

# Neutrinoless Double Beta Decay with nEXO: Experiment Concept, R&D, and Sensitivity

LNGS Seminar

More details in [arXiv:1710.05075](https://arxiv.org/abs/1710.05075)

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November 8, 2017



# Neutrino Physics

## Knowns

- $\nu$  flavor change
- Non-zero  $\nu$  masses
- 3 light interacting neutrinos
- Observed  $\nu$  from atmospheric, reactor, solar, supernovae, beam, outer space

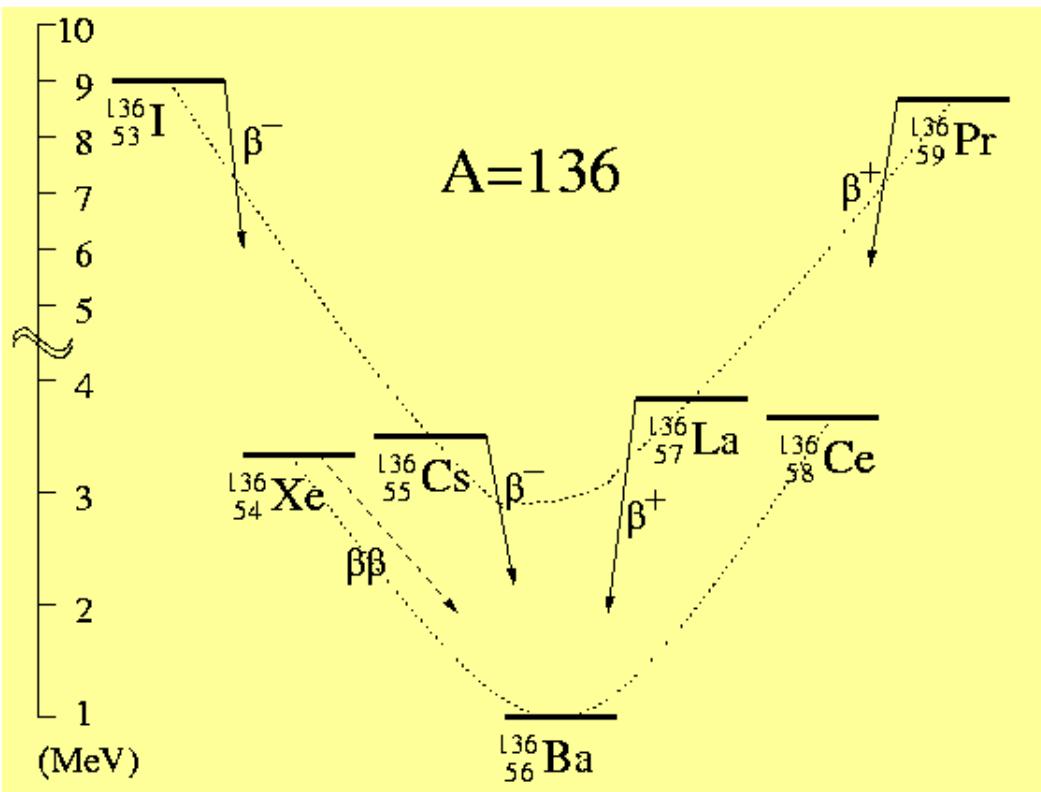
## Unknowns

- Absolute  $\nu$  masses
- $\nu$  mass ordering
- $\nu$  nature: Majorana or Dirac particles?
- Sterile neutrinos?
- CP violation?
- Why  $\nu$  much lighter than other fermions?
- ...

Profound consequences:

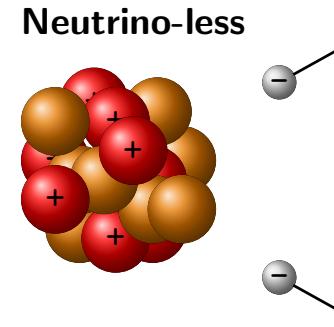
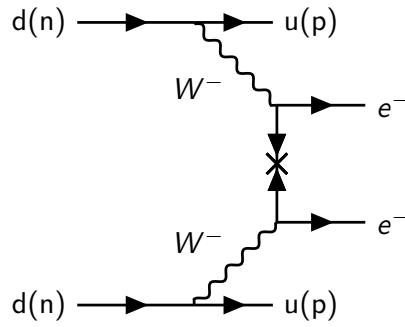
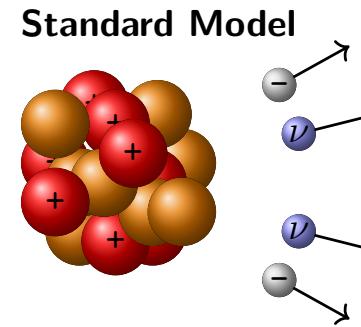
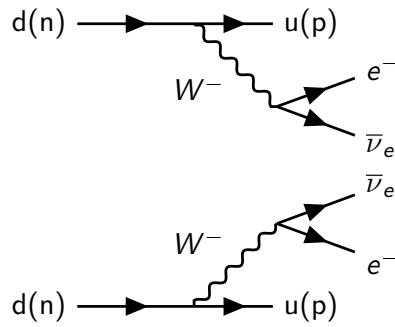
- physics beyond the Standard Model Physics
- origin of the matter/antimatter asymmetry in the universe

# Double Beta Decay



Decay	Q	i.a. %
$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$	4.271	0.187
$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$	<b>2.040</b>	<b>7.8</b>
$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$	2.995	9.2
$^{96}\text{Zr} \rightarrow ^{96}\text{Mo}$	3.350	2.8
$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$	3.034	9.6
$^{110}\text{Pd} \rightarrow ^{110}\text{Cd}$	2.013	11.8
$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$	2.802	7.5
$^{124}\text{Sn} \rightarrow ^{124}\text{Te}$	2.228	5.64
$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$	<b>2.533</b>	<b>34.5</b>
$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$	<b>2.458</b>	<b>8.9</b>
$^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$	3.367	5.6

# Neutrinoless Double Beta Decay ( $0\nu\beta\beta$ )



- $\beta\beta0\nu$  observation implies:
  - Lepton number non conservation
  - Existence of new class of particles: Majorana fermions

# $0\nu\beta\beta$ and Neutrino Mass

- Under assumption of  $0\nu\beta\beta$  being mediated by a light Majorana  $\nu$  exchange:

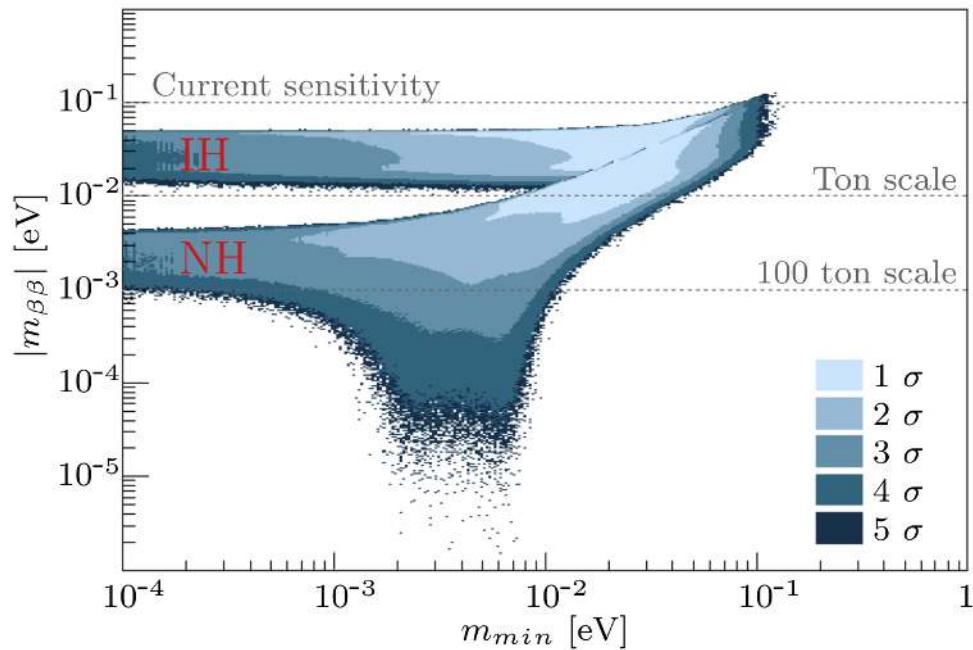
$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} |M^{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

phase space factor  
 $\sim Q^5$

nuclear matrix elements  
» uncertainties

effective Majorana neutrino mass

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^3 U_{ei}^2 m_i \right|$$

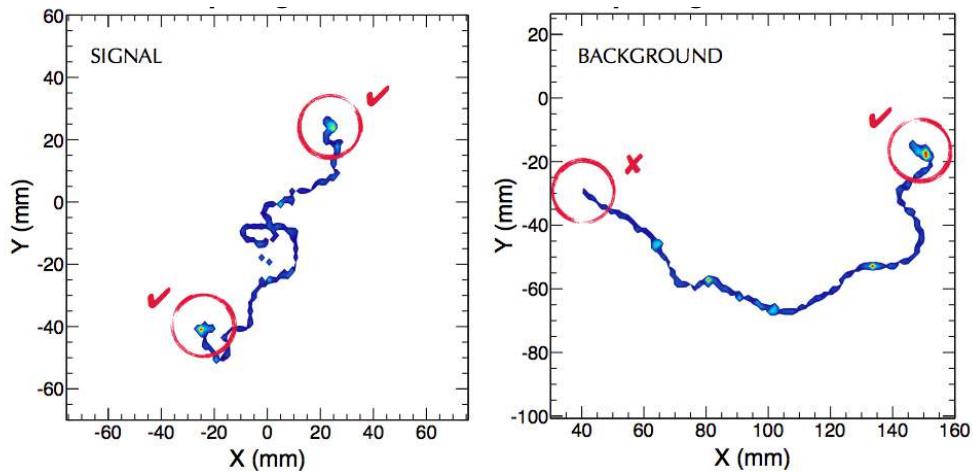
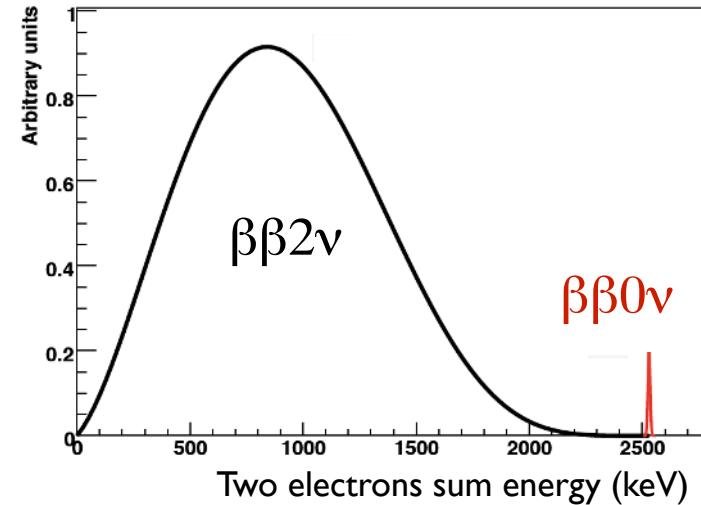


**Fig. 6** Effective Majorana mass as a function of the lightest neutrino mass with the application of the cosmological bound. The different colors correspond to the  $1, \dots, 5 \sigma$  coverage regions.

arXiv:1510.01089, G. Benato, 15Oct2015  
Also, arXiv:1705.01945, A. Caldwell et al

# $0\nu\beta\beta$ Detection Signatures

- Mono-energetic line at  $Q_{\beta\beta}$  in the sum electron-energy spectrum
- Localized interaction
- Position (e.g. correlates with source distribution)
- Emission of two correlated electrons
- Daughter nuclide produced
- Constant decay rate, uncorrelated with other events

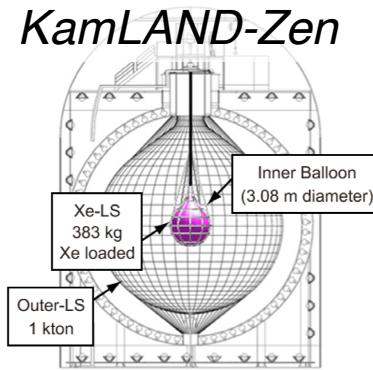


# $0\nu\beta\beta$ with $^{136}\text{Xe}$

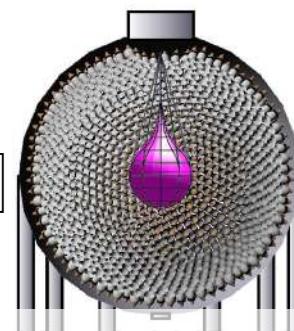
- $^{136}\text{Xe}$  can be employed in a range of highly-scalable detectors, as part of a broad, world-wide program employing multiple isotopes/technologies
- Existing  $^{136}\text{Xe}$  experiments reach sensitivities of  $T_{1/2} > 5 \times 10^{25} \text{ yr}$ , with next-generation experiments aiming for  $\sim 10^{28} \text{ yr}$

## Liquid (organic) scintillators:

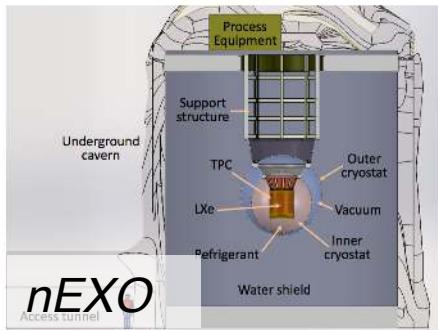
*KamLAND-Zen*



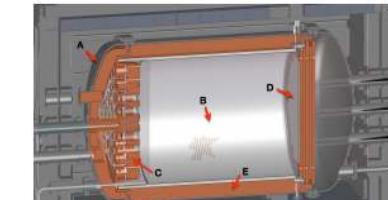
*KamLAND2-Zen*



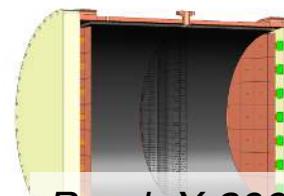
## Liquid Xe TPCs:



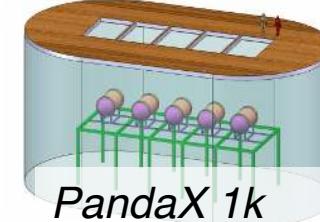
## Gas Xe TPCs:



*NEXT-100/NEXT-ton*



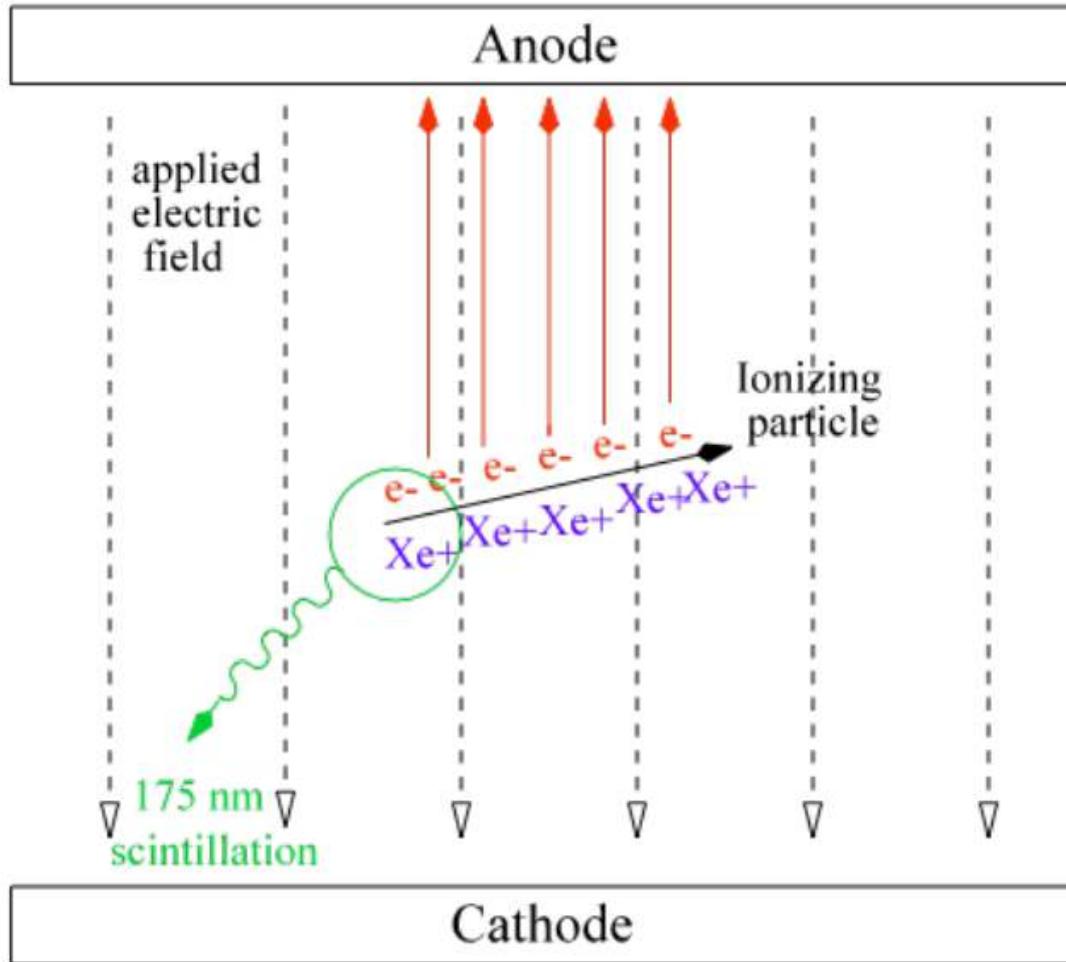
*PandaX 200*



*PandaX 1k*

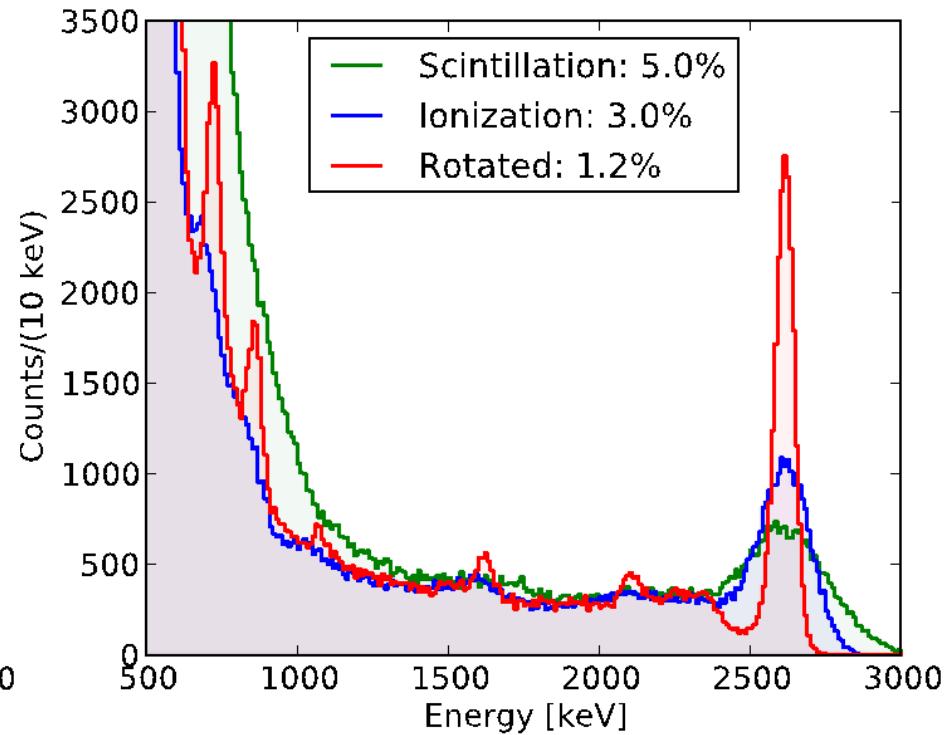
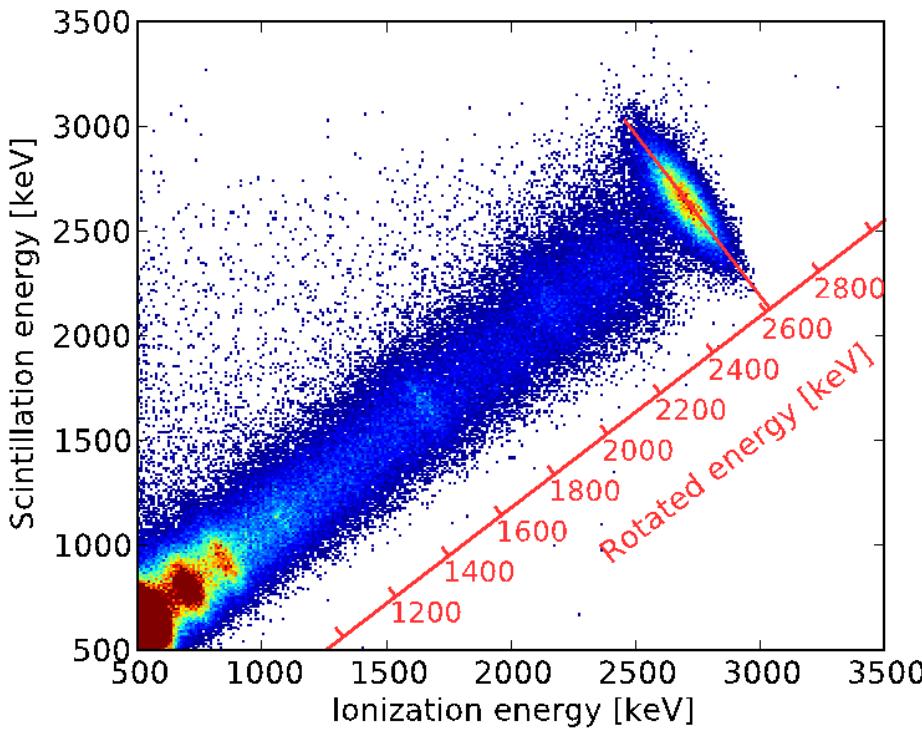
From D. Moore

# Liquid Xe TPCs



# Large LXe TPCs: a Technology for Discovery

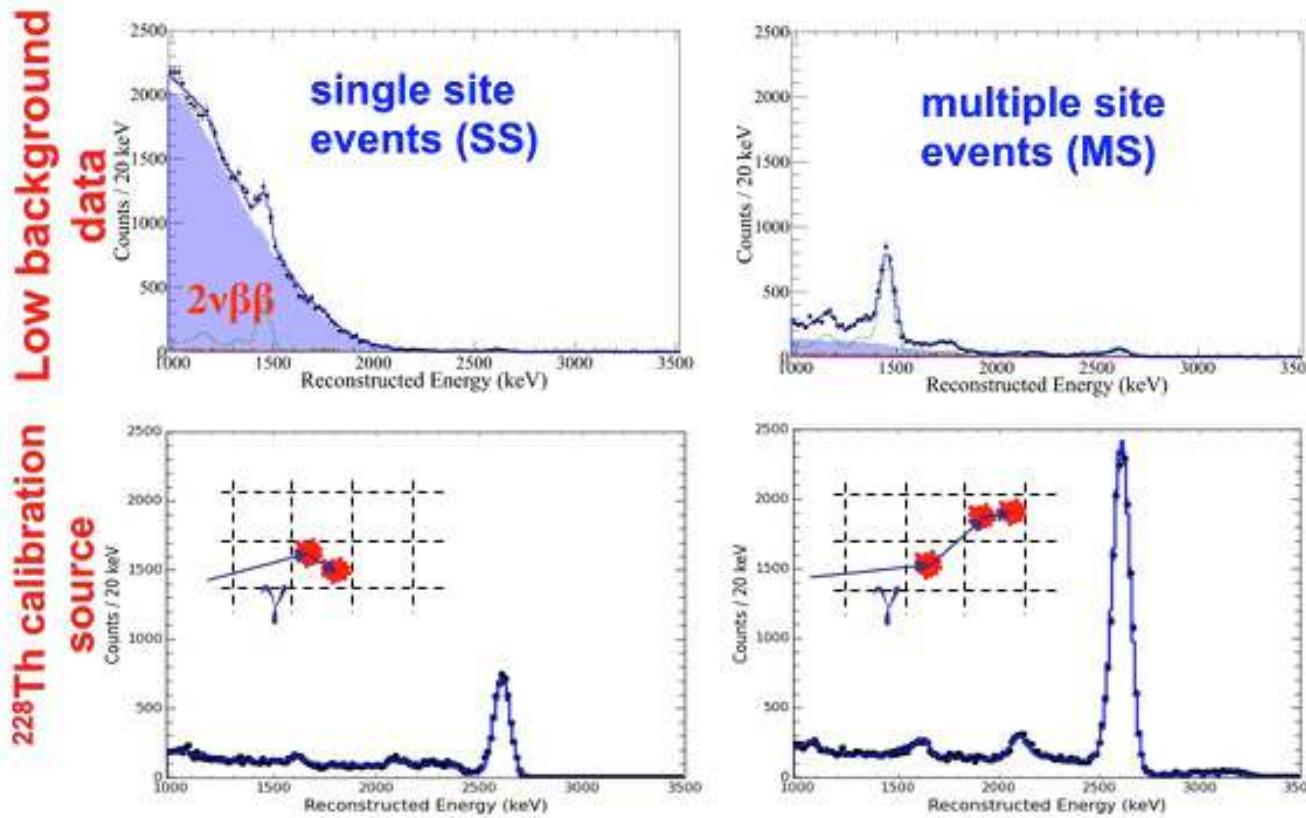
- A LXe Time Projection Chamber like nEXO allows a **multi-parameter measurement**:
  1. Interaction **energy** from combined ionization/scintillation



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

# Large LXe TPCs: a Technology for Discovery

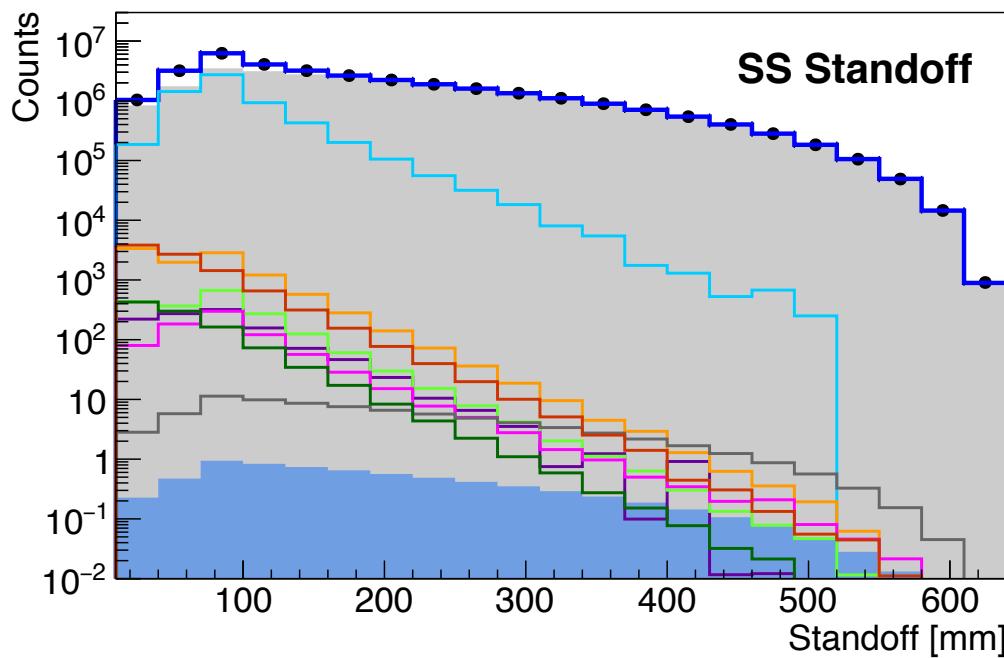
- A LXe Time Projection Chamber like nEXO allows a multi-parameter measurement:
  1. Interaction **energy** from combined ionization/scintillation
  2. Interaction **multiplicity** i.e. Single-Site (SS) or Multi-Site (MS)



Multiplicity can be used to characterize backgrounds

# Large LXe TPCs: a Technology for Discovery

- A LXe Time Projection Chamber like nEXO allows a multi-parameter measurement:
  1. Interaction **energy** from combined ionization/scintillation
  2. Interaction **multiplicity** i.e. Single-Site (SS) or Multi-Site (MS)
  3. **Stand-off distance** from interaction 3D position

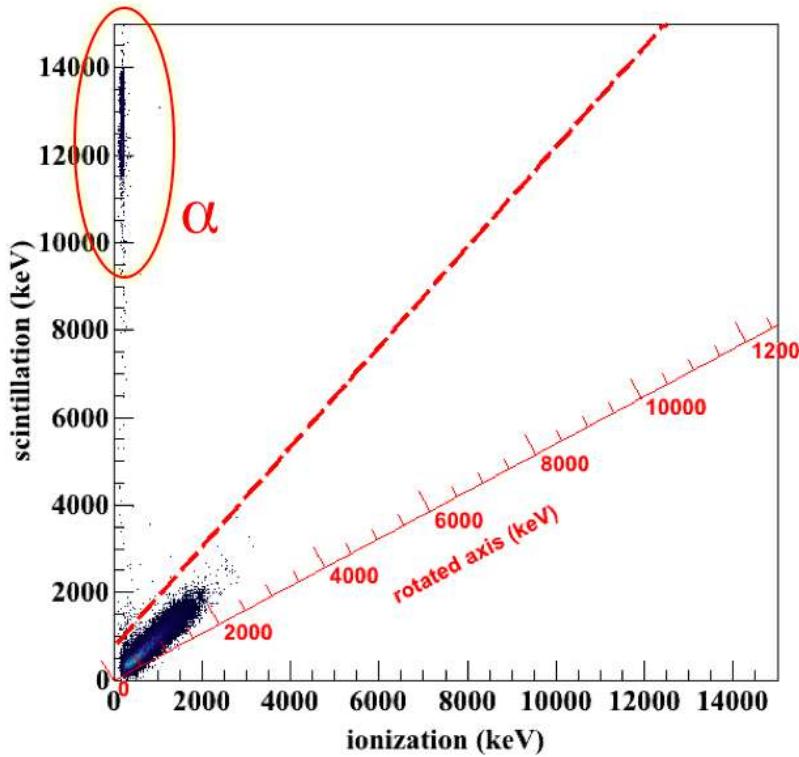


External backgrounds rapidly reduced by Xe attenuation

Internal events (signal or background) uniformly distributed

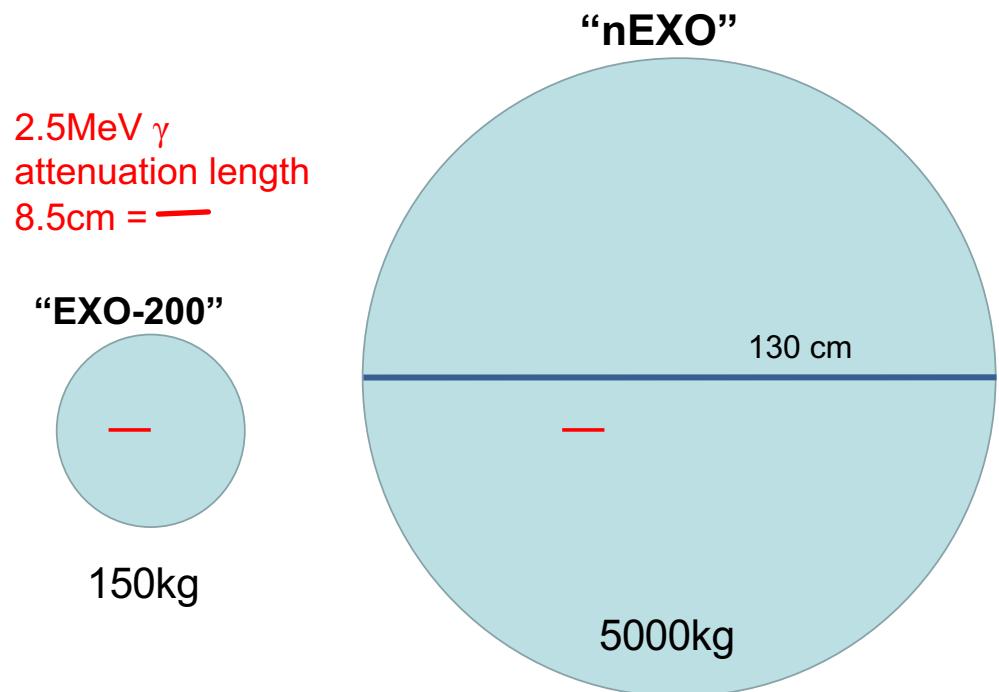
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  4. **Particle type**



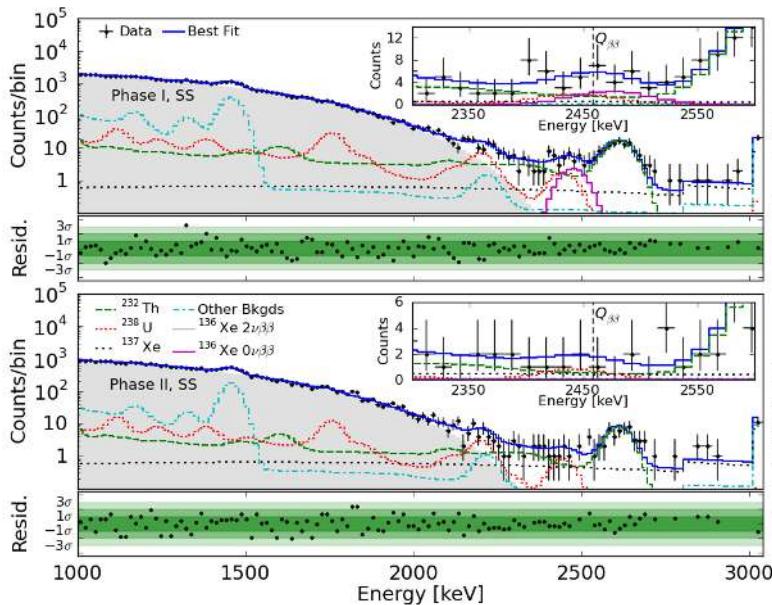
# Large LXe TPCs: a Technology for Discovery

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  3. **Stand-off distance** from interaction 3D position
  4. **Particle type**
- Homogenous detectors



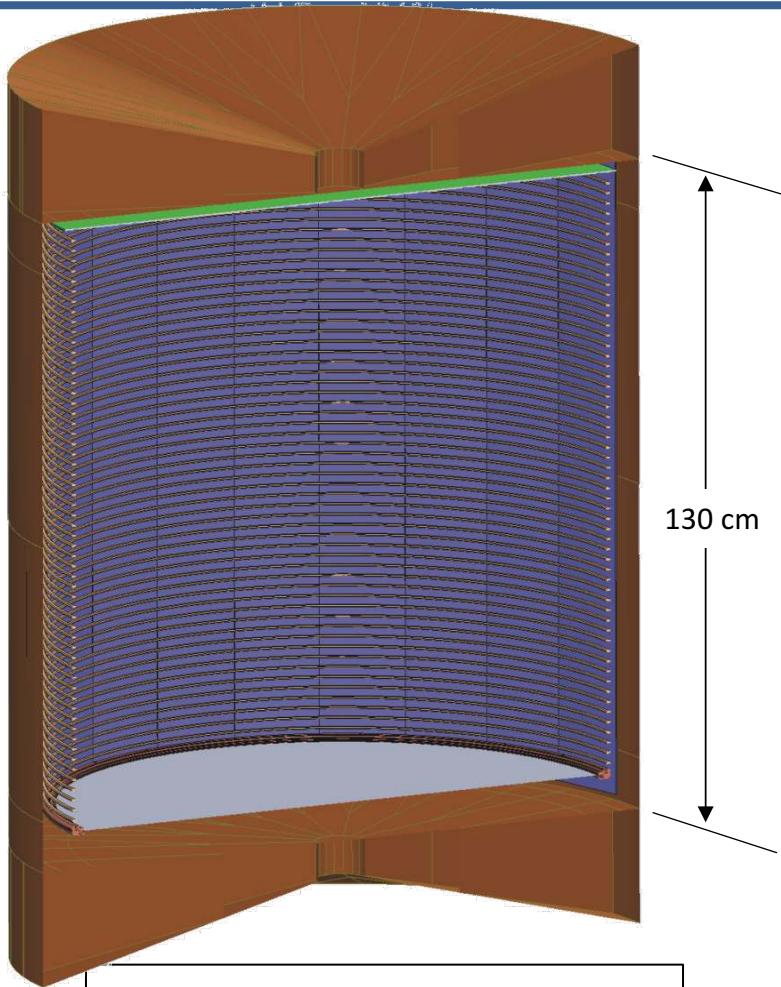
# Building on EXO-200 Experience

- Performance:
  - Energy resolution:  $1.23\% \sigma/Q_{\beta\beta}$
  - Fraction of SS event:  $\sim 20\%$
  - Electron lifetime  $\sim 3$  ms
- Multi-parameter analysis
- Background composition
  1. Th+U background from external components
  2.  $^{137}\text{Xe}$  (cosmogenic)
  3.  $^{222}\text{Rn}$
- Background model from fit match pre-data taking background predictions from radioassay



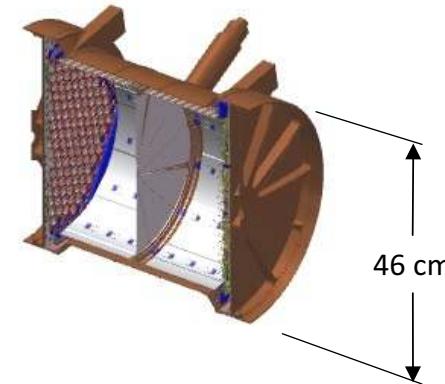
Method	$^{232}\text{Th}$ cnts in $Q_{\beta\beta} \pm 2 \cdot \sigma_{\beta\beta}$	$^{238}\text{U}$ cnts in $Q_{\beta\beta} \pm 2 \cdot \sigma_{\beta\beta}$
EXO-200 data	10.3-13.9	5.3-7.1
EXO-200 radioassay	0.5-7.7	2.0-9.5
Pre-data prediction	0.9-10.3	6.3-26.8

# nEXO Design



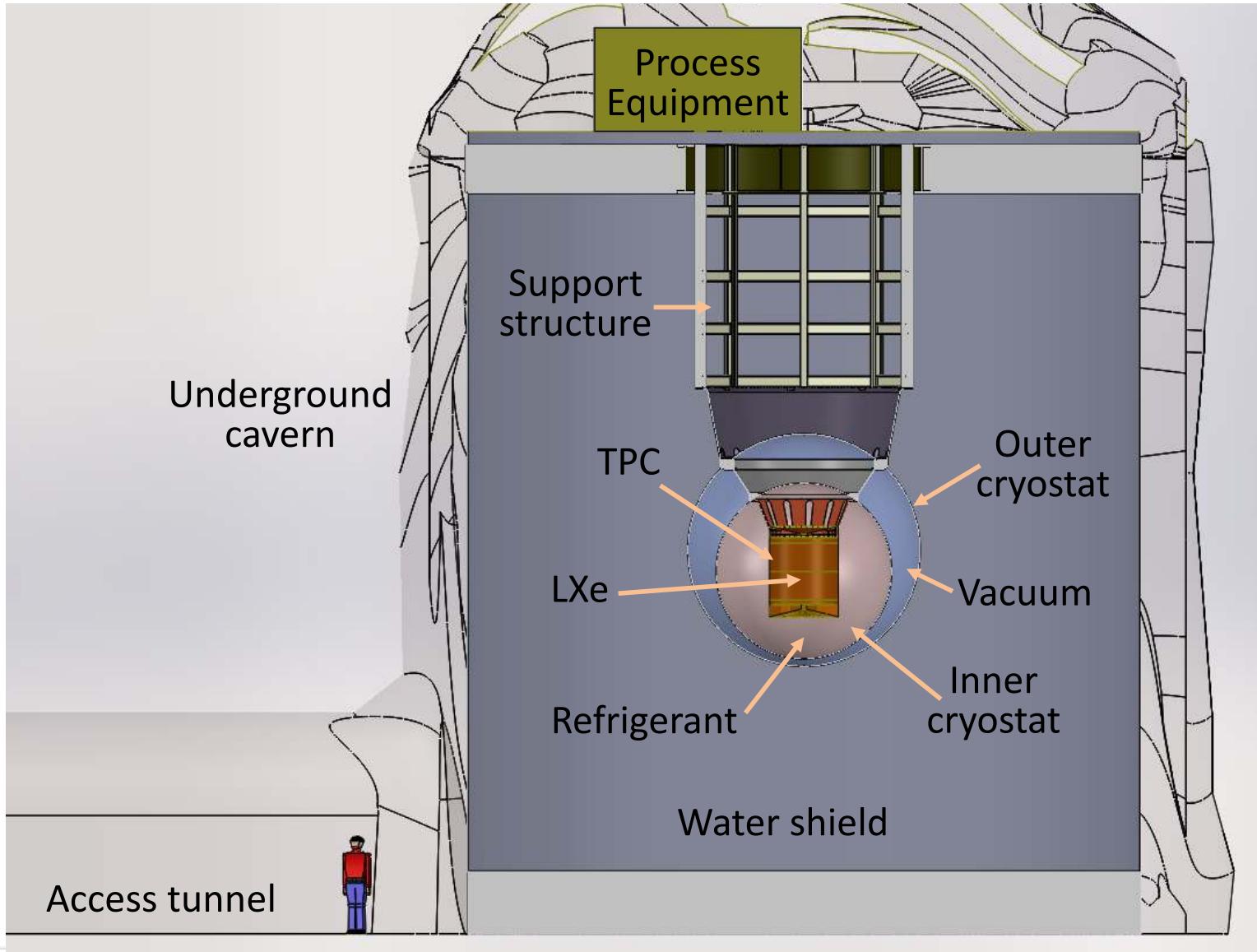
**nEXO**  
 $9.2 \times 10^{27}$  y proj. sens.  
90% CL, after 10 y. arXiv:1710.05075

A 5000 kg enriched (90%)  
LXe TPC, directly  
extrapolated from EXO-200

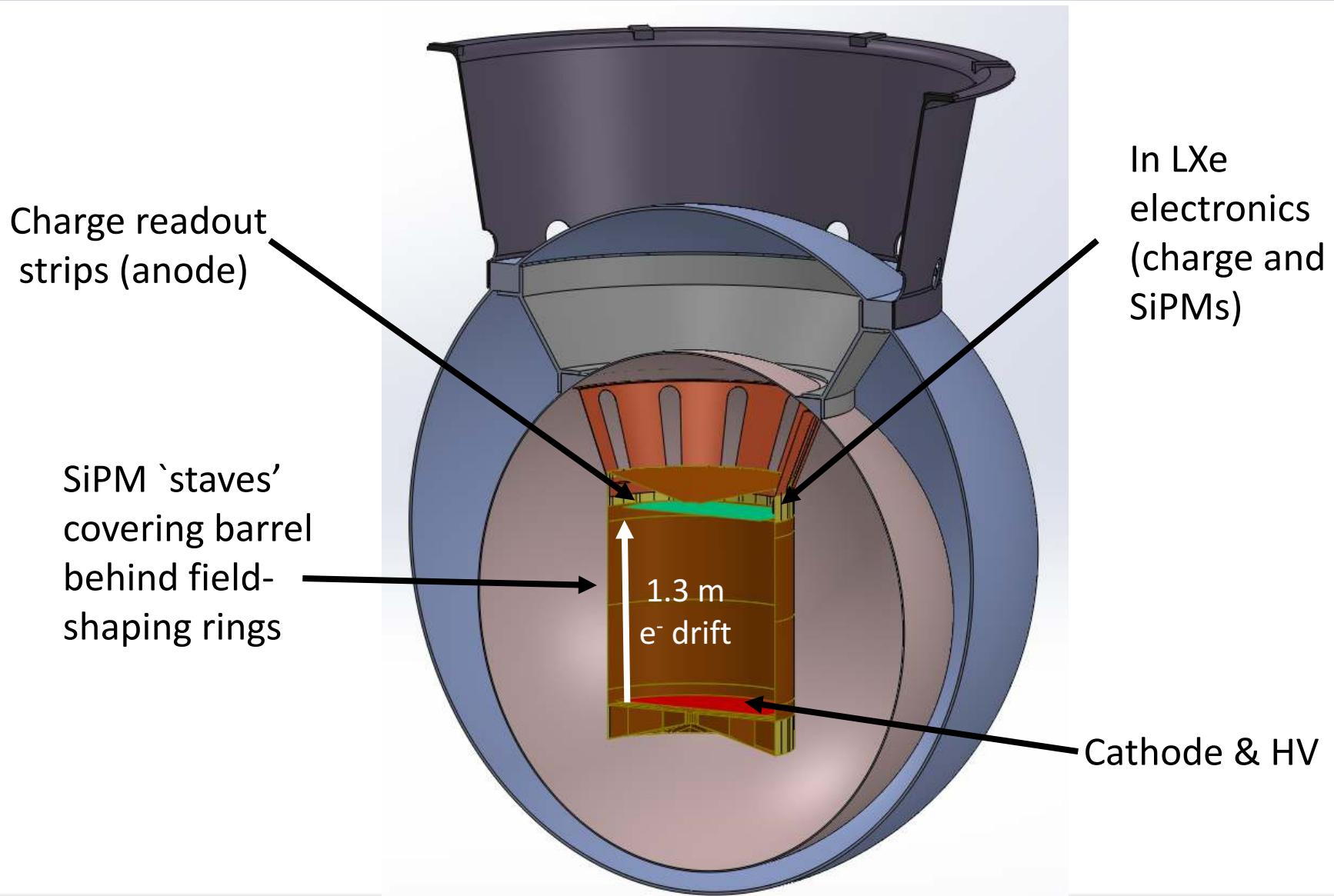


**EXO-200**  
 $3.7 \times 10^{25}$  y sensitivity  
90% CL, 177.6 kg.y. arXiv:1707.08707

# nEXO Design



# nEXO Technological Improvements



# High Voltage R&D Test Setups

30l LXe Bern HV test setup now at **Carleton U.** with cryogenic cameras



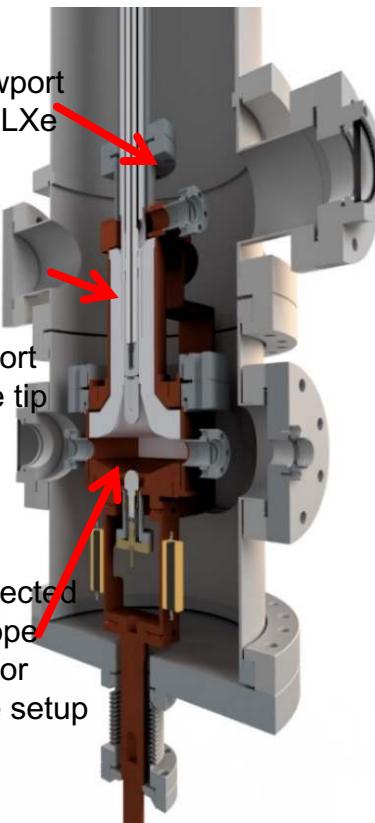
HV tests of ~30cm scale geometries

400 cc LXe HV setup at **SLAC**

Upper viewport just below LXe Level.

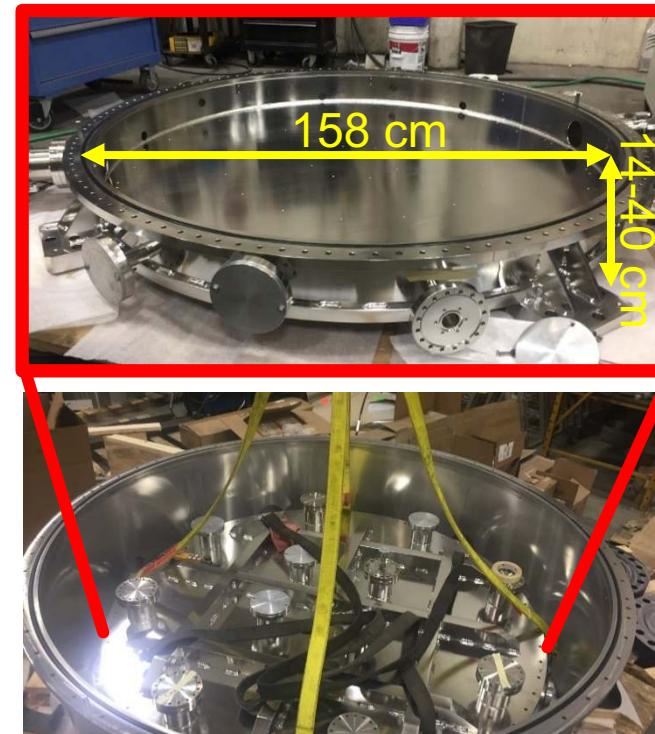
Lower viewport and Cathode tip

Anode connected to oscilloscope, glitch detector or HV probe setup



Test of breakdown voltage in LXe for different small size geometries

Max 800 kg LXe setup at **LLNL** to accommodate full or near-full size parts horizontally

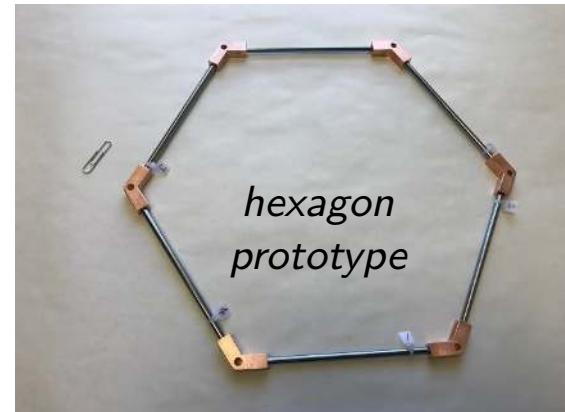
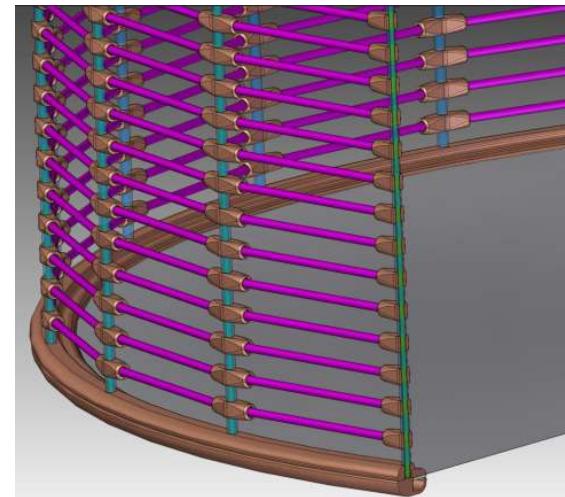


HV tests in LXe for different full-nEXO diameter size geometries

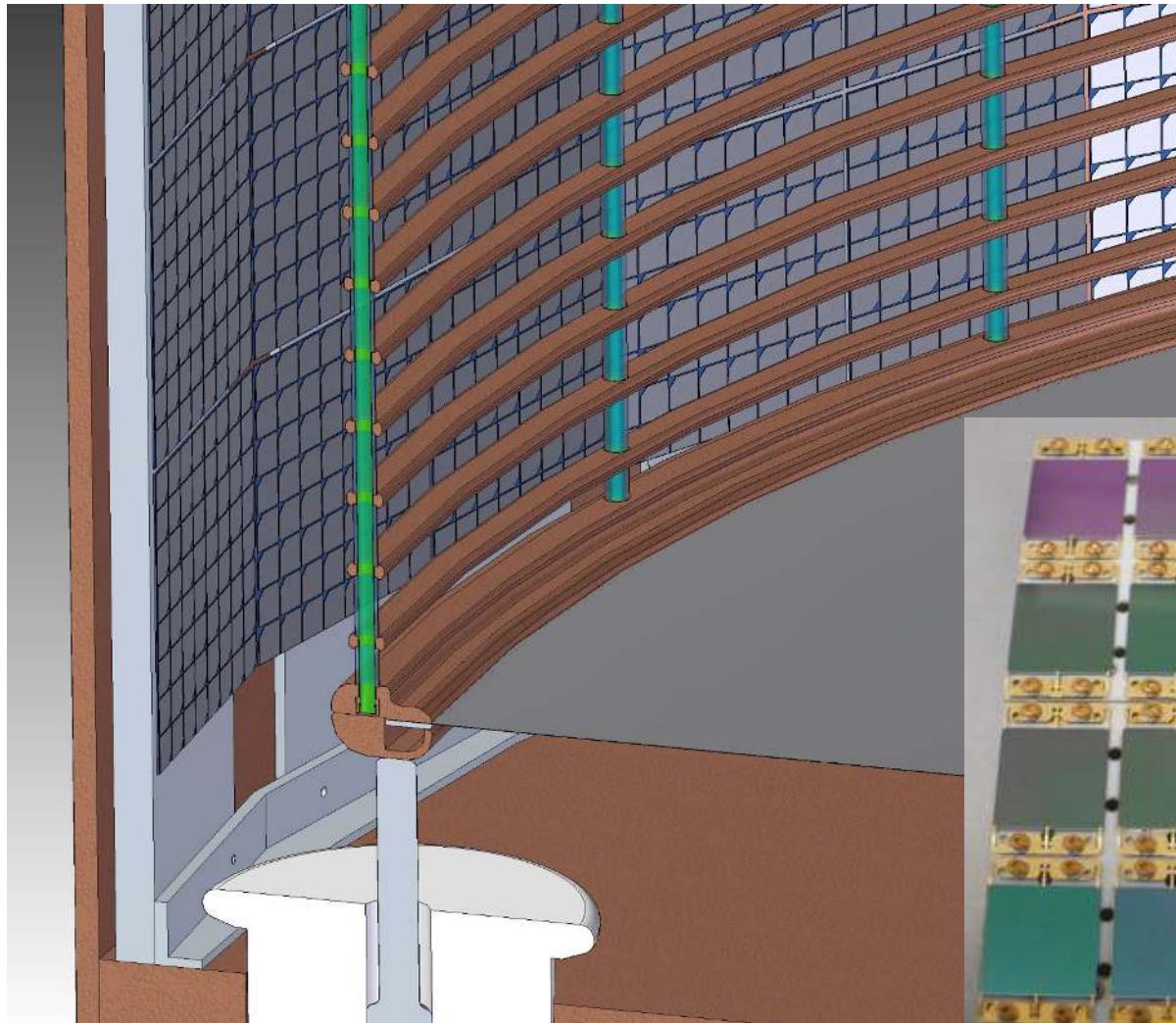
# High Voltage & TPC R&D

- Spark mitigation: ensure stable operation at -100 kV
- Protection of electronics and components in case of HV breakdown
- TPC design: high-reflectivity and optically open field cage
- Low radioactivity

Novel high-resistivity Si field cage (SLAC)



# Photosensors R&D



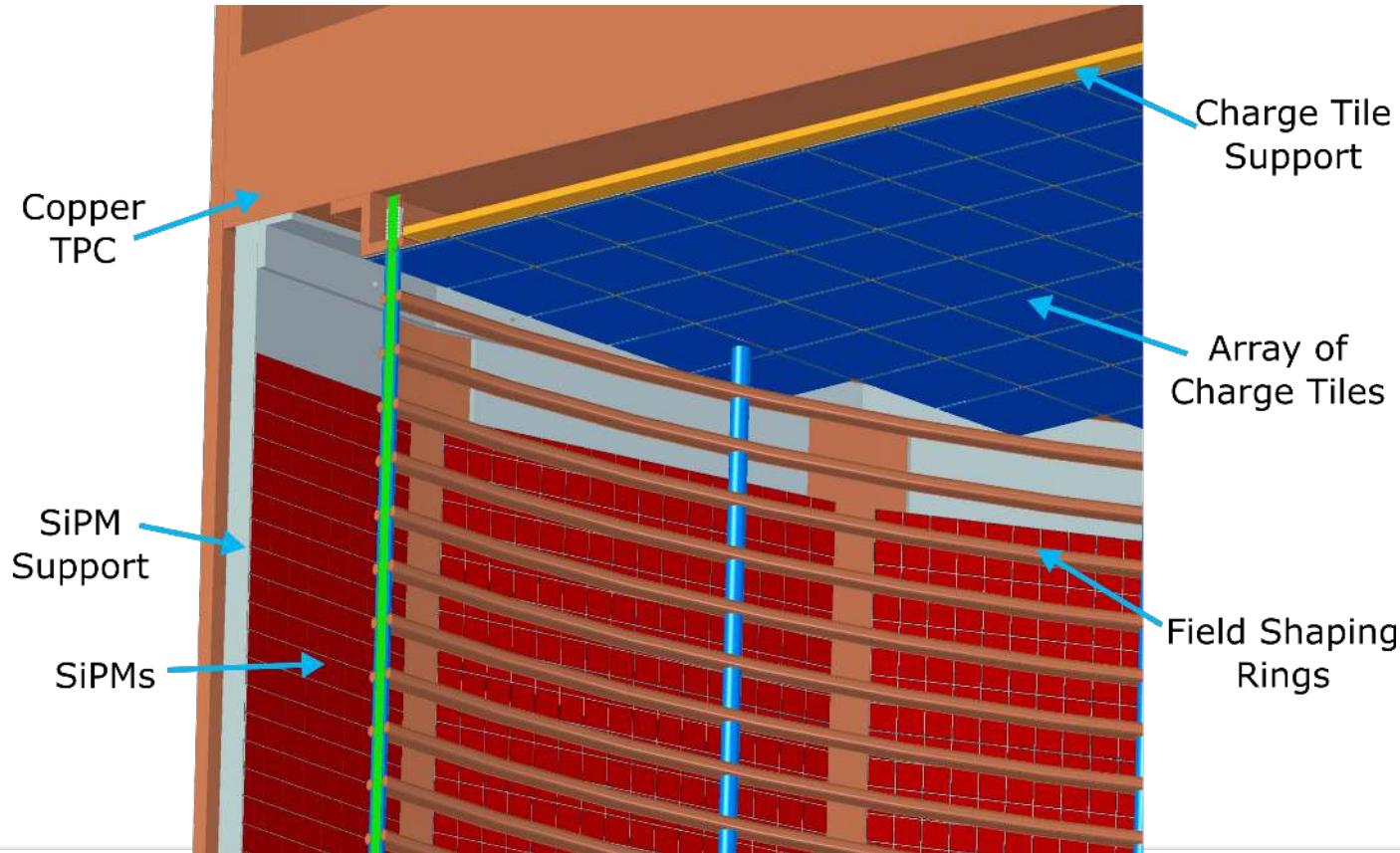
- ~4m<sup>2</sup> of VUV-sensitive SiPMs
- No HV required
- Larger gain & lower noise than APDs



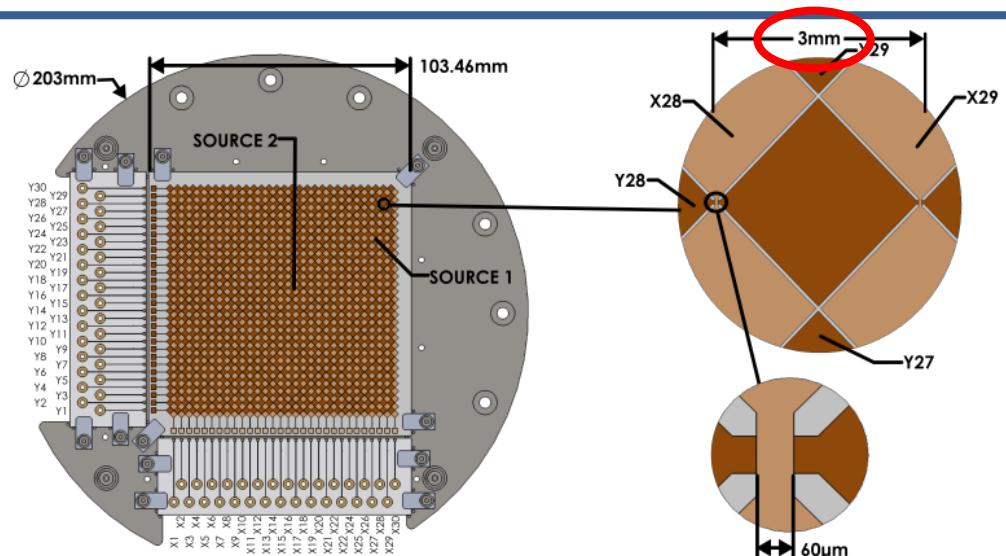
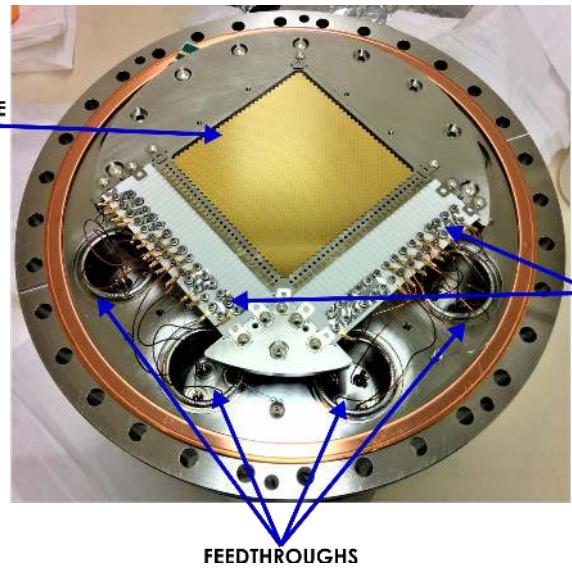
# Charge Readout R&D

Charge will be collected on arrays of strips fabricated onto low background dielectric wafers

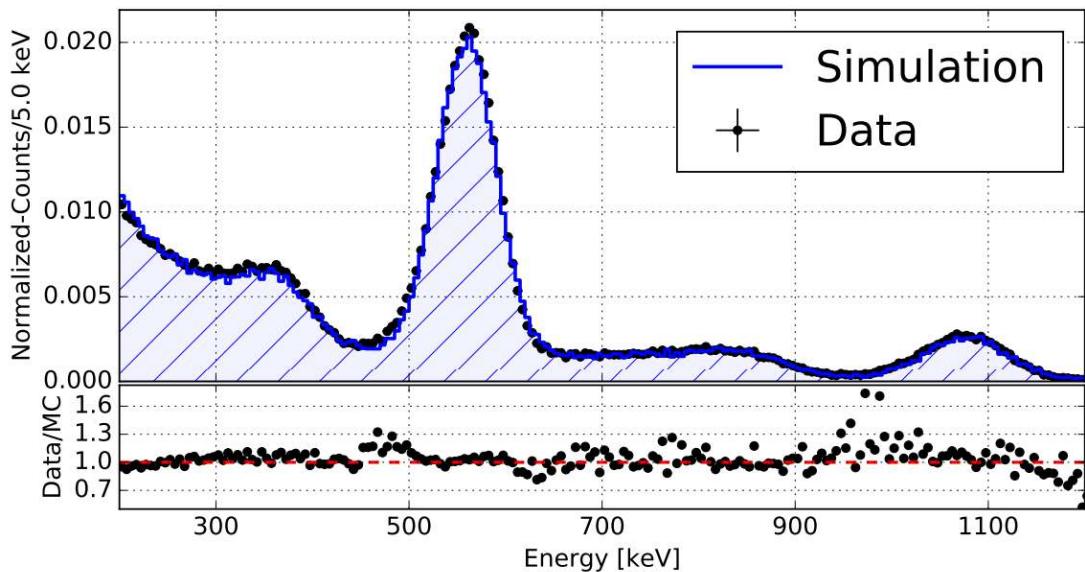
- Self-supporting/no tension
- Built-on electronics (on back)
- Far fewer cables
- Ultimately more reliable, lower noise, lower activity



# Charge Readout Prototyping

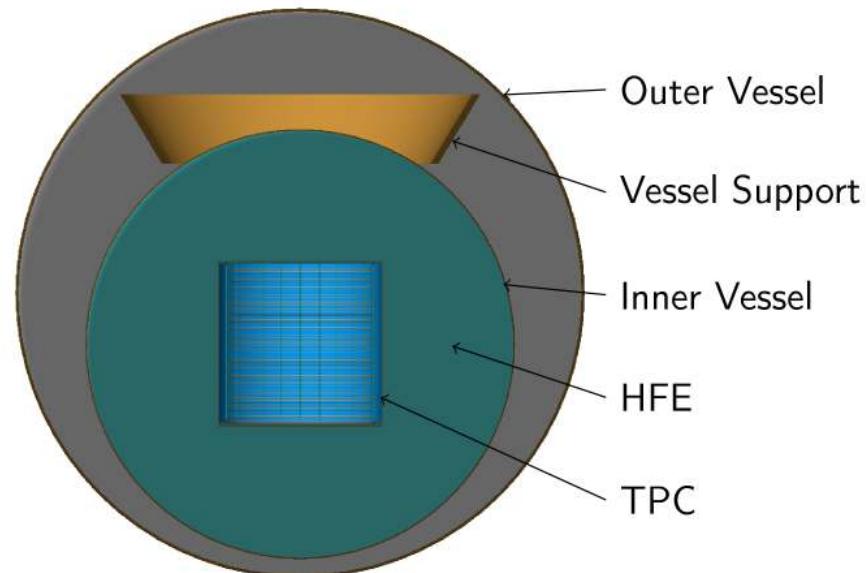
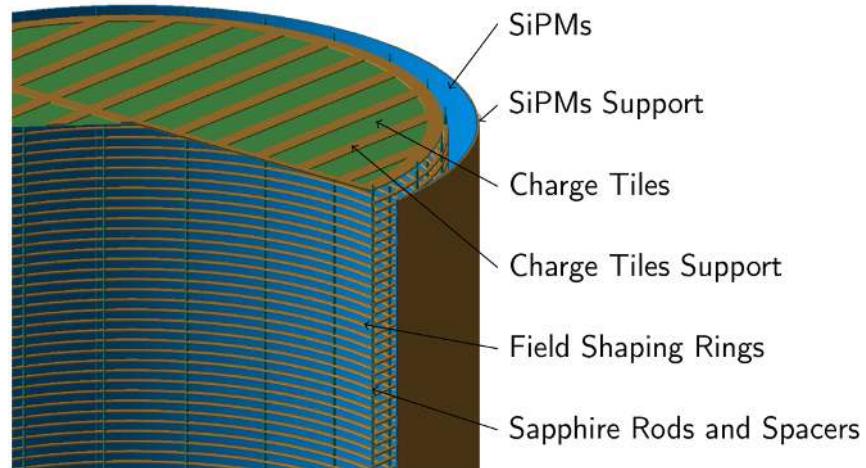


Results of first  
prototype testing at  
[arXiv:1710.05109](https://arxiv.org/abs/1710.05109)



# nEXO Monte Carlo Simulations

- Detailed GEANT4 Monte Carlo includes all important components
- Reconstruction:
  - 1% energy resolution
  - 3 mm clustering → 10% SS fractions
  - >10ms electron lifetime
- Validation via full modeling of the charge (arXiv:1710.05109) and light readout

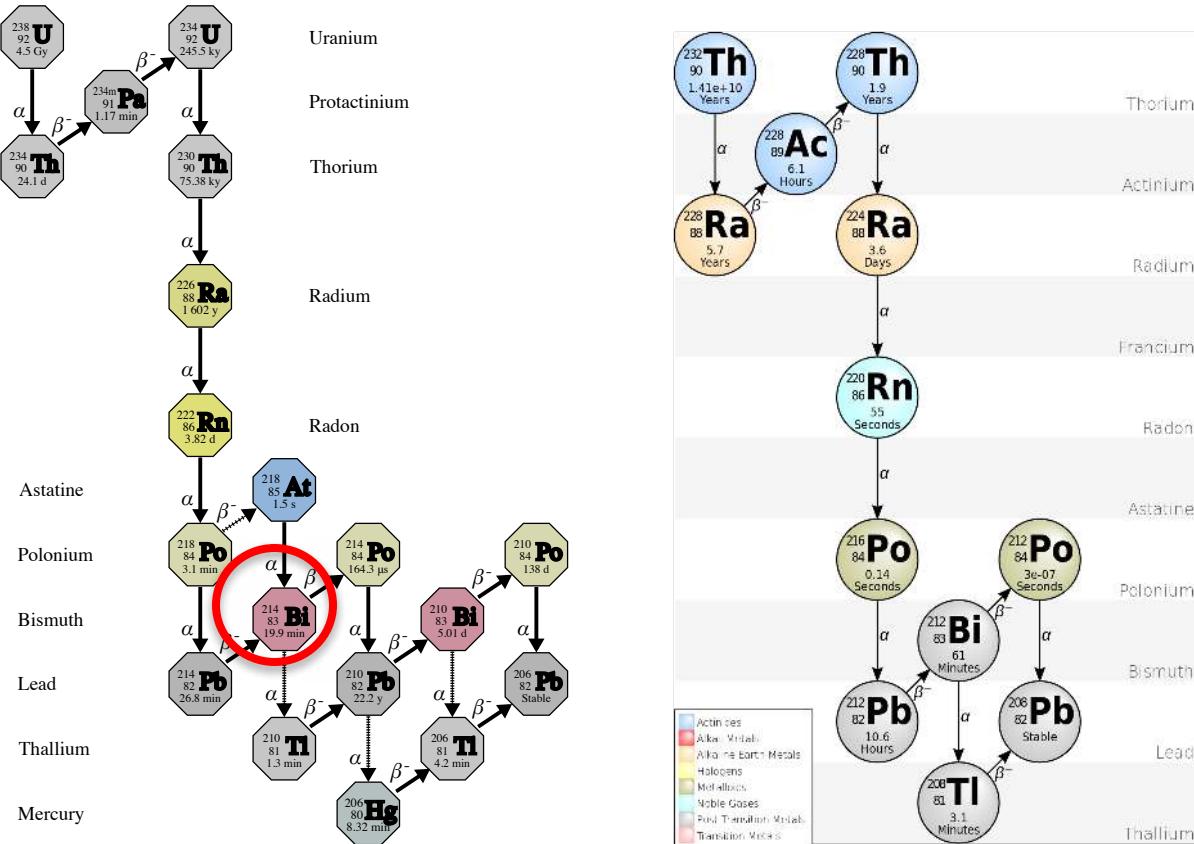


# Background Sources

- Long-lived radionuclides
- Cosmogenic radio-nuclides
- Neutrino-induced backgrounds
- $^{214}\text{Bi}$  from  $^{222}\text{Rn}$  in steady-state
- Neutron activation from  $(\alpha, n)$  reactions

# Long-lived Radionuclides

- $^{238}\text{U}$ ,  $^{232}\text{Th}$  gamma and beta decays
- $^{137}\text{Cs}$ ,  $^{60}\text{Co}$ ,  $^{40}\text{K}$  included but negligible near  $Q_{\beta\beta}$
- Surface backgrounds manageable (as in EXO-200)
- $2\nu\beta\beta$



By User:Tosaka - File:Decay chain(4n+2, Uranium series).PNG, CC BY 3.0,

<https://commons.wikimedia.org/w/index.php?curid=33293646>

By User:BatesIsBack - File:Decay\_Chain\_of\_Thorium.svg, CC BY-SA 3.0,

<https://commons.wikimedia.org/w/index.php?curid=16983885>

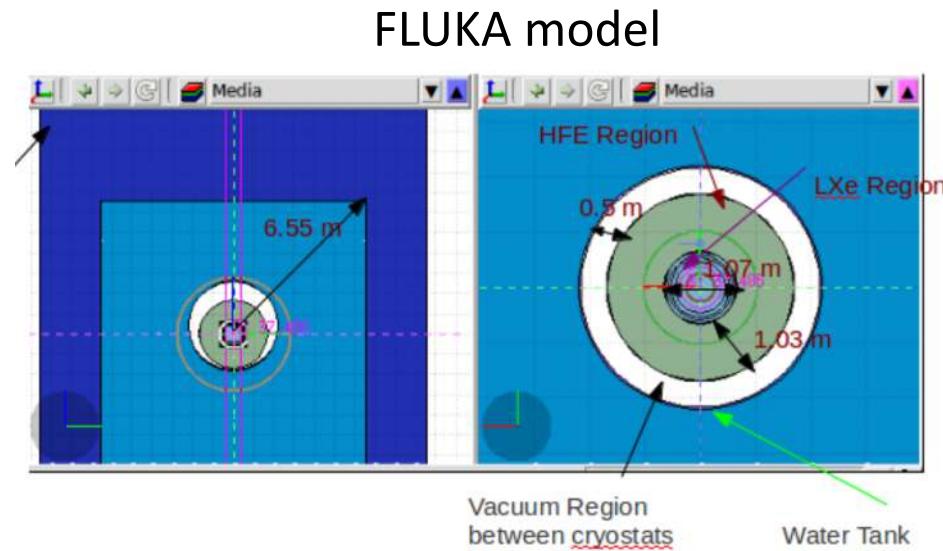
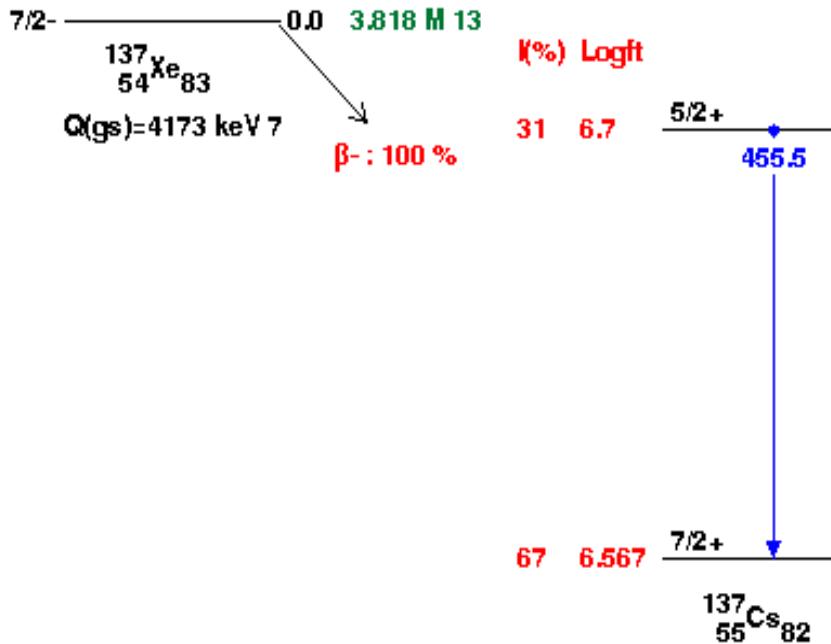
# No Assumptions on Material Radiopurity

- Measurement campaign is in progress to assay all materials used for nEXO construction using variety of techniques
- Only materials with measured radioassay levels are used in the nEXO sensitivity estimation

Material	Supplier	Method	K [ppb]	Th [ppt]	U U [ppt]	$^{60}\text{Co}$ [ $\mu\text{Bq}/\text{kg}$ ]
Copper	Aurubis	ICPMS/Ge/GDMS	<0.7	0.13±0.06	0.26±0.01	<3.2
Sapphire	GTAT	NAA	9.5±2.0	6.0±1.0	<8.9	-
Quartz	Heraeus	NAA	0.55±0.04	<0.23	<1.5	-
SiPM	FBK	ICPMS/NAA	<8.7	0.45±0.12	0.86±0.05	-
Epoxy*	Epoxies Etc.	NAA	<20	<23	<44	-
Kapton*	Nippon Steel Cables	ICPMS	-	<2.3 pg/cm <sup>2</sup>	4.7±0.7 pg/cm <sup>2</sup>	-
HFE*	3M HFE-7000	NAA	<0.6	<0.015	<0.015	-
Carbon Fiber	Mitsubishi Grafil	Ge	550±51	58±19	19±8	-
ASICs	BNL	ICPMS	-	25.7±0.7	13.2±0.1	-
Titanium	TIMET	Ge	<3.3	57±5	<7.3	-
Water	SNOLAB	Assumed	<1000	<1	<1	-

# Cosmogenic Radionuclides

- Aboveground: manageable with proper material handling to limit cosmic rays exposure
- Underground:  $^{137}\text{Xe}$  steady-state production from n capture

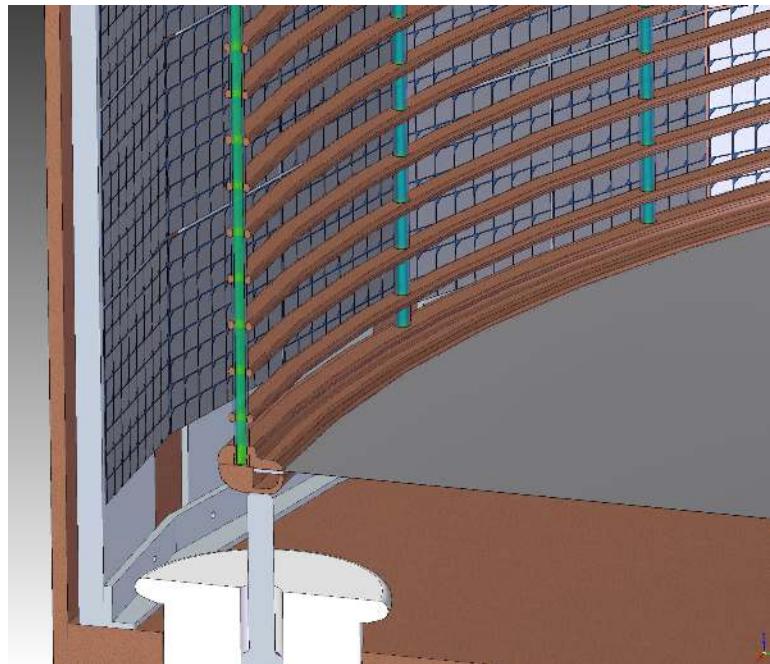
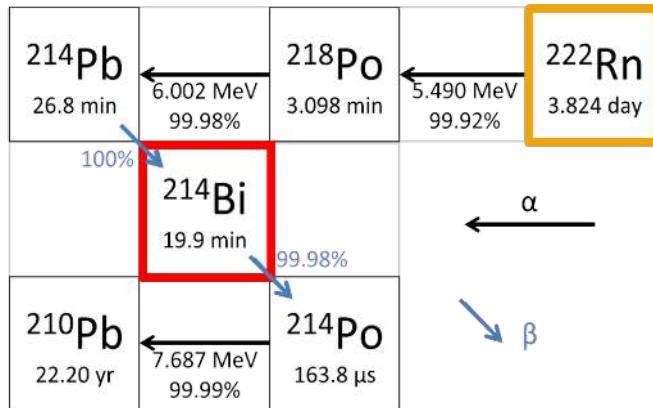


# Neutrino-induced Backgrounds

- Electron-neutrino elastic scattering       $\nu + e^- \rightarrow \nu + e^-$ 
  - Calculable
  - Small: ~0.02 SS events/(FWHM.2000kg.y)
- Charge-current neutrino capture       $\nu + {}^{136}\text{Xe} \rightarrow e^- + {}^{136}\text{Cs}$ 
  - Estimated ~ 20 interactions / (2000kg.y)
  - Prompt radiation: negligible fraction of  $e^-$  have right energy
  - Delayed  ${}^{136}\text{Cs}$  decay: very high single-site rejection
- Neutral-current inelastic scattering

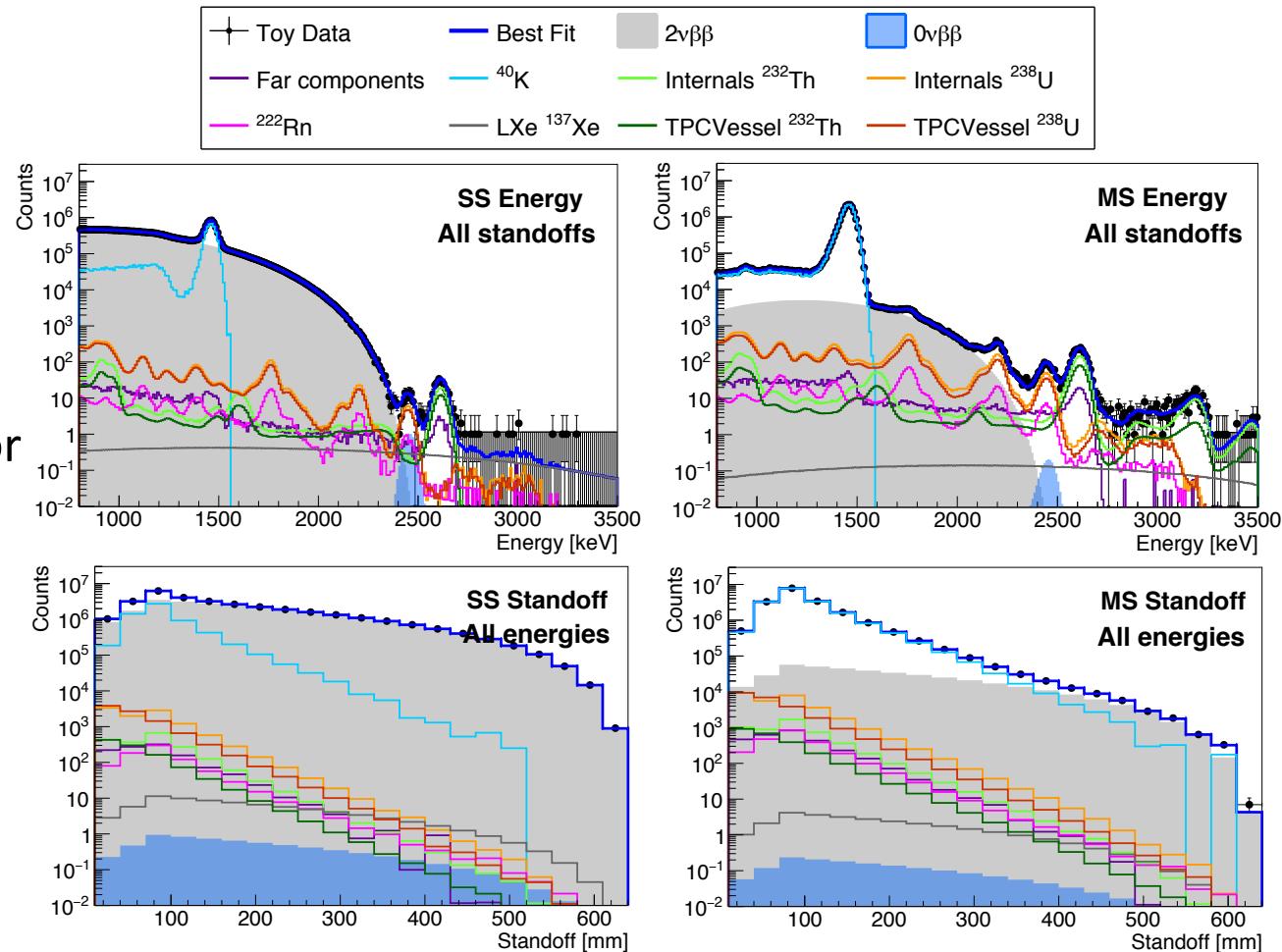
# Steady-state $^{222}\text{Rn}$ : an “external” background

- $^{222}\text{Rn}$  from emanation of materials in the xenon piping
- Estimate ~600 atoms steady-state in nEXO based on EXO-200 extrapolation
- Three components:
  - LXe inside TPC (17%)
  - LXe outside TPC + Cathode (84%)
- Bi-Po tagging

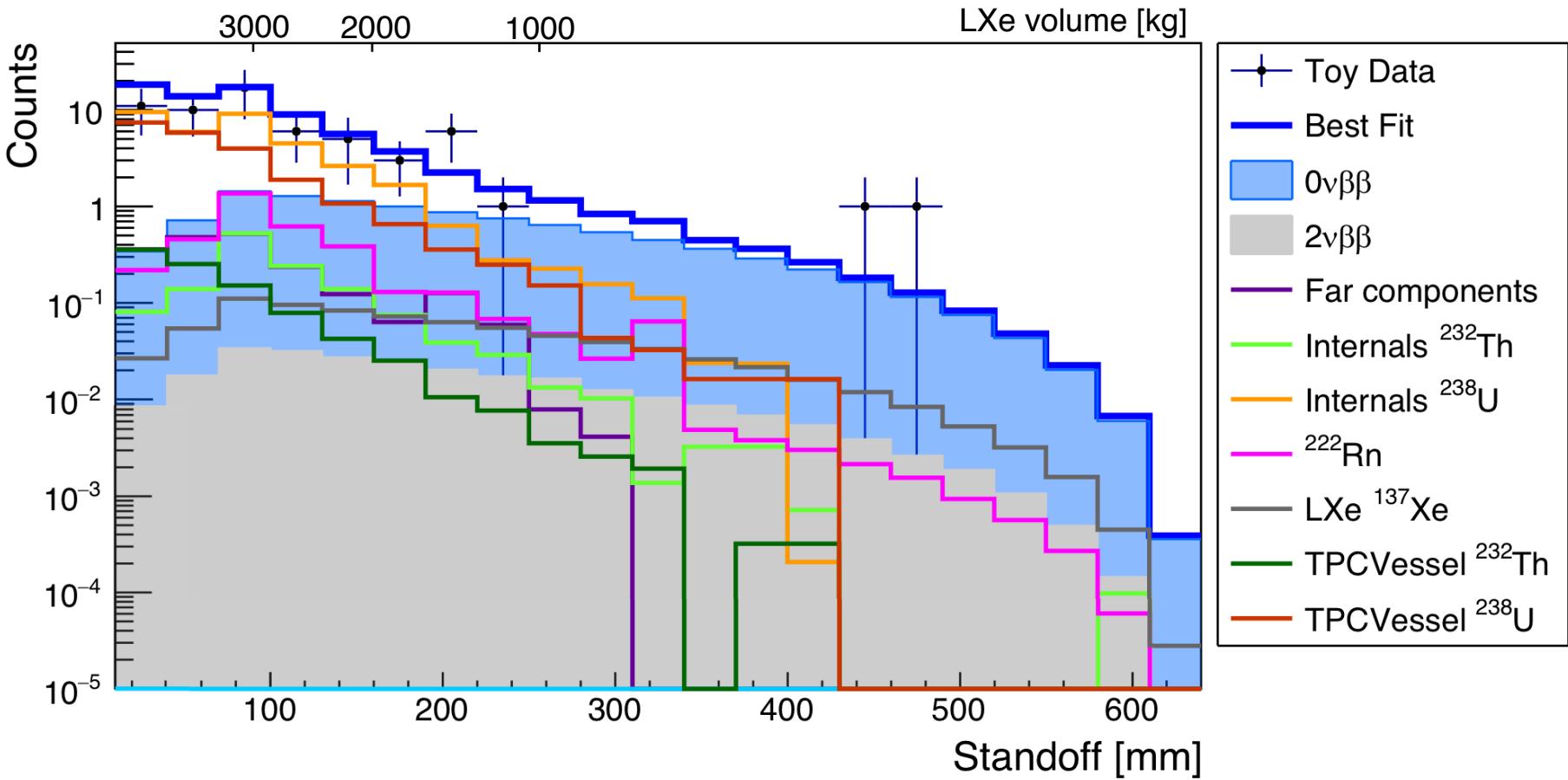


# Analysis and Fit Results

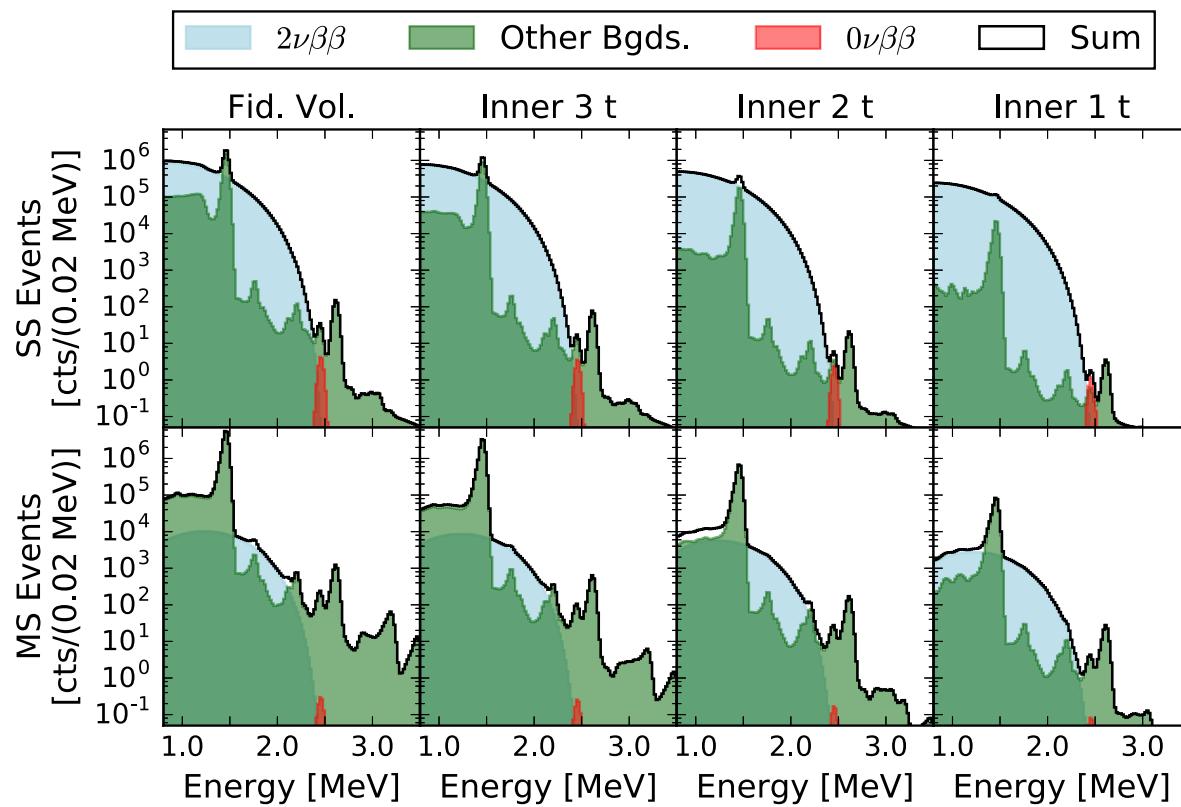
- Frequentist approach to sensitivity calculation
- "Toy" experiments generated from radioassay values and fit using log-likelihood technique
- Simultaneous fit of energy, standoff distance, and multiplicity (SS/MS)
- Example of fit result for one toy experiment →



# Fit Results in the FWHM around $Q_{\beta\beta}$

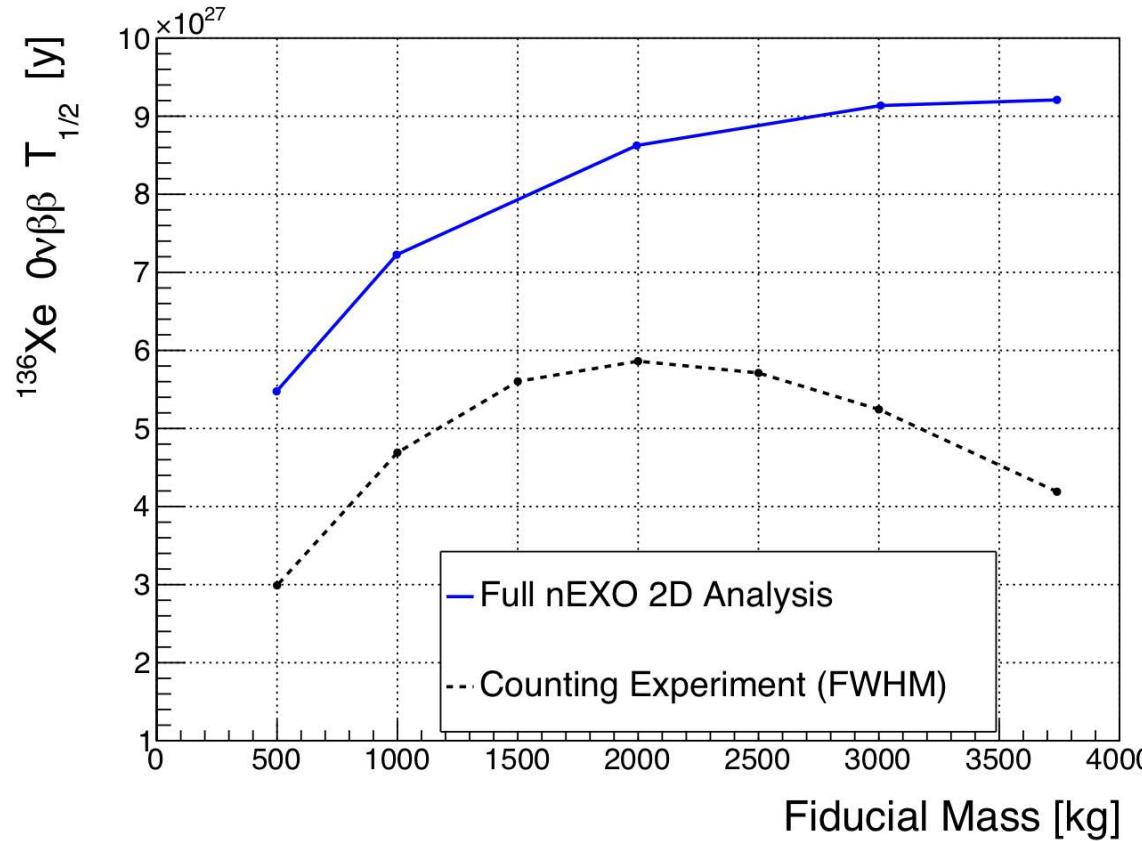


# The Advantages of a Homogenous Detector



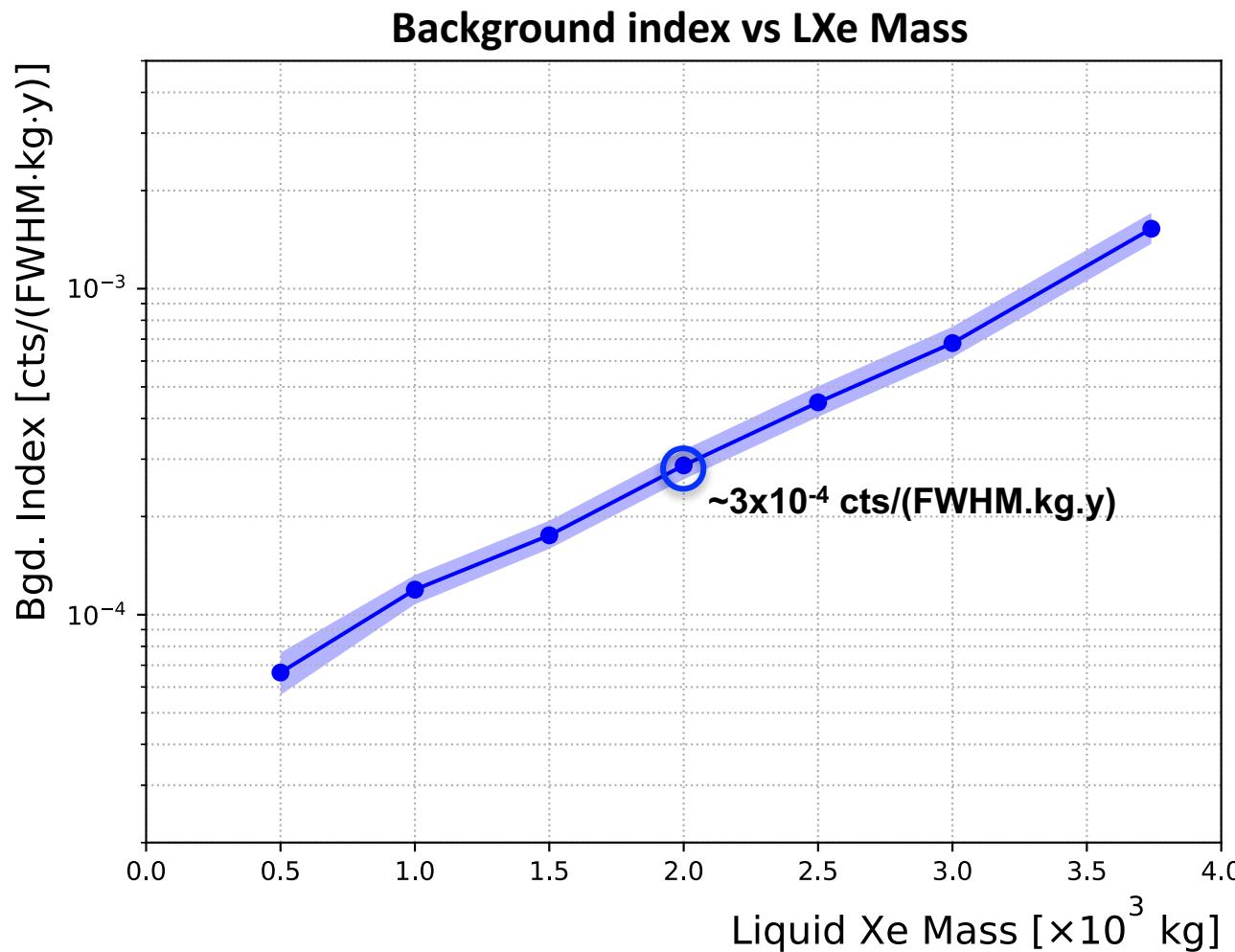
- Power of using a simultaneous fit of energy, multiplicity and event position. This is not a one-dimensional peak search.
- Optimal use of the LXe mass: the inner mass provides sensitivity to signal while the outer regions allow to constrain the background.

# The Advantages of a Homogenous Detector



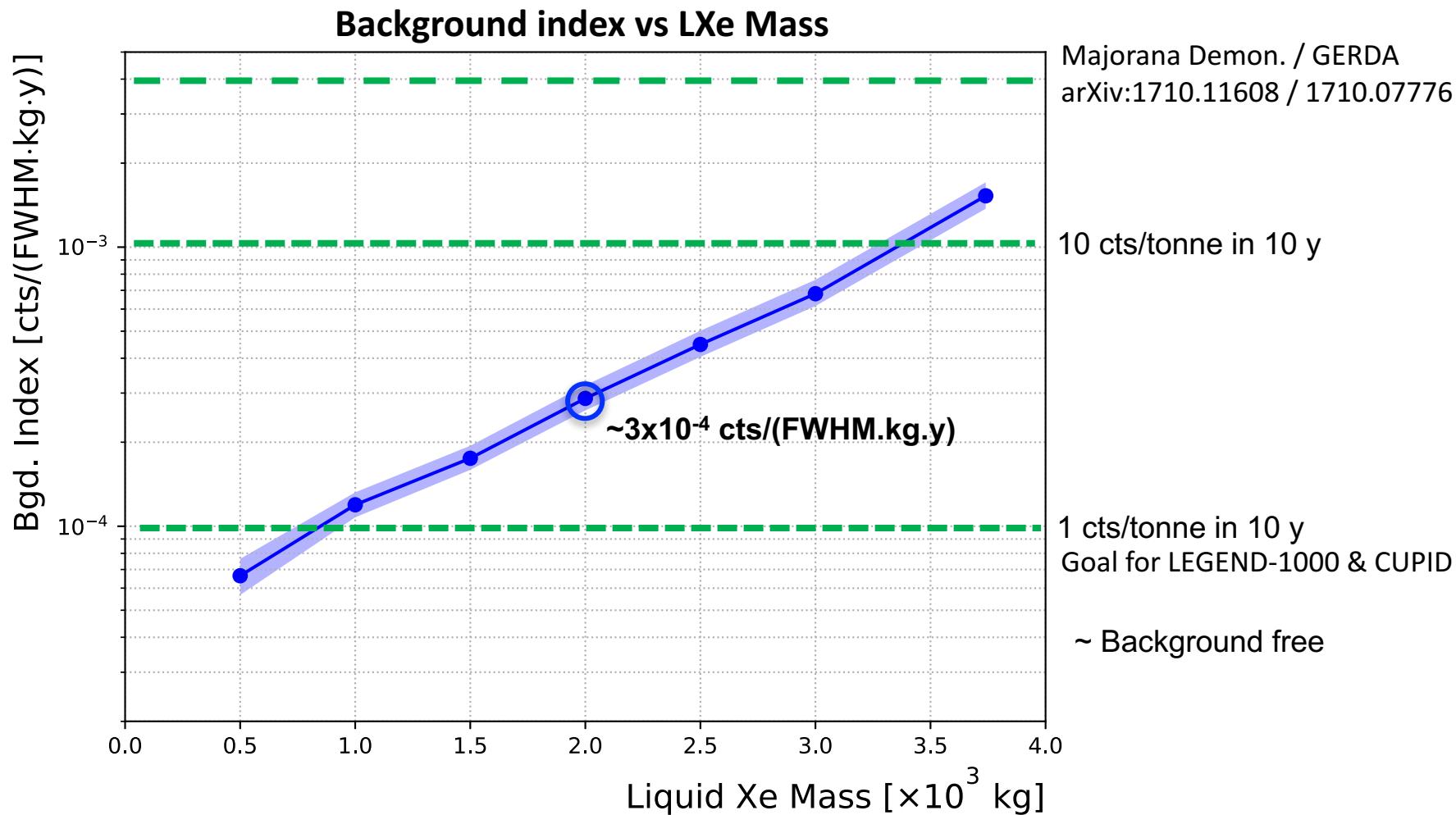
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# nEXO background index is not a single number!



- Single background index not sufficient to describe nEXO
- External backgrounds dominate

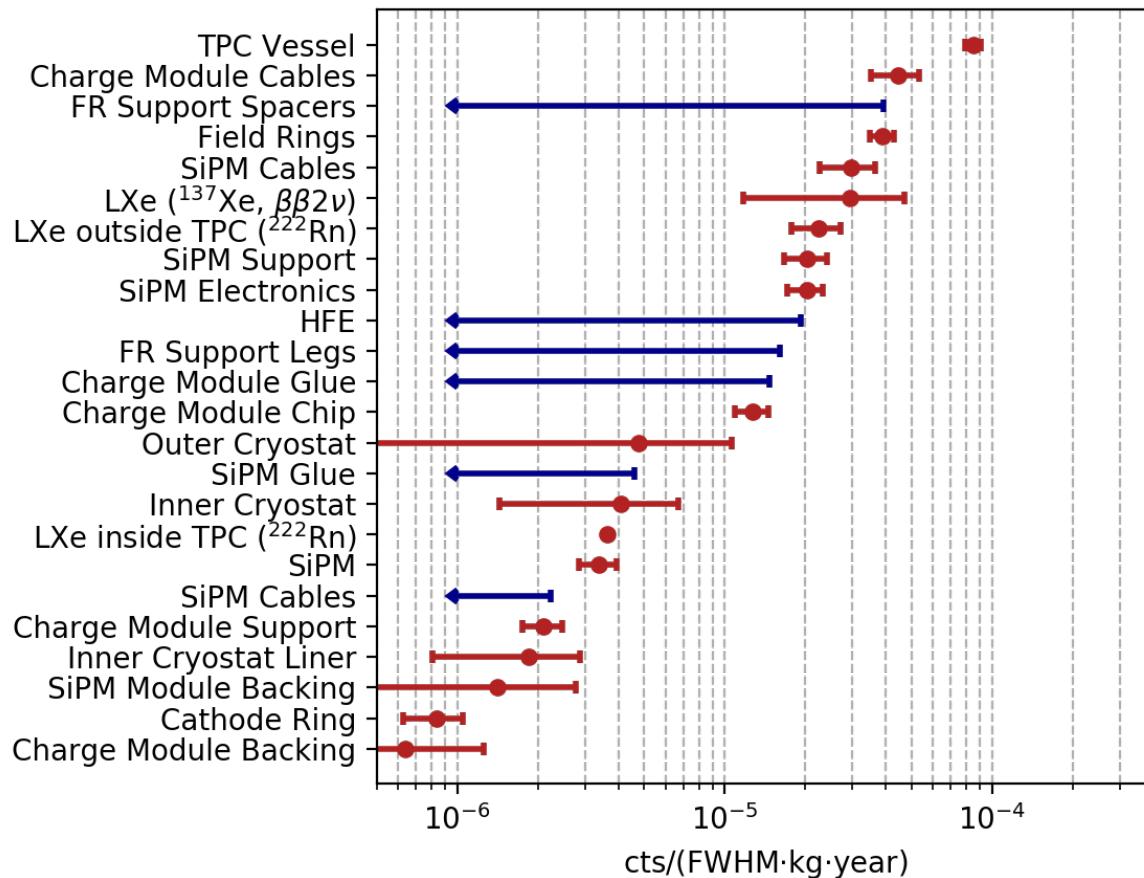
# nEXO background index is not a single number!



For nEXO, the simple physics of  $\gamma$  attenuation in LXe, coupled with multi-parameter discrimination, drives the background estimation

# Estimated Background Budget

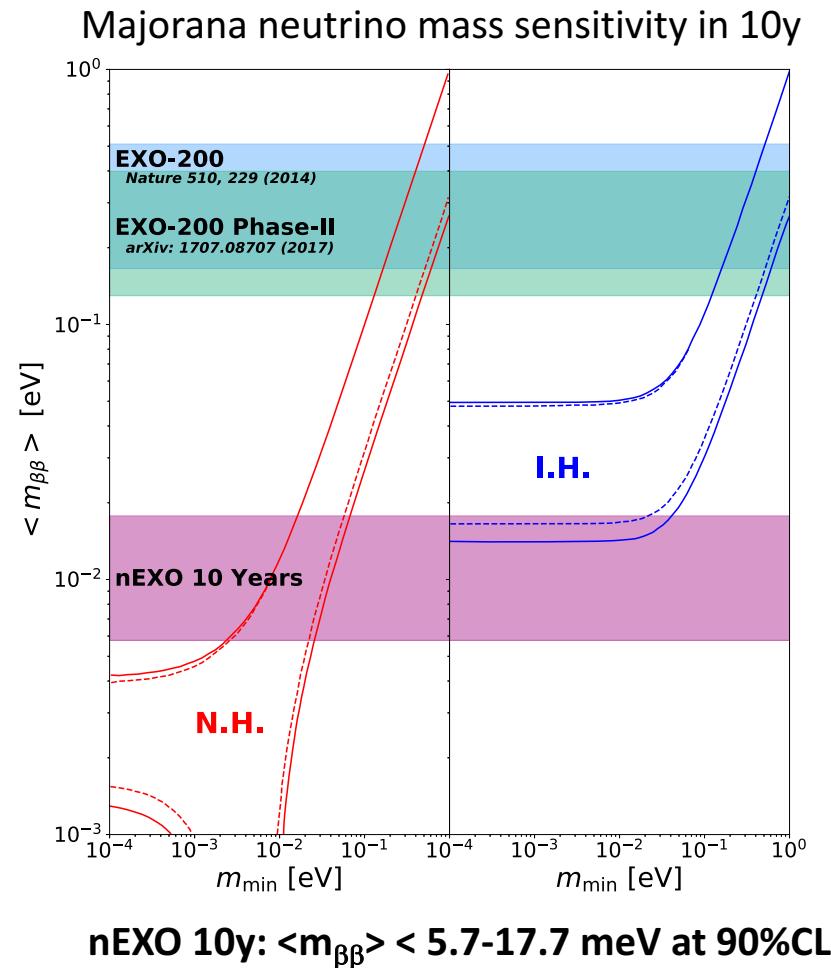
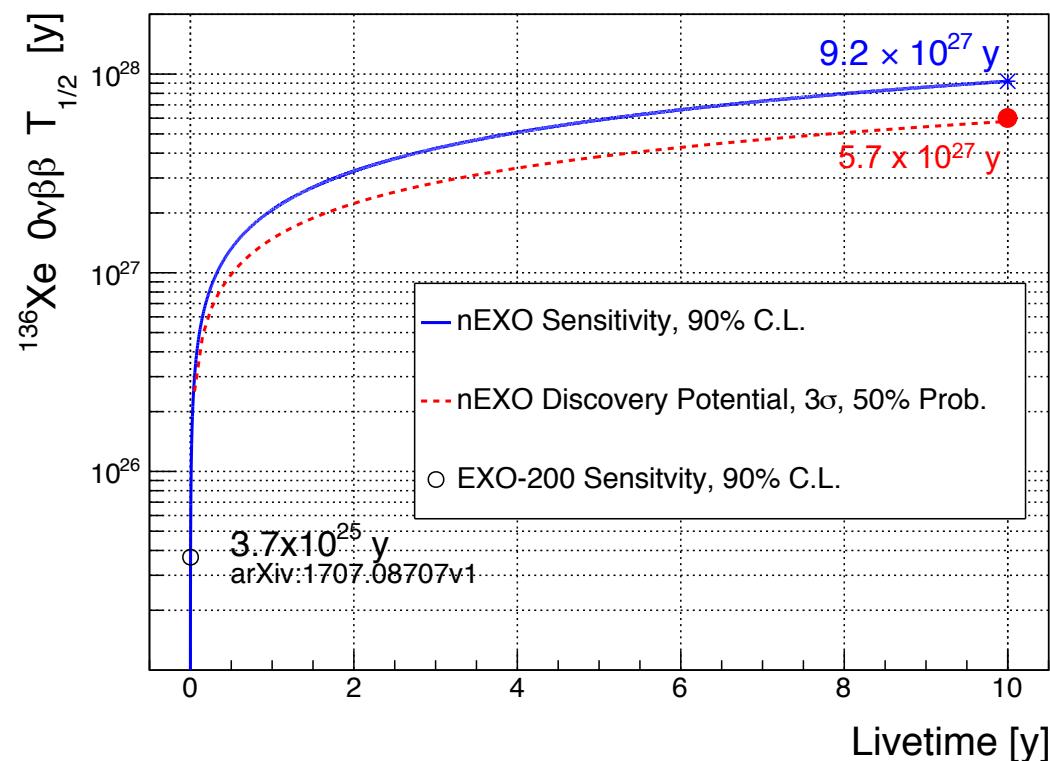
Background budget in the inner 2000 kg



- Same procedure validated for EXO-200
- Internal components dominate, as expected
- Several radioassay entries with only 90% CL limit (more measurements may improve the estimated background)

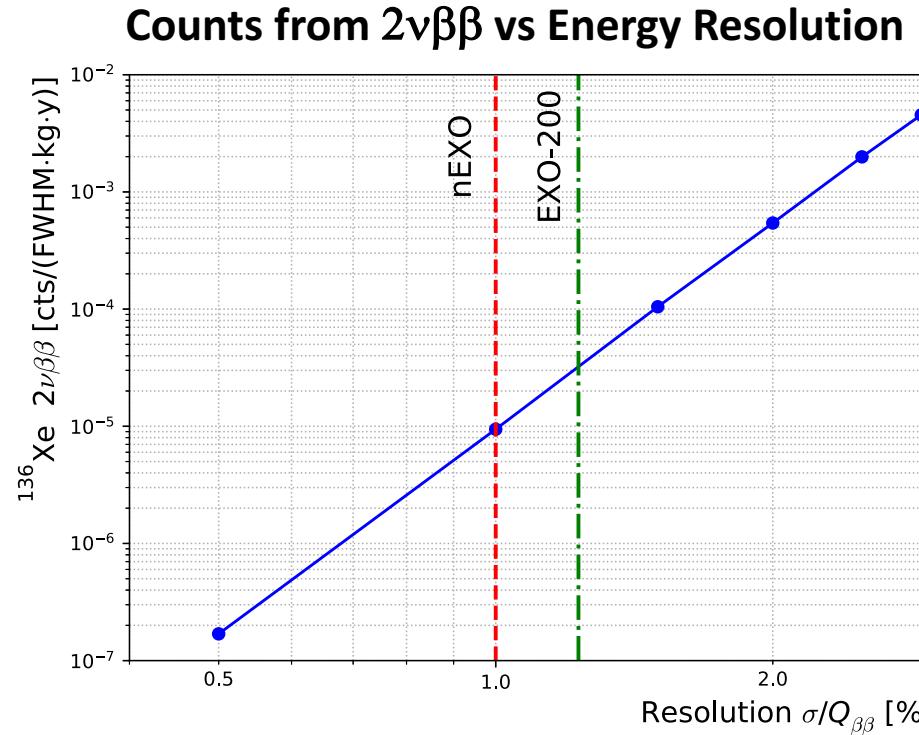
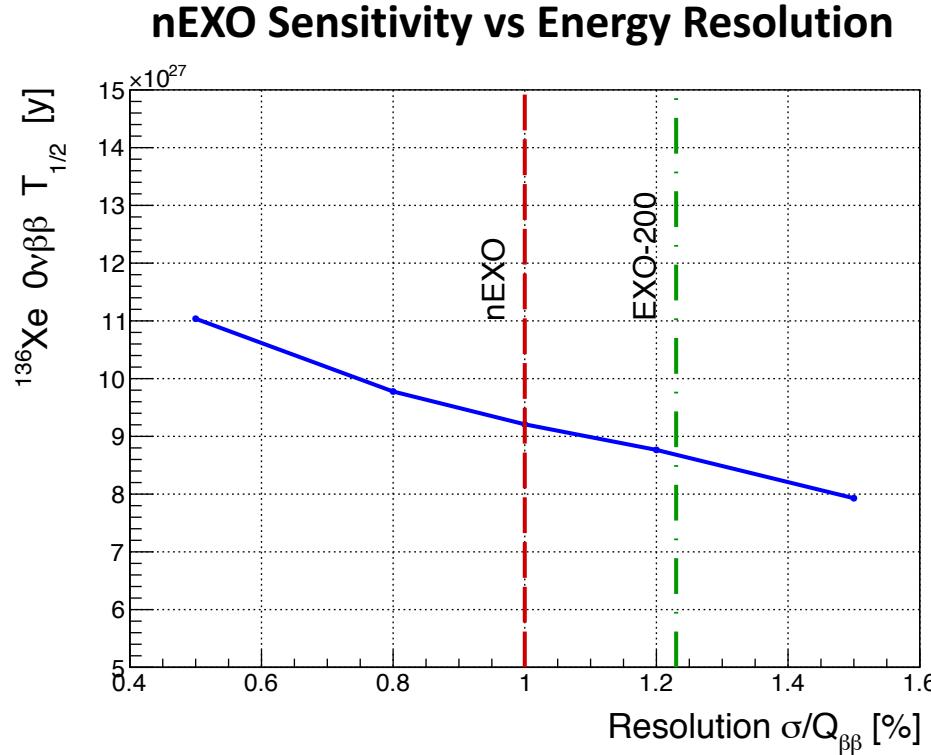
# Sensitivity and Discovery Potential Results

- Exclusion limit at 90% CL computed as the median upper limit of an ensemble of  $10^4$  toy experiments and without assuming Wilks's theorem



Allowed masses from oscillations: 90% CL, D.V. Forero et al, PRD 90 (2014) 093006 and M. Tortola private comm.; Unquenched  $g_A$ ; See arXiv:1710:05075 for details on NME

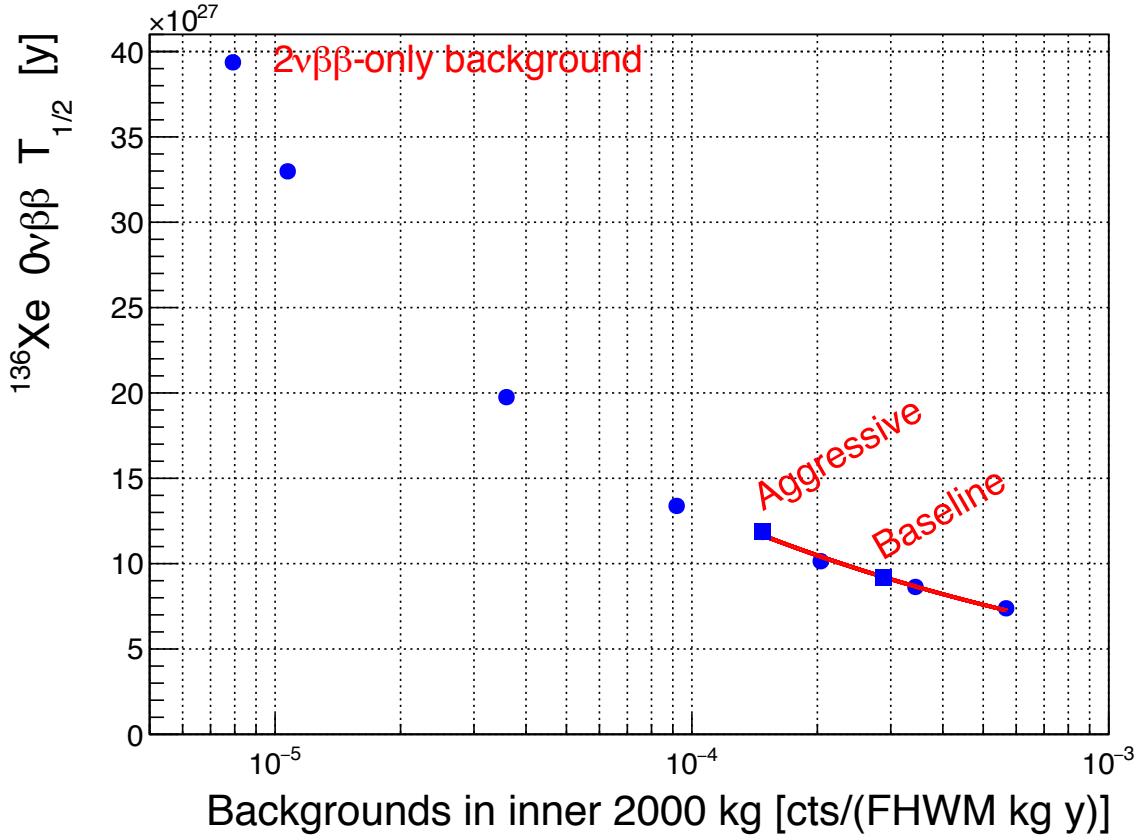
# The (Small) Role of Energy Resolution



- Only relatively small improvement from improved energy resolution
- Further improvements not critical to reach compelling sensitivity

- $2\nu\beta\beta$  is almost negligible in nEXO: 0.34 counts in 10 years in the entire LXe
- Rapidly worsen with increasing energy resolution

# Sensitivity with improved backgrounds



- “Baseline” = radioassay-based background estimate
- “Aggressive” = arising from plausible improvements from R&D
- “2νββ-only” = limit case
- Power law fit gives:
$$T_{1/2} \propto \frac{1}{B^{0.35}}.$$
nEXO is not as sensitive to backgrounds as a naïve  $\sqrt{B}$  scaling would imply.

# Conclusions

- $0\nu\beta\beta$  could reveal fascinating new physics
- LXe TPC is a proven technology for  $0\nu\beta\beta$  search. Multi-parameter reconstruction in a homogenous detector allows to optimally "resolve" signal and backgrounds.
- nEXO's sensitivity reach is solidly grounded in
  - EXO-200 experience
  - $\gamma$  attenuation in a large LXe detector
  - measured material radiopurity
- The nEXO collaboration is ready to build an experiment with:
  - ultra-low background:  $\sim 3 \times 10^{-4}$  cts/(FWHM.kg.y) in the inner 2000 kg
  - compelling discovery potential ( $5.7 \times 10^{27}$  y at  $3\sigma$ )
  - reach on the Majorana neutrino mass  $\sim 10$  meV range
- More details in: nEXO Collaboration, "Sensitivity and Discovery Potential of nEXO to Neutrinoless Double Beta Decay", [arXiv:1710.05075](https://arxiv.org/abs/1710.05075)

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