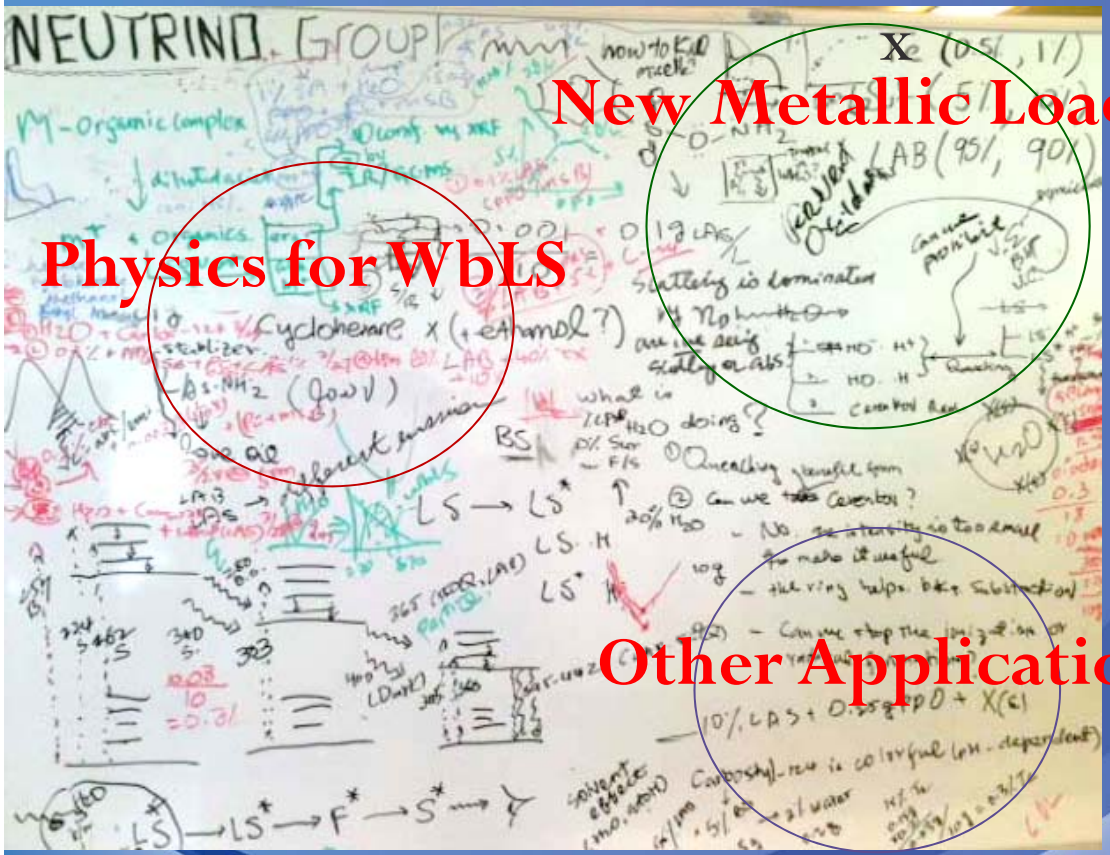
New Scintillation Water for Large Physics Experiments



BNL Particle-physics Seminar

Minfang Yeh

Brookhaven National Laboratory

Neutrino & Nuclear Chemistry

B-555, Upton, NY11973

BROOKHAVEN NATIONAL LABORATORY

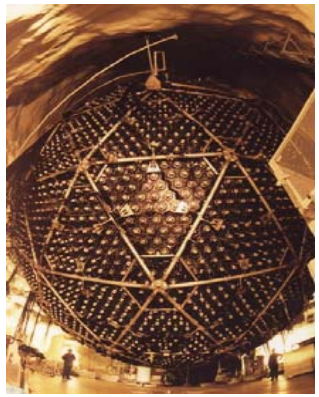
a passion for discovery

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.

BNL Neutrino and Nuclear Chemistry







Neutrino 50 Chemistry

HOMESTAKE — 615-t $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$

Gallex — 30-t $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

1-kt D2O CC/NC — SNO

200-kt H_2O or 37-kt LAr — LBNE

120-t 8% In-LS — LENS

200-t 0.1% Gd-LS — Daya Bay

1-kt 0.1% Nd-LS — SNO+

Nonproliferation & Reactor Monitoring by Li-, B- or Gd- LS — ν-application

(metallic-loaded) multi-physics detection medium — Water-based LS

Radiochemical

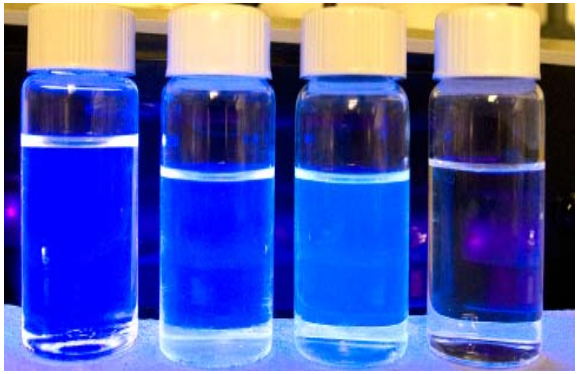
Cerenkov

Scintillator

Hybrid

1960 1970 1980 1990 2000 2010 2020

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.

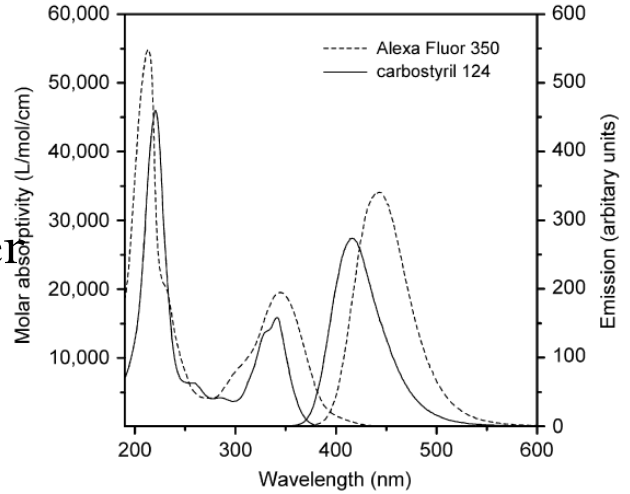
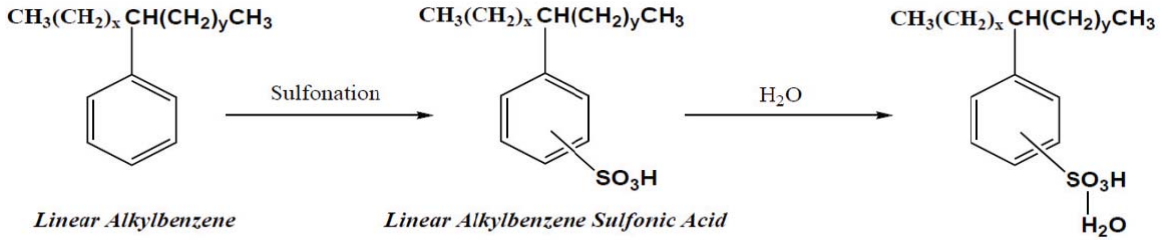
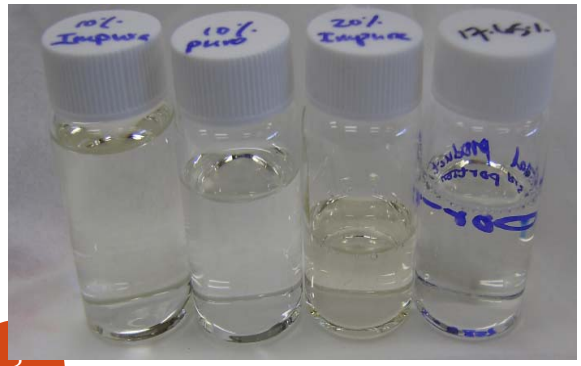


Fig. 2. The UV/VIS absorption (left) and fluorescence emission spectra (right) for carbostyril 124 and Alexa Fluor 350.



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



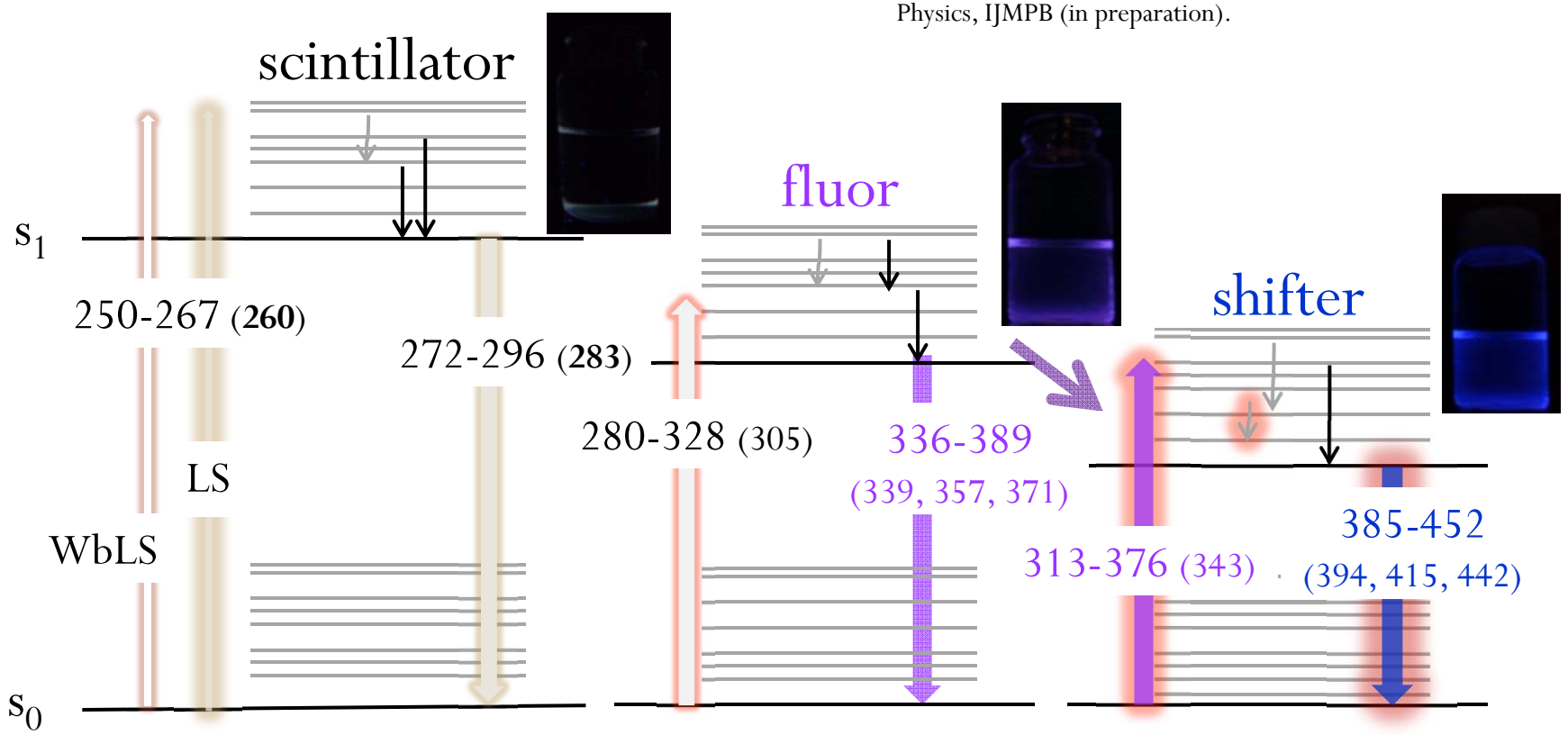


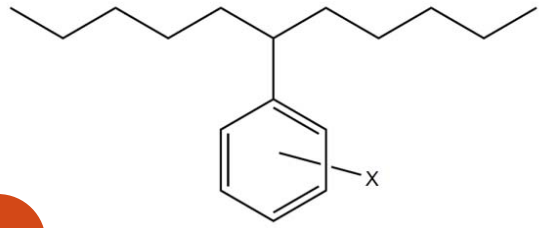
A scintillation water serves as energy spectrometer that probes physics below Cerenkov threshold.

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

Scintillation Matrix

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

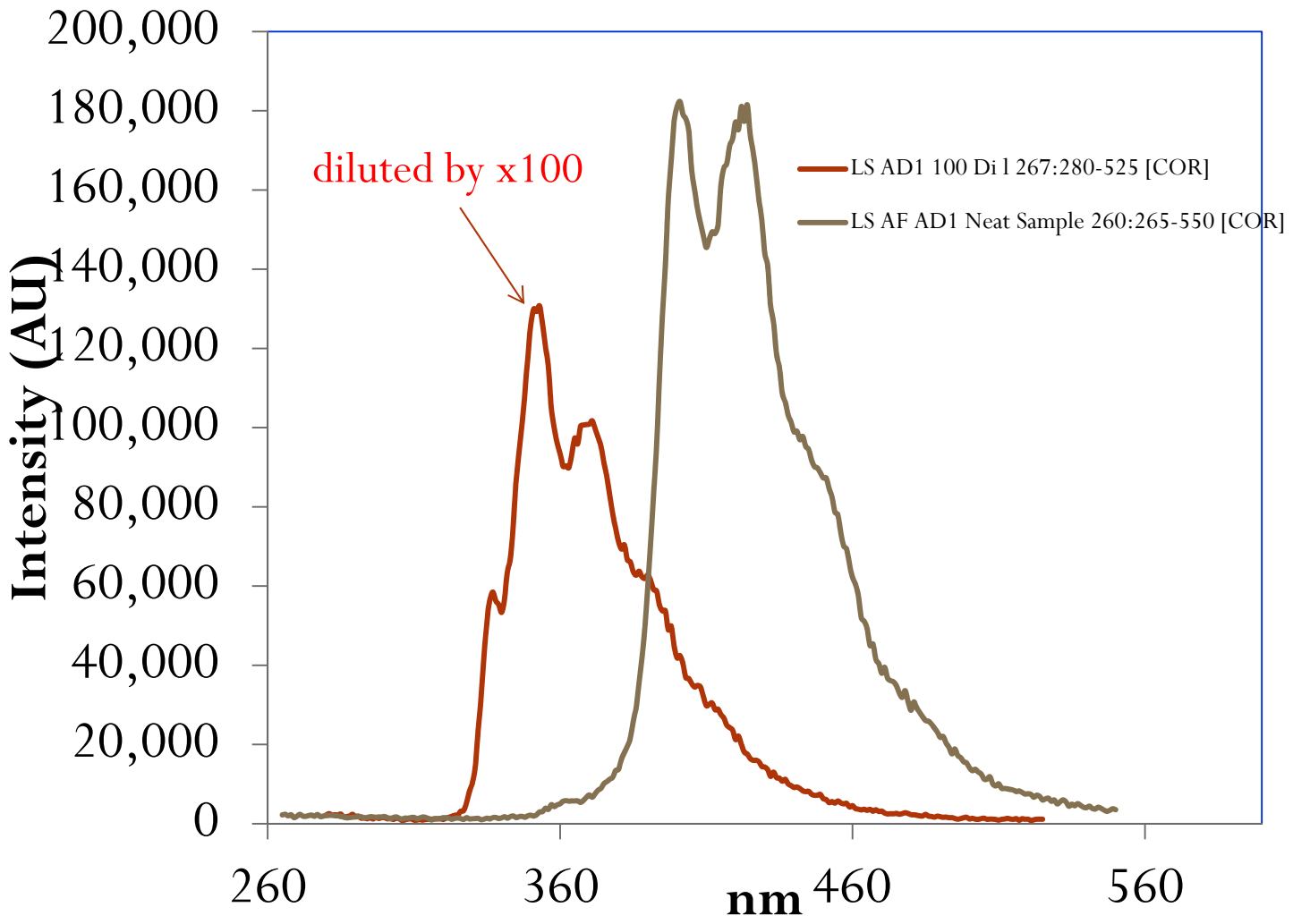




- ability to catch ionization radiation
- photon-transferring mechanisms once excited (S/F/S)

$$LS \rightarrow LS^* \rightarrow h\nu$$

Non-radiative fluorescence energy transfer (PPO / MSB)



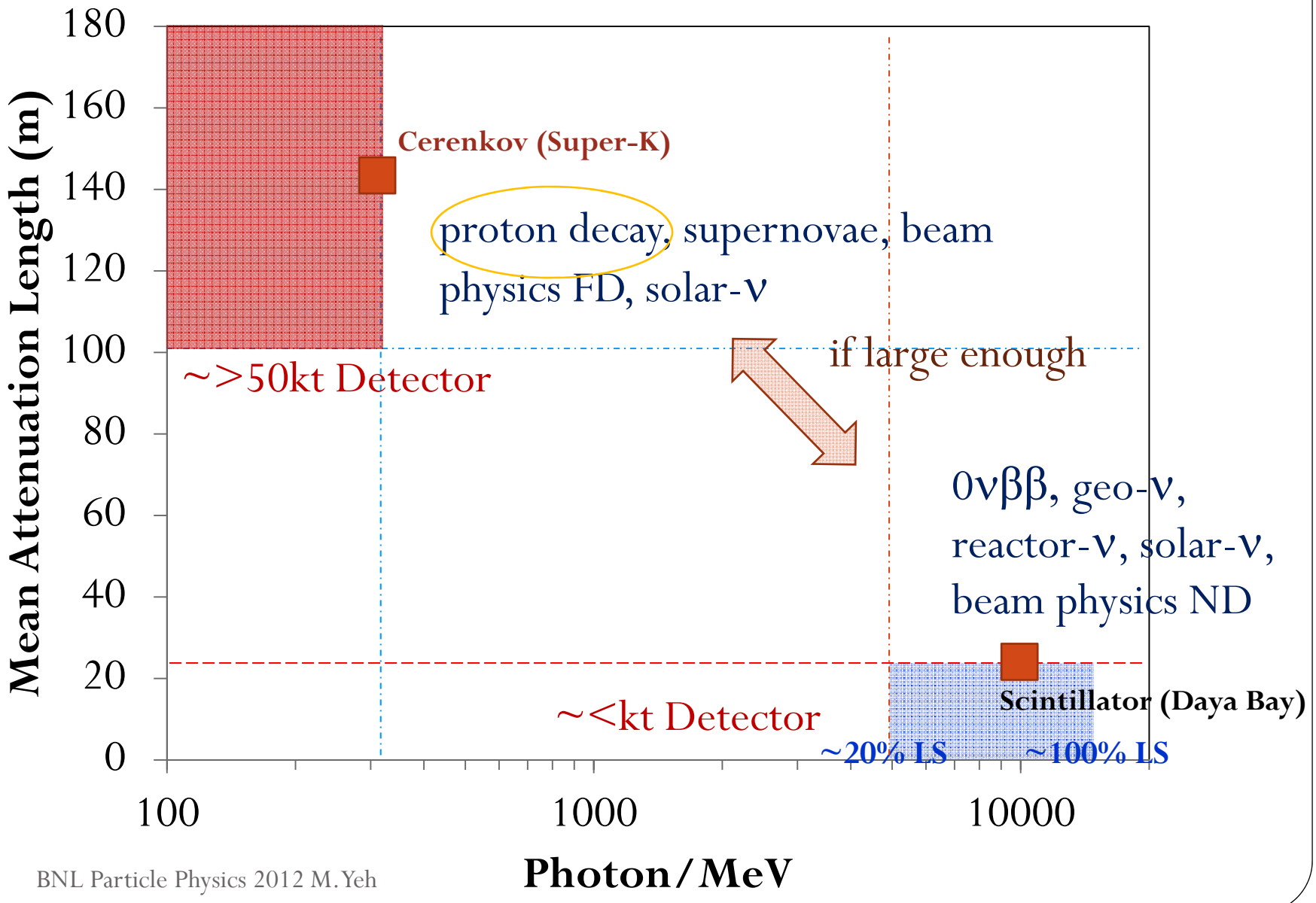
See-Saw of organic% in the water-based medium

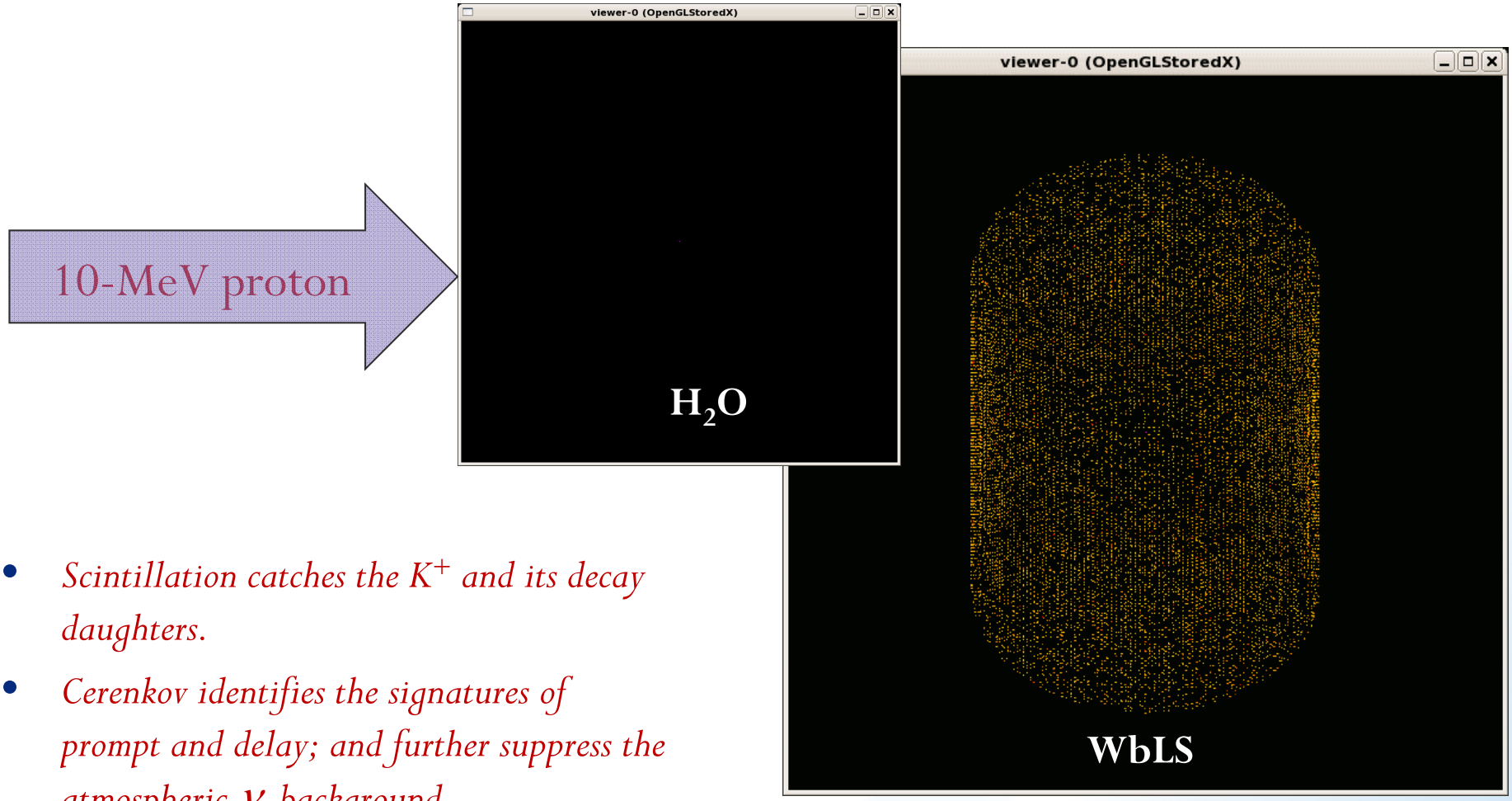


- *Proton decay*
- *Double-beta decay*
- *Supernovae neutrino*
- *Low-energy neutrino*

A Multi-Physics Water-based Scintillation Detector

Typical Cerenkov & Scintillation Detectors





- *Scintillation catches the K^+ and its decay daughters.*
- *Cerenkov identifies the signatures of prompt and delay; and further suppress the atmospheric ν background.*

Proton decay – physics below Cerenkov

SUSY-favored PDK^+ Mode

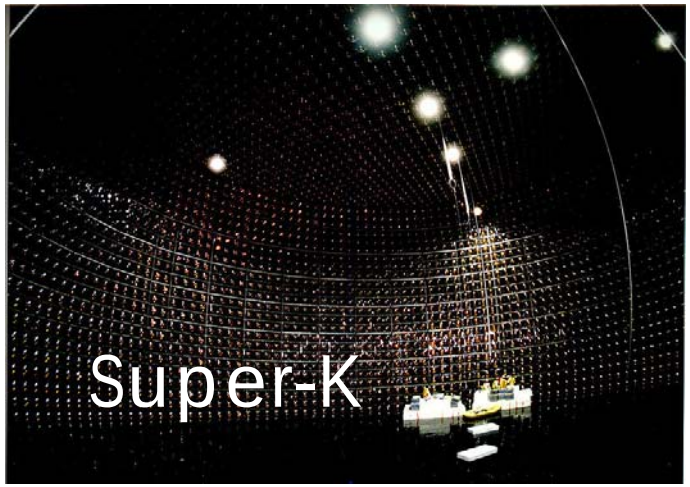
- $p \rightarrow k^+ \bar{\nu}\ (T_{k+} = 105\ MeV, \tau = 12.8ns)$
  - $k^+ \xrightarrow{63.5\%} \mu^+ \nu\ (T_{\mu^+} = 152\ MeV)$
    - $\mu^+ \rightarrow e^+ \nu\nu\ (\tau = 2.2\mu s)$
  - $k^+ \xrightarrow{20.7\%} \pi^+ \pi^0\ (T_{\pi^+} = 108\ MeV)$
    - π^0 (E=135 MeV) $\rightarrow 2\gamma$
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

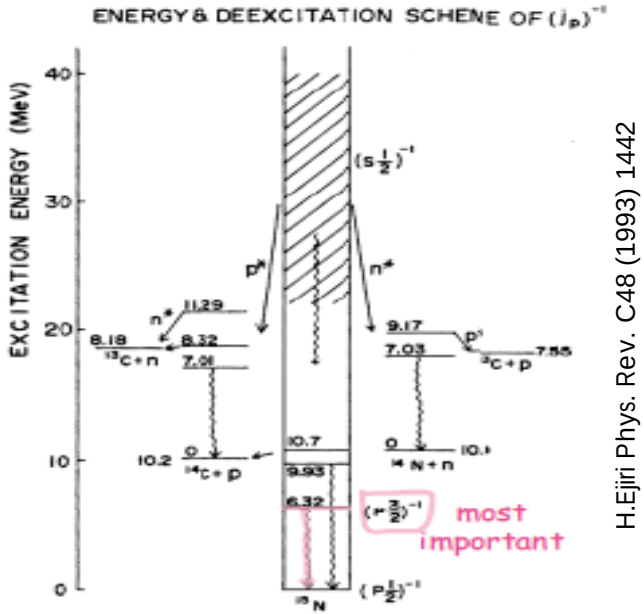
can be explored by Cerenkov or Scintillation via different decay channels

Super-K proton decay

The SUSY SU(5) model predicts the K-decay mode to be dominant with a partial lifetime varying from 10^{29}y to 10^{35} yrs !

$$\tau(p \to k^{+}\bar{\nu}) > 2.3\times10^{33}\,\text{yrs}$$





H.Ejiri Phys. Rev. C48 (1993) 1442

FIG. 2. Level scheme of proton-hole states in ^{15}N and their deexcitation modes. Energies are given in units of MeV. p^* and n^* are the protons and neutrons emitted from the continuum (unbound) region, respectively.

- 22.5-kT (7.5 x 10^{33} protons & 6.0 x 10^{33} neutrons) at 40% coverage
- T_{K+} ~105 MeV: below Cerenkov threshold
- $^{16}O\ (p_{3/2}) \rightarrow {}^{15}N^{*} + \gamma_{6.3\ \text{MeV}}$

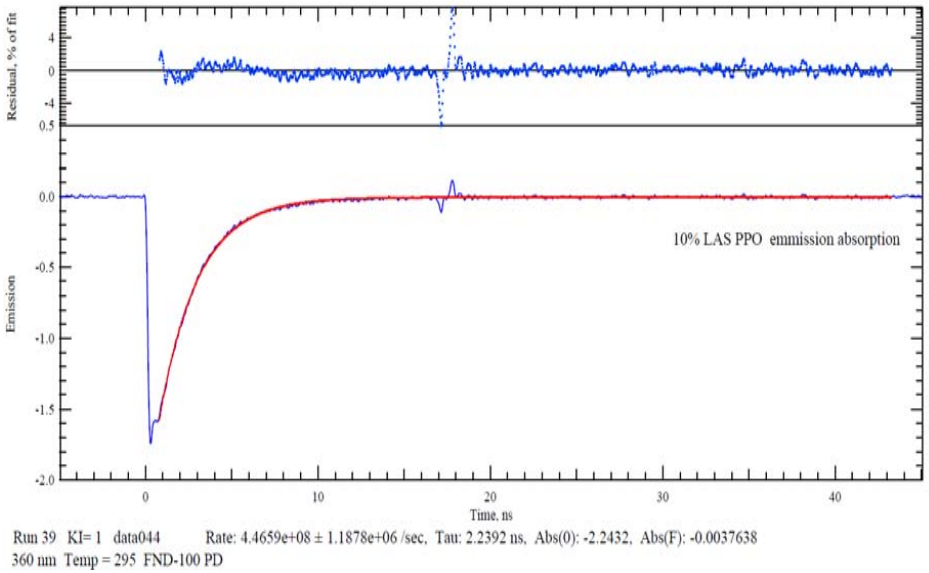
For proton decay, a pulse that is

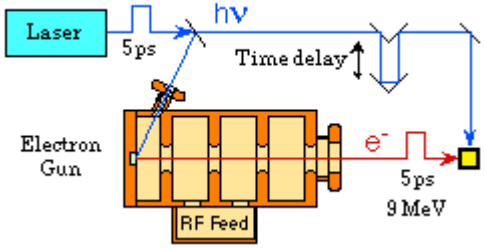
- *<12ns*
- *long attenuation length*
- *with Cerenkov or Scintillation capabilities*
- *deep UG*

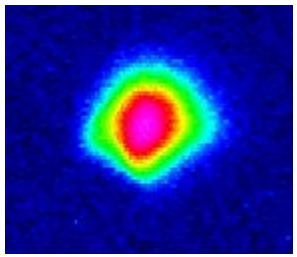
- *Timing structure (10-MeV electron-beam by LEAF; time-resolved fluorescence)*
- *Mean attenuation length (UV normalized to Super-K absorption curve; followed by simulation) and Emission Spectra (fluorescence)*
- *Light-yield (Cs-137) and (1-GeV p-beam)*

WbLS Characterizations

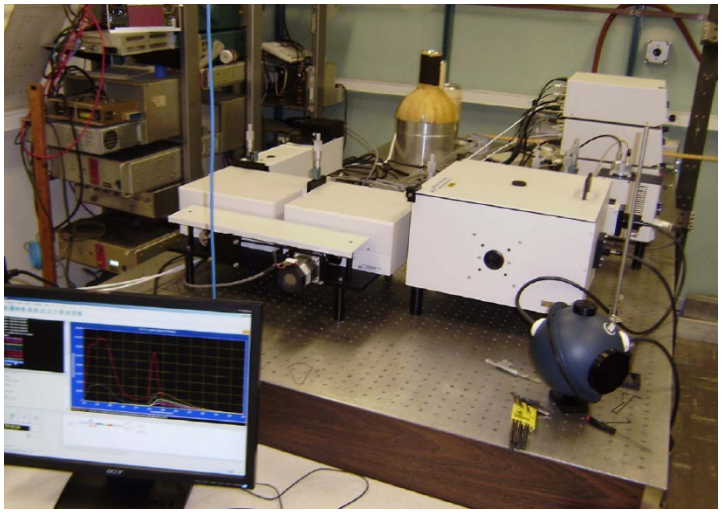
$\tau_{WbLS(PPO)}$ between 2 – 4 ns



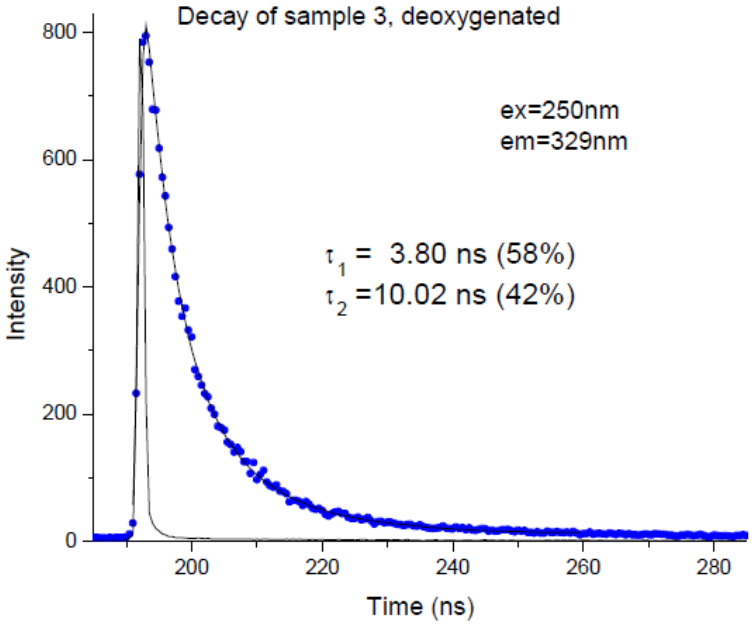




10-MeV e⁻ beam at LEAF

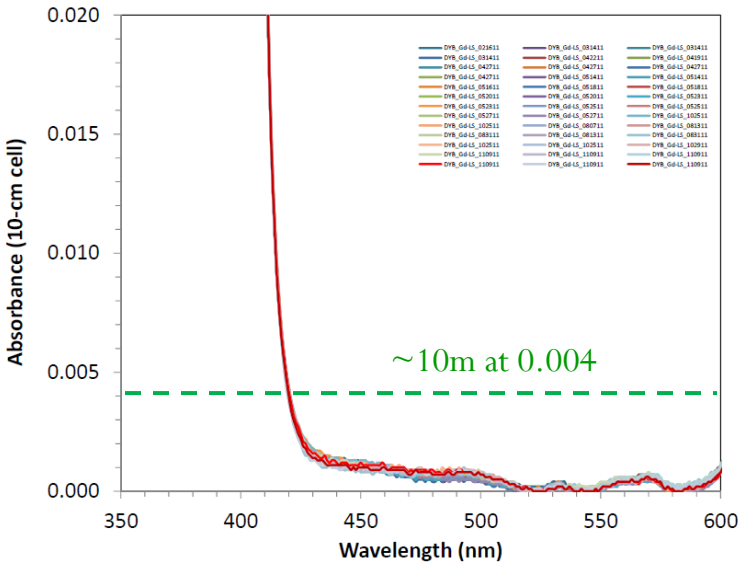


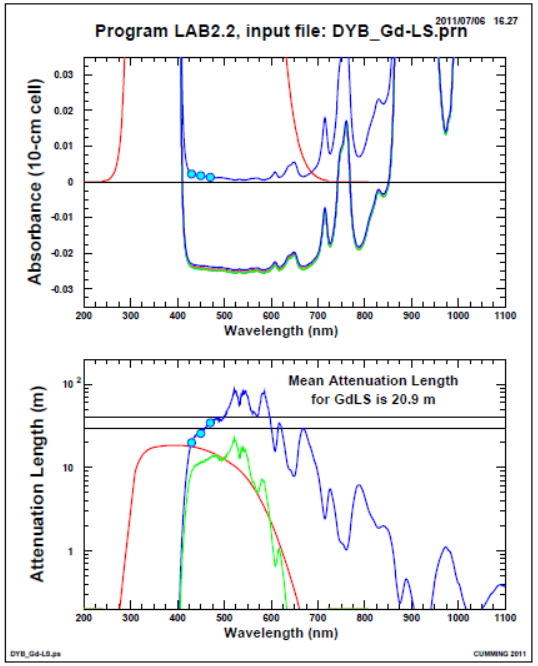
Time-resolved fluorescence system

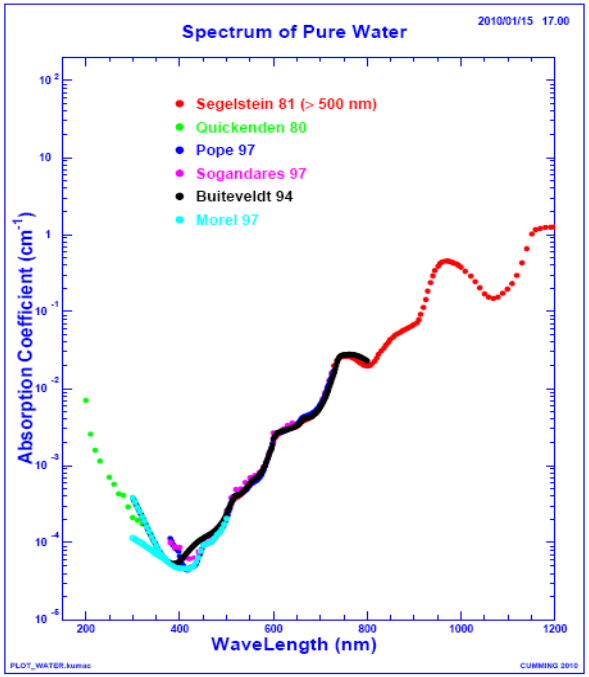


Absorption Length Calculation









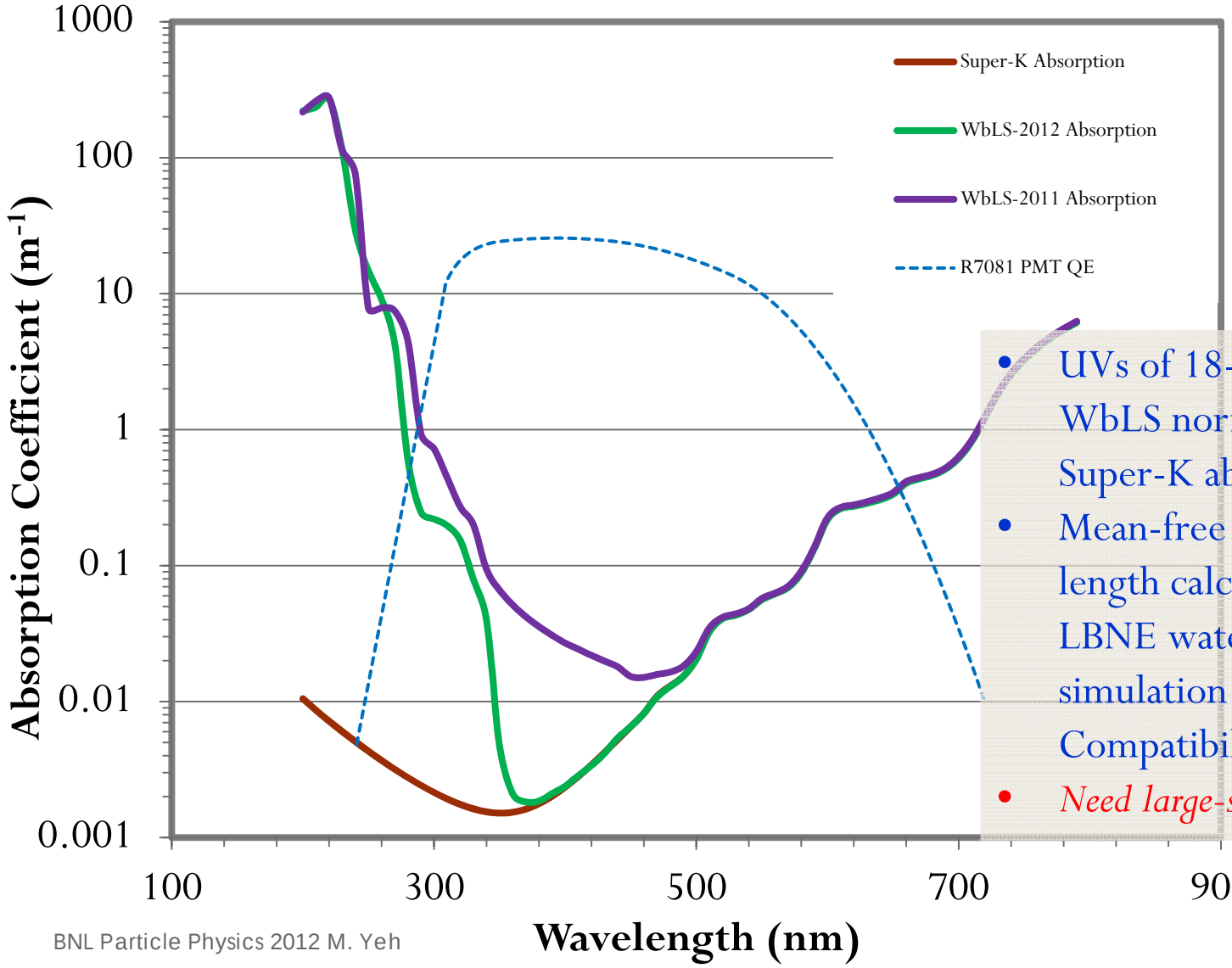
UV + $\lambda_{1/e}$ LBNE simulation match with the 2-m measurement very well!

	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

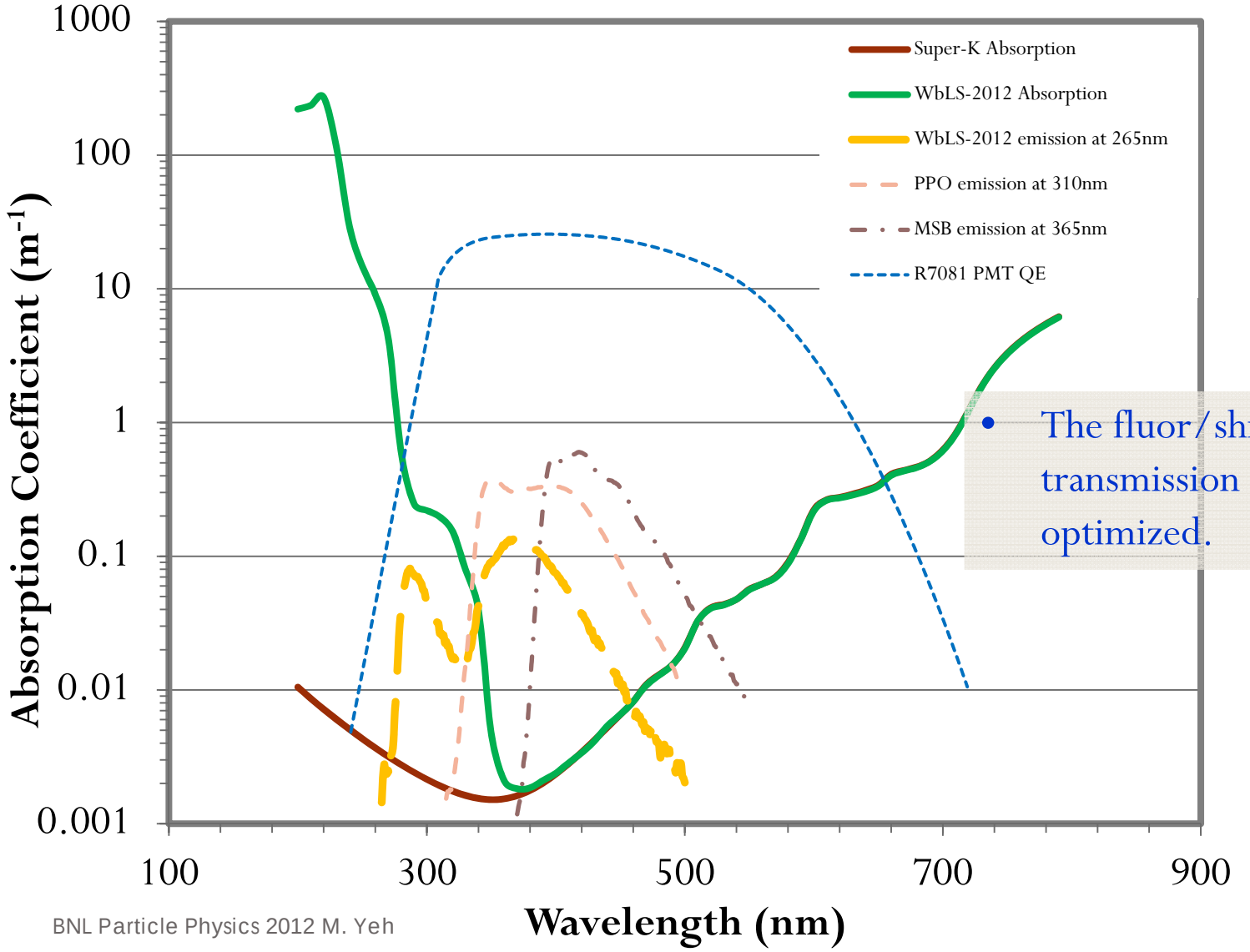
Mean-Free Attenuation Length close to pure water after 400nm

- improvement of optical transmission over the past 6 months



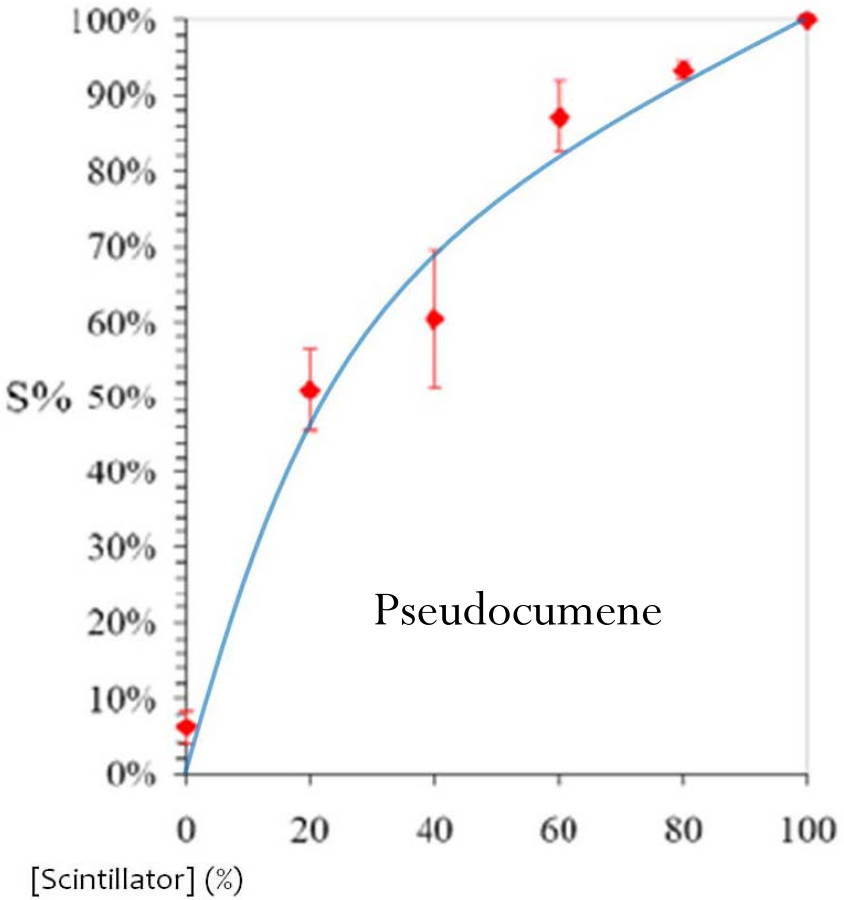
- UVs of 18-MΩ water and WbLS normalized to Super-K abs. curve.
- Mean-free absorption length calculated by LBNE water attenuation simulation (developed for Compatibility test).
- *Need large-scale verification*

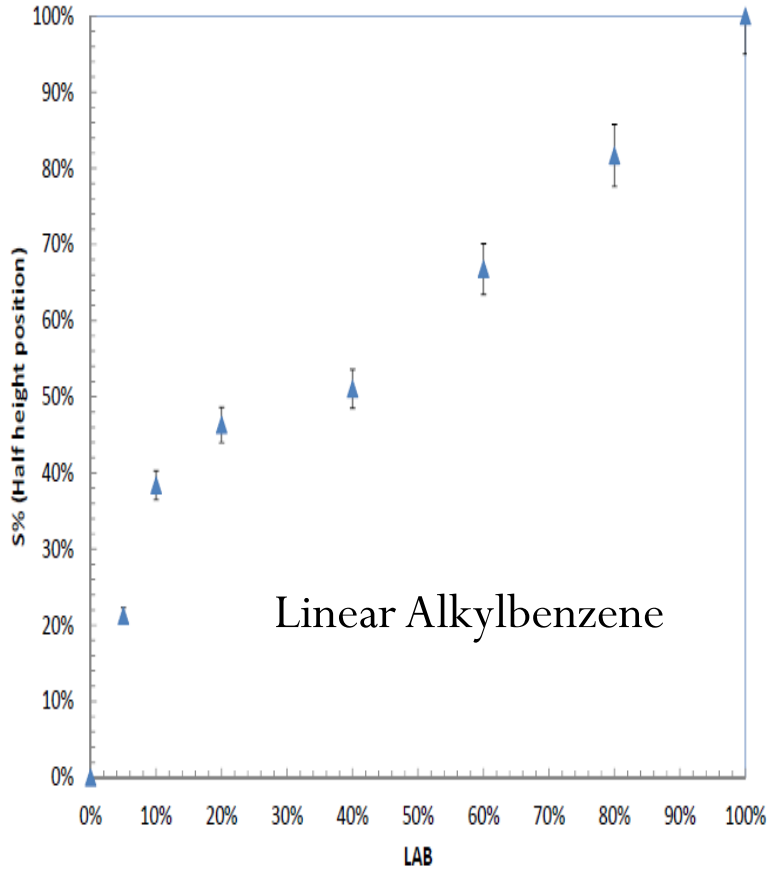
Emission at the PMT sensible region is almost clean



- The fluor/shifter transmission needs to be optimized.

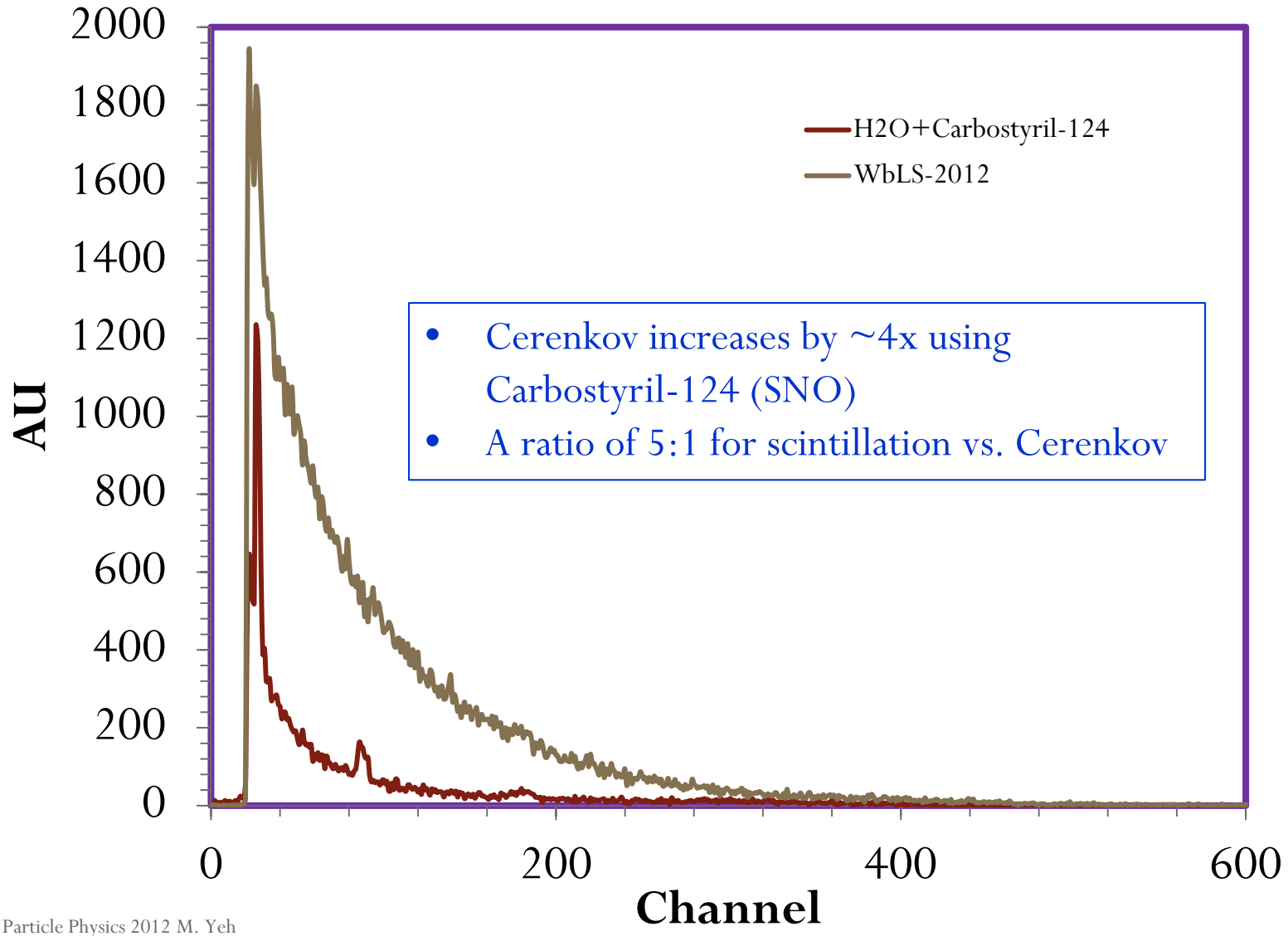
Little LS gives away lots of light





photon-yield function of liquid scintillator % in the cocktail is not linear!

WbLS Scintillation vs. Cerenkov (Cs-137)



WbLS at NSRL high-energy particle-beam in 2011





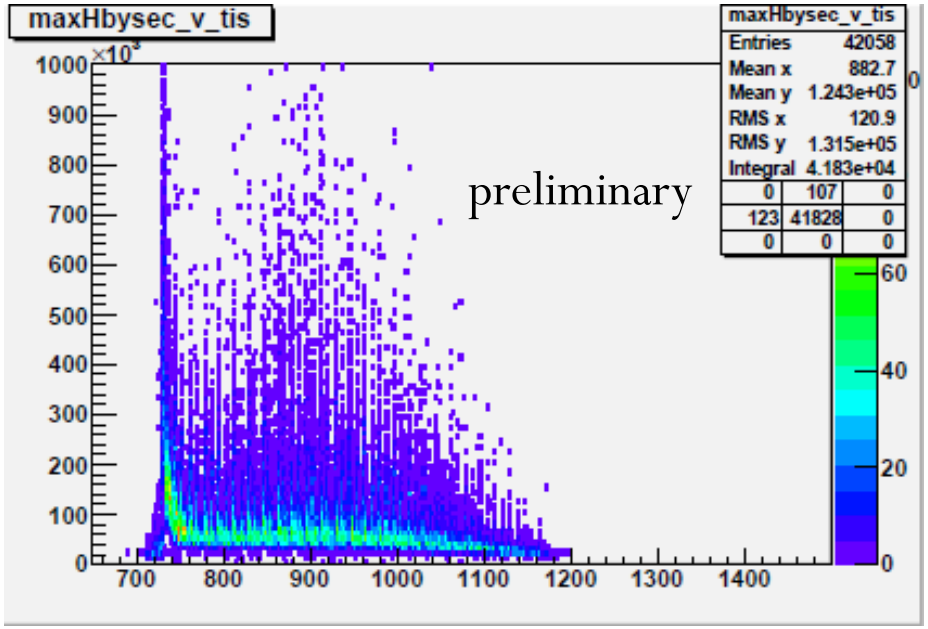


Figure 2: The instantaneous intensity in Hz as a function of time in spill in ms.

- 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.).

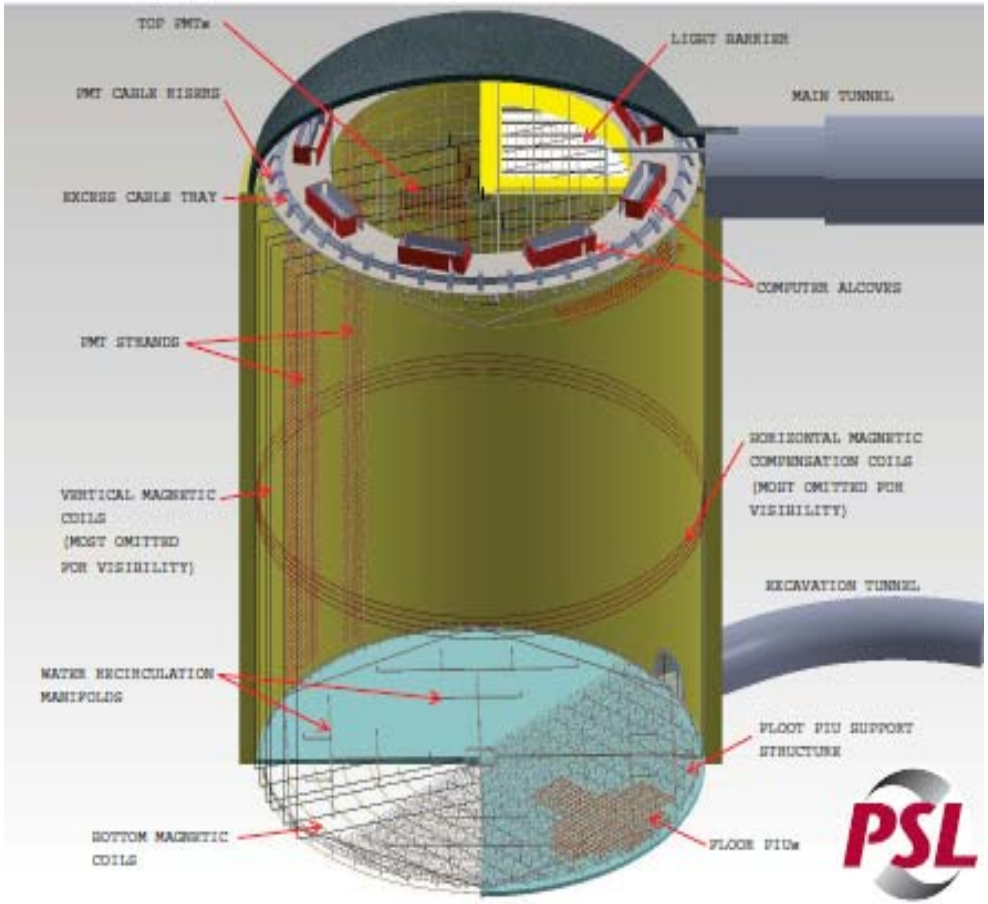
How much Scintillation can be added to keep the Cerenkov valid?

WbLS has a fast, long attenuation-length pulse with Cerenkov + Scintillation

Simulation Parameters (tunable)

X% -WbLS (d = 0.9945 g/cm^3) + PPO					
Element Composition (%)	H	O	S	N	C
	65.9	30.9	0.09	0.0058	3.1
Timing (τ)	1.23 ns (26%) + 9.26ns (74%)				
Refractive Index	1.3492 (580-nm) (*need wavelength-dependent measurement*)				
Rayleigh scattering	same as water (*need measurement*)				

- *Based on the WCSim software (used for LBNE detector simulation)*
- *changed the material to match WbLS*
- *Added the Scintillation process for WbLS*
- *Temporary code repository: https://github.com/czczc/WbLS*
- *Xin Qian (Caltech)*
  - *LBNE baseline*
- *Chao Zhang (BNL)*
  - *Super-K geometry*

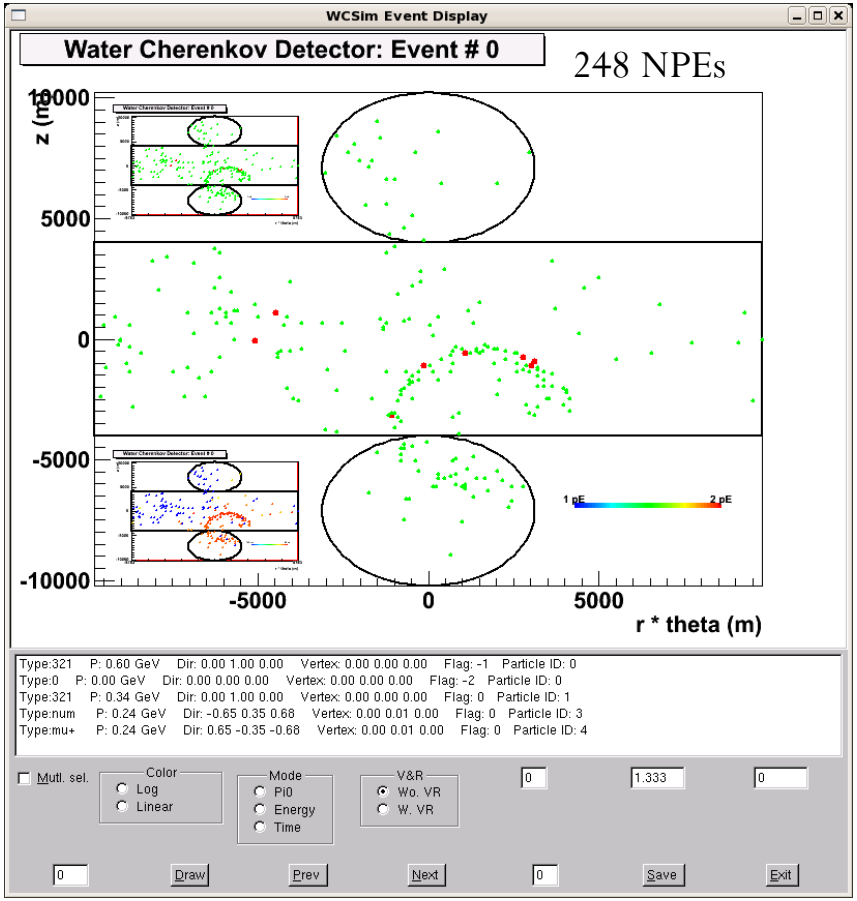


- 200-kt
- 10% coverage
- 12-inch HQE PMT(~30%)

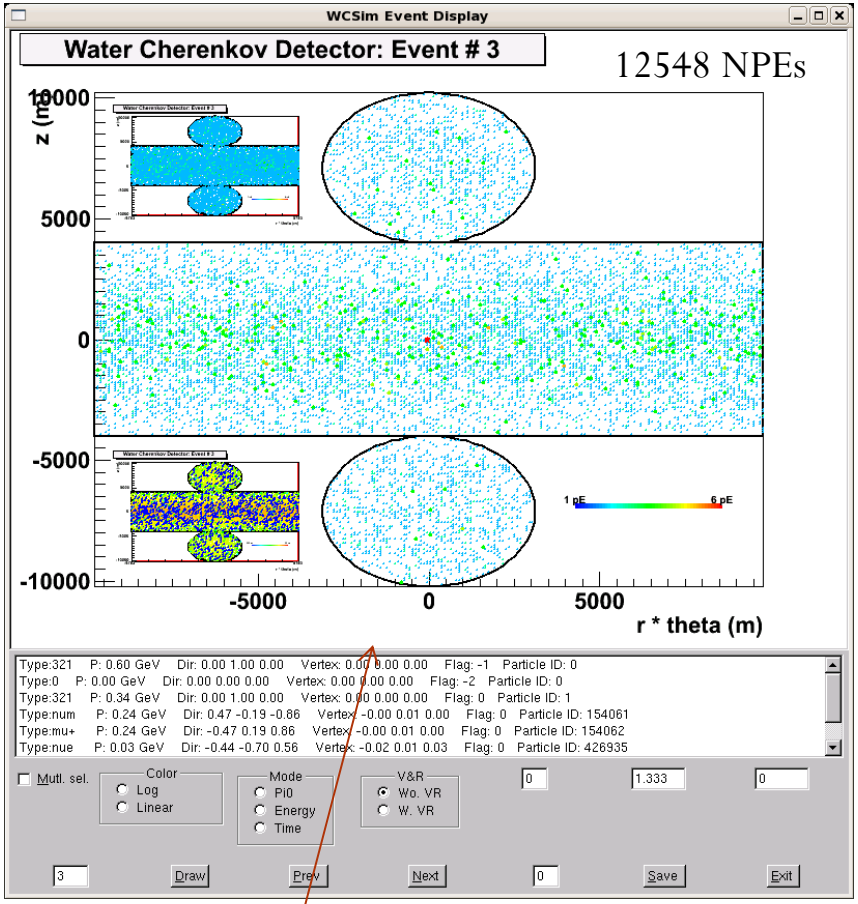
WbLS at LBNE Geometry

105-MeV $k^+ \rightarrow \mu^+ \nu_\mu$ (br. 63%) at 1800 γs/MeV

H_2O

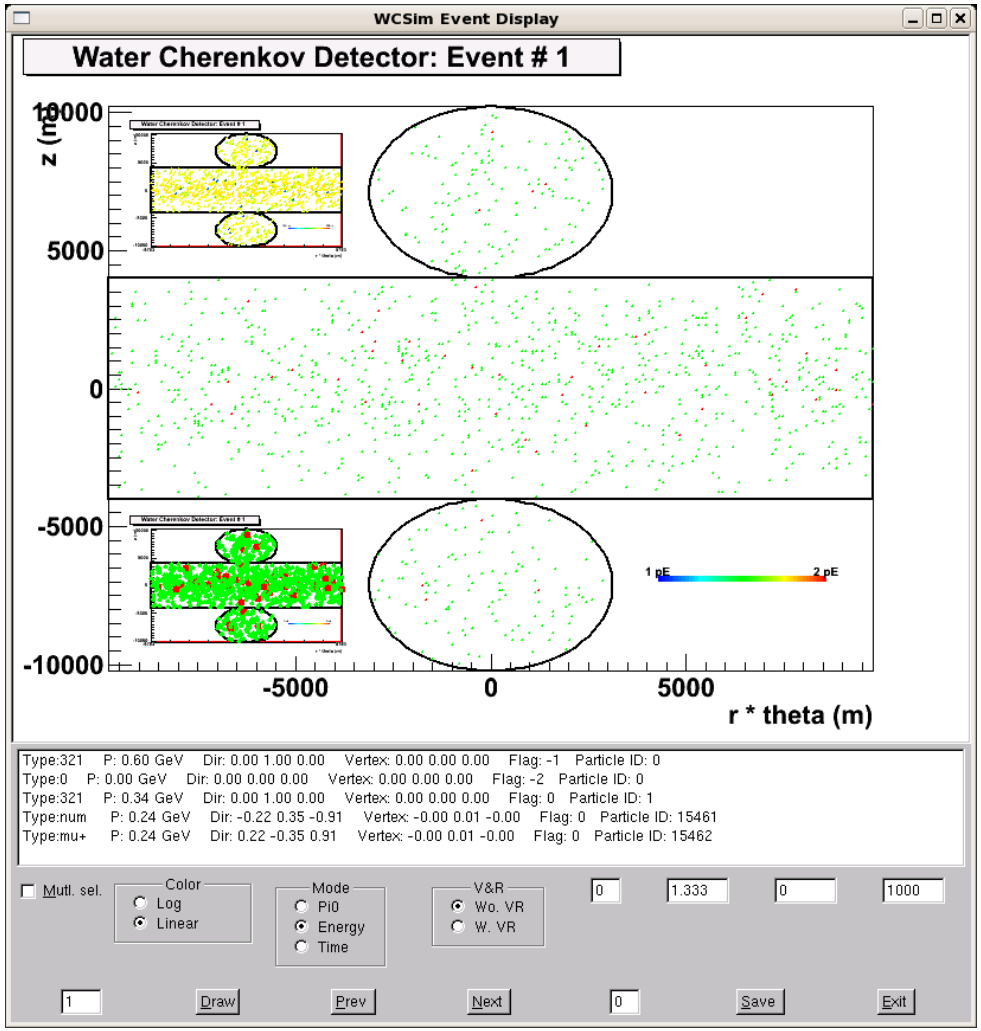


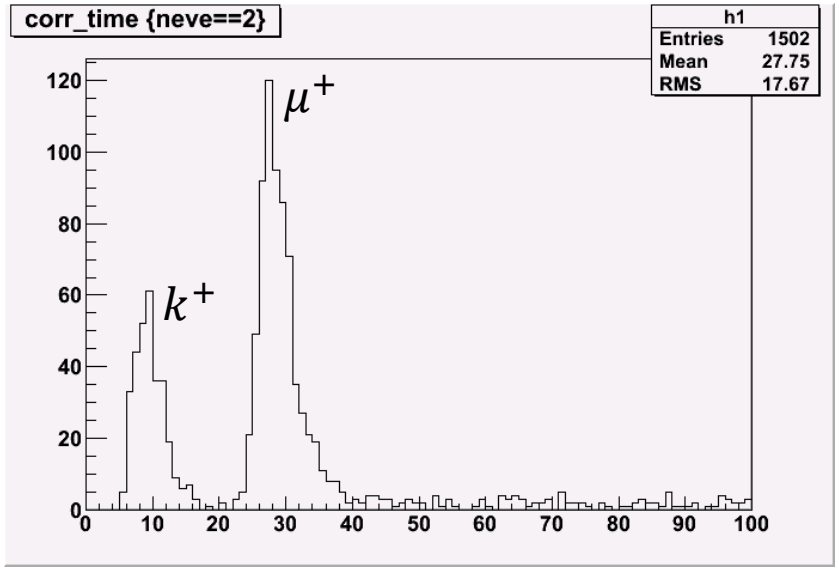
WbLS



Scintillation lights swamp Cerenkov rings

Adjust the scintillation light to 180 γs/MeV

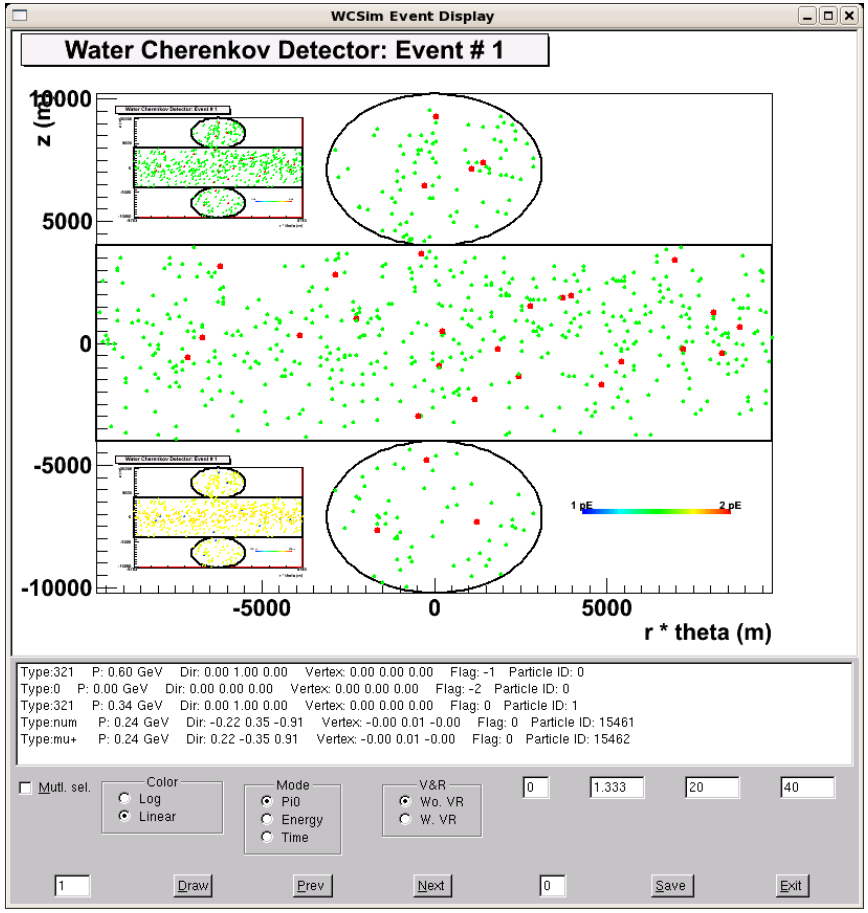


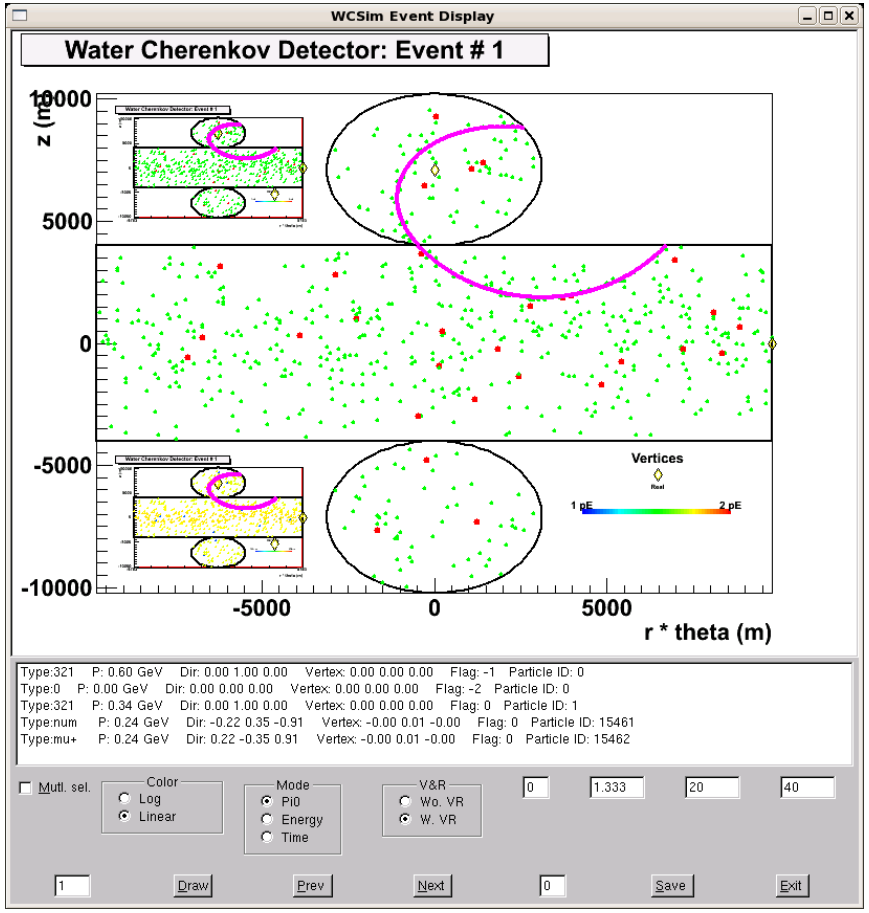


one event and <u>No Cut</u>

next to select the μ^+ by 20-40ns timing-cut

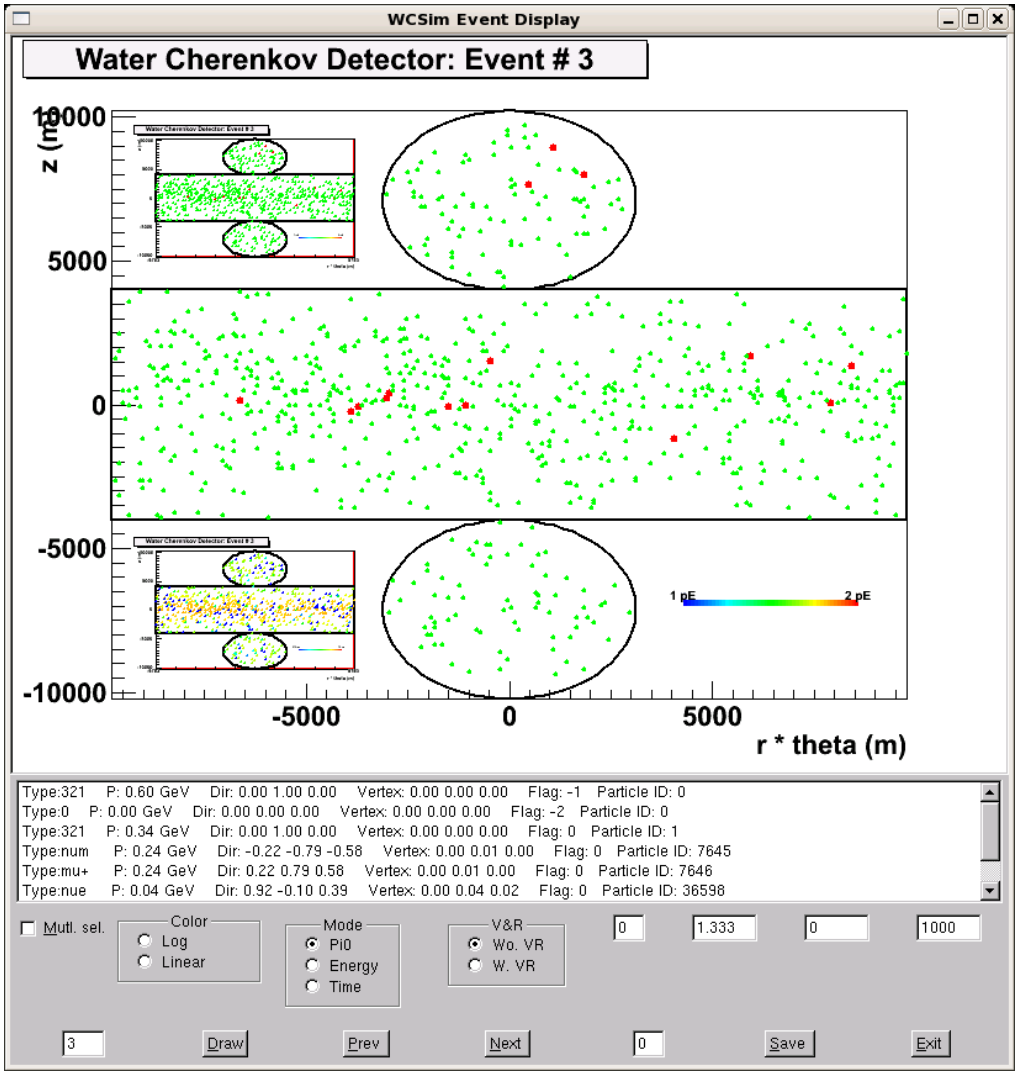
select the μ^+ window (20→40 ns)

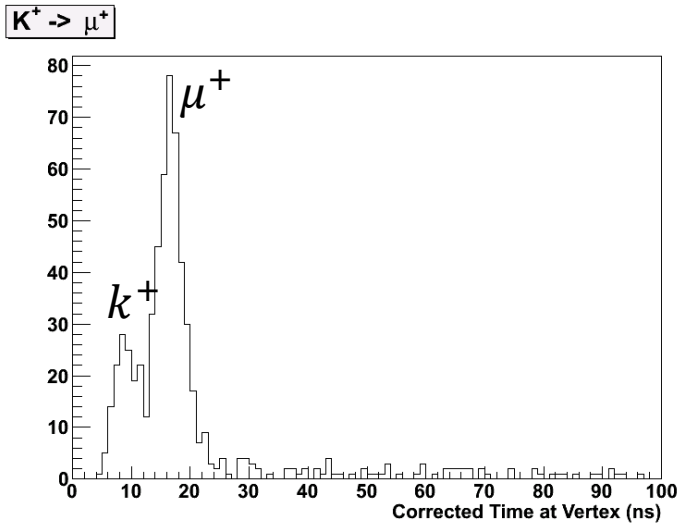




can ID the rings by either eye- or software-view!

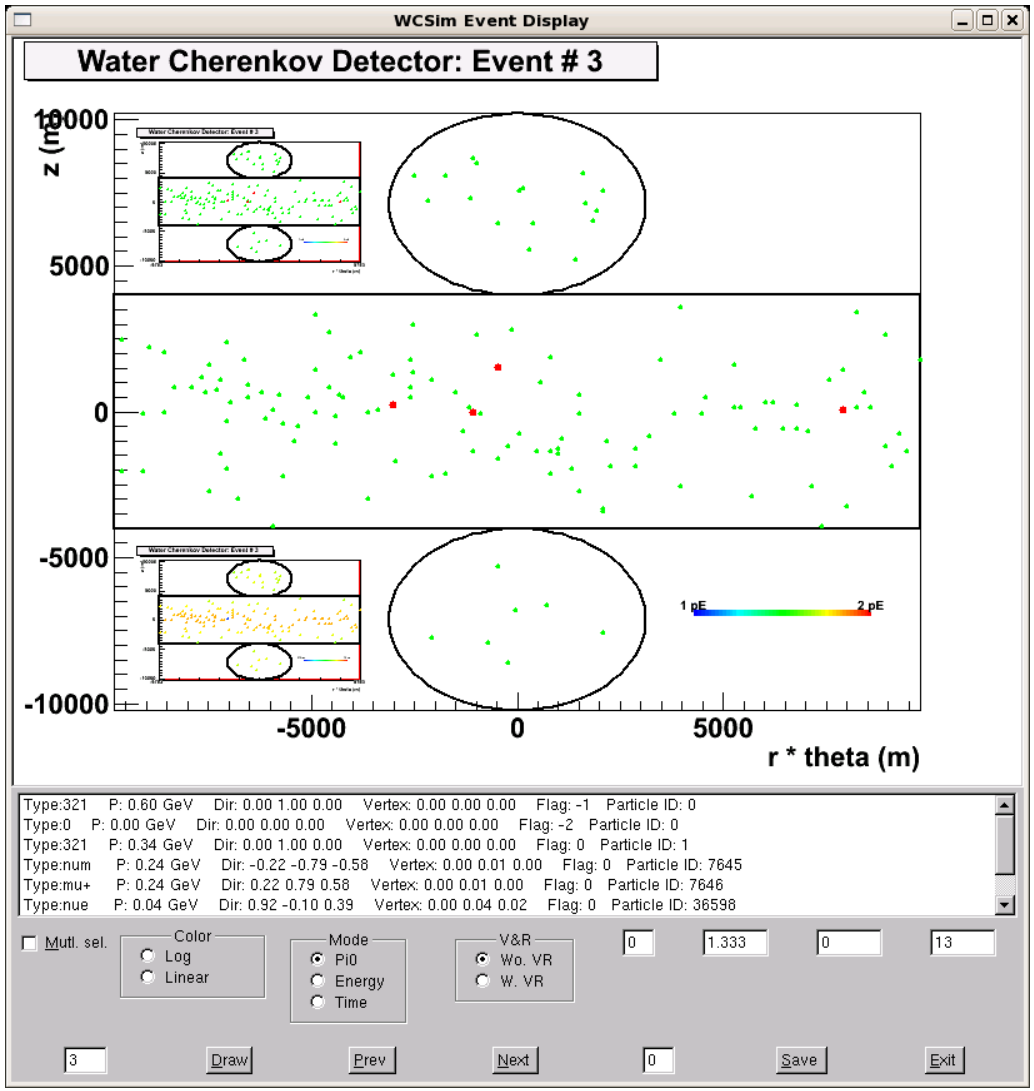
reduce the light further to 90 γs/MeV





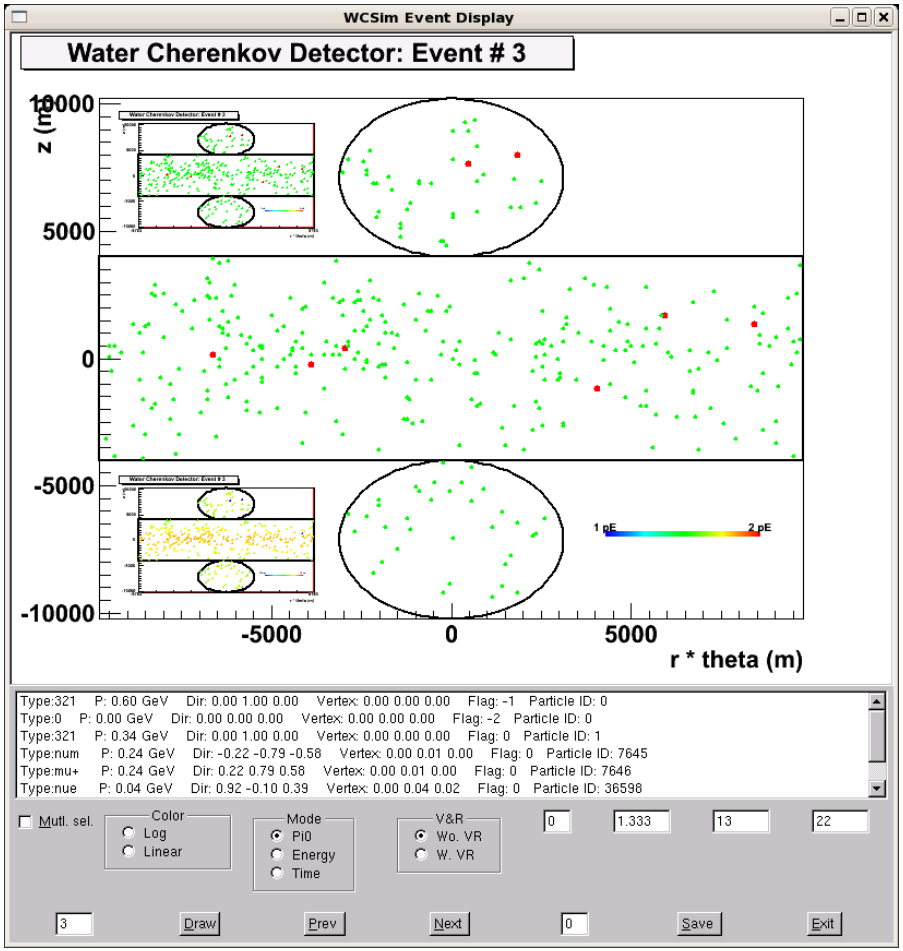
- one event No Cut
- select different timing windows for k^+ and μ^+ events

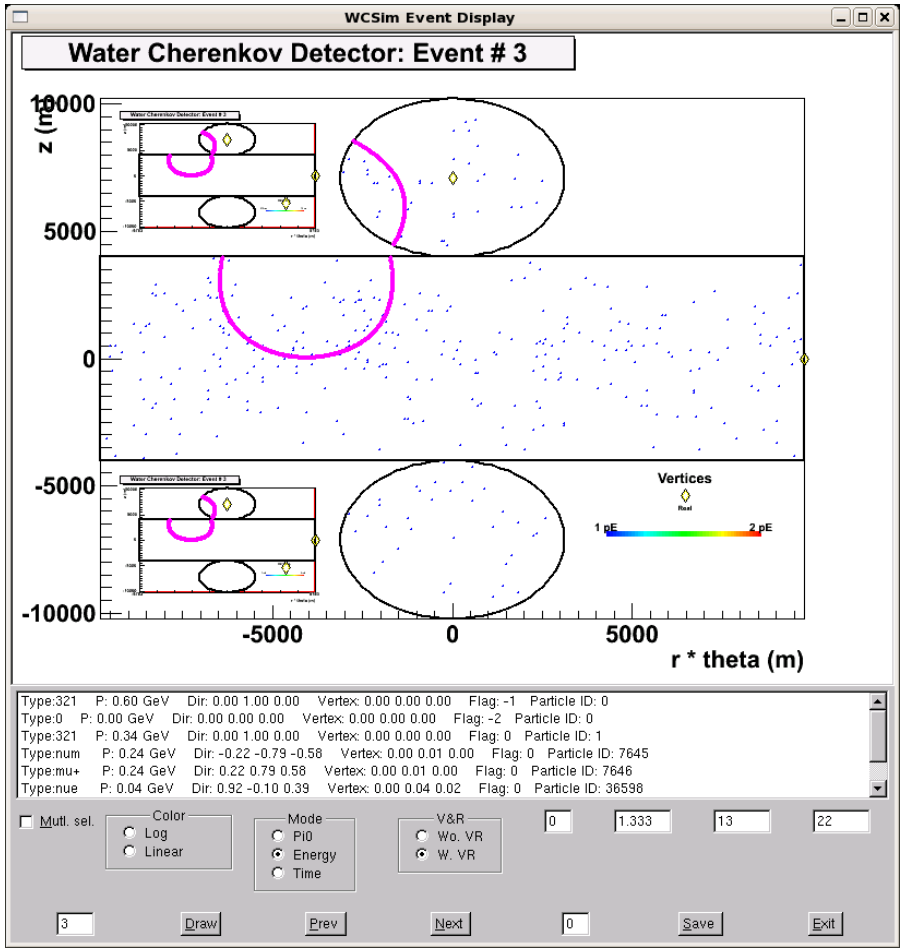
select the k^+ Window (0 →13ns)



- scintillation light only
- no Cerenkov ring

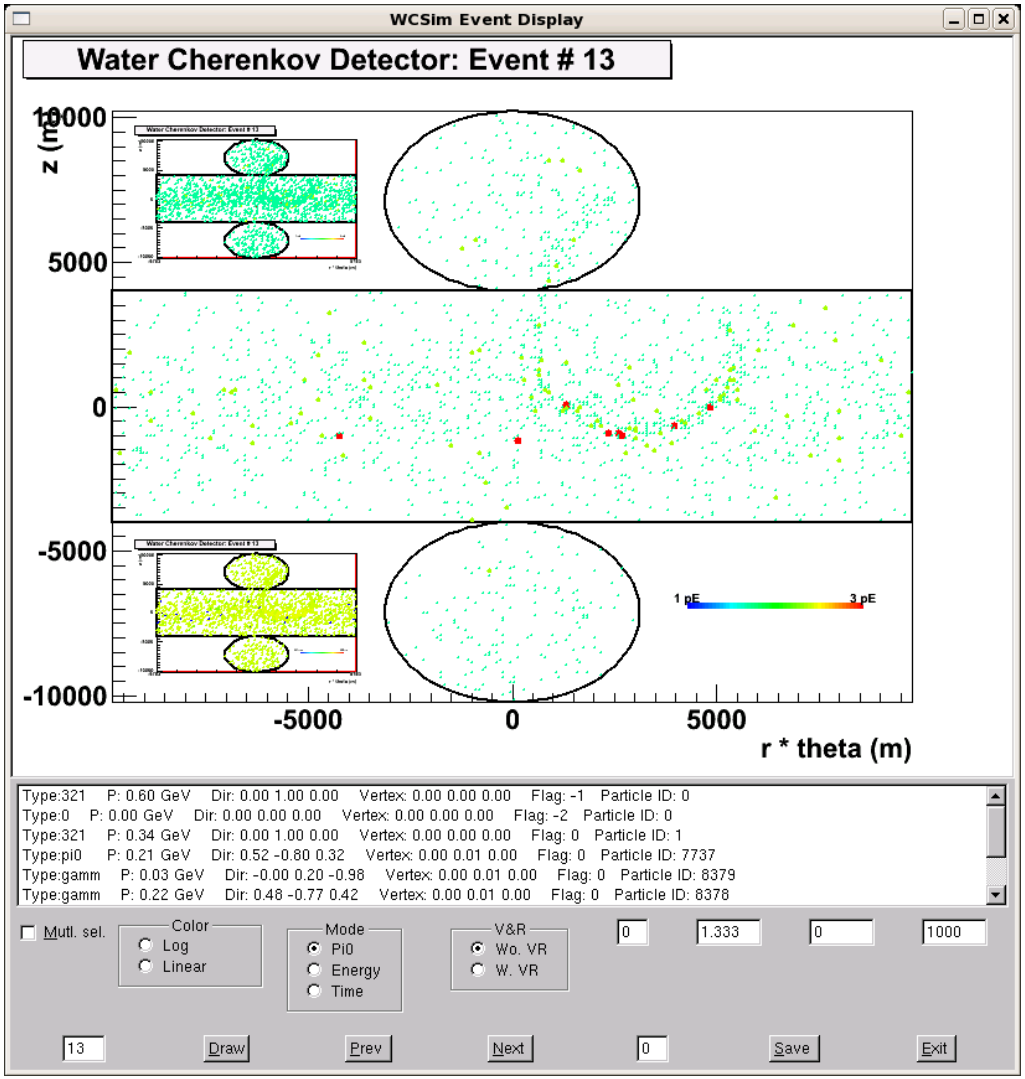
select the μ^+ window (13→22ns)

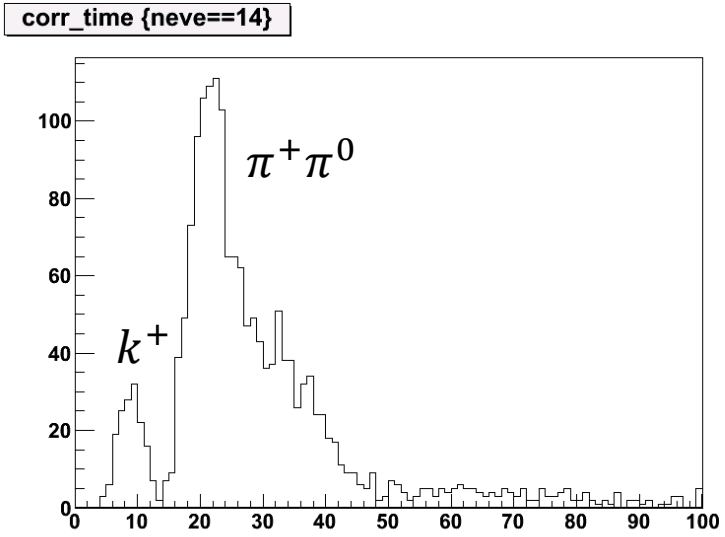




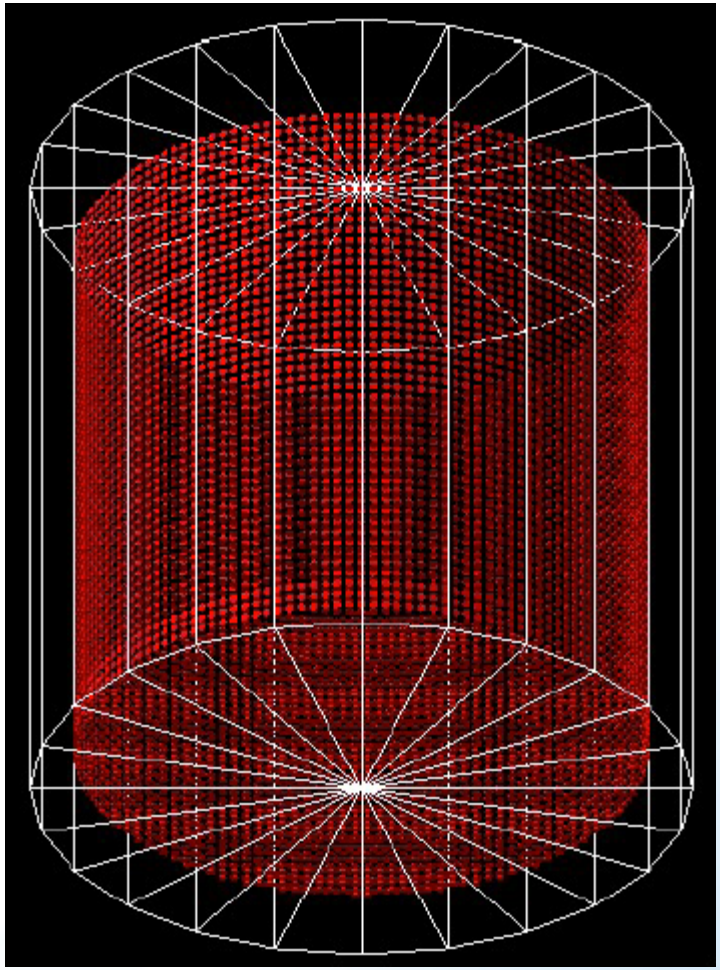
clean μ-rings can be identified among scintillation

A quick look of $k^+ \to \pi^+\pi^0$





- Very clear Cerenkov ring even without cut



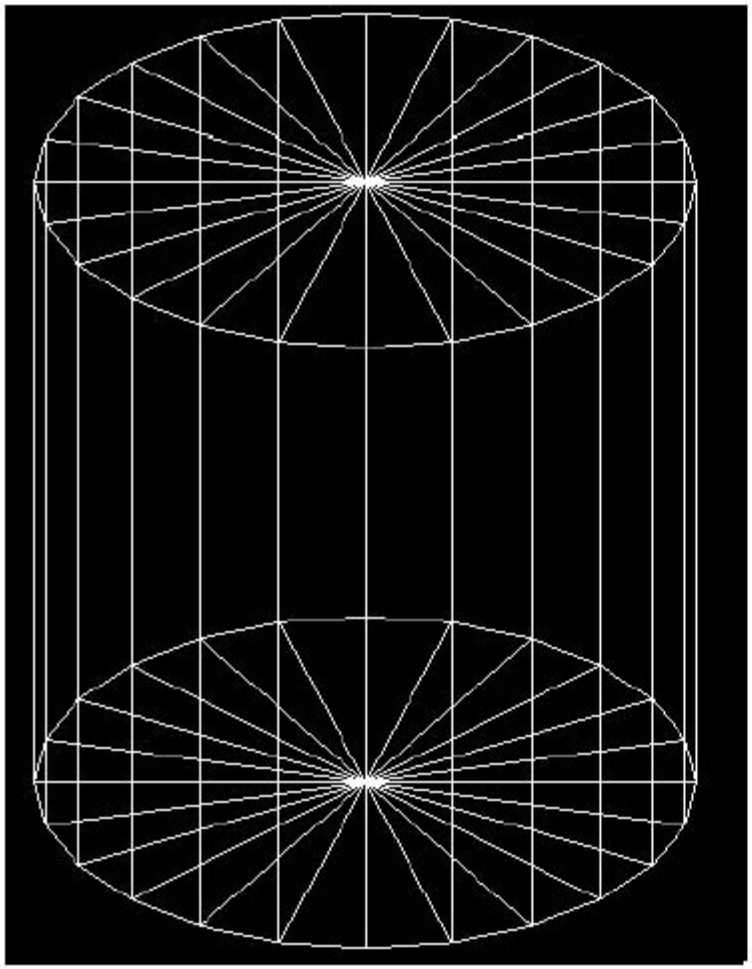
- 50 kton
- 40% coverage
- 20-inch PMT (~20%)

WbLS at Super-K Geometry

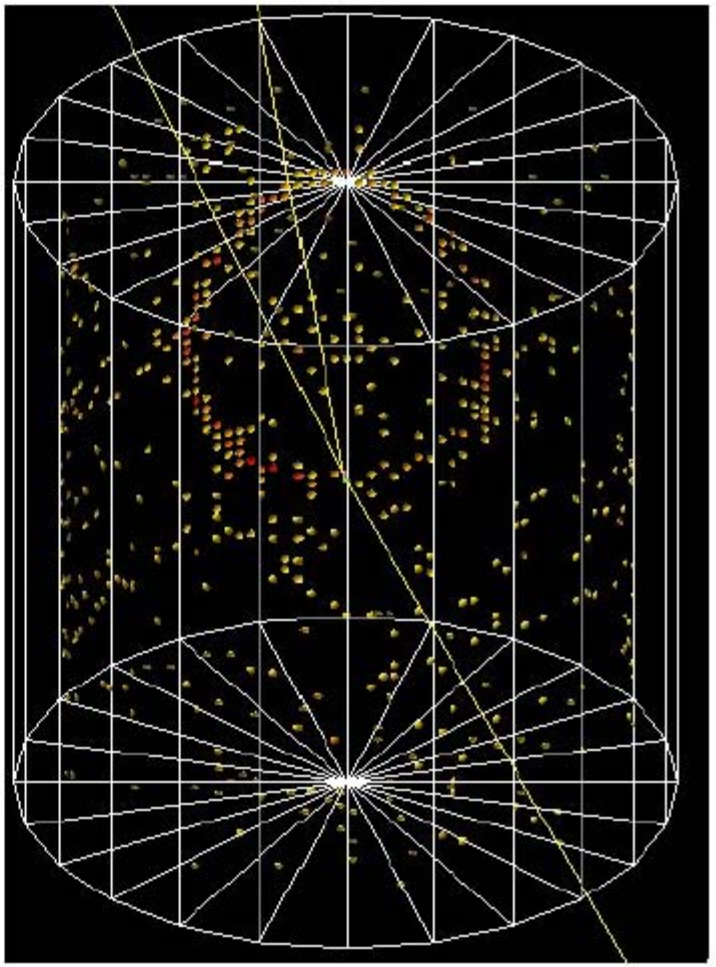
Sanity Check I

- Set Photon Yield to zero (only Cerenkov light)

100 MeV Proton



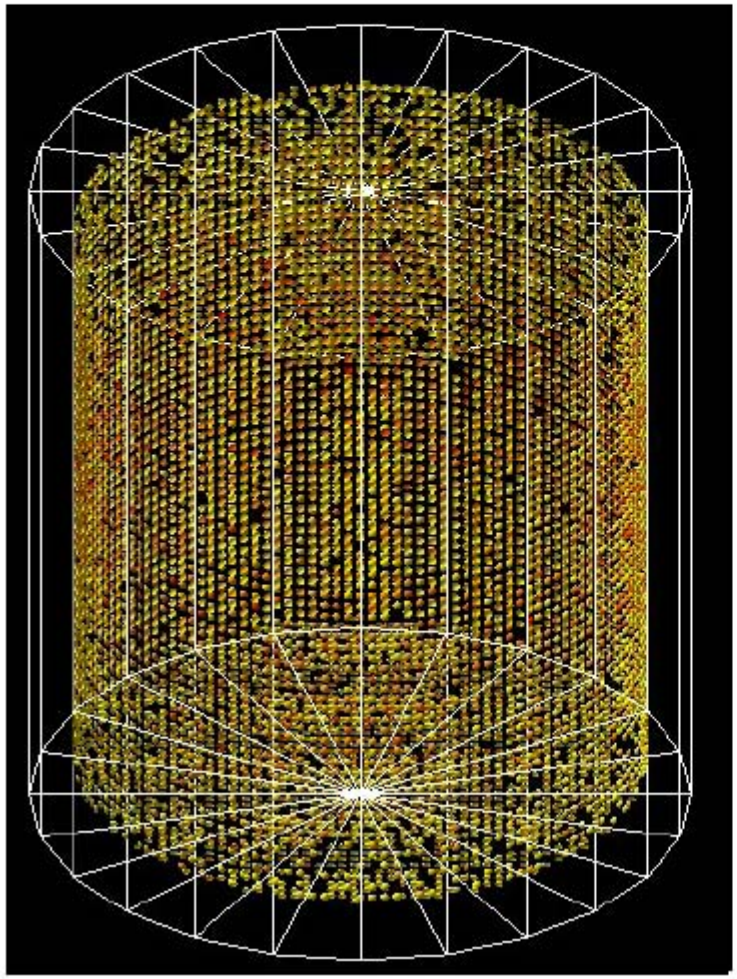
1 GeV Proton



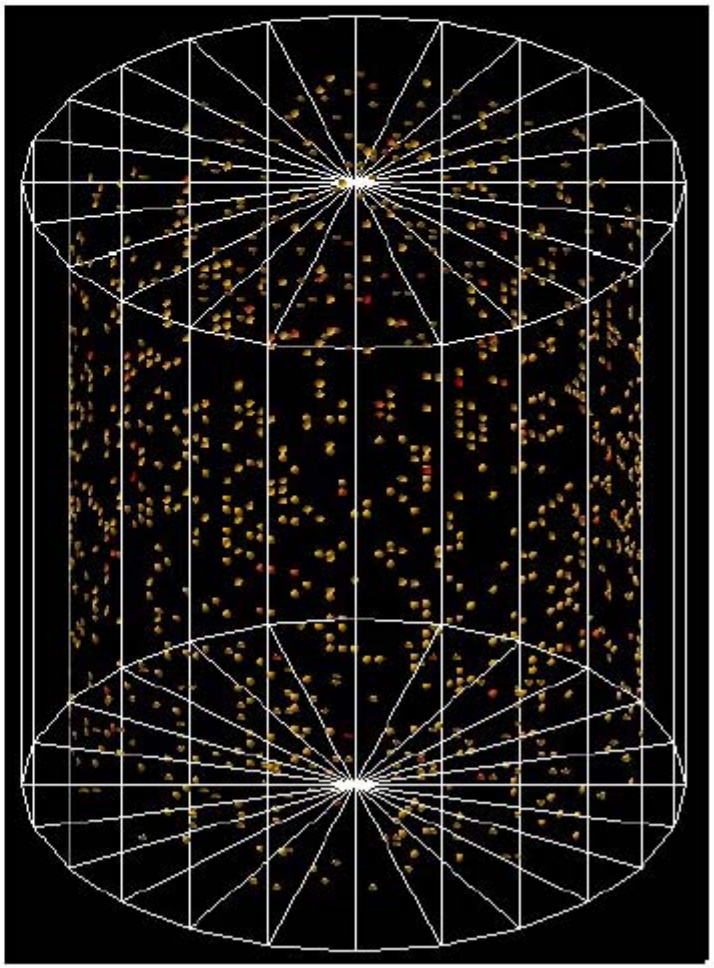
Sanity Check II

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

100 MeV Proton



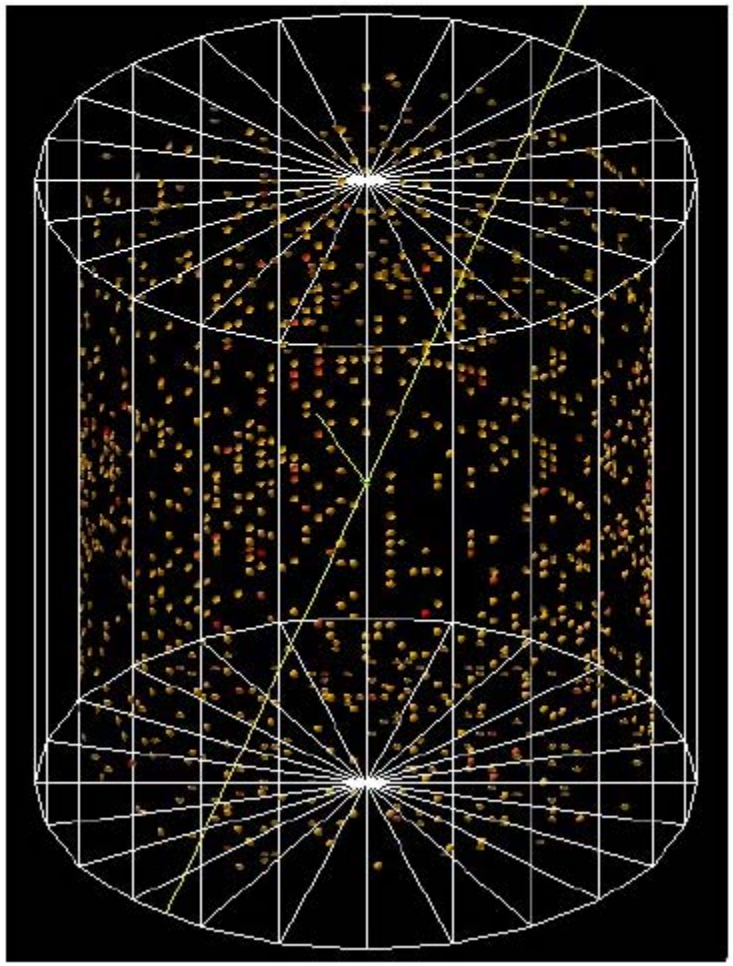
10 MeV Proton



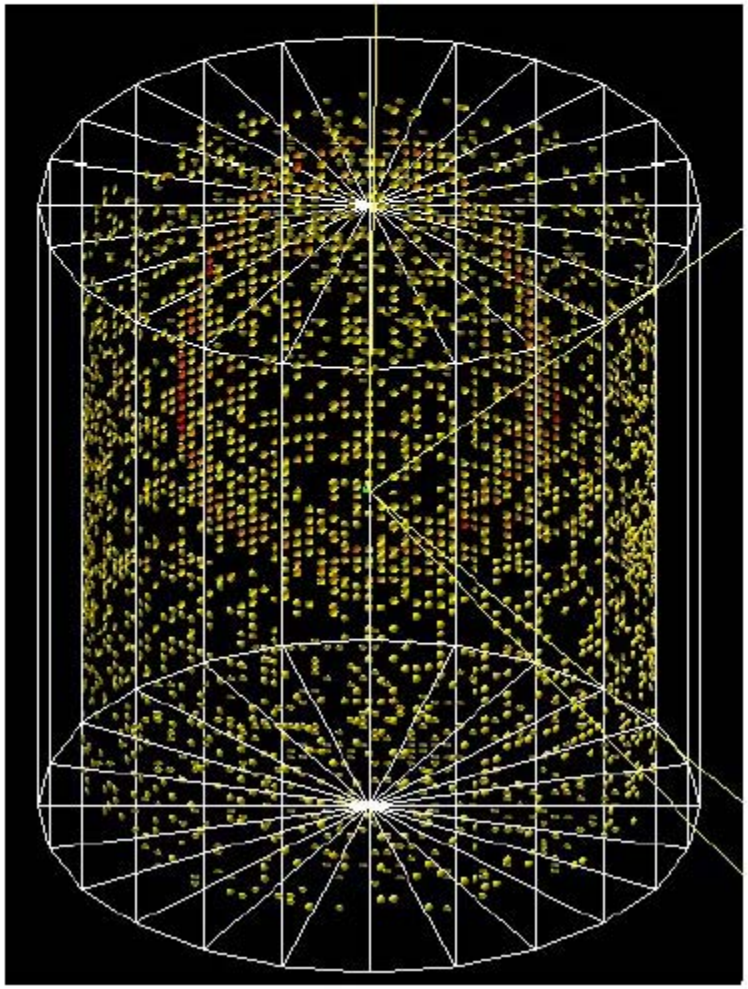
Sanity Check III

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

105 MeV K^+

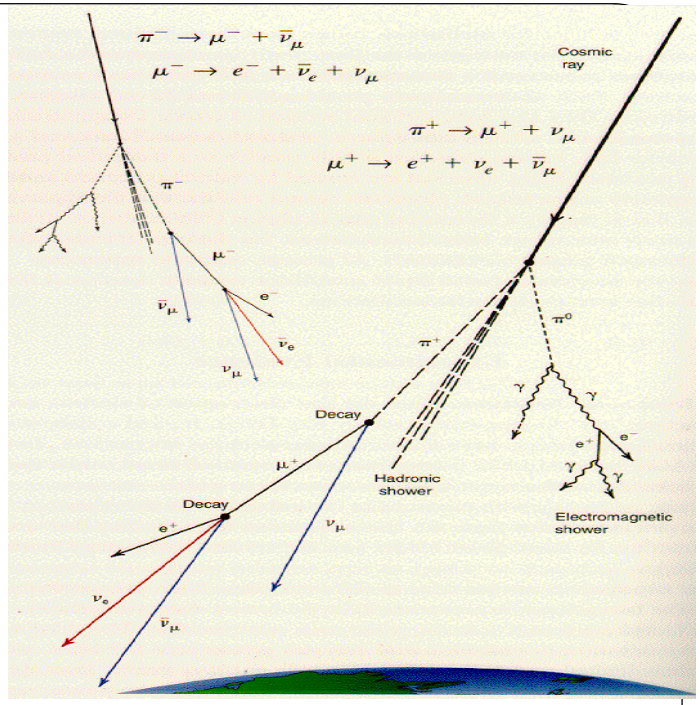


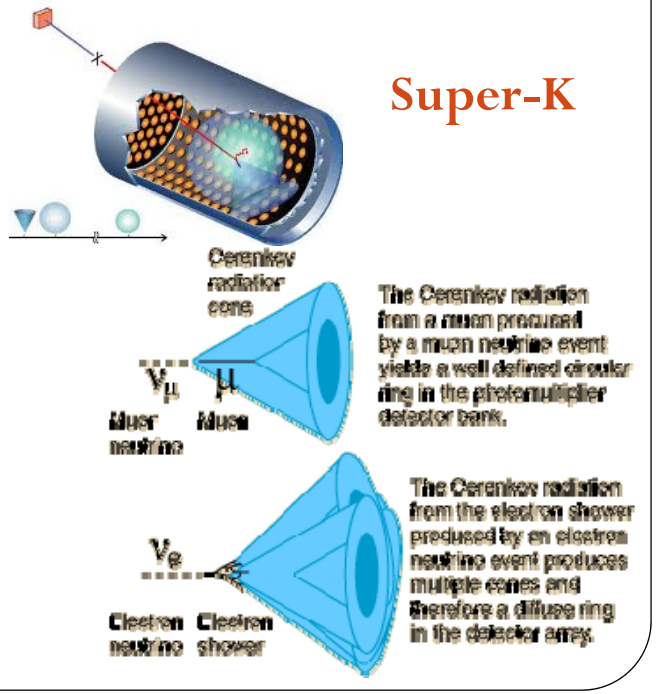
500 MeV Muon



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.
- >100 publications/talks address this studies.
- A proposal submitted to study this background.
- Most atmospheric background events associated with multi Michel electrons, while either π^+ or μ^+ from PDK$^+$ mode only gives one electron.





Sensitivity with Scintillation + Cerenkov

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

- ***WbLS signal-like:***

Prompt

- **K^+ scintillation**

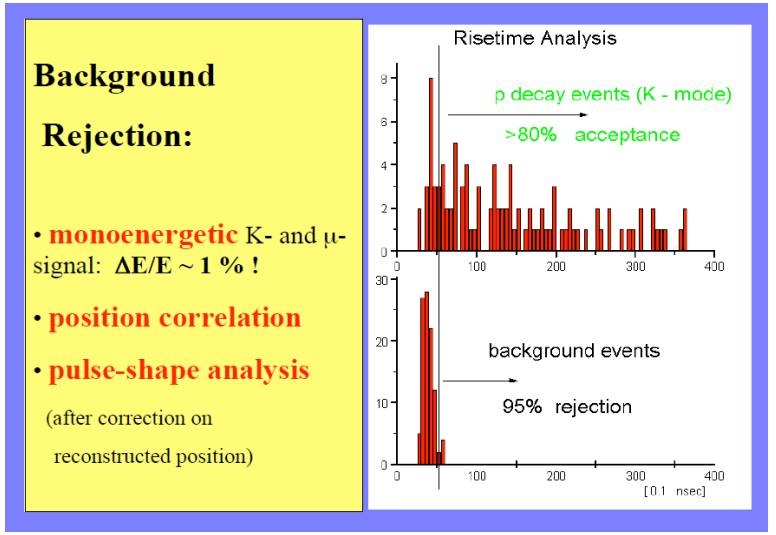
Delay

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

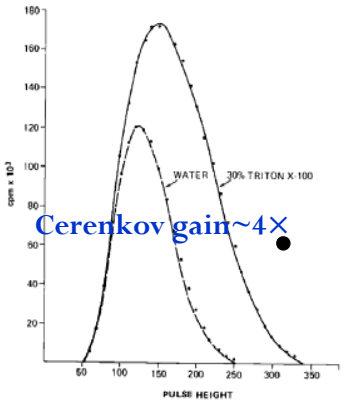
Event Selection Rules

- **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…**

Will extra Cerenkov help?



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

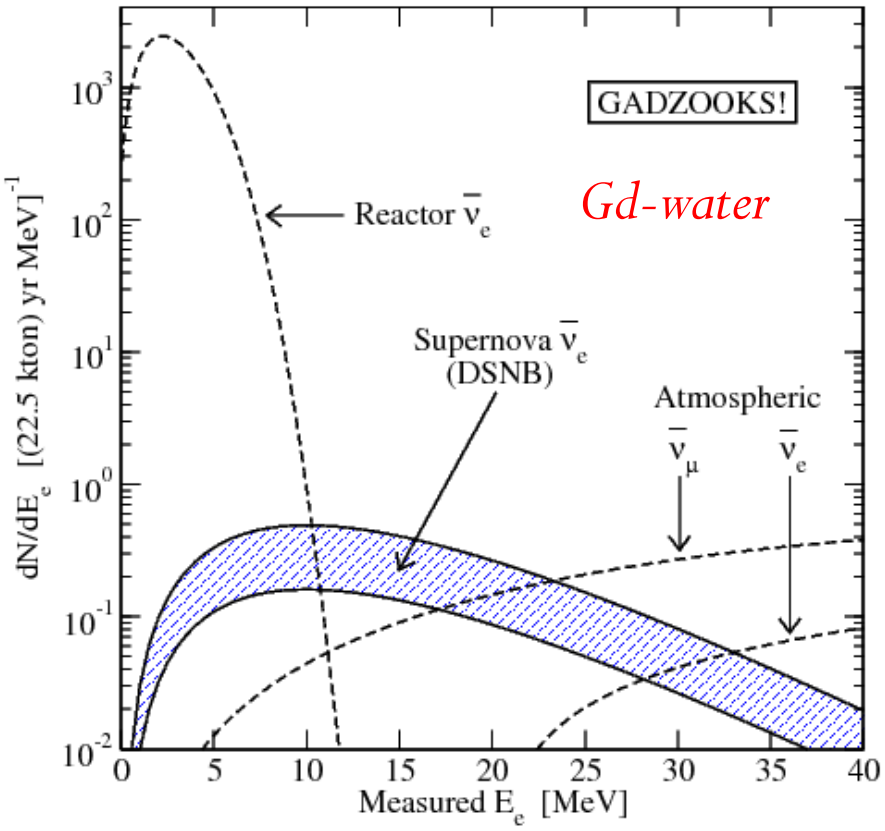


- Compare to SK (170event/1489days), the 3-fold coincidence cuts down to ~5/y; PSD can further suppress the bkg. event to 0.25/y.
- 10-yr run could reach a sensitivity of 10^{34} for the PDK^+ mode).

P.N.P. Chow, VOLUME I. PHYSICAL ASPECTS, (1970).

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?

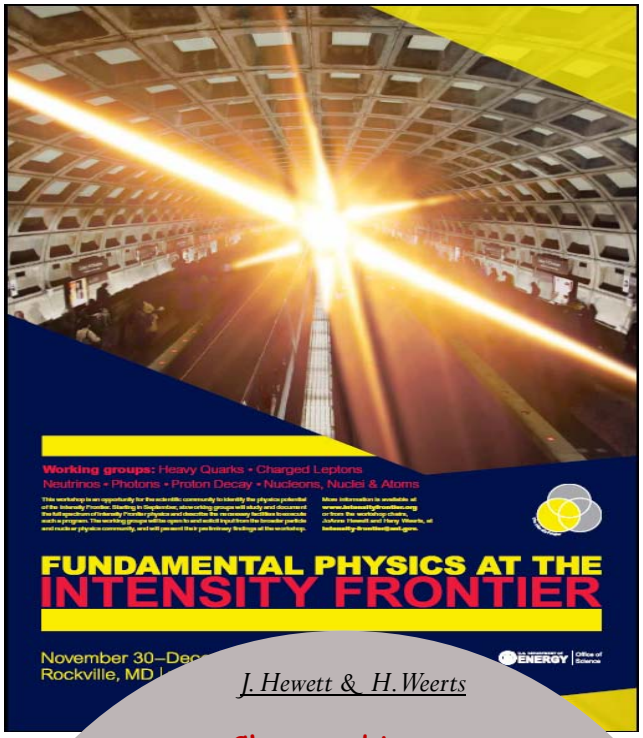
Cerenkov & Scintillation for WbLS

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.

Proton-decay in US

- Proton-decay is one of Intensity-Frontier research topics.
- LBNE is asked to revise the scope to reduce the cost; and even so-be-approved after revision, it's >10-yr from now.
- A megaton water Cerenkov detector is unlikely to be happening in 10-yrs.
- *It might not be so crazy* to propose a mid-range, 50-kt WbLS detector for proton-decay and other physics (at DUSEL? SNOLAB?).
- need MC simulations to guide the design and understand the performances.



J. Hewett & H. Weerts

Charged Leptons

Proton Decay

Heavy Quarks

Intensity Frontier

Neutrinos

Nucleons, Nuclei & Atoms

Hidden Sector Photons, Axions & WISPs



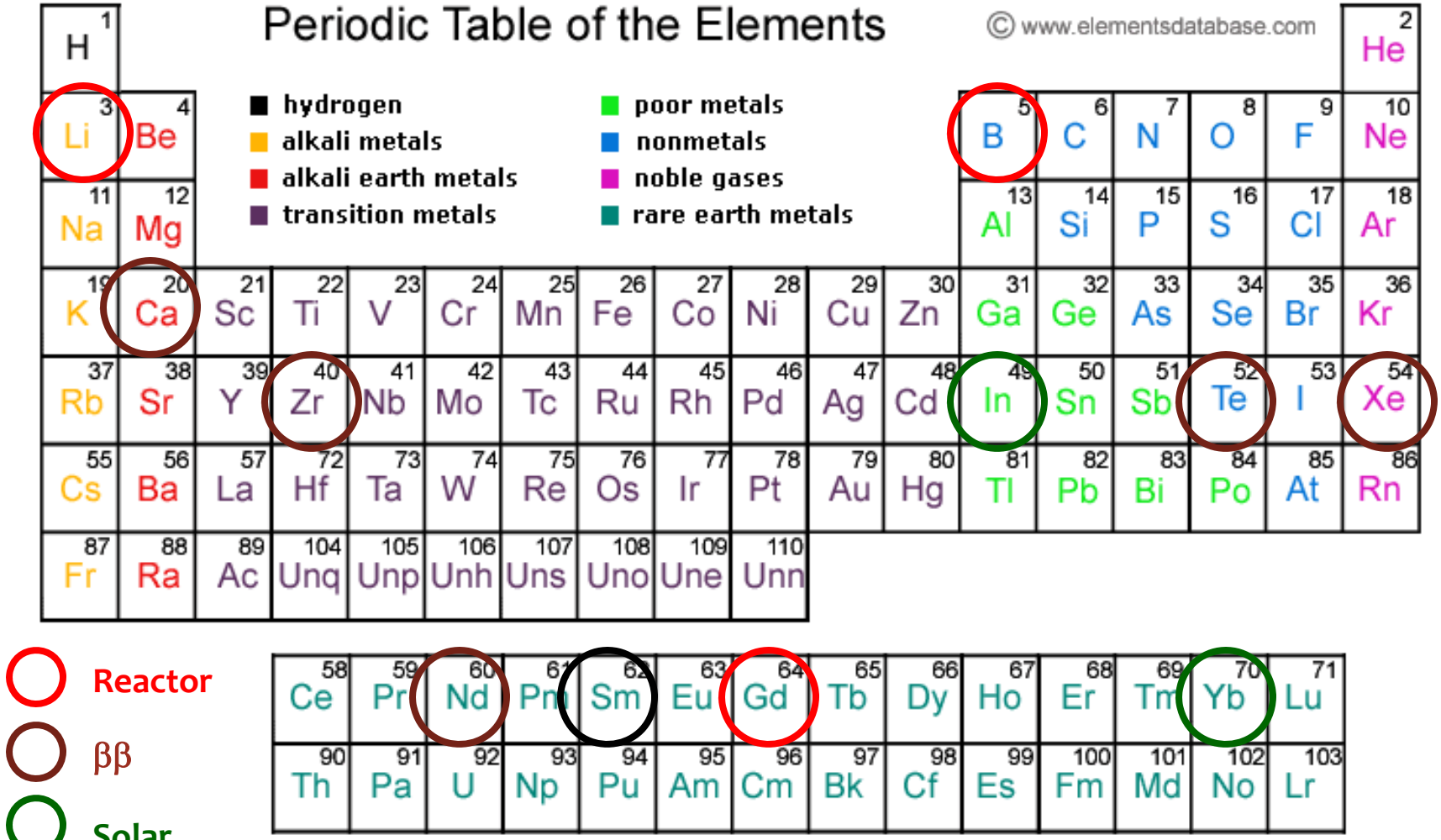




- *Double-beta decay*
- *Reactor neutrino*
- *Geo neutrino*
- *Supernovae alarm*

A new way of loading Hydrophilic Isotopes in 80+% LS

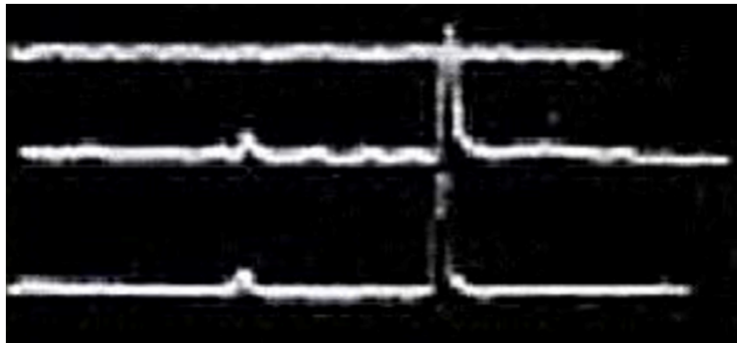
BNL Metal-loaded LS for Physics



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

Inverse Beta Decay Detection

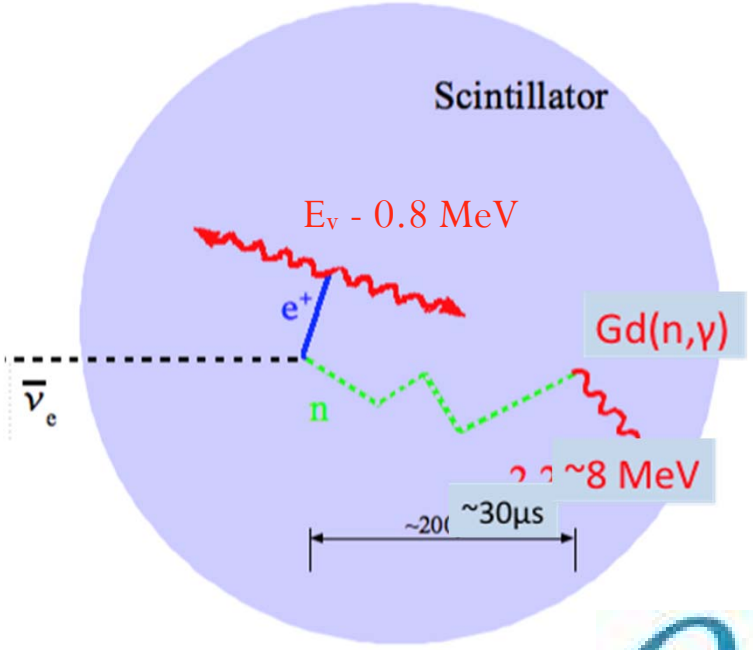
- $E_{threshold} = 1.8$ MeV
- 'Large' cross section $\sigma \sim 10^{-42}$ cm^2
- Distinctive coincidence signature in a large liquid scintillator detector



Cowan & Reines, Savannah River 1956

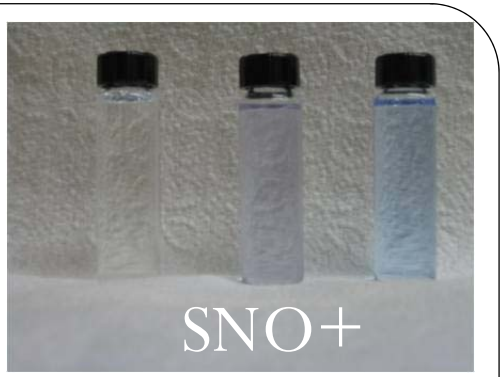
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

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



Double-beta Decay

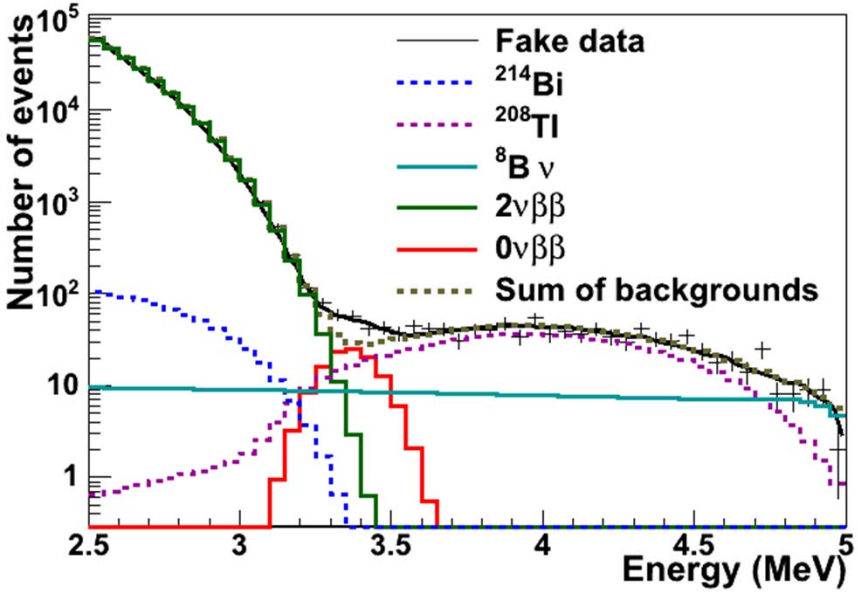
Isotope	$G^{0\nu}$ ($\times 10^{-15}$ y^{-1})	Q-value (MeV)	Abundance %
^{48}Ca	75.8	4.27	0.2
^{76}Ge	7.6	2.04	7.8
^{82}Se	33.5	3.00	9.2
^{76}Zr	69.7	3.35	2.8
^{100}Mo	54.5	3.03	9.6
^{116}Cd	58.9	2.80	7.5
^{130}Te	52.8	2.53	34.5
^{136}Xe	56.3	2.48	8.9
^{150}Nd	249.0	3.37	5.6



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

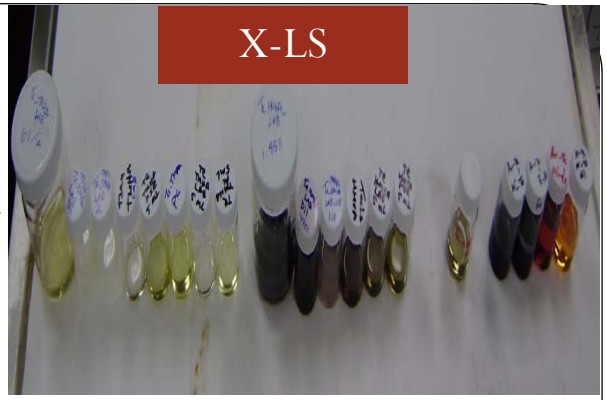
- whether neutrinos are Dirac or Majorana particles
- probe neutrino masses at the level of tens of meV; A m_{bb} limit of ~20 meV would exclude Majorana neutrinos in an inverted hierarchy.

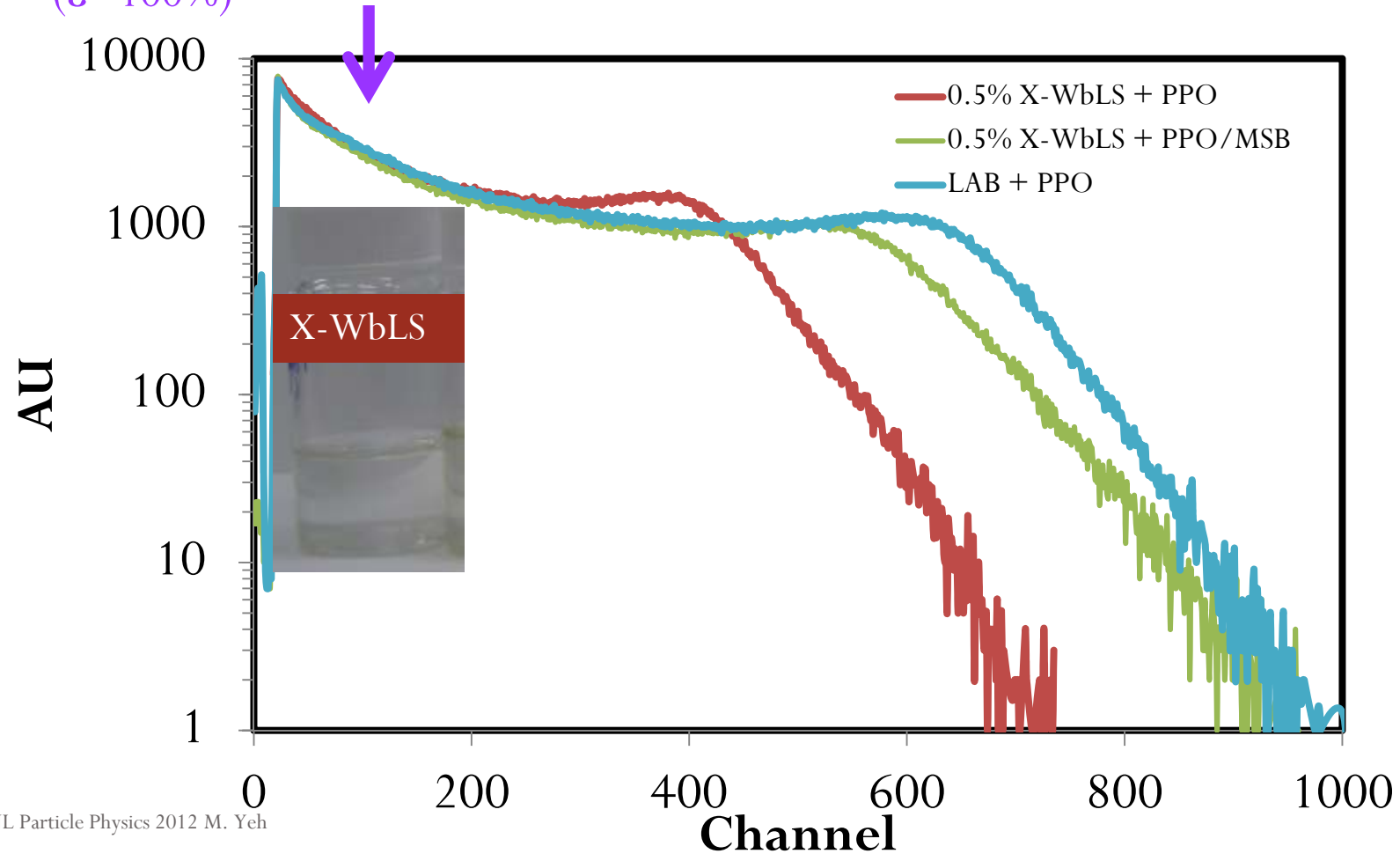
- SNO+ is the only metal-loaded liquid scintillation detector.
- Flexible and easy scale-up
- Any hydrophilic DDB isotopes that cannot be done in pure LS; NOW is possible.



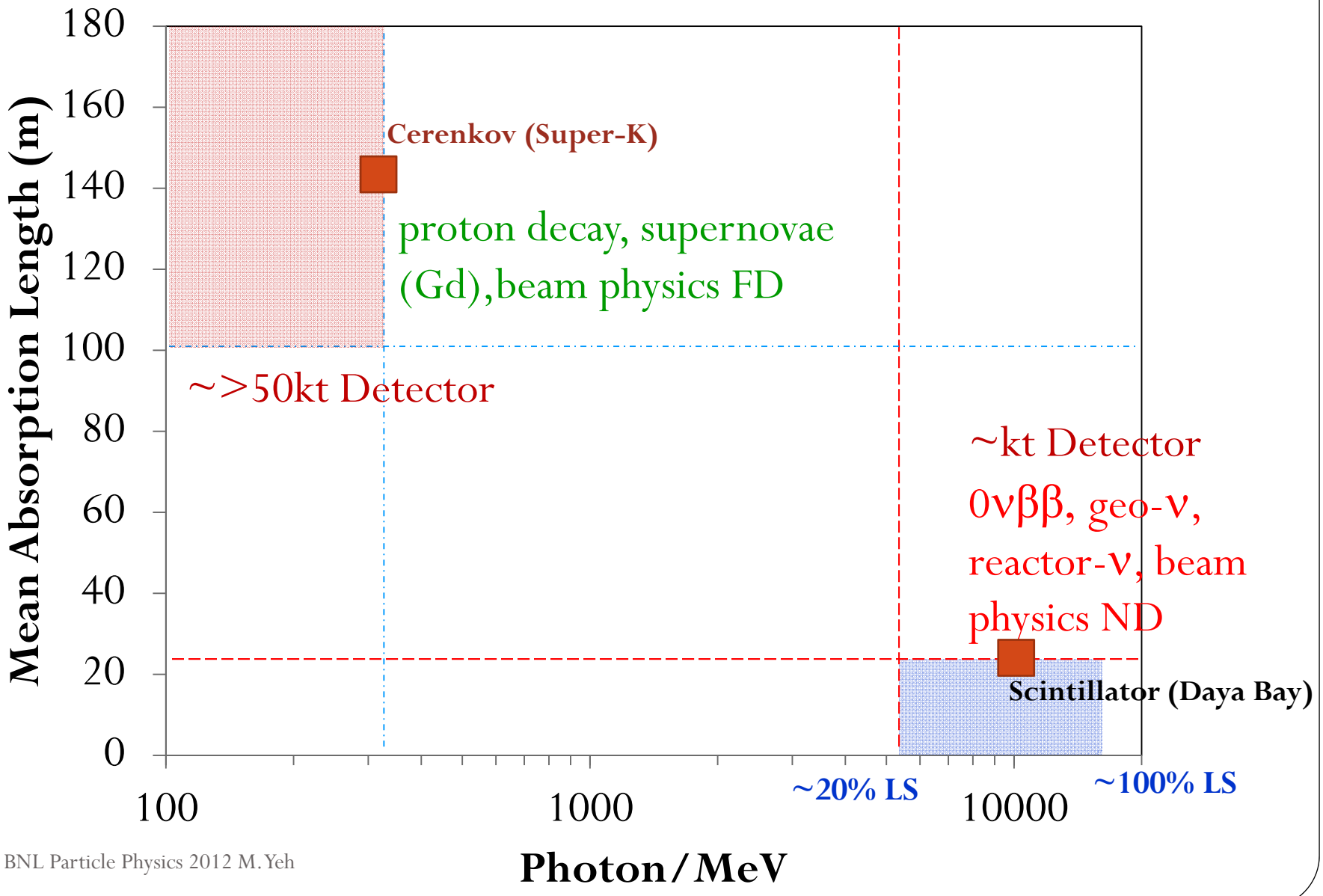
First DBD isotope in WbLS

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

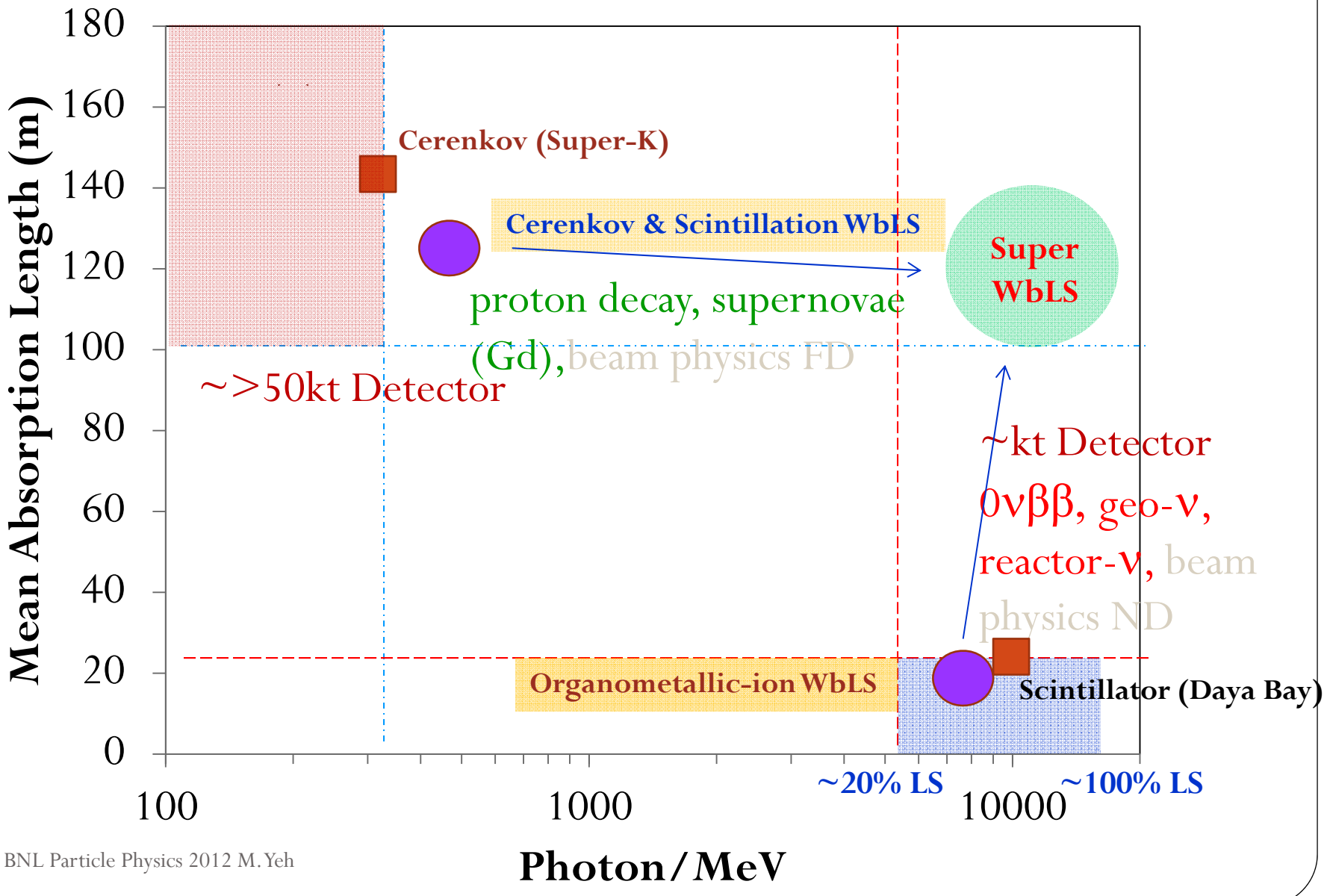




A balance of light-yield vs. attenuation-length



Two WbLS-formulas for proton-decay and for DBD expts.

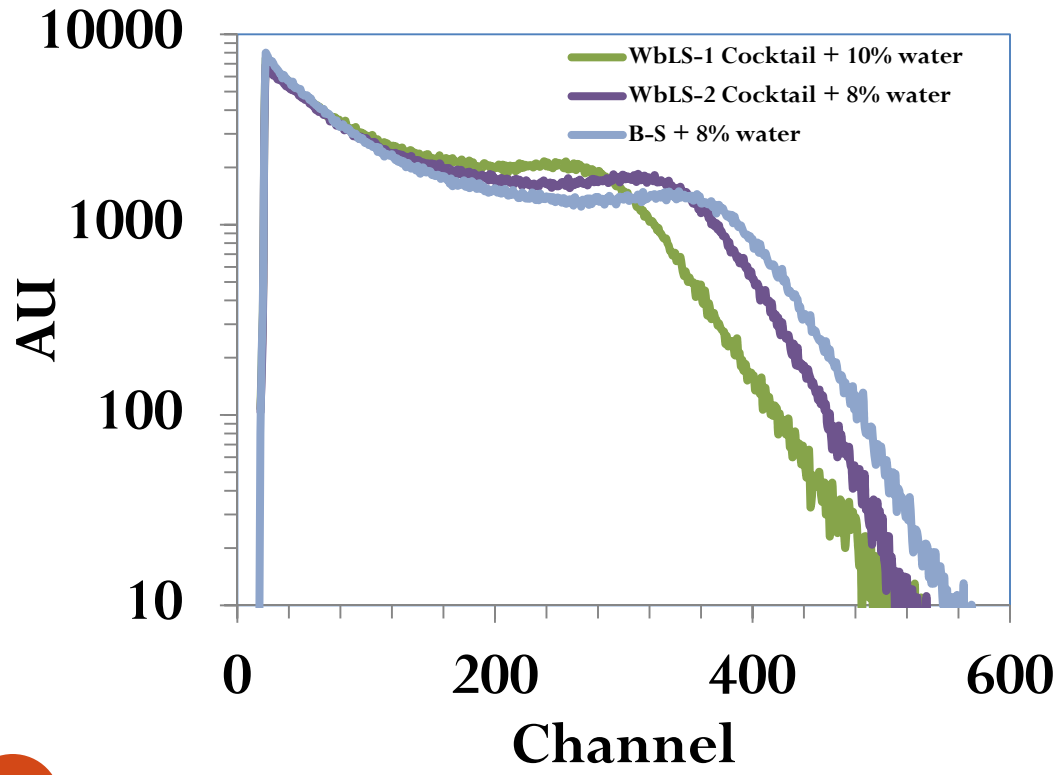


- *Biodegradable liquid scintillator cocktail*
- *Veto system*
- *Short half-life calibration source*

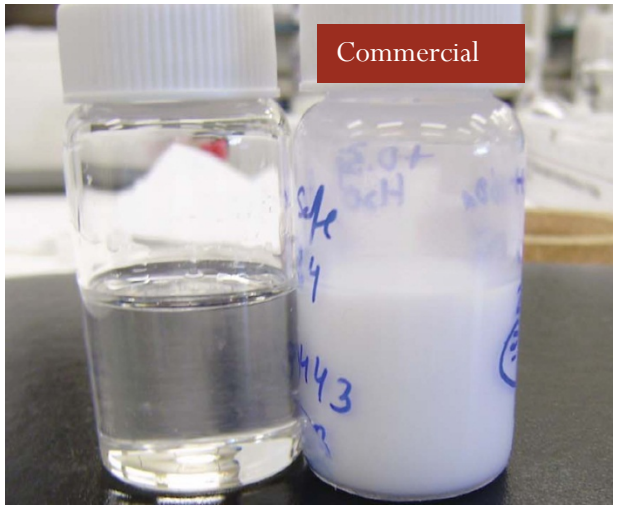
Other Applications

BiodegradableWater-based Scintillation Cocktail

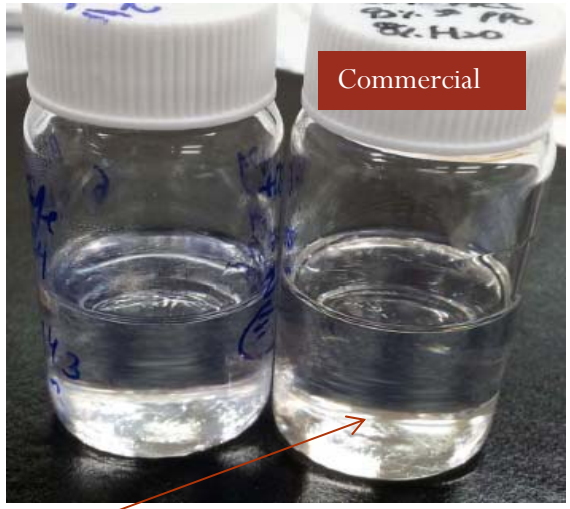
- Take more % aqueous sample than commercial product
- No permeation of scintillation vials (long-stable counting)
- Environmentally friendly (easy disposed)



20 minutes



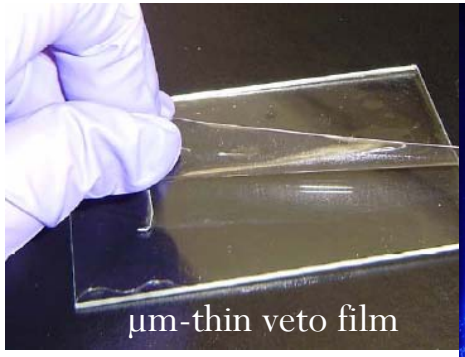
>24-hrs

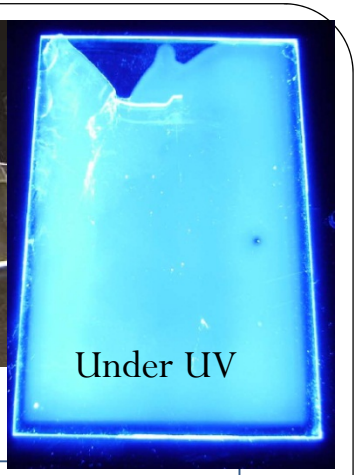


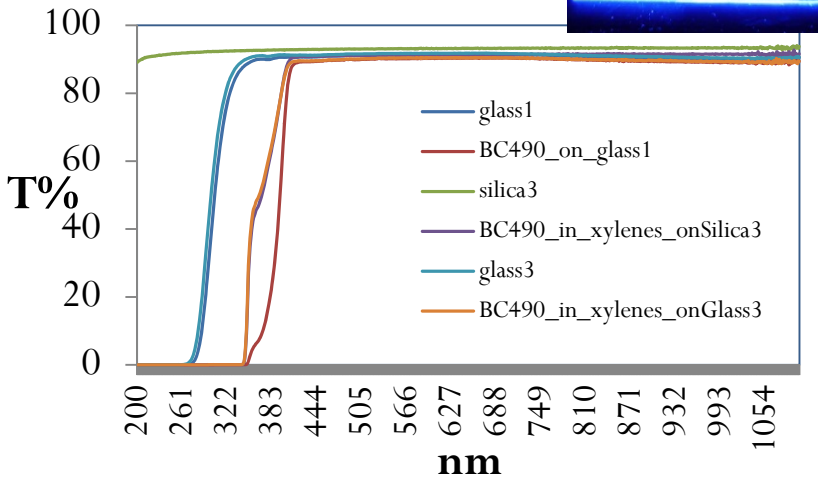
temperature-sensitive

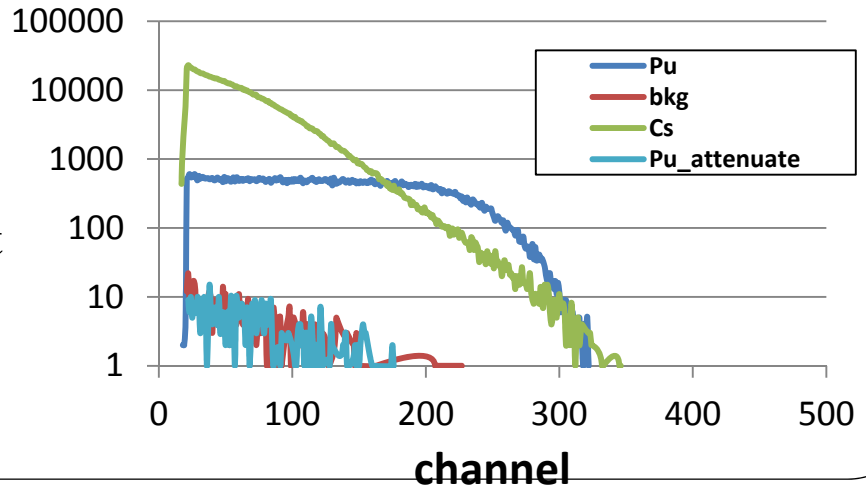
Veto film for cryogenic or solid-state detector

- 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.

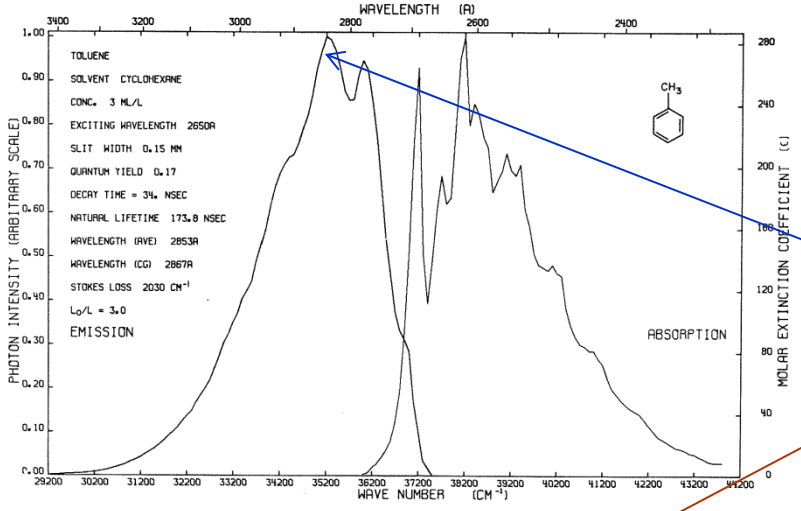


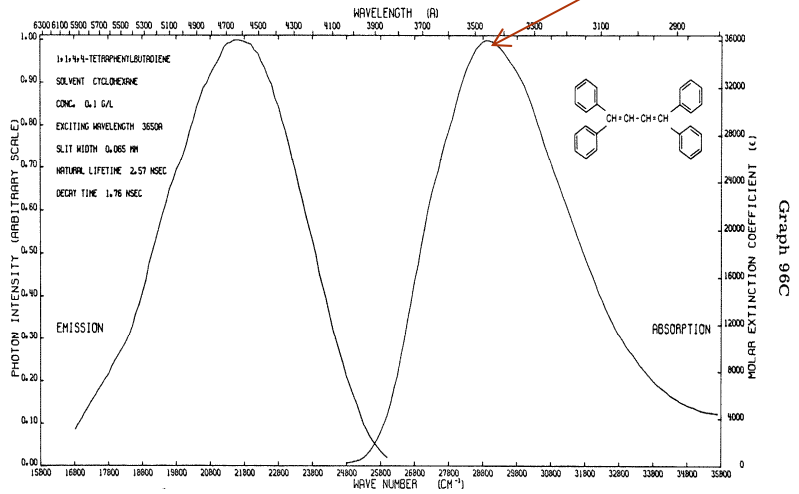






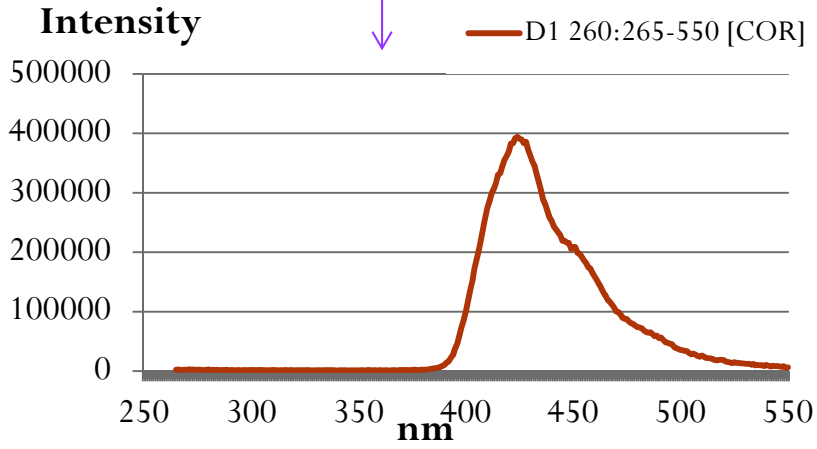
LAr light collection





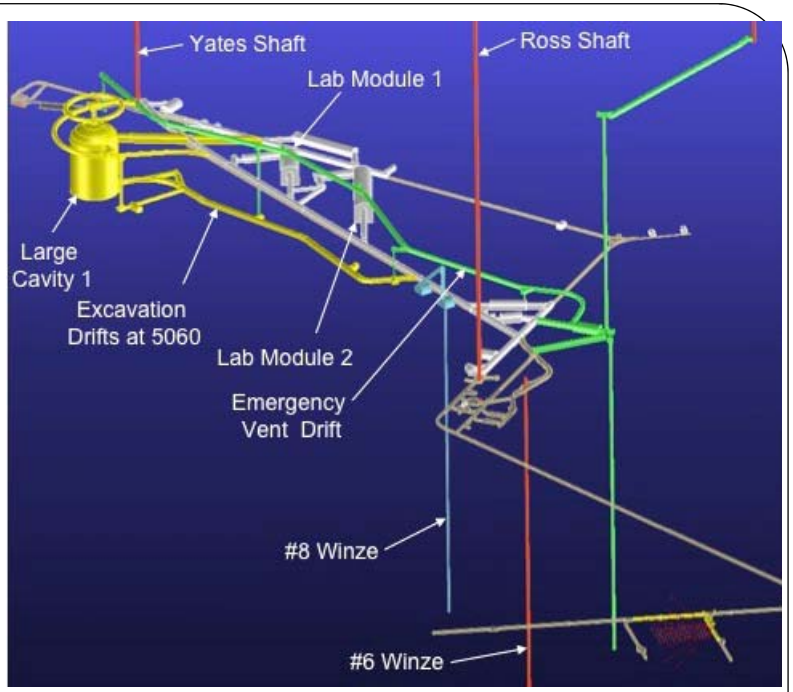
Handbook of Fluorescence Spectra of Aromatic Molecules, 1967

- 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***).



WbLS veto system

- Scintillation water could serve as a large and economic Cerenkov/Scintillator veto system.
  - LBNE (LAr) proposing large 20%PC+80%DD LS; if not at 4850.
  - LUX and other dark matter researches are looking for veto system (Gd-water, LS, Gd-LS, etc.).
  - Long-range reactor monitoring.
  - etc.



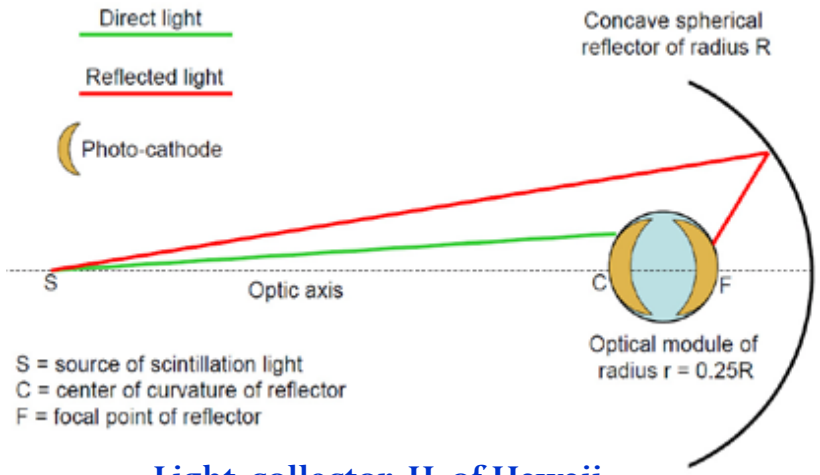
WbLS can be molded as a surrounding shielding or multiple NoVA-type segmentations

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

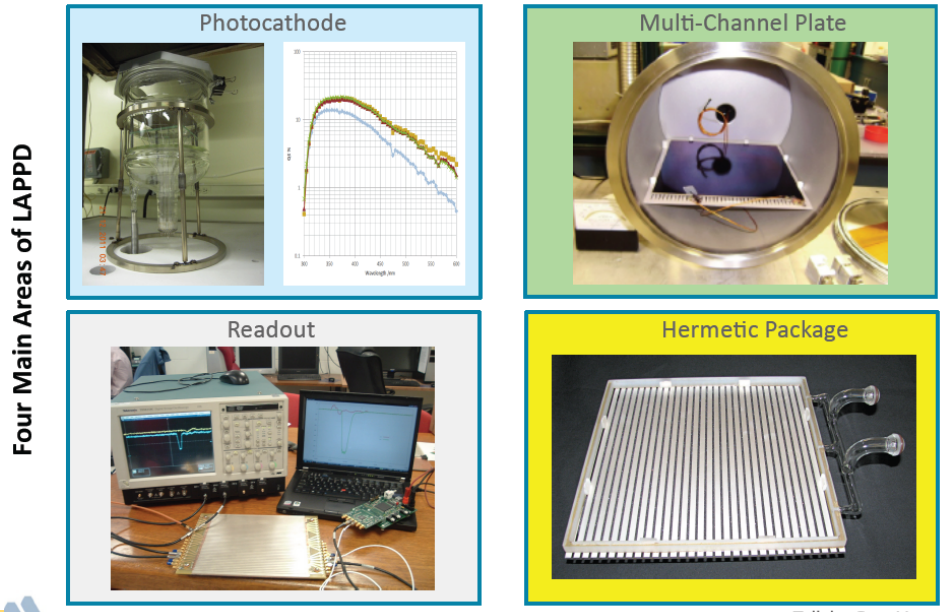
Short Half-live Calibration Sources

- 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…

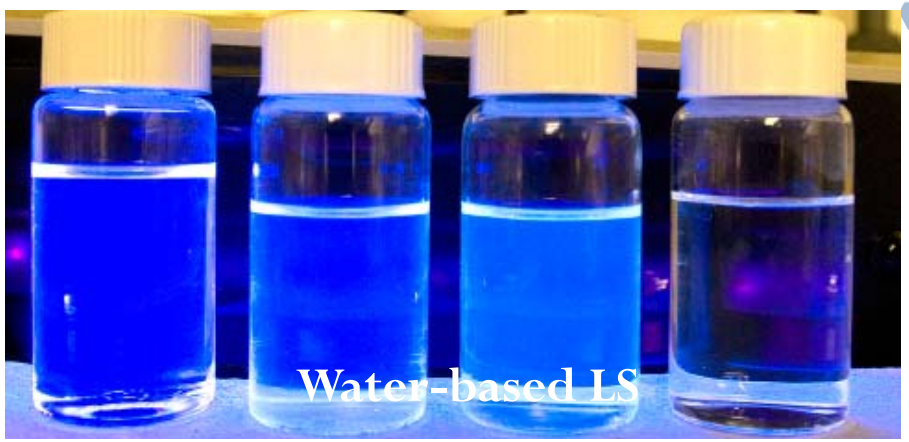
1-ton WbLS demonstrator at neutrino-beam or reactor-site



Light-collector, U. of Hawaii



LAPPD, ANL



WbLS, BNL

what if

build the demonstrator with few generic detector R&D pieces together?

Summary

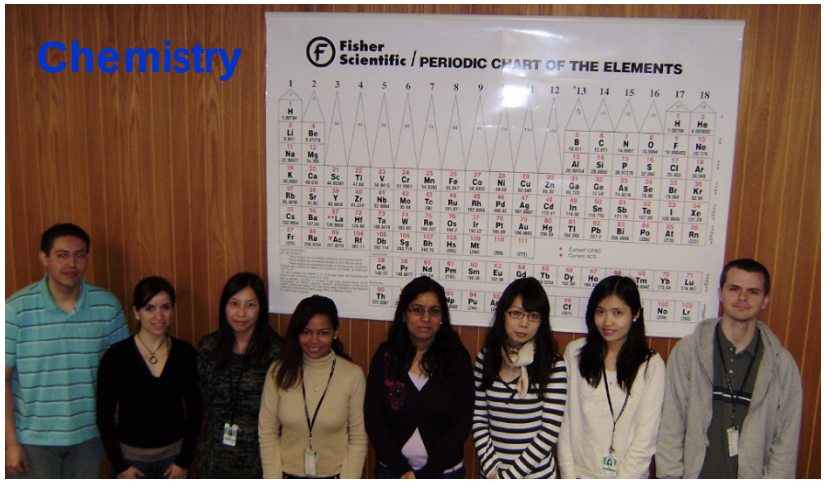
- A multi-physics, new detection medium with long attenuation length and *Scintillation* & *Cerenkov* features to explore the *physics below Cerenkov* (*nucleon decay*).
- A tunable detector that can adjust photon production vs. attenuation length for different physics.
- A new metallic loading technology 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.

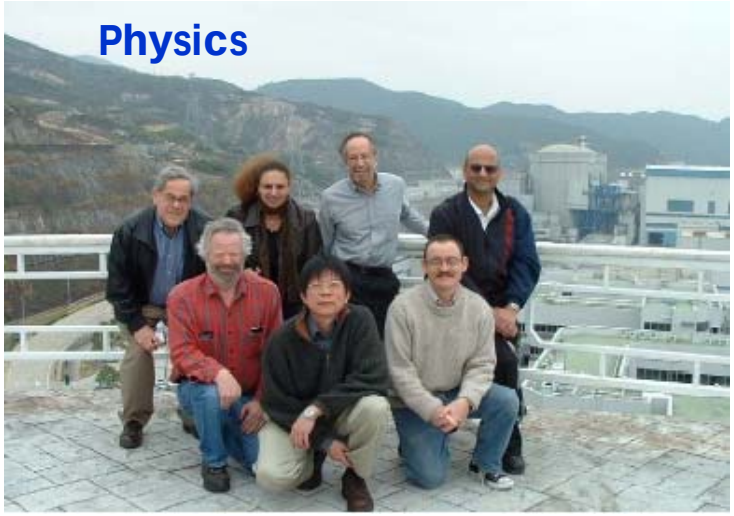
Futures:

- (1) long-pathlength measurements, (2) confirmation of light-propagation (scintillation/Cerenkov), (3) fluor/shifter optimization, (4) ***simulations***, (5) ***ton-scale demonstrator***, (6) super-WbLS R&D

Acknowledgement

- Minfang Yeh (group leader)
- Sunej Hans
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- Visiting Scientist: Maria Laura Di Vacri





- Milind Diwan, David Jaffe, Brett Viren, Hide Tanaka, Dana Beavis, Jiajie Ling, Chao Zhang, Lisa Whitehead

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