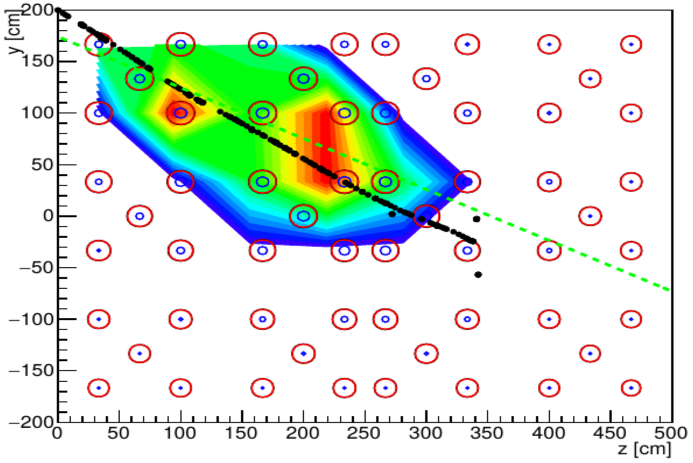
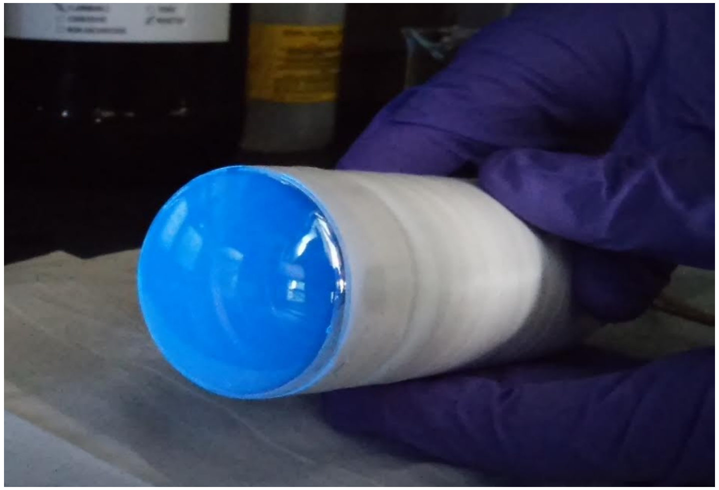
Shining Light on Neutrino Interactions

Andrzej Szelc

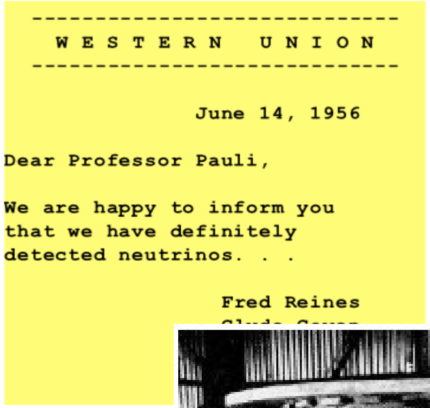
(University of Manchester)





A short history of Neutrinos

- The neutrino was proposed in 1930 by W. Pauli to save energy conservation in β-decays.
- It was discovered by Reines and Cowan in 1956 (despite Pauli's fear of it interacting too weakly to be discovered).
- Neutrinos from extra-terrestial sources were discovered: the Sun and cosmic rays.
- Very quickly it was discovered that there are fewer neutrinos than expected.
- This has now been confirmed to be a result of ν-oscillations.


WESTERN UNION

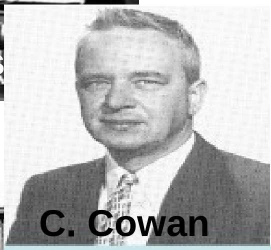
June 14, 1956

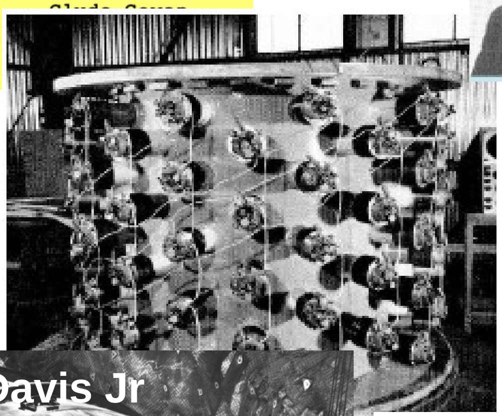
Dear Professor Pauli,

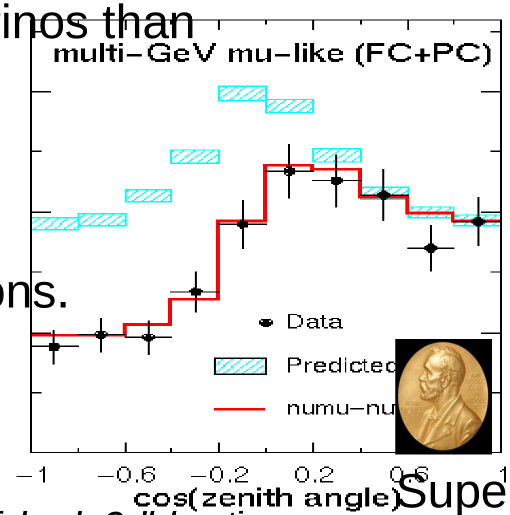
We are happy to inform you that we have definitely detected neutrinos. . .

Fred Reines


F. Reines

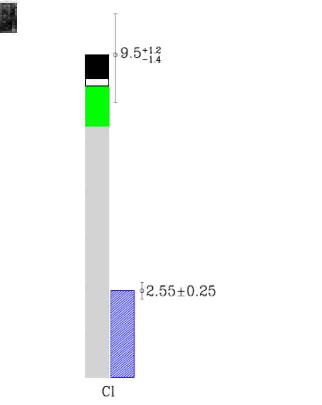

C. Cowan



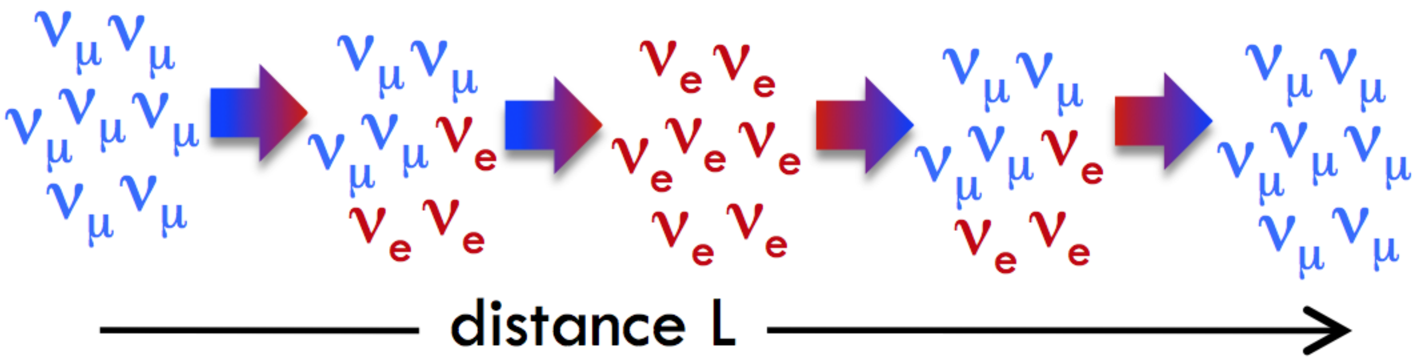


Super-Kamiokande

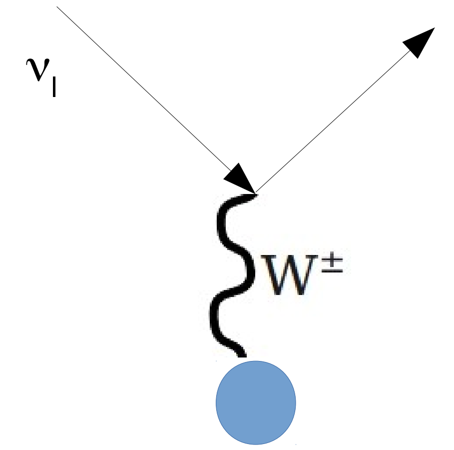
Super-Kamiokande Collaboration
Phys. Rev. Lett. 81, 1562–1567 (1998)



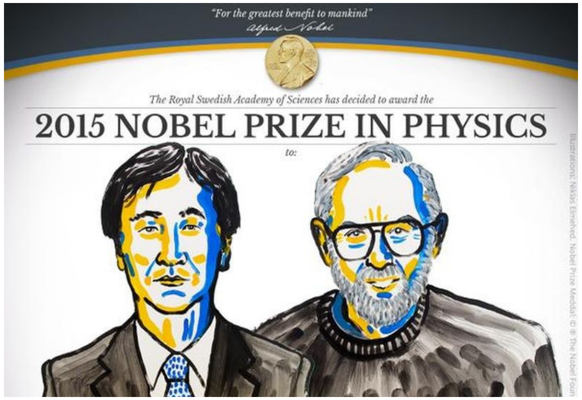
Measuring Neutrino Oscillations



- In oscillation physics we usually start with one type of neutrino and measure how it changes into another.
- We can do this by detecting the new neutrinos (appearance) or registering the loss of original (disappearance).
- We know three neutrino flavors: ν_e, ν_μ **and** ν_τ . We tell them apart by the effect of their "Charged Current" interactions.
- By changing the energy of neutrinos and the distance of observation we can address surprisingly different questions.



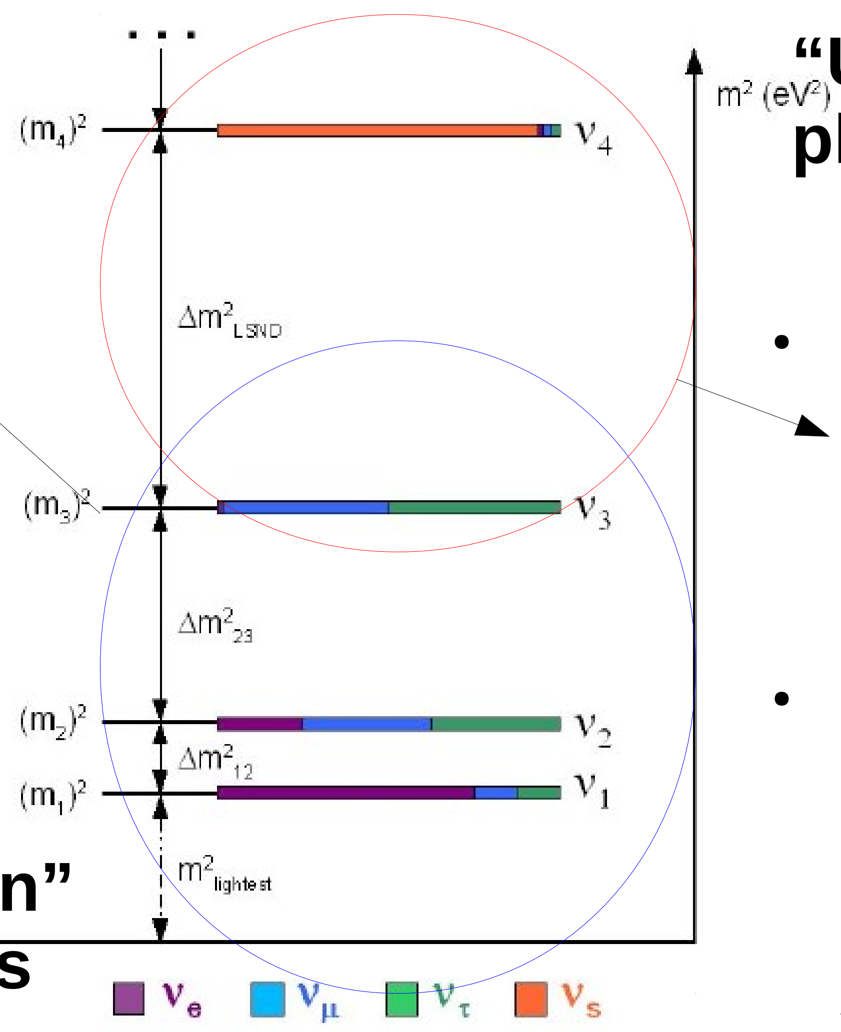
Nucleon



The neutrino model

Our picture of Neutrinos in the standard model is almost complete.

"Large" mixing angle θ_{13} opens the way to measurements that could explain the **matter – antimatter asymmetry** in the Universe



"Unknown" physics

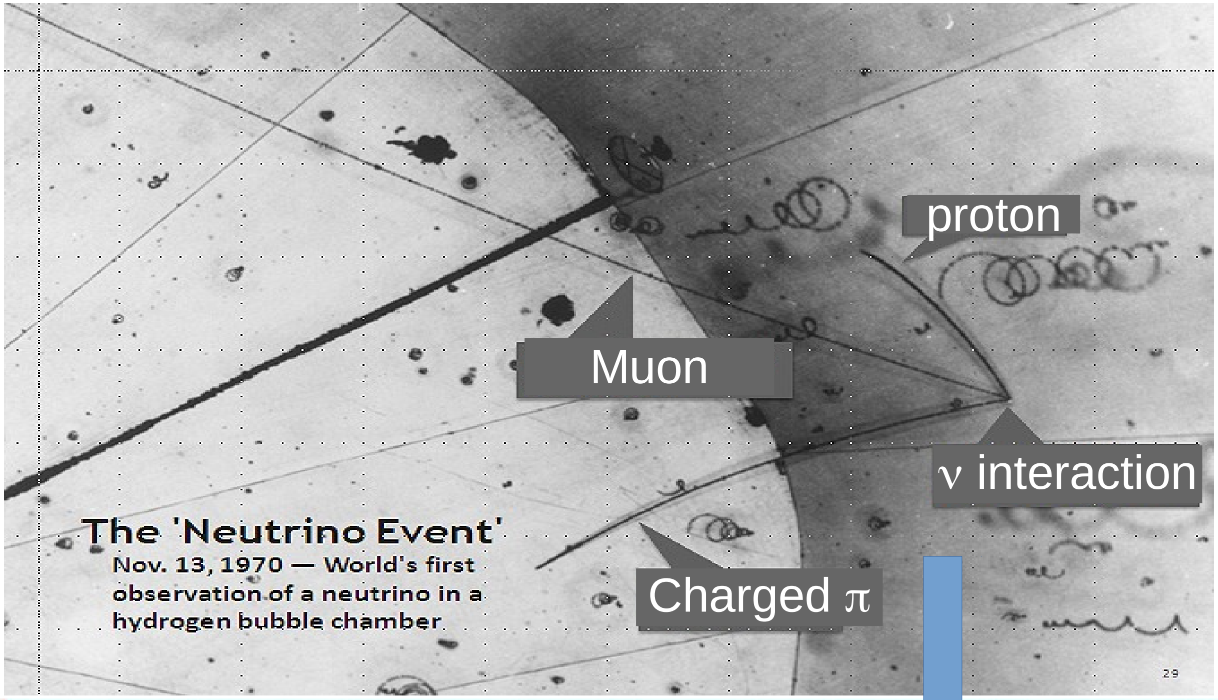
"Known" physics

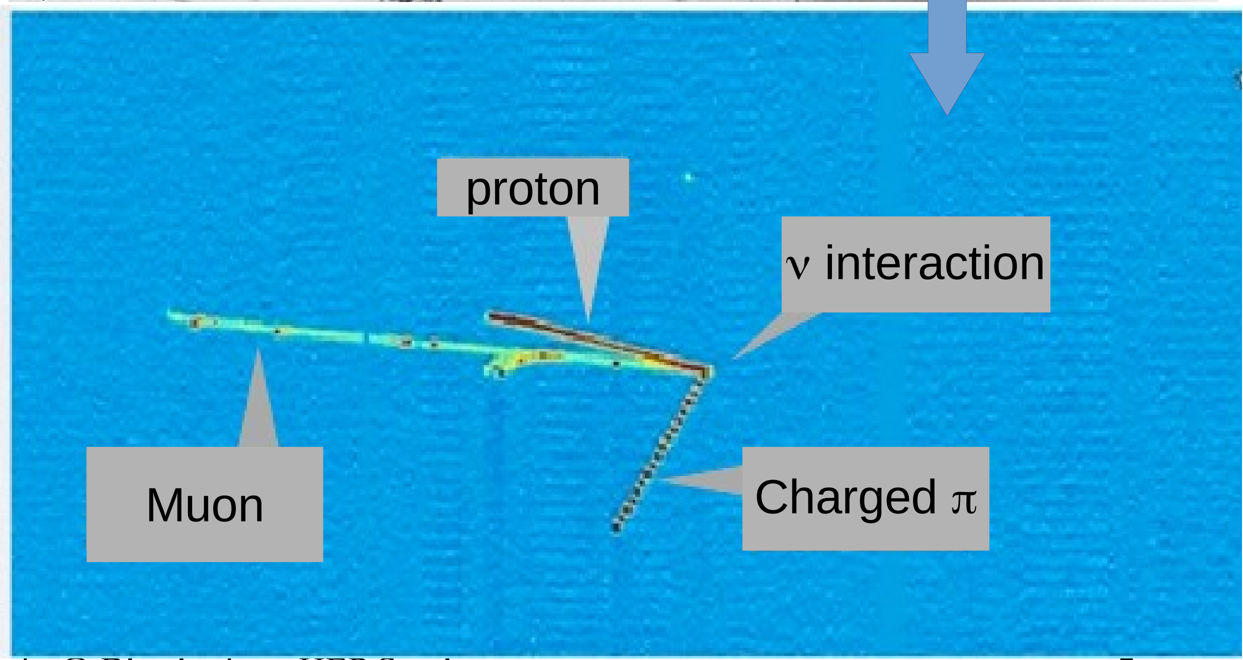
- Short baseline measurements hint at oscillations **incompatible with 3 neutrino model**.
- Tantalizing anomalies that could be interpreted as a new neutrino state – **the sterile neutrino.** At tension with results from MINOS+, DayaBay and IceCube.

Detecting neutrinos in a LArTPC

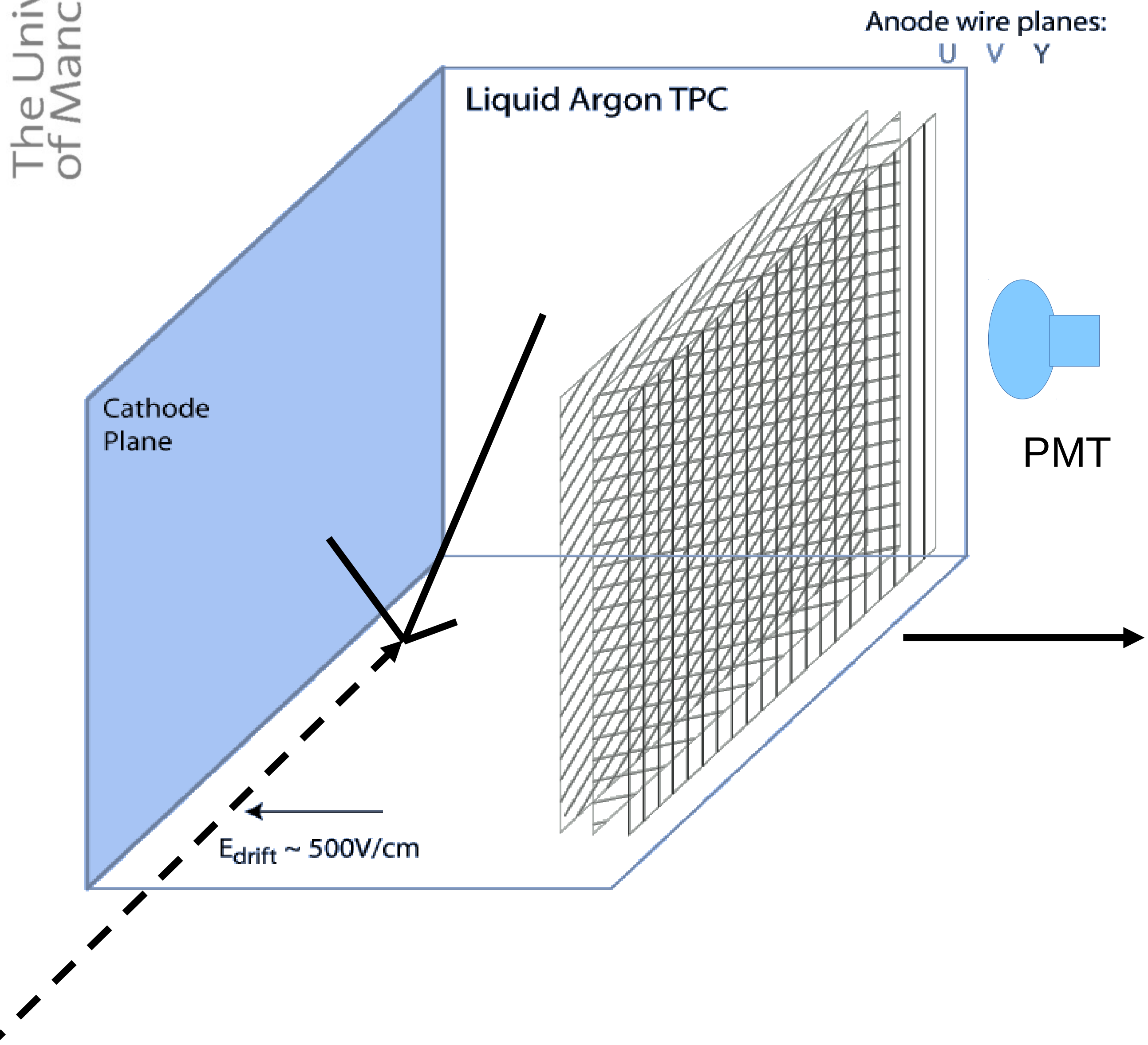
The University of Manchester

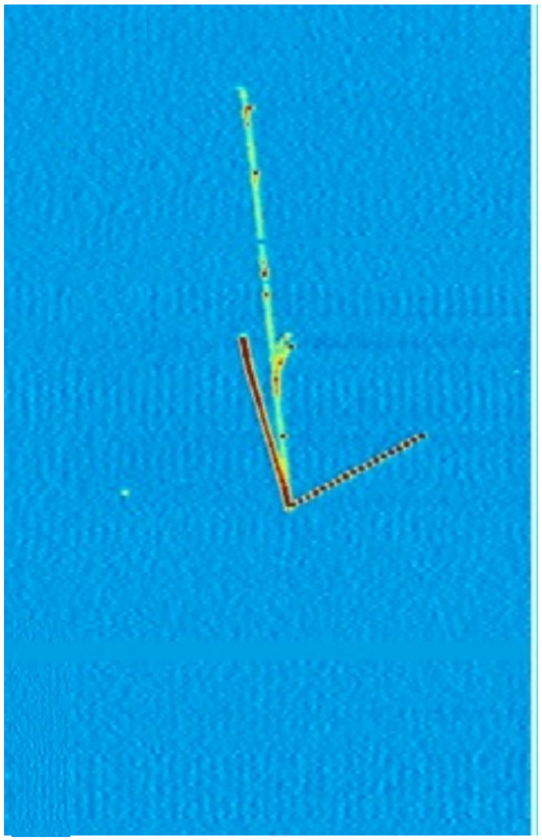
- Neutrino measurements are difficult.
- Due to the photon backgrounds ν_e appearance is particularly challenging.
- The LArTPC and its bubble chamber-like data gives us strong background rejection tools.



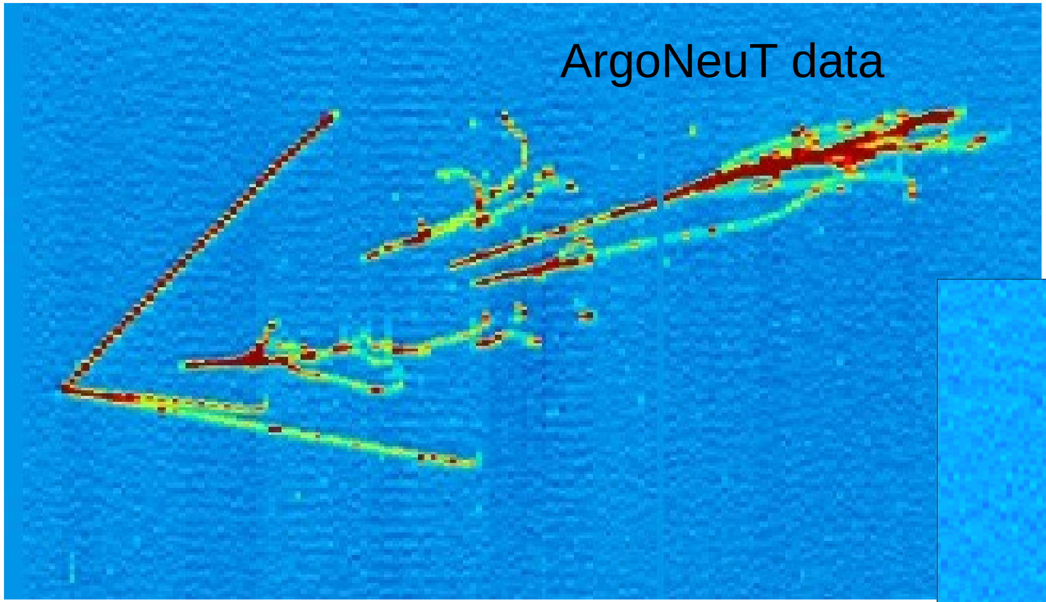


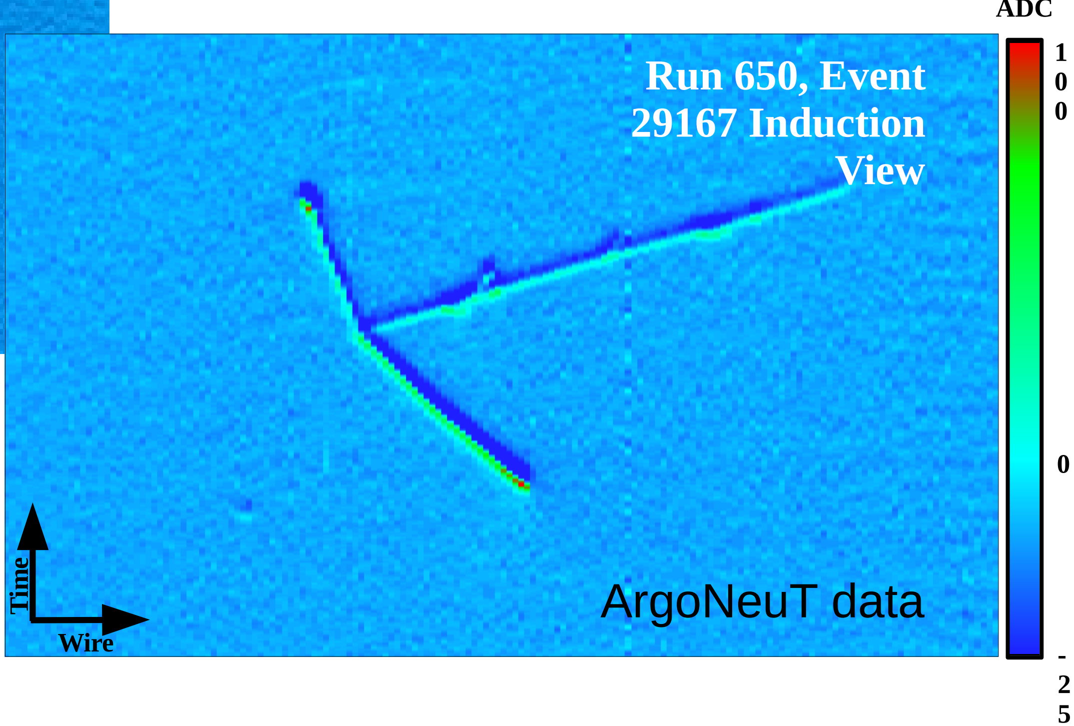
LArTPC Operation

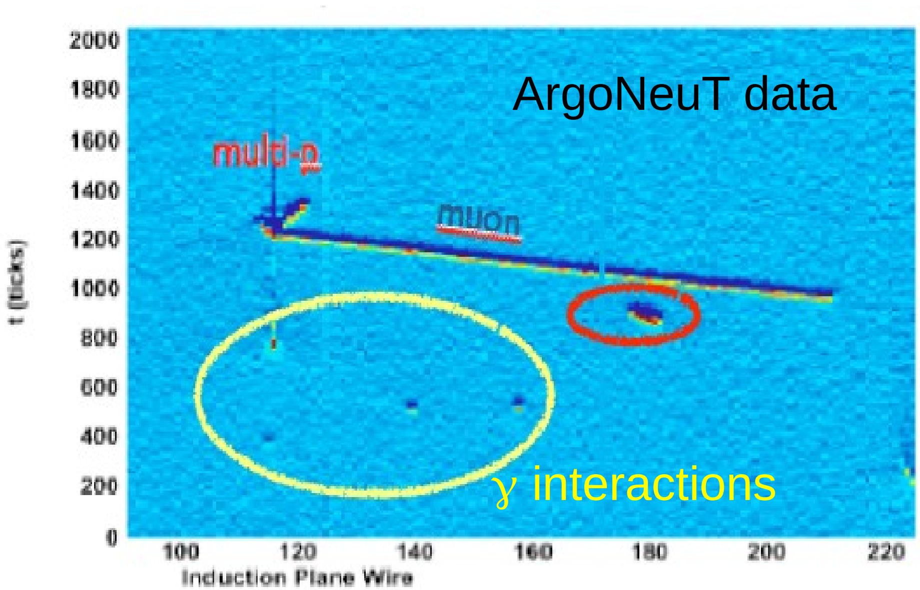




Neutrino interactions in LArTPCs







US based LArTPC Program

Yale TPC


Location: Yale University
Active volume: 0.002 ton
operational: 2007

Bo

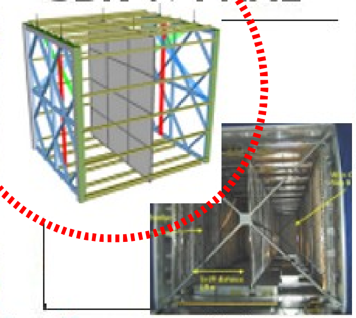

Location: Fermilab
Active volume: 0.02 ton
operational 2008

ArgoNeuT

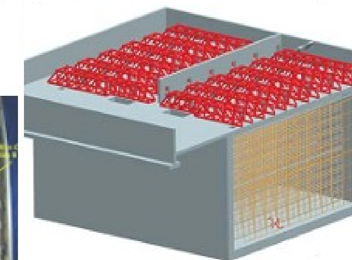

Location: Fermilab
Active volume: 0.3 ton
operational: 2008
First neutrinos: June 2009

MicroBooNE


Location Fermilab
Active volume: 0.1 kton
Operational: 2015

SBN @ FNAL


Location: Fermilab
Active volume: 0.1 + 0.6 kton
Construction start: 2017

LBNE


Location: Homestake
Active volume: 35 kton
Construction start 202?

Luke

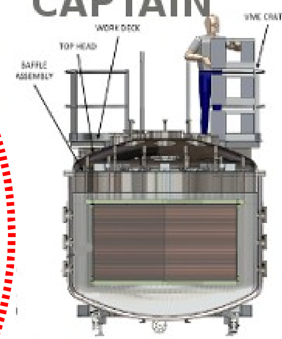

Location: Fermilab
Purpose: materials test st
Operational: since 2008

LAPD

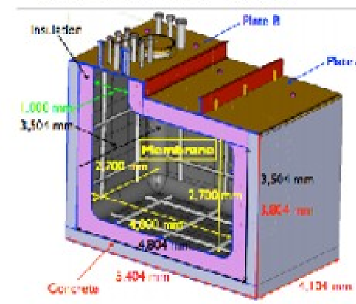

Location: Fermilab
Purpose: LAr purity demo
Operational: 2011

LArIAT


Location: Fermilab
Purpose: LArTPC calibration
Operational: 2014 (phase 1)

CAPTAIN


Location: LANL
Purpose: LArTPC calibration
Operational: 2014

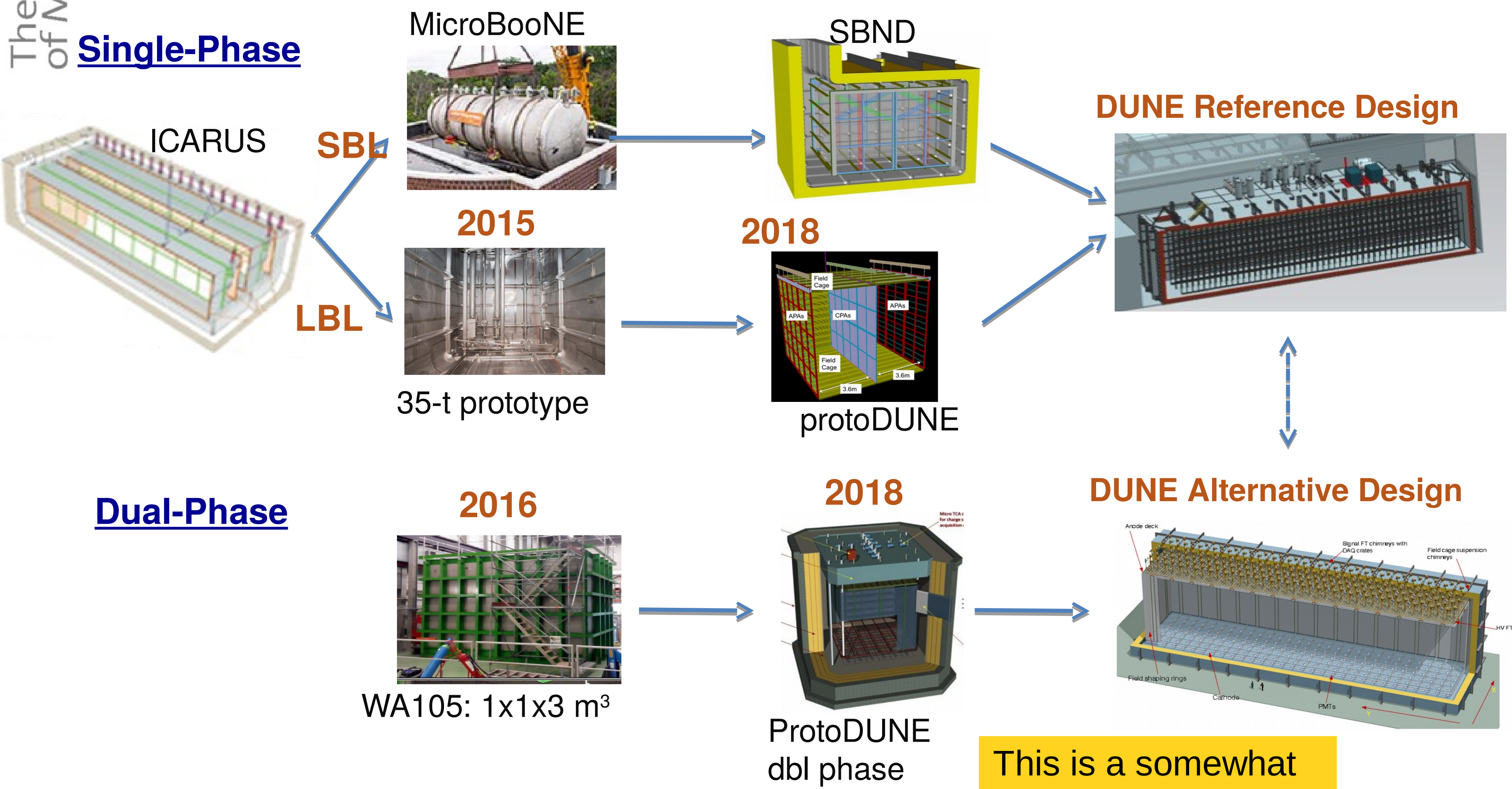
LBNE 35 Ton


Location: Fermilab
Purpose: purity demo
Operational: 2013

Two Years ago, this was a reasonably accurate slide...

LArTPC development

Development and prototyping through the Fermilab SBN and CERN neutrino platform programmes



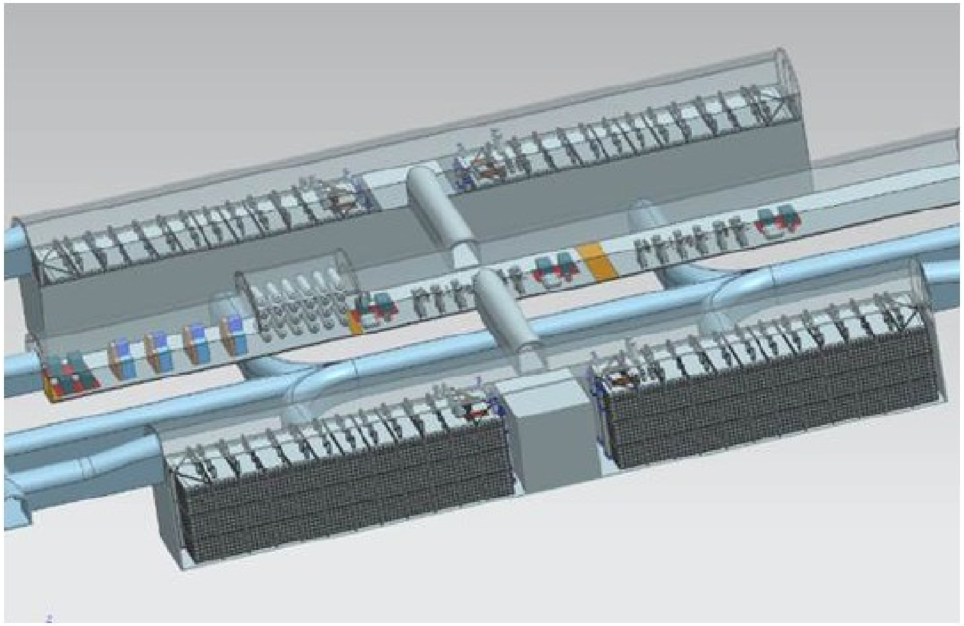
This is a somewhat simplified drawing...

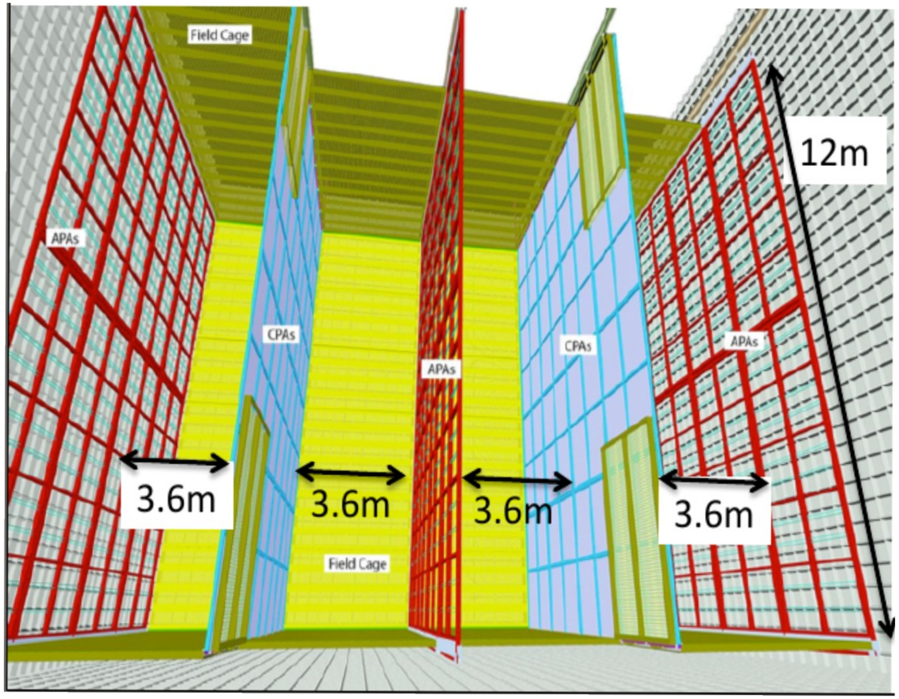
DUNE

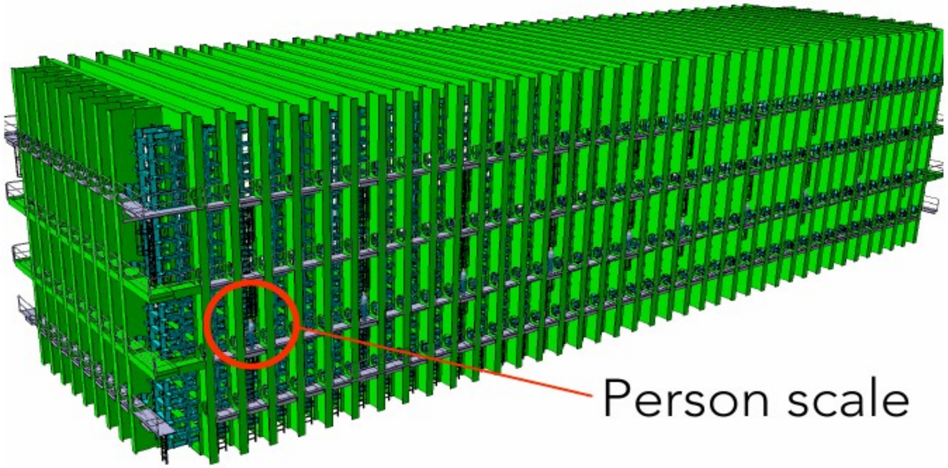
40 kT of liquid argon at SURF (South Dakota)

A huge effort going on now to design and build.

Starting with protoDUNE prototype at CERN.

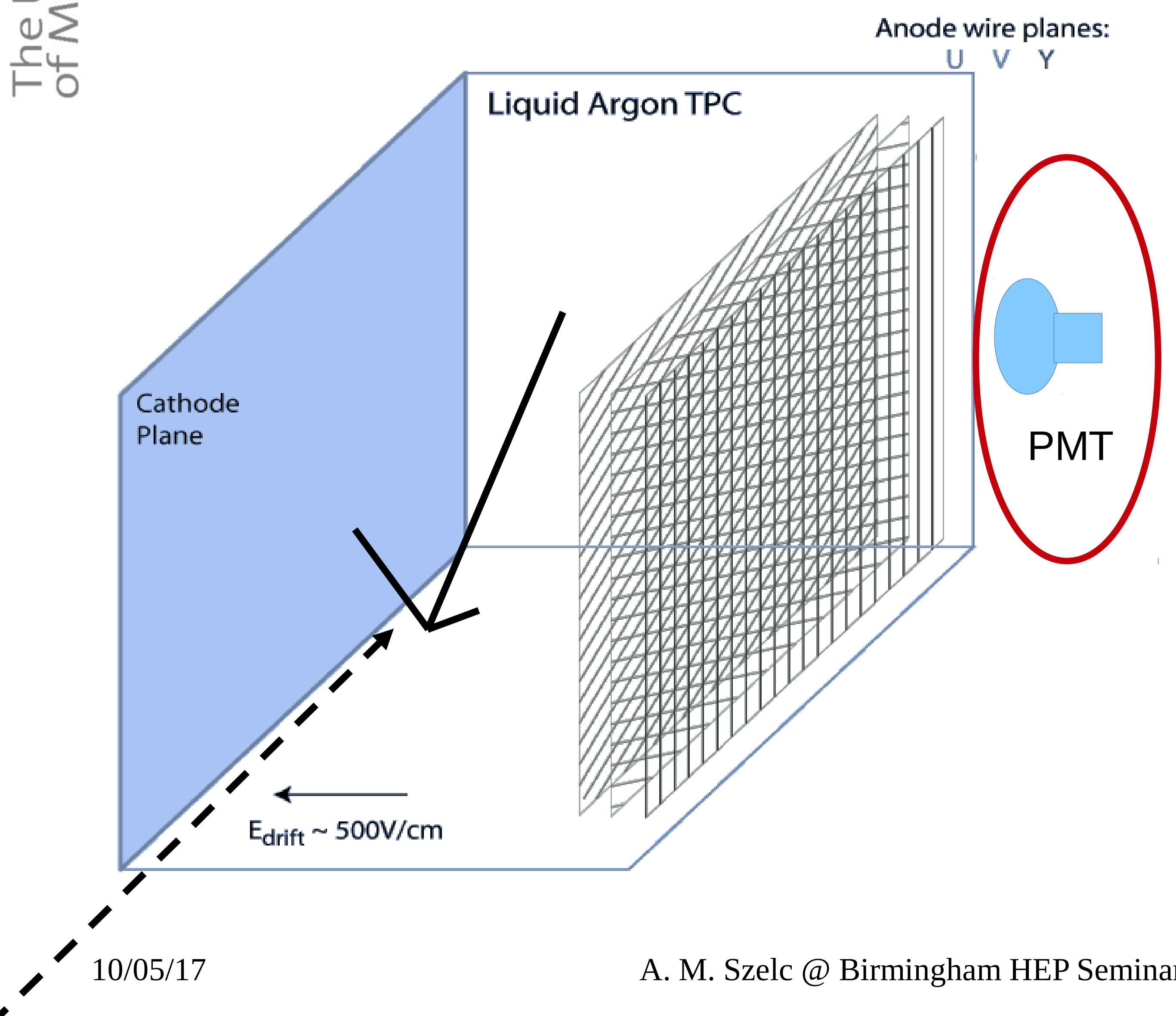






DUNE Far Detector Module (10 kTons)

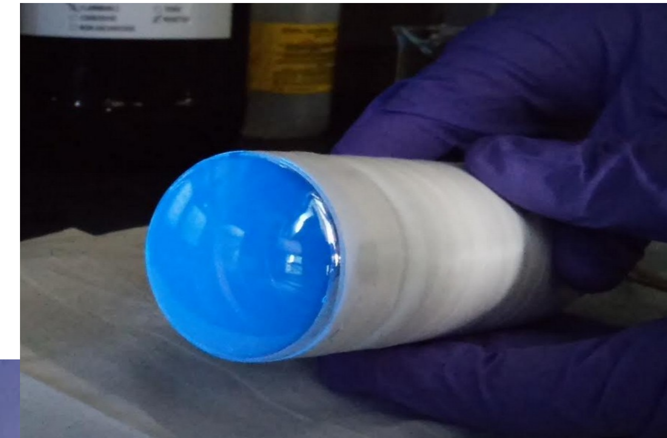
LArTPC detectors (2)

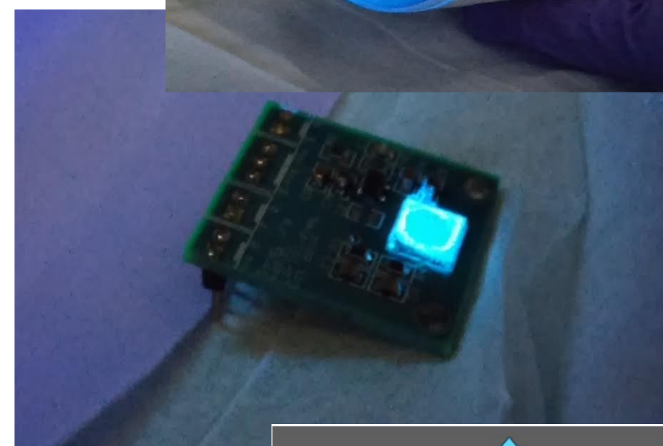


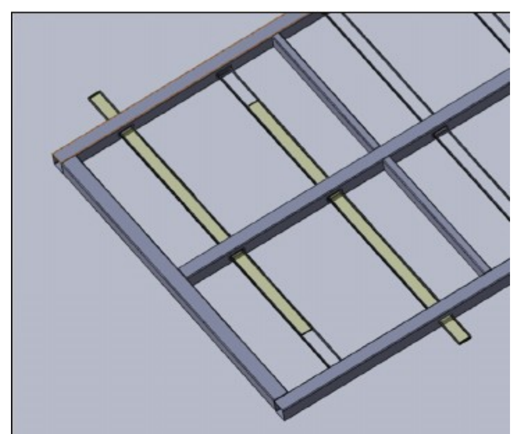
- LArTPCs seem to do a good job using ionization charge.
- Why do we care about scintillation light?

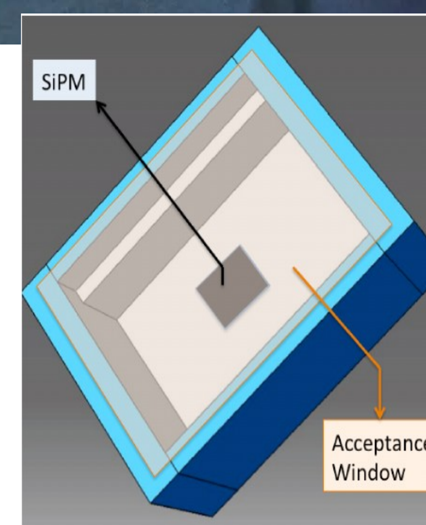
Scintillation Light

- Liquid argon is a prolific scintillator.
- The light is always there, complementary to the charge.
- This is the most active field of development in LArTPCs.



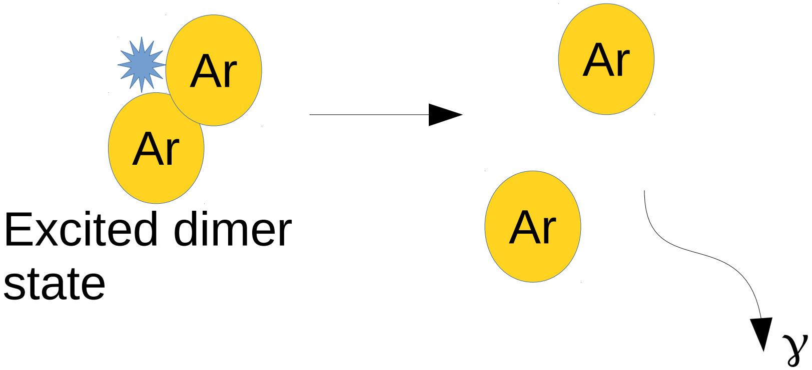






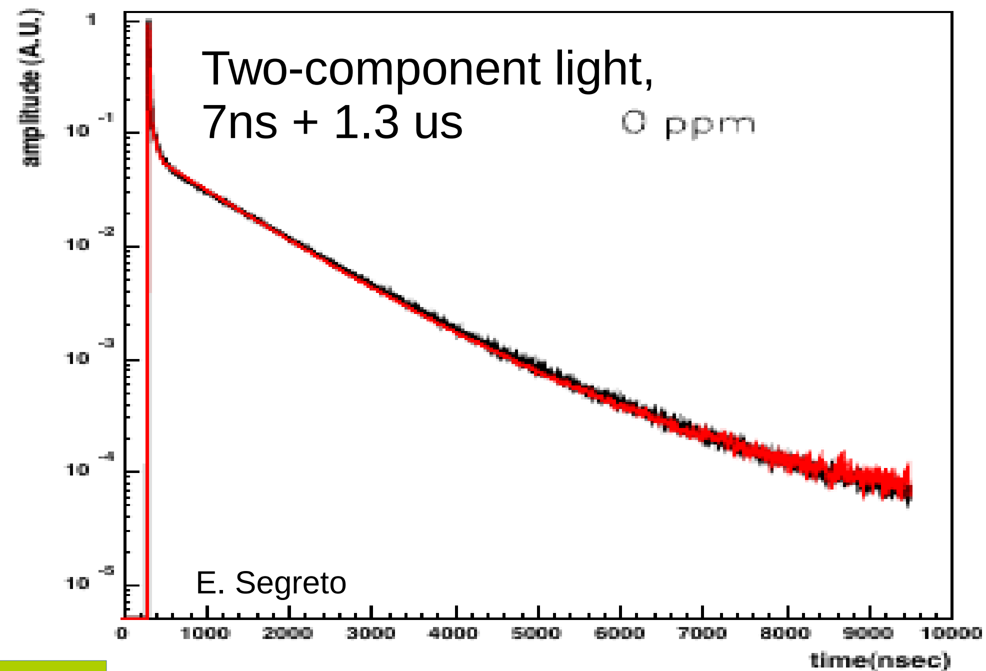
Scintillation Light in Argon

Emission:



Photons are all ~128 nm – VUV

Light consists of two components: fast and slow. Their relative amplitudes depend on ionization density (theory).



(practice) the shape can be affected by transport, contamination and WLS effects (next slides)

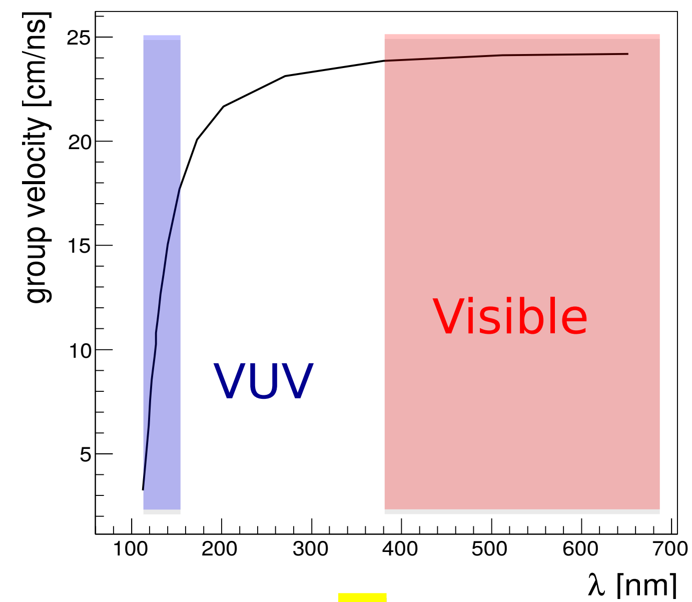
Scintillation Light in Argon (2)

Transport:

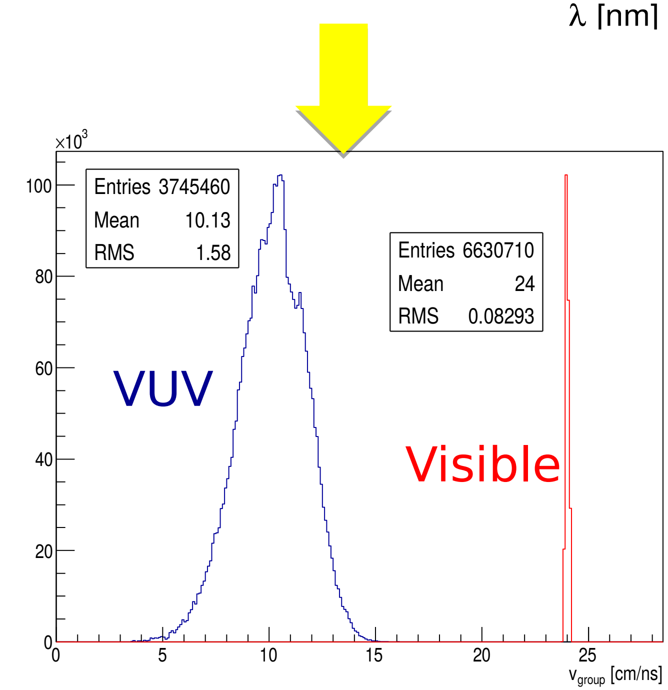
Liquid argon is mostly transparent to its own scintillation.

At longer distances effects like:
- Rayleigh scattering ~55cm f(λ)
- absorption, e.g. on nitrogen ~30 m @2ppm N2

begin to play a role.



Note high refractive index ~1.5 and gradient of for VUV → relatively slow light.



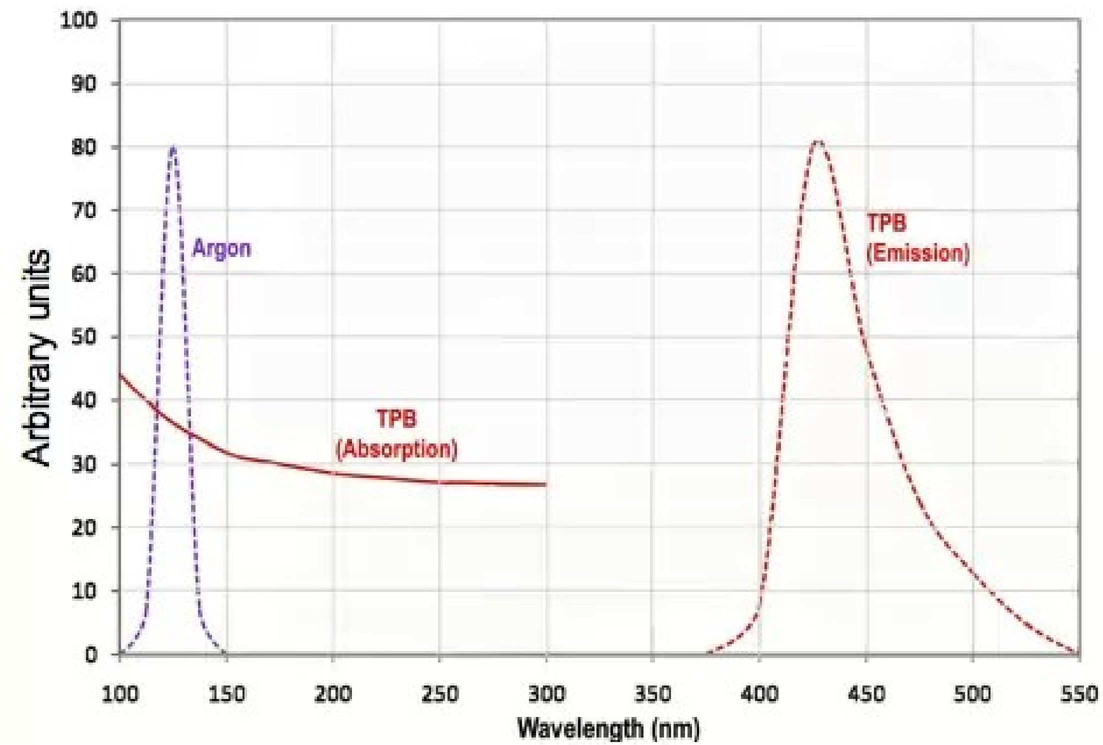
Scintillation Light in Argon (3)

Detection:

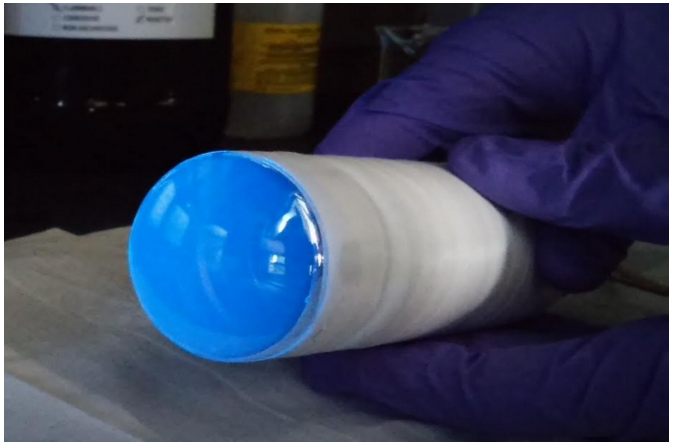
Liquid argon is almost the **only** thing transparent to its scintillation.

Detection is challenging – most often need to use Wavelength shifting compounds, like TPB.

Can deposit WLS on Light detection components or inside the detector.

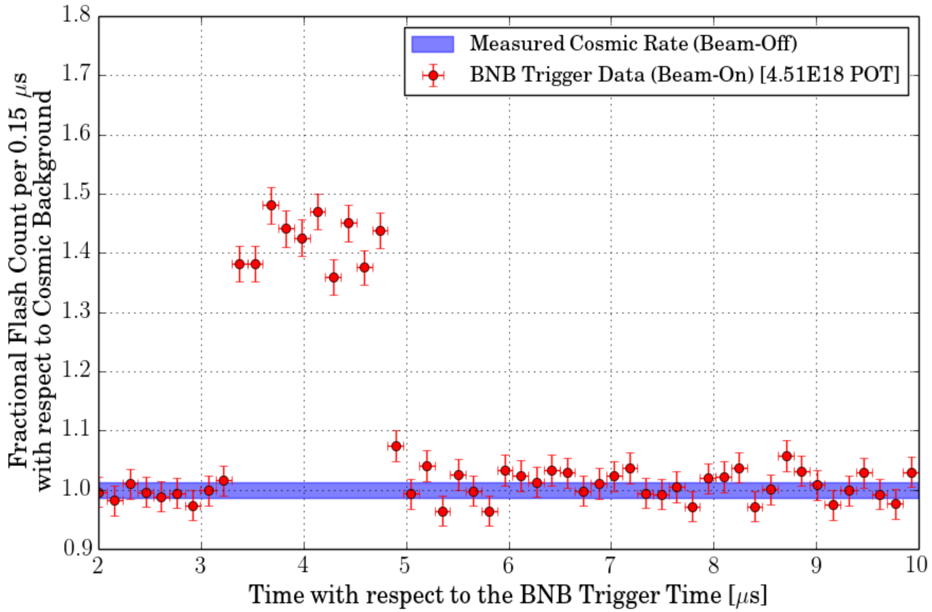


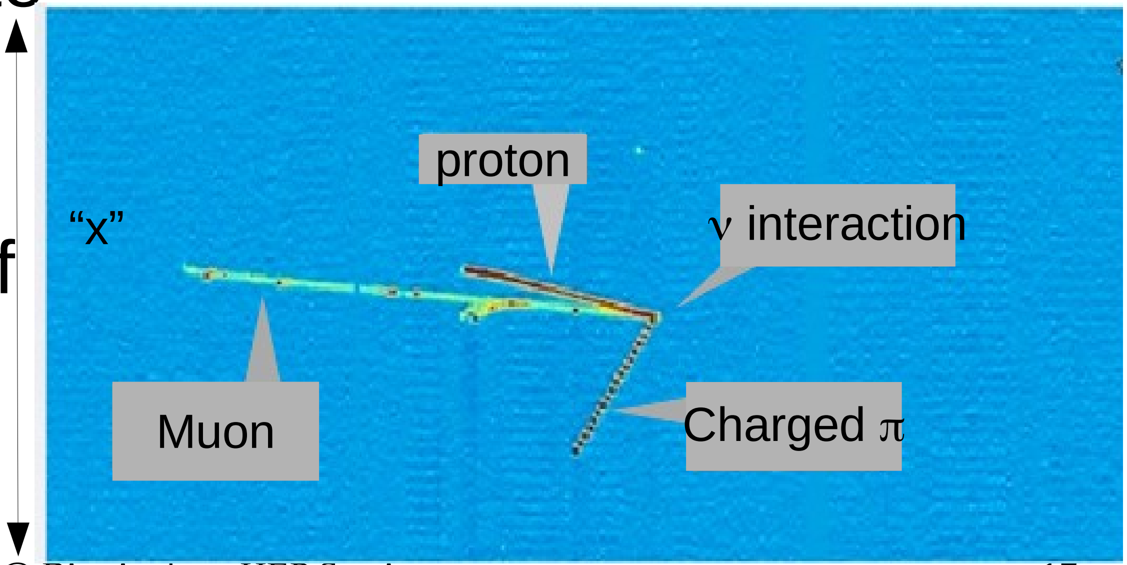
VUV sensitive SiPMs prototypes have appeared very recently.



Scintillation Light in LArTPCs: trigger

- A scintillation burst during the beam gate gives an indication that a neutrino signal happened.
- Provides a “t_0” - necessary to calculate x-position.
- Needed to apply corrections for loss of charge.





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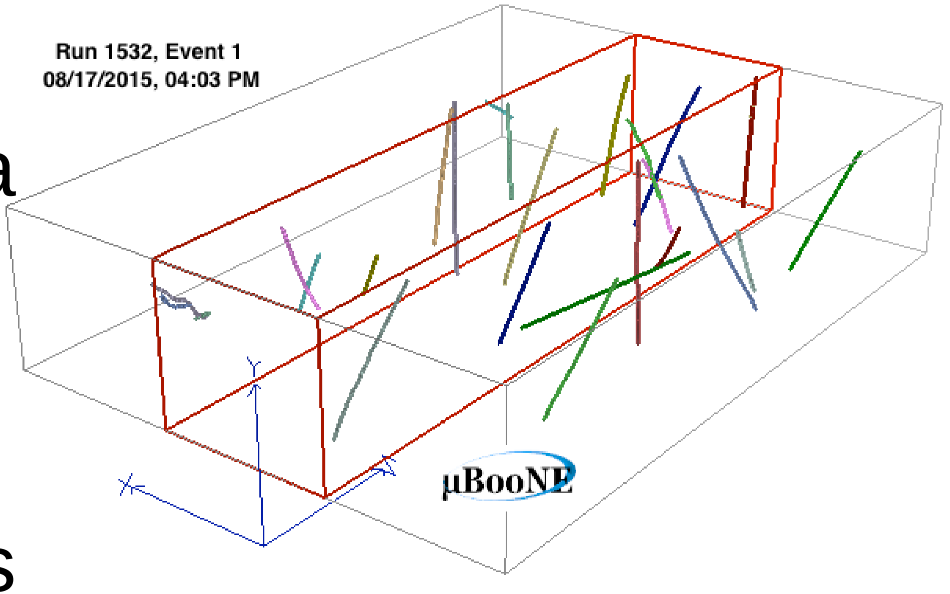
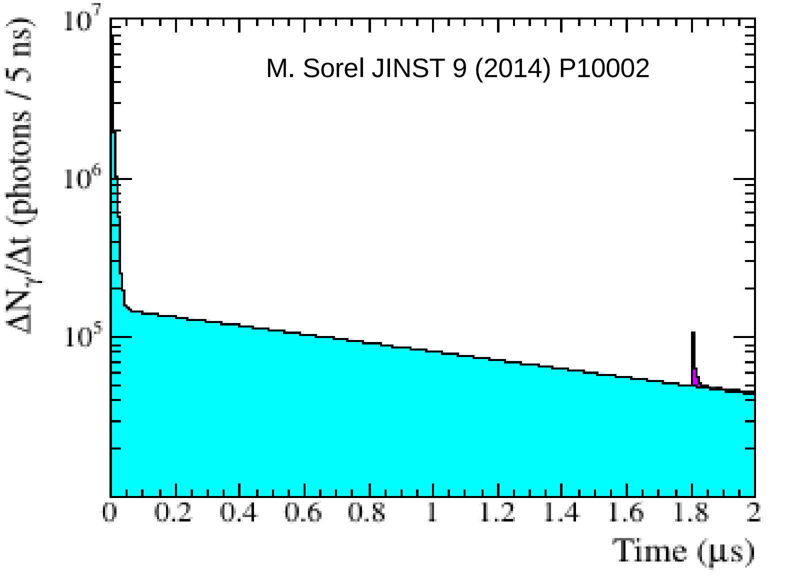
Scintillation Light in LArTPCs:
cosmic background removal

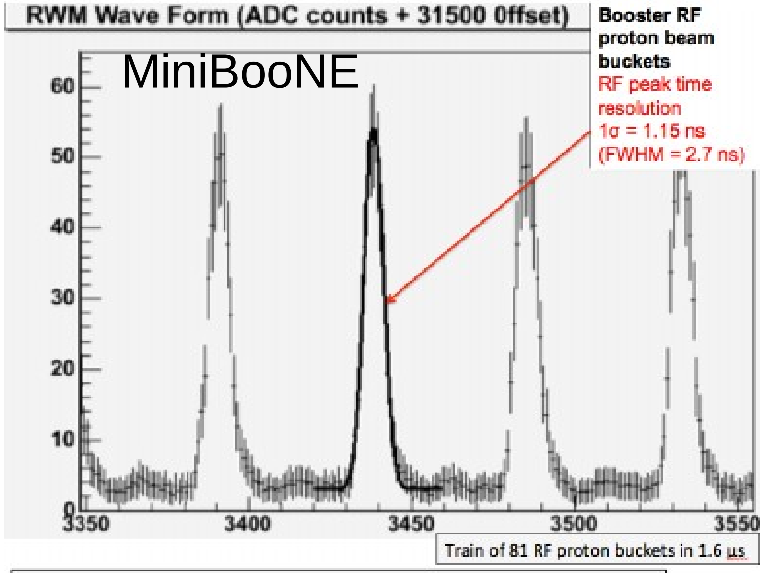
- LArTPCs on the surface see several cosmic rays in one readout frame.
- Need to match flashes to a charge deposition in the chamber.
- Allows rejecting backgrounds from cosmics and assign "t_0" to each event.



Scintillation Light in LArTPCs: timing

- LArTPCs are relatively slow detectors (1 frame is ~1ms).
- Improving timing resolution opens new physics possibilities:
  - **Few 100ns:** Tag Michel electron decays through timing
  - **1-2 ns:** resolve beam bucket structure
  - ? ns: beam exotics heavier than neutrinos.

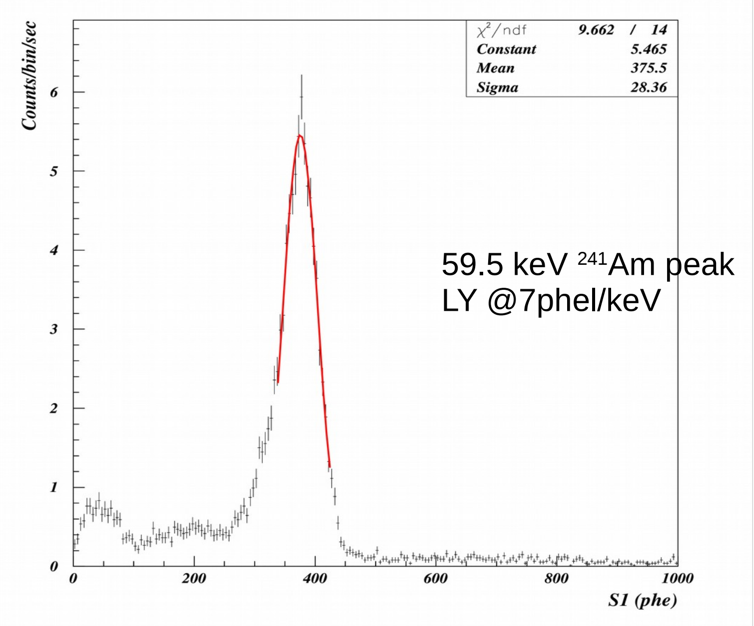




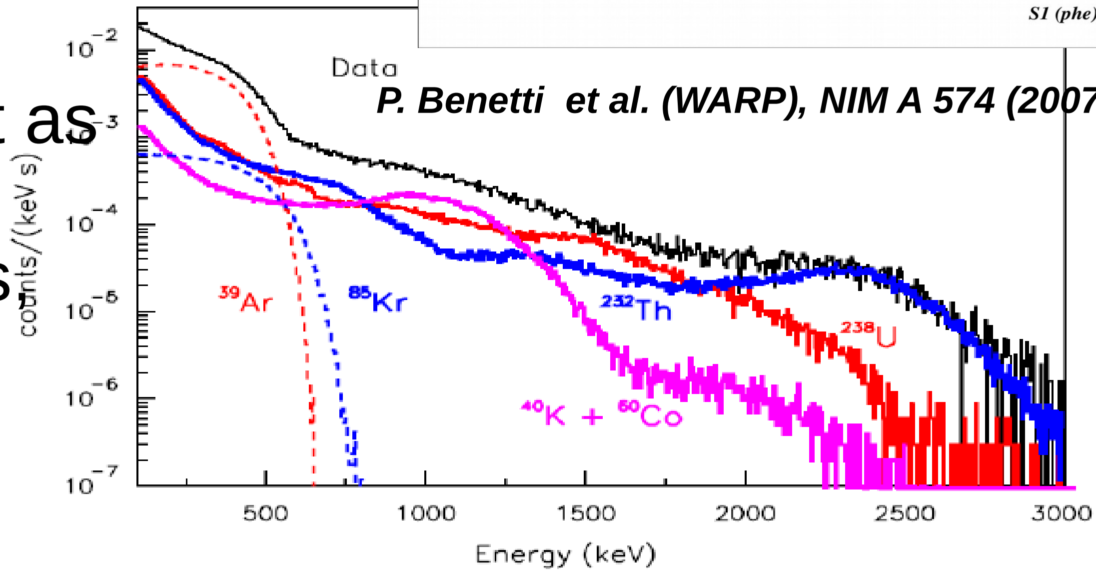
Scintillation Light in LArTPCs:
energy resolution

- Quantity of scintillation light is complementary to charge.
- Registering both will improve energy resolution.
- Knowing position will maximise precision.
- Largest benefits at lower energies, where TPC not as sensitive: Supernova neutrinos, nuclear effects, missing hadronic energy

R Acciarri et al. 2012 JINST 7 P01016



P. Benetti et al. (WARP), NIM A 574 (2007) 83



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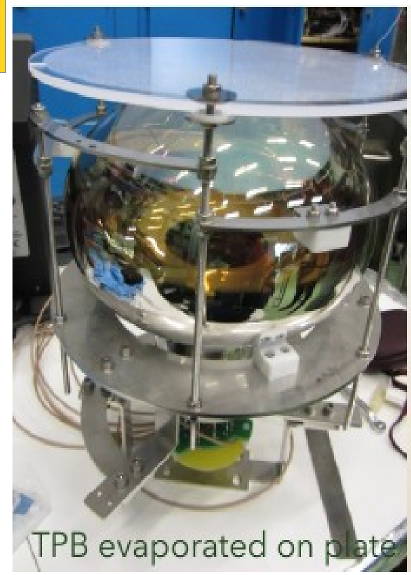
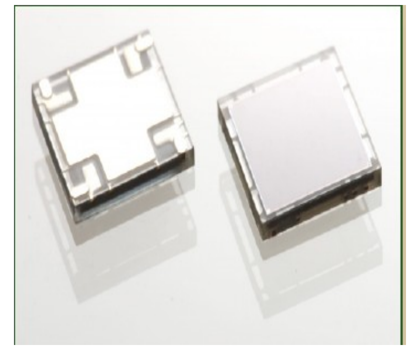
PMTs vs SIPMs

PMTs

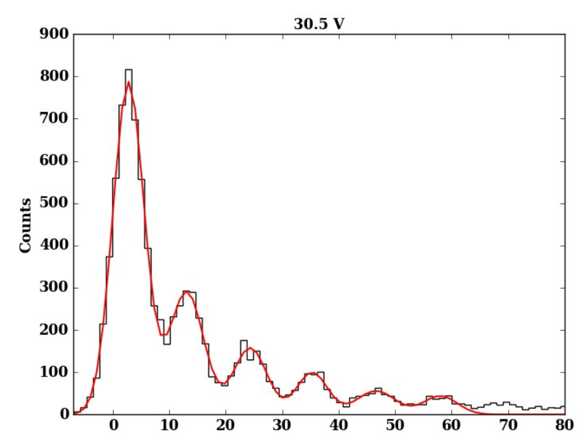
- Proven detector technology in liquid argon.
- Excellent timing resolution ~ ns.
- e.g. Hamamatsu R5912 8” PMTs
- Small channel/active area ratio.
- Non-negligible size, relatively high voltage.





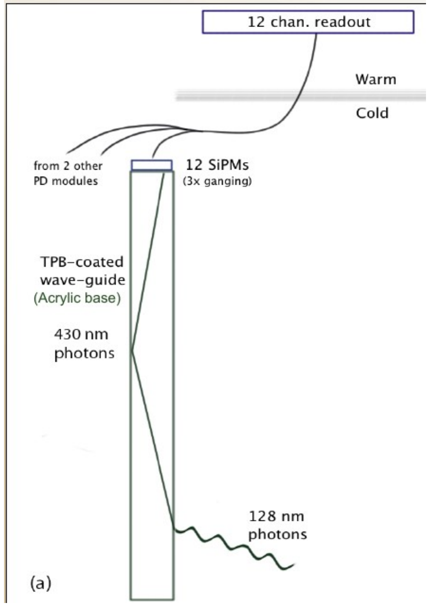
SiPMs

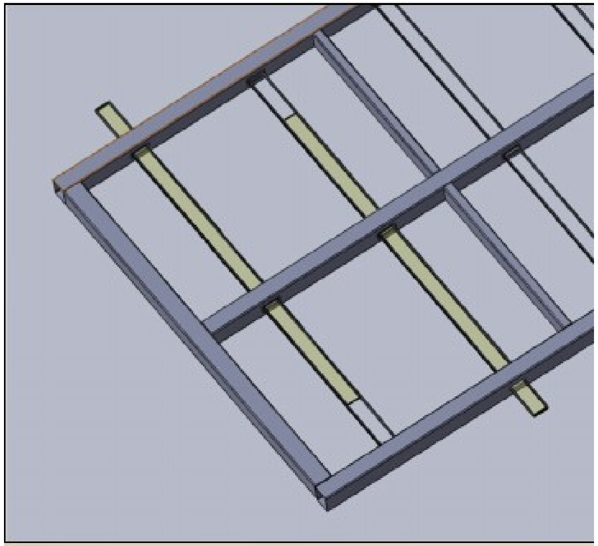
- SiPMs: Relatively new on the block.
- Excellent performance in liquid argon. Small voltage needed to operate.
- Small active size – need to be clever to avoid large channel number.

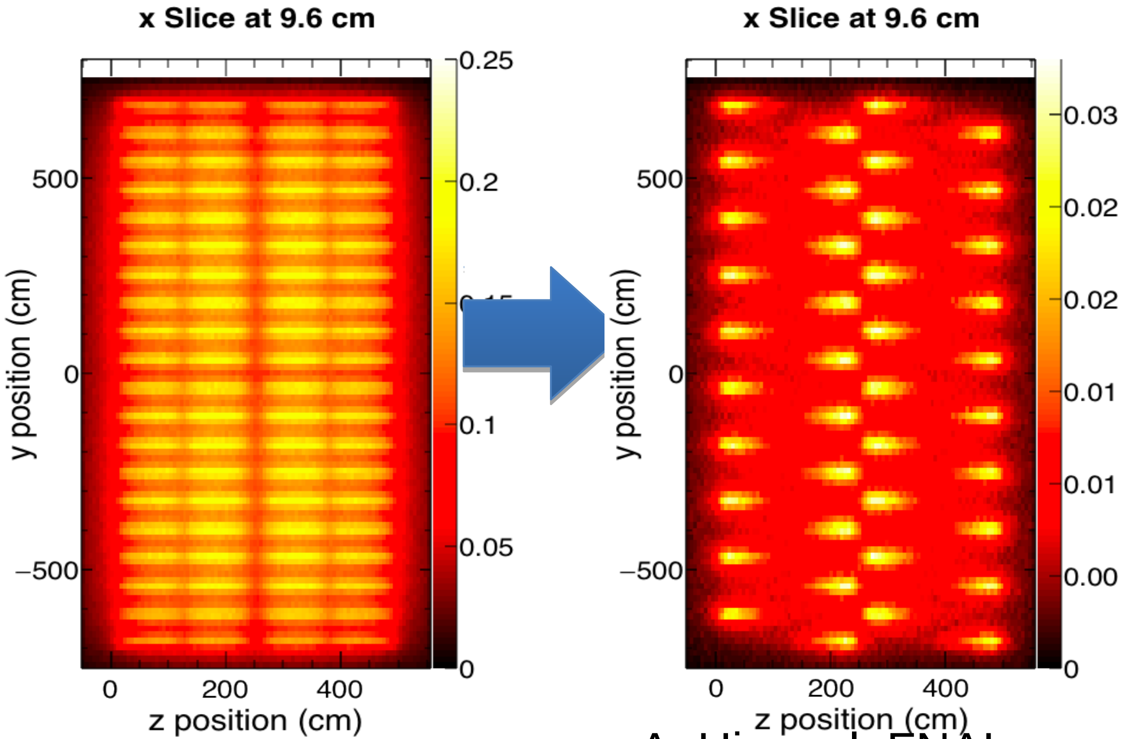


SiPMs + coated bars

- WLS coated bars coupled to SiPMs (current DUNE baseline design).
- SiPM timing not as good as PMTs (Industry is working on this).
- Photon travel time in bar adds to this.
- Work ongoing to minimize attenuation in bars.
- Tested in 35ton – prototype and test-stands.



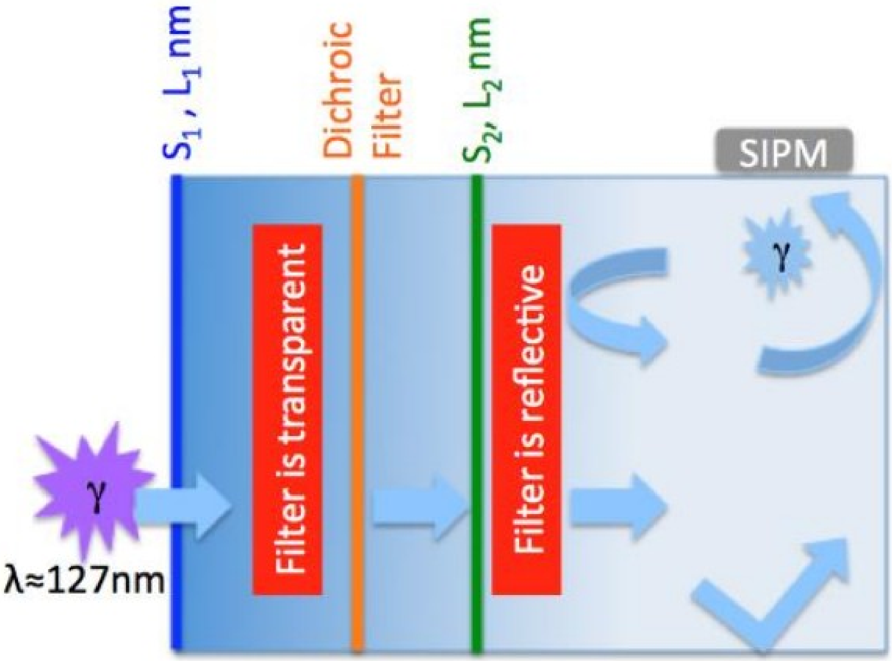




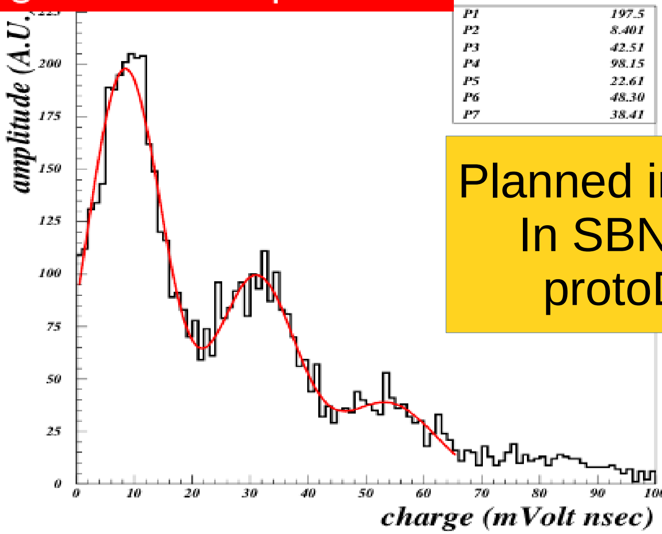
A. Himmel, FNAL

The ARAPUCA light trap

- A way to enlarge the active surface without increasing number of channels.
- Use dichroic filters + 2 WLS



Single electron spectrum



Planned installation In SBND and protoDUNE

E. Segreto & A. Bergamini-Machado

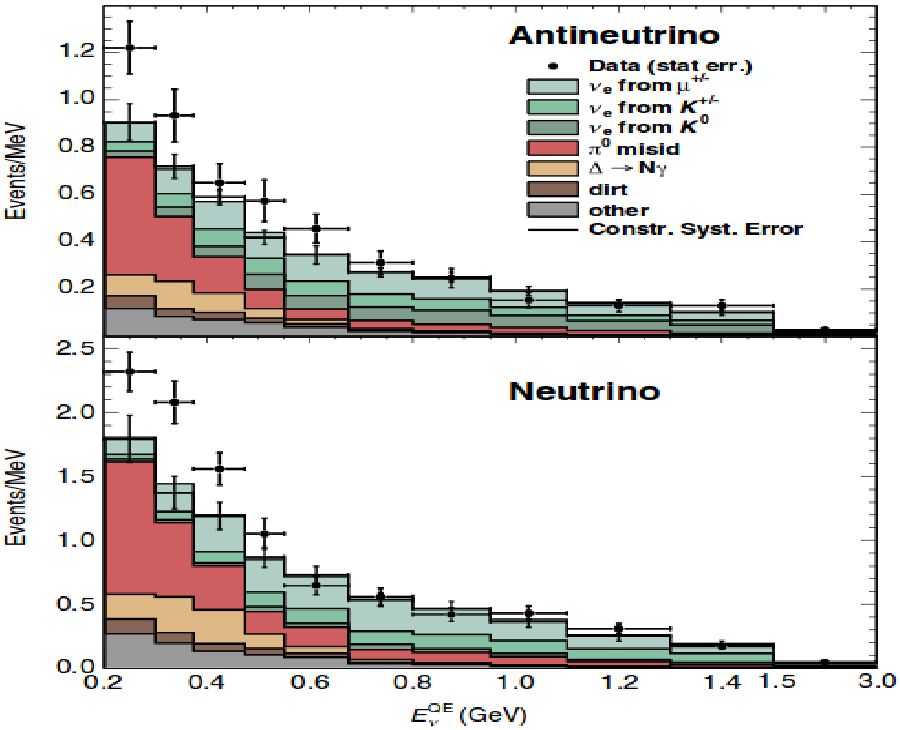
From Theory to “Practice”

“Now, this is just a simulation of what the blocks will look like once they're assembled.”

SBN Physics

- Recalculation of reactor neutrino fluxes and analysis of sources in gallium experiments.
- MiniBooNE confirms its excess with the final data set.

Phys. Rev. Lett. 110, 161801 (2013)



Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv:1204.5379 [hep-ph], (2012)

- Very different experimental techniques are hinting at short baseline oscillations.
- Tension with other experiments, e.g. long-baseline.

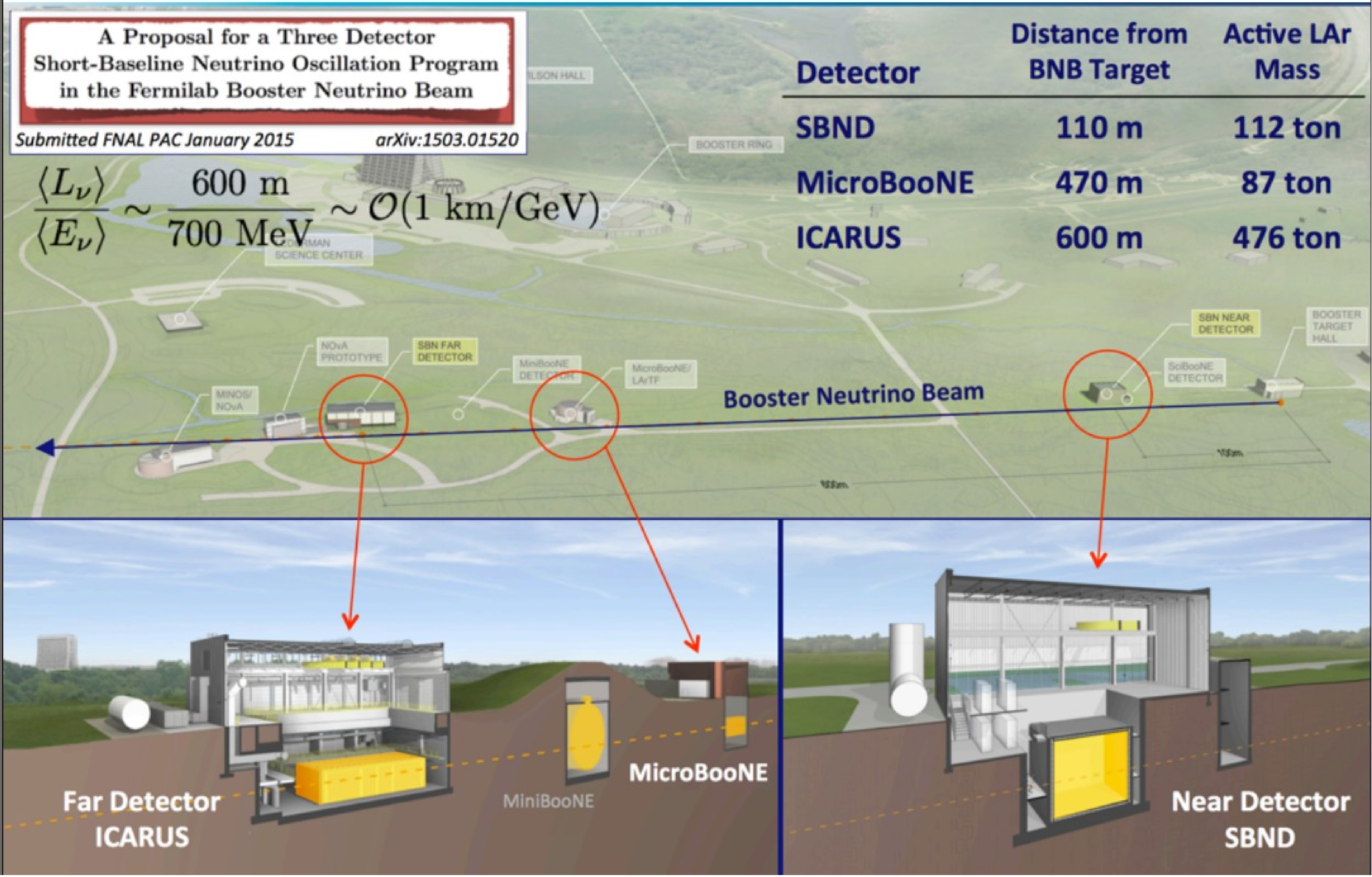
SBN Program at Fermilab

A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

Submitted FNAL PAC January 2015 *arXiv:1503.01520*

$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \mathrm{m}}{700\ \mathrm{MeV}} \sim \mathcal{O}(1\ \mathrm{km/GeV})$$

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton



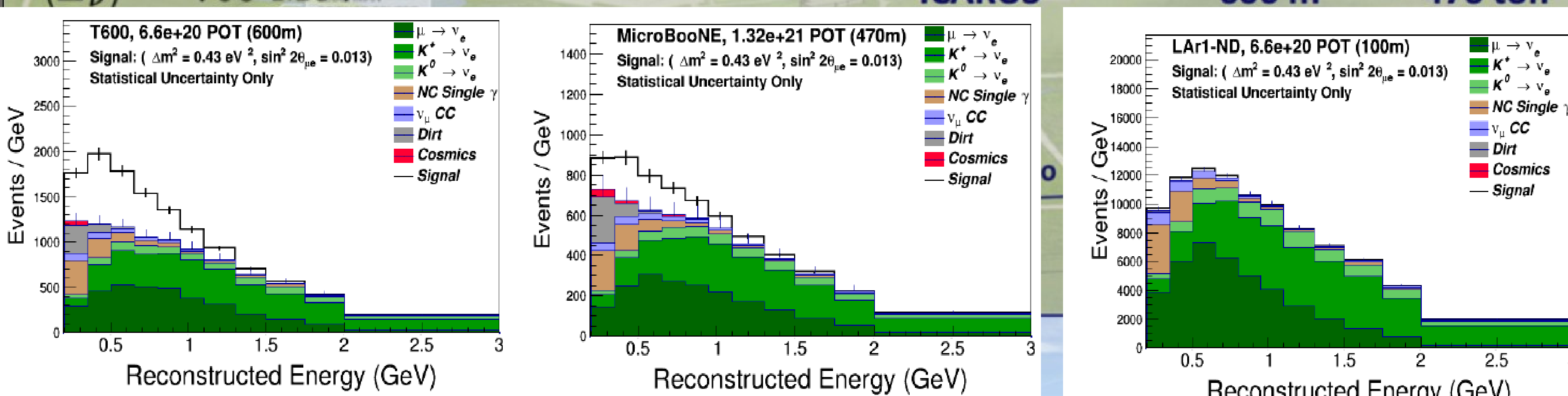
SBN Program at Fermilab

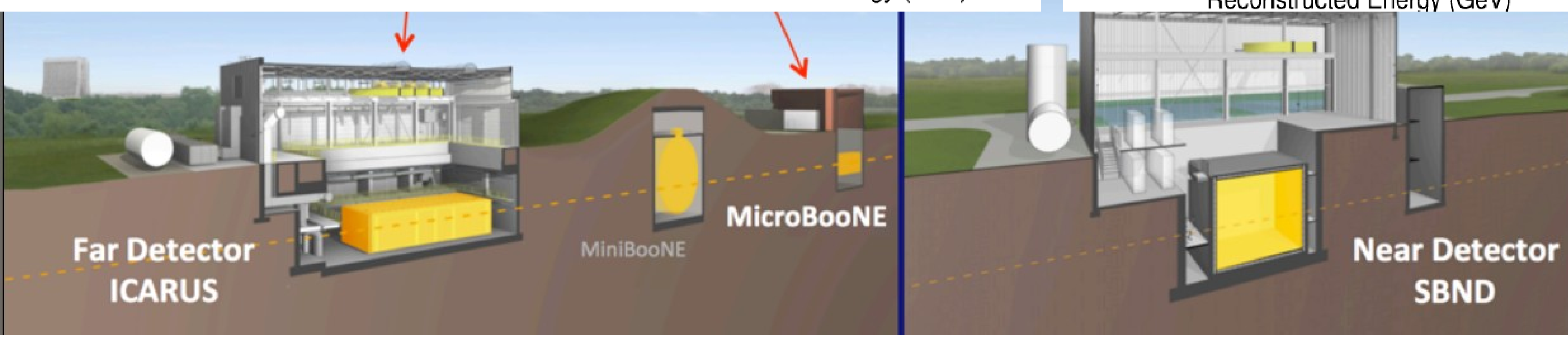
A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

Submitted FNAL PAC January 2015 *arXiv:1503.01520*

$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \text{m}}{700\ \text{MeV}} \sim \mathcal{O}(1\ \text{km/GeV})$$

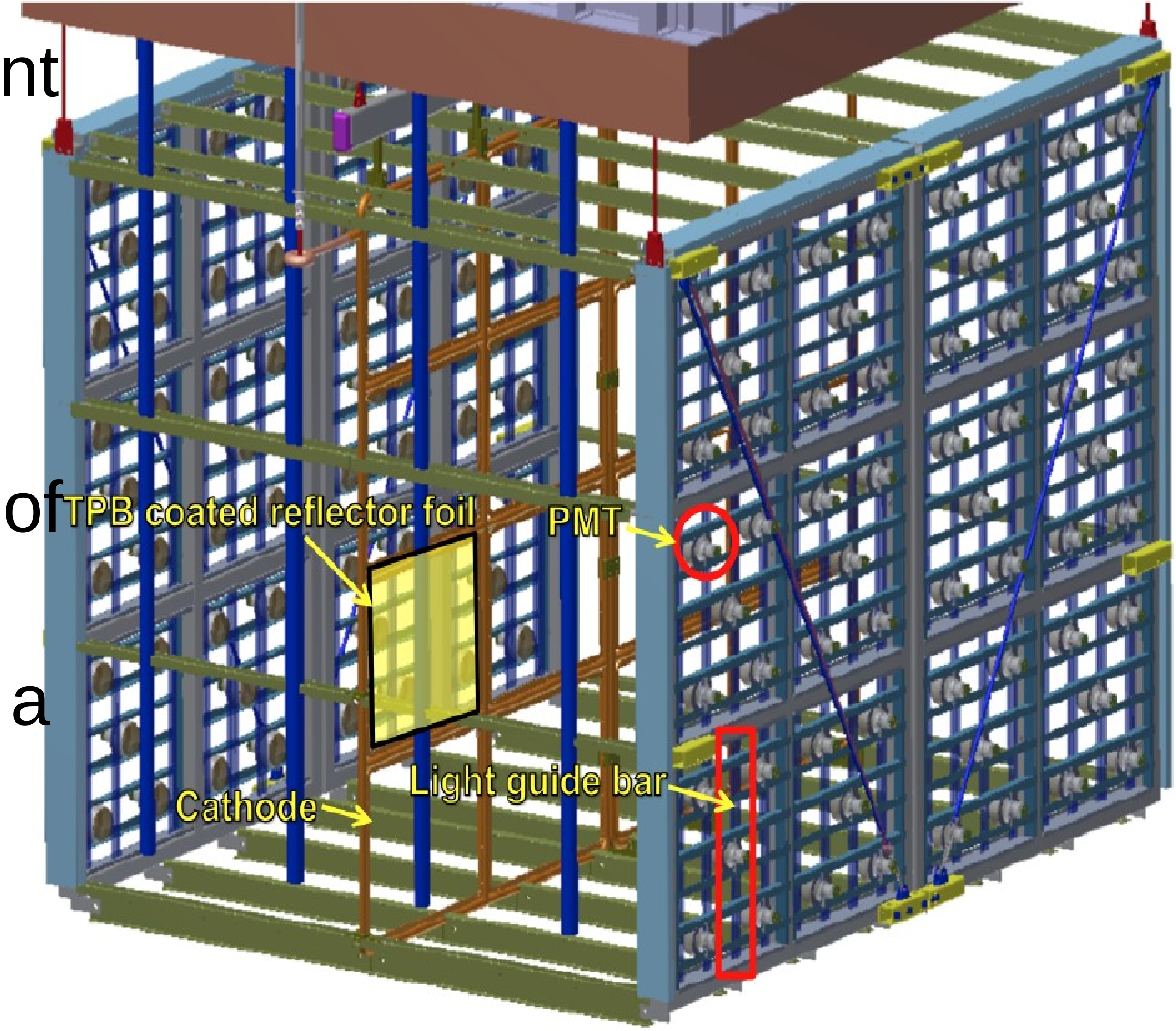
Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton





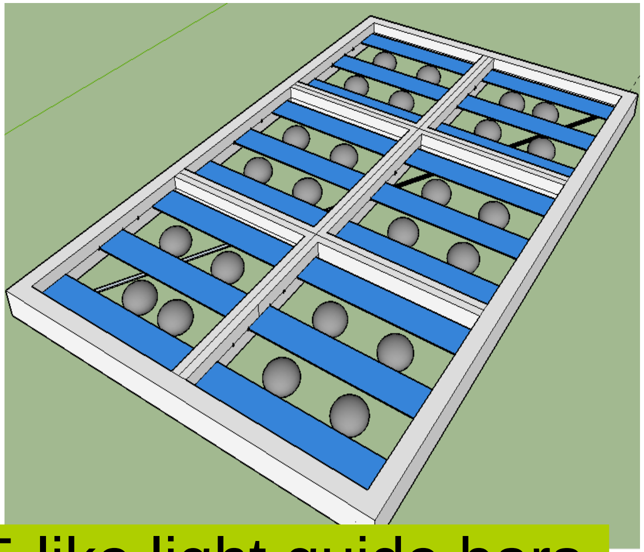
Light Detection in SBND

- R&D is an important part of the mission of SBND.
- Scintillation light is one of the most important aspects of this R&D.
- Plan to implement a multi-technology setup .

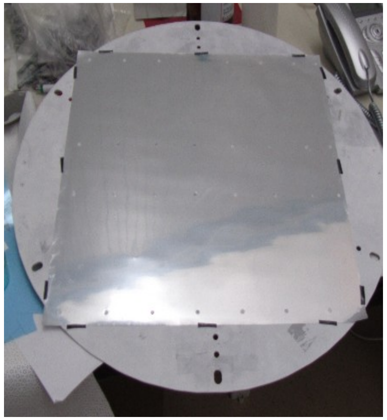


SBND Light Detection Systems

- Enhanced MicroBooNE design.
- 60 8" 14 dynode Ham PMTs/TPC.



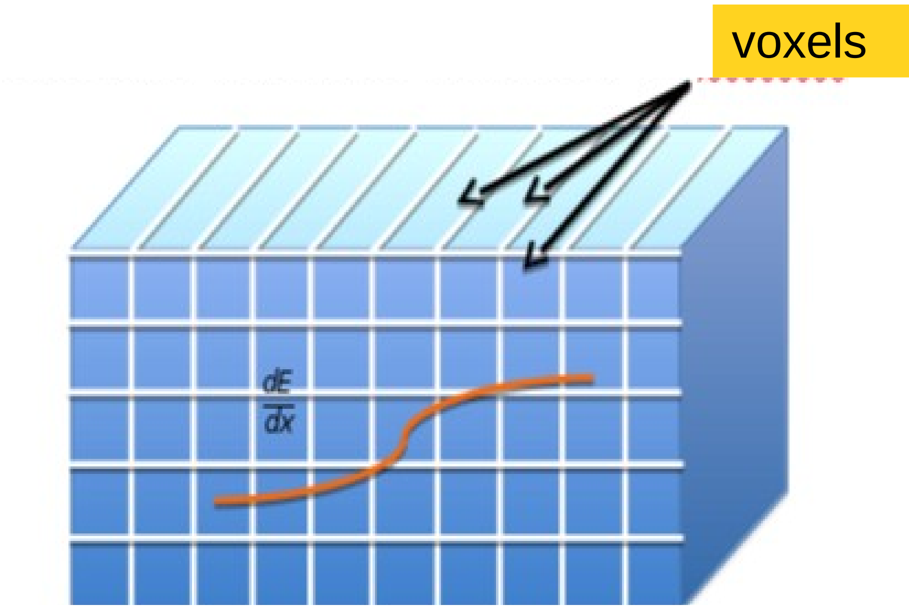
DUNE-like light guide bars (secondary)
SiPMs coupled to WLS covered light guide bars



- WLS covered reflector foils.
- Increase uniformity of light collection.
- R&D for future experiments.

Simulating light in argon (LArSoft)

- Argon is a prolific scintillator, so at beam neutrino energies simulating each optical photon is not feasible.
- We use an optical lookup library (developed by uBooNE) to mitigate this problem.

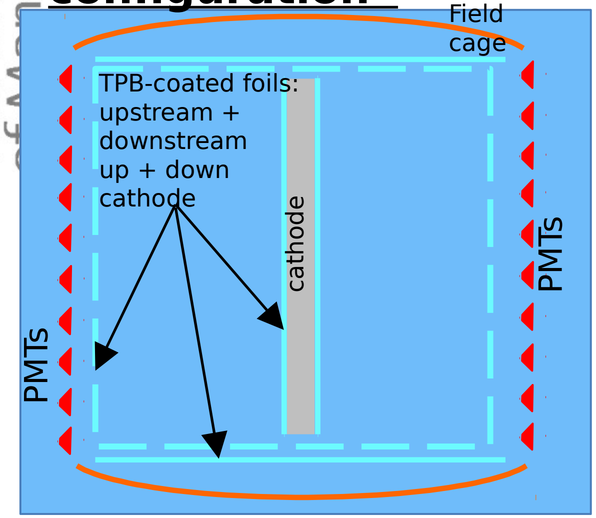


$$\langle N \rangle_{PMT-hits} = \left(\frac{dE}{dx}_{step} \cdot Length_{step} \right) \cdot LY \cdot visibility_{step}^{PMT}$$

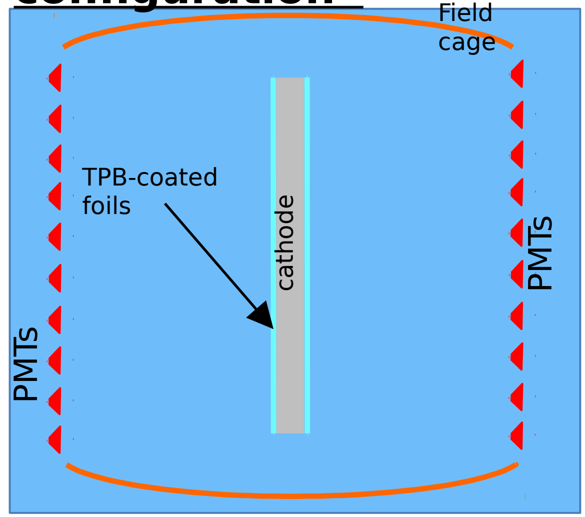
Next slides, largely work by D. Garcia-Gamez, Manchester

Considered configurations

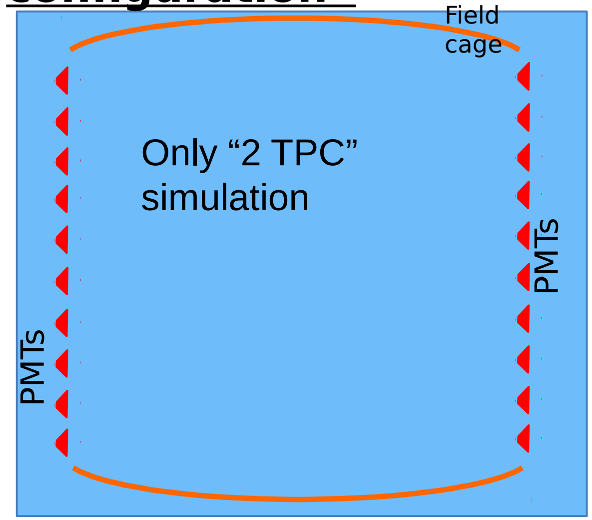
"Full coverage configuration"



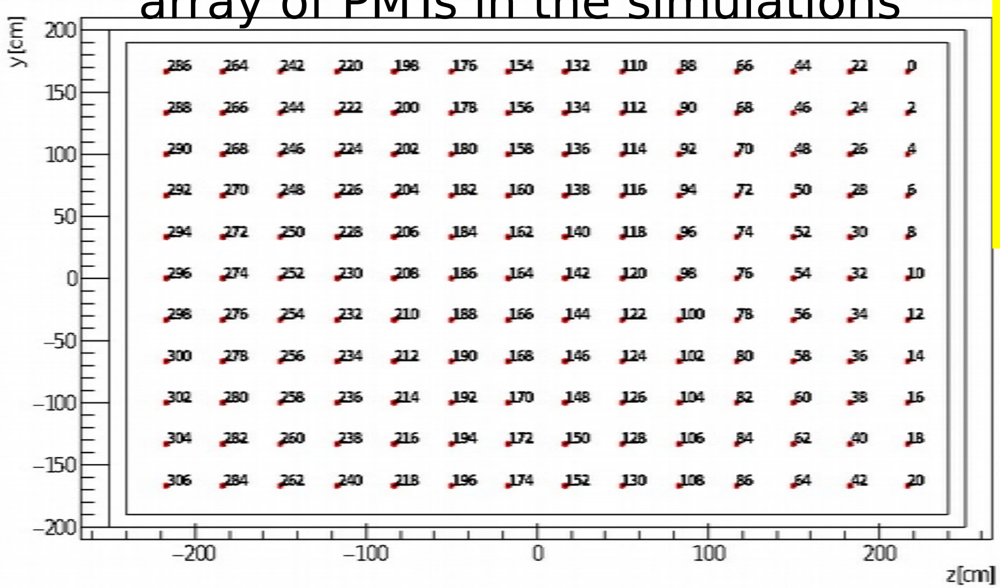
"Cathode only configuration"



"No foils/cathode configuration"



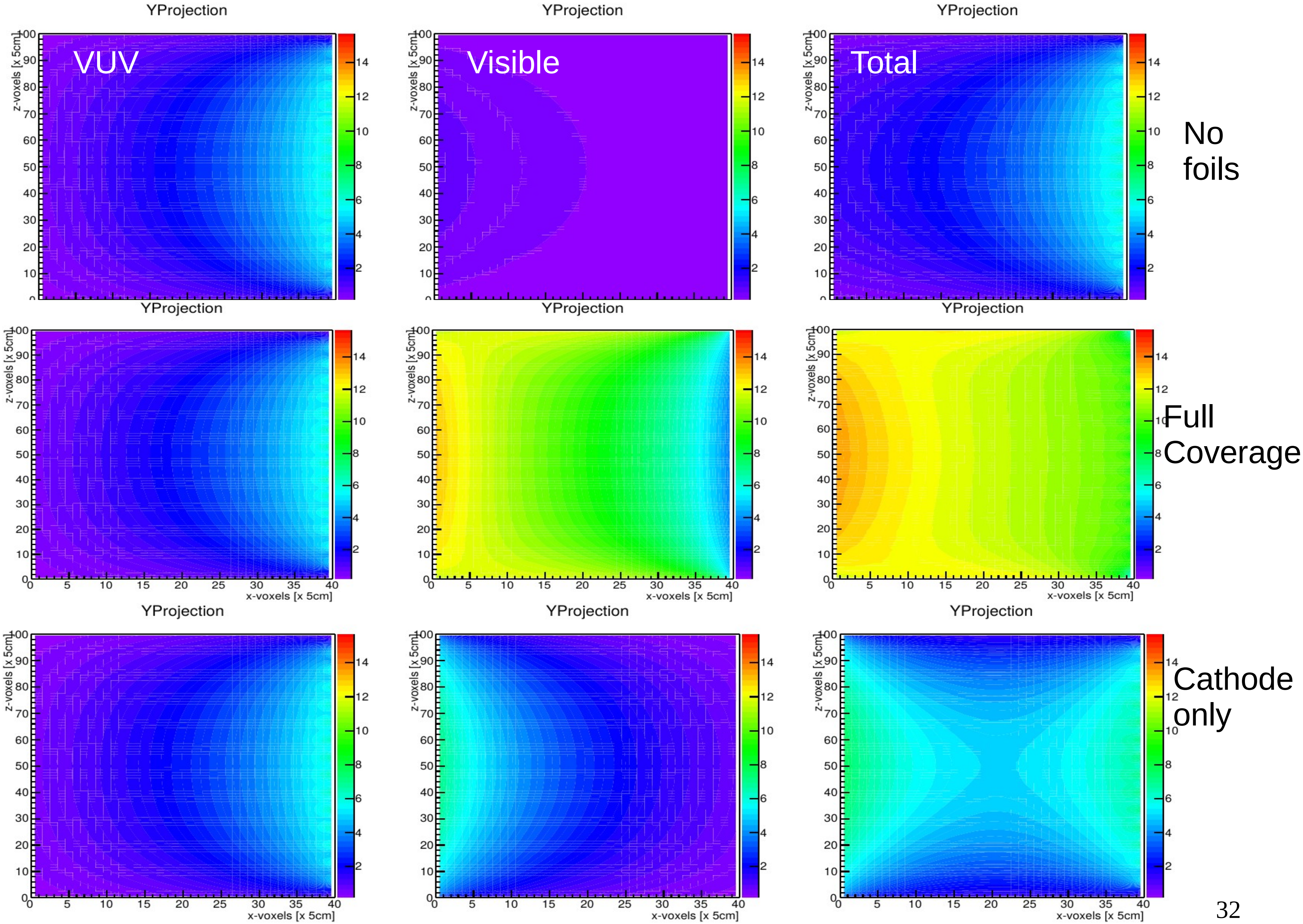
array of PMTs in the simulations



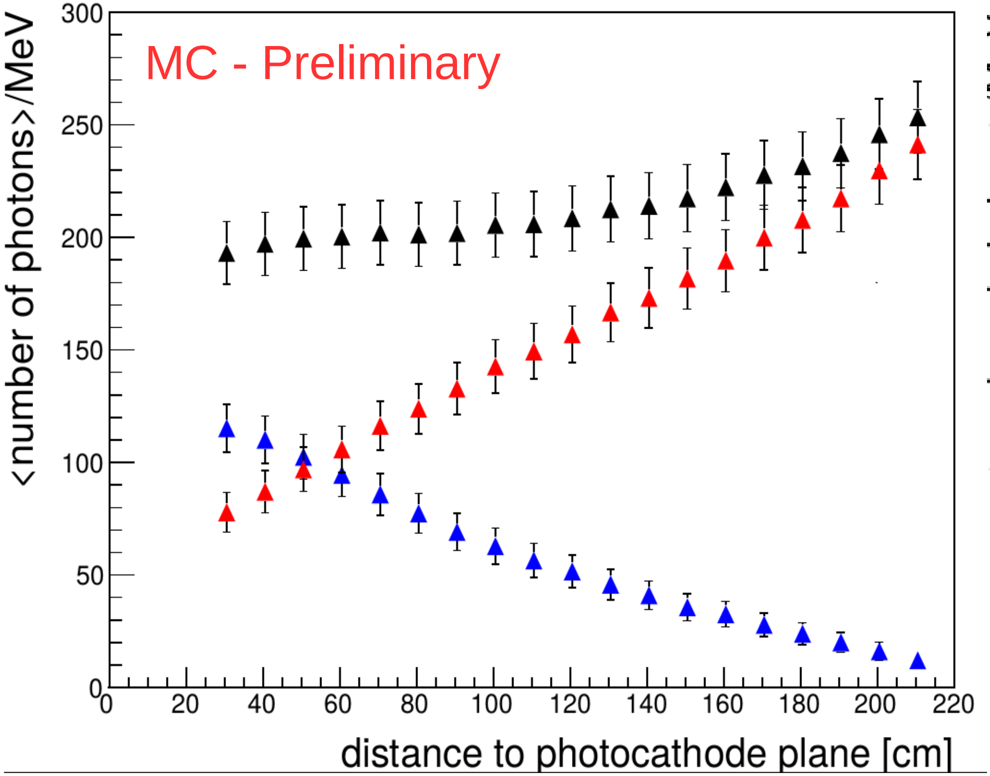
We use the symmetry of the system. Overshoot number of PMTs (11 x 14 PMTs / TPC 8'' diameter) to be able to switch them On/Off

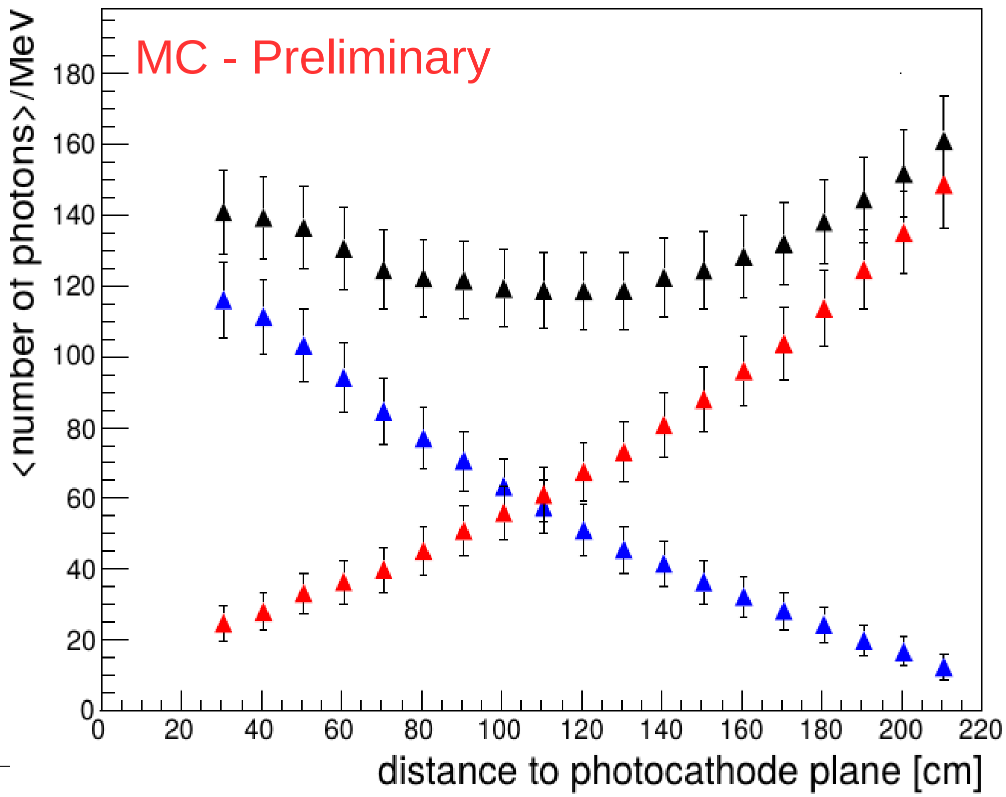
Note: from now on, **visible** refers To light wavelength-shifted and reflected off of the foils, while **VUV** refers to light directly hitting the PMTs.

Light Yield Uniformity



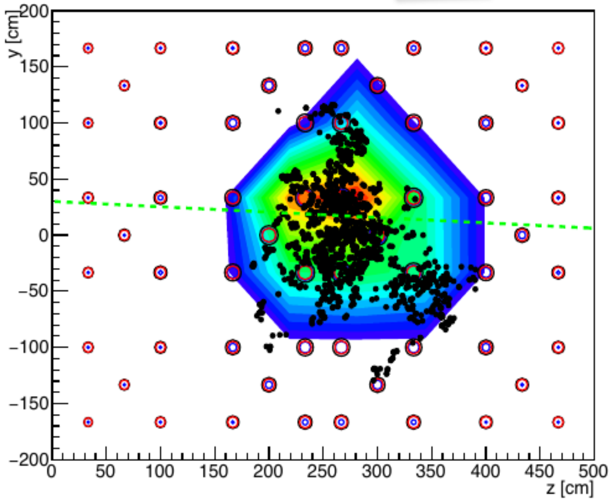
Light Yields



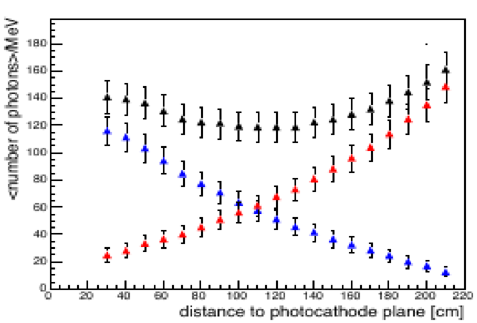


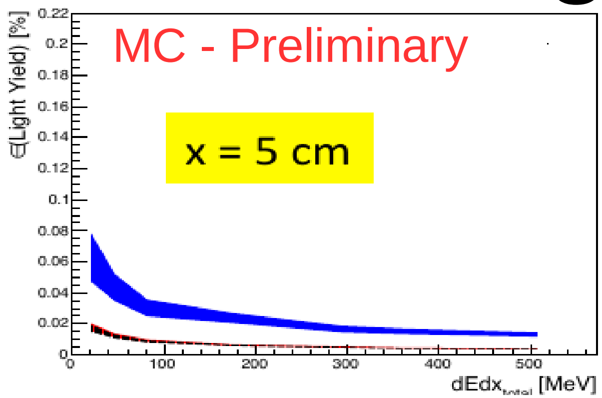
Average number of photons/event/MeV (adding the signal in all the PMTs) vs X position (drift distance to the photocathode plane)

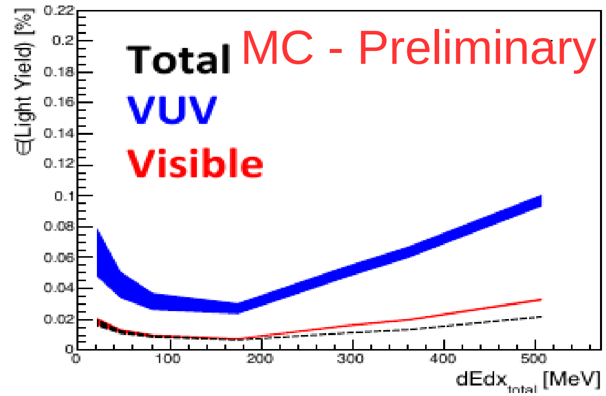
Calorimetry with Scintillation Light

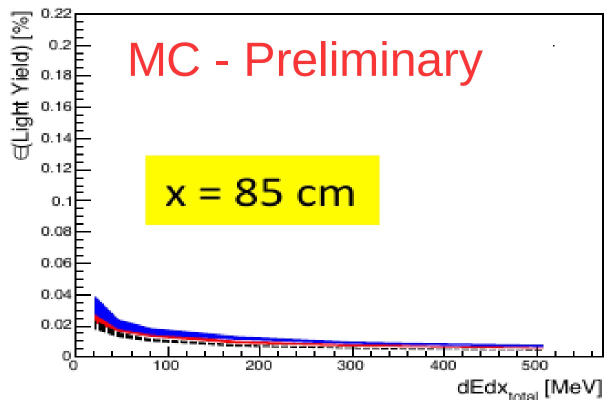


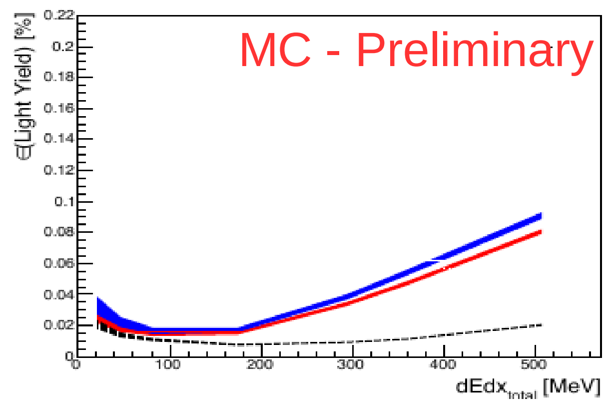
For protons interacting inelastically a large fraction of the energy is lost to the TPC.

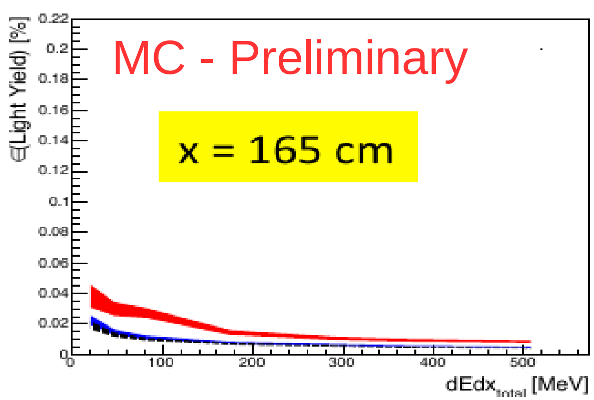


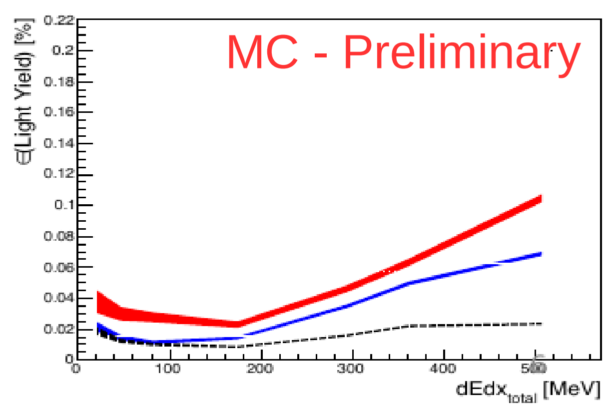






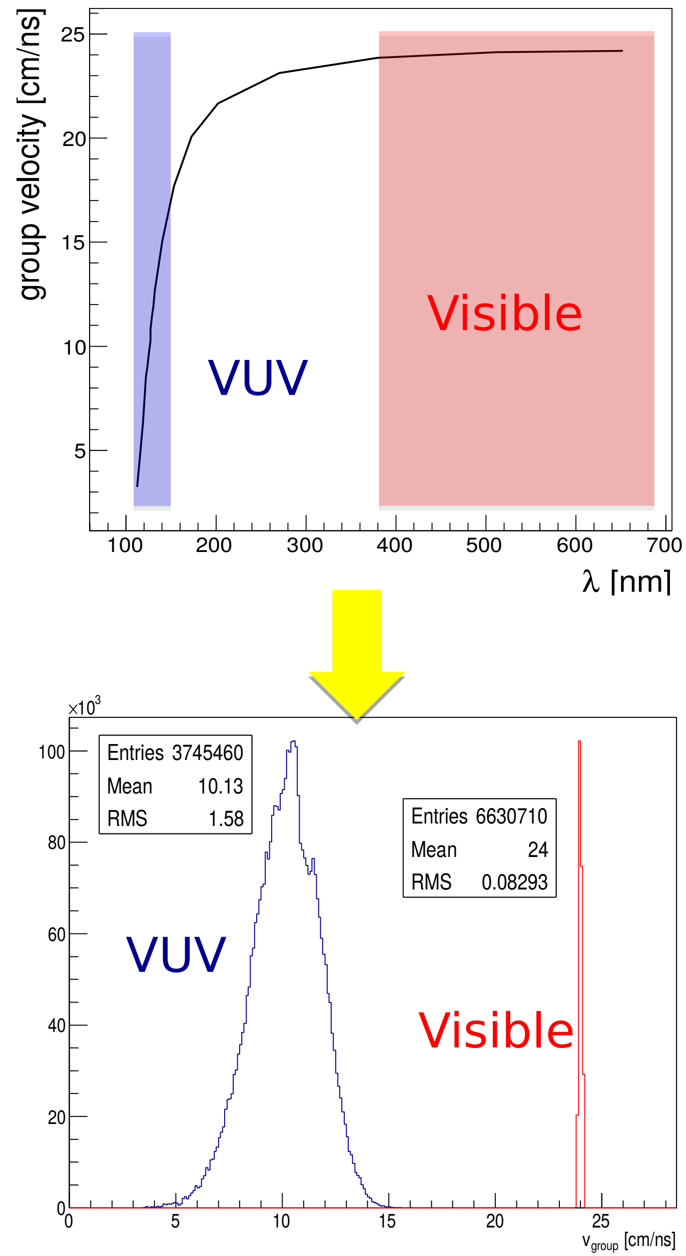






Timing

- To see if ~ns resolutions can be achieved need to account for second order effects, e.g. Rayleigh scattering.
- impossible to do using a lookup library (memory) -> ***parametrization of arrival times.***
- Assume we can model Argon Scintillation timing (in principle optimistic).



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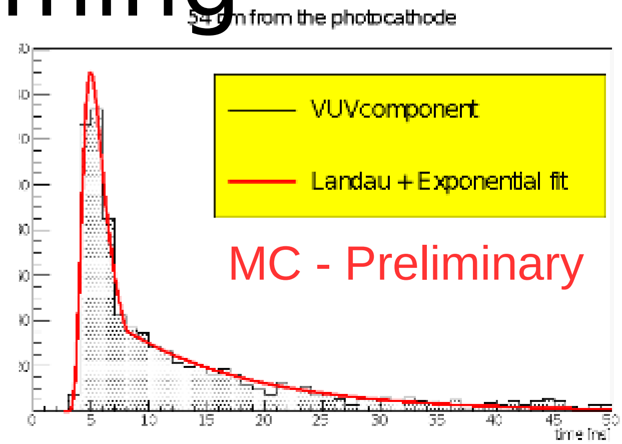
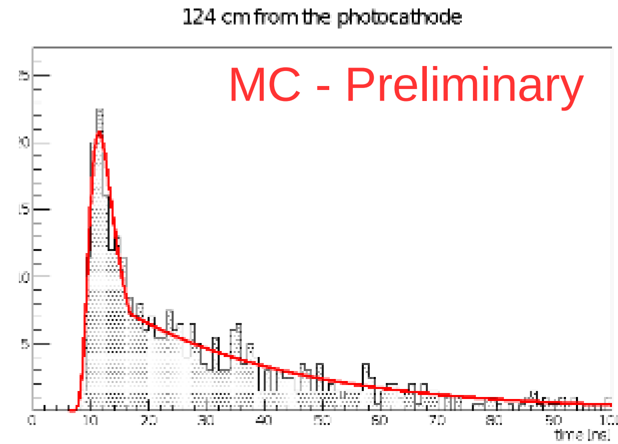
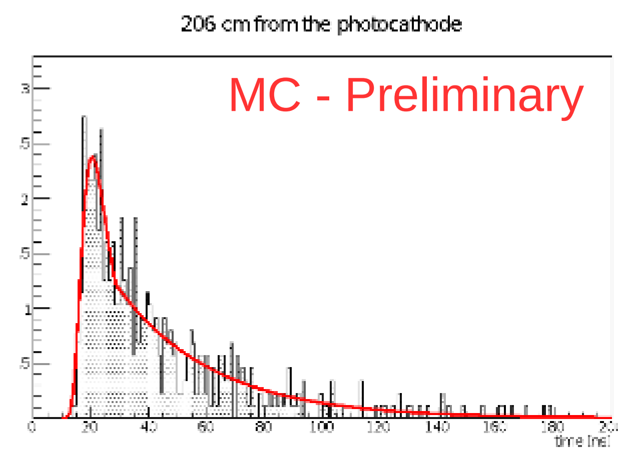
Direct light (VUV) timing parametrization:

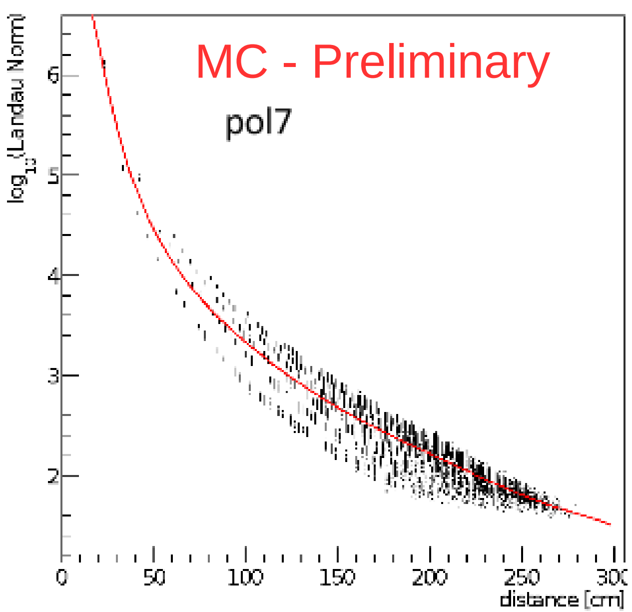
A combination of Landau and exponential functions fits practically every distribution of photon arrival times.

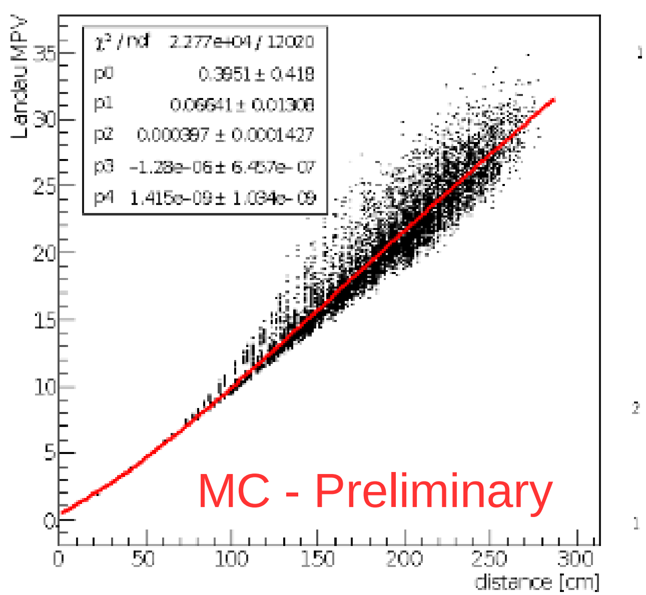
The fit parameters turn out to be monotonic functions of distance.





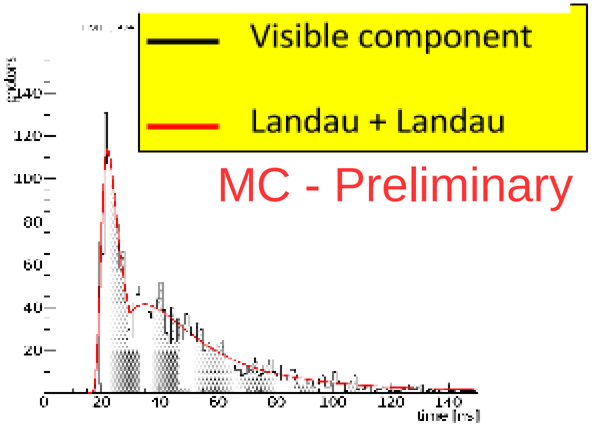




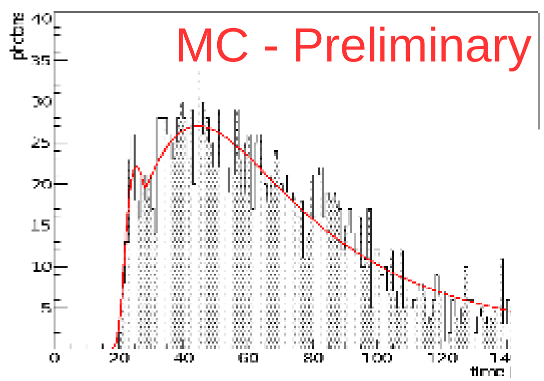


Works for Visible Light too:

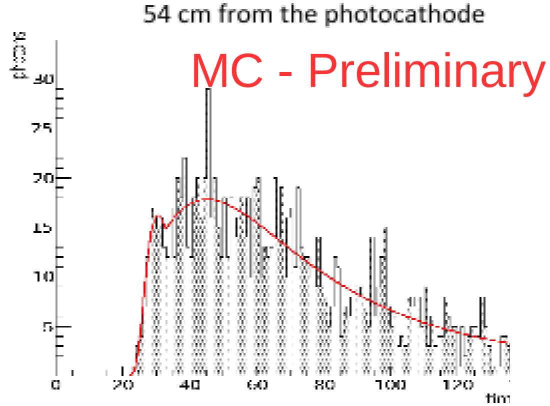
376 cm from the photocathode



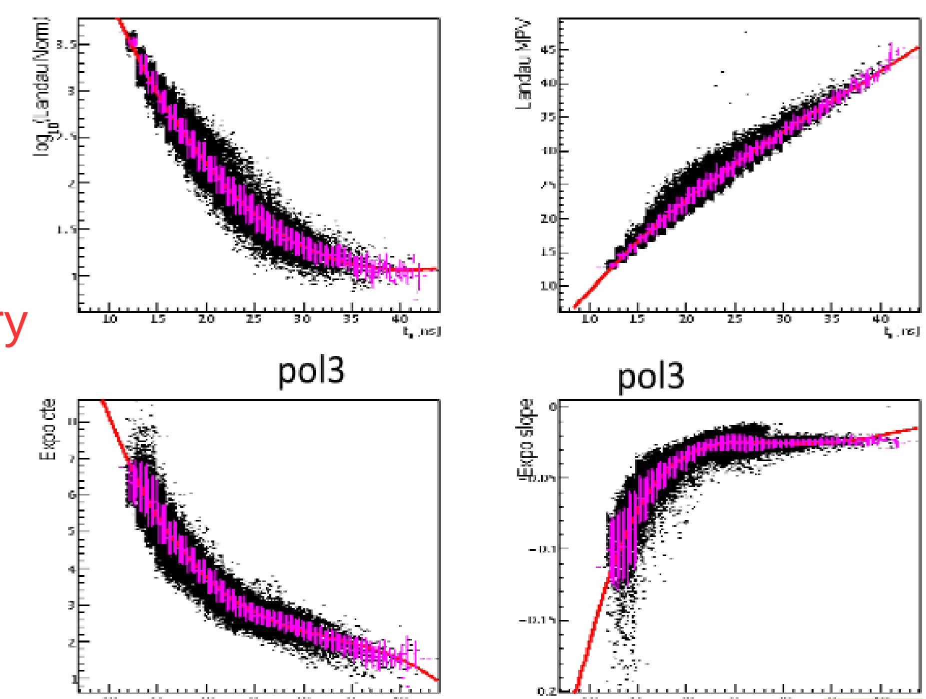
146 cm from the photocathode

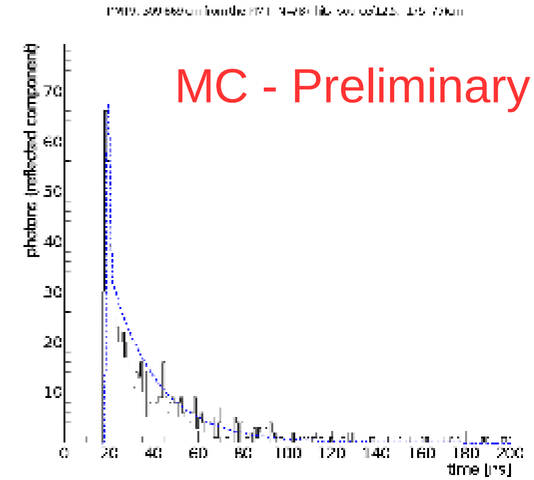


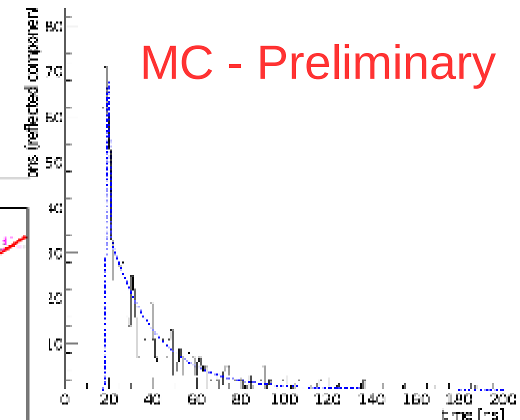
54 cm from the photocathode

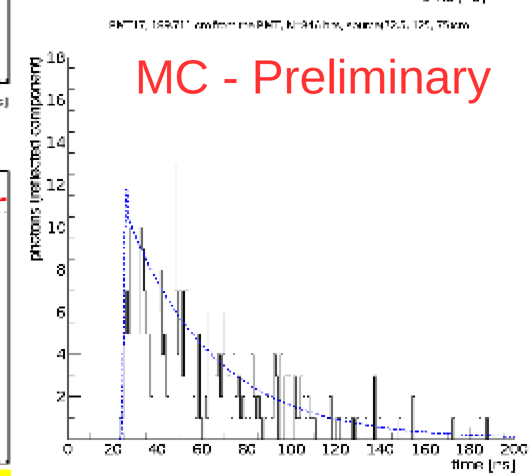


Cathode only configuration is much easier to model - Path of light easier to "predict".









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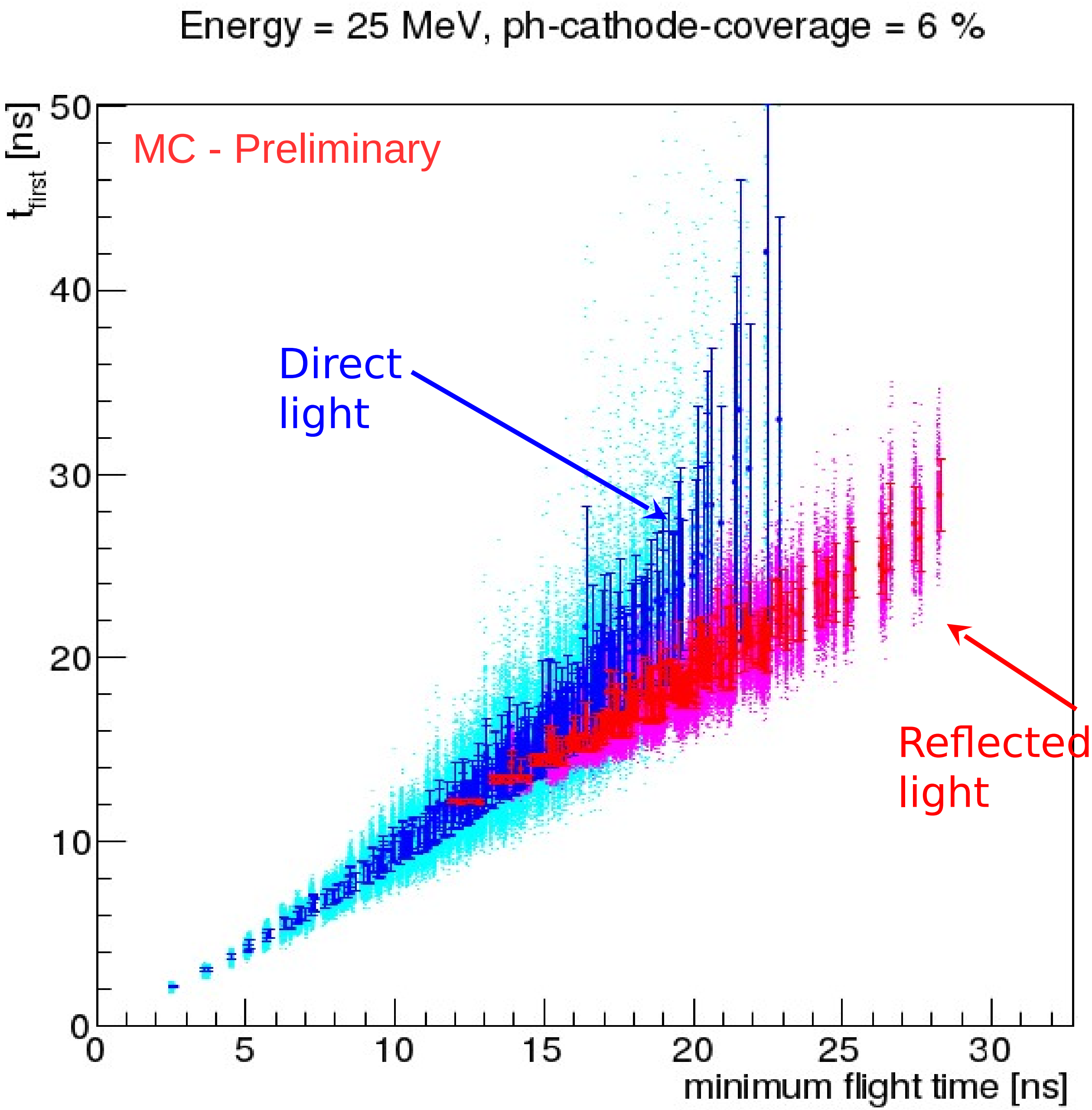
Single PMT time resolution



Note that flight time scales differently wrt distance for reflected/visible and VUVlight.

Timing

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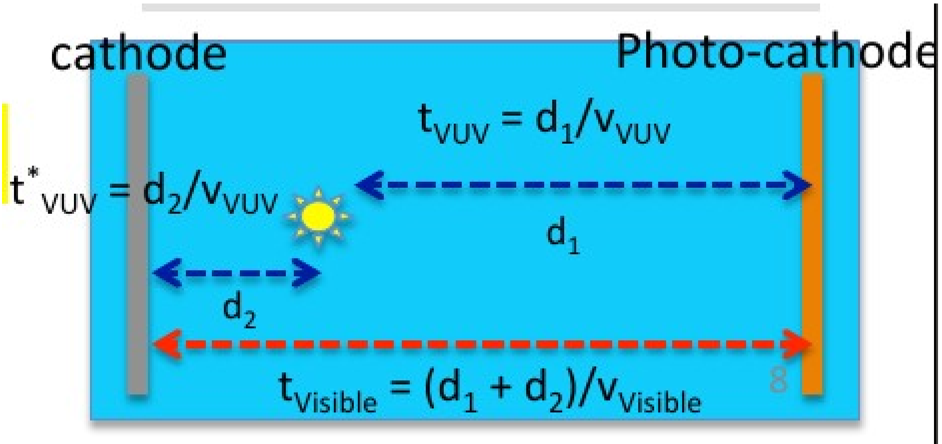
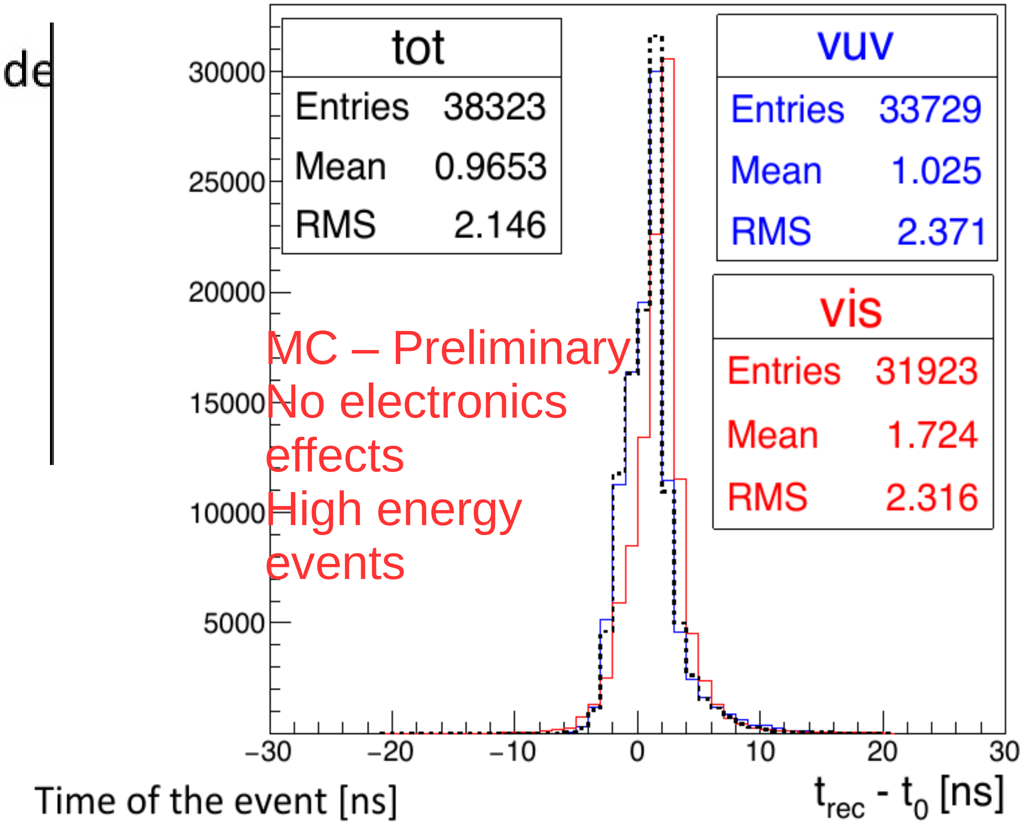
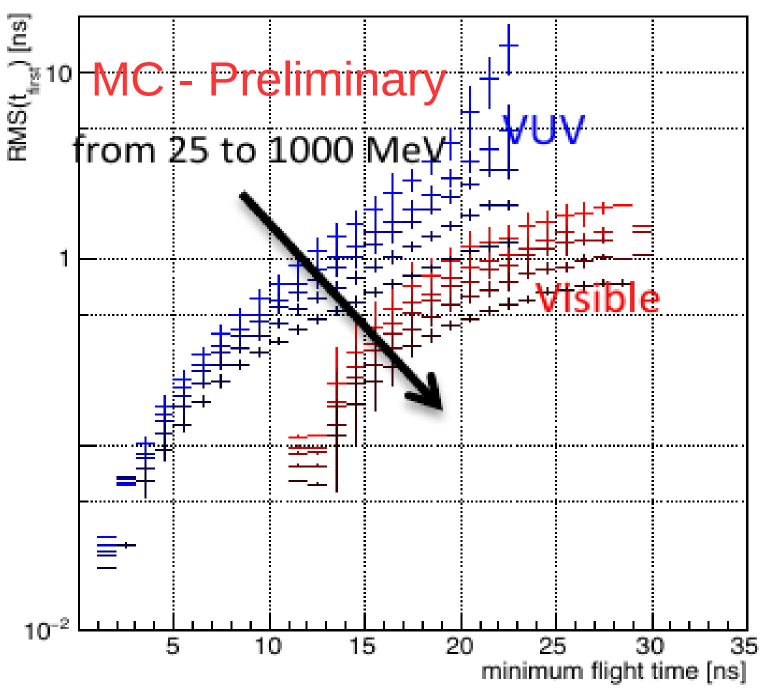






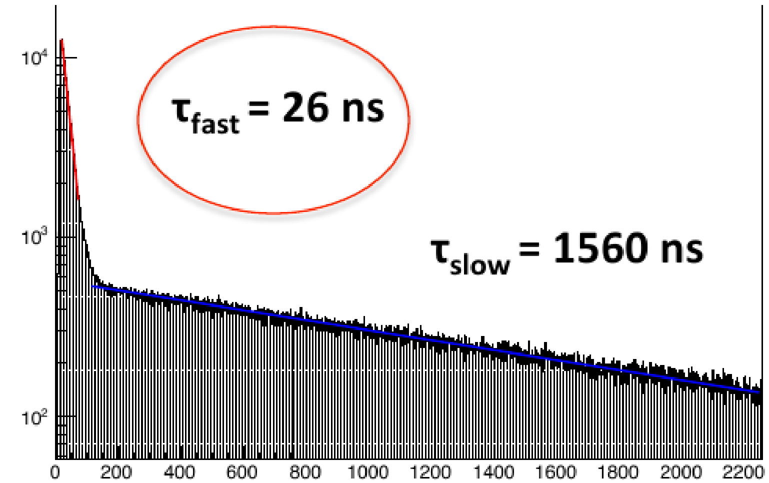
Timing resolution depends on the quantity of arriving light (smaller chance of missing photons coming in)

Effects on timing constants

Scintillation:
$0.3 \times \tau_{fast}(6\ ns) + 0.7 \times \tau_{slow}(1590\ ns)$

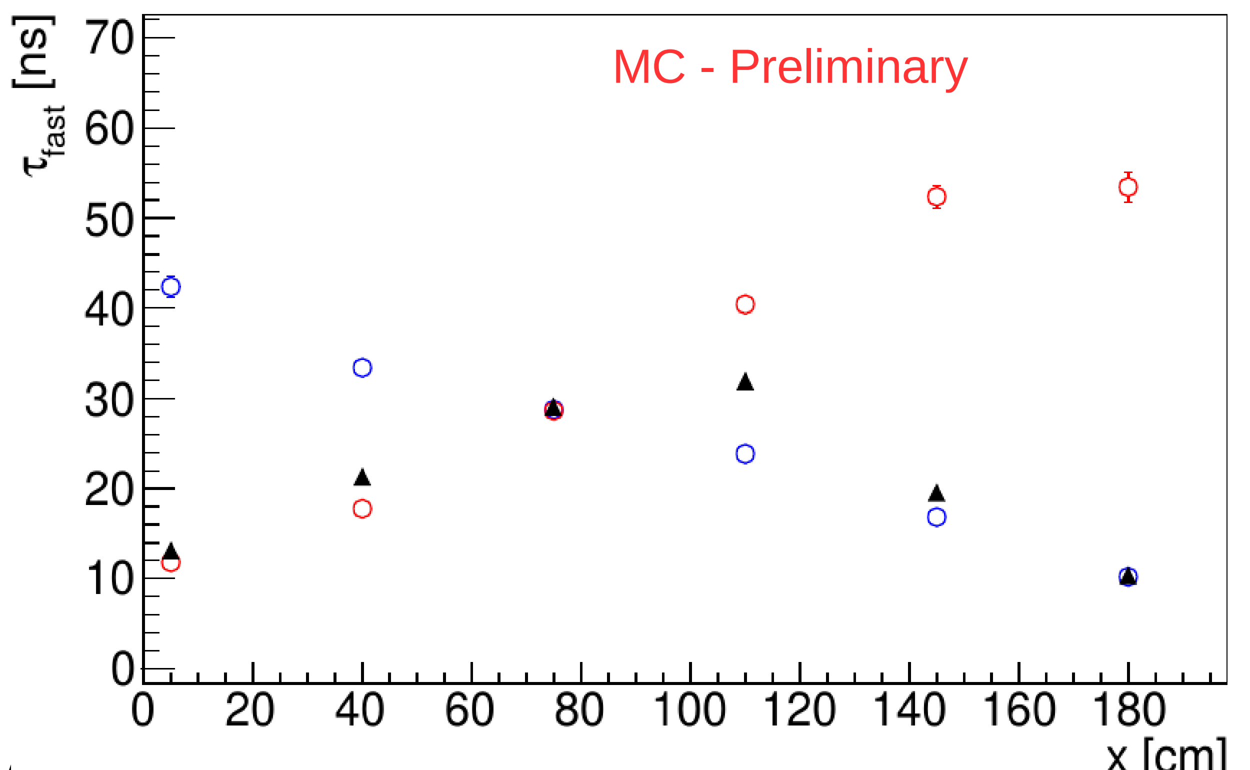
+

Propagation:
Direct transportation + Rayleight Scattering



Fast component life time changes as a function of distance.

Will affect triggers focusing on the fast component



Position Resolution

- The high density of PMTs in SBND allows reasonable position reconstruction with light only.
- It cannot be as good as the charge information, but it is fast. And it allows tagging events.

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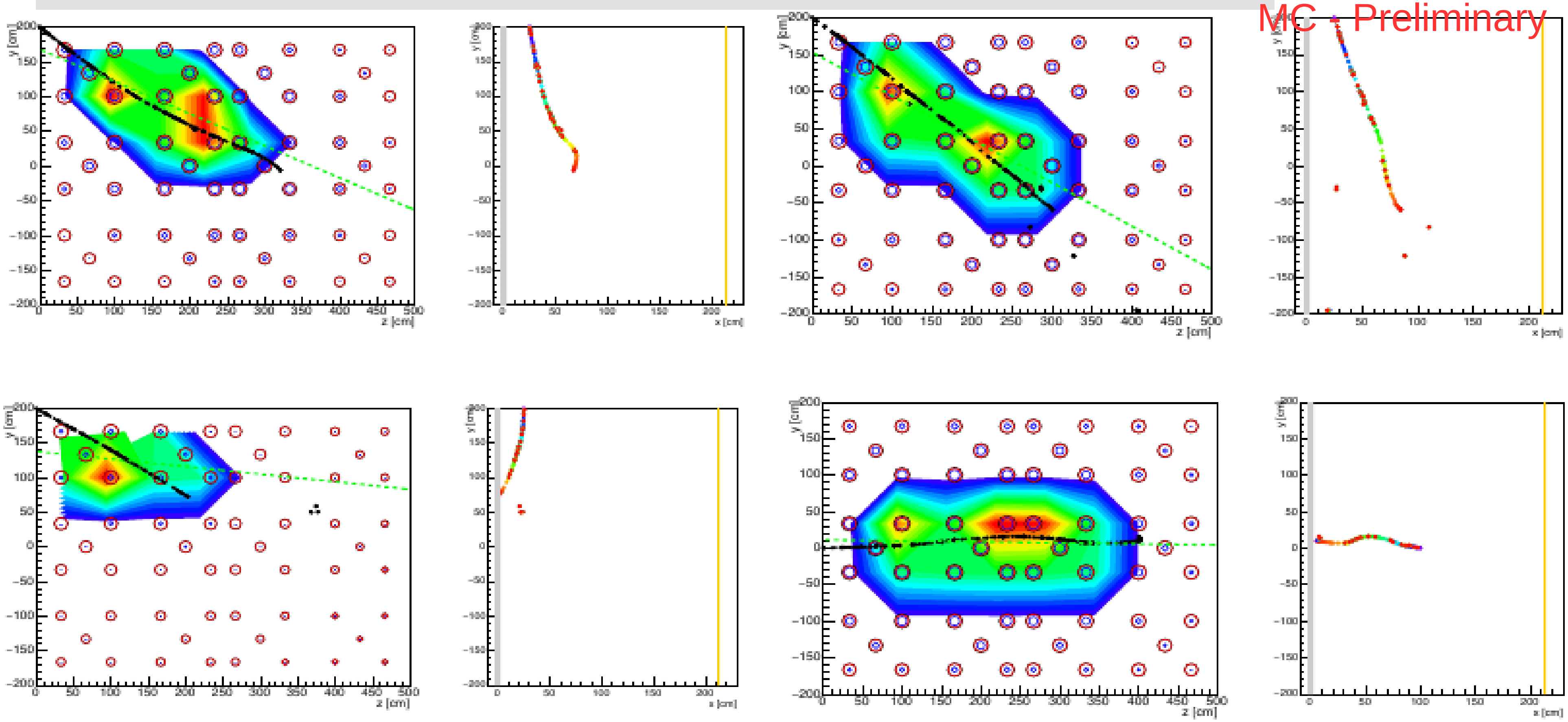
Y-Z Positional Resolution

"Tracking" the events with light: "cosmics"

1GeV muons
VUV + Visible components
Contours = hottest PMTs with the 30% of the total detected light

"Realistic" PMT system → 60 PMTs/TPC

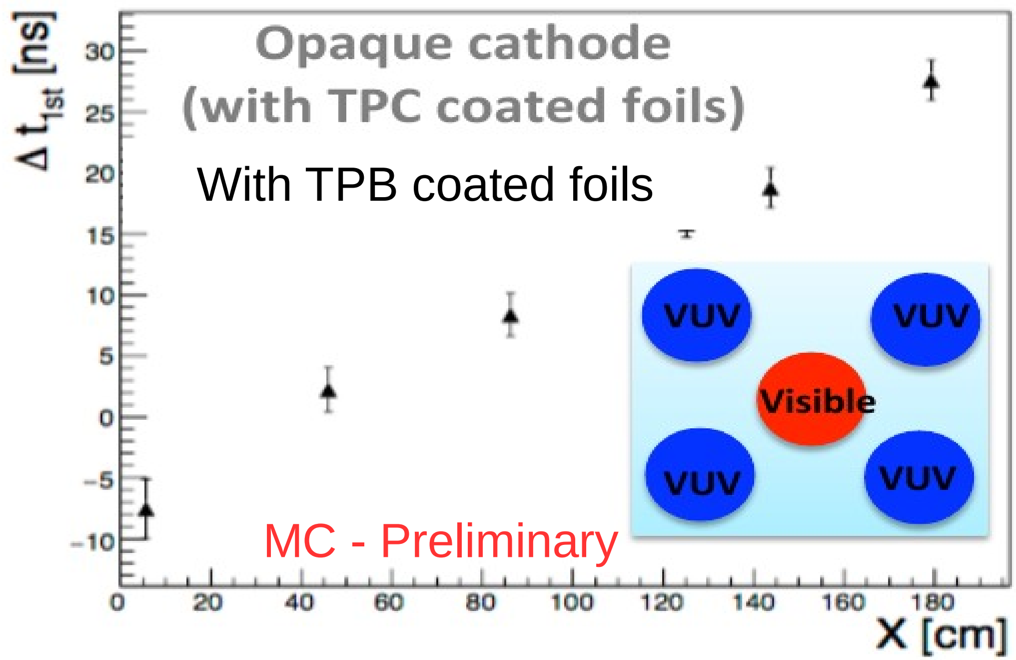


Very simple assumption → Big room for improvements!

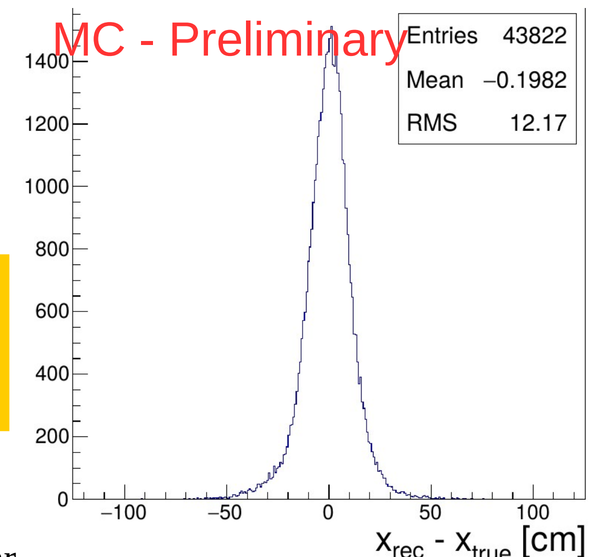
D. Garcia-Gamez

X-drift position resolution

- If able to differentiate VUV from Visible (re-emitted) possible to get position in x on the fly.
- Additional information, crucial for disentangling multiple events in the same frame.
- Could decide to readout just parts of detector.



New idea for LArTPCs!



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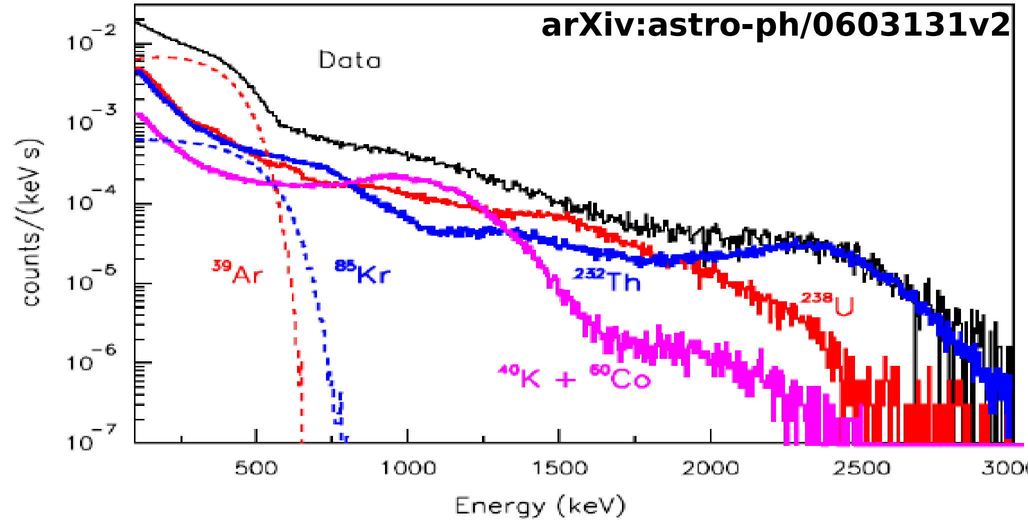
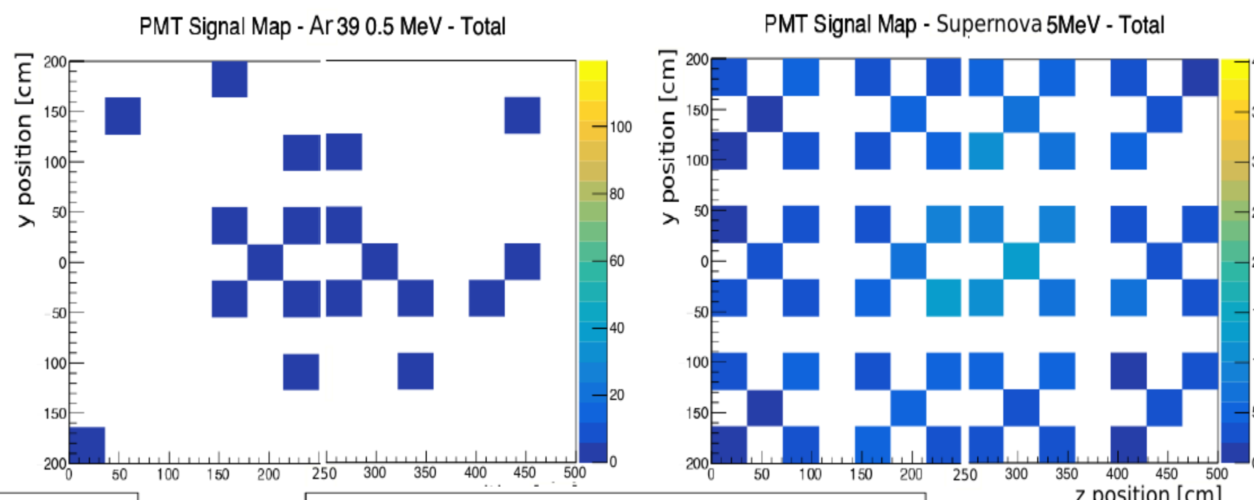
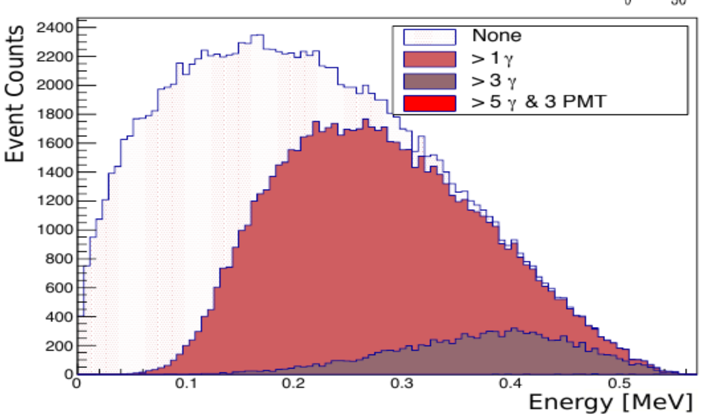
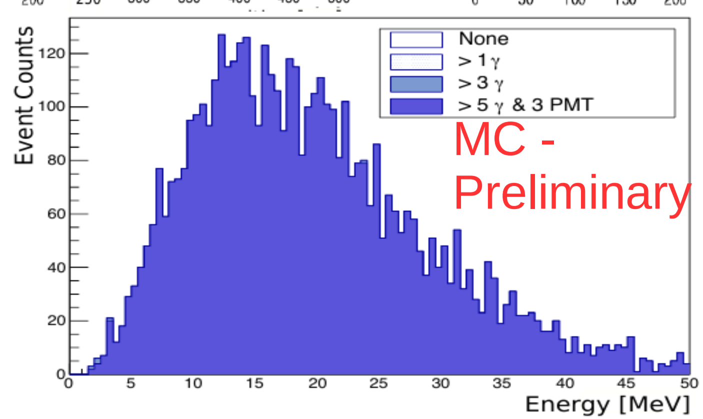
^{39}Ar – how big of a problem is it really?

- ^{39}Ar is a beta- emitter with an end point at 565 keV. average energy of electron ~ 236 keV
- Measured rate is 1Bq/kg.
- Could it overwhelm the trigger?





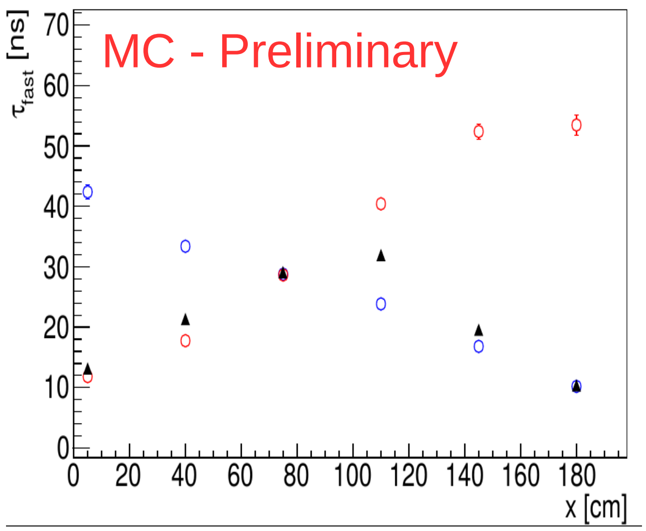


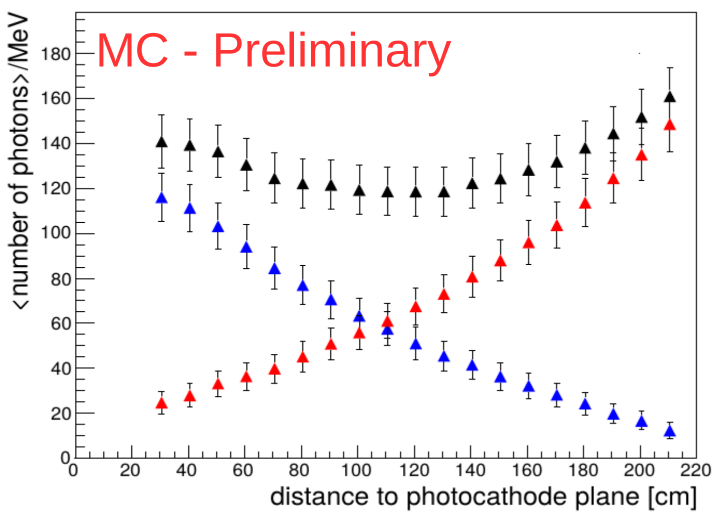


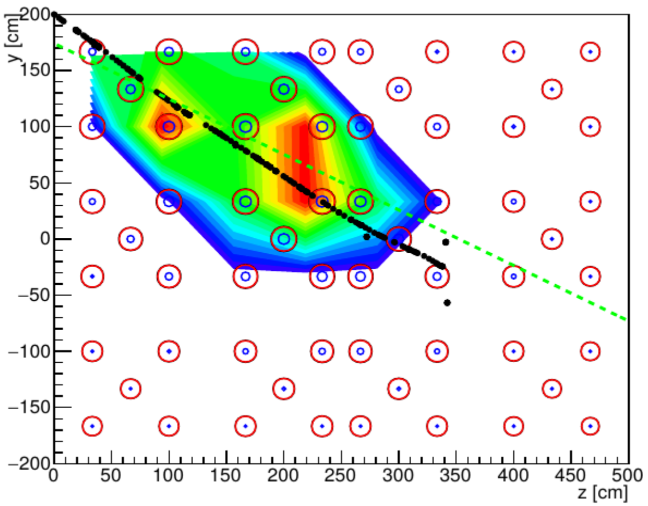
C. Hill, Manchester

What simulations can tell us

- Simulations show that a High LY light detection system can help determine timing, calorimetry and position resolution.
- Adding WLS-covered reflector foils improves the overall performance of the system.



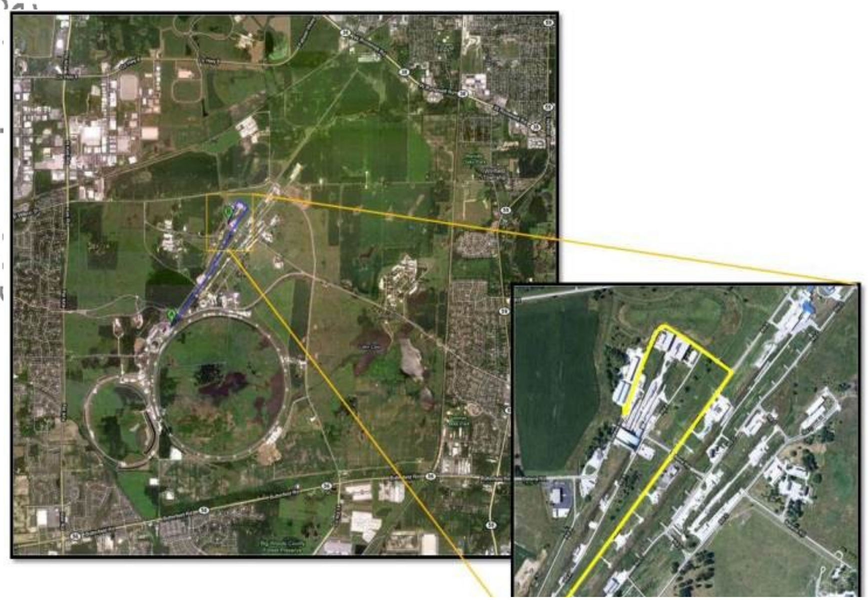




From “Practice” to Reality

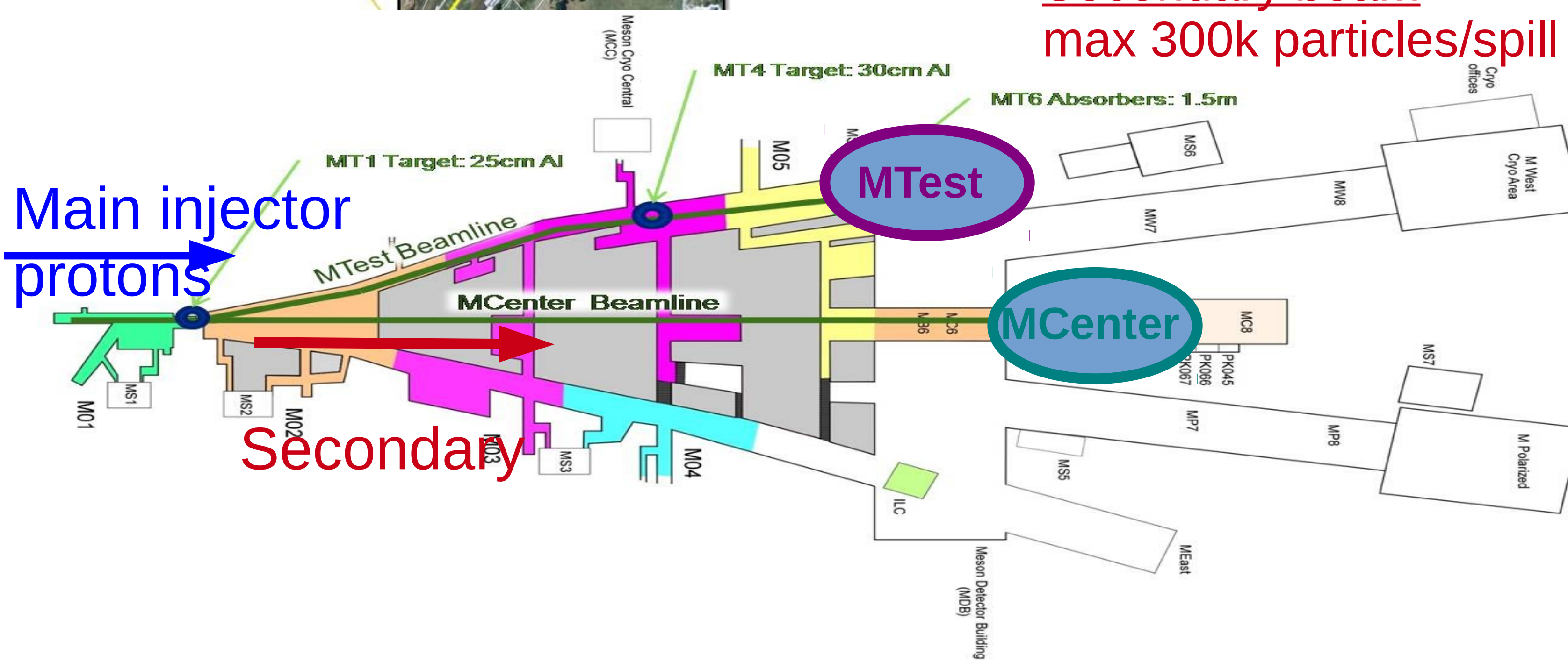
Or:
Back From the Future

Fermilab Testbeam Facility

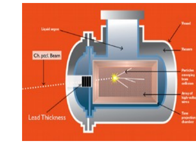


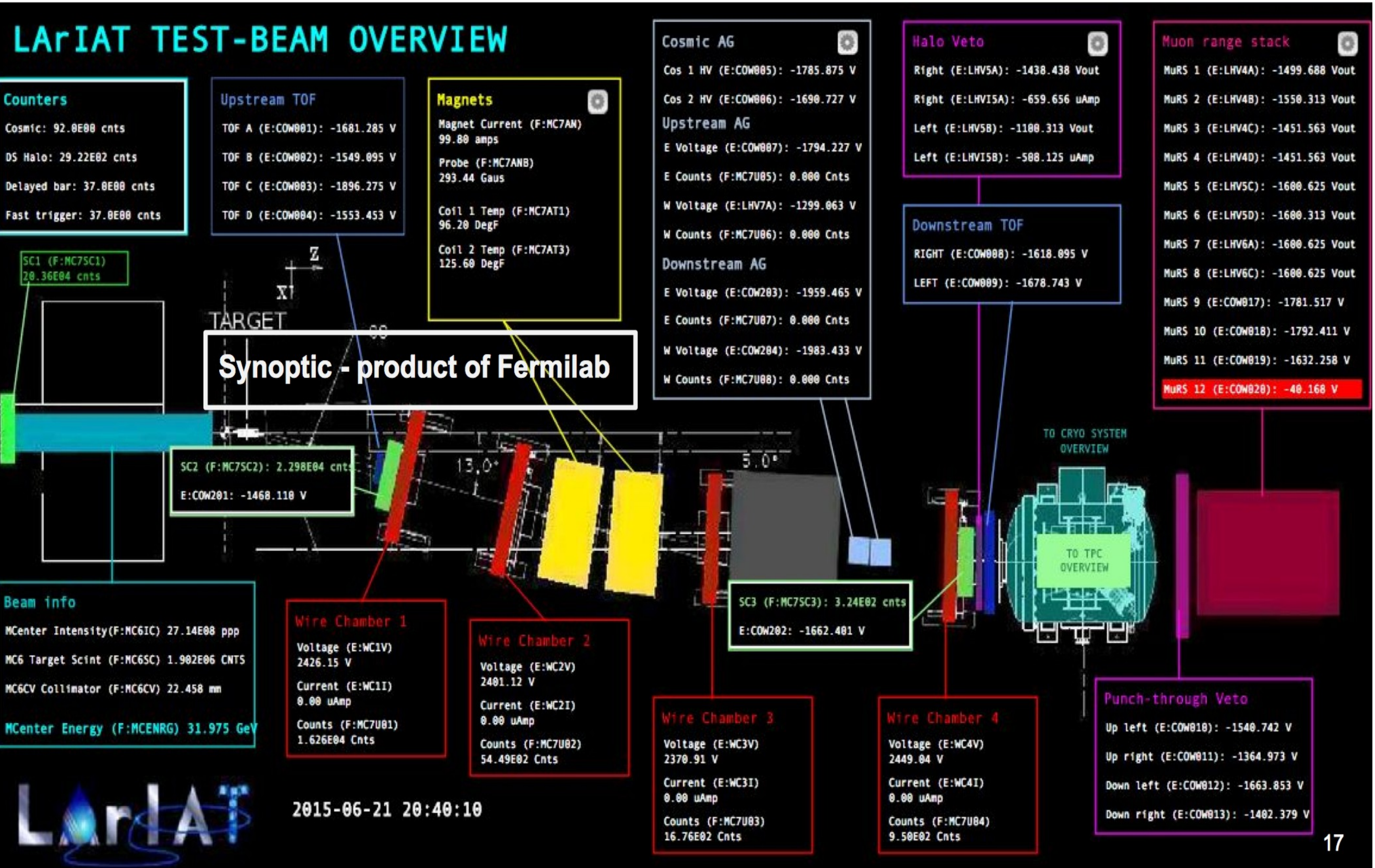
The LArIAT testbeam experiment is running in MCenter – allows long term occupation (as opposed to MTest).

Main Injector
One 4s long spill per minute
Secondary beam
max 300k particles/spill

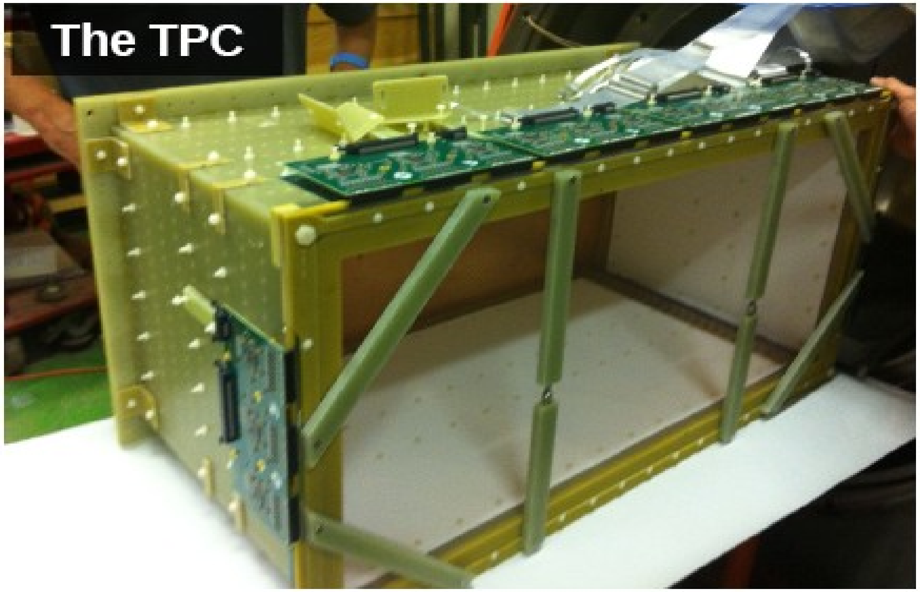


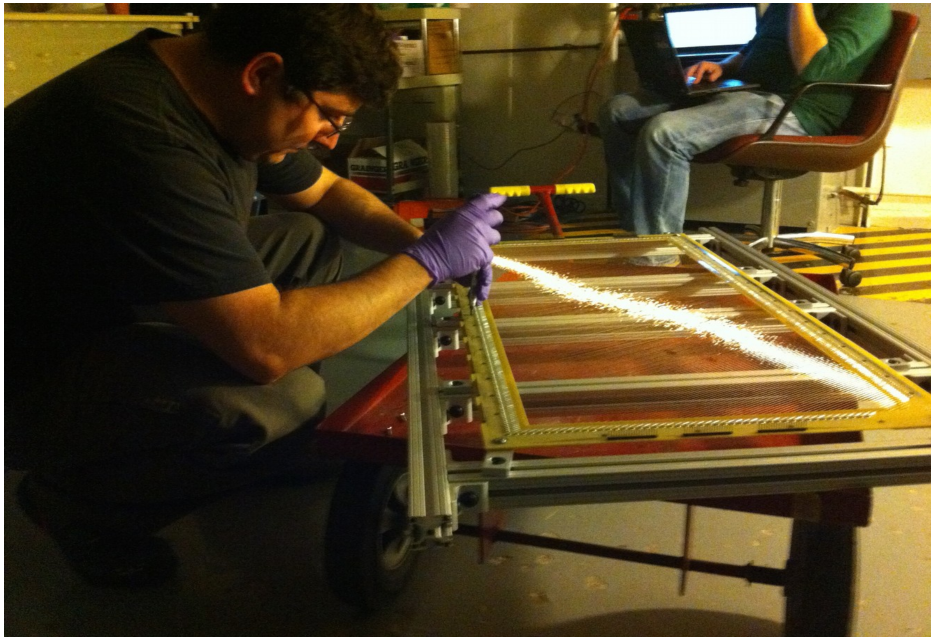
LArIAT Beamline

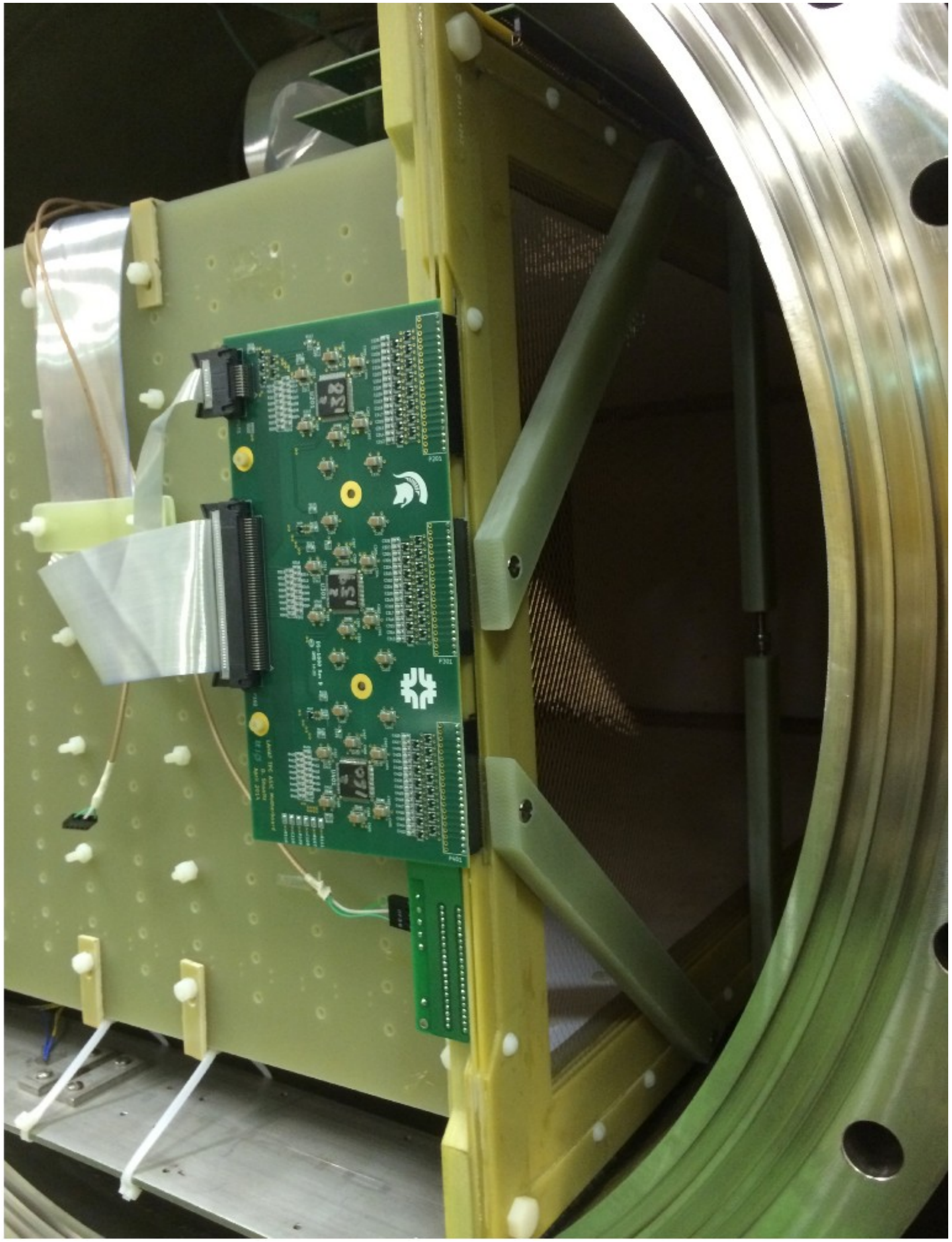




Time Projection Chamber

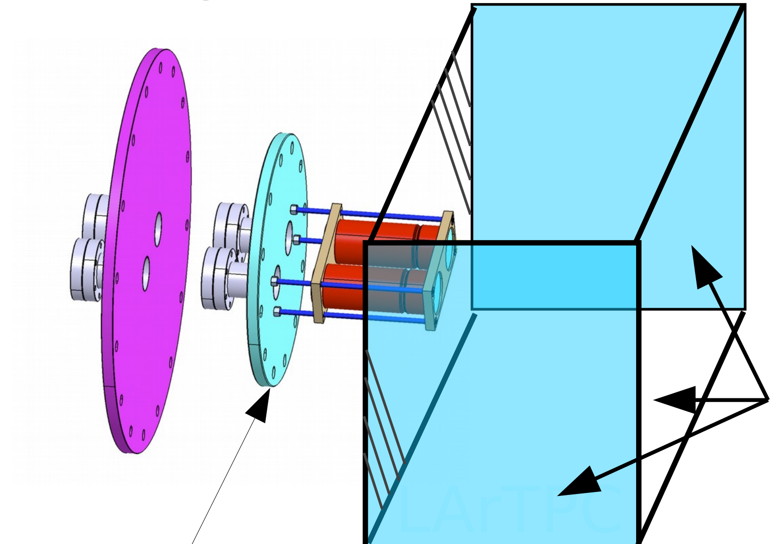






LArIAT Light Readout

- LArIAT is an excellent test-bed for new ideas, like WLS – covered foils. .



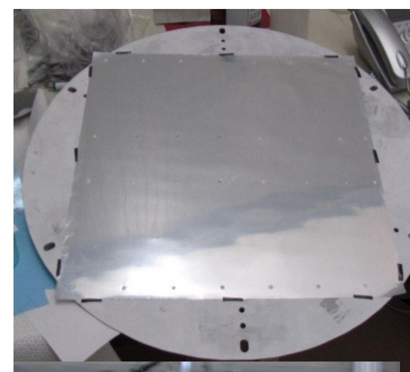
Two cryogenic PMTS
- one 3" high QE (30%)
- one 2" standard QE (20%)
+3 SiPMs

Wavelength shifting reflector foil

Hamamatsu R11065

ETL D757KFL (2")

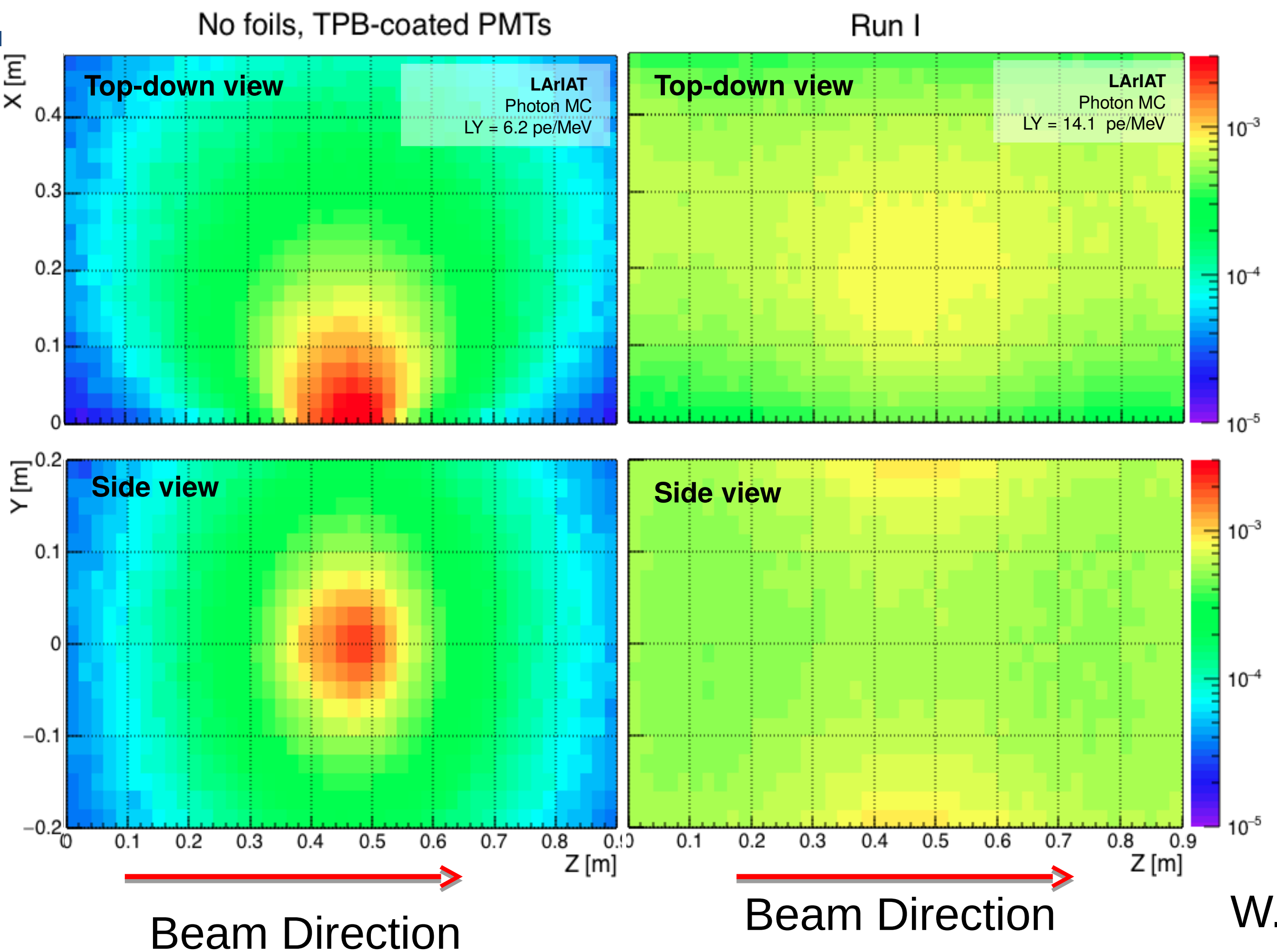
- *First test of TPB coated reflector foils in a running TPC (at beam neutrino energies).*



Applying TPB to the reflective foil that will line the inside of the LArIAT TPC

Using the same simulation tools as SBND

- In fact, the tools were developed for LArIAT first, and adapted for SBND.



Excellent uniformity in the detector.

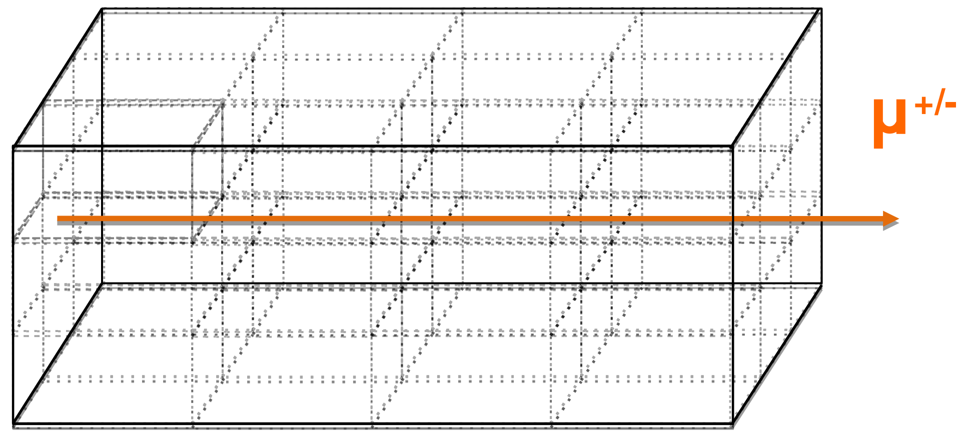
Two full runs completed (Not all PMTs were always on).

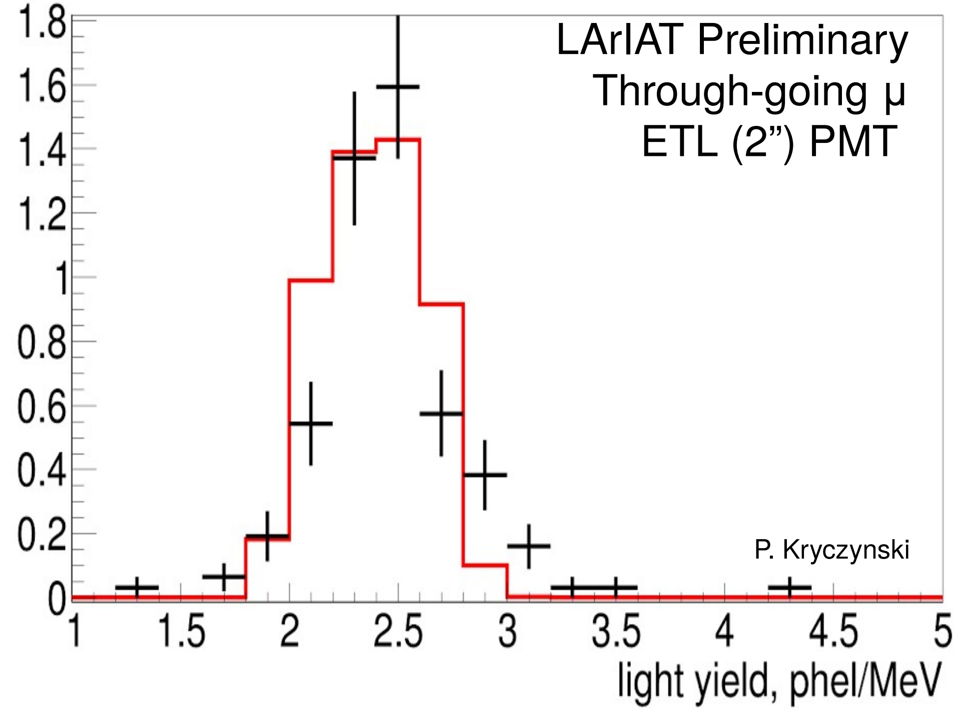
Data analysis in progress.

W. Foreman

Validating the Simulation

- Simplest topology – easy to understand.
- Great to test predictions vs reality.
- Data agrees with MC predictions (in progress).

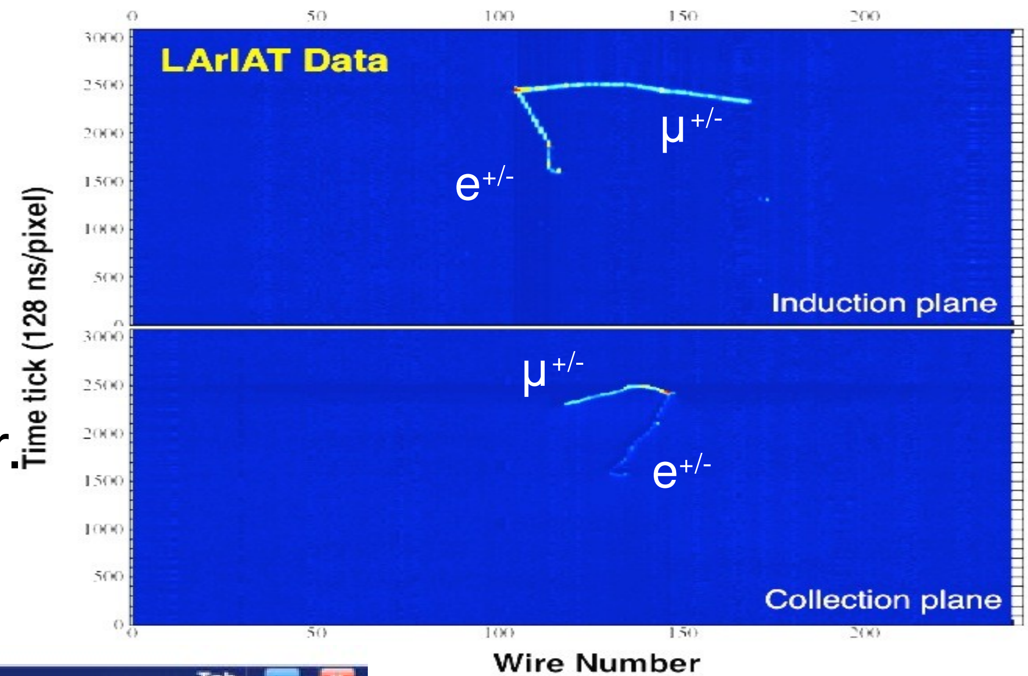


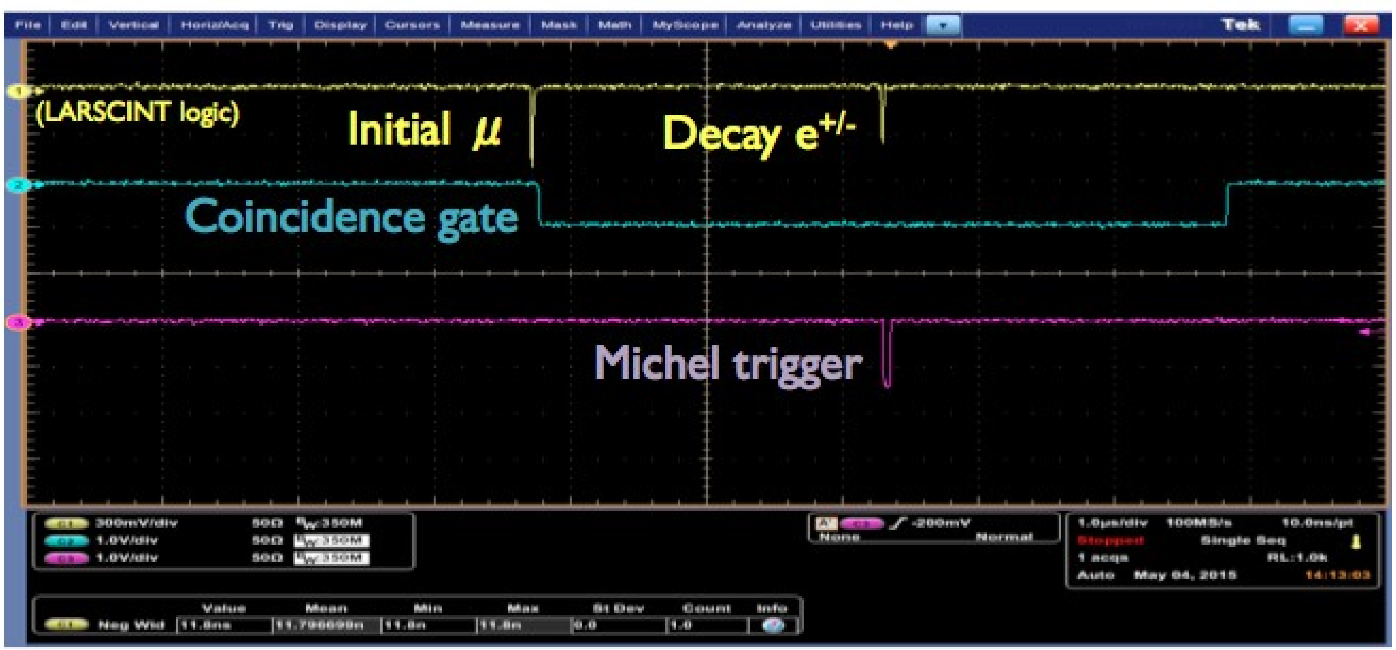


Michel Electrons

$\mu^{+/-}$ (at rest) $\rightarrow$ $e^{+/-} + \nu_\mu + \bar{\nu}_e$

- Well known energy spectrum.
- Great to perform calibrations.
- Need scintillation light to trigger.





Real-time triggering on Michel e's from stopping cosmic μ's using **light signals**

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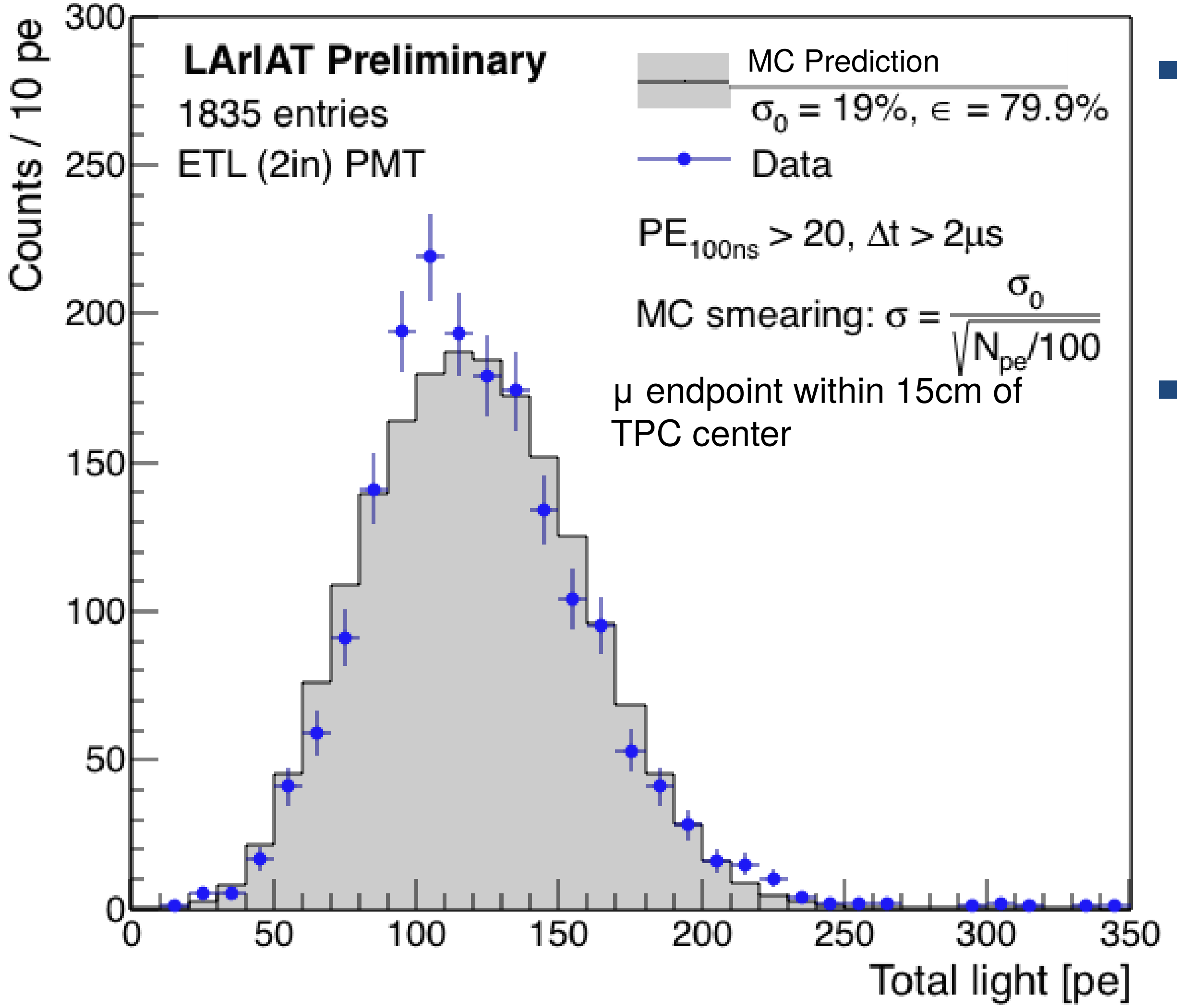
Energy Calibration with Michels



- Michel-candidate signals integrated to get PE spectrum
- Data in approximate agreement with preliminary MC
  - Gives confidence in MC-predicted LY: 2.4 pe/MeV for 2” ETL PMT (Run I)

End goal: combine charge + light to get full energy reconstruction.

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Physics with Michels

μ^- have a predicted 75% capture rate on argon nuclei (no Michel electron present).

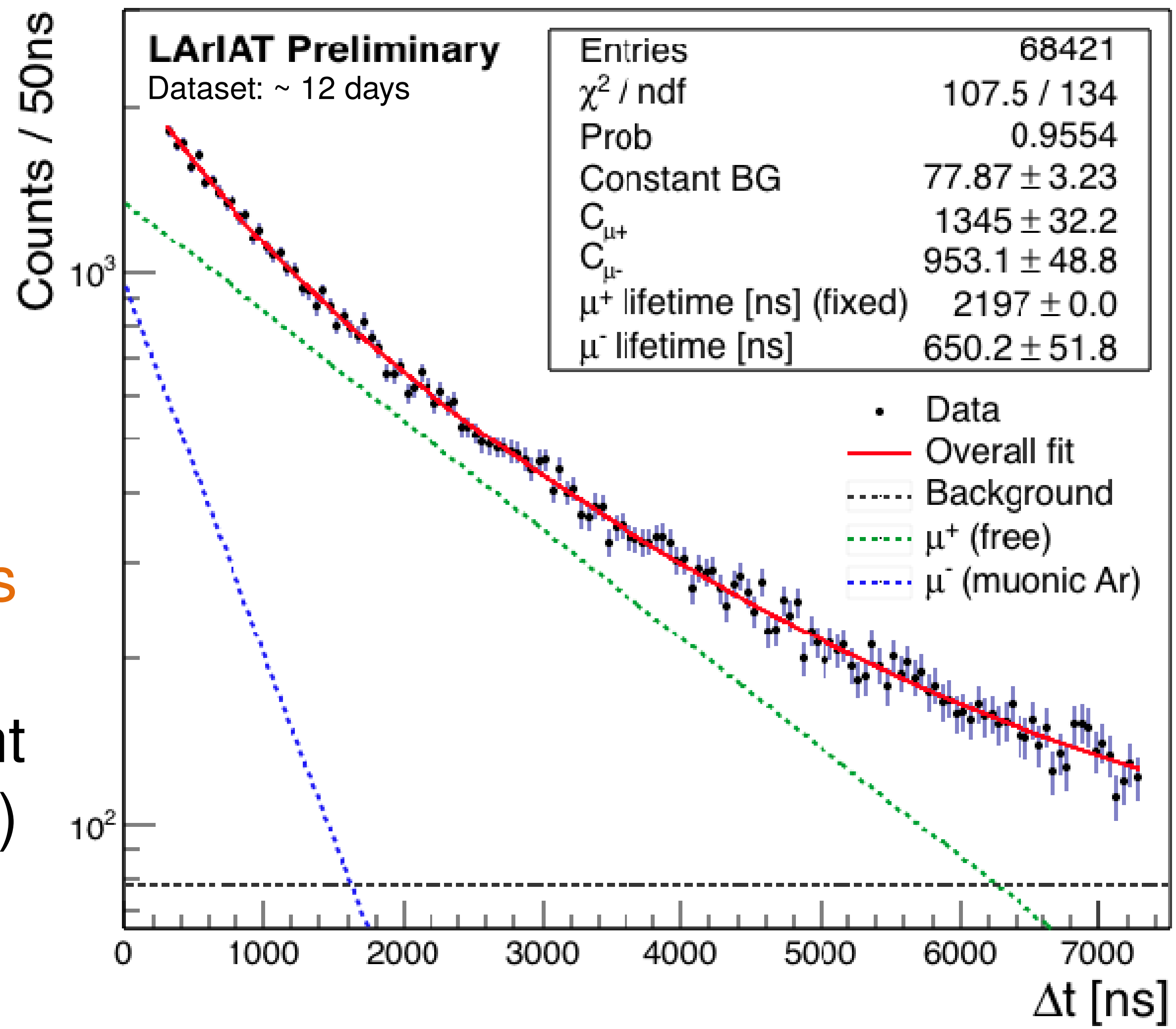
Neutrino-anti-neutrino discrimination possible?

$$\tau_{\mu-} = \left(\frac{1}{\tau_c} + \frac{Q}{\tau_{free}} \right)^{-1}$$

$\tau_{\mu-}$: 650 ± 52 ns (from fit result, preliminary)

τ_c: 918 ± 109 ns

Early results agree w/ recent measurement[1] (854 ± 13 ns) and theory prediction[2] (851ns)



LIDINE 2015 Proceedings, JINST 11 C01037

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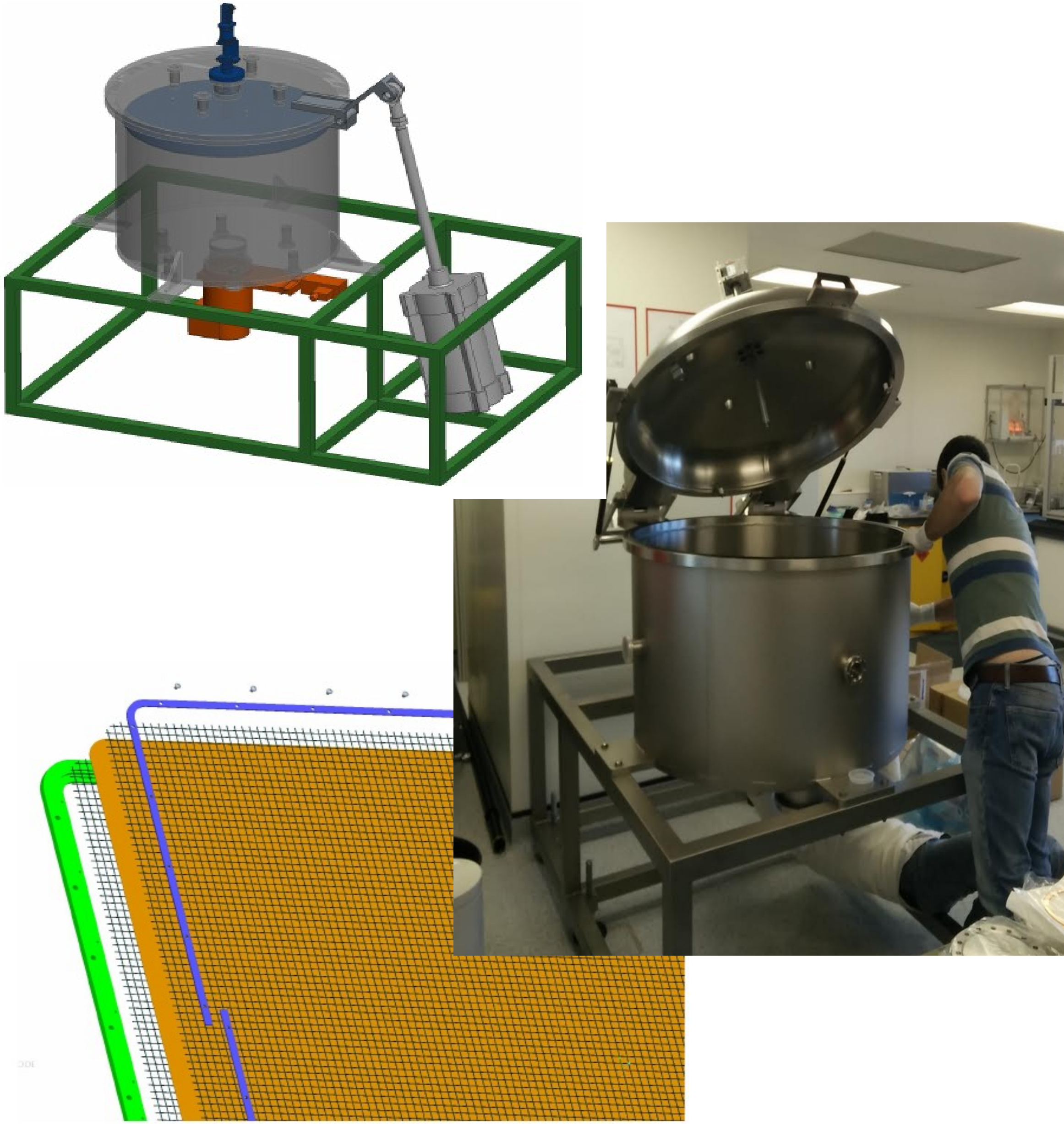
[1](Klinskih et al., 2008)
[2](Suzuki & Measday, 1987)

(Near) Future

- LArIAT analyses on using light and combined light + charge for calorimetry, particle ID are finishing.
- The infrastructure needed to manufacture the reflective foils for SBND is practically ready.
- Beginning to apply the simulation tools to understand effects on DUNE physics (low energy events, SN neutrinos)

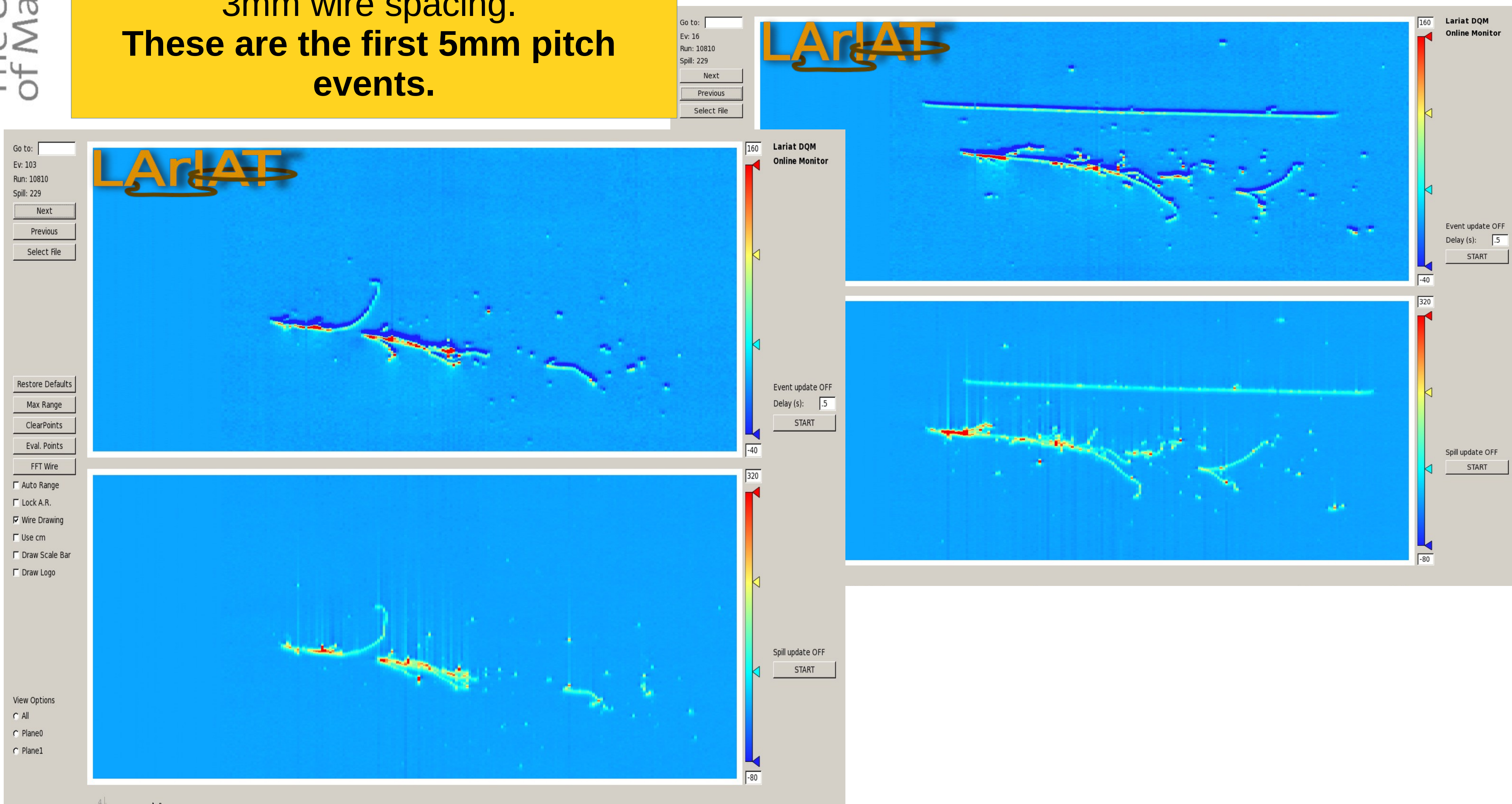


Test run with mesh cathode

Prototype of SBND mesh cathode manufactured in Manchester was installed in LArIAT beginning of march. Will run with and without foils (change over in a few weeks).

Fresh off the press!

LArIAT RUN III began in March.
It is dedicated to testing
the differences between 5mm and
3mm wire spacing.
These are the first 5mm pitch events.



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Summary

- Scintillation light will be a powerful tool in enhancing the physics goals of liquid argon neutrino detectors, from SBND to DUNE.
- There is still some uncharted territory and room for new ideas and improvements.
- Using existing, or soon to be built detectors, like LArIAT and SBND is a great way to test these new ideas and solutions.
- Stay tuned for results from LArIAT run III and previous data.

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Thank You for your Attention