Exploring Neutrino Physics with the Deep Underground Neutrino Experiment

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UCDAVIS
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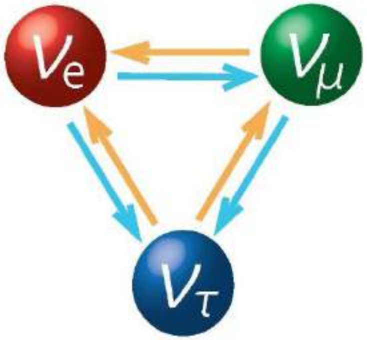
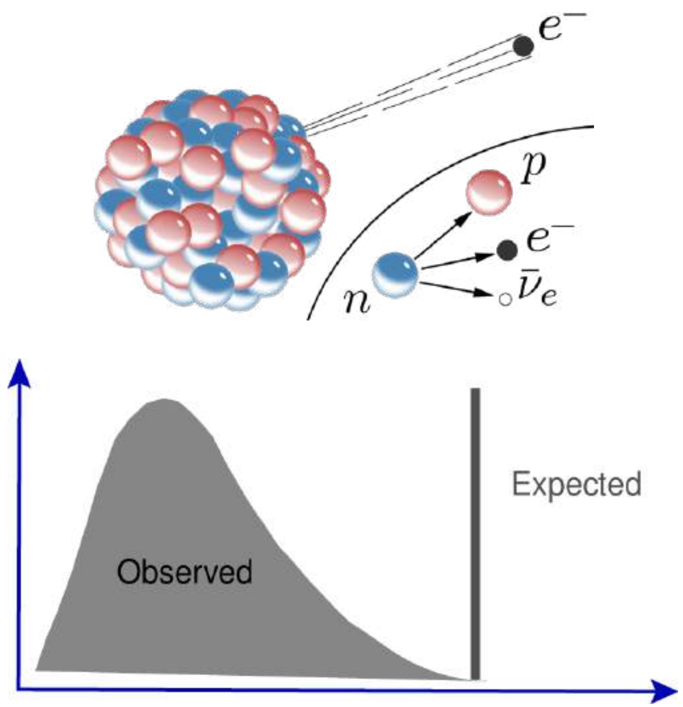


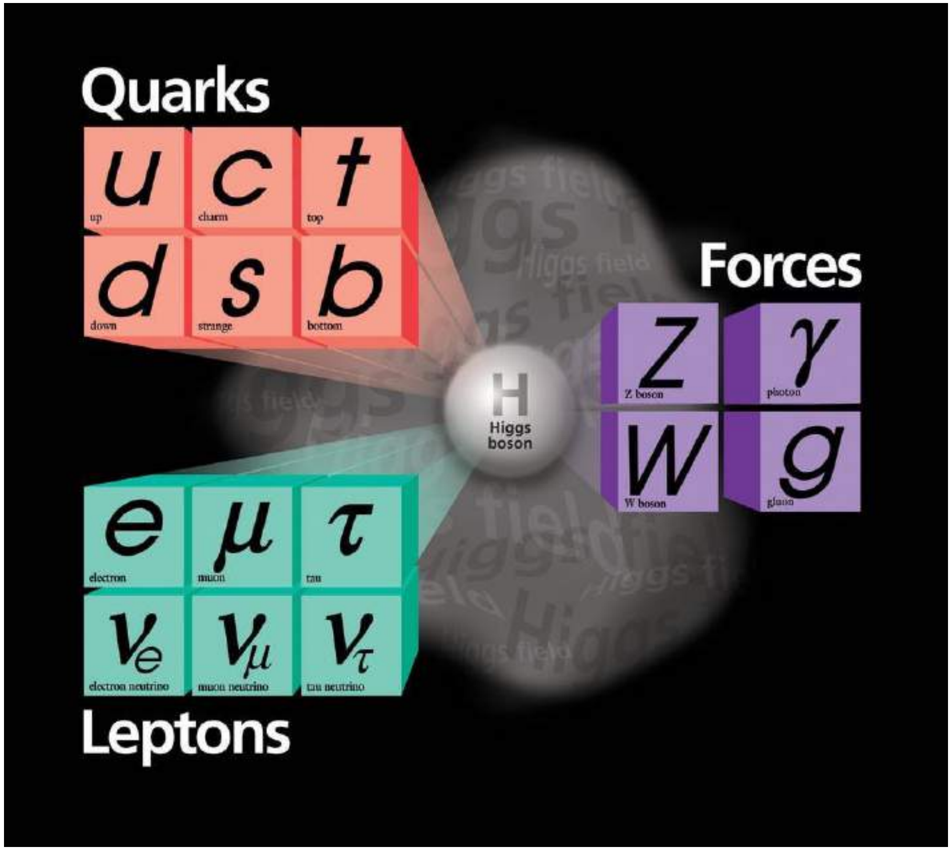
Neutrino is with us for a long time

- The neutrinos were first suggested by Wolfgang Pauli in 1930
- Used to explain the continuous spectrum of electrons from beta decays
- Pauli proposed the neutrino in a letter to a conference
- Initially thought to be massless and hard to detect



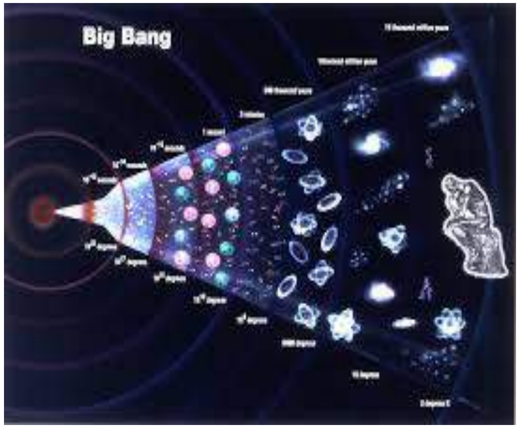
Neutrino in the Standard Model

- Key components of the “Standard Model”
- ¼ of the fermions, but look quite different
- Very little mass ($<10^{-6}\ m_e$)
- No charge, only sensitive to weak force and gravity
- All neutrinos are left-handed. All anti-neutrinos are right-handed.

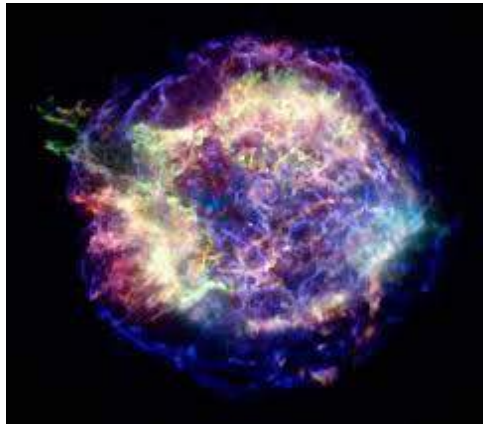


Neutrinos are Everywhere

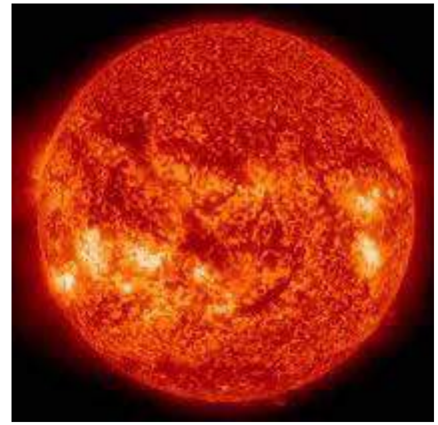
Big bang: 300/cm^3



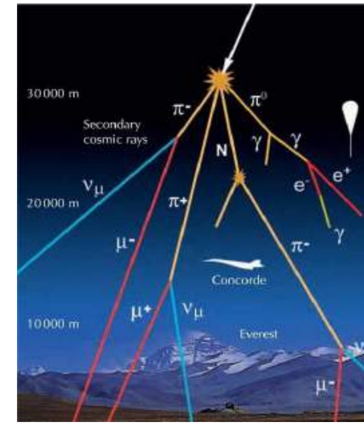
Supernova: 10^9/cm^2/s



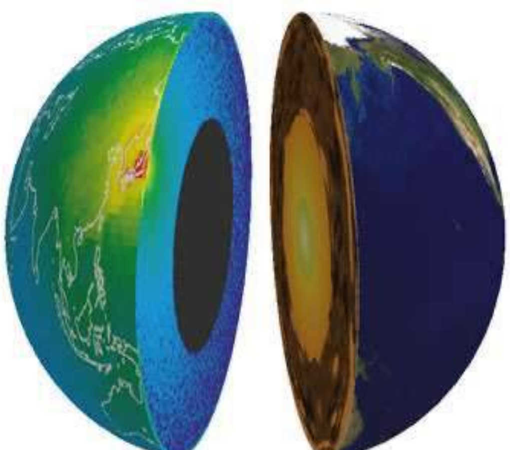
Solar: 10^{10} /cm^2/s



Atmospheric : ~10/cm^2



Geoneutrino: 10^6/cm^2/s



Reactor

Accelerator

Neutrinos Can Oscillate!

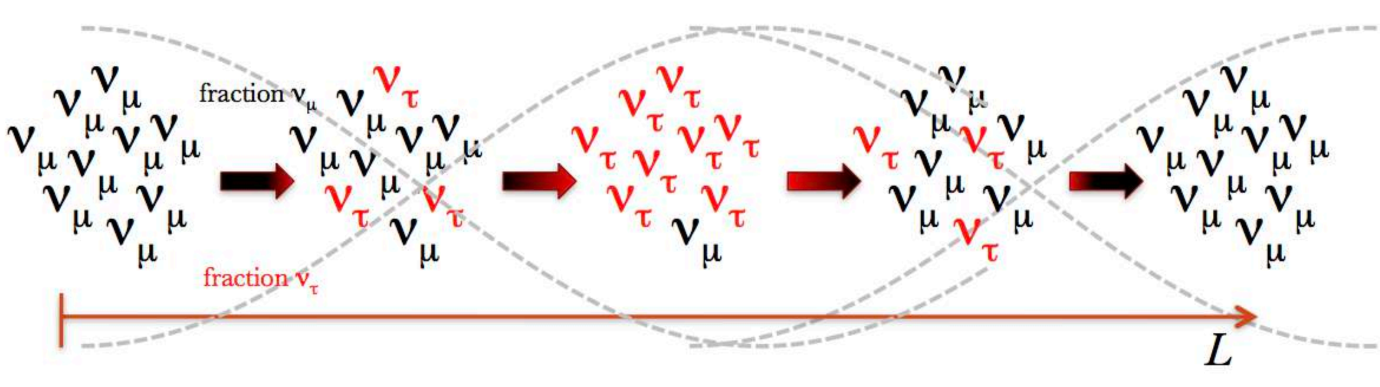
- **It's the process of neutrinos changing from one flavor to another: requires *NON-ZERO* neutrino mass!**

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, mass states propagate as waves with different frequencies.
- The superposition of mass states changes over distance, which makes the neutrinos oscillate.



Three-Neutrino Mixing

The PMNS matrix can be parametrized into three sectors

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\textbf{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\mathrm{C_{ij}} = \cos\theta_{ij}$, $\mathrm{S_{ij}} = \sin\theta_{ij}$

Atmospheric + Accelerator disapp | **Reactor + Accelerator app** | **Solar + KamLAND (reactor)**

Six Parameters:

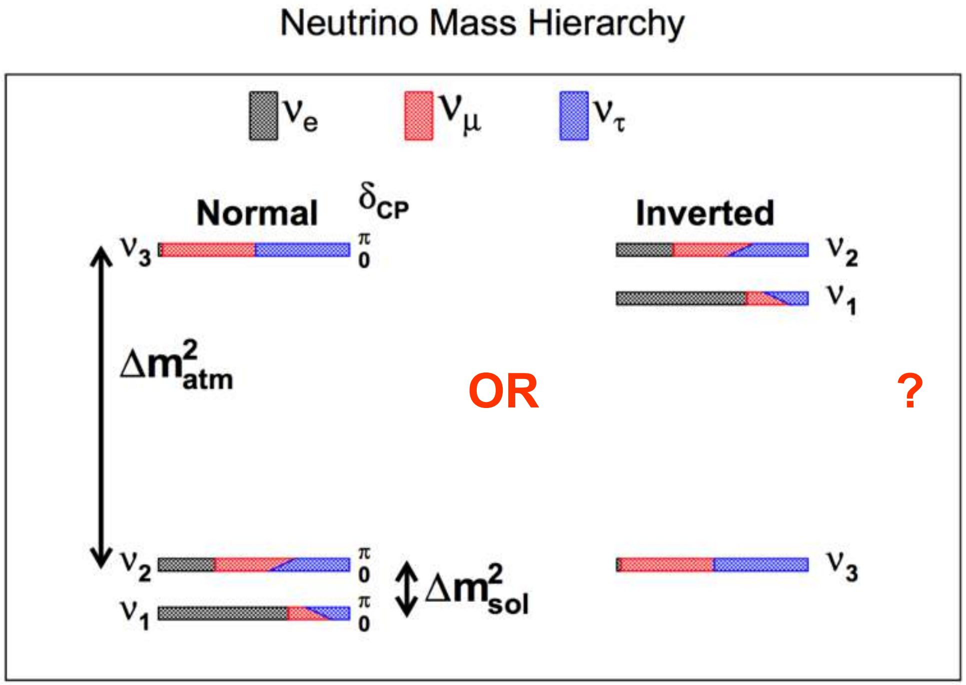
- **3 mixing angles:** $\theta_{12}, \theta_{23}, \theta_{13}$
- **2 mass splittings:** $\Delta m^2_{32}, \Delta m^2_{21}$
- **1 CP violating phase:** δ_{CP}

What we know:

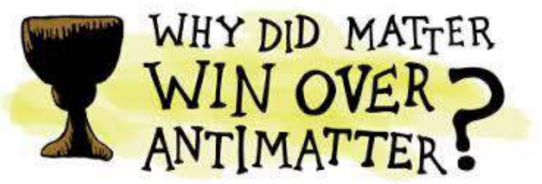
- ✓ θ_{12} ~ 33° (Solar)
- ✓ θ_{23} ~ 45° (Atmospheric)
- ✓ θ_{13} ~ 8° (Reactor)
- ✓ $|\Delta m^2_{21}| = 7.5 \times 10^{-5}\ \mathrm{eV}^2$ (Solar)
- ✓ $|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$ (Atmospheric)

Mystery: Mass Ordering (Hierarchy)

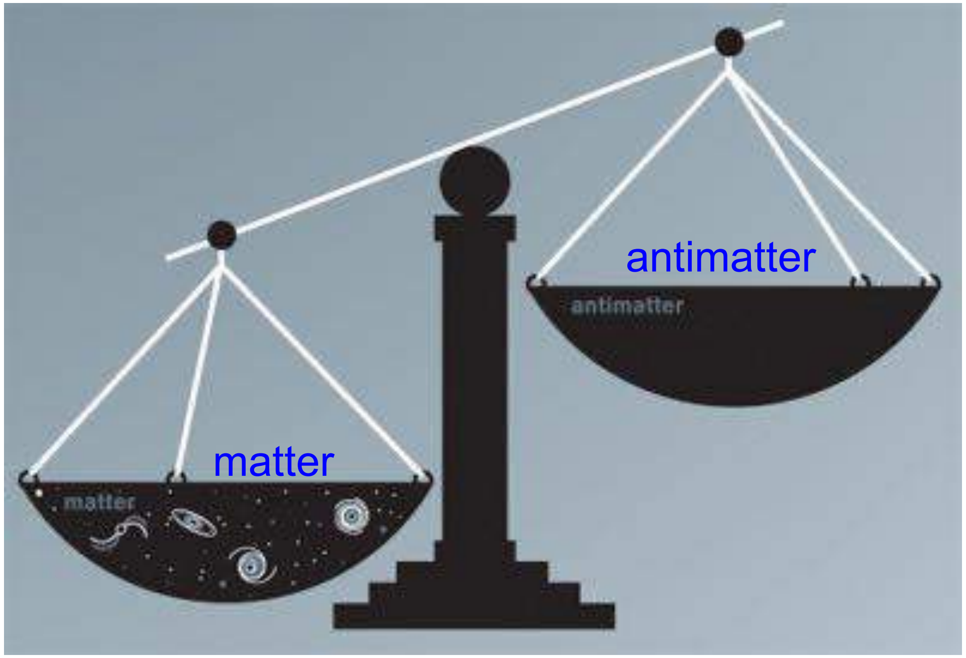
- What is the **mass ordering**? Is it "**normal**" or "**inverted**"? Don't know if m_3 is the heaviest or the lightest neutrino mass
- The mass ordering is important for developing models about the early universe
- Knowing the mass ordering is important for the **CP violation** measurement



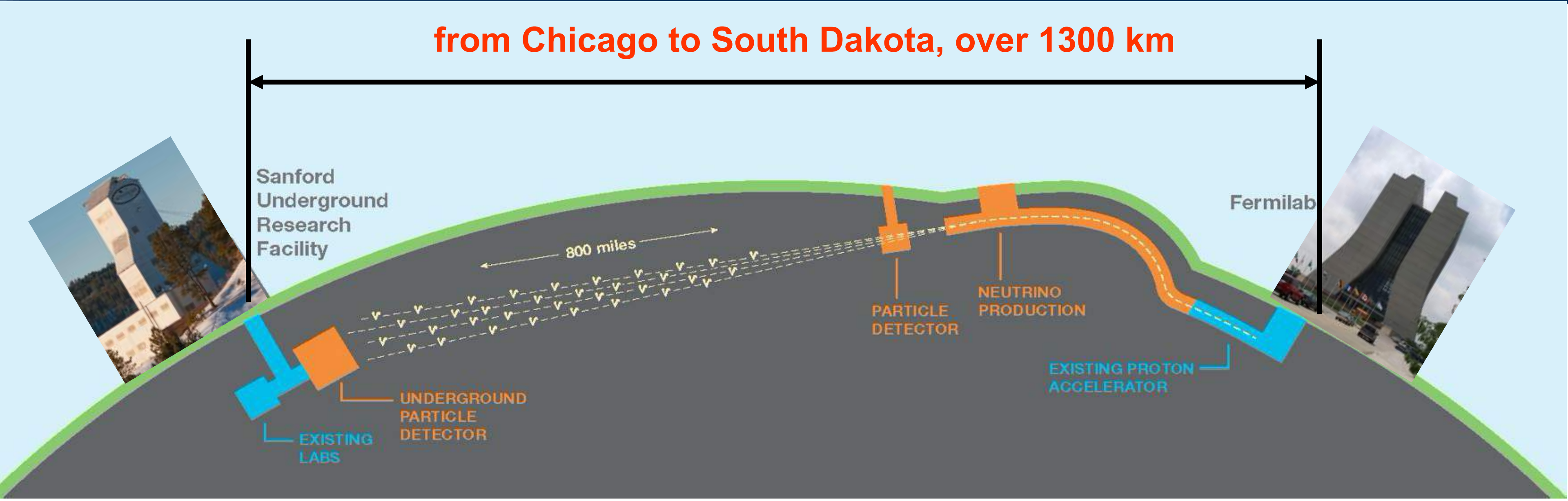
Mystery: CP violation



- 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's not strong enough to explain the matter-antimatter asymmetry.
- A promising way is looking for the leptonic CP violation in **NEUTRINOS.**
- Neutrino oscillation mechanism offers a way to **probe CP violation.** Requires next-generation precision detectors, such as **DUNE**.

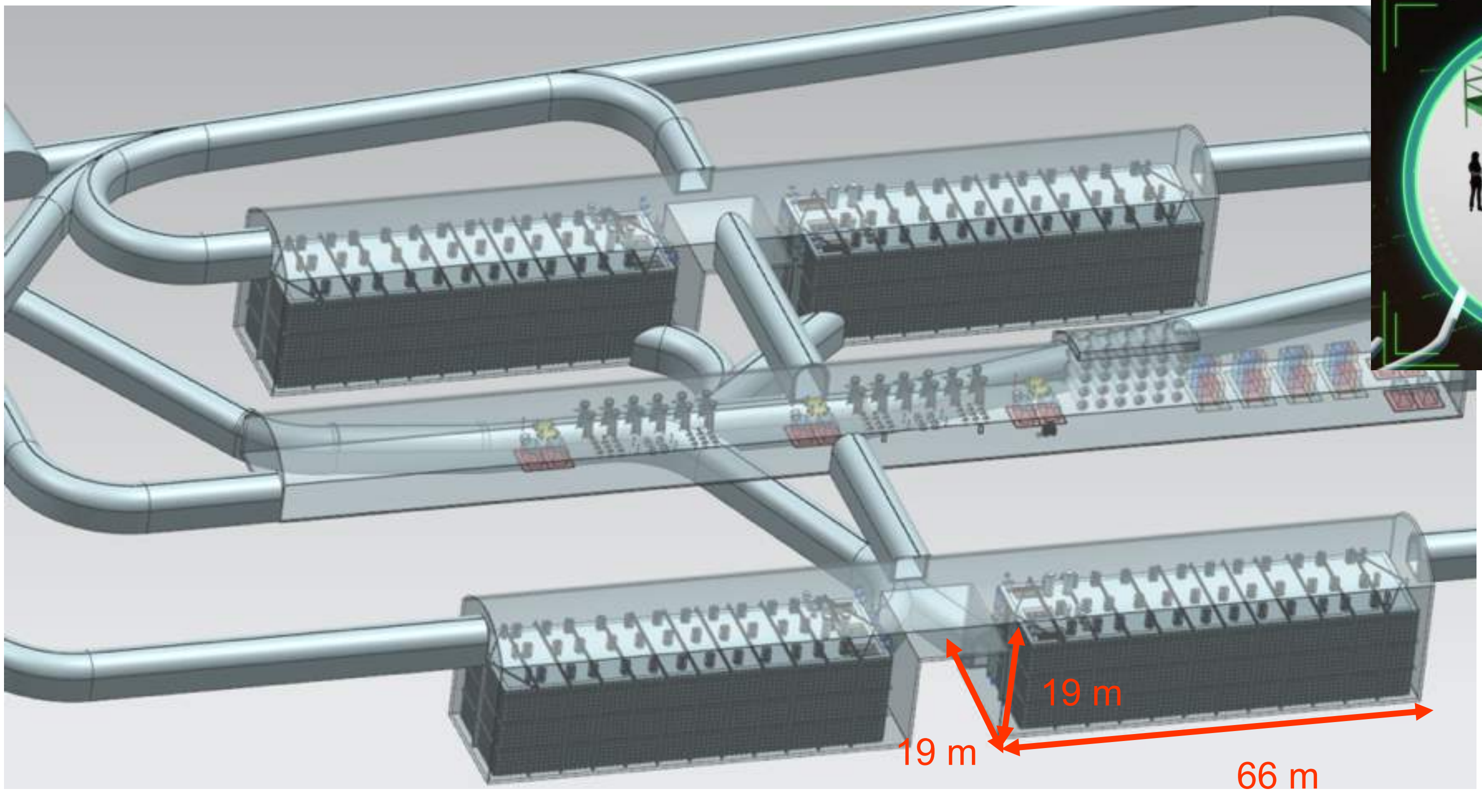


DUNE: DEEP UNDERGROUND NEUTRINO EXPERIMENT



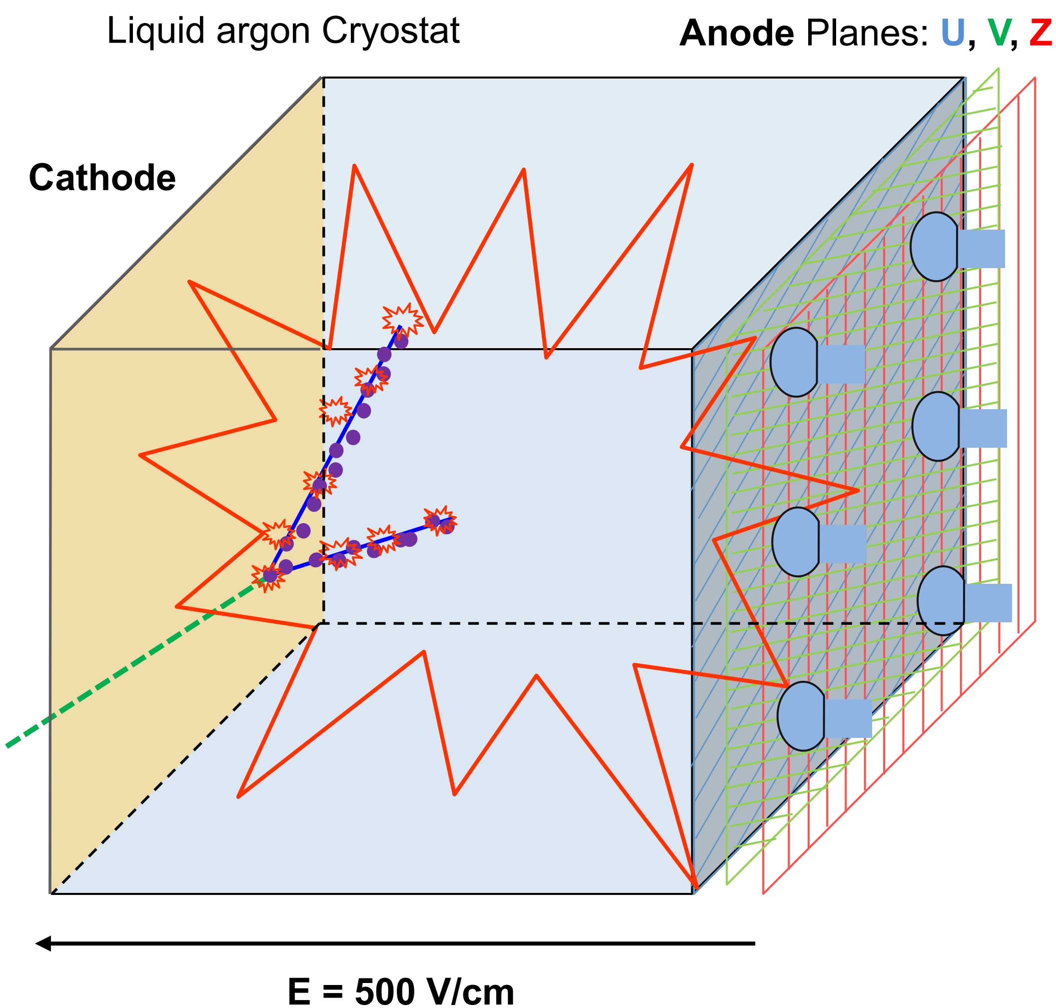
- **Next generation long-baseline neutrino experiment in the US**
- **A high-intensity neutrino beam** sent from Fermilab to South Dakota through a **1300 km** baseline
- **A near detector** at Fermilab to characterize the beam before oscillation.
- **A ~ 4 x 10 kt fiducial mass liquid argon far detector 1.5 km underground** at SURF to measure the neutrinos after oscillation
- Physics: Neutrino Oscillation, supernova observation, nucleon decay…

The Far Detector



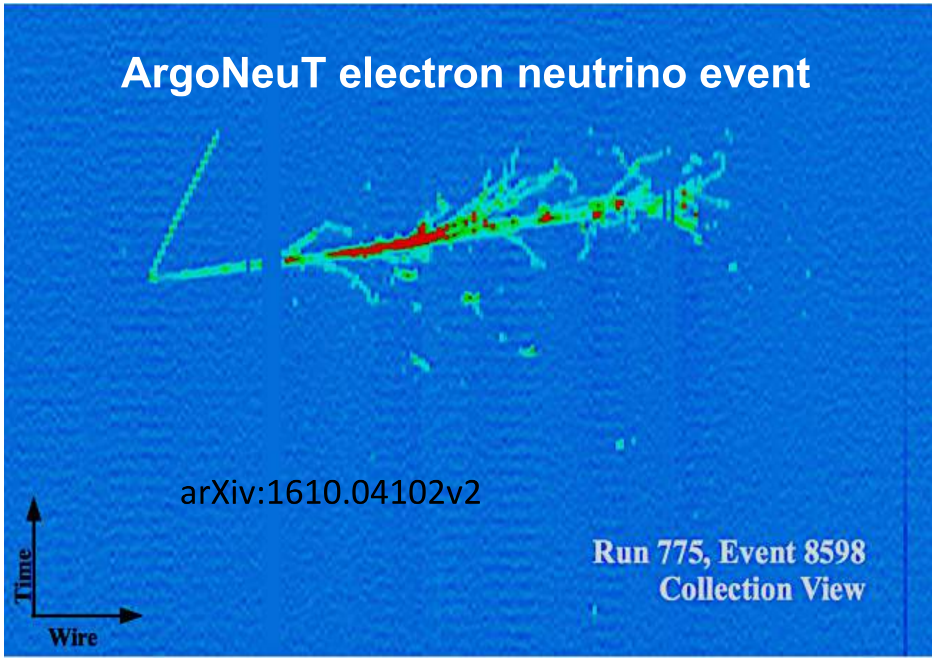
- Four caverns hosting four independent modules.
- Each module is a **10 kt** fiducial mass (17.5 kton total) **Liquid Argon Time Projection Chamber (LArTPC)**
- First module deployment in 2024. Others follows shortly.

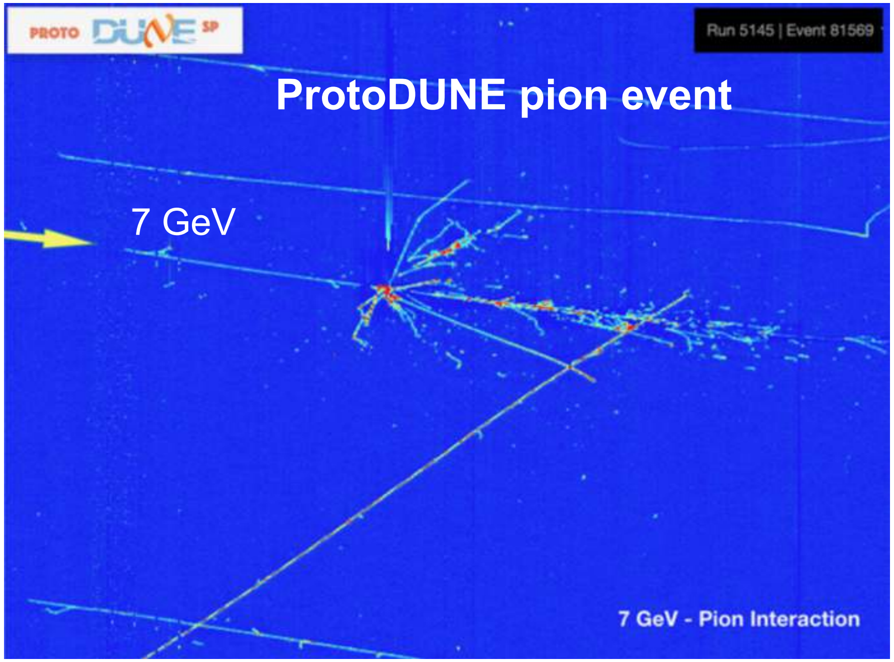
Liquid Argon Time Projection Chamber



- 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 volume, and is detected by photodetectors, providing start time of the event
- Electrons drift towards anode (1.6 mm/us), detected by the readout wires
- Coordinate along E is reconstructed using drift time

LArTPC Features



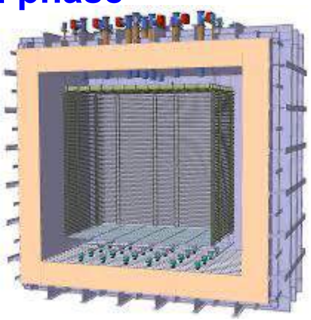


- **mm-level spatial resolution** to “see” the details of interaction
- **High energy resolution** through calorimetric measurement
- **Excellent particle identification** in various ways: energy loss, track displacement, event topology, etc…

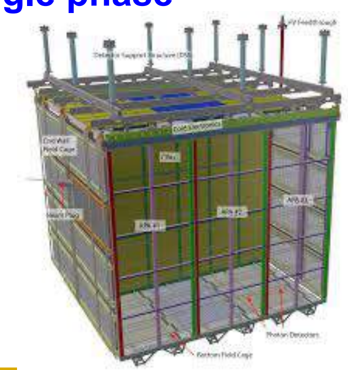
DUNE needs prototypes: ProtoDUNE @CERN

- **Two LArTPC prototypes at the charged particle test beam at CERN**
  - ~800 ton liquid argon TPC, ~5% of the DUNE-FD module
- **ProtoDUNE main goals:**
  - Validate the design and technologies for the DUNE far detector
  - Take beam data to understand the detector response to charged particles

Dual phase

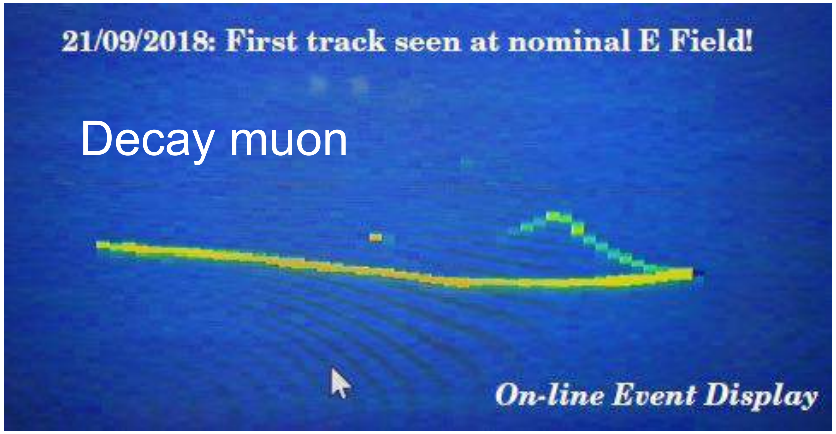


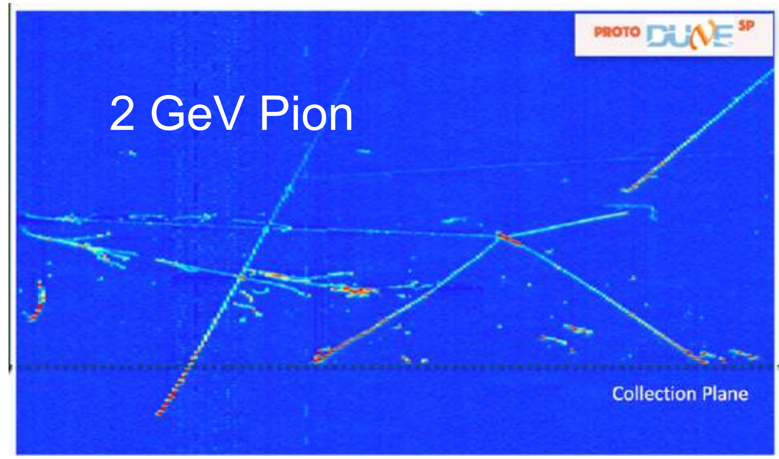
Single phase

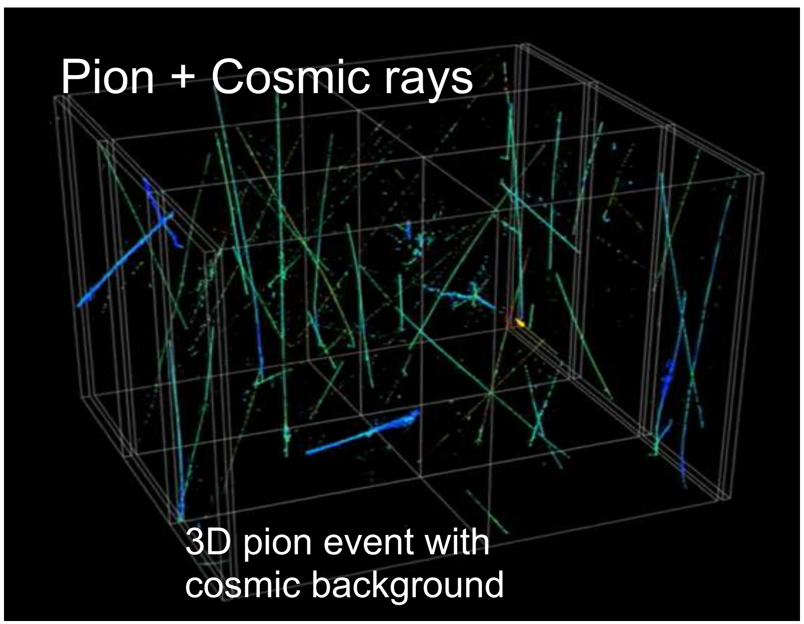


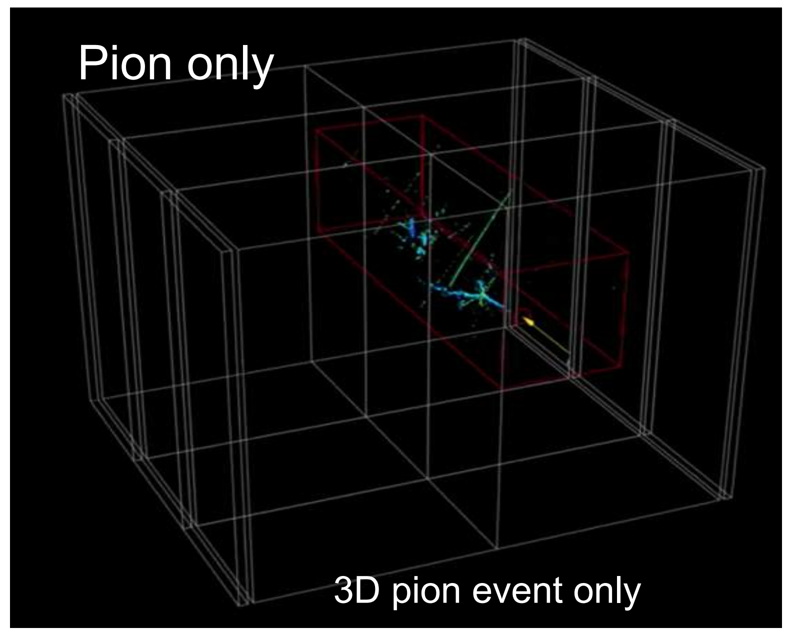
ProtoDUNE-SP construction

ProtoDUNE-SP events





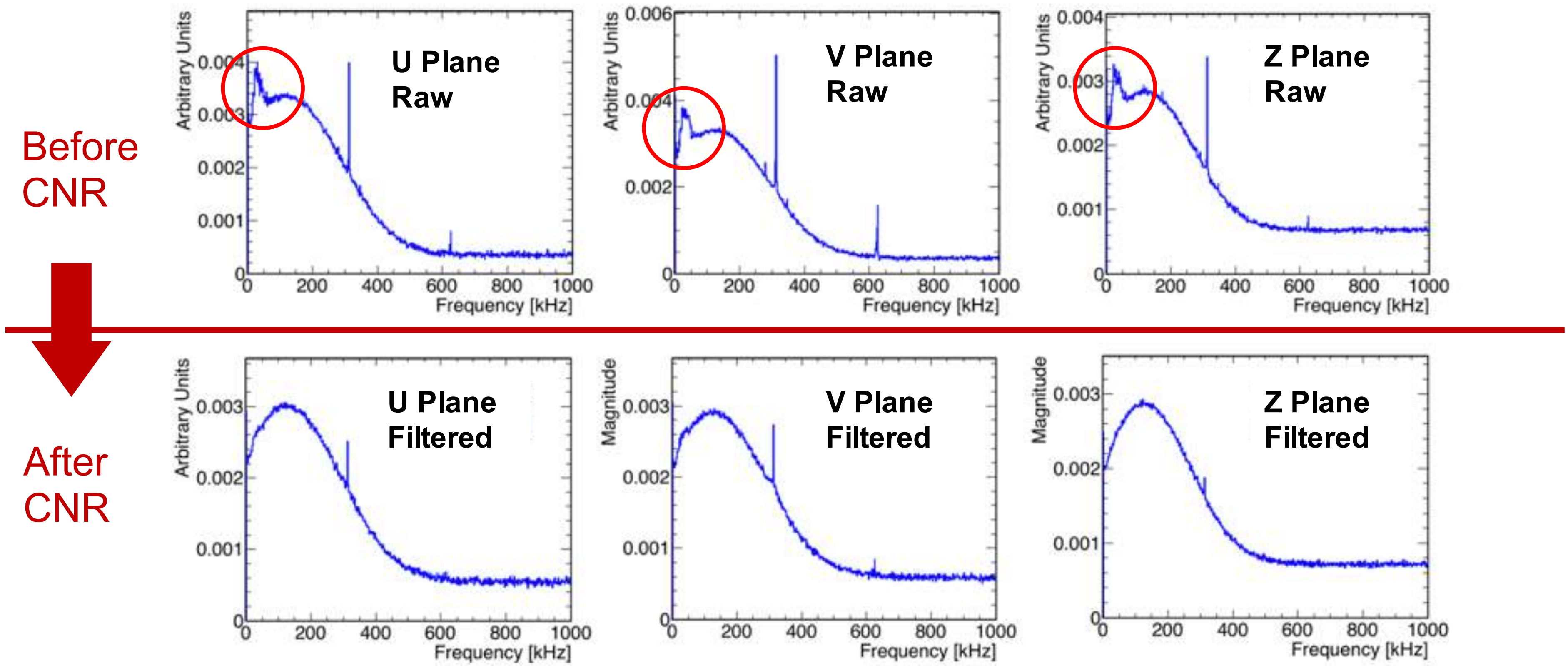




Noise Mitigation In ProtoDUNE-SP

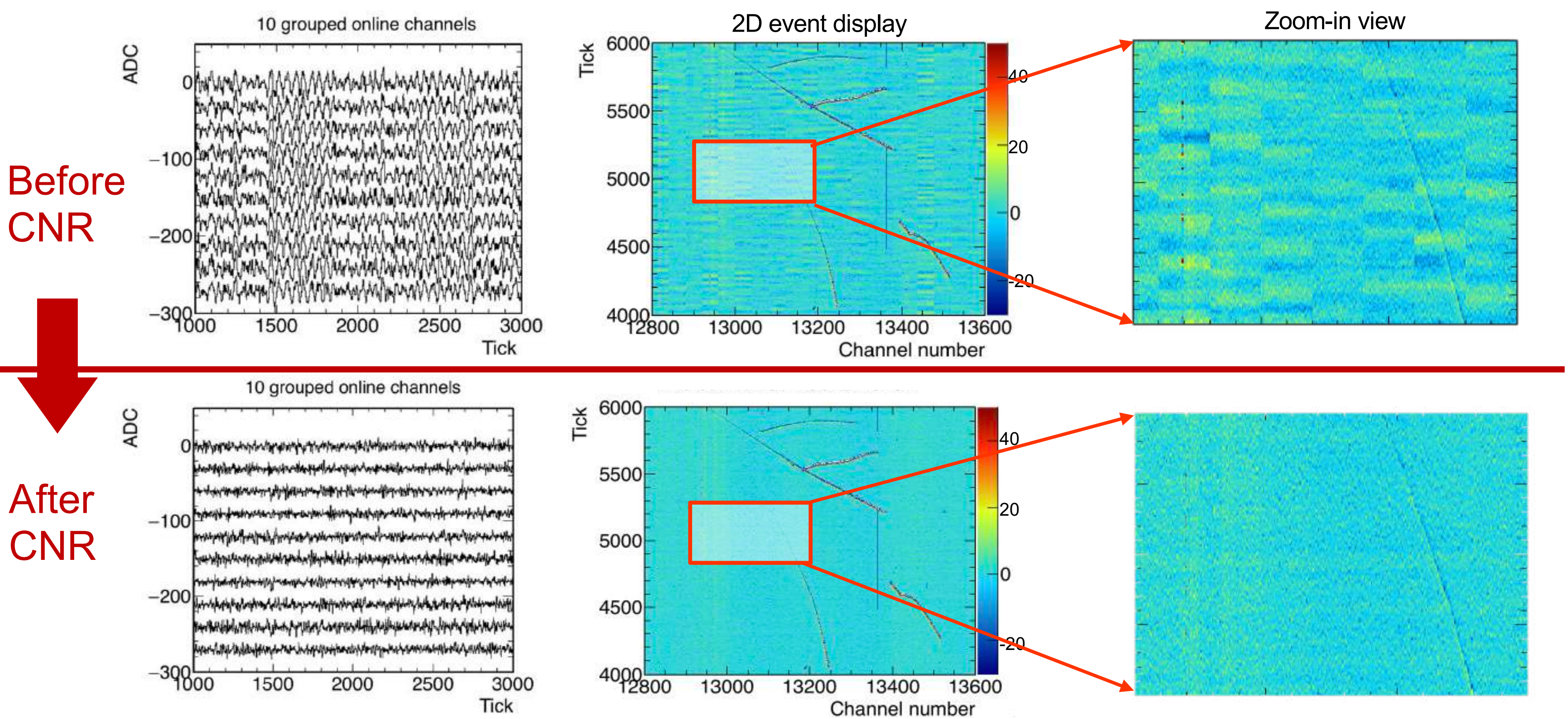
- The dominant source is the Coherent Noise coming from a group of channels sharing the same electronics unit (FEMB/CHIP/ASIC)
- FFT analysis shows that the frequency of coherent noise is around 45 kHz. Can be suppressed by Coherent Noise Removal (CNR)

FFT Analysis for collection (Z) and induction (U, V) planes

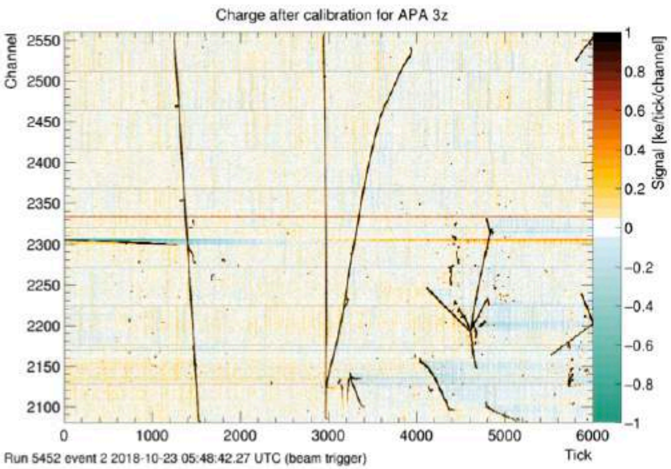


Coherent Noise Removal (CNR)

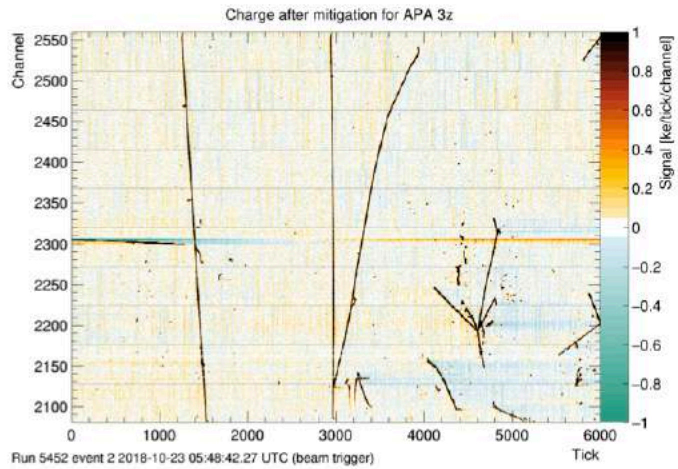
- Coherent Noise Remove is done in the time domain
  - Calculate the average ADC for each tick outside the protected signal region
  - Subtract the averaged ADCs from each waveform



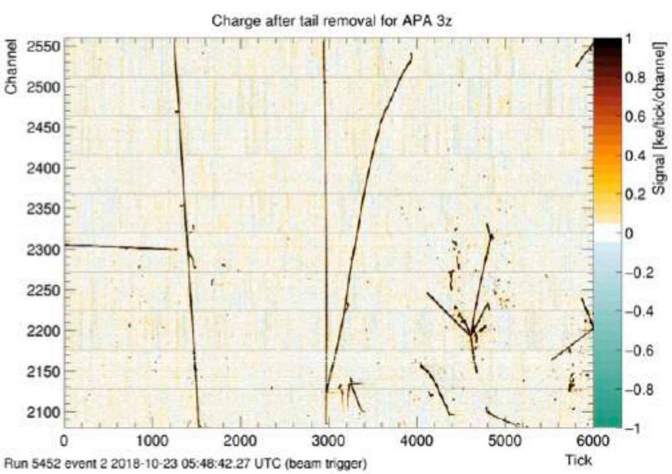
ProtoDUNE-SP Signal-to-Noise is High



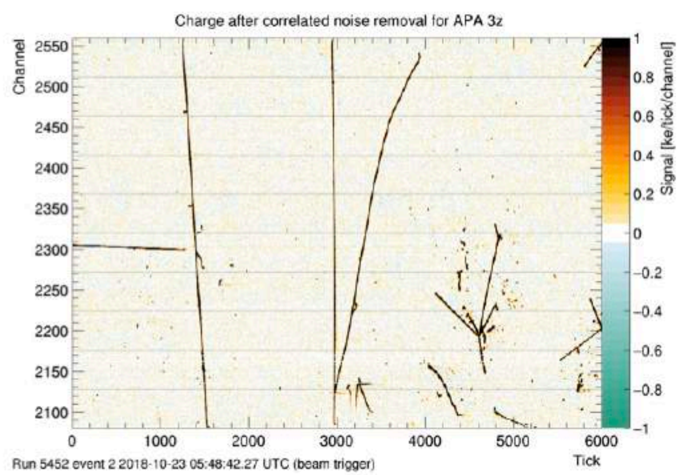
After pedestal calibration



After ADC code mitigation



After tail removal



After Coherent Noise Removal

ProtoDUNE-SP performance paper

Signal-to-Noise (Raw → Filtered):

Collection plane:
30.9 → 40.3

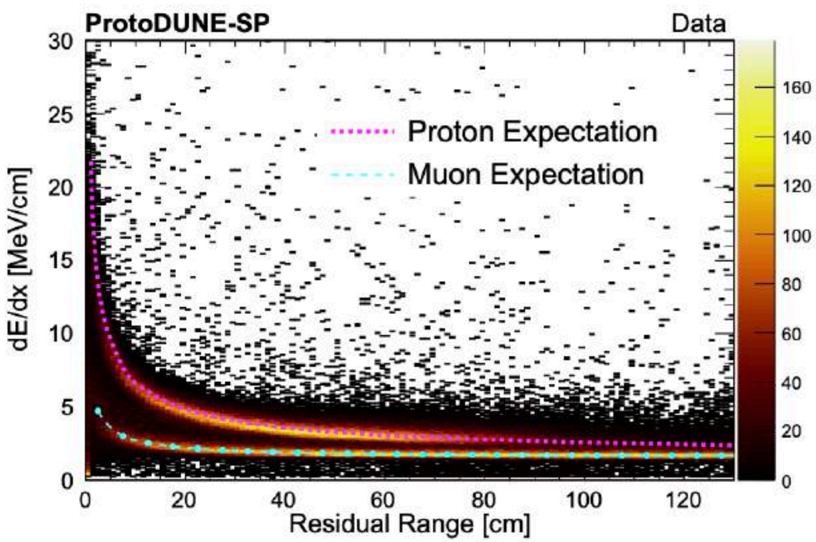
Induction plane U:
12.1 → 15.6

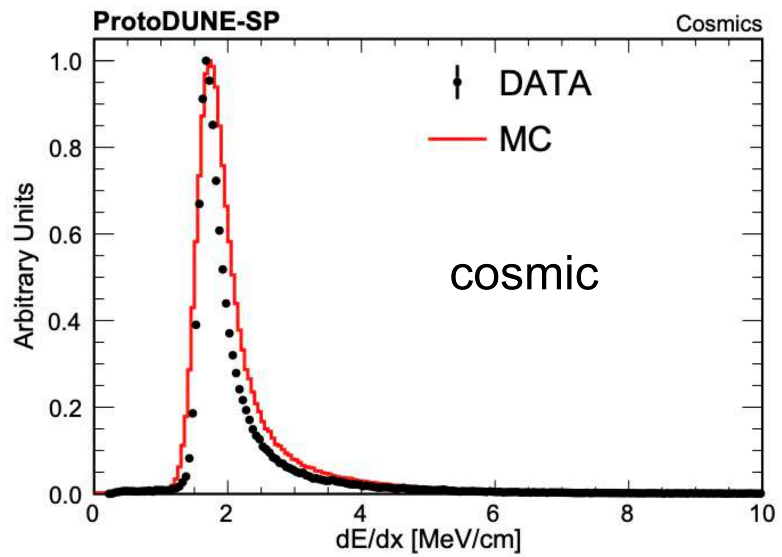
Induction plane V:
14.9 → 18.7

ProtoDUNE-SP PID is Excellent

One example:

ProtoDUNE-SP performance paper

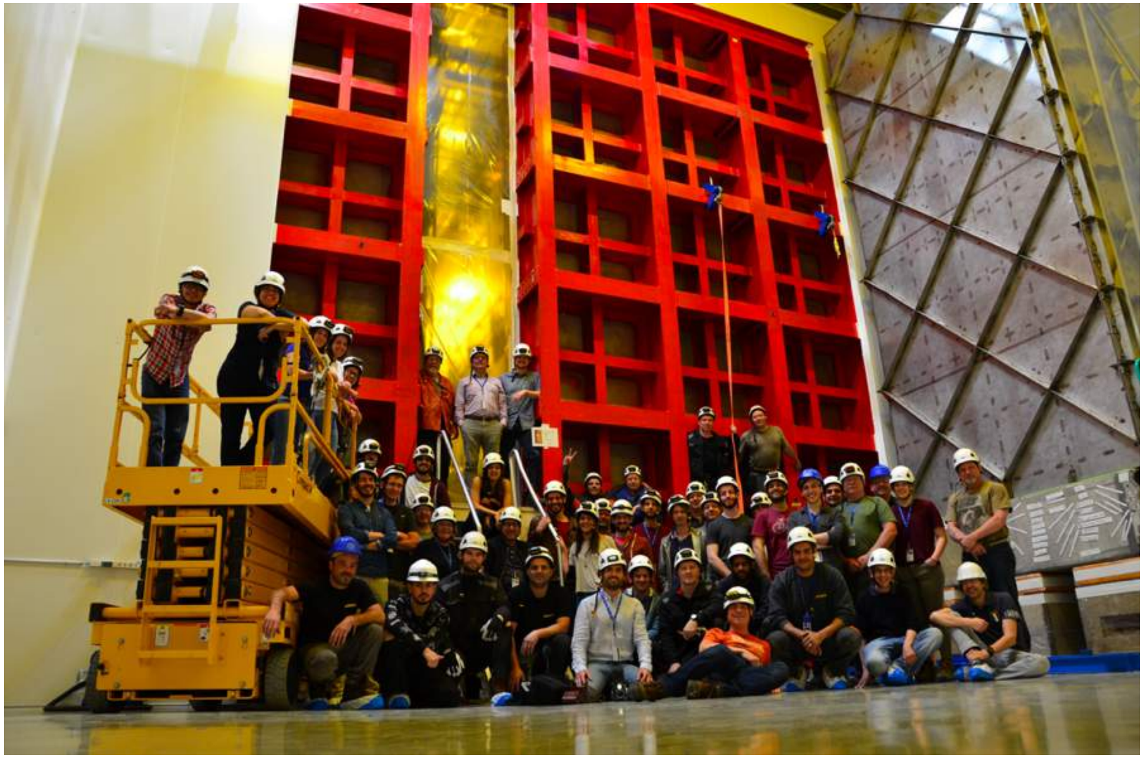


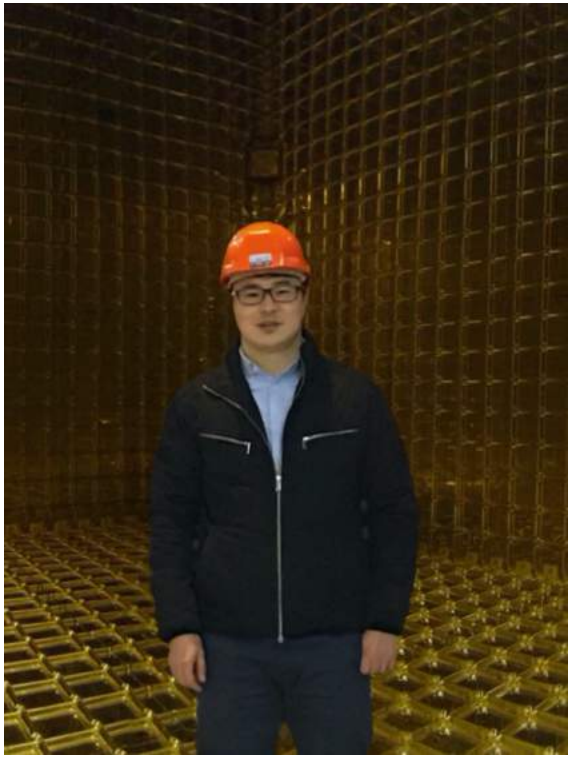


- Very well understood detector response to particles of different species
- Excellent separation of muons and protons using calorimetric information
- Data outperforms MC simulation!

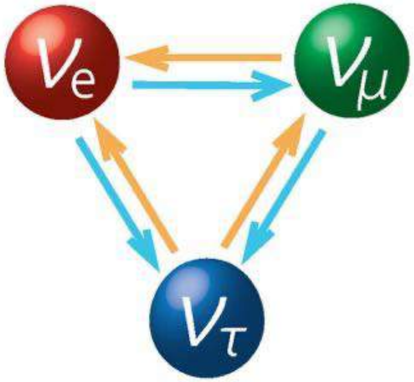
Status of ProtoDUNE

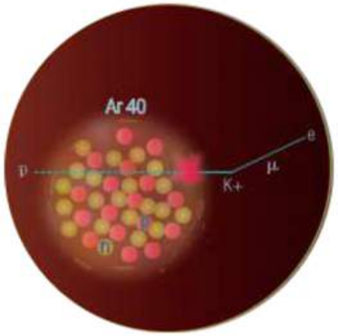
- ProtoDUNE-SP took beam data for three months in 2018
- ProtoDUNE-DP completed construction and is taking cosmic data
- I've been working on ProtoDUNE-SP since 2017. I worked on online monitoring.
- **Now, I'm very interested in neutrons in ProtoDUNE for reasons I'll talk about shortly.**





DUNE science





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

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

DUNE physics is ambitious

A broad range of physics studies in a single experiment!

Precision measurement of neutrino oscillation:

CPV, MH, θ_{23}

Baryon number violation:

Proton decay

Many other BSM physics:

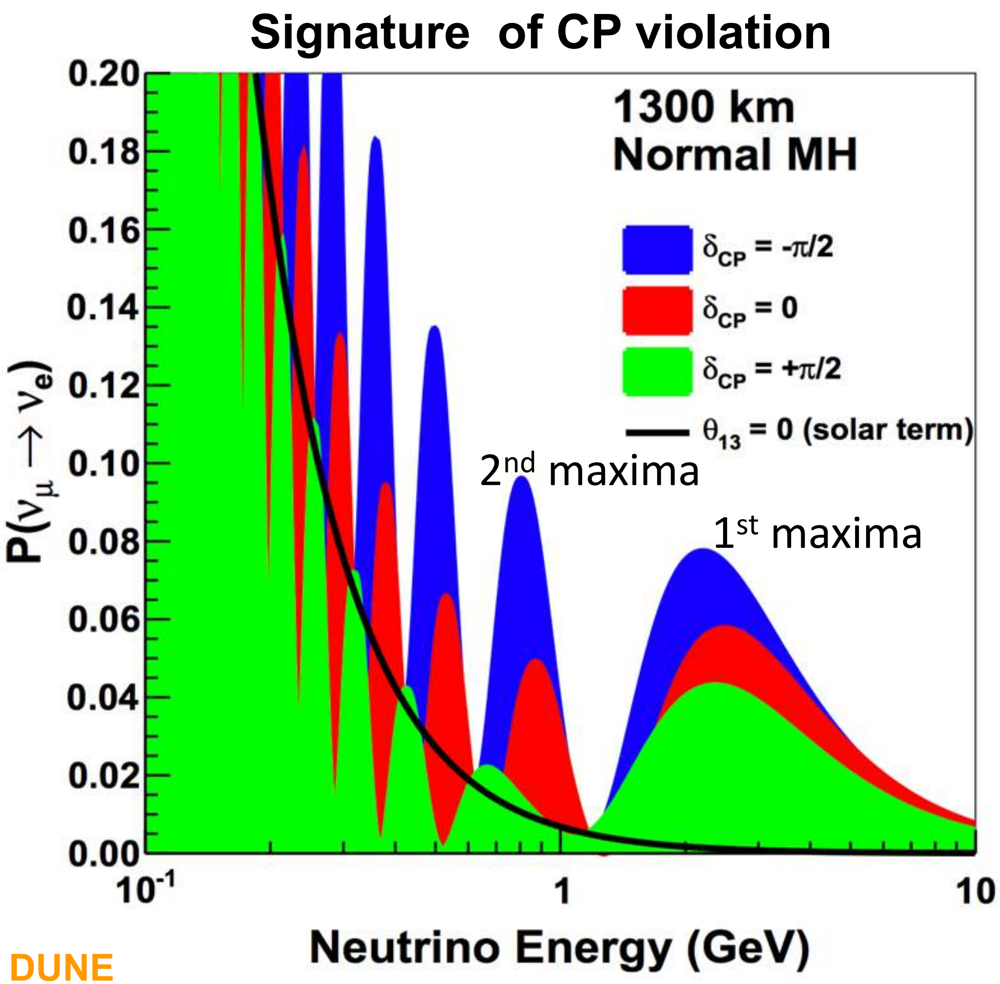
Sterile neutrino,
Light dark matter,
Boosted dark matter,
Non-standard interactions,
CPT violation,
non-unitary mixing,
Large extra dimensions
…

Supernova neutrino:

sensitive to υ_e

Precision Solar neutrino

DUNE oscillation strategy



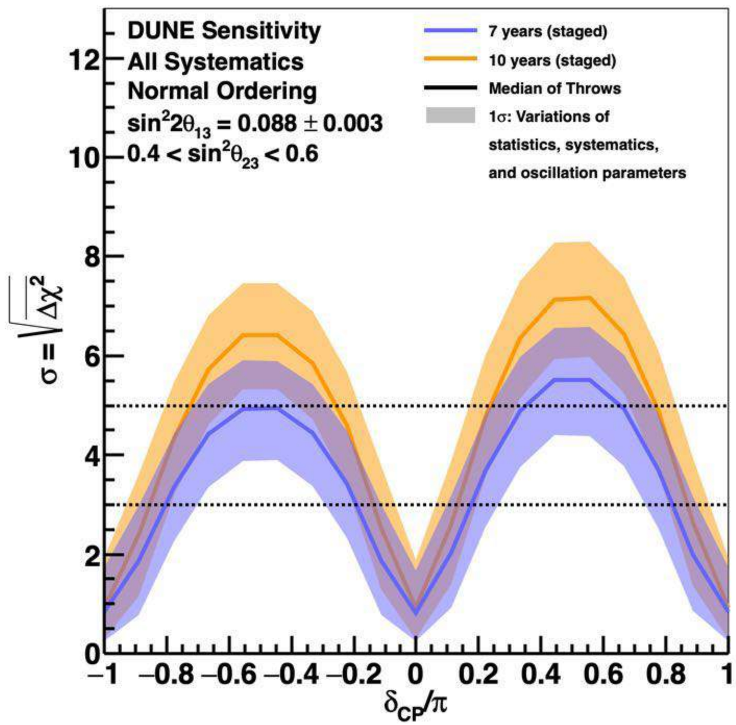
DUNE CDR

- **Oscillation probability is modulated by δ_{CP} phase**
- **Wide-band neutrino beam** (0-5 GeV) covers 1st and 2nd maxima
- Measure both ν_e **appearance** and ν_μ **disappearance** for neutrinos and antineutrinos (**four spectra**)
- Simultaneously fit four spectra to extract the oscillation parameters **in a single experiment**

DUNE CP Violation Sensitivity

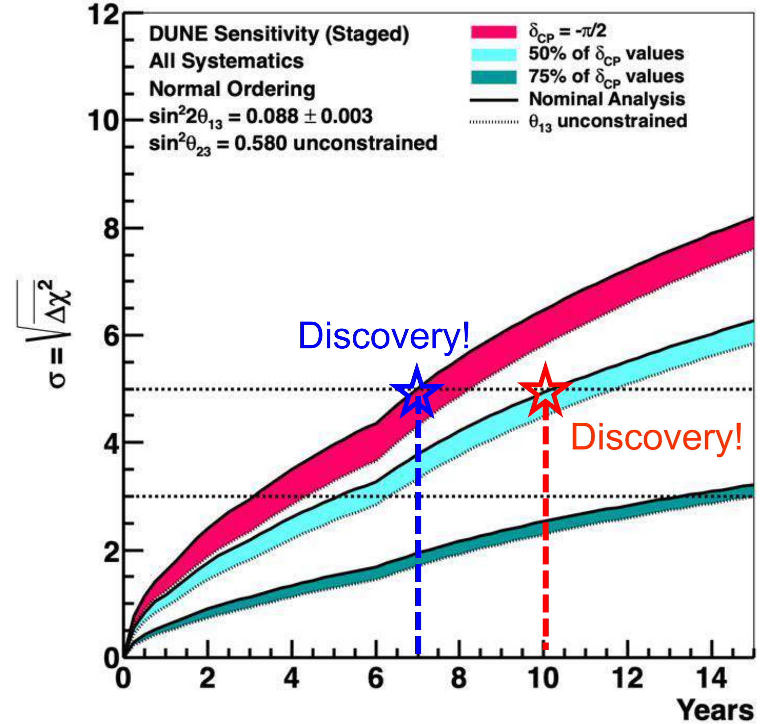
- CP violation significance over **a range of possible δ_{CP} phases**
  - **5σ significance** after 7 years data taking if **δ_{CP} is maximal** ($\delta_{CP} = -\pi/2$)
  - **5σ significance** over 50% of δ_{CP} phases after 10 years

CPV sensitivity for Normal Ordering



Width of band indicates variation in sensitivity for θ_{23} values

CPV sensitivity VS time



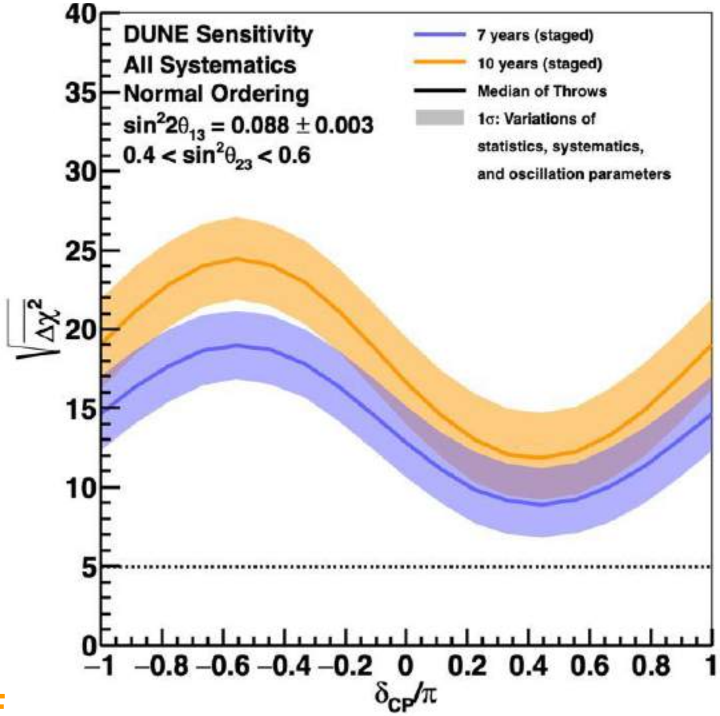
width of band shows impact of external constraint on θ_{13} values

DUNE TDR

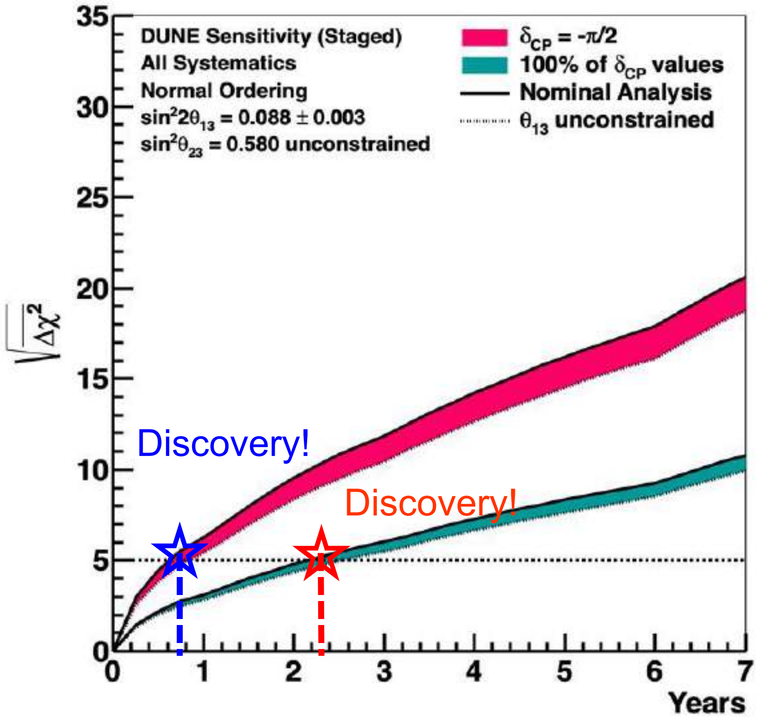
DUNE Mass Ordering Sensitivity

- Determine the Mass Ordering (Hierarchy) for **all possible δ_{CP} phases**
  - **5σ in 1 year** if $\delta_{CP} = -\pi/2$
  - **5σ in 2-3 years over entire δ_{CP} phase space**

MO sensitivity for Normal Ordering



MO sensitivity VS time



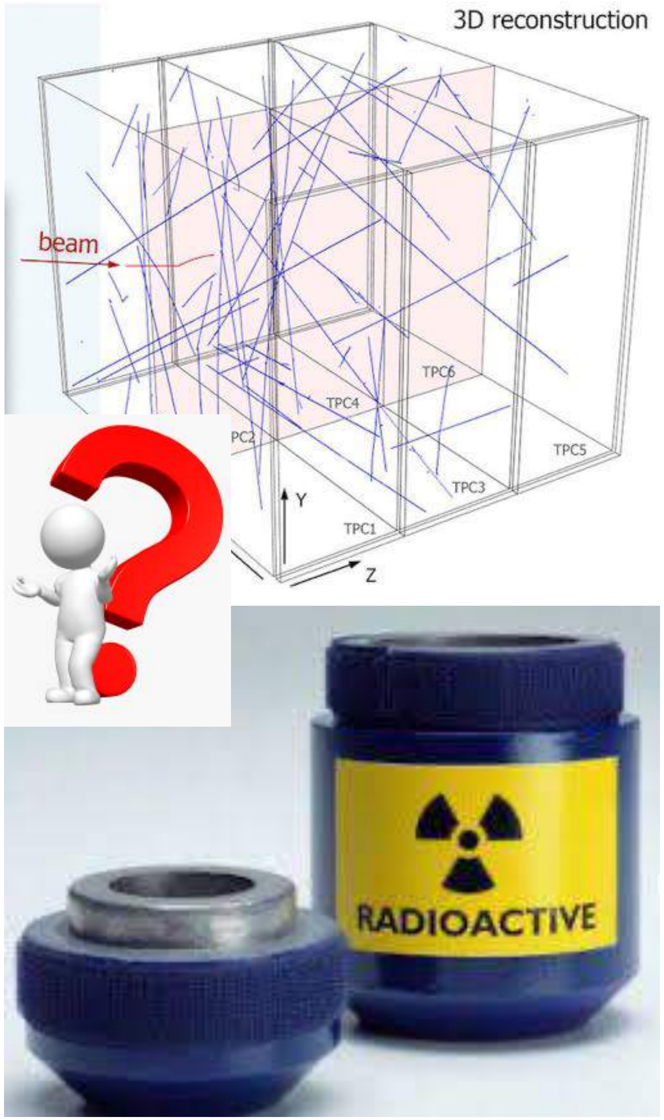
DUNE TDR

Width of band indicates variation in sensitivity for θ_{23} values

width of band shows impact of external constraint on θ_{13} values

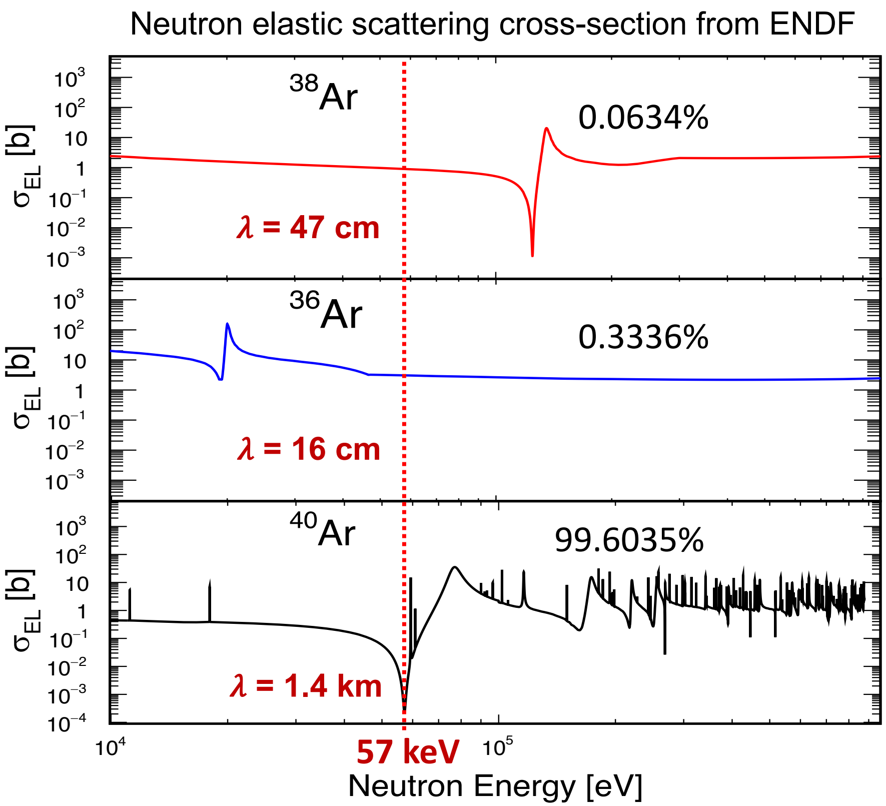
DUNE detector needs calibration

- Neutrino oscillation is an L/E dependent process
  - DUNE needs to understand the energy scale and resolution within 2% level
- **DUNE far detector calibration is challenging**
  - **Deep underground** → very few cosmic rays: 30 stopping muons and 20 Michel electrons /day/10 kt
  - **Large Volume** → difficult to use radioactive source: spatial coverage, contamination, field distortion
- I am developing the **Pulsed Neutron Source (PNS)** as a new calibration technique.



How can neutrons help?

- ^{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 in natural argon is ~30 m**



Neutrons above the anti-resonance will lose **4.8%** of energy per scatter until they “fall in the dip” – most neutrons will fall into the dip, and it takes a few scatters for them to get out.

$n + {}^{40}Ar = {}^{41}Ar + 6.1\ MeV$

Low-threshold photon detection may reveal the signature of neutron capture (~150 μs)

Advantages of Using Neutrons

- **External deployment: neutrons mostly ignore the stainless steel membrane of the cryostat**
  - No contamination to argon purity, no field distortion

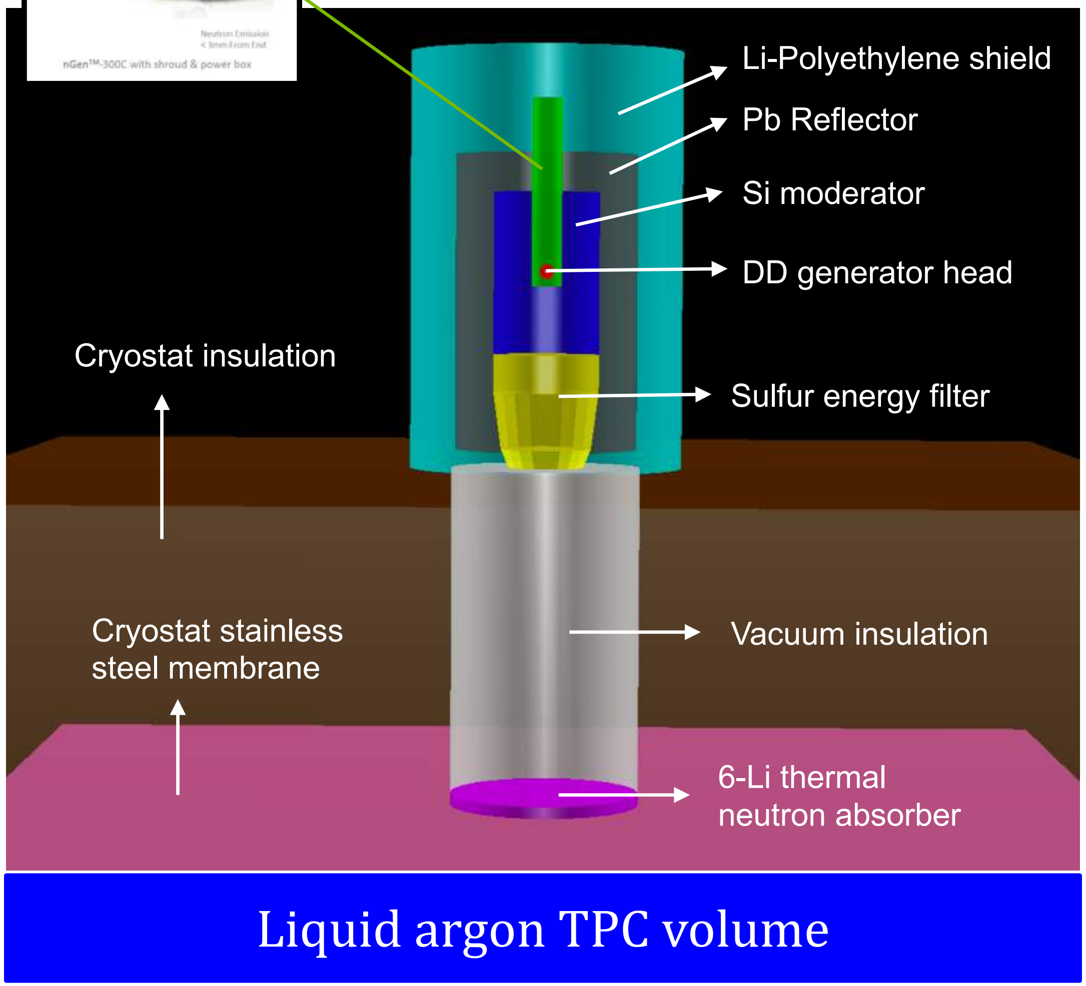
- **Pulsed trigger: use a pulsed DD generator to produce neutrons:**
  - Well defined t0 allows reconstruction of neutron capture location

- **Multi-gamma output: neutron capture emits 6.1 MeV gamma cascade**
  - Fixed energy deposition as a “standard candle” to calibrate the energy response

- **Wide coverage: anti-resonance neutrons can travel long distance**
  - Scattering length is long: 30 m in natural argon
  - Mean fractional energy loss per scatter is 4.8%.

How to make anti-resonance neutrons?

JINST paper in preparation

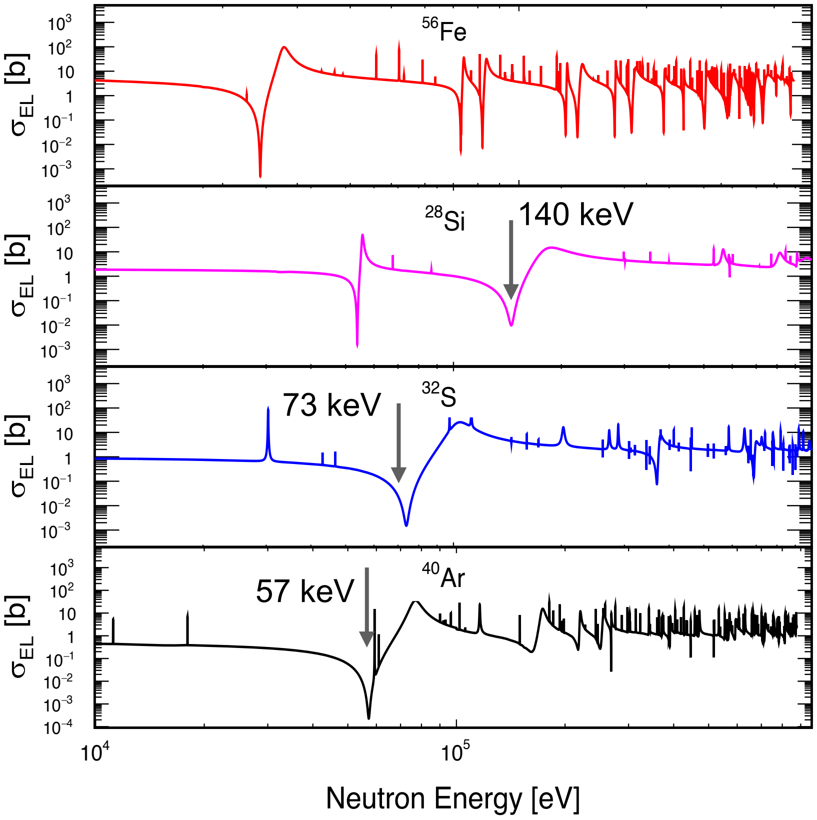


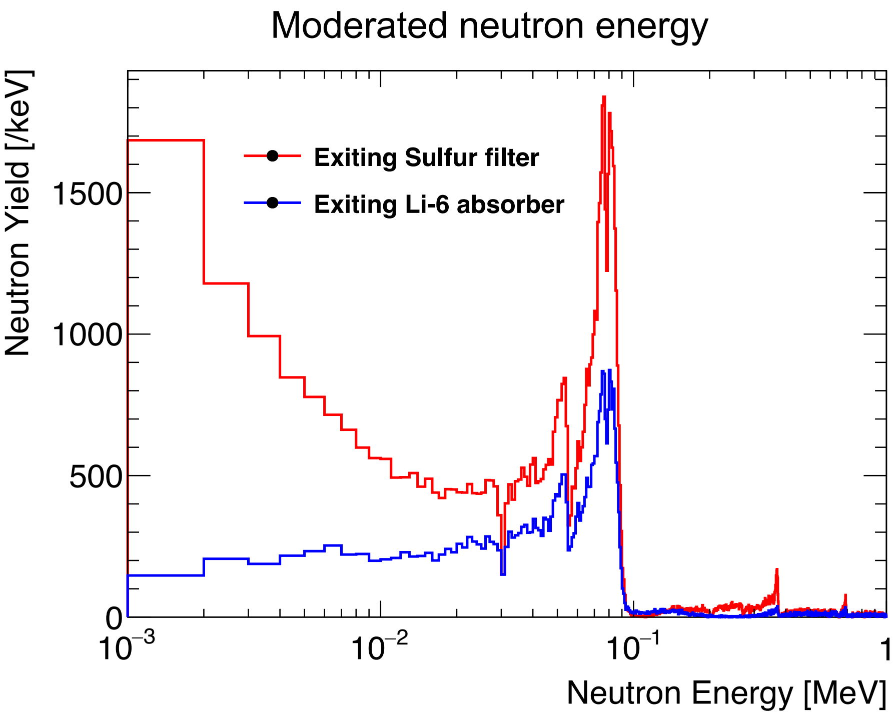
Pulsed Neutron Source:

- **DD generator** → 2.5 MeV neutrons
- **Si moderator** → efficiently reduce energy down to below 1 MeV
- **Sulfur filter** → select 73 keV neutrons
- **Pb reflector** → Increase neutron yield
- **6-Li absorber** → suppress thermal neutron fraction
- **Li-Polyethylene shield** → radiation protection

Simulated Moderator Performance

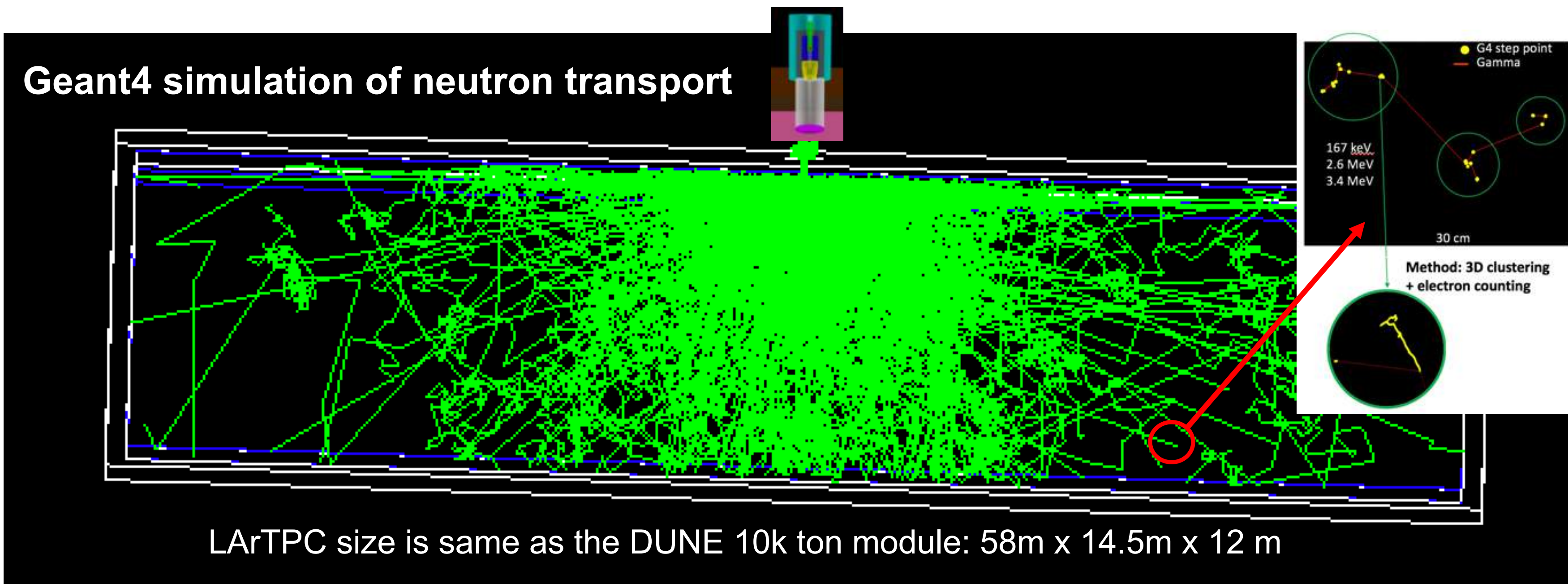
- Moderator makes use of the anti-resonance features of the moderating materials: silicon, sulfur
- The moderator is expected to make 50-80 keV neutrons (4.5% of the primary DD generator neutrons)





Pulsed Neutron Source is Accepted by TDR

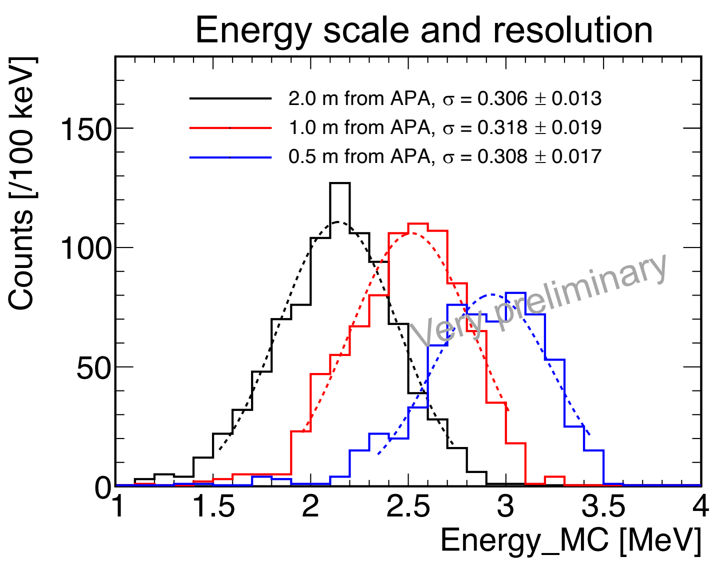
- The Pulsed Neutron Source system has been **accepted by DUNE TDR** as one of the two major calibration systems.
- To develop this idea, I was awarded the **Fermilab Intensity Frontier Fellowship**. I am currently supported by DUNE as a **Project Scientist** to lead the program.
- We will build a prototype and send it to CERN for testing in ProtoDUNE Run-2 (summer 2021)

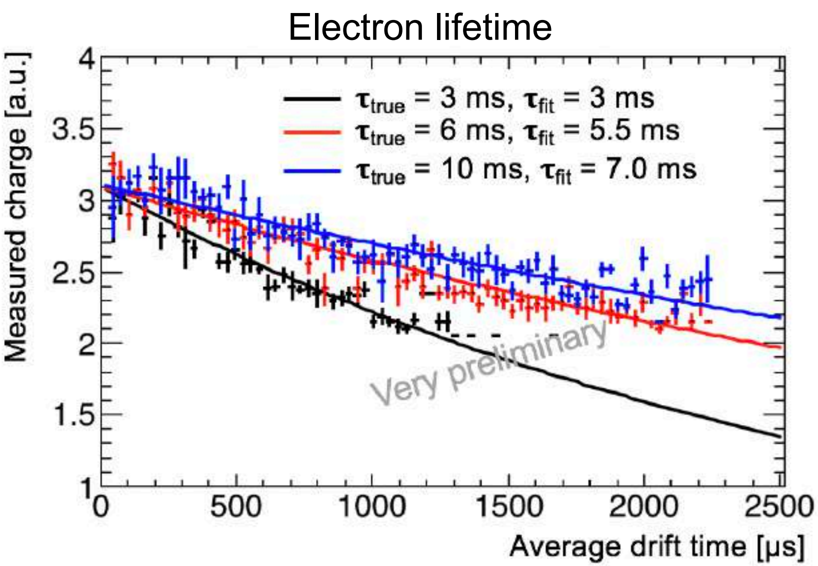


What Can be Measured by PNS?

- Simulation of neutron captures has shown sensitivity to relevant physics
  - **Energy scale, electron lifetime**
- Neutron capture position is determined by TPC reconstruction
  - Rough t_0 is provided by the DD generator pulse: smeared by the pulse width (can be tuned down to 10 μs) and the neutron capture time (150 μs)
  - Precise t_0 could be provided by the photodetector system
- **Ideally, measure the neutron captures for every m^3 voxel.**

Idealized simulation with no corrections for recombination and argon purity



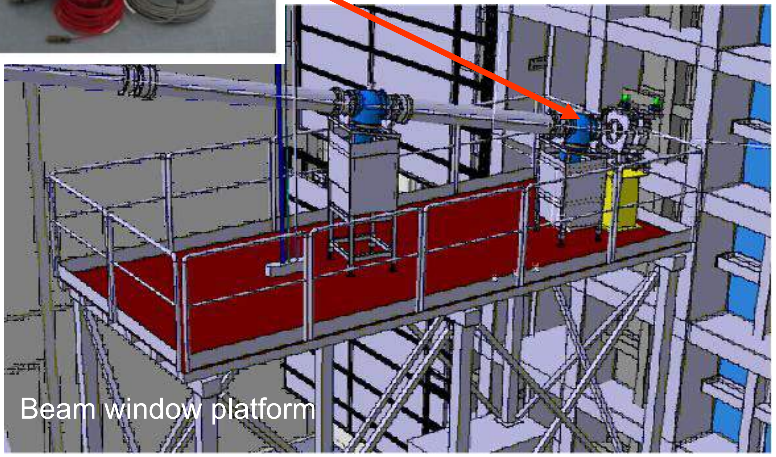


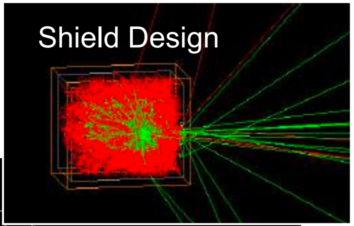
DD Generator Test at ProtoDUNE

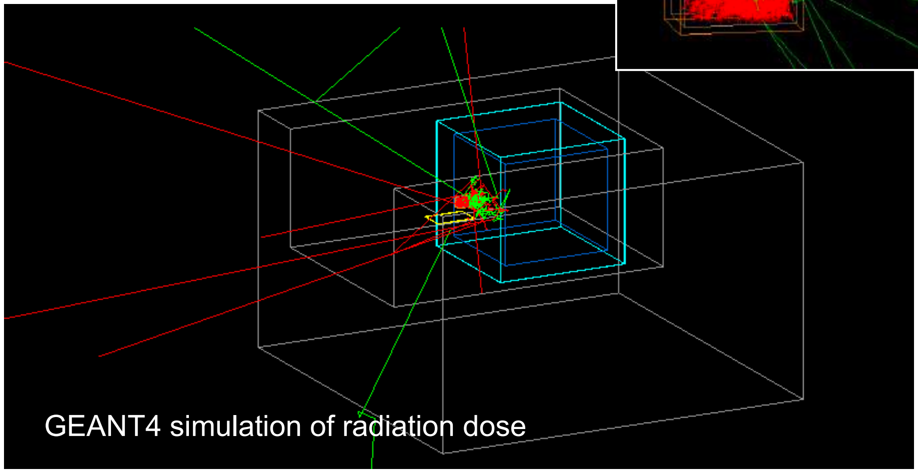
- The PNS working group is planning a DD generator test at ProtoDUNE-SP in April 2020 before the detector shutdown
- Goal is to take neutron capture data and gain experience on DD generator
  - Plan to inject neutrons into the TPC through the beam plug.
  - Designed a shield for the DD generator and evaluated the radiation dose rate

LANL DD generator

Effort supported by DUNE Project



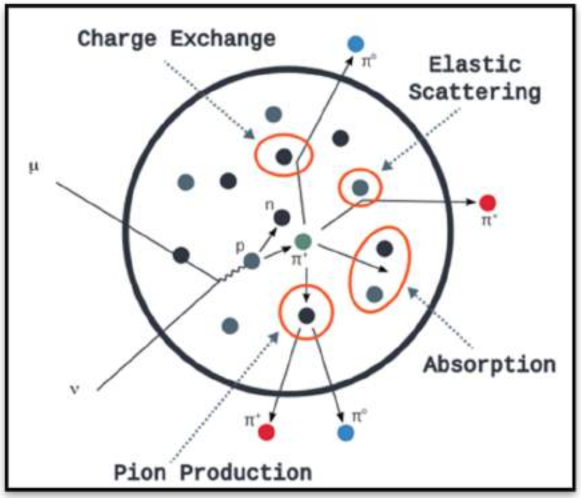




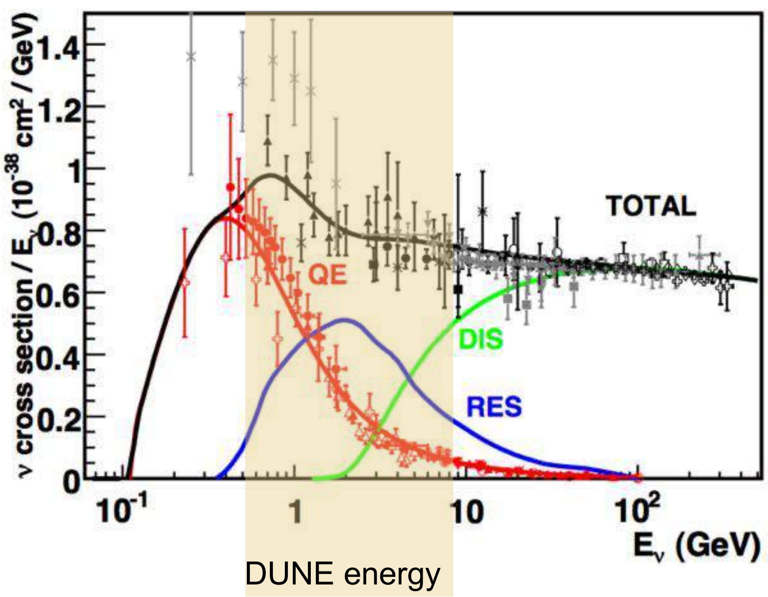
Neutrons are important for oscillation physics

- To turn neutrino physics into a precision science, we need to understand the complex **neutrino-nucleus interactions**
  - Neutrino-nucleus interaction is hard to model. Neutron yield is model dependent.
  - Neutrino could go through RES and DIS interactions. Neutrons carry away a large fraction of energy (20%), but they are difficult to detect
- **Lack data about neutron yield. Mis-modeling affects the physics sensitivity**

Neutrino-nucleus interaction



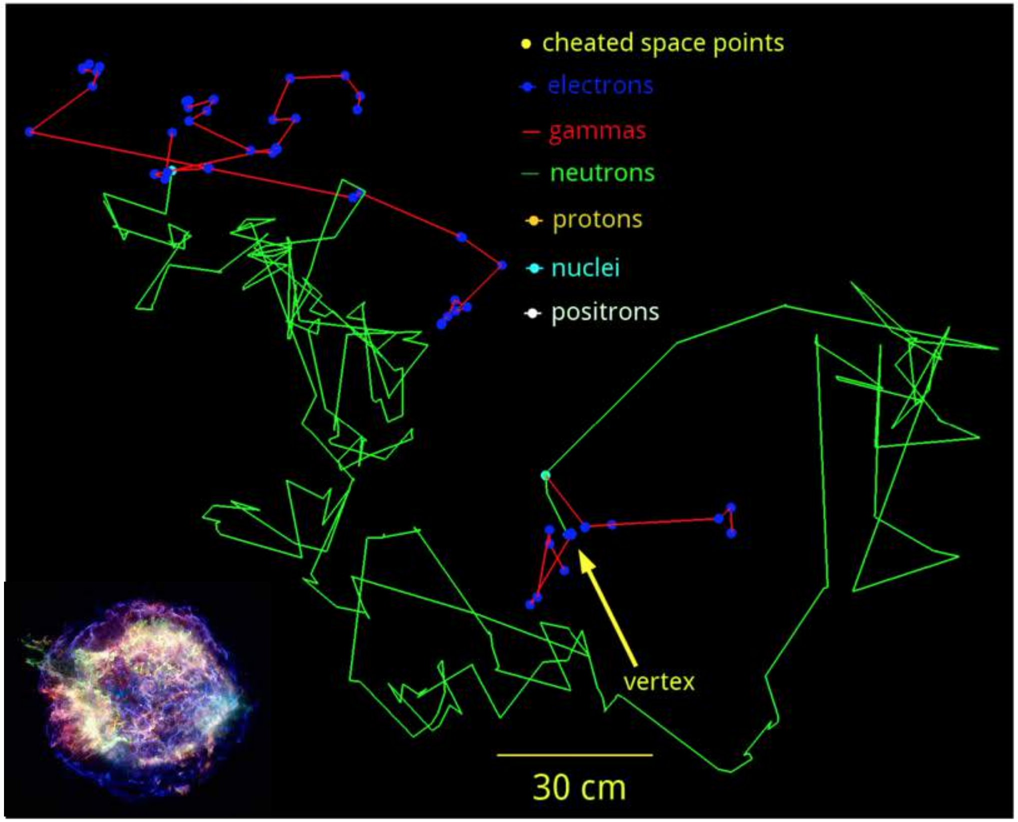
Neutrino interaction cross-section



Neutrons in Supernova Neutrino Physics

- **Neutrons are part of the 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



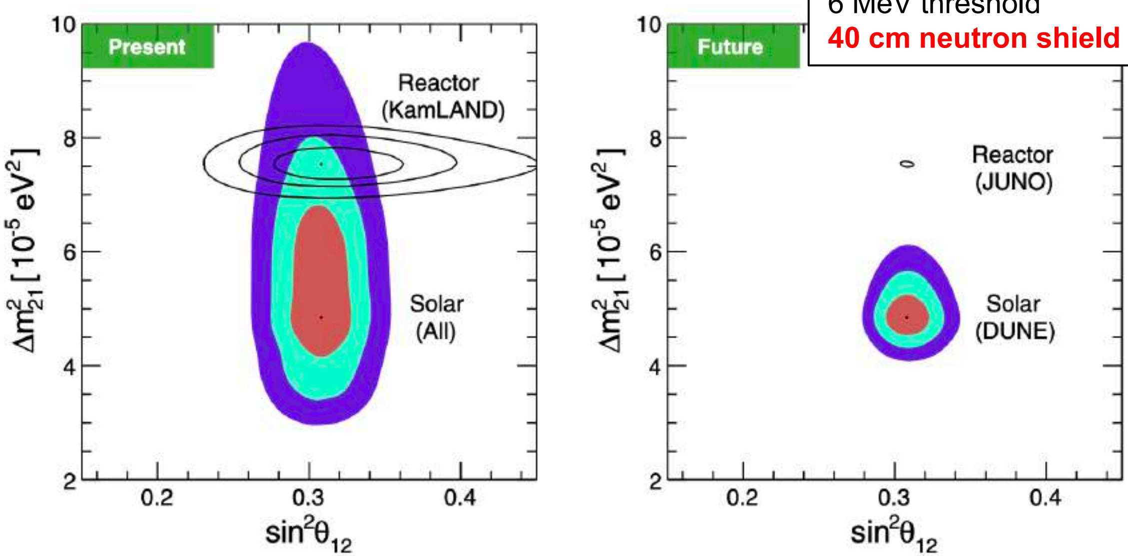
- **Difficult to model the process**
  - Neutron scattering cross-section below 100 keV not well measured
  - Neutron capture cross-section and emitting gammas not well understood

This is what we can measure on a neutron beam!

Neutrons in Solar Neutrino Physics

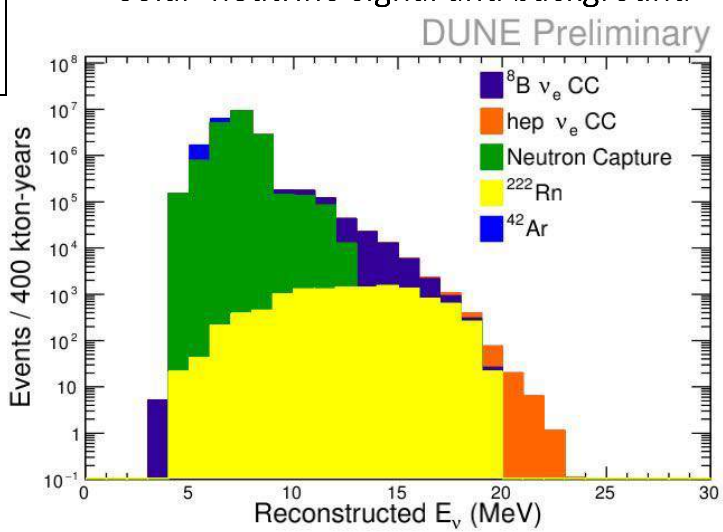
- DUNE is considering the potential sensitivity to solar neutrinos
  - $\gtrsim 10^5$ signal events above 5 MeV electron energy for 100 kt-yr exposure.
- A 10-kt far detector module expects to get about **100 neutrons/second** from the rock.
  - These neutrons could transport for long distances into the detector and the capture gives 6.1 MeV gamma cascades that look like solar neutrinos

DUNE TDR



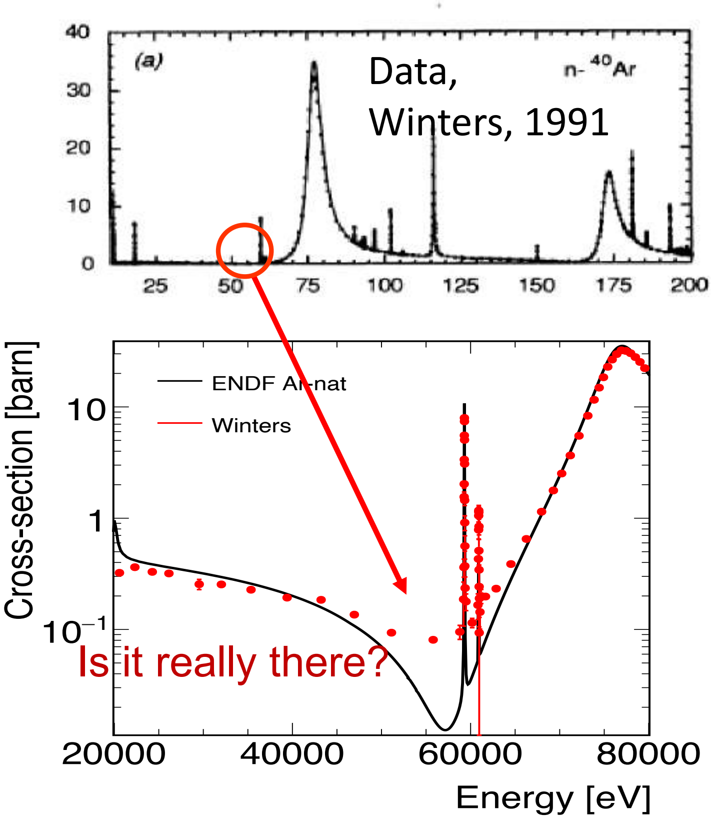
Assumptions:
7% energy resolution
6 MeV threshold
40 cm neutron shield

Solar neutrino signal and background

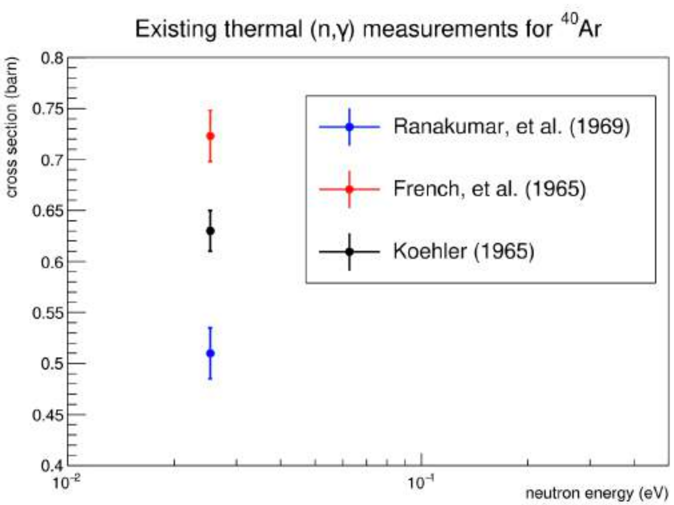


What's Our Knowledge about Neutrons?

- Question: **do neutrons *really move* deep into the liquid argon volume?**
- Question: **how well do we understand the neutron capture?**



$n + {}^{40}Ar = {}^{41}Ar + 6.1$ MeV



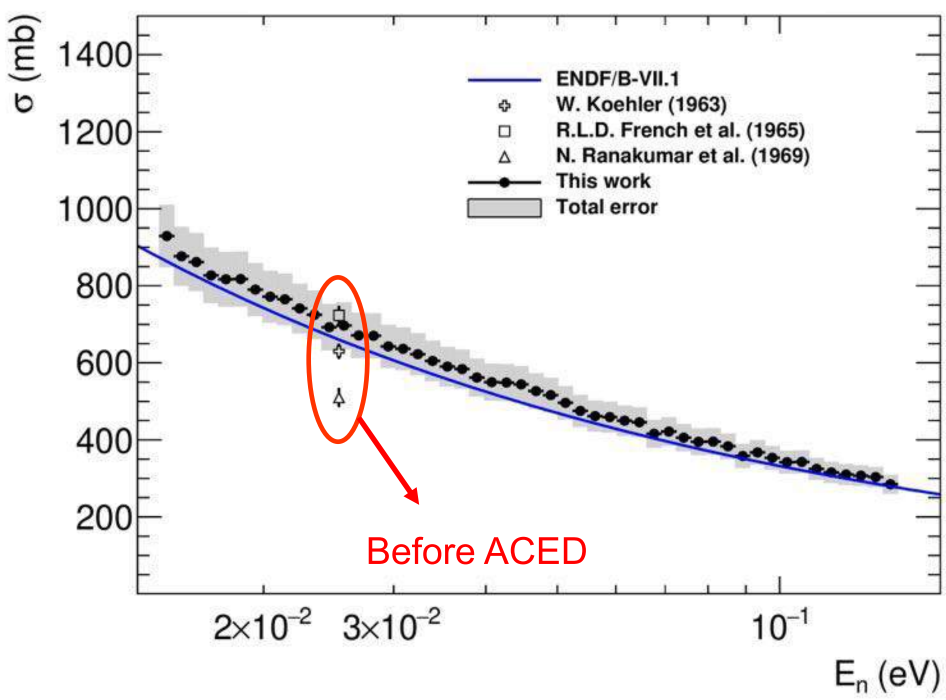
Which capture cross-section is right?
What's the correlated gamma cascade like?

- **I did two experiments using Time-of-Flight neutron beam at LANL**

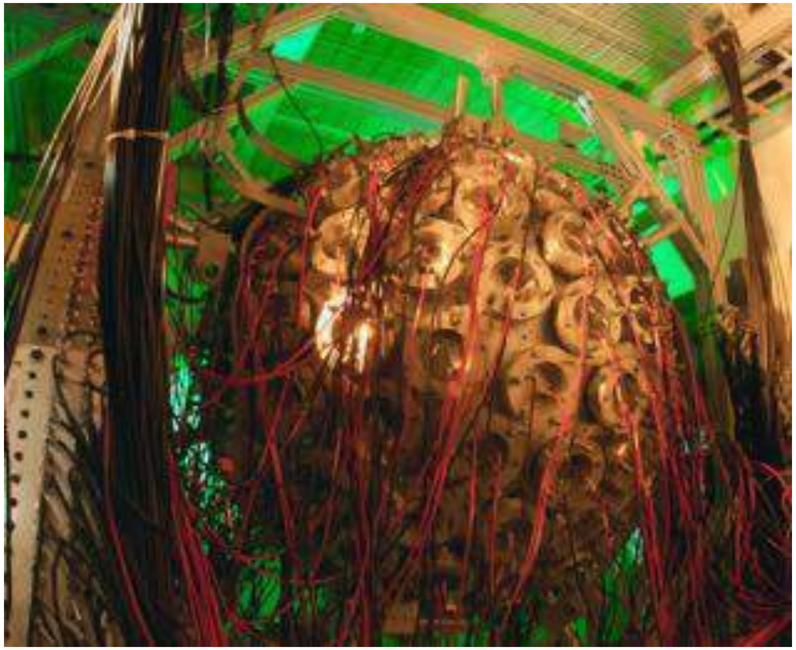
Argon Capture Experiment at DANCE (ACED)

- ACED collaboration measured the **thermal neutron capture cross-section** and the **correlated-gamma cascade** (never measured before)
- **Two papers published:**
  - **Neutron capture cross section:** *arXiv:1902.00596* (**PRD**)
  - **Thermal neutron beam calibration** using sodium: *arXiv:1902.01347* (**NIM A**)

Neutron capture cross-section

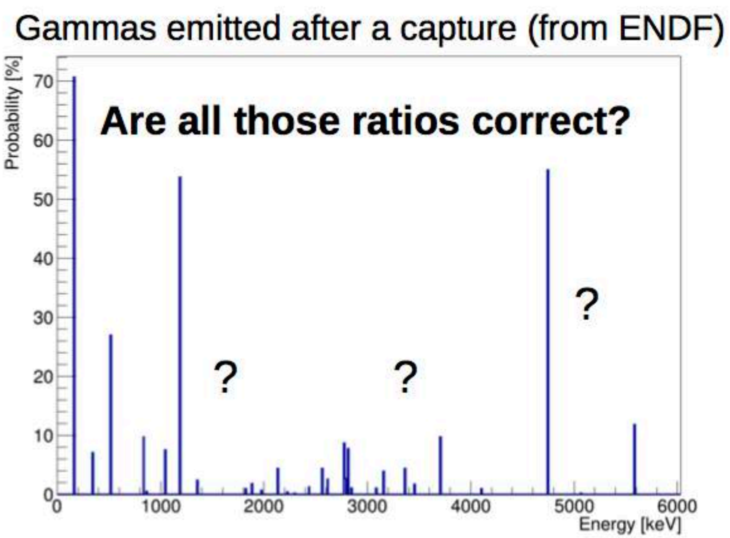


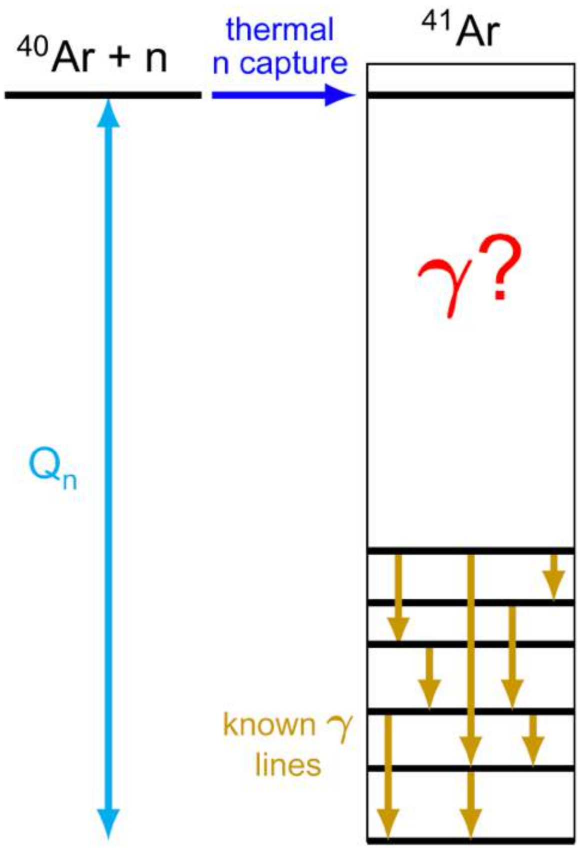
DANCE detector @lujan- FP14



ACED Analysis: Gamma Cascade

- The 3rd paper will be about the **correlated gamma cascade**
- **Problem: Branching ratios of known gamma lines could be incorrect**
- **Problem: Many high-lying levels where gammas are unknown, and are difficult to model theoretically**
- ACED will use a statistical method to study the correlation of gammas in cascades





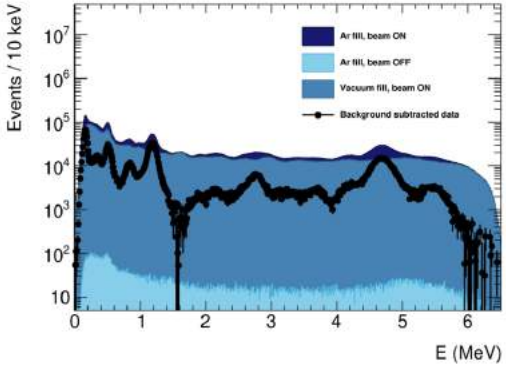
ACED Analysis: Gamma Cascade

- Use **DICEBOX** to generate realistic decay schemes for ^{41}Ar
- Simulate gammas in the well-tuned DANCE simulation
- Data-simulation comparison to find the most compatible solution

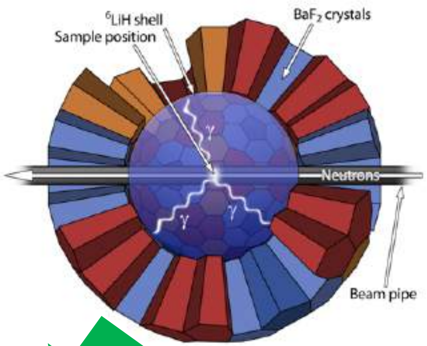
Data analysis close to be finalized

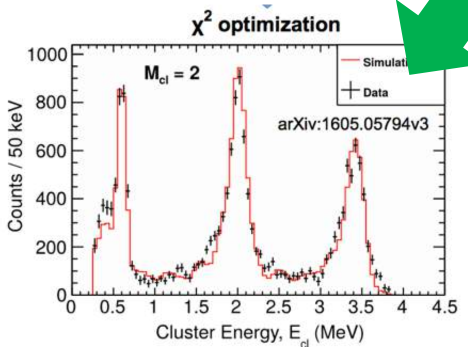
DICEBOX

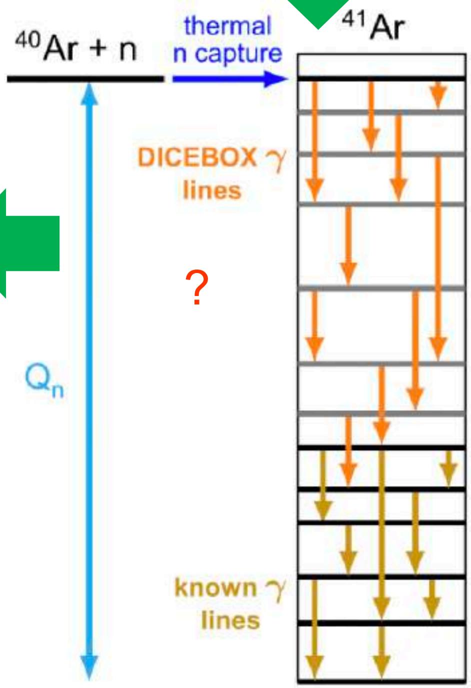
ACED Measurement



MC Simulation

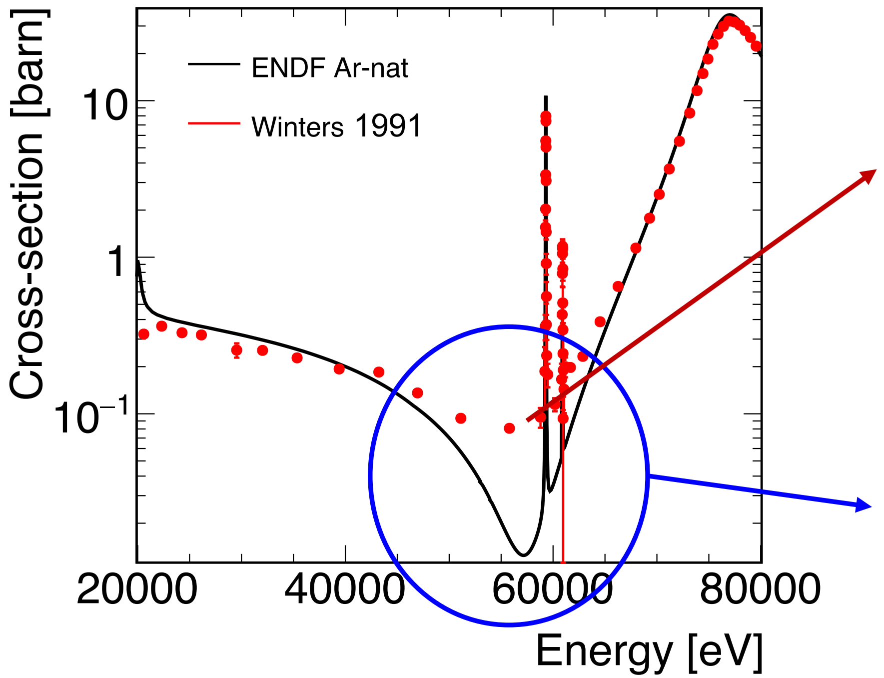






Argon Resonant Transport Interaction Experiment (ARTIE)

- There is a large between ENDF prediction and Winters' data (1991).
- ARTIE measured the neutron **total cross-section** in argon around **57 keV,** with much higher precision than Winters' measurement.



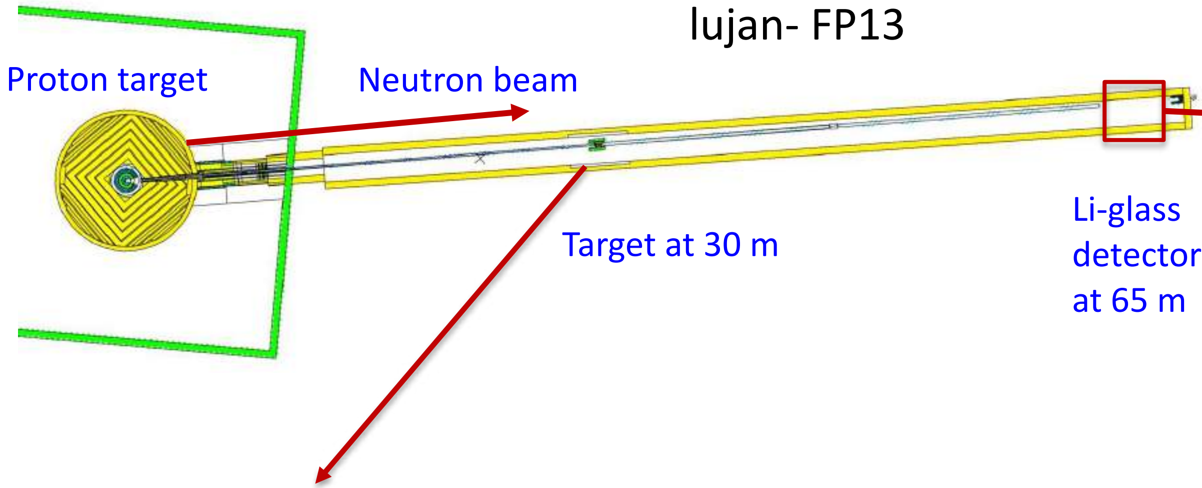
Winters' measurement:

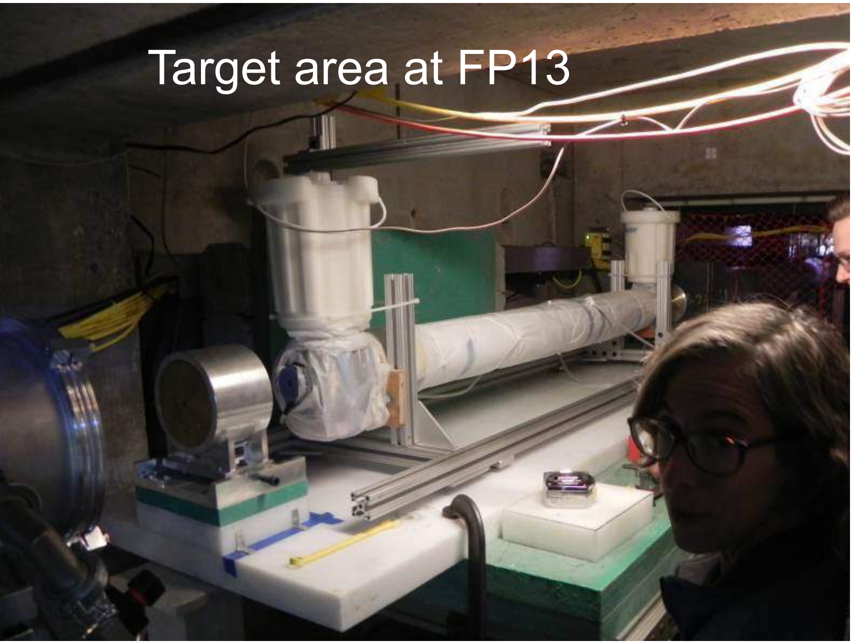
- 2.216 meter long gas target with **0.211 atoms/barn** density: sensitive to high cross-section, but not sensitive to low cross-sections

ARTIE measurement:

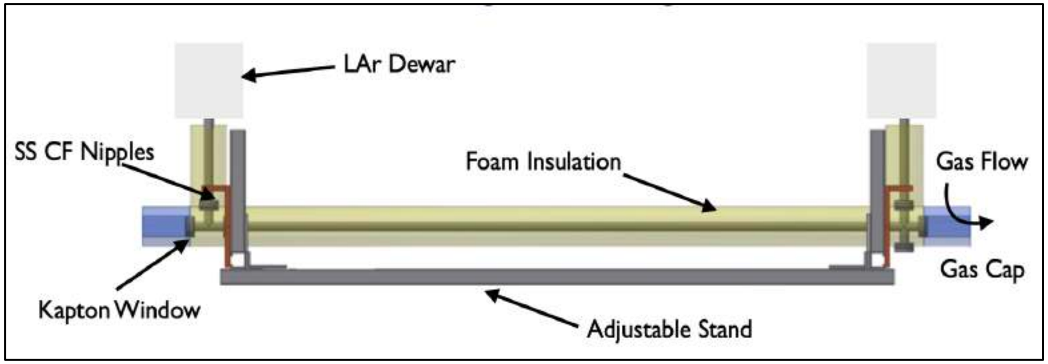
- 168 cm long liquid argon target with **3.5 atoms/barn** density: blind to high cross-section but very sensitive to low-cross sections

ARTIE Experimental Design



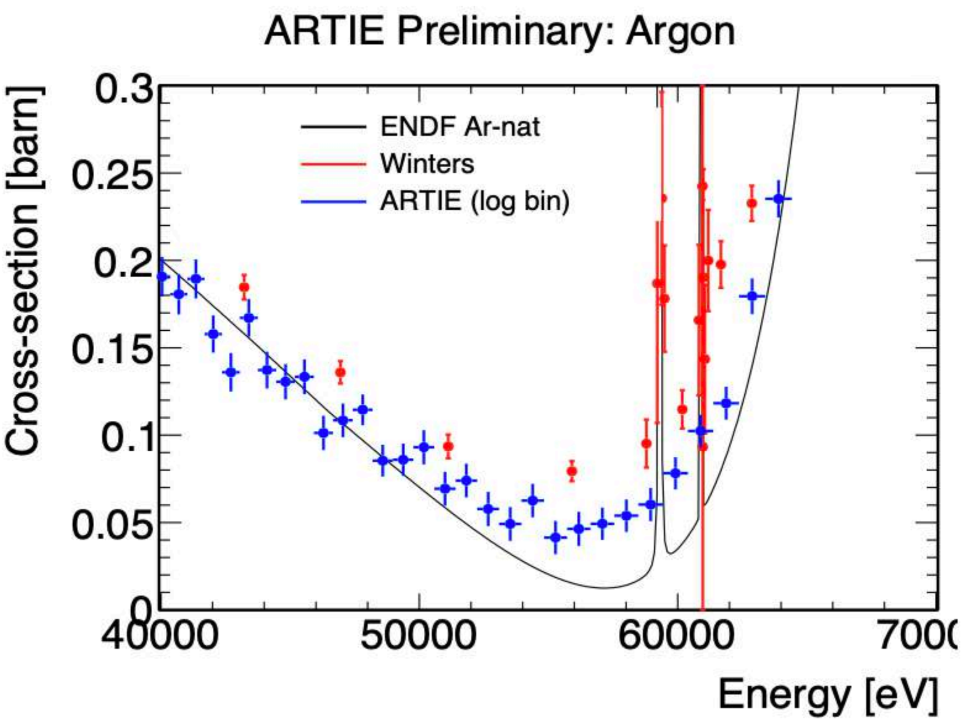


- 1” OD target is wrapped by foam and sealed by Kapton windows on both ends
- Kapton windows are protected from air moisture by flushing dry nitrogen through the gas cap
- Thermometers are used to monitor the liquid level



ARTIE Preliminary Analysis

- We took data at **LANL** in 10/2019. I led the design of this experiment, and am currently leading the data analysis
- **Currently working on background and systematic uncertainties.**
- Result is important for the PNS calibration idea, and is also of particular interest to supernova and solar neutrino physics (prepare to submit a paper to PRL)

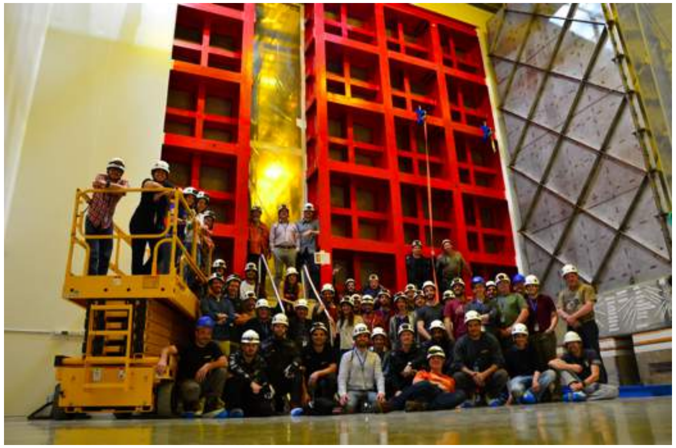


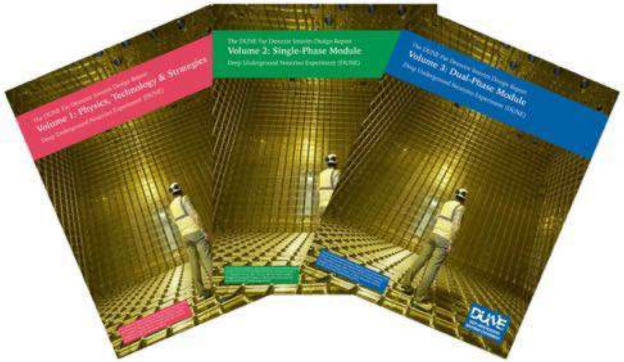
No background subtraction applied

Result shown here is the upper bound

First results reported to DUNE Collaboration Meeting in 01/2020. (More details in backup slides)

DUNE Timeline





2018 ProtoDUNE

↓

2019 Far Detector TDR

↓

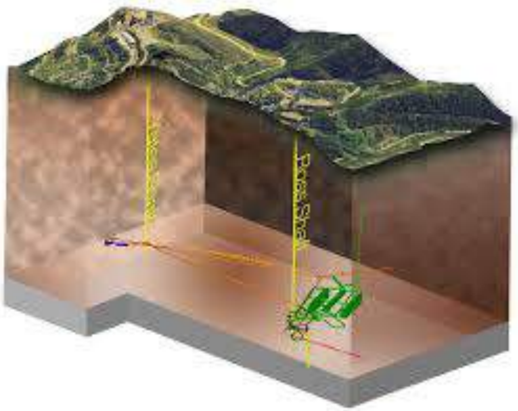
2019: Far Site Primary Excavation Begins

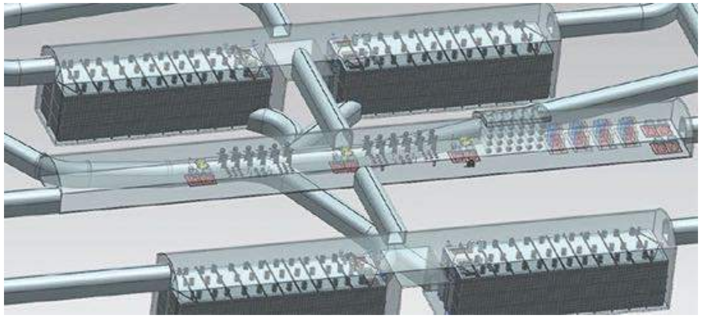
↓

2024: First Module Installation Begins

↓

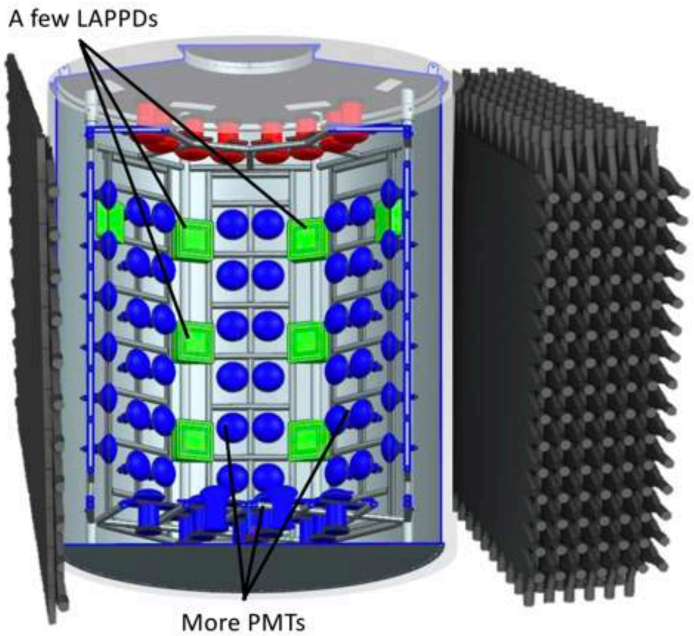
2026: Neutrino Beam + 2 Far Detectors

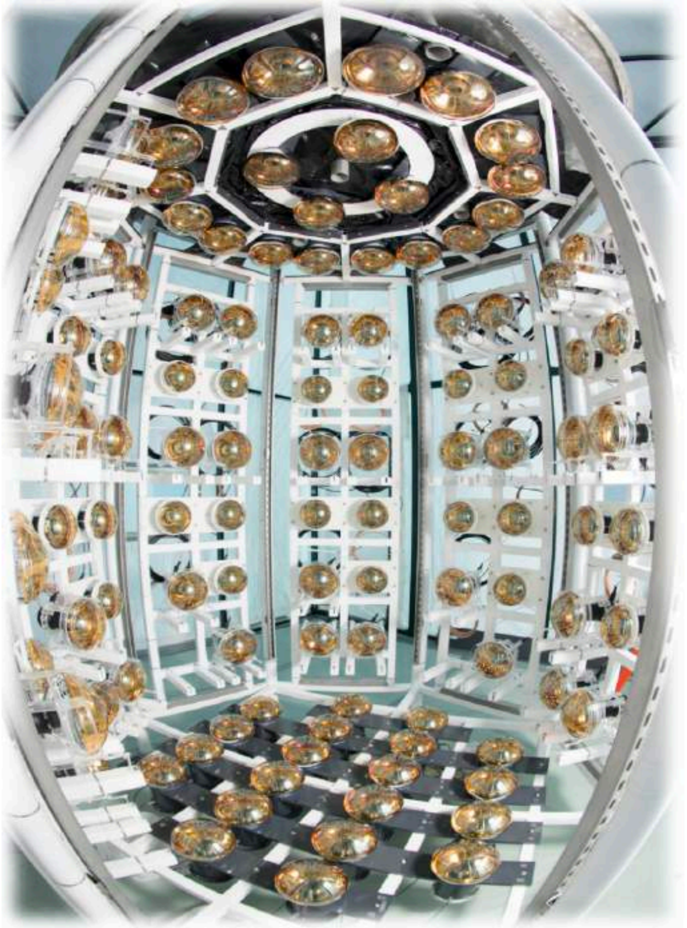




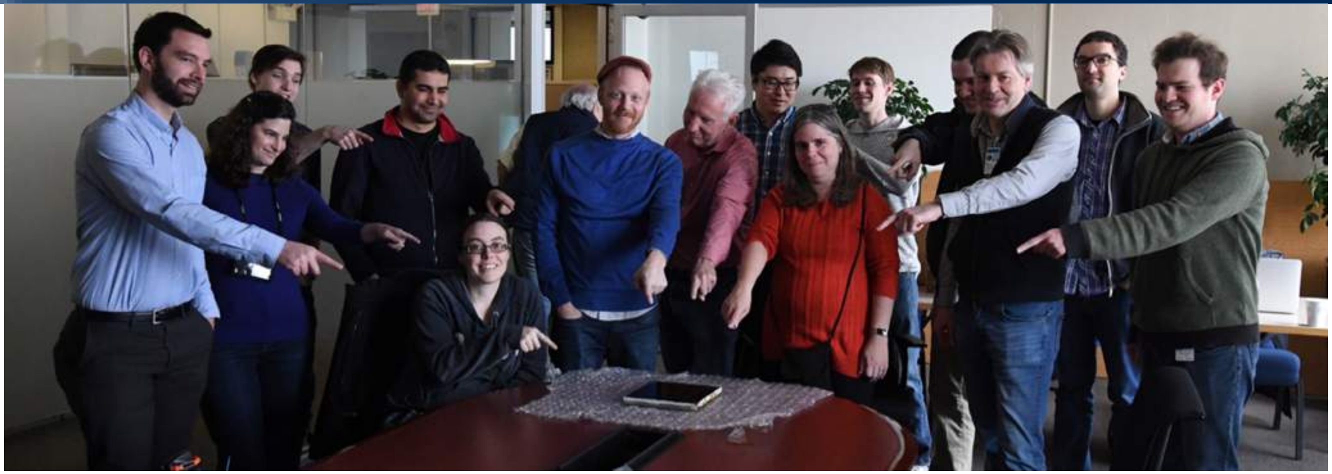
ANNIE: Accelerator Neutrino Neutron Interaction Experiment

- 26-ton Gd-loaded water Cherenkov detector at BNB at Fermilab
- Physics goal: Measure the neutron multiplicity from neutrino interaction in water.
- **Same measurement needed for argon: might be possible to deploy a small argon target in ANNIE tank**

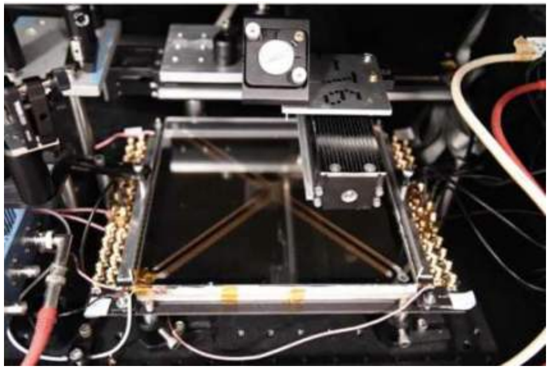




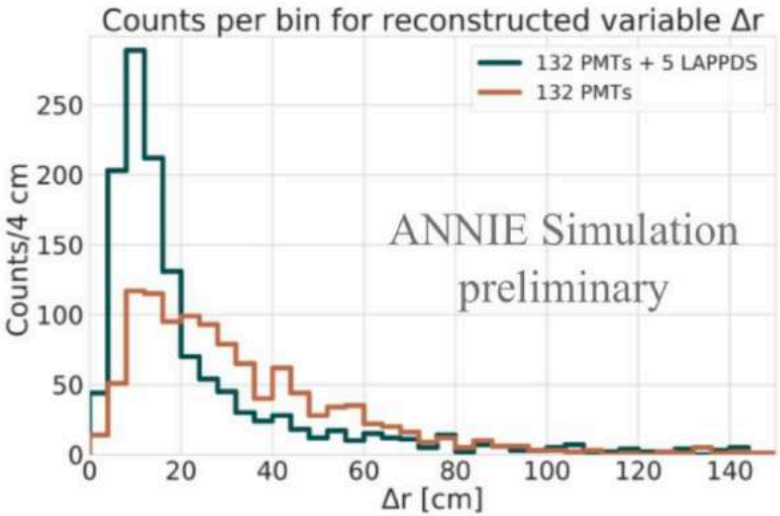
LAPPD-based Reconstruction



LAPPD



- **Technological goal**: Large Area Picosecond PhotoDetector (LAPPD)
- I am leading the fast-timing-based vertex reconstruction in ANNIE
- Adding five LAPPDs can improve the vertex resolution by a factor of two.
- Phase-I completed. Phase-II started

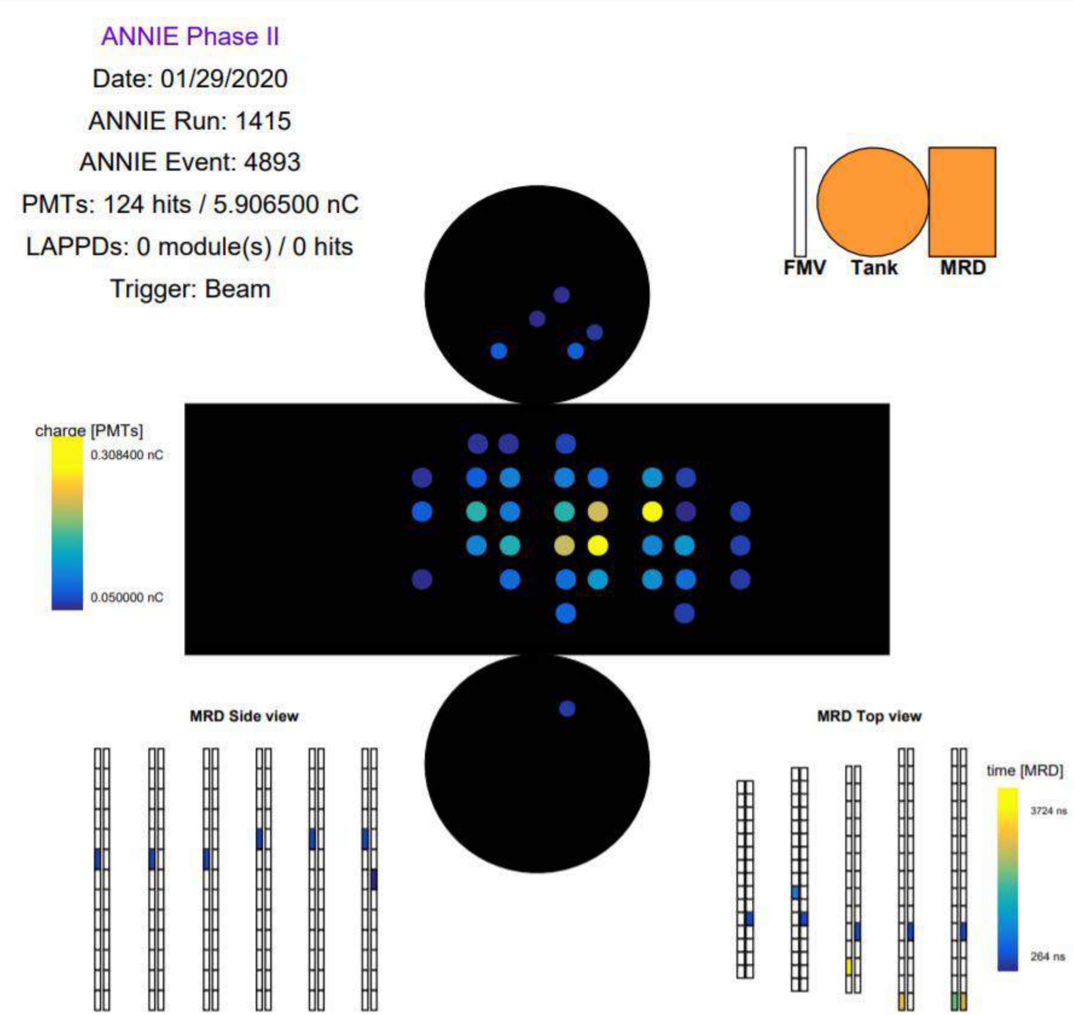


ANNIE is Taking Phase-II Physics Data!

- **First neutrino candidates**
  - Clear Cherenkov ring in the tank.
  - Well defined track in both MRD views.

- We will keep taking Phase-II neutrino data for more than a year.

- ANNIE will become the testbed of **Water-based Liquid Scintillator (WbLS)** technology that could be selected to build the 4th module of DUNE far detector



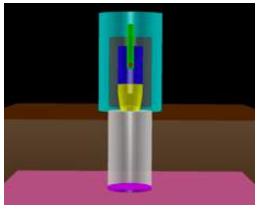
ANNIE Work Last Week

AmBe source deployment into ANNIE tank

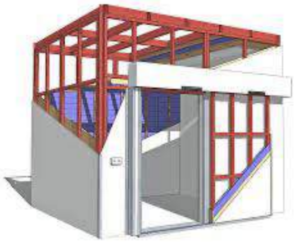
My Timeline in Next Two Years

DD generator
test at CERN

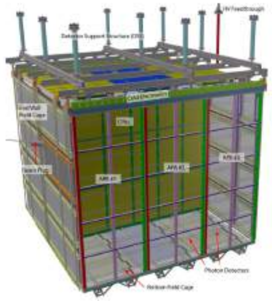
Build a PNS prototype



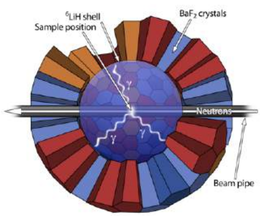
Build a Neutron lab



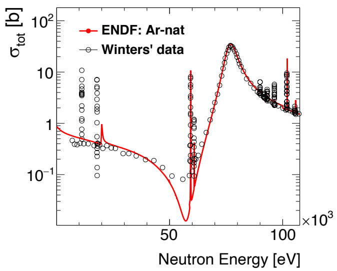
Test at ProtoDUNE Run-2



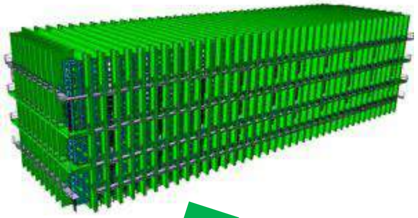
ACED



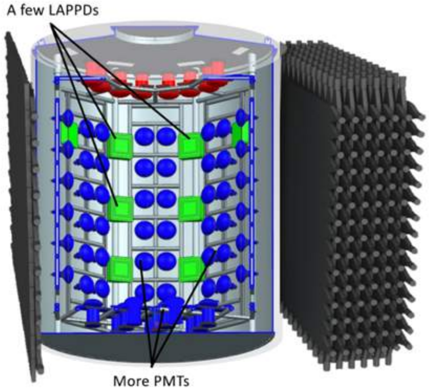
ARTIE



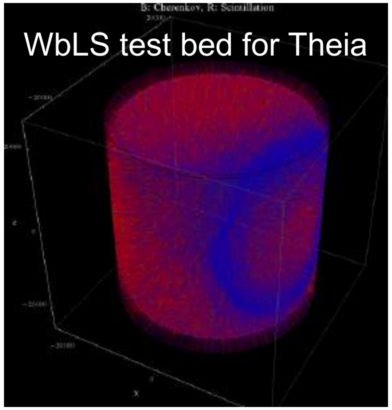
PNS production



ANNIE Phase-II



ANNIE Phase-III?



DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Neutrino Open Questions

Mass ordering? Normal or inverted?

Lepton CP violation? What is δ_{CP}?

More than three neutrinos? “Sterile” neutrinos?

Matter-antimatter asymmetry? Leptogenesis? B-L conserved?

Origin of the neutrino mass? Higgs or Seesaw?

Majorana or Dirac? Neutrino is its own antiparticle?

Neutrino Open Questions

Lepton CP violation? What is δ_{CP}?

Mass ordering? Normal or inverted?

More than three neutrinos? “Sterile” neutrinos?

Matter-antimatter

Majorana or Dirac?

The history of neutrino research has been full of surprises. What’s the next surprise waiting for us?


Thanks for your attention!
BROOKHAVEN
NATIONAL LABORATORY