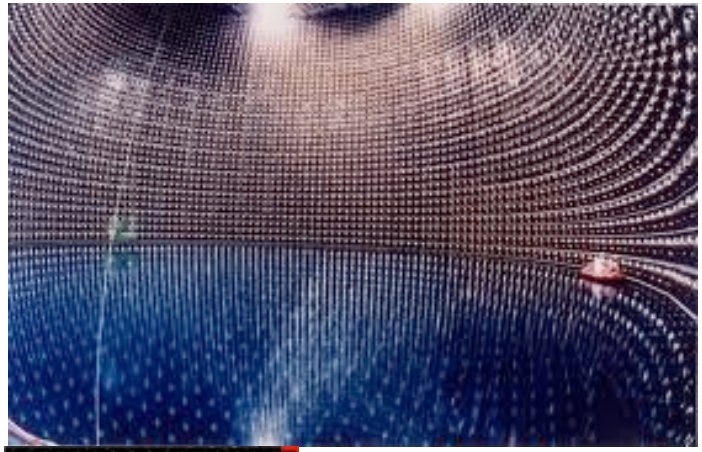
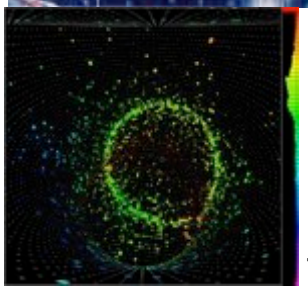
# Sensitivity of a Water-based Liquid Scintillator detector to $p \to K^+\bar{\nu}$

David Jaffe


April 2013 Intensity Frontier Workshop

# Can we combine the best part of a Cherenkov Detector with a Liquid Scintillator Detector?





1GeV muon

Clear particle ID
Direction information
Highly transparent
Cost effective
Safe to handle

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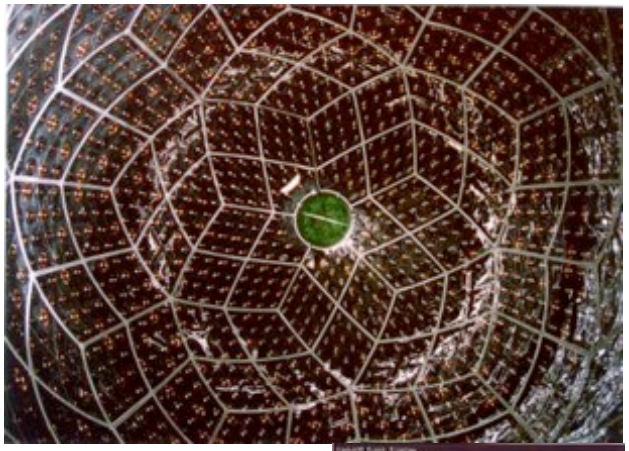
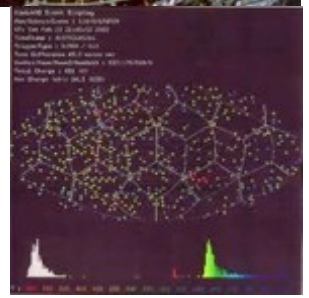
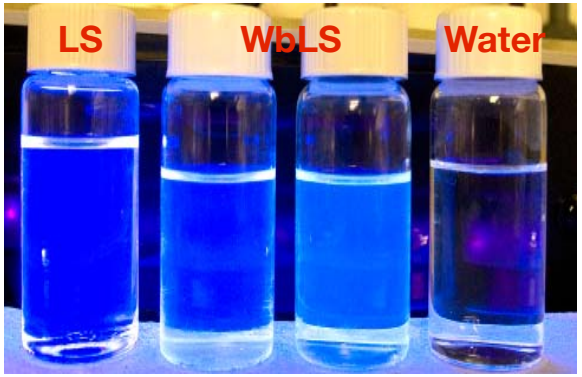




2MeV positron
& photon

Lots of light
High efficiency
(even at low energy)

**Water-based Liquid Scintillator**



# The $p \to K^+\overline{\nu}$ Channel in Cerenkov Detectors

$$p \to K^+\overline{\nu}$$

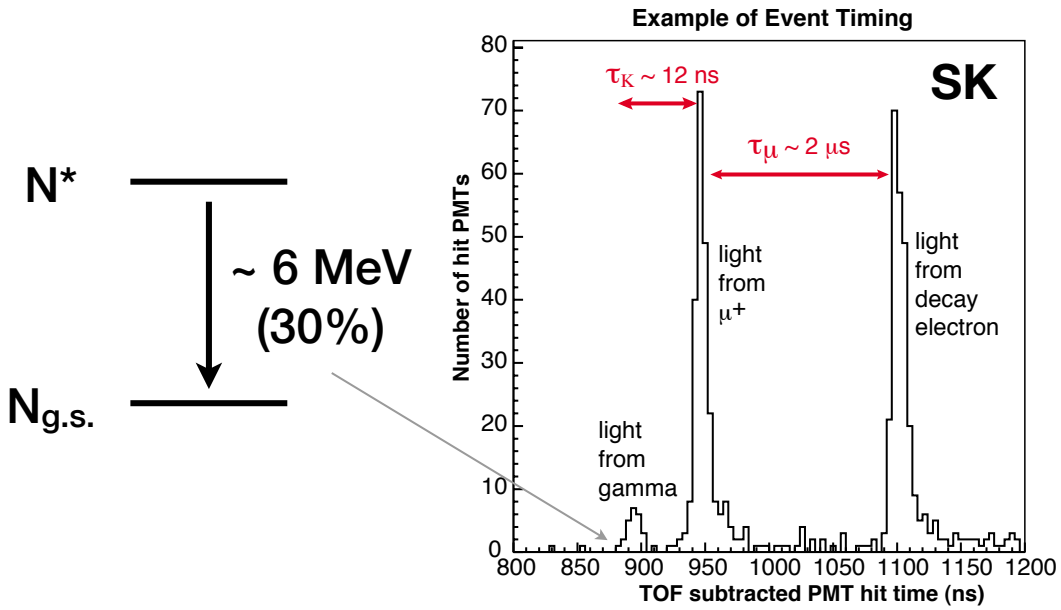
12.4 ns

63% $K^+ \to \mu^+\nu_\mu$

21% $K^+ \to \pi^+\pi^0$

Favored SUSY decay mode

Kinetic Energy of $K^+$ is 105 MeV,
invisible in water Cerenkov detectors




**SK Limit** $\tau(p \to K^+\overline{\nu}) > 2.8\times10^{33}$ yrs at 90% C.L.

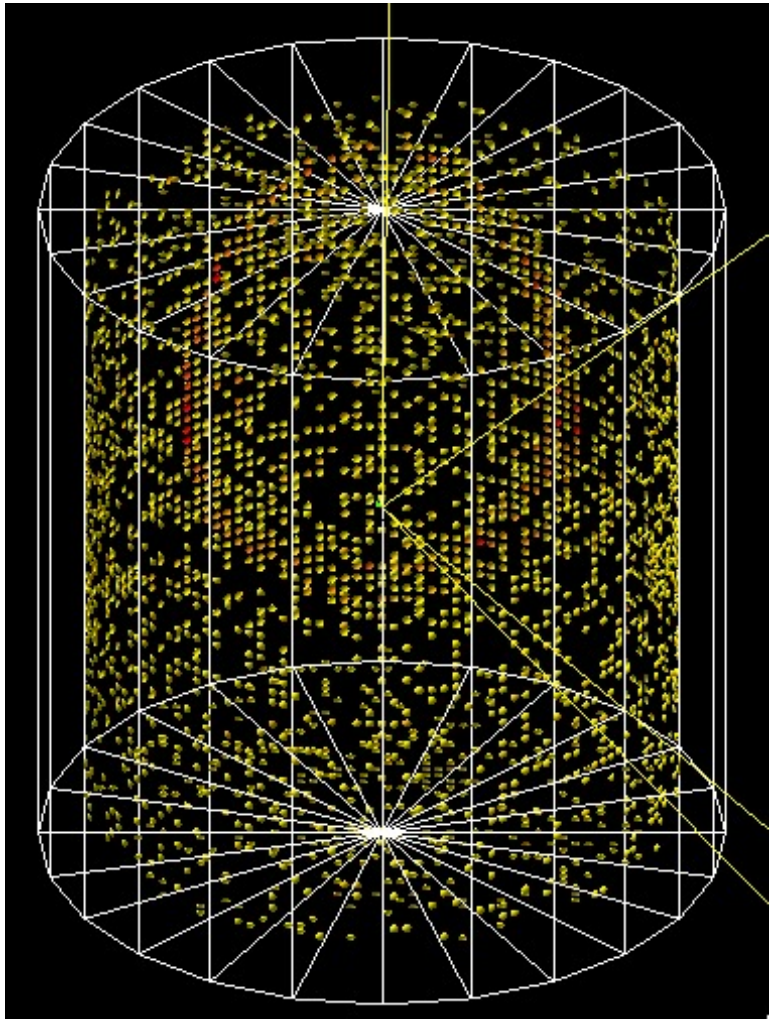
*M. Shiozawa, NNN09*

**In WbLS, the Kaon prompt signal is suddenly visible**

# Simulation of a Large WbLS Detector

- Based on WCSim software (Geant4-based simulation used in LBNE Water detector concept design)
- SK-like geometry, 22.5 kton Fiducial Volume
- SK 20” PMT, 40% coverage
- WbLS material + scintillation + wavelength shifting

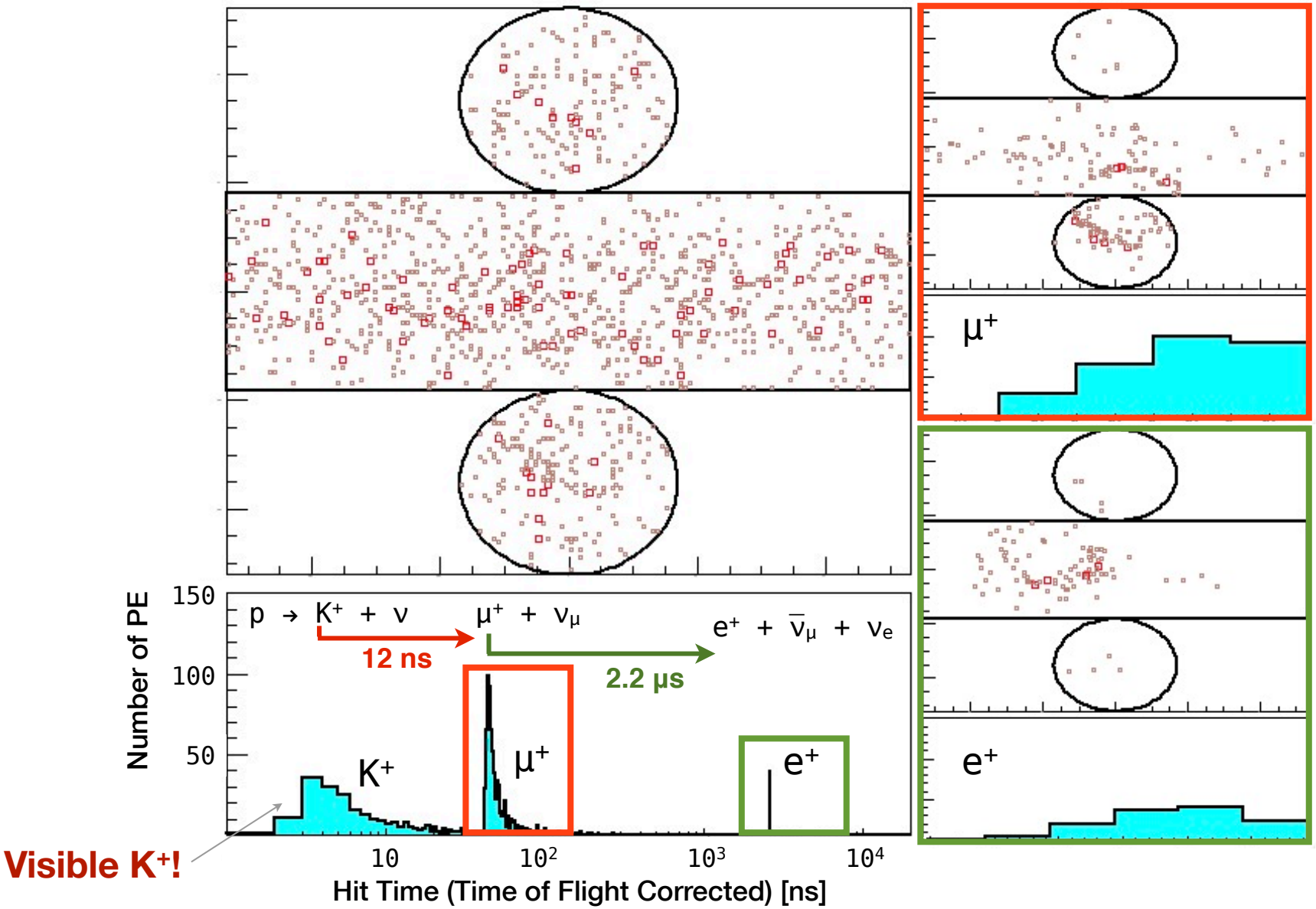
| x%-WbLS (d=0.9945 g/cm$^3$) +PPO | | | | | |
|---|---|---|---|---|---|
| Element composition (%) | H | O | C | S | N |
| | 65.9 | 30.9 | 3.1 | 0.09 | 0.006 |
| Refractive Index | 1.3492 @580nm | | | | |
| Timing | 1.23 ns (26%) + 9.26 ns (74%) | | | | |
| Absorption length | 50m @430 nm | | | | |
| Birks Constant | 0.124 mm/MeV | | | | |
| photon yield | 90 / MeV (tunable) | | | | |

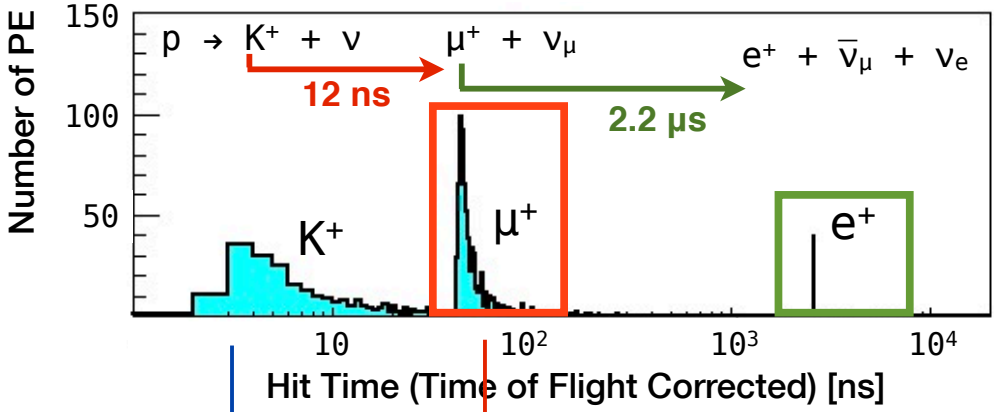


Example: a 500 MeV Muon

# The $p \to K^+\overline{\nu}$ Channel in WbLS Detectors

**A simulated event with 90 scintillation photons/MeV**

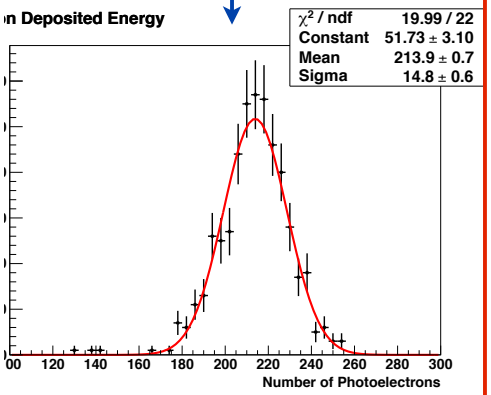




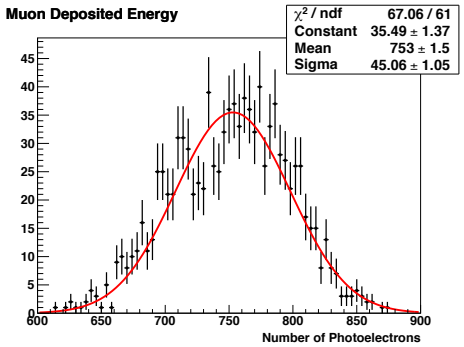

## Main background: atmospheric $\nu_\mu$

Reduce by:

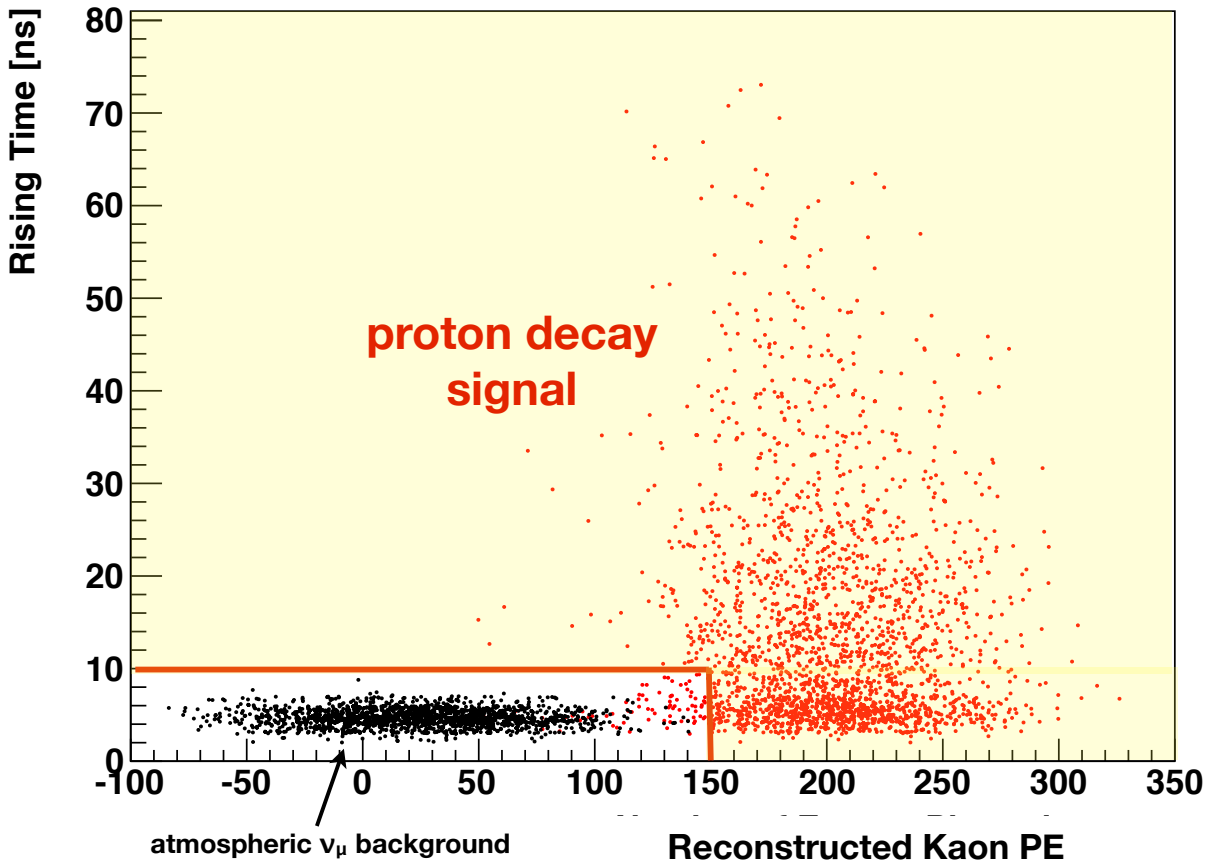
- **Rising-time cut**: distinguishes one-pulse (background) from two-pulse (signal) by rising-time (from 15% to 85% of maximum pulse height) of the pulse shape
- **Reconstructed Kaon energy cut**: by subtracting the reconstructed muon energy




Kaon: 105 MeV -> 213 PE




Muon: 152 MeV -> 753 PE

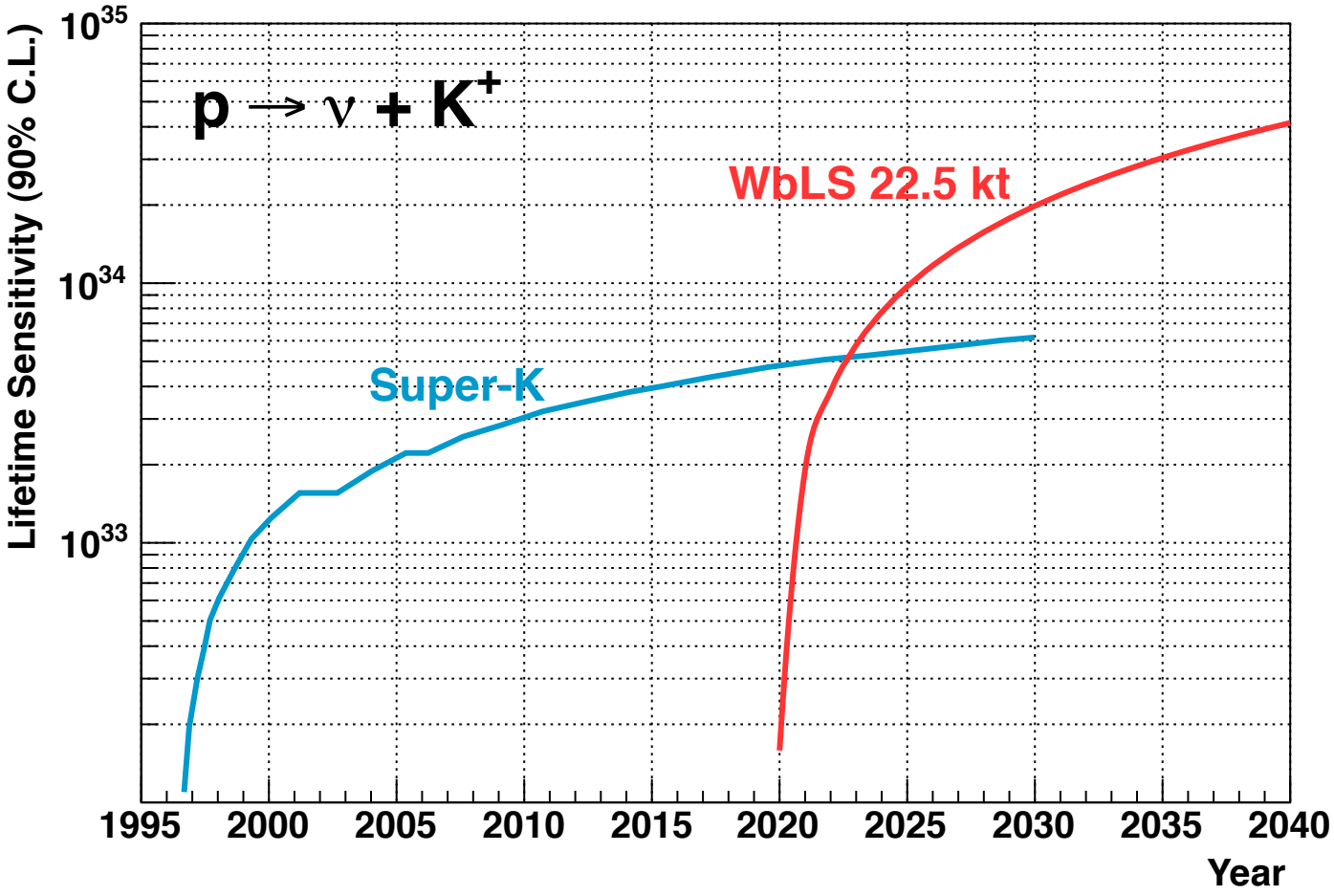


# Summary of Efficiency, Signal, Background

| Selection | Efficiency | |
|---|---|---|
| 800 < PE in first 100 ns < 1100 | 96.8% | |
| One Michel positron | 99.2% | |
| Muon decay later than 100 ns | 95.6% | |
| Rising time >= 10 ns or Reconstructed Kaon PE > 150 | Free Protons | Bound Protons |
| | 96.4% | 75.2% |
| Total Efficiency | 88.5% | 69.0% |
| #Protons | 1.53E+33 | 5.98E+33 |
| Predicted Signal Events (in 10 y, $t_{1/2}$=2.8E33 y) | 15.2 | |
| Predicted Background (in 10 y) | 0.1 | |

Predictions assume a 22.5kT fiducial volume

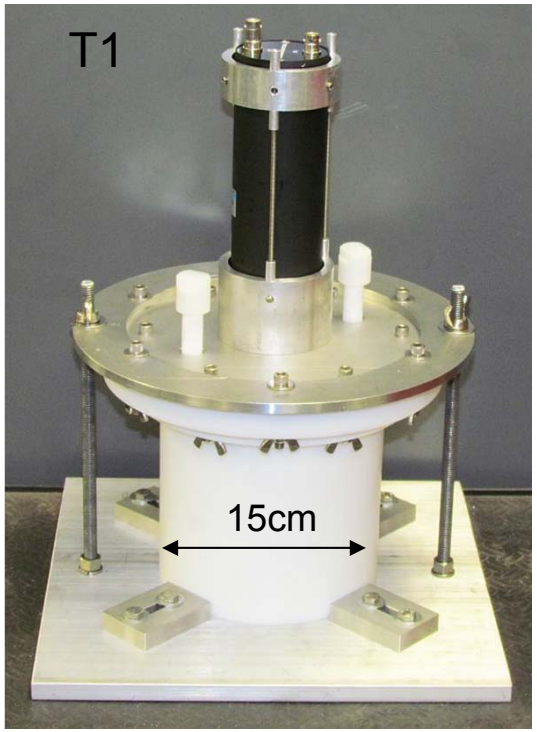
# Projected Sensitivity




$$\tau(p \to K^+\bar{\nu}) > 2 \times 10^{34}\text{y at 90\% C.L. in 10 years}$$

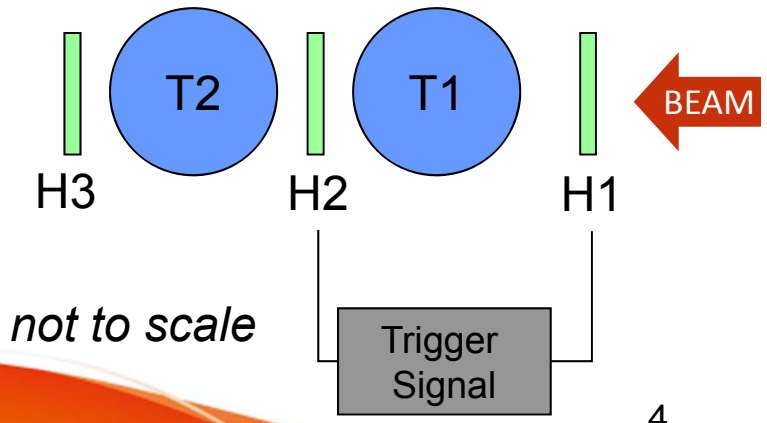
# Experimental Setup

- Two tubs with 2" PMT readout:
  - T1 from PTFE (white Teflon, highly reflective)
  - T2 from Al, coated with black Teflon
- Readout by 14bit Flash ADC (CAEN V1729A)




- NASA Space Radiation Laboratory at BNL (NSRL) with proton beam energies:
  - 210MeV (~dE/dx of $K^+$ from free proton decay)
  - 475MeV (water Čerenkov thresh.)
  - 2GeV (~minimum ionizing)
  - Low intensity narrow beam

❖H1,H2,H3 – 2cm x 2cm horoscopes




- 4 samples tested:
  - ✓ Water (purified)
  - ✓ WbLS-1: 0.4%LS
  - ✓ WbLS-2: 0.99%LS
  - ✓ LS: 100% LS

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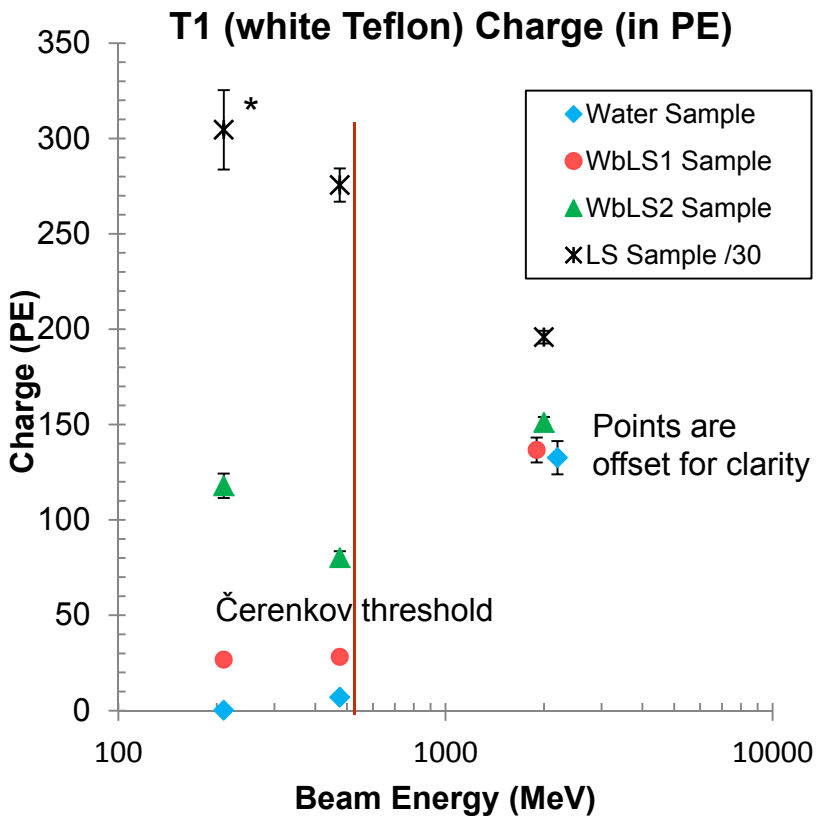
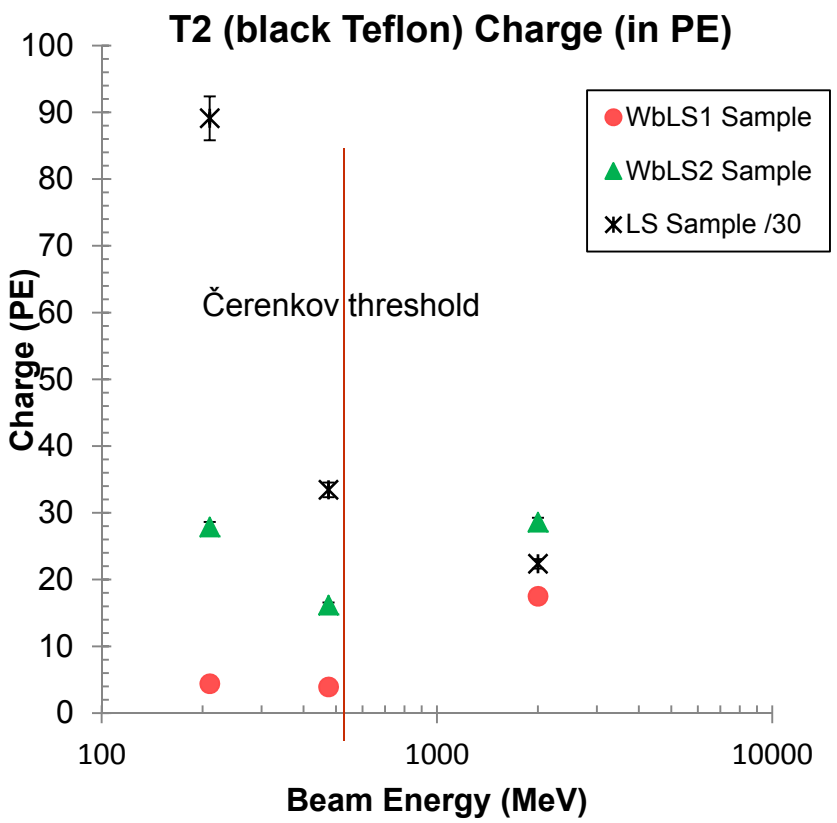
# Data from All Samples

- **At 2GeV, light yield from Čerenkov dominates for water and WbLS**
- **Here, LS sample response is divided by 30 to fit on the same scale**




*Non-linear PMT response

- **Difference in light yield changes at 475MeV and 210MeV for different samples suggests non-linear scintillator response**




No water sample data shown due to technical difficulty with T2 water run

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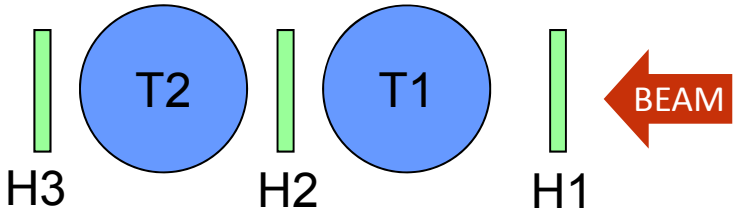
# Energy Deposition in Samples

- Deposited energies in T1 and T2 using NIST's proton stopping power and range tables (PSTAR)
- Material properties of WbLS and LS approximated by water and toluene, respectively.
- Preliminary estimate of energy deposited uncertainty is ~10%.
- Detailed Geant4 simulation in progress




*not to scale*

| Beam energy (MeV) | Sample | T1 energy deposit (MeV) | T2 energy deposit (MeV) |
|---|---|---|---|
| 210 | Water, WbLS | 70 | *113* |
| | LS | 59 | *124* |
| 475 | Water, WbLS | 39 | 42 |
| | LS | 34 | 36 |
| 2000 | Water, WbLS | 28 | 28 |
| | LS | 24 | 24 |

D. Jaffe, HyperK meeting presentation "Preliminary results on water-based liquid scintillator in a proton beam"

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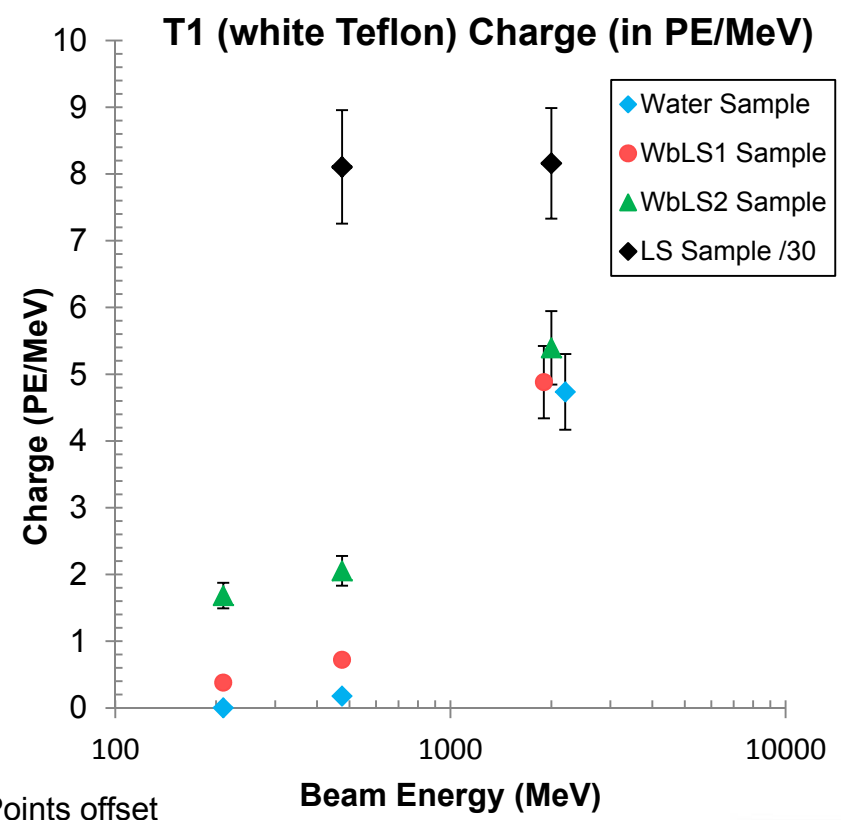
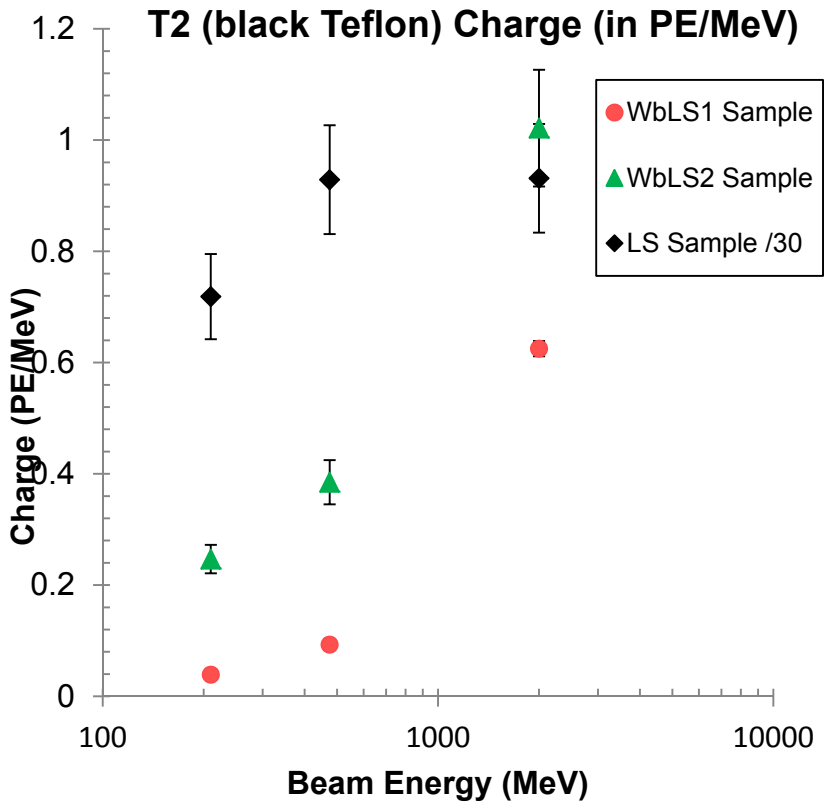
# Light Yield in PE/MeV

- Same light yield for 2GeV and 475MeV data for LS
- Minimal Čerenkov contribution at 475MeV – can use the data at this energy for WbLS to LS comparison
  - Note that LS sample response is divided by 30 to fit on the same scale




Points offset for clarity

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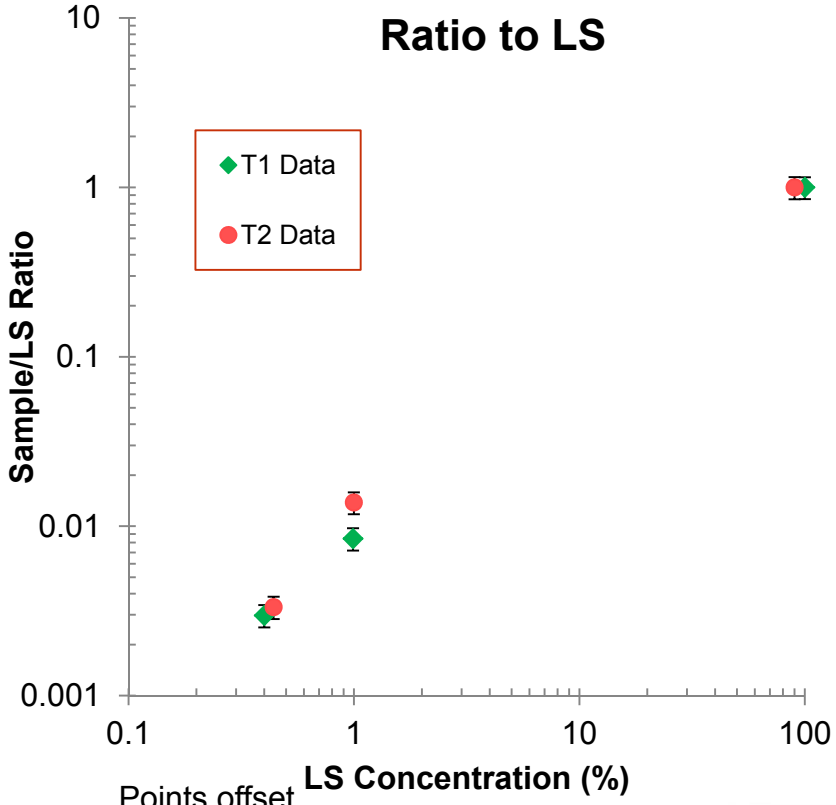
# PE/MeV Yield vs. Concentration

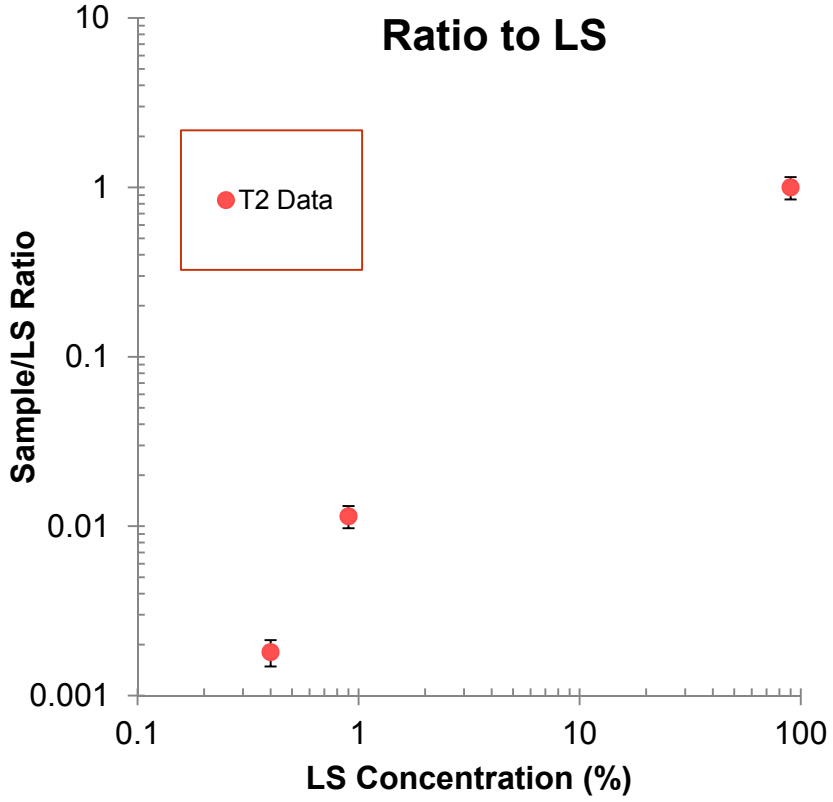
LY of WbLS2 sample with 0.99% LS is approximately 1% of pure LS

**At 475 MeV**




Points offset for clarity

**At 210MeV**

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# Conclusions

- Simulation of a large WbLS detector shows that 90 optical photons per MeV would provide excellent sensitivity to $p \to K^+\bar{\nu}$
- The light yield for WbLS with 0.99% LS is measured to be $\sim$1% of pure LS
- Typical light yield for pure LS is $\sim$10k optical photons per MeV
- We can fabricate WbLS that satisfies the light yield requirements for $p \to K^+\bar{\nu}$

# Plans

- NSRL run on 6 May with new detector designed to better separate Čerenkov and scintillator components of light yield
- Improved Geant4 simulation to obtain better estimate of optical photons per MeV
- Attenuation length measurements in 2 m apparatus

Many thanks to Chao Zhang and Dima Beznosko for their April 2013 APS slides, and to S.Hans, R.Rosero, H.Themann, B.Viren, E.Worcester, M.Yeh

Also see Whitepaper on Water-based Liquid Scintillator

# Backup

# WbLS Formulation: "Do oil & water mix?"

- Organic solvents, such as liquid scintillator (LS), are immiscible in water mainly due to the differences in polarities.
- A surfactant that contains lypophilic and hydrophilic groups is necessary to emulsify (or aggregate) the organic liquid scintillator into the water solvent.
- Engineering of a complexing medium to stabilize the lypophilic and hydrophilic molecules in a water medium with appropriate optical transmission and long stability is the key to WbLS development.
- Non-ionic surfactants of linear alkyl benzene derivatives (sulfonate and amine) were identified for different applications. Linear Alkylbenzene Sulfonic acid (LAS) is used.
- A stable, first-generation, WbLS with sufficient scintillation light has been developed.

# WbLS stability and purification(1)

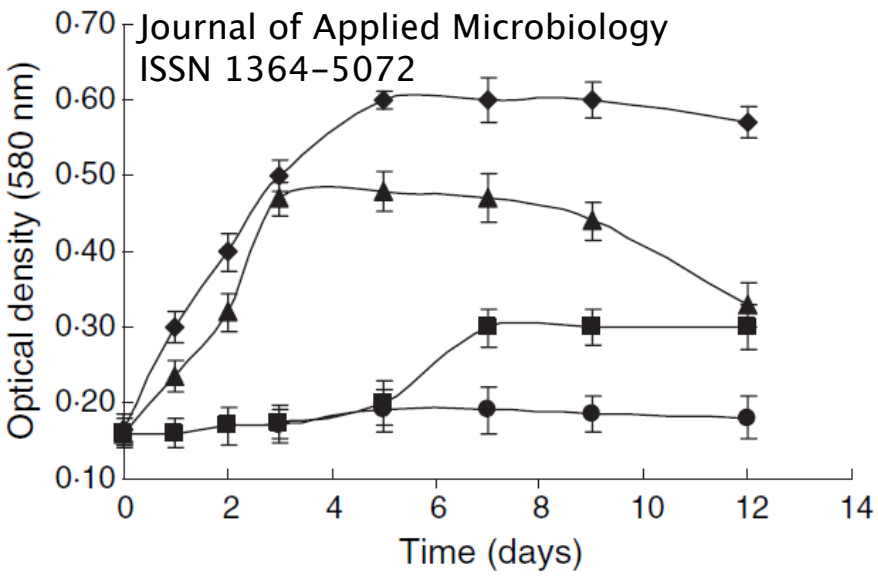


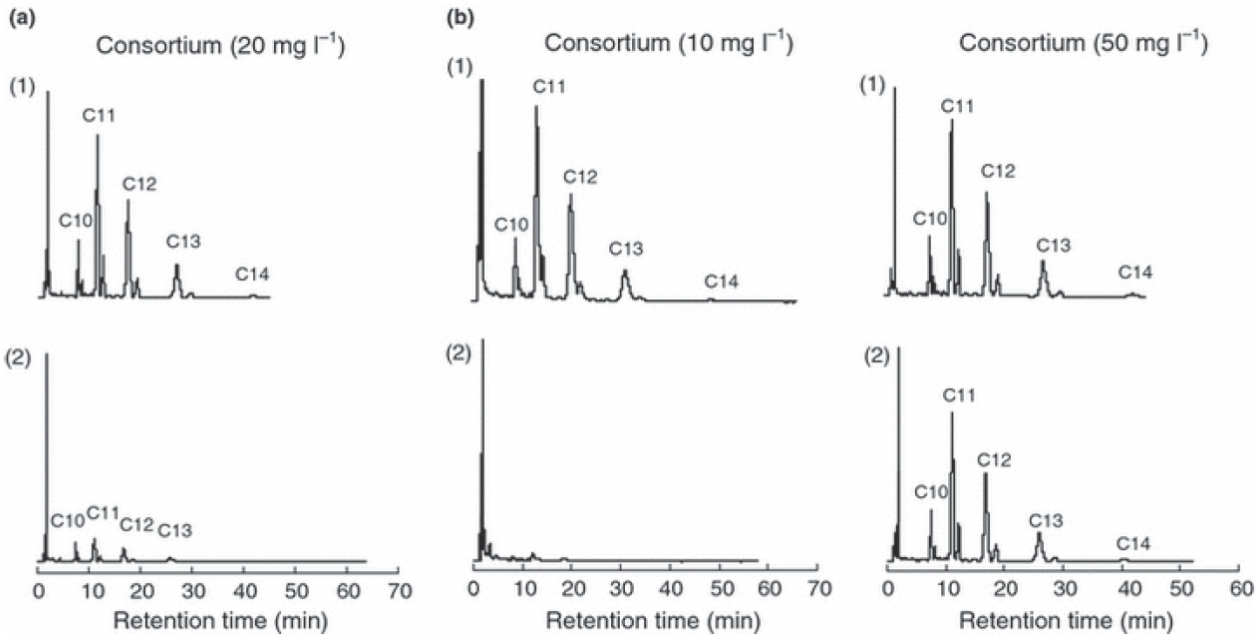

**Figure 5** Time-course analysis of consortium growth at different linear alkylbenzene sulfonate concentrations (in mg $l^{-1}$): (◆) 10; (▲) 20; (■), 50; and (●) 100. Values are means ± standard deviations for three replicates.

- LAS degradation only occurs at <50mg/L
- LAS stability and compatibility (acrylic) stable for 2+ years since formulatior
- LAS at ≥100mg/L completely inhibits bacteria growth (extensive studies by environmental-research groups in academia and industry).

# WbLS stability and purification(2)

- Micro-organism growth is known to degrade attenuation length in water detectors and requires constant circulation
- Inorganic metallic ions can be removed either by vacuum distillation (SNO+) or multi-filtration (GADZOOKS)
- WbLS, a mix of LAS, PC, water and PPO can simplify the online-purification process
  - WbLS can be vacuum distilled
  - 10% LS-loaded water can pass 0.1$\mu$ teflon filter without loss. Testing with ultra/nanofilters planned.
  - Testing with ion exchange and reverse osmosis also planned
- Purification plan
  - All raw materials will be purified before synthesis
  - LAS/PC inhibits bio-activity; is circulation needed? If so, apply filtration and/or distillation.

# Biodegradation

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- LAS degradation only occurs at 50mg/L (0.05%) or lower
- Stability and compatibility (acrylic) are under monitoring; no change since synthesis (2-years+)

Cn: n = # of carbons hooked to benzene ring.

"Retention time" analogous to column height in chromatograph.