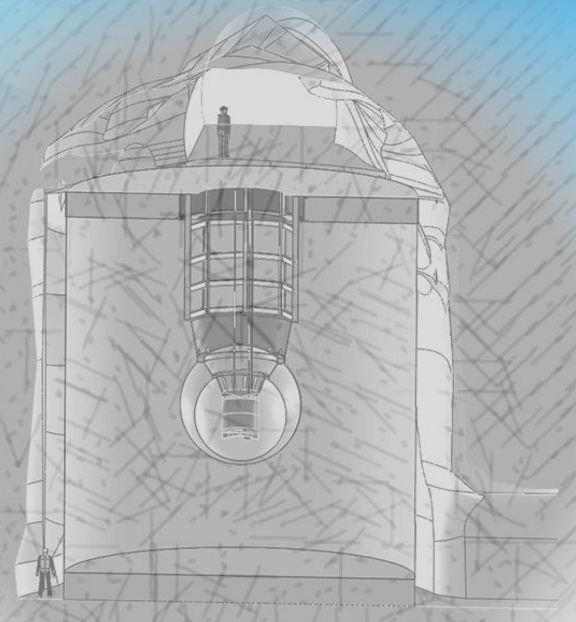


nEXO Low Background Techniques

Brian Mong

November 7, 2023

nEXO - A search for 0νββ

TPC containing 5000 kg enriched liquid xenon searching for $^{136}Xe \longrightarrow ^{136}Ba$ via 0νββ

0νββ decay is new physics B.S.M.

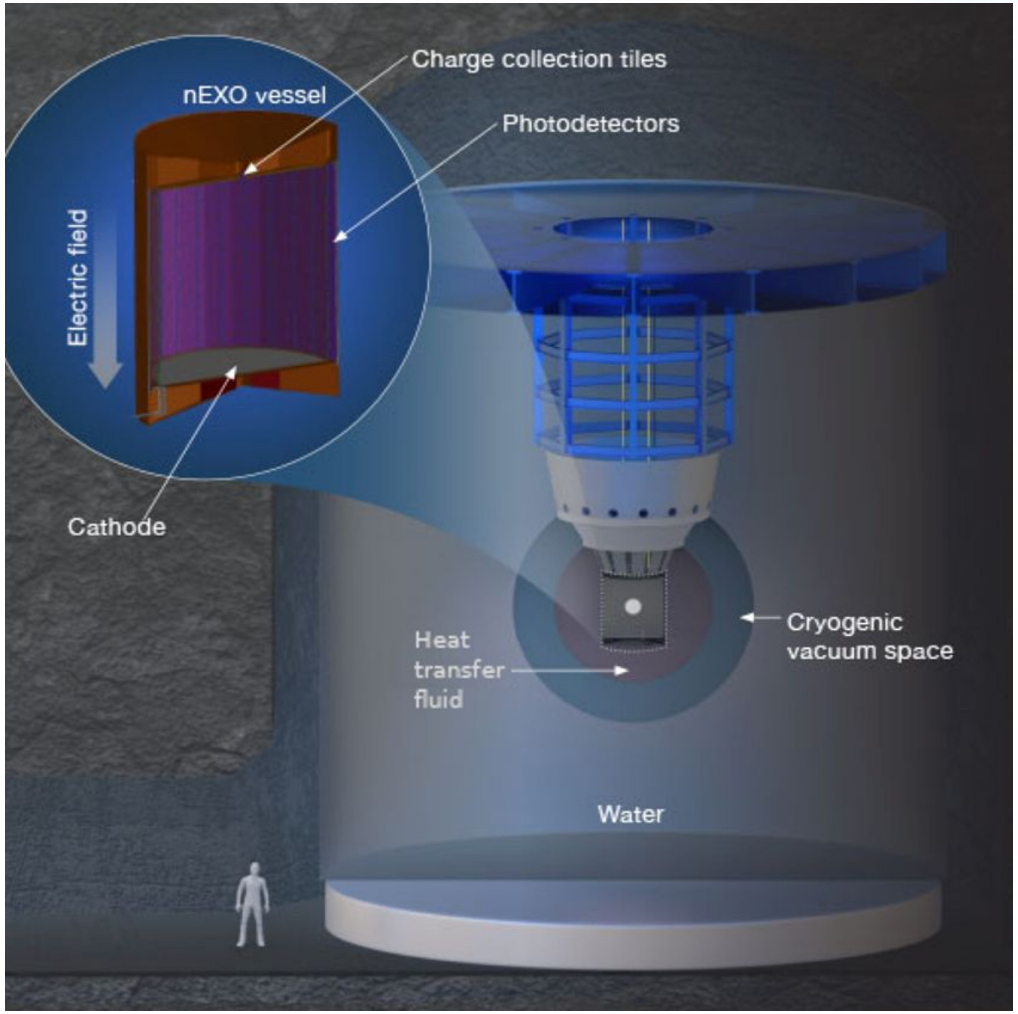
- Lepton number violation
- Majorana fermions: neutrinos are own antiparticle

0νββ is 1 (of 5) top recommendations in DOE-NP LRP

Located deep underground (at SNOLAB) to shield from cosmogenics (6 km.w.e.)

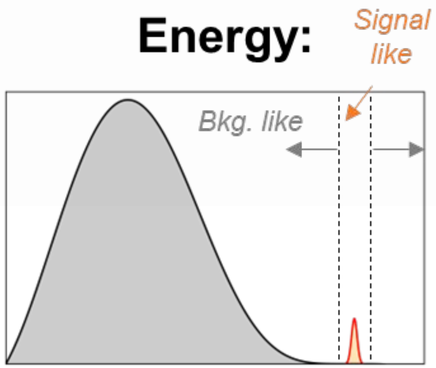
A very low and well understood background required to claim discovery

LXe is unique that the isotope can be replaced to confirm discovery

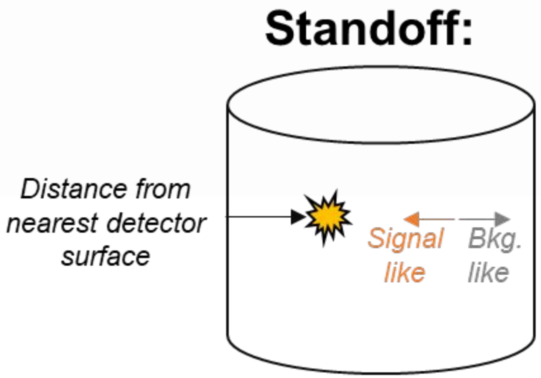


nEXO Goals

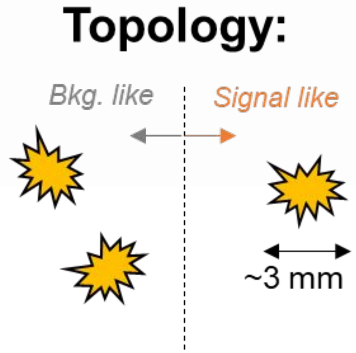
nEXO design is a multidimensional search utilizing a low background homogeneous liquid-Xe TPC sensitive to $0\nu\beta\beta$ $T_{1/2} > 10^{28}$ years



$0\nu\beta\beta$ decay of ^{136}Xe at 2.5 MeV (ROI)



uniformly distributed



single-site like event

Large homogeneous design precisely measures BGs in situ while central region is nearly BG free

(The inner 3000 kg BG-Index is better than 10^{-3} (kg yr FWHM)$^{-1}$)

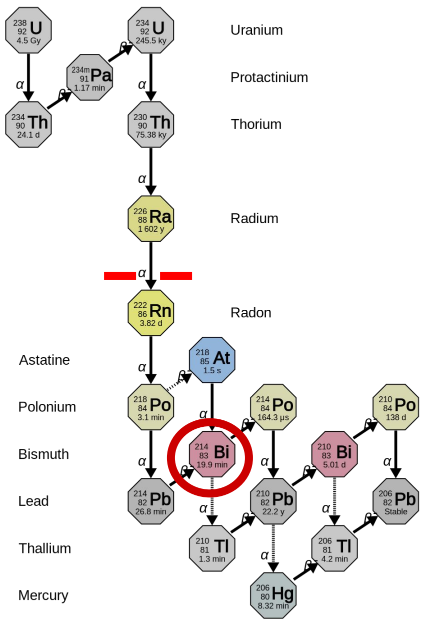
nEXO sensitivity was estimated using candidate material assays and a full Geant4 detector model (https://doi.org/10.1088/1361-6471/ac3631)

nEXO Background Sources

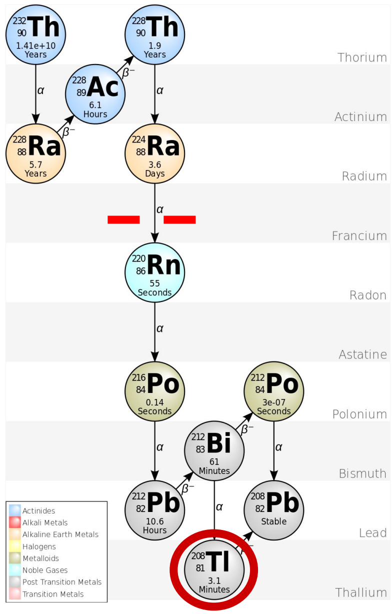
Intrinsic Material (49%)

Materials used in detector construction need to be low in gamma lines at the ROI

$^{238}U \longrightarrow {}^{214}Bi$

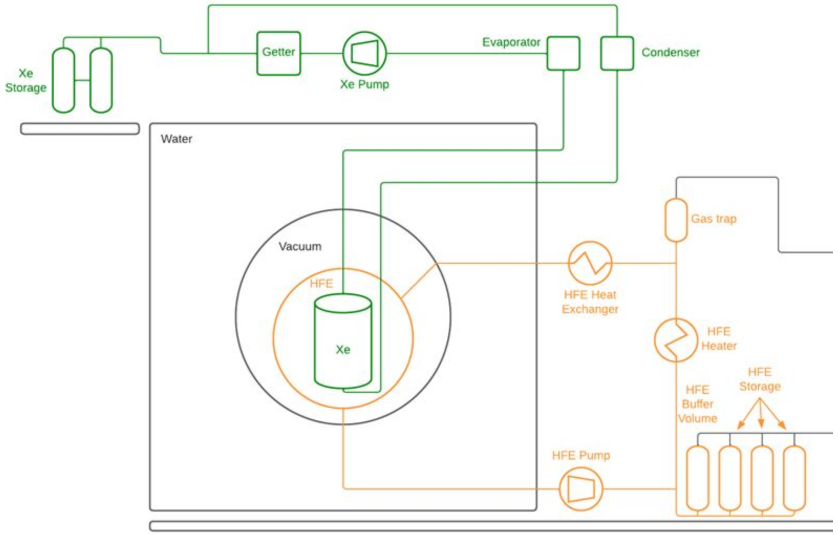


$^{232}Th \longrightarrow {}^{208}Tl$



Radon Emanation (48%)

^{222}Rn outgassing from materials in the fluid systems carried to the detector, eventually decaying to ^{214}Bi



Exposure Based (3%)

Cosmogenic: Some materials can be activated by cosmic rays that emit γ's in the ROI (or ^{136}Xe β)

Dust: Dust contains ppm ^{238}U and ^{208}Tl

α-n: Low Z nuclei can emit neutrons when hit by α particle that can activate ^{136}Xe (Q_β=4.2 MeV)

nEXO Material Screening

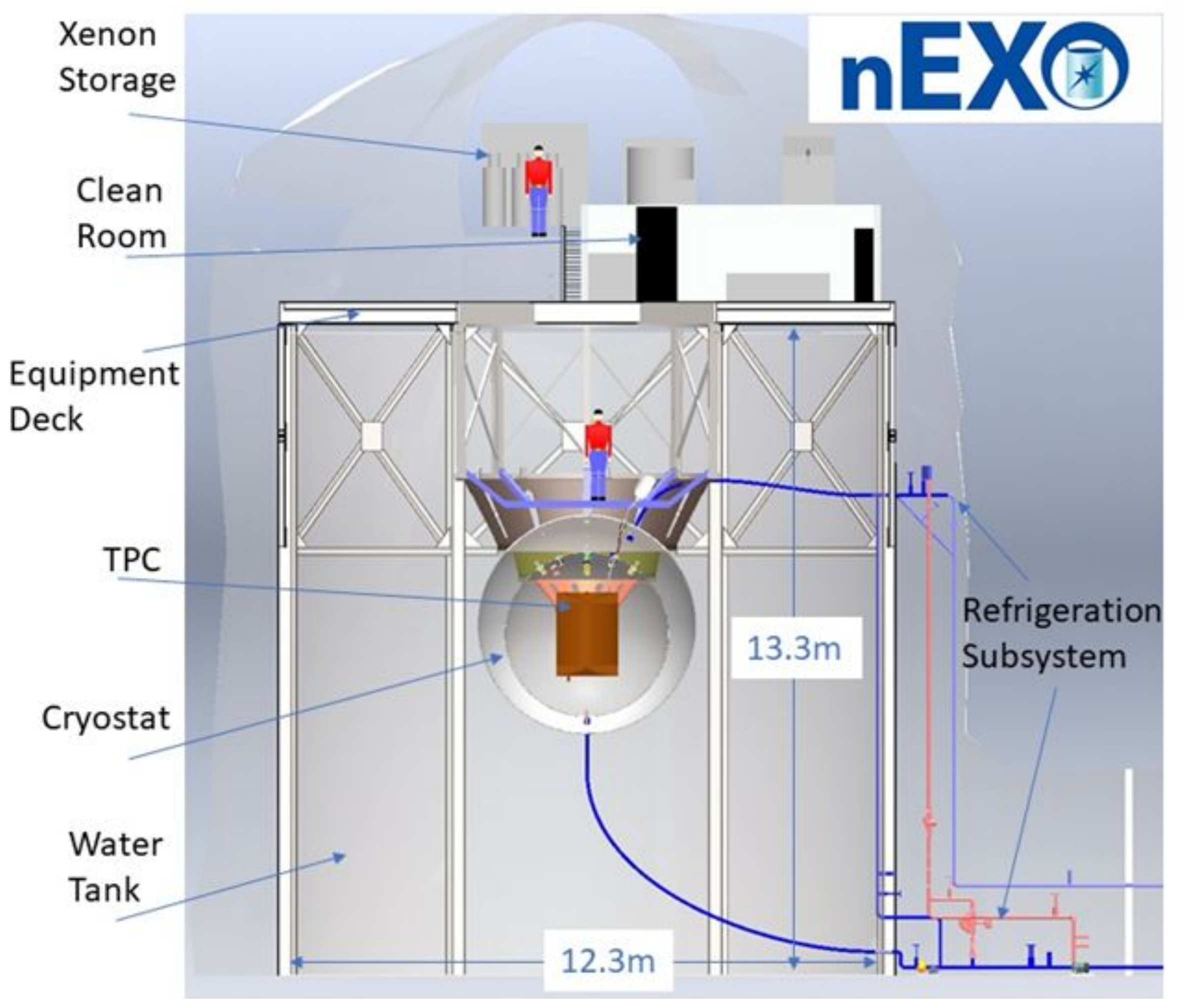
Screening is used during design and construction to build a detector with a predictable BG (and sensitivity) - before turning on.

Screen all material within the water shield for Bi/Tl (U/Th)

Assay all Xe and Refrigerant wetted surfaces for ^{222}Rn

Track exposure of all sensitive parts to dust, cosmogenics, and radon during construction.

EXO-200 accurately predicted the BG measured by the detector.
(https://doi.org/10.1103/PhysRevC.92.015503)



Material Assay Techniques

Sensitivities reported are expressed as [$^{232}Th/^{238}U$]

Direct Methods (Bi/Tl)

Ge counting on surface

[300/150 ppt]

Ge counting underground

[2.3/1.2 ppt achieved]

Indirect Methods - U/Th Heads Only *

Nuclear Activation Analysis (NAA)

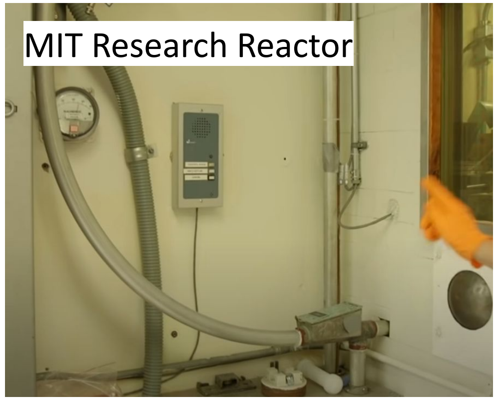
[1/1 ppt, 0.02/0.02 ppt achieved]

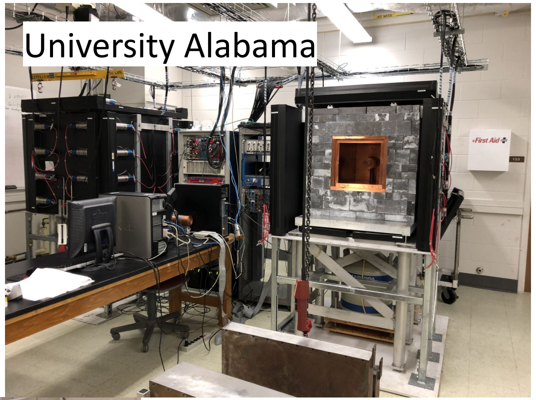
Inductively coupled plasma mass spec. (ICP-MS)

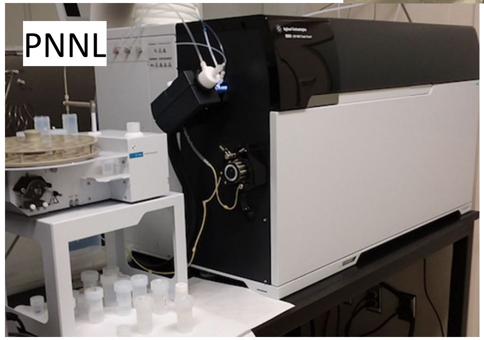
[1/1 ppt, 0.008/0.01 ppt achieved]

(https://doi.org/10.48550/arXiv.1805.11142)

*The most sensitive techniques ***assume*** chain equilibrium, an unavoidable risk that LZ, XENON, Majorana, and EXO-200 successfully managed.







Going Beyond: ICP-MS Concentration

ICP-MS assays materials digested in acids

Some materials (e.g. Cu, Pb) can be separated from the U/Th via "chemistry" to concentrate

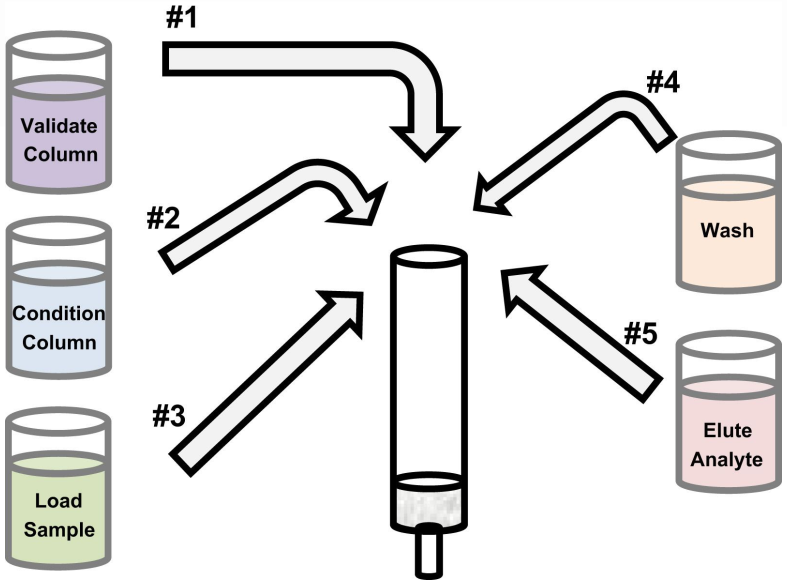
Technique developed by PNNL is use of anion exchange resins to separate $^{238}U/^{232}Th$ from Cu.

Efficiency is determined with tracers of $^{233}U/^{229}Th$.

Electroformed Copper assay <0.01 PPT $^{232}U/^{228}Th$

Demonstrated improved sensitivity by 100x in Cu

(https://doi.org/10.1016/j.nima.2014.11.052)



Flow diagram for column preparation and separation steps used for Cu/Pb

Going Beyond: Ge-Ge coincidences

Sapphire (Al_2O_3) is a desirable material to build the nEXO field cage but is difficult to assay - expensive and can't be digested for ICP-MS

Traditional NAA method achieved <8.9 ^{238}U (ppt), 6.0±1.1 ^{232}Th (ppt)

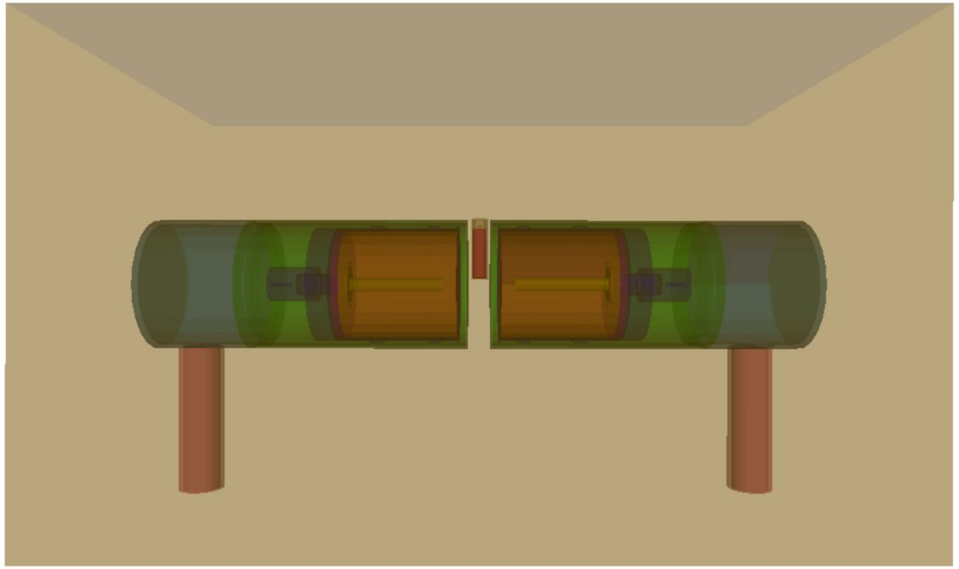
NAA ($^{238}U \rightarrow ^{239}U \rightarrow ^{239}Np$) of Sapphire activation produces side-activations (of Al) that interfere with the ^{239}Np detection

^{239}Np has two useful γ-cascades:
(106→277) keV and (106→228) keV
to exploit w/ γ-γ coincidence counting

We estimate for Sapphire a Ge-Ge counter could increase sensitivity to U-chain by **8x**

(https://doi.org/10.1088/1748-0221/16/10/P10007)

Waiting for the MIT reactor to restart to try!



Ge-Ge geometry used in the published analysis.

nEXO Radon Assay

nEXO's BG model assumes 600 atoms of ^{222}Rn in the LXe in steady state (1.2mBq)

Electrostatic Counters are primary tool we use for Rn Assay

1. Carrier gas is pumped through sample and ESC chamber continuously, mixing ^{222}Rn uniformly
2. Probability Rn decays in ESC chamber based on volumes
3. Alpha decays to +ion ~80-90% of the time in gas.
4. Ions in ESC chamber are collected to the negatively biased SiDiode, ions outside the chamber stopped by input filter
5. Subsequent decays on diode have 50% chance to enter diode and be counted

Technique developed by SNO for ^{226}Ra assay of water and others (https://doi.org/10.1016/S0168-9002(98)01230-3)

EXO-200 primarily used detectors built for SNO

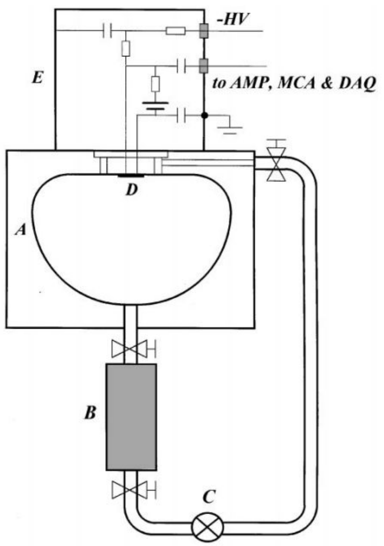
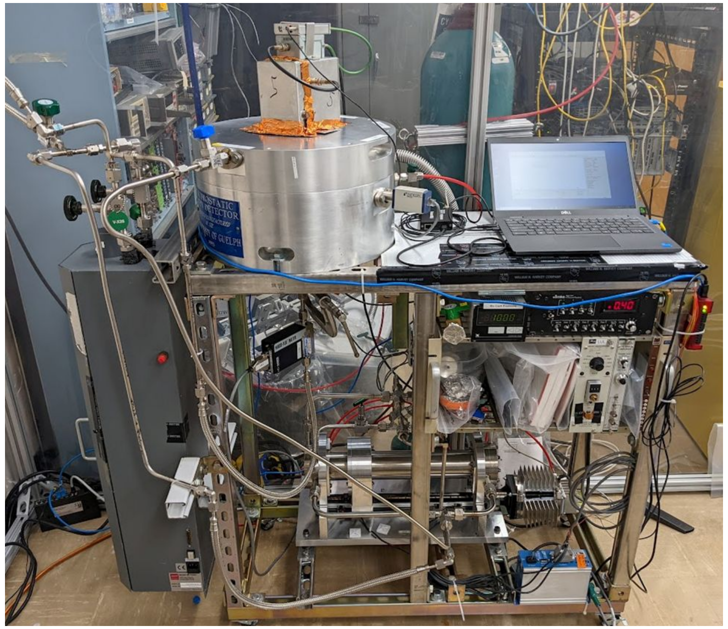


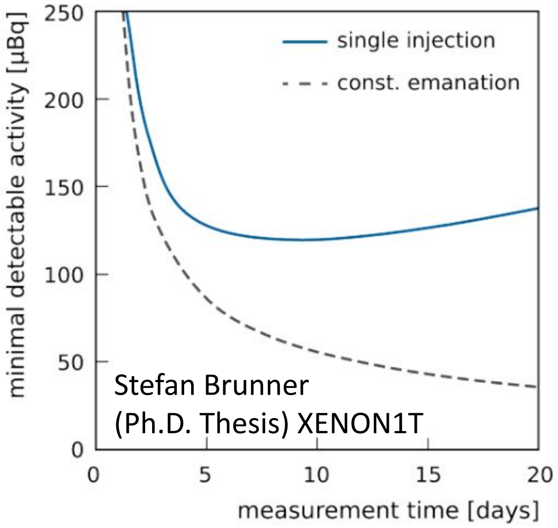
Image from: Jian-Xiong Wang, Tom C Andersen, and John J Simpson. "An electrostatic radon detector designed for water radioactivity measurements". In: NIM-A, (1999)

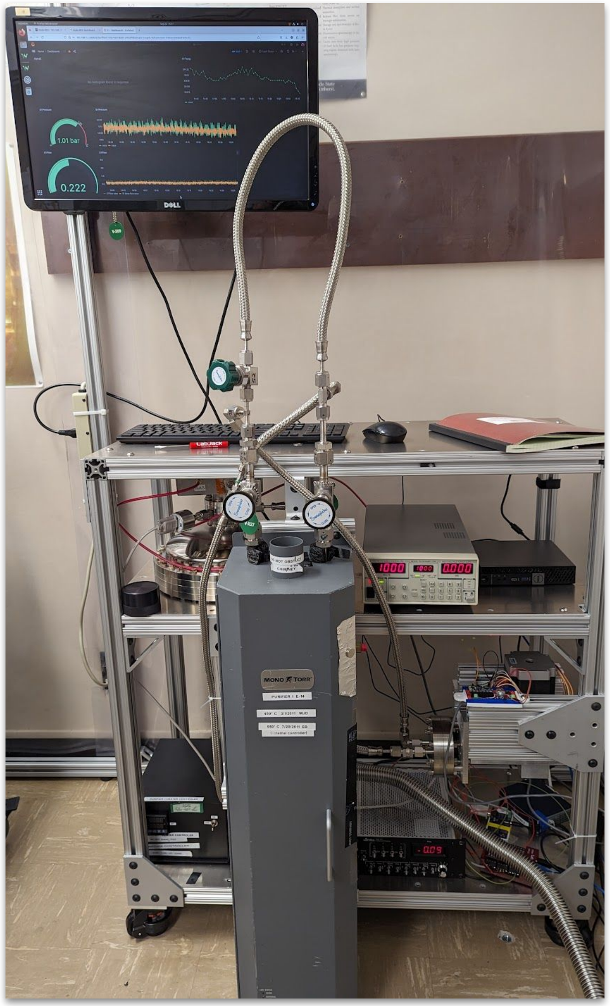


Going Beyond: High Sensitivity ESC

SLAC has developed new high sensitivity electrostatic counters (ESC):

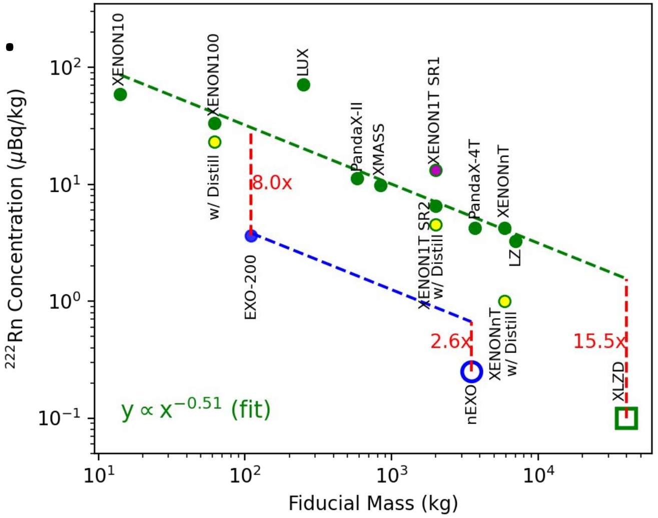
- UHV components throughout
- Custom all metal recirculation pump





Source plumbed into system, emanates continuously providing better statistics.

Sensitivities ~30μBq achieved with SLAC recirculating system.



Backup Slides

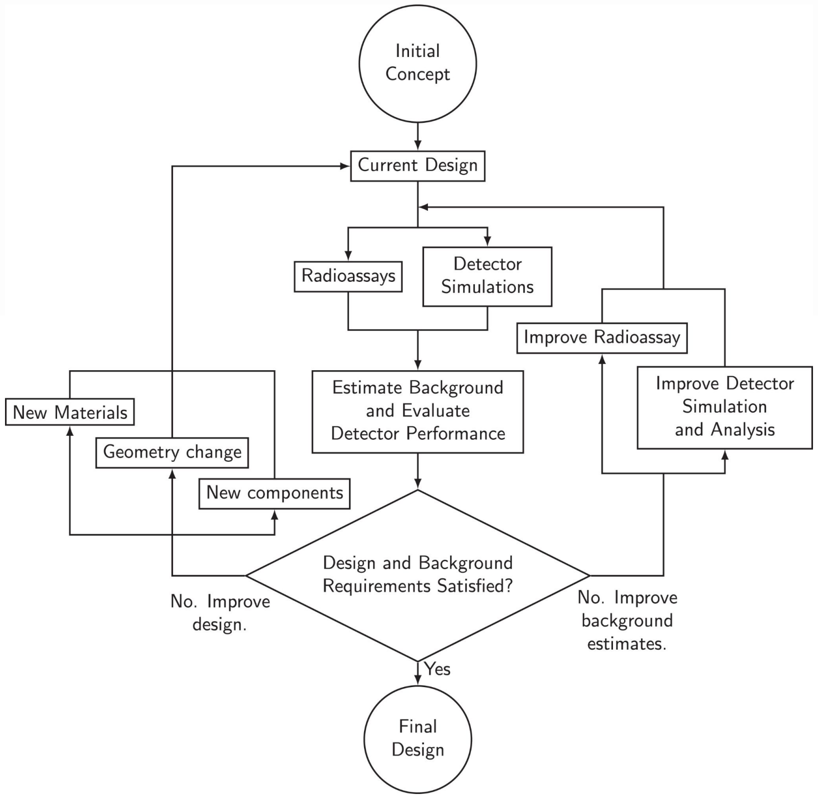
Thank You

Materials Database

A custom built web-application that:

- Inputs Geant4 detector model data
- Inputs Radioassay Data
- Outputs Background Model (Excel) with figure of merit BG to inform design decisions
- Provides a number of useful calculators:
  - Sample requirements per ANSI Z1.9-2003
  - Assay request forms to submit samples
  - BG calculator for crude estimates

(https://doi.org/10.1016/j.nima.2023.168477)

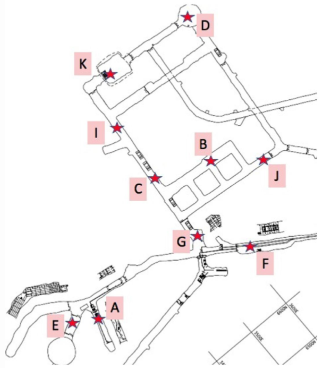


Monitoring Dust via ICP-MS

Witness vials set out in labs where sensitive parts are handled can be assayed directly for U/Th exposure.

SNOLAB, with the help of PNNL, have performed these measurements around the clean labs

(https://doi.org/10.1016/j.nima.2021.165051)



A: South Drift LBL.

B: Room 127.

C: Drift F.

D: Room 141.

E: SNO+ control room.

F: Room 104.

G: Room 123.

I: Drift F/J.

J: Room 132.

K: Room 137.

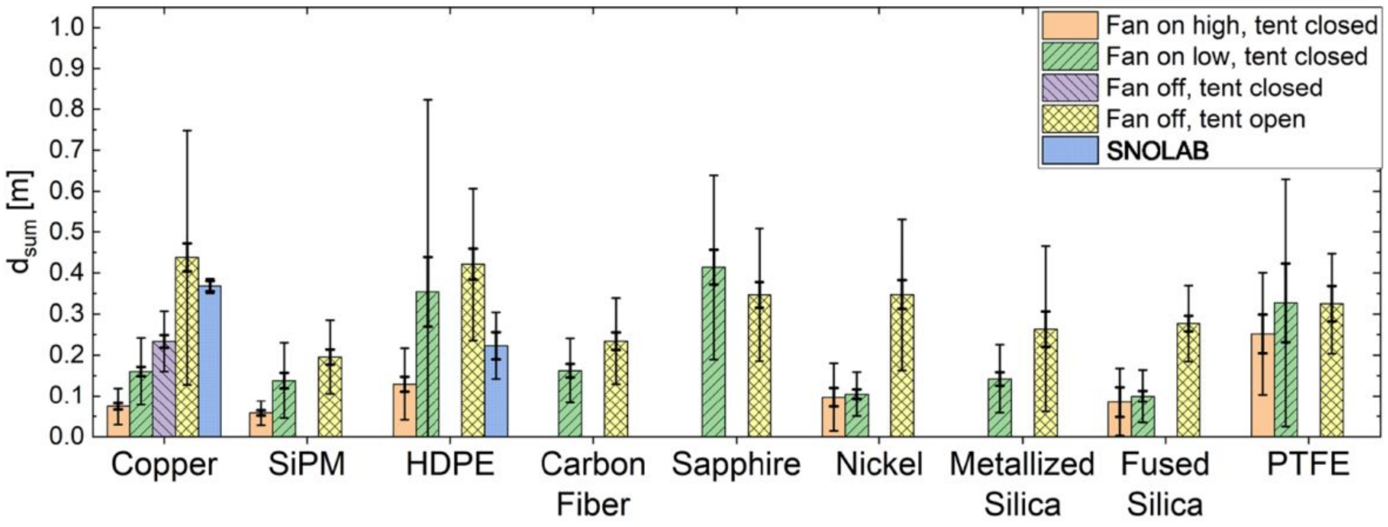
Location	Accumulation rate [μBq·day^{-1}·cm^{-2}]			
	^{40}K	^{210}Pb	^{232}Th	^{238}U
A	$(4.6\pm0.7)\cdot10^{-5}$	$(3.2\pm1.5)\cdot10^{-7}$	$(2.0\pm0.8)\cdot10^{-7}$	$(5.9\pm1.4)\cdot10^{-7}$
B	$(1.3\pm0.8)\cdot10^{-4}$	$(2\pm3)\cdot10^{-8}$	$(1.3\pm1.1)\cdot10^{-6}$	$(2.6\pm1.3)\cdot10^{-6}$
C	$(1.1\pm0.5)\cdot10^{-5}$	$(2.4\pm1.4)\cdot10^{-10}$	$(1.8\pm1.3)\cdot10^{-7}$	$(4\pm2)\cdot10^{-7}$
D	$(1.3\pm1.4)\cdot10^{-5}$	$(2\pm3)\cdot10^{-9}$	$(5.5\pm0.8)\cdot10^{-8}$	$(2\pm3)\cdot10^{-7}$
E	$(1.6\pm0.5)\cdot10^{-4}$	$(1.9\pm1.4)\cdot10^{-8}$	$(3.2\pm1.1)\cdot10^{-7}$	$(1.5\pm0.5)\cdot10^{-6}$
F	$(2.9\pm0.4)\cdot10^{-3}$	$(2.9\pm1.3)\cdot10^{-7}$	$(1.3\pm0.2)\cdot10^{-4}$	$(2.5\pm0.6)\cdot10^{-4}$
G	$(4.9\pm0.8)\cdot10^{-5}$	$(5\pm2)\cdot10^{-9}$	$(3.5\pm0.2)\cdot10^{-6}$	$(5.8\pm1.3)\cdot10^{-6}$
H	$(1.83\pm0.06)\cdot10^{-3}$	$(3.0\pm0.5)\cdot10^{-8}$	$(1.3\pm0.5)\cdot10^{-4}$	$(8.0\pm0.6)\cdot10^{-5}$
I	$(8\pm3)\cdot10^{-5}$	$(1.9\pm1.1)\cdot10^{-9}$	$(2.1\pm0.8)\cdot10^{-6}$	$(6\pm4)\cdot10^{-7}$
J	$(4.1\pm1.6)\cdot10^{-4}$	$(9.9\pm0.1)\cdot10^{-8}$	$(2.4\pm1.5)\cdot10^{-5}$	$(1.8\pm1.1)\cdot10^{-5}$
K	$(2\pm3)\cdot10^{-5}$	$(6\pm2)\cdot10^{-10}$	$(9\pm4)\cdot10^{-7}$	$(6\pm3)\cdot10^{-7}$

Radon daughter plateout

Studied the plateout of ^{218}Po and ^{214}Po onto surfaces as ^{210}Po ($T_{1/2}$=22yr) can create alphas (5.4MeV) over the course of a experiment

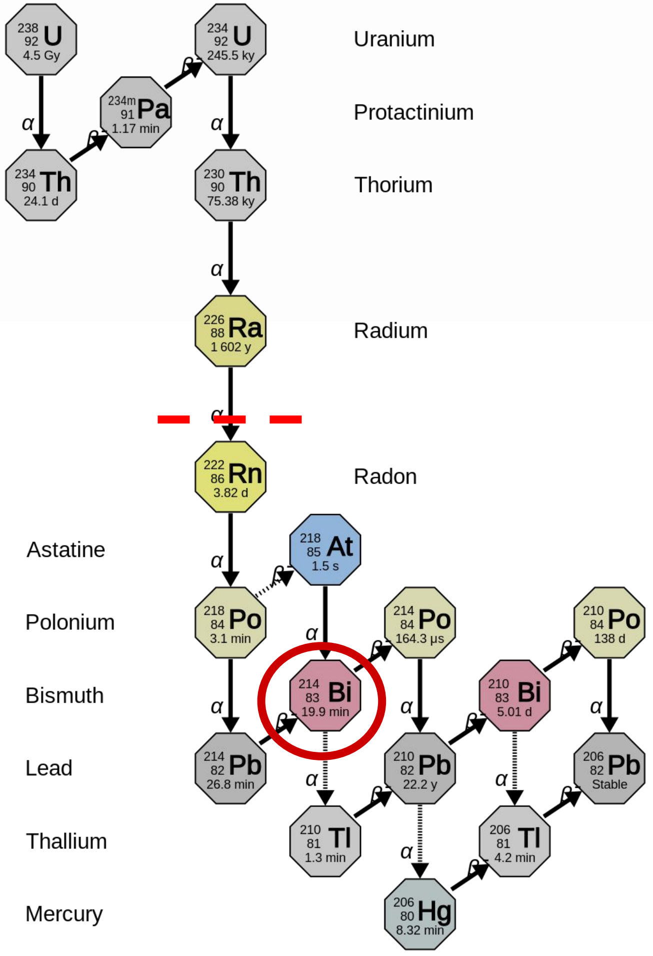
Alphas can liberate neutrons of low Z materials like Fluorine in the HFE

Plateout distance (d_{sum}) relates the Rn concentration (Bq/m^3) to to the surface concentration (Bq/m^2)



https://doi.org/10.1103/PhysRevC.107.065802

nEXO Intrinsic Materials



^{238}U and ^{232}Th are found in trace amounts in all terrestrial materials at the ppm to ppb levels.

^{214}Bi and ^{208}Tl contain gamma lines that occasionally create photoelectron (S.S.) events in LXe at the 0νββ energy

nEXO to be built from materials extremely low in ^{214}Bi and ^{208}Tl to maximize sensitivity to 0νββ