Impact of Nickel Cryostats in the nEXO Detector

1. 0νββ Motivations
2. The nEXO Experiment
3. Cryostat Vessels: From Carbon Fiber Composite (CFC) to Nickel
4. HFE Shielding
5. Design Implications

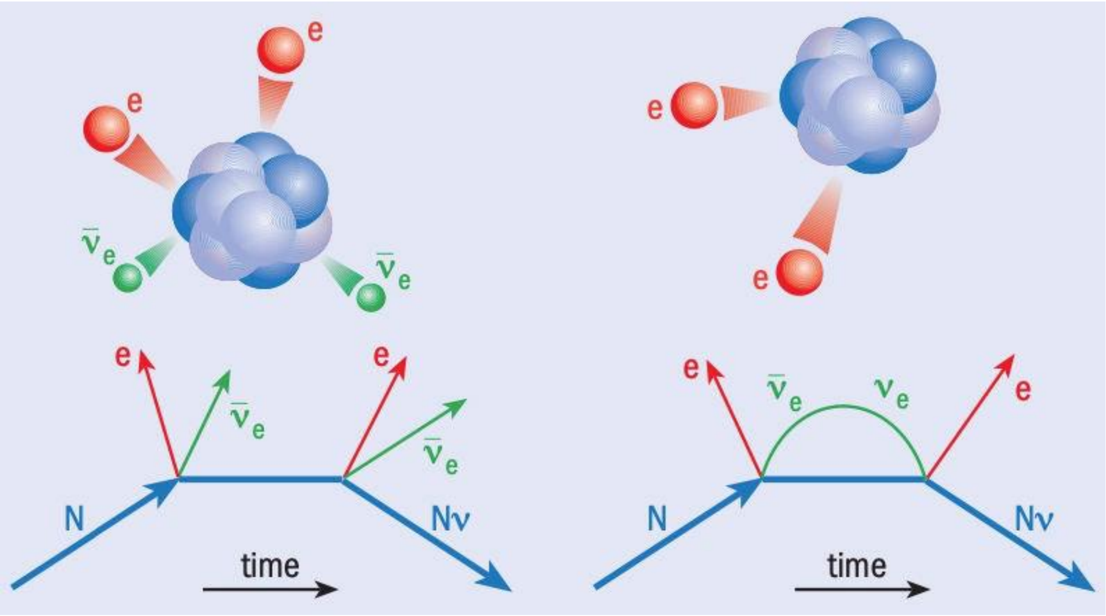
Crepes recipe included

Antoine Amy, Julien Masbou, Andrea Pocar
JRJC - November 28th 2024
nEXO Collaboration

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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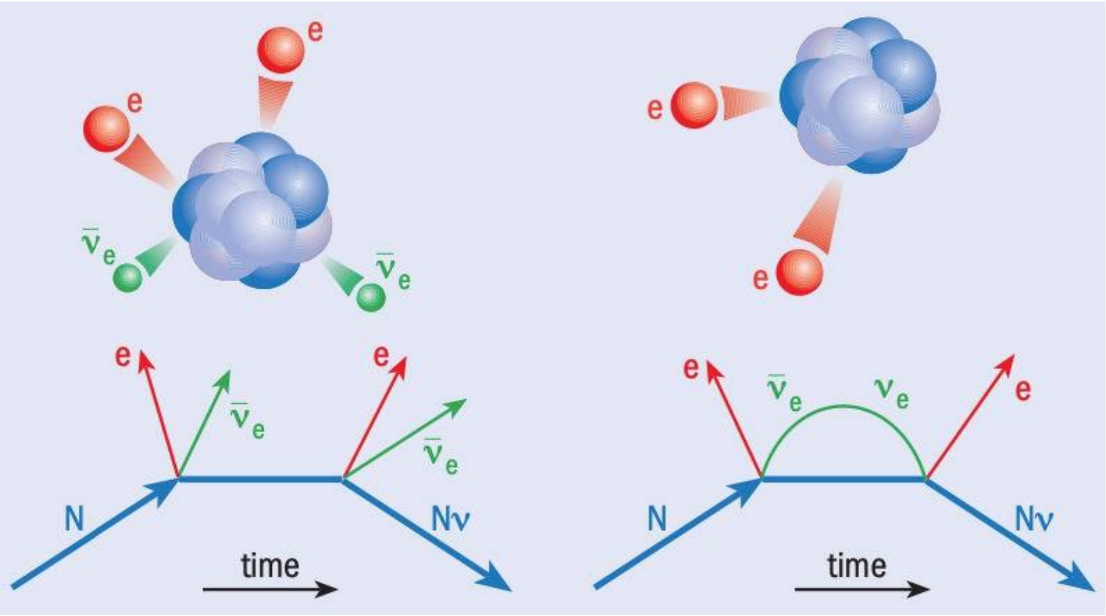

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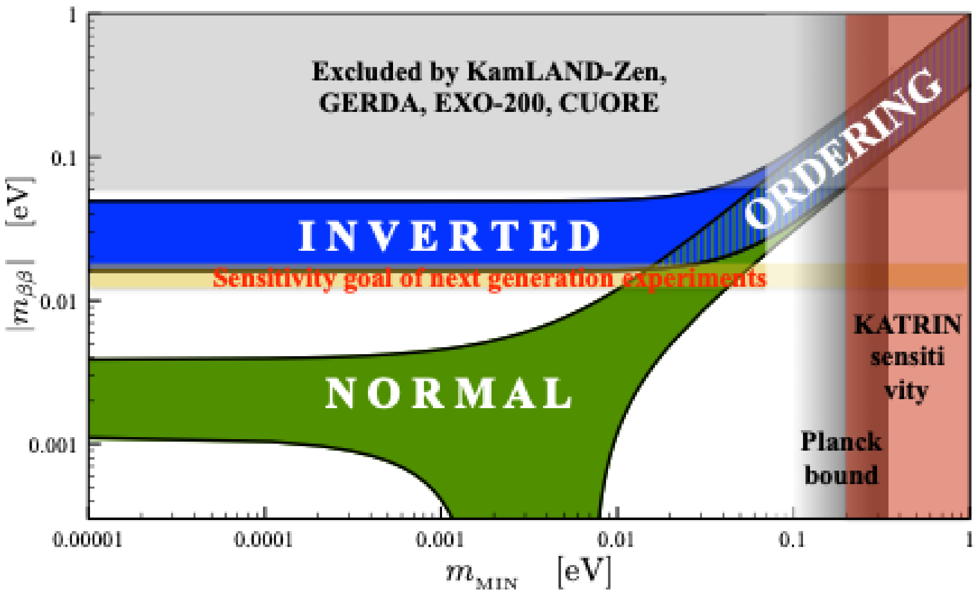


*For reference: Age of the Universe: 10^{10} years

The nEXO Experiment: Neutrinoless Double Beta Decay

Detecting ^{136}Xe 0νββ requires:

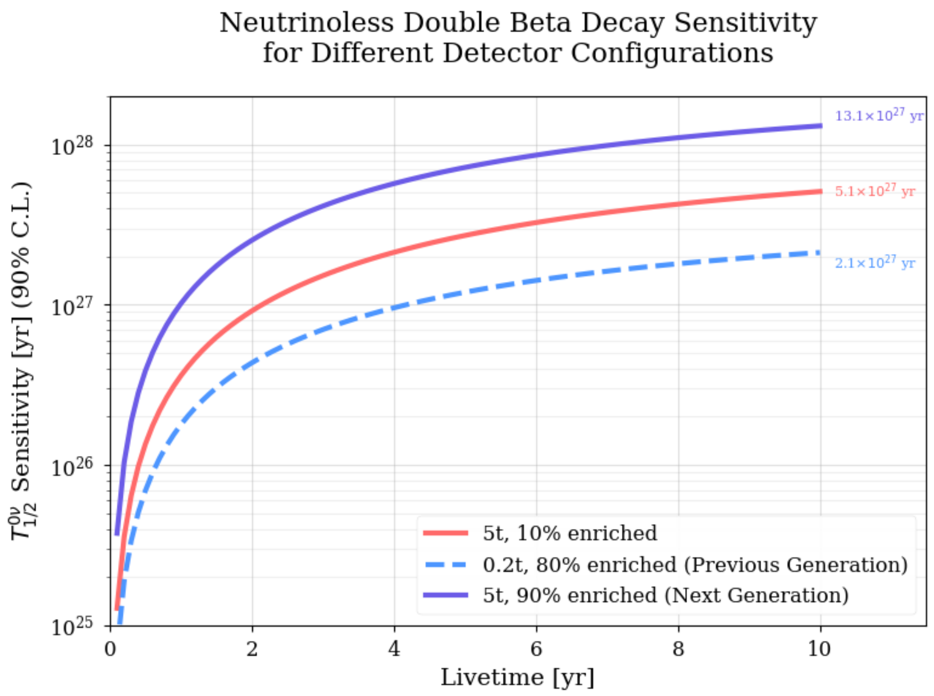
1. (α, M) Large mass of enriched isotope*
2. (t) Long detection time
2. (ΔE) Good energy resolution (< 1% σE/E)
3. (b) Low background (< 0.5 counts/y/2t/ROI)

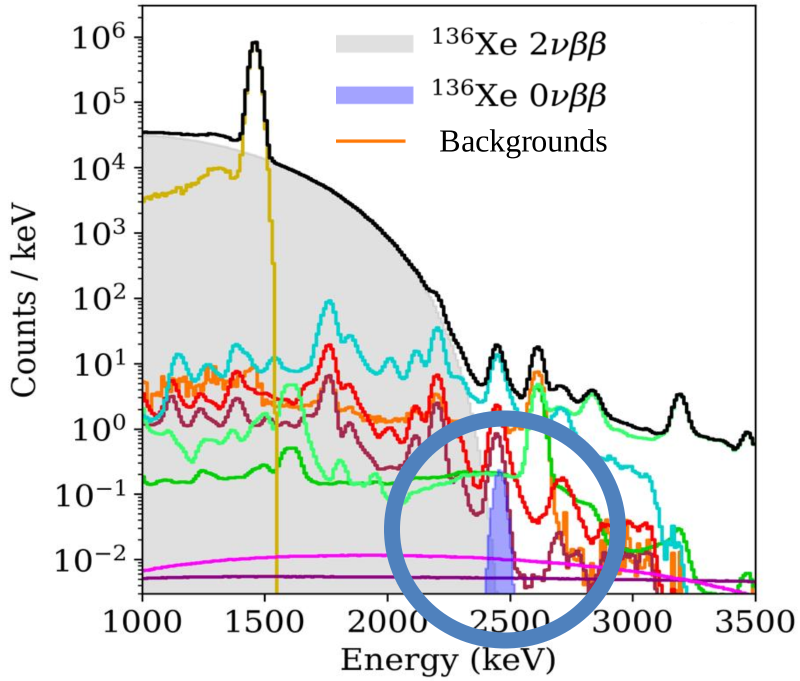
Sensitivity figure of merit:

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

α: Isotope abondance
A: Atomic mass
M: FV mass
T: Livetime
ΔE: Energy resolution
B: Background index

Should be high; should be low



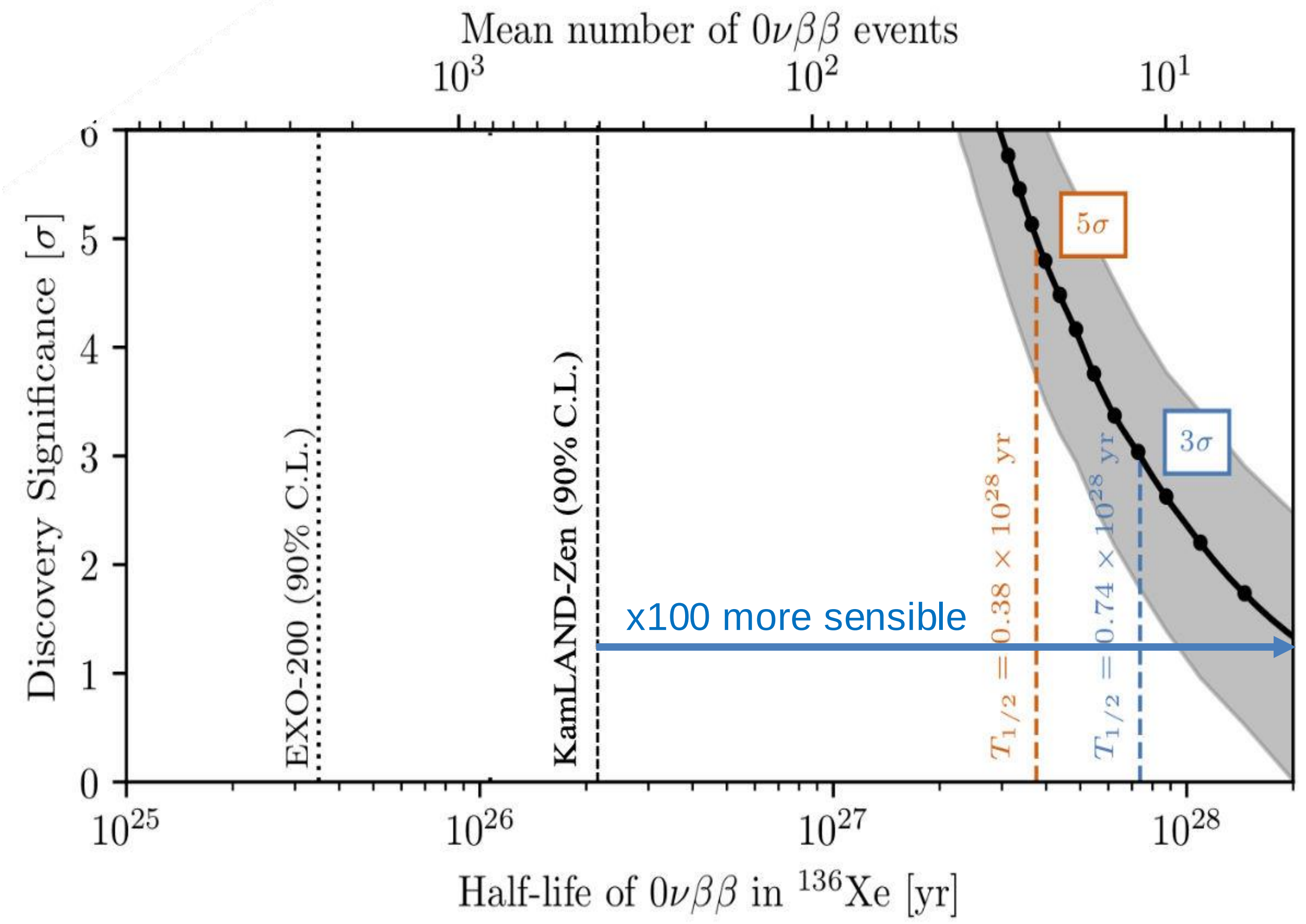


*Natural abondance ^{136}Xe=8.9%

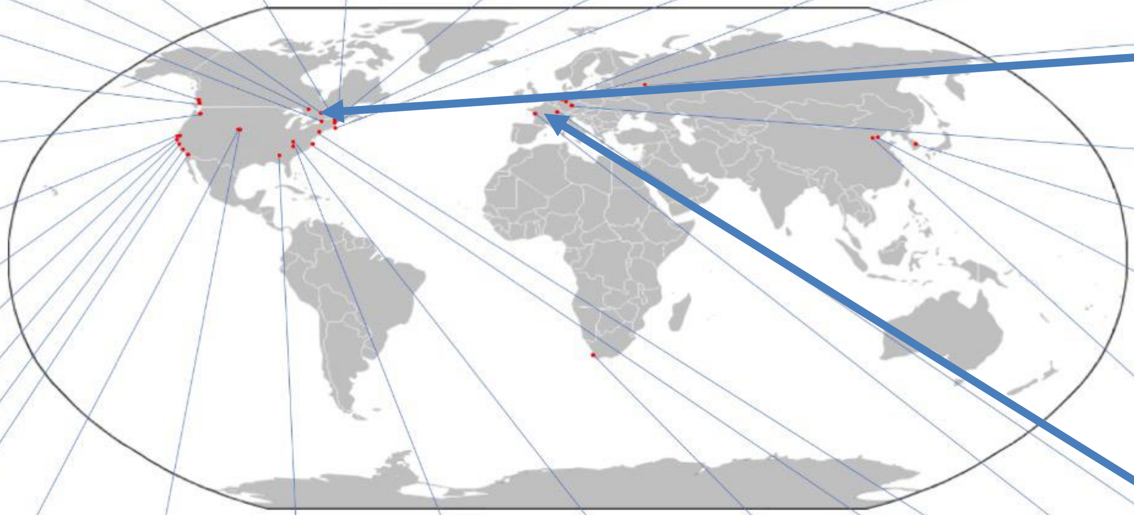
The nEXO Experiment: A Large Unexplored Parameter Space

nEXO=New 0νββ Detector Generation

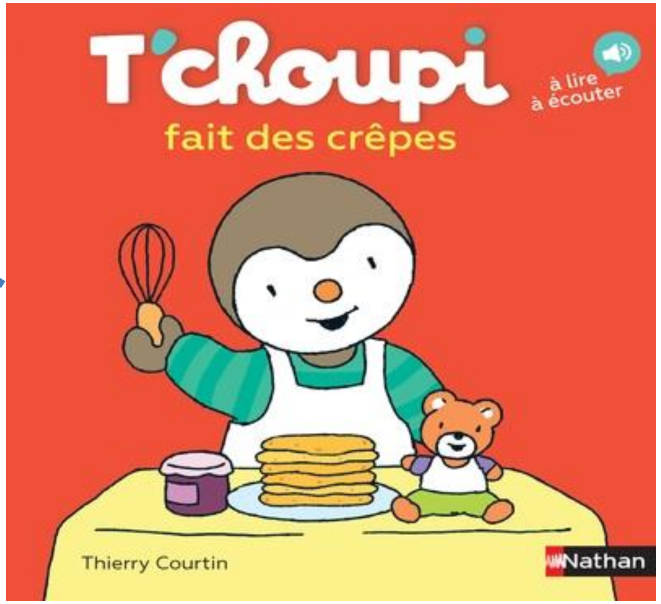
- EXO-200=previous generation
  - Was a success
  - Discovery of 2νββ decay of ^{136}Xe
- nEXO will have a limit x100 better than the current best experiment



The nEXO Experiment: A World Wide Effort



SNOLAB, Canada



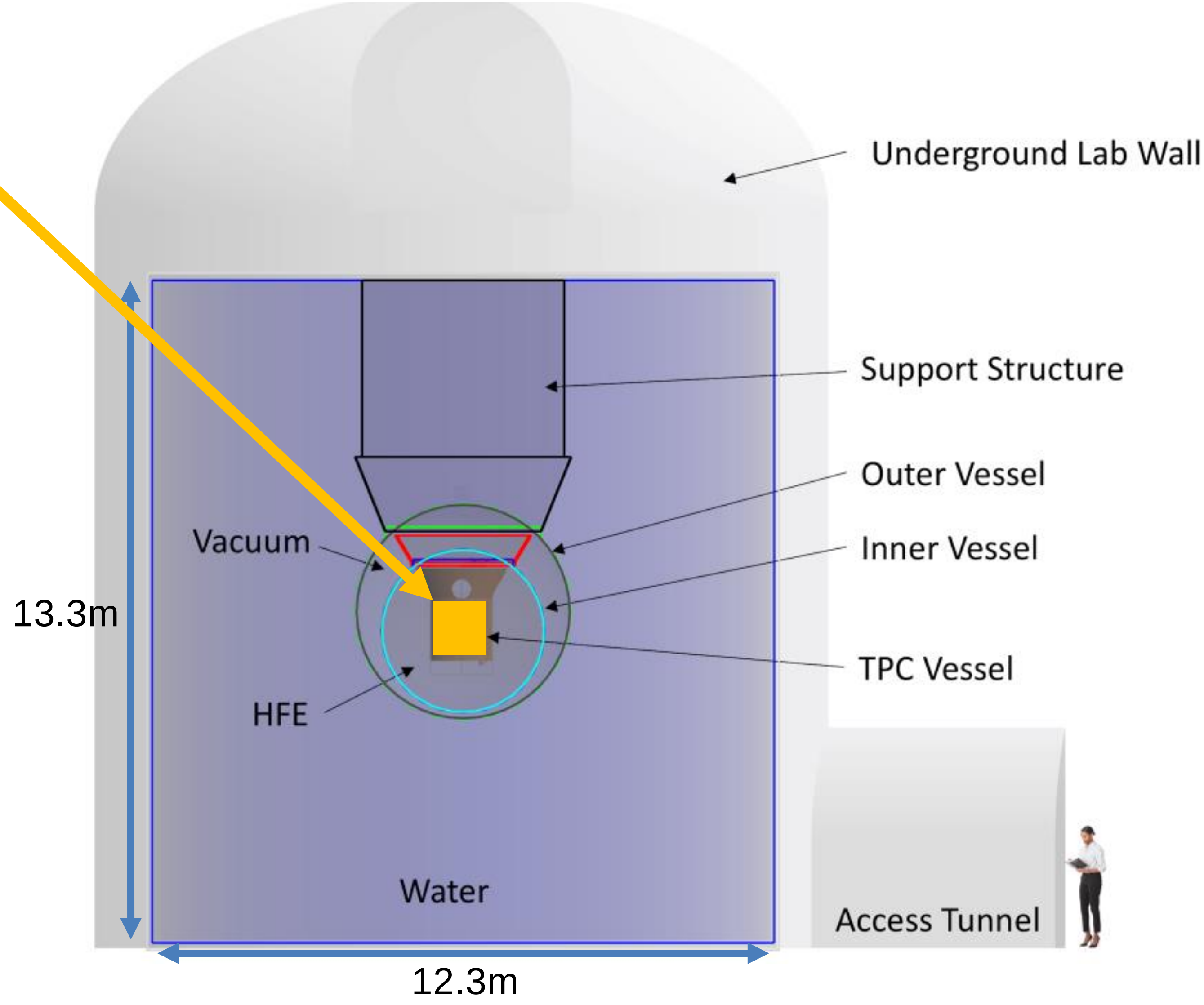
9 countries, 34 institutions, ~200 collaborators

The nEXO Experiment: Overview

Detection volume

Detector's Geometry: Multi-Layer Shielding

- @ SNOLAB, 6000 m.w.e (2500 m more than Gran Sasso)
- Big volume of water: Active muon veto
- Dual cryostats: Vacuum insulation barrier
- 32 tons HFE[1]: Gamma/neutron shield + cryo stability
- Radiopure copper Single Phase TPC
- 5 tons 90%[2] Liquid ^{136}Xe at 165K



[1]dense HydroFluoroEther liquid; [2]Natural abondance: 8.9%

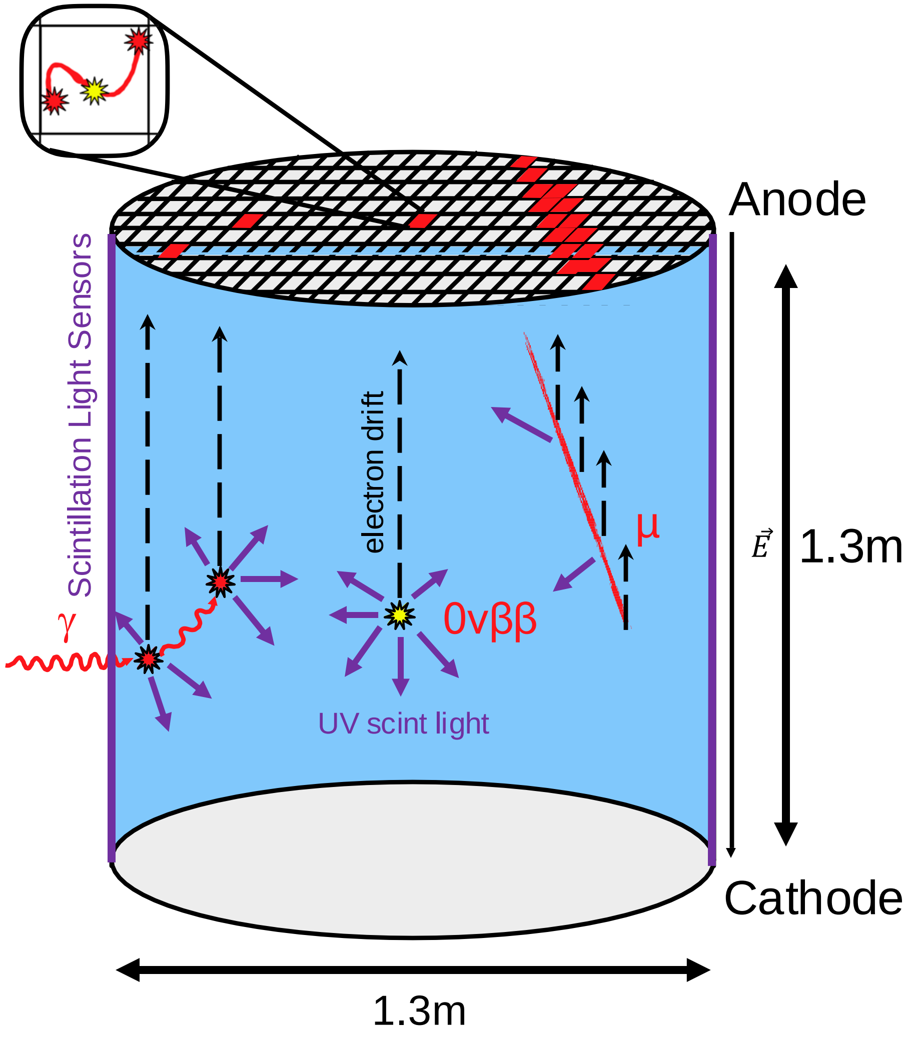
The nEXO Experiment: Signal Detection

Signals Generation & Detection

- Xenon is both the source and detection medium
- Ionizing radiation produces:
  - prompt scintillation (S1) 175nm 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

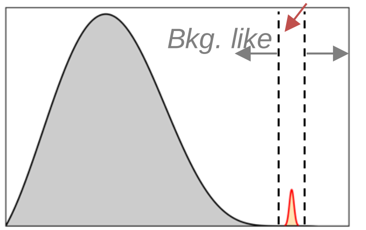


The nEXO Experiment: Background Definition

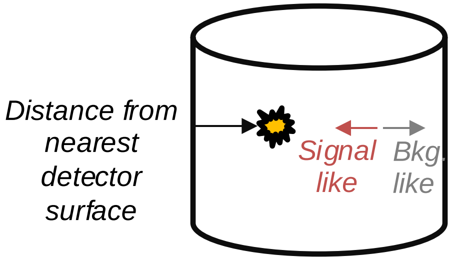
Selection Criteria

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

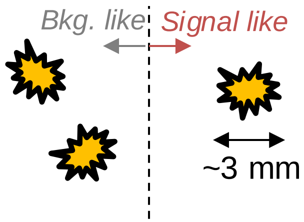
Energy:

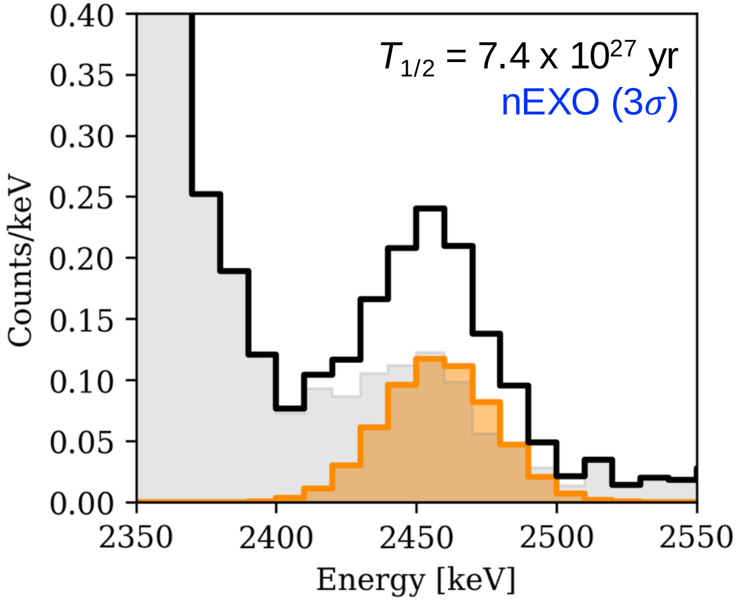


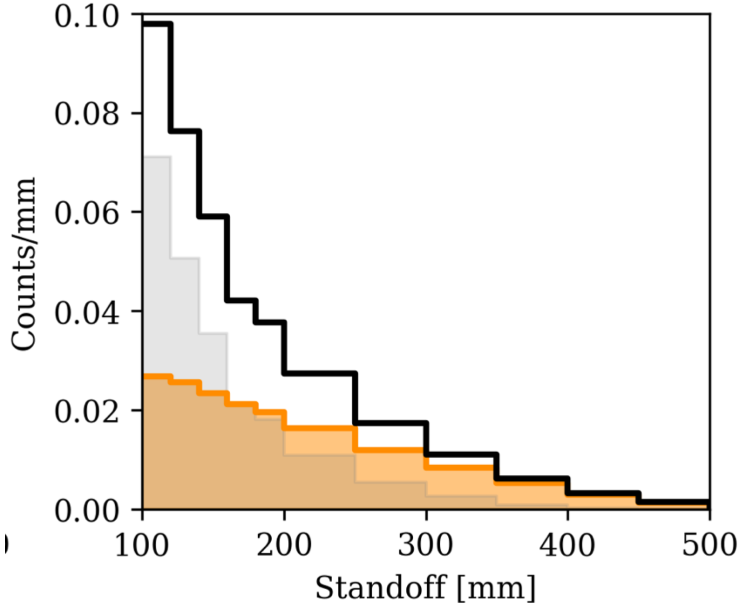
Standoff:

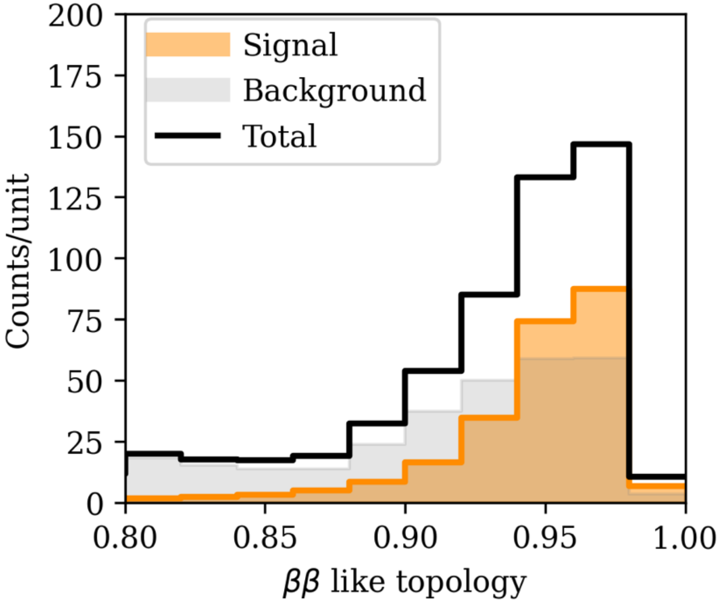


Topology:







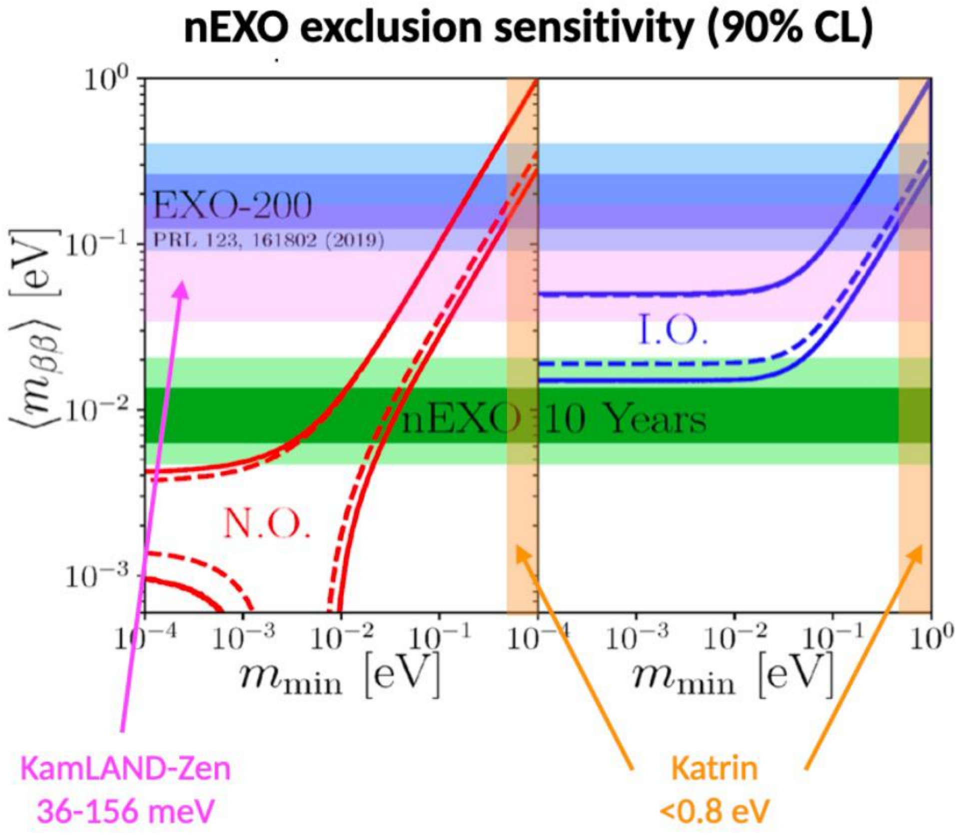


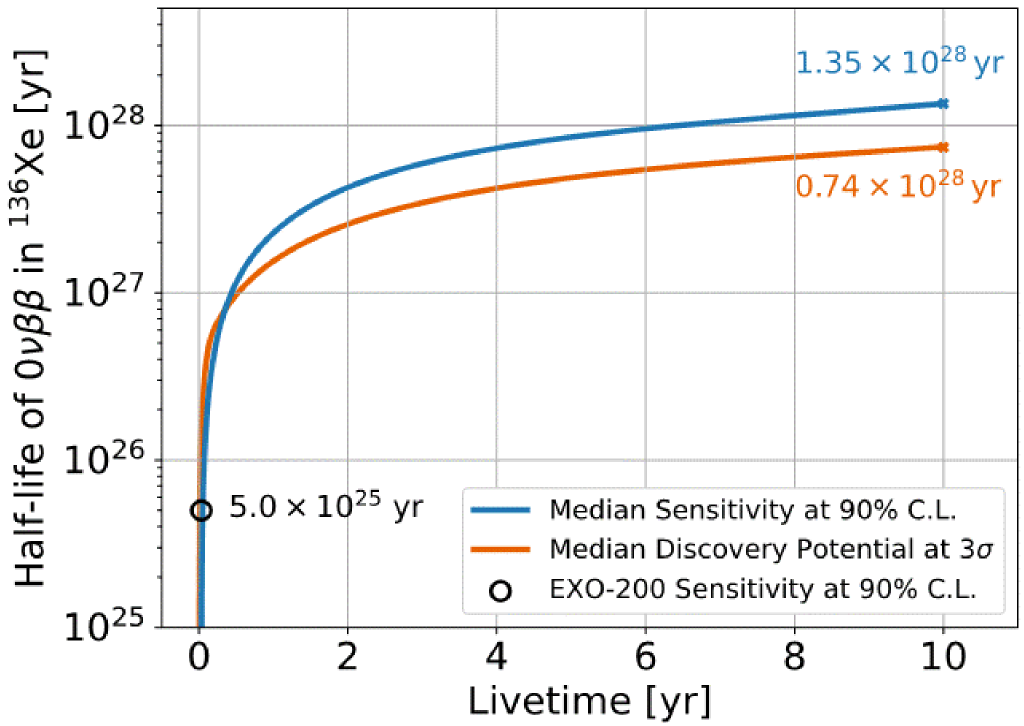
*: As a reference. Weighted by spatial probability distribution. No hard fiducial cut applied.

The nEXO Experiment: Expected Sensitivity

Expected Sensitivity

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





The nEXO Experiment: Internal Background

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)

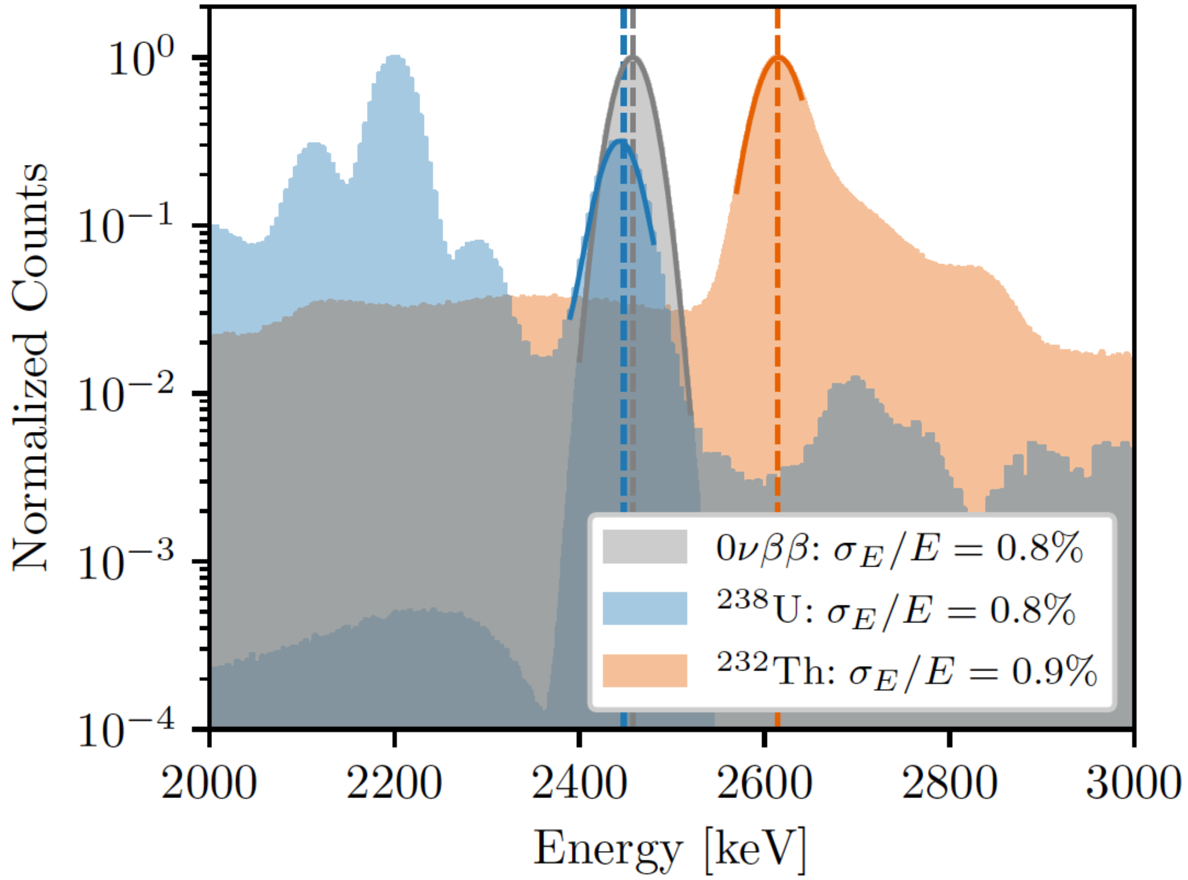
Component Background Contribution

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

m : component's mass

a : component's material activity

ε: component's hit efficiency



Hit Efficiency Definition (ε): The probability of a decay event becoming a background count

*: then soft Compton in HFE to get in ROI

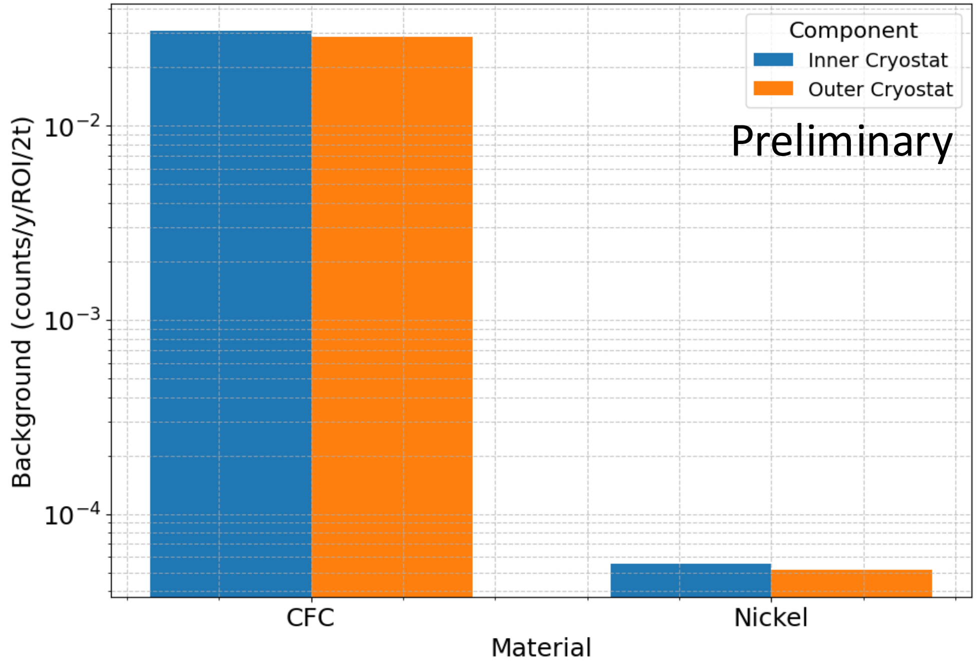
CFC to Nickel Cryostats: Impact on Background

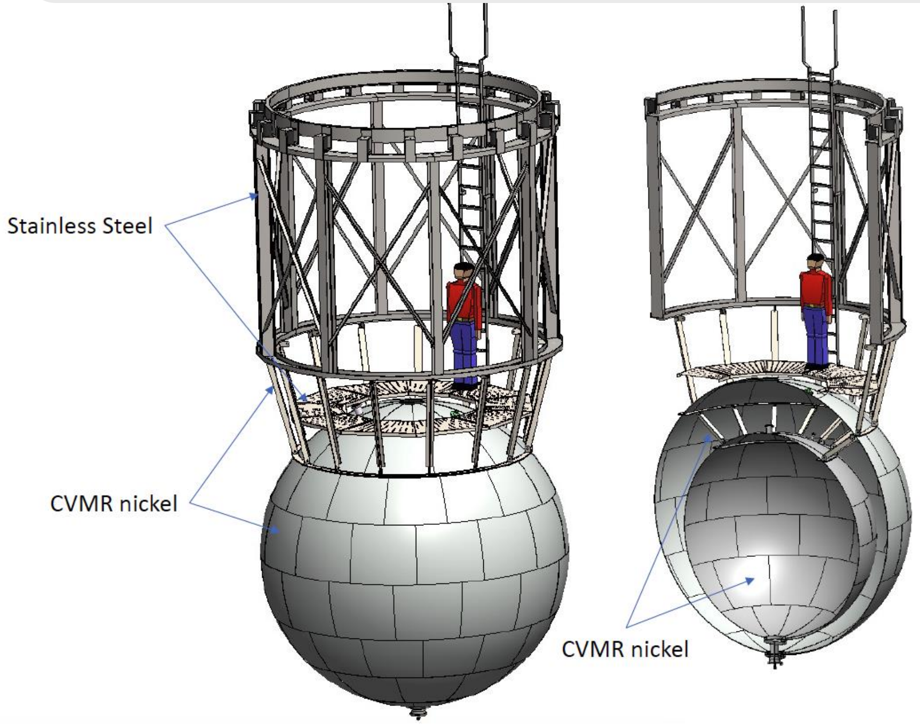
Why use Nickel instead of CFC (previous plan)?

- Cryostat Vessels are prominent internal background sources
- Searched for new ultra radiopure material: low-activity Nickel samples
- Background contribution reduction of a Factor ~300
- Nickel=new baseline for the cryostat vessels

Cryostats Design Values (for now)

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





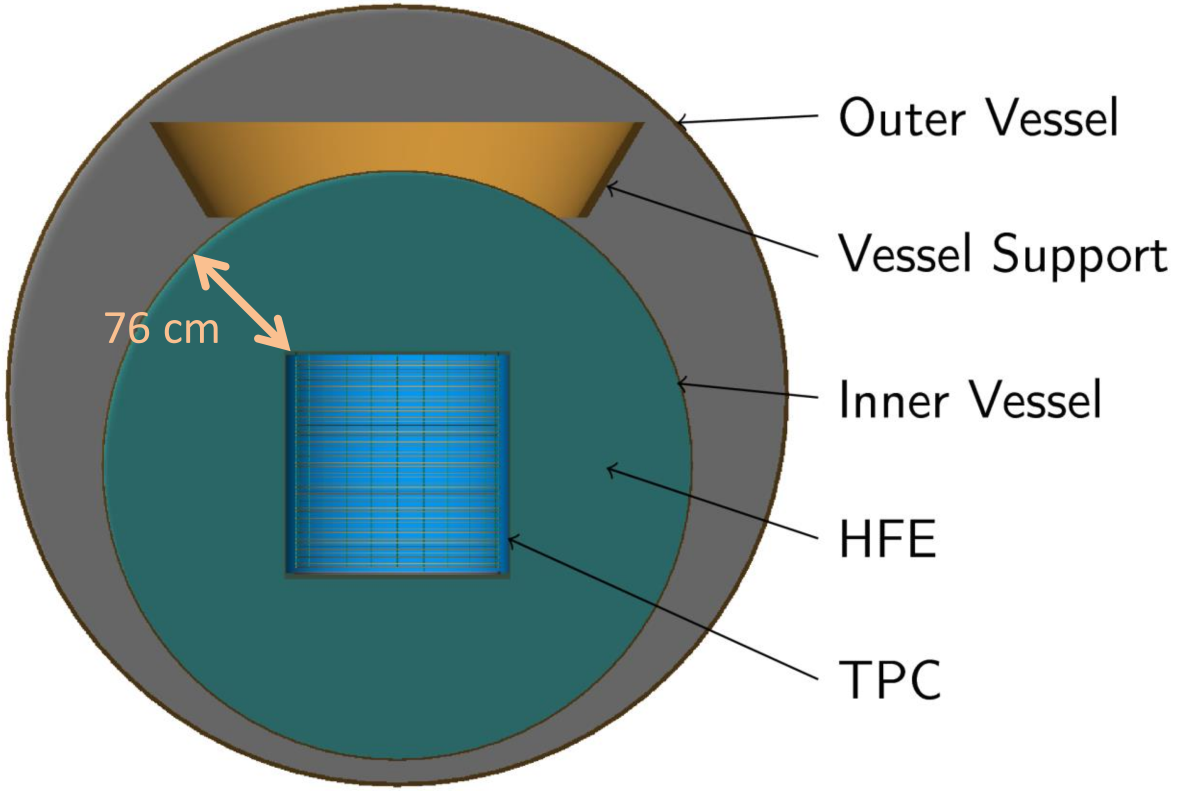
HFE Shielding

Motivations to Use an HFE-7200 Bath

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

Baseline Dimensions of the HFE Bath

- Min. Thickness: 76 cm (for 1.7 m IV)
- HFE-7200 mass: 32 tons (for 1.7 m IV)

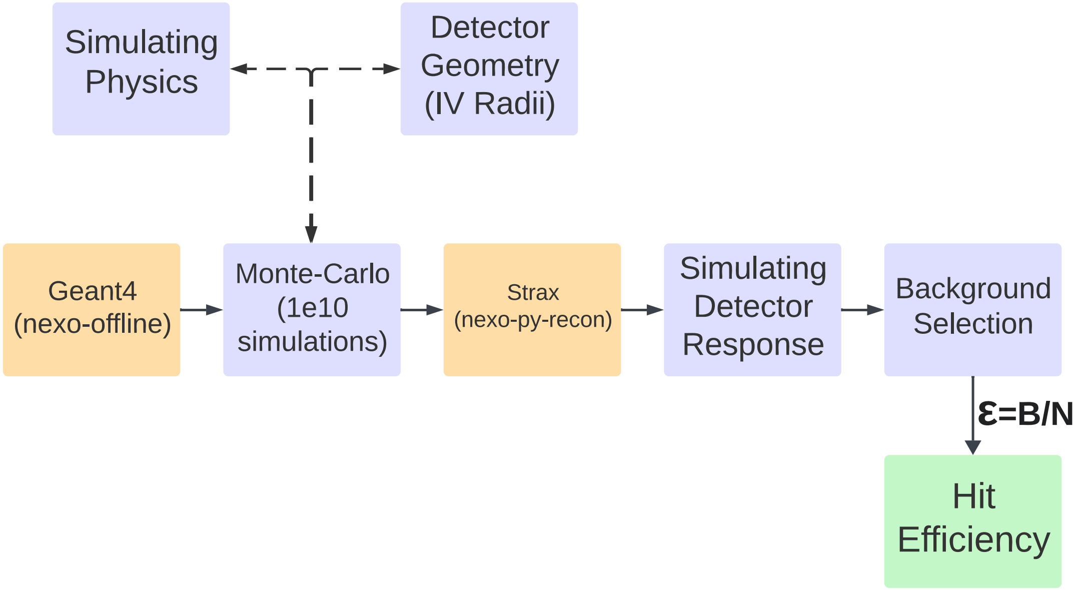


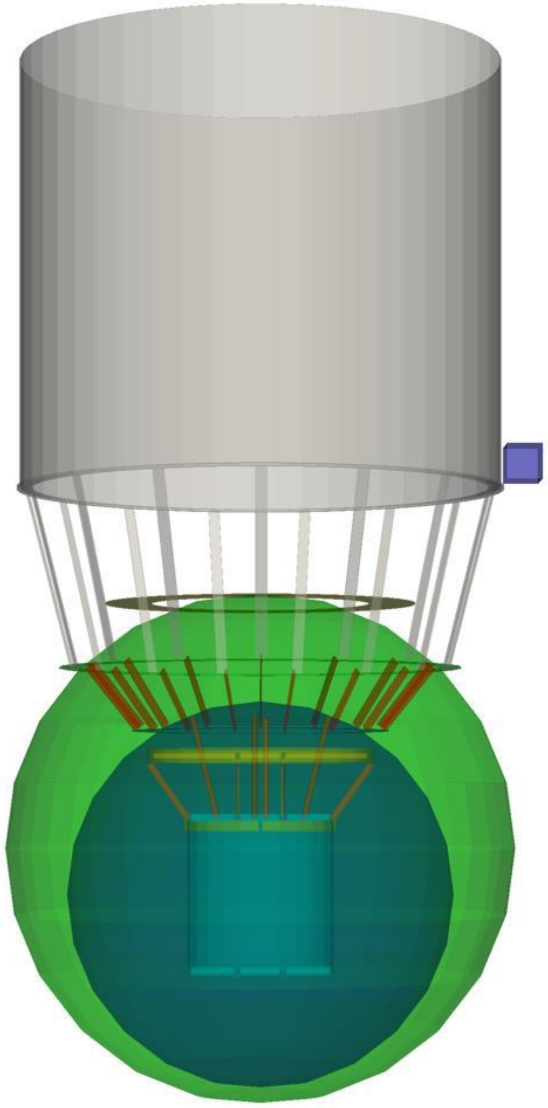
Vessel materials less radioactive → Possibility of reducing HFE thickness (while keeping the same background contribution)

HFE Shielding: Simulation tools

Testing with Less HFE

1. Using Geant4: 1e10 ^{214}Bi & ^{208}Tl decays
   - Decays in cryostat vessels
   - Testing multiple IV radii* (from 1.7 → 1 m)
2. Reconstruction with Strax
   - Neural Network still in development; initial preliminary results only





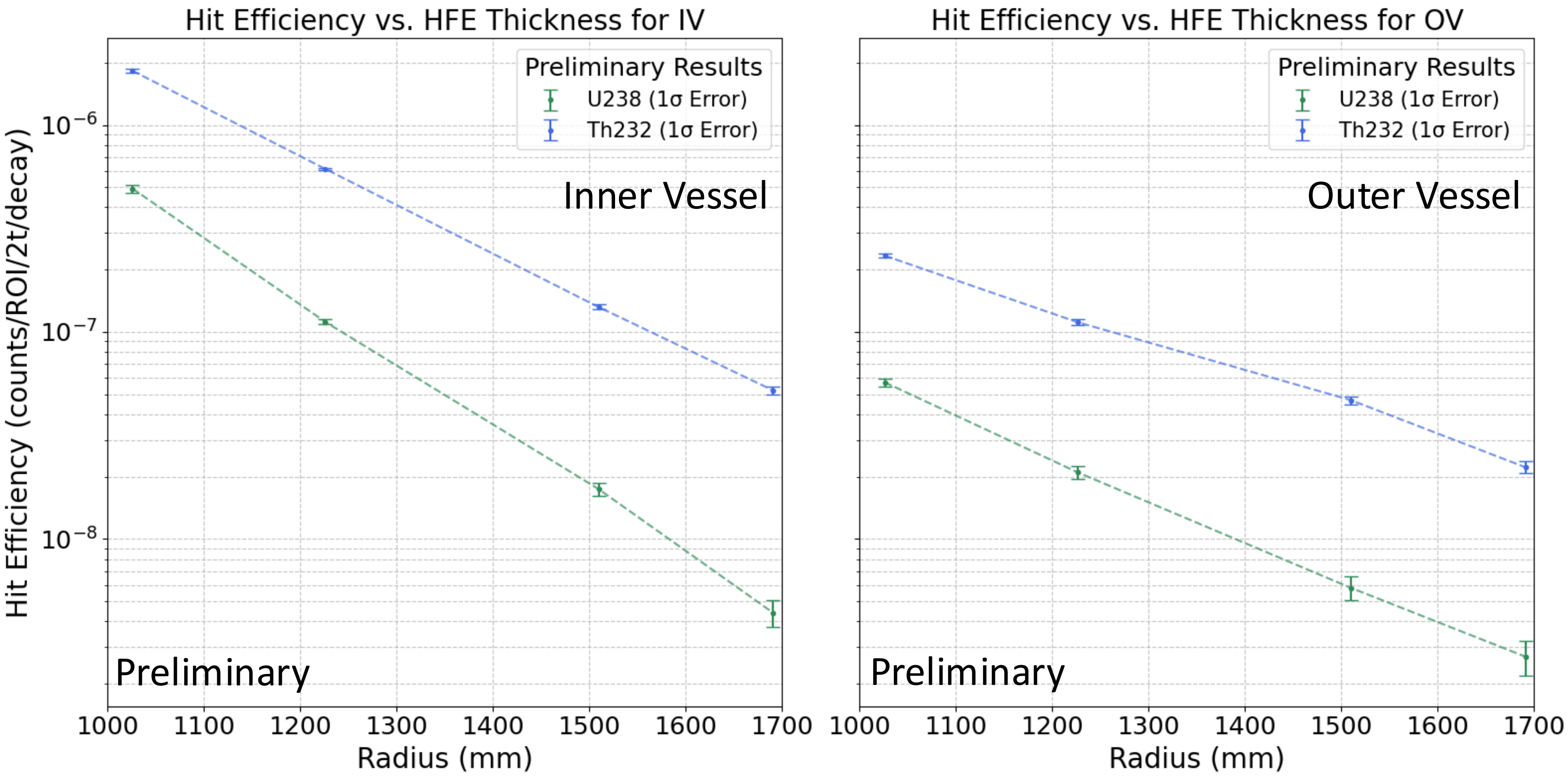
Geometry in Geant4

*HFE volume adjusted accordingly

HFE Shielding: Monte Carlo Studies

Vessels Hit Efficiency vs HFE Thickness

- Cross-checked with previous studies
- Exponential evolution (expected with attenuation law)



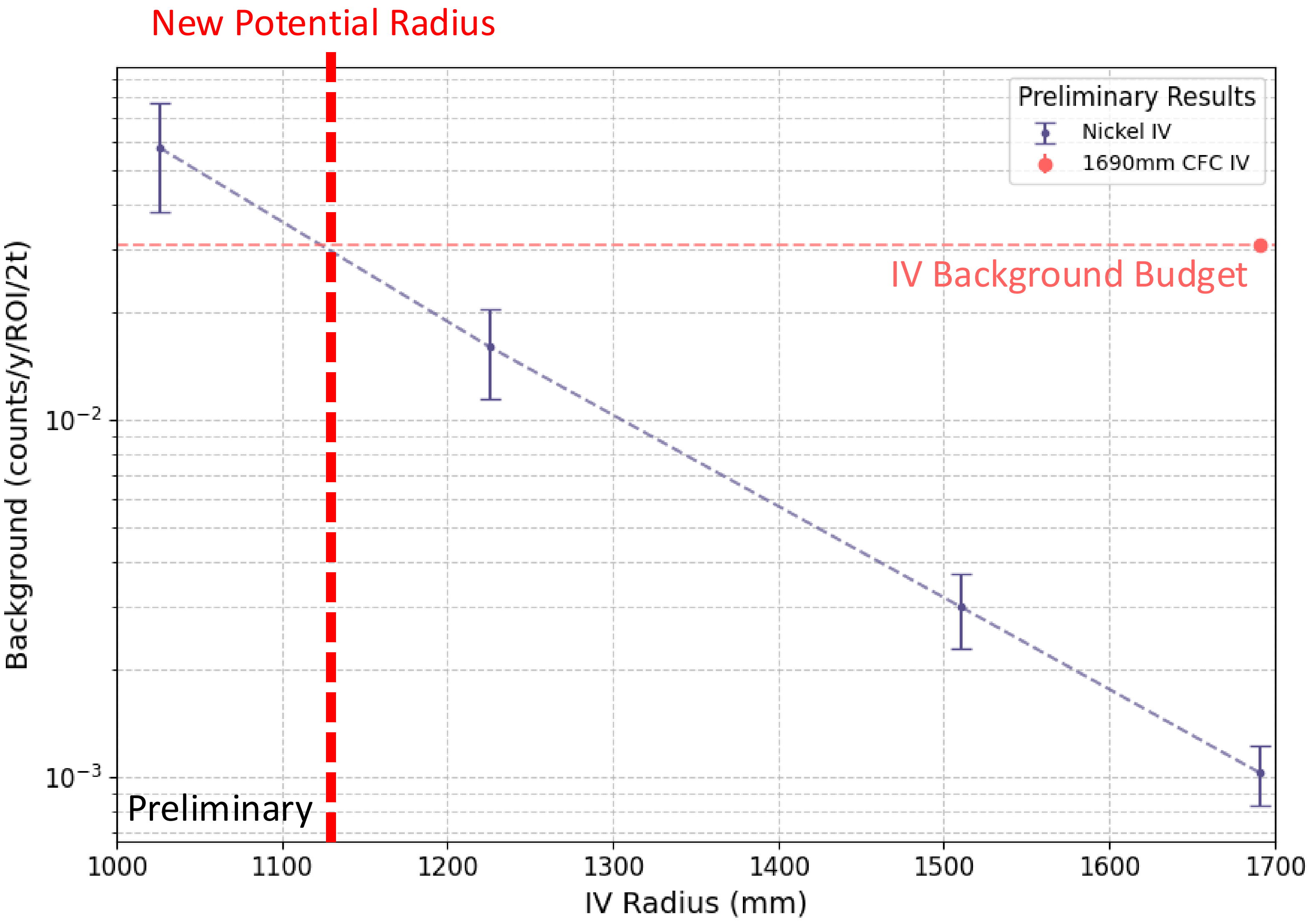
HFE Shielding: Monte Carlo Studies

IV Background Contrib. vs HFE Thickness

- Sum of ^{232}Th & ^{238}U contributions
- Activities measurements from Ni. samples
- Same procedure will be done for OV (after finalized Neural Network)

CFC to Nickel Background Equivalent

- IV bkgd budget: 0.032/y/FWHM/2t
- IV radius 1.7 m → 1.125 m



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

Design Implications: HFE quantity

Reducing HFE Shielding

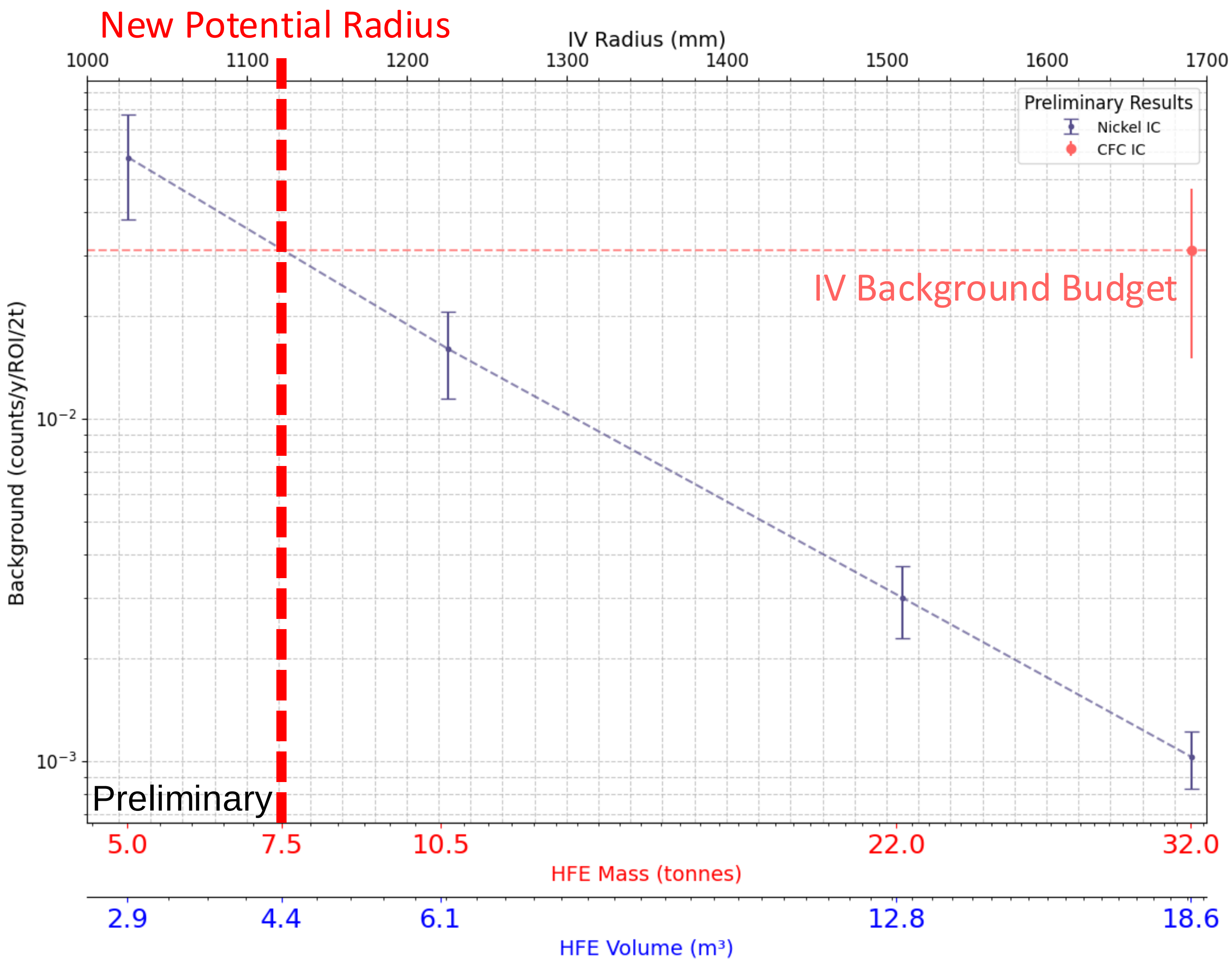
- Assuming IV Radius : 1.125 m
- Less HFE = Less storage needed; more space available
- Cost reduction

Possible Reductions (Radioactivity Only)

▼ Mass: 32 → 7.5 tons (price ~/4)

▼ Volume: 18.5 → 4.4 m^3

▼ Min. thickness: 76 → 25 cm



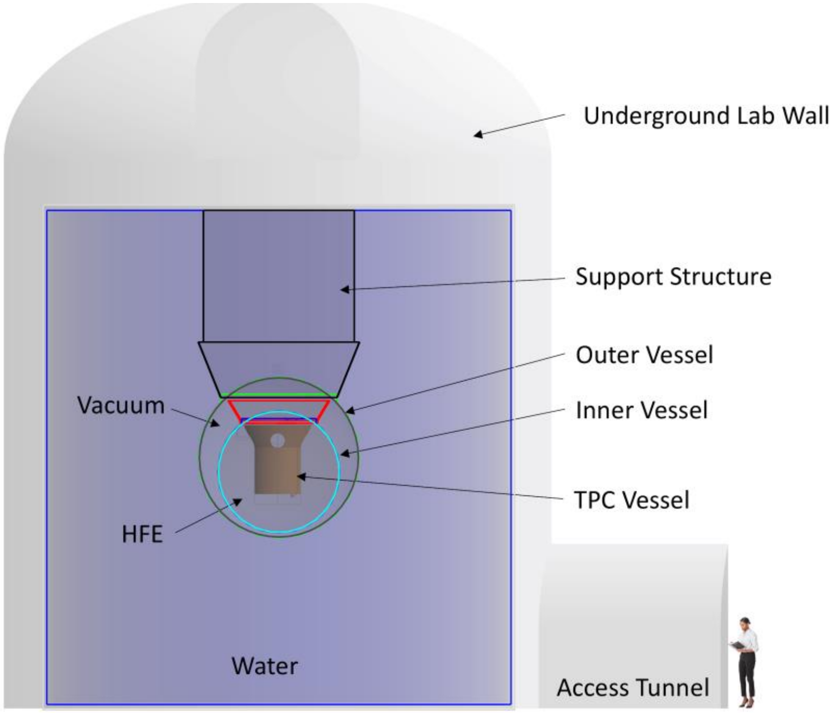
Design Implications: External Background

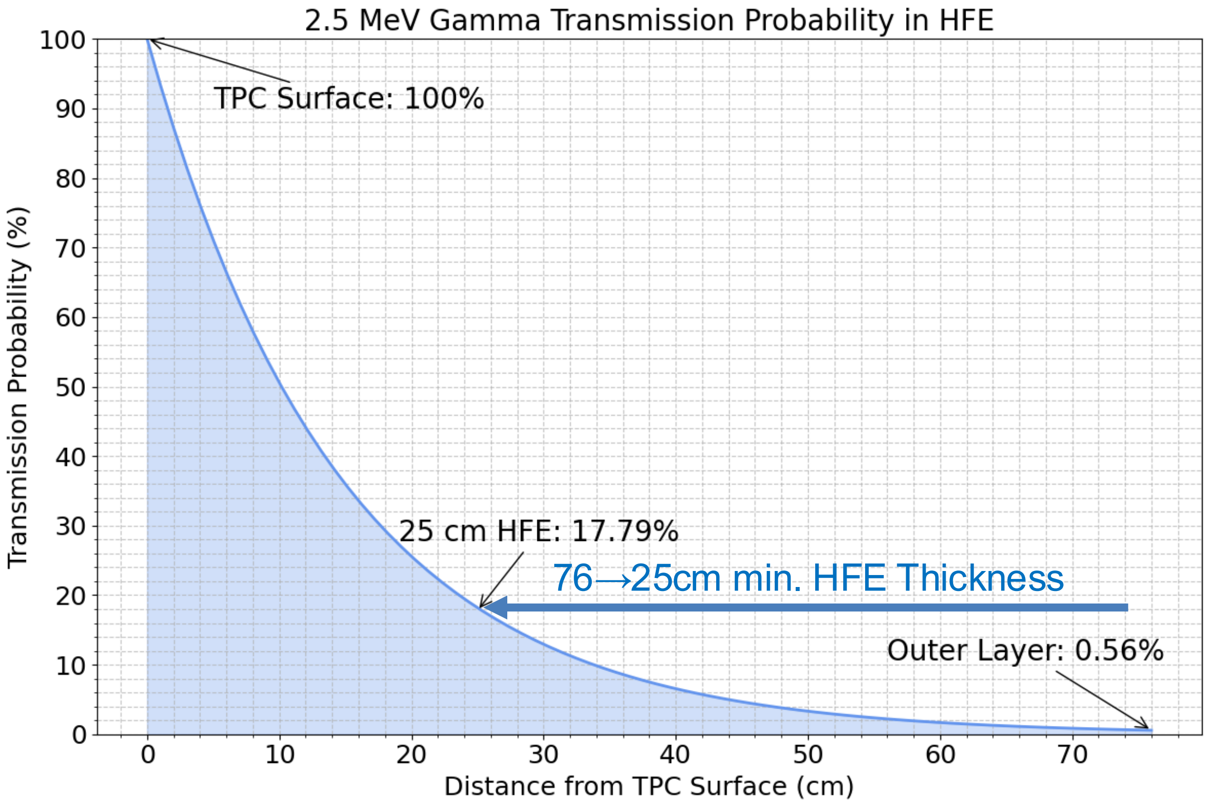
Less HFE = External Background Increased

- From OV, ^{222}Rn from water, …
- Can be quantified with the attenuation law (before MC results)

Min. HFE Thickness 76 → 25 cm means*

- ▼ Shielding efficiency /30 ⇔ External radioactivity: 30x greater impact
- ▼ Maximal allowable radon concentration decreased
- 25cm target, to be adjusted based on external background levels





*i.e. 1.7 →1.1m IV radius

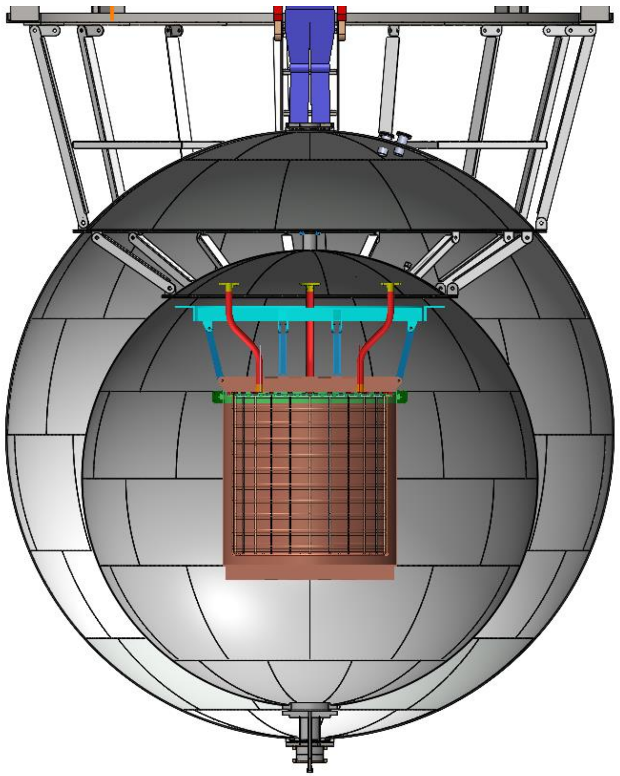
Design Implications: Cold Mass

HFE Cold Mass Reduction

- LXe needs to stay stable at 165K
- ▼ 4x less HFE = 4x less HFE 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**



Summary

Main Message (using Nickel)

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

Outlook

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

Implications Discussed

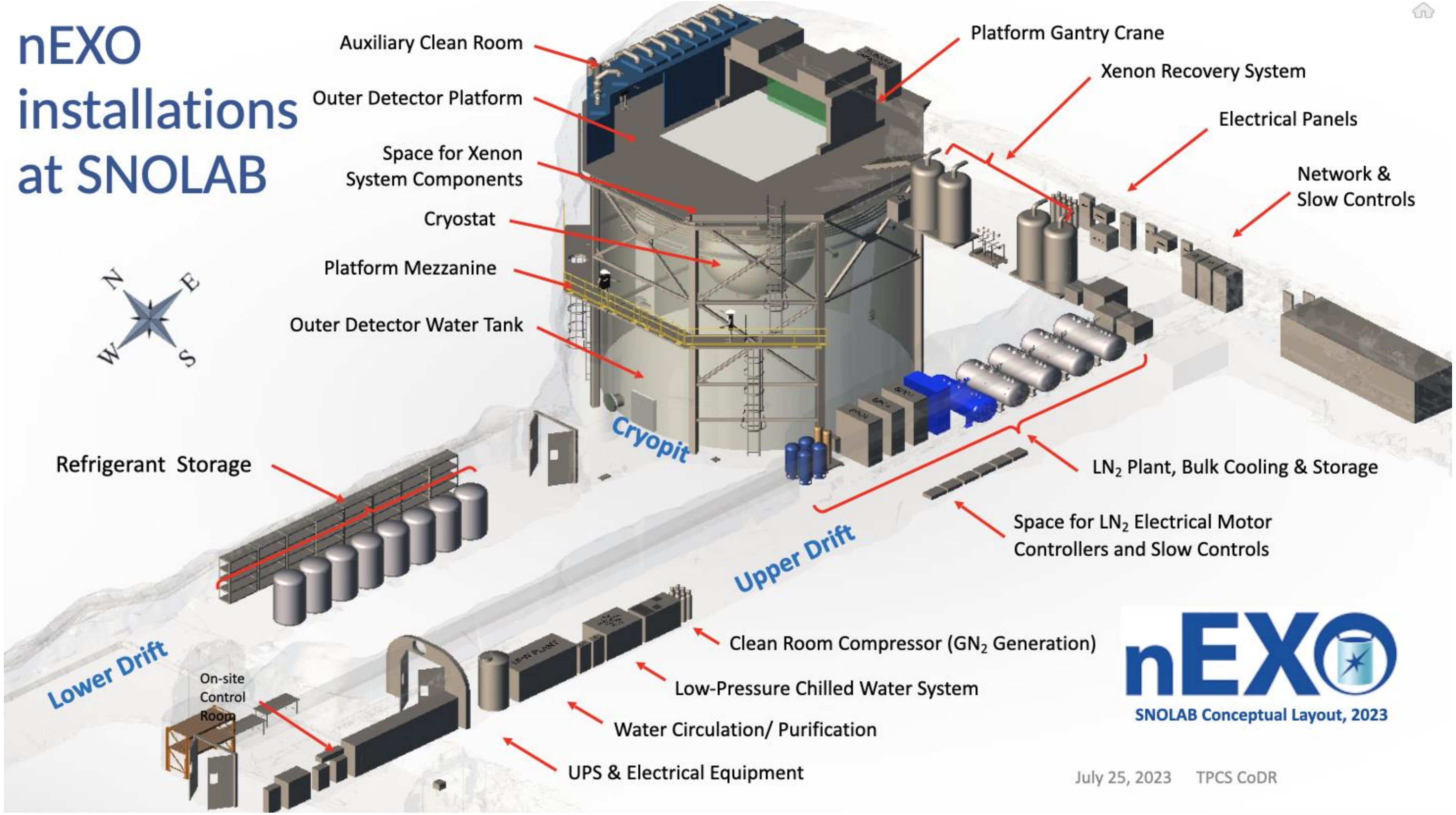
Impact	Pros	Cons
Economic	HFE cost reduction (32 → 7.5 tons)	
Spatial	Reduced storage requirements	
Design	Cryostats easier to build	
	Potential thinner IV & OV	Redesign requirements
	Possibility to increase water shielding	More radon from water
Operational	Faster cooling time	Reduced cold mass

*i.e. Min. HFE thickness: 76 → 25 cm

Backup

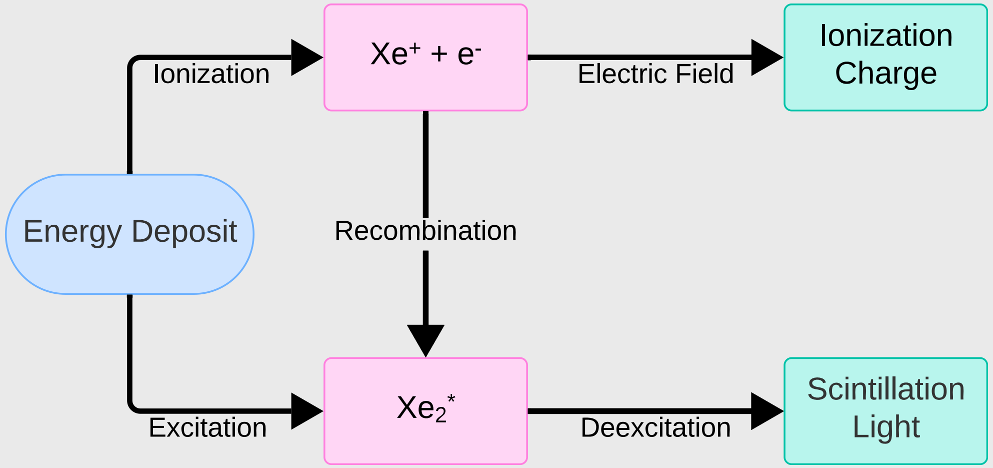
Space Required

- Around 5000 m^3 total
- 3500 m^3 needed for the Veto Tank



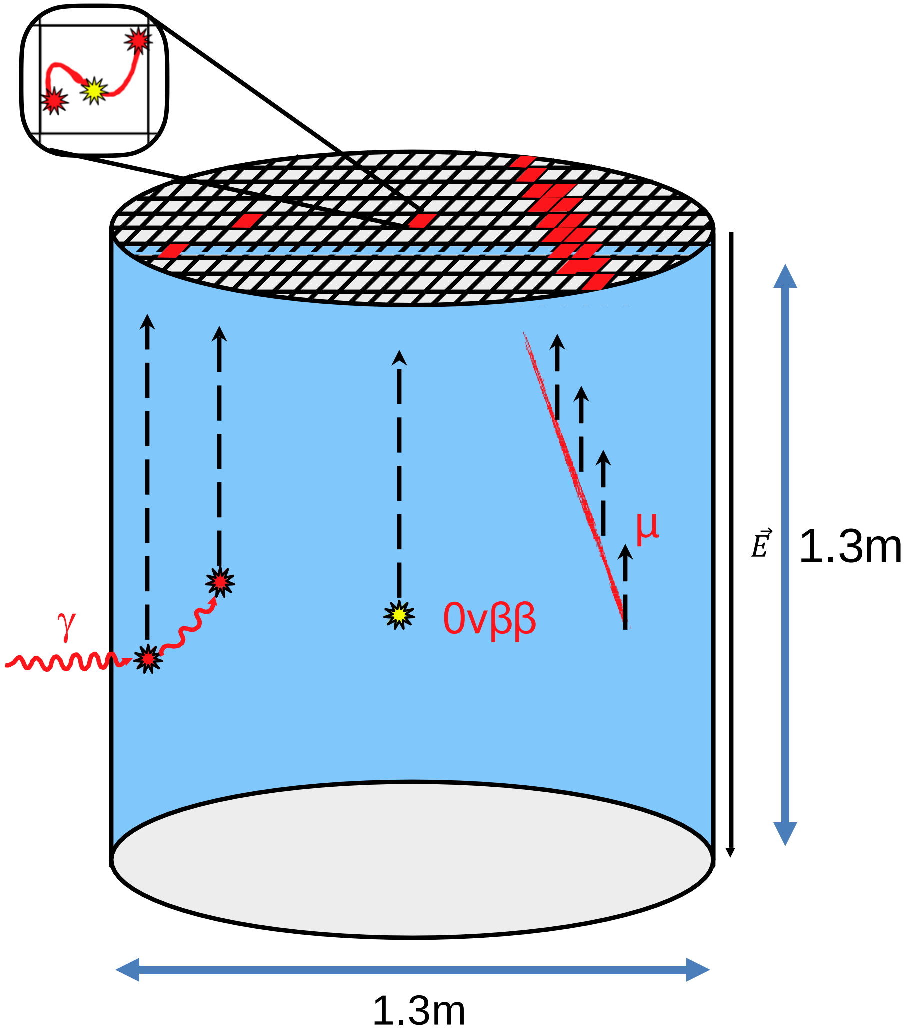
Signals Generation

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



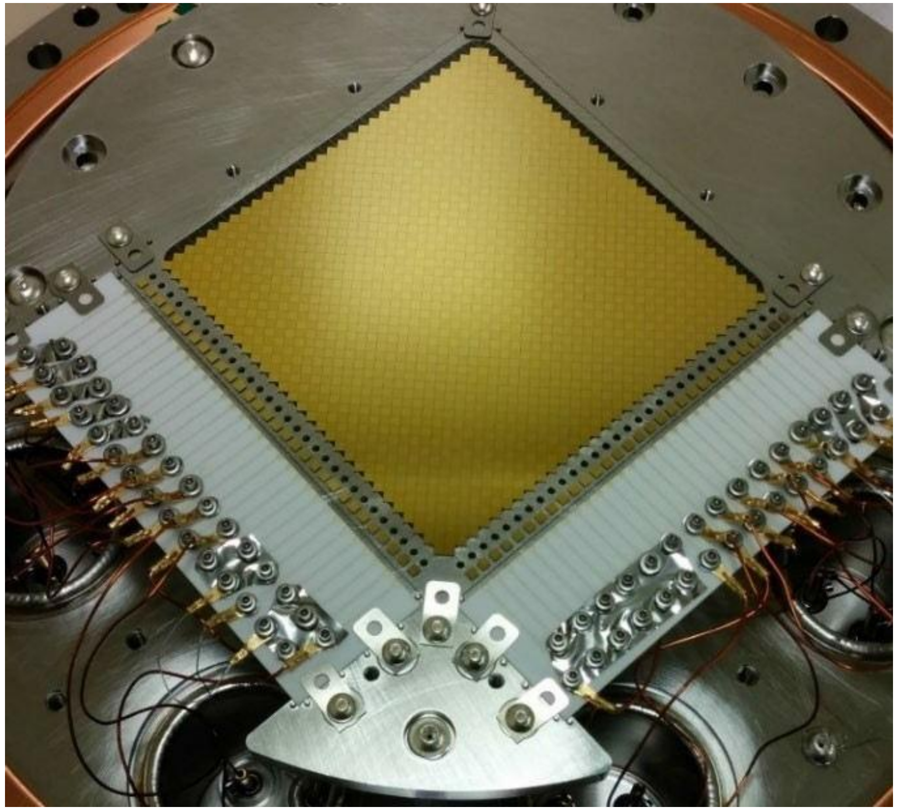
Signals Detection & Analysis

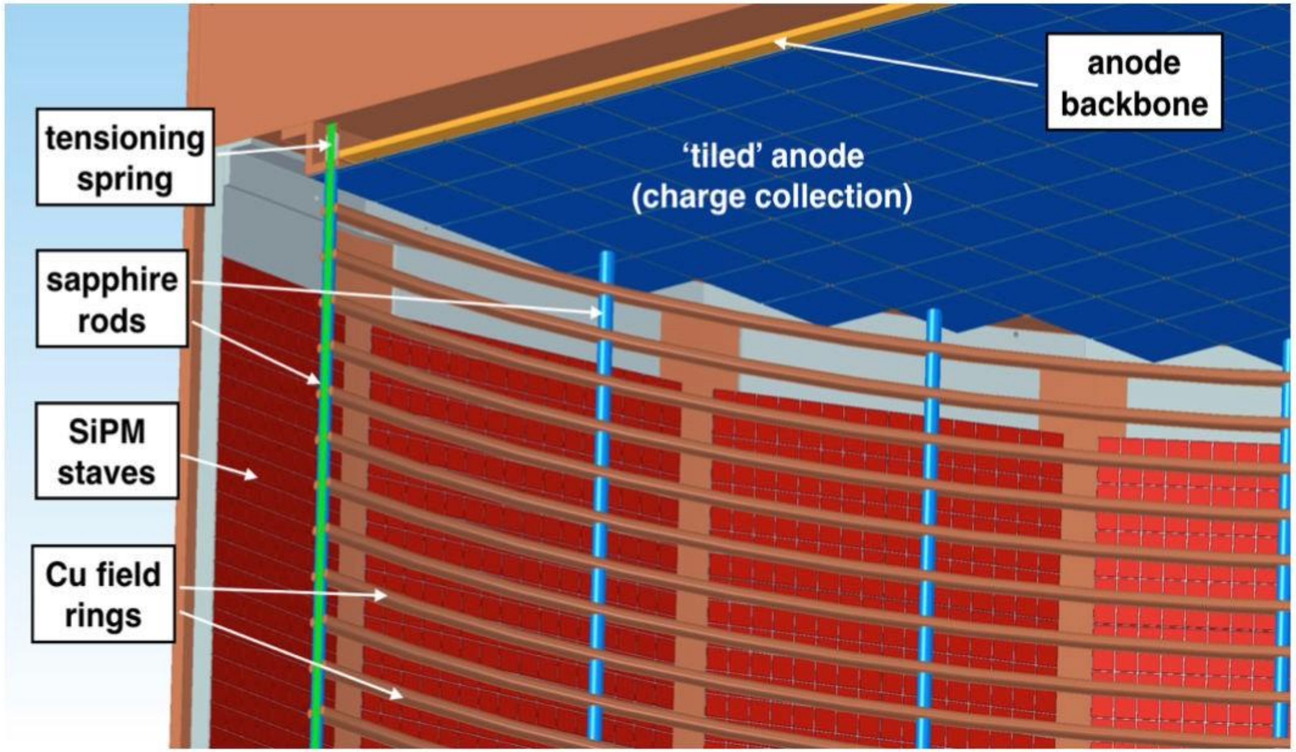
- Photons immediately detected by SiPMs around the barrel
- Electrons drifted to charge collection tiles at the top



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

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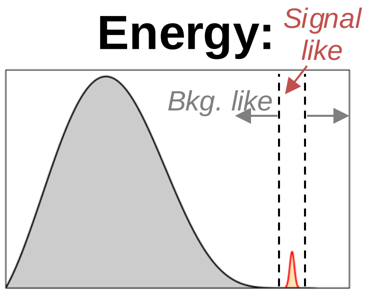
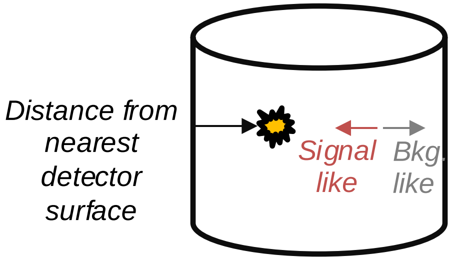
- In the inner 2 tons of LXe*
- Single Site: Neural Network>0.85

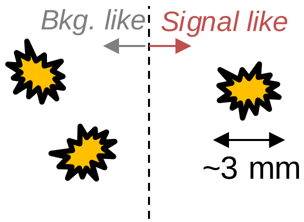
Energy:



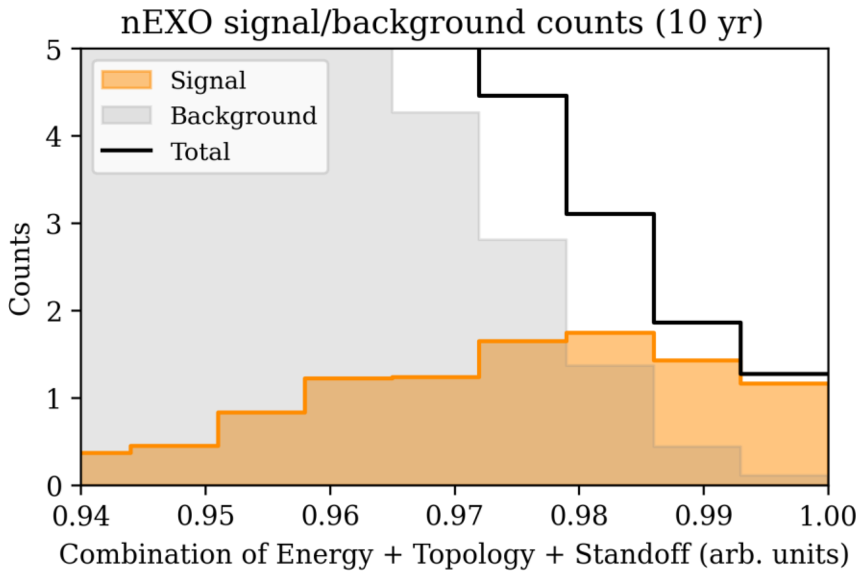
Standoff:



Topology:



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

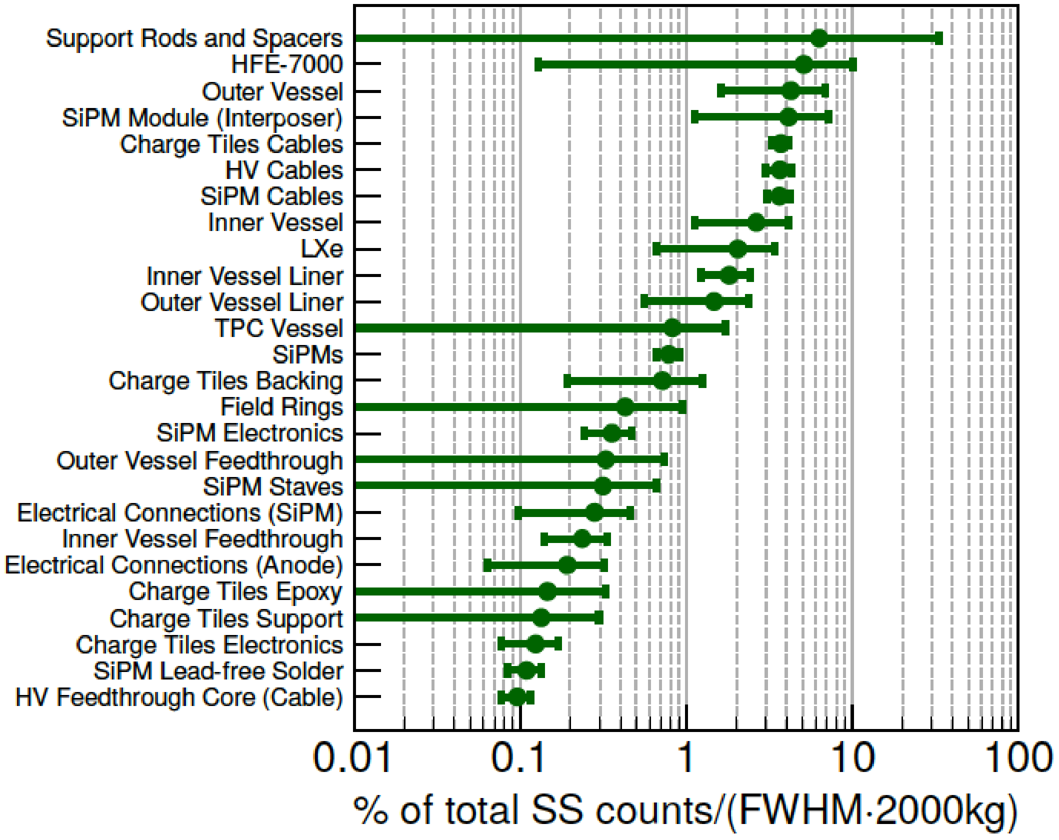


0 ← Background-like **Signal-like →1**

*: 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



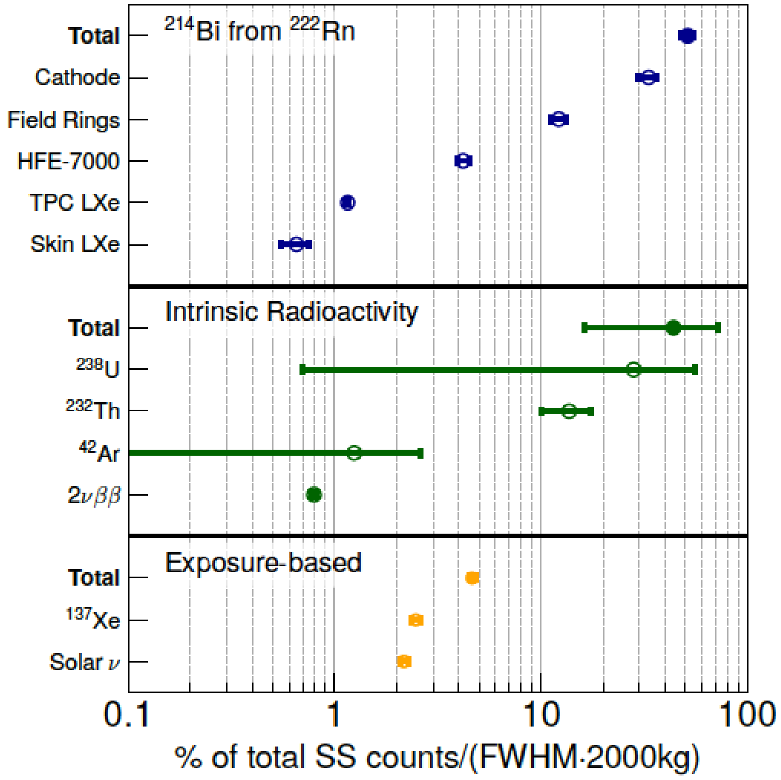
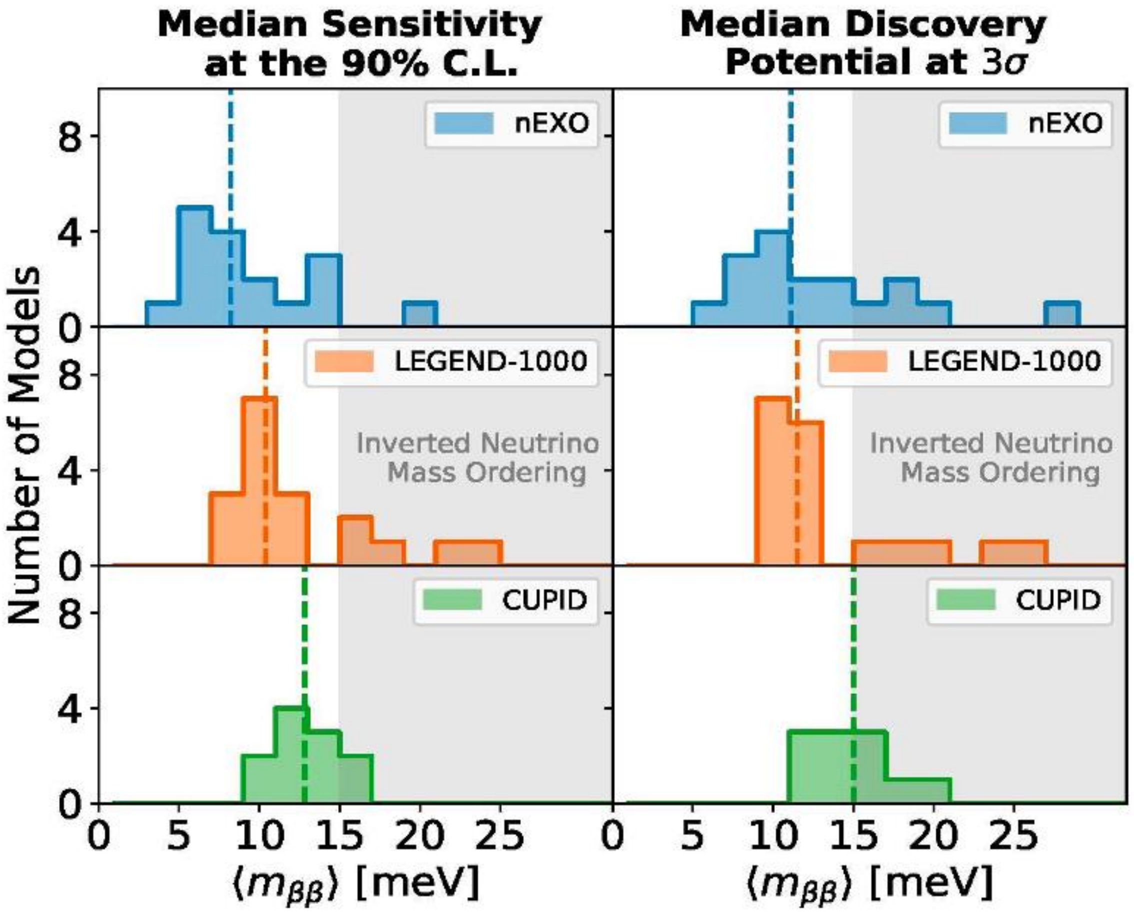
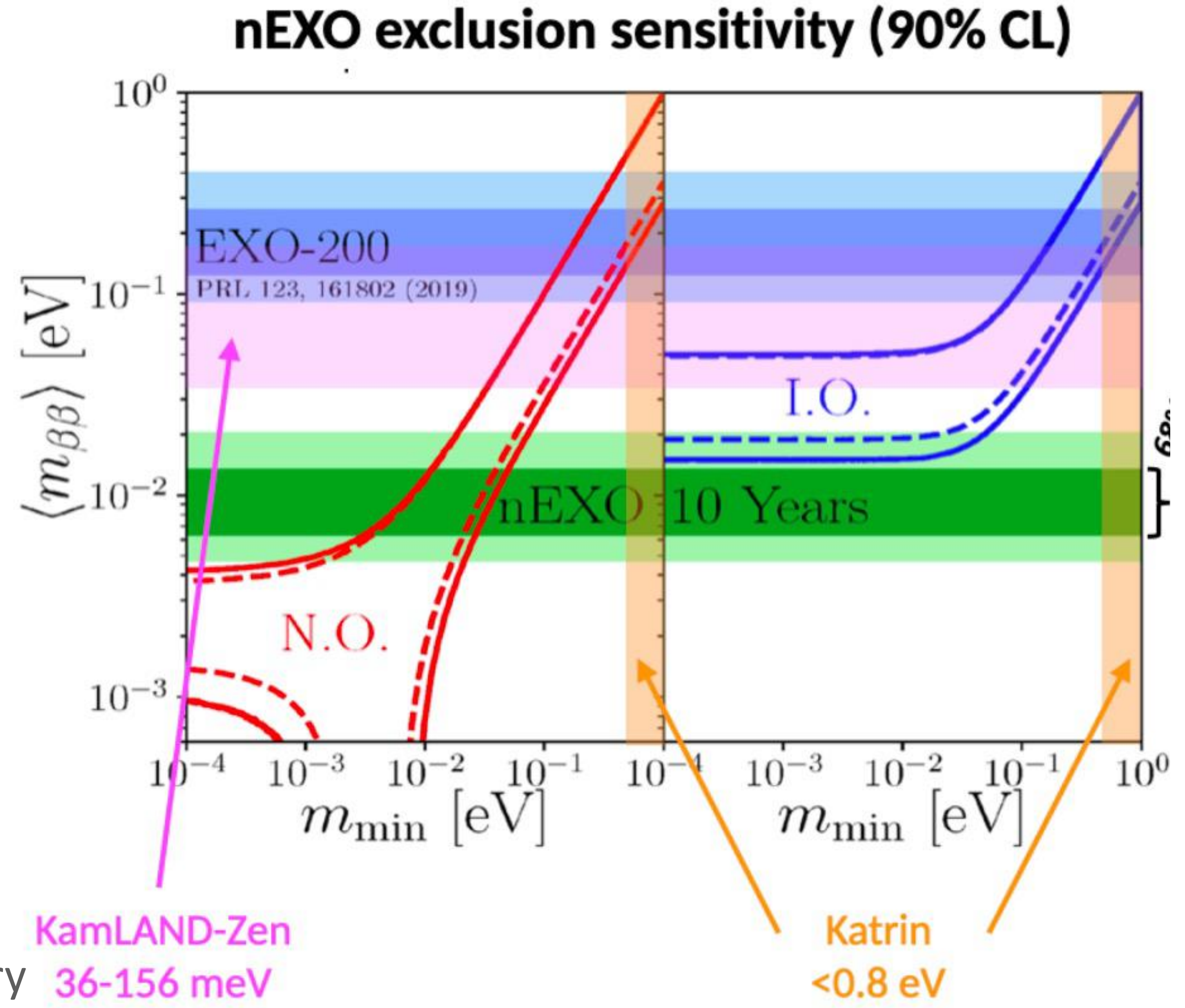


Figure 8. SS-like fractional background contributions with energy within $Q_{\beta\beta}\pm$FWHM/2 and in the inner 2000 kg. The contributions are grouped by category, as described in the text. For each category, the total contribution is shown by the solid marker, while individual contributions are 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.





- >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)

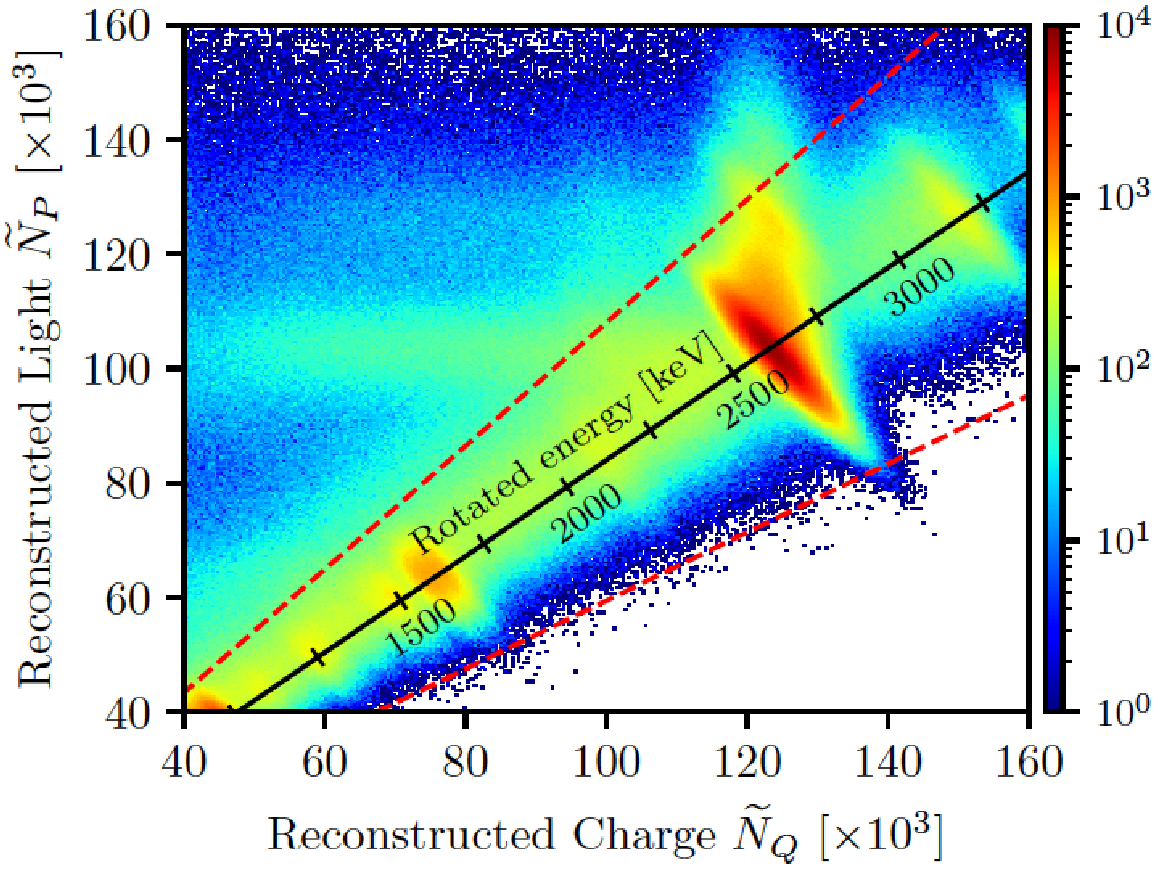
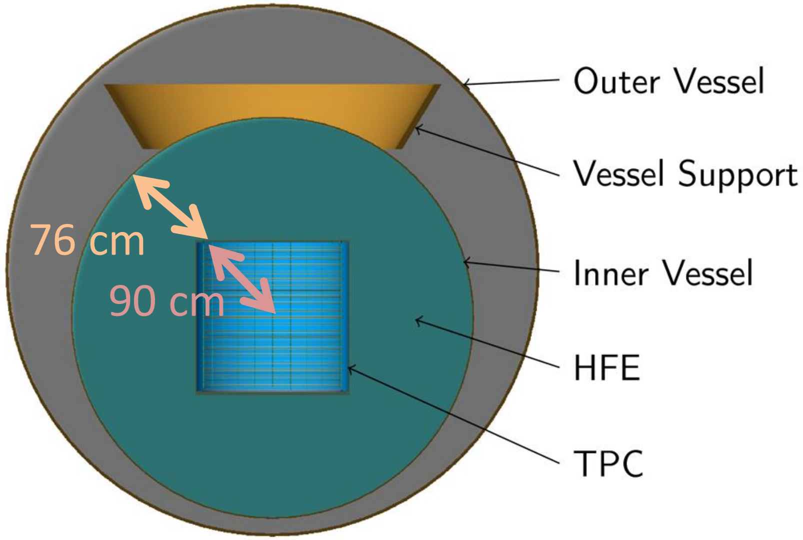


Figure 5. Reconstructed light and charge signals of all events in the FV from simulated ^{232}Th decays in the TPC vessel. The dashed lines indicate the location of the diagonal cut, described in the text. The rotated axis indicates the scale of the rotated energy.

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

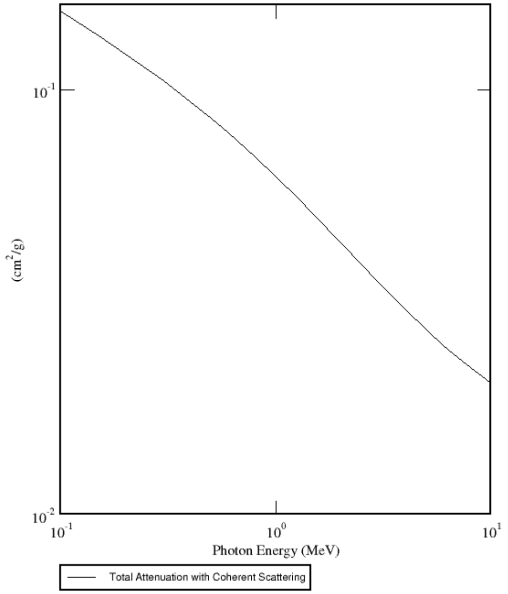


Typical Physical Properties

Table 1

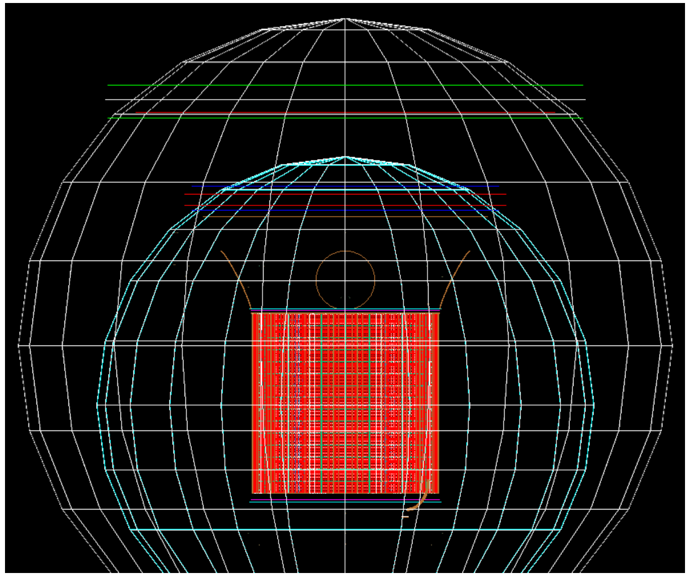
Properties	3M™ Novec™ 7200 Engineered Fluid	3M™ Novec™ 7100 Engineered Fluid	HFC-4310mee	HCFC-225 ca/cb
Formulation	$C_4F_9OC_2H_5$	$C_4F_9OCH_3$	$C_5H_2F_{10}$	$C_3Cl_2HF_5$
Molecular Wt.	264	250	252	203
Boiling Point (°C)	76	61	54	54
Freeze Point (°C)	-138	-135	-80	-131
Liquid Density (g/ml)	1.43	1.52	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



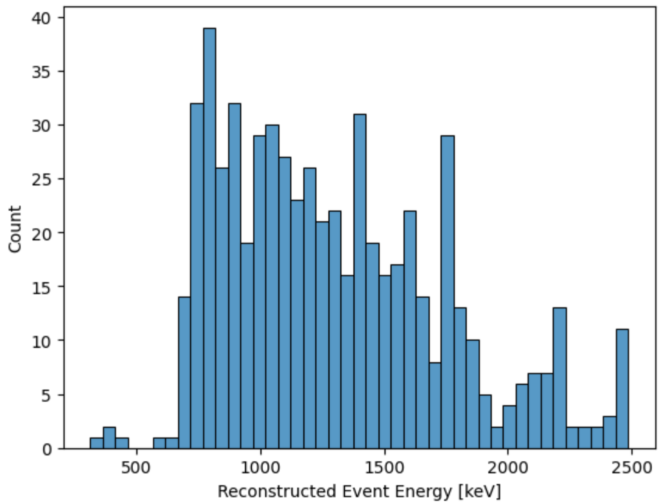
Simulation Geant4

- 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



Design Implications: Radon from water

Less HFE = External Background

Increased

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