Neutron Transport & High-Voltage Systems for Liquid Argon TPCs

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University of California, Davis

Outline

1. Neutron transport in LAr via the ARTIE experiment
    a. Neutron detection challenges
    b. ARTIE setup
    c. Analysis and results
2. High voltage development for DarkSide-20k
    a. Brief DS-20k rundown
    b. High-voltage development @ UCD

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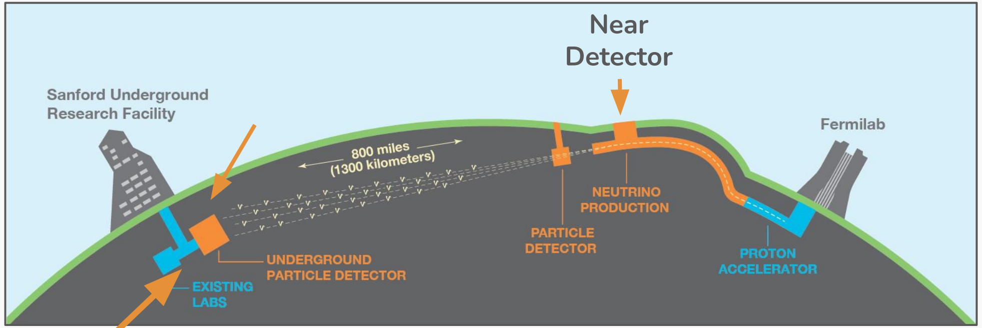
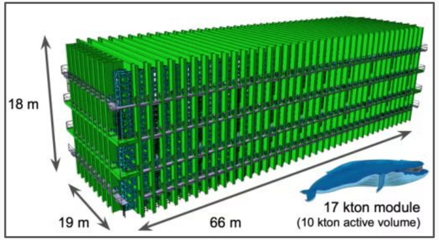
His name is Nico

Neutron transport in LAr via the ARTIE experiment

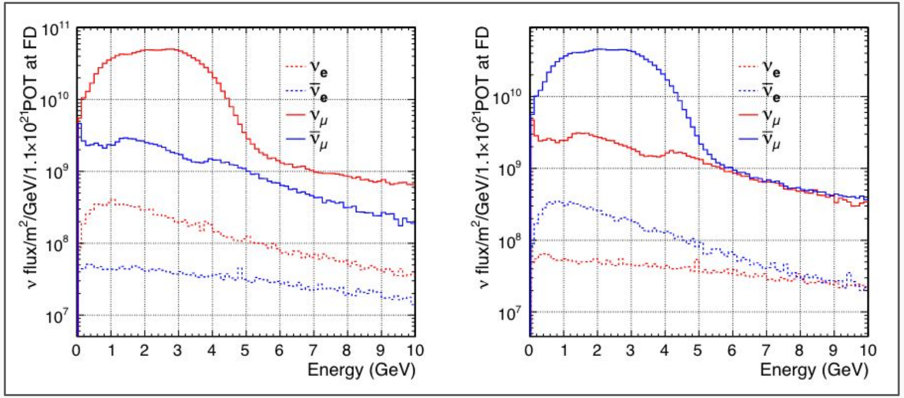
Context: Deep Underground Neutrino Experiment (DUNE)

- 2.4 MW neutrino beam
  - ν and anti-ν modes
- Near and Far Detector LAr TPCs
  - Drift/collect charge in an electric field
- High energy ν-CC events can result in final state neutrons
- Neutrons are largely invisible in TPCs!
  - No charge ⇒ no dE/dX losses





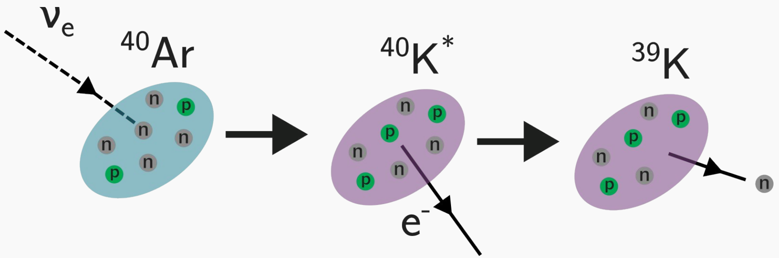
Far Detector (x4)

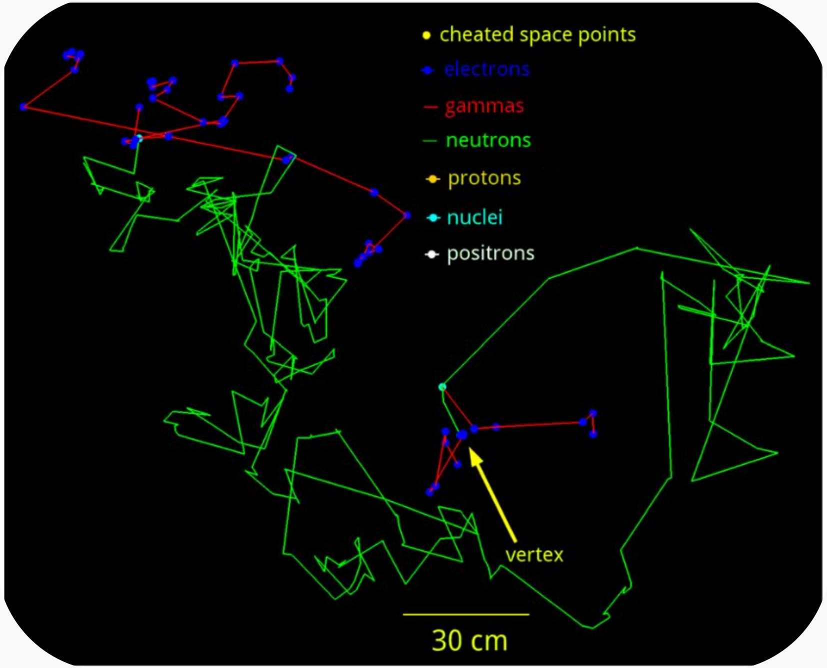


DUNE FD TDR (2020), doi: 10.48550/arXiv.2002.03005

Neutrons are hard to detect in TPCs

- No charge ∴ no dE/dx losses
- Only kinetic E depositions
  - But are very small
- However, can reliably capture on nucleus
  - Fixed γ-cascade, Q=6.1MeV
- But mean lifetimes λ ~O(100μs)
- Spatial and temporal coincidences for vertex assignments?





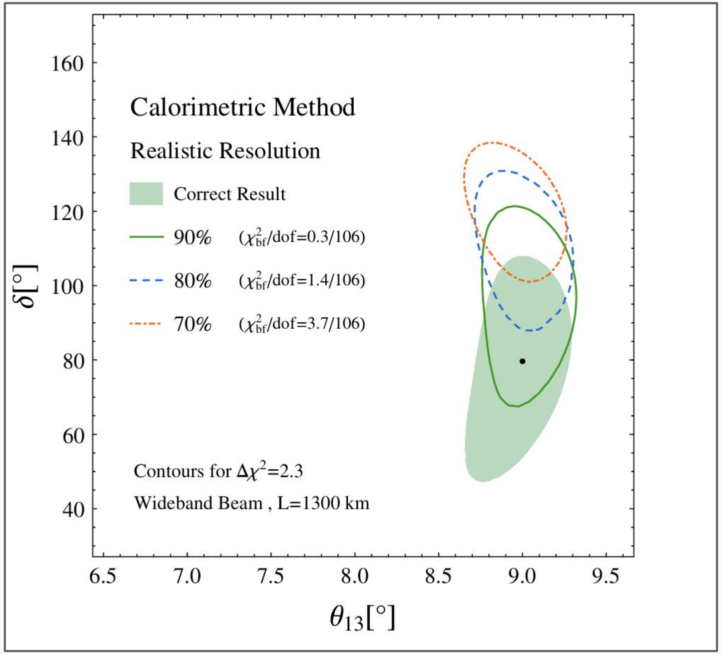
MARLEY, *Gardiner, doi: 10.2172/1637626*

$$\nu_e + {}^{40}\mathrm{Ar} \to e^- + n + {}^{39}\mathrm{K}$$
$$E(\nu_e) = 16.3\,\mathrm{MeV}$$

…and can carry significant energy!

- For example 11MeV CC-$\boldsymbol{\nu}_e$ (supernovae)
  - 16%, avg. of energy is carried away by the neutron **MARLEY,** *Gardiner, doi: 10.2172/1637626*

- At higher energies, CCQE anti-$\boldsymbol{\nu}_\mu$ can have a "leading" neutron
  - Incomplete calorimetry can bias the reconstruction of $\boldsymbol{\delta}_{CP}$



Ankowski, Coloma et al., doi:10.1103/PhysRevD.92.091301

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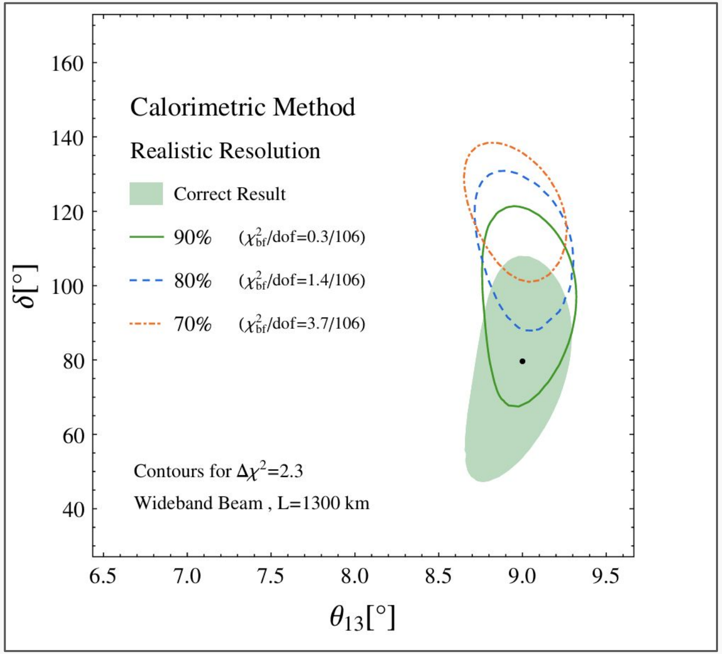
As long as neutrons capture on a nucleus quickly, what's the problem?



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Can scatter into lower cross sections

- Neutrons can scatter multiple times
  - Losing energy

A: *# nucleons*

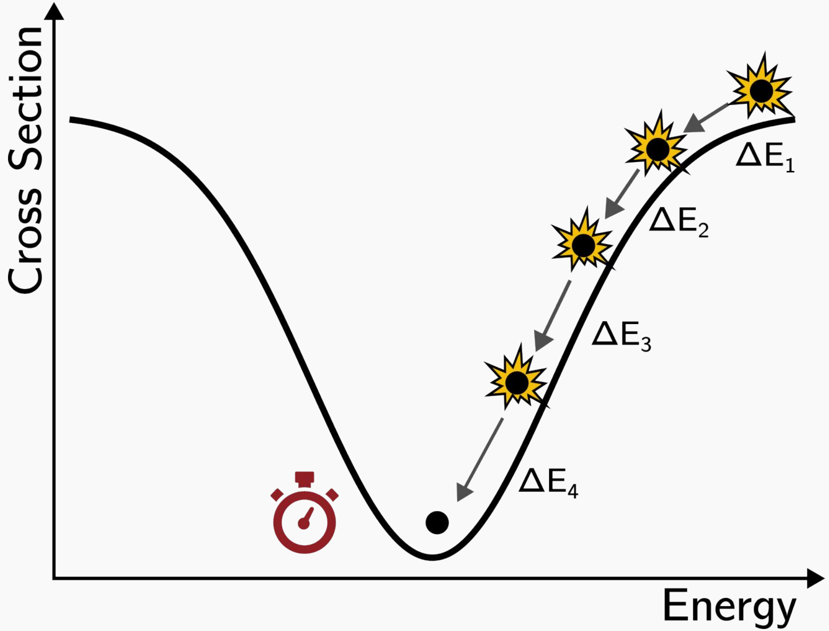
$$E_n = E_0\left[\frac{A^2+1}{(A+1)^2}\right]^n$$

- Probability of scattering

$$P = 1 - e^{-n\sigma}$$

$$\longrightarrow \lambda \propto \frac{1}{\sigma}$$

Mean interaction length



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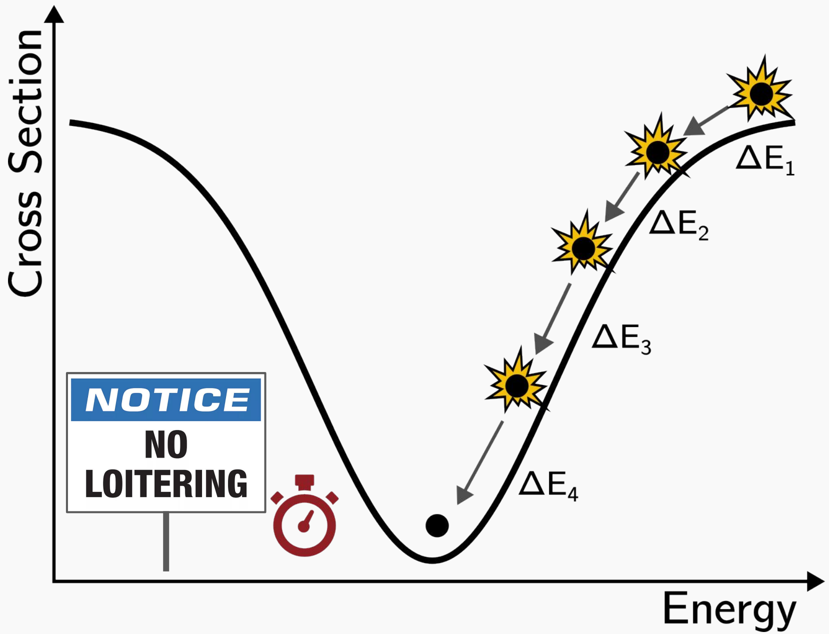
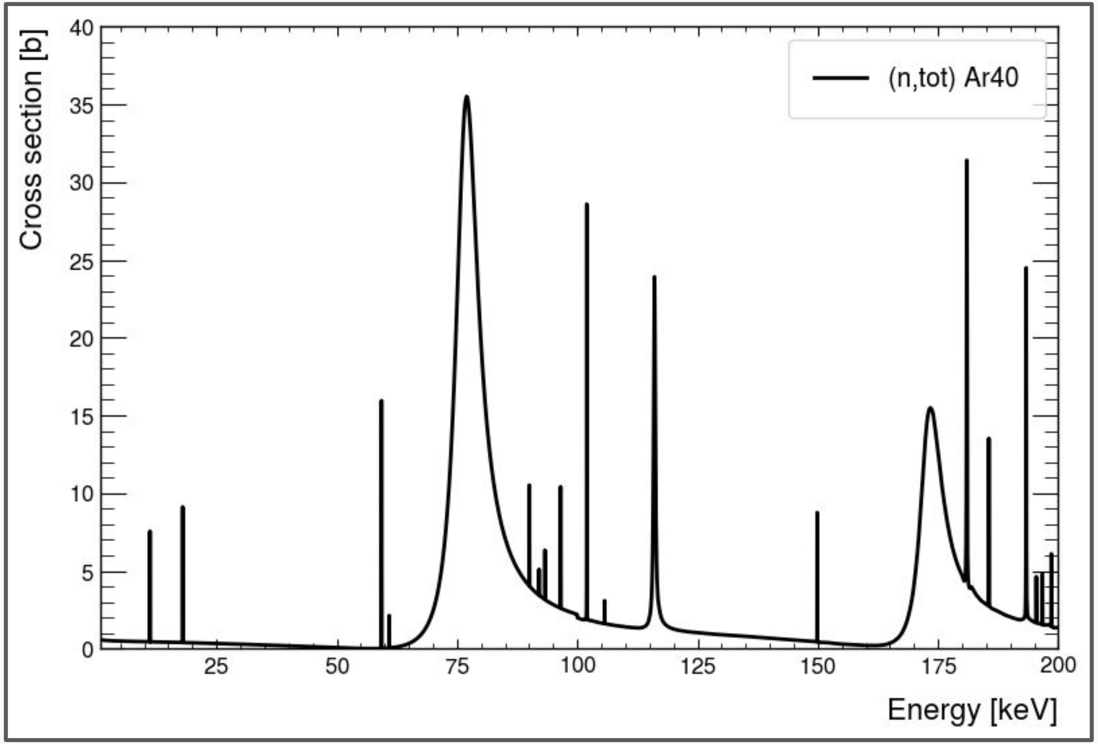


Neutrons which scatter into wells can persist on long time scales!

Total cross section of Argon 40

- (n,tot)^{40}Ar fairly well measured 1-200keV
  - Due to high >1b xsecs



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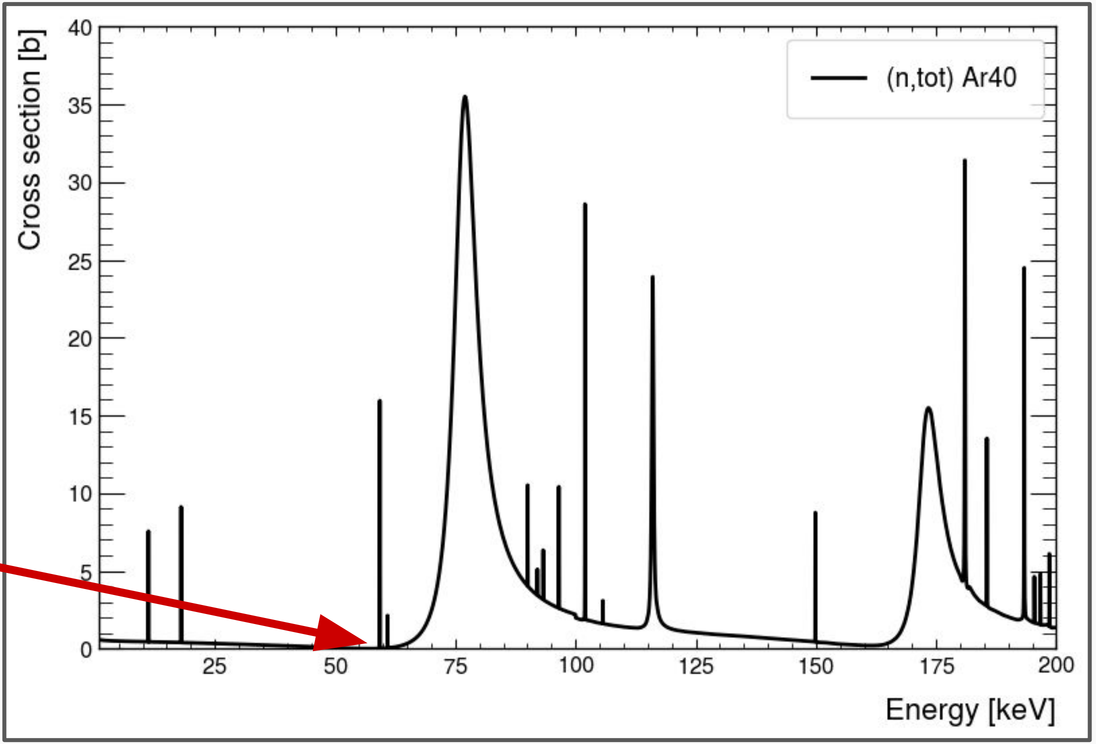
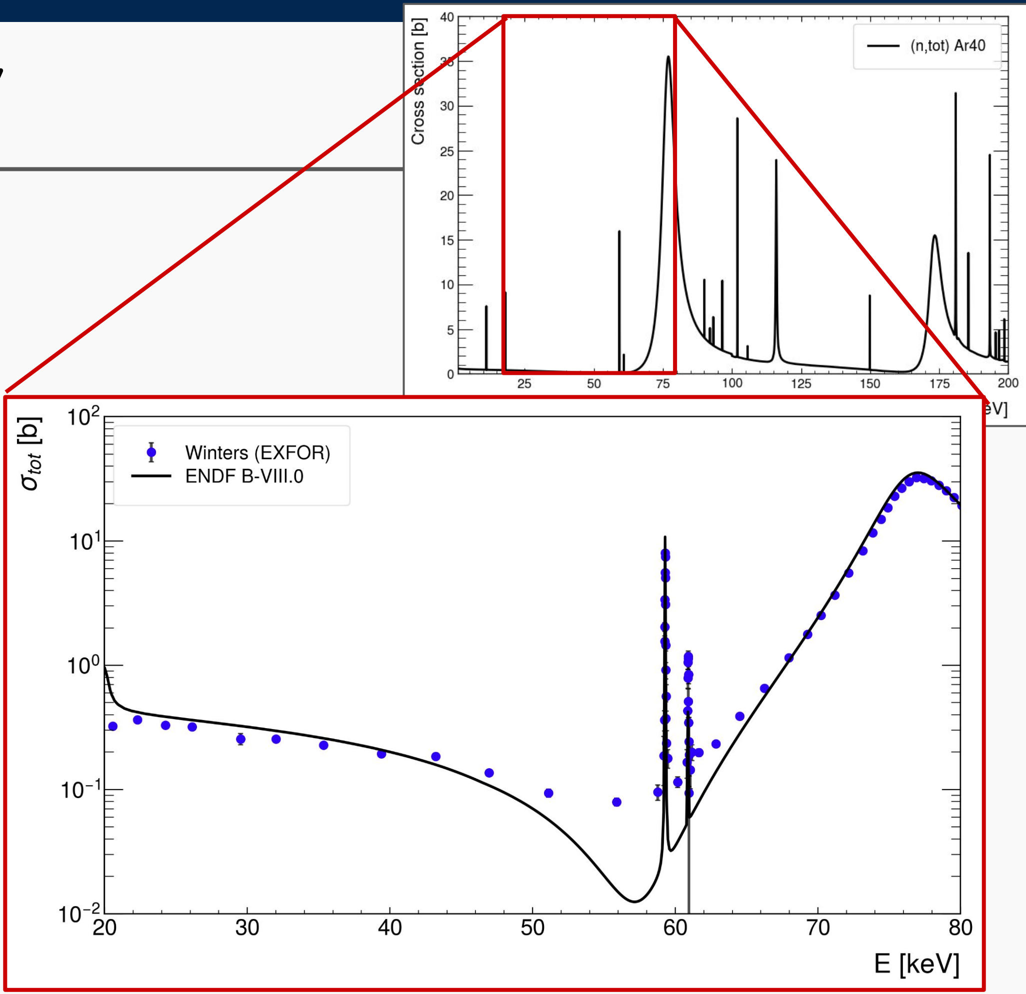
Except...



Contention at around 57keV

- Around 57 keV, an interference feature (dip)
- Disagreement
  - ENDF empirical-based model **(blk)**
  - Measurement by Winters' in 1991 (blue) Winters et. al. (1991) doi: 10.1103/PhysRevC.43.492
- Difference between neutron mean free path is **30m** (blk) and **4m** (blue)
- Completely changes how long neutrons persist in your detector



Winters' Experiment Not Sensitive?

- Winters' used pressurized gaseous argon
  - Column density, n = 0.2 atoms/barn
  - Optimized for high cross sections

Neutrons which survive

Neutrons sent in

$$N = N_0 \exp^{-n\sigma}$$

$$T \equiv N/N_0$$

- Using this column density
  - T = 0.998 @ ENDF, σ = 0.015b
  - T = 0.984 @ Winters', σ = 0.1b

~1.4% difference!

$$\sigma(E) = -\frac{\ln T(E)}{n} \longleftrightarrow T(E) = e^{-\sigma(E)n}$$

Winters' Experiment Not Sensitive?

- Winters' used pressurized gaseous argon
  - Column density, n = 0.2 atoms/barn
  - Optimized for high cross sections

Considering resolution, might not be resolvable

- Using this column density
  - T = 0.998 @ ENDF, σ = 0.015b
  - T = 0.984 @ Winters', σ = 0.1b

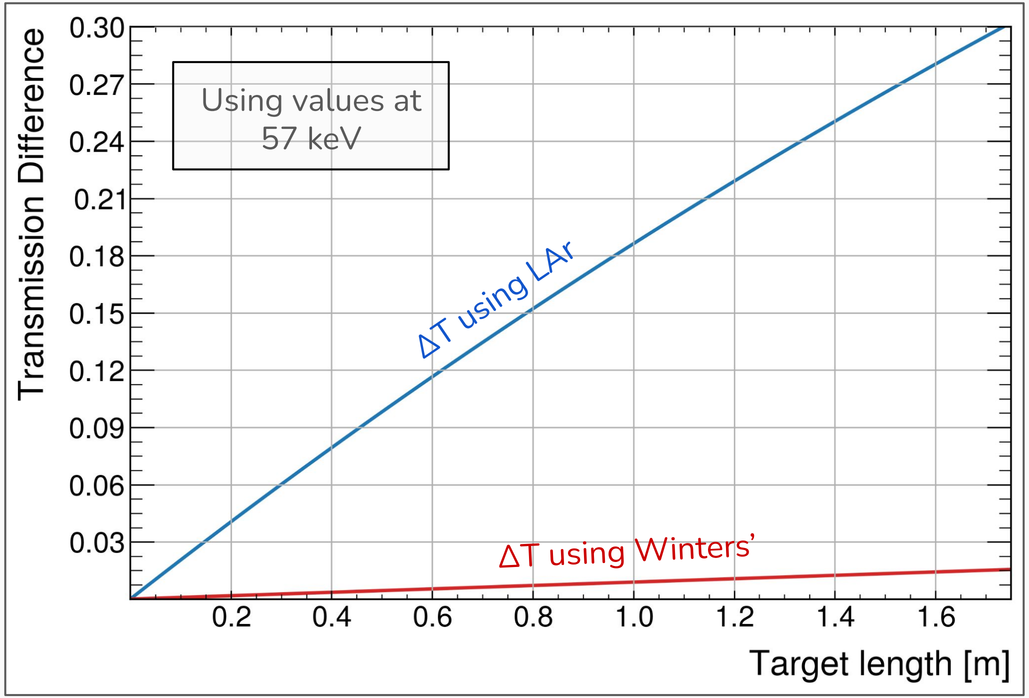
~1.4% difference!

$$\sigma(E) = -\frac{\ln T(E)}{n} \longleftrightarrow T(E) = e^{-\sigma(E)n}$$

Need a thicker target!

- Need thicker target to resolve ENDF/Winters' difference
- If we just use liquid argon
  - 2.2 atoms/b/meter
  - >1m gets good T separation

- And that's what the ARTIE experiment did

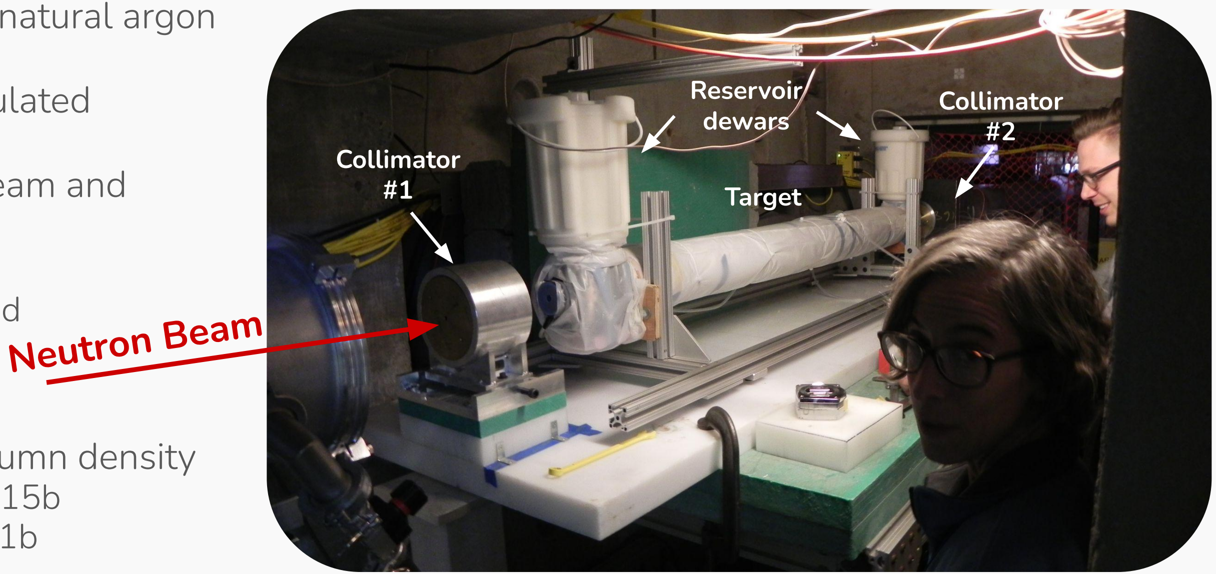


Argon Resonant Transport Interaction Experiment

<u>ARTIE target</u>

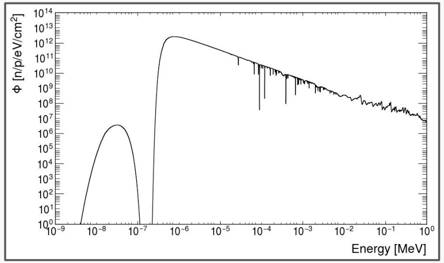
- 1.65m long SS tube filled with natural argon
- Kapton film windows
- Open, unpressurized, foam-insulated
- Two, 2-liter reservoir dewars
- Two 6” brass collimators upstream and downstream
- Graphite and aluminum filters
  - Cross check and background

- ARTIE used a 3.3atom/barn column density
  - $T = 0.97$ @ ENDF, $\sigma = 0.0015$b
  - $T = 0.76$ @ Winters’, $\sigma = 0.1$b

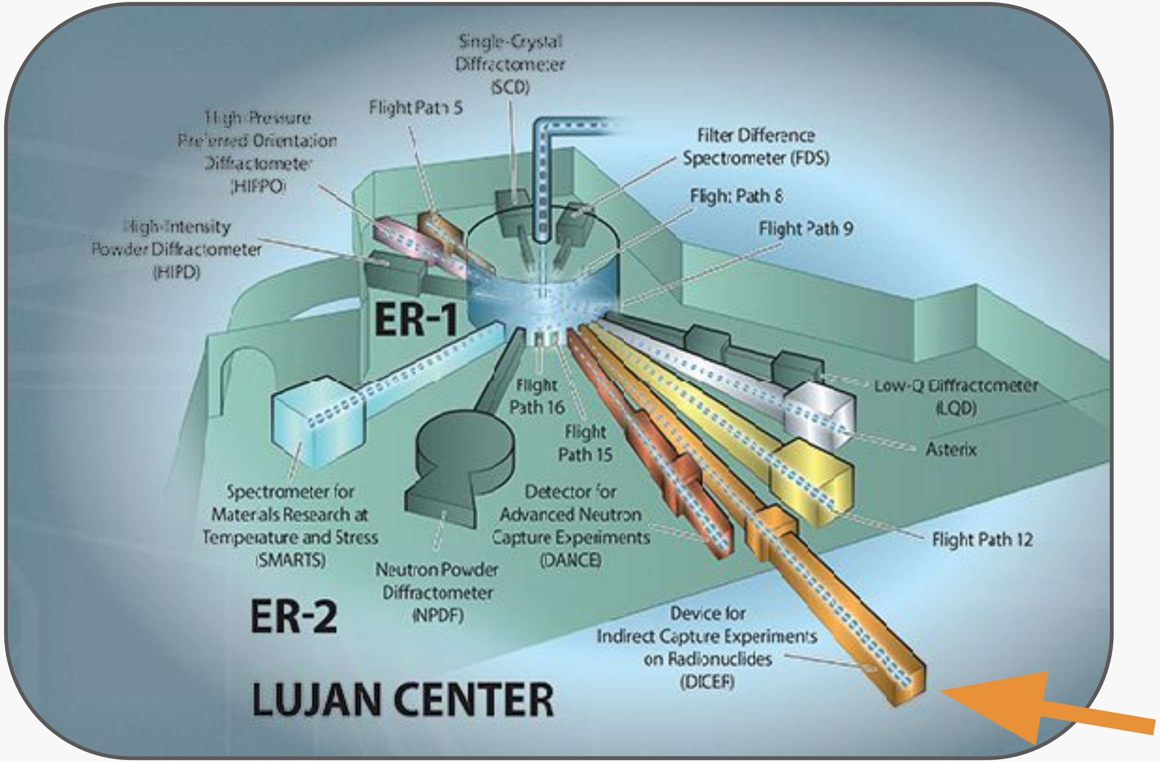


LANSCE Neutron Beamline at Los Alamos

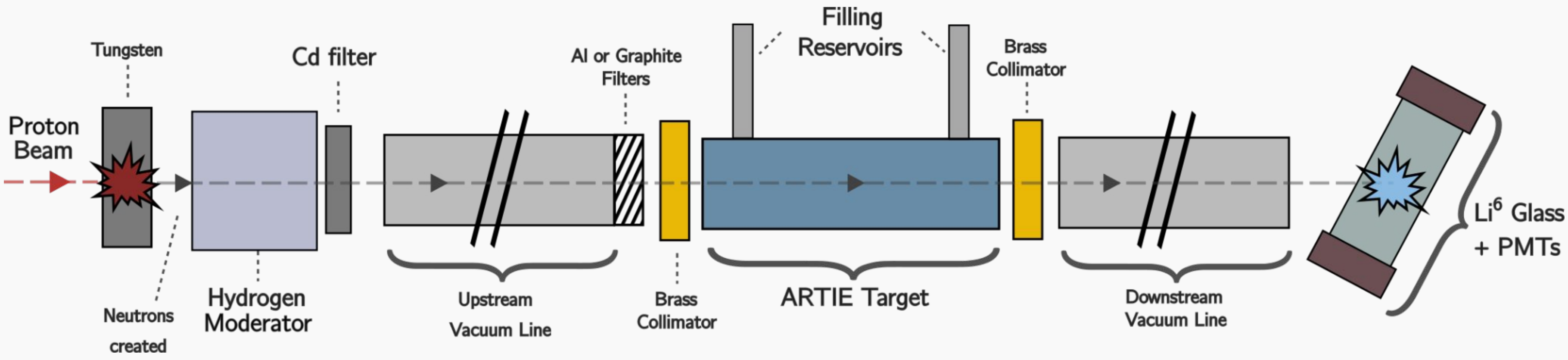
- **Flight Path 13** at LANSCE
- 800-MeV protons onto W
  - Cd to absorb thermal neutrons
  - 20Hz pulse rate
  - Liquid hydrogen to create ~1/E spectrum

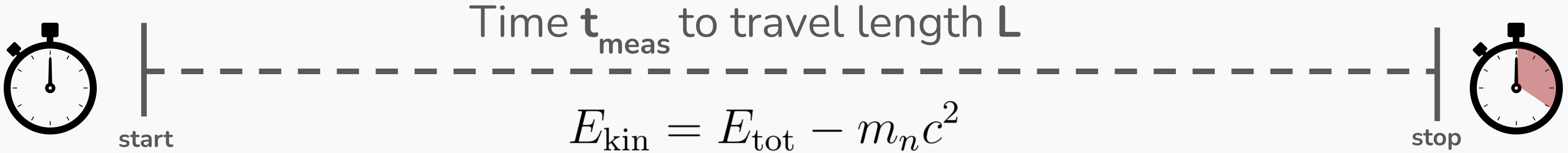


- FP13 is a time-of-flight beam hall
  - ^{6}Li-glass, 2 PMTs



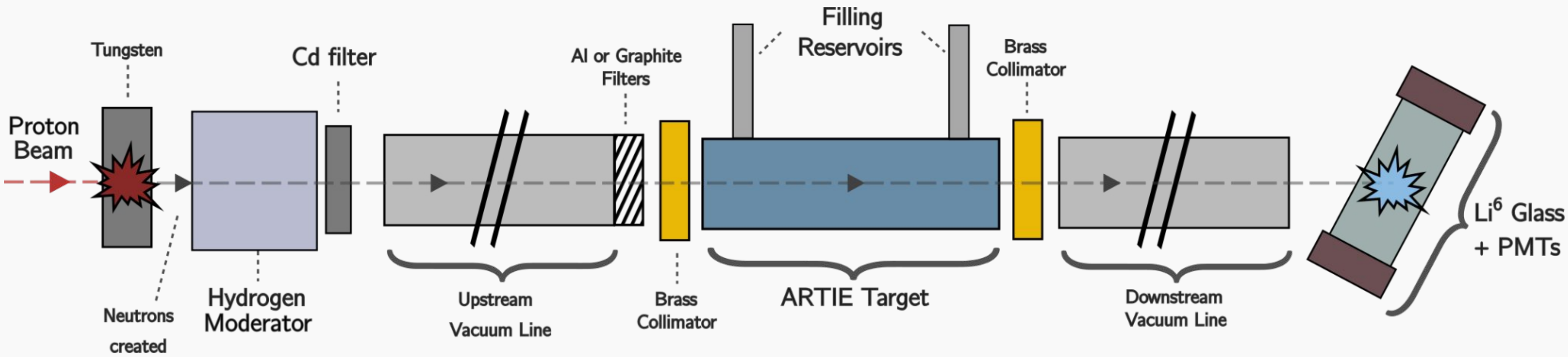
Full ARTIE Beamline Diagram





$$E_{\text{kin}} = E_{\text{tot}} - m_n c^2$$
$$= (\gamma - 1) m_n c^2$$

Full ARTIE Beamline Diagram



But how do we use this to get a cross section measurement?

Extracting a Cross Section

- Measuring with just LAr measures transmission of *everything*
- To isolate the interactions from only LAr, we can divide out the transmission of an "empty" target
  - In this case we use gaseous argon as "empty"

Neutrons which survive

Neutrons sent in

$$N = N_0 \exp^{-n\sigma}$$

Transmission: $T \equiv N/N_0$

$$T_{\text{tot}} = \underbrace{T_{\text{apparatus}} \cdot T_{\text{vacuum line}} \cdot \ldots \cdot T_{\text{dead bug}}}_{\text{not interesting}} \cdot T_{\text{target}} \longrightarrow T_{\text{target}} = \frac{T_{\text{tot}}}{T_{\text{foo}}}$$

Extracting a Cross Section

- Two runs: "In" and "out"

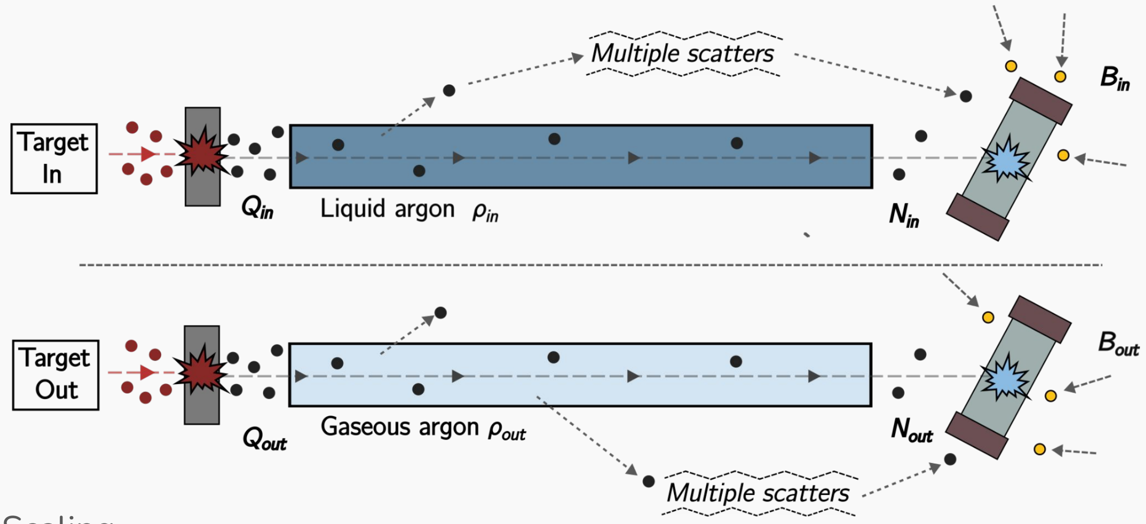
Target In = LAr
Target Out = GAr

$$T(E) = \frac{\boxed{N_{in}(E)} - \boxed{B_{in}(E)}}{\boxed{N_{out}(E)} - \boxed{B_{out}(E)}} \cdot \boxed{\frac{Q_{out}}{Q_{in}}}$$

Counts in any E bin

Bkg counts in any E bin

Charge Scaling Factor, "normalization"



<u>Need work to get:</u>

- Energy calibration (this talk)
- Background estimation (this talk)
- Systematics (briefly)

ARTIE Analysis Branches

- My dissertation was planned to be a cross-check
  - While supporting larger ARTIE analysis tasks
- Due to COVID-19 and personnel shortages, many parts of my analysis got incorporated
- The most influential difference was the *Energy Calibration*

Main analysis

ARTIE Analysis Branches

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  - While supporting larger ARTIE analysis tasks
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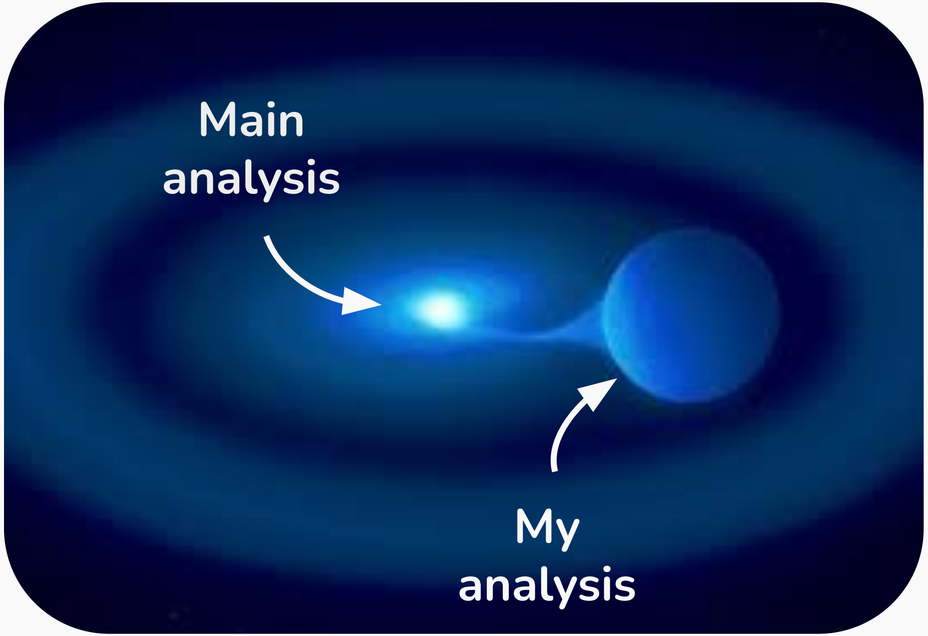
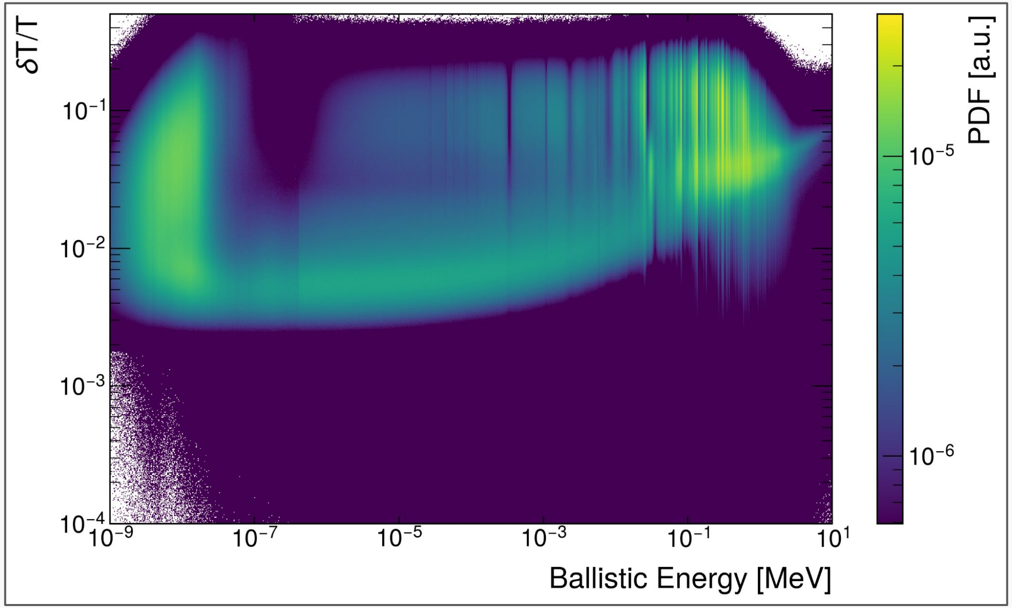


How to map t_{meas} to energy?

- Want to map t_{meas} to ballistic energy, E_B
  - More complicated than just using rel. kinematics
- t_{meas} encapsulates some *delays*
- Most notably: the Moderator Response Function (MRF), t_{mod}
- Cabling, detector, temporal beam spread, jitter t_d
  - Reasonable to assume $t_d \propto N(\mu,\sigma)$

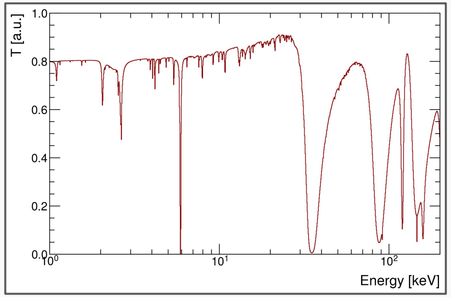


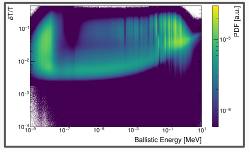
Zavorka et. al. "Benchmarking of the MCNPX predictions of the neutron time-emission spectra at LANSCE"

Use a MC, fit to our data

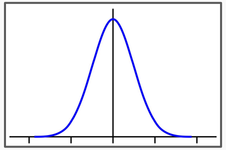
Convolve a “clean” aluminum ENDF transmission spectra with timing delays and fit to our aluminum data

$$\underbrace{t_{\text{meas}}}_{\text{Data}} = \underbrace{\frac{L}{v(E_B)}}_{t_B} + \underbrace{t_{\text{mod}}(E_B) + t_{\text{d}}(\mu, \sigma)}_{\text{Delay model}}$$

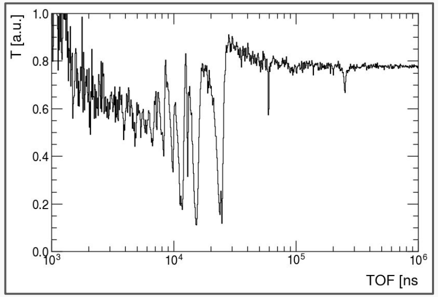




$t_{mod}(E_B)$



$t_d(\mu,\sigma)$

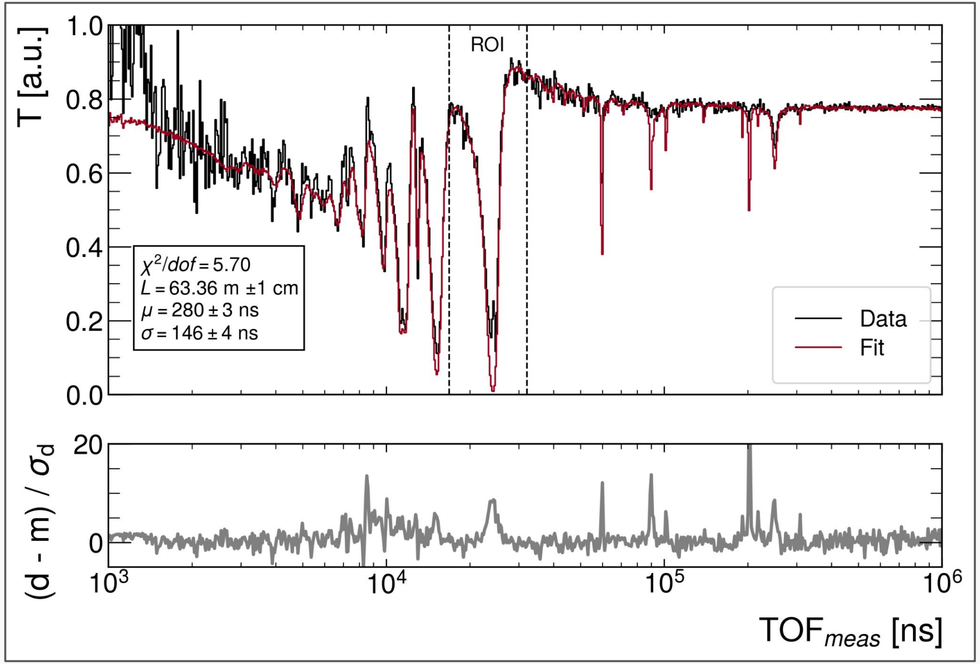


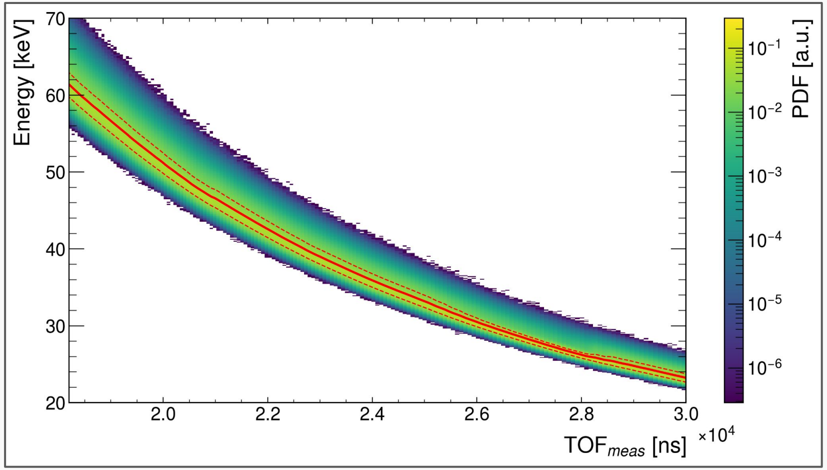
1: Grab ENDF Al spectra, convert to T using 1” Al

2: Sample across E_B, assigning delays from t_{mod} and t_d

3: Fit to our aluminum data

My Energy Calibration





- Can then create a t_{meas} to E_B map!
- Note, our "clean" spectra was for a common Al alloy, 6061
  - Missing peaks are easily seen in the residuals

Background Subtraction

- Backgrounds are of the form

$$B(t) = B_0 + B_n(t) + B_\gamma(t) + B_{\text{therm}}(t) + B_{\text{sky}}(t)$$

- B_0: time-independent
- $B_{sky}(t)$: skyshine, from nearby experiments
- $B_{therm}(t)$: slow thermal wraparound
- $B_\gamma(t)$: prompt gamma emission
- $B_n(t)$: multiple scatter

Background Subtraction

- Backgrounds are of the form

$$B(t) = \cancel{B_0} + B_n(t) + B_\gamma(t) + \cancel{B_{\text{therm}}}(t) + \cancel{B_{\text{sky}}}(t)$$

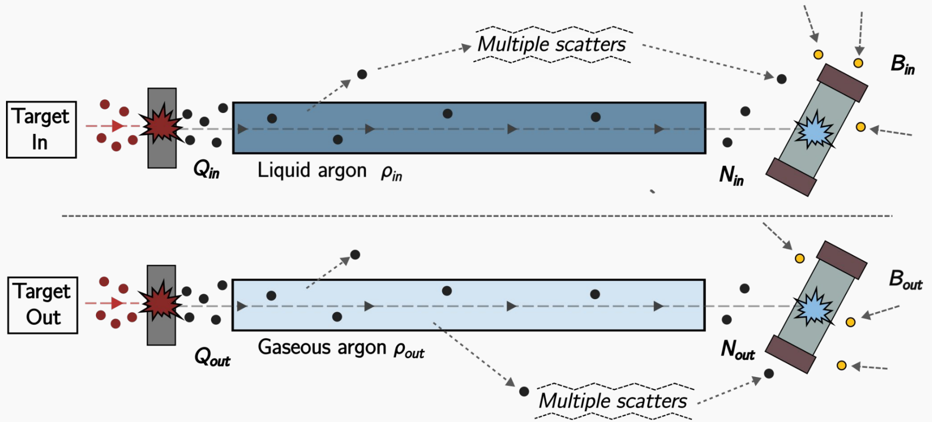
- ~~B_0: time-independent~~
- ~~$B_{sky}(t)$: skyshine, from nearby experiments~~

Shutter closed data

- ~~$B_{therm}(t)$: slow thermal wraparound~~ *1e6 suppression via Cd filter*
- $B_\gamma(t)$: prompt γ emission
- $B_n(t)$: multiple scatter

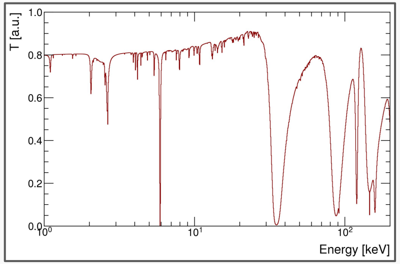
Flat in our roi

Stamatopolous et. al. doi: 10.1016/j.nima.2021.166166

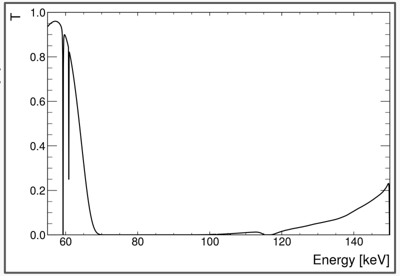


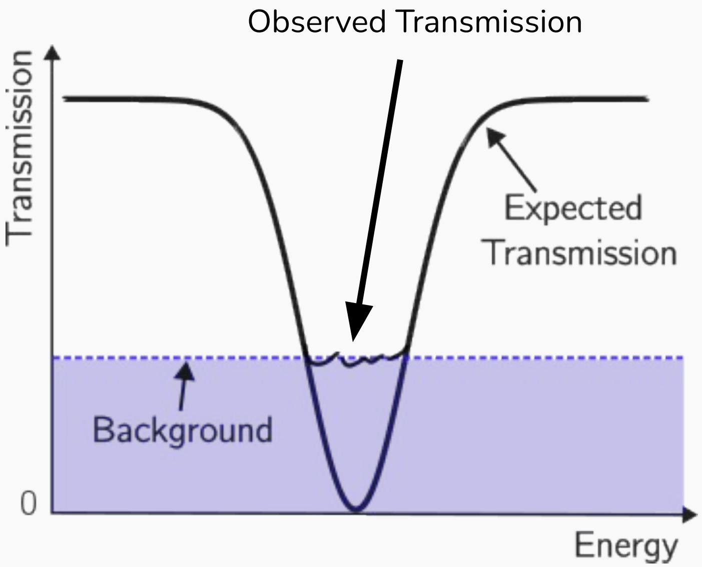
Background Subtraction

- “Black notch” method, *Schillebeeckx et. al. (2012) doi: 10.1016/j.nds.2012.11.005*
  - Use high resonances which make T → 0
  - Any events which do show up *must be background*
- **GAr, Target-out**
  - 1” Aluminum filter: **6, 35 and 88keV**



- **LAr, Target-in**
  - Don’t have Al data
  - But argon has a broad one: **77keV**

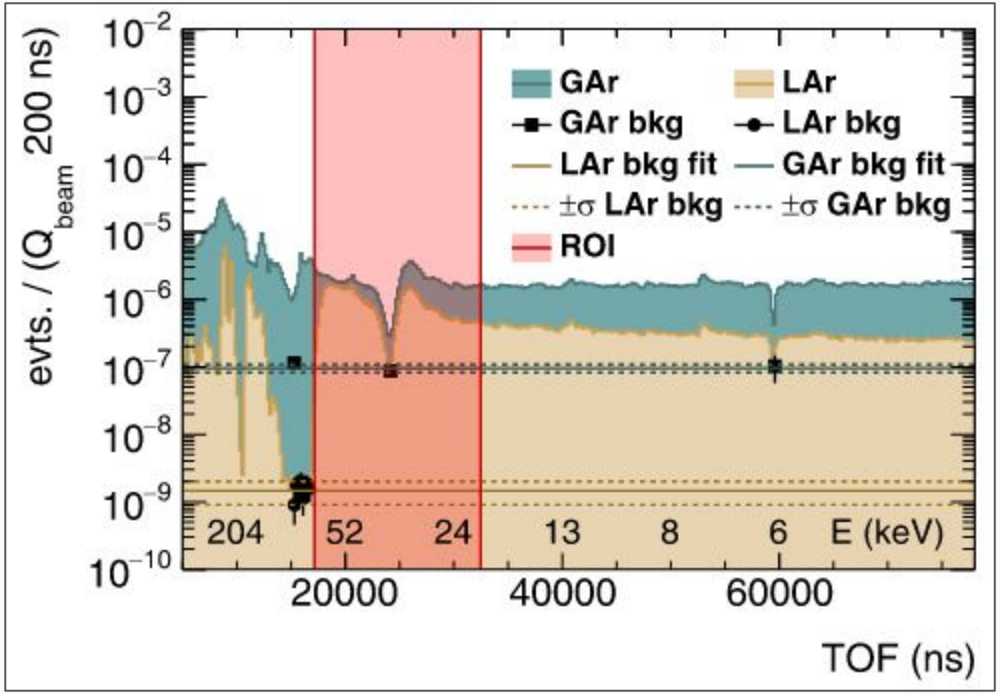




Background Subtraction

- Filters also attenuate background
  - Corrected for via $\mathbf{R}_{in,f/out}$
- $\mathbf{R}_{in,f/out}$: ratio of filter-in, filter-out counts
- **T(E):** expected transmission, given the filter thickness

$$B_{out}(E) = \frac{N_{in,f}(E) - R_{in,f/out}\, N_{out}(E)\, T(E)}{R_{in,f/out}(E)(1 - T(E))}$$



Systematics Galore!

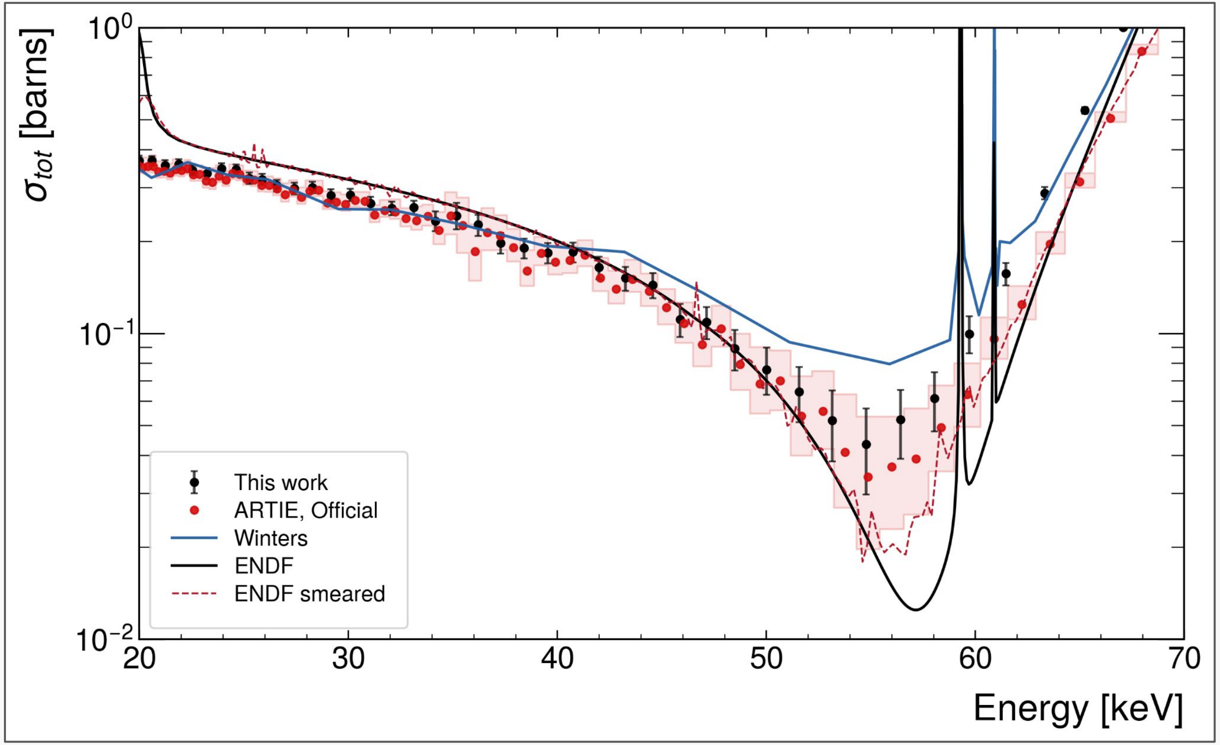
- Target density
  - LAr was constantly boiling, reducing density → 5.9% gas
  - Also caused collimator misalignment, affects LAr data → -0.8%
- Deadtime, GAr: ~1.5%, LAr: ~0.5%
  - Surprisingly non-trivial, but also not large → Monte Carlo/analytical method
- Afterpulsing (negligible)
  - Removed by a 100ns coincidence between each PMT
- Proportionality of Q_{out}/Q_{in} GAr:[-3.93%,3.14%], LAr: [-1.06%,0.69%]
  - Daily modulation of event rate correlated with outside temperature
- Ice build-up on windows , <0.3%
- Air in beamline, atmospheric pressure, <0.5%

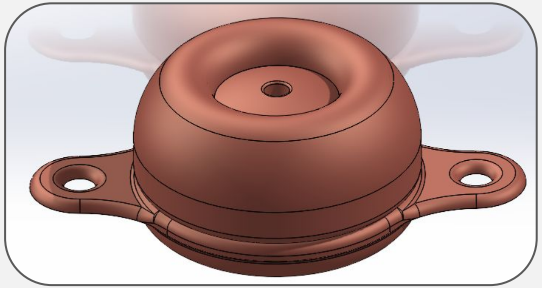
Me, measuring gas mixture of boiling LAr within the ARTIE target

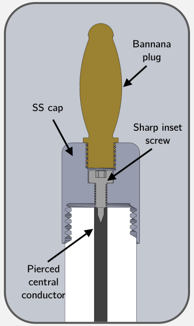
Results

- **ARTIE: $0.34^{+0.19}_{-0.14}$ b** @54.9keV
  - λ =14.0 m
- **Mine: $0.46^{+0.13}_{-0.12}$ b** @54.9keV
  - λ =10.3 m
- Generally agree, but errors are large

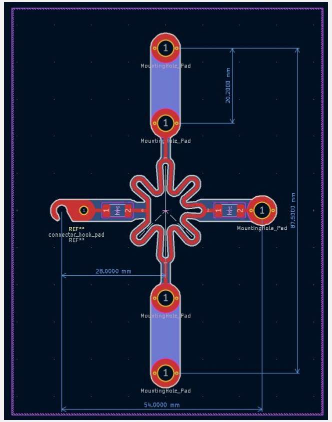
<u>Official analysis</u>
Andriga, Erjavec et. al. (2023)
doi:10.1103/PhysRevC.108.L011601

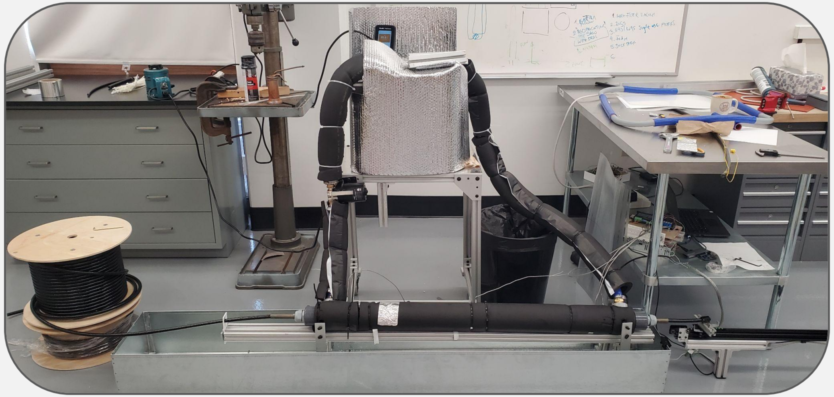


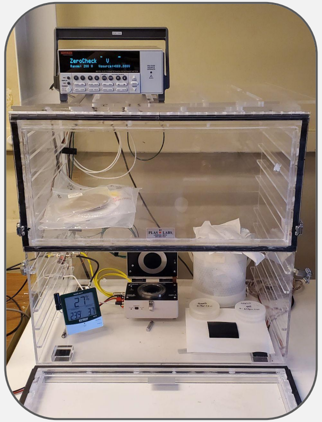




HV Development For DarkSide-20k

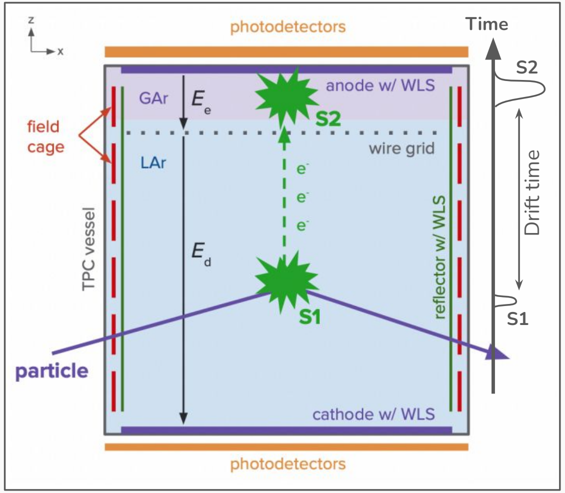




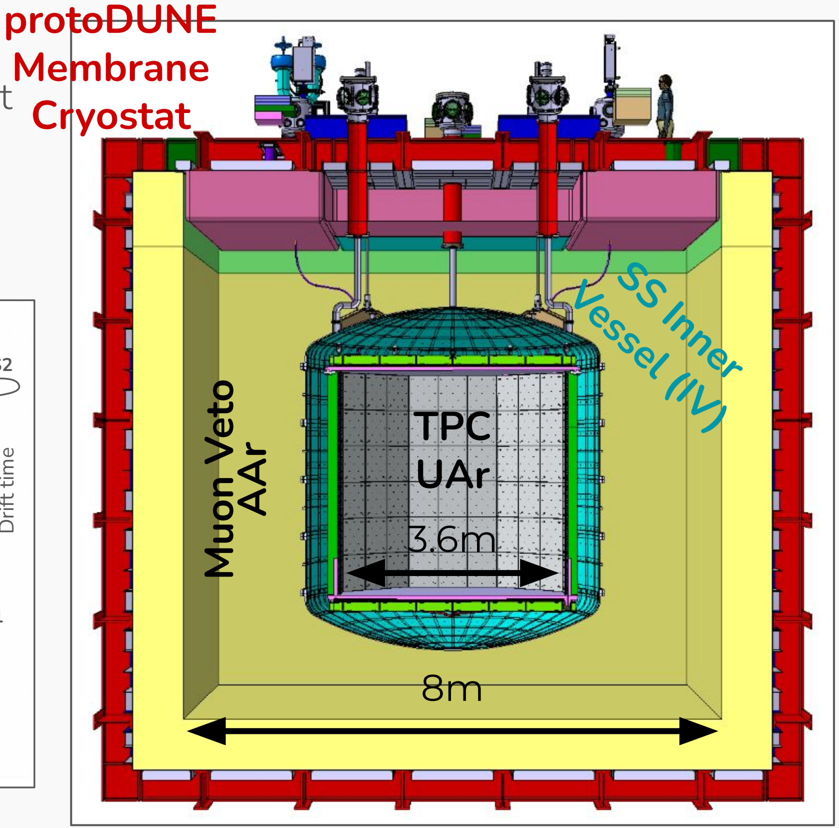


DarkSide-20k: Brief Overview

- Dual-phase LArTPC, active (fiducial) volume of 49.7t (20t) underground argon (UAr)
- Surfaces coated in WLS
- 21 m^2 of SiPMs
- Nestled in 700t of AAr to reject cosmic rays

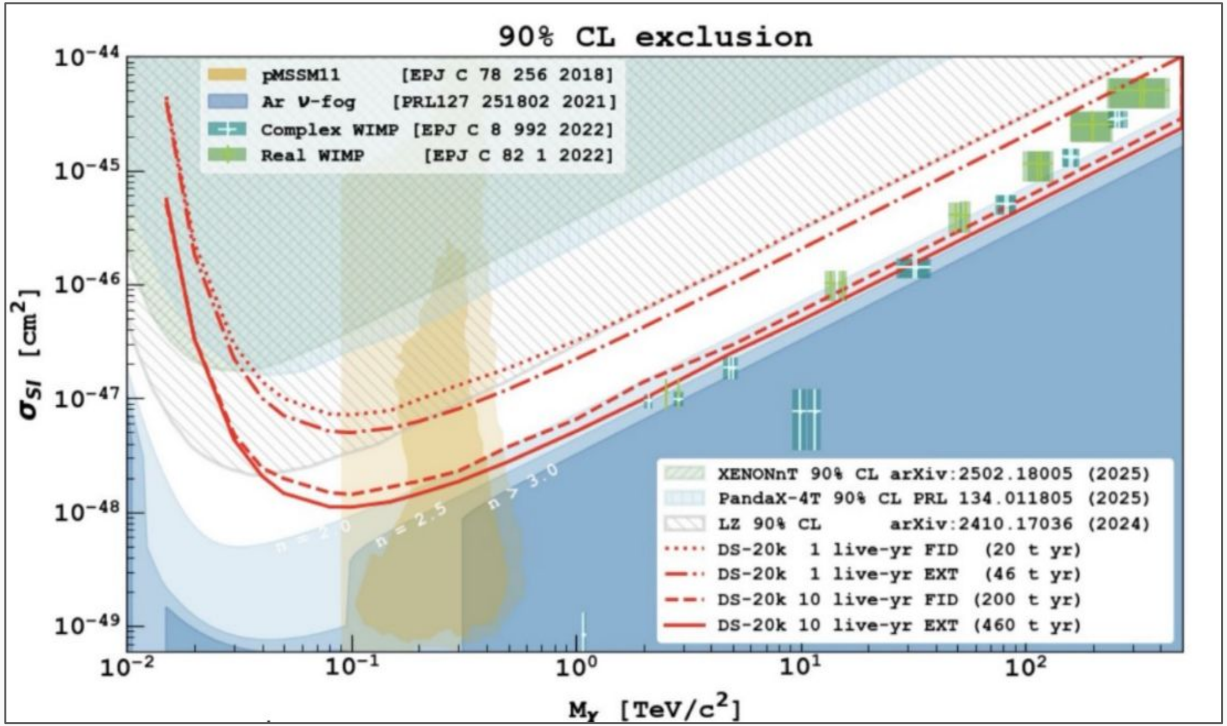


Courtesy of Dr. Michael Poehlmann



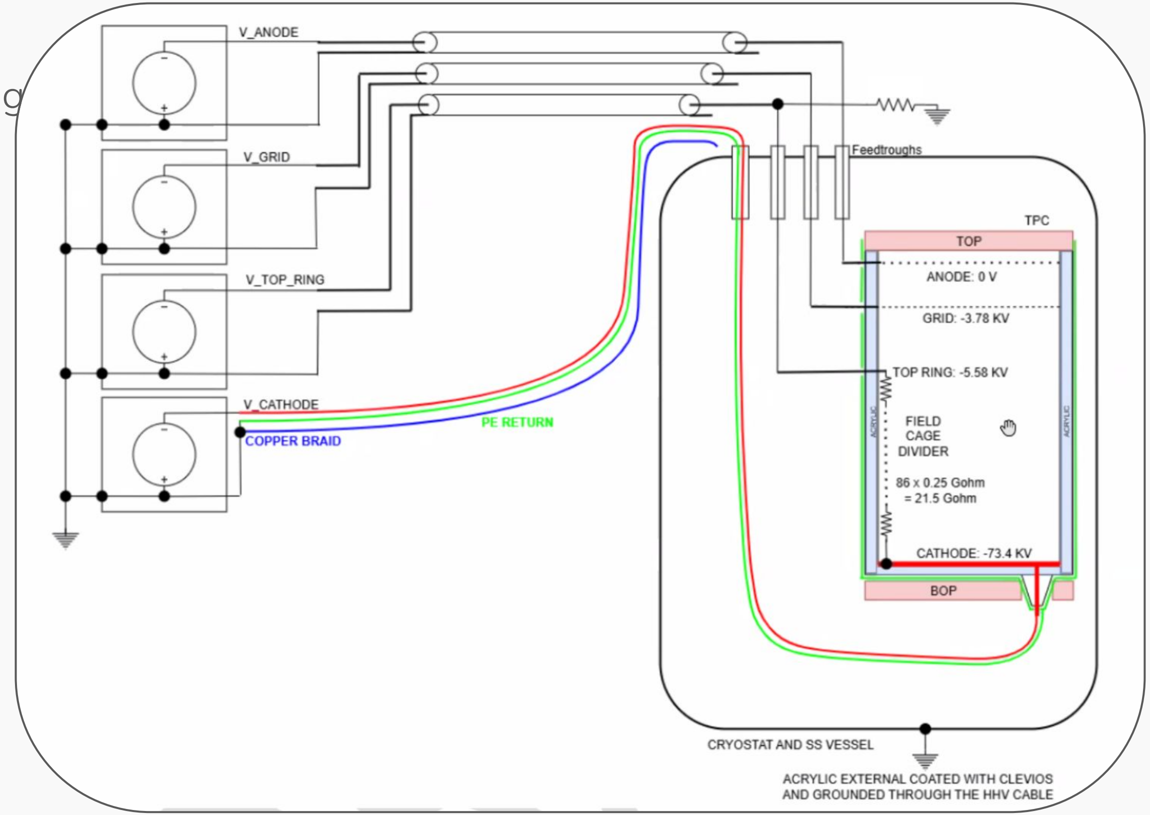
DarkSide-20k: Brief Overview

- Planned 10y exposure
  - 200 ton·yr
- Spin-independant WIMP-nucleon xsecs
- Low backgrounds
  - ~0.1 evts, ROI: 30-200keV (NRs)
  - CEνNS dominant, 3.2 evts



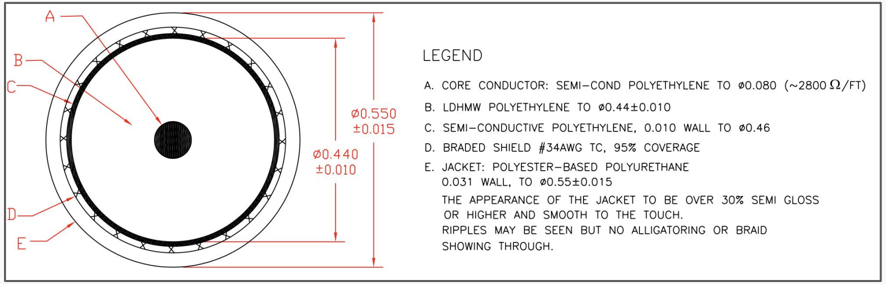
HV Development in DS-20k

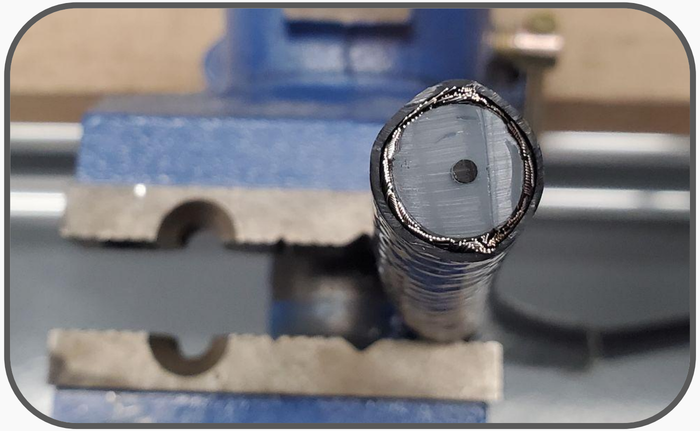
- Fields set up by cathode, field ring, grid, and anode
  - Electrode surfaces coated in Clevios, conducting
- Design field of 200V/cm over 350cm
  - →-75kV on cathode
- Extraction field of 5.2kv/cm, 1cm gas
  - 20-30PE/e^-
- **UC Davis is responsible for HV generation and distribution**



HV Distribution: the cable

- Use a completely plastic cable
  - Dielectric sciences DS2353
  - Similar to LZ's SK160318
- Similar CTEs prevent cracks
- Resistive conductor limits current
- Rated to 150kV
- Also used in nEXO and protoDUNE



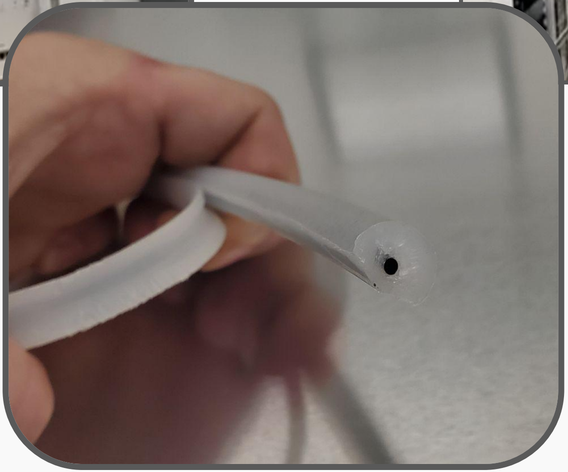


Many thanks to Knut Skarpass III (SLAC) for early discussions on his experiences with this cable!

Cable **Must** be Annealed

- The cable must be annealed
  - Or it explodes
  - Leftover stresses from manufacturing
- Stresses can reach 8kg/mm^2 at 84° K ...or **78MPa**!
  - *Kajihara (2021) doi: 10.1007/s41871-020-00090-3*
- How to anneal 16m of cable *uniformly*?
- Others have annealed *short* pieces via water bath

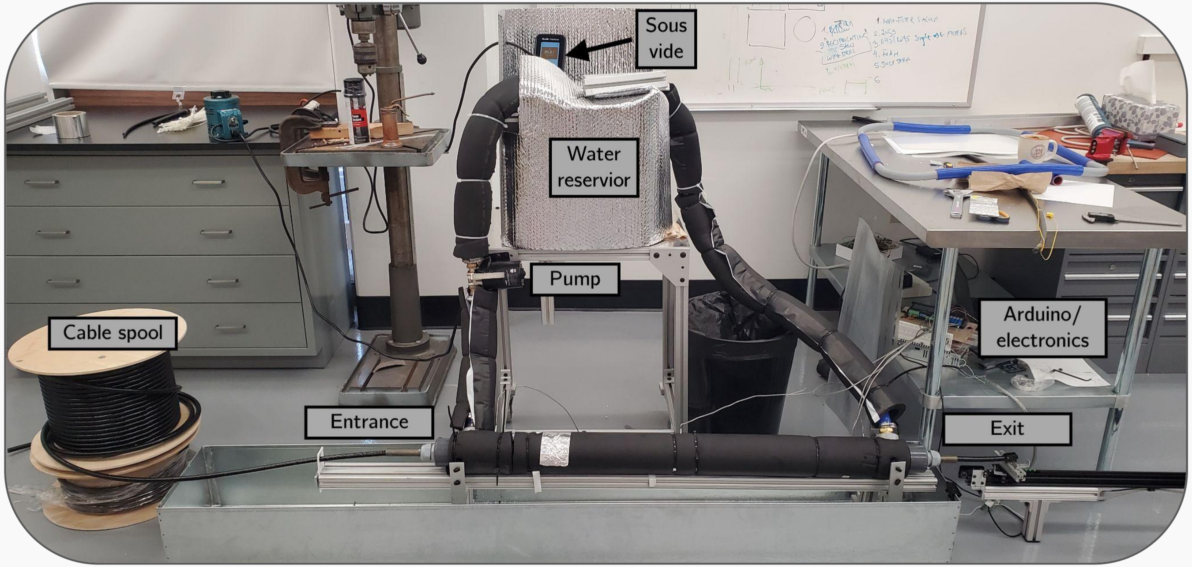
1/60th second later



Cable Annealing Oven

- Enclose two concentric pipes and flow hot water
  - Use a sous vide
- Pass cable through central pipe

- Stepper motor and carriage controlled
- Reproducible, user interfaceable

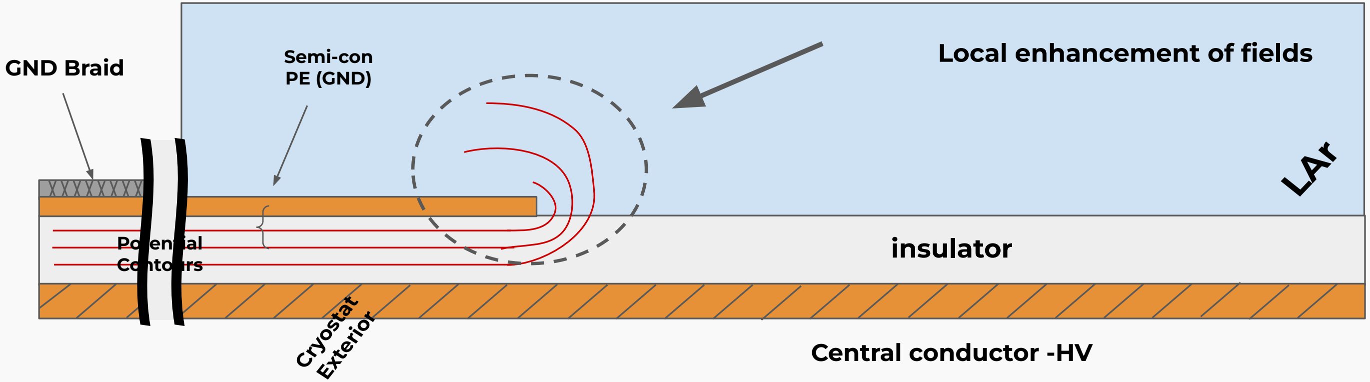


Current Annealing Recipe:

Temp: 87 ±1.5C
4.8inches/hr

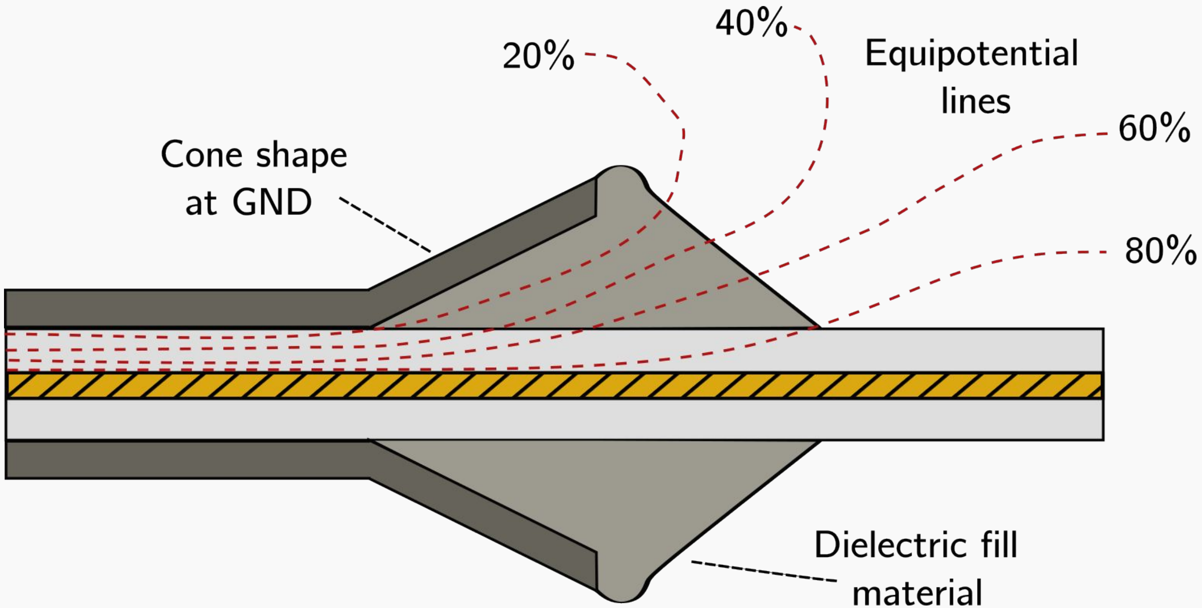
HV Termination and Field Grading

- Need to break ground before cathode connection
  - Very high fields → LAr breakdown *as low as 40kV/cm Blatter et. al doi: 10.1088*
- Field will seek ground *however they want,* $\nabla \cdot E = \rho/\epsilon_0$
- Three knobs we can turn
  - Space
  - Geometry
  - Materials



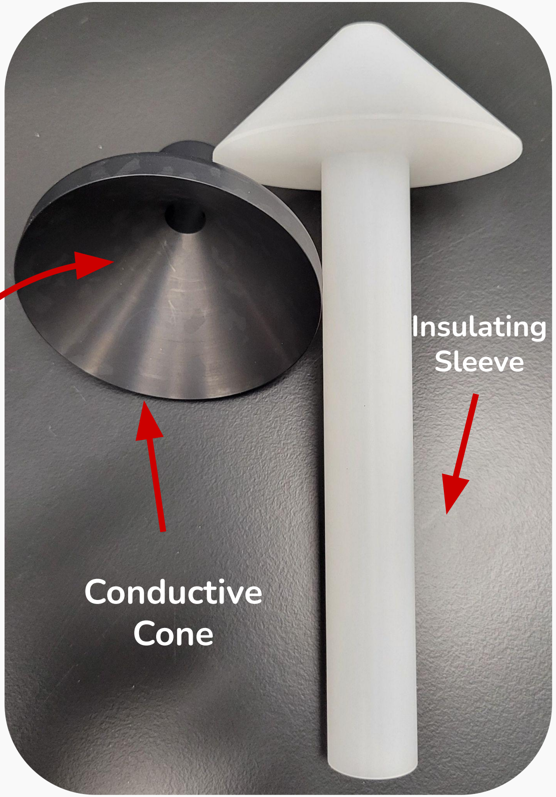
Geometrical Gradings

- Commonly called a ***stress cone***
- Gradually pulls contours apart
    - But requires space



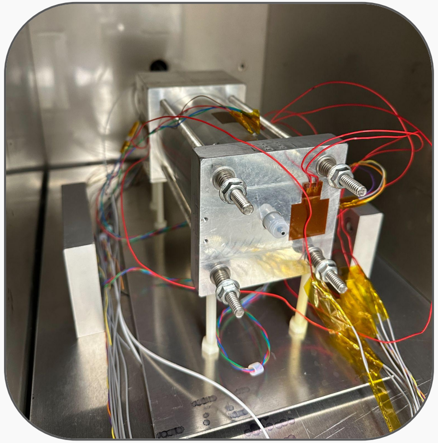
Custom Stress Cone

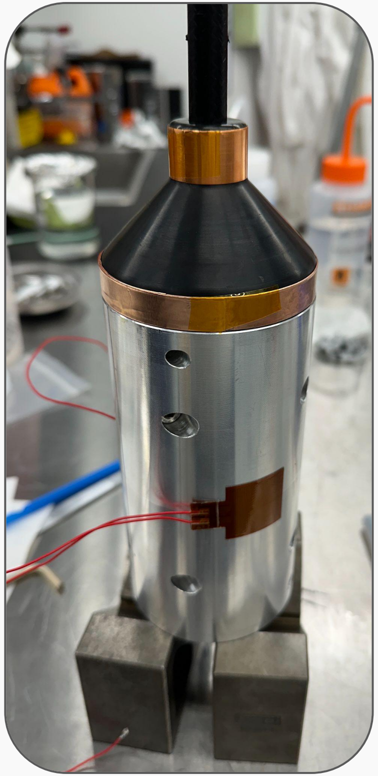
- Want to avoid high fields in LAr
  - → a monolithic structure
- Fuse the structure to the cable
- 3 Parts
  - Cable
  - LDPE insulating sleeve
    - Machined
  - Conductive LDPE outer cone
    - Compression molded with pellets



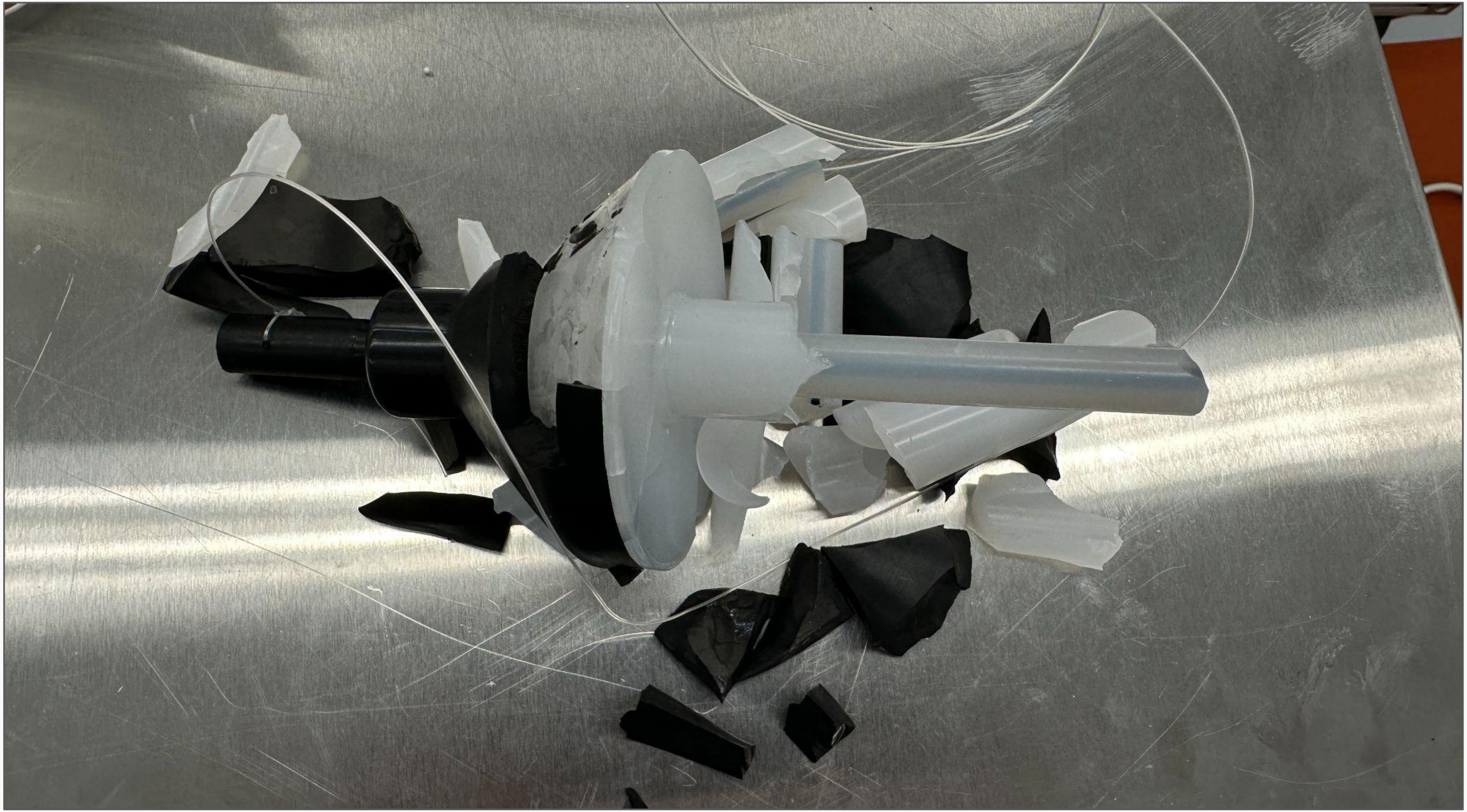
Custom Stress Cone

- Pieces are assembled and placed into a compression mold
  - Temperature control *very important* to avoid melting the cable
- After removal, needs to be annealed again





If you don’t anneal it properly?

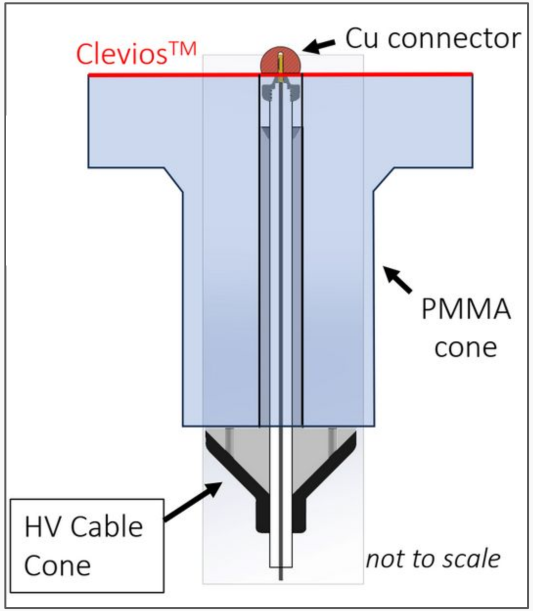


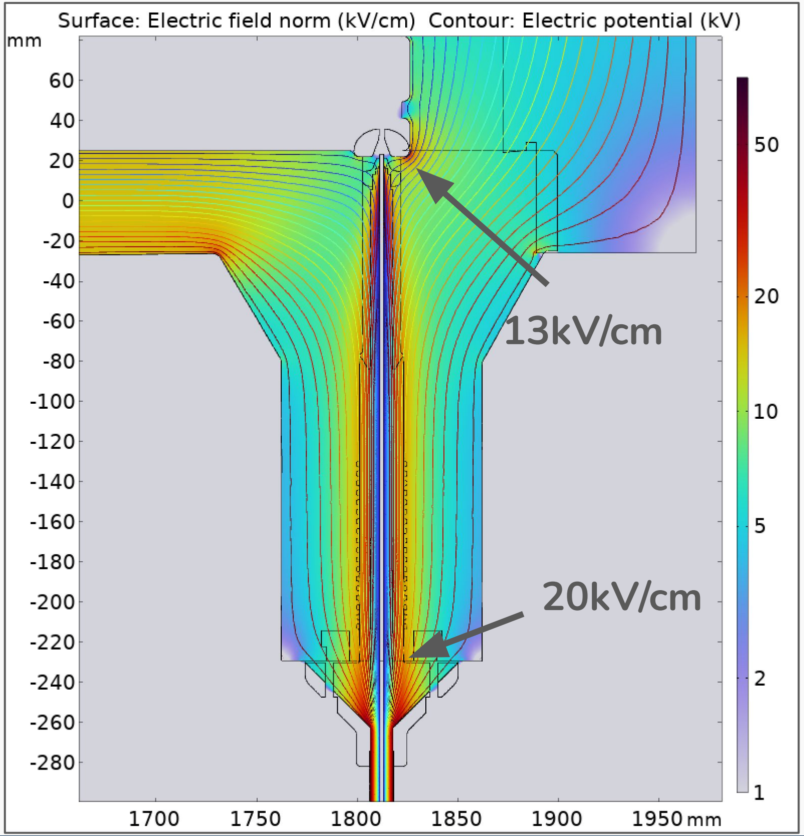
COMSOL Assessment and Validation

- COMSOL sims show regions of high-ish fields

<u>Regions of concern</u>

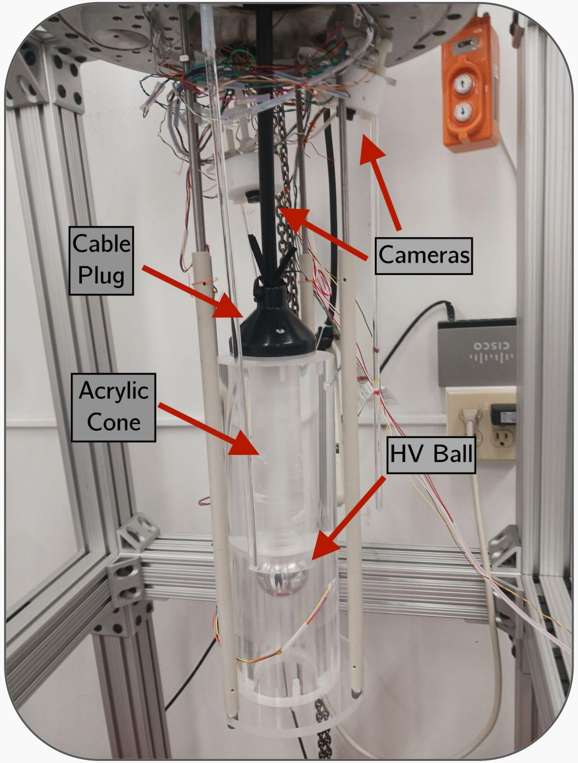
- 13kV/cm below Cu connector
- 20kV/cm between PMMA cone and cable plug

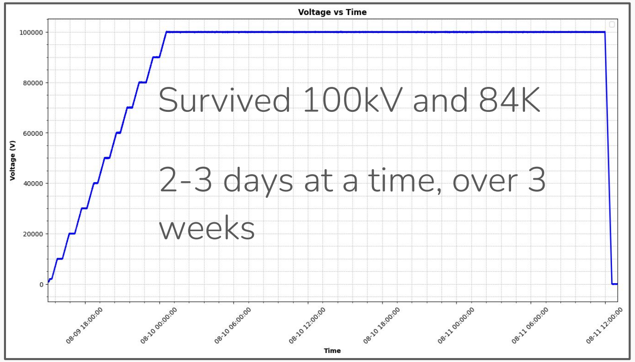




Local Testing At UC Davis

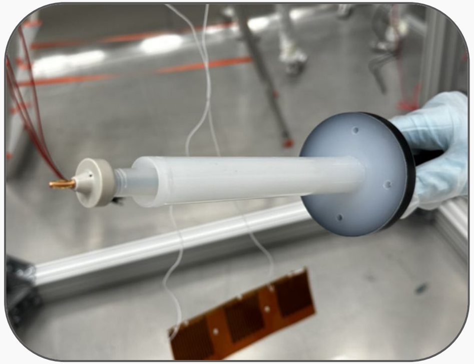
- Cable assm. inserted into PMMA cylinder and HV ball
- Setup mimics local fields in the concerning region
- Two analog, cryo-ruggedized cameras
  - Sparks and bubbles
- 99.997% argon
  - Real purity unknown

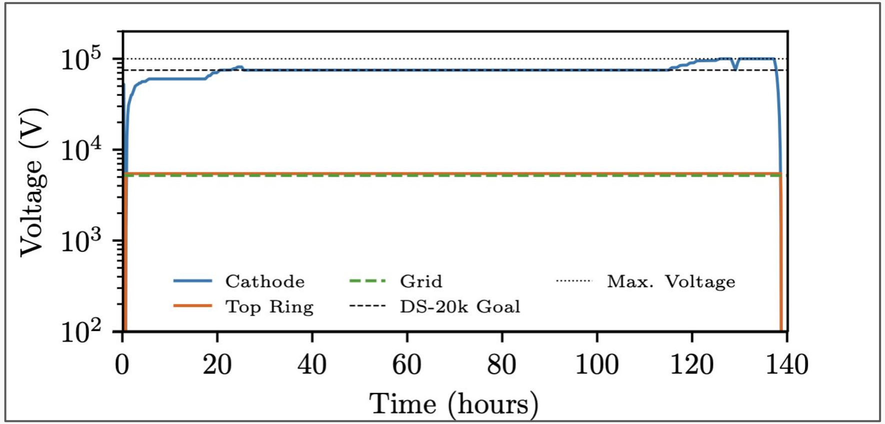


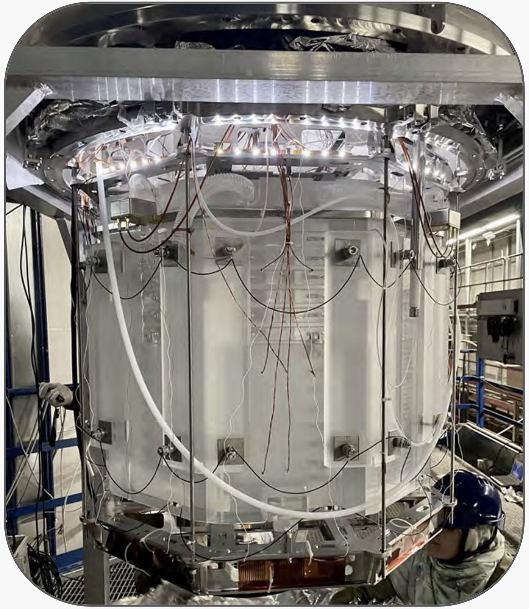


HV Cone Assembly at LNGS

- "Mockup" detector ran in March
  - A shorter version of DS-20k
- Biased at 100kV @84K for 5 days
  - Nominal upon warm-up





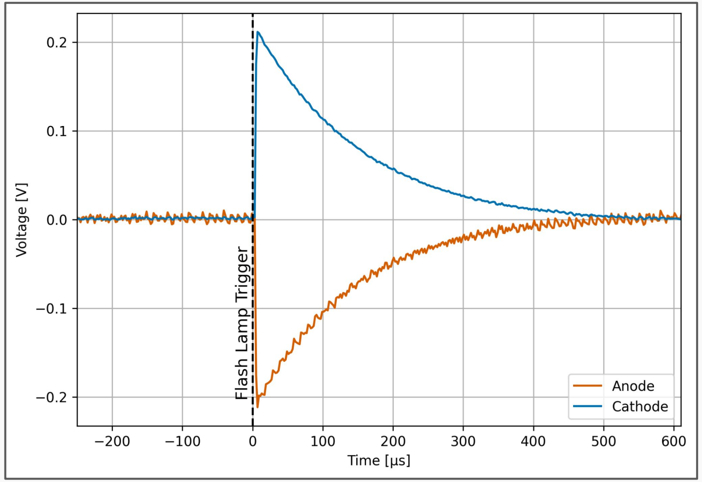


Next Steps: Determine LAr purity

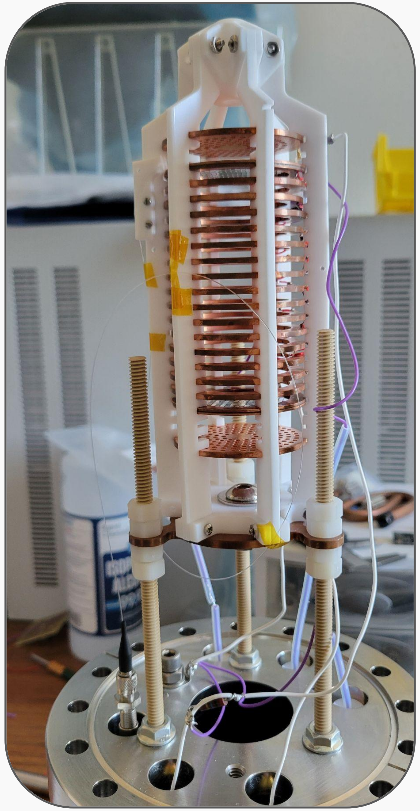
- Need to assess LAr purity
  - Impurities can *quench* breakdowns

→ LAr purity monitor!

- “Mini-tpc”
  - Flash lamp, eject electrons
  - Diff. measurement b/w electrodes
- Undergone vacuum testing, cryogenic testing imminent



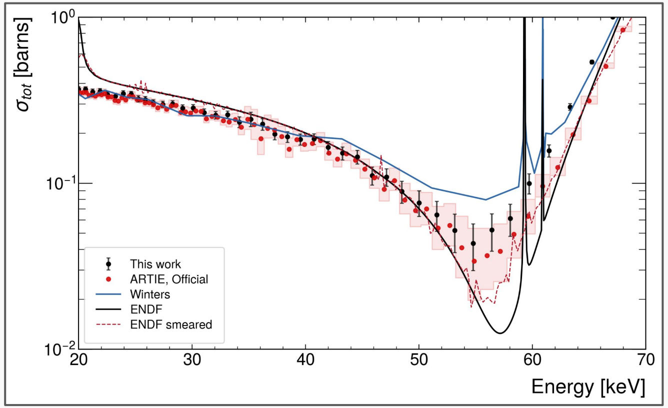
$$\frac{Q_A}{Q_C} = e^{-t_D/\tau_e}$$



Conclusions

Neutron Transport in LAr via ARTIE

- Measured total neutron cross section on natural argon, confirming interference feature near 57keV
    - More inline with the ENDF measurement, ~10-14 meters
    - Important for neutrino event reconstruction and calorimetry!



Hardware Development for DarkSide-20k

- We developed a first-of-its-kind stress cone which withstands 84K and 100kV
- Further testing with high-purity argon forthcoming

Thank you!

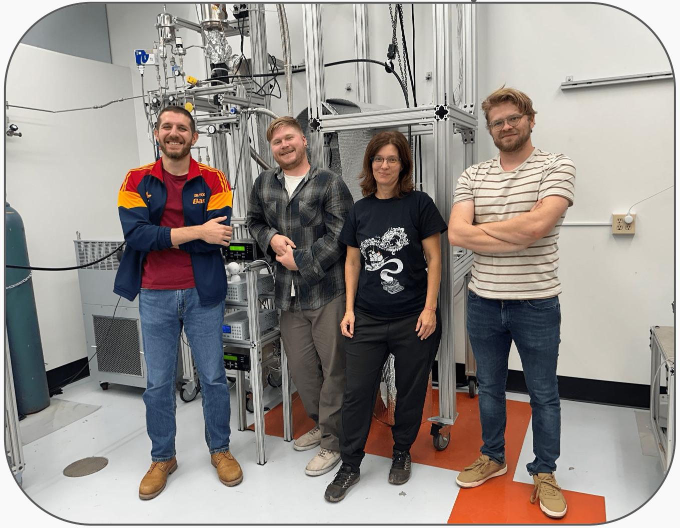
Many thanks to

- SLAC Team for the seminar invitation!
- Prof. Pantic, Dr. Luzzi, Dylon, Fleming
- Prof. Bob Svoboda, Prof. Michael Mulhearn, and the rest of the ARTIE Collaboration
- DarkSide Collaboration
- UC Davis Machine Shop

ARTIE Team

Bottom Left to Top: Me, Prof. Bob Svoboda, Dr. Sofia Andriga

Pantic Group



Left to Right: Ludivico Luzzi (postdoc), Dylon Fleming (grad student), Prof. Emilija Pantic, me

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