The nEXO neutrinoless double beta decay experiment

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Lake Louise Winter Institute 2022
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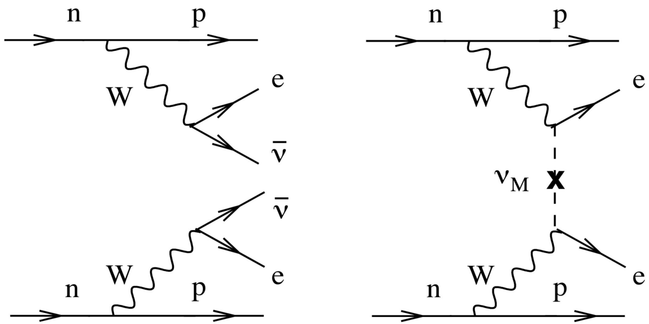
nEXO

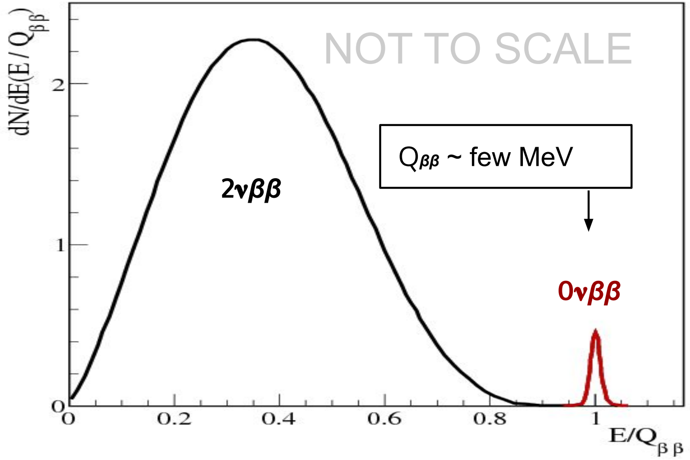
Searching for new physics via 0νββ

0νββ decay is a powerful probe of physics beyond the standard model:

- Majorana nature of neutrino ($\nu = \bar{\nu}$?)
- Lepton number violation
- Connections to absolute neutrino mass scale, matter/antimatter asymmetry



Avignone, Elliott, & Engel *Rev. Mod. Phys.* **80** (2008)



L. Winslow, *JINST* **7** 2012

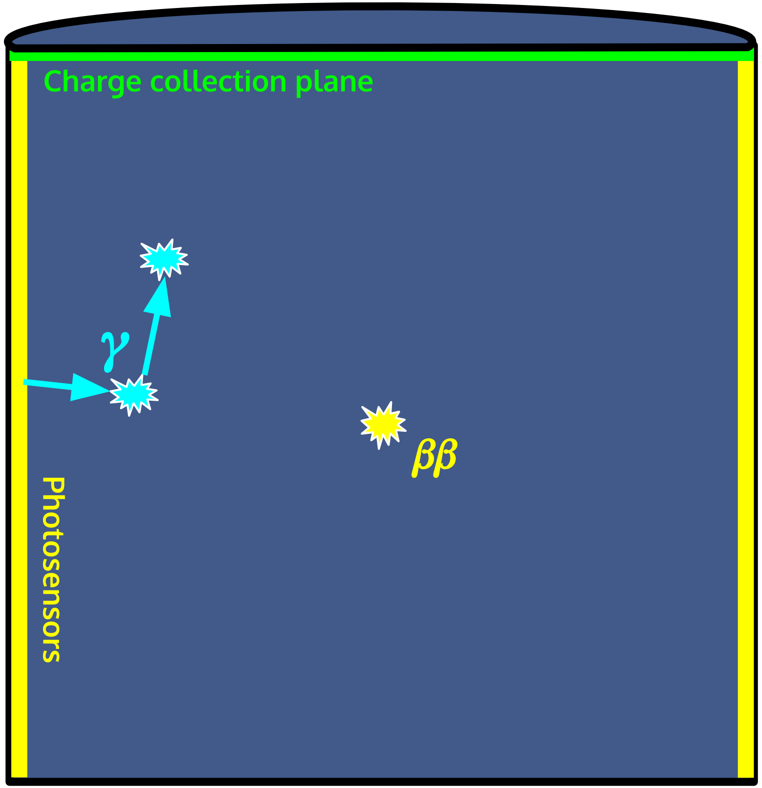
Current $T_{1/2}$ limits: >10^{26} years!

Requirements for next-gen 0νββ experiments:

- O(1) tonne of the isotope of interest (>10^{27} atoms)
- Ultra-low radioactivity detector(s)
- Strong signal/background discrimination
- Good energy resolution

The nEXO collaboration

Liquid xenon TPCs for next-gen 0νββ



A LOT of the ββ isotope (^{136}Xe)

- Ton-scale LXe TPCs are already operating for DM
- Enrichment is straightforward

Low, well-characterized backgrounds in MeV range (low radioactivity)

- Low intrinsic backgrounds & excellent self-shielding

Good energy resolution

- Combining charge and light can reach <1%

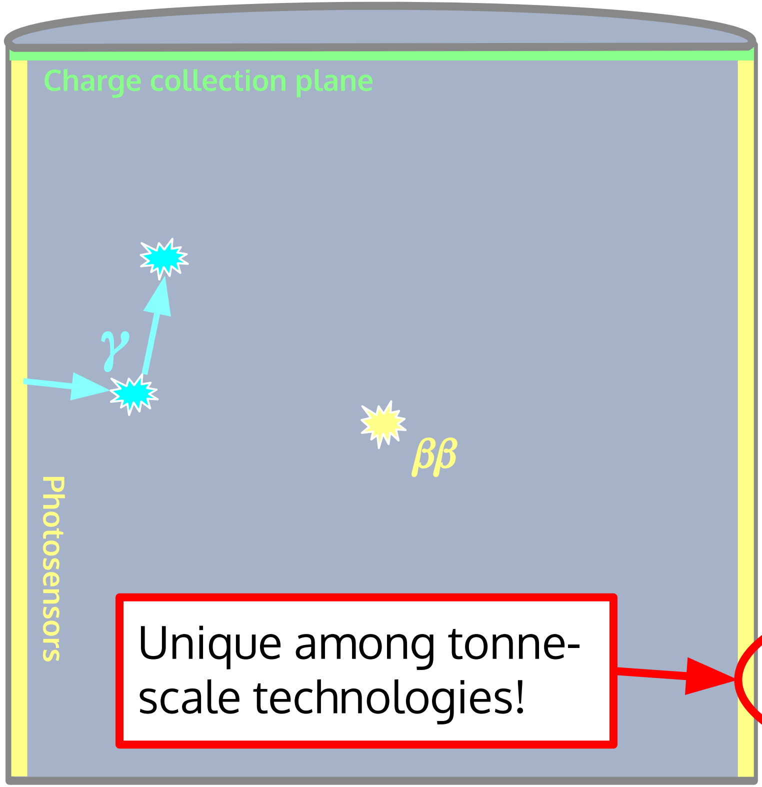
Signal/background discrimination

- Powerful position reconstruction and multi-site rejection to characterize and reject BG

Possibility of a control experiment

- Can run with both enriched and depleted xenon to confirm a discovery

Addressing the challenges for next-gen 0νββ



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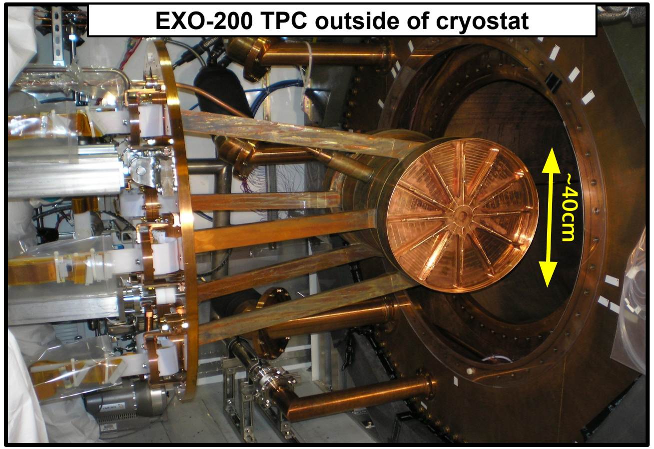
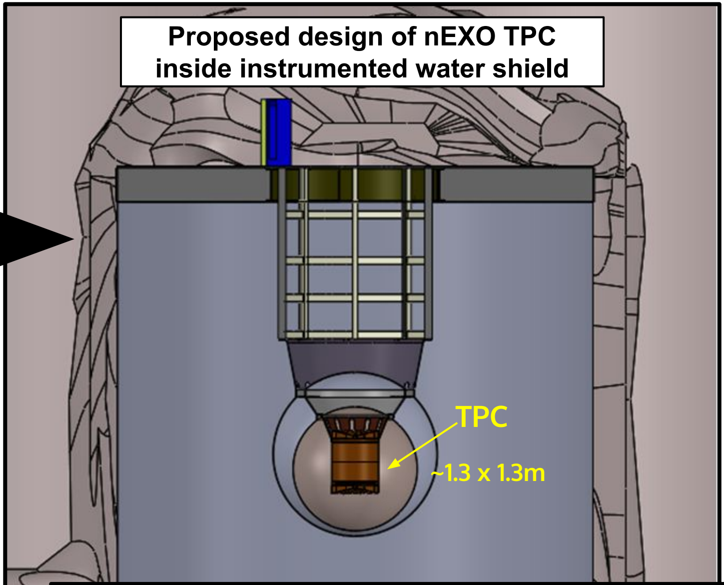
Scaling up from EXO-200 to nEXO





EXO-200: 2011 - 2018

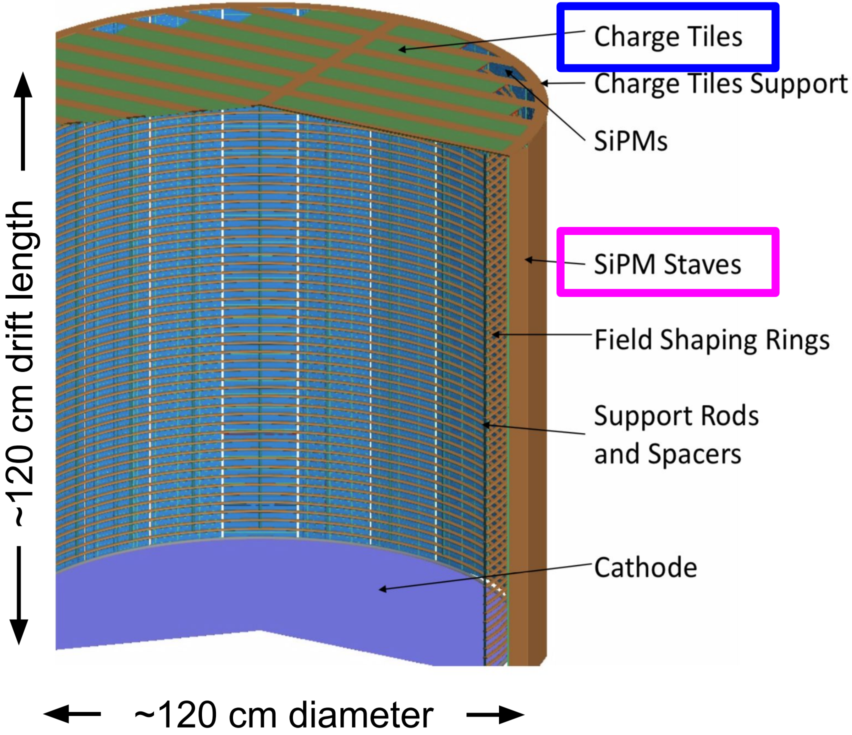
- First 100kg-class 0νββ search
- Discovered 2νββ in ^{136}Xe
- $T_{1/2} > 3.5 \times 10^{25}$ yr for 0νββ in ^{136}Xe (*PRL* **123**, 2019)
- Multiple leading limits on other decay modes of ^{136}Xe and ^{134}Xe
- Pioneered ultra-low-background LXe TPC technology

nEXO:

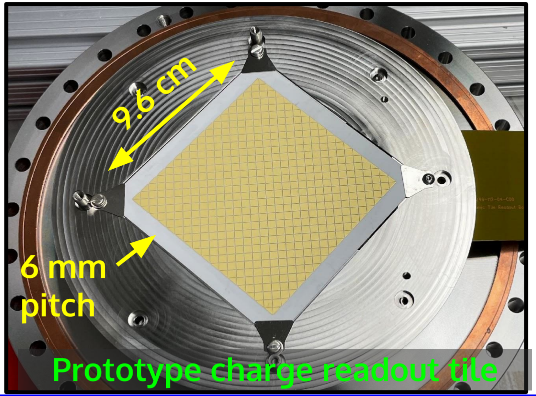
- **More ^{136}Xe:** 200 kg -> 5000 kg
- **More shielding:** >10x10m active water shield
- **Larger overburden:** 2000m underground
- **Upgraded instrumentation:** SiPMs for light, new "tiles" for charge, all with cold electronics

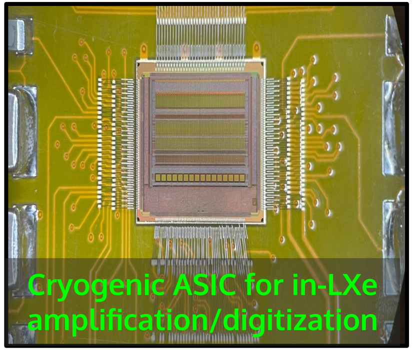
Major ongoing R&D: instrumentation

The nEXO TPC

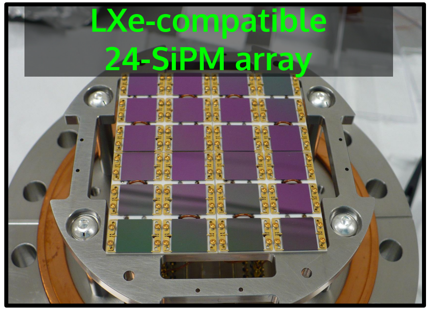


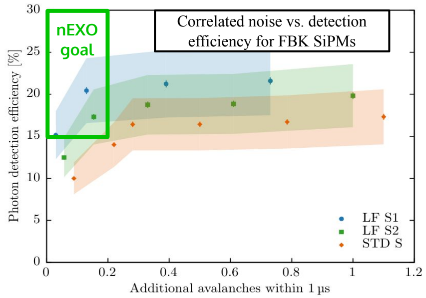
Charge sensing with modular tiles and cold electronics





~4.5 m^2 array of VUV silicon photomultipliers (SiPMs)

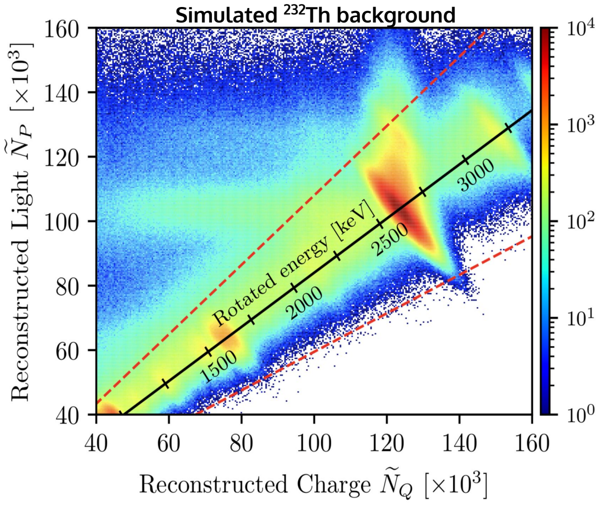




Multi-parameter background rejection

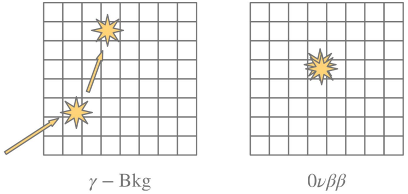
Energy

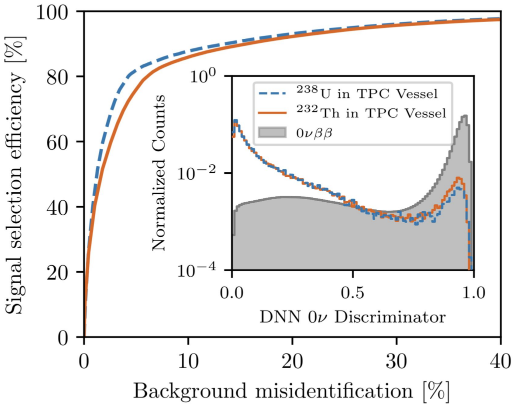
Reconstructed as sum of scintillation photons and ionization electrons: $E = W\,(N_{ph} + N_e)$



3D event topology

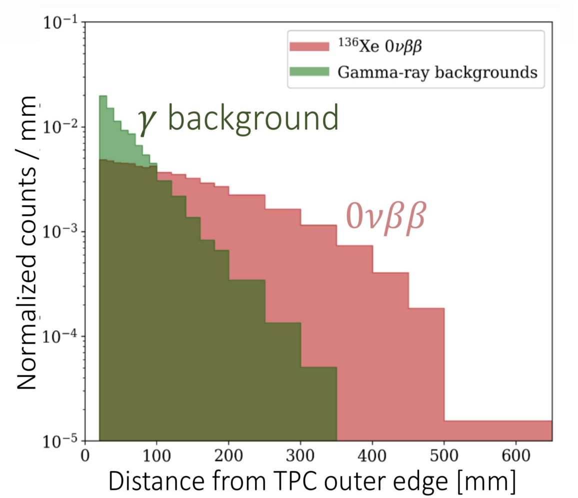
Discrimination between single-site (ββ-like) and multi-site (γ-like) events, enhanced by deep neural net



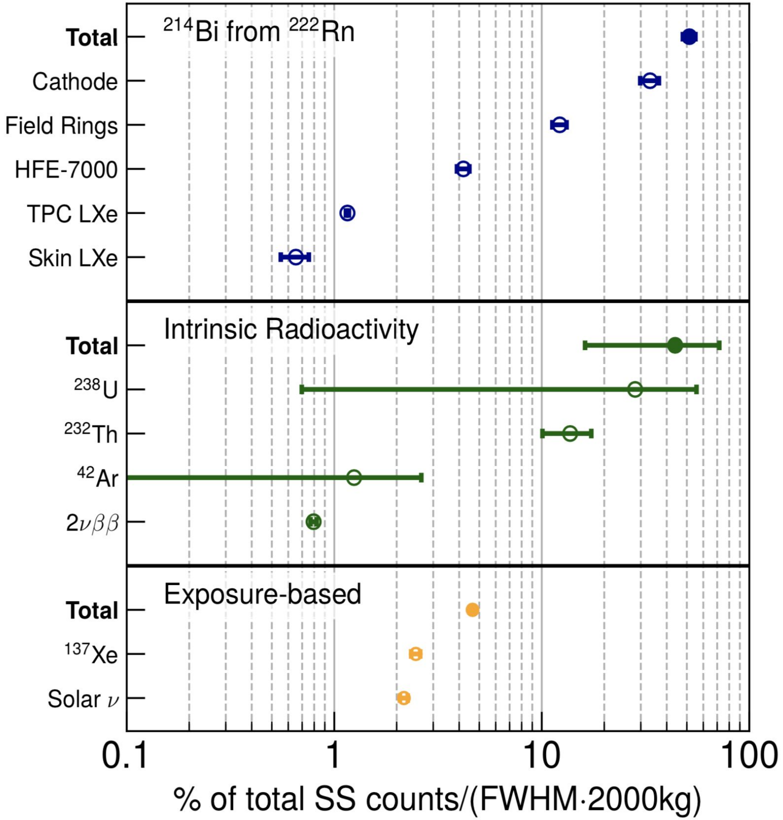


Standoff distance

Self-shielding of liquid xenon reduces backgrounds in central region of detector



Data-driven background modeling

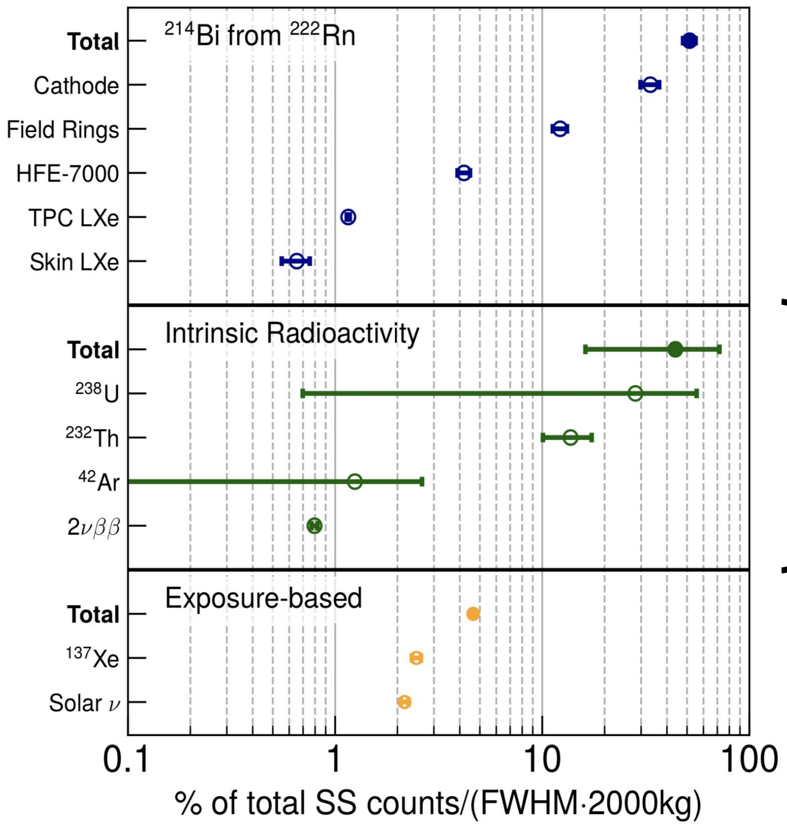


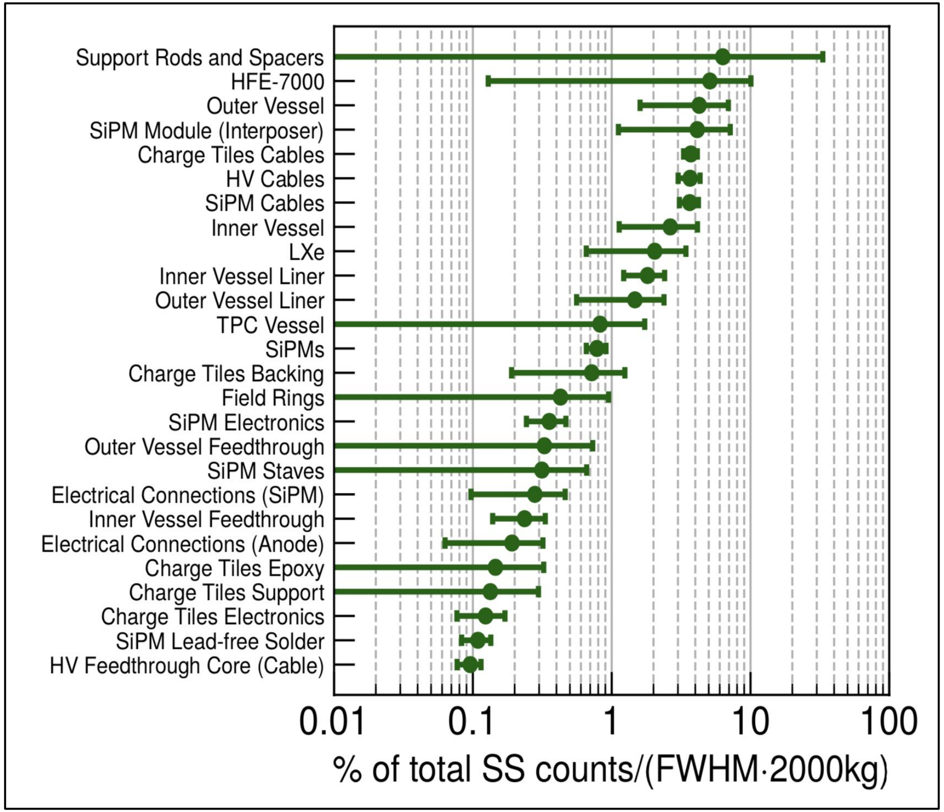
Extrapolated from EXO-200

Radioassay measurements of materials

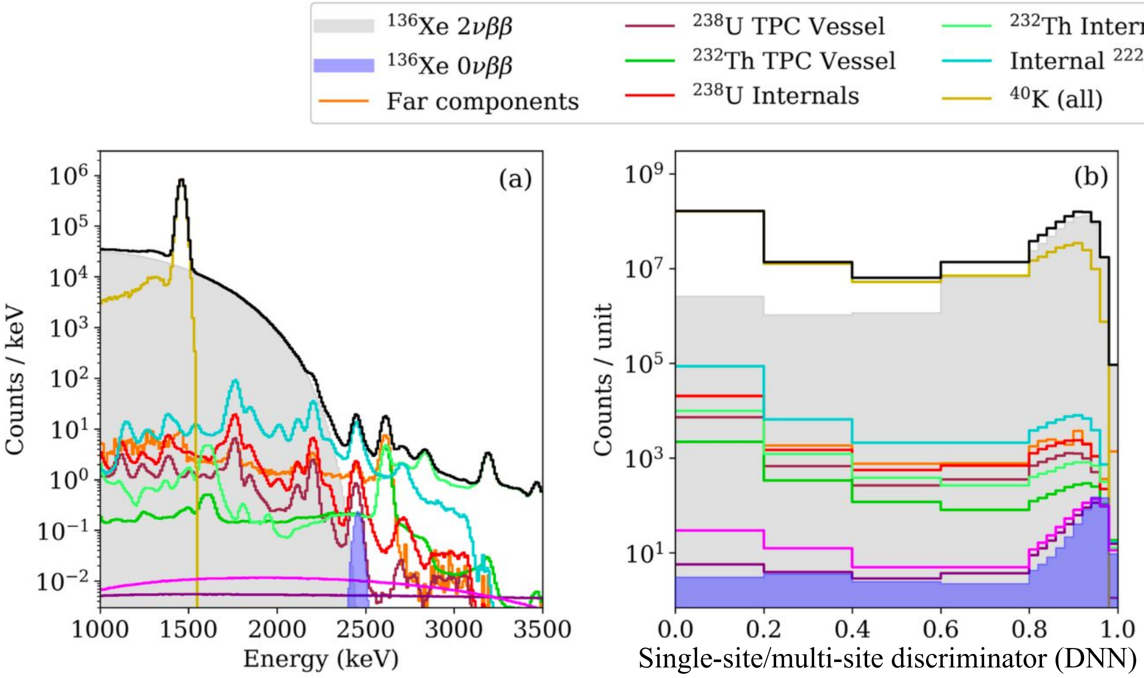
Predicted via external measurements

Data-driven background modeling





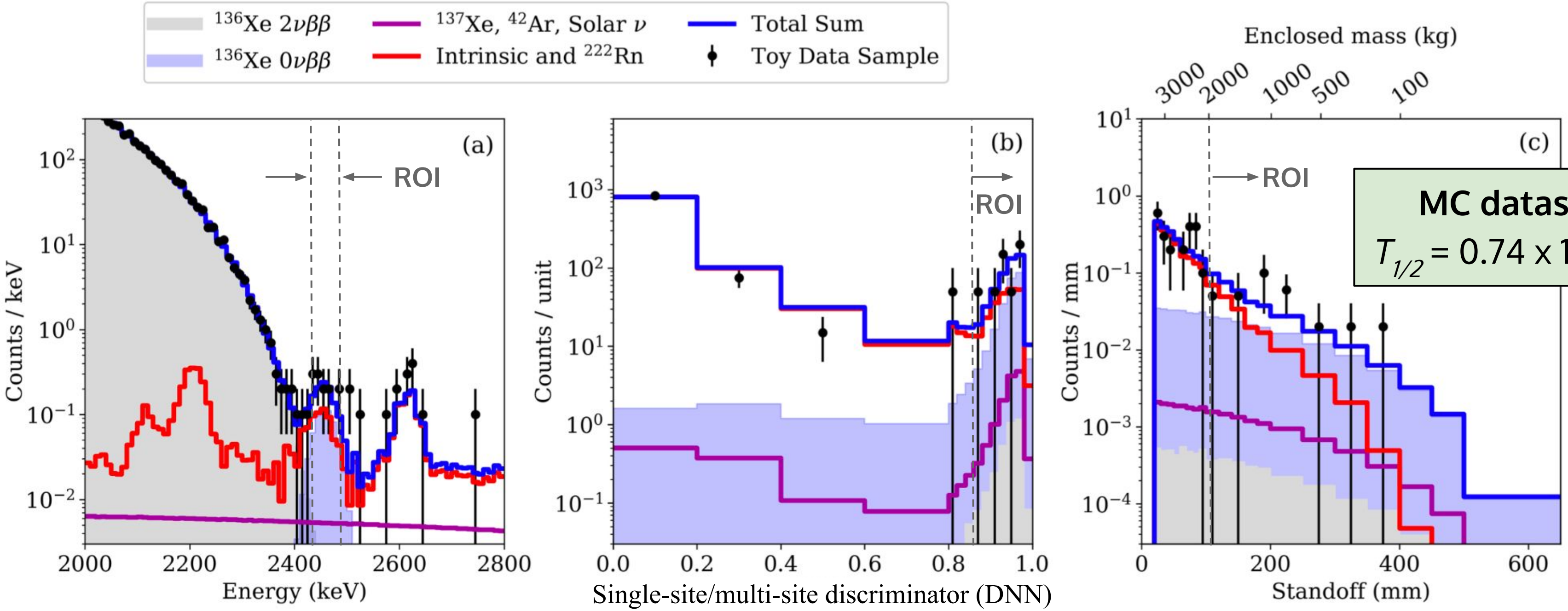
Projected event distributions in nEXO



Event distributions in "region of interest" (ROI)

nEXO's ROI is defined as:

- Energy within 0$\nu\beta\beta$ FWHM
- DNN > 0.85 ("single-site" events)
- Innermost 2 tonnes of liquid Xe (cut on standoff)

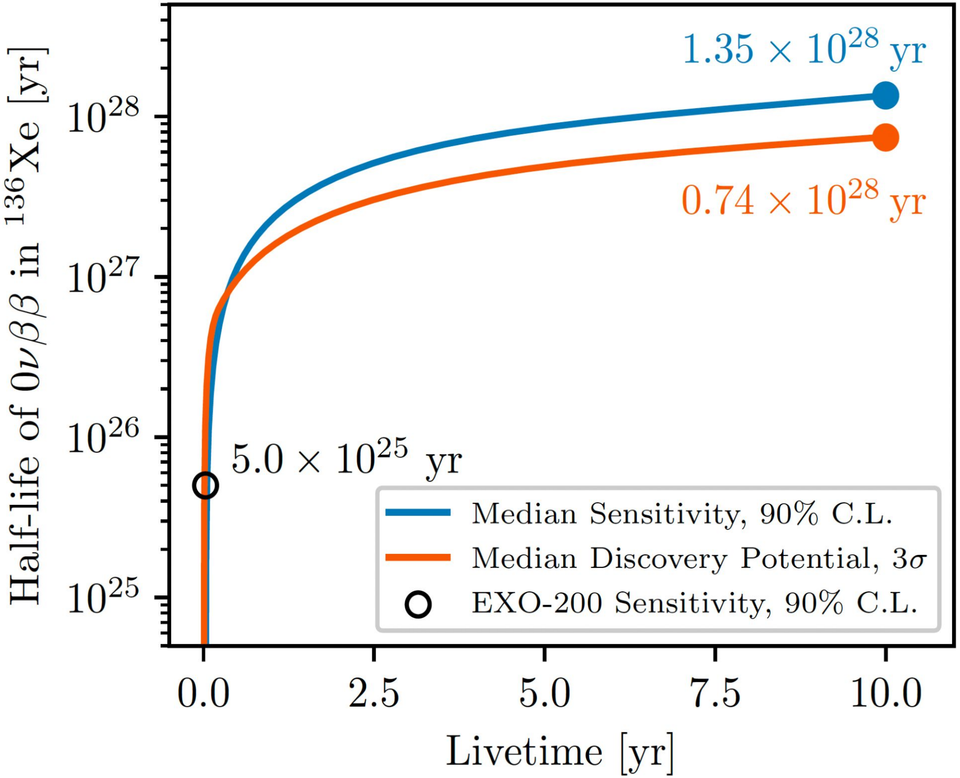


MC dataset:

$T_{1/2} = 0.74 \times 10^{28}$ yr

nEXO's sensitivity

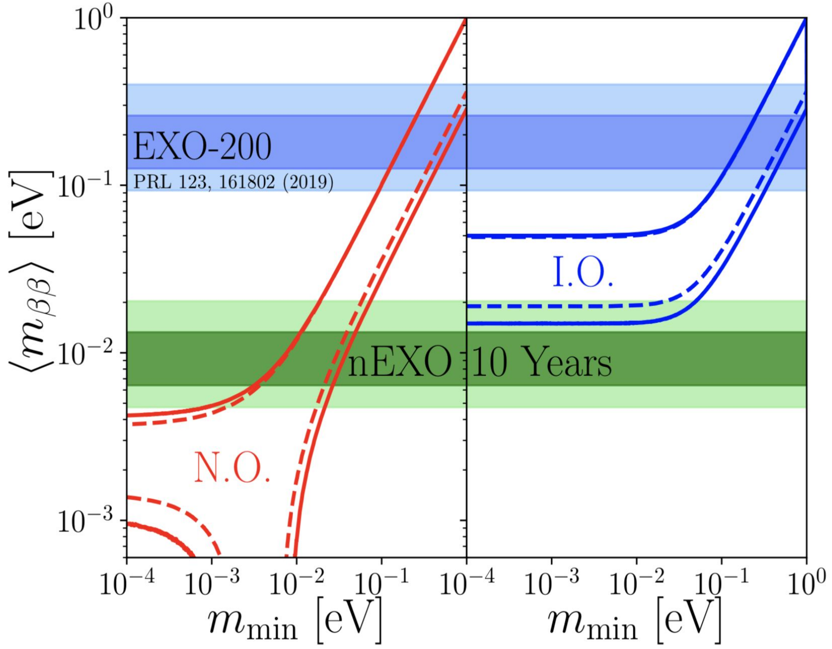
Adhikari et al., ***J. Phys. G*** **49 (2022)**, arXiv:2106.16243



>2 orders of magnitude

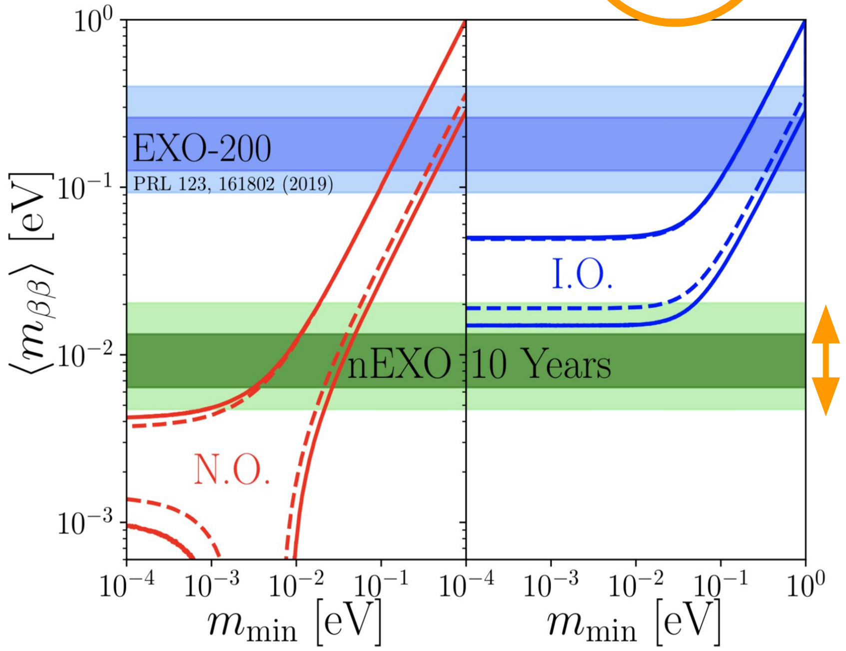
Physics reach

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



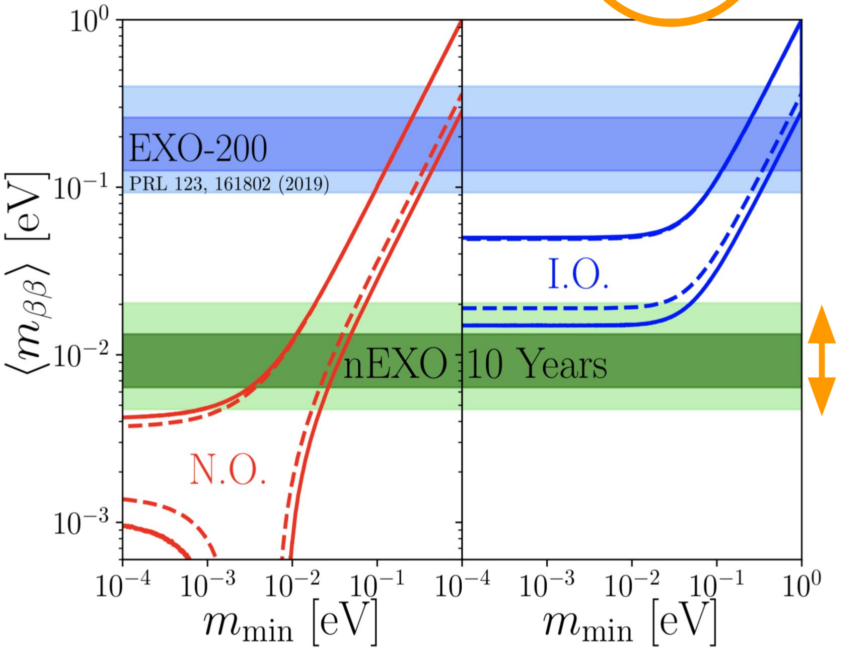
Physics reach

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

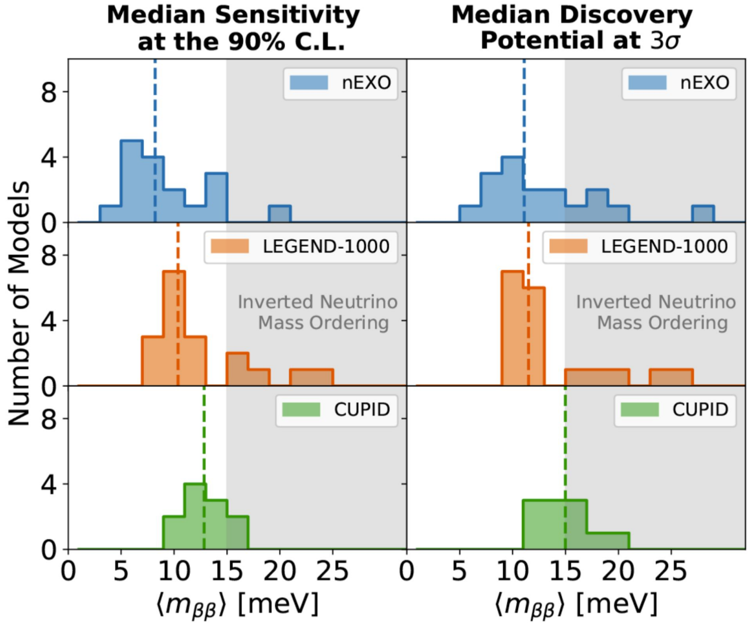


Physics reach

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



Distribution of nuclear matrix element calculations*



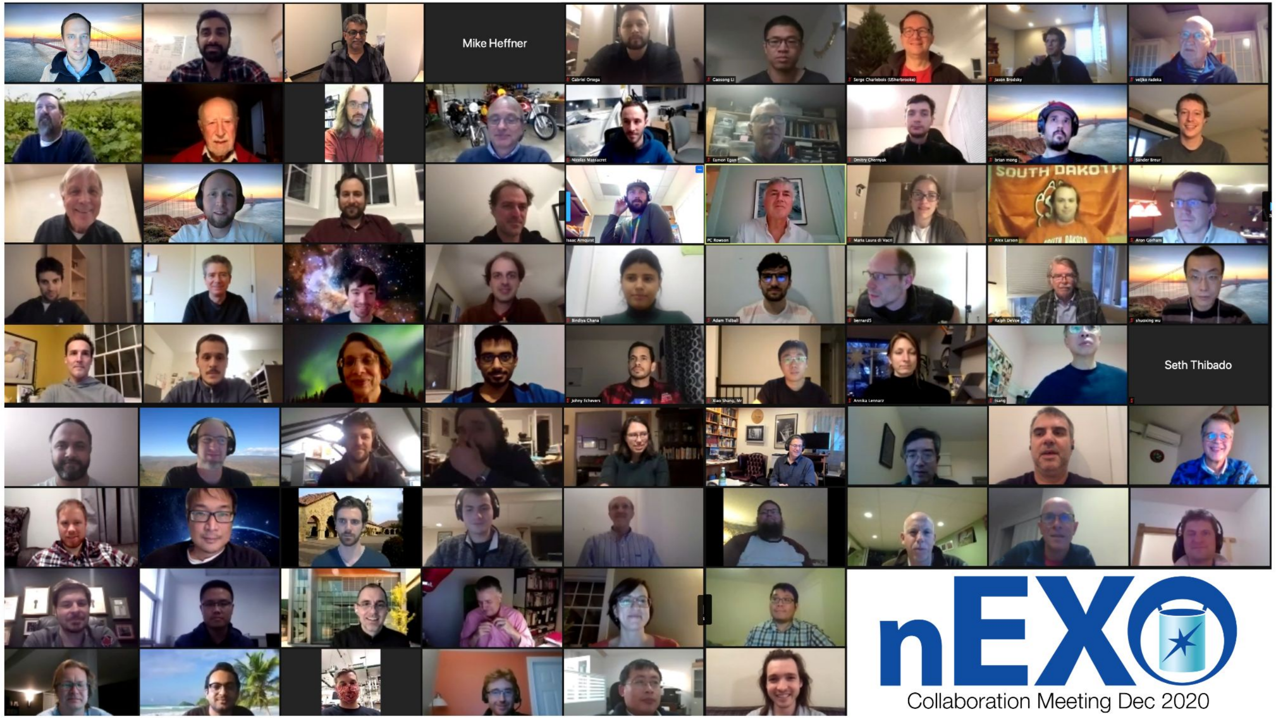
Deeper physics reach

*Note: NMEs are *not* statistical…there is only one correct value. But calculations are challenging.

Conclusions

1. **Neutrinoless double beta decay is a powerful way to search for physics beyond the standard model**
    - Most sensitive probe of lepton number violation
    - Potentially connected to neutrino mass and matter/antimatter asymmetry
2. **The nEXO experiment will perform a next-generation search using a liquid xenon TPC, building on a robust design with unique capabilities**
    - Multi-variate analysis for signal/background identification
    - Can perform a control experiment using non-enriched xenon in the same detector
3. **The next generation of experiments will push two orders of magnitude in sensitivity to the half-life, with significant discovery potential for new physics**
    - Very exciting time for $0\nu\beta\beta$!

Thank you!


Mike Heffner
Seth Thibado
nEXO
Collaboration Meeting Dec 2020

Why look for 0$\nu\beta\beta$?

PHYSICAL REVIEW D **95,** 115010 (2017)

Lepton-number-violating searches for muon to positron conversion

Jeffrey M. Berryman,[1] André de Gouvêa,[1] Kevin J. Kelly,[1] and Andrew Kobach[2]
[1]*Northwestern University, Department of Physics & Astronomy, 2145 Sheridan Road, Evanston, Illinois 60208, USA*
[2]*Department of Physics, University of California, San Diego, La Jolla, California 92093, USA*
(Received 12 December 2016; published 8 June 2017)

EFT analysis for LNV operators

0v$\beta^-\beta^-$ decay

$T_{1/2}$ > 1.06 × 10^{26} years (KAMLAND-Zen)

$\mu^- \rightarrow e^+$ conversion

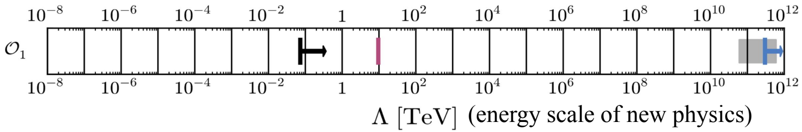
R < 1.7 × 10^{-12} (SINDRUM II)

Conclusion: 0vββ decay is the most sensitive probe of lepton number violation…*by far*

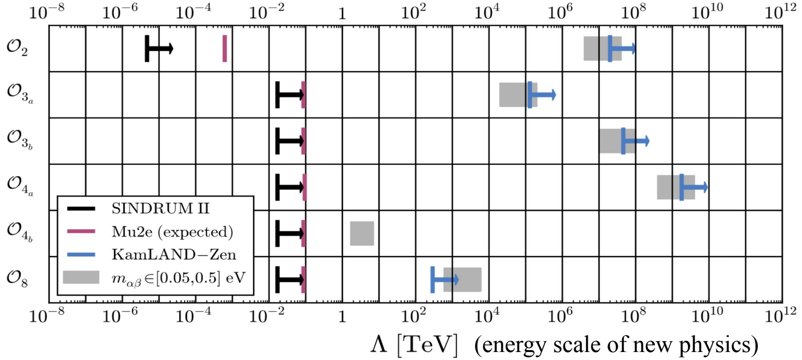
TABLE III. Same as Table I, for the dimension-nine operators featured in this analysis. Naming convention follows from Refs. [11,15], with the exception of the singlet operator $\mathcal{O}_s$ [17].

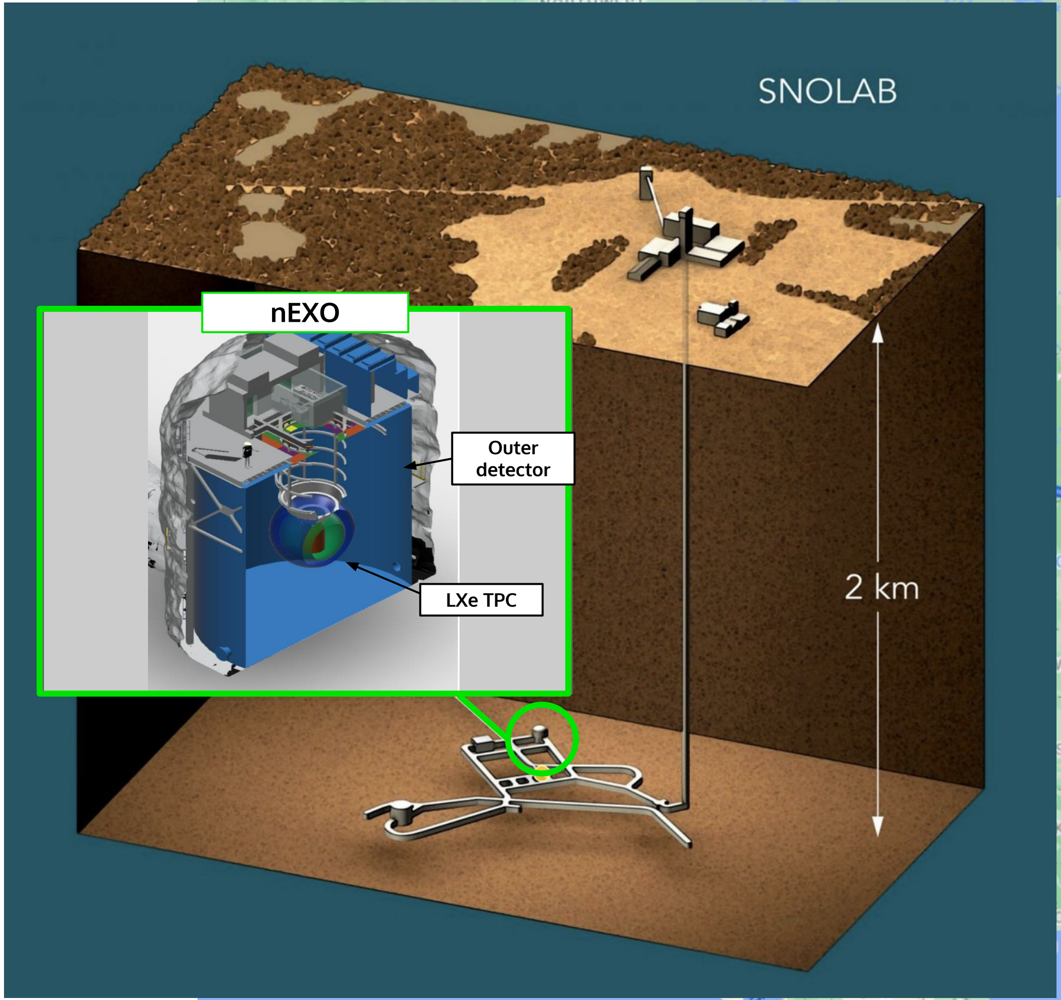
$\mathcal{O}$	Operator	Λ [TeV]	$T_{0\nu\beta\beta}$ / $R_{\mu^- e^+}$
$\mathcal{O}_5$	$(L\bar{H})(LH)(QH)d^c$	$6 \times 10^{4-5}$	$\ln(2)(\frac{\sqrt{2}}{G_F})^2 q^2 \frac{\Lambda^2}{Q^{11}}[(\frac{G_F}{\sqrt{2}})^2 \frac{1}{q^2}(\frac{y_b v^2}{(16\pi^2)^2})^2 + (\frac{v}{16\pi^2\Lambda^2} + \frac{v^3}{\Lambda^4})^2]^{-1} \sim 10^{25}$–$10^{27}$ yr $\frac{1}{q}\frac{Q^6}{\Lambda^2}[(\frac{G_F}{\sqrt{2}})^2 \frac{1}{q^2}(\frac{y_b v^2}{(16\pi^2)^2})^2 + (\frac{v}{16\pi^2\Lambda^2} + \frac{v^3}{\Lambda^4})^2] \sim 10^{-40}$–$10^{-38}$
$\mathcal{O}_6$	$(LH)(L\bar{H})(\bar{Q}H)\overline{u^c}$	$2 \times 10^{6-7}$	$\ln(2)(\frac{\sqrt{2}}{G_F})^2 q^2 \frac{\Lambda^2}{Q^{11}}[(\frac{G_F}{\sqrt{2}})^2 \frac{1}{q^2}(\frac{y_t v^2}{(16\pi^2)^2})^2 + (\frac{v}{16\pi^2\Lambda^2} + \frac{v^3}{\Lambda^4})^2]^{-1} \sim 10^{25}$–$10^{27}$ yr $\frac{1}{q}\frac{Q^6}{\Lambda^2}[(\frac{G_F}{\sqrt{2}})^2 \frac{1}{q^2}(\frac{y_t v^2}{(16\pi^2)^2})^2 + (\frac{v}{16\pi^2\Lambda^2} + \frac{v^3}{\Lambda^4})^2] \sim 10^{-37}$–$10^{-35}$
$\mathcal{O}_7$	$(LH)(QH)(\bar{Q}H)\overline{e^c}$	$4 \times 10^{1-2}$	$\ln(2)(\frac{\sqrt{2}}{G_F})^2 q^2 \frac{\Lambda^2}{Q^{11}}[(\frac{G_F}{\sqrt{2}})\frac{v}{(16\pi^2)^2} + \frac{v}{16\pi^2\Lambda^2} + \frac{v^3}{\Lambda^4}]^{-2} \sim 10^{22}$–$10^{24}$ yr $\frac{1}{q^2}\frac{Q^6}{\Lambda^2}[(\frac{G_F}{\sqrt{2}})\frac{v}{(16\pi^2)^2} + \frac{v}{16\pi^2\Lambda^2} + \frac{v^3}{\Lambda^4}]^2 \sim 10^{-34}$–$10^{-32}$
$\mathcal{O}_9$	$(LL)(LL)e^c e^c$	$3 \times 10^{2-3}$	$\ln(2)(\frac{\sqrt{2}}{G_F})^4 q^4 (\frac{16\pi^2}{y_t v})^4 \frac{\Lambda^2}{Q^{11}} \sim 10^{25}$–$10^{27}$ yr [illegible] $\sim 10^{-38}$–10^{-36}

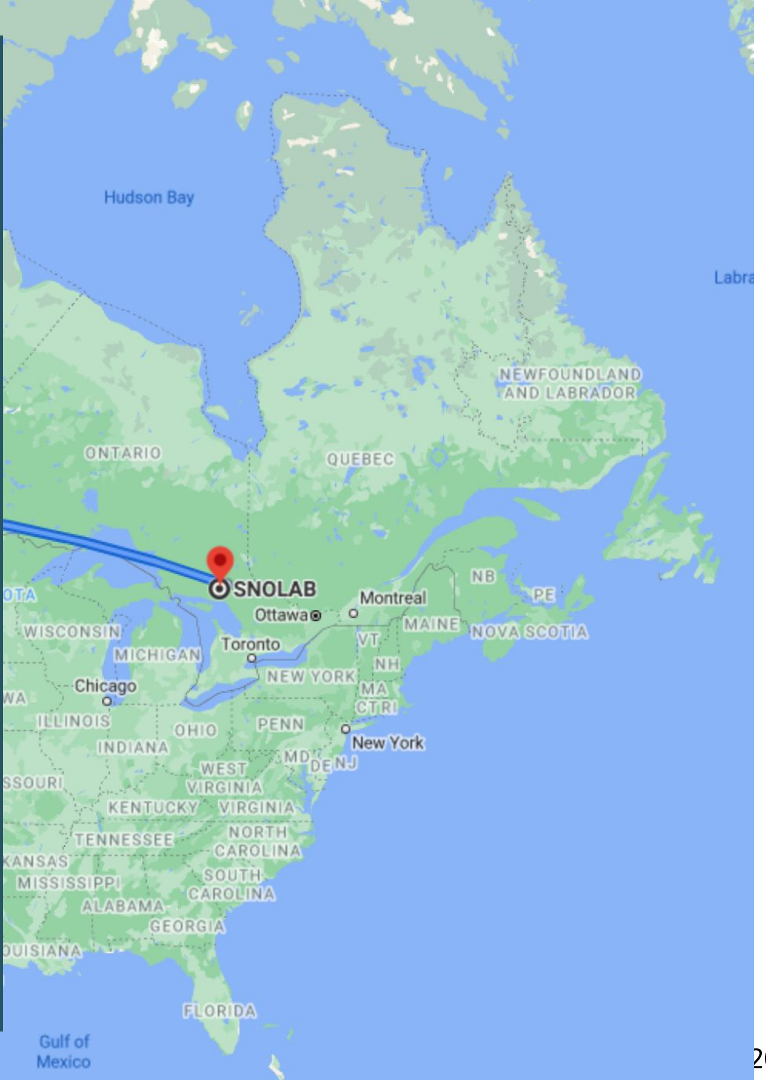
Dimension 5 Weinberg operator



Dimension 7 operators




SNOLAB
nEXO
Outer detector
LXe TPC
2 km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