MicroBooNE and Short Baseline Neutrino Program at Fermilab

Kazuhiro Terao @ Columbia University
on behalf of
MicroBooNE & SBN Program

NuFact 2015

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NEVIS LABORATORIES

Fermilab

MicroBooNE and Short Baseline Neutrino Program at Fermilab

Outline

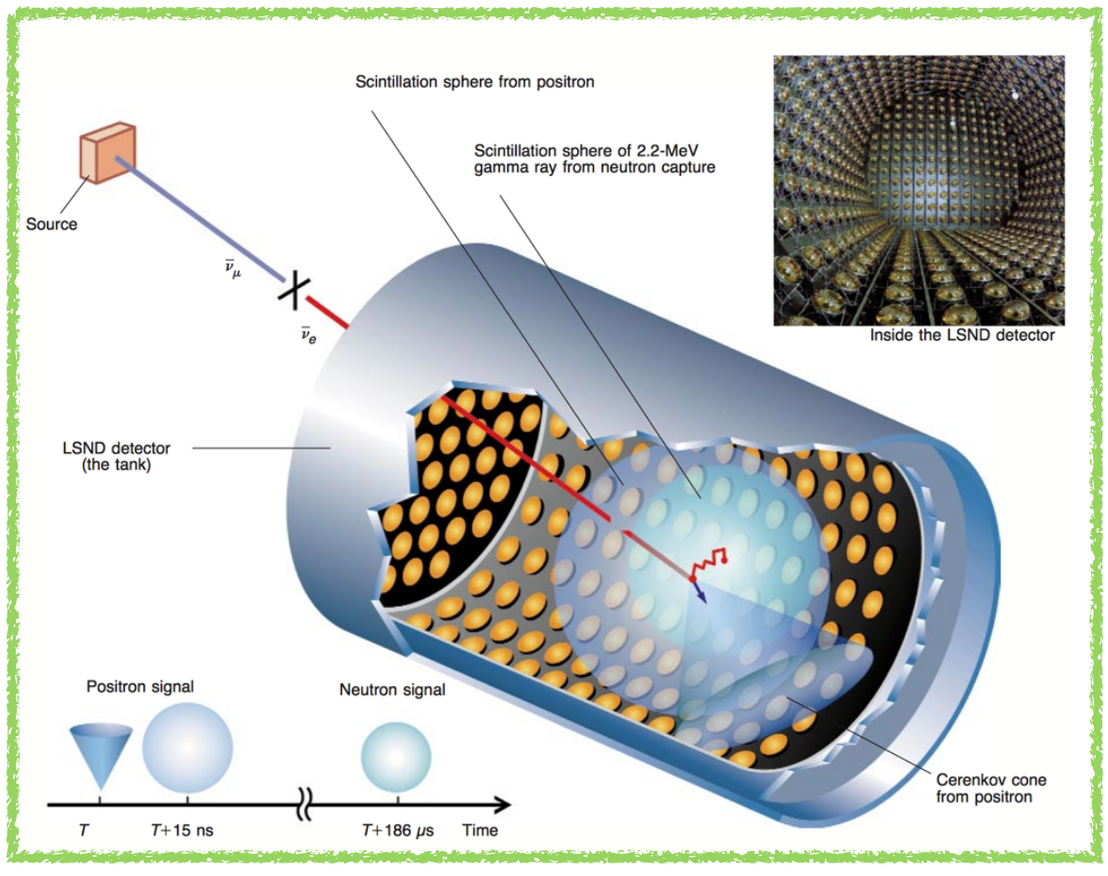
- Sterile Neutrinos: Physics Motivations
- MicroBooNE: LArTPC Experiment
- Short Baseline Neutrino Program
- Breaking News From MicroBooNE
- Summary

"Sterile Neutrino" : High Δm^2 Oscillation

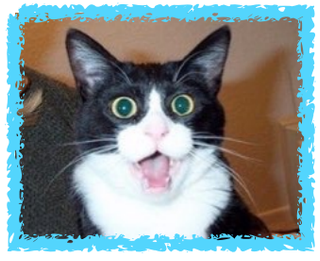
- **Liquid Scintillator Neutrino Detector (LSND)**
  - Oscillation mode: $\bar{\nu}_\mu \Rightarrow \bar{\nu}_e$ ... **L/E ≃ *O* (1 m/MeV)**
  - Result ***can be interpreted*** as **oscillation at high Δm^2**

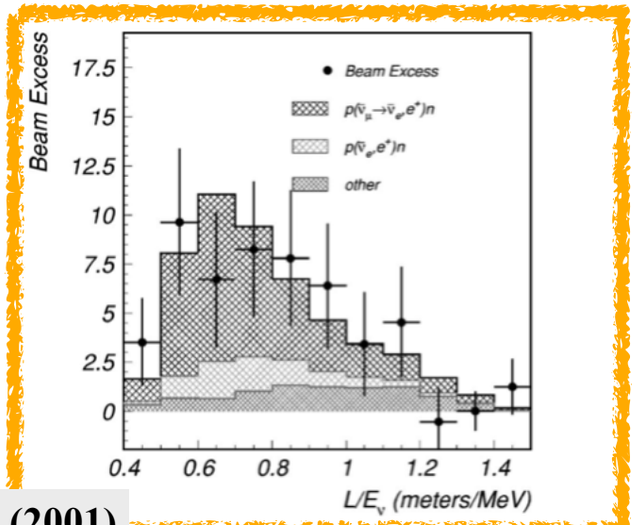
$$(\sin^2 2\theta, \Delta m^2)_{best\text{-}fit} = (0.003, 1.2\ \text{eV}^2).$$

  - ▸ 4th mass eigenstate ... "**sterile neutrino**"

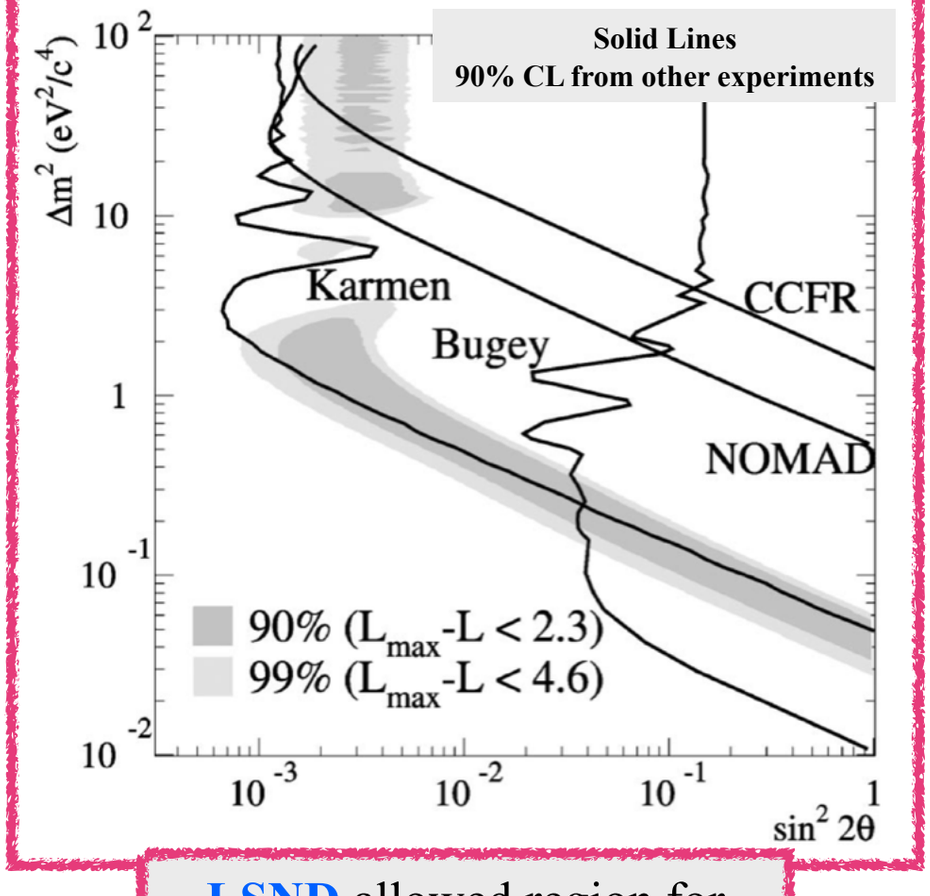


LSND Detection Channel





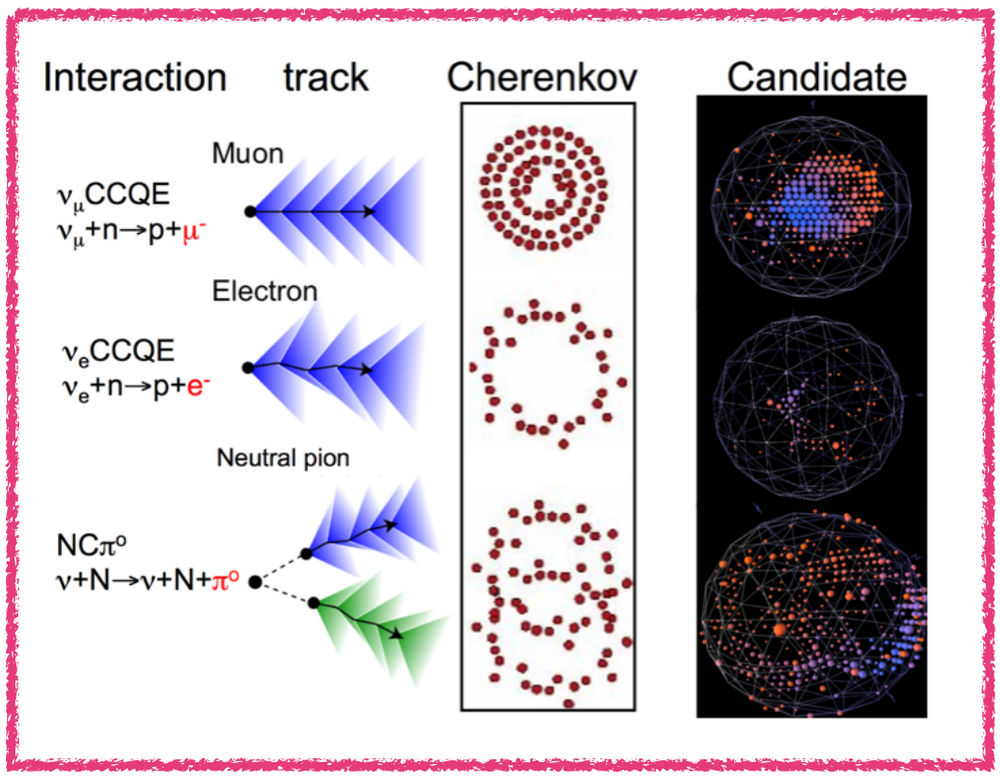
PRD 64, 112007 (2001)



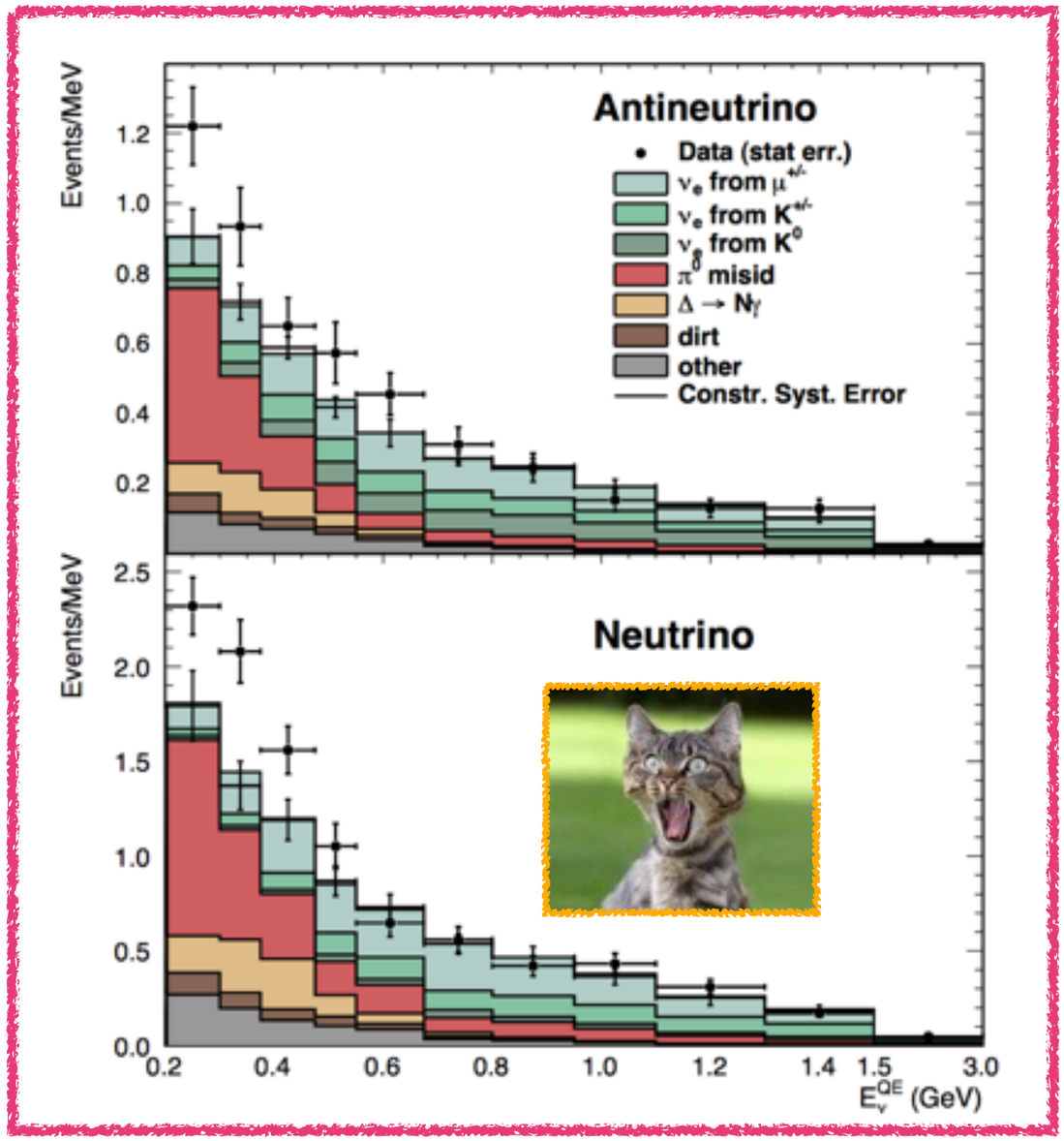
LSND allowed region for
Δm^2 vs. $\sin^2 2\theta$
Possible $\Delta m^2 \in [0.2, 2.0]$ eV^2

"Sterile Neutrino" : High Δm^2 Oscillation

- **MiniBooNE: Booster Neutrino Experiment @ Fermilab**
  - Oscillation mode: $\nu_\mu \Rightarrow \nu_e$ & $\bar{\nu}_\mu \Rightarrow \bar{\nu}_e$ … **L/E ≃ *O* (1 m/MeV)**
  - Cherenkov detector w/ mineral oil
  - Source: **Booster Neutrino Beam (BNB)**
- MiniBooNE **also saw an excess!**
  - …with $\Delta m^2 \simeq 1\ eV^2$
    - **Another hint for high Δm^2 oscillation**
    - "**Low energy excess**" (different from LSND?)



PRL 110, 161801(2013)



"Sterile Neutrino" : High Δm^2 Oscillation

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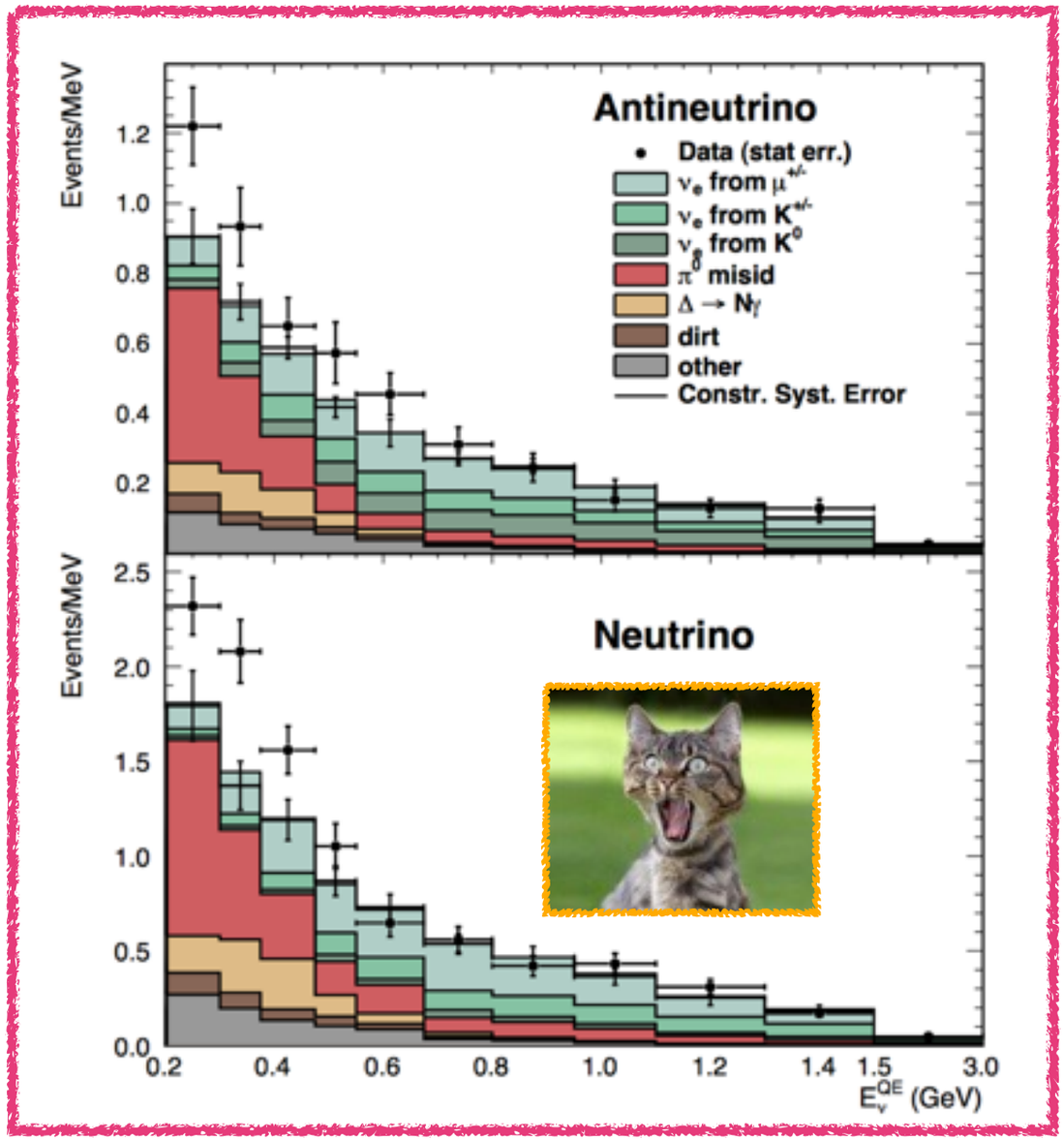
  - …with **$\Delta m^2 \simeq 1\ eV^2$**
    - **Another hint for high Δm^2 oscillation**
    - "**Low energy excess**" (different from LSND?)

- **What is the nature of "excess"?**
  - Region dominated by γ background
  - **Is it single e^- or γ ?**
  - **MicroBooNE** provides a definitive answer
- **What's the physics behind excess?**
  - Modern approach: **multiple detector**
  - **Short Baseline Neutrino Program**

PRL 110, 161801(2013)



MicroBooNE
LArTPC
at
Fermilab Booster Neutrino Beamline

MicroBooNE!

- **Short Baseline Neutrino Oscillation Experiment @ Fermilab**
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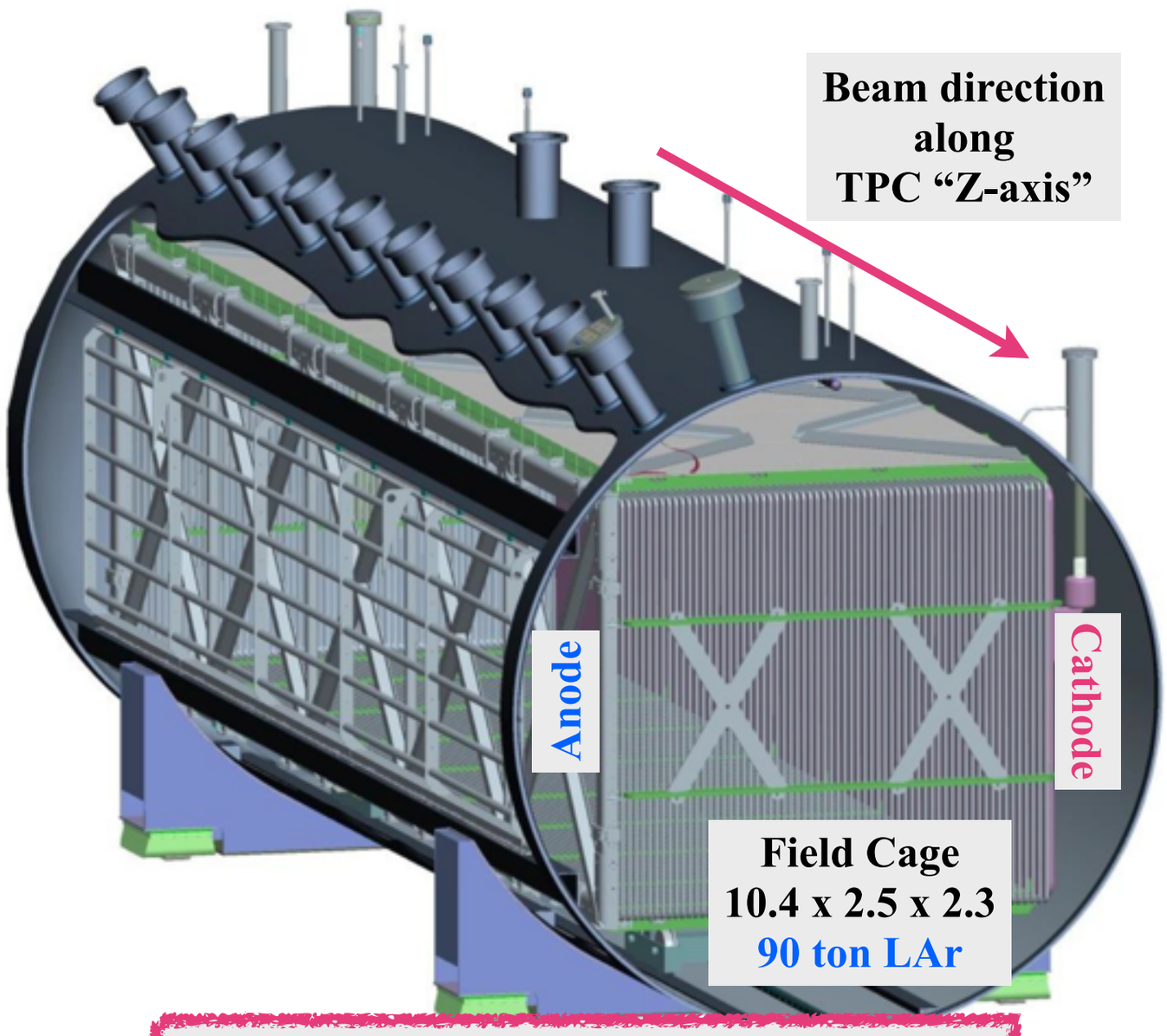


MicroBooNE Cryostat & TPC

- **Neutrino source**
  - Booster Neutrino Beam (BNB)
    - Accelerator @ Fermilab
    - Identical to MiniBooNE!
- **Detector (nu-target)**
  - 170 ton of liquid argon (LAr)
  - Time Projection Chamber

Three Objectives

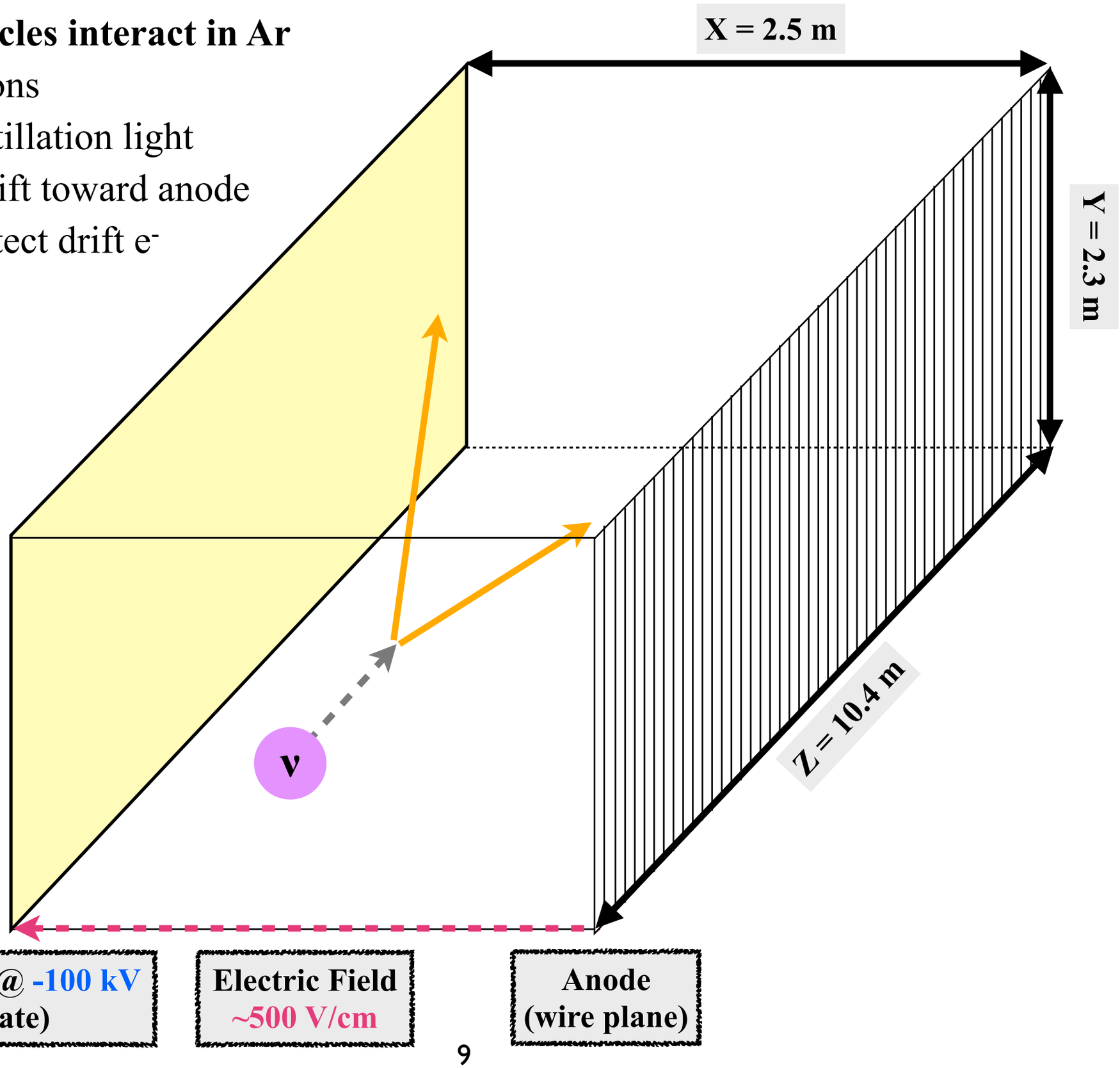
1. **MiniBooNE low E excess**
2. **Low E ν-Ar cross-section**
3. **LArTPC R&D**

MicroBooNE Detector

TPC Working Principle

1. Charged particles interact in Ar
- Ionize electrons
- Produce scintillation light

2. Ionization e^- drift toward anode
3. Wire planes detect drift e^-



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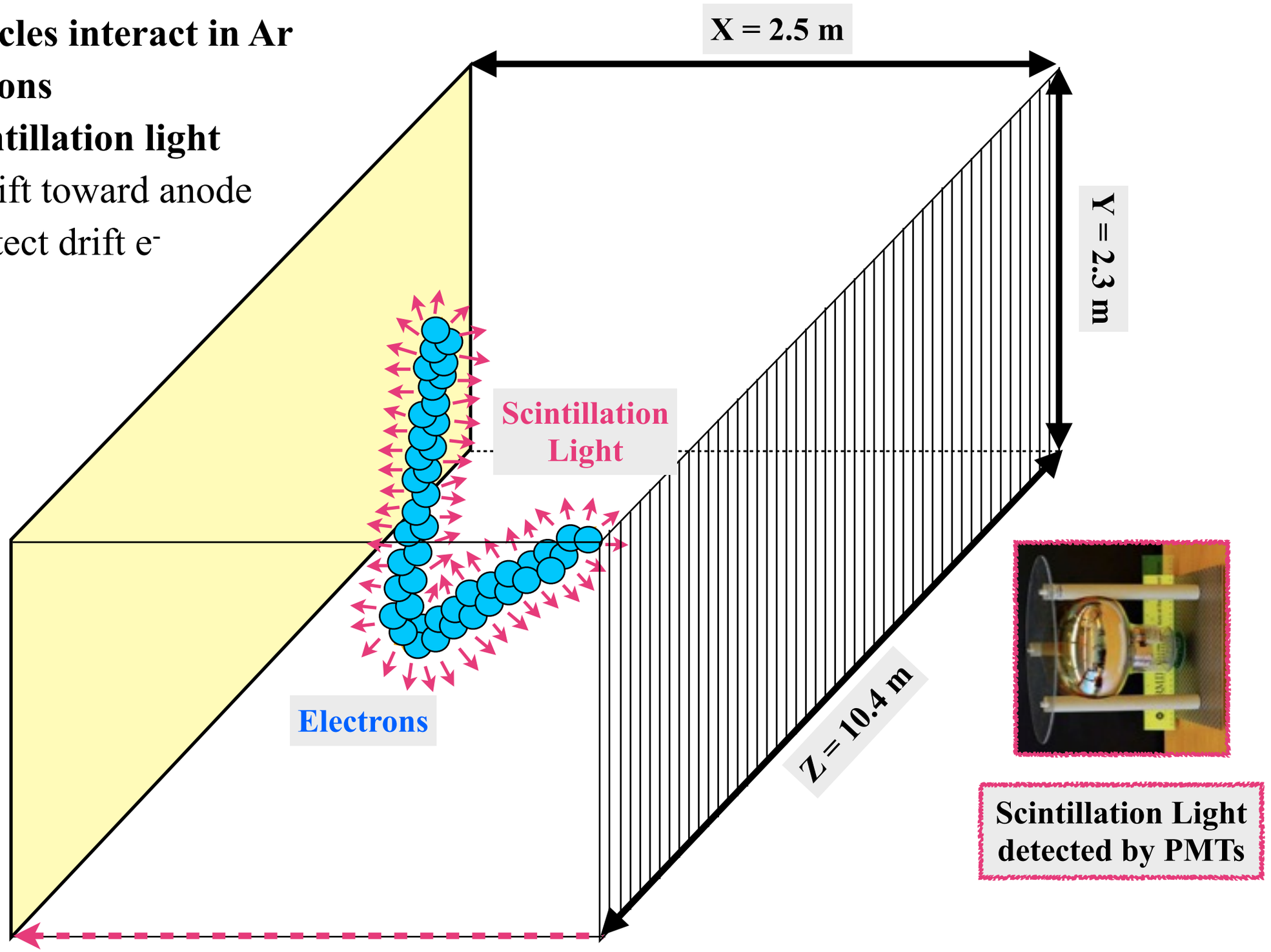

Scintillation Light detected by PMTs

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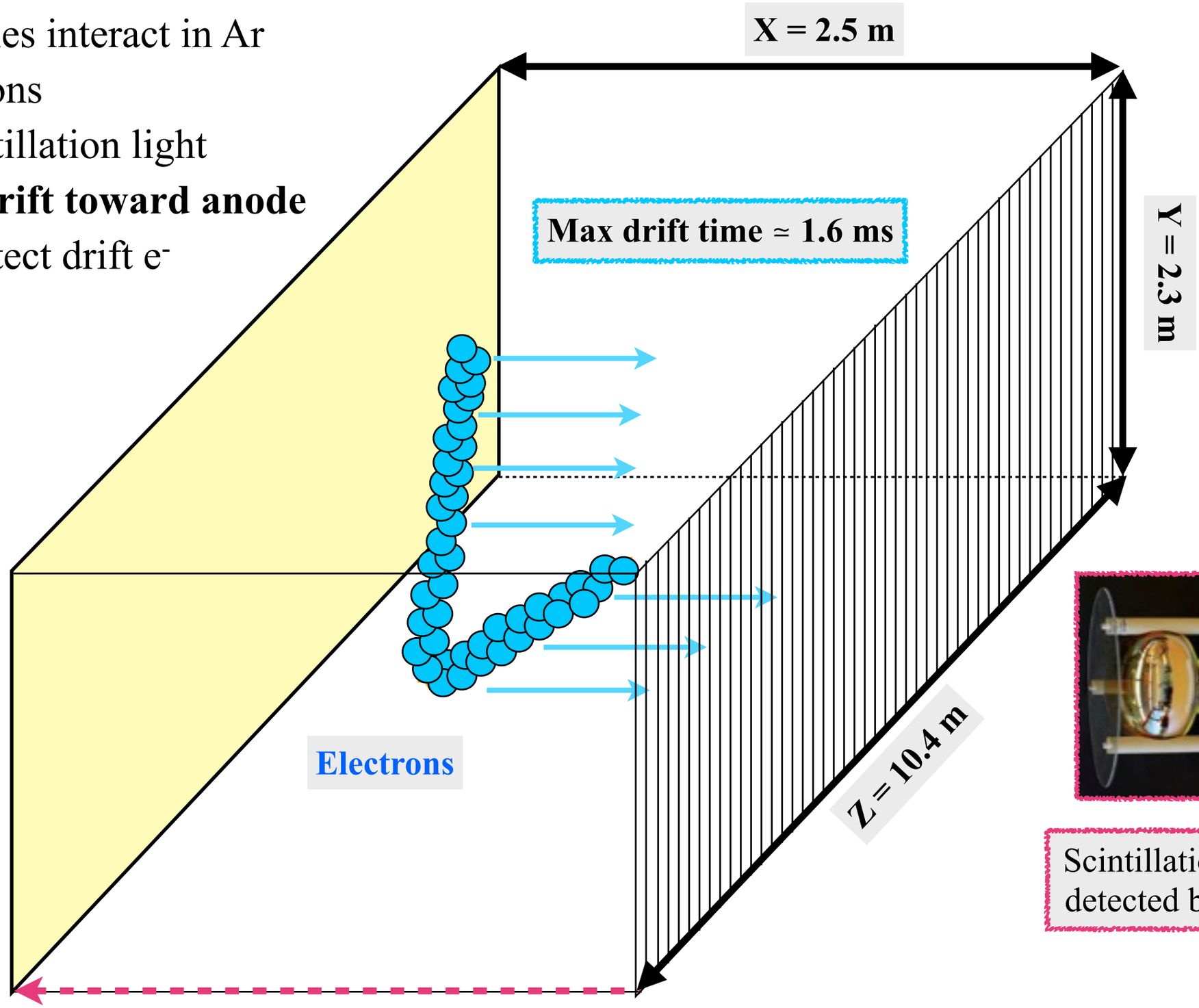

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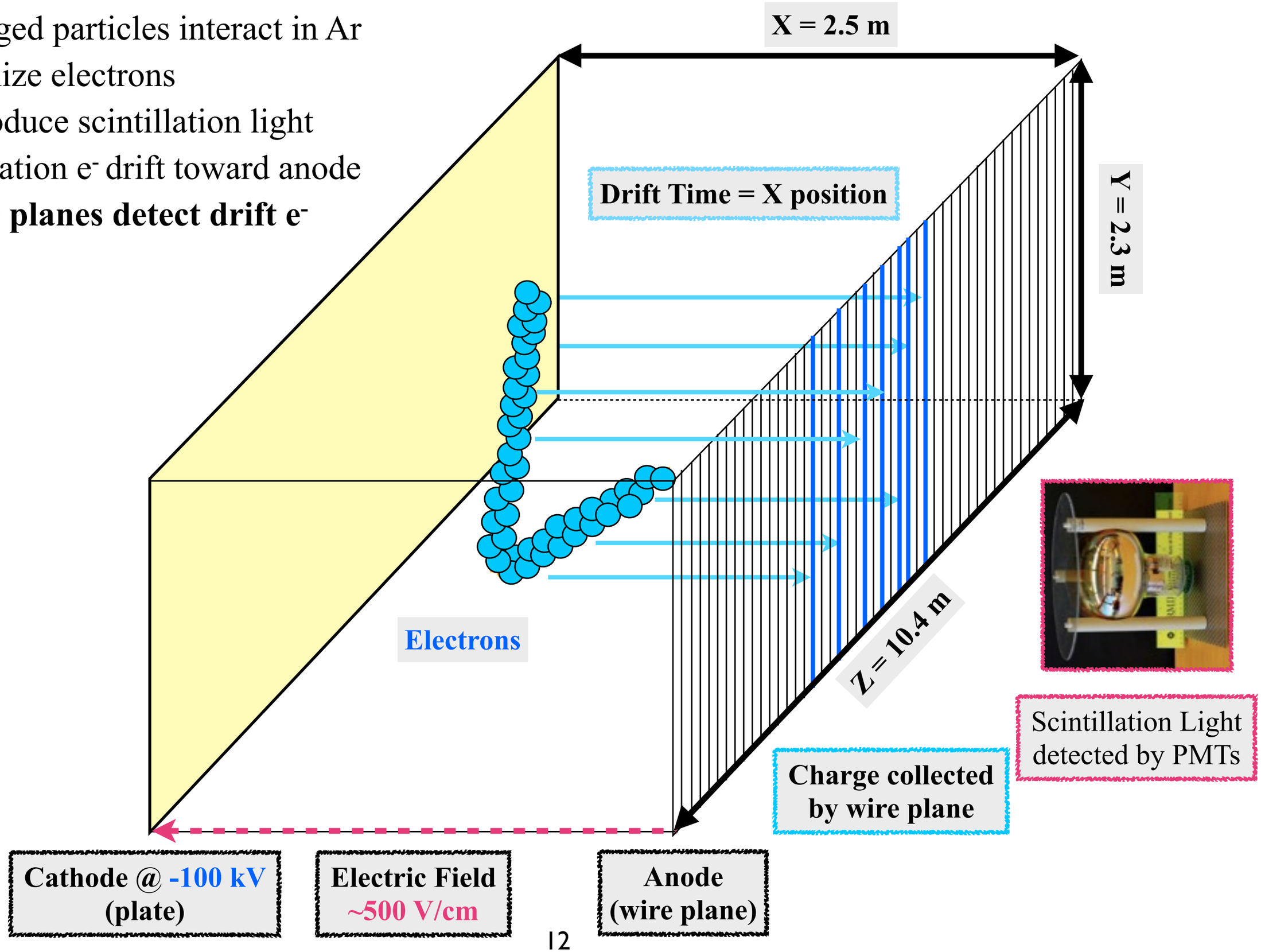
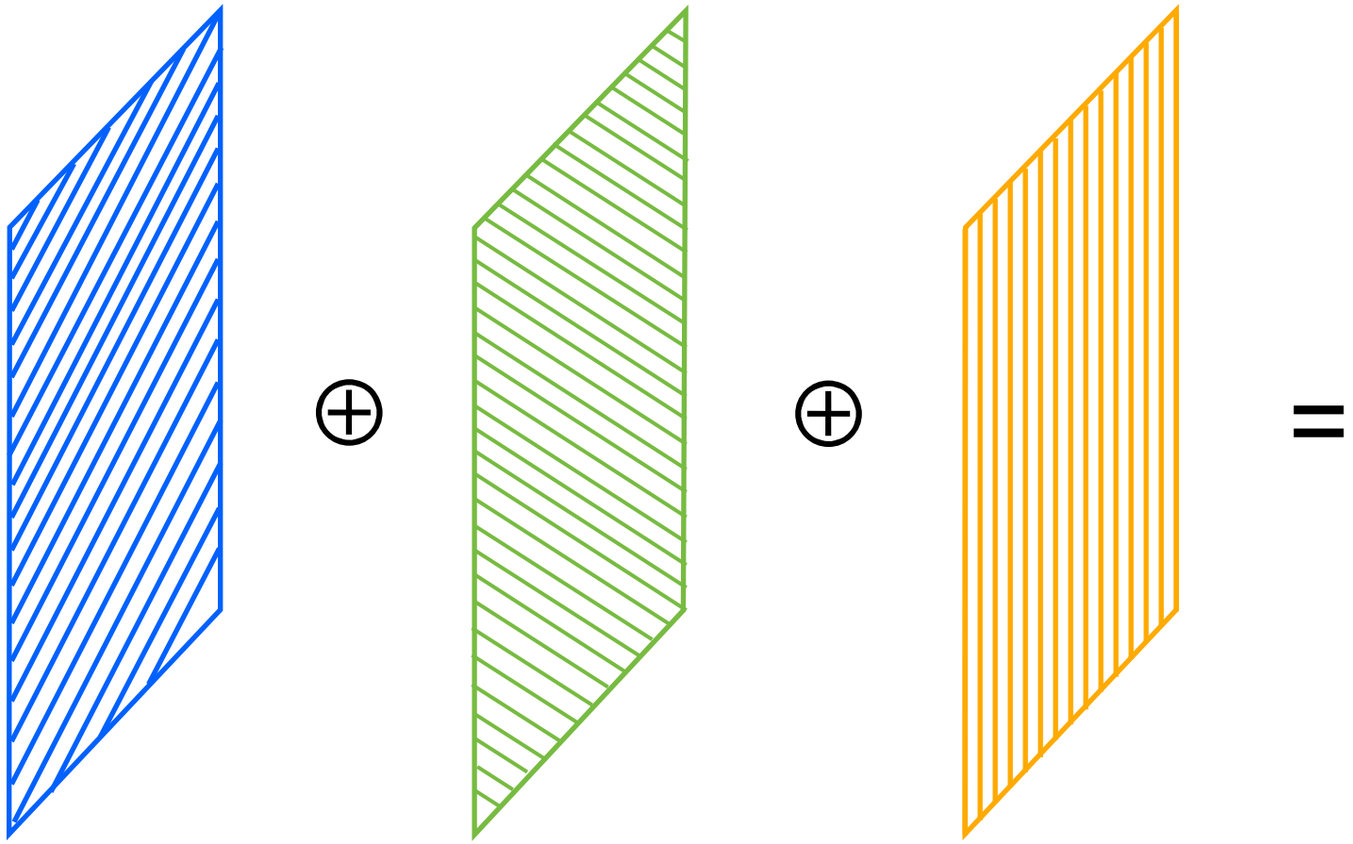


Three Wire Planes

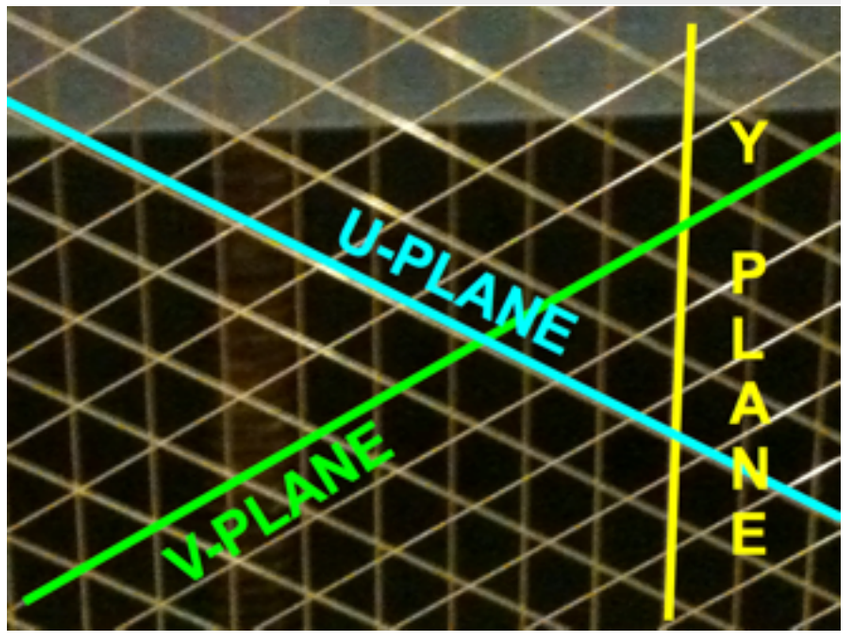


U plane (induction)

V plane (induction)

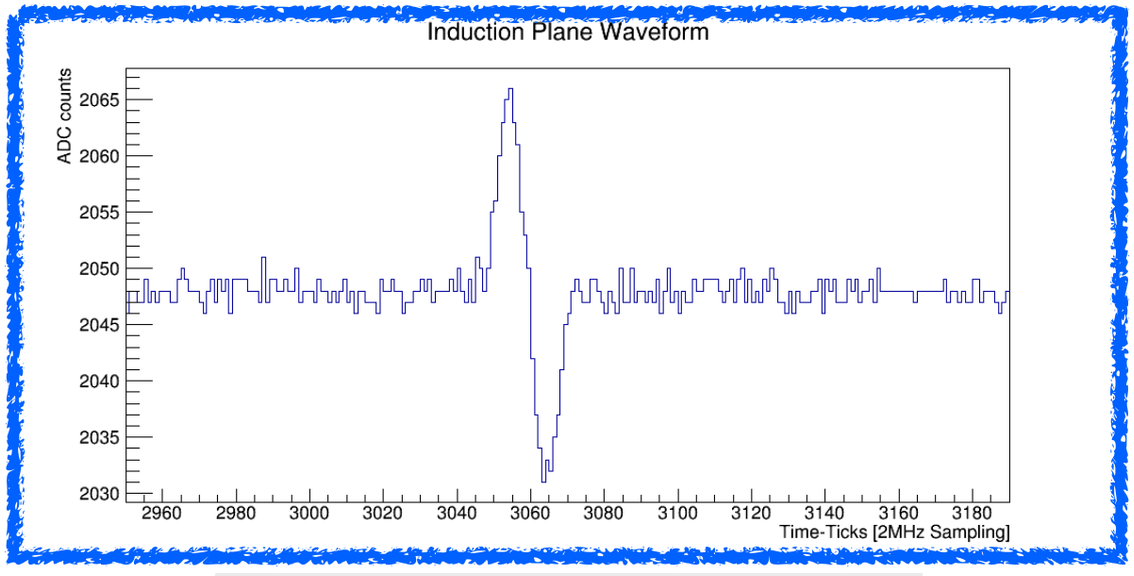
Y plane (collection)

Picture courtesy of J. Asaadi



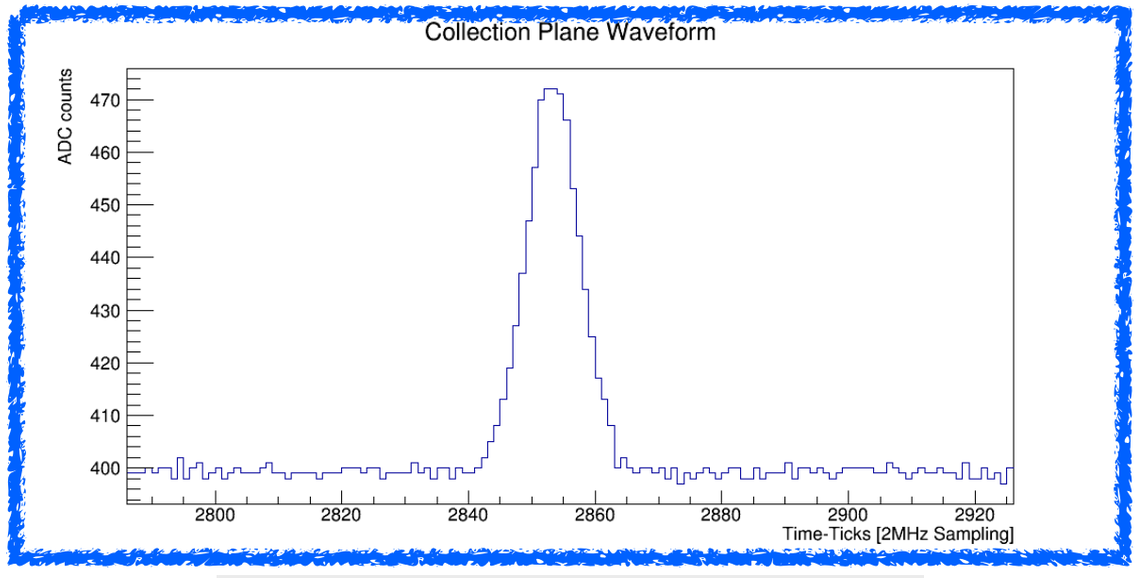
8256 wires w/ pitch = 3mm

(Y, Z) = coincidence on wire



Induction Plane MC Waveform

(Bi-polar pulse as e^- pass through)

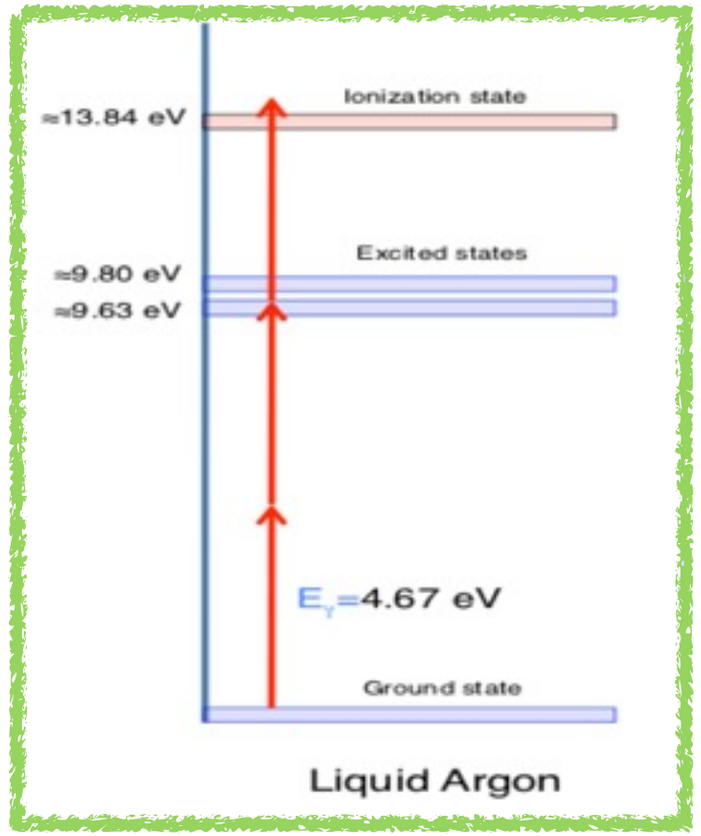


Collection Plane MC Waveform

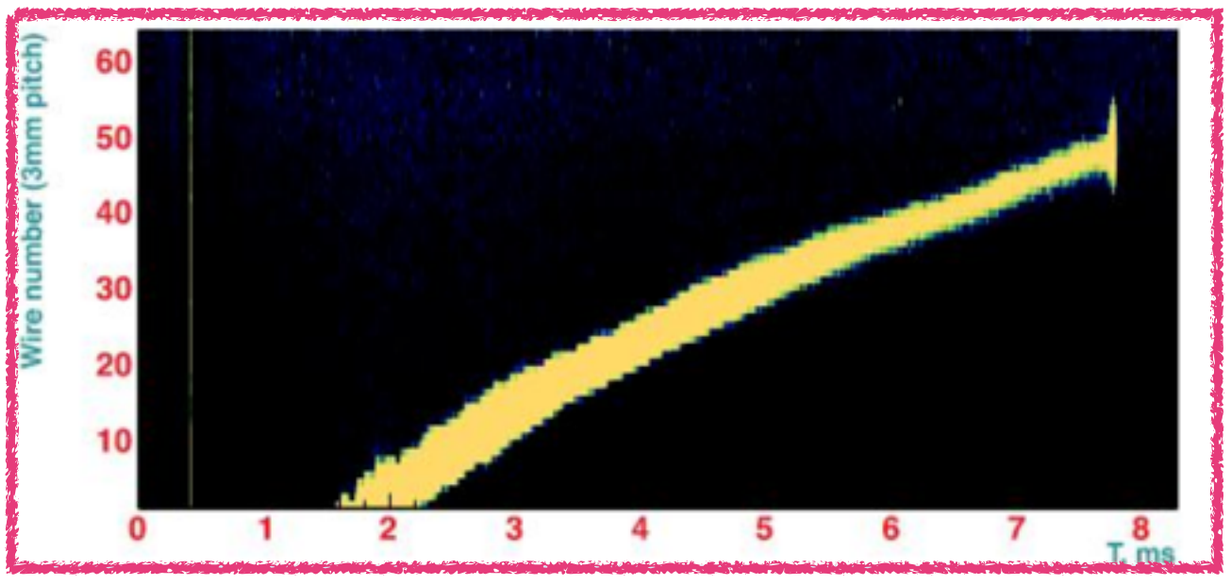
(Uni-polar pulse as e^- collected)

Calibrating LArTPC Field Uniformity

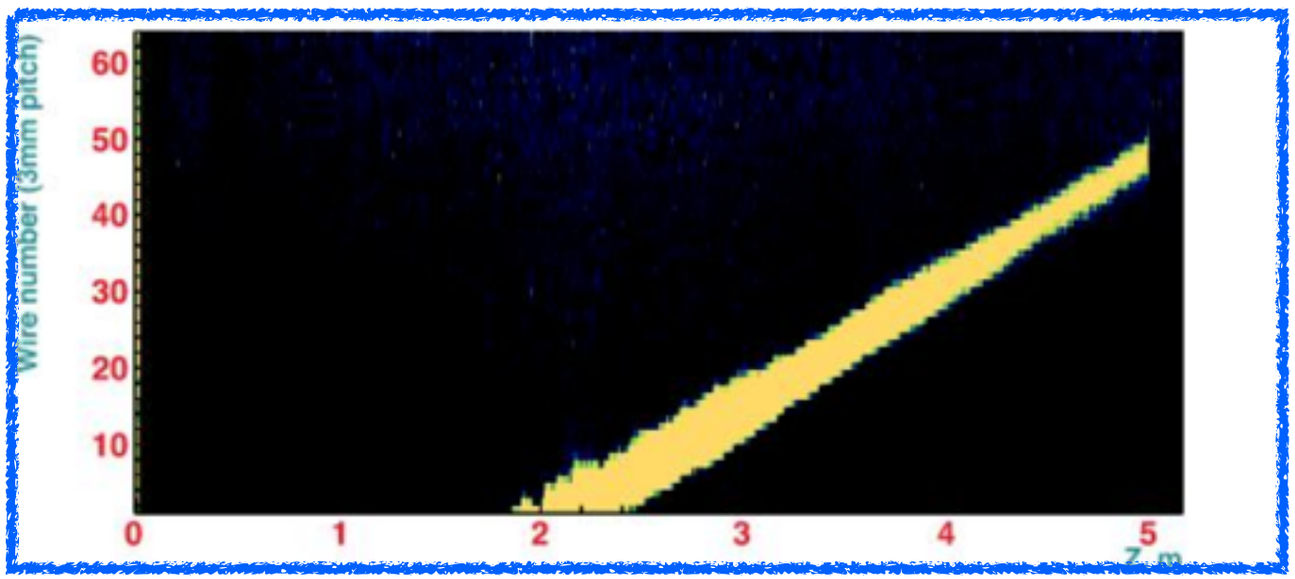
- Field non-uniformity arise
  - Distortion expected by Ar^+ accumulation @ cathode
  - Needs to be calibrated out
- Laser Calibration System (LCS)
- LCS inject laser to ionize Ar along the path
  - $\lambda \cong 266$ nm, need high intensity to ionize
  - Distortion shows up in the reconstructed signal path



Plot & Diagram ... courtesy of C. Rudolf



Laser path @ ArgonTube
(**Uncalibrated**)



Laser path @ ArgonTube
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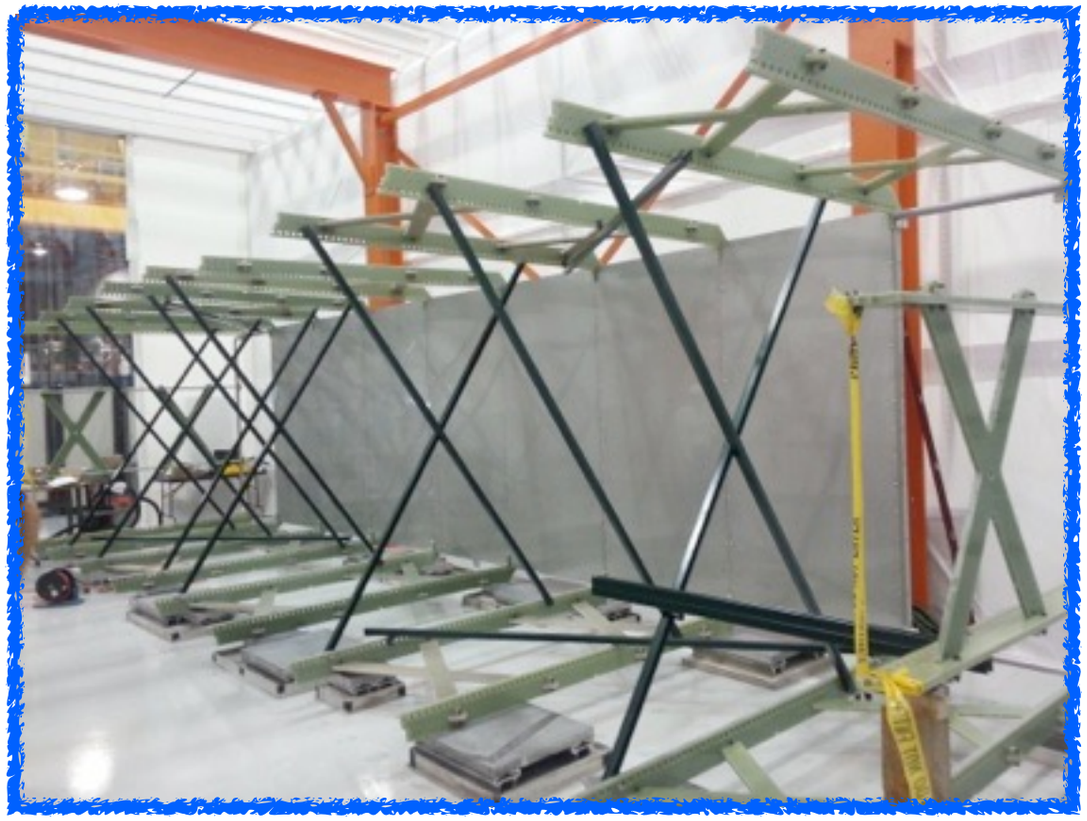
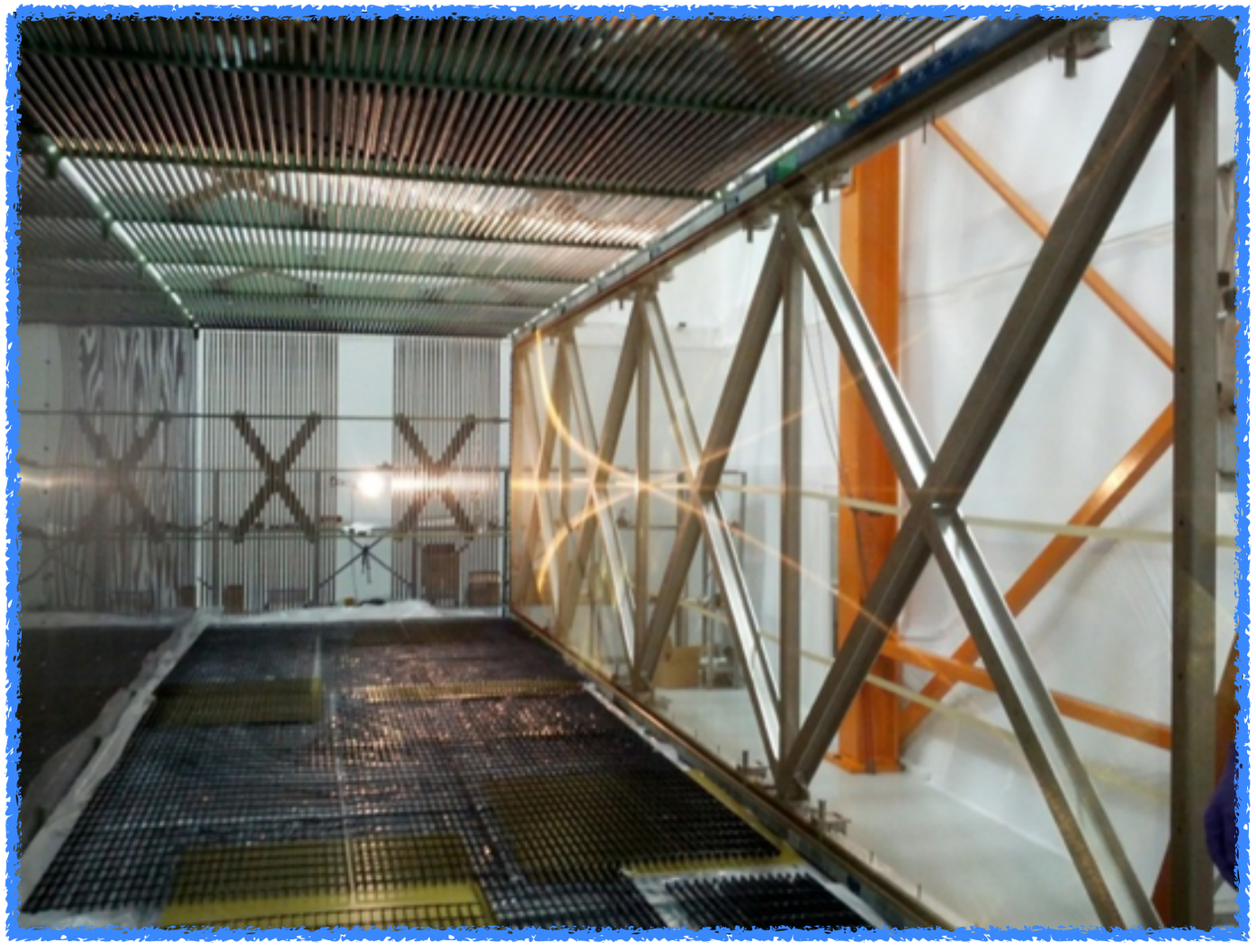
TPC Preparation

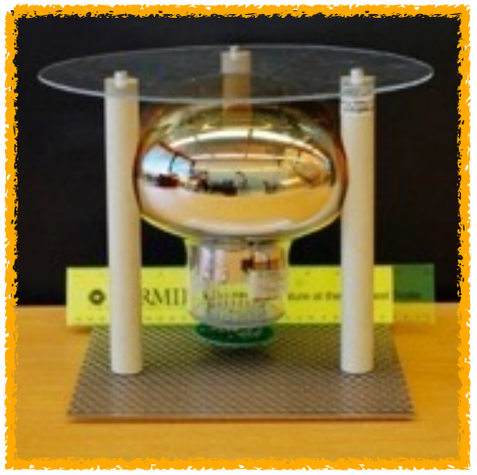




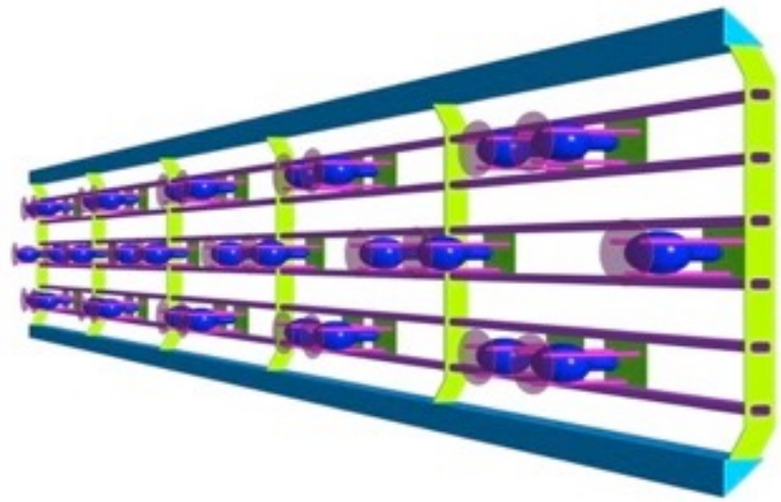
TPC built w/ 8256 wires!
w/ big effort on doing everything right :)

Optical Detector

- **What is it? What for?**
  - 32 8” PMTs
  - Crucial roles
    - **Getting trigger**
    - **Reconstructing YZ**
      - ✓ **Cosmic background rejection**



MicroBooNE PMT



Array of 32 PMTs

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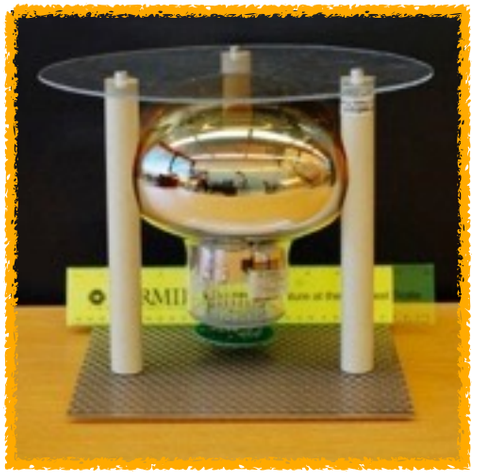
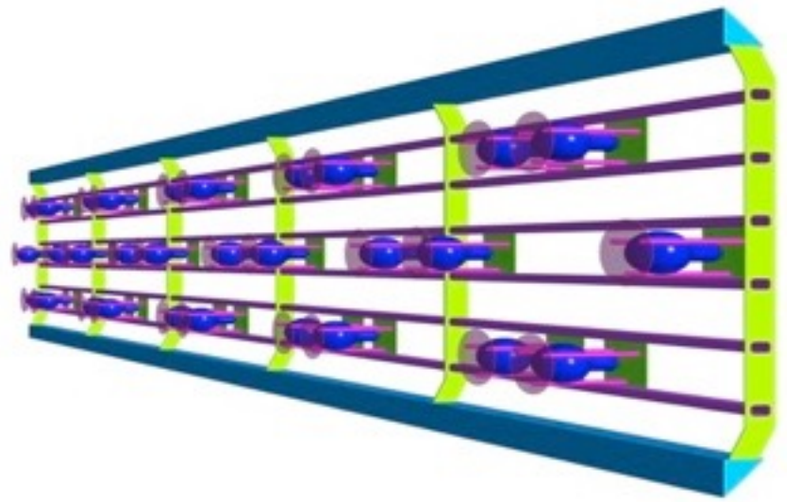
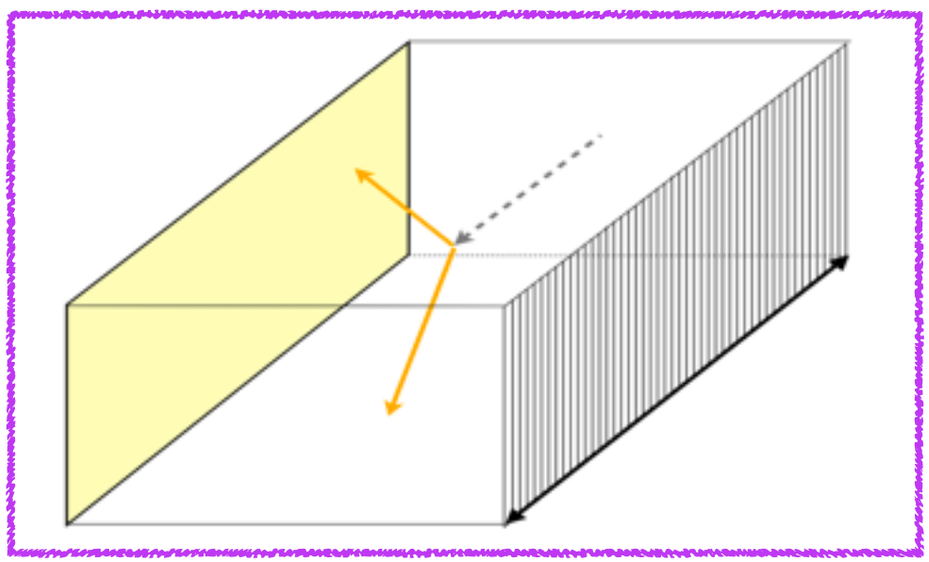


MicroBooNE PMT

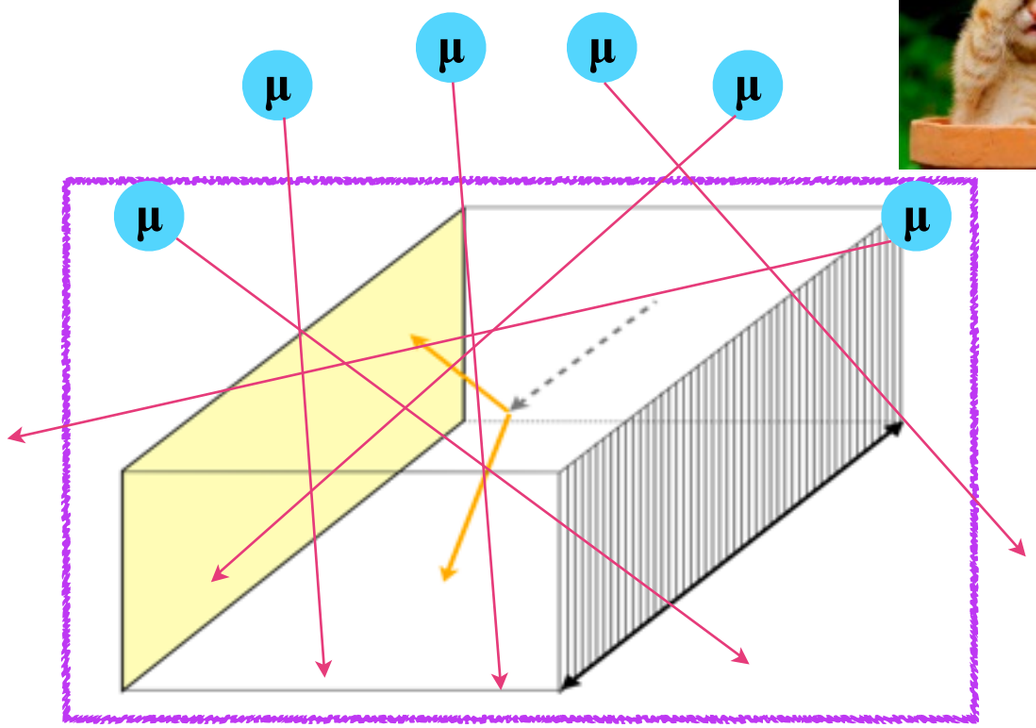


Array of 32 PMTs

Crucial for MicroBooNE
because of
high cosmic ray rate (~5kHz) @ surface!

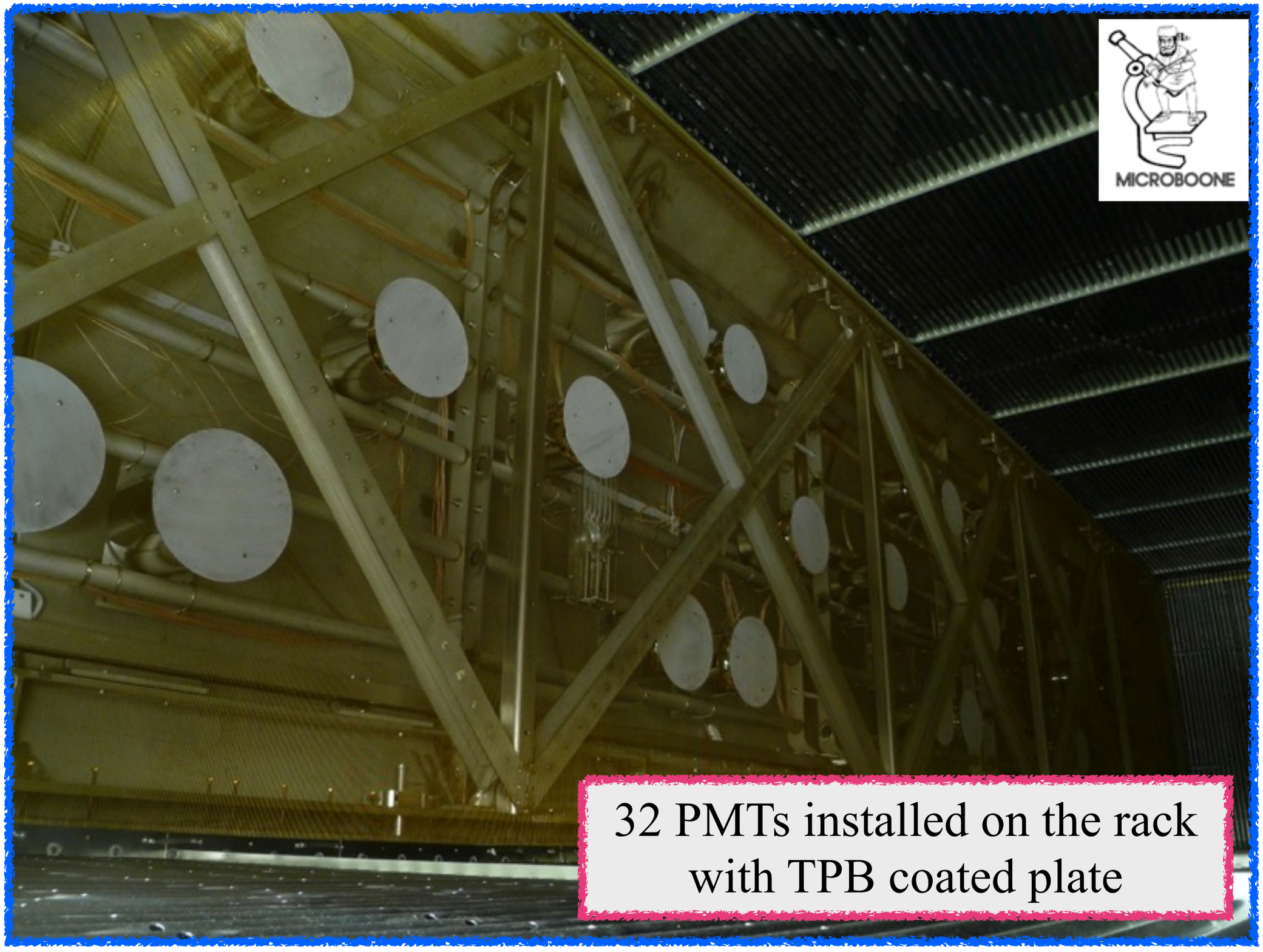


What we want



What we will have
several cosmics within
the **same drift time period (1.6 ms)**

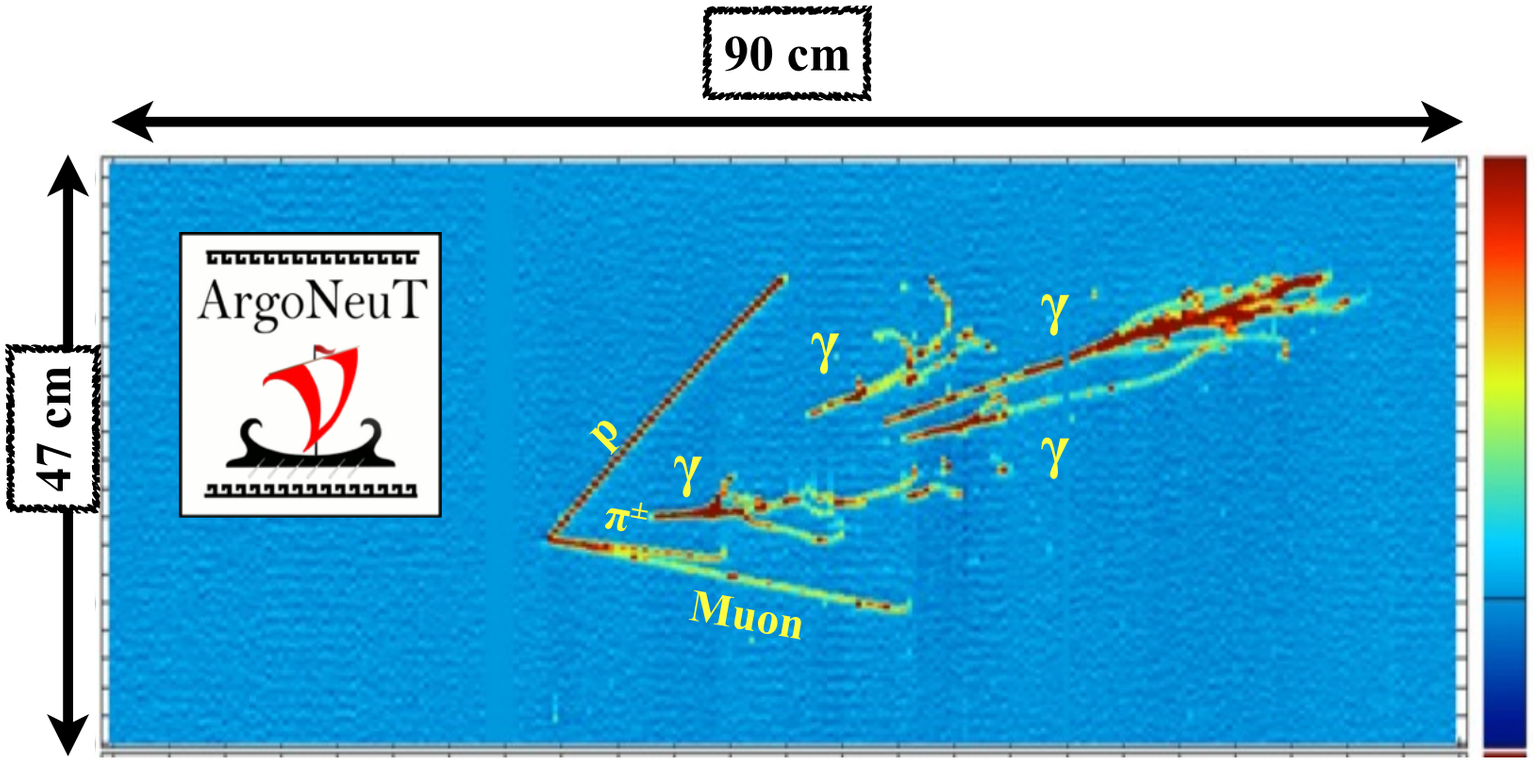
Optical Detector



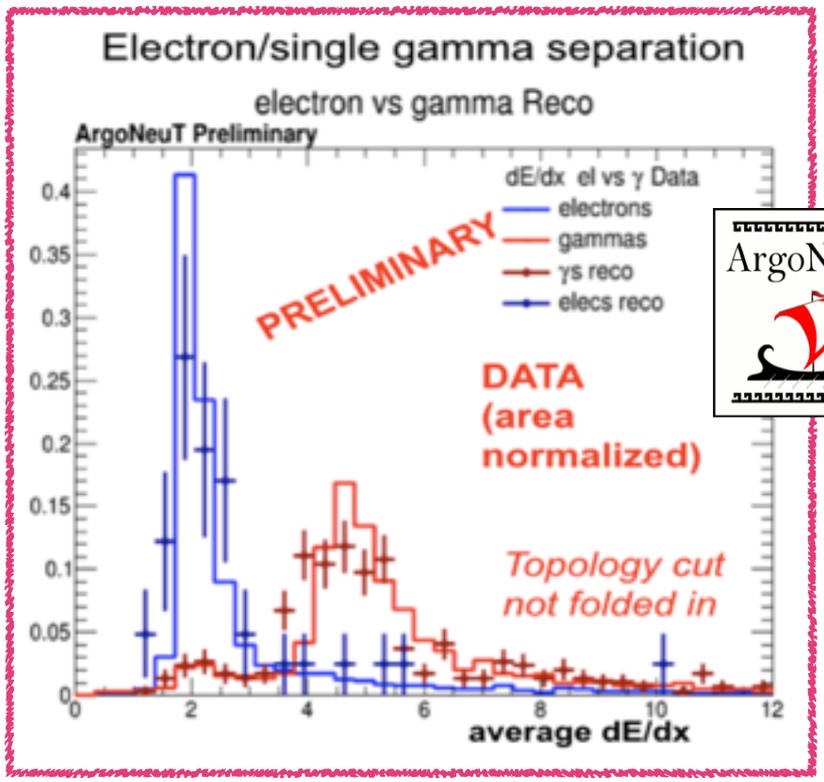
This picture is taken with 60 [s] exposure time in covered (dark) cryostat
Courtesy of Christoph Rudolf von Rohr

…When Everything Works Out…

- **LArTPC** provides great details of particle interaction in LAr
  - **3D geometric topology** of charged particle trajectories, EM showers
  - **Calorimetric information** for dE/dX and total energy deposition
- Rich event topology allows detailed XS measurement
- Geometry + dE/dX allows us e-/gamma separation



Example DIS event
(courtesy of ArgoNeuT collaboration)



Data vs. MC comparison for
Single γ and e⁻ selection
Andrzej S. from **ArgoNeuT**

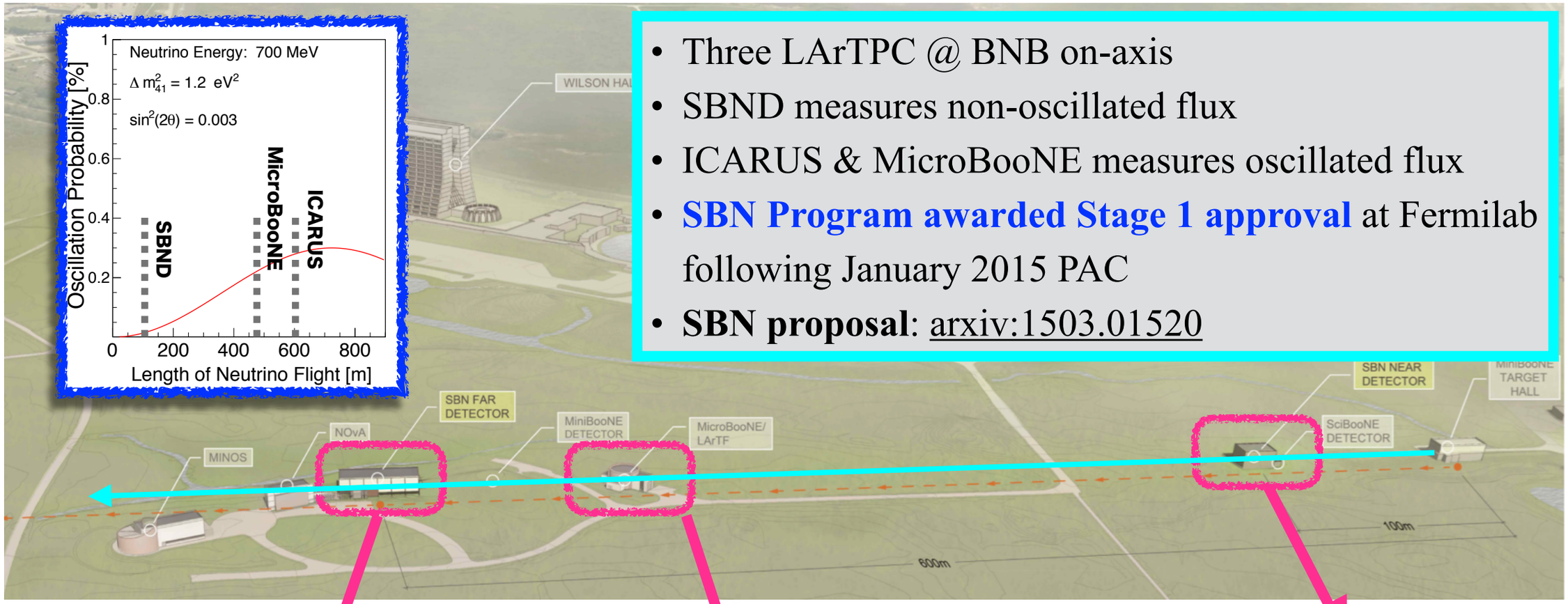
MicroBooNE … then What?

- MicroBooNE tells us whether the excess is electron or photon like
- Then we want to understand the nature of this physics!
  - Understand flux: measure un-oscillated neutrino flux
  - More statistics: a detector of a larger mass
- **Short Baseline Neutrino (SBN)** program is launched @ Fermilab

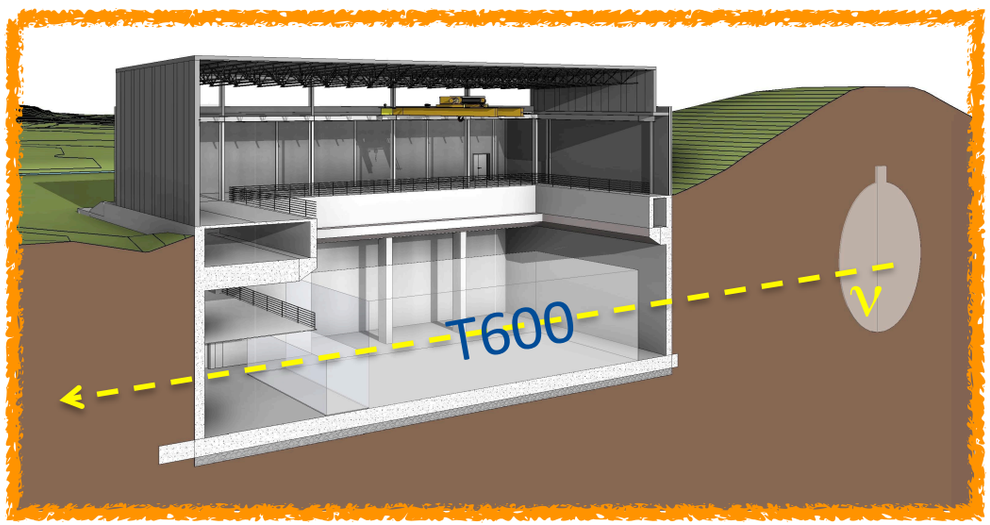
Short Baseline Neutrino Program

~ Understanding Physics of Low Energy Excess ~

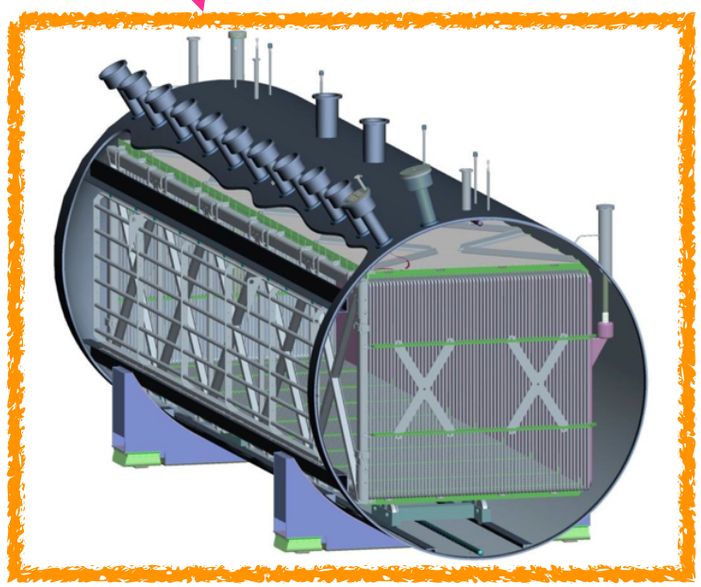
Three LArTPC Detectors @ Fermilab



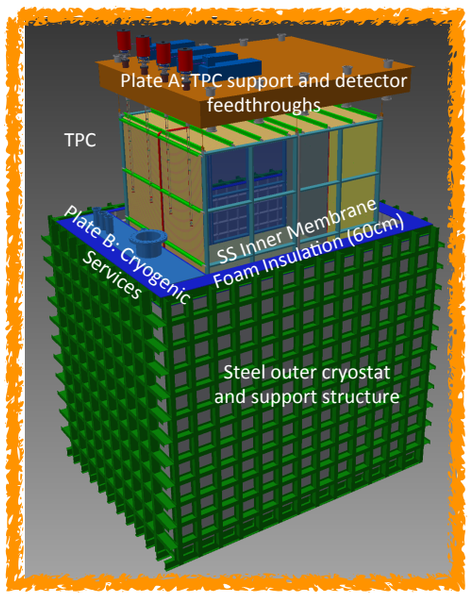
- Three LArTPC @ BNB on-axis
- SBND measures non-oscillated flux
- ICARUS & MicroBooNE measures oscillated flux
- **SBN Program awarded Stage 1 approval** at Fermilab following January 2015 PAC
- **SBN proposal**: arxiv:1503.01520



ICARUS T600
~476 ton @ 600 m

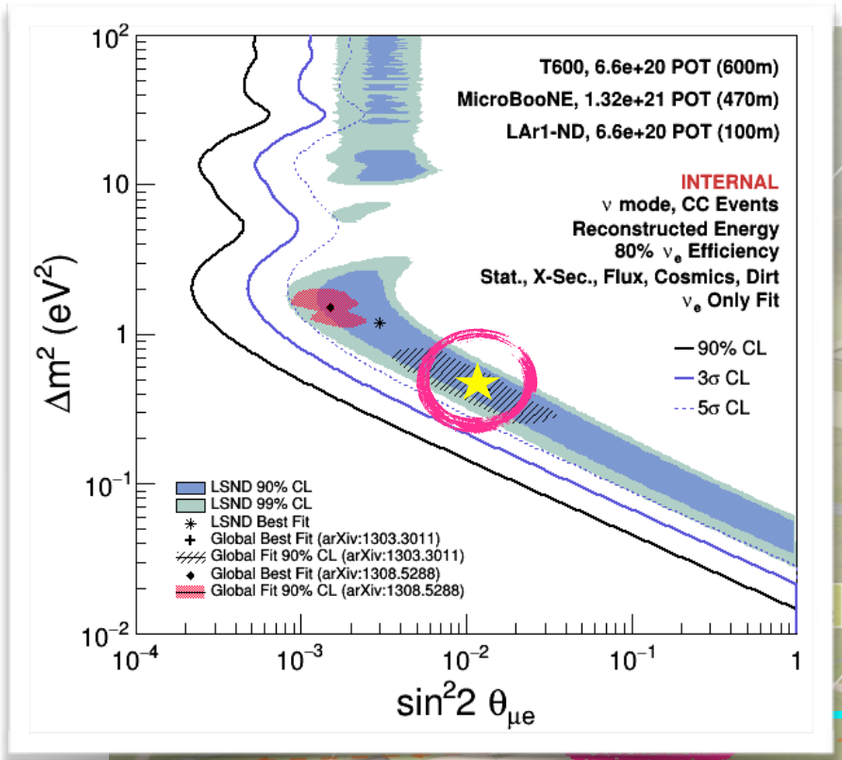


MicroBooNE
~87 ton @ L = 470 m



SBND
~112 ton @ L = 110 m

Three LArTPC Detectors @ BNB



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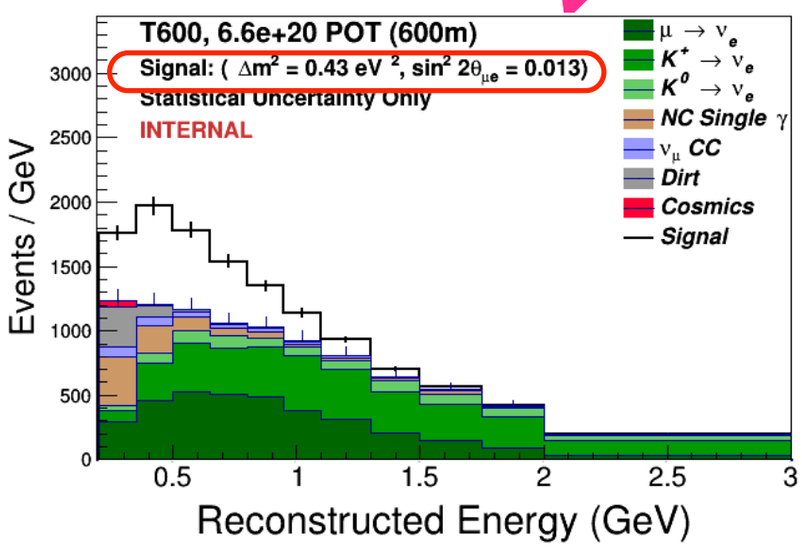

ICARUS T600
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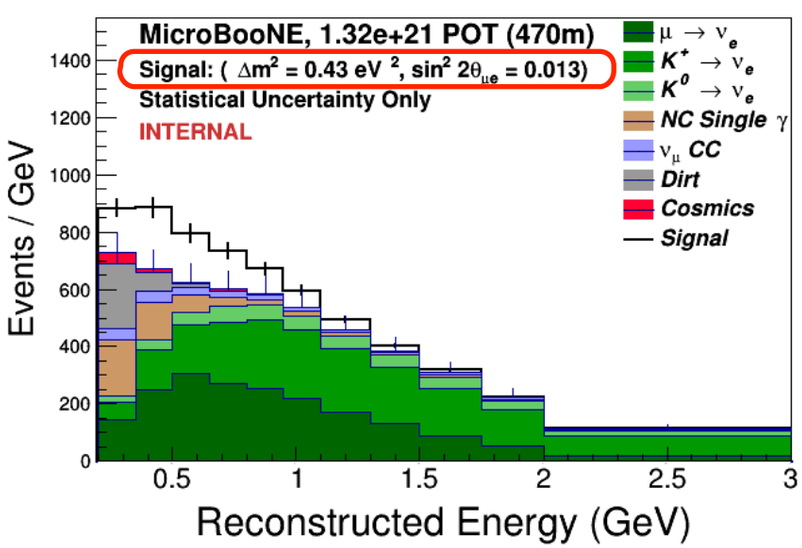

MicroBooNE
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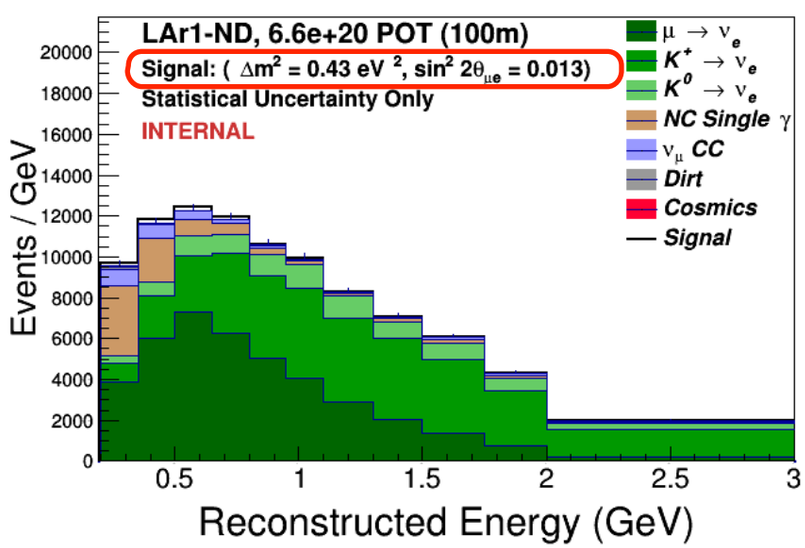
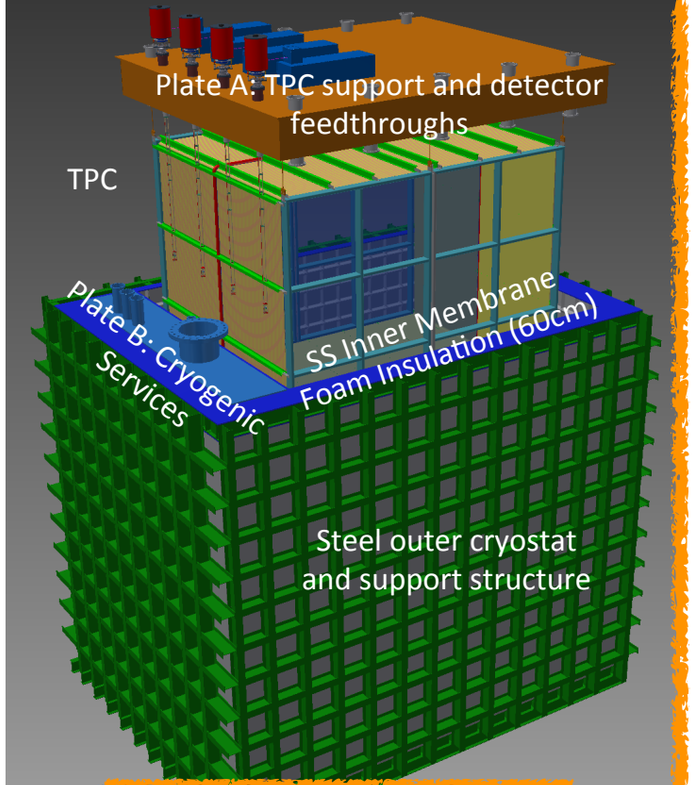


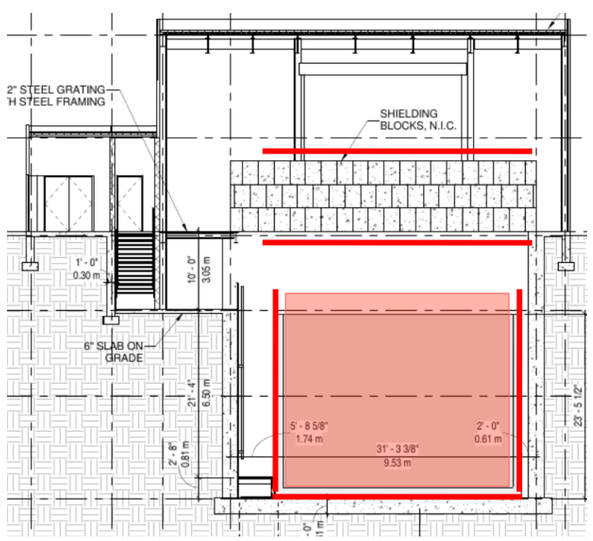
SBND
~112 ton @ L = 110 m

Short-Baseline Near Detector



SBND Finalized Design

- **Measures un-oscillated flux**
- Records **1.5e6 neutrino events every year**
  - detailed measurement on **rarer interactions**
- Detector design processing rapidly
- Finalizing design of near detector building
- **Construction begins @ November 2015**
- SBND website: **http://sbn-nd.fnal.gov**



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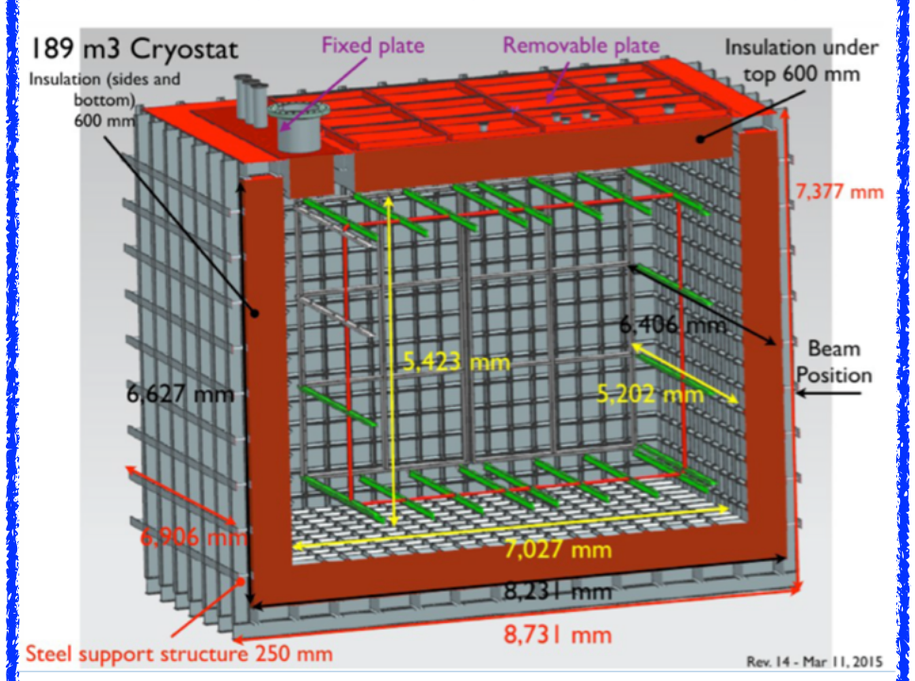
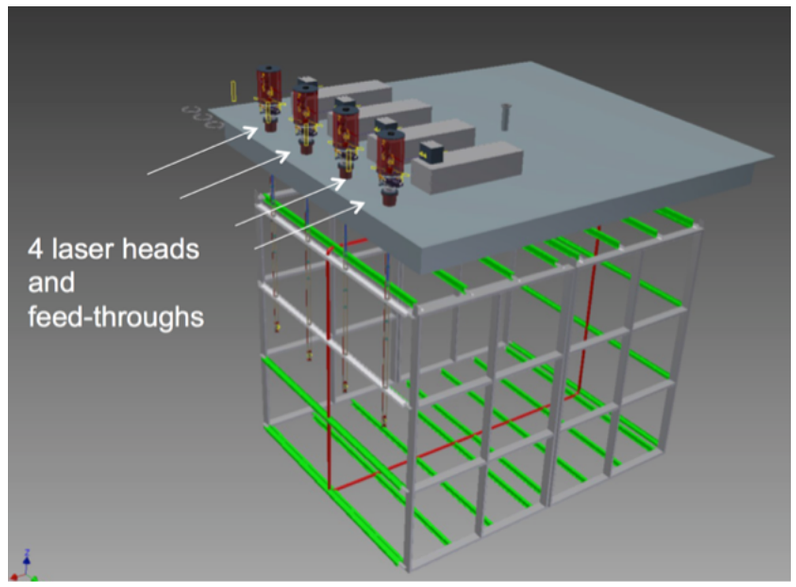
Muon Tagger



Cryostat & TPC



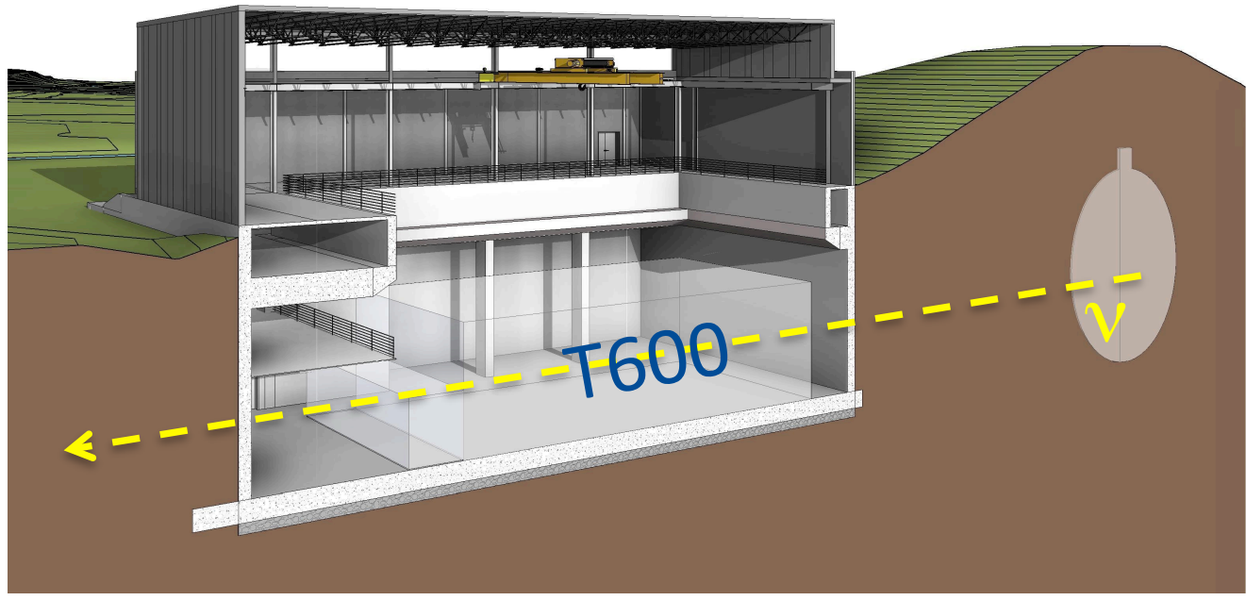
Laser System

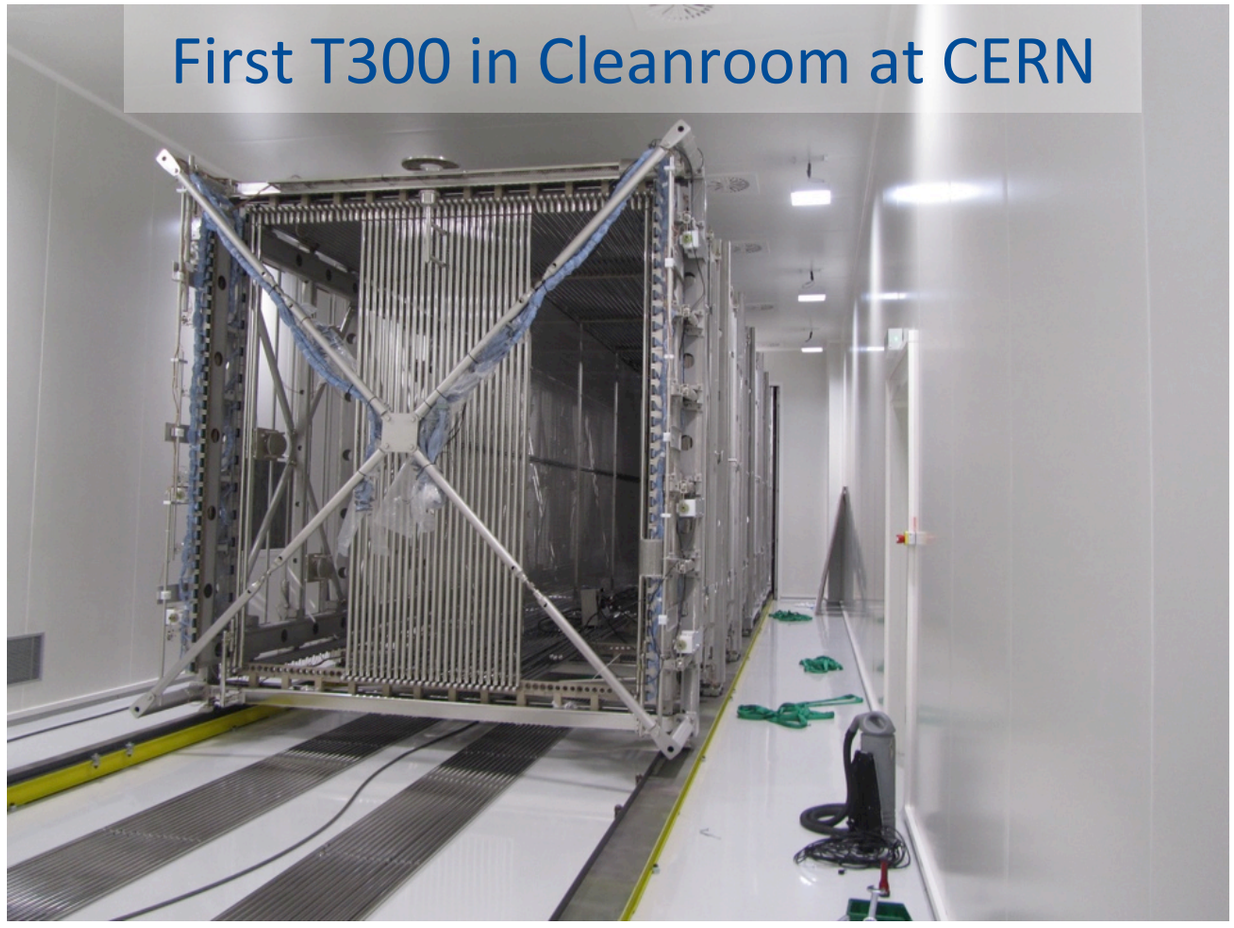
Progress in ICARUS T600

- The design of the far detector building has been finalized with construction started last month!

- The refurbishment of the T600 has already begun at CERN

- The first of the two T300 modules will be finished by the end of 2015 and the second module by the end of 2016



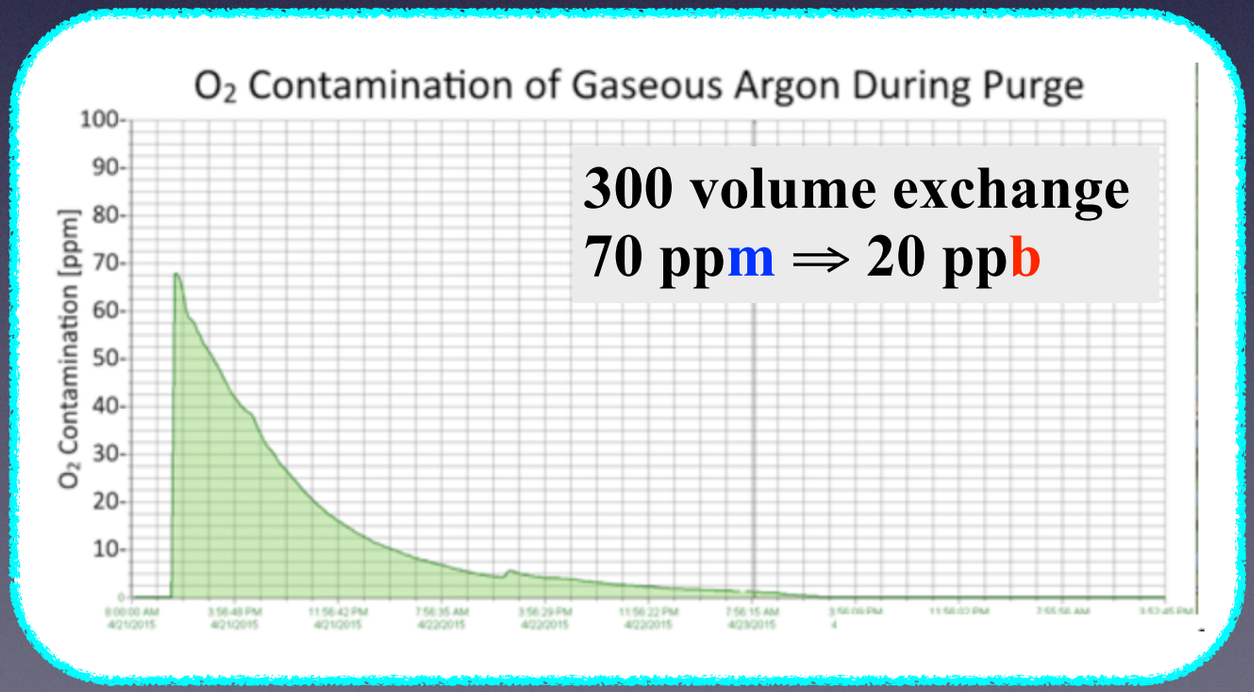


Slide: courtesy of Joseph Z.

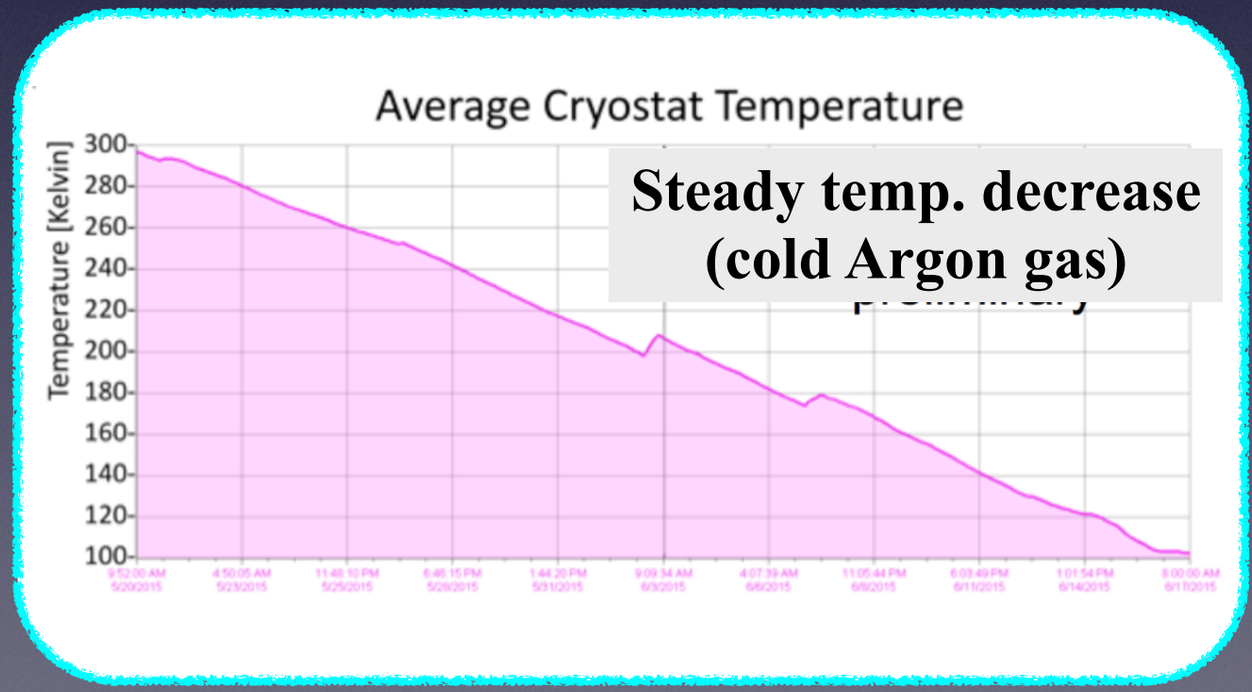
MicroBooNE News of Detector Commissioning

MicroBooNE in 2015

- Our detector placed in BNB in 2014
- Followed by huge installation effort
  - Platform, racks, circulation system, etc
  - Software to control/monitor all of them
- Purging and cooling very successful
  - Contamination level sufficiently decreased
  - Steady temperature drop
  - Demonstrated no evacuation needed
- Of course we moved onto filling LAr :)

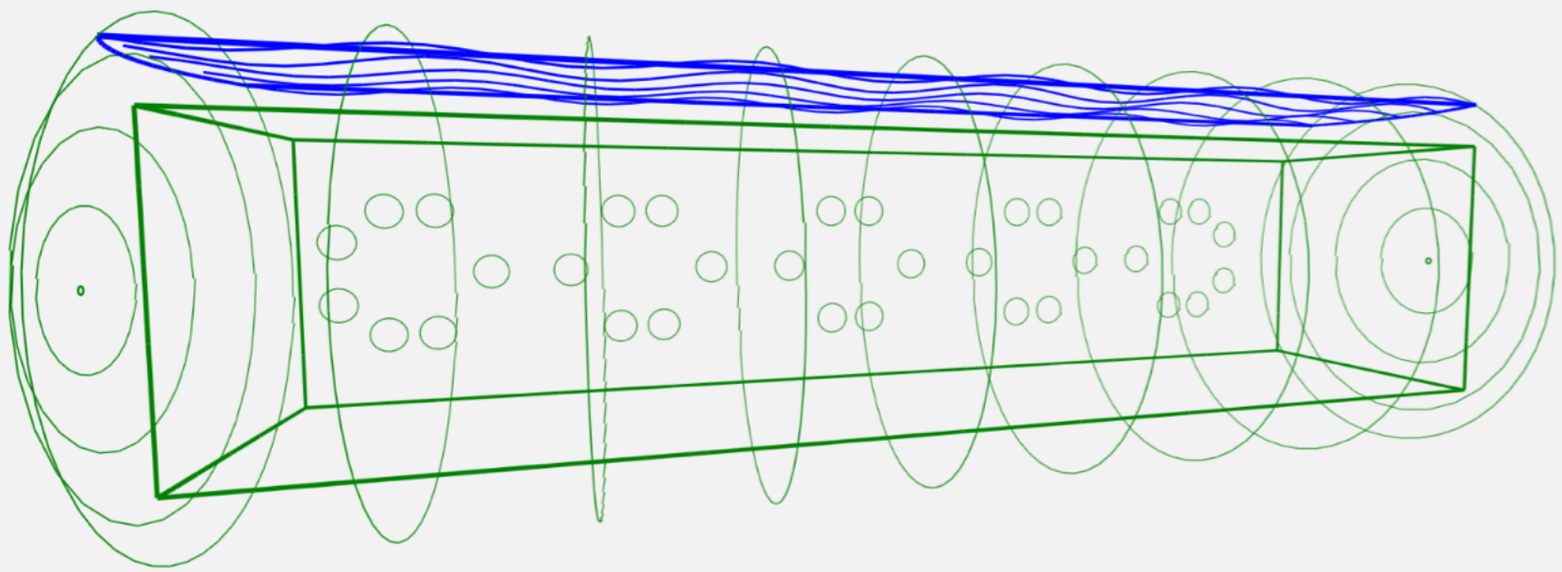


O2 level decreasing during purging



Monitoring temperature while cooling

MicroBooNE in 2015



MicroBooNE
July 9 · Edited ·

July 9th!

Today, we passed a major milestone. The MicroBooNE vessel is officially full!! It took 9 tanker trucks and ~34,000 gallons of high purity liquid argon. Many thanks to our cryogenic experts, Mike Zuckerbrot and Michael Geynisman, and to Steve Gaugel in procurement for getting us to this point! Next, we start turning on each of our detector sub-systems one-by-one and further purifying the argon. We could not be more excited!

Like · Comment · Share

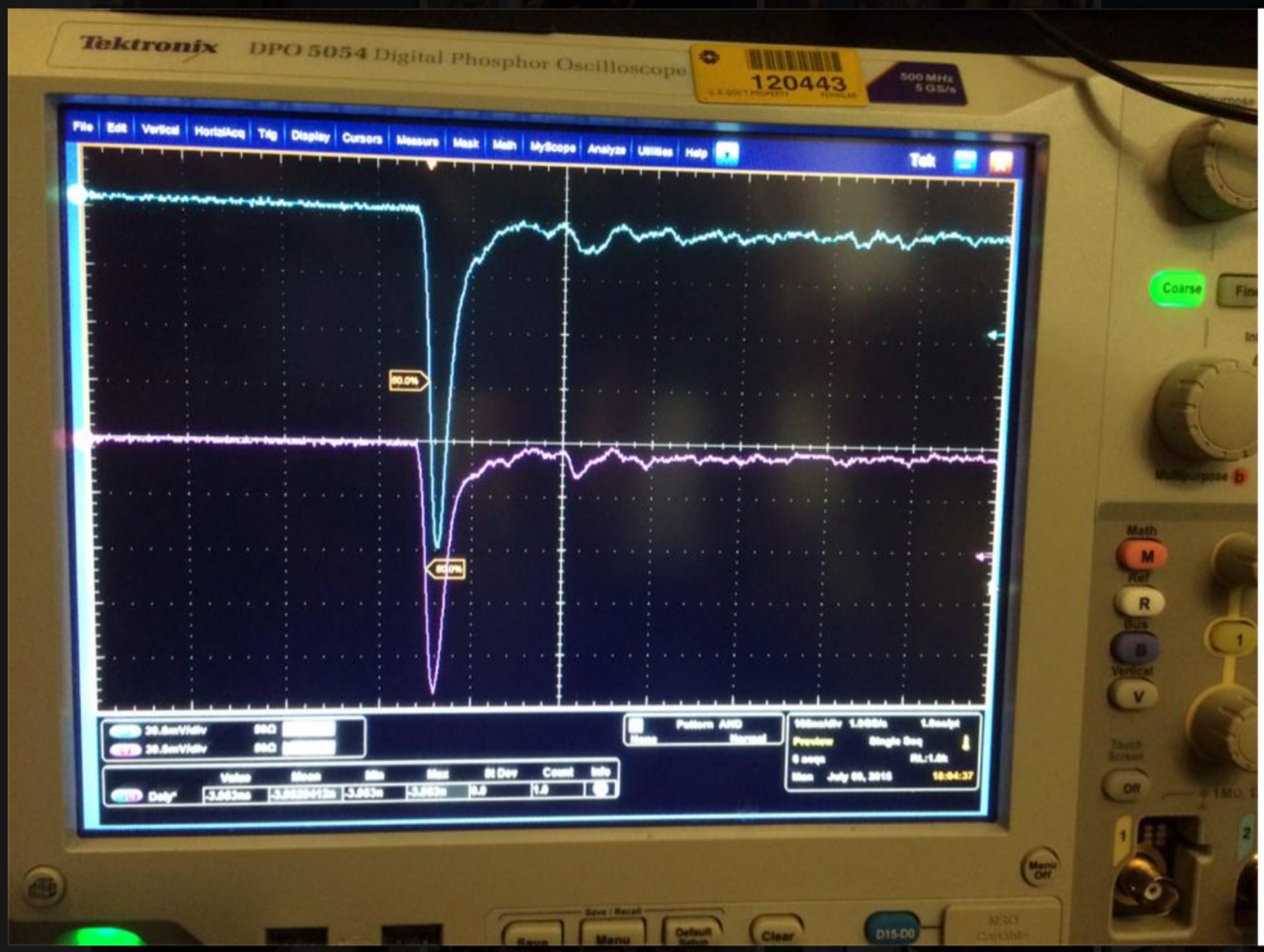
Lindley Winslow, Teppei Katori, Yun-Tse Tsai and 50 others like this.

2 shares

Write a comment...

Filling was monitored by an interactive app!
… and of course broadcast :) …

MicroBooNE in 2015



MicroBooNE
July 9 · Edited ·

July 9th!

Here's another one. We turned on 2 adjacent PMTs and we see two signals in coincidence. This is what you might expect for a signal from a muon. We are not running at nominal voltage yet, so it just gets better from here!

Like · Comment · Share

Teppei Katori, Yun-Tse Tsai, Aleena Rafique and 39 others like this. Most Recent

1 share

Aleena Rafique Great
Like · Reply · July 9 at 9:49pm

Doug Wiegand Over my head. Thank goodness when we hang out you don't talk business.
Like · Reply · July 9 at 9:51pm

Write a comment...

People You May Know See All

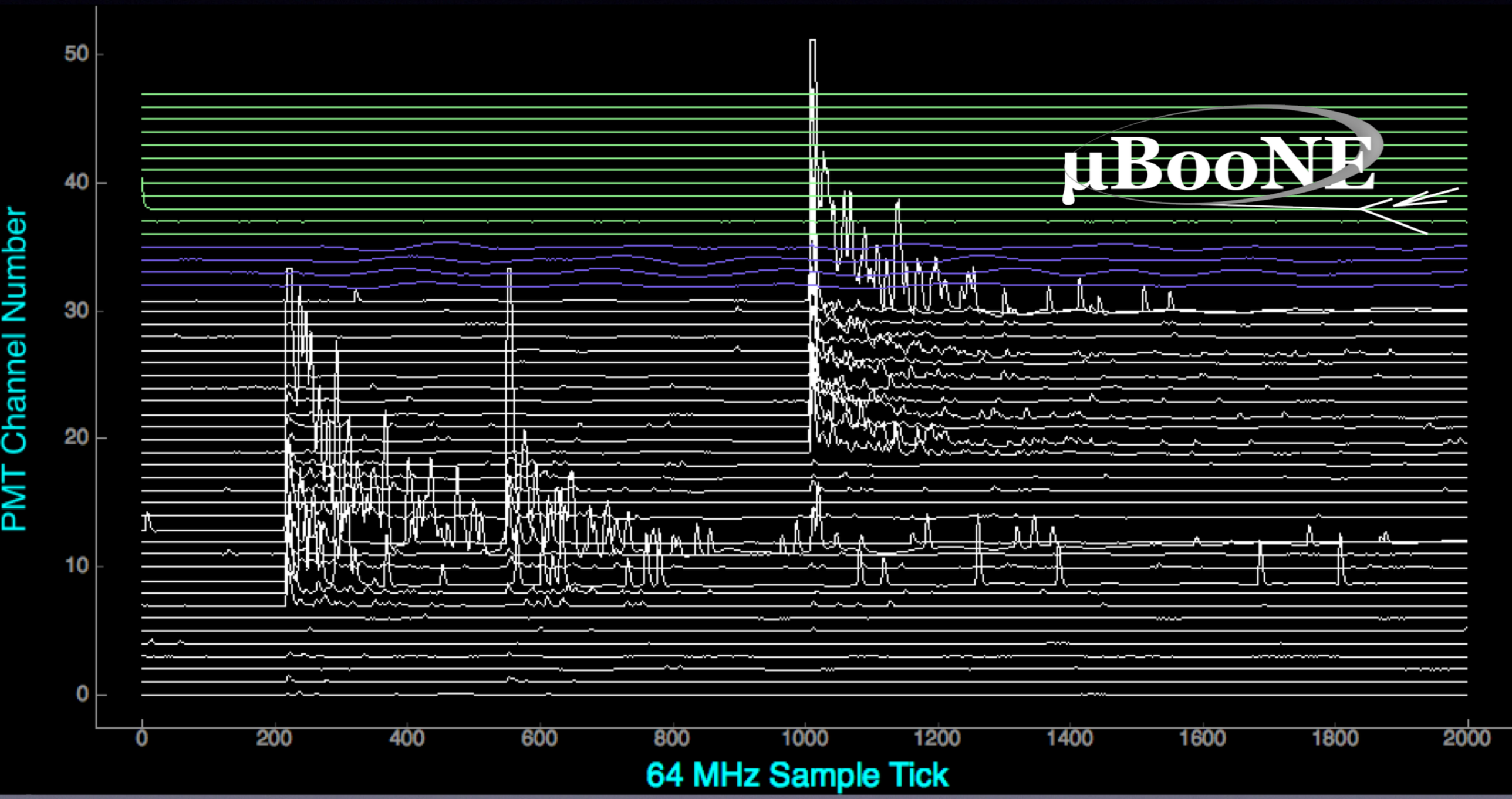
Roberto Acciarri
13 mutual friends
Add Friend

Same day, we turned on PMTs….
and VERY LIKELY Cosmic Signal observed :)

MicroBooNE in 2015

Digitized PMT Waveforms From Readout

Cosmic rays make time coincident large amplitude waveforms



MicroBooNE in 2015

Digitized PMT Waveforms From Readout

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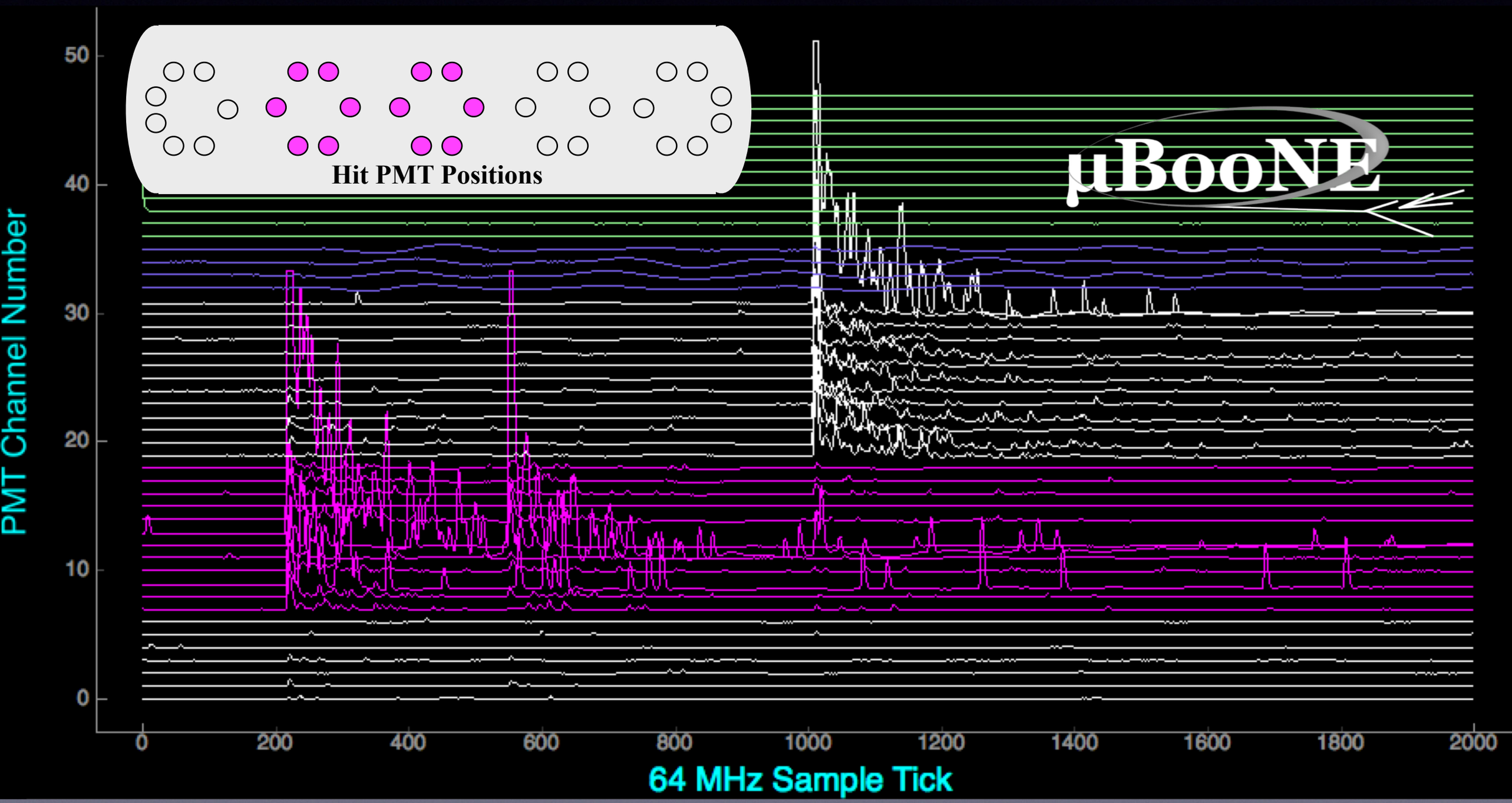

MicroBooNE in 2015

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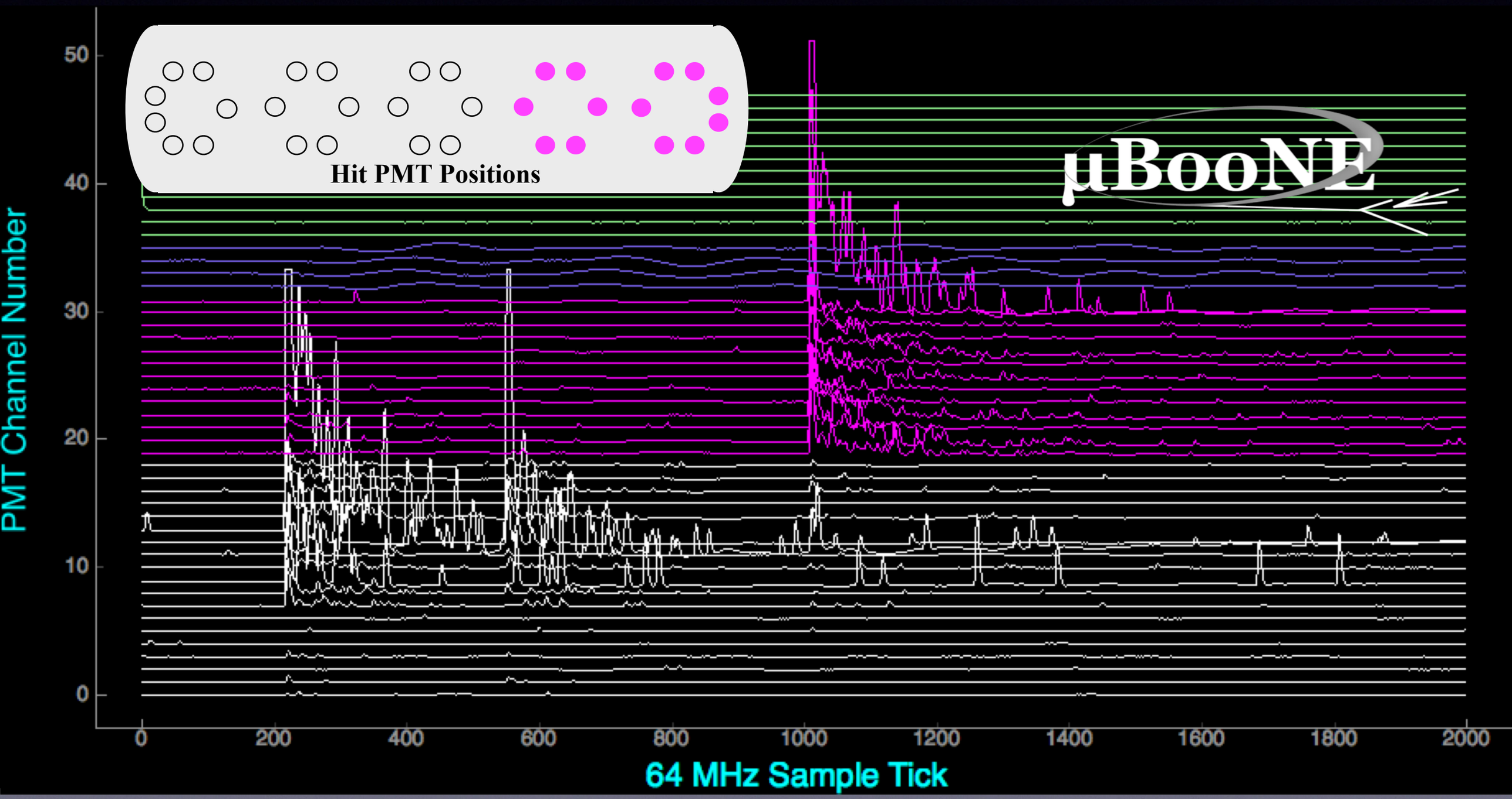


MicroBooNE in 2015

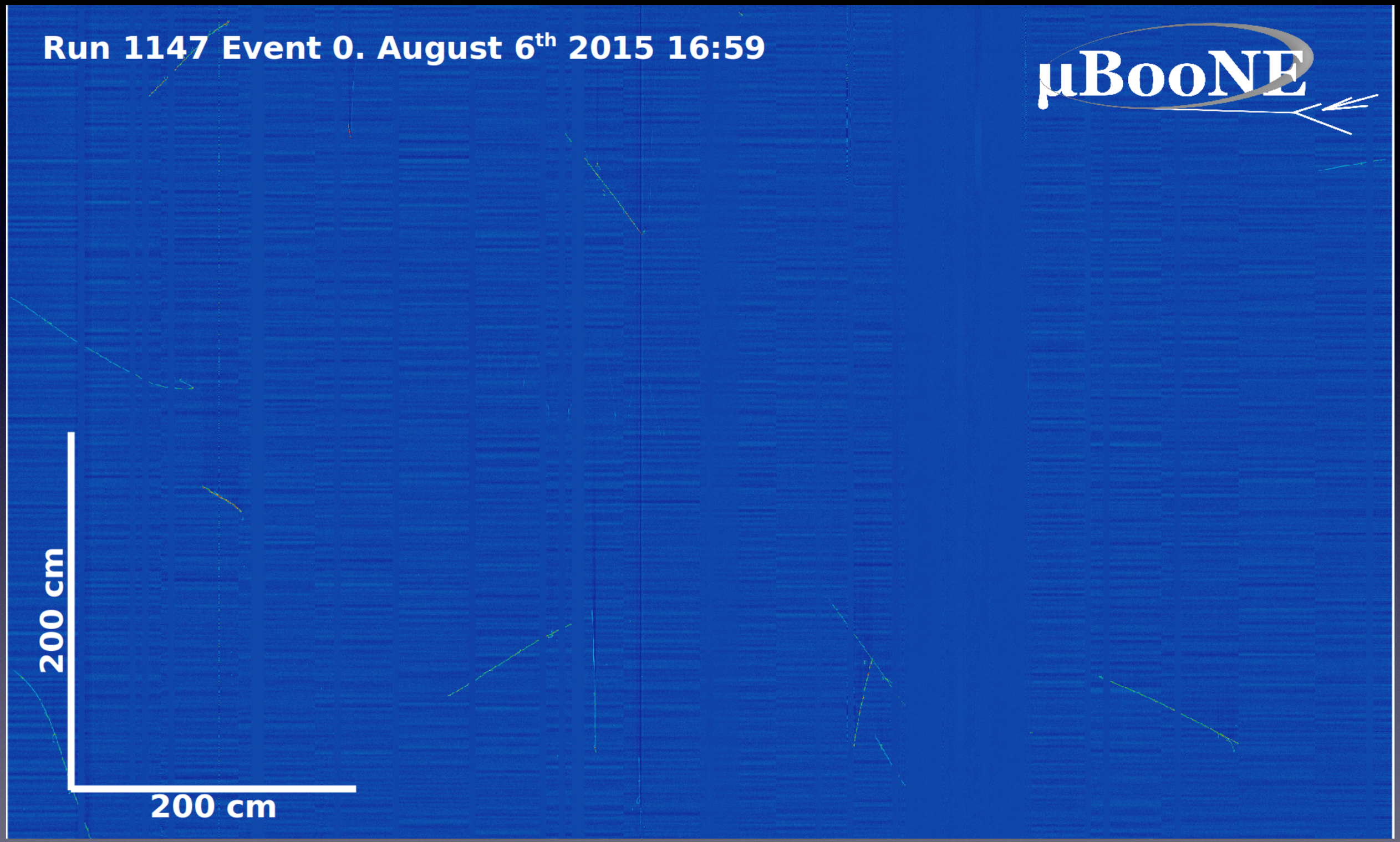
Fun also outside the detector
… nailed it …

MicroBooNE in 2015

- **Initial drift HV ramp-up** on August 6th
  - Smooth operation to ramp up to ~1/2 target (58kV)
  - Complete “Slow”Monitoring/Control + immediate data taking/processing
  - Data became available for analysis within minutes

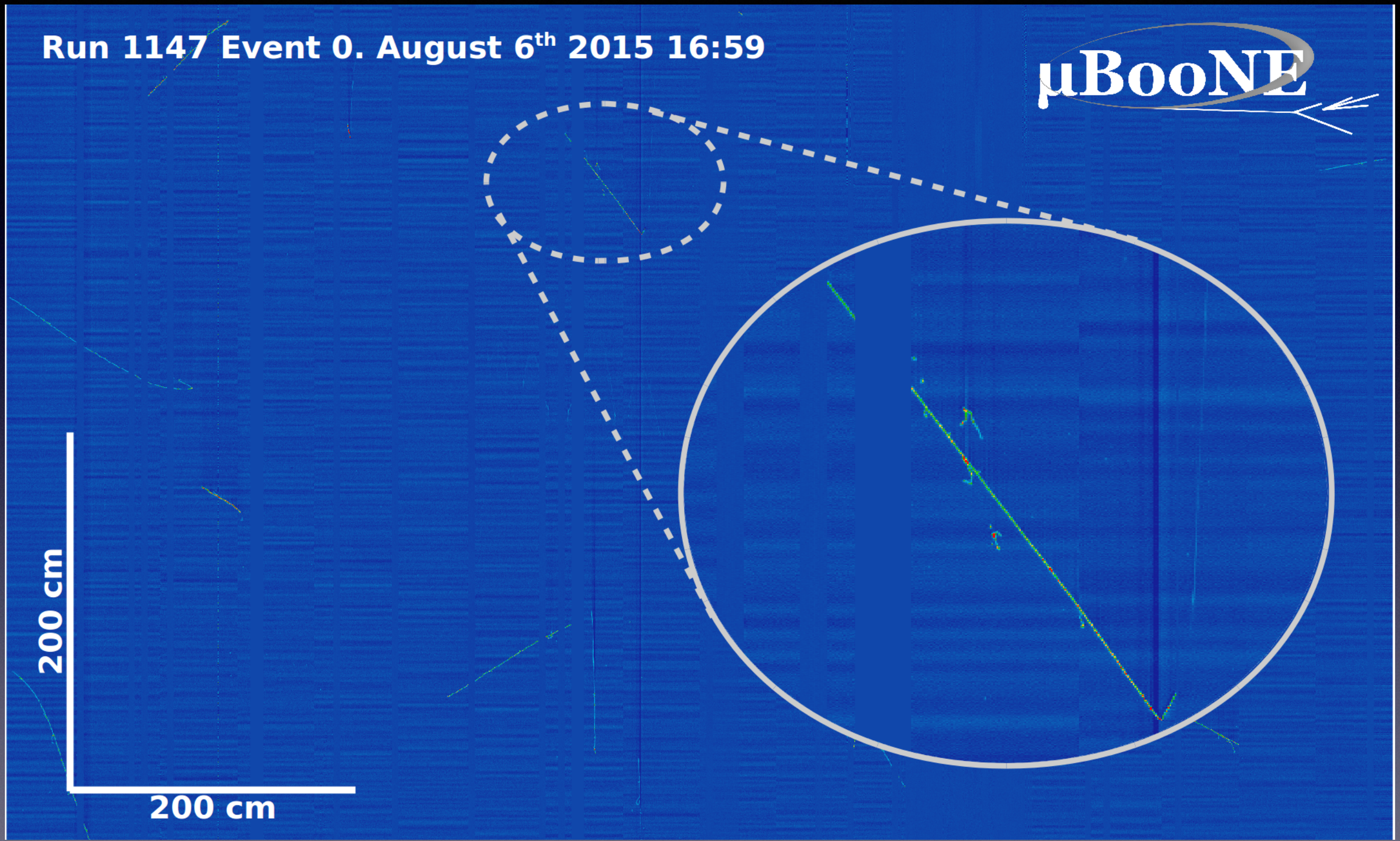
… in tense …
nervous & exciting
atmosphere :)

MicroBooNE in 2015



Cosmic track observed! @ First Event @ 58 kV

MicroBooNE in 2015



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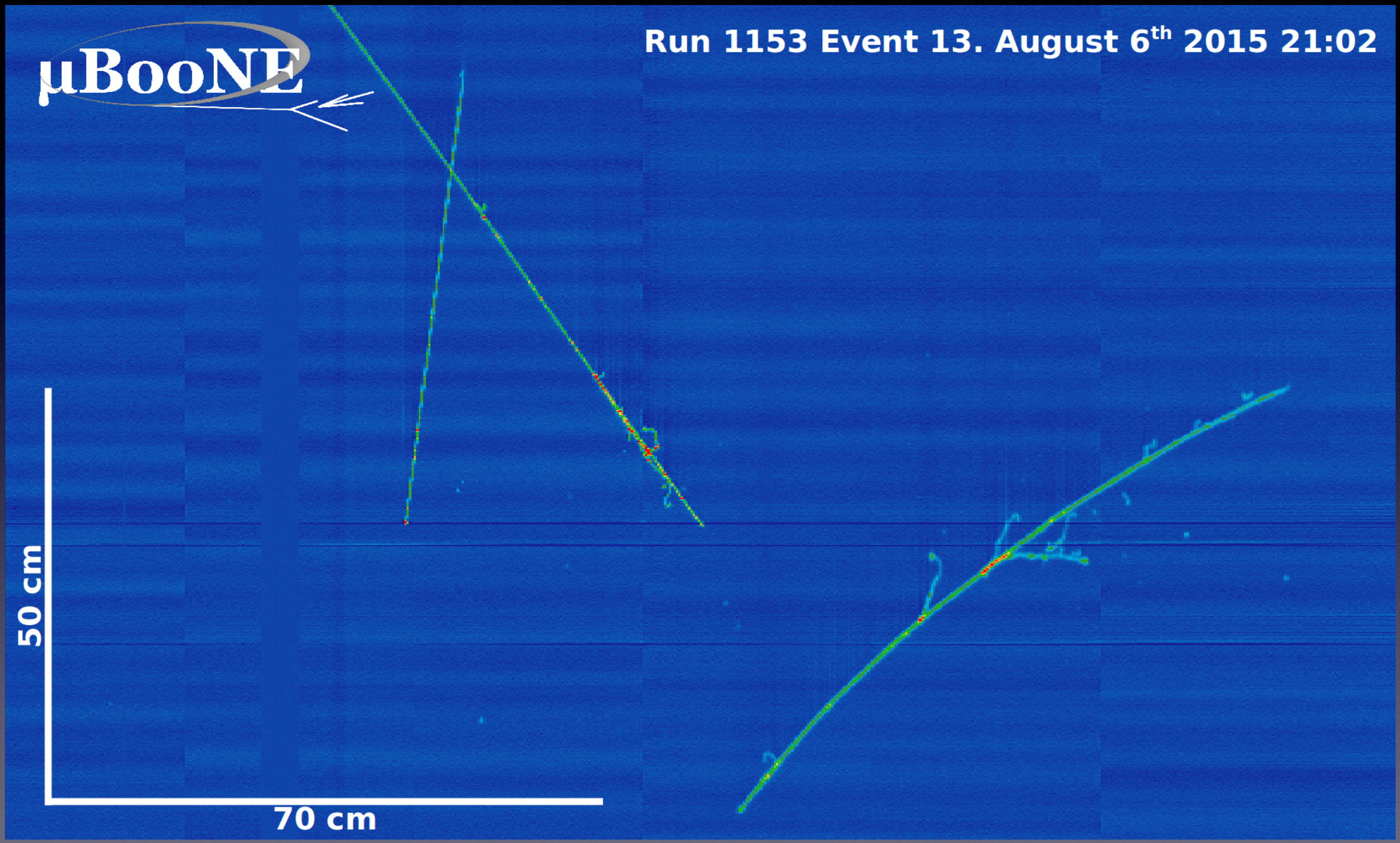
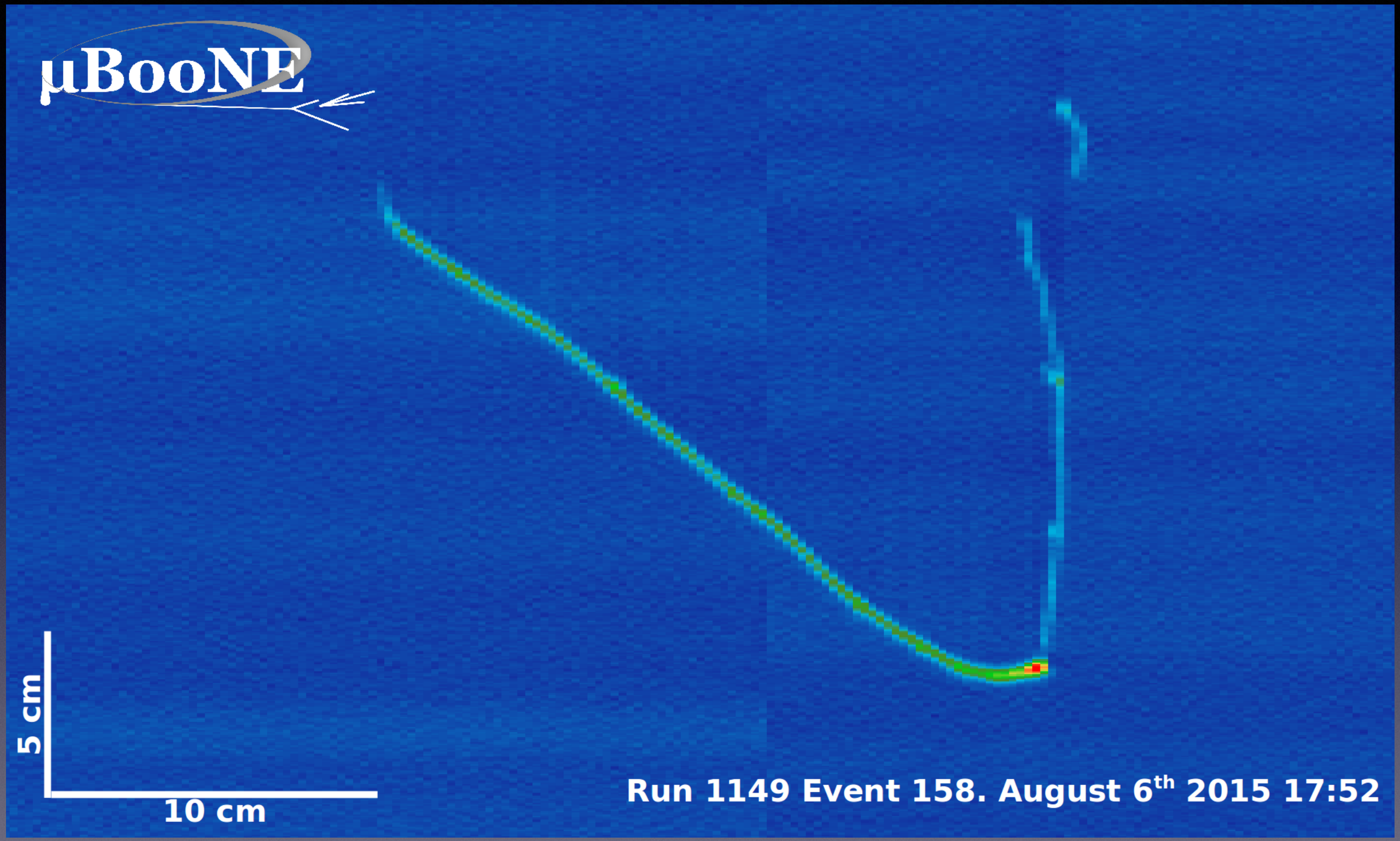
MicroBooNE in 2015



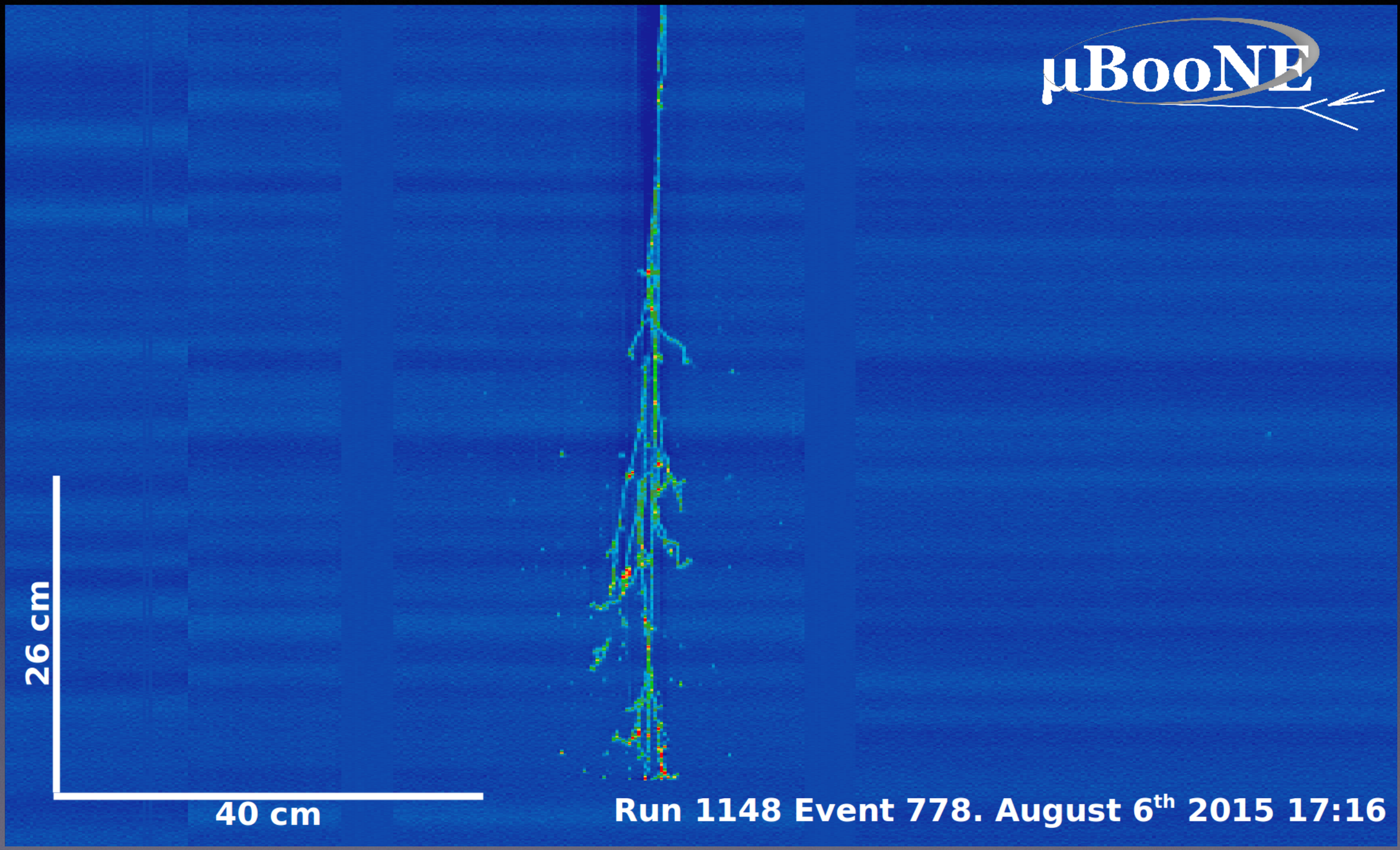
Cosmic rays & delta rays

MicroBooNE in 2015



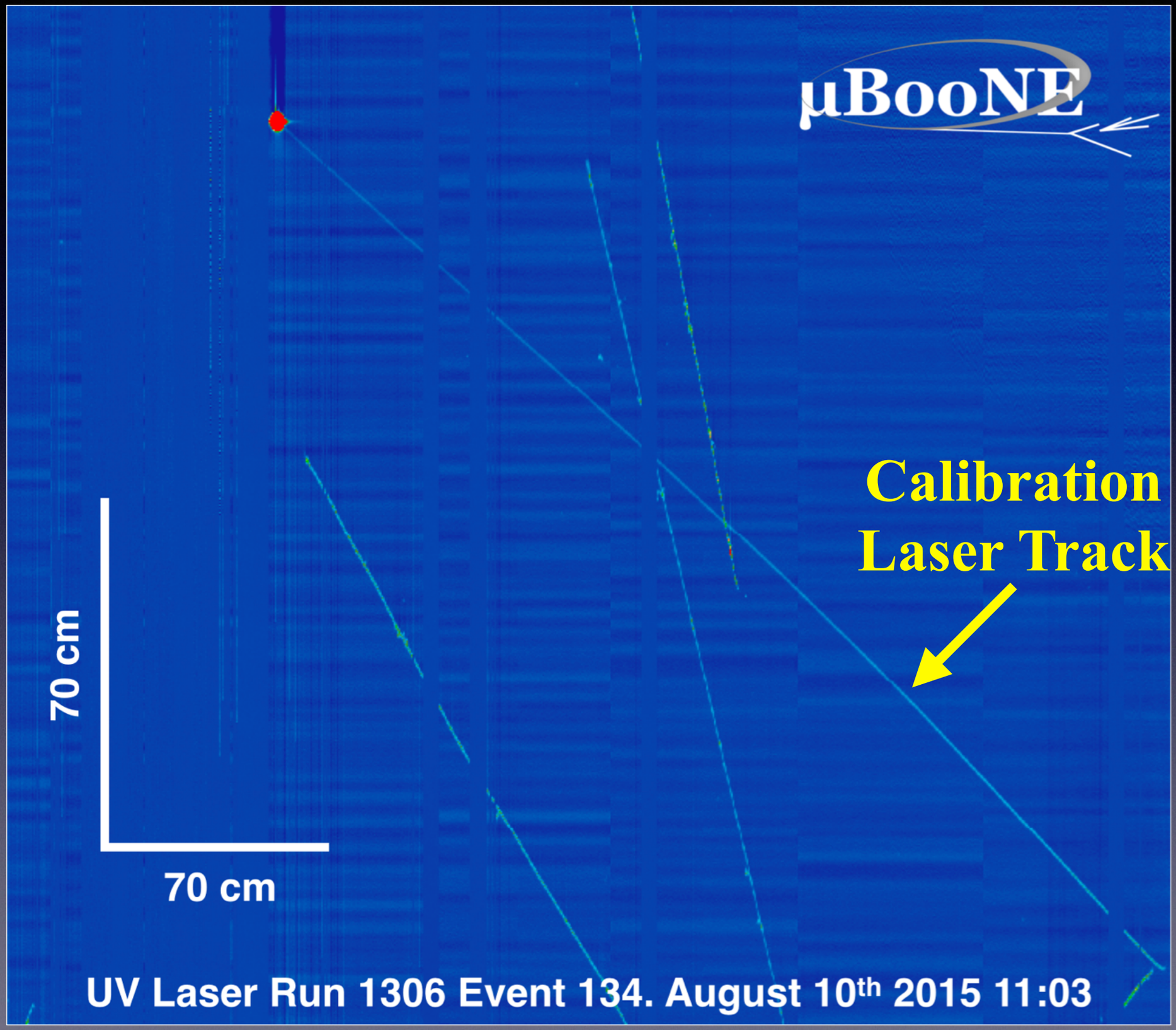
Likely muon decaying into michel electron

MicroBooNE in 2015

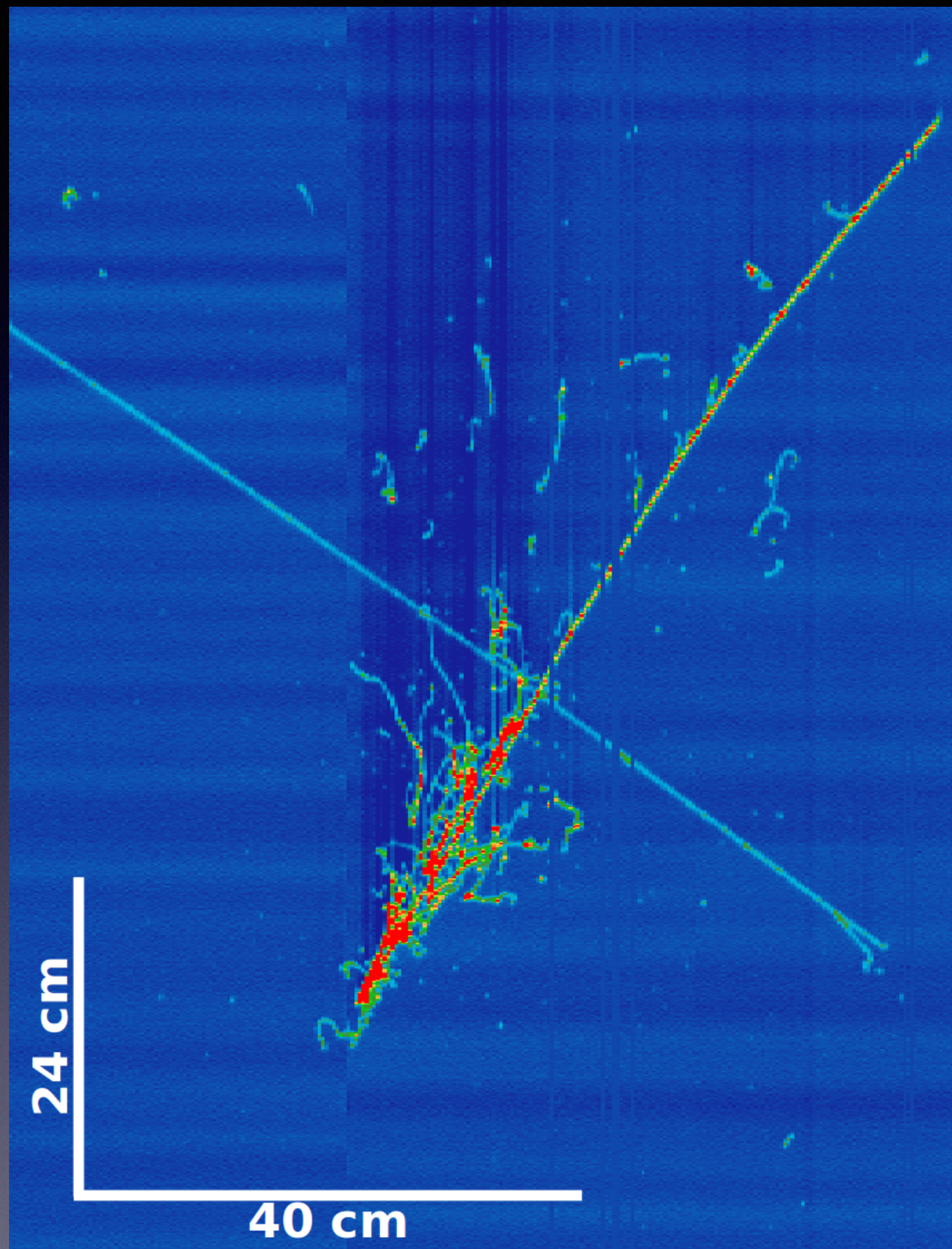


EM Shower!

MicroBooNE in 2015



MicroBooNE in 2015



μBooNE

Very Successful 1st Step!

More excitement to come!

Run 1153 Event 40. August 6th 2015 21:07

EM Shower!

Summary & Outlook of Short Baseline Neutrino Program

Summary

- **Short Baseline Neutrino Program @ Fermilab**
  - **High Δm^2 sterile neutrino oscillation search** with well understood BNB source
  - **Three LArTPC detector at different L/E** to maximize sensitivity
  - Part of a larger LArTPC neutrino program in the U.S.
- **MicroBooNE**
  - **Commissioning!**: detector purging, cooling, LAr filling all successful
  - **Track/Shower seen** @ initial drift HV ramp-up to 58 kV!
  - **Finish commissioning before beam** (October 2015)
  - Plan to take **high statistics cosmic BG sample**
- **SBND**
  - **Very active front**, rapid progress in 2015 **(construction @ November!)**
- **ICARUS T600**
  - Preparation of T300 modules on-going @ CERN

Thank you for …

Your attention (please wake up now)

NuFact 2015 local organizers

Brazil for great food, weather, and culture

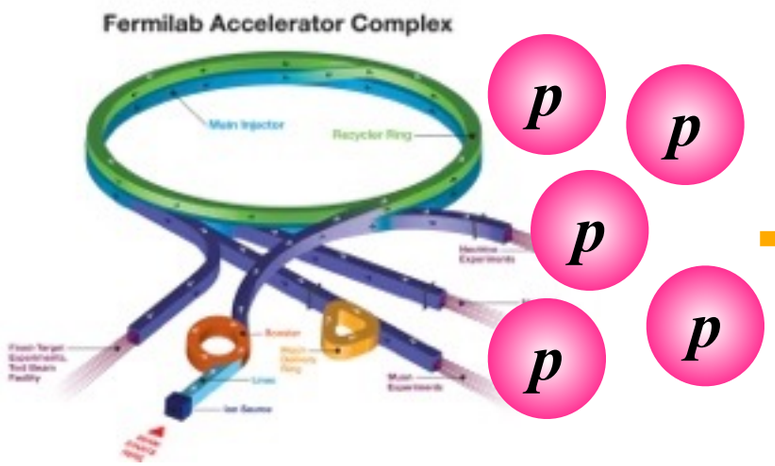
My personal excitement in 2015

First baby in January 5th :)

Detector Back Ups

BNB: Neutrino Source

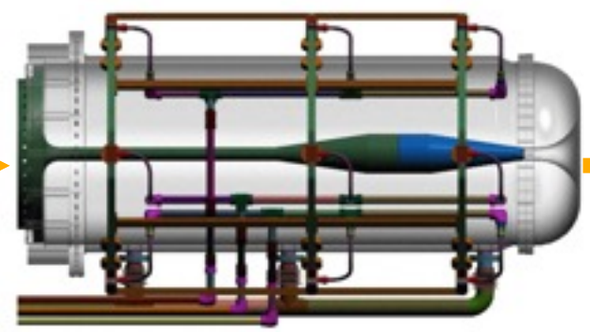
- 8 GeV protons from Booster hits Beryllium target to produce mesons



p p p p p

Booster
(8 GeV Protons)

Beryllium Target
"Thin & Long"

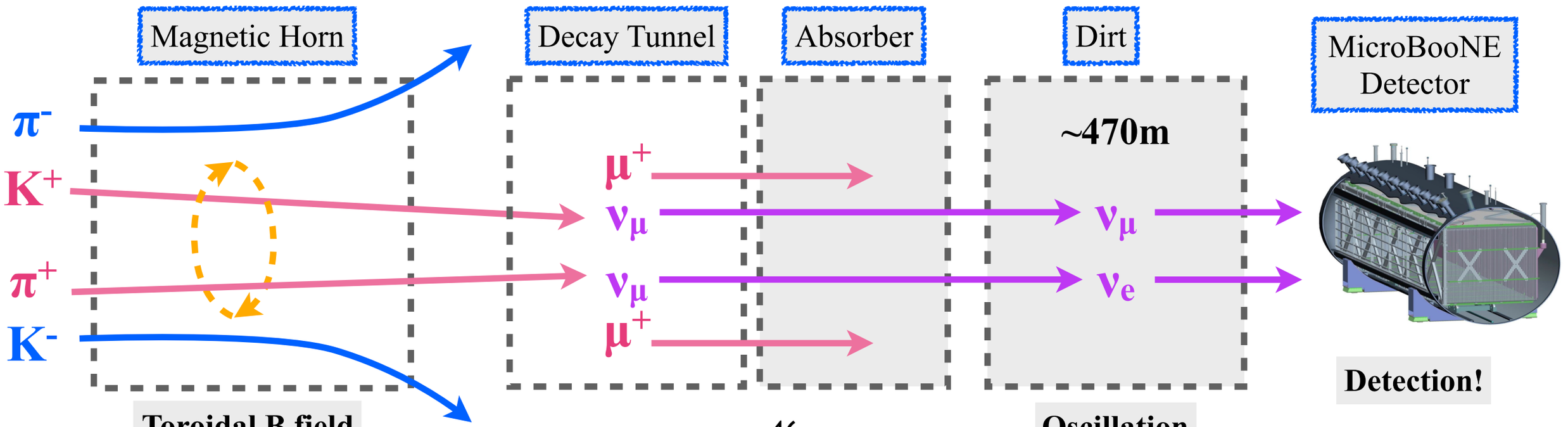


Magnetic Horn
(Meson Focusing)

K π π π K K π π

***New* Horn**
(replaced in 2015)

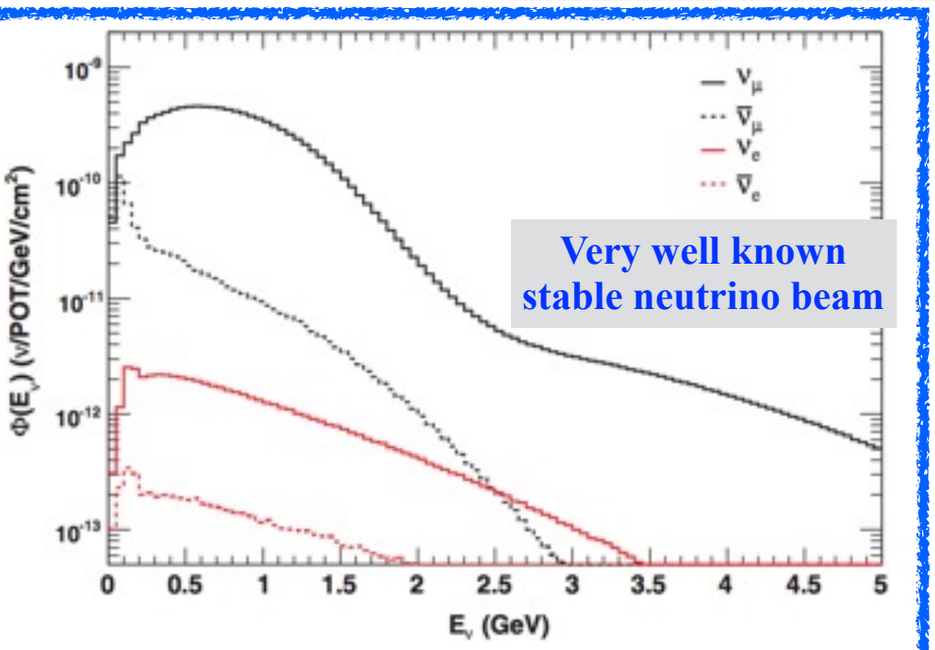
- Horn focuses positive (negative) mesons to produce neutrinos (anti-nu)



BNB: Providing Neutrinos Over a Decade

MicroBooNE @ FNAL

PRD 79, 072002 (2009)



Very well known stable neutrino beam

Horn: Neutrino Mode

Event Rate Break Down

(flux & xs)

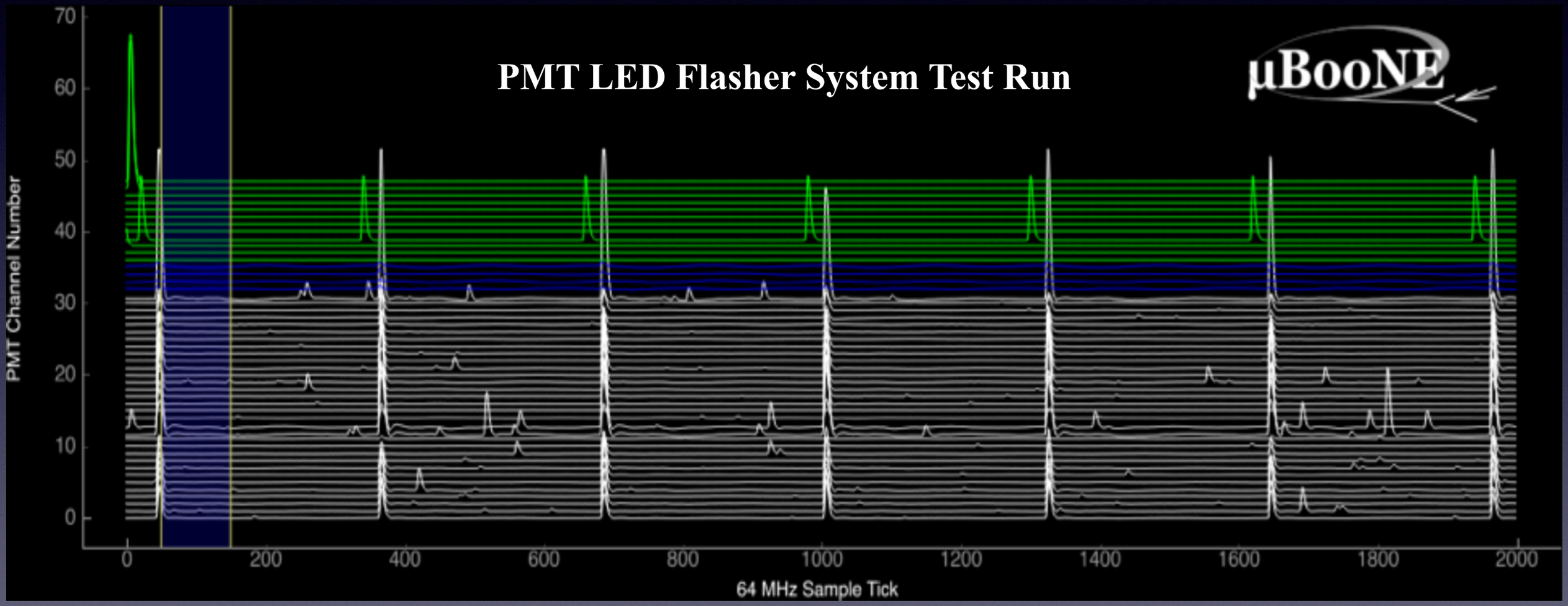
- $\nu_\mu \simeq 93.6\%$
- $\bar{\nu}_\mu \simeq 5.86\ \%$
- $\nu_e \simeq 0.5\ \%$
- $\bar{\nu}_e \simeq 0.05\ \%$

… **high purity ν_μ beam** …

MicroBooNE in 2015

Digitized PMT Waveforms From Readout

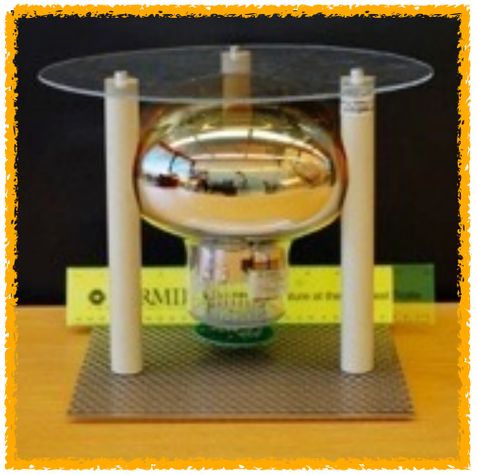
From LED Flasher calibration system test run



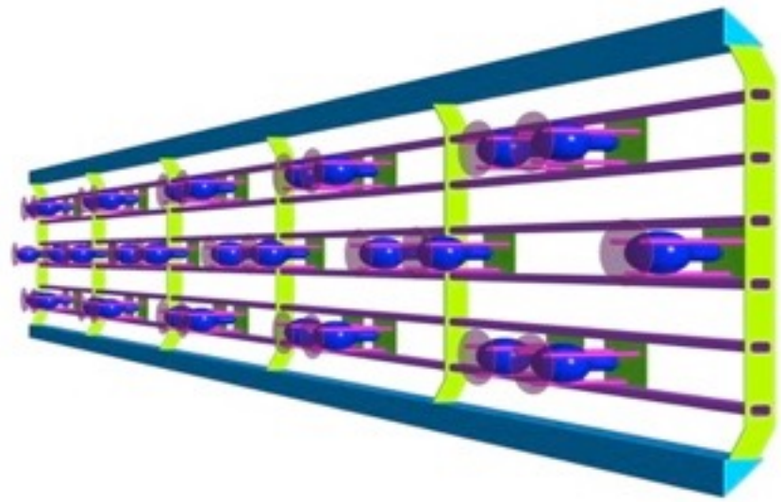
LED Flasher sends LED light to each PMTs (green pulse @ Ch. 39)
seen by each PMTs shortly after (time-coincident signal)

Optical Detector

- **What is it? What for?**
  - 32 8” PMTs
  - Crucial roles
    - **Getting trigger**
    - **Reconstructing YZ**
      - ✓ **Cosmic background rejection**



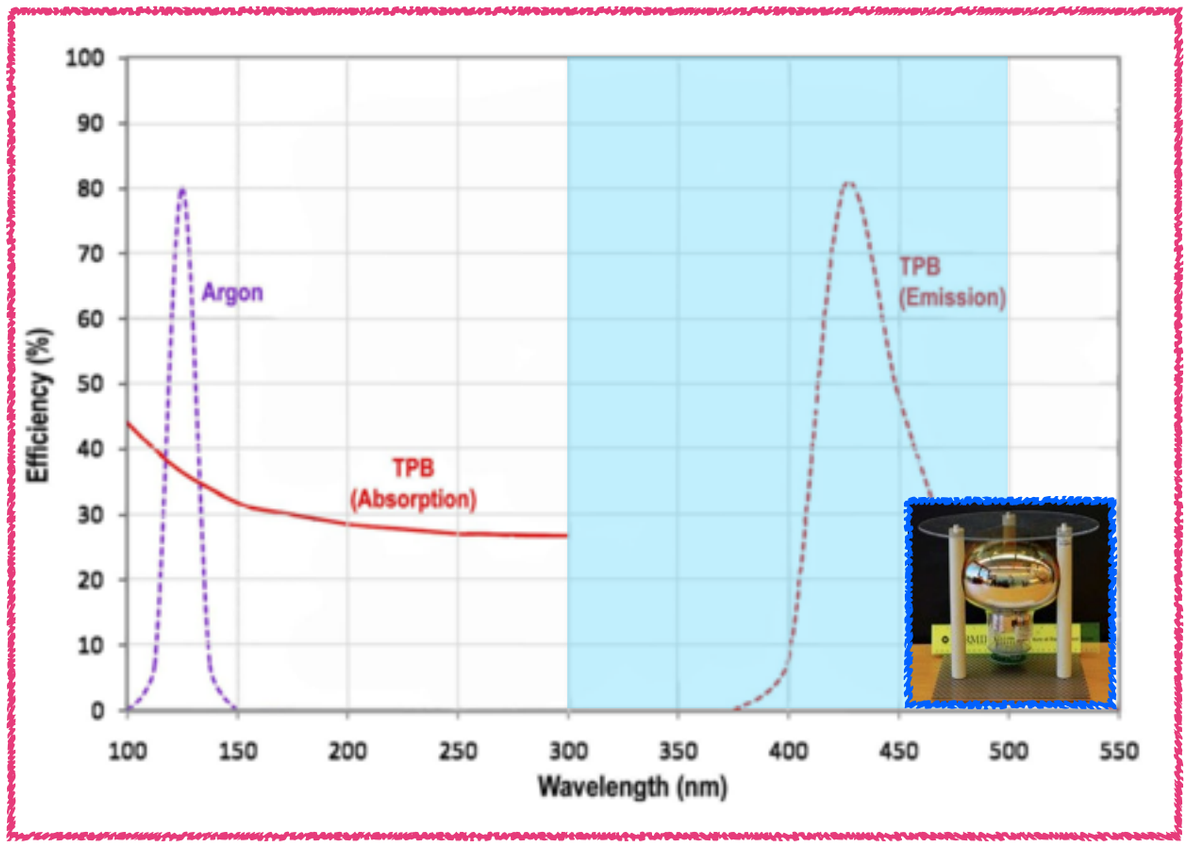
MicroBooNE PMT



Array of 32 PMTs

Crucial for MicroBooNE
because of
high cosmic ray rate (~5kHz) @ surface!

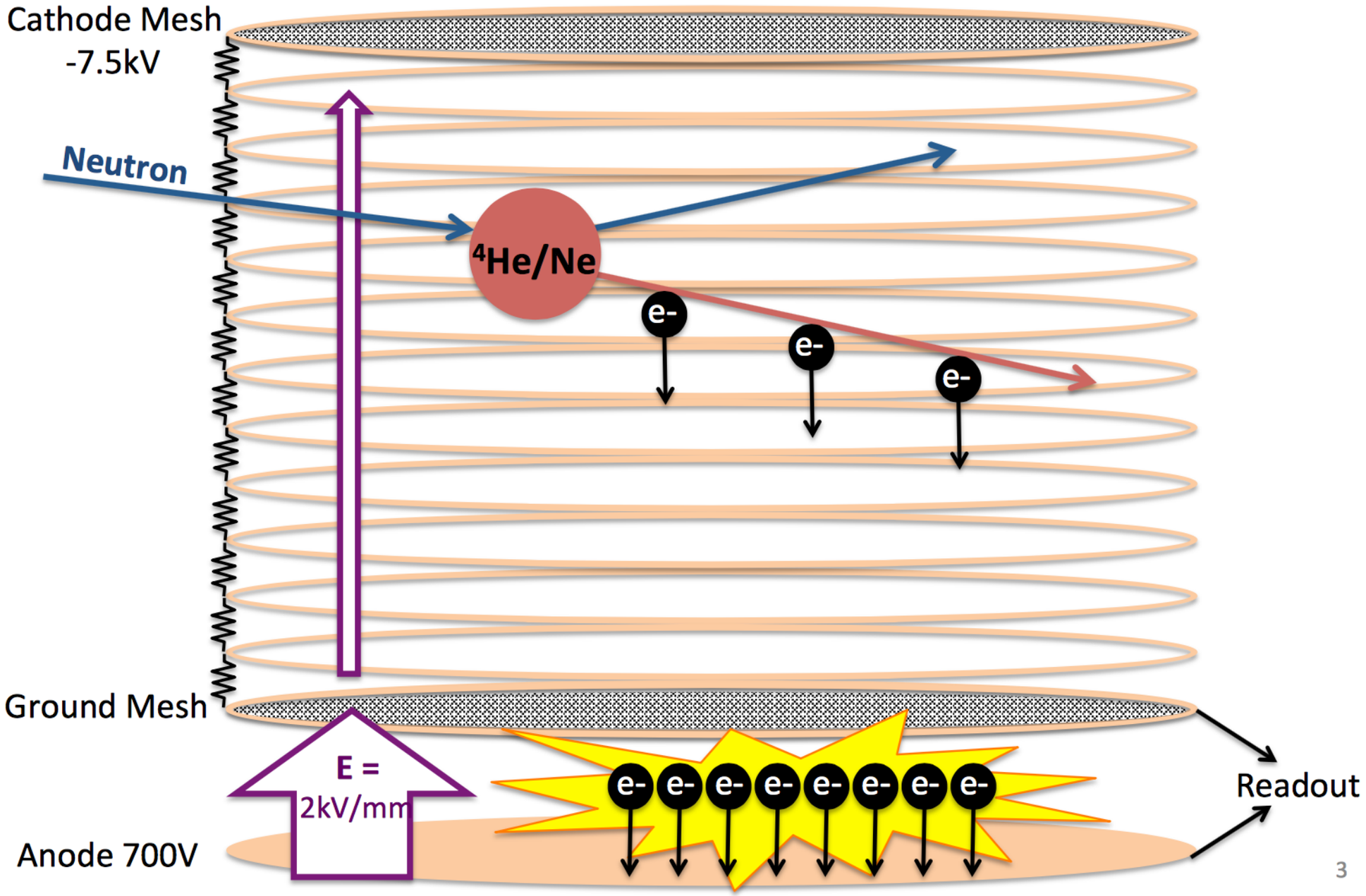
- **LAr optical properties**
  - No detail here... but LOTS of physics!
    - Read arxiv 1306.4605 for instance
  - Produced within **6 ns** of interaction
  - High light yield ≃ 6000 photons / MeV
  - **“Transparent” to its own light**
    - No re-scintillation (does Rayleigh scatter)
    - Wavelength shift by **TPB**



TPB shifts wavelength from 128 nm to 430 nm, appropriate for PMTs

Neutron TPC

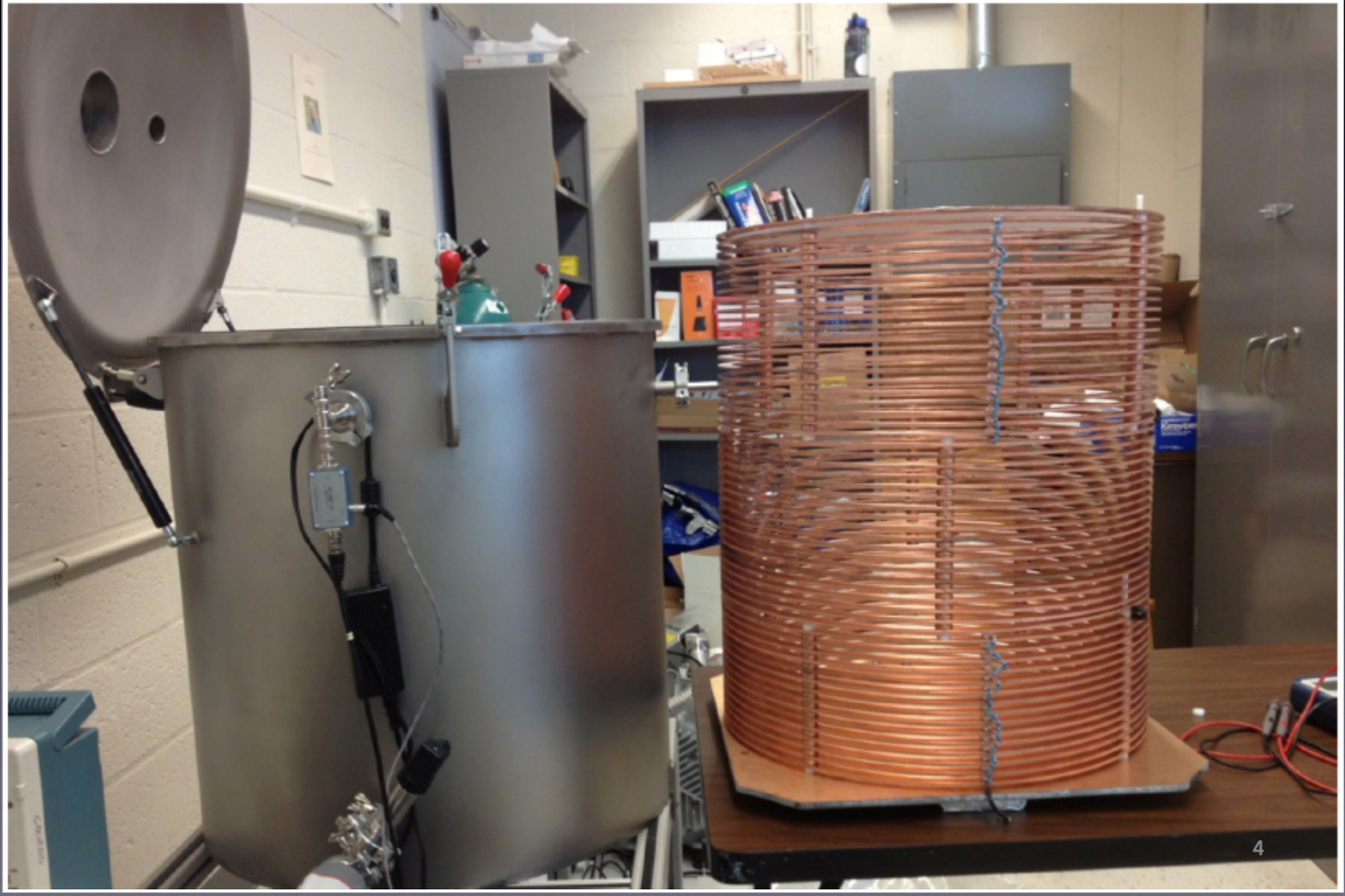
87.5% ^{4}He/Ne + 12.5% CF_4 @ 600 Torr



Courtesy of Marjon Moulai @ MIT
From DPF 2015

Neutron TPC

Field cage outside of chamber



Courtesy of Marjon Moulai @ MIT
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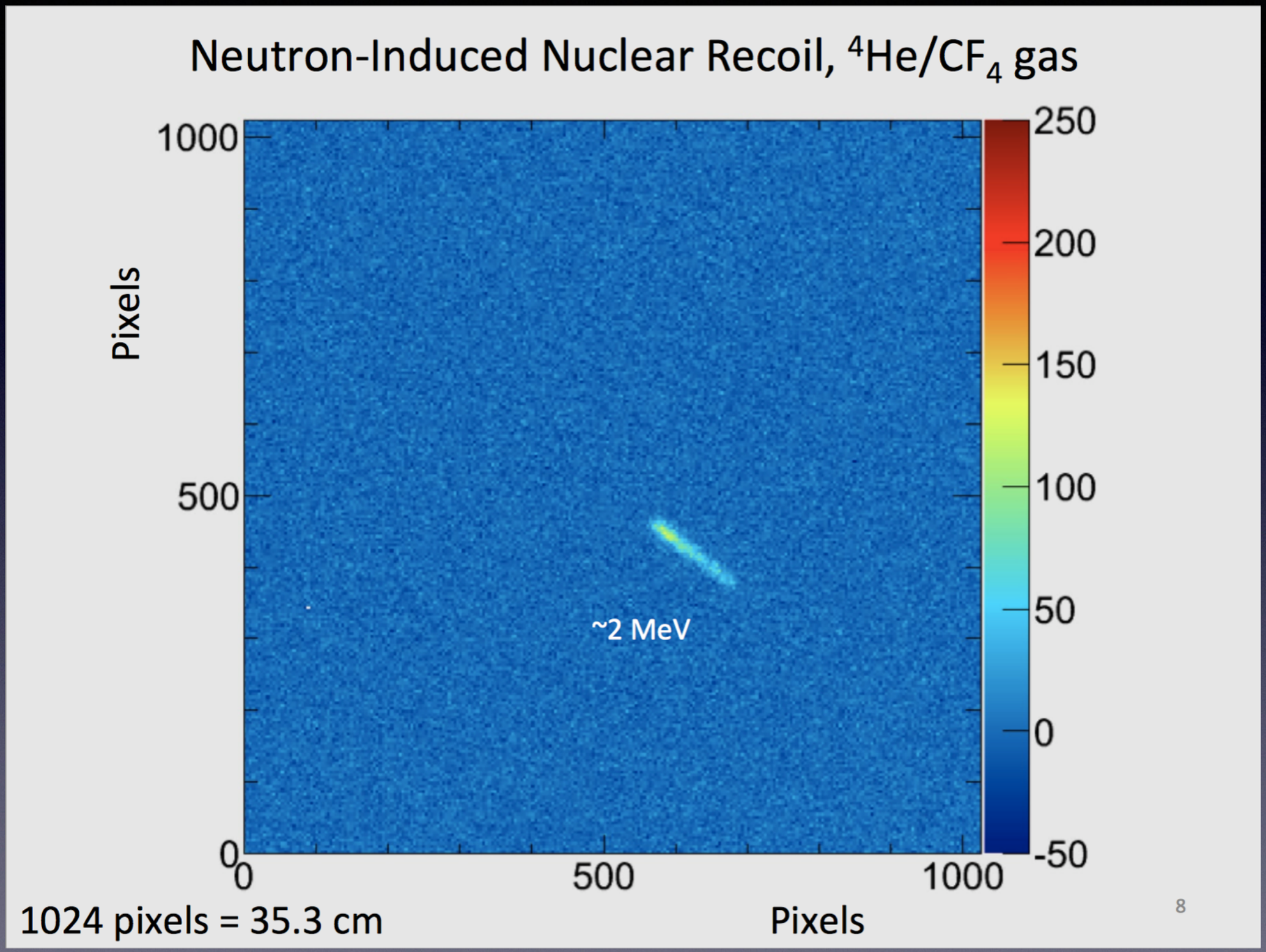
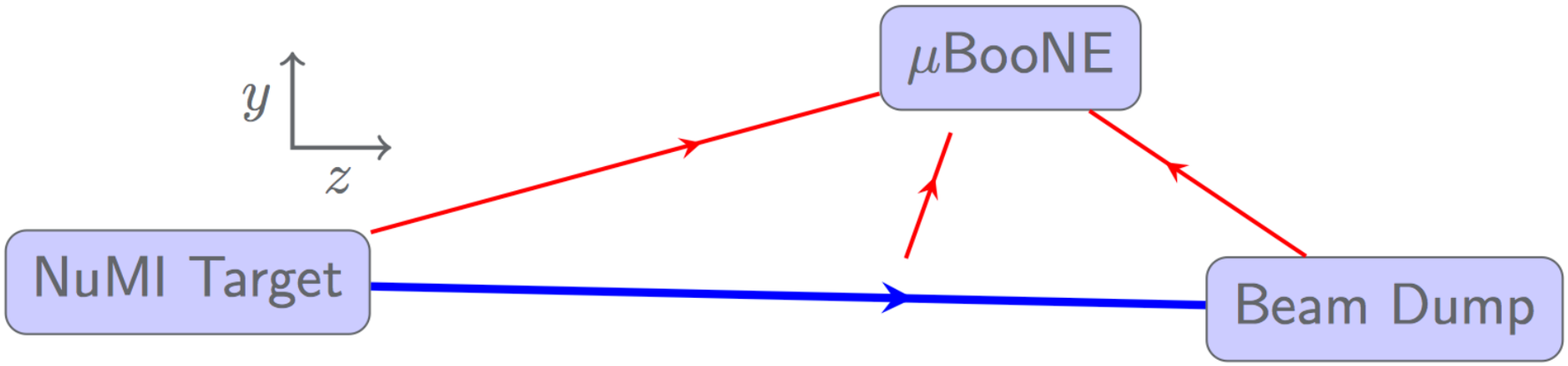
Neutron TPC



Courtesy of Marjon Moulai @ MIT
From DPF 2015

NuMI @ MicroBooNE

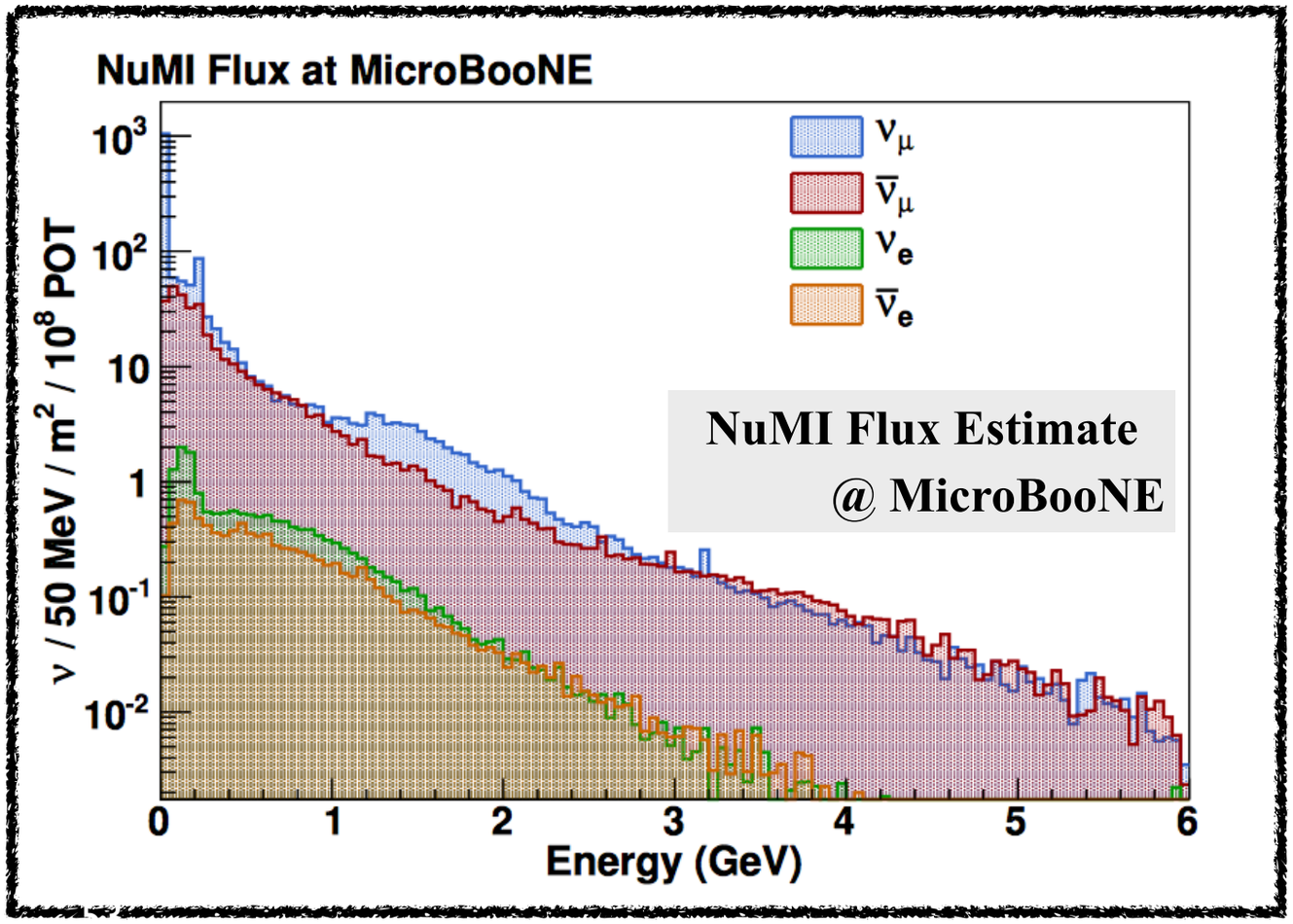


- We can trigger on NuMI beam
  - "Off-Axis" ≃ 25°
  - Target-Detector ≃ 690 m
  - Absorber-Detector ≃ 100 m

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

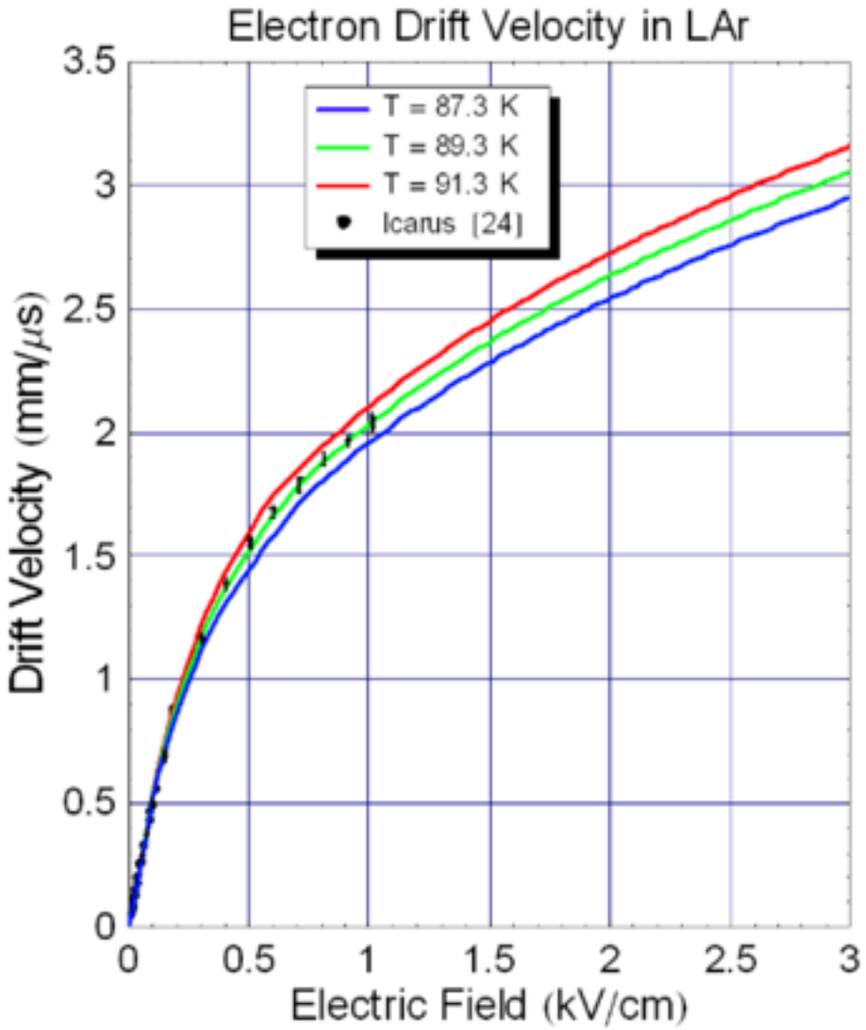
Expected Event Rate (2~3 years running)

Plots/Numbers/Diagram Courtesy of D. Davis



LArTPC: Temperature & HV

- **Stability** ... key for stable operation & detector systematics
  - Argon **temperature** and **HV**
  - LAr purity (later slide)



Temperature & **Electric field**
affect **drift velocity**!

Drift velocity depends on **T** & $|\boldsymbol{E}|$

$$v_d(T,|\boldsymbol{E}|) = (P_1(T - T_0) + 1)\left(P_3|\boldsymbol{E}|\ln\left(1 + \frac{P_4}{|\boldsymbol{E}|}\right) + P_5|\boldsymbol{E}|^{P_6}\right) + P_2(T - T_0).$$

W. Walkowiak NIM A449 p.288 (2000)

which **affects measurement of X position**

LArTPC: Temperature & HV

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  - Argon **temperature** and **HV**
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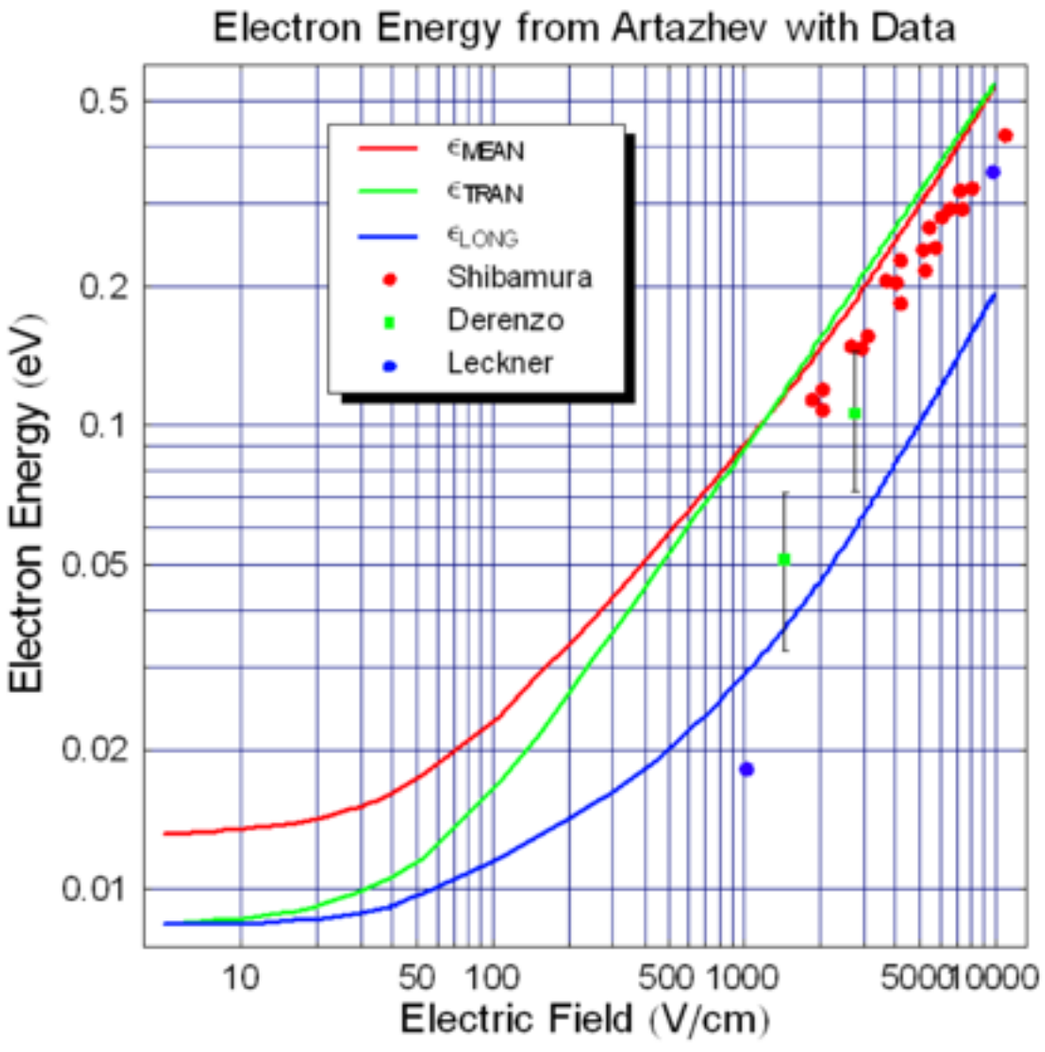


Electric Field
affects **Electron Energy**

Drift velocity depends on **T** & $|E|$

$$v_d(T,|E|) = (P_1(T - T_0) + 1)\left(P_3|E|\ln\left(1 + \frac{P_4}{|E|}\right) + P_5|E|^{P_6}\right) + P_2(T - T_0).$$

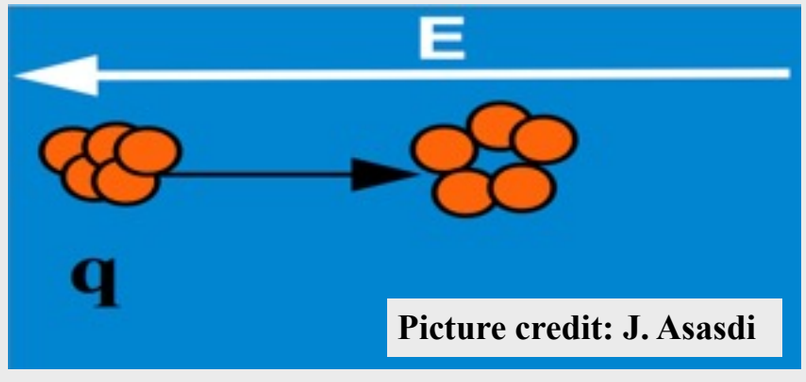
W. Walkowiak NIM A449 p.288 (2000)

which **affects measurement of X position**

Diffusion (σ) depends on **drift distance** & $|E|$

$$\sigma = \sqrt{\frac{2\varepsilon z}{E}}$$

ε : electron energy
z : drift distance
E: field strength

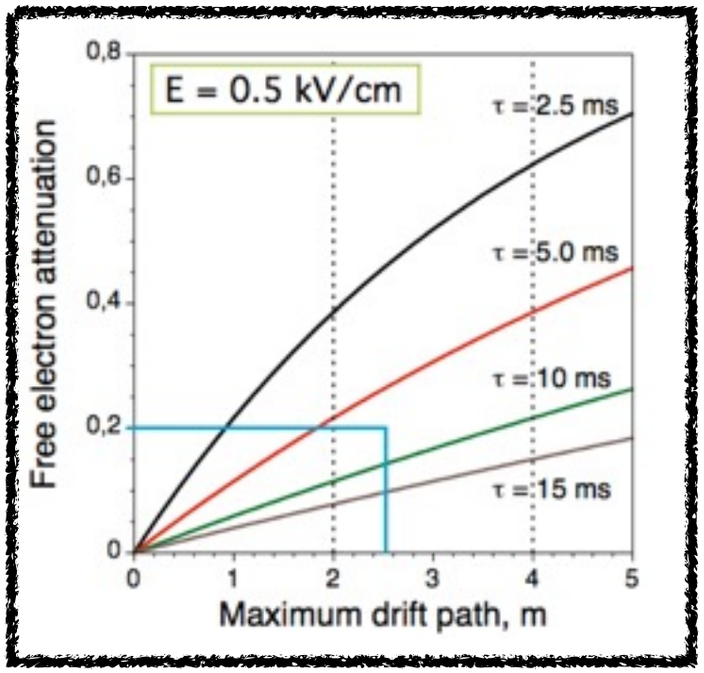


Temperature & HV are keys to understand detector response

LAr Purity

- High purity LAr necessary for 2.5 m drift!
  - Water & Oxygen affect **electron lifetime**
    - shorter lifetime = larger attenuation
  - Nitrogen causes **scintillation light quenching**
  - Goal: O_2 < 100 ppt & N_2 < 1 ppm

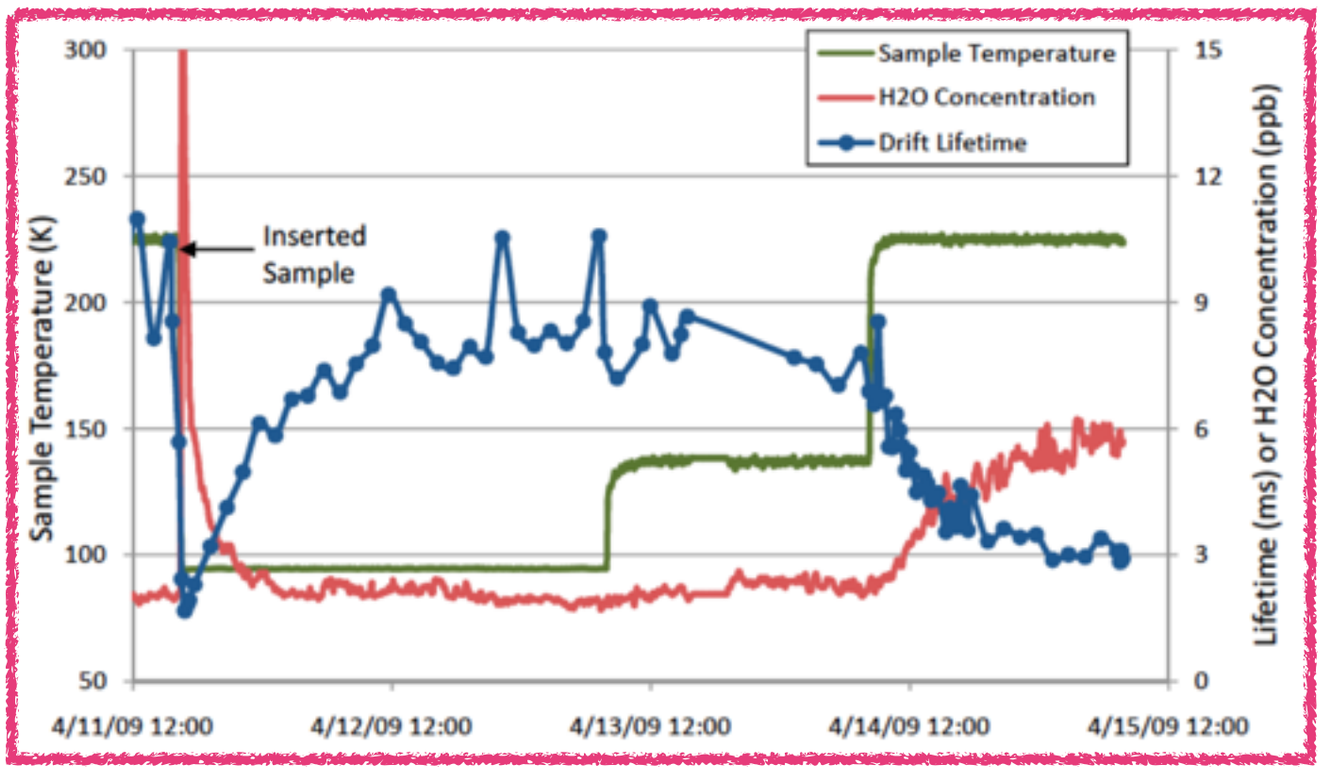
From C. Montanari, June 2007



τ_e & e^- attenuation

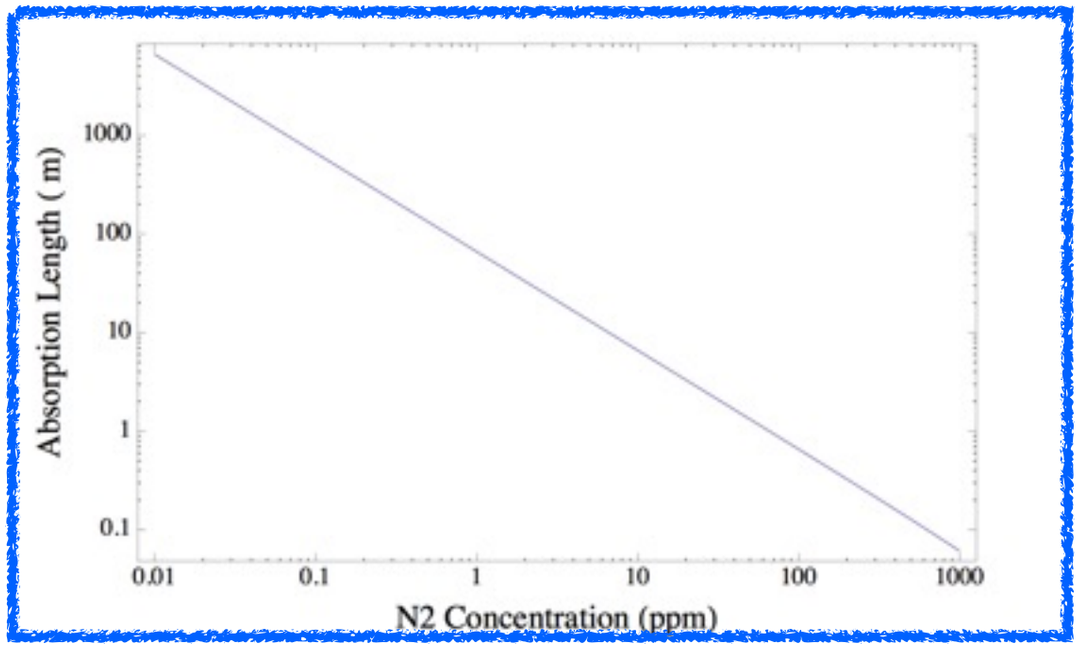
Example

H_2O Conc. vs. Lifetime



NIM A605, 396 (2009)

arxiv 1306.4605

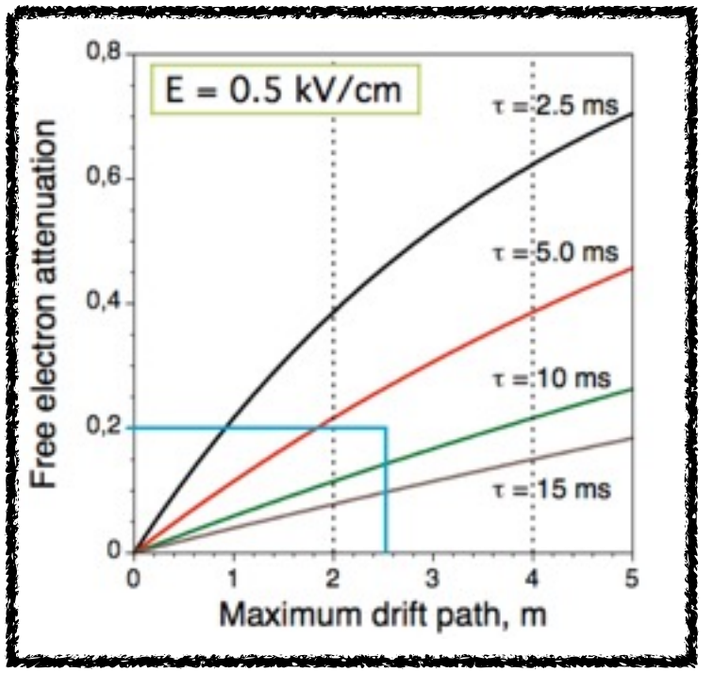


Example
N_2 Conc. vs. Light Attenuation

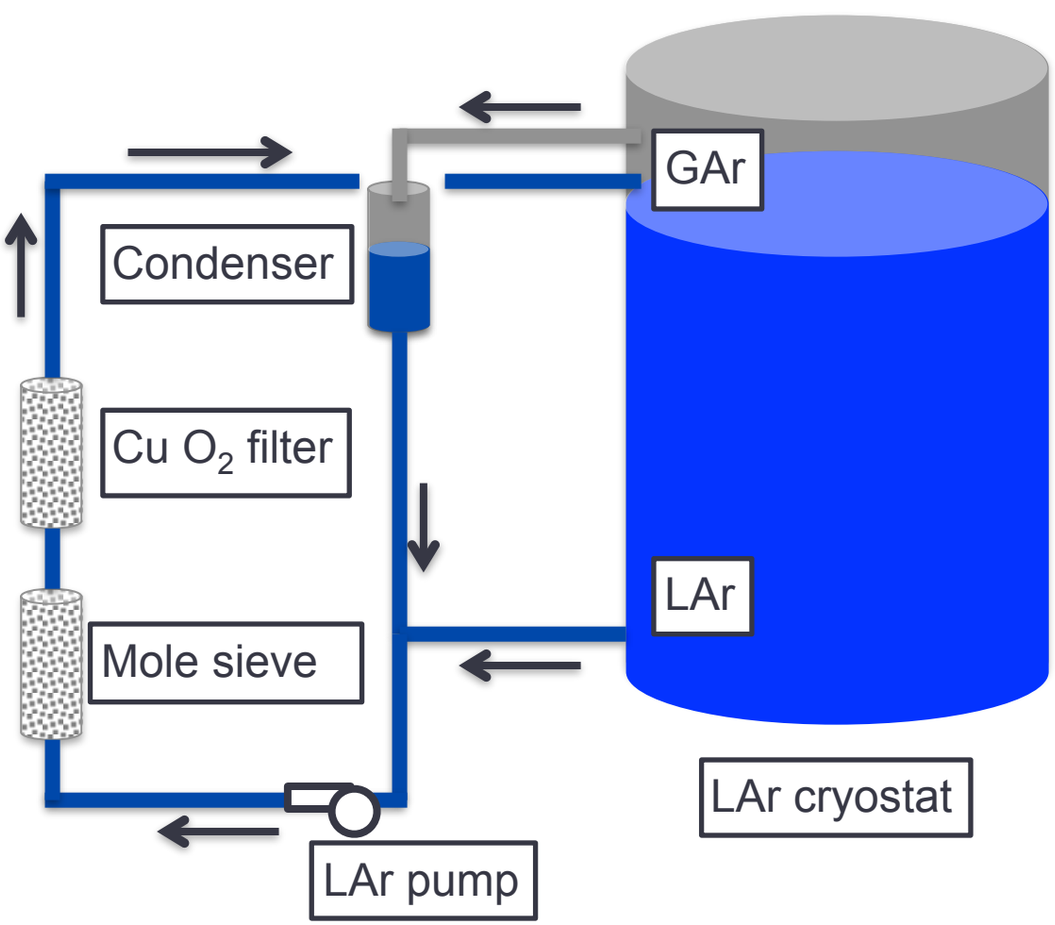
LAr Purity

- High purity LAr necessary for 2.5 m drift!
  - Water & Oxygen affect **electron lifetime**
    - shorter lifetime = larger attenuation
  - Nitrogen causes **scintillation light quenching**
  - Goal: O_2 < 100 ppt & N_2 < 1 ppm
- Filling & Purification System ... LAPD
  - **Purge the detector with GAr first**
    - Evacuating a large TPC volume is not very practical

From C. Montanari, June 2007



τ_e & e^- attenuation



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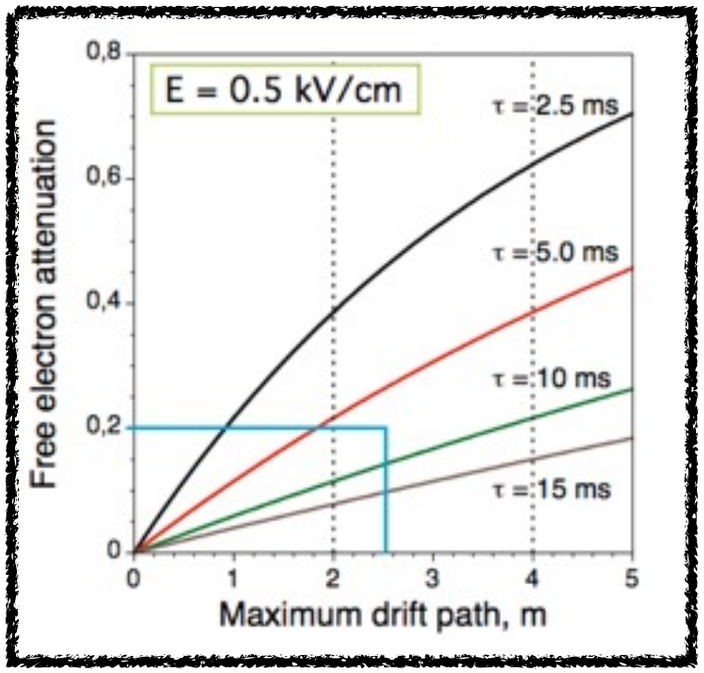
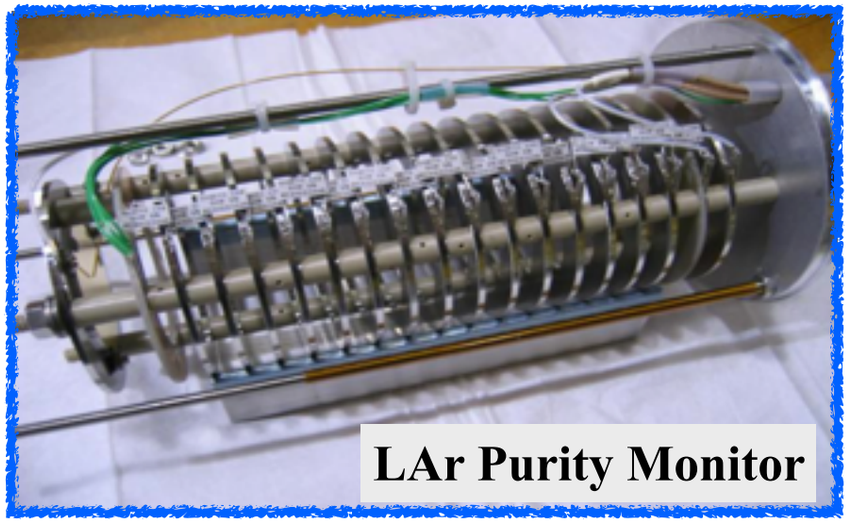


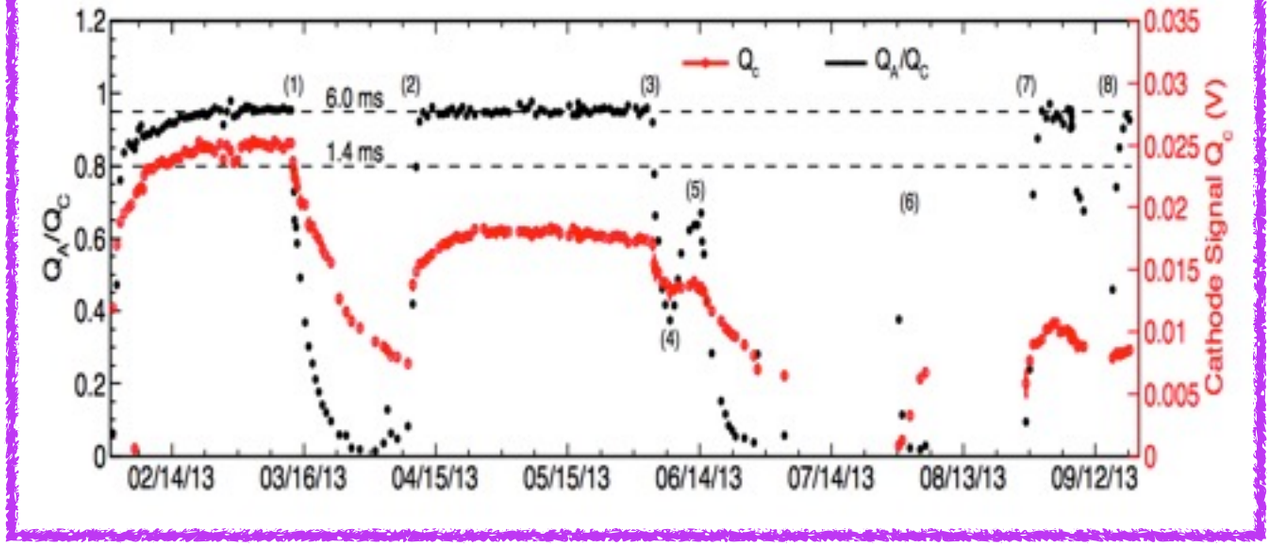
τ_e & e^- attenuation

- LAr Purity Monitor ... field cage w/ cathode & anode (design from ICARUS)
  - Xe flash lamp to liberate electrons
    - $Q_{anode}/Q_{cathode}$ tells us τ_e



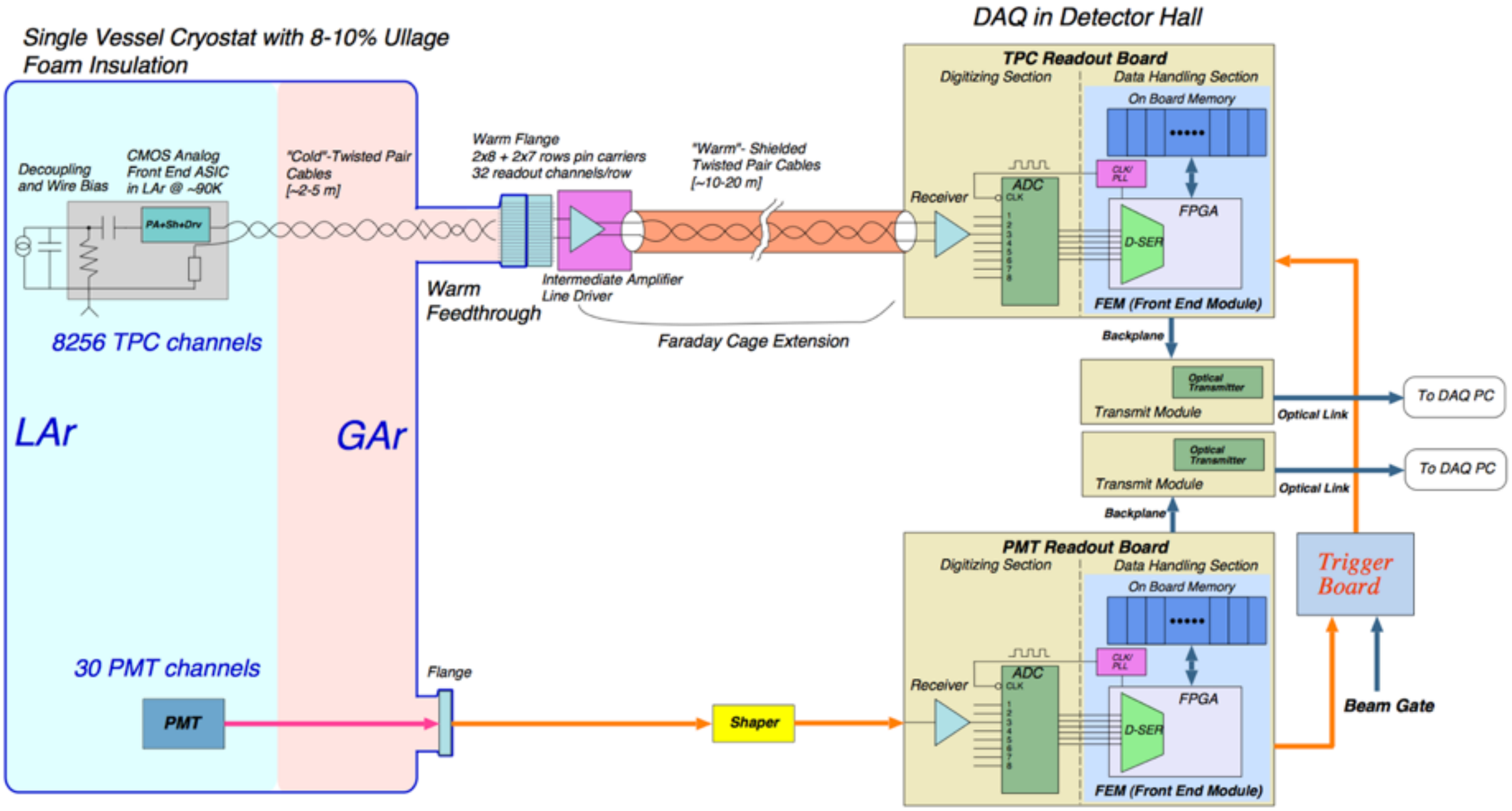
LAr Purity Monitor

Demonstrated & Works
$\tau_e \simeq$ 6ms for many weeks!



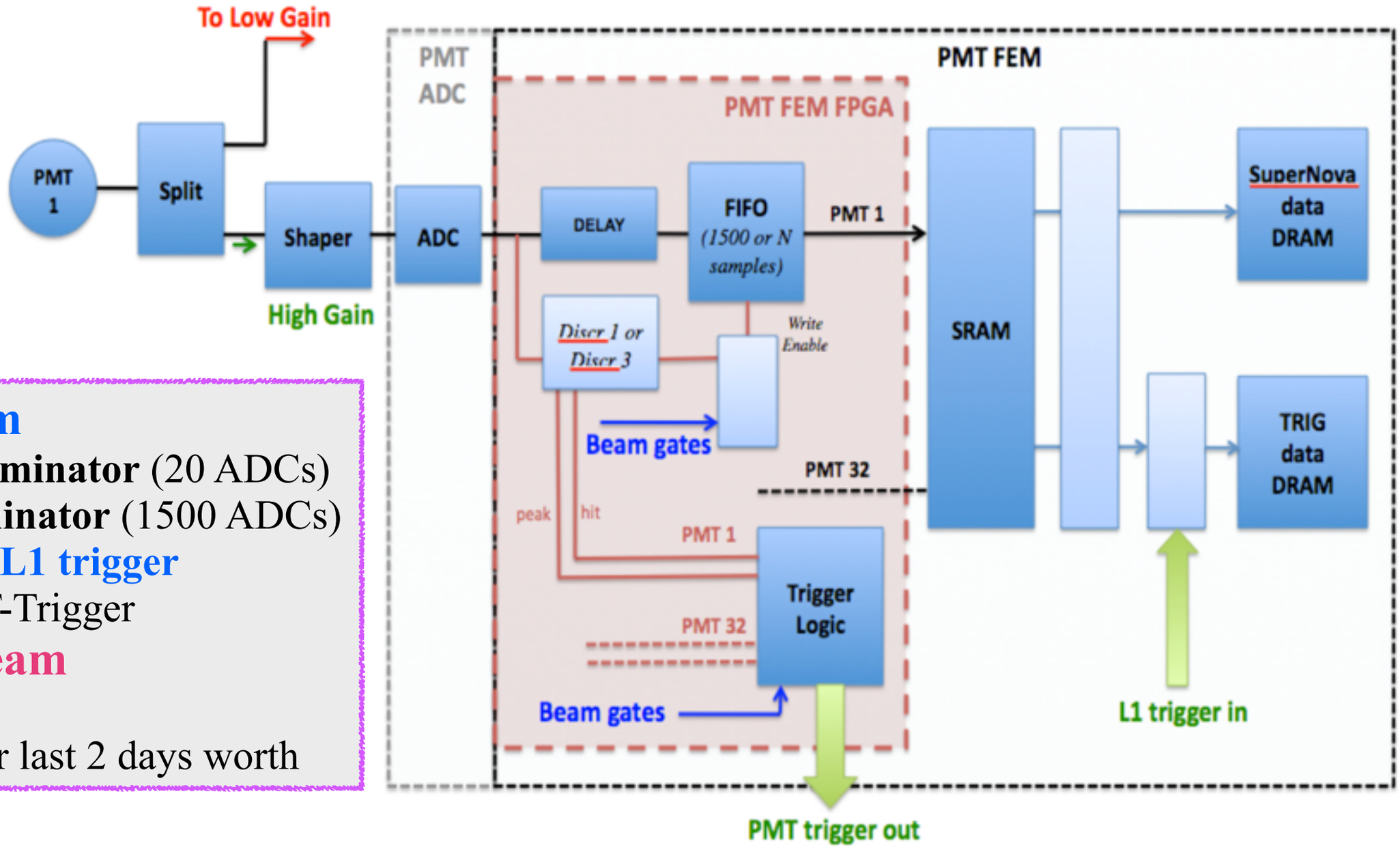
Cold Readout

- **Reading signal from LAr**
  - "**Cold electronics**" (by BNL) resides in LAr (reduced noise)
    - first stage amplification & shaping of signal
  - "**Warm electronics**" (by Nevis) resides in DAQ racks
    - Trigger & signal readout



Warm Readout

- **Optical detector readout**
  - "High" & "Low" gain ... 32 x 2 channels, **shaped & digitized** @ 64 MHz
  - Two readout stream to store waveform using **discriminator logic**
    - **Neutrino** (triggered readout)
    - **SuperNova** (continuous)

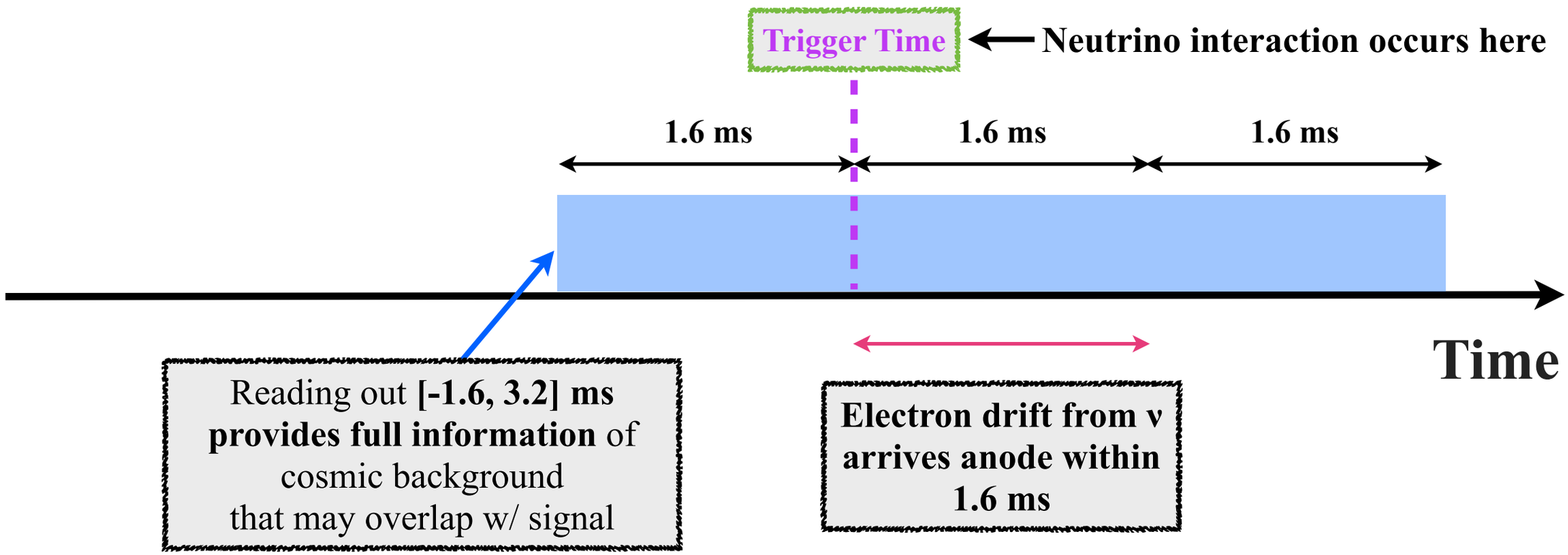


Neutrino stream
- **Cosmic discriminator** (20 ADCs)
- **Beam discriminator** (1500 ADCs)
- Readout upon **L1 trigger**
- Generate PMT-Trigger

SuperNova stream
- Continuous
- Stored only for last 2 days worth

Warm Readout

- Optical detector readout
  - "High" & "Low" gain ... 32 x 2 channels, **shaped & digitized** @ 64 MHz
  - Two readout stream to store waveform using discriminator logic
    - **Neutrino** (triggered readout)
    - **SuperNova** (continuous)
- **TPC readout**
  - 8256 channels digitized @ 2 MHz ... **Neutrino** & **SuperNova** readout stream
    - **Neutrino** records [-1.6, 3.2] ms upon trigger
    - **SuperNova** records every 1.6 ms



Warm Readout

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    - **Neutrino** records [-1.6, 3.2] ms upon trigger
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Easy Math Quiz

What is the data rate for 15 Hz beam ... readout with 16 bit data word for 6.4 ms @ 2MHz digitization for 8256 channels?

Online Data Handling

- "On-the-fly" data size reduction
  - Huffman compression (lossless)
  - Zero suppression (for SN)
- Readout trigger
  - Only interesting event (next slide)

If stored "raw" ... ≃ 4.8 GB/s!

Data size feasible :)

Warm Readout

- Optical detector readout
  - "High" & "Low" gain ... 32 x 2 channels, **shaped & digitized** @ 64 MHz
  - Two readout stream to store waveform using discriminator logic
    - **Neutrino** (triggered readout)
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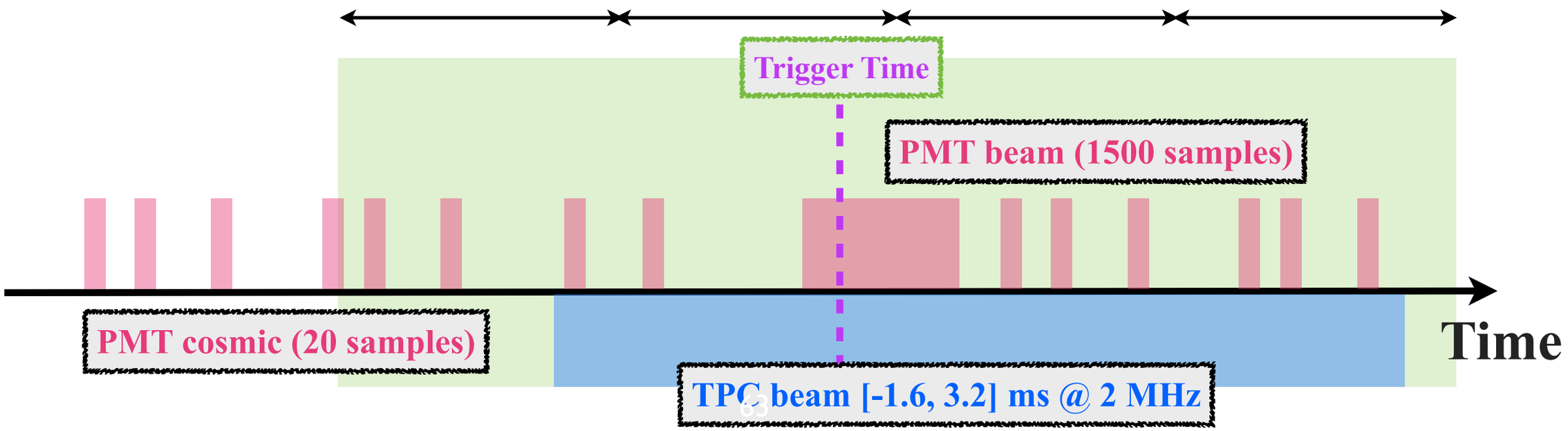
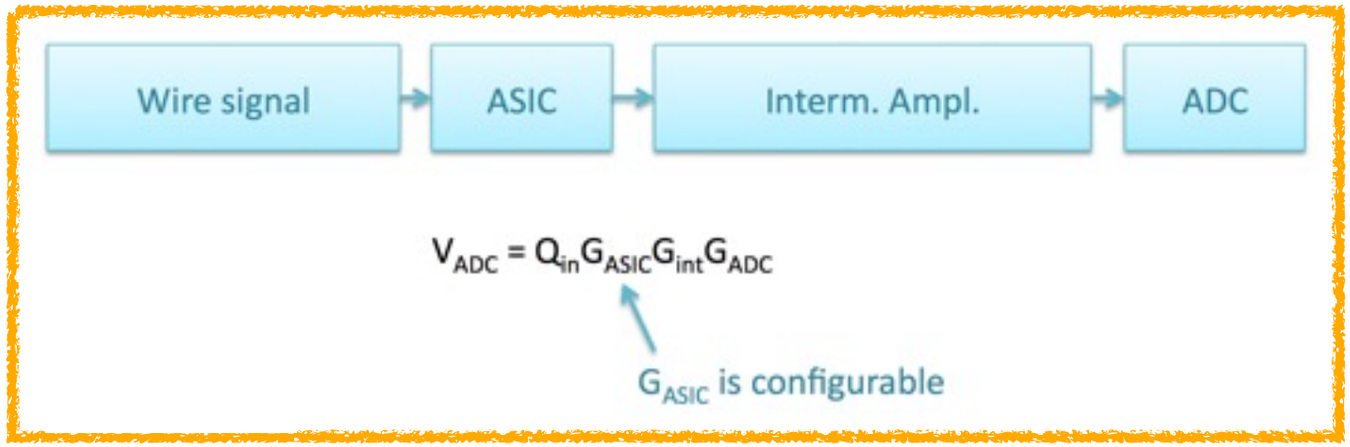
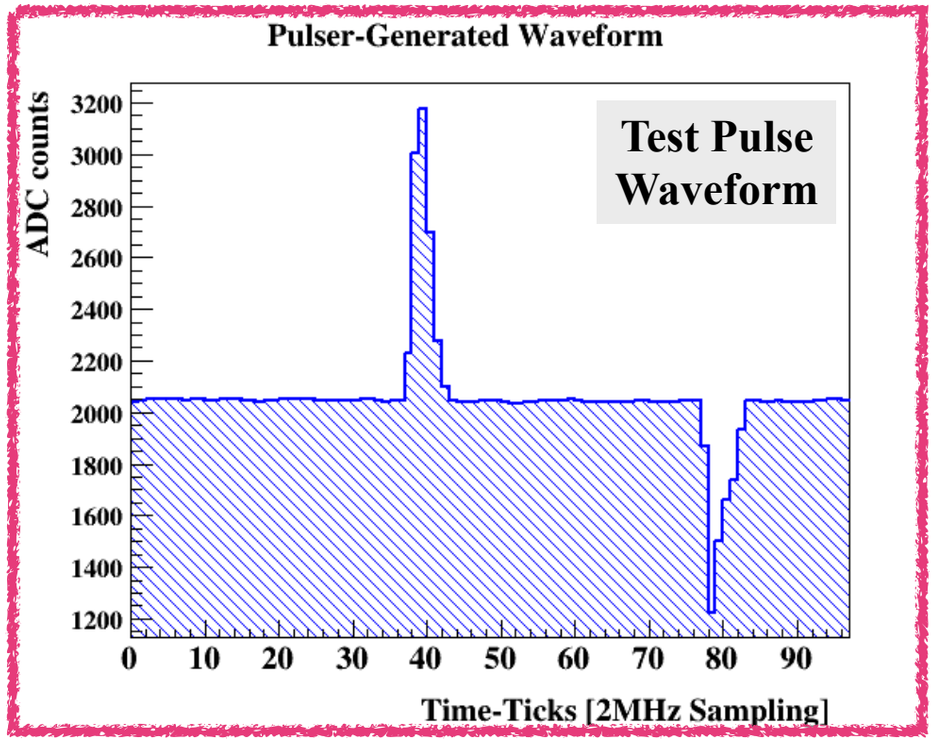
- TPC readout
  - 8256 channels digitized @ 2 MHz ... **Neutrino** & **SuperNova** readout stream
    - **Neutrino** records [-1.6, 3.2] ms upon trigger
    - **SuperNova** records every 1.6 ms
- **Trigger**
  - Readout **4 x 1.6 ms frames @ coincidence of beam pulse & PMT-Trigger**



Readout Calibration

- Need to figure out how many electrons in our signal!

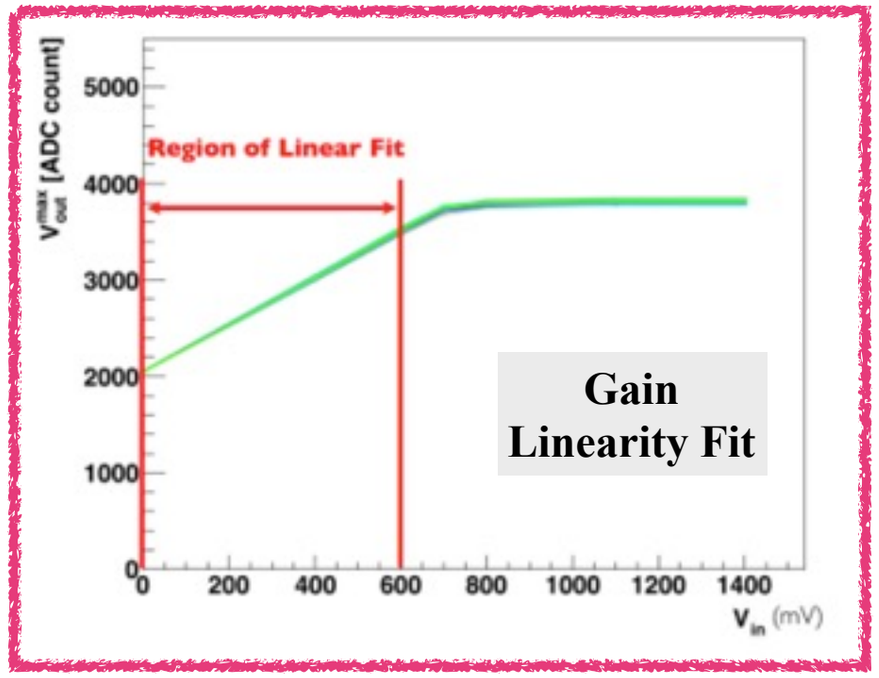




$$\text{Gain} = \frac{\text{Output Charge (ADC)}}{\text{Input Charge (\# electrons)}}$$

NEEDED
for 1st step of reconstruction!

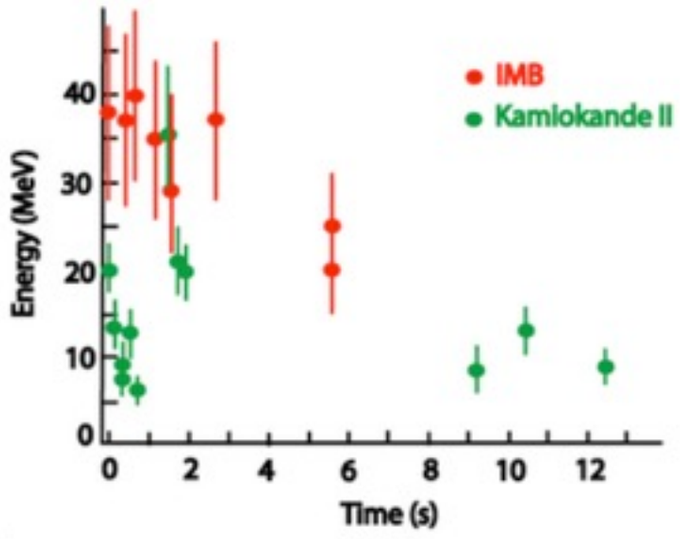
- How to calibrate?
  - Inject test pulse with known charge
  - Compare with output charge
  - Fit a linear relationship to obtain gain



Physics Back Ups

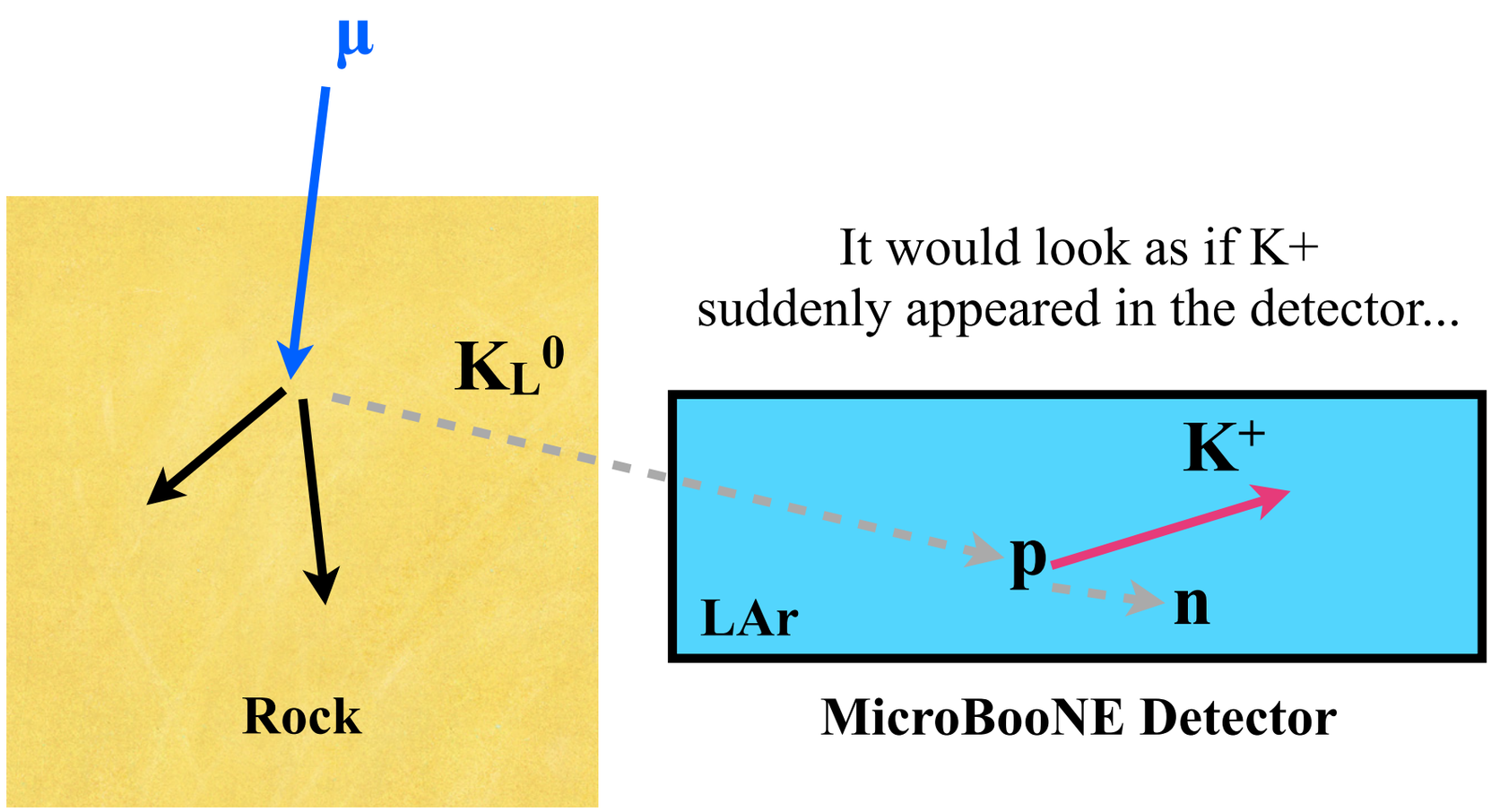
MicroBooNE Physics: More

- **SuperNova**
  - ν's detected from SN1987A
    - Characteristic short burst
    - Nobel prize (2002)!
  - We **can** detect ν_e capture on Ar
  - We **cannot** trigger on its own
    - **... small volume & too much cosmics!**
- But we **can** analyze SuperNova data upon ***SNEWS***
  - **That's why we have dedicated data stream!**

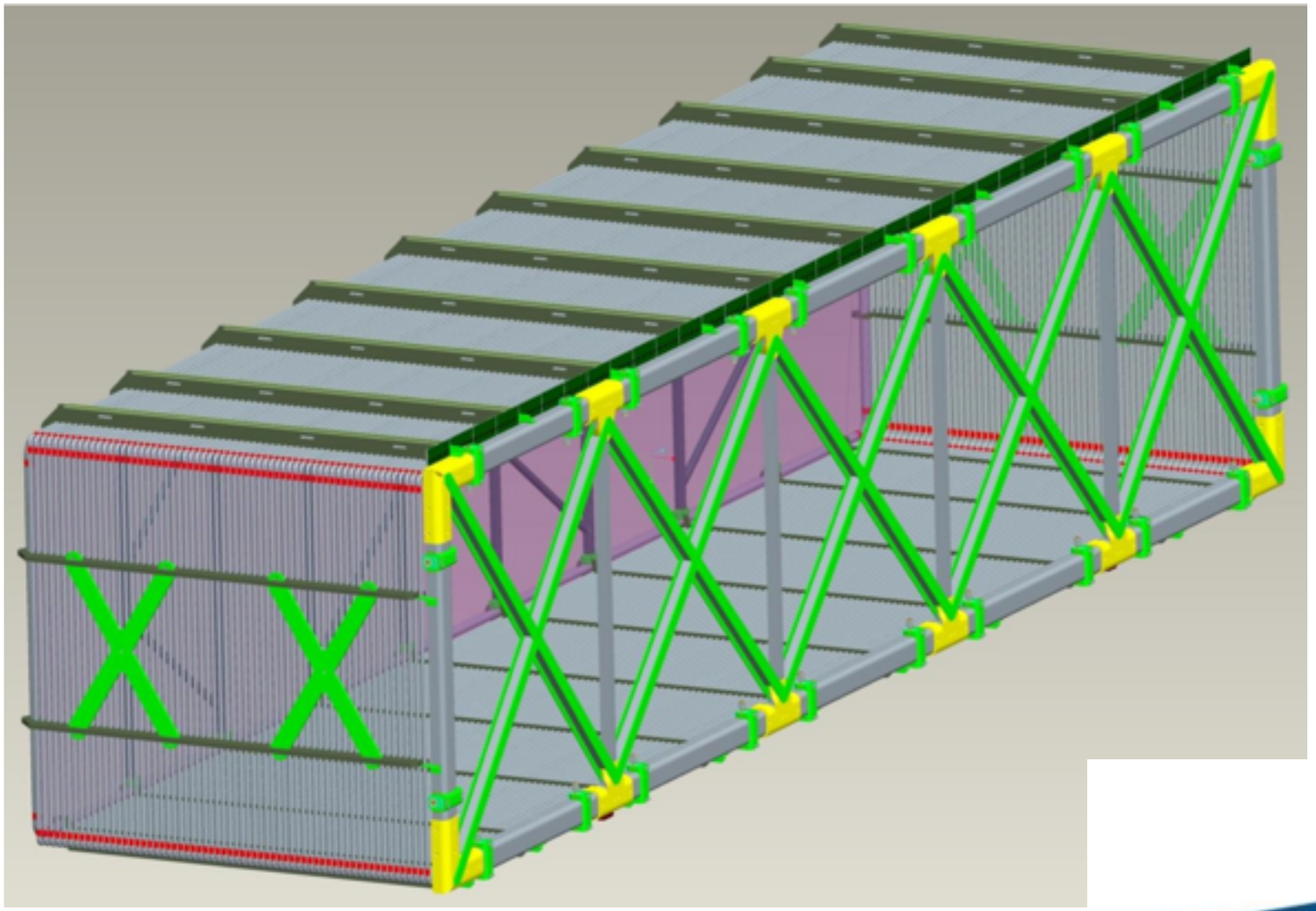


MicroBooNE Physics: More

- **Proton Decay**
  - **Cannot** study proton decay: $p \Rightarrow K^+ \nu$ ... **too small :(**
  - **Can** study cosmic induced background rate: $K^0 p \Rightarrow K^+ n$
    - **Important measurement for future LArTPC**
    - High cosmic rate can be helpful sometimes :)



MicroBooNE Detector: Numbers

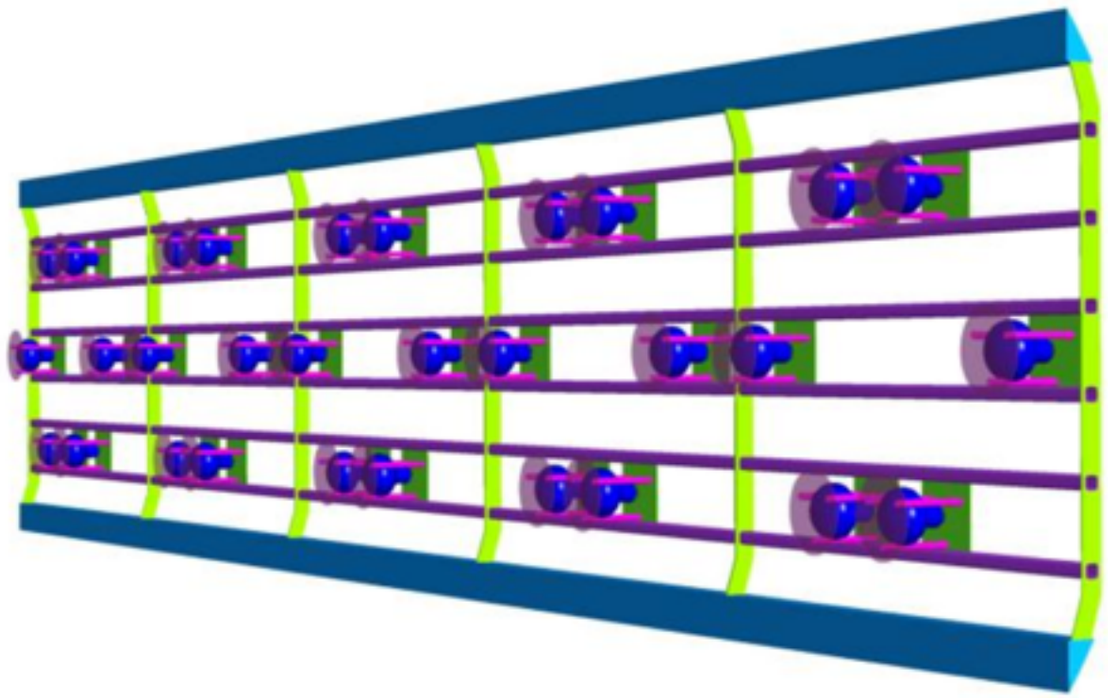


TPC

TPC Volume [ton]	90
Dimension [m]	10.4 x 2.5 x 2.3
# Channels	8256
Wire Diameter [mm]	0.15
Wire Pitch [mm]	3
Operating Temp. [K]	87
Max Drift Length [m]	2.53
Electric Field	500 V / cm

Light Collection System

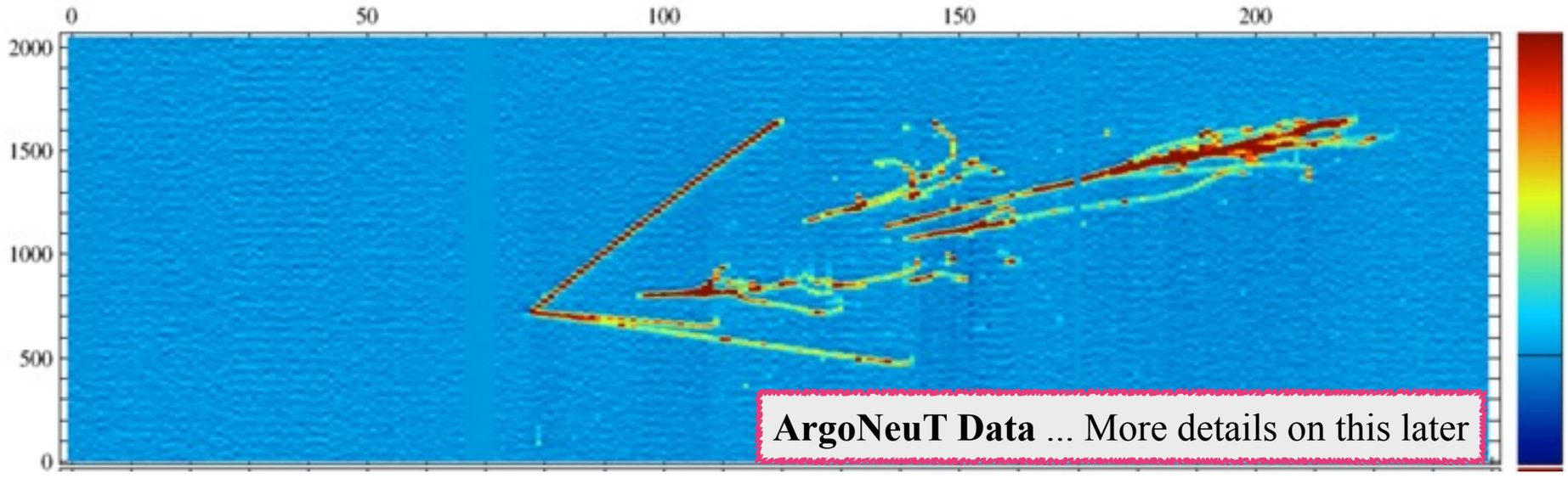
PMT Type	Hamamatsu R5912-02
PMT Size	8”
# Channels	32
Wavelength Shifter	TPB coated acrylic plate



Basics

What Is MicroBooNE?

- MicroBooNE is ...
  - a short baseline neutrino oscillation experiment @ Fermilab
    - Oscillation: $\nu_\mu \Rightarrow \nu_e$ @ **L/E ≈ *o* (1 m/MeV)**
    - neutrino source = running Booster Neutrino Beam @ Fermilab
  - a Liquid Argon Time Projection Chamber (LArTPC)
    - mass = 170 ton (active = 90 ton)
    - provides excellent particle ID and calorimetry



LArTPC provides "photo quality image" of particle interaction!
Basically digitized "bubble chamber" image!

What Is MicroBooNE?

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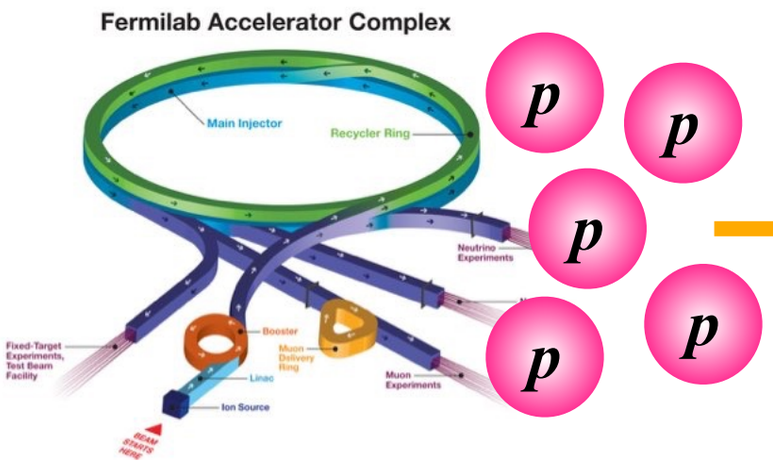
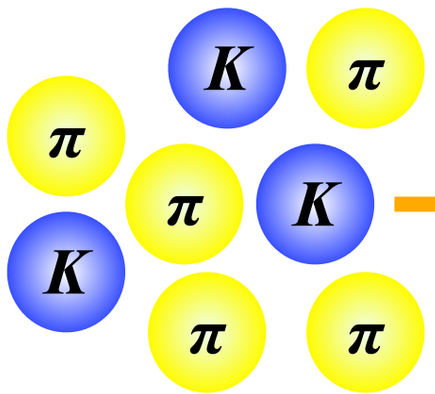
    - neutrino source = running Booster Neutrino Beam @ Fermilab

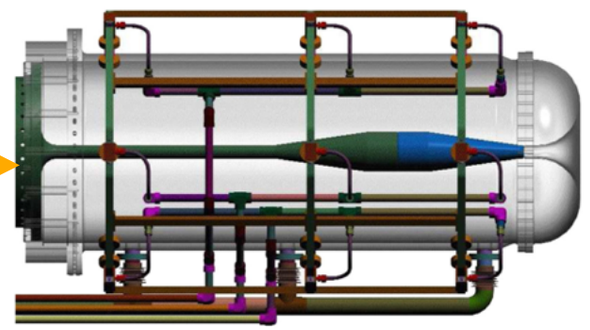
8 GeV protons from Booster
hits Beryllium target to produce mesons



Booster
(8 GeV Protons)

Beryllium Target
"Thin & Long"





Magnetic Horn
(Meson Focusing)

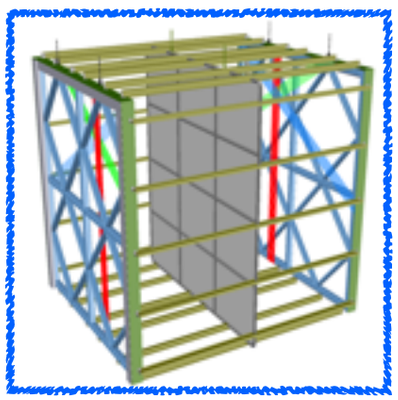
U.S. based R&D Program for LArTPC

- Wide effort on LArTPC R&D in the U.S.
- MicroBooNE has an important role as the next large scale LArTPC

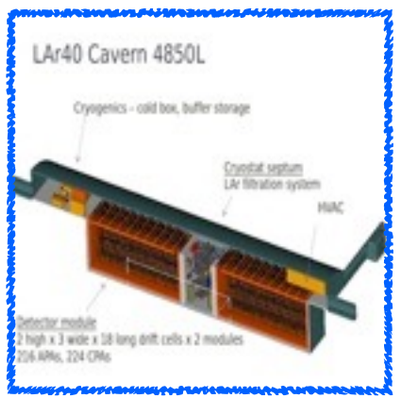
Bo TPC
0.02 ton

ArgoNeuT
0.3 ton

MicroBooNE
0.1 kilo-ton



SBN
0.05 + 0.6 kilo-ton

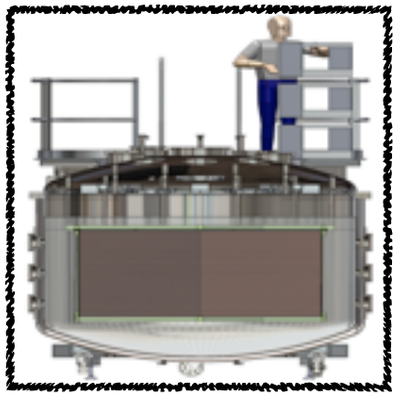


DUNE Far Detector
34 kilo-ton

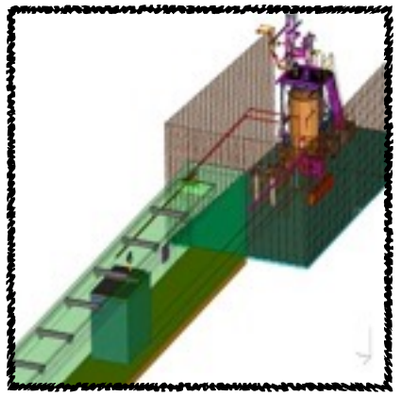
LUKE
(Material Test Stand)

LAPD
Purity Demonstrator

LArIAT
TPC Calibration



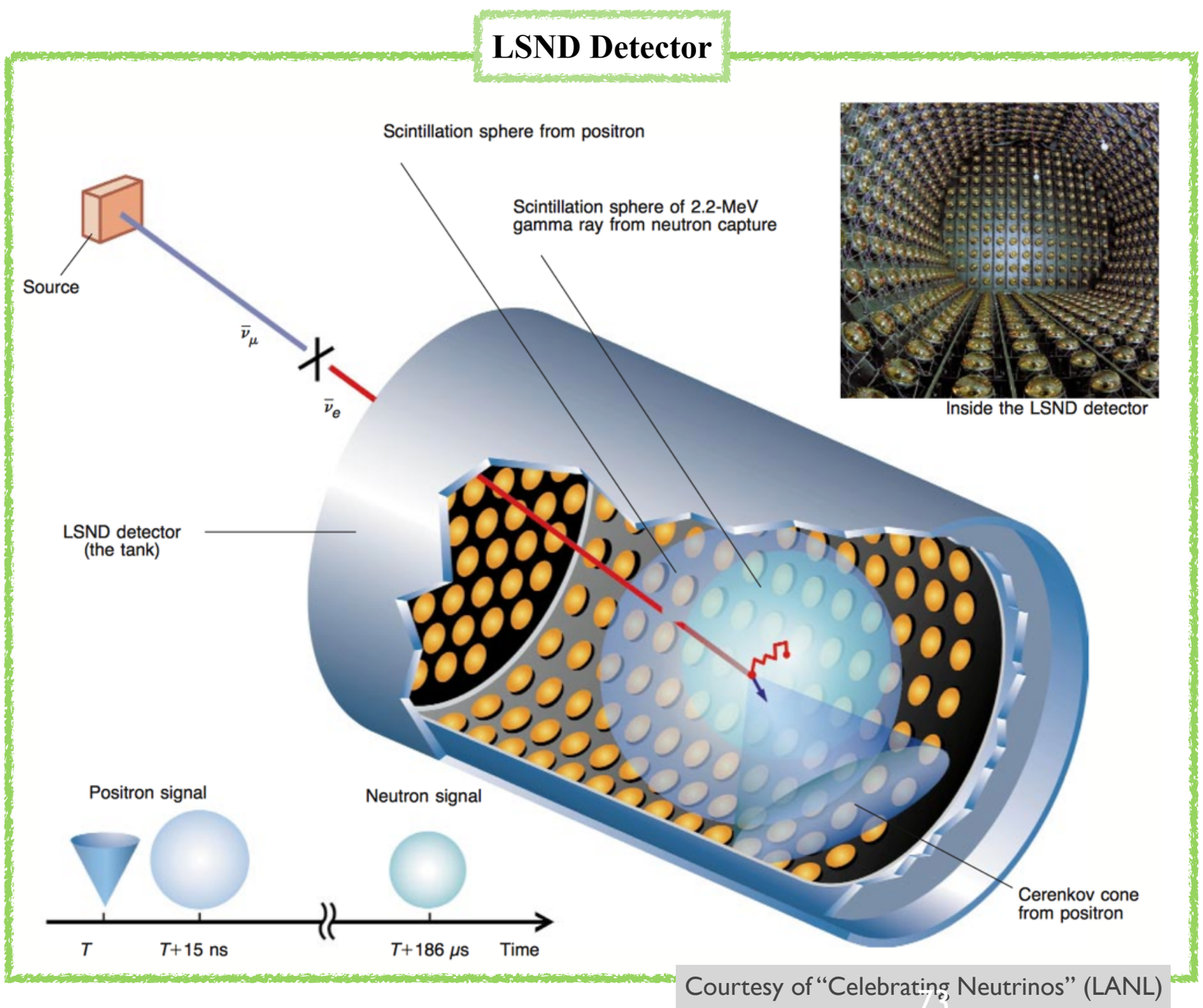
CAPTAIN
TPC Calibration



LBNE 35 ton
Purity Demonstrator

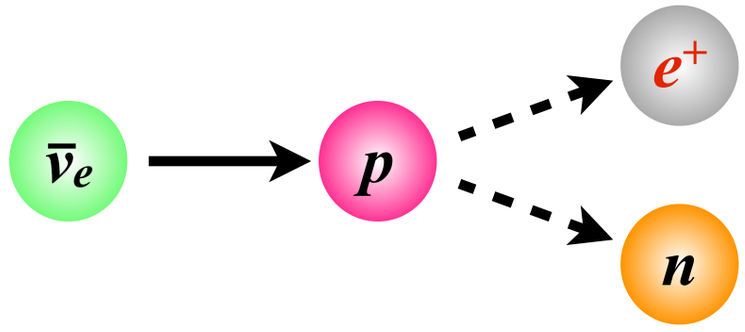
Why MicroBooNE? … LSND

- **Liquid Scintillator Neutrino Detector (LSND)**
  - Primary oscillation mode: $\overline{\nu}_\mu \Rightarrow \overline{\nu}_e$ … **L/E ≃ *o* (1 m/MeV)**



Courtesy of "Celebrating Neutrinos" (LANL)

Inverse Beta Decay



- e+ release energy
  - Cerenkov + annihilation
  - ≃ E_ν - 0.8 MeV
- n capture ~ 200 μs later
  - 2.2 MeV gamma ray

Thermal Neutron Capture