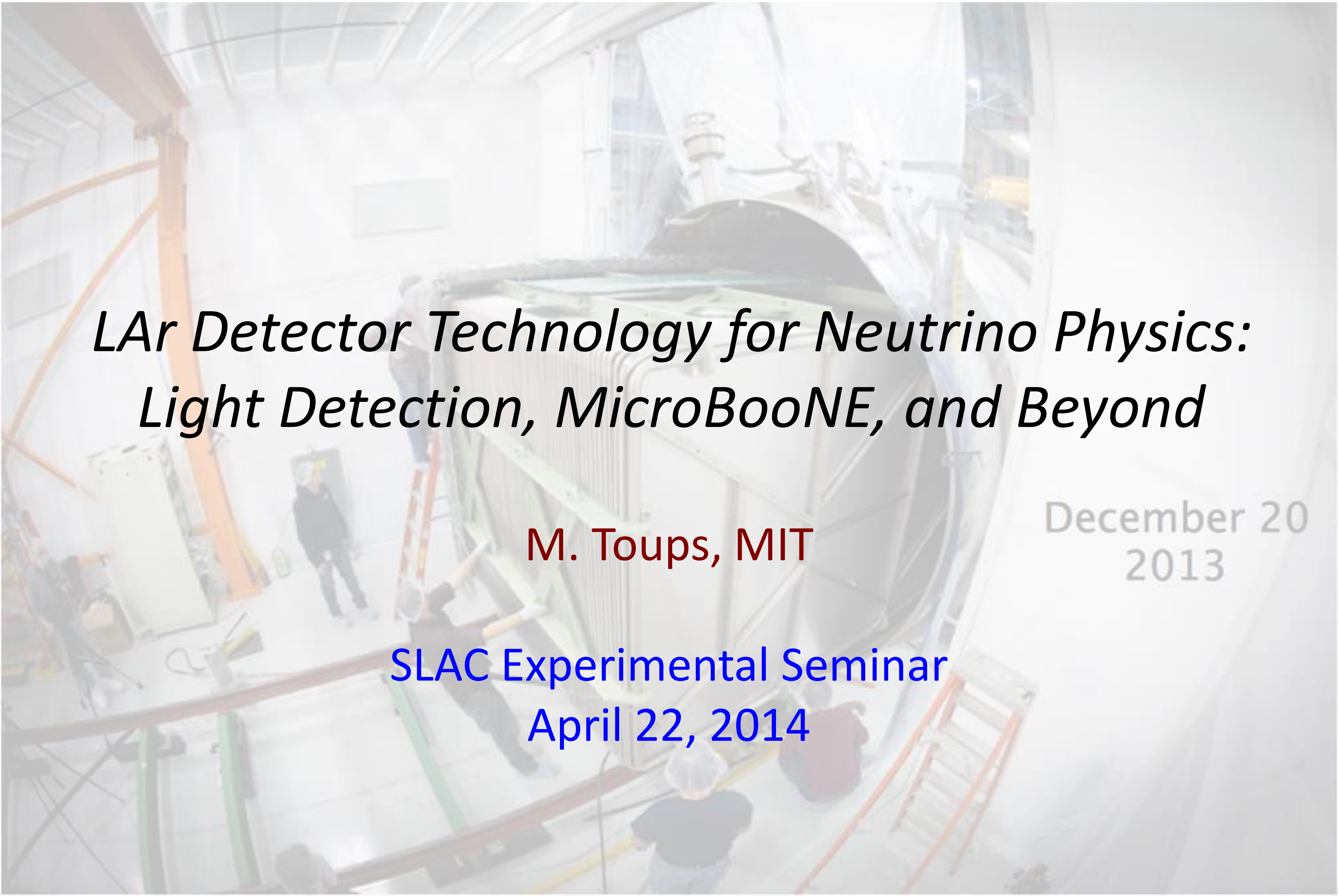

LAr Detector Technology for Neutrino Physics: Light Detection, MicroBooNE, and Beyond

M. Toups, MIT

SLAC Experimental Seminar
April 22, 2014

Outline

- Neutrino Oscillation Physics
  - Experimental Approaches
- Liquid Argon Time Projection Chambers (LArTPCs)
  - MicroBooNE
- Liquid Argon Scintillation Light
- LAr Light Studies at Fermilab
  - Nitrogen Contamination in LAr
  - Argon/Methane Mixtures
  - Characterizing LAr Light Guide Performance

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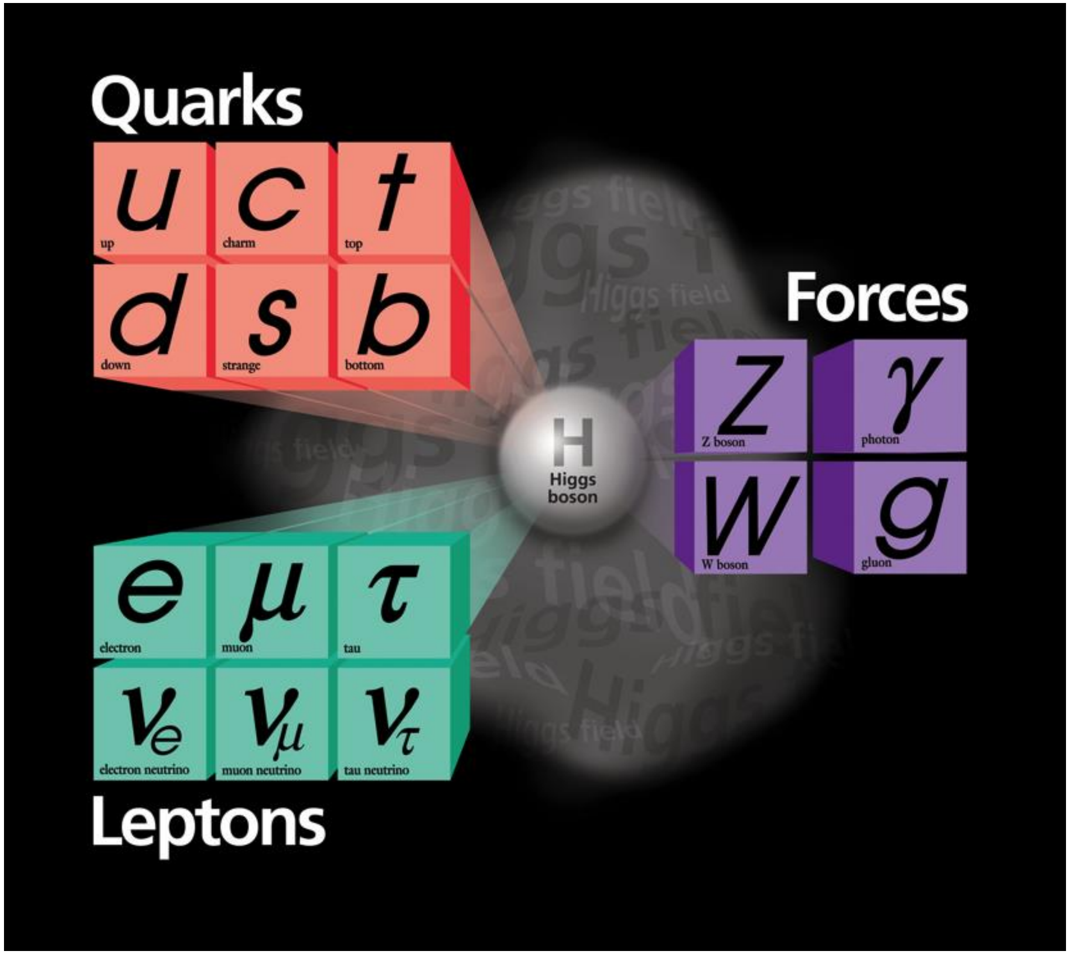
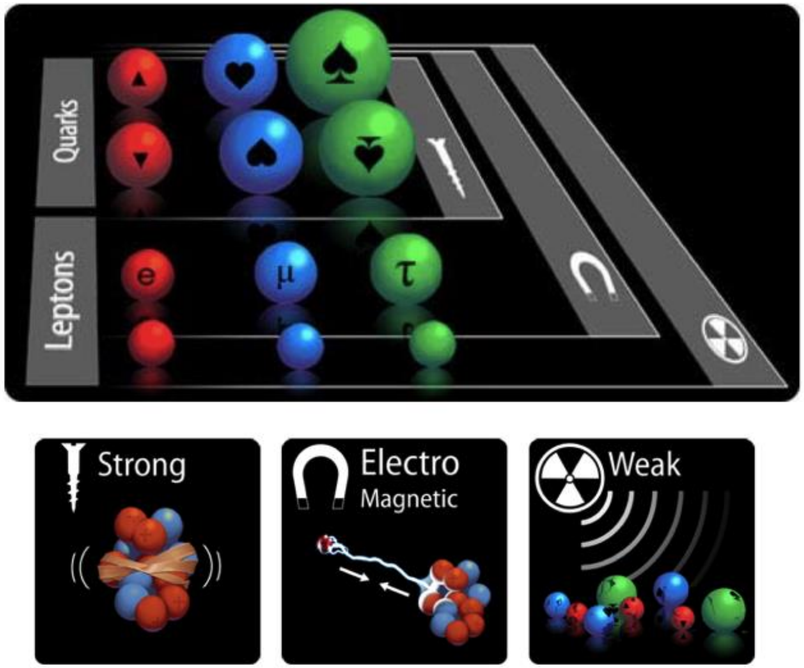
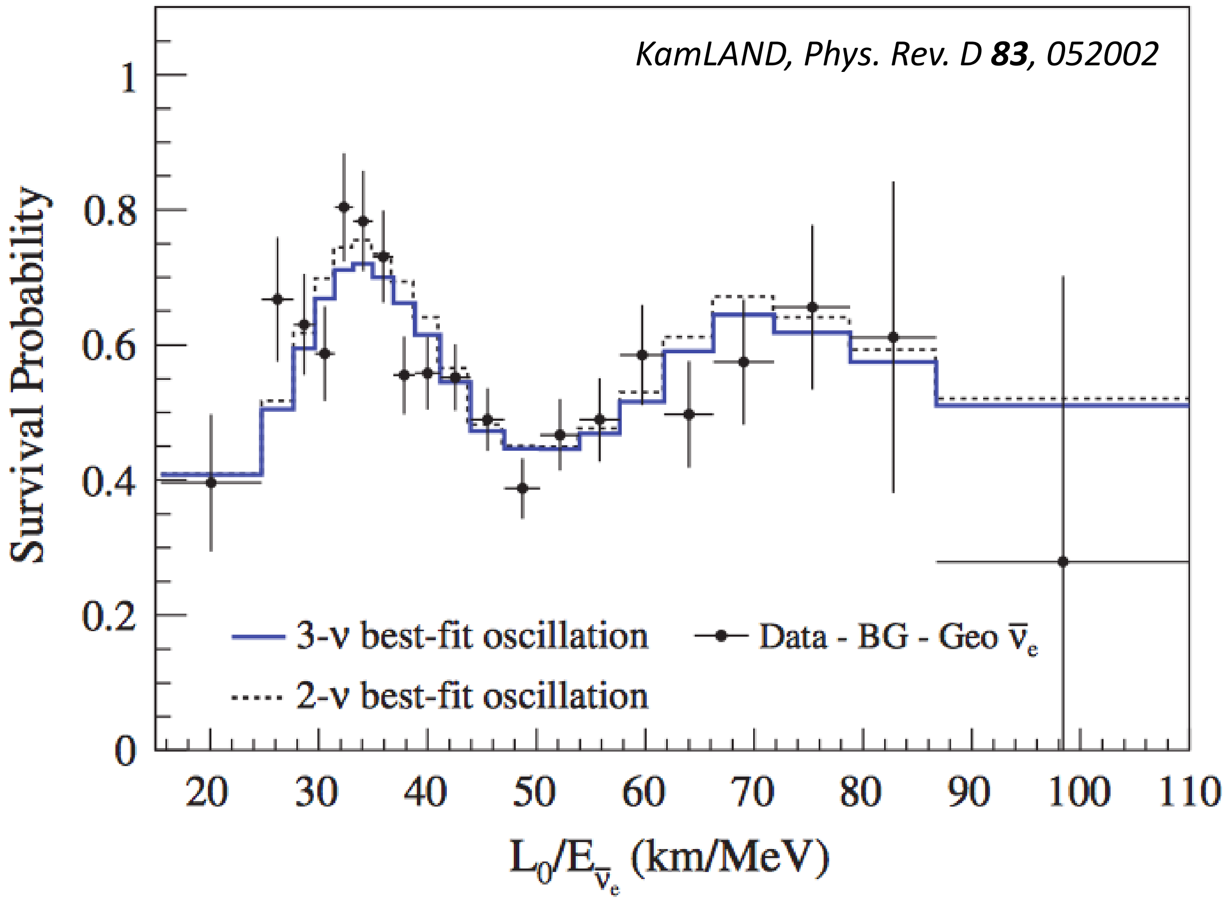
Neutrinos in the Standard Model





Neutrino Flavor Change a.k.a. "Oscillations"

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{1267\Delta m^2[\text{eV}^2]L\ [\text{km}]}{E_\nu\ [\text{MeV}]}\right)$$

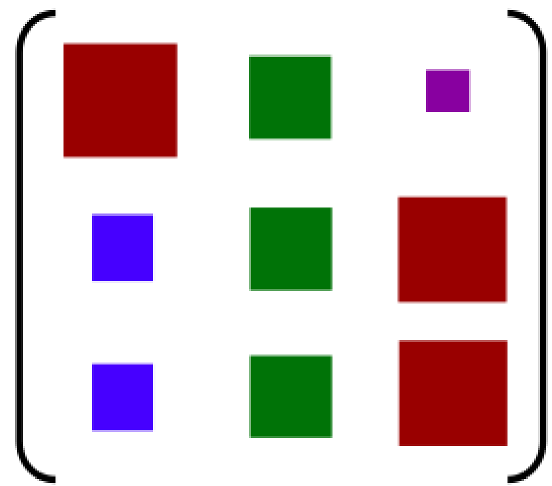


What Have We Learned from ν Oscillations?

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

Neutrino Flavor Eigenstates | Unitary Mixing Matrix | Neutrino Mass Eigenstates

$$|U_{\alpha i}| = \begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}e^{i\delta}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix} =$$

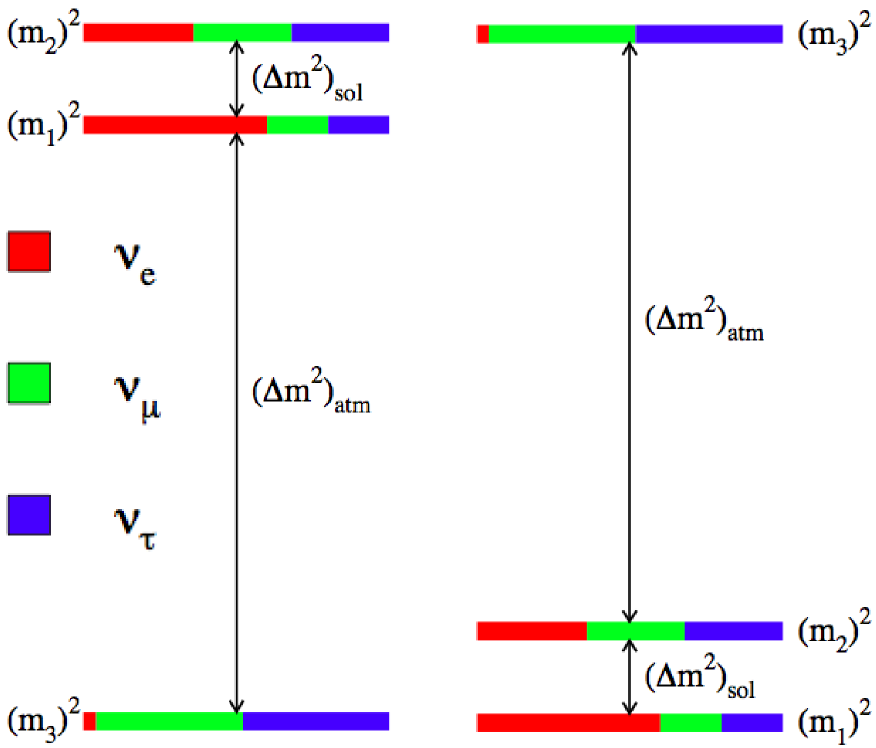


$$\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}\ \mathrm{eV}^2$$

$$|\Delta m^2_{32}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$$

What More Can We Learn From ν Oscillations (I)?

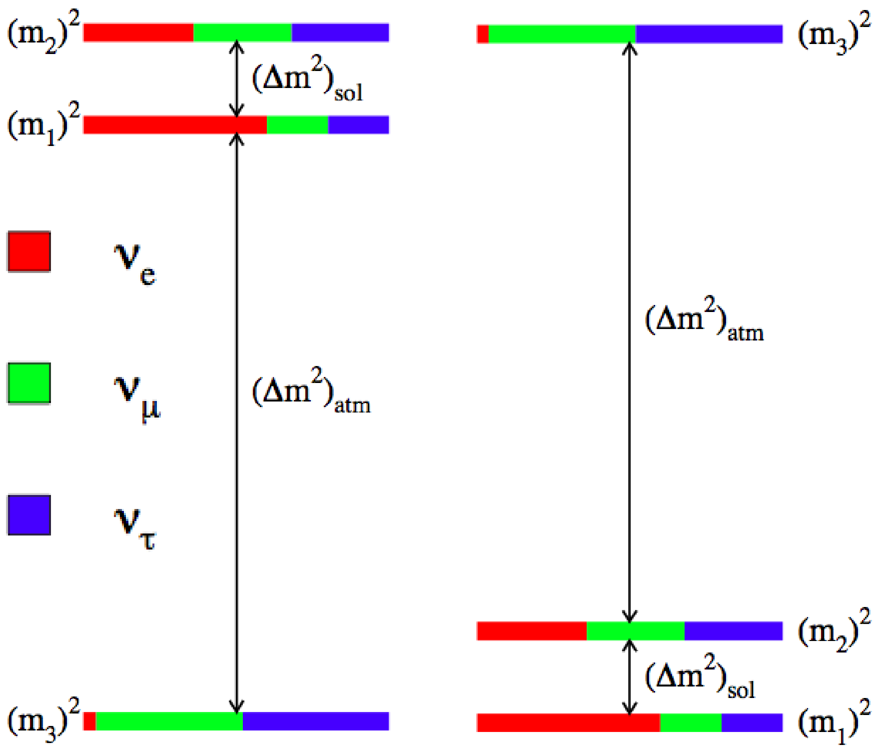
Mass Hierarchy



"Inverted" "Normal"

What More Can We Learn From ν Oscillations (I)?

Mass Hierarchy



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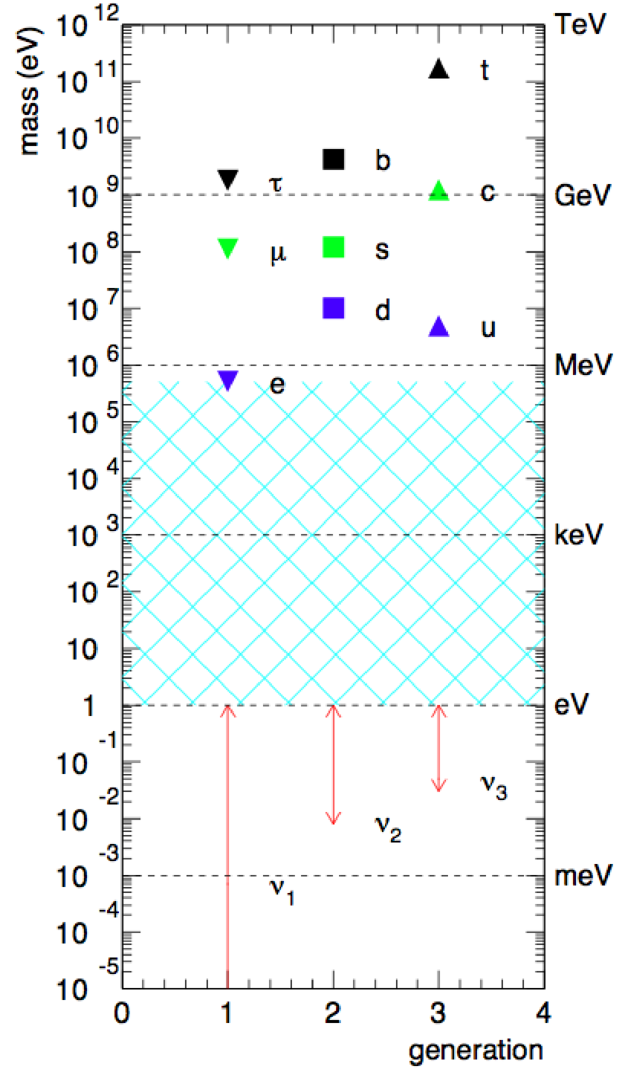
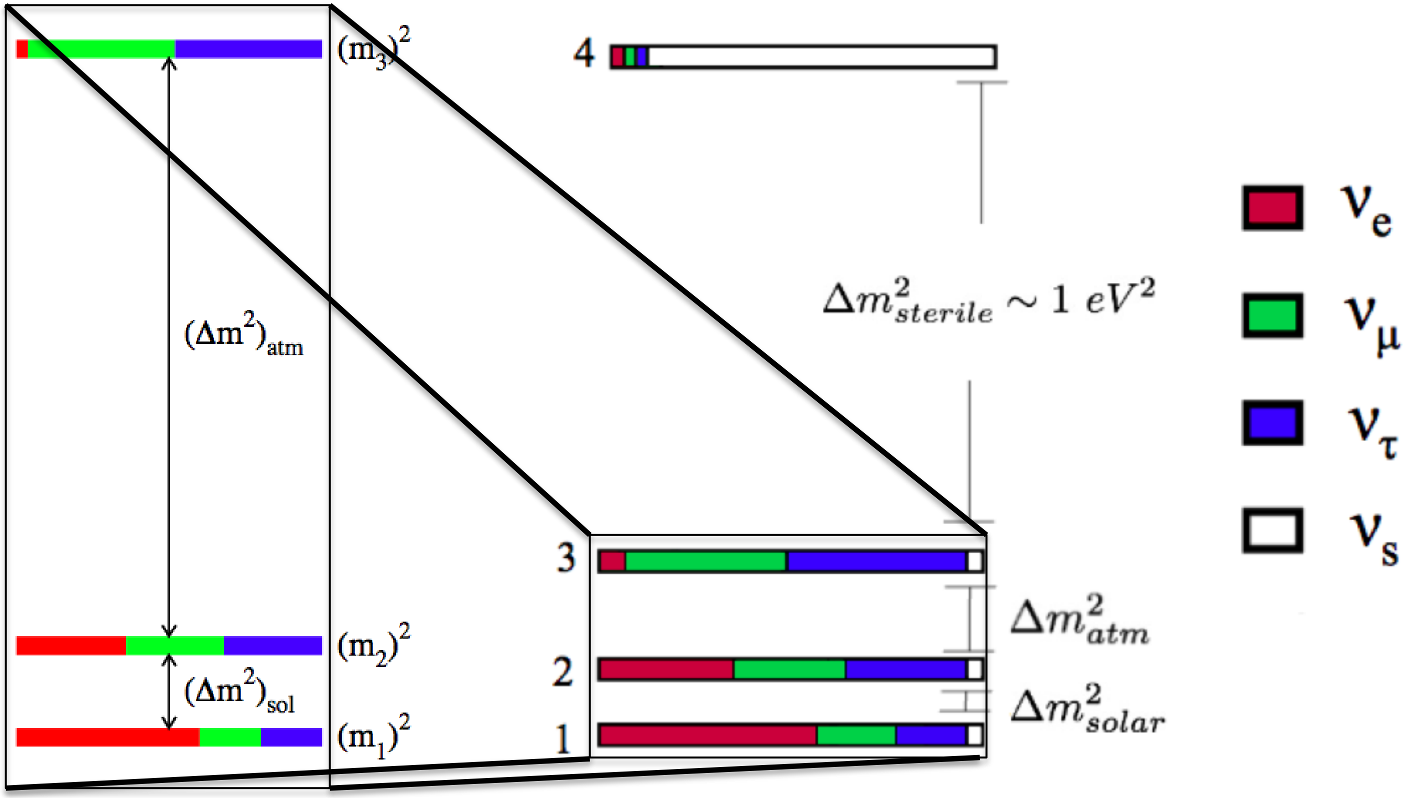
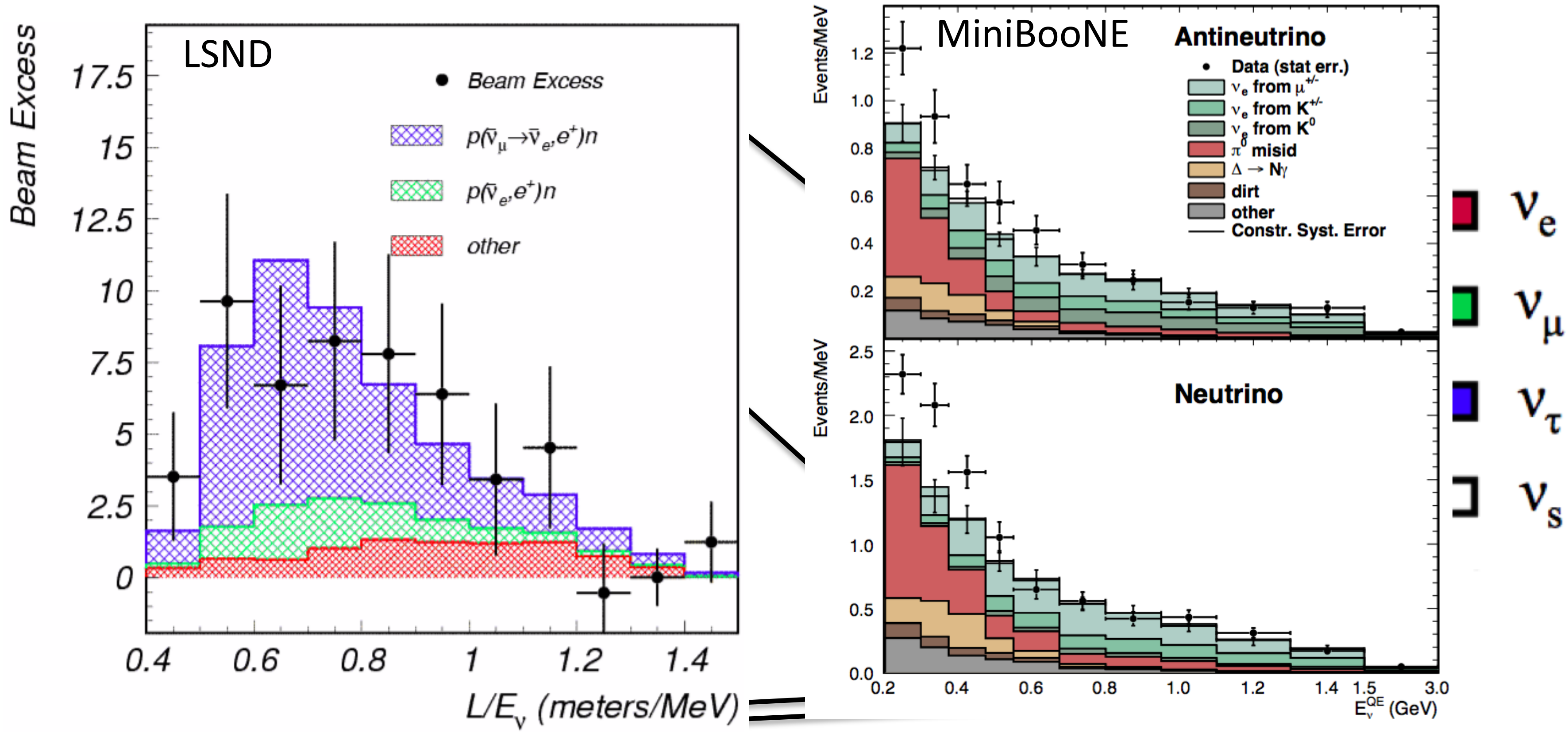


What More Can We Learn From ν Oscillations (II)?



Are there light sterile neutrinos?

What More Can We Learn From ν Oscillations (II)?



Are there light sterile neutrinos?

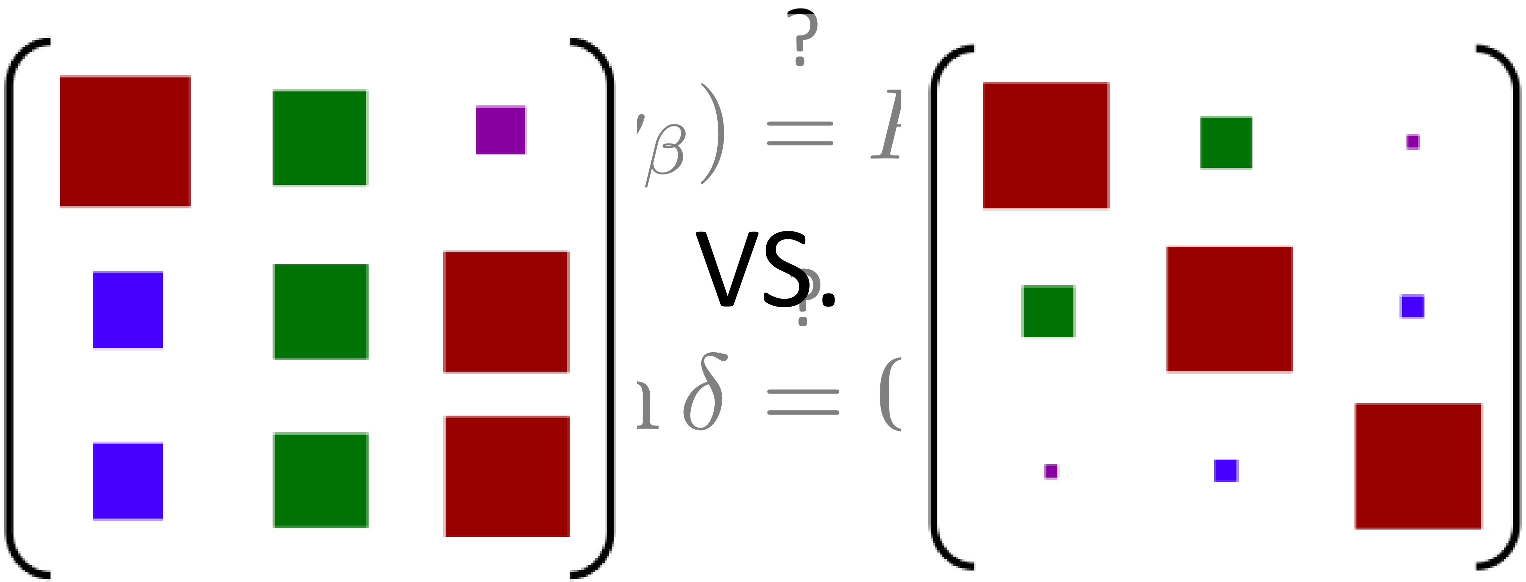
What More Can We Learn From ν Oscillations (III)?

$$P(\nu_\alpha \to \nu_\beta) \stackrel{?}{=} P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

$$\sin\delta \stackrel{?}{=} 0$$

Do neutrinos violate CP?

What More Can We Learn From ν Oscillations (III)?



Do neutrinos violate CP?

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- Mass Hierarchy & CP violation
  - "Long baseline" (> 100 km) oscillation experiments

- Sterile Neutrinos & MiniBooNE Low Energy Excess
  - "Short baseline" (< 1 km) oscillation experiments
    - OscSNS, MicroBooNE, plus a dozen others

- Mass Hierarchy & CP violation
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NOvA

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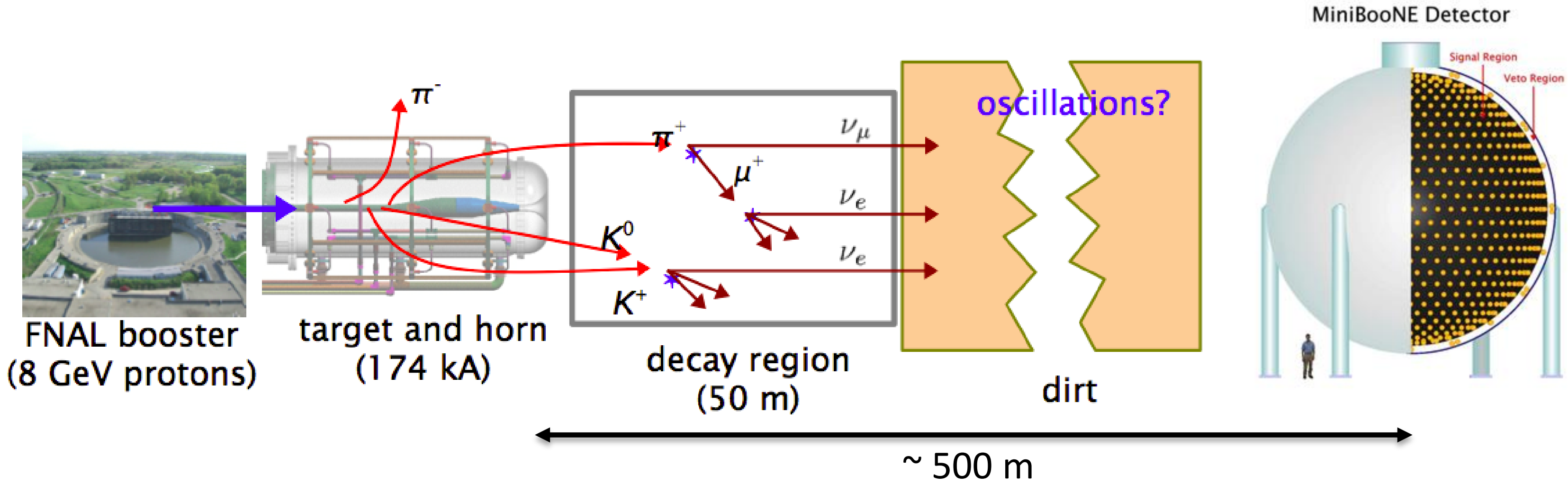
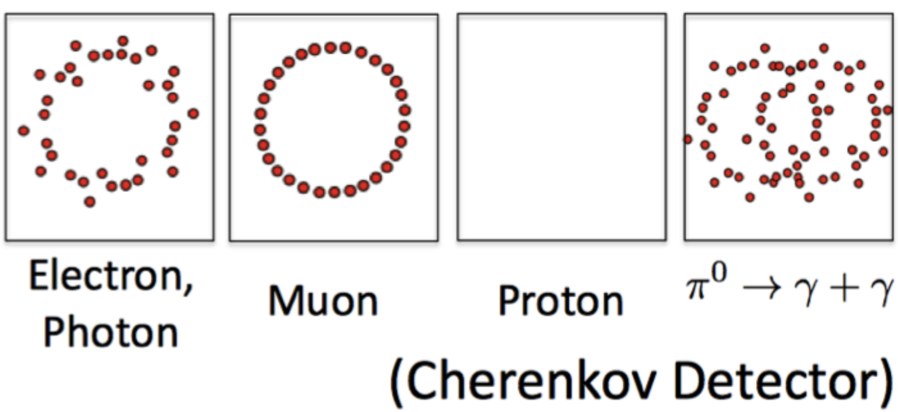
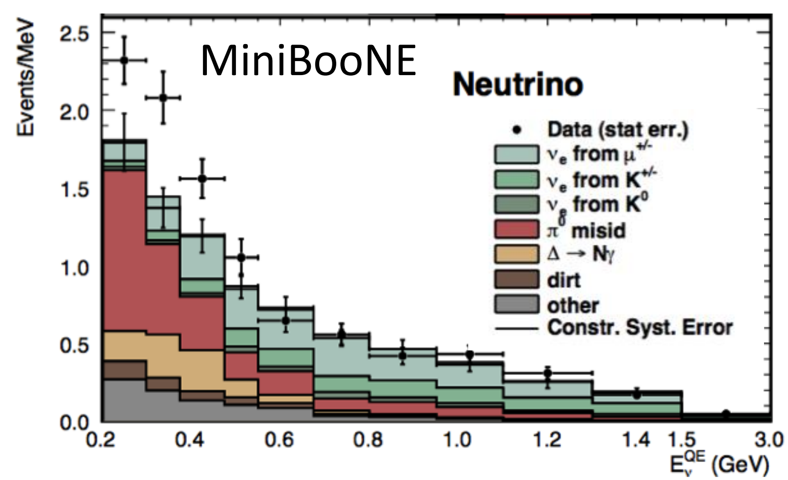
    - OscSNS, MicroBooNE, plus a dozen others

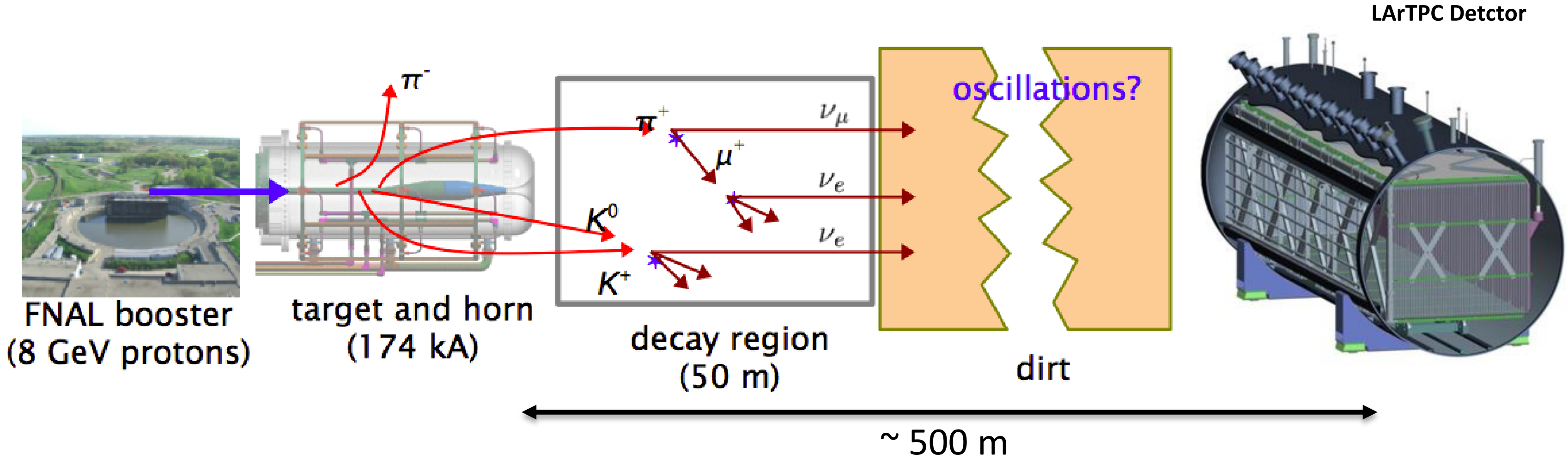
Addressing the MiniBooNE "Low-Energy Excess"

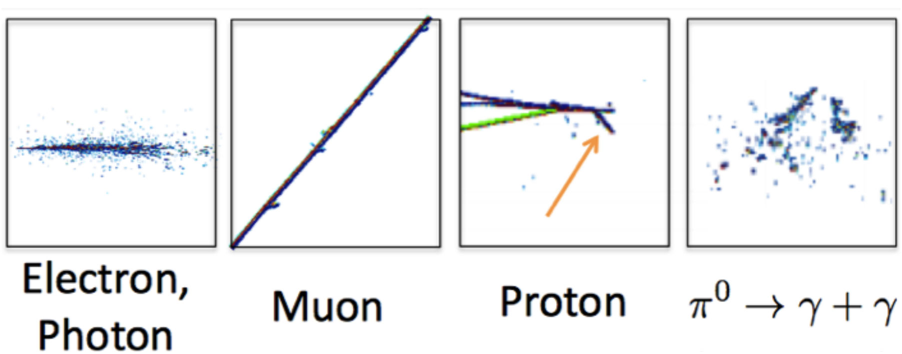




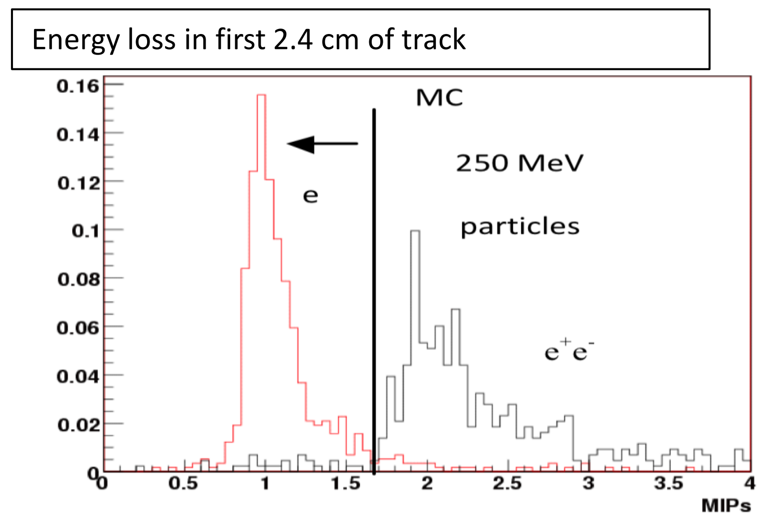


Addressing the MiniBooNE "Low-Energy Excess"





Liquid Argon Time Projection Chamber (LArTPC)



LArTPC = "Modern Bubble Chamber" with 3D track reconstruction

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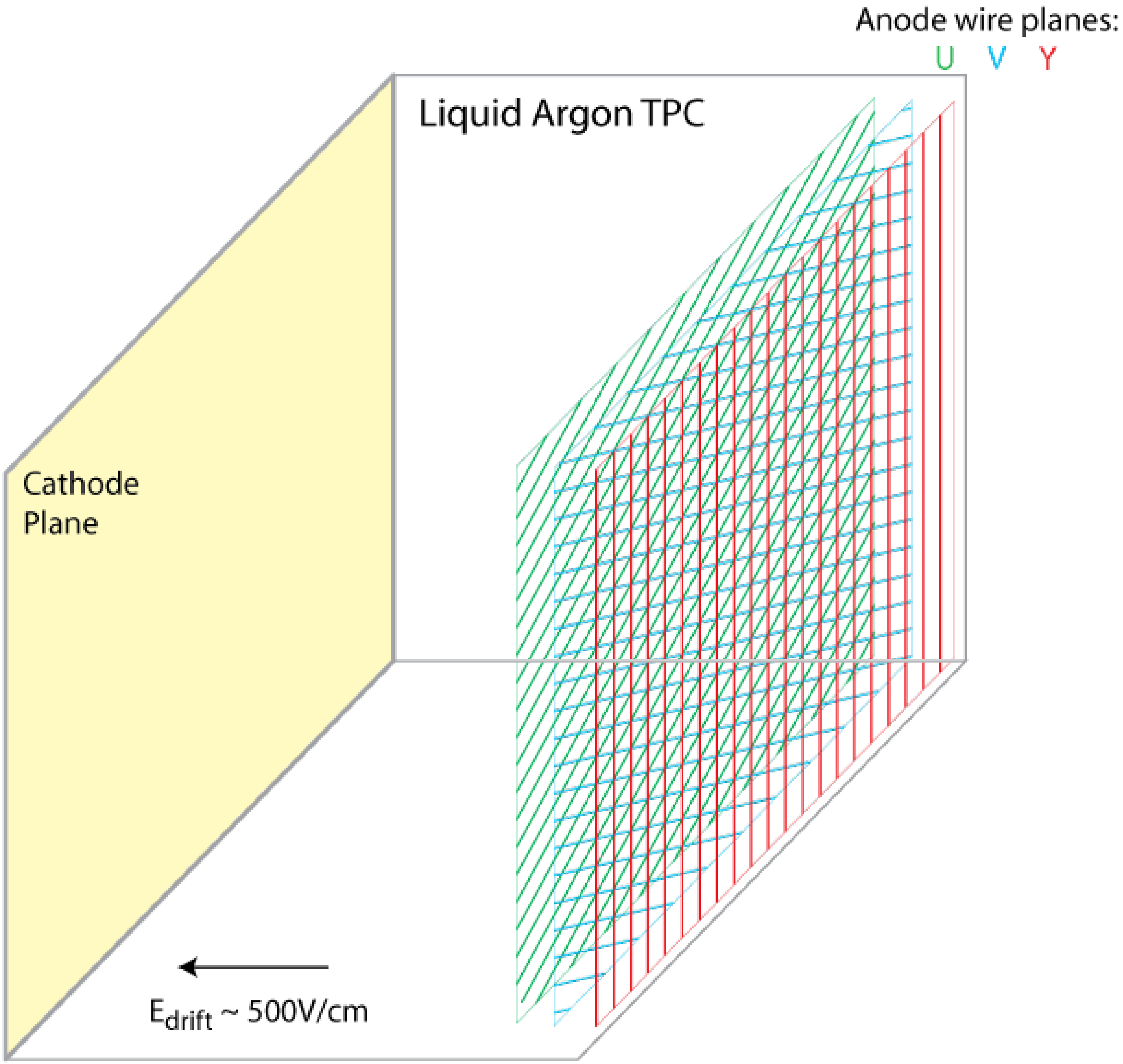
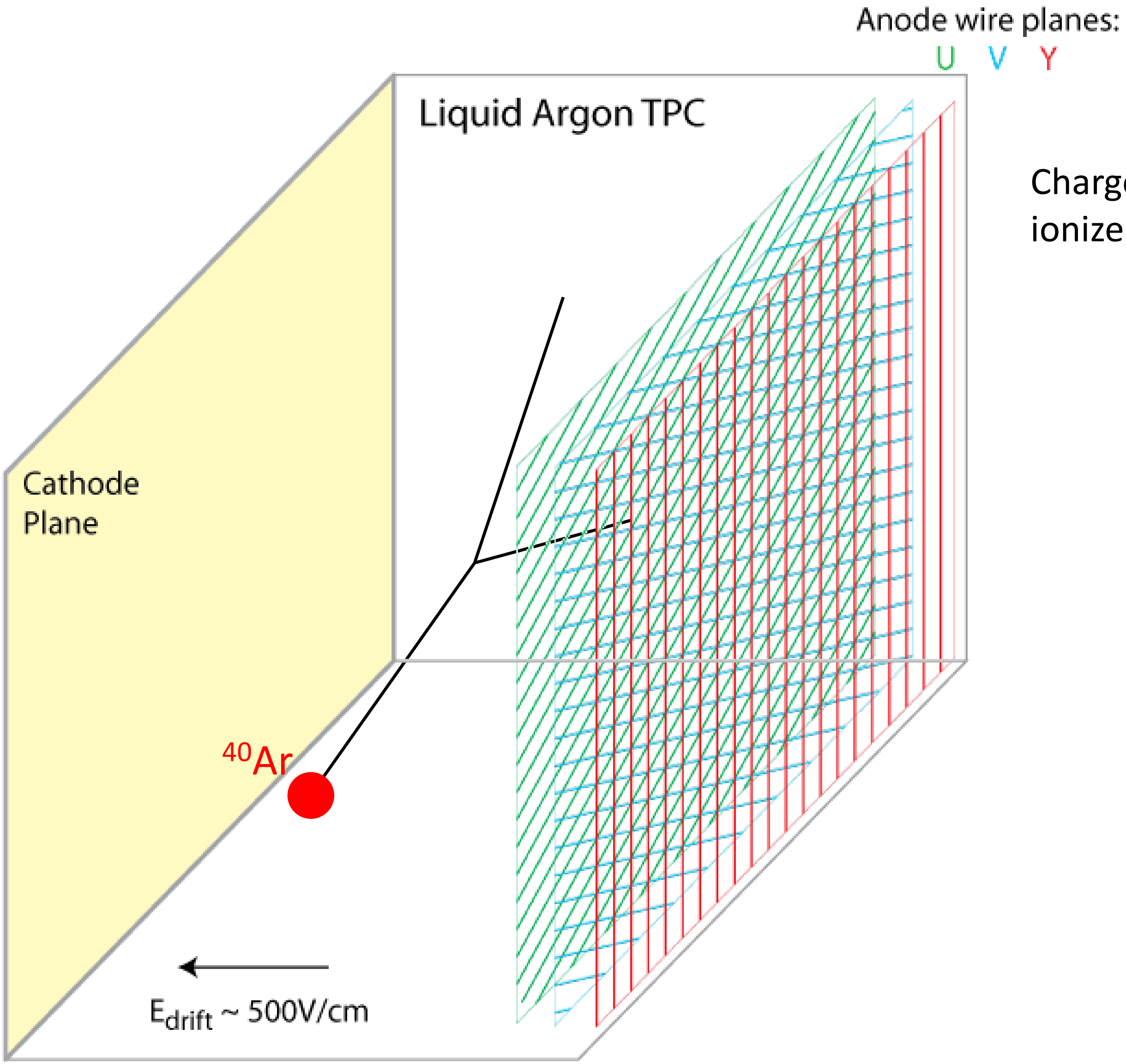
Bo Yu (BNL)



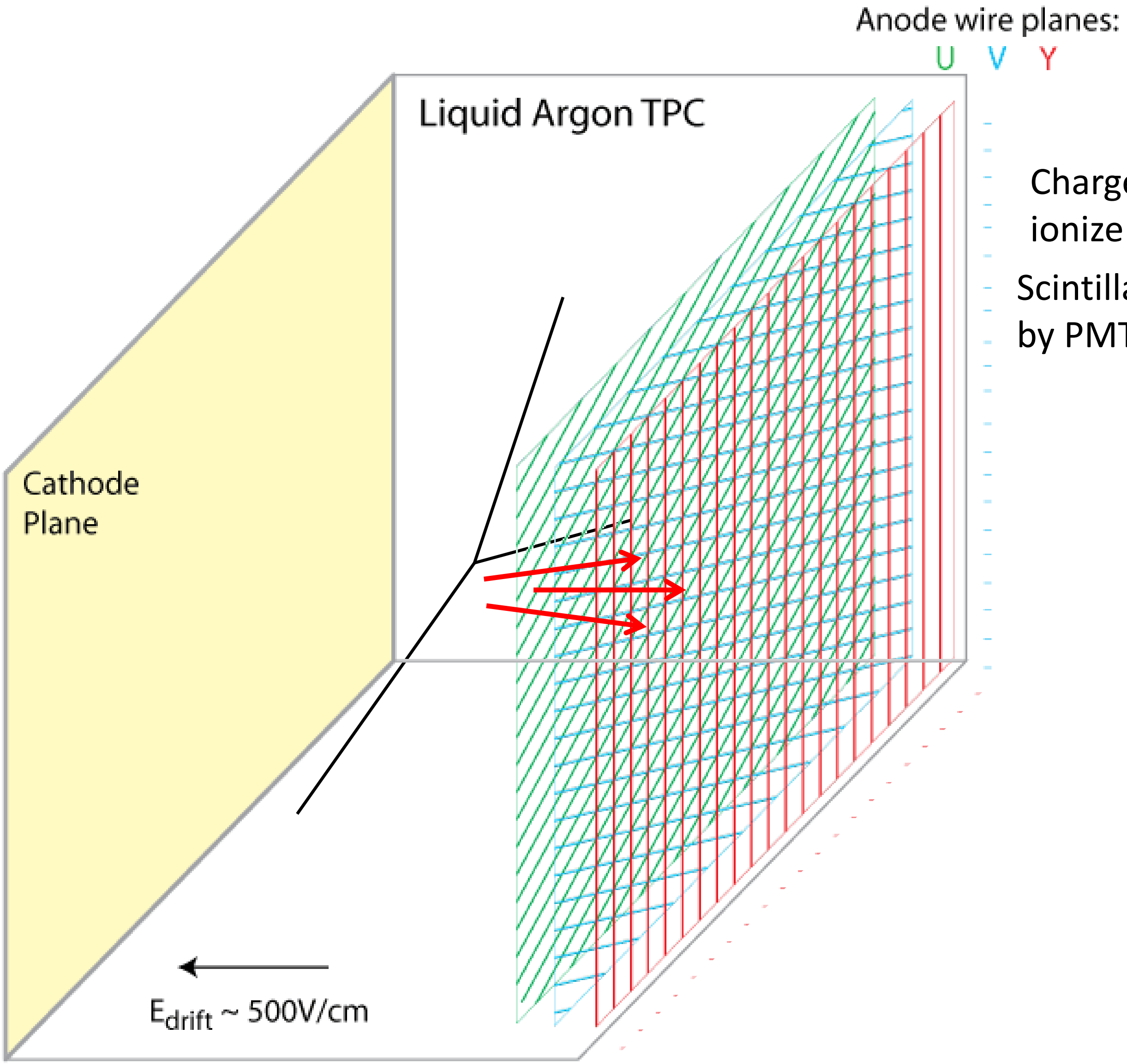
Anode wire planes:
U V Y
Liquid Argon TPC
Cathode Plane
E_{drift} ~ 500V/cm

Bo Yu (BNL)



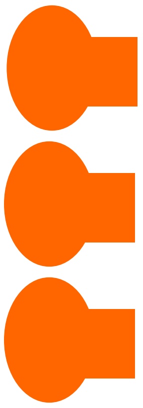
Charged particle tracks ionize Argon atoms

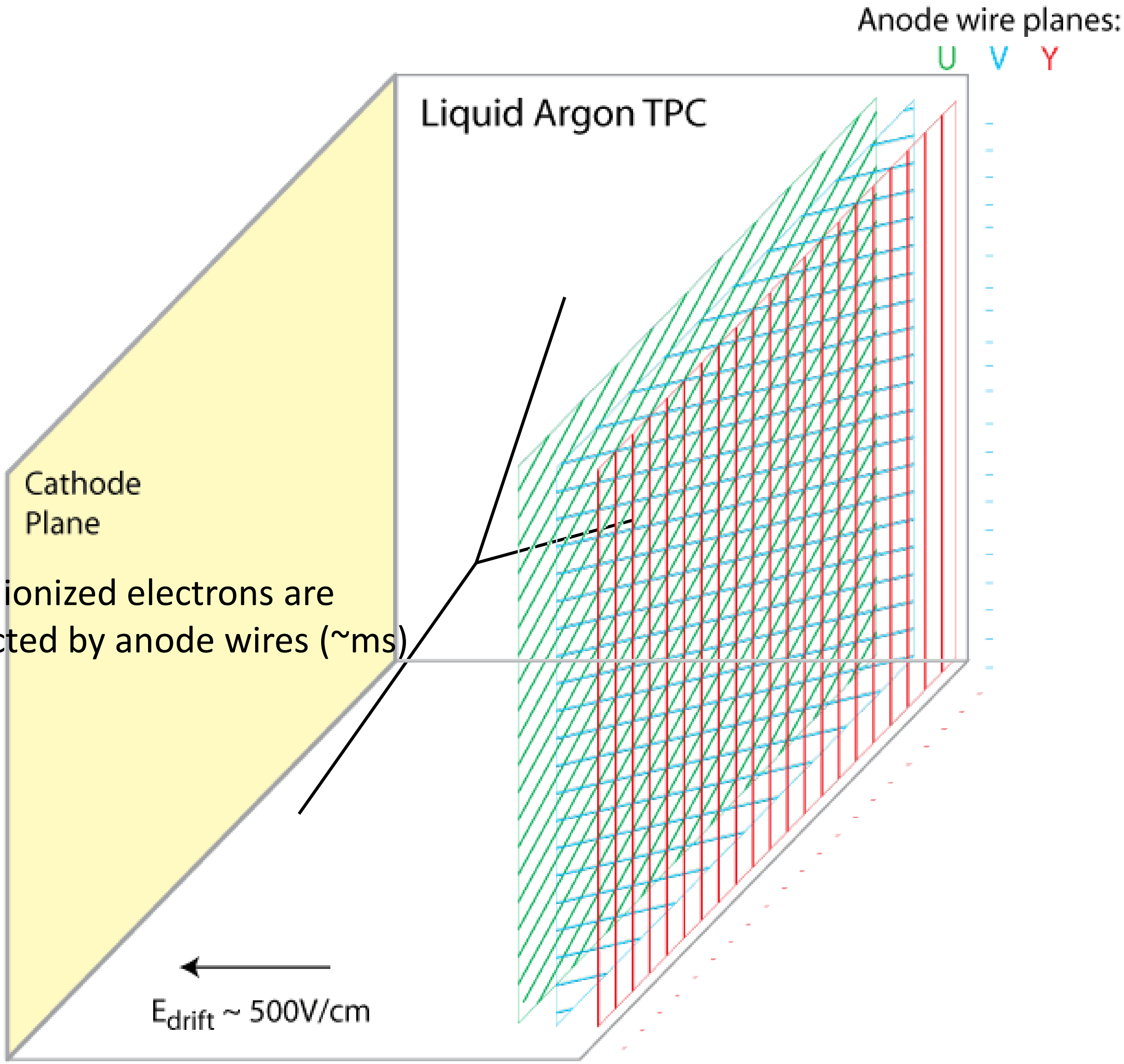
Bo Yu (BNL)



Charged particle tracks ionize Argon atoms

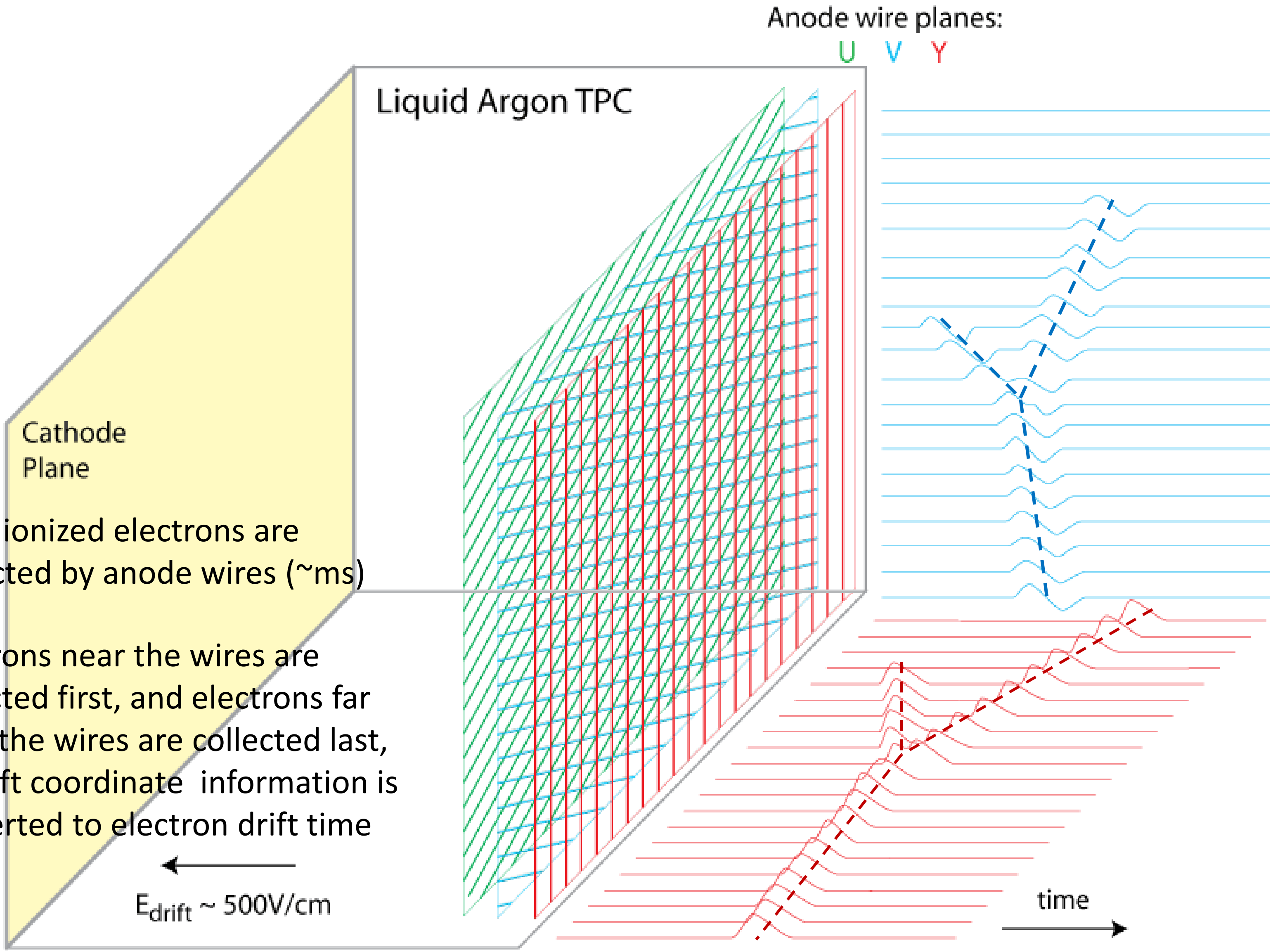
Scintillation light (~ns) is detected by PMTs at same time





Then ionized electrons are collected by anode wires (~ms)

Bo Yu (BNL)



Then ionized electrons are collected by anode wires (~ms)

Electrons near the wires are collected first, and electrons far from the wires are collected last, so drift coordinate information is converted to electron drift time

Why LAr?

- Relatively inexpensive, easy to obtain, easy to purity
- Ionization electrons can be drifted over large distances
- Good dielectric properties accommodate high voltages necessary for large drift fields
- Bright scintillator (transparent to its own scintillation light)

M. Soderberg

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

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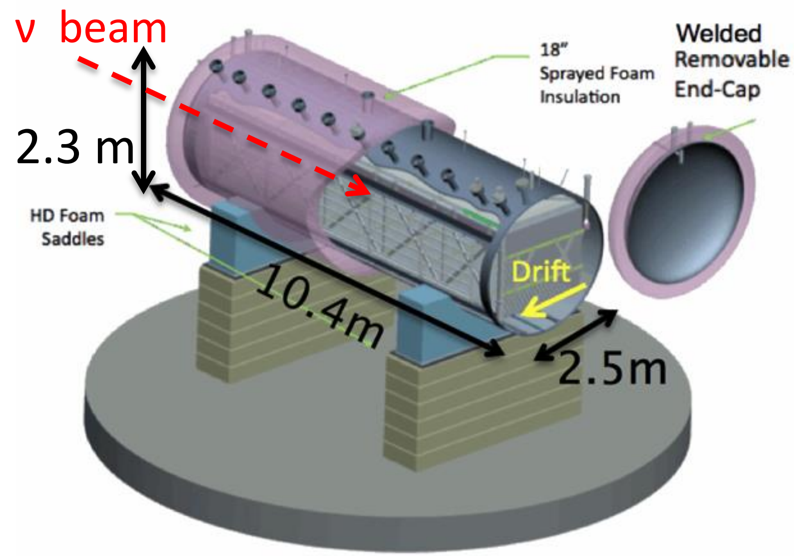
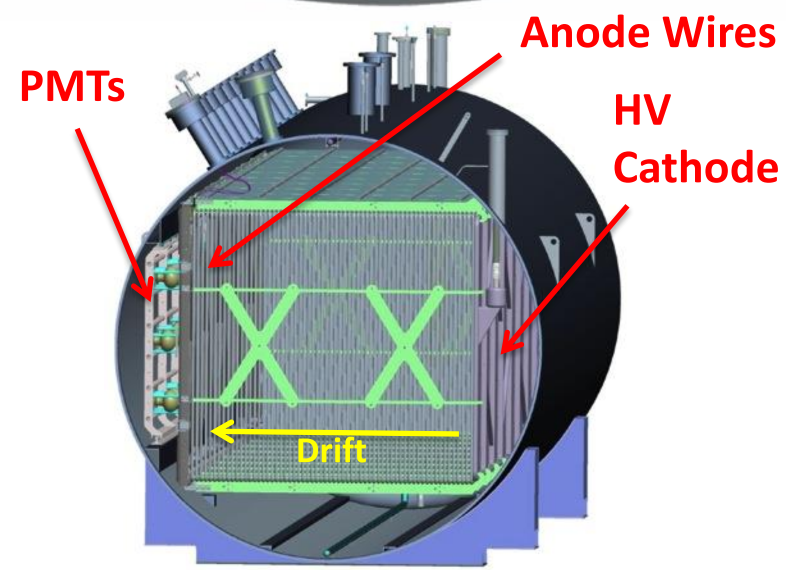
The MicroBooNE Detector

- Largest LArTPC in America (80 ton active mass)
- 8256 wires (3 mm pitch)
  - 3456 collection channels (oriented vertically)
  - 4800 induction channels (oriented at ±60˚)
- 32 8” Cryogenic PMTs + 4 light guide “paddles”
- UV laser calibration system

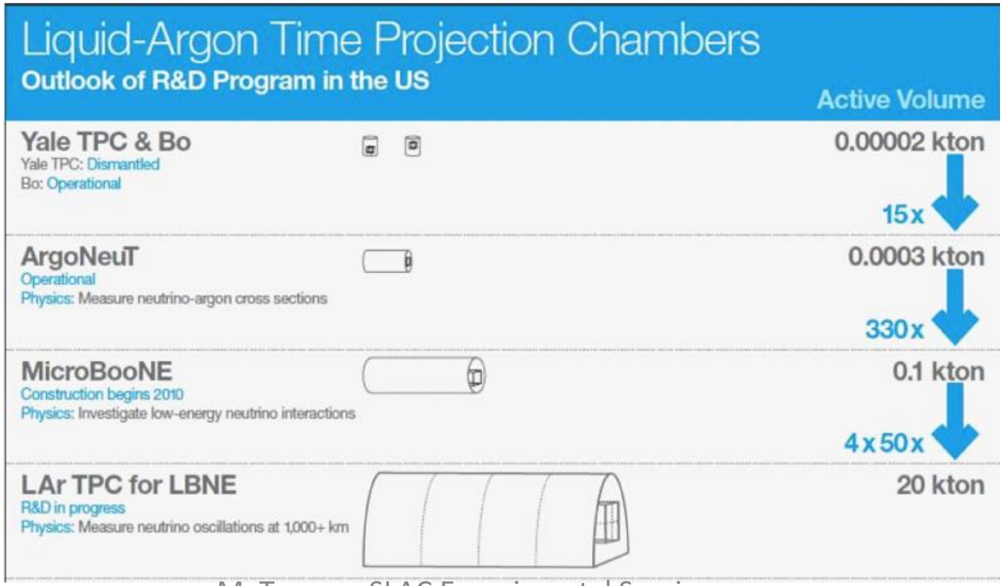




MicroBooNE Goals

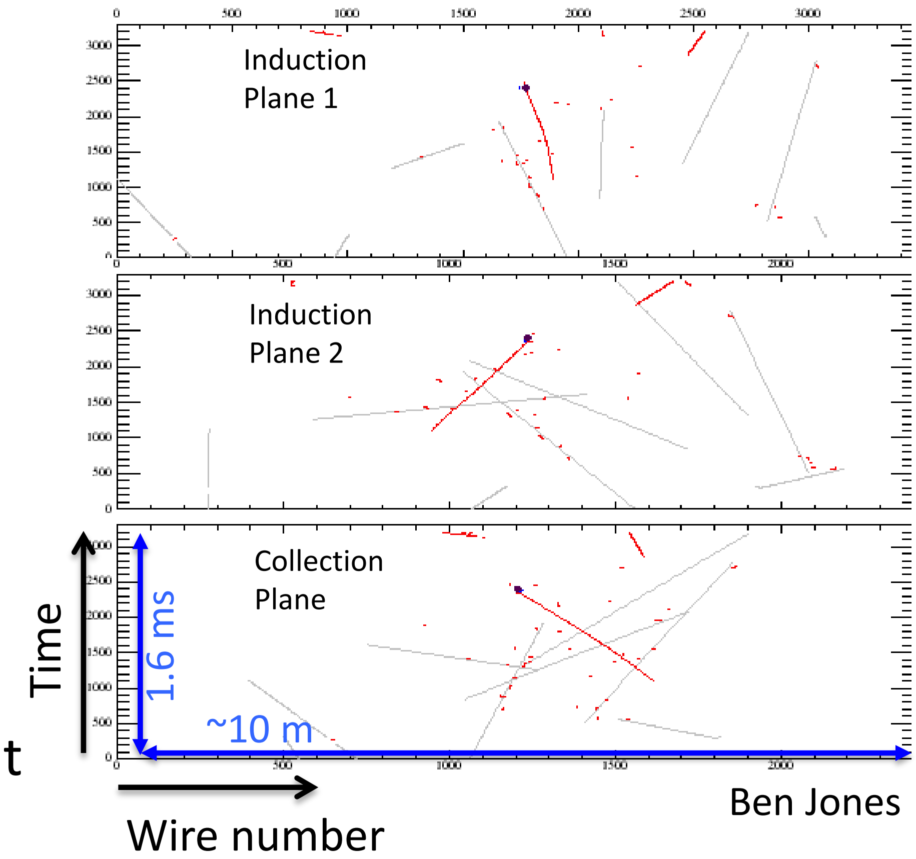
- Address MiniBooNE low energy excess
- ν cross section measurements on Argon
- R&D for future LArTPCs
  - Long drift length (2.5 m)
  - Cold electronics (CMOS ASICs in LAr)
  - LAr fill without evacuation (GAr purge)

Related to scalability

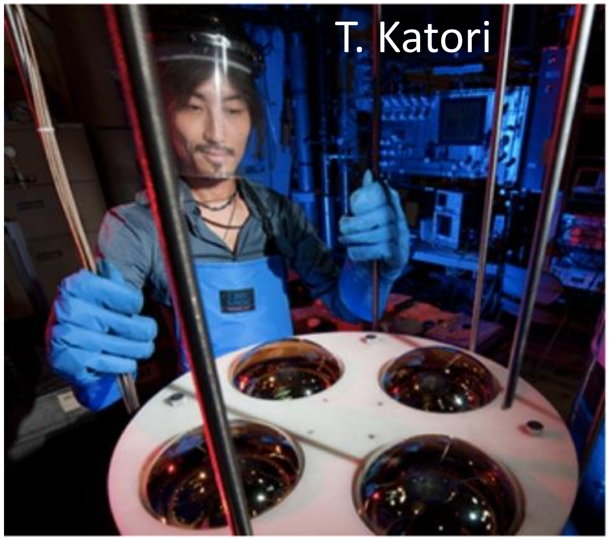


Light Detection in MicroBooNE

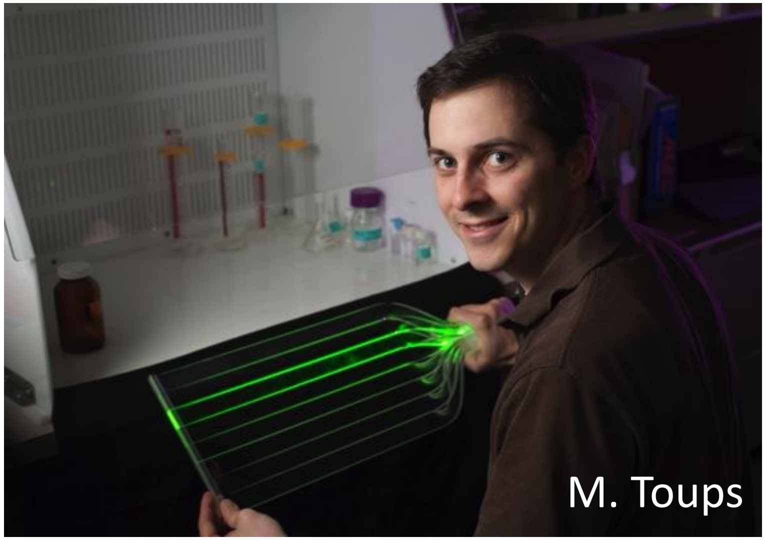
- Provides interaction time for non-accelerator events
- Triggers detector readout
- Input to reconstruction (particle ID, lower E_{thresh}, etc.)
- Cosmic background rejection
  - Essential for a surface LArTPC!
- Test bed for future technologies (light guide detectors)

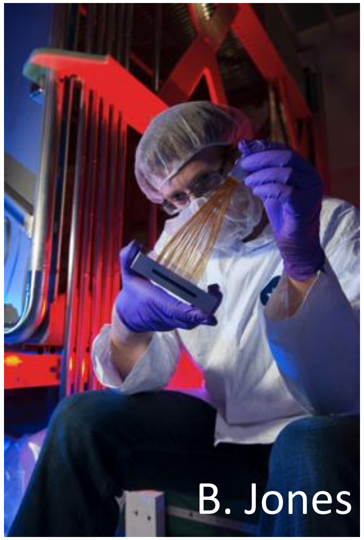


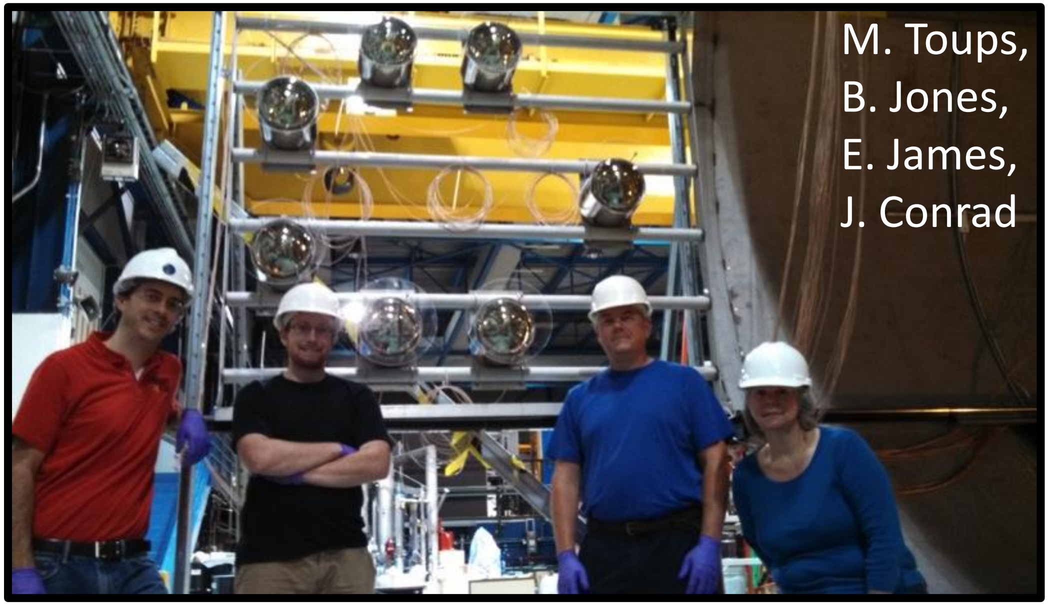
Our Role in MicroBooNE



T. Briese, et. al., JINST 8 (2013) T07005

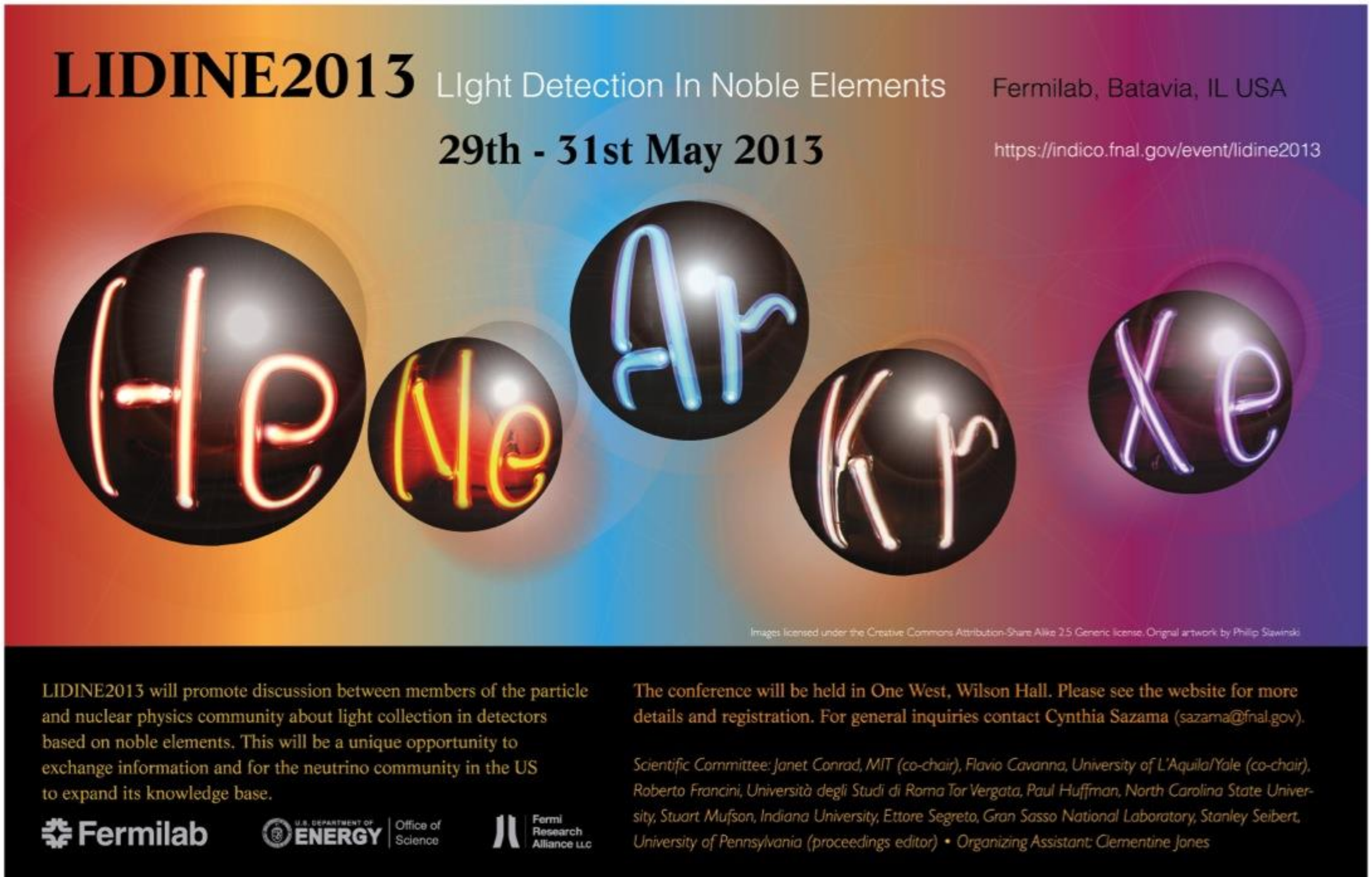






Light Detection Beyond MicroBooNE

Dark matter, neutron EDM, neutrinoless double beta-decay, etc.



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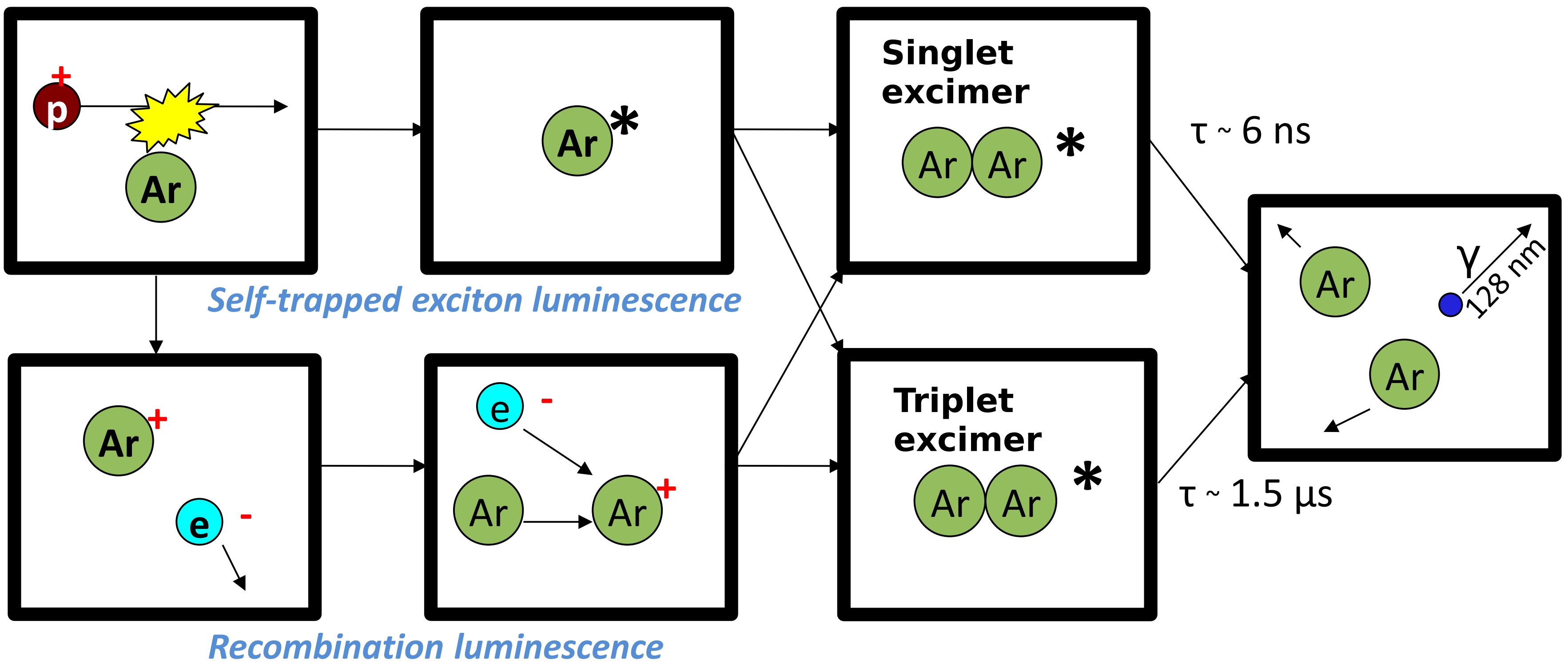
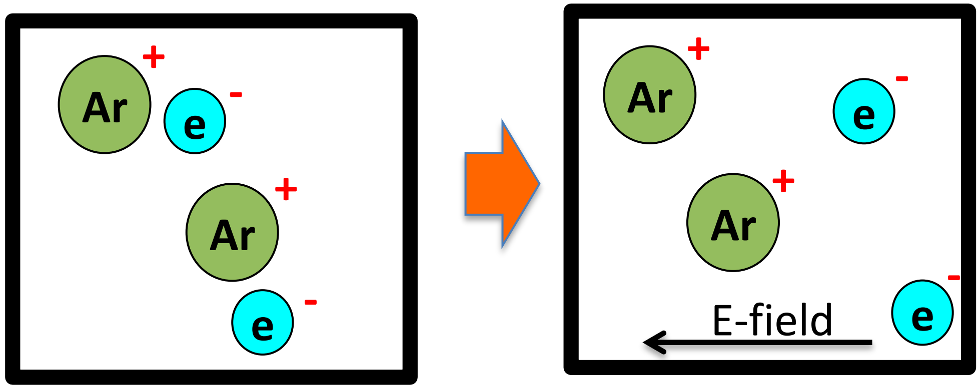
Production Pathways

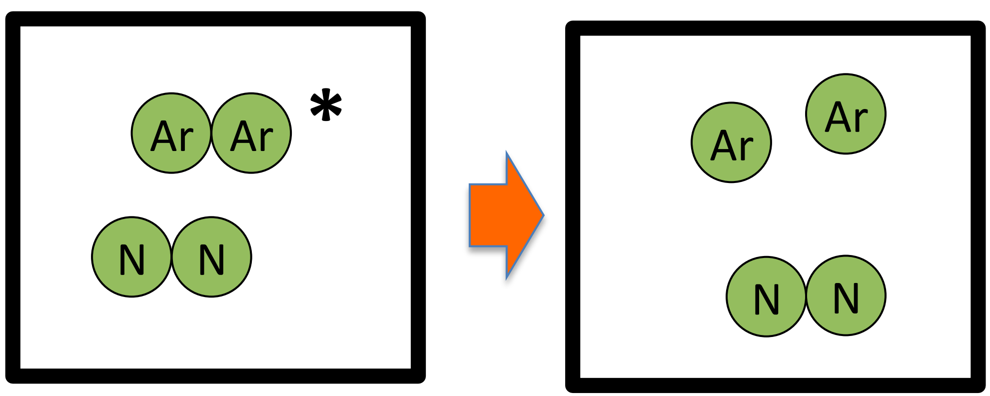


Production ratio depends on ionization density ⟶ particle ID!

Quenching Processes



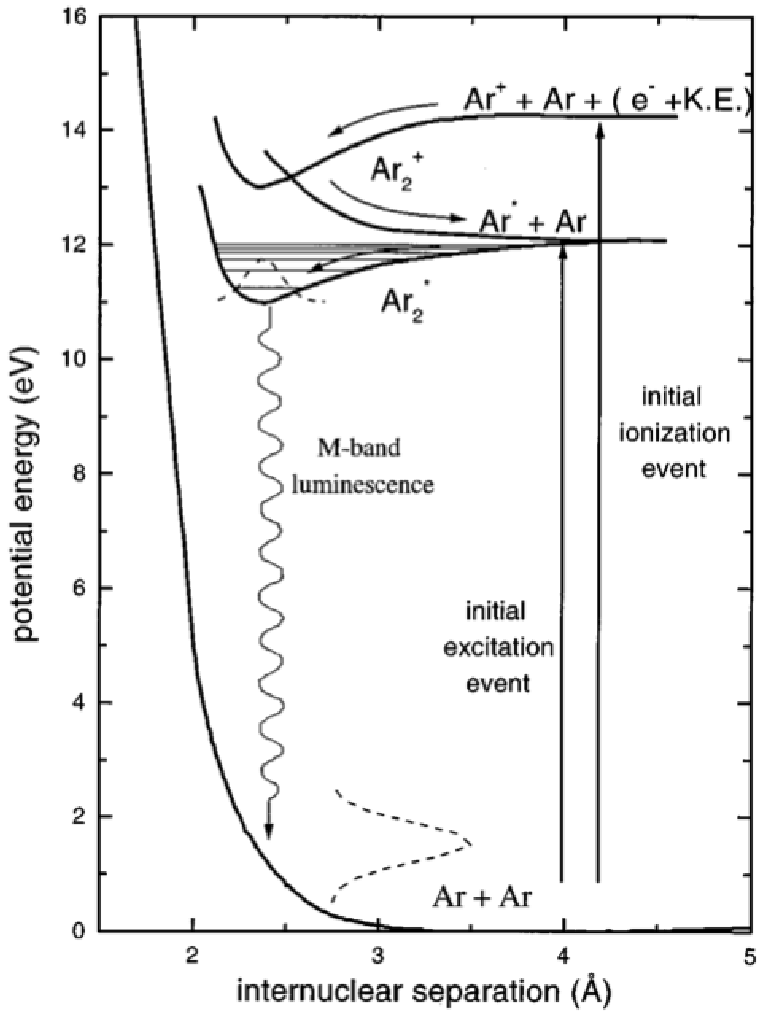
In an electric field



By trace impurities

→ Sets strict limits on impurity concentrations in LArTPCs

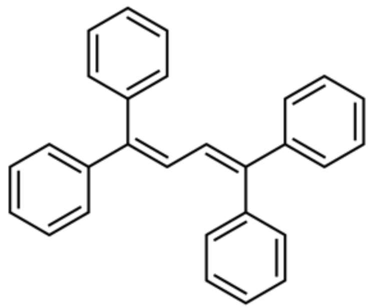
Propagation: LAr is self-transparent



D.E. Grosjean et al., Phys. Rev. B 56 (1997) 6975-6981.

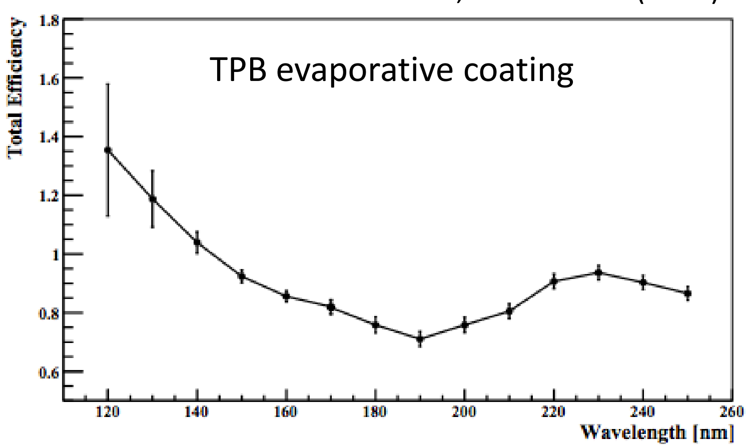
Wavelength-shift to Visible Spectrum

Tetraphenyl butadiene (TPB)

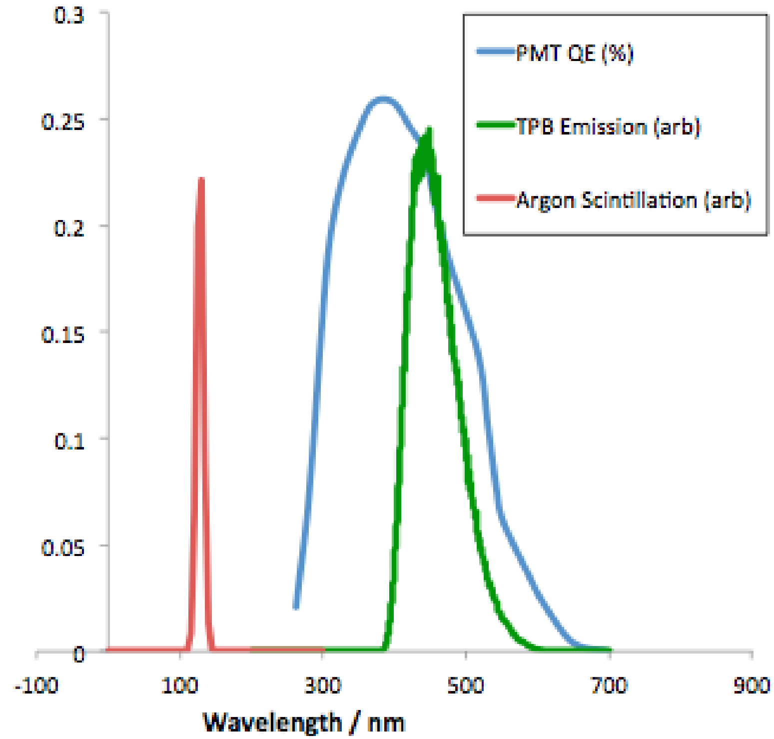


C.S. Chiu, et al. JINST 7 (2012) P07007

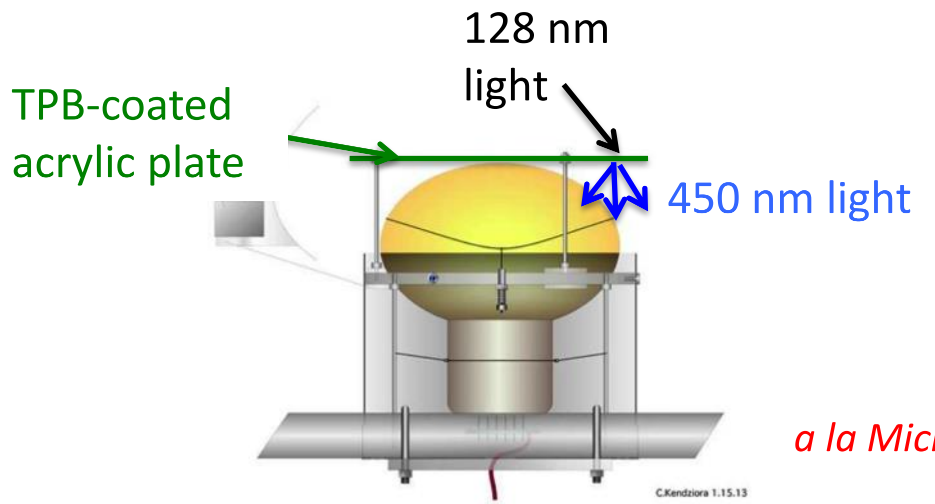
B.J.P. Jones, et al JINST 8 (2013) P01013



V. Gehman et al, NIM A 654, 116 (2011)

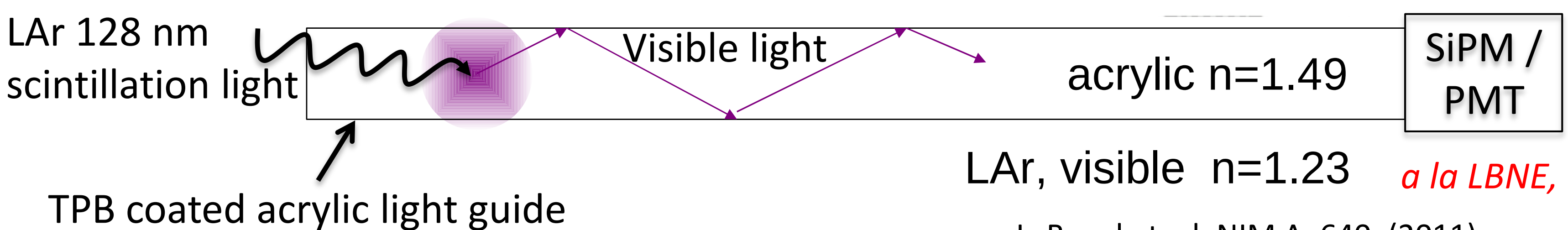


Photodetection



a la MicroBoonE

In large neutrino LArTPCs thin profile photo-detectors are desirable to maximize TPC active regions—



a la LBNE, LAr1-ND

L. Bugel et. al. NIM A, 640, (2011)

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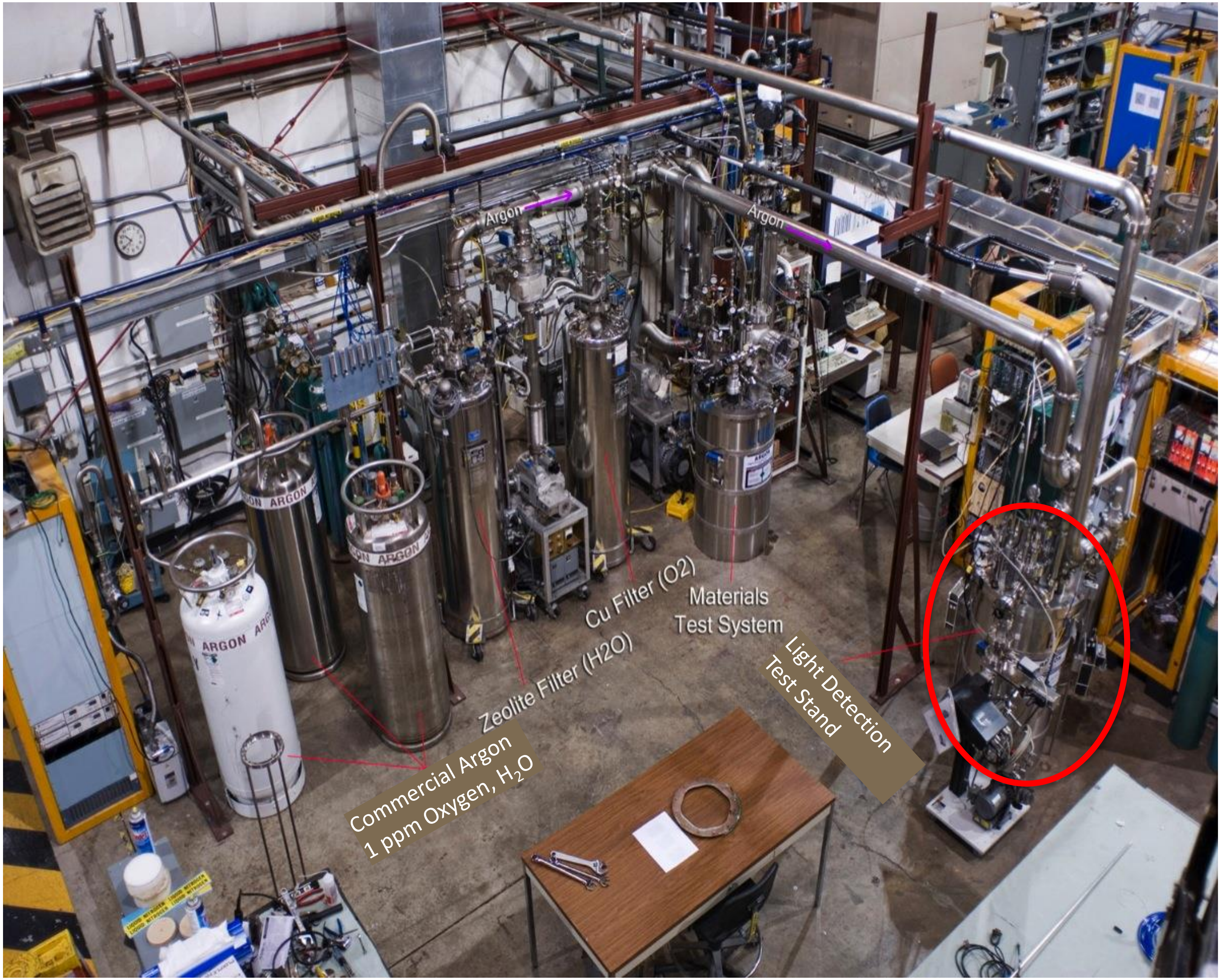
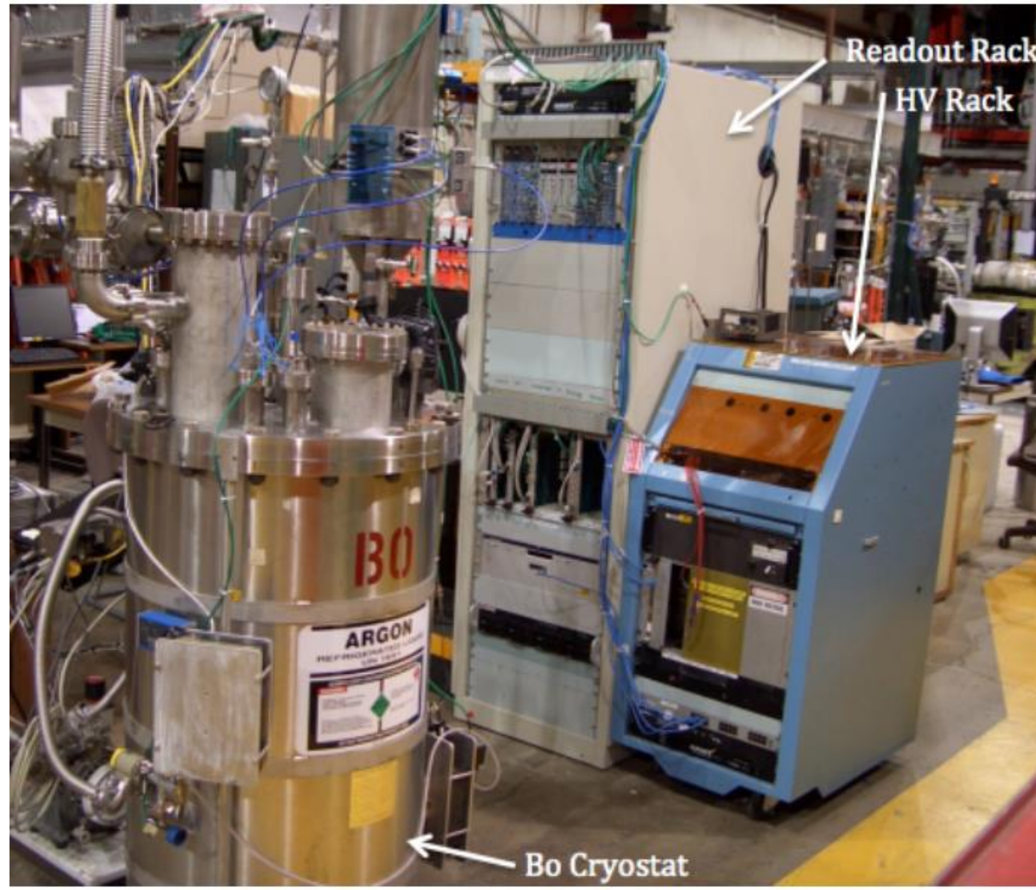

Argon
Argon
Cu Filter (O2)
Materials
Test System
Light Detection
Test Stand
Zeolite Filter (H2O)
Commercial Argon
1 ppm Oxygen, H2O

“Bo” Light Detection Test Stand

- 40”, 250 L vacuum-insulated cryostat
  - Recently upgraded to 84” (“Tall Bo”)
- High purity LAr delivery system
- Condenser tower allows for closed system operation



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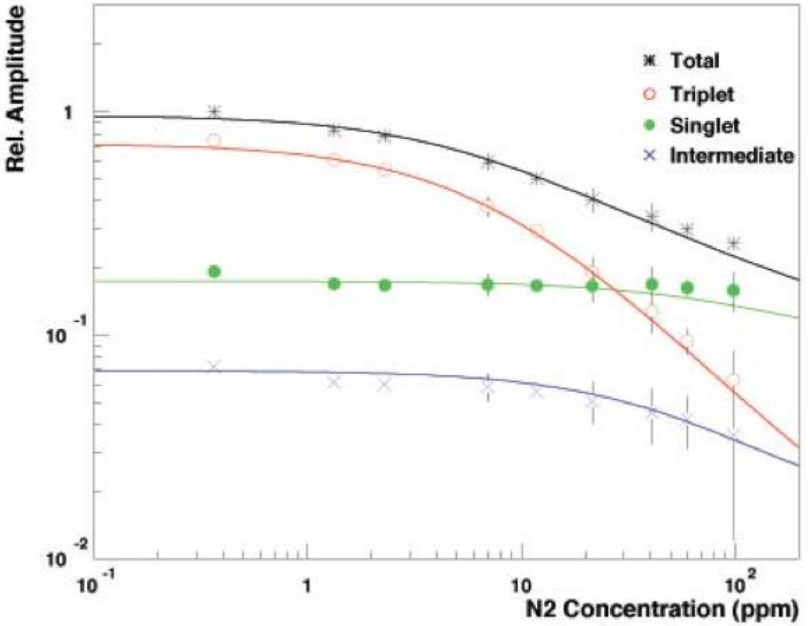
Two distinct effects on light collection

- LAr scintillation light production may be quenched by impurities

- LAr scintillation light en route to a photo-detector may be absorbed by impurities in the bulk material

→ No measurements of this existed!

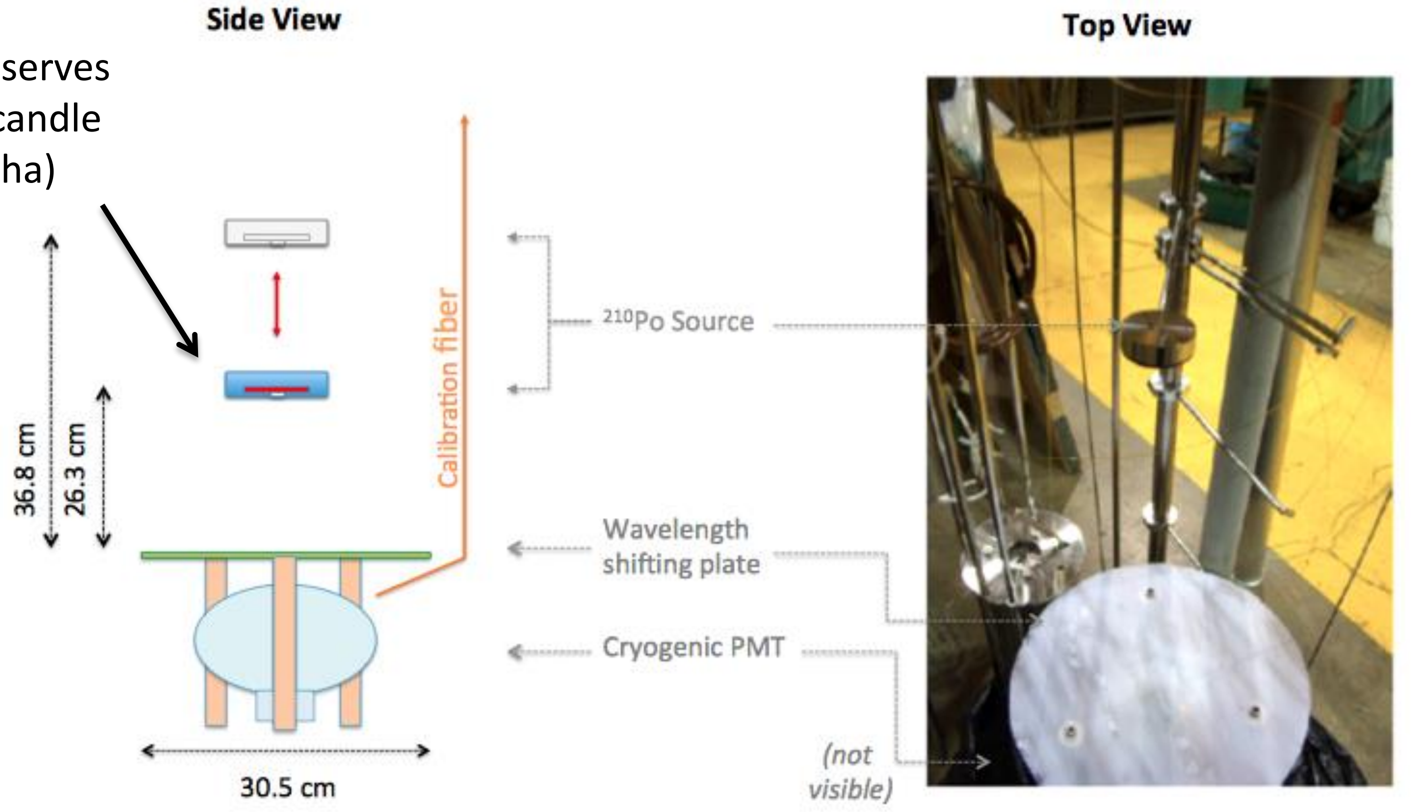


R Acciarri *et al* 2010 *JINST* **5** P06003

Argon Specification	Concentration of N_2
Measured N_2 concentration of clean argon for this study	37 ppb
AirGas research (grade 6) argon [25]	1 ppm
MicroBooNE cryogenic specification	2 ppm
Start of liquid recirculation phase of Liquid Argon Purity Demonstrator, Run 2 [26,27]	8 ppm
AirGas industrial (grade 4) argon [25]	100 ppm

The Experiment Setup

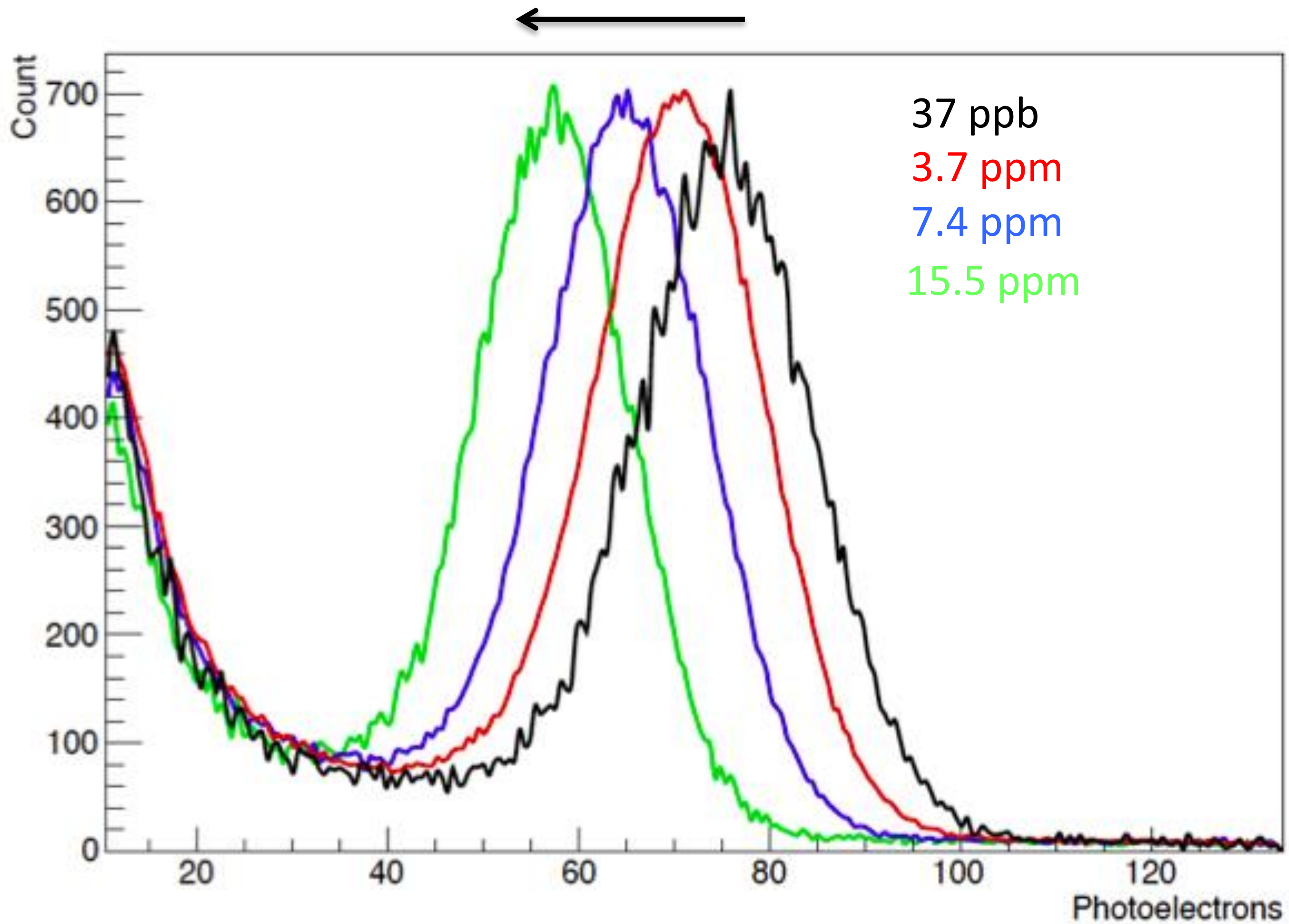
^{210}Po source serves as standard candle (5.3 MeV alpha)



Inject controlled quantities of Nitrogen in Bo and look for:

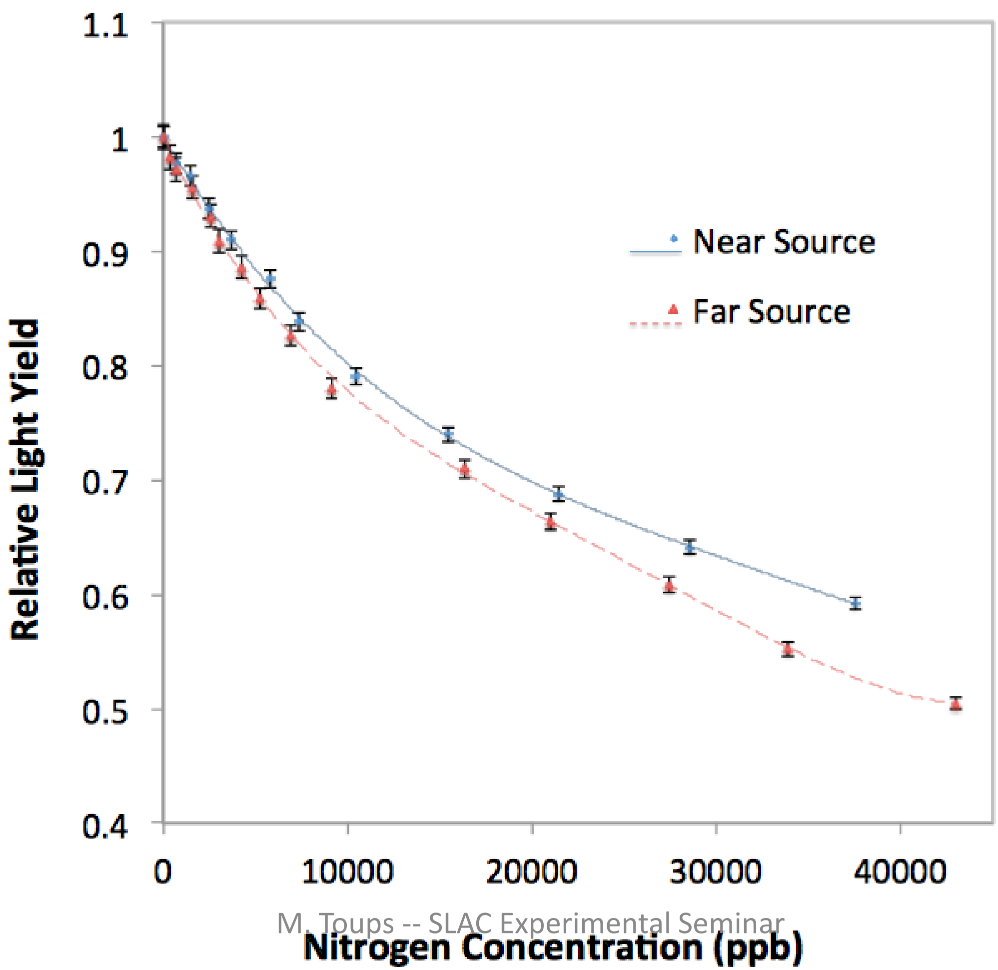
- Differences in the relative amount of light seen from a mono-energetic alpha source as a function of Nitrogen concentration for 2 source-detector distances

Peak of pulse area distributions decreases as a function of nitrogen concentration



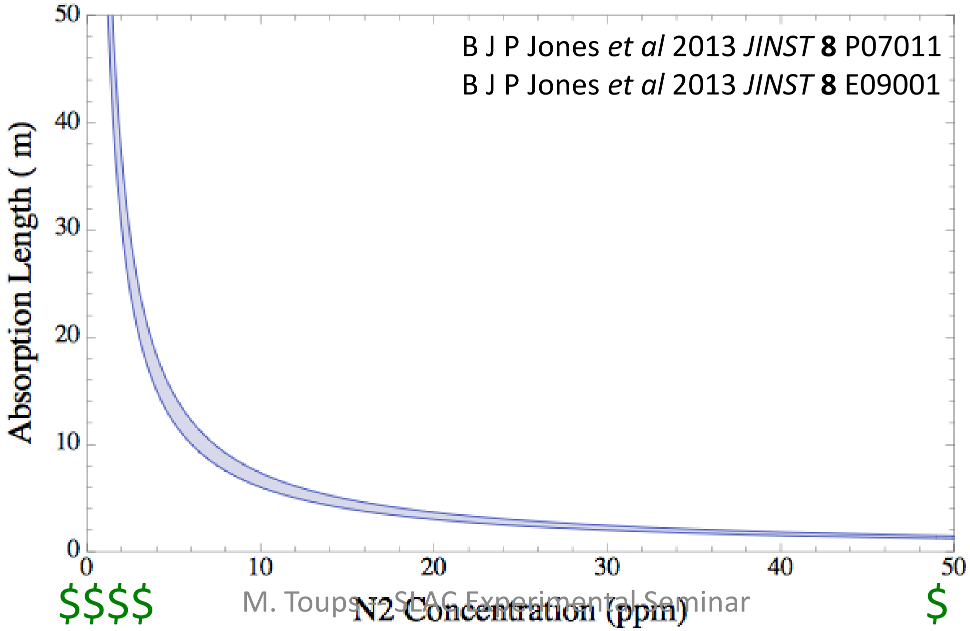
For a given nitrogen concentration, quenching has the same effect on both source configurations

The fact that the two curves diverge tells us there is a distance-dependent light loss mechanism at play



Relatively loose purity specifications of ppm-level nitrogen contamination required by current- and next-generation LAr particle physics experiments

Argon Specification	Concentration of N_2	Absorption Length
Measured N_2 concentration of clean argon for this study	37 ppb	1790 ± 160 m
AirGas research (grade 6) argon [25]	1 ppm	66 ± 6 m
MicroBooNE cryogenic specification	2 ppm	30 ± 3 m



Outline

- Neutrino Oscillation Physics
  - Experimental Approaches
- Liquid Argon Time Projection Chambers (LArTPCs)
  - MicroBooNE
- Liquid Argon Scintillation Light
- LAr Light Studies at Fermilab
  - Nitrogen Contamination in LAr
  - Argon/Methane Mixtures
  - Characterizing LAr Light Guide Performance

Why Study Light Production in CH_4-doped LAr?

- Long electron drift distances demonstrated for CH_4 concentrations of several %

- Introduces inverse-beta-decay interaction channel $(\bar{n}_e + p \rightarrow e^+ + n)$
  - Potentially broadens low-energy neutrino physics program of LArTPCs

- Some evidence in the literature that CH_4 may act as a wavelength-shifter

- May provide an important input for LAr-based dark matter detectors that produce Ar from underground CO_2 wells and rely on light collection

ELSEVIER
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 253, Issue 2, 1 January 1987, Pages 273–277

Drifting electrons over large distances in liquid argon-methane mixtures

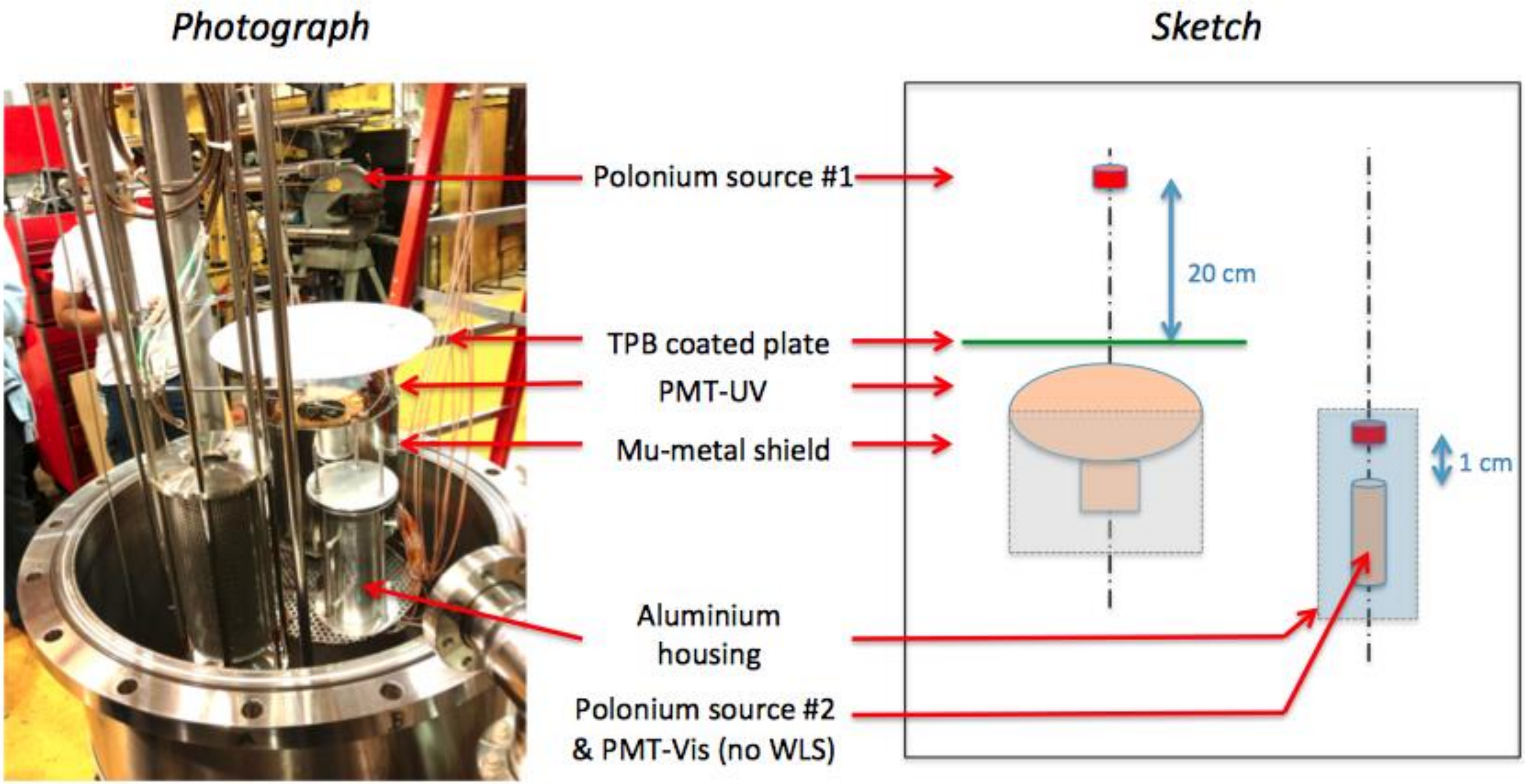
E. Aprile*, K.L. Giboni**, C. Rubbia

Table 2: Gas concentrations from the Kinder Morgan Doe Canyon CO_2 wells.

Gas Type	Well Concentration
Carbon Dioxide	96%
Nitrogen	2.4%
Methane	5,700 ppm
Helium	4,300 ppm
Other hydrocarbons	2,100 ppm
Water	1,000 ppm
Argon	600 ppm
Oxygen	Below sensitivity

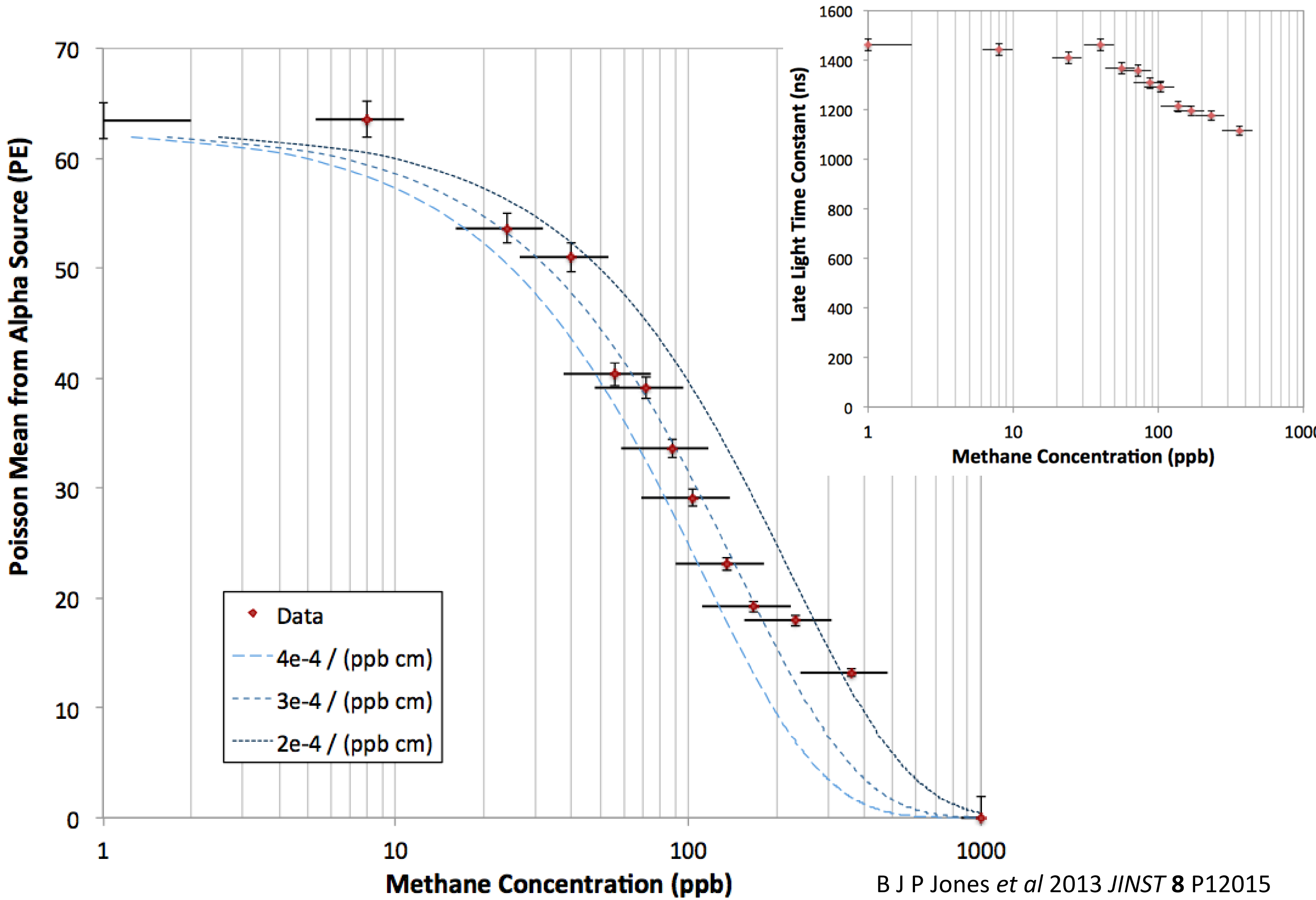
arXiv:1204.6024v2 [astro-ph.IM]

The Experiment Setup



Inject controlled quantities of CH_4 in Bo and look for:

1. Quenching and/or absorption of LAr scintillation light
2. LAr scintillation light wavelength shifted to visible light



B J P Jones *et al* 2013 *JINST* **8** P12015

- For detectors larger than O(1 cm), CH_4 concentration should be < O(100) ppb to limit absorption losses to less than a few percent
- Quenching is also at observed, but is subdominant
- No significant amount of LAr scintillation light is wavelength-shifted to visible

Outline

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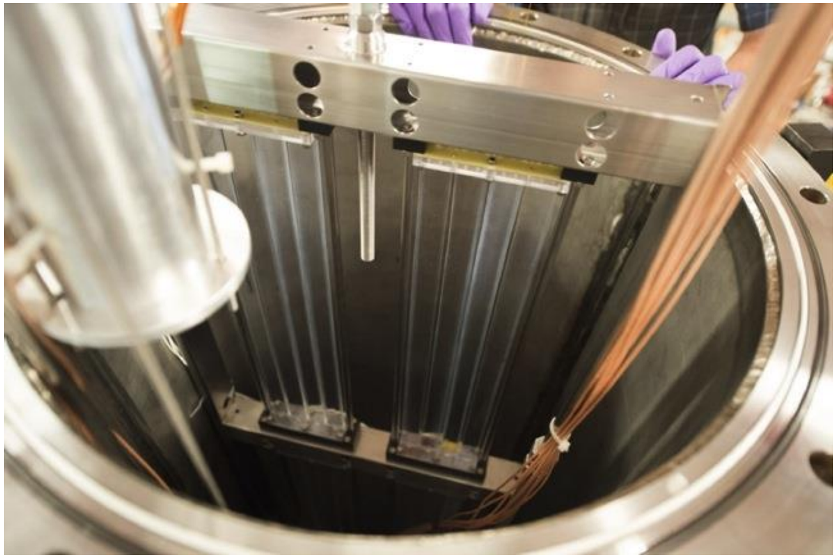
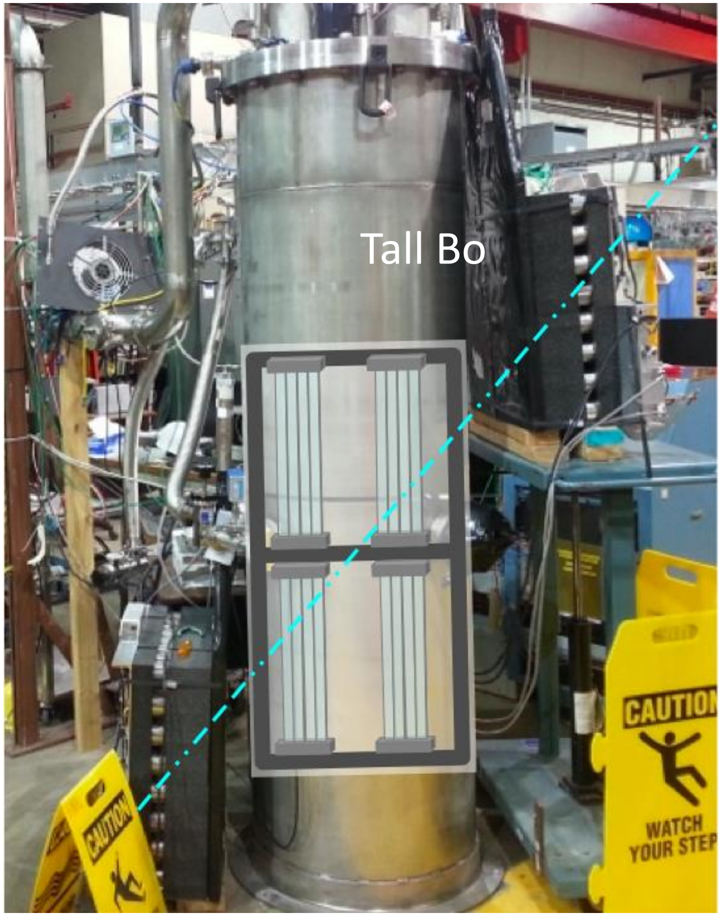
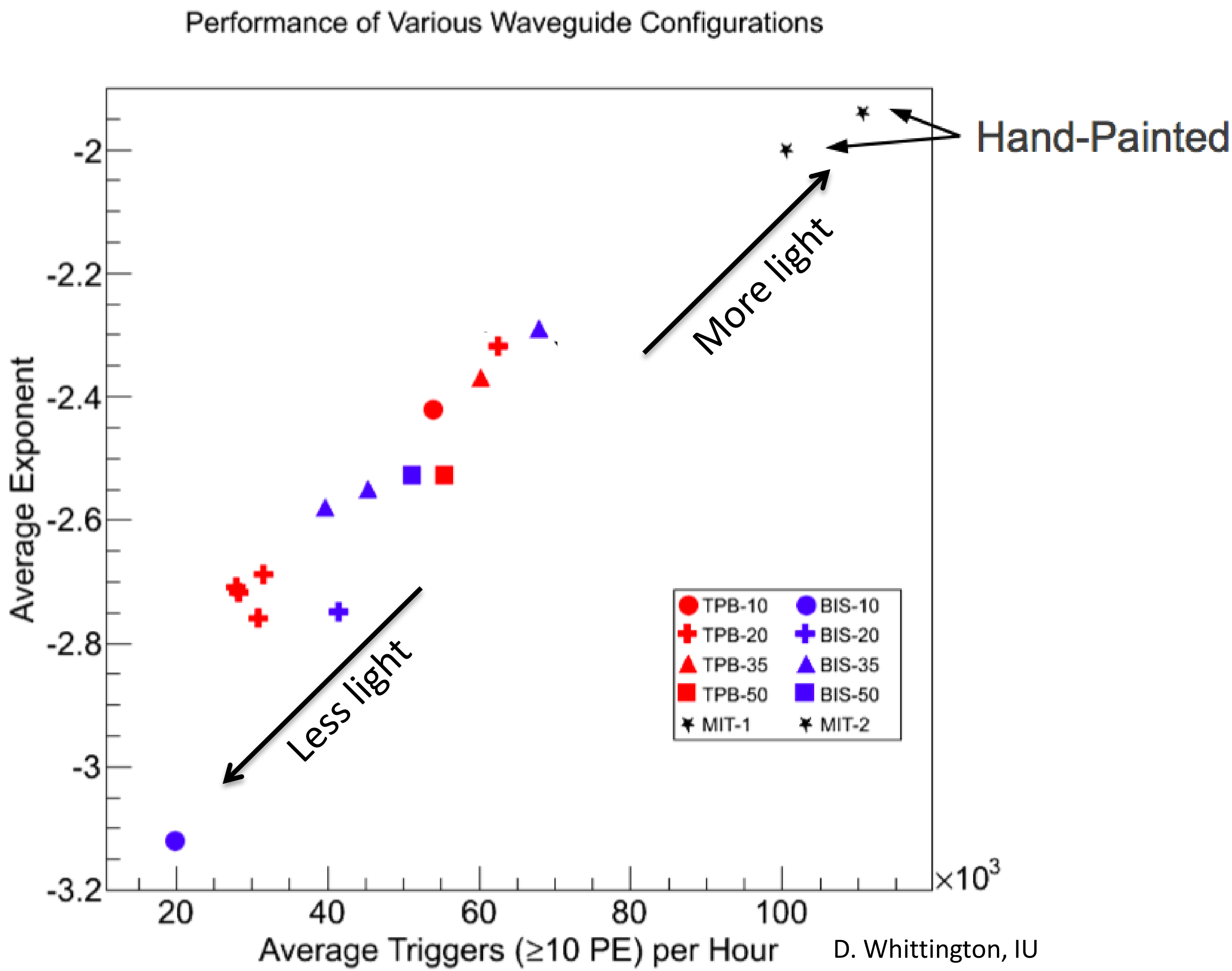
Different Wavelength-Shifting (WLS) Coatings

- IU spray coatings with WLS melted into surface
  - TPB vs. bis-MSB
  - Compare 10, 20, 35, & 50 coats
- MIT hand-painted TPB coatings
  - arXiv:1210.3793 [physics.ins-det]





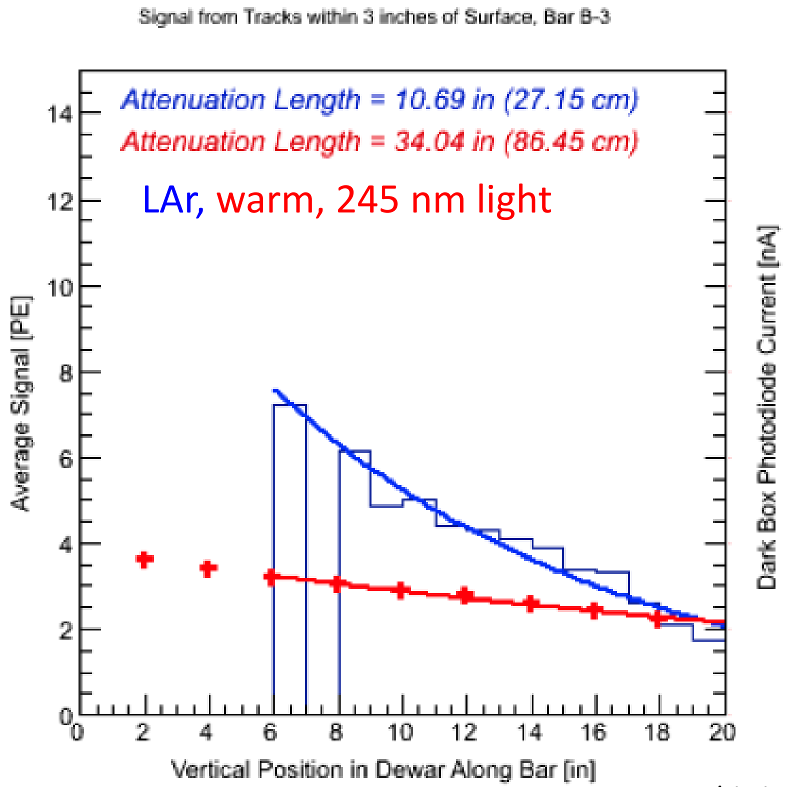
All cosmic data triggering SiPMs



D. Whittington, IU

We would like to evaluate the performance of these light guides by measuring their attenuation lengths at room temperature

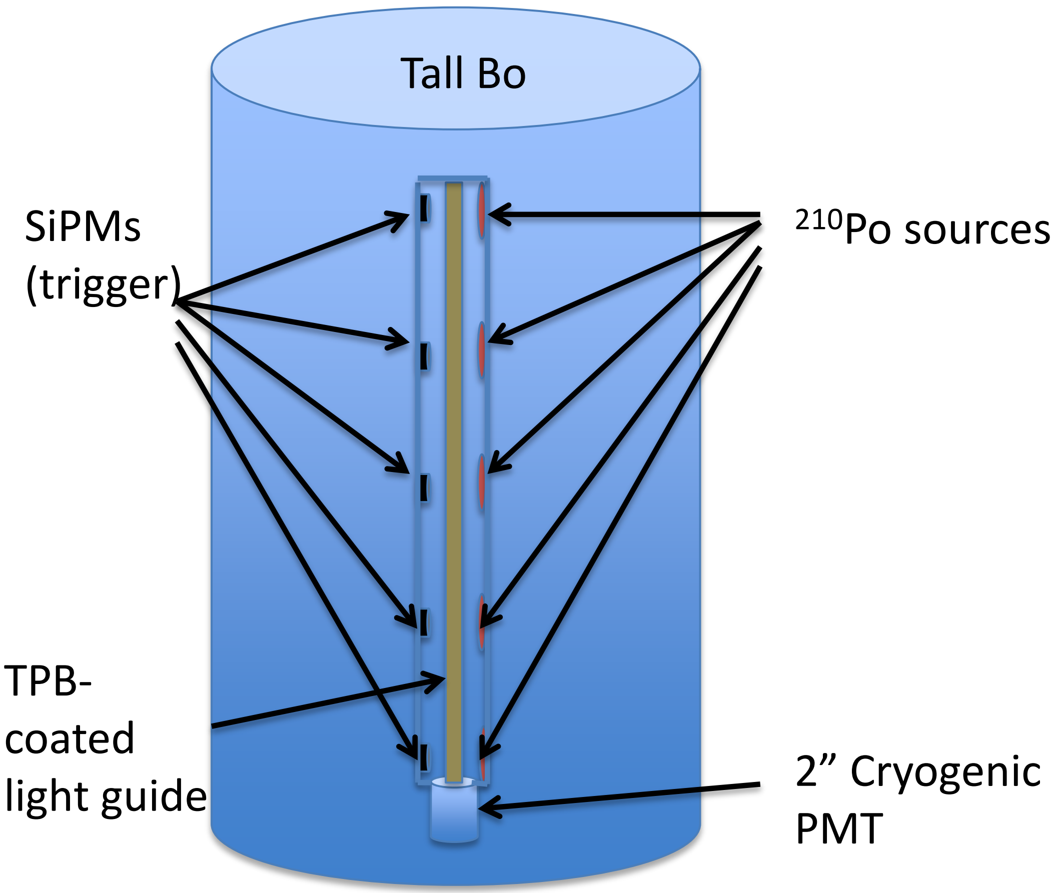
But attenuation lengths measured at room temperature do not track attenuation lengths measured with cosmics in LAr



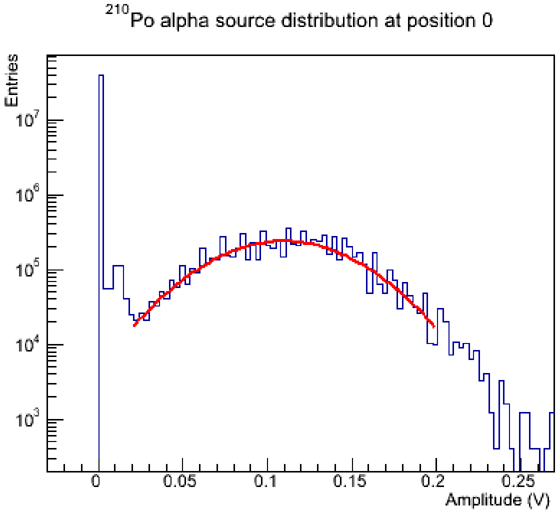
D. Whittington, IU

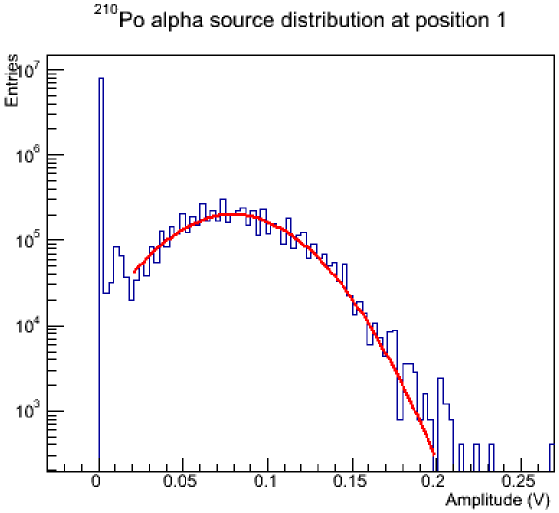
Attenuation Length Measurement

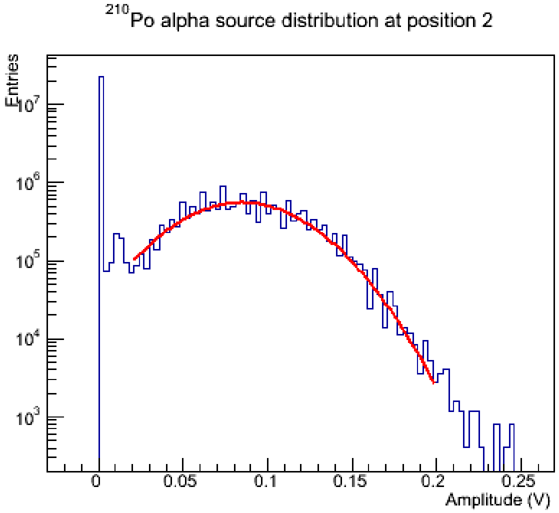
- Set up currently installed in Tall Bo to make this measurement
- Expect results soon!

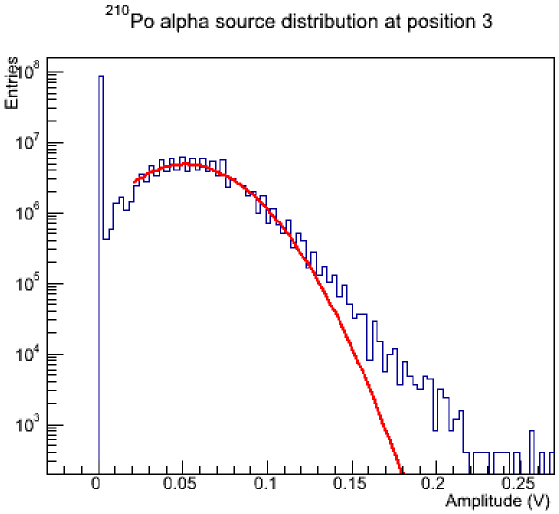


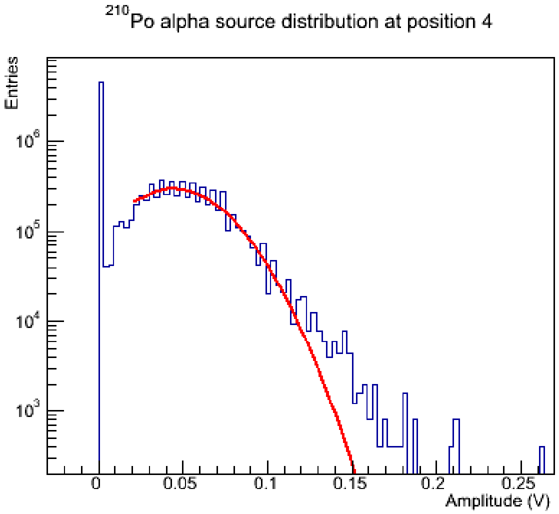
Preliminary Results

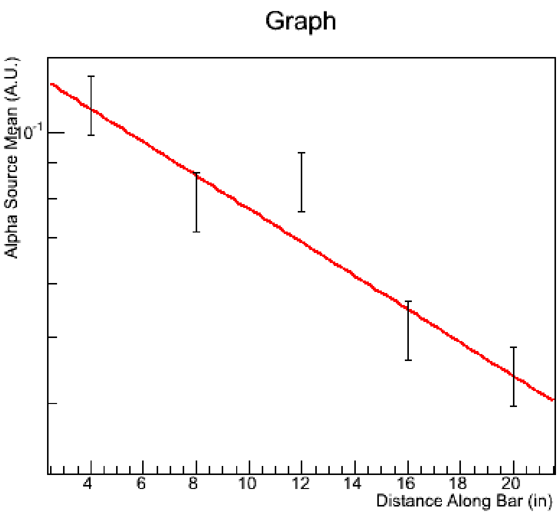












More LAr Light Studies Yet To Come

- MicroBooNE-specific R&D
- LAr Scintillation Light Time Constants
- Rayleigh Scattering
- ^{222}Rn Tracing in LAr
- Ar/Xe Mixtures

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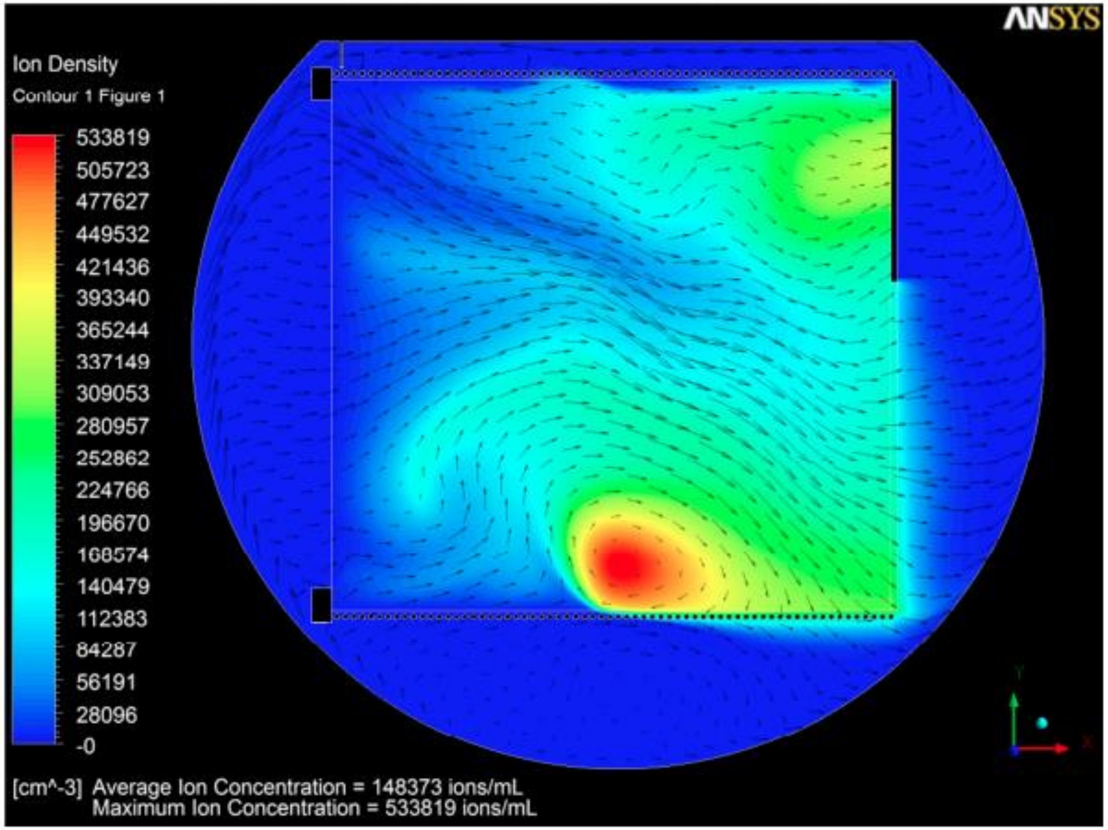
^{222}Rn Tracing in LAr

Mapping LAr Flows

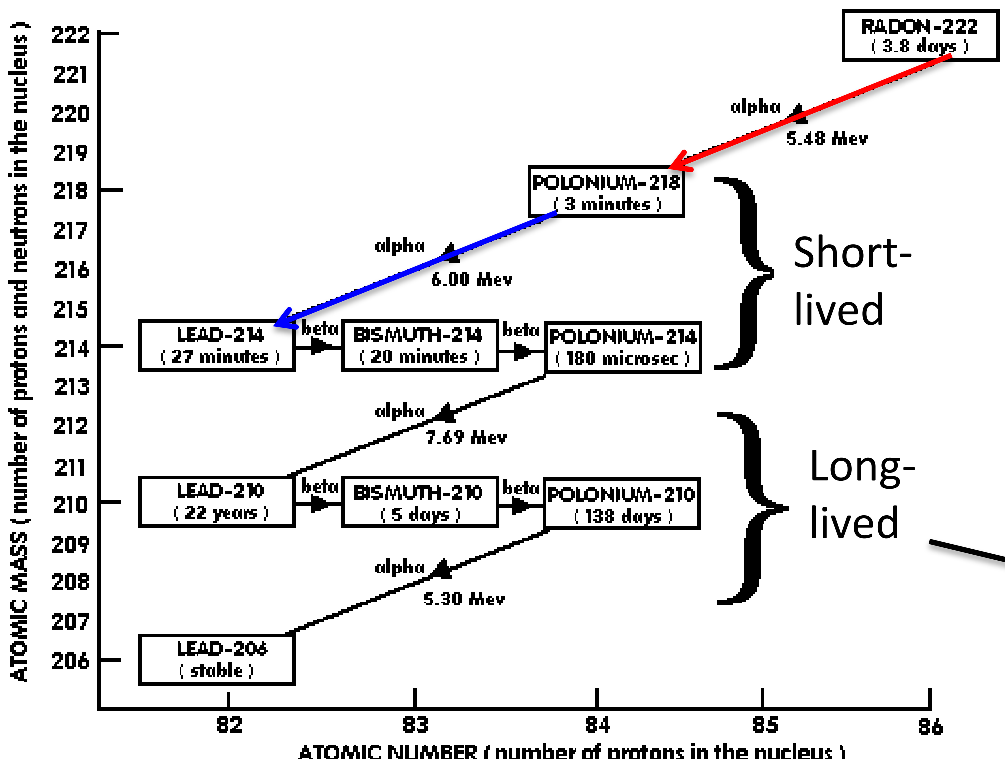


E. Voirin,
for µBooNE

Ion concentration for velocity field (fluid velocity + drift velocity of 8 mm/sec)

^{222}Rn Tracing

- A new technique to map flows in a neutrino LArTPCs
- Inject ^{222}Rn into detector and look for correlated ^{222}Rn-^{218}Po decays
  - Reconstruct positions to measure flow



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5.48MeV alpha
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These will remain in your detector, but accelerator-based neutrino experiments only require negligible background in beam

We would like to test this idea in Bo

- New infrastructure is required
  - Field cage (for drift)
  - Array of SiPMs (for position reconstruction)
  - Radon injection system

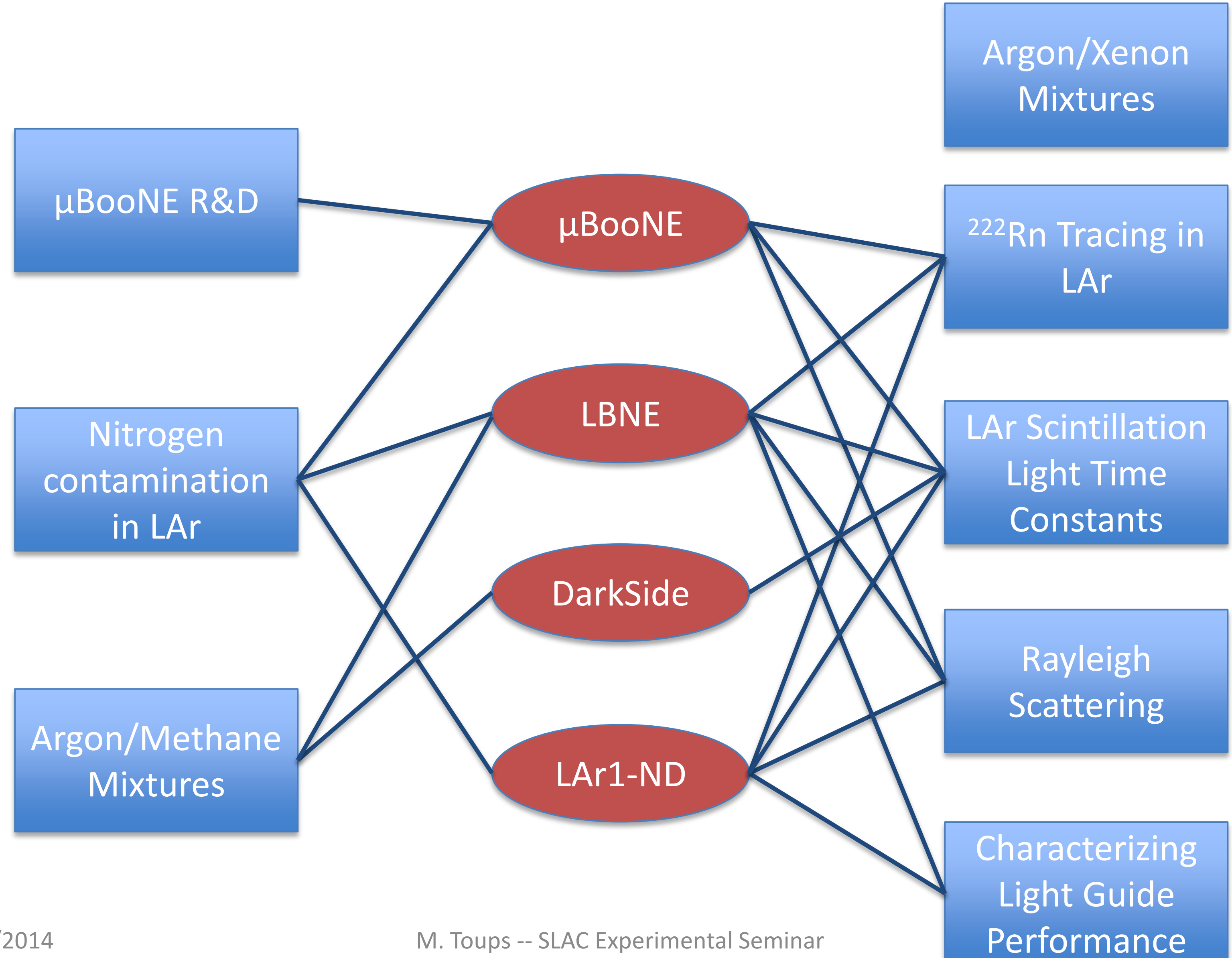
- We have already located enough Ra at FNAL to generate enough ^{222}Rn for this test!

Argon/Xenon Mixtures

Adding O(10 -100 ppm) Xe to LAr

- Shifts light to earlier times
  - Roughly 3/4 of the LAr scintillation light produced by a MIP is in the slow component with τ = 1.6 μs
  - Doping with Xe shifts the time scale of this slow component from O(1 μs) → O(10 ns)
    - ➢ Easier to collect in a neutrino LArTPC
- Wavelength-shifts light to 175 nm
  - At concentrations of O(100 ppm) LAr scintillation (late) light is converted to 175 nm
    - ➢ More efficient detection
- We have already made one attempt to inject Xe in Bo, and we would like to pursue this further

In a Nutshell



Summary (I Hope I Convinced You That):

- Light detection is an important (and often overlooked) part of neutrino LArTPCs
- Research in noble liquid light detection cuts across many fields
- There is plenty of room for improving our use of light information in noble liquid detectors


End.

μBooNE R&D

PMT Vertical Slice Test

Bo was used to develop a full vertical slice of the μBooNE optical system, including:

- 8” PMT, base, mount, and wavelength shifting plate
- PMT cables and feed through
- PMT splitter
- High voltage + interlocks
- Readout electronics

This was an incredibly valuable resource for the development of a new LAr optical system and led to tweaks in the design of almost every item on the above list

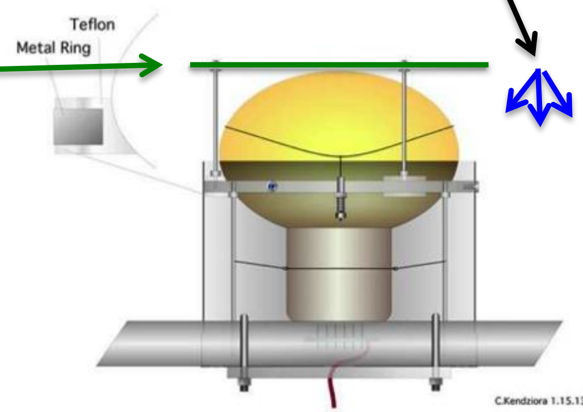
Quantum Efficiency Studies

^{210}Po source serves as standard candle (5.3 MeV alpha)

128 nm light

TPB-coated acrylic plate

450 nm light

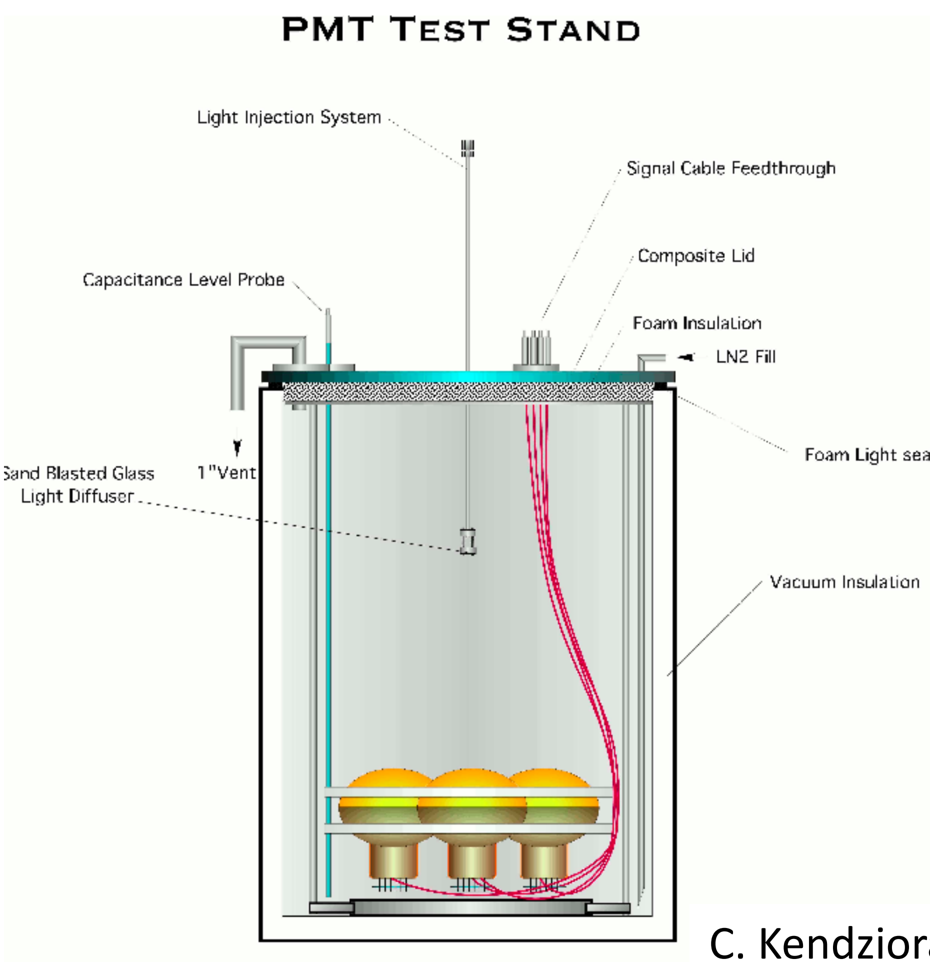


Light yield incident on TPB plate predicted from known LAr light yield, alpha energy, and solid angle subtended by plate

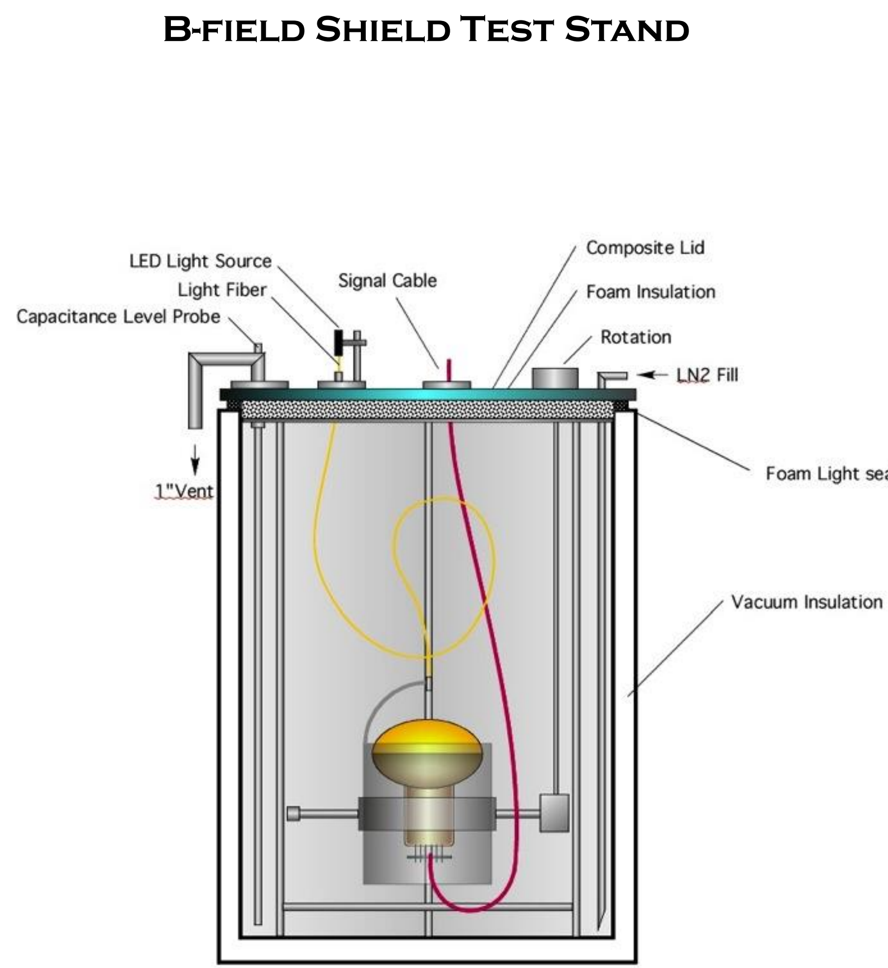
Measured photo electrons then gives global efficiency (photoelectrons/incident photon) for input to MC

→ Can use this technique for other optical detectors as well

PMT Reception Testing and B-Field Shield R&D



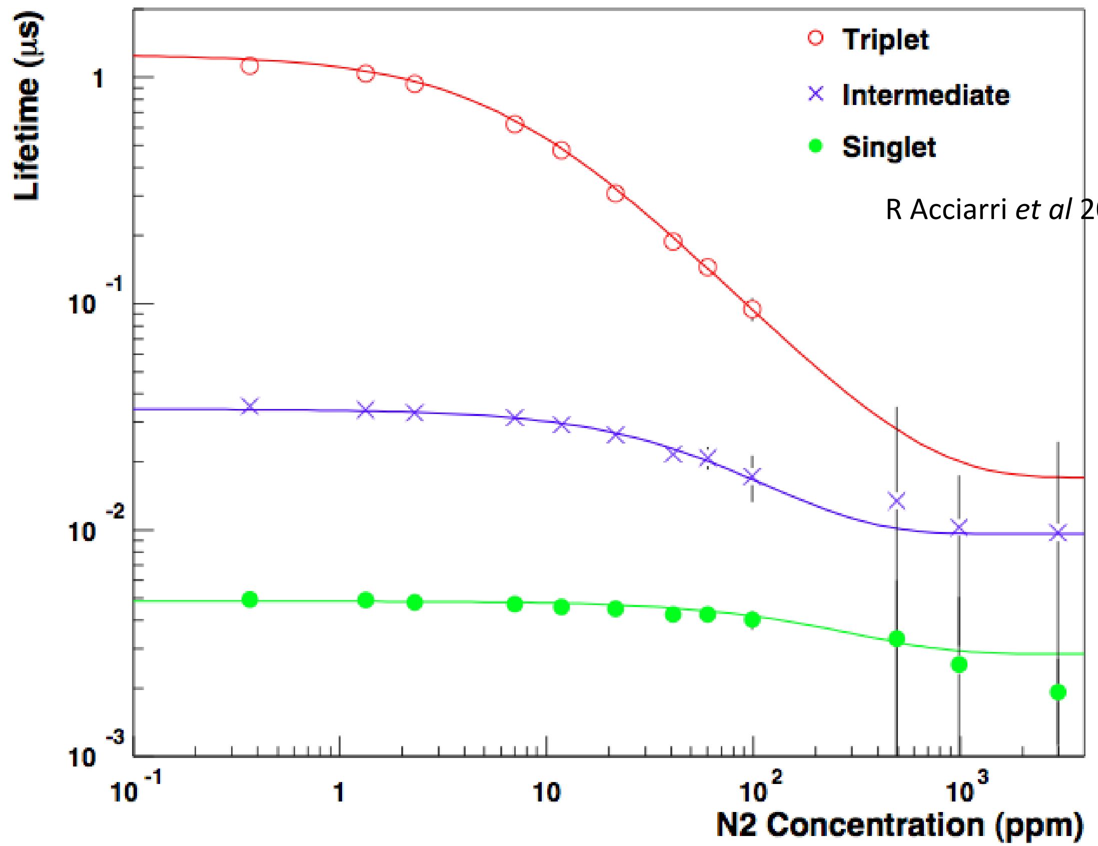
C. Kendziora



T Briese *et al* 2013 *JINST* **8** T07005

LAr Scintillation Light Time Constants

Intermediate LAr scintillation time constant reported by WArP but attributed to PMT instrumental effects



R Acciarri *et al* 2010 *JINST* **5** P06003

We submitted an NSF grant proposal to study this effect in Bo

Single Photo-Electron Coincidence Counting

Measure LAr scintillation light time profile in SPE regime and use SiPMs as well as PMTs to understand potential instrumental effects

^{210}Po source with wavelength shifter

8” cryogenic (trigger) PMT (multi-PE regime)

6 mm x 6 mm SensL SiPM (SPE regime)

2” cryogenic PMT inside enclosed cylinder with pin hole (SPE regime)

Rayleigh Scattering

In Large ν LArTPCs Rayleigh Scattering is Important

Predicted to be 90 cm ± 35%, which is in *rough* agreement with the data

Table 3
Rayleigh scattering length for liquefied rare gases

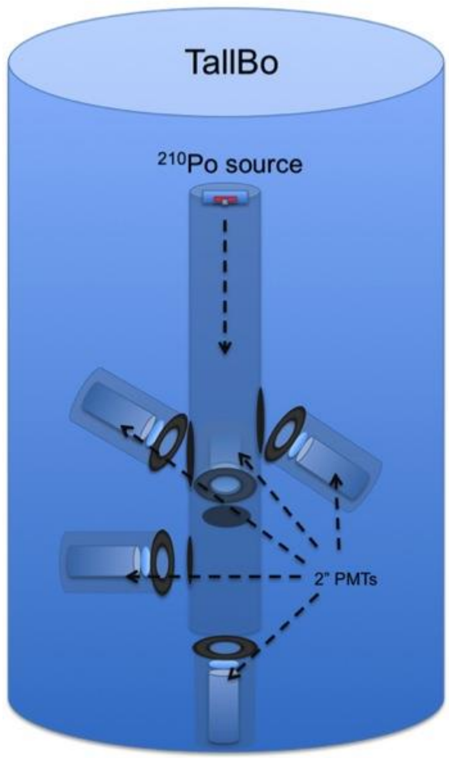
Liquid	Scintillation wavelength (nm)	Dielectric constant	Scattering length calculated (cm)	Scattering length measured (cm)
He at 4.2 K	78	1.077[a]	600	
He at 0.1 K	78	1.089[a]	2×10^4	
Neon	80	1.52[b]	60	
Argon	128	1.90[b]	90	66[d]
Krypton	147	2.27[c]	60	82[d], 100[e]
Xenon	174	2.85[c]	30	29[d], 40[f], 50[g]

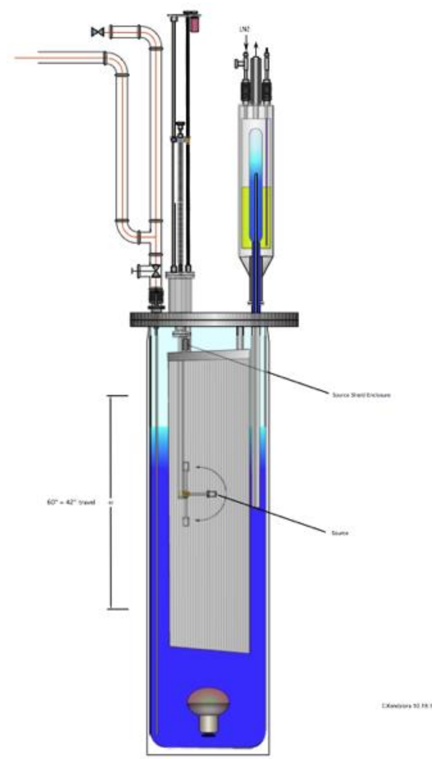
G. Seidel, et. al. NIM A489 (2002) 189-194

N. Ishida, et. al. NIM A384 (1997) 380-386.

Measuring Scattering Lengths in LAr

- We would like to study scattering lengths and angular distributions under known purity conditions in Bo
- We plan to build a lift system to remotely articulate sources inside Bo
  - This a general-purpose tool useful for many future LAr studies
  - Design by C. Kenziora based off of system used in Luke





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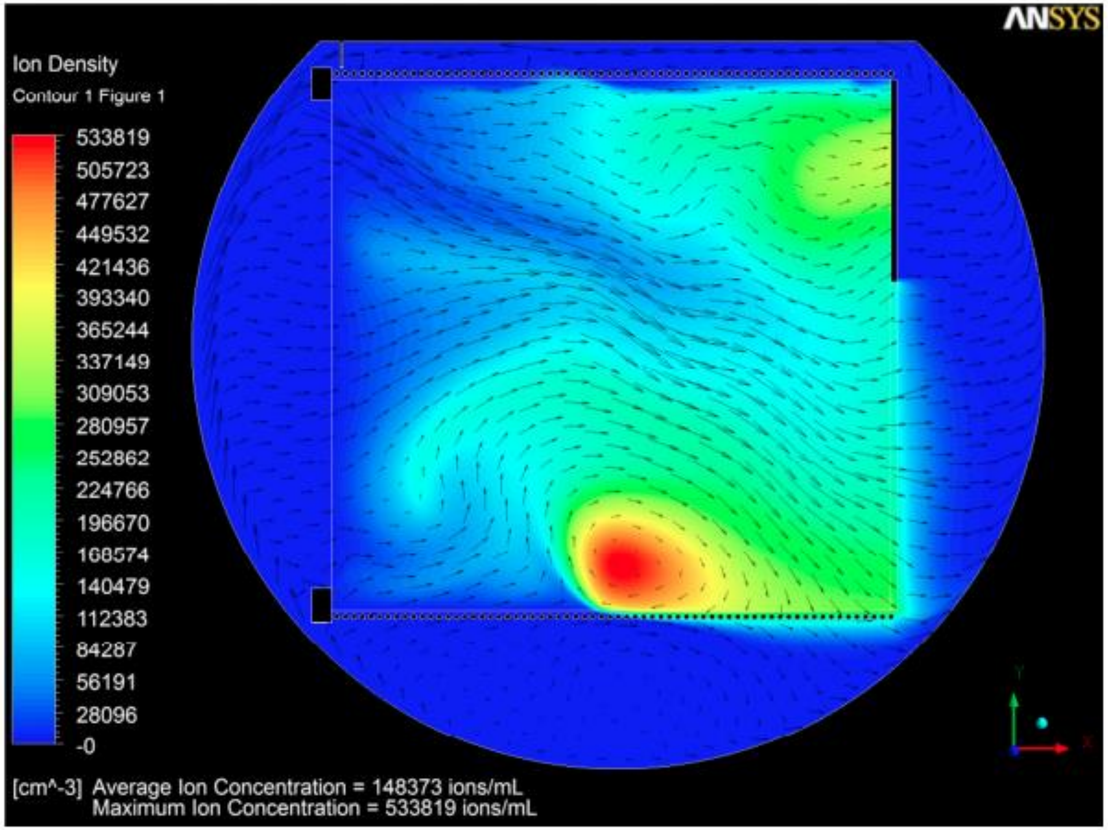
^{222}Rn Tracing in LAr

Mapping LAr Flows



E. Voirin, for µBooNE

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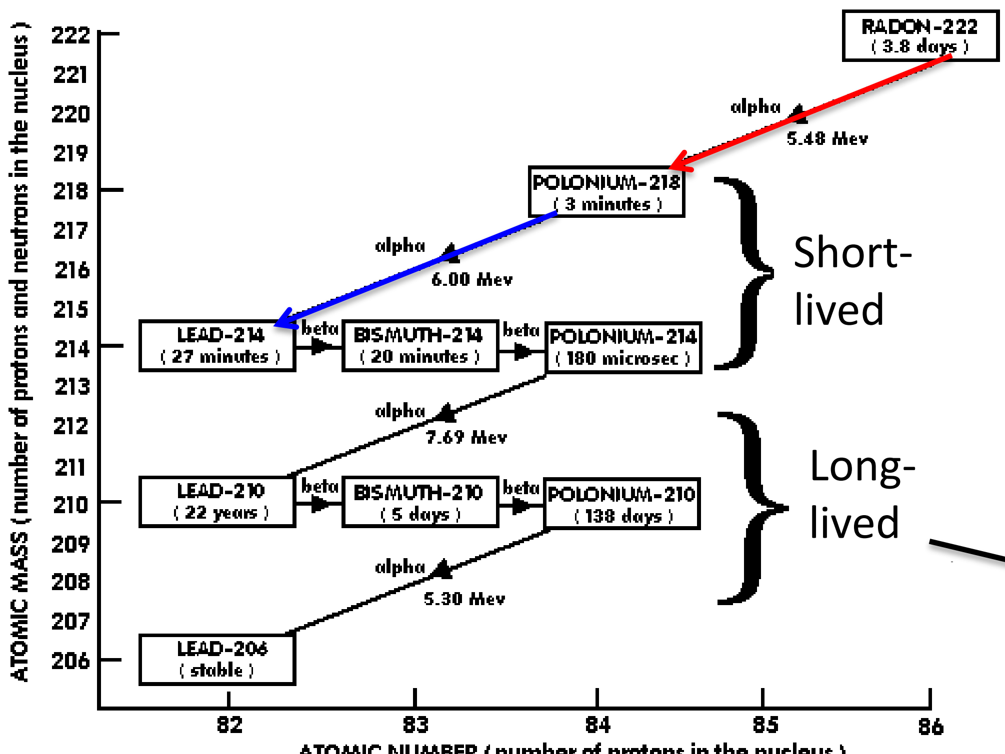

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Papers from LAr light studies at Fermilab

[1] B. J. P. Jones, T. Alexander, H. O. Back, G. Collin, J. M. Conrad, A. Greene, T. Katori, S. Pordes, and M. Toups, "The Effects of Dissolved Methane upon Liquid Argon Scintillation Light," JINST **8** (2013) P12015.

[2] B. J. P. Jones, C. S. Chiu, J. M. Conrad, C. M. Ignarra, T. Katori, and M. Toups, "A Measurement of the Absorption of Liquid Argon Scintillation Light by Dissolved Nitrogen at the Part-Per-Million Level," 2013 *JINST* **8** P07011

[3] T. Briese, L. Bugel, J. M. Conrad, M. Fournier, C. Ignarra, B. J. P. Jones, T. Katori, R. Navarrete-Perez, P. Nienaber, T. McDonald, B. Musolf, A. Prakash, E. Shockley, T. Smidt, K. Swanson, and M. Toups, "Testing of Cryogenic Photomultiplier Tubes for the MicroBooNE Experiment," 2013 *JINST* **8** T07005

Published Papers

[4] B. Baptista, L. Bugel, C. Chiu, J. M. Conrad, C. M. Ignarra, B. J. P. Jones, T. Katori and S. Mufson, "Benchmarking TPB-coated Light Guides for Liquid Argon TPC Light Detection Systems," arXiv:1210.3793 [physics.ins-det].

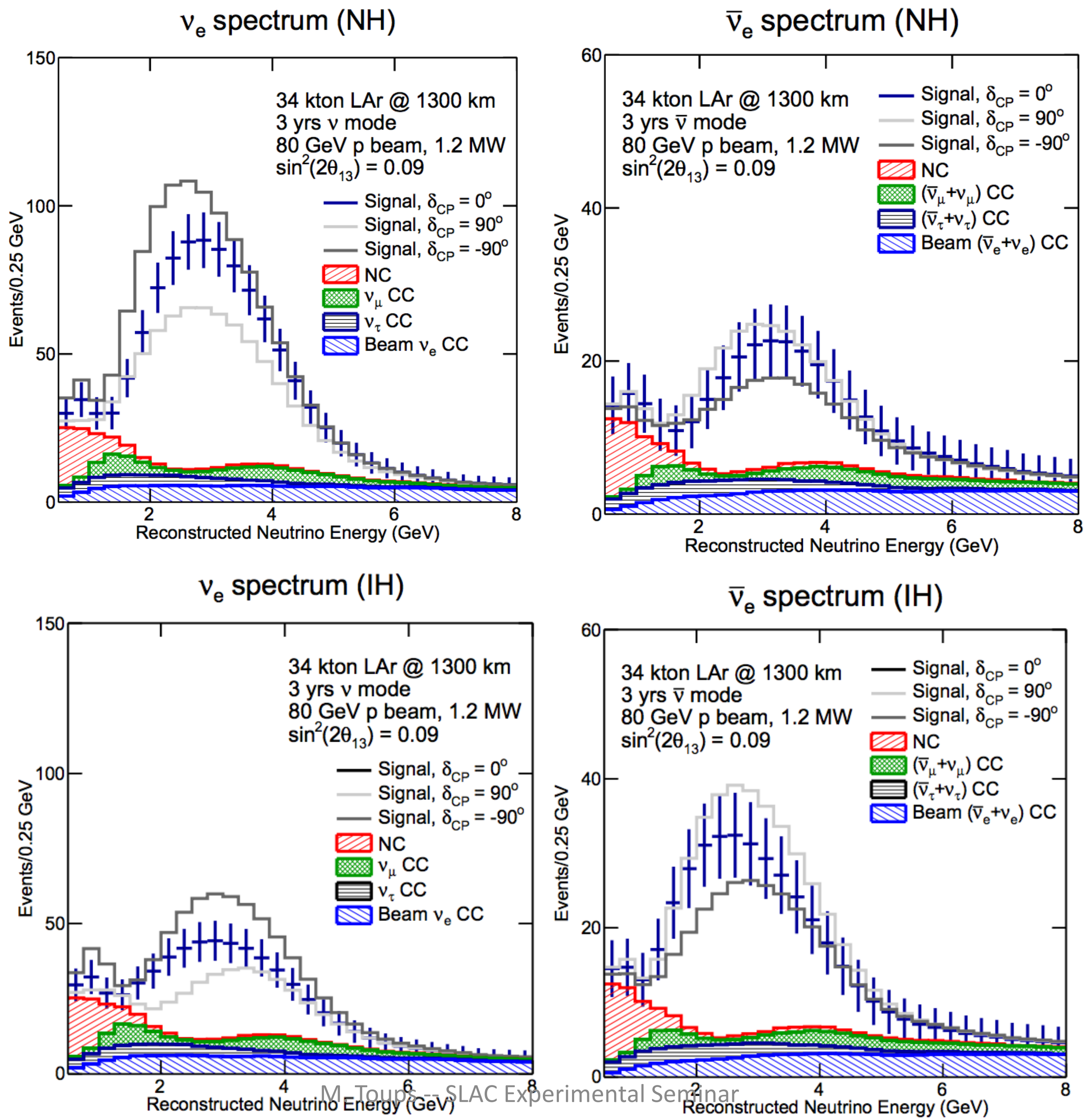
Whitepaper for LIDINE

[5] C. M. Ignarra, "TPB-coated Light Guides for Liquid Argon TPC Light Detection Systems," JINST **8**, C10005 (2013) [arXiv:1307.8036].

[6] B. J. P. Jones, "Results from the Bo Liquid Argon Scintillation Test Stand at Fermilab," JINST **8**, C09003 (2013).

[7] B. J. P. Jones, "A simulation of the optical attenuation of TPB coated light-guidedetectors," JINST **8**, C10015 (2013) [arXiv:1307.6906].

LIDINE Proceedings (Peer Reviewed)


ν_e spectrum (NH)
34 kton LAr @ 1300 km
3 yrs ν mode
80 GeV p beam, 1.2 MW
$\sin^2(2\theta_{13}) = 0.09$
Signal, $\delta_{CP} = 0^o$
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NC
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Beam ν_e CC
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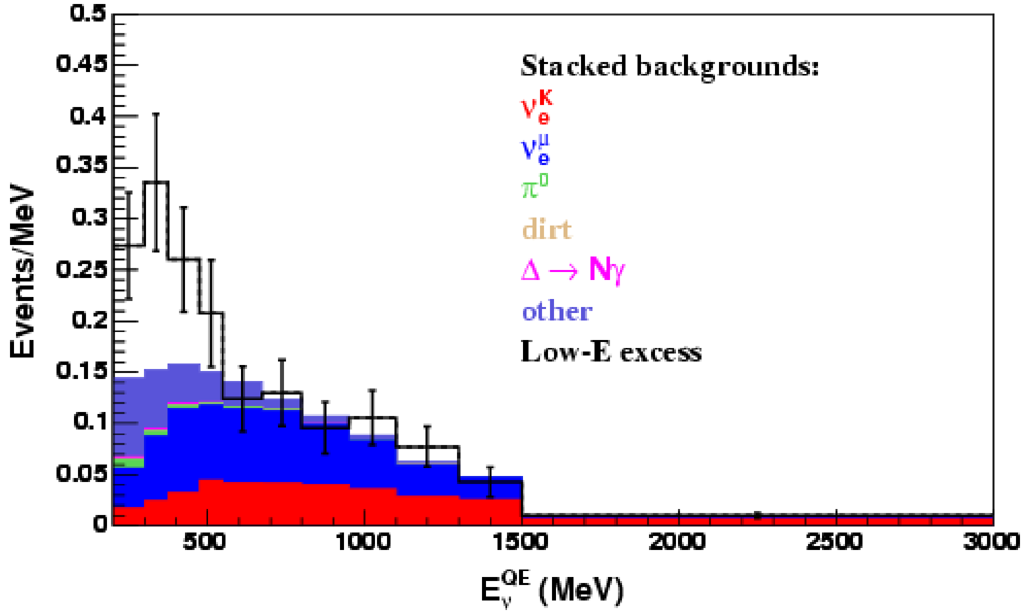
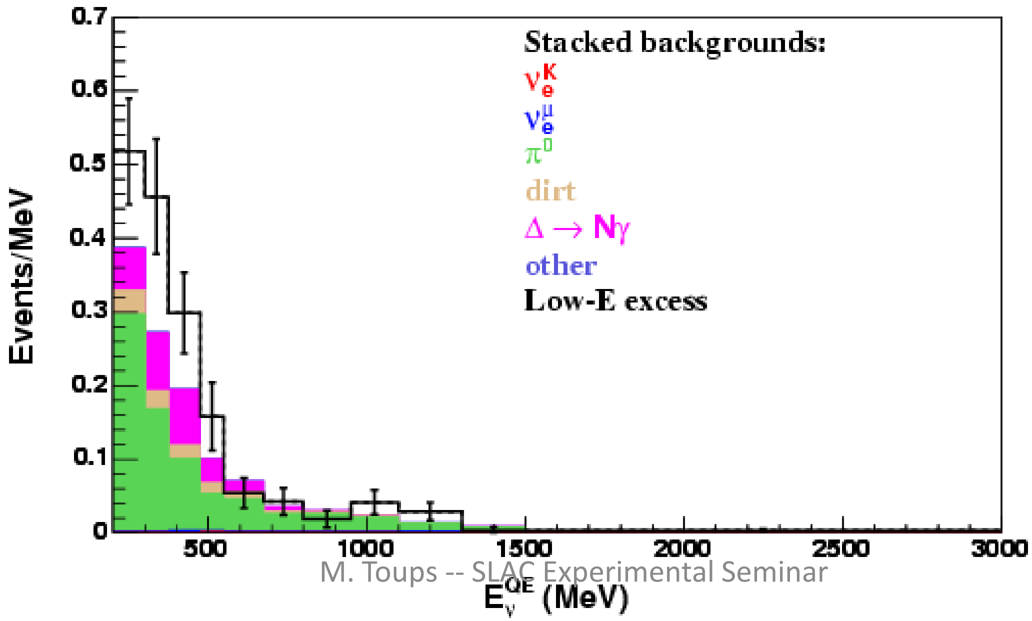
MicroBooNE Sensitivities (6e20 POT)



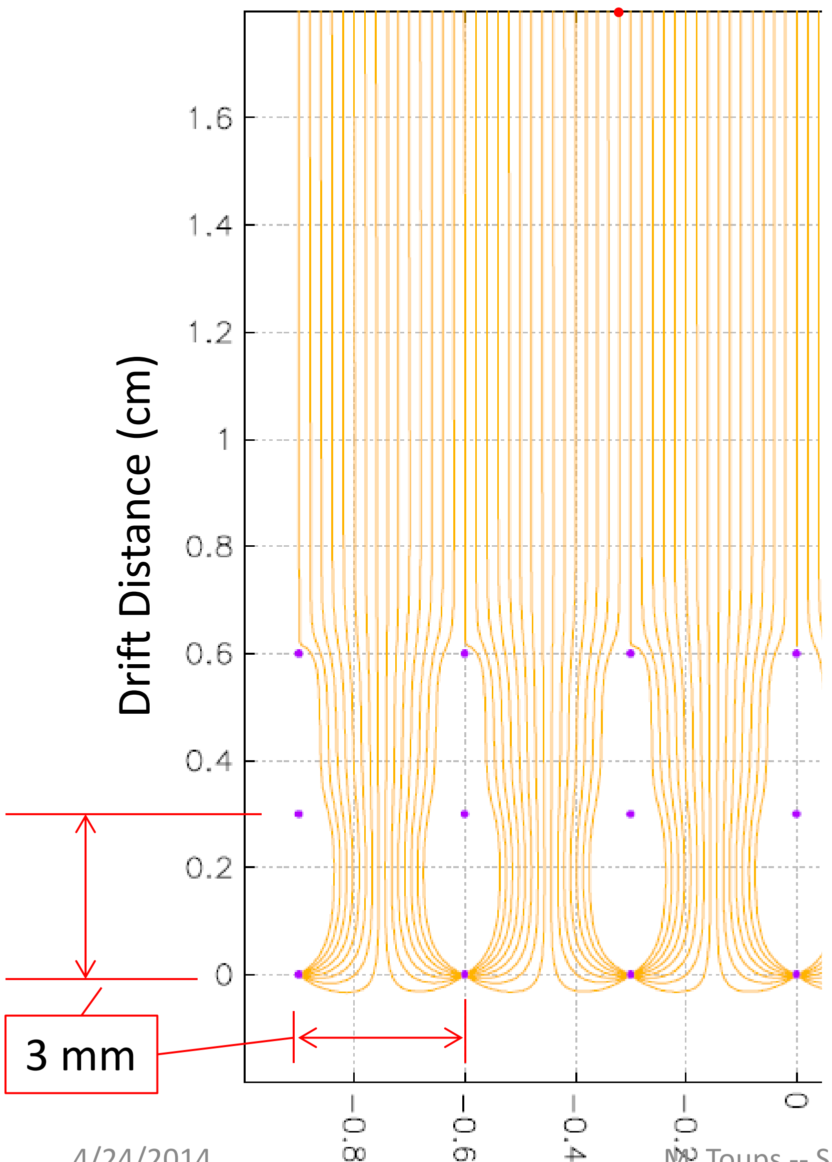
Low energy excess events are electrons

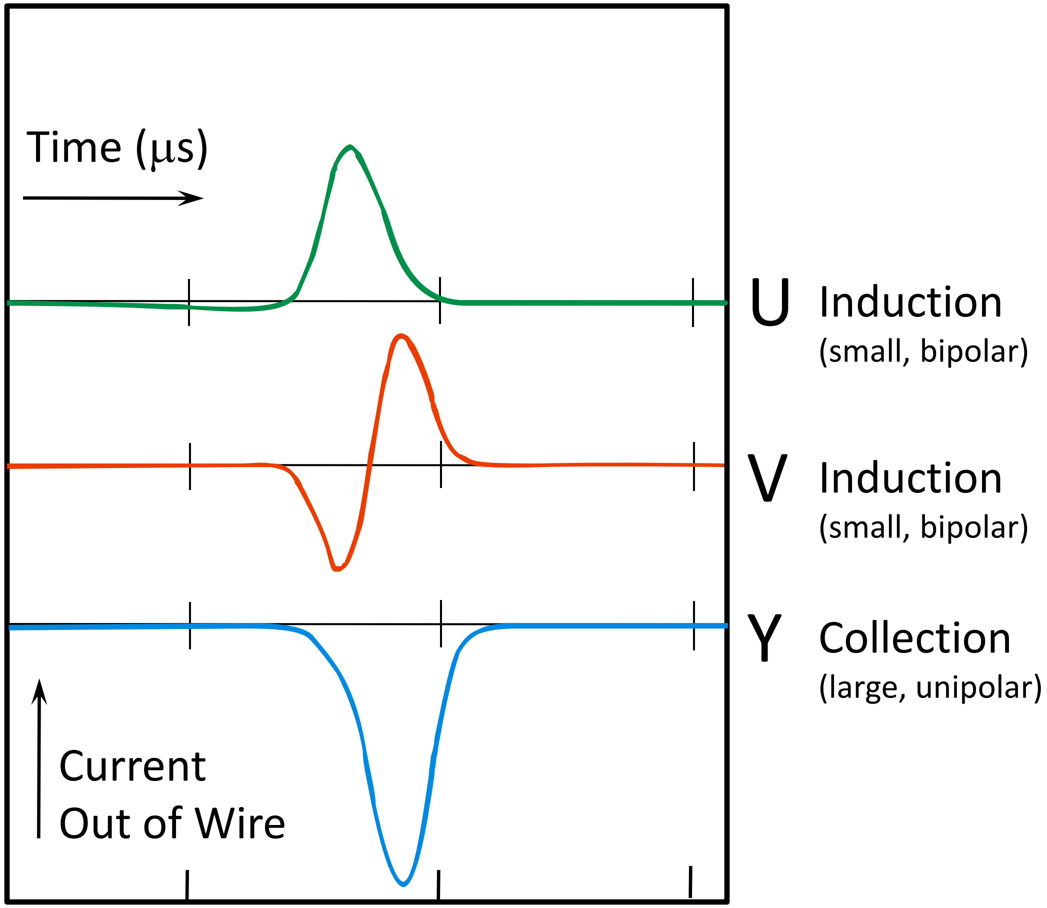


Low energy excess events are photons

Bo Yu (BNL)

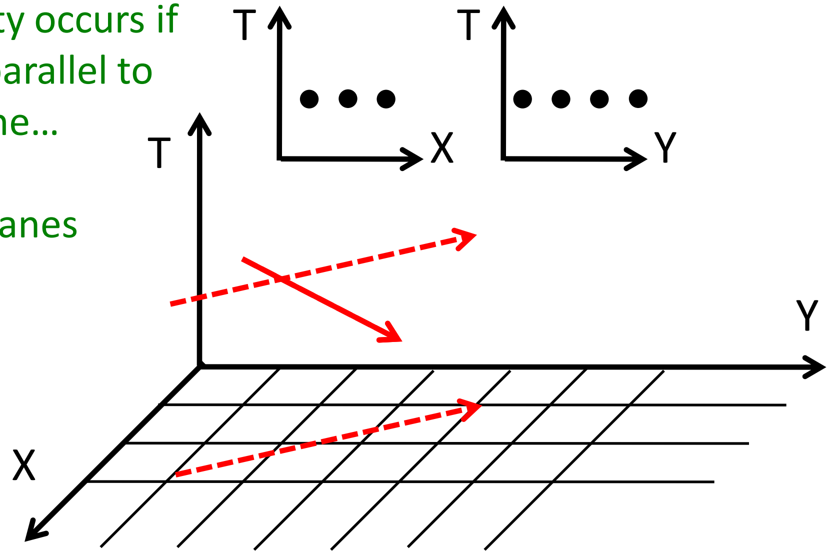
Charge Signal Formation

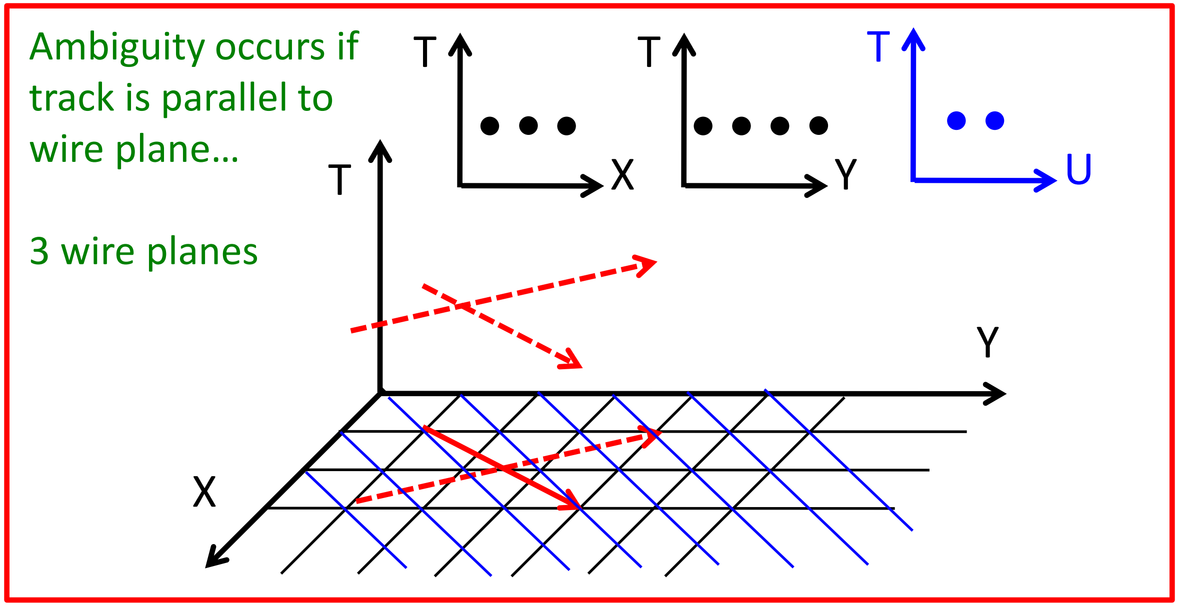




Ambiguity occurs if track is parallel to wire plane…

2 wire planes




Ambiguity occurs if track is parallel to wire plane…
3 wire planes
T
X
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T
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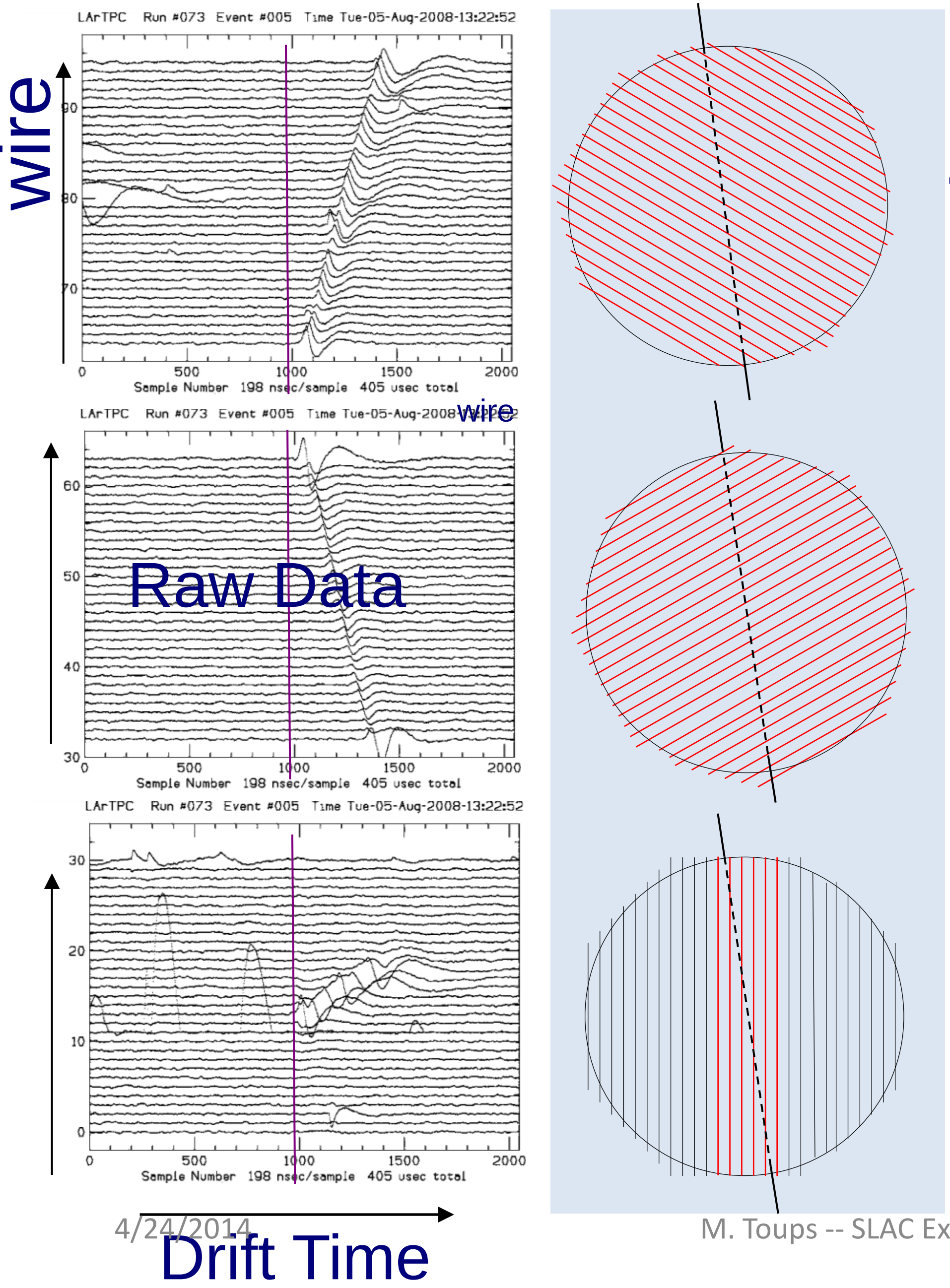
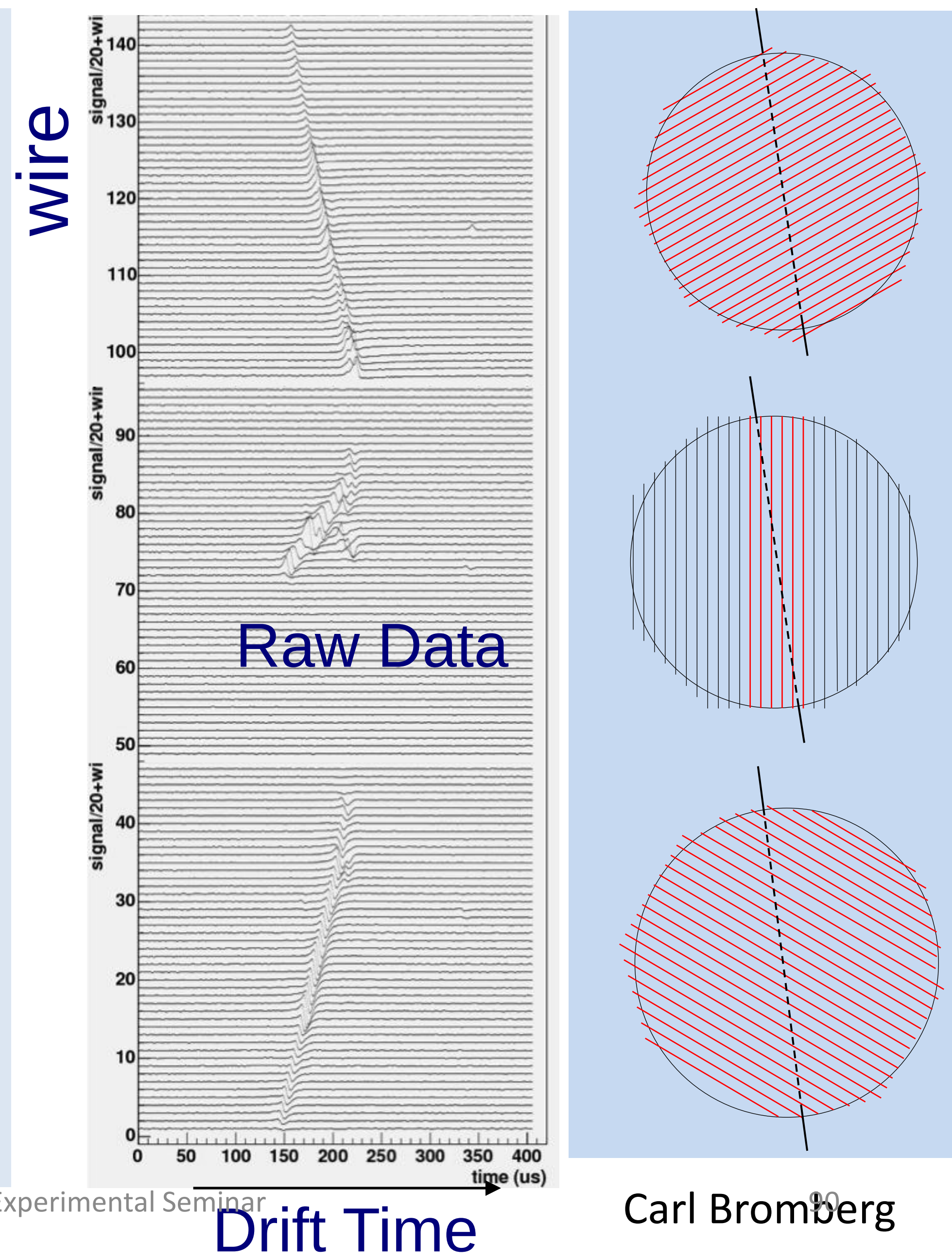
X

Warm amps S/N = 15   Amps in liquid S/N >30



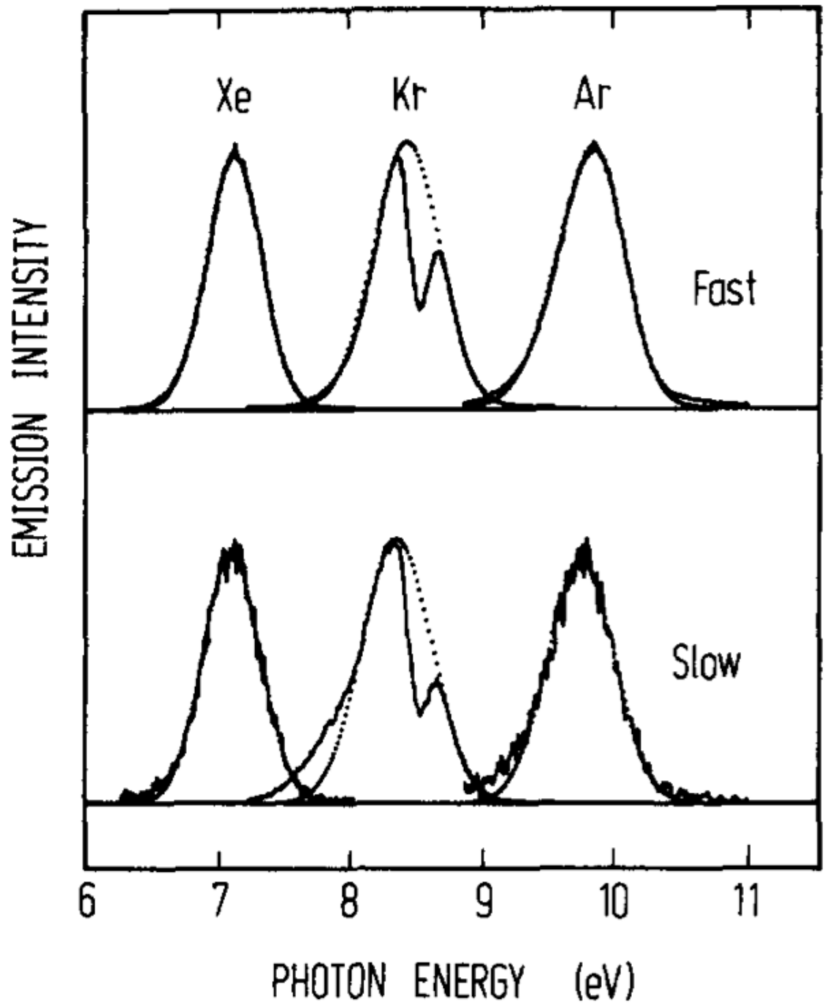


Carl Bromberg

LArTPCs: A Historical Perspective

- 1968: L.W. Alvarez proposes the use of Liquid Noble Gases for particle detectors
- 1974: W. Willis and V. Radeka propose the use of LAr ionization chambers
- 1977: Carlo Rubbia proposes LArTPC for neutrino physics
- 1985: ICARUS proposal at Gran Sasso

LAr scintillates at 128 nm



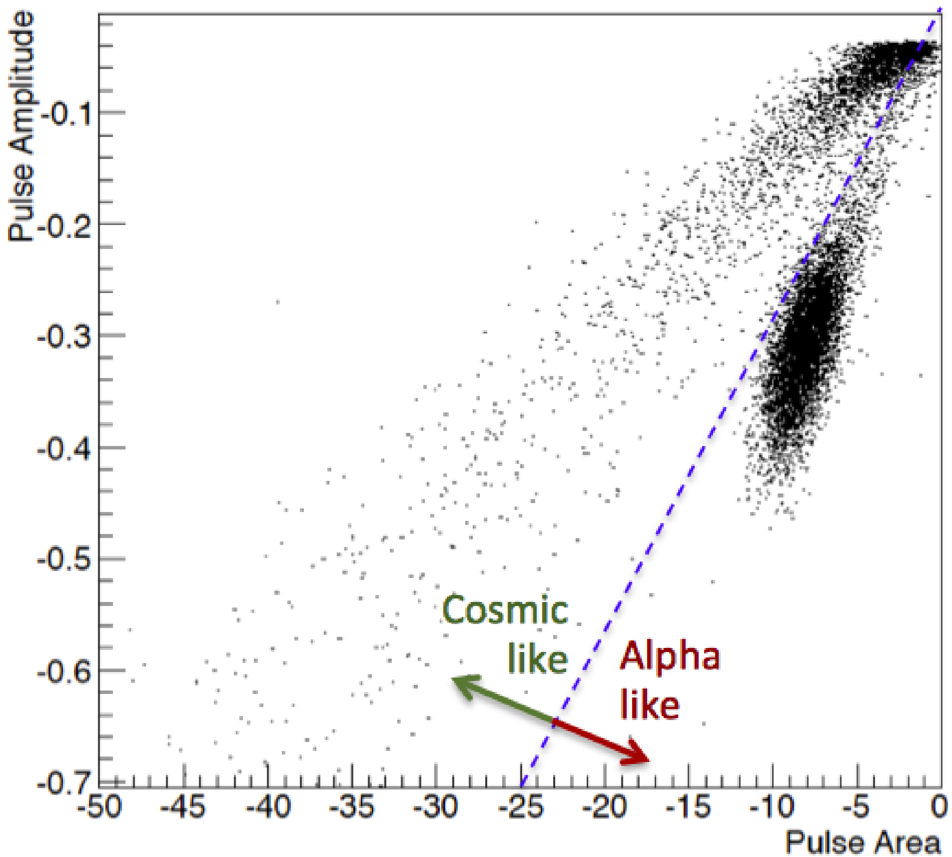
E Morikawa et al., J Chem Phys vol 91 (1989) 1469

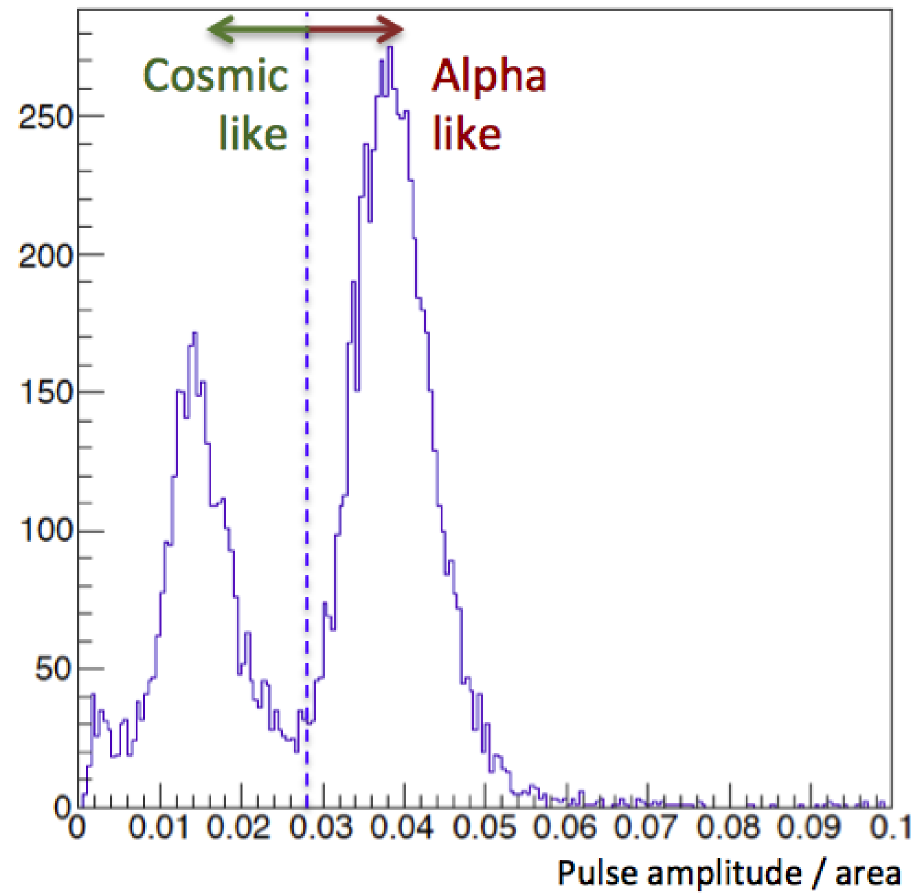
MIT LAr Studies Program

- We have performed both experiment-specific and generic R&D with the Bo high purity test stand over the past 2 years
- We are responsible for the light detection system in MicroBooNE
- We first proposed LAr light guide detectors, which are integral to the LBNE reference design

arXiv:1101.3013v1 [physics.ins-det]

Pulse shape discrimination





Nitrogen Absorption Sanity Check