Status of the MicroBooNE LArTPC and Prospective low-energy neutrino interaction measurements in Argon

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(on behalf of the MicroBooNE collaboration)

NuInt14, London (UK)

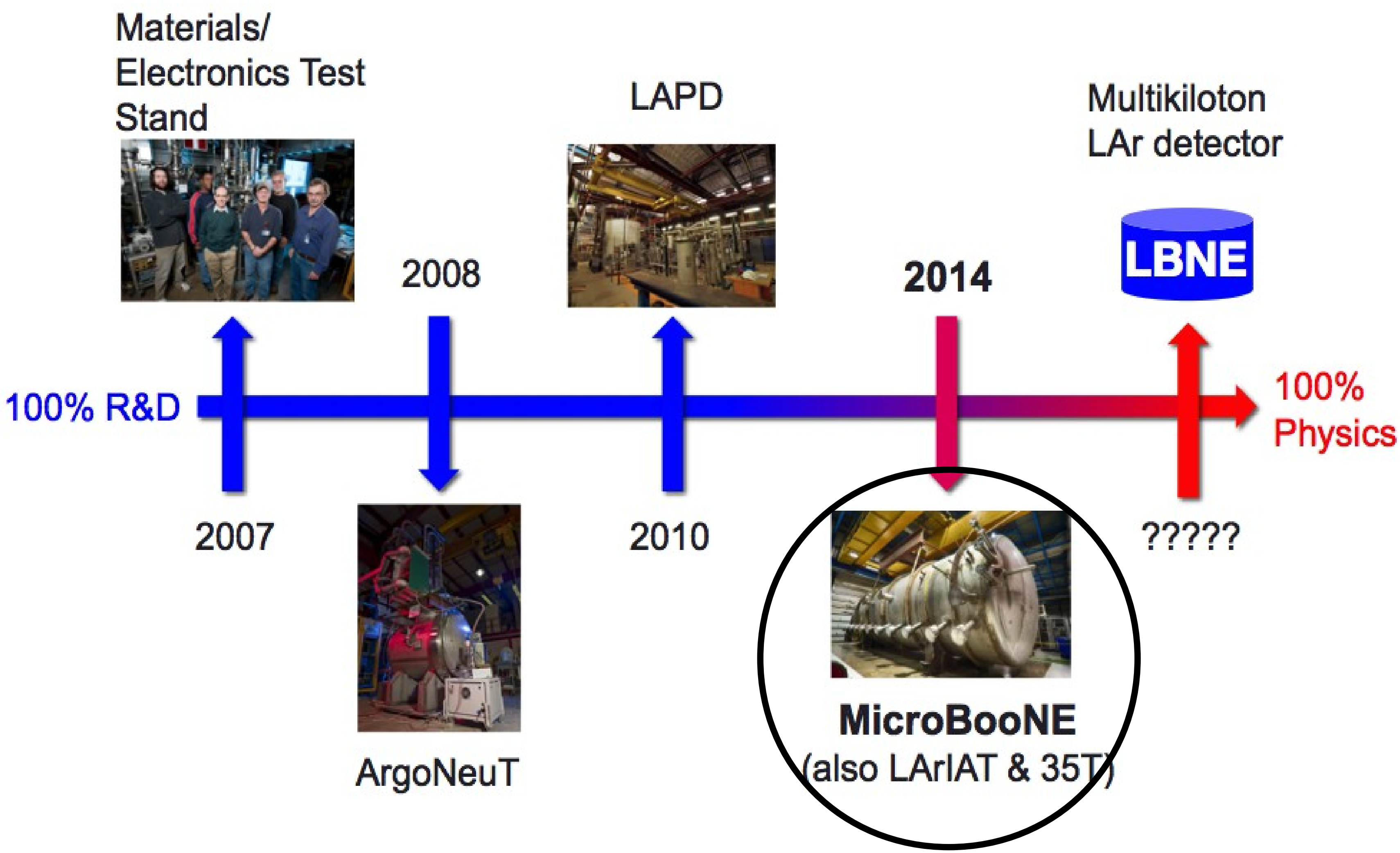
Introduction

- **Liquid argon time projection chambers (LArTPC) are quickly becoming the technology choice for future neutrino detectors**
  - **Make great precision neutrino detectors**
    offer excellent spatial resolution and calorimetry
  - **Can address wide array of physics goals**
    low-energy neutrino cross section measurements, proton decay searches, supernova neutrinos, dark matter searches etc.

- **MicroBooNE is a new 170-ton LArTPC neutrino experiment (largest so far in the U.S.!) being built on the Fermilab Booster Neutrino Beam (BNB) line.**

  Main physics goals
  - Address the low-energy electron-like excess observed by the MiniBooNE experiment
  - Make first high-statistics measurement of low-energy (~1GeV) neutrino interactions in Argon and study nuclear effects

Role of MicroBooNE in LArTPC R&D



MicroBooNE is an important step towards LArTPC R&D in establishing large-scale detectors in the U.S.

Outline

- Principle of LArTPC & why LAr?
- The MicroBooNE LArTPC
  - Design and current status
- MicroBooNE physics
  - MicroBooNE location
  - Physics motivation
  - Cross section measurements
- Summary

Why LAr as neutrino target?

Noble liquids, in general, make great neutrino targets:

→ dense!

→ easily ionizable

→ highly scintillating (provides another detection method!)

→ If pure => high electron mobility => long drift lengths!

→ Great dielectric medium => can hold very high voltages etc.

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm³]	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	

From M. Soderberg

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LAr is all of that
& abundant (1% of atmosphere)..

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From M. Soderberg

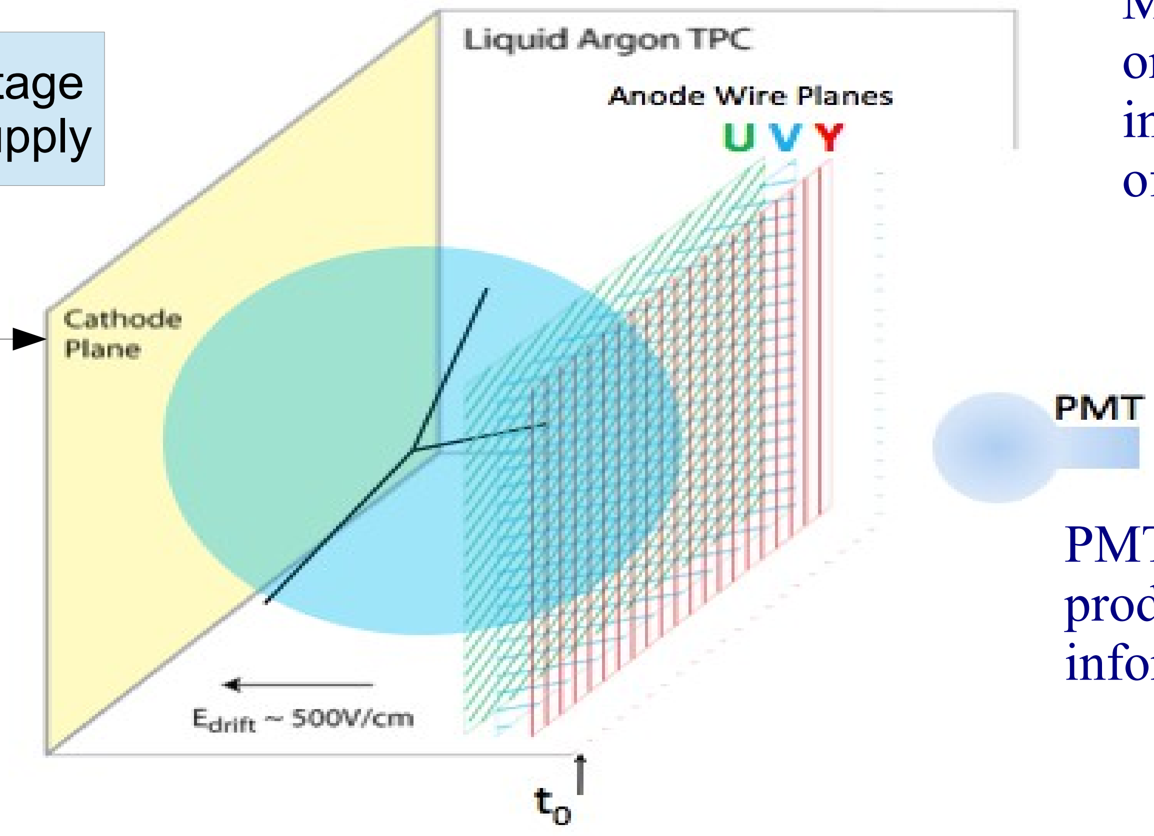
Principal of LArTPC

Neutrino interactions with LAr in the TPC produces charged particles that cause Ionization and excitation of Argon

→ High E field drifts electrons towards finely segmented anode wire planes

→ Excitation of Ar produces prompt scintillation light giving "t_0" of the interaction

High voltage power supply



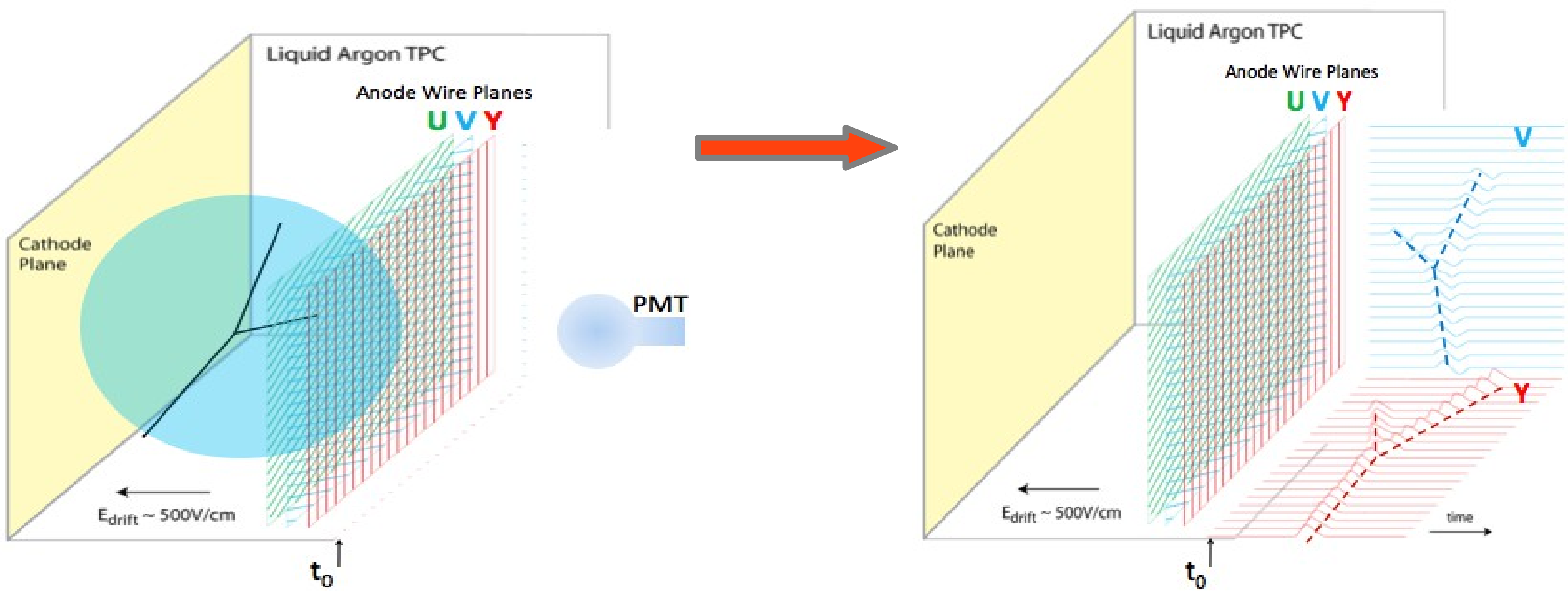
Multiple wire orientations give independent views of the same event!

PMTs detect the light produced giving timing information

Principal of LArTPC

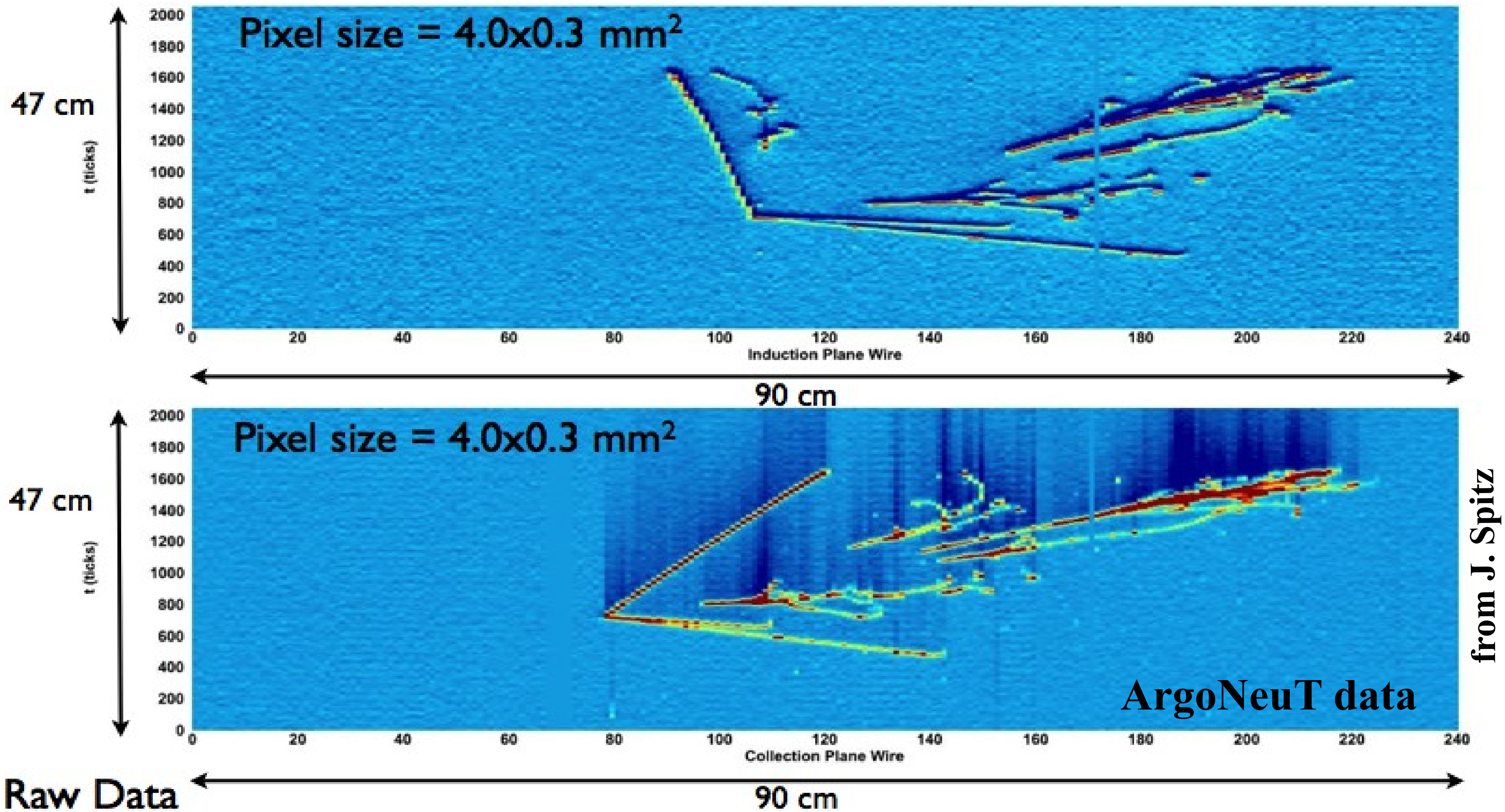
LArTPCs make 3D reconstruction possible!

- wire planes give 2D position information
- the third dimension is obtained by combining timing information with drift velocity (v_d): $x = v_d(t-t_0)$ $\rightarrow$ hence, a "Time projection chamber"



LArTPCs are “imaging” detectors

Bubble chamber quality images only in HD!

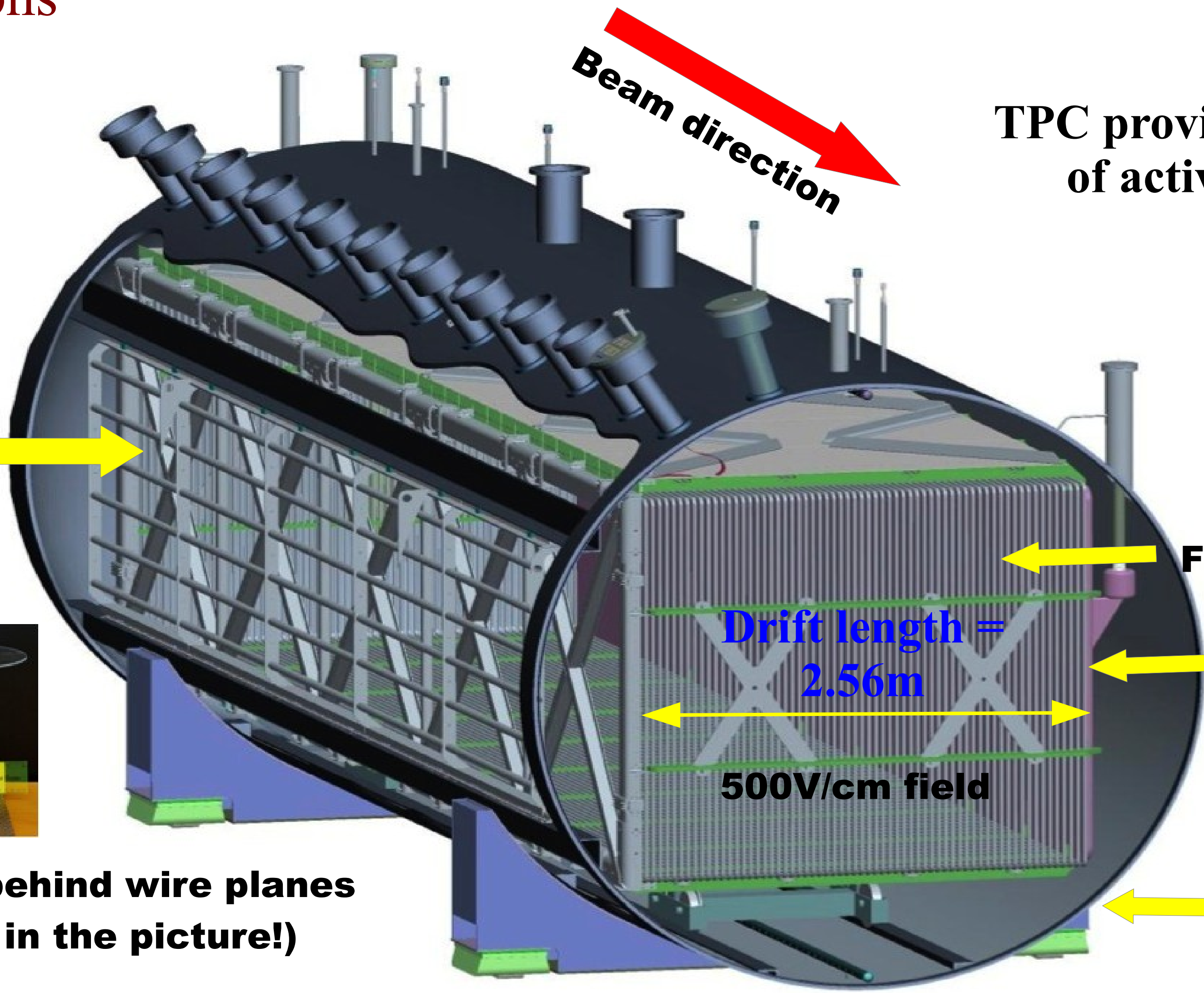


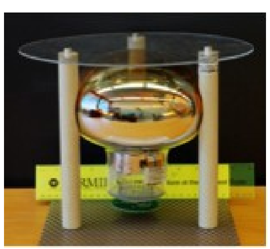
A charged current neutrino DIS event with two pi0 decays.

LArTPCs provide unprecedented amount of details to study neutrino interactions in Argon!

The MicroBooNE LArTPC

MicroBooNE Will be the first largest LArTPC in U.S. to study neutrino interactions

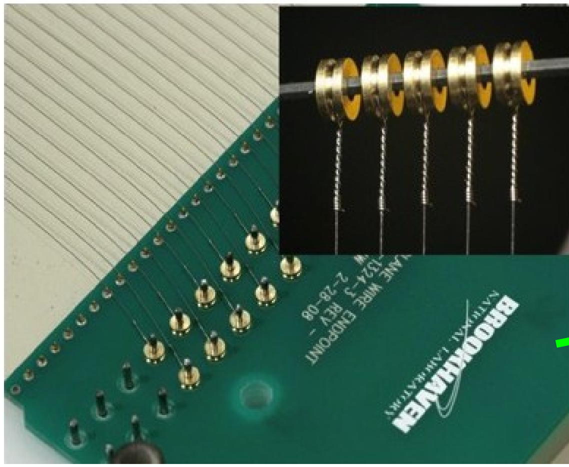




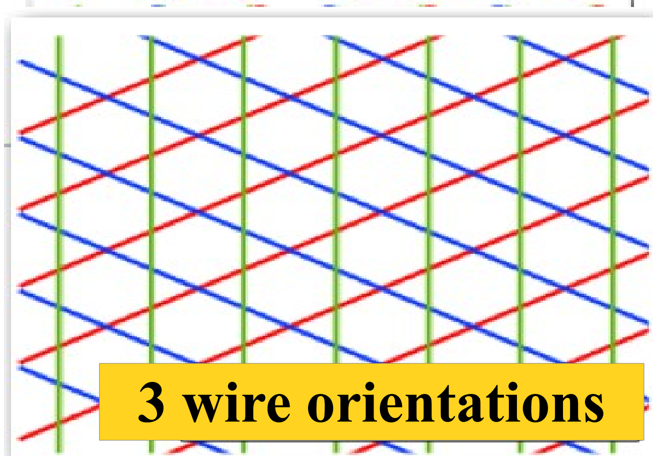
PMTs sit just behind wire planes
(not shown in the picture!)

MicroBooNE TPC and Anode wires

Wires attach to wire carrier boards for mounting on to the TPC frame



collection (vertical, Y)



induction 1
+60^0 w.r.t. Y

induction 2
–60^0 w.r.t. Y

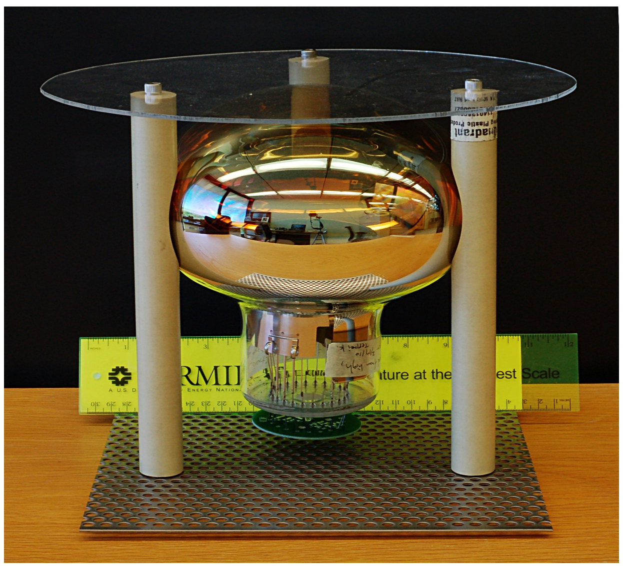
Rectangular in shape

(H = 2.33m; L = 10.37m; W = 2.56m)

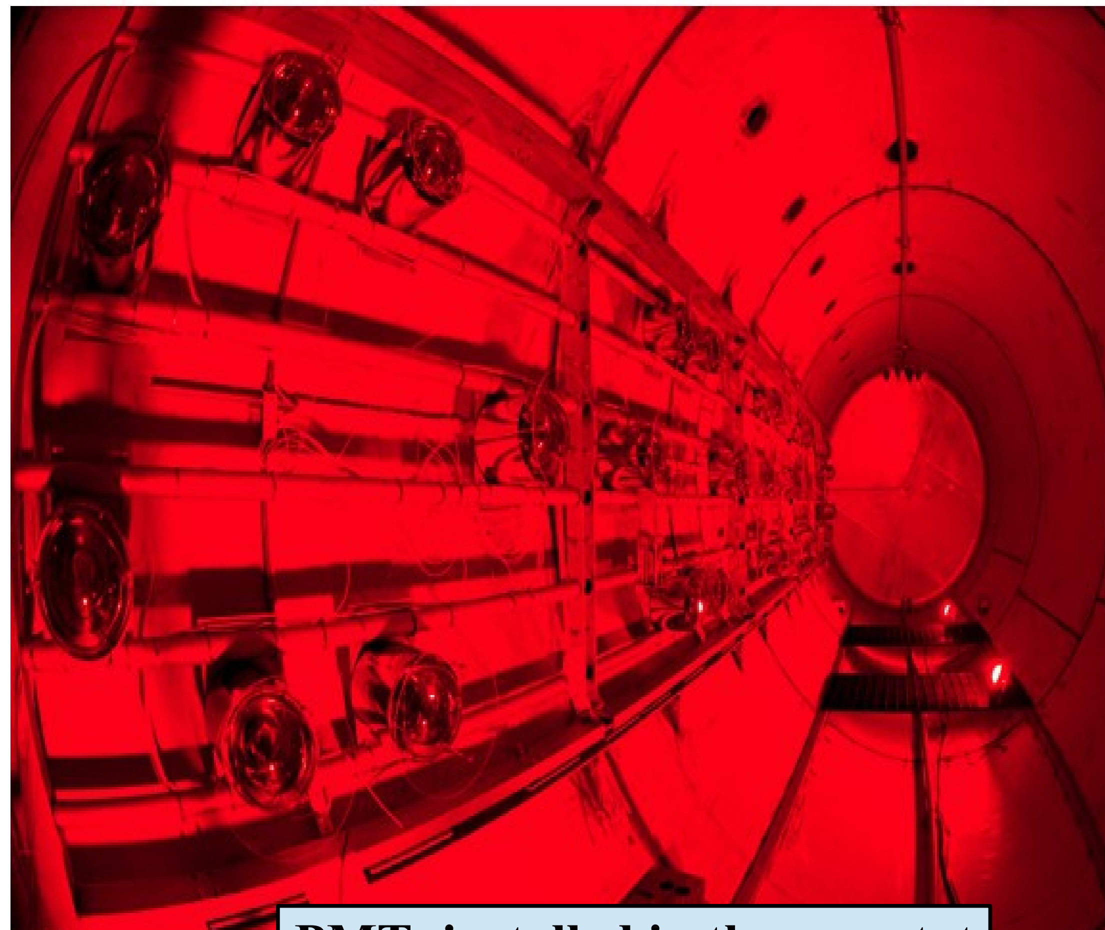
all wires installed as of Summer 2013

Light collection system

- **MicroBooNE optical system contains 32 8-inch Photo multiplier tubes (PMT)**
- **De-excitation and recombination processes produce scintillation light in LAr**
  - Ar emits scintillation light at 128 nm → vacuum ultraviolet (VUV) range
  - Tetraphenyl Butadiene (TPB) coated acrylic plates in front of PMTs as wavelength shifters



- **Timing information very crucial for rejecting out-of-time cosmics from in-time beam interactions**
  match "t_0" with beam gate to trigger on neutrino events
- **Reduces data through-put from 200MB/s to 2MB/s**



PMTs installed in the cryostat (September 2013)

LArTPC challenges

Great technology comes with great technical challenges:

- **Argon purity**
  - Argon needs to be kept ultra pure
  - Why? Impurities can capture drifting electrons affecting your signal
    → Cryogenics play a crucial role!
- **High Voltage in LAr**
  - This area is not well understood (major effort from MicroBooNE)
  - Need to understand/test physics of HV in clean argon
- **Cold Electronics**
  - Wire signals are small, so, pre-amplifiers are immersed in the cold very close to the wire read-out → improves signal to noise ratio
- **Reconstruction Software**
  - No pre-existing fully automated reconstruction software for LArTPCs
  - A major reconstruction challenge!

MicroBooNE's R&D will address all of these challenges AND serve as a "proof of principle" for future large-scale LArTPC detectors!

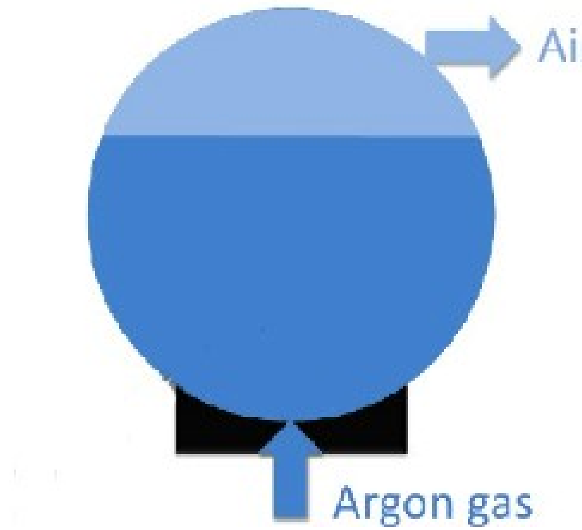
The Cryogenics System

Argon gas purge

- To ensure Ar purity, cryostat need to be evacuated prior to filling LAr
- Traditional vacuum evacuation of cryostats is expensive for large scale LArTPCs

MicroBooNE will purge the cryostat with Ar gas to remove air before filling

→ **a major R&D step to guide future detectors**

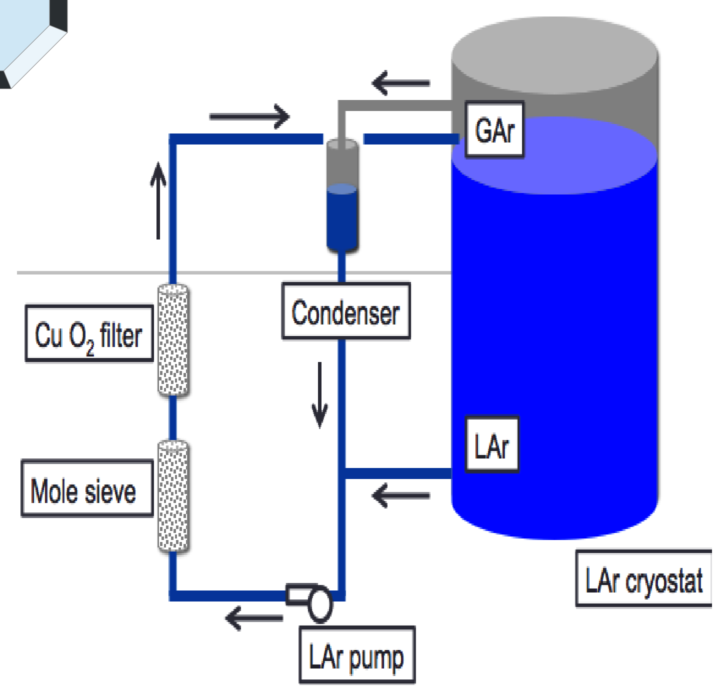


Argon gas purge has already been demonstrated to work in Liquid Argon Purity Demonstrator (LAPD) test cryostat at Fermilab

Argon Purity

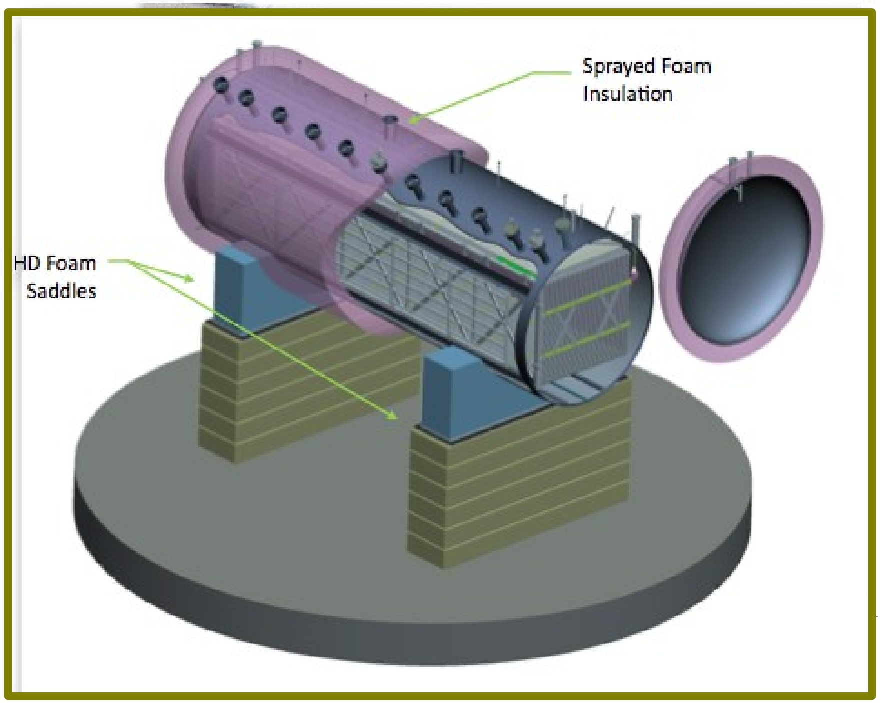
- The impurities of concern are ***water, oxygen and nitrogen***
- Nitrogen is bad for scintillation light
- Impurities need to be kept

  <100 ppt (for Oxygen)
  <1 ppm (for Nitrogen)



The Cryostat

- MicroBooNE cryostat is single-walled steel cylinder with 3.5m diameter
- Can hold 170 tons of LAr
- Once inserted, cryostat will be sealed and moved to the new building and then foam insulated

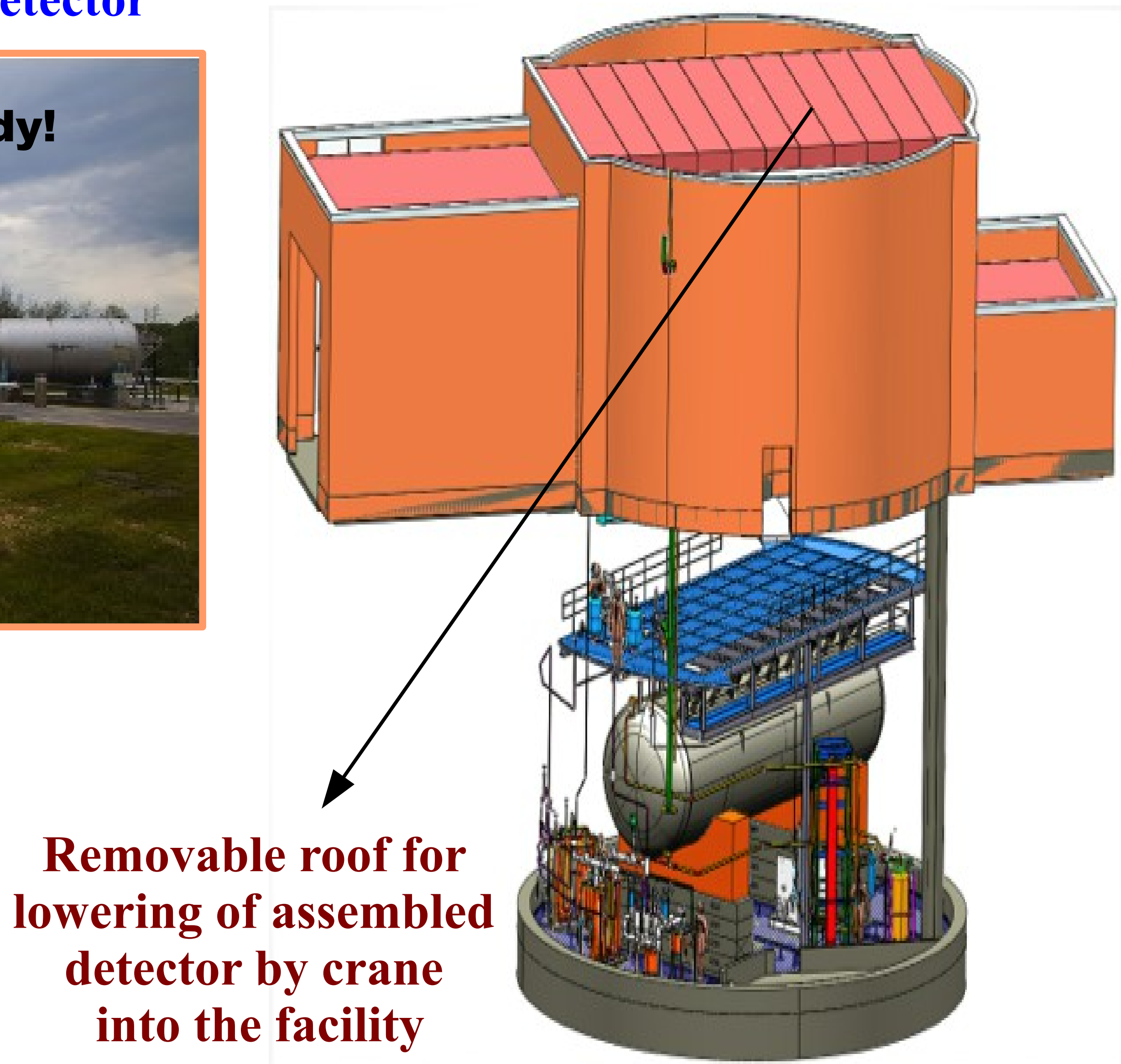


Insertion of TPC into the cryostat at D0 Assembly building (Fermilab)

Liquid Argon Testing Facility (LArTF)

The specially designed LArTF building will house the MicroBooNE detector

LArTF actual building design



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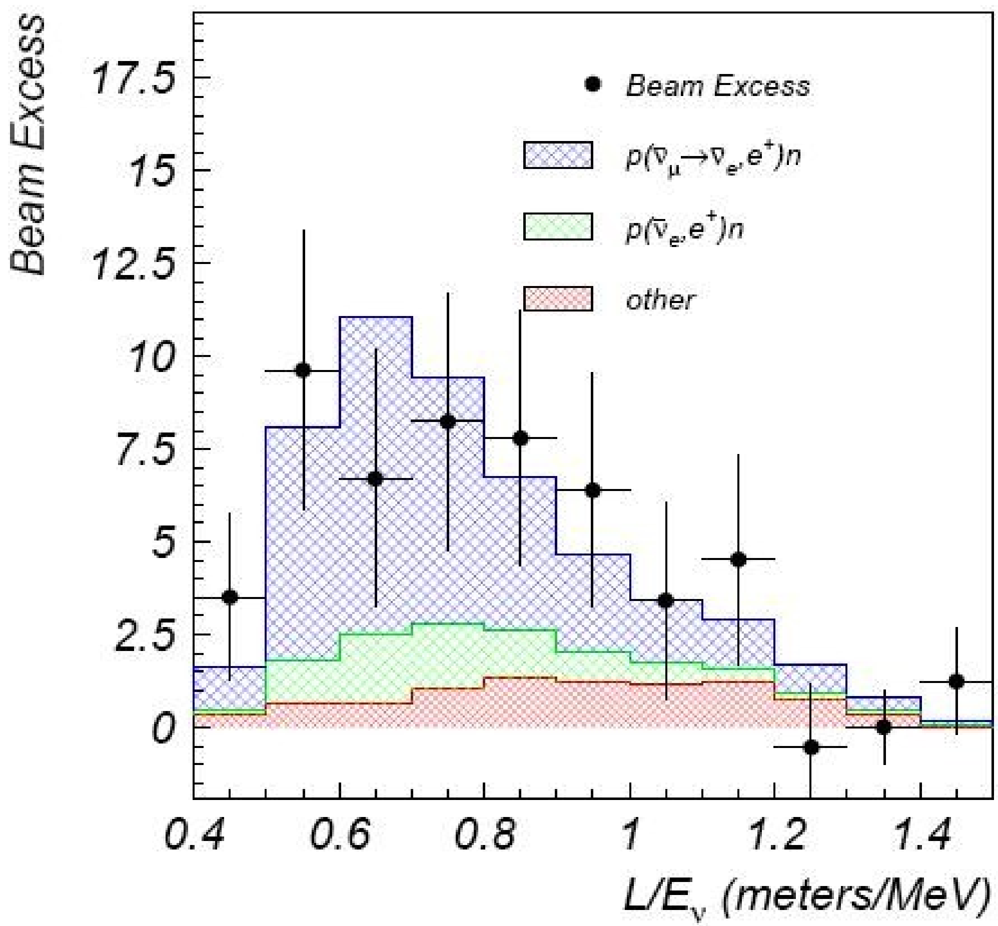
Physics Motivation: The LSND anomaly

- The Liquid Scintillator Neutrino Detector (LSND) experiment at Los Alamos lab saw excess of anti-ν_e in an anti-ν_μ beam originated by μ^+ at rest with $<E_\nu> \approx 30$ MeV and $L \approx 30$m.

Excess of 87.9 ± 23.2 at 3.8σ



→ this corresponds to an oscillation probability of,

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27L\Delta m^2}{E}\right)$$

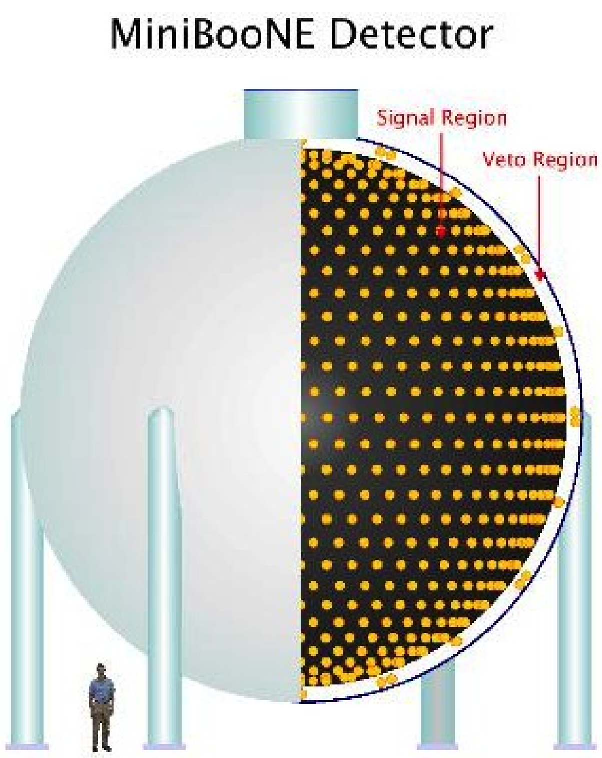
$$= 0.245 \pm 0.081\%$$

(for $L/E_\nu \approx 0.5 - 1$ m/MeV)

→ However, an appearance signal at such a small distance from the source can only correspond to non-standard oscillations (large $\Delta m^2 \sim 1$ eV^2)!

Physics Motivation: The MiniBooNE anomaly

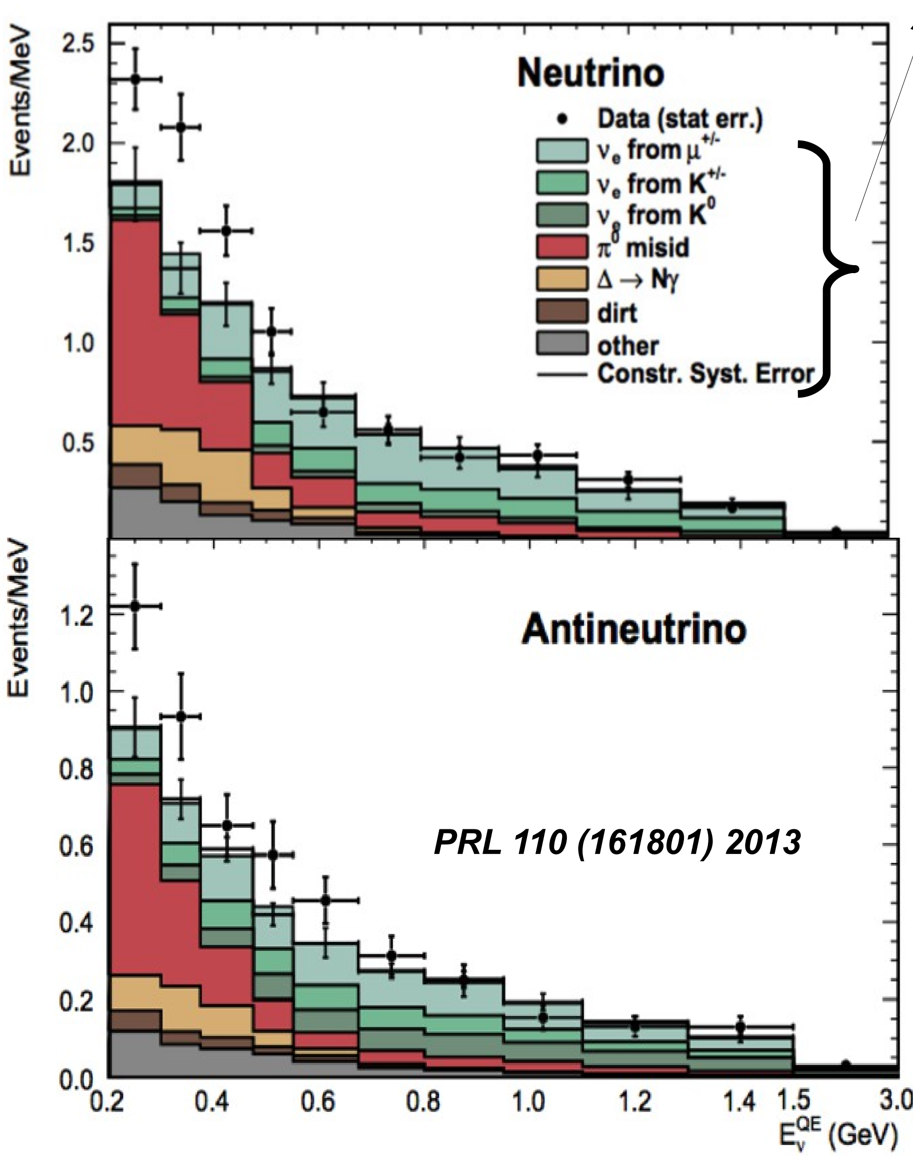
MiniBooNE, a 12m diameter cherenkov detector filled with 800 tons of mineral oil was initially conceived as an ultimate test of the LSND anomaly.
→ MiniBooNE sits on the Booster neutrino beam line.



→ Similar L/E_ν (~ 1m/MeV) as LSND,
Distance from source, L ~ 500m
Typical E_ν ~ 500 MeV
(entirely different systematics and backgrounds than those of LSND)

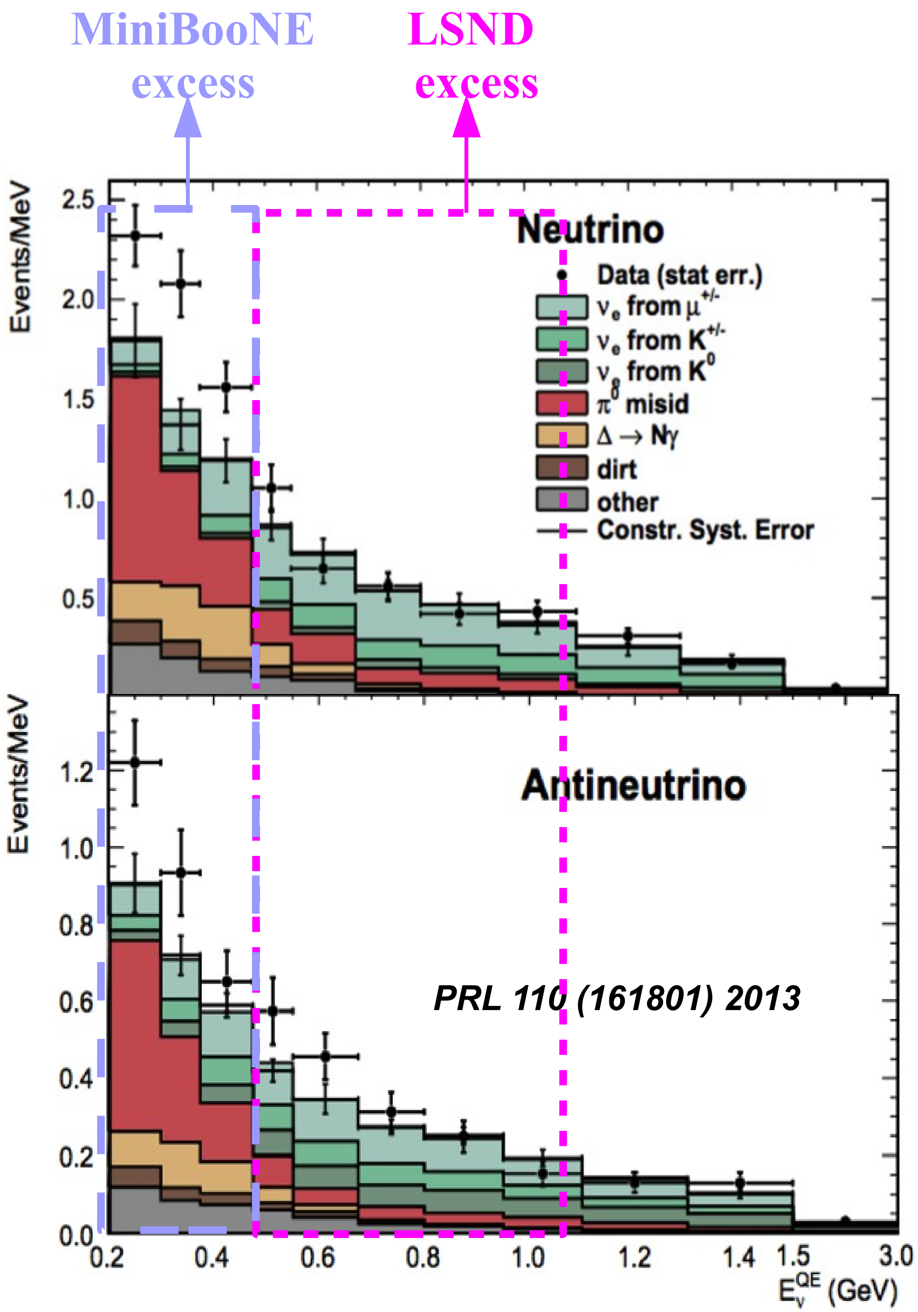
Physics Motivation: The MiniBooNE anomaly

Background processes



→ MiniBooNE's oscillation analysis saw pronounced excesses in both *neutrino* and *anti-neutrino* modes

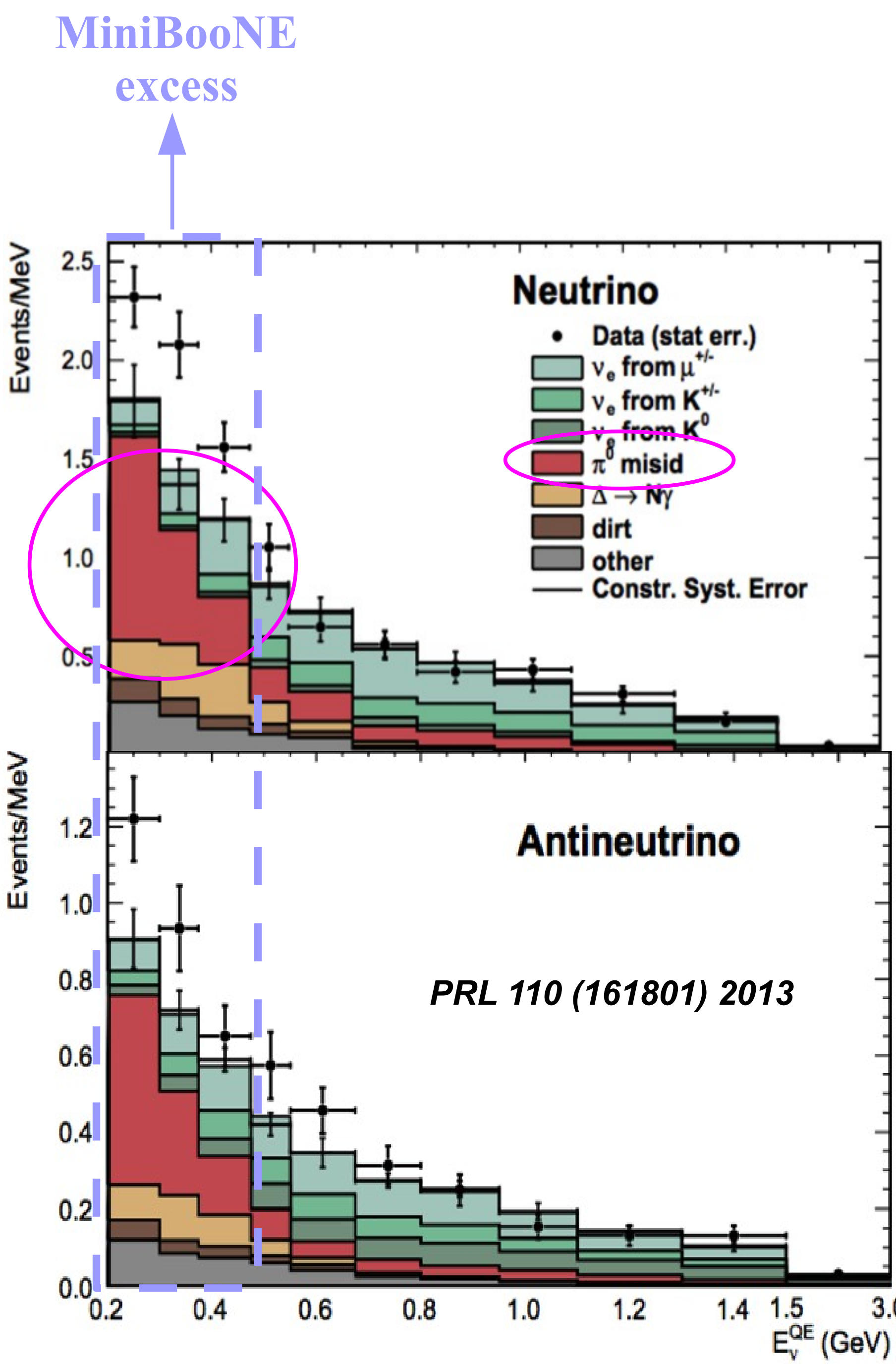
Motivation: The MiniBooNE anomaly



→ MiniBooNE's oscillation analysis saw pronounced excesses in both *neutrino* and *anti-neutrino* modes ***But, in a different region than the LSND excess!***

→ for energies b/n 0.2 – 0.475 GeV excess of 240.0 ± 62.9 at 3.8σ

Understanding MiniBooNE excess



The real problem

Excess could be a mis-identified background!?

- Background processes such as ($\pi^0 \to \gamma\gamma$ & $\Delta \to N\gamma$) dominate in this energy range!
- ***A cherenkov detector problem,*** doesn't offer good single e^- (signal) to γ (background) discrimination!

Possible cases:

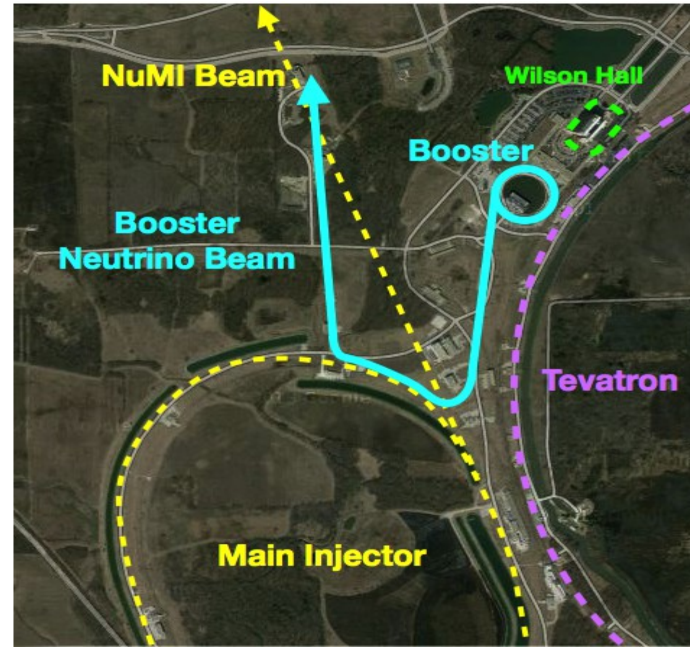
γ misidentified as $\to e^-$ for $\Delta \to N\gamma$ events

and/or

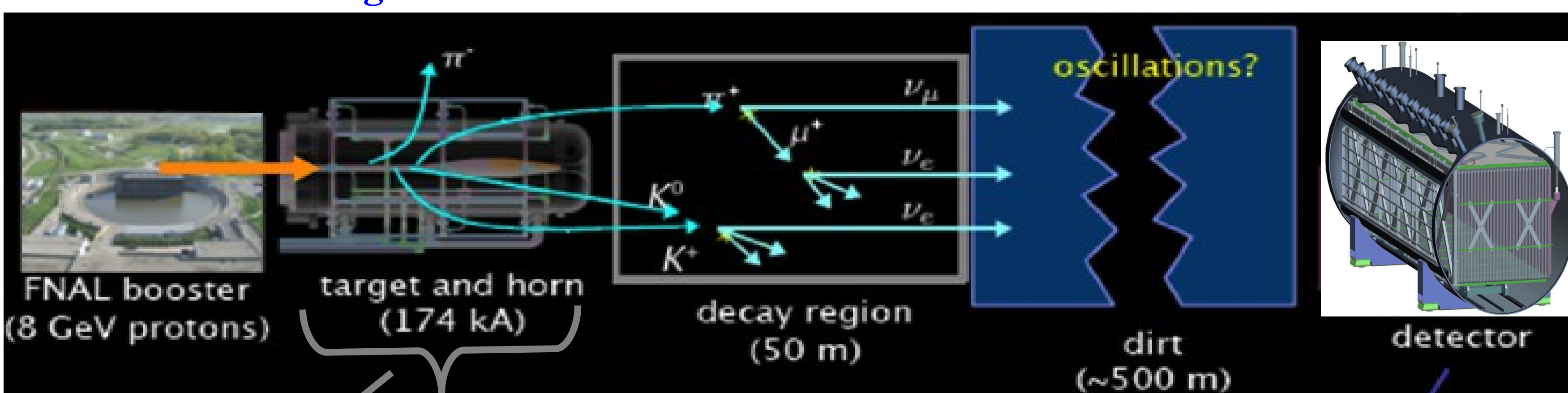
Only one γ detected in $\pi^0 \to \gamma\gamma$ events and misidentified as $\to e^-$

MicroBooNE location

- MicroBooNE will sit just below surface in on-axis Booster Neutrino beam (BNB) and off-axis Main Injector (NuMI) beam
- 8 GeV (120 GeV) protons feeding the BNB (NuMI) beam hit Beryllium (Carbon) target to produce mesons which there by decay into neutrinos



How are neutrinos generated from BNB?



MicroBooNE

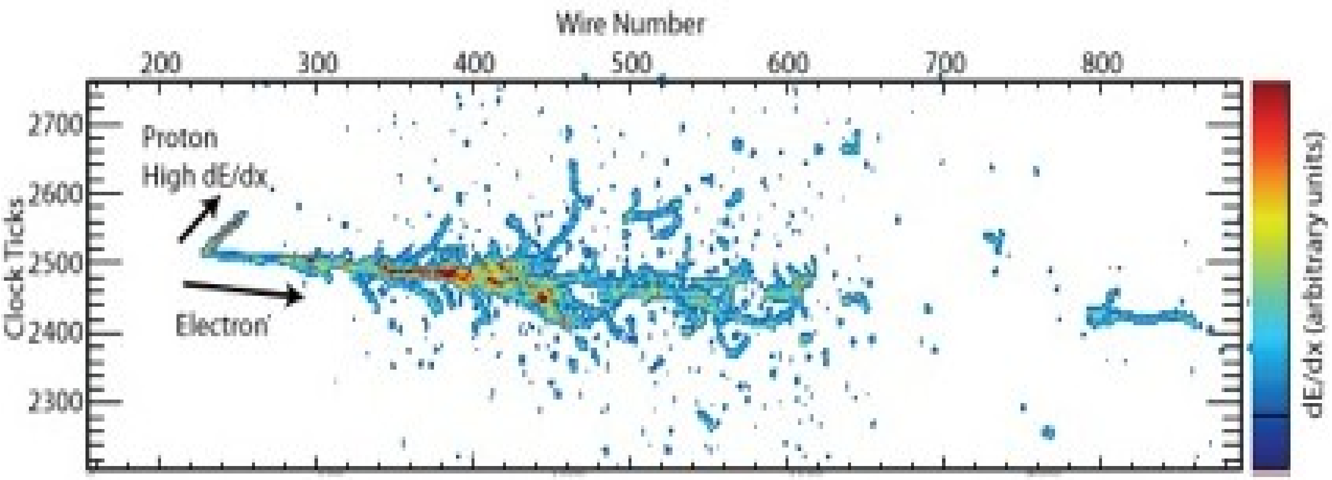
Switching the horn polarity, focuses negatively charged mesons, yielding a anti-ν_μ beam

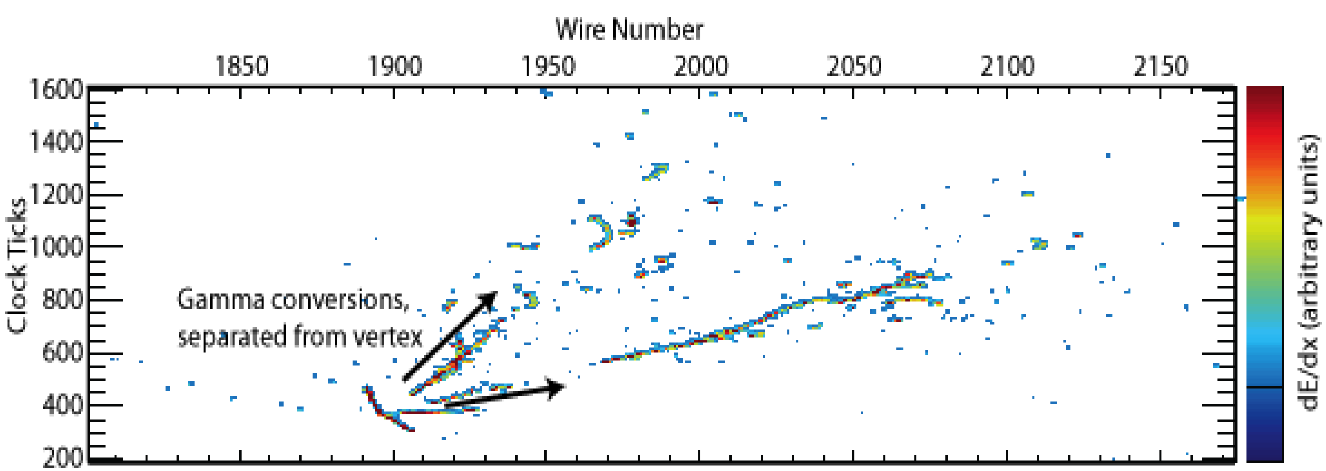
Gives similar L/E as MiniBooNE

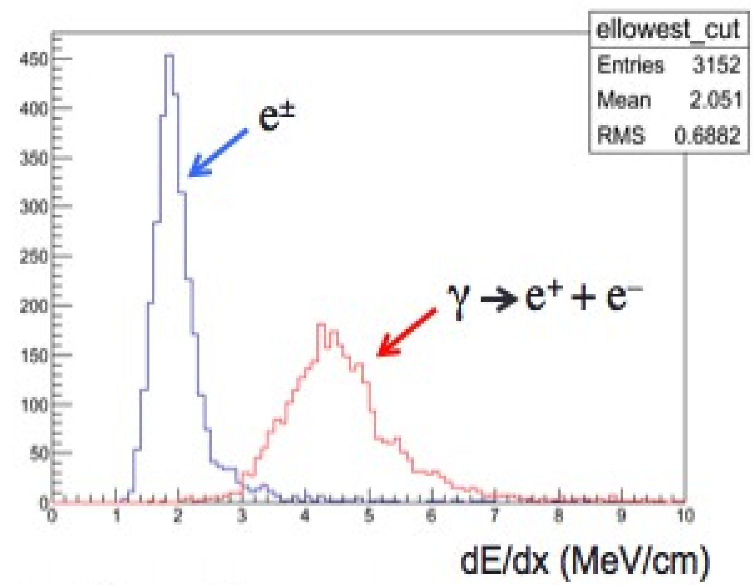
Can MicroBooNE address the MiniBooNE excess?

- LArTPCs excellent dE/dx resolution capability,
  - allows one to measure dE/dx in the first 3 cm of an EM interaction

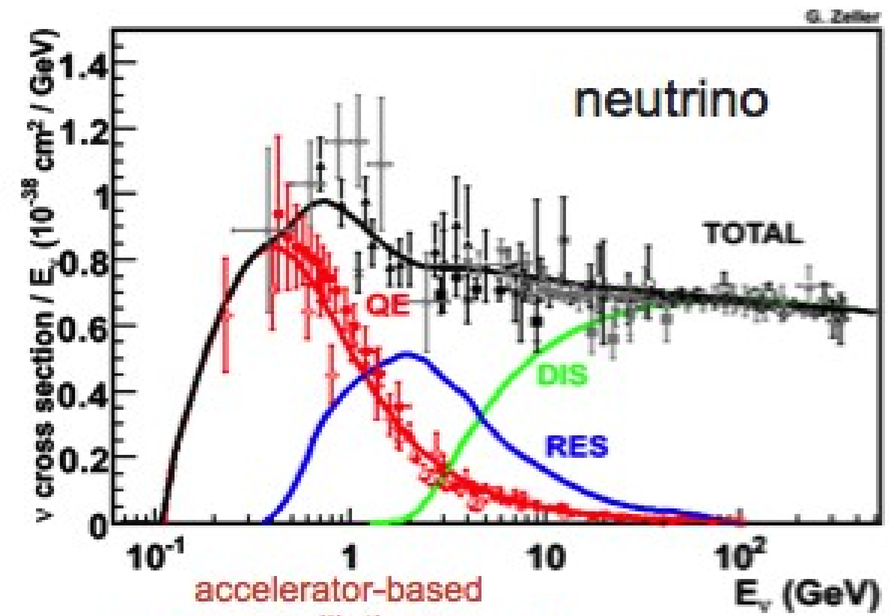
low dE/dx ~ 1 MIP => e^- ; high dE/dx ~ 2 MIPS => γ (e^+e^- pair)

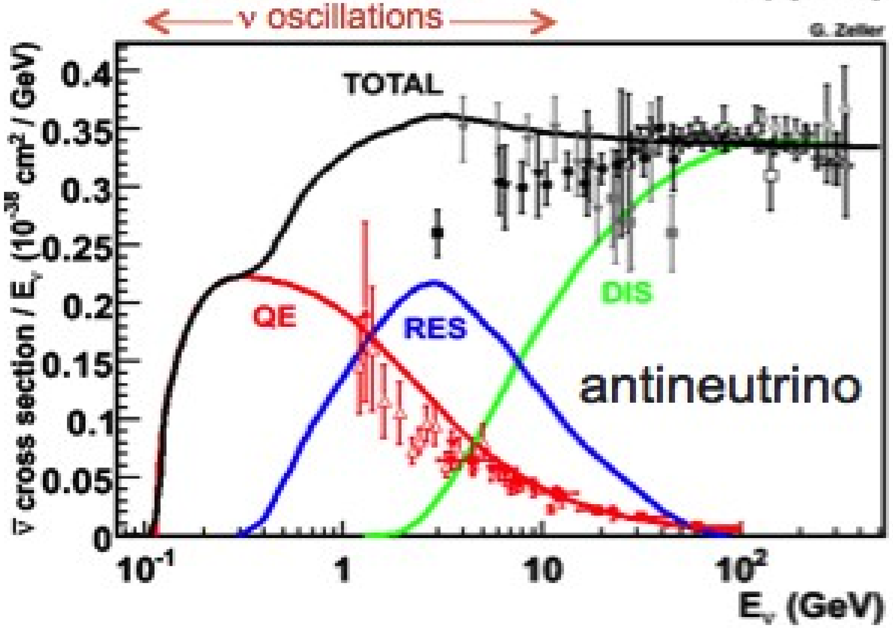






Neutrino cross-sections





Why measure low-energy neutrino cross sections in Argon?

Historically, low energy (up to ~1 GeV) σ_ν are not well understood/explored
Recent realization of the importance of low-energy neutrino cross-section measurements in the context of future oscillation experiments

Improved nuclear models
Understanding final state interactions and other nuclear effects in argon will help towards this

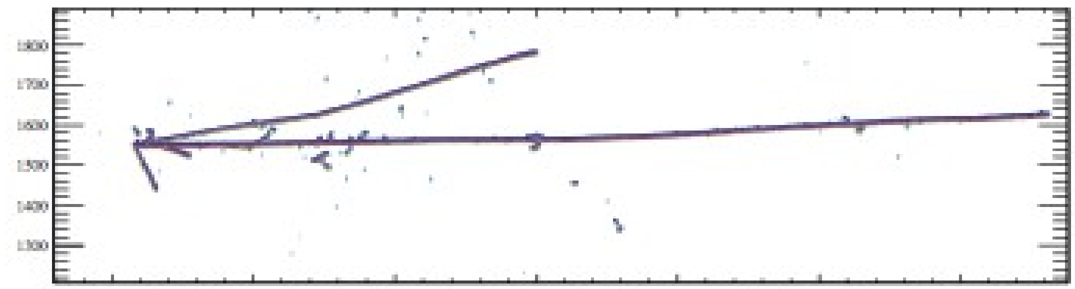
MicroBooNE, with its superior PID and calorimetry, will be able to make high-precision σ_ν measurements in argon

Expected Statistics for cross section measurements

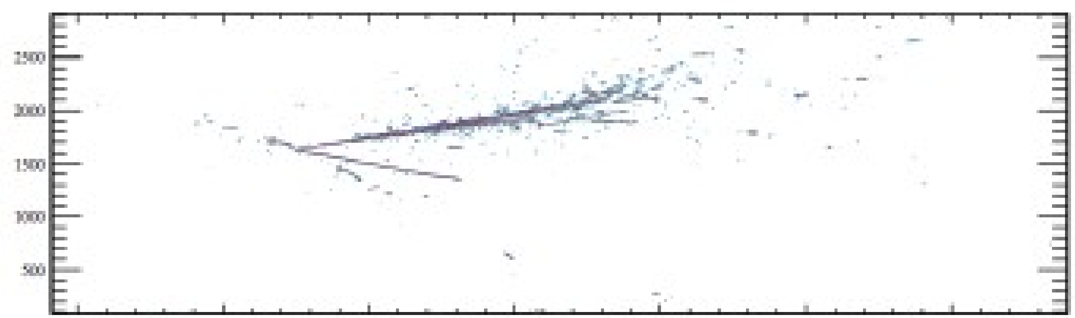
3 years of BNB run
(rates assuming 6.6E20 POT)

production mode	# events
CC QE ($\nu_\mu n \to \mu^- p$)	60,161
NC elastic ($\nu_\mu N \to \nu_\mu N$)	19,409
CC resonant π^+ ($\nu_\mu N \to \mu^- N \pi^+$)	25,149
CC resonant π^0 ($\nu_\mu n \to \mu^- p \pi^0$)	6,994
NC resonant π^0 ($\nu_\mu N \to \nu_\mu N \pi^0$)	7,388
NC resonant $\pi^\pm$ ($\nu_\mu N \to \nu_\mu N' \pi^\pm$)	4,796
CC DIS ($\nu_\mu N \to \mu^- X$, $W > 2$ GeV)	1,229
NC DIS ($\nu_\mu N \to \nu_\mu X$, $W > 2$ GeV)	456
NC coherent π^0 ($\nu_\mu A \to \nu_\mu A \pi^0$)	1,694
CC coherent π^+ ($\nu_\mu A \to \mu^- A \pi^+$)	2,626
NC kaon ($\nu_\mu N \to \nu_\mu K X$)	39
CC kaon ($\nu_\mu N \to \mu^- K X$)	117
other ν_μ	3,678
total ν_μ CC	98,849
total ν_μ NC+CC	133,580
ν_e QE	326
ν_e CC	657

Simulated events in MicroBooNE



$\nu_\mu + {}^{40}\mathrm{Ar} \to \mu^- + p + p + n + p$



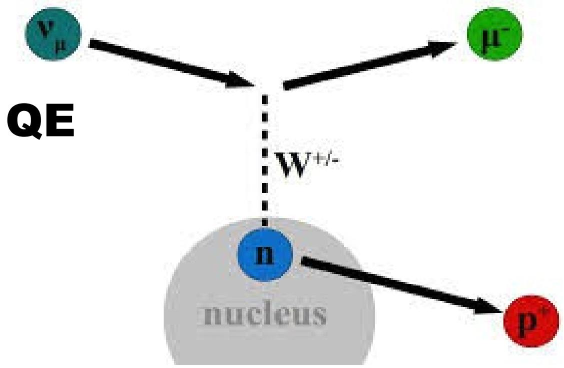
$\nu_e + {}^{40}\mathrm{Ar} \to e^- + p + p + \pi^0 + p$

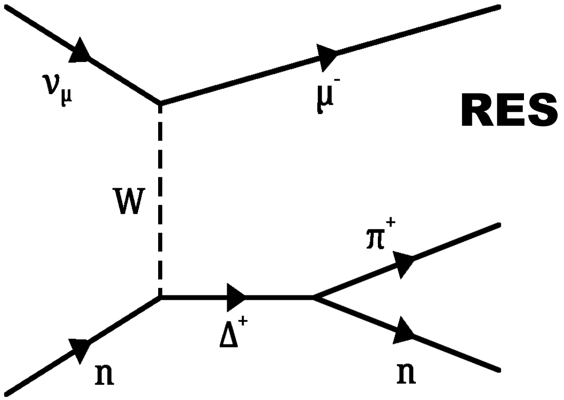
Well understood BNB flux will result in expeditious cross section measurements

Nuclear effects in ν-Ar interactions

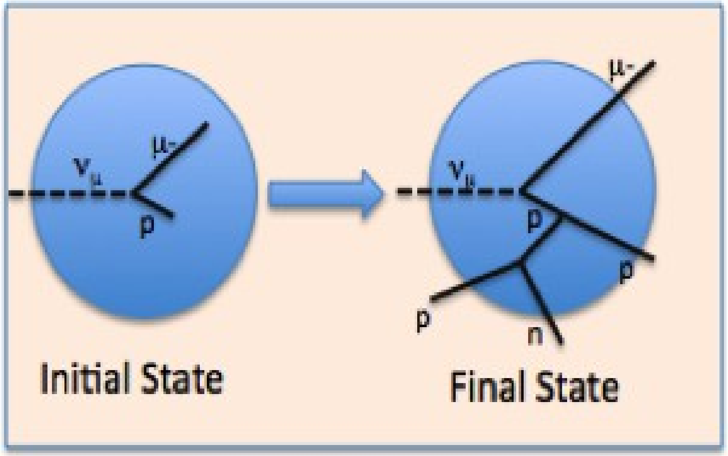
- The Argon nucleus (18 protons and 22 neutrons) presents a complicated environment for a neutrino to interact within!

- This is particularly challenging for exclusive channels like Quasi elastic (QE), resonance pion production (RES) etc. where nuclear effects can have dramatic effects on final states



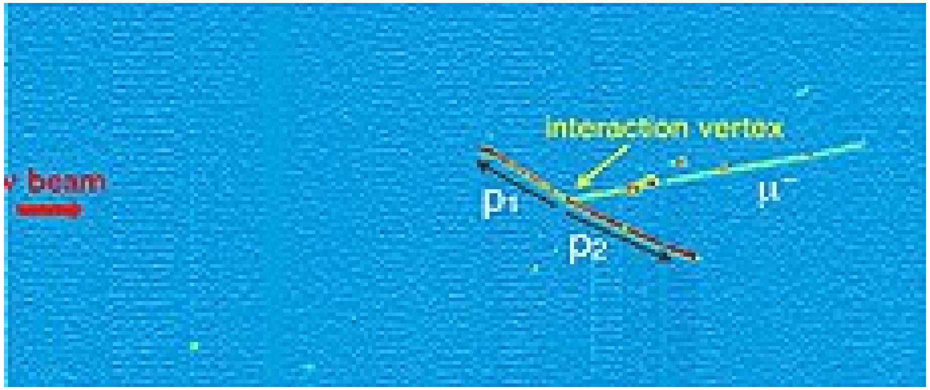


- Due to **final state interactions** and **possible effects of correlation between target nucleons**, **a genuine QE interaction can often contain additional nucleons or de-excitation gammas or pions in its final state**

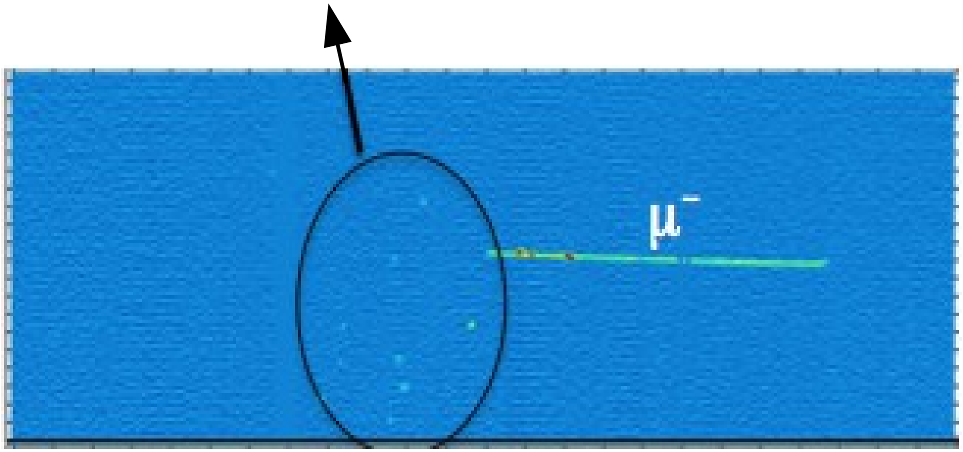


Hints of Nuclear effects from ArgoNeuT experiment

One case of Multi-nucleon correlations: Neutrino interacting with a nucleon-pair emitting back-to-back protons



De-excitation gammas



Protons and other particles emitted as part of FSI are usually low in energy (of the order of few MeV) which makes them hard to detect, this is where strength of LArTPC technique come into play:

- **LArTPCs superior vertex resolution and particle identification will make it possible to identify protons and disentangle nuclear effects with extraordinary sensitivity**
- **ArgoNeuT already shows that they can reconstruct protons down to 20 MeV!**
  → MicroBooNE, a bigger/better version of ArgoNeuT will only do better!

Summary

- **TPC is fully assembled and inserted into the cryostat on December 20, 2013**
- **All cold and warm electronics tested successfully with the DAQ read out**
  → MicroBooNE is performing some final HV tests at DAB. once done, cryostat will be sealed.
- **LArTF is ready for the arrival of Cryostat, Cryogenics installation at LArTF is progressing rapidly**
- **MicroBooNE will start taking data soon**
  - **Lot to do with cosmics – calibration, commissioning of DAQ etc.**
  - **Expect some early results on neutrino cross-sections**
  - **Oscillation results require at least 3 years of data to give "statistically" sensible results**

Wait for MicroBooNE to uncover some rich and diverse physics all while trying to solve the MiniBooNE mystery!

Thanks very much for your attention!

Please come for a tour of MicroBooNE next time you are at Fermilab!

Supplementary slides

The MicroBooNE collaboration

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Sergio Rescia
Andres Ruga
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Eric James
Hans Jostlein
Mike Kirby
Sarah Lockwitz
Byron Lundberg
Alberto Marchionni
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Sowjanya Gollapinni
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David McKee

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Jackie Gonzales
Wes Ketchum
Bill Louis
Geoff Mills
Zarko Pavlovic
Richard Van de Water

Massachusetts Institute of Technology
William Barletta
Len Bugel
Gabriel Collin
Janet Conrad
Christina Ignarra
Ben Jones
Teppei Katori
Matt Toups

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Matt Graham
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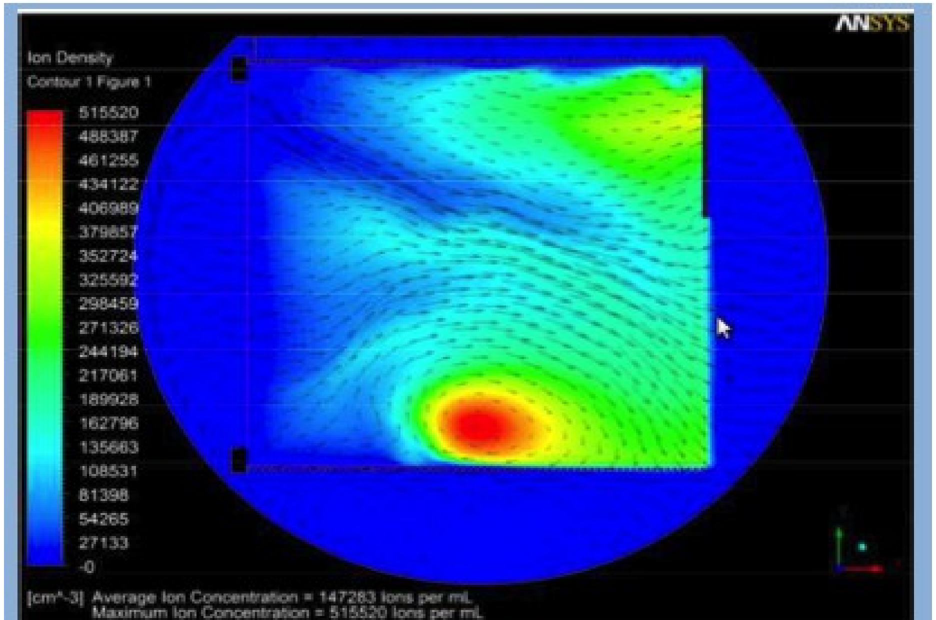
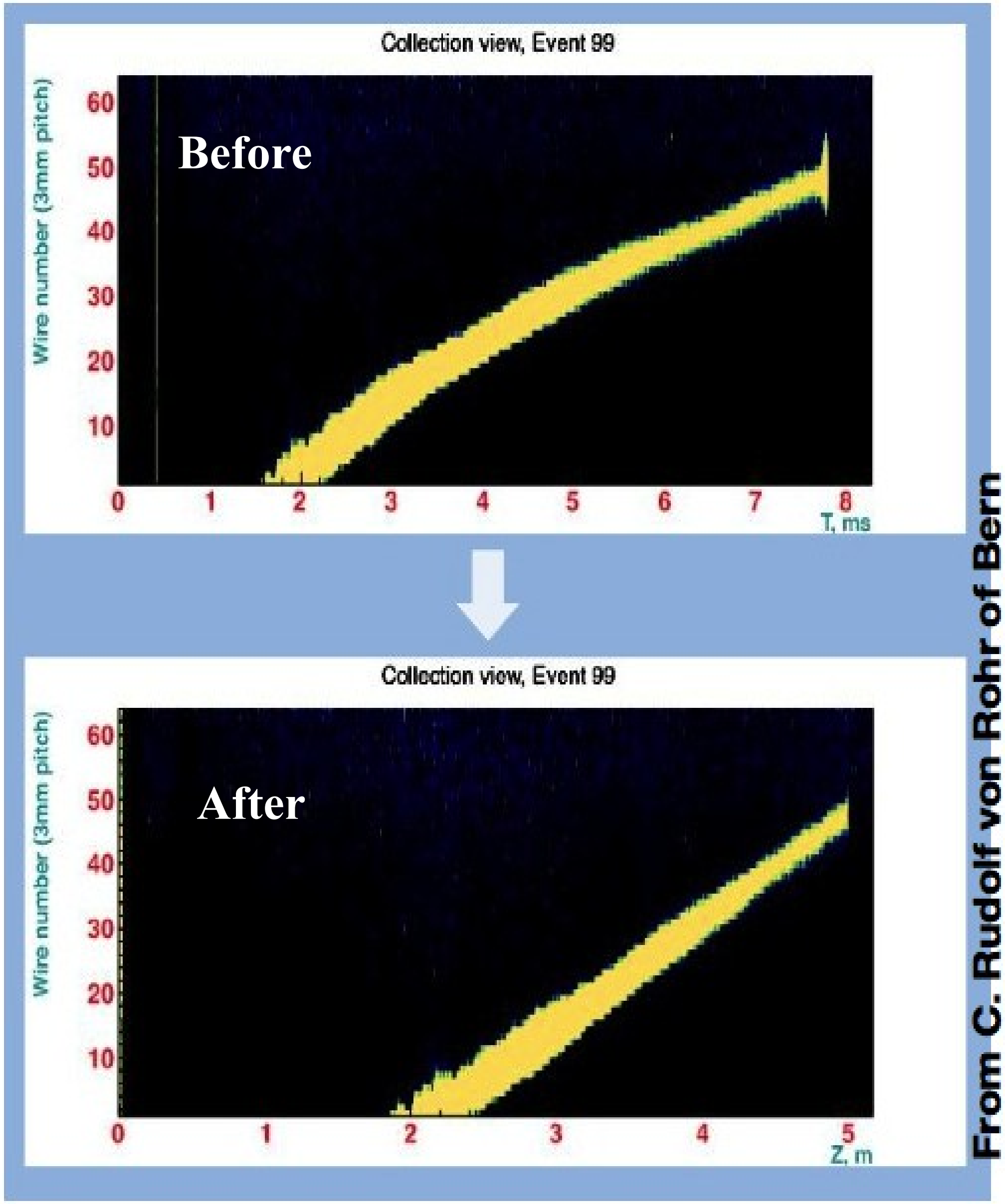
Christina Brasco
Eric Church
Bonnie T. Fleming (*)
Ellen Klein
Ornella Palamara
Flavio Cavanna
Roxanne Guenette
Kinga Partyka
Andrzej Szelc

Laser Calibration

- The cosmic traffic produces significant excess of Ar+ ions which drift very slowly to the cathode (~cm/s) thus causing ion space charge accumulation
- This results in E-field distortions, that together with Ar circulation can potentially affect the tracking efficiency



Eric Voirin: MicroBooNE-doc-1895-v4



From C. Rudolf von Rohr of Bern

- A laser delivers a straight path correcting for field distortions

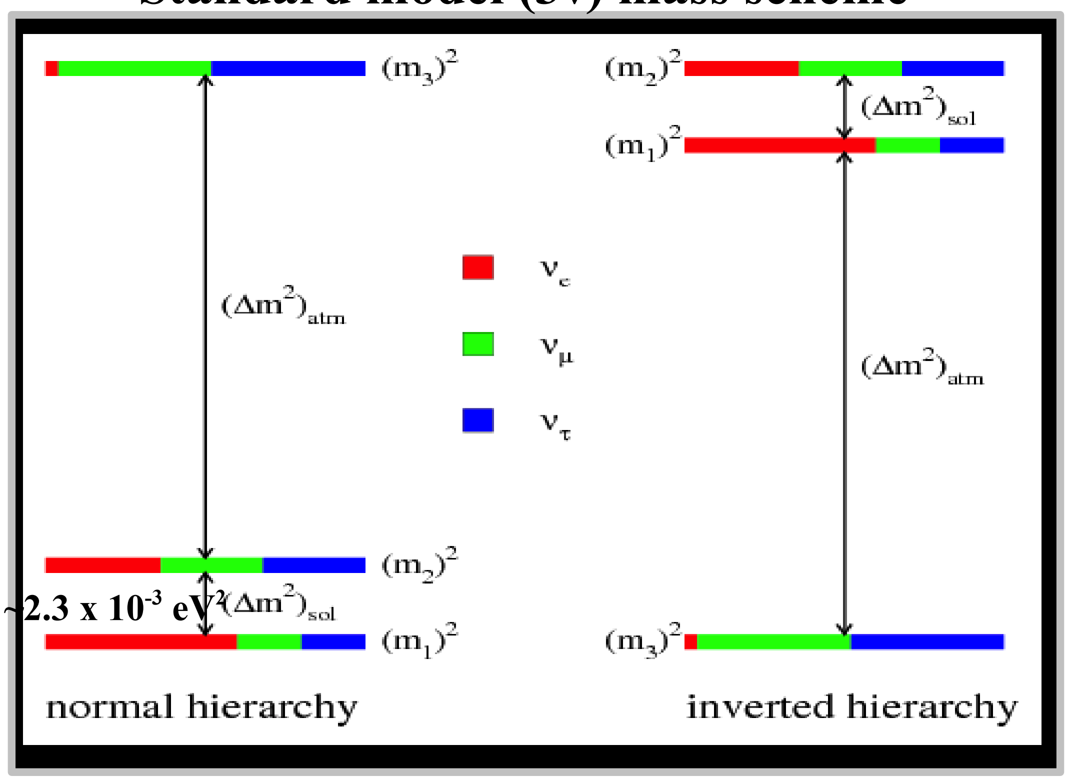
3+1 sterile neutrino model
(as a possible solution to LSND)

- Neutrino mass differences within Standard model:

$$(\Delta m^2)_{atm} \sim 2.3 \times 10^{-3}\ eV^2 \quad \text{and} \quad (\Delta m^2)_{sol} \sim 7.6 \times 10^{-5}\ eV^2$$

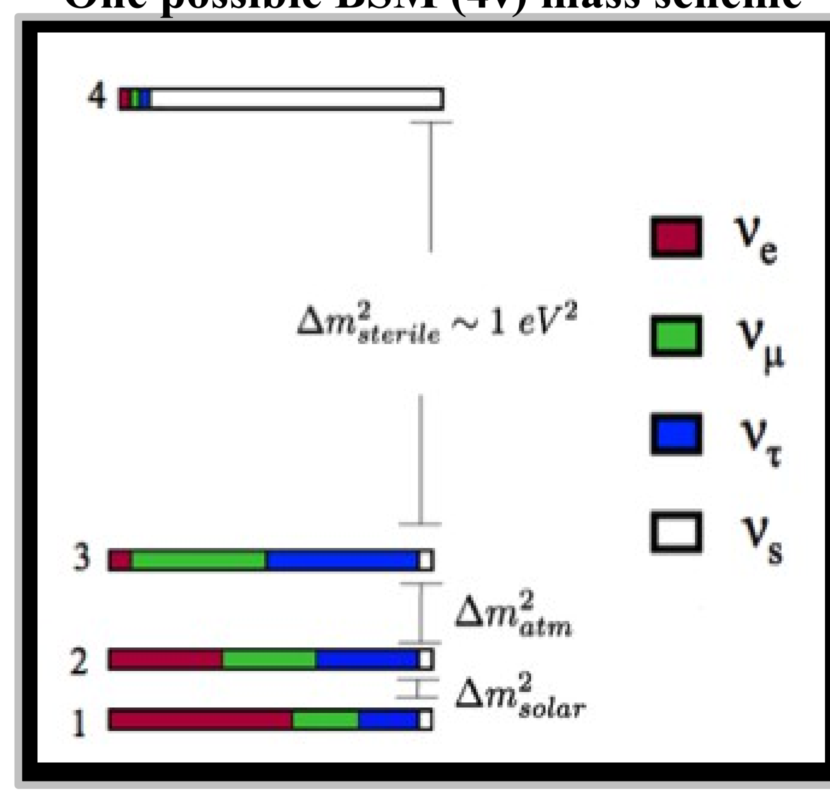
- Now, consider a fourth neutrino that doesn't interact via weak interaction but can oscillate to any of the 3 active neutrino states
  - this is possible if the $(\Delta m^2)_{Sterile} >> (\Delta m^2)_{Atm}$ and $(\Delta m^2)_{Sterile} >> (\Delta m^2)_{Sol}$

Standard model (3ν) mass scheme



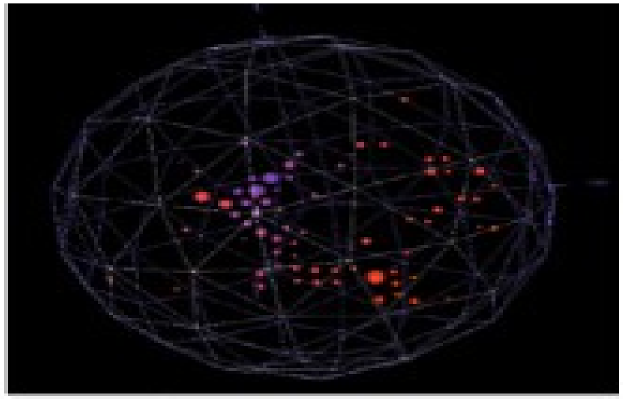
LSND

One possible BSM (4ν) mass scheme

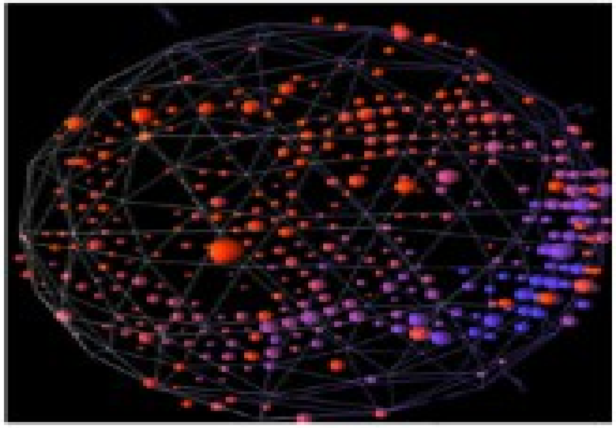


The MiniBooNE particle identification

→ Cherenkov rings provide the primary means of identifying neutrino interactions in the detector



A fuzzy ring corresponds to a e or γ candidate
(indistinguishable b/n the two)



Neutral pion event ($\pi^0 \rightarrow \gamma\gamma$) creates two overlapping fuzzy rings

Shown here,
two "clearly" identifiable fuzzy rings
(a "good" example)

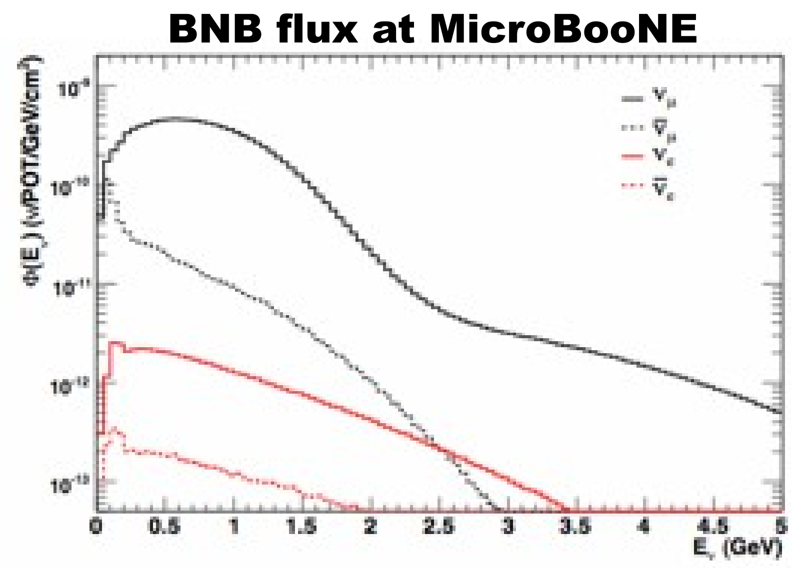
Now, imagine bad cases, where,
→ the two fuzzy rings appear like one ring, or,
→ one fuzzy ring is missing

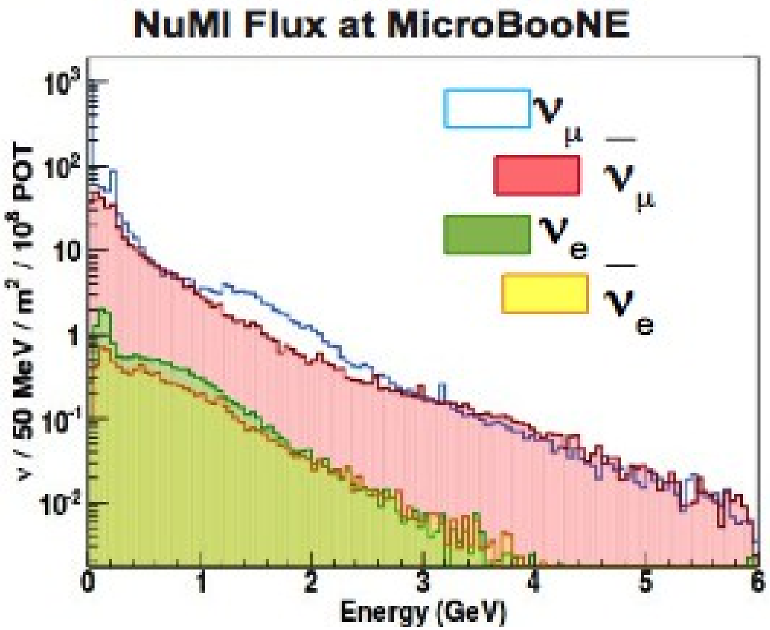
→ γ can easily be misidentified as an electron!

BNB and NuMI fluxes

Predicted event rates for MicroBooNE from BNB and NuMI over the next 3 years

	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}

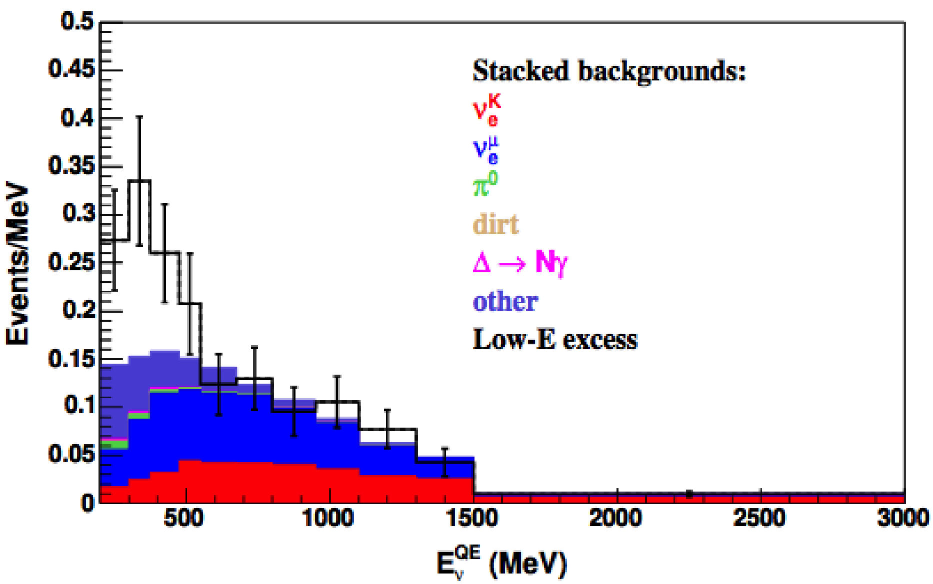


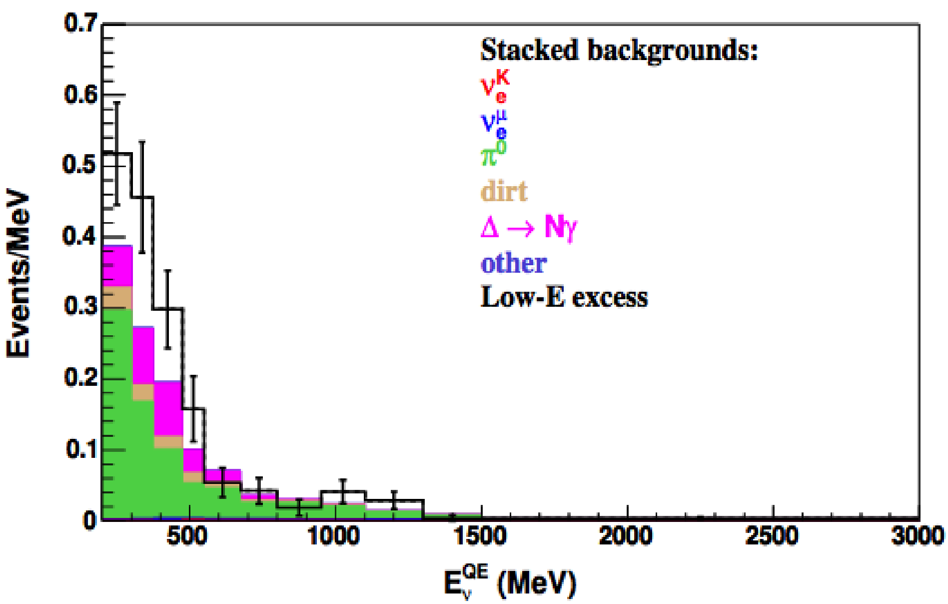


- BNB is up and running for the past 10 years
- Well understood beam systematics will result in expeditious physics measurements

So, what can MicroBooNE tell us?

(projections assume $6.6xE^{20}$ protons on target in neutrino-mode from BNB)





If the excess were electron-like
(Analysis is done favoring electrons and rejecting photons)
→ likely indicate beyond SM Oscillations involving sterile Neutrinos (3+1, and other... models)

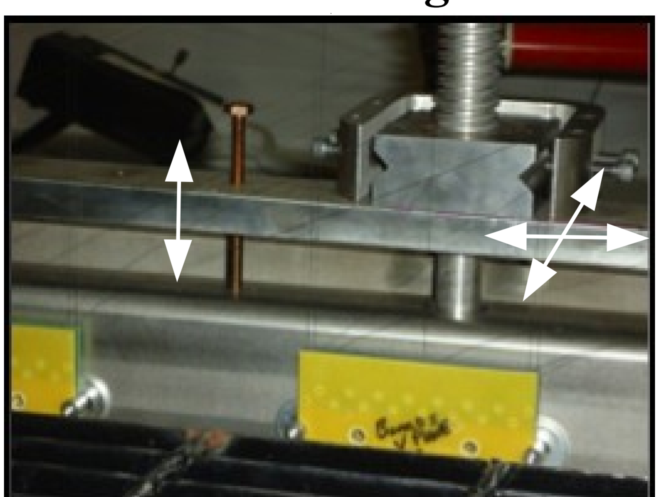
If the excess were photon-like
(Analysis is done favoring photons and rejecting electrons)
→ New unknown cross-sections?

Wire tensioning

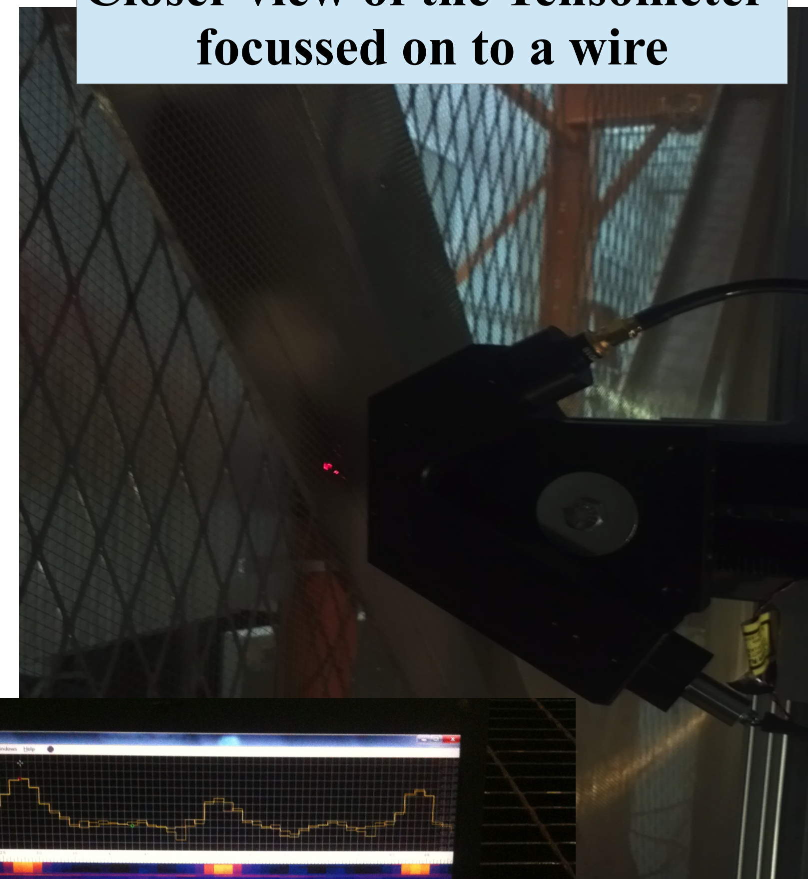
- Wires need to be tensioned to an optimum value, to prevent sagging and/or breakage!
- Tension goal was ~0.7 kg
- A laser tensometer (from UW Madison) was used to measure and set wire tensions

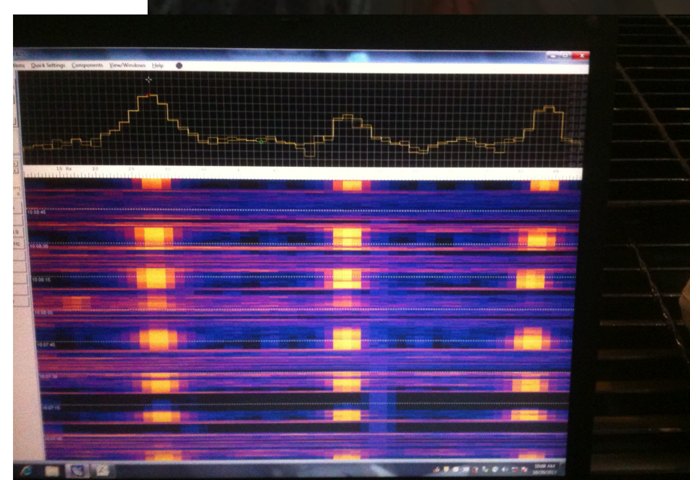
  Laser illuminates a wire, photo diode catches the reflection. Frequency is readout when the wire vibrates and is then fed into a spectrum analyzer

TPC frame has adjustable support bars that can be used to change wire tensions



Closer view of the Tensometer focussed on to a wire





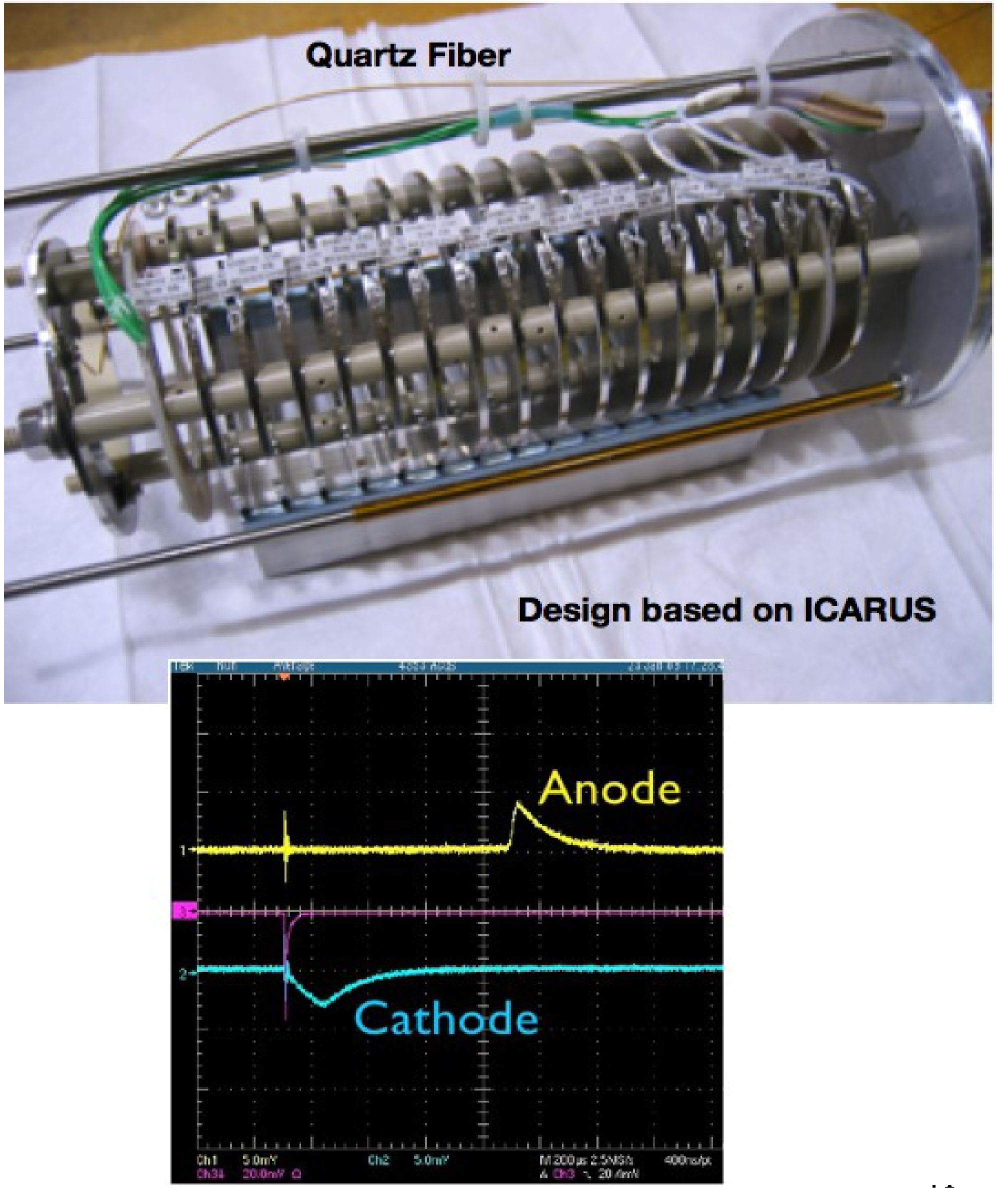
Spectrum analyzer showing uniform results on each of the wires

LAr Purity monitoring

- MicroBooNE's inline purity monitors measure argon purity
  Two monitors are placed in the cryostat and one is installed downstream of the filters

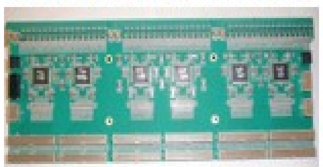
- Purity monitors contain a photocathode and an anode.
  A xenon flash lamp liberates electrons off of the photocathode

- Purity is measured by finding the electron lifetimes to the anode

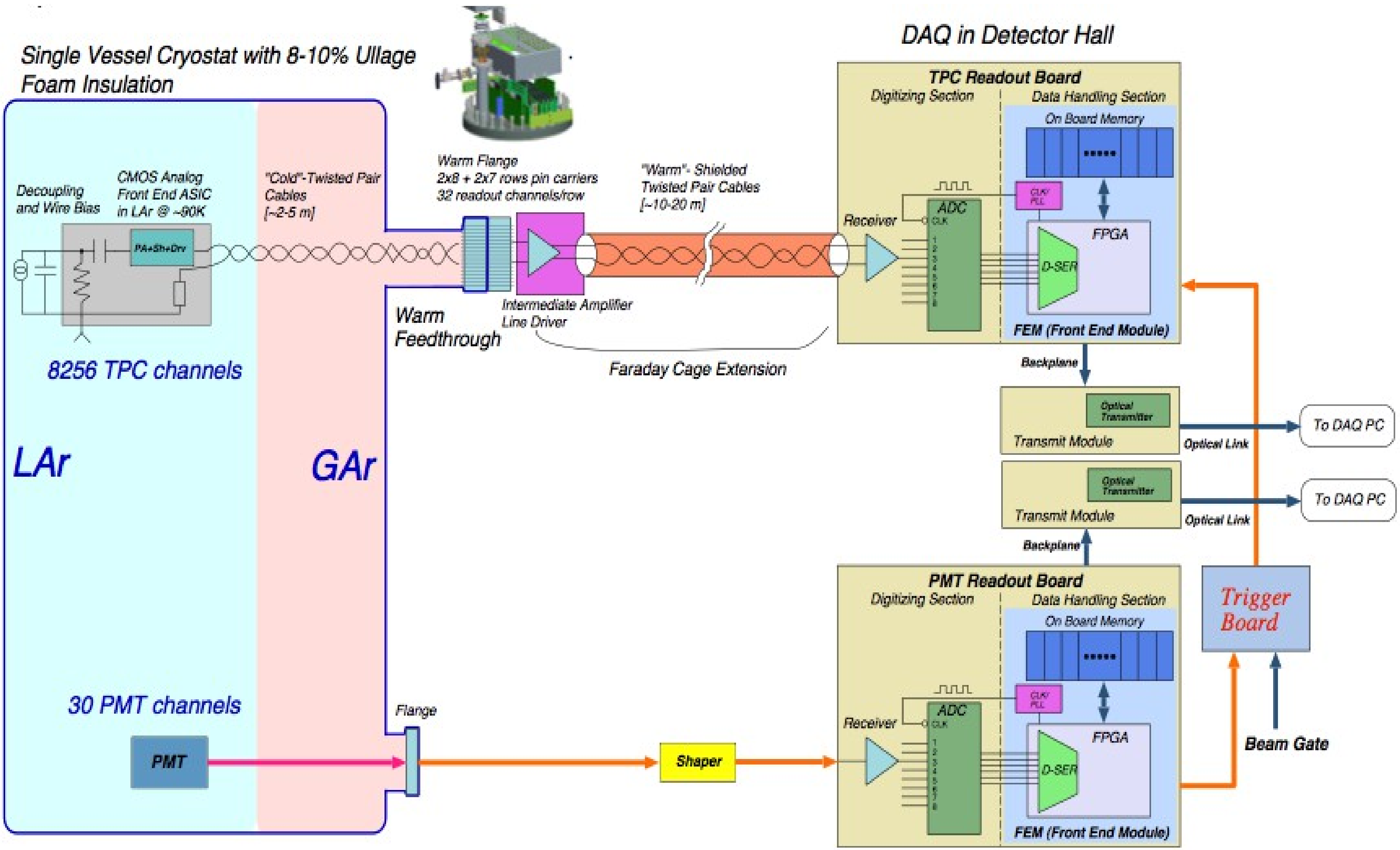


Detailed Read-out electronics chain

Cold MotherBoards



Wire-carrier Board

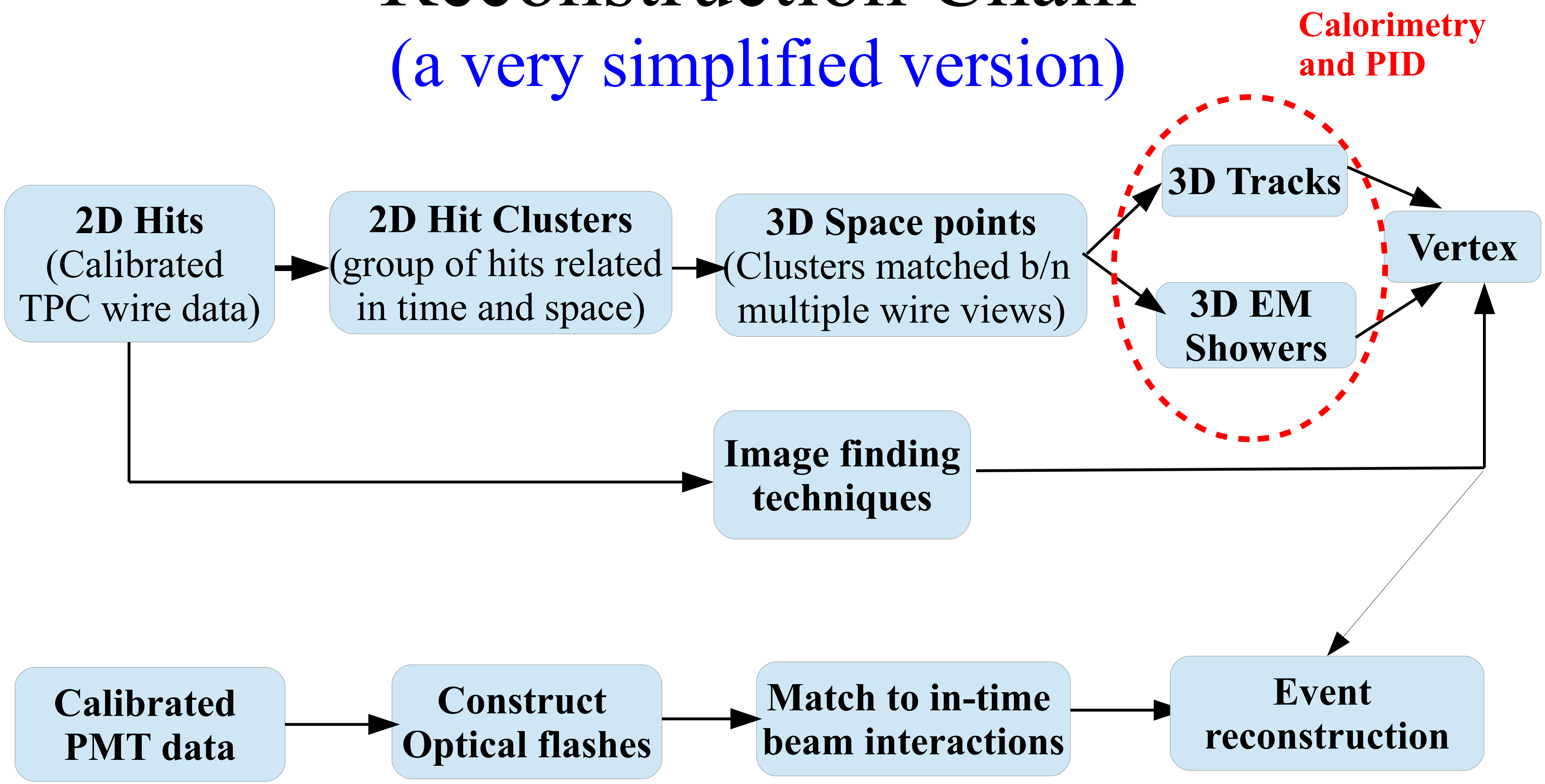


Refs:

1.) *Readout Electronics Design Considerations for LAr TPC*, H. Chen, ANT2013 Conference

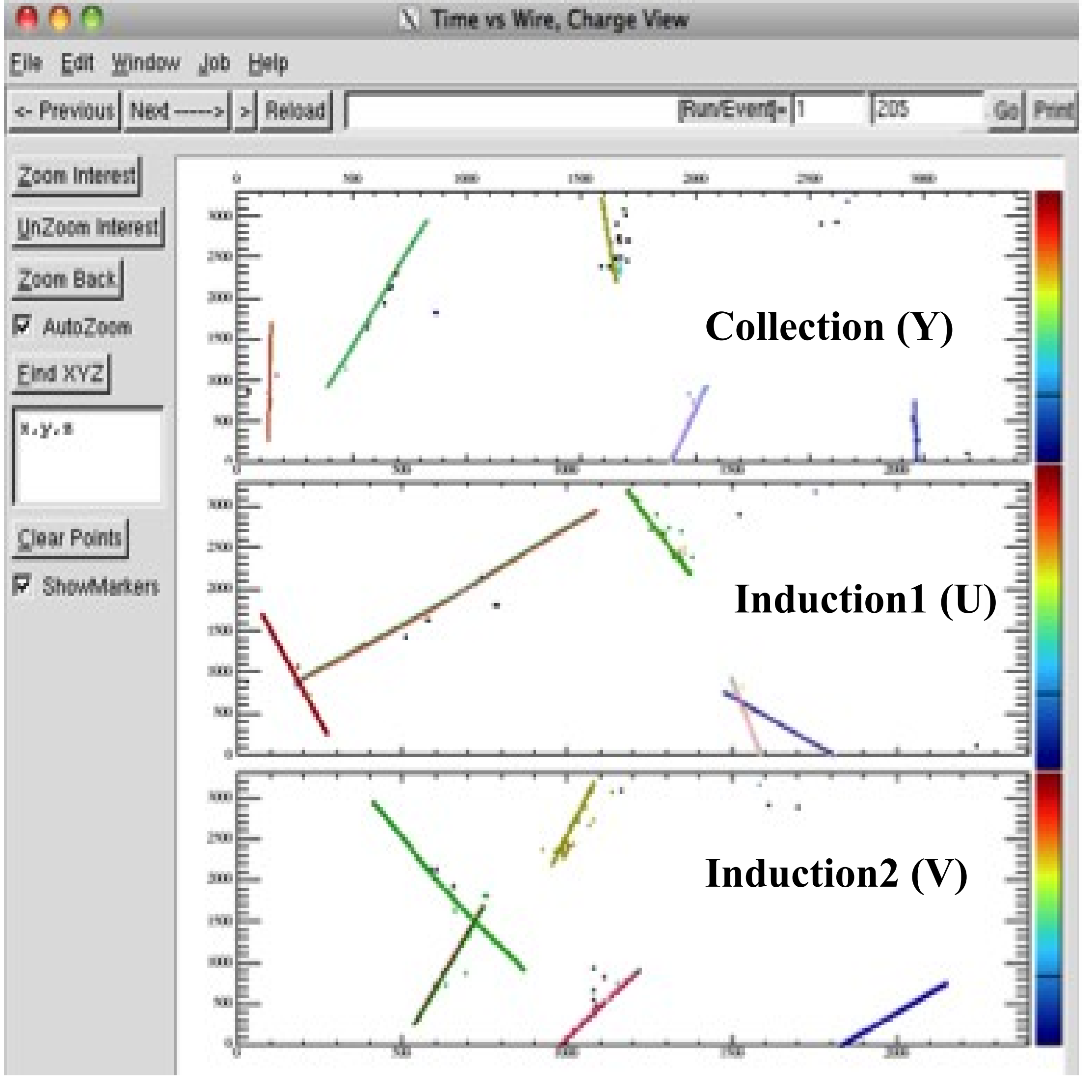
Reconstruction Chain

(a very simplified version)



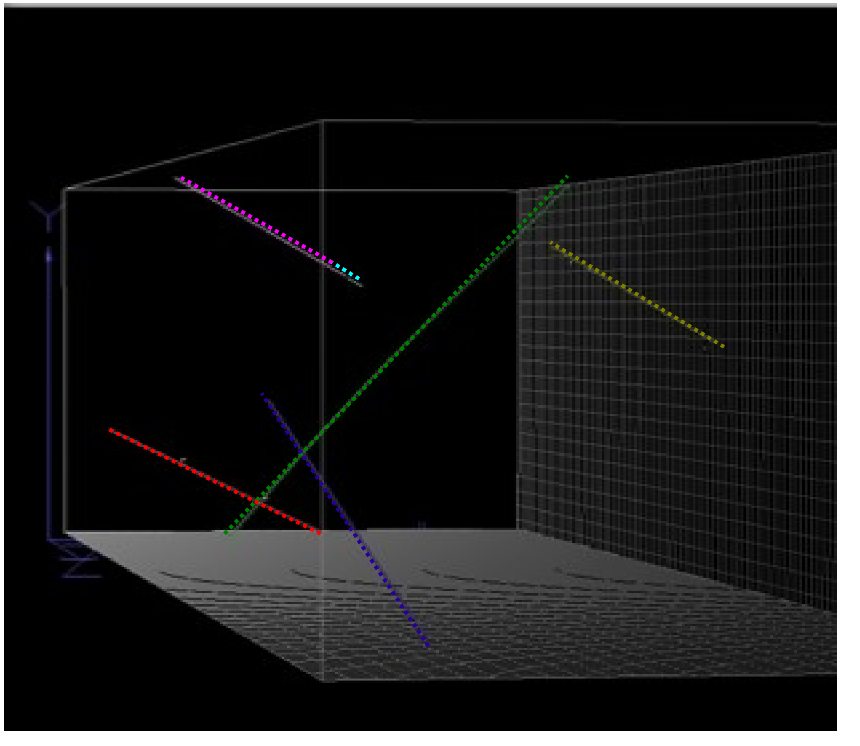
Tracking

2D views of the tracks in 3 wire plane views



Tracking algorithms maturing fast!

3D event display of cosmic tracks reconstructed with Bezier tracker



Algorithm author: Ben Jones (Bezier tracking)

Proton decay background

Some GUT models explicitly break the baryon number symmetry, thus, predicting proton decay!

MicroBooNE is not big enough to study proton decay itself

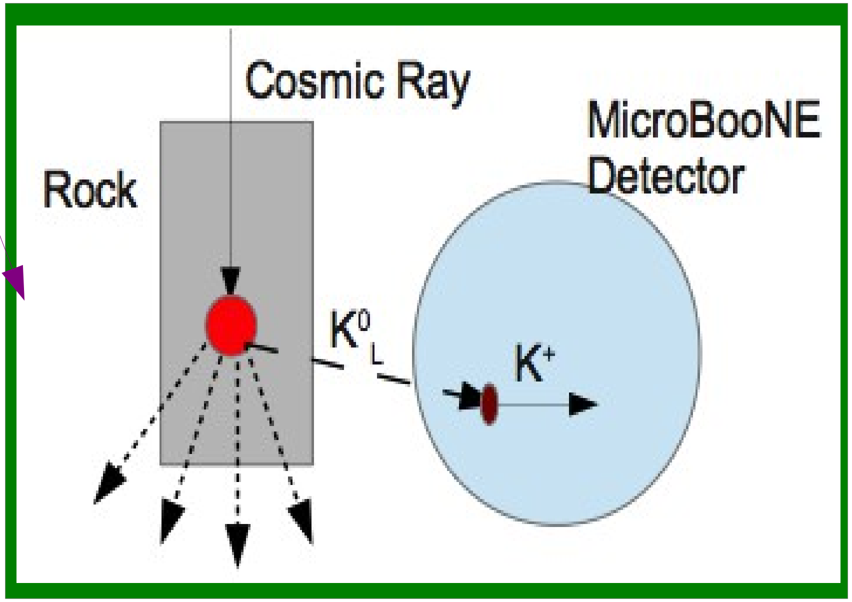
– But, MicroBooNE can study proton decay backgrounds for future experiments!

Proton decay background

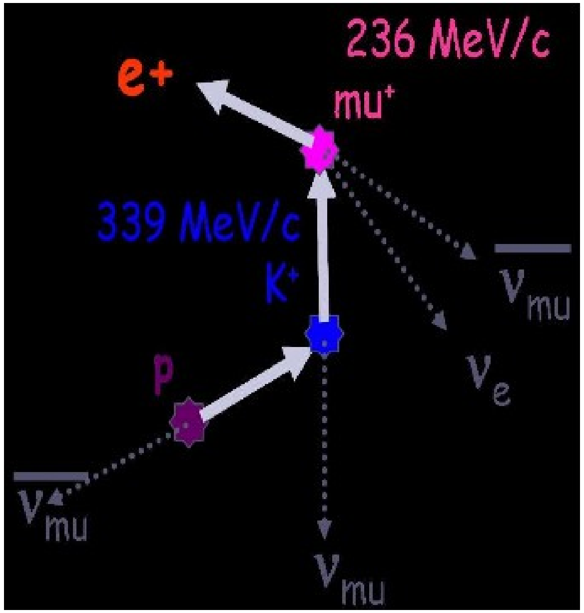
A cosmic muon interacts in a rock near the detector, produces a K^0_L which then charge exchanges, $K^0_L p \rightarrow K^+ n$ = looks like a K^+ from proton decay if right energy (339 MeV/c).

Decay mode of interest to MicroBooNE: $p \rightarrow K^+\nu;\ K^+ \rightarrow \mu^+\nu_\mu;\ \mu^+ \rightarrow e^+\nu_e(\text{anti-}\nu_\mu)$

– the distinct dE/dx pattern enables study of this 3-fold decay mode

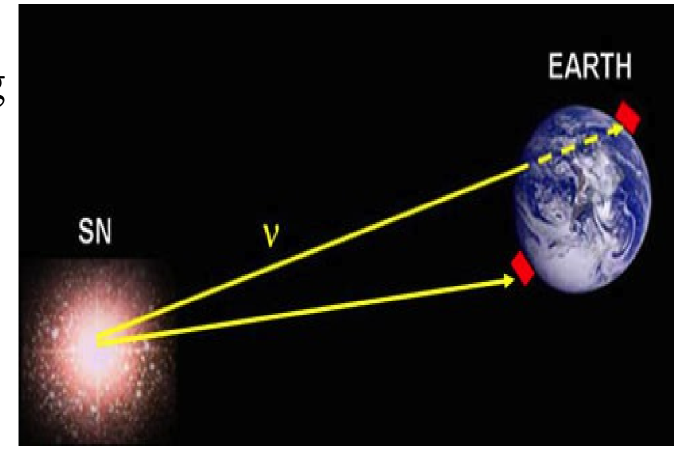


From J. Esquivel



Supernovae neutrinos

A core-collapse supernova **(SN)** produces, in addition to enormous light, **a burst of neutrinos of all flavors (in few-tens-of-MeV range)**
→ physics of oscillations of SN neutrinos very interesting
→ critical information on key astronomical phenomena



Water and liquid scintillator neutrino detectors,
→ **primarily sensitive to electron anti-neutrinos**
$\boldsymbol{anti\text{-}\nu_e + p \rightarrow n + e^+}$ *(inverse beta decay on free protons)*

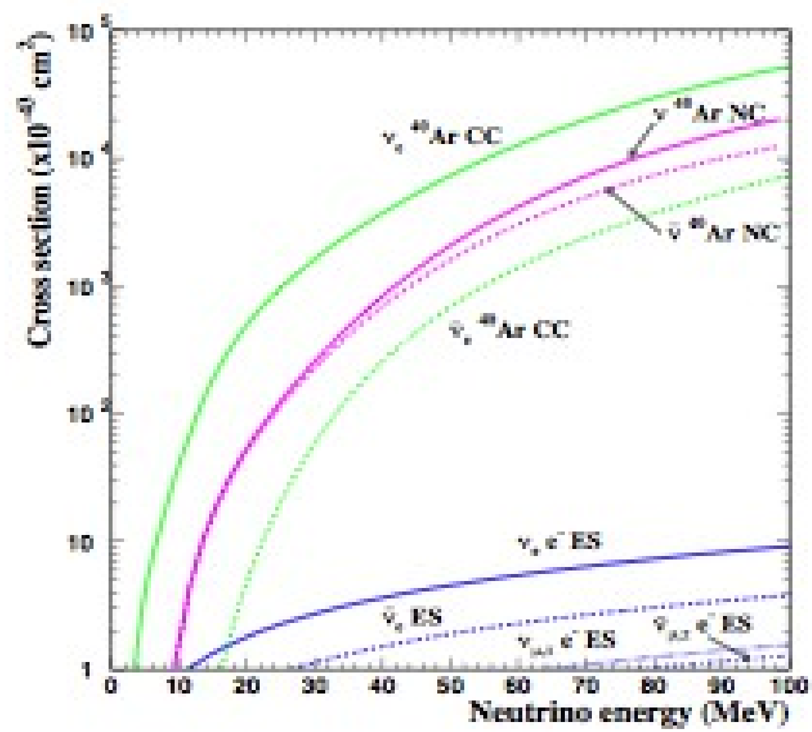
LArTPCs posses unique capability to detect SN *electron neutrinos*

1. CCν_e capture of SN neutrinos on Ar
   $$\nu_e + Ar^{40}(18) \rightarrow K^{40}(19) + e^-$$

Other processes:

2. Neutral current excitation of Ar^{40}
   $$\nu_{e,\mu,\tau} + Ar^{40}(18) \rightarrow Ar^{*40}(18) + \nu_{e,\mu,\tau}$$

3. Elastic scattering off electron
   $$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$$



Supernovae neutrinos

Detection requires sensitivity to low-energy gammas (<50 MeV) and electrons

- CCν_e capture on Ar can be tagged via the coincidence of emitted electron and accompanying de-excitation gamma cascade

Due to small size of MicroBooNE,

- will only see about *10-20 SN neutrinos in a duration of about 20 seconds*
- A multi-kiloton detector (like LBNE) will be able to see a few hundred SN events!

SNEWS

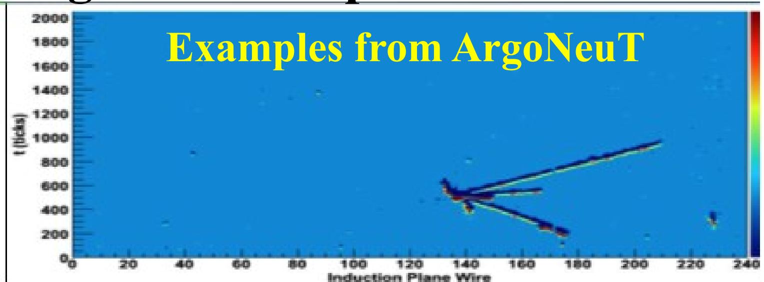
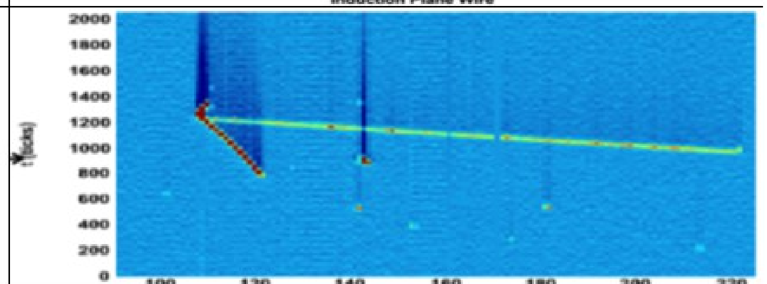
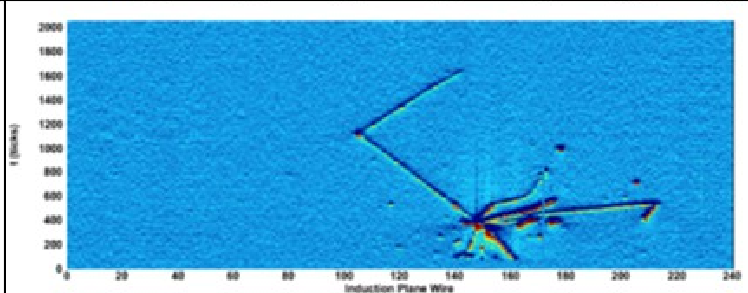
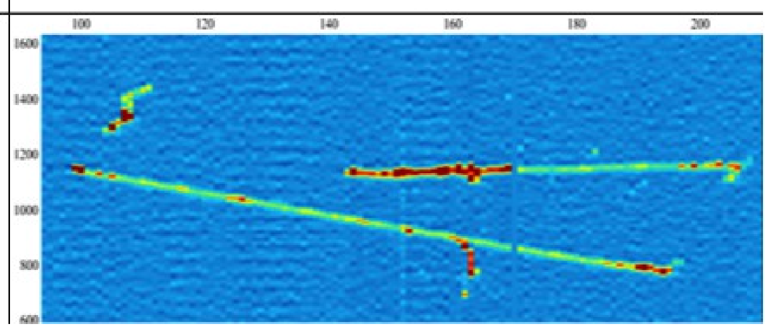
Supernova Early Warning System

Triggering on Supernovae events,

- MicroBooNE sits just below surface, *too much cosmic traffic to have its own trigger!*
- MicroBooNE will subscribe to SNEWS!

Exploring Final state particle multiplicities

Examples for charged current processes

$\nu_\mu + Ar \rightarrow 1\mu + X$ (ν_μ-CC inclusive Cross Section)	
$\nu_\mu + Ar \rightarrow 1\mu + 0\,\pi + (n_p\, \boldsymbol{p} + n_n\, \boldsymbol{n})$ $[n_p, n_n = 0$, or 1, or 2] (ν_μ-"0-pion" CC Cross Section)	
$\nu_\mu + Ar \rightarrow 1\mu + 1\,\pi^\pm + (n_p\, \boldsymbol{p} + n_n\, \boldsymbol{n})$ $[n_p, n_n = 0$, or 1, or 2] (ν_μ-"1-$\pi^\pm$" CC Cross Section)	
$\nu_\mu + Ar \rightarrow 1\mu + 1\,\pi^0 + (n_p\, \boldsymbol{p} + n_n\, \boldsymbol{n})$ $[n_p, n_n = 0$, or 1, or 2] (ν_μ-"1-π^0" CC Cross Section)	

Understanding Final state (FS) particle multiplicity is crucial for measuring exclusive channels accurately

Classifying events based on FS particle multiplicity will make it most sensitive to nuclear effects