Kilotonne scale Xe detectors for 0vbb and new physics searches

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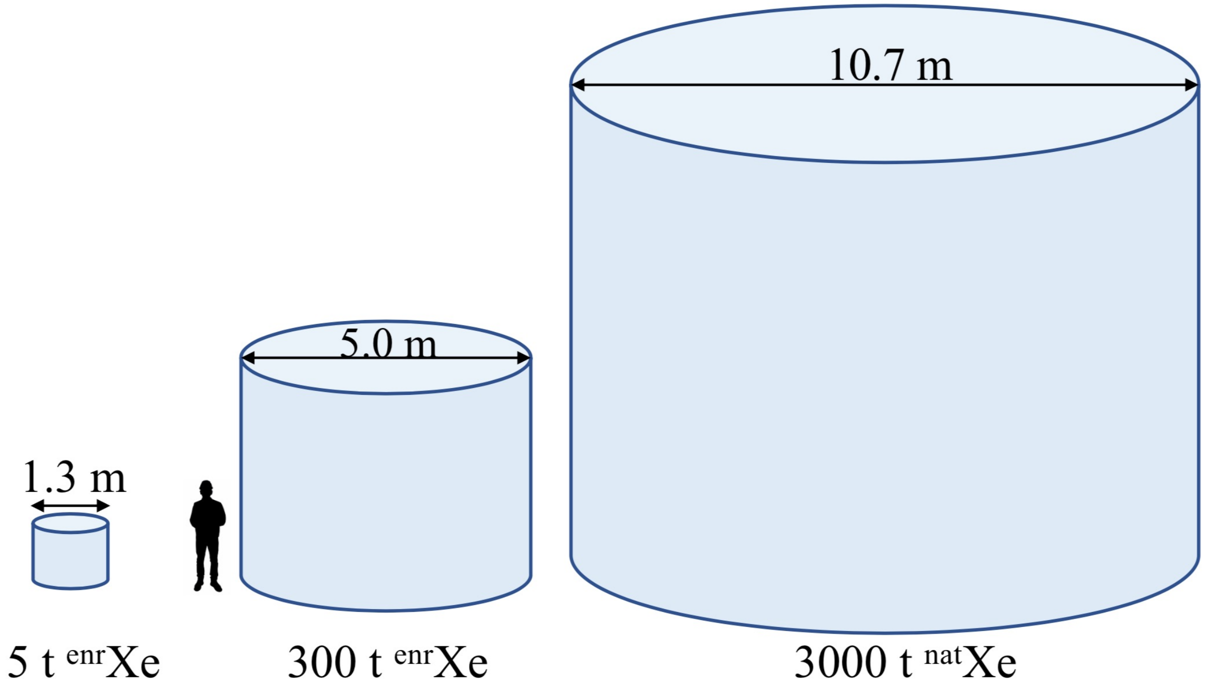
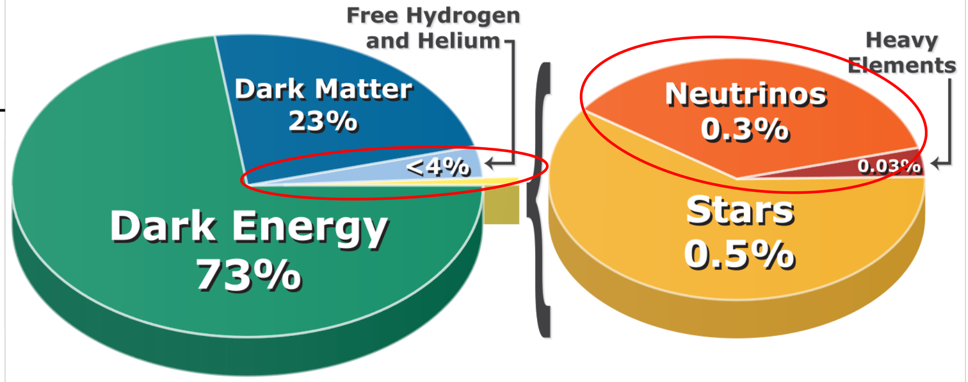
Background in underground physics:

- Dark matter (CDMS II, 2006-2012) [Soudan]
- Neutrinoless double beta decay:
  - EXO-200, 2012-present [WIPP]
  - nEXO, planned in coming years [Conceptual design @ SNOLAB]
  - Future ktonne Xe detector?



Science questions



- **Big questions:**
  - What is the origin of the small (but non-zero) neutrino masses?
  - Why is there matter in the Universe (rather than antimatter)?
    - Is lepton number conserved?

→ Searches for neutrinoless double beta decay, possibly eventually reaching the minimal masses possible in normal hierarchy

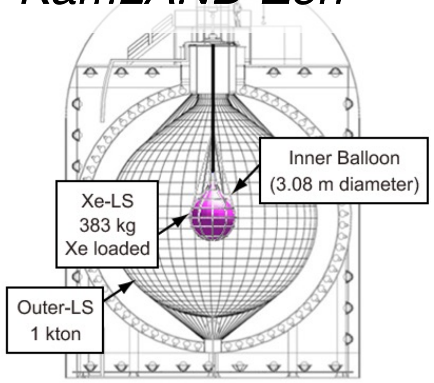
- Other motivations for very large Xe TPCs (with ~keV threshold):
  - Dark matter (mostly beyond WIMPs), CEvNS from solar, atmospheric, or supernovae neutrinos, tagging of CC interactions of solar ν (e.g. CNO ν or ^{7}Be lineshape)

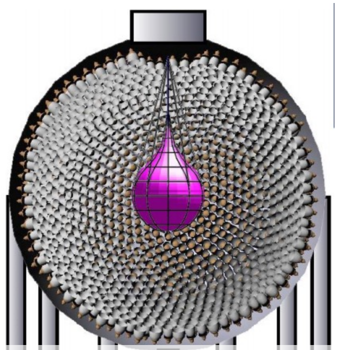
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.102.072009

Existing/proposed ^{136}Xe 0vbb detectors

Liquid (organic) scintillators:

KamLAND-Zen





KamLAND2-Zen

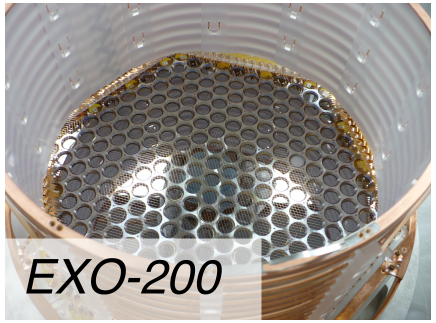
Also possibly THEIA, JUNO

$T_{1/2}$ > 1.1 x 10^{26} yr

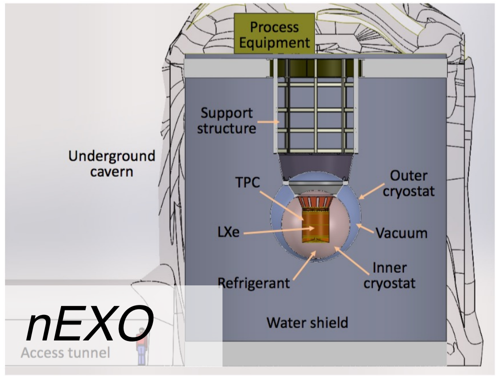
Phys. Rev. Lett. 117, 082503 (2016)

$T_{1/2}$ ~ 10^{27}-10^{28} yr

Liquid Xe TPCs:



EXO-200



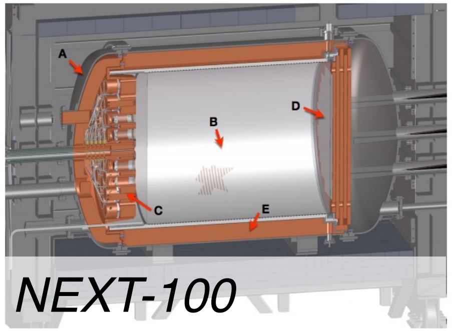
nEXO

$T_{1/2}$ > 0.35 x 10^{26} yr

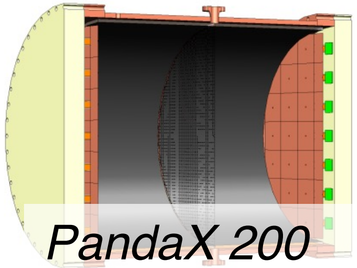
Phys. Rev. Lett. 123, 161802 (2019)

$T_{1/2}$ ~ 10^{28} yr

Gas Xe TPCs:

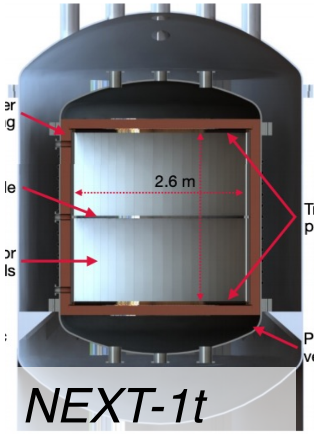


NEXT-100

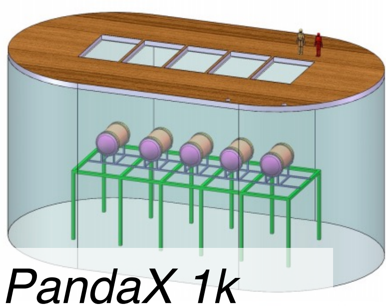


PandaX 200

$T_{1/2}$ ~ 10^{25}-10^{26} yr



NEXT-1t



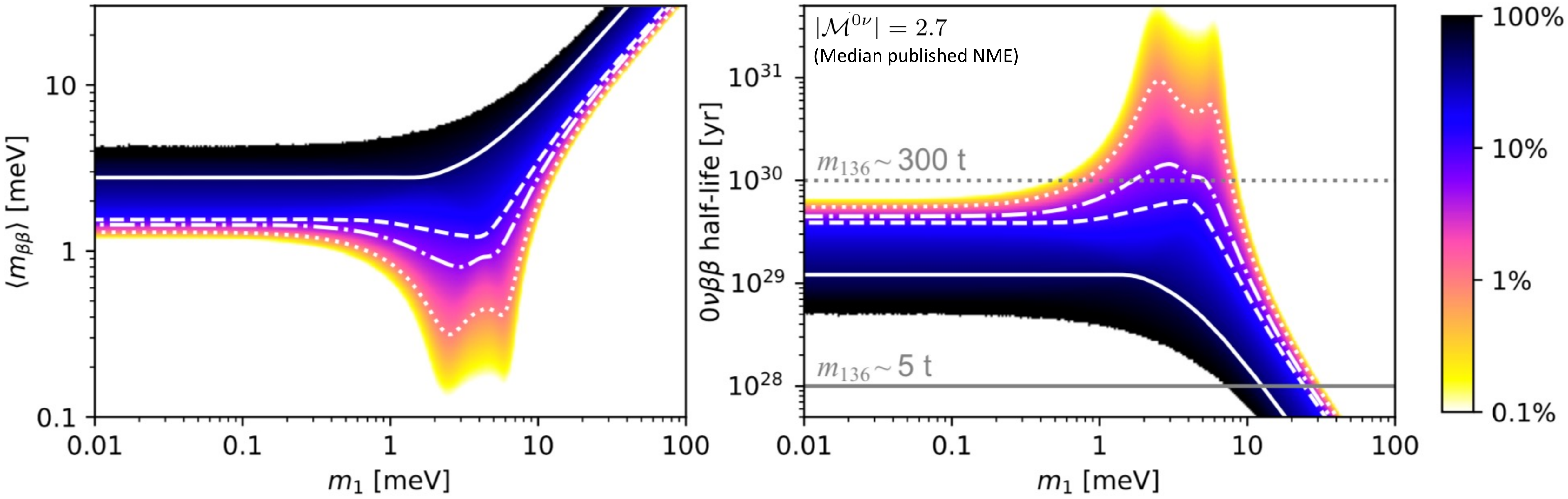
PandaX 1k

$T_{1/2}$ ~ 10^{28} yr

0vbb at 10^{30} yr

- If ton-scale detectors do not discover 0vbb, eventual sensitivities of 10^{30} yr may be required to explore majority of parameter space in normal hierarchy

Allowed parameter space (normal hierarchy only, Nu-Fit 5.0):



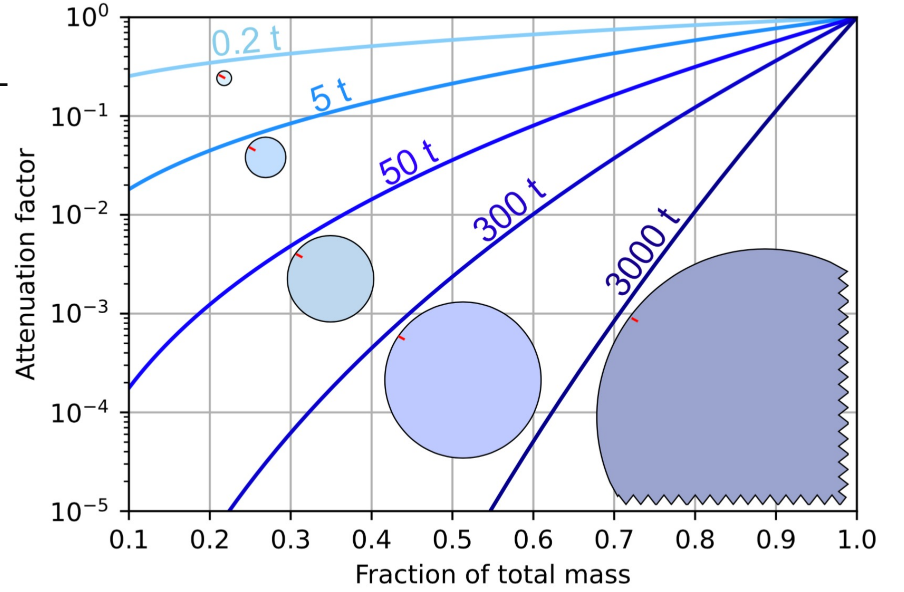
Xe acquisition

- Primary challenge to extending Xe TPCs (gas or liquid) to ktonne scale is likely the acquisition of the Xe itself
    - E.g., LArTPCs at this scale exist, and substantially larger experiments are underway (see talks yesterday)
- For Xe, the enabling technology is isotope procurement
    - Current production (reliant on steel industry) is 50-100 tonnes per year
    - Alternative production path likely required to realize detectors beyond 10s of tons scale
        - Note that the amount of air required is << that needed to capture 1 Gton CO_2, although engineering challenges can be different due to lower concentration (89 ppb for Xe)
- Enrichment is not necessarily required, but if desirable enrichment by centrifuge with dedicated plants may be possible (but expensive)
- Backgrounds at this scale must also be demonstrated for any technology (see following slides)

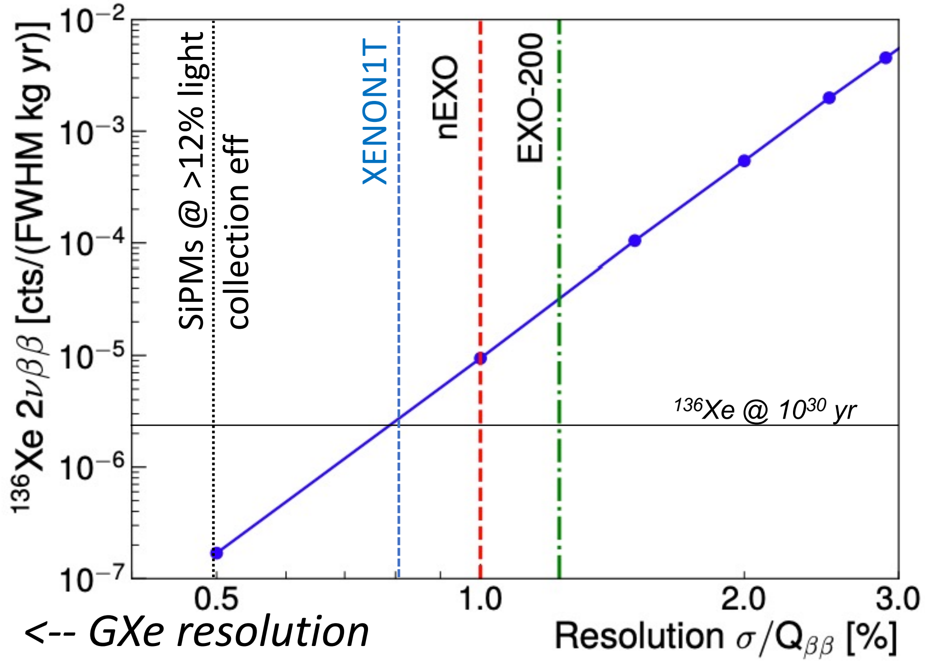
Backgrounds

- If Xe could be procured in ktonne scale quantities, several advantages to incorporating it directly into a TPC:
  - **Self-shielding:** external U/Th backgrounds (as well as Rn induced backgrounds) substantially mitigated by scaling to large size
  - **Energy resolution:** sufficient to remove otherwise irreducible background from 2vbb decay
  - **Solar v backgrounds:** ^{nat}Xe (with ~10% isotope fraction) or ^{enr}Xe minimize inactive material in the detector volume, and single versus double beta discrimination possible in GXe
  - **Unknown backgrounds:** homogeneous detector gives multiple handles for tagging possible backgrounds, e.g. from possible rare cosmogenic activation products
- Sensitivity estimates for gas/liquid concepts appear to indicate sensitivities as long as 10^{30} yr are achievable (300 t of ^{136}Xe)

Shielding of external backgrounds in LXe TPCs:



$2\nu\beta\beta$ background vs resolution:



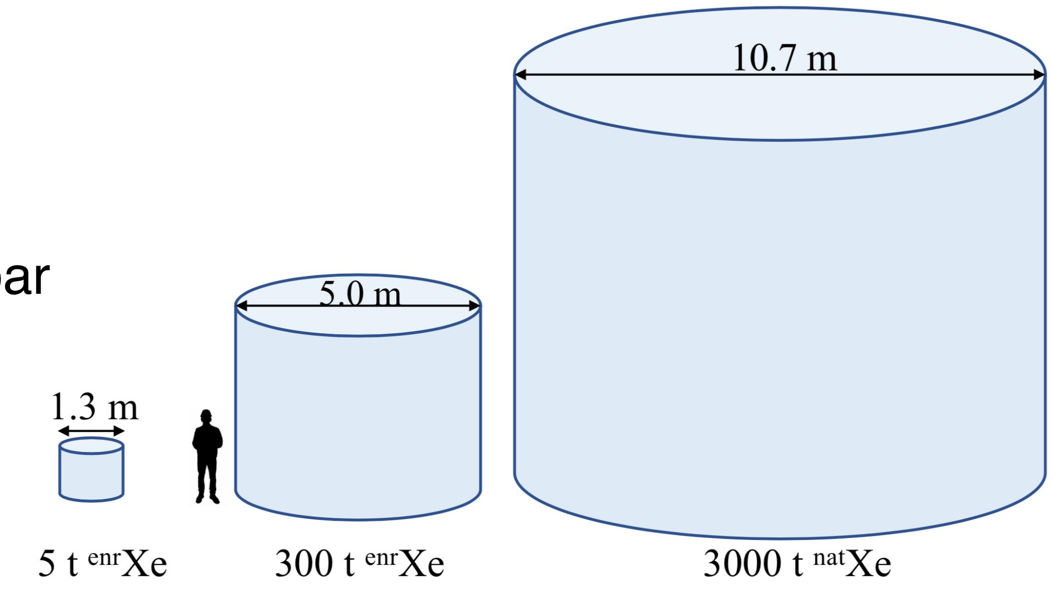
https://journals.aps.org/prc/abstract/10.1103/PhysRevC.97.065503

Detector concepts

- Ultimate 0vbb detector might be ktonne scale, although intermediate detectors also possible, e.g.:
  - Sensitivity ~10^{29} yr with 50 t of ^{enr}Xe
    - Possible complementarity with WIMP searches at the neutrino floor
  - Other possibilities might be 300 t ^{nat}Xe detector (~10^{29} yr), which can later be filled with ^{enr}Xe (~10^{30} yr) if desired

- Optimal choice between gas and liquid depends on backgrounds and engineering constraints
  - LXe detectors more compact for same mass
  - GXe detectors typically operate between 15-50 bar (6x to 30x lower density)

LXe detector size vs mass:



Summary

- Ktonne scale Xe detectors might be possible with new methods of Xe acquisition
    - R&D underway to explore various options (led by M. Heffner, LLNL)
    - Publication describing these ideas is in preparation
- If Xe could be procured in these quantities, extremely sensitive detectors for rare events may be possible, including 0vbb at ~10^{30} yr half-lives
- Large underground spaces would be required by such detectors, but similar e.g. to scale of currently planned LAr TPCs