nEXO, search for $0\nu\beta\beta$ beyond 10^{28} years

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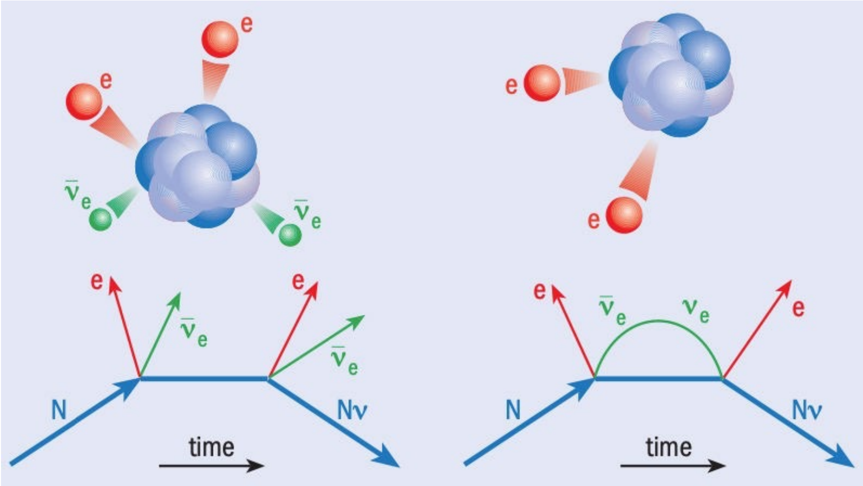
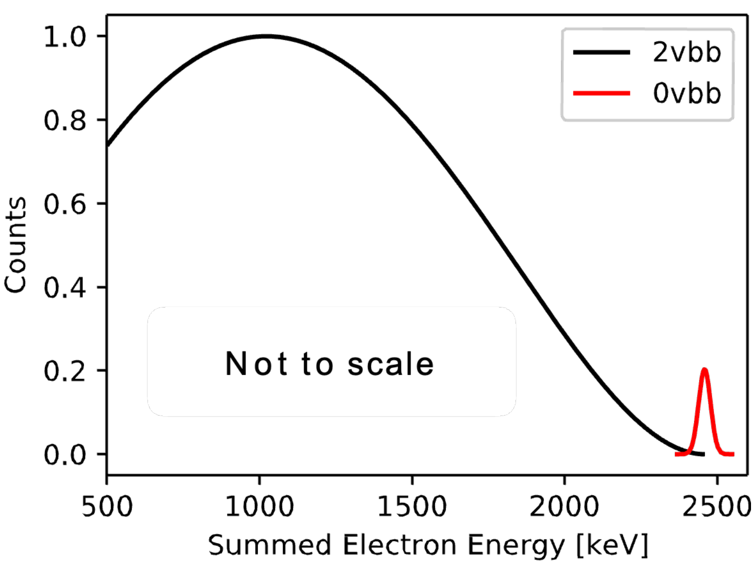
Subatech – Université de Nantes

$0\nu\beta\beta$ decay

- Finding $0\nu\beta\beta$ always implies new physics
  - Lepton number violation
  - Neutrinos are Majorana fermions ($\nu \equiv \bar{\nu}$)
  - Origin of neutrino masses
  - Insight into absolute neutrino mass scale
  - Possibly linked to matter and anti-matter asymmetry

- Experimental signature is a peak at the Q-value (2458 keV for ^{136}Xe)





nEXO: A world wide effort

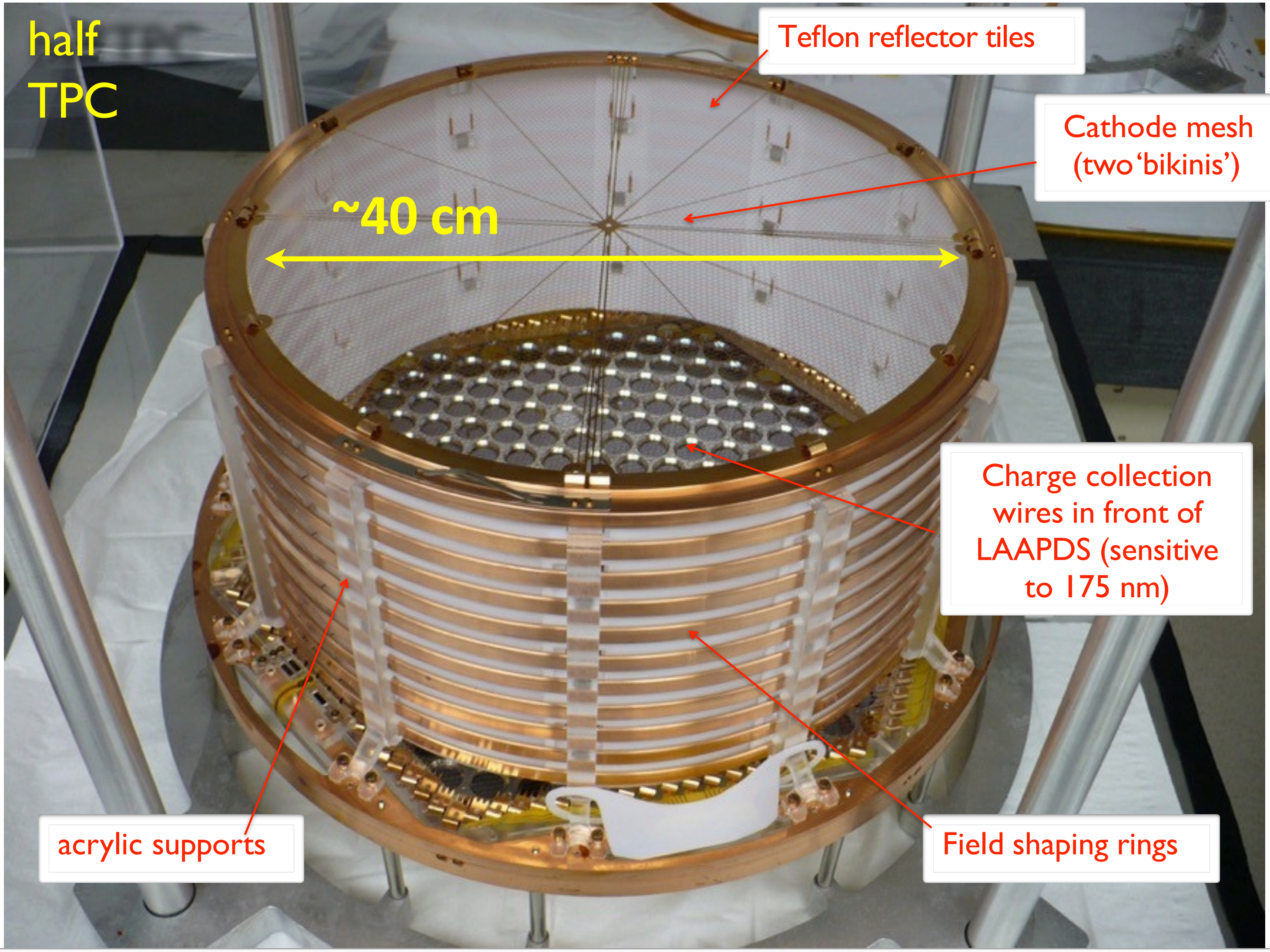
Laurentian University / Université Laurentienne
Carleton University
McGill
Université de Sherbrooke
UMass Amherst
Yale University
Brookhaven National Laboratory
WWU Münster
FAU Friedrich-Alexander Universität Erlangen-Nürnberg
Rensselaer
The University of British Columbia
TRIUMF
Pacific Northwest National Laboratory
ИТЭФ
Technical University of Munich
Skyline College
ibs Institute for Basic Science
Lawrence Livermore National Laboratory
IHEP
SLAC National Accelerator Laboratory
IMECAS
Stanford University
u^b Universität Bern
Caltech
UC San Diego
Colorado School of Mines
Colorado State University
The University of Alabama 1831
Oak Ridge National Laboratory
University of Kentucky
University of the Western Cape
UNCW University of North Carolina Wilmington
Drexel University
Subatech

9 countries, 33 institutions, ~200 collaborators

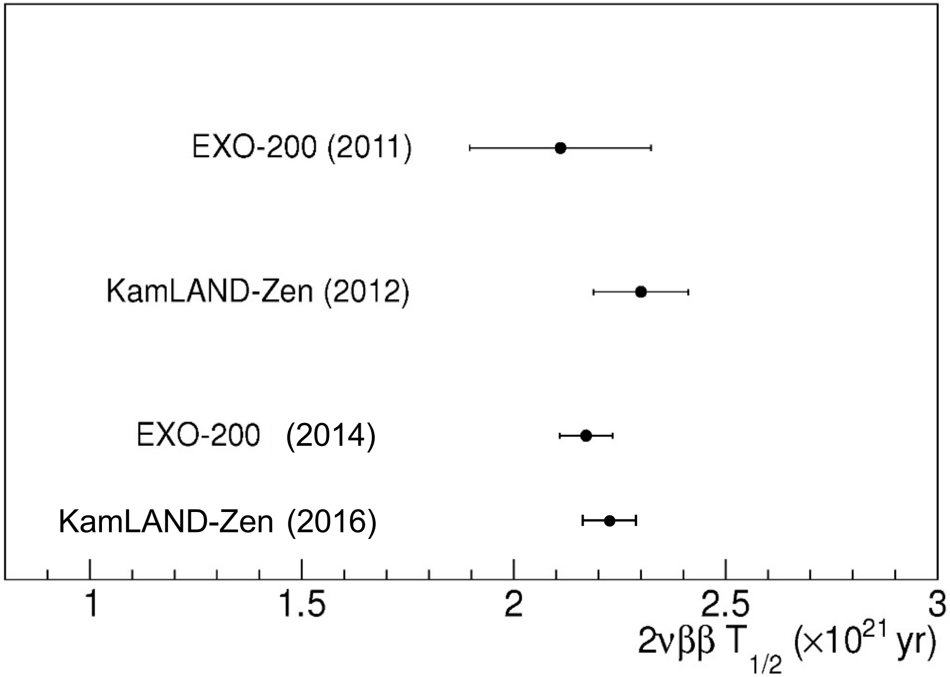
nEXO in the $0\nu\beta\beta$ decay landscape

- The global $0\nu\beta\beta$ decay program is gearing up for the so-called "tonne-scale" phase (as communicated by the European and North American funding agencies at the 10/2021 International Forum at LNGS)
- Three major experiments with different isotopes:
  - nEXO (^{136}Xe), Legend-1000 (^{76}Ge), CUPID (^{100}Mo)
  - very different experimental techniques, healthy program
- nEXO plans a 5-tonne, single phase, LXe TPC (90% enriched in 136 isotope)
  100-fold increase in sensitivity wrt current experiments
- nEXO builds on the successful EXO-200 program which has demonstrated the key technical features of this technology at scale, such as:
  - Effectiveness of self-shielding and low intrinsic background
  - Energy resolution via collection of ionization and scintillation
  - Event topology (β vs. γ) and particle ID (β/γ vs. α)
  - Continuous purification of the source

EXO-200 TPC


half
TPC
~40 cm
Teflon reflector tiles
Cathode mesh
(two 'bikinis')
Charge collection
wires in front of
LAAPDS (sensitive
to 175 nm)
acrylic supports
Field shaping rings

Precision measurement of 2νββ



Discovery of 2νββ decay of ^{136}Xe
[PRL 107, 212501 (2011)]

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

Precision measurement (~3%)
[PRC 89, 015502 (2014)]

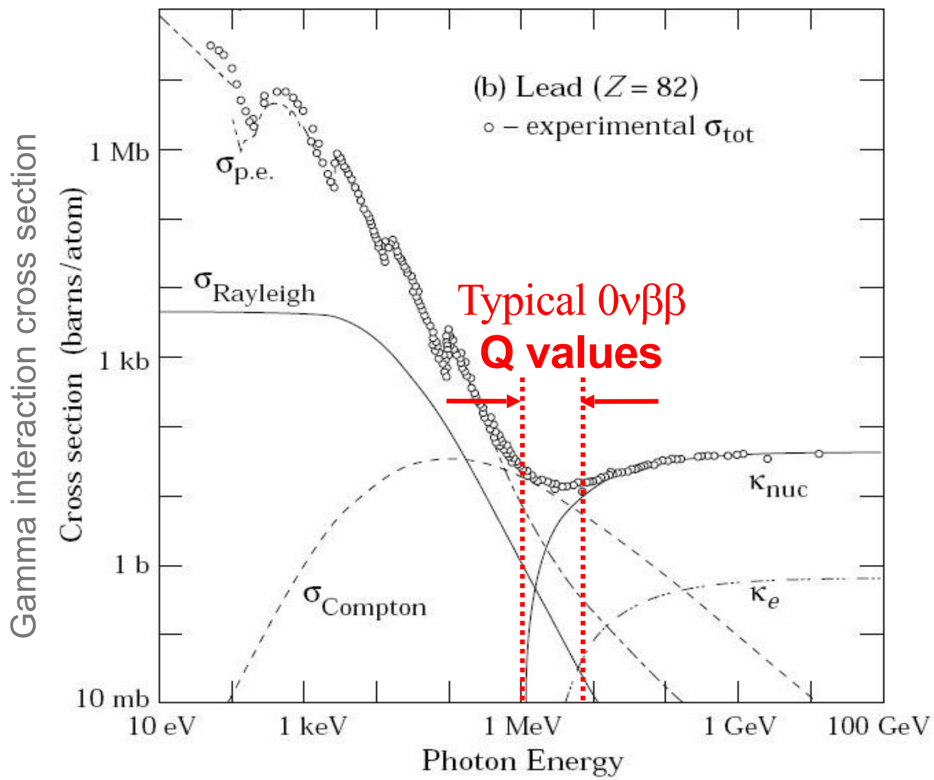
Precision by KamLAND-Zen
[PRL 117, 082503 (2016)]

$$T_{1/2} = (2.165 \pm 0.016(\mathrm{stat}) \pm 0.059(\mathrm{syst})) \mathrm{x} 10^{21}\ \mathrm{yr}$$

(longest, first to be precisely* (directly) measured 2νββ decay of all 'practical' isotopes)

(* Ge-76 and Te-130 have similarly precise measurements)

Key requirement: shielding from MeV γ-rays

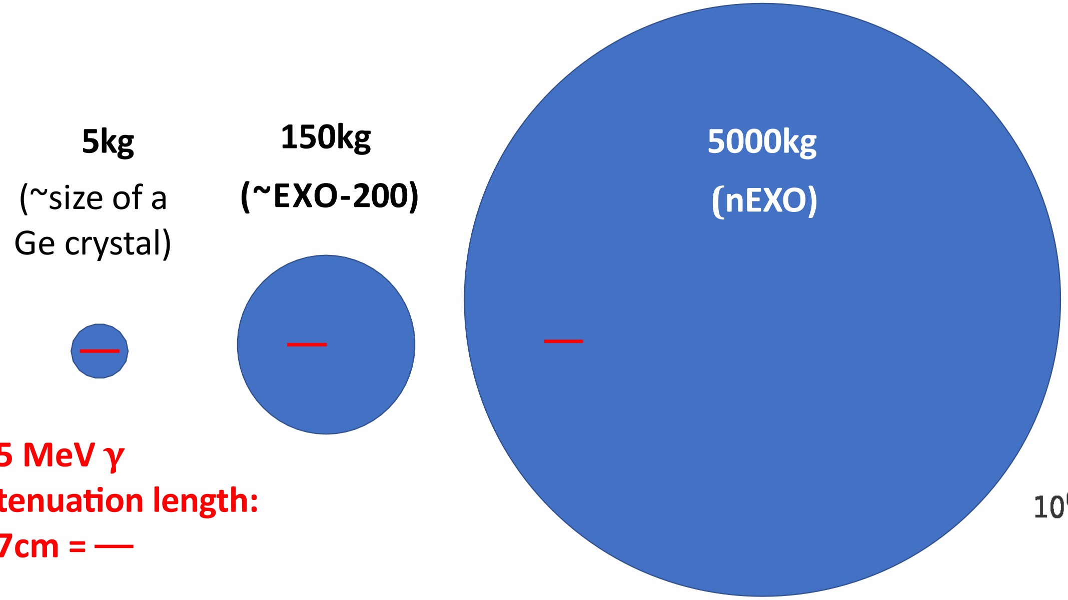


Shielding ββ decay detectors from external electromagnetic background is harder/different than shielding Dark Matter detectors

We are entering the "golden era" of ββ decay experiments as detector sizes exceed gamma-ray interaction lengths

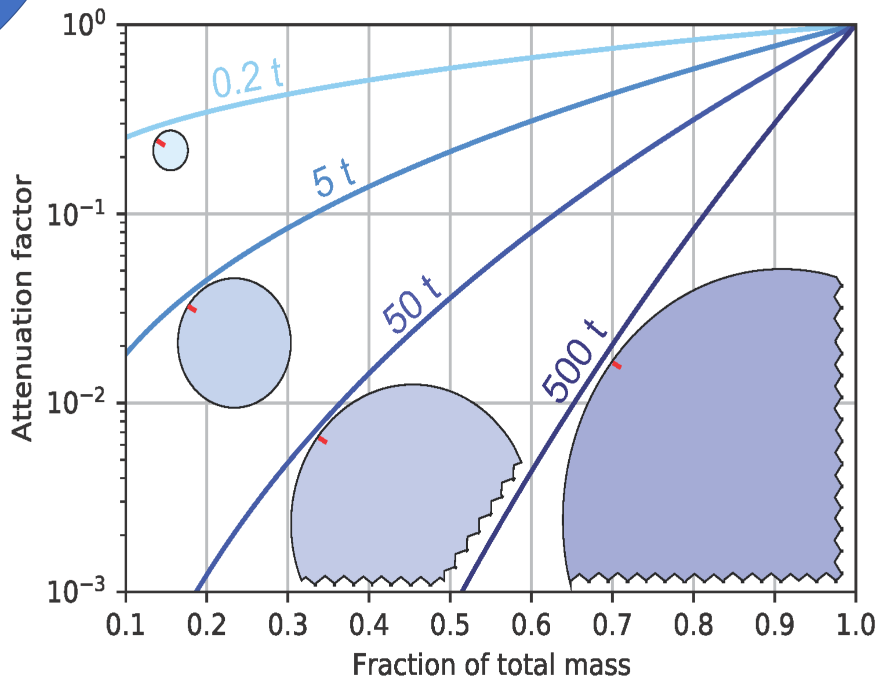
E.g: the γ-ray interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector

Monolithic, self-shielding & homogeneous detector



2.5 MeV γ attenuation length: 8.7cm = —

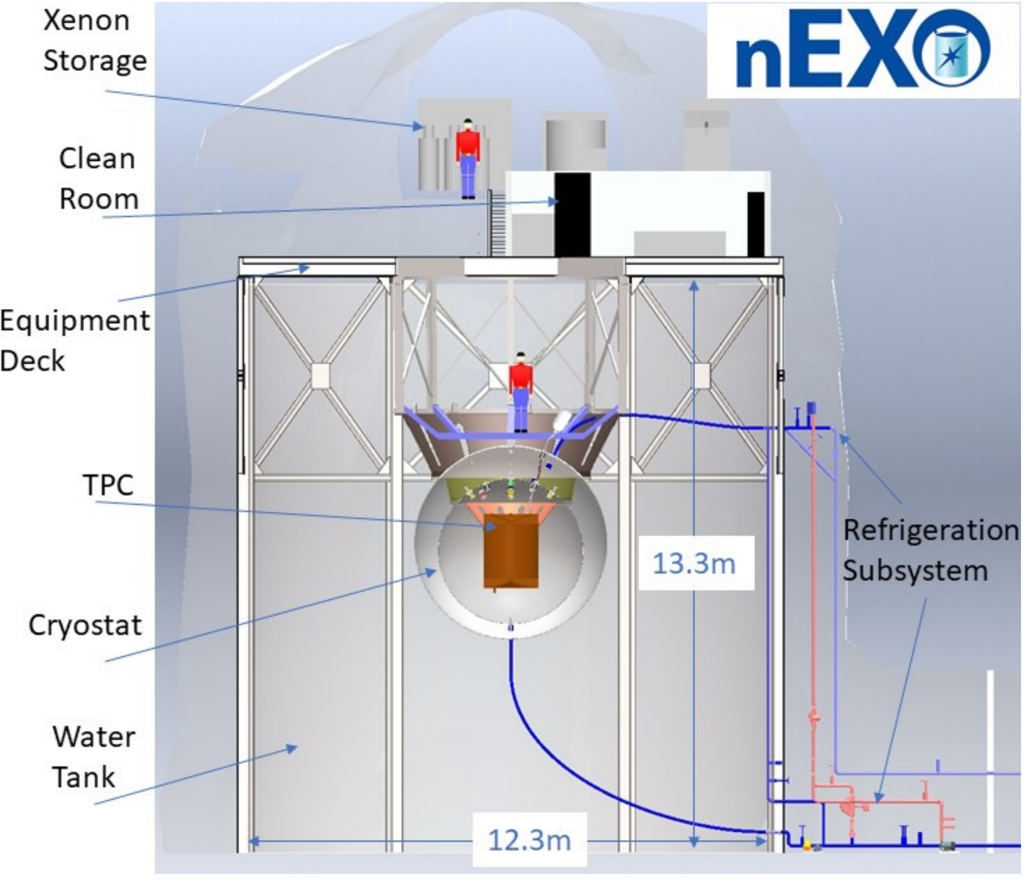
LXe mass (kg)	Diameter / length (cm)
5000	130
150	40
5	13



Advantages of LXe technology for 0νββ:

- Scalable, re-purification, transferable between detectors
- Low intrinsic background (fully exploited at the tonne scale)
- Particle ID(β/α), event topology (β/γ)
- Possibility of no-source control experiment

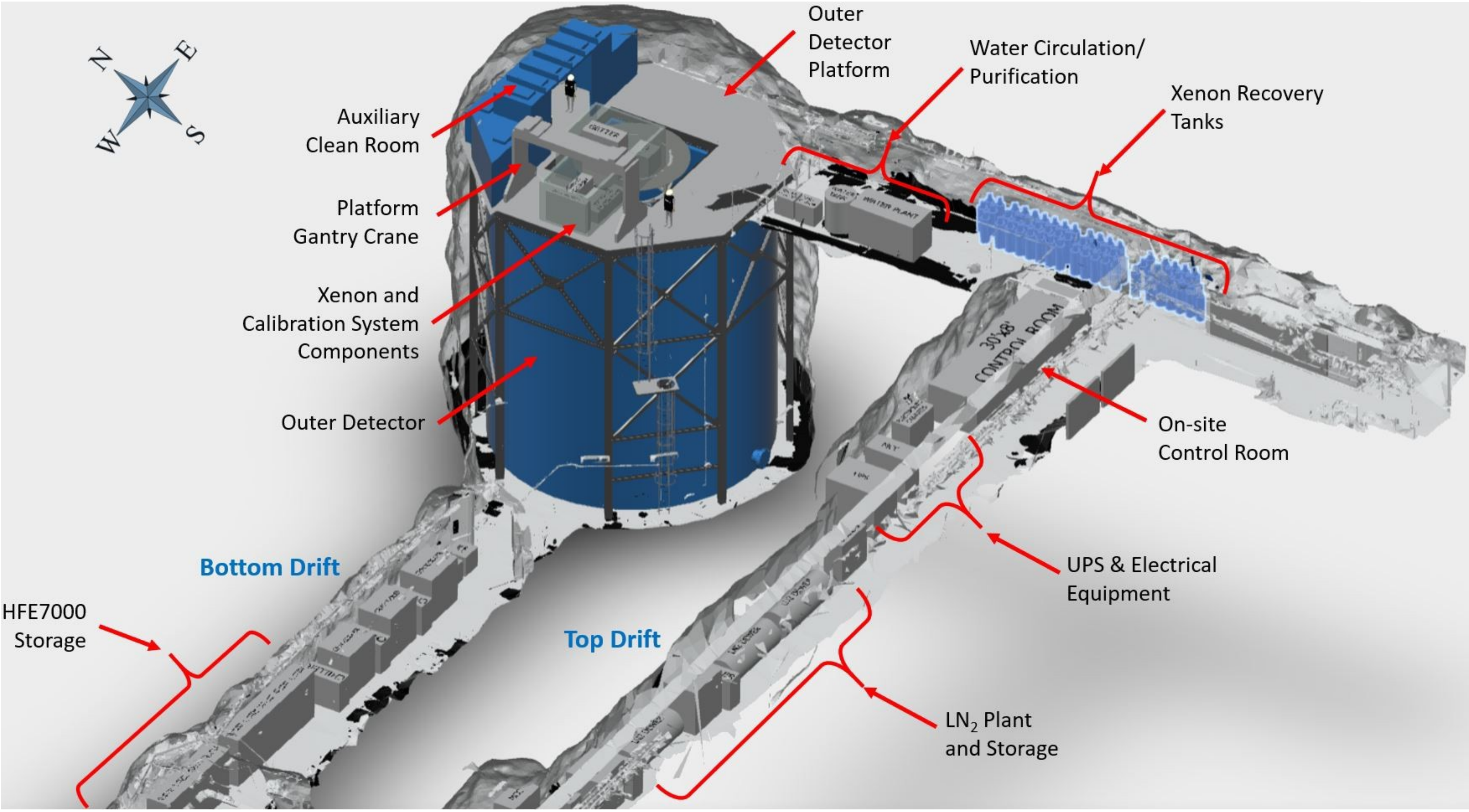
Overview of the nEXO Detector



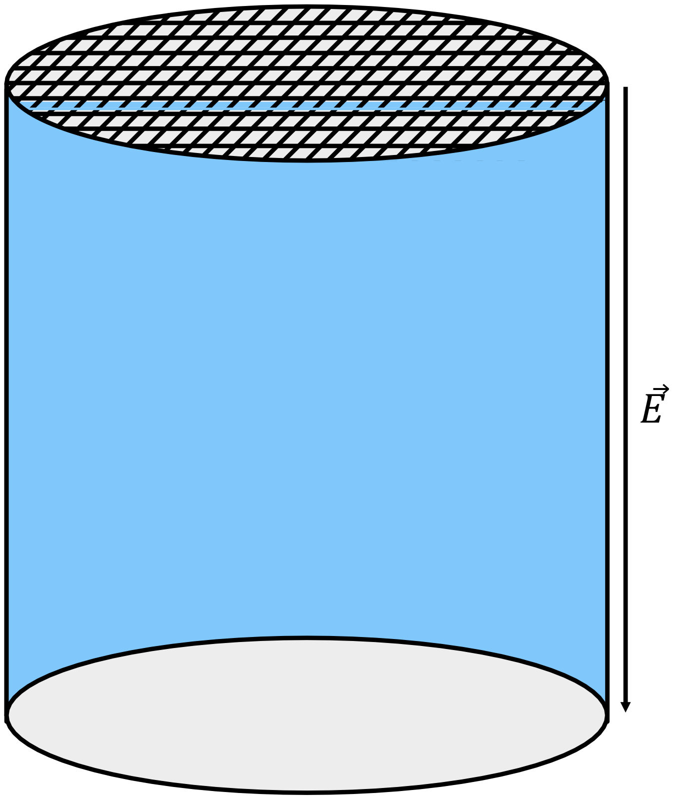
nEXO pre-conceptual Design Report
arXiv:1805.11142

- Double-walled, vacuum-insulated carbon composite cryostat
- Refrigeration via 32 tonnes of Hydro-fluoro ether (HFE) 3M Novec-7000
- Design proven with EXO-200
- HFE-7000 intrinsically ultra radio-pure
- Excellent temperature stability (~165K)
- Thermal storage in case of power loss
- Lightweight, ultra-low background Xe vessel (pressure set at the Inner Cryostat)
- Active water-Cherenkov muon veto

Conceptual layout at SNOLAB (preferred site)

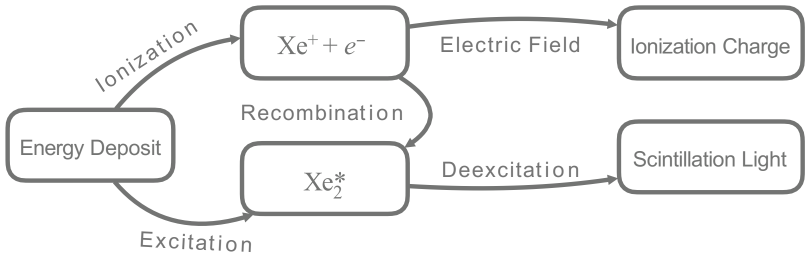


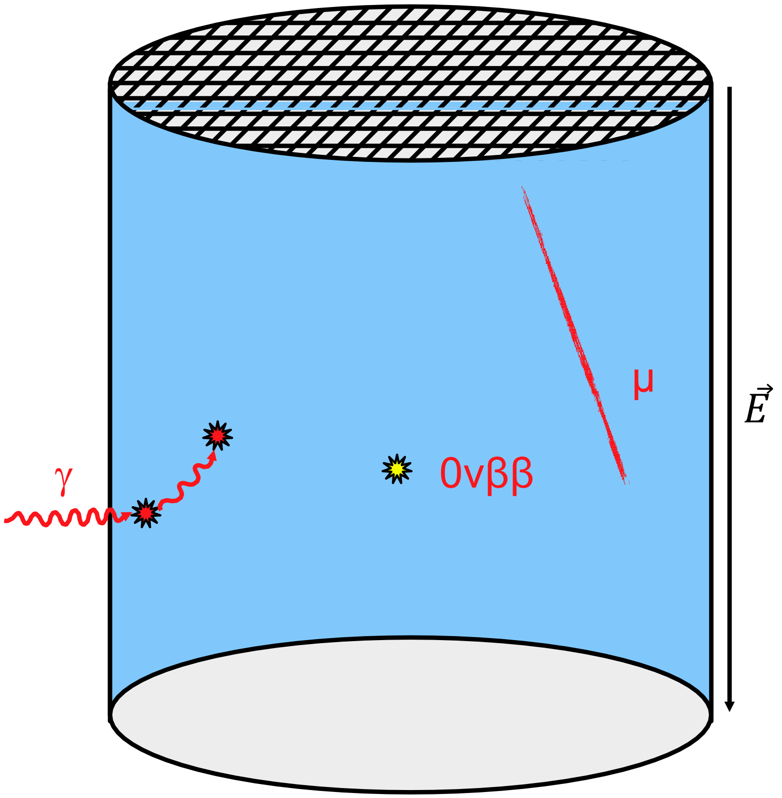
Detection in nEXO's TPC



Detection in nEXO's TPC

- Ionizing radiation will either ionize or excite Xe atoms





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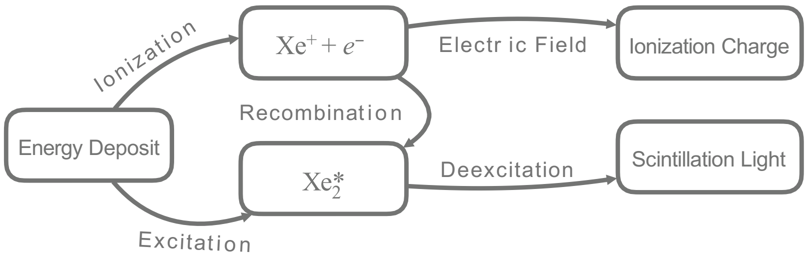
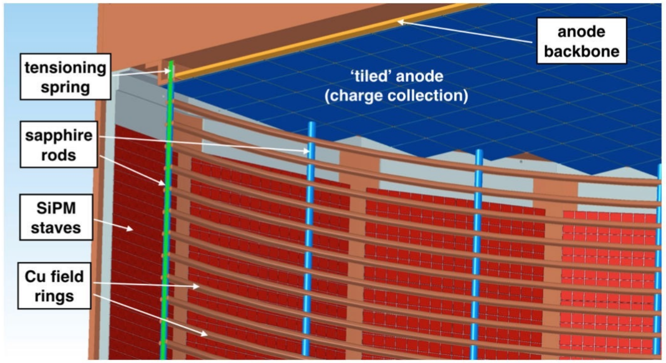
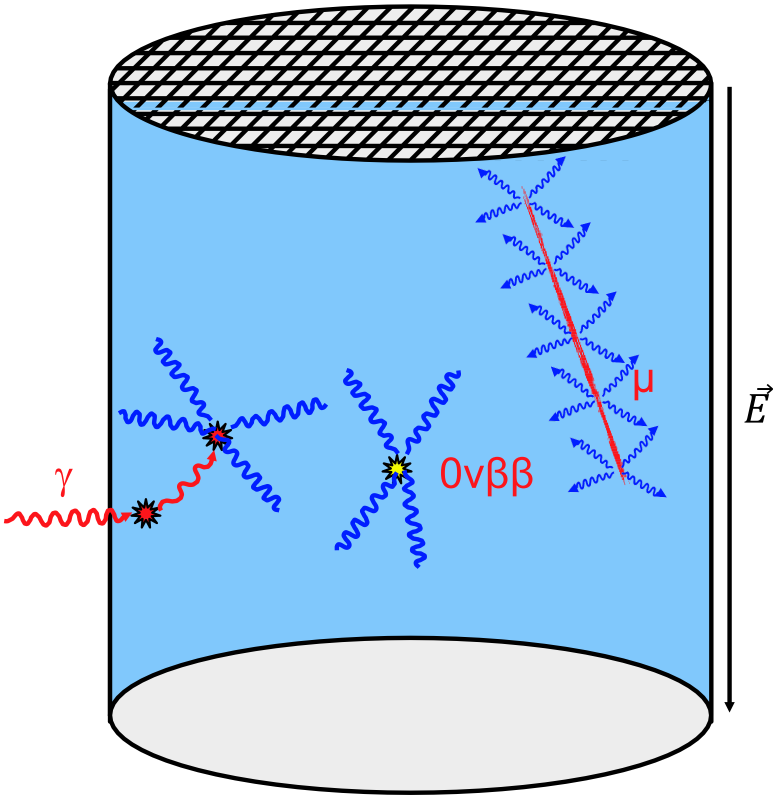


- Photons are immediately detected by the SiPMs around the barrel and provide a time stamp Ionizing





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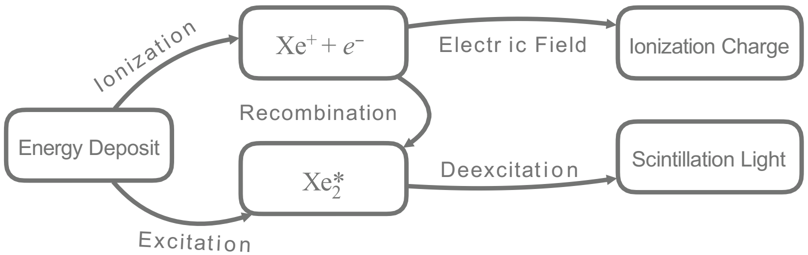
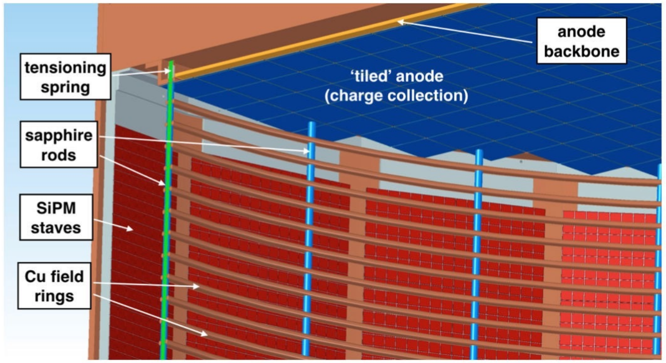
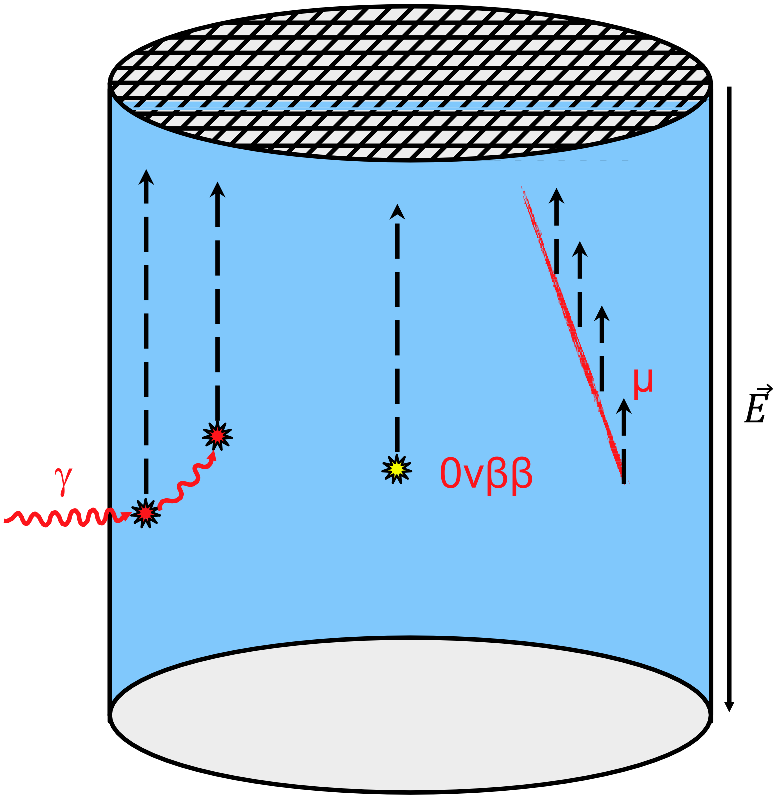


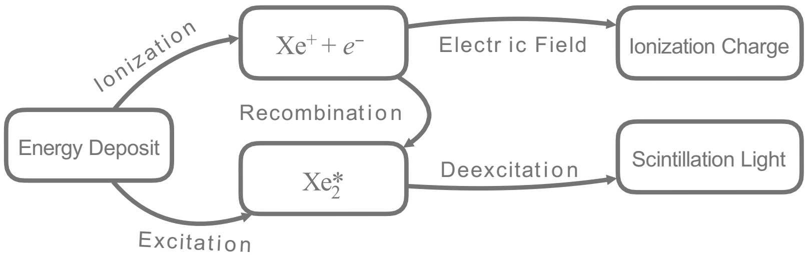
- Photons are immediately detected by the SiPMs around the barrel and provide a time stamp Ionizing
- Electrons are drifted to charge collection tiles at the top

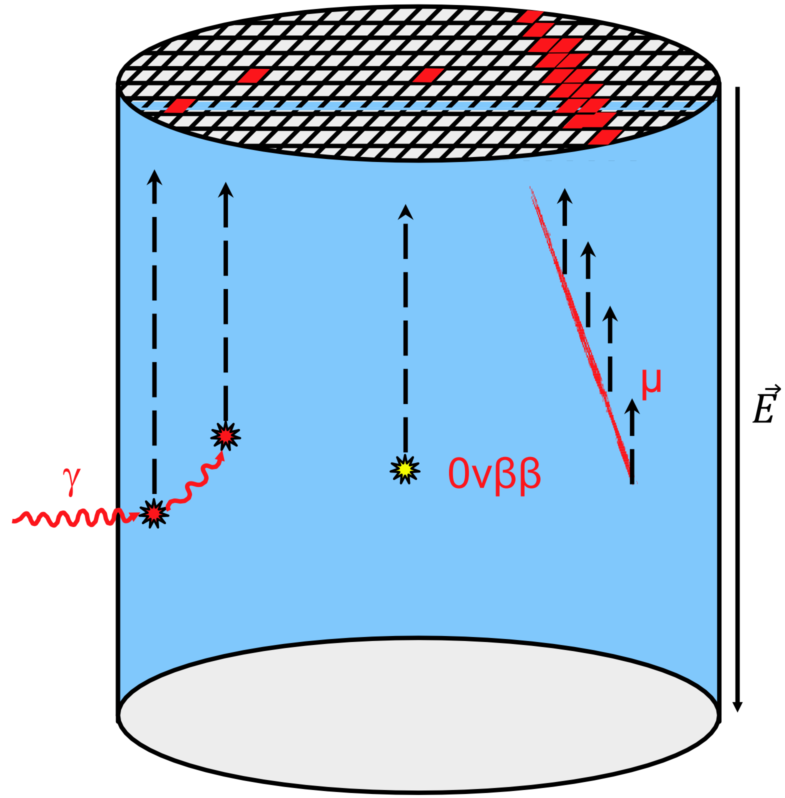




Detection in nEXO's TPC

- Ionizing radiation will either ionize or excite Xe atoms

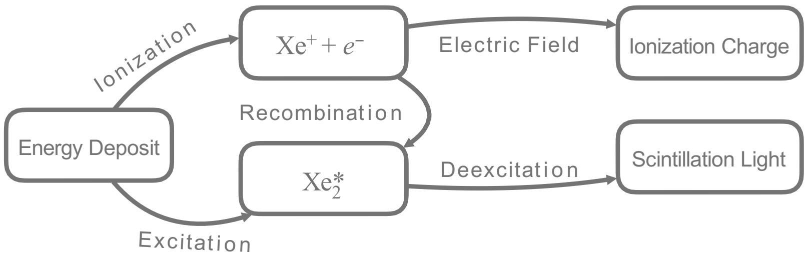




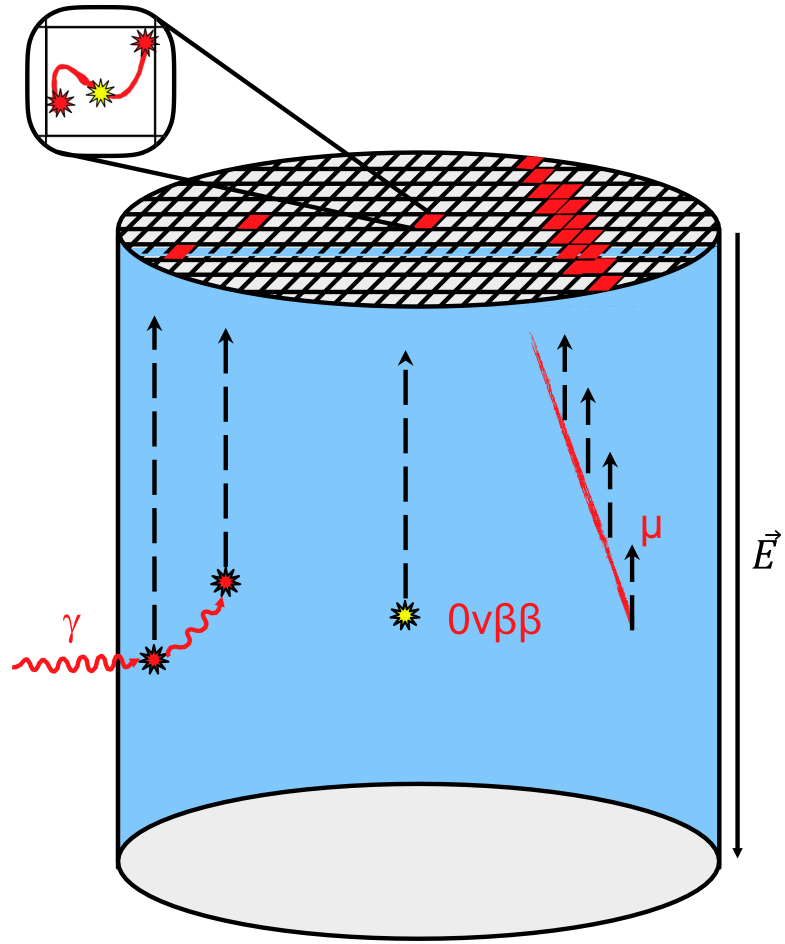
- Photons are immediately detected by the SiPMs around the barrel and provide a time stamp Ionizing
- Electrons are drifted to charge collection tiles at the top
- Charge collection tiles with 3mm pitch strips detect e-

Detection in nEXO's TPC

- Ionizing radiation will either ionize or excite Xe atoms

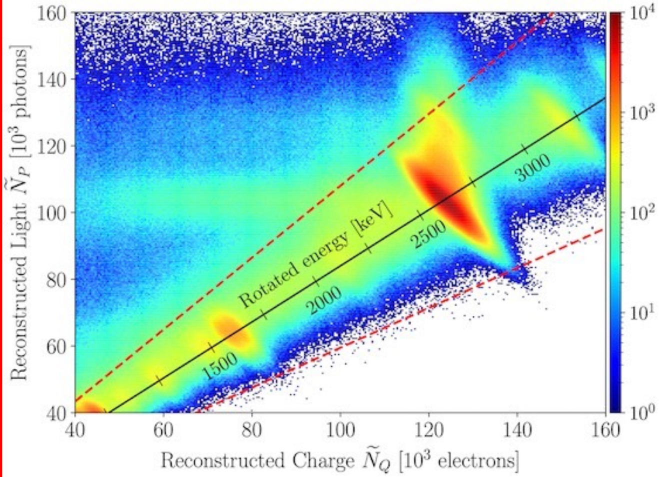


- Photons are immediately detected by the SiPMs around the barrel and provide a time stamp Ionizing
- Electrons are drifted to charge collection tiles at the top
- Charge collection tiles with 3mm pitch strips detect e-
- 0νββ charge is mostly spatially contained (unlike γ's)



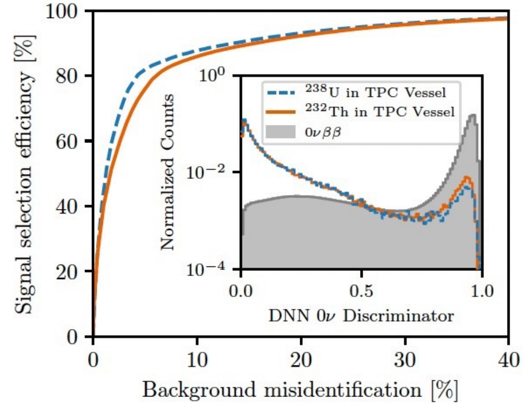
Multidimensional Event Analysis

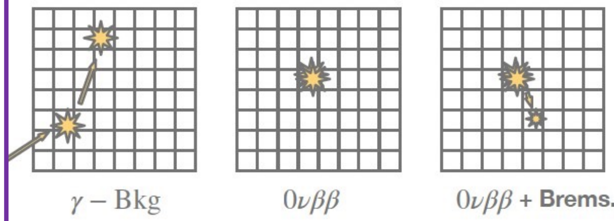
Energy



- Event-by-event anticorrelation between ionization and scintillation (known since the early EXO R&D)
- Improved energy resolution
  - expect σ/Qββ = 0.8% (1.2% with EXO-200)
- Optically open TPC field cage

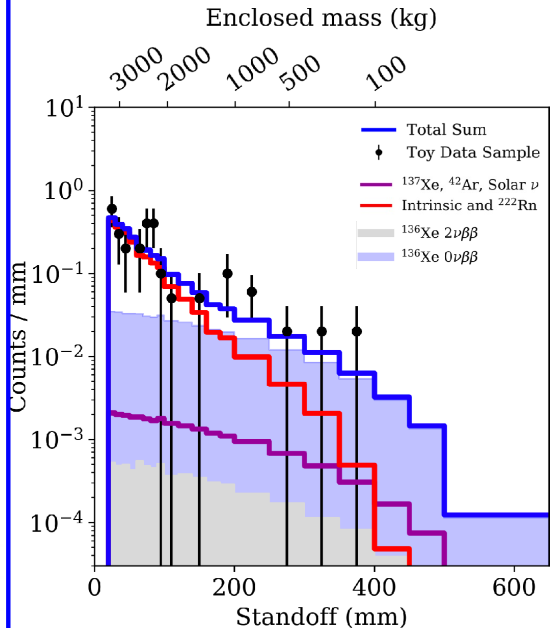
Topology





Single- vs. multisite energy depositions

Standoff Distance

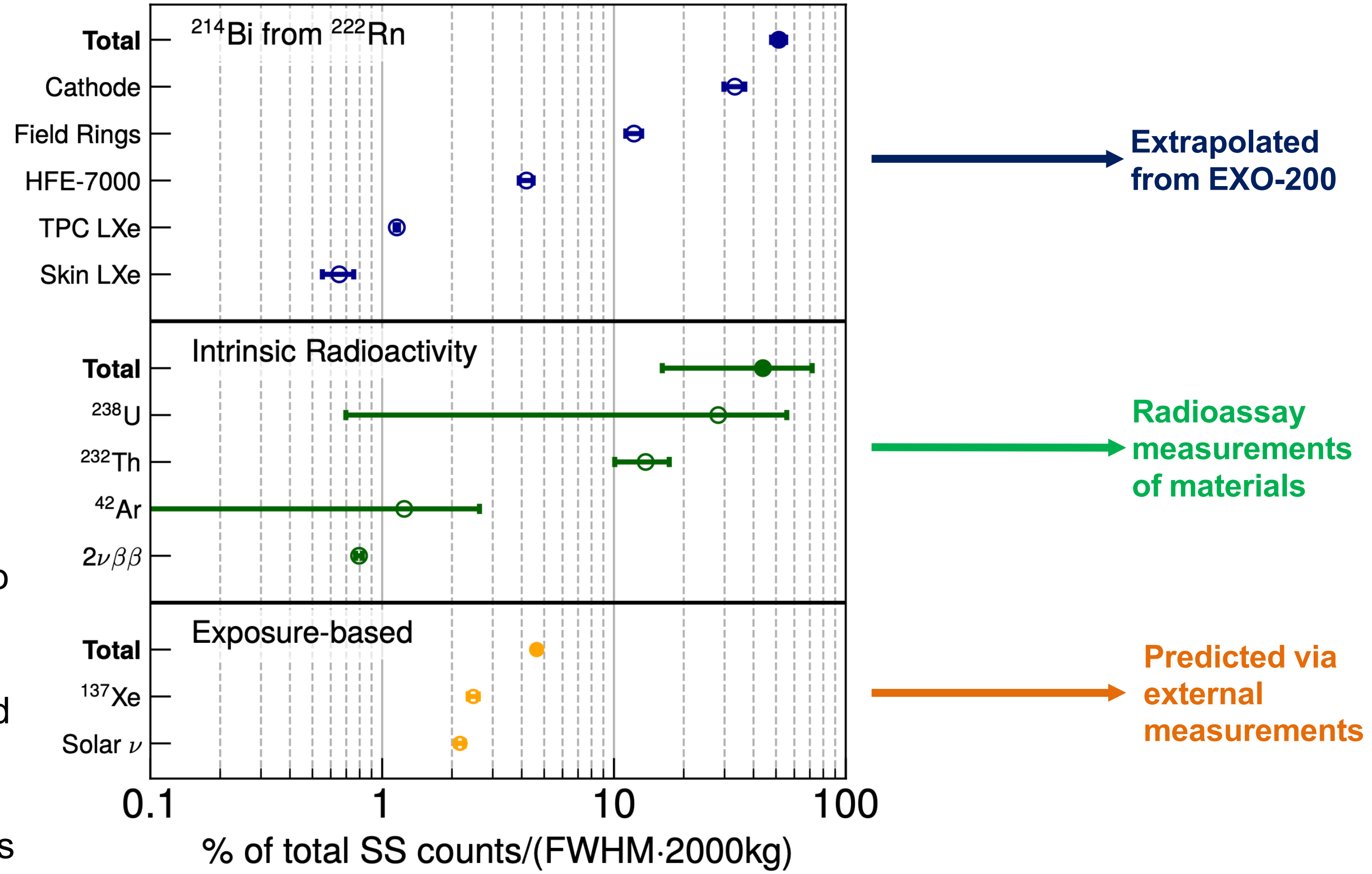


- ββ events are uniformly distributed in the LXe volume
- Most backgrounds originate from outside of the TPC

nEXO Sensitivity and Discovery Potential: J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)

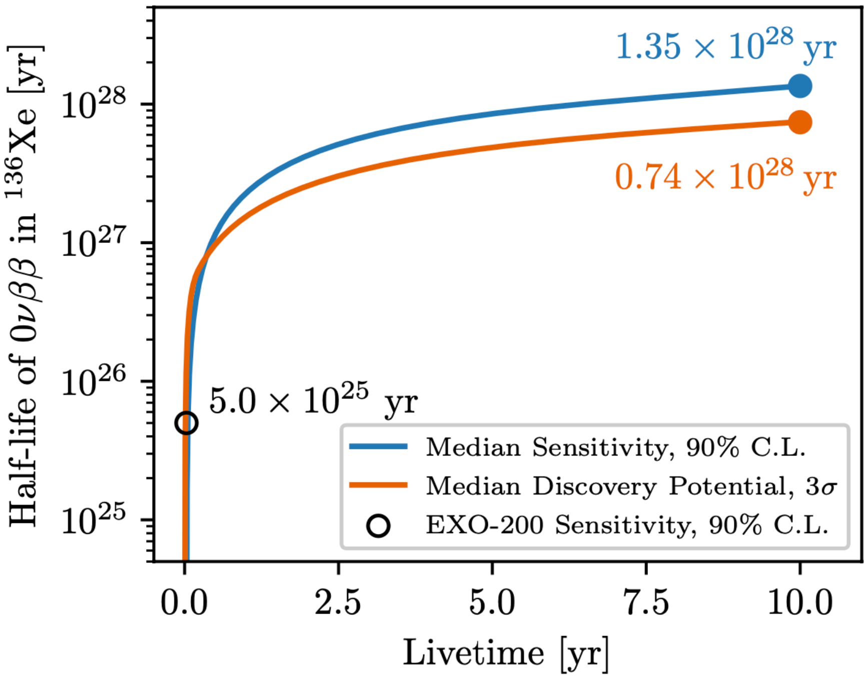
Background model

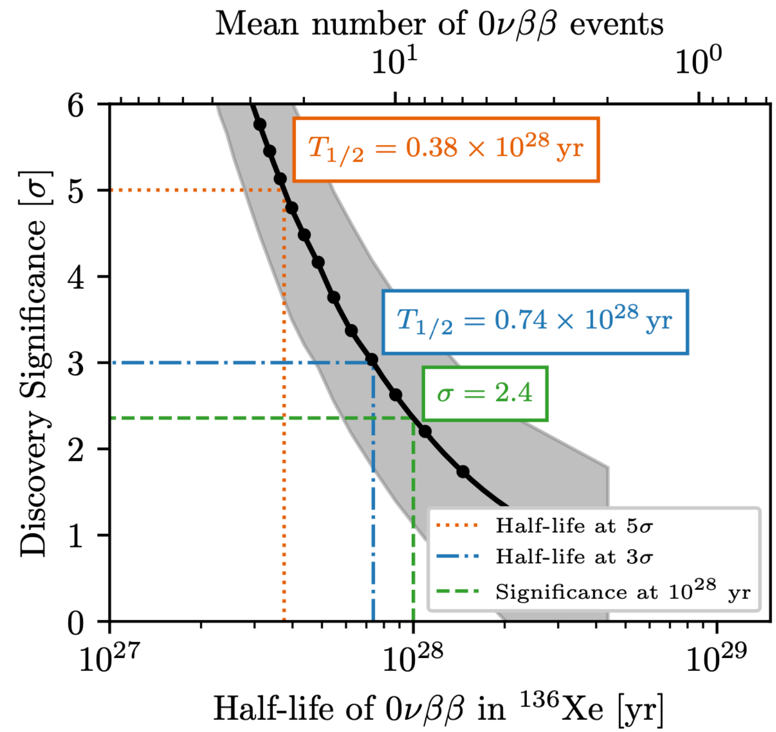
- Bottom-up estimate of background budget through extensive screening of all detector materials
- In-house electro-formed copper for some TPC components to significantly reduce intrinsic radioactivity from ^{238}U and ^{232}Th
- Ongoing R&D looking into further reduction of ^{222}Rn
- Cosmogenically produced ^{137}Xe can be vetoed with at least 70 % efficiency and negligible lifetime loss



nEXO sensitivity and discovery potencial

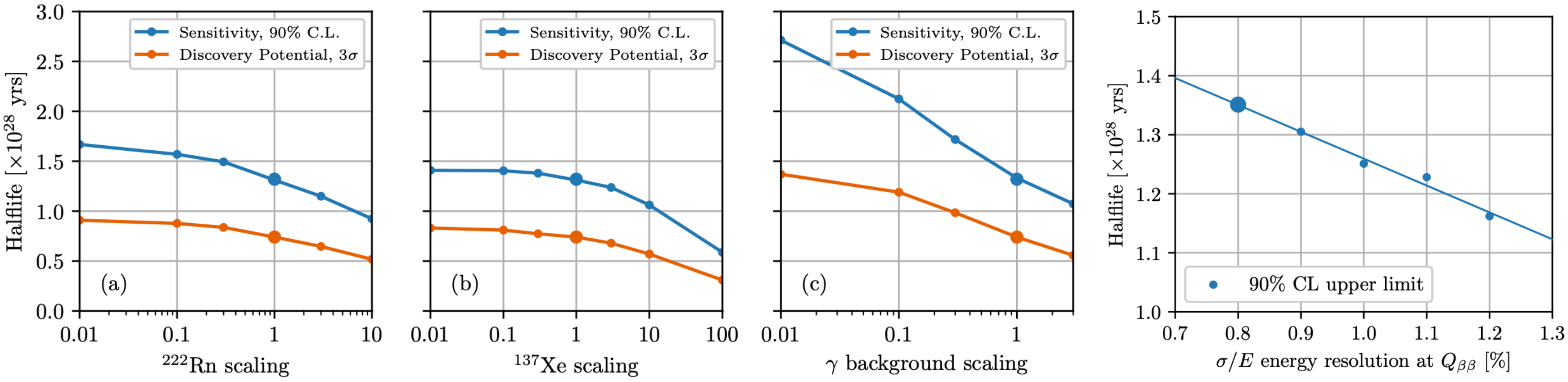
Increase by **two orders of magnitude** in half-life sensitivity over current generation experiments!





- $>10^{28}$ year sensitivity reach in 10 years
- Can provide compelling evidence of 0νββ decay discovery
- Probes $m_{\beta\beta}$~ 15 meV (model and NME dependent)

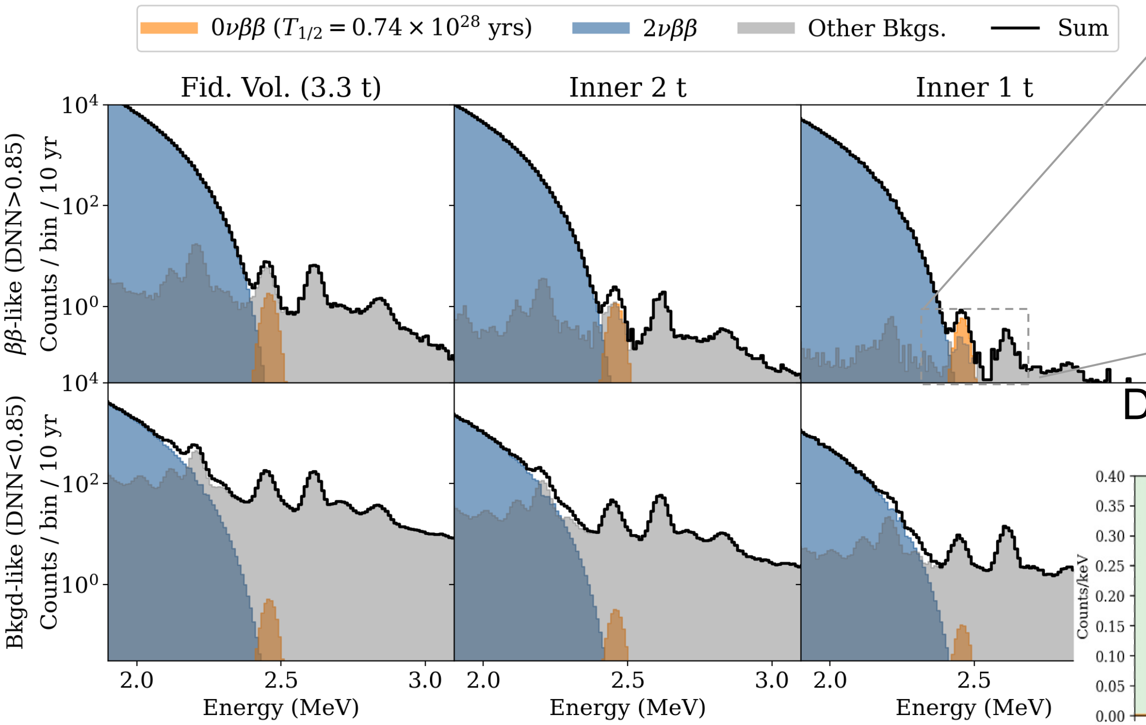
Robust background modeling

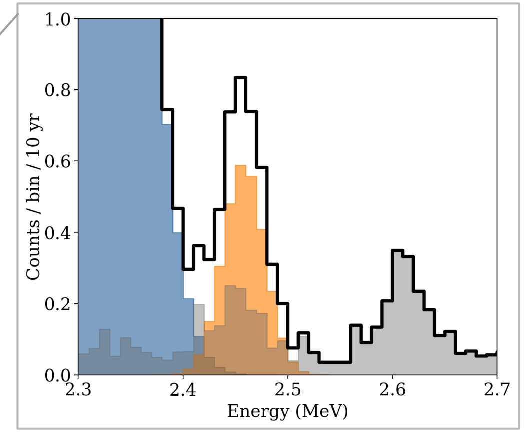


- Point design (=1)
  - ^{222}Rn: 600 atoms in steady state (EXO-200 has ~200)
    - ^{137}Xe: 0.85x10^{-3} atoms/kg/year
- Good data/MC agreement was demonstrated with EXO-200
- nEXO sensitivity is robust against background mis-estimations

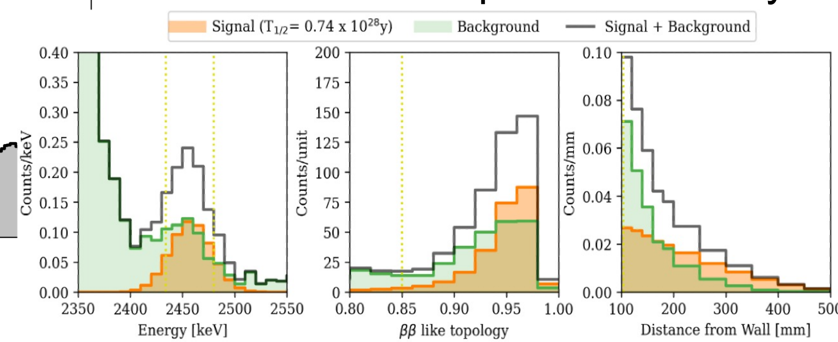
Sensitivity – tonnes scale $0\nu\beta\beta$

Traditional cut-based analysis example:





Distributions for multi-parameter analysis:



- nEXO sensitivity results from a powerful combination of energy resolution, event topology, and self-shielding. Multi-parameter analysis also makes the measurement robust against any currently unknown backgrounds.
- Since there is no internal passive materials, any unknown gamma lines give a very clear reading in the multi-site channel.

Neutrino mass sensitivity

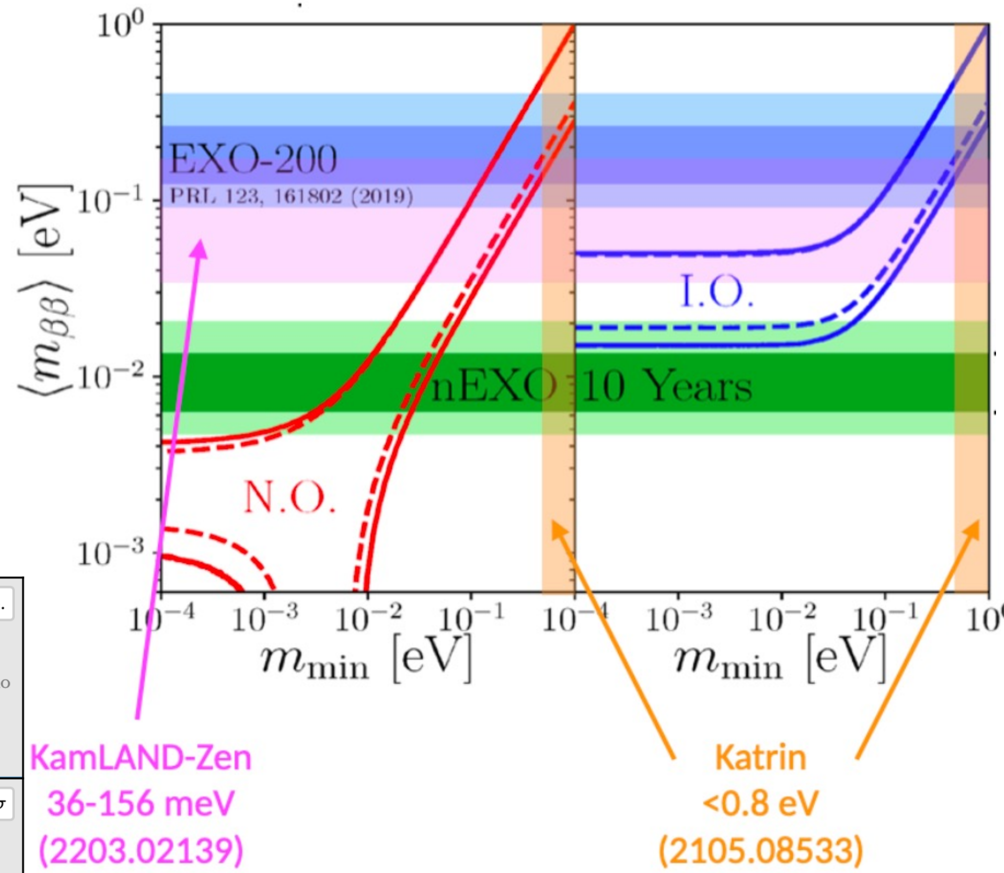
Phase-space factor
J. Kotila and F. Iachello, Phys Rev C 85, 034316 (2012)

Axial coupling
$g_A = 1.27$

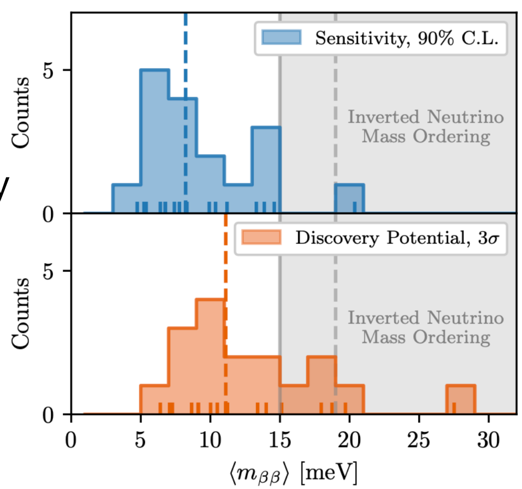
$$\frac{1}{T^0_{1/2}} = \frac{< m_{\beta\beta} >^2}{m_e^2} G^{0\nu} g_A^4 \left|\mathcal{M}^{0\nu}\right|^2$$

Nuclear Matrix Element

nEXO exclusion sensitivity (90% CL)



- Agnotic approach: show all published NMEs
- nEXO 3σ discovery sensitivity for the median NME is 11.1 meV (I.O. tested)

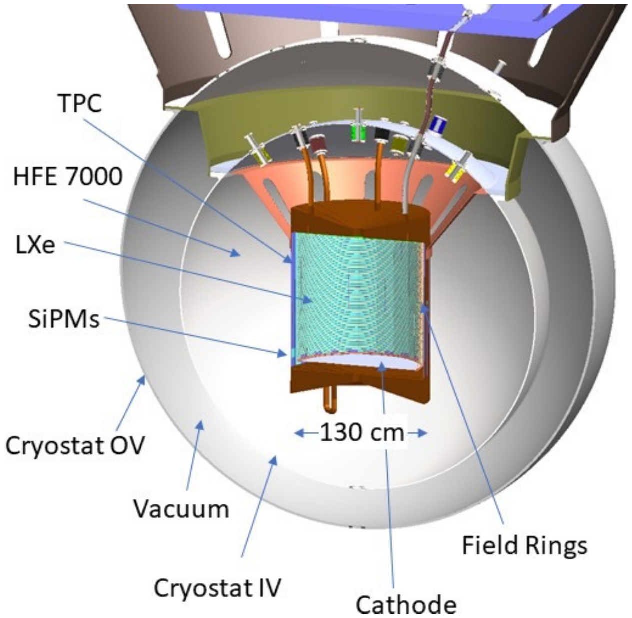


Outlook

- nEXO utilizes a tonne-scale LXe TPC to search for $0\nu\beta\beta$ in 136 Xe
  - Low intrinsic and well-understood background
  - Good energy resolution
  - Powerful background discrimination using multi-variate analysis
  - Robust background model, powerful background discrimination
  - Capability for running a control experiment with natXe
  - Benefits from and contributes to rapid evolution of LXe technology

- nEXO will explore beyond the current 0nbb decay sensitivity 100-fold
  - Are neutrinos their own antiparticles?
  - Origin of neutrino mass
  - Matter/antimatter asymmetry

The nEXO detector: an evolution from EXO-200



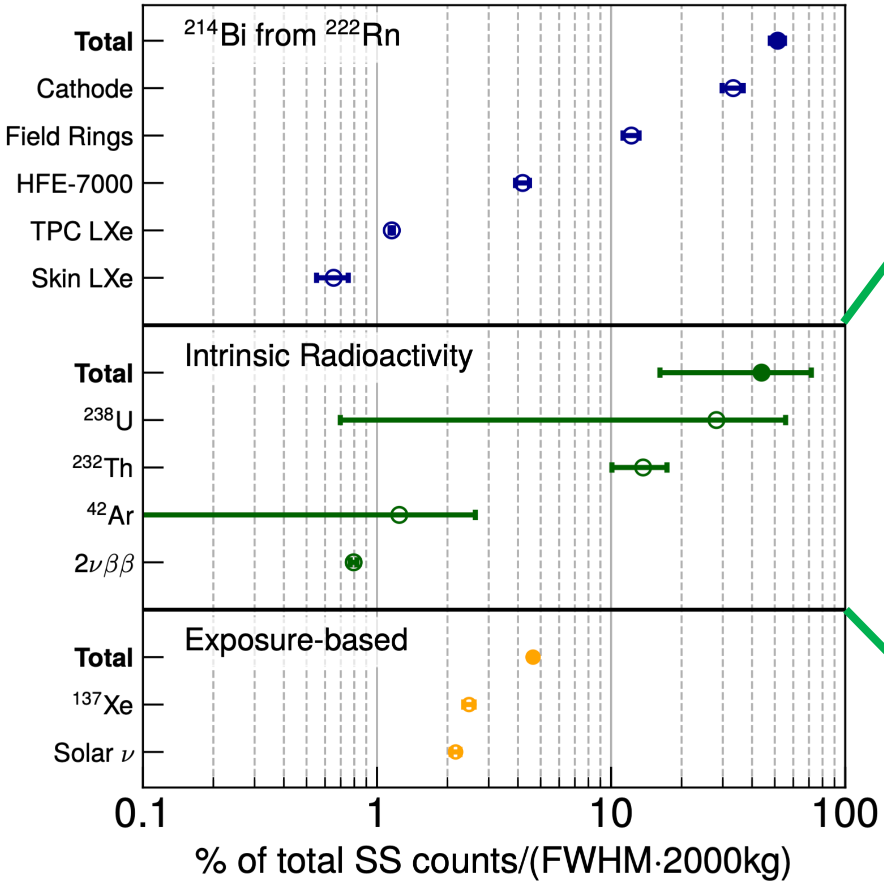
	EXO-200:	nEXO:	Improvements:
Vessel and cryostat	Thin-walled commercia Cu w/HFE	Thin-walled electroformed Cu w/H E	Lower background
High voltage	Max voltage: 25 kV (end-of-run)	Operating voltage: 50 kV	Full scale parts tested in LXe prior to installation to minimize risk
Cables	Cu clad polyimide (analog)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

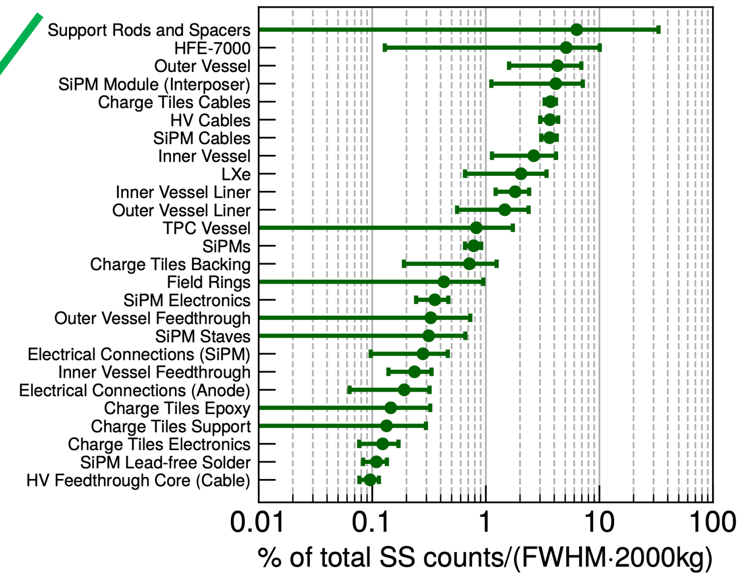
5000 kg of 90%-enriched LXe
Single 120 cm dri volume; 130 cm
diameter Drift E- Field ~400 V/cm

Ionization electrons collected on charge detectors at the anode (no gain), ~6,000 channels

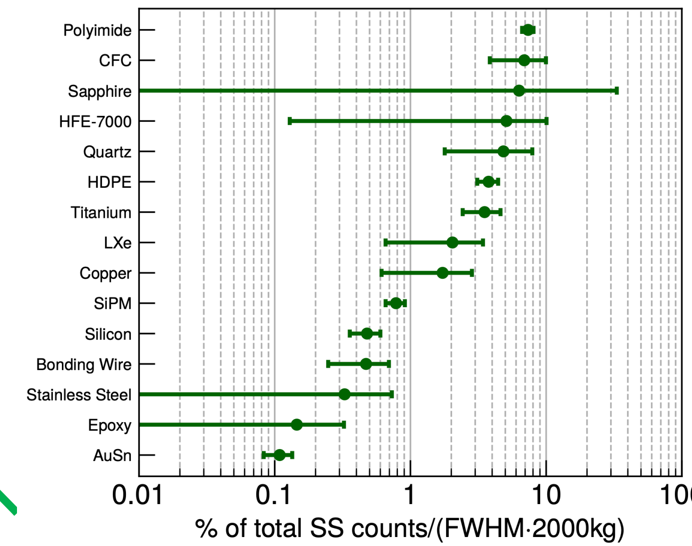
VUV (178 nm) scintillation light is detected by a large array of SiPMs (~45,000 devices, ~4.5 m2)

Background model





Radioassay measurements of materials

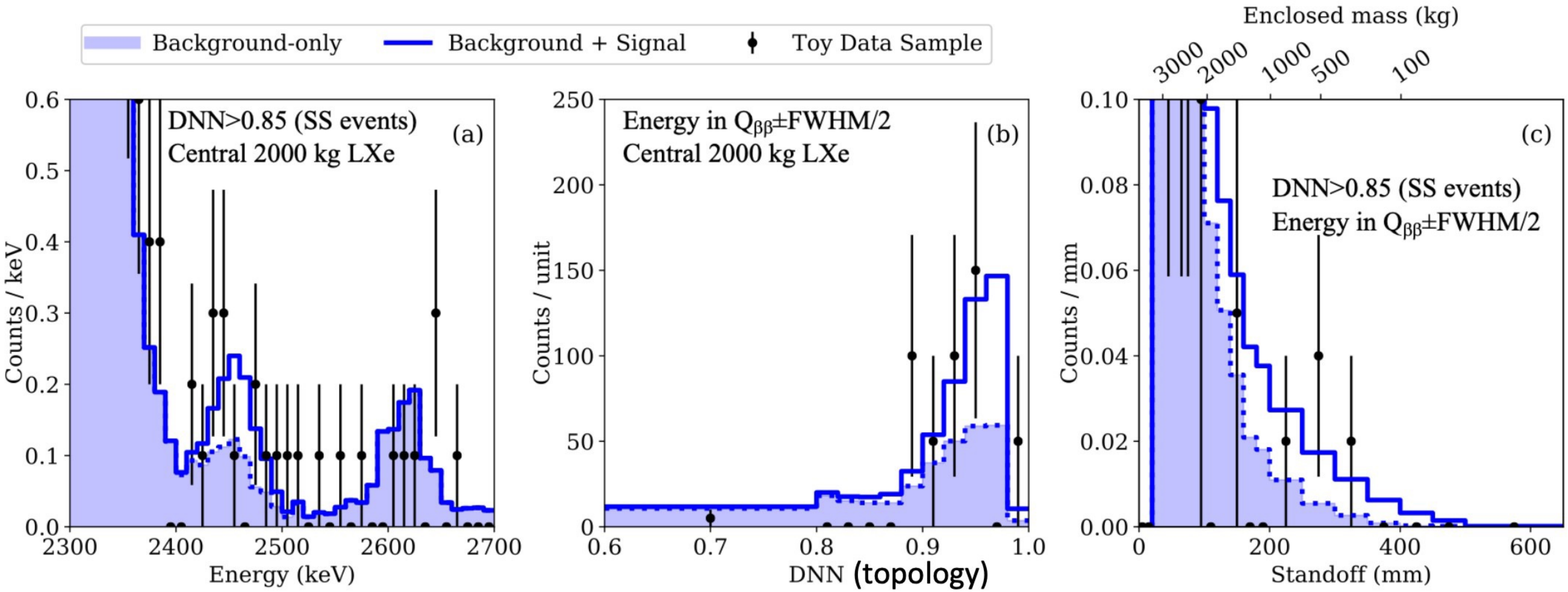


Detection in nEXO's TPC

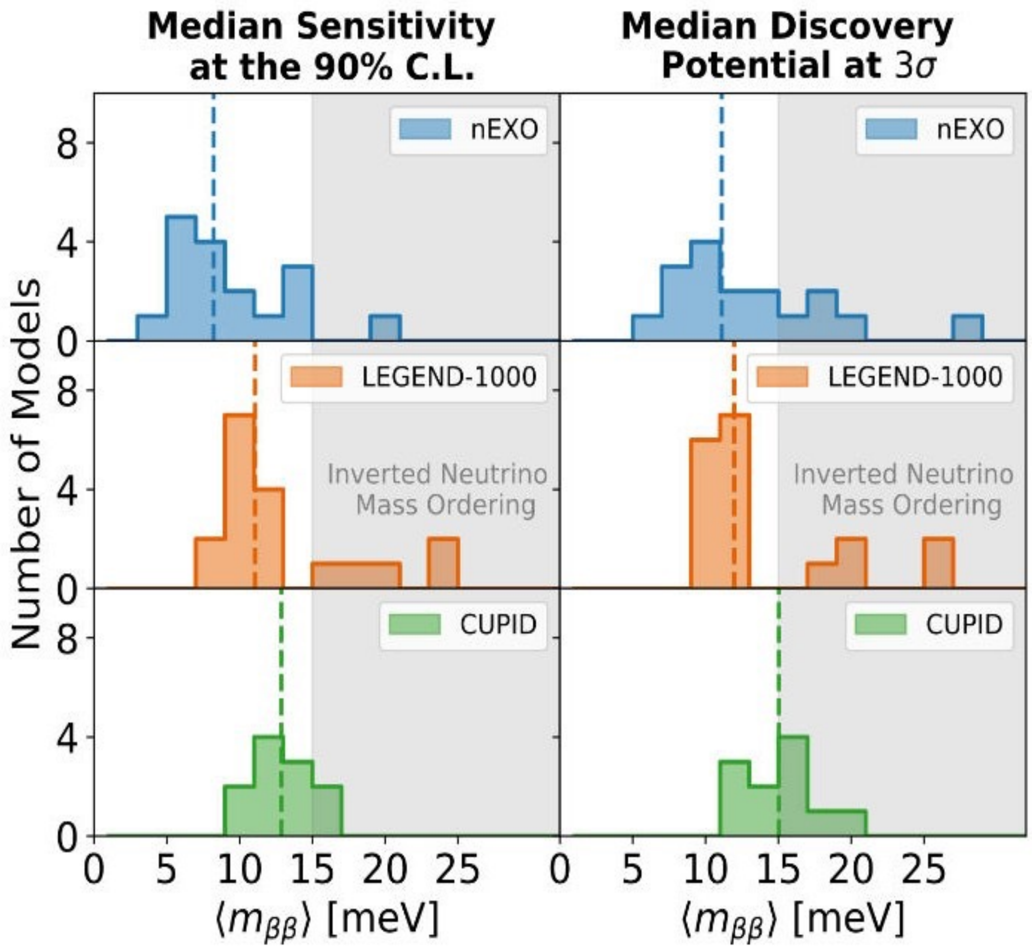
- Simulated $0\nu\beta\beta$ signal strength at $T_{1/2} = 0.74 \times 10^{28}$ yr

- Possible to run control experiment with depleted xenon to confirm discovery!

Region of Interest:
- $E \in Q_{\beta\beta} \pm$ FWHM/2
- DNN > 0.85 (signal-like events)
- Innermost 2 tonnes of LXe (Standoff > 20 mm)



Sensitivity – tonnes scale $0\nu\beta\beta$



NMEs values don't follow a statistical distribution. Only a single value is true. However, calculations are difficult and have large uncertainties