# The MicroBooNE Experiment at FNAL


**Jyoti Joshi**

**(for the MicroBooNE Collaboration)**


WINP2015 | Workshop on the Intermediate Neutrino Program

BROOKHAVEN NATIONAL LABORATORY

# Outline

## MicroBooNE Collaboration + Project Team

*Brookhaven:* M. Bishai, J. Joshi, H. Chen, K. Chen, S. Duffin, J. Farrell, B. Kirby, F. Lanni, Y. Li, D. Lissauer, G. Mahler, D. Makowiecki, J. Mead, M. Mooney, X. Qian, V. Radeka, S. Rescia, A. Ruga, J. Sondericker, C. Thorn, B. Yu, C. Zhang
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*University of Chicago*: W. Foreman, J. Ho, D. Schmitz, J. Zennamo
*University of Cincinnati*: R. Grosso, J. St. John, R. Johnson
*Columbia University*: N. Bishop, L. Camilleri, D. Caratelli, C. Chi, V. Genty, G. Karagiorgi, D. Kaleko, B. Seligman, M. Shaevitz, B. Sippach, K. Terao, B. Willis
*Fermilab*: R. Acciarri, L. Bagby, B. Baller, D. Bogert, B. Carls, F. Cavanna, H. Greenlee, C. James, E. James, H. Jostlein, M. Kirby, T. Kobilarcik, S. Lockwitz, B. Lundberg, A. Marchionni, O. Palamara, Z. Pavlovic, S. Pordes, J. Raaf, G. Rameika+, B. Rebel, A. Schukraft, S. Wolbers, T. Yang, G.P. Zeller*
*Illinois Institute of Technology*: R. An, B. Littlejohn, M. Xu, X. Zhang
*Kansas State University:* T. Bolton, S. Farooq, S. Gollapinni, G. Horton-Smith, V. Meddage
*Los Alamos:* G. Garvey, J. Gonzales, W. Ketchum, B. Louis, G. Mills, R. Van de Water
*MIT:* W. Barletta, L. Bugel, G. Collin, J. Conrad, C. Ignarra, B. Jones, J. Moon, M. Moulai, J. Spitz, M. Toups, T. Wongjirad
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*Otterbein University*: N. Tagg
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*Princeton University*: K. McDonald, B. Sands
*Saint Mary's University of Minnesota*: P. Nienaber
*SLAC*: M. Convery, B. Eberly, M. Graham, D. Muller, L. Rochester, Y-T. Tsai, T. Usher
*Syracuse University*: J. Asaadi, J. Esquivel, G. Pulliam, M. Soderberg
*University of Texas at Austin:* S. Cao, J. Huang, K. Lang
*University of Bern, Switzerland:* A. Ereditato, D. Goeldi, I. Kreslo, M. Luethi, C. Rudolf von Rohr, T. Strauss, M. Weber
*Virginia Tech:* A. Ankowski, M. Jen, L. Kalousis, C. Mariani. R. Pelkey
*Yale University*: C. Adams, E. Church, B. Fleming*, E. Gramellini, A. Hackenburg, B. Russell, A. Szelc

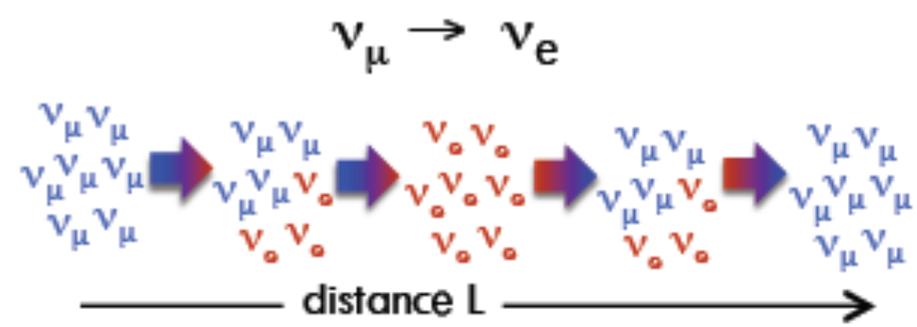
total team (collaboration + project):
23 institutions
142 collaborators
(includes project team)
30 postdocs
29 grad students

* spokespeople,
\+ project manager

- Physic Goals/Motivations
- LArTPC Technology
- The MicroBooNE Detector
- Reconstruction Chain

# Neutrino Oscillations

* Since 1998 observation of non-zero neutrino mass, neutrino oscillations phenomenon is of great interest




* The oscillations depend on the energy of the neutrinos and the distance they travel

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m^2_{ij}\frac{L}{E}\right)$$

The mixing angle, θ, determines the amplitude of the oscillation

$\Delta m^2$ determines the shape of the oscillation as a function of L (or E)

Atmospheric & Long-baseline accelerator neutrinos

3 Neutrino flavor states

Solar & Long-baseline reactor neutrinos

$$L/E = 500 \text{ km/GeV}$$

$$\Delta m^2_{atm} = 2.43^{+0.13}_{-0.13} \times 10^{-3}\text{eV}^2$$

$$L/E = 15,000 \text{ km/GeV}$$

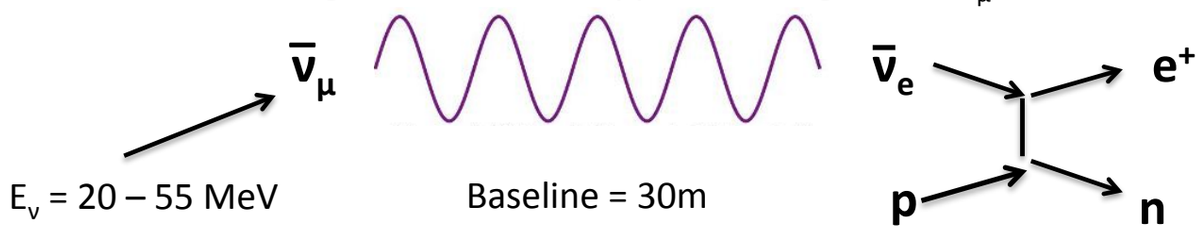
$$\Delta m^2_{sol} = 7.59^{+0.20}_{-0.21} \times 10^{-5}\text{eV}^2$$

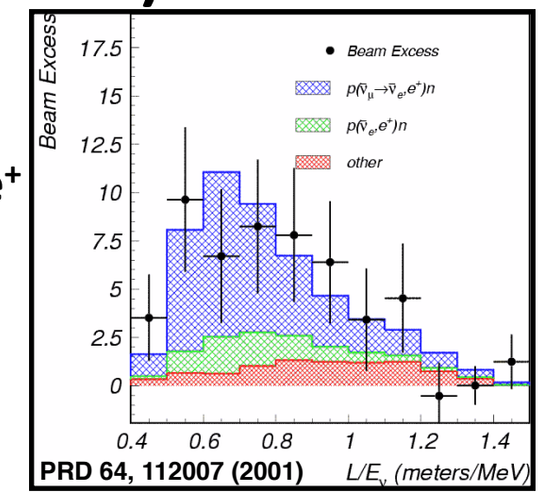
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

# Short Baseline Oscillation $\nu_\mu \rightarrow \nu_e$ Anomalies

## LSND (Liquid Scintillator Neutrino Detector):

Looking for an electron appearance signal in a $\nu_\mu$ beam.



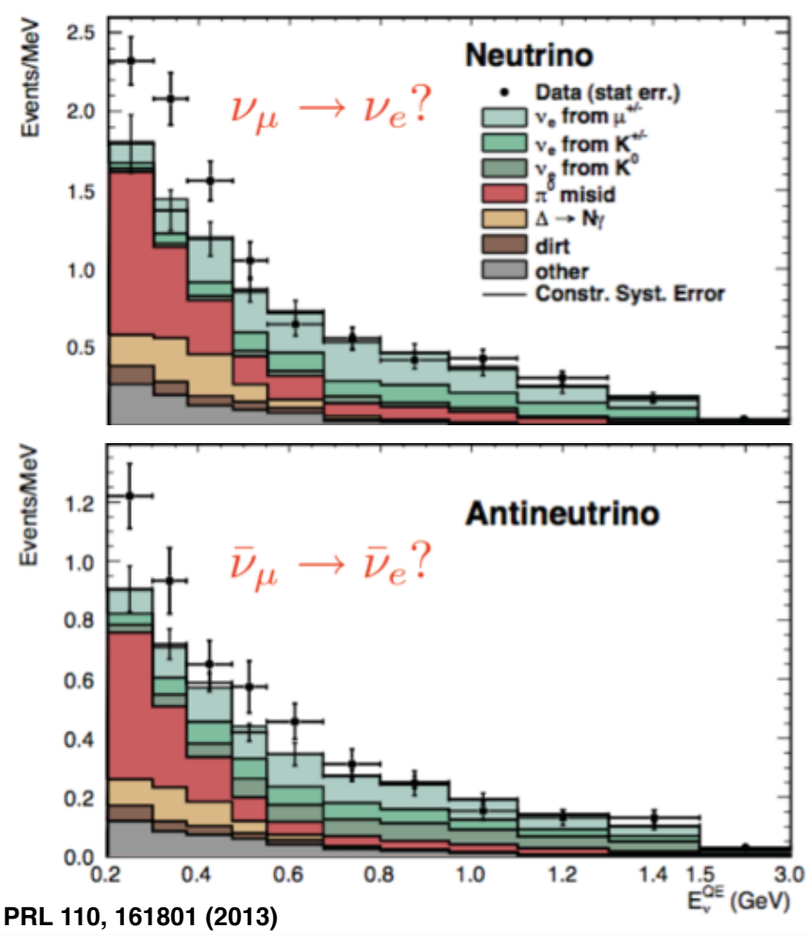




PRD 64, 112007 (2001)

Observed 87.9 ± 22.4 ± 6.0 events above background
Oscillation Probability: 0.26%

Consistent with a $\Delta m^2$ on the order of 1 $eV^2$ (not consistent with 3 flavor picture)

## MiniBooNE Result:




PRL 110, 161801 (2013)

**Neutrino mode:**

- Excess: 162.0 ± 47.8 (3.4σ)

**Antineutrino mode:**

- Excess: 78.4 ± 28.5 (2.8σ)

**Combined:**

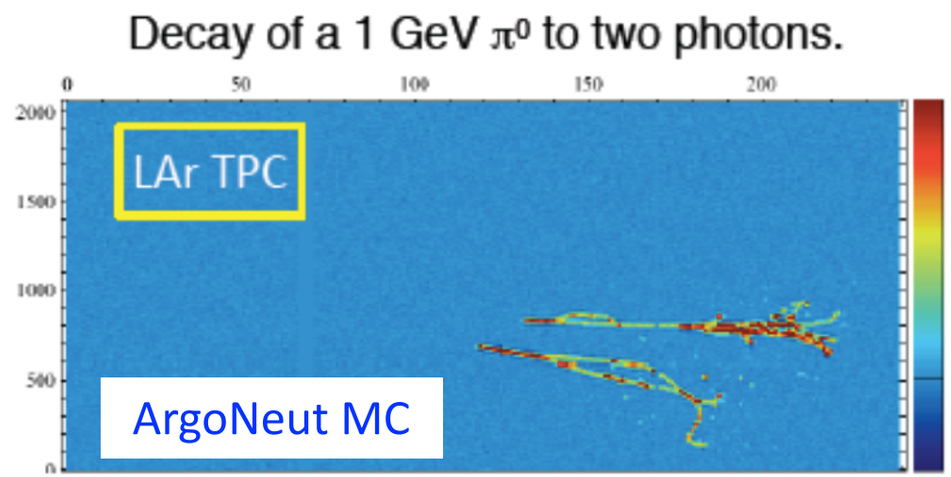
- Excess: 240.3 ± 34.5 ± 53.6
- **3.8σ significance**

Excess of low energy electromagnetic events in neutrino and antineutrino mode.

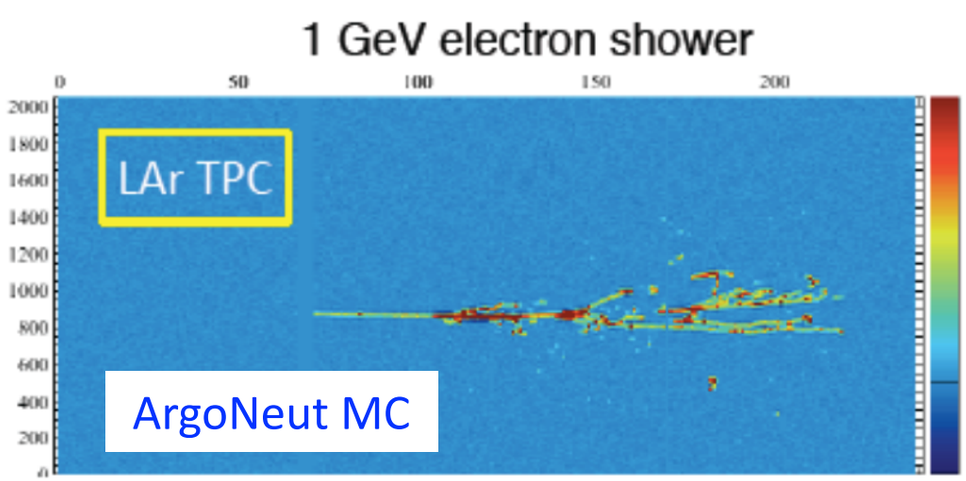
**But MiniBooNE can't differentiate between electrons and gammas!**

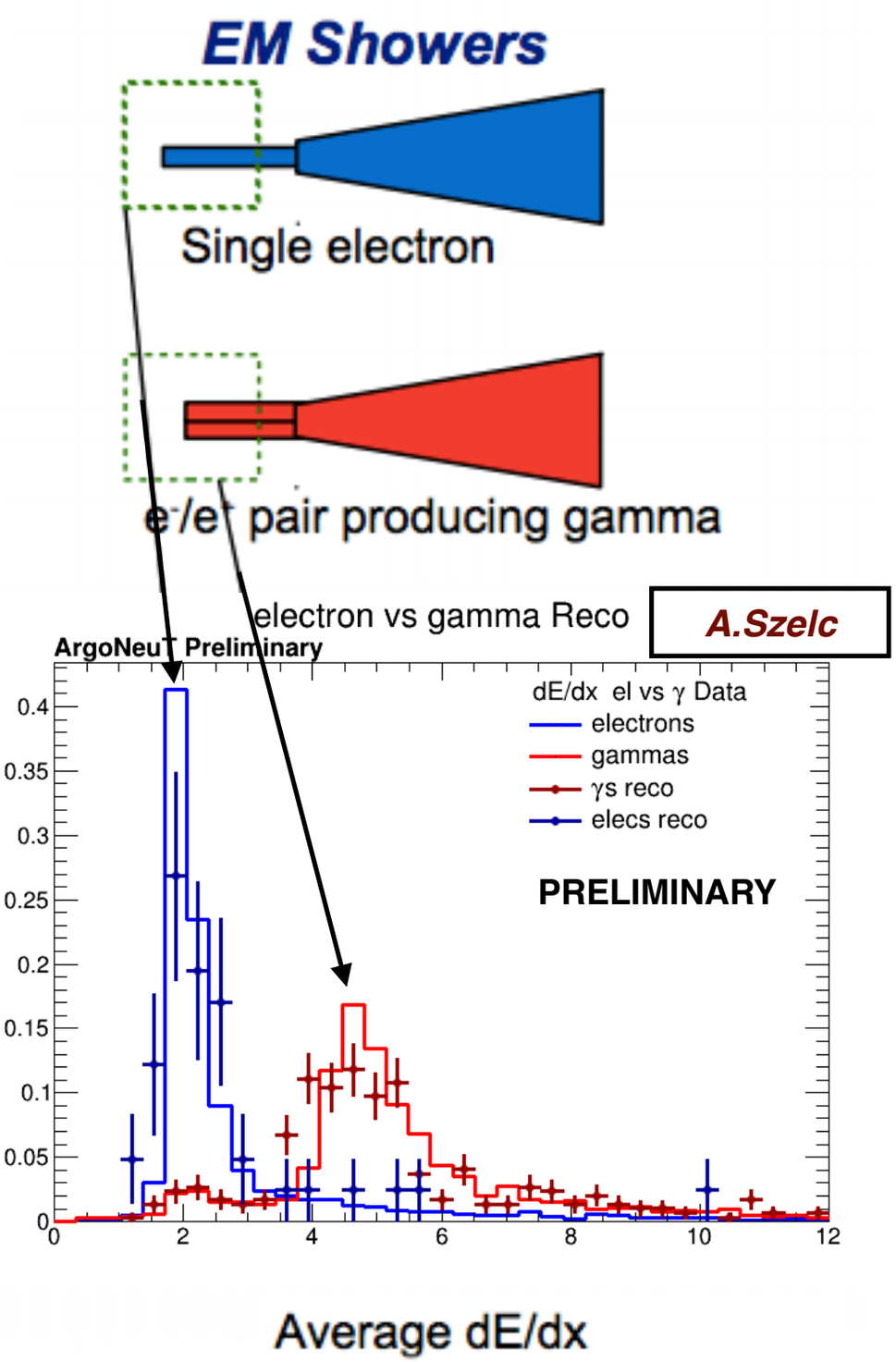
# e/γ Separation with LArTPC

**Case 1**: The neutral **γ**($\pi^0$) is observed as a gap between vertex and EM shower or between showers




**Case 2**: If the gap is too small to be observed, the charge at the start of the shower can be reconstructed through a measurement of dE/dx



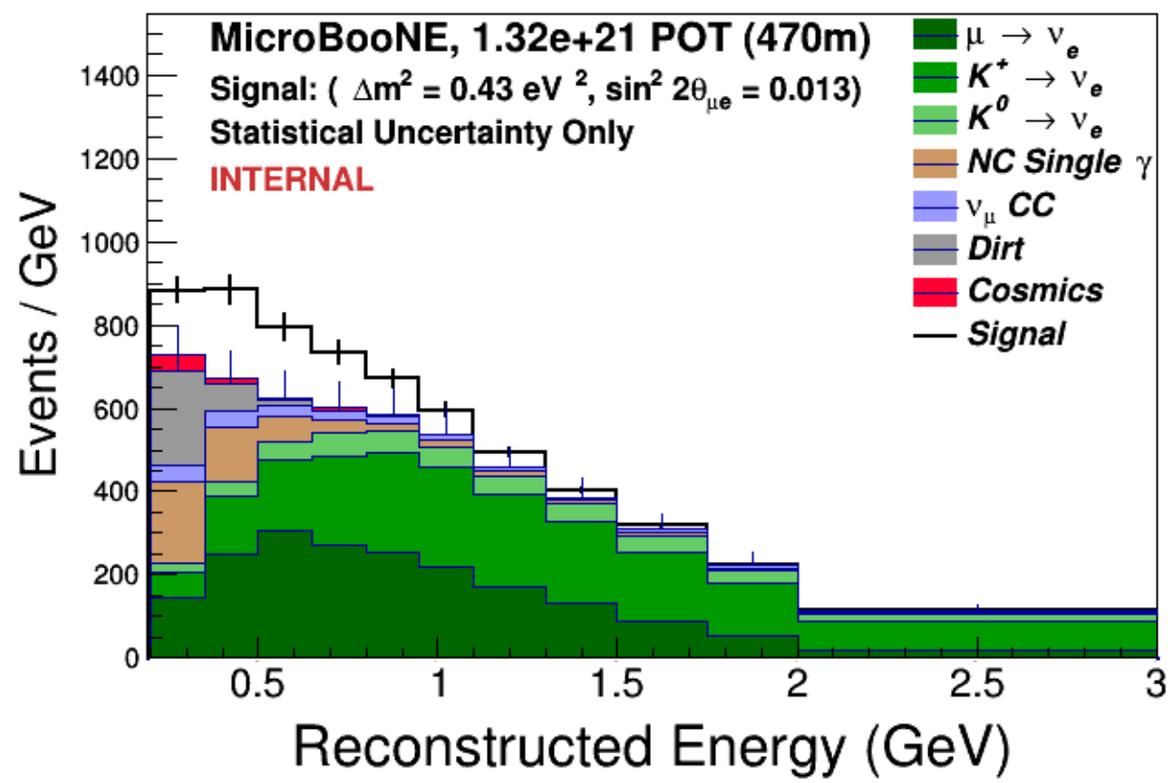
# MicroBooNE may see?

**With Improved e/γ separation, MicroBooNE can determine the nature of low-E excess**

**Approach to investigate the excess:**

- Same beam
- Same baseline
- Detector that can distinguish e and γ

**For an e-like excess** *C.Adams*



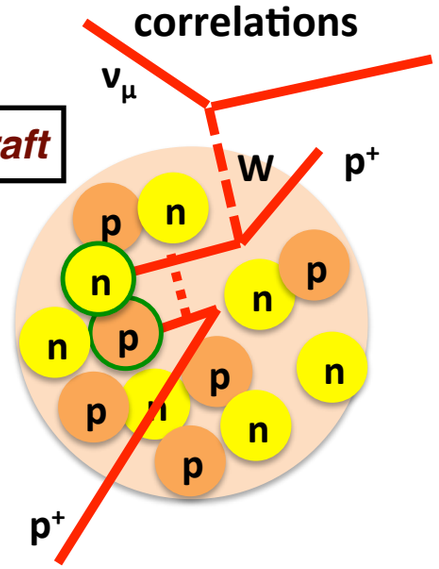

* If electron : Sterile Neutrino ?

* If photons : neutral current backgrounds

# Nuclear Effects with LArTPC

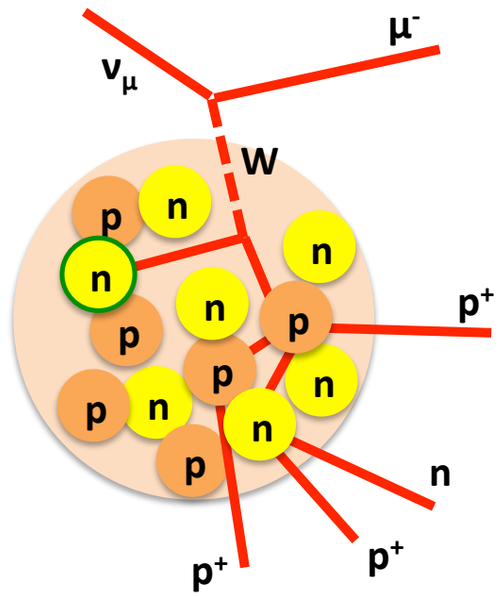
**Short-range nucleon-nucleon correlations**

A.Schukraft

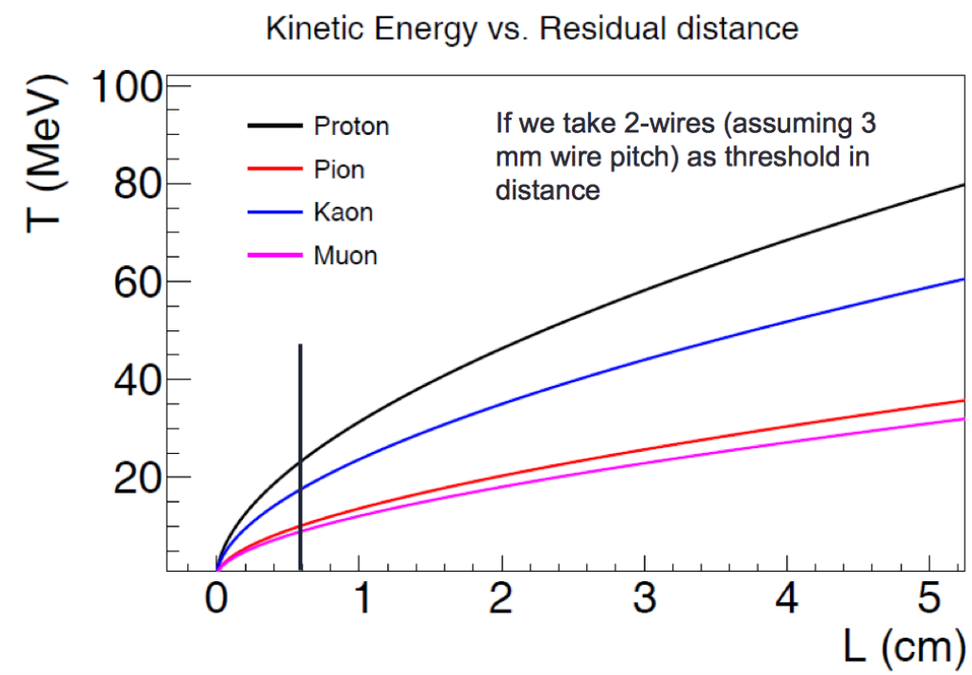



Two nucleons in correlation
Means for the experimentalist:
**Multi-nucleon knockout!**
The pair has:
large relative momentum,
small total momentum

**Final state interactions**




Multi-nucleon knockout through re-interaction of the outgoing nucleon



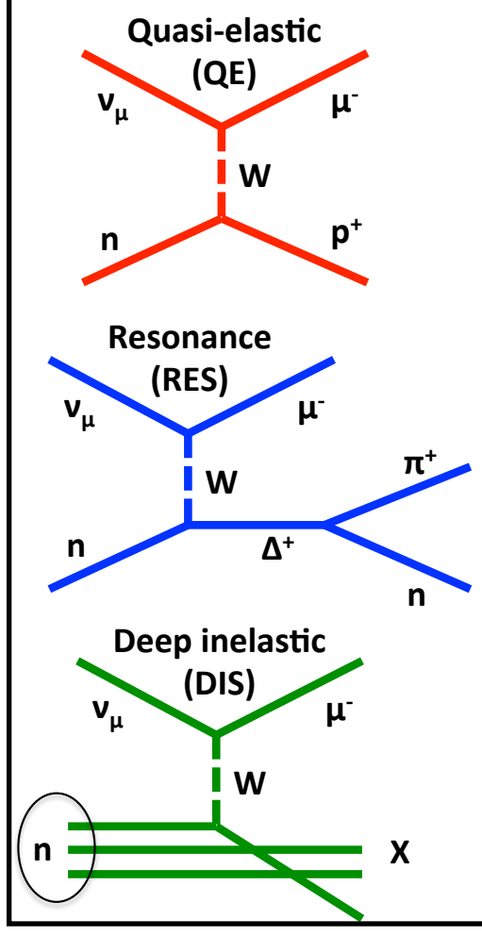

| Particle | Proton | Pion | Kaon | Muon |
|---|---|---|---|---|
| Threshold | 22 MeV | 10 MeV | 17 MeV | 10 MeV |

* Nuclear effects play a major role in ν-N interactions for heavy nuclear targets
* **The Time Projection Chamber technology opens new perspective for detailed reconstruction of the final state event topologies with low energy threshold**
* **MicroBooNE will provide high statistics sample!**

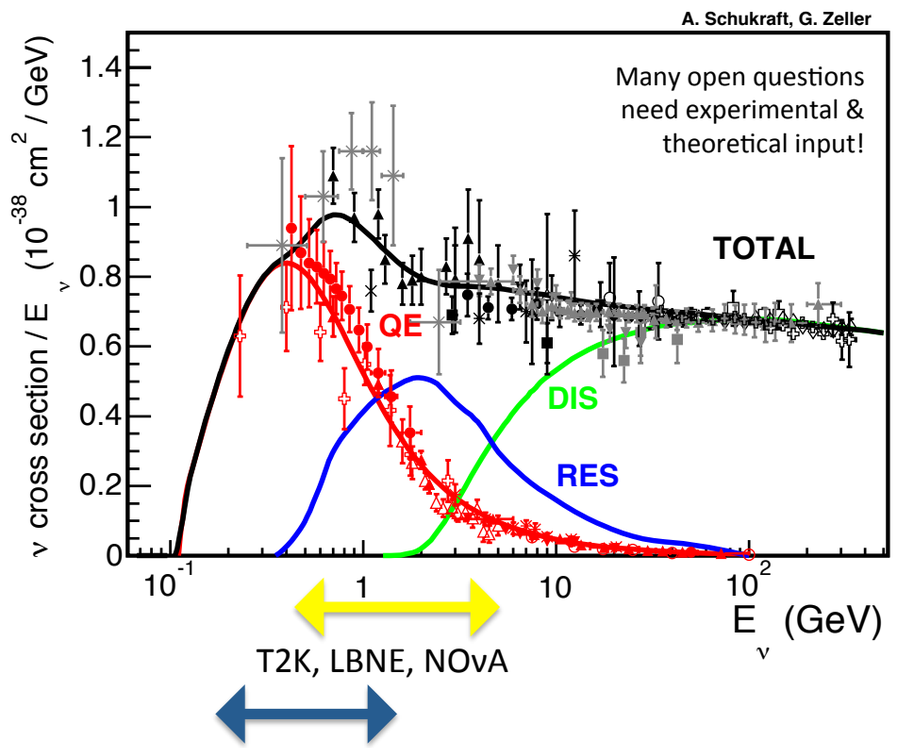
# Neutrino Interaction Cross-section

* Understanding low energy cross sections is crucial to many oscillation searches
* This MicroBooNE energy range covers the second oscillation maximum of ELBNF
* Good understanding of ν-Ar cross section and event topology is crucial for the MH determination and future precision measurement of CP phase

Neutrinos interacting with nucleons

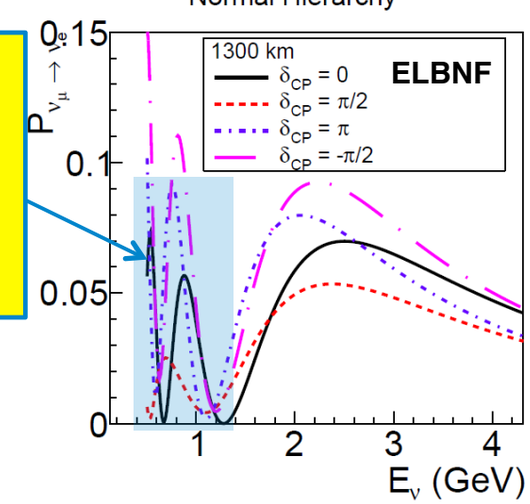


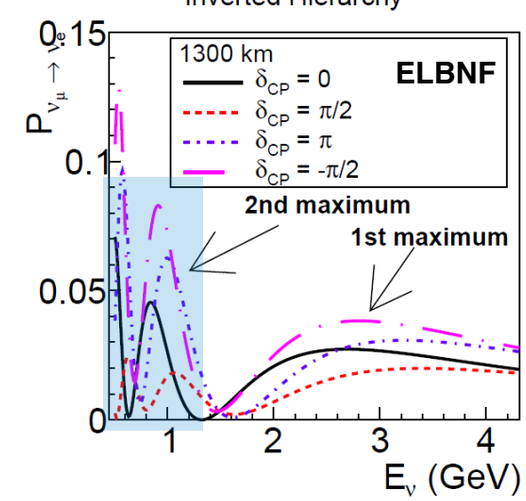

Lots of interesting (nuclear) physics over all energy ranges.




**MicroBooNE:** perfect to explore the QE regime!

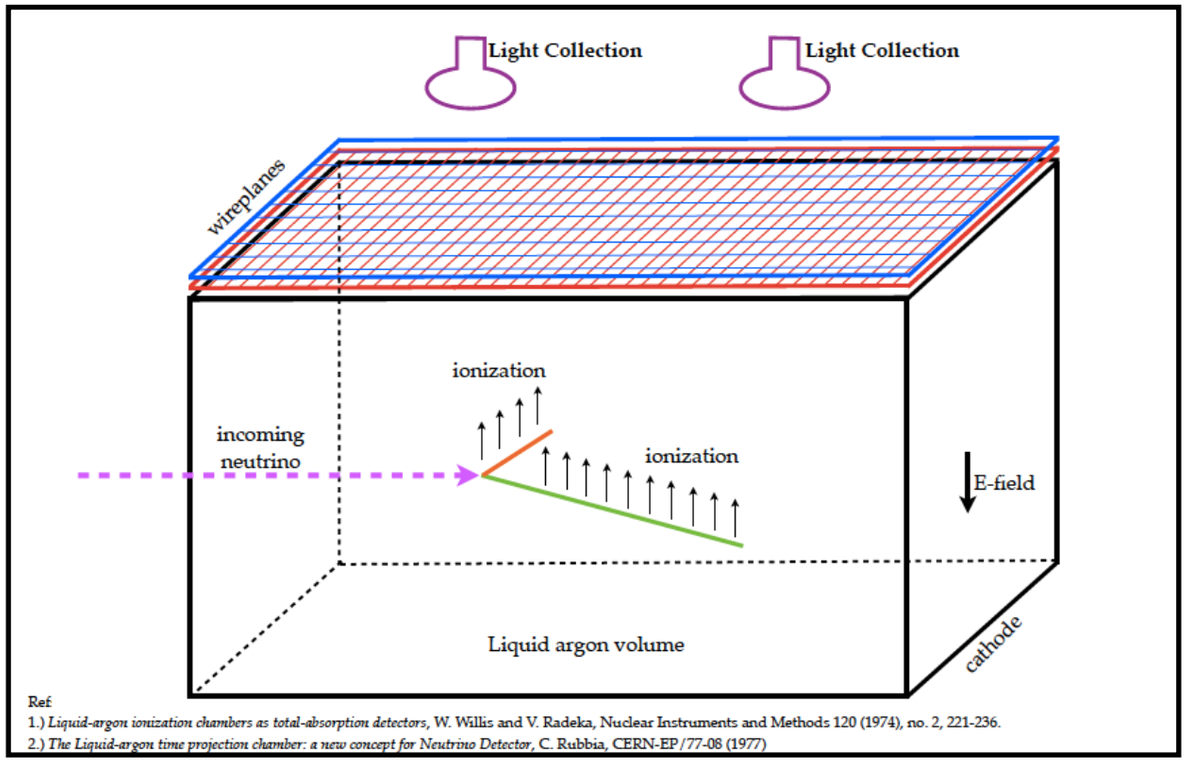
uBooNE neutrino energy range



# LArTPC Technology

# Liquid Argon Time Projection Chambers




*M.Soderberg*

**Excellent Resolution and Calorimetry!**

## Why argon ?

* Ionization charges drifted through macroscopic distances
* High Scintillation yield (40,000 $\gamma$/MeV)
* Argon is rather cheap and abundant in nature ($5/kg)
* Dense detectors can be made (1.4 g/cm$^3$)

* Ionization electrons detected by a series of wire planes
  - Particle Identification, calorimetry and tracking

* Scintillation light collection system
  - Trigger and $t_0$ reconstruction

# Fermilab's Booster Neutrino Beam (BNB)

**Linac**
Length: 150m
Proton Energy: 400 MeV

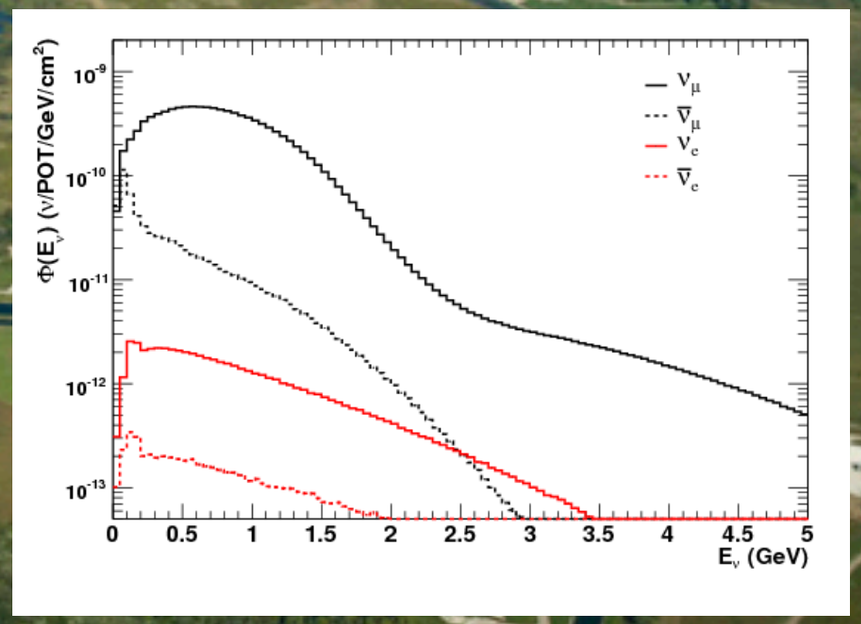
**Booster**
Circumference: 468m
Proton Energy: 8 GeV

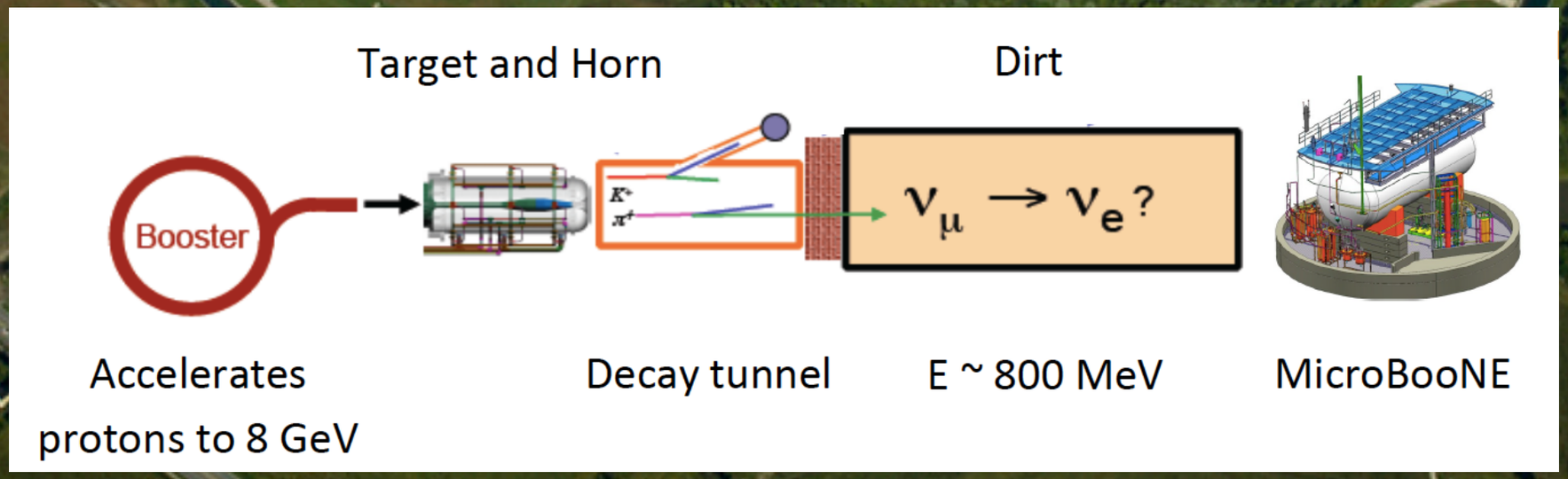
Protons

Neutrinos

MicroBooNE detector

Fermilab's **low-energy** neutrino beam
<Eν> ≈ 700 MeV



# The MicroBooNE LArTPC

- The first TPC to use electronics immersed in LAr
- The first TPC to use passive insulation & filling w.o. evacuation

* **Time Projection Chamber:**

- Three planes of wire at 3mm pitch
  - One Collection plane at 0° from vertical
  - Two induction planes at ±60°
- Total 8256 channels
- 1.6 ms drift time (2.5 m drift length @ 500 V/cm)

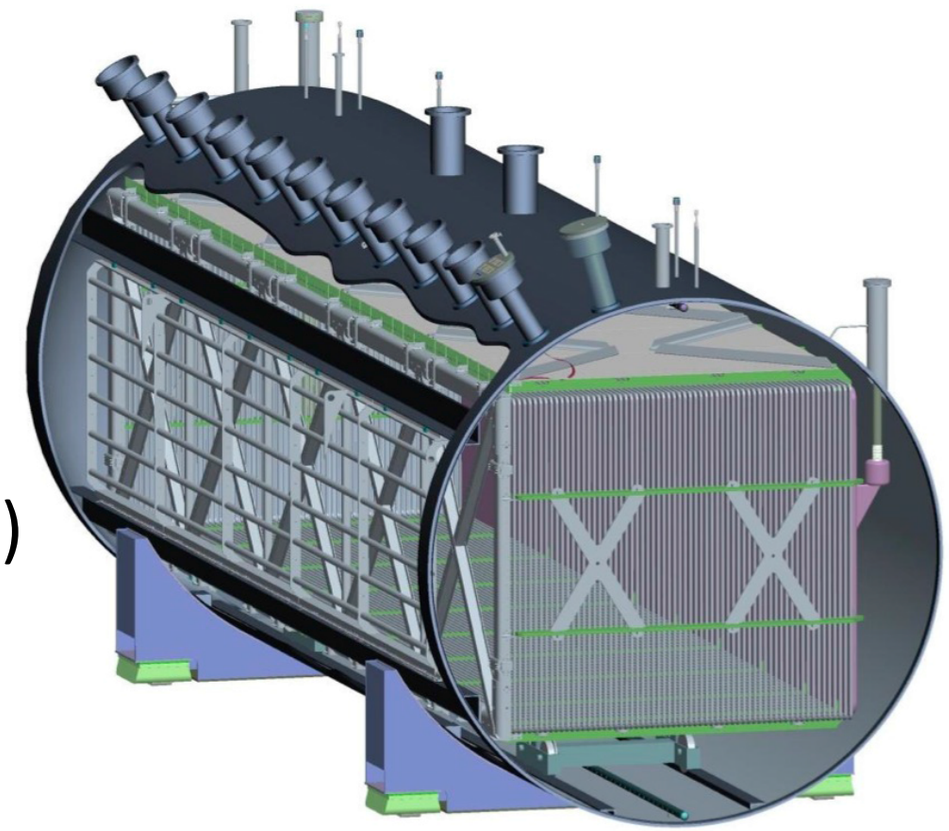
* **Optical System:**

- 32 cryogenics photomultipliers (PMT)
- LED based light injection system

* **UV Laser Calibration System**

* **High Voltage System**

**Many Innovations in detector technology**



**** 10.3 m x 2.3 m x 2.5 m***
**** Uniform field of 500 V/cm***
**** 170 tons of purified LAr (active volume ~80 tons)***

Cryostat

Cryostat

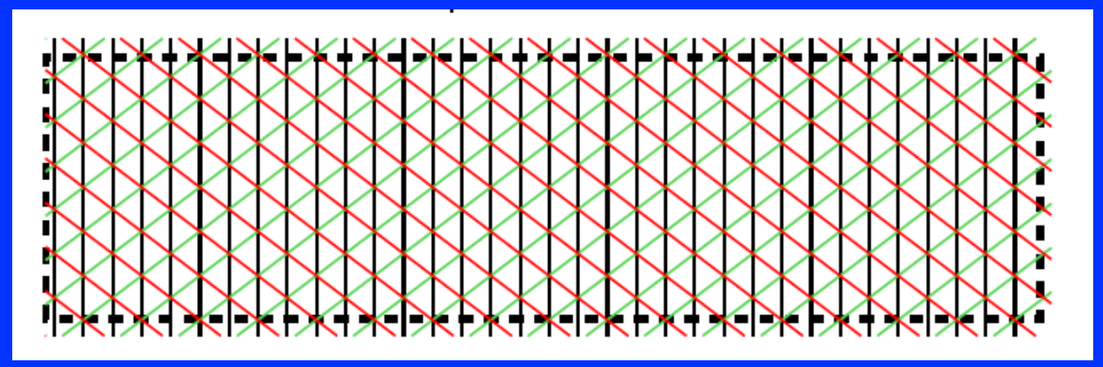
Optical System

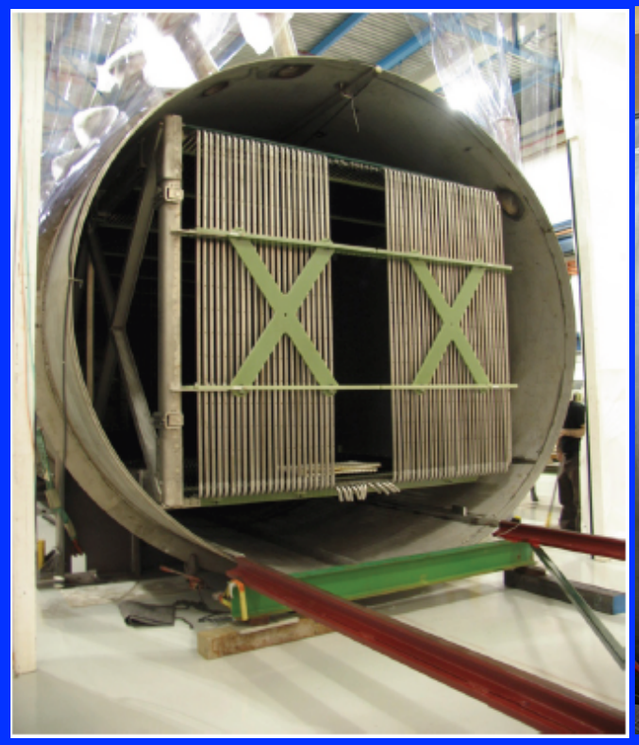
PMT

TPC Pipes

**Successfully passed the CD4 review!**

Three wire planes



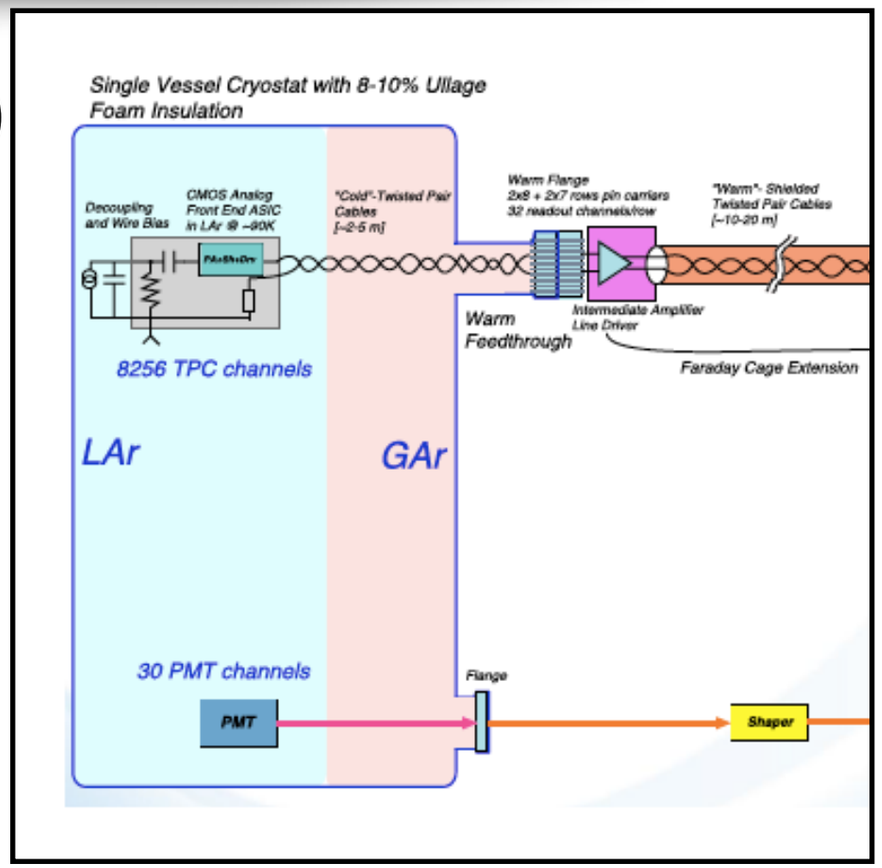


# Signal Readout: Electronics

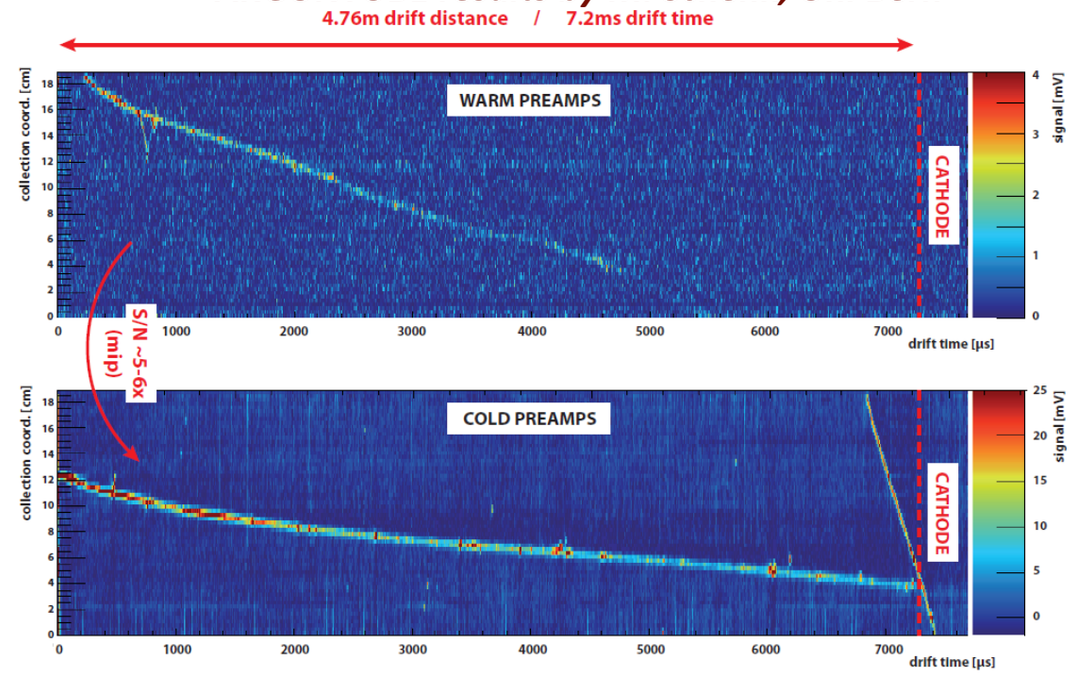
* **Cold Electronics** (*Veljko R., Hucheng C., Bo Y., Gianluigi G., Craig T.*)
  - CMOS ASIC-based design developed at BNL
    - Reduces noise and hence increased sensitivity
  - Electronics calibration
  - Transport (analog) signal through liquid and gaseous argon

* **Warm Electronics**
  - Intermediate amplifiers for additional amplification with minimal noise
  - Cables of ~10 m in length from cryostat feedthrough to readout crate

* **Front End Modules**
  - Signal digitization at 2 MHz sampling rate
  - Signal processing via FPGA




*ARGONTUBE results by M. Schenk, Uni Bern*



# UV Laser Calibration - Space Charge

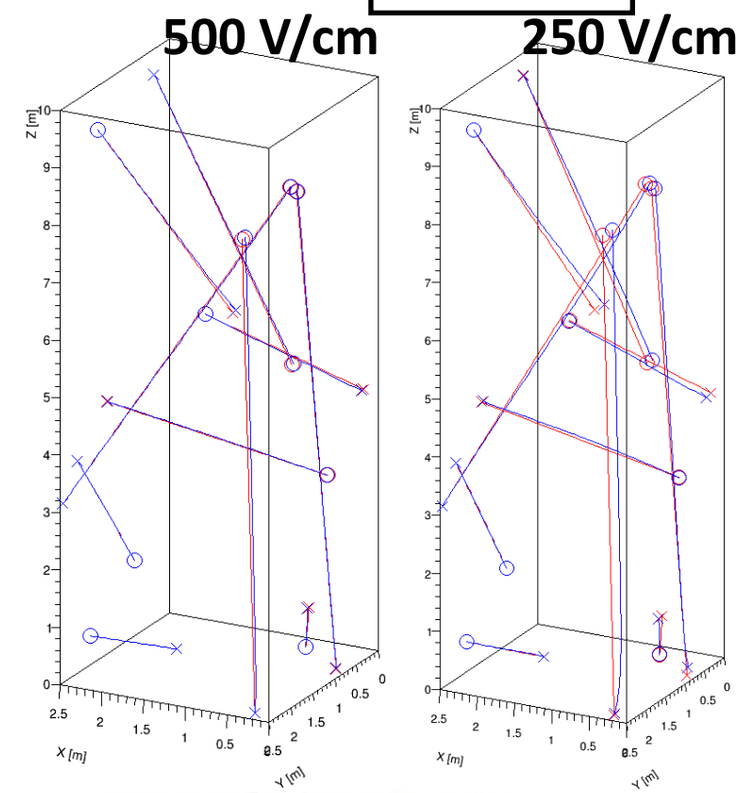
**Space Charge effect -** modifications of E field in TPC due to build-up of positively charged ions from cosmic rays

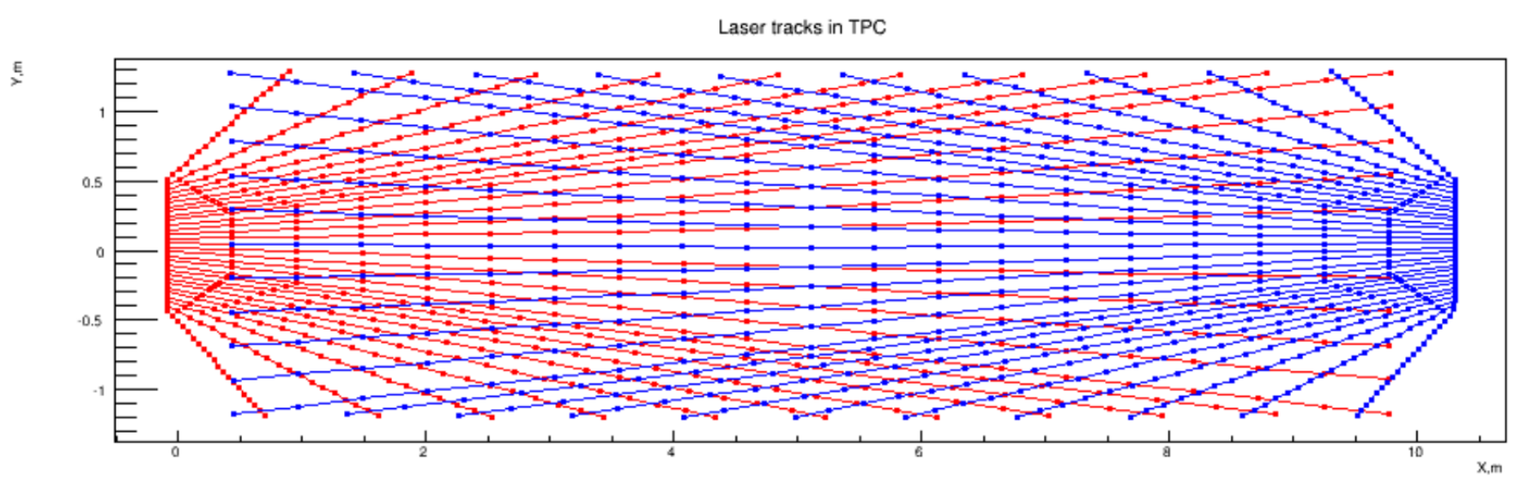
* Impacts on reconstruction of tracks/showers in detector

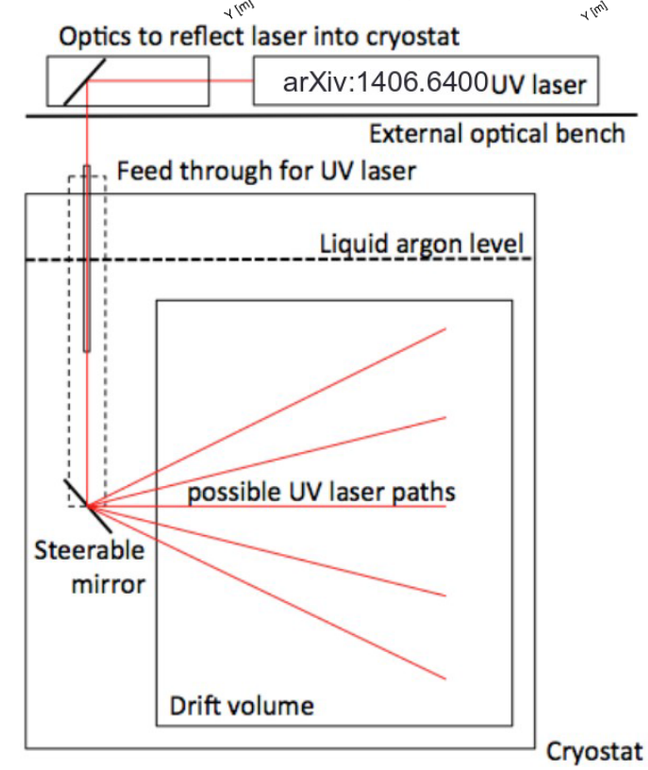
**Laser system** together with cosmic muons can be used to calibrate out space charge effect and other sources of E field inhomogeneity

* True laser track + reconstructed laser track -> measured ionization correction map

M.Mooney

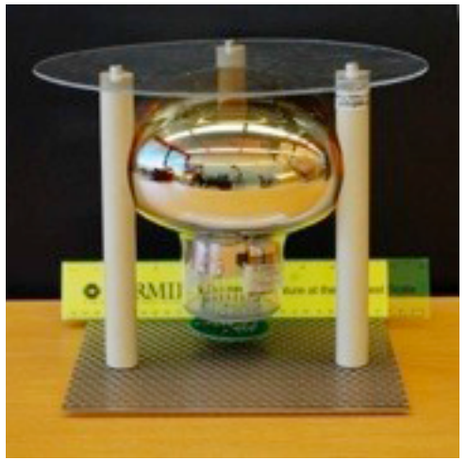


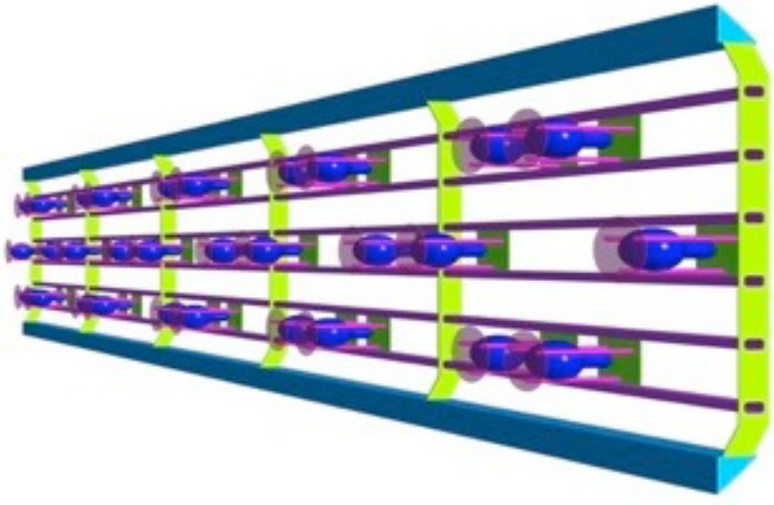



# Photo-Detection System

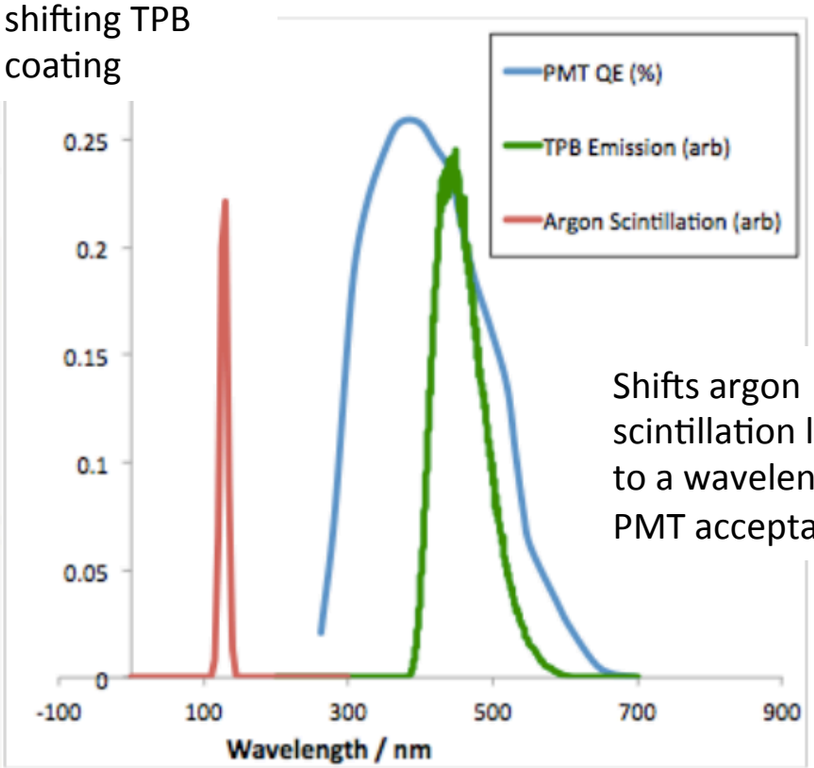
* Array of 32 PMTs sits behind the TPC wires
  - TPB-coated acrylic plates wavelength shift 128-nm light
  - Two gain settings





* PMTs provide important timing information
  - Precise "$t_0$" for start of electron drift
  - Time and position of out-of-time ionization
    - Cosmic ray overlap

Wavelength shifting TPB coating



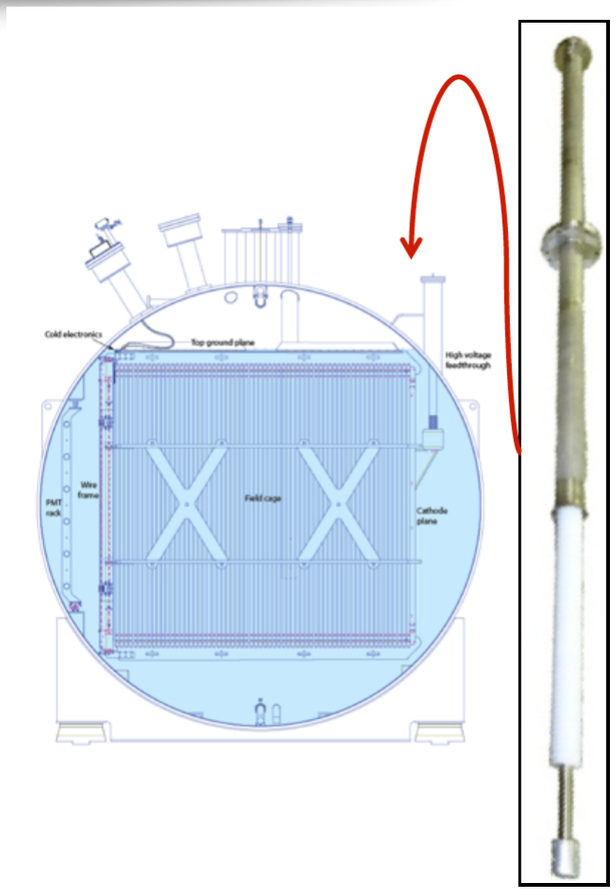

Shifts argon scintillation light (VUV) to a wavelength in the PMT acceptance region

B.J.P. Jones, et al JINST 8 (2013) P01013

# The High Voltage System

* HV feedthrough is modeled on ICARUS feedthrough
  - A stainless steel outer ground tube
  - An UHMW PE insulating layer (Ultra high molecular weight polyethylene)

* Design voltage is 128 kV for 500 V/cm
  - Highest Voltage in LArTPC neutrino beam detector
    - Need it for the long drift



## Lesson Learned

* From literature, dielectric strength of LAr is ~ 1.4 MV/cm

  D. Swan et al. J.Electrochem.Soc., vol. 107, no. 180, 1960.

* Recent studies from FNAL (1408.0264) and Bern group (1401.6693) shows breakdown at fields as low as 40 kV/cm

* Bern group : using polymer coating dielectric breakdown can be suppressed in LAr ionization detectors(1406.3929)

# Mitigate HV Damage

* If feedthrough or cathode discharges, very high voltage can damage field cage resistors and can lead to downtime

**On First 16 of 64 field cage rings**

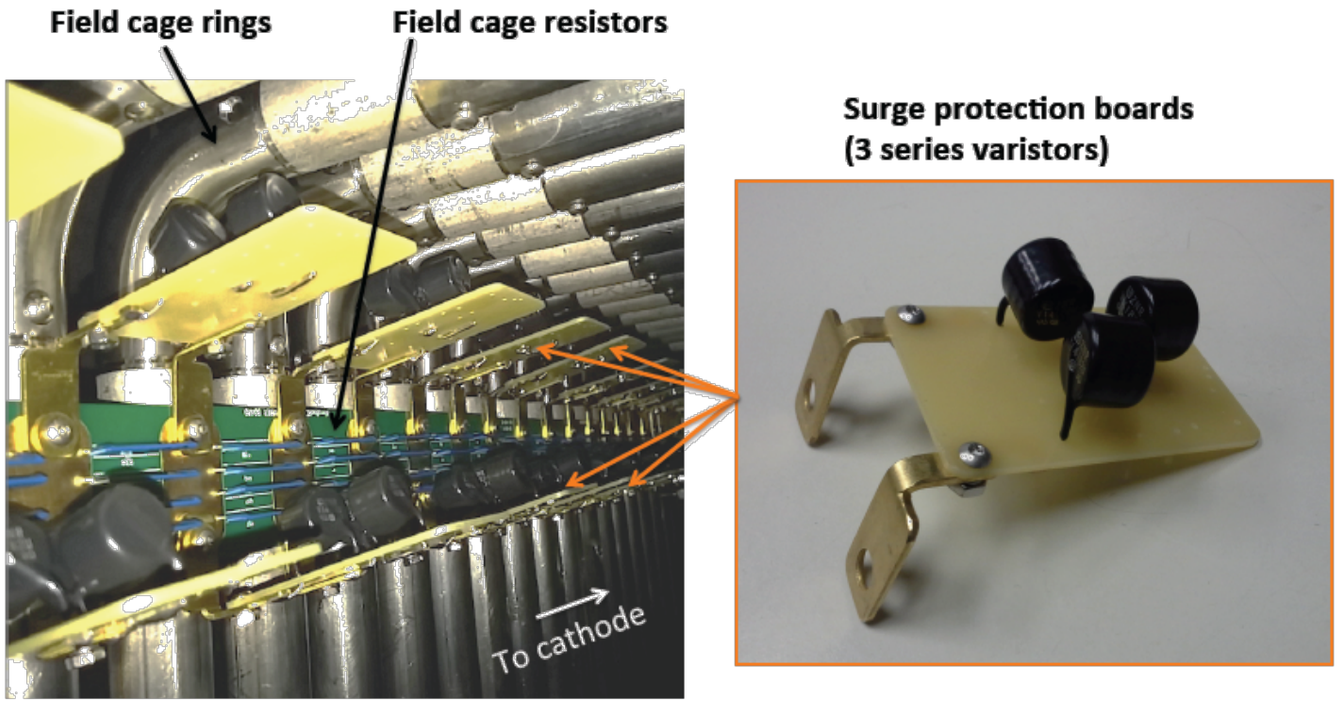
**Figure 10.** The Metallux HVR 969.23 resistors mounted on the 16 field cage loops closest to the cathode.

## Surge Protection

* Use durable resistors on 1/4 of the TPC with high power and voltage ratings, 48 kV rating (in air) (1408.4013 )

**On First 32 of 64 field cage rings**

* Use varistors on the first 1/2 of the TPC to protect the resistors (1406.5216)



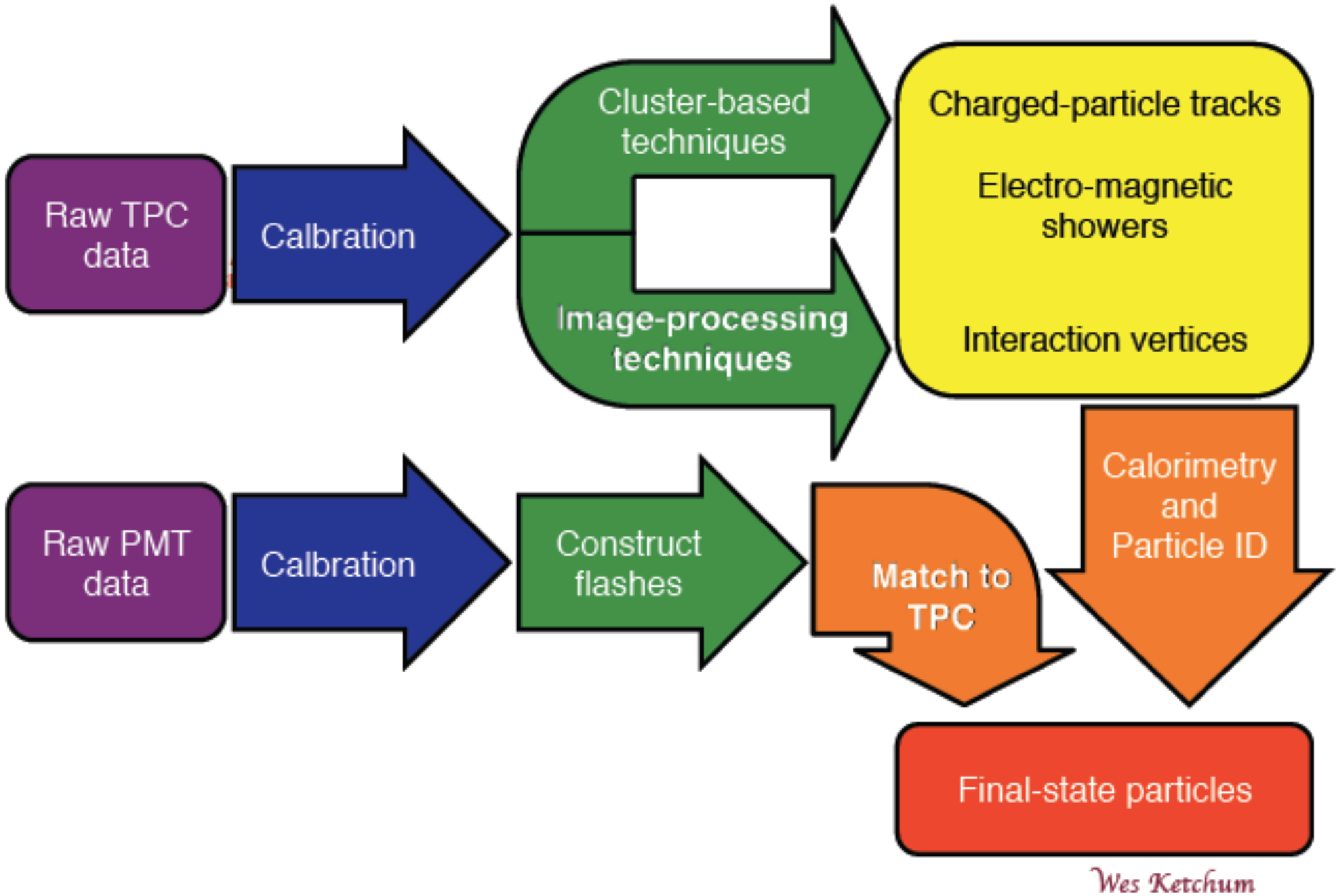

**For More detail:**

*Sarah Lockwitz's WINP talk* : Link

# Reconstruction Framework

# Reconstruction Chain

Fine grained events -> Lots of information -> Challenging reconstruction!



# Signal Processing

Number of ionized electrons

↓ Field Response

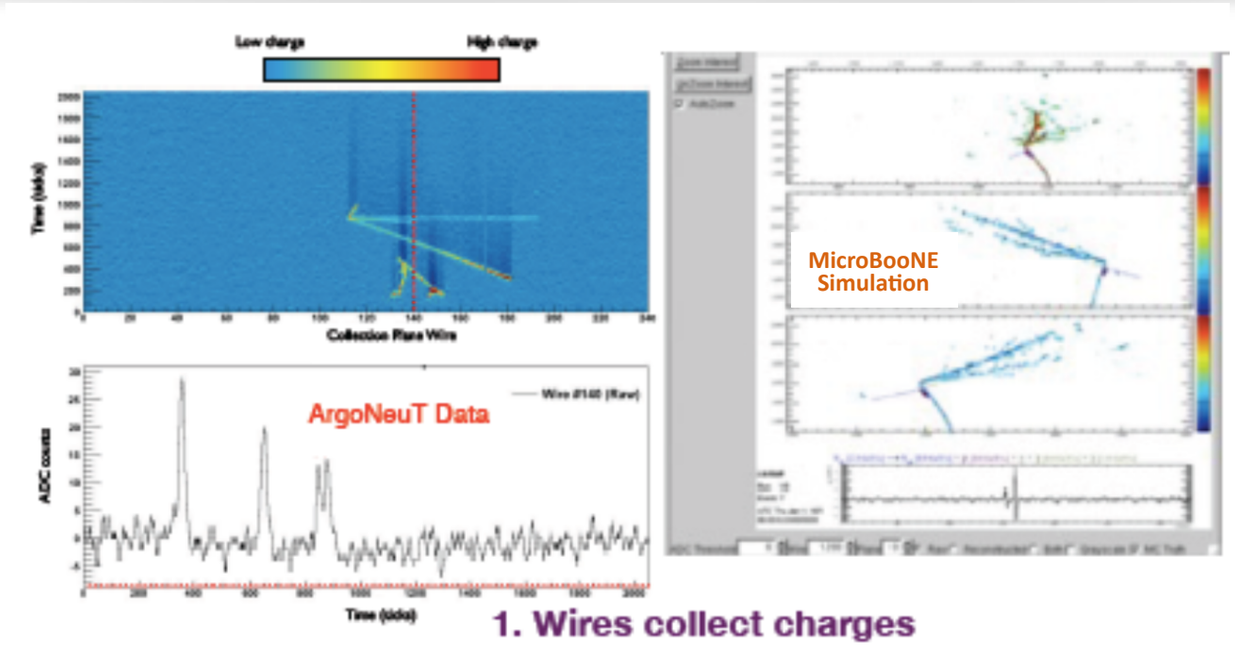
Signal on Wire Plane

↓ Electronics Response

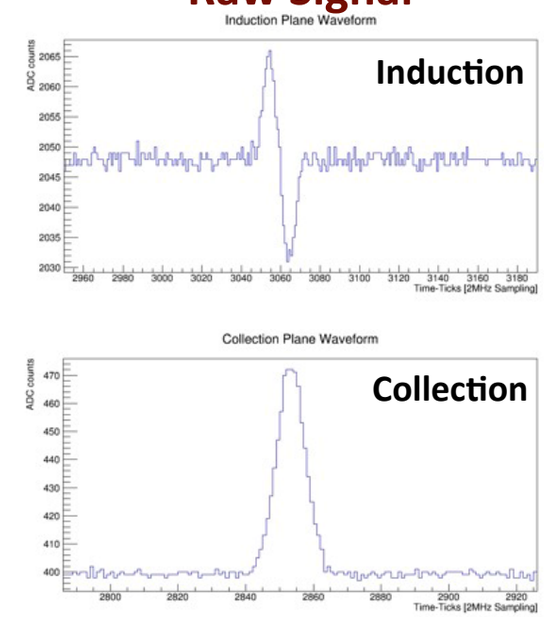
Signal to be digitized by ADC

↓ Deconvolution

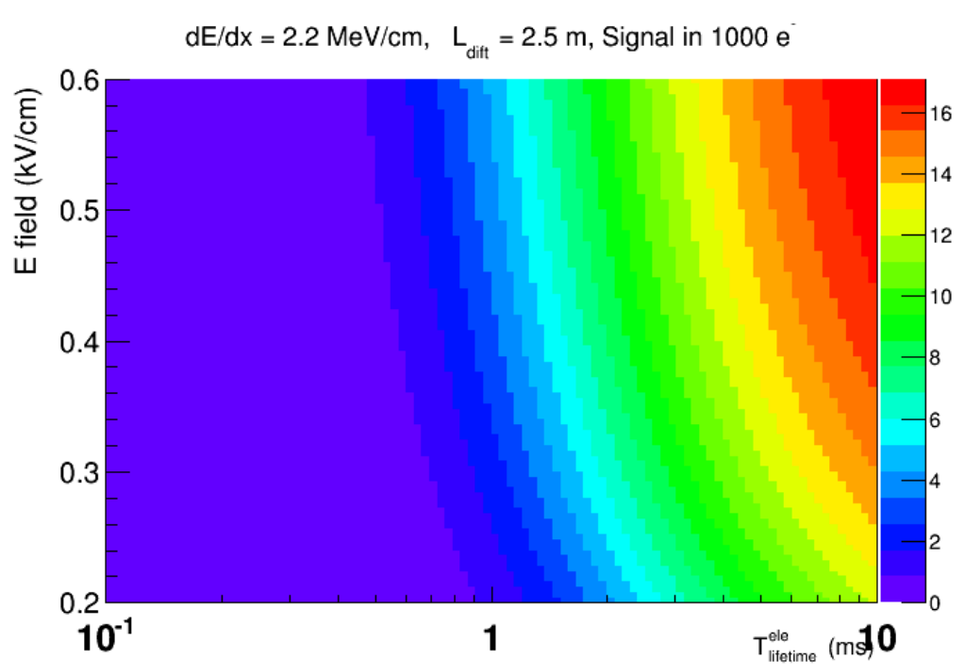
High-level tracking
...



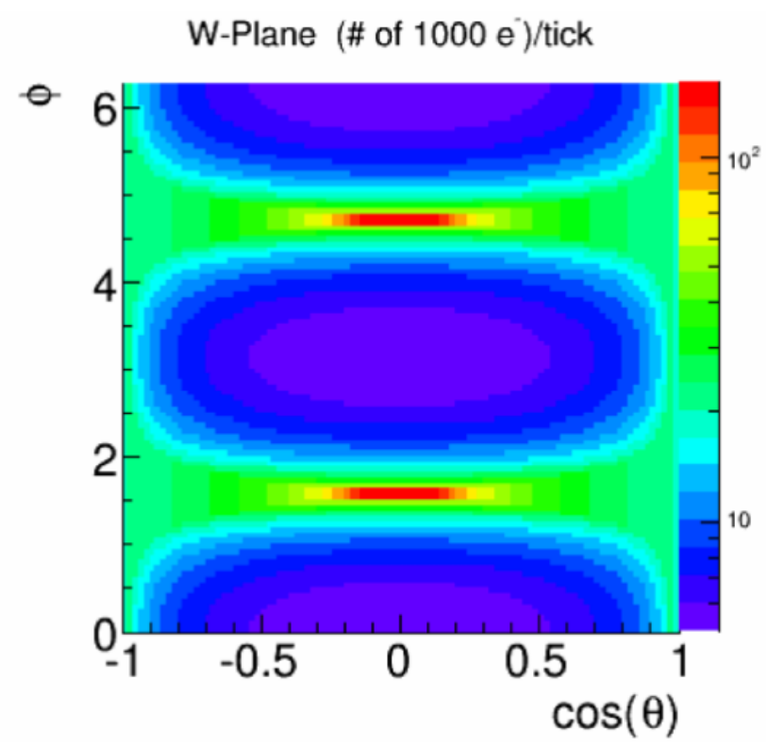

## Raw Signal



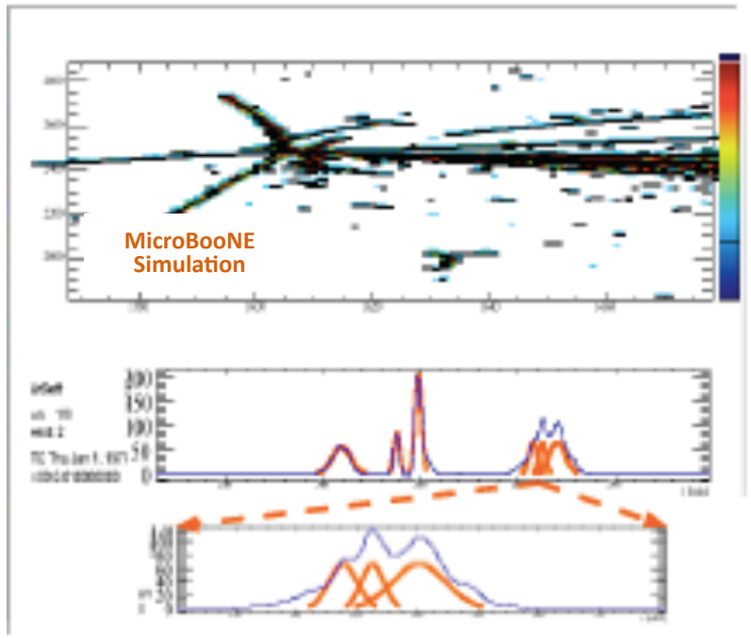

## Signal Strength in terms of E.F & Electron Lifetime



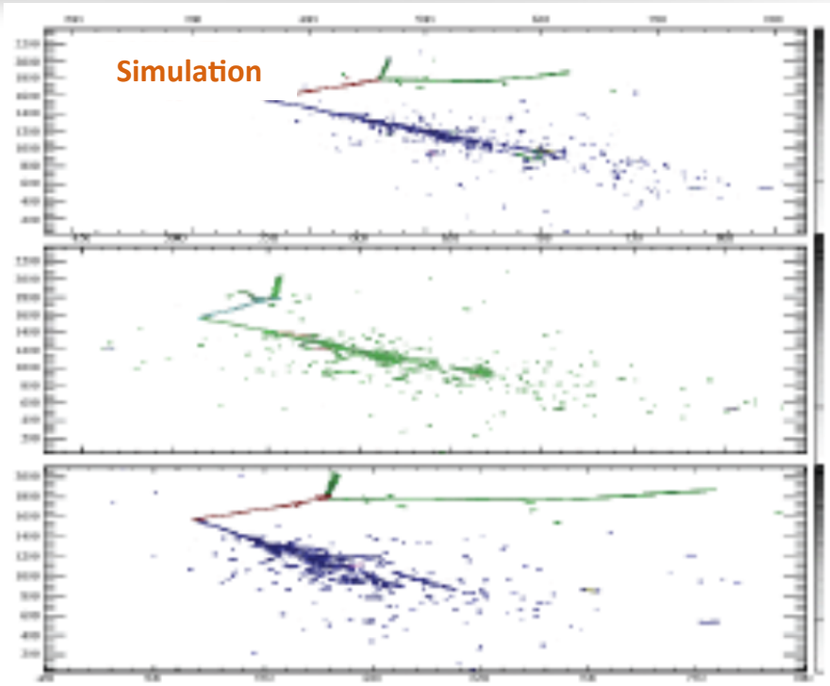

## Signal in terms of distance to wire plane and angles



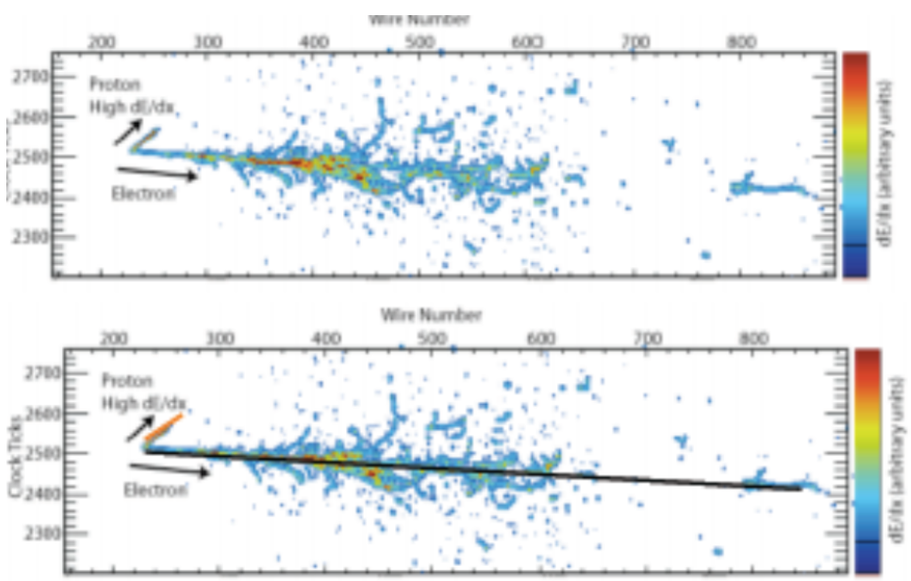
# Event Reconstruction




2. Find hits by fitting Gaussians

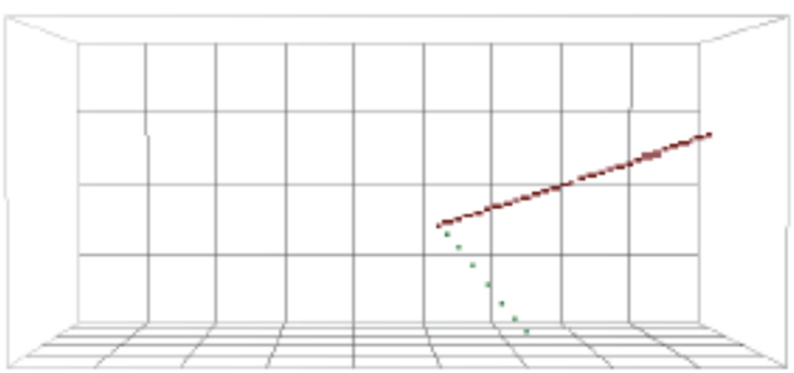



3. Clustering

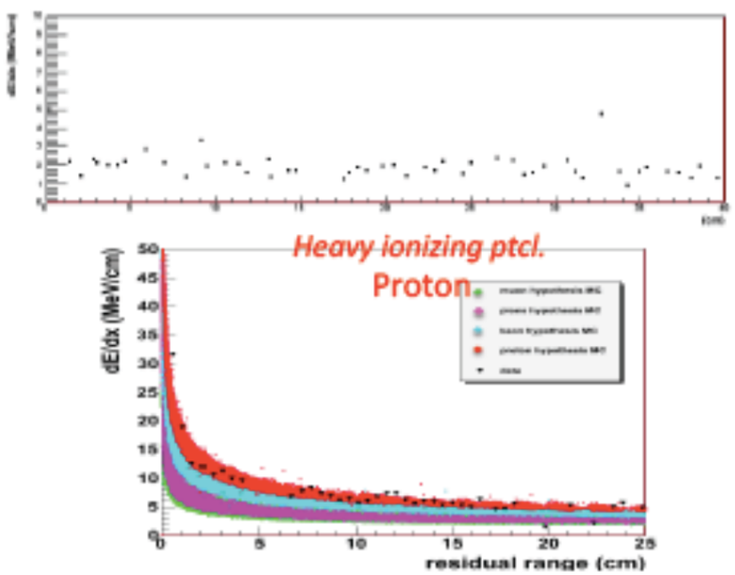



4. Shower and track finding

5. 3D reconstruction

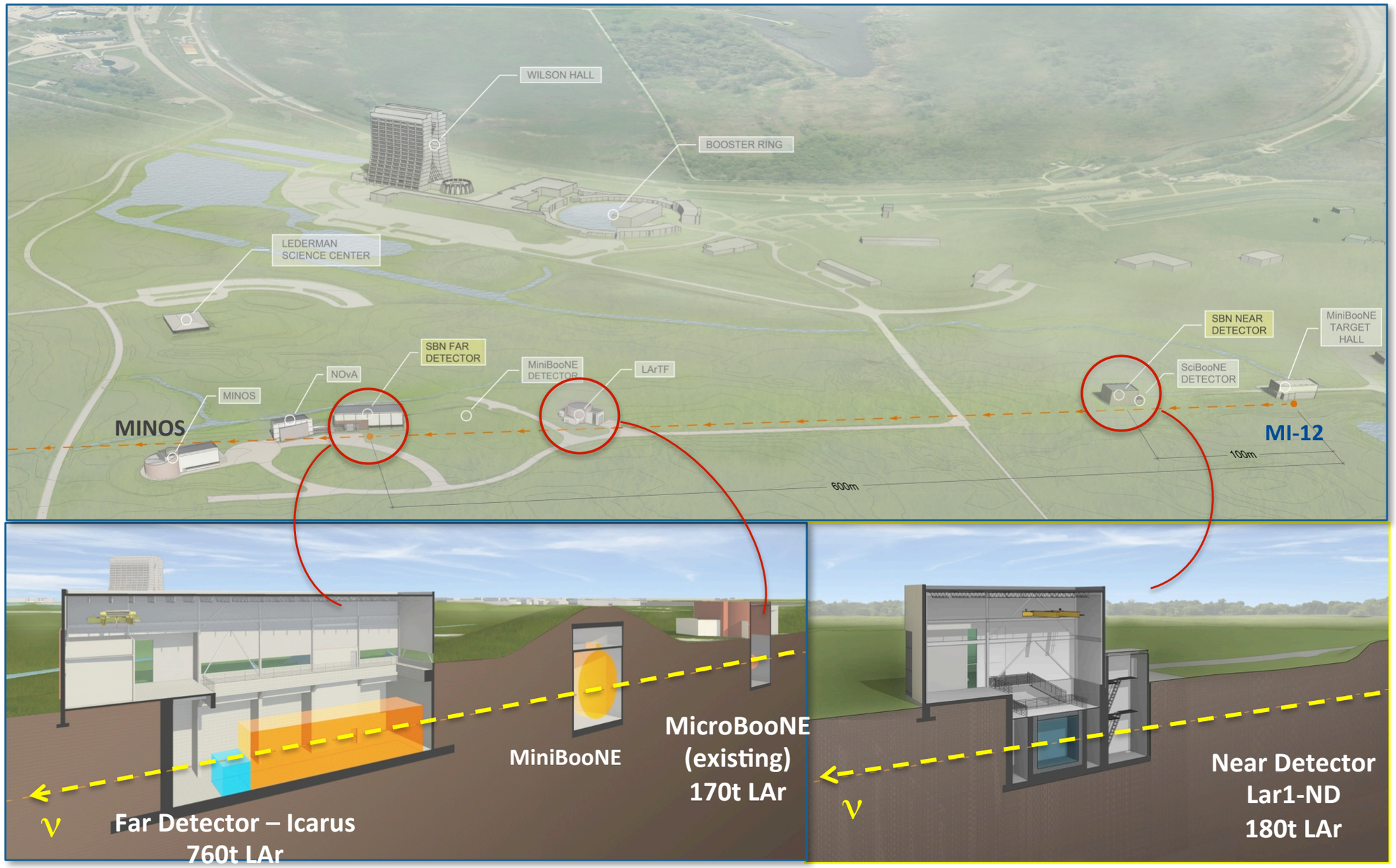


6. Calorimetry and PID



# Future of Short Baseline Program

**Plans to add two additional LAr TPC detectors on BNB for an enhanced sterile neutrino search!**




Peter Wilson I SBN Program Implementation

# Concluding Remarks

* LArTPC is an exciting detector technology for use in precision neutrino physics measurements

* MicroBooNE is the first and key component of Short Baseline Program and is an important test bed for ELBNF:
  - Interesting physics reach for ~eV sterile neutrino and neutrino-Ar cross section
  - Innovation in technology
    - Design, manufacture and use of cold electronics
    - Fill without evacuating
    - Long drift length (HV and purity)
    - Automated reconstruction and improvement in simulation

* Data taking is expected in 2015!

**Stay tuned for an exciting physics program…!!**

# BACKUP

# Fermilab's Booster Neutrino Beam (BNB)

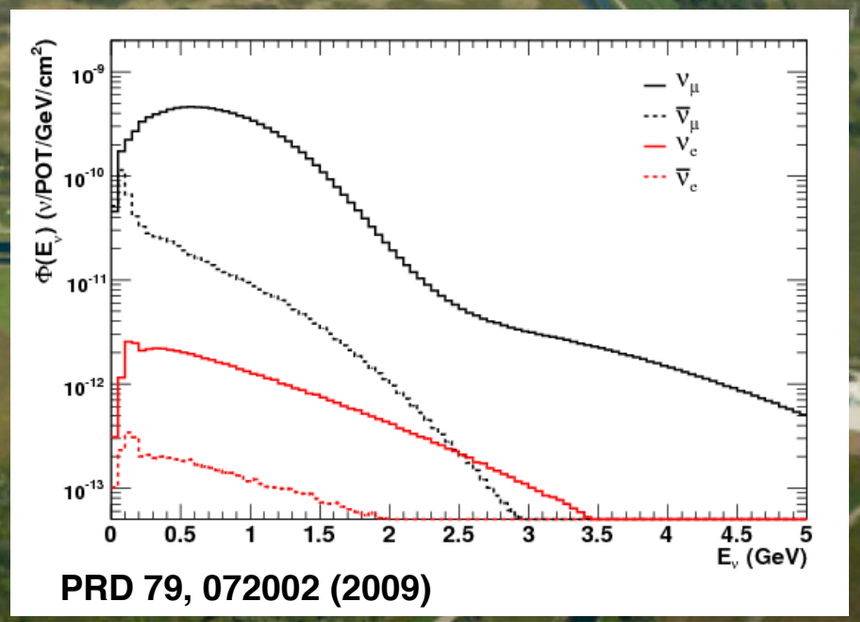
**Linac**
Length: 150m
Proton Energy: 400 MeV

**Booster**
Circumference: 468m
Proton Energy: 8 GeV

Protons

Neutrinos

Fermilab's **low-energy** neutrino beam
<Eν> ≈ 700 MeV




PRD 79, 072002 (2009)

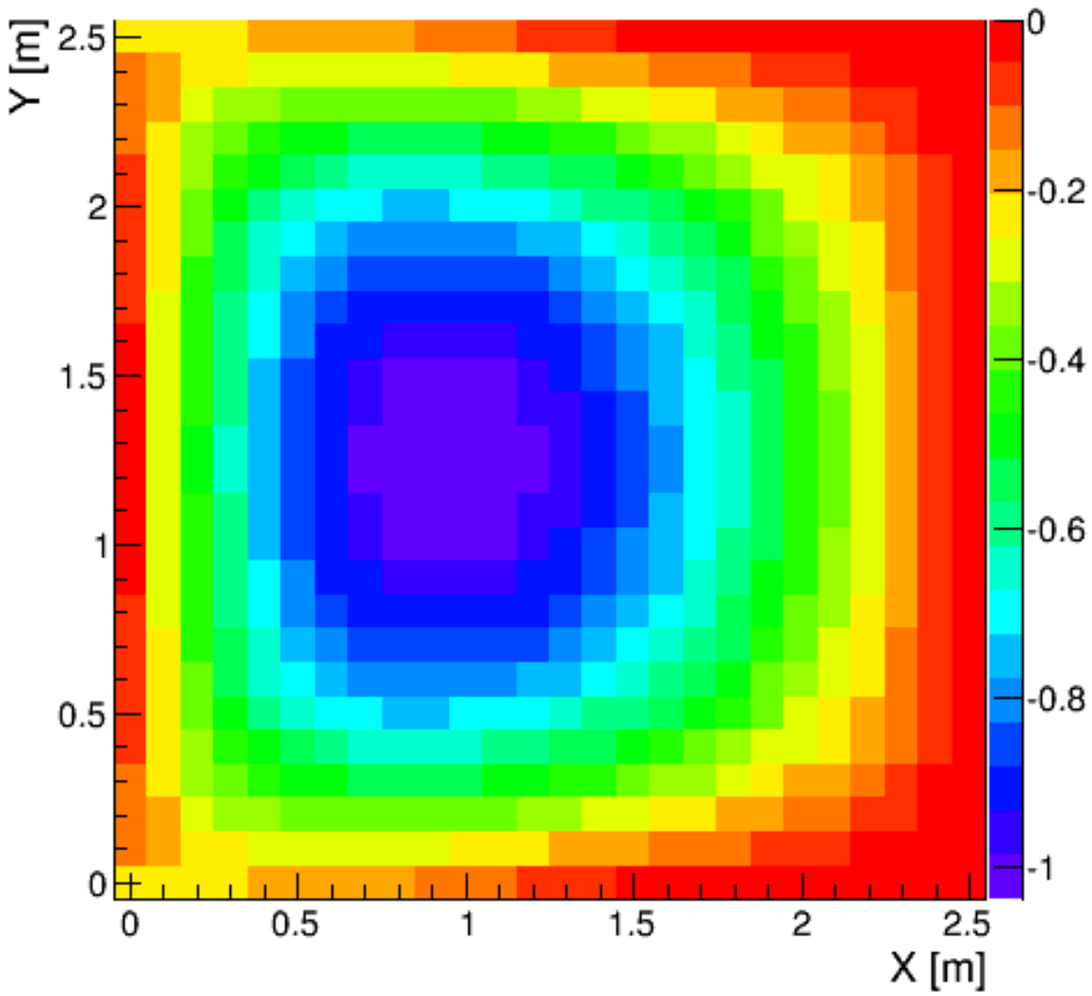
**Event Rate Break Down**

**(flux & xs)**

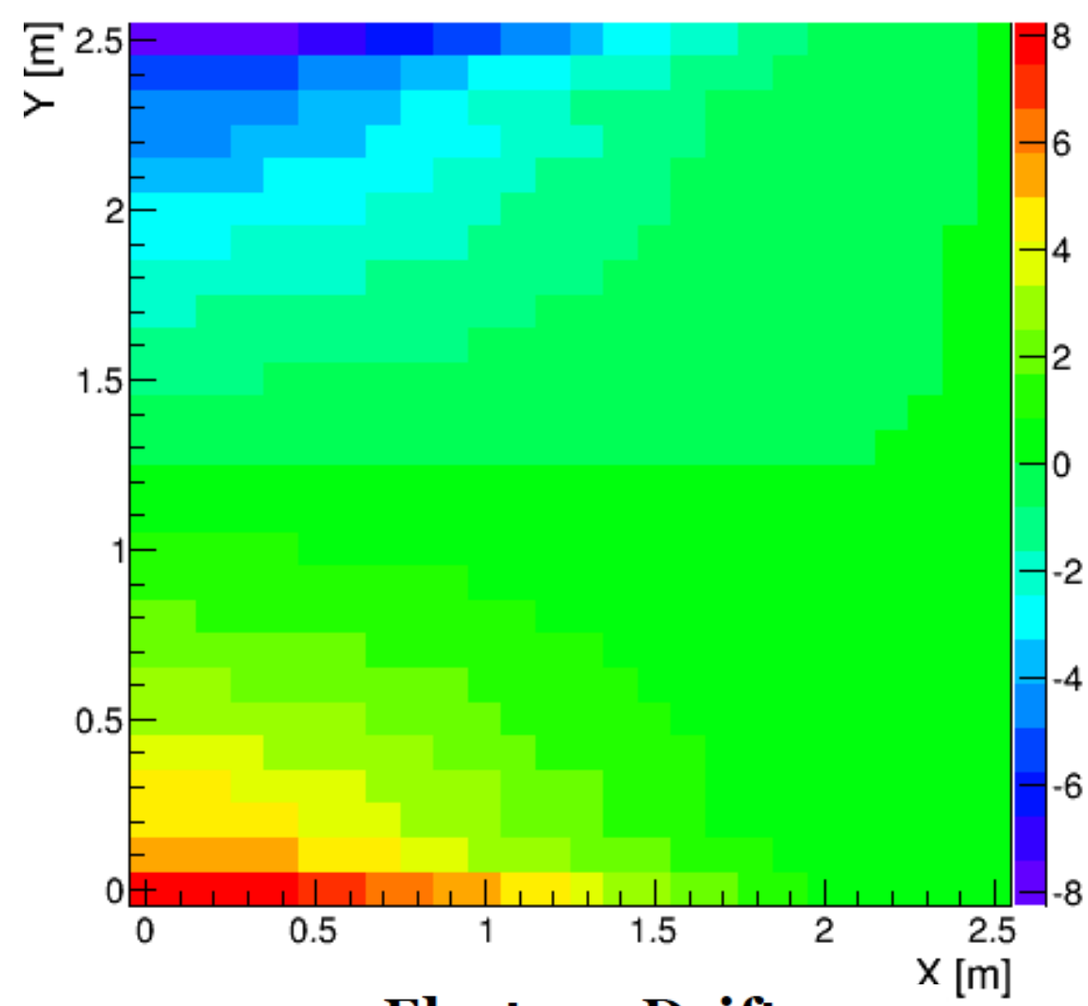
- $\nu_\mu \simeq 98.6\%$
- $\bar{\nu}_\mu \simeq 0.8\ \%$
- $\nu_e \simeq 0.6\ \%$
- $\bar{\nu}_e \simeq 0.02\ \%$

... **high purity $\nu_\mu$ beam** ...

# Space Charge




**Electron Drift**

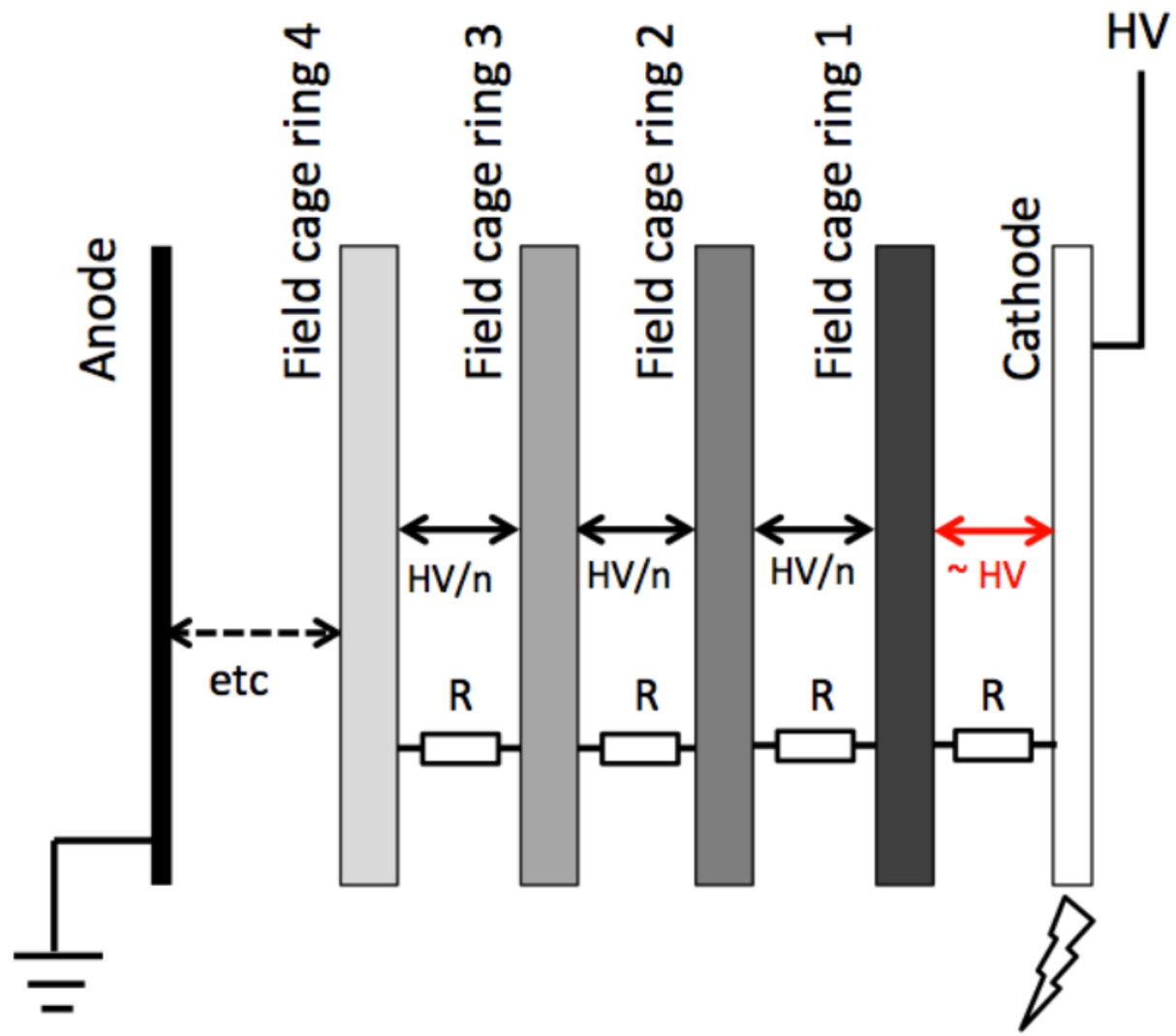



**Electron Drift**

# HV Breakdown

B.Jones

- Consider cathode discharge to ground.
- Field cage tubes have a capacitance so remain charged.
- Large resistances prevent charge redistributing in the field cage.
- Capacitances O(1 nF) and resistances O(100 MΩ) lead to relaxation times O(0.1 s)
- Similar (sometimes worse) behavior if a field cage tube discharges.

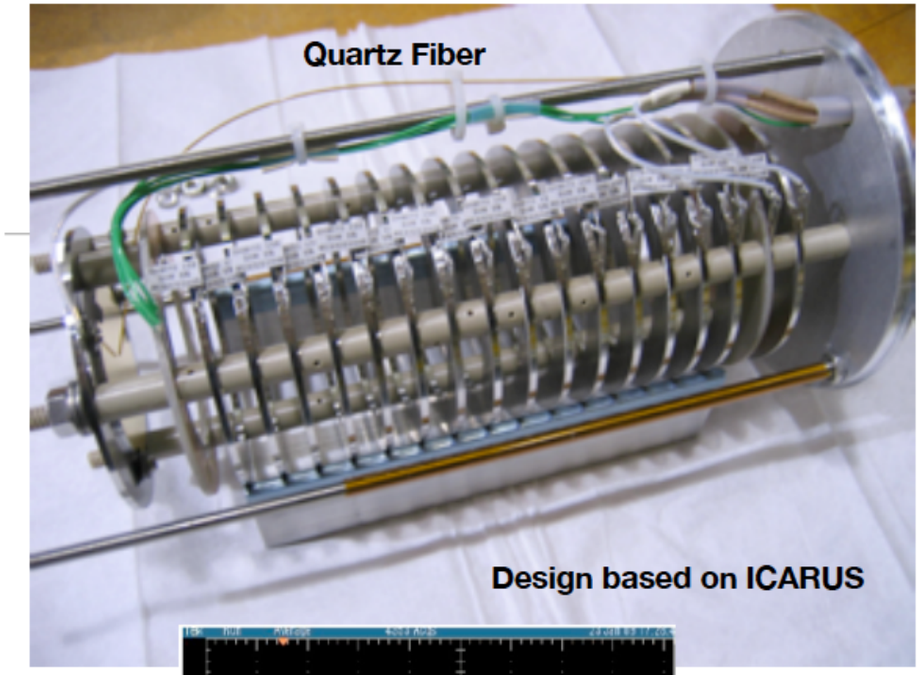



*The exact voltages evolved depend on **all** the capacitances in the TPC-Cathode-Cryostat system*

# Cryogenics System

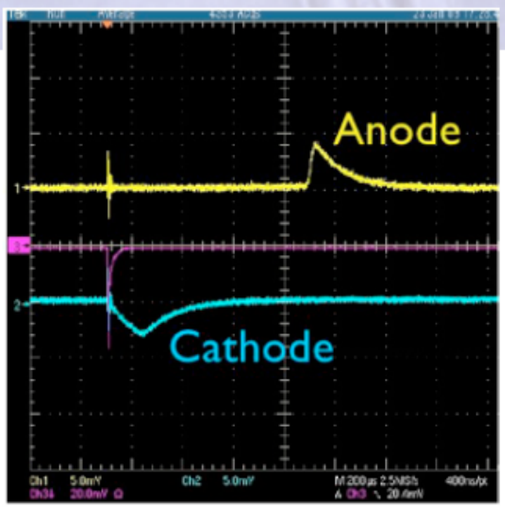
## Filtering system

- MicroBooNE will continuously pump argon from cryostat through to remove impurities
  - < 100 ppt $O_2$
- Molecular sieve to remove water
- Rechargeable copper filter removes oxygen



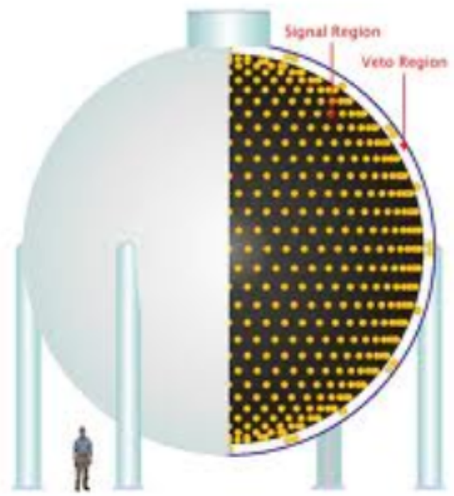

## Purity monitoring

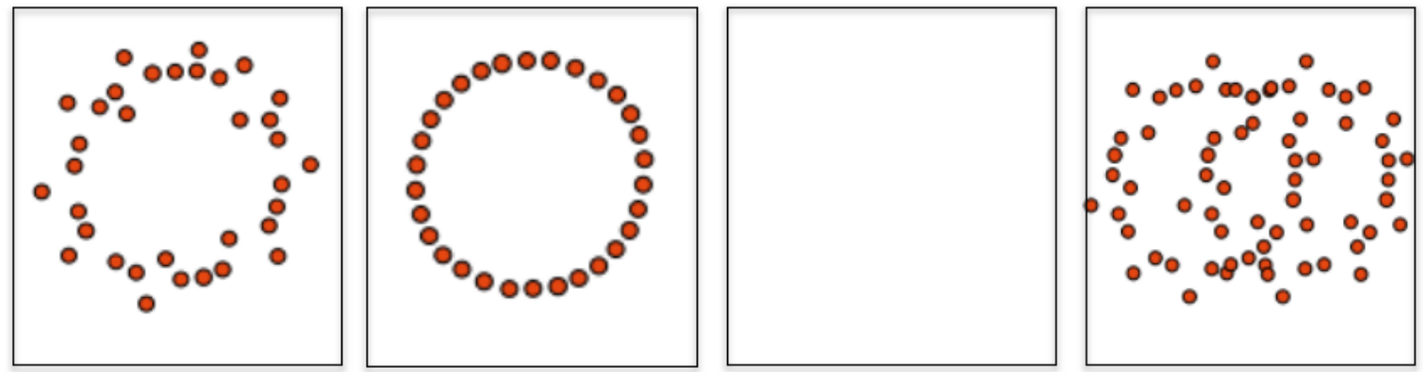
- Mini-TPC: liberate charge on photocathode with xenon flash lamp, and measure collected charge on anode
  - Measure attenuation in electron drift directly



# LSND/MiniBooNE Signal with LArTPC

## MiniBooNE

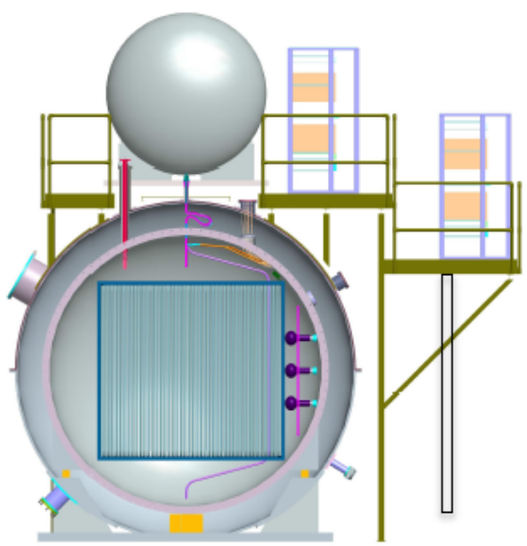


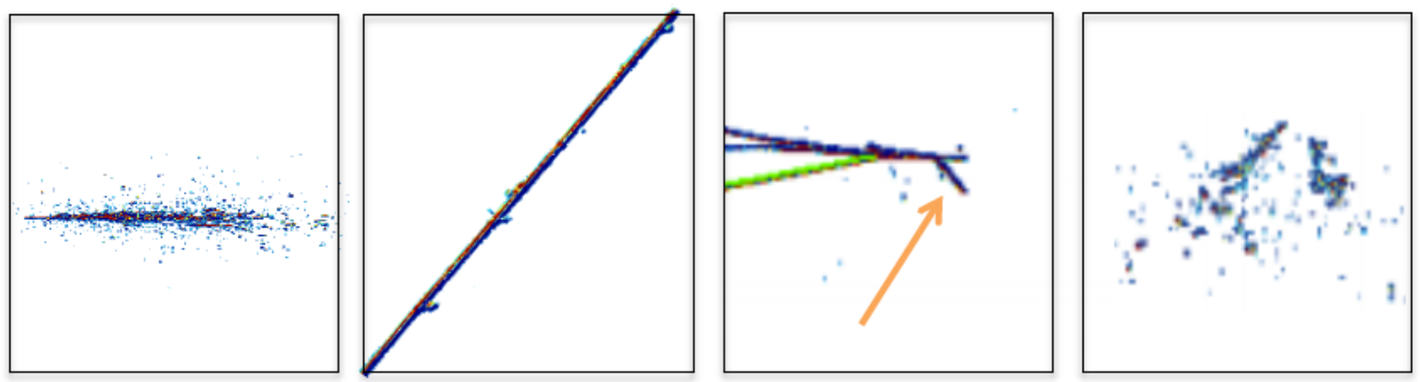



Electron, Photon | Muon | Proton | $\pi^0 \rightarrow \gamma + \gamma$

(Cherenkov Detector)

## MicroBooNE



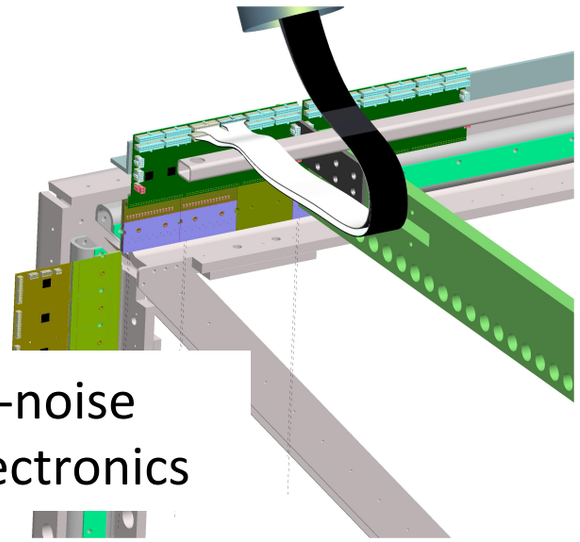


Electron, Photon | Muon | Proton | $\pi^0 \rightarrow \gamma + \gamma$

(LArTPC)

# New technologies in MicroBooNE

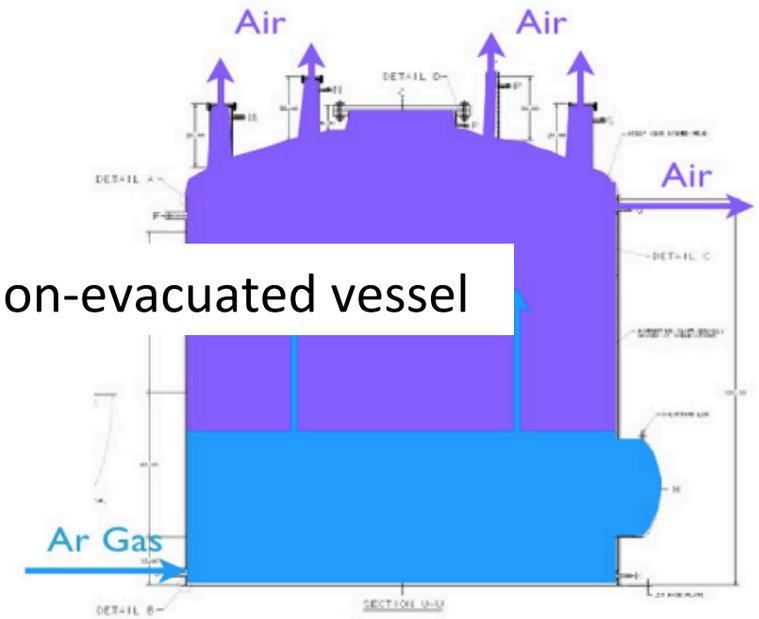
MicroBooNE adds some new technologies to the LArTPC development:



Cold low-noise readout electronics

UV laser calibration system

Long drift/ high HV




Application of surge protection devices

**More later…**