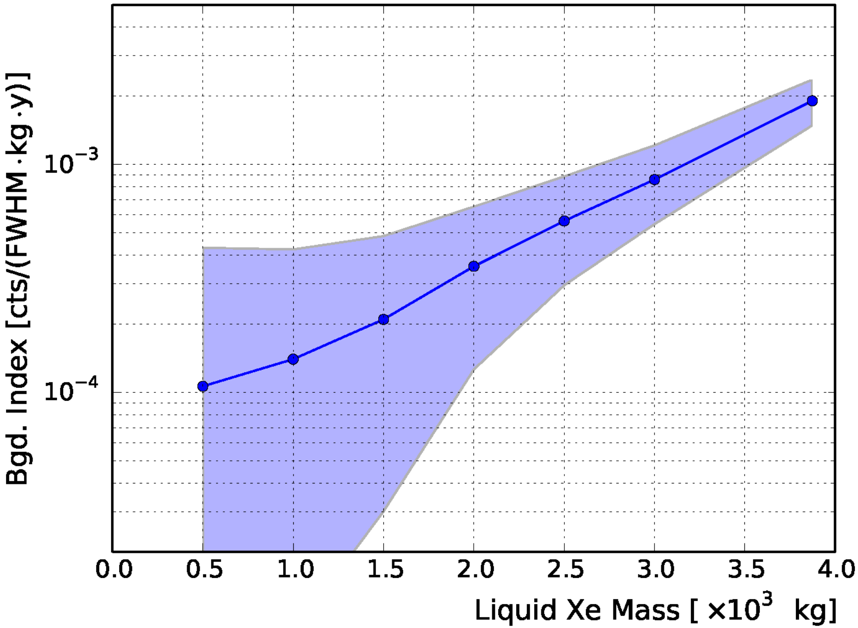

^{136}Xe $2\nu\beta\beta$ [cts/(FWHM·kg·y)]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
nEXO
EXO-200
0.5
1.0
2.0
3.0
Resolution $\sigma/Q_{\beta\beta}$ [%]

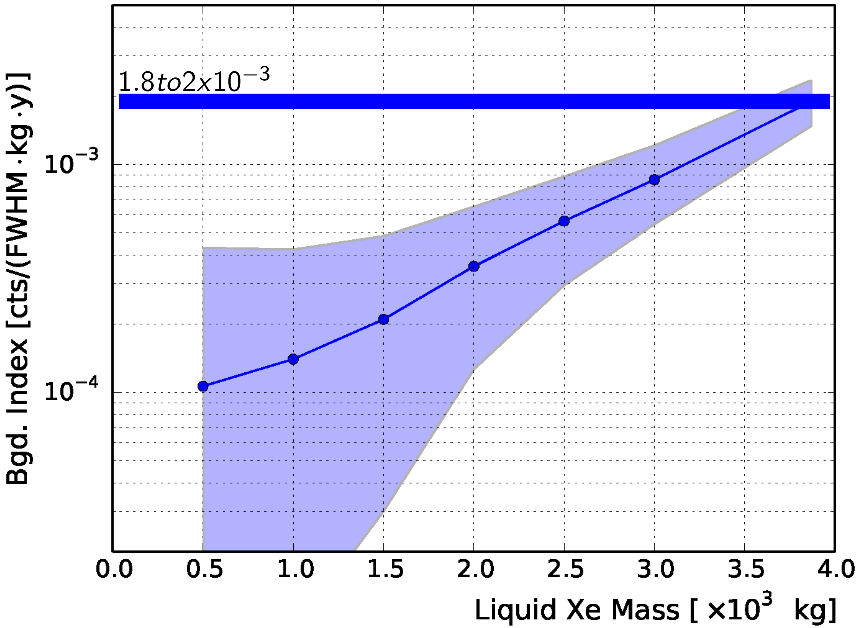

$\times 10^{27}$
15
14
13
12
11
10
9
8
7
6
5
0.4
0.6
0.8
1
1.2
1.4
1.6
nEXO
EXO-200
^{136}Xe $0\nu\beta\beta$ $T_{1/2}$ [y]
Resolution $\sigma/Q_{\beta\beta}$ [%]

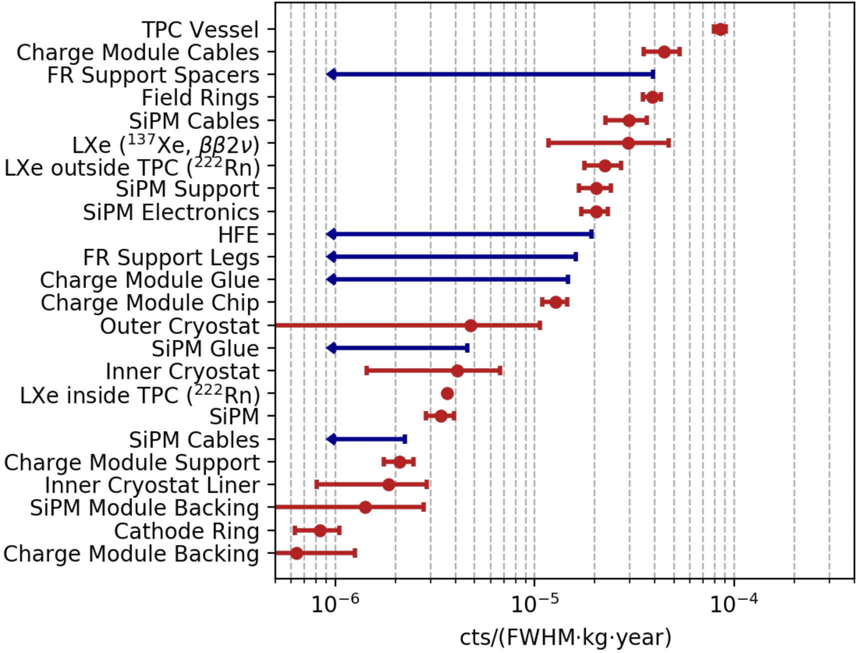

1000000
100000
10000
1000
100
10
1
Intensity
0
500
1000
1500
2000
2500
3000
Energy (keV)
K-40
Bi-214
(U-238)
Tl-208
(Th-232)
ββ0ν Q values:
Ge-76
Xe-136
Te-130

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

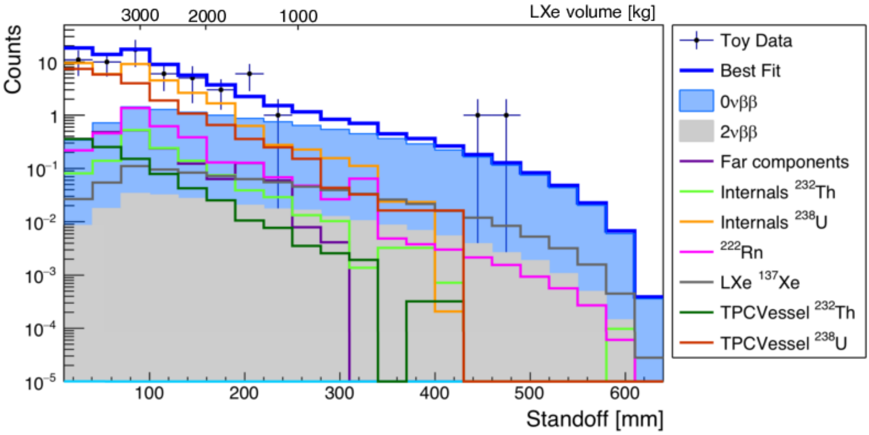



Bgd. Index [cts/(FWHM·kg·y)]
10^{-3}
10^{-4}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Liquid Xe Mass [×10^3 kg]


$1.8 to 2 x 10^{-3}$
Bgd. Index [cts/(FWHM·kg·y)]
10^{-3}
10^{-4}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Liquid Xe Mass [$\times 10^3$ kg]



Inner 2000kg


LXe volume [kg]
3000
2000
1000
Counts
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
100
200
300
400
500
600
Standoff [mm]
Toy Data
Best Fit
0νββ
2νββ
Far components
Internals ^{232}Th
Internals ^{238}U
^{222}Rn
LXe ^{137}Xe
TPCVessel ^{232}Th
TPCVessel ^{238}U

Discovery Probability

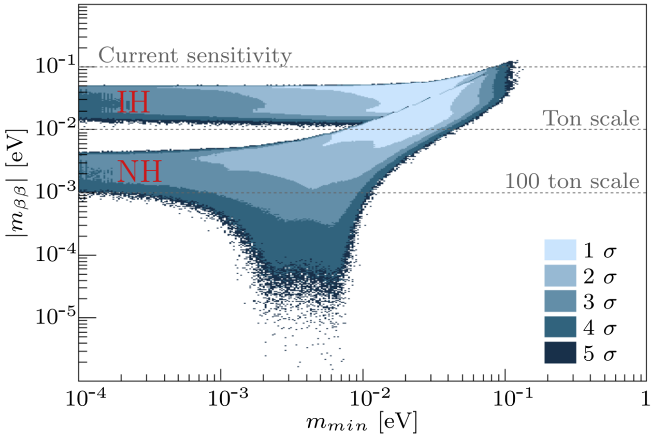
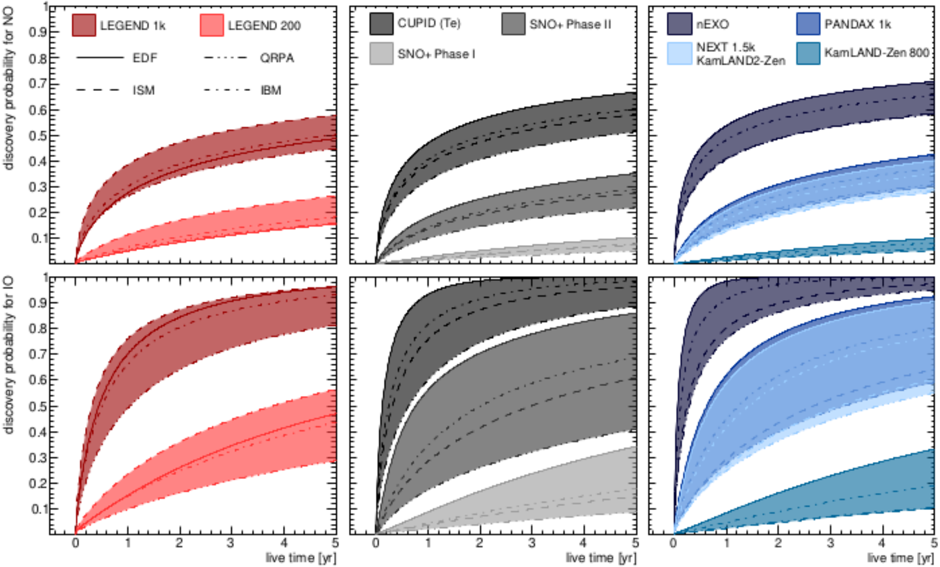


Fig. 6 Effective Majorana mass as a function of the lightest neutrino mass with the application of the cosmological bound. The different colors correspond to the 1,. . . ,5 σ coverage regions.

arXiv:1510.01089, G. Benato, 15Oct2015

Discovery Probability (arXiv:1705.02996)

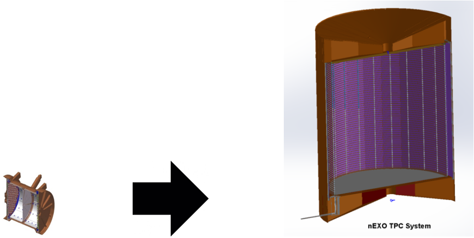


Additional Features of LXe TPC

- Excellent TPC medium (Good electron transport, Bright scintillator, good attenuation length for 175nm)
- Non-toxic, non-reactive (easy to purify, fewer safety issues)
- Commercially available natural xenon at the quantities needed
- Straight forward enrichment (8.9%)
- The xenon can easily be recovered for other experiments
- Depleted xenon can easily be introduced to nEXO for confirmation.

R&D

nEXO: to first order, just a scale up of EXO-200



9 **Towards a Project** **165**

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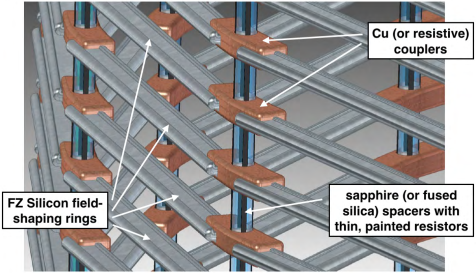
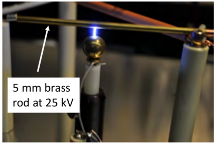
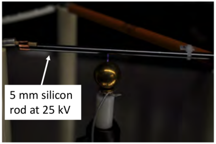
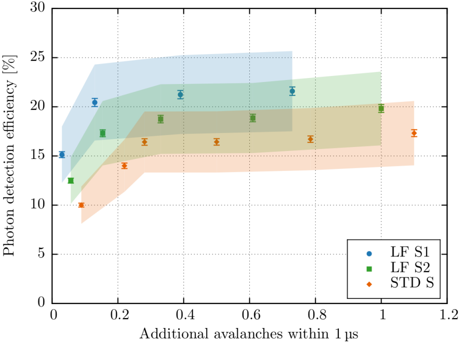
9.12 Simulation and Data Analysis 173

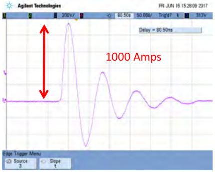


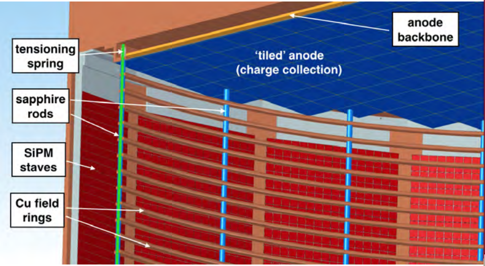
Parameter	Value
Total instrumented area	$\simeq 4.5\ \mathrm{m}^2$
Overall light detection efficiency	$\epsilon_o > 3\ \%$
SiPM PDE (175 nm, normal incidence)	$\epsilon_{PD} > 15\ \%$
Overvoltage	$> 3\ \mathrm{V}$
Dark noise rate	$< 50\ \mathrm{Hz/mm}^2$
Correlated avalanche rate	< 0.2

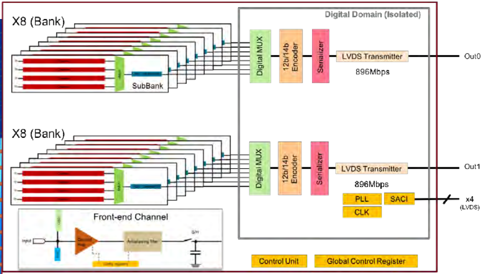


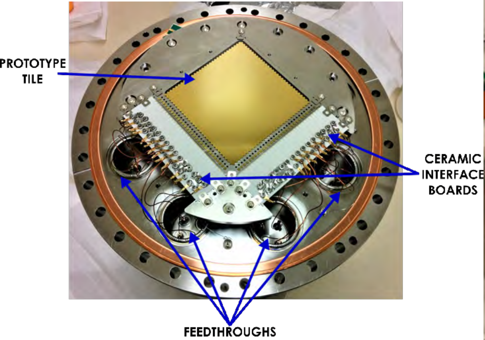







tensioning spring
sapphire rods
SiPM staves
Cu field rings
anode backbone
'tiled' anode (charge collection)

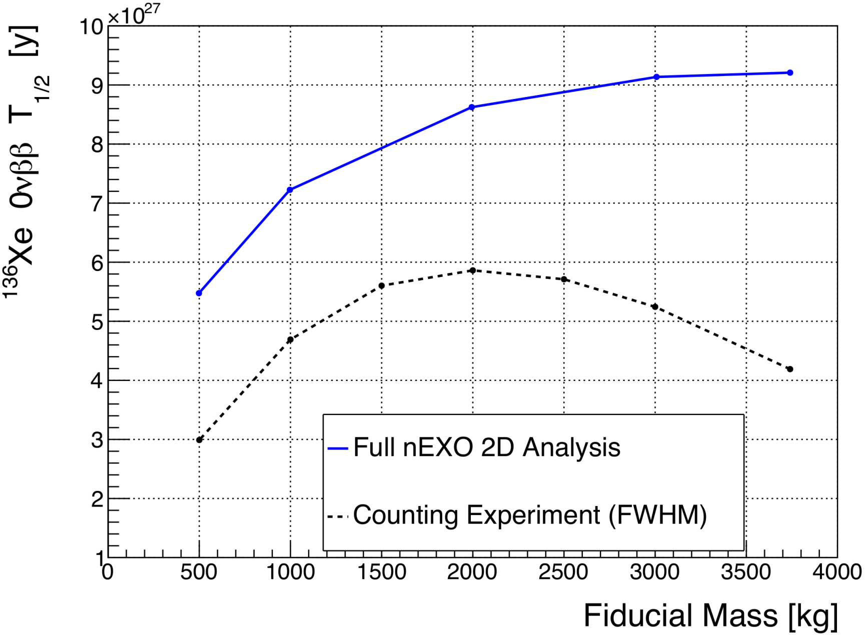

X8 (Bank)
SubBank
X8 (Bank)
Front-end Channel
Digital Domain (Isolated)
Digital MUX
12b/14b Encoder
Serializer
LVDS Transmitter
896Mbps
Out0
Digital MUX
12b/14b Encoder
Serializer
LVDS Transmitter
896Mbps
Out1
PLL
SACI
CLK
x4 (LVDS)
Control Unit
Global Control Register

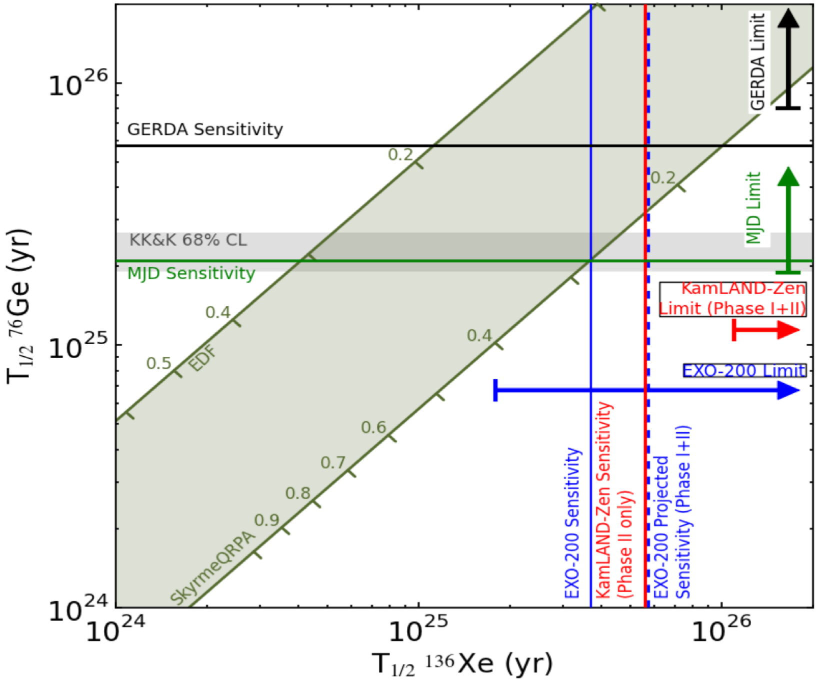

PROTOTYPE TILE
CERAMIC INTERFACE BOARDS
FEEDTHROUGHS

Conclusion

- Discovery of a majorana neutrino would be an exciting event, and a $\approx$100X improvement in experimental sensitivity for this search is within reach
- A liquid xenon TPC has a number of advantages
  - A full analysis of a realistic/conservative tonne scale LXe TPC has shown that this technology will meet the physics goals.
  - Technology was "prototyped" and returned results over 6 years ago (EXO-200)
  - No miracles required
  - Cost may be lower than other technologies
  - Xenon TPCs are likely extendable beyond the tonne scale
  - Upgrades are possible
  - Xenon can be moved between experiments and swapped for depleted in the case of a discovery
- nEXO is a US led collaboration with scientists around the globe that is rapidly making R&D progress on the LXe TPC technology

EXTRAS


^{136}Xe 0νββ $T_{1/2}$ [y]
×10^{27}
10
9
8
7
6
5
4
3
2
1
0
500
1000
1500
2000
2500
3000
3500
4000
Fiducial Mass [kg]
Full nEXO 2D Analysis
Counting Experiment (FWHM)



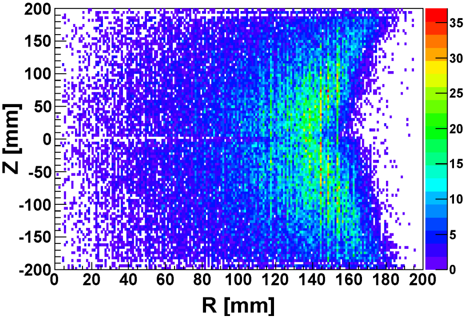
GERDA Sensitivity
GERDA Limit
0.2
0.2
MJD Limit
KK&K 68% CL
MJD Sensitivity
KamLAND-Zen Limit (Phase I+II)
0.4
0.5
EDF
0.4
EXO-200 Limit
0.6
0.7
0.8
0.9
SkyrmeQRPA
EXO-200 Sensitivity
KamLAND-Zen Sensitivity (Phase II only)
EXO-200 Projected Sensitivity (Phase I+II)
10^{26}
10^{25}
10^{24}
$T_{1/2}$ ^{76}Ge (yr)
10^{24}
10^{25}
10^{26}
$T_{1/2}$ ^{136}Xe (yr)

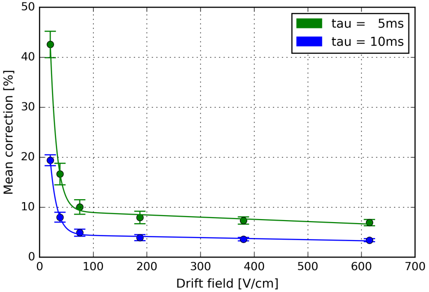
nEXO Requires Stable High Voltage

High voltage in noble liquids... ,2014 JINST 9 T08004

> *Indeed, a common element among the successful experiments is that the high voltage system was treated as a major focus of the design from the beginning.*

- HV moves charge to collection electrodes
- Detector performance is tied to electric field





Accessible Lifetime is Limited by Exposure

Event Rate for a 10^{26} Year Lifetime

Radioactive Decay

$$\frac{dN}{dt} = \frac{ln(2)}{T_{1/2}} N$$

$$\frac{dN}{dt} = 30 \text{ events/tonne/year}$$

Atoms per Tonne ^{136}Xe

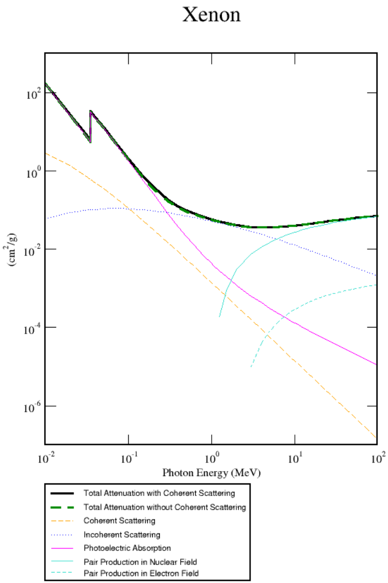
136g/mole

$6.022x10^{23}$ atoms/mole

$N = 4.4x10^{27}$ atoms/Tonne

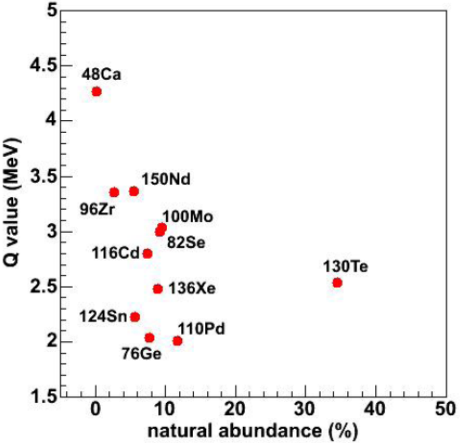
lifetime	events/tonne/yr
10^{26}	30
10^{27}	3
10^{28}	0.3
10^{29}	0.03
10^{30}	0.003

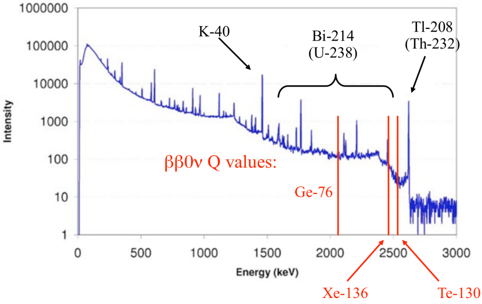
Photon Interaction in Xenon

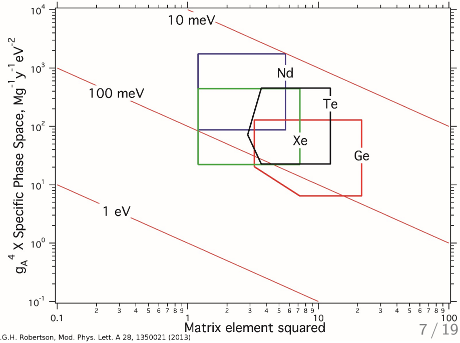


- From the NIST website http://physics.nist.gov/cgi-bin/Xcom/xcom3_1
- ratio of Compton to PE at 2.5MeV is 35. This is the most gain one can get from SS/MS differentiation.

Elements that can decay via $0\nu2\beta$







R.G.H. Robertson, Mod. Phys. Lett. A 28, 1350021 (2013)

Experimental techniques

Liquid (organic) scintillators:

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

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

Cons: Not very specific, 2v background

Crystals:

- GERDA, Majorana Demonstrator (^{76}Ge)
- CUORE, CUPID (^{130}Te)

Pros: Superb energy resolution, possibly 2-parameter measurement

Cons: Intrinsically fragmented

Low density trackers:

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

Pros: Superb topological information

Cons: Very large size

Liquid TPC:

- EXO-200, nEXO (^{136}Xe)

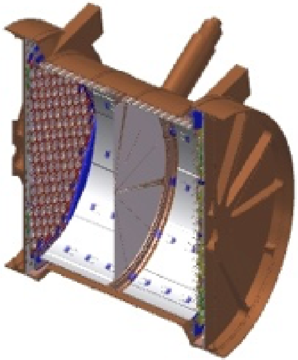
Pros: Homogeneous with good E resolution and topology

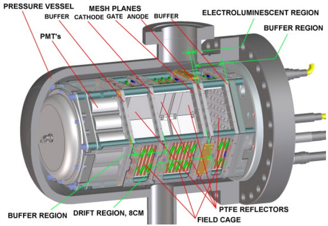
Cons: Does not excel in any single parameter

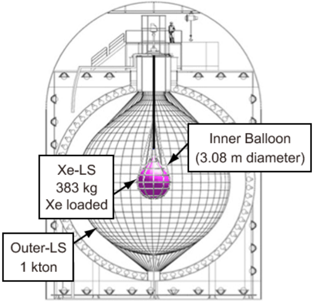
Xenon Experiments

3 technologies

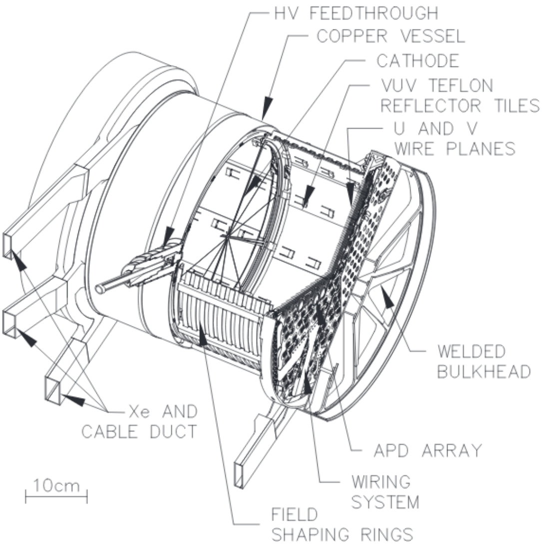
- Gas TPC $T_{1/2}^{0\nu2\beta} < 3x10^{23}$ yrs
- Liquid TPC $T_{1/2}^{0\nu2\beta} < 1.8x10^{25}$yrs
- Loaded Liquid Scintillator $T_{1/2}^{0\nu2\beta} < 1.1x10^{26}$ yrs







EXO-200

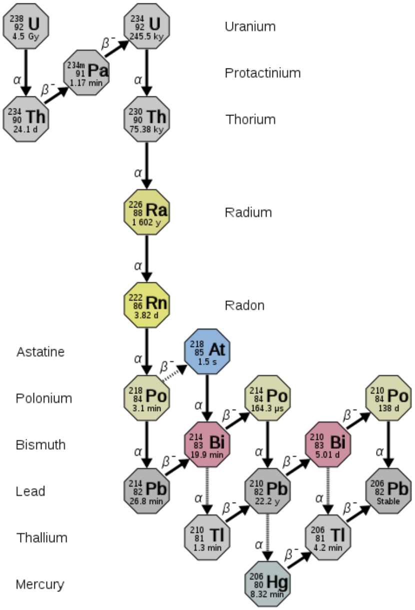


$2\nu2\beta\, T_{1/2} = 2.11x10^{21}$ yrs

$0\nu2\beta\, T_{1/2} > 1.6x10^{25}$ yrs
Phys. Rev. Lett. 109
(July2012)

A Low Risk (non-optimal), Tonne Scale Experiment

Radiopurity and Background Discrimination are Essential



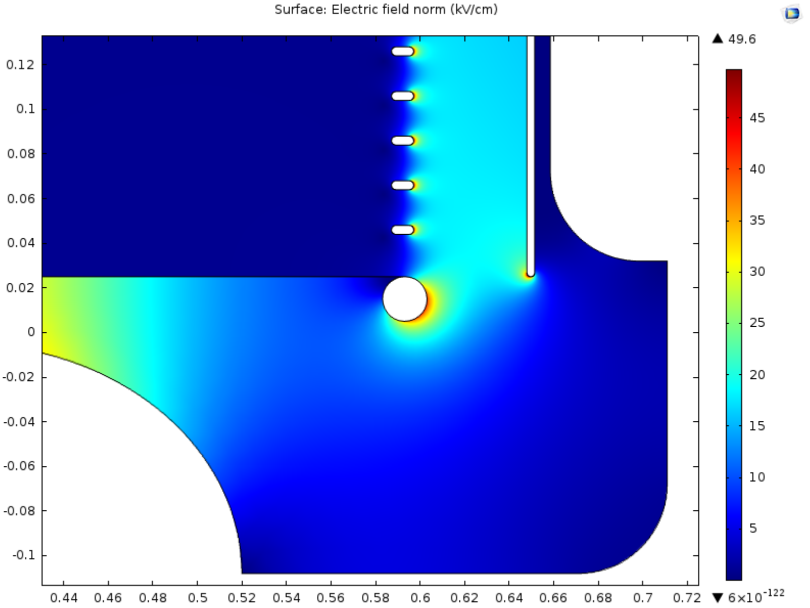
A cartoon (at $10^{28} yr$) to illustrate...

Background – from ^{214}Bi (^{238}U)

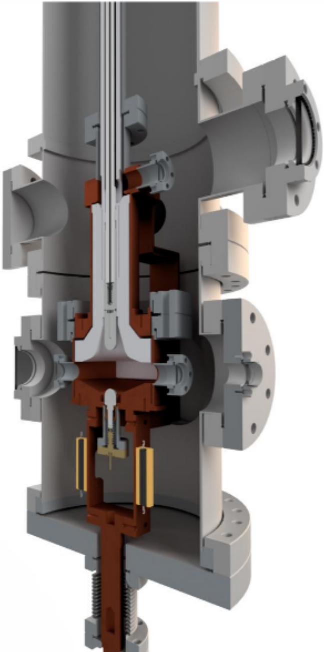
$T^{238U}_{1/2} = 4.5 \cdot 10^9$ yrs, so the required rejection ratio is $\frac{T^{0\nu2\beta}_{1/2}}{T^{238U}_{1/2}} \approx 2.2 \cdot 10^{18}$

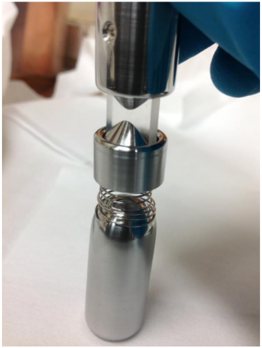
Item	**Rejection**
Natural abundance	10^6
Selection of material	10^7
Copper to xenon number ratio	5.8
Solid angle	2
Energy Resolution	≈ 0
$S = \sqrt{B}$	15
SS/MS (cross section ratio)	35
Self shielding	≈ 55
Total	$3 \cdot 10^{18}$

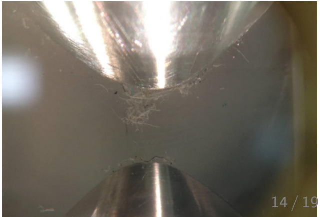
Critical HV region



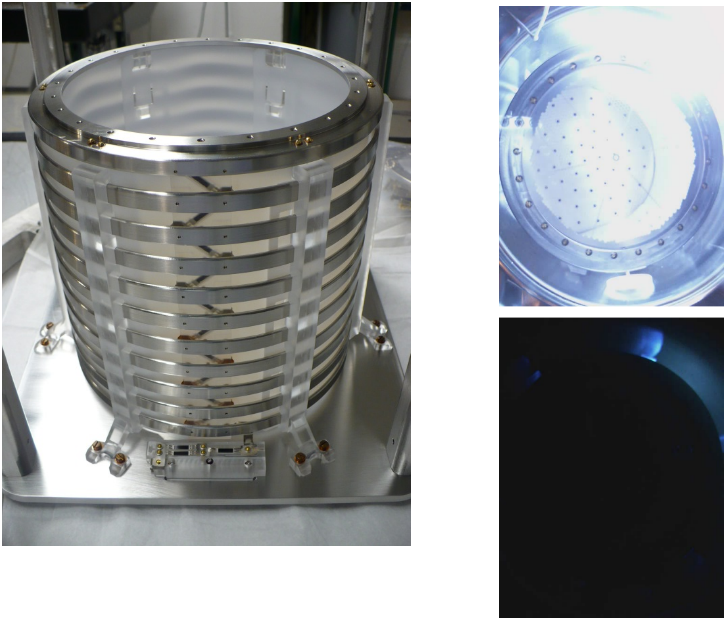
High Voltage R&D – Testing Ideas at a Small Scale



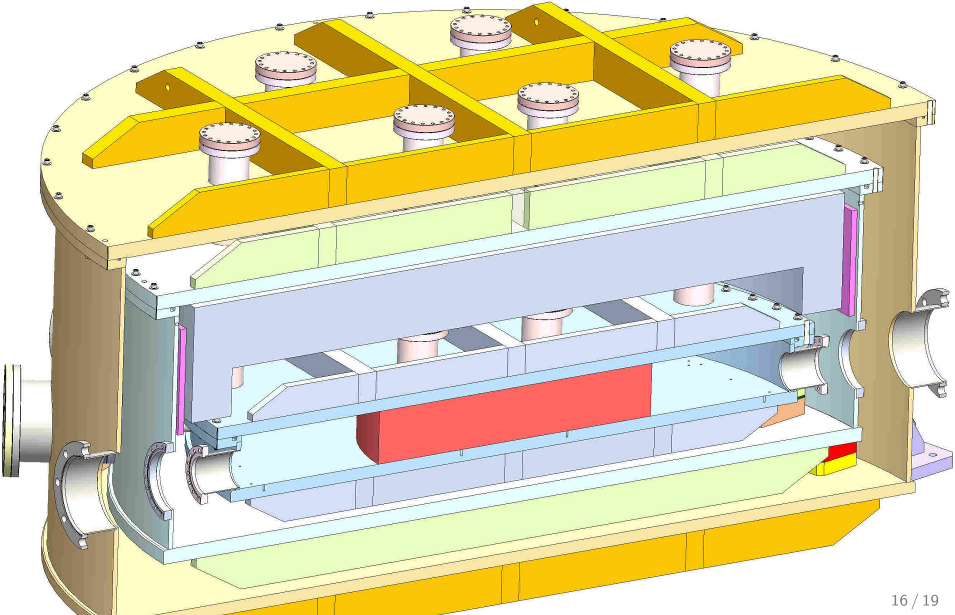




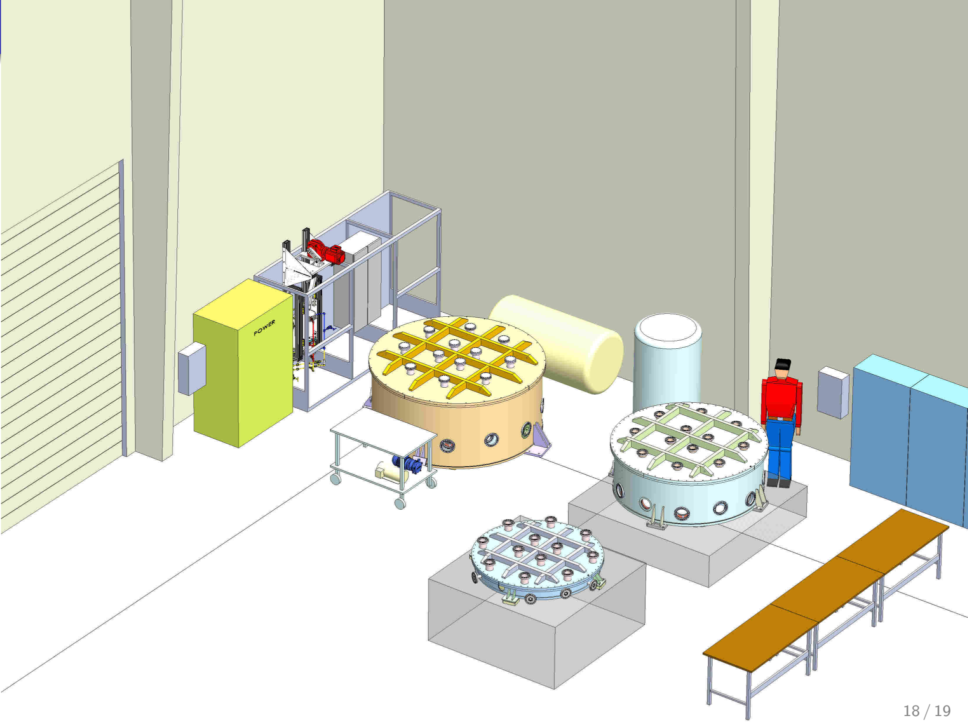
High Voltage R&D – 1/2 Scale Model of EXO200



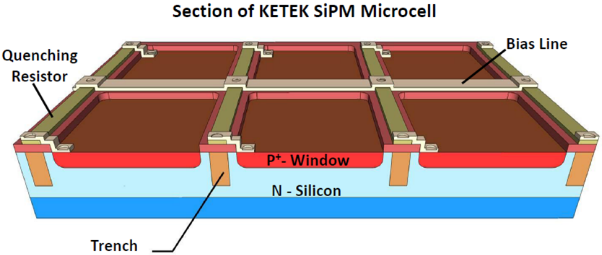
High Voltage R&D – Full nEXO Scale



High Voltage R&D – Full nEXO Scale


POWER

SiPM



Requirements

- Radiopurity
- Efficiency
- Dark Noise
- Correlated avalanches
- Total Power
- And others (gain, pulse shape, dynamic range, capacitance, speed...)