Kiloton-scale xenon detectors for neutrinoless double beta decay

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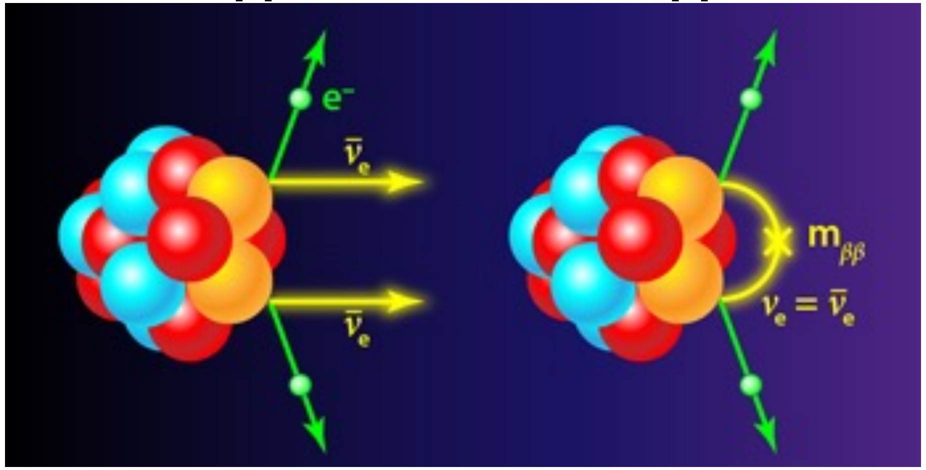
Wright Laboratory

Yale

Neutrino masses and 0νββ

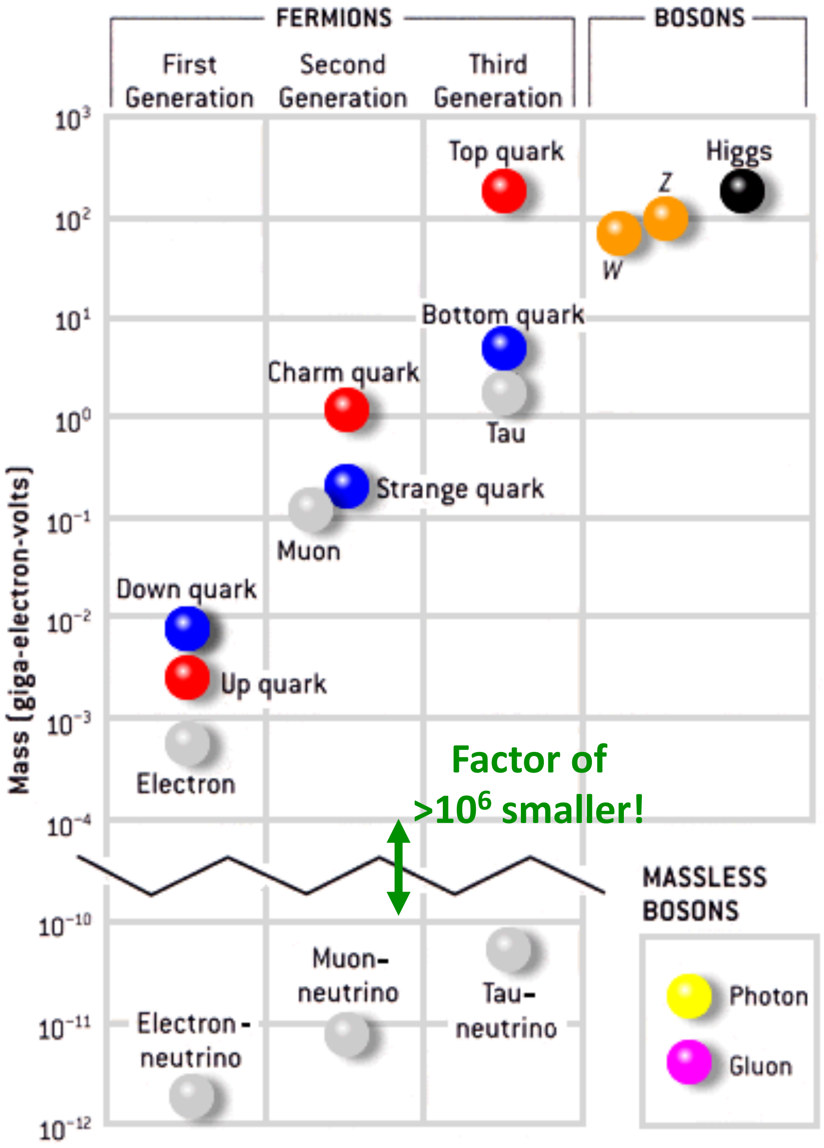
- The most direct evidence for physics beyond the Standard Model comes from neutrinos
- Oscillation experiments indicate neutrinos have small, non-zero masses
- Observation of 0νββ would provide:
  - A beyond the Standard Model, lepton-number violating process
  - Imply neutrinos are Majorana particles ($\nu = \bar{\nu}$)
  - Constrain the absolute neutrino mass scale

2νββ: **0νββ:**



https://physics.aps.org/articles/v11/30

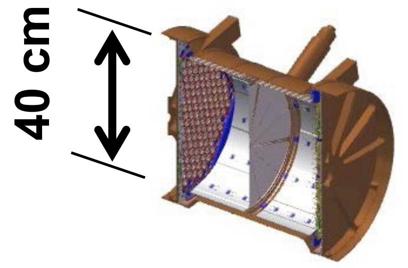
Particle masses in the Standard Model:



LXe TPCs for 0νββ

- Liquid xenon time projection chambers provide an extremely sensitive, and scalable technology for search for 0νββ
  - Provides both the source (^{136}Xe) and detector for the decay

EXO-200

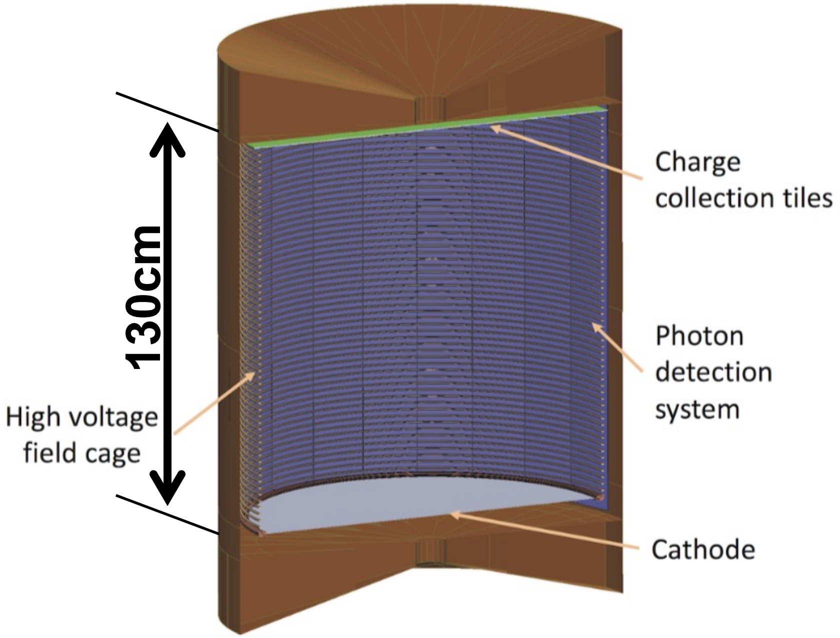


~150 kg ^{136}Xe

2011 - 2018

$T_{1/2}$ = 0.5 x 10^{26} yr

nEXO

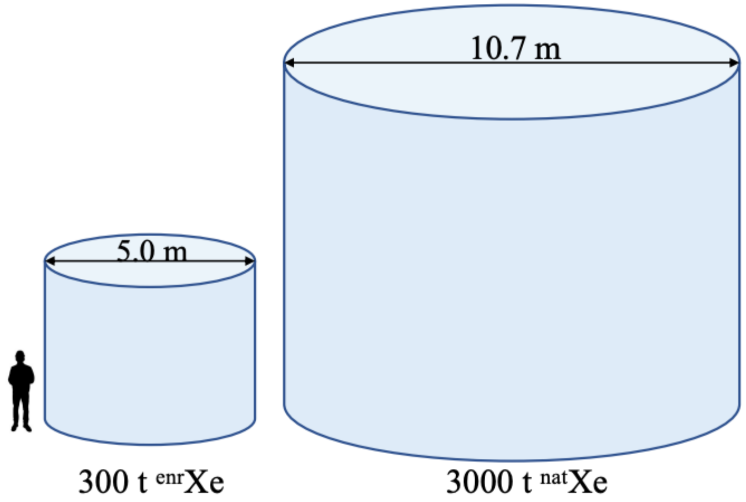


~5000 kg ^{136}Xe

Operation in ~2028

$T_{1/2}$ = 1.4 x 10^{28} yr

Future kton scale detector (?)



~300 t ^{136}Xe

Operation in ?

$T_{1/2}$ = 10^{30} yr

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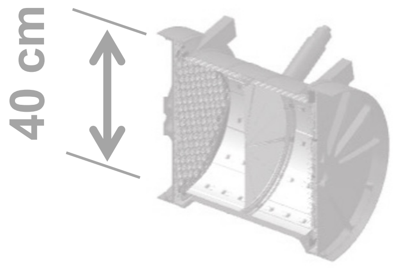

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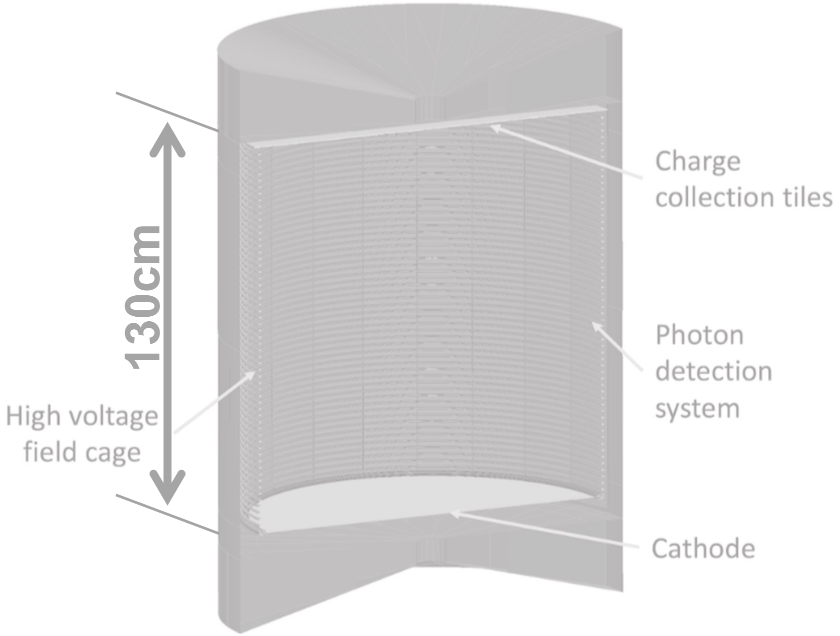

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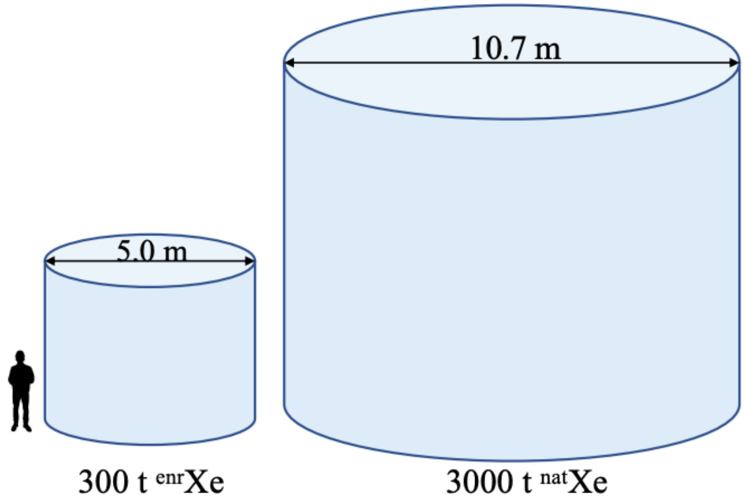
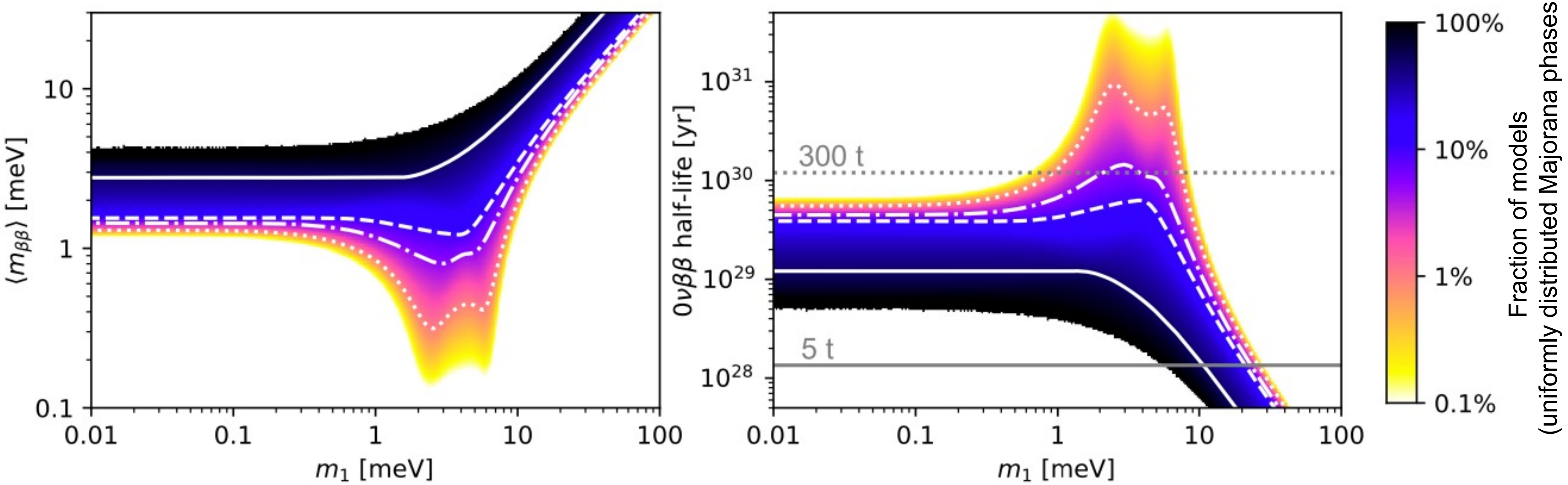


~300 t ^{136}Xe
Operation in ?
$T_{1/2}$ = 10^{30} yr

Beyond the ton scale

- While nEXO has substantially discovery potential, if it does not observe 0vββ, larger detectors will be needed to fully explore the parameter space
- Reaching half-life sensitivity of 10^{30} yr would allow sensitivity to the vast majority of remaining parameter space in the normal hierarchy

Allowed 0vββ parameter space (normal hierarchy):



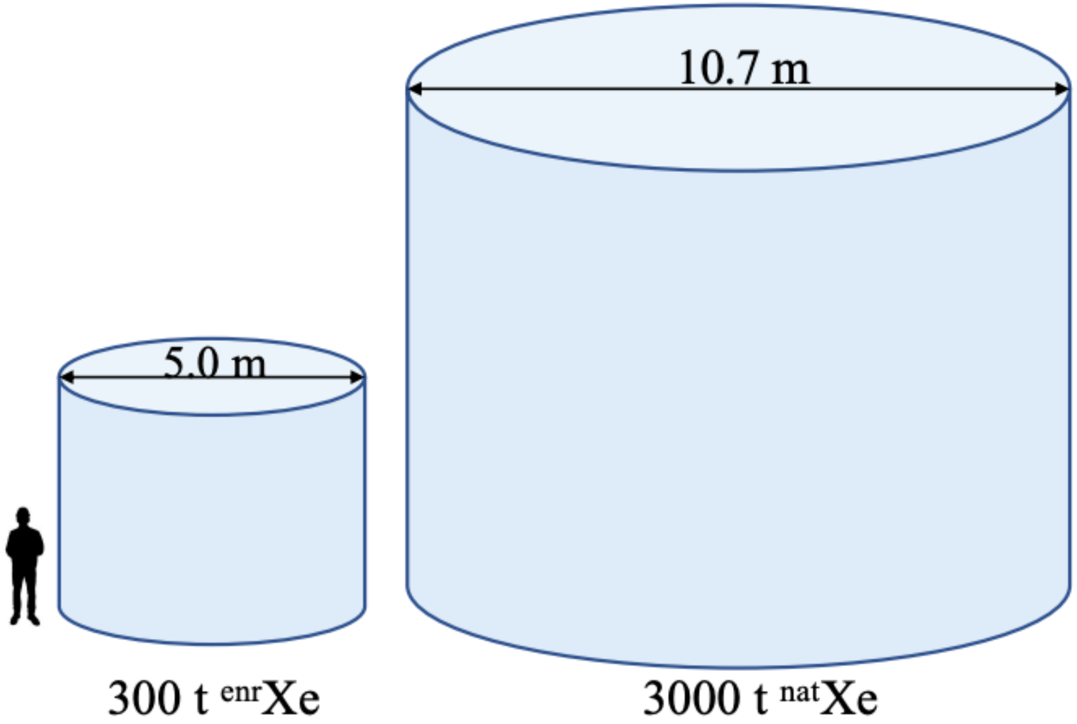
A. Avasthi et al., "Kiloton-scale xenon detectors for neutrinoless double beta decay and other new physics searches," Phys. Rev. D 104, 112007 (2021)

0νββ signal

- At 10^{30} year half-life, the rate of decays is:

$$R = 0.3 \text{ decays/yr} \left(\frac{m_{136}}{100 \text{ t}}\right) \left(\frac{10^{30} \text{ yr}}{T_{1/2}}\right)$$
$$= 2.3 \text{ decays/(kt yr FWHM)} \left(\frac{10^{30} \text{ yr}}{T_{1/2}}\right)$$

Schematic of kton-scale LXe detector size:



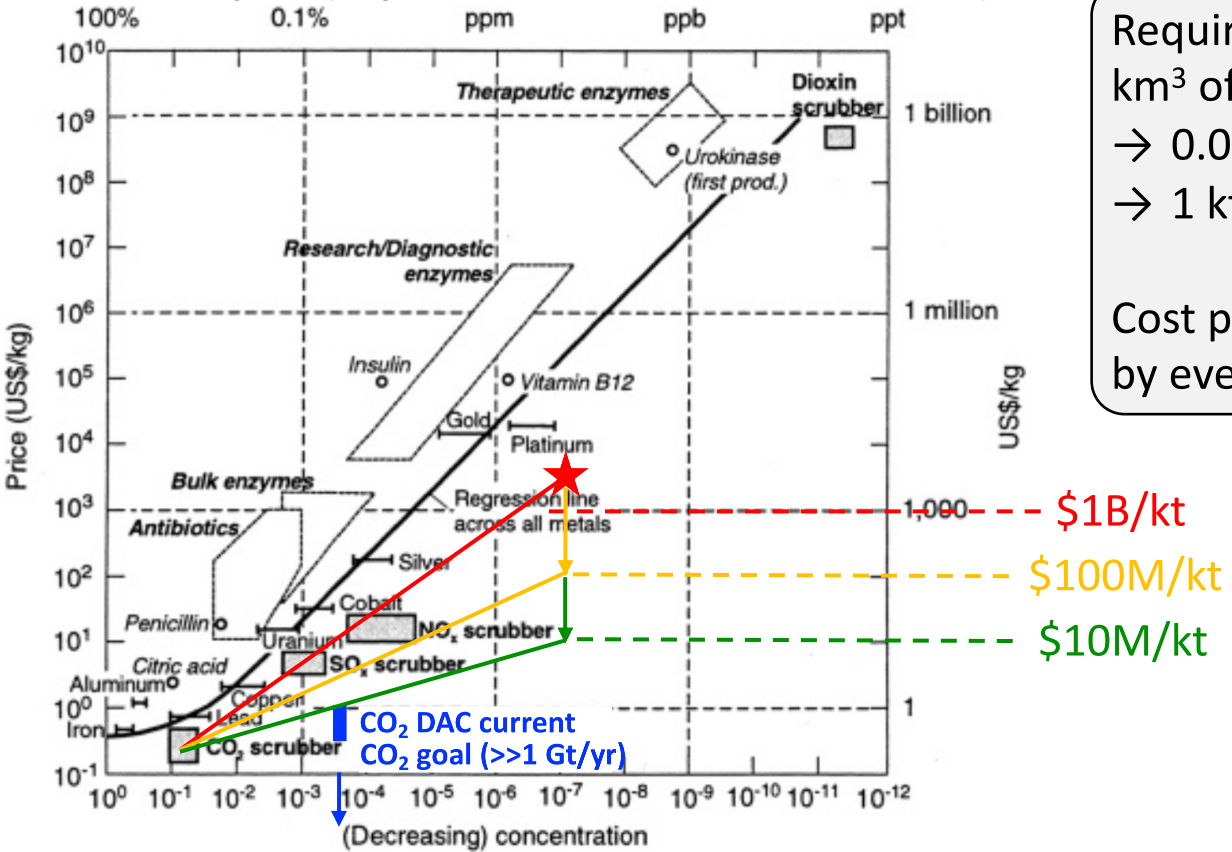
- Even a background free, perfectly efficient detector would require a kton yr exposure of ^{136}Xe to see on average 3 events
- Realistic backgrounds, fiducialization require ~3x larger mass (see following slides)
- LAr TPCs of required size already exist, with 14 kt DUNE modules under development
- Gas TPC (15 bar) with 3 kt ^{nat}Xe would be 17 m radius square cylinder
  - Might be possible for the cavern itself to provide the pressure vessel

kton Xe acquisition

- Xe is present in the earth's atmosphere at 87 ppb (~0.2 Gt total)
- Current production is parasitic process in air liquefaction for steel industry
  - Inelastic supply limited to 50-100 tons per year globally
- Direct air capture (DAC) could be both more efficient and substantially expand supply

Basic Oxygen Furnace (steel industry):

Sherwood plot (separation cost vs concentration):



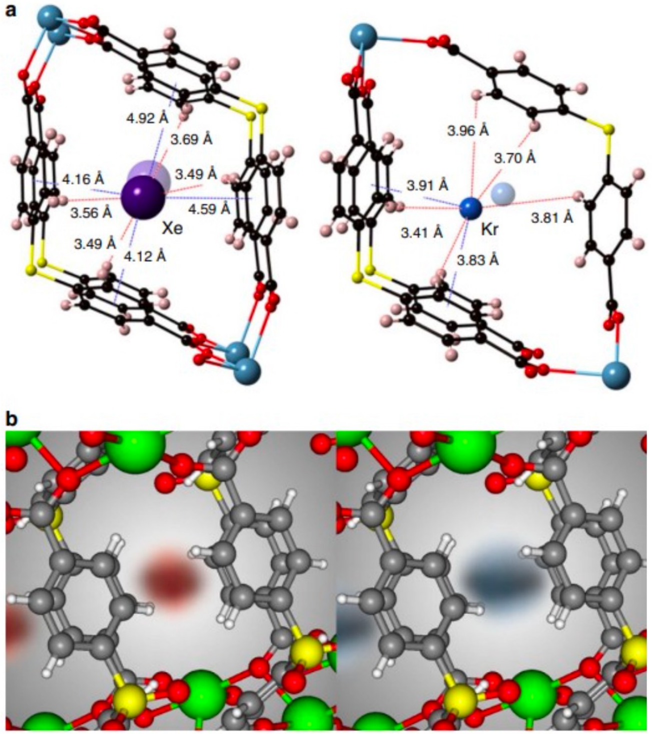
Requires processing 8000 km^3 of air:
→ 0.004 Gt CO_2 (400 ppm)
→ 1 kt Xe (90 ppb)

Cost prohibitive to compress by even a few PSI!

Xe adsorption

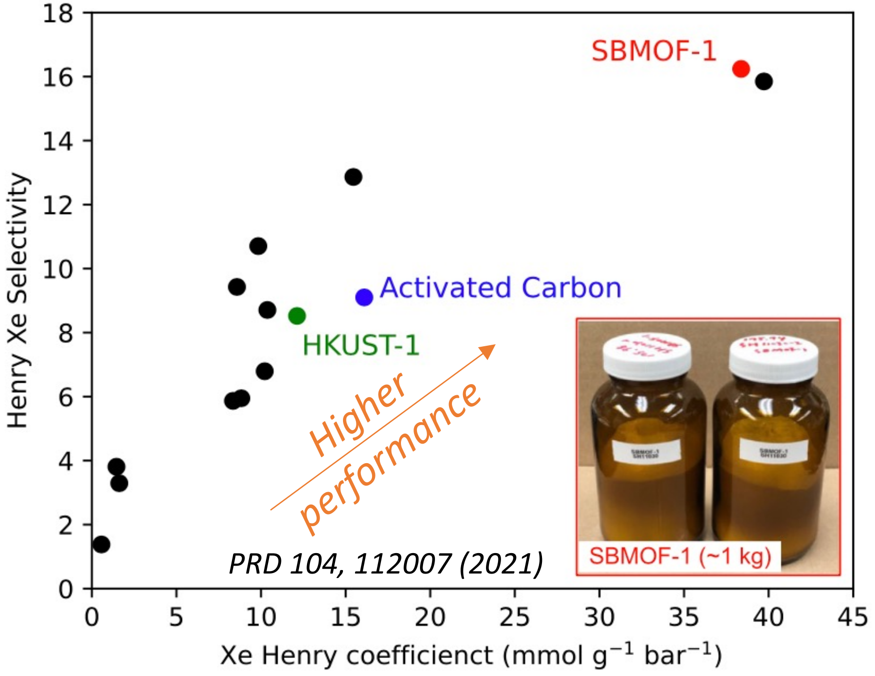
- Work at LLNL is underway to demonstrate DAC of Xe using advanced adsorbent materials (Mike Heffner and Samuele Sangiorgio), with a goal of eventually scaling to a pilot plant
- Concept is based on thermal swing adsorption using structured adsorbent bed (SBMOF-1)
- Laminates with SBMOF-1 have been produced, and tests are underway towards initial proof-of-principle demonstration

Metal-organic framework (MOF) adsorbent for Xe:



*Banerjee et al. "Metal–organic framework with optimally selective xenon adsorption and separation," Nat Commun **7**, 11831 (2016)*

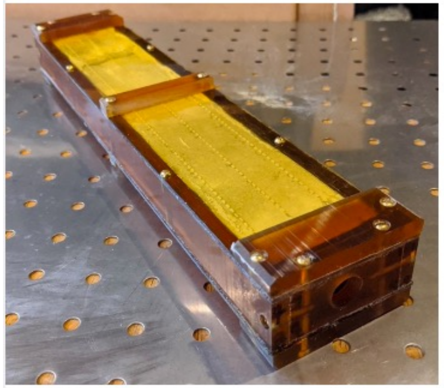
Selectivity vs Henry coefficient for various materials:



Structured adsorbent bed prototypes (LLNL):

Large area sample of SBMOF-1 coated adsorbent foil

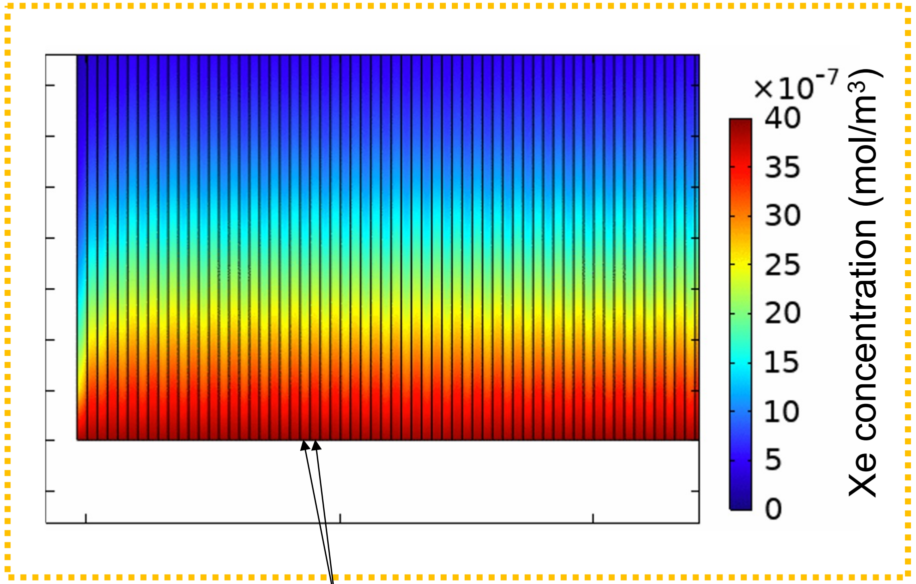
Laminate adsorbent bed



Xe adsorption (simulation)

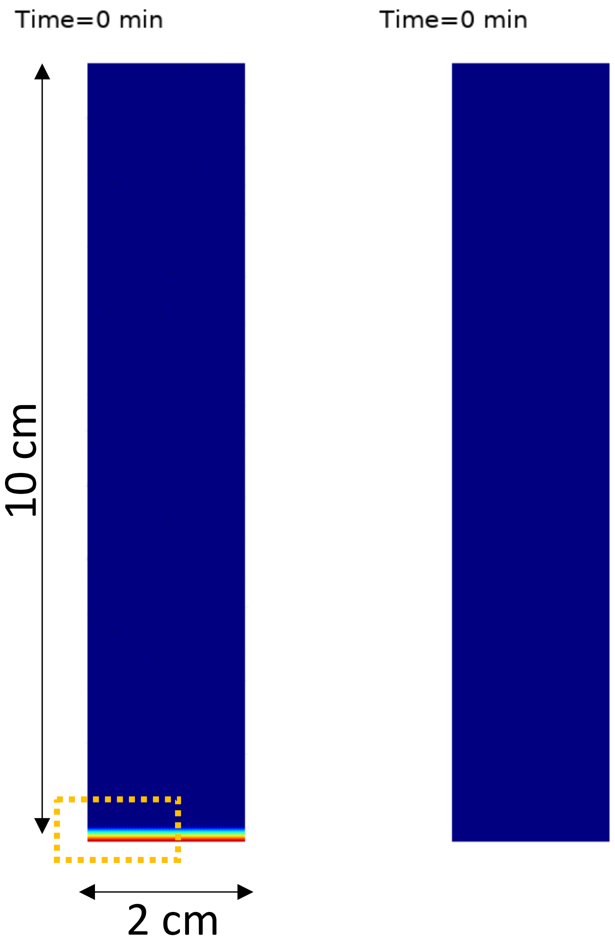
- Ongoing work at Yale to simulate adsorption in structured bed and optimize bed design, process parameters, and cycle (concentrations, temperature, adsorption/desorption)
  - Detailed model aims to inform the ultimate efficiency (and cost) that are achievable, validated with ongoing proof-of-principle scale laboratory tests

Zoom of concentration vs position (*t* = 6 s):

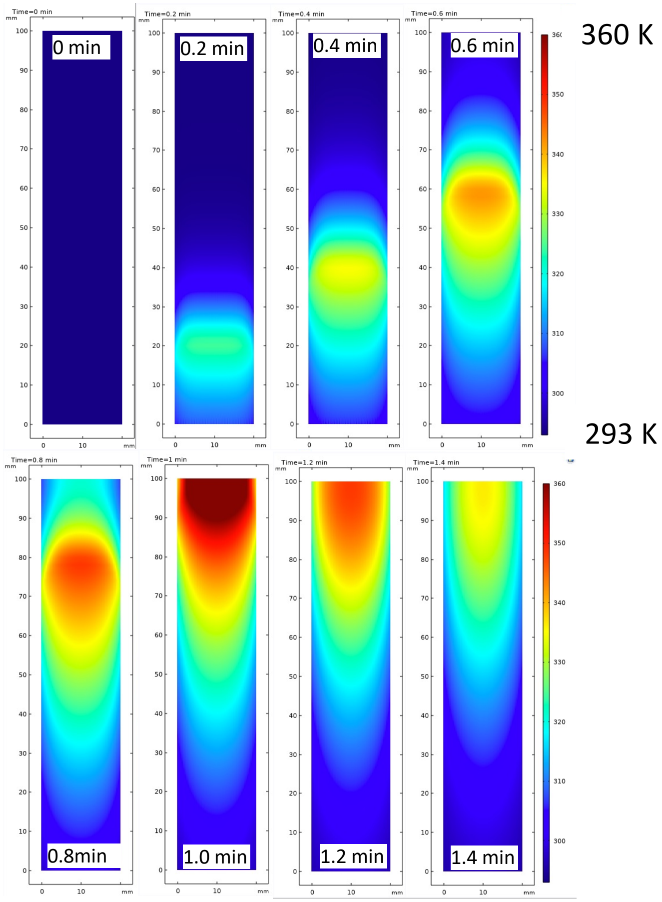


0.2 mm alternating adsorbent sheets and slots

Concentration **Temperature**



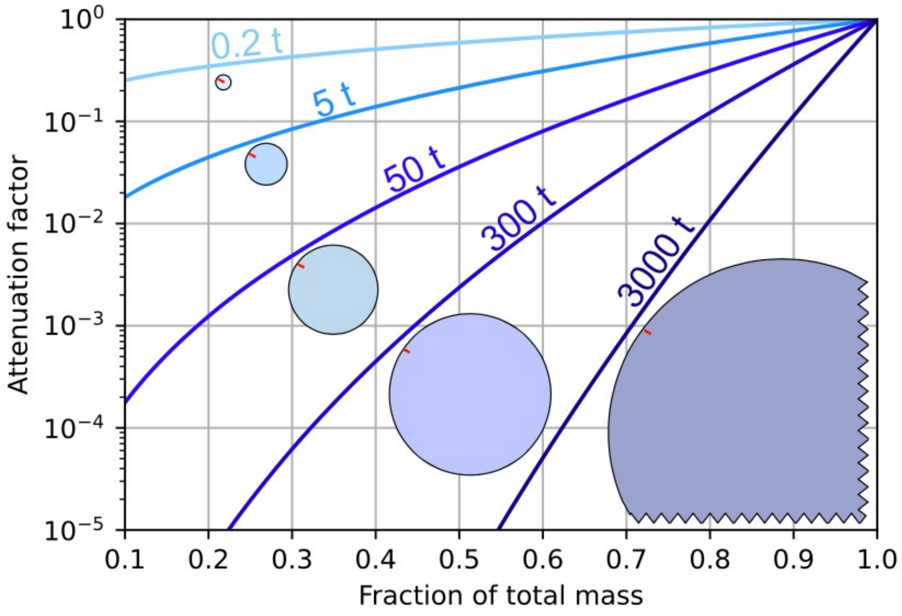
Temperature profile vs time:



Backgrounds

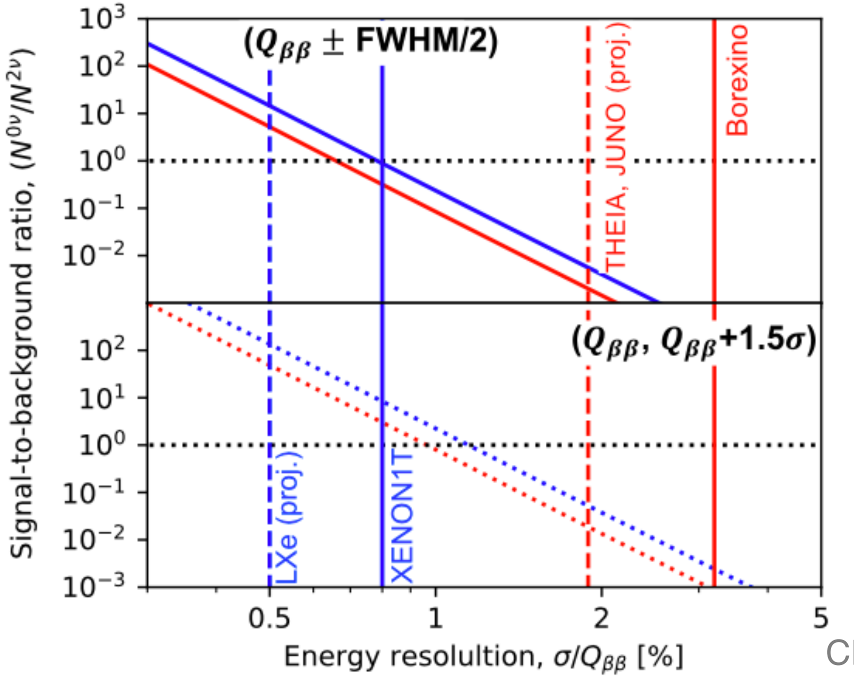
- External backgrounds (including ^{222}Rn daughters) become subdominant at kton scale
- Instead, 2νββ and solar ν are the primary concerns:
  - Rejection of 2νββ backgrounds requires $\lesssim 0.5\%$ energy resolution
  - Avoiding solar ν background requires eliminating materials other than the isotope of interest
- In contrast to other technologies for kton-scale detectors, gas or liquid phase Xe TPCs meet both of these requirements!

Attenuation of external backgrounds vs size:

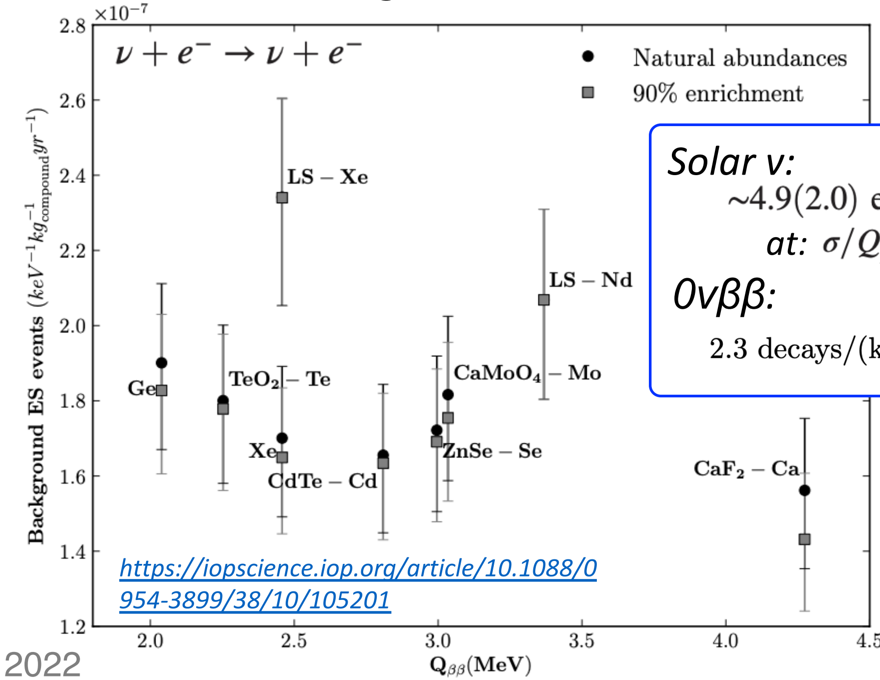


Length for 10x reduction

2νββ/0νββ signal-to-background ratio:



Solar ν background rate vs material:



https://iopscience.iop.org/article/10.1088/0954-3899/38/10/105201

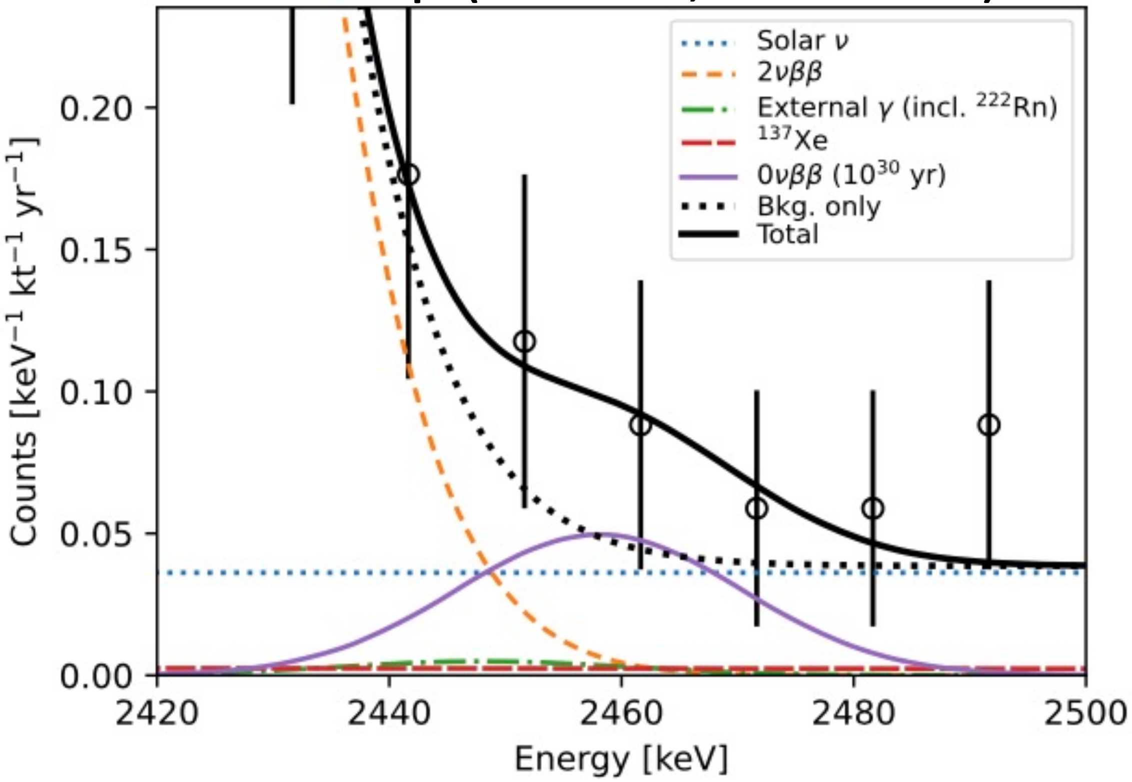
Solar ν:
~$4.9(2.0)$ evts/[kt yr FWHM]
at: $\sigma/Q_{\beta\beta} = 0.5\%$ (0.2%)

0νββ:
$$2.3 \text{ decays/(kt yr FWHM)} \left(\frac{10^{30}\text{ yr}}{T_{1/2}}\right)$$

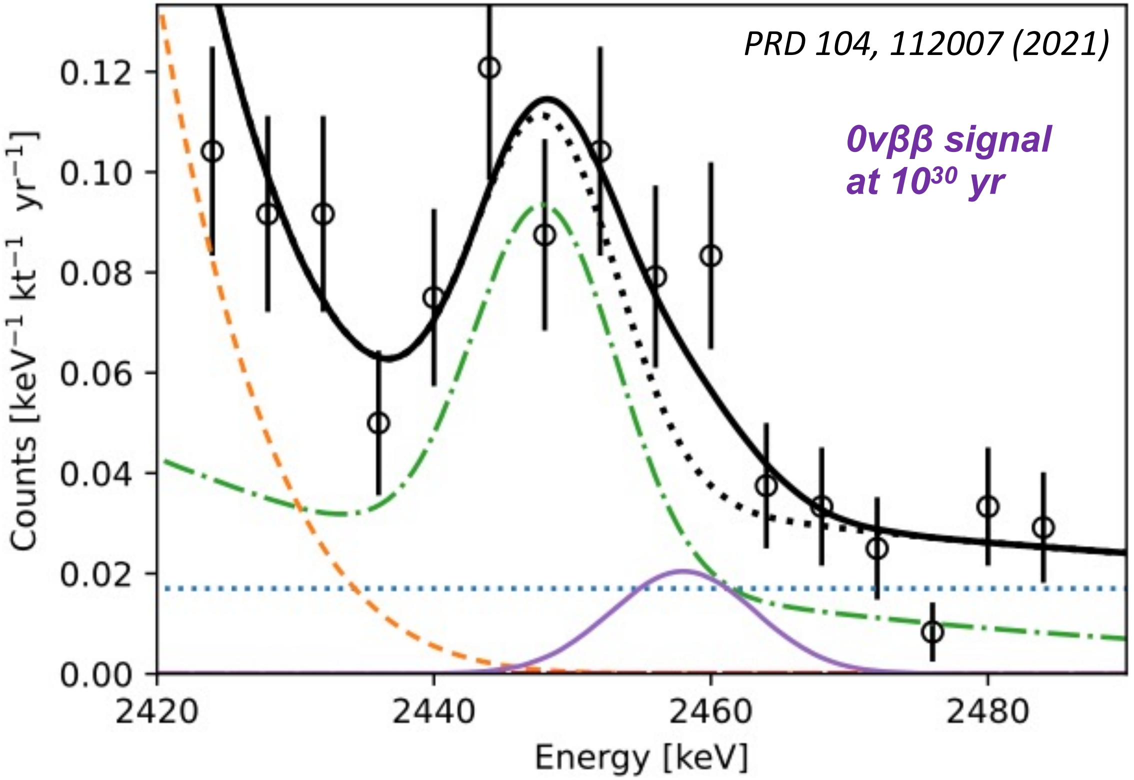
Gas/liquid concepts

- Concepts for either gas or liquid phase kton-scale TPCs were simulated, with sensitivity at the 10^{30} yr scale
- Gas phase avoids solar ν backgrounds due to better energy resolution and β vs $\beta\beta$ rejection, at the cost of less self-shielding (more difficult external backgrounds)
- Liquid phase eliminates external backgrounds, but solar ν are challenging without enrichment

LXe concept (300 t ^{136}Xe, 90% enriched):



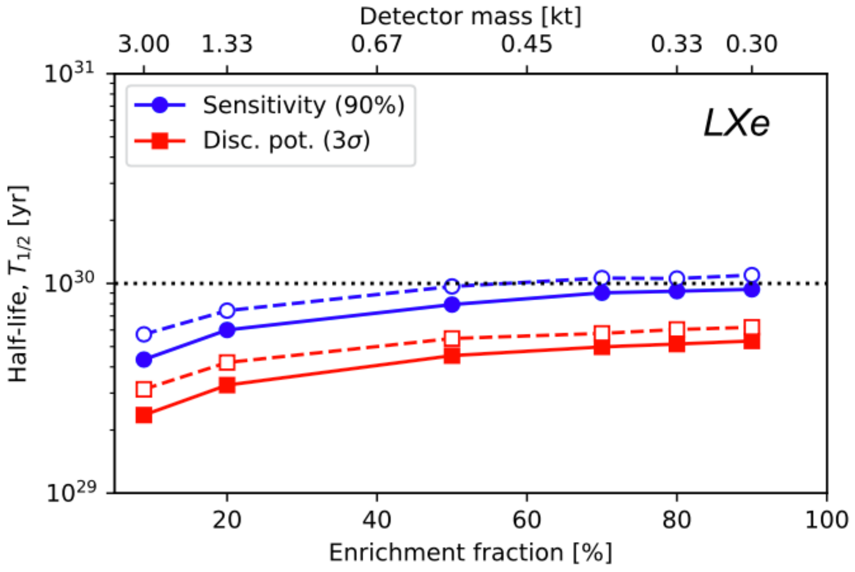
GXe concept (3000 t ^{nat}Xe, unenriched):



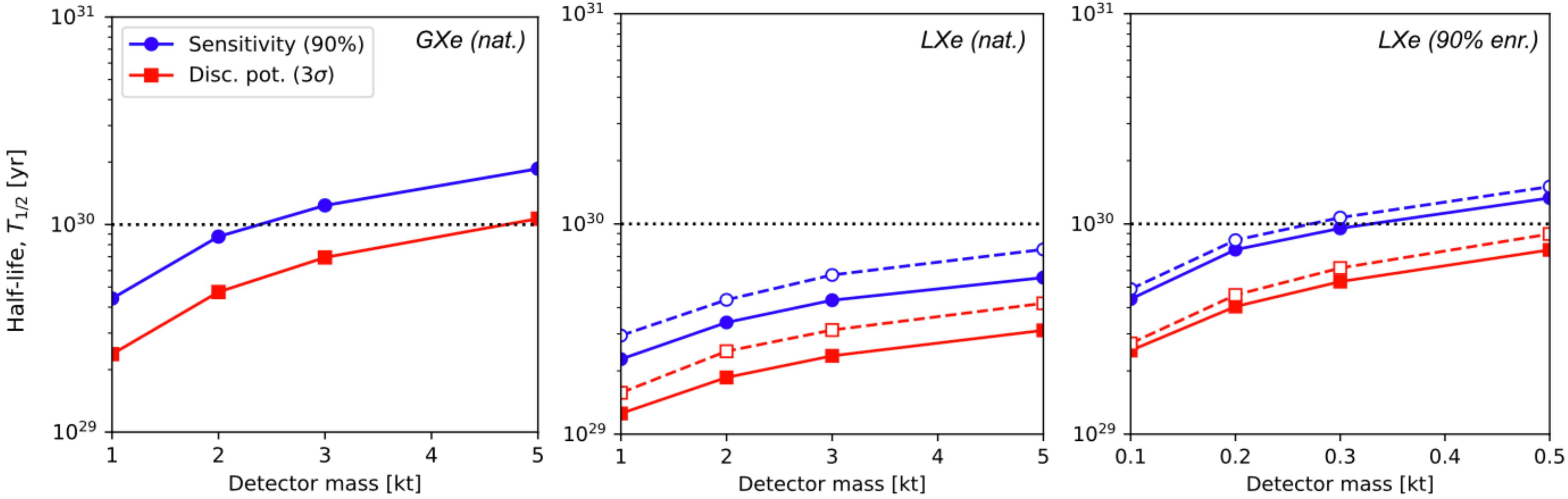
Sensitivity projections

- Either concept can reach sensitivity in the range of 10^{30} yr
  - Enrichment not required for GXe, while >50% is optimal for LXe
- Key enabling technology is Xe acquisition at this scale
- Neutrino mass measurements (e.g. cosmology) and theoretical progress on NMEs may also narrow target $T_{1/2}$ range

Projected sensitivity versus enrichment fraction:



Projected sensitivity versus detector mass:



Comparison of technologies

- If Xe could be acquired in the required quantities, there are several advantages to incorporating it in a gas or liquid phase TPC rather than other detector technologies:

Detector technology			Isotope acquisition	External backgrounds	Internal backgrounds	Energy resolution ($2\nu\beta\beta$)	Isotope mass fraction (solar ν)	Detector technology maturity (kton scale)
Segmented detectors								
	HPGe		?	✗	?	✓	✓/?	✗
	Bolometers		✓/?	✗	?	✓	✓/?	✗
	Tracking/CCDs	Se based	✓	?/✗	?	✓	✓	✗
Monolithic detectors								
	Liquid scintillator	Te doped	✓	✓	?	✗	✗	✓
		Xe doped	✗	✓	✓	✗	✗	✓
	TPCs	Gas Xe	✗	✓	✓	✓	✓	✓/?
		Liquid Xe	✗	✓	✓	✓	✓/?	✓
		Xe doped Ar	✗	✓	✗/?	✗/?	✗	✓
		SeF_6 (ion drift)	✓	✓	?	?	✓/?	✗

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Segmented detectors								
	HPGe		?	✗	?	✓	✓/?	✗
	Bolometers		✓/?	✗	?	✓	✓/?	✗
	Tracking/CCDs	Se based	✓	?/✗	?	✓	✓	✗
Monolithic detectors								
	Liquid scintillator	Te doped	✓	✓	?	✗	✗	✓
		Xe doped	✗	✓	✓	✗	✗	✓
	TPCs	Gas Xe	✗	✓	✓	✓	✓	✓/?
		Liquid Xe	✗	✓	✓	✓	✓/?	✓
		Xe doped Ar	✗	✓	✗/?	✗/?	✗	✓
		SeF_6 (ion drift)	✓	✓	?	?	✓/?	✗

This chart may change in the coming years
→ Isotope acquisition is key for GXe/LXe TPCs

Summary

- Large liquid Xe TPCs are extremely sensitive detectors for 0νββ:
  - EXO-200 operated from 2011-2018 and reached 0.5×10^{26} yr sensitivity
  - The nEXO project has now started, and will aim to reach 10^{28} yr sensitivity
  - A future kton scale gas or liquid Xe TPC may reach 10^{30} yr sensitivity
- R&D is underway towards Xe acquisition to enable kton scale experiment
- If successful, directly incorporating this Xe into a TPC has several advantages compared with other technologies beyond the ton-scale