Detecting Supernova ν_e CC Events in Large Xenon Detectors

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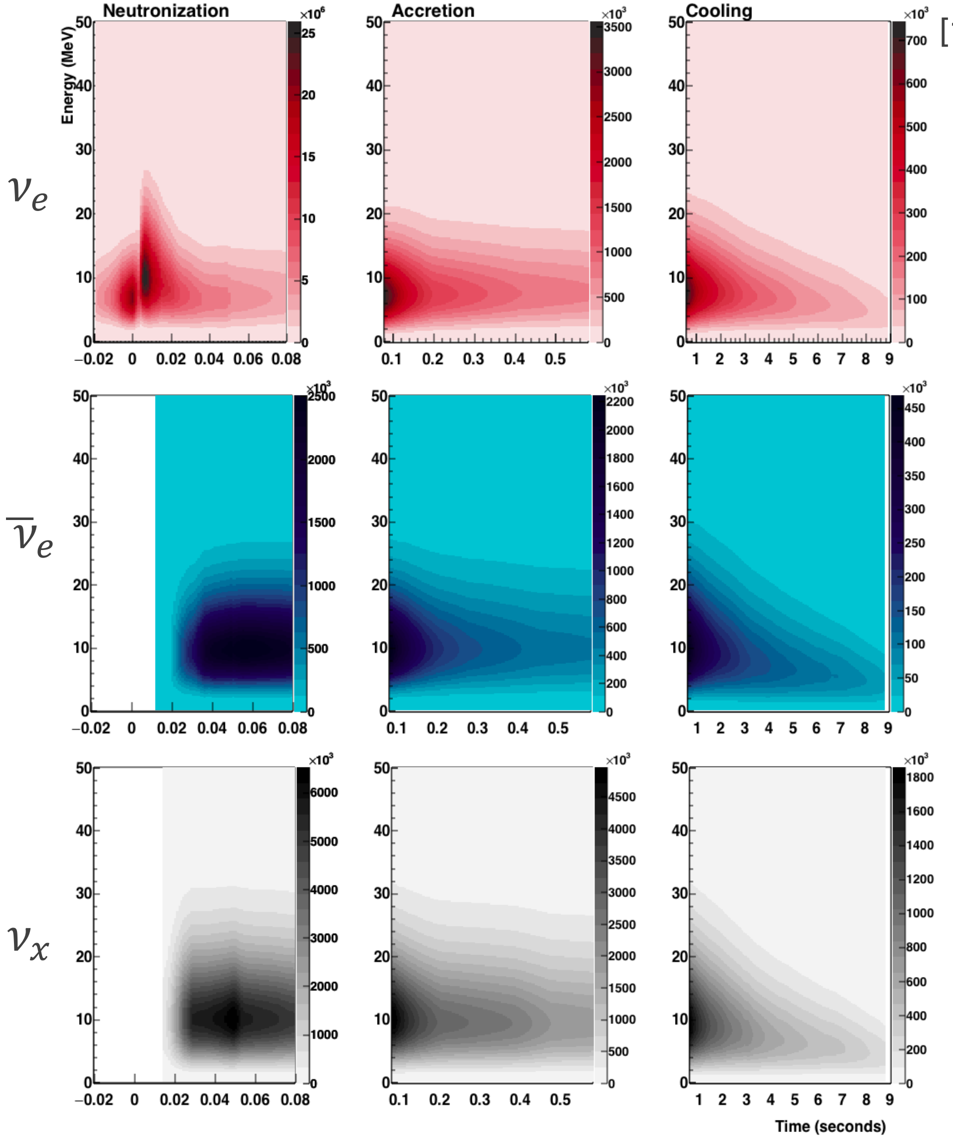
What can we learn from supernova neutrinos?

1. An early warning signal for astronomers
2. A tool for studying neutrino properties
3. Insight into supernova explosion dynamics
   - Majority of existing detectors primarily sensitive to $\overline{\nu}_e$, unique information in ν_e component
   - Neutrino-nucleus charged-current (CC) interactions can study these neutrinos through

$$\nu_e + {}^{134,136}\mathrm{Xe} \rightarrow e^- + {}^{134,136}\mathrm{Cs}^*$$

   - Focus on detector w/nEXO enrichment, 90% ^{136}Xe, 10% ^{134}Xe



[1] B. Abi, et al., *arXiv:2002.03005* (2020)

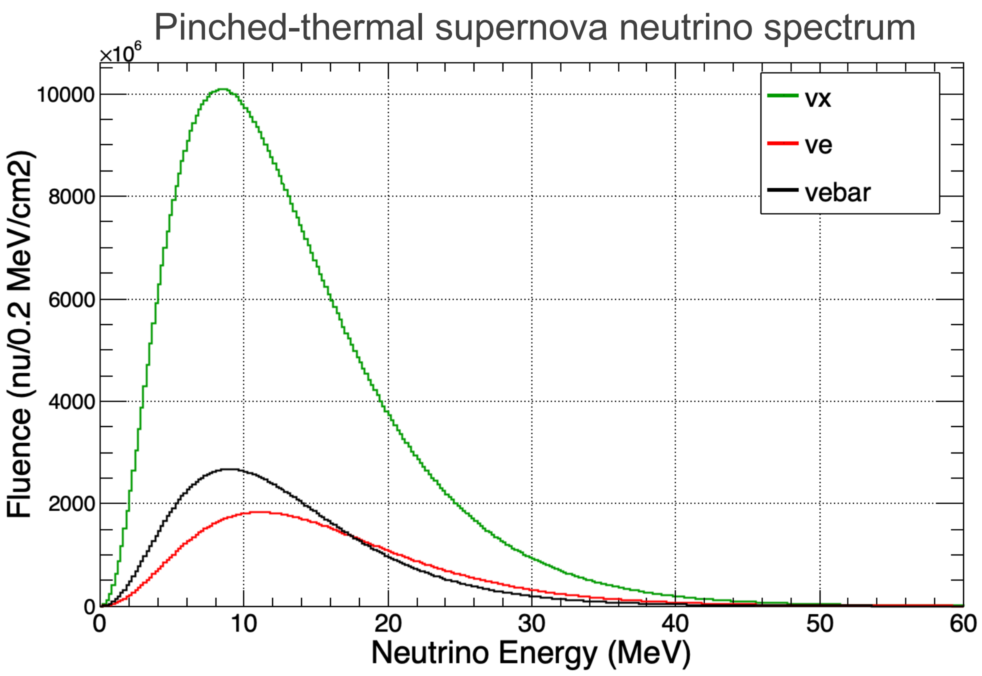
Why use a xenon $0\nu\beta\beta$ detector?

Why xenon?

- Low thresholds: ^{136}Xe: 0.09 MeV, ^{134}Xe: 1.24 MeV
  - 15.4 MeV for ^{16}O, 17.3 MeV for ^{12}C
- CC cross sections large—scale approx. with A-Z[1]
  - Predicted to be ~3.5x larger for ^{136}Xe compared to ^{40}Ar
  - CC channel significantly larger than elastic $\nu_e - e^-$

Why use a xenon $0\nu\beta\beta$ detector?

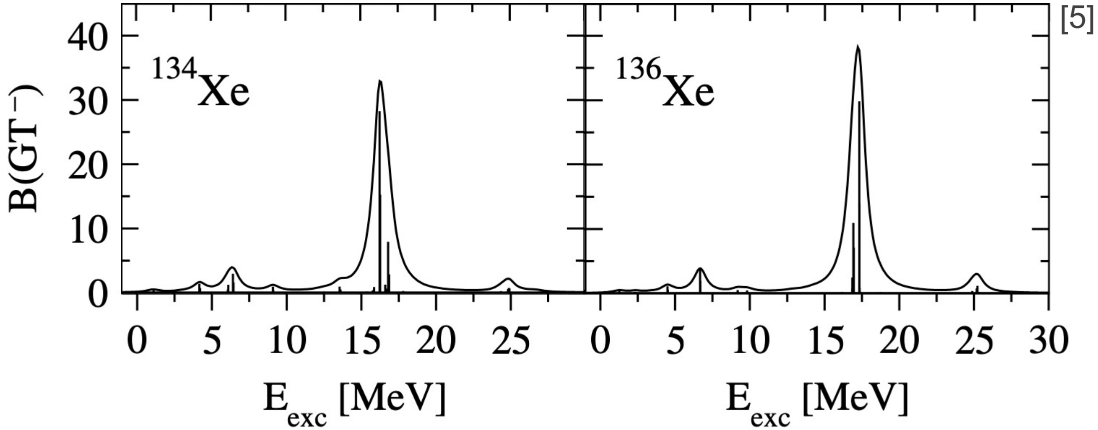
- Deep underground, low-background
- "Similar" energy scale—MeV-to-10s-of-MeV particles from CC events
- Long exposures

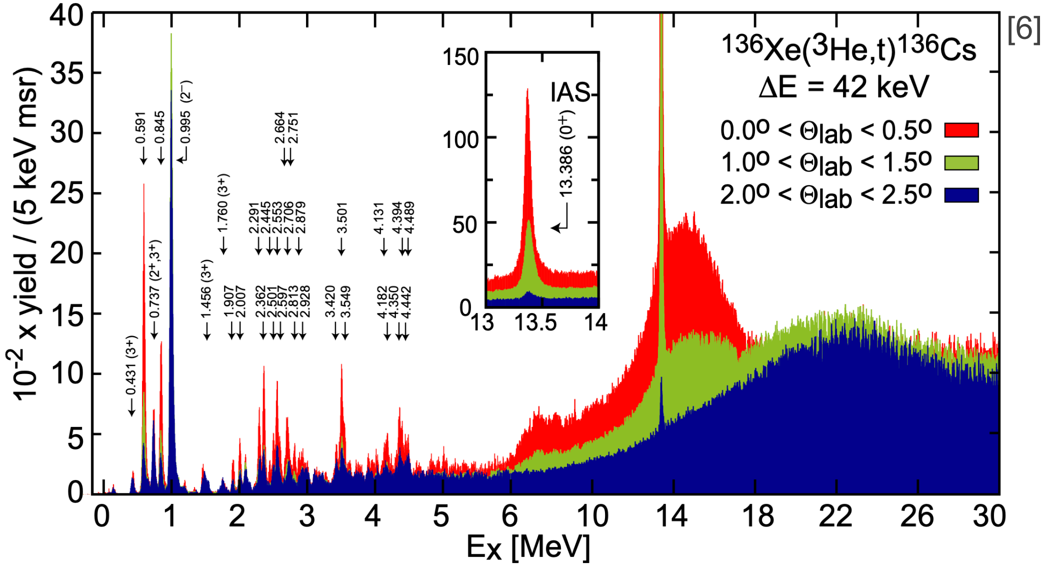


[1] S L Mintz, *J. Phys. G: Nucl. Part. Phys.* **28**, 451 (2002)

Existing work

- Existing work[1-3] focuses on cross sections, not detectable signatures
- Our calculations use on the MARLEY[4] event generator
  - Simulates allowed ν_e-Xe interactions
  - Inputs are *B(GT)* and *B(F)* strengths—can use theory calculations[5] or measurements via (p,n) or (^{3}He,t) scattering[6]
  - Output are predictions for cross sections, particles generated by CC interactions

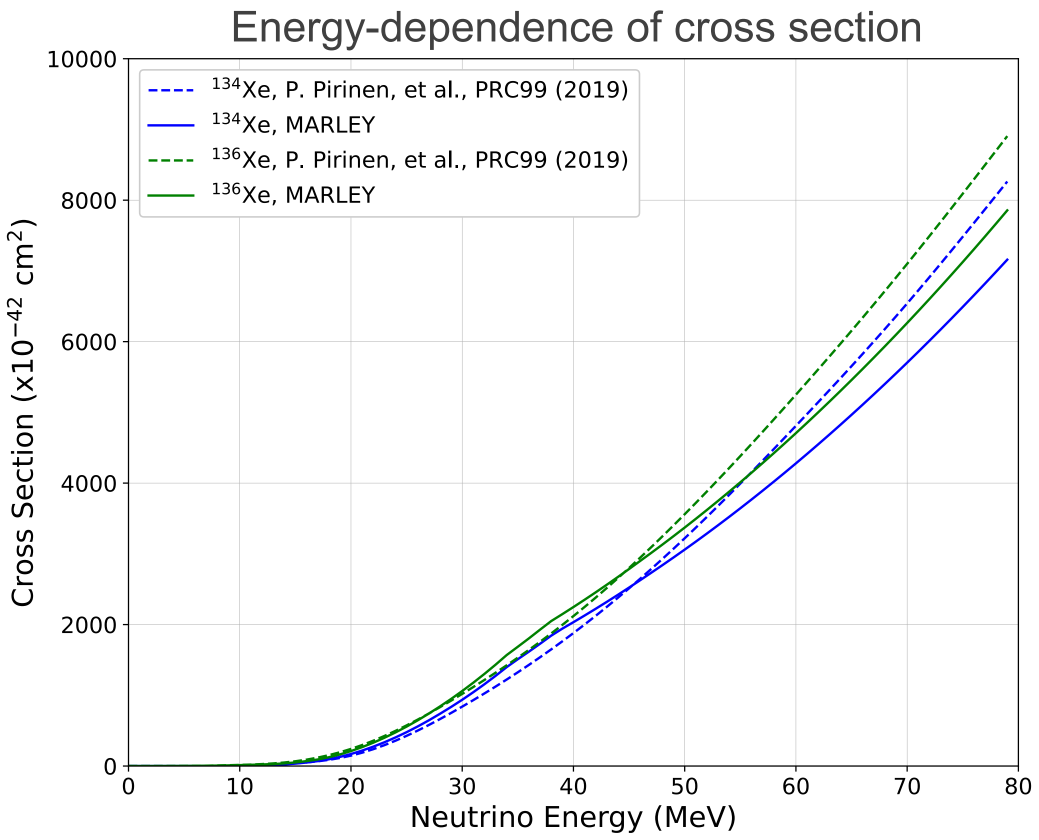




[1] P. C. Divari, *Advances in High Energy Physics* **2013**, 143184 (2013)
[2] P. Pirinen, J. Suhonen, and E. Ydrefors, *Phys. Rev. C* **99**, 014320 (2019)
[3] P. Bhattacharjee, et al., *Phys. Rev. D* **106**, 043029 (2022)
[4] https://www.marleygen.org/
[5] O. Moreno, et al., Phys. Rev. C **74**, 054308 (2006)
[6] D. Frekers and M. Alanssari, Eur. Phys. J. A **54**, 177 (2018)

MARLEY's predictions: ^{134}Xe, ^{136}Xe CC x-sections

- Overall see good agreement between MARLEY and *P. Pirinen, et. al*
- See slight suppression in cross section at higher energies—expected due to lack of forbidden transitions in MARLEY model



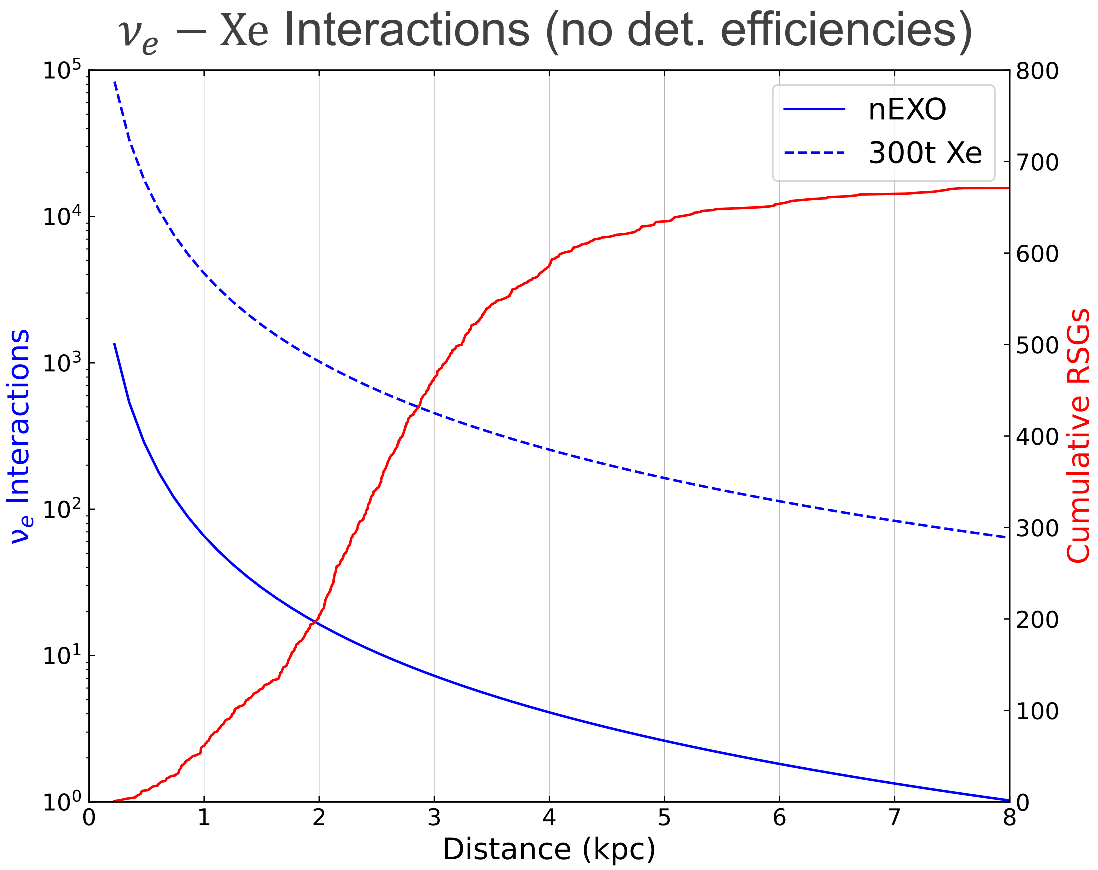
Flux-averaged inclusive cross sections

Flux Model	Pirinen, et al. [4]	MARLEY
^{136}Xe		
GKVM [2]	3.15	3.10
Livermore [5]	0.89	0.83
Pinched-thermal	0.43	0.38
^{134}Xe		
GKVM [2]	2.49	2.68
Livermore [5]	0.63	0.67
Pinched-thermal	0.28	0.28

TABLE I. Cross sections are per atom in units of 10^{-40} cm^2, without including the effects of neutrino-oscillations. For the predictions from MARLEY, Gamow-Teller matrix elements come from Ref. [1, 3] for ^{136}Xe and Ref. [3] for ^{134}Xe. A quenched $g_A = 0.7$ is used for all theoretical matrix elements, and an unquenched $g_A = 1.26$ is used for experimentally-measured matrix elements. For the GKVM and Livermore calculations with data from Ref. [4], a spline interpolation is used to evaluate the cross section within the specified model from interaction threshold to 80 MeV, whereas all MARLEY cross sections are evaluated up to 100 MeV

MARLEY predictions: CC interaction rates

- nEXO most sensitive to candidate RSGs[1] (red supergiants) within a few kpc
- Sensitivity greatly enhanced with a 300t detector (same isotopic abundances)



[1] RSG candidate list from S. Healy, et al., *arXiv:2307.08785* (2023)

MARLEY's predictions: exclusive x-sections

- MARLEY generates prediction for exclusive channel cross sections
  - Neutron emission channel dominant, although some disagreement seen between MARLEY's prediction for ~30 MeV neutrinos[1][2]
- Also use MARLEY for predictions for elastic $\nu_e - e^-$ scattering

Flux-averaged exclusive cross sections (w/MSW)

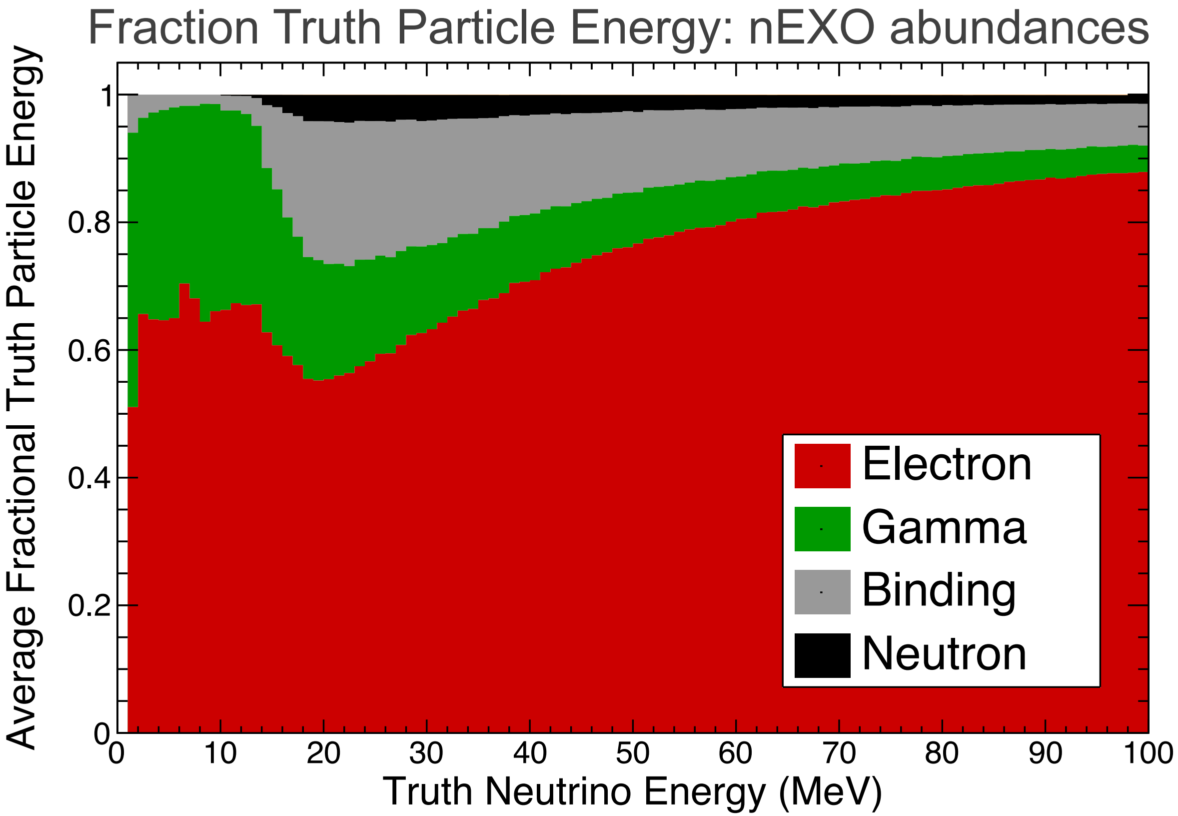
Channel	GKVM [2]	Livermore [5]	Pinched-thermal
^{136}Xe			
$^{136}\mathrm{Xe}(\nu_e, e^-)$	2.82	6.30	2.39
$^{136}\mathrm{Xe}(\nu_e, e^-)^{136}\mathrm{Cs_{bound}}$	0.59	1.01	0.56
$^{136}\mathrm{Xe}(\nu_e, e^- + n)^{135}\mathrm{Cs}$	2.21	5.23	1.82
$^{136}\mathrm{Xe}(\nu_e, e^- + 2n)^{134}\mathrm{Cs}$	0.02	0.06	0.01
^{134}Xe			
$^{134}\mathrm{Xe}(\nu_e, e^-)$	2.44	5.57	2.04
$^{134}\mathrm{Xe}(\nu_e, e^-)^{134}\mathrm{Cs_{bound}}$	0.52	0.97	0.48
$^{134}\mathrm{Xe}(\nu_e, e^- + n)^{133}\mathrm{Cs}$	1.91	4.57	1.56
$^{134}\mathrm{Xe}(\nu_e, e^- + 2n)^{132}\mathrm{Cs}$	0.01	0.03	0.01
$\nu_e - e^-$			
$\nu_e - e^-$	0.08	0.11	0.08

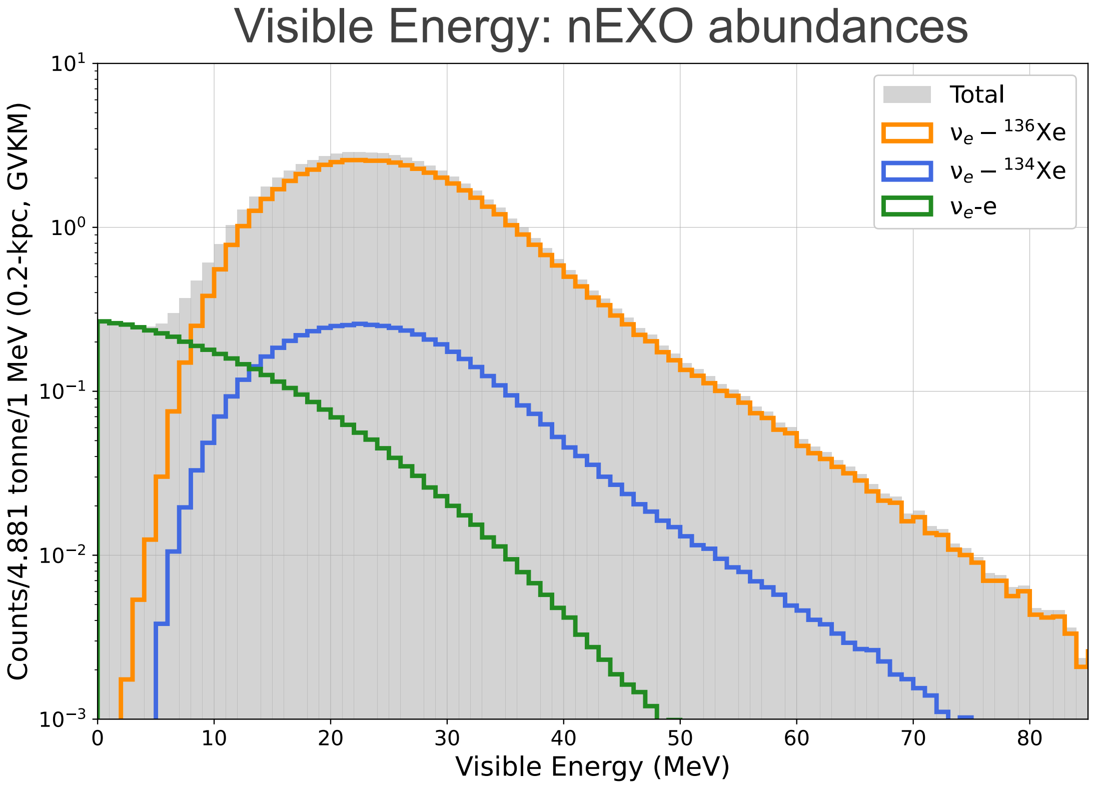
TABLE II. Cross sections are per atom in units of 10^{-40} cm^2, and use the assumption of MSW oscillations in the normal mass hierarchy. Predictions from MARLEY use the same assumptions as in Tab. I.

[1] P. An, et al., *Phys. Rev. D* 108, 072001 (2023)
[2] P. An, et al., *arXiv:2305.19594* (2023)

MARLEY's predictions: experimental signatures

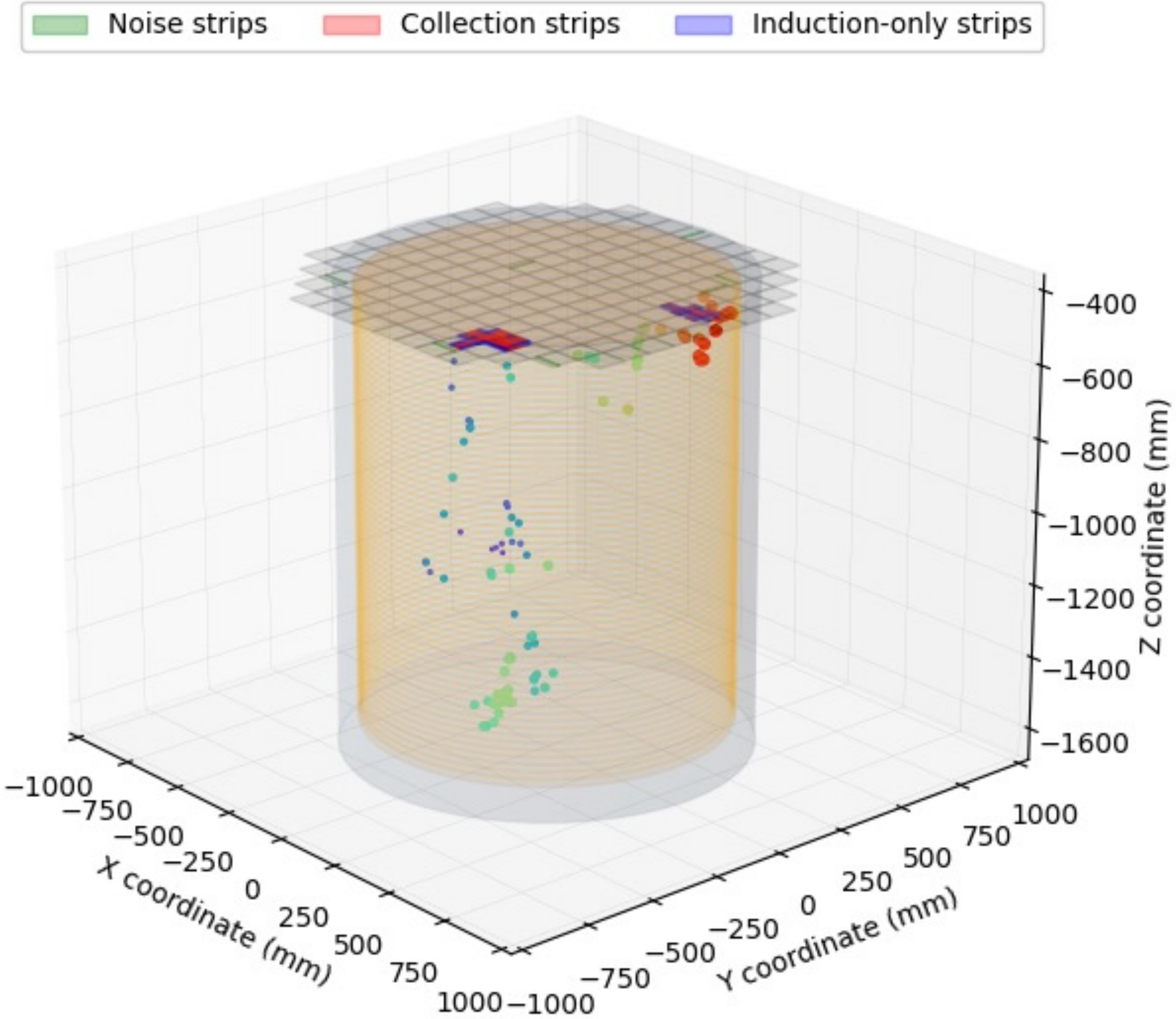
- MARLEY predicts fraction of neutrino energy going into different channels
- Visible energy (prompt) defined as $E_{vis} = E_{e^-} + E_\gamma + E_{NR,\, quenched}$





Outlook

- Simulating MARLEY events in `nexo-offline` to study reconstruction, detector efficiency
- Plan to extend work to 300t detector with same isotopic abundances
- Natural Xe requires B(GT) for odd isotopes (^{129,131}Xe make up 47.6% of natural Xe)
  - Not easy to calculate theoretically, no measurements
- Work would benefit from measurements of *B(GT)* strengths or improved theory calculations, more measurements of excited states and de-excitations



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