Entering an Era of Precision Neutrino Physics

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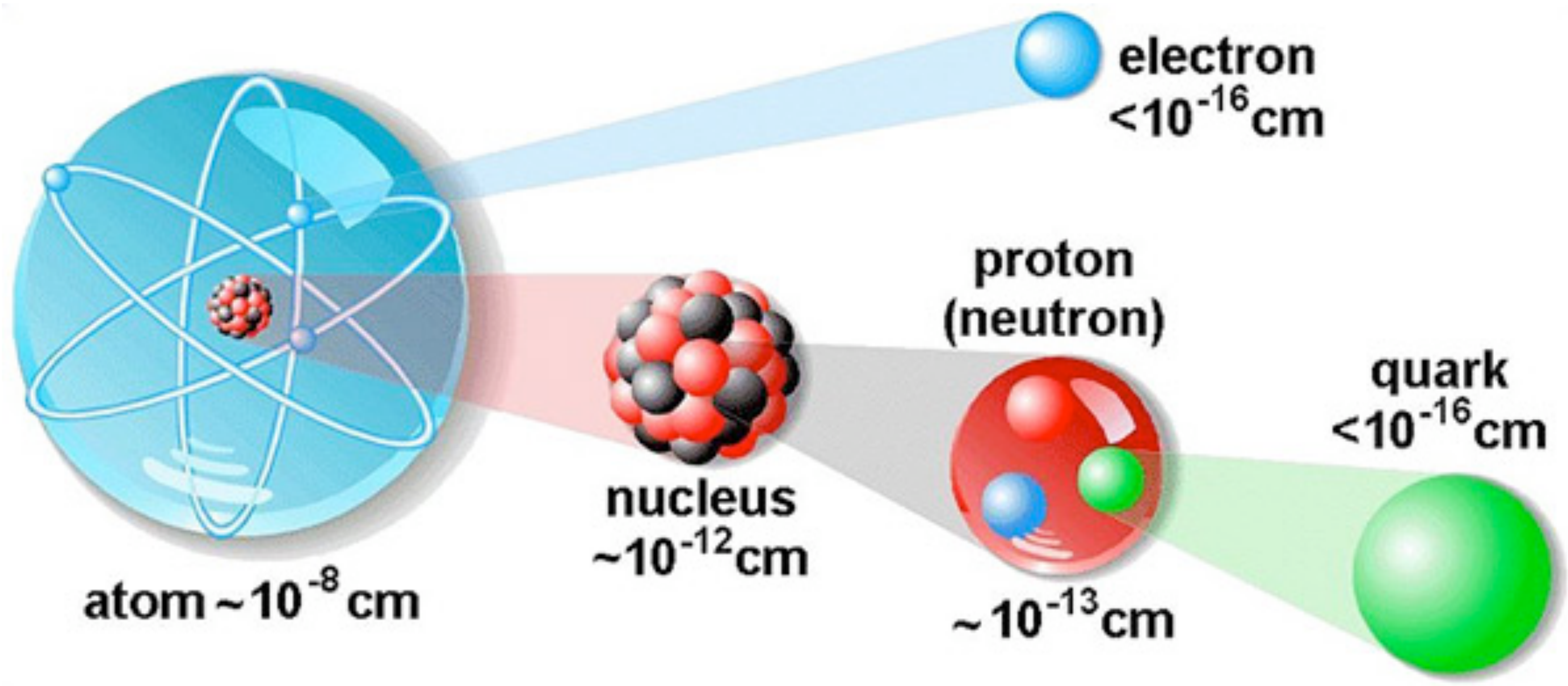
Outline

- Introduction to Neutrinos
  - How to Study Neutrinos
    - Precision Detectors for Neutrino Physics
      - Future Explorations

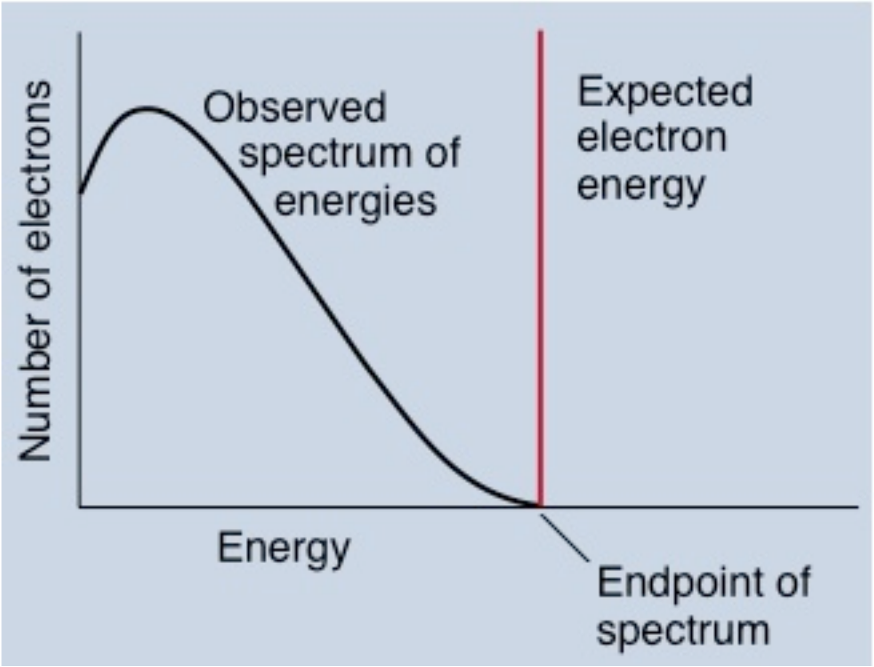
Particle Physics

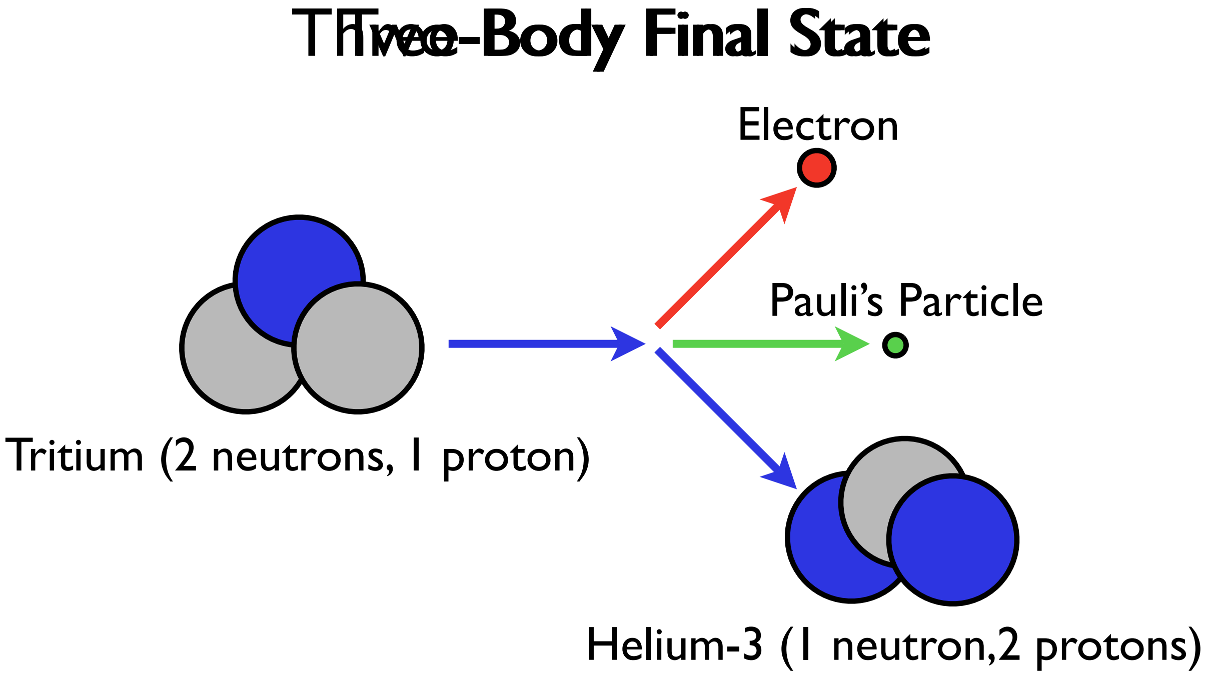
- Particle Physicists study the most fundamental constituents of the universe.
- These objects that are vanishingly small, but have big implications for the way our universe behaves.
- Today I'll be focusing on the smallest of the small...neutrinos.



Beta Decay

- Beta decay is a process in which an atom can increase its atomic number by 1
- In the early 1900s, Beta decay was producing some puzzling results.
- Beta particles (i.e. - energetic Electrons) should have been produced with a specific kinetic energy...but were observed to have a range of kinetic energies.
- In 1930 Wolfgang Pauli postulated there must be also be a very small neutral particle involved in Beta decay to explain the unexpected spectrum and maintain Conservation of Energy.
    - This neutral particle had to have a very small mass to allow the occasional decay where the electron ended up with most of the available kinetic energy.





Pauli's Desperate Remedy

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant…

Now called **neutrinos**

"I have done a terrible thing. I have postulated a particle that cannot be detected."

Photo: AIP, Emilio Segrè Visual Archives

26 years later...Neutrinos Detected!

(anti)Neutrinos first detected experimentally in 1956 by Cowan and Reines

- They placed two tanks (~200 liters total) of water next to a nuclear reactor, and surrounded the water with detectors that could observe photons.
- By looking for a unique signature of coincident+delayed photons, they could count the rate of neutrinos.
- By turning the nuclear reactor off, they confirmed that the neutrino rate diminished.

$$\overline{\nu_e} + \mathrm{p}^+ \rightarrow \mathrm{n} + e^+$$

$$e^+ + e^- \rightarrow \gamma + \gamma$$

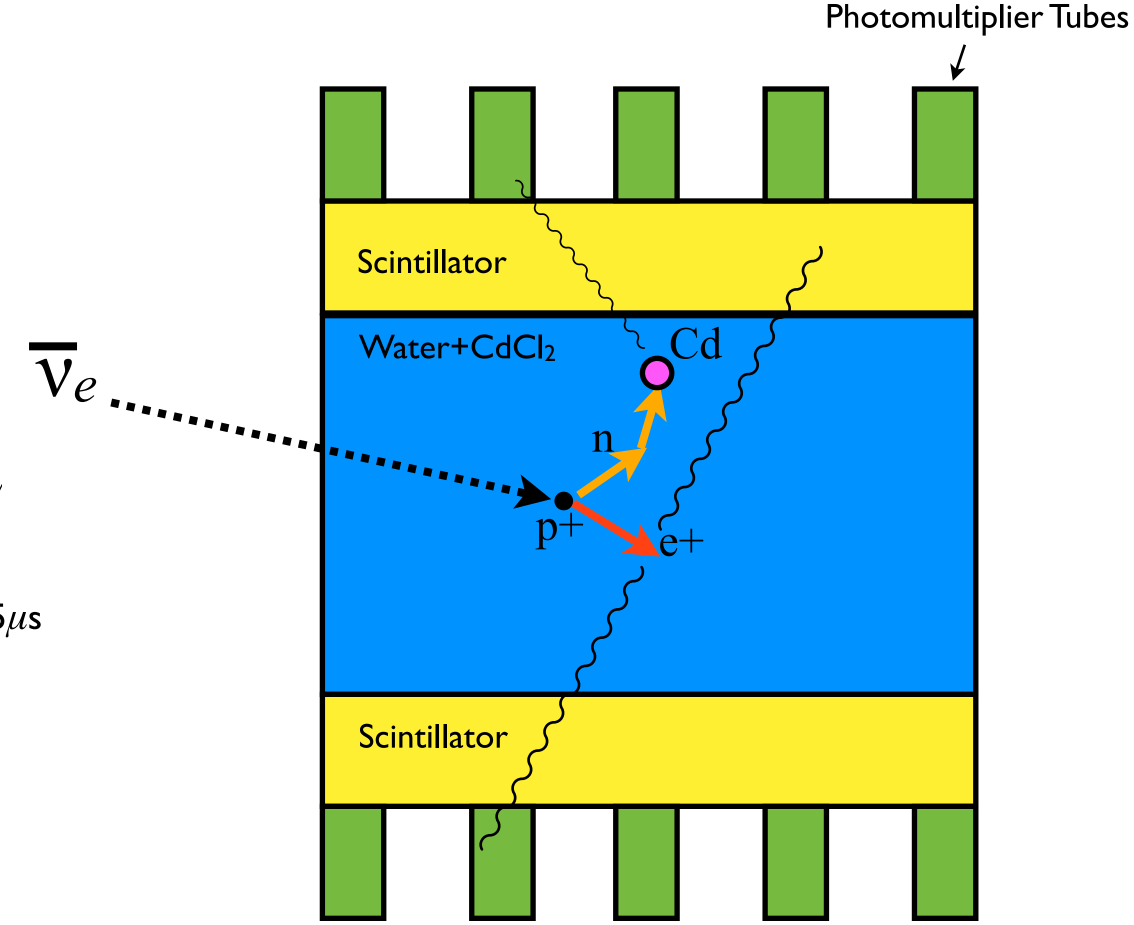
$$\mathrm{n} + {}^{108}\mathrm{Cd} \rightarrow {}^{109}\mathrm{Cd}^* \rightarrow {}^{109}\mathrm{Cd} + \gamma$$

From nearby nuclear reactor

Delayed by ~5μs

"Thanks for message. Everything comes to him who knows how to wait."

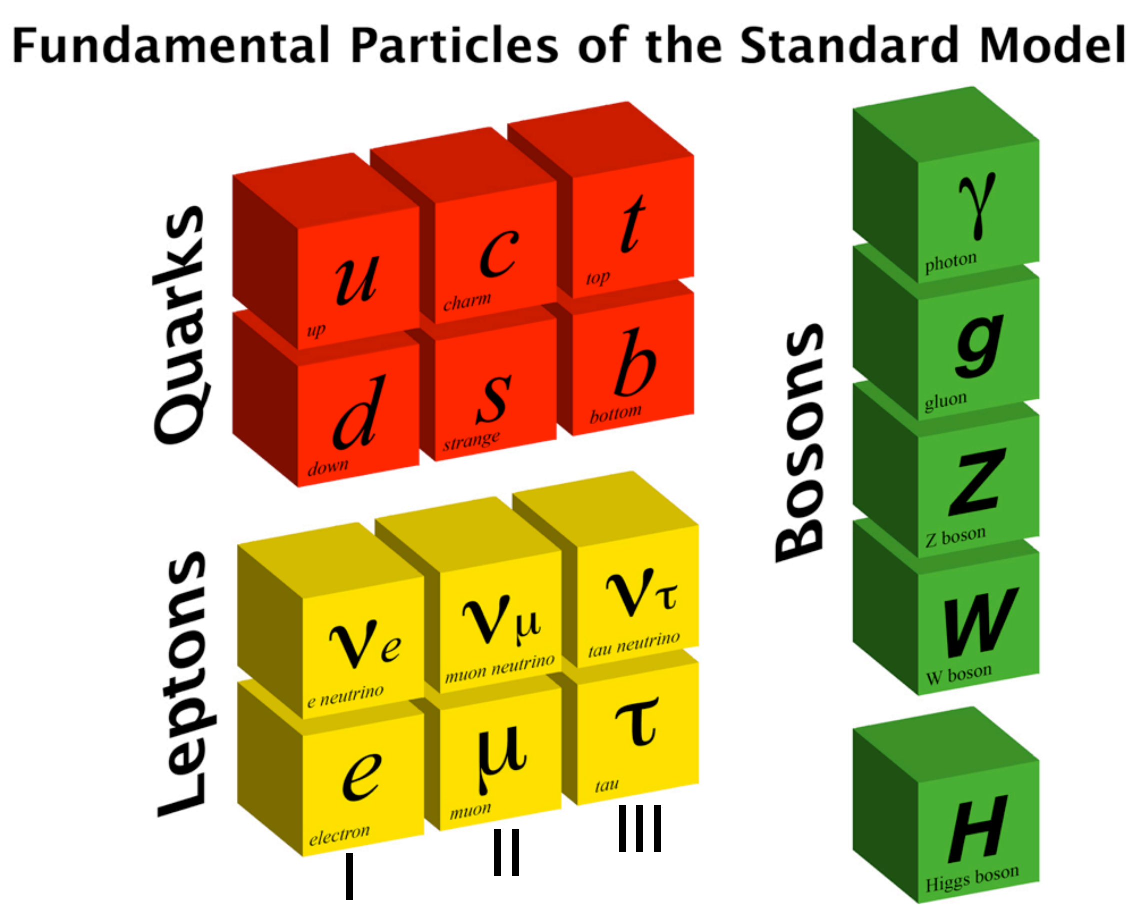
- Pauli, upon receiving news of neutrino discovery.



Water target, doped with $CdCl_2$, surrounded by scintillation detectors.

Neutrinos in the Modern Era

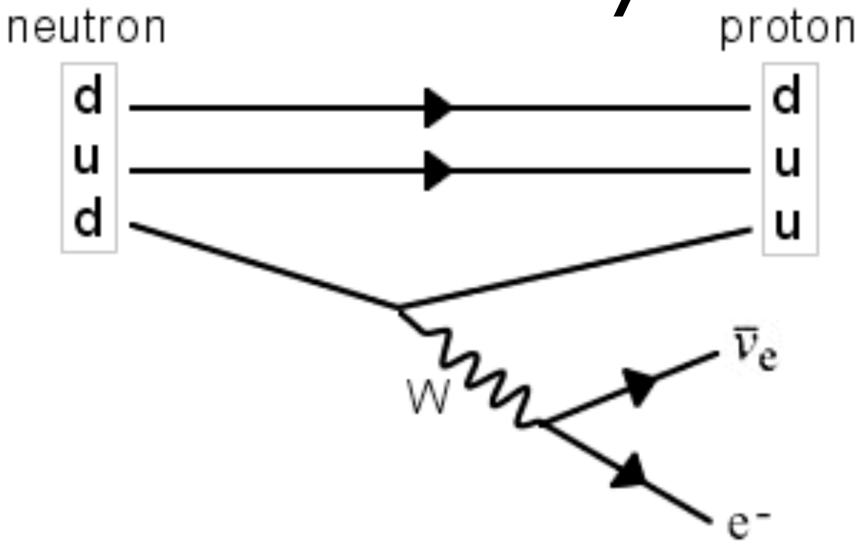
- We have a very successful theory of particle physics called the Standard Model.
- Explains interactions of "matter particles" (a.k.a. - Leptons and Quarks) and "Force Carrier particles" (a.k.a. - Bosons).
- In this model Neutrinos are neutral **massless** leptons that only interact via the Weak force.
- Three generations (or flavors) of particles with similar properties...so three flavors of neutrino.



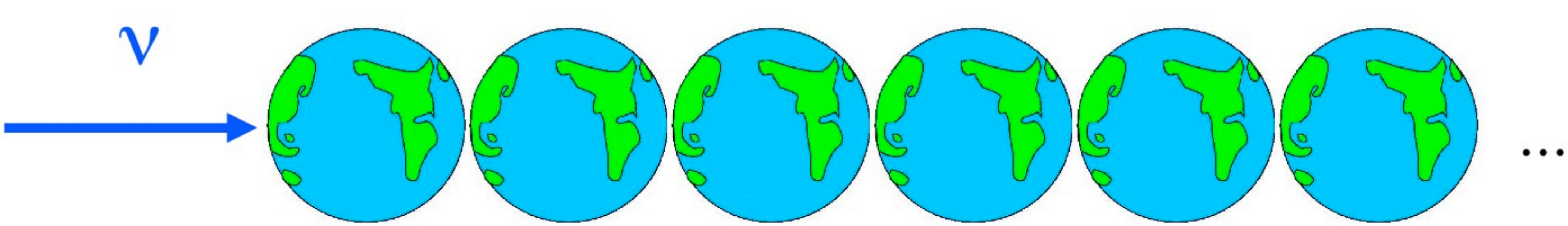
The Weak Force

- The Weak force is conveyed by W and Z bosons.
  - Beta Decay is an example of a process caused by the Weak force.
- "Charged-Current" Weak interactions (W-boson mediated) connect a neutrino of a given flavor to its charged lepton partner.
- Neutrinos are *almost* transparent to matter, able to pass through ~200 earths worth of matter before interacting.

Beta Decay



Weak force is 10^{-11} the strength of the electromagnetic force



A Neutrino Mystery

In the late 1960s the number of neutrinos from the Sun was measured by Ray Davis (in the Homestake Mine*) to be ~2/3 lower than predicted.

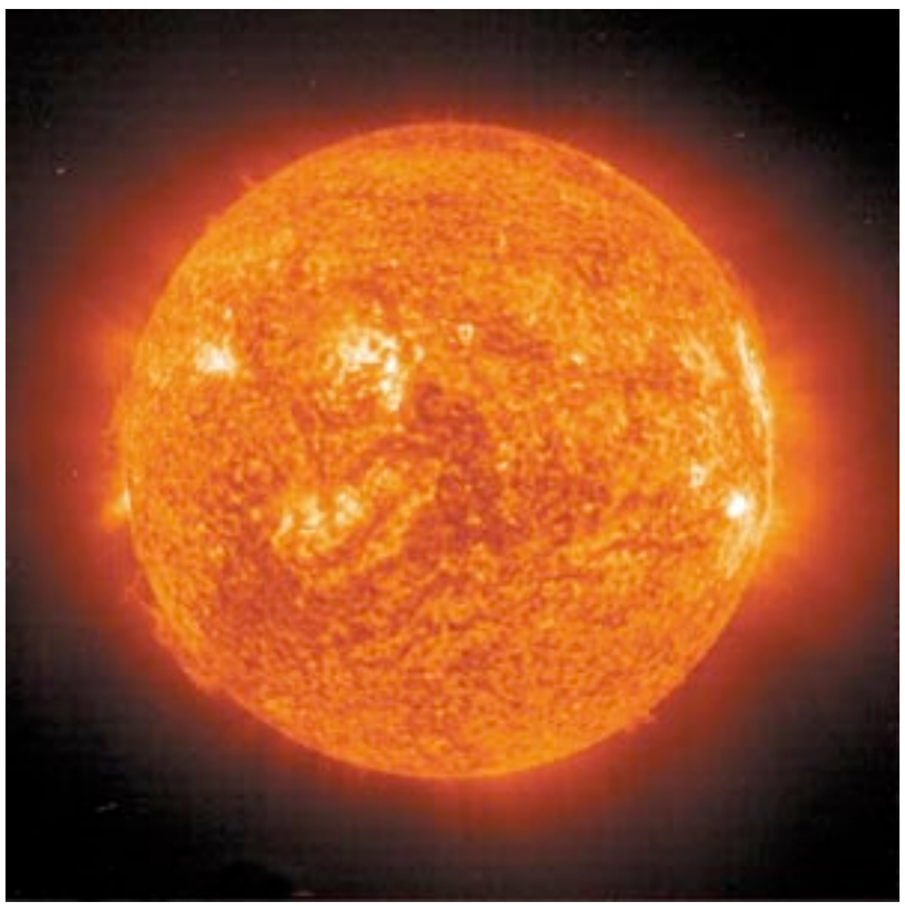
- This experiment was located ~4800 feet underground so that only neutrinos could penetrate down through the rock
- This deficit of neutrinos was referred to as the "Solar Neutrino Problem"

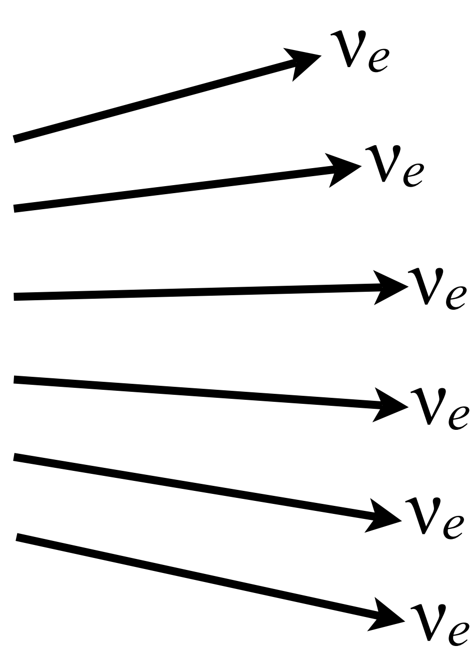
From the Sun

Half-life of 35 days.

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$$

~65,000,000,000 neutrinos from the Sun stream through every square centimeter on the Earth every second!





$$\mathrm{p}^+ + \mathrm{p}^+ \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$$

Solar Fusion

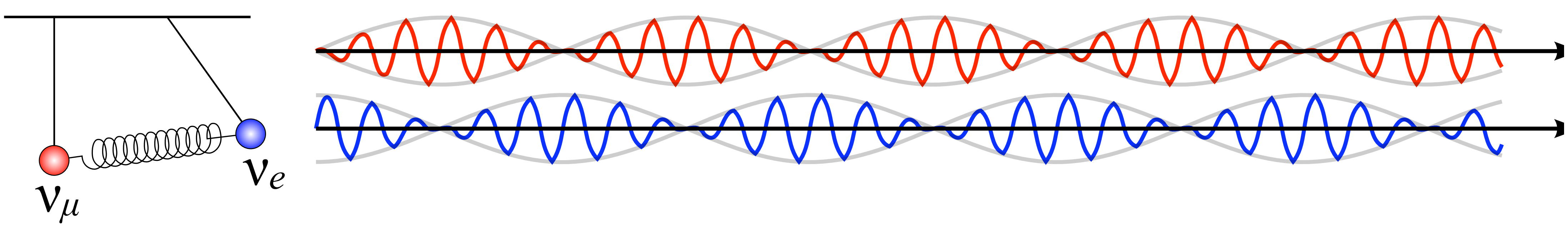
*Remember for later

~600 tons of C_2Cl_4

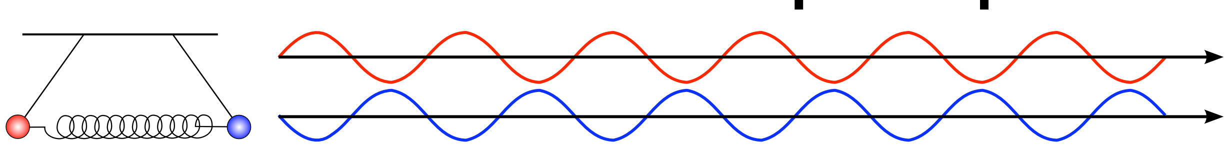
Where Do The Missing Neutrinos Go?

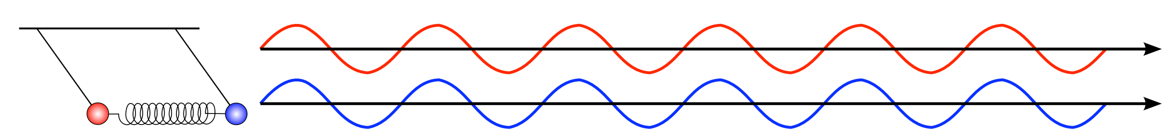
- What if the neutrinos aren't really missing, but rather changing their identity before they get detected?
- Suppose neutrino flavor eigenstates (i.e. - the states that participate in the Weak interaction), travel as superpositions of mass eigenstates.
- Over time/distance the underlying mass states come in/out of phase with one another, producing a change in the flavor state.

Consider the neutrino as a coupled-pendulum system:



The neutrino mass states are like the "normal modes" that underly the motion of the coupled pendulum.





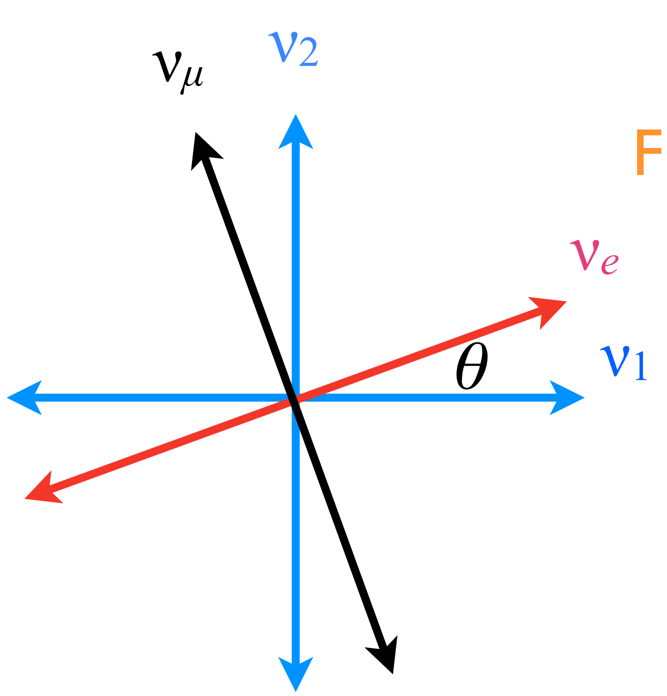
Neutrino Oscillations

- In modern Quantum Mechanics description the relation between flavor and mass states is parameterized by a mixing matrix, U.
- Probability for a neutrino to oscillate flavors is dependent on:
  - The length (L) over which the neutrino travels before detection.
  - The energy (E) of the neutrino
  - The square of the mass-splitting (Δm^2) between neutrino mass states.
  - Some parameterization of how the mass/flavor states are related (θ)
- A neutrino that's initially 100% muon neutrino can evolve into an electron neutrino!

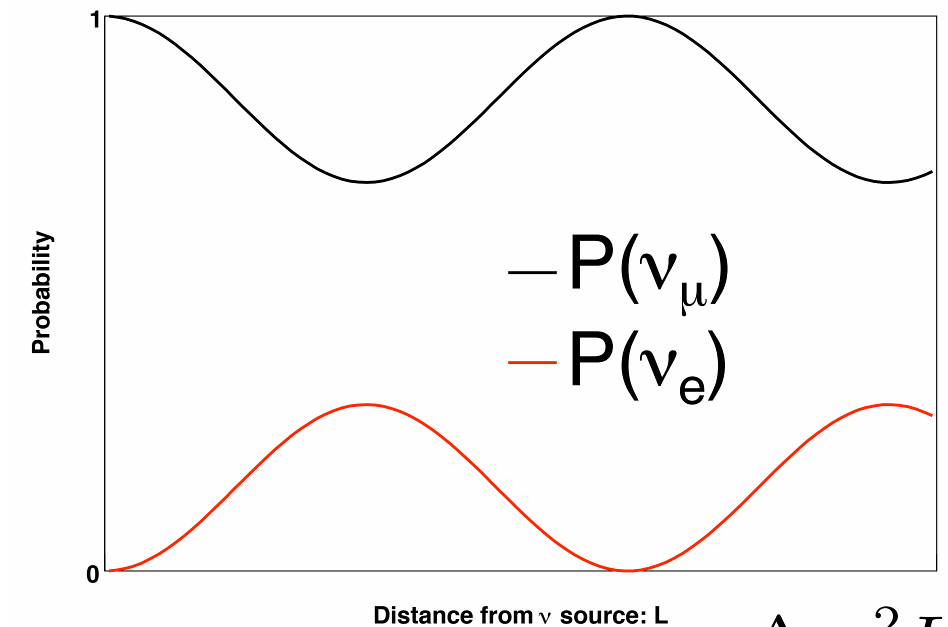
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Flavor state

Mass state



Simplified 2-neutrino oscillations in vacuum



$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

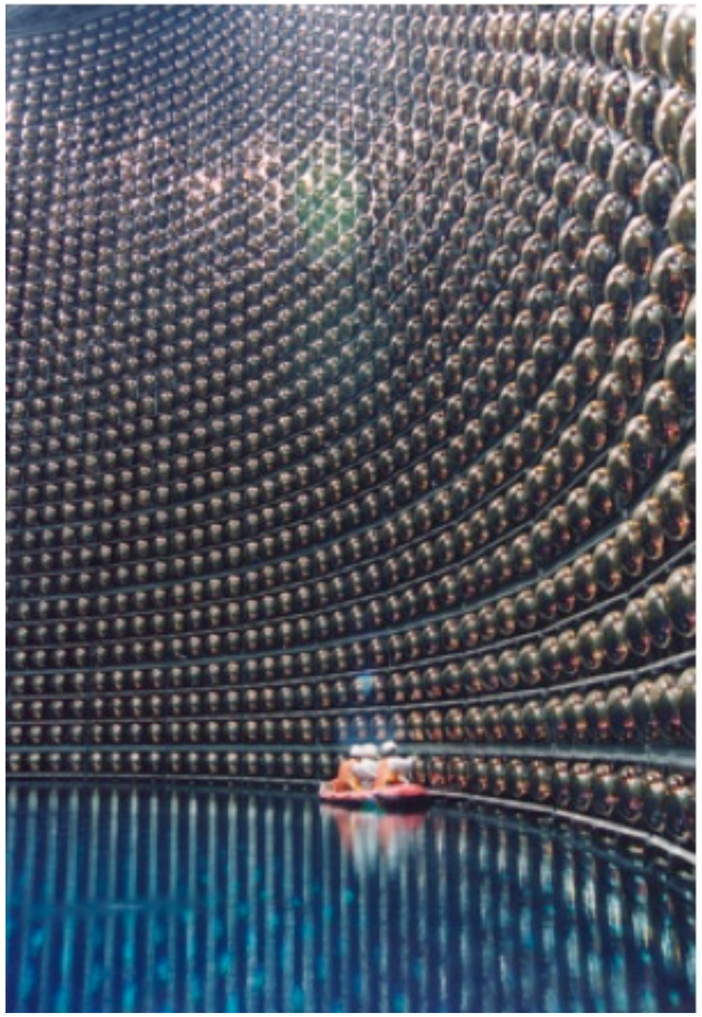
$$\mathrm{P}_{osc} = \sin^2(2\theta)\sin^2(1.27\frac{\Delta m^2 L}{E})$$

Neutrino Oscillations

- Not just theoretical speculation...flavor oscillations really happen!
- June 1998: Super Kamiokande experiment in Japan confirms neutrino oscillations using neutrinos from cosmic-rays entering the Earth's atmosphere.
    - **Oscillations imply that neutrinos must have nonzero masses.**
    - Oscillations also imply that Lepton flavor is not conserved.
    - Subsequent experiments confirm that Solar neutrino problem originates from neutrino oscillations.

"Just yesterday in Japan, physicists announced a discovery that tiny neutrinos have mass. Now, that may not mean much to most Americans, but it may change our most fundamental theories -- from the nature of the smallest subatomic particles to how the universe itself works, and indeed how it expands."
"The larger issue is that these kinds of findings have implications that are not limited to the laboratory. They affect the whole of society -- not only our economy, but our very view of life, our understanding of our relations with others, and our place in time."

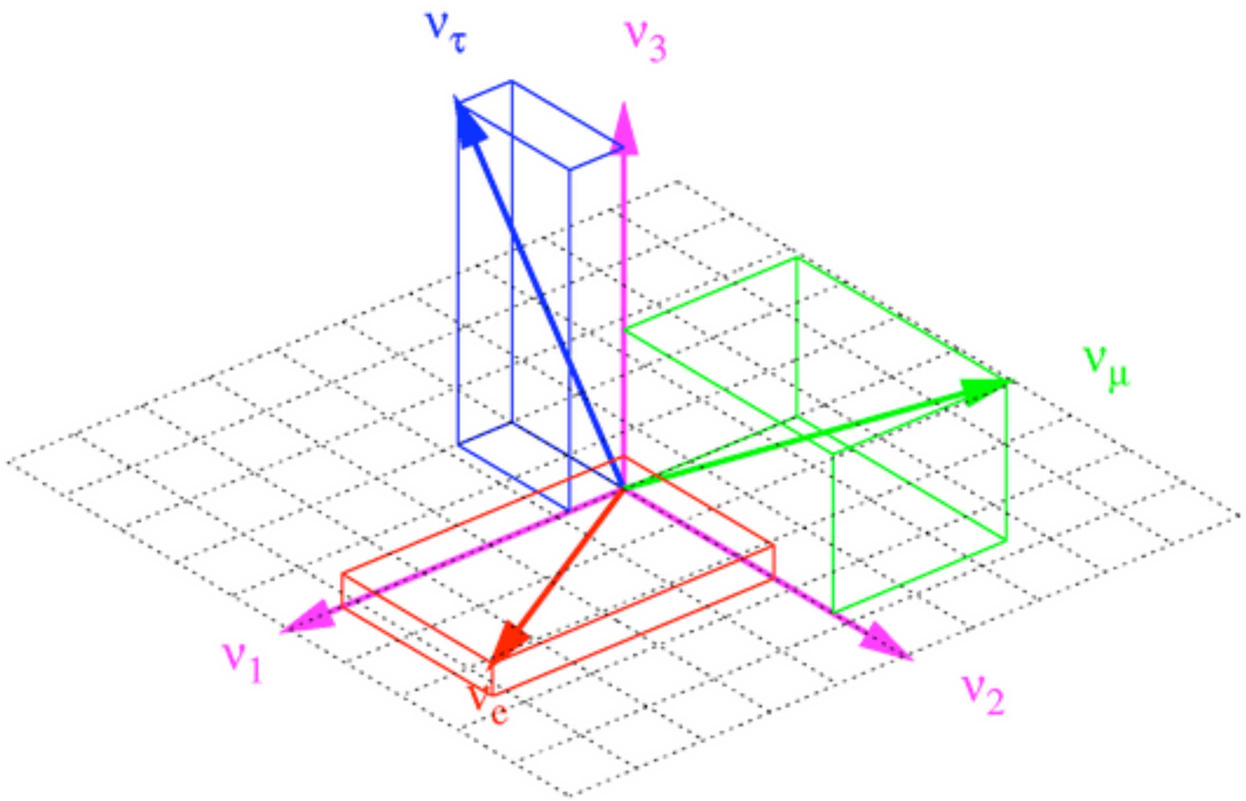
- President Clinton at MIT commencement



Super Kamiokande

Neutrino Oscillations

• We know there are three active flavors of neutrinos, so three corresponding mixing angles, and two independent mass splittings.



Three possible rotations when all neutrino flavors are included

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Mixing Matrix:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\ 0 & -\sin(\theta_{23}) & \cos(\theta_{23}) \end{pmatrix} \times \begin{pmatrix} \cos(\theta_{13}) & 0 & \sin(\theta_{13})e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin(\theta_{13})e^{i\delta} & 0 & \cos(\theta_{13}) \end{pmatrix} \times \begin{pmatrix} \cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\ -\sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrino Oscillations

- Most mixing angles and mass splittings have been measured.
- Neutrino Mixing angles are quite large.
- $\Sigma m < 1 eV$ (total mass of 3 flavors of neutrino)

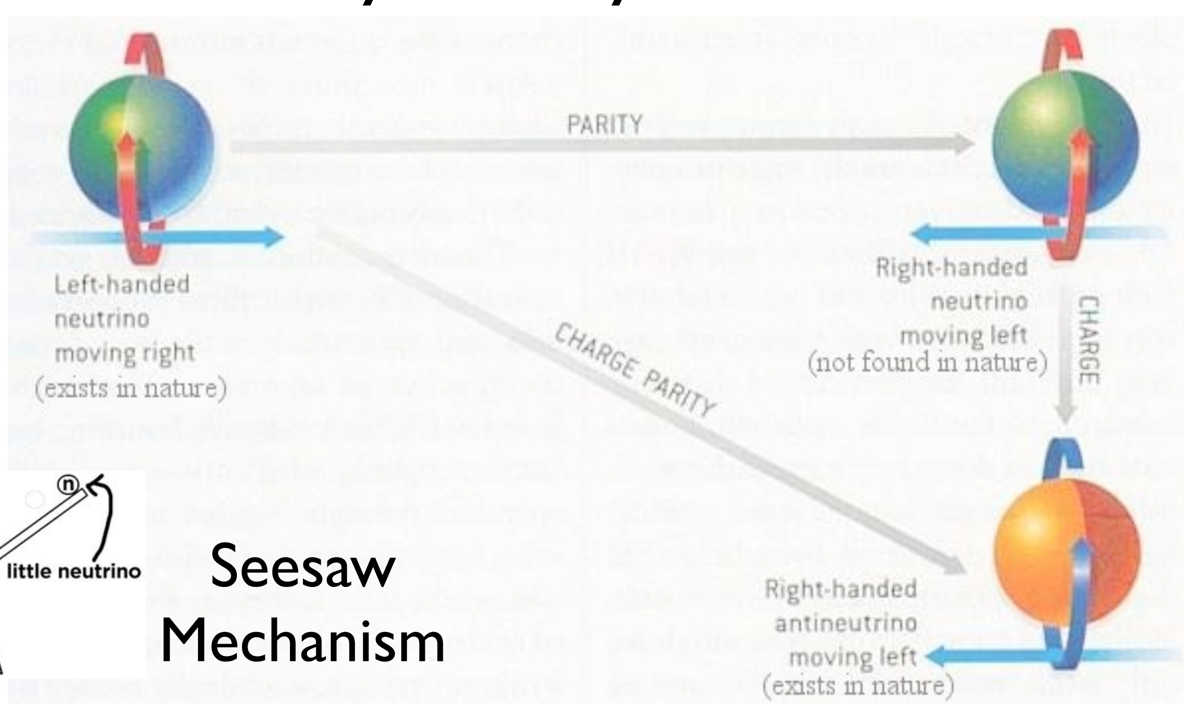
Very small
...unmeasured so far →

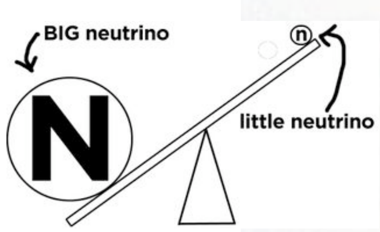
Δm_{21}^2	8×10^{-5} eV^2
Δm_{32}^2	2.4×10^{-3} eV^2
θ_{12}	~34°
θ_{23}	~37°
θ_{13}	$\sin^2(2\theta_{13}) < 0.19$
δ_{CP}	CP Violation?

GeV/c^2 is a typical unit of mass and energy (we let c=1):
1GeV= 1.8E-27 kg = mass of 1 proton
0.5MeV= 9.1E-31 kg = mass of 1 electron

CP Violation?

- CP = Charge Parity transformation
- Violation of CP means a process is different for a particle and its antiparticle.
- "Leptogenesis"+"See-saw" - Postulates there are very heavy right-handed neutrinos (N) with masses near the GUT (10^{15} GeV) scale, produced in the Big Bang, that have a leptonic decay that violates CP.
- Creates an imbalance of charged-leptons, which gets converted into observed matter-antimatter asymmetry of the universe.
- If the heavy right-handed heavy neutrinos violate CP, it's possible their light left-handed partners might also.
- CP violation observed in the quark sector, but its not enough to account for the matter-antimatter asymmetry of our universe.

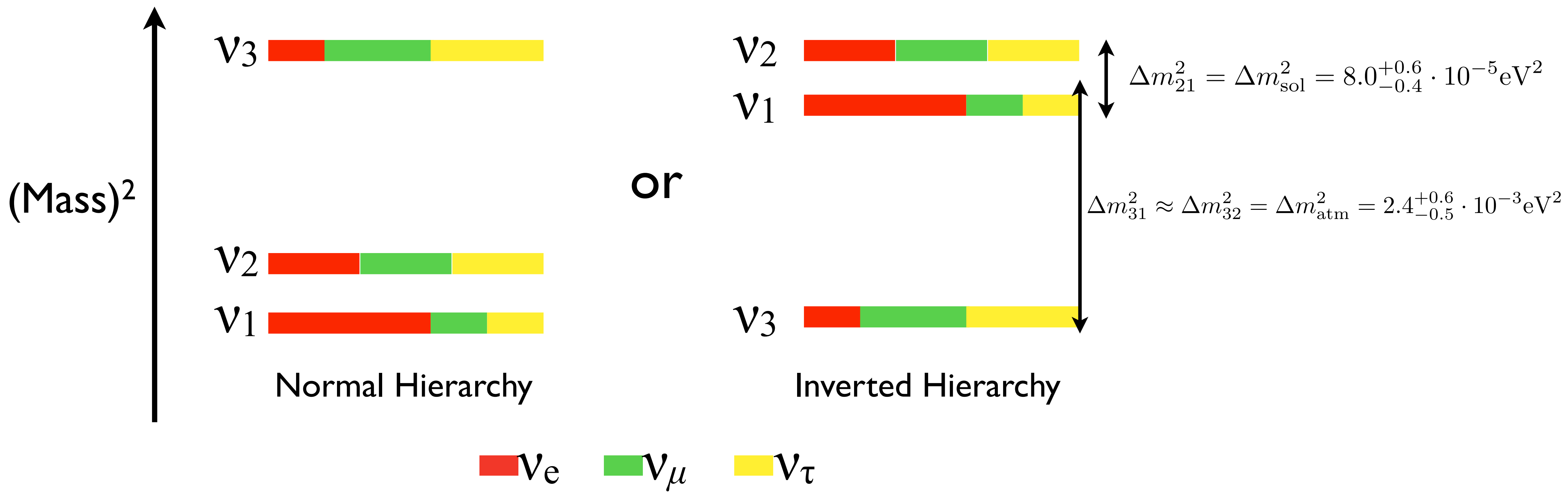




Seesaw Mechanism

Neutrino Physics Goals

- Observe $\nu_\mu \rightarrow \nu_e$ transitions, measure θ_{13}
- Measure the CP-violating phase, δ_{CP} (Could this explain matter/antimatter asymmetry of universe?)
- Determine Mass Hierarchy:



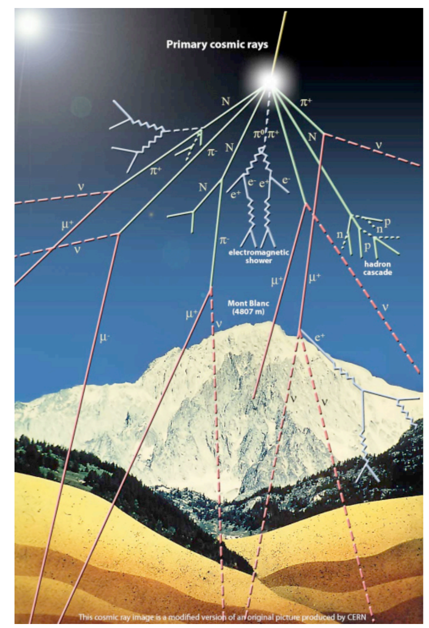
Intense neutrino beam and **massive** detector with good background rejection required for much of this physics....

How do we study neutrinos?

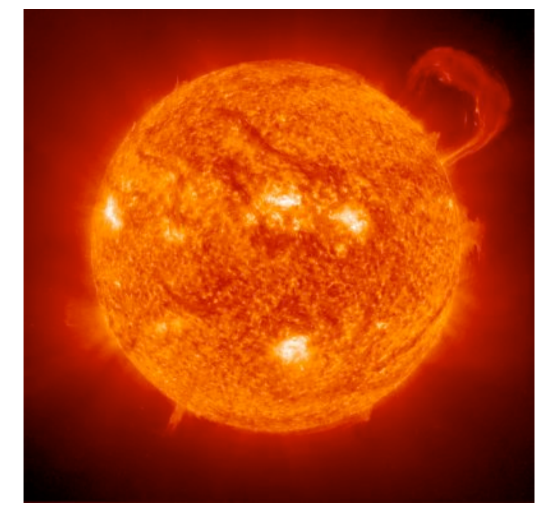
Studying Neutrinos

- To study neutrino oscillations we need:
  - A source (many different types available...intensity is important)
  - Big Detectors (to accumulate sizeable statistics)
  - Good understanding of signal vs. background

Nuclear Reactors

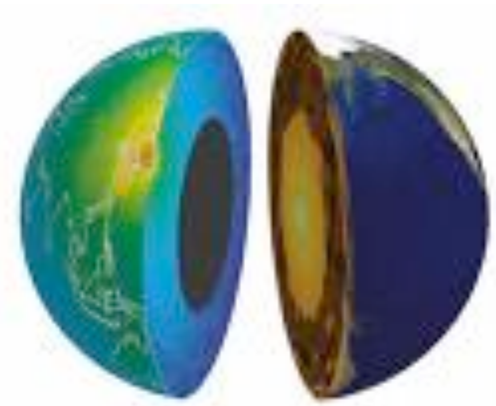


Cosmic Ray Showers

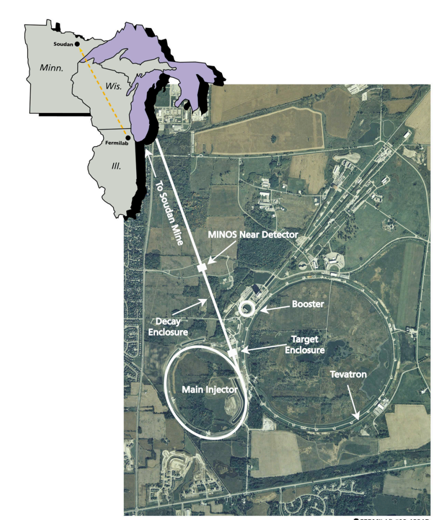


The Sun

Astrophysical (SuperNova/Big Bang)



The Earth (Radioactive Elements)



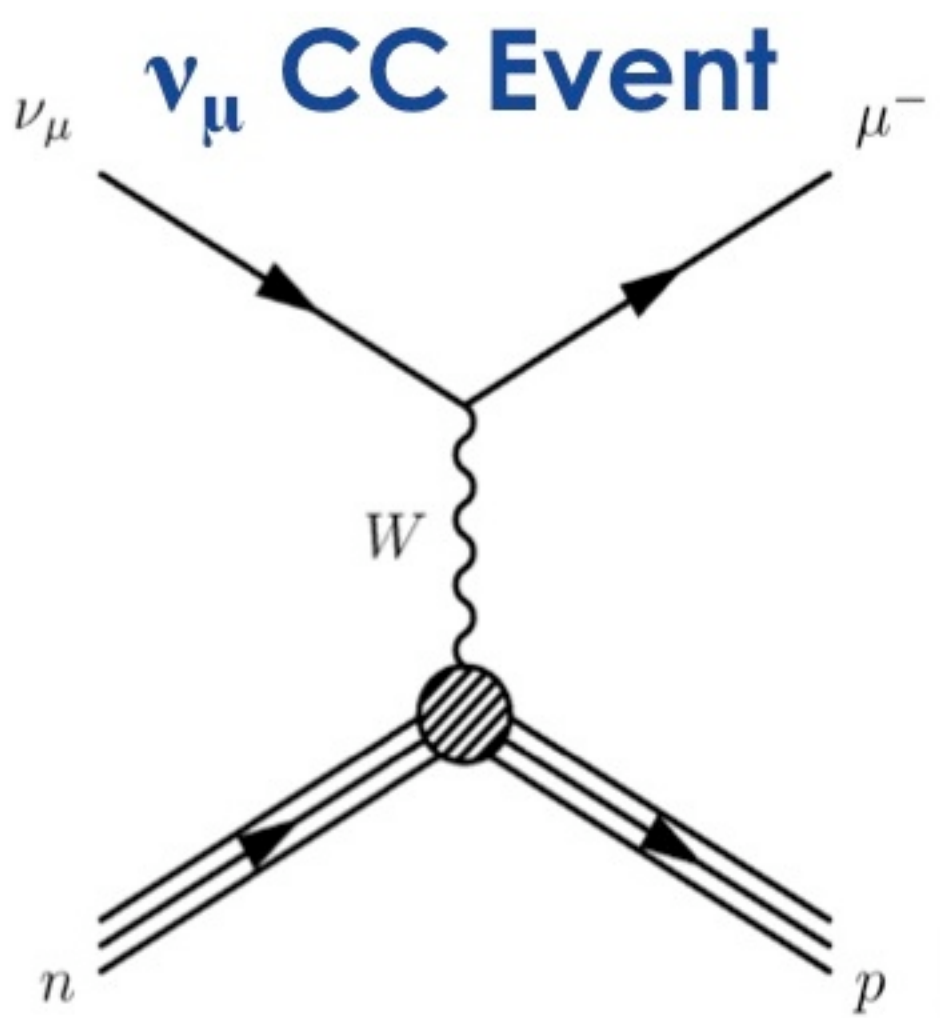
Accelerators

Neutrino Interactions I

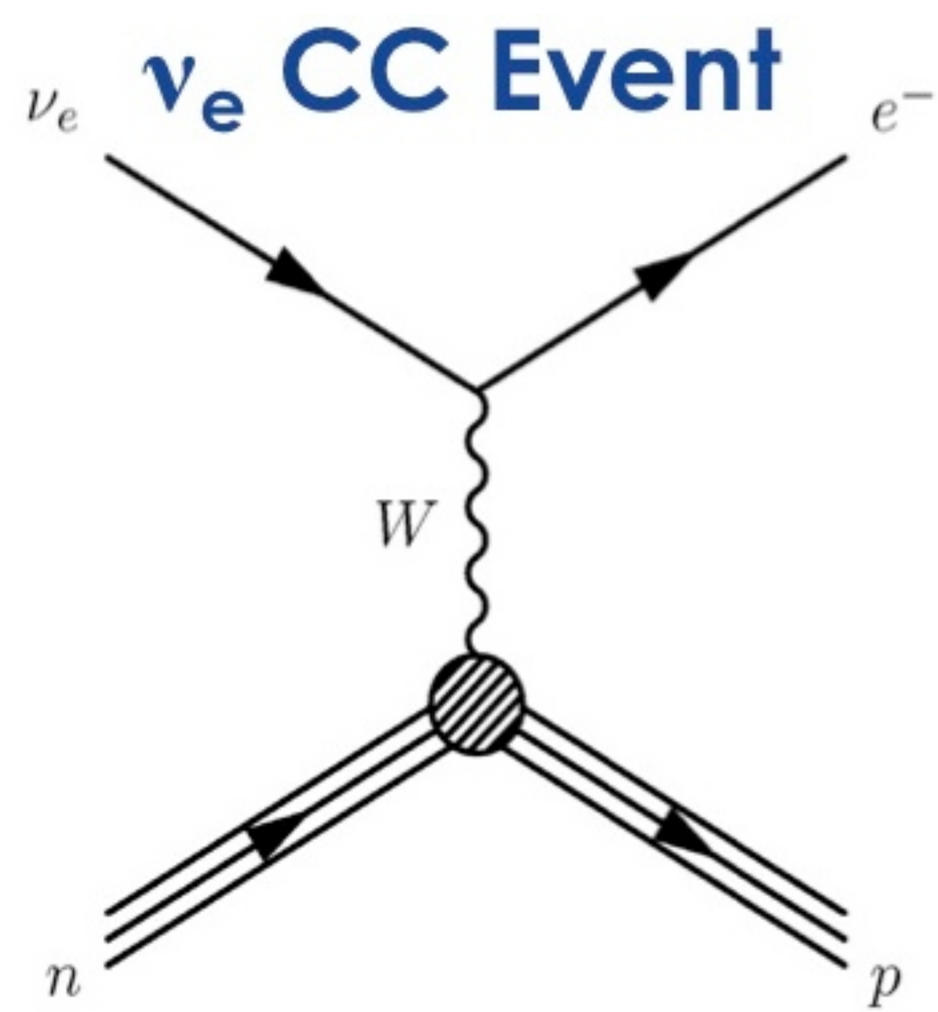
• Accelerator neutrino experiments look for oscillations by studying the data observed when a very pure beam of muon neutrinos is aimed at a far detector:

- "appearance" - Do we see an excess of electron neutrino events?
- "disappearance" - Do we see a deficit of muon neutrino events?

• Charged-Current interactions are the "signal" events that allow the neutrino flavor to be identified, via identification of the charged lepton flavor.



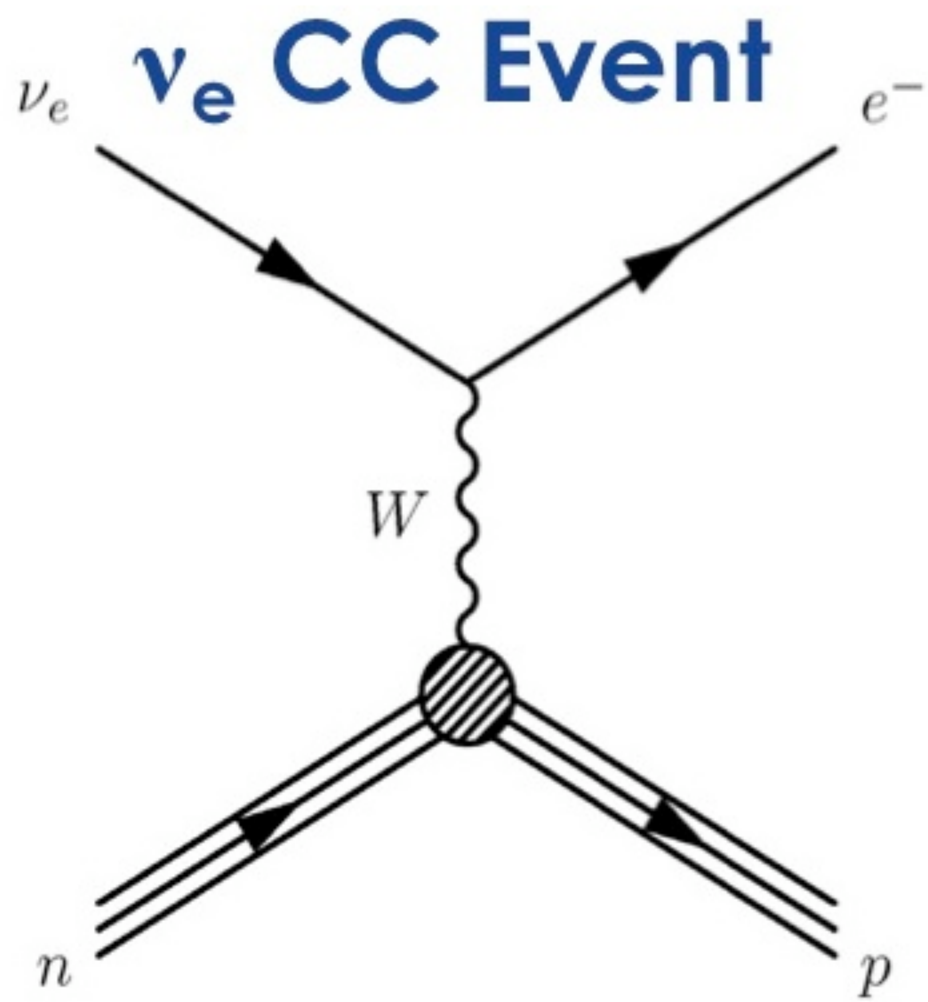
"disappearance" signal



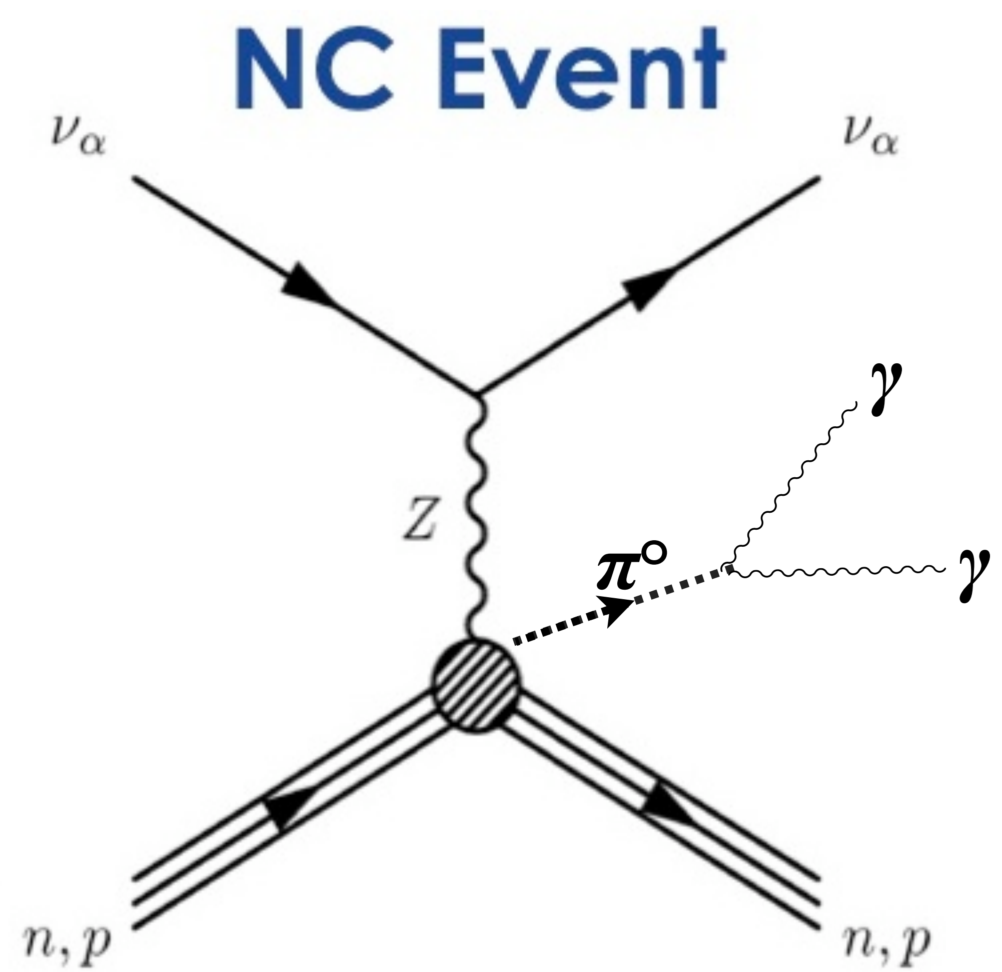
"appearance" signal

Neutrino Interactions II

- Background processes can confuse a measurement.
  - Like asking a color-blind person to count the numbered of red jelly beans in a jar of all colors.
- There are background processes in appearance and disappearance analyses.
  - Example: Neutral Current (NC π°) events where a π° is produced can fake CC ν_e if one of the gammas from the π° decay get misidentified as an electron.



“appearance” signal

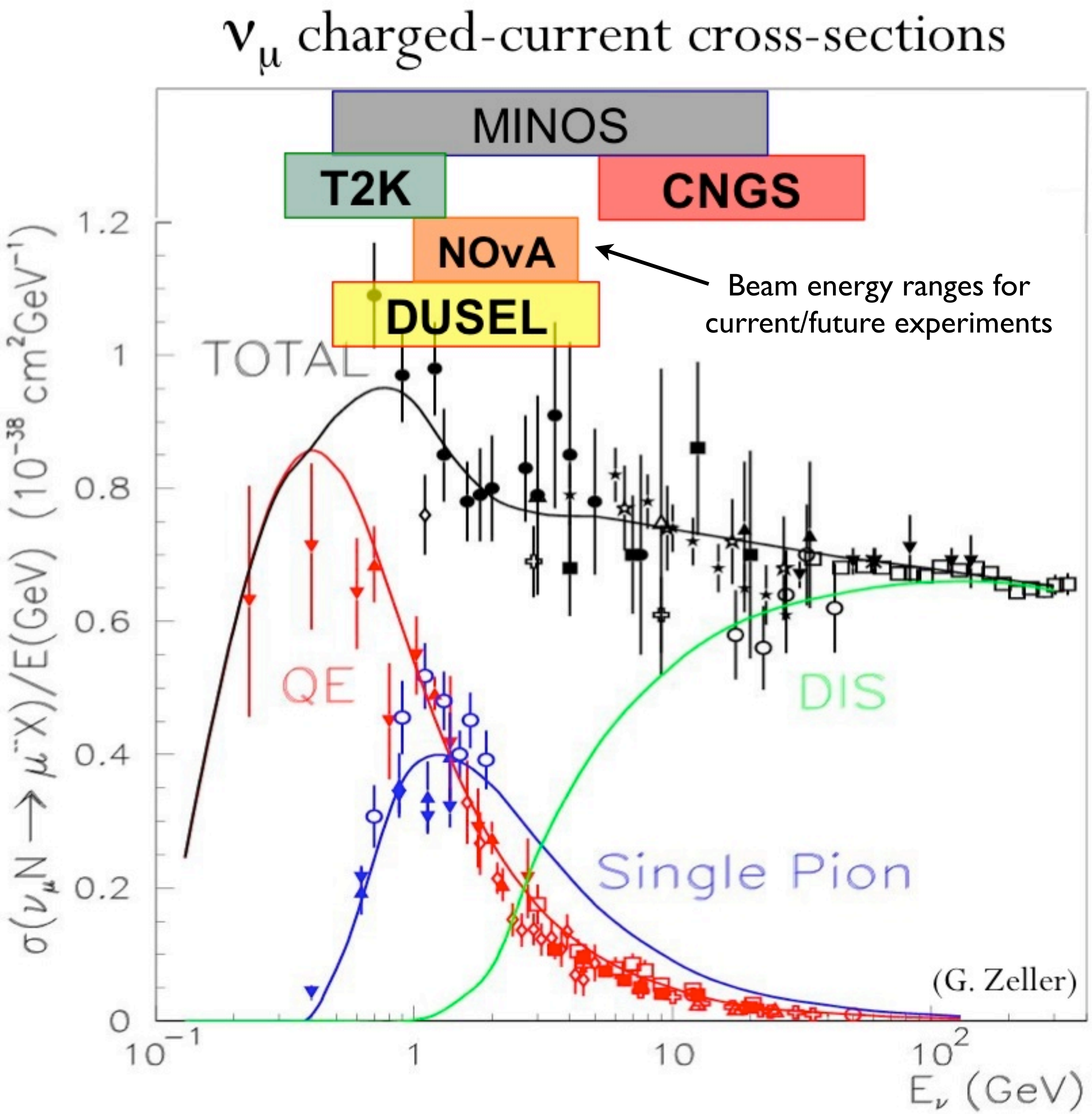


“appearance” background

Neutrino Interactions III

- Energy range of current/ future neutrino oscillation experiments is in the range where both signal and background processes are relevant.

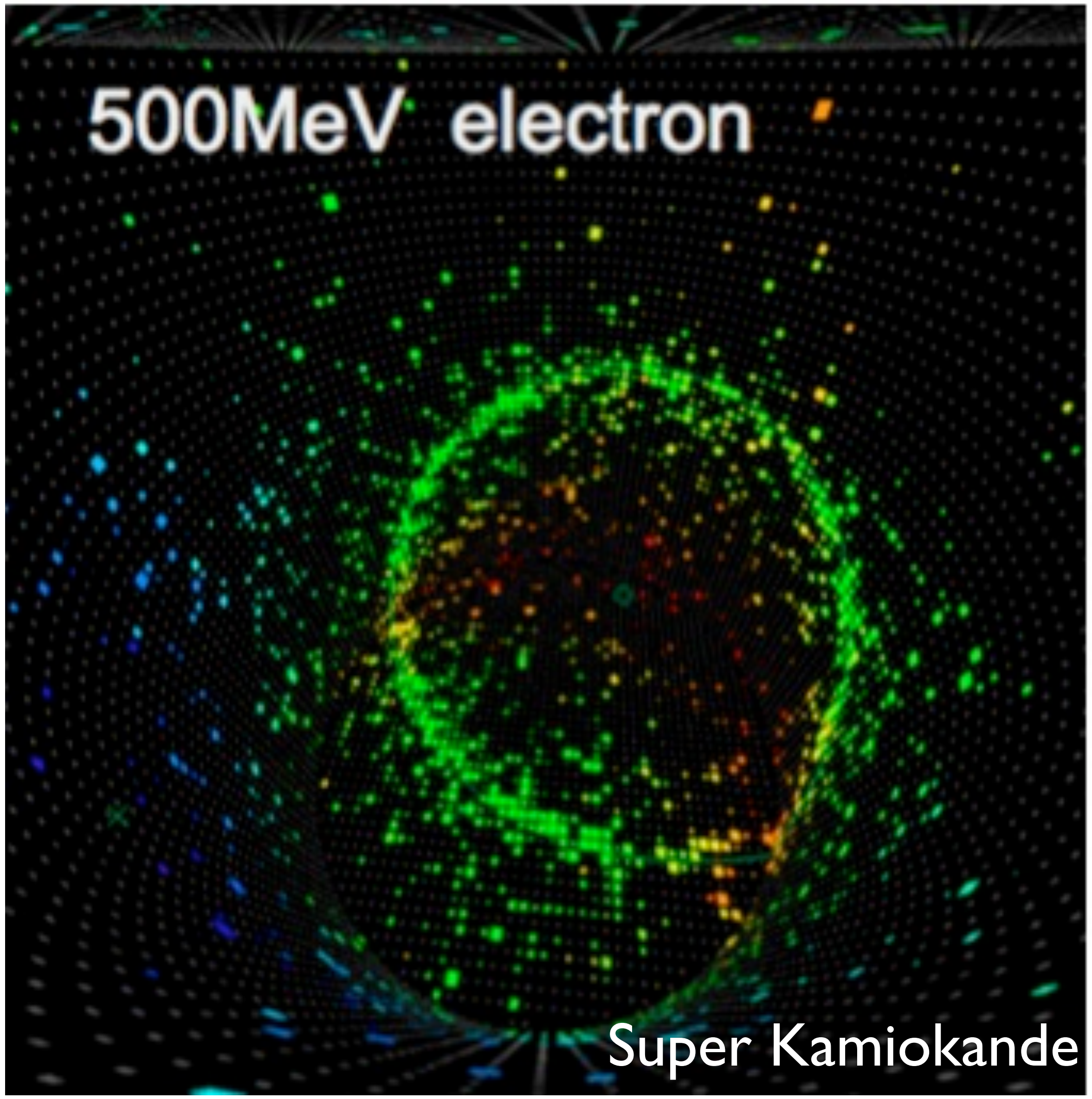
- Improving cross-section measurements and increasing background rejection would benefit future oscillation experiments.

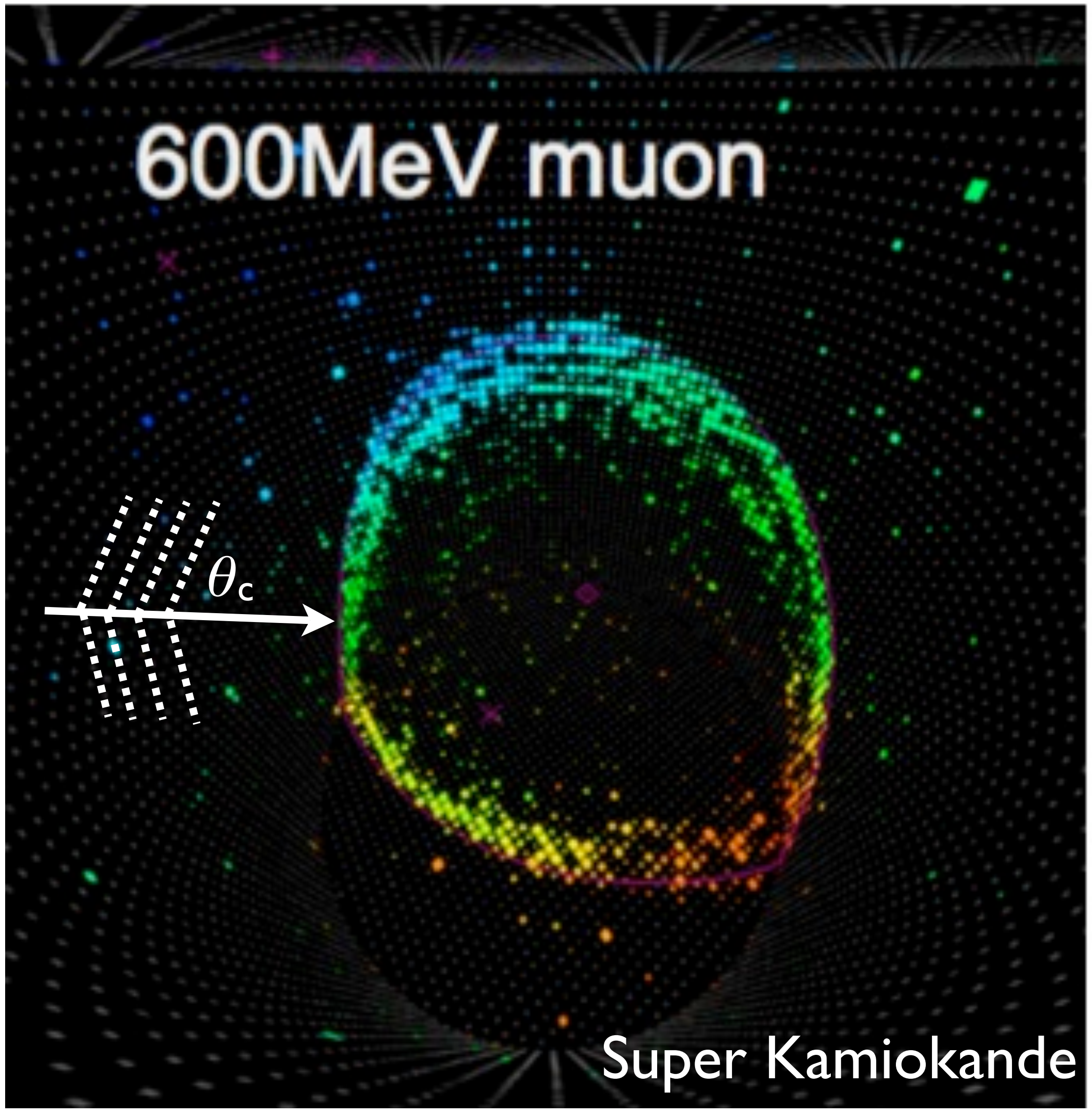


Neutrino Detectors

Cerenkov Detectors:

- Particles traversing medium faster than light emit Cerenkov light at a characteristic angle.
- Cerenkov light collected and produces signals on PhotoMultiplier Tubes (PMTs)
  - Muons: straight trajectories lead to crisp rings
  - Electrons: showering and multiple scattering produce fuzzy rings
  - π^os: decay into two gammas, which each appear as electron-like rings

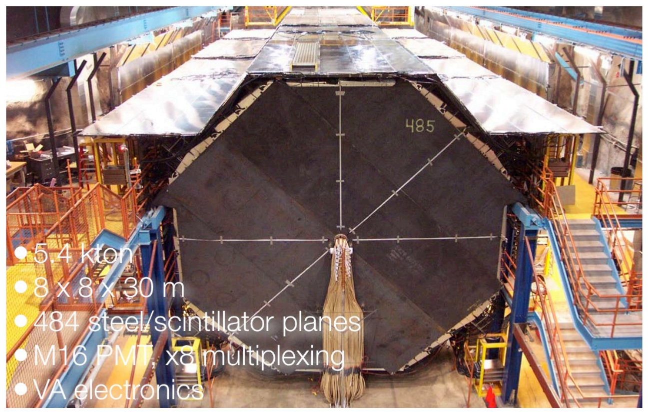




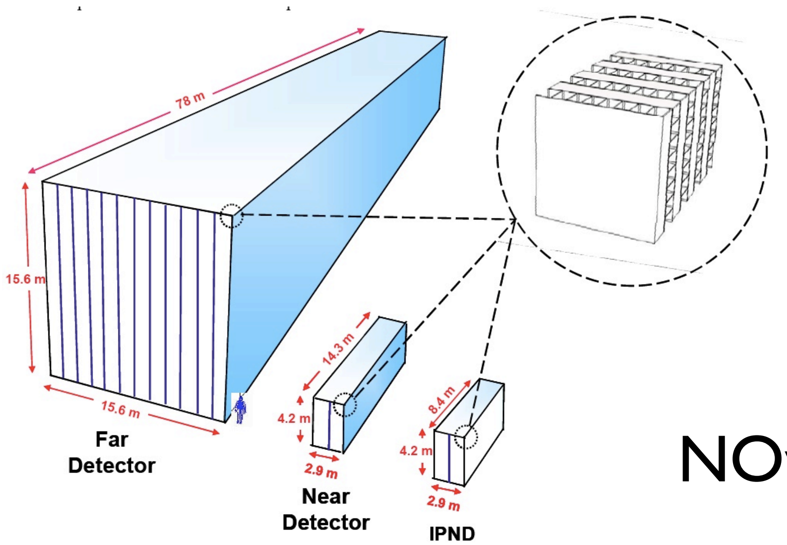
Neutrino Detectors

Tracking calorimeter detectors.

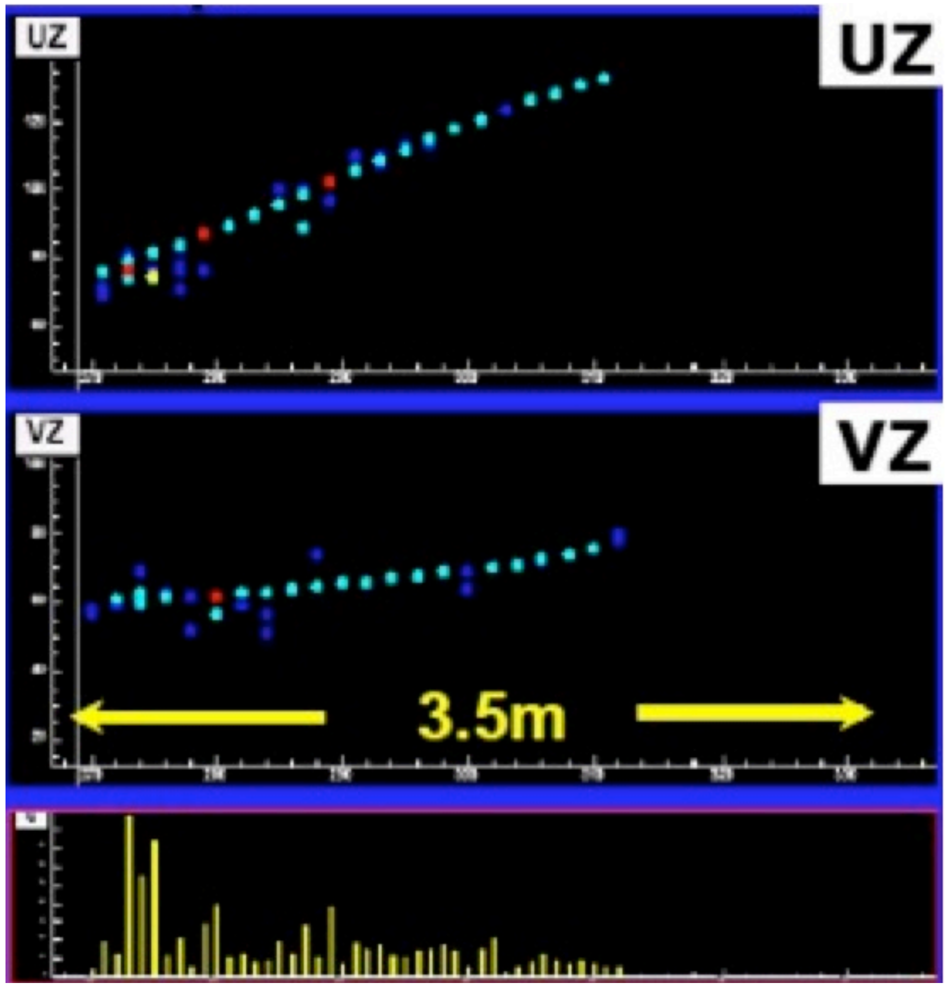
- Use scintillating strips distributed throughout detector that produce light when particles pass through.
- Collect scintillator light via fiber optic readout that connects to a PMT.
- Reconstruct event in 3D by merging information from alternate coordinate views.

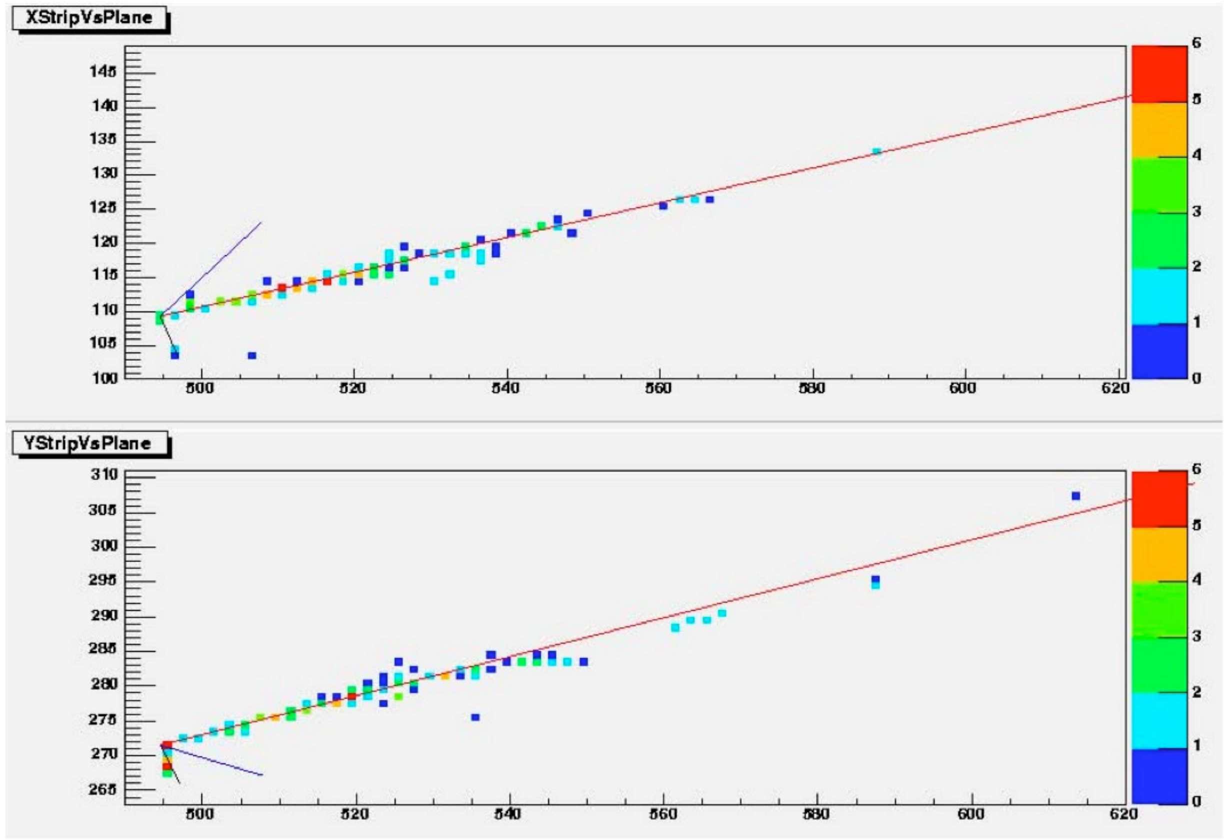


MINOS



NOvA





$\nu_e p \to e^- p \pi^+$

E_ν=2.5GeV

E_e=1.9GeV

E_p=1.1GeV

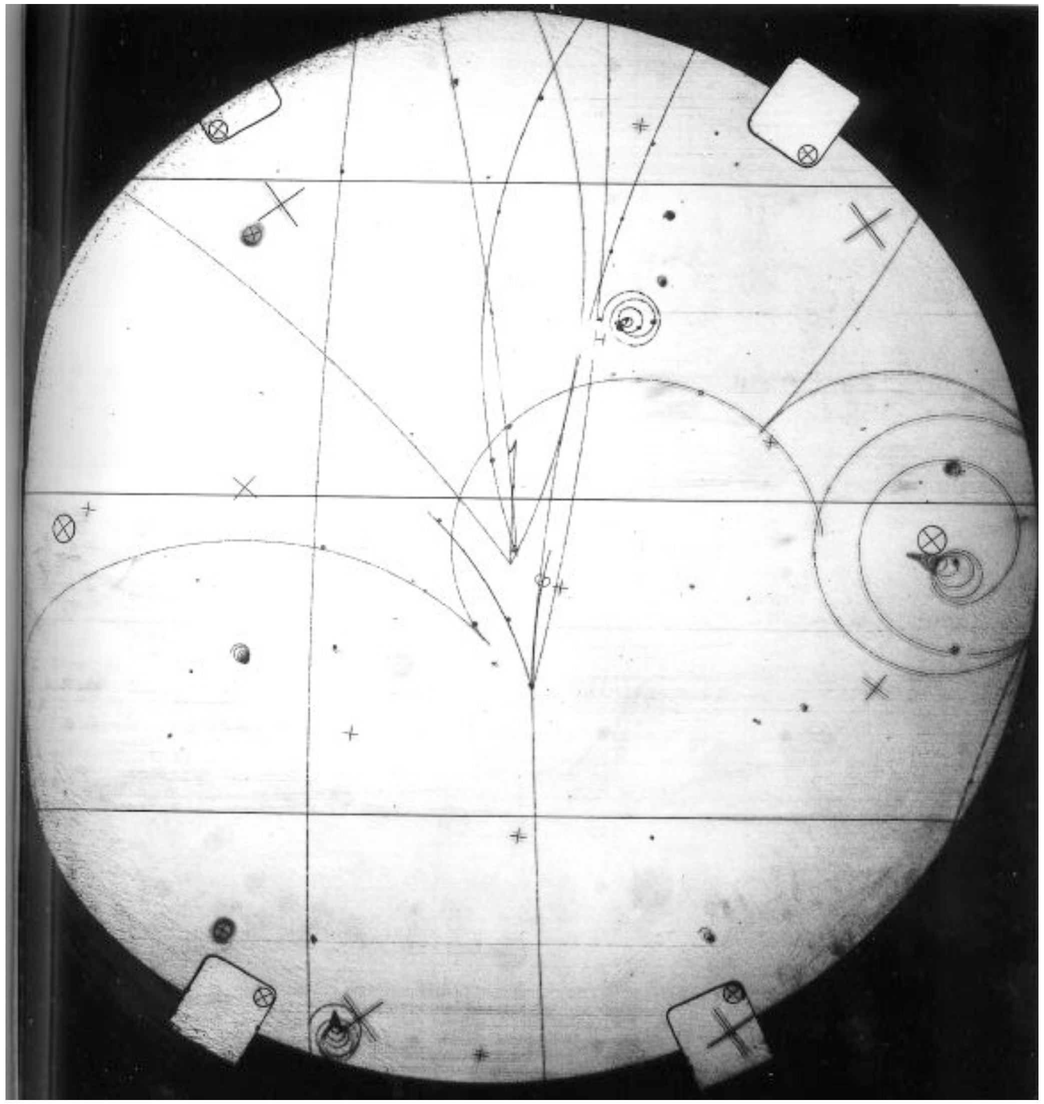
E_π=0.2GeV

Neutrino Detectors

For the next-generation of experiments...

- Would love to have a neutrino detector with the image quality of a bubble-chamber, and a few modern upgrades:

1.) Scalable
2.) Fast electronic readout
3.) Not infinitely expensive



Hydrogen bubble chamber, exposed to 8.8 GeV/c antiprotons

Are there any modern bubble-chambers?

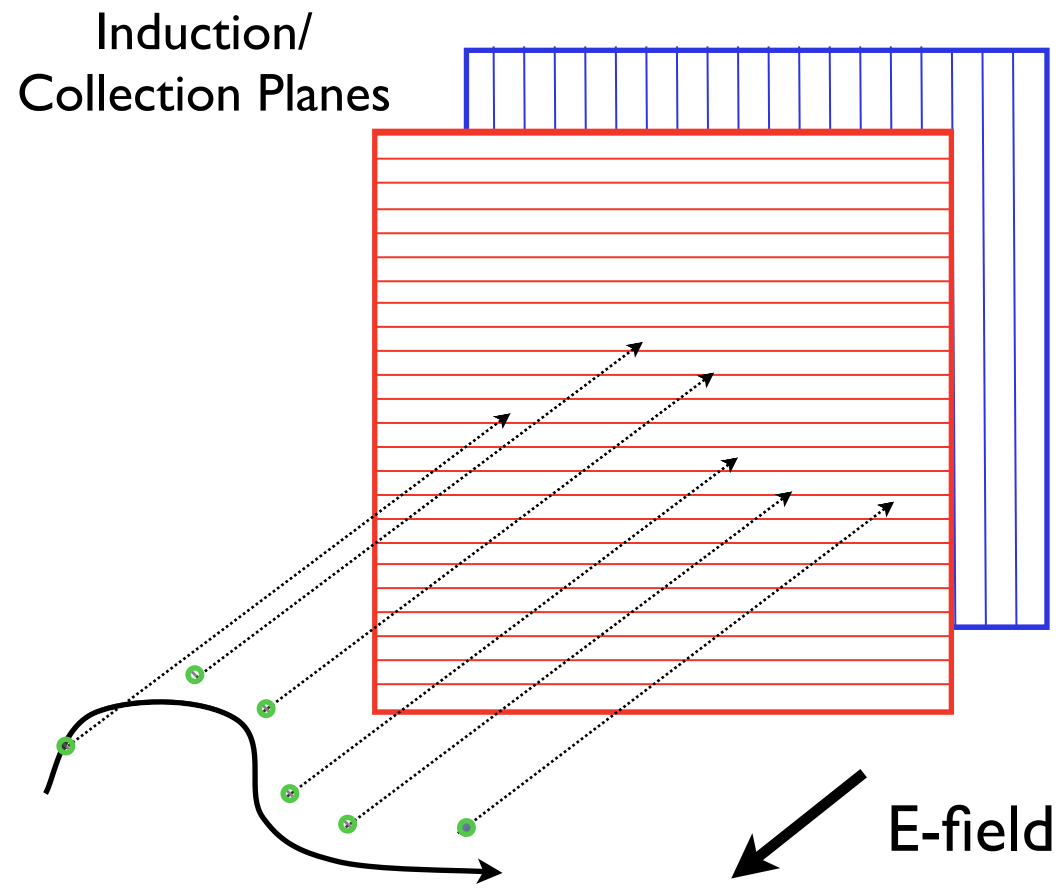
Yes! Liquid-Argon Detectors

Liquid Argon Detectors for Neutrino Physics

LArTPC Principle

TPC = Time Projection Chamber

- Neutrino interactions inside a TPC produce particles that ionize the argon as they travel (55k e^-/cm).
- Ionization is drifted along E-field to wireplanes, consisting of wires spaced a few mm apart.
- Location of wires within a plane provides position measurements...multiple planes give independent views.
- Timing of wire pulse information is combined with drift speed to determine drift-direction coordinate.
- Scintillation light also present, can be collected by Photomultiplier Tubes and used in triggering.

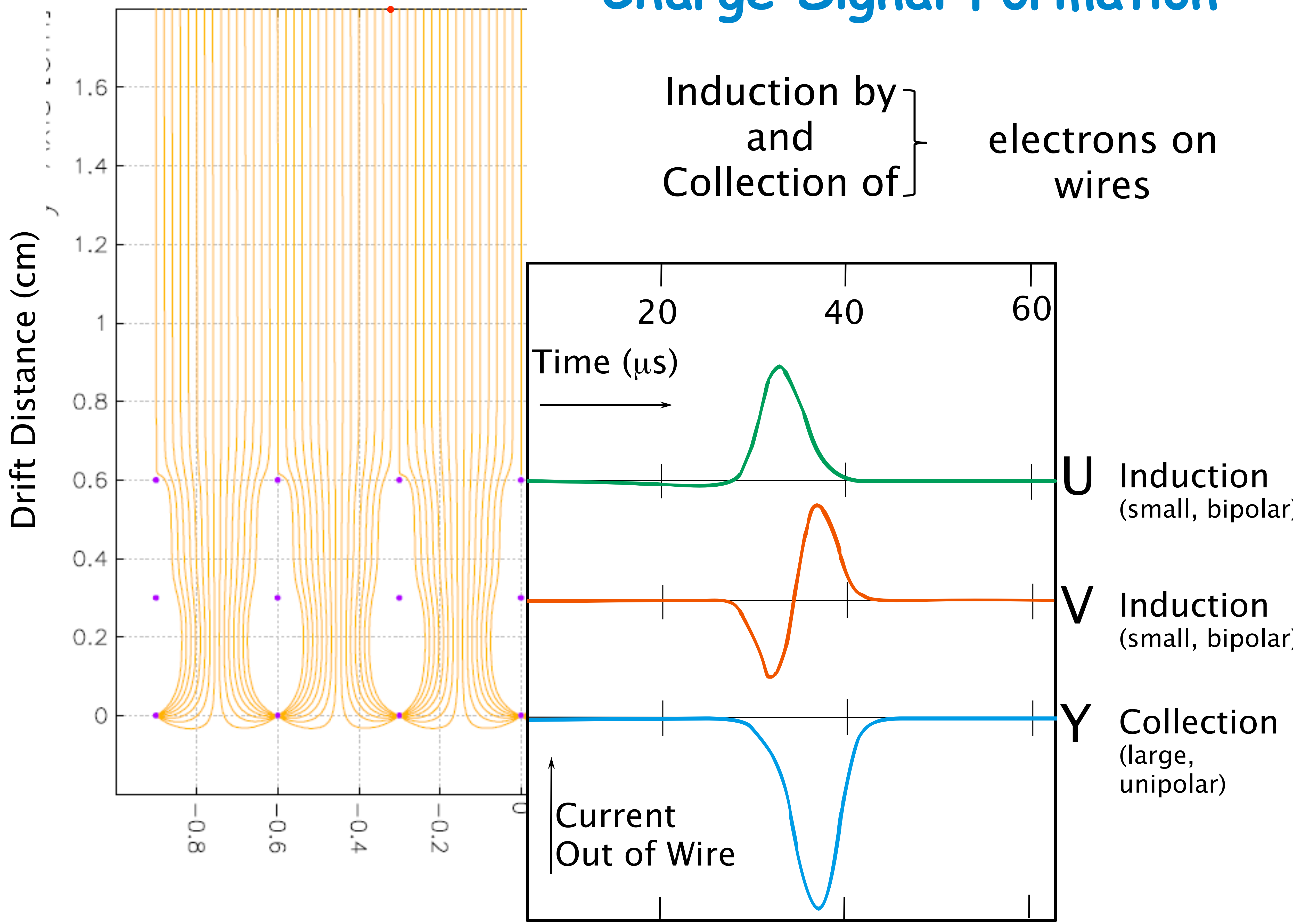


Refs:
1.) *The Liquid-argon time projection chamber: a new concept for Neutrino Detector*, C. Rubbia, CERN-EP/77-08 (1977)

Charge Signal Formation

Induction by
and
Collection of

} electrons on wires



Why Noble Liquids for Neutrinos?

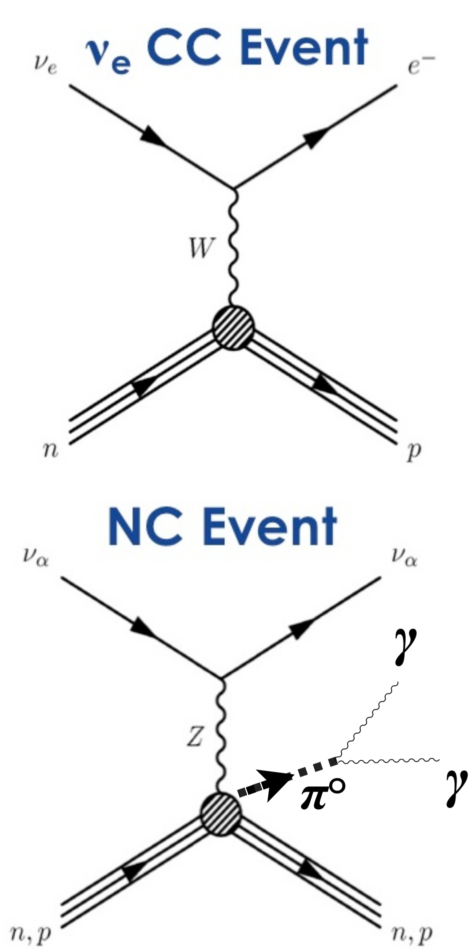
- Abundant ionization electrons and scintillation light can both be used for detection.
- If liquids are highly purified (<0.1ppb), ionization can be drifted over long distances.
- Excellent dielectric properties accommodate very large voltages.
- Liquids are dense, so they make a good target for neutrinos.
- **Argon** is relatively cheap and easy to obtain (1% of atmosphere).

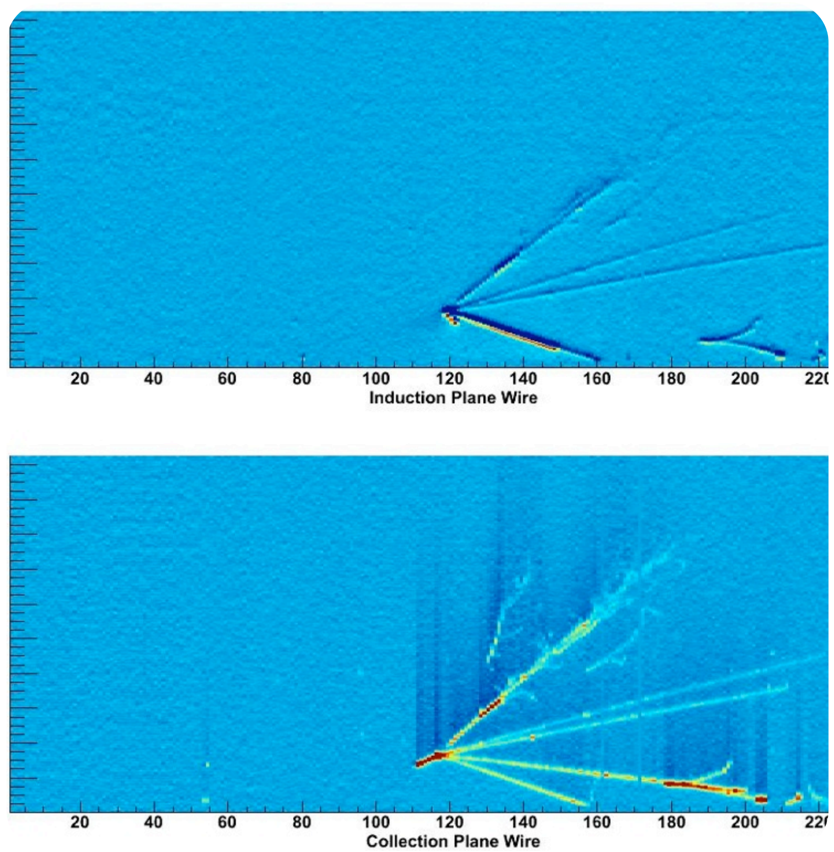
	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm^3]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

LArTPC Advantages

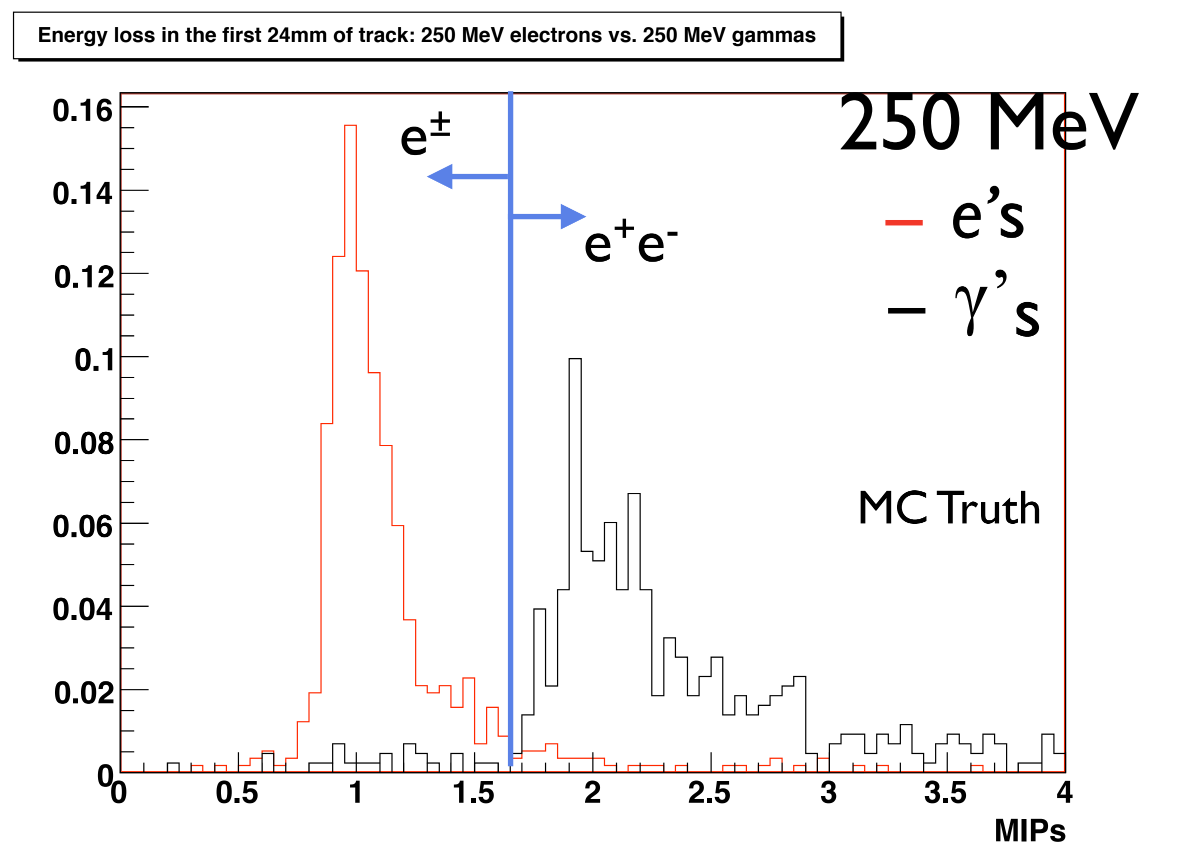
excellent e/γ separation → superior background rejection

- Particle identification comes primarily from dE/dx (energy deposited) along track.
  - Millimeter wire spacing plus rapid sampling provides fine-grained resolution
- ν_e appearance: Excellent signal (CC ν_e) efficiency and background (NC π^0) rejection
  - Topological cuts will also improve signal/background separation
- Scalable to large sizes.
- Beautiful, bubble-chamber like events!





ArgoNeuT Event

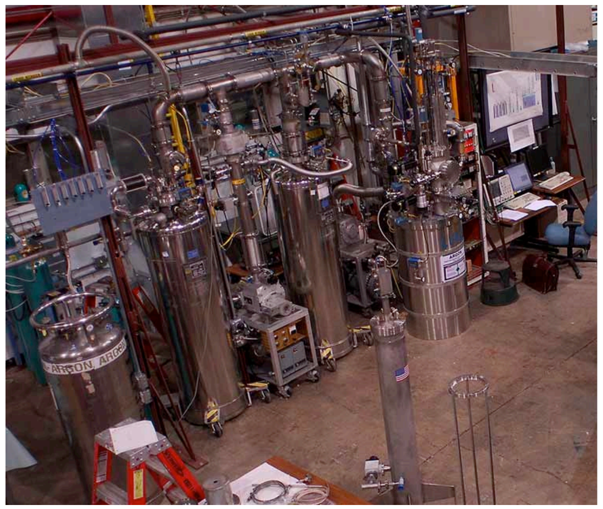


dE/dx for electrons and gammas in first 2.4 cm of track

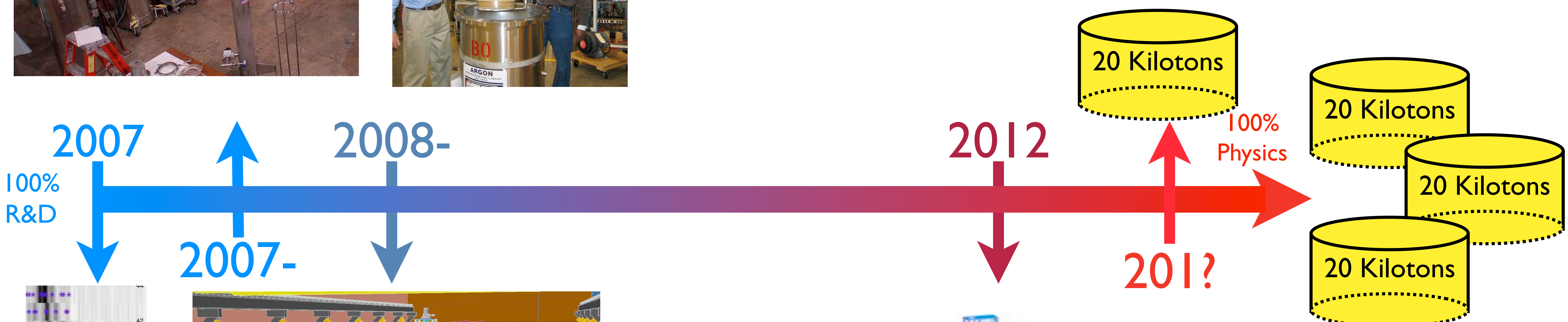
Liquid Argon in the U.S.

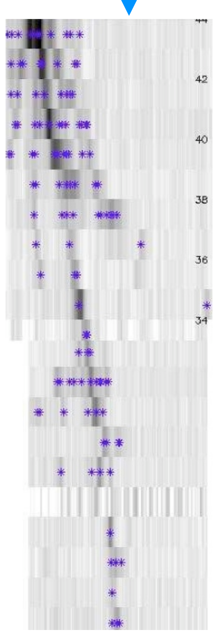
- Rapid progress in LArTPC development in past few years.
- Developing an integrated plan to get to massive detector(s).

Materials Test Stand

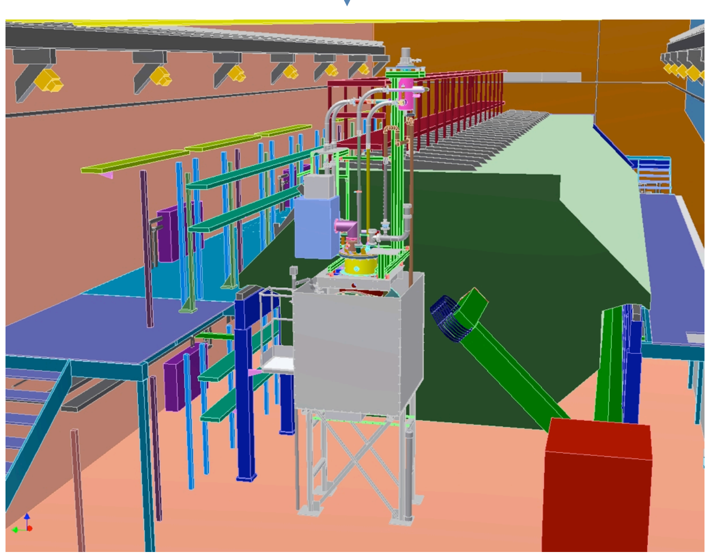


Bo

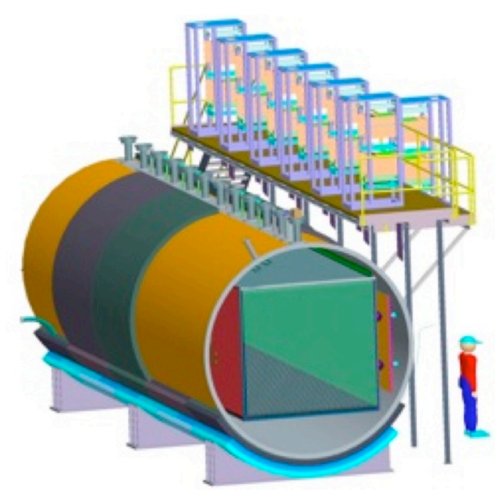




Yale Tracks

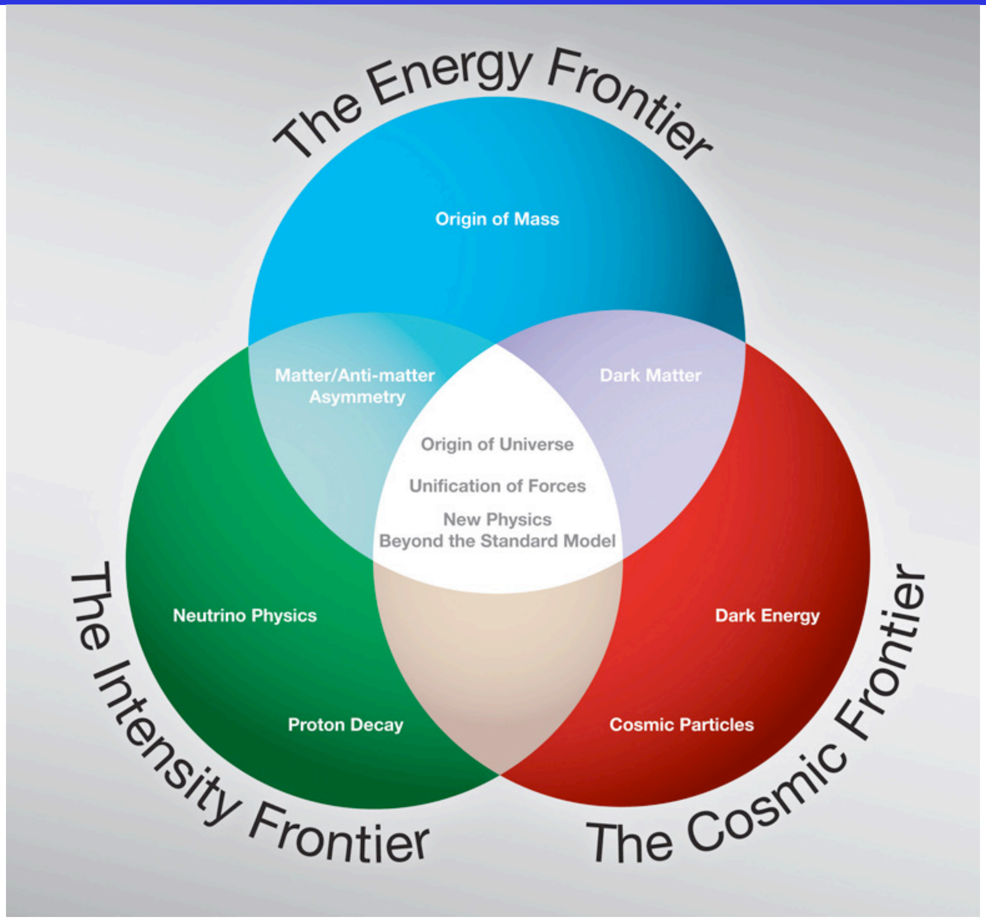


ArgoNeuT



MicroBooNE

Frontiers of High Energy Physics



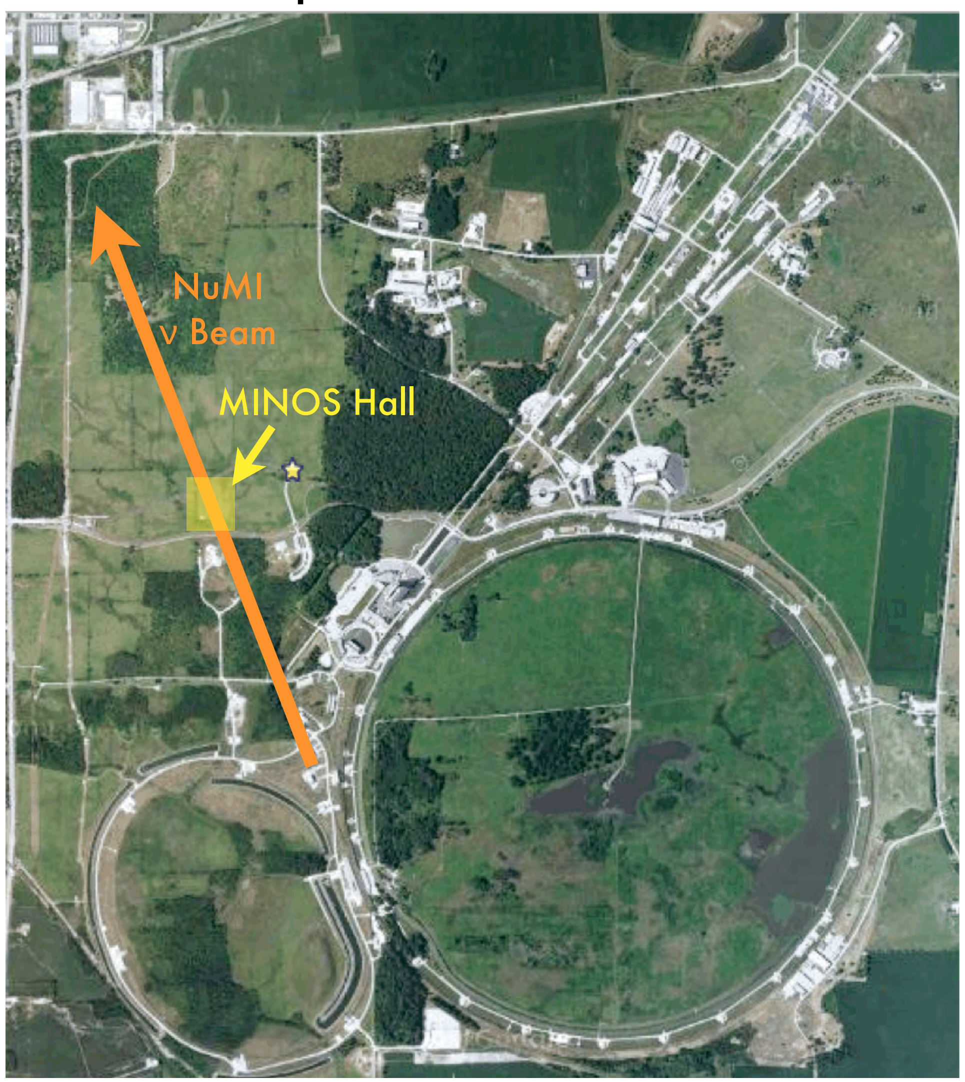
Recommendations from the Report of the P5 Panel to HEPAP, May 29, 2008:

"The panel recommends support for a vigorous R&D program on liquid argon detectors and water Cerenkov detectors in any funding scenario considered by the panel. The panel recommends designing the detector in a fashion that allows an evolving capability to measure neutrino oscillations and to search for proton decays and supernovae neutrinos."

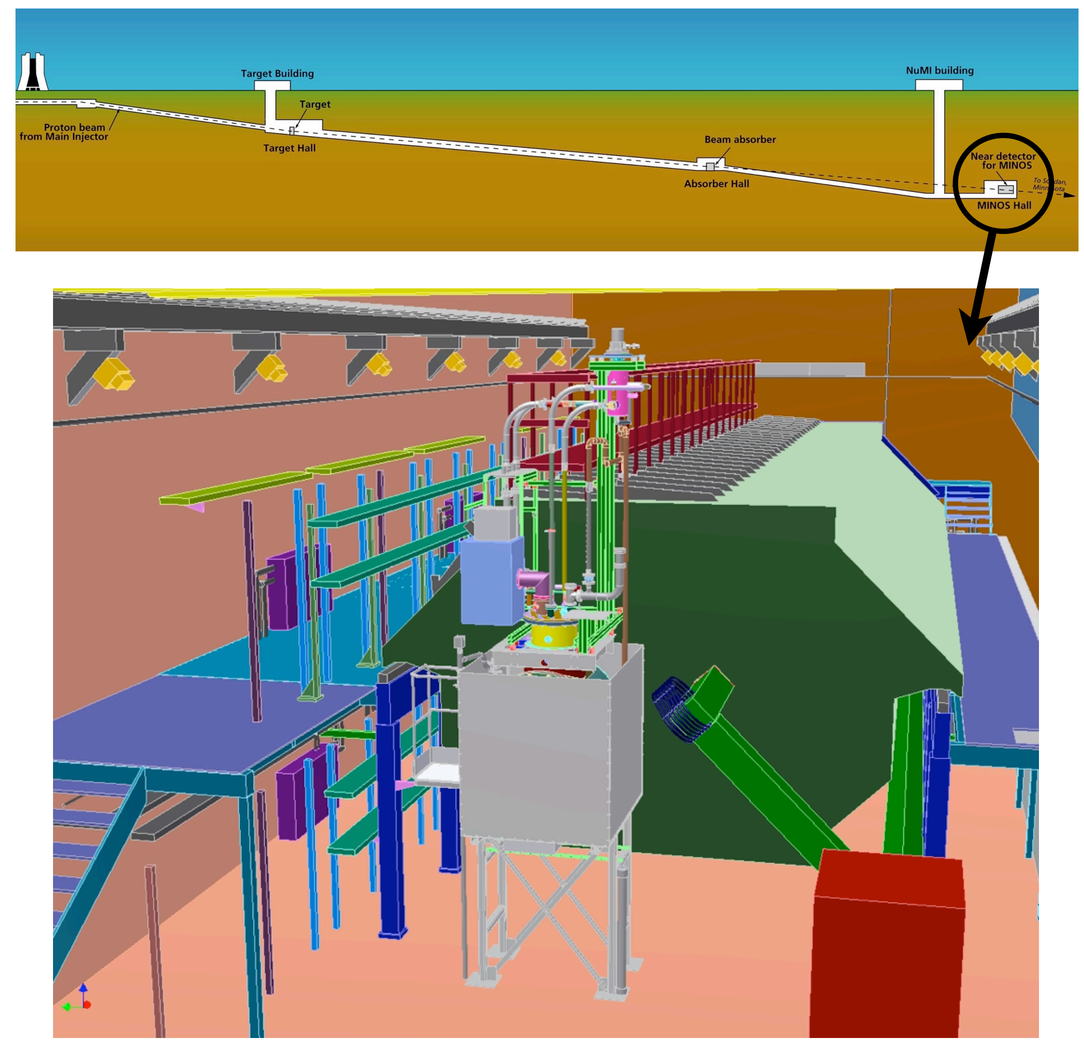
ArgoNeuT

ArgoNeuT

- ArgoNeuT is a ~175 liter LArTPC
- Jointly funded by DOE/NSF
- Sits in NuMI beam at Fermilab, in front of MINOS near detector (to aid in muon reconstruction).
- Goals:
  - Gain experience building/running LArTPCs.
  - Accumulate neutrino/antineutrino events (1st time in the U.S., 1st time ever in a low-E beam).
  - Confront <u>some</u> aspects of underground running and safety.
  - Develop simulation of LArTPCs and compare with data.



Fermilab



MINOS Hall at Fermilab

ArgoNeuT: Collaboration

6 Institutions,
20 collaborators

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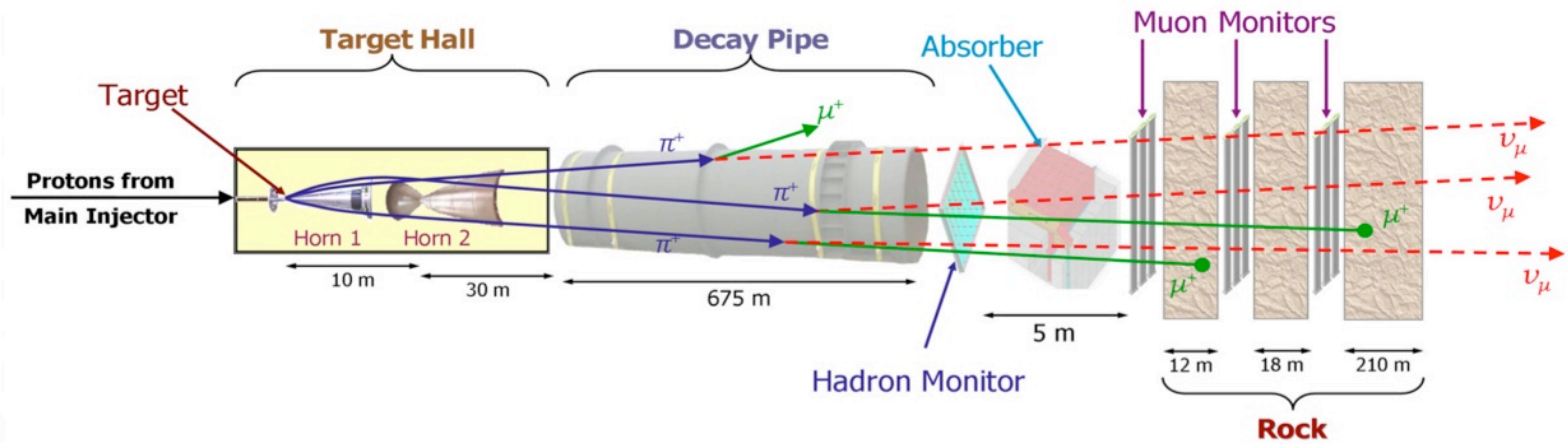
C. Bromberg, D. Edmunds, P. Laurens, B. Page
Michigan State University

S. Kopp, K. Lang
The University of Texas at Austin

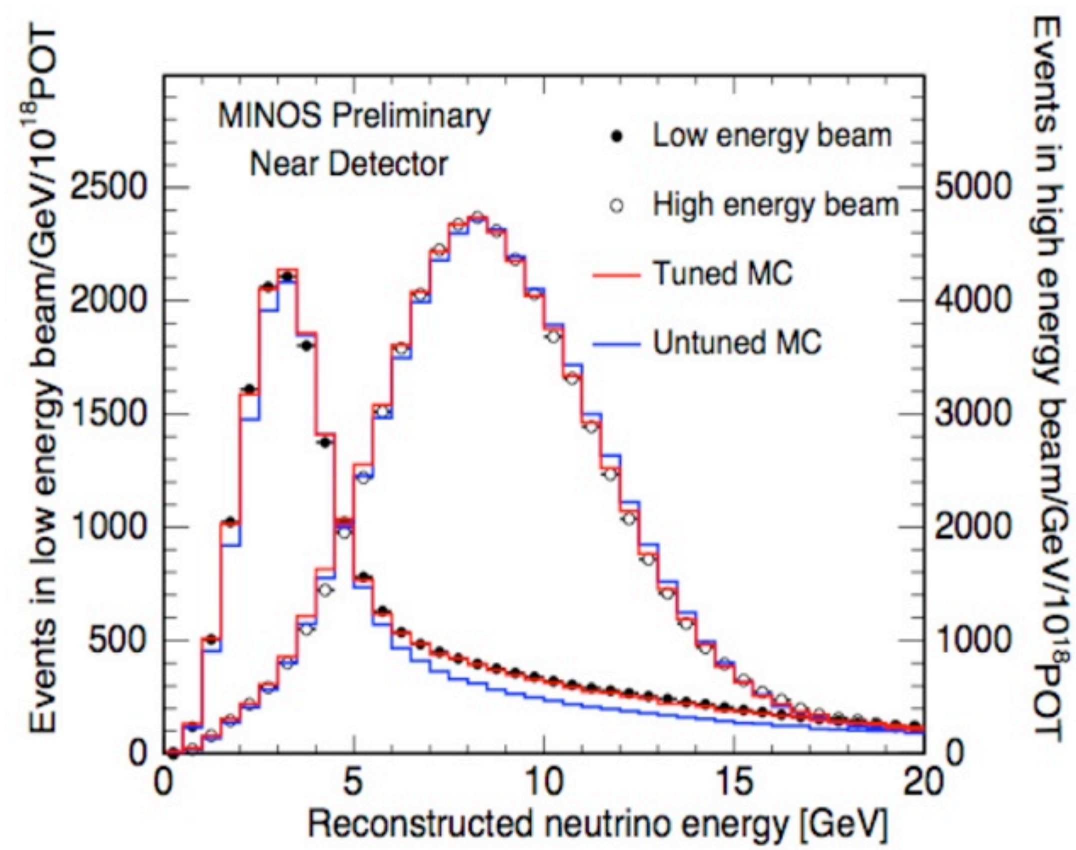
C. Anderson, B. Fleming, S. Linden, K. Partyka, M. Soderberg*, J. Spitz
Yale University

* = *Spokesperson*

ArgoNeuT: NuMI Beam



- 120GeV protons from Main Injector hit graphite target and produce pions, kaons.
- Charged mesons are focused by a pair of magnetic horns, then allowed to decay in flight.
- Absorber removes all but neutrinos.
- "Low Energy" horn configuration during ArgoNeuT's run.
- Neutrino beam: 91.8% ν_μ, 6.9% $\overline{\nu}_\mu$, 1.3% $\nu_e+\overline{\nu}_e$



ArgoNeuT: TPC

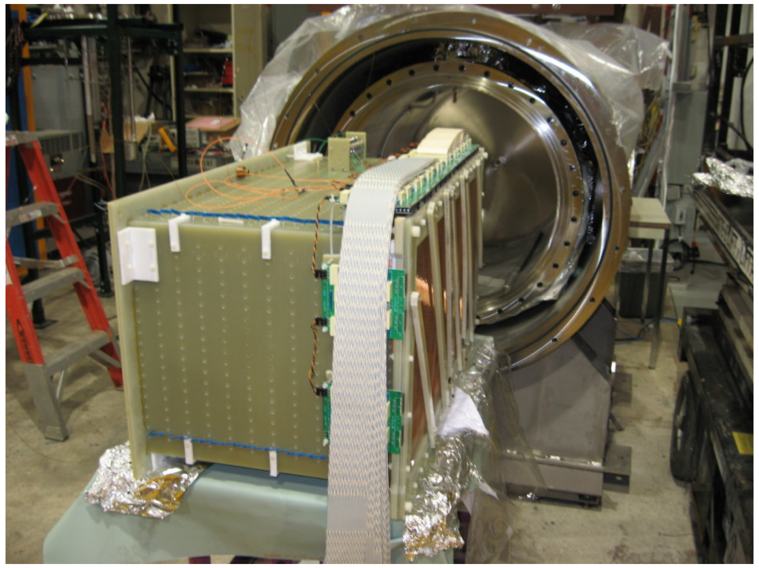
Cryostat Volume	500 Liters
TPC Volume	175 Liters
# Electronic Channels	480
Wire Pitch	4 mm
Plane Separation	4 mm
Electric Field	500V/cm
Max. Drift Time	330μs
Wire Properties	0.15mm diameter BeCu

Collection Induction #1 Induction #2

±60° wires

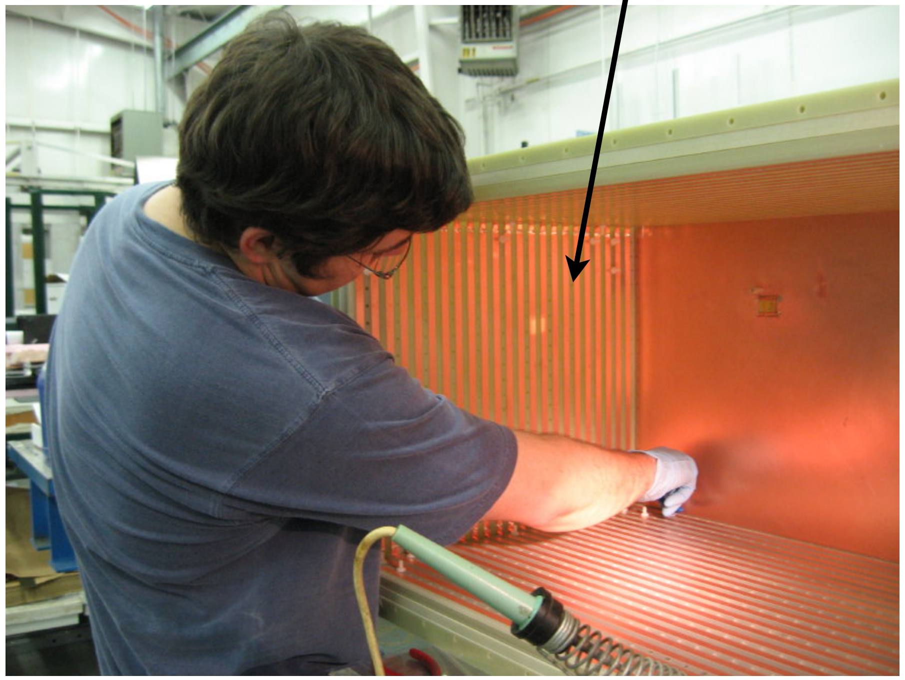
ν beam →

Wire Orientations



TPC About to Enter Cryostat

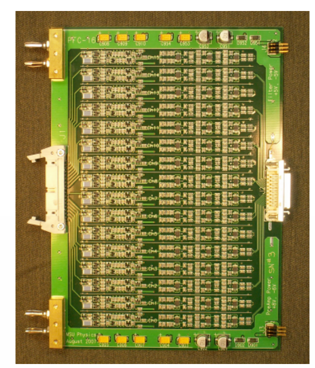
Electric Field Rings

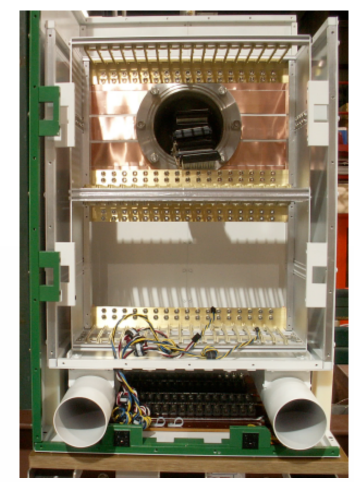


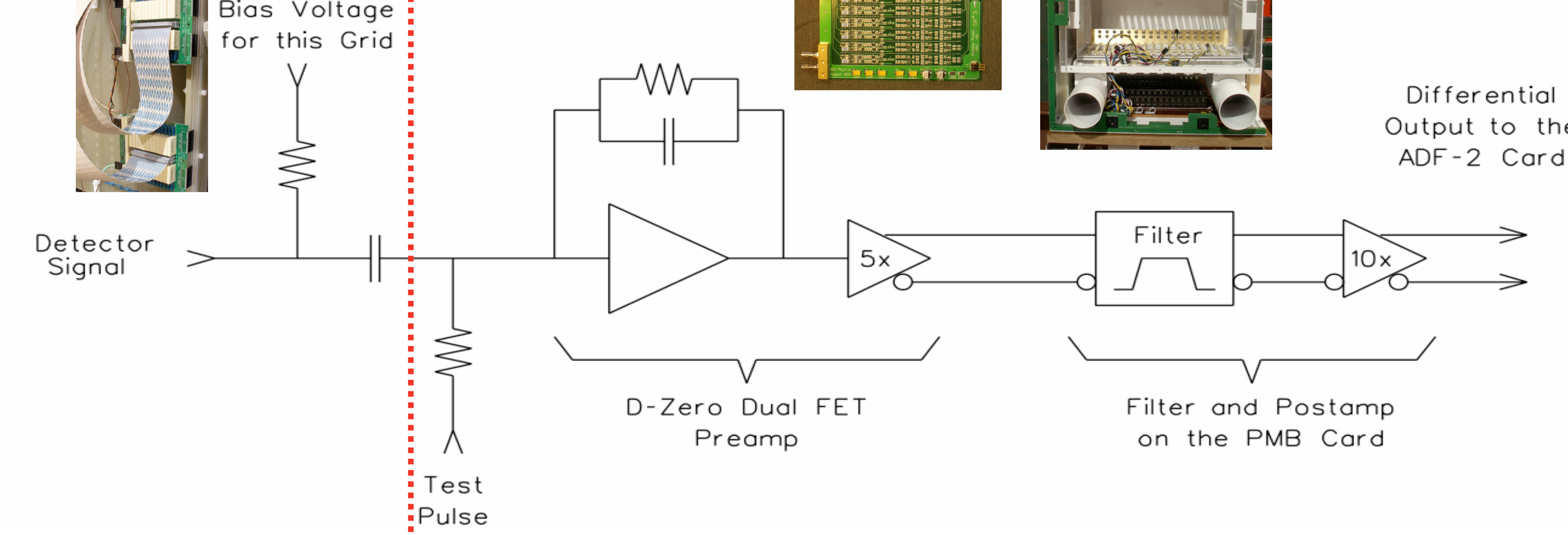
TPC Field Cage formed out of copper-clad G10 boards

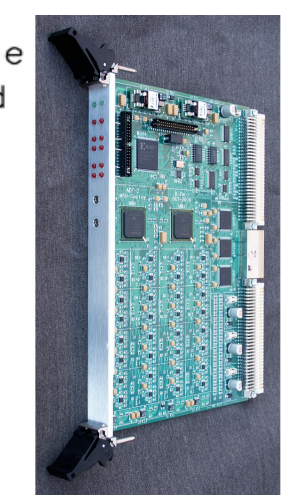
ArgoNeuT: Electronics

- Bias voltage distribution & blocking capacitors on the TPC
- FET preamplifier similar to D0/ICARUS front-end
- Wide bandwidth filtering (10 - 159 kHz, now)
  - Full information on most hits/tracks
  - Employ DSP to extract hit/track parameters
- Digitization boards sample at 5 MHz (198ns), 2048 samples/channel
- Minimize noise sources
  - Double shielding of feed-through and preamplifiers
  - Remote ducted cooling
  - Extensive DC power filtering



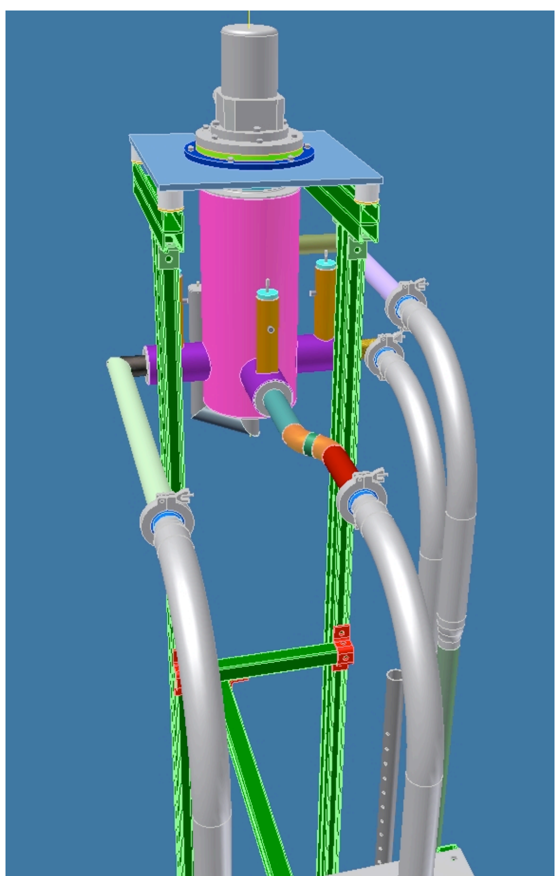




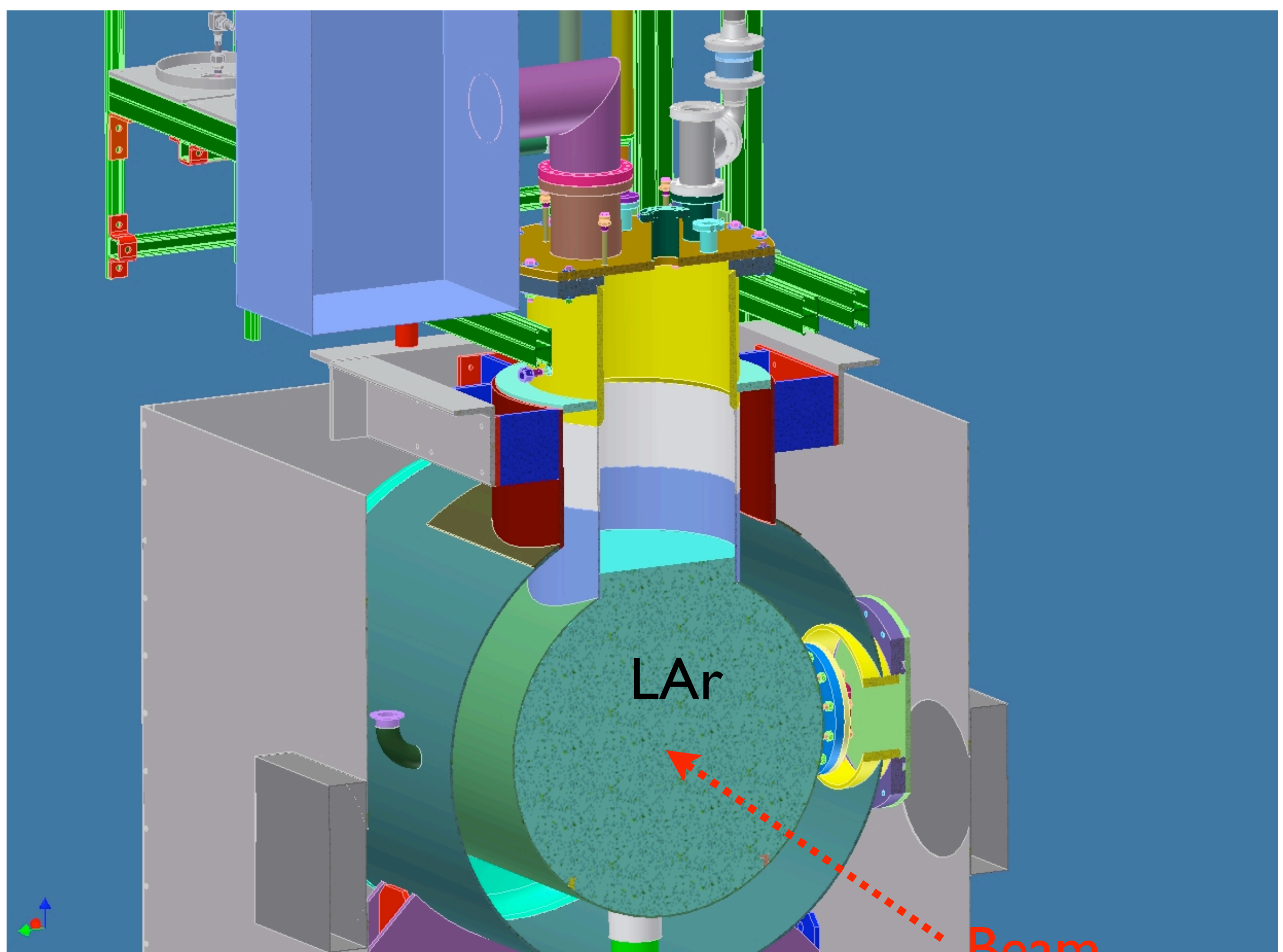


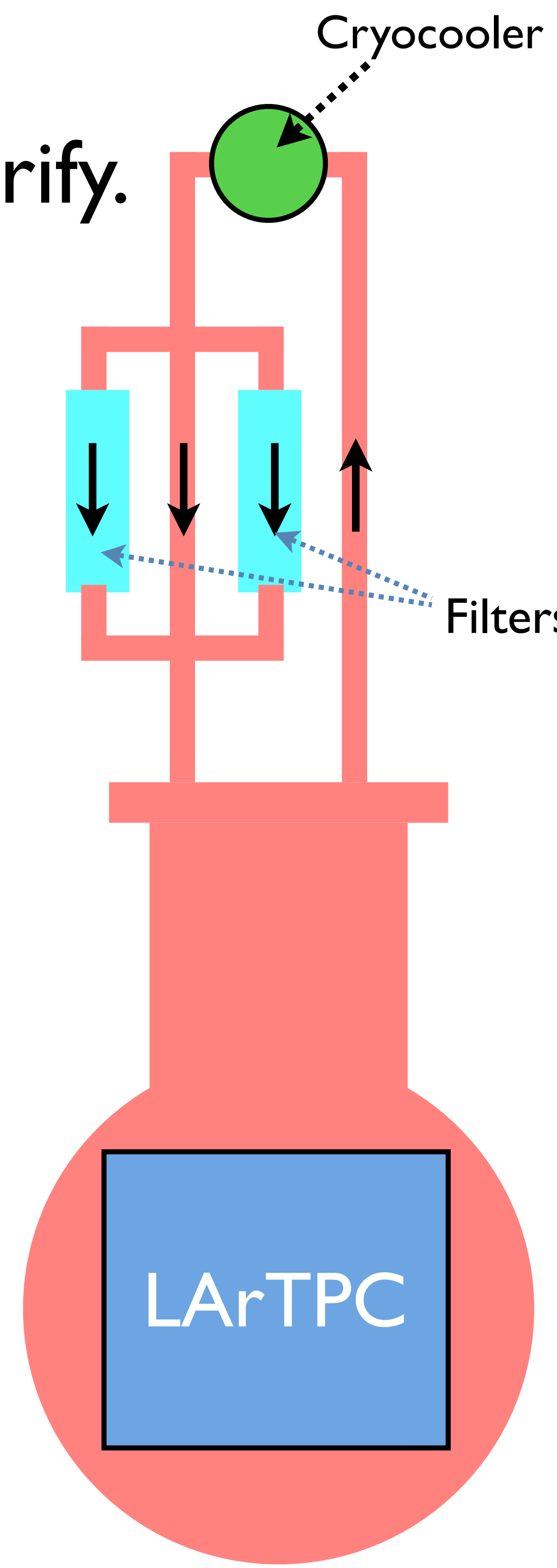
ArgoNeuT: Cryogenics

- Self-contained system....no refills.
- Continuously circulate argon through filters to purify.
- Cryocooler utilized to condense boil-off gas.
- Vacuum jacketed cryostat has 550 liter capacity.



300W Cryocooler

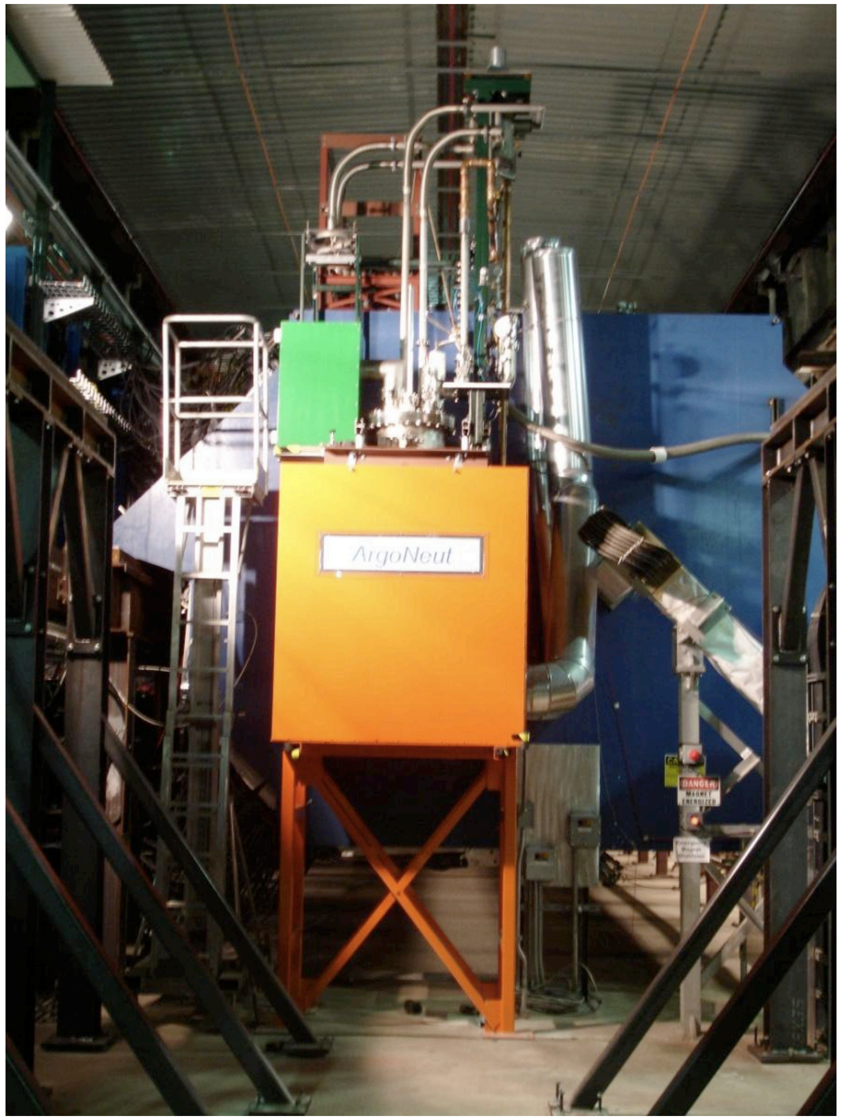




ArgoNeuT: Status

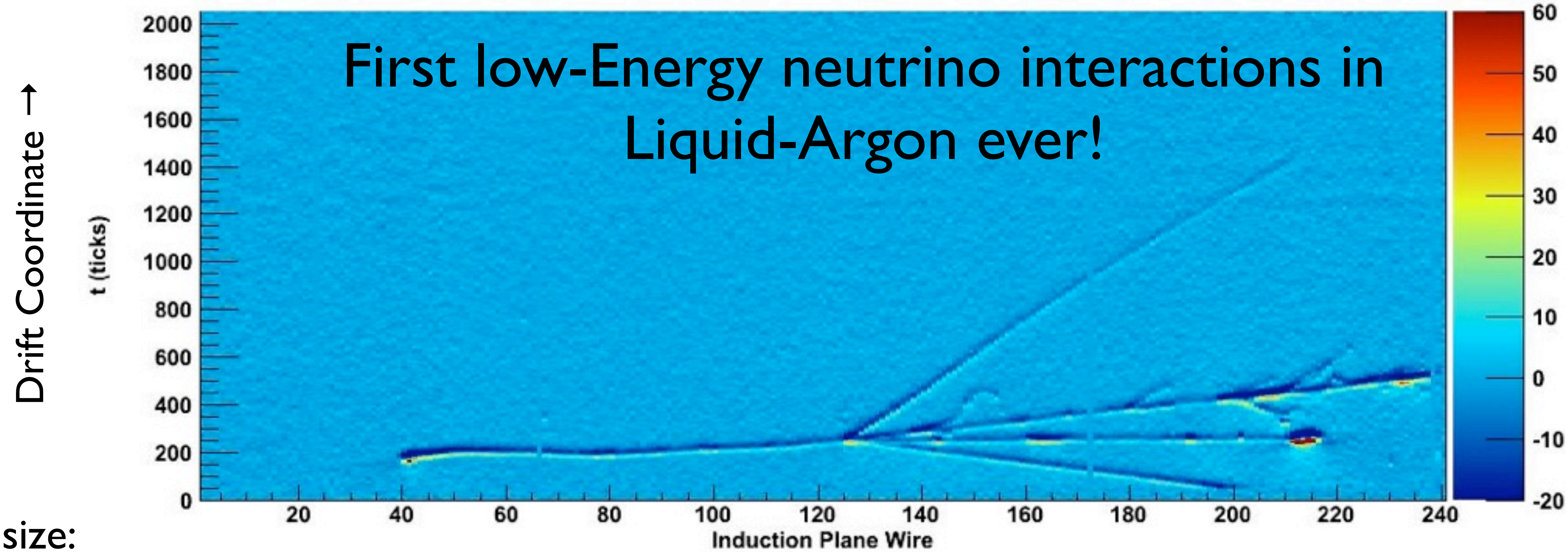
- Filled the detector on Friday, May 8, 2009
- Initial argon purity was low....recirculating cleaned things up.
- Acquired neutrino data for ~1 month before summer 2009 shutdown...continued running in the Fall, mostly in antineutrino mode
- Cryo. system operated continuously since initial fill, (modulo cryocooler repair for ~2 weeks in October).
- Currently planning what to do with ArgoNeuT after NuMI run, which ended yesterday (Feb. 22)!

Moving underground
(lowering down 350 ft. shaft)

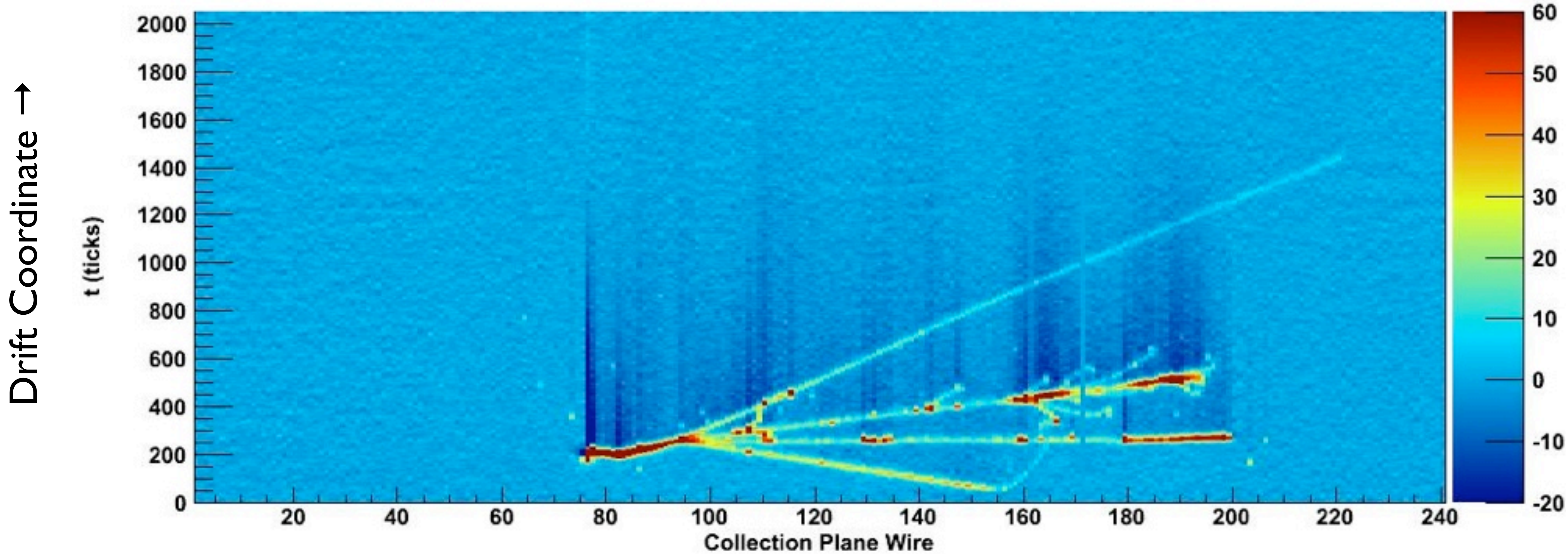


Installing underground.

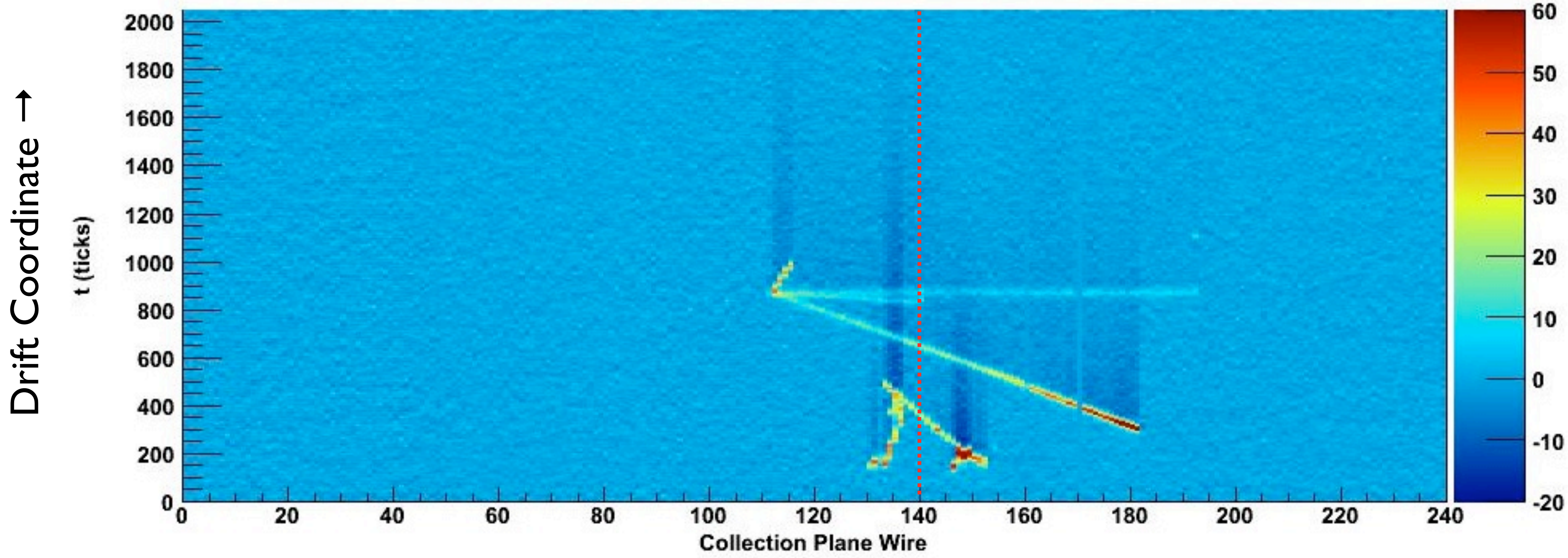
ArgoNeuT Neutrino Event

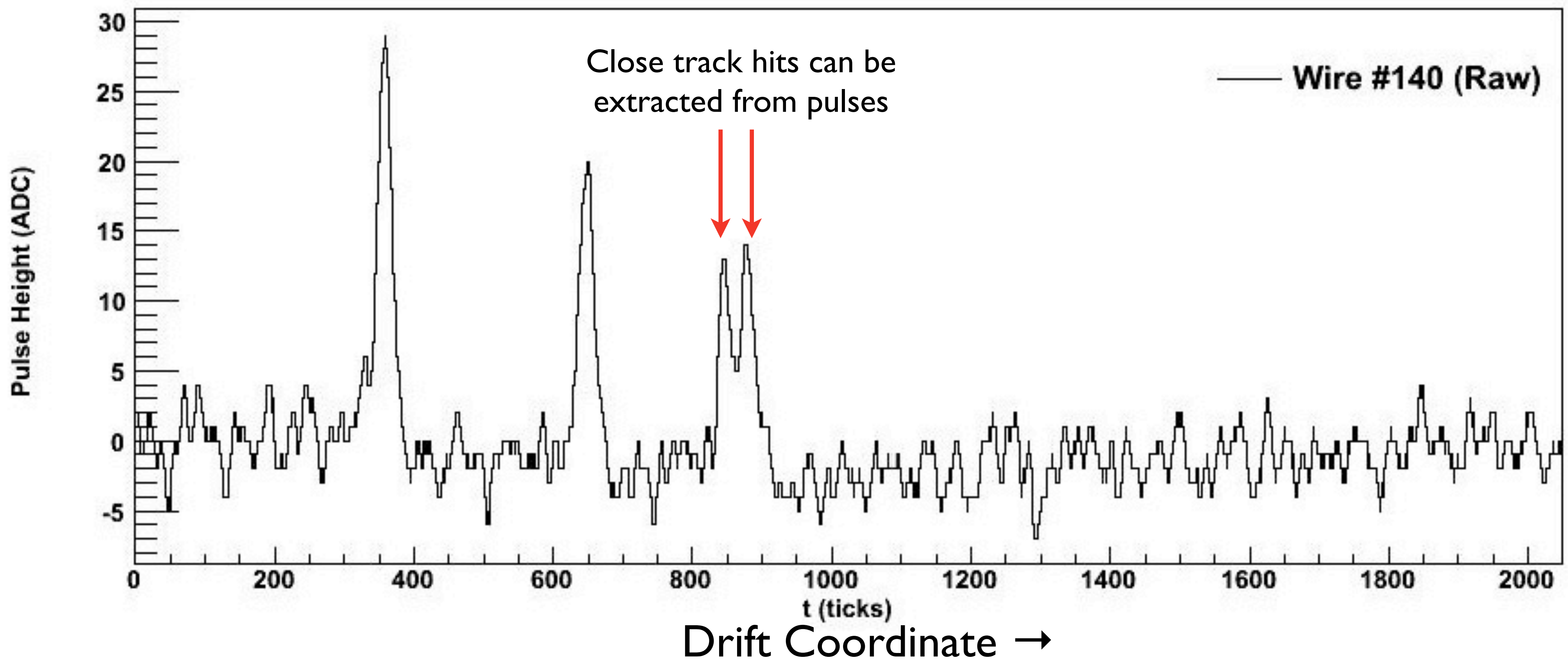


Pixel size:
4mm x 0.3mm



ArgoNeuT Neutrino Event

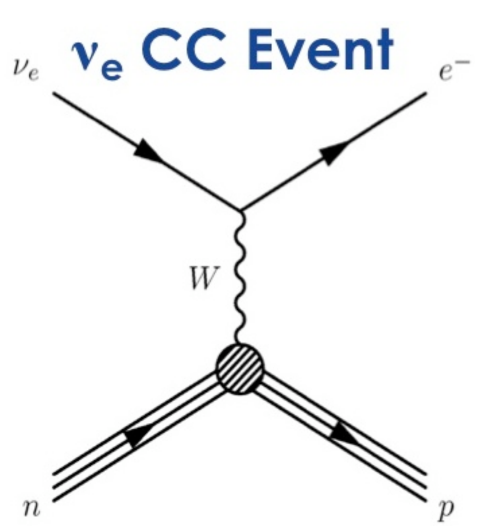


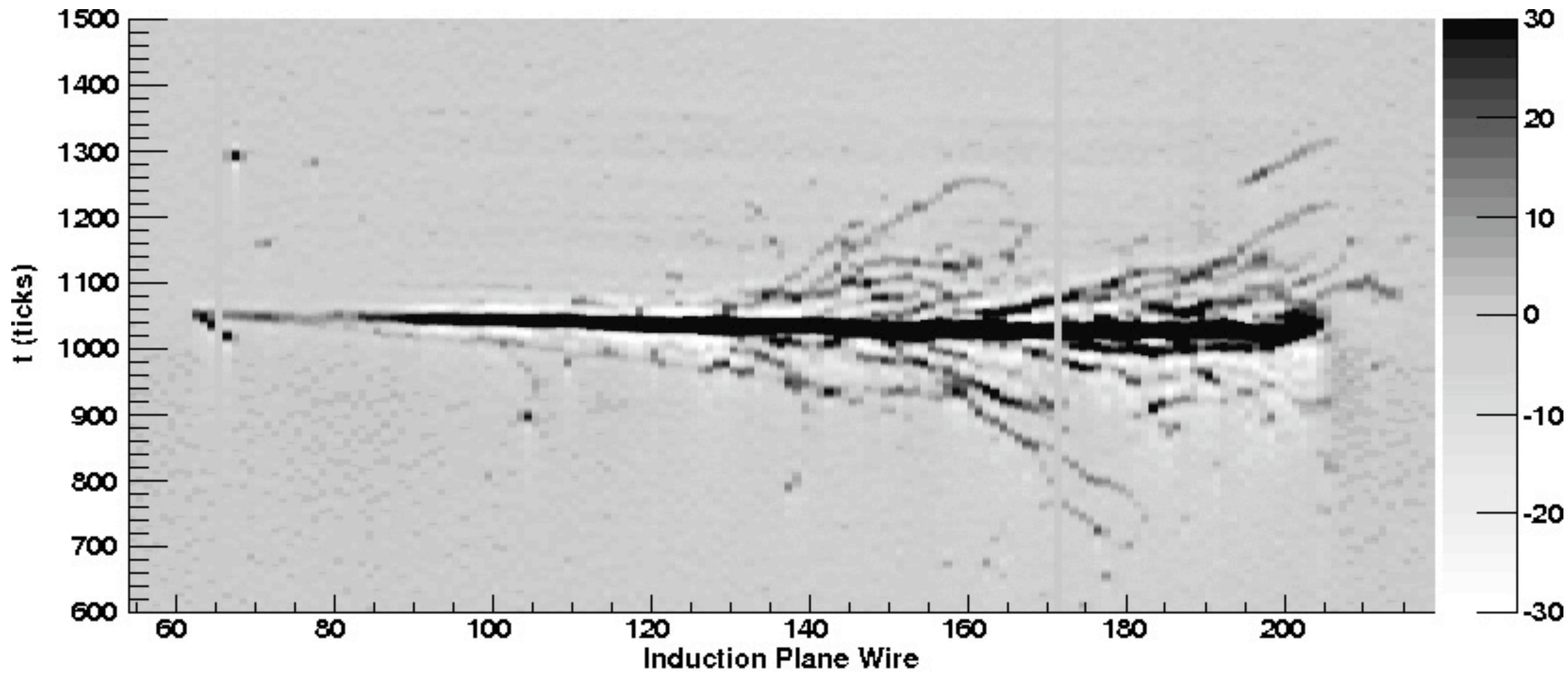


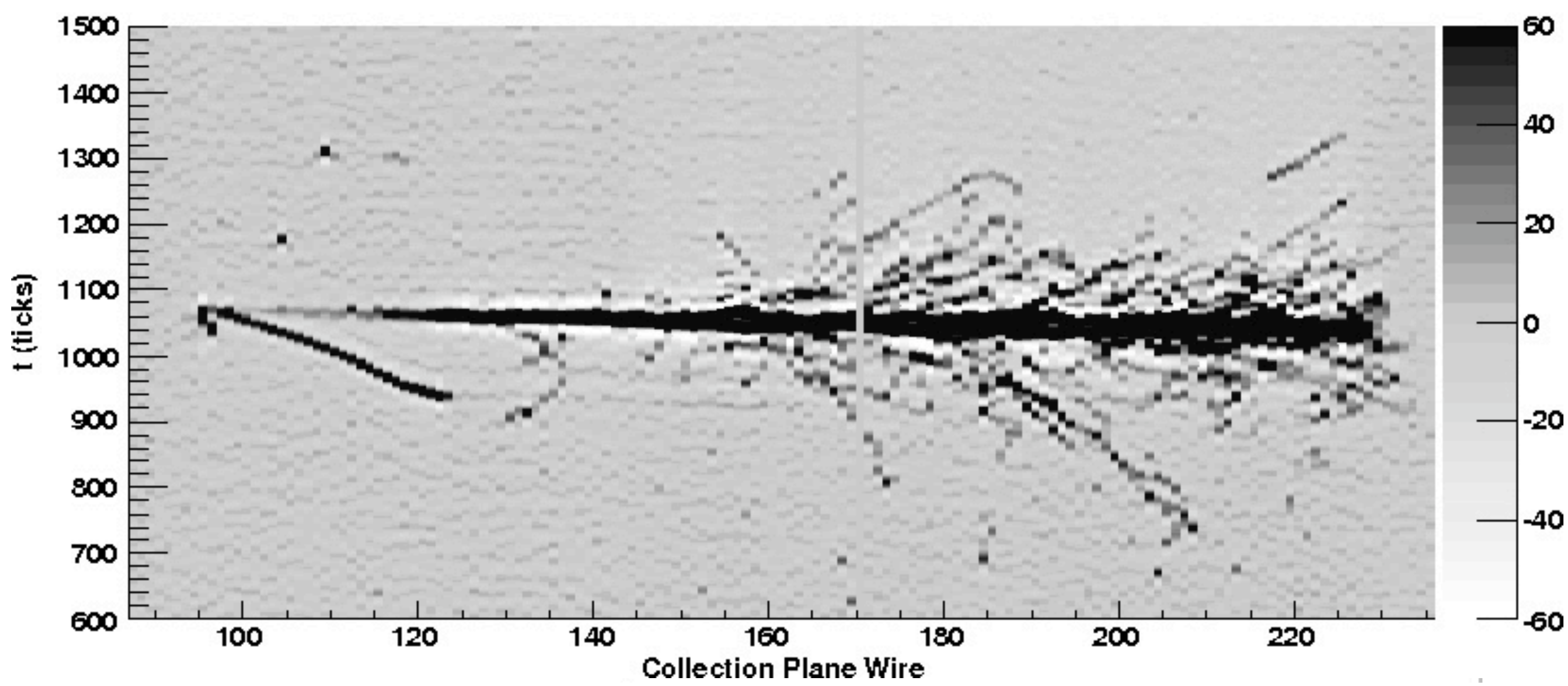
ArgoNeuT Neutrino Event

Electronics response removed by Fourier Deconvolution

CCQE ν_e candidate (Sept. 2009)

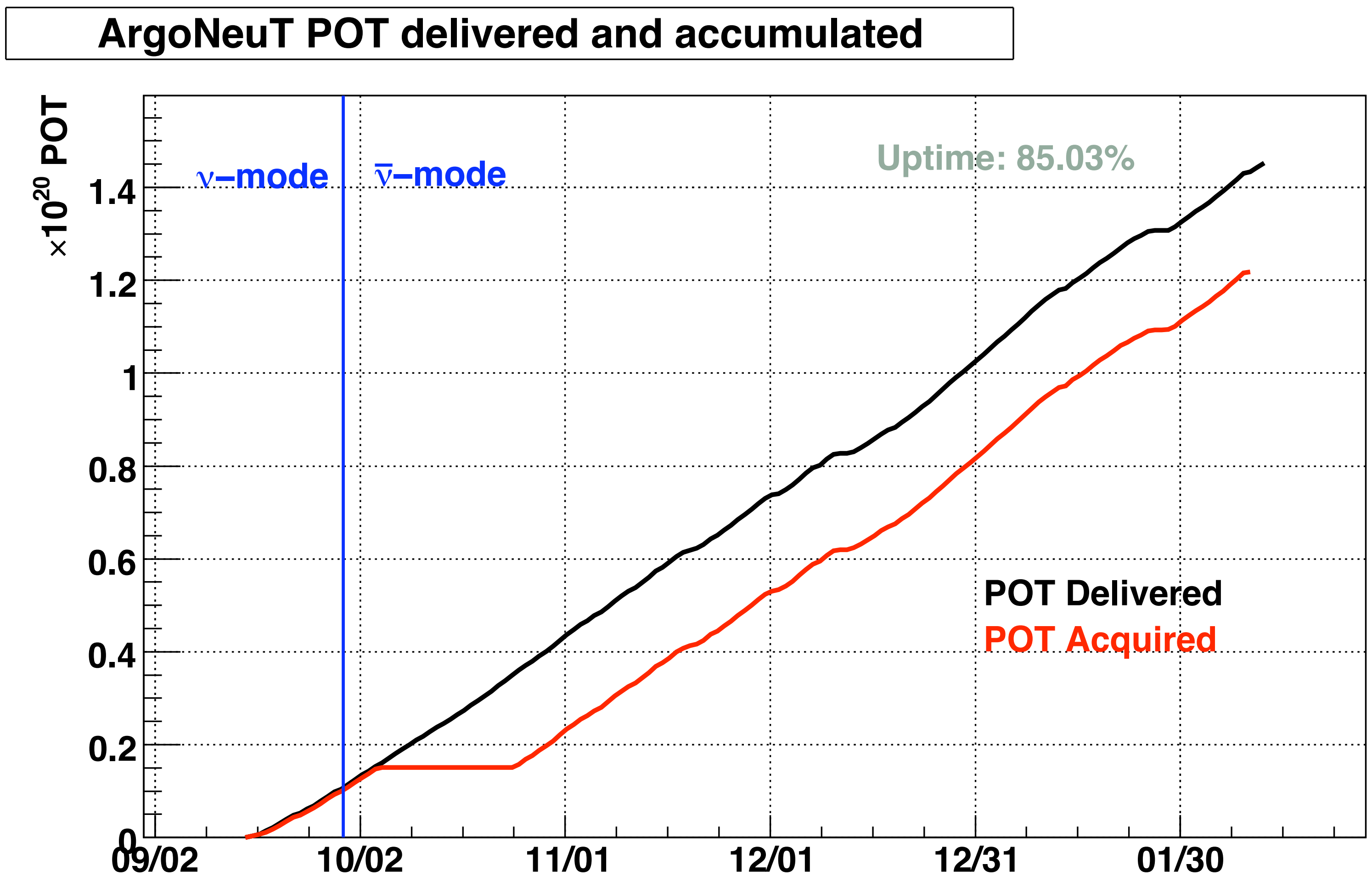






ArgoNeuT Physics

- ArgoNeuT should acquire ~1.4E20 Protons On Target (P.O.T.) by the end of its run, mostly in anti-neutrino mode.
- This data is being used to develop techniques for reconstructing events in 3D.
- Proving dE/dx particle identification effectiveness using data will be an important result.
- We also hope to obtain several cross-section measurements for the first time in a LAr experiment!



Event Type	# in 180 days (1.4×10^{20} POT)
ν_μ CC	28800
$\overline{\nu_\mu}$ CC	2520
ν_e CC	540
NC	9720

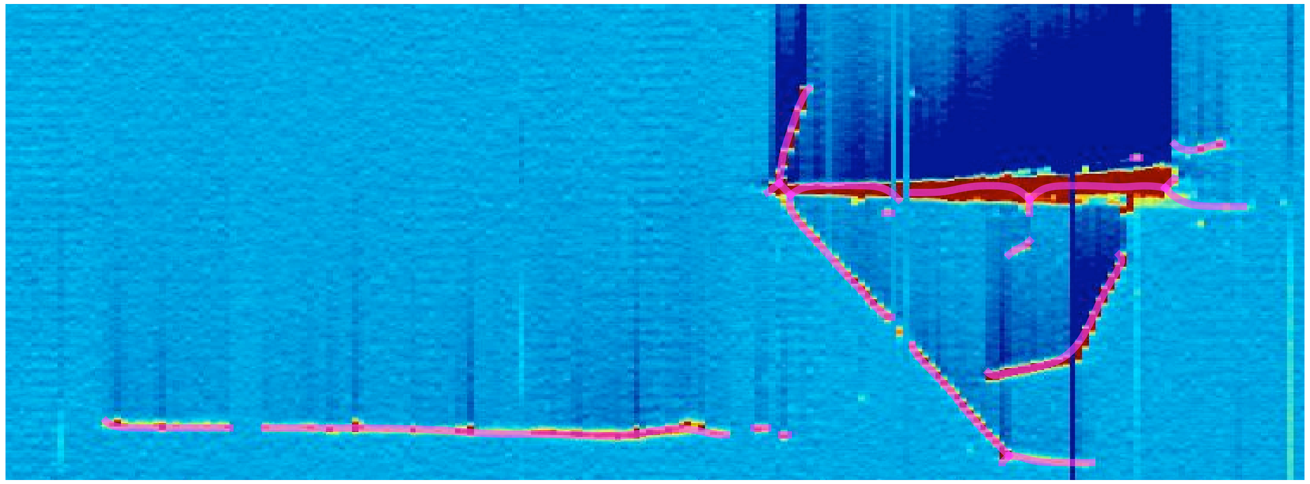
Neutrino Mode

Event Type	# in 180 days (1.4×10^{20} POT)
ν_μ CC	9026
$\overline{\nu_\mu}$ CC	8111
ν_e CC	175
NC	5933

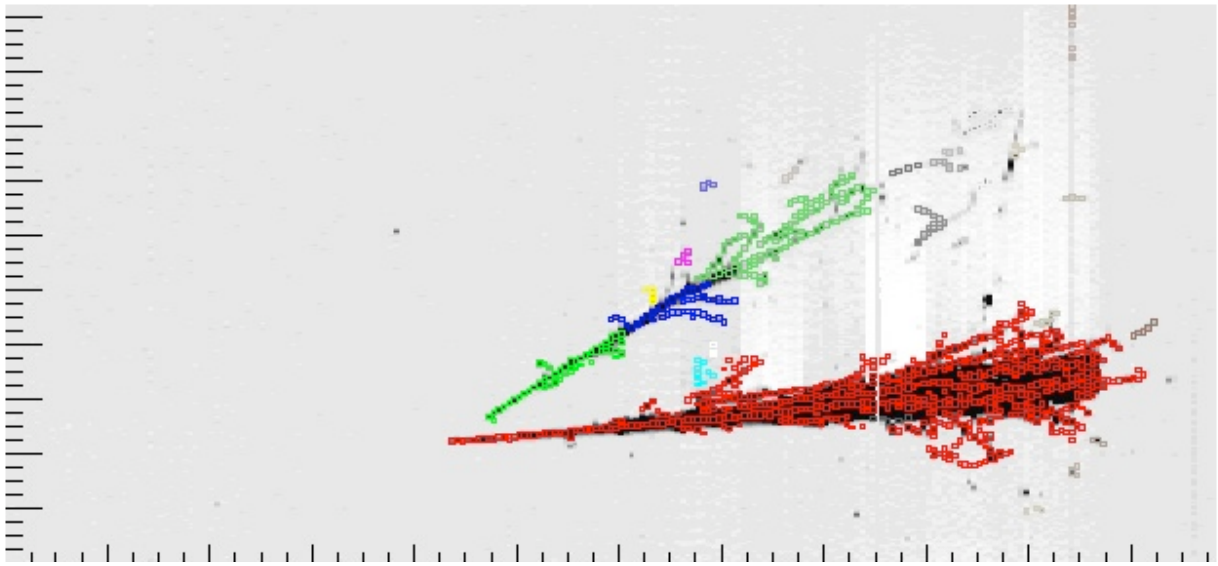
AntiNeutrino Mode

ArgoNeuT Software

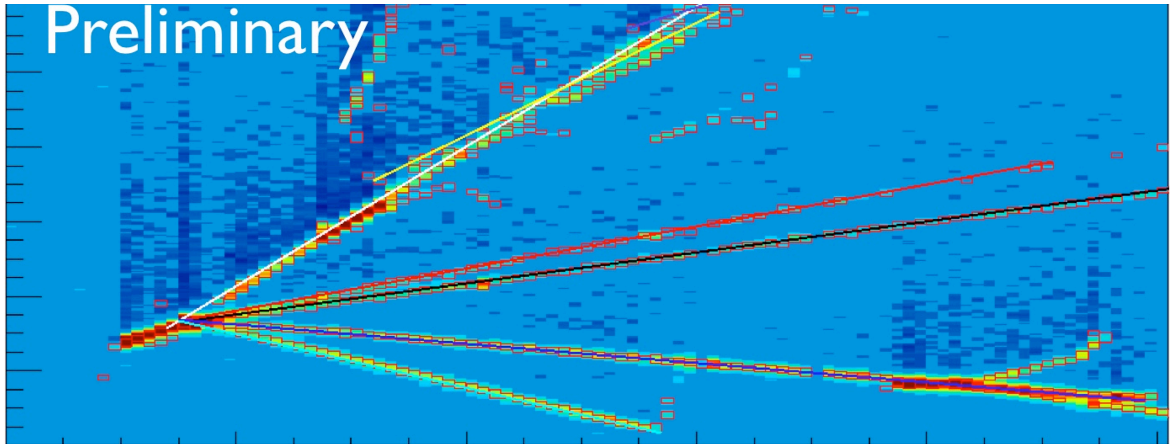
- ArgoNeuT (anti)neutrino data inspiring lots of software/analysis work.
- No automated event reconstruction exists for LArTPCs, so we're creating one.
- "LArSoft" is simulation/reconstruction/analysis code that can be used for all LAr experiments.
- LArSoft being developed using FMWK code environment (from NOvA experiment)
- Example: Different reconstruction techniques being developed...



Computer vision techniques for clustering

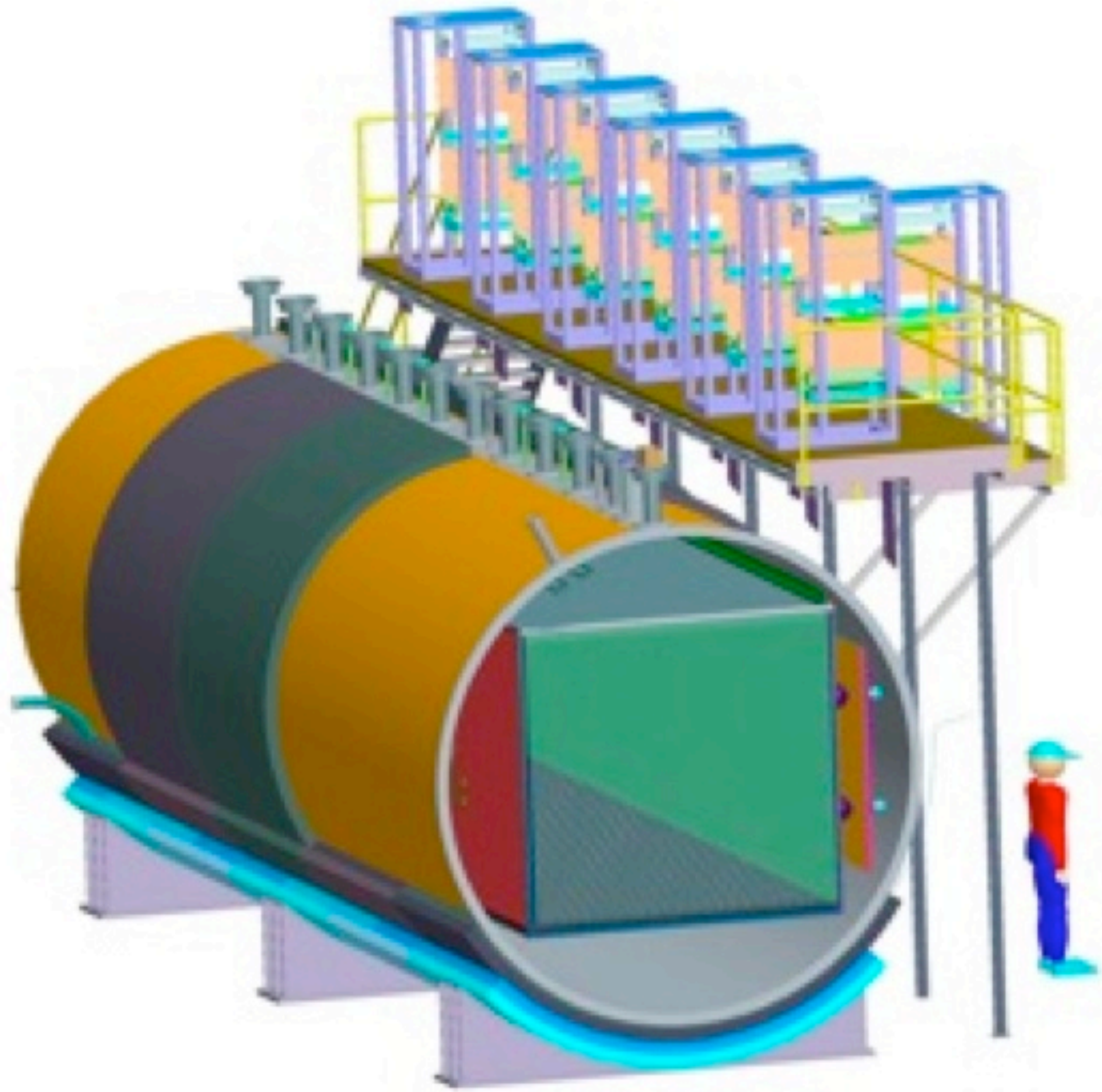


Density-based clustering.



Straight-line reconstruction using Hough Transform.

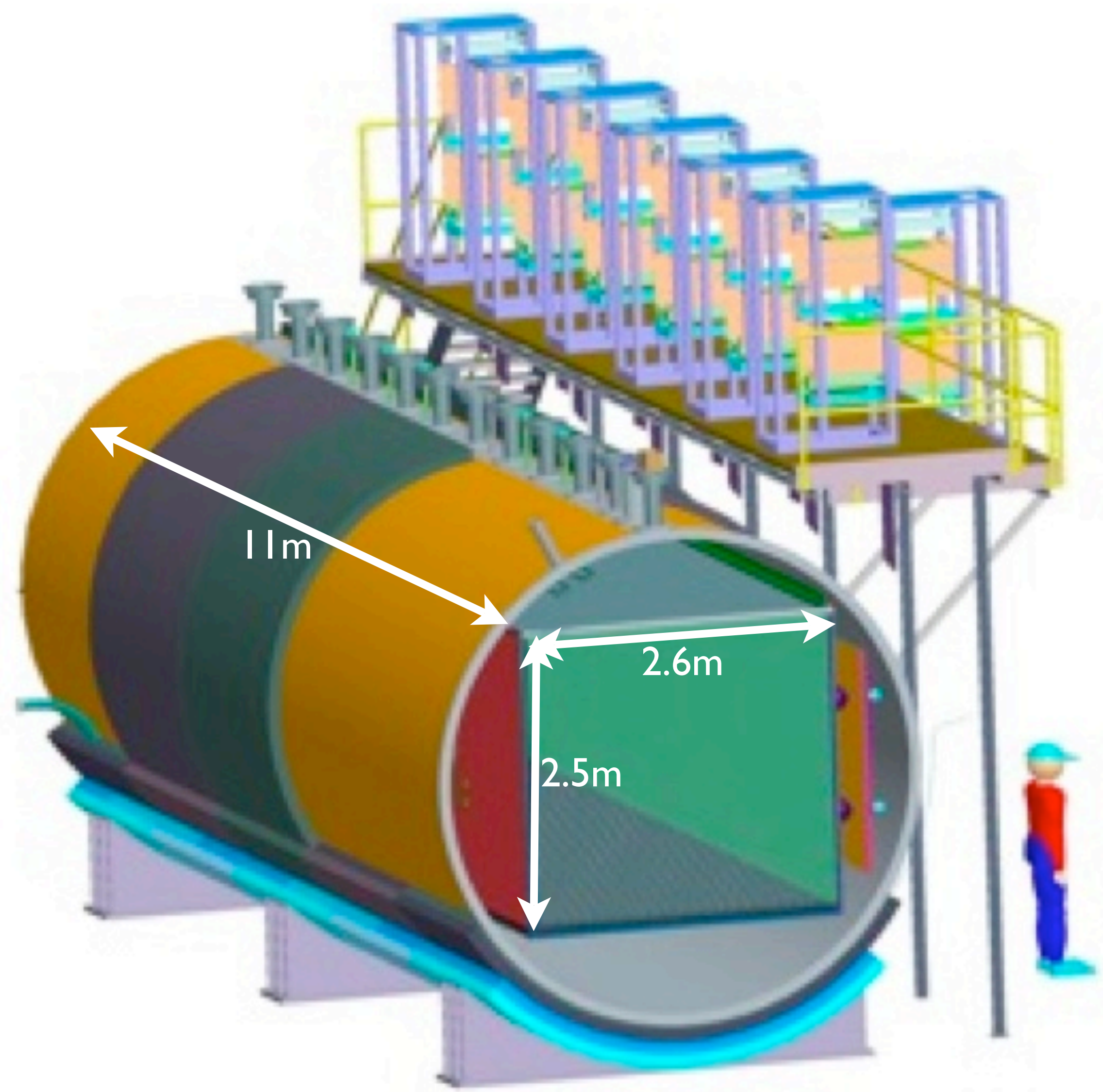
MicroBooNE



MicroBooNE

- MicroBooNE is a LArTPC experiment that will operate in the on-axis Booster neutrino beam and off-axis NuMI neutrino beam on the surface at Fermilab.
- Combines timely physics with hardware R&D necessary for the evolution of LArTPCs.
  - MiniBooNE low-energy excess
  - Low-Energy Cross-Sections
  - Cold Electronics (~10000 channels)

★Stage 1 approval from Fermilab directorate in June 2008
★CD-0 (Mission Need) in October 2009
★CD-1 soon...(March)
★CD-2 (Dec. 2010)



➡Joint NSF/DOE Project
➡$1.1M NSF MRI for TPC (Yale), PMTs

MicroBooNE: Collaboration

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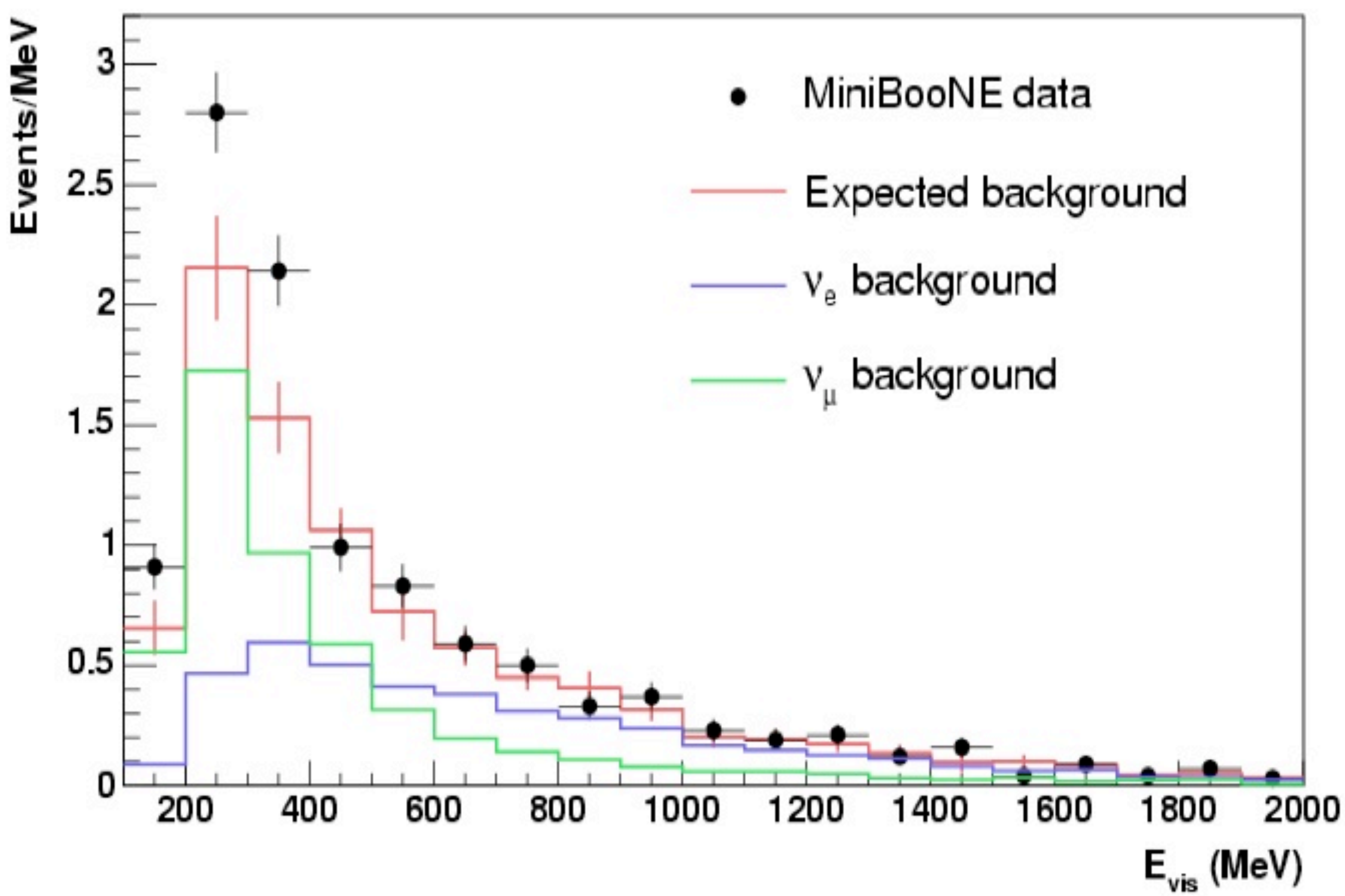
Yale University, New Haven, CT

13 Institutions, 60 Collaborators

† = *Spokesperson*
‡ = *Deputy Spokesperson*

MicroBooNE: Physics

- Address the MiniBooNE low energy excess
  - MiniBoone is a Cerenkov detector that looked for ν_e appearance from a beam of ν_μ
  - Does MicroBooNE confirm the excess?
  - Is the excess due to a electron-like or gamma-like process?
- Prove effectiveness of electron/gamma separation technique (using dE/dX information).
- Low Energy Cross-Section Measurements (CCQE, NC π^o, $\Delta \rightarrow N\gamma$, Photonuclear, ...)
- Continue development of automated reconstruction (building on ArgoNeuT's effort).



MiniBooNE Result Excess

200-300MeV: 45.2±26.0 events

300-475MeV: 83.7±24.5 events

MicroBooNE will have 5σ significance for electron-like excess, 3.3σ for photon-like excess.

Refs:

1.) *Unexplained Excess of Electron-Like Events From a 1-GeV Neutrino Beam* MiniBooNE Collaboration, Phys. Rev. Lett. 102, 101802 (2009)

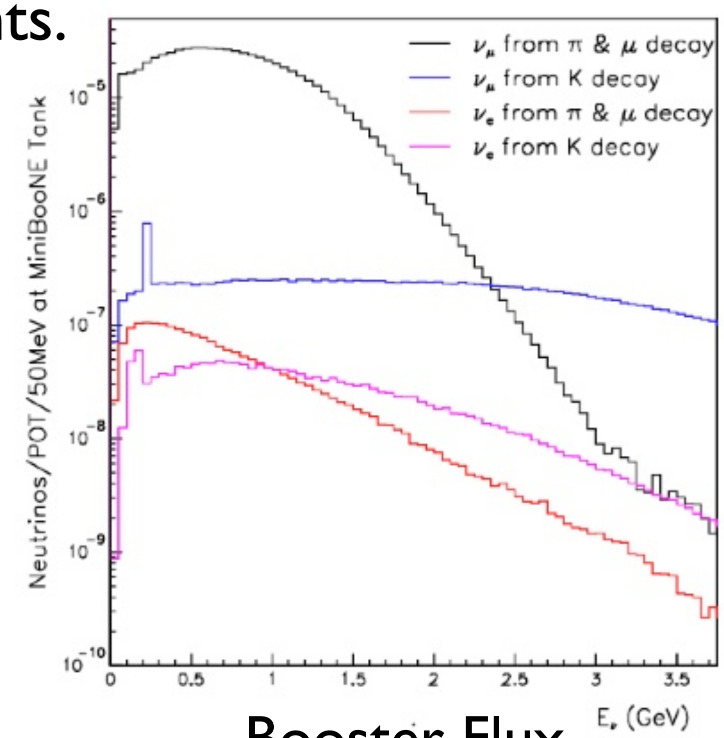
MicroBooNE: Location

- MicroBooNE will sit on surface in on-axis Booster beam (BNB), and off-axis (ME) NuMI beam.
- Planning to remove MiniBooNE and reuse its building.
- Large event samples will allow a variety of cross-section measurements.

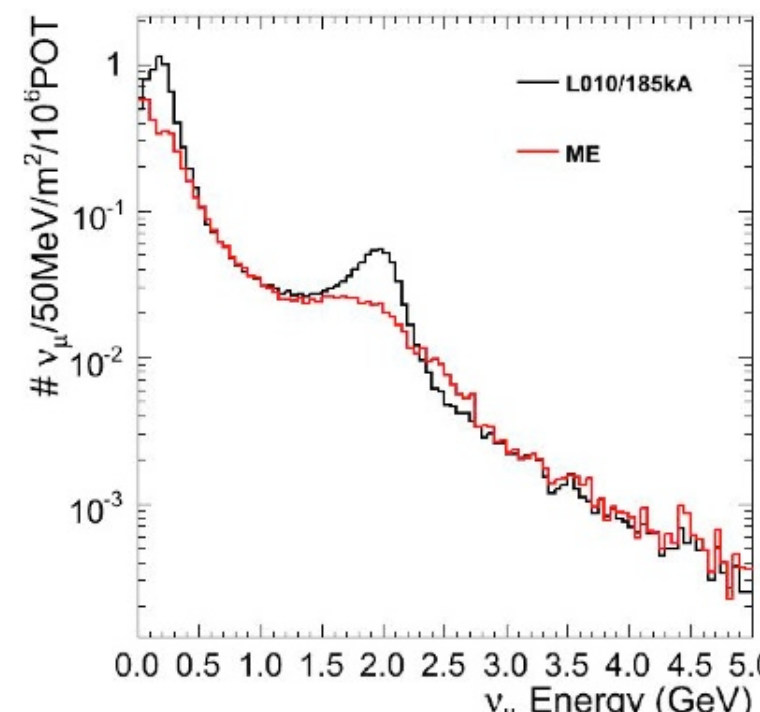
	BNB	NuMI
Total Events	**145k**	**60k**
ν_μ CCQE	68k	25k
NC π^0	8k	3k
ν_e CCQE	0.4k	1.2k
POT	6×10^{20}	8×10^{20}

Projected Event Rates for MicroBooNE in 2-3 years.

Neutrino Beams at Fermilab



Booster Flux



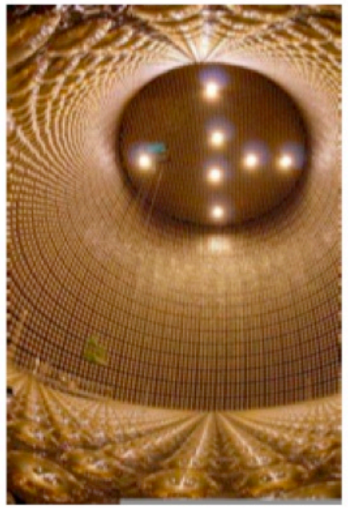
NuMI Off-Axis Flux

Massive Liquid Argon Detectors

Next Generation Neutrino Expts.

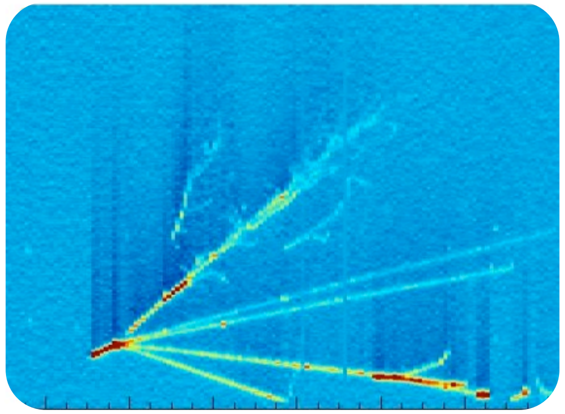
- To improve chances of observing CP-violation in the lepton sector in a reasonable time, need to build a very large detector(s).
- Deep Underground Science and Engineering Laboratory (DUSEL) at the Homestake Mine in South Dakota will be the home of these detectors.
- Two detector technologies considered (so far) for the future U.S. long-baseline program: Water Cerenkov and Liquid Argon
  - Water detector aiming for total fiducial mass of 300ktons, LAr aiming for 60 ktons.
  - LAr can be smaller but provide equivalent physics reach.
- These detectors will provide a very rich physics program, including: neutrino oscillations, supernova neutrinos, and proton decay.

Water Cerenkov
imaging detector



(3 x 100 kton modules
total = 300 kton)

Liquid Argon TPC
very fine-grained tracking detector



(20-60 kton)

LBNE Collaboration

- Long Baseline Neutrino Experiment (LBNE) collaboration is working on beam and near/far-detector ideas.

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(currently ~150 people from 33 institutions)

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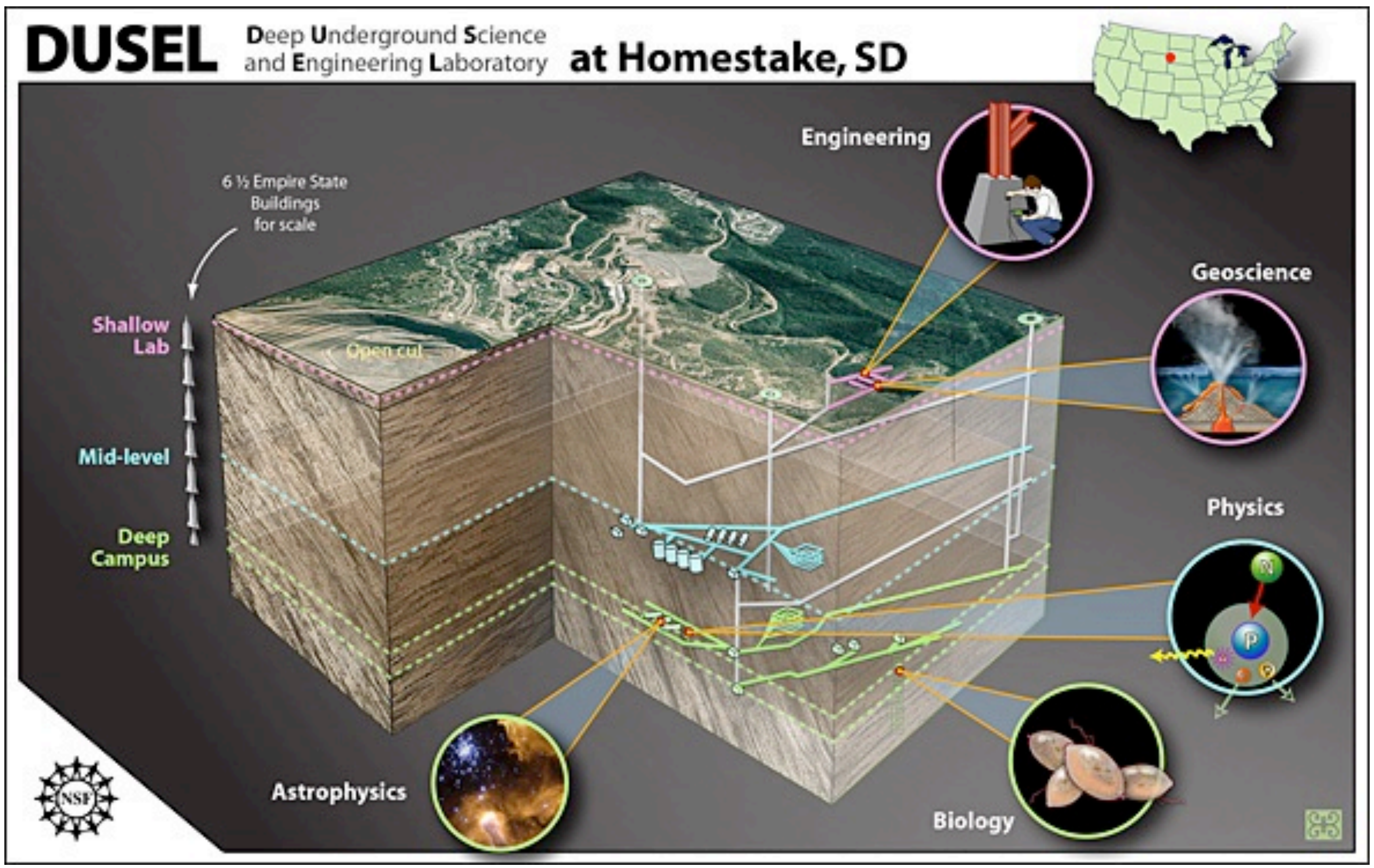
B. Fleming, M. Soderberg

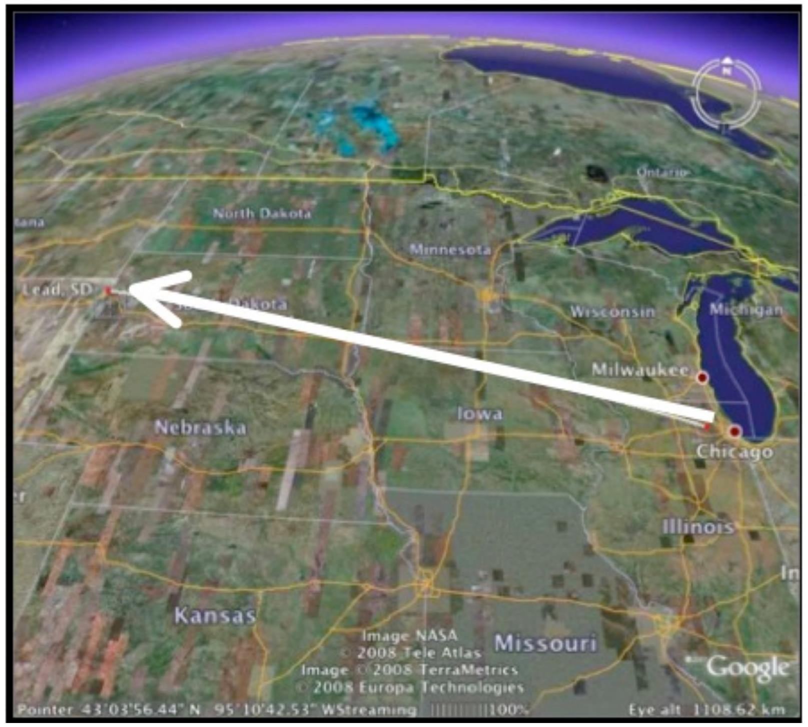
Recommendations from the Report of the P5 Panel to HEPAP, May 29, 2008:

"The panel recommends a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector in the proposed DUSEL laboratory and a high-intensity neutrino source at Fermilab"

Massive Detector Location

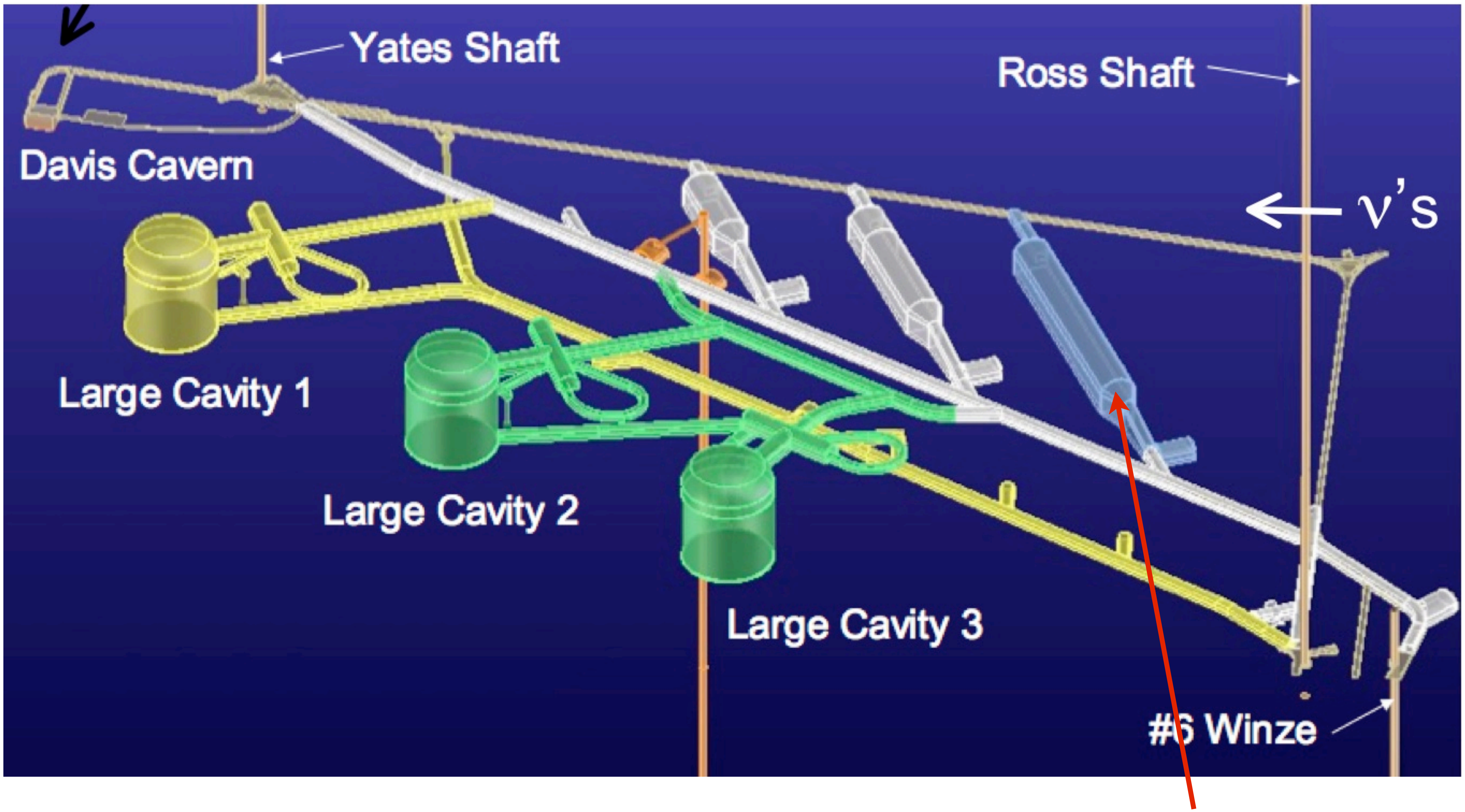
- Prefer to put this huge detector someplace deep to reduce cosmic background.
  - Exact depth required is still unknown (could be 300ft. or 4800ft. level)
- "Project X" at Fermilab could send intense neutrino beam 1300km to this far-site location.
  - 1st stage of LBNE plan does not include Project X (starts with 700kW beam, and a large far-site detector module)
  - Can upgrade this to Project X (2.3MW) beam + more modules





Neutrino beam from Fermilab to DUSEL

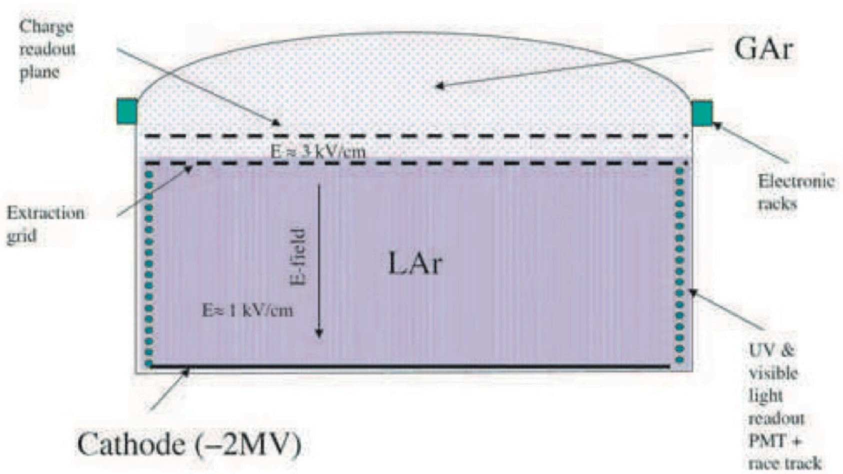
Massive Detector Location



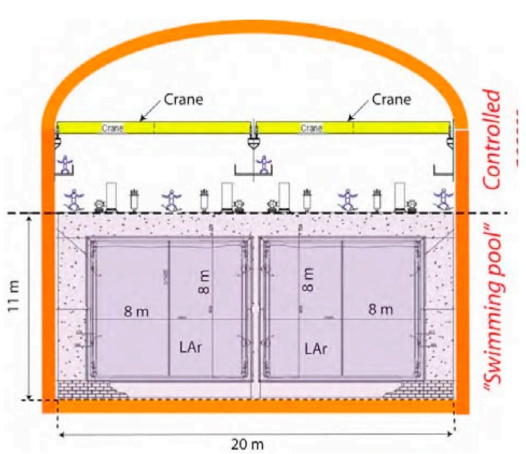
LArTPC experiment could reside in "lab modules", that can be oriented towards Fermilab.

Massive LAr Detectors

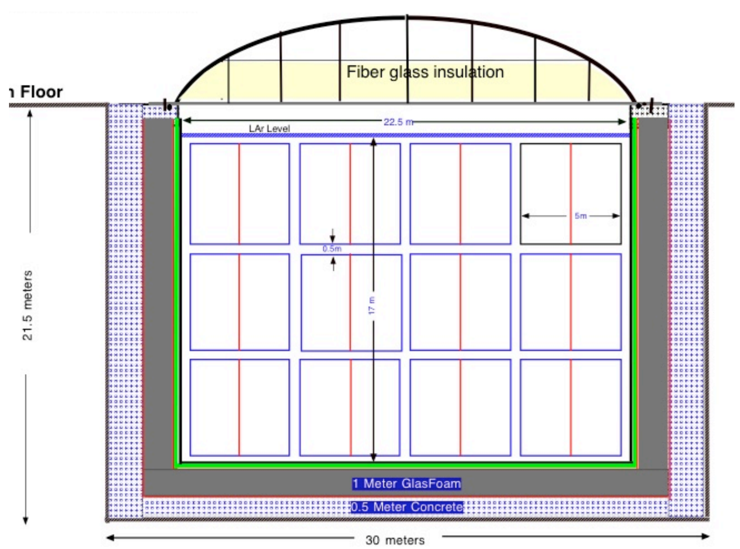
- Desired LArTPC detector mass is on the scale of 60 kilotons
- Many opinions on how to approach something this big...building it up out of smaller modules seems desirable.



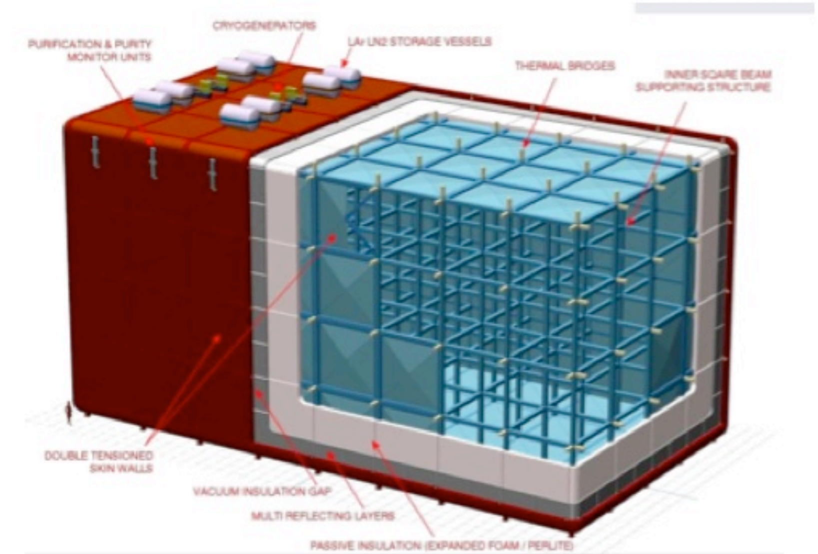
GLACIER

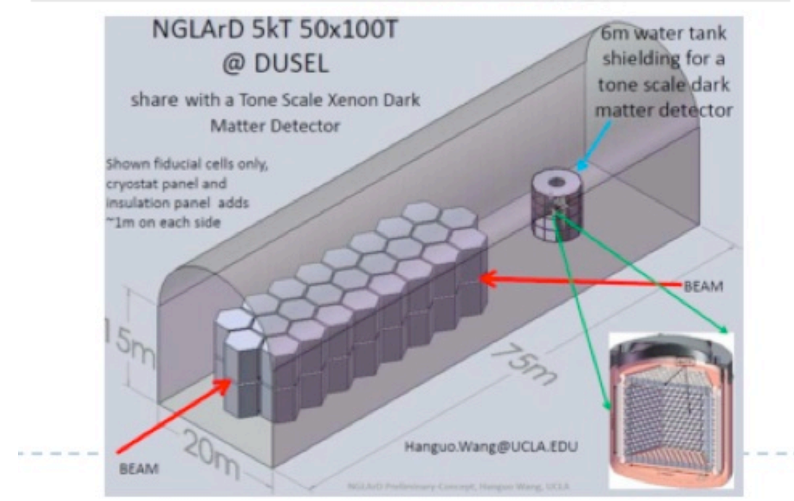


MODULAR



Membrane-style cryostat anchored to rock walls

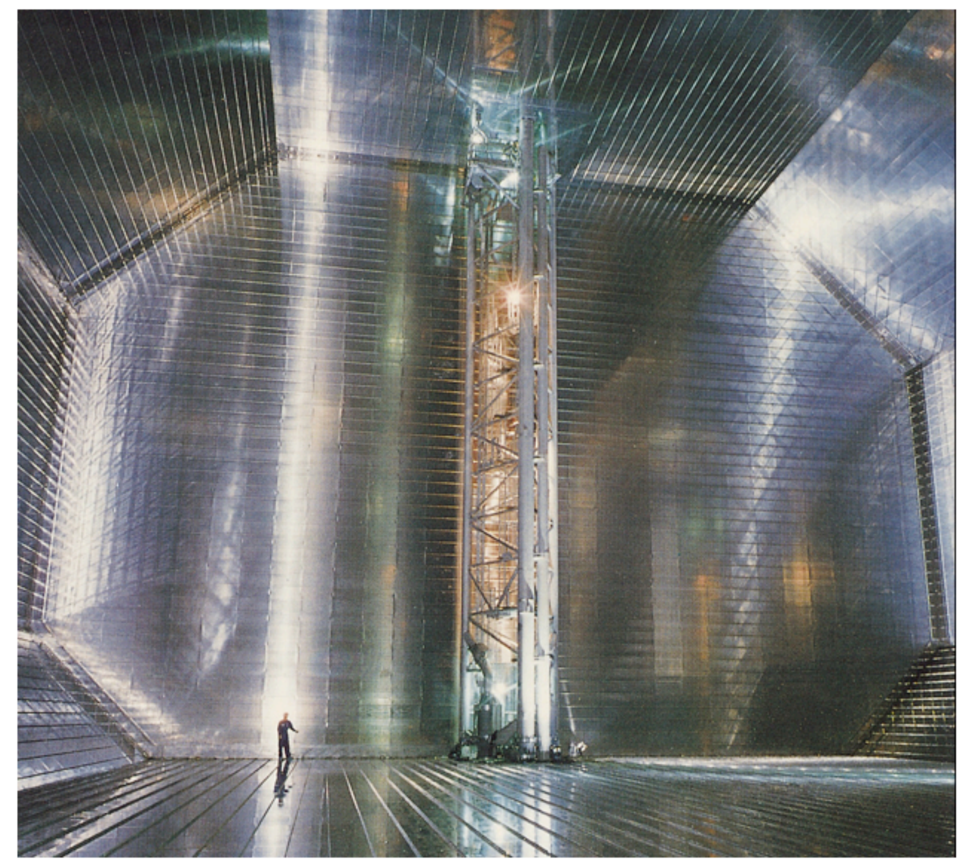




Massive LAr Detectors

- Massive storage of cryogenic liquids not such a crazy idea....
- Industrial companies use ocean liners to transport Liquified Natural Gas (LNG) since it's the most economical way (gas density is 1/600 of liquid) to move a large quantity of natural gas.
- LNG cooled to -162C (111 K)...almost as cold as LAr (87 K).

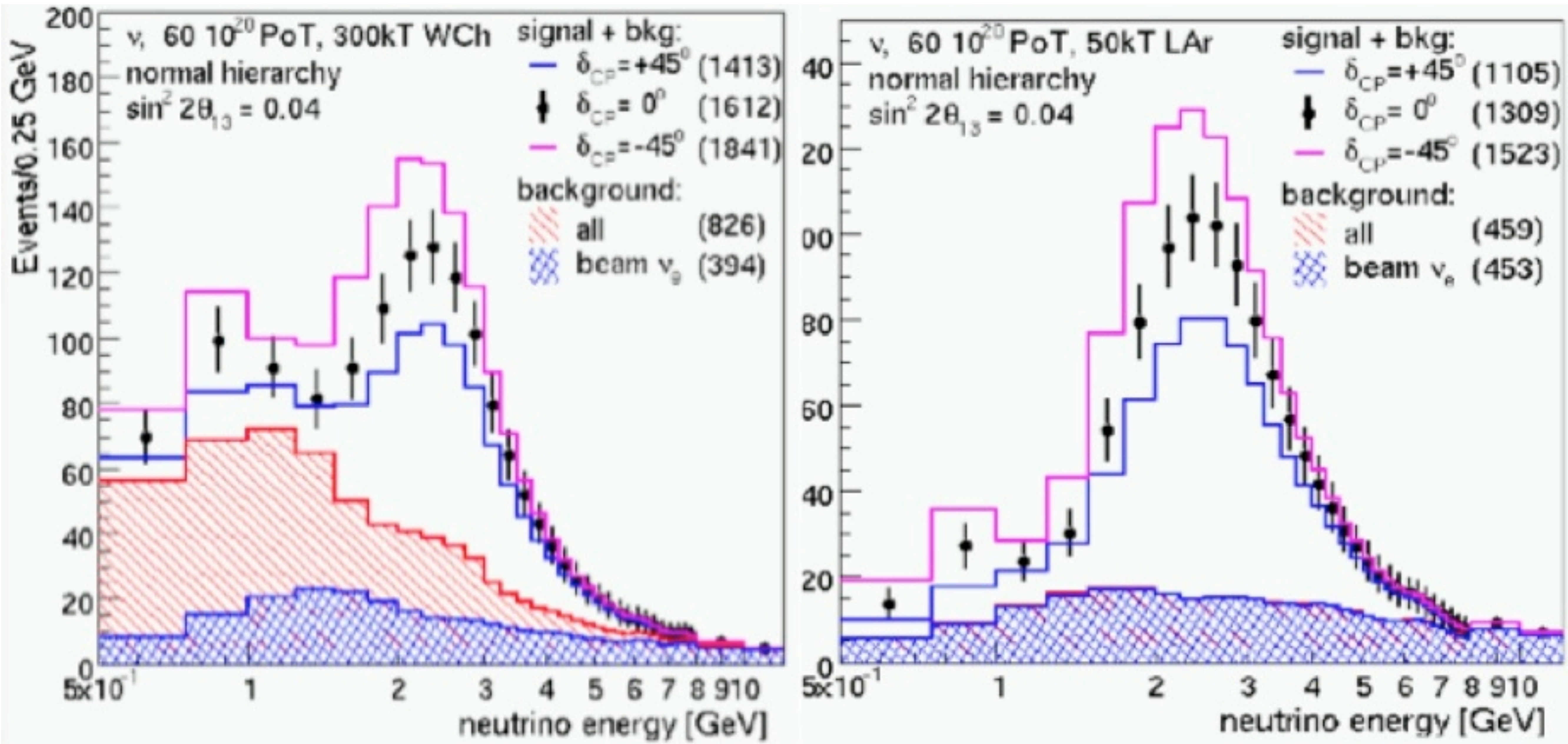
Q-Max LNG Carrier
Capacity: 266,000m^3



"Membrane" Interior

Massive Detector: Physics Reach

- Expected “appearance” distributions:

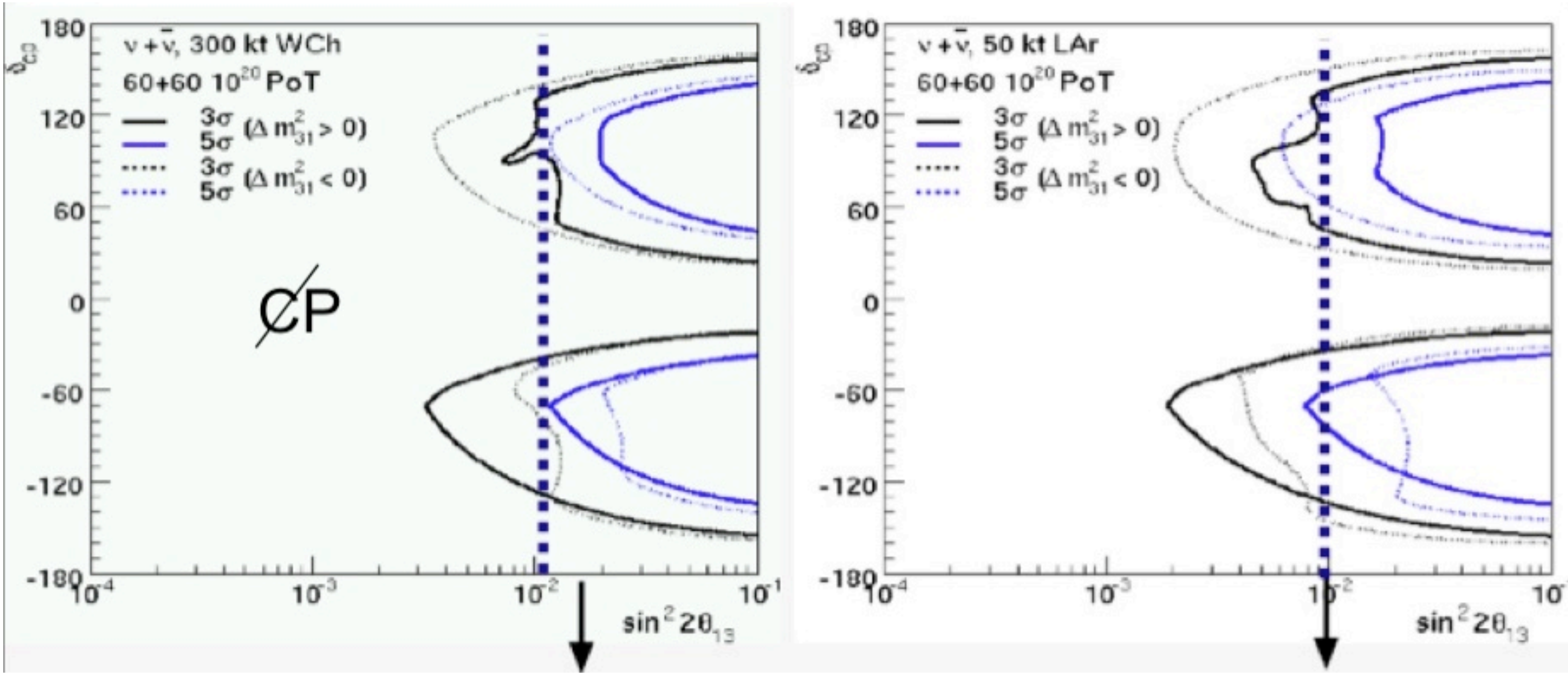


- Plots Assume:
  - WBB design for LBNE
  - 120 GeV Protons
  - 5% background uncertainty
  - ν + anti-ν running for CP sensitivities

Plot by M. Dierckxsens

Massive Detector: Physics Reach

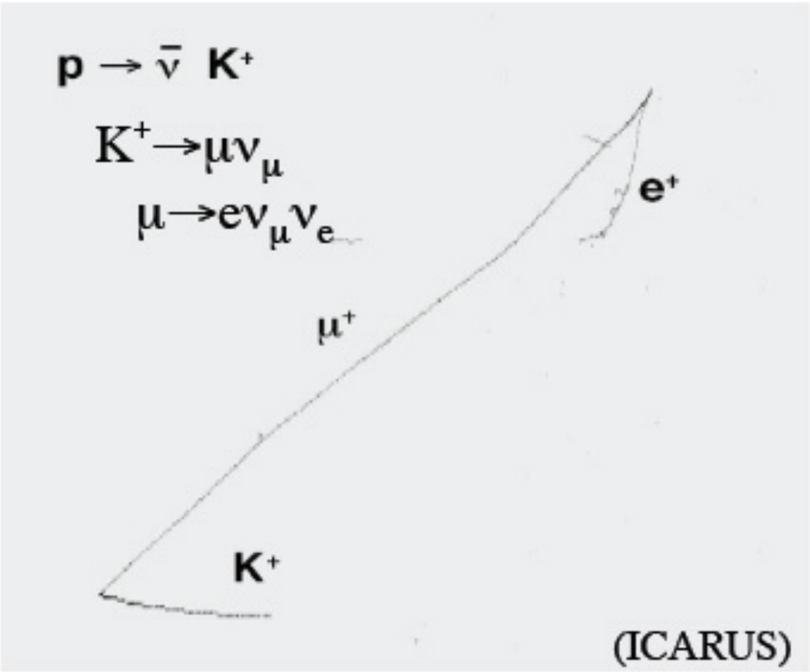
- Tremendous sensitivity when large LArTPC and intense neutrino beam are combined.
- CP-violation sensitivities below show ~6:1 equivalence between Water Cerenkov and LAr.



- Plots Assume:
  - WBB design for LBNE
  - 120 GeV Protons
  - 5% background uncertainty
  - ν + anti-ν running for CP sensitivities

Plot by M. Dierckxsens

Massive Detector: Proton Decay



In this proton decay channel Kaon is produced below Cerenkov threshold, so LArTPCs have advantage.

$p \rightarrow K^{+}\nu$

Plot by E. Kearns

- Plots Assume:
  - WC Efficiency = 0.14
  - WC Background = 1.2evts/100kty
  - LAr Efficiency = 0.98
  - LAr Background = 0.1evts/100kty
  - $N_{obs} = N_{bg}$

Massive Detector: SuperNova ν's

Sizeable statistics for a SuperNova observed by either detector.

100 kt H_2O, SN@10 kpc

Interaction	Rates (x10^4)
$\overline{\nu}_e + p \rightarrow n + e^+$	2.3
$\nu + e \rightarrow \nu + e$	0.1
$\nu_x + {}^{16}O \rightarrow {}^{16}O + \nu_x$	0.05
$\nu_x + {}^{16}O \rightarrow {}^{16}F + e$	0.2

100 kt of LAr, SN @ 10 kpc

Interaction	Rates ($\times 10^4$)
ν_e CC (^{40}Ar, ^{40}K*)	2.5
ν_x NC (^{40}Ar*)	3.0
ν_x ES	0.1
anti–ν_e CC (^{40}Ar, ^{40}Cl*)	0.054

Conclusion

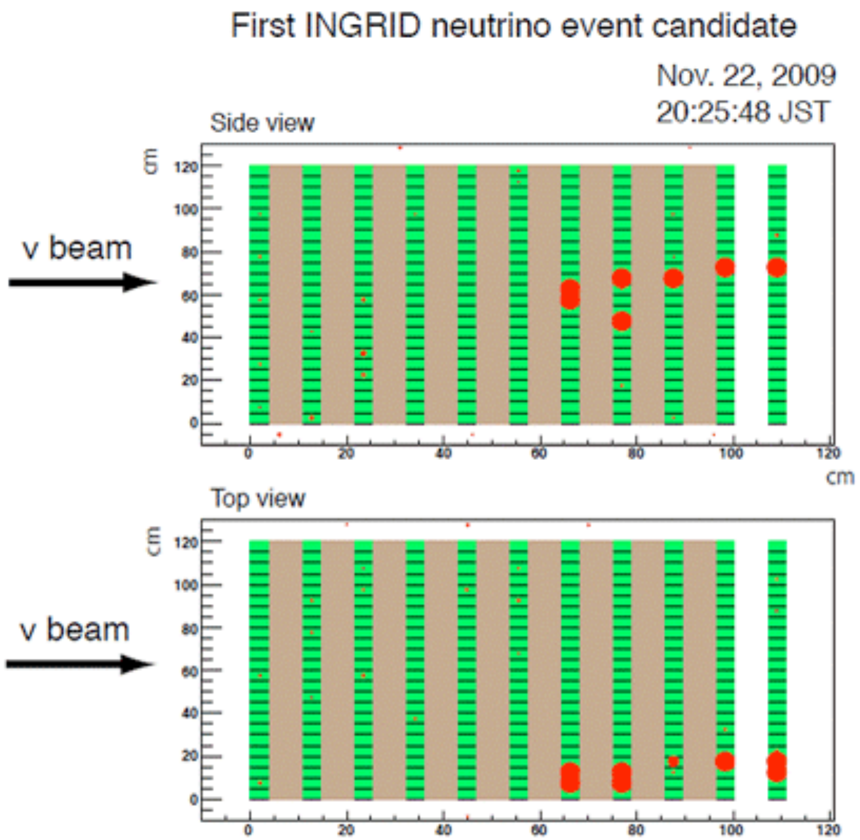
- Neutrinos are exciting and could play a role in answering some very important questions, like matter-antimatter asymmetry of the universe.
- **Neutrinos will be a major component of the future U.S. HEP program for the Intensity Frontier.**
- Liquid Argon detectors provide exceptional capabilities for neutrino physics, and will play a major role in this program.

Back-Up Slides

Long Baseline Experiments

- Several neutrino experiments will be running in the coming years
  - MINOS still running for several more years.
  - NOvA (L=810km, 0.9° off-axis) construction has recently begun.
  - T2K (L=295km, 2.5° off-axis) commissioning now in Japan.

Both hope to measure θ_{13}

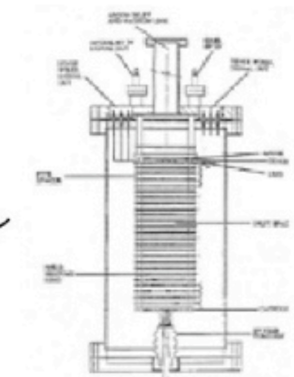


First T2K Near-Detector Events

NOvA far-detector Location in Minnesota

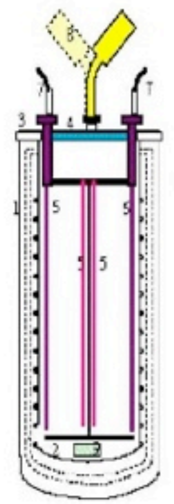
Liquid Argon Abroad

There is a considerable history of development in Europe for ICARUS program



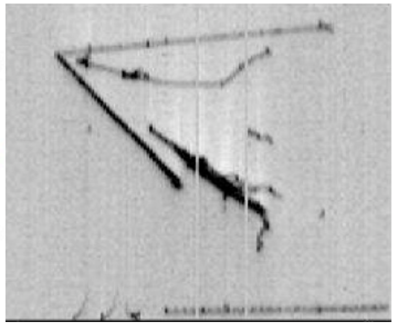
24 cm drift wires chamber

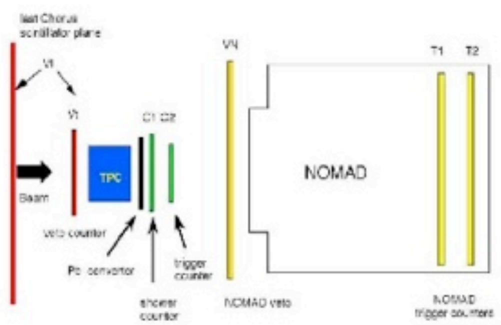
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.



3 ton prototype

1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.



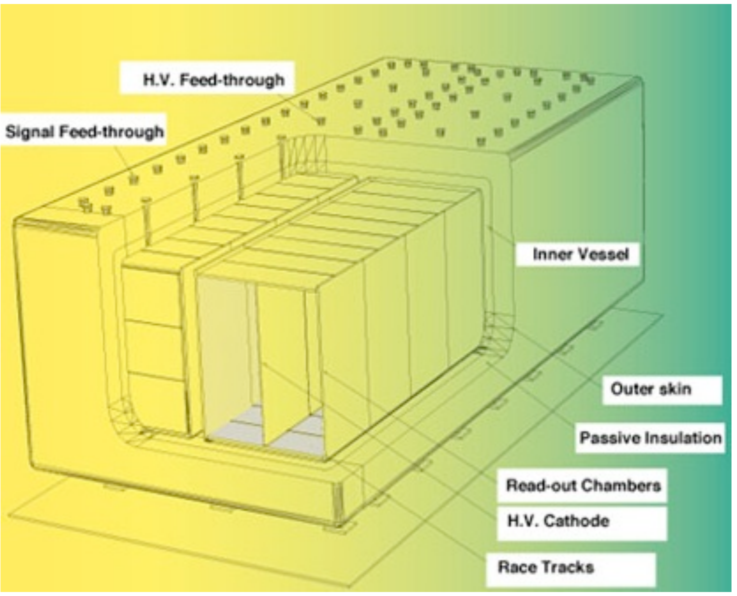


50 litres prototype 1.4 m drift chamber

1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

10 m^3 industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.



ICARUS T600

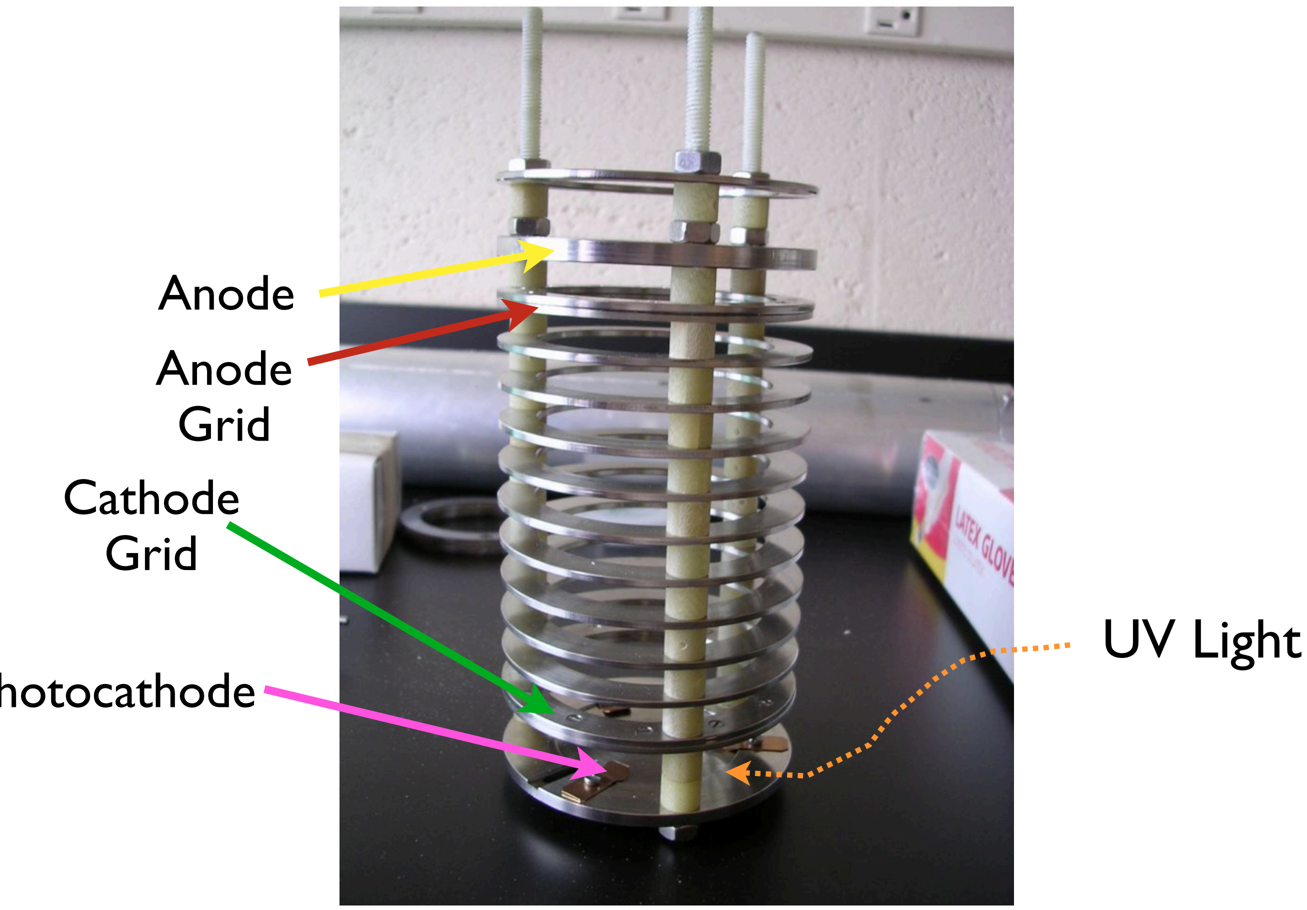
LArTPC Challenges

- Argon purity level required (parts per trillion) is demanding.
  - High purity necessary for long-drifts (~5m) characteristic of a very large detector.
  - Detector materials' impact on purity must be understood.
- Safety issues.
  - Oxygen Deficiency Hazard (ODH) if argon spills in a confined space.
  - Pressurized vessels need to have adequate safety controls.
- Electronics.
  - Wire signals are small, so sources of electronic noise must be strictly controlled.
  - High sampling rate × long drift × many wires = Flood of raw data.
- Vacuum/Cryogenic environments take special care...
  - Every penetration into the cryostat must be leak tight.
  - Heat load on the system must be understood for stable cryogenic operation.

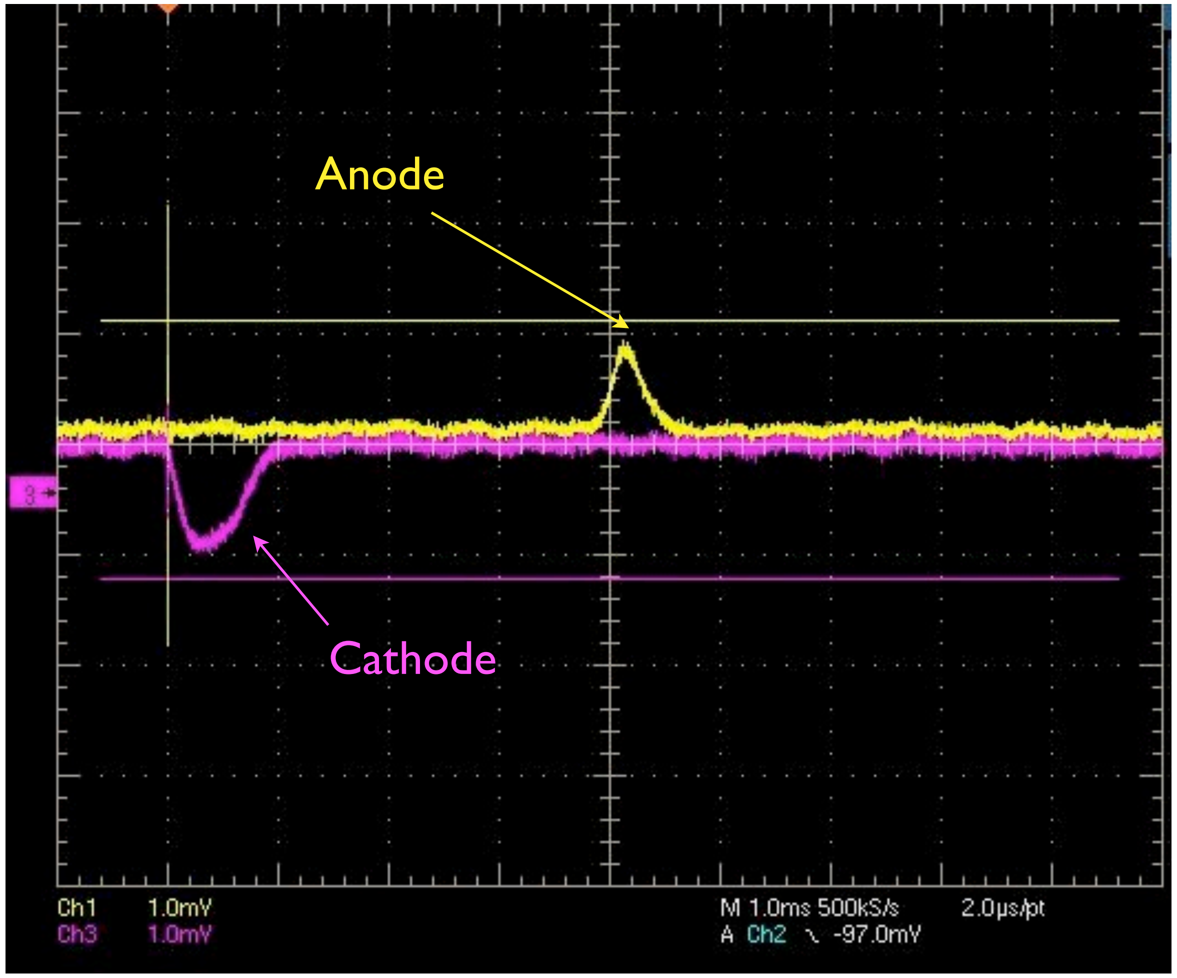
Current program of LArTPC development will address many of these challenges

Argon Purity

- To drift electrons through several meters of liquid argon, electronegative impurities (Oxygen, Water, etc..) must be removed to achieve necessary ionization electron lifetimes.
- We send the LAr through TRIGON filter(s) to remove contaminants.
- Purity monitors are used *in-situ* to measure charge absorbed during drift through liquid argon.
- Fermilab group has done extensive work to develop new filters* and purity monitors.
  - Can routinely achieve lifetimes of 10ms (i.e. - corresponds to drift lengths of >10 meters !)



ICARUS style Purity Monitor

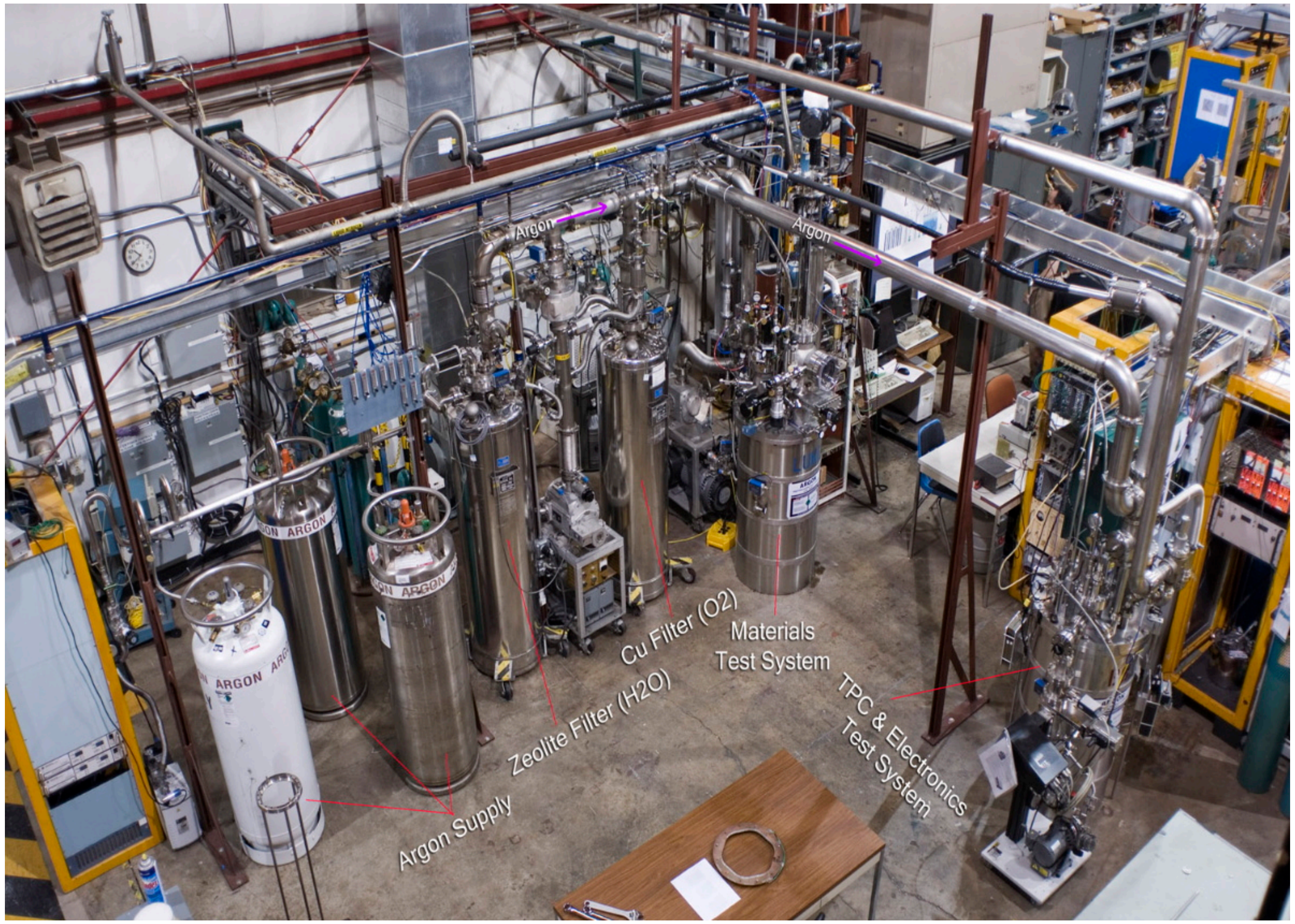


FNAL Purity signal (4ms)

Refs:

*.) *A Regenerable Filter for Liquid Argon Purification*, A. Curioni *et. al*; *NIM A* 605 (2009) 306-311

Purity Systems at Fermilab



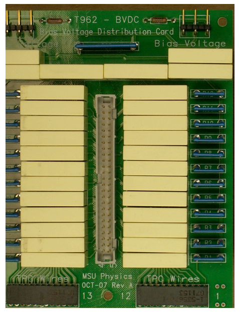
Materials Test Stand at Fermilab

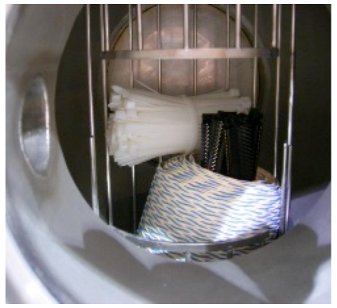
Cryostat for 30-ton test

- Controlling argon purity is vital for the LArTPCs to function.
- Fermilab group has two projects focused on better understanding argon purity.
  - Materials Test Stand is used to study the impact of different materials on argon purity.
  - 30-ton purity demonstration will shed light on whether purity can be achieved starting from a non-evacuated environment.

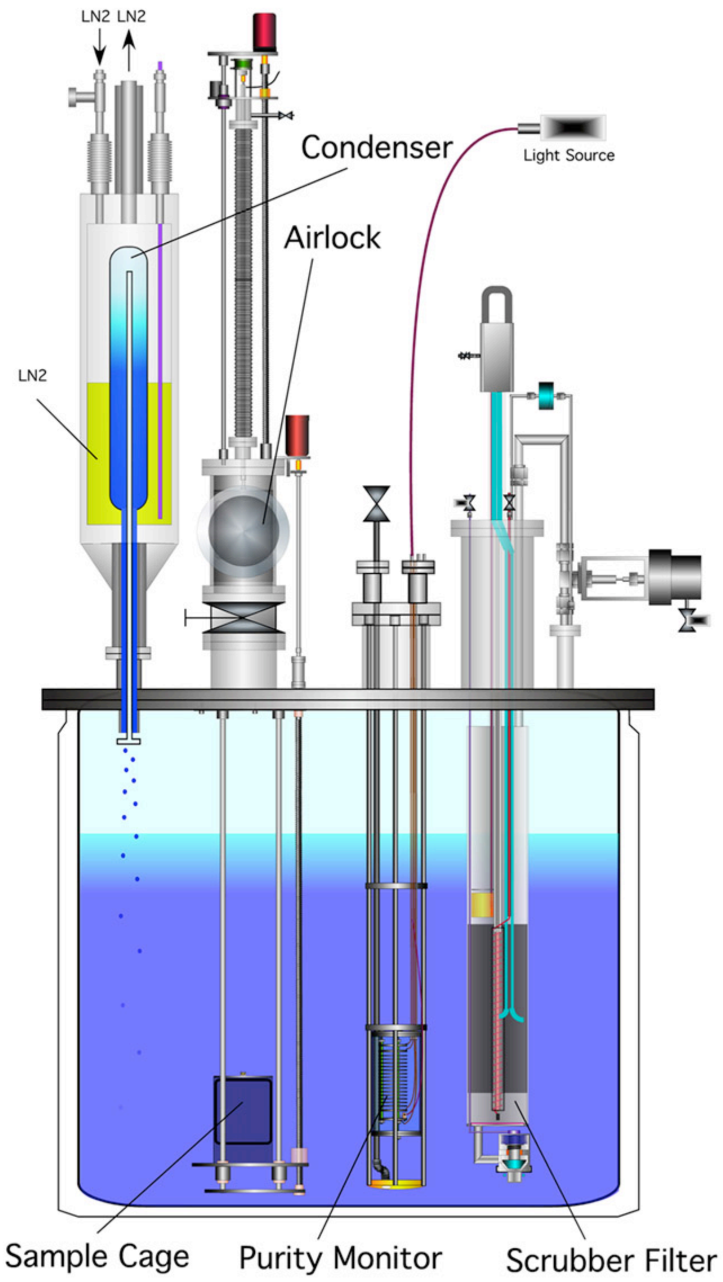
Materials Test System at Fermilab

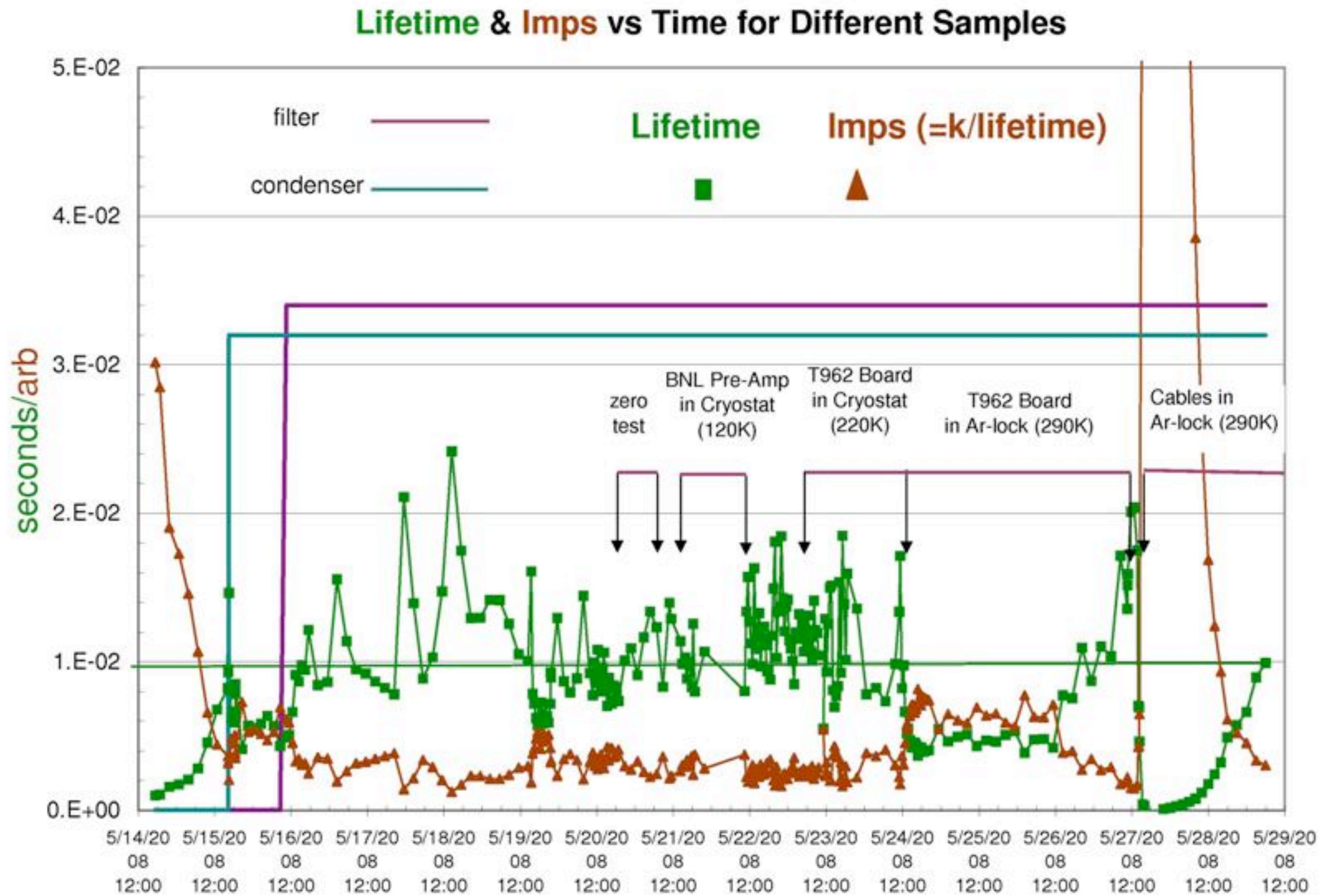

BNL 4-ch Amp


ArgoNeuT Bias Board


Cables/Cable-Tie Bundle

Measurements with the Materials Test System

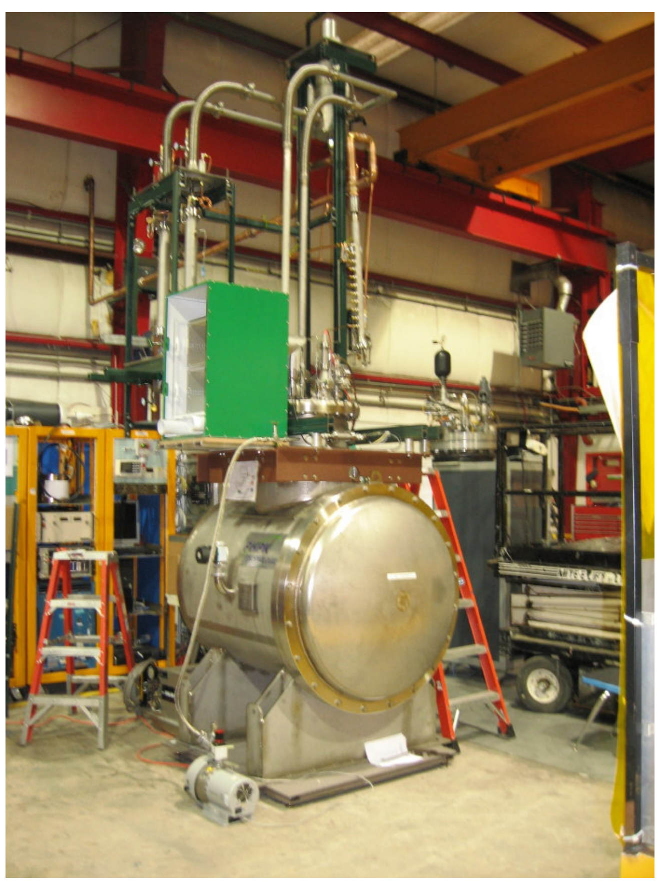




ArgoNeuT: Underground

Many safety issues addressed to prepare for move underground and maintain ODH-0 rating of NuMI tunnel:

- ArgoNeuT sits in a bathtub, which acts as tertiary containment in case both cryostats fail.
- All pipes/hoses/valves/vessels outfitted with relief valves.
- Relief piping is routed to vent line (runs up and out shaft), to ensure no argon released in tunnel.
- 2 ODH monitors trigger (many) alarms if potential leak is detected.
- Slow control system mirrored on screens in tunnel and online.

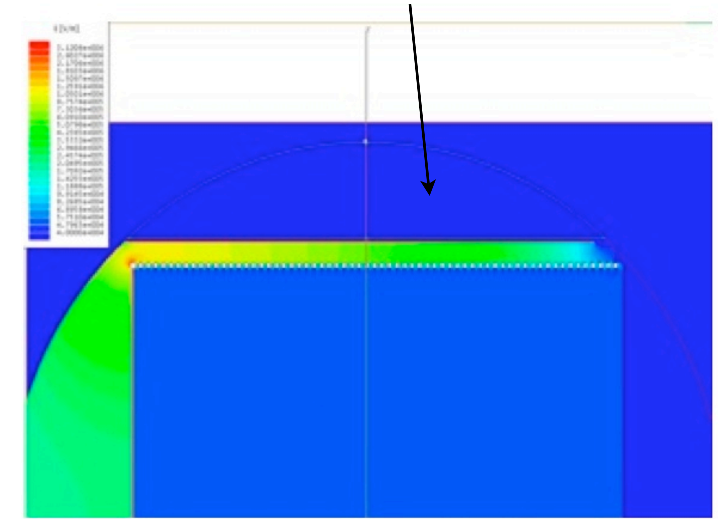


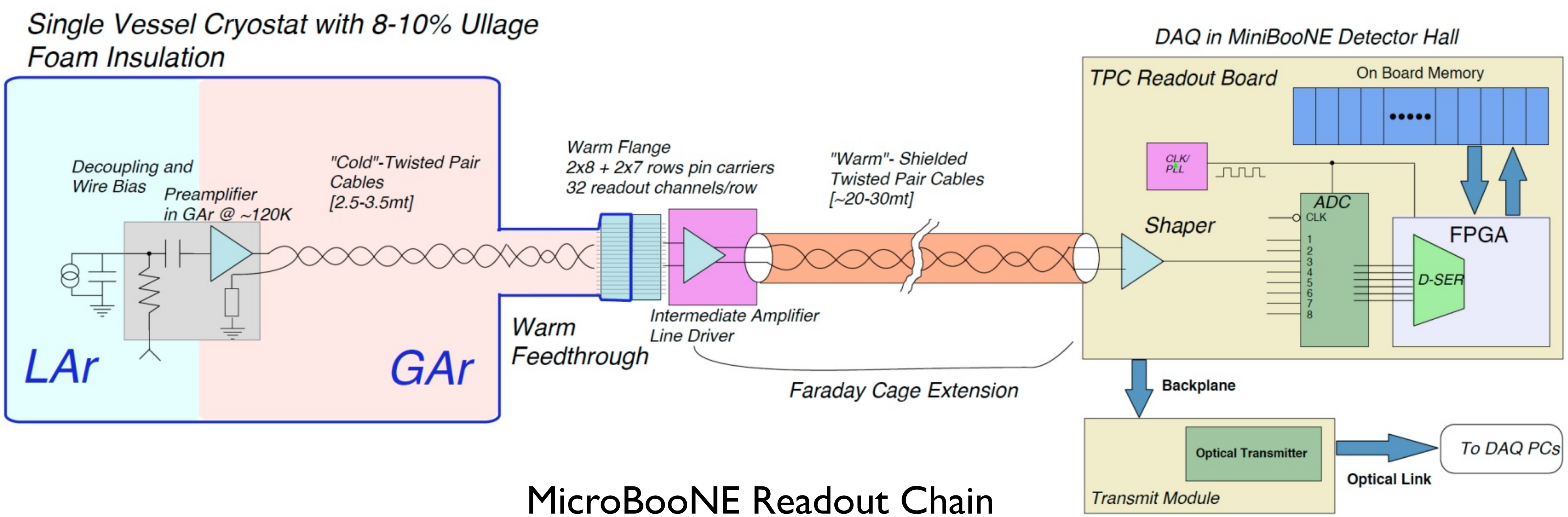
ArgoNeuT under construction (summer 2008).

MicroBooNE: Cold Electronics

- MicroBooNE has 10000 channels spread over 3 instrumented wireplanes.
- Preamplifiers will be placed inside the cryostat in cold (120K) argon gas.
  - x3 better S/N compared with room temperature performance.
  - Necessary step along the path to large detectors where signals must make long transits.
- Many future electronics questions can be answered by MicroBooNE.
  - JFET/CMOS performance (~4 year development required for CMOS).
  - Maintaining purity with electronics inside cryostat.
  - Controlling heat load due to power output of electronics in cryostat.
  - Multiplexing signals inside tank (helps reduce required feedthroughs).

PreAmps in cold gas

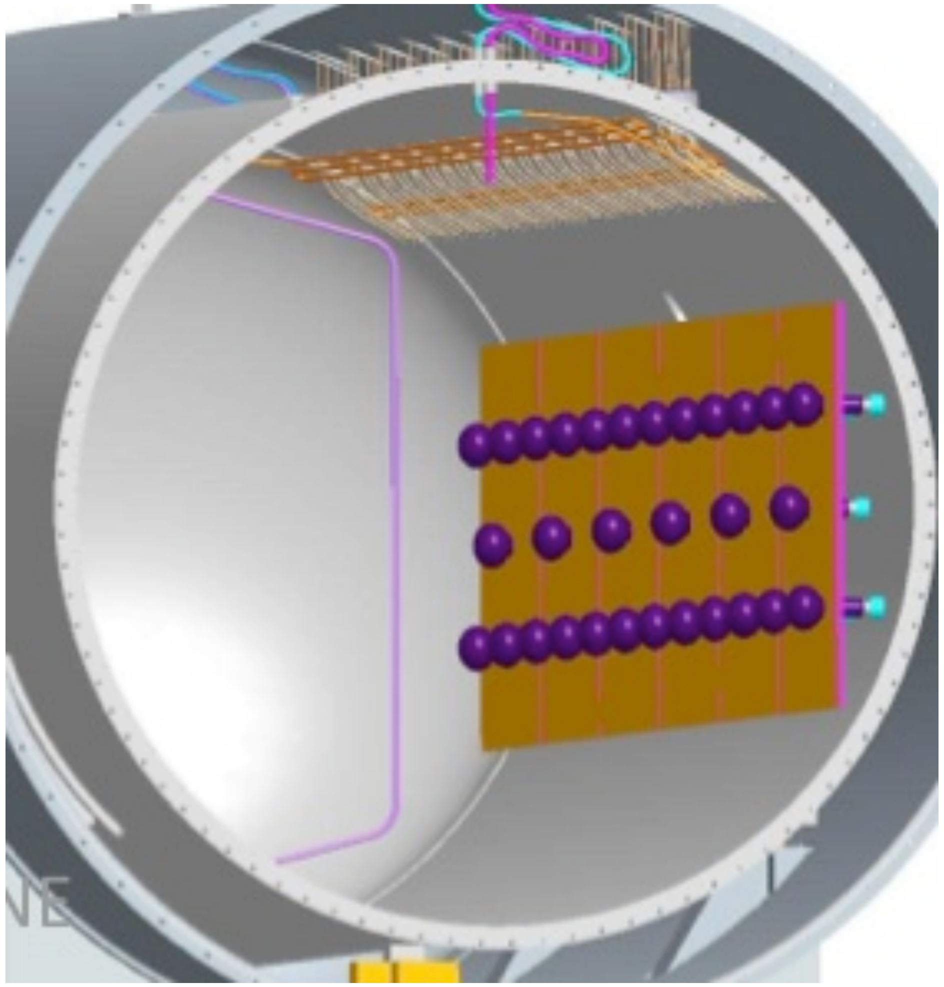




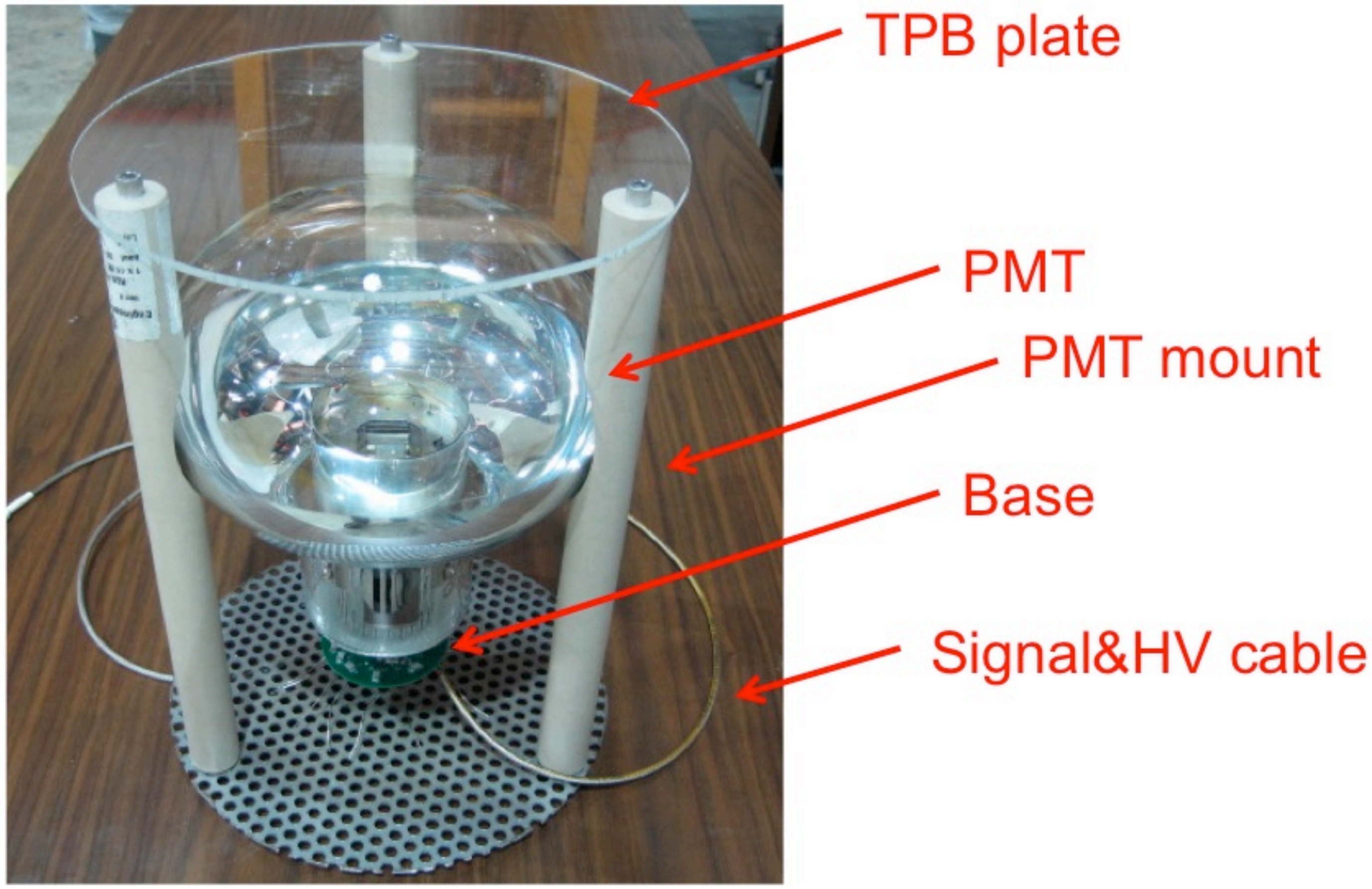
MicroBooNE Readout Chain

MicroBooNE: Light Collection

- ~30 PMTs to aid in event t_0 determination and help reduce data load
  - *i.e.* - require coincidence of beam spill and light signal in PMTs before recording data.
- Plan to use 8" tubes from Hamamatsu
- Operate with wavelength shifter (TPB = tetraphenyl-butadiene) to allow collection of VUV light.
- Design work on PMT mount/base/geometry/feedthroughs/etc.. ongoing.

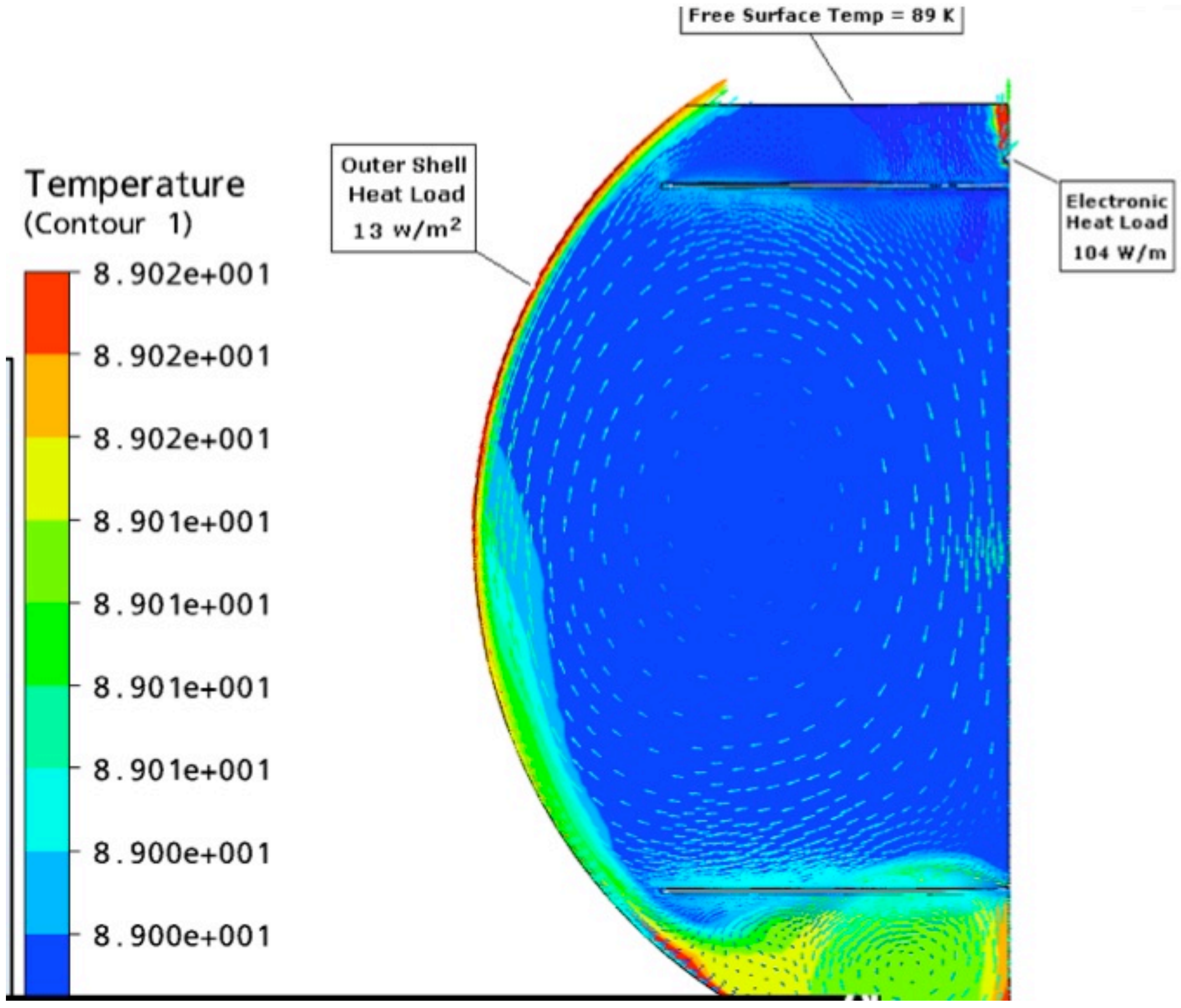


~30 PMTs facing TPC

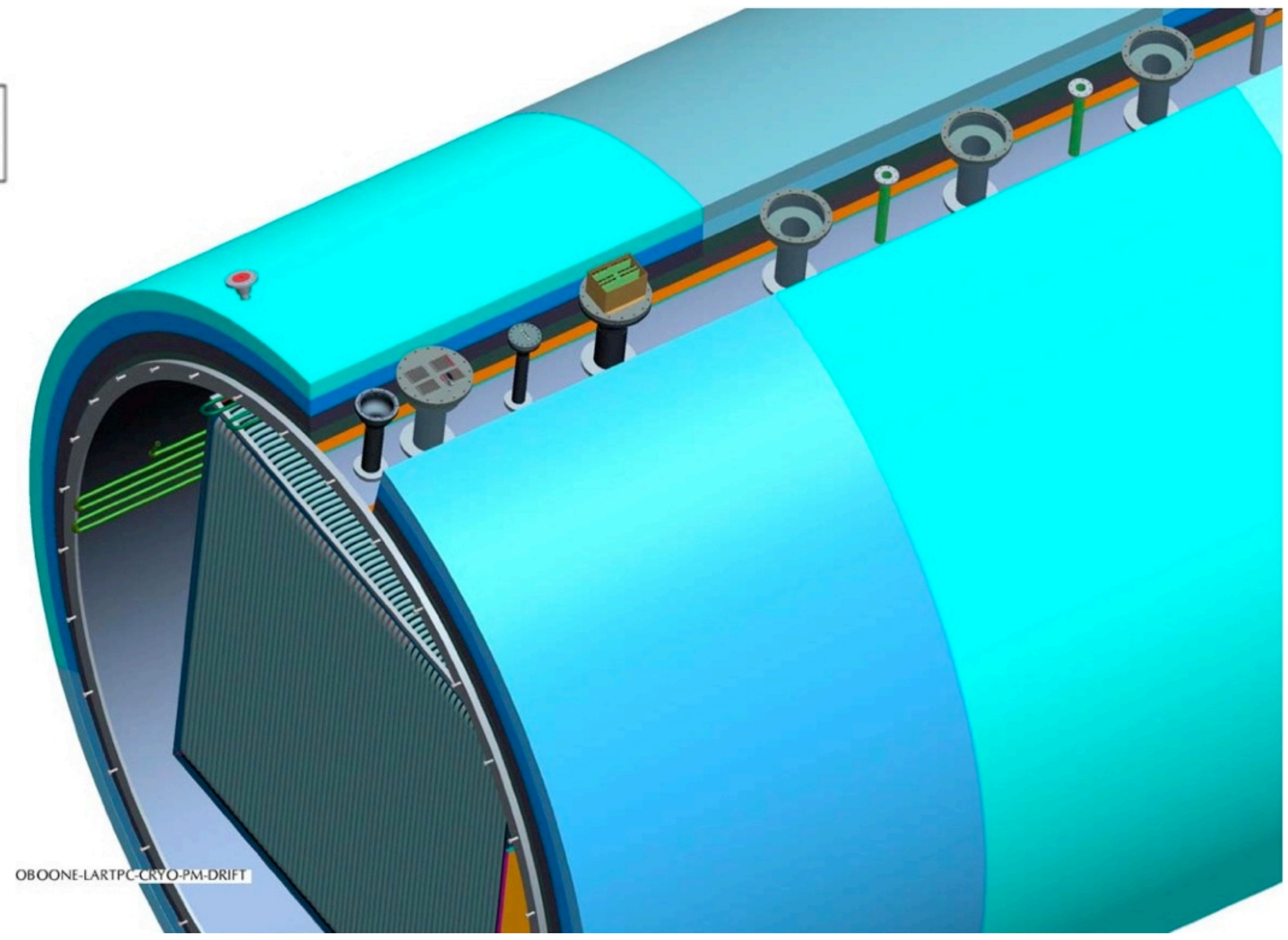


MicroBooNE Cryogenics

- Preliminary studies have been performed to understand thermal load of system.
- ~16 inches (~40 cm) glass foam insulation
- 3.4kW total load ($13 W/m^2$)
- Temp. gradient <<0.1K - crucial to reducing track distortions.
- Services and TPC integration currently being designed.



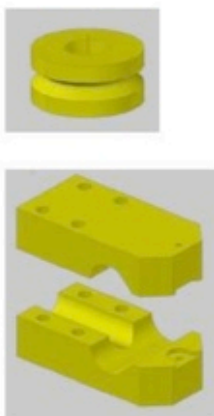
Temperature distribution

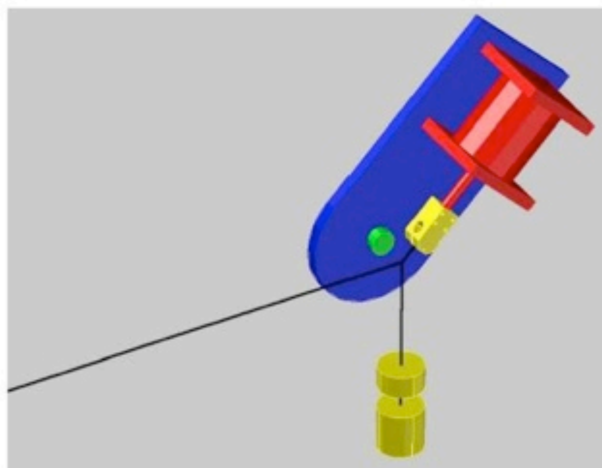


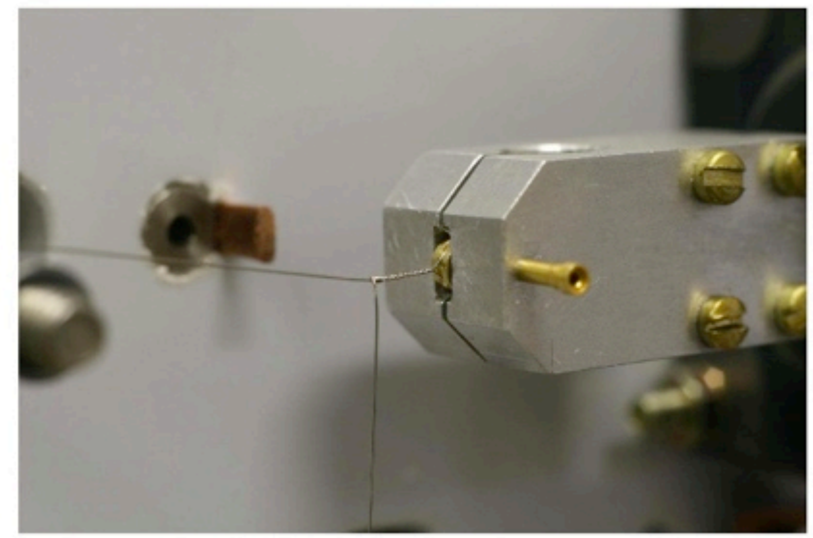
Detailed view of insulation/feedthroughs

MicroBooNE Wire Properties

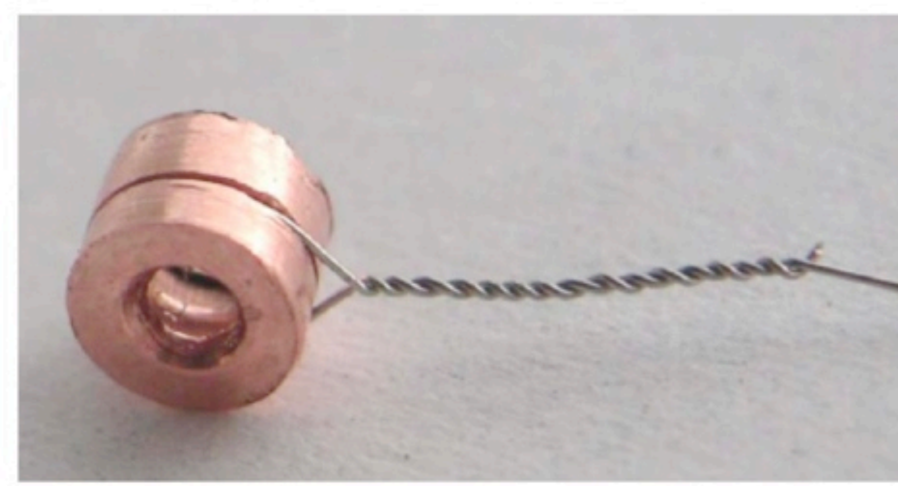
- Have studied properties of CuBe vs. gold-coated Stainless Steel wire.
- 1kg tension → 7mm expansion (on 2.5m long wire)
- Wire contraction when cooled to 90K (and frame is at RT): 6.8mm
- Nominal tension ~1kg







	SS304V (Fort Wayne)	CuBe (Little Falls Alloy)
Young's modulus @ RT	170GPa	121GPa
Young's modulus @ LN2	183GPa (8% increase)	136GPa (12% increase)
Integral CTE	0.22%	0.29%
Tension increase due to cooling	~750g	~730g
Max. tension with termination	~3kg	~2kg



MicroBooNE: Wire Connections

- Wire connections from 3 wireplanes made in tight space
- Decoupling capacitors located on wireplane assembly.
- BNL group has developed wire winding apparatus.
- Several wires being considered. Must withstand tension increase of cooldown.