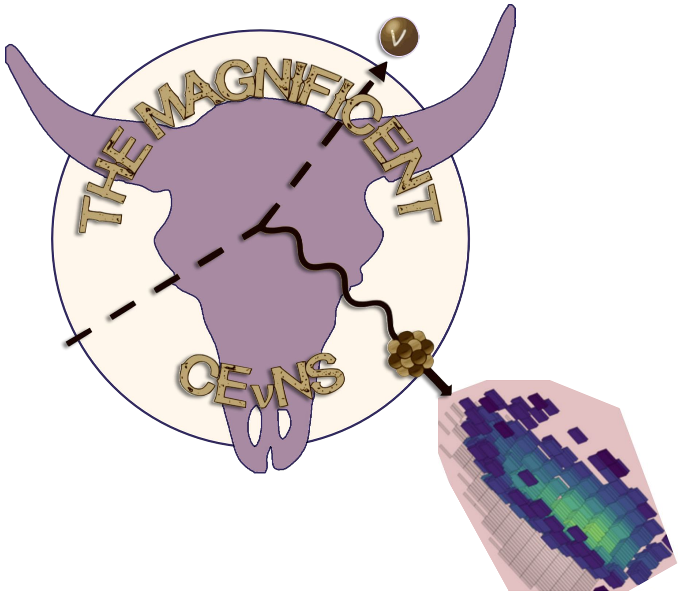
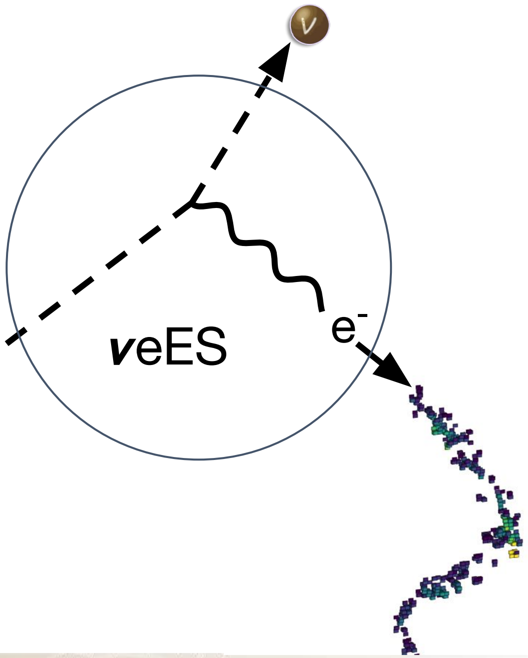
Optimizing the directional detection of low-energy electron recoils

Majd Ghrear
majd@hawaii.edu

Department of Physics and Astronomy
University of Hawai'i





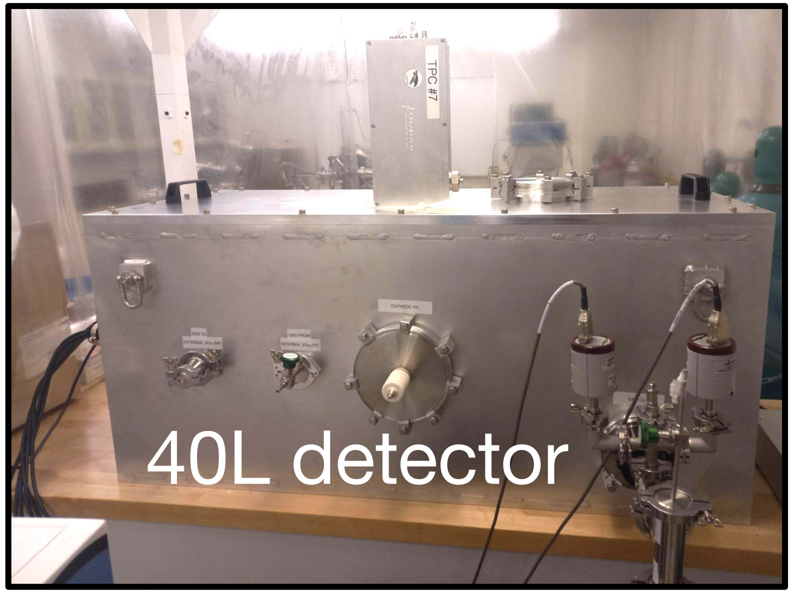
Motivation

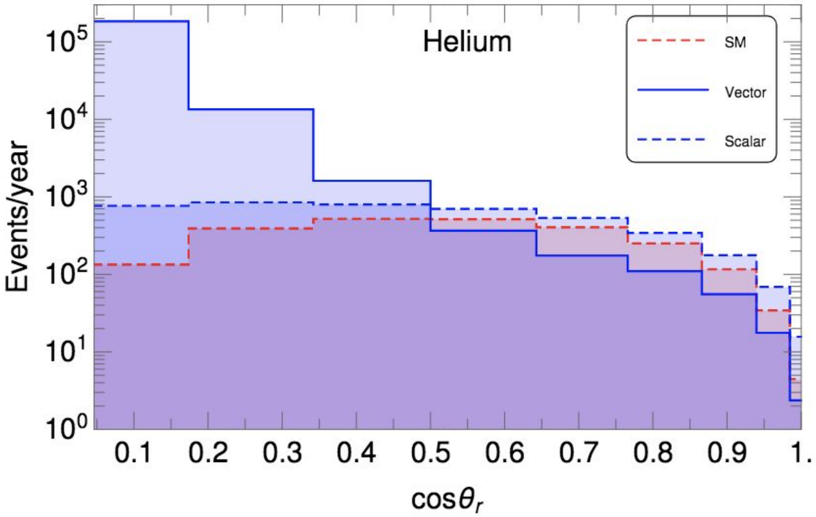
Background:

- Our group is developing gaseous detectors of nuclear and electron recoils, uniquely capable of providing 3D recoil direction
- 40L thesis detector (https://indico.cern.ch/event/1358339/contributions/5899430/)
- Exploring deploying detectors at SNS Oak Ridge

Directionality is desirable:

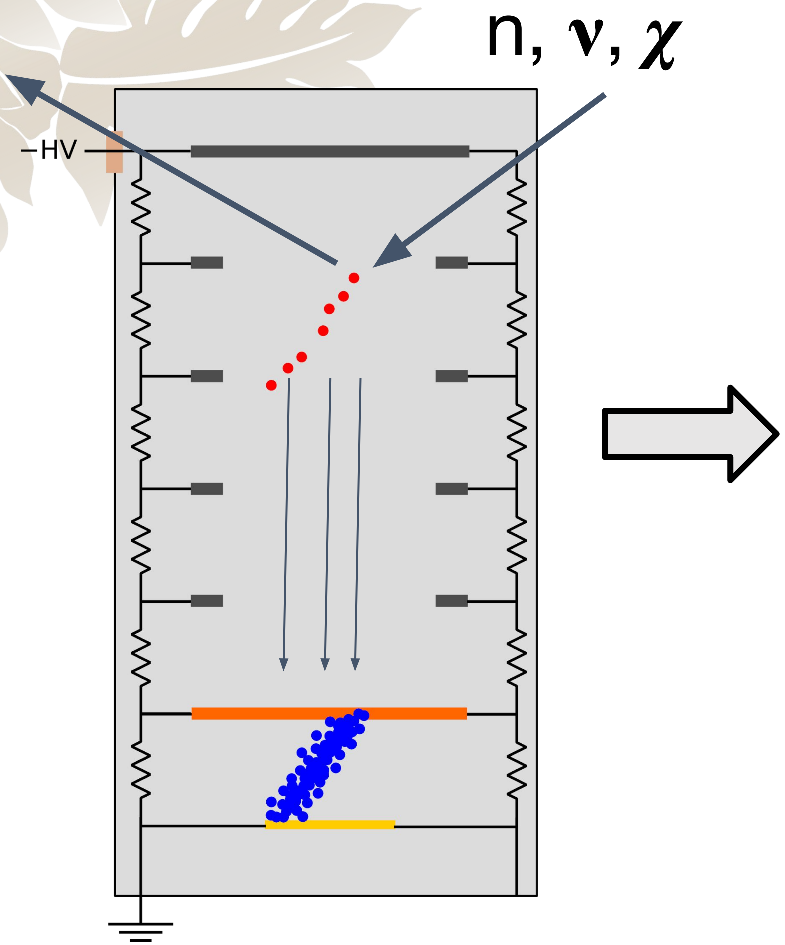
- Can provide valuable information in discerning new physics from CEvNS experiments (Abdullah et. al. 2003.11510, Sierra et. al. 2103.10857)
- Solar Neutrino Spectroscopy (Lisotti, O'hare et. al. 2404.03690)
- DM searches / pointing / etc. (Vahsen, O'hare, Loomba 2102.04596)

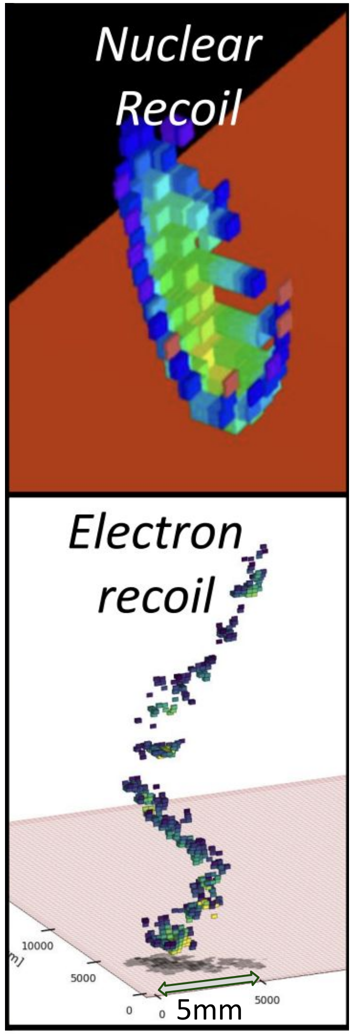




Abdullah et. al.

Directional Recoil Detection in Gas TPCs



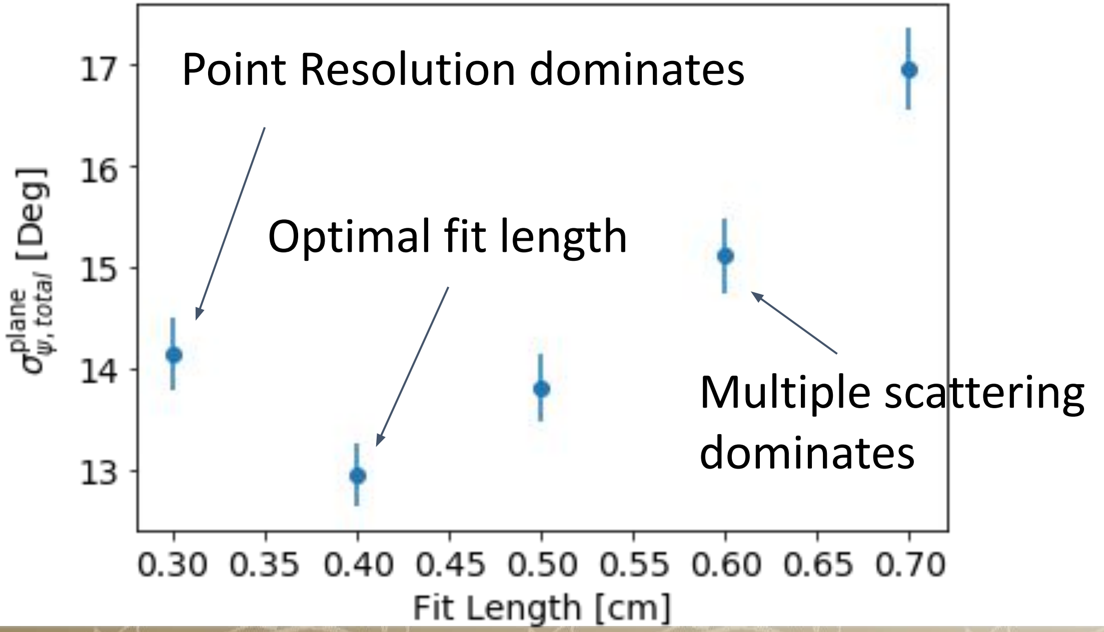


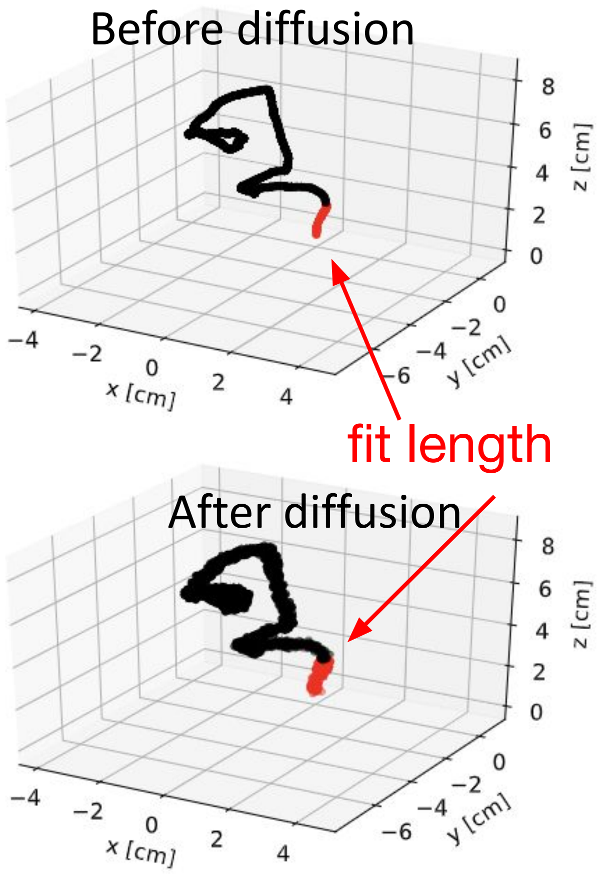
- Gas TPC are the only candidate technology for *directional* detection of low energy (order 1-100 keV) recoils.
- Present two techniques for optimizing directionality:
  1. Predicting the angular resolution of electrons in gas
  2. Probabilistic deep learning for 3D direction

Focus on electrons (more complex) here

Angular Resolution of Electron Recoils

- Two first-order effects influencing angular resolution:
  - Multiple scattering of the electron (or nucleus)
  - Effective point resolution of the detector (diffusion + readout resolution)
- Multiple scattering dominates at longer fit length, point resolution dominates at shorter fit lengths.





Degrad simulation of a 150 keV electron recoil in He : CF4.

Multiple scattering

PDG Review of Particle Physics "Passage of Particles Through Matter"

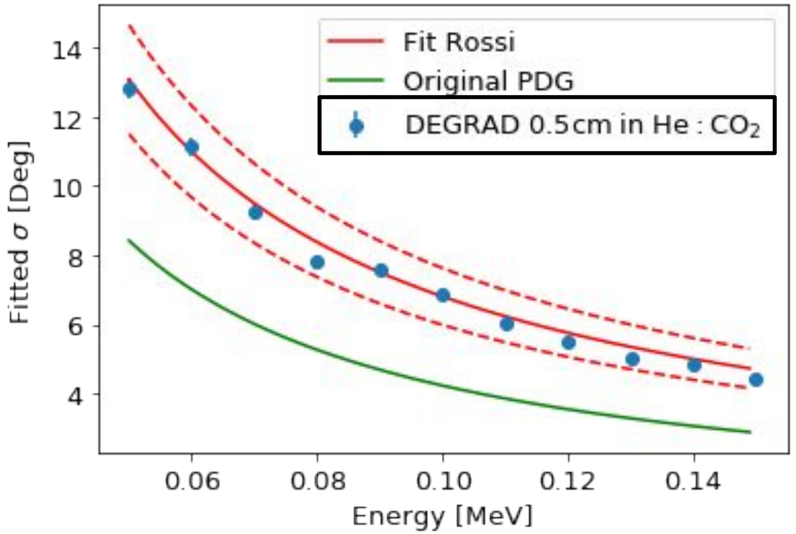
Multiple scattering through small angles

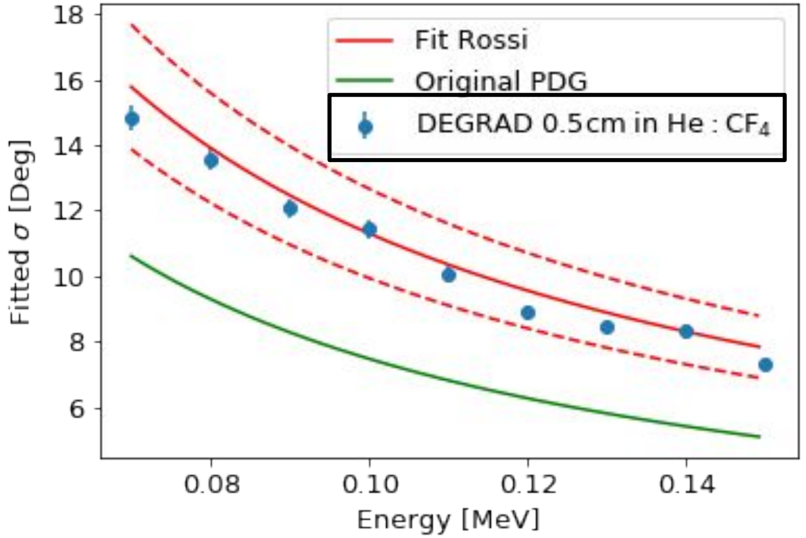
$$\sigma_{\psi}^{\text{plane}} = \frac{z}{\sqrt{3}}\frac{13.6\text{MeV}}{\beta c p}\sqrt{\frac{x}{X_o}}\left[1+0.038ln(\frac{xz^2}{X_o\beta^2})\right]$$

This formula is actually a fit for simulations of heavy particles. It does not work for electrons.

Following the same procedure for electron we obtain.

$$\sigma_{\psi,\text{MS}}^{\text{plane}} = \frac{1}{\sqrt{3}}\frac{13.1\pm1.5\text{MeV}}{\beta c p}\sqrt{\frac{x}{X_o}}.$$





Effective Point Resolution

- The Multiple Scattering formula alone is insufficient, need to consider effective point resolution for a more complete picture

- Conversion from point resolution to angular resolution

Angular resolution

Effective point resolution: Diffusion and readout

$$\sigma_{\psi,\mathrm{PR}}^{\mathrm{plane}} = \frac{\sqrt{12}\sigma_{x,y,z}}{x\sqrt{N}}.$$

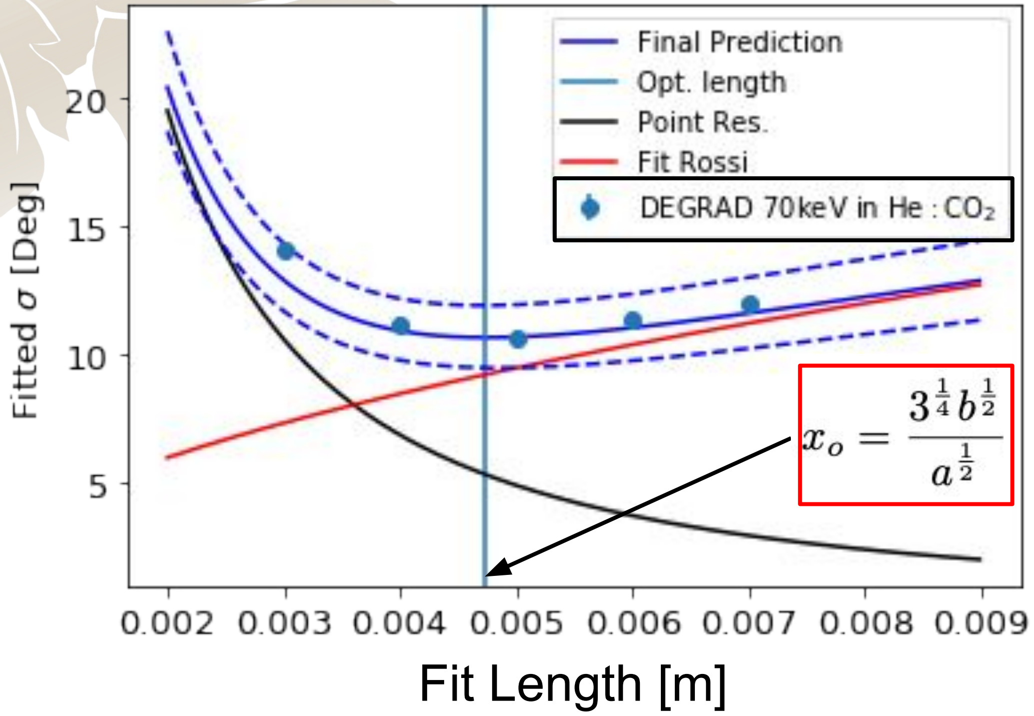
- We combine the point resolution and multiple scattering effects in quadrature

$$\sigma_{\psi,\mathrm{total}}^{\mathrm{plane}} = \sqrt{a^2 x + b^2 x^{-3}}. \qquad a \equiv \frac{1}{\sqrt{3}} \frac{13.1\mathrm{MeV}}{\beta c p \sqrt{X_o}} \qquad b \equiv \sigma_{x/y/z}\sqrt{\frac{12W}{dE/dx}}$$

3-D tracking in a miniature time projection chamber https://doi.org/10.1016/j.nima.2015.03.009

Results

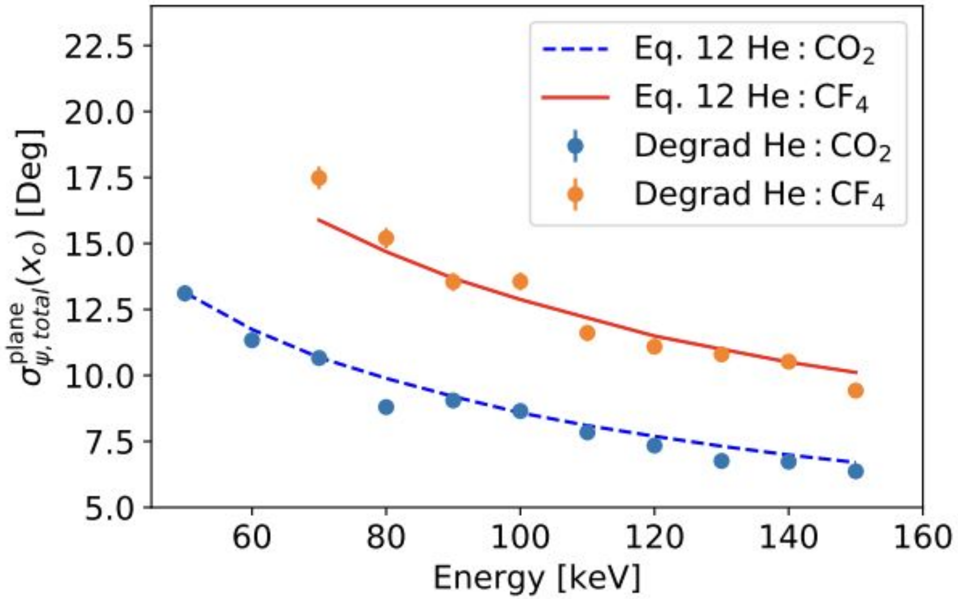
70 keV electron recoils in 70% He 30% CO_2



- The optimal track length is well predicted
- The angular resolution near the optimal length is well predicted

This provides a quick way to estimate the angular resolution of electron recoils as

$$\sigma^{\text{plane}}_{\psi,\text{total}}(x_o) = \frac{2a^{\frac{3}{4}} b^{\frac{1}{4}}}{3^{\frac{3}{8}}}.$$

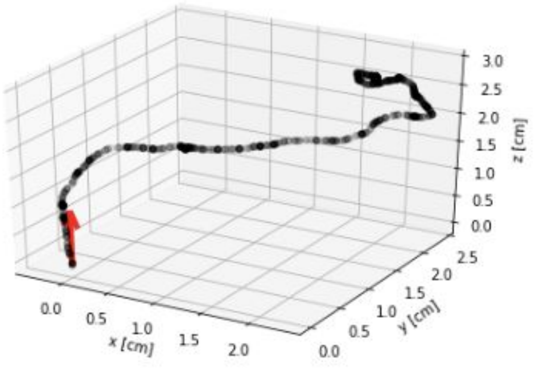


- This formula can be used for design optimization.
- We are working on experimental validation

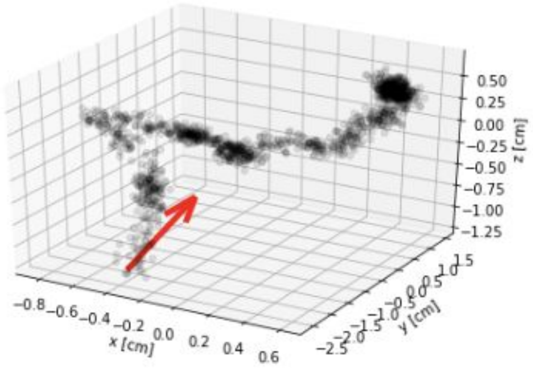
Probabilistic Deep Learning for 3D Direction

Simulations:

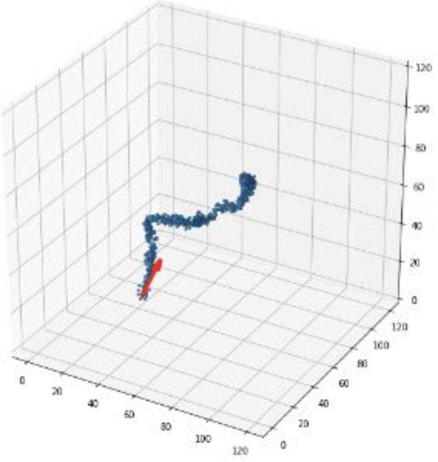
- 10^6 electron recoils at 40,45,50 keV using DEGRAD
- 70% He : 30% CO_2 at 20 Celsius and 760 Torr
- Recoils are generated isotropically with known true direction
- Diffusion drawn uniformly between 160-466 μm
- Binned into $(500\ \mu m)^3$ voxels



(a) Raw Degrad simulation



(b) Processed simulation

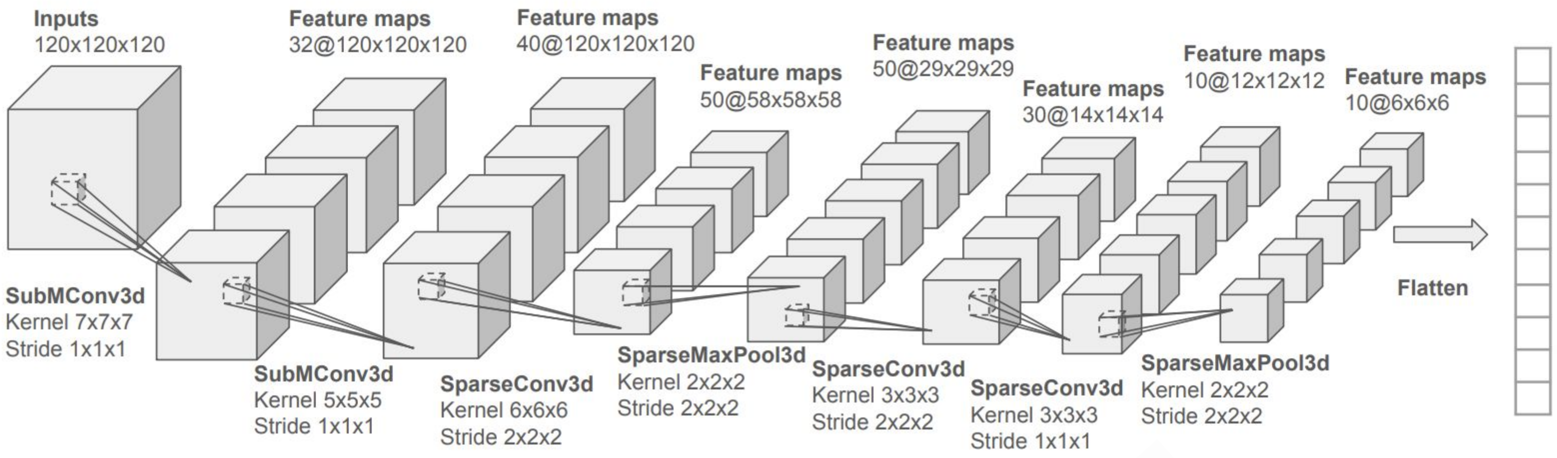


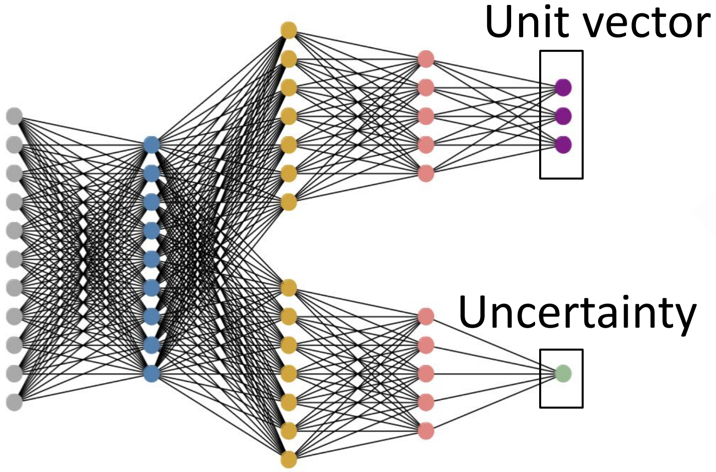
(c) Voxilized simulation

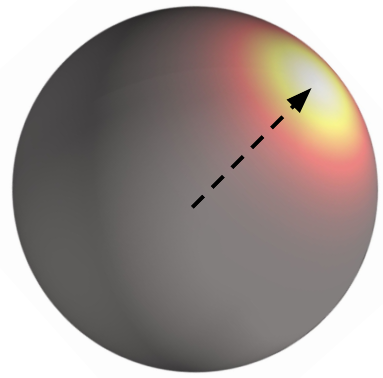
Deep probabilistic 3D angular regression

Architecture:

- Every event has 1,728,000 features.
- In a typical event, ~0.01% of the features are non-zero
- Sparsity is common in highly-segmented 3D data and it is essential to take advantage of it
- Dual-head architecture for heteroscedastic regression







Deep probabilistic 3D angular regression

Loss function

- Derived from the Kent / von Mises-Fisher distribution
- Requires approximations to stabilize training
- **This is the first probabilistic deep learning framework for predicting 3D directions**

Predicted Uncertainty

Label

$$\frac{-\ln \mathcal{L}}{N} = \frac{-1}{N} \sum_{i=1}^{N} \ln\left(\frac{\kappa_i}{4\pi \sinh(\kappa_i)}\right) + \kappa_i(\boldsymbol{y}_i \cdot \boldsymbol{y}_{pred_i})$$

Predicted direction

15th order Taylor series about $\boldsymbol{\kappa}_i = 0$

$$\mathrm{NLL} = \frac{-1}{N} \sum_{i=1}^{N} \texttt{torch.where}\left(\kappa_i < 2.65, T_{15}(\kappa_i), \ln(\frac{\kappa_i}{2\pi}) - \kappa_i\right) + \kappa_i(\mathbf{y}_i \cdot \hat{\mathbf{y}}_i)$$

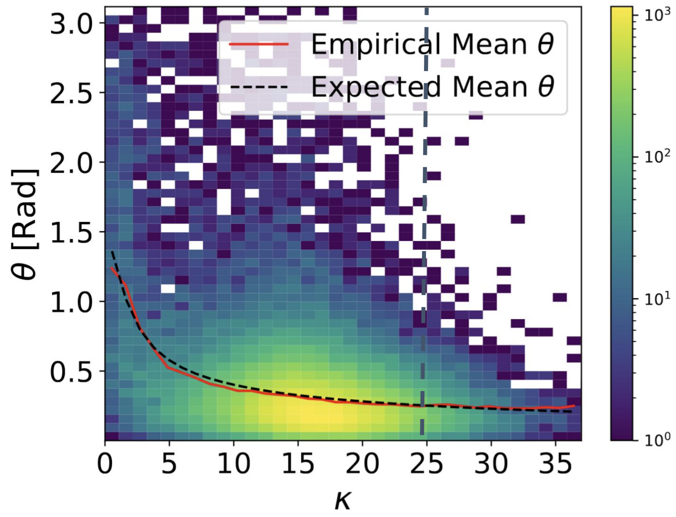
Deep probabilistic 3D angular regression

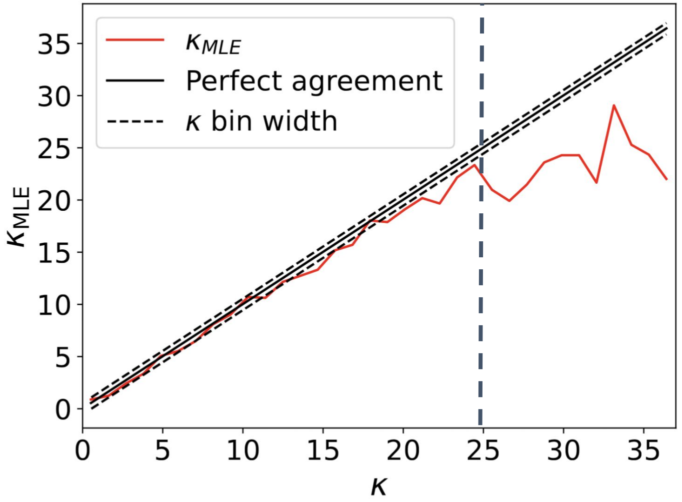
This framework solves 3 problems at once:

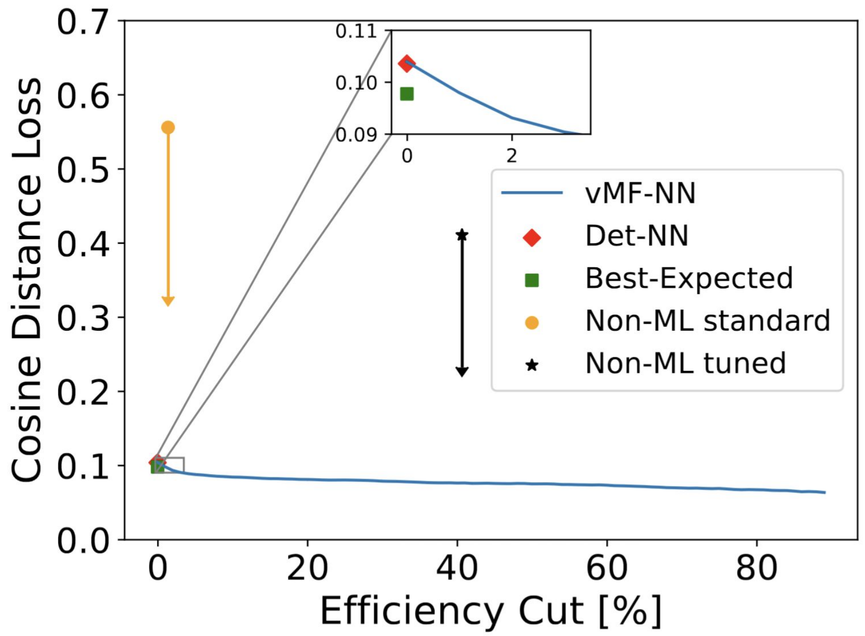
- It determines the Head/Tail
- It significantly improves angular resolution
- It estimates uncertainty accurately
  - can be leveraged to remove high-uncertainty events

https://arxiv.org/abs/2403.15949
Accepted by Machine Learning: Science and technology

40 keV electron recoils in He:Co2



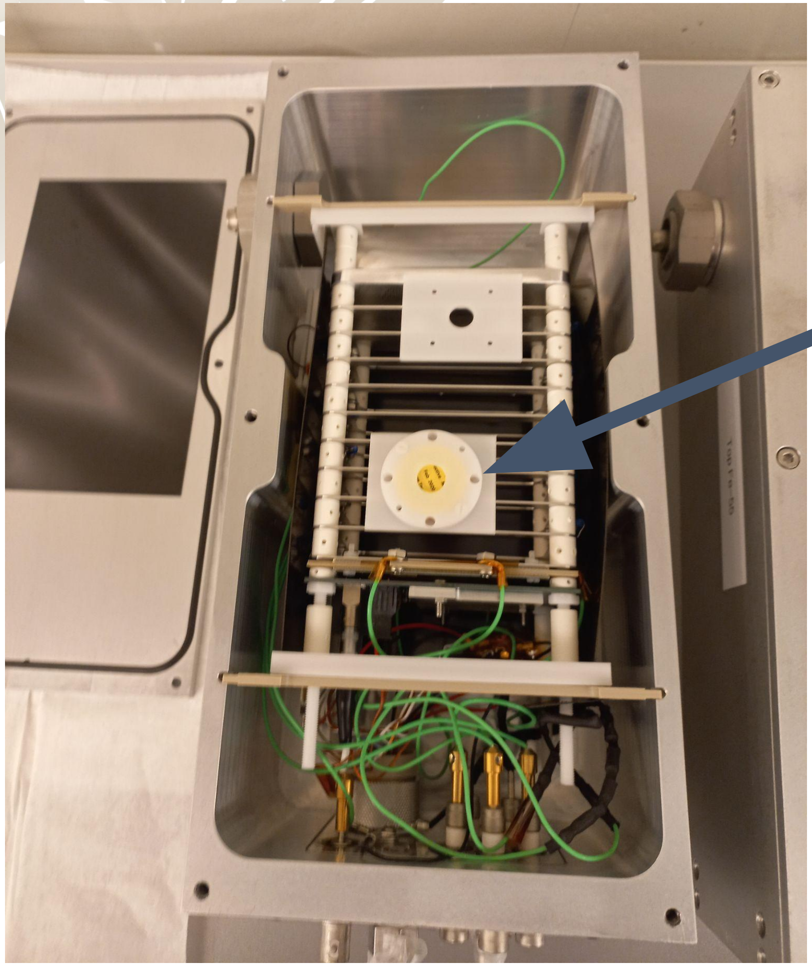




Conclusion

- Directional detection is challenging at low energies!
- We developed two techniques to maximize directionality
  - A formula which predicts the best achievable angular resolution given recoil energy, gas properties, and the effective point resolution (paper in preparation)
  - A probabilistic deep learning method for fitting complex 3D recoil tracks (paper accepted)

Ongoing: Experimental Validation



Sr-90

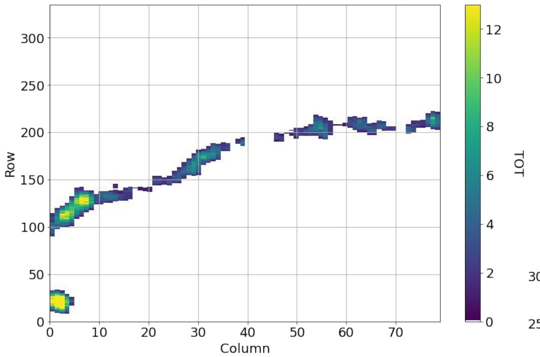
PHYSICAL CHARACTERISTICS

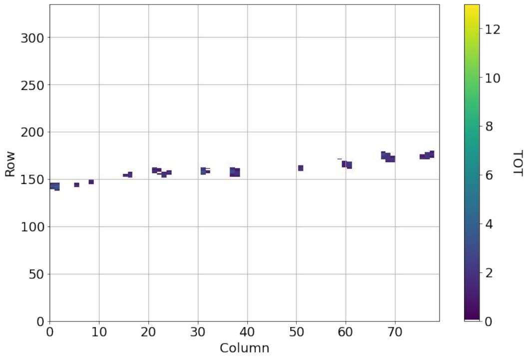
HALF-LIFE: 28.8 years

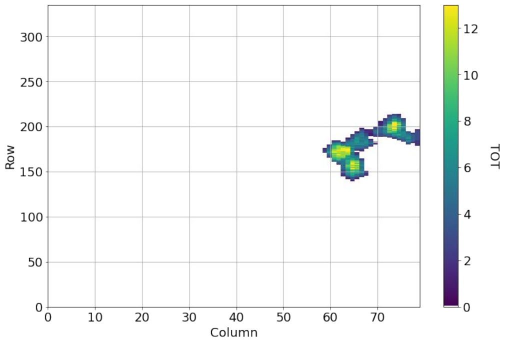
DECAY EMISSIONS

Includes Y-90 emissions under the assumption of secular equilibrium

Gammas / X-rays		Betas / Positrons (+) / Electrons*		Alphas	
E (keV)	%	E (keV, Ave)	%	E (keV)	%
		196	100		
		933	100		







Thank you!

majd@hawaii.edu