Proposal of nEXO@Yemilab

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IBS Center for Underground Physics

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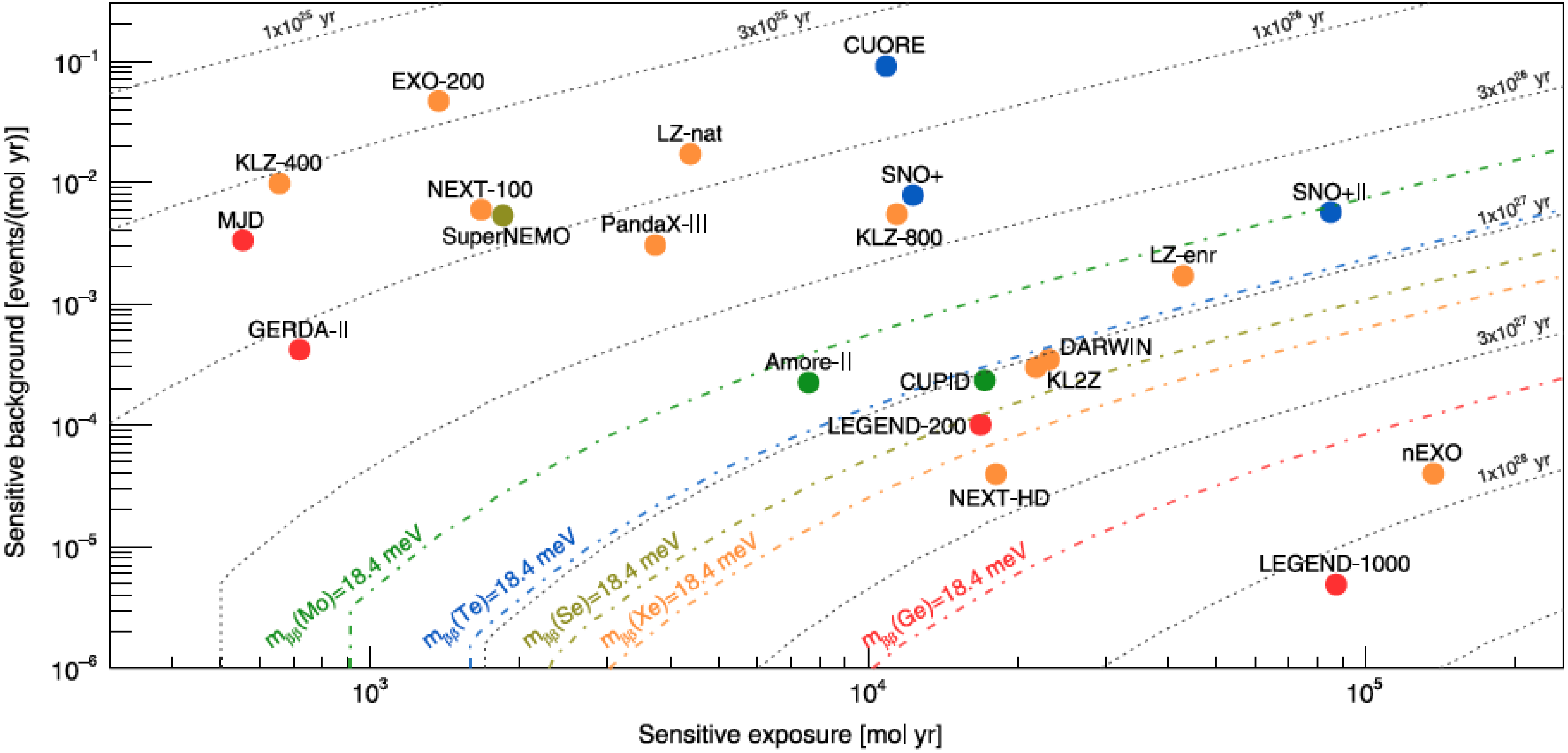
Outline

- Puzzles
  - How can we understand the mass of elementary particles ?
  - Neutrino mass : Dirac or Majorana fermions ?
- Experimental searches for neutrinoless double beta decays
- Overview of nEXO
- Challenges at shallower depth
  - 137Xe
  - Spallation backgrounds
- Plan for
  - Detector
  - Site
  - Cost
- Proposal
  - International Collaboration Project
  - Roles

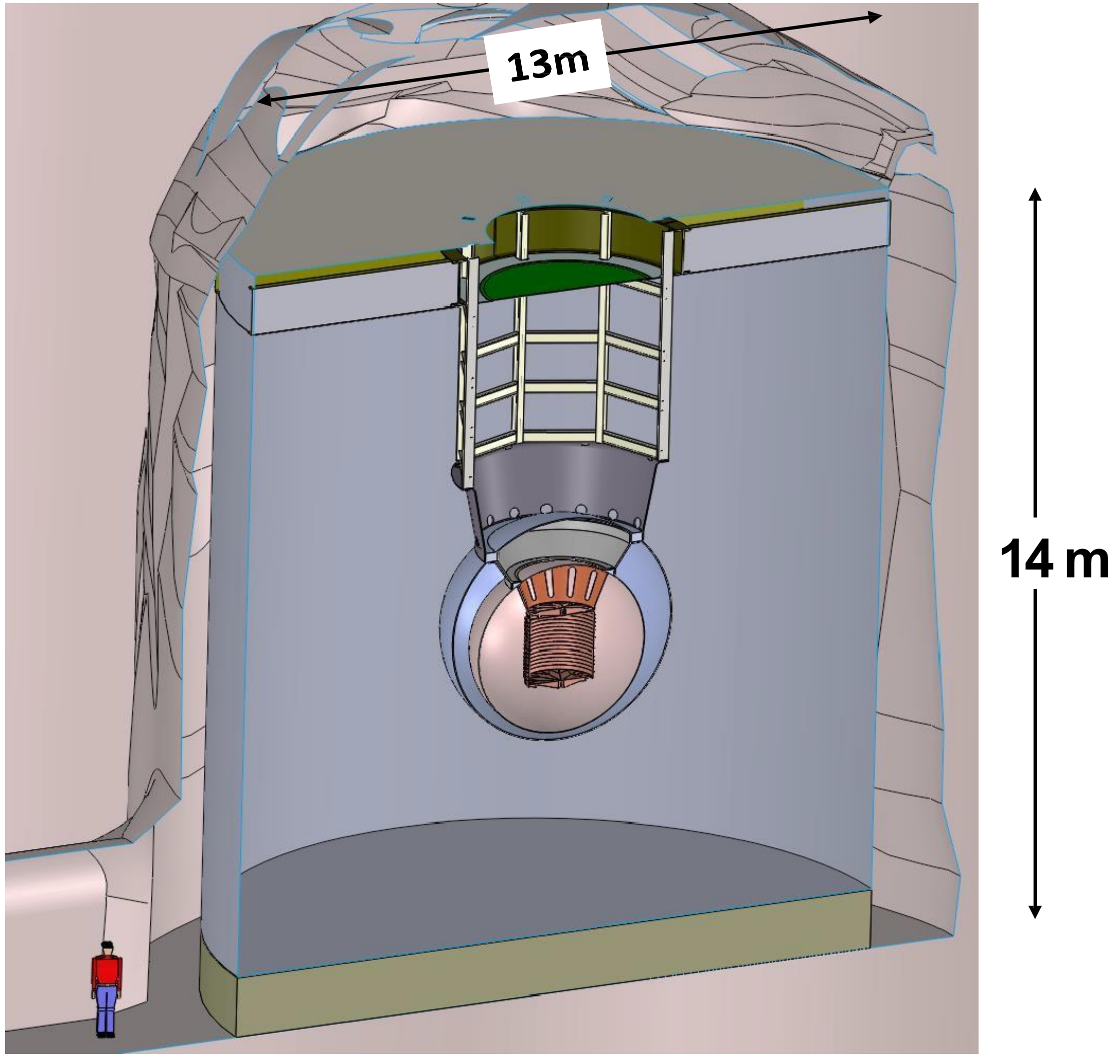
nEXO in comparison

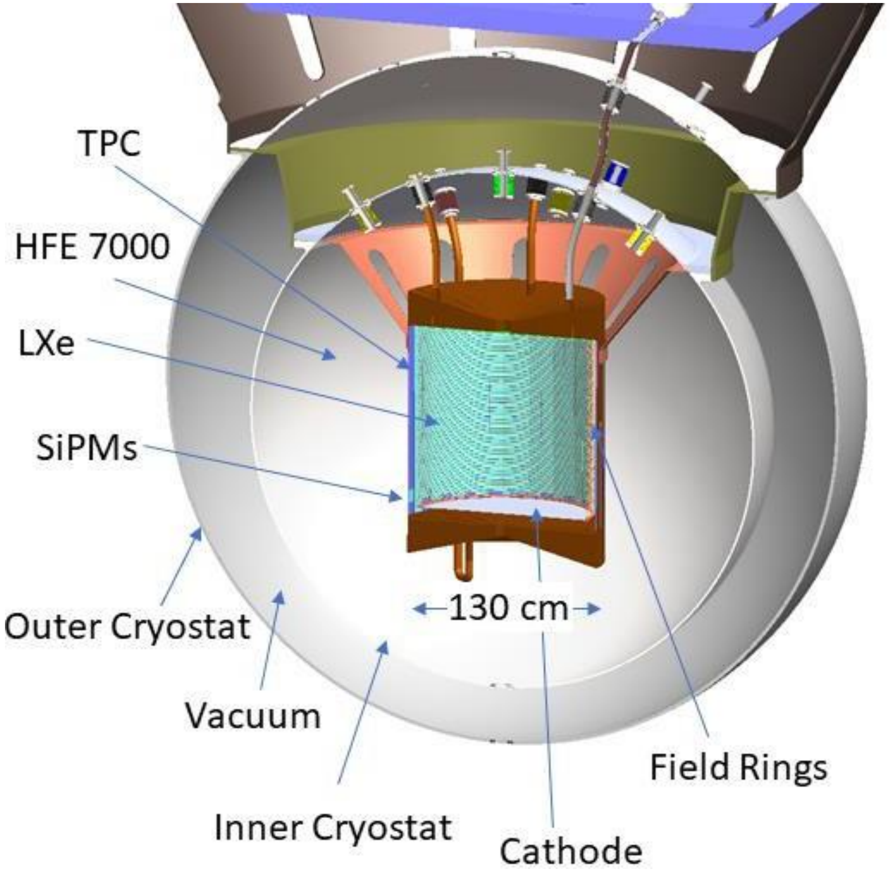
nEXO, with LEGEND-1000 & CUPID+AMoRE, is the most sensitive experiment with realistical plan.



Overview of nEXO

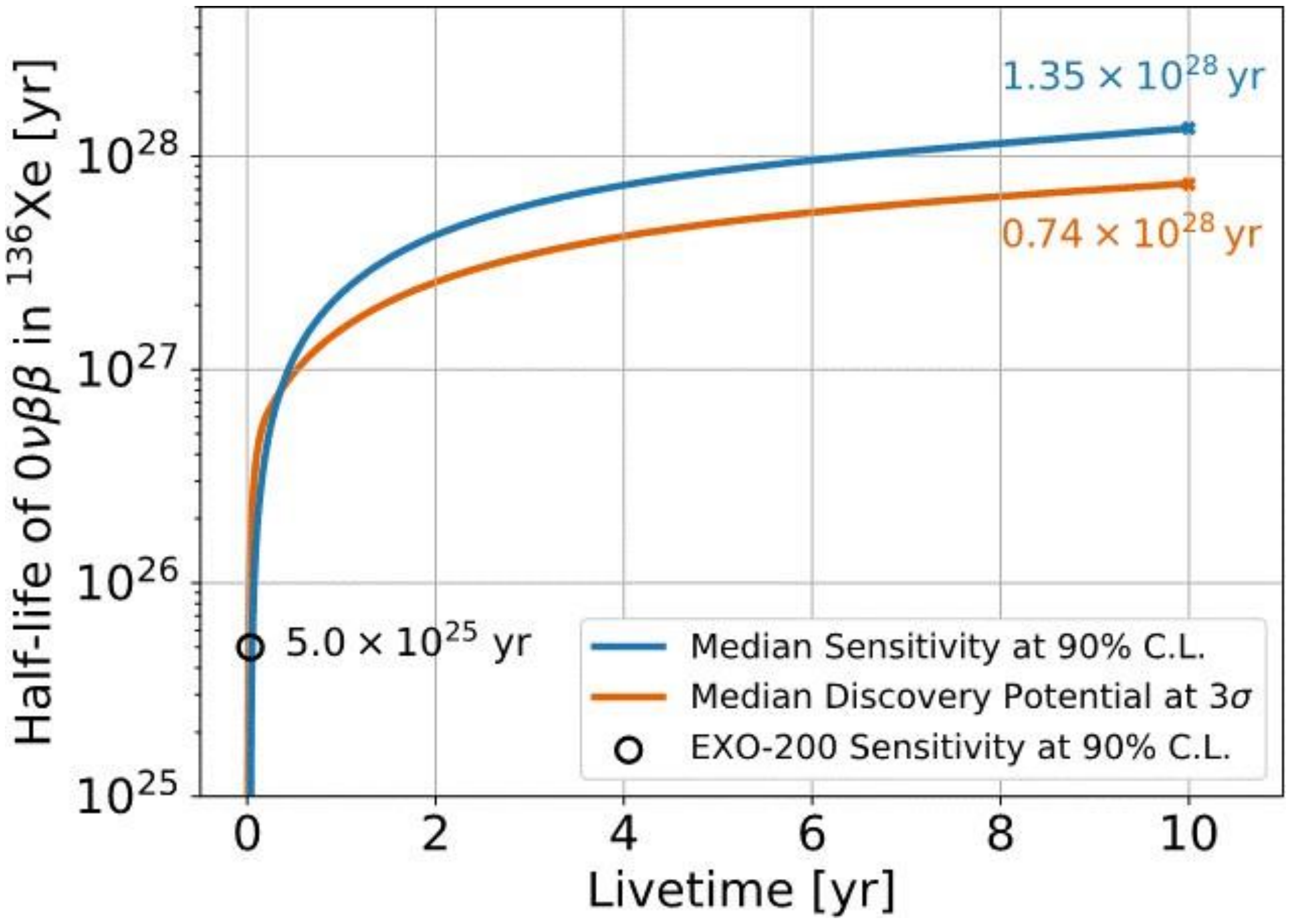
A 5000 kg enriched LXe TPC,

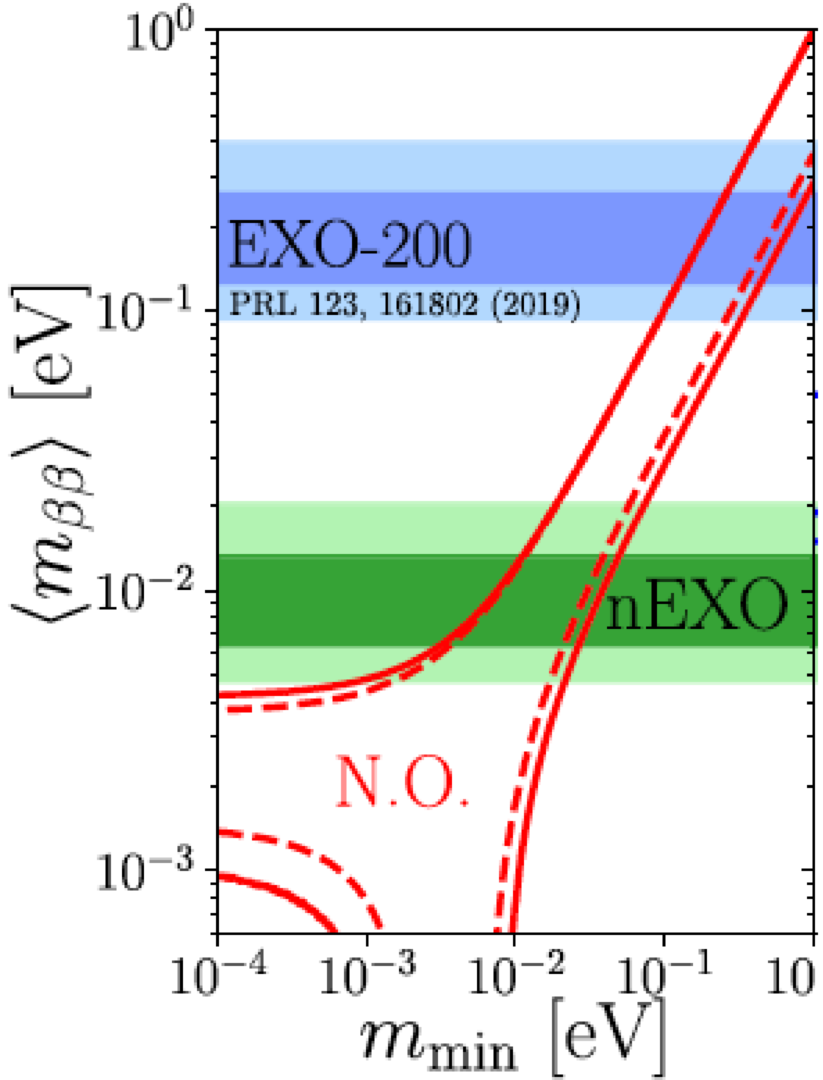




nEXO expectations

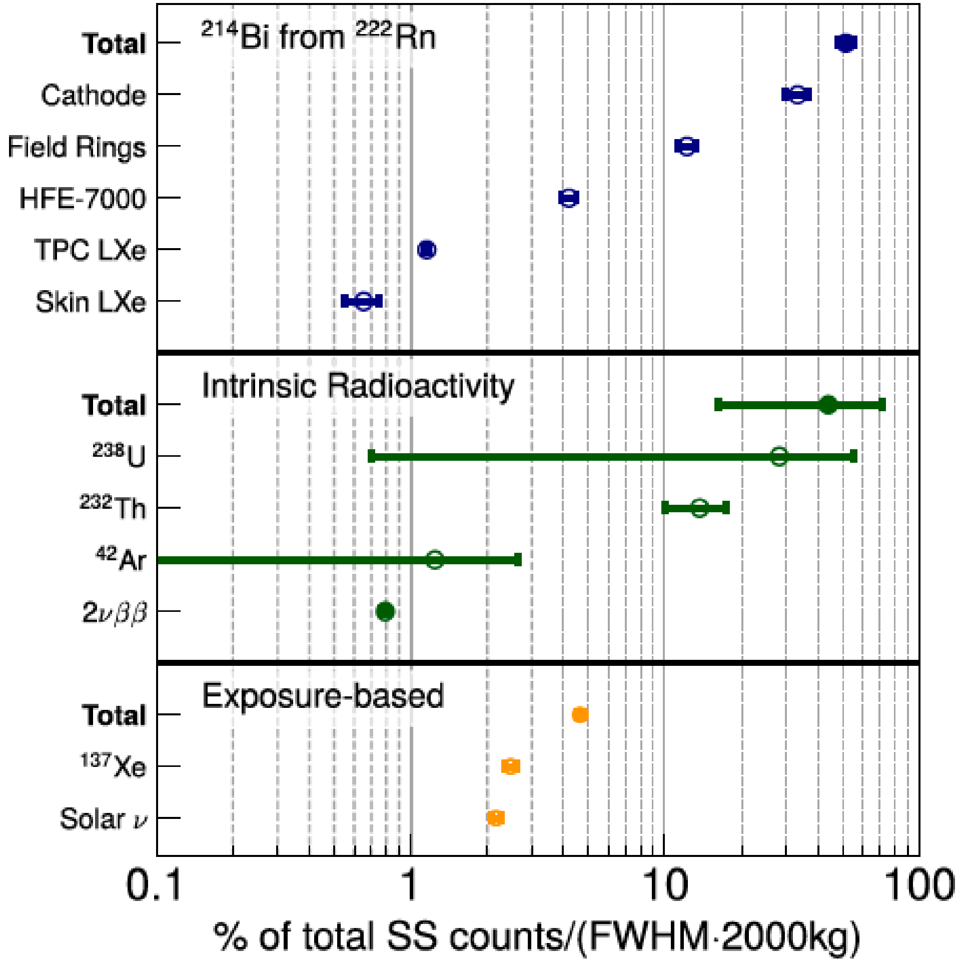
- Energy resolution (sigma) : 0.8%(Goal), Q=2458 keV → 46 keV FWHM
- Background level : Total $6x10^{-6}$ counts/keV/kg/year





nEXO @ Yemilab

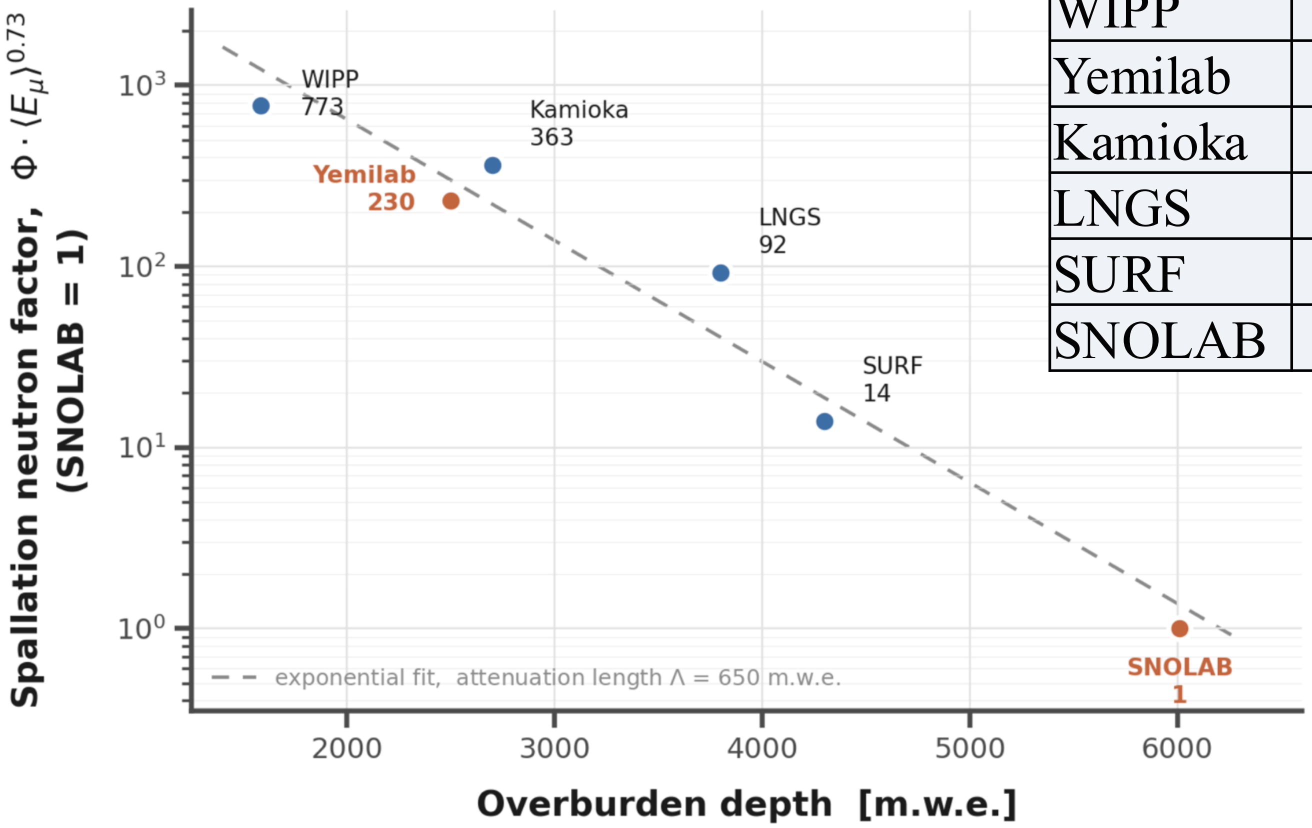
Fraction of each background sources in nEXO



- nEXO background @ SNOLAB
  - 50% ^{222}Rn
  - 45% Other radio-impurities in material
  - 5 % exposure (^{137}Xe, solar nu) – not significant.
- Challenges at shallower depth
  1. ^{137}Xe background from ^{136}Xe(n,γ)^{137}Xe
  2. Radioisotopes other than ^{137}Xe from muon induced spallation.

Muon-Induced Isotope Production — Site Normalization Factors (SNF)

- Production rate per unit target mass $\propto \Phi_\mu \times \langle E_\mu \rangle^{0.73}$.
- Both neutron and isotope production rate are proportional to this production factor

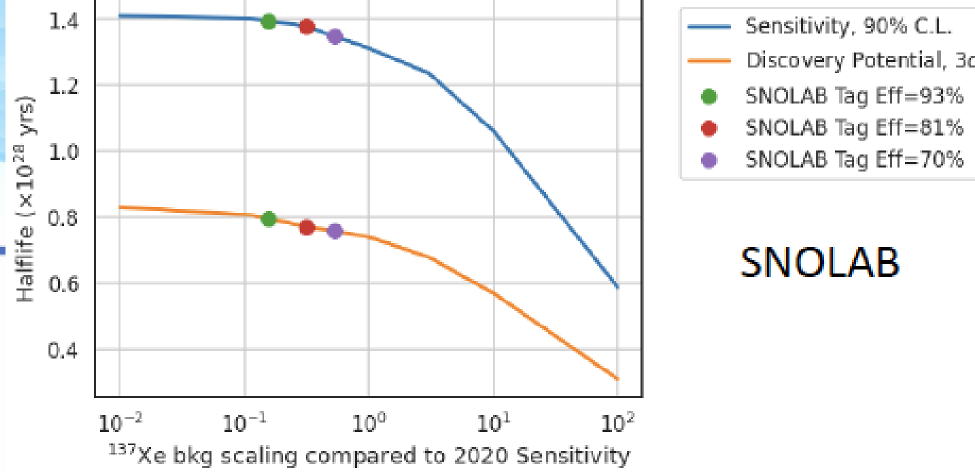


Site	Depth (m.w.e.)	Muon flux Φ (cm^{-2} s^{-1})	⟨E_μ⟩ (GeV)	Prod. factor Φ·⟨E⟩^0.73	SNF
WIPP	1585	4.07×10^{-7}	200	1.95×10^{-5}	773
Yemilab	2500	1.00×10^{-7}	260	5.79×10^{-6}	230
Kamioka	2700	1.58×10^{-7}	260	9.15×10^{-6}	363
LNGS	3800	3.41×10^{-8}	322	2.31×10^{-6}	92
SURF	4300	5.31×10^{-9}	308	3.48×10^{-7}	14
SNOLAB	6010	3.31×10^{-10}	378	2.52×10^{-8}	1

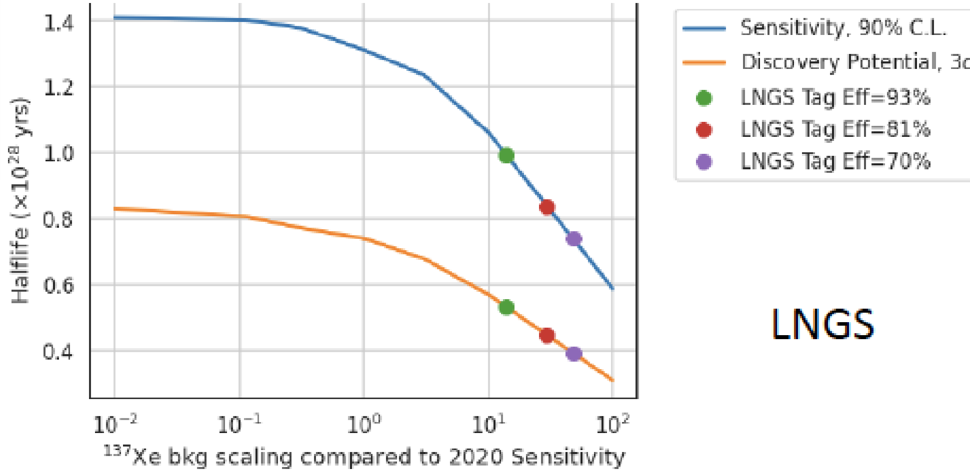
^{137}Xe Background and $0\nu\beta\beta$ Sensitivity Results

- Sensitivity was estimated assuming Wilks's approximation and the nEXO 2020 baseline used in the 2021 sensitivity paper
- The sensitivity scaling with 137Xe from the paper was shown to still hold even after accounting for the full distribution of 137Xe atoms
- Sensitivity for 10 years of exposure

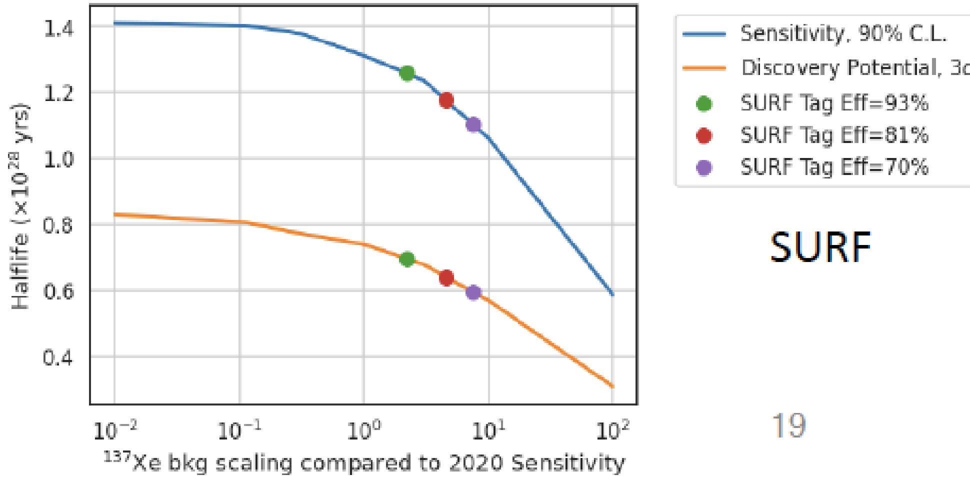
Site	^{136}Xe n-capture tagging eff	Mean ^{137}Xe ROI Background [cts / y]	^{137}Xe Total Background Fraction [%]	90% CL $0\nu\beta\beta$ Sensitivity [10^{28} y]	Discovery Potential, 3σ [10^{28} y]
SNOLAB	81 %	0.006	1.1%	1.38	0.77
LNGS	81 %	0.44	45%	0.84	0.45
SURF	81 %	0.07	11%	1.18	0.64
WIPP	81 %	6.5	92%	0.2	nc



SNOLAB



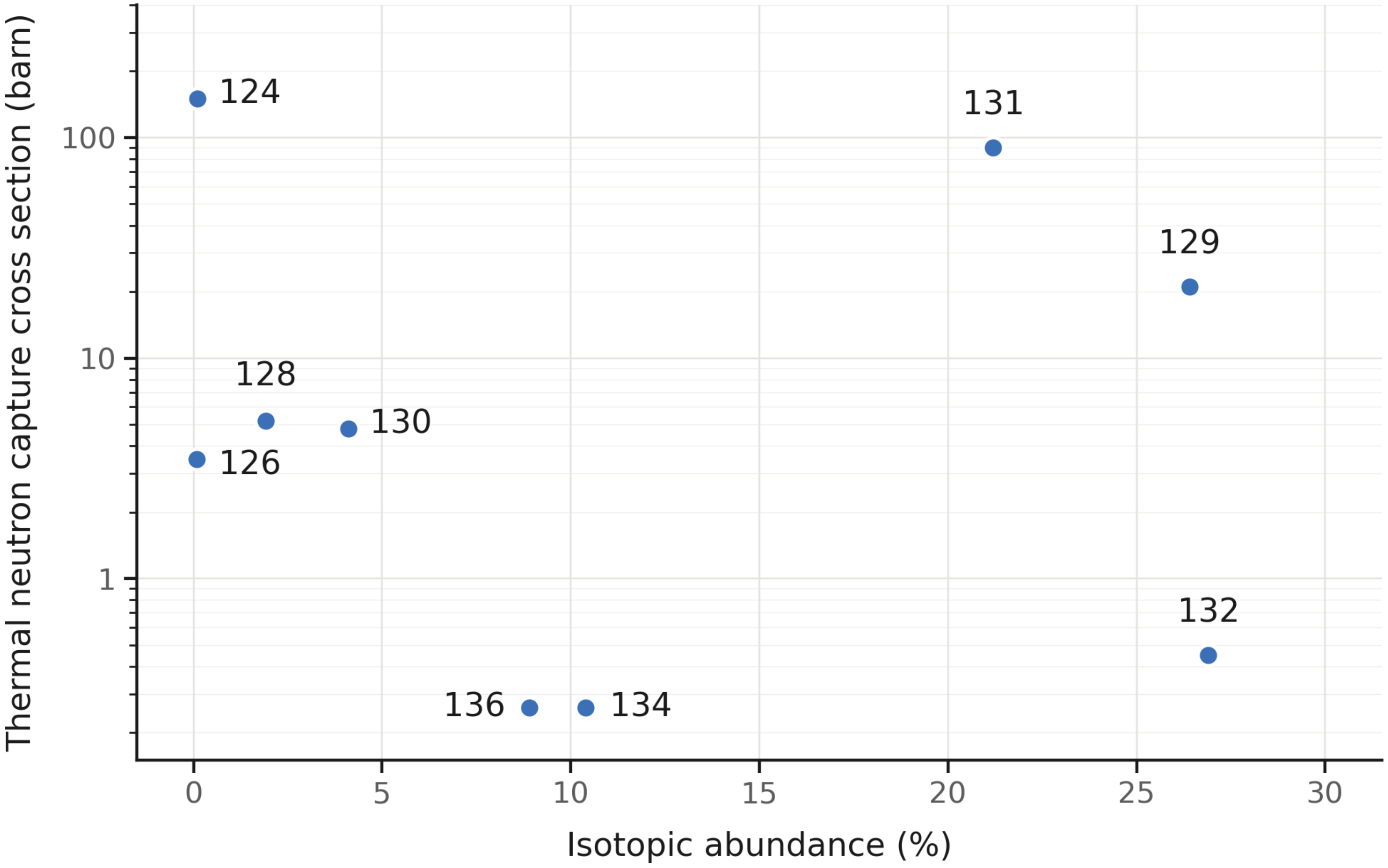
LNGS



SURF

(1) Mitigation of ^{137}Xe

Capture c.x. vs Abundance



Adding Xe-131 90% enriched.

	Baseline	Proposed
90 % ^{136}Xe stock	5000 kg	4700 kg
90 % ^{131}Xe stock	0 kg	300 kg

In "Baseline" case, 90% of neutron capture is by Xe-1 36, but in "Proposed" case, only 3.9% is by Xe-136.

- R=4.1/90=0.046

	Capture CX (barn)	Baeline			Proposed		
		Abun (%)	N Capture	Capture (%)	Abun (%)	N Capture	Capture (%)
131	90.0	0	0		5.6	504.0	95.3
132	0.45	0	0		0.6	0.3	0.1
134	0.26	10.1	2.6	10.0	9.5	2.5	0.5
136	0.26	89.9	23.3	90.0	84.3	21.9	4.1

- As shown in Dr. Lin Si's simulation, the reduction factor is ~ 5.
- We need additional mitigation method.

Boric Acid (BA) powder as a neutron absorber.

Requirements for BA powder purity by Dr. Lin Si's Simulation

- A(^{214}Bi) < 6μBq/kg ~ 0.5 ppt
- A(^{228}Th) < 40μBq/kg ~ 10 ppt

CUP's measurements : Alpha Aesar Boric Acid:

- Lowest contamination has been identified.

Al	K	Ca, Cu	Cr, Mn, Fe, Co, Ni, W, Ir	Sr	Zr	Ba	Tl	Pb	**Th**	**U**
ppb	ppb	ppb	ppb	ppt	ppt	ppt	ppt	ppt	**ppt**	**ppt**
<30	622	<200	<20	275	<100	176	<2000	<150	**18**	**<3**

- Further background reduction more than factor 10 is foreseen.
  - UTEVA-SPE analysis of Th and U in this acid will give us sub-ppt sensitivity
  - Purification via recrystallization.

    Solubility (@ 20 ˚C) ~ 4.72 g/(100 g water)

    Solubility (@100 ˚C) ~ 27.53 g/(100 g water)

Boric Acid Plates

1. Acrylic Box

Ultra-low radioactivity is reported for acrylic of JUNO experiment. Acrylic itself is produced by a local company (Donchamp in China)

This level will be equivalent to Electroformed copper vessel in terms of background.

Material	^{238}U	^{214}Bi	^{232}Th	^{228}Th
	ppt	mBq/kg	ppt	mBq/kg
Acrylic bulk, JUNO	0.13±0.07		0.23±0.07	

2. Paraffin mixture for borix acid

- Dodecane is used in KamLAND experiment, a type of paraffin, is purified down to 0.0001 ppt level of U, Th.
- Many types of hydrocarbon material

3. Electroformed copper box

- Electroformed copper, same material of TPC vessel, of ~ 0.5 mm thick container.
- About 40 cm curved containers can cover the surfaces of TPC vessel.

Optimized boron absorber

Enriched Boron Plates. (~ 1mm thick)

- Use Enriched Boron (95% ^{10}B)
- Purify enriched boric acid (< 7 mBq/kg for ^{214}Bi, <39mBq/kg for ^{228}Th.) required by Lin's simulation.
- Choose the best container or mixture. R&D necessary.

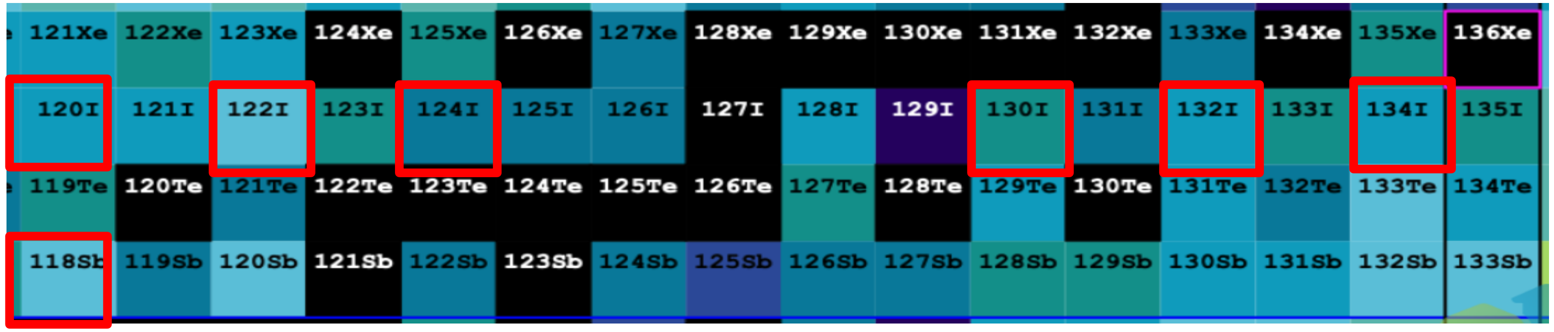
(2) Cosmogenic spallation background

Isotopes other than ^{137}Xe with long hal-life and high Q-value are potential background.

- **^{130}I, ^{132}I, ^{134}I, ^{135}I, ^{120}I, ^{122}I, ^{124}I, ^{118}Sb** are most signifant.

Albert et al., JCAP04, 2016, 029

Region/ Nuclide	Half-life	Total energy (keV)	2.3–2.6 MeV efficiency	EXO-200 SS ROI efficiency	Geant4 rate (yr^{-1})	FLUKA rate (yr^{-1})
HFE-7000 ^{16}N	7.1 s	10420	0.015%	0.001%	2380 ± 90	2910 ± 110
TPC vessel ^{60}Co	5.3 y	2823	0.19%	0.0002%	2.6 ± 0.3	2.9 ± 0.6
TPC LXe ^{130}I	12 h	2949	8.5%	0.001%	7.3 ± 0.5	21.6 ± 1.8
TPC LXe ^{132}I	2.3 h	3581	5.5%	0.013%	7.7 ± 0.5	22.2 ± 1.8
TPC LXe ^{134}I	53 m	4175	4.5%	0.012%	7.3 ± 0.5	20.4 ± 1.7
TPC LXe ^{135}I	6.6 h	2627	2.9%	0.035%	8.6 ± 0.6	21.6 ± 1.8
TPC LXe ^{135}Xe	9.1 h	1165	—	—	1110 ± 40	1060 ± 40
TPC LXe ^{137}Xe	3.8 m	4173	4.1%	1.5%	439 ± 17	403 ± 16



Other cosmogenics at shallow sites - report

Measurement of cosmic-ray muon spallation products in a xenon-loaded liquid scintillator with KamLAND

arXiv:2301.09307

TABLE IX. Simulated production rate of dominant isotopes in $2.35 \leq E \leq 2.70$ MeV in Xe-LS.

	$\tau_{1/2}$ (s)	Q (MeV)	(kton day)$^{-1}$ ROI	Total
^{88}Y	9.212×10^6	3.62 (EC/$\beta^+\gamma$)	0.110	0.136
^{90m1}Zr	8.092×10^{-1}	2.31 (IT)	0.012	0.093
^{90}Nb	5.256×10^4	6.11 (EC/$\beta^+\gamma$)	0.024	0.095
^{96}Tc	3.698×10^5	2.97 (EC/$\beta^+\gamma$)	0.012	0.059
^{98}Rh	5.232×10^2	5.06 (EC/$\beta^+\gamma$)	0.011	0.076
^{100}Rh	7.488×10^4	3.63 (EC/$\beta^+\gamma$)	0.088	0.234
^{104}Ag	4.152×10^3	4.28 (EC/$\beta^+\gamma$)	0.012	0.160
^{104m1}Ag	2.010×10^3	4.28 (EC/$\beta^+\gamma$)	0.018	0.111
^{107}In	1.944×10^3	3.43 (EC/$\beta^+\gamma$)	0.019	0.135
^{108}In	3.480×10^3	5.16 (EC/$\beta^+\gamma$)	0.089	0.194
^{110}In	1.771×10^4	3.89 (EC/$\beta^+\gamma$)	0.053	0.236
^{110m1}In	4.146×10^3	3.89 (EC/$\beta^+\gamma$)	0.066	0.351
^{109}Sn	1.080×10^3	3.85 (EC/$\beta^+\gamma$)	0.027	0.122
^{113}Sb	4.002×10^2	3.92 (EC/$\beta^+\gamma$)	0.036	0.231
^{114}Sb	2.094×10^2	5.88 (EC/$\beta^+\gamma$)	0.020	0.297
^{115}Sb	1.926×10^3	3.03 (EC/$\beta^+\gamma$)	0.031	0.839
^{116}Sb	9.480×10^2	4.71 (EC/$\beta^+\gamma$)	0.071	0.939
^{118}Sb	2.160×10^2	3.66 (EC/$\beta^+\gamma$)	0.165	1.288
^{124}Sb	5.201×10^6	2.90 (EC/$\beta^-\gamma$)	0.016	0.054
^{115}Te	3.480×10^2	4.64 (EC/$\beta^+\gamma$)	0.012	0.124
^{117}Te	3.720×10^3	3.54 (EC/$\beta^+\gamma$)	0.052	0.594
^{119}I	1.146×10^3	3.51 (EC/$\beta^+\gamma$)	0.053	0.533
^{120}I	4.896×10^3	5.62 (EC/$\beta^+\gamma$)	0.091	0.953
^{122}I	2.178×10^2	4.23 (EC/$\beta^+\gamma$)	0.289	1.965
^{124}I	3.608×10^5	3.16 (EC/$\beta^+\gamma$)	0.190	1.654
^{130}I	4.450×10^4	2.95 ($\beta^-\gamma$)	0.195	1.188
^{132}I	8.262×10^3	3.58 ($\beta^-\gamma$)	0.148	0.427
^{134}I	3.150×10^3	4.18 ($\beta^-\gamma$)	0.043	0.183
^{121}Xe	2.406×10^3	3.75 (EC/$\beta^+\gamma$)	0.100	0.540
^{125}Cs	2.802×10^3	3.09 (EC/$\beta^+\gamma$)	0.012	0.266
^{126}Cs	9.840×10^1	4.82 (EC/$\beta^+\gamma$)	0.011	0.080
^{128}Cs	2.196×10^2	3.93 (EC/$\beta^+\gamma$)	0.031	0.229

TABLE IV. Number of target nuclei (kton^{-1}) in KamLAND-LS and Xe-LS. KamLAND contains 1 kton of KamLAND-LS and 24 ton of Xe-LS.

Element	KamLAND-LS	Xe-LS
Hydrogen	8.47×10^{31}	8.39×10^{31}
Carbon	4.30×10^{31}	4.17×10^{31}
Nitrogen	5×10^{27}	8.31×10^{27}
Oxygen	5×10^{27}	8.31×10^{27}
Xenon	-	1.39×10^{29}

Production rates of radioisotopes from xenon spallation, identified in KamLAND-Zen, were scaled by the ratio of the muon flux at Kamioka to the different sites (spallation rates/muon match Borexino data to ~ 10-20%)

- The rates were then adjusted to account for the better energy resolution in nEXO vs KamLAND
- Not enough time to simulate each isotope and evaluate hit efficiency.
- However, 85% are positron emitters (in red) and the rest always include beta+gammas.
- Since these decays occur in the xenon, the MS/SS ratio is large
- SS/MS fraction estimated to be 1.4% based on simulations of positrons in xenon

Location	Rate before SS/MS Cut [ev/10yr]	Rate after SS/MS Cut [ev/10yr]
SNOLAB	0.2	**0.003**
LNGS	13	0.18
SURF	2.3	0.03
WIPP	252	3.5

Cosmogenic spallation background at Yemilab

FWHM=46keV with nEXO, ckky=counts/keV/kg/year, cfty=count/fwhm/ton/year

- nEXO Total background estimated:

  0.26 cfty (or 5.7×10^{-6} ckky) for the inner 2ton (Gratta's slide)

- Other cosmogenics background @SNOLAB:

  0.003 events/10years for ~ 4.8 ton (→0.000063 cfty) from the report.

  → 0.02% of total background

- Expectecd cosmogenic level @Yemilab: 230XRate@SNOLAB = **0.014 cfty**

  → 4.5-6 % of total background. Need to study in detail.

Very preliminary estimation.

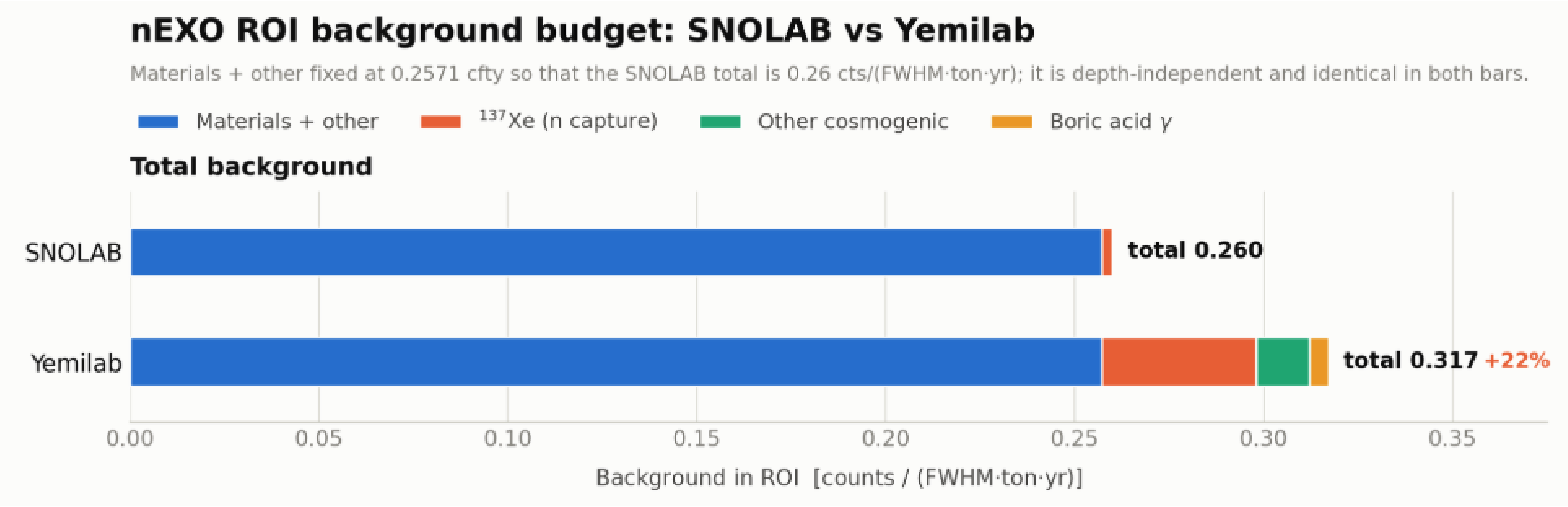
- Should simulate individual beta spectra with nEXO's 3D analysis.
- Need to compare the production rate by FLUKA.

Summary of background @ Yemilab

- The main background from muon-induced background @ Yemilab is still ^{137}Xe even affter reduction by neutron absorbers.
- Cosmic spallation is estimated about 1/3 of ^{137}Xe, but need more studies.
- Other backgroud due to material purity and environment is still dominant background (>70%) @ Yemilab, and could be improved.

Source	type	Background(cfty)		Sx
		@SNOLAB	@Yemilab	
^{137}Xe	^{137}Xe	0.00286	0.041	14.4
Cosmogenic	^{137}Xe	0.000063	0.014	5.1
Total				19.5
Boric Acid	γ		0.005	1.07
Total				

Summary of additional background @ Yemilab



	90% Sensitivity (10^{28} years)	Discovery (10^{28} years)
SNOLAB	**1.38**	**0.77**
Yemilab	**0.91**	**0.48**

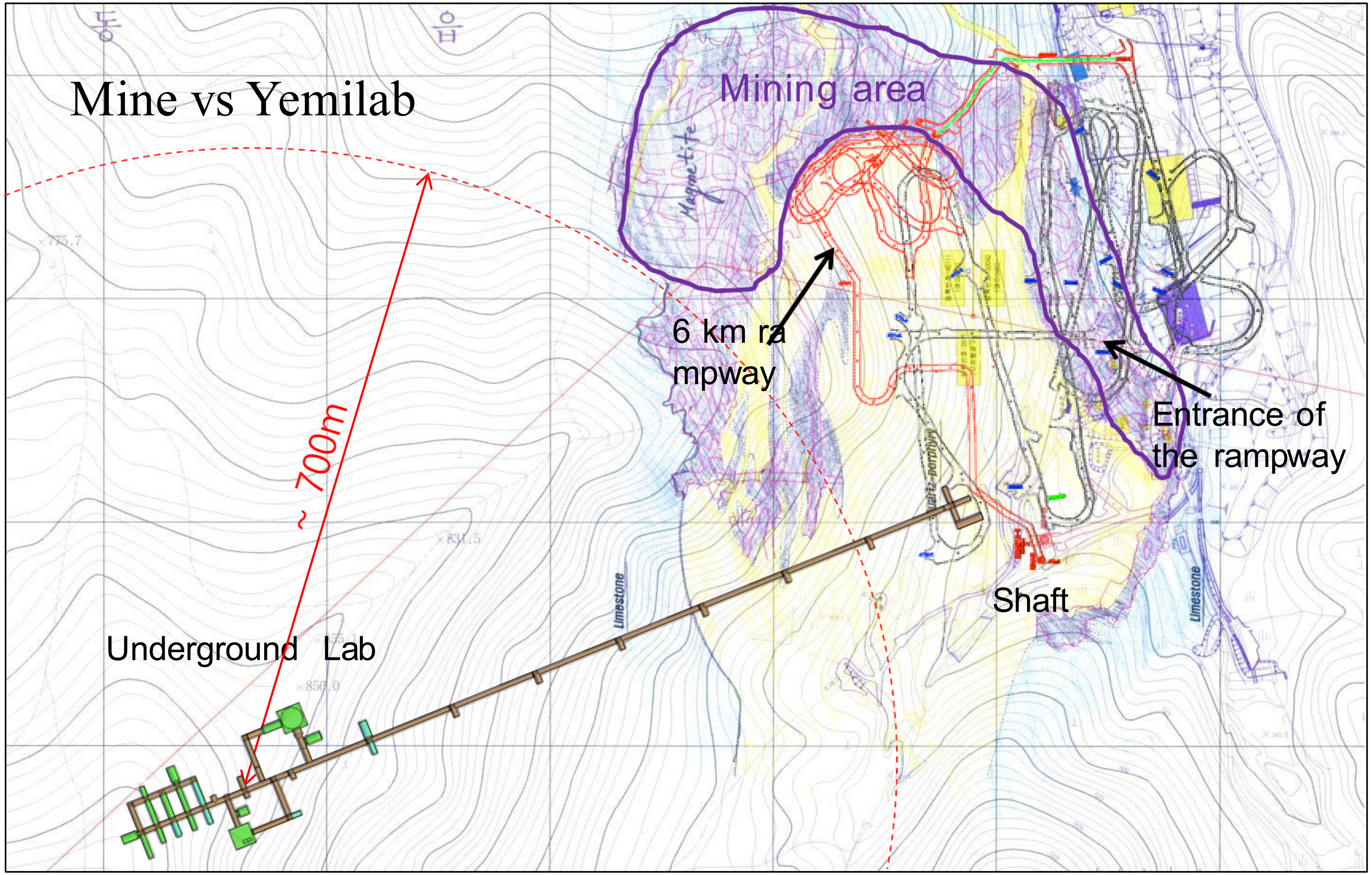
Budget - Price for Xenon

- The price of 90% enriched Xenon is ~ 40 times higher than natural Xenon.
- Total price of 5ton enriched Xenon ~ 100 M$.
- Total price of 5ton enriched Xenon adding ^{131}Xe ~ 120 M$.

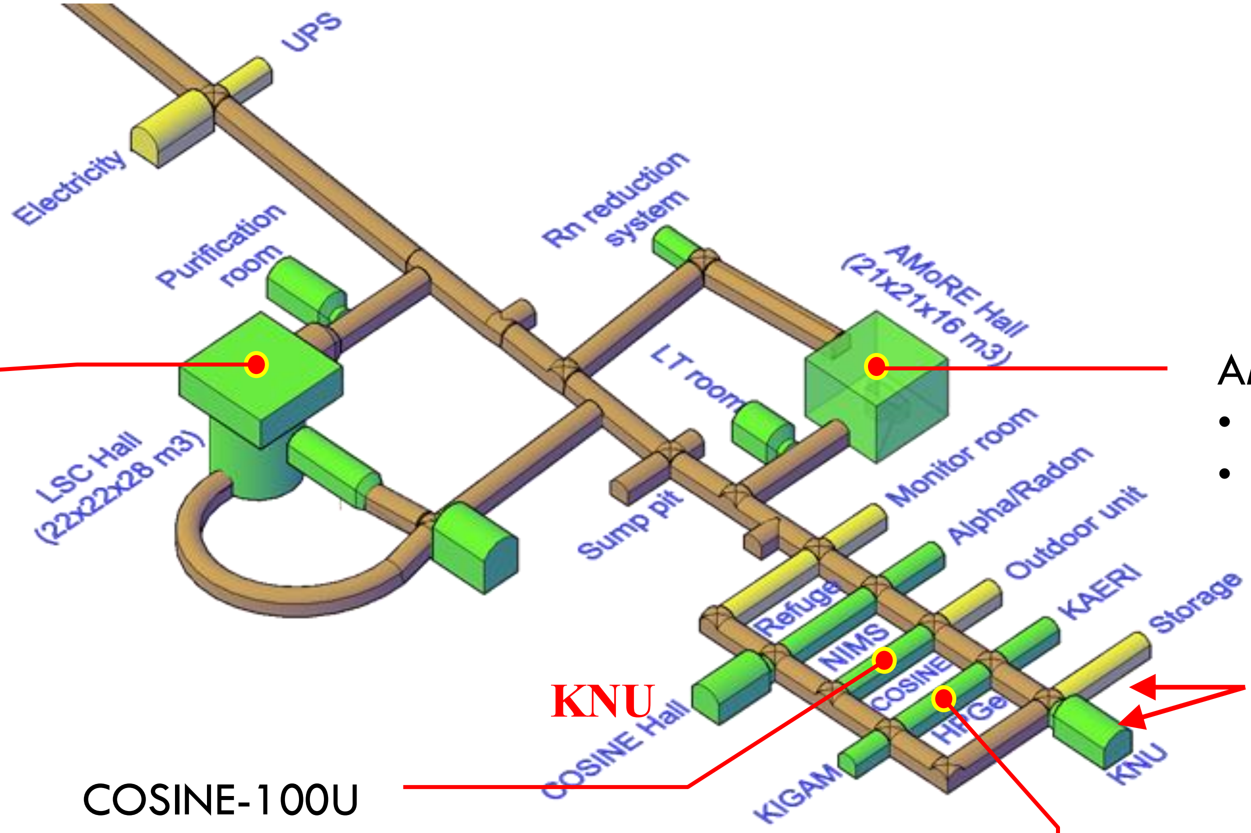
PRODUCT	Abun	Mass	Total Price	Price/ton
	%	kg	M$	M$
136-90	90	5000	98.5	19.7
131-90	90	300	21.3	71.1
136-Nat	8.86	5500	2.94	0.53

Yemilab Site

- The UL is located further away from the active mining area by ~ 700 m



Experimental area of Yemilab



LSC Hall 10-ton crane

- Completion June 2023

AMoRE-II

- Shield structure done
- Late 2024, commissioning

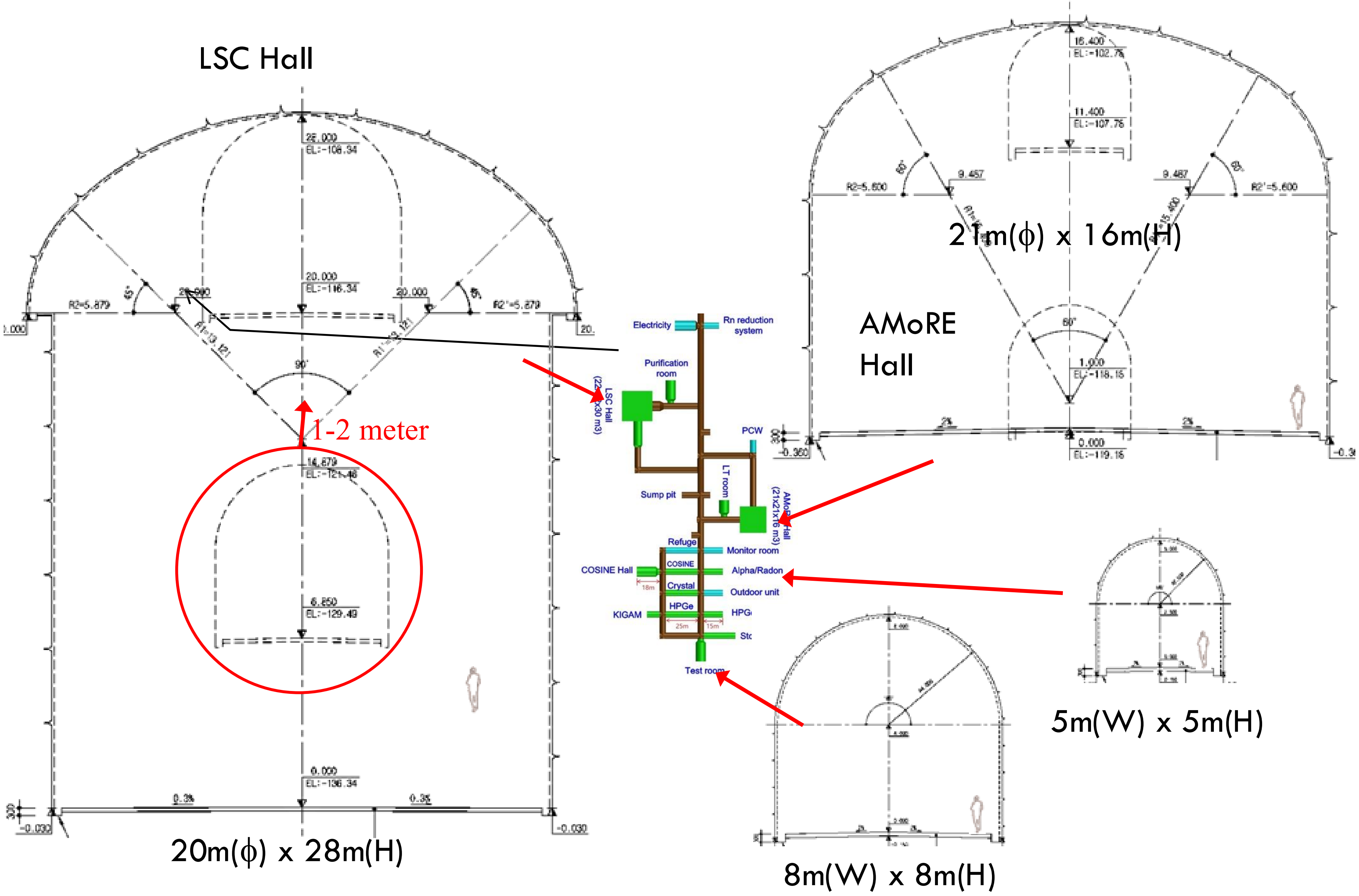
COSINE-100U

- -30℃ low-temp. room
- Moving Y2L detector to the room
- Early 2024, commissioning

HPGe

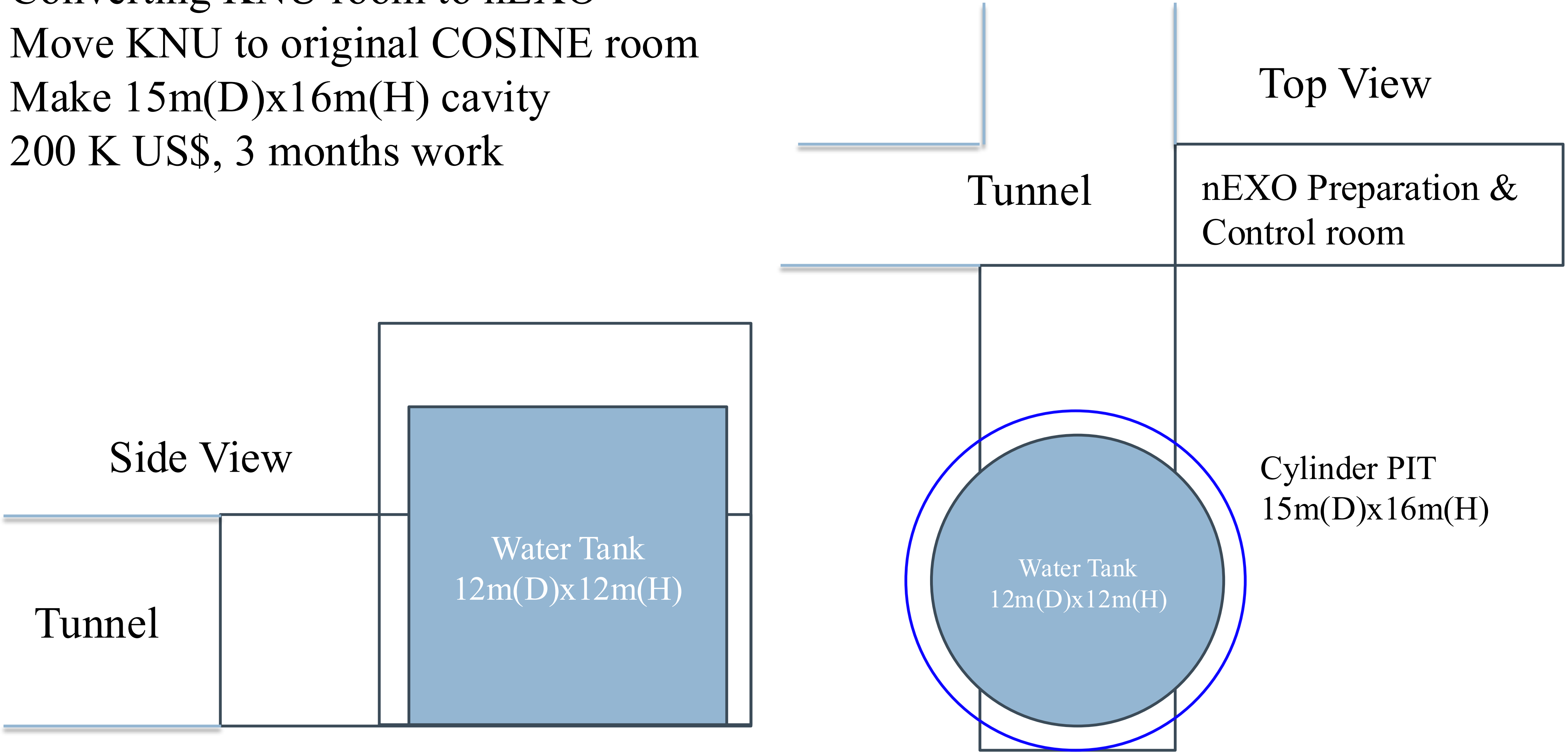
- Moving from Y2L
- Feb. 2024, start

Standard cross sections



Excavation plan for nEXO@Yemilab

- Converting KNU room to nEXO
- Move KNU to original COSINE room
- Make 15m(D)x16m(H) cavity
- 200 K US$, 3 months work



nEXO@Yemilab Consortium

- Korea
  - Universities
    - Eunil Won (Korea University), Changhyun Ha (Chung-Ang University), Seonho Choi (SNU), Hongjoo Kim(KNU), +….
  - IBS
    - Hyunsu Lee, Yeongduk Kim, Eunju Jeon, Douglas Leonard, Seungpyo Chang, Su-yeon Park, +….
- USA
  - nEXO collaboration
- + ….

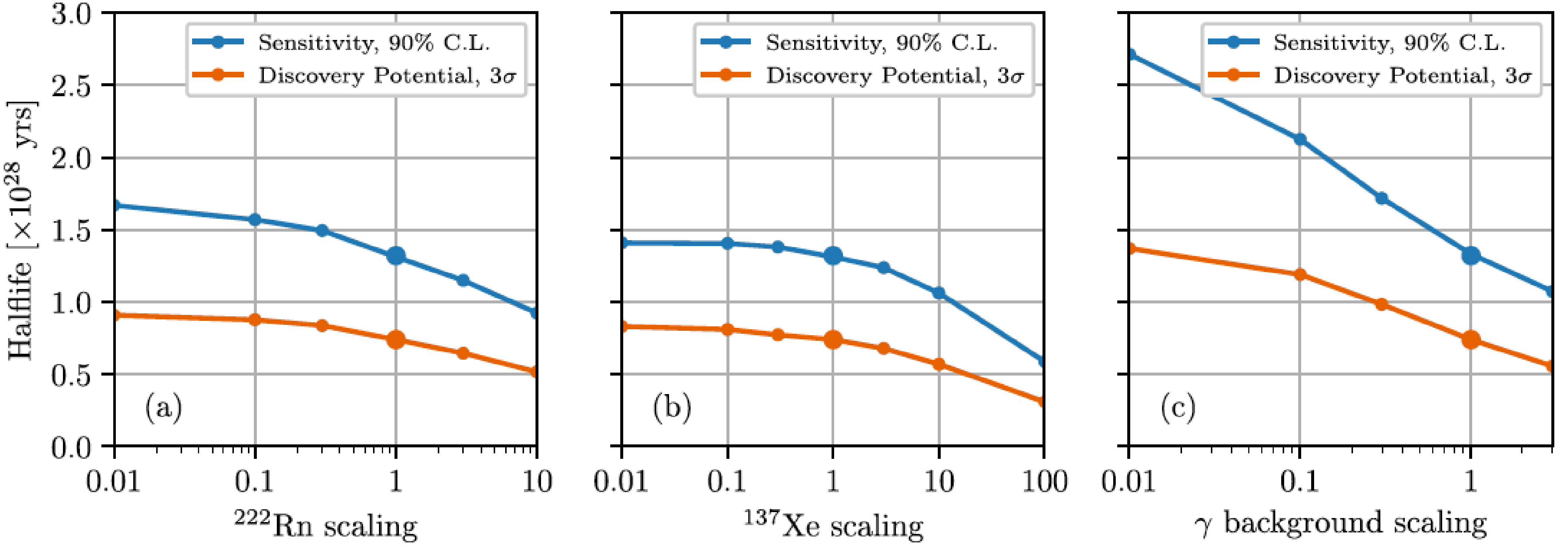
Proposal of nEXO at Yemilab

We want to propose nEXO experiment at Yemilab to reach 10 meV effective neutrino mass as an international collaboration program between USA and Korea.

What is to be done in 2026.

- October: Write a proposal (both in English & Korean)
  - Submit as an international program to the Center for International Collaboration (ICC) at IBS.
  - Write a paper for publicaiton on the background reduction studies at Yemilab.
- November: Contact to Korean Government (S&T)
  - Ask them to contact with USA Governmenrt about making this proposal as an inter-Governmental program.
  - Find out what would be counter benefit for USA.
- December: Finalize the proposal.

Summary of additional background @ Yemilab



For ^{137}Xe &
other cosmogenic isotopes