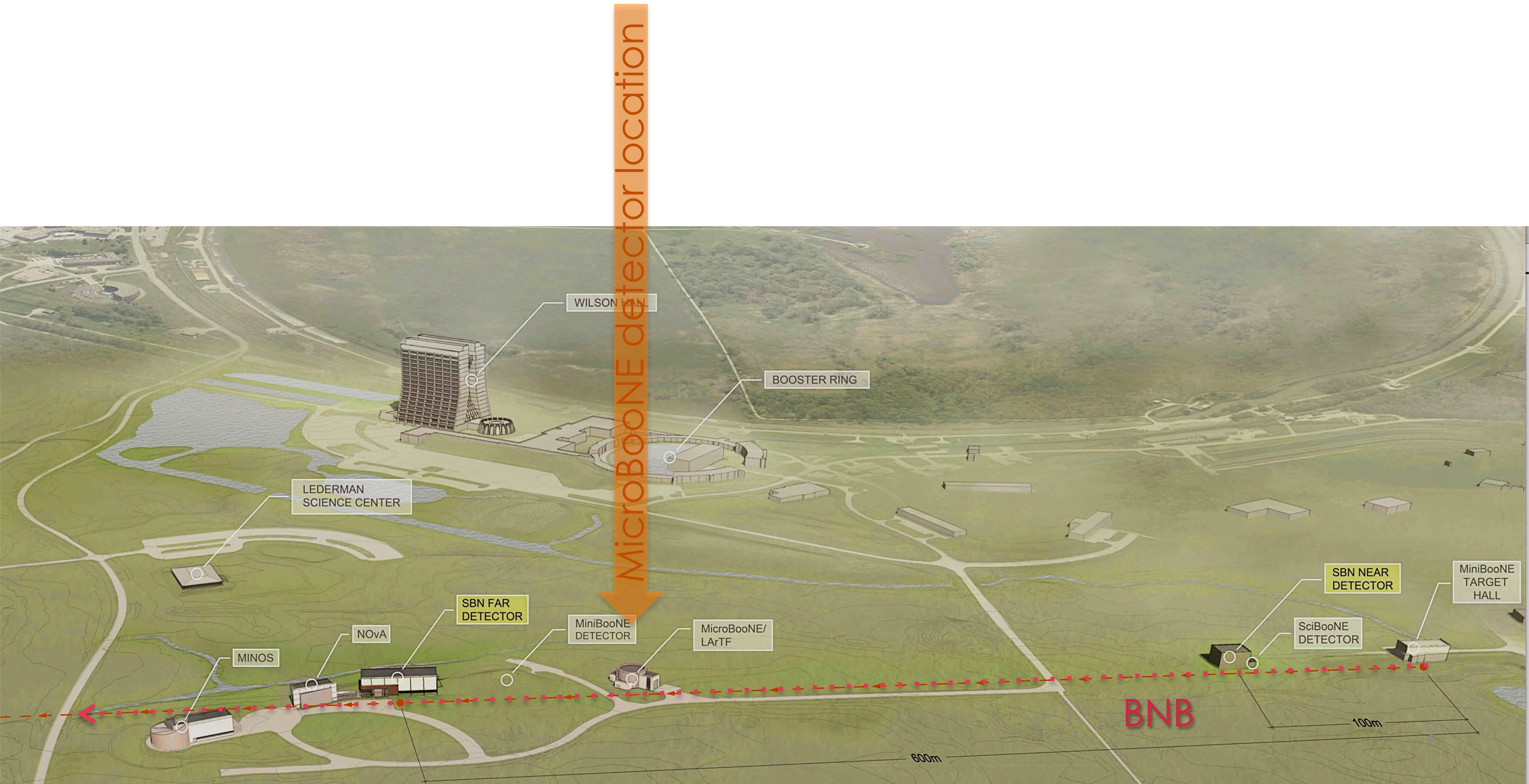
# Latest $\nu$'s from MicroBooNE

**Georgia Karagiorgi**
**University of Manchester**

**Particle Seminar at Edinburgh**
**February 10, 2016**

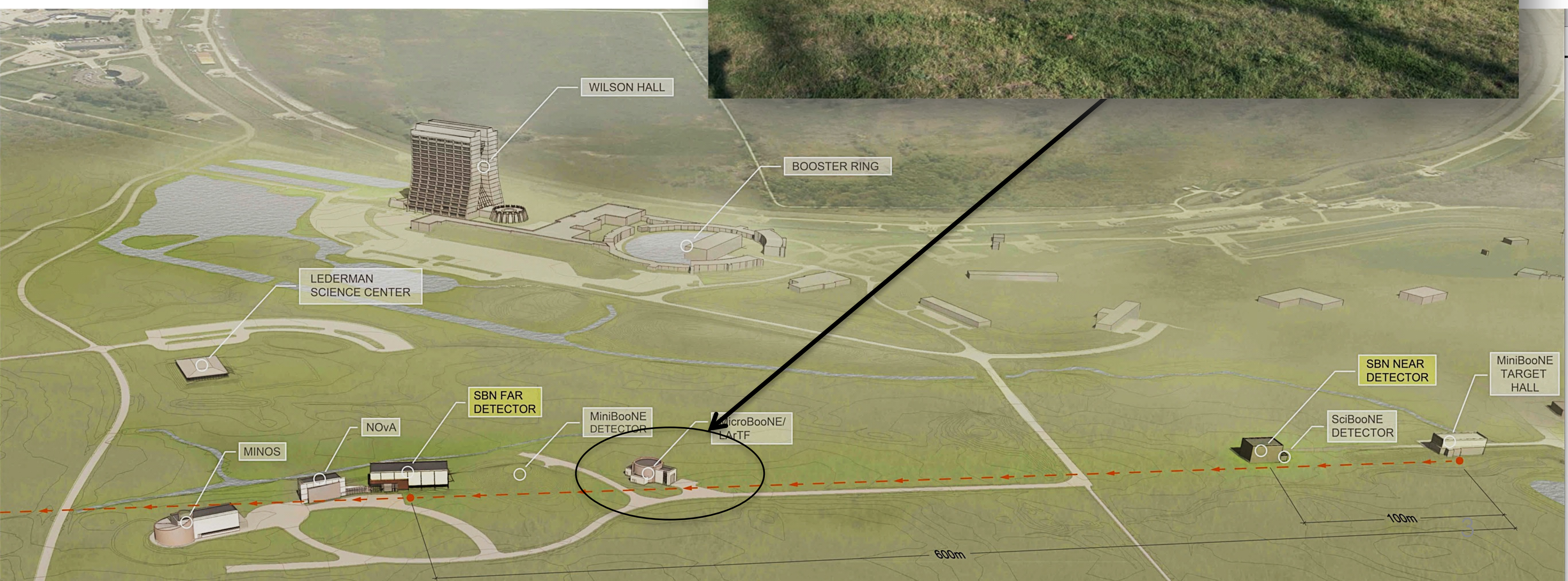
# Micro Booster Neutrino Experiment @ Fermilab

Intermediate-scale liquid argon time projection chamber detector
Situated in the Booster Neutrino Beamline, on-site at Fermilab



# Micro Booster Neutrino Experiment @ Fermilab

146 collaborators
28 institutions
(6 non-U.S., including 4 U.K.)

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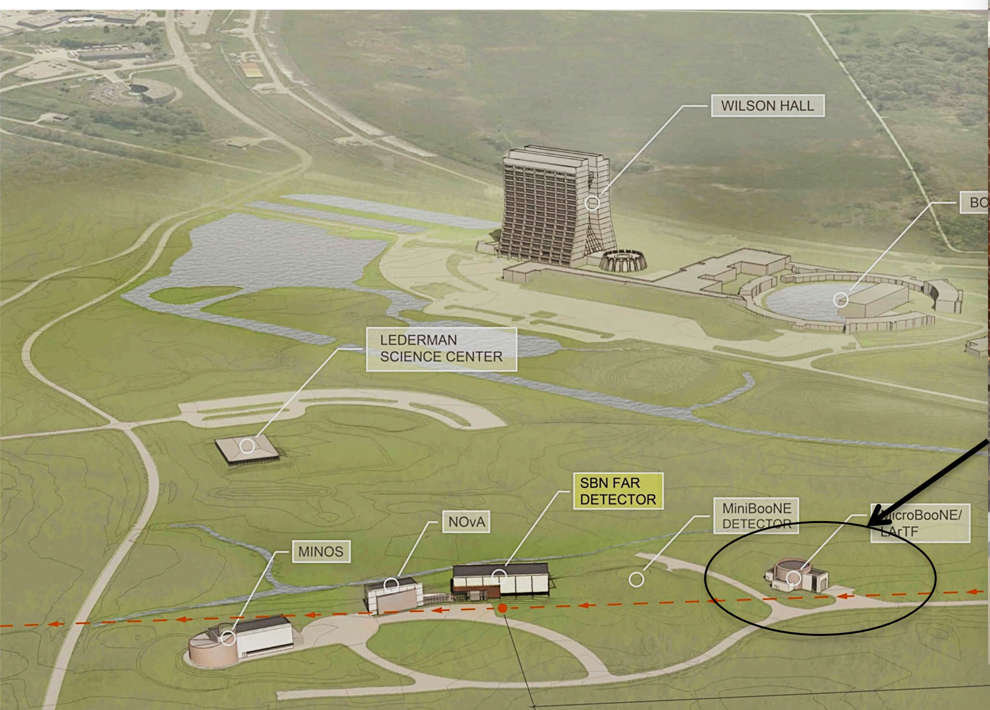


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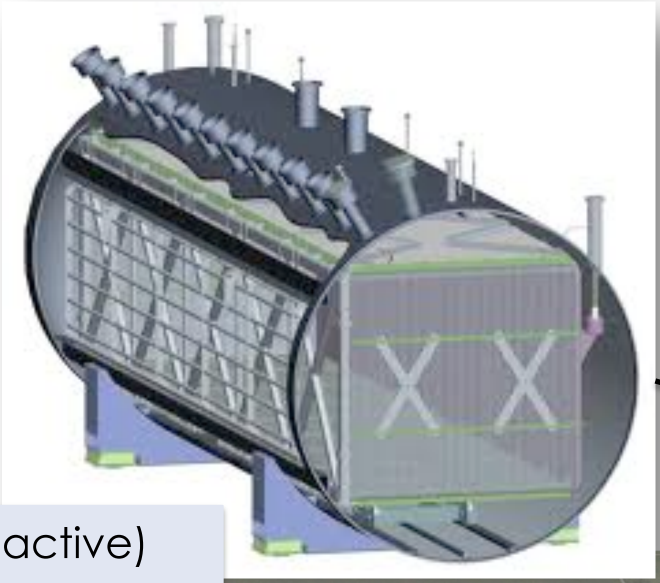
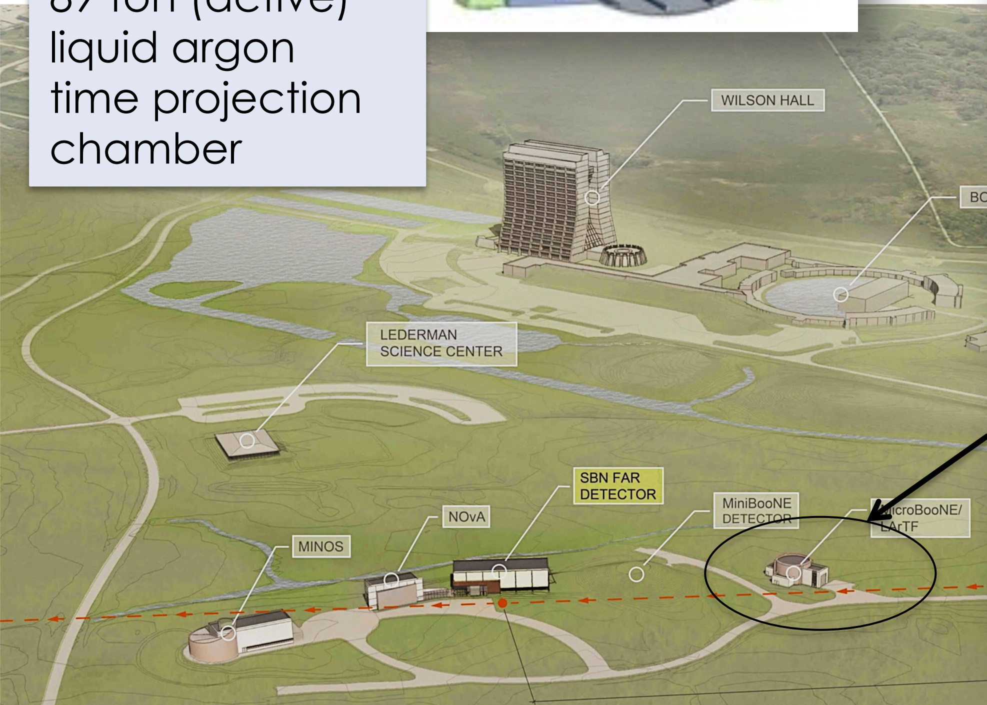
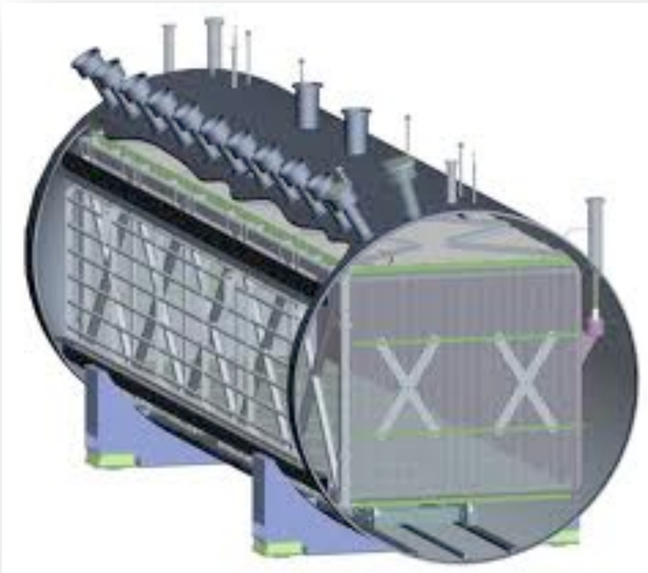


89 ton (active)
liquid argon
time projection
chamber

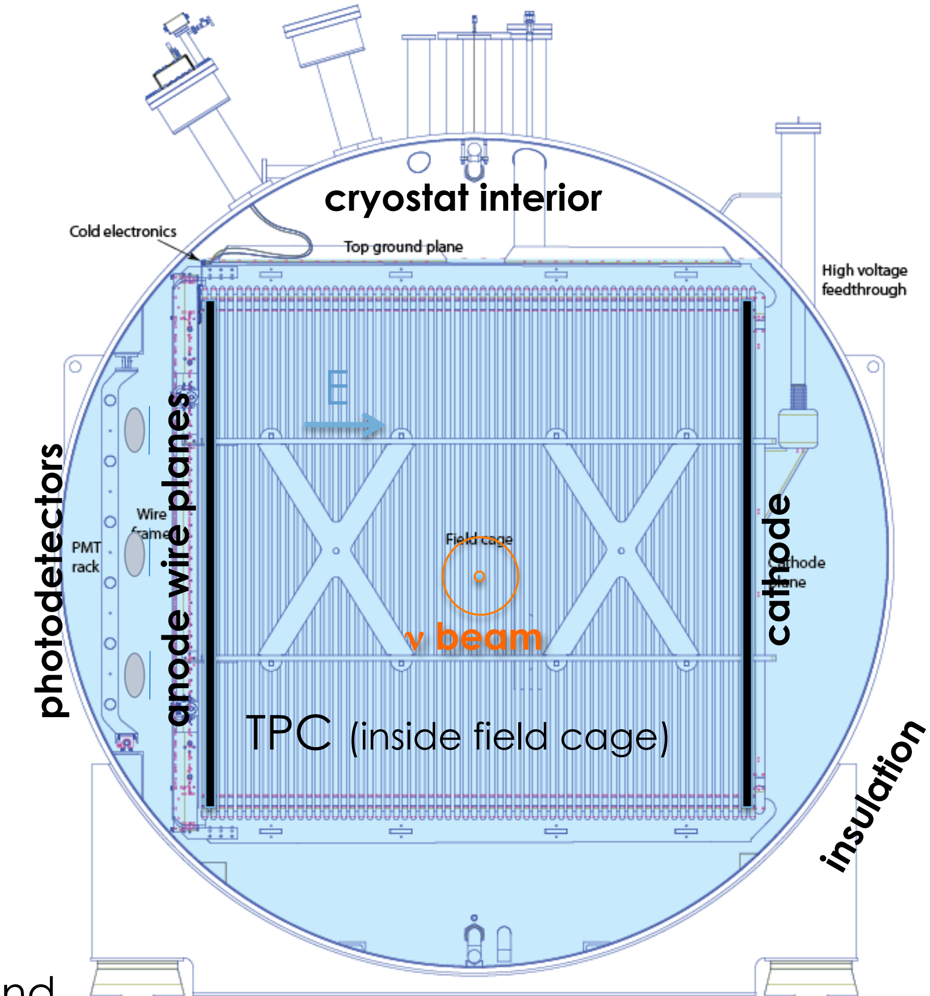



# Detector Parameters

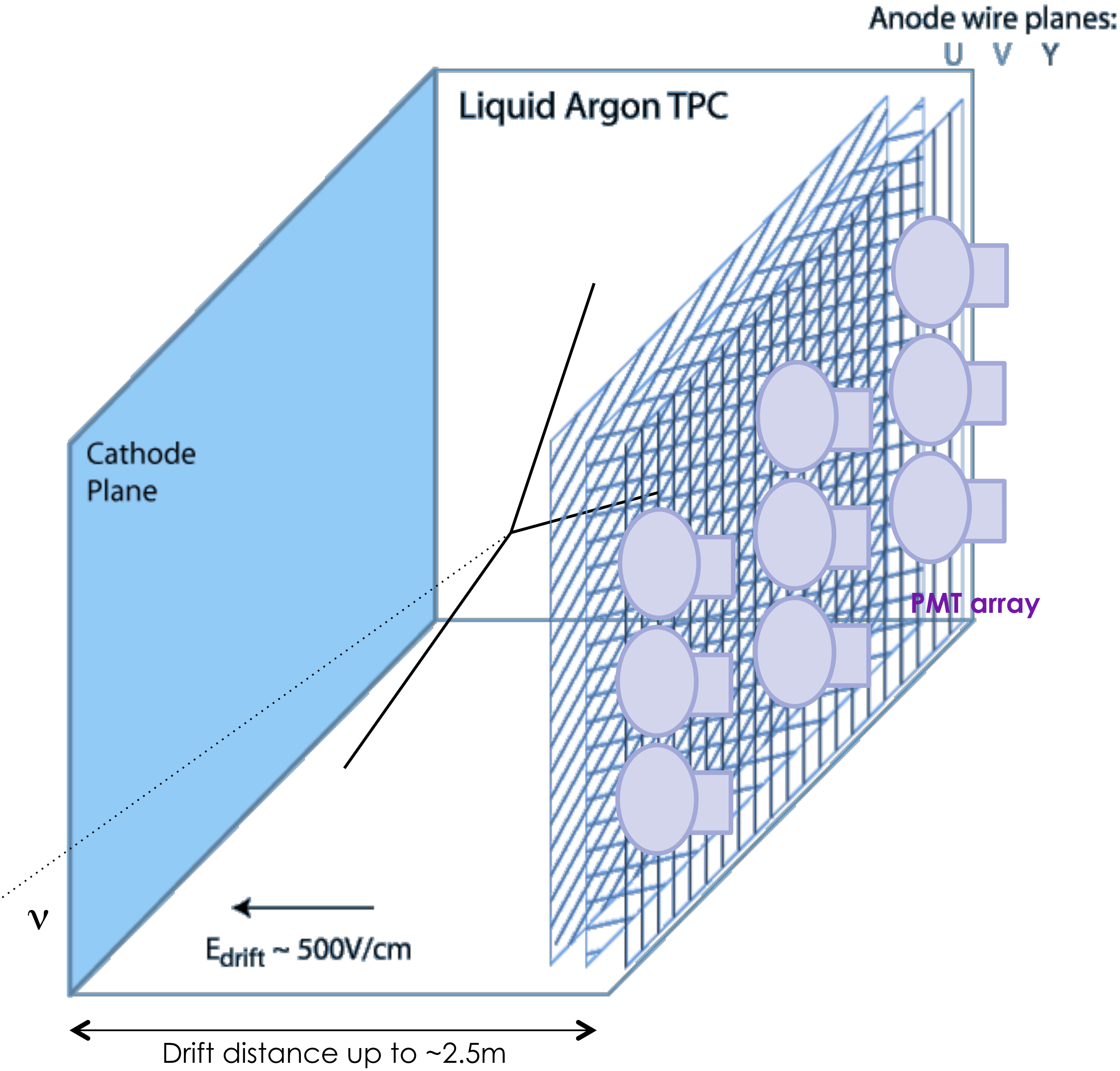


- 2.5 m x 2.3 m x 10.2 m TPC
- **170 (89) tons total (active) LAr mass**
- 2.5 m drift length
  -128kV on cathode (design)
- 3 wire planes: 0, ±60° from vertical,
  3 mm wire separation
- 8256 wires, digitized at 2MHz
- 32 PMT's digitized at 64MHz
  for $t_0$, drift coordinate determination, and triggering for empty beam spill rejection

## Cross section of detector:



# LArTPC working principle



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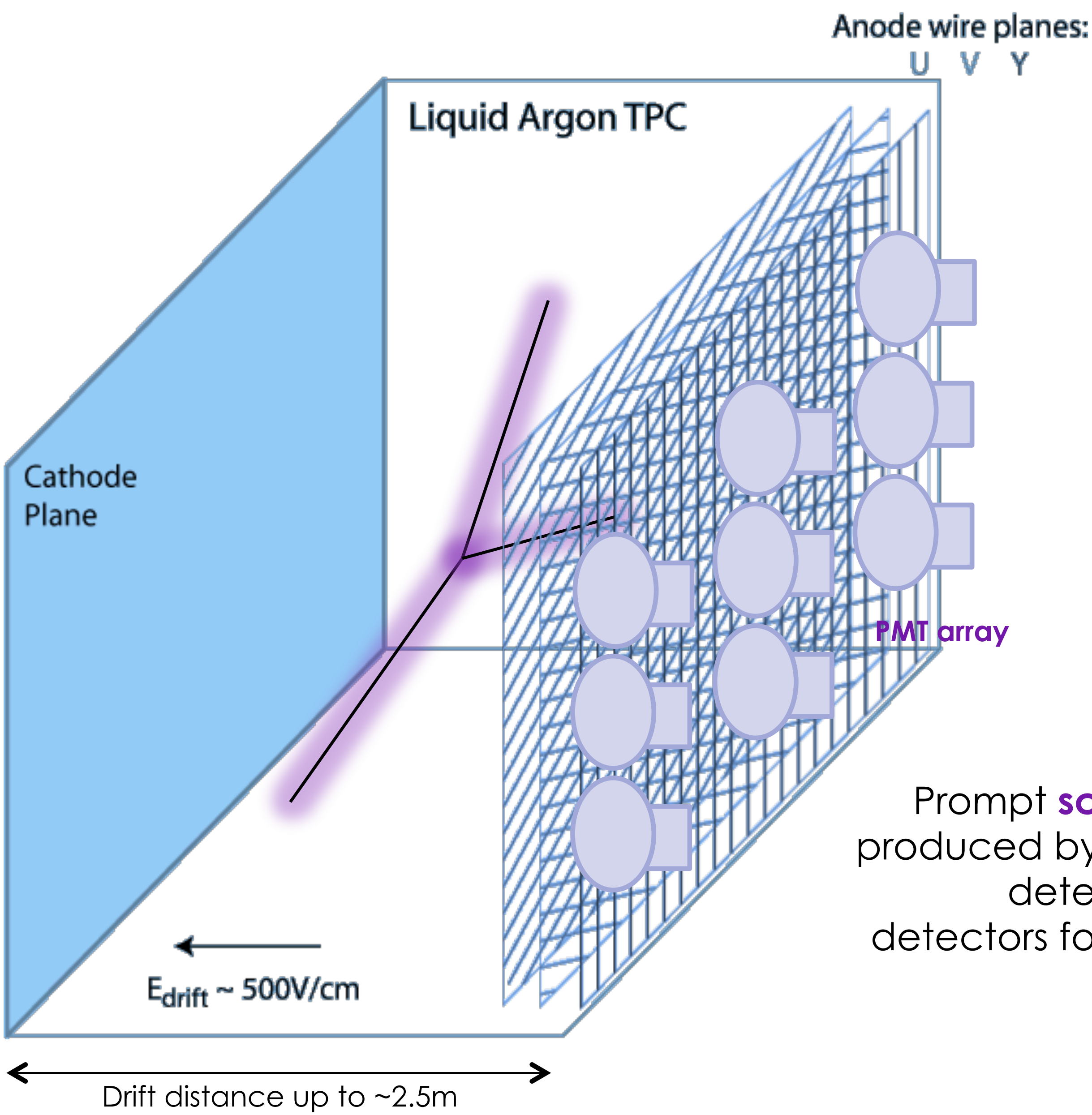
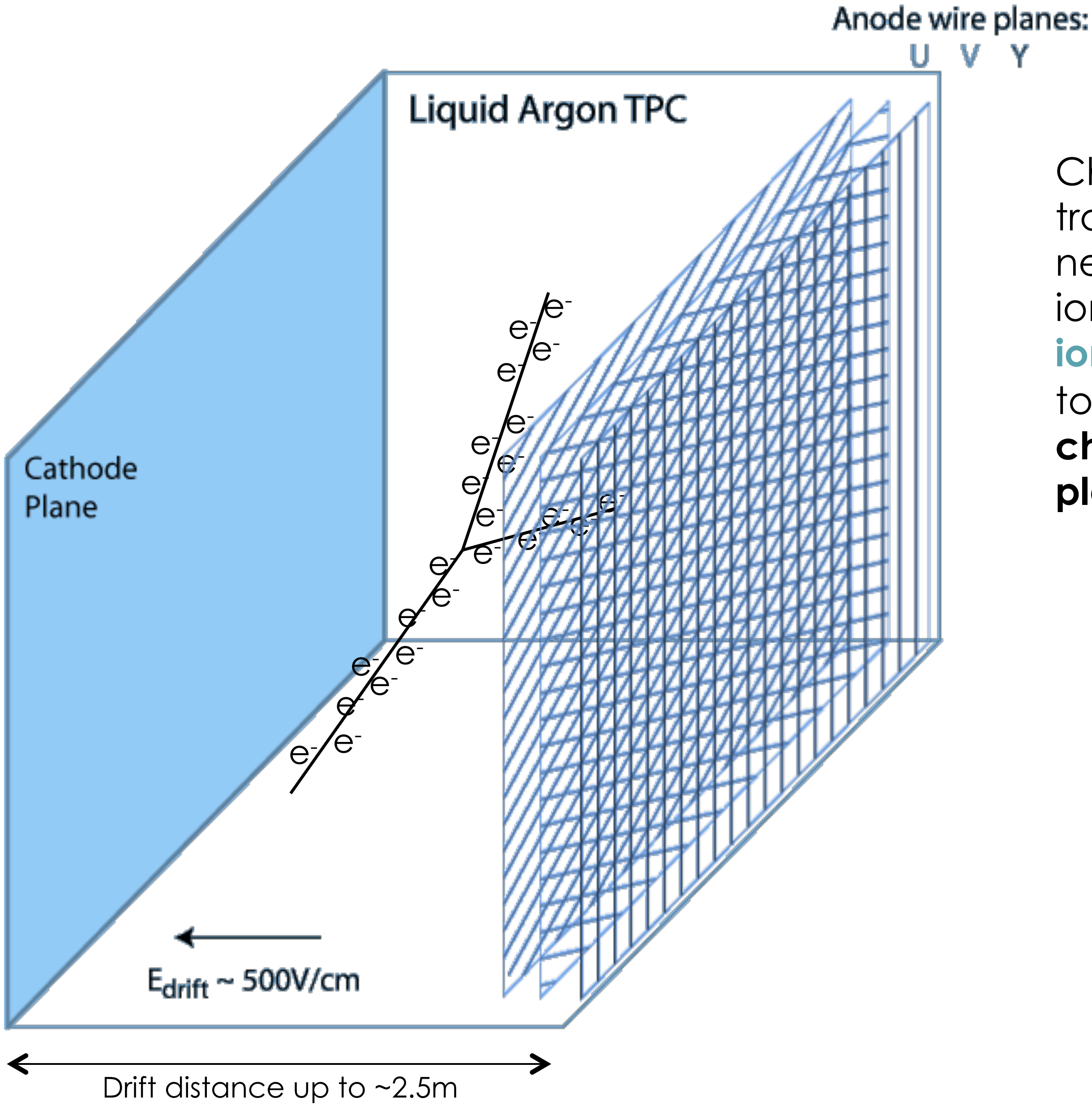



Prompt **scintillation light** (**~few ns**) produced by interaction products is detected by photo-sensitive detectors for **event $t_0$** determination (allows for triggering)

# LArTPC working principle




Charged particle tracks produced in neutrino interaction ionize argon atoms; ionization charge drifts to **finely segmented charge collection planes** over ~1-few ms.

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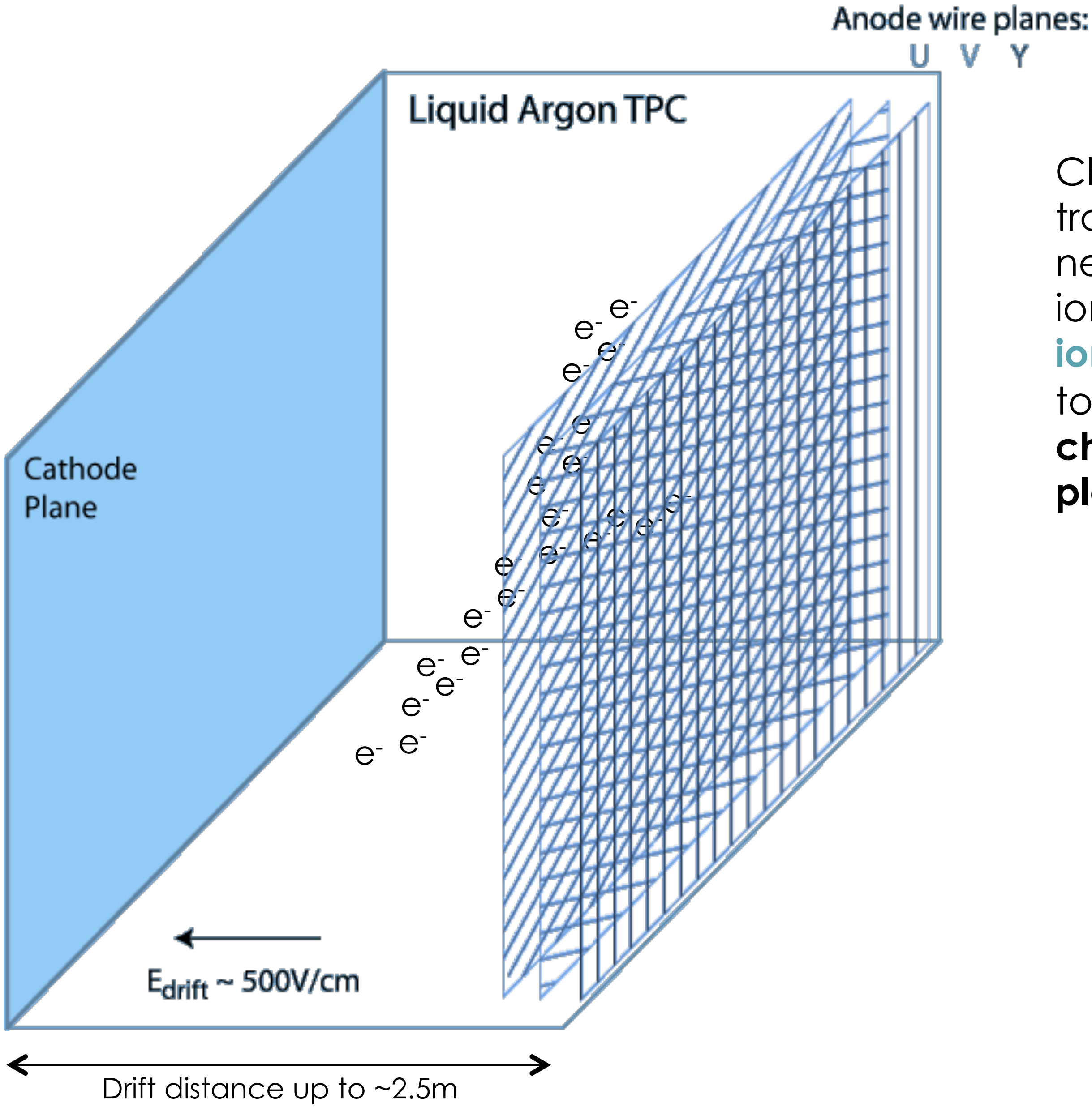


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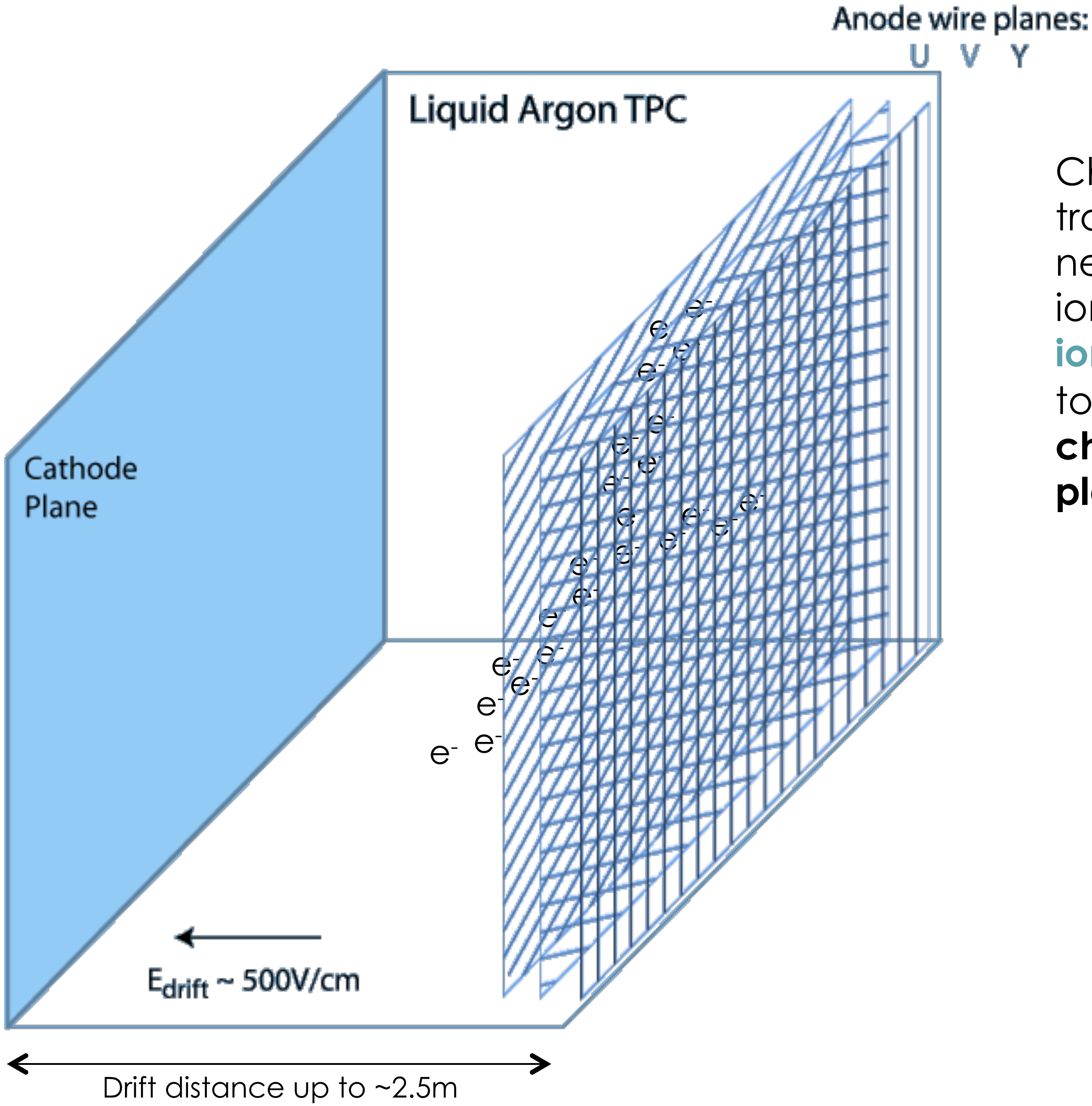


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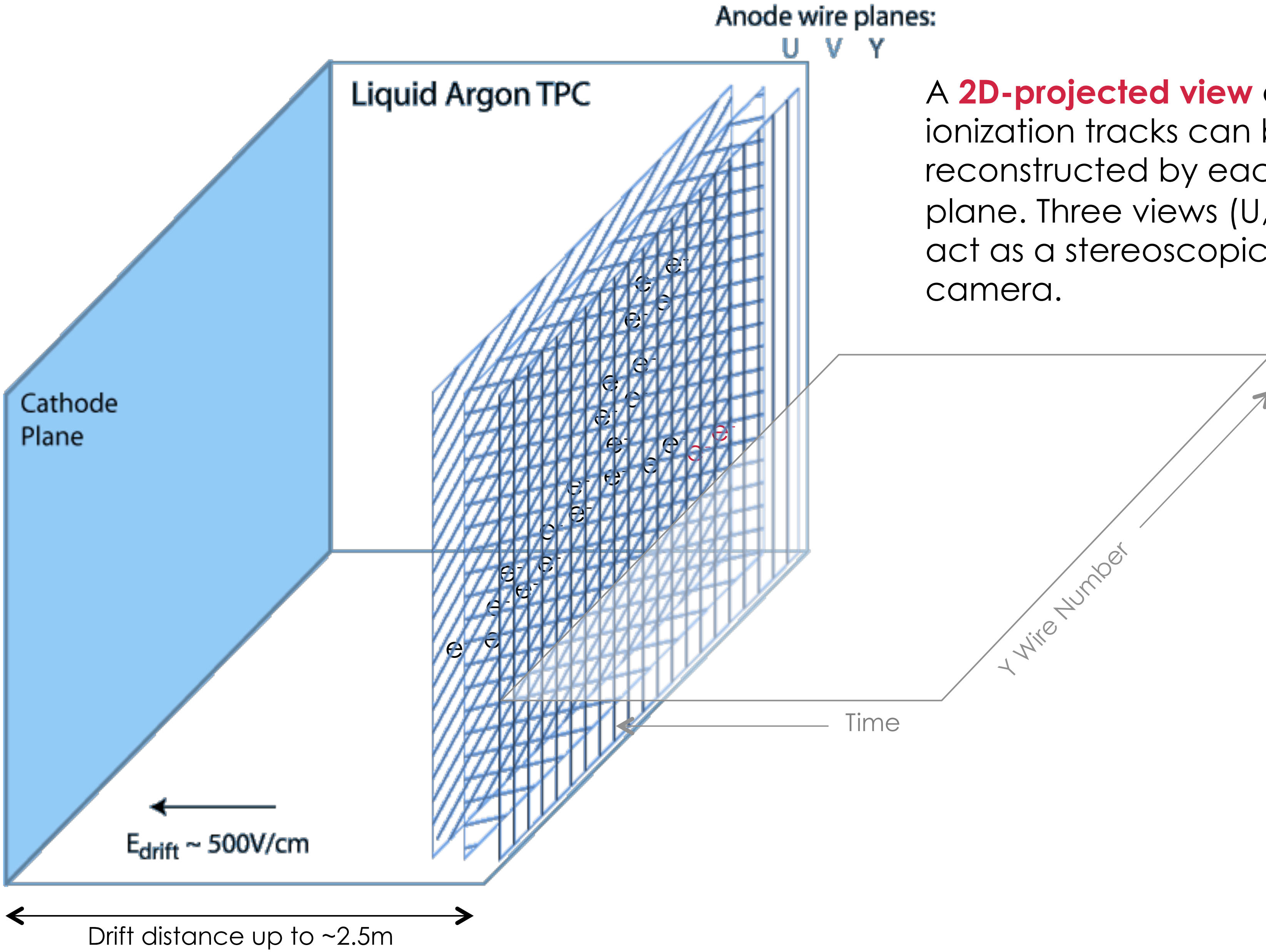


A **2D-projected view** of the ionization tracks can be reconstructed by each wire plane. Three views (U, V, Y) act as a stereoscopic camera.

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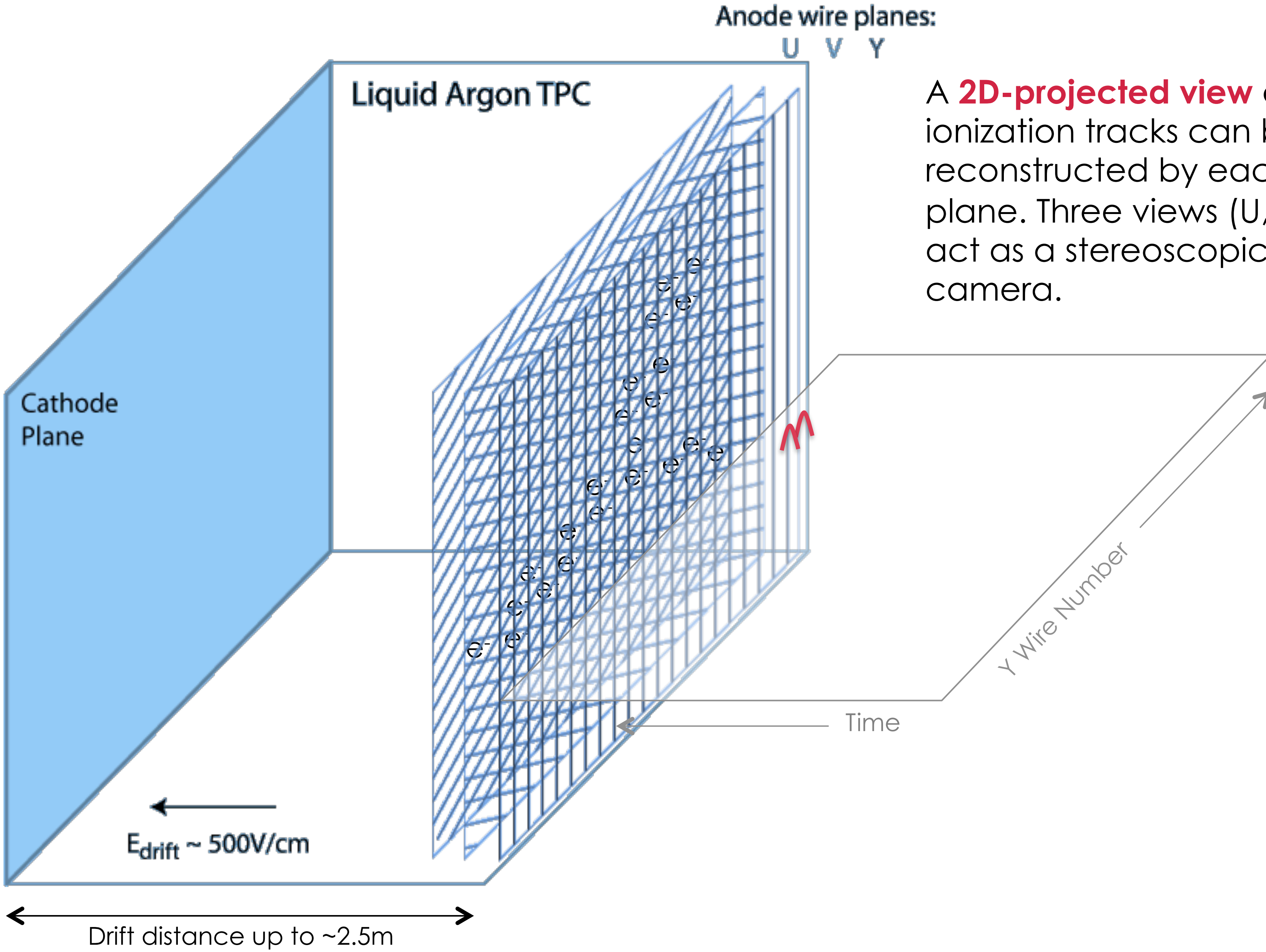


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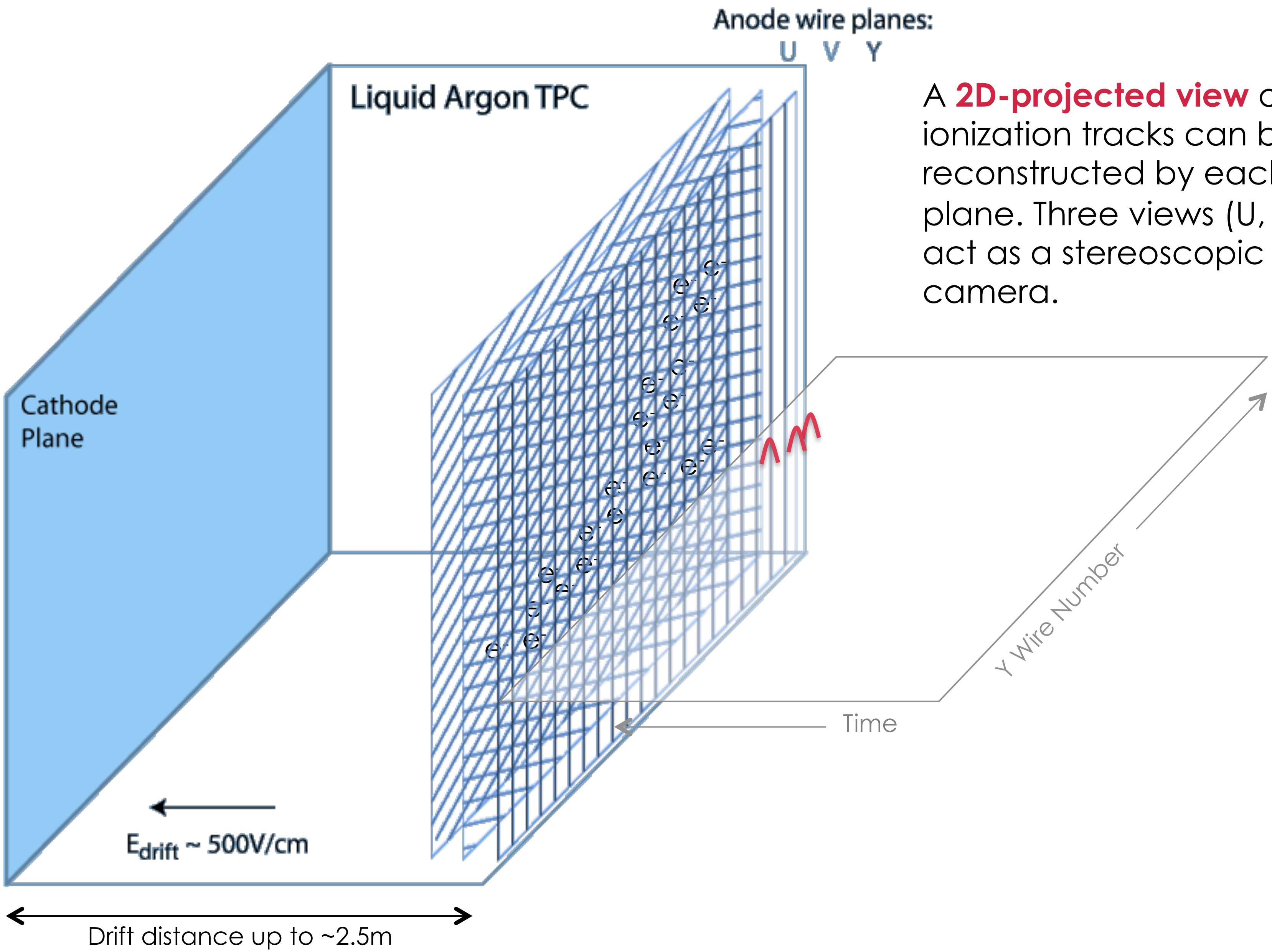


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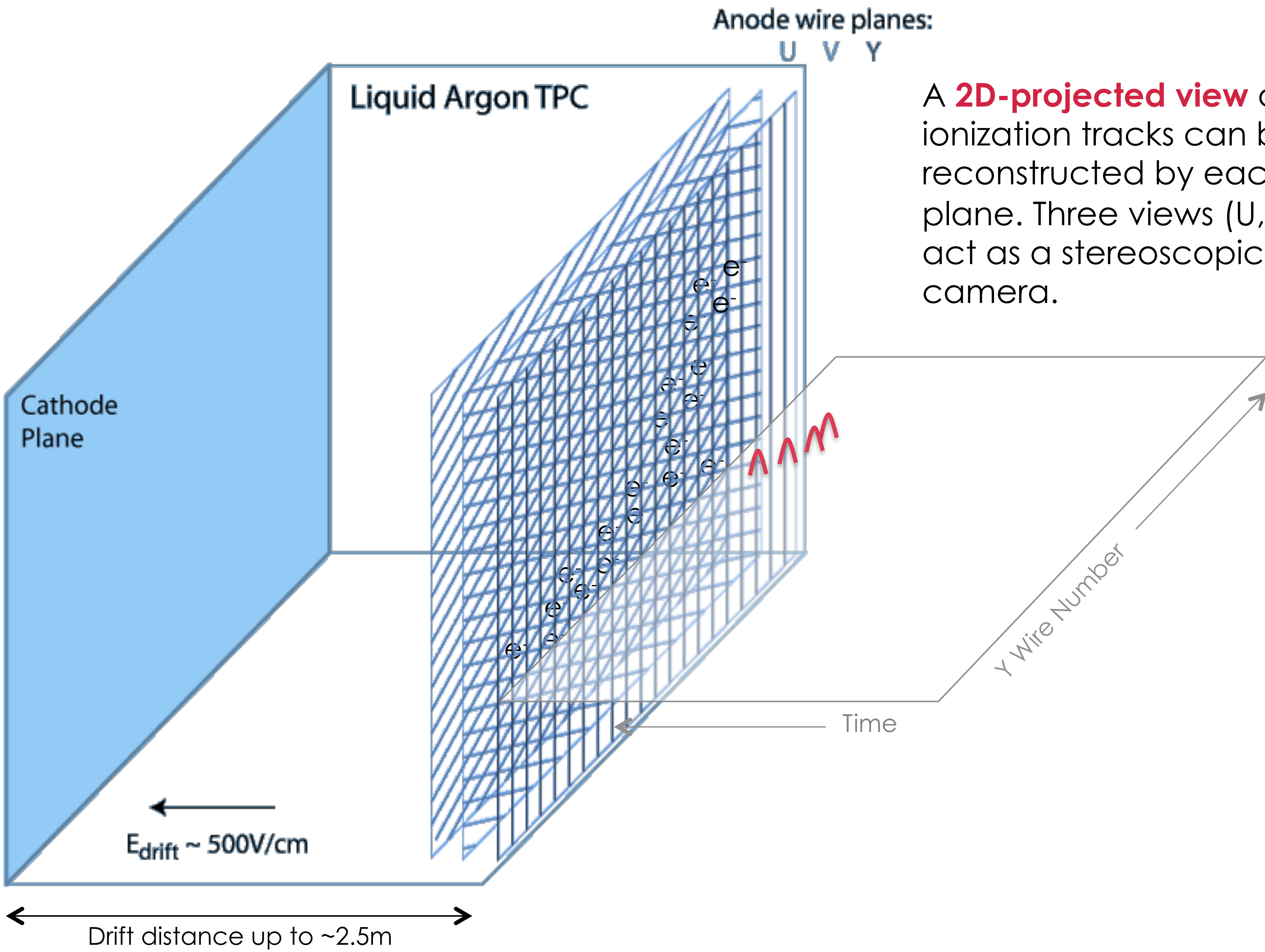


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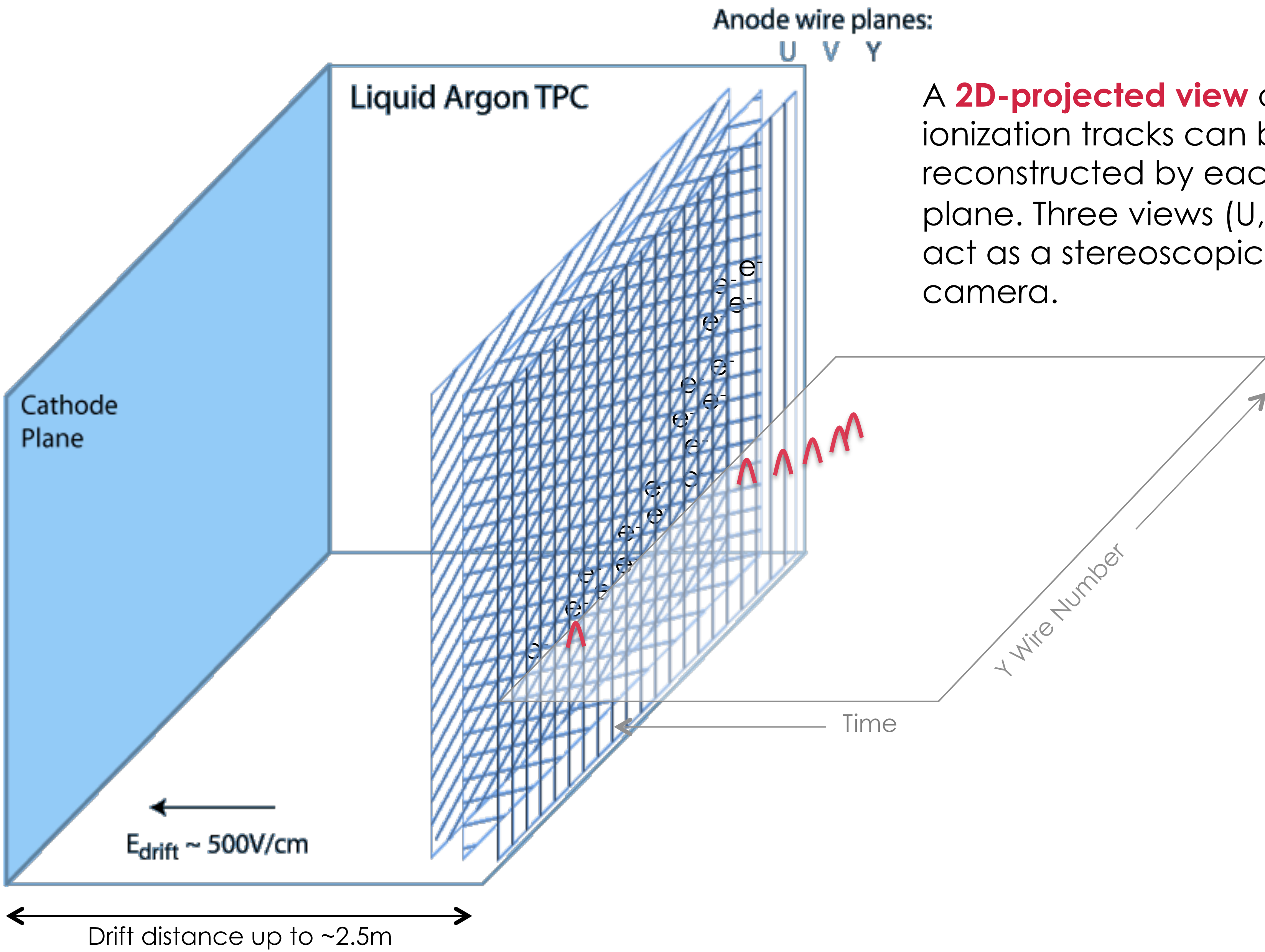


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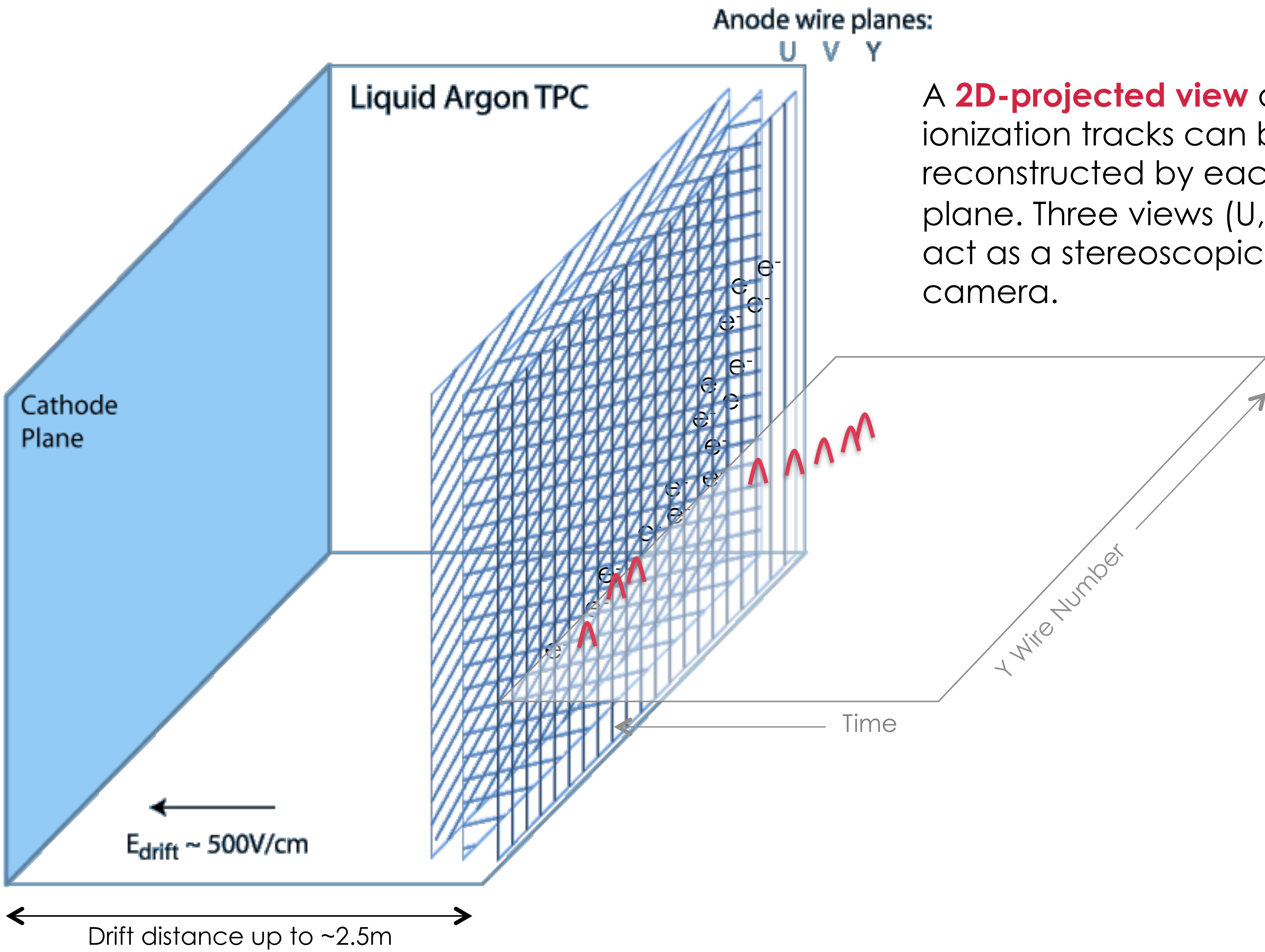


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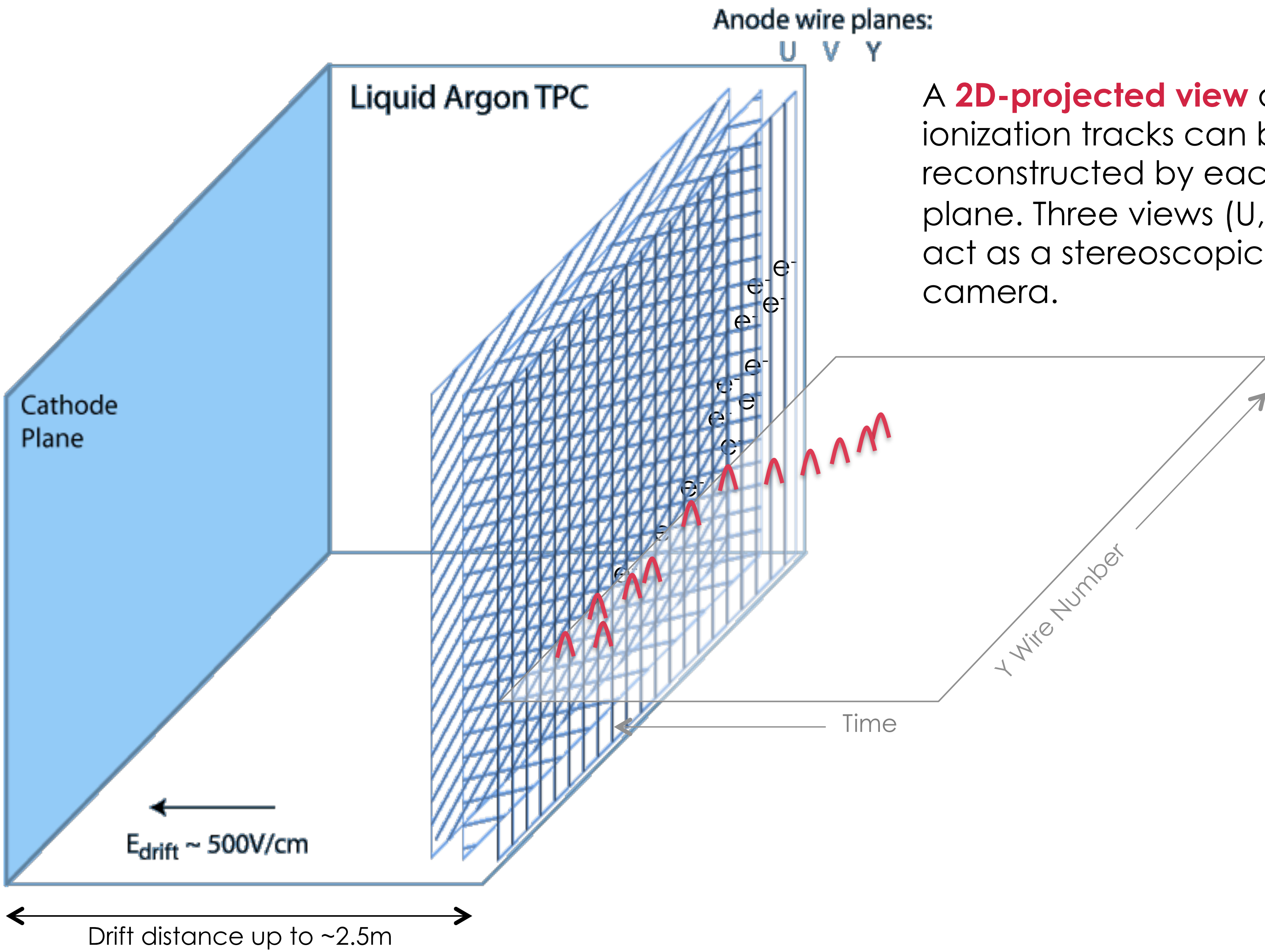


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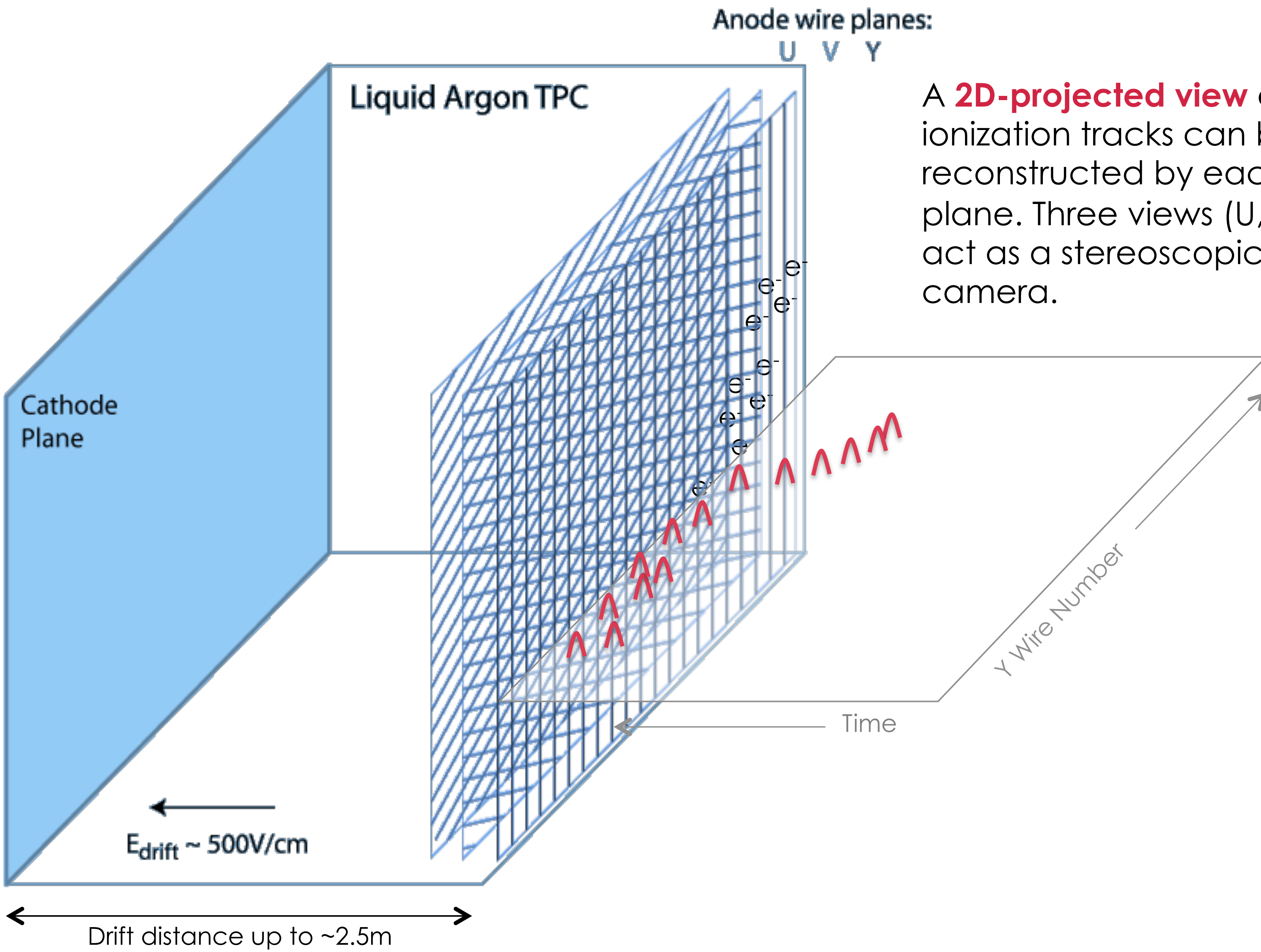


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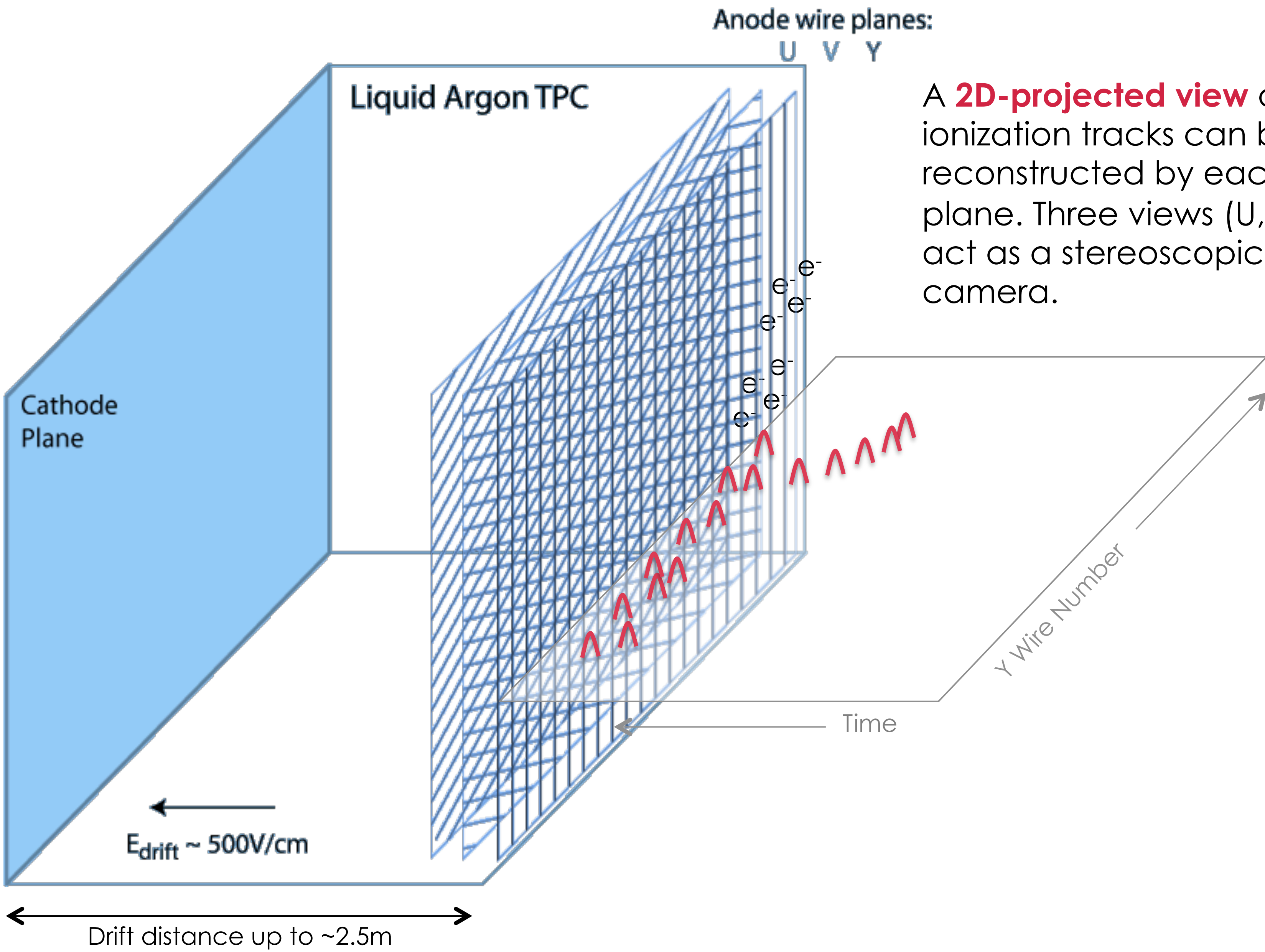


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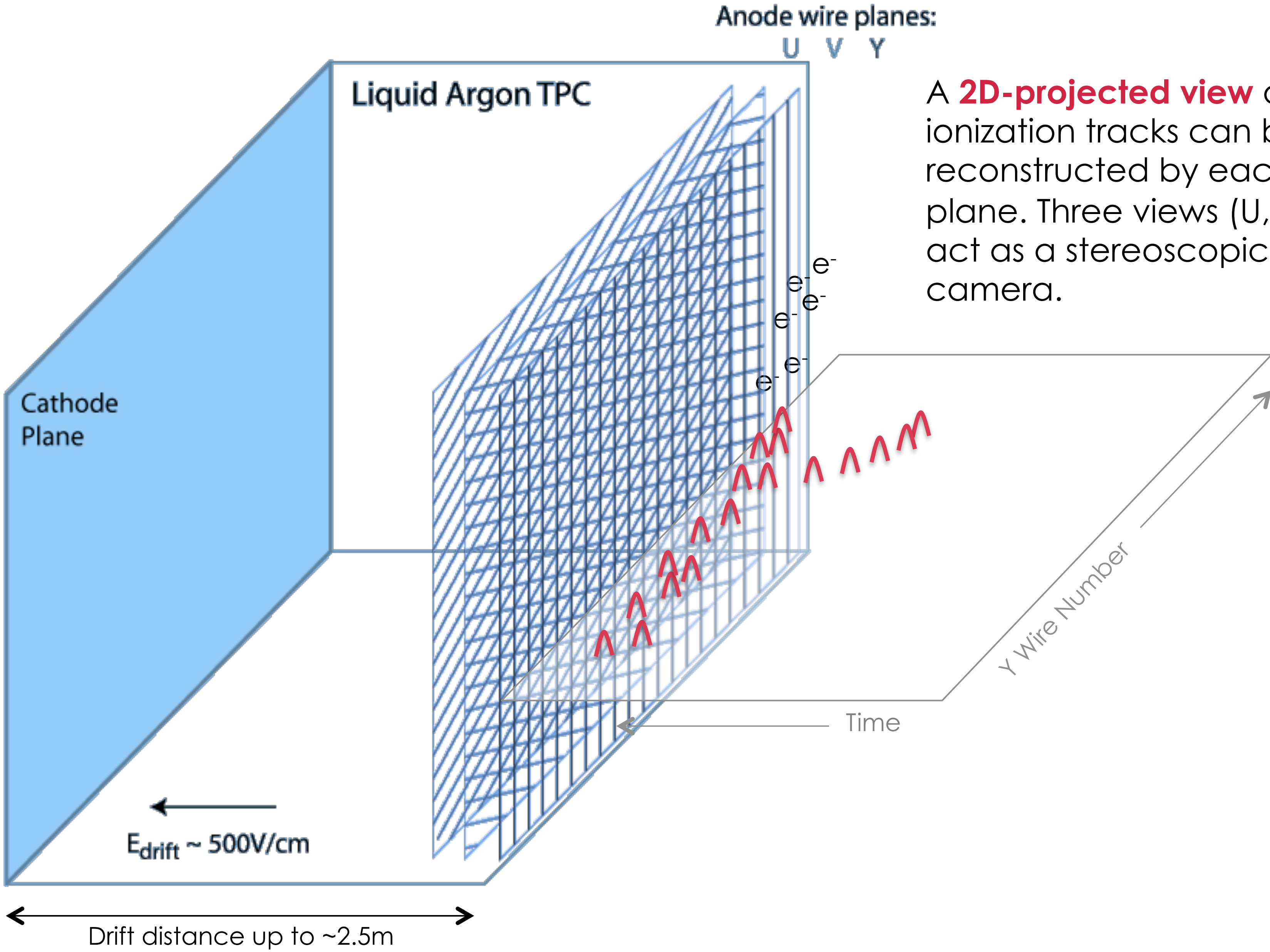


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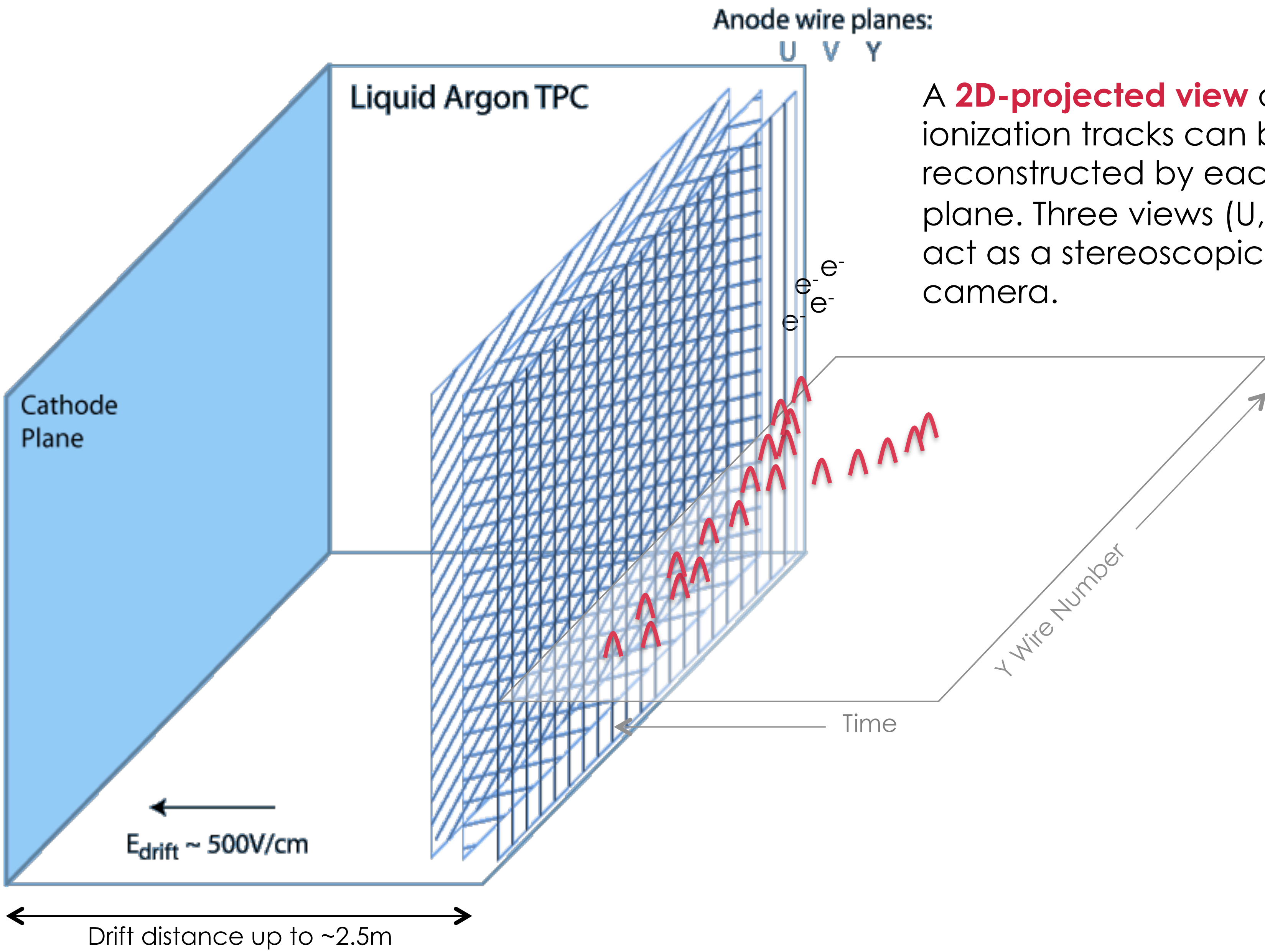


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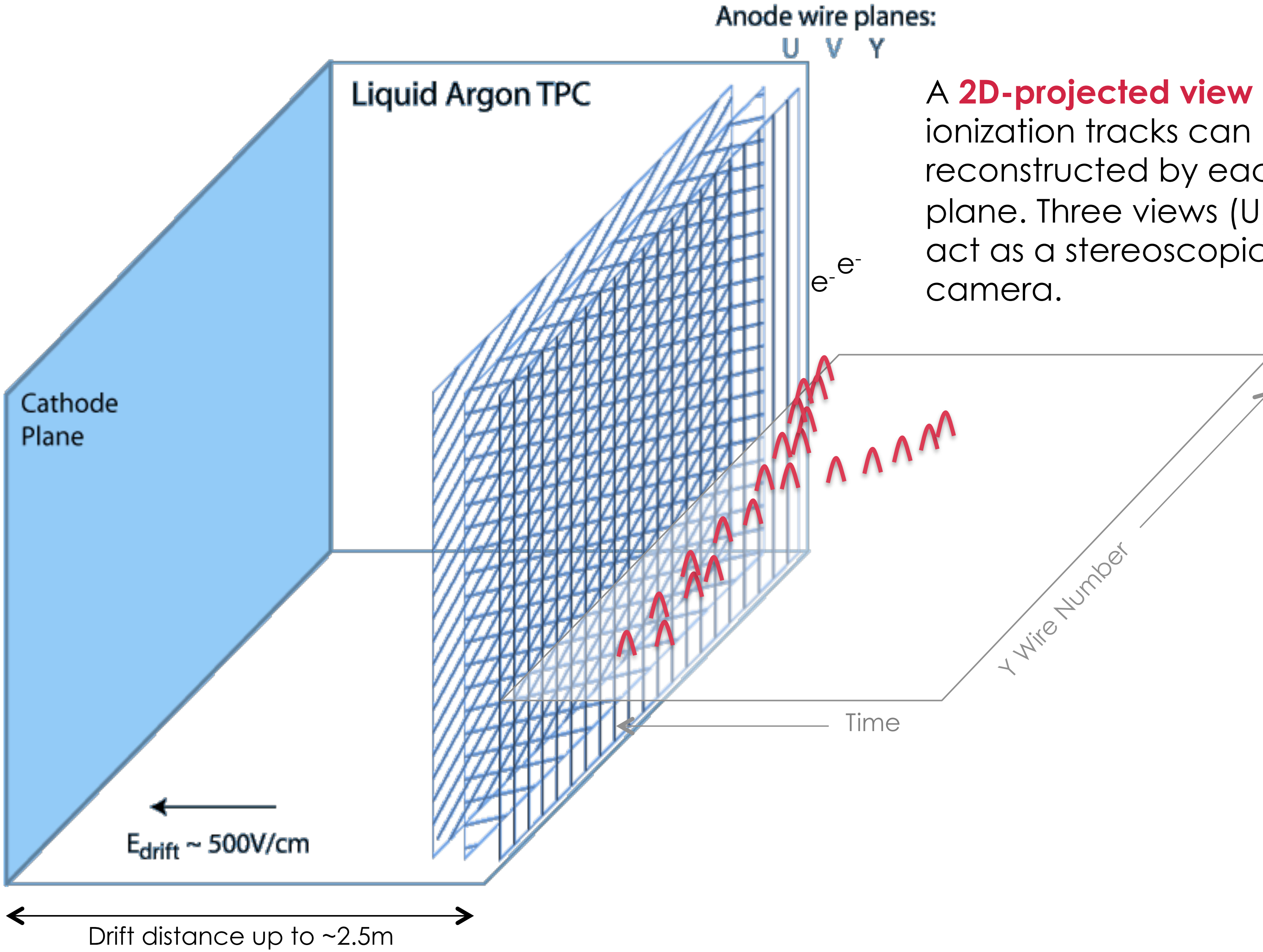


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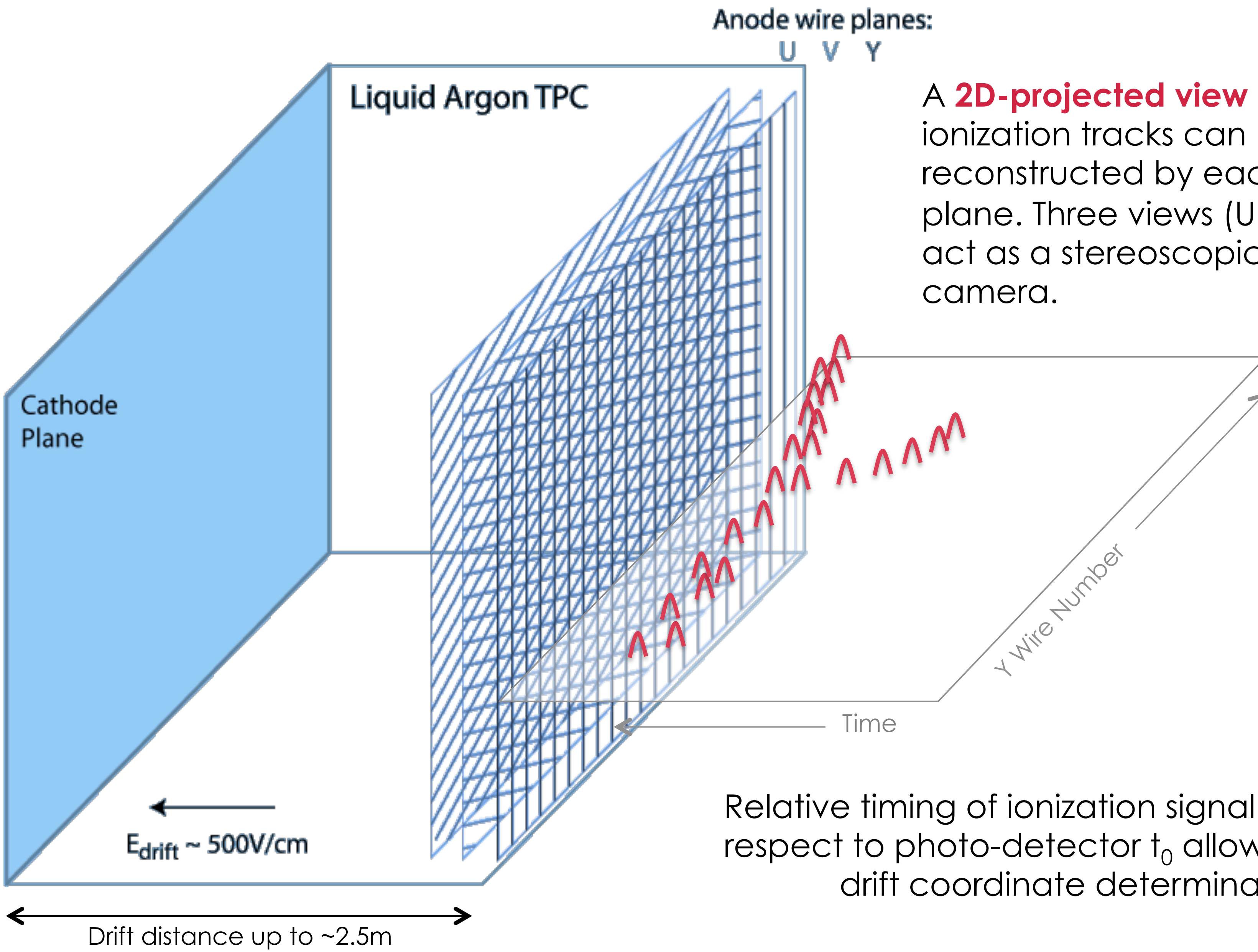
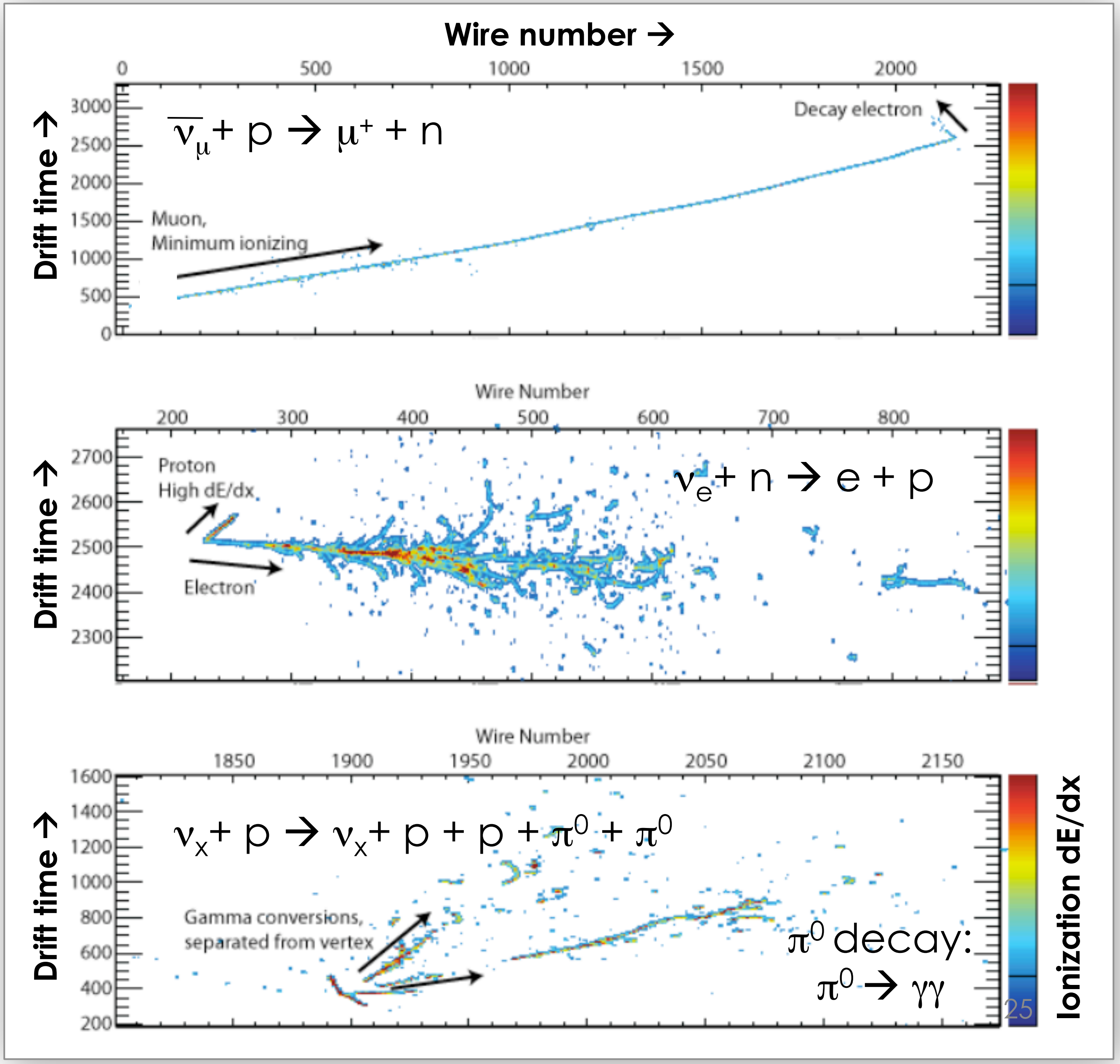



A **2D-projected view** of the ionization tracks can be reconstructed by each wire plane. Three views (U, V, Y) act as a stereoscopic camera.

Relative timing of ionization signal with respect to photo-detector $t_0$ allows for drift coordinate determination.

# LArTPC neutrino event topologies: "wire plane view"

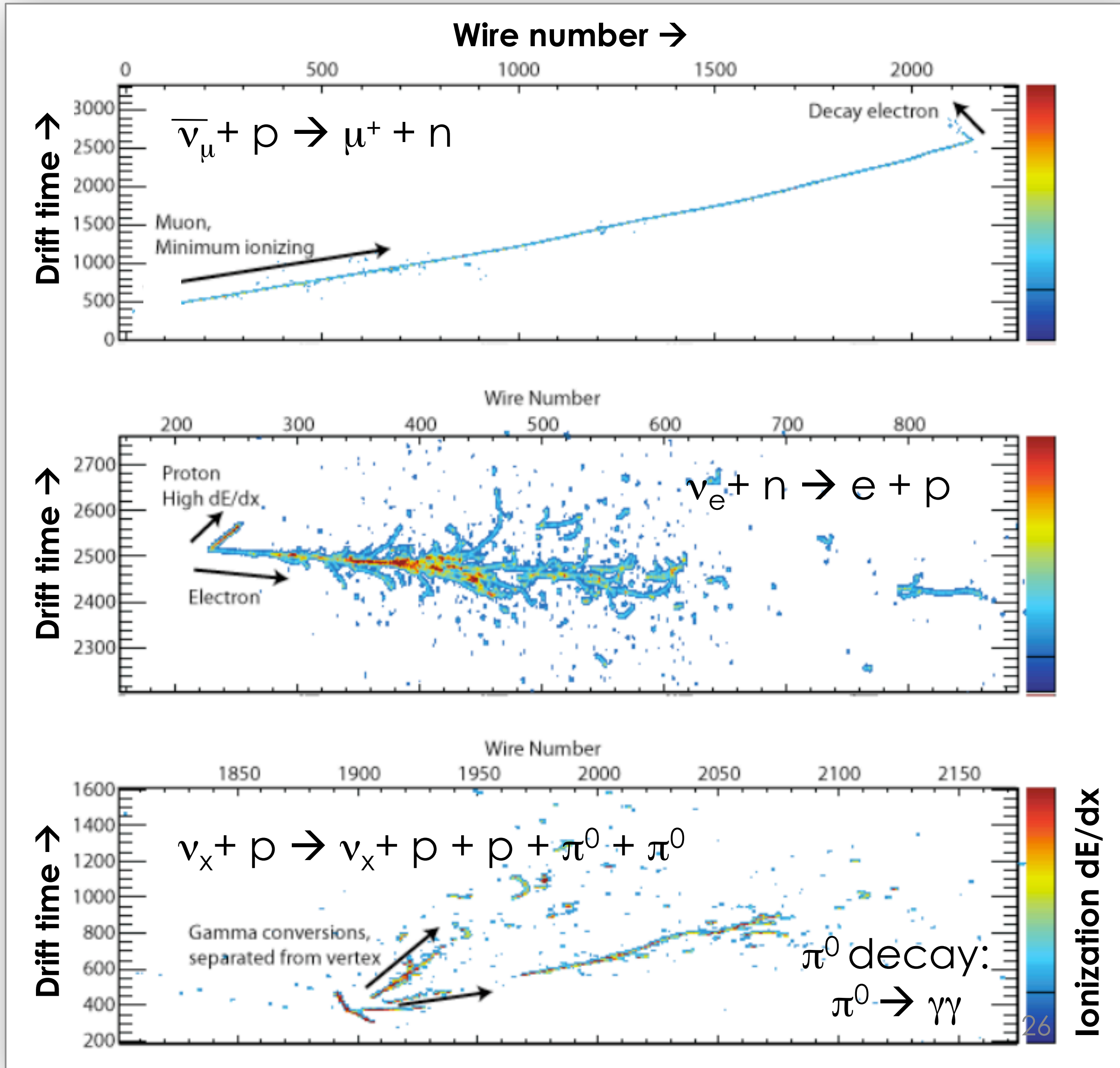



**Example simulated neutrino events ($E_\nu$ ~ 0.5-1 GeV)**

# LArTPC neutrino event topologies: "wire plane view"

Bubble chamber-quality data, with calorimetric information (position resolution and ionization dE/dx)

High event selection efficiency and excellent background rejection!

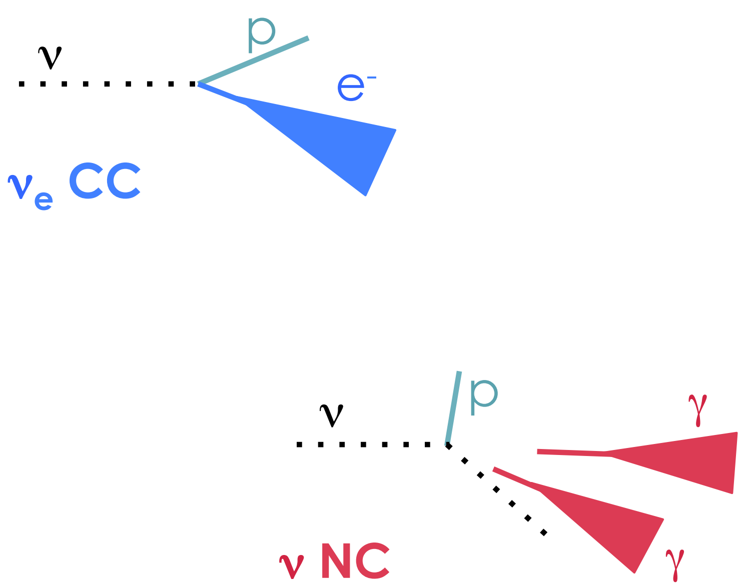


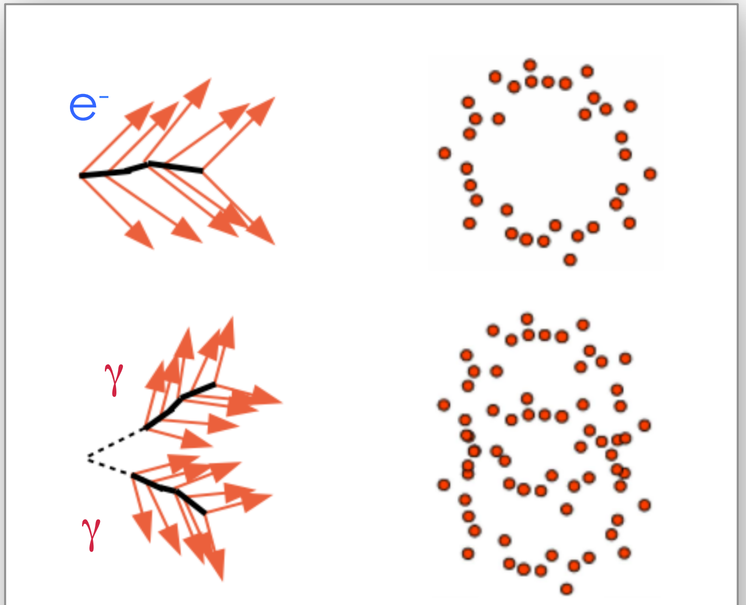

**Example simulated neutrino events ($E_\nu$ ~ 0.5-1 GeV)**

# LArTPC electron/photon separation

A **single e** and a **single $\gamma$** are indistinguishable in a Cherenkov detector;
$\nu_e$ CC measurements are plagued by NC $\pi^0 \rightarrow \gamma\gamma$ or other single-photon backgrounds…

but not in a LArTPC!



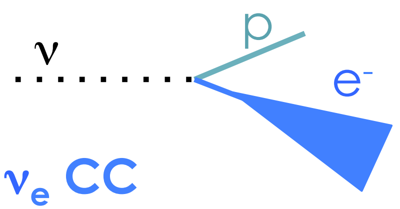



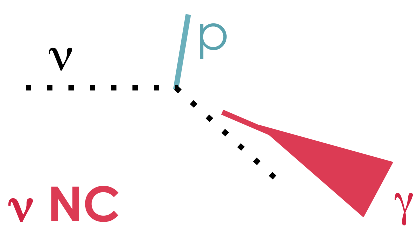
Cherenkov detector

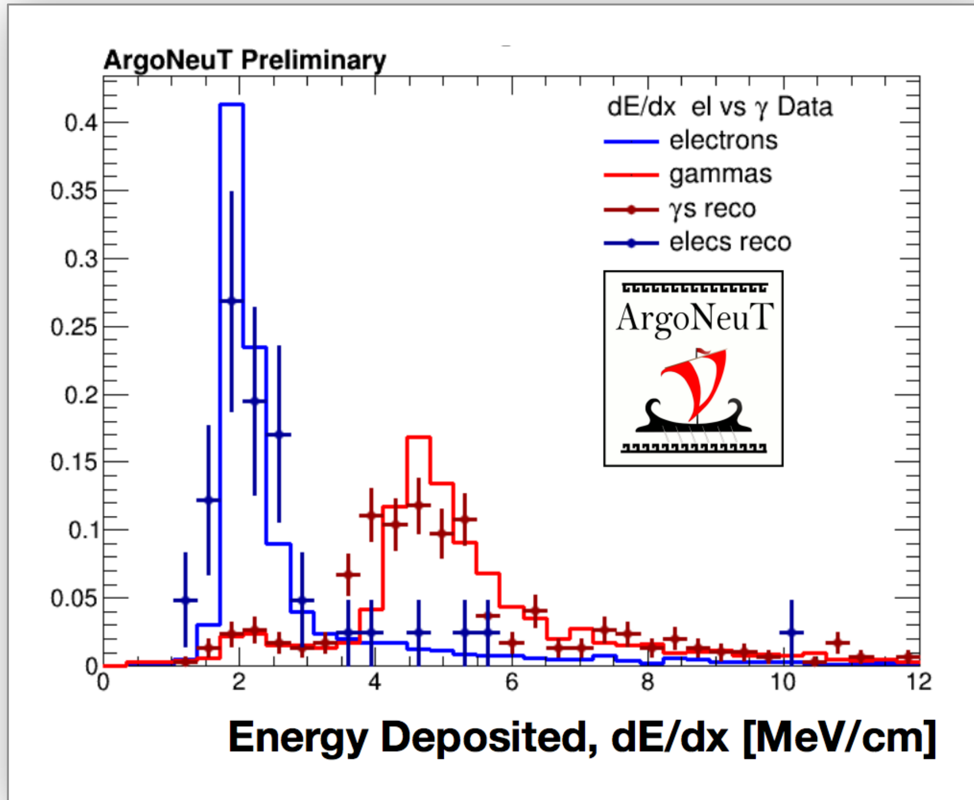
# LArTPC electron/photon separation

Neutrino events with γ are differentiated on the basis of:

1. Detached shower vertex from neutrino interaction vertex
2. Larger dE/dx deposited at the beginning of the shower (2 MIP vs 1 MIP)




**Typical e/γ separation: ~90% → Ideal technology for $\nu_e$ measurements**

# Neutrino-physics-driven experimental design

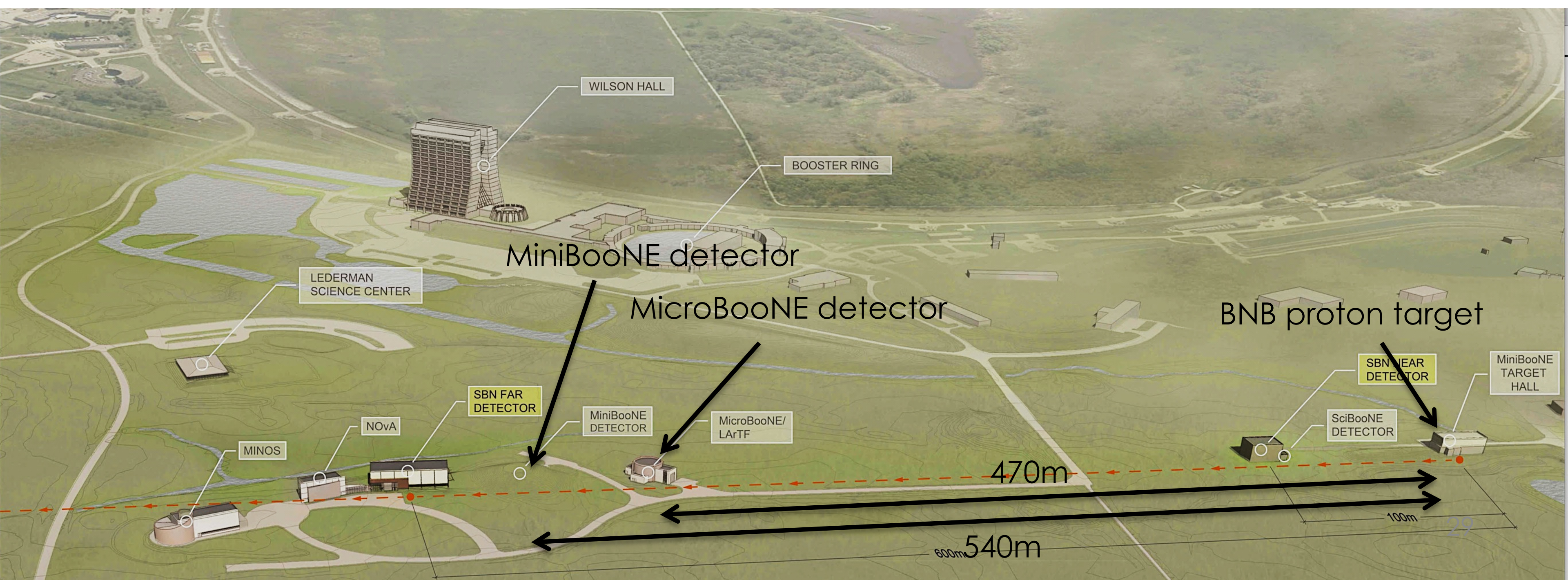
large neutrino flux ✚ argon interaction target ✚ calorimetric reconstruction

= **precise neutrino-argon cross-sections measurements**

~ 0.5-1 GeV neutrino energy ✚ ~MiniBooNE location (short-baseline)

✚ electron/photon separation

= **nature of MiniBooNE "low-energy excess"**

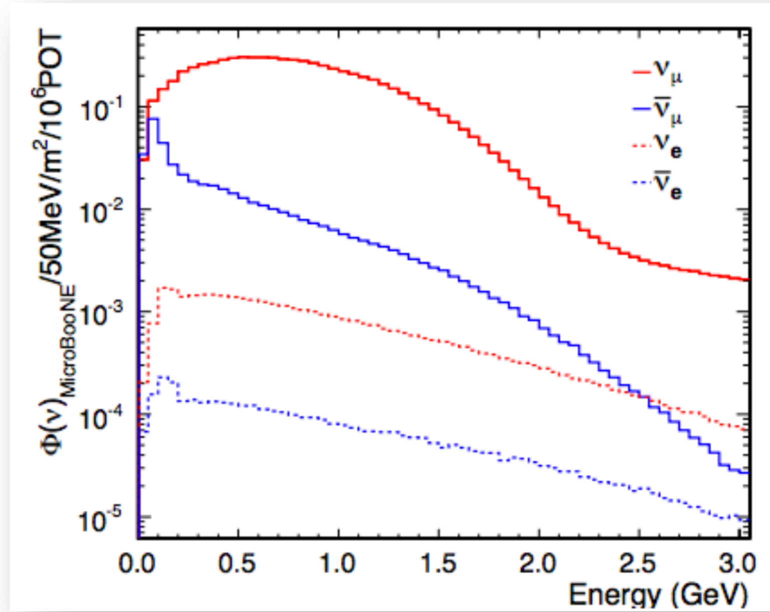


# Flux Parameters

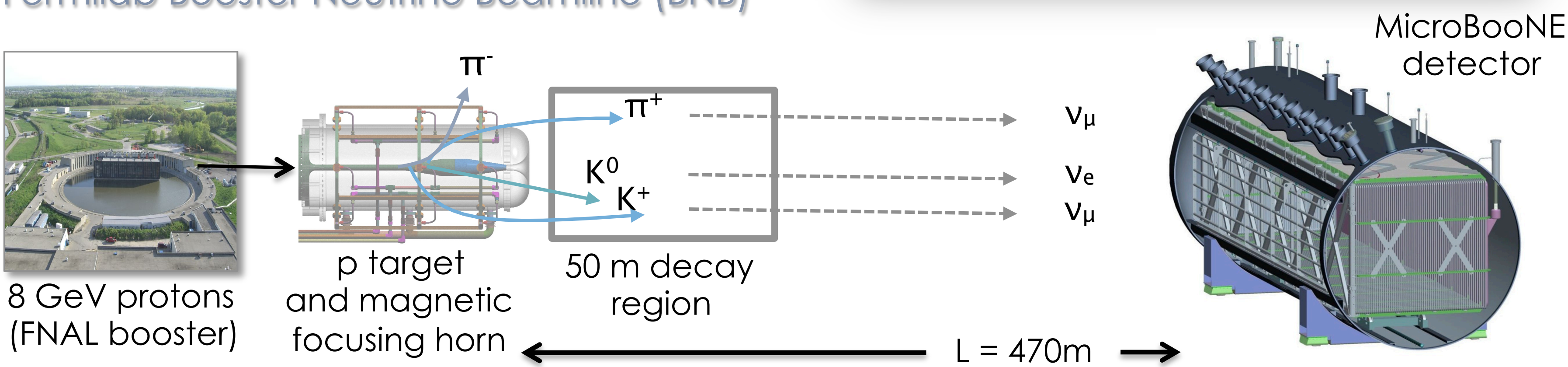
Neutrino flux at MicroBooNE detector:

>99% muon (anti)neutrino
~0.5% electron (anti)neutrino

Neutrino mode running ongoing
(statistics goal: 6.6E20 POT)




## Fermilab Booster Neutrino Beamline (BNB)

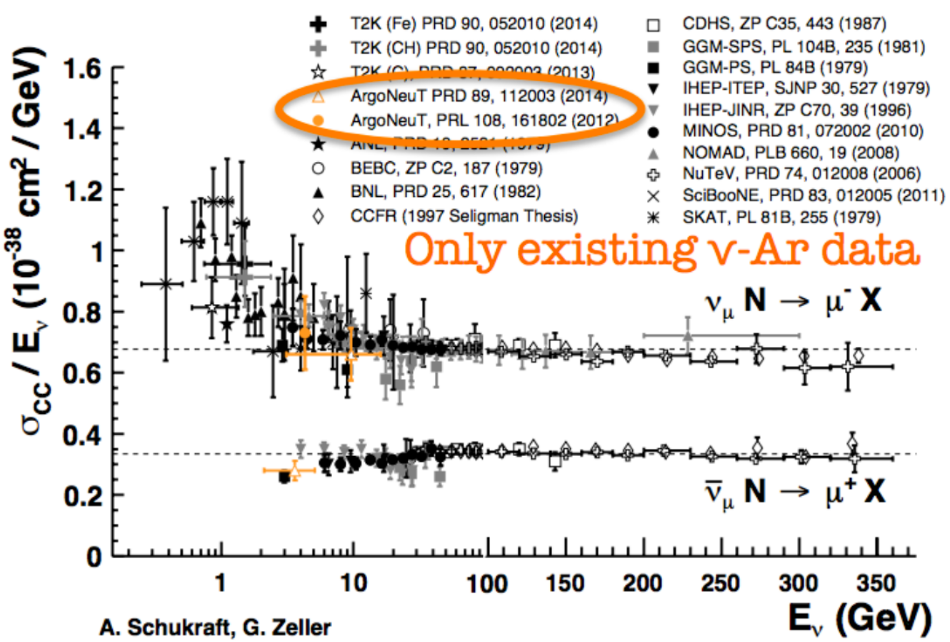



Beam is pulsed at up to 15 Hz; beam spill is 1.6μs wide.

# Primary physics goal 1: Neutrino-argon cross sections

Argon: target material for many future neutrino detectors

Need more experimental data to learn about nuclear effects and neutrino energy reconstruction

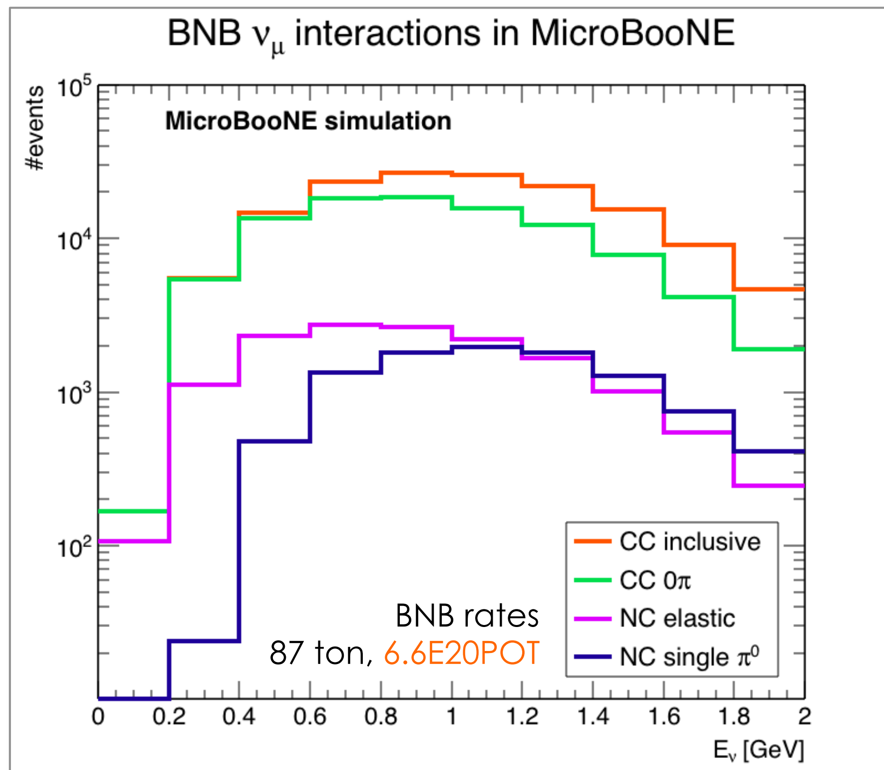


# Primary physics goal 1: Neutrino-argon cross sections

First LArTPC with high-statistics event samples in 1 GeV neutrino energy range (QE and RES regime)!

During its ~3 years of running, MicroBooNE will collect (up to hundreds of) **thousands** of exclusive and inclusive neutrino interactions on argon.

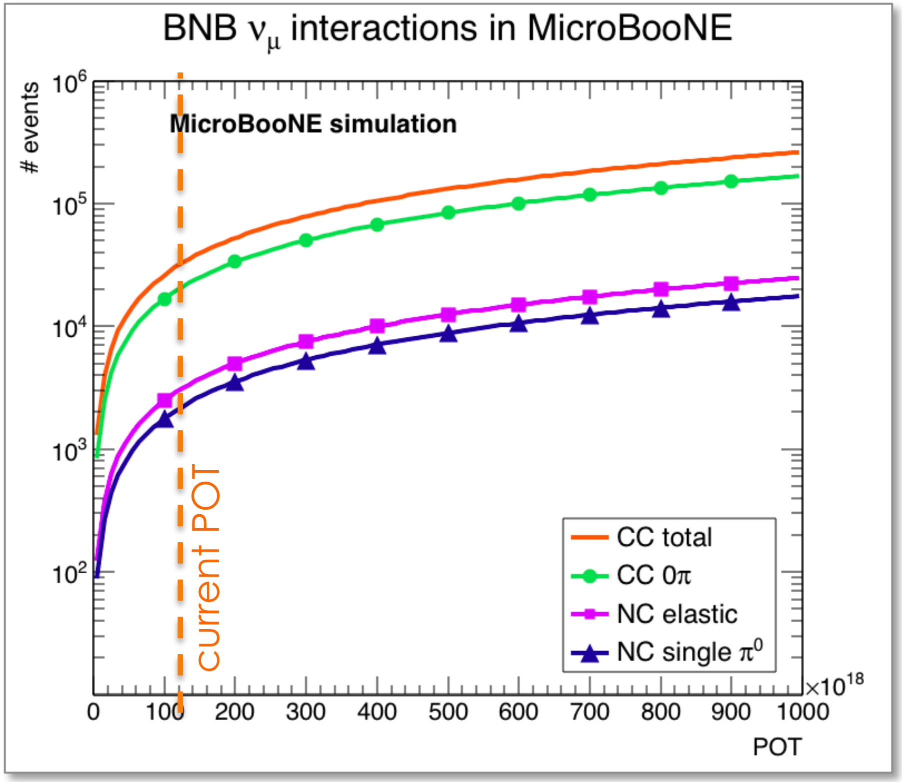
In addition to BNB neutrinos, MicroBooNE will also be able to measure **NuMI off-axis** neutrino interactions.

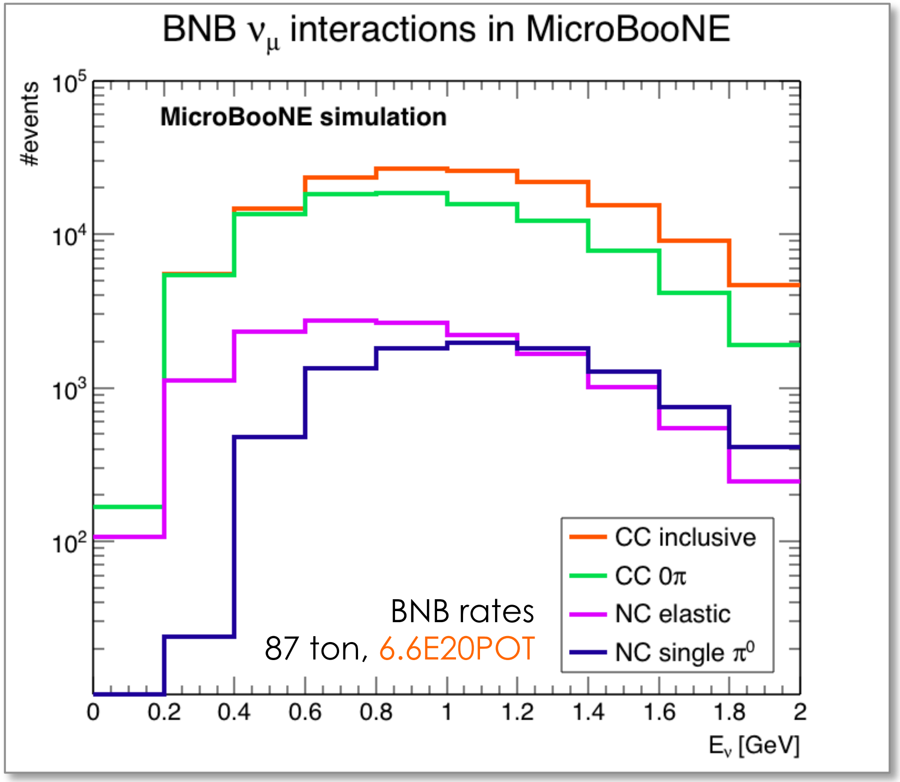


# Primary physics goal 1: Neutrino-argon cross sections

First LArTPC with high-statistics event samples in 1 GeV neutrino energy range (QE and RES regime)!

In just first 3 months of data taking (1.2E20 POT), thousands of events in several exclusive and inclusive topologies.



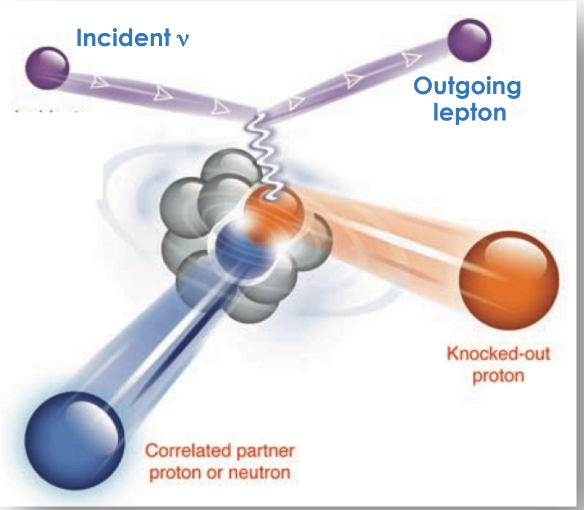
# Primary physics goal 1: Neutrino-argon cross sections

What MicroBooNE can add:

- Classification in terms of exclusive final states
- Study of nuclear effects, which we now know play a critical role on event rate and event final state information

- Event topology and final state information (e.g. proton multiplicity in QE-like interactions, final state kinematics) can be studied with sufficiently low momentum reconstruction thresholds

- Investigate the role of hadronic effects and kinematics on energy reconstruciton



# Primary physics goal 1: Neutrino-argon cross sections

**ArgoNeut Results**
**Phys. Rev. D 90, 012008 (2014)**

**The detection of back-to-back proton pairs in Charged-Current neutrino interactions with the ArgoNeuT detector in the NuMI low energy beam line**


R. Acciarri,[1] C. Adams,[2] J. Asaadi,[3] B. Baller,[1] T.Bolton,[4] C. Bromberg,[5] F. Cavanna,[2,6] E. Church,[2] D. Edmunds,[5] A. Ereditato,[7] S. Farooq,[4] B. Fleming,[2] H. Greenlee,[1] G. Horton-Smith,[4] C. James,[1] E. Klein,[2] K. Lang,[8] P. Laurens,[5] R. Mehdiyev,[8] B. Page,[5] O. Palamara,[2,9,*] K. Partyka,[2] G. Rameika,[1] B. Rebel,[1] M. Soderberg,[3,1] J. Spitz,[2] A.M. Szelc,[2] M. Weber,[7] T. Yang,[1] and G.P. Zeller[1]

(ArgoNeuT Collaboration)

[1]*Fermi National Accelerator Laboratory, Batavia, IL 60510 USA*
[2]*Yale University, New Haven, CT 06520 USA*
[3]*Syracuse University, Syracuse, NY 13244 USA*
*...anhattan, KS 66506 USA*
*...ast Lansing, MI 48824 USA*
*... INFN, L'Aquila, Italy*
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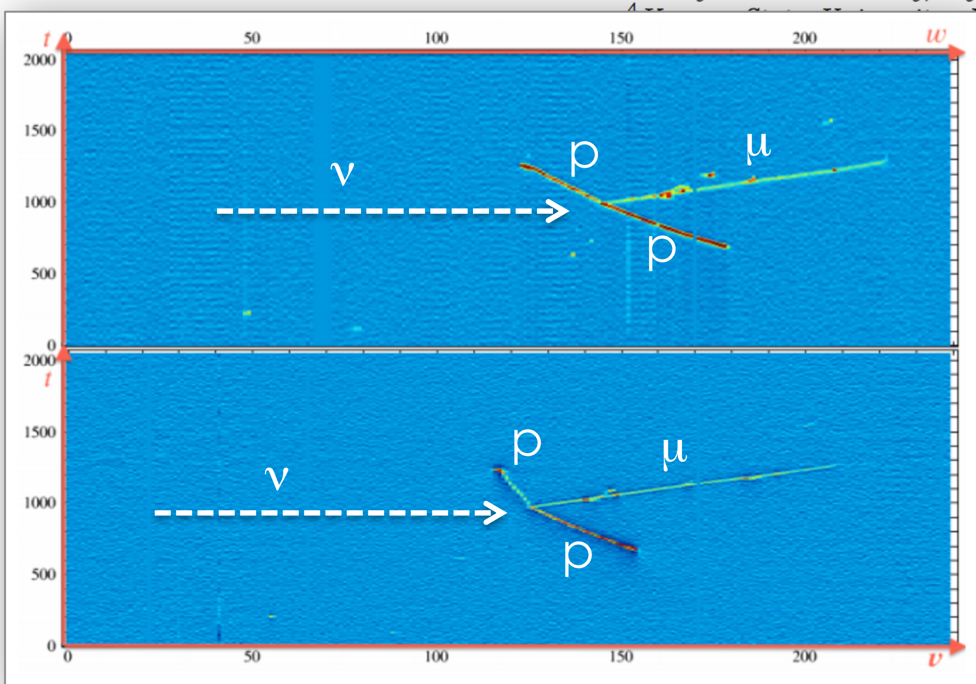
*...stin, Austin, TX 78712 USA*
*...del Gran Sasso, Assergi, Italy*


... 19, 2014)

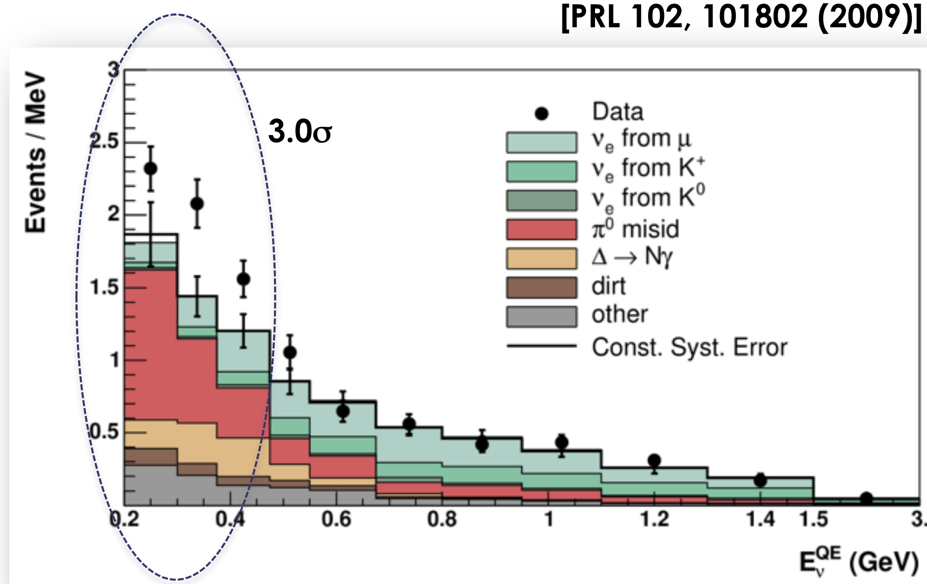



**Back-to-back "hammer" events**
suggest nucleon-nucleon short-range correlations.
Inferred kinematics from recoil nucleons in CM frame (before interaction) support this.

# Primary physics goal 2: MiniBooNE “low-energy excess”

**MicroBooNE will resolve the nature of the MiniBooNE low-energy excess.**

**MiniBooNE unexplained “low energy excess”**
**[PRL 102, 101802 (2009)]**




MiniBooNE’s **search for electron neutrino appearance in the BNB** due to oscillations at an L/E ~ 1m/MeV, revealed an unexplained excess of events at low reconstructed neutrino energy.

The search looks for events with a single electromagnetic shower cherenkov ring.

Events with either a single observable electron or a single observable photon contribute indistinguishably to the electron neutrino sample in MiniBooNE.

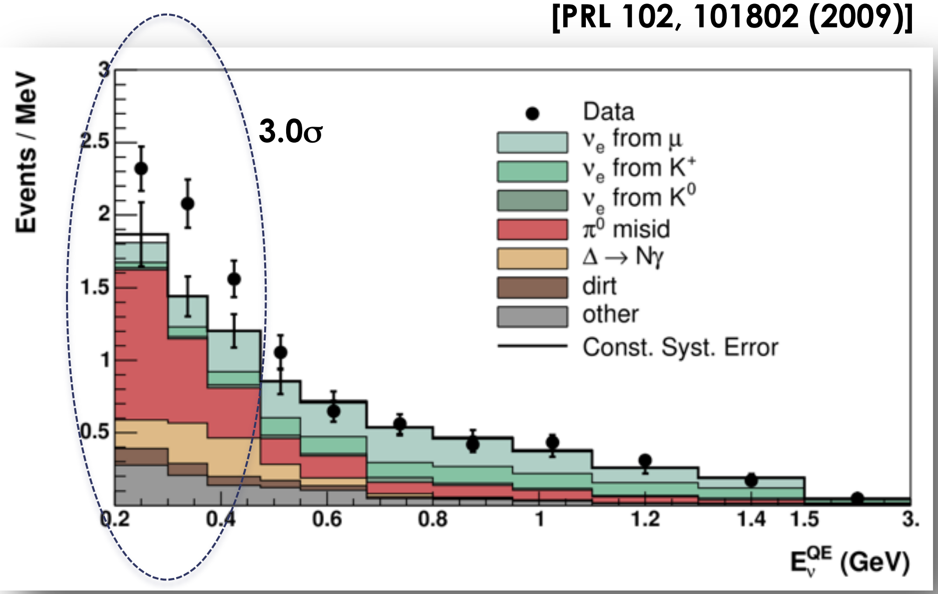
# The MiniBooNE low-energy excess

The MiniBooNE excess can be interpreted as sterile neutrino oscillations at an L/E ~ 1m/MeV,.

However, this interpretation conflicts with constraints from other (null) short-baseline experiments.

The L/E shape of the excess is also somewhat problematic…

**MiniBooNE unexplained "low energy excess"**
**[PRL 102, 101802 (2009)]**




Unaccounted $\nu_e / \nu_\mu$ disappearance?

Energy (mis)reconstruction? Cross-section/ nuclear effects?

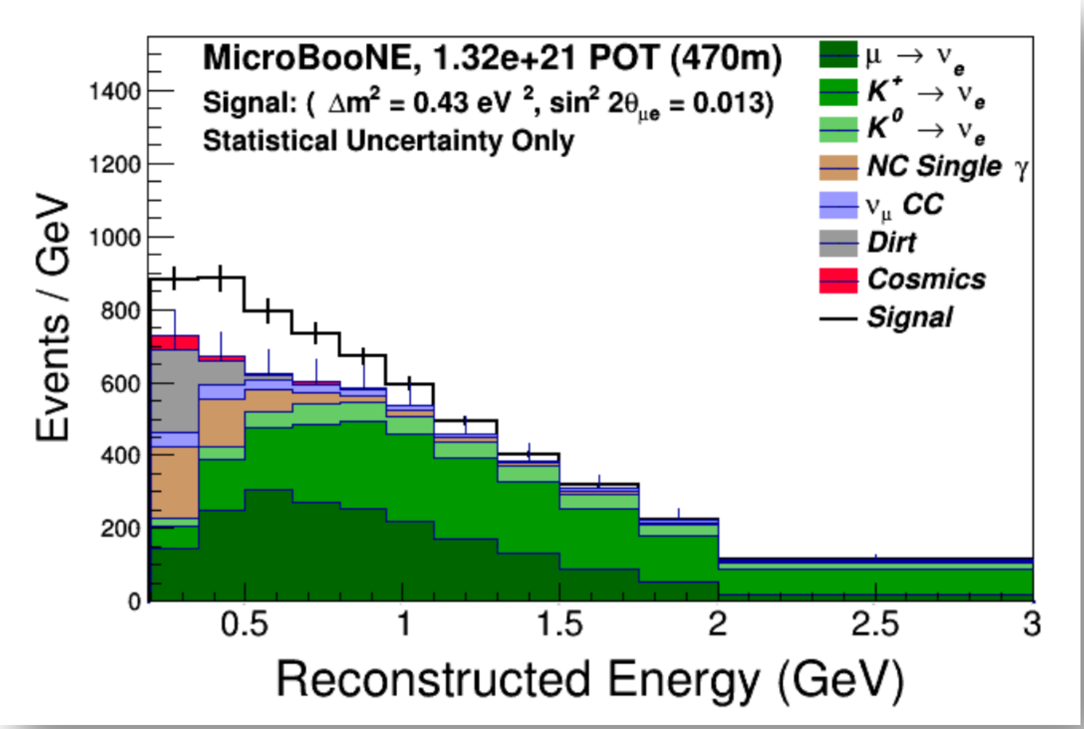
Misestimated or new electron-like background?

Misestimated or new photon-like background?

# Primary physics goal 2: MiniBooNE "low-energy excess"

- If an excess is observed and found to be due to **photons**, MicroBooNE could make the first measurement of a novel photon-production mechanism, to be included in neutrino interaction generators, as it could impact future $\nu_e$ appearance measurements

- If the excess is due to **electrons**: MicroBooNE could be seeing $\nu_e$ appearance (sterile neutrino oscillations, NSI, extra dimensions) or be in position to measure some other novel production mechanism (?)

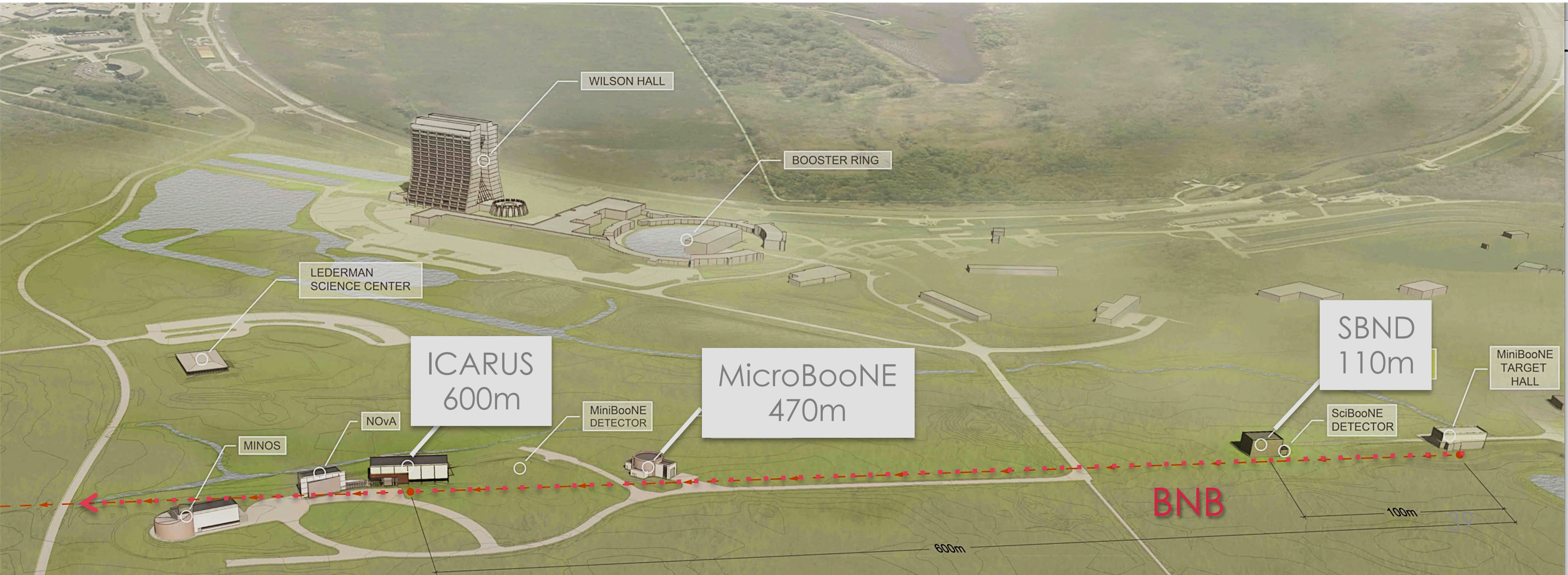


# SBN @ Fermilab

MicroBooNE is part of a larger Short-Baseline Neutrino (SBN) programme at Fermilab.

SBN physics goal: Perform a definitive test of MiniBooNE/LSND sterile neutrino oscillation interpretation

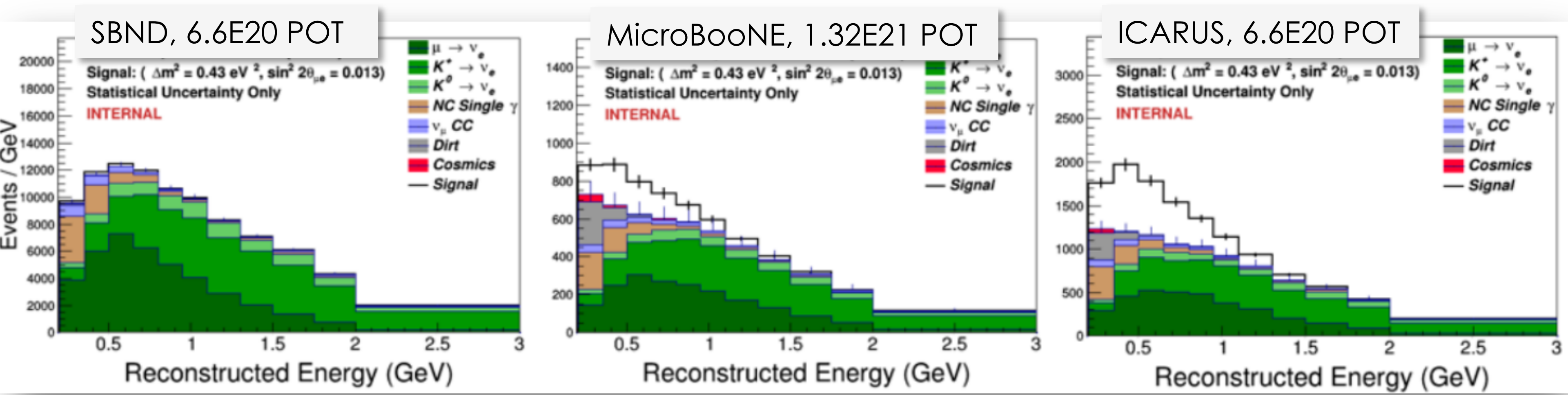
Near/Mid/Far comparison of neutrino flux
MicroBooNE: First out of three SBN detectors, already operational



# SBN @ Fermilab: Appearance search

SBND's high statistics constrain the expected $\nu_e$ background event rates

ICARUS' large mass provides necessary statistical power for an electron neutrino appearance search



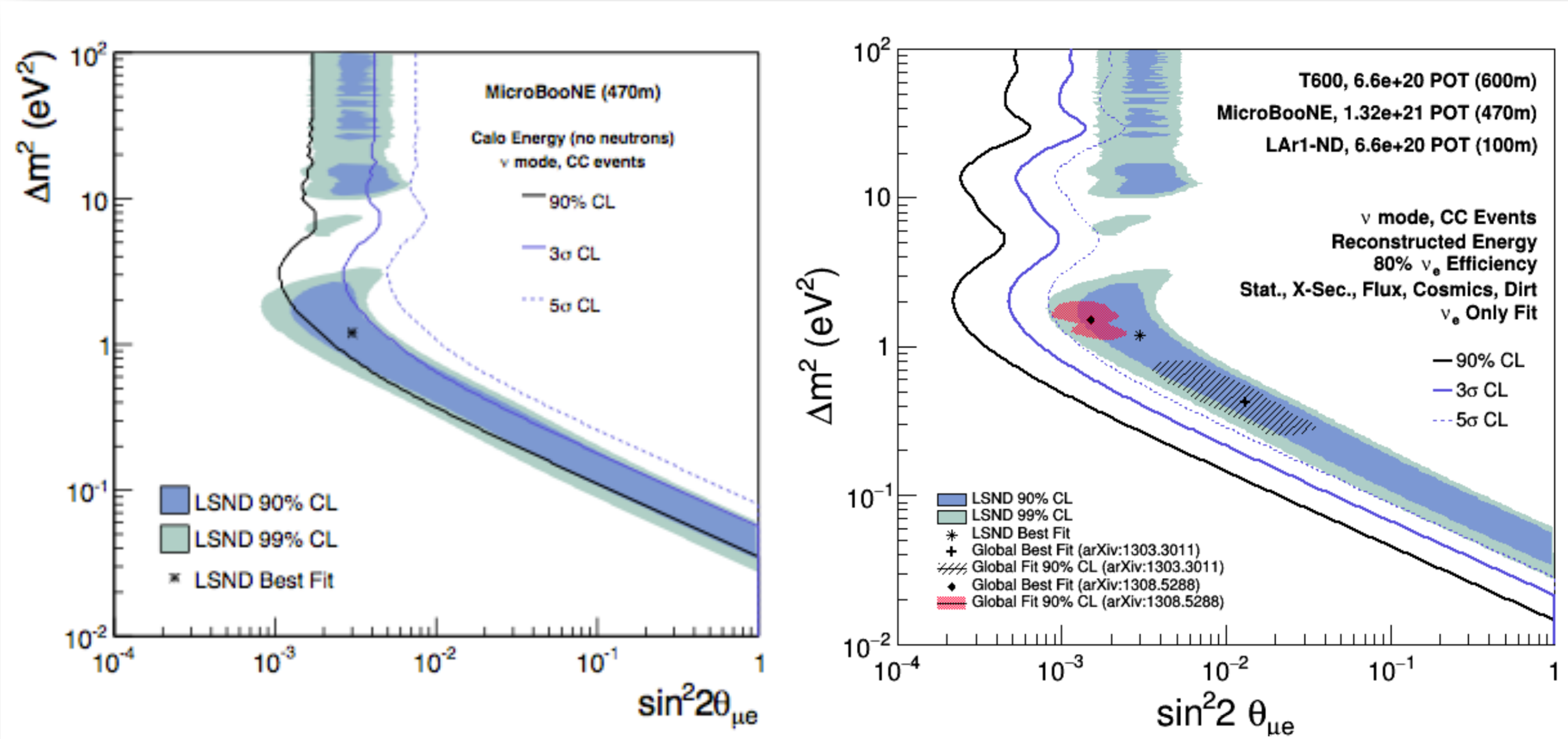

[SBN Proposal 2015]

- The dominant background: beam **intrinsic** backgrounds
- The **dirt** and **cosmic** backgrounds depend greatly on the detector geometry and location within the beam

# SBN @ Fermilab: Appearance search

[SBND Proposal 2013, SBN Proposal 2015]

**Three-detector SBN program**



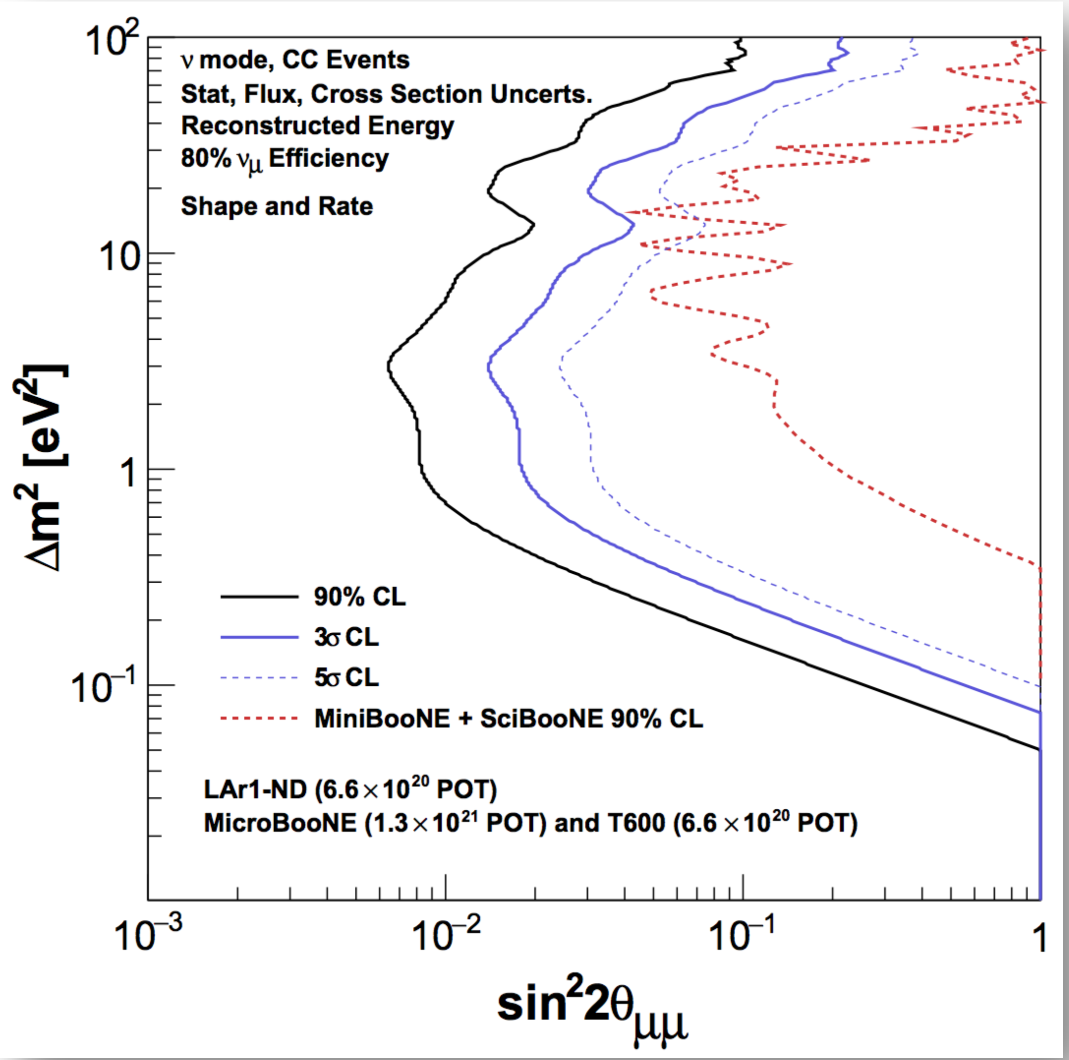

**MicroBooNE-only**, 6.6e20 POT
20% uncorrel. systematic uncertainty
on backgrounds

# SBN @ Fermilab: Disappearance search

SBN can also perform a competitive search for **muon neutrino disappearance**.

Needed to fully interpret any excess of electron neutrino events as oscillations involving sterile neutrinos:

a corresponding disappearance of muon neutrinos with ~greater than or equal probability




[SBN Proposal 2015]

# Additional MicroBooNE physics goals

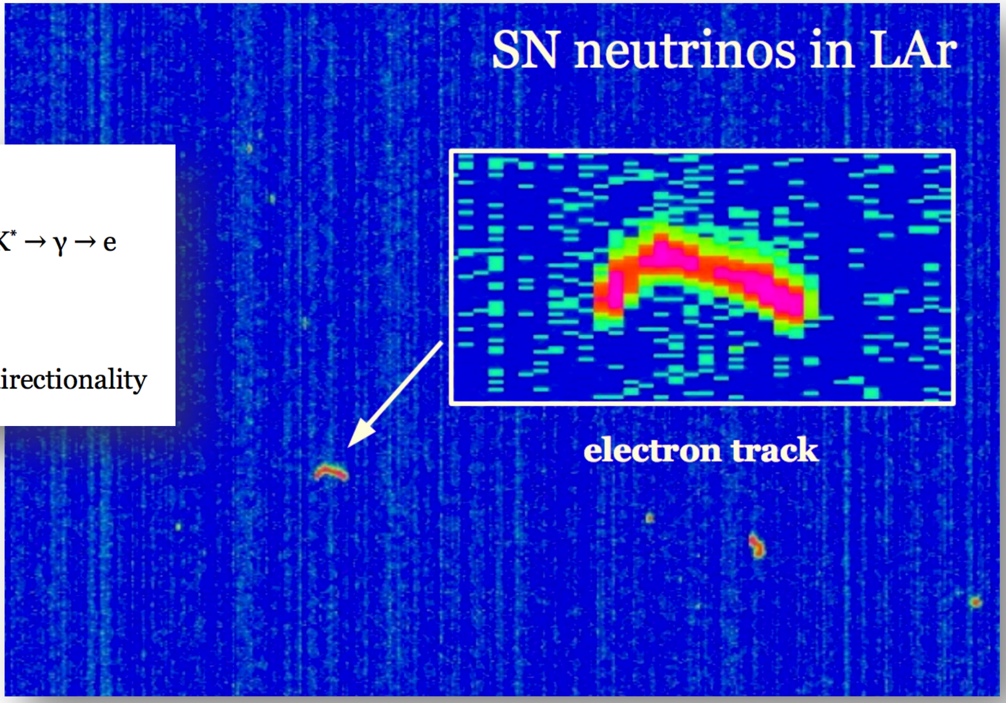
- Demonstrate background rejection capabilities and constrain cosmogenic background predictions to future searches for baryon number violation (proton decay, neutron-antineutron oscillations,…)
- Search for supernova core collapse neutrinos, should a nearby supernova occur during MicroBooNE's life span

Visible channels:

| | |
|---|---|
| $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ → | CC: Largest statistics. ${}^{40}K^* \rightarrow \gamma \rightarrow e$ |
| $\bar{\nu}_e + {}^{40}Ar \rightarrow e^- + {}^{40}Cl^*$ → | CC: Lower xsec |
| $\nu_x + e^- \rightarrow \nu_x + e^-$ → | NC: All $\nu$ species. Good directionality |

10 kpc SN neutrino event rate predictions for MicroBooNE (60 tons):

~a few to a few tens of events



# Seeking definitive answers to "Big Questions" in neutrino physics

Fundamental questions

What is the value of $\delta_{CP}$?

Is the neutrino mass spectrum normal, or inverted?

What are the absolute neutrino masses?

Are neutrinos dirac or majorana fields?

Are there additional, "sterile" neutrino states? ✓

Do we understand exclusive and inclusive neutrino cross sections on nuclear targets? ✓

Pressing experimental questions

Directly addressed by MicroBooNE

# Seeking definitive answers to "Big Questions" in neutrino physics

Fundamental questions

Addressed by future LArTPC's

What is the value of $\delta_{CP}$? ✓

Is the neutrino mass spectrum normal, or inverted? ✓

What are the absolute neutrino masses?

Are neutrinos dirac or majorana fields?

Are there additional, "sterile" neutrino states? ✓ ✓

Do we understand exclusive and inclusive neutrino cross sections on nuclear targets? ✓ ✓

Pressing experimental questions

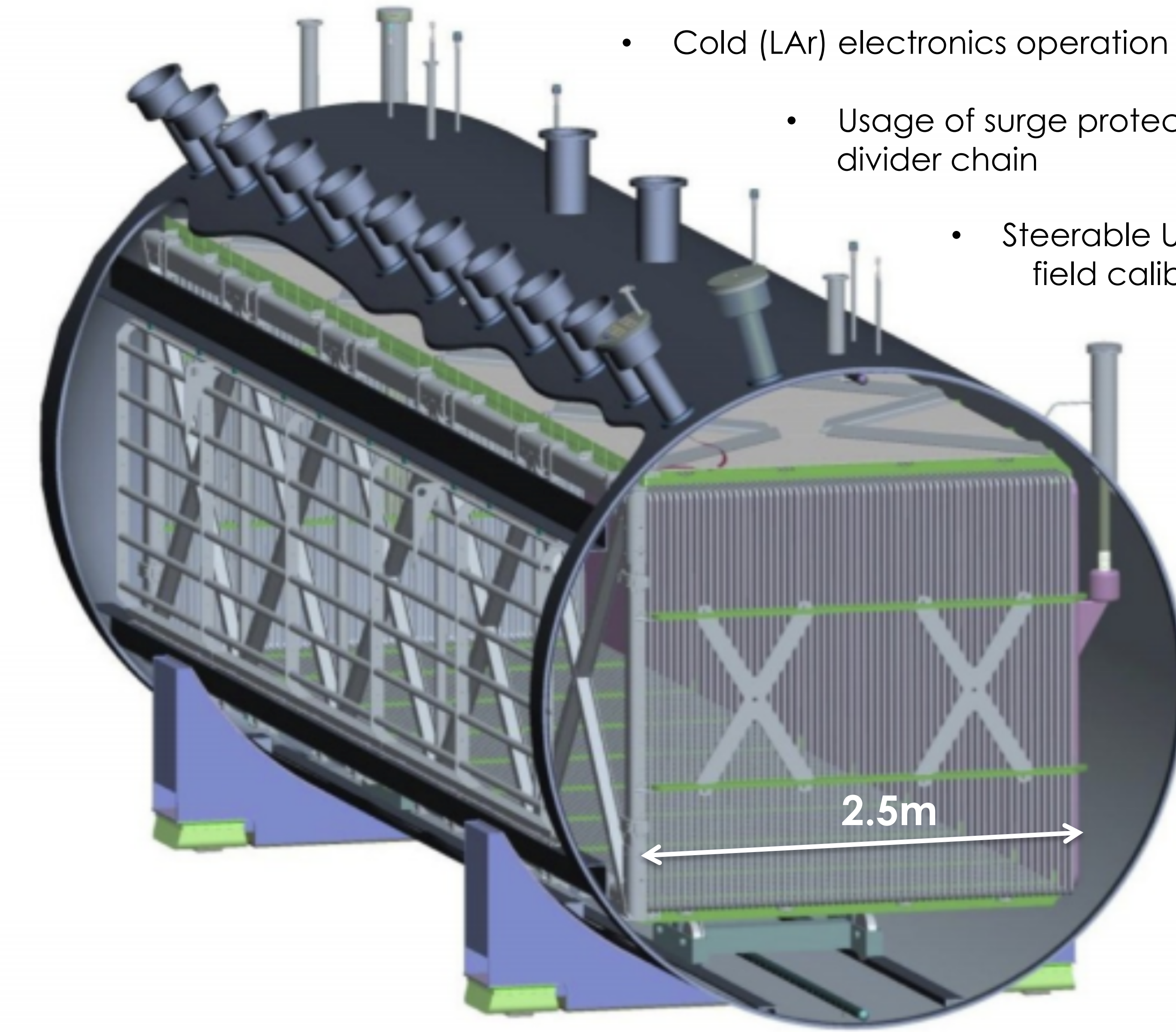
Directly addressed by MicroBooNE

# Driving Nu Physics…

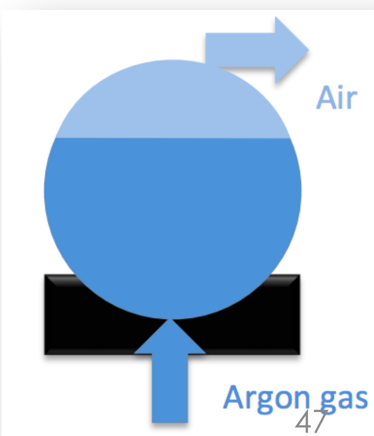

… and LArTPC R&D!

# Driving LArTPC R&D

- Longest drift distance in a LArTPC detector
- Cold (LAr) electronics operation (CMOS ASICs)
- Usage of surge protection devices along voltage divider chain
- Steerable UV lasers for electric field calibration
- Purity without evacuation, via argon gas purge




Piston purge:



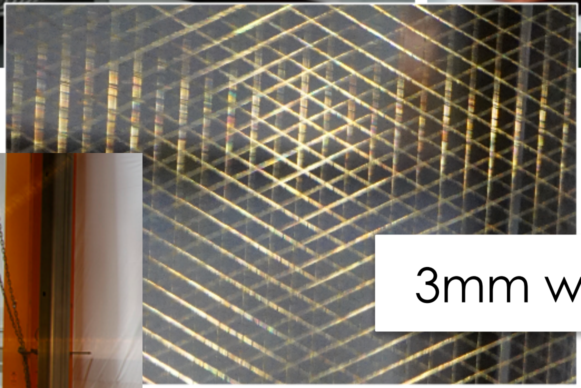
# Driving LArTPC R&D

**Publications by MicroBooNE collaborators:**


1. B. Carls, et al., **“Design and Operation of a Setup with a Camera and Adjustable Mirror to Inspect the Sense Wires of the TPC Inside the MicroBooNE Cryostat”**, JINST 10, T08006 (2005)
2. J. Conrad et al., **"The Photomultiplier Tube Calibration System of the MicroBooNE Experiment"**, arXiv: 1502.04159 [physics.ins.det]
3. L.F. Bagby et al., **"Breakdown Voltage of Metal Oxide Resistors in Liquid Argon"**, JINST 9, T11004 (2014)
4. R. Acciarri et al., **"Liquid Argon Dielectric Breakdown Studies with the MicroBooNE Purification System"**, JINST 9, P11001 (2014)
5. A. Ereditato et al., **"First Working Prototype of a Steerable UV Laser System for LAr TPC Calibrations"**, JINST 9, T11007 (2014)
6. J. Asaadi et al., **"Testing of High Voltage Surge Protection Devices for Use in Liquid Argon TPC Detectors"**, JINST 9, P09002 (2014)
7. M. Auger et al., **"A Method to Suppress Dielectric Breakdowns in Liquid Argon Ionization Detectors for Cathode to Ground Distances of Several Millimeters"**, JINST 9, P07023 (2014)
8. A. Blatter et al., **"Experimental Study of Electric Breakdown in Liquid Argon at Centimeter Scale"**, JINST 9, P04006 (2014)
9. T. Briese et al., **"Testing of Cryogenic Photomultiplier Tubes for the MicroBooNE Experiment"**, JINST 8, T07005 (2013)
10. B.J.P. Jones et al., **"Photodegradation Mechanisms of Tetraphenyl Butadiene Coatings for Liquid Argon Detectors"**, JINST 8 P01013 (2013)
11. B.J.P. Jones et al., **"A Measurement of the Absorption of Liquid Argon Scintillation Light by Dissolved Nitrogen at the Part-Per-Million Level"**, JINST 8 P07011 (2013)
12. C.S. Chiu et al., **"Evironmental Effects on TPB Wavelength-Shifting Coatings"**, JINST 7, P07007 (2012)
13. A. Ereditato et al., **"Design and Operation of ARGONTUBE: a 5m Long Drift Liquid Argon TPC"**, JINST 8, P07002 (2013)

# MicroBooNE construction highlights

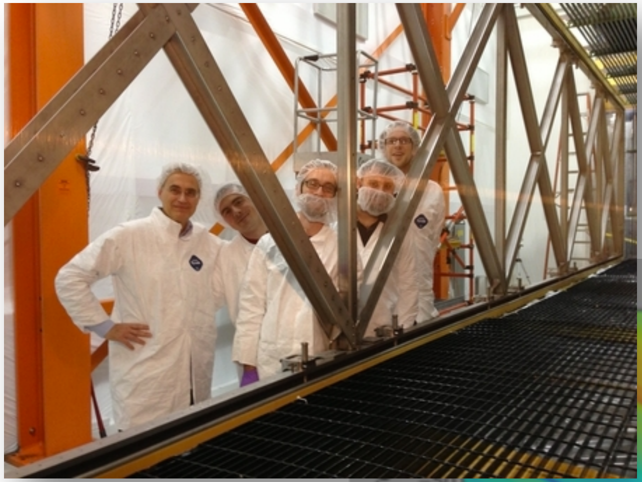
TPC construction: 2013



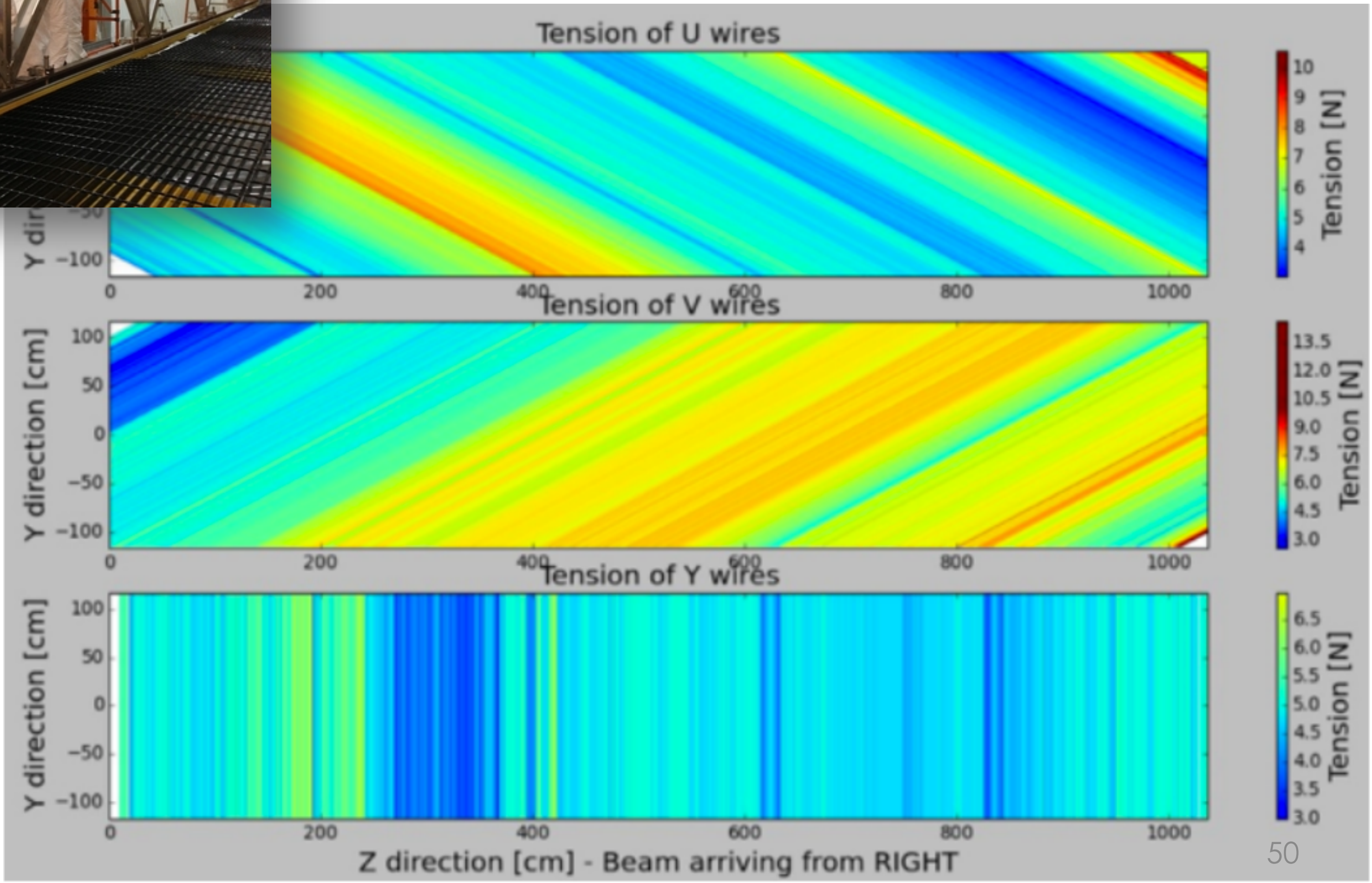
3mm wire spacing

# MicroBooNE construction highlights

TPC construction: 2013



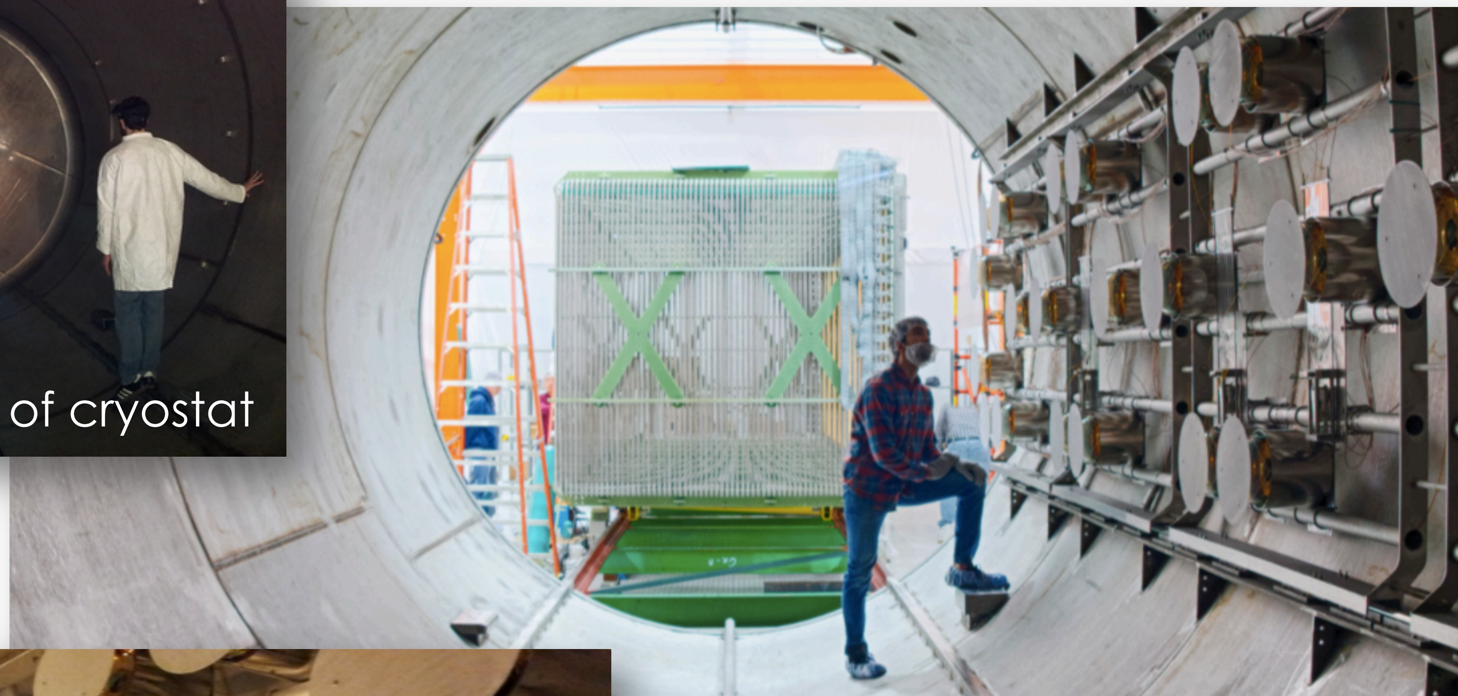
Verified every wire's tension prior to installation of TPC in cryostat

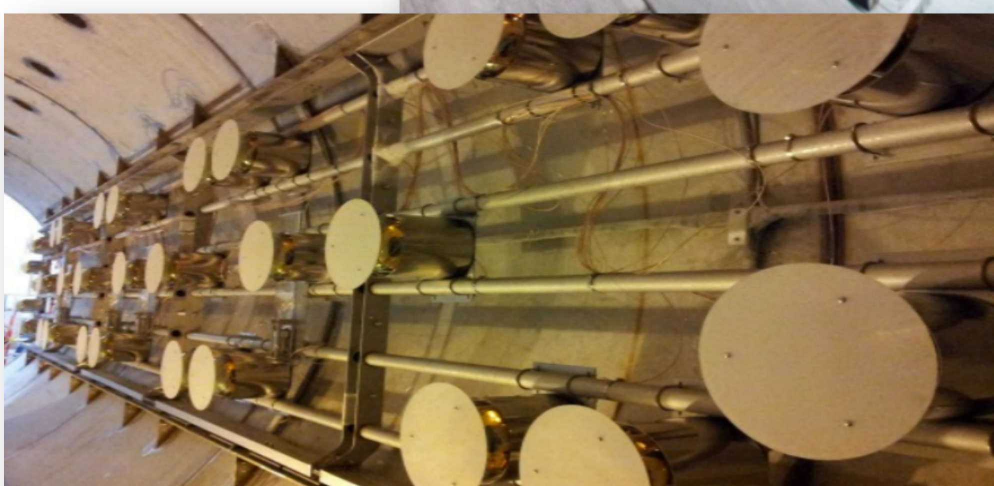


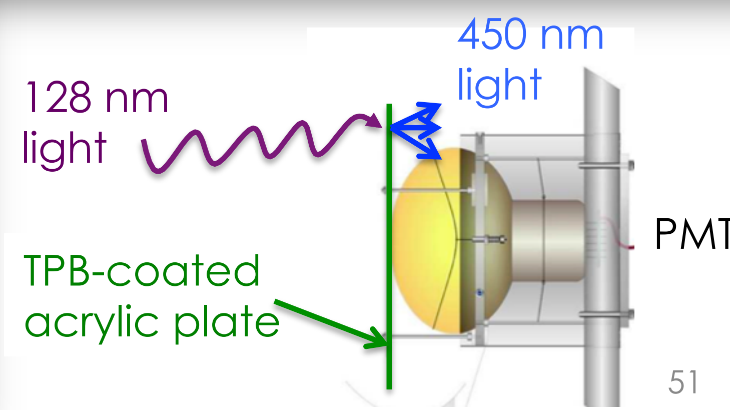
# MicroBooNE construction highlights


Power-washing of cryostat

PMT system installation: Dec. 2013







# MicroBooNE construction highlights

TPC insertion into cryostat

Dec. 23, 2013

# MicroBooNE construction highlights

Detector move to LArTF: June 23, 2014


Everything in the cryostat went along:

electronics, TPC (including wires), and PMTs (not full of argon yet though)

# MicroBooNE construction highlights

At LArTF, detector insulated with foam: July 2014

Detector components (readout electronics, trigger, control systems, cryogenics) installed, cabled up, and granted final safety clearance **Dec. 10, 2014**

# MicroBooNE commissioning highlights

Prior to cooling and filling the detector:

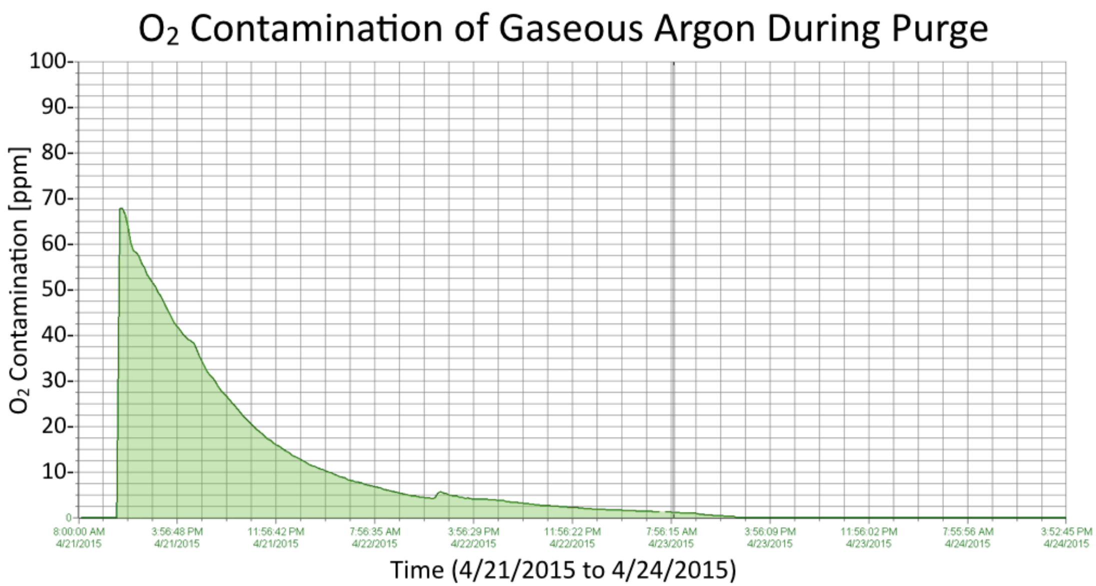
DAQ and readout commissioning; exercised to understand detector electronics response, noise levels, grounding issues, …

Then, from room T air to high-purity liquid argon in 4 steps:

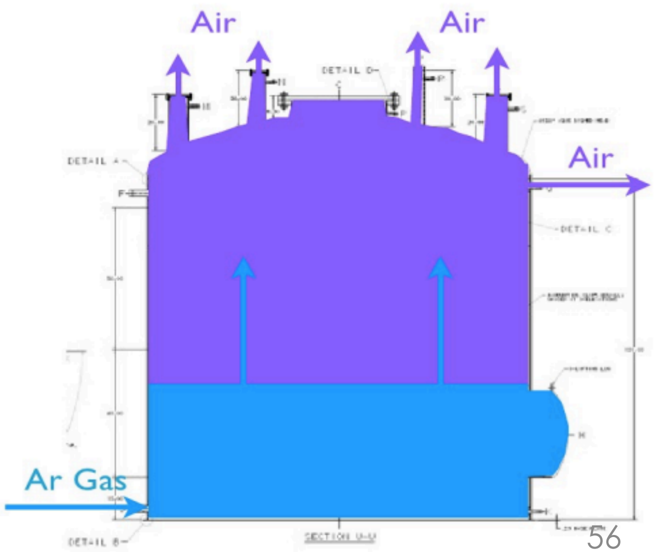
1. Argon gas purge
2. Argon gas cooling
3. Liquid argon fill
4. Liquid argon filtration

# MicroBooNE commissioning highlights

1. Argon gas circulation (purging without evacuation): April - May 2015

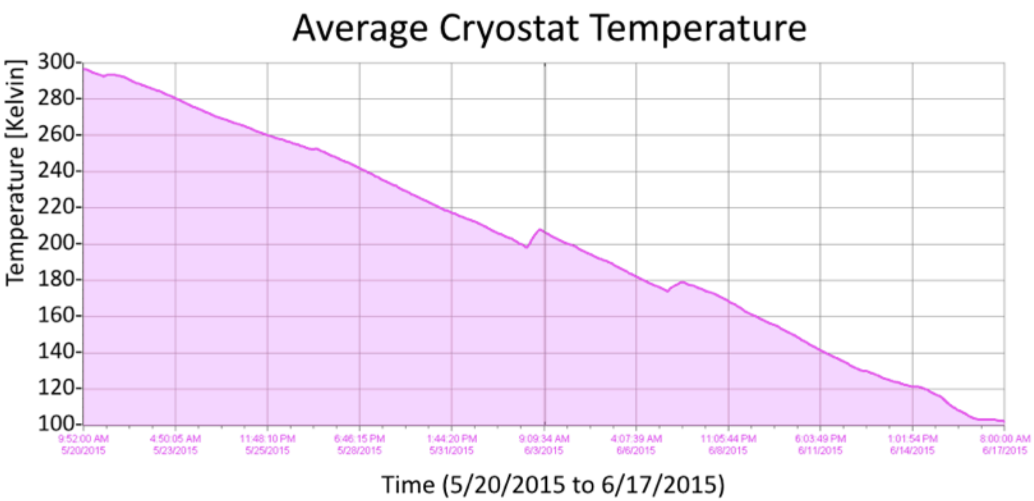



Reduced $O_2$ from 70 ppm ⇒ 20 ppb over the course of 300 volume exchanges

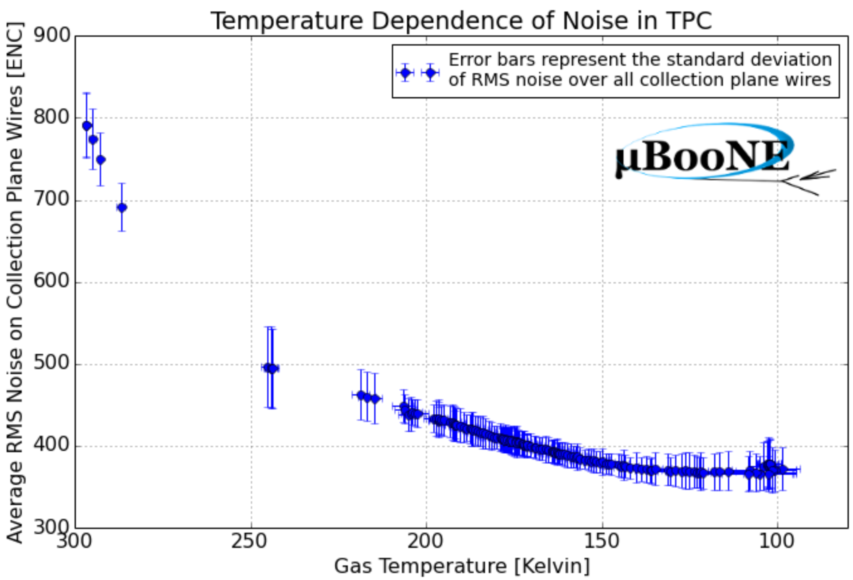


# MicroBooNE commissioning highlights

2. Argon gas cool-down: May-June 2015




Detector cooled down before introduction of liquid argon



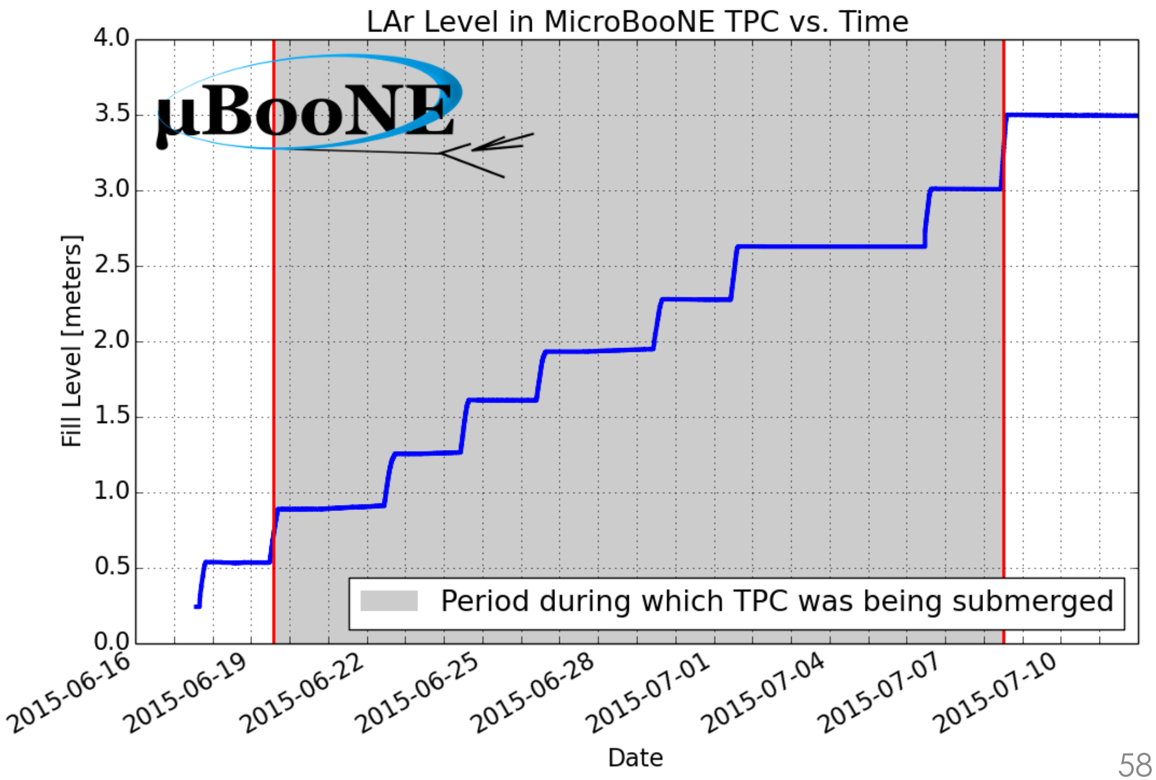

ASIC noise decreases as expected during gaseous Argon cool-down

Cold electronics: excellent signal:noise performance (40:1, 4x ICARUS)

# MicroBooNE commissioning highlights

3. Liquid argon fill completed:
July 9, 2015

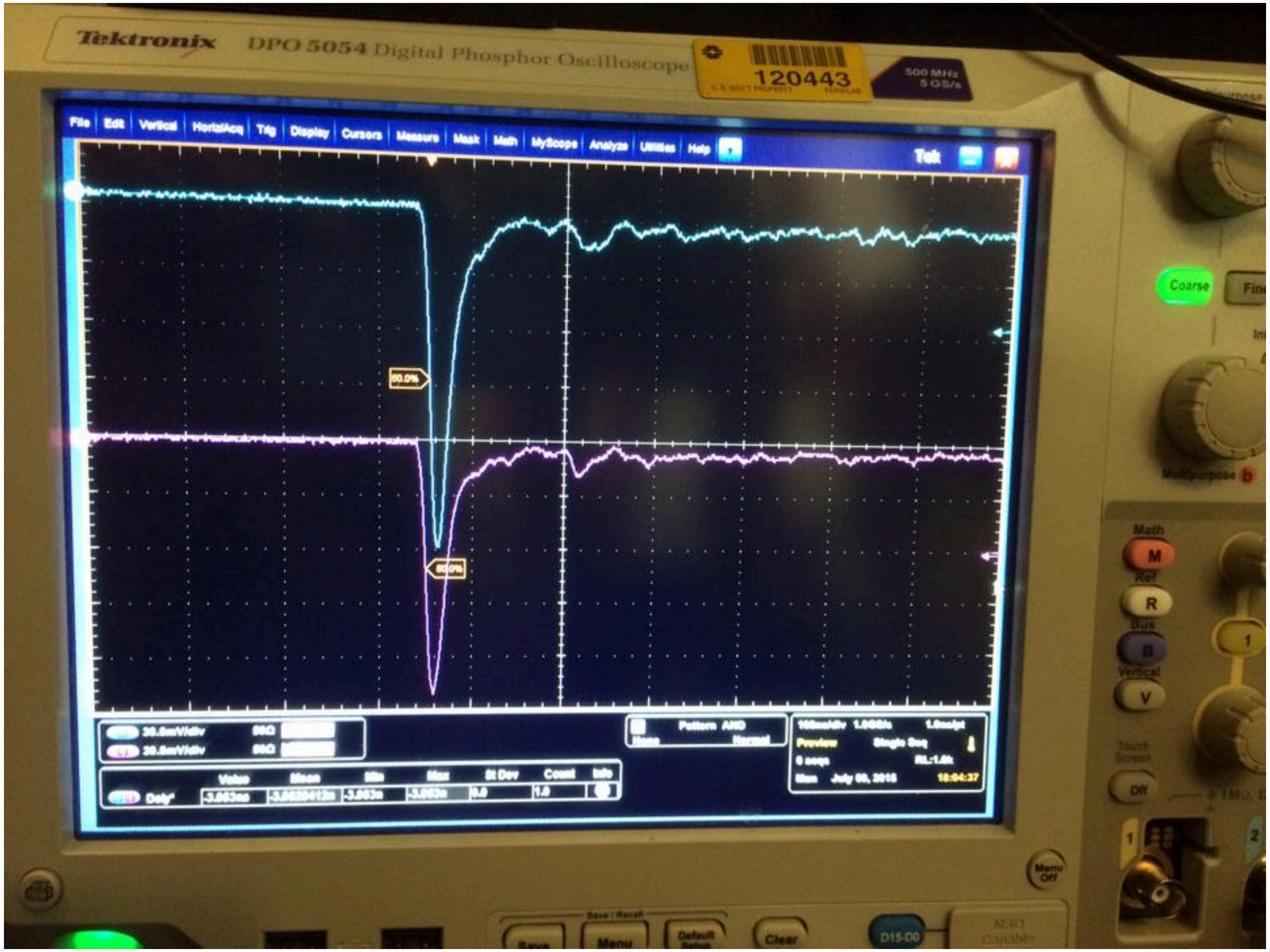
It took 9 tanker trucks and ~34,000 gallons of high-purity liquid argon (28 days)

# MicroBooNE commissioning highlights

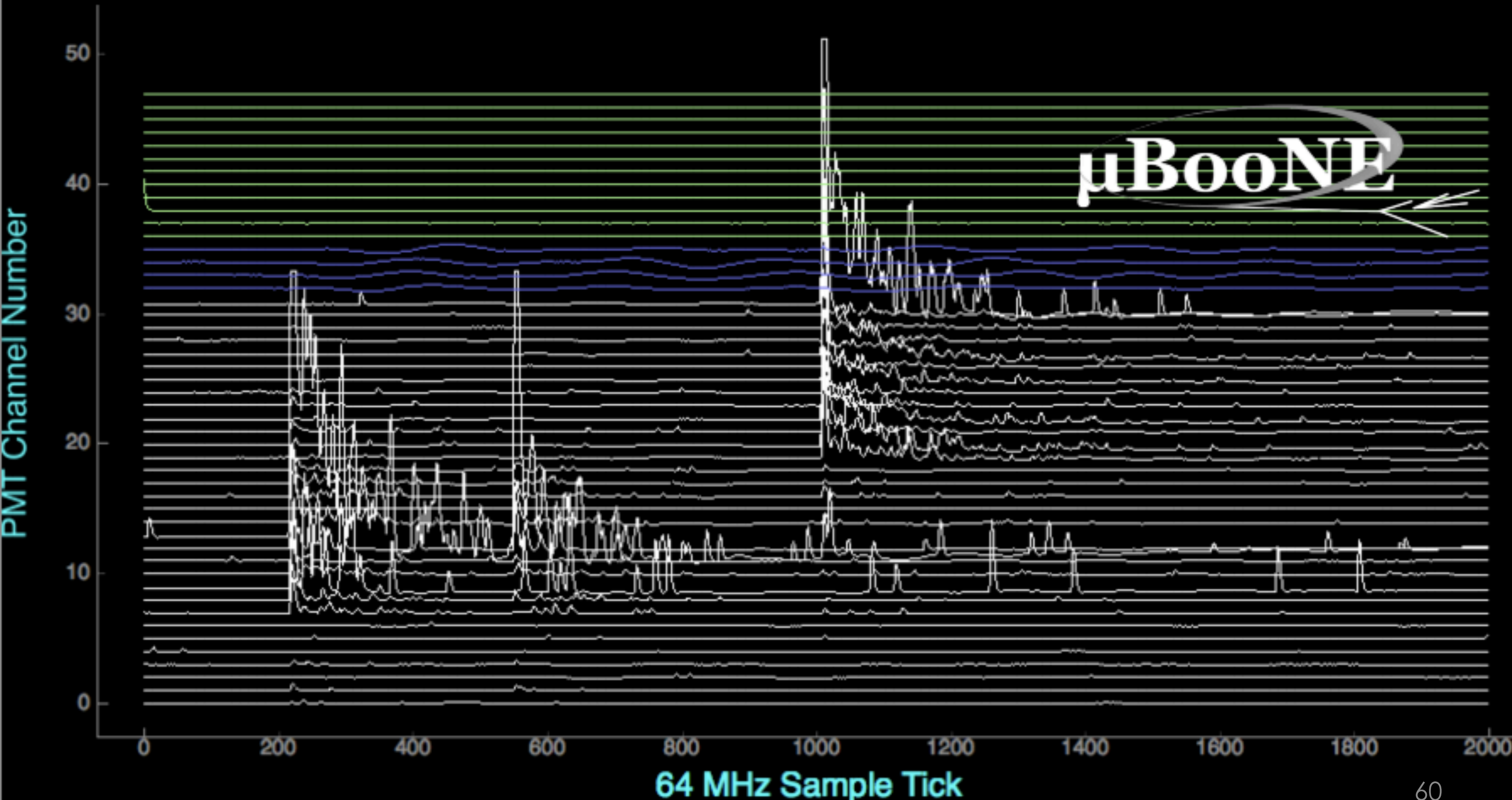
PMT's turned on same day!

Coincident pulses seen on adjacent PMTs



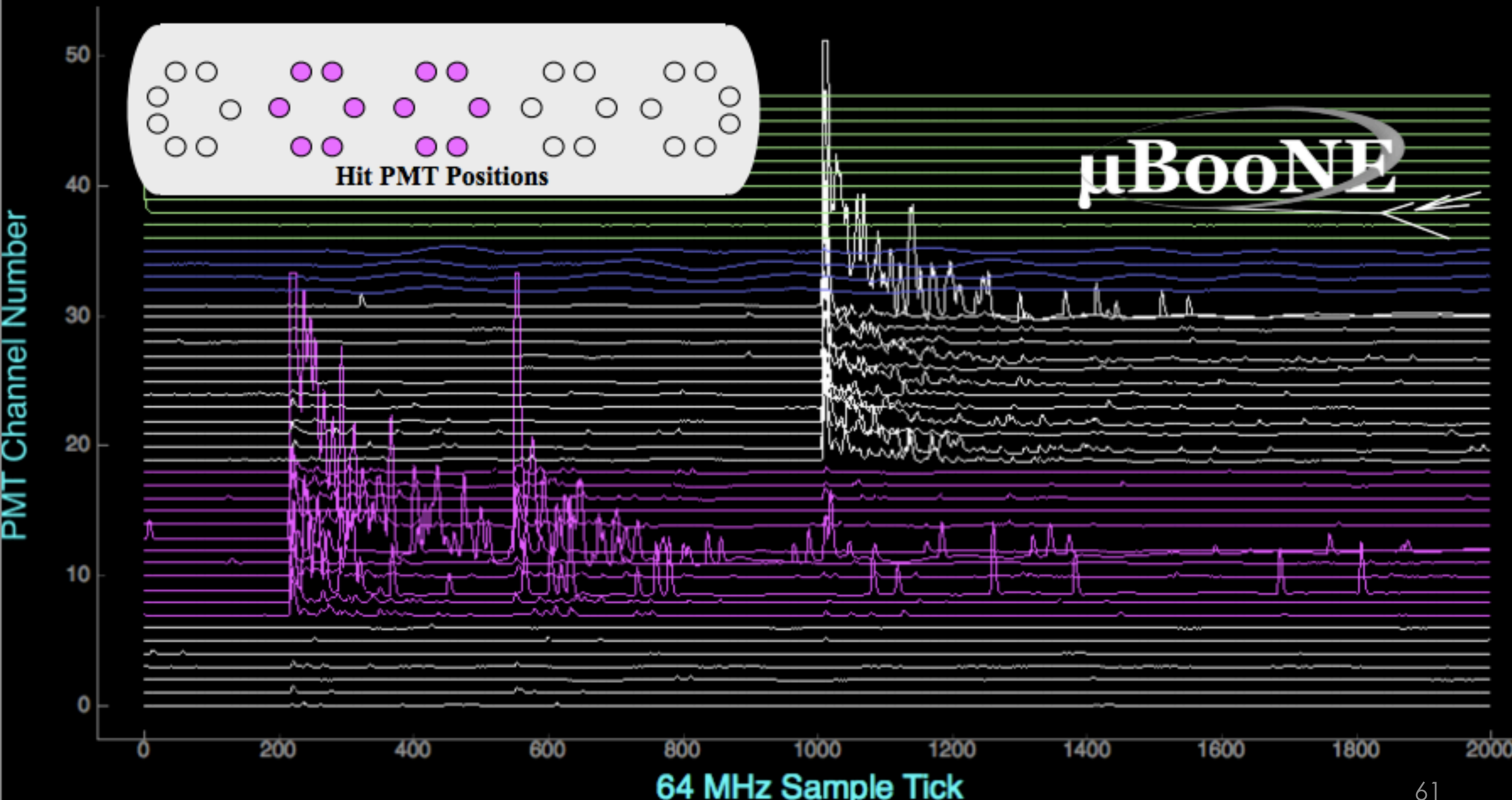
# MicroBooNE commissioning highlights

Days After Filling



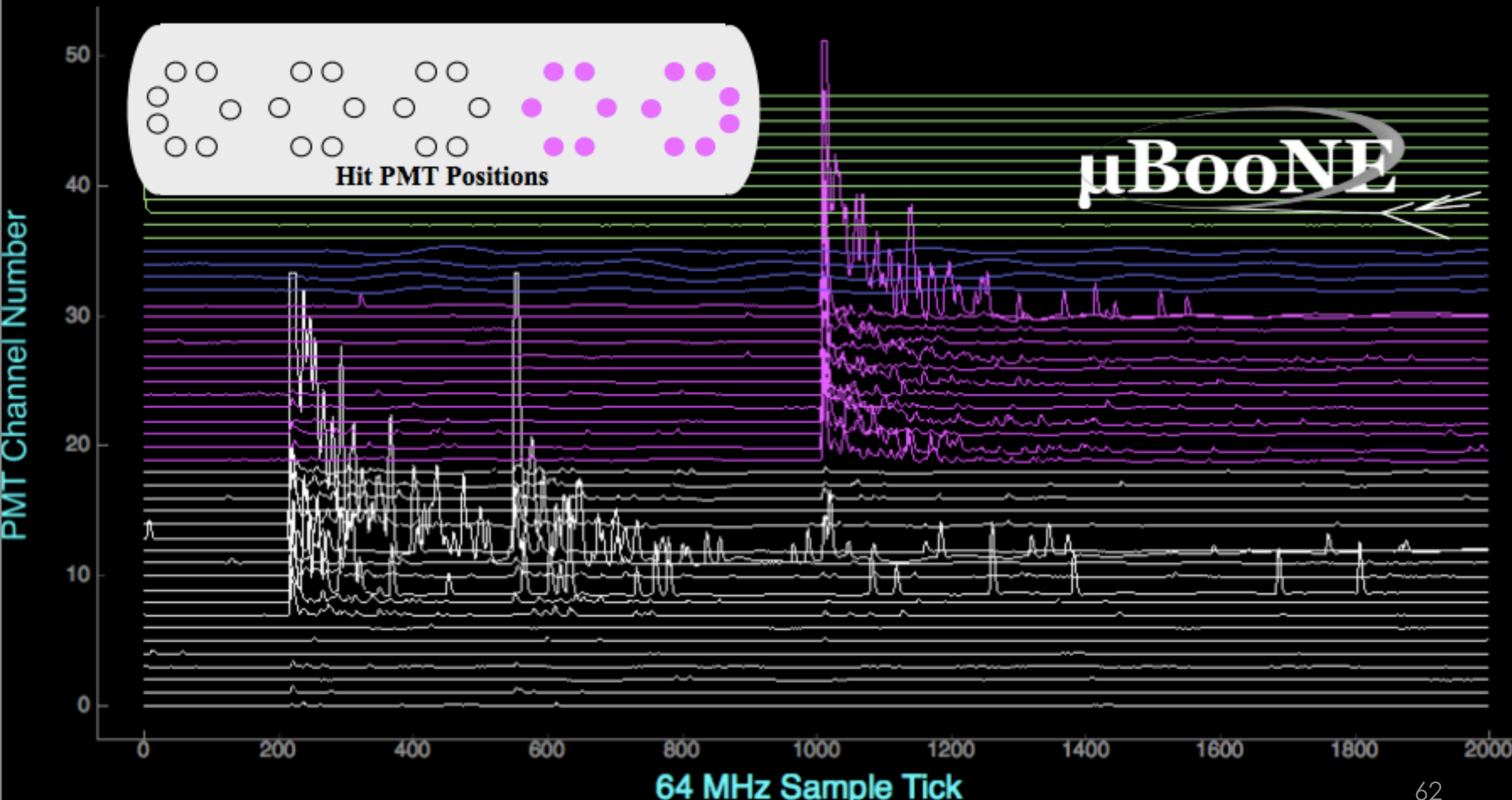
# MicroBooNE commissioning highlights

Days After Filling



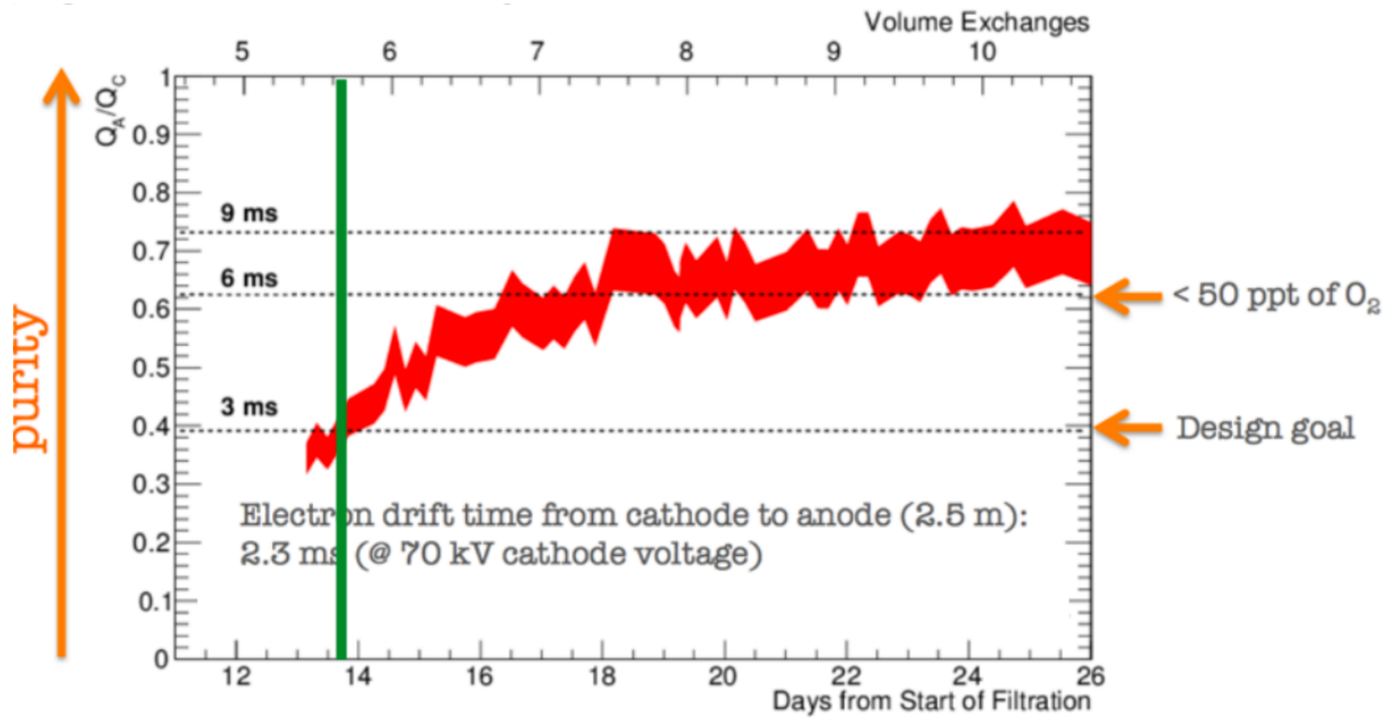
# MicroBooNE commissioning highlights

Days After Filling



# MicroBooNE commissioning highlights

4. Drift electron lifetime in liquid argon, after a two week liquid argon filtration process (5-6 volume exchanges):

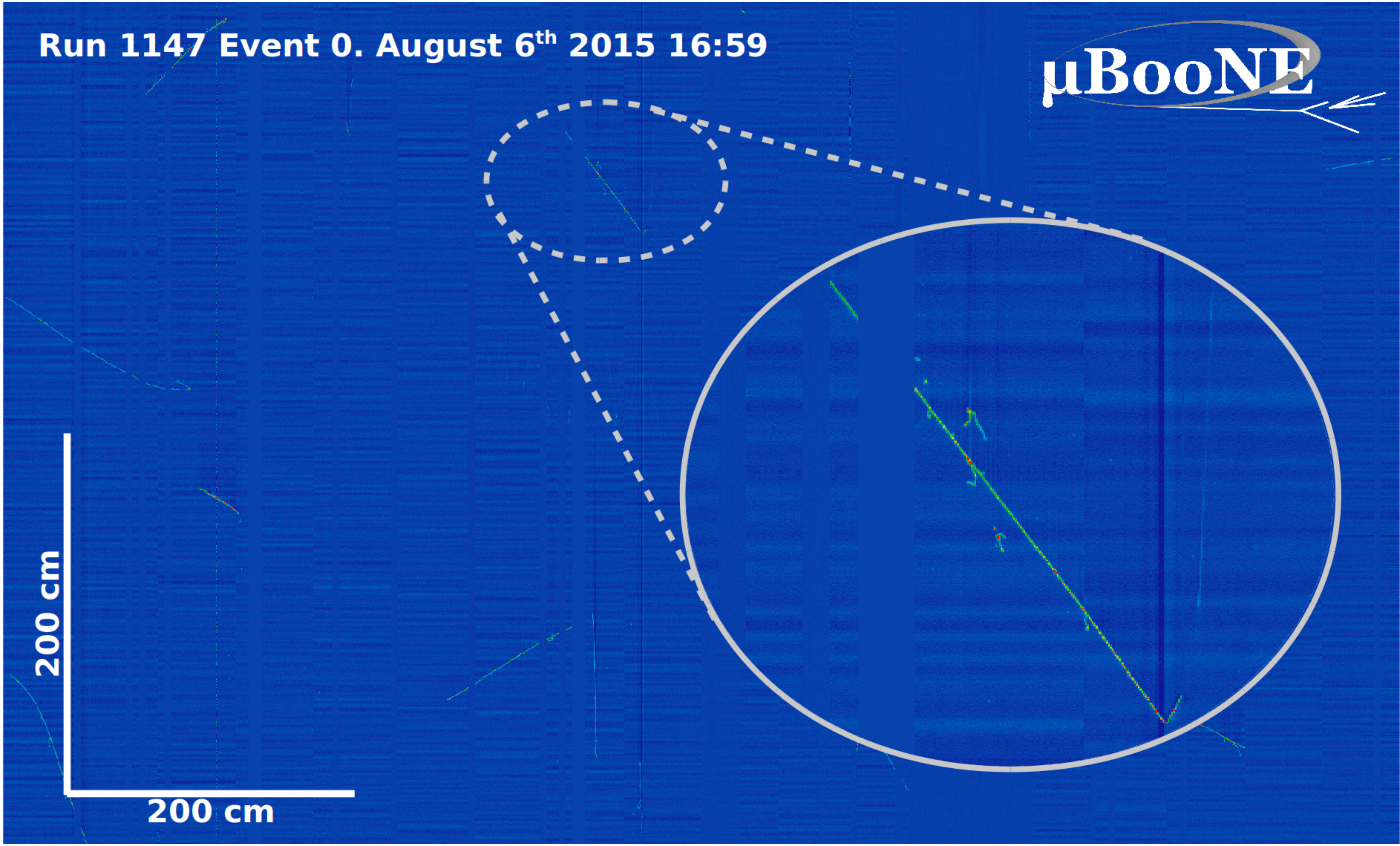



Achieved (surpassed!) one of our main R&D goals:
High purity without evacuation of a fully-instrumented cryostat

# MicroBooNE commissioning highlights

HV ramp-up: August 6, 2015

# MicroBooNE: First cosmic track data!



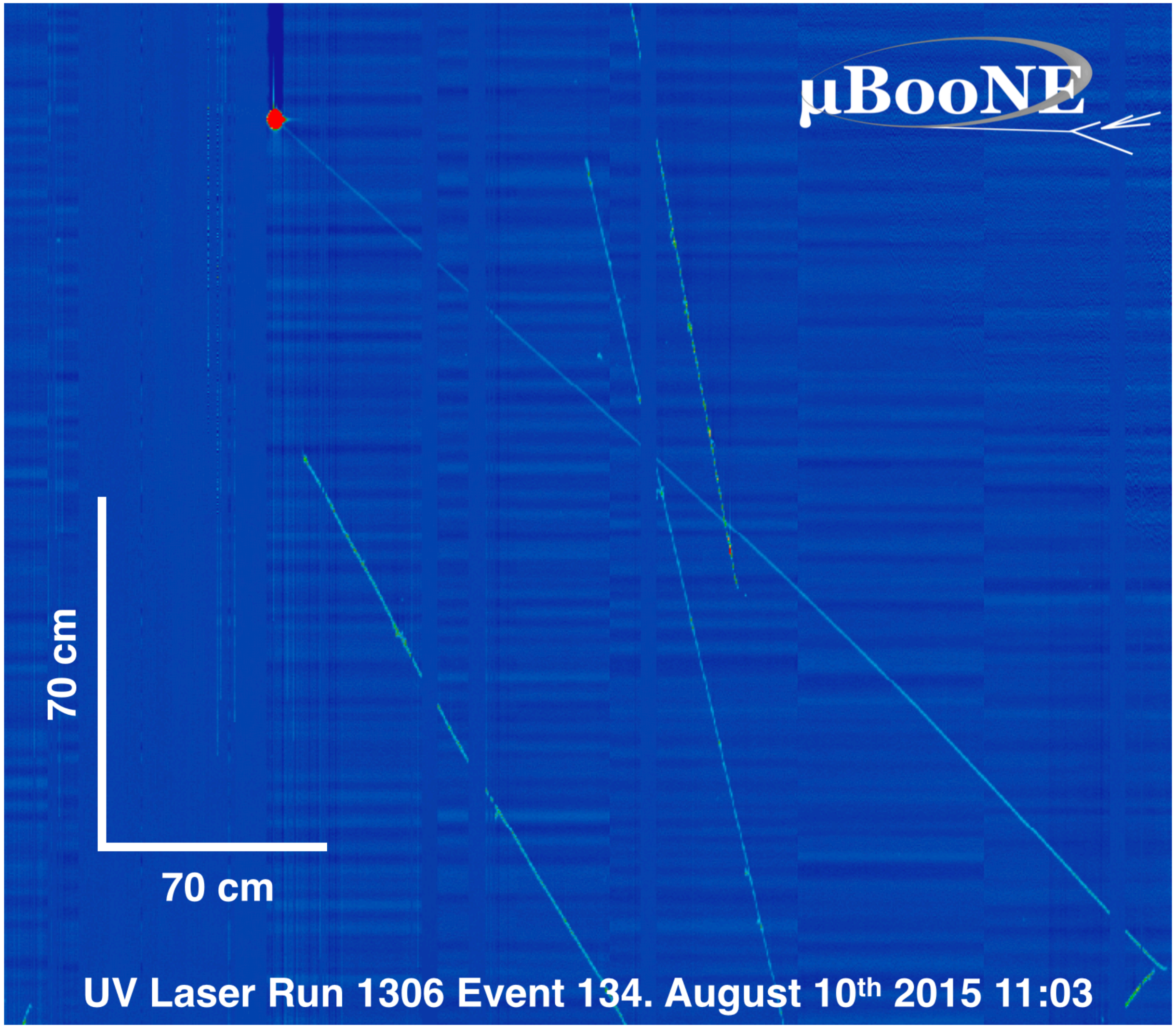

First MicroBooNE recorded cosmic event. Collection plane image.
Drift HV: 58 kV (half the design HV)

# MicroBooNE: Laser run data

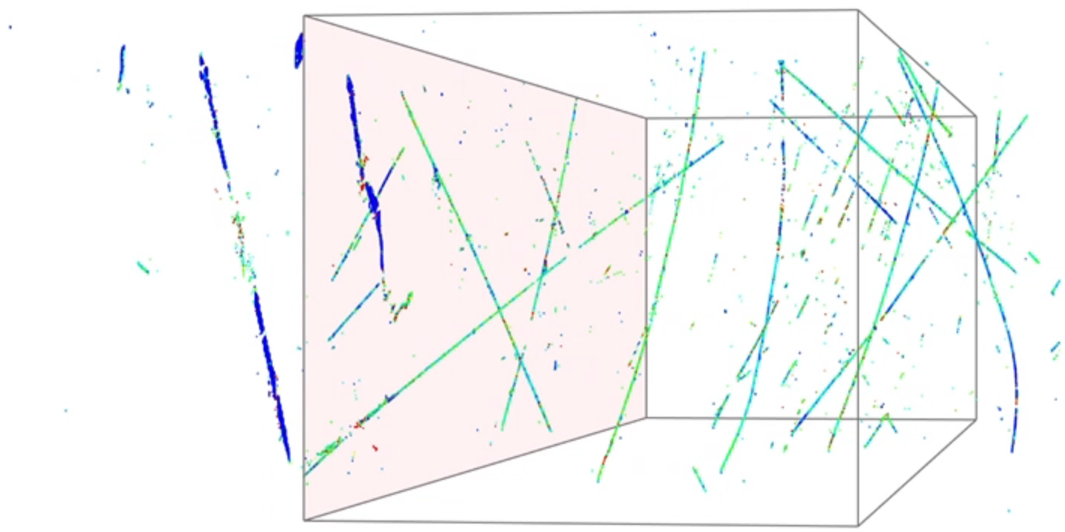
The two UV lasers produce tracks we know are straight

We can calibrate for space charge and other field distortions

Allows measurements of the electron drift lifetime



# Cosmic tracks automated 3D hit reconstruction

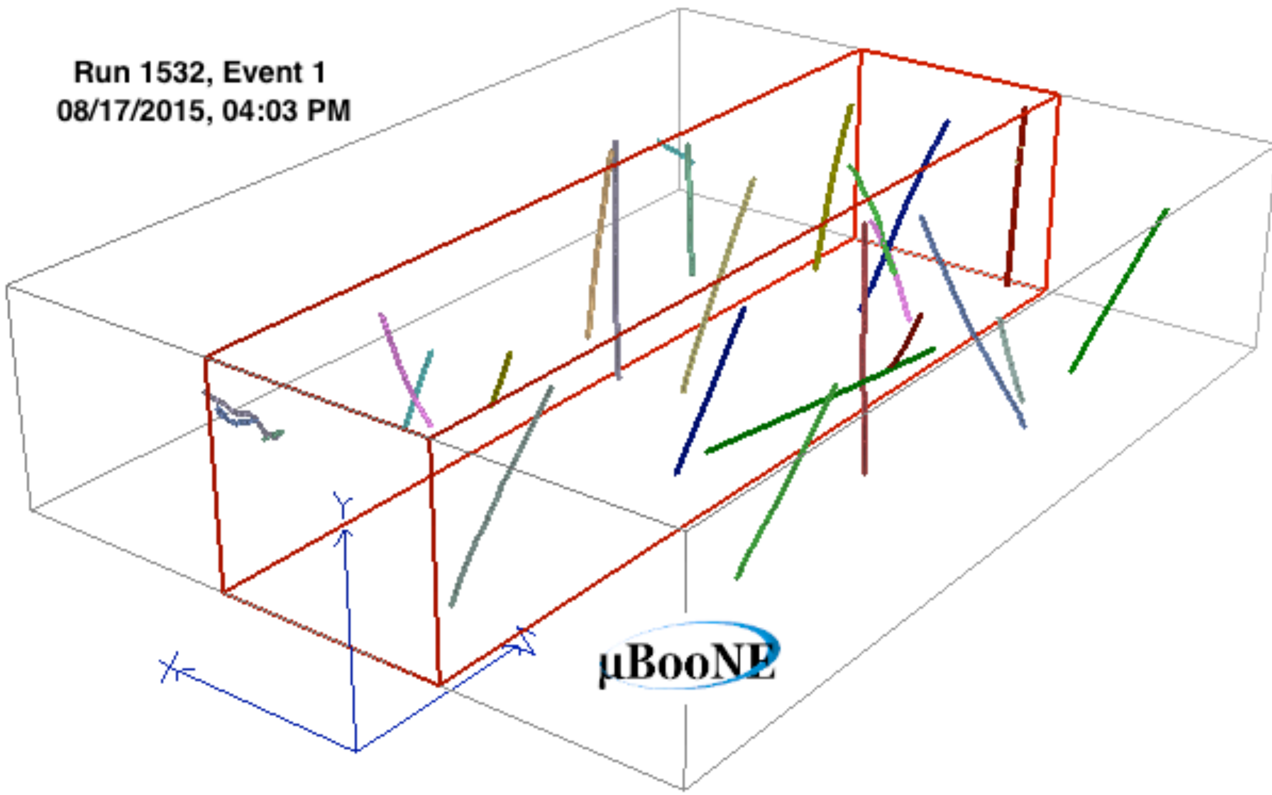


Reconstructed MicroBooNE Cosmic Data at 58 kV

# Cosmic tracks automated 3D reconstruction

LArSoft event display, showing 3D Tracks

Red wireframe represents the physical detector
Display shows the full readout time of 4.8 ms (longer than drift time)




Different colors are different tracks

Reconstructed MicroBooNE Cosmic Data at 58 kV

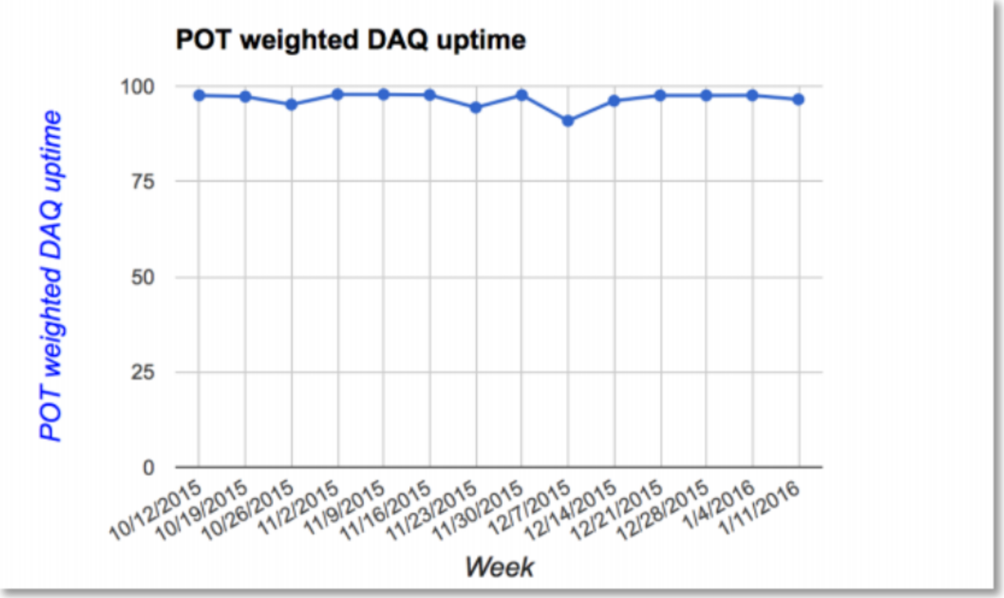
# MicroBooNE: Beam on!

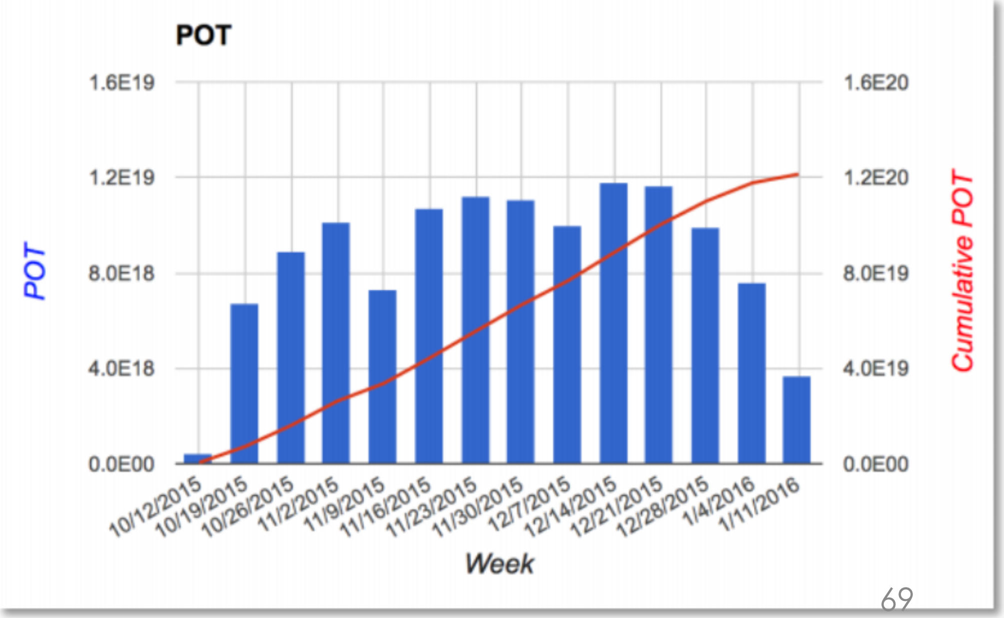
On **Oct. 15, 2015**, BNB neutrino beam was turned on!

Excellent detector and DAQ uptime since then.

DAQ typically running at >97% uptime (when receiving beam)

Typically running at 6 Hz with capability to run up to 10 Hz



# MicroBooNE: Beam on!

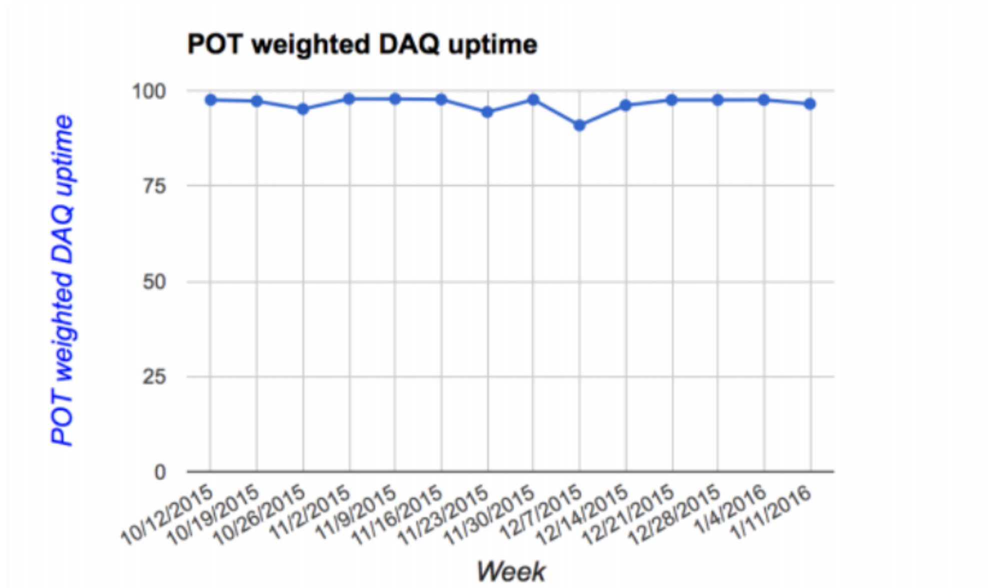
On **Oct. 15, 2015**, BNB neutrino beam was turned on!

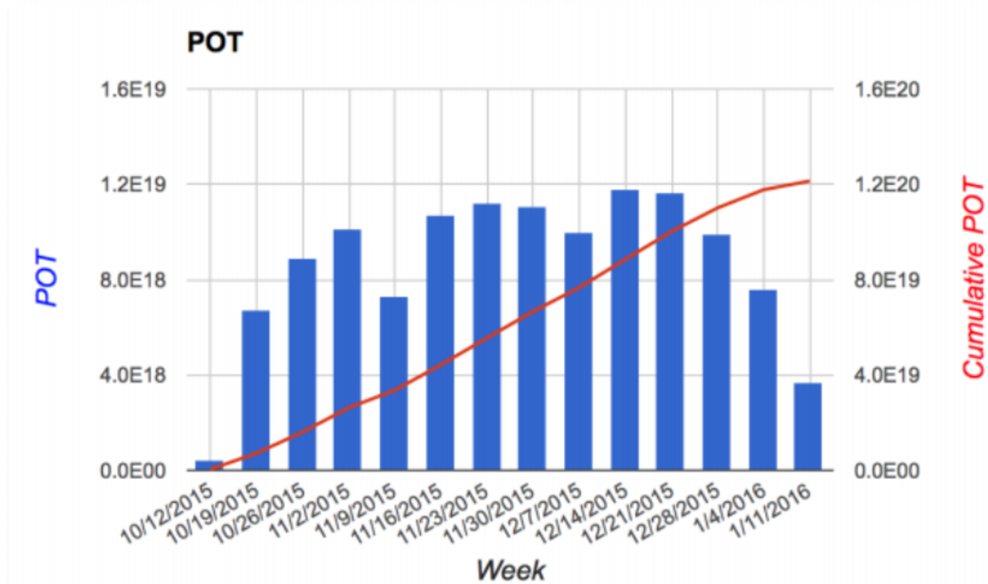
Excellent detector and DAQ uptime since then.

Collecting significant POT – months of 5Hz running!

We have already collected **more than 1.2E20 POT** since the start of data taking (~2x what we had projected)

Goal for physics analyses: 6.6E20 POT

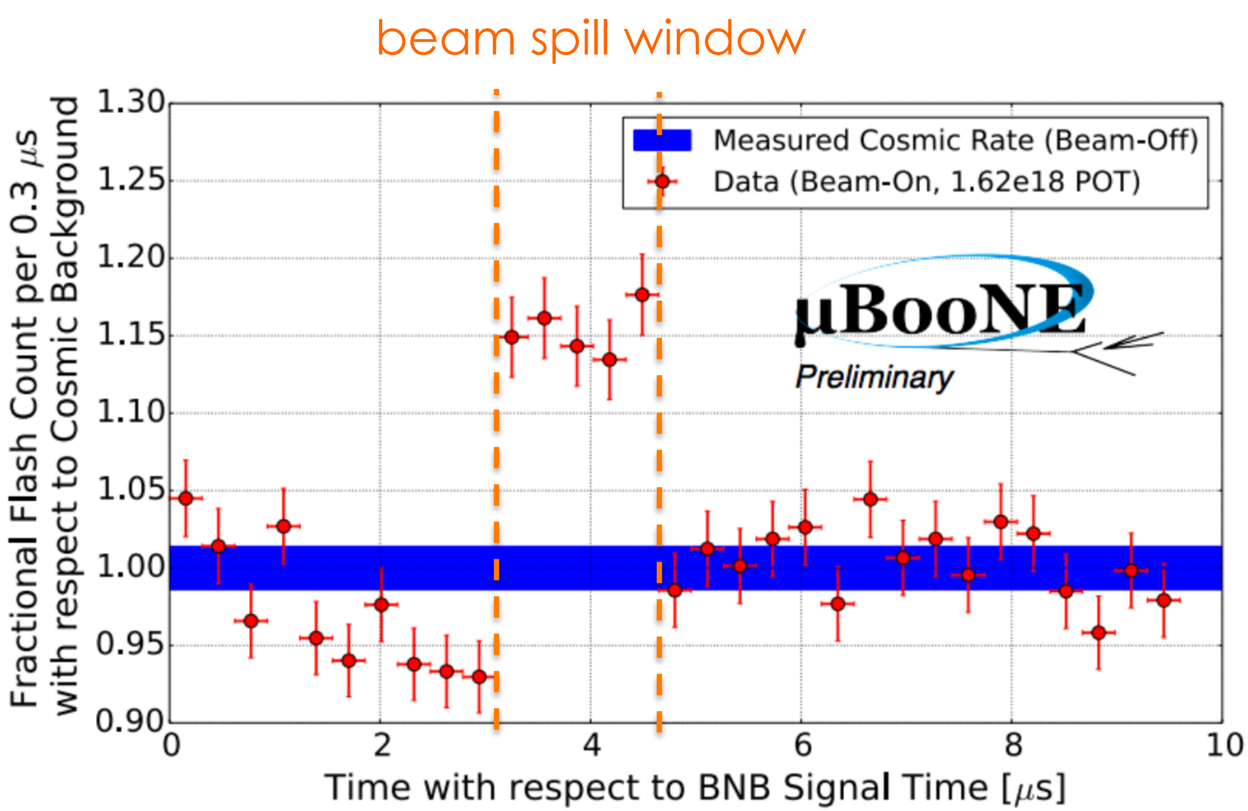


# Finding neutrinos…

Not every beam spill will produce a neutrino interaction in the detector. Most recorded beam events contain only cosmic induced tracks.

Cosmic muon tracks come randomly (flat distribution). Neutrinos come during the beam spill window (1.6 μs).




Timing of scintillation light signals detected with the PMT light system

# First fully automated reconstruction and selection

Reconstruct events in 2D & 3D

- Select neutrino-like topology
- Aiming for: minimum reconstruction effort, and high purity, but not high efficiency

Total number of events that pass the optical cuts and the 3D topological selection, along with the expected background of non-beam-induced interaction event:

MicroBooNE Preliminary
First $\nu$ identification $1.86 \times 10^{18}$ POT, BNB

| Number of events | Optical + 3D-based | Optical + 2D-based |
|---|---|---|
| Non-beam background (expected from off-beam measurements) | $4.6 \pm 2.6$ | $385 \pm 24$ |
| Total observed (during beam) | 18 | 463 |

## First fully automated reconstruction and selection

TPC neutrino ID possible with cuts on a few key quantities

For example, the analysis using **automated** 3D-reconstruction:

- Two or more reconstructed tracks with start points within 5cm of each other
- All tracks must be fully-contained
- Longest track must satisfy $\cos(\theta) > 0.8$
- >5sigma CL observation of neutrinos with the TPC!

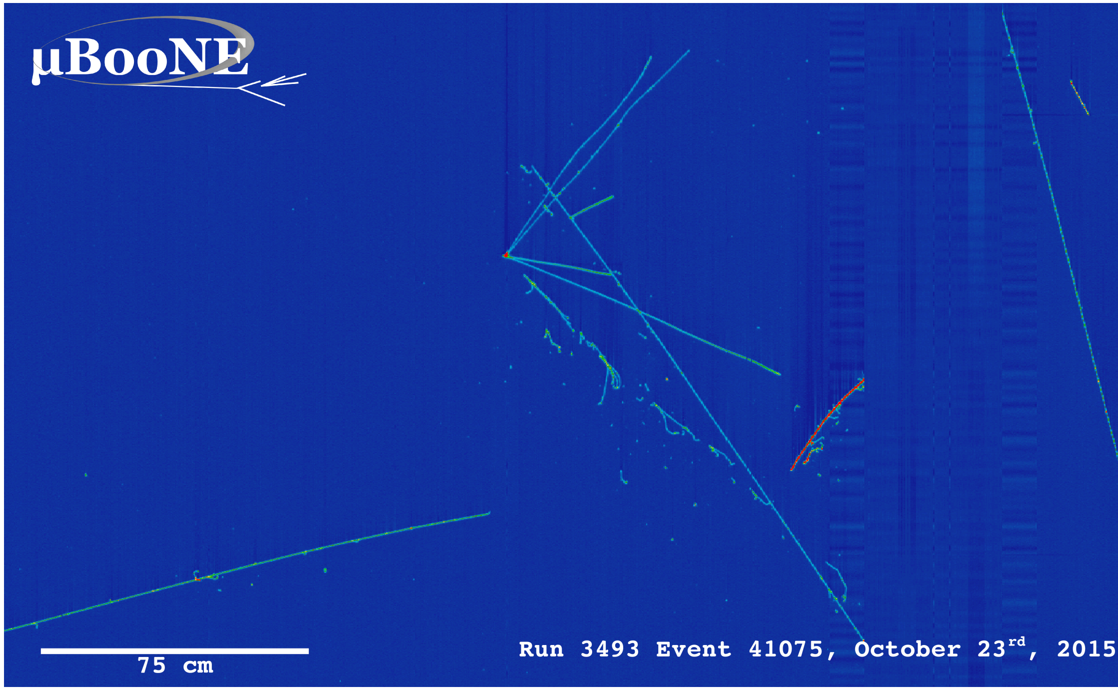
Have a similar **automated** algorithm for 2D reconstruction

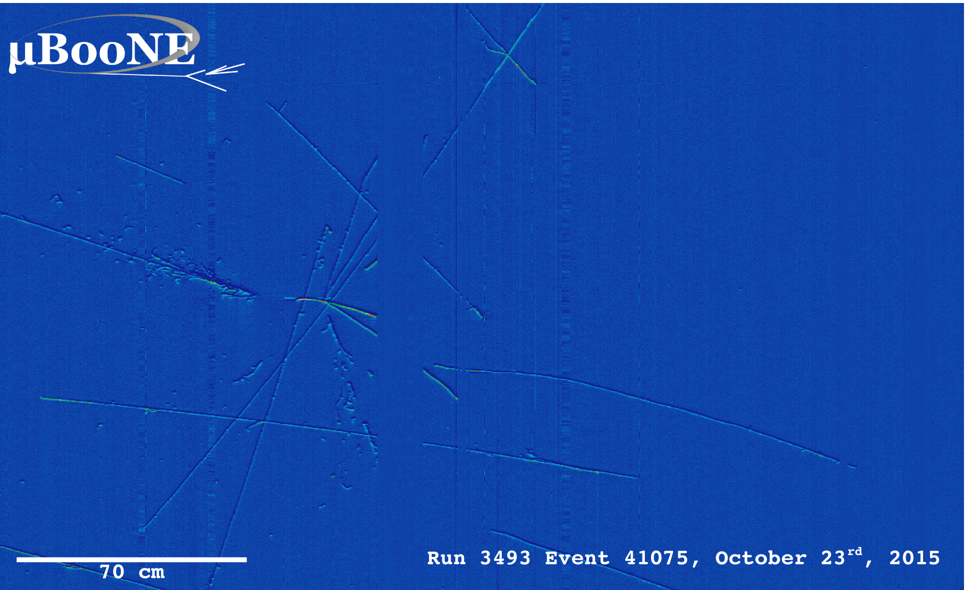
MicroBooNE Preliminary
First $\nu$ identification $1.86 \times 10^{18}$ POT, BNB

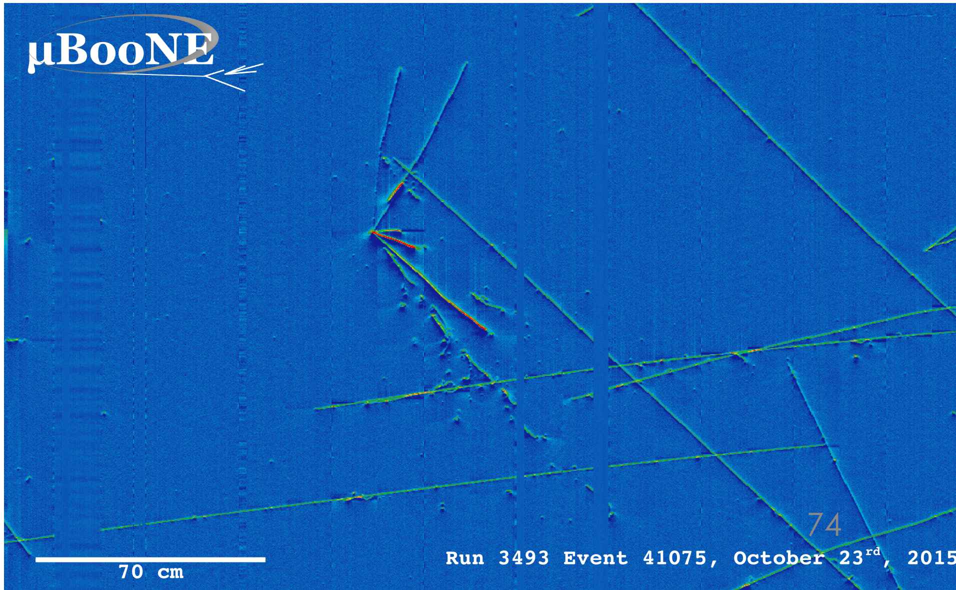
| Number of events | Optical + 3D-based | Optical + 2D-based |
|---|---|---|
| Non-beam background (expected from off-beam measurements) | 4.6 ± 2.6 | 385 ± 24 |
| Total observed (during beam) | 18 | 463 |

# First neutrino event candidates in MicroBooNE!

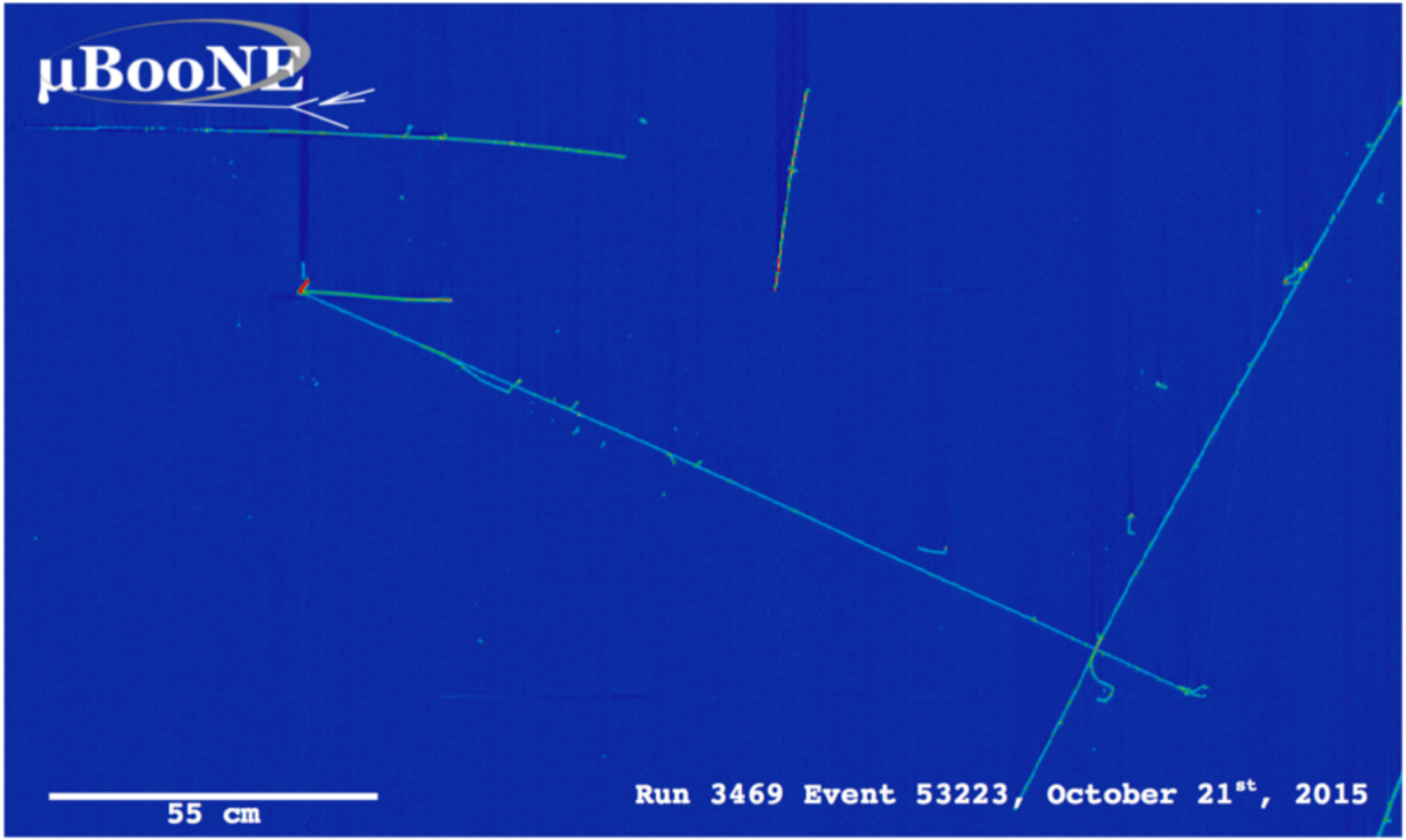
Press release on Nov. 2, 2015
(MicroBooNE's 8th birthday!)



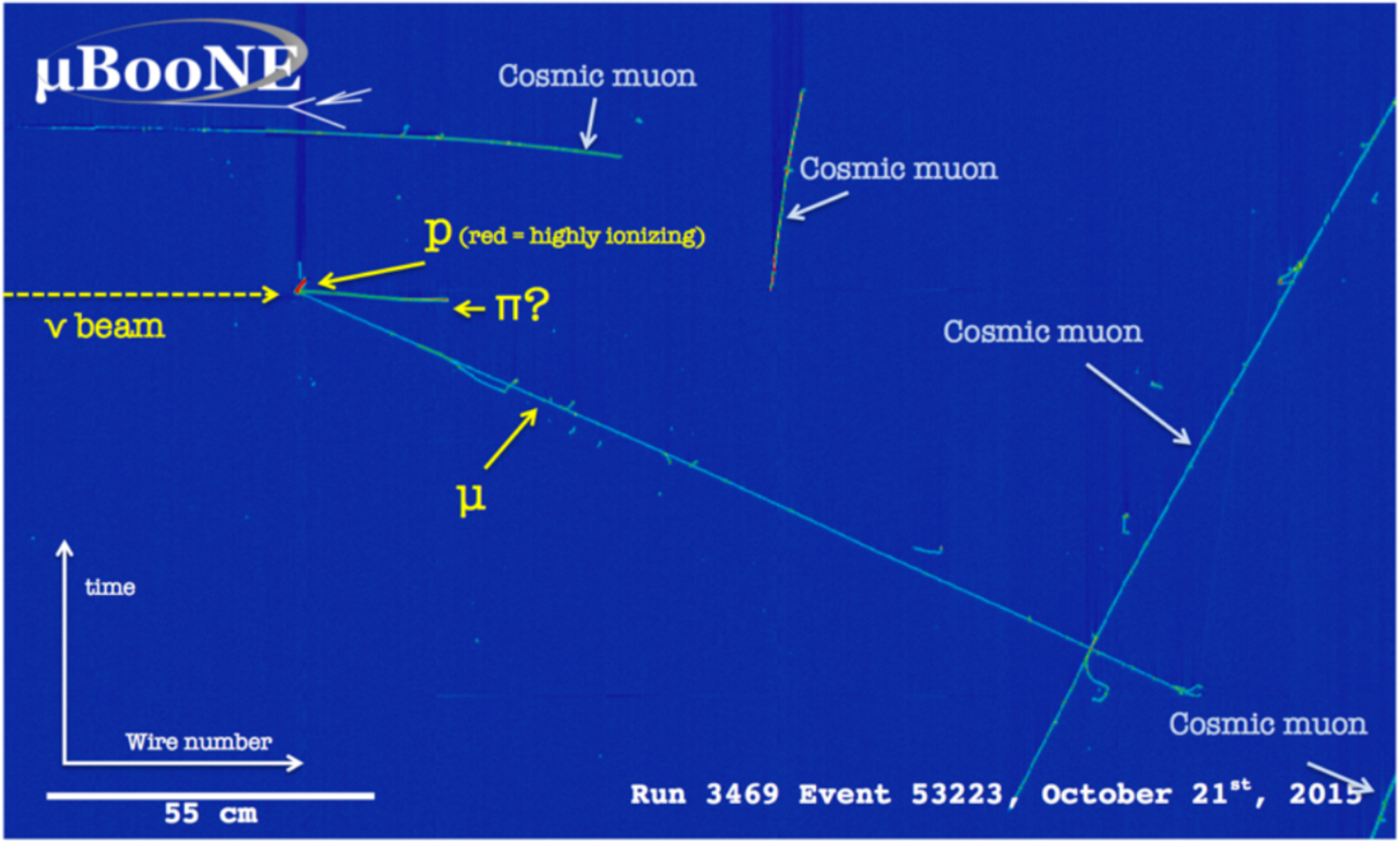



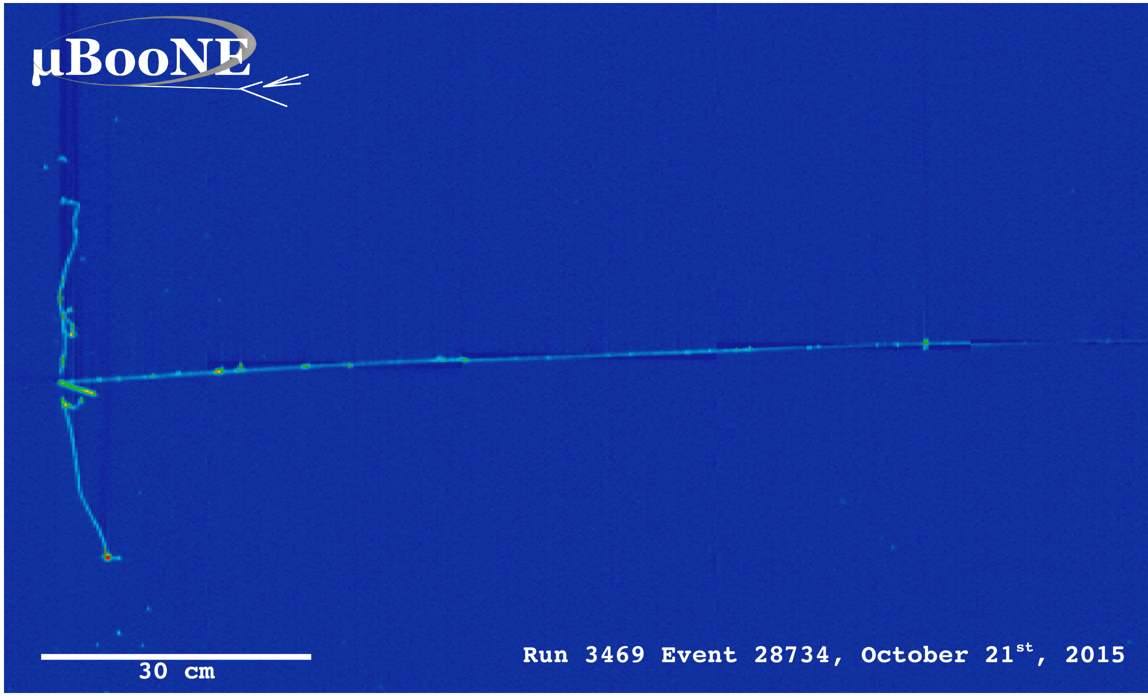
# First neutrino event candidates in MicroBooNE!

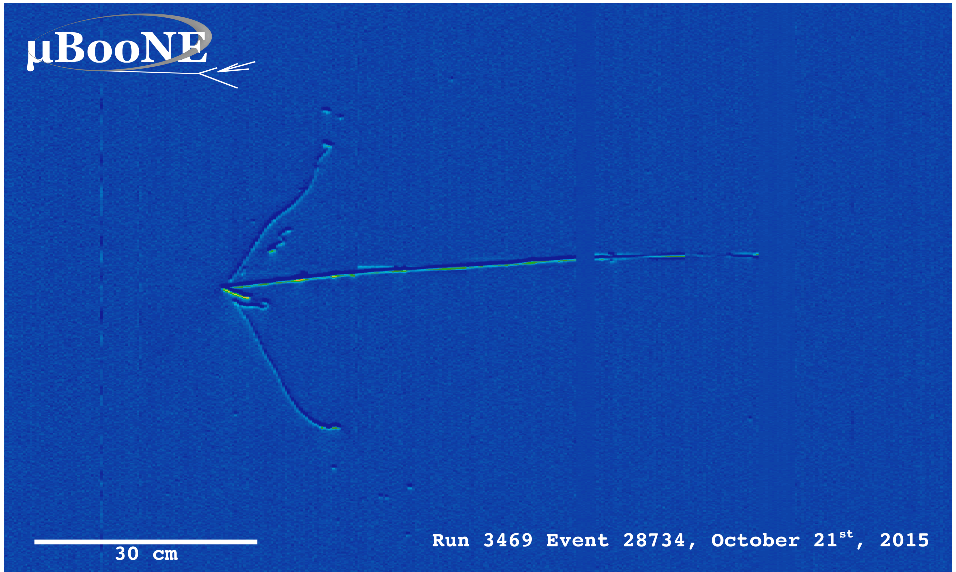


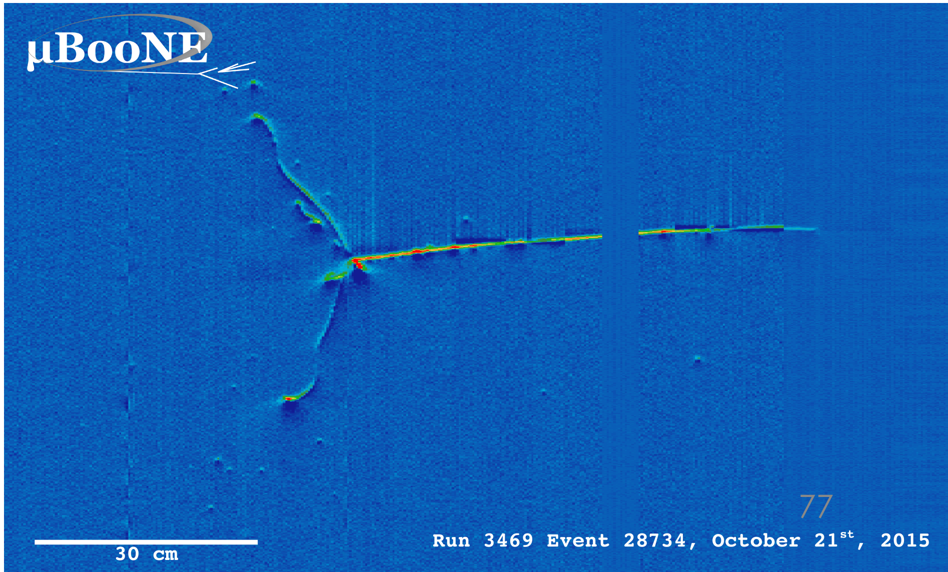
# First neutrino event candidates in MicroBooNE!



# First neutrino event candidates in MicroBooNE!



# Current status

Neutrino data is being collected as we speak.

Work ongoing to understand the detector
—Recombination
—Diffusion
—Lifetime measurements
—Field distortions

Reconstruction and analyses in development. Aiming for first cross-section results in time for summer conferences.

Detector operation upgrades:
—PMT trigger commissioning
—Continuous data readout (with lossy zero suppression) commissioning

# Latest ν's from MicroBooNE

MicroBooNE has successfully started operations and is observing beautiful neutrino interactions.

Fully-automated reconstruction is being optimized and physics analyses are being developed.

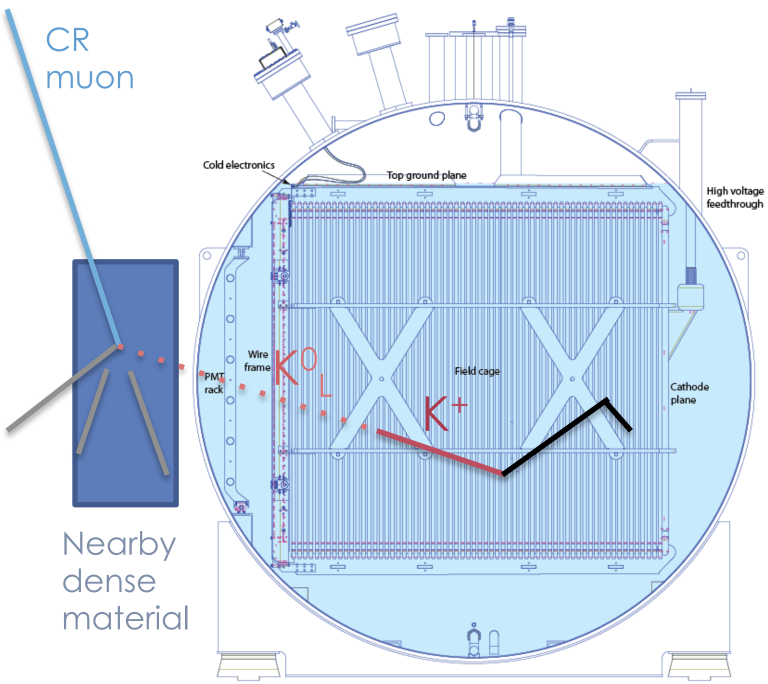
We will be able to produce interesting physics results using the data accumulated during the first few months of beam running.

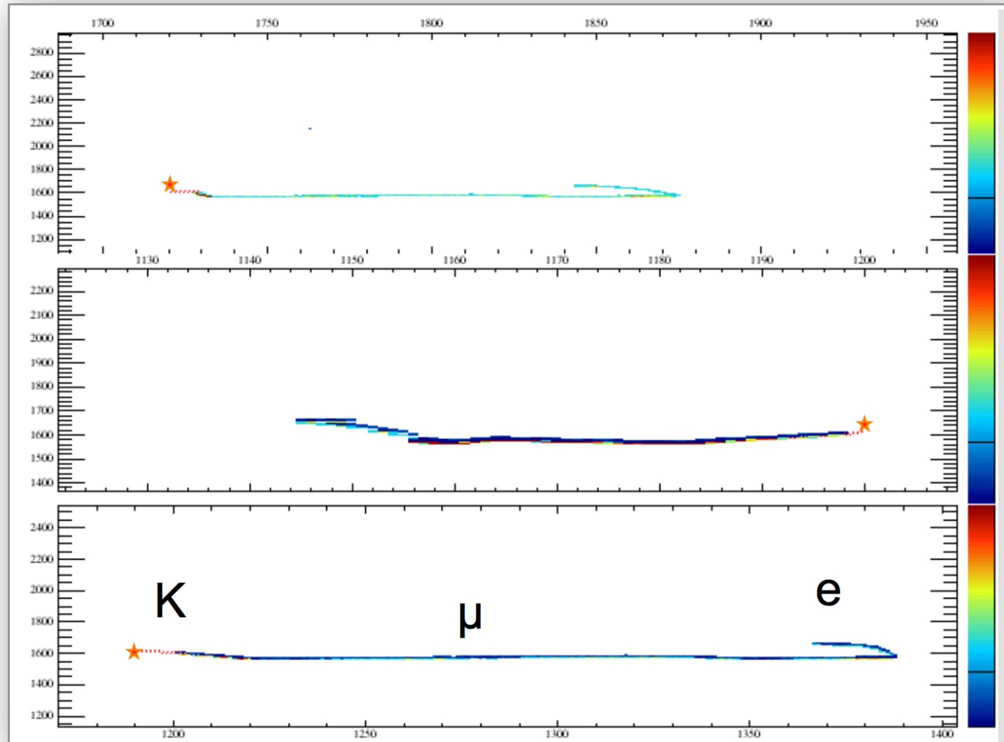
# Thank you!

# Background studies for BNV

## Additional physics opportunities (II):

- Investigate backgrounds to baryon number violating processes for larger (underground) detectors
- E.g. **proton decay $p \rightarrow K^{+}\bar{\nu}$**



# Background studies for BNV

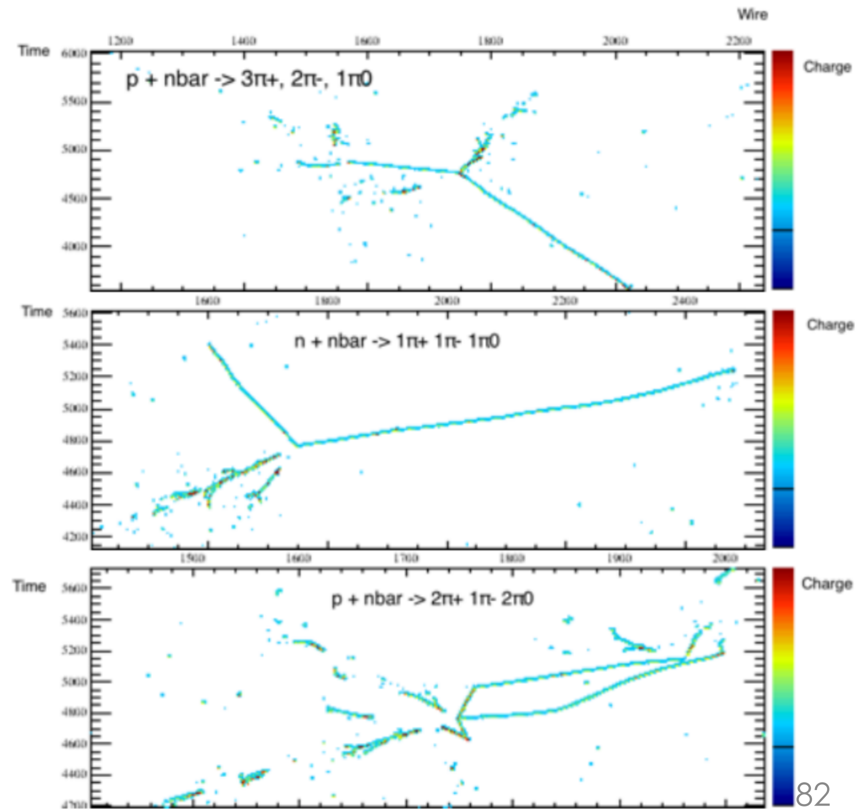
## Additional physics opportunities (II):

- Investigate backgrounds to baryon number violating processes for larger (underground) detectors
- E.g. **neutron-antineutron oscillation**

"Star event" topology:
multiple pions from
$\bar{n}$ annihilation with
nearby p or n (in Ar nucleus)

- Cannot look for this rare process with MicroBooNE; instead,
  - Develop reconstruction, particle ID & event selection.
- Use simulated events, cosmogenic backgrounds, high-energy neutrinos and in-situ data rates to test signal selection and background rejection.

Example events using $n - \bar{n}$ event generator with MicroBooNE simulation chain:



# Supernova neutrino detection

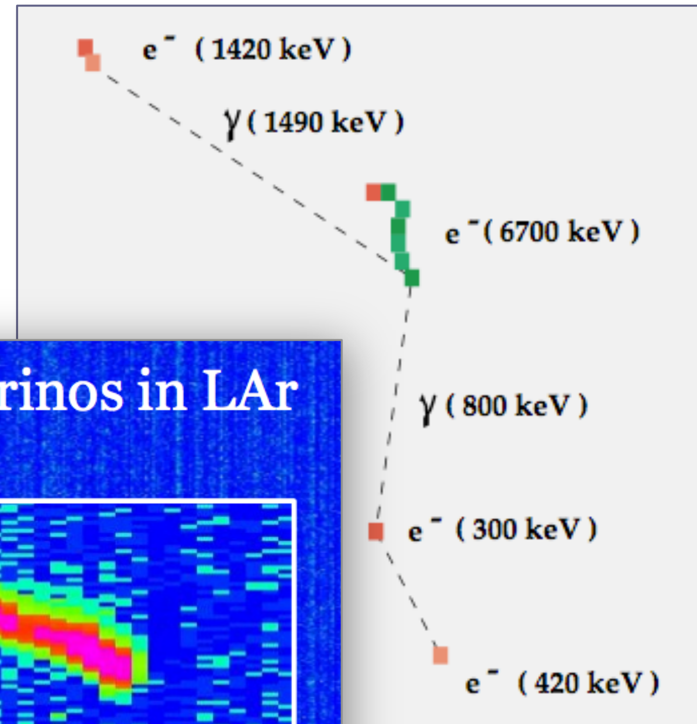
## Additional physics opportunities (I):

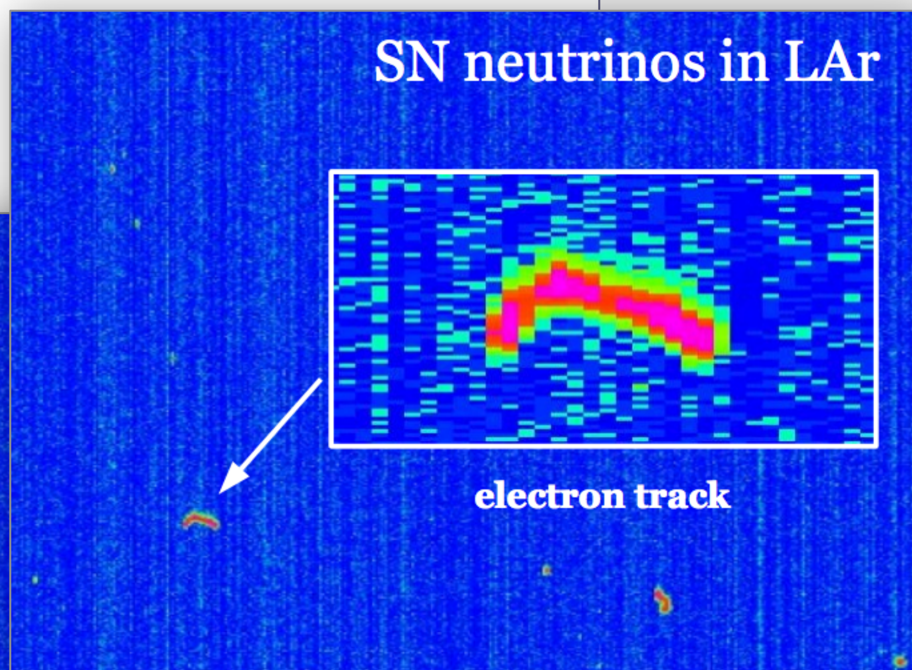
- Detect and study neutrinos from (nearby) supernova collapse

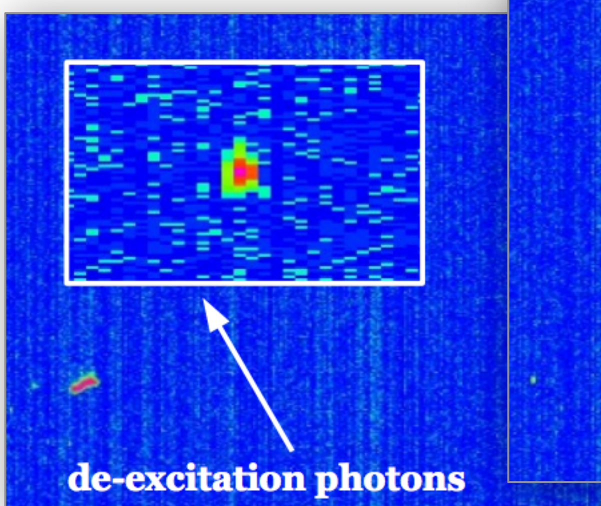
10kpc SN neutrino event rate predictions for MicroBooNE (60 tons):

~a few to a few tens of events!

Signature of low energy $\nu_e$ CC absorption on Ar



# Off-beam searches are challenging!

## A lot of data, which we cannot afford to record continually and without data loss

**Each MicroBooNE event: 160 MB**

8256 wires
read over 4.8 ms (3x drift size window)
digitized at 2 MHz
12-bit ADC (16-bit packets)

Per event, MicroBooNE will record 10x more data than ATLAS

Event rate of ~0.1-15 Hz
→ need **compression**:
Huffman (lossless) compression for beam/trigger provides sufficient (x ~few) reduction

**Being 100% live for SuperNova neutrino search: >30 GB/s !**

Solution:
Implement additional zero suppression to achieve x 80 reduction and only retain ~few hrs of data on tape at any time

## MicroBooNE commissioning highlights

TPC and Readout:
90% of channels operational
Three wire planes – redundant so even with 10% of channels not operational, we have >95% of the detector with 2 wire plane readout
Non operational wires largely due to unresponsive channels associated with ASICs in a bad state or consecutive channels grouped by ASIC or wire carrier board that are unresponsive

Cold Electronics:
Excellent performance at liquid argon temperatures
Signal to Noise of 40:1 (ICARUS: 10:1)

# MicroBooNE commissioning highlights

DAQ:
Excellent performance, typically running at >97% uptime (when receiving beam)
Typically running at 6Hz with capability to run up to 10 Hz
(5 Hz BNB + 0.7 Hz Numi + ~0.2 Hz external triggers)

Electrical Integration:
Comprehensive noise studies to understand and eliminate noise sources.
Some eliminated, others mitigated in software.

Drift HV:
Running at 70kV – below design voltage but operationally fine, given excellent purity

PMTs:
All operational and running at design voltages

Muon tagger system:
Operational and regular runs with tagger for calibration data

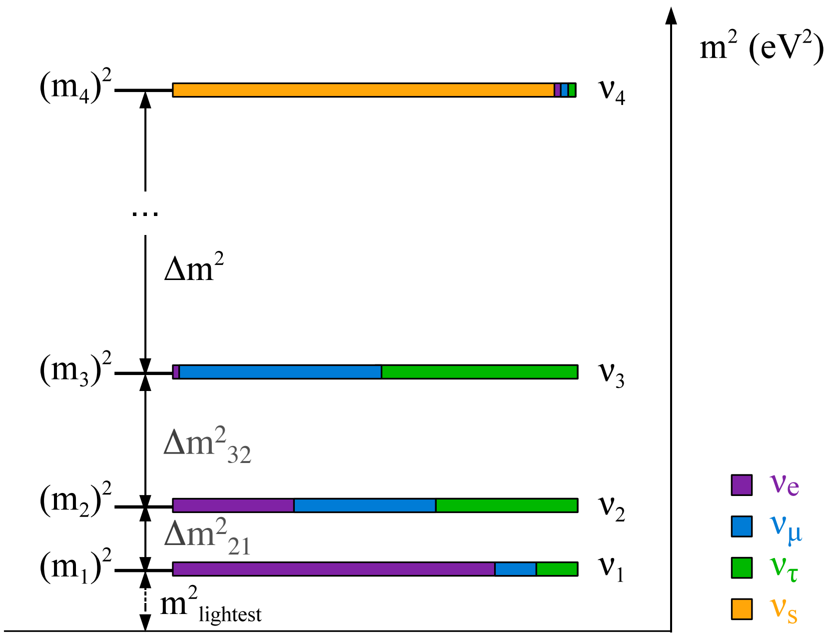
Laser system:
Operational – images coming up

# Possible interpretation: sterile neutrino

Additional neutrino “flavor” (and mass) state which has **no weak interactions** (through the standard W/Z bosons)

Additional mass state is assumed to be produced through mixing with the standard model neutrinos

→ Can affect neutrino oscillations through mixing



# Sterile Neutrino Oscillation Formalism

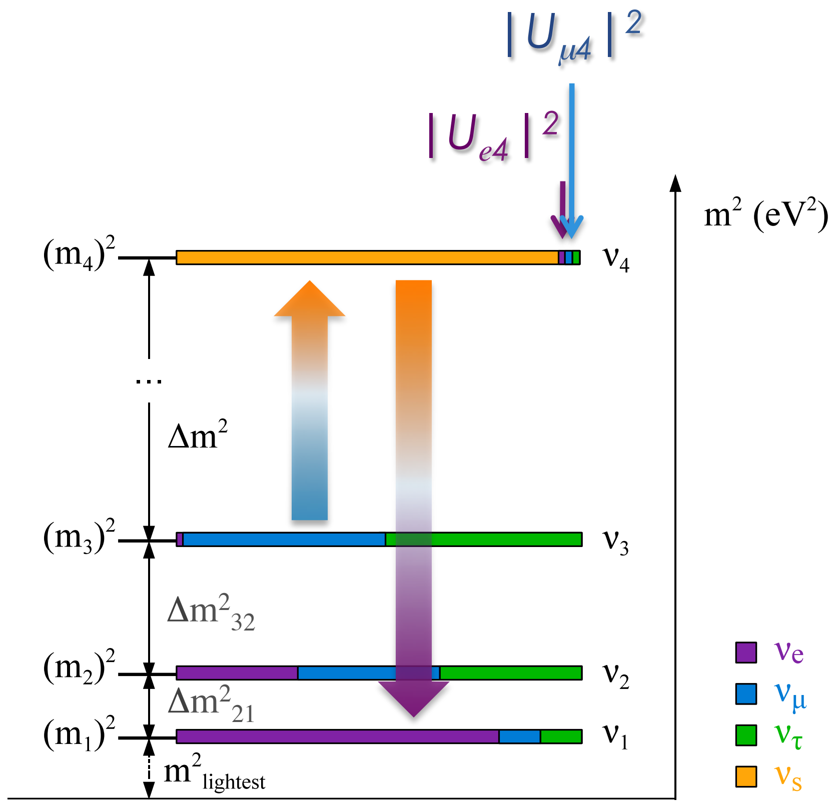
**Oscillation effects:**

$\nu_\mu \rightarrow \nu_e$ appearance*:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27 \Delta m^2 L/E)$$

$$\hookrightarrow \quad 4|U_{e4}|^2 |U_{\mu 4}|^2$$

**Explains LSND result but needs independent confirmation!**




(3+1)

*Approximation: $m_1, m_2, m_3 << m_4 \rightarrow m_1, m_2, m_3 = 0$

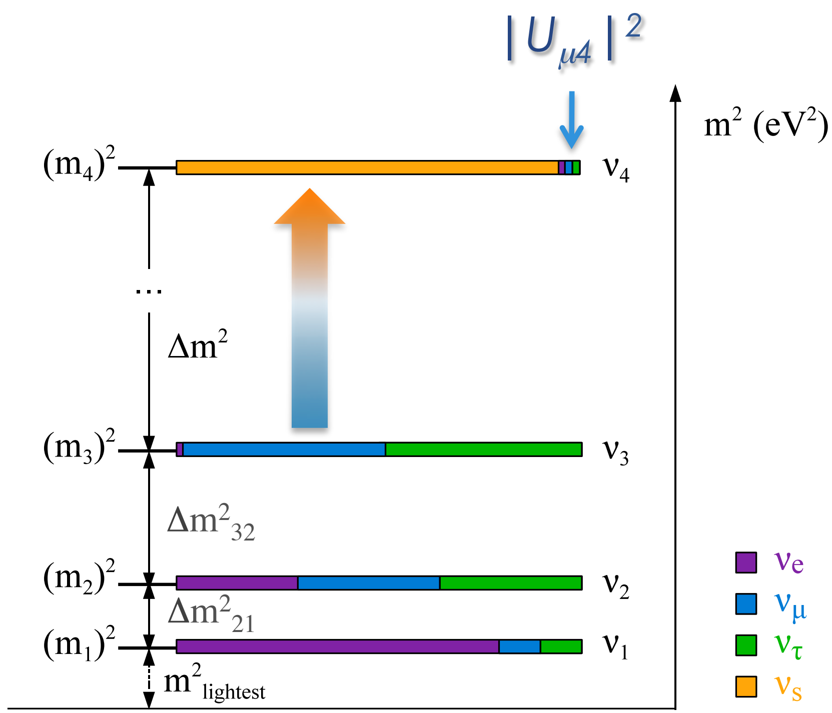
# Sterile Neutrino Oscillation Formalism

**$\nu_\mu \rightarrow \nu_e$ appearance implies $\nu_\mu$ and $\nu_e$ disappearance!**

$\nu_\mu$ disappearance*:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\vartheta_{\mu\mu} \sin^2(1.27\Delta m^2 L/E)$$

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu 4}|^2\left(1-|U_{\mu 4}|^2\right)$$




(3+1)

*Approximation: $m_1, m_2, m_3 \ll m_4$ → $m_1, m_2, m_3 = 0$

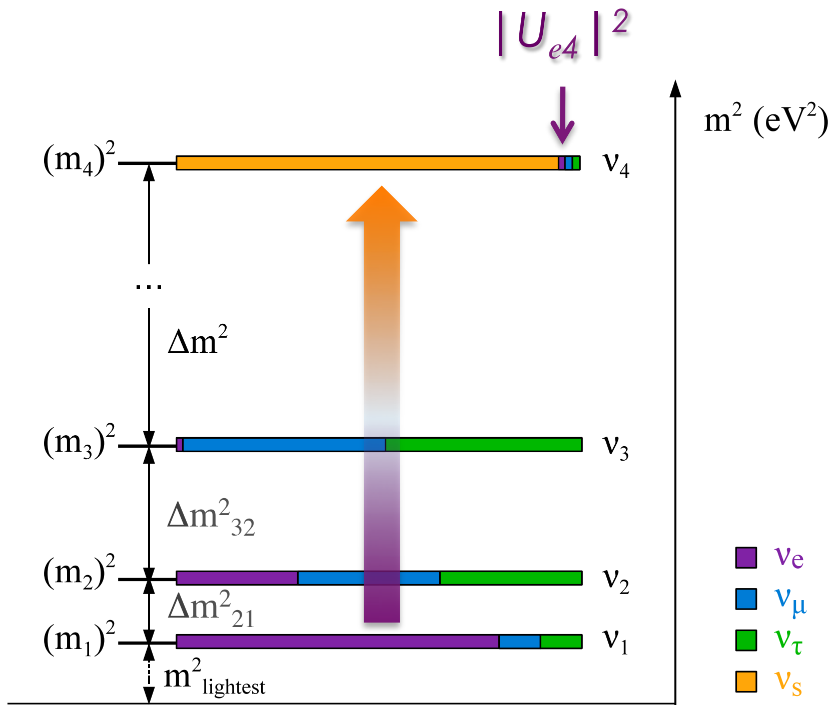
# Sterile Neutrino Oscillation Formalism

**$\nu_\mu \rightarrow \nu_e$ appearance implies $\nu_\mu$ and $\nu_e$ disappearance!**

$\nu_e$ disappearance*:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27\Delta m^2 L/E)$$

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2\left(1-|U_{e4}|^2\right)$$

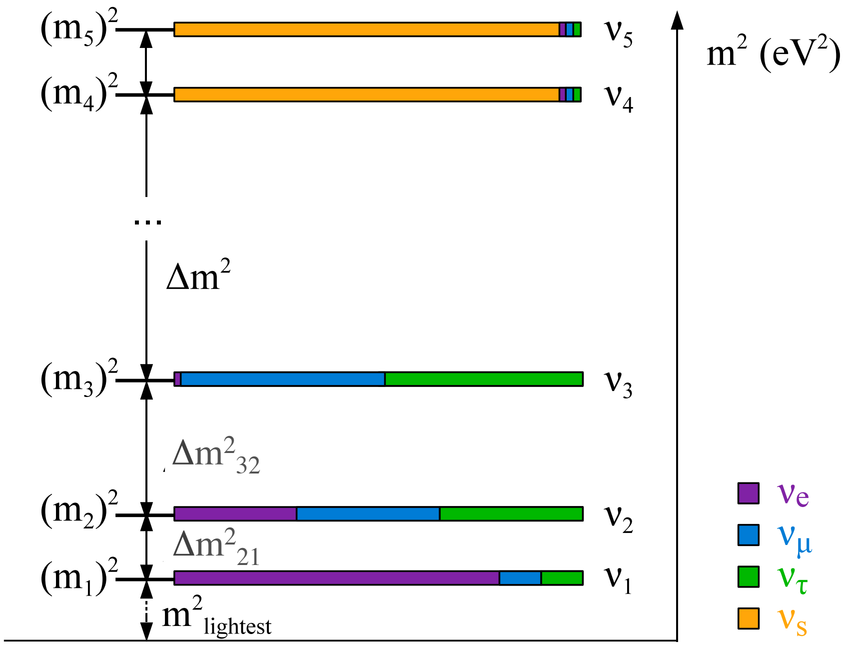



(3+1)

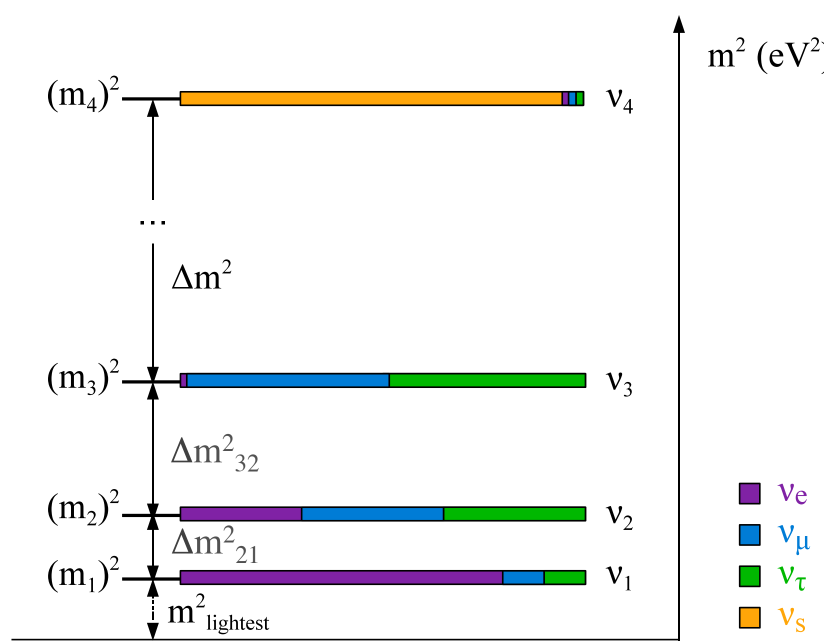
*Approximation: $m_1, m_2, m_3 \ll m_4$ → $m_1, m_2, m_3 = 0$

# Extended models: E.g. CP violation

**Can have more than one new state…**




(3+2)




(3+1)

# Extended models: E.g. CP violation

Disappearance:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2) \cdot (|U_{\alpha 4}|^2 \sin^2 x_{41} + |U_{\alpha 5}|^2 \sin^2 x_{51}) + |U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 x_{54}]$$

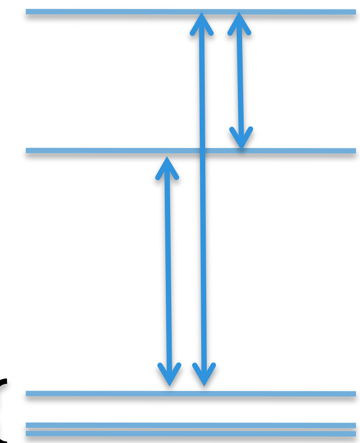
Appearance:

$$P(\nu_\alpha \to \nu_{\beta \neq \alpha}) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 x_{41} + 4|U_{\alpha 5}|^2 |U_{\beta 5}|^2 \sin^2 x_{51} + 8|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \sin x_{41} \sin x_{51} \cos(x_{54} - \phi_{45})$$

$$x_{ji} \equiv 1.27 \Delta m^2_{ji} L/E$$

CPV phase

assumed degenerate {

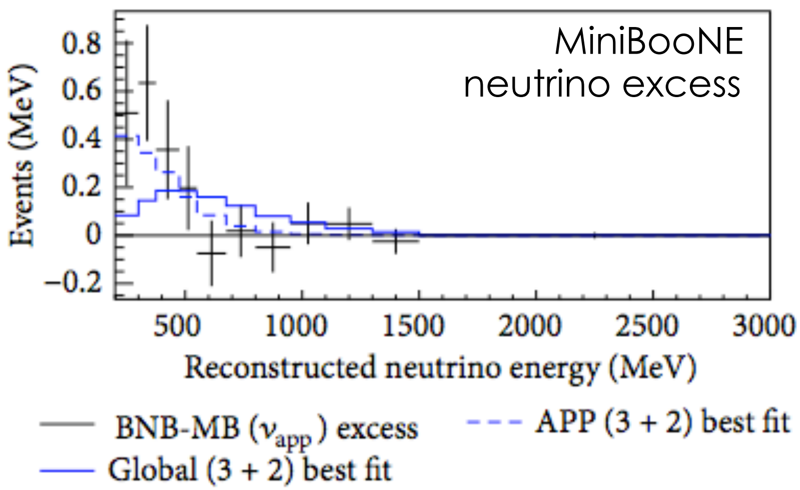


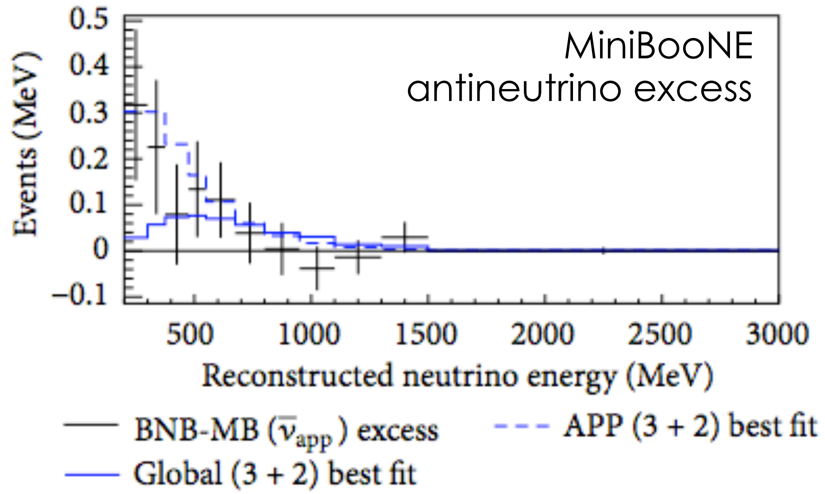
→ 2 effective $\Delta m^2$

(3+2) is attractive because of **CP violation**

# Extended models: E.g. CP violation

(3+2) global best fit




**(3+2) with CP violation cannot explain MiniBooNE low E excess, unless we throw out disappearance constraints!**

[Conrad, Ignarra, GK, Shaevitz, Spitz, Adv.High Energy Phys. 2013 (2013) 163897]