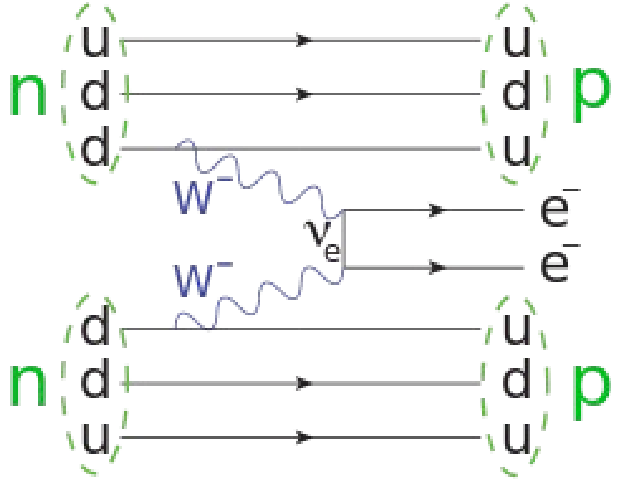
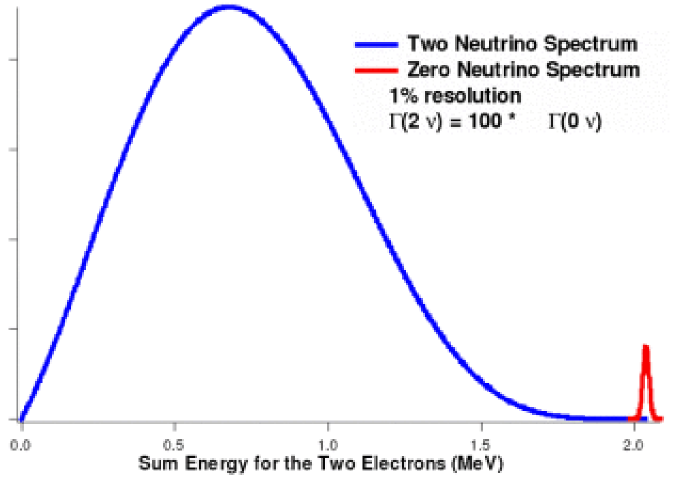
Probing Majorana neutrinos in the normal mass hierarchy with time projection chambers

Zixin Chen, Yale College, Class of 2023.5

Review on $0\nu\beta\beta$





Effective Majorana mass: $$m_{\beta\beta} = \left| \sum_{\mathrm{i}} U_{\mathrm{ei}}^2 \cdot m_{\nu_{\mathrm{i}}} \right|$$

- **$0\nu\beta\beta$ is a hypothetical mode of double-β decay**
- Neutrinos are Majorana particles
- Lepton number violation
- Neutrino mass scale constrained by $|m_{\beta\beta}|$
- **Long half-life**
- Current limit (for ^{136}Xe): 1.07×10^{26} yr

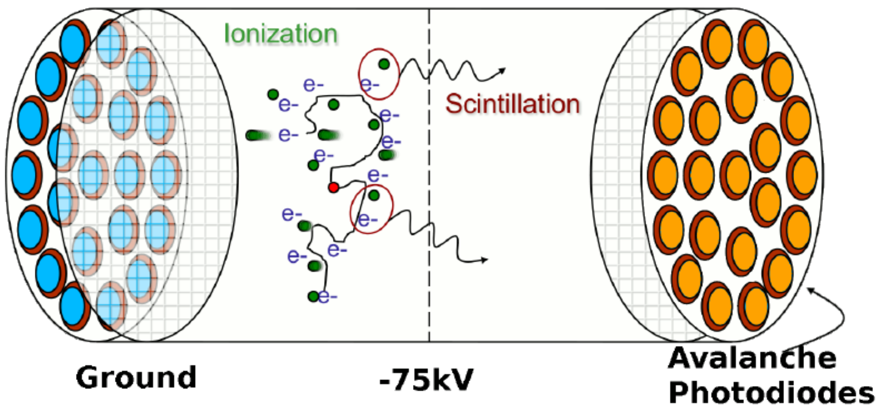
- **Experimental signature**
- **Choose ^{136}Xe as decay source and scintillator**

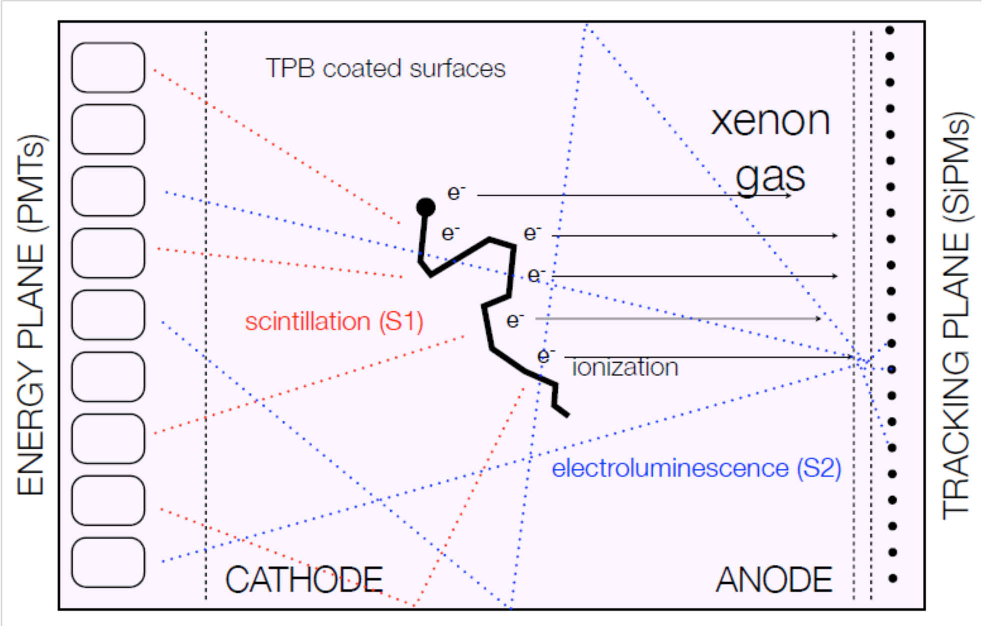
Review on Time projection chambers (TPCs)

Liquid phase:
- Collect both scintillation light and ionization charges

Gas phase:
- Use electroluminescence to convert ionization signals to UV light
- Sub-percent energy resolution

EXO-200 schematic





Outline

Motivation:

- No current detector design has demonstrated sensitivity for half-life in the normal mass regime
- Evidence from neutrino oscillations and others favors the normal mass hierarchy

Main goal:

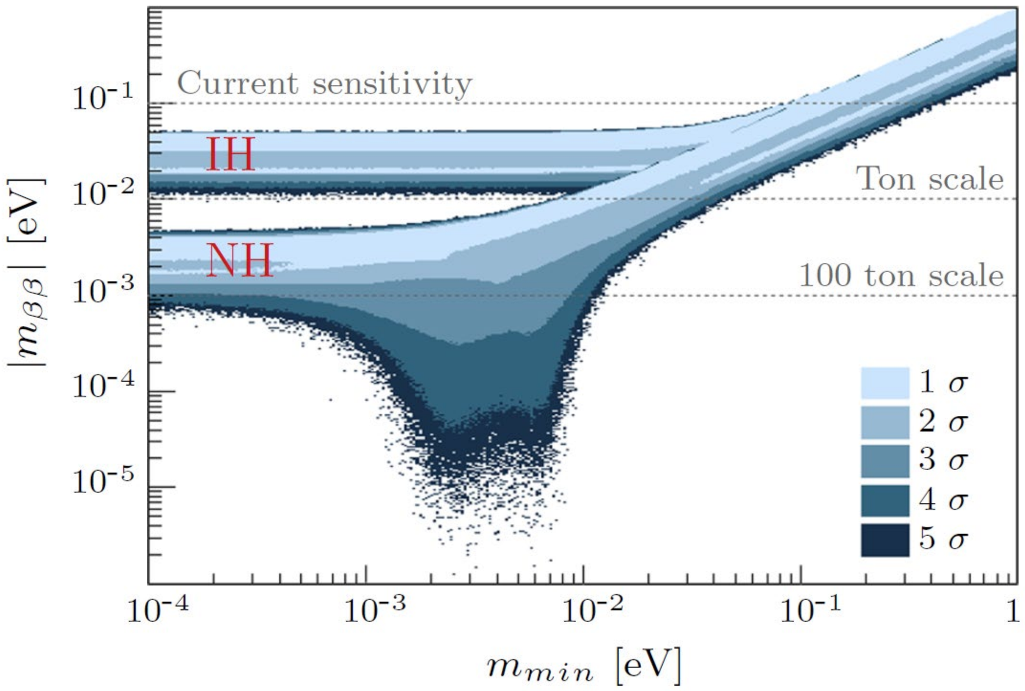
- Estimate the main backgrounds, sensitivity and discovery potential for a hundred-ton scale TPC $0\nu\beta\beta$ detector

Outline:

- $0\nu\beta\beta$ decay half-life and detector mass
- Background estimation
- Sensitivity and Discovery Potential
- Energy resolution and detector design
- Discussions and outlook

$0\nu\beta\beta$ decay half-life and detector mass

Allowed parameter space $|m_{\beta\beta}|$



Benato, G. Eur. Phys. J. C 75, 563 (2015)

Effective Majorana mass: $m_{\beta\beta} = \left|\sum_{i} U_{ei}^2 \cdot m_{\nu_i}\right|$

Decay half-life: $\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \frac{|m_{\beta\beta}|^2}{m_e^2}$

- Need: (1) half-life (2) decay rate
- More than 95% probability for detection at $|m_{\beta\beta}| \sim 10^{-3}$eV
- Corresponding half-life $\sim 8.72 \times 10^{29}$ yr
- Corresponding ^{136}Xe mass ~ 298 ton at decay rate of 1 event/yr
- Round up to 0.3 kiloton (kt) mass in the active volume

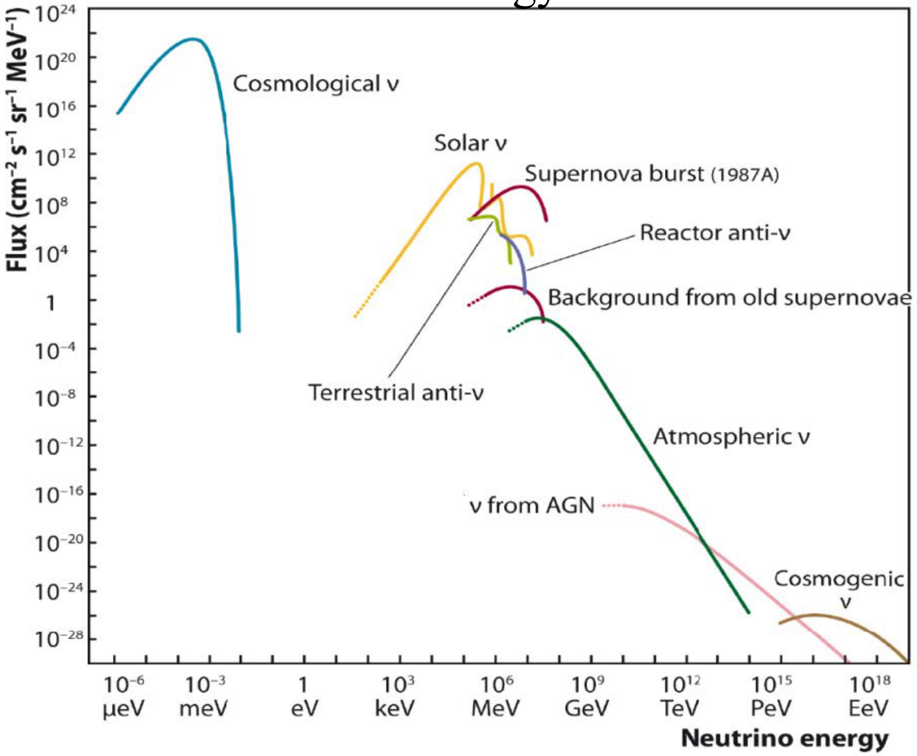
Background: Overview

^{136}Xe Q value = 2458.07±0.31 keV, subject to multiple backgrounds:

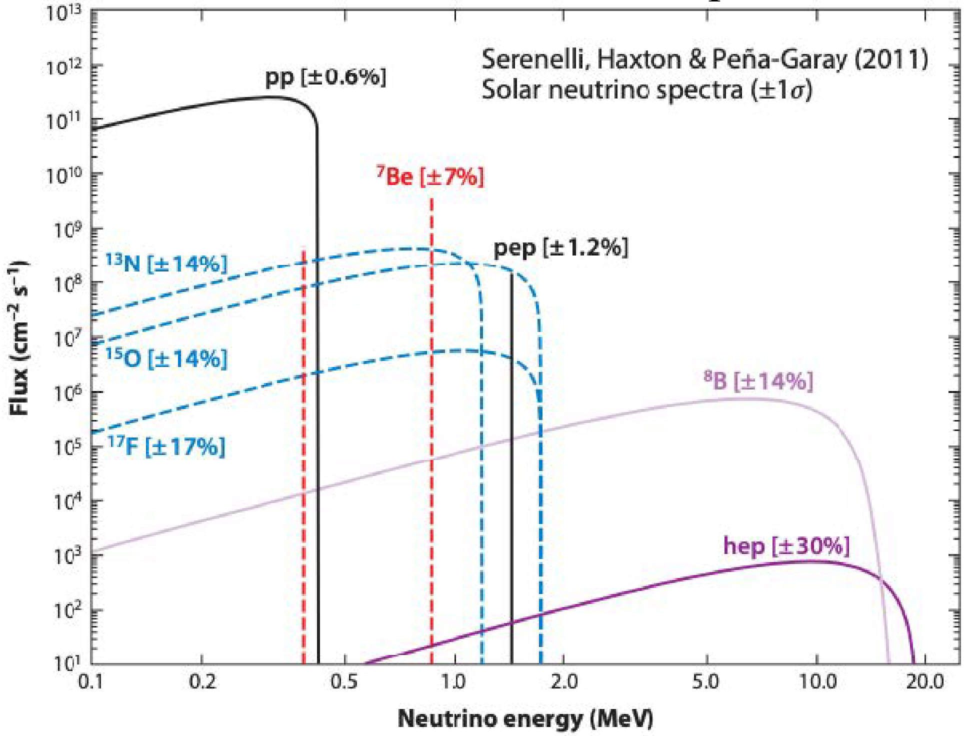
- Charged current (CC) and neutral current interactions (NC) from solar neutrinos
- ^{136}Xe $2\nu\beta\beta$
- ^{238}U and ^{232}Th natural decay chains
- Neutron capture on ^{136}Xe and ^{137}Xe β decay

Background: NC and CC interactions

Neutrino flux verses energy for various sources



Predicted solar neutrino spectra



Charged current: $\nu_e + {}^{136}\mathrm{Xe} \rightarrow e^- + {}^{136}\mathrm{Cs}$

- Three different backgrounds due to different excitation states of ^{136}Cs
- But the dominant one is ^{136}Cs β decay, so need the CC capture rate only
- Capture energy threshold: 0.59 MeV

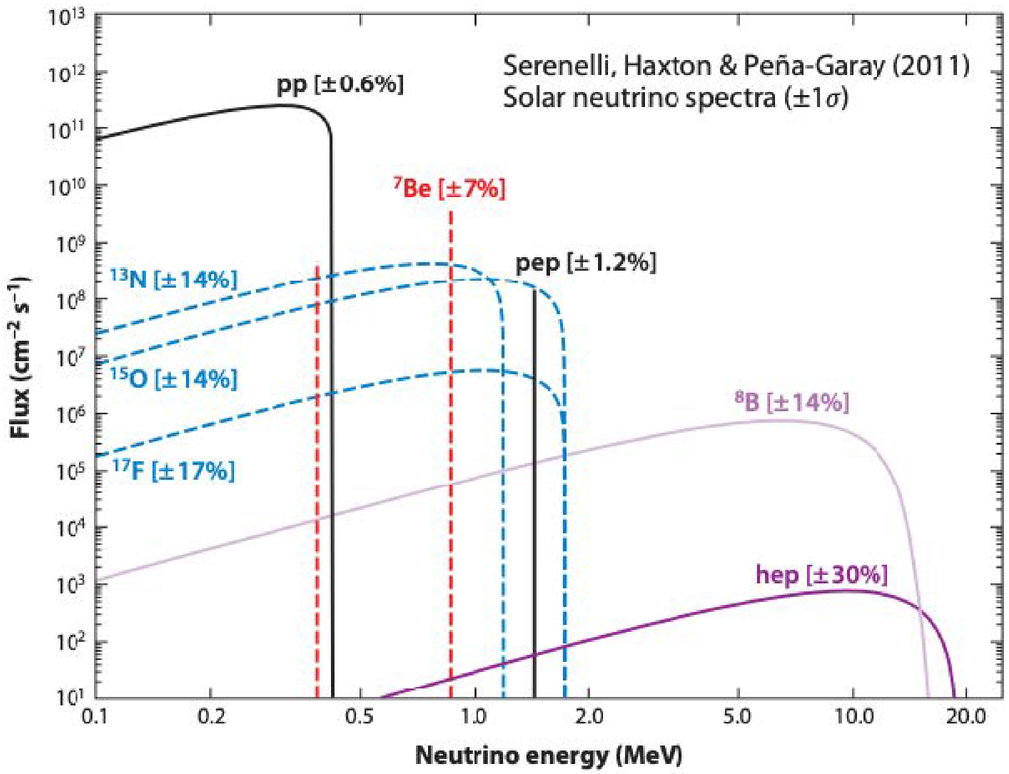
Neutral current: $\nu_e + e^- \rightarrow \nu_e + e^-$

- Recoil electron needs to have kinetic energy near ^{136}Xe Q value: ~2.458 MeV
- Only neutrinos with energies near ~2.458 MeV matter

* Inelastic scattering do not produce background near ROI

Background: CC interaction

Predicted solar neutrino spectra



Interaction rate estimated at:
$\sim 6.47 \times 10^{-35}$ [per atom per second]
(^{136}Cs production rate)

Cross section, survival probability and rate integral

$$\sigma_k = \frac{G_F^2 \cos^2\theta_c}{\pi} p_e E_e F(Z, E_e) \left[B(F)_k + \left(\frac{g_A}{g_V}\right)^2 B(GT)_k \right]$$
$$= (1.597 \times 10^{-44} \mathrm{cm}^2) p_e E_e F(Z, E_e)$$
$$\times \left[B(F)_k + \left(\frac{g_A}{g_V}\right)^2 B(GT)_k \right]$$

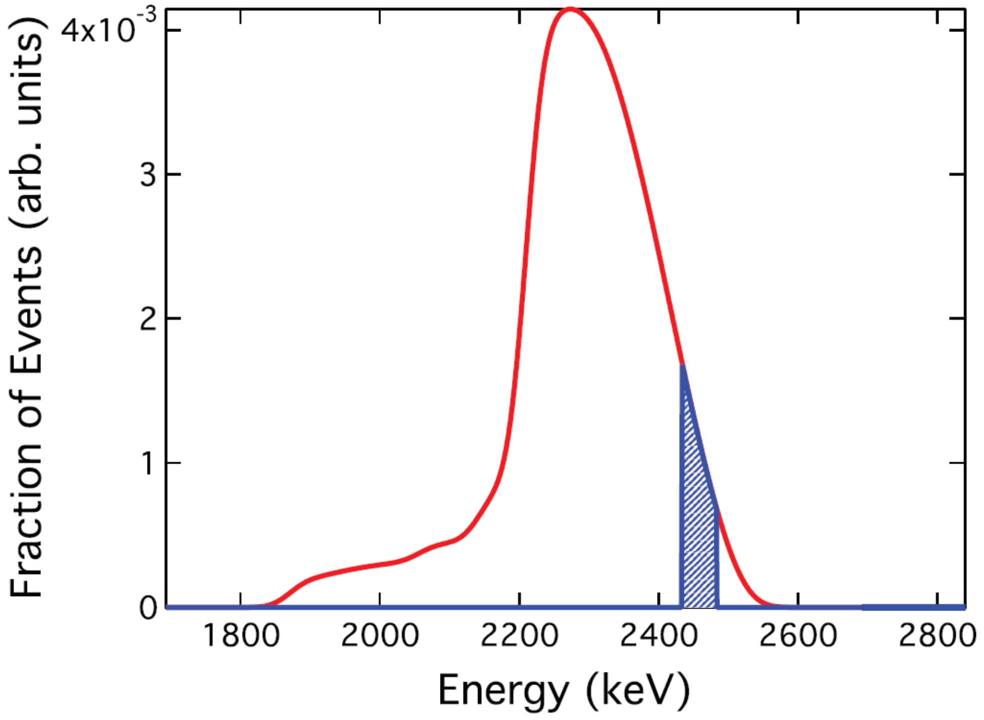
$$P_{E_\nu} = 0.336 + 0.117 e^{\frac{-E_\nu - 0.1}{4.82}} + 0.119 e^{\frac{-E_\nu - 0.1}{4.88}}$$

$$R = \sum_k \int \sigma_k(E_\nu) \frac{d\phi_\nu}{dE_\nu} P_{E_\nu} dE_\nu$$

H. Ejiri and S. R. Elliott
Phys. Rev. C ***89****, 055501*

Background: CC interaction

Approximate $\beta - \gamma$ ray energy spectrum for ^{136}Cs decay, shaded area covers the ROI at 2%FWHM



H. Ejiri and S. R. Elliott
Phys. Rev. C ***89****, 055501*

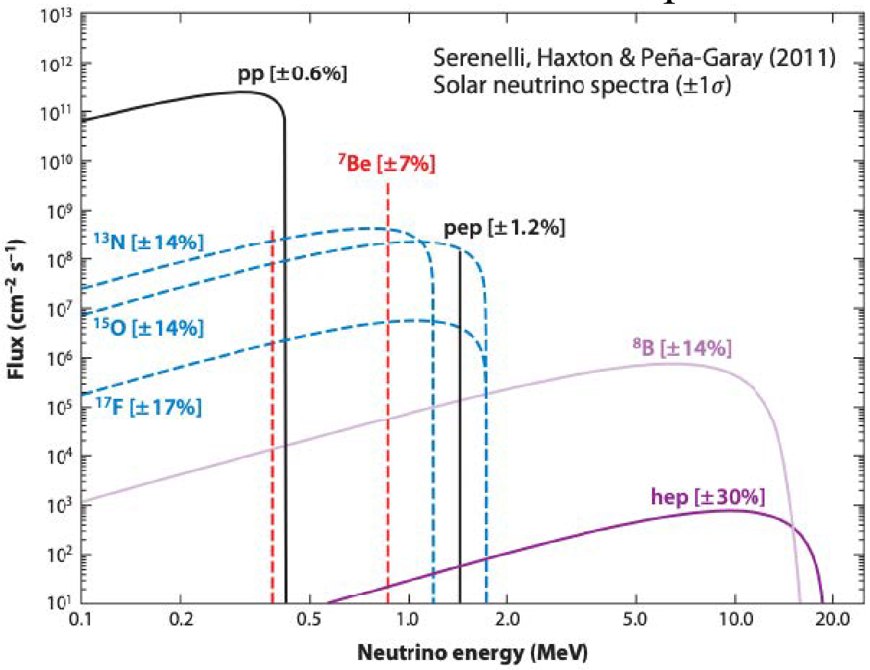
$$^{136}\mathrm{Cs} \rightarrow e^{-} + {}^{136}\mathrm{Ba} + \nu_e \ (+\gamma)$$

- ^{136}Cs has a half-life of 13.16-d, hard to tag from CC captures
- Background rate: ~ 0.06 [events/ton yr] at 0.2% FWHM*

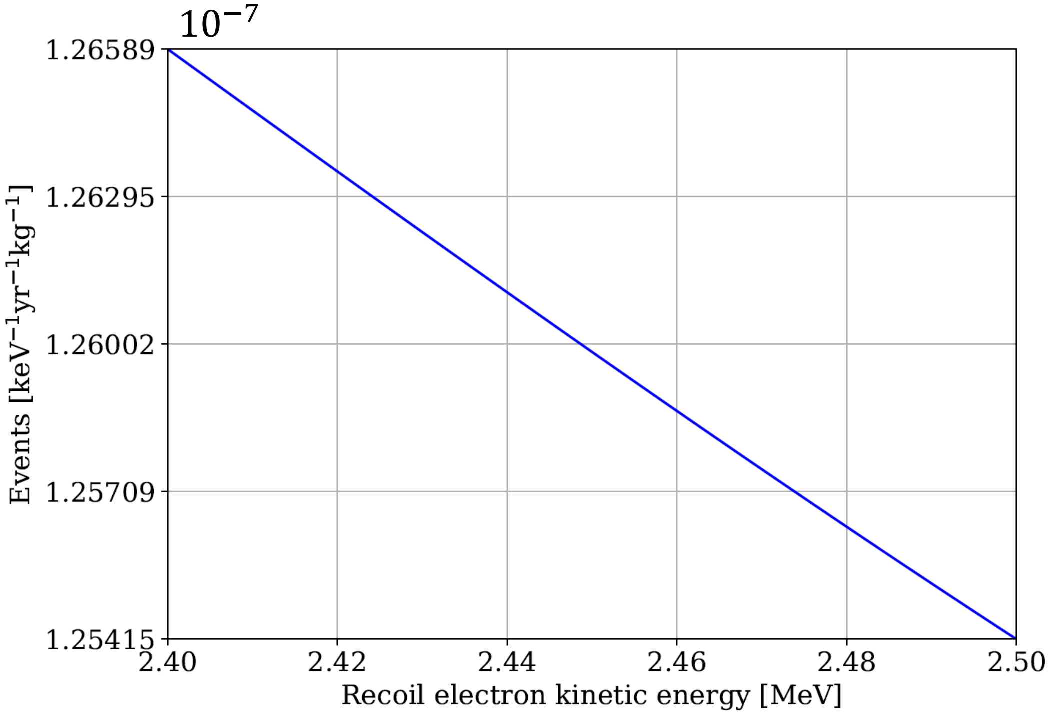
*Estimated by Ejiri and Elliott

Background: NC interaction

Predicted solar neutrino spectra



Background rate verses recoil electron kinetic energy



Cross section, rate integral (survival probability as before)

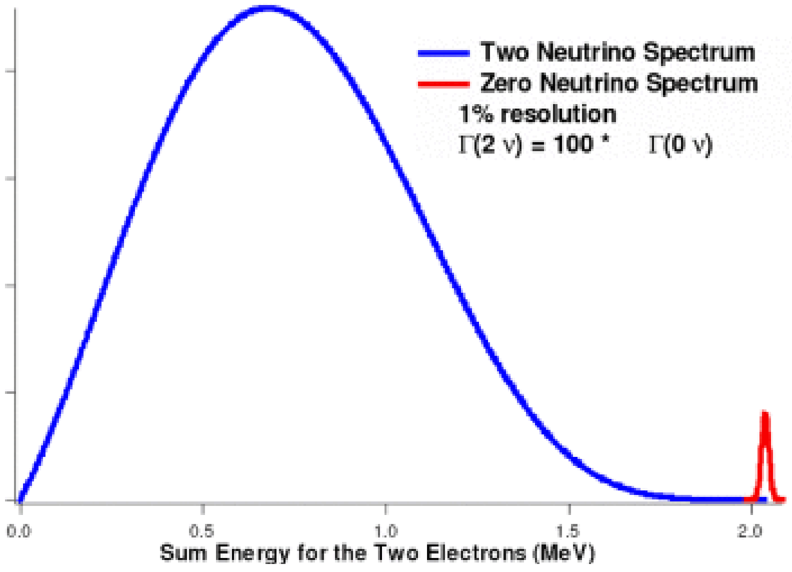
$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi} \times \left[g_L^2 + g_R^2 \left(1 - \frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu} \right]$$

$$R' = \int_{2.4}^{2.5} \frac{d\sigma}{dT} P_{E_\nu} \frac{d\phi'}{dE_\nu} dE_\nu$$

- Background rate at 0.2% FWHM : ~ 0.0014 [events/ton yr]
- ~10x smaller than that of CC captures

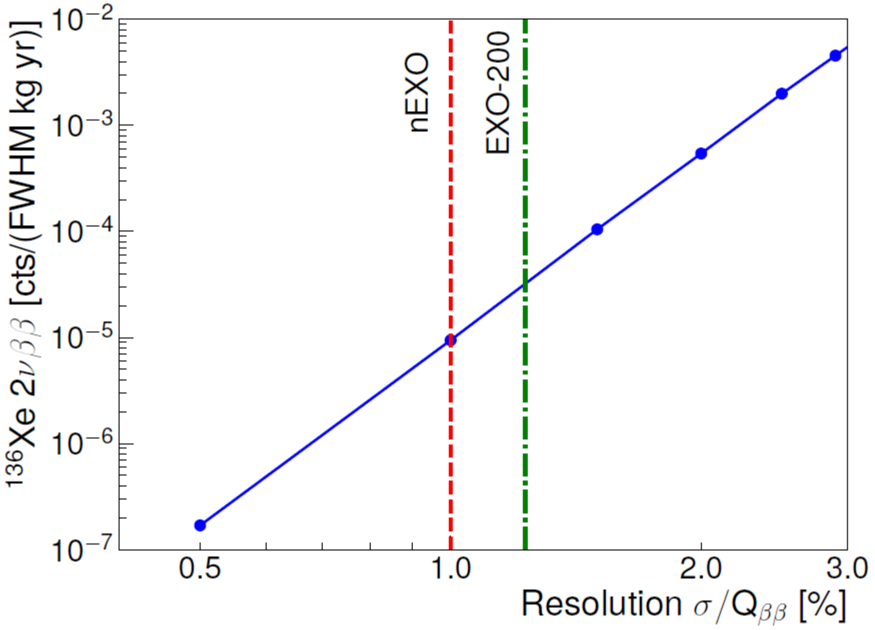
Background: $2\nu\beta\beta$

$0\nu\beta\beta$ energy spectrum (exaggerated)



- 0ν signal peak can get smeared over
- Energy resolution is important

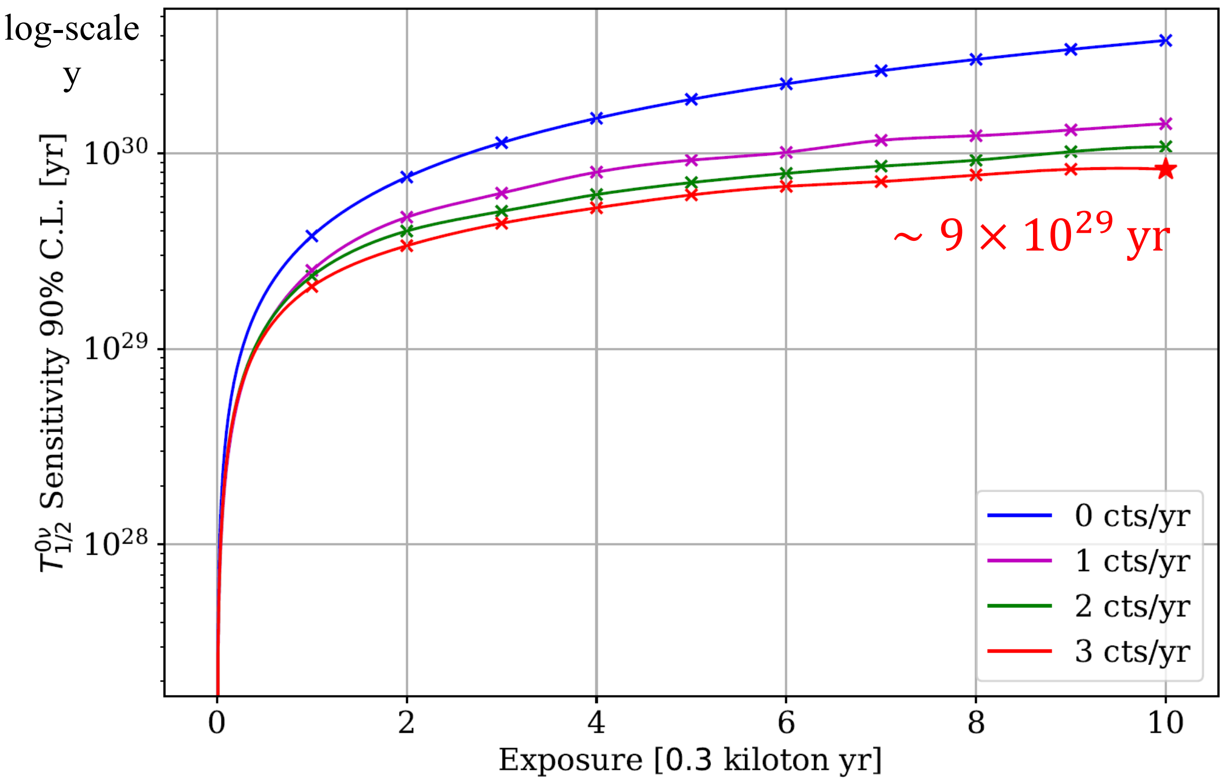
$2\nu\beta\beta$ background rate versus resolution

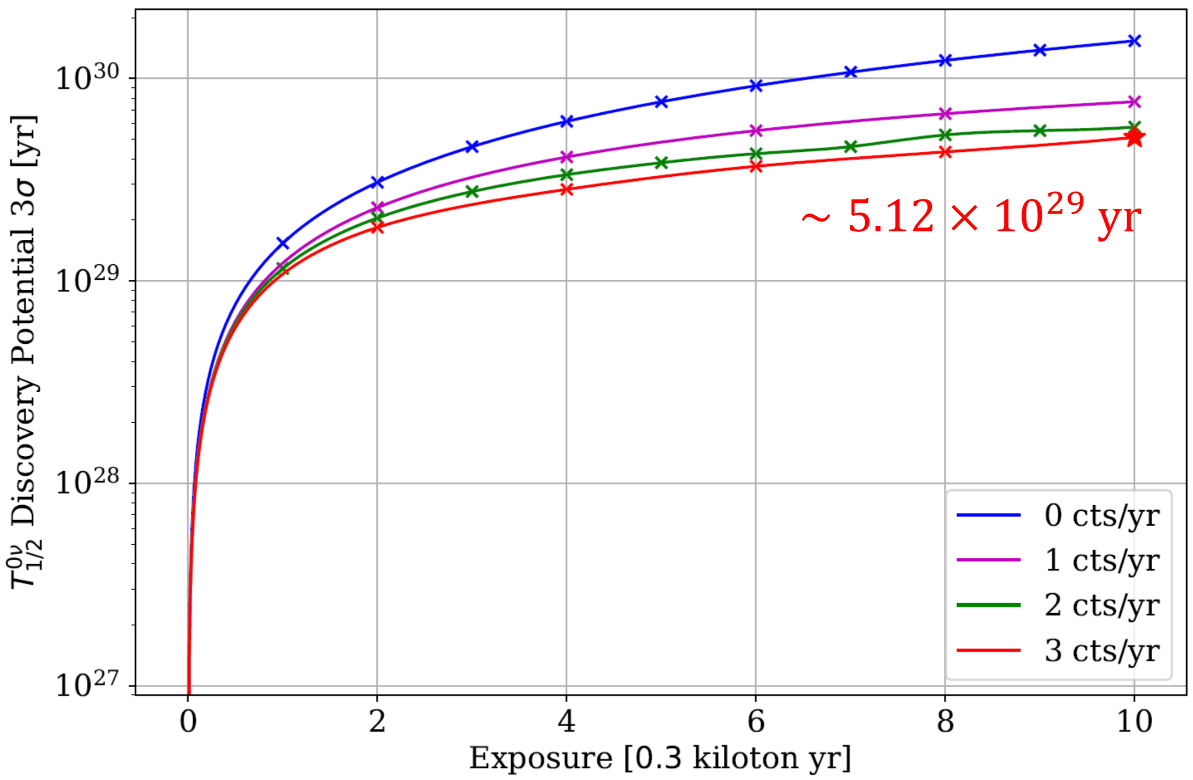


- Background rate: $\sim 10^{-4}$ [events/ton yr] at 0.5% FWHM
- Already ~100x smaller than that of CC captures, ~10x smaller than that of NC elastic scattering

EXO Collaboration Phys. Rev. C 97, 065503 (2018)

Sensitivity and Discovery Potential



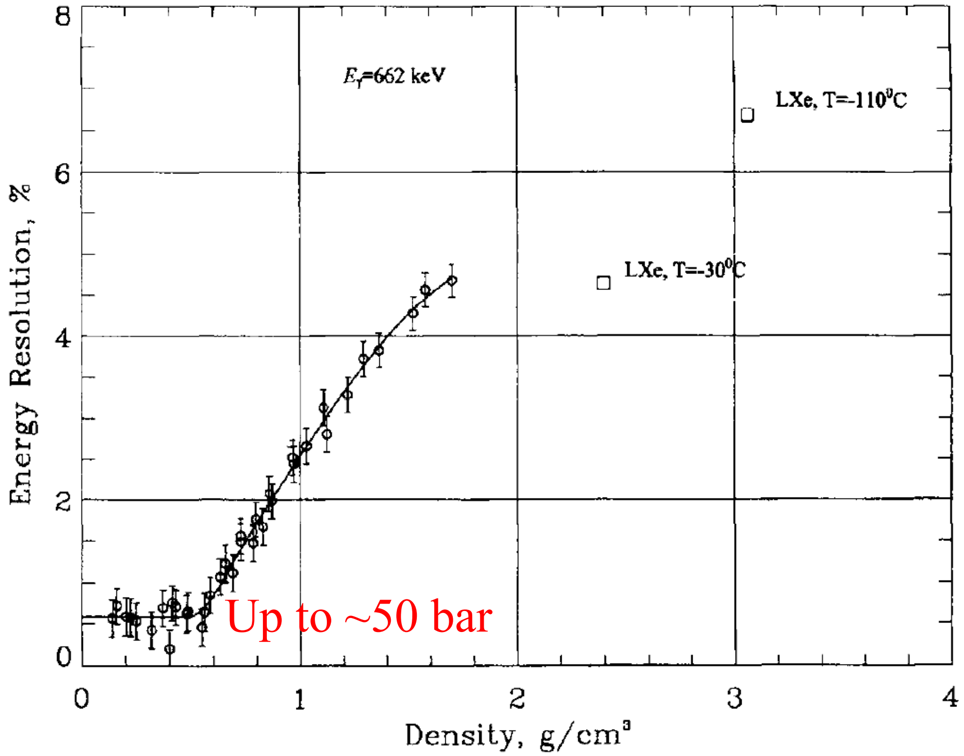


Calculated via ROOT, signal rate 1 cts/yr, legends on background rate

- Estimated raw background rate at 0.1% FWHM resolution: ~9.21 [cts/(0.3 kt yr)]
- Background from CC capture alone: ~9 [cts/(0.3 kt yr)]
- Strict demand on low background and/or good energy resolution

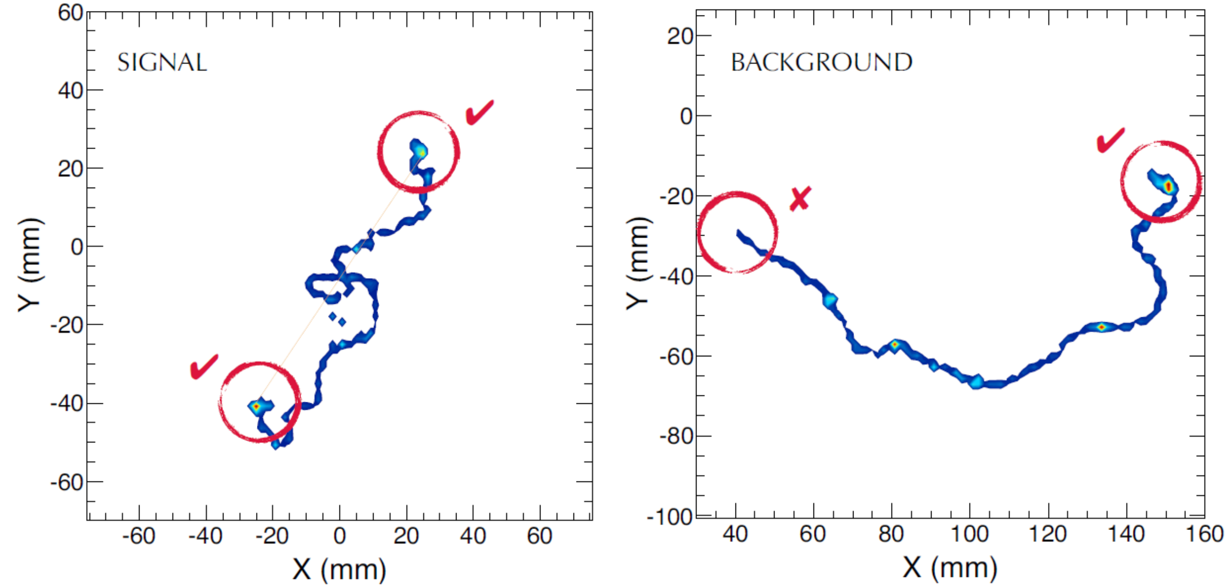
Energy Resolution

Density dependencies of the intrinsic energy resolution in Xe measured for 662 keV γ rays



Aleksey Bolotnikov, Brian Ramsey, Nucl. Instrum. Methods Phys. Res. Section A, Volume 396, Issue 3

Simulated trajectory for $\boldsymbol{\beta\beta}$(left) and $\boldsymbol{\beta}$(right) in Xe gas



NEXT Collaboration, Journal of Instrumentation 12.01 (2017): T01004

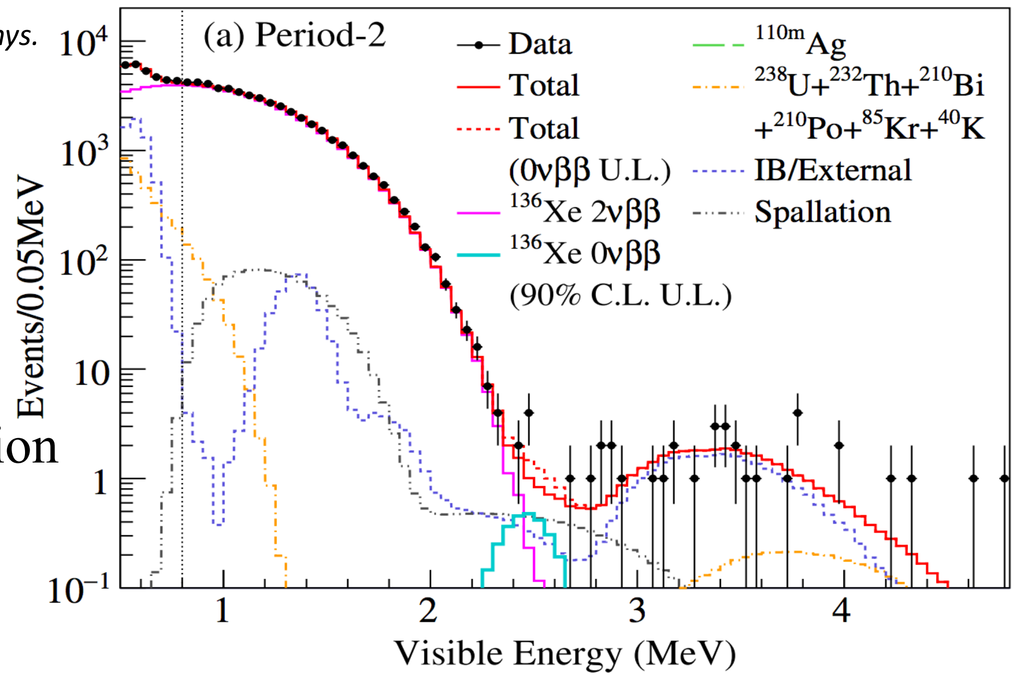
- Sub-percent energy resolution demands HPgXeTPC
- Using ionization signal alone, energy resolution superior by a factor of $(F_{HPXe}\ /F_{LXe})$^$(1/2)$ = 0.087
- Less impressive improvement in TPC so far
- At least 0.5% energy resolution has been demonstrated in the smaller $0\nu\beta\beta$ HPgXeTPC

Discussions and Outlook

- **Energy resolution VS detector mass**
- **Rejection of the CC capture background**
- Topological discrimination (track; MS, SS)
- **Summary**
- To probe the normal mass hierarchy with TPCs, we will need kt-scale HPgXeTPC detectors with good topological discrimination ability.

KamLAND-Zen Collaboration Phys. Rev. Lett. 117, 082503

KamLAND-Zen Spectrum



- **Caveat about sensitivity calculation**
- Meant to demonstrate the importance of energy resolution, not to indicate an ideal way to achieve the target sensitivity
- A more exhaustive search over decay rate (detector mass) and background rate may be required. (Note: the search is non-trivial and not so meaningful given that we only have the raw background rate, not a veto-ed one, thus is not carried out.)
- **Final caveat about everything**
- Many details about detector design are ignored and no simulation is made. Should take all estimations and their combinations with a grain of salt.

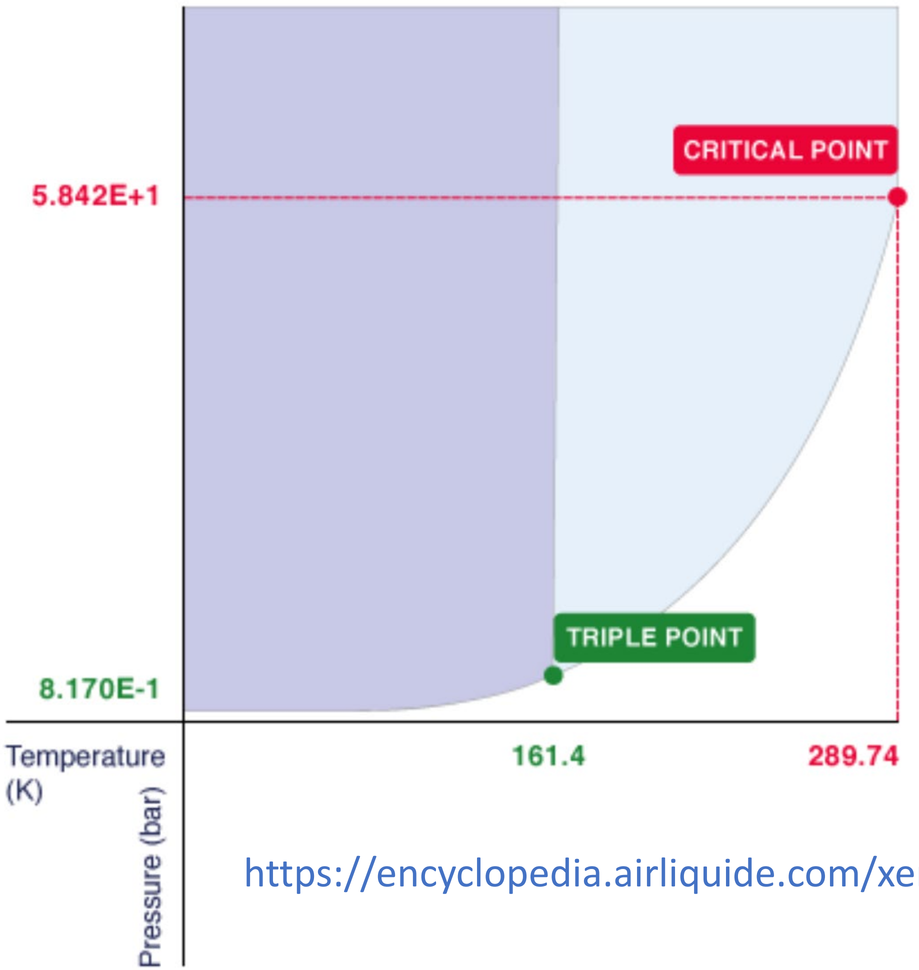
Acknowledgements

- The speaker would like to thank Prof. David Moore and TA Ako Jamil for their tremendous help with the project,
- and Hao Chen, Huaijin Wang for useful discussions,
- finally, everyone here for listening.

Thanks

Detector Design

Under solid (grey), liquid (blue) and vapor states (white) along the equilibrium curves



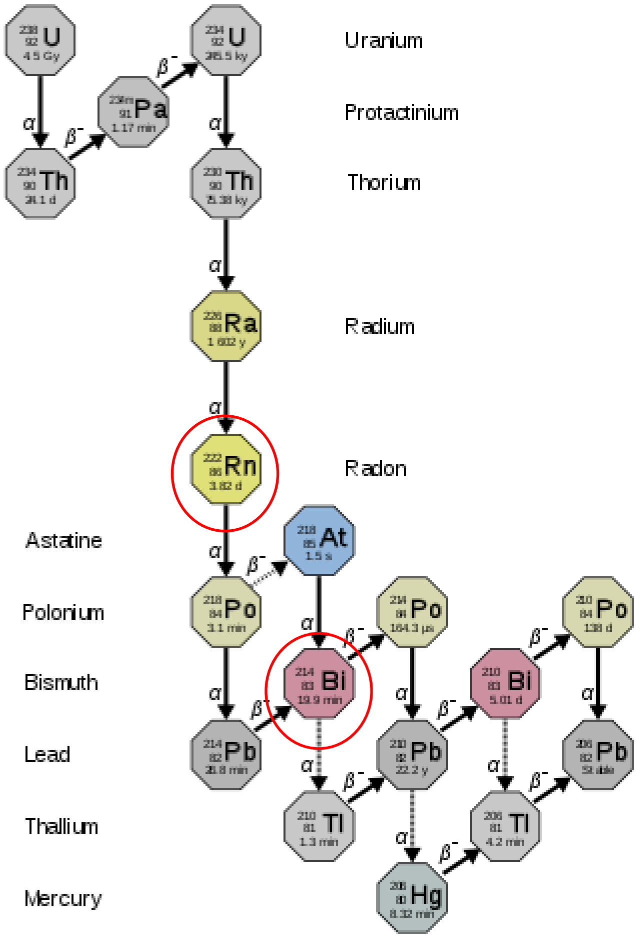
https://encyclopedia.airliquide.com/xenon

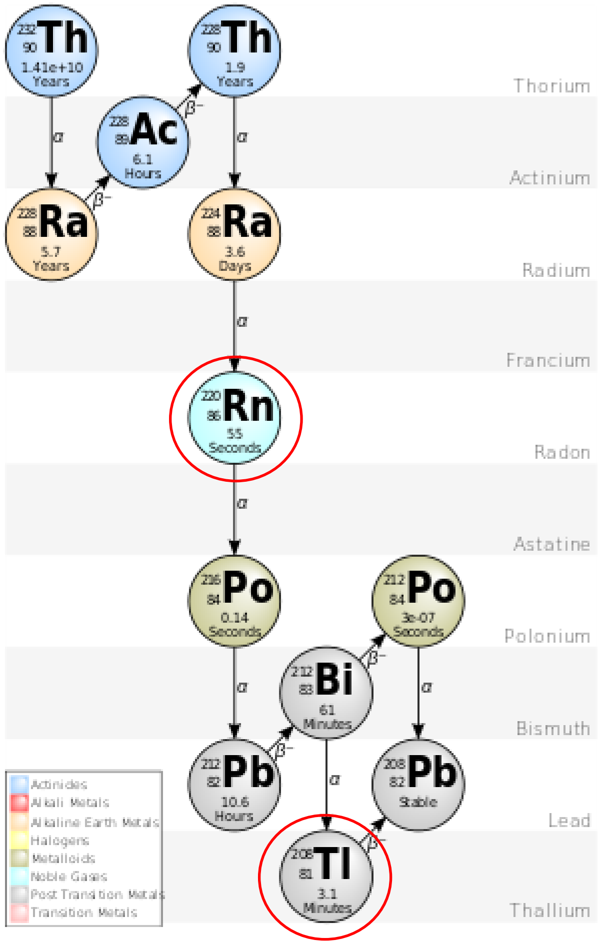
Ideal Gas Law:

$$PV = nRT$$

- Current $0\nu\beta\beta$ HPgXeTPC detectors have pressure up to ~20 bar
- Xenon L-V saturation gas density at 20 bar, 242.85K : $0.1736\ \mathrm{g/cm^3}$
- Estimated size in cylinder of radius R, height d=2R: R ~ 9.71 m

Background: other veto-systems





- **^{238}U and ^{232}Th natural decay chains**
  - In detector material – cannot penetrate into the active volume
  - ^{222}Rn, ^{214}Bi – rejected via Bi-Po α tag ($\geq$99% in the active volume)
  - ^{220}Rn, ^{208}Tl – 55s half-life, cannot penetrate into the active volume
  - Note: this list is incomplete, only major concerns are listed.

NEXT Collaboration J. High Energ. Phys. ***2016,*** *159 (2016)*

- **^{137}Xe β decay**
  - Rejected via distinctive cascade of γ rays following thermal neutron capture, Q value = 4025.5±0.3 keV

EXO Collaboration JCAP, 029 (April 2016)

Discussions and Outlook

- **Energy resolution VS detector mass**
- **Rejection of the CC capture background**
- Topological discrimination (track; MS, SS)
- Purification
- **Xenon production**
- 0.5 kt ^{136}Xe enriched at 20$/g costs about ~billion dollars
- **Caveat about enrichment**
- Not considered
- **Caveat about detector size**
- Taken an extreme condition which may impose technological difficulties
- **Caveat about sensitivity calculation**
- Meant to demonstrate the importance of energy resolution, not to indicate an ideal way to achieve the target sensitivity
- A more exhaustive search over decay rate (detector mass) and background rate may be required. (Note: the search is non-trivial and not so meaningful given that we only have the raw background rate, not a veto-ed one, thus is not carried out.)
- **Final caveat about everything**
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KamLAND-Zen Spectrum

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