Impact of Nickel Cryostats in the nEXO Detector

1. $0\nu\beta\beta$ Motivations
2. The nEXO Experiment
3. Cryostat Vessels: From Carbon Fiber to Nickel
4. HFE Shielding
5. Design Implications

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Heure Thésarde - February 6th 2025
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nEXO Collaboration

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The nEXO Experiment: A World-Wide Effort

1.5 years here

SNOLAB, Canada

1.5 years here

9 countries, 34 institutions, ~200 collaborators

The nEXO Experiment: Neutrinoless Double Beta Decay

Double beta decay (2νββ): $2n \rightarrow 2p + 2e^{-} + 2\overline{\nu_e}$

- 2x β radioactive decay
- Transformation of 2 neutrons ⇔ 2 protons
- Already observed in several isotopes
- Rare process (^{136}Xe 2νββ half life: 10^{21} years)

Neutrinoless double beta decay (0νββ): $2n \rightarrow 2p + 2e^{-}$

- $\overline{\nu_e}$ self annihilation or no emission
- Forbidden in the SM (lepton number violation)
- Never observed (^{136}Xe 0νββ current limits: 10^{26} years)
- Could explain neutrino nature, matter-antimatter asymmetry,…

*For reference: Age of the Universe: 10^{10} years

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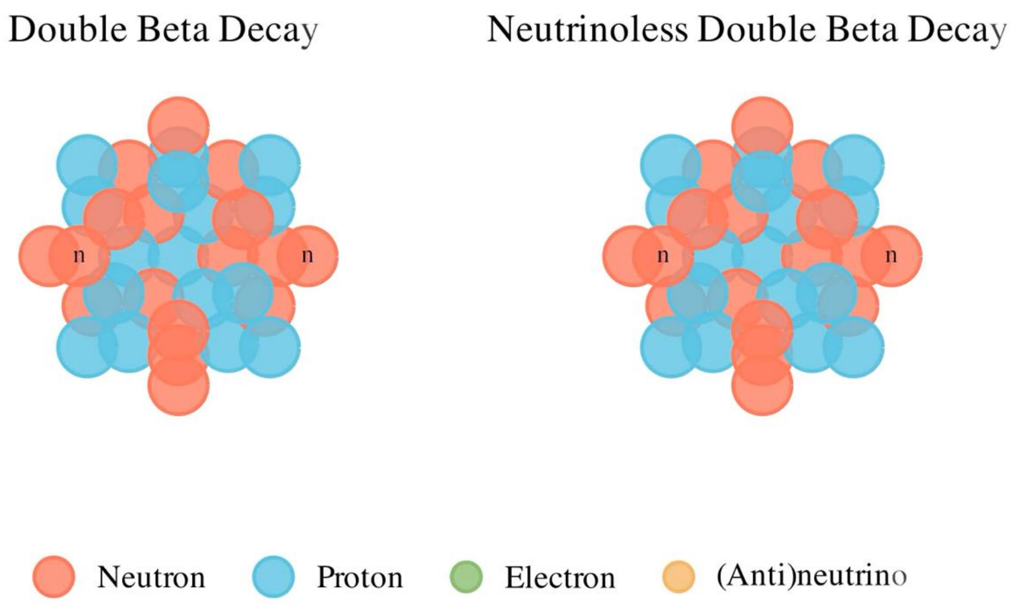

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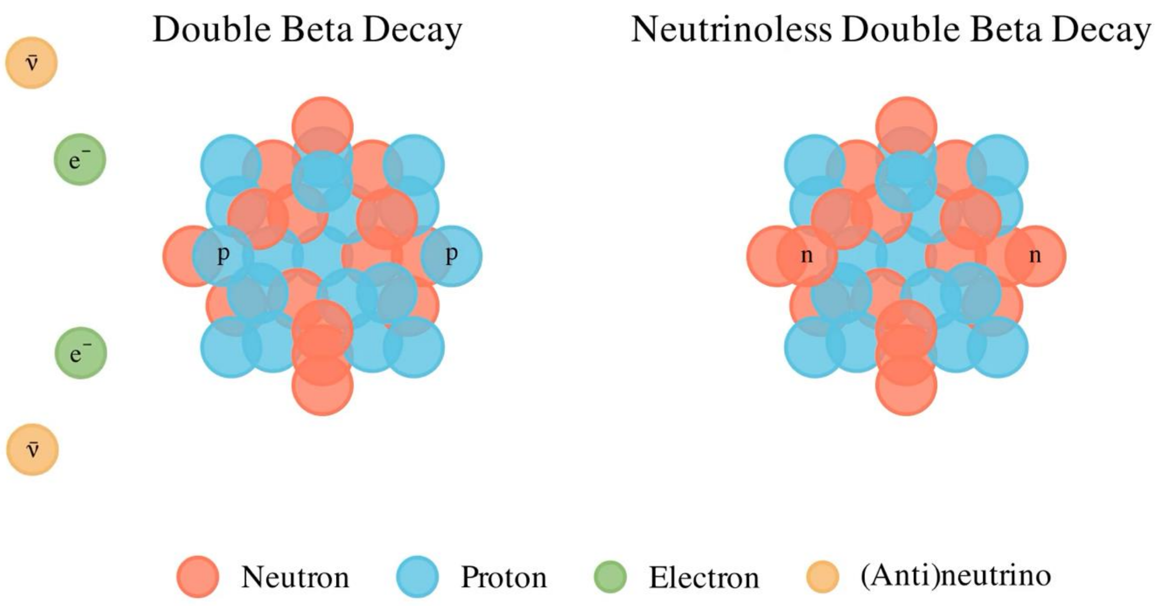
Neutrinoless double beta decay (0νββ): $2n \rightarrow 2p + 2e^{-}$

- $\overline{\nu_e}$ self annihilation or no emission
- Theorized, but forbidden in the Standard Model
- Never observed (^{136}Xe 0νββ current limits: 10^{26} years)
- Could explain neutrino nature, matter-antimatter asymmetry,…



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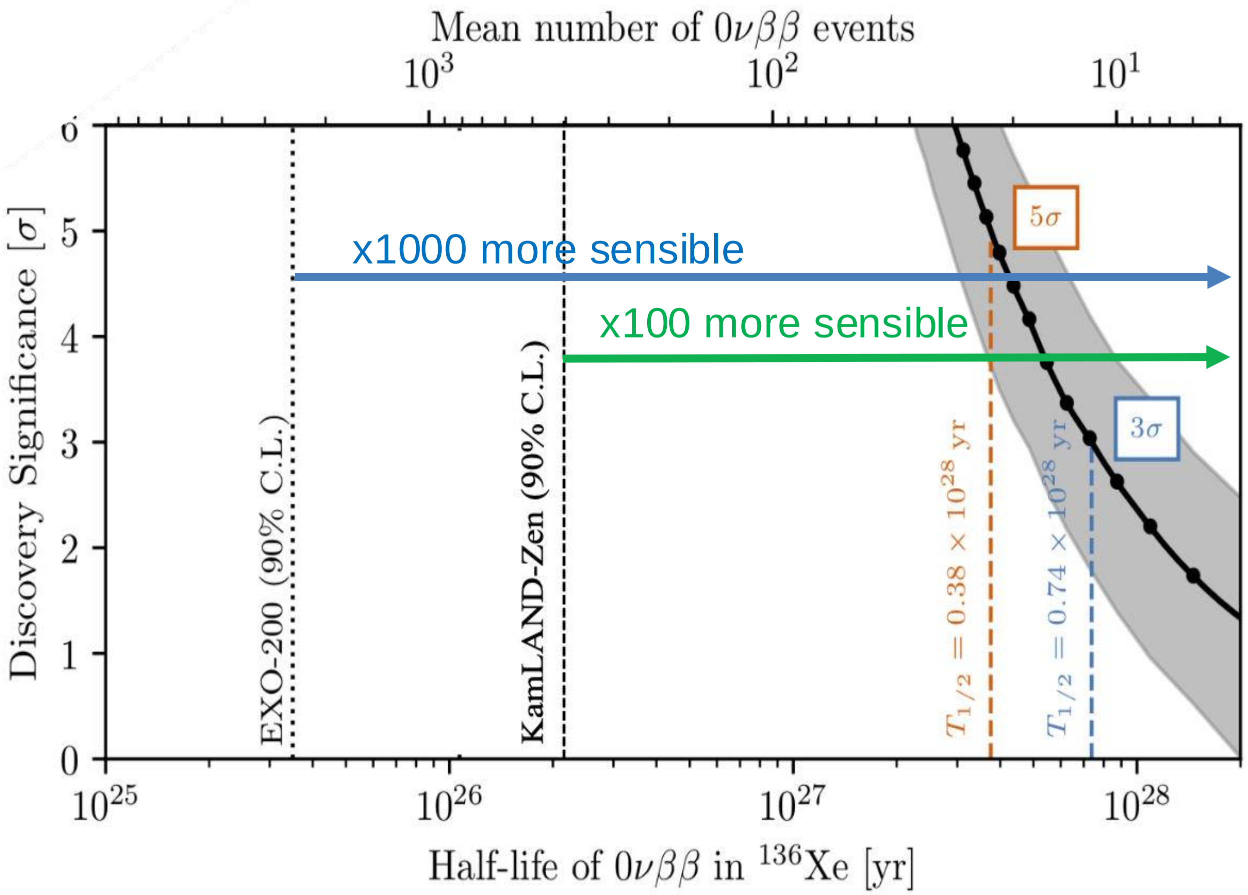
The nEXO Experiment: A Next Generation Detector

Detecting ^{136}Xe 0νββ requires:

1. Large mass of Xenon
2. High isotope enrichment*
3. Long detection time

- Previous Gen.: EXO-200
  ^{136}Xe 2νββ discovery
- Current Best: KamLAND-Zen

Experiment	Mass [kg]	Enrichment	Live Time
EXO-200	175	80%	3 years
KamLAND-Zen	745	90%	4 years
nEXO (projected)	5000	90%	6.5 years



nEXO will reach a 0νββ half-life of 10^{28} years in 6.5 years data taking

*Natural Isotopic Abondance ^{136}Xe=8.9%

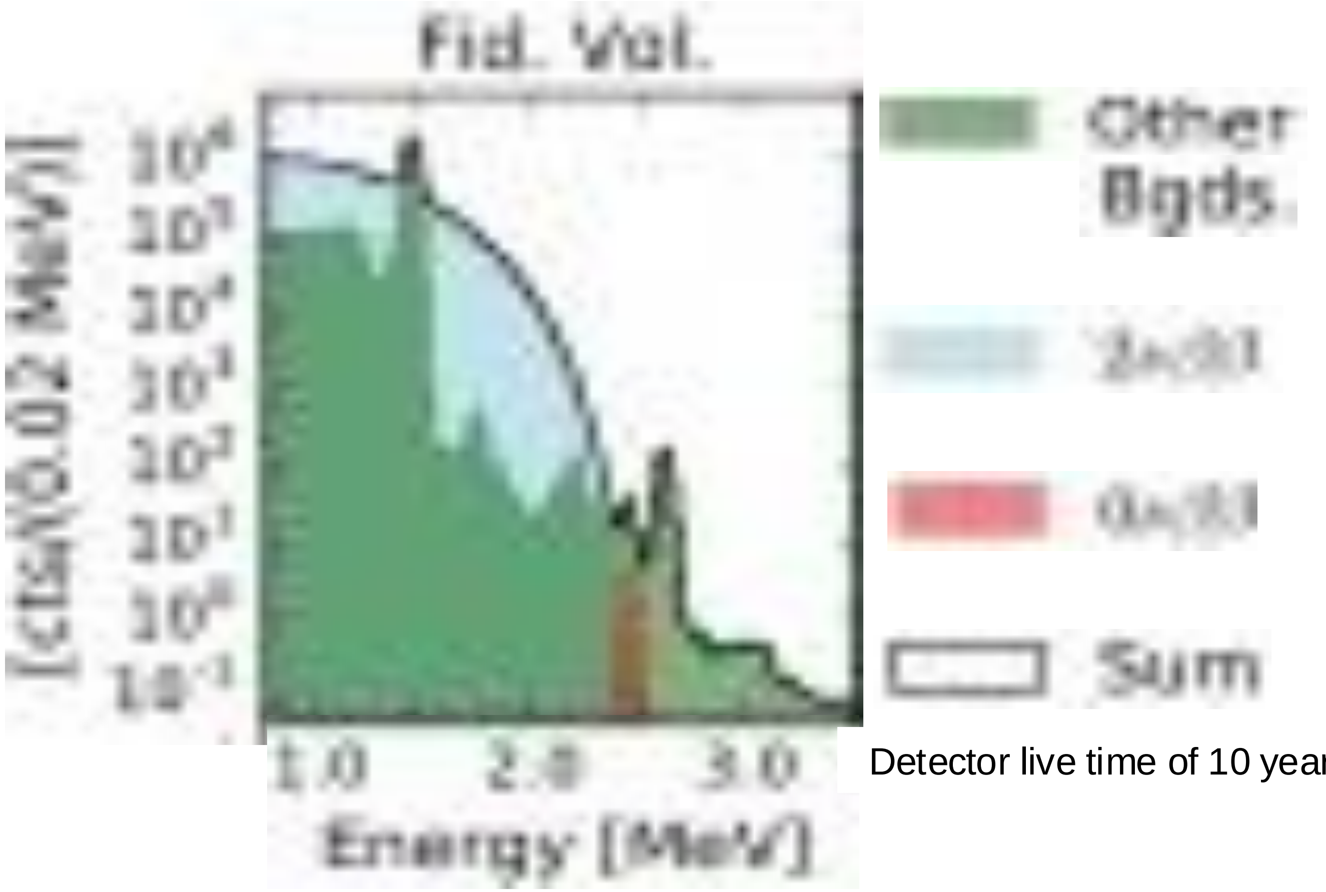
The nEXO Experiment: Signals vs Backgrounds

Detecting ^{136}Xe 0νββ

- Sharp peak at Q-value (2458 keV)
- Requires low background (signal-like events)
  - Good energy resolution
  - Good topology reconstruction

Background Sources

- ^{136}Xe 2νββ
  - Standard 2νββ
  - Continuous spectrum, dominant at low energy
- External Sources
  - Cosmic rays
  - Solar neutrinos
  - Natural ^{42}Ar
- Material Radioactivity
  - ^{222}Rn: Noble gas contamination
  - Natural decay chains (Th, U) in detector components



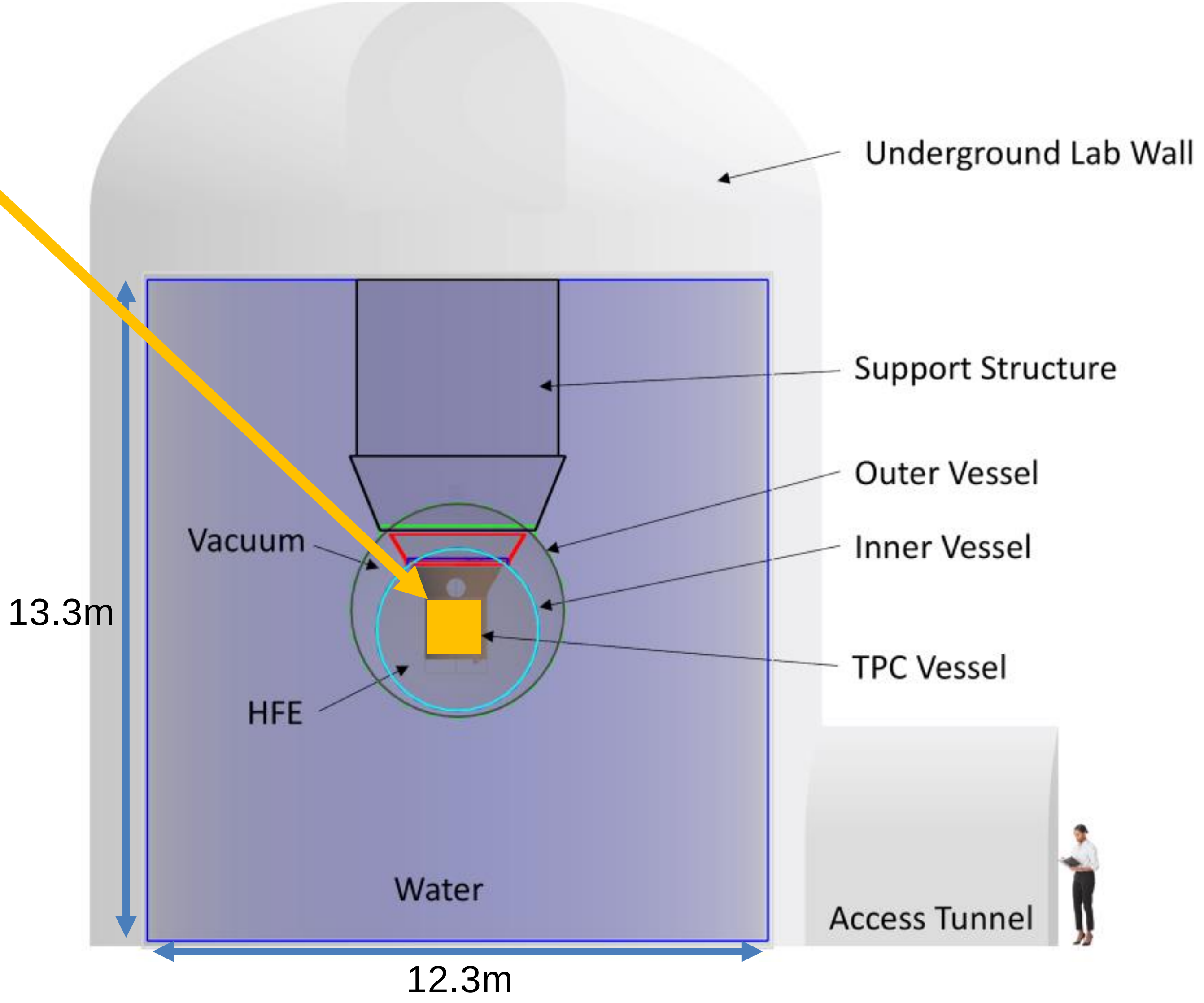
Detector live time of 10 years

The nEXO Experiment: Overview

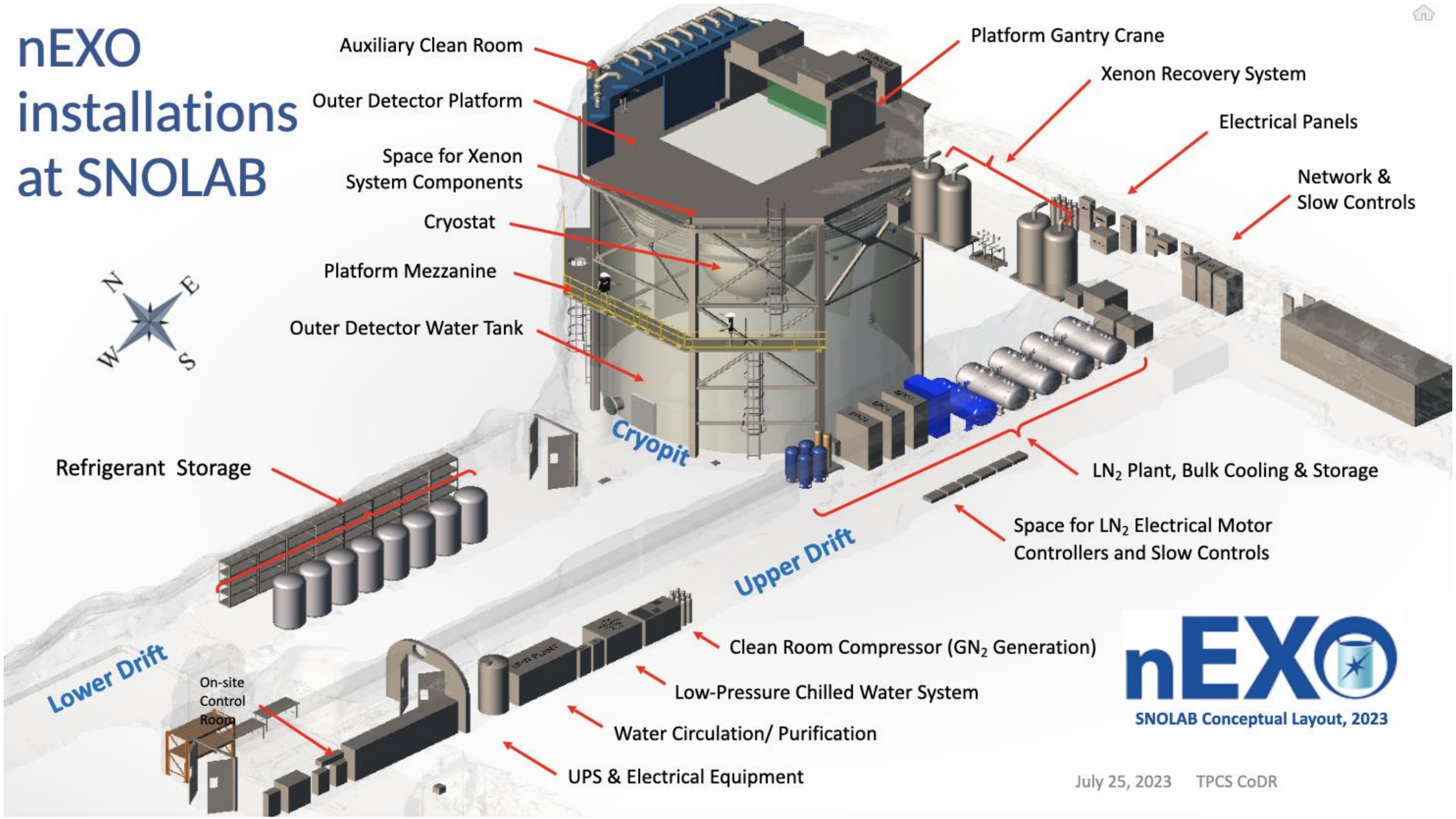
= Detection volume

Detector's Geometry: Multi-Layer Shielding

- 5 tons 90% Liquid (165K) ^{136}Xe inside a copper vessel
- 32 tons HFE[1]: Dense shielding liquid
- Dual cryostats: Vacuum insulation barrier
- Cosmic ray shield:
  - Big water volume
  - @ SNOLAB, underground cave (6000 m.w.e)



[1]HydroFluoroEther



Space Required: Around 5000 m^3 total (3500 m^3 for the Veto Tank)

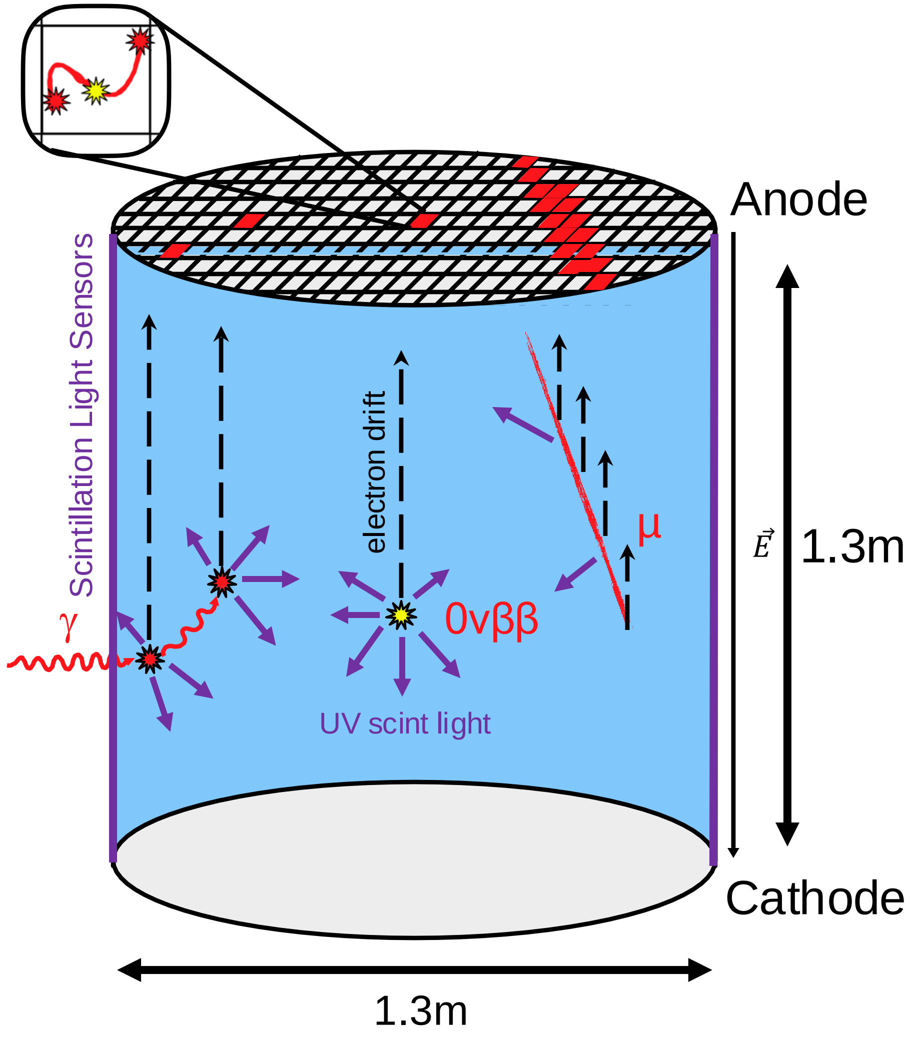
The nEXO Experiment: Signal Detection

Signals Generation & Detection

- Xenon is both the source and the detection medium
- Ionizing radiation produces:
  - prompt scintillation (S1) 175 nm UV photons → immediately detected by SiPMs around the barrel
  - Ionization electrons (S2) → drifted to charge collection tiles at the top

Signals Analysis

- Dual signal enables 3D event reconstruction
- Multiparameter identification to differentiate with γ, μ,… background

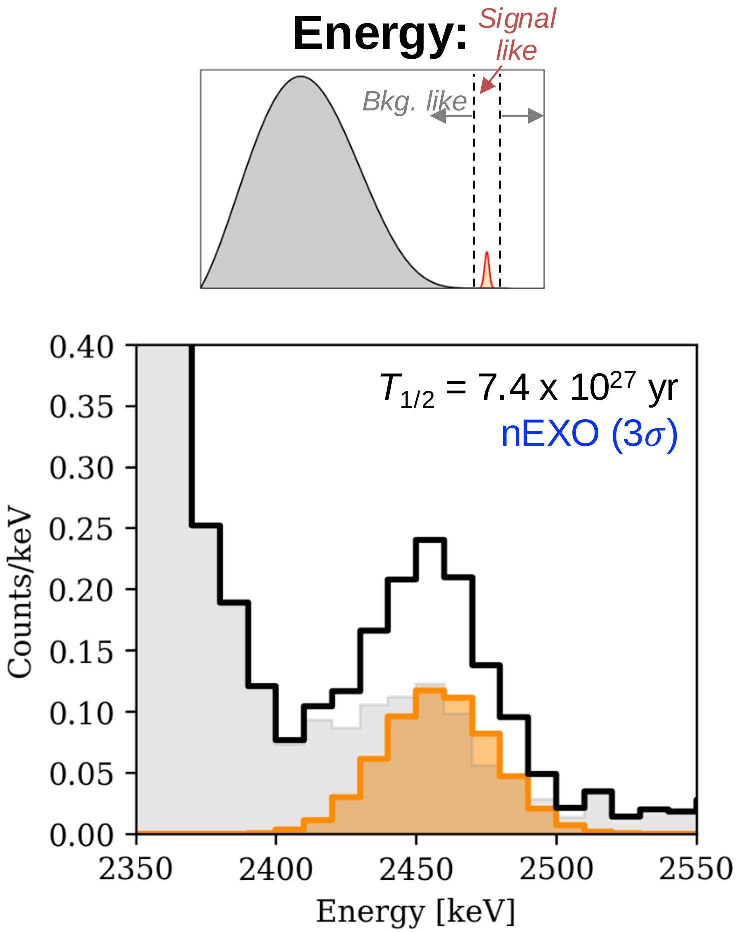


The nEXO Experiment: Background Definition

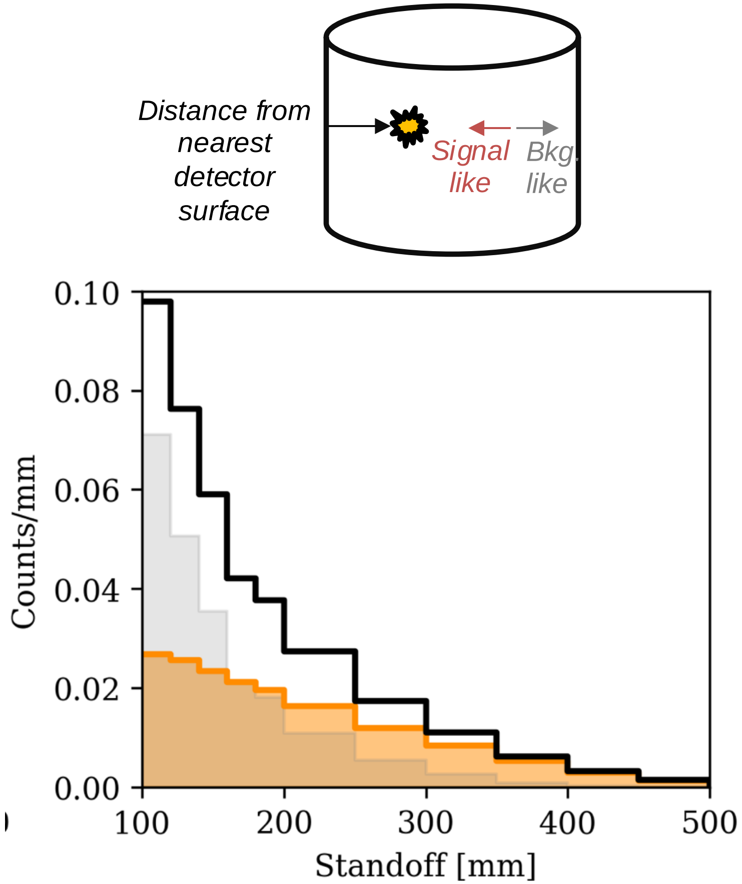
Selection Criteria

- Energy near the 0νββ region of interest
- In the inner 2 tons of LXe*
- Single Site: Neural Network > 0.88

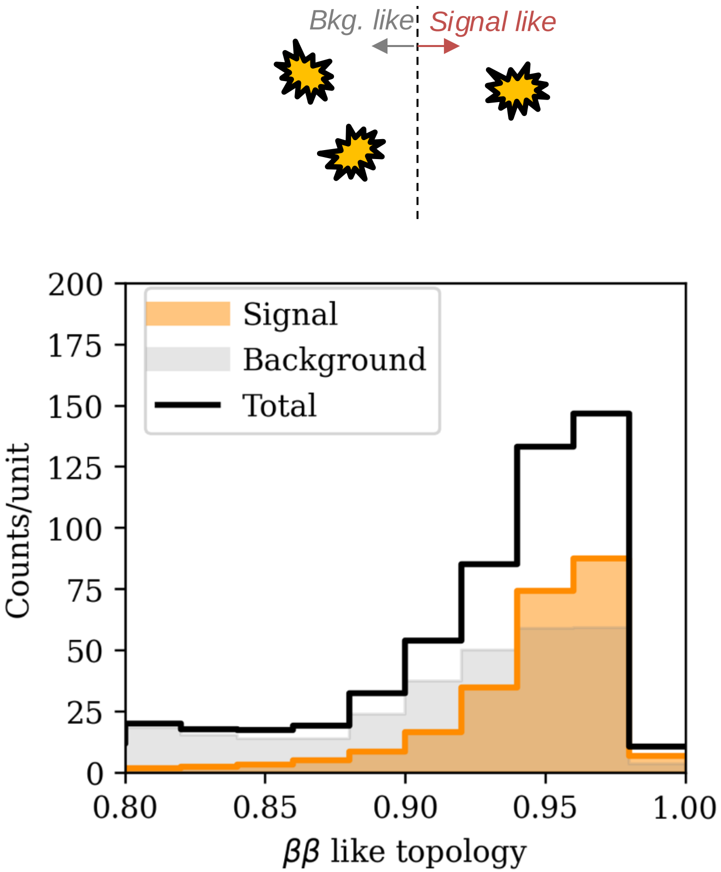
Energy:



Standoff:



Topology:



*: As a reference. Weighted by spatial probability distribution. No hard fiducial cut applied.

Internal Background Sources

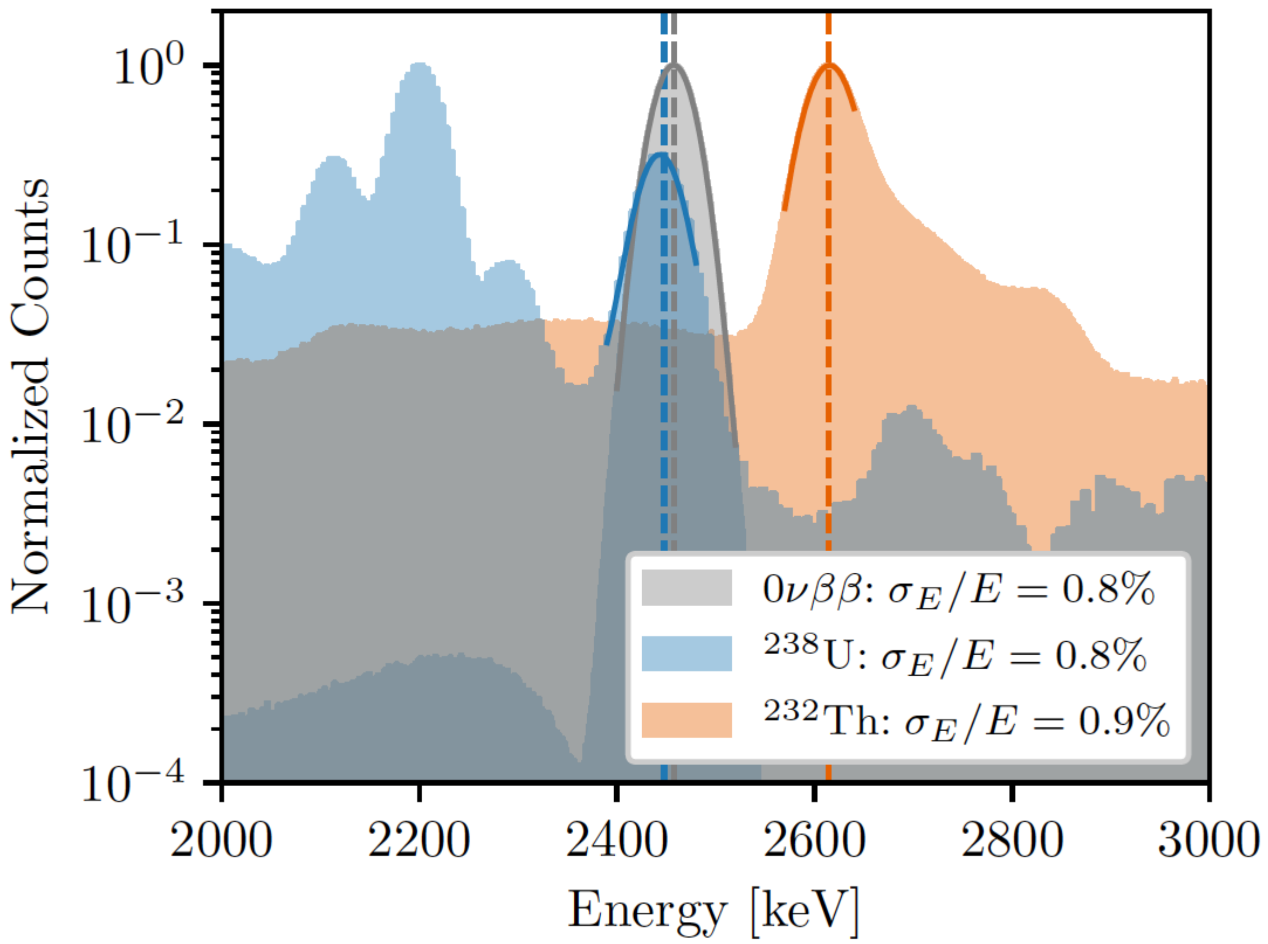
- Mainly from to γ-rays emitted by decaying nuclides
- From: ^{232}Th (mainly ^{208}Tl: 2615 keV*)

  ^{238}U (mainly ^{214}Bi: 2448 keV)

Quantify Component Background Contribution

$$B = B_U + B_{Th} = m \times (a_U \times \varepsilon_U + a_{Th} \times \varepsilon_{Th})$$

m : component's mass
a : component's material activity
ε: component's hit efficiency (probability of a decay event becoming a background count)



Why are we focusing on the cryostat?

*: then soft Compton in HFE to get in ROI

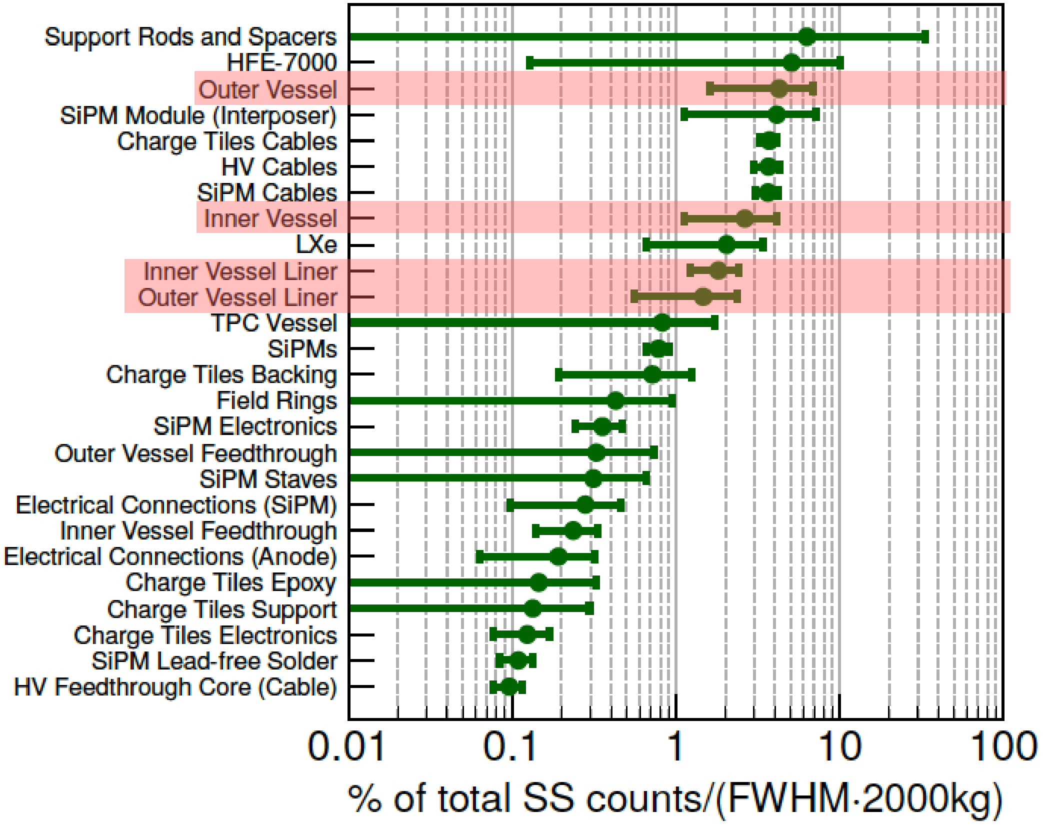
Carbon Fiber to Nickel Cryostats: Cryostat Characterisitics

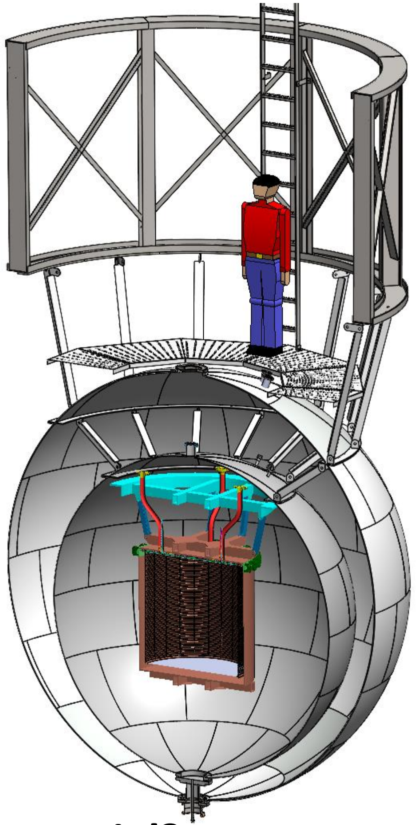
Why are we Focusing on the Cryostat?

- Cryostat Vessels are prominent internal background sources

Baseline Cryostats Design Values

- Inner Vessel (IV) radius: ~1.7 m
- Outer Vessel (OV) radius: ~2.2 m





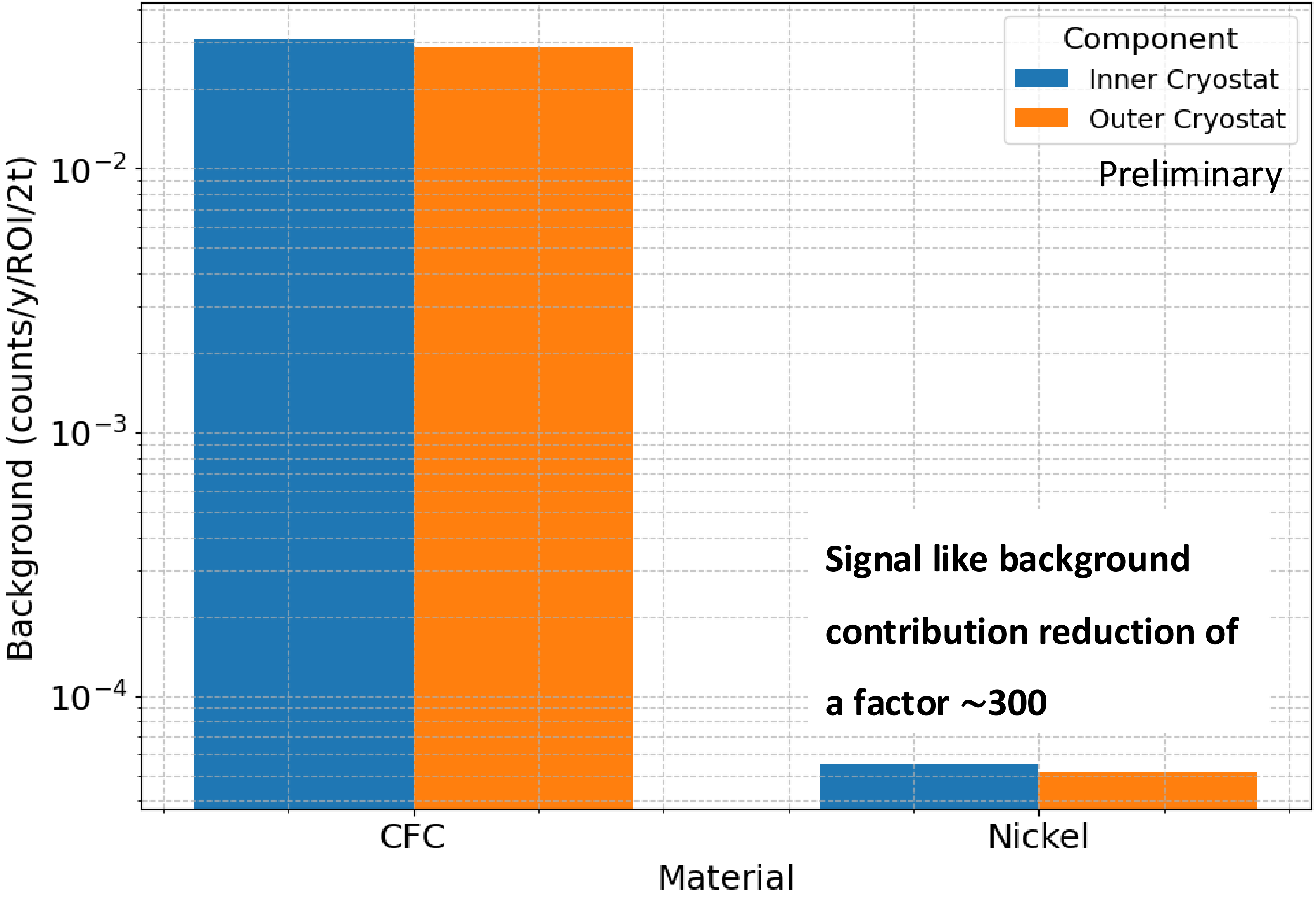
How to reduce this background contribution? With a new material?

Carbon Fiber to Nickel Cryostats: Impact on Background

Nickel vs Carbon Fiber

Searched for new ultra radiopure material

- Got low-activity Nickel samples



Signal like background contribution reduction of a factor ~300

Nickel = new baseline for the cryostat vessels

HFE Shielding

Cryostat material less radioactive → Possibility of reducing the HFE thickness
(while keeping the same background contribution)

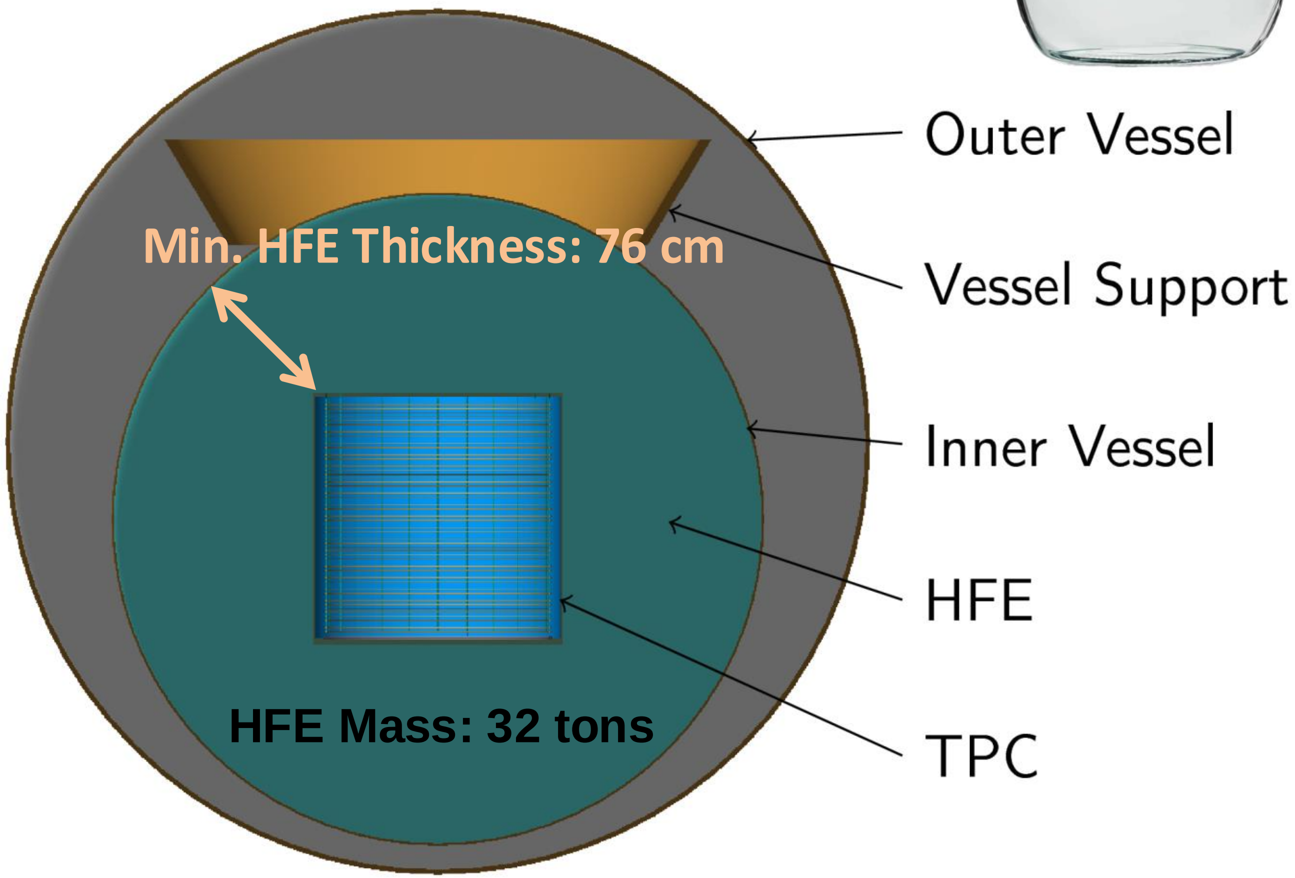
Motivations to Use an HFE Bath

- Dense liquid at room & cryo. temperatures
  - Efficient external γ-ray shield
- Ensures cryogenic system stability at 165K

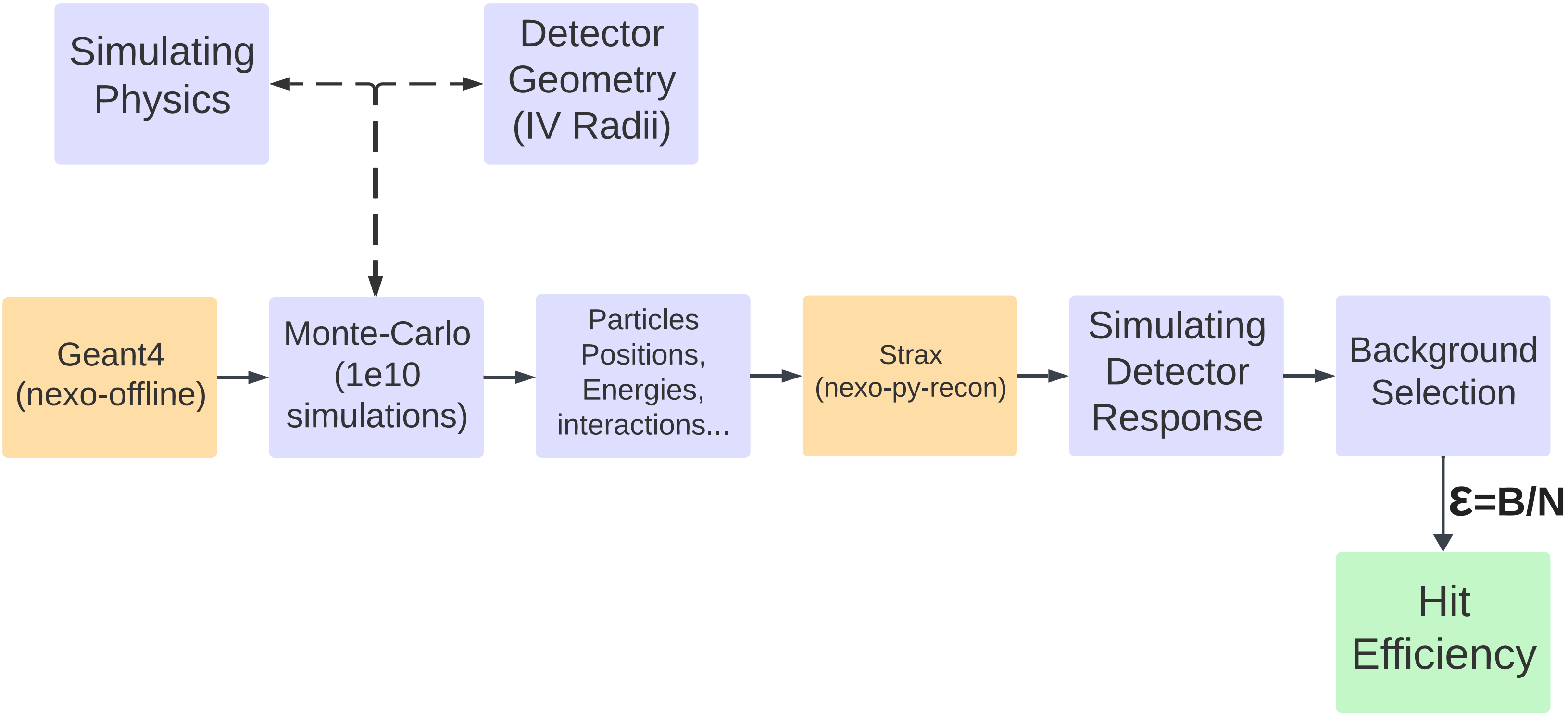
Why reduce its quantity

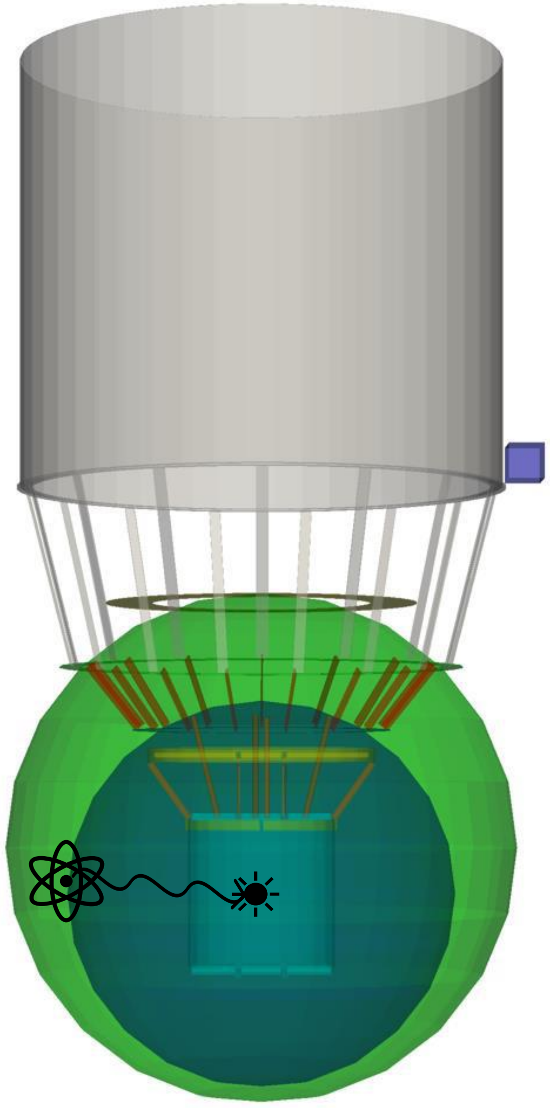
- Expensive
- Large quantity = Big background contribution

Baseline Design



Computing the background impact from a smaller HFE volume





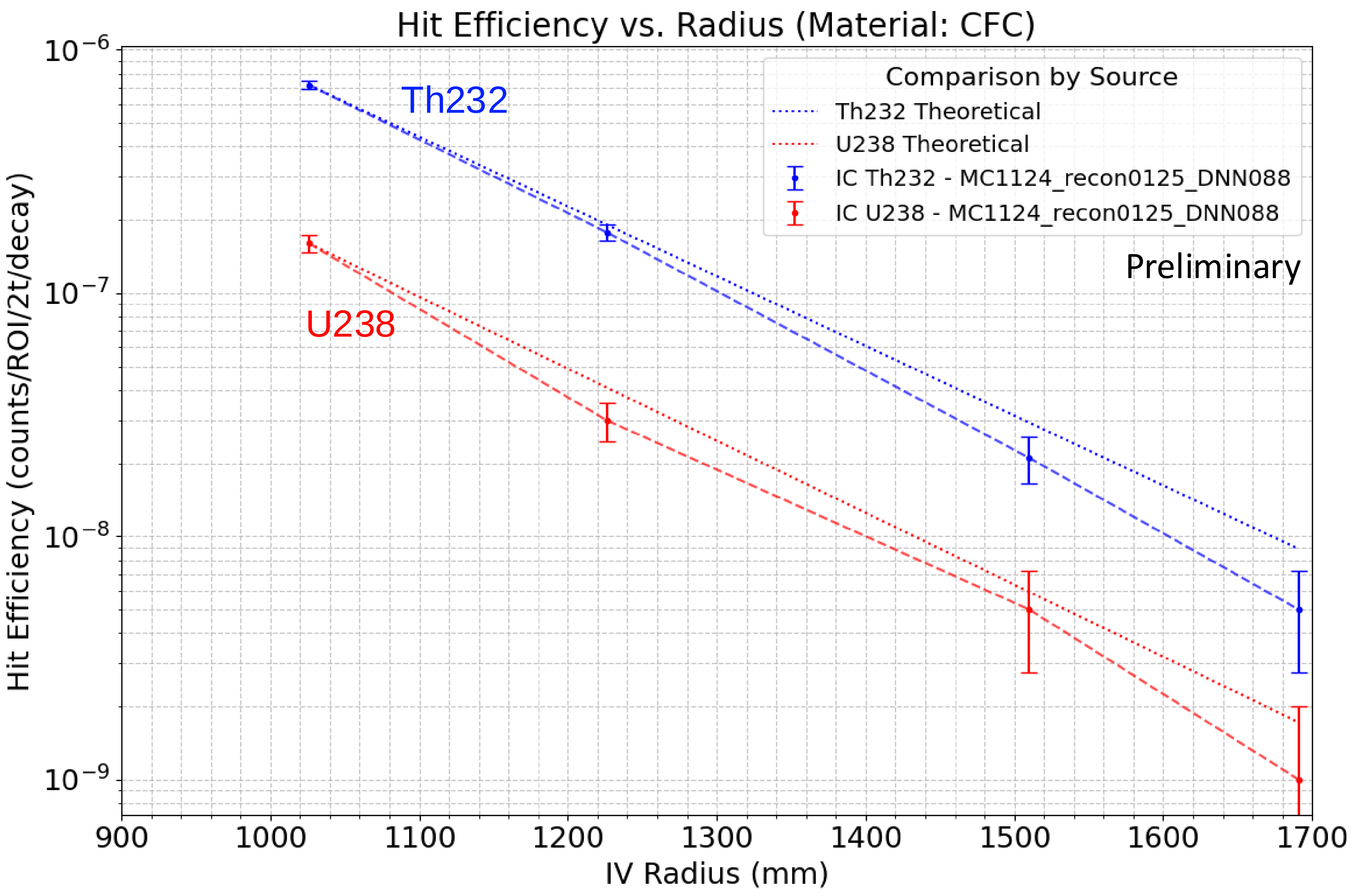
Geometry in Geant4

*HFE volume adjusted accordingly

HFE Shielding: Monte Carlo Studies

IV Hit Efficiency vs HFE Thickness

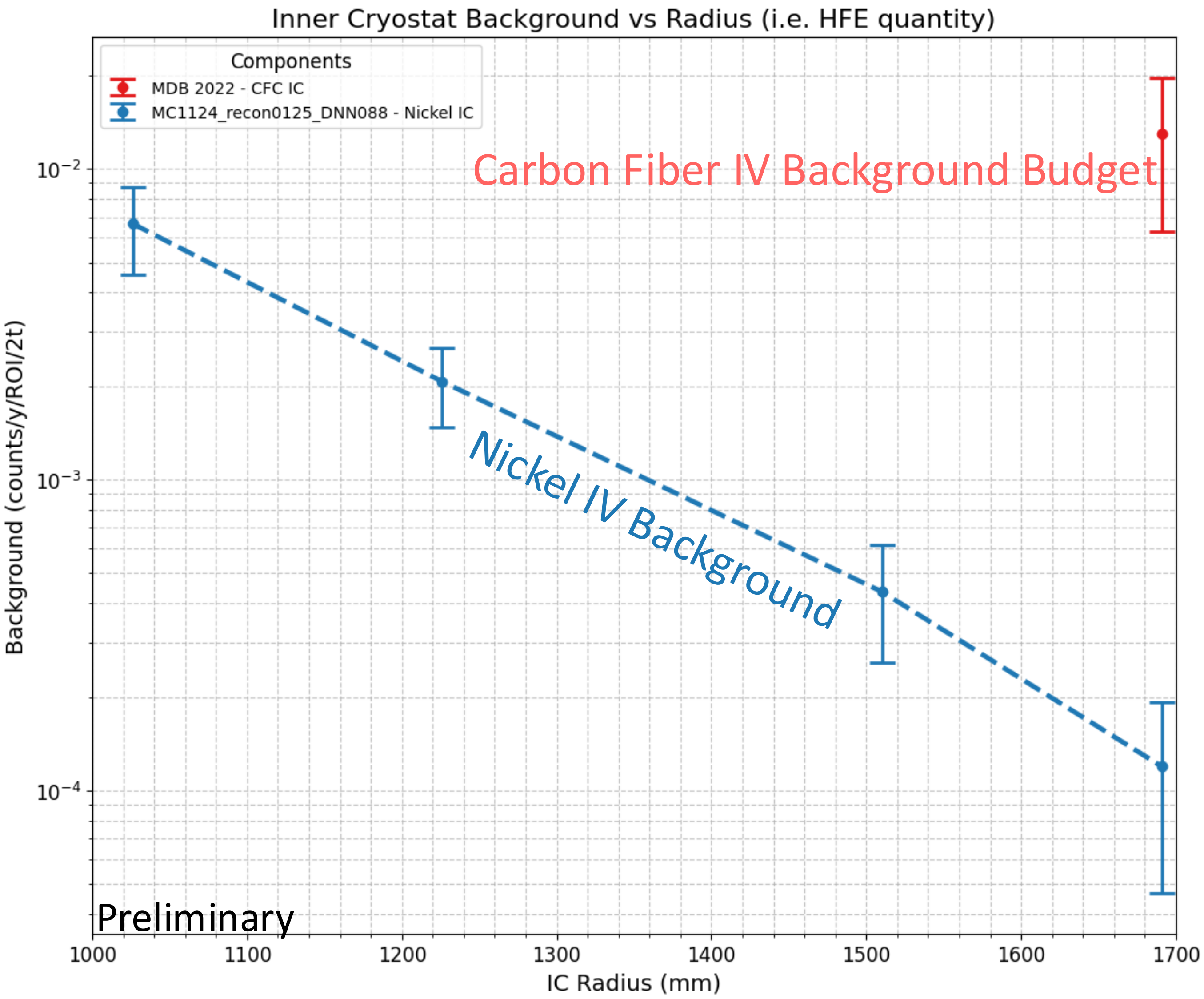
- Exponential evolution
- Close to attenuation law (2.5 MeV gamma in HFE)
- OV has similar efficiencies evolutions



HFE Shielding: Monte Carlo Studies

IV Background Contrib. vs HFE Thickness

- Using Nickel activity & shell mass:
  - $B = B_U + B_{Th} = m \times (a_U \times \varepsilon_U + a_{Th} \times \varepsilon_{Th})$
- Previous IV bkgd budget: 0.032/y/FWHM/2t
- Same procedure will be done for OV



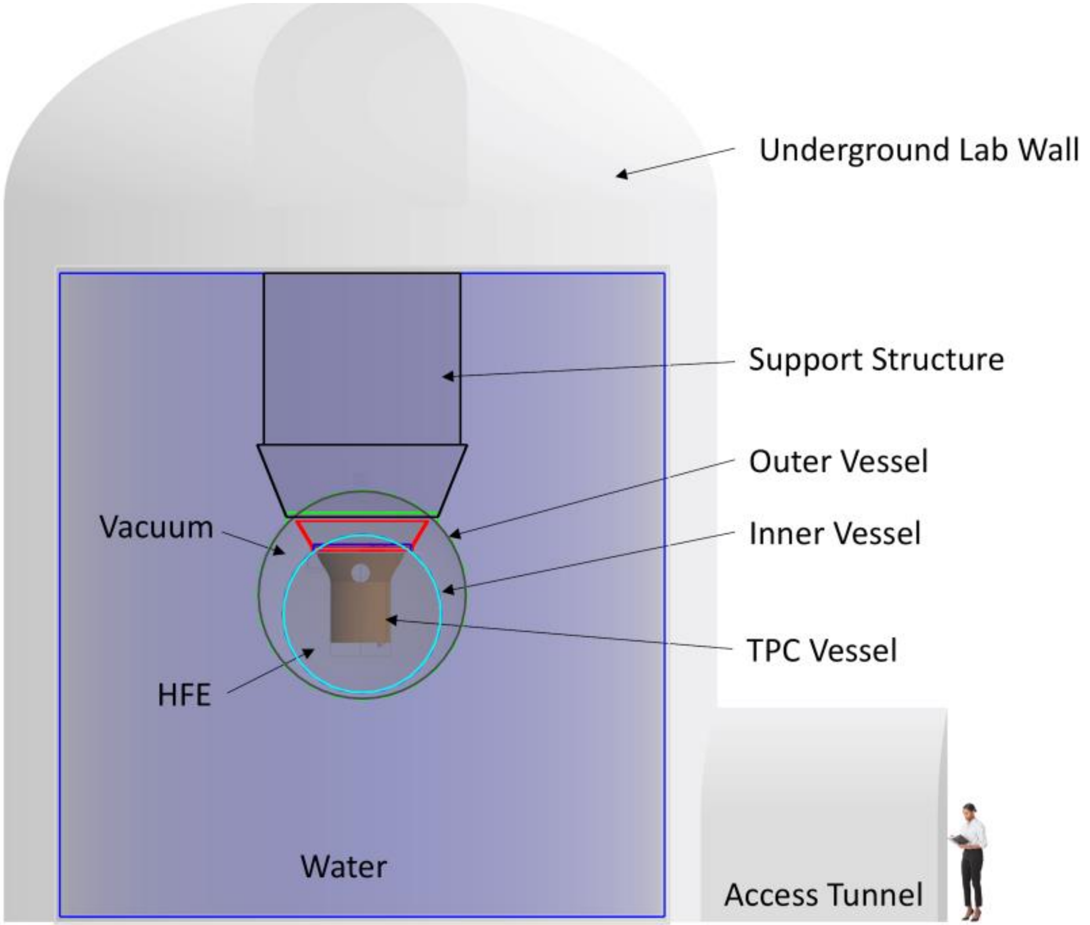
Nickel Cryostat background is always below the limit → HFE quantity can be reduced

As a reminder: $B = B_U + B_{Th} = m \times (a_U \times \varepsilon_U + a_{Th} \times \varepsilon_{Th})$

Design Implications: External Background

Less HFE = External Background Increased

- From:
  - ^{222}Rn from water,
  - Support structure,
  - …
- Can be quantified with the attenuation law



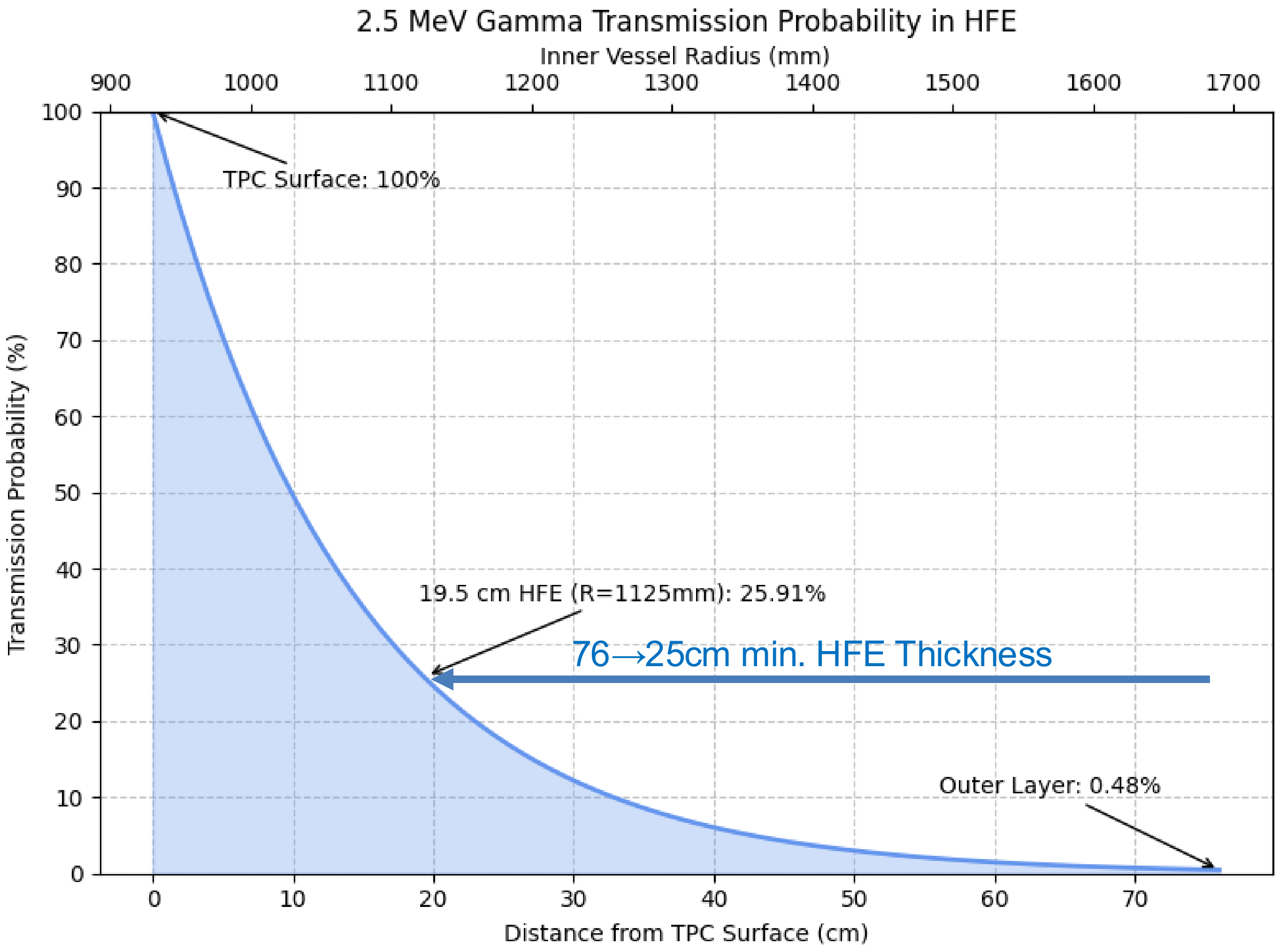
Main limitation factor is now the external background levels

*i.e. 1.7 →1.125 m IV radius

Design Implications: External Background

Giving a water radioactivity limit

- Using the attenuation law with the minimal HFE thickness
- Going from 1.7 m → 1.125 m IV would:
  - Shielding efficiency /50 ⇔ External radioactivity: 50x greater impact
  - ▼ Maximal allowable radon concentration decreased by the same factor



What would be the other impacts of a 1.125 m IV radius?

Design Implications: HFE quantity

Using a 1.125 m Radius Inner Vessel

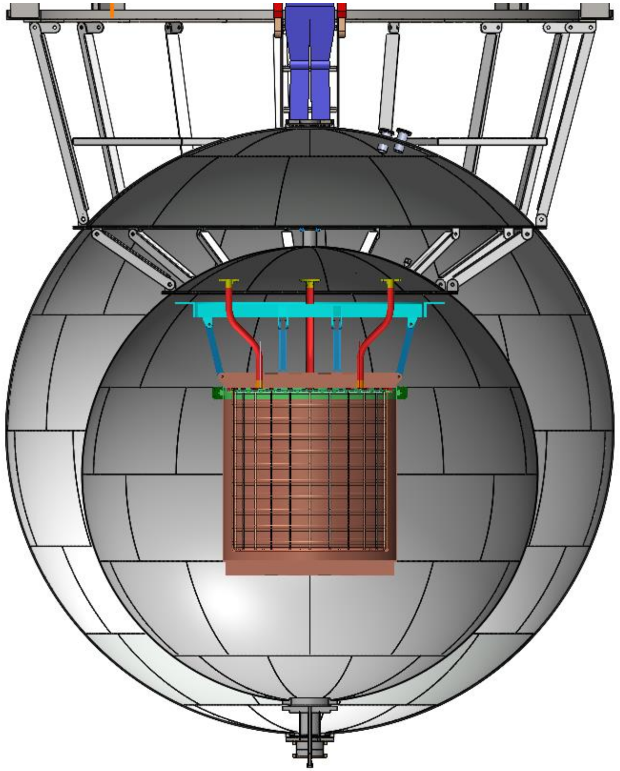
- ▼ Mass: 32 → 7.5 tons
- ▼ Volume: 18.5 → 4.4 m^3
- ▼ Min. thickness: 76 → 19.5 cm
- ▼ HFE cost reduction (price ~/4)
- ▼ Less storage needed
- ‼ Cold mass reduction

Design Implications: Cold Mass

HFE Cold Mass Reduction

- LXe needs to stay stable at 165K
- ▼ 4x less HFE ≈ 4x less cold mass
- Still the largest cold mass: 5x more than LXe

Component	Mass (tons)	Energy for 1K rise (MJ)
LXe	5	2
HFE (baseline quantity)	32	40
HFE (reduced quantity)	7.5	10
Cryostat IV (Ni)	2	1
Total (reduced HFE)	**14.5 tons**	**13 MJ**



HFE quantity is still enough for thermal stability

Summary

Main Message (using Nickel)

- Radioactivity: 300x better than Carbon Fiber
- IV radius could be reduced: 1.7 → 1.125 m
- HFE is still the main cold mass

Outlook → Implementation of a new HFE volume

- Other components background impact
- Thermal mass inertia study
- Mechanical study necessary

Implications Discussed

Impact	Pros	Cons
Economic	HFE cost reduction (32 → 7.5 tons)	
Spatial	Reduced storage requirements	
Design	Cryostats easier to build	
	Potential thinner IV & OV	Redesign requirements
	Possibility to increase water shielding	More radon from water
Operational	Faster cooling time	Reduced cold mass

Backup

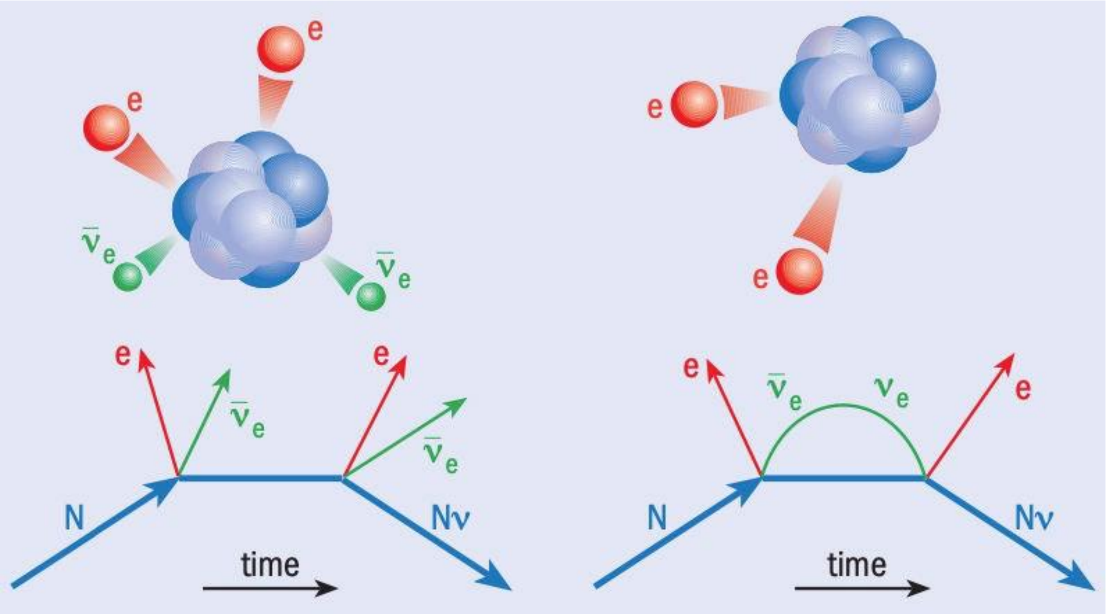
The nEXO Experiment: Neutrinoless Double Beta Decay

Double beta decay (2νββ)

- Allowed in the SM
- Already observed in several isotopes
- Rare process (^{136}Xe 2νββ half life: 10^{21} years)

Neutrinoless double beta decay (0νββ)

- Forbidden in the SM (lepton number violation)
- Never observed (^{136}Xe 0νββ current limits: 10^{26} years)
- Could explain matter-antimatter asymmetry
- The new physics reach can also be parametrized in the effective Majorana mass



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

*For reference: Age of the Universe: 10^{10} years

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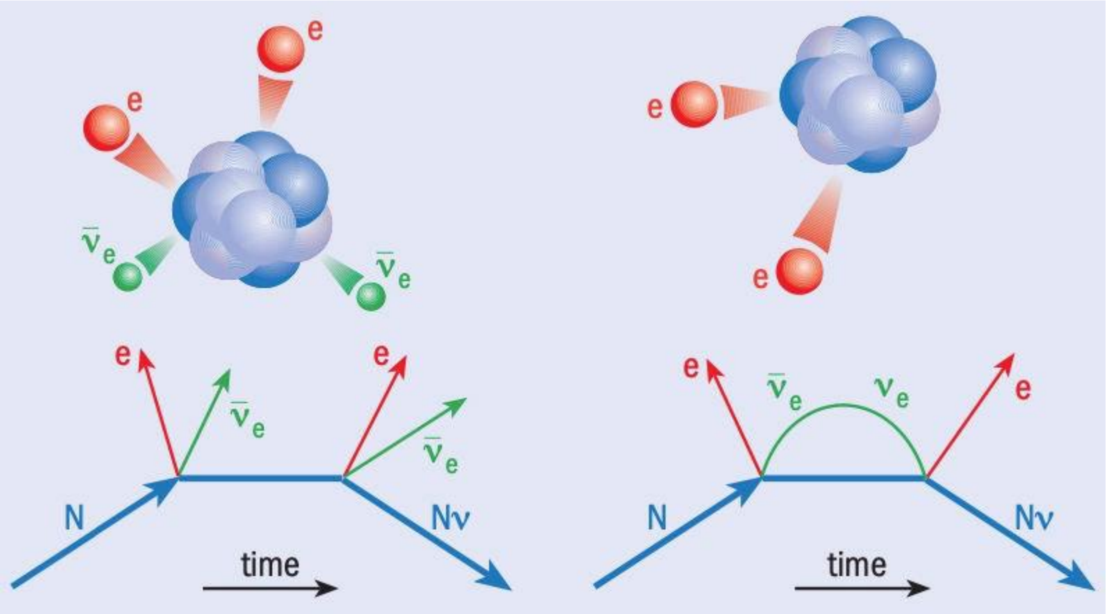
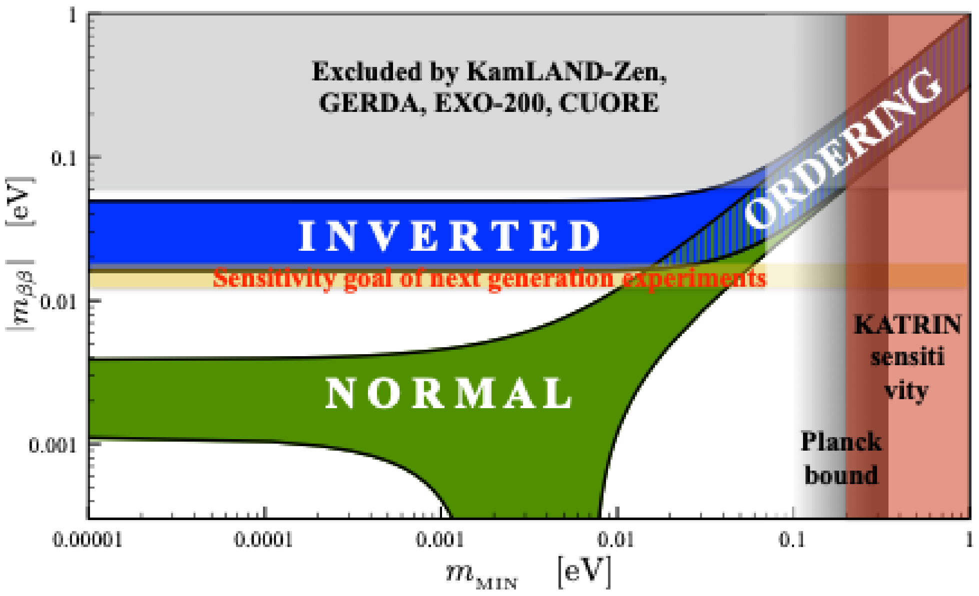




*For reference: Age of the Universe: 10^{10} years

The nEXO Experiment: Neutrinoless Double Beta Decay

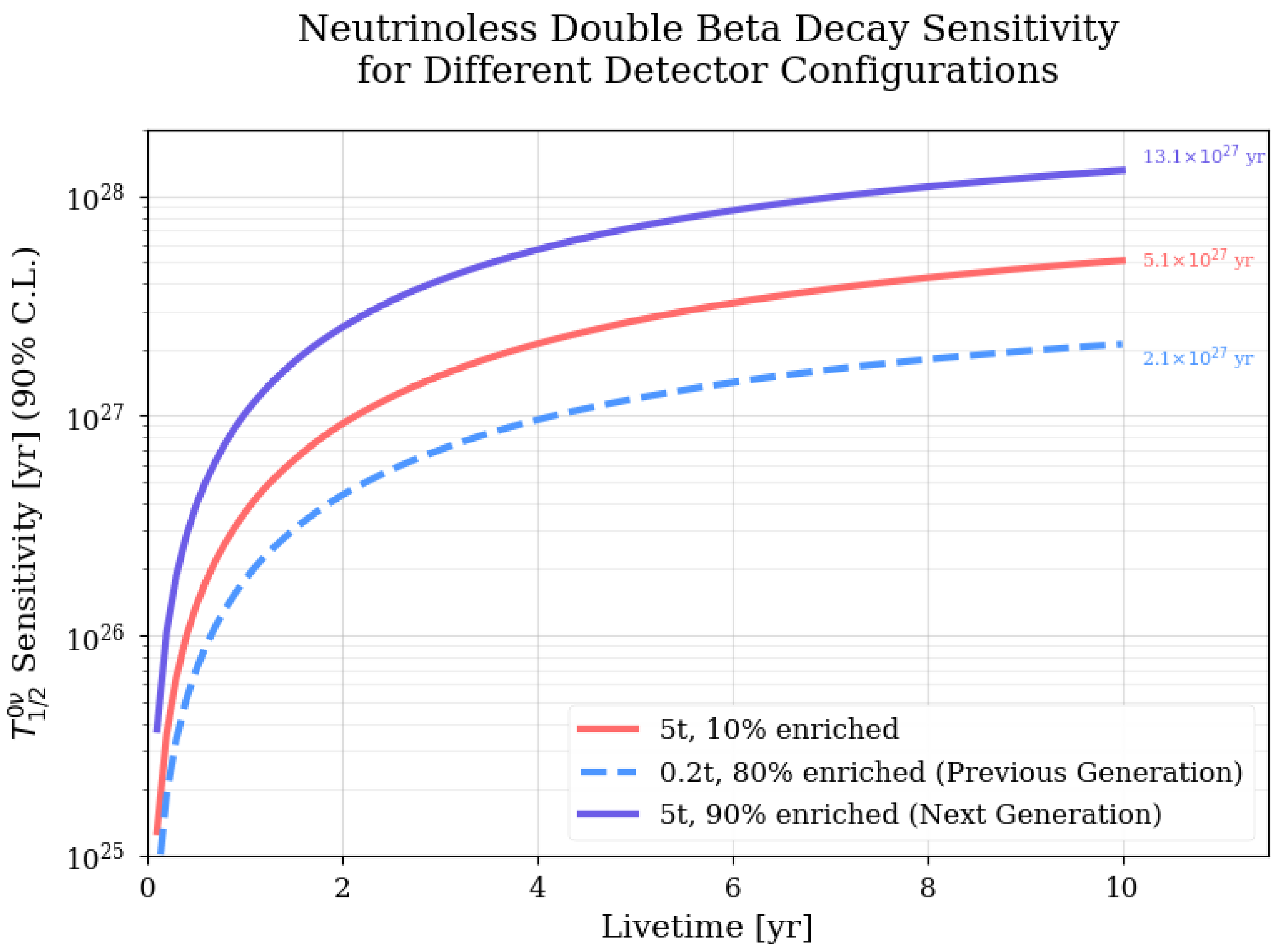
Sensitivity figure of merit:

$$S^{0\nu} \propto \frac{\alpha}{A} \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot b}}$$

Should be high

Detecting ^{136}Xe 0νββ requires:

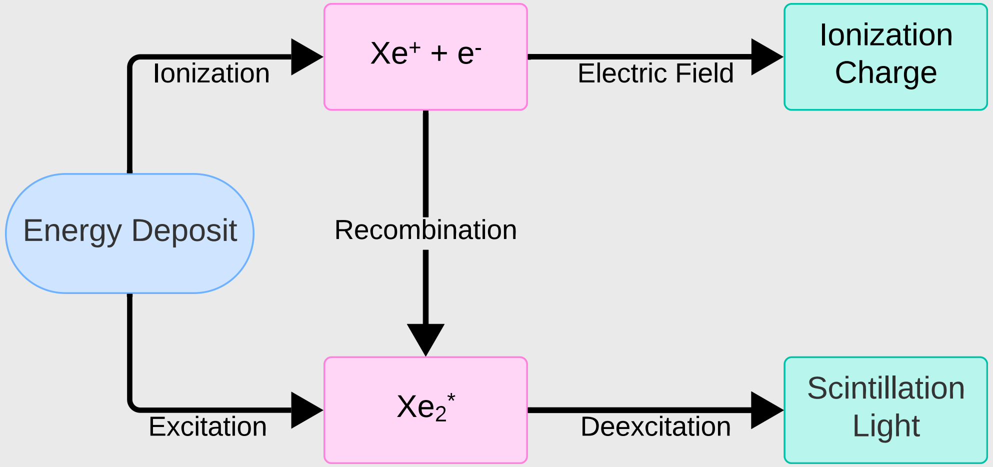
1. (α, M) Large mass of enriched isotope*
2. (A) Atomic mass
3. (t) Long detection time
4. (ΔE) Good energy resolution (< 1% σE/E)
5. (b) Low background index (< 0.5 counts/y/2t/ROI)

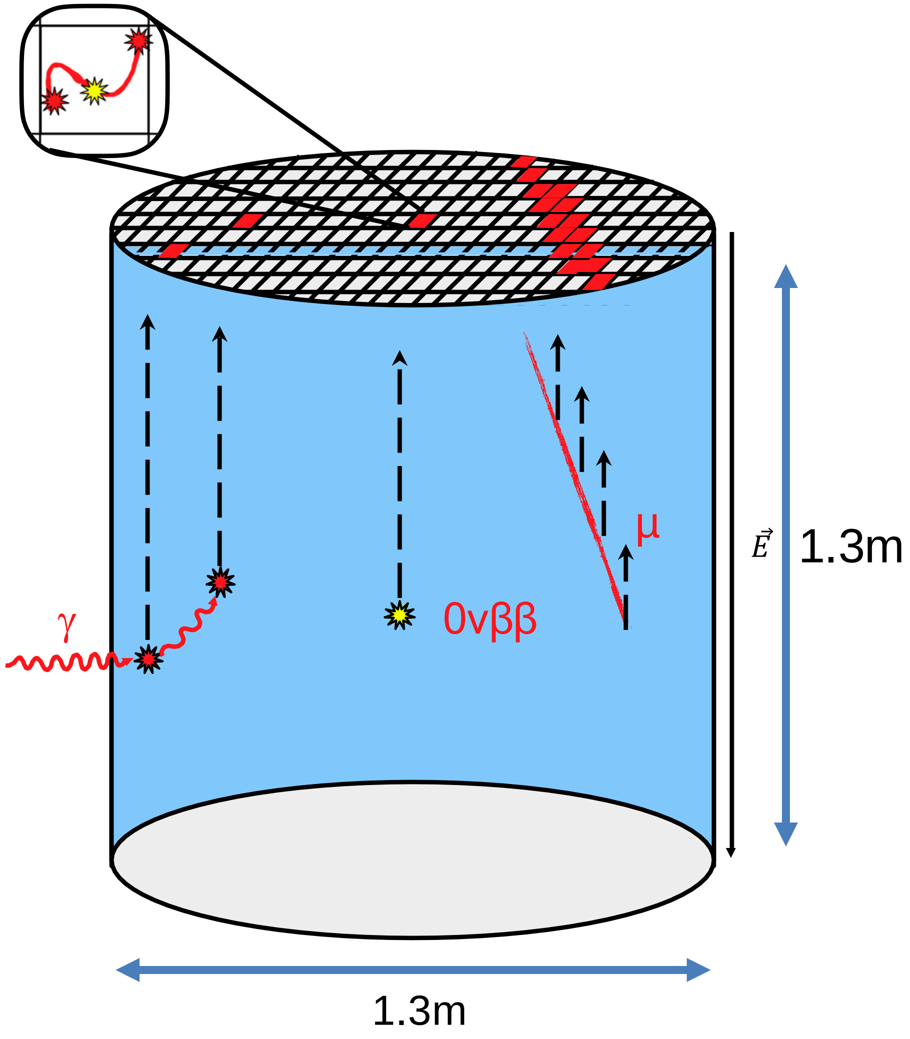


*Natural Isotopic Abondance α ^{136}Xe=8.9%; M is the FV Mass

Signals Generation

- Ionizing radiation will either ionize or excite Xe atoms
- Xenon is both the source and detection medium



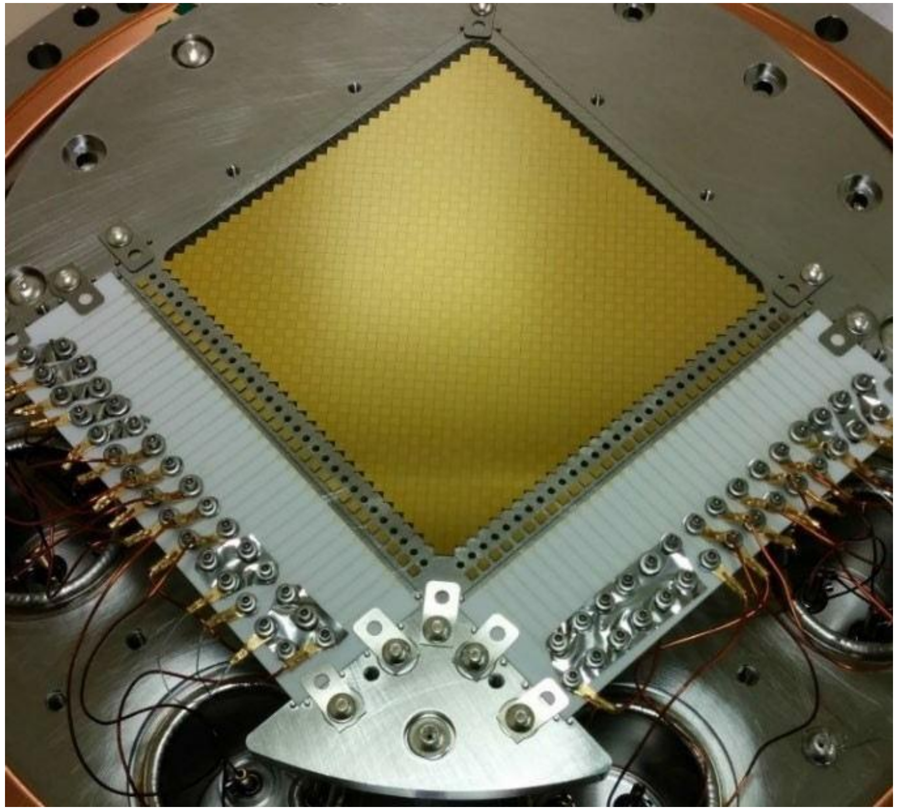


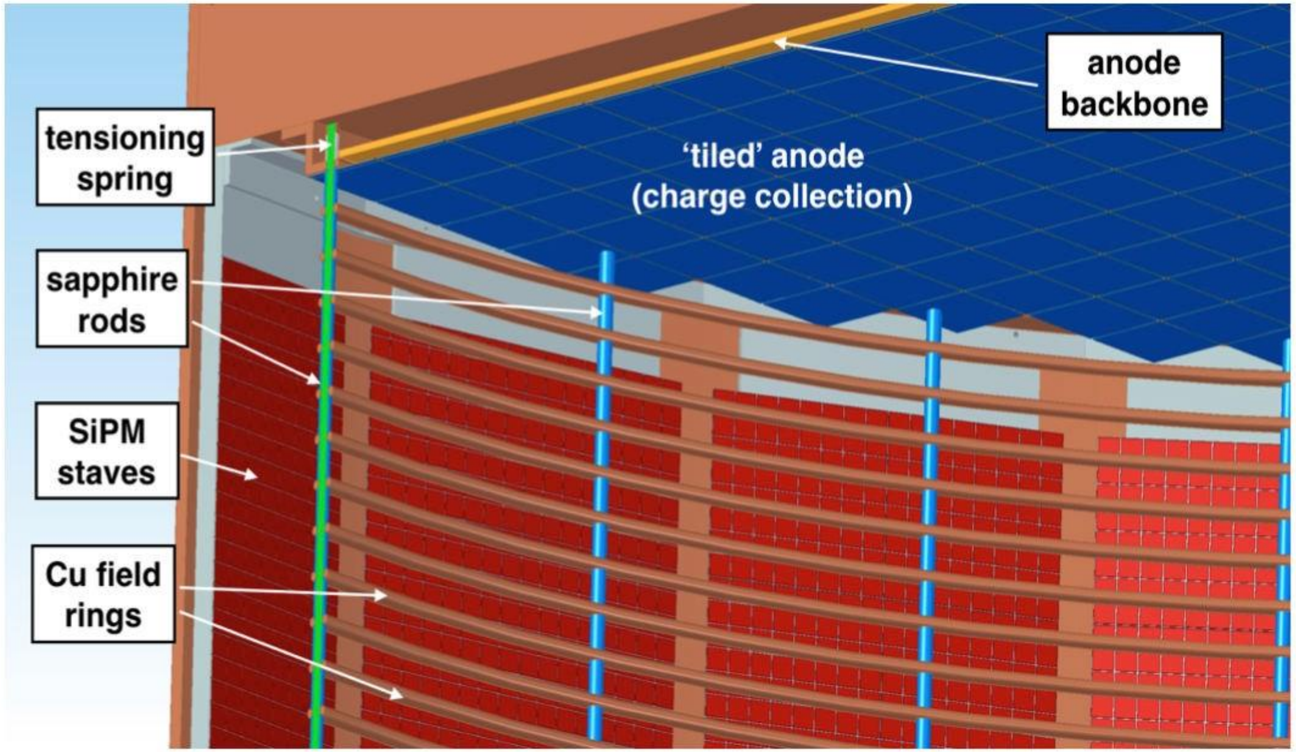
Signals Detection & Analysis

- Photons immediately detected by SiPMs around the barrel
- Electrons drifted to charge collection tiles at the top

Charge Collection Tiles

- Electrons are drifted to charge collection tiles at the top
- 10cm x 10cm charge collection tiles with 3mm pitch strips detect e-

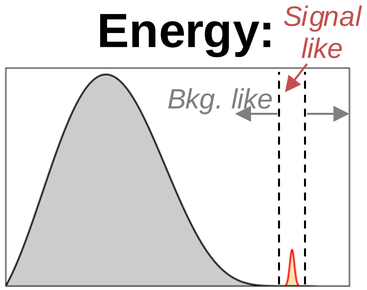




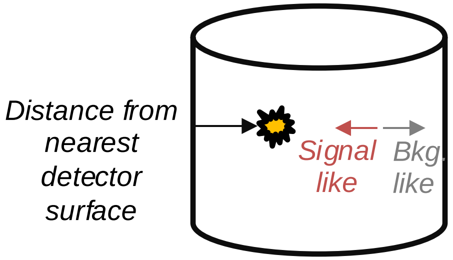
Selection Criteria

- Energy in the FWHM of the 0νββ ROI
- In the inner 2 tons of LXe*
- Single Site: Neural Network>0.85

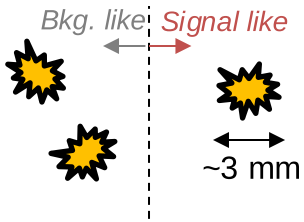
Energy:



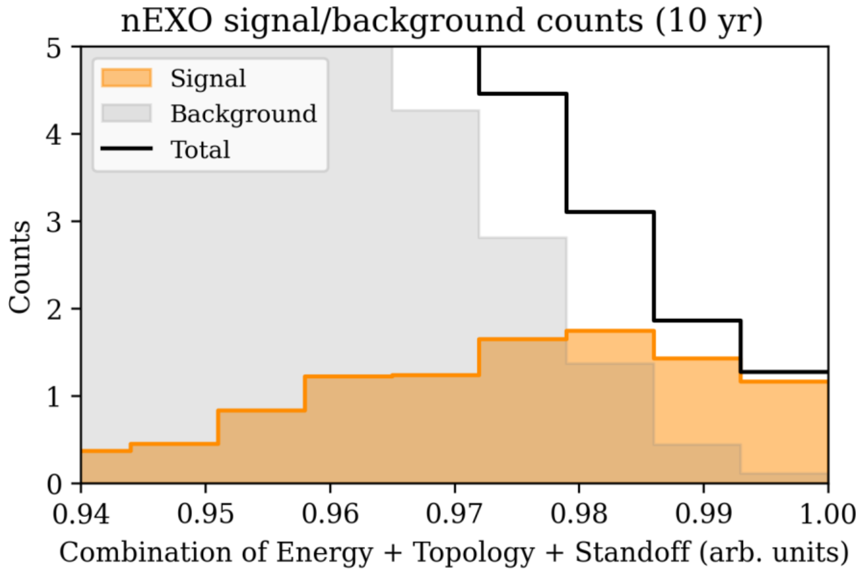
Standoff:



Topology:



3D bins ordered by S/B in 1D: Visualizes signal-background separation while preserving correlations

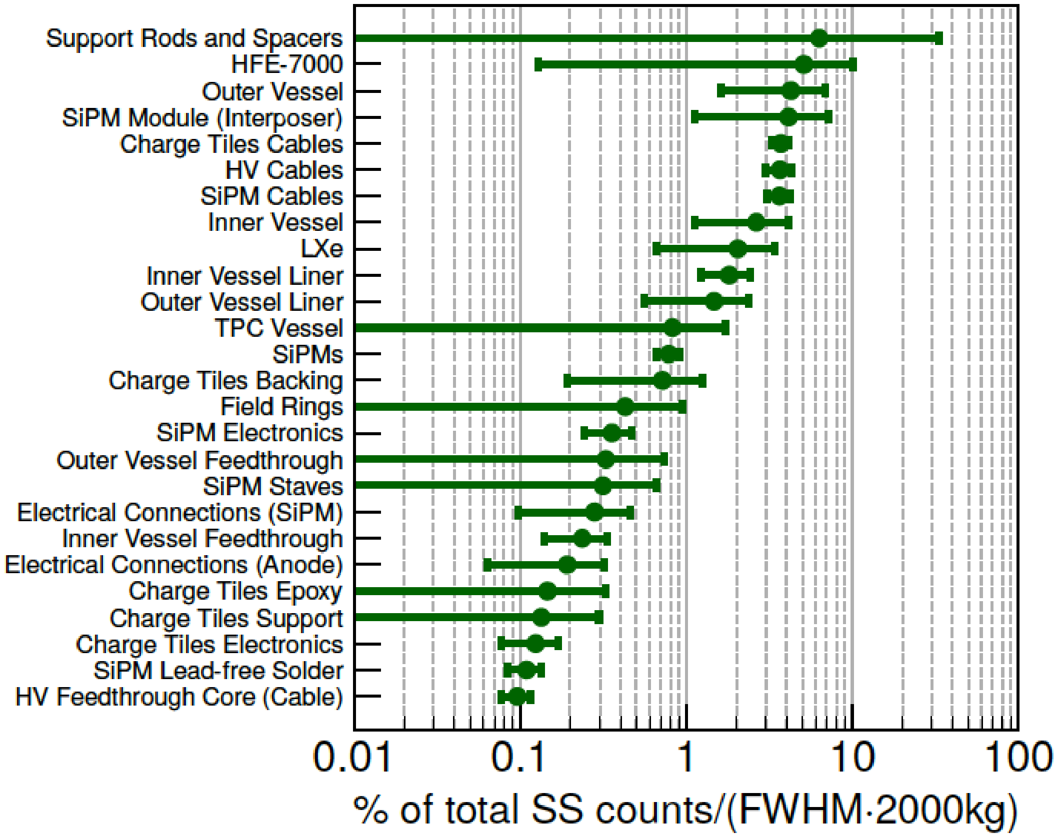


0 ← Background-like **Signal-like →1**

*: As a reference. Weighted by spatial probability distribution. No hard fiducial cut applied.

Other Sources of Background

- CFC Cryostat Vessels were a dominant internal background source
- Other backgrounds now play a more prominent role



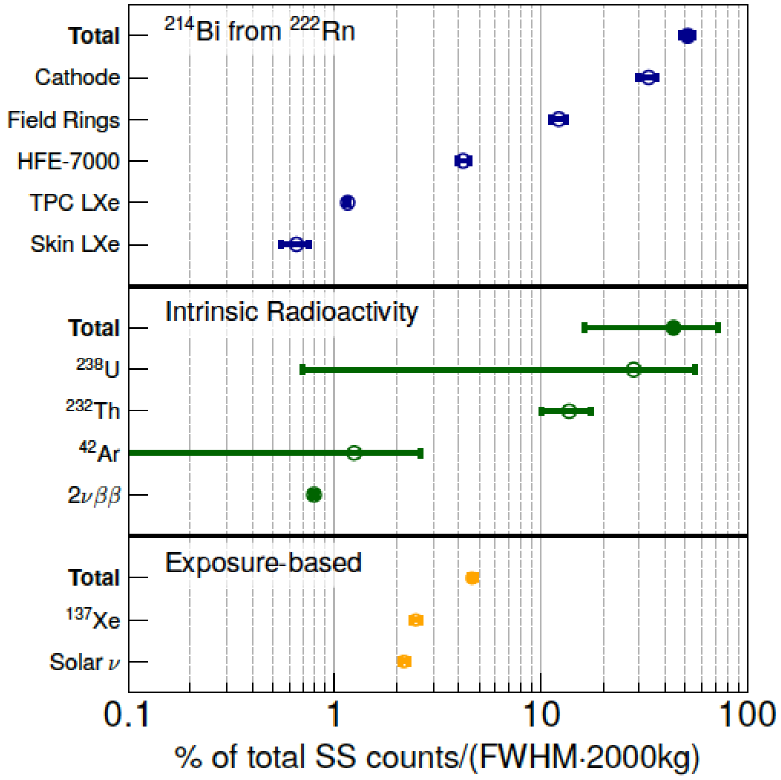
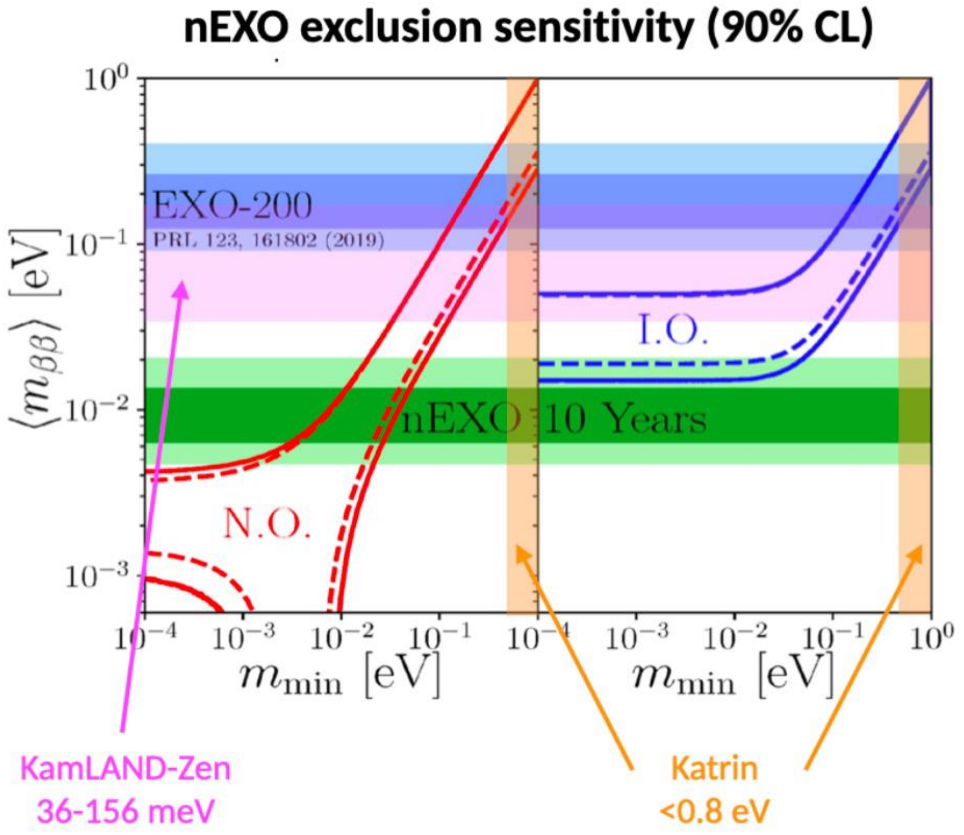


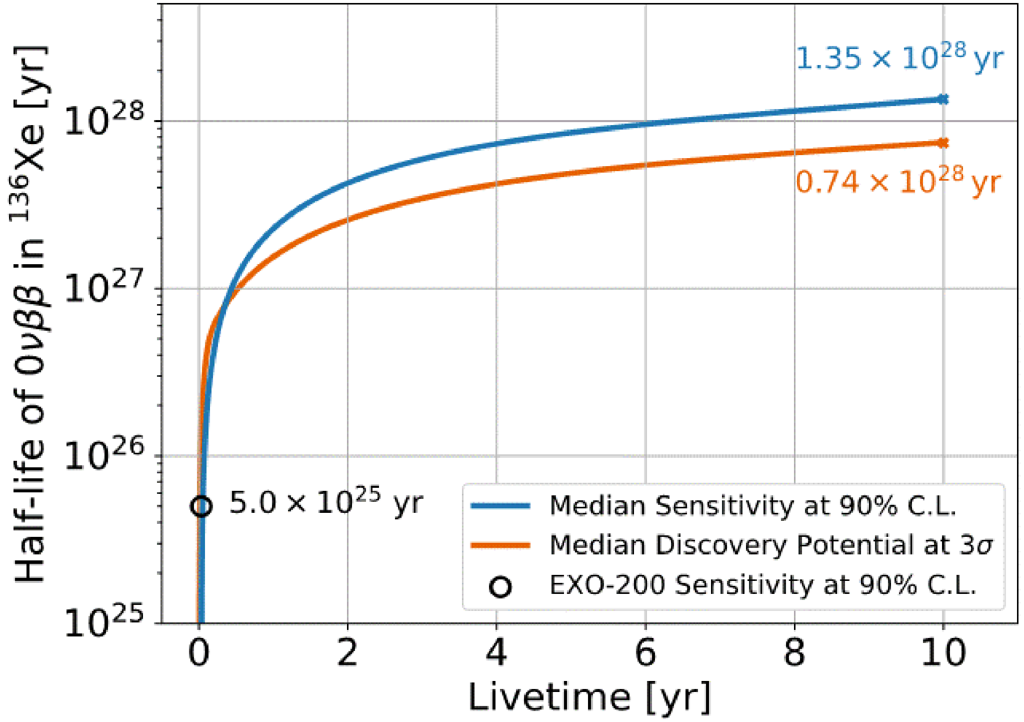
Figure 8. SS-like fractional background contributions with energy within $Q_{\beta\beta}\pm$FWHM/2 and in the inner 2000 kg. The contributions are grouped by category, as described in the text. For each category, the total contribution is shown by the solid marker, while individual contributions are indicated by open circles. Negligible contributions are not shown. For ^{222}Rn backgrounds, the breakdown by ^{214}Bi decay location (based on Table 6) is shown. Breakdown by the individual source terms is given for the other two background categories.

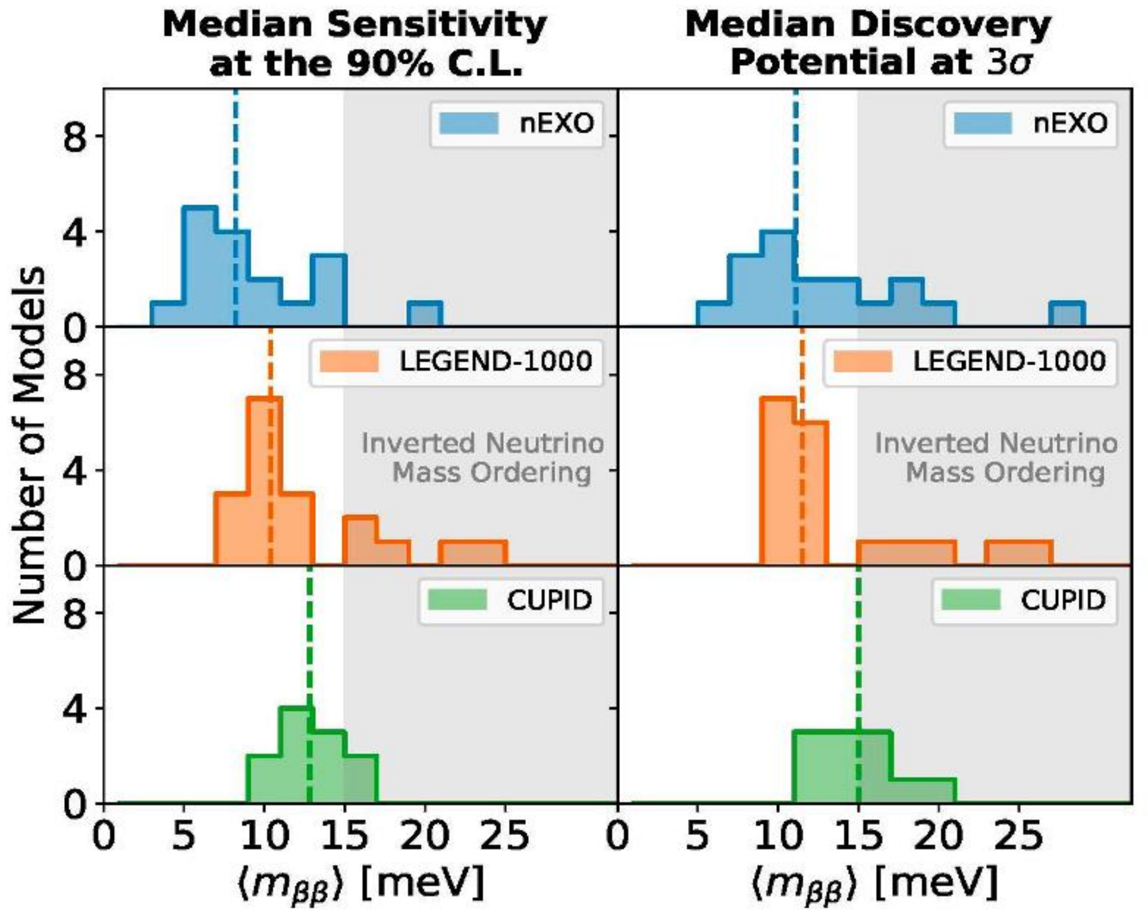
The nEXO Experiment: Expected Sensitivity

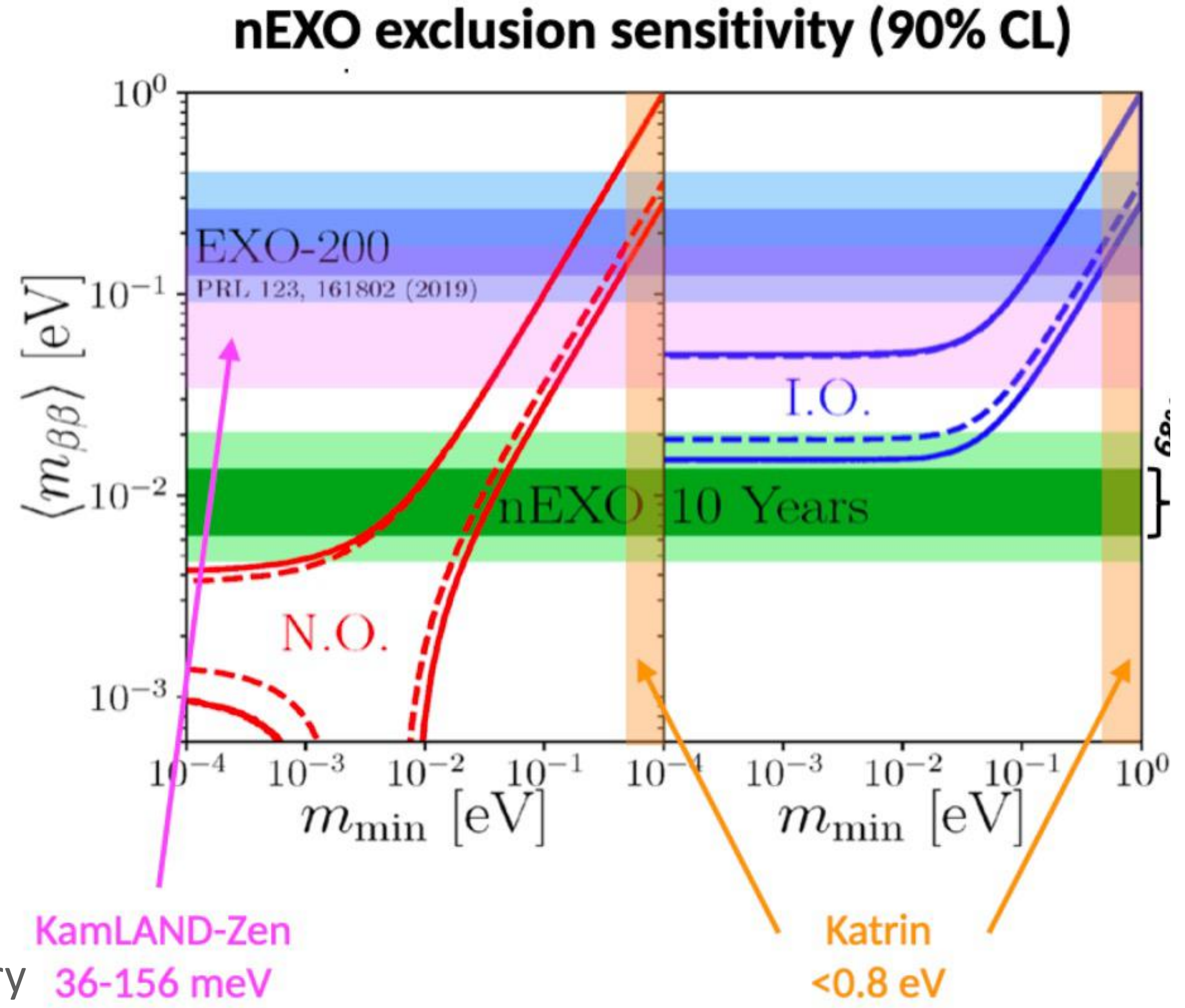
Expected Sensitivity

- A large unexplored parameter space
- Reach a $0\nu\beta\beta$ half-life of 10^{28} years in 6.5 years data taking
- x1000 more sensible than the previous generation (EXO-200)









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

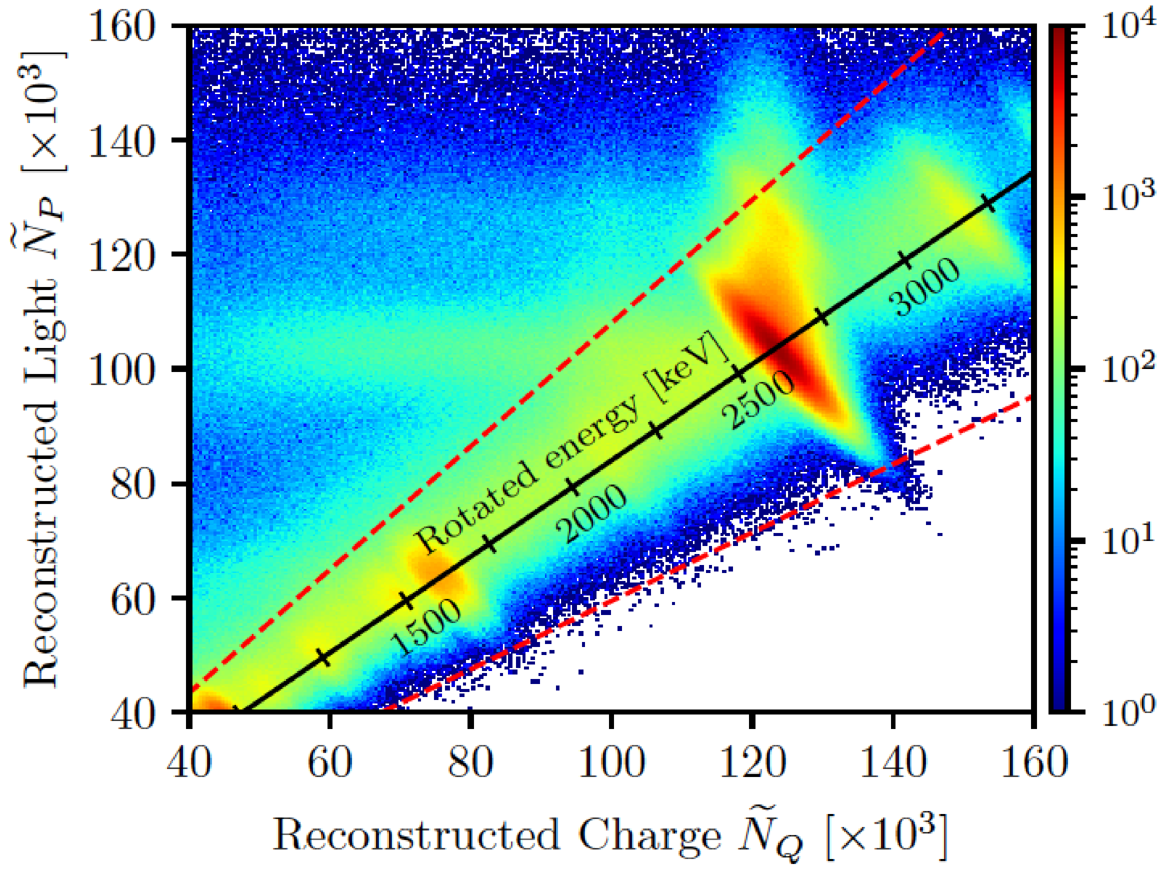
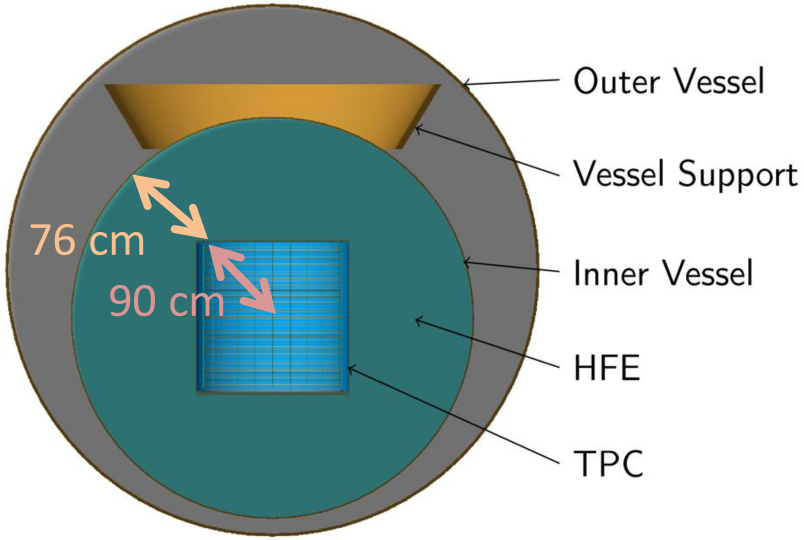


Figure 5. Reconstructed light and charge signals of all events in the FV from simulated ^{232}Th decays in the TPC vessel. The dashed lines indicate the location of the diagonal cut, described in the text. The rotated axis indicates the scale of the rotated energy.

HFE 2.5 MeV γ Attenuation

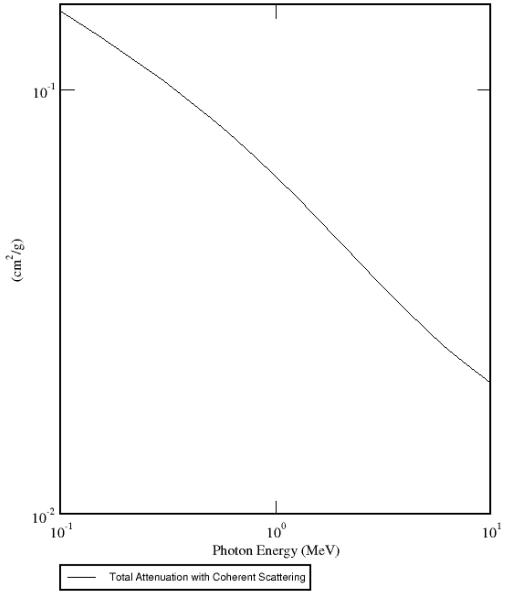
- "3M™ Novec™ 7200 Engineered Fluid is a liquid composed of Ethoxy-nonafluorobutane ($C_4F_9OC_2H_5$), 99% minimum."
- Dense liquid at room & cryo. Temperatures → Efficient γ-ray shield
- Highly radiopure material



Typical Physical Properties

Table 1

Properties	3M™ Novec™ 7200 Engineered Fluid	3M™ Novec™ 7100 Engineered Fluid	HFC-4310mee	HCFC-225 ca/cb
Formulation	$C_4F_9OC_2H_5$	$C_4F_9OCH_3$	$C_5H_2F_{10}$	$C_3Cl_2HF_5$
Molecular Wt.	264	250	252	203
Boiling Point (°C)	76	61	54	54
Freeze Point (°C)	-138	-135	-80	-131
Liquid Density (g/ml)	1.43	1.52	1.58	1.55
Surface Tension (dynes/cm)	13.6	13.6	14.1	16.2
Solubility of Solvent in Water (ppmw)	<20	12	140	330
Solubility of Water in Solvent (ppmw)	92	95	490	310
Vapor Pressure (mmHg)	109	202	226	290
Viscosity (cps)	0.61	0.61	0.67	0.59
Heat of Vaporization (cal/g @ boiling point)	30	30	31	34.6
Specific Heat (cal/g°C)	0.29	0.28	0.27	0.24



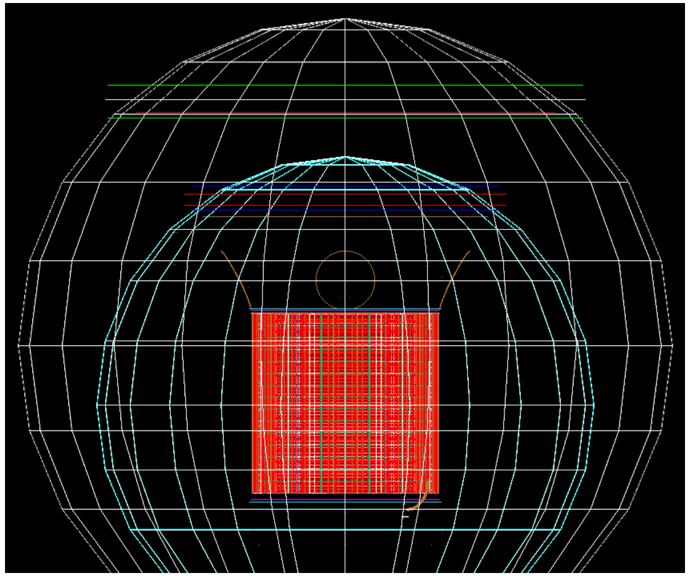
All values at 25°C unless otherwise specified

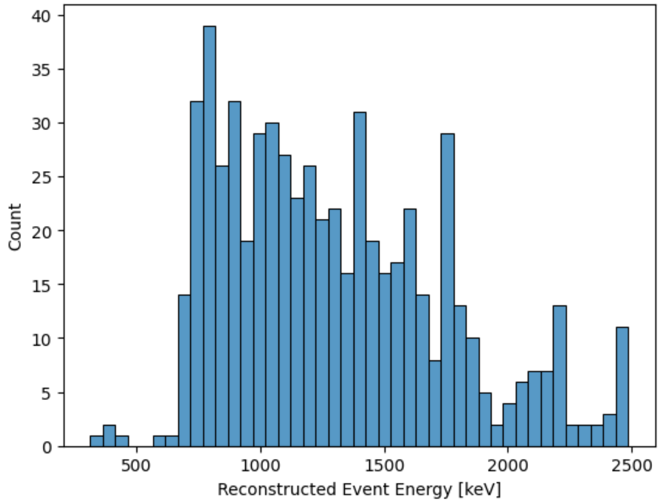
Simulation Geant4

- Code version: commit 9e001b0 (G4 10.7.2)
- Generated ^{214}Bi and ^{208}Tl as primaries in vessels liners (to be conservative)
- Launched 8 Slurm jobs: 1026, 1226, 1510, 1690 mm IV
- HFE volume is parameterized, no TPC Support
- 1e10 primaries

Reconstruction Strax

- Code version: commit b325f0e
- Using new DNN (June 2024)
- Defined BackgroundAlg plugin:
  - (2481 < evt["energy"] > 2435) & (evt["standoff"] > 100) & (dnn_value > 0.85)
- Did reconstruction and background selection in Slurm jobs

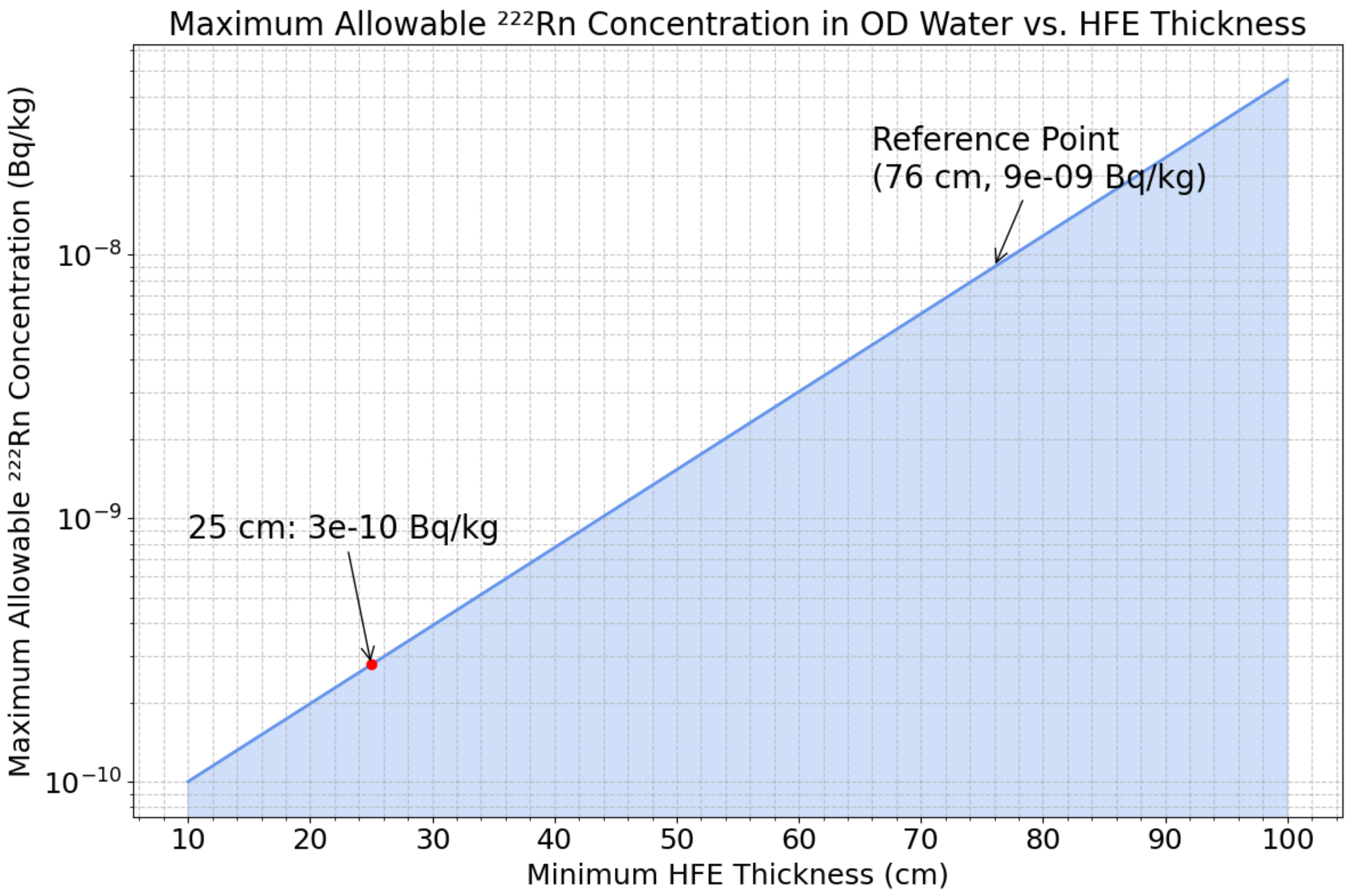




Less HFE = External Background

Increased

- OV, ^{222}Rn from water, …
- Can be quantified with the attenuation law
- Geant4 simulations will be done



The nEXO Experiment: A Large Unexplored Parameter Space

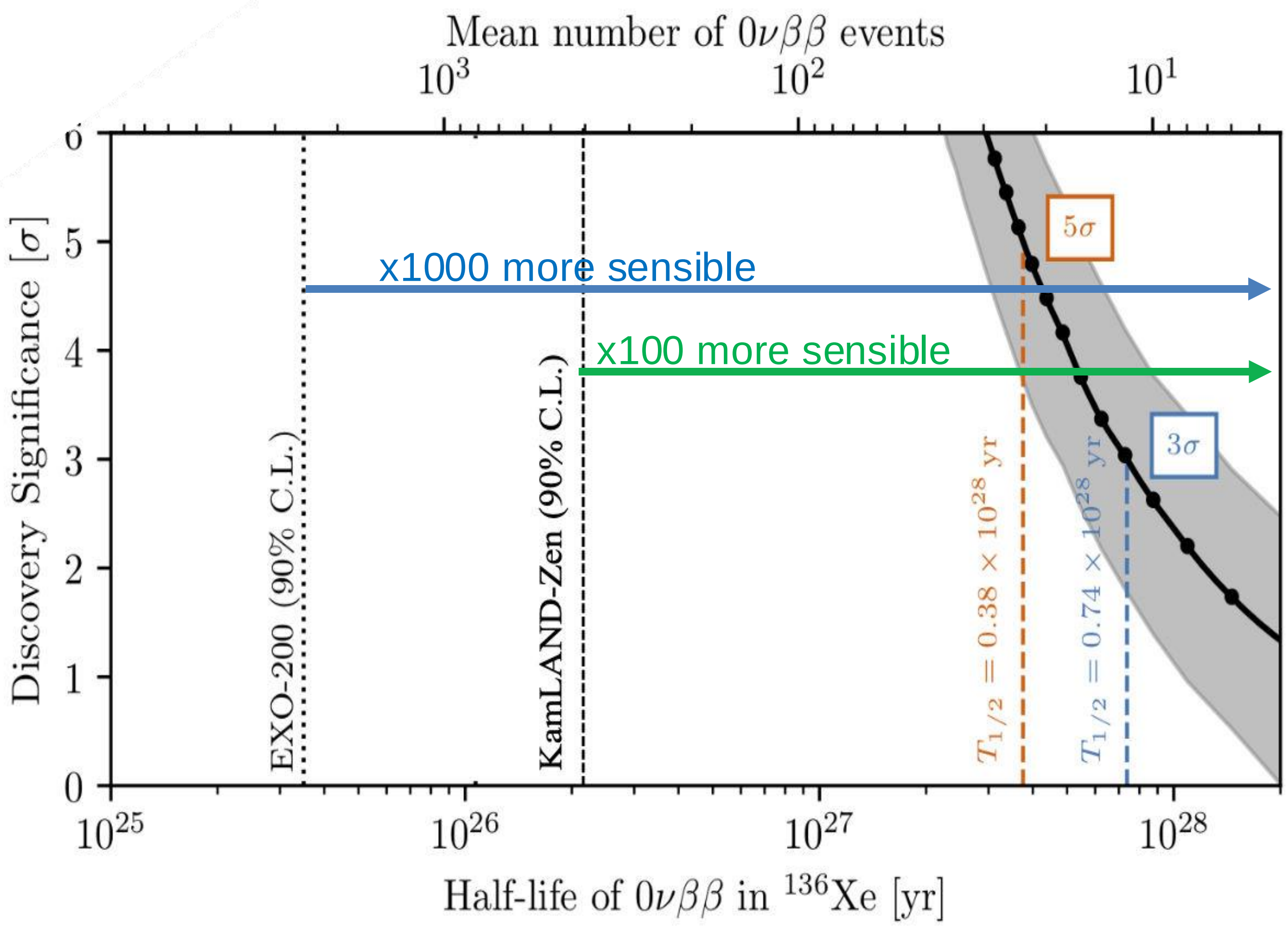
Experiment	Mass [kg]	Enrichment	Live Time
EXO-200	175	80%	5 years
KamLAND-Zen	383	90%	7 years
nEXO (projected)	5000	90%	10 years

Previous Gen.: EXO-200

- Discovery of 2νββ decay of ^{136}Xe

Current Best: KamLAND-Zen

- nEXO will have a x100 better limit



nEXO will reach a 0νββ half-life of 10^{28} years in 6.5 years data taking