Search for $0\nu\beta\beta$ beyond 10^{28} yr half-life sensitivity with nEXO

Ako Jamil for the nEXO Collaboration

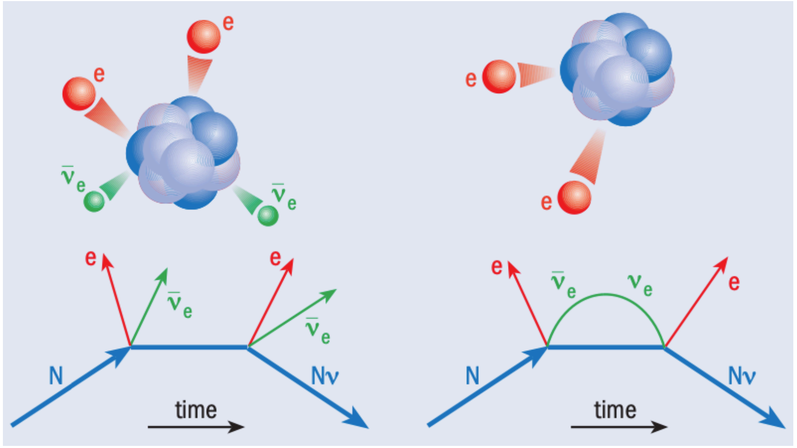
Yale University

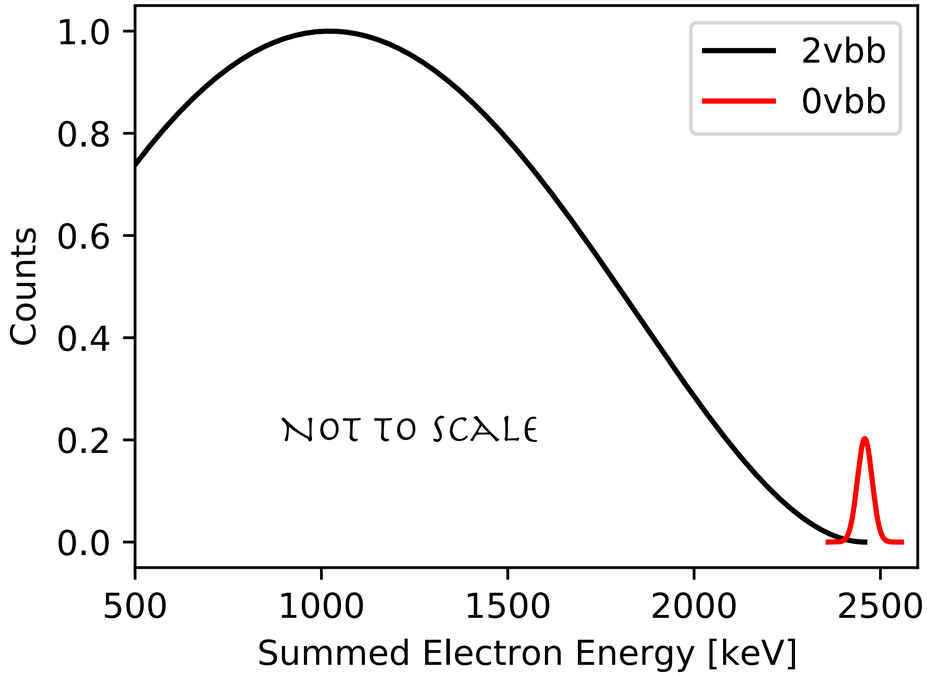
May 12, 2022

CoSSURF, Rapid City

Motivation for Neutrinoless Double 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 ($2458\,\mathrm{keV}$ for $^{136}\mathrm{Xe}$)



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TRIUMF
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nEXO
Skyline College
Lawrence Livermore National Laboratory
SLAC National Accelerator Laboratory
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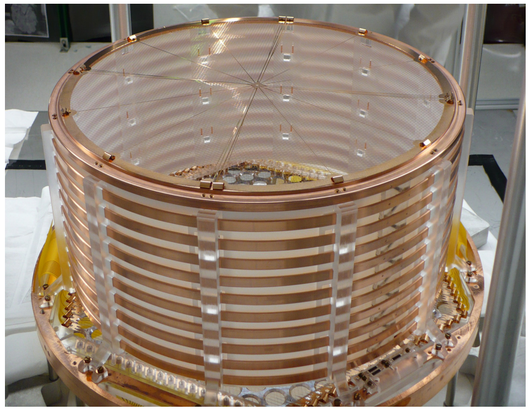
Liquid Xenon Detectors for $0\nu\beta\beta$

EXO-200



- First $100\,\mathrm{kg}$-class $0\nu\beta\beta$ search
- Discovered $2\nu\beta\beta$ in $^{136}\mathrm{Xe}$ in 2011
- Limit: $T^{0\nu}_{1/2} > 3.5 \times 10^{25}\,\mathrm{yr}$
- Sensitivity: $T^{0\nu}_{1/2} > 5.0 \times 10^{25}\,\mathrm{yr}$
- Pioneered ultra low-background LXe TPC technology

Phys. Rev. Lett. 123, 161802 (2019)

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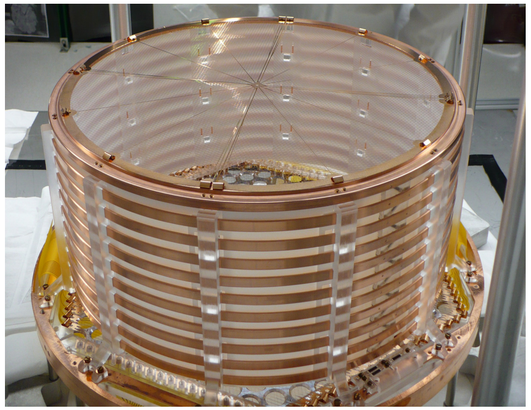

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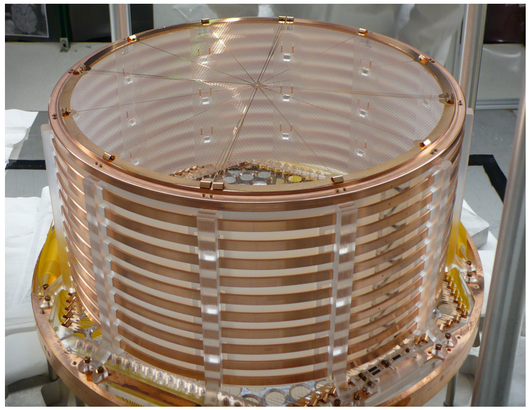
Search for $0\nu\beta\beta$ with the Complete EXO-200 Dataset

https://indico.sanfordlab.org/event/28/contributions/313/

Liquid Xenon Detectors for $0\nu\beta\beta$

EXO-200



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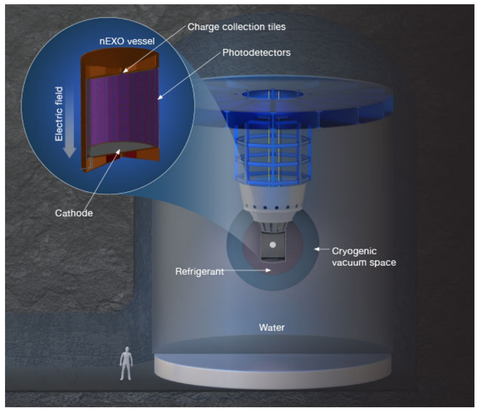
>2 ORDERS OF MAGNITUDE IMPROVEMENT IN HALF-LIFE SENSITIVITY

nEXO

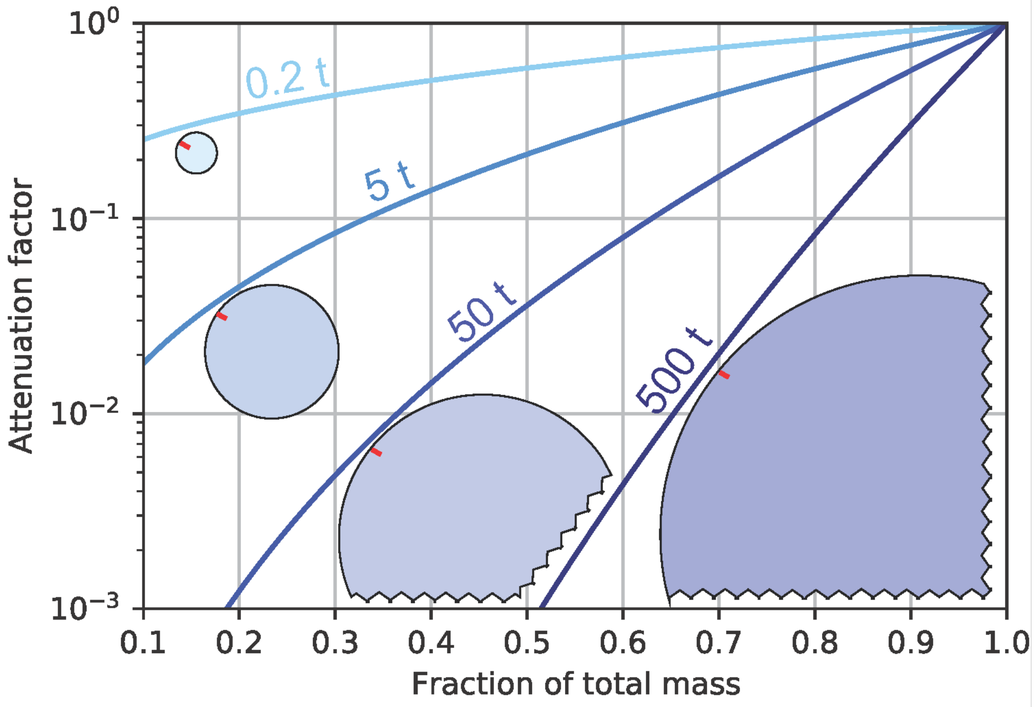


- $5\,\mathrm{tonnes}$ of liquid xenon
- Better self-shielding and external shielding
- Improved charge (tiles) and light (SiPM) readout
- Projected Sensitivity: $T^{0\nu}_{1/2} > 1.35 \times 10^{28}\,\mathrm{yr}$

J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)

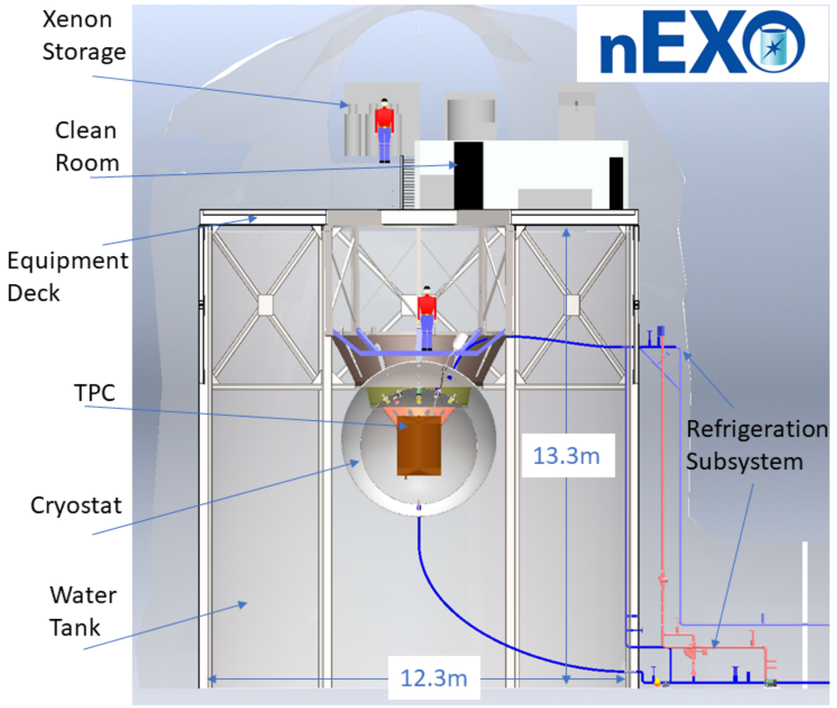
Why a Liquid Xenon Detector?

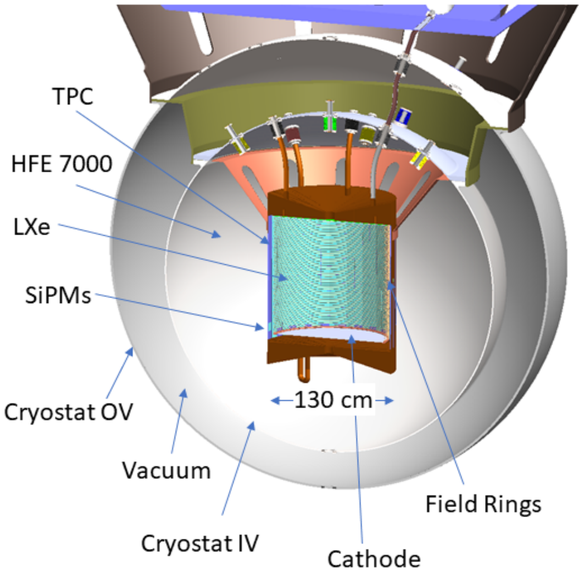
- Advantages of the Liquid Xenon Technology for $0\nu\beta\beta$
  - Scalability
  - Low intrinsic background
  - Good energy resolution
  - Topological discrimination of backgrounds
  - Possibility of a control experiment



Overview of the nEXO Detector

- Single Phase Time Projection Chamber (TPC)
  - **5000 kg** of liquid xenon
  - **90 %** enriched in ^{136}Xe
  - Single **1.2 m** drift length
  - Energy resolution $\sigma/Q_{\beta\beta} = 0.8\,\%$
  - Active water Cherenkov muon veto
- Preferred site: SNOLAB

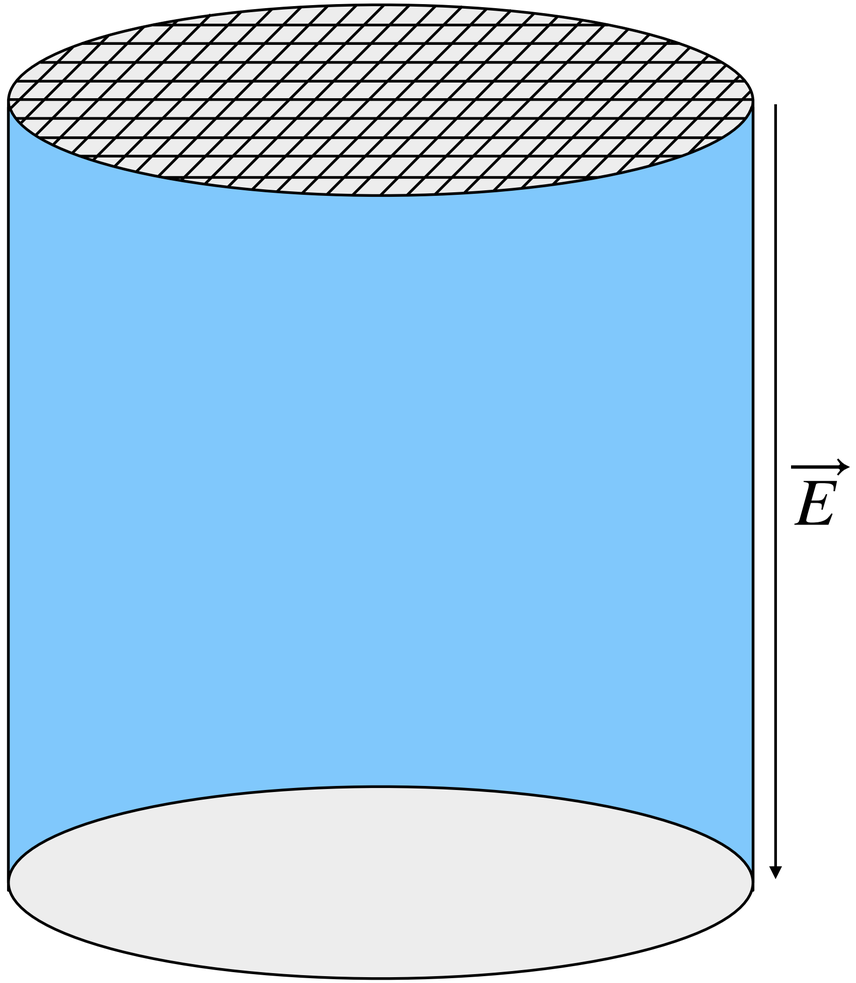




nEXO pre-conceptual Design Report:
arXiv:1805.11142

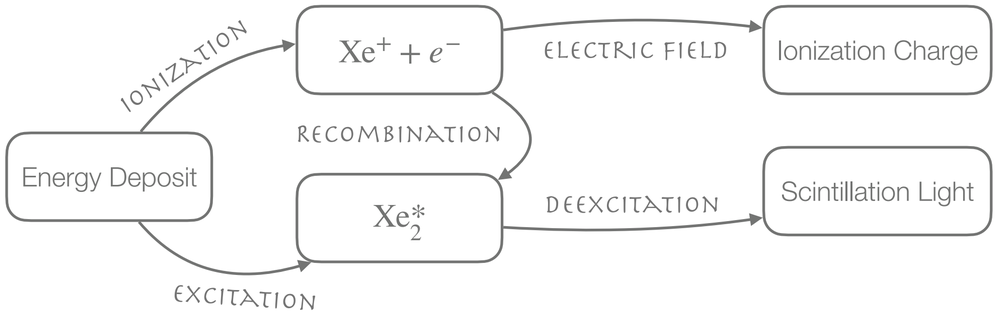
nEXO Sensitivity and Discovery Potential:
J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)

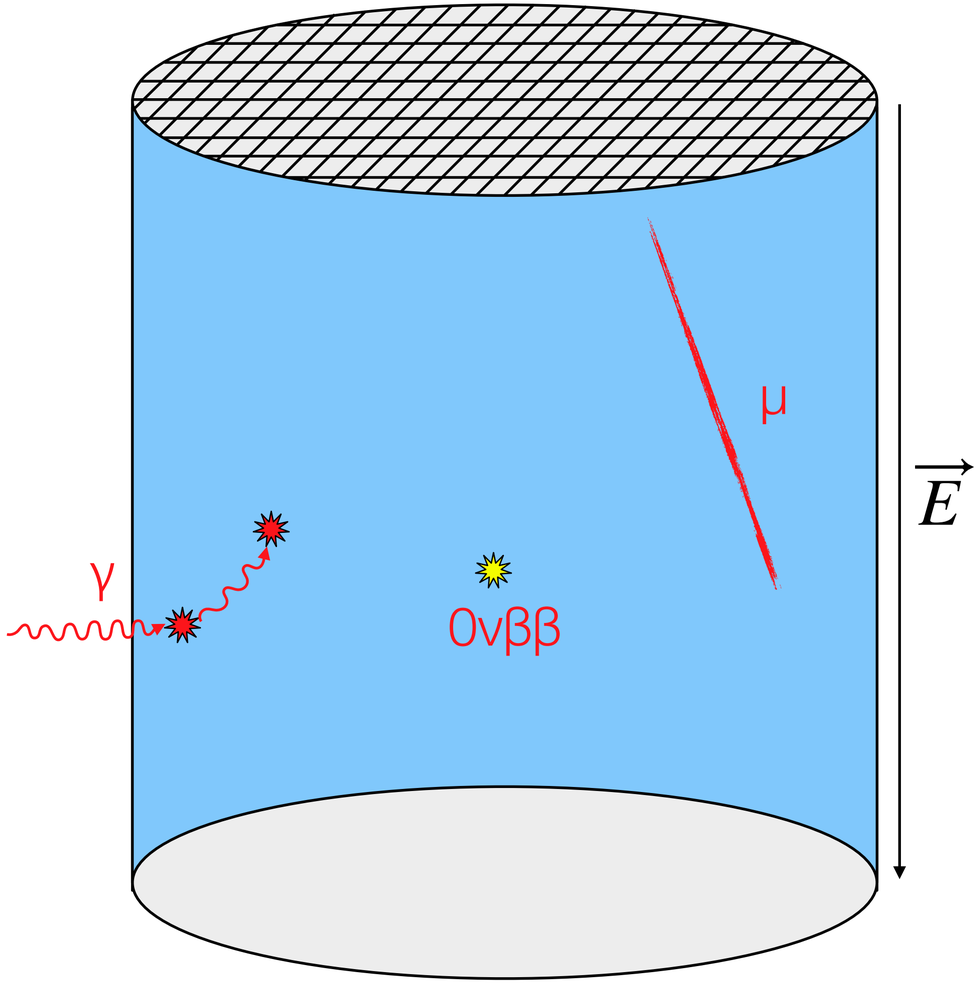
Signal in a Liquid Xenon TPC



Signal in a Liquid Xenon TPC

- Ionizing radiation will either ionize or excite Xe atoms





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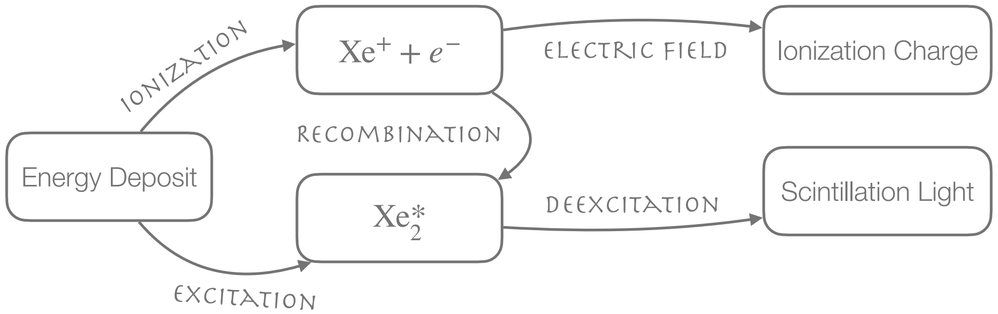
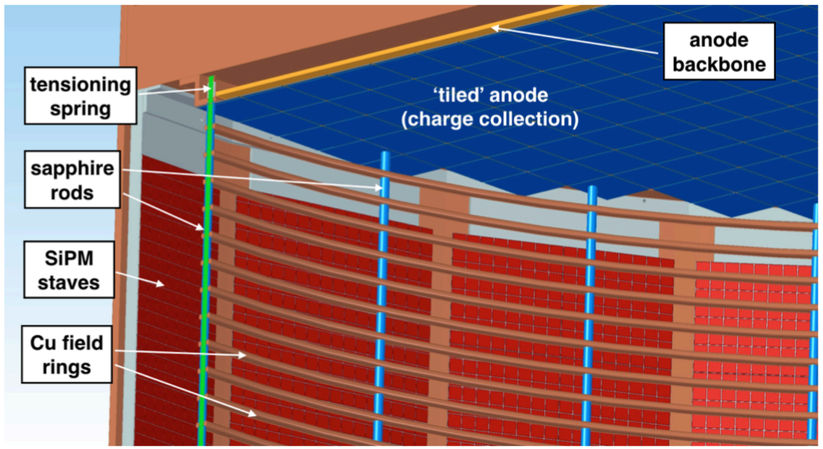
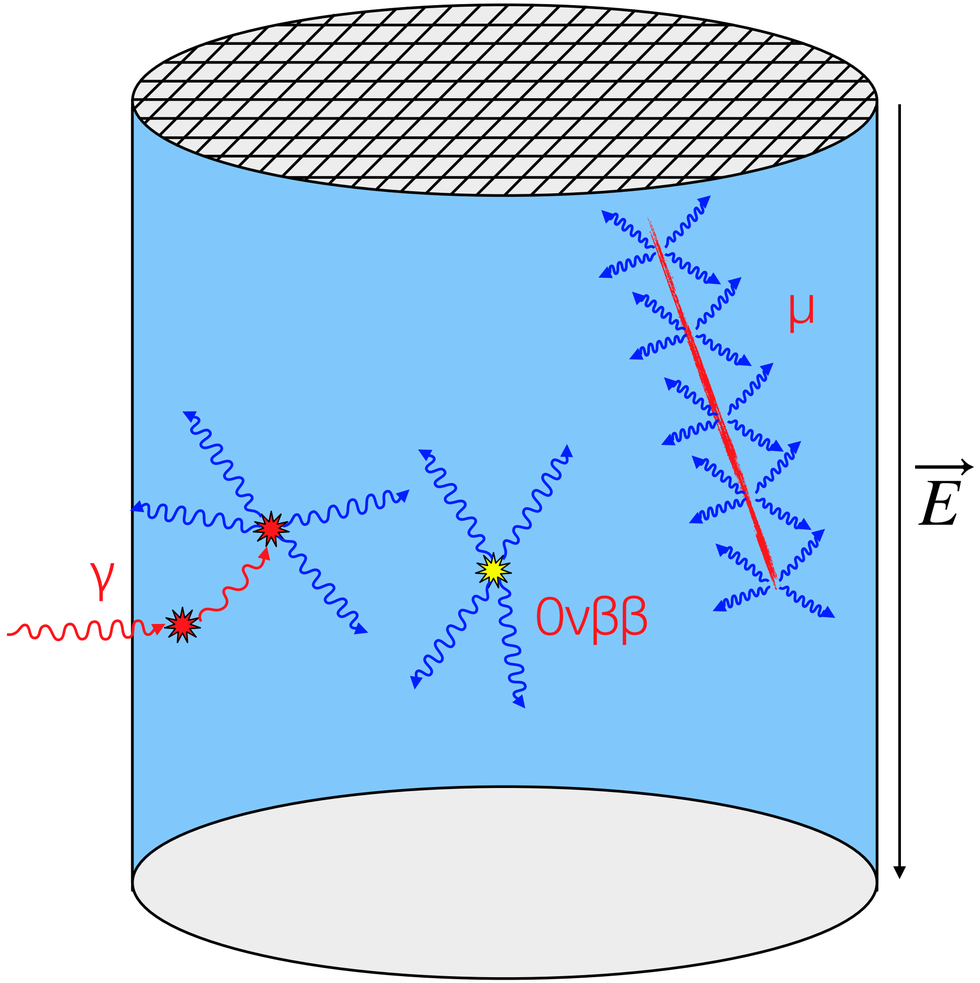


- Photons are immediately detected by the SiPMs around the barrel and provide a time stamp





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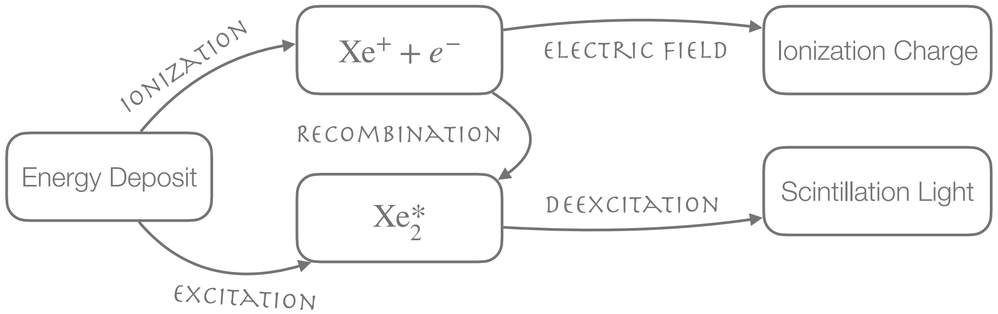

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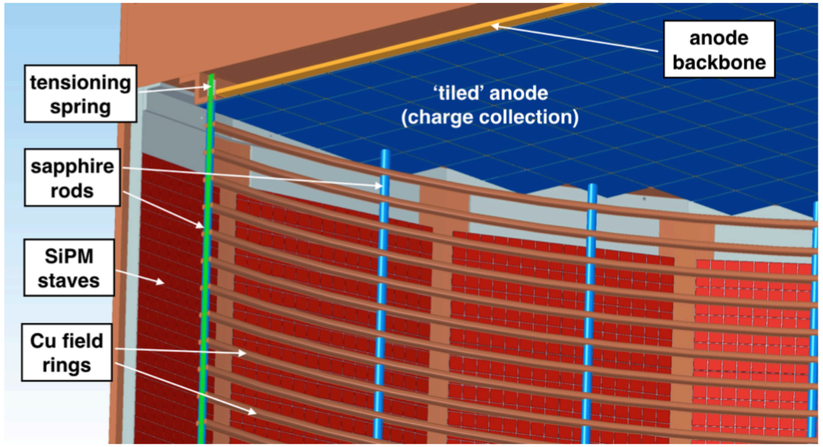
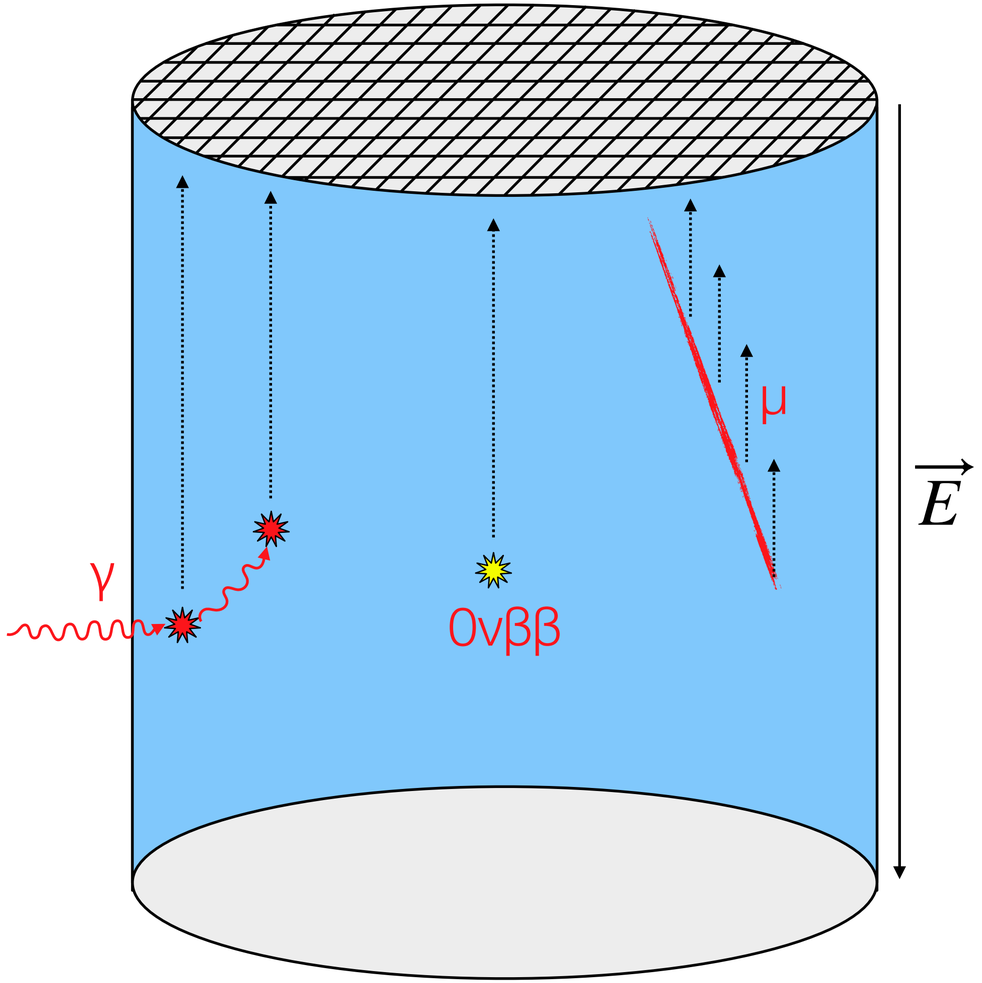
- Electrons are drifted to charge collection tiles at the top





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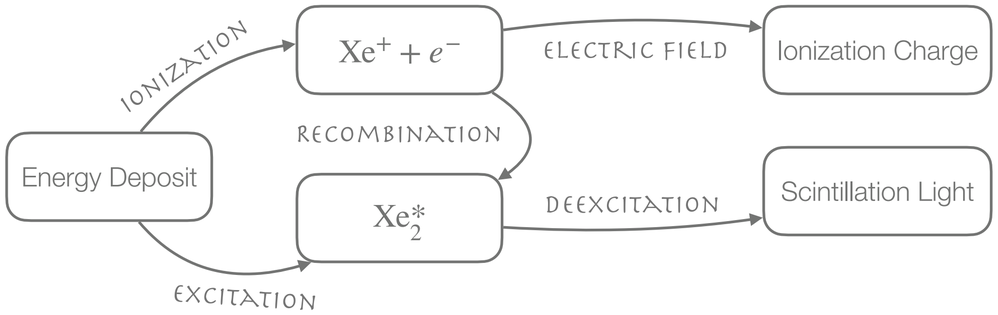

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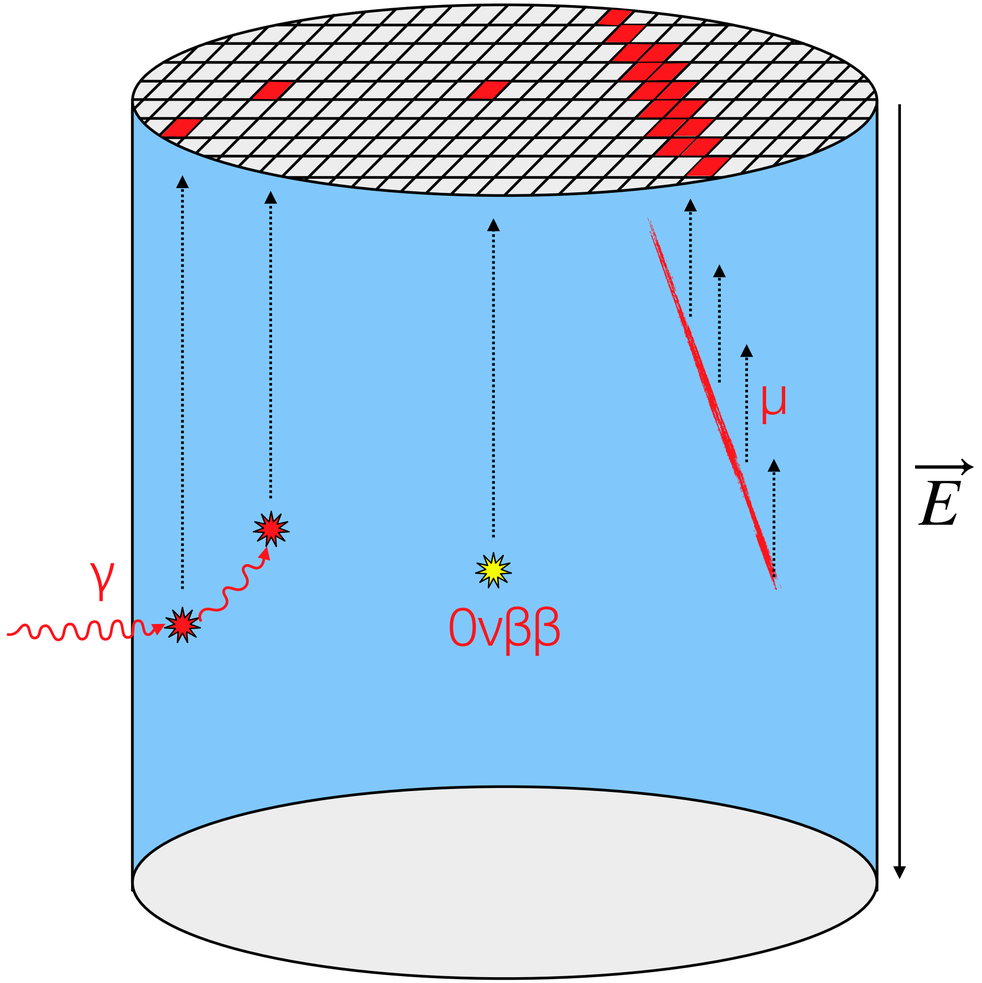
- Charge collection tiles with 3mm pitch strips detect e^-



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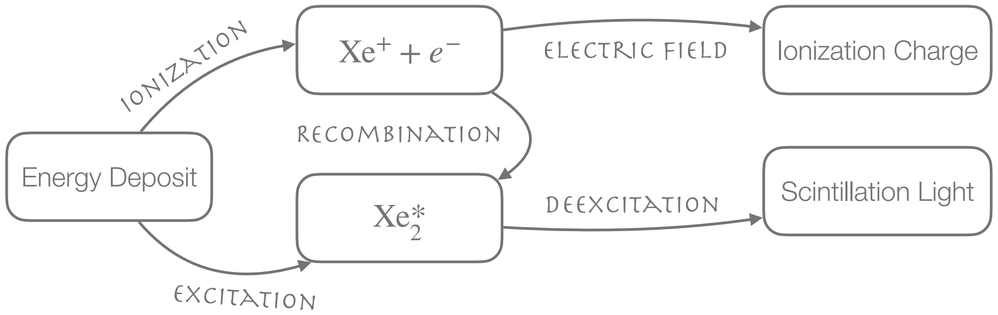

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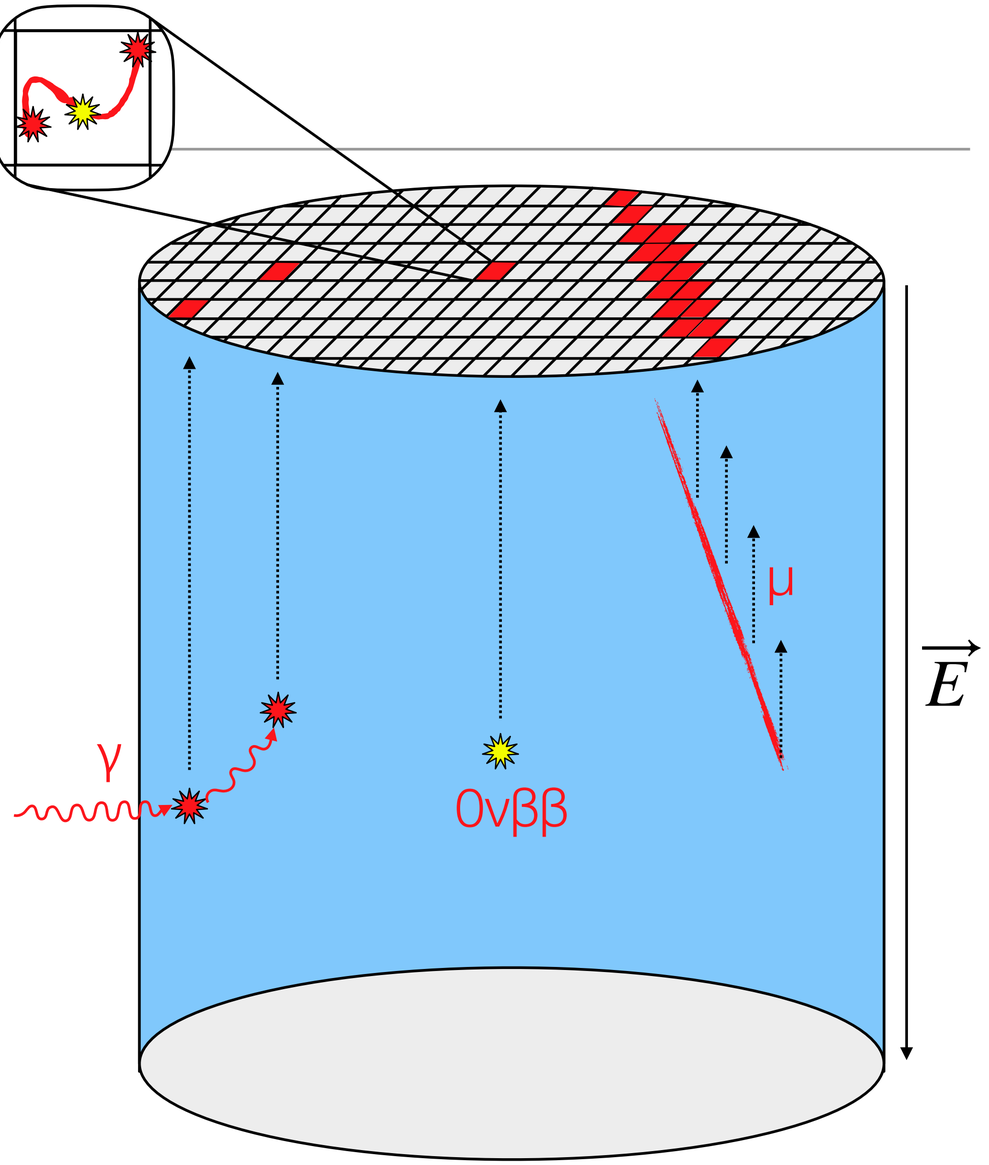
- Electrons are drifted to charge collection tiles at the top
- Charge collection tiles with 3mm pitch strips detect e-
- $0\nu\beta\beta$ charge is mostly spatially contained (unlike γ's)



Multidimensional Event Analysis

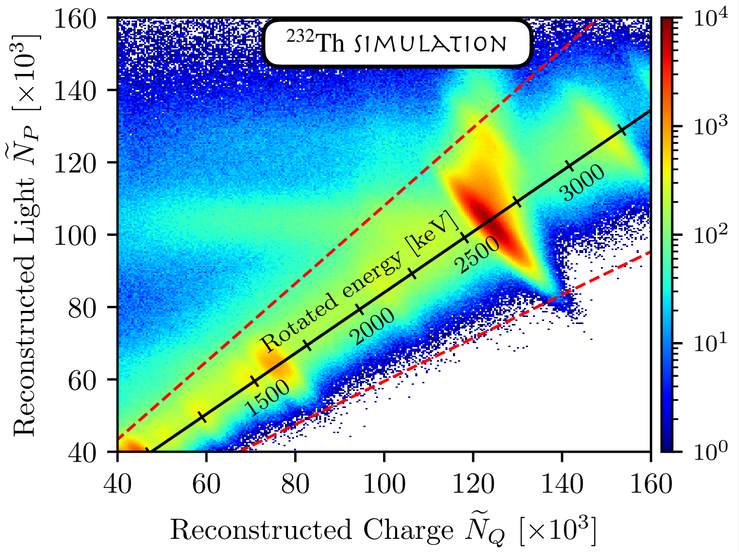
nEXO Sensitivity and Discovery Potential: **J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)**

Multidimensional Event Analysis

Energy

Anti-correlation between number of light and charge quanta can be exploited for improved energy resolution

—> Expect $\sigma/Q_{\beta\beta} = 0.8\,\%$



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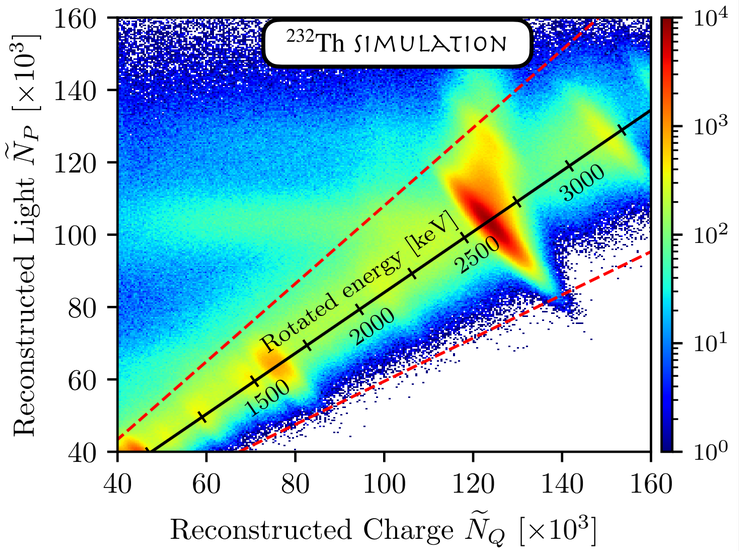
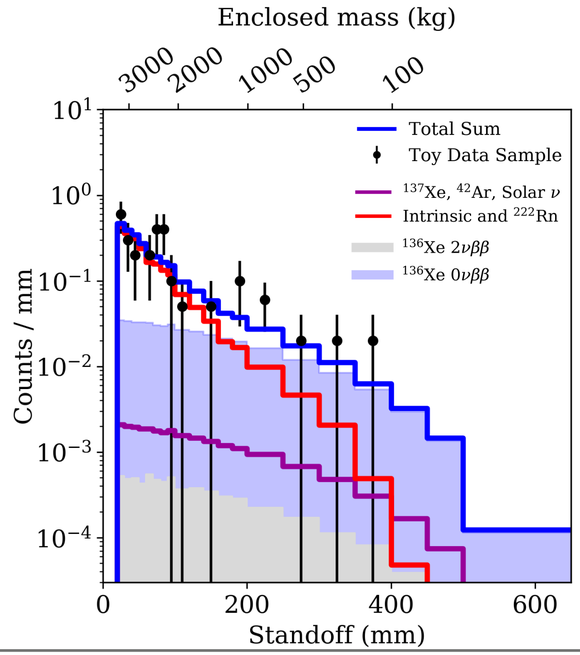


Standoff Distance

Most backgrounds originate from outside the fiducial volume

$0\nu\beta\beta$ events are uniformly distributed



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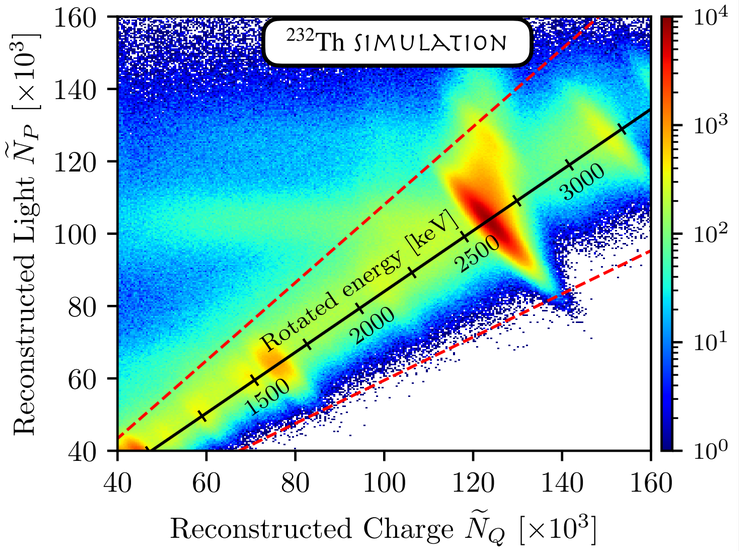

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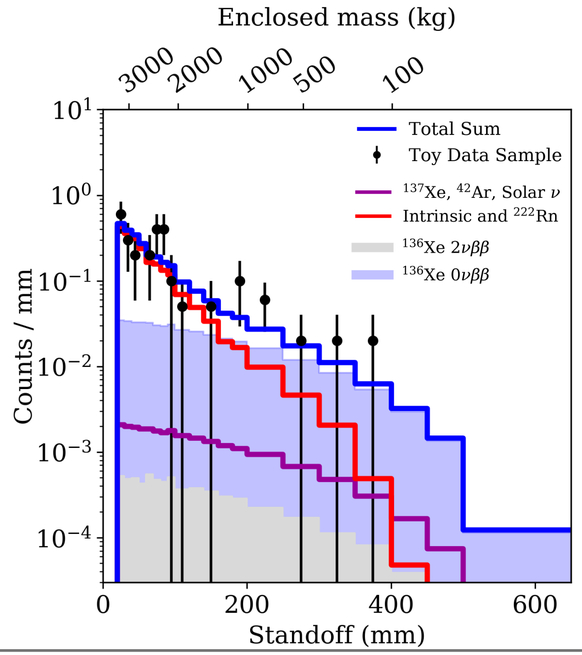
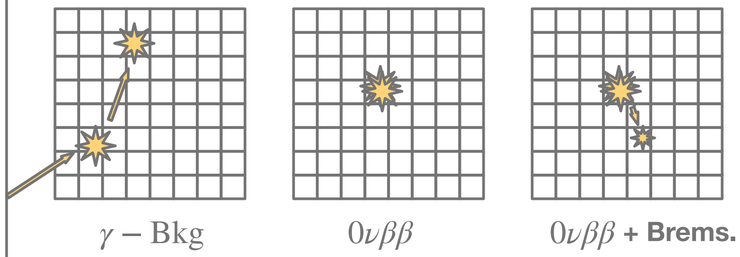
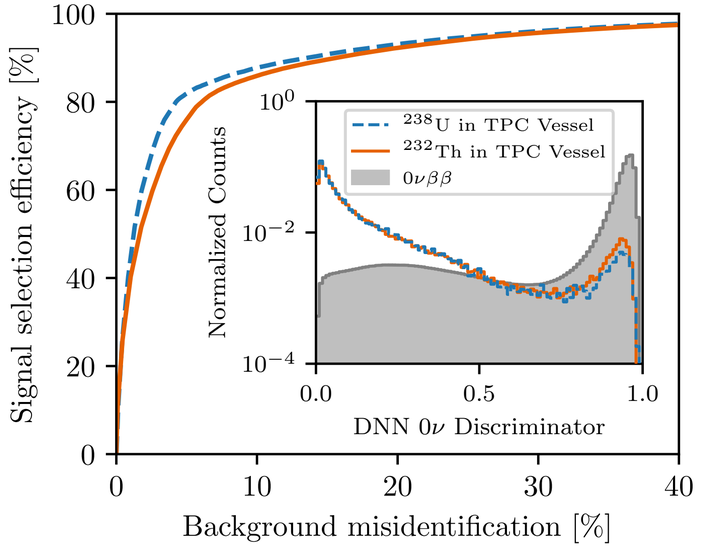


Topology





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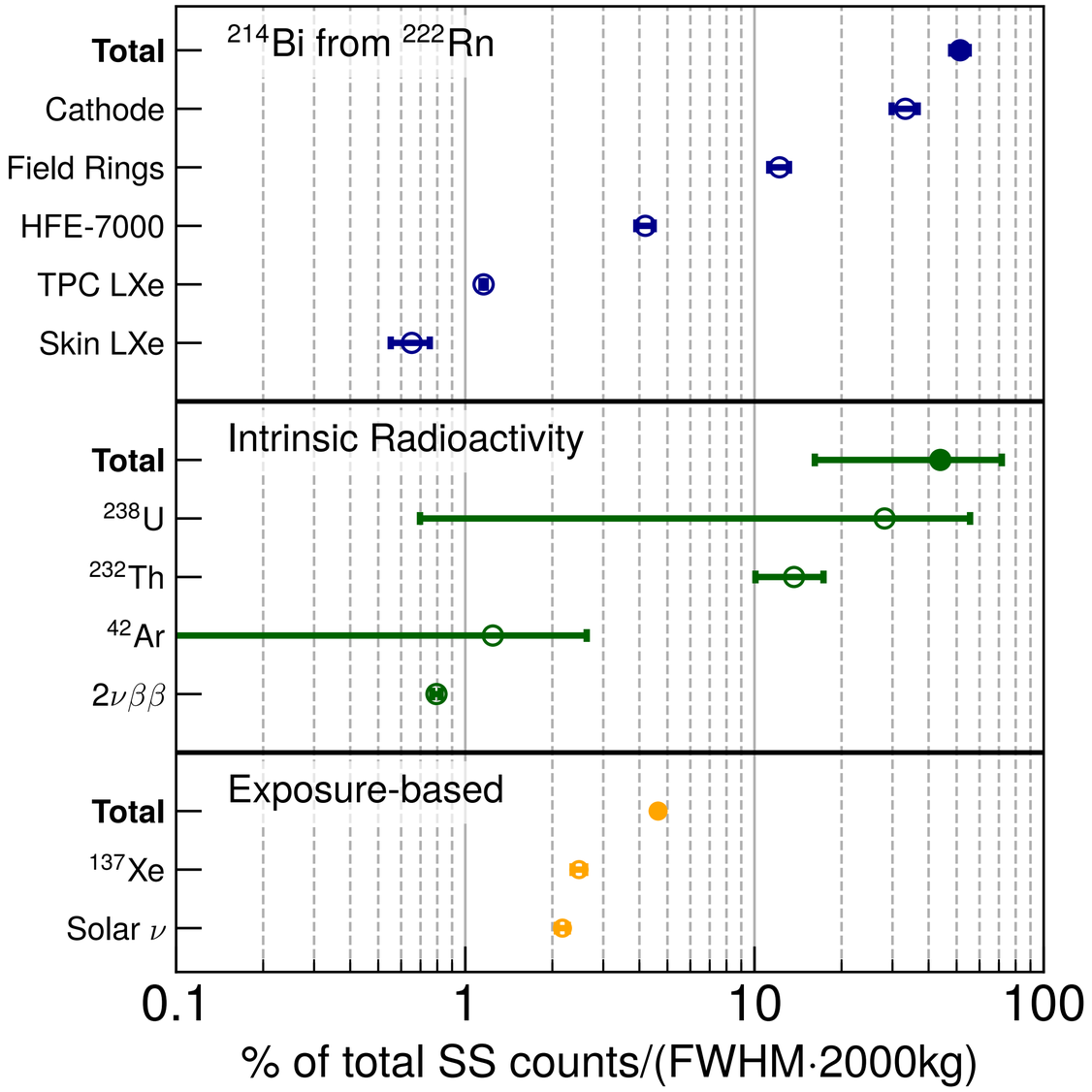
Data-Drive Background Model

- 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



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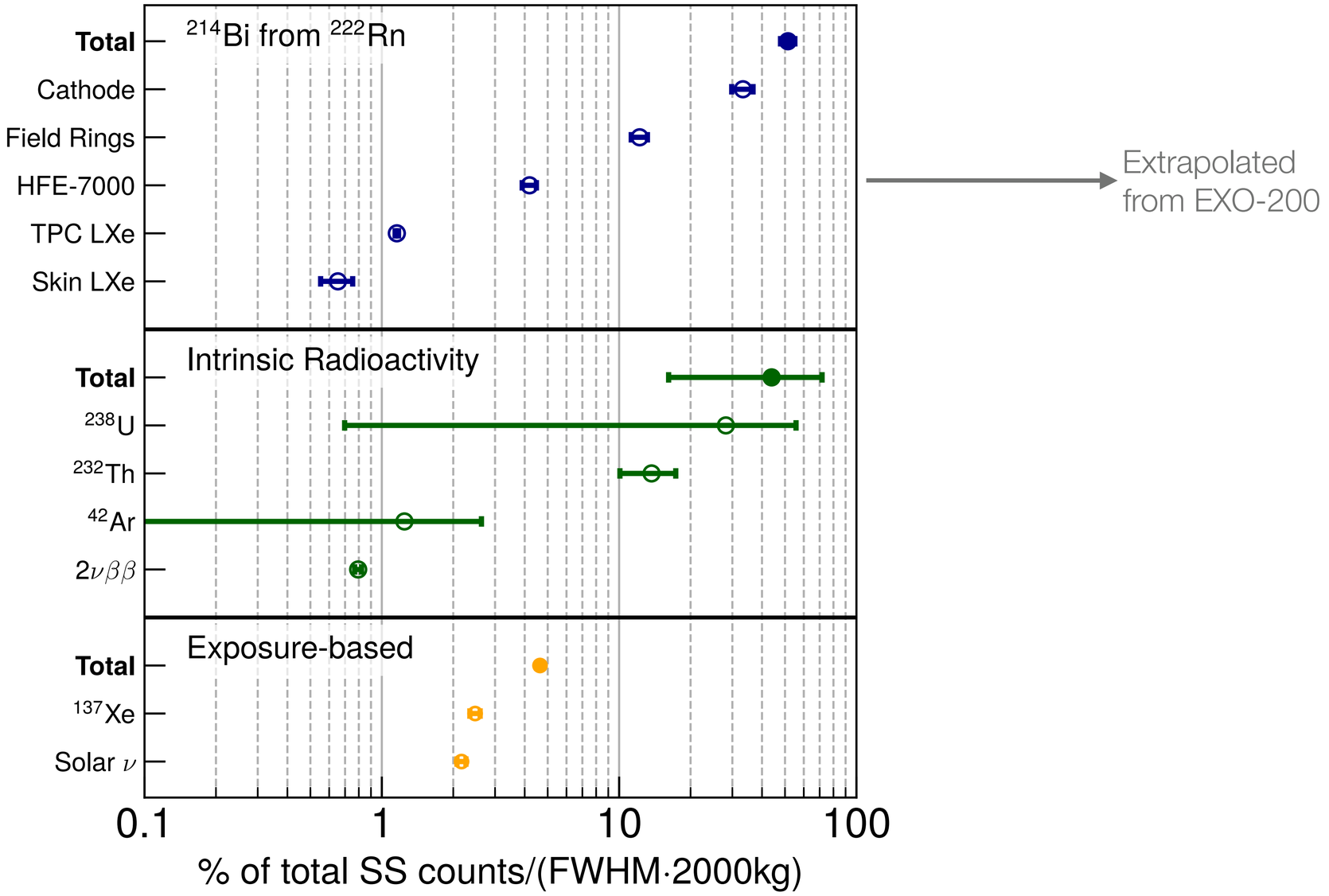

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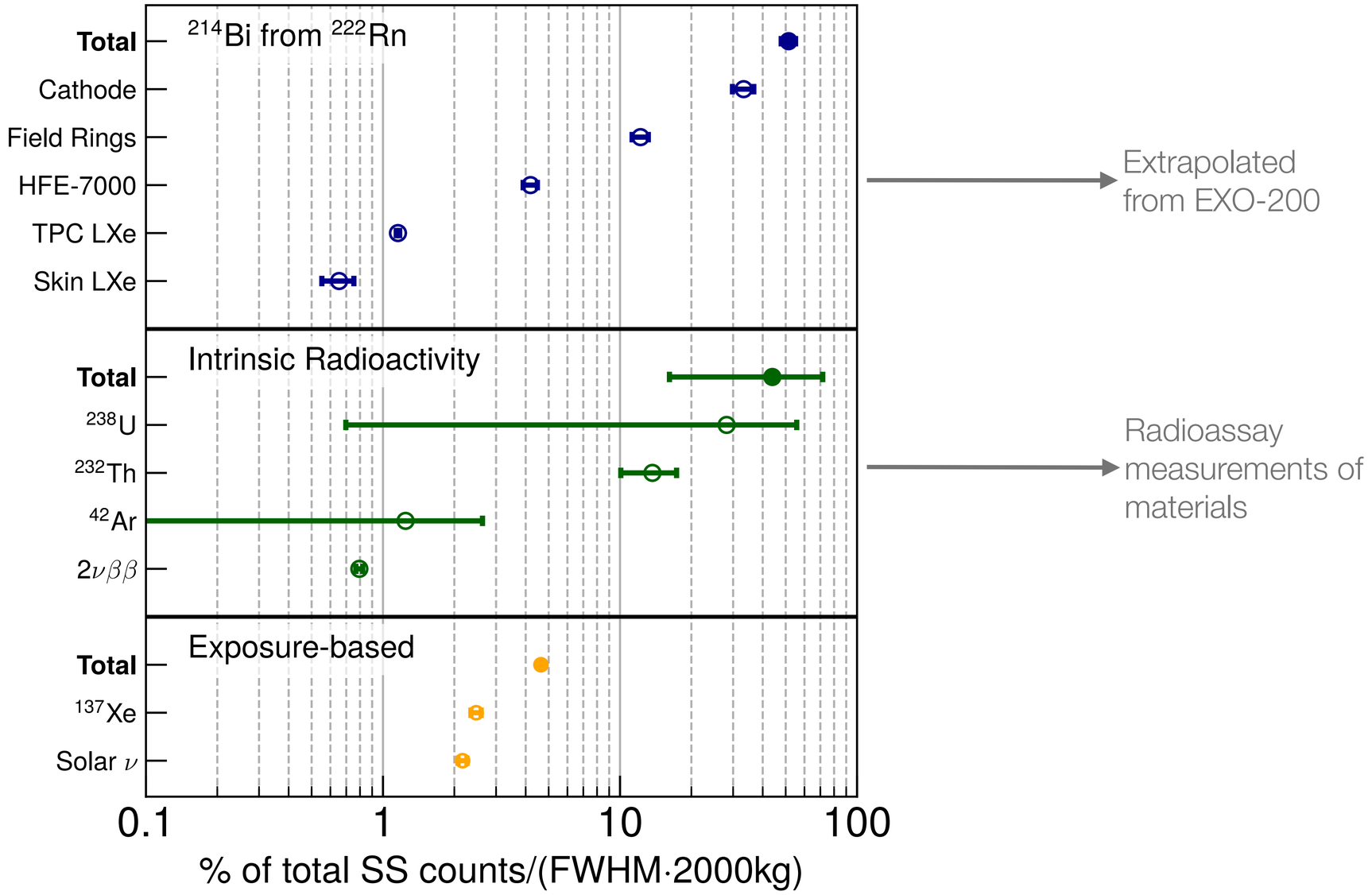

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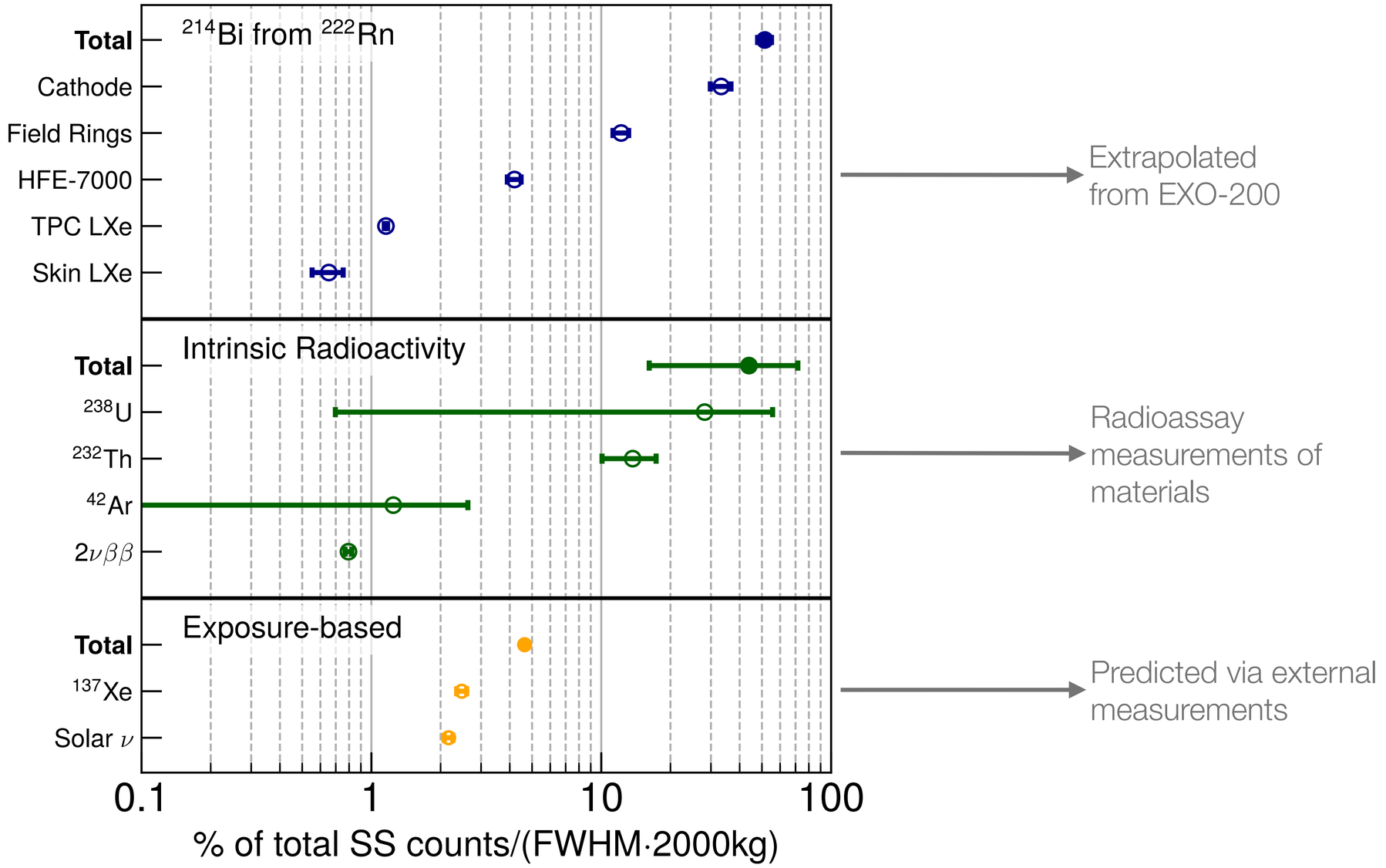

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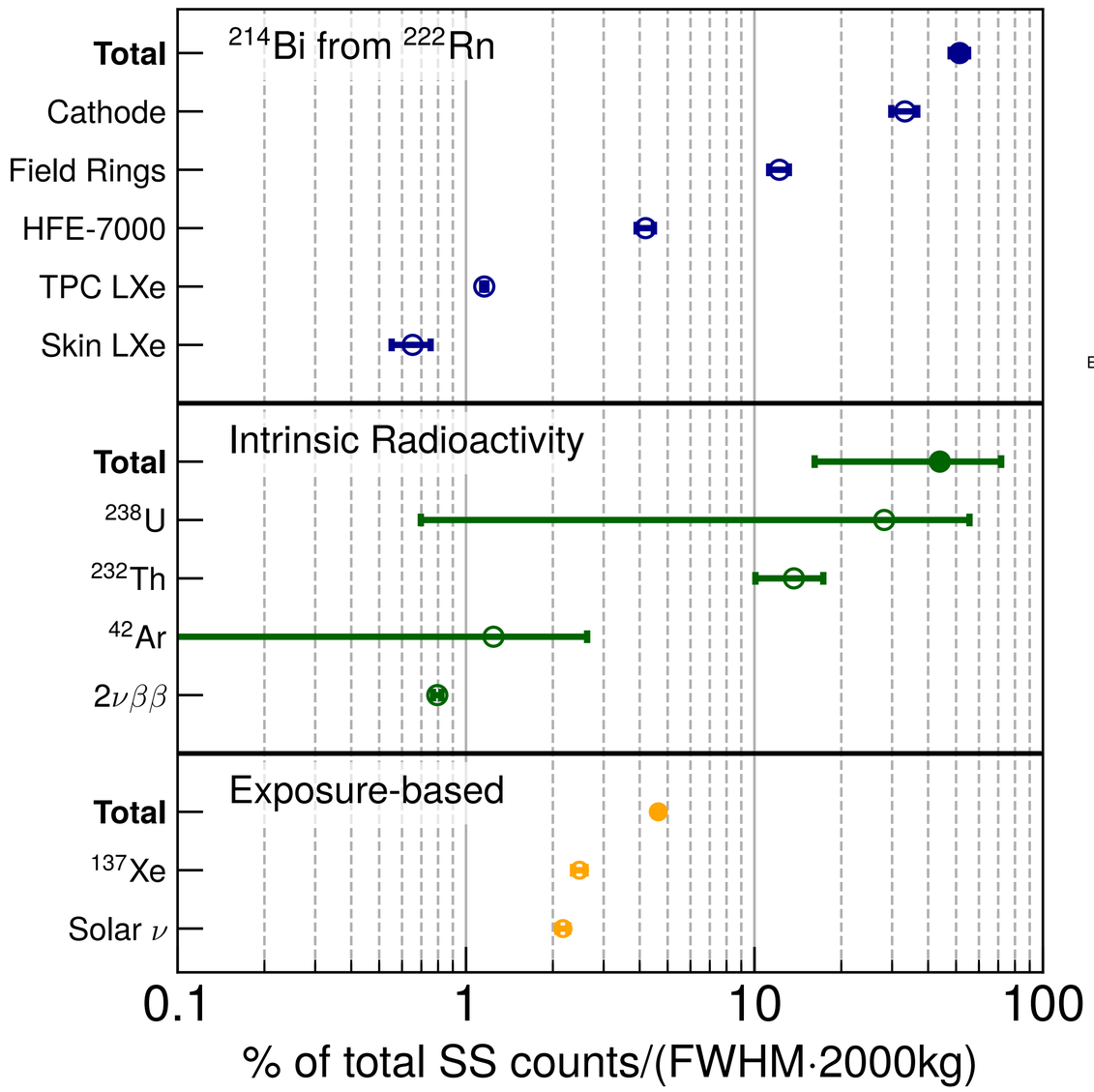
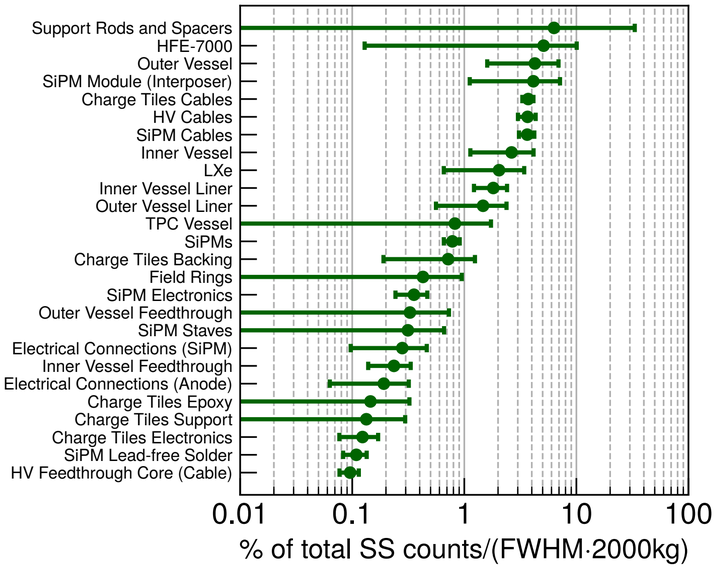
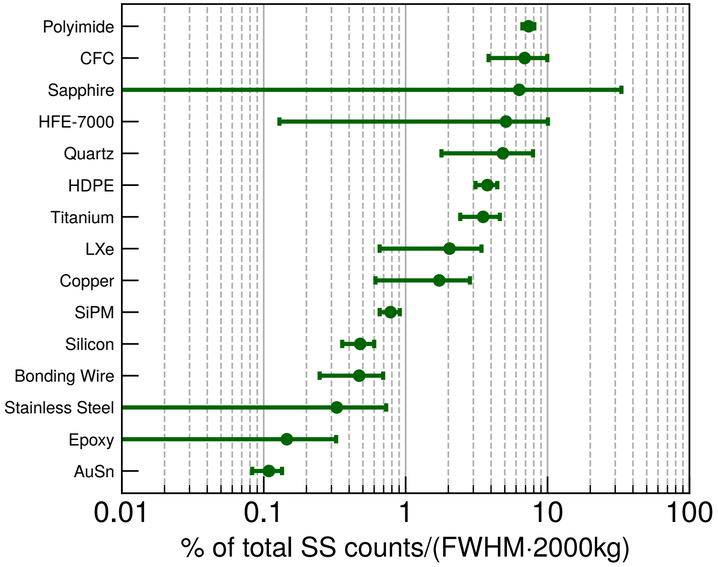
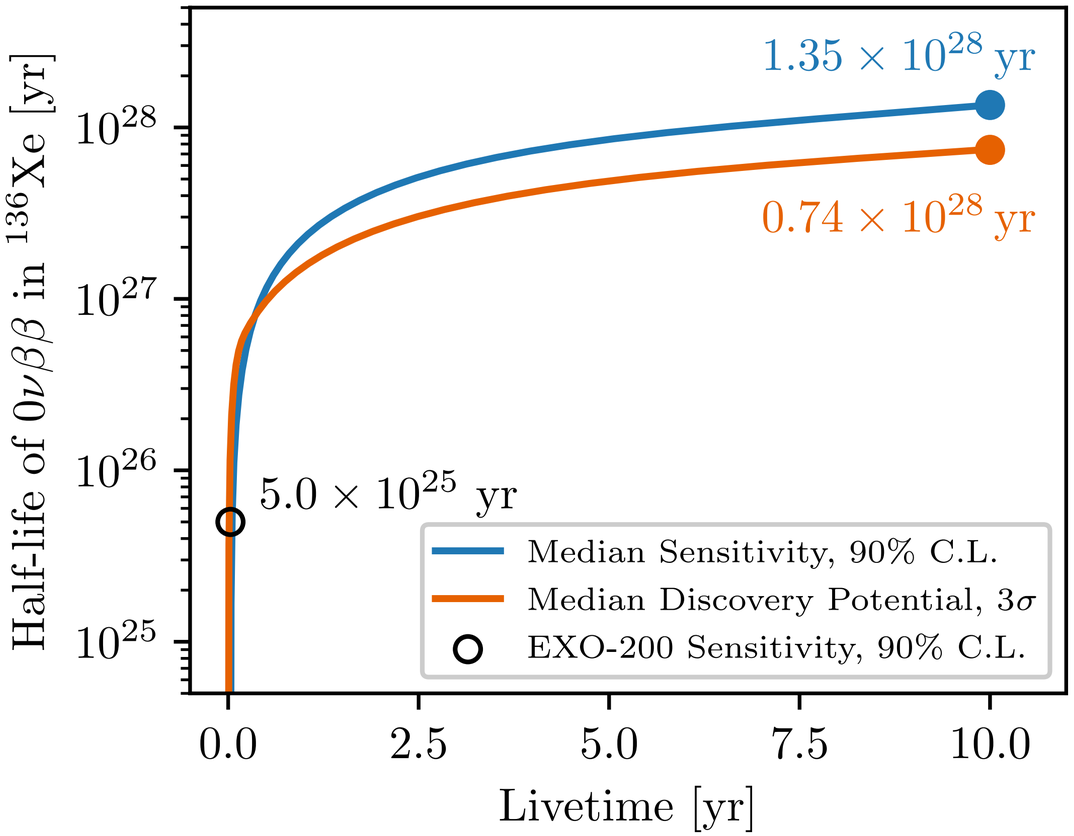






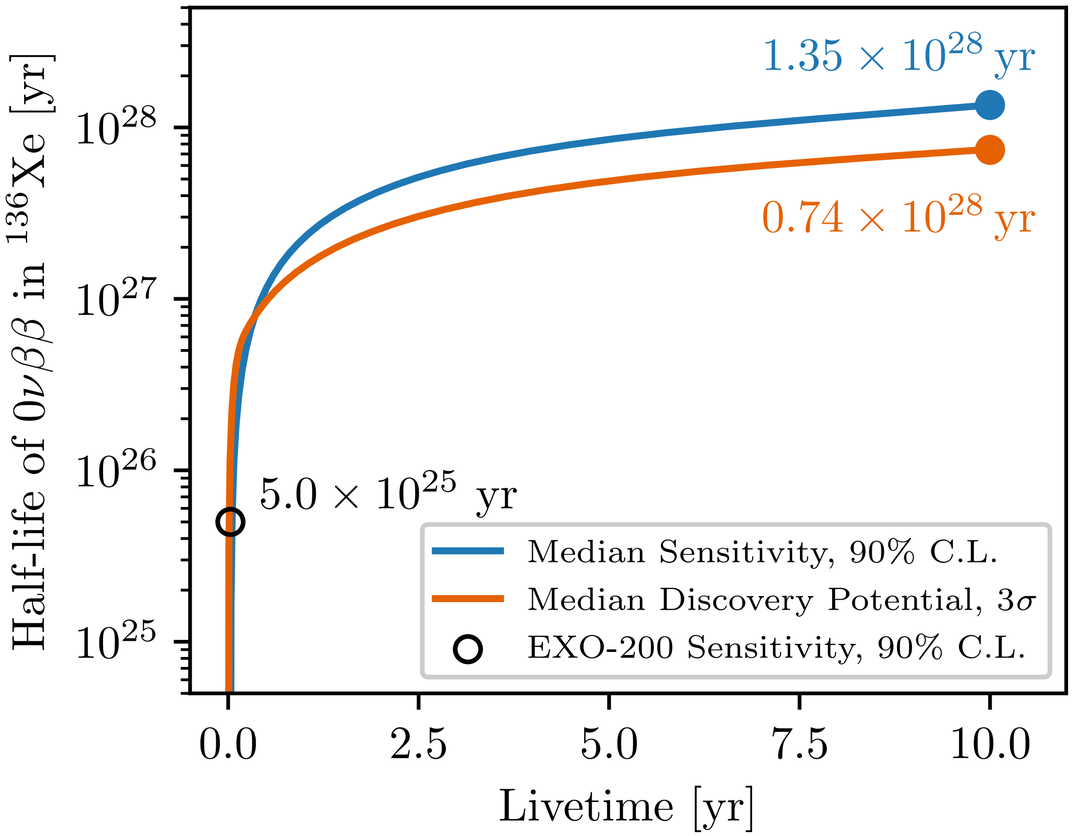
nEXO's Sensitivity and Discovery Potential



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

nEXO's Sensitivity and Discovery Potential

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



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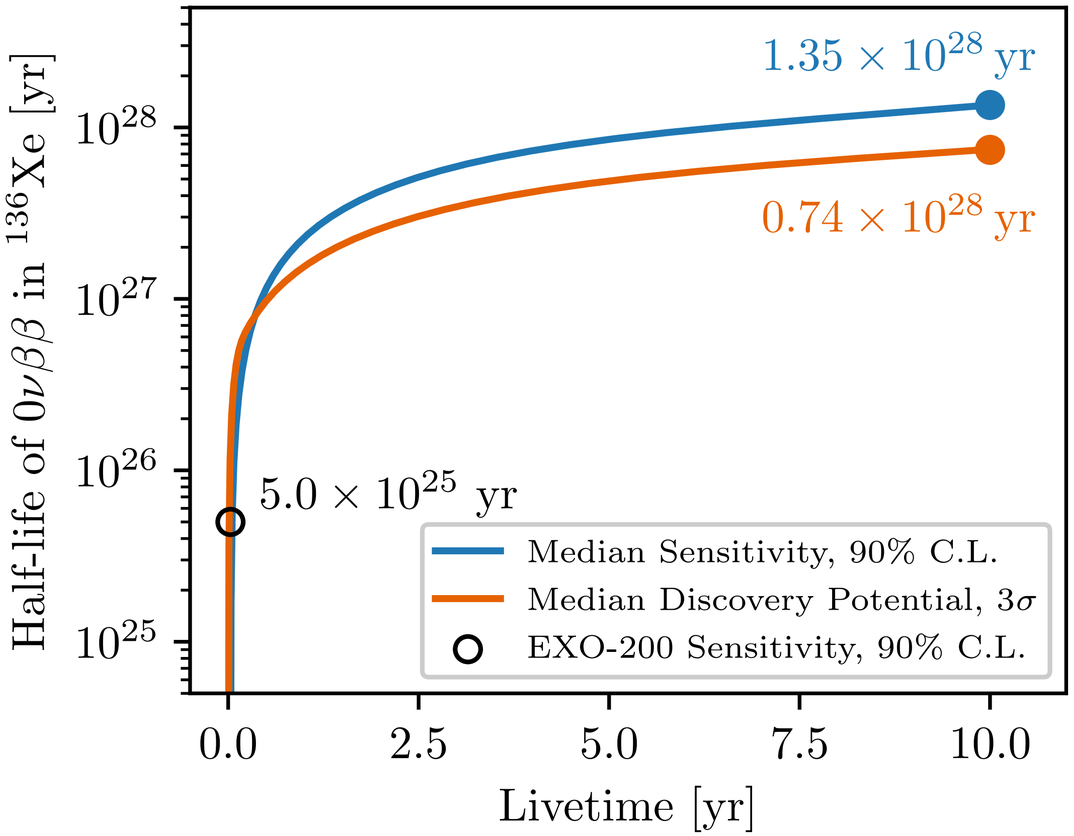

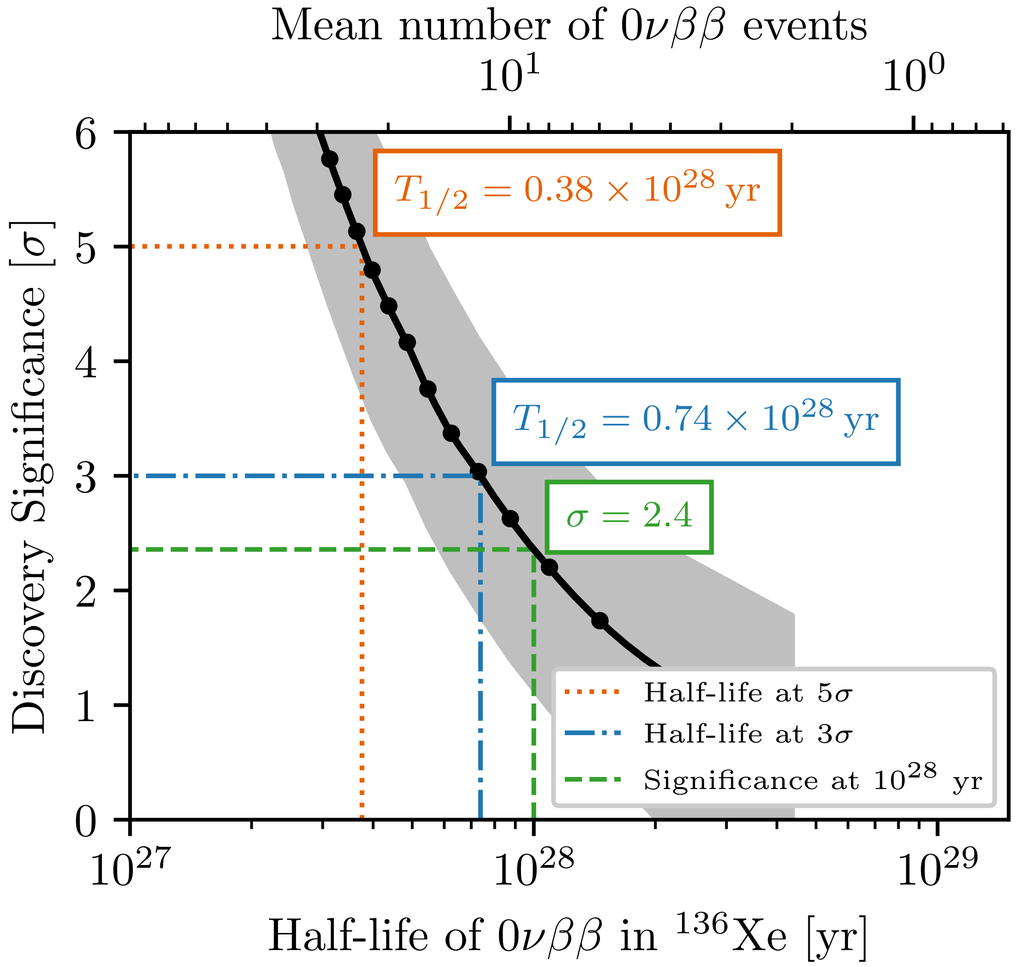

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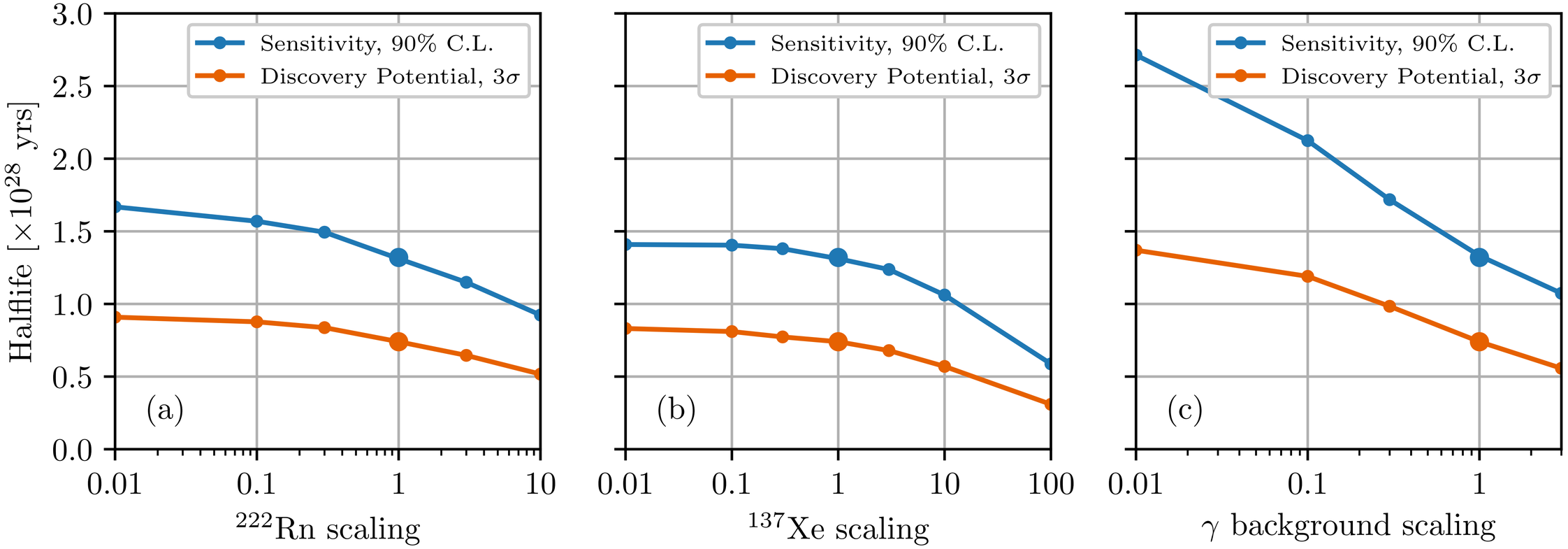
Impact of Background Modeling on the Sensitivity

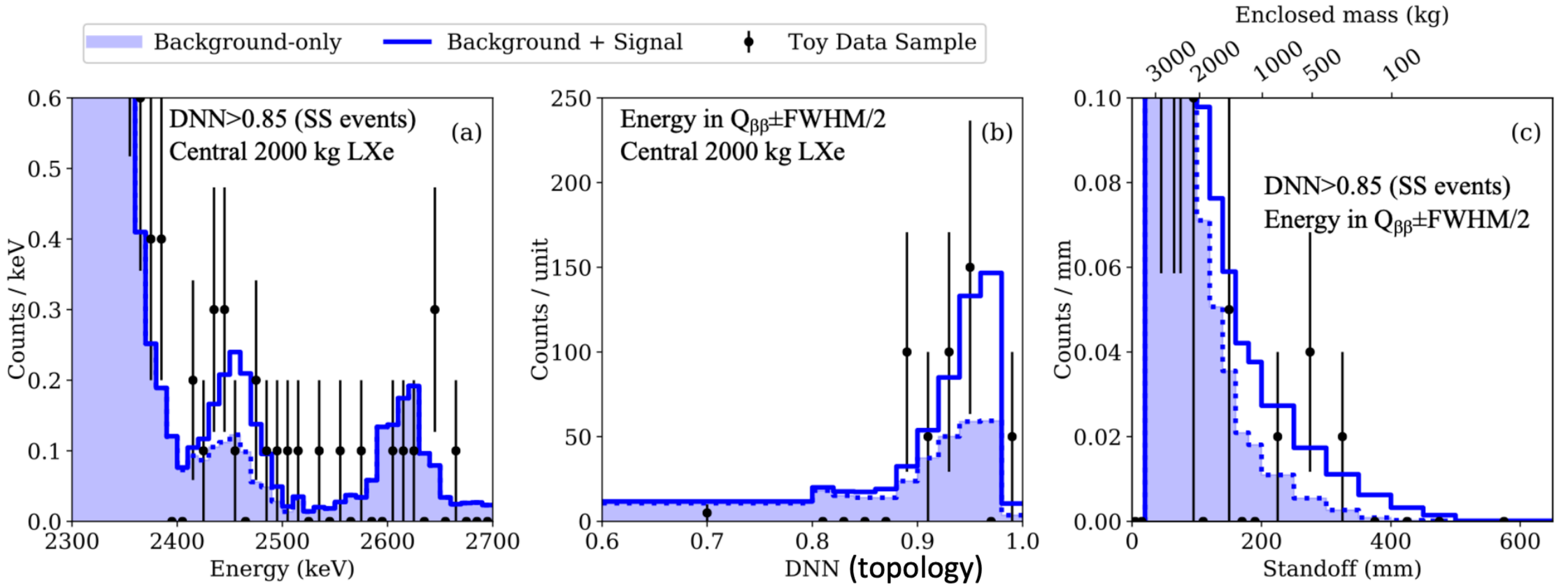
- Credible background estimation, founded on radioassay data and coupled with a detailed MC model
  - Good agreement between prediction and data demonstrated by EXO-200
- nEXO's sensitivity is robust even against misestimates of background components



Potential Discovery of $0\nu\beta\beta$ in nEXO

- Simulated $0\nu\beta\beta$ signal strength at $T_{1/2} = 0.74 \times 10^{28}\,\mathrm{yr}$
- A positive signal in nEXO unlikely to be mistaken for an unknown background!
- Possible to run control experiment with depleted xenon to confirm discovery

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



Physics Reach of nEXO

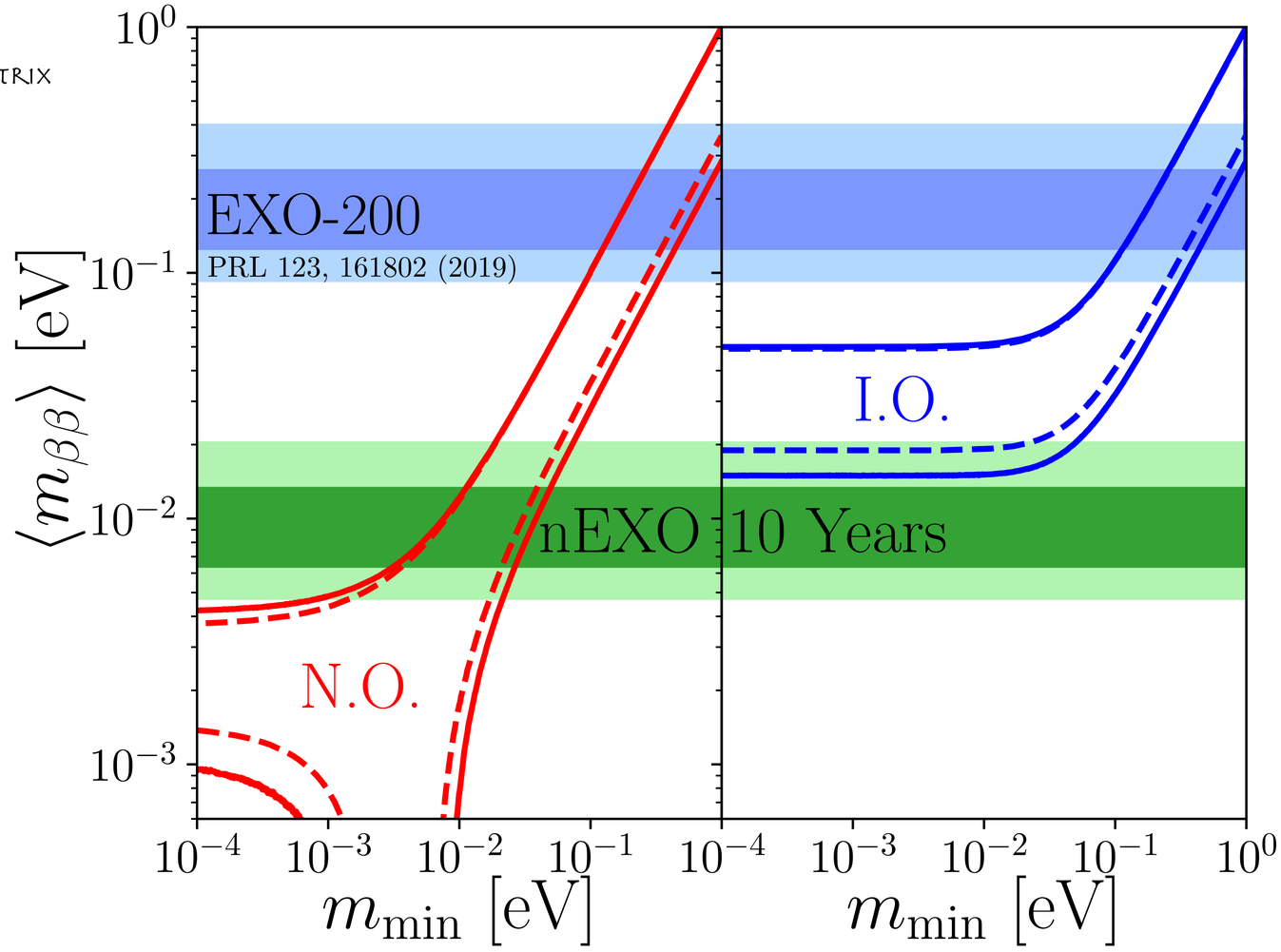
EFFECTIVE MAJORANA NEUTRINO MASS

PHASE SPACE FACTOR

NUCLEAR MATRIX ELEMENT

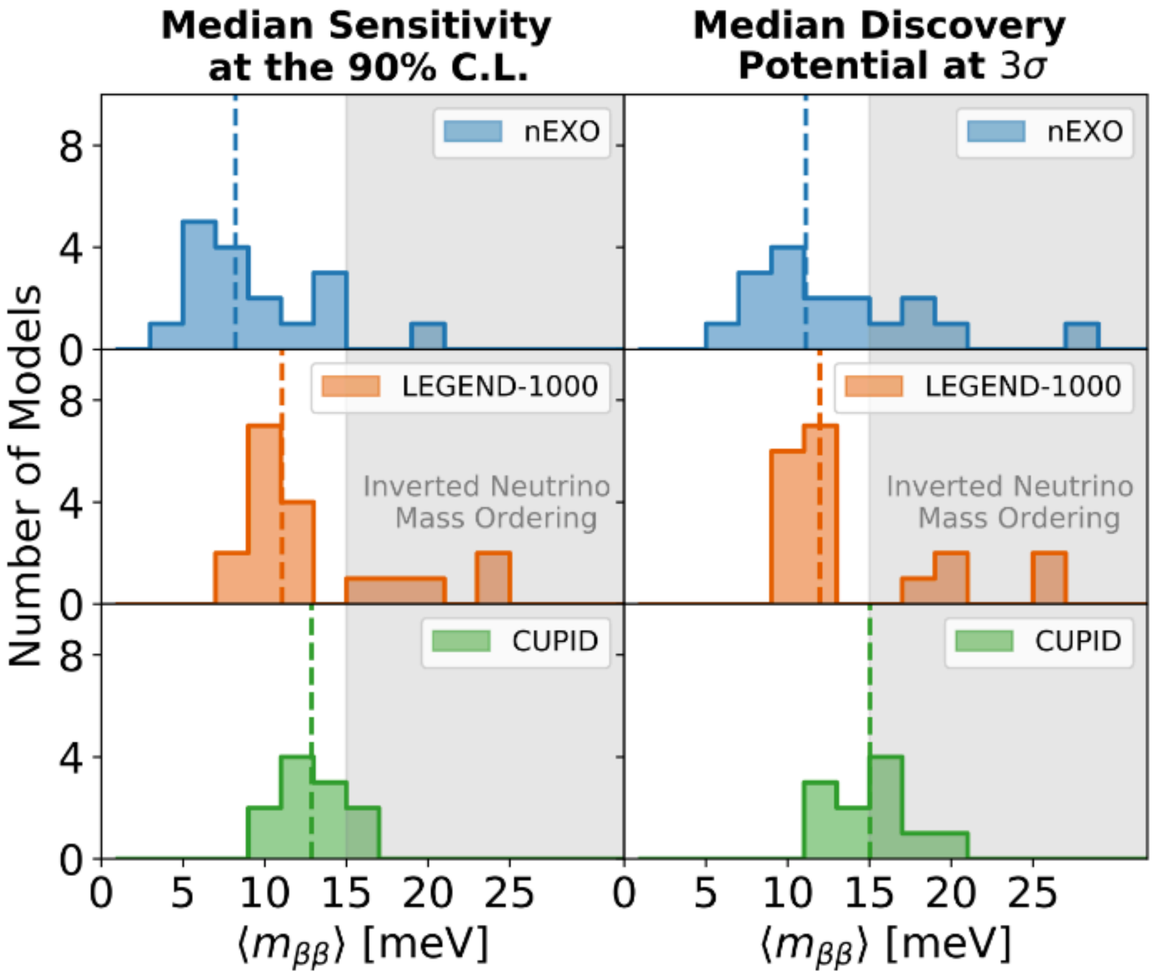
$$\frac{1}{T_{1/2}^{0\nu}} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} \left| \mathcal{M}^{0\nu} \right|^2$$

- Experimental limit on $T_{1/2}^{0\nu}$ translated into limit on $m_{\beta\beta}$
  - $T_{1/2}^{0\nu} > 1.35 \times 10^{28}\,\mathrm{yr}$
  - $\langle m_{\beta\beta}\rangle < (4.7 - 20.4)\,\mathrm{meV}$
- nEXO will completely cover the Inverted Neutrino Mass Ordering



Tonne-Scale $0\nu\beta\beta$

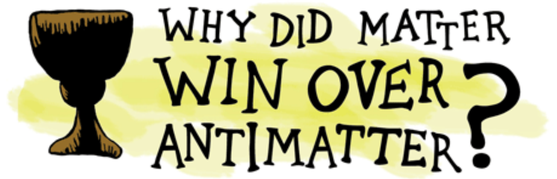
- Agnostic selection of NMEs over last 20 years
- Great promise for next-generation experiments to make a discovery
- Multi-isotope confirmation of $0\nu\beta\beta$ needed to understand physics mediating this decay
  - Additional mechanism beyond light Majorana neutrino exchange



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

Summary

- Searches for $0\nu\beta\beta$ are a powerful tool to probe physics beyond the Standard Model
- nEXO utilizes a tonne-scale LXe TPC to search for $0\nu\beta\beta$ in $^{136}\mathrm{Xe}$
  - Low intrinsic and well-understood background
  - Good energy resolution
  - Powerful background discrimination using multi-variate analysis
  - Capability for running a control experiment with natXe
- This is a very exciting time for $0\nu\beta\beta$ and a discovery might be just around the corner!!



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nEXO
Collaboration Meeting Dec 2020

BACKUP SLIDES

Improved Realism of Detector Simulation and Reconstruction

Light Simulation

- Data-driven optical properties for SiPMs
- Conservative values for reflectivities of passive TPC components
- Detailed understanding of photon propagation

Charge Simulation

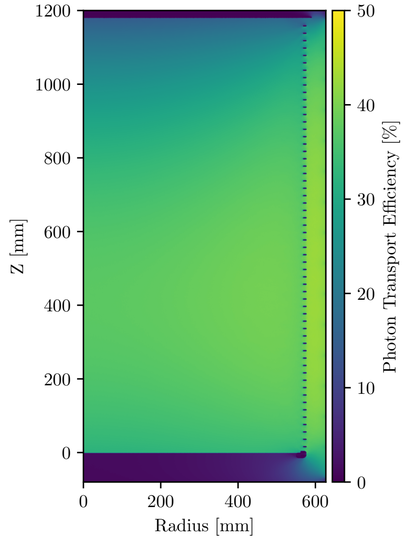
- Complete charge propagation through TPC
- Inclusion of diffusion & electron lifetime effects
- Realistic ASIC electronics noise added to waveforms

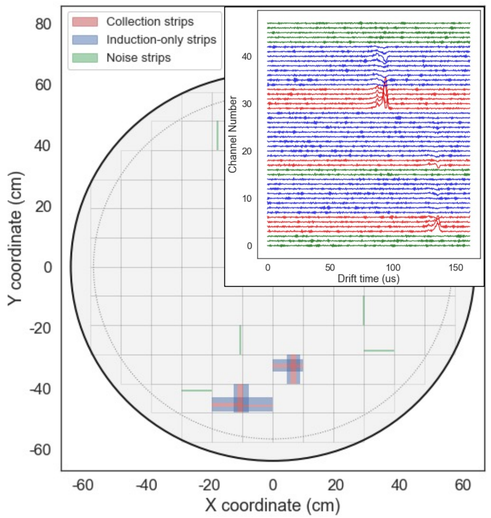
Rotated Energy

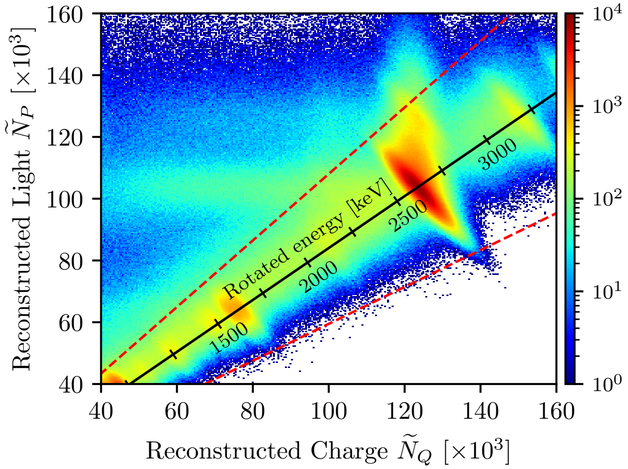
- Anti-correlation between light and charge exploited by combining both for energy estimate
- LXe “skin” effects due to open-field cage design is well understood (arXiv:2009.10231v2)

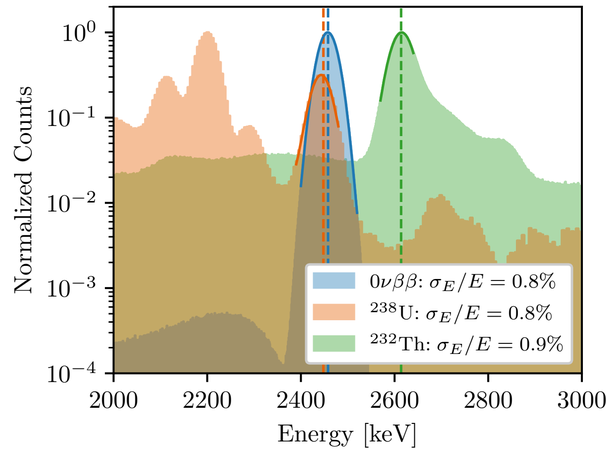
Energy Resolution

- Not dominated by either light or charge channel
- Estimated to be $\sigma_Q/Q = 0.8\,\%$
- In good agreement with semi-empirical resolution model (validated by EXO-200)









Light and Charge Detection

ENERGY RESOLUTION IN NEXO

$$\frac{\sigma_E}{E} = \frac{\sqrt{F\cdot(Q+S) + \frac{Q(1-e^{-t/\tau})}{e^{-t/\tau}} + \frac{Q^2}{(e^{-t/\tau})^2}\left(\frac{t}{\tau}\right)^2\sigma_\tau^2 + \frac{\sigma_{Q,\mathrm{noise}}^2}{(e^{-t/\tau})^2} + \frac{S}{\epsilon}\left[(1-\epsilon) + \frac{\Lambda}{(1+\Lambda)^2}\right] + \frac{\mathrm{DC}+\eta_{\mathrm{noise}}}{\epsilon^2(1+\Lambda)^2} + S^2\sigma_{lm}^2}}{Q+S}$$

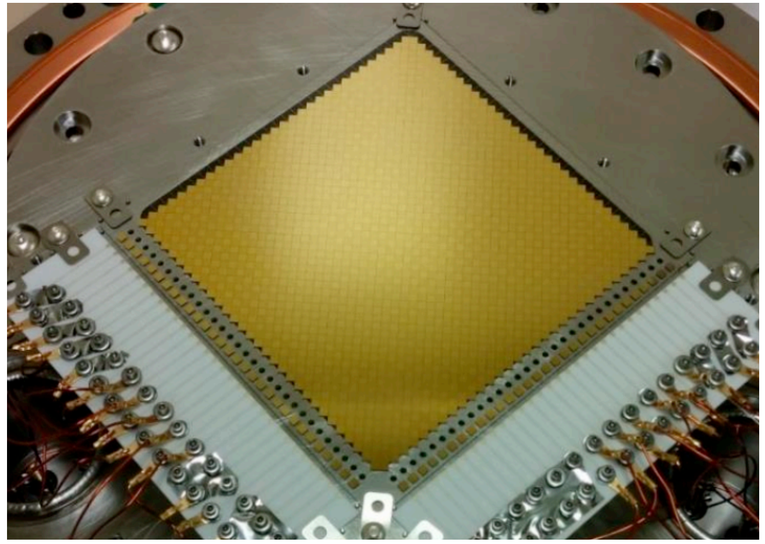
Fano noise

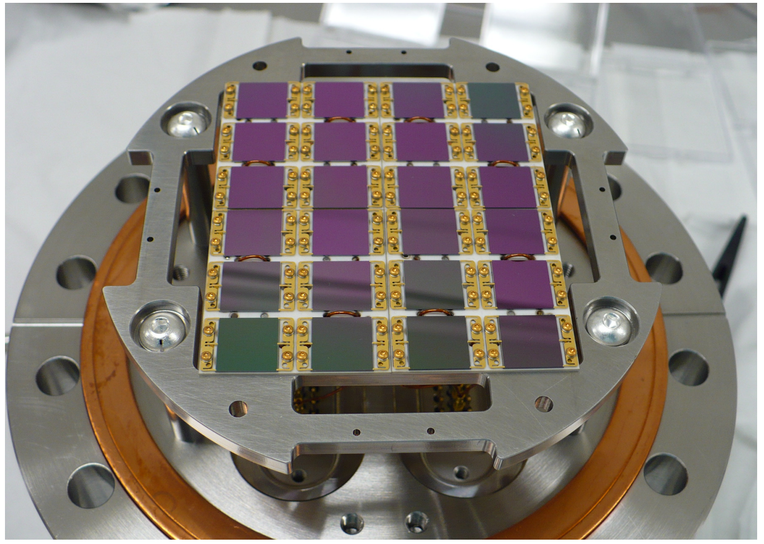
Charge Channel

- Charge collection
- e- lifetime systematic
- charge electronics

Light Channel

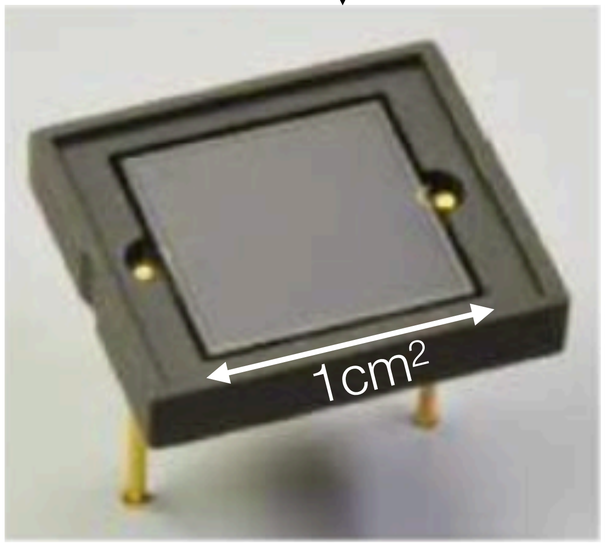
- Light collection
- Correlated avalanches
- Dark current and gain
- Lightmap Error

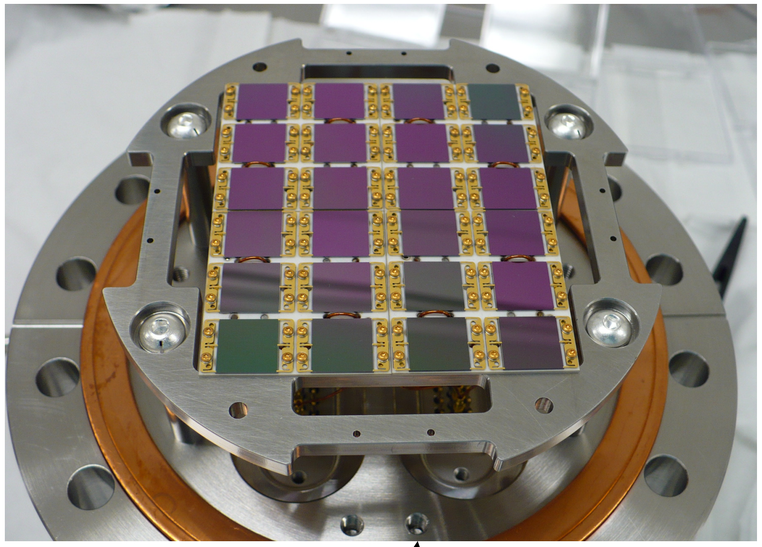




Light Detection in nEXO

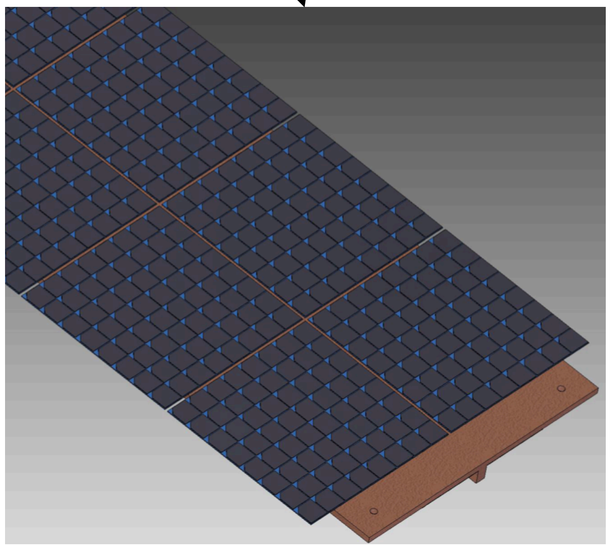
SINGLE SIPM

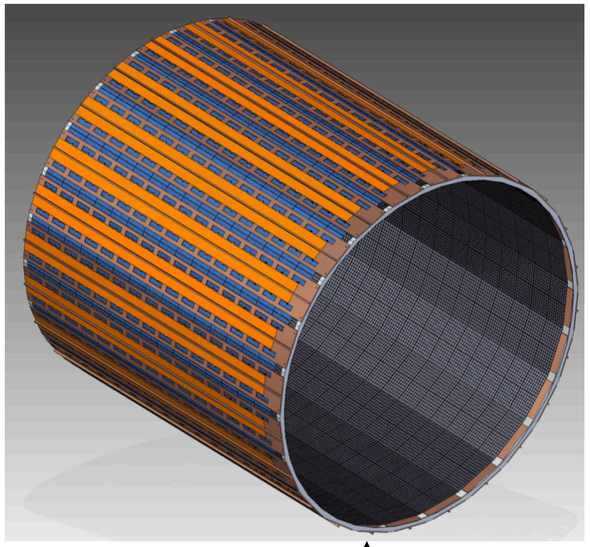




SIPM ARRAY

SIPM STAVE





FULL LIGHT DETECTION SYSTEM

Light Transport Simulations

- Crucial to optimize Photon Transport Efficiency for increased light collection

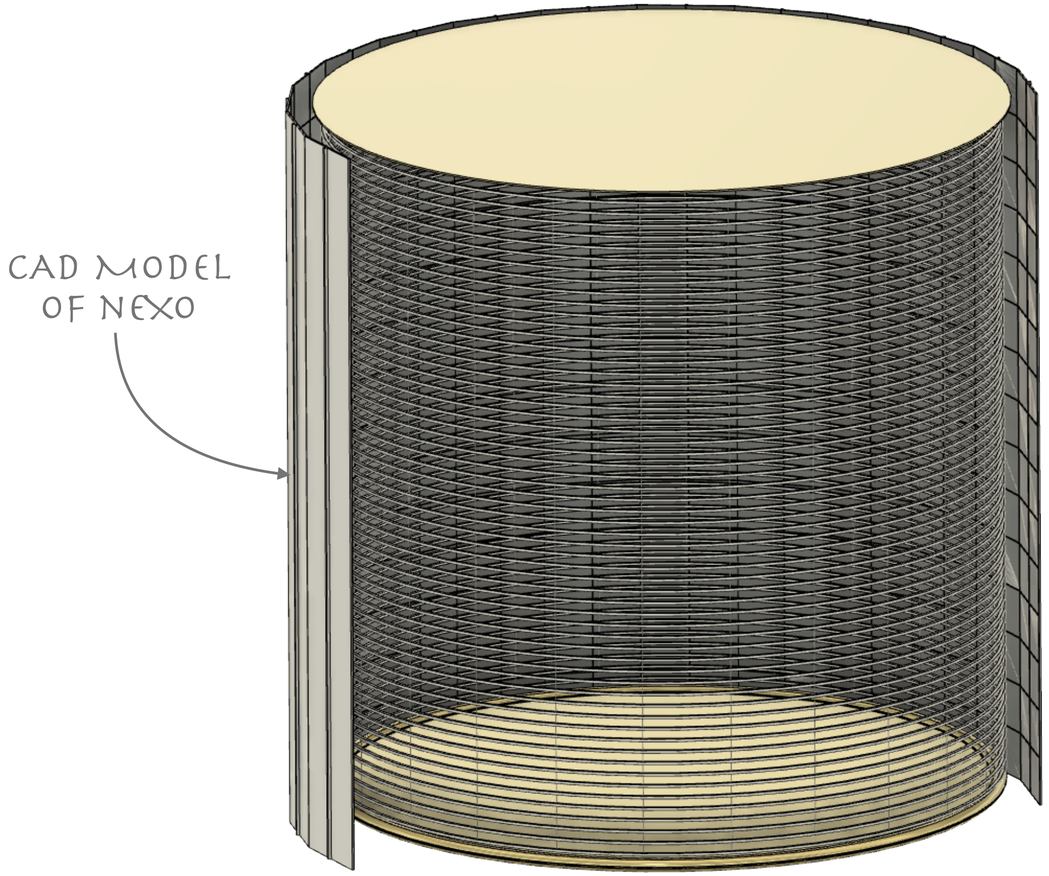
$$\epsilon = \mathrm{PDE} \cdot \mathrm{PTE}$$

- Highly dependent on reflectivity of TPC components

- Developed new light simulation of nEXO with GPU-based Chroma software
  https://github.com/nEXO-collaboration/chroma

  - > 300x faster

  - More detailed geometry

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        Light Simulation for nEXO
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Lightmap Simulation

nEXO Sensitivity and Discovery Potential: arXiv:2106.16243

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- Varied optical parameters and evaluated systematic error

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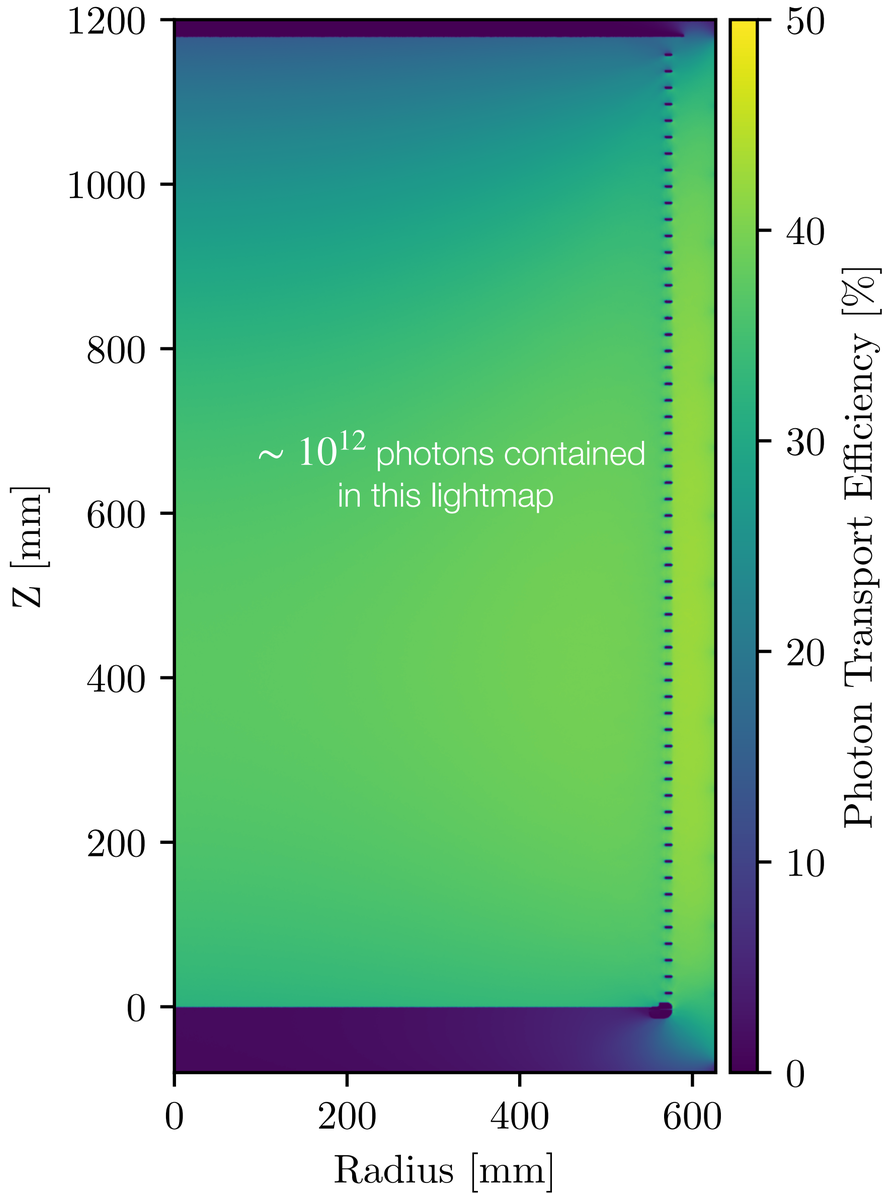
- Estimated PTE combined with measured PDE results in

$$\epsilon = \mathrm{PDE} \cdot \mathrm{PTE} \approx 6.7\,\%$$



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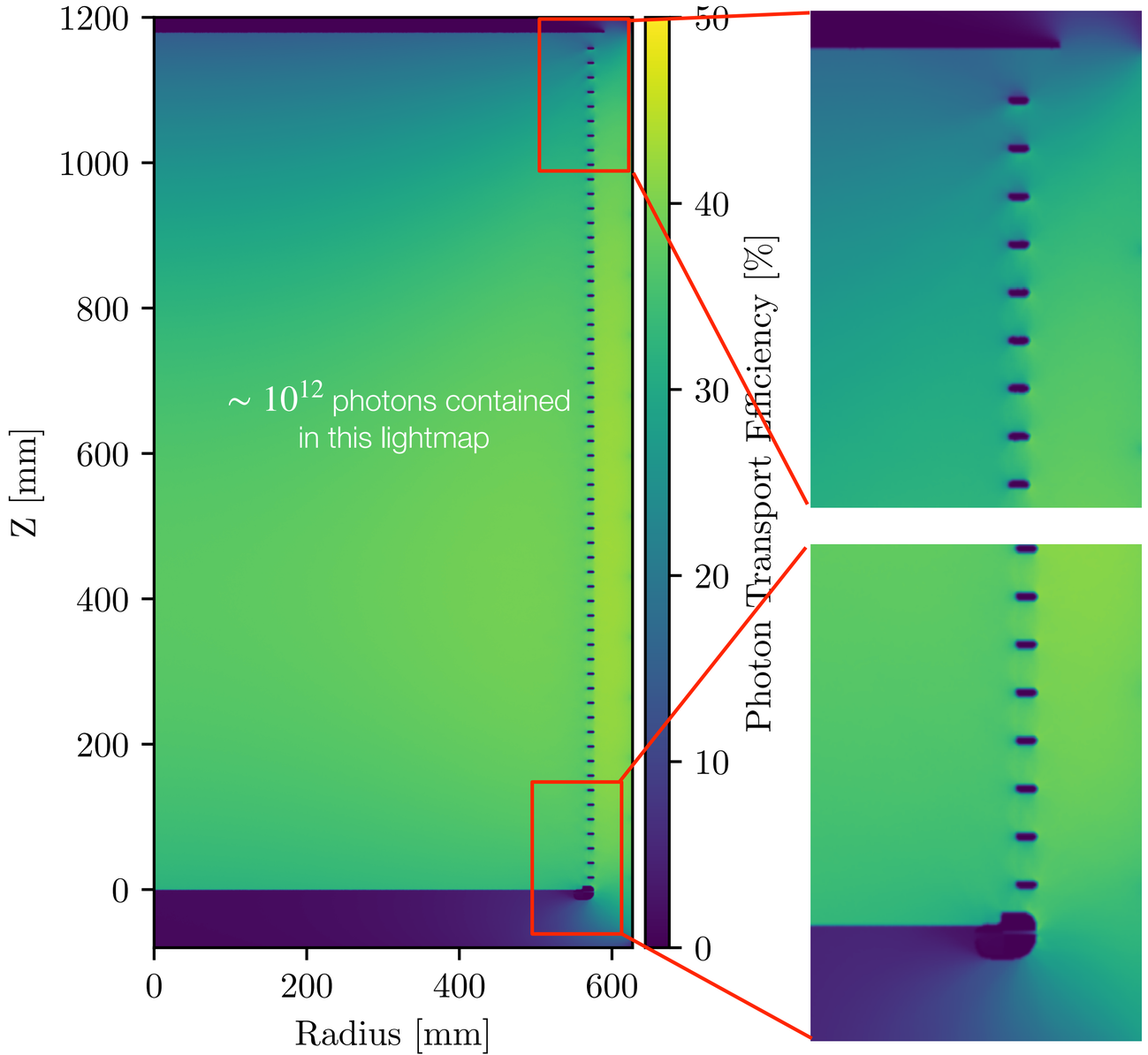
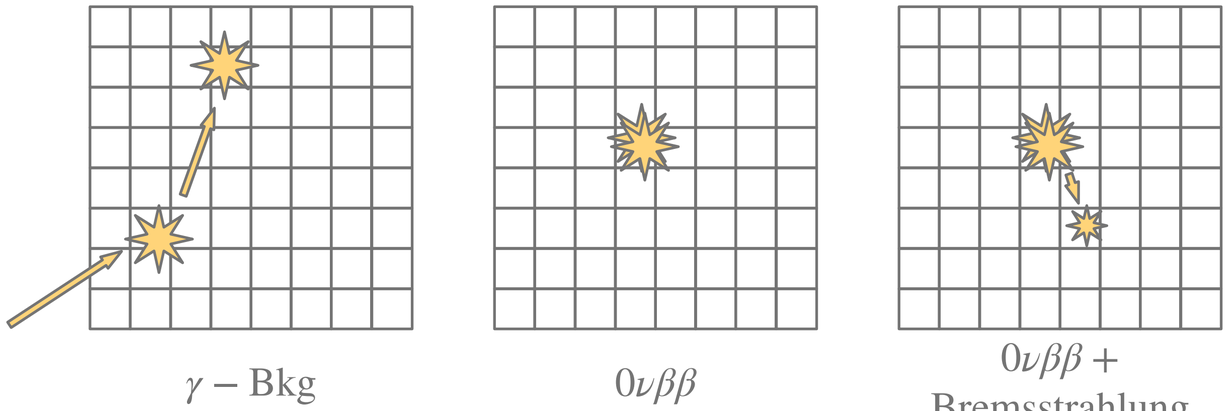
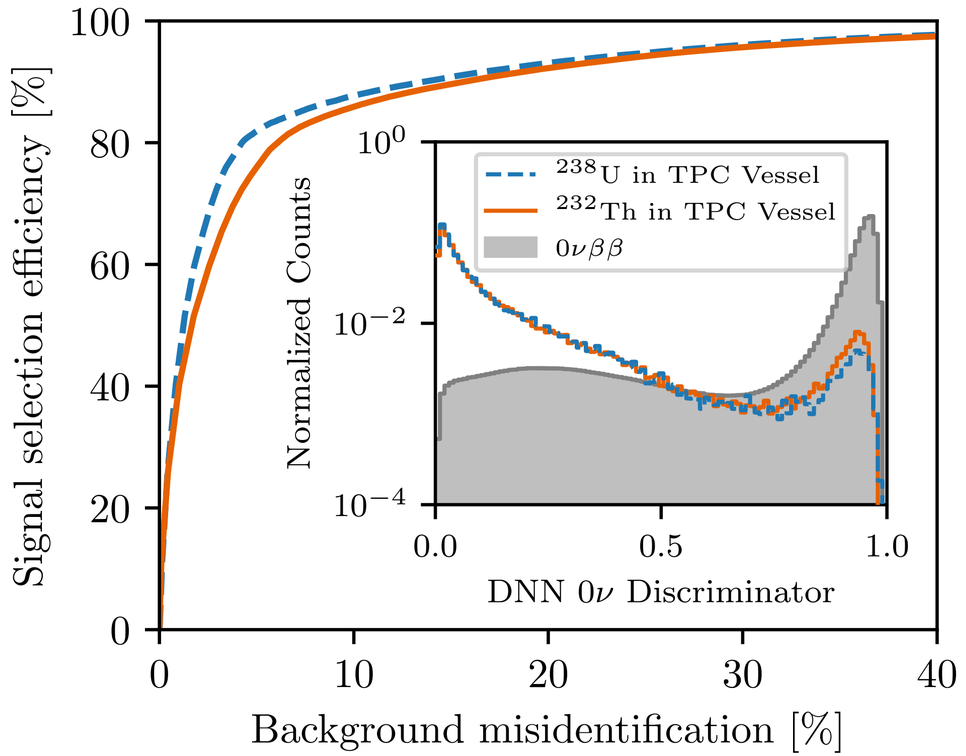


DNN-based Signal and Background Discrimination

- Motivated by success in EXO-200
  - Allows equivalent discrimination with improved signal efficiency due to recovering of signal events accompanied by Bremsstrahlung
- Trained on waveform-level simulations, as we would with real data
- Training dataset: $0\nu\beta\beta$ and γ's with
  - Uniform energy between $900\,\mathrm{keV} - 3600\,\mathrm{keV}$
  - Uniform and random distribution in the detector
- Disentangled DNN variable from the other two fit dimensions
- Expect $\sim 80\,\%$ signal efficiency at $\sim 5\,\%$ background misidentification

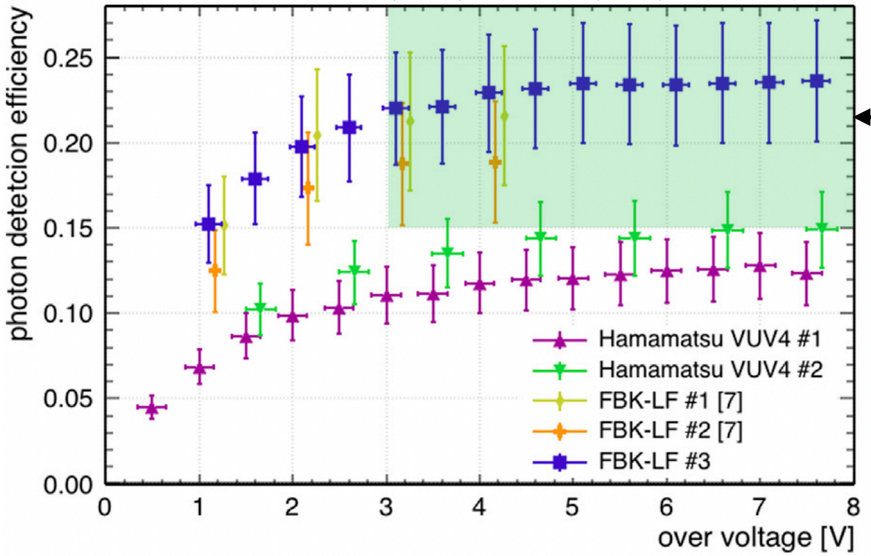




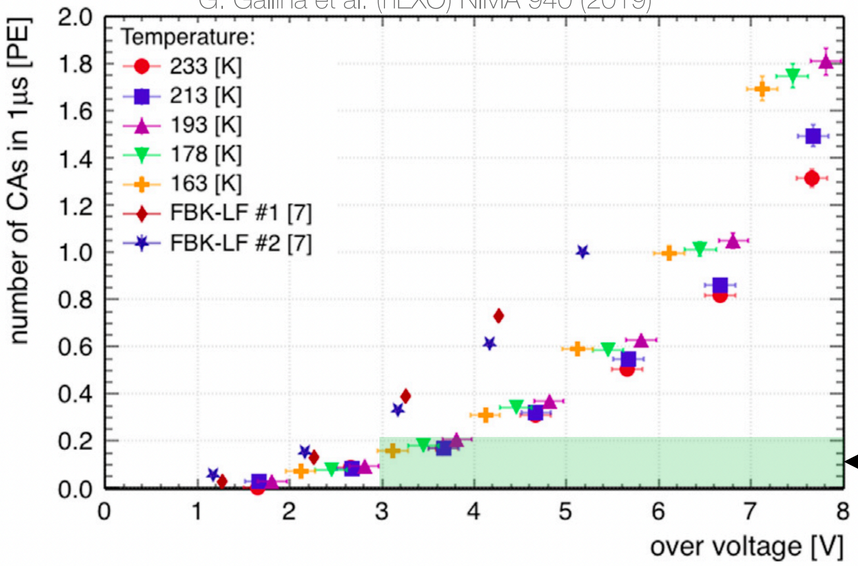
Characterization of SiPM Performance

- nEXO is running an extensive characterization campaign with several setups measuring
  - Absolute PDE in vacuum
    - Ostrovskiy et al. (nEXO) IEEE TNS 62 (2015)
    - A. Jamil et al. (nEXO) IEEE TNS 65 (2018)
    - G. Gallina et al. (nEXO) NIMA 940 (2019)
  - Have identified devices that meet our requirement
  - Working together with vendors to increase operational range

G. Gallina et al. (nEXO) NIMA 940 (2019)



G. Gallina et al. (nEXO) NIMA 940 (2019)

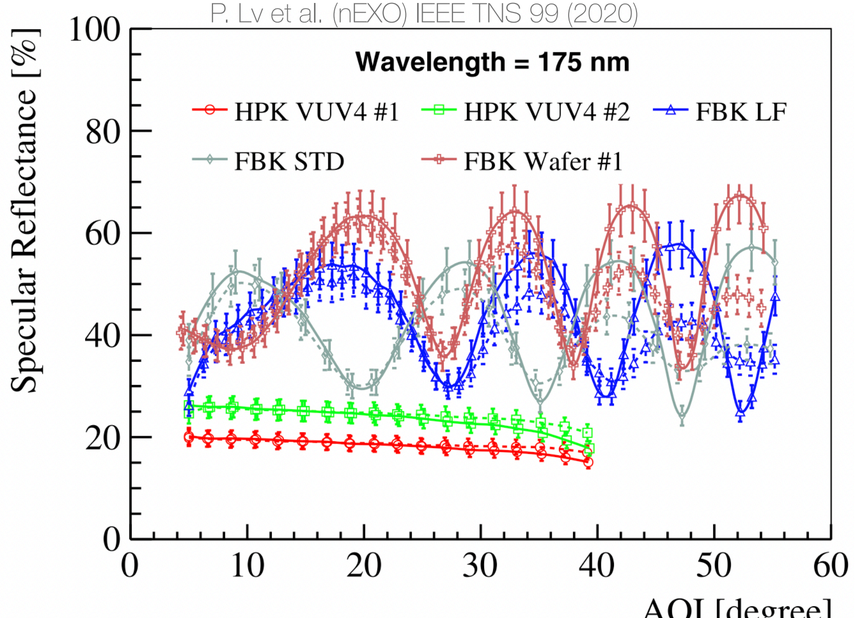


Within nEXO requirements

Characterization of SiPM Performance

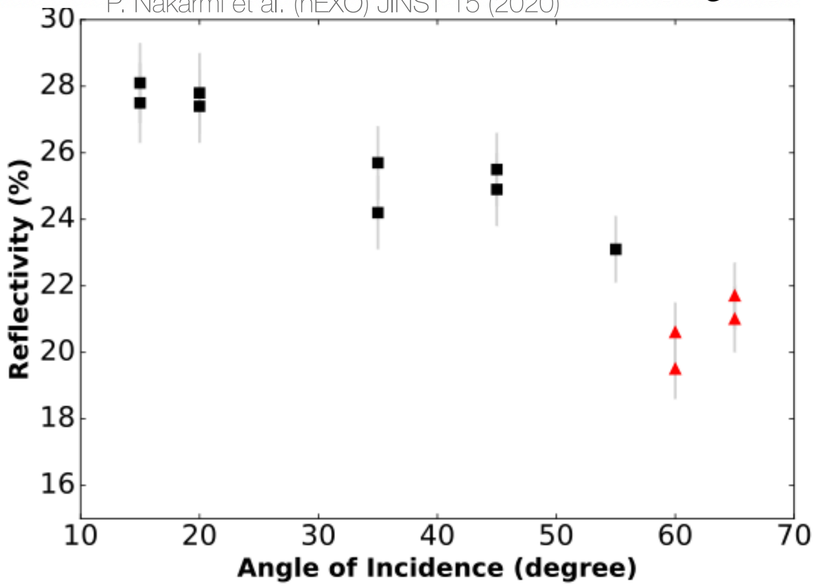
- nEXO is running an extensive characterization campaign with several setups measuring
  - Reflectivity in vacuum and LXe
    - P. Nakarmi et al. (nEXO) JINST 15 (2020)
    - P. Lv et al. (nEXO) IEEE TNS 99 (2020)
    - M. Wagenpfeil et al. (nEXO) In prep. (2021
  - Photons reflected from SiPM surface can be detected by other SiPMs
  - Reflectivity of passive TPC components crucial for good light collection efficiency

P. Lv et al. (nEXO) IEEE TNS 99 (2020)



Vacuum

P. Nakarmi et al. (nEXO) JINST 15 (2020)



Liquid xenon