Scintillation Detector

- General introduction and physics of liquid scintillator
- Metal-loaded liquid scintillator
- Future liquid scintillator

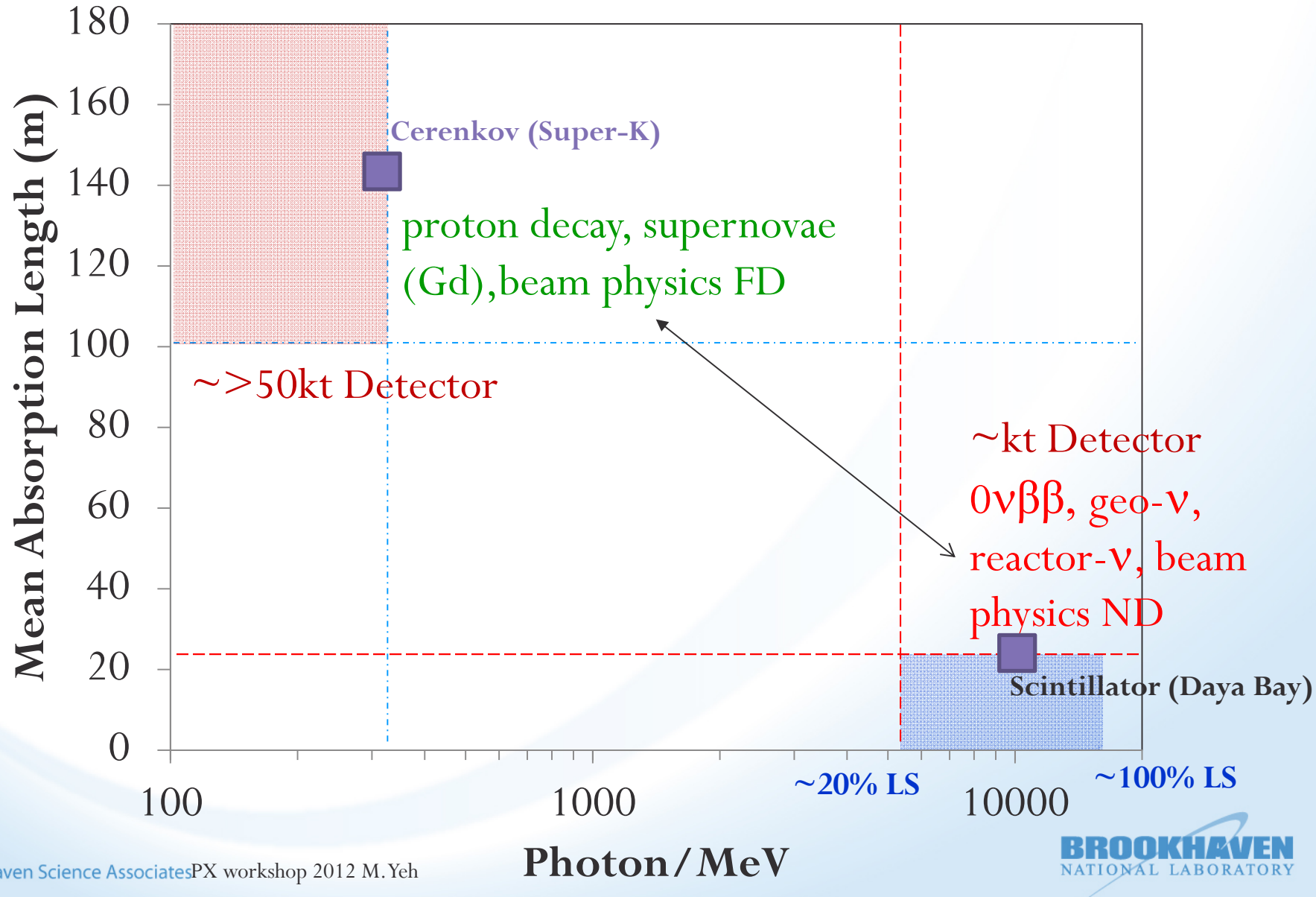
Minfang Yeh (BNL)

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

Typical Cerenkov and Scintillation Detectors



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Main Neutrino Interactions in Liquid Scintillator

- $\bar{\nu}_e + p \rightarrow n + e^+;\ n + p \rightarrow d + \gamma$
- $\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B \rightarrow {}^{12}C + e^- + \bar{\nu}_e$
- $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N \rightarrow {}^{12}C + e^+ + \nu_e$
- $\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^* \rightarrow {}^{12}C + \gamma$
- $\nu_x + e^- \rightarrow \nu_x + e^-$

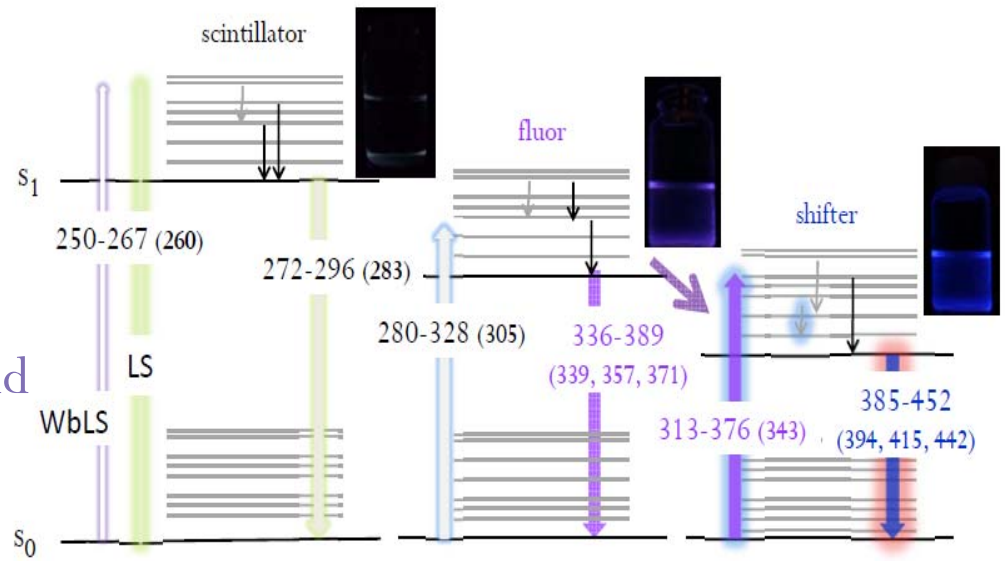
J.M.A. Winter (TU Munchen)

- $\nu_x + p \rightarrow \nu_x + p$
- *Excellent detection medium for neutrino in MeV range; need NC background reduction in GeV range*
- *Profound physics program for Solar-, Geo-, Reactor- &, Supernova-Neutrinos, Neutrino Oscillation, Proton Decay.*
- *Different LS combinations to meet the need of various physics*

BNL Liquid Scintillator Development Facility

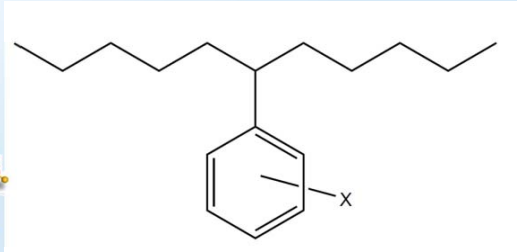
- Collaboration between Physics and Chemistry at BNL with expertise in low-background counting, organic scintillators, and in particular metal-loaded organic scintillator
  - Interest of neutrino and neutron detectors (Daya Bay, SNO+, LENS)
- Investigation of a large variety of liquid scintillators
  - PC, PCH, DIN, PXE, LAB
- Metal-loaded and water-based scintillators with high light-yield, long attenuation length and low flammability.
- Capability of purifying and synthesizing materials in-house and of controlling the chemical processes.

Scintillation mechanism



M. Yeh, Review of Metal-loaded Liquid Scintillator for Neutrino Physics, IJMPB (in prep.).

- ability to catch ionization radiation
- photon-transferring mechanisms once excited (S/F/S)



Comparisons of Liquid Scintillators for Neutrino Expt's

Table 1
The chemical properties and physical performance of selected LS

first identified by SNO+

	LS[a]						
	PC	PCH	DIN	PXE	LAB	MO	DD
Molecular formula	C_9H_{12}	$C_{12}H_{16}$	$C_{16}H_{20}$	$C_{16}H_{18}$	$C_{18}H_{30}$[b]	C_nH_{2n+2}[c]	$C_{12}H_{26}$
Can Gd be loaded into the LS?	Yes	Yes	Yes	Yes[d]	Yes	No	No
Density (g/ml)	0.89	0.95	0.96	0.99	0.86	0.85	0.75
$abs_{430,beforepurification}$	0.008	0.072	0.040	0.044	0.001	0.002	0.001
$abs_{430,afterpurification}$	0.002	0.001	0.023	0.022	~0.000	0.001	~0.000
Purification method[e]	v.d.	c.e.	c.e.	c.e.	c.e.	c.e.	c.e.
Index of refraction[f]	1.504	1.526	1.565	1.565	1.482	1.461	1.422
S%[g]	1	0.46	0.87	0.87	0.98	n.a.	n.a.
H-atoms per c.c. ($\times 10^{22}$)	5.35	3.72	5.45	4.34	6.31	8.05	4.77
Flash point (°C)	48	99	>140	145	130	215	71

[a]See the text in Section 3.4 for the chemical names of these organic compounds.
[b]With alkyl side chain containing 12 carbon atoms.
[c]$n \approx 30$ [17].
[d]Only stable for few months.
[e]v.d. = vacuum distillation; c.e. = column extraction with solid Al_2O_3.
[f]Optical index of refraction at 20 °C, except DIN at 25 °C (cited from Material Safety Data Sheets and Ullmann's Encyclopedia of Industrial Chemistry, 5th ed., vol. A, Wiley, November 1991).
[g]Scintillation yield normalized to 100% PC; n.a. = non-aromatic compounds which do not scintillate.

M. Yeh et al. / Nuclear Instruments and Methods in Physics Research A 578 (2007) 329–339

Past & Present Liquid Scintillator experiments

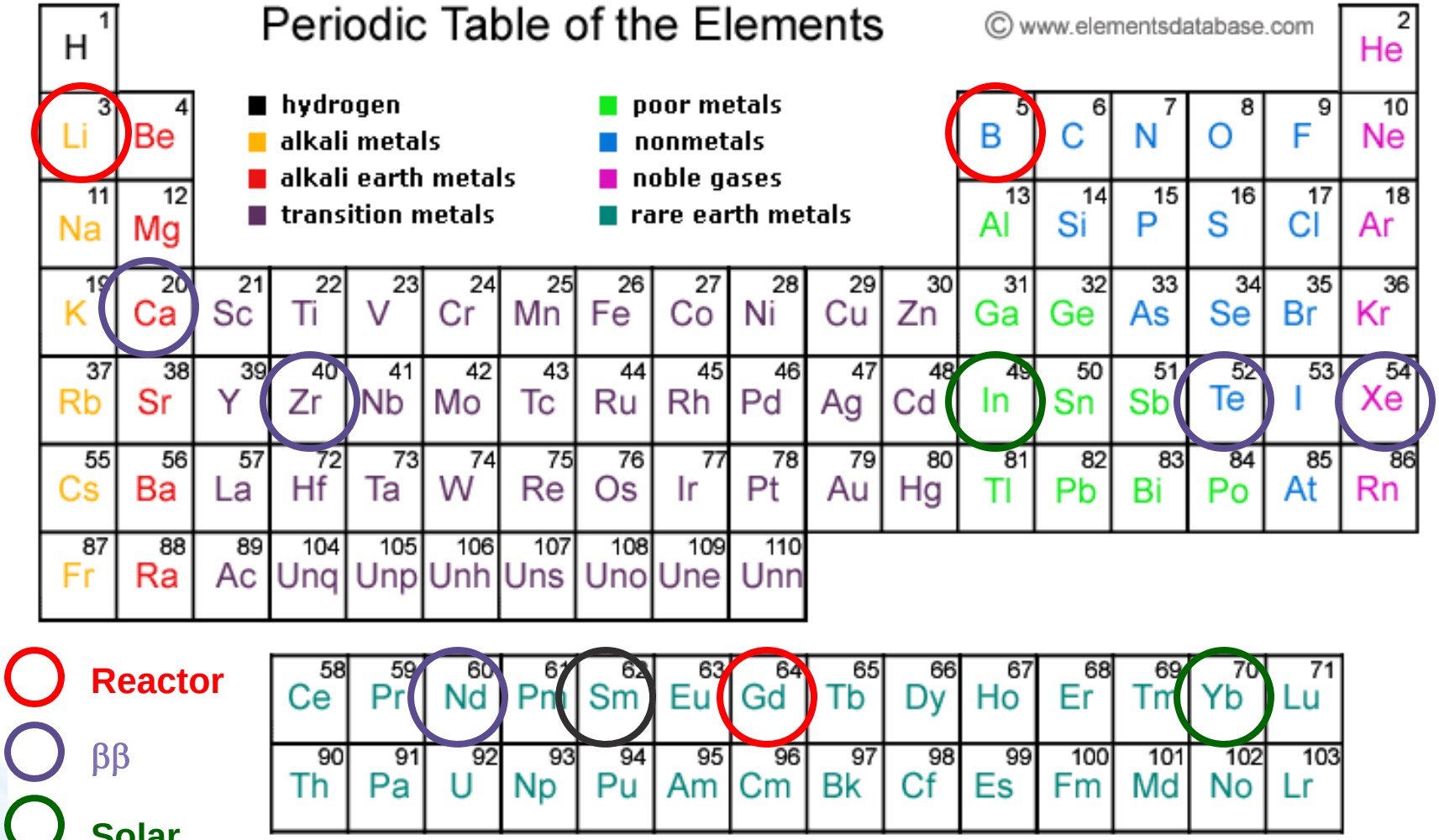
Experiment	Scintillator Mix
Palo Verde	40% PC + 60% Mineral oil
CHOOZ	50% paraffinic liquid + IPB (isopropylbiphenyl)
Borexino	PC
LENS	LAB (PC)
MiniBOONE	MO
Daya Bay	LAB
SNO+	LAB
RENO	LAB
Double-CHOOZ	20%PXE + 80%dodecane
KamLAND^2	20% PC + 80%dodecane
NOvA	5% PC + 95% MO

Possible Future Liquid Scintillator Experiments

Newly Proposed Experiments (selected)
Accelerator-based
LENA
OscSNS
IsoDAR
Reactor-based
Daya Bay-II, RENO-II
SCRAAM, Stereo, NIST
ν-sources
Ce-LAND
LENS-Sterile

- *LS not decided; but LAB is the favor*
- *Gd-loaded for most reactor expt's*

Metal-loaded LS for Physics



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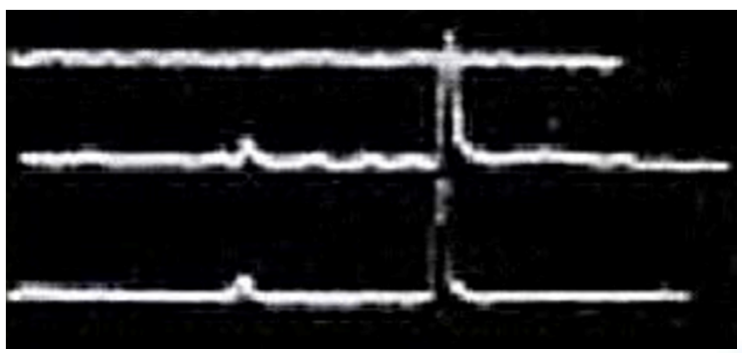
Inverse Beta Decay Detection with Gd

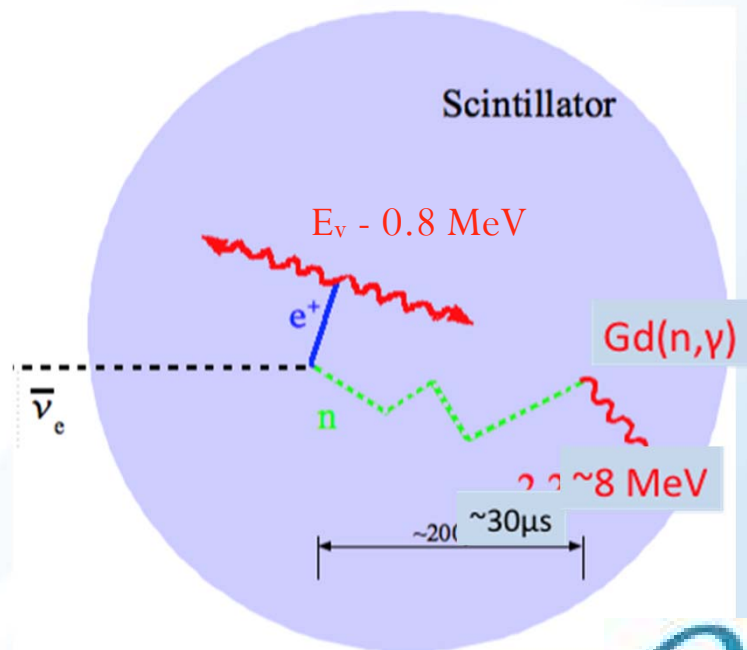
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\mathrm{n} + {}^{A}\mathrm{Gd} \rightarrow {}^{A+1}\mathrm{Gd} + \gamma's$$

- $E_{threshold} = 1.8\ MeV$
- *'Large' cross section* $\sigma \sim 10^{-42}\ cm^2$
- *Distinctive coincidence signature in a large liquid scintillator detector*

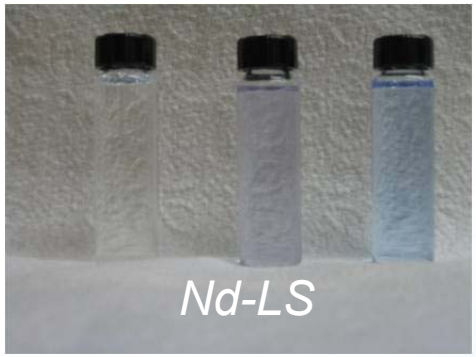


Cowan & Reines, Savannah River 1956



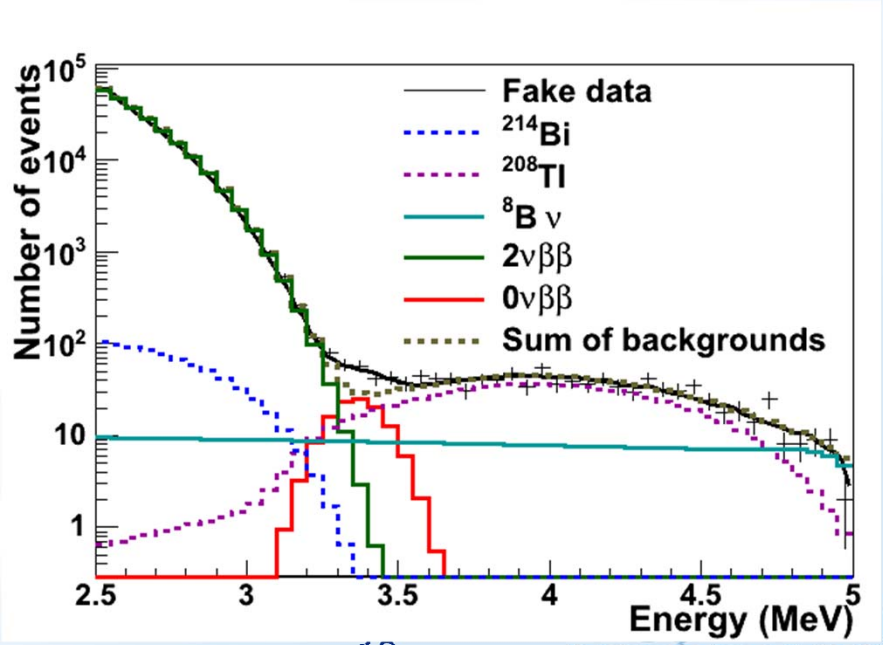
Double-beta Decay using Nd

Isotope	$G^{0\nu}$ (x 10^{-15} y^{-1})	Q-value (MeV)	Abundance %
^{48}Ca	75.8	4.27	0.2
^{76}Ge	7.6	2.04	7.8
^{82}Se	33.5	3.00	9.2
^{76}Zr	69.7	3.35	2.8
^{100}Mo	54.5	3.03	9.6
^{116}Cd	58.9	2.80	7.5
^{130}Te	52.8	2.53	34.5
^{136}Xe	56.3	2.48	8.9
^{150}Nd	249.0	3.37	5.6



Searching for $0\nu\beta\beta$-decay to answer:

- *whether neutrinos are Dirac or Majorana particles*
- *probe neutrino masses at the level of tens of meV; A m_{bb} limit of ~20 meV would exclude Majorana neutrinos in an inverted hierarchy.*



- SNO+ is the only metal-loaded liquid scintillation detector.
- Flexible and easy scale-up
- Any hydrophilic DDB isotopes that cannot be done in pure LS; NOW is possible.
- *Installation and production in FY13*

Low Energy Neutrino Spectroscopy (LENS)

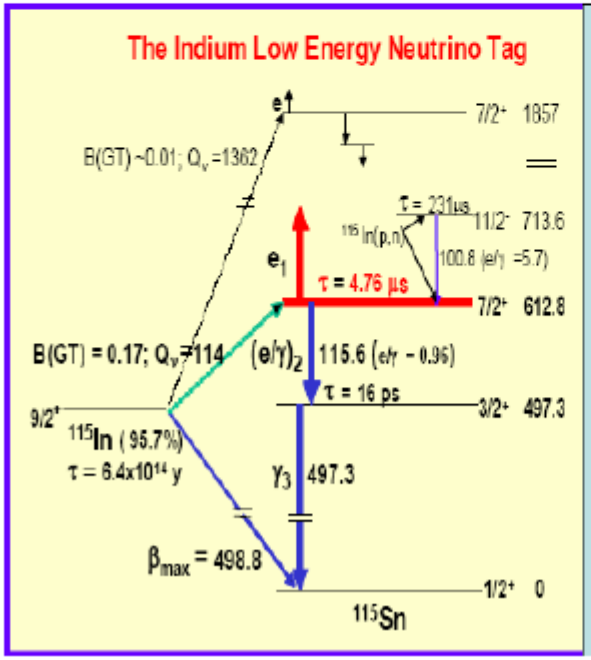
detection of pp, ^{7}Be, CNO and pep solar ν in In-LS, Luminosity of Sun

Tagged ν –capture reaction in Indium

→LENS is the only developed CC real time detector for solar neutrinos

$$\nu_e + {}^{115}In \rightarrow e^- + {}^{115}Sn^* \rightarrow 2\gamma + {}^{115}Sn$$

signal delay Tag cascade



Unique:

- Specifies ν Energy
  $E_\nu = E_e + Q$

→ Complete LE nu spectrum

- Lowest Q known→ 114 keV
  →access to 95.5% pp nu's
- Target isotopic abundance ~96%
- Powerful delayed coinc. Tag
  Can suppress bgd =10^{11} x signal

Downside:

- Bgd from ^{115}In radioactivity to
  (pp nu's only)→ rate= 10^{11} x signal

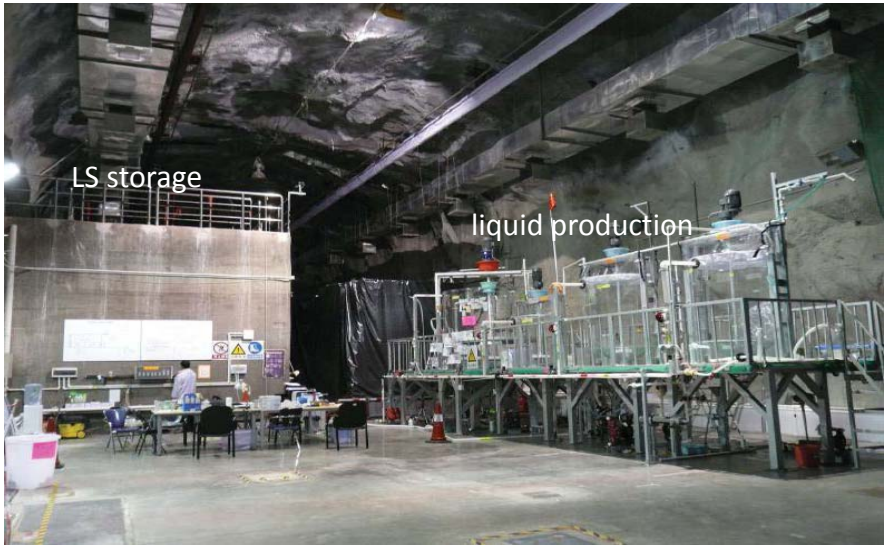
Tools:

1. Time & Space coinc.→ Granularity
   (10^6suppression)
2. Energy Resolution
   In betas <500 keV; ∑Tag = 613 keV
3. Other analysis cuts

- *8% Indium loaded LS meets the experiment needs*
- *micro-LENS is ongoing in Kimberton mine with mini-LENS in preparation*

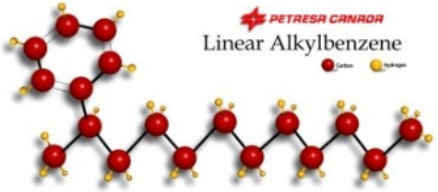
- *Synthesis procedure*
- *Purification (radioactive & optical)*
- *QA/QC*

How to make a clean and stable metal-loaded LS?



Ex. of Gd-LS production at Daya Bay:

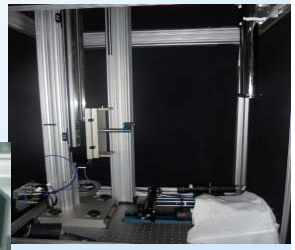
- *Gd-LS production done in 3 months*
- *>3-yrs R&D and >1-yr 1-t prototype monitoring on Gd-LS stability*
- *Optical improvement and U/Th removal*
- *QA/QC during and after production*



Low flash point, compatible light-yield, know-how production, high compatibility

Self-scavenge, PH-controlled Gd salt purification

+



Self-scavenge Gd purification

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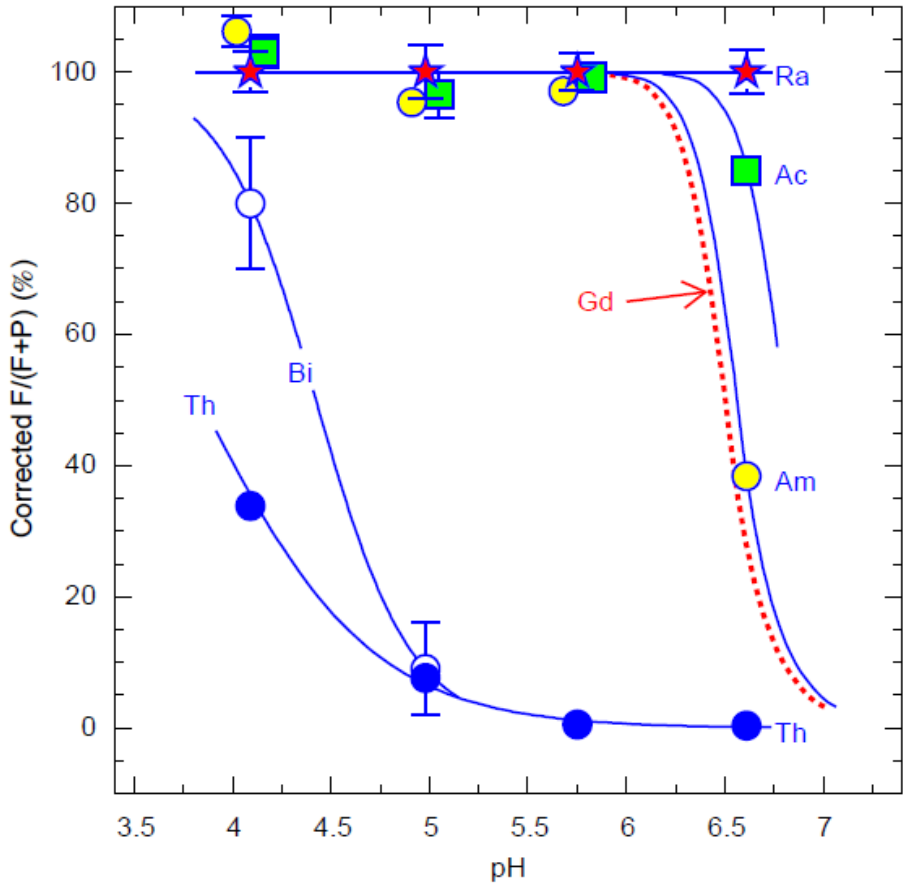


Fig. 7. Fraction of the activity of tracers for five elements remaining in the filtrate as a function of pH. Values are in percent of the total recovered activity, corrected for losses to the precipitate. The horizontal line at 100% for Ra is a consequence of the use of ^{225}Ra to correct for those losses, see text. The dashed curve is based on

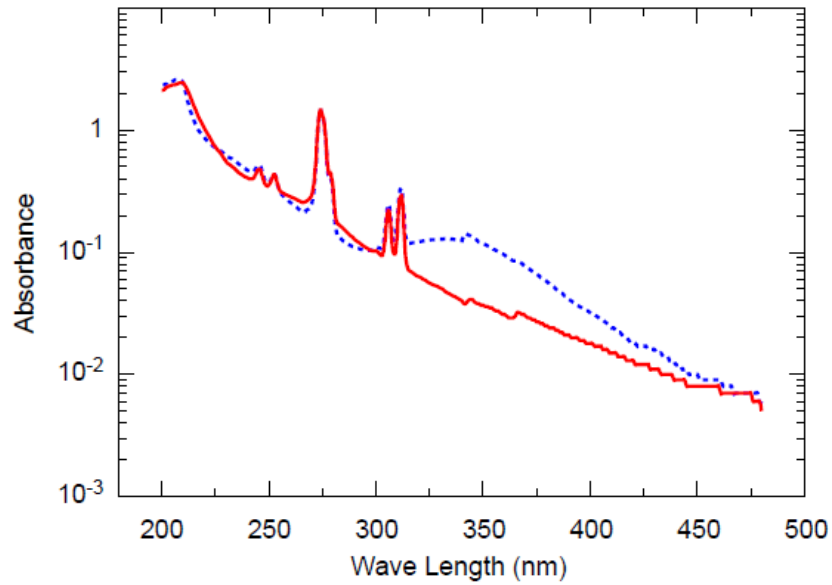


Fig. 8. Optical spectra of a 2.4% aqueous $GdCl_3$ solution before (dashed) and after (solid) adjustment to pH 6.0 and filtration. Removal of the broad band at ~340 nm due to iron is apparent. Peaks due to Gd remain essentially unchanged.

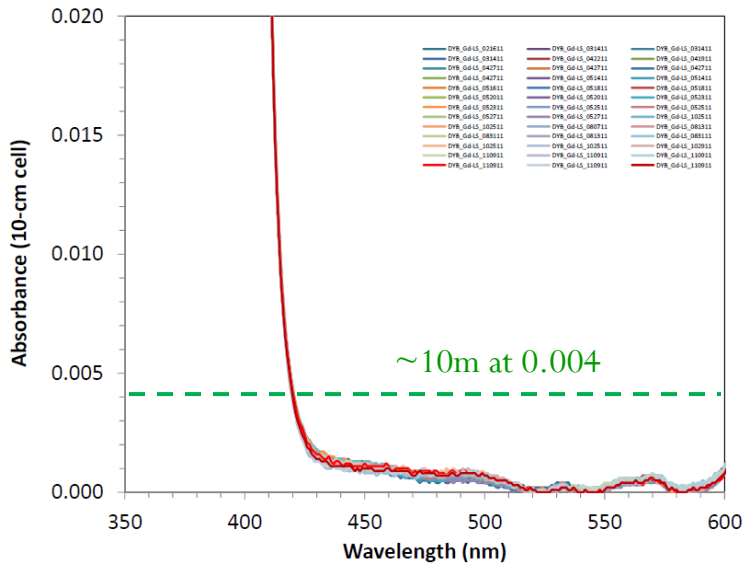
- *U/Th removed to < 0.1 ppb*
- *Optical improvement by 2x from 300-450nm*

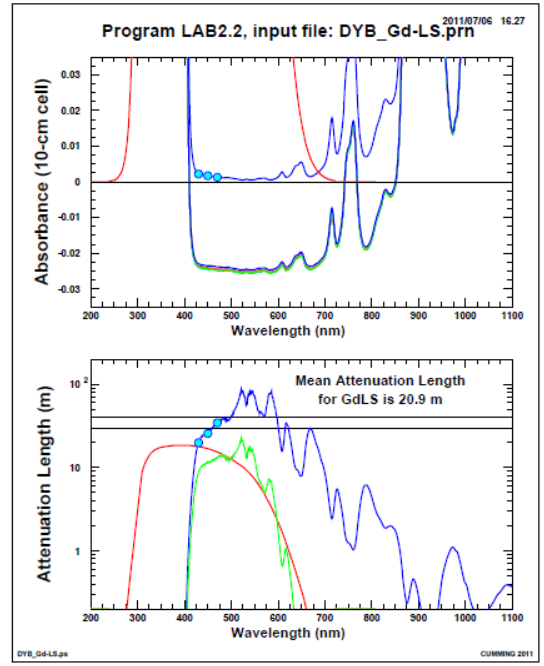
Complexing acid and PPO purifications

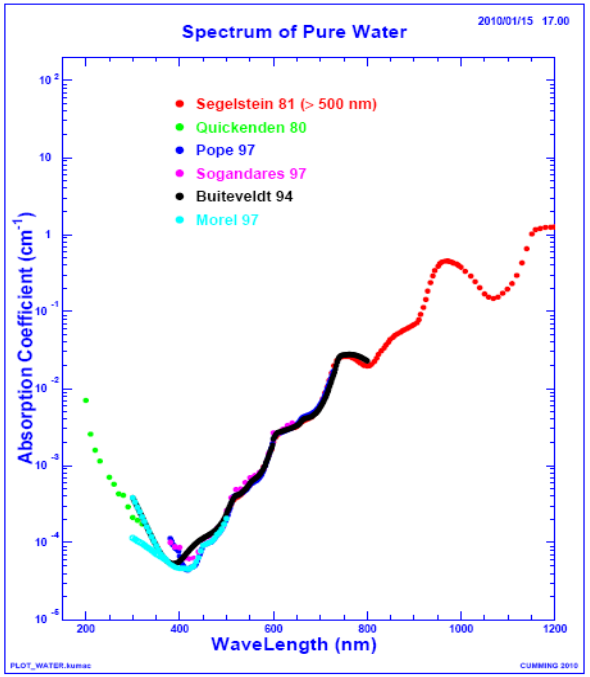
- *Purification is a must for optical and stability improvements.*
- *LAB produced specially by the vendor.*
- *PPO purified by re-crystallization after washes (can also purified by mixing in PC or LAB by direct distillation)*
- *Gd-complexing ligand purified by thin-film vacuum distillation.*

heavy potion removed from the ligand solvent by 3x in 300-500nm

Absorption Length Calculation







UV + $\lambda_{1/e}$ LBNE simulation match with the 2-m measurement very well!

	Gd-LS	LS	LAB
λ (m)	20.9	20.4	22.8

Water has long attenuation lengths (136 – 200m) observed by Super-K, SNO, etc.; dominated by scattering <350nm

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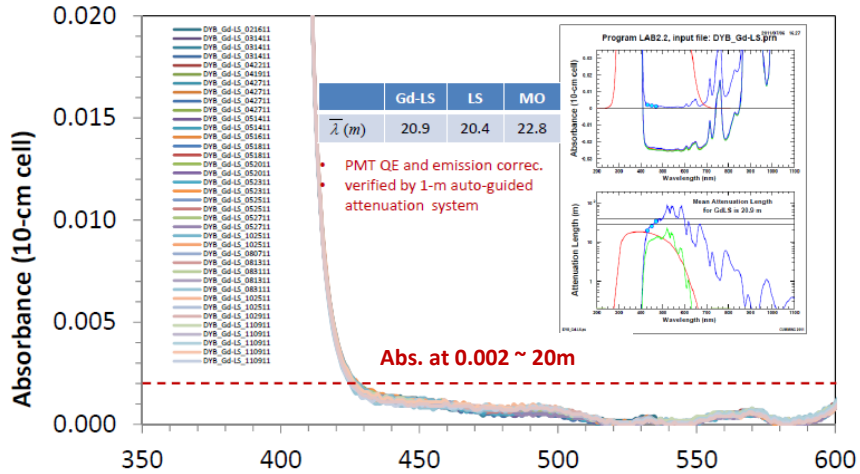
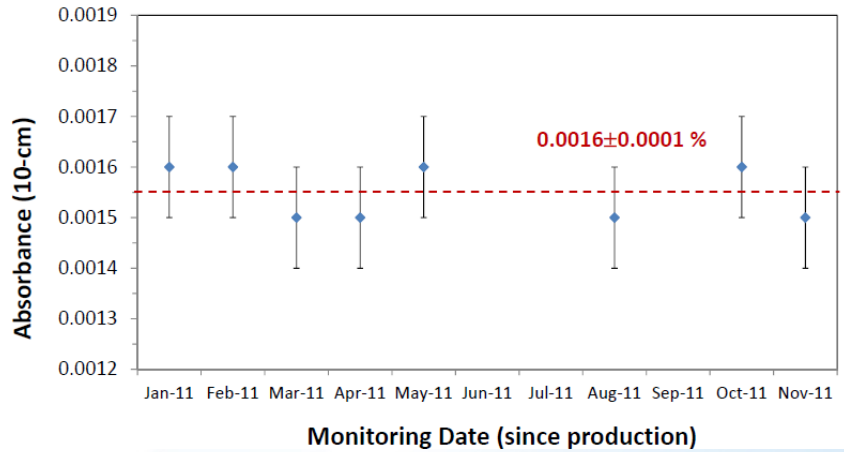
QA/QC and AD Identification

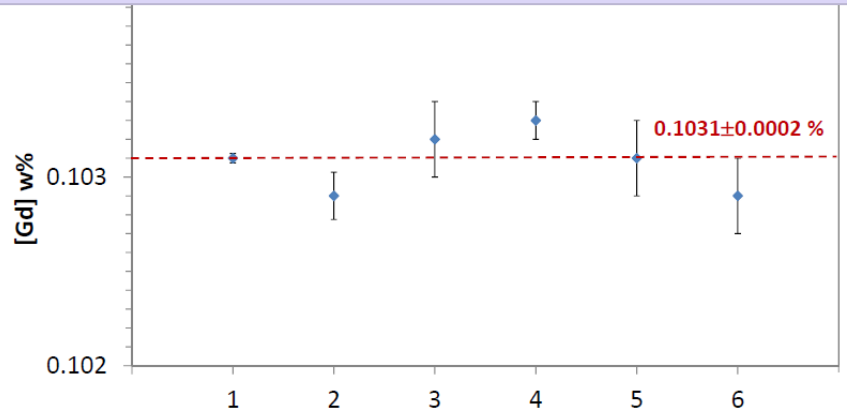
- *Stability*

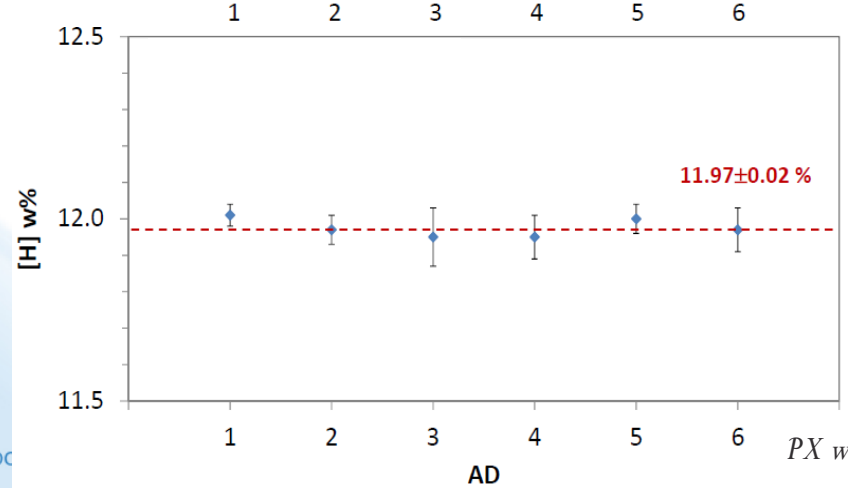
All 6 ADs:

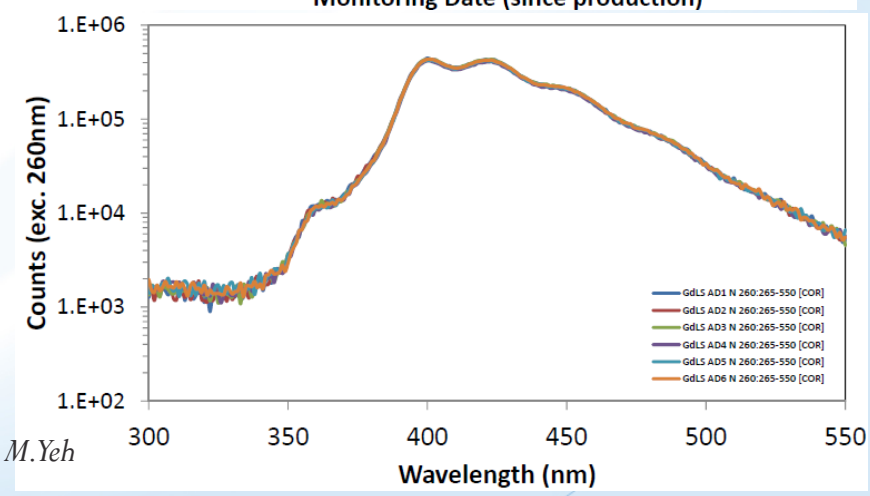
- *[Gd] agrees within 0.16%*
- *[H] agrees within 0.17% (Combustion analysis)*
- *[Gd-LS] $\lambda_{ave.}$ >20m*
- *Light-yield emission agrees within 1% (Fluorescence Spectroscopy)*











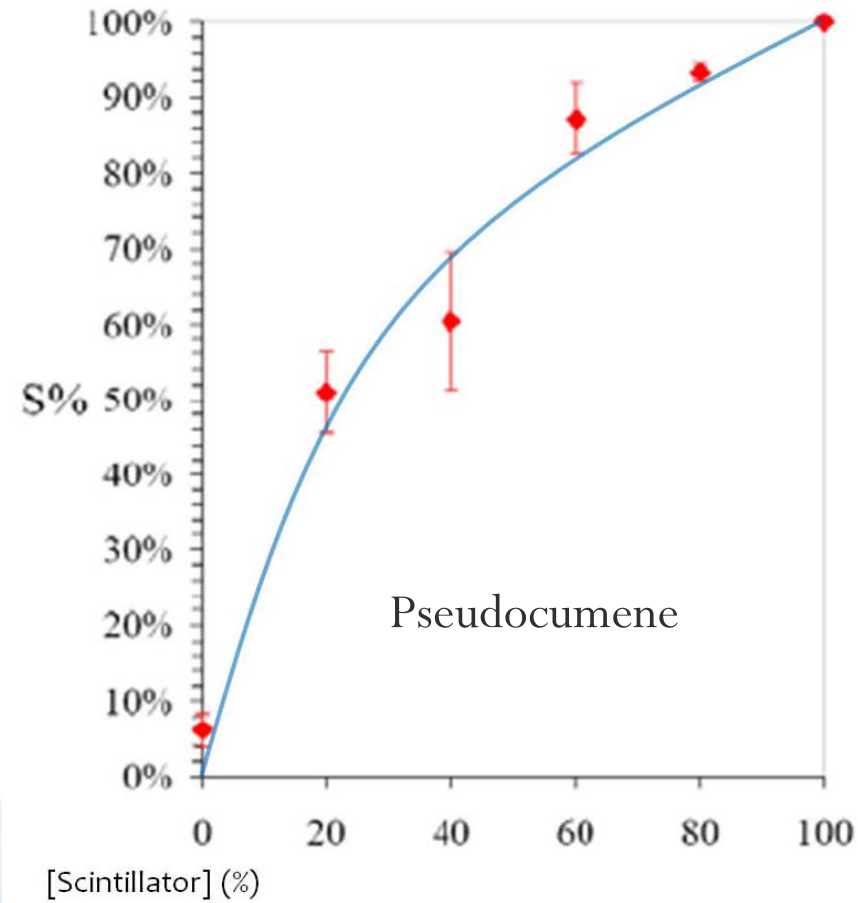
PX workshop M.Yeh

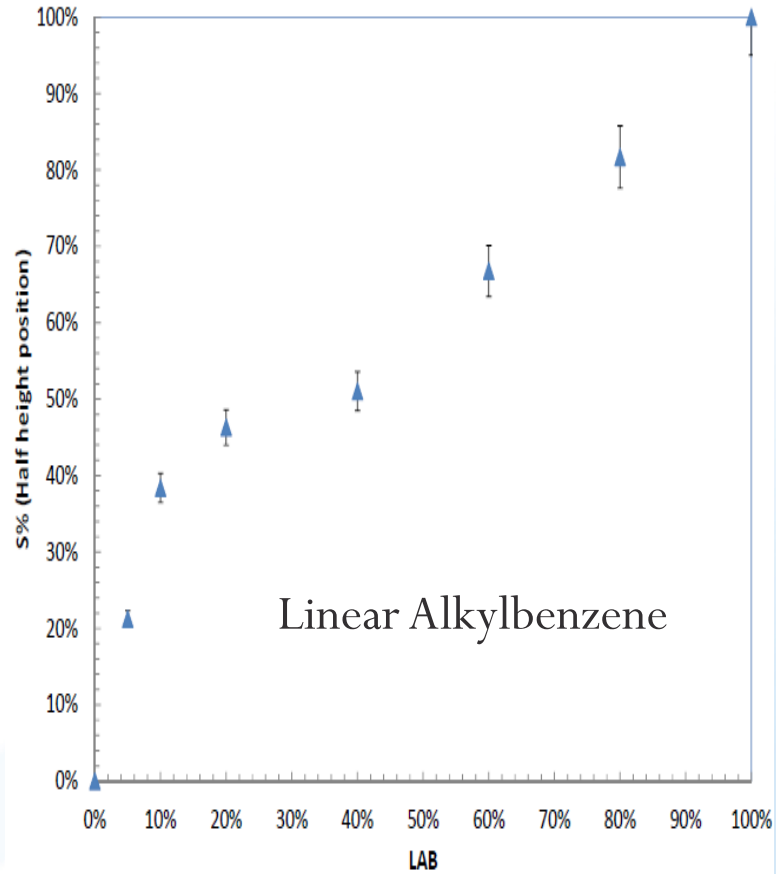
- *Binary liquid scintillator*
- *Singular liquid scintillator*
- *Water-based liquid scintillator*

Liquid scintillator Options for future experiments

Option-1: Binary scintillating liquid system

Linear Alkylbenene + dodecane or mineral oil



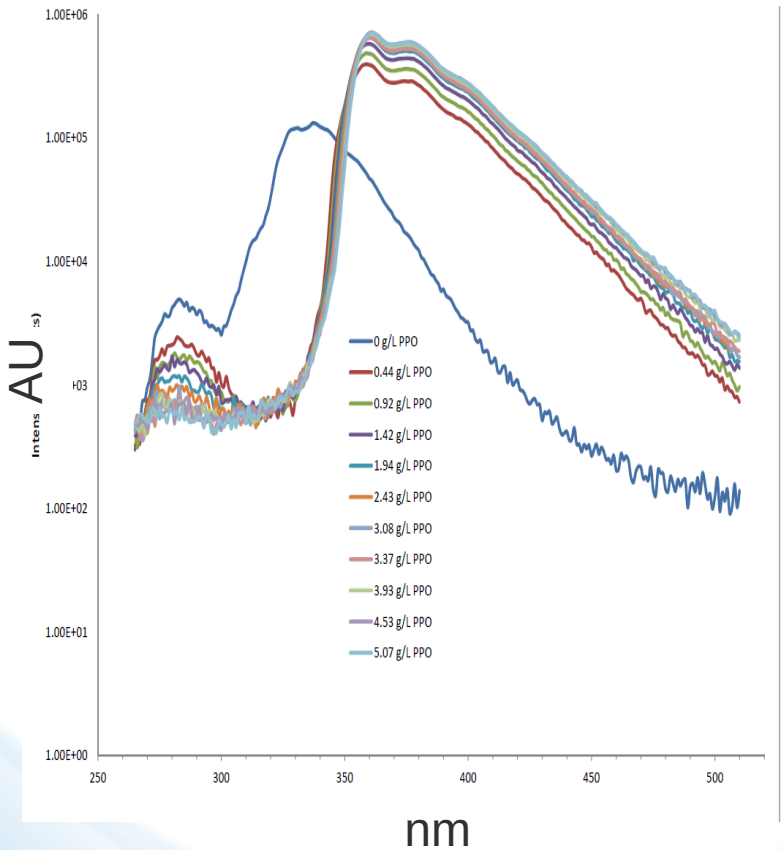


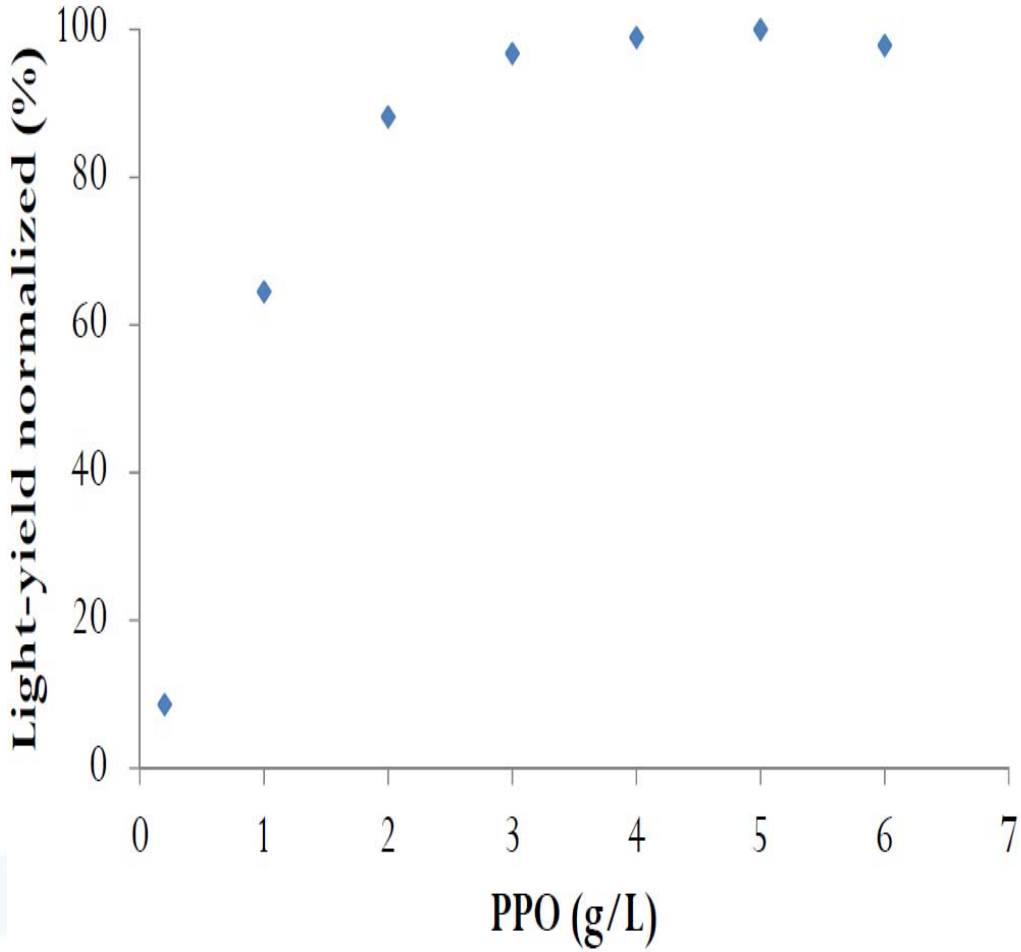
Density Matching and Solvent Purity are the keys to the stability of binary system

- *For the bottle with 2 phases, the top layer is light mineral oil at 80% with 0.00529%Gd and the bottom layer is PC at 20% with 0.01149%Gd.*
- *Others of Gd in PC and DD with and without shifters have been stable since 2005.*

Option-2 singular liquid scintillator

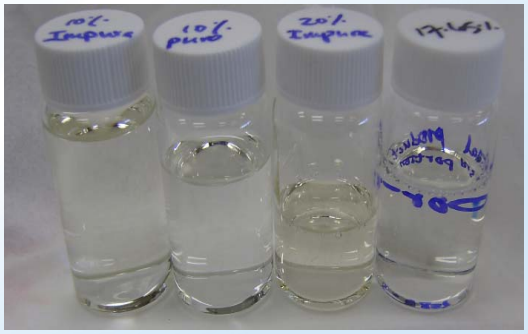
LAB + PPO (3g/L) + bis-MSB (15 mg/L) ~ 10,000 γ's / MeV



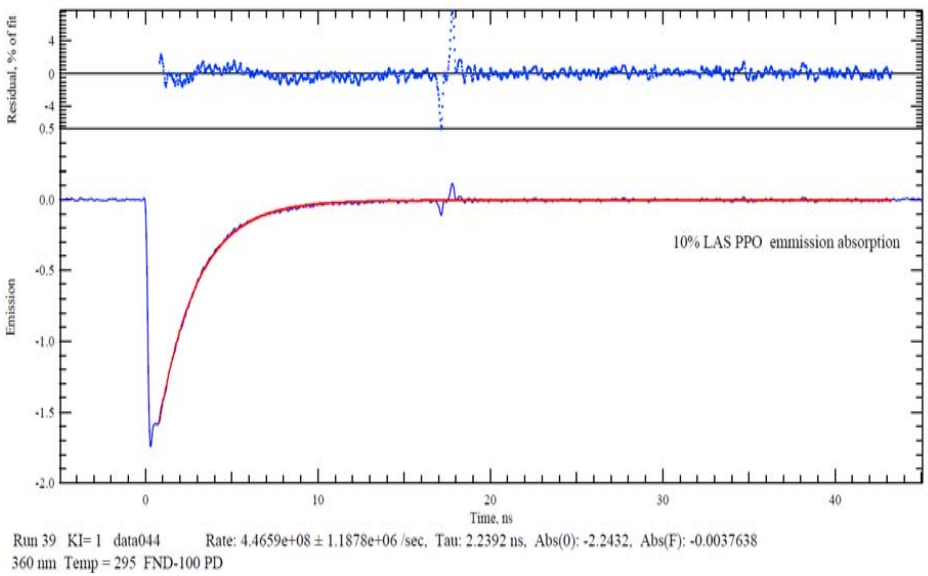


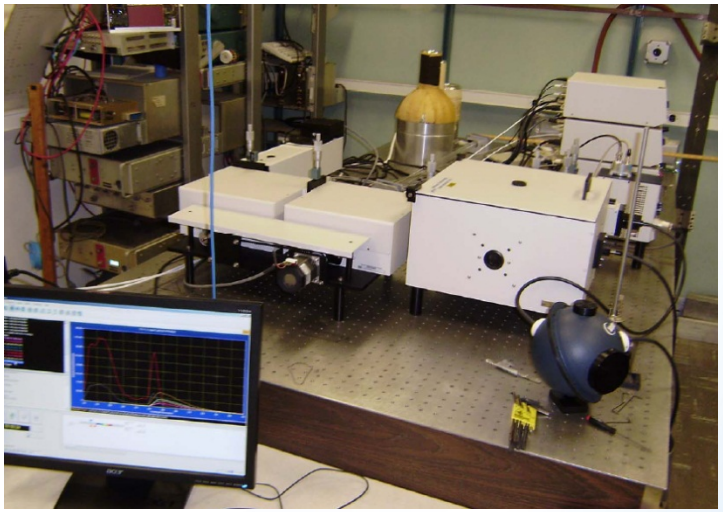
Option-3: Water-based Liquid Scintillator

- *Cost-saving for larger detector (see talk in cost-effective detector session)*
- *Clean Cerenkov cone with scintillation at few hundreds of photons per MeV (tunable)*
- *Fast pulse and long attenuation length with minimum ES&H concerns*
- *A new technology ready to use:*
  - *Excellent detection medium for proton decay; and other physics*
  - *Easy to be handled for large detector*
  - *Gd-soluable*
  - *A economic large veto solvent*

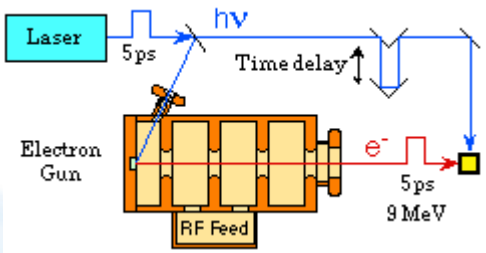


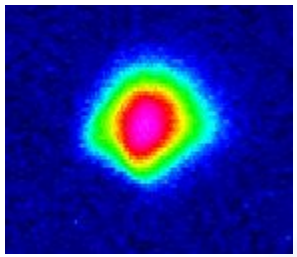
$\tau_{WbLS(PPO)}$ *between 2 – 4 ns*



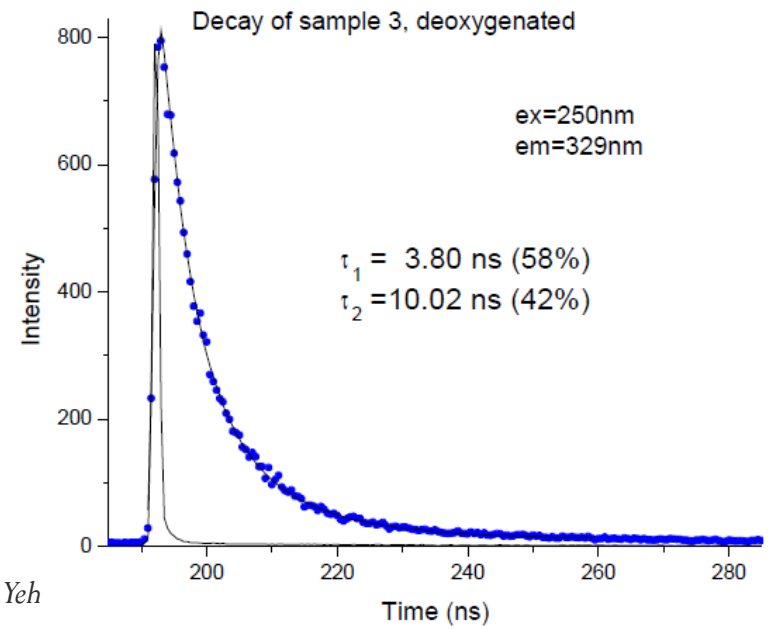


Time-resolved fluorescence system

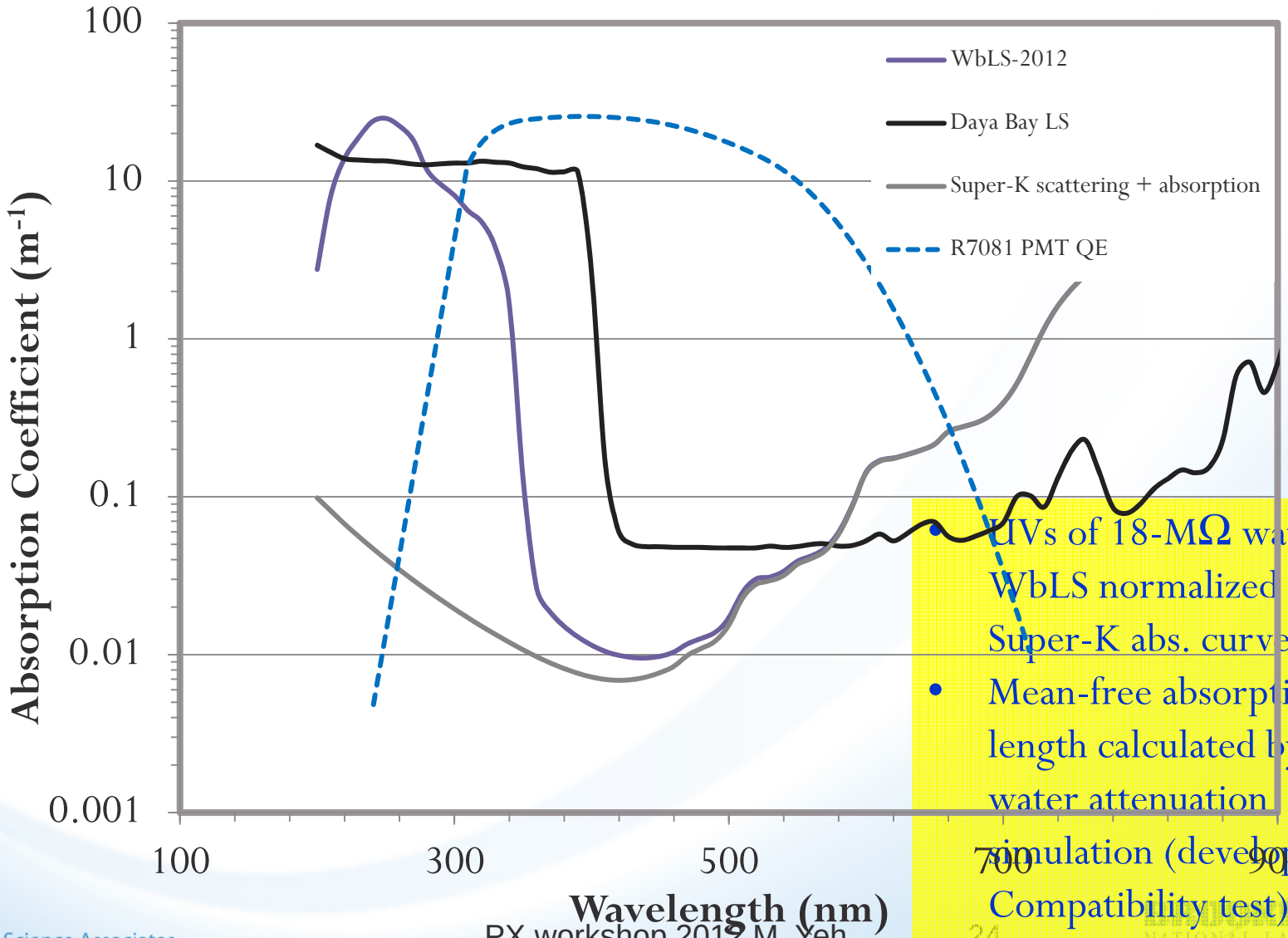




10-MeV e⁻ beam at LEAF

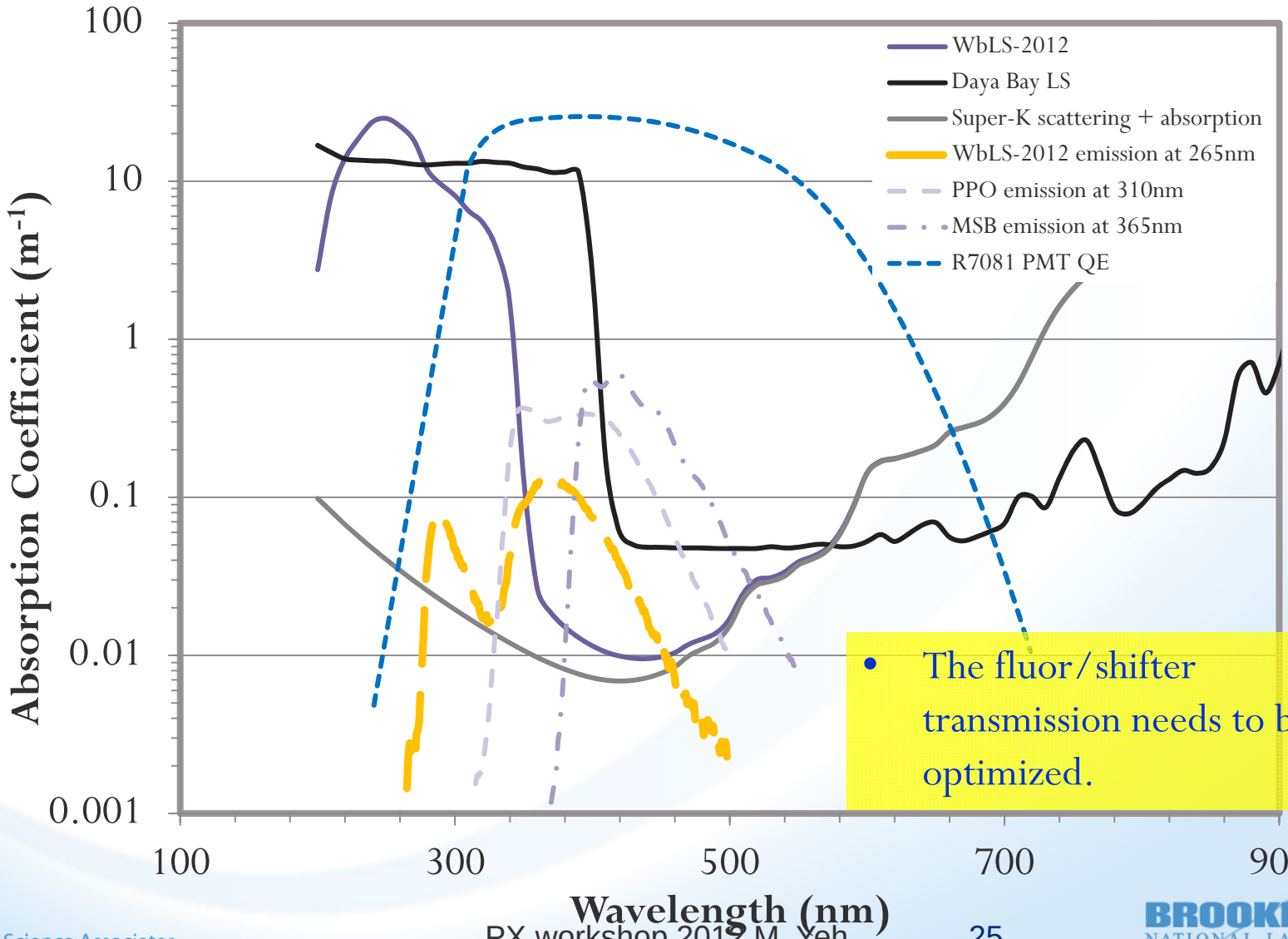


WbLS Attenuation Length close to pure water after 400nm



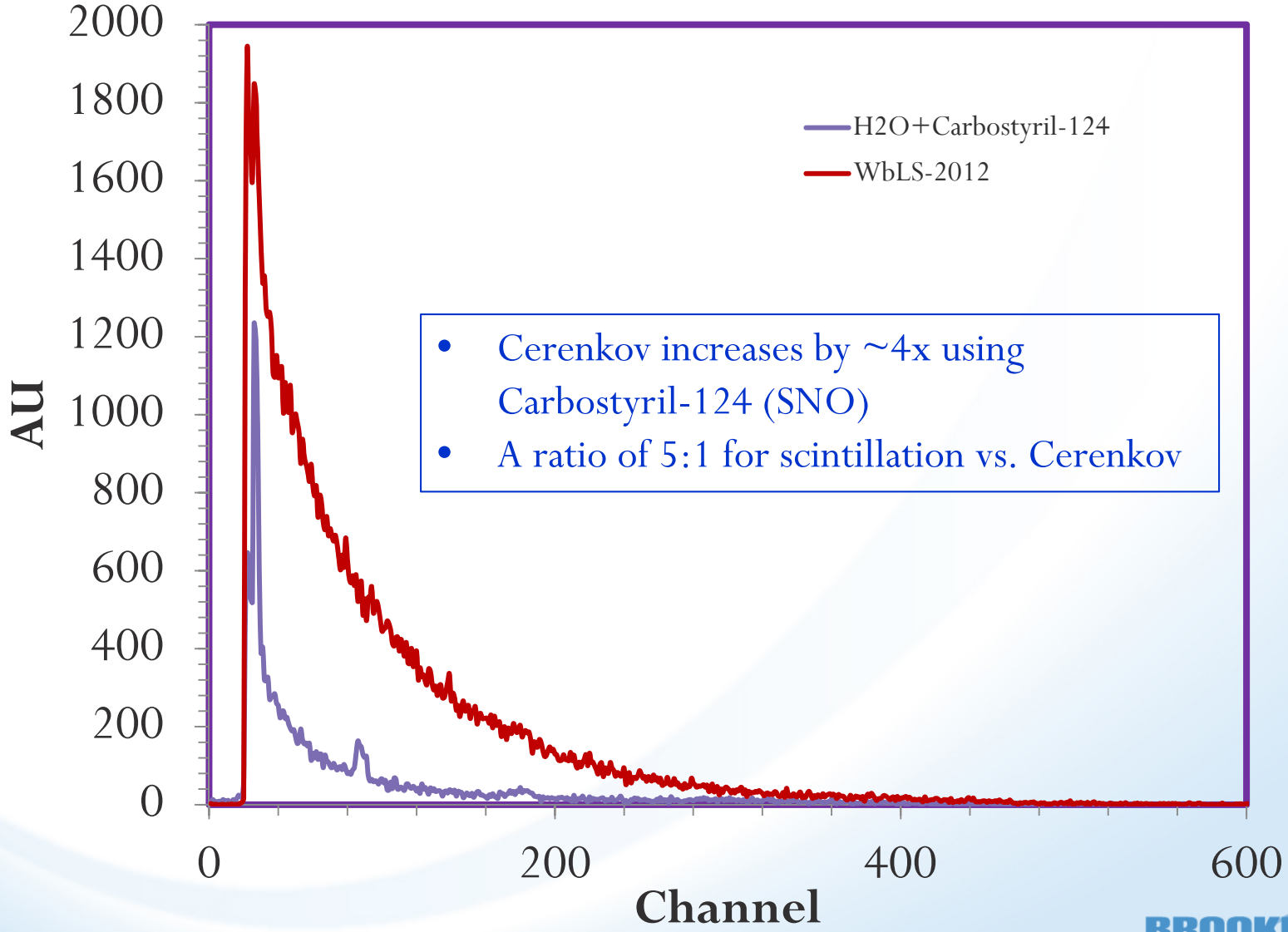
- UVs of 18-MΩ water and WbLS normalized to Super-K abs. curve.
- Mean-free absorption length calculated by LBNE water attenuation simulation (developed for Compatibility test).
- *Need large-scale verification*

Emission at the PMT sensible region is very 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

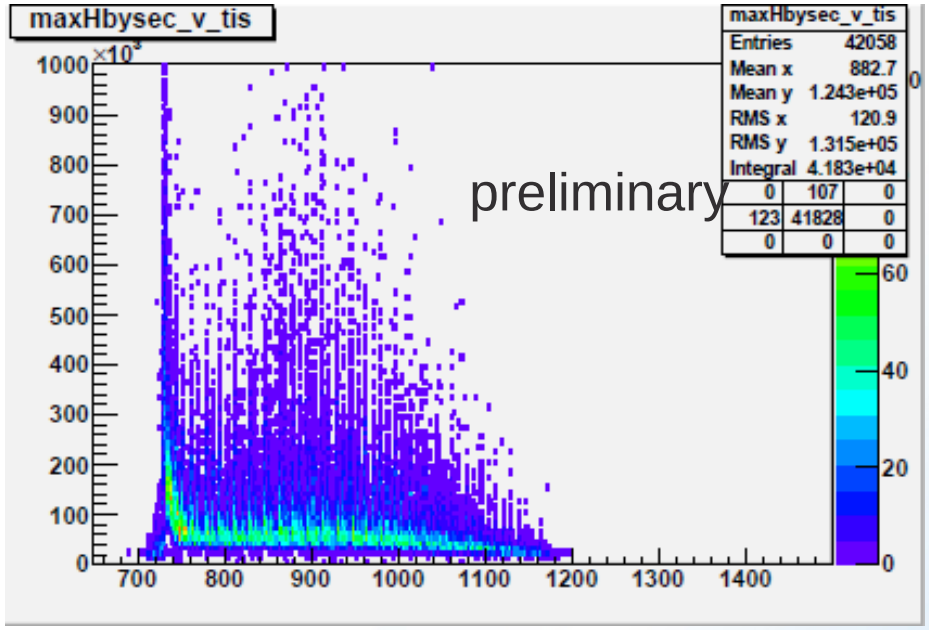
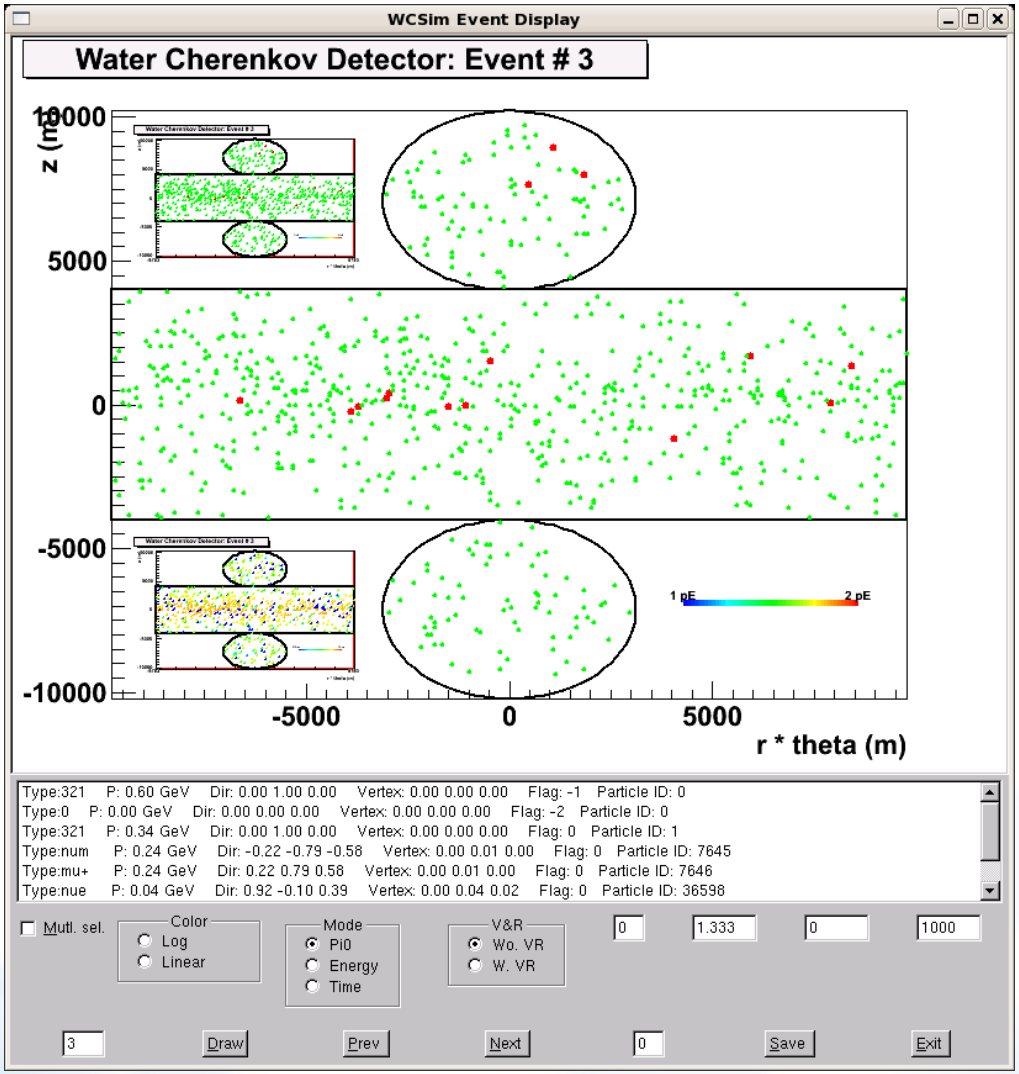
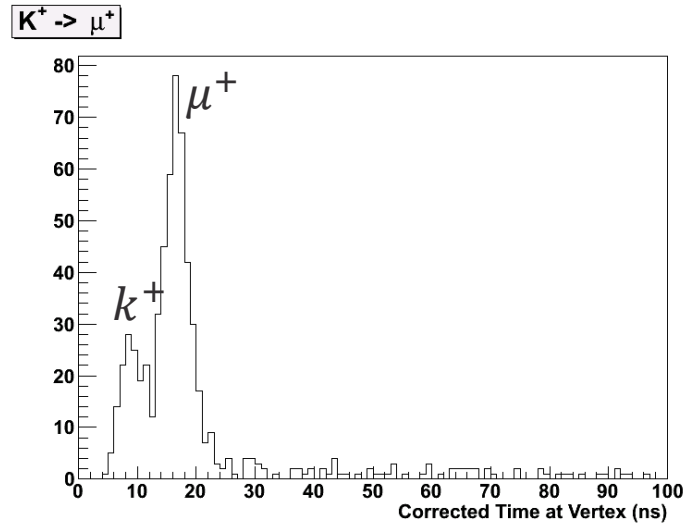


Figure 2: The instantaneous intensity in Hz as a function of time in spill in ms.

- 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.).

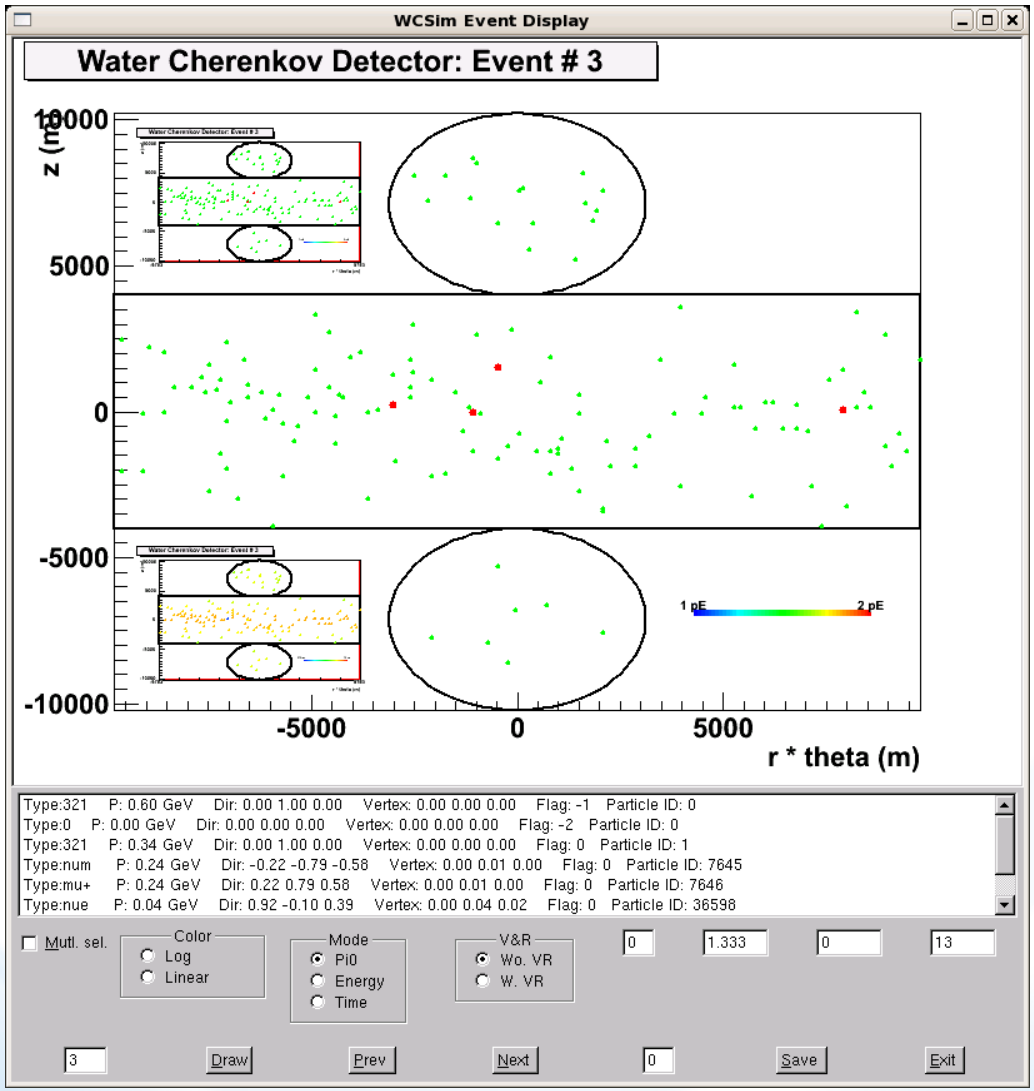
Scintillation light at 90 γs/MeV





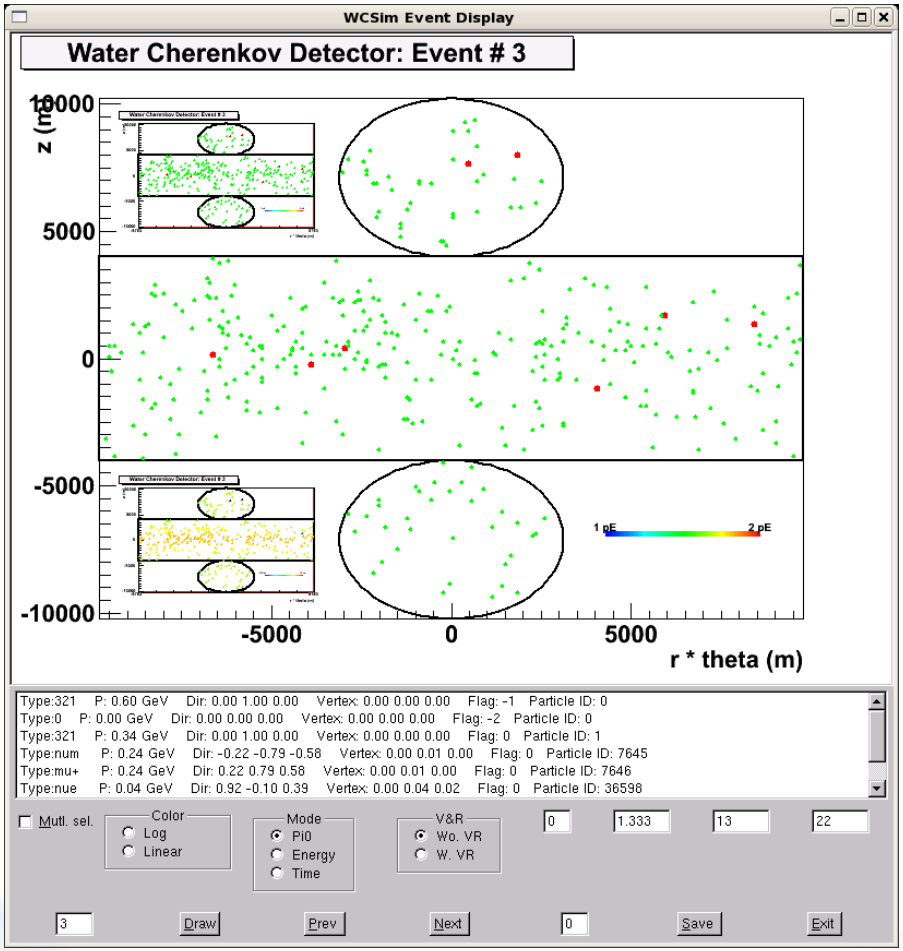
- one event <u>No Cut</u>
- select different timing windows for k^+ and μ^+ events

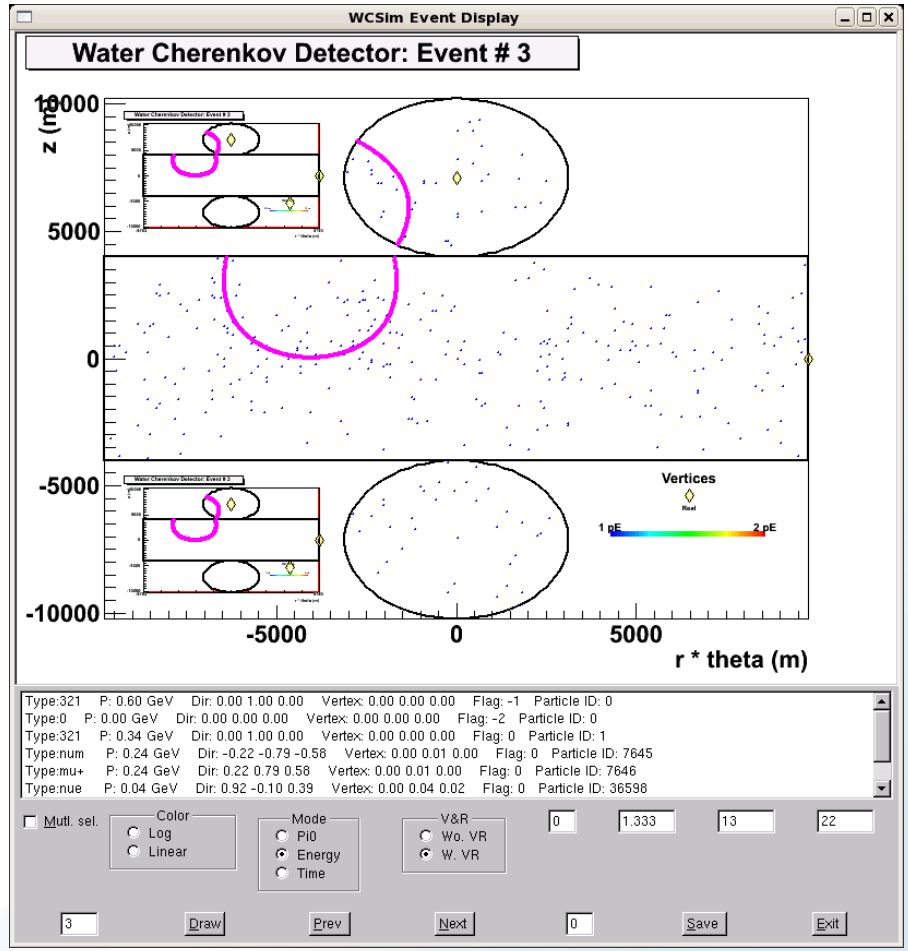
Select the k^+ Timing Window (0 →13ns)



- *scintillation light only*
- *no Cerenkov ring*

Select the μ^+ window (13→22ns)





clean μ-rings can be identified among scintillation

Sensitivity of WbLS for PDK+

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

  Prompt
  - **K^+ scintillation**

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

- *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.*

- ***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…**

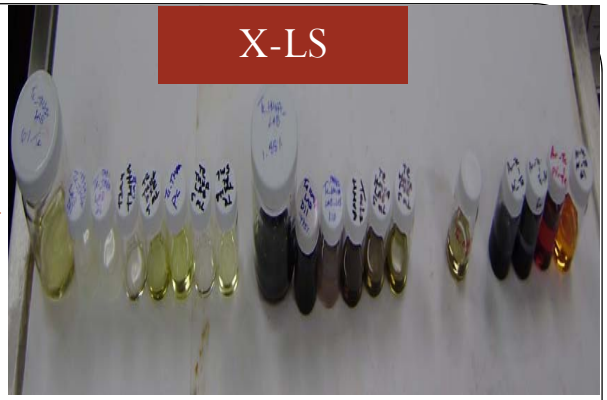
- *10-yr run could reach a sensitivity of 10^{34} for the PDK^+ mode).*

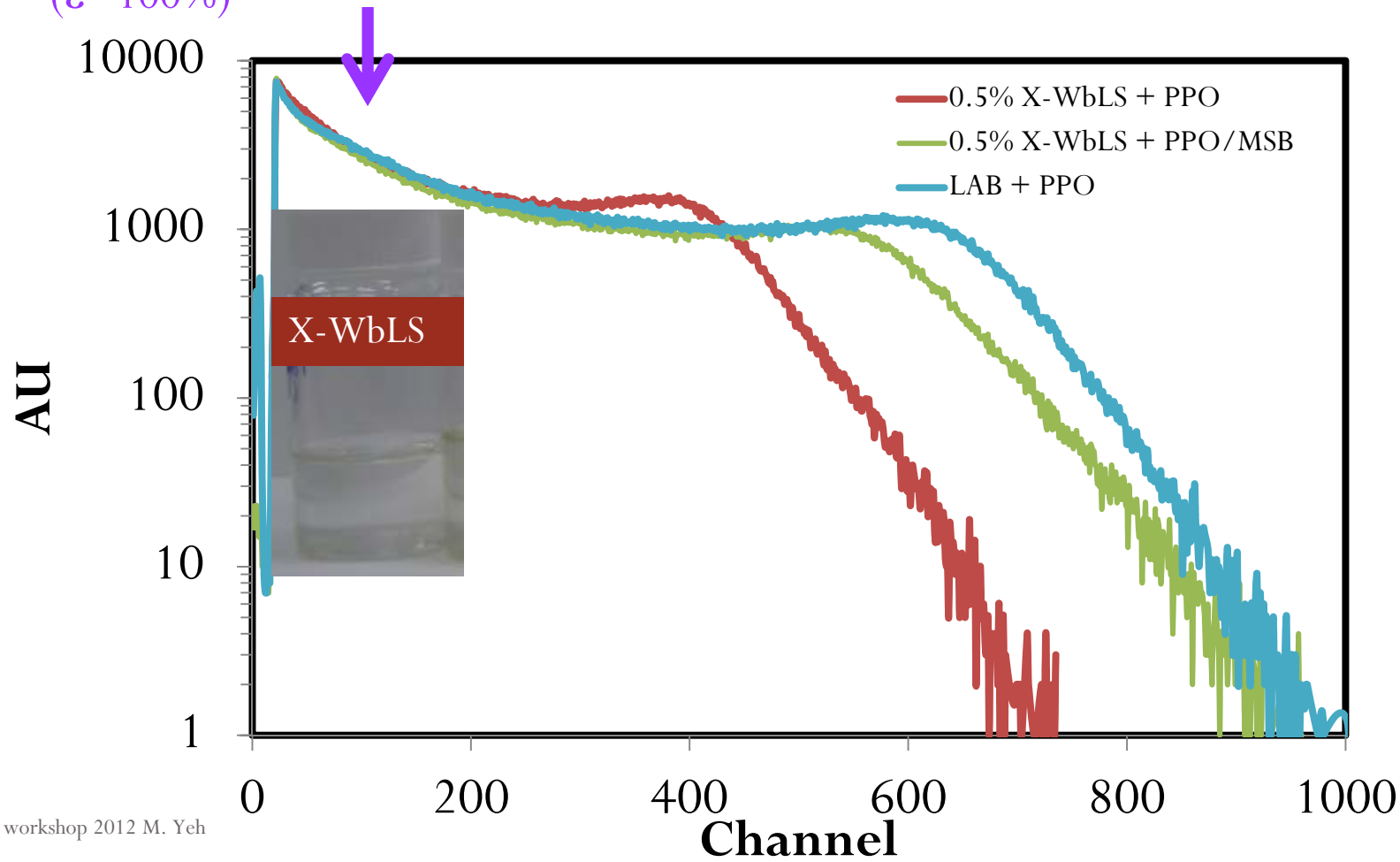
- *Double-beta decay*
- *Reactor neutrino*
- *Geo neutrino*
- *Supernovae neutrino*

A new way of loading hydrophilic metallic ions (Li, Ca, Te, etc) in scintillator

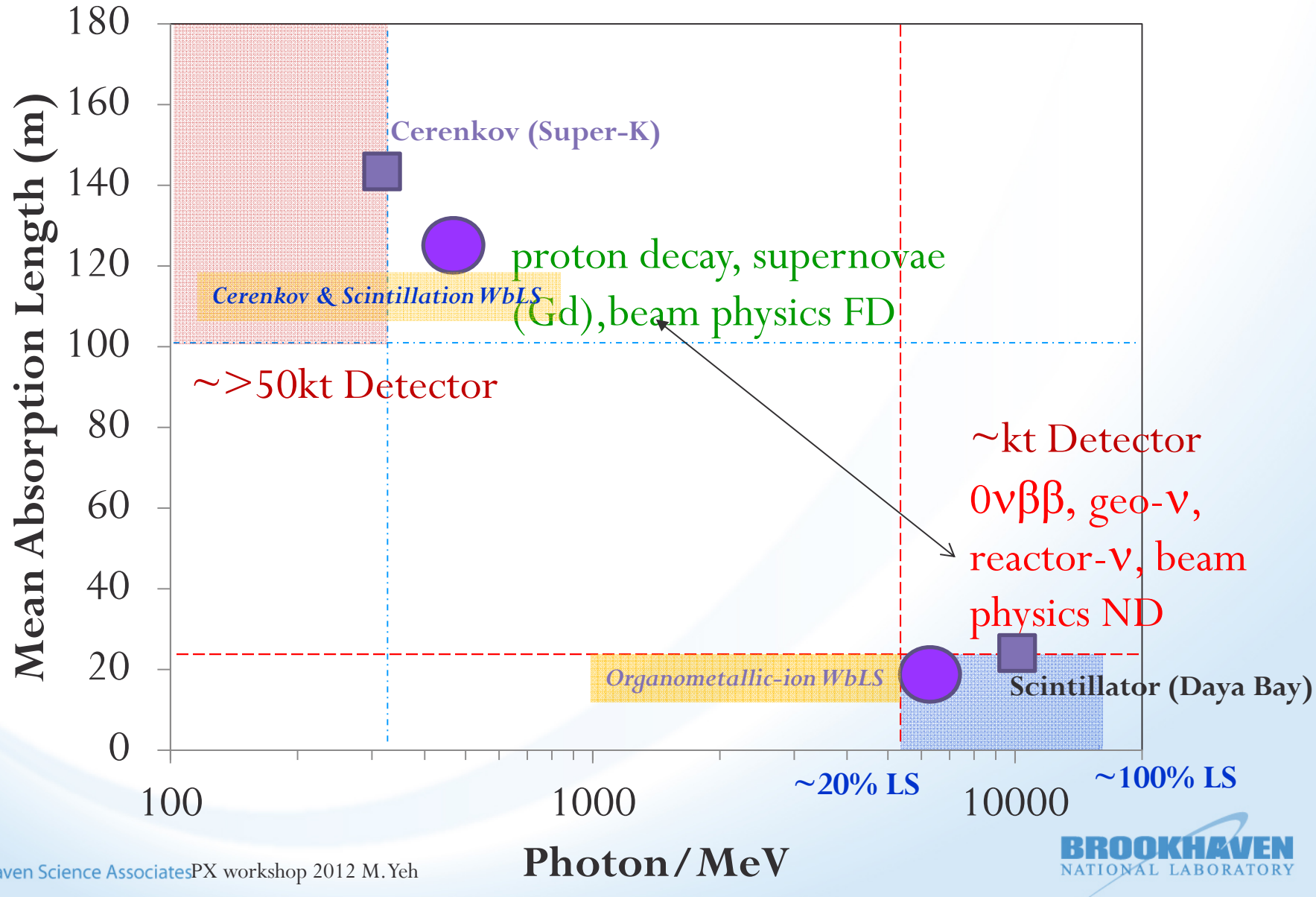
First DBD isotope in WbLS

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





Typical Cerenkov and Scintillation Detectors



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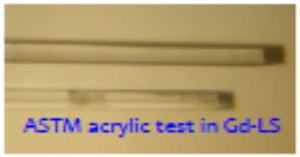
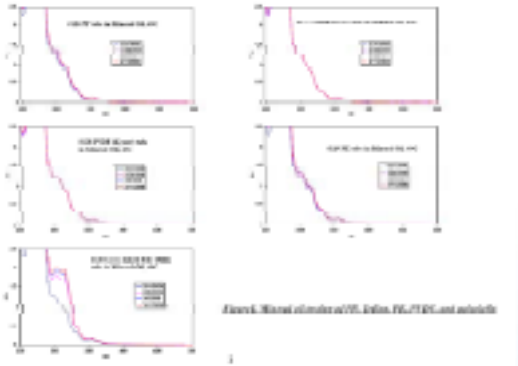
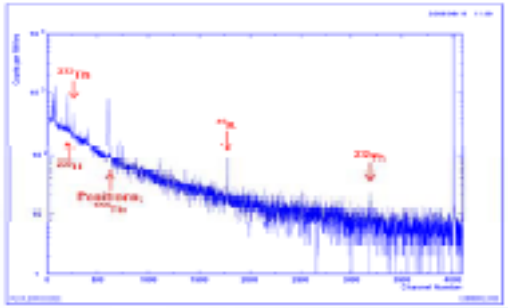
LS reactivity (compatibility) favors LAB

Material Compatibility and Cleaning Program

- Current study
  - the liquid-effect on material
  - the material-effect to liquid
  - Kinetics of leaching
  - ~400 samples being tested in H_2O, LS and Gd-LS
- Future study:
  - develop pre-cleaning procedures to reduce the cost and time for purification
  - identify the leaching-materials by GC-MS, ICP-MS, XRF
  - compile a database for science community







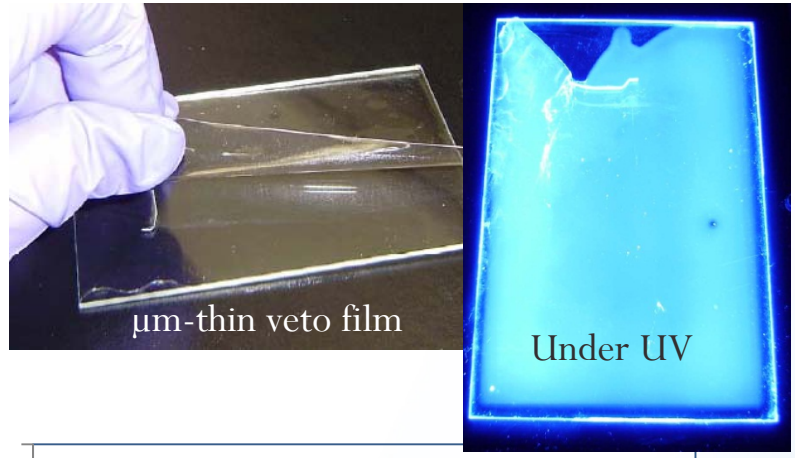
Material and chemical QC/QA Assessment

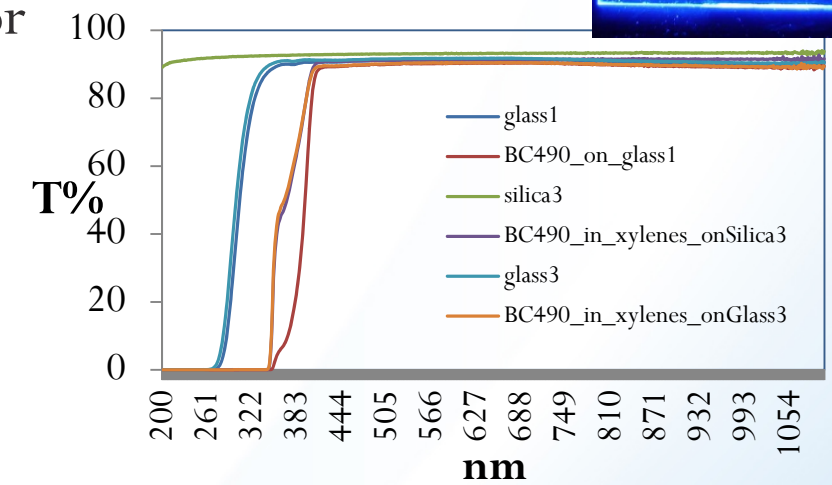
BNL leading the role of

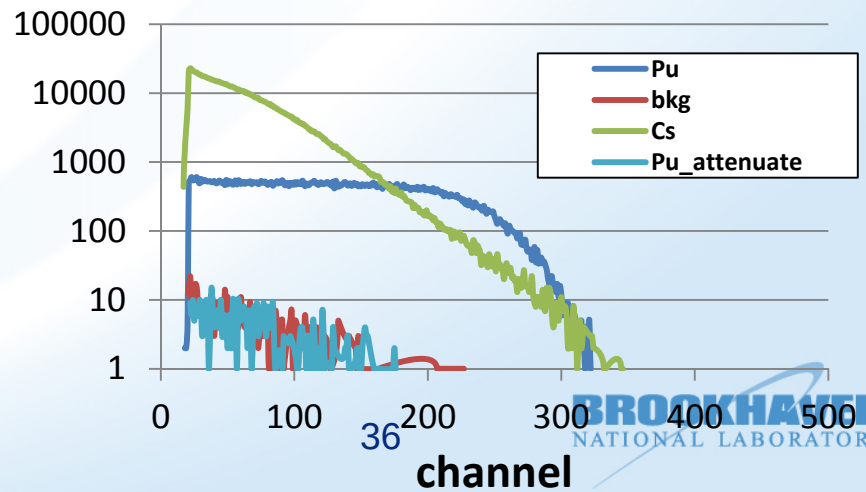
- developing QA/QC assessments for material selection and liquid qualification
- conducting radioactivity screening
- setting up a well-equipped QA/QC lab for neutrino experiments

Liquid Scintillation Veto film

- current experience with LS veto-film (a project in collaboration with LNGS) to produce μm-thin, Teflon-based films targeting surface α/β for background reduction.
- Related applications to LAr light collection.
  - Current PVT (polyvinyl toluene) – based polymer deteriorates under UV-light; *questionable* to be used under cryogenic condition.
  - Current toluene-TPB (tetraphenyl butadiene) combination is not the best match for LAr emission at 128nm.







Summary

- *Liquid scintillator continues to play a key role for neutrino detection in (non)accelerator, reactor, double-beta decay experiments.*
- *There are several liquid options for the future detector; depending on the physics requirements and costs.*
- *The technology of meal-loaded LS is well developed; and its M%, attenuation length, and photon-production are tunable as needed.*
- *The synthesis technology, material compatibility, and cost of production & purification of scintillator have been worked out and demonstrated to be stable.*
- *WbLS with scintillation & Cerenkov detections is an excellent medium for proton decay (and other physics) and can be used for neutron tagging (enhanced by Gd loaded) .*
- *A cost-effective large detector as well as veto system for future experiment*