Water-Soluble Scintillation Detector

- Characteristics of WbLS
- Proton-decay and other physics
- Other applications

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BROOKHAVEN NATIONAL LABORATORY

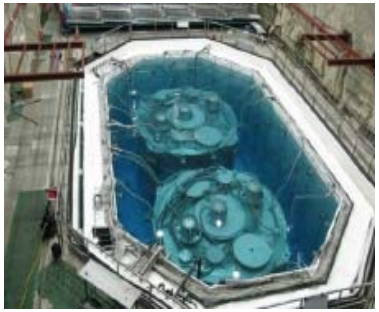
a passion for discovery

Project-X workshop

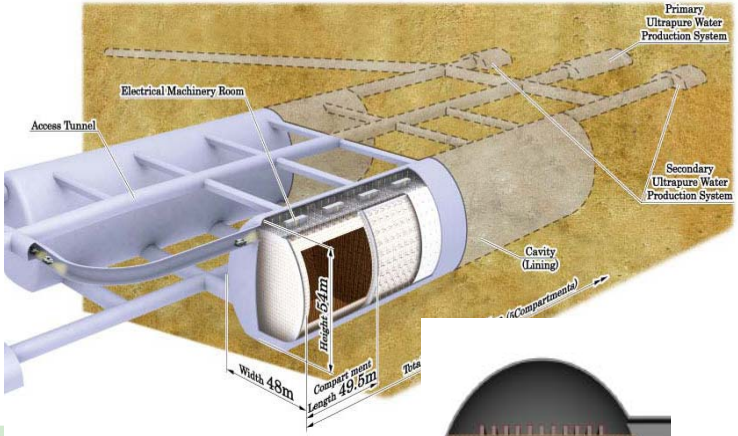
Office of Science
U.S. DEPARTMENT OF ENERGY

Research sponsored by the U.S. Department of Energy, Office of Nuclear Physics and Office of High Energy Physics, under contract with Brookhaven National Laboratory – Brookhaven Science Associates.

$Sin^2 2\vartheta_{13}$~0.1 opens to future large detector



Hyper-Kamiokande

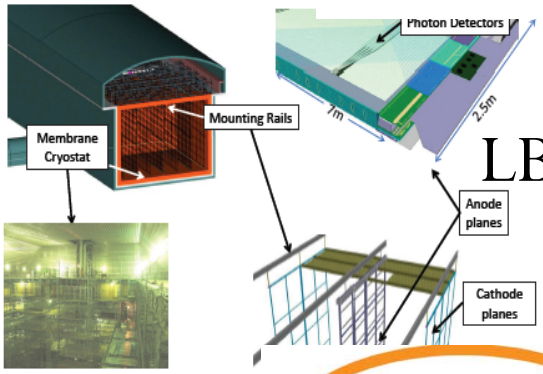


Accelerator-based (with synergy of beam physics):

- ν oscillation
  - **long baseline**
  - Atmospheric ν
  - Solar ν

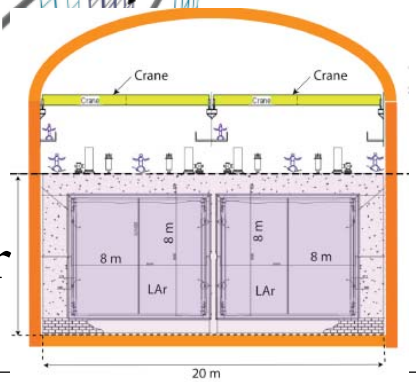
Non-accelerator-based:

- ν oscillation
- Astrophysics
- Geophysics
- Nucleon decay
- etc.



LBNE

LENA



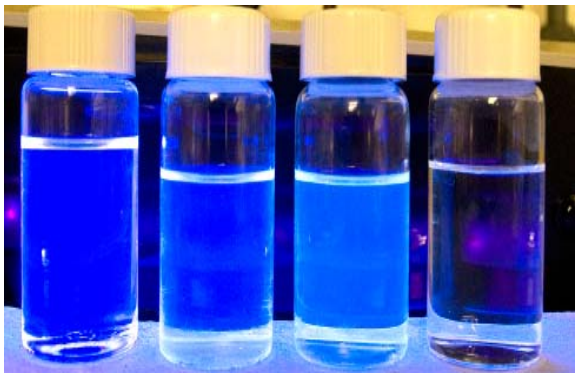
Glacier

Motivations of Generic R&D:
Water-based Liquid Scintillator (WbLS)

- *A multiple physics detection technology; particularly below Cerenkov threshold*
- *A diversity of physics applications including Veto system*
- *Cost-effective by :*
  - *combining Cerenkov & scintillation to reduce the size*
  - *cutting down the cost of liquid scintillator*
  - *less ES&H concerns and reduce waste management*

a cost-effective, large detector with Cerenkov & Scintillation functions

What is water-based LS?



WbLS is not a mix of water and fluor or shifter.

A net light gain of 4.4 ±0.5

X. Dai et al., NIM-A 589 (2008) 290.

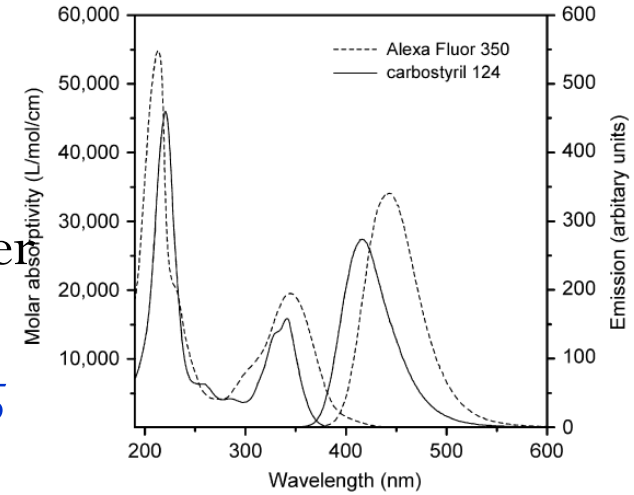
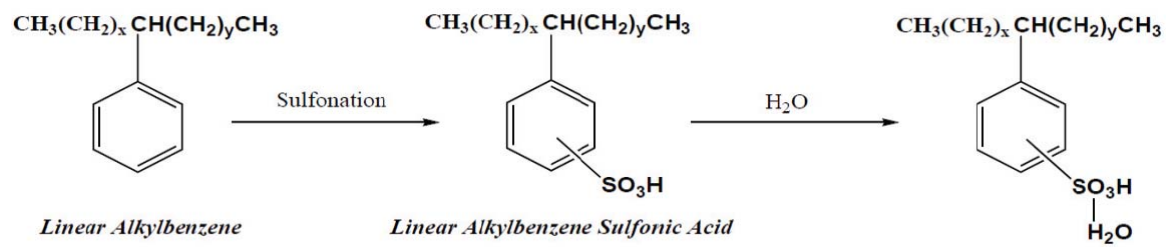


Fig. 2. The UV/VIS absorption (left) and fluorescence emission spectra (right) for carbostyril 124 and Alexa Fluor 350.

Previous WbLS trials are either gel-like or not stable over time.



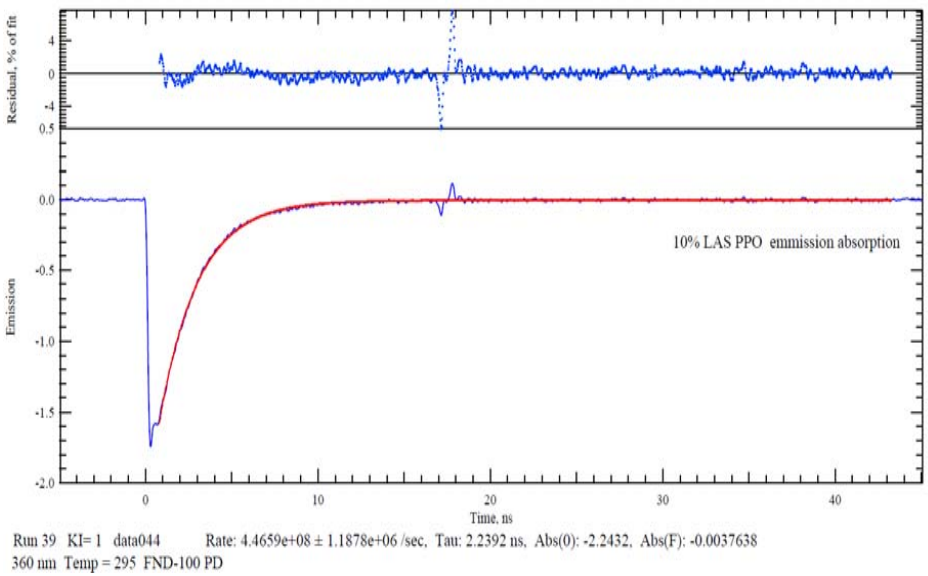
A scintillation water serves as energy spectrometer that probes physics below Cerenkov threshold.

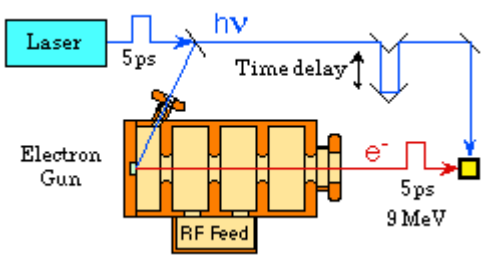
bridged by non-ionic syurfactant, i.e. LAB derivatives, sulfonate, sulfonic amine, etc.

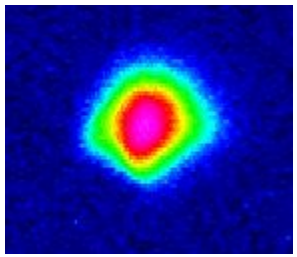
- *Timing structure (10-MeV electron-beam by LEAF; time-resolved fluorescence)*
- *Mean attenuation length (UV normalized to Super-K absorption curve; followed by simulation) and Emission Spectra (fluorescence)*
- *Light-yield (Cs-137) and (1-GeV p-beam)*

WbLS Characterizations

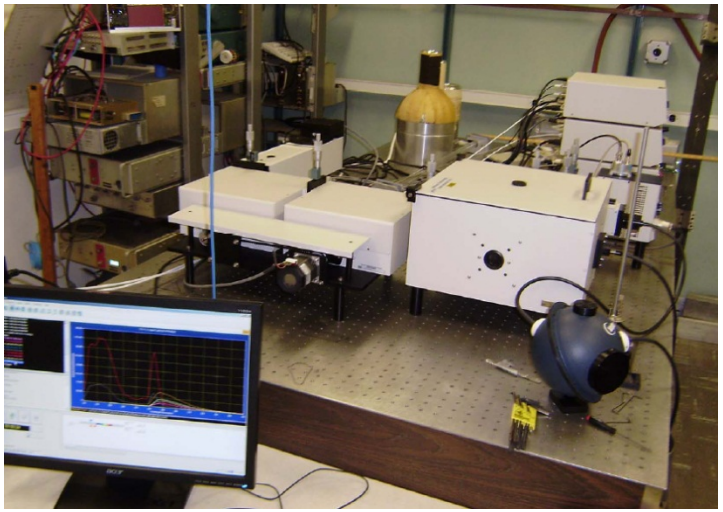
$\tau_{WbLS(PPO)}$ between 2 – 4 ns



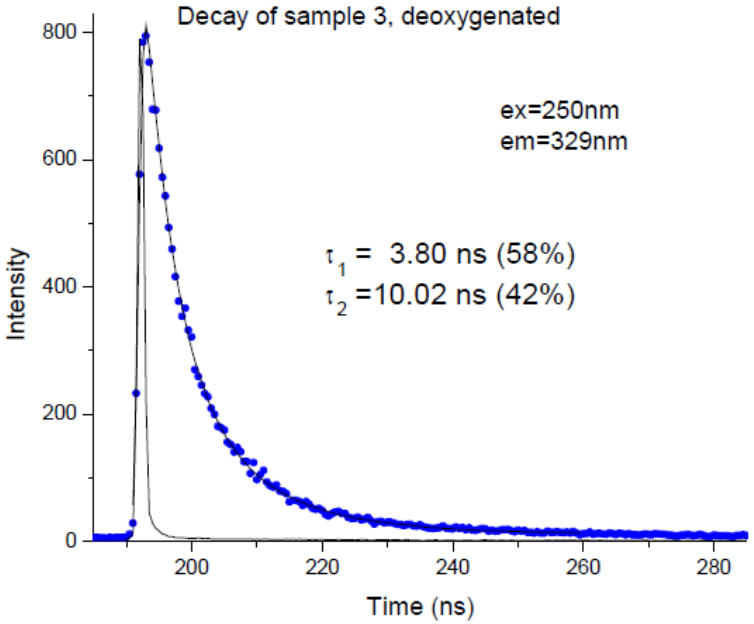




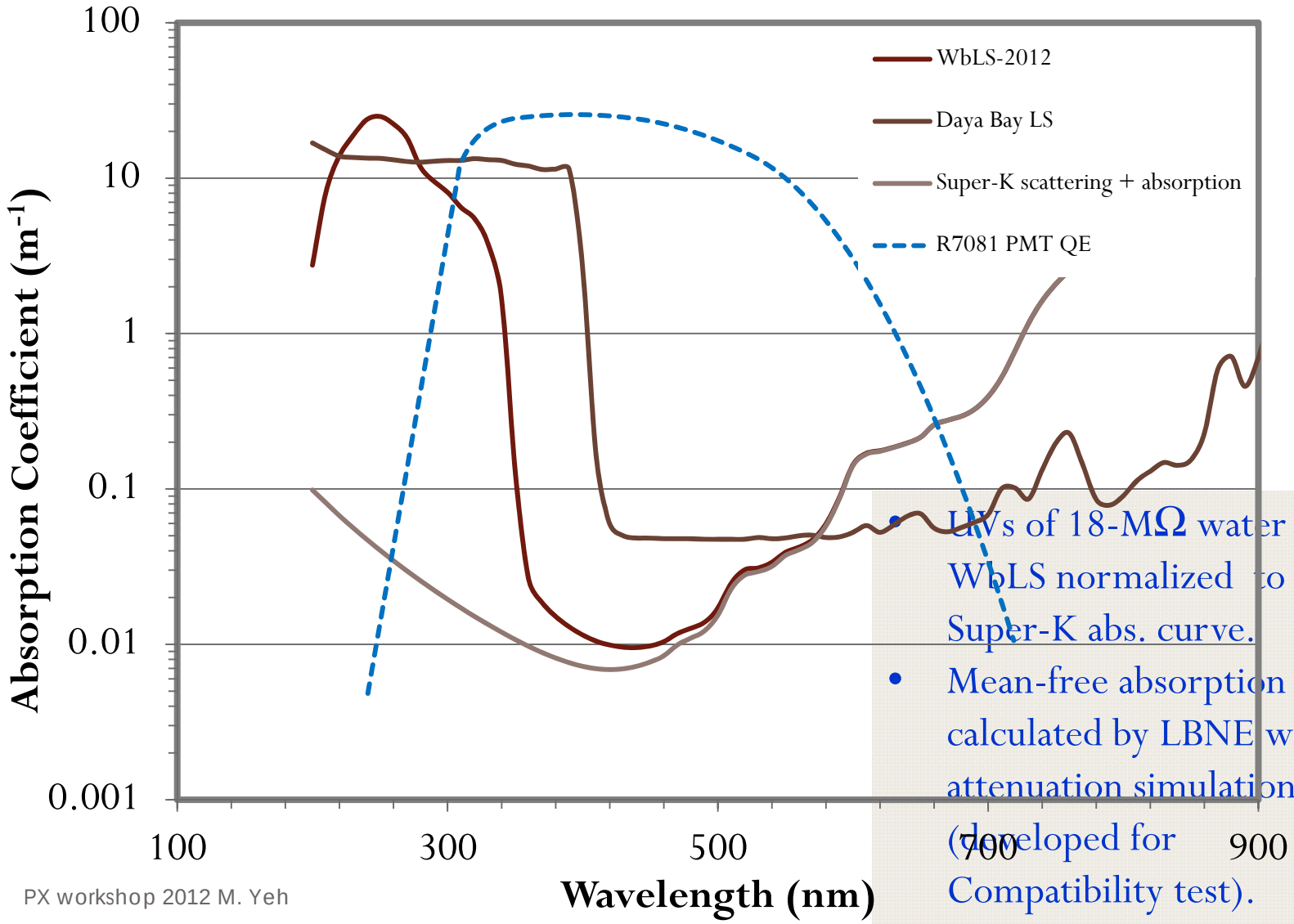
10-MeV e⁻ beam at LEAF



Time-resolved fluorescence system

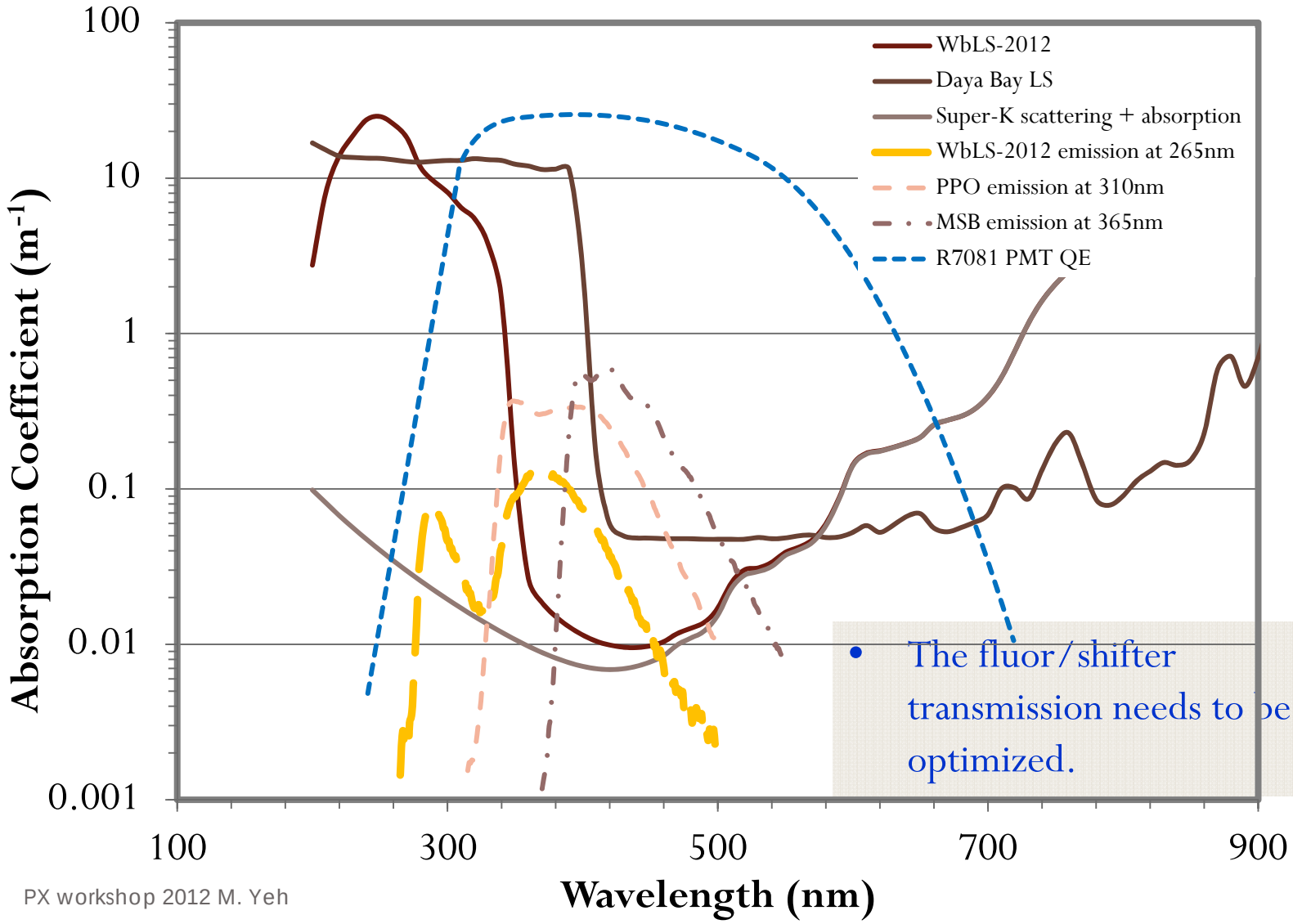


Mean-Free Attenuation Length close to pure water after 400nm



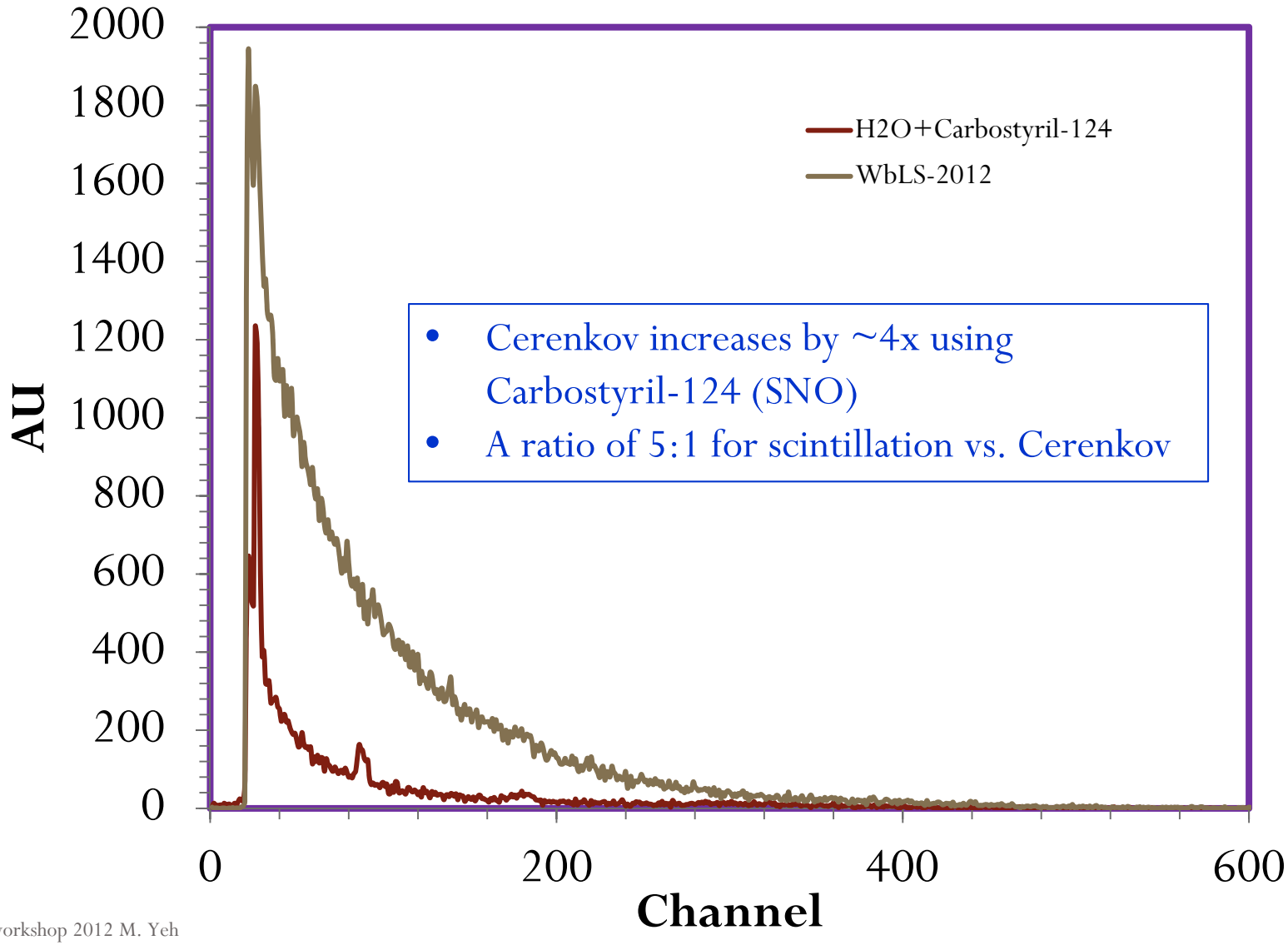
- UVs of 18-MΩ water and WbLS normalized to Super-K abs. curve.
- Mean-free absorption length calculated by LBNE water attenuation simulation (developed for Compatibility test).
- *Need large-scale verification*

Emission at the PMT sensible region is almost clean



- The fluor/shifter transmission needs to be optimized.

WbLS Scintillation vs. Cerenkov (Cs-137)



- Cerenkov increases by ~4x using Carbostyril-124 (SNO)
- A ratio of 5:1 for scintillation vs. Cerenkov

WbLS at NSRL high-energy particle-beam in 2011

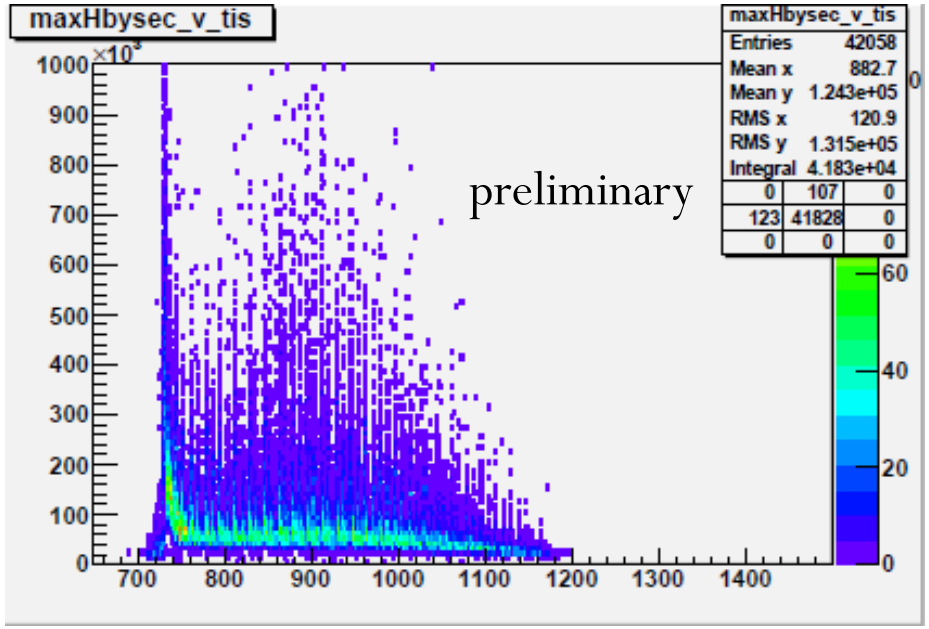


Figure 2: The instantaneous intensity in Hz as a function of time in spill in ms.

- 1-GeV proton beam
- Daya Bay sees ~32:1 of Scintillation vs. Cerenkov in pure LS.
- WbLS obtains ~1/3 of LS light (10:1 compared to water-filled)
- Reinvestigate with 100 – 300 MeV p-beam this fall (LDRD funded, Hide et. al.).

A multi-physics detector; first look at nucleon decay: SUSY-favored PDK^+ Mode

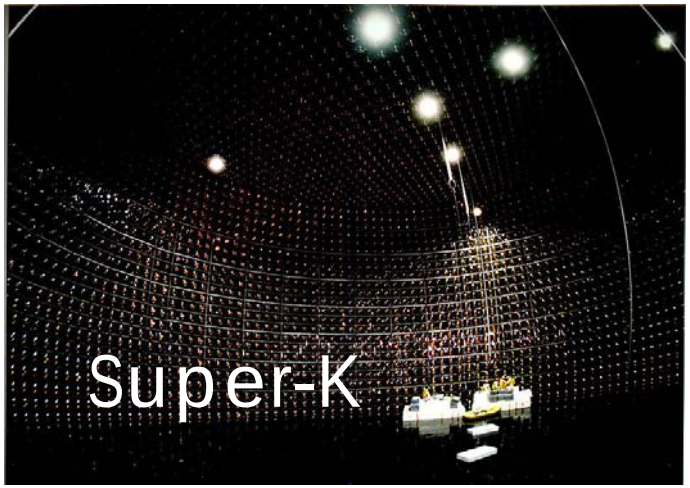
- $p \rightarrow k^+\bar{v}\ (T_{k+} = 105\ MeV, \tau = 12.8ns)$
  - $k^+ \xrightarrow{63.5\%} \mu^+ v\ (T_{\mu^+} = 152\ MeV)$
    - $\mu^+ \rightarrow e^+ vv\ (\tau = 2.2\mu s)$
  - $k^+ \xrightarrow{20.7\%} \pi^+\pi^0\ (T_{\pi^+} = 108\ MeV)$
    - π^0 (E=135 MeV) $\rightarrow 2\gamma$
    - $\pi^+ \rightarrow \mu^+ v\ (T = 4MeV)$
      - $\mu^+ \rightarrow e^+ vv\ (\tau = 2.2\mu s)$

can be explored by Cerenkov or Scintillation via different decay channels

$$\tau(p \rightarrow k^+\bar{v}) > 2.3 \times 10^{33}\ \text{yrs}$$

detection medium with

- *<12ns*
- *long attenuation length for large detector*
- *with Cerenkov or Scintillation capabilities*
- *deep UG*



Cerenkov and Scintillation together can explore all channels

- ***Event Signal-like:***

  Prompt
  - **K^+ scintillation**

  Delay
  - **π^+ and μ^+ scintillation**
  - **π^0 scintillation**
  - **Cerenkov rings from μ^+, π^+, π^0, Michel electron, etc.**

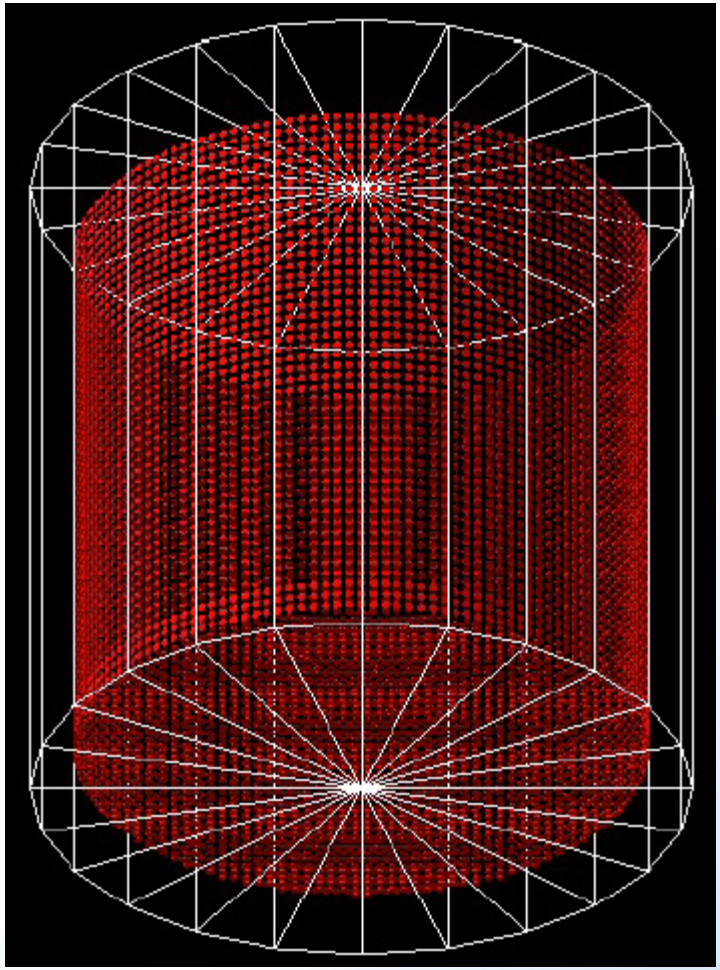
  Event Selection Rules
  - **12.8 ns between prompt and delay.**
  - **No ring in Prompt.**
  - **Energy Cut on prompt event.**
  - **Rings in delay**
  - **Energy cuts in delay with rings**
  - **etc…**

How much Scintillation can be added to keep the Cerenkov valid?

Based on the WCSim software (used for LBNE detector simulation) by C. Zhang

- *Adopt SuperK geometry for comparison*
- *Changed the material to match WbLS*
- *Added the Scintillation process for WbLS*

- 50 kton
- 40% coverage
- 20-inch PMT (~20%)

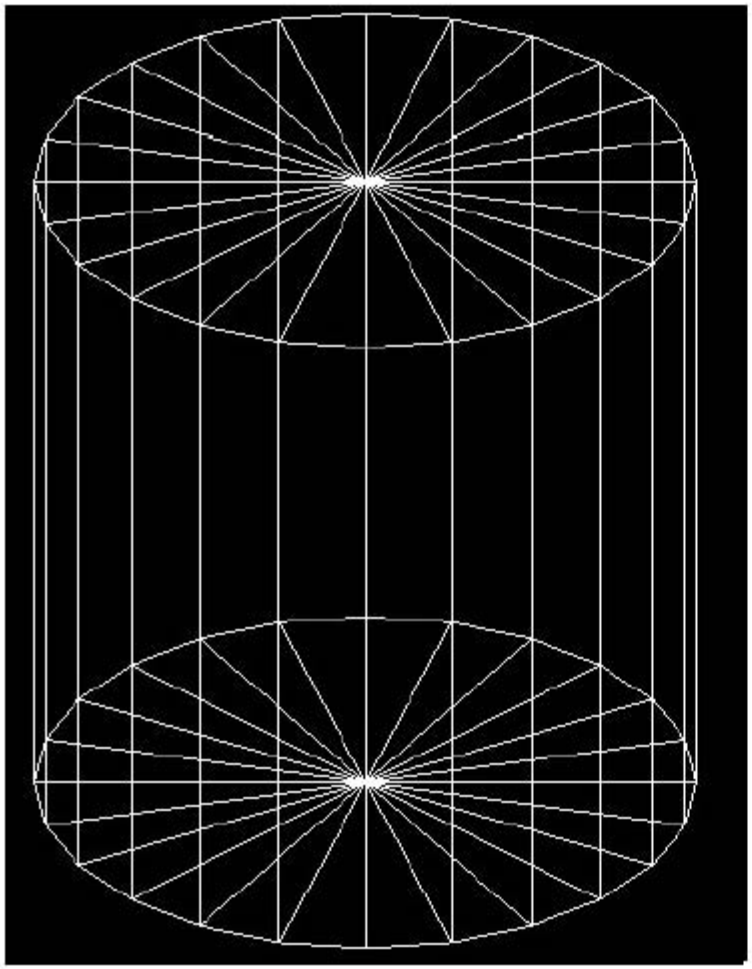


WbLS at Super-K Geometry

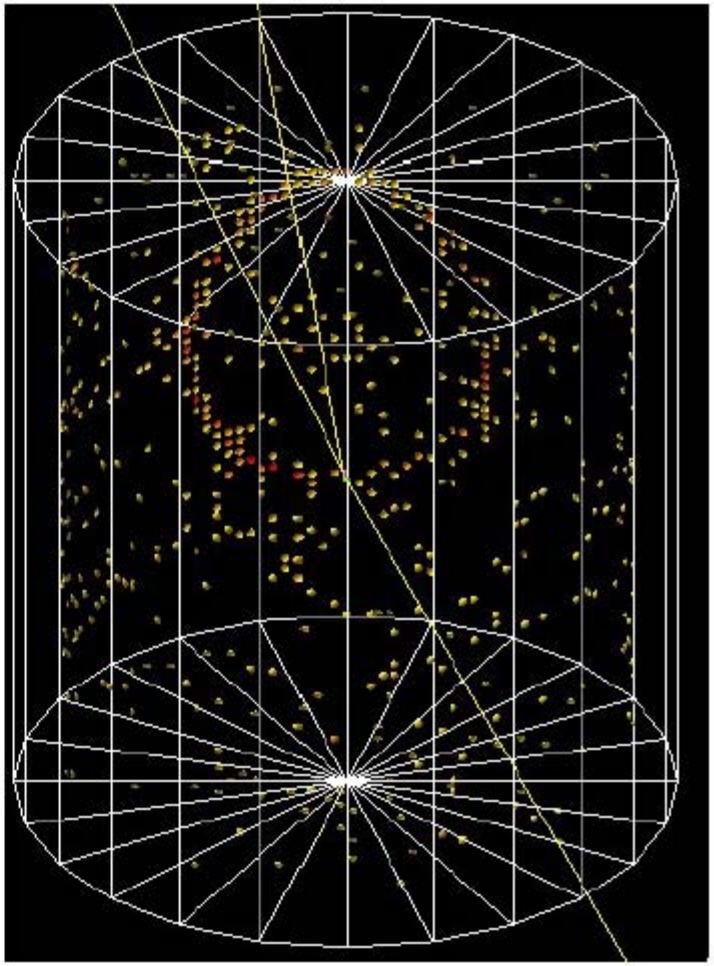
Sanity Check I

- Set Photon Yield to zero (only Cerenkov light)

100 MeV Proton



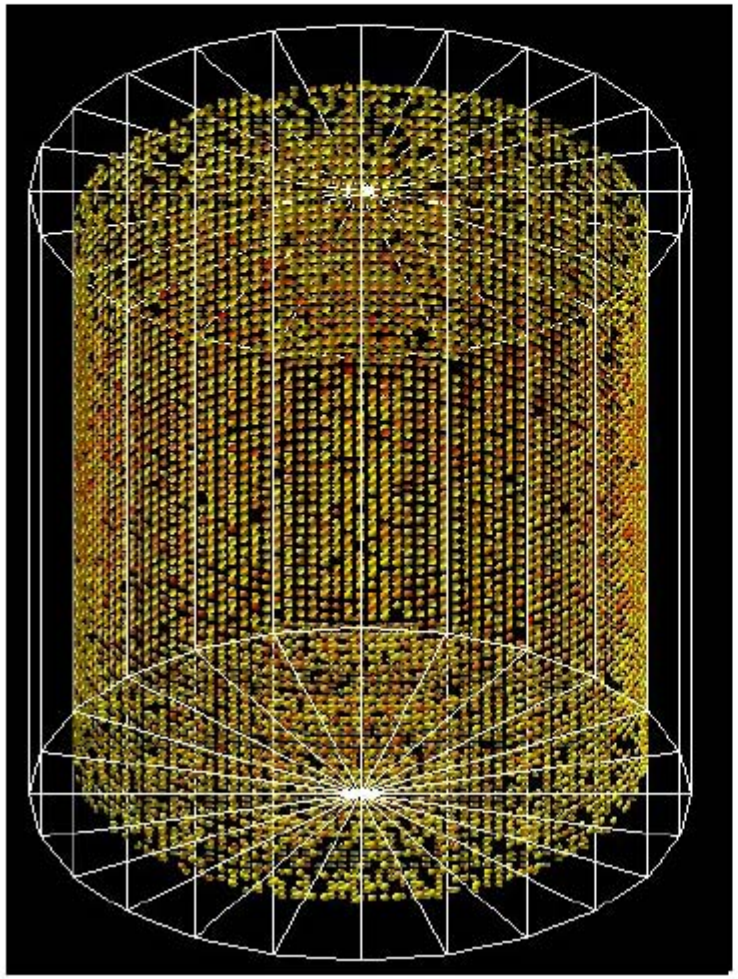
1 GeV Proton



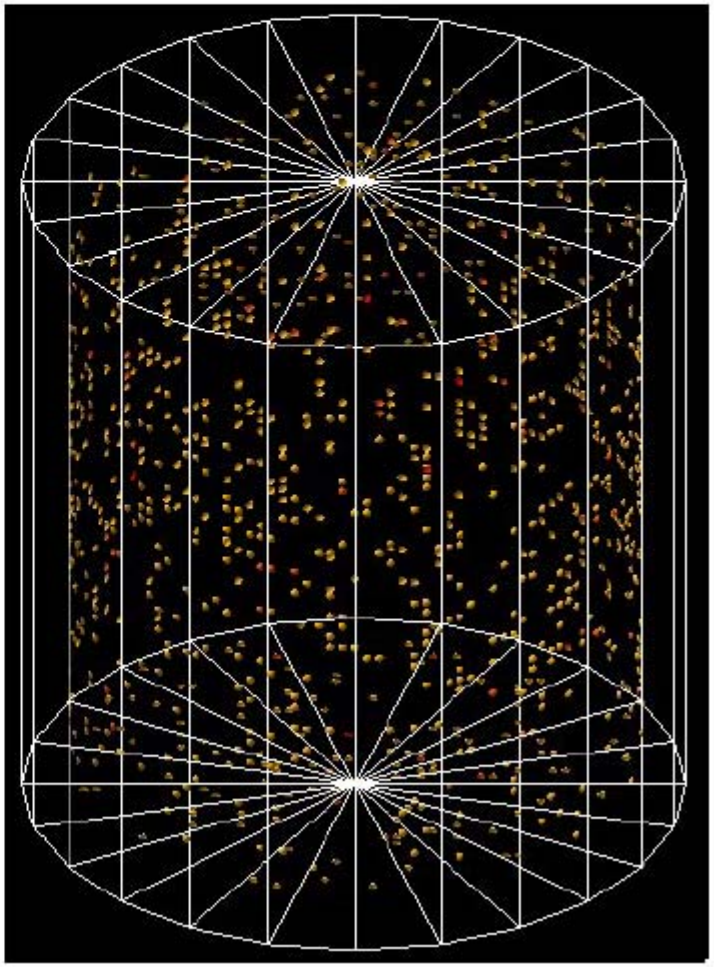
Sanity Check II

- Set Photon Yield to 9000 photons/MeV (Like pure LS)

100 MeV Proton



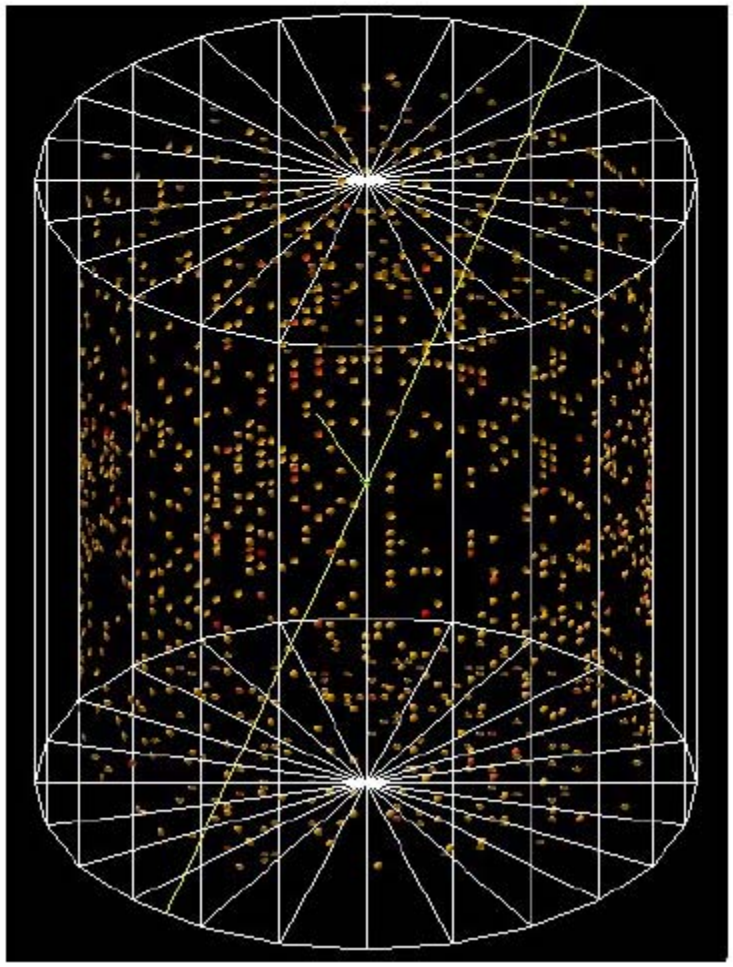
10 MeV Proton



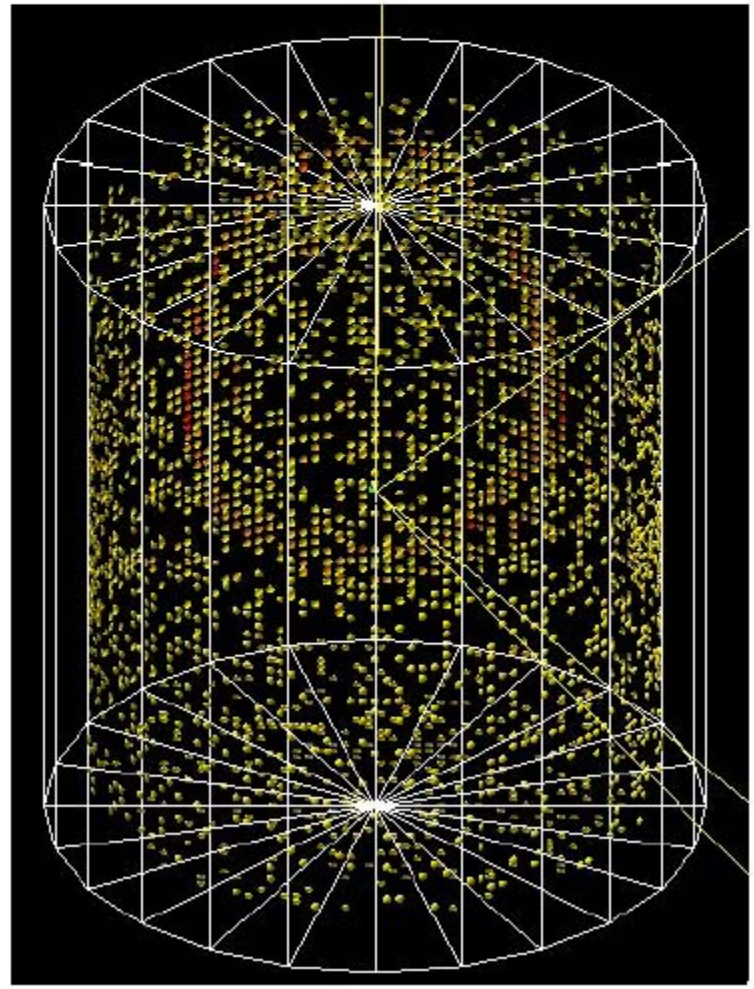
Sanity Check III

- Set photon yield to 90 photons/MeV (to keep a reasonable Scintillation/Cherenkov ratio)

105 MeV K^+



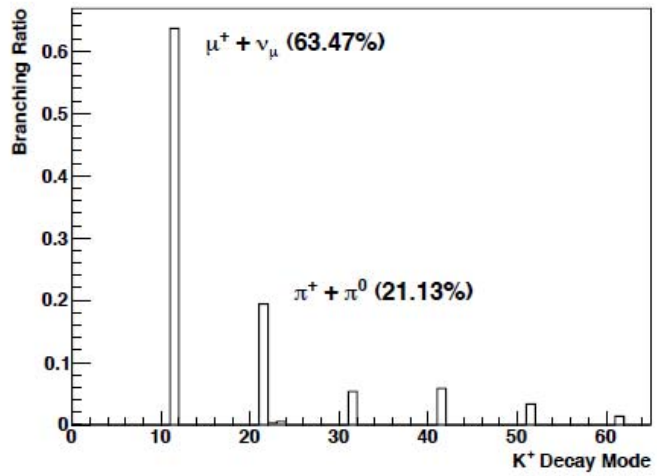
500 MeV Muon



Simulation of K^+ Decay

- Event generator: mono-energetic (105MeV) K^+ at the center of the detector
- Let Geant4 take care of the decay branches
- Total 4000 decays simulated

$$K^+ \to \mu^+ + \nu_\mu \quad (63.47\%)$$
$$K^+ \to \pi^+ + \pi^0 \quad (21.13\%)$$
$$K^+ \to \pi^+ + \pi^+ + \pi^0 \quad (5.58\%)$$
$$K^+ \to \pi^0 + e^+ + \nu_e \quad (4.87\%)$$
$$K^+ \to \pi^0 + \mu^+ + \nu_\mu \quad (3.27\%)$$
$$K^+ \to \pi^+ + \pi^0 + \pi^0 \quad (1.73\%)$$



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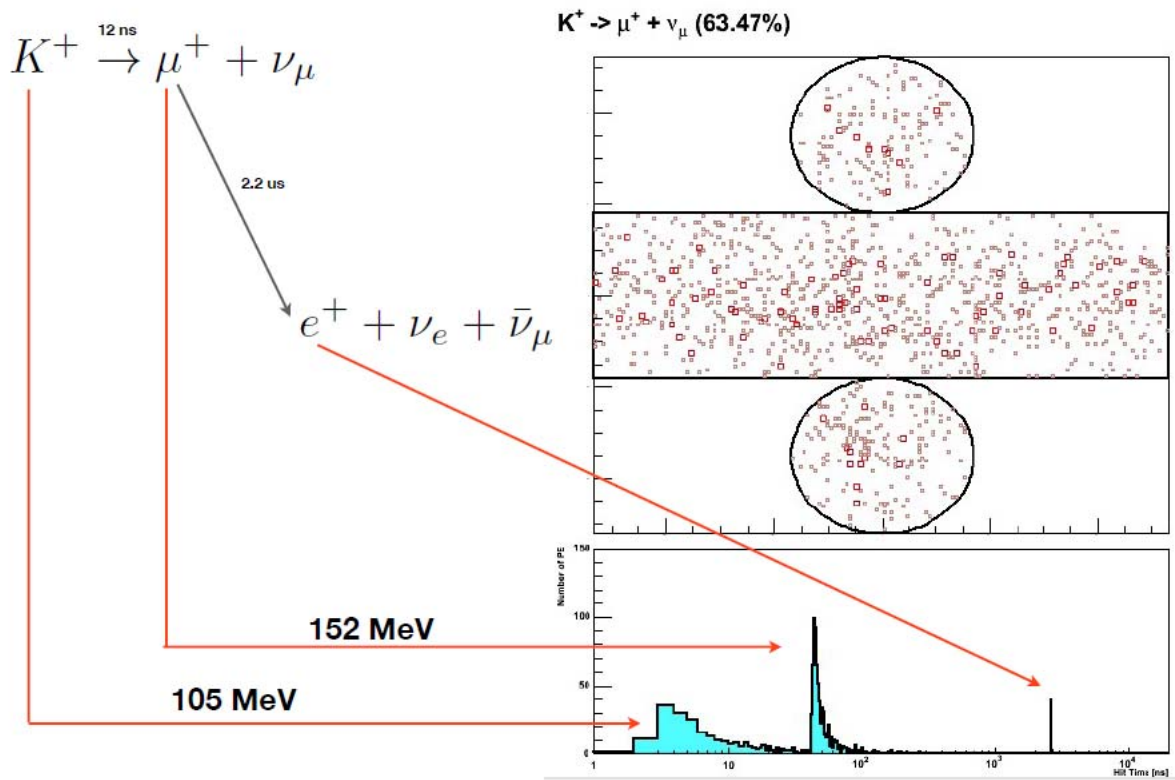
Good Event Example



There should be two rings in the hit patten (mu+, e+.) Can you find them?

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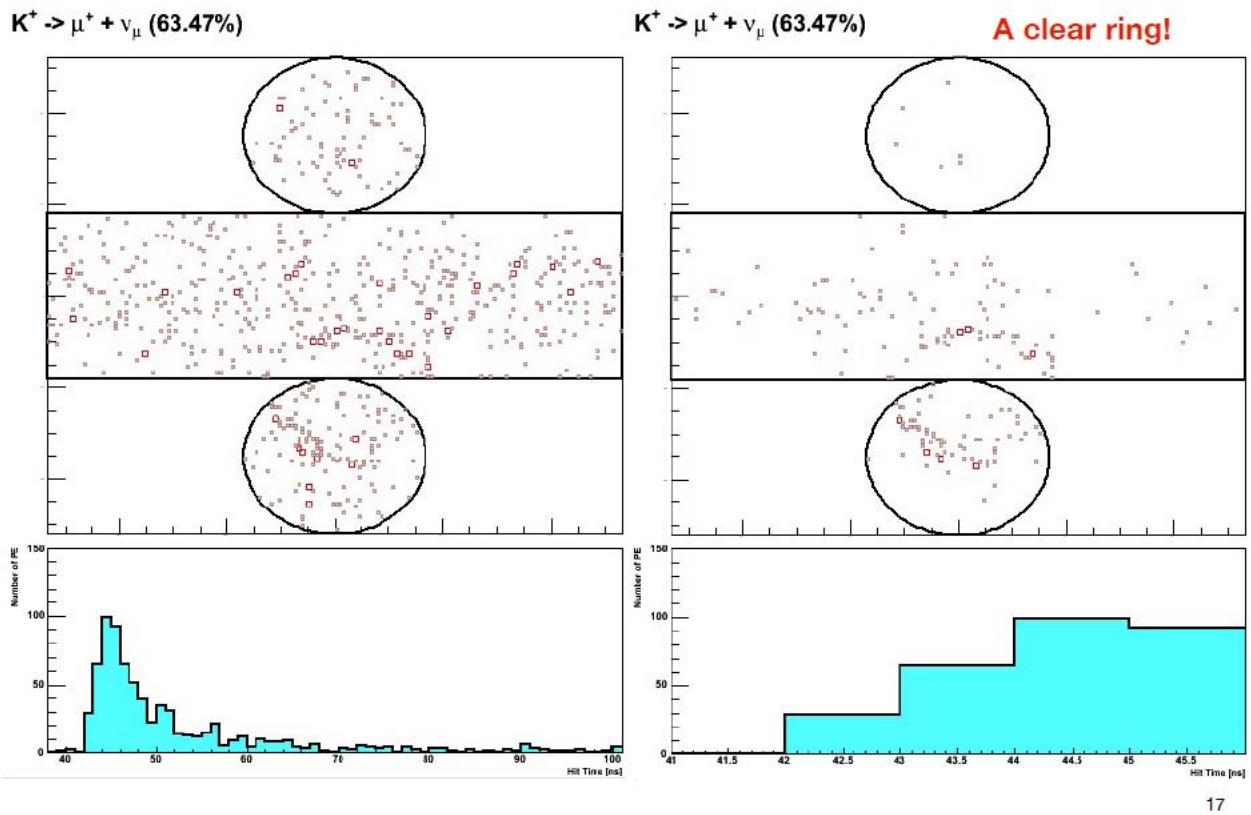
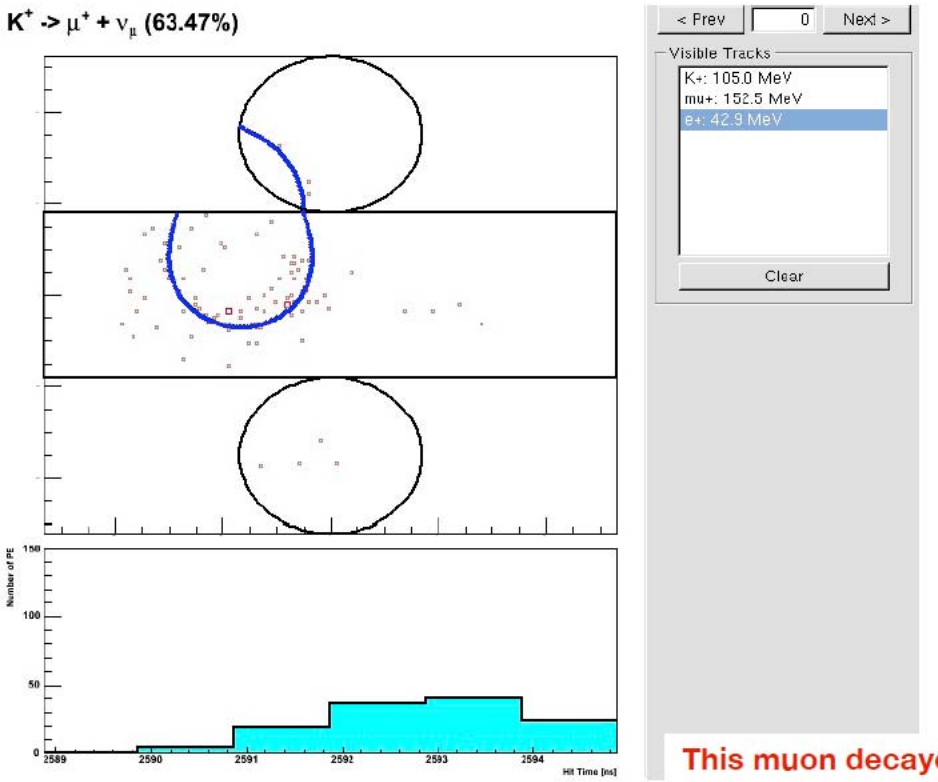
The Cherenkov Rings



This Kaon decayed at ~40ns

Selecting only the muon hits (40 ns, 100ns), now the ring is much clear (maybe …)

What About the Michel Positron



Can see the ring as well

This muon decayed at ~2.6us

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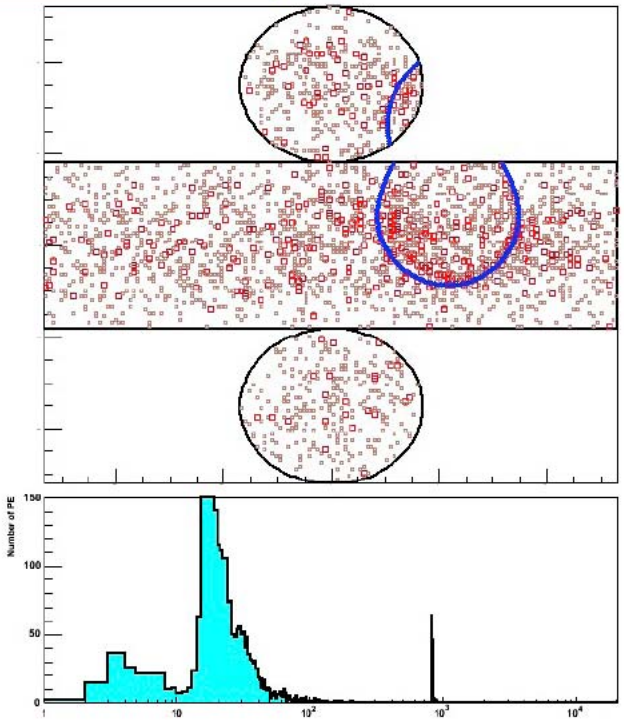
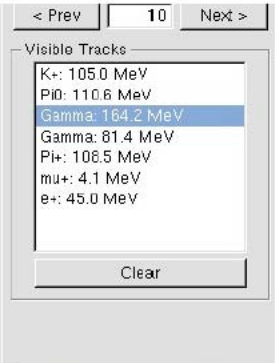
The Other Signal Channel

$K^+ \rightarrow \pi^+ + \pi^0$ (21.13%)





- Three correlated pulses
  - First: 105MeV Kaon, no ring
  - Second: ~12 ns, sum of
    - 2 gamma (246 MeV, 1strong ring + 1 weak ring)
    - pi+: 109 MeV
  - Third: <50MeV Positron, ~2.2us

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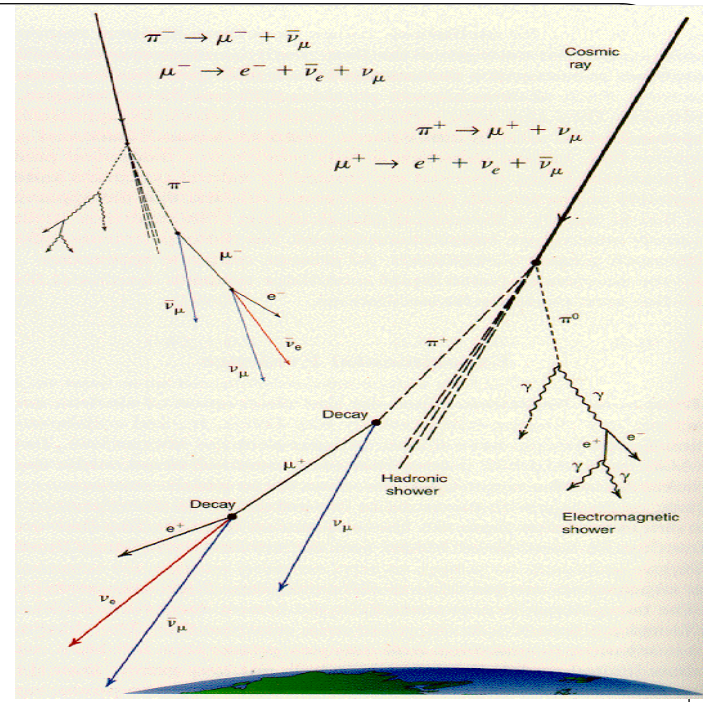
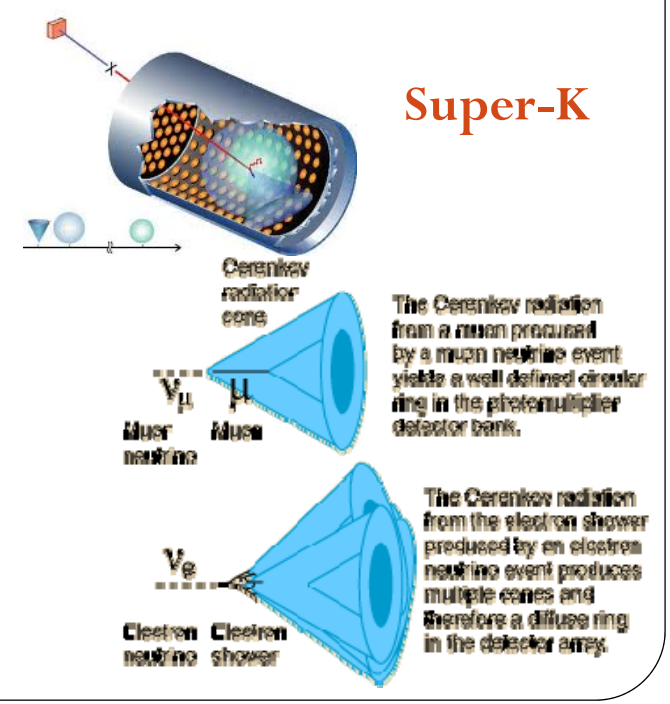
Atmospheric Neutrino Background

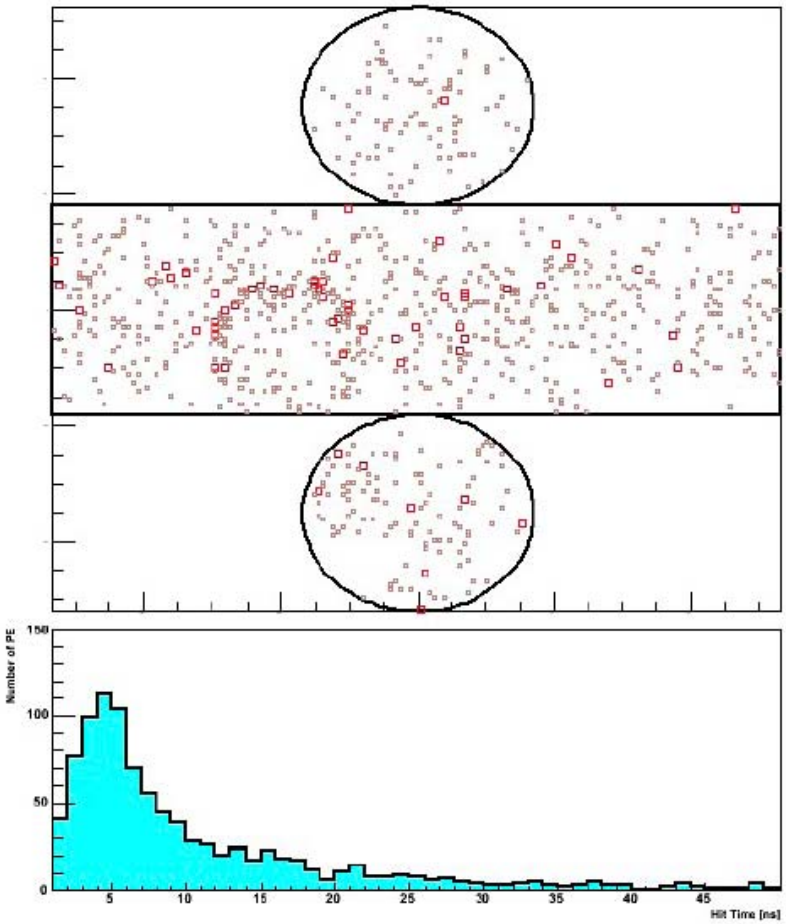
- Atmospheric neutrino interaction is a complicated process.
- $\bar{\nu}_\mu + \nu_e + \nu_\mu + \bar{\nu}_e$ generated from $\mu^\pm$ and $\pi^\pm$ interaction.
- IMB, Super-K, Soudan-2, and other experiments study the bests of it.
- Most atmospheric background events associated with multi Michel electrons, while either π^+ or μ^+ from PDK$^+$ mode only gives one electron.



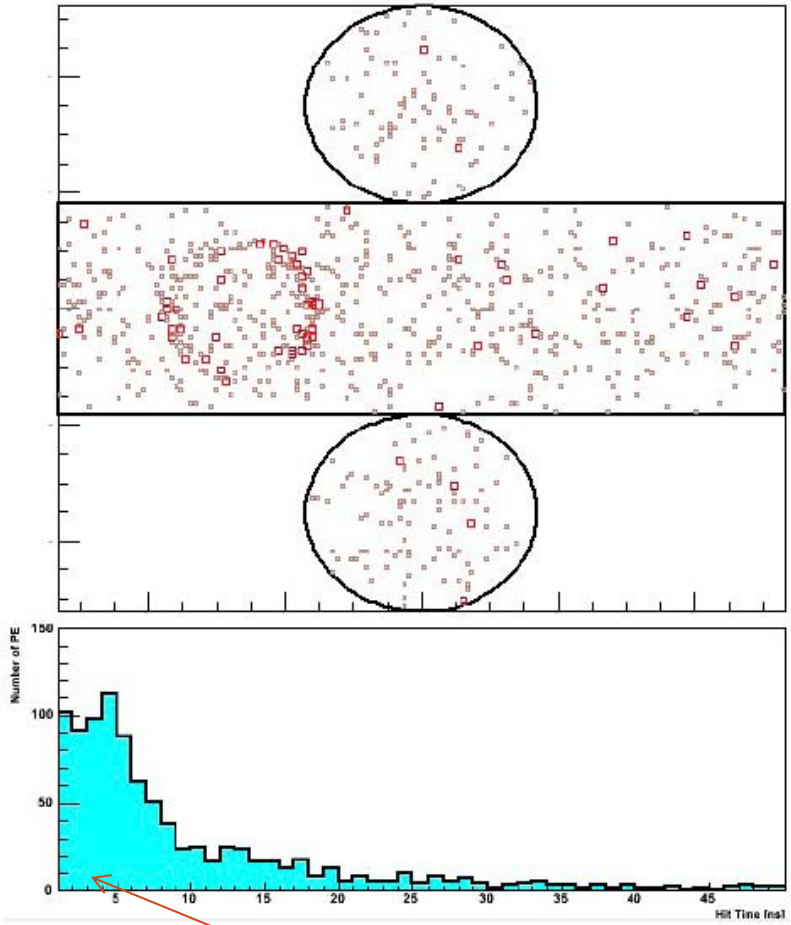


Background: Atmospheric Muon-neutrino

$K^+ \rightarrow \mu^+ + \nu_\mu$ (63.47%)



Background: Muon



If nu_mu has the 'right' energy, it becomes a background to 'early-decay' kaons

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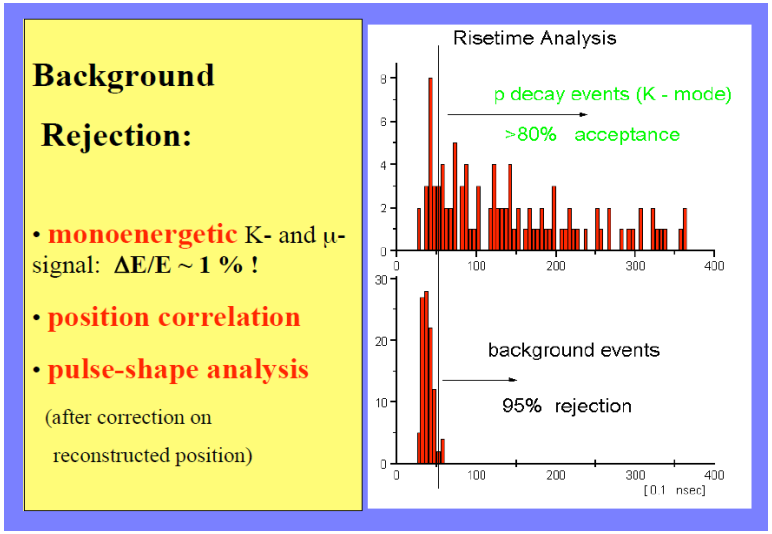
Need PSD/position cut to removve

Sensitivity with Scintillation + Cerenkov

– how much can we improve on a Super-K type detector?



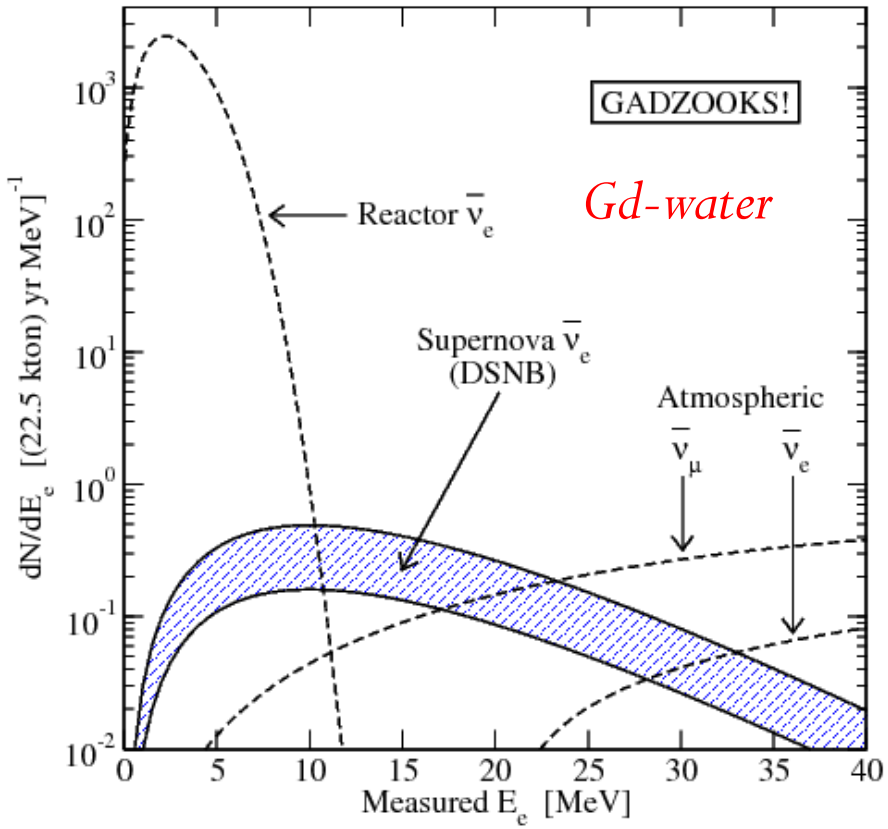
(LENA Monte Carlo, F. Von Feilitzsch, L. Oberauer, W. Potzel)

- *Compare to SK (170 events in 1489 days), the 3-fold coincidence cuts down to ~5/y; PSD/Michel position cut can further suppress the bkg. event to 0.25/y.*

10-yr run could reach a sensitivity of 10^{34} for the PDK^{+}

Other Physics

- **SRN**
  - DSNB
  - Important for low-energy electron neutrino and proton decay
- SN at 10kpc
- Solar-neutrino
- Geo-neutrino
- Reactor-neutrino
- etc.



J. Beacom, M Vagins. Phys.Rev.Lett. 93 (2004) 17110 arXiv:hep-ph/0309300v1
J. Beacom. Ann.Rev.Nucl.Part.Sci.60:439-462,2010 arXiv:1004.3311v1

Why not Gd-scintillating water?

Cerenkov & Scintillation for WbLS

50-kt	LENA	WbLS	Super-K
Protons (free)	3.70×10^{33}	3.32×10^{33}	3.35×10^{33}
Protons (bound)	1.29×10^{33}	1.34×10^{34}	1.34×10^{34}
Scintillation p → K+ capture	√	√	
Cerenkov ring ID		√	√
Cerenkov yield	√	√	√

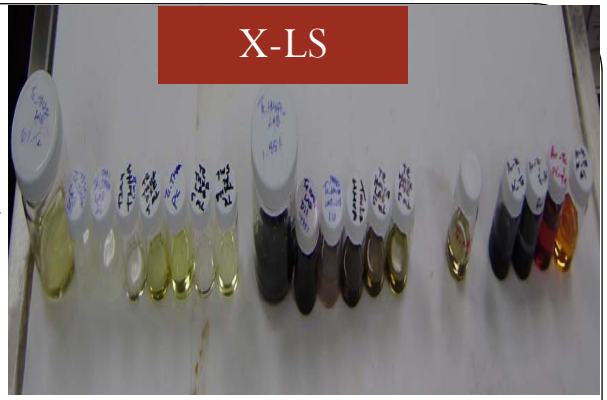
Fermi motion and secondary particle collisions are important for $p \rightarrow \pi^0 e^+$.
39% with 180° for ^{16}O (Gabriel, T.A. and Goodman, M.S. Physical Review D, 25, 9 (1982) 2463-2465.

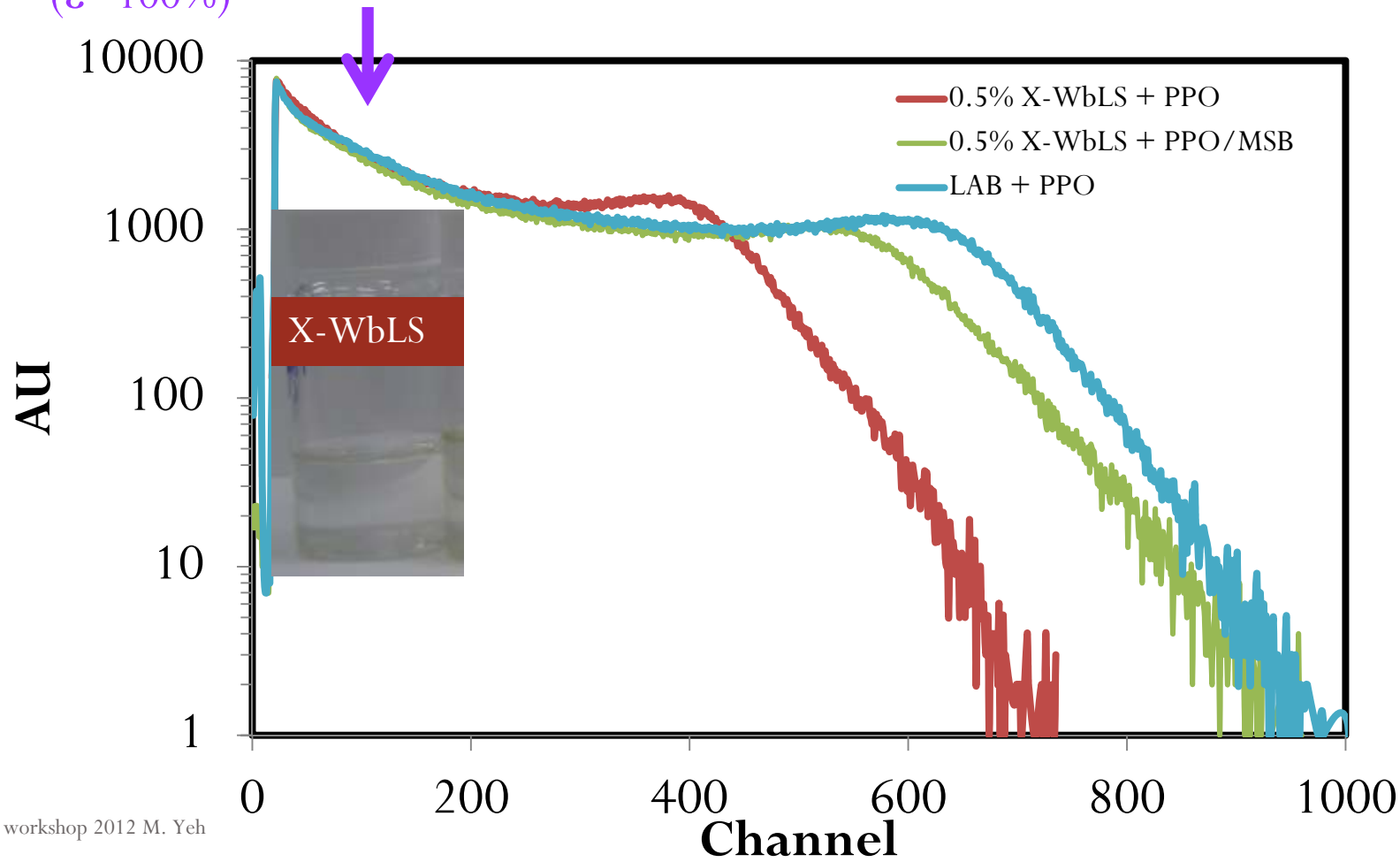
- *Double-beta decay*
- *Reactor neutrino*
- *Geo neutrino*
- *Supernovae alarm*

A new way of loading Hydrophilic Isotopes in 90+% LS

First DBD isotope in WbLS

- Efforts to load certain metallic-ions in pure LS (ε=80%)
- Quick and straight in preparation of X-WbLS (ε=100%)



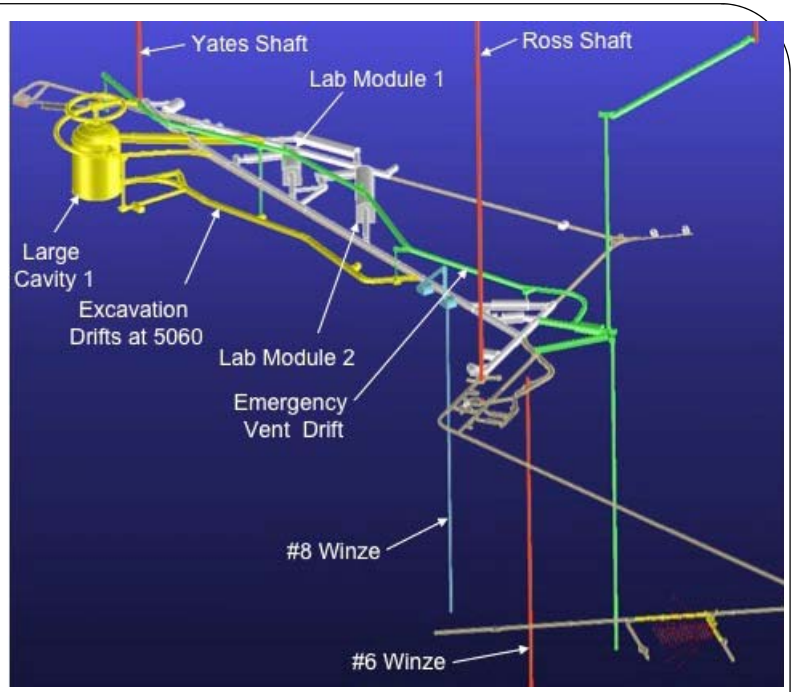


- *Veto system*
- *Biodegradable liquid scintillator cocktail*
- *Short half-life calibration source*

Other Applications

WbLS as veto system

- Scintillation water could serve as a large and economic Cerenkov/Scintillator veto system.
  - LBNE (LAr) on surface
  - LUX and other dark matter researches are looking for veto system (Gd-water, LS, Gd-LS, etc.).
  - Long-range reactor monitoring.
  - etc.

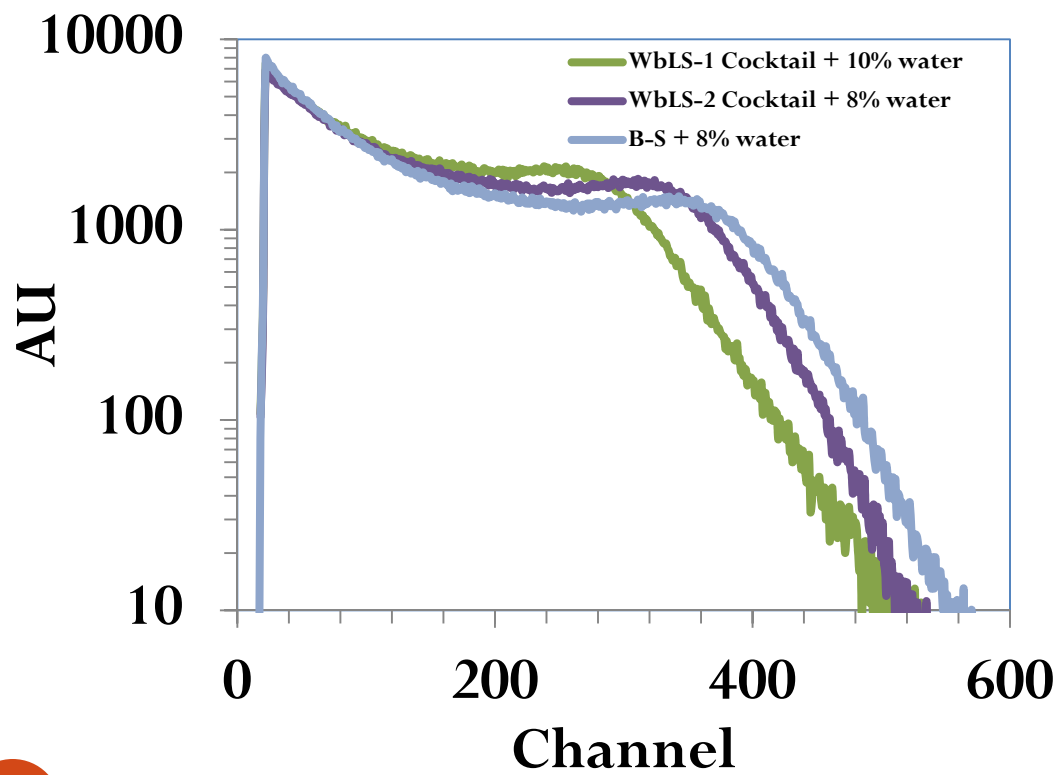


WbLS can be molded as a surrounding shielding or multiple NoVA-type segmentations

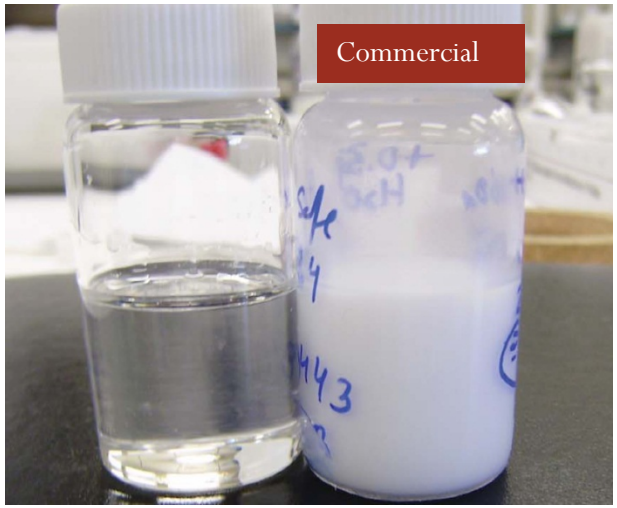
- *Cost-saving than pure LS*
- *Nonflammable & ESSH (95%+ water)*
- *Scintillator & Cerenkov & can be Gd-loaded….*

Biodegradable Water-based Scintillation Cocktail

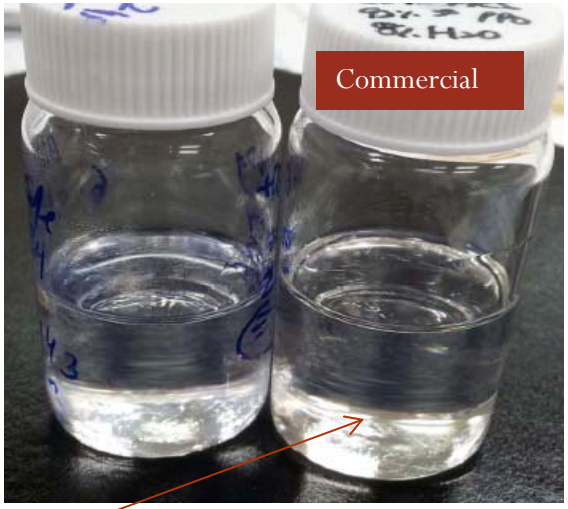
- Take more % aqueous sample than commercial product
- No permeation of scintillation vials (long-stable counting)
- Environmentally friendly (easy disposed)



20 minutes



>24-hrs



temperature-sensitive

Short Half-live Calibration Sources

- Conventional method of loading metallic-ion into pure LS takes ~1-day.
- WbLS opens a quick and easy way to add metallic isotopes into liquids (~a hour) that can be blended into either organic or aqueous solvents (detectors).
  - *Positron isotopes mostly have short half-life (<1 day); A calibration source for IBD event, such as reactor-ν experiments.*
  - *Short half-life naturally-occurring isotopes: Pb-212 (10.6-h), Bi-212 (60.6m), or Tl-208(3.1-m) calibration sources for low-energy neutrino experiments.*
  - *etc…*

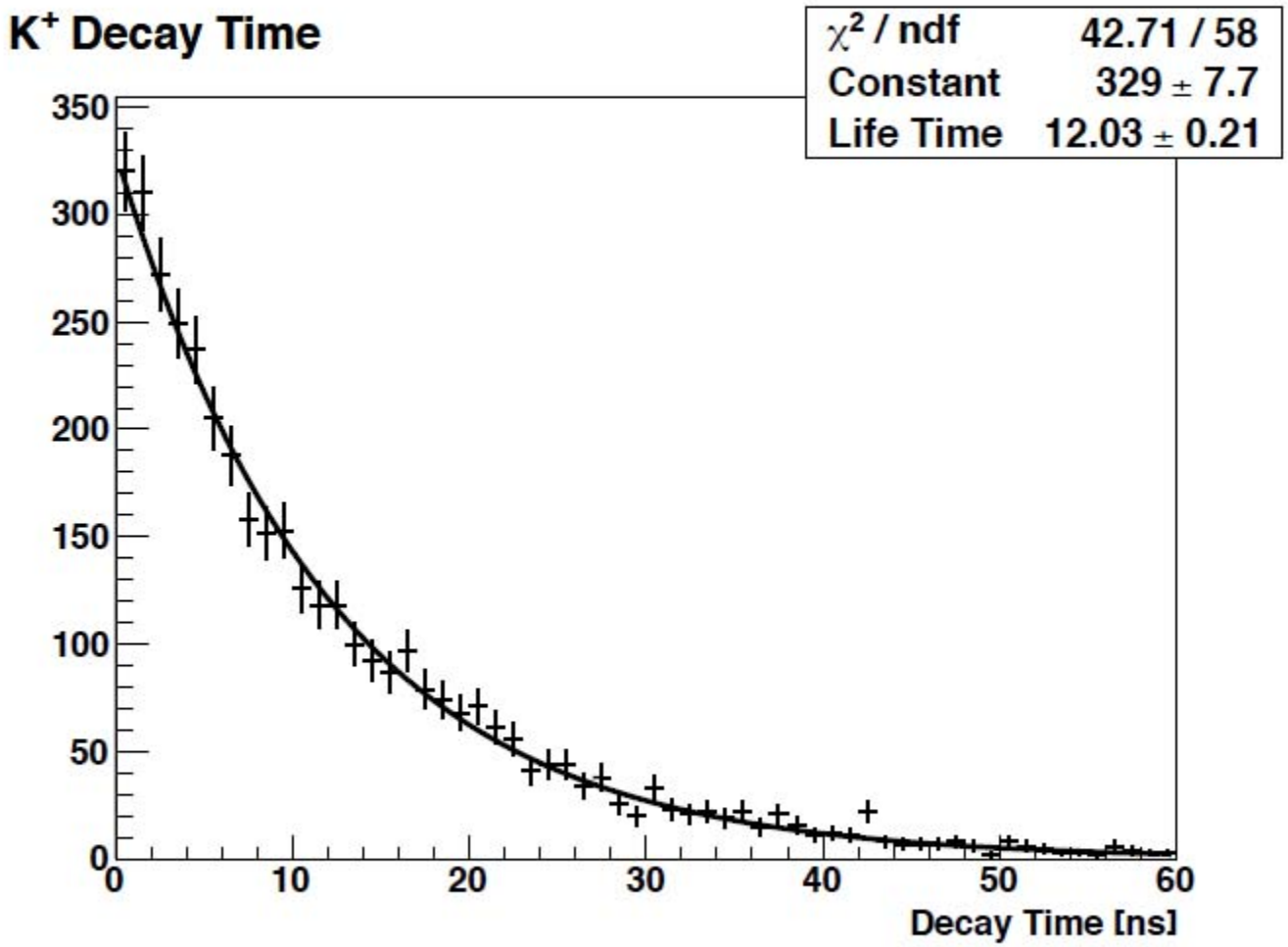
Summary

- A multi-physics, new detection medium with long attenuation length and *Scintillation* & *Cerenkov* features to explore the *physics below Cerenkov* (*nucleon decay*).
- A tunable detector that can adjust photon production vs. attenuation length for different physics.
- A new metallic loading technology that opens the doors for some double-beta decay, reactor and other physics that cannot be done before.
- A long-term stable and ease-mixed scintillation cocktail for aqueous (environmental) samples.
- A new matrix detector that is environmentally friendly, low-cost and easy to dispose; compare to pure scintillation solvent.

R&Ds:

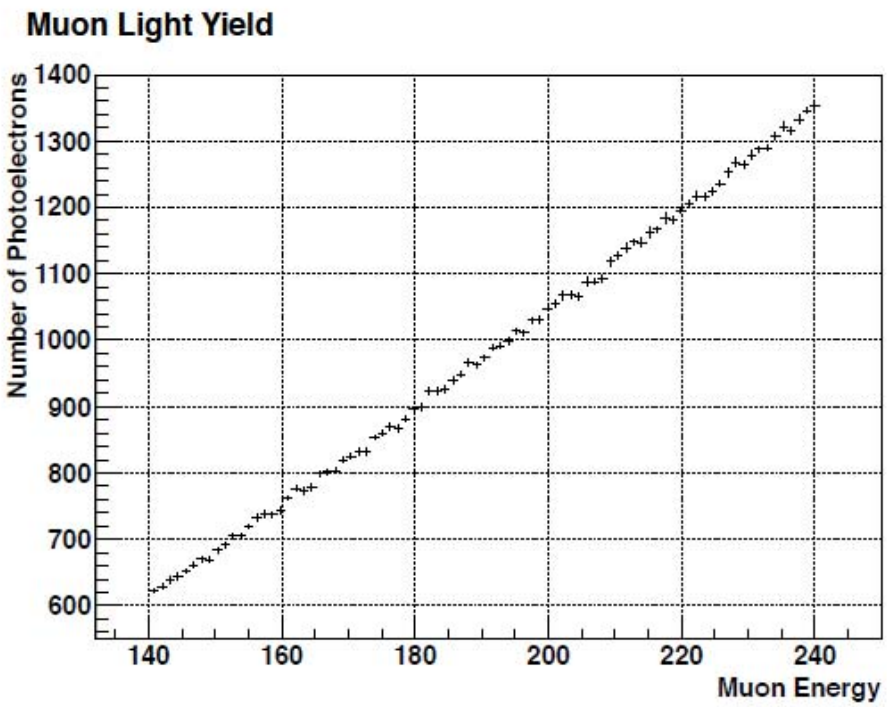
- ***ton-scale demonstrator***
  - ***Research reactor***
  - ***Accelerator at FNAL***
- ***Veto efficiency study***
- ***Sensitivity check for other physics (simulations)***

Sanity Check: Kaon Decay Time



Decay time of 12 ns is reproduced

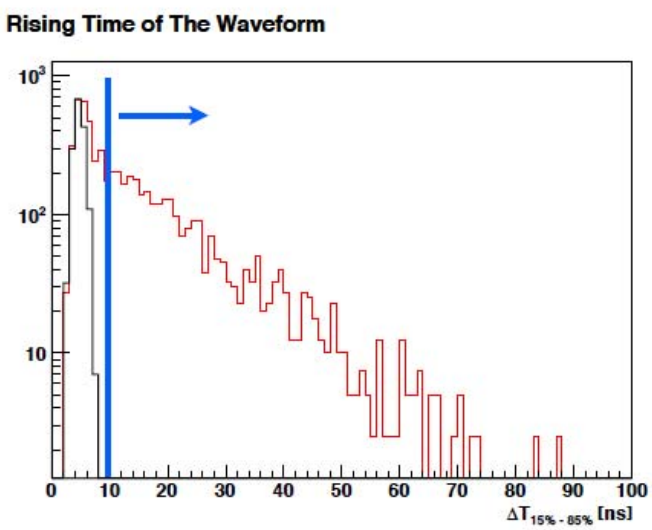
Background: Atmospheric Muon-neutrino



From 4000 muon background event simulation

- Prompt energy cut 800 < PE < 1100 corresponds to 170 MeV < muon energy < 210 MeV
- The atmospheric neutrino background in this energy window is about 2 event/kt/year (scaled from SK and LENA paper)

Pulse Shape Discrimination



- Red: Signal Black: Background
- A cut at rising time > 10 ns gives
  - Signal Efficiency: 54.0%
  - Background Acceptance: 0

- Define a PSD variable to distinguish 'two-pulse' signal from 'one-pulse' background
  - Rising time from 15% of the maximum pulse to 85% of the maximum pulse
  - A timing spread of 2.2 ns has been applied to make the timing more realistic
    - PMT TTS (jitter): 2 ns
    - vertex recon resolution: 20 cm

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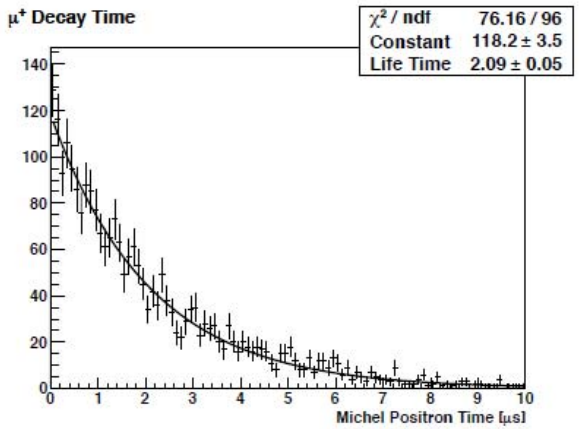
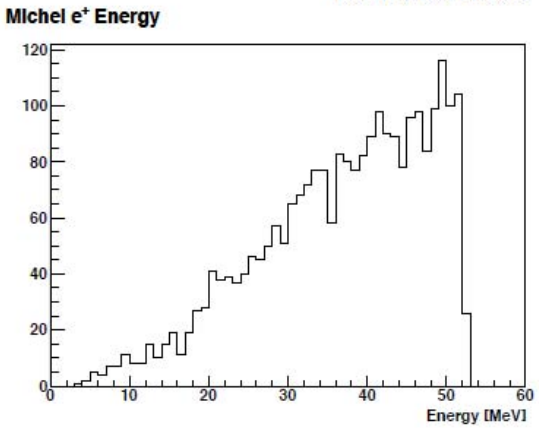
Michel Positron Cut





- For signal events, we require one and only one Michel positron be identified
- From scintillation light curve we assume that if muon decays within 10 ns, the Michel Positron signal cannot be separated from the parent muon signal. The inefficiency due to t_decay < 10 ns is 0.45%
- To reduce the random coincidence from radioactive background, we require the energy of Michel positron > 6 MeV (~50 PE). The efficiency of the cut is 99.7%

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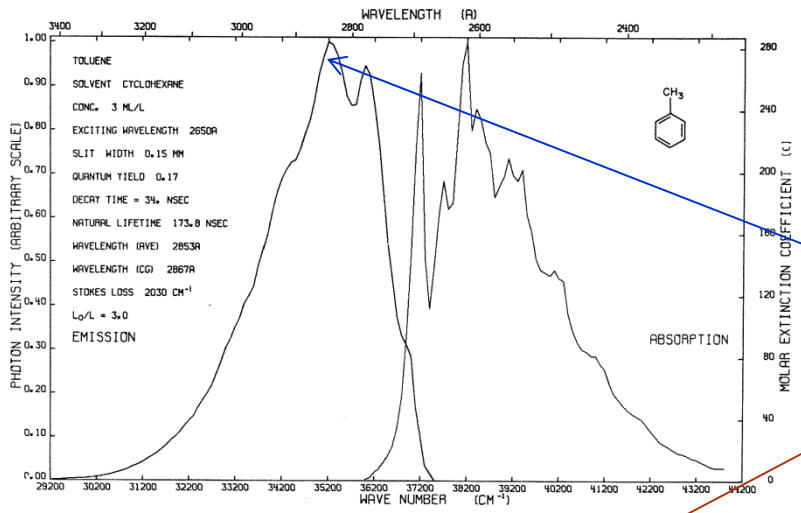
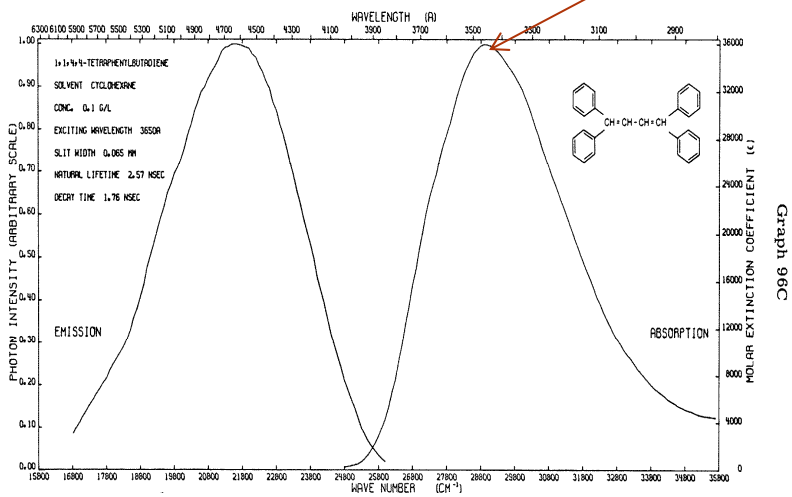
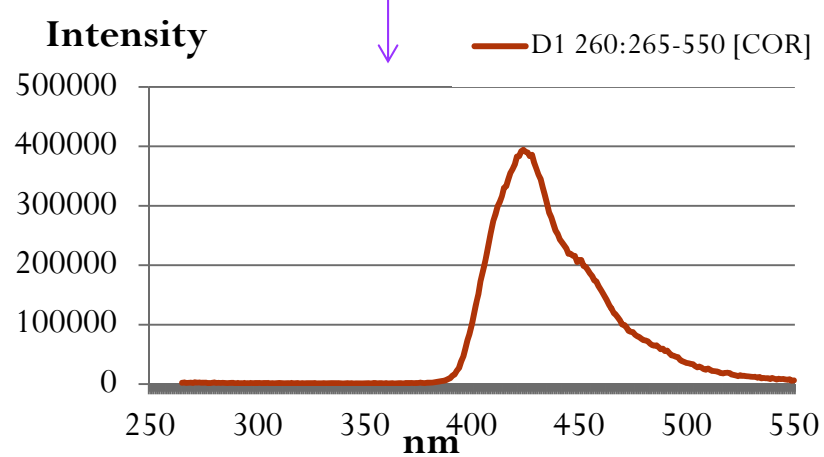
LAr light collection





Handbook of Fluorescence Spectra of Aromatic Molecules, 1967

- Toluene QY is only 0.17 or ~½ of liquid scintillators (PC, LAB, PXE, etc.).
- TPB absorption at *350nm* doesn't match with toluene emission at *300nm* well and emission at 460nm is not the most sensible zone of PMT
- A *(LAB or PC)-PPO/MSB*-mixed, Teflon-based film could improve the light collection efficiency significantly (***cost-saving***).