Argon Capture Experiment at DANCE (ACED): Measuring neutron capture in argon

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Outline

- Deep Underground Neutrino Experiment (DUNE)
- Why study neutrons in liquid argon?
- ACED: Argon Capture Experiment at DANCE
  - Thermal neutron capture cross section
  - Correlated gamma cascade
- Beyond ACED
  - Argon Resonance Transmission Interaction Experiment (ARTIE)
  - Pulsed Neutron Source for detector energy calibration
- Summary

Neutrino Oscillation

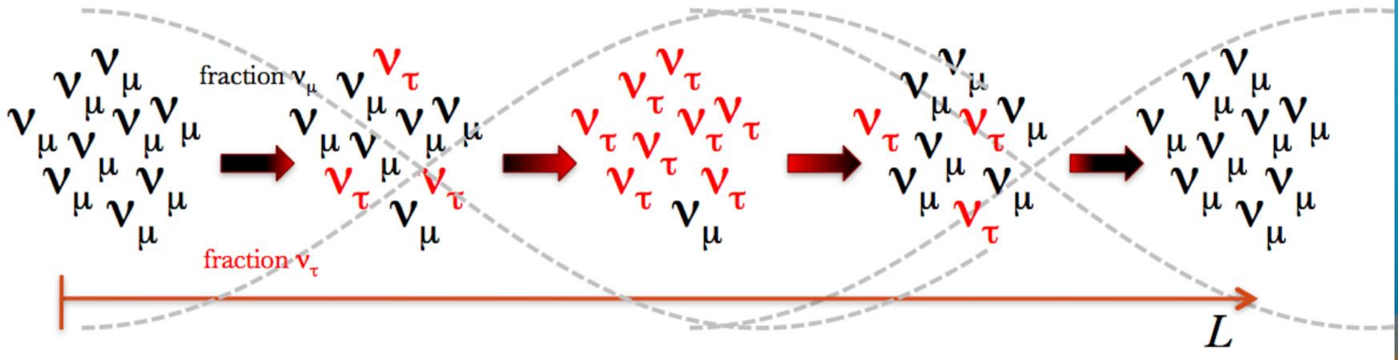
- **It's the process of neutrinos changing from one flavor to another**
- **This can happen because neutrinos have two identities:**

Flavor: how they interact

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass: how they propagate

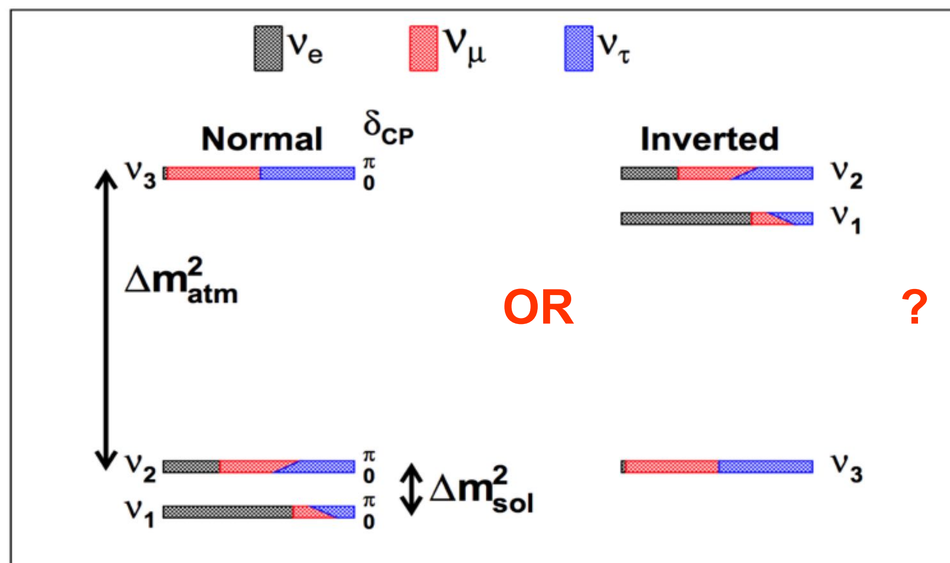
- As the neutrinos travel through space, each mass state propagates with a different frequency.
- The linear combination of mass states changes over distance, which makes the initial flavor "oscillate" to other flavors



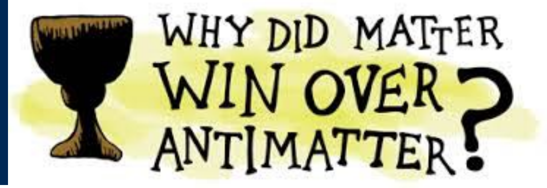
Mystery: Mass Ordering

- Neutrinos must have mass: known from oscillation experiments
- What is the **mass ordering**? Is it "**normal**" or "**inverted**"? Don't know don't if m_3 is the heaviest or the lightest neutrino mass
- The mass ordering is important for developing models about the early universe
- Knowing the mass ordering is important for the **CP violation** measurement

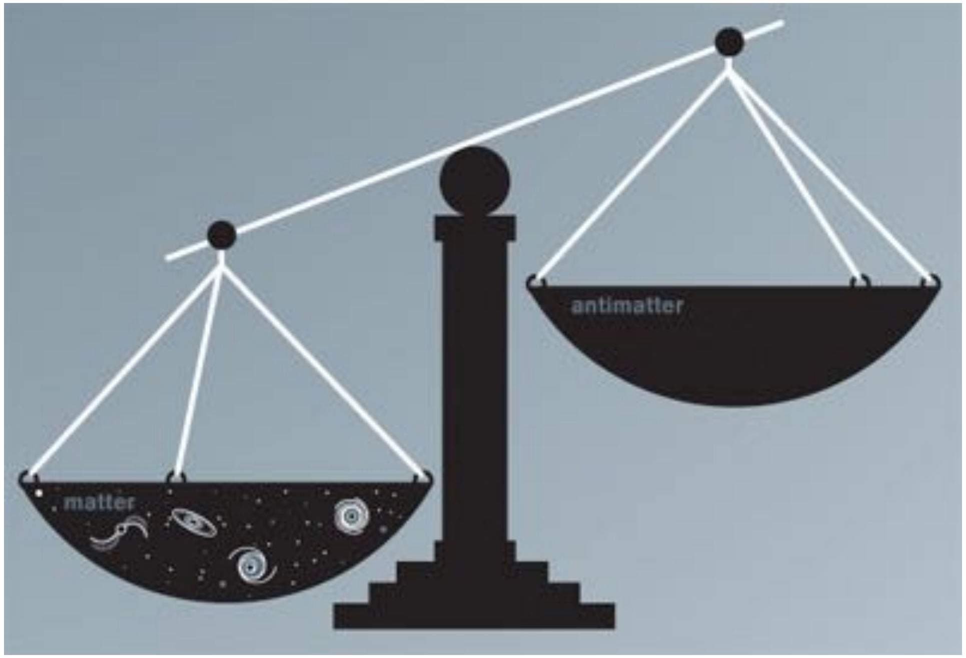
Neutrino Mass Hierarchy



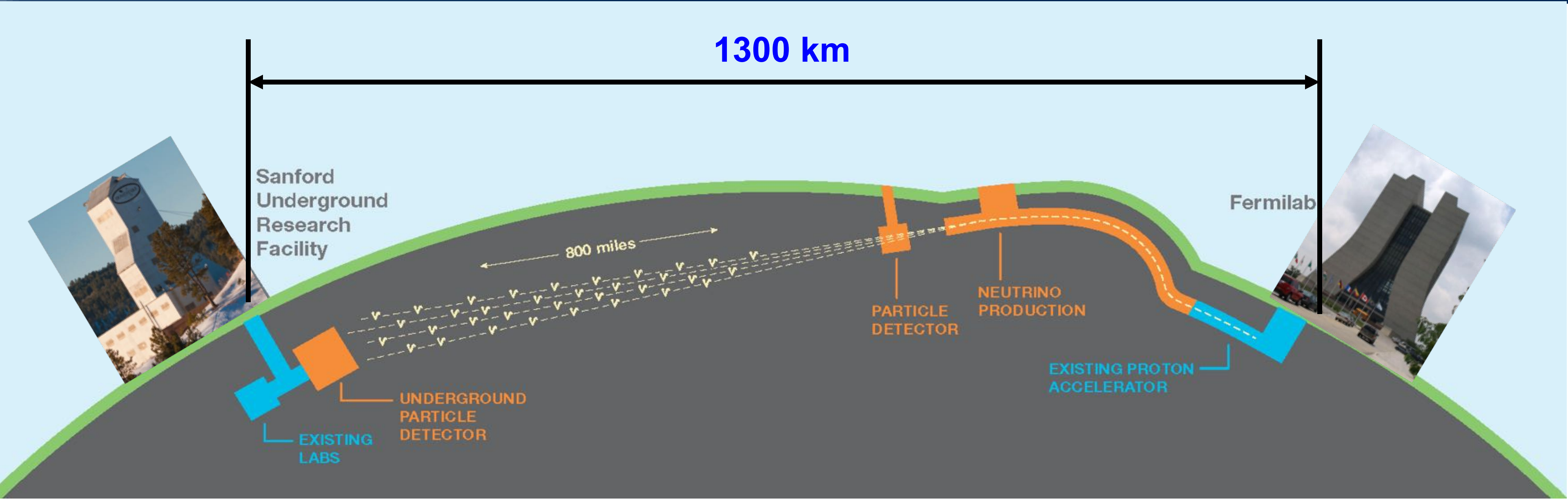
Mystery: CP violation



- In the big bang, if CP was conserved, the amount of matter and antimatter would be the same. But, this is certainly not the case, because we (matter) exist!
- The baryonic CP violation was discovered, but it is not strong enough to explain the matter-antimatter asymmetry
- A promising way seems to be looking for the leptonic CP violation with **NEUTRINOS**
- Neutrino oscillation mechanism offers a way to **probe CP violation**
- Requires next-generation detectors which can make precision measurements

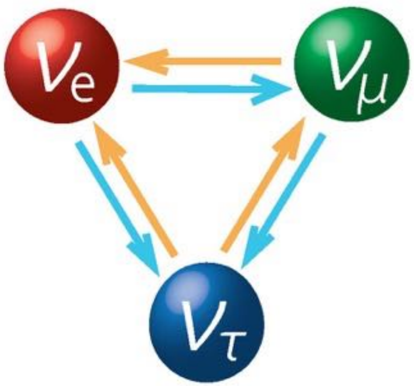


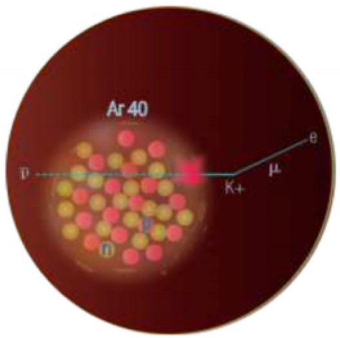
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



- **Next generation long-baseline neutrino experiment in the US**
- **Interaction collaboration**: **1180** collaborators from **177** institutions in **31** countries
- **Intense neutrino beam** from Fermilab to South Dakota, over **1300 km** baseline
- **A near detector** to measure the neutrino flux before oscillation
- **A ~ 40 kt fiducial mass liquid argon far detector** at SURF's **1.5 km** level

DUNE Science

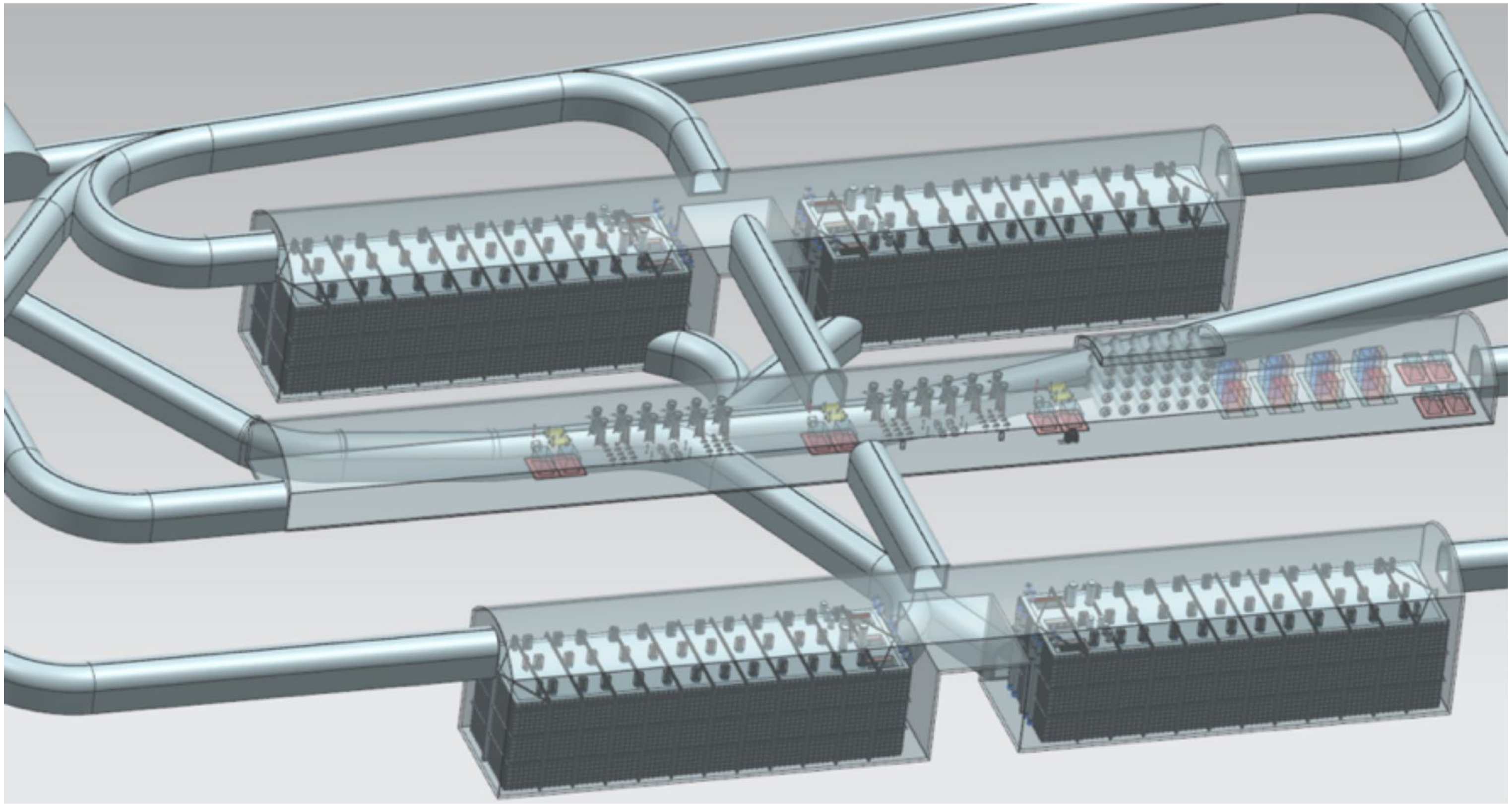




Focus on fundamental open questions in particle physics and astro-particle physics:

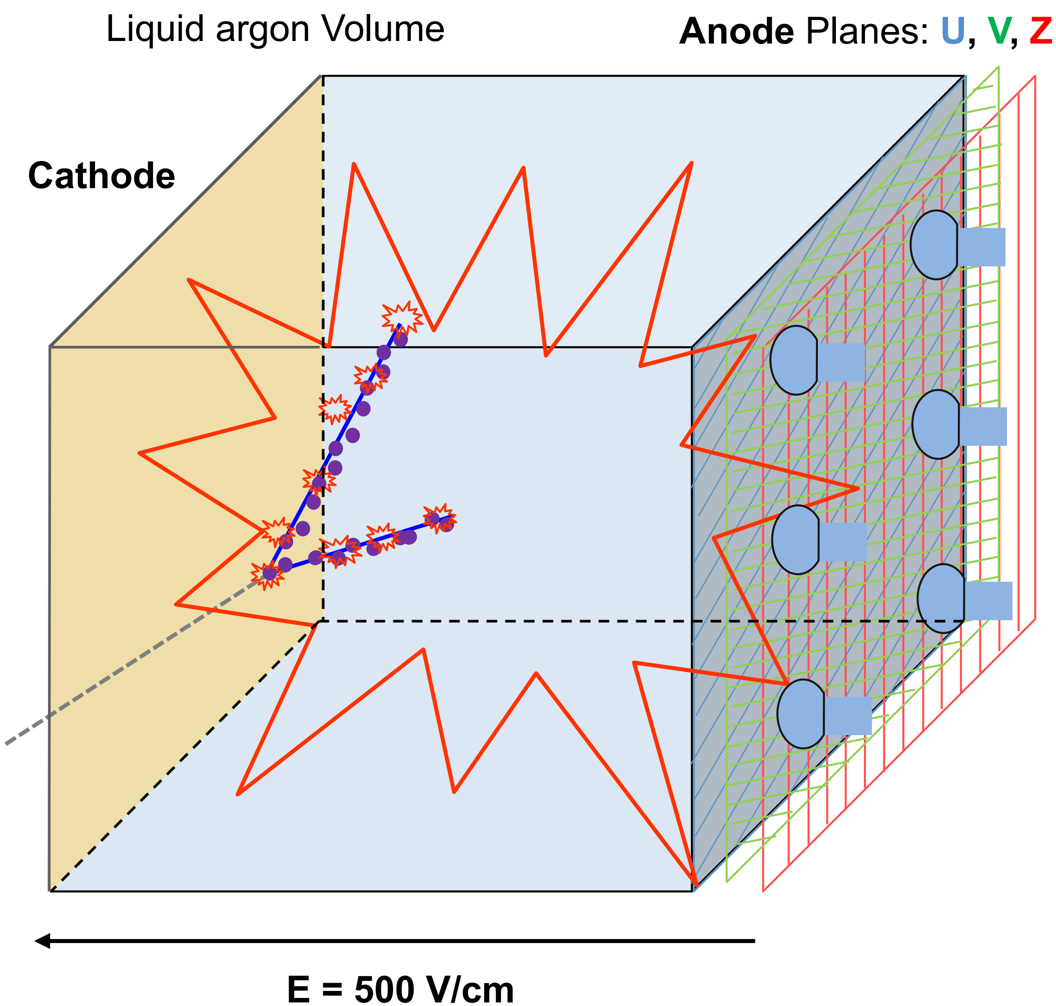
- **Neutrino Oscillation Physics**
  - Measurement of CPV in the leptonic sector
  - Definitive determination of neutrino mass hierarchy
  - Testing the 3-flavor paradigm (θ_{23} octant, …)
- **Nucleon Decay and Baryon Number Violation**
  - Nucleon decay, e.g. $p \rightarrow K^+ + \bar{\nu}$
- **Supernova burst physics & Astrophysics**
  - Core-collapse supernova, sensitivity to ν_e Supernova Burst Neutrinos
- **And many more:** sterile neutrinos, solar neutrinos, Non-standard interactions…

The DUNE Far Detector



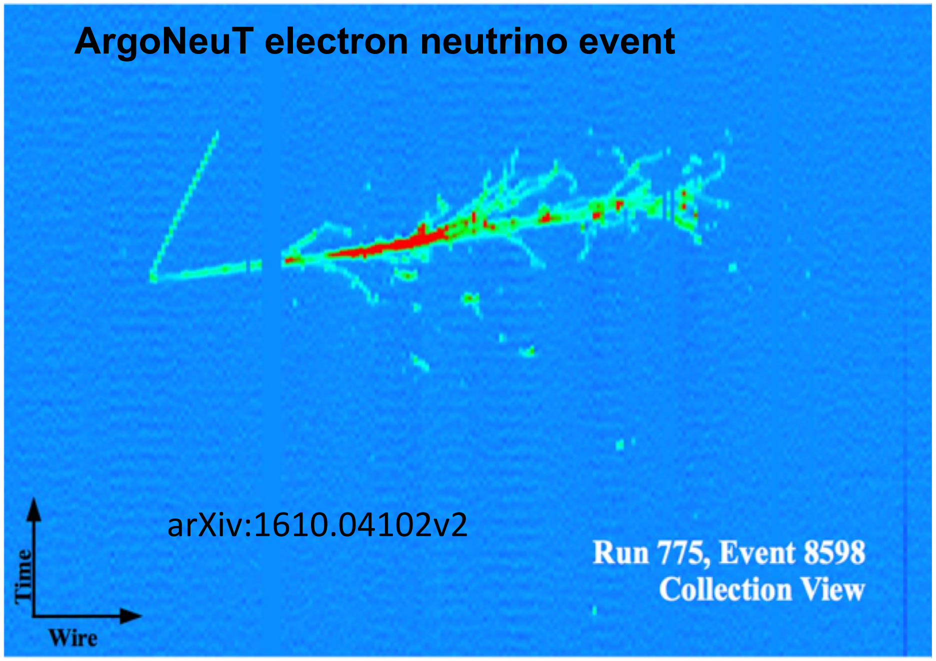
- Four caverns hosting **four** independent 10 kt fiducial mass (17.5 kton total) liquid argon TPC modules
- Four identical cryostats: external size of 19.0 (W) x 19.0 (H) x 66 (L) m^3

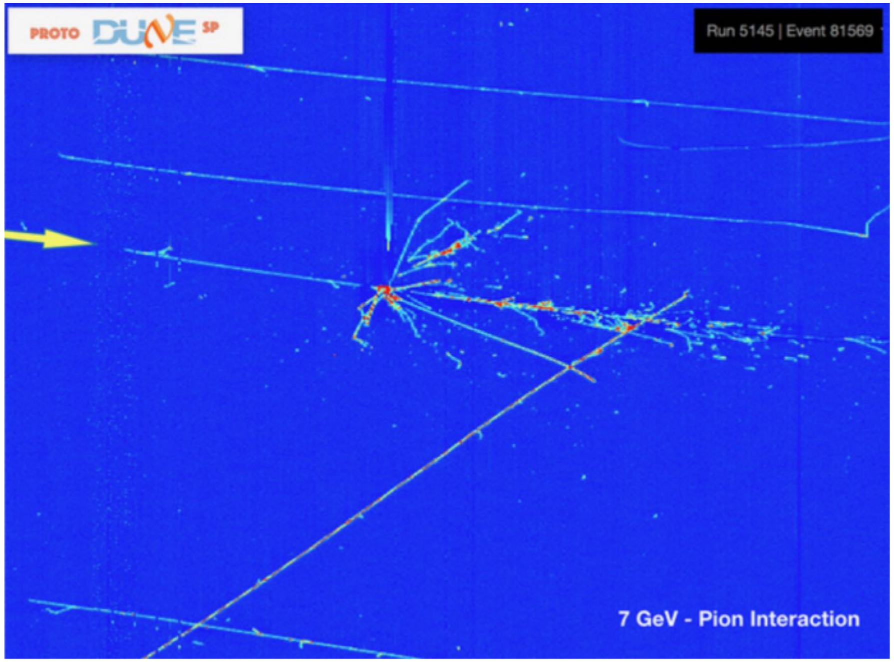
Liquid Argon Time Projection Chamber



- Incoming neutrino interacts with argon, producing secondary charged particles
- Charged particle create ionization electrons and scintillation light along their tracks
- Prompt scintillation light propagates to the whole detector, and is detected by photodetectors, providing the start time of the event
- Electrons drift towards anode (1.6 mm/us), and are readout by the readout wires

LArTPC Features

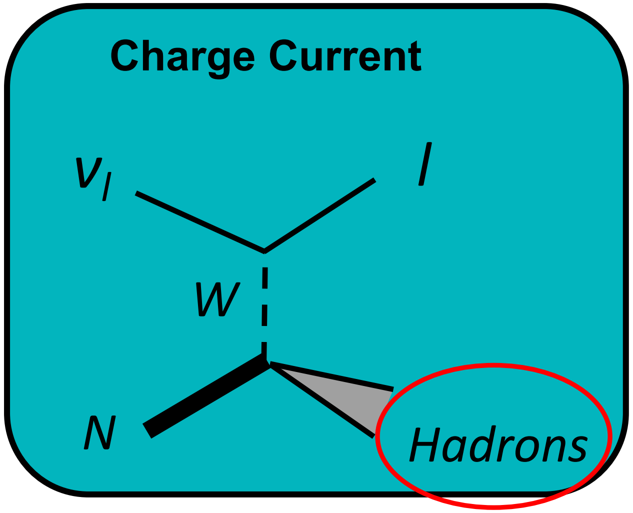


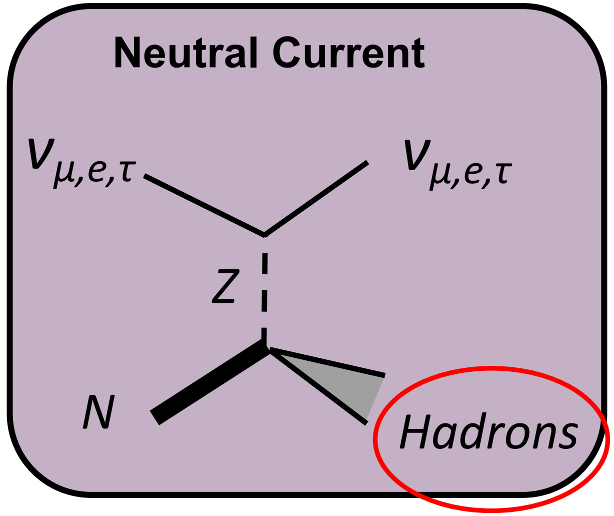


- **mm spatial resolution** to “see” the details of an interaction
- **Excellent particle identification capability** through various ways: energy loss, track displacement, event topology, etc…
- **High energy resolution** through calorimetric measurement
- However, neutrons are difficult, because they **don’t create any ionization tracks.**

Neutrons in Liquid Argon TPC

- Neutrons may come from **neutrino interactions**
  - Neutrino typically produces a proton. Antineutrino typically produces a **neutron**
  - The secondary hadrons may contain: more than one protons and **neutrons**, $\pi^{\pm}, \pi_0$
  - Protons, $\pi^{\pm}$ and π_0 can be detected in LArTPC, but neutrons are difficult.





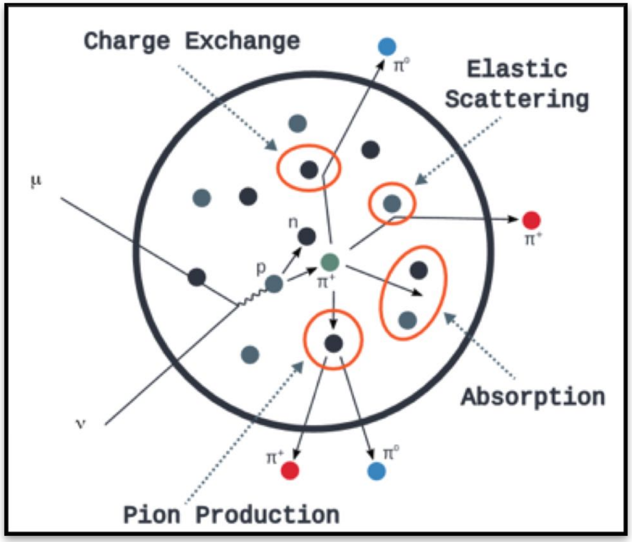
- Neutrons may be produced by the **cosmic rays** interacting with materials
- Neutrons may also come from the **spontaneous fission** in the rocks
- **In liquid argon TPC, neutrons deserve a special attention**

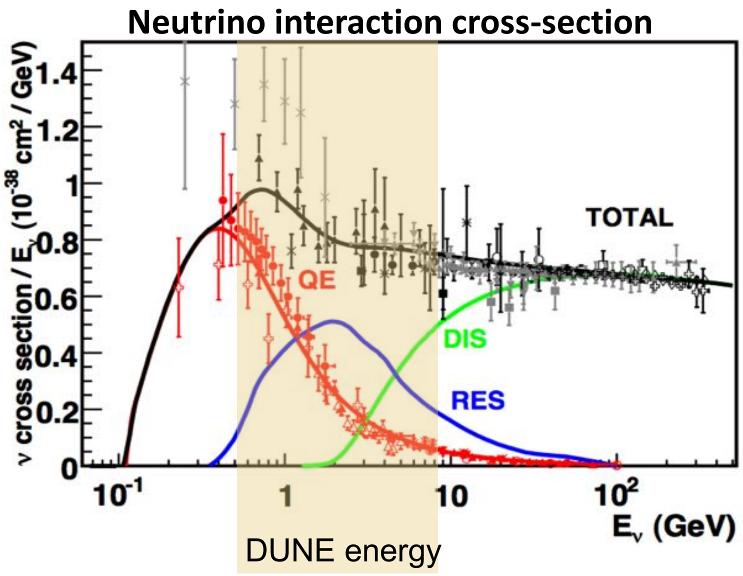
Why interested in neutrons?

- Neutrons are important in DUNE energy reconstruction for beam neutrinos
- Neutrons are part of the supernova neutrino signal in DUNE
- Neutrons are important background for low-energy physics experiments
- Neutrons could enable a possible LArTPC calibration technique

Neutrons are important in DUNE

- To turn neutrino physics into a precision science, we need to understand the complex neutrino-nucleus interactions
- In DUNE, a large fraction of the neutrino interactions go through **RES** and **DIS**
  - About **20%** of the energy is carried by prompt neutrons associated to the vertex
- Mis-modeling of neutrons can result in significant bias in the neutrino energy reconstruction, thus affects CP violation sensitivity.
- **Need to understand the physics of neutron production and transport**

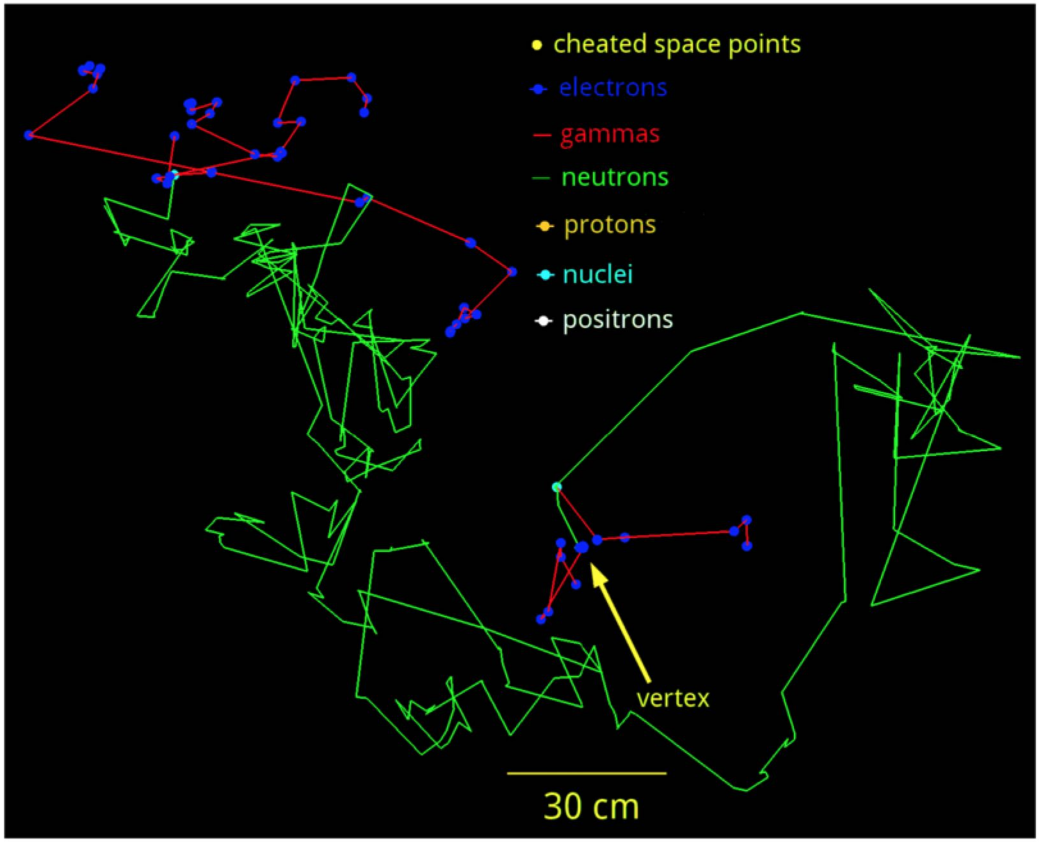




Neutrons in DUNE supernova physics

- **Neutrons are part of the DUNE supernova neutrino signal**
  - Dune's official supernova generator MARLEY suggests that **15-30%** of supernova events involve neutron emission
  - Missing neutron energy leads to large uncertainty in energy reconstruction

Particle trajectories from a simulated SN event in DUNE

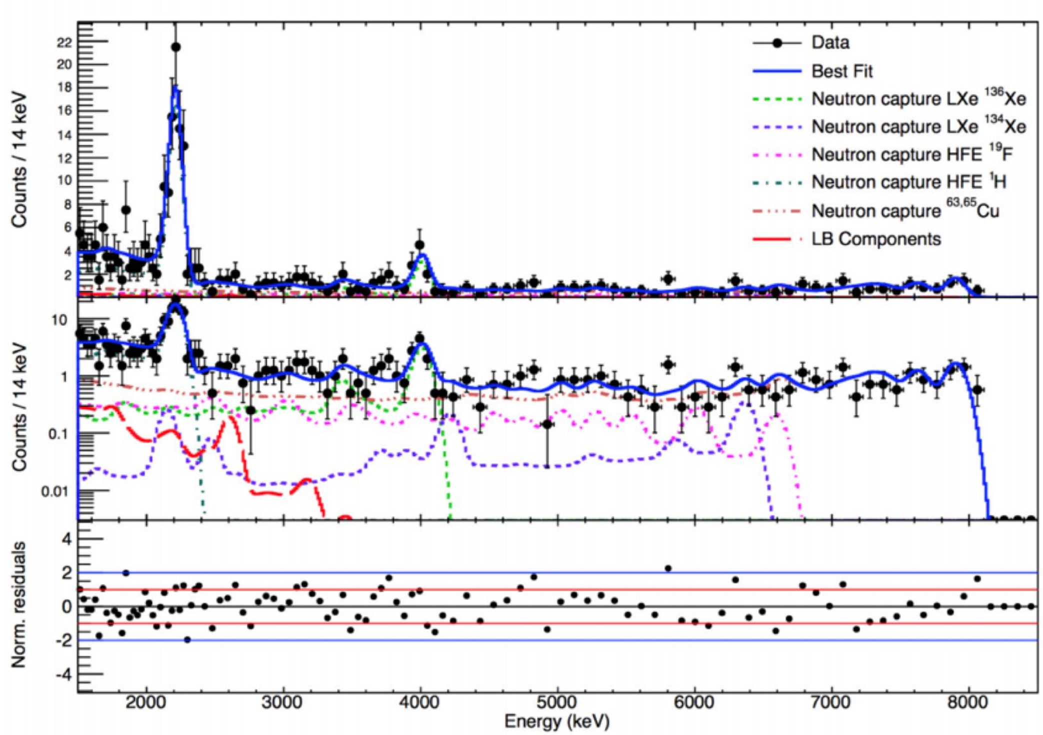


- **Difficulties to model the process**
  - The **event-by-event capture γ-ray distributions** are unmeasured (would be valuable to tag these neutrons)
  - Thermal neutron capture cross-section is not well measured

- **THIS IS WHAT WE WANT TO MEASURE!**

Neutrons in Low Background Experiment

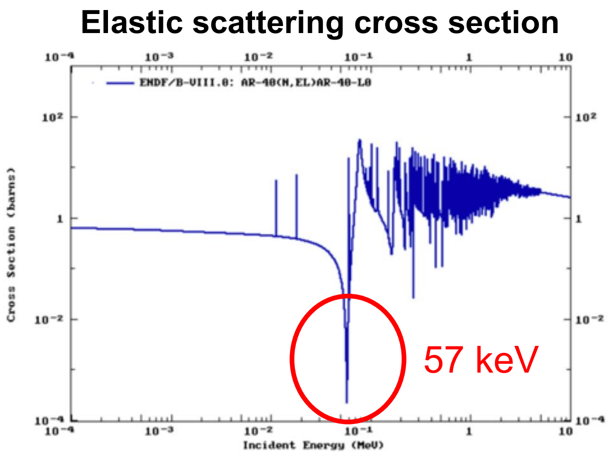
- Neutrons could be significant background in low energy experiments
- Possible to use neutron tagging to **characterize background**
  - Vetoing neutron scatters (dark matter experiments) or neutron capture gammas (0νββ experiments)
- Low background LAr detectors:
  - Darkside-50/Darkside-20k
  - DEAP-3600/DEAP-50t
  - MiniCLEAN
  - GERDA (active shield)

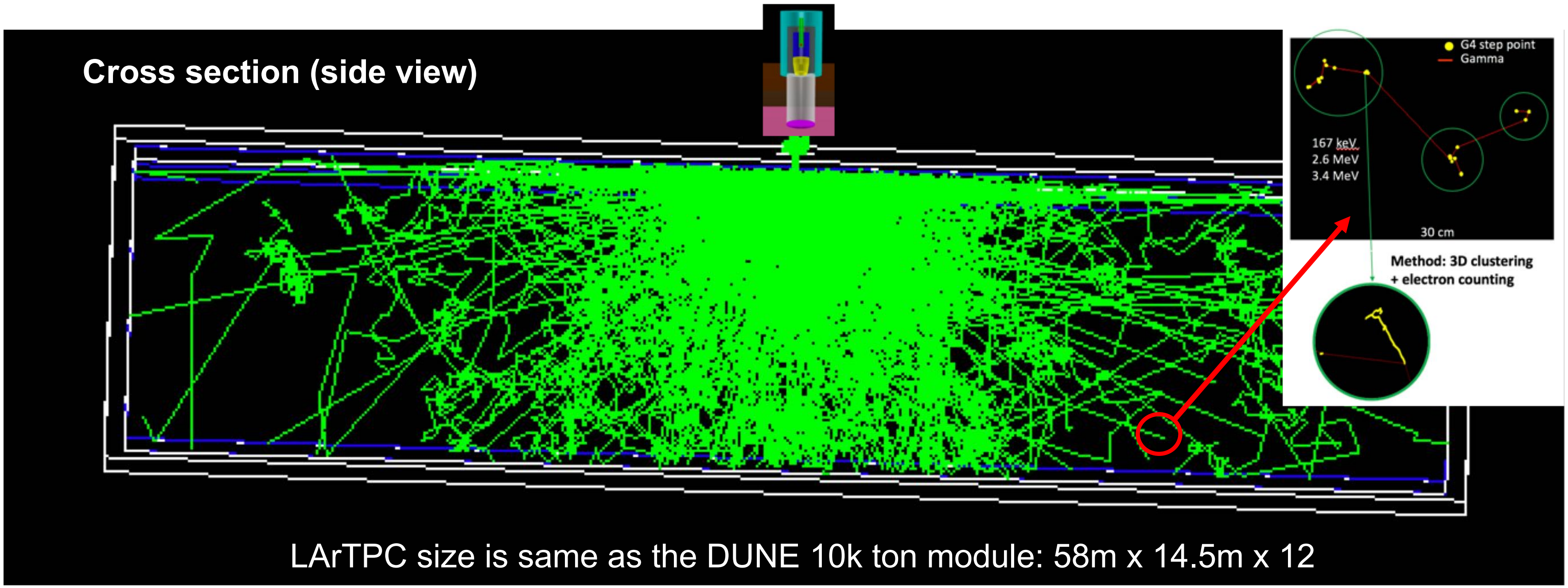


EXO-200 measured the flux of neutrons in a xenon detector by fitting the spectra of correlated γ-rays from neutron capture on xenon and surrounding materials

Neutrons for Detector Calibration

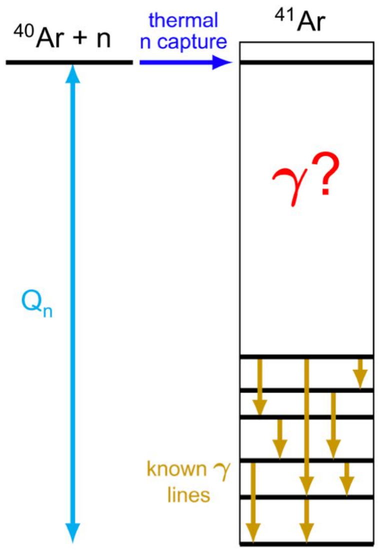
- Neutrons at 57 keV “anti-resonance” can travel far
- It’s possible to inject below 100 keV neutrons into liquid argon TPC
- Use the **6.1 MeV** gammas from the neutron capture in ^{40}Ar as the “standard candle” energy deposition to calibrate the detector response



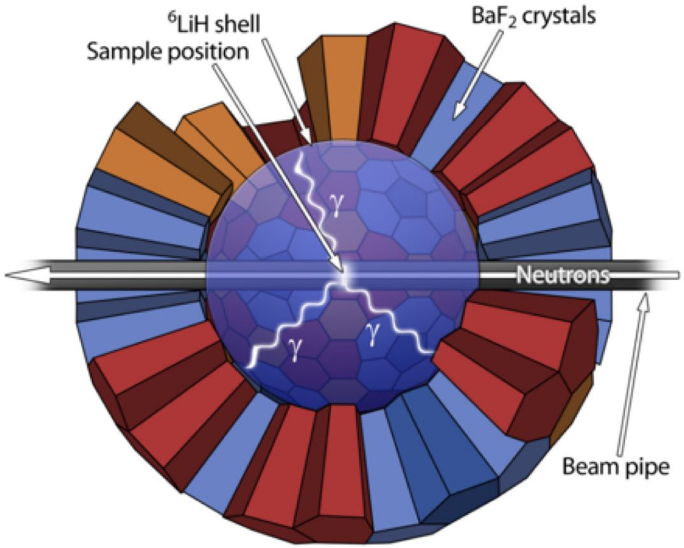


Argon Capture Experiment at DANCE

ACED is a measurement of neutron capture properties on **^{40}Ar** using the Detector for Advanced Neutron Capture Experiment (**DANCE**) and the **Time-of-Flight** neutron beam at Los Alamos National Laboratory

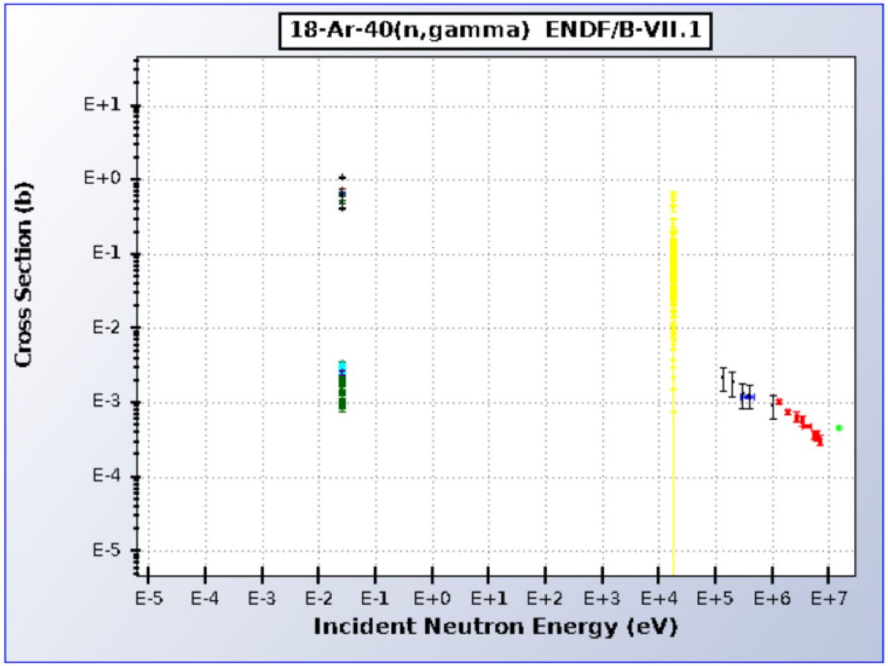


- **ACED goals:**
  - Measure the radiative neutron capture cross section on ^{40}Ar at thermal energies
  - Measure the branching ratios of the correlated gamma cascade on event-by-event basis



Neutron Capture Cross Section in Argon

- It's known that **neutron captures in ^{40}Ar creates 6.1 MeV gamma cascades.**
- However: the radiative neutron capture cross section isn't well known
  - Data points not well distributed over the energy range



National Nuclear Data Center (NNDC)

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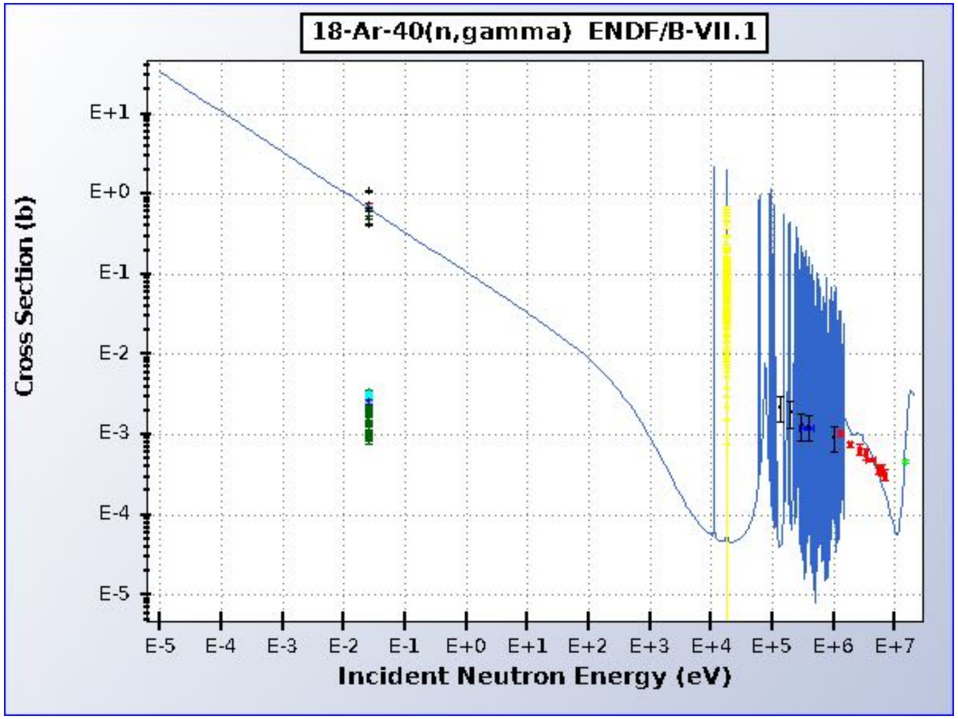

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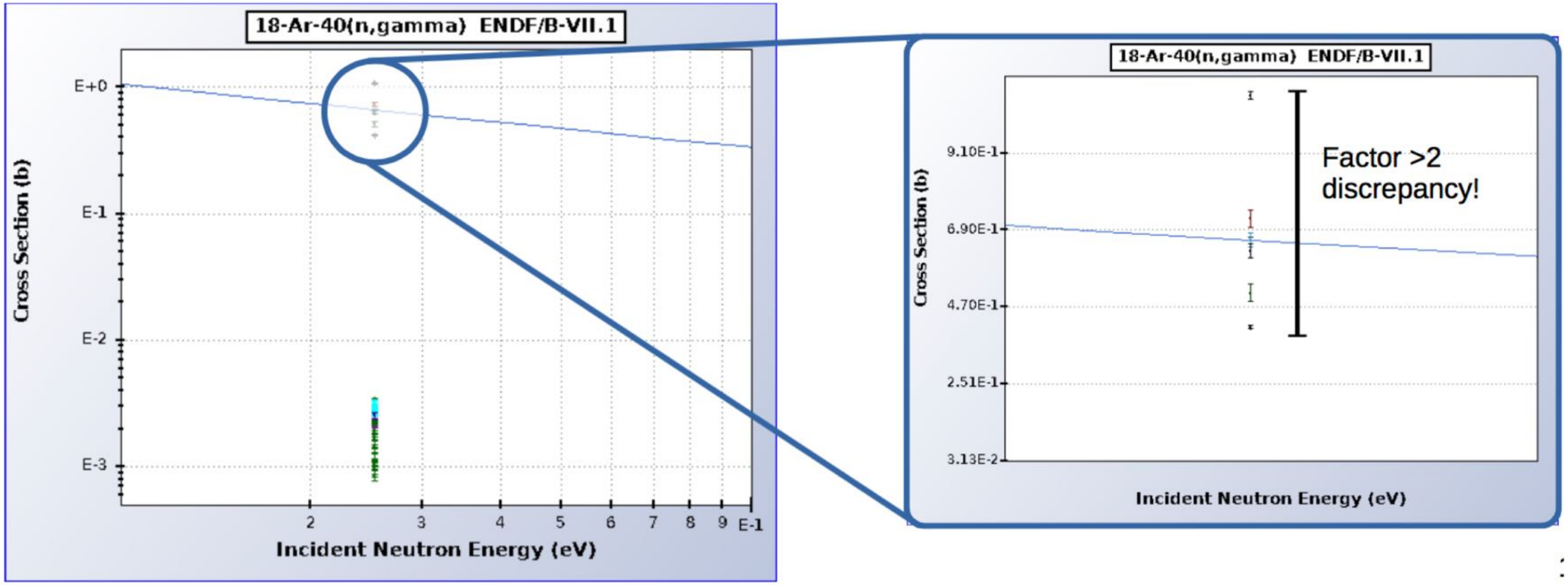
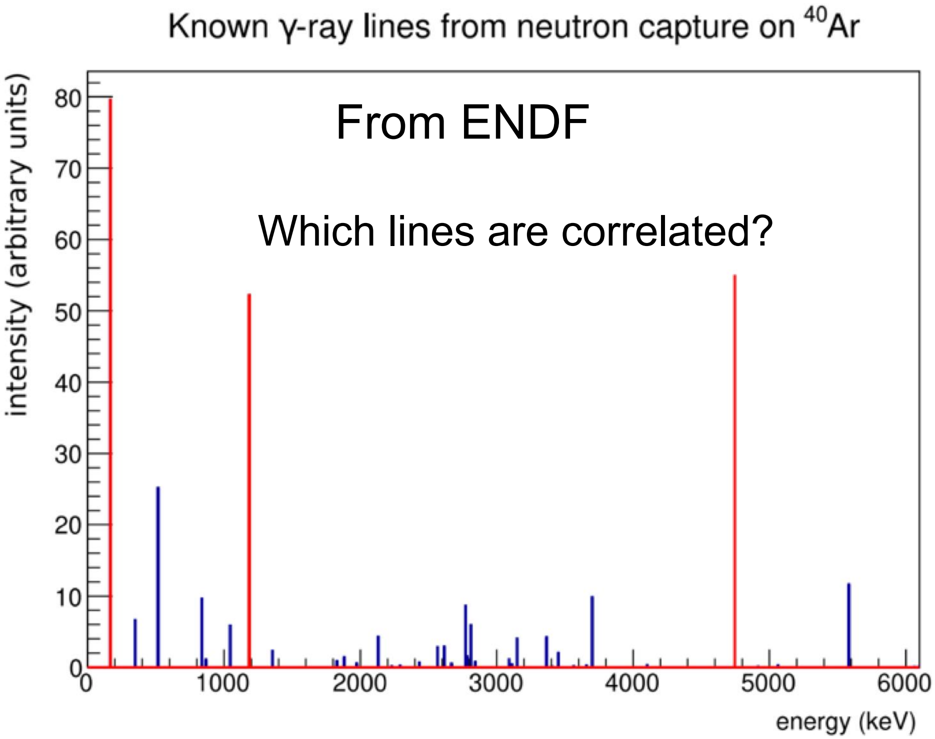
- However: the radiative neutron capture cross section isn't well known
  - Data points not well distributed over the energy range
  - Extrapolation is purely based on theoretical assumptions
  - Measurements/evaluations at **thermal energies** don't agree well



Neutron Capture Gammas in Argon

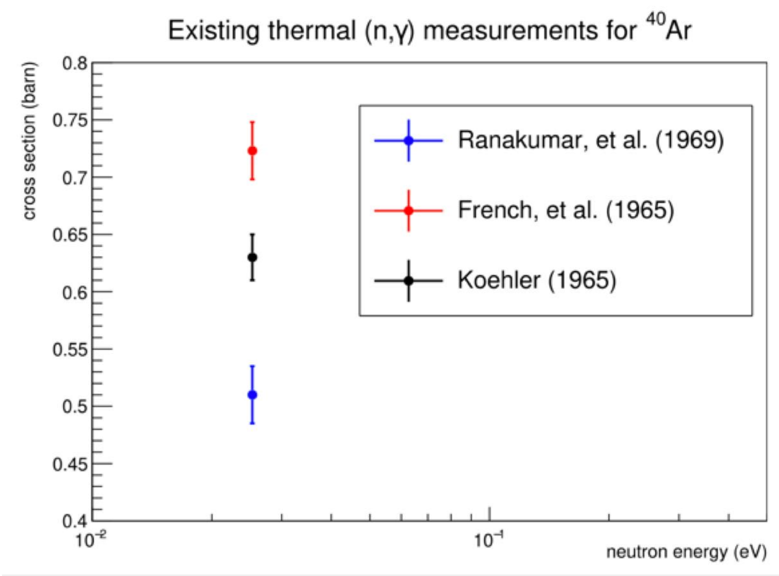
- The energy of the **individual de-excitation gammas is not well understood either**
  - Some lines have been measured by looking at ^{41}Ar decays in activation experiments
  - Uncertainties on the branching ratios are quite high (>15% for some)
  - Other lines are purely based on theoretical models and have not been observed

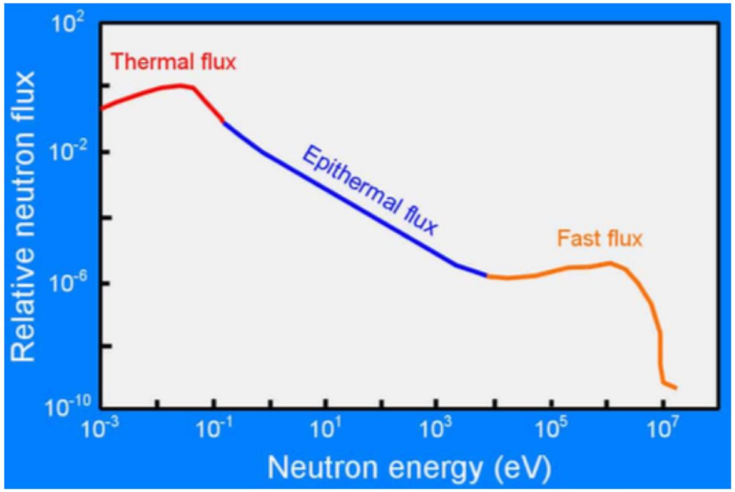


- There was no measurement of full event-by-event **correlated gamma cascade** from neutron capture in argon
- **To understand the neutron transport in argon, these issues have to be fixed**

Previous Neutron Capture Measurements

- **Before ACED, there were only three measurements for thermal-neutron capture**
  - Measurements not consistent
  - Argon samples were activated in a nuclear reactor. Beta decay of ^{41}Ar daughter was counted in a gamma spectrometer
  - Energy of individual neutrons is unknown.
  - The spectrum is mostly thermal but has **non-negligible amount of epithermal and fast neutrons**





From nuclear-power.net

Convention on thermal capture cross-section

- If neutrons are thermalized, their energy and velocity follow the Maxwell-Boltzmann distribution
- Conventionally, the **thermal** neutron capture cross-section is reported as the **cross-section at the most probable velocity** at room temperature (2200 m/s at 293 K, σ^{2200})
- In reactor experiments, the cross-section is measured as the **average value** over the whole energy spectrum. Corrections were needed to convert to the standard thermal capture cross section
- Need good understanding of the neutron energy spectra. May introduce additional uncertainty.

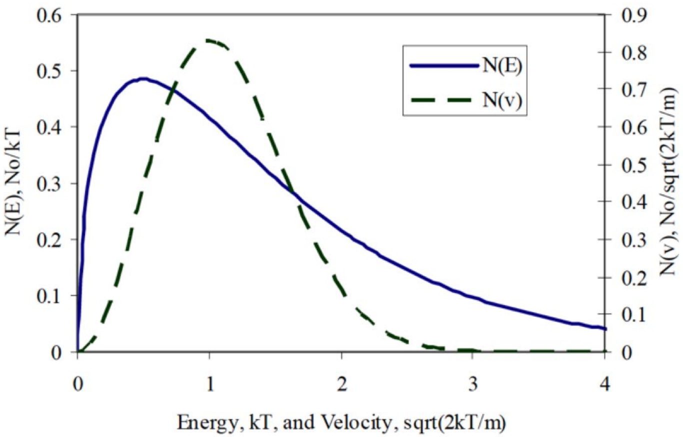
$$T = 293\ K$$

$$v_{mp} = \sqrt{\frac{2kT}{m}} \approx 2200\ m/s$$

$$\bar{\sigma} = \frac{\int \sigma(v) v f(v) dv}{\int v f(v) dv} = \frac{\sigma_{mp} v_{mp}}{\int v f(v) dv} = \frac{\sigma_{mp} v_{mp}}{\bar{v}}$$

$$\boldsymbol{\sigma_{mp} = \frac{2}{\sqrt{\pi}} \bar{\sigma}}$$

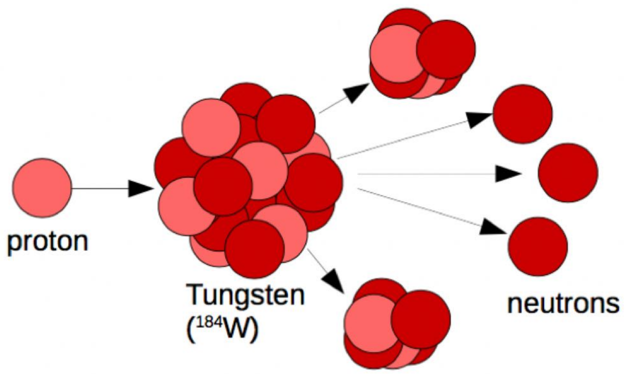
Maxwell-Boltzmann distribution



...Perhaps Using a Neutron Beam!

- Ideally, we want **a triggered neutron source** with a way to tell the single neutron energy event by event!

- **Possible in a neutron beam:**
  - Neutrons created through **spallation** reactions of protons on bigger atoms
  - Neutrons are **moderated and collimated** down a beam pipe
  - Neutron energy can be determined on event-by-event basis using **"Time-of-Flight"**
  - No need to make spectral corrections as that in conventional reactor measurements

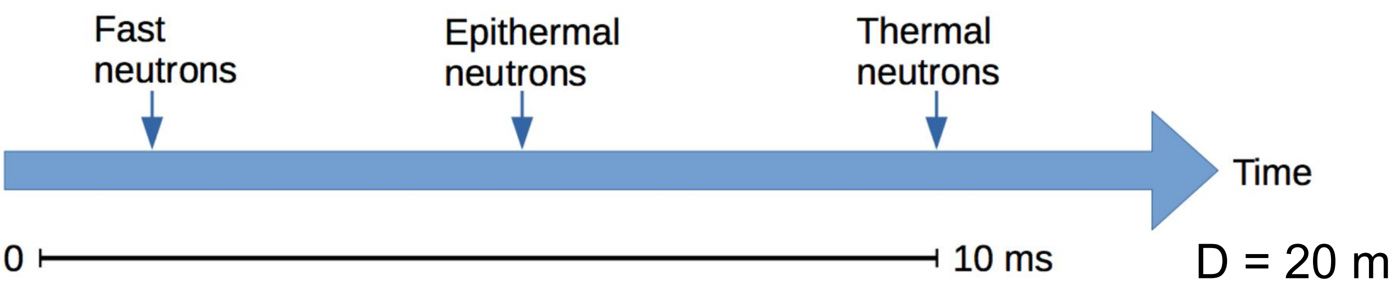


Time-of-Flight Technique

- **Neutrons below ~MeV level are not relativistic so** $E_{neutron} = 1/2\, mv^2$
- For example: a 0.025 eV **thermal neutron** travels at **2200 m/s**

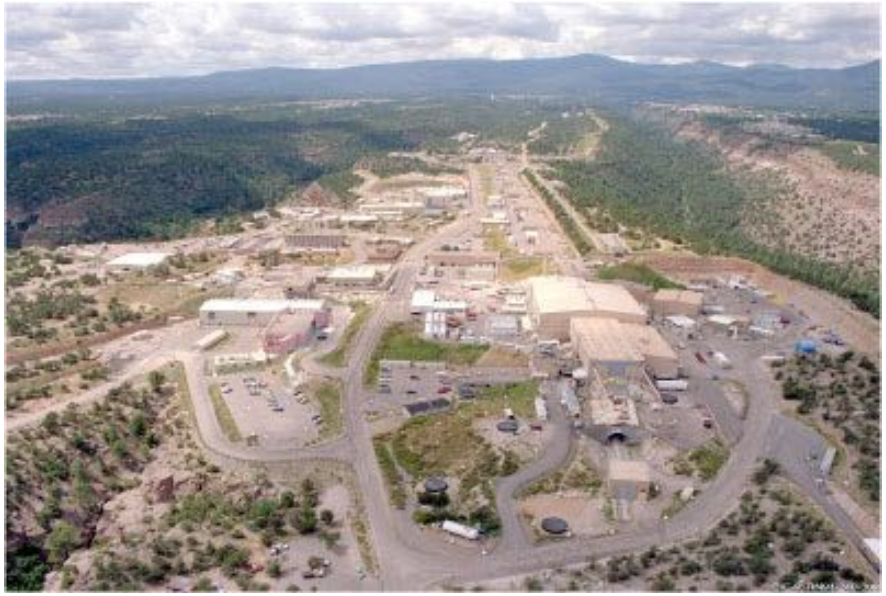
As fast as this guy

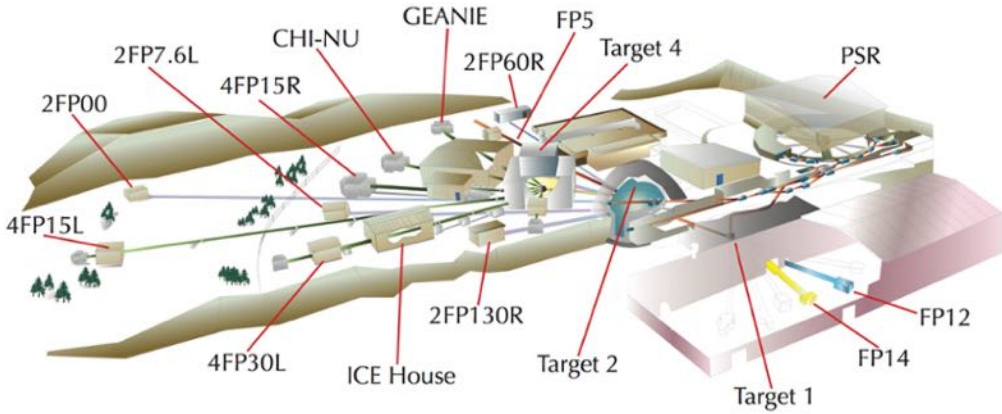
- **In a TOF neutron beam:**
  - Using the time difference between the proton pulse and the neutron arrival, one can get the **neutron speed (hence its energy)**
  - **More energetic neutrons arrive faster** while it takes about 10 ms for thermal neutrons to travel through a 20 m distance
  - ns-level time resolution allows a precise measurement of the energy



The LANSCE facility at LANL

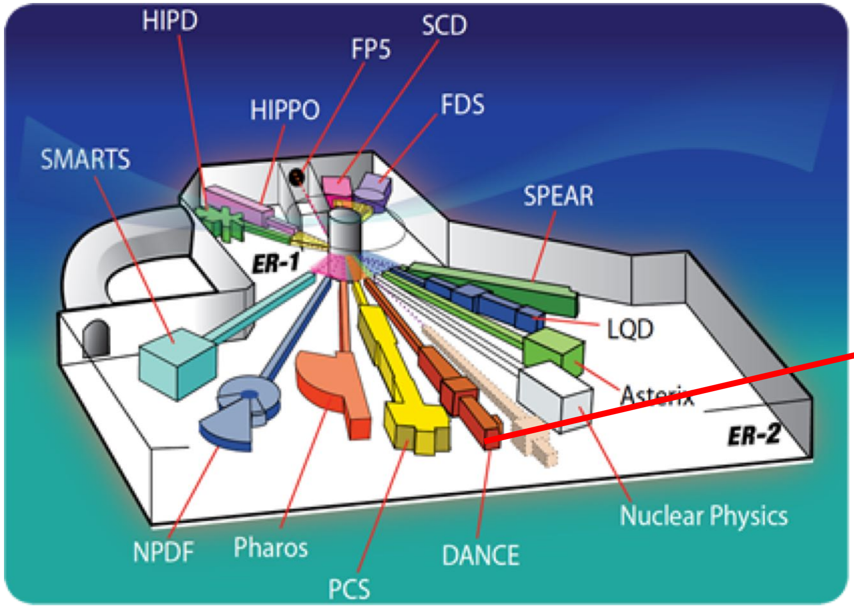
- **Los Alamos National Laboratory** (LANL) lies on the beautiful mesas of **New Mexico**
- **Los Alamos Neutron Science Center (LANSCE)**
  - Proton and neutron beams for different purposes
  - Collaboration with physicists in the US and worldwide
- **800 MeV proton beams** delivered to several targets
- Many neutron flight paths aiming at different researches





LANL Lujan Neutron Center

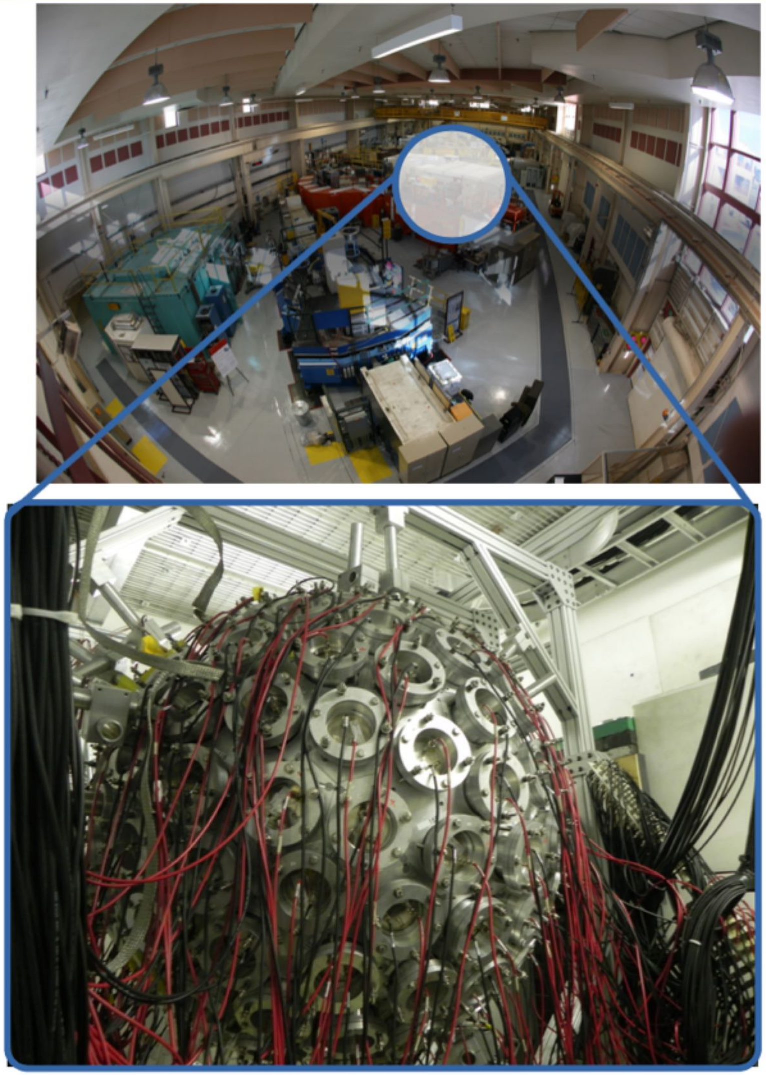
- The Lujan Center is one of five user facilities at LANSCE.
- The Lujan Center instruments operate in time-of-flight mode, receiving neutrons from a tungsten spallation target
- Neutrons **are moderated in water** and travel to **Flight Path 14**
- Neutrons travel 20 m down the vacuum-filled beam pipe and go through the **DANCE detector**



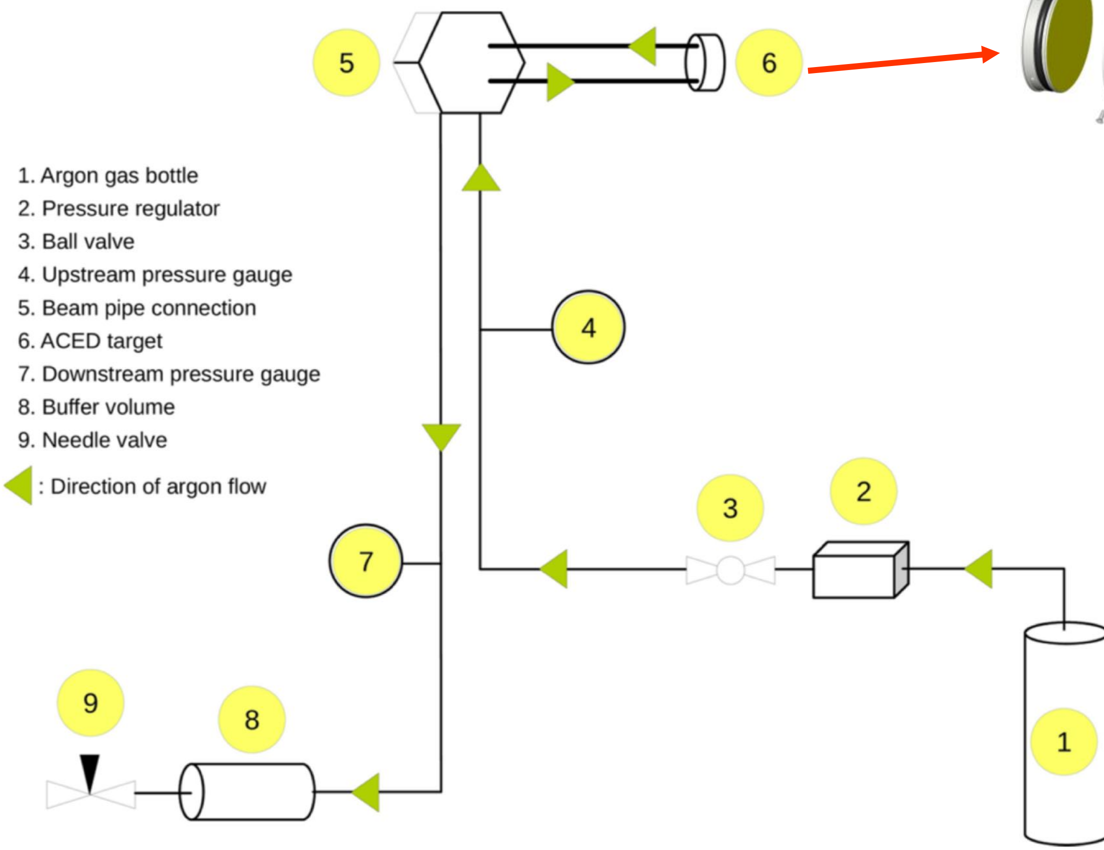
DANCE Detector

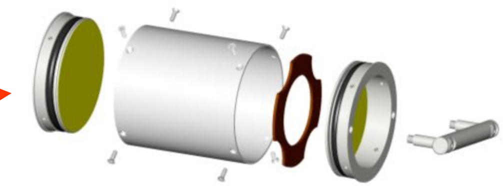
Detector for Advanced Neutron Capture Experiments (DANCE)

- Sphere of **160 BaF_2** crystals, each coupled to a PMT
- Nearly **4π coverage**
- Segmentation allows to make gamma multiplicity measurement
- Inner **^{6}LiH** shell **to absorb** scattered neutrons that may otherwise be captured on the crystals
- Neutron energies determined by **Time-of-Flight**
- Upstream monitors measure energy-dependent neutron beam flux



ACED Argon Target Design





- **Hollow aluminium cylinder**: 2.9 cm long, 3 cm diameter
- Cylinder closed by **Kapton windows** allowing the neutrons to pass through
- 30 mg **natural argon gas**
- Constant pressure kept at 1.1 bar by **regulators** and monitored by two pressure **gauges**

How to Measure a Cross Section?

- Very rough definition
  - Cross section ~ Probability for a process to happen ~ **Number of events / (Nb targets * Nb incident particles)**
- In ACED, the neutron capture cross section is calculated as:

Neutron capture cross section

$$\sigma_i = \frac{A}{a_{40}\,\rho\,L\,N_A}\,\frac{G_i}{\epsilon\,N_i} - \xi_i$$

- A: Target atom number
- N_A: Avogadro's number
- G_i: Number of neutron capture events
- ξ_i: Correction for ^{36}Ar
- a_{40}: 40-Ar abundance
- ρ: Target density
- L: Target thickness
- ϵ: γ cascade detection efficiency
- N_i: Number of incident neutrons seen by the beam monitor

Beam-independent Term

$$\sigma_i = \frac{A}{a_{40}\,\rho\,L\,N_A}\frac{G_i}{\epsilon\,N_i} - \xi_i$$

$a_{40} = 99.604\%$

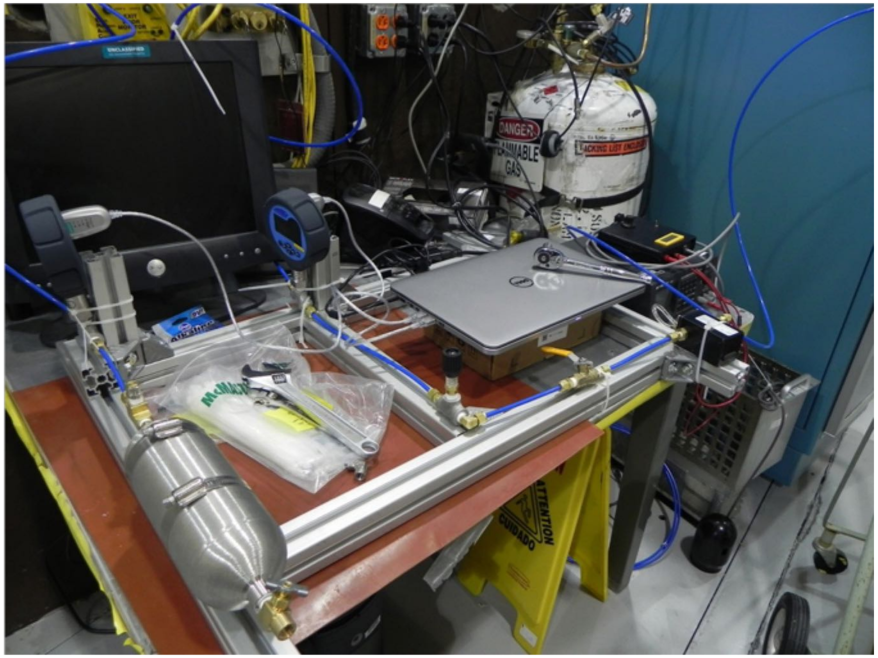
$\rho = (1.779 \pm 0.006)\times 10^{-3}\,\frac{g}{cm^3}$

$L = 2.9$ cm

$N_A = 6.02\times 10^{23}$ /mol

- **Length of the target**
  - 2.2% uncertainty
- **Abundance of ^{40}Ar**
- **Argon pressure in the target**
  - Obtained using two presure gauges upstream and downstream to the target
  - Temperature dependence is corrected
  - Conservative precision of 0.3%

The ACED gas system



ACED Measurement Strategy

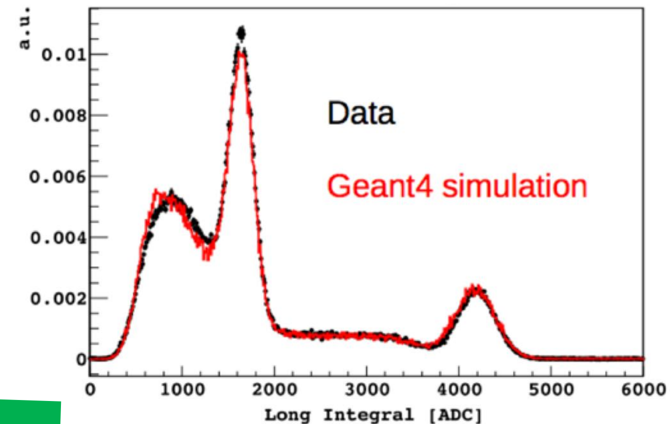
- Observed hundreds of thousands of neutron captures
- **Calibration source data** (^{22}Na, ^{60}Co etc.) to evaluate detection efficiency and crystal response
- Took three datasets to subtract the background
  - **Argon target filled beam on**: **neutron captures seen by DANCE**
  - **Argon target filled beam off**: understand **constant-in-time backgrounds** (e.g., α radioactivity in BaF_2 crystals)
  - **Vacuum filled beam on:** understand **beam-related backgrounds**

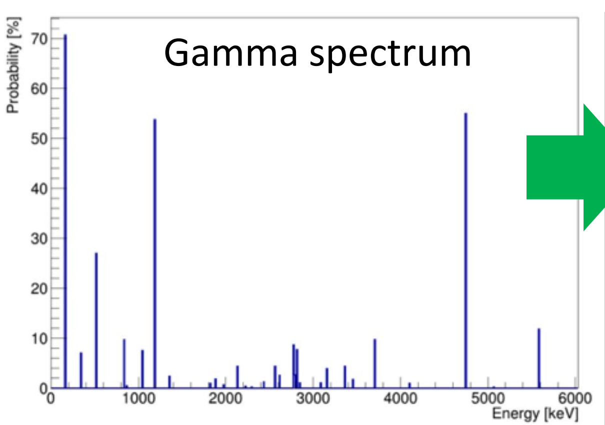
- Adjacent crystals contributing to a single gamma are grouped into a cluster. The number of clusters is used for data selection.

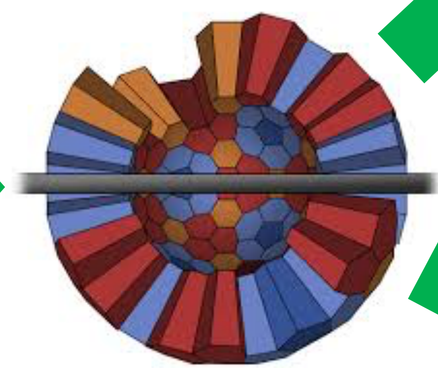
Detector Calibration and Data-MC Comparison

- We **upgraded the official DANCE Geant4 simulation** to include the ACED target and known detector effects (threshold, resolution)
- Both **calibration source gammas** and **argon capture gammas** are fed into the simulation
- **Very good Data-MC agreement**
  - Efficiency for individual crystal
  - Efficiency for the neutron capture gammas

Individual crystal spectrum with calibration source ^{22}Na

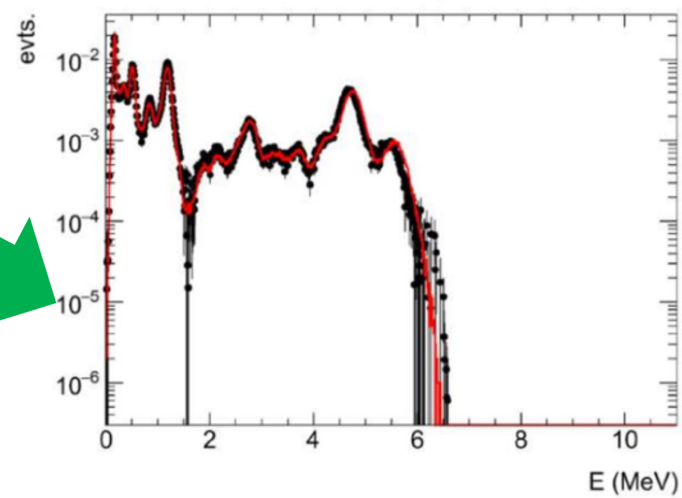






Geant4 model of DANCE crystals and beam pipe

Argon capture Gamma spectrum



Background subtraction

- **Three different datasets were acquired**
  - argon target filled data with incident beam (**A**)
  - argon target filled data with no neutron beam (**S**)
  - vacuum target filled (no argon) data with incident beam (**V**)

Isolated neutron captures on argon target

$$\Phi^A \sigma_a = D_A - \frac{T_0^A}{T_0^S} D_S - \frac{\Phi^A}{\Phi^V} \left(D_V - \frac{T_0^V}{T_0^S} D_S \right)$$

Overall data term: Total Number of events measured, including background

Beam off target term: Intrinsic radioactivity of the crystals (Constant-In-Time)

Beam on vacuum term: Neutron captures from surrounding materials (non-argon captures)

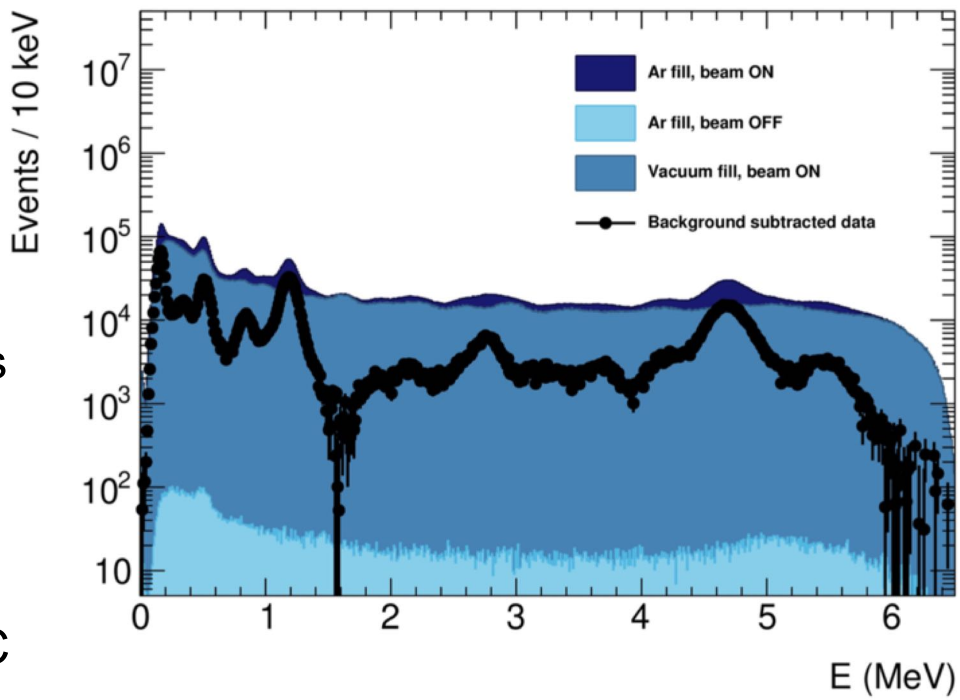
Selection cuts for neutron capture counting

$$\sigma_i = \frac{A}{a_{40}\,\rho\,L\,N_A}\,\frac{G_i}{\epsilon\,N_i} - \xi_i$$

Number of neutron capture events

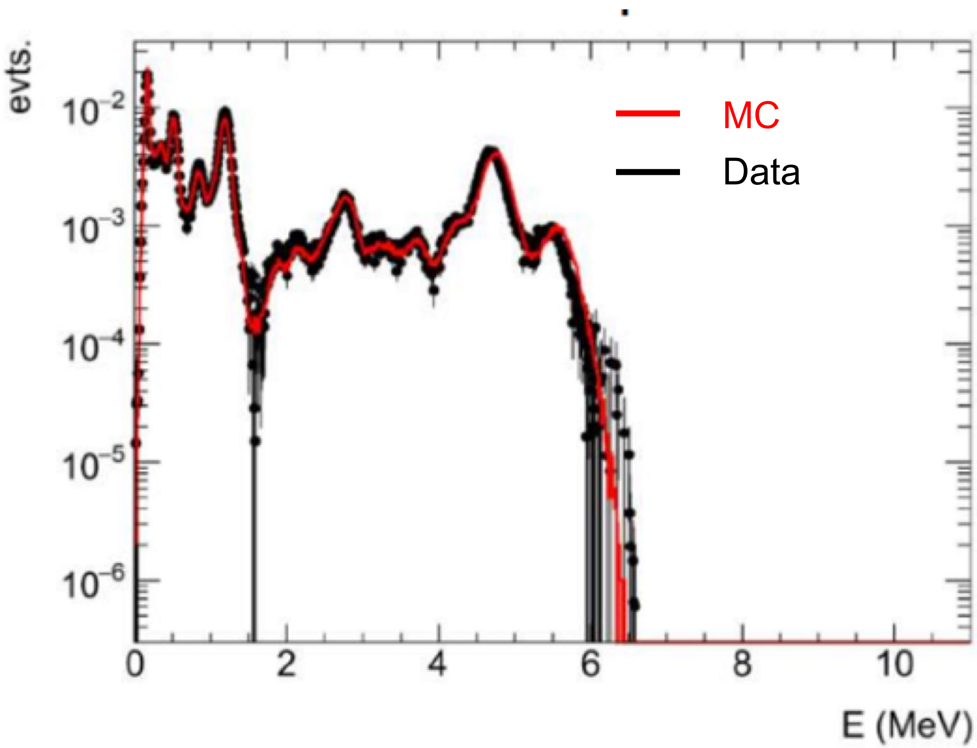
γ cascade detection efficiency

- Detector performance quality cut: 75% efficiency
- **Two gamma cascade cuts to select capture on ^{40}Ar:**
  - **Q value cut**: energy between [5.2,6.6] MeV for ^{40}Ar neutron capture.
  - **Cluster multiplicity cut:** selected events with more than one clusters
  - Two cuts are correlated, efficiency can't be determined individually from data
  - 98.9% efficiency obtained from MC



Cascade detection Efficiency obtained from MC

$$\sigma_i = \frac{A}{a_{40}\, \rho\, L\, N_A} \frac{G_i}{\epsilon\, N_i} - \xi_i$$



- Generate cascade samples from literature PhysScr 1, 85 (1970).
- Propagate the gammas with DANCE MC simulation
- Apply the same selection cuts as data
- The number of survival samples tells the gamma cascades detection effeciency
- This procedure includes the combined effect of the Q-value and cluster multiplicity cuts.

Neutron Flux at DANCE

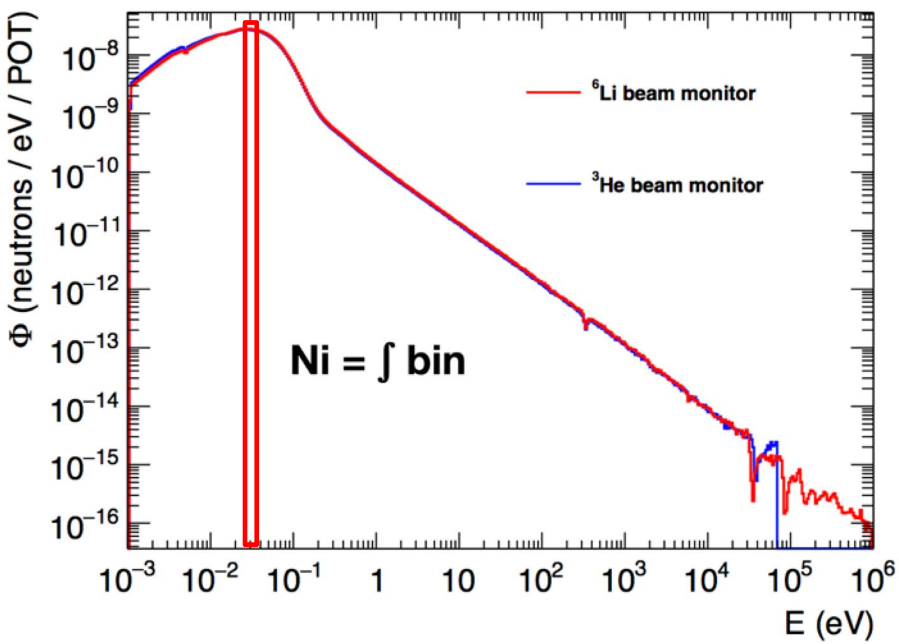
- The neutron flux at DANCE was measured using three beam monitors (helium, lithium, uranium)
- But the flux normalization at the thermal energies doesn't reach the precision that we need.
- The DANCE collaboration usually performs relative cross sections measurements (relative to a known resonance or known material)…
- but, we need an **absolute number of incident neutrons at thermal energy**
- So, we decided to normalize the beam by ourselves

$$\sigma_i = \frac{A}{a_{40}\,\rho\,L\,N_A}\,\frac{G_i}{\epsilon\,N_i} - \xi_i$$

Helium: $^{3}He + n \rightarrow p + {}^{3}H$

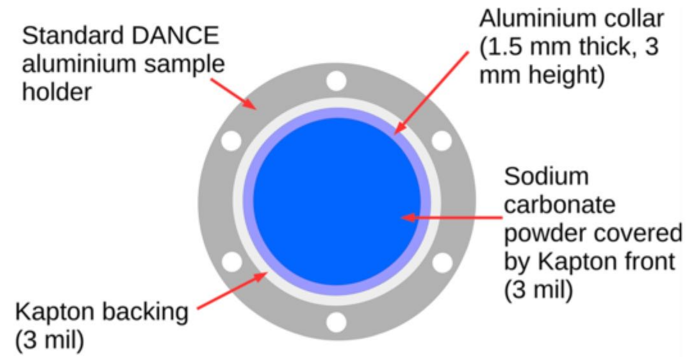
Lithium: $^{6}Li + n \rightarrow {}^{4}He + {}^{3}H$

Uranium: $^{235}U + n \rightarrow$ fission

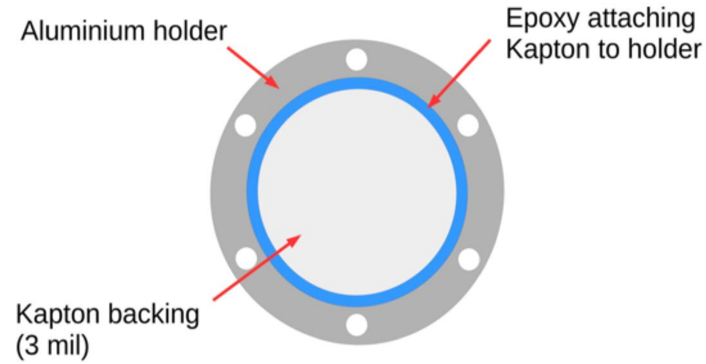


ACED Beam Normalization Run

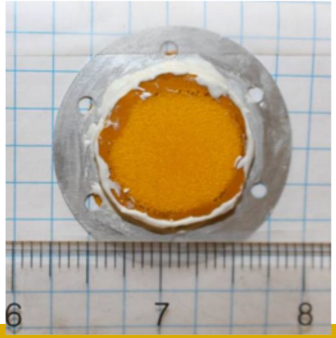
- We measured the thermal flux the same way we would do it in a reactor
  → Use a material with well known neutron capture cross section
- We built a **sodium carbonate** target (Na_2CO_3) that fits in the beam pipe at the center of DANCE
- After irradiating the target, we counted the gammas using a High Purity Germanium detector and obtained the amount of radioactive sodium created
- Since "Radioactivity ~ Stable targets x Cross section x Flux", **we obtained a value of the neutron flux**
- **Uncertainty of 5%** on the flux.
  Published in [NIM A 929, 97 (2019)10]



Front view



Back view



Small correction on ^{36}Ar

- Correction for neutron captures on ^{36}Ar is based on theoretical calculation, and the contribution turns out to be ~1% level
- **Now we know all quantities!**

Neutron capture cross section

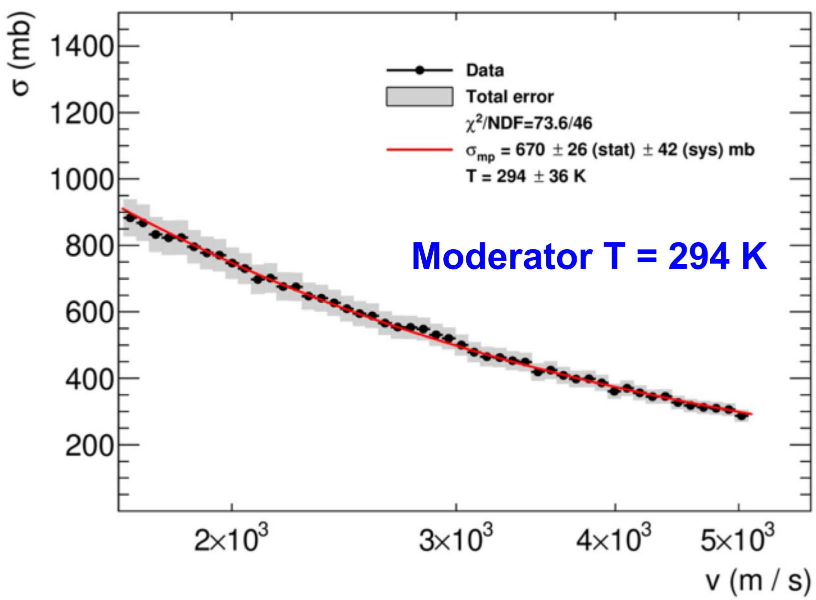
$$\sigma_i = \frac{A}{a_{40}\,\rho\,L\,N_A}\,\frac{G_i}{\epsilon\,N_i} - \xi_i$$

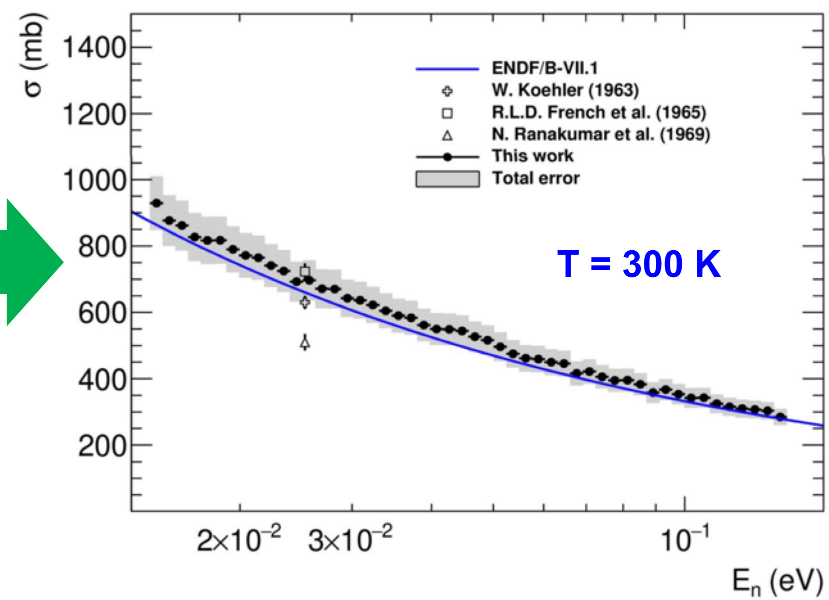
- A: Target atom number
- N_A: Avogadro's number
- G_i: Number of neutron capture events counted from gamma spectrum
- ξ_i: Correction for ^{36}Ar
- a_{40}: 40-Ar abundance
- ρ: Target density
- L: Target thickness
- ϵ: γ detection efficiency (detector + cuts)
- N_i: Number of incident neutrons seen by the beam monitor

The ACED cross section result

- Using Time-of-Flight, the neutron velocity can be calculated on event-by-event basis.
- First measurement over a wide range around thermal energies
  - Not available from reactor-based measurement
- Results published in [PhysRevD 99, 103021 (2019)]

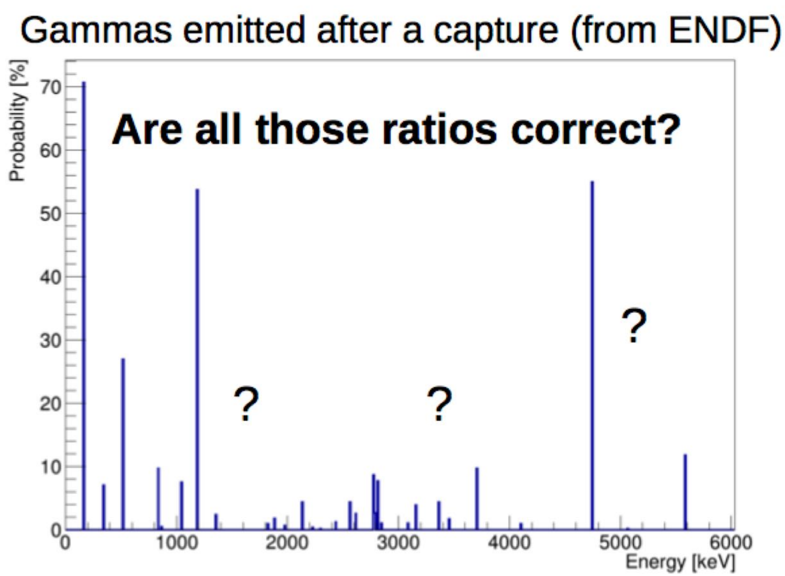
σ_{2200} = 673 ± 26 (stat.) ± 59 (sys.) mb

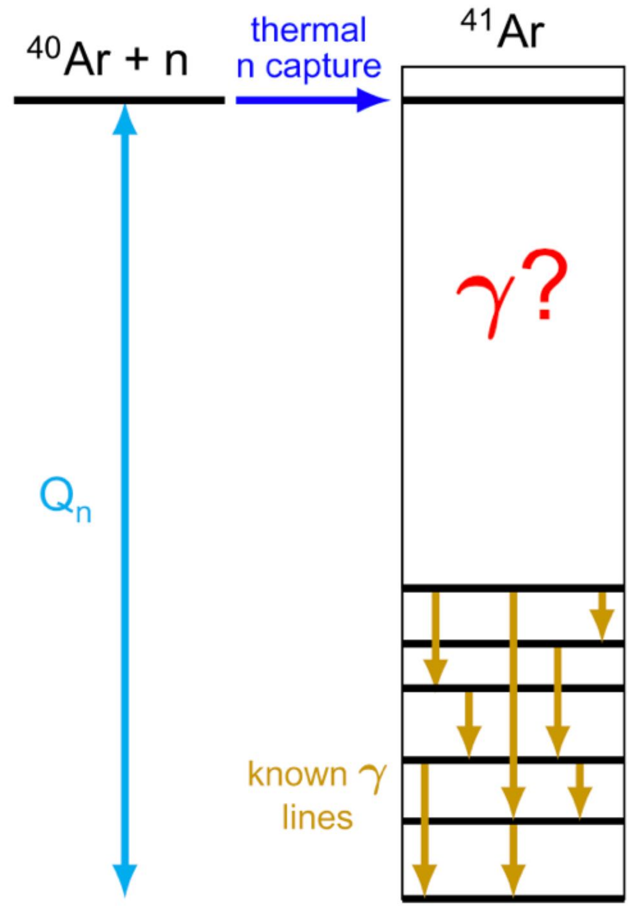




Next ACED Analysis: Gamma Cascade

- The **gamma cascade** from neutron captures has to be **better understood and modeled**
- Problem: Many high-lying levels and γ-rays are unknown, and are difficult to be determined theoretically
- ACED allows will use a statistical method to study the gamma cascade

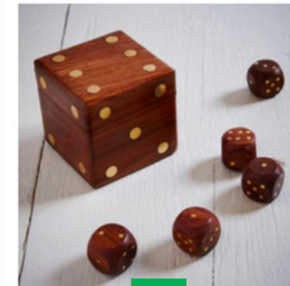




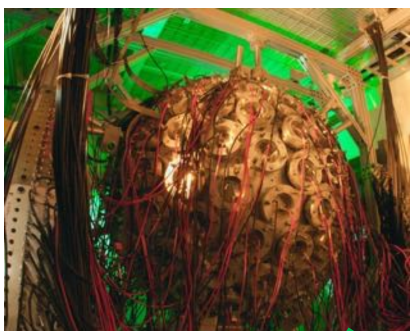
Next ACED Analysis: Gamma Cascade

- Use **DICEBOX** to generate realistic decay schemes for ^{41}Ar as a function of well-known lines and nuclear theory
- **Simulate gammas** in the well-tuned DANCE simulation
- **Data-simulation comparison to find the most compatible solution**

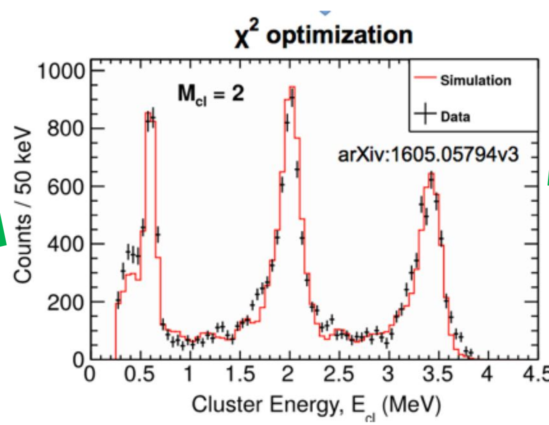
DICEBOX

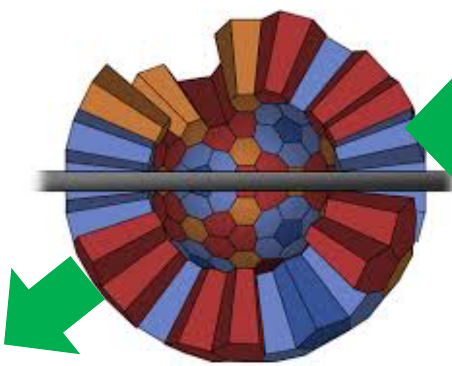


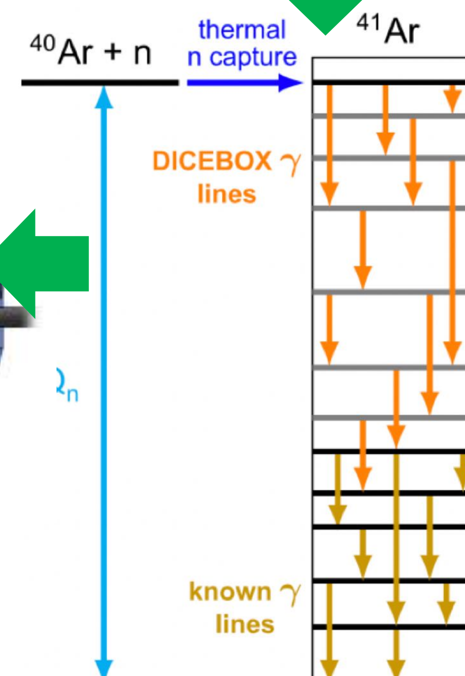
DANCE Measurement



Data analysis underway

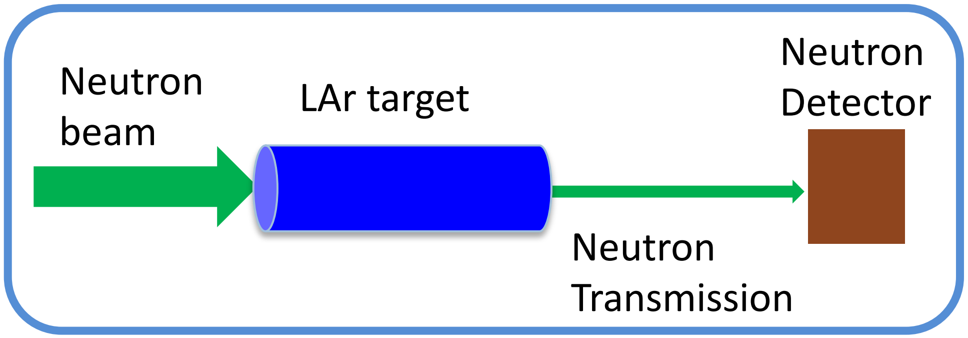




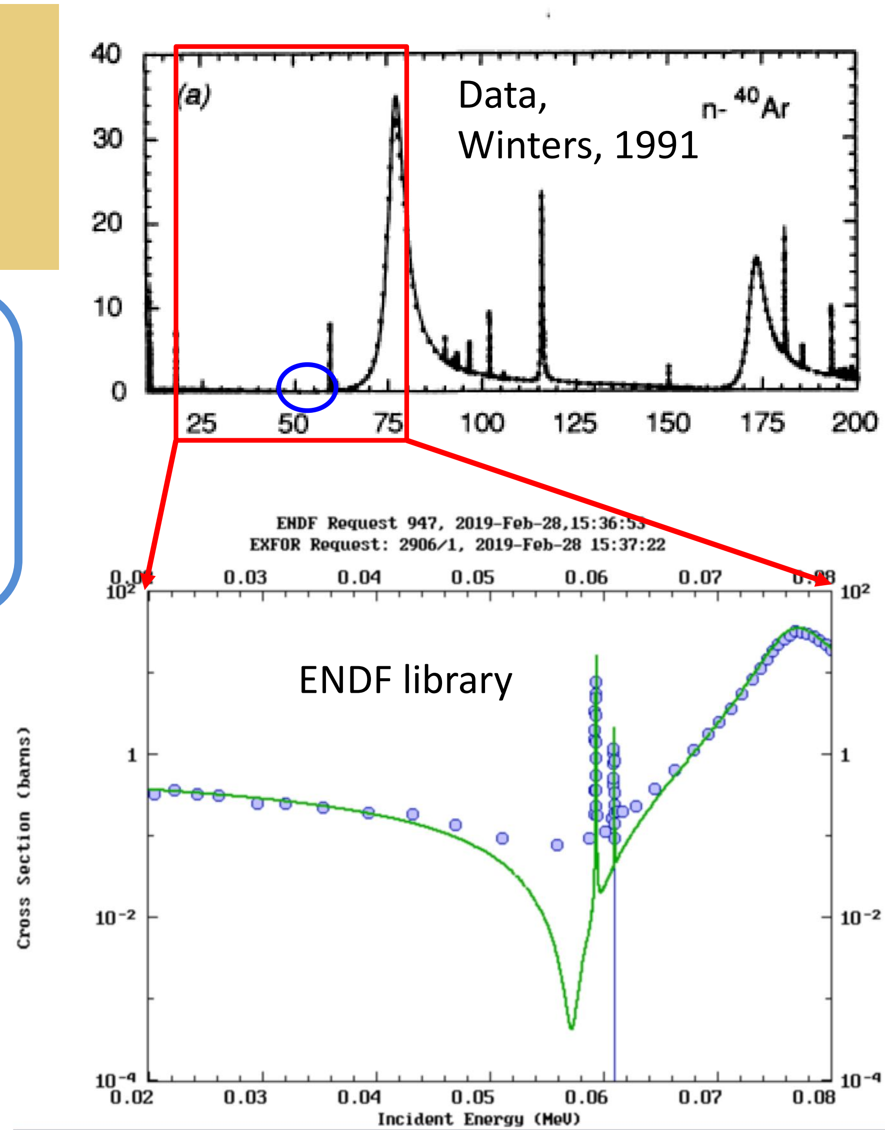


Beyond ACED: ARTIE

Proposed the **Argon Resonance Transmission Interaction Experiment (ARTIE)** to Los Alamos National Laboratory to measure the neutron total cross-section in argon

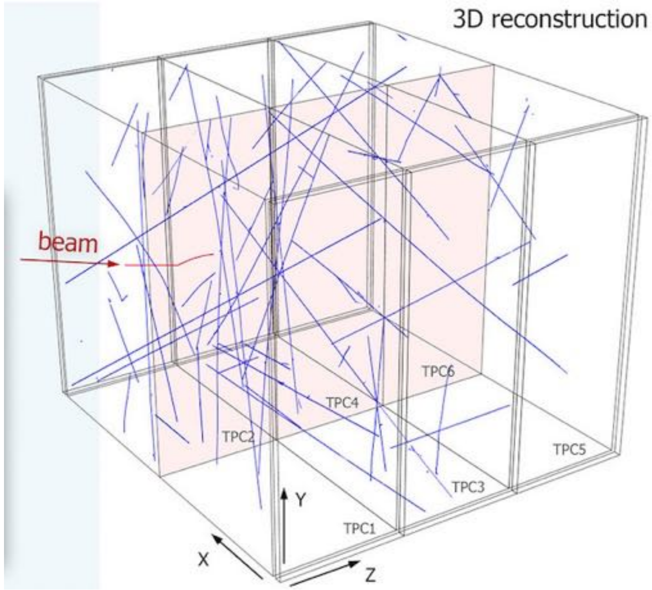


- Previous Ar measurement around 57 keV was not sensitive enough to probe the resonance dip
- Measurement needs to be done with high precision
- Opportunity at Lujan center at LANL (proposal submitted)



Neutrons could help to calibration the detector

- Neutrino **oscillations** is a **L/E dependent** process → DUNE **needs to understand the energy scale and resolution within 2% level**
- **DUNE far detector calibration is challenging**
  - **Deep underground** → only 30 stopping muons and 20 Michel electrons /day/10 kt
  - **Large Volume** → spatial coverage of traditional calibration methods is limited
- **Could use an external Pulsed Neutron Source (PNS) system**
  - A technique under development (similar method used by SNO and Super-K)
  - One of the main strategies in TDR



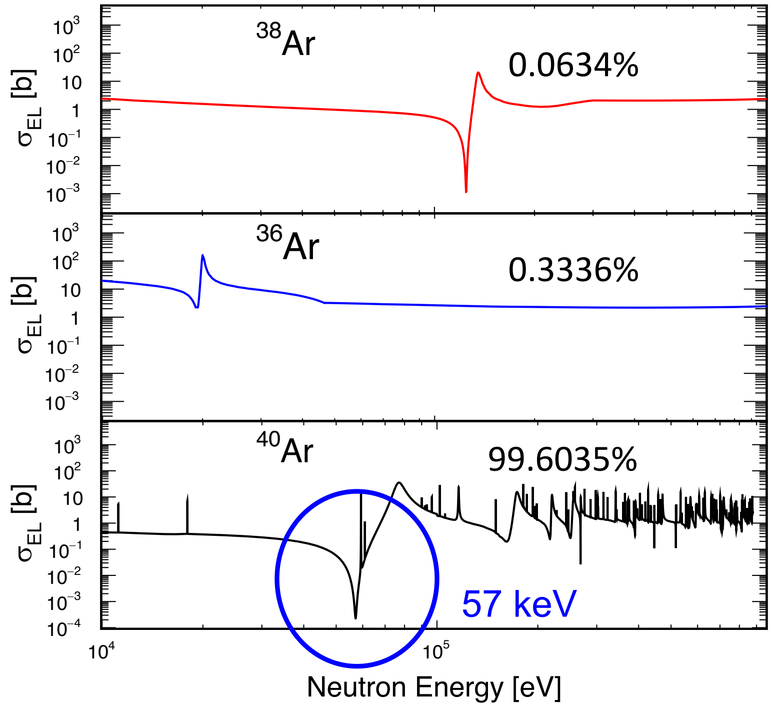
How can neutrons help?

- Key is to make use of neutrons at “anti-resonance” energy
- 40-Ar is near transparent to 57 keV neutrons at the "anti-resonance “dip”
- 38-Ar and 36-Ar have different resonance structures that keep the natural argon from being totally transparent
- **The effective scattering length is ~30 m in natural argon**

38-Ar
λ = 47 cm @ 57 keV

36-Ar
λ = 16 cm @ 57 keV

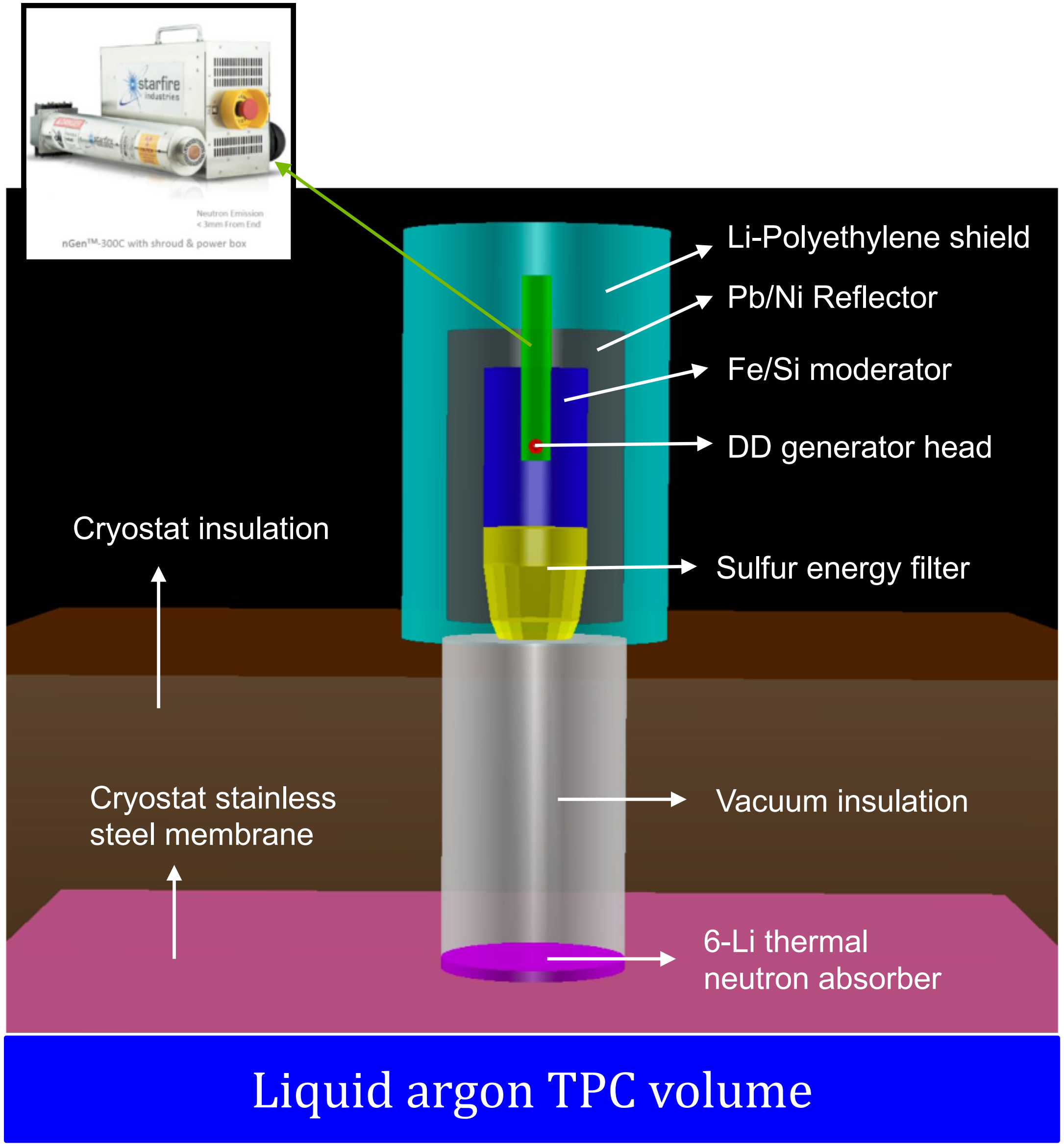
40-Ar
λ = 1.5 km @ 57 keV



How can neutrons help?

- **Wide coverage: anti-resonance neutrons can travel long distance**
  - Scattering length is long: 1.5 km in 40-Ar, 30 m in natural argon
  - Mean fractional energy loss per scatter is 4.8%: a large
- **Multi-gamma output: neutron capture emits 6.1 MeV gamma cascade**
  - Fixed energy deposition as a “standard candle” for energy deposition calibration
- **External deployment: neutrons mostly ignore the stainless steel cryostat**
  - External deployment
  - No contamination to argon purity
- **Pulsed trigger: neutrons can be created with a DD generator:**
  - Triggered source
  - High neutron yield (~10^6 neutrons per pulse)

Make Anti-resonance neutrons with a moderator

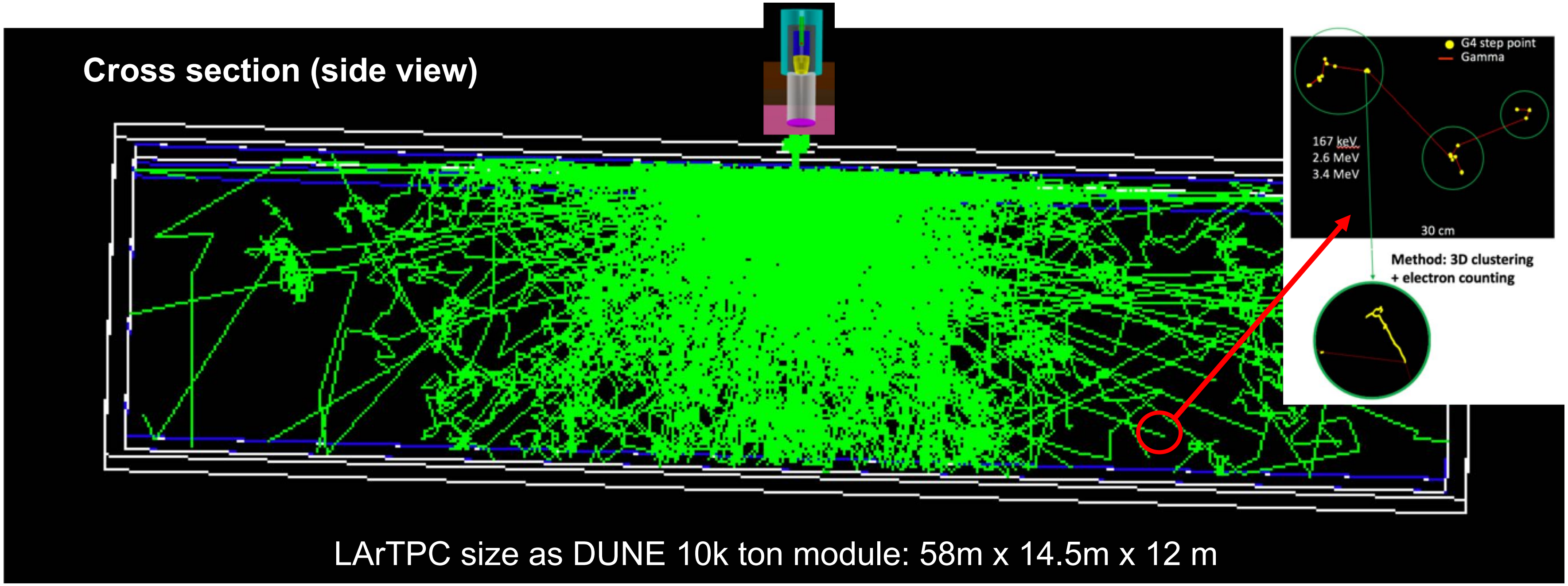


Pulsed Neutron Source:

- **DD generator** → 2.5 MeV neutrons
- **Fe/Si moderator** → efficiently reduce energy down to below 1 MeV
- **Sulfur filter** → select 73 keV neutrons (Note: 73 keV neutrons get into the 57 keV anti-resonance window after a few scatters)
- **Pb/Bi reflector** → Increase neutron yield
- **6-Li absorber** → suppress thermal neutron fraction
- **Li-Polyethylene shield** → radiation protection

Neutron Transport in DUNE-size TPC

- **One source covers about 1/3 the DUNE-TPC.** Having **several** sources **is sufficient to cover the entire detector volume**
- Measurement of the **energy response at low energy (6.1 MeV)**
  - Provide energy scale and resolution at (x, y, z)
  - Access various detector response parameters: electron lifetime…
- **Anti-resonance cross-section at 57 keV will be verified by ARTIE**



Summary

- Neutrons are important for liquid argon detectors
- ACED measured the thermal neutron capture cross section
  - **σ_{2200} = 673 ± 26 (stat.) ± 59 (sys.) mb**
- The correlated gamma cascade is being analyzed using DICEBOX
- Proposed ARTIE to measure the total cross section around 57 keV
- Pulsed Neutron Source can be used to calibration the large scale liquid argon TPC