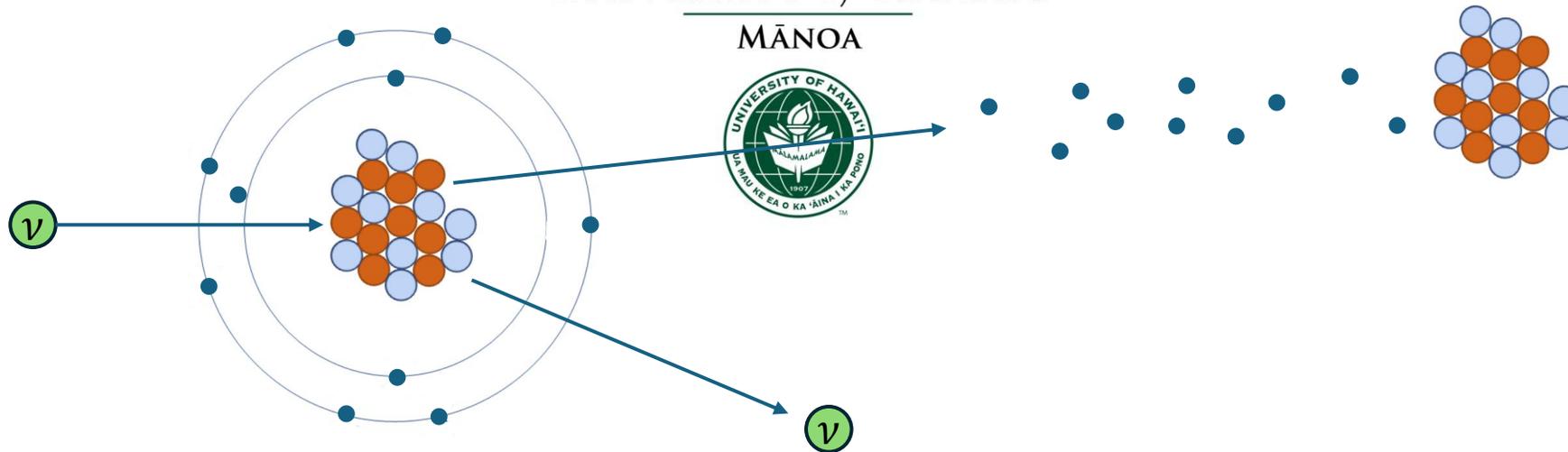


# Development of a scalable 40L gaseous TPC module with micromegas strip readout for directional reconstruction of low-energy nuclear recoils

Michael Litke

UNIVERSITY of HAWAII<sup>®</sup>

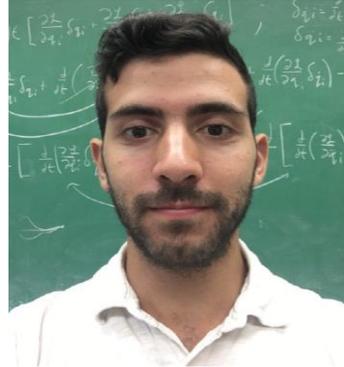
MĀNOA



# Vahsen lab TPC R&D



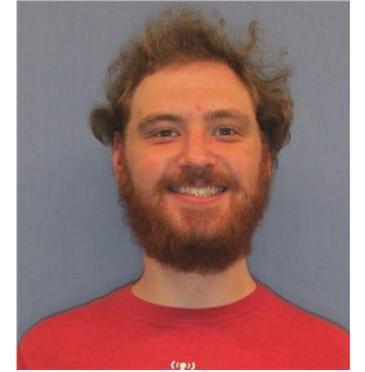
Prof Sven Vahsen



Dr Majd Ghrear (frmr PhD student)



Shashank Jayakumar (post doc)



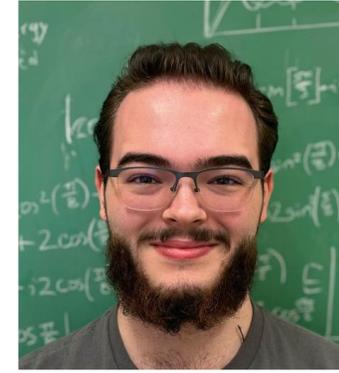
Michael Litke (PhD Student)



Aleczander Paul (PhD student)



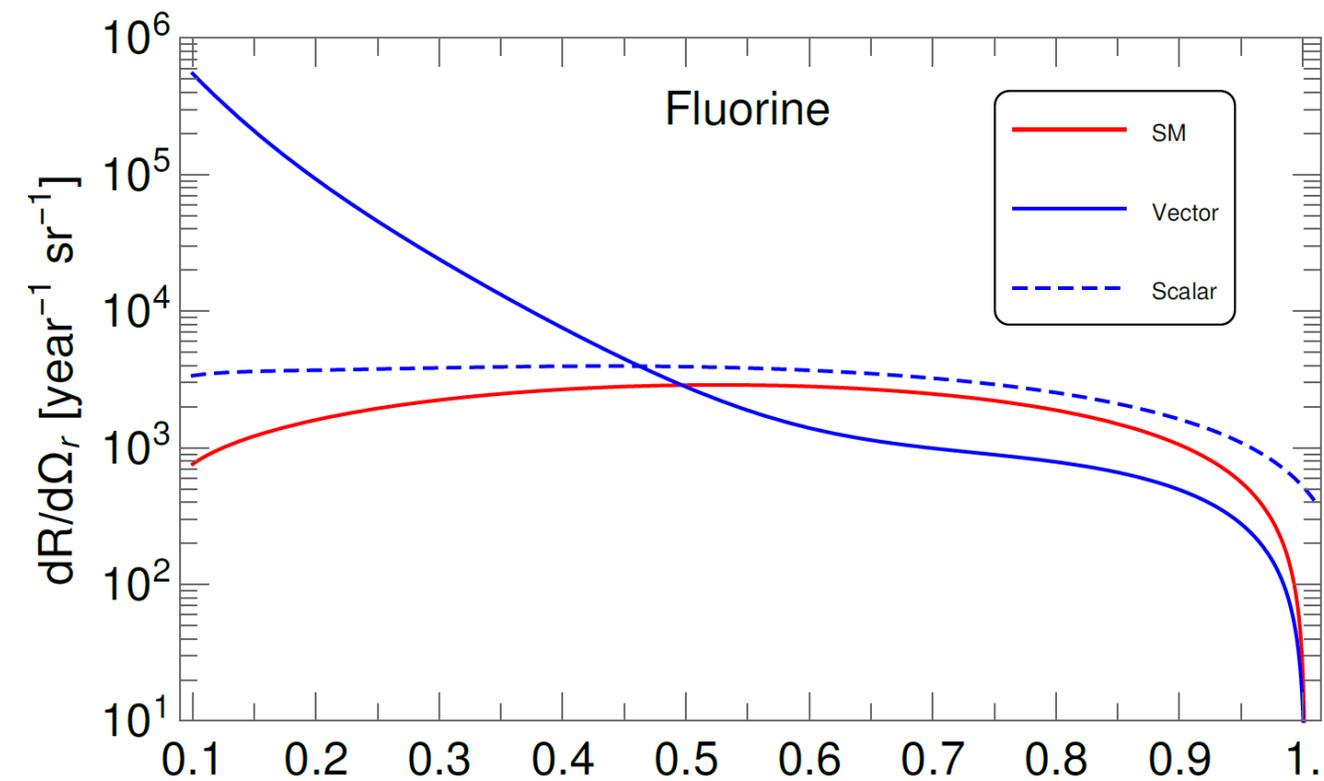
Sola Long (PhD Student)



Gage Wettlaufer (frmr undergrad)

- Motivation for directional recoil detection
  - 
  -
- Scaling up directional recoil detection
  - 
  -
- 40 L TPC commissioning
  - 
  -
- Plans at Oak Ridge National Lab

# Potential BSM physics probed by directional recoil detection

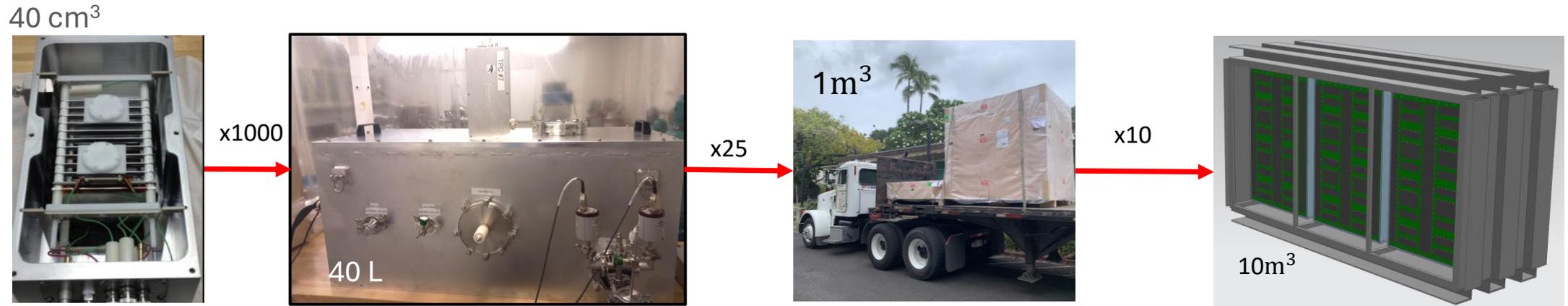


- If there is beyond the standard model physics involved in CE $\nu$ NS the angular distribution of nuclear recoils is sensitive to it
- Directional detection provides an opportunity to probe physics that so far has been **unexplored**
- 10-30 events per year might be enough to probe this

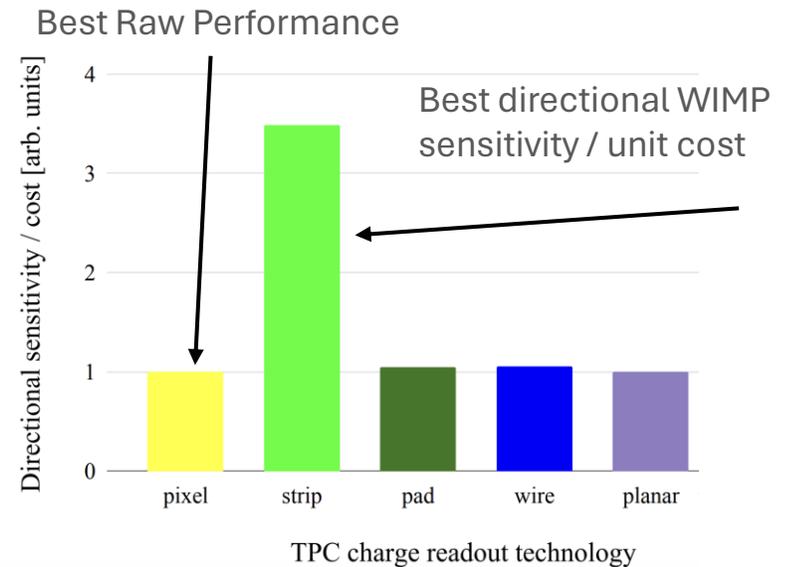
The angular distribution of CE $\nu$ NS recoils assuming light scalar and vector mediators Abdullah et al

[arXiv:2003.11510](https://arxiv.org/abs/2003.11510)

# Scalable Directional Detectors

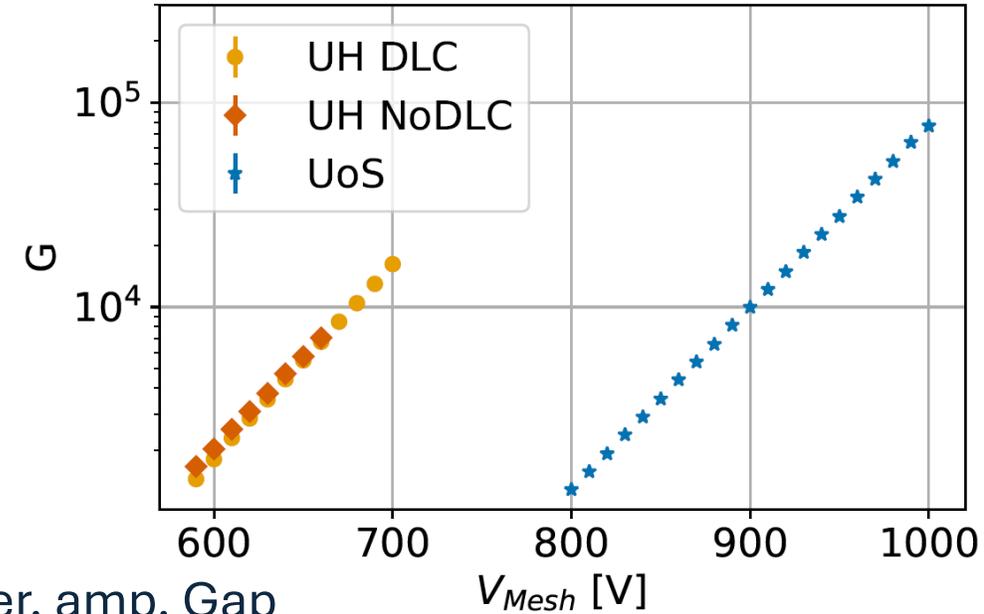
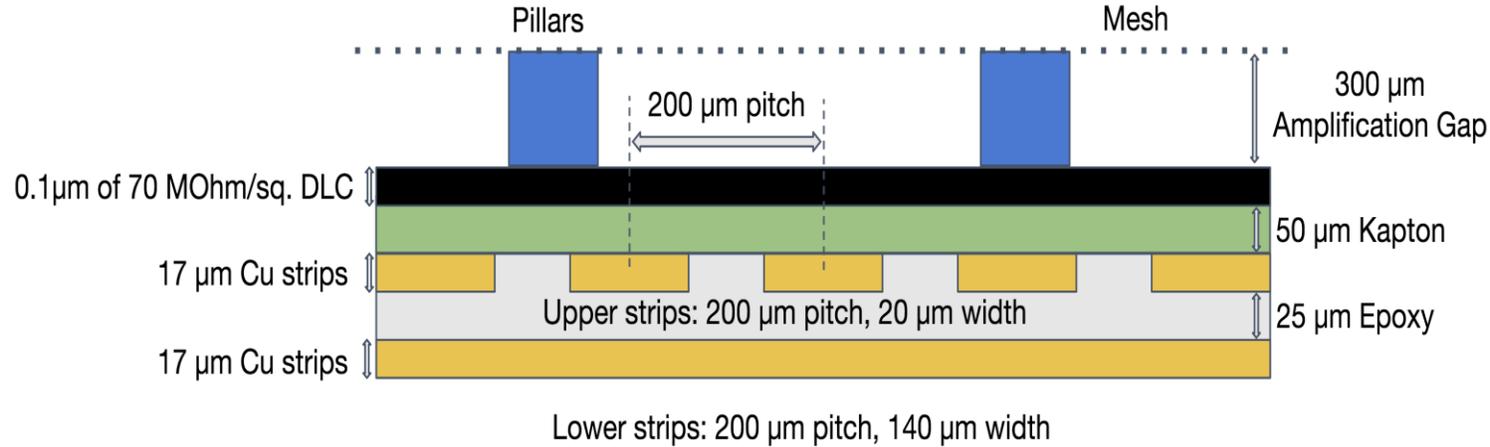


- Main barrier to scaling up is cost
  - ASIC pixel readouts are very expensive per unit area
- 3 key changes
  - GEMs → Micromegas
  - Pixel → strip readout
  - Continuous volume → separated gas volumes



# New Readout structure

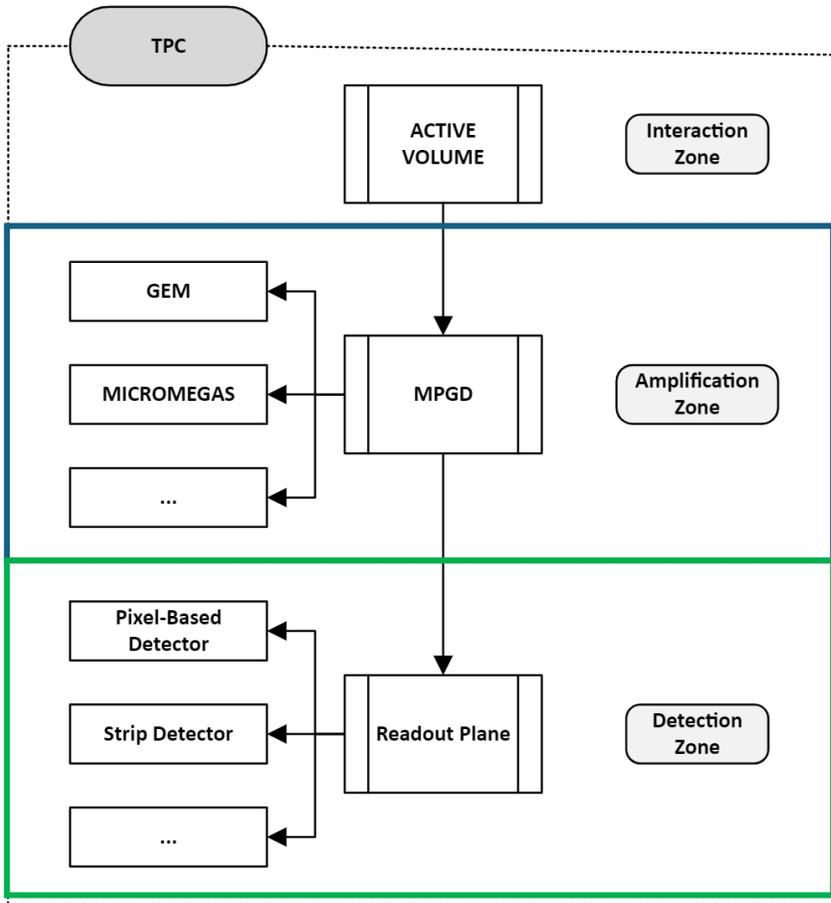
Ghrear et al [2410.00048](#)



## Finding a new readout plane:

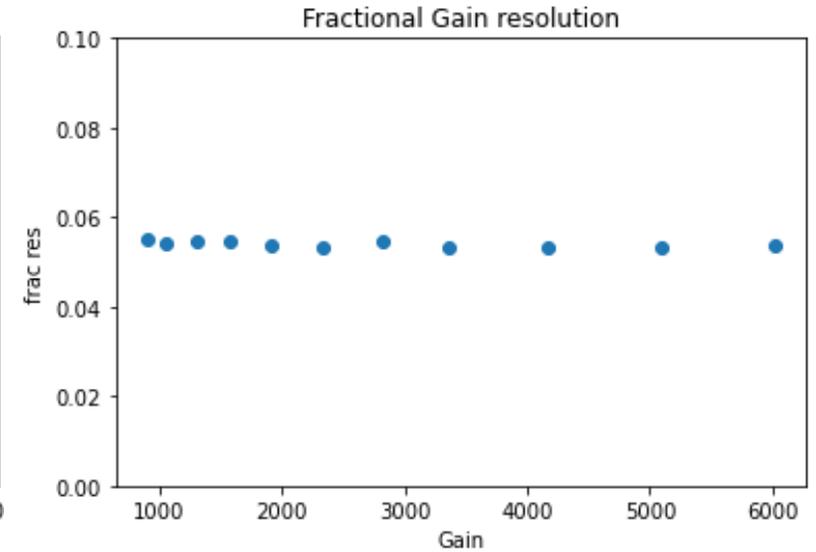
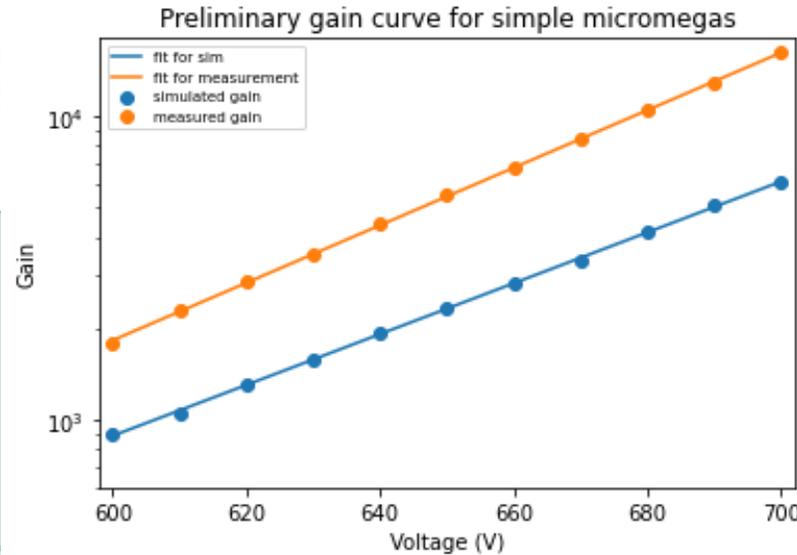
- Compared 9 readouts with varying upper strip width, DLC layer, amp. Gap
- Compare gain, energy resolution, charge sharing
- Found the optimal strip width for both upper and lower strips
- We found that 300 μm amp gap give gain  $> 10^5$ , sufficient to compensate for the higher noise of strips
- Found DLC layer allows higher gains before sparking, no damage to readout electronics after sparking
- Ordered new plane with best parameters (listed in above diagram), to be installed in 40 L later this year

# Simulating the new readout system



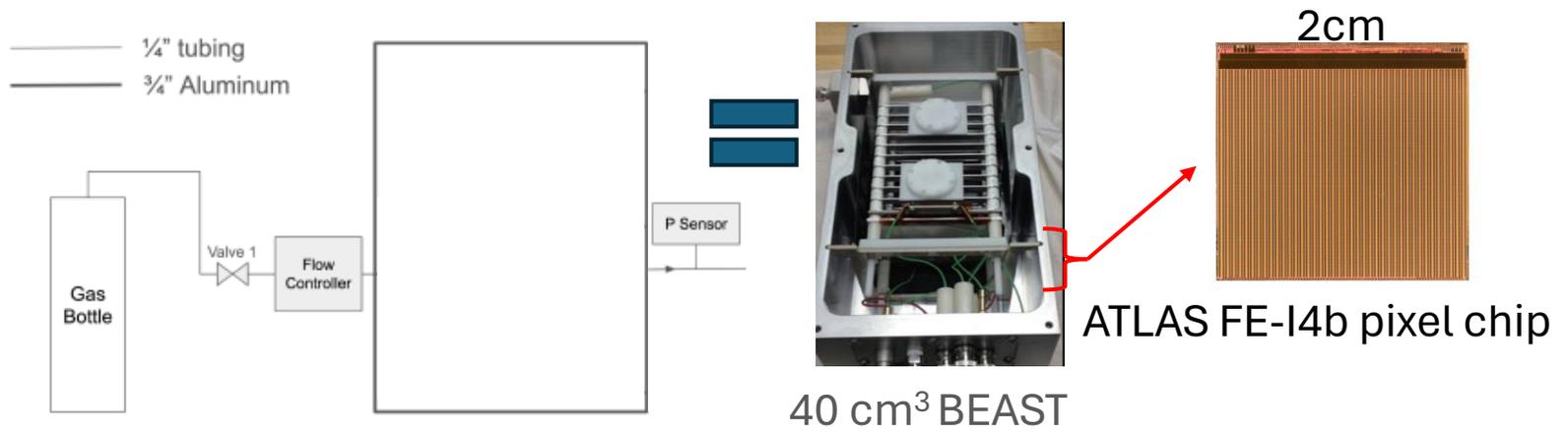
• Current area of simulation

• Future work

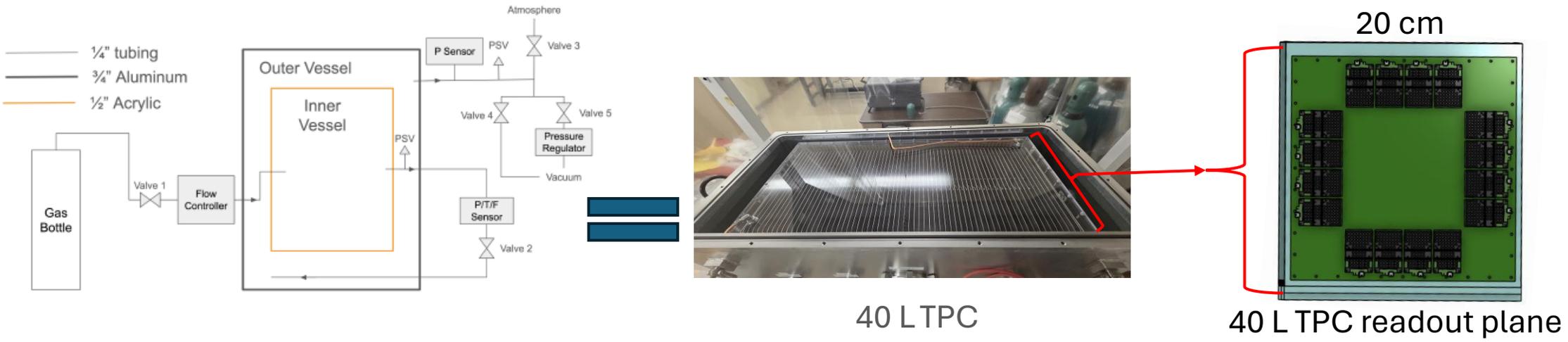


- Simulated gain curve is exponential and grows at very nearly the same rate as the measured gain curve, but there is an overall discrepancy of about a factor of 2
- The fractional resolution of our simple micromegas approaches 5.3%, which is about half of the measured value.
- We observed no positional dependence for the simulated gain

# The new gas system



- Strip readout separates detection elements from amplifiers, so we can move them outside the active volume
- Separated active and dirty volumes should increase gas purity
- To be confirmed experimentally



# 40L TPC commissioning plan

- Detector has been assembled, high voltage spark testing is completed
- Remaining commissioning plan is as follows

10/15	11/1	11/15	12/1	12/15	2026
Gas system commissioning					
Low voltage testing					
Calibration with sources					

Source calibration progression:

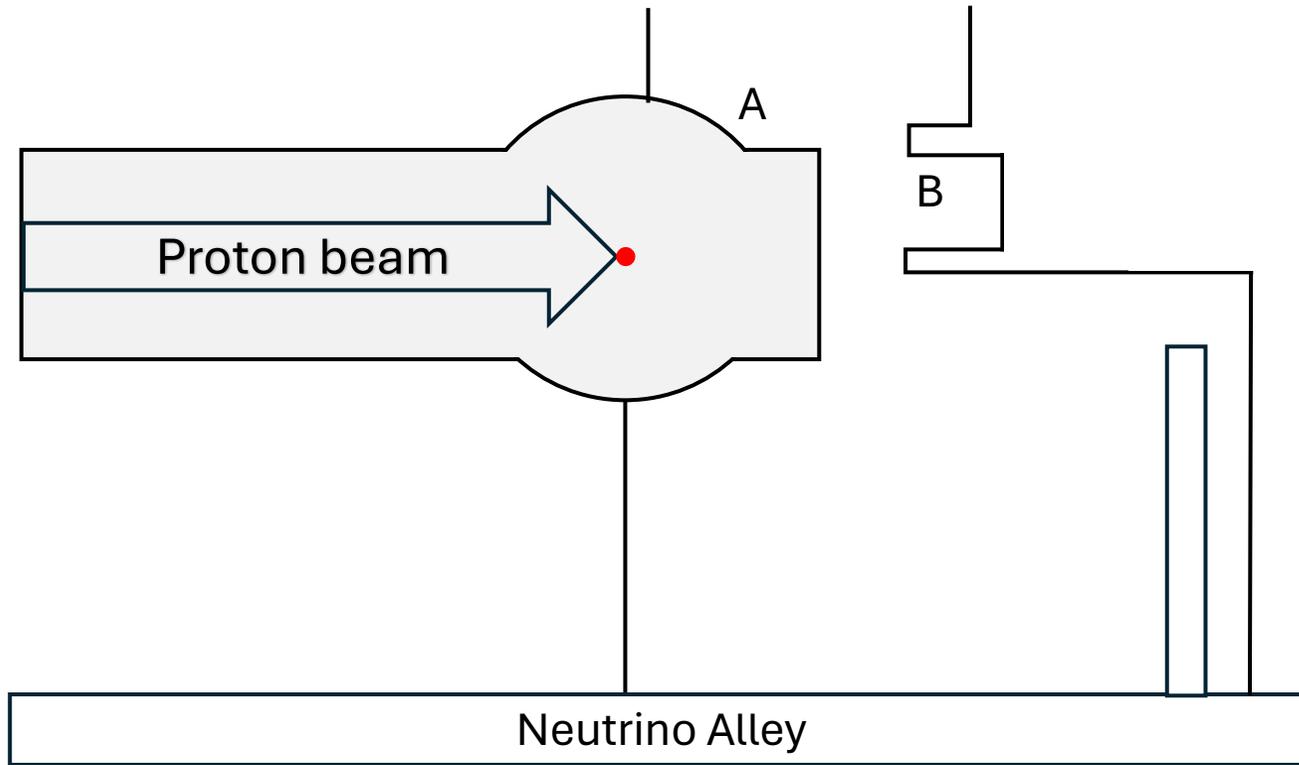
- Fe-55 for gain calibration, gain resolution measurement
- Angular resolution measurement with alpha particles
- Neutron source to conduct first nuclear recoil measurements

# Plans at Oak Ridge



- Next stage of our program is a directional  $CE\nu NS$  measurement at Oak ridge SNS
  - Highest rate pulsed neutrino source in the US
  - Directional  $CE\nu NS$  detection at Oak Ridge is an important logistical and financial middle ground between current detectors and ones capable of a DM search

# Site selection at SNS



A: 6-meter position B: 12-meter position

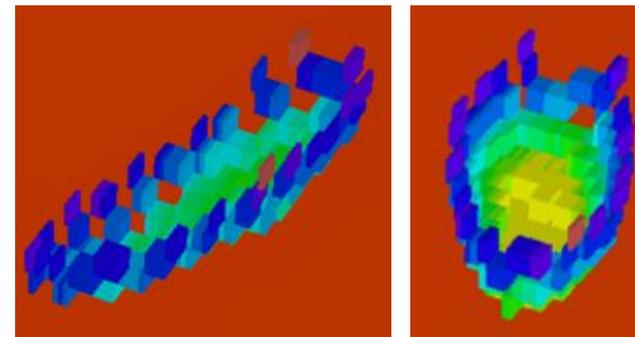
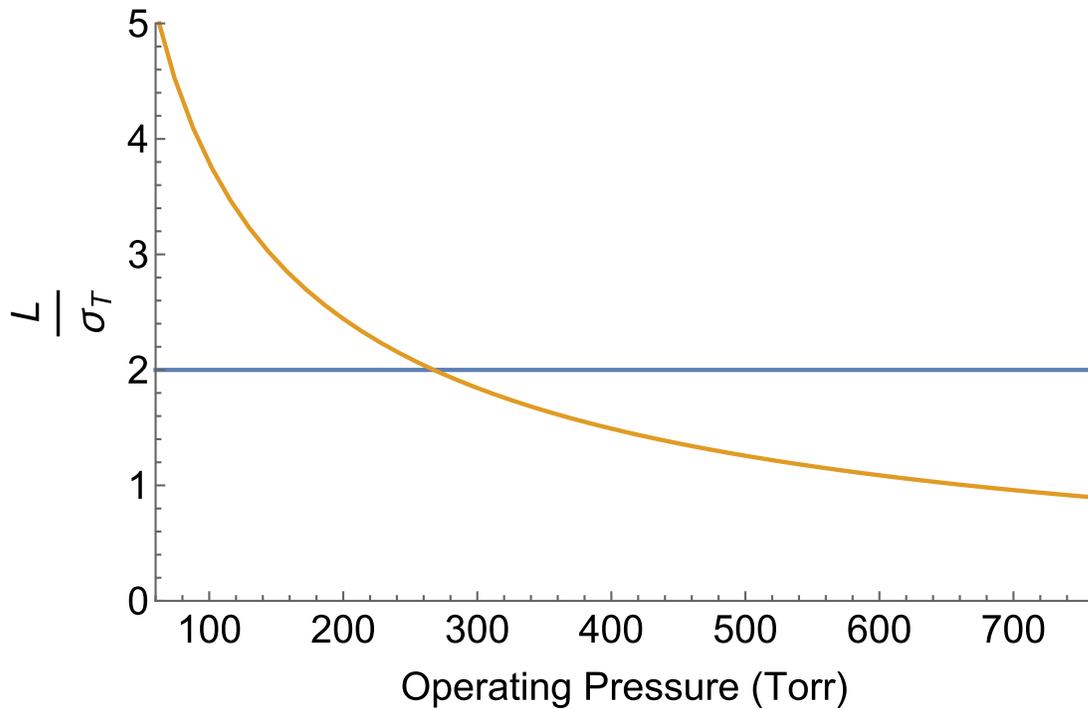


Prof Vahsen standing in position B

- Neutrino alley not suitable for low pressure GAS TPC, new site is needed
- Neutron background measurements at A&B using BEAST TPCs and 40L planned for next year. Looking at background and possible shielding

# Future work: Gas optimization and plans for Oak Ridge

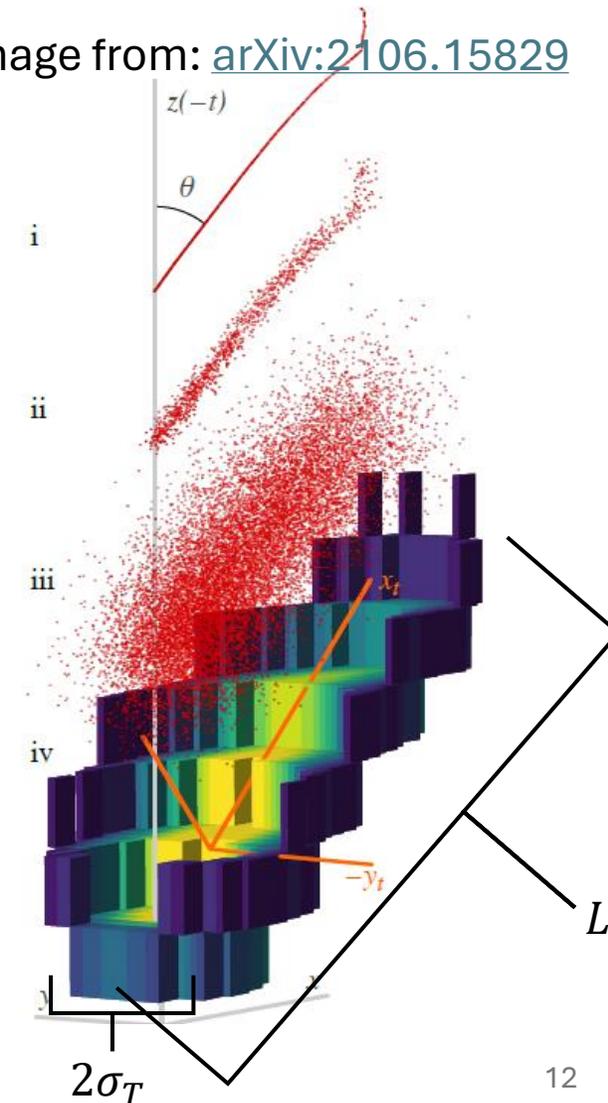
- An event directional if the un-diffused recoil track length  $L$  is more than twice the transverse width of the electron cloud  $\sigma_T$ :  $\frac{L}{\sigma_T} \geq 2$
- Assuming 1.3 GeV protons, beam power of 2 mw, 5000 hours/year (SNS projections for 2026) 12 m from the source,  $1\text{m}^3$  detector running  $\text{CF}_4$
- 276 Torr is the optimal pressure
- We estimate 18 directional fluorine events in a year of operation



More directional

less directional

Image from: [arXiv:2106.15829](https://arxiv.org/abs/2106.15829)

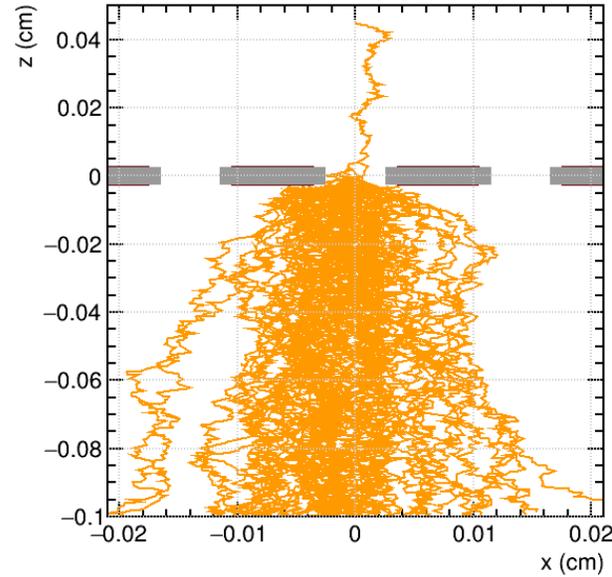
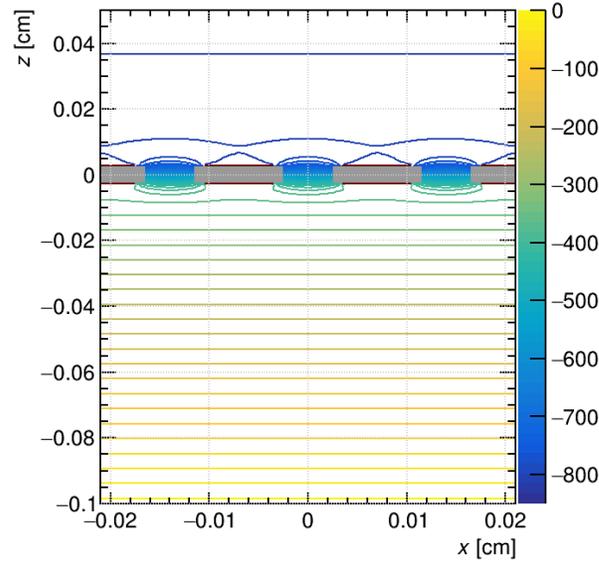
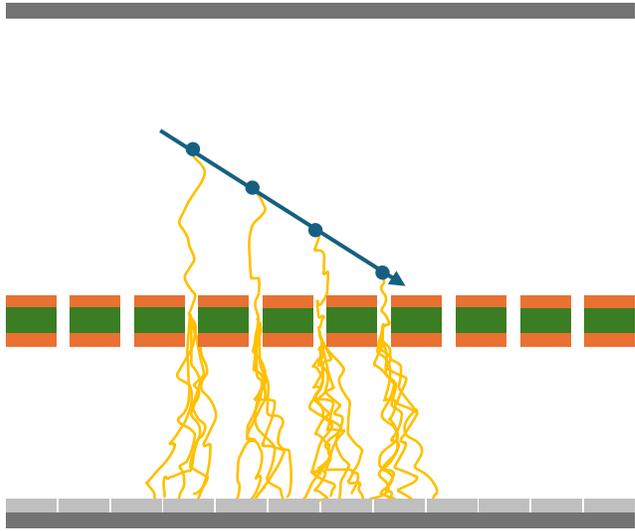


# Conclusions and plans for next year

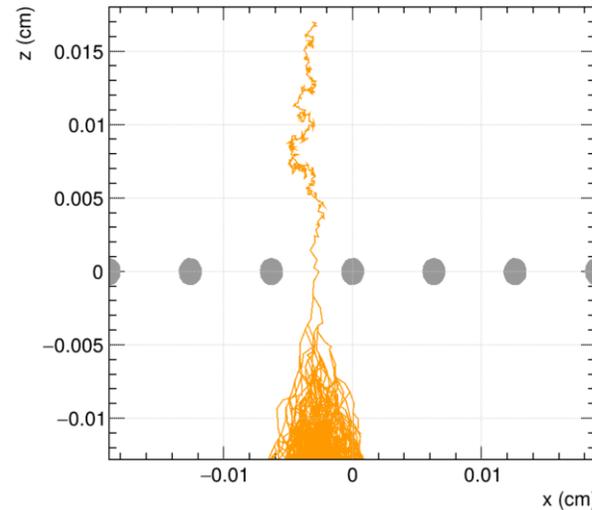
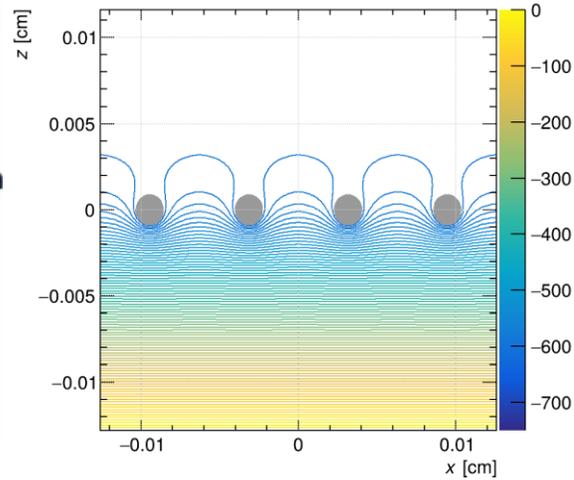
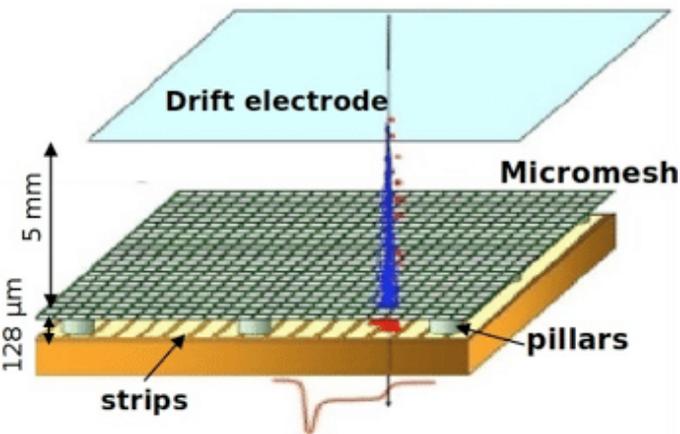
- We have scaled up from  $40 \text{ cm}^3$  to 40 L active volume
- Commissioning of the 40 L prototype is underway, with plans to use it for neutron background measurements at ORNL next year
- Readout simulations and gas selection are in process
- Plan to build a  $1\text{--}10 \text{ m}^3$  detector to conduct first directional CE $\nu$ NS measurement

# Backup

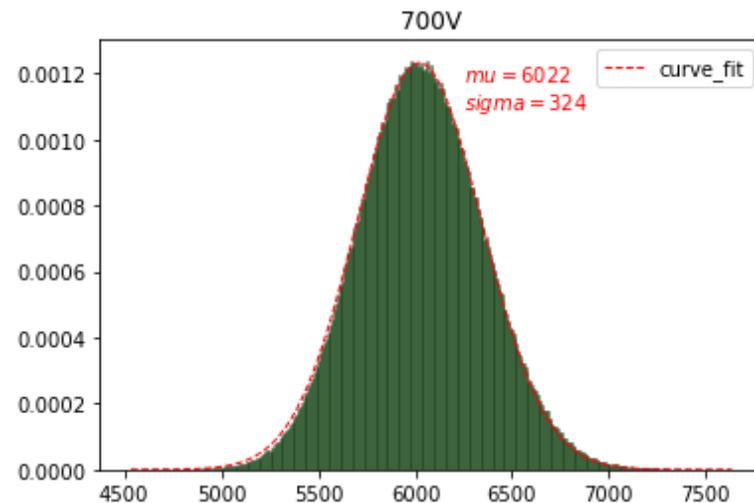
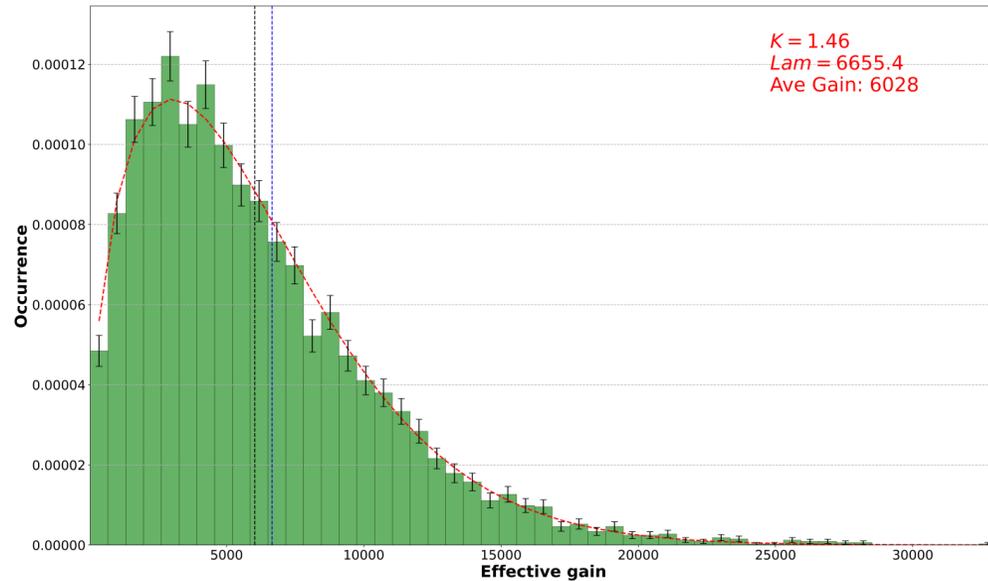
# Gems to Micromegas



- GEMs above Micromegas below
- Micromegas + strips combo is well established and reduced cost vs gems + pixels



# Backup slide: Gain distributions

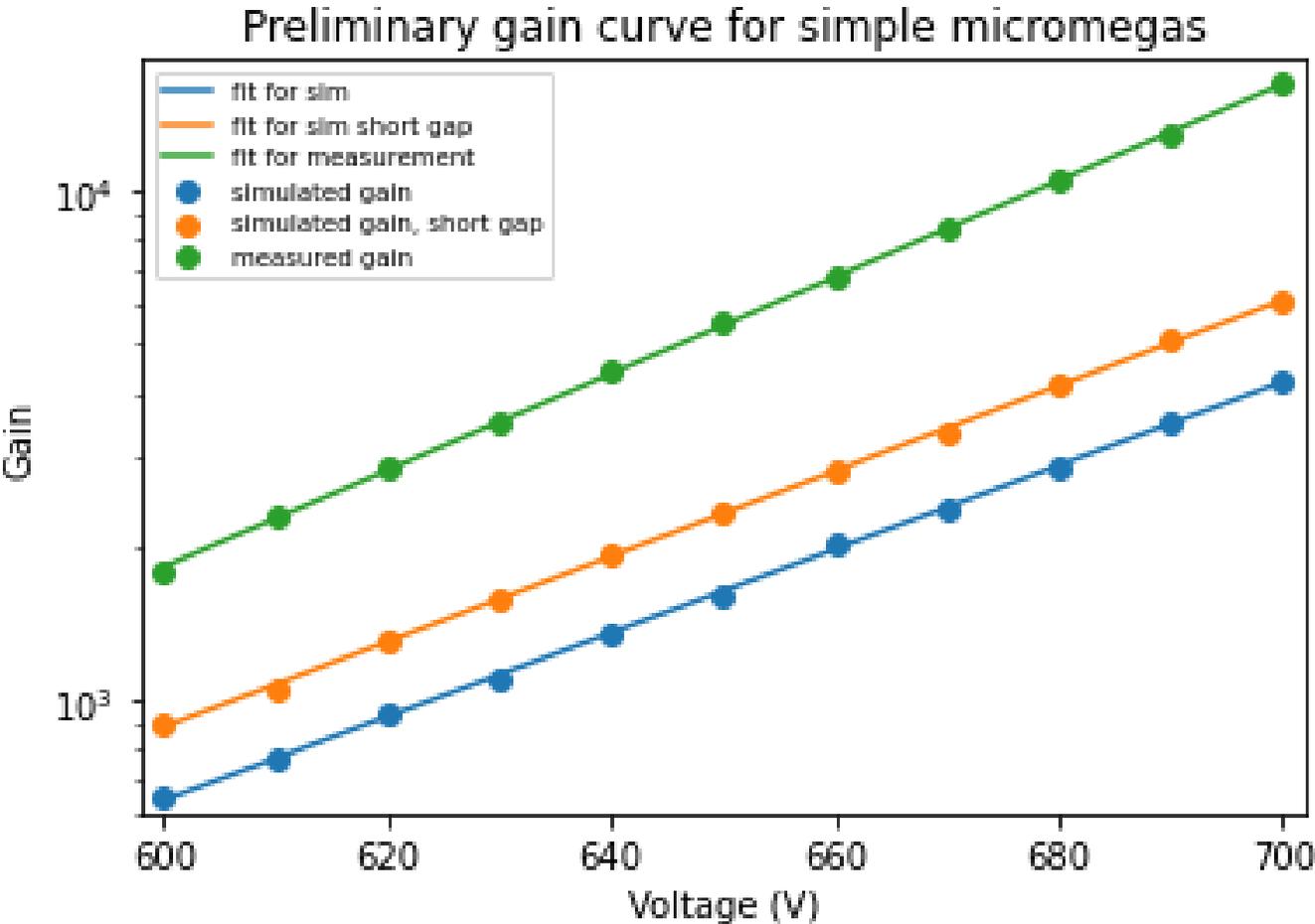


- Top: gain distribution for a series of single electrons each starting above the center of an opening in the mesh, with the mesh voltage at -700V relative to ground. Fit is a Weibull distribution:

$$f(x, k, \mu) = \frac{k}{\mu} \cdot \left(\frac{x}{\mu}\right)^{k-1} \cdot \exp\left(-\left(\frac{x}{\mu}\right)^k\right)$$

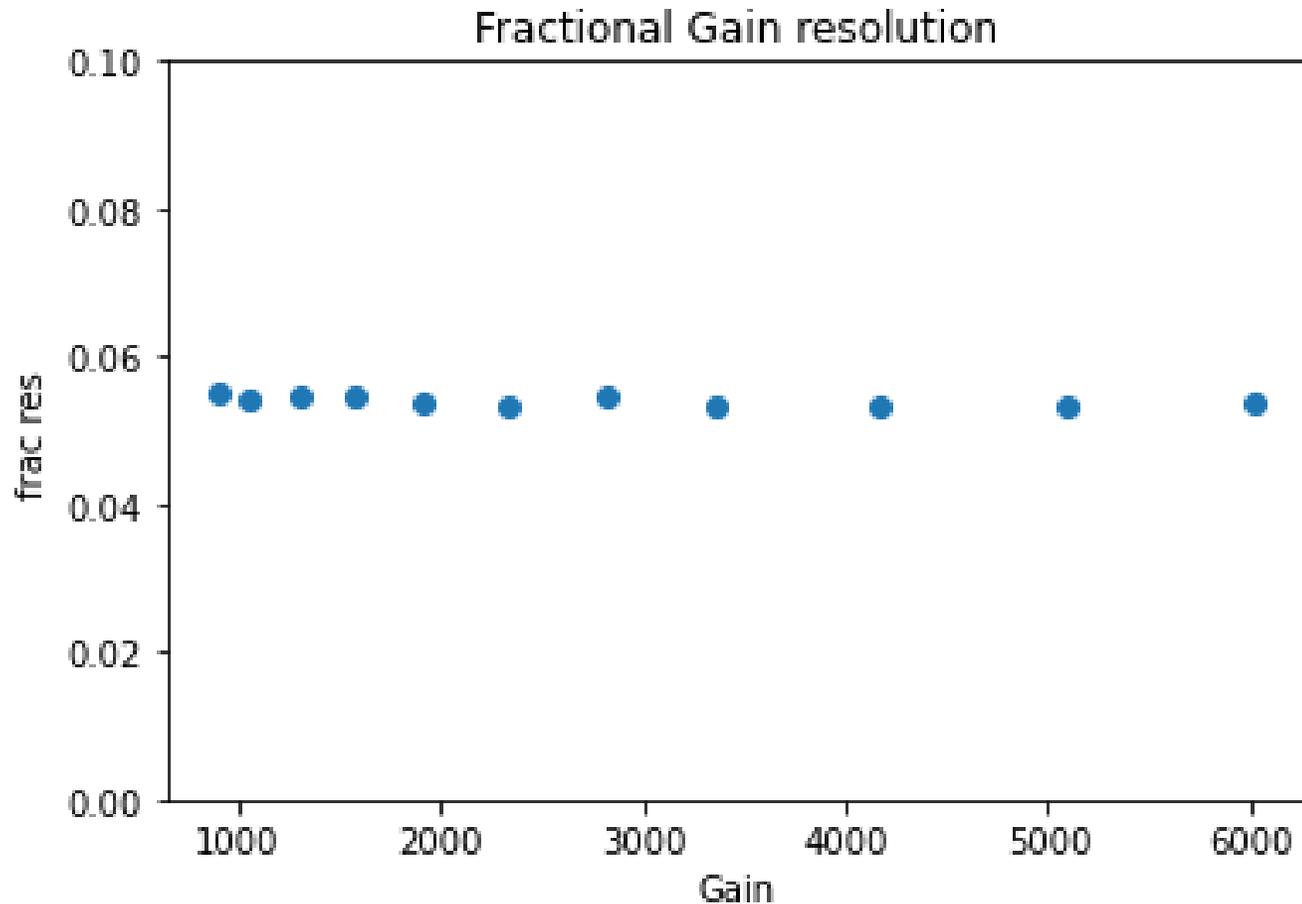
- Bottom: Average gain of many samples of the Weibull distribution. This is equivalent to what you would get from measuring the gain for a series of multi-electron events, since each one effectively samples the above distribution many times and the gain you measure is the average of those samples. Due to the central limit theorem this is a gaussian with an average value equal to the average value of the Weibull distribution 16

# Backup slide: Gain curve



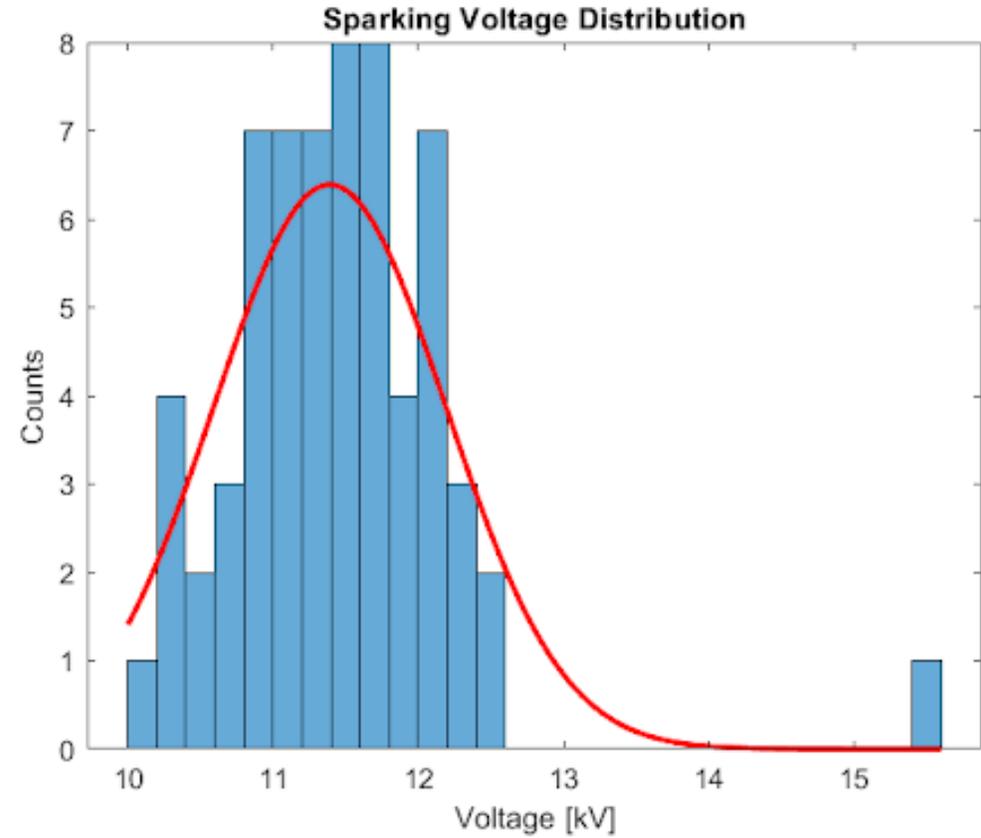
- The simulated gain curve is exponential and grows at very nearly the same rate as the measured gain curve
- The overall difference between the curves is about a factor of 2 and can be mostly attributed to a combination of variability in actual detector gain based on things like the specific gas bottle used, and on the amp gap distance being poorly constrained.
  - Small differences in the amp gap will change the field strength and thus the gain dramatically
  - The measured gain varied by up to 50% between gas bottles

# Backup slide: Fractional gain resolution



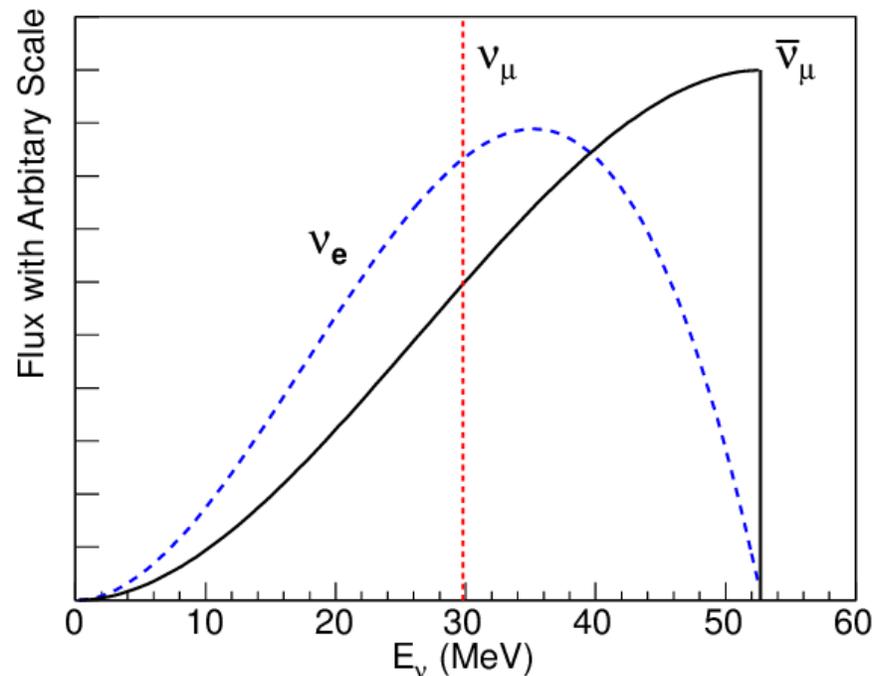
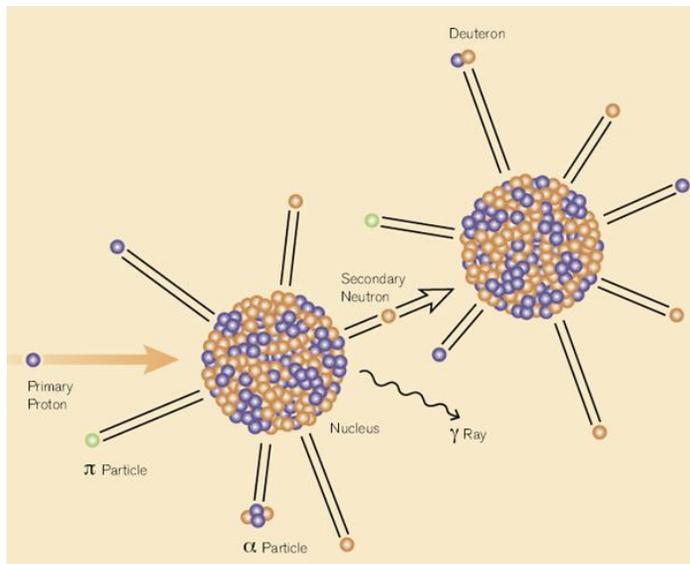
- Fractional gain resolution is defined as  $\frac{\sigma}{\mu}$ . We care about the value of this at high gains, since it asymptotically approaches its minimum value, and we operate at the highest achievable gain for a given physical detector. The pointier the distribution the lower the fractional resolution, the better.
- The simulated fractional gain resolution at high gain has a value of .053
- This is lower than the measured gain by quite a bit (real fractional gain resolution is about 11%, not 5.3%). This is expected since this simulation does not account for ionization statistics or variation in primary ionization due to changes in the gas mixture

# Spark testing



Spark testing conducted in air, with a target minimum sparking voltage of 6428 V to avoid sparking at 816 V in operation with He:CO<sub>2</sub>

# Neutrino generation

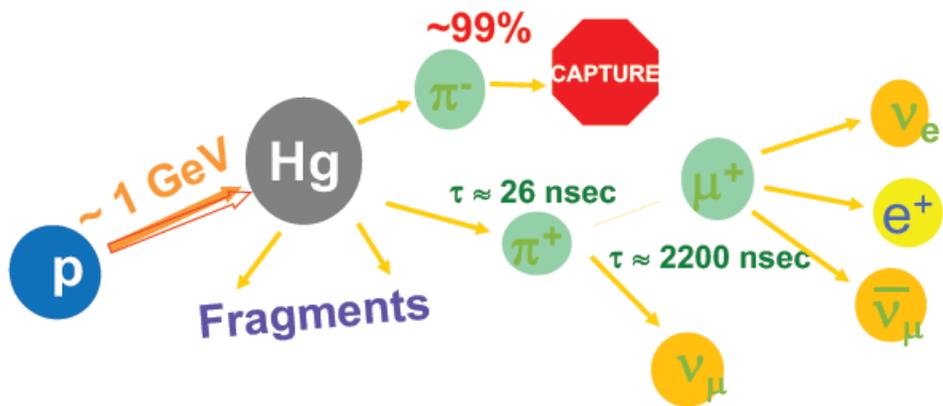


The energy spectra of the resulting neutrinos follow well defined functions very closely:

$$\mathcal{F}_{\nu_\mu}(E_\nu) = \frac{2m_\pi}{m_\pi^2 - m_\mu^2} \delta\left(1 - \frac{2E_\nu m_\pi}{m_\pi^2 - m_\mu^2}\right)$$

$$\mathcal{F}_{\nu_e}(E_\nu) = \frac{192}{m_\mu} \left(\frac{E_\nu}{m_\mu}\right)^2 \left(\frac{1}{2} - \frac{E_\nu}{m_\mu}\right)$$

$$\mathcal{F}_{\bar{\nu}_\mu} = \frac{64}{m_\mu} \left(\frac{E_\nu}{m_\mu}\right)^2 \left(\frac{3}{4} - \frac{E_\nu}{m_\mu}\right)$$



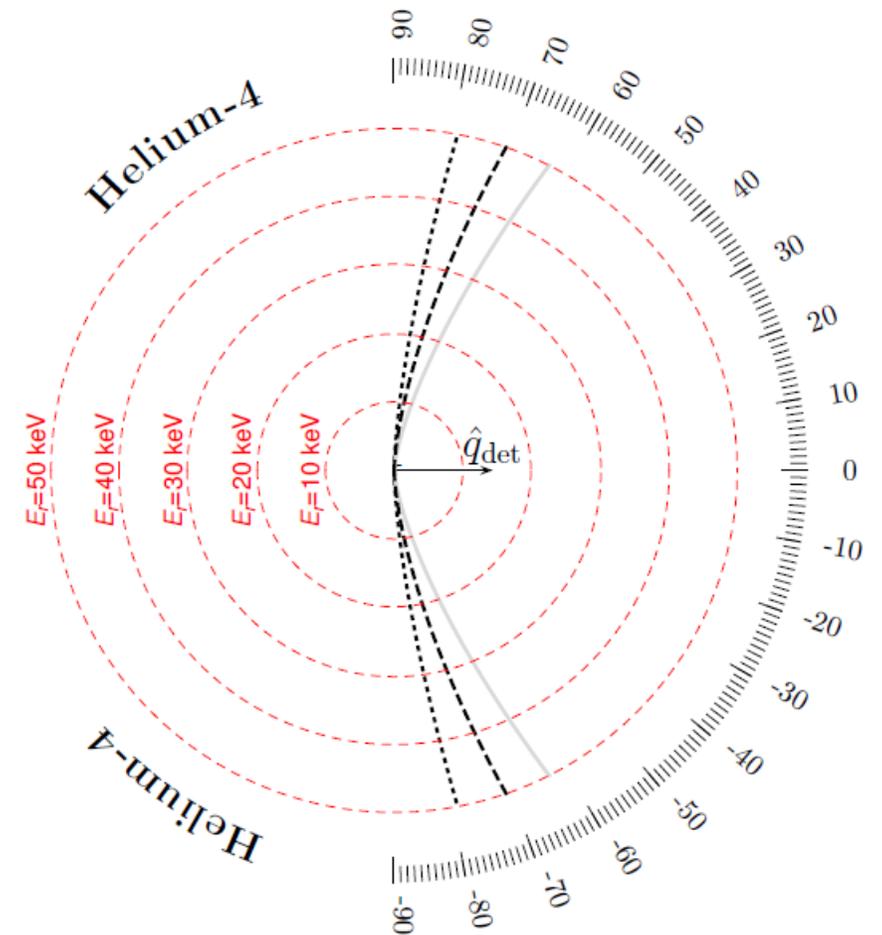
- $\pi^+ \rightarrow \mu^+ + \nu_\mu$  is a 2-body decay, and therefore monoenergetic
- $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$  is a 3-body decay so it produces a range of energies for the decay products
- Cutoff at 52.85 MeV for  $\bar{\nu}_\mu$  is from kinematics. Specifically, it is half of the muon mass

# Picking and optimizing a new gas

- Currently using a 70:30 He:CO<sub>2</sub> mix picked for neutron detection in the BEAST TPCs & 40L detector.
  - Helium has a low neutron number, so we looked at how CF<sub>4</sub> would perform over a year.
- Pressure is proportional to events and inversely proportional to directionality, so we have to optimize pressure to get most directional events possible

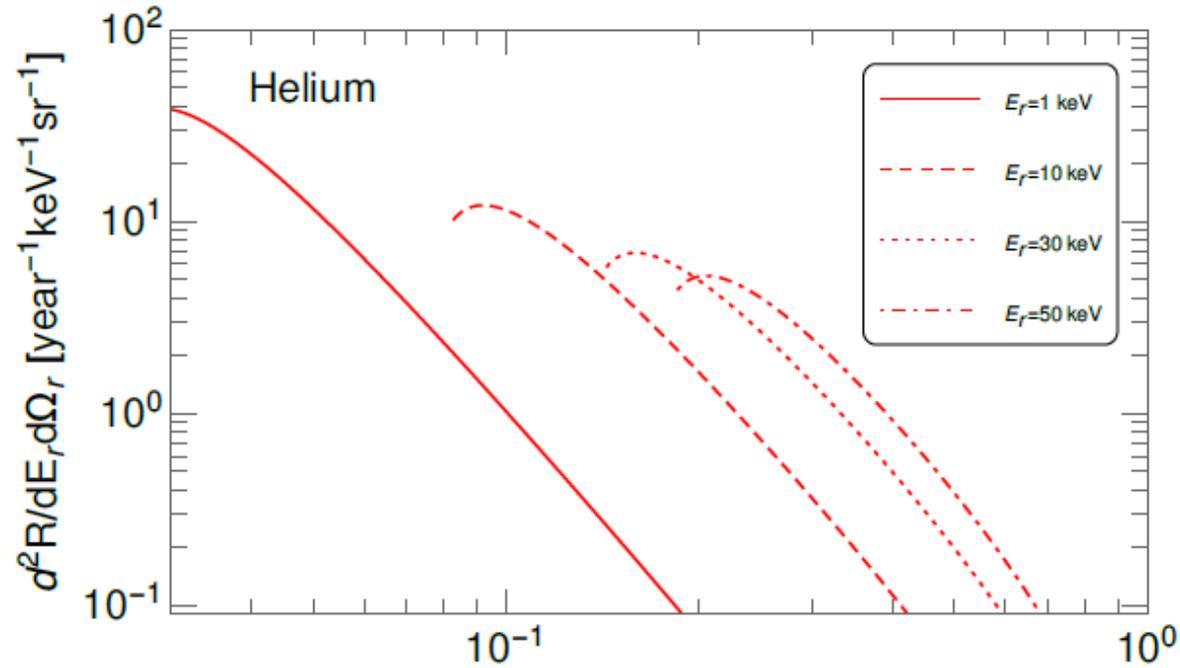
# Assessing and optimizing detector performance

- There are 5 things we need to calculate to assess and optimize the performance of a hypothetical detector
  - Differential rate  $\frac{dR}{dE}$  of CE $\nu$ NS events
  - Angular distribution  $\frac{dR}{d\Omega_r}$  of CE $\nu$ NS events
  - A measure of directionality
  - Total number of directional CE $\nu$ NS events
  - The best operating pressure for a given gas
- The first 2 can be derived from the double differential cross section:
 
$$\frac{d^2\sigma}{dE_r d\Omega_r} = \frac{1}{2\pi} \frac{d\sigma}{dE_r} \delta(\cos(\theta_r) - \frac{E_\nu + m_N}{E_\nu} \sqrt{\frac{E_r}{2m_N}})$$
- The directionality can be calculated based on event parameters and gas properties, which we can use to calculate the best operating pressure

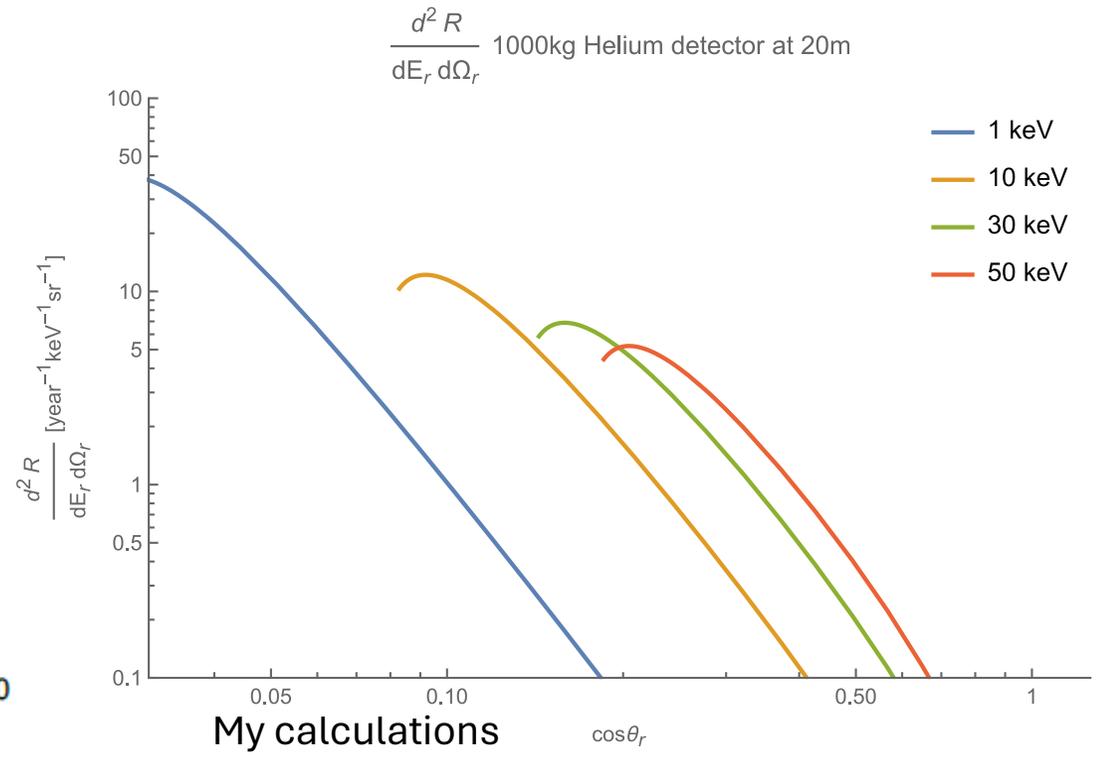


Allowed recoil angles for a He-4 at SNS (dotted black curve) [[arXiv:2003.11510](https://arxiv.org/abs/2003.11510)]

# Comparing calculations to the literature: $\frac{d^2 R}{dE_r d\Omega_r}$



Plot from [arXiv:2003.11510](https://arxiv.org/abs/2003.11510)  $x_r = \cos \theta_r$

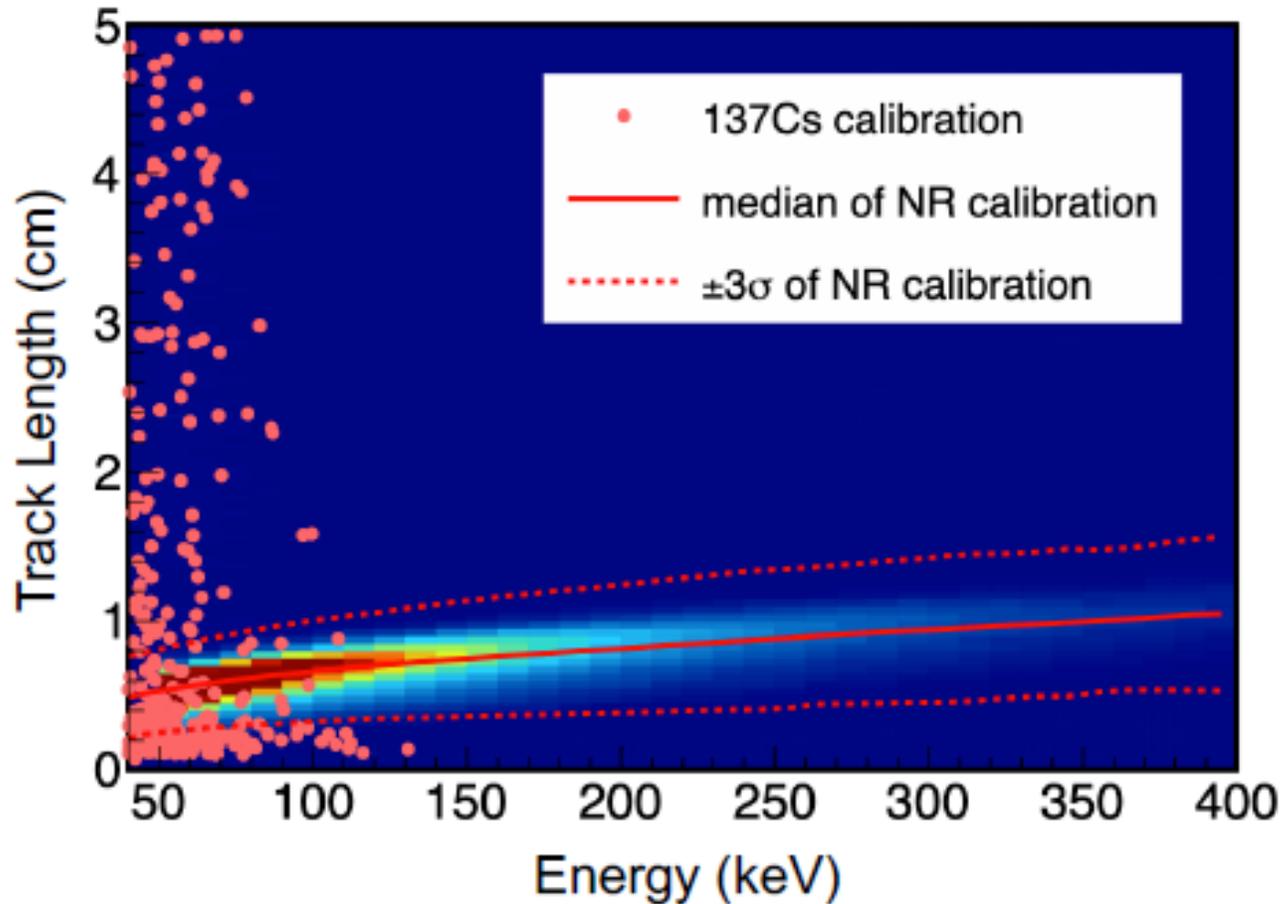


- Paper calculates total of 2300 events for a year of runtime I get 2350

# Inputs and assumptions for the performance estimate

- There are 4 inputs to estimating the number of directional events
  - A measure of directionality (next slide)
  - Electron transport and recoil track length properties of CF4 (obtained from the work done by DM-TPC and CYGNUS NEWAGE in [arXiv:0905.2549](https://arxiv.org/abs/0905.2549) and [arXiv:2101.09921](https://arxiv.org/abs/2101.09921) respectively)
  - Double differential rate  $\frac{d^2\sigma}{dE_r d\Omega_r}$  of CE $\nu$ NS events (my calculation is ~50% lower than the literature [[arXiv:2003.11510](https://arxiv.org/abs/2003.11510)], so this estimate is conservative)
- Assuming 1.3 GeV protons with a beam power of 2 mw for 5000 hours per year at SNS (sns projections for 2026) at the 12-meter position with a 1 cubic meter detector running CF4 taking data for a year

# Recoil track length



- The CYGNUS NEWAGE group in Japan measured the recoil track length of nuclear recoils in cf4 at 75 torr

- Track length scales as  $\frac{1}{p}$ , so we multiply their curve by  $\frac{75 \text{ torr}}{p}$  to get  $L(E_r, p)$