Liquid Scintillator Challenges for Physics Frontiers

Minfang Yeh

Brookhaven National Laboratory

RENO-50, SNU, Korea

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a passion for discovery

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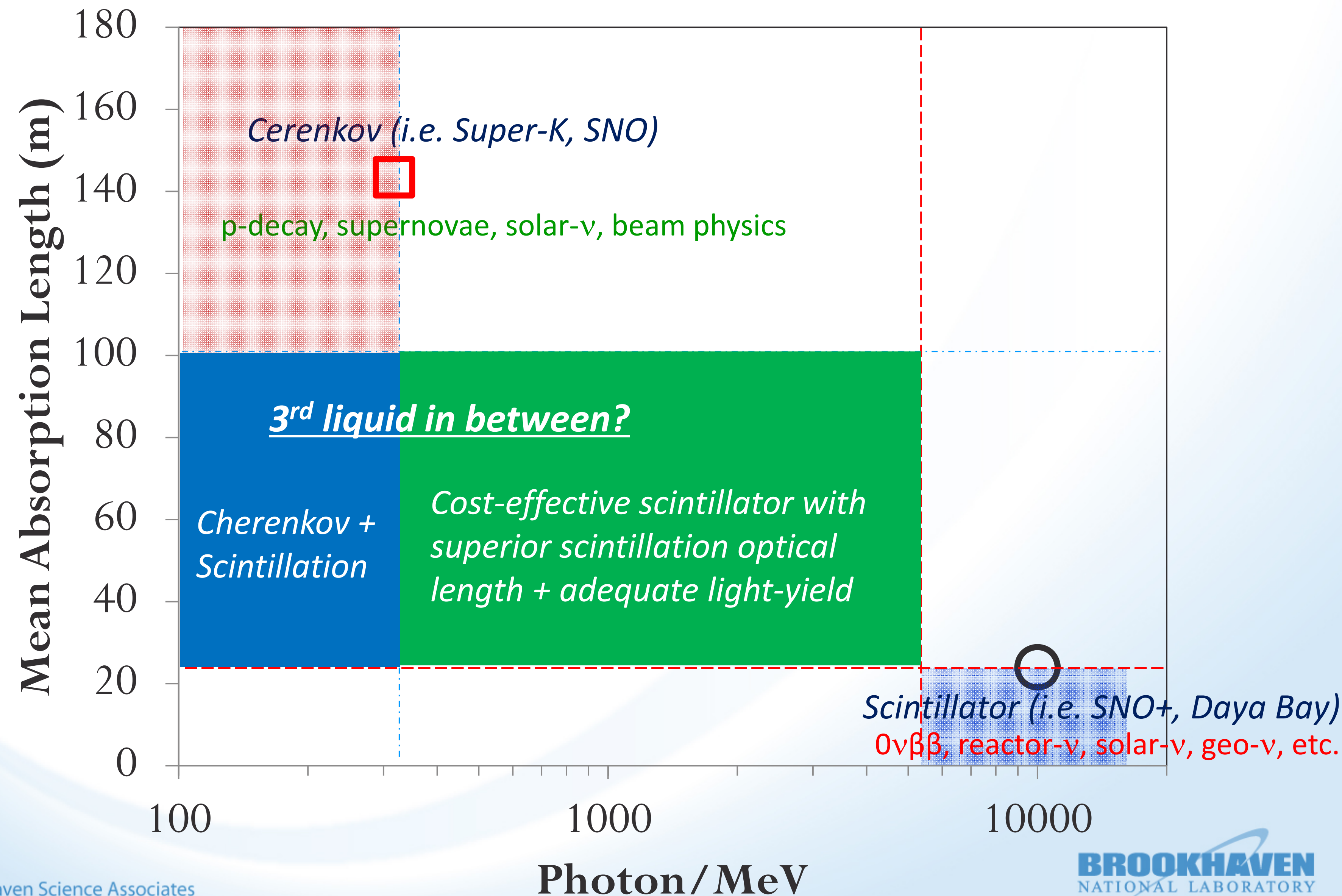
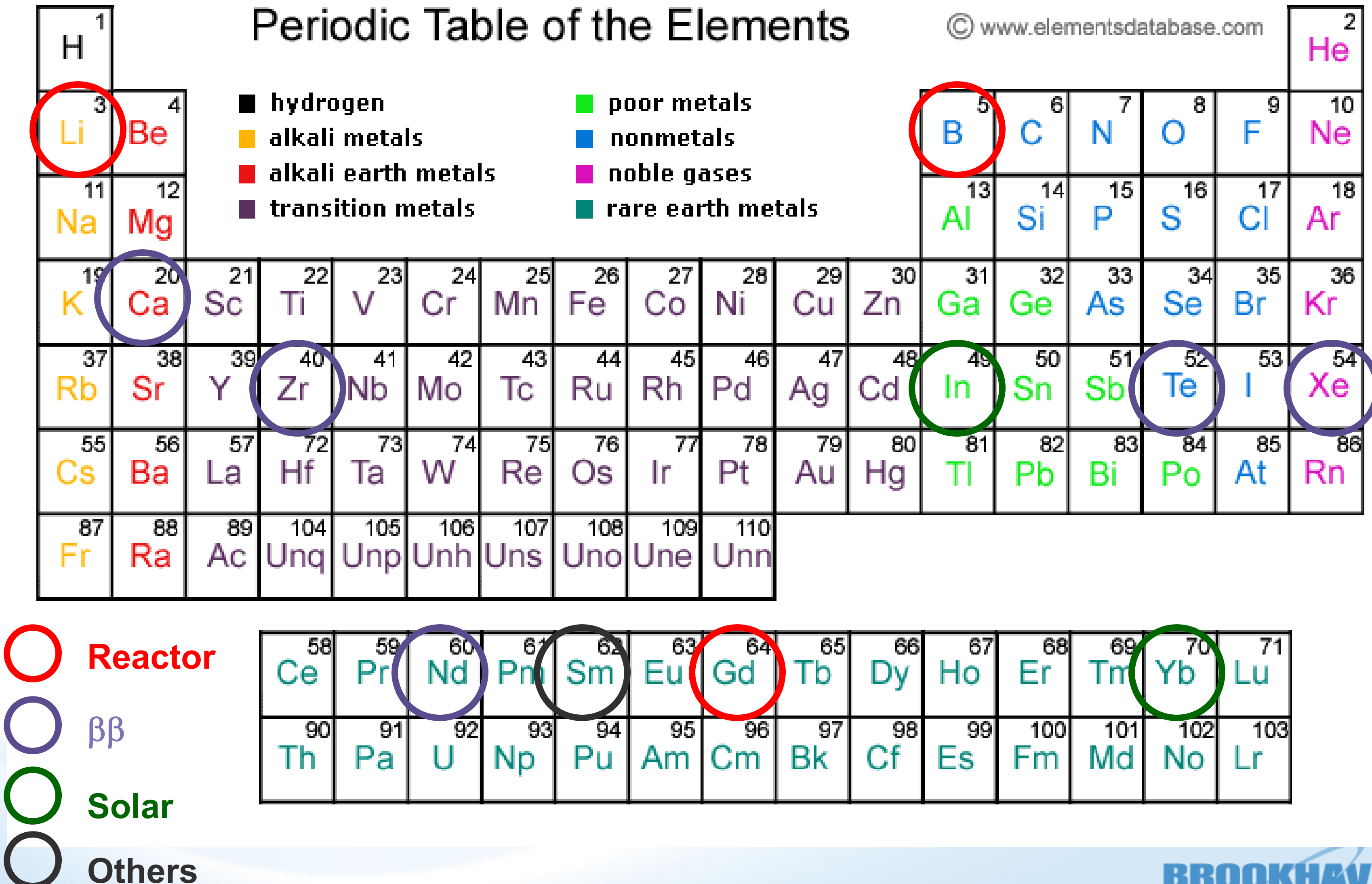
Cherenkov and Scintillation Detectors



Metal-loaded LS for Physics Frontiers



Liquid Scintillator for Future Frontiers

$0\nu\beta\beta$
Neutrino Mass and Hierarchy

Short Baseline, OscSNS, or ν-source
Sterile ν vs. reactor anomaly

Nucleon Decay

Common features between detectors

Liquid Scintillator
(Metal-loaded & Water-based)

unique requirement for individual detector

Nonproliferation & Medical Imaging

Dark Matter
WIMP detection

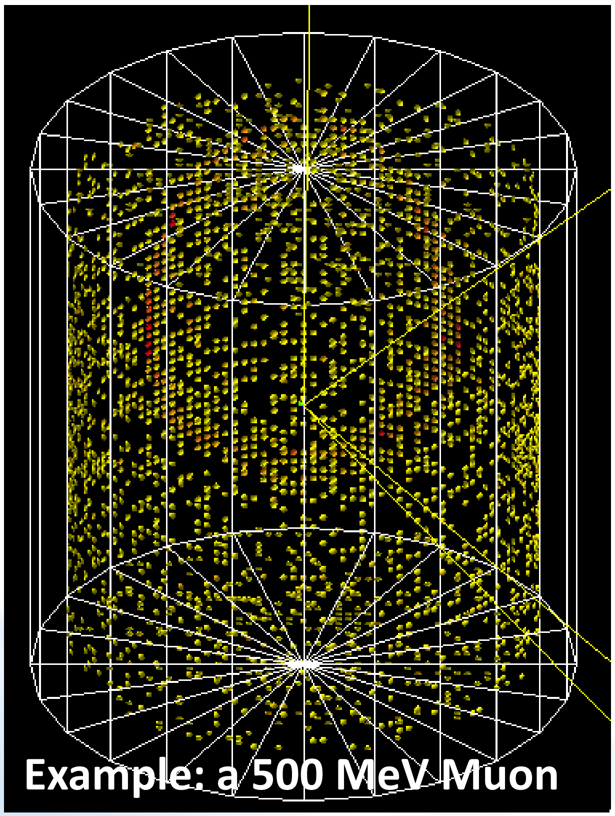
Long Baseline
Neutrino Hierarchy
θ_{12}, Δm^2_{21} and Δm^2_{32}
Solar-ν, Geo-ν, etc.

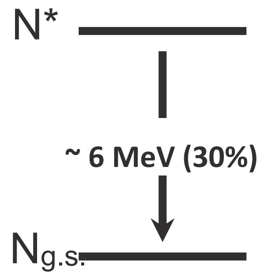
Water-based Liquid Scintillator

- *A new detection medium in search for proton decay*

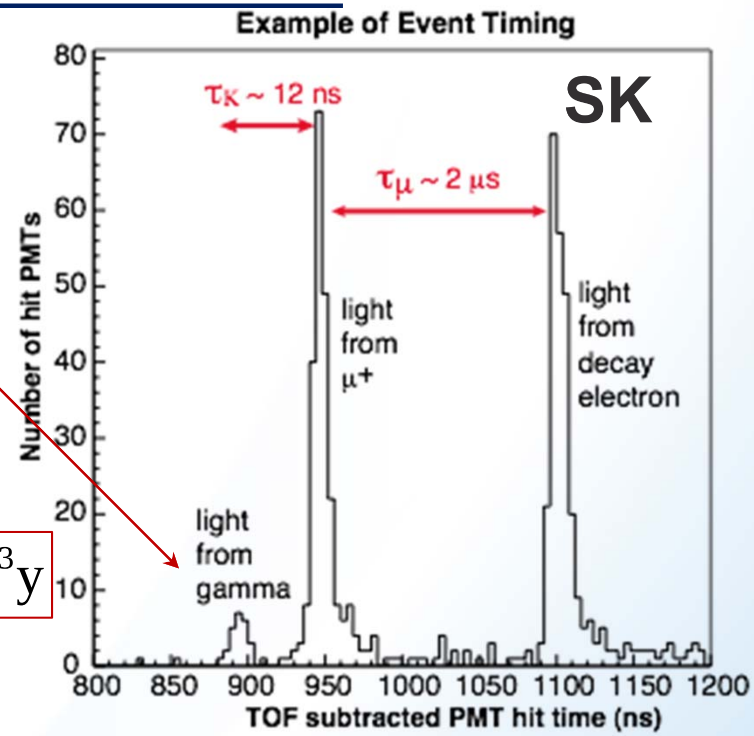
$$p^{+} \rightarrow K^{+}\overline{\nu}$$

- *K^{+} is below Č threshold!*





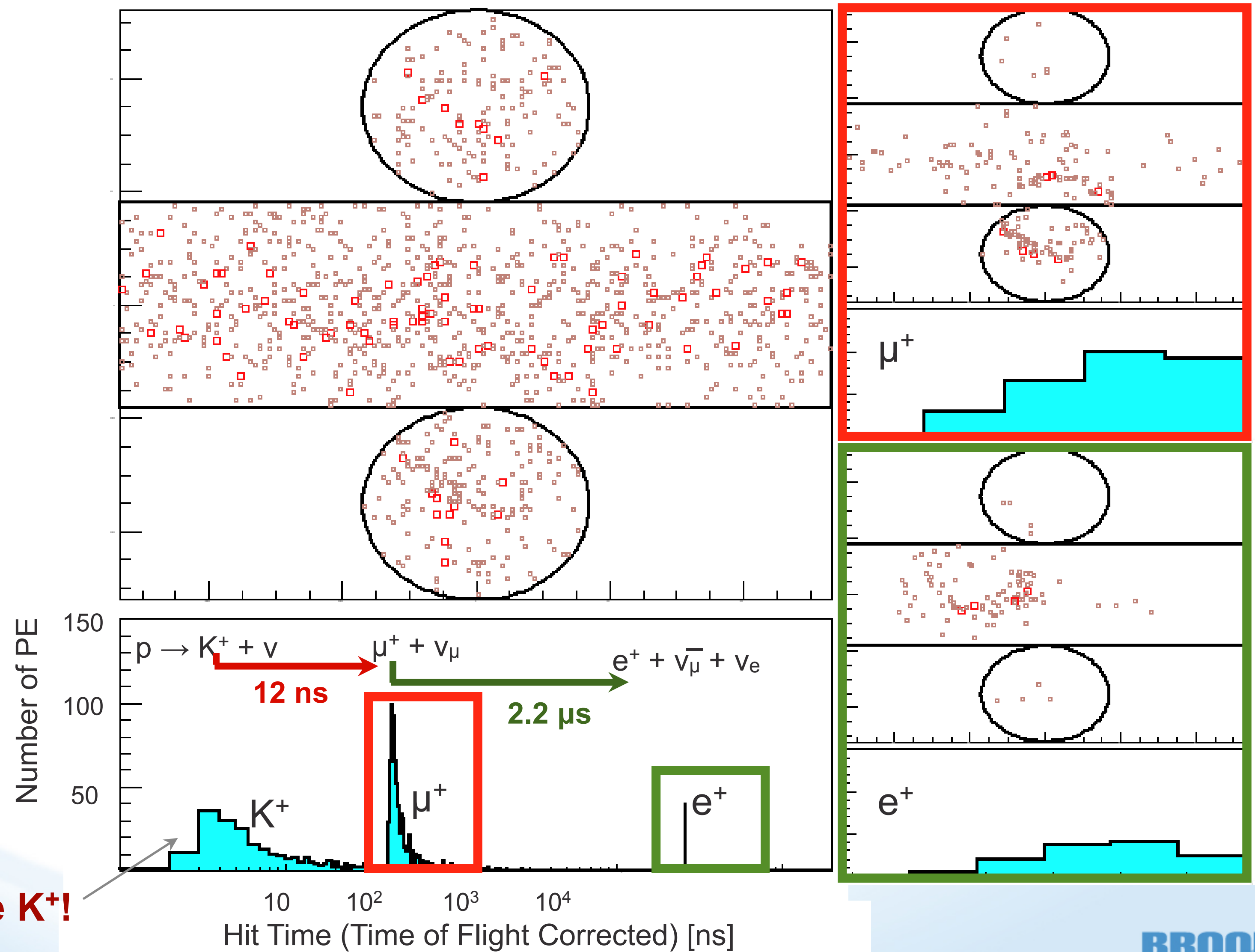
$$\tau(p \rightarrow k^{+}\overline{\nu}) > 2.3\times10^{33}\text{y}$$



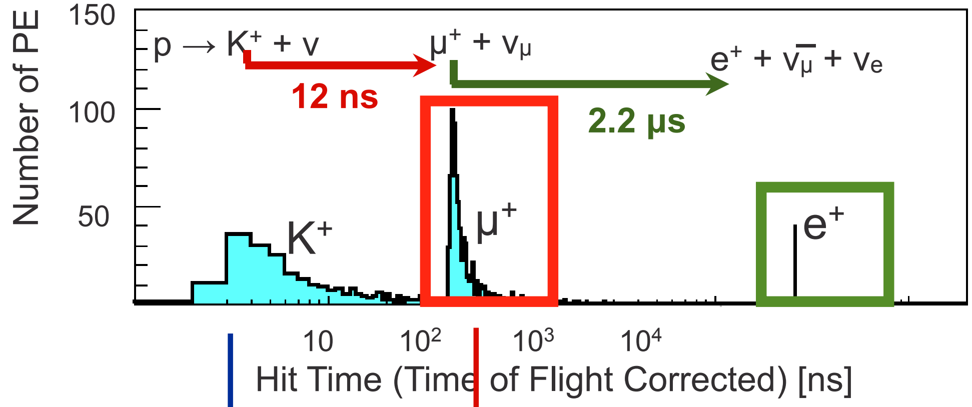
- *Simulation of a Large WbLS Detector*
  - *Based on WCSim software (Geant4-based simulation used in LBNE Water detector concept design)*
  - *SK-like geometry, 22.5 kton Fiducial Volume*
  - *SK 20'' PMT, 40% coverage*
  - *WbLS material + scintillation + wavelength shifting*

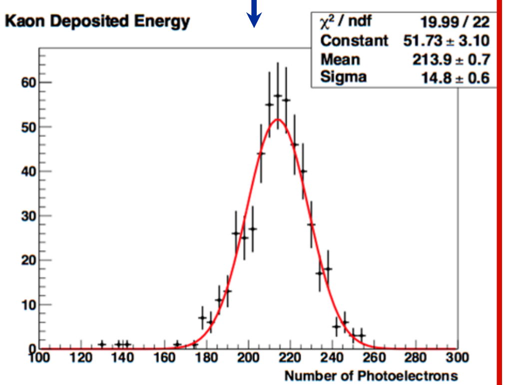
The $p^+ \to K^+\overline{\nu}$ Channel in a WbLS Detector

A simulated event with 90 scintillation photons/MeV

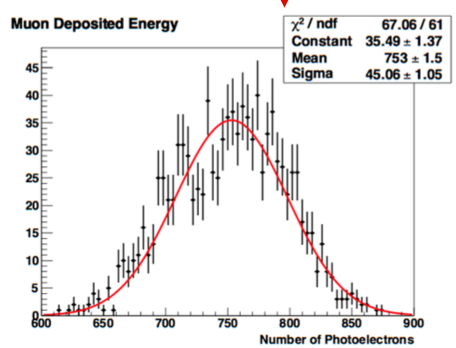


Visible K+!





Kaon: 105 MeV -> 213 PE

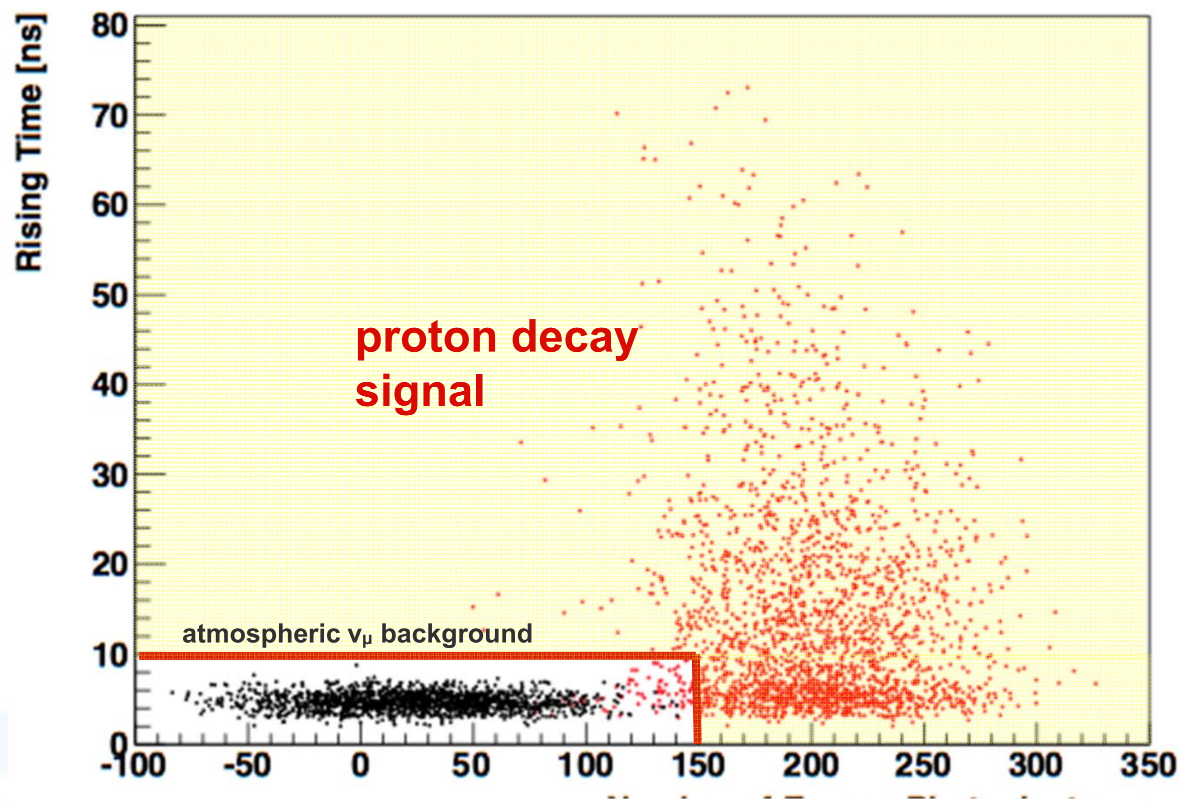


Muon: 152 MeV -> 753 PE

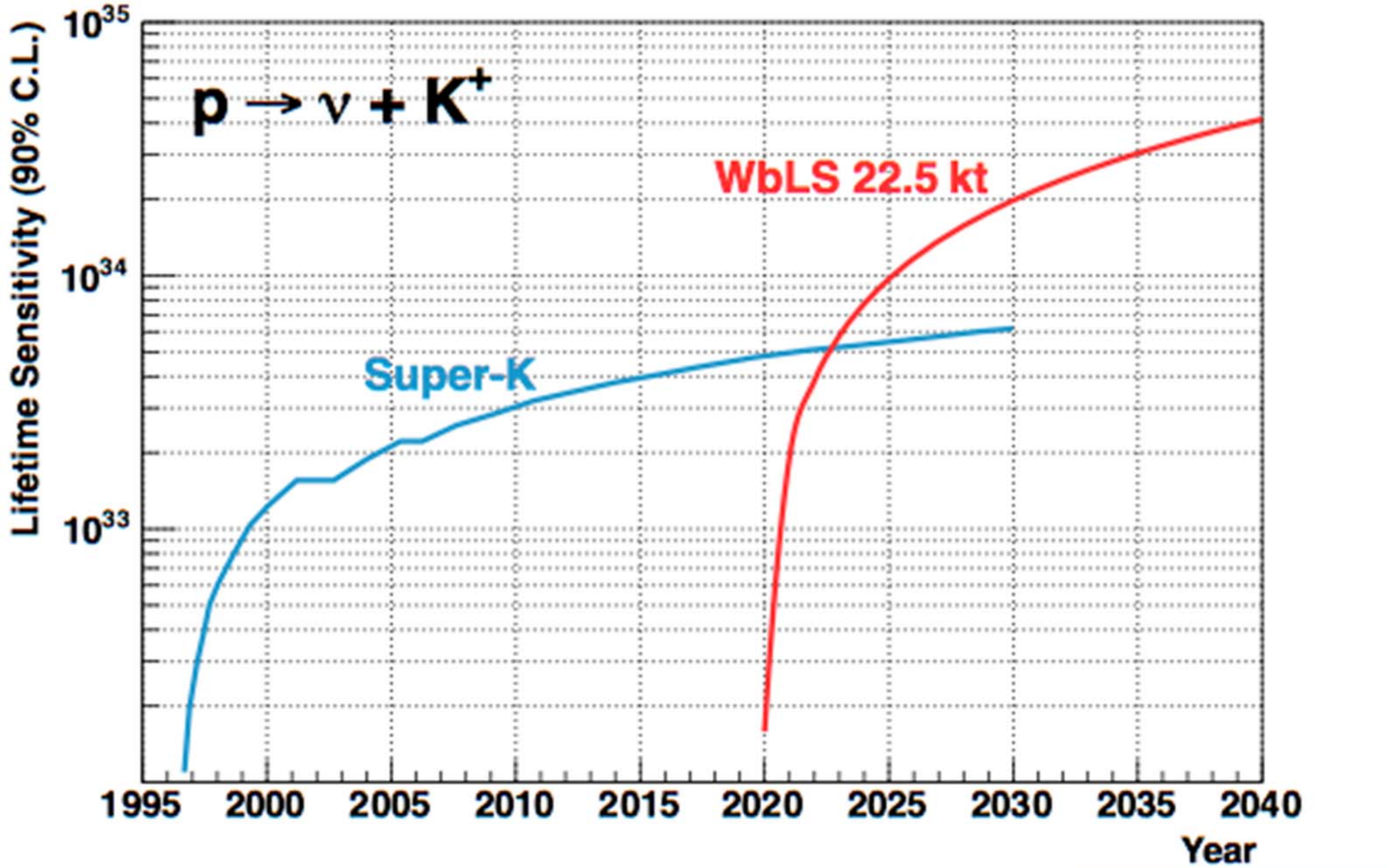
Main background: atmospheric ν_μ

Reduce by:

- **Rising-time cut**: define a PSD to distinguish background from 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

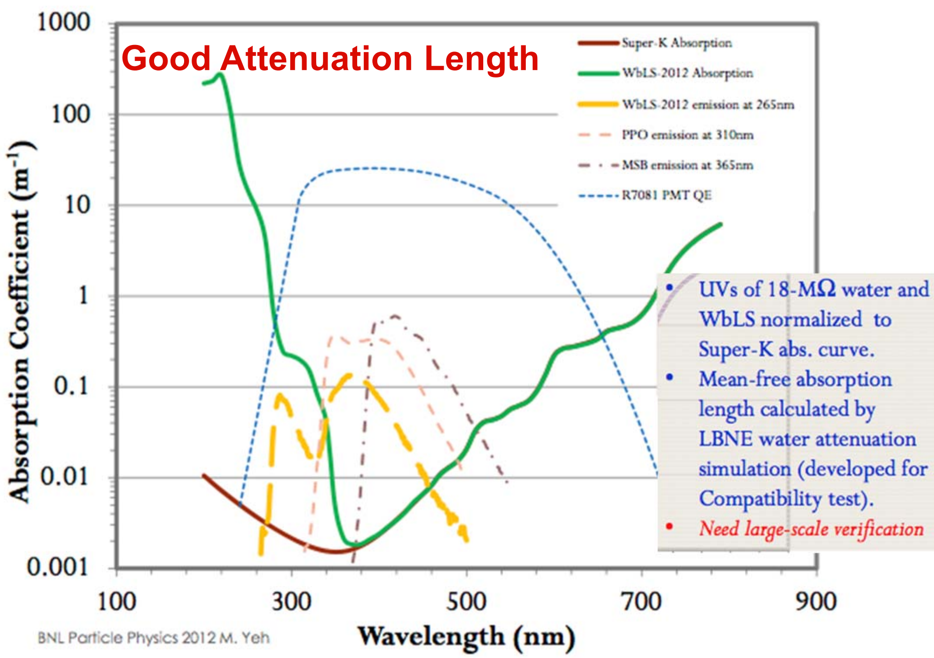


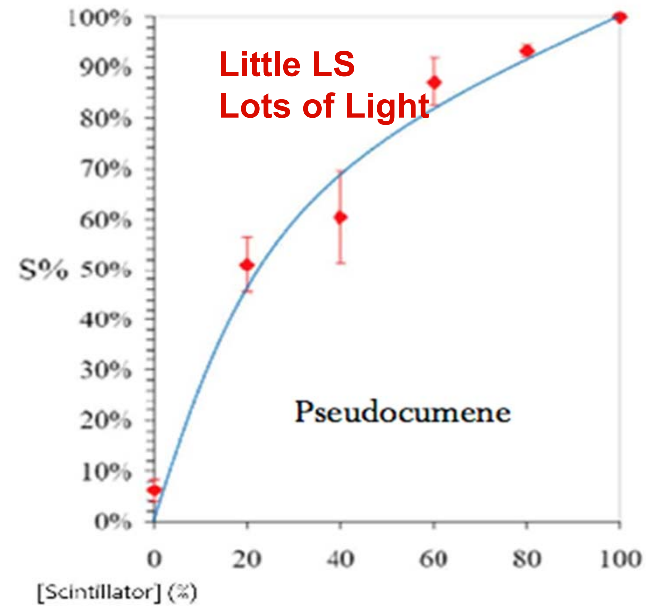
Projected Sensitivity

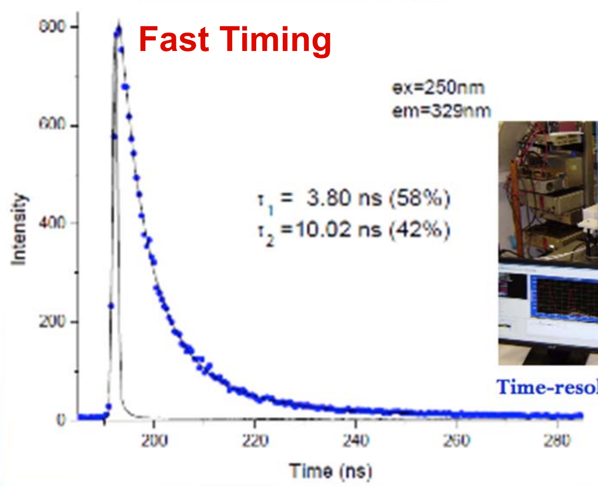


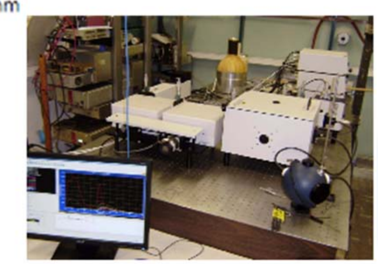
$$\tau(p \rightarrow K^+\bar{\nu}) > 2 \times 10^{34}\text{y at } 90\% \text{ C.L. in 10 years}$$

Properties of Water-based Liquid Scintillator







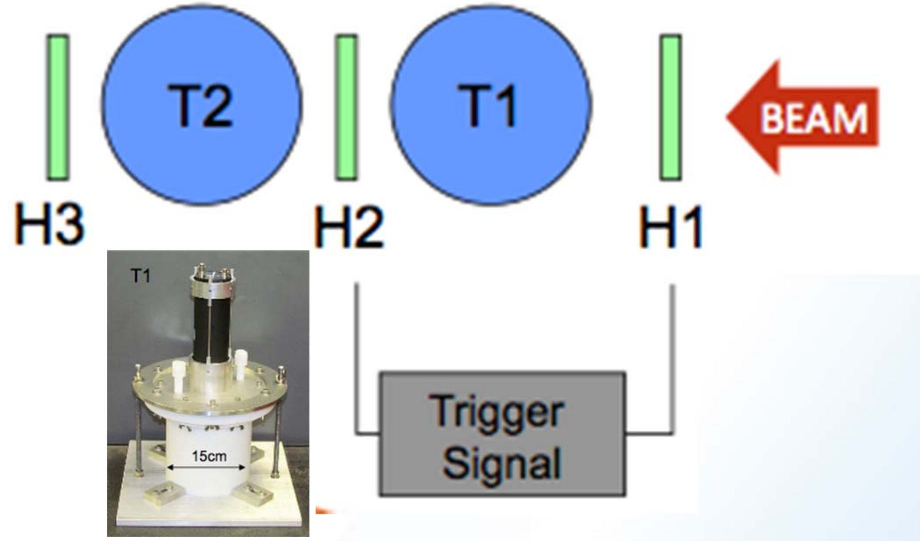


Time-resolved fluorescence system

- *Take advantages of nonlinear light-yield as a function of scintillator % and superior optical property of water.*
- *A fast scintillation pulse to probe physics below Cerenkov.*

Can we achieve 90 photons per MeV?

WbLS Detectors



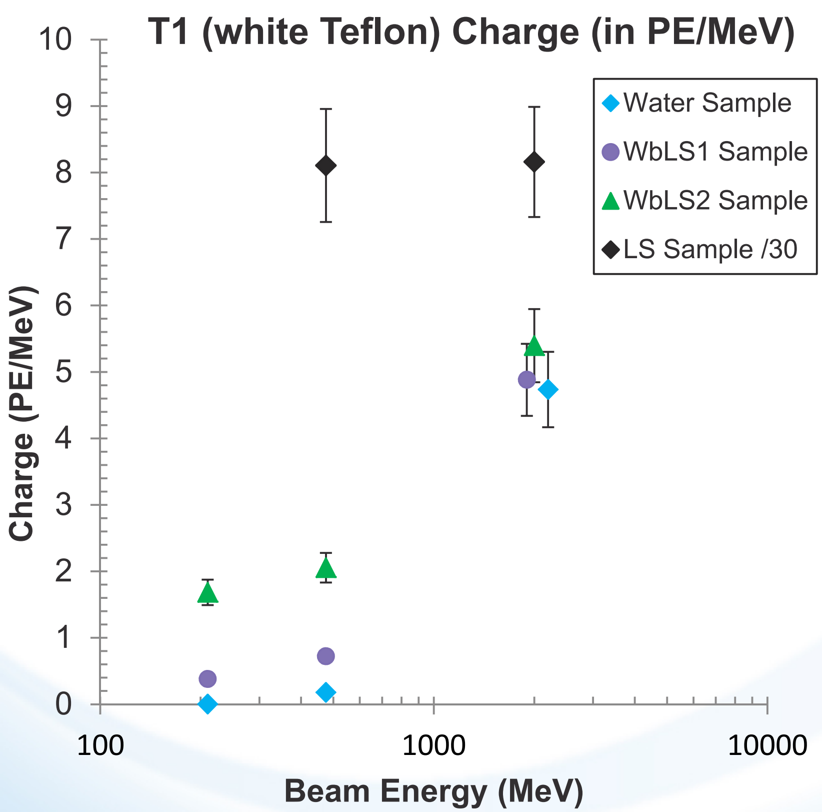
3 low Intensity Proton Beams	
210 MeV	dE/dx ~ K+ from PDK
475 MeV	Cerenkov threshold
2 GeV	MIP

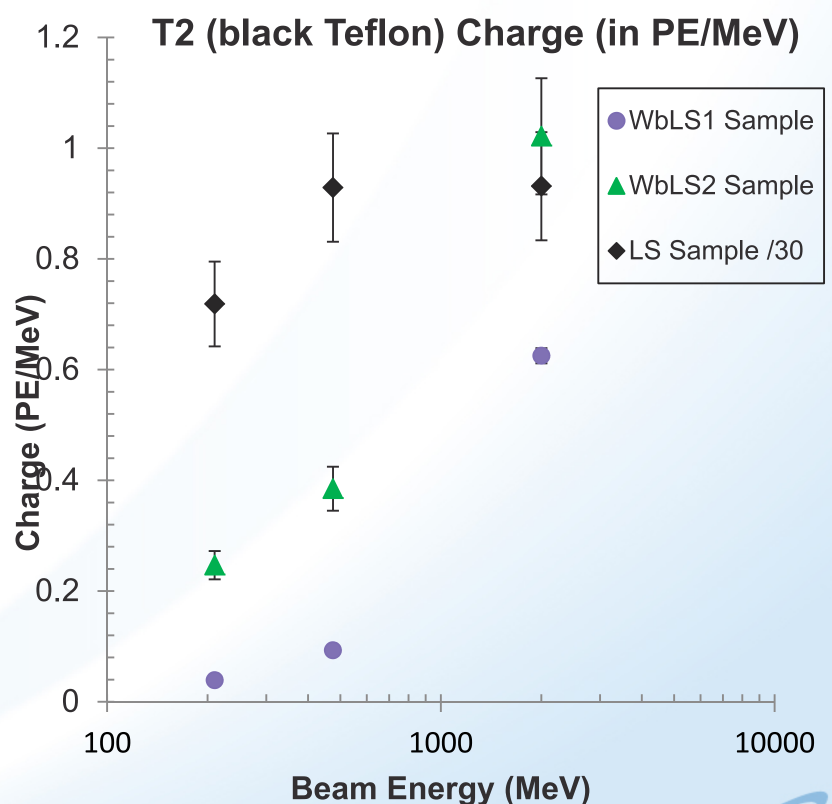
4 Material Samples	
Water	pure water
WbLS 1	0.4% LS
WbLS 2	0.99% LS
LS	pure LS

2 Detectors	
Tub 1	PTFE (highly reflective white Teflon)
Tub 2	Aluminum coated with black Teflon

Light-yield in PE/MeV

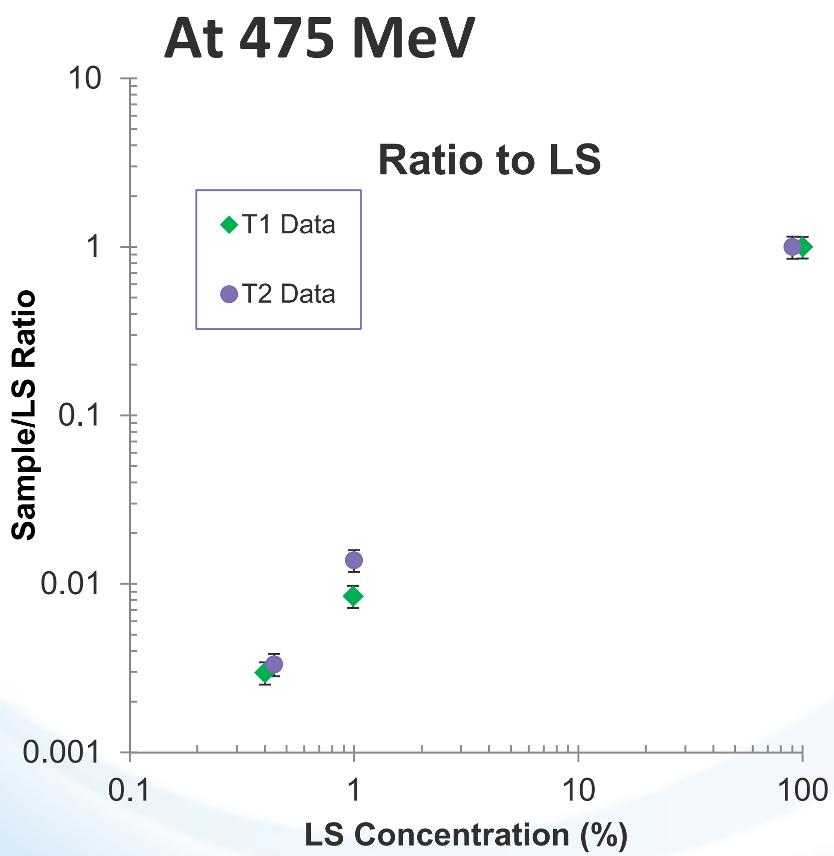
- *Cerenkov dominates at 2GeV while scintillation takes over at 475MeV and below*
- *Minimal Čerenkov contribution at 475MeV – can use the data at this energy for WbLS to LS comparison*
  - *Note that LS sample response is divided by 30 to fit on the same scale*

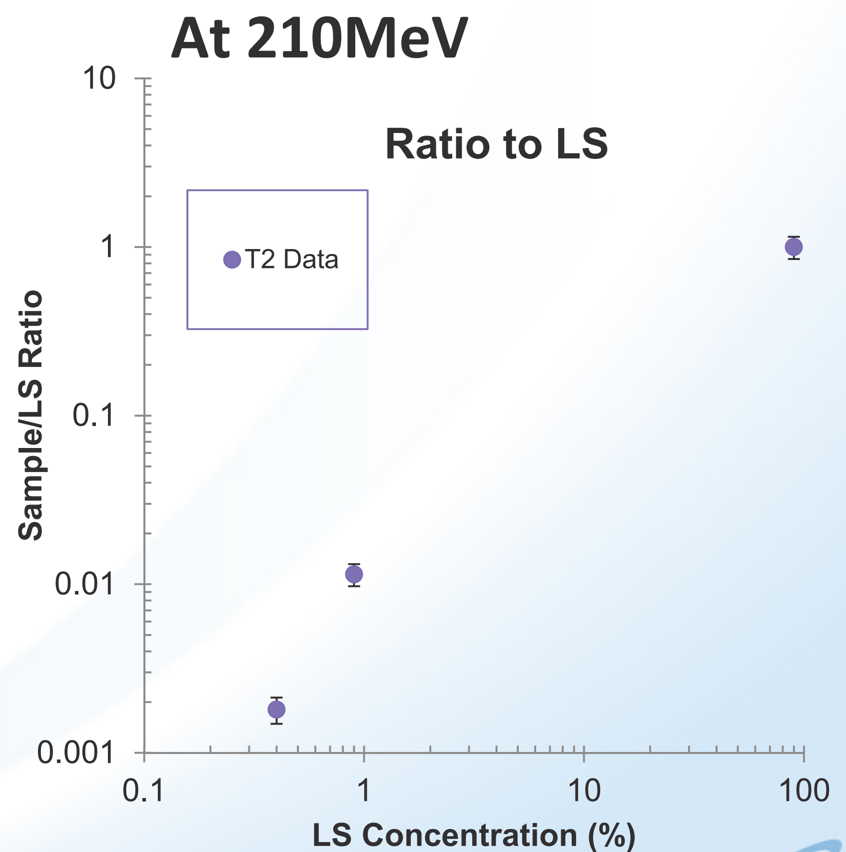




PE/MeV Yield vs. Concentration

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

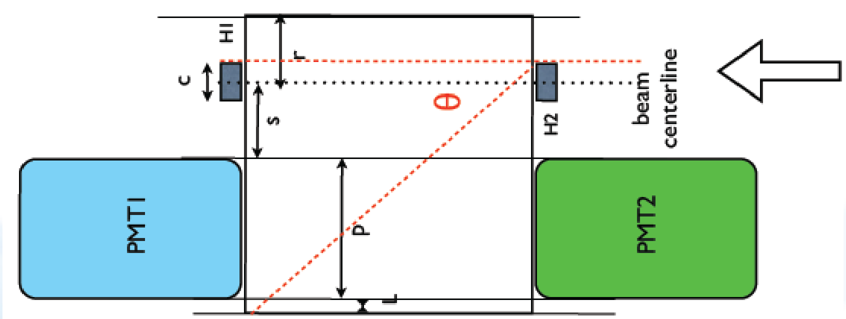


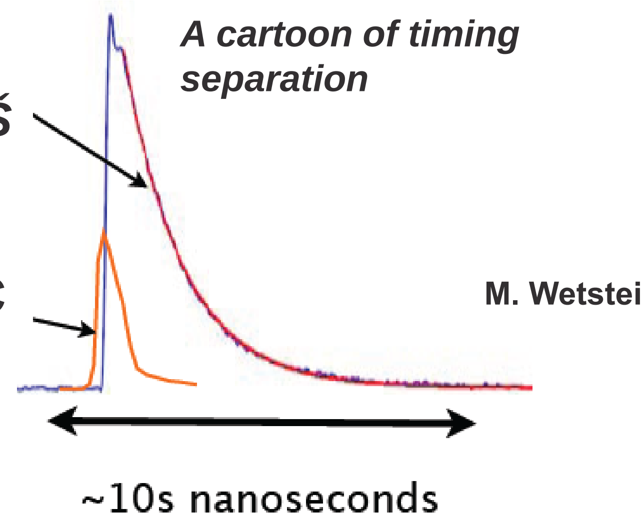


WbLS next-step

3rd low-intensity proton-beam run on May 6; preli. results are consistent with previous runs

- *Same WbLS liquid measured 7 months ago (Stability).*
- *Only downstream PMT sees the light (Č above threshold) at 2-GeV.*
- *Both PMTs see the light (Š or Č + Š) at 475- and 2000-MeV.*





- *1-ton demonstrator for*
  - *Absorption & scattering measurement*
  - *Cerenkov imaging separation*
  - *Circulation & stability test*
  - *Possibly reactor neutrino run.*
  - *(e+/e-) calibration source deployment for (nonlinear) energy responses.*
- *R&D of slow down scintillation for better Cerenkov separation.*

Water-based Liquid Scintillator is a novel particle detection medium that is

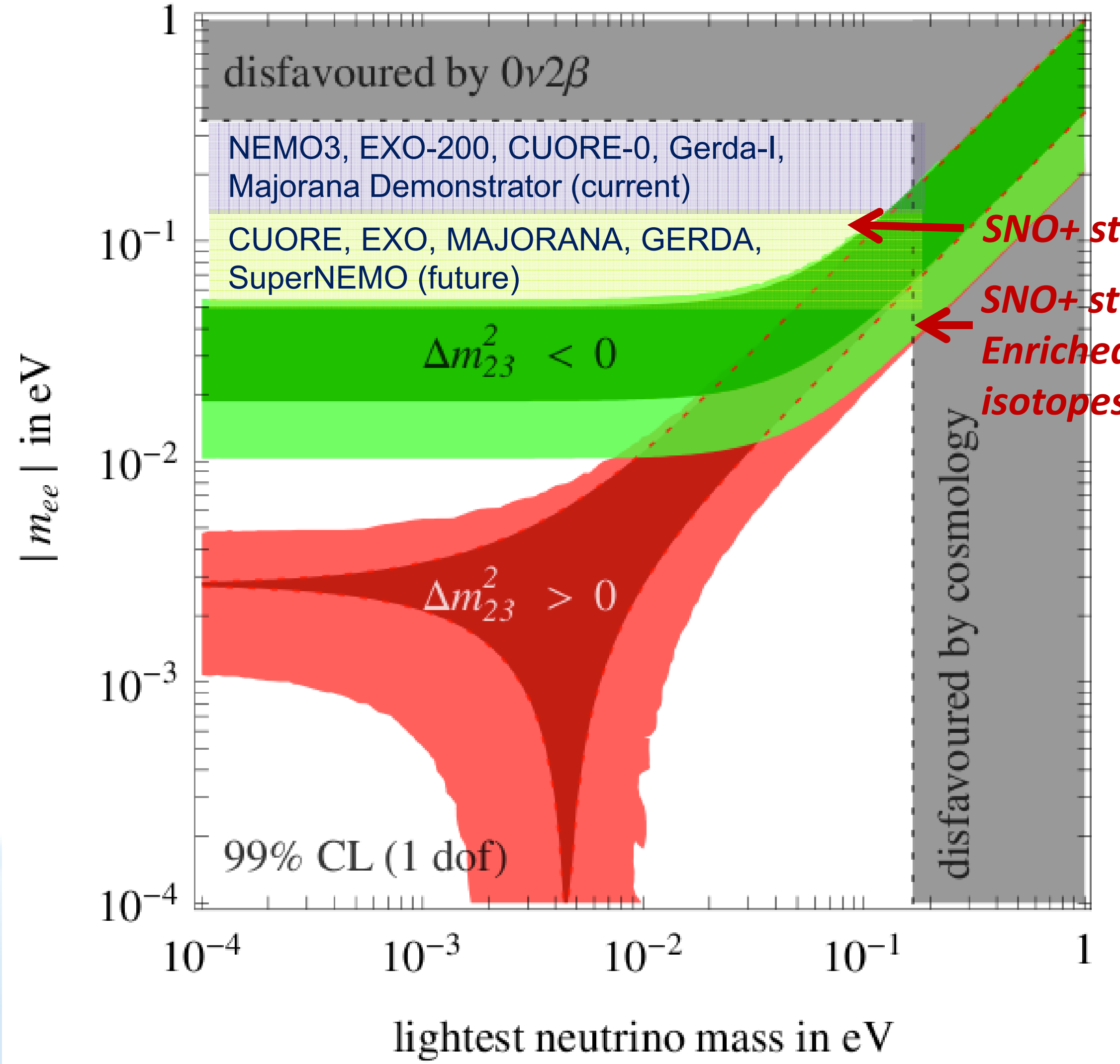
- *mass-producible*
- *cost-effective*
- *safe to handle*
- *with high optical performance.*

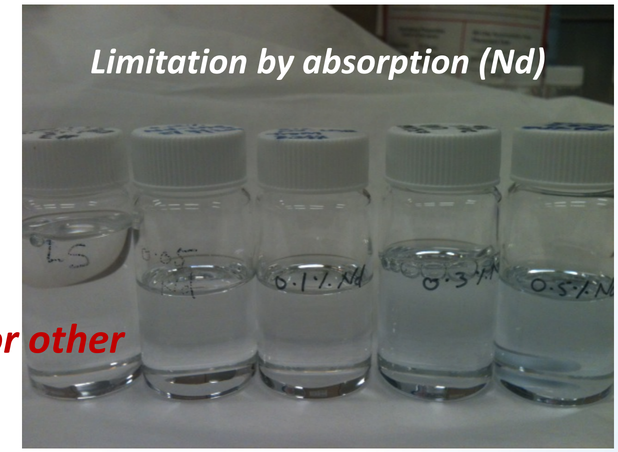
WbLS detector can adjust light production for different physics applications

- *nucleon decay (detection below Cerenkov threshold); 100 optical photons per MeV is achievable and demonstrated by the proton-beam runs*
- *reactor monitoring, veto system, etc.*

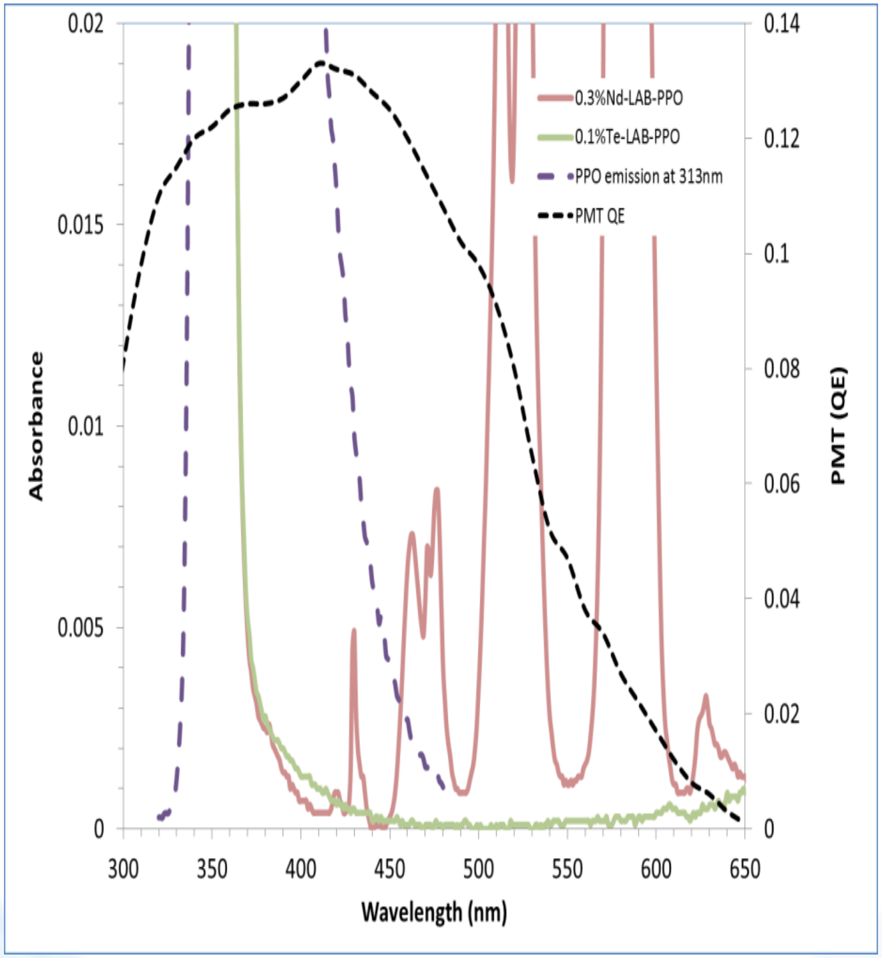
WbLS has another application of loading hydrophilic ions: A new avenue for scintillator detectors for Intensity Frontiers

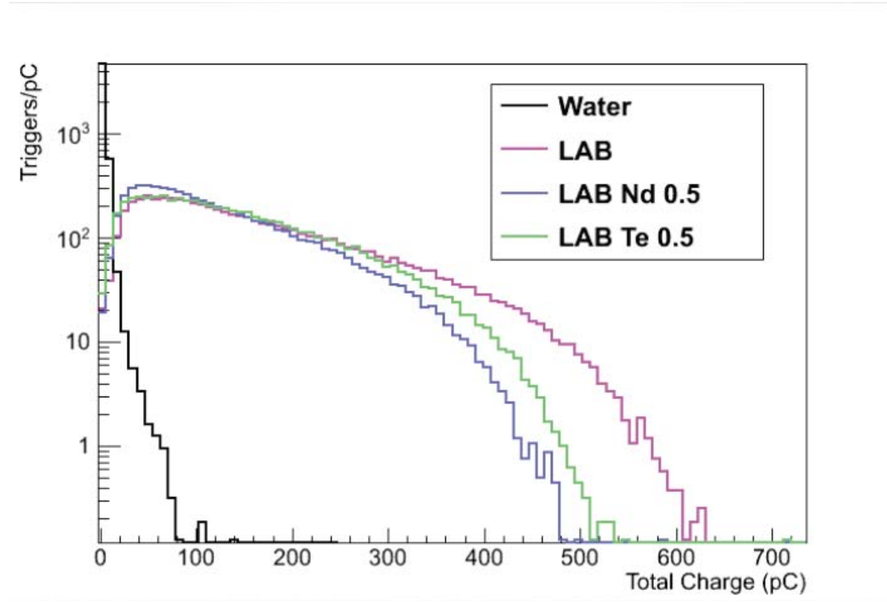
Challenge for 0νββ Search





WbLS loading application:
A new Te-doped LS for SNO+ (first WbLS detector)



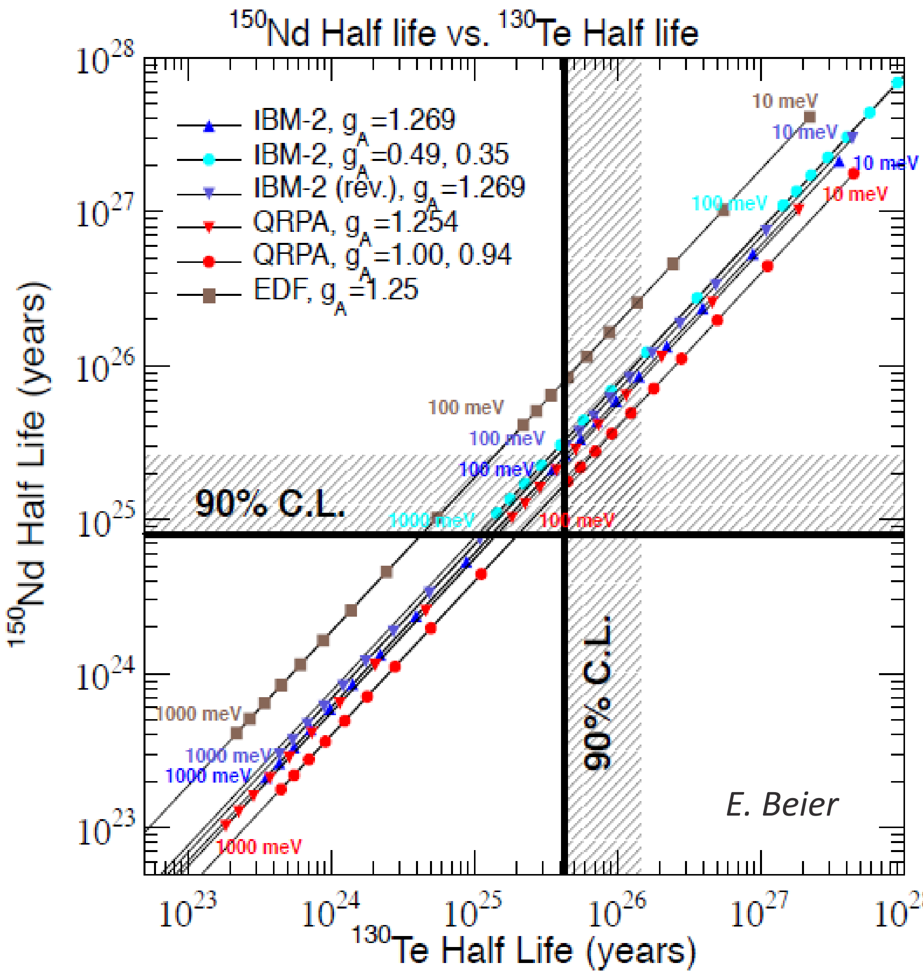


- *A successful sub-percent (0.3%) tellurium doped scintillator that*
  - *has good optical transmission and suitable light-yield.*
  - *is stable and compatible in acrylic for >1 y since preparation.*

R&D toward

Tellurium vs. Neodymium

- *Te-LS is optical and light-yield better than that of Nd.*
- *Purification principals for all core materials of Te-LS have been proven and demonstrated in lab-scale.*
- *Te has ~×30 less 2ν rate.*
- *Scalability of Te (34.1% ^{130}Te.):*
  - ***2% loading = ~1-ton ^{130}Te (at R < 3.5m cut)***
- *New baseline of 0.3%Te-LS with interests in*
  - *Enriched ^{150}Nd (team with superNEMO) and nano-Nd LS*



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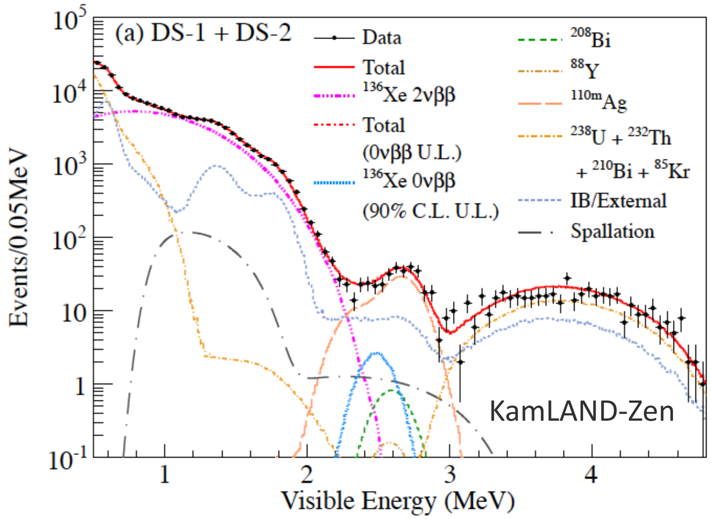
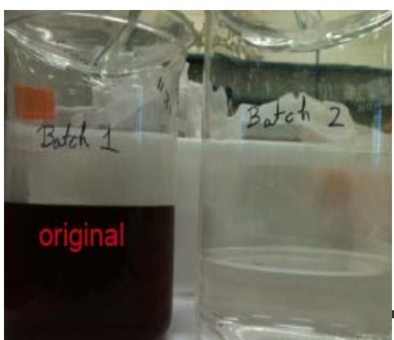
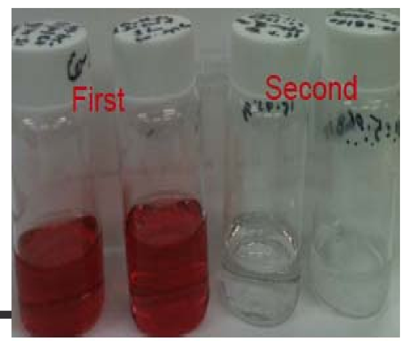
How do we discover 0νββ?





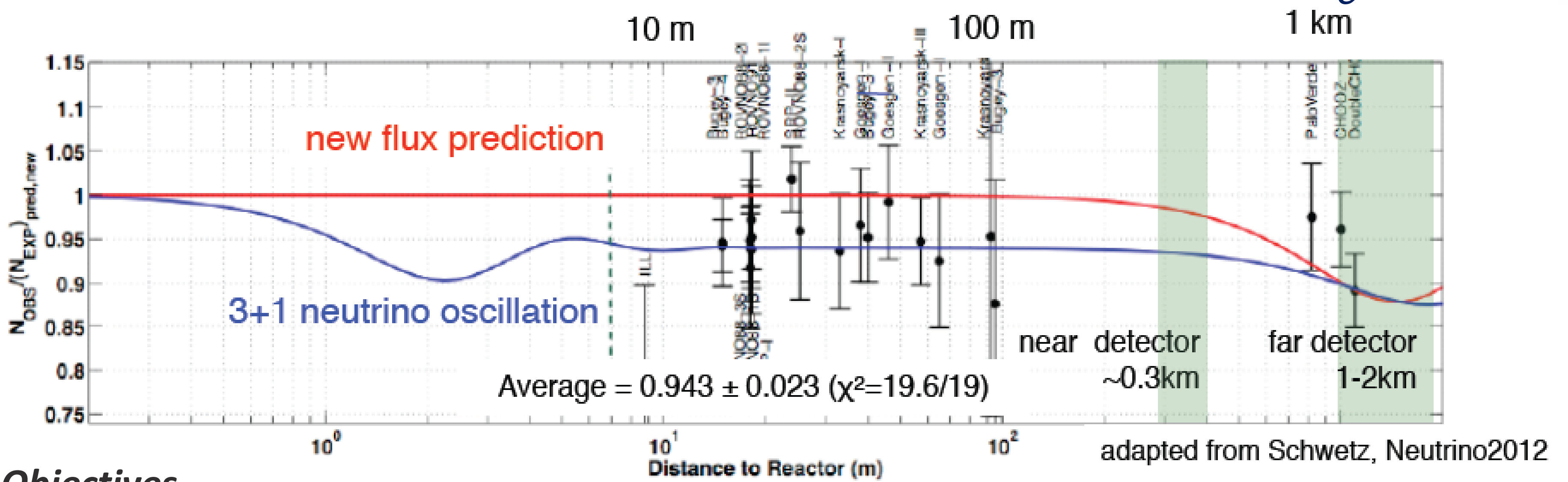


Purification (i.e. Co: K_1=1.49x10^3; k_2=3.66x10^5)

Source	E_{recon}		NHITs		Gaussian Smear	
	Minfang	Minfang^2	Minfang	Minfang^2	Minfang	Minfang^2
^{124}Sb	355.80	1.50	416.60	1.70	396.10	1.60
^{126}Sn	70.70	0.40	92.10	0.60	61.20	0.00
^{22}Na	4.40	0.00	5.70	0.00	7.80	0.00
^{26}Al	2.30	0.00	5.20	0.10	0.20	0.00
^{42}K	1.60	0.00	2.10	0.00	1.50	0.00
^{44}Sc	1.20	0.00	1.5	0.00	0.90	0.00
^{68}Ga	0.40	0.00	0.60	0.00	0.80	0.00
^{60}Co	3.10	0.00	3.30	0.00	3.60	0.00
^{110}Ag	10.00	0.00	14.80	0.10	5.10	0.00
^{82}Rb	0.10	0.00	0.10	0.00	0.10	0.00
^{106}Rh	0.20	0.00	0.2	0.00	0.20	0.00
^{102}Rh	0.00	0.00	0.4	0.00	0.60	0.00
^{88}Y	70.60	0.30	67.60	0.20	31.00	0.10
Total Cosm.	*520.40*	*2.20*	*610.20*	*2.10*	*509.10*	*1.70*
PMT β-γ ^{214}Bi	0.045	0.045	0.075	0.075	0.098	0.098
PMT β-γ ^{208}Tl	0.097	0.097	0.16	0.16	0.21	0.21
H_2O ^{214}Bi	0.00	0.00	0.20	0.20	0.00	0.00
H_2O ^{208}Tl	0.40	0.40	0.60	0.60	0.30	0.30
AV ^{214}Bi	0.56	0.56	0.56	0.56	0.40	0.40
AV ^{208}Tl	0.70	0.70	0.80	0.80	0.50	0.50
AV dust	0.00	0.00	0.20	0.20	0.00	0.00
Ropes	0.00	0.00	0.00	0.00	0.00	0.00
Total Ext.	*1.80*	*1.80*	*2.60*	*2.60*	*1.51*	*1.51*
Pileup	0.00	0.00	0.00	0.00	0.00	0.00
^{214}Bi	1.16	1.16	1.50	1.50	1.10	1.10
^{208}Tl	0.04	0.04	0.12	0.12	0.00	0.00
^{8}B	5.34	5.34	10.20	10.20	7.10	7.10
2ν	1.82	1.82	12.00	12.00	2.50	2.50
Total Int.	*8.36*	*8.36*	*23.82*	*23.82*	*10.70*	*10.70*
Total I+E	10.16	10.16	26.42	26.27	12.21	12.21
Total I+E+C	530.56	12.36	636.62	28.97	521.71	14.31

- *external bkg. doesn't scale up with Te*
  - *measure before Te loading.*
  - *measure after Te removal.*
- *Liquid purification, self-shielding (~2.5m), fast timing to compensate the resolution.*

Challenges of Short Baseline Reactor $\bar{\nu}_e$

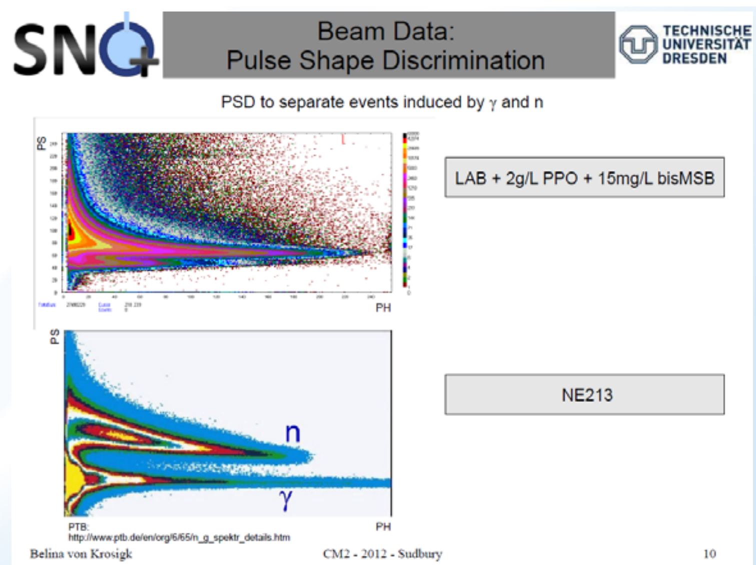


Objectives

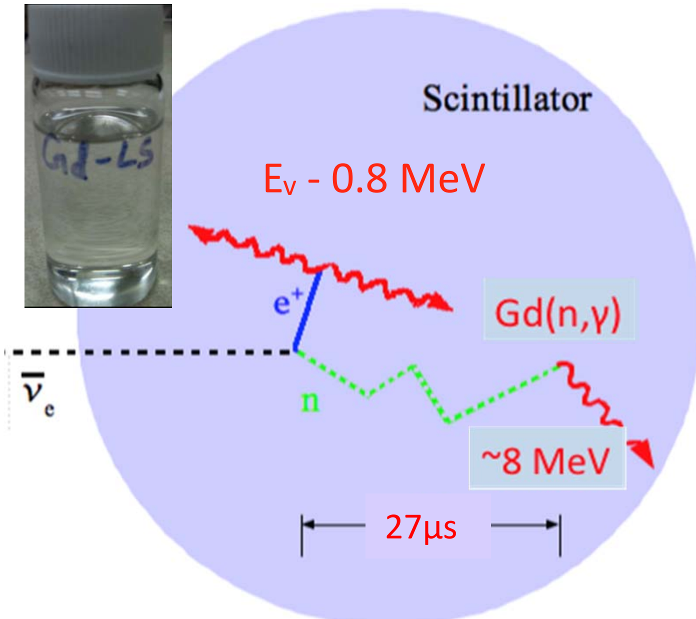
- *short-baseline neutrino oscillation search with high sensitivity, probe of new physics*
- *test of the oscillation region suggested by reactor anomaly and $\bar{\nu}_e$ disappearance channel*
- *precision measurement of reactor $\bar{\nu}_e$ spectrum for physics and safeguards*

Challenges

- *Reactor-related neutron and cosmic-muon shielding and rejection by a doped scintillator with high neutron detection and PSD capability.*



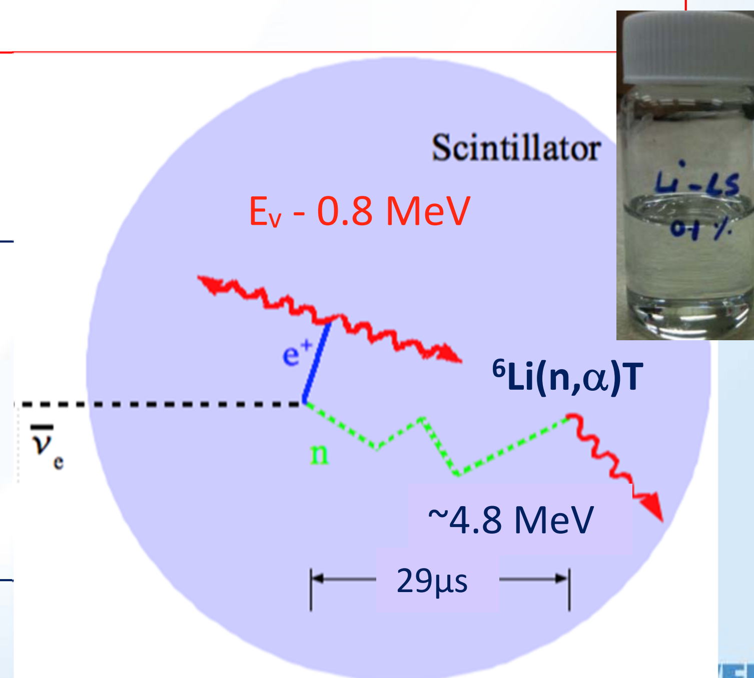
Challenges for Short Baseline Reactor $\bar{\nu}_e$



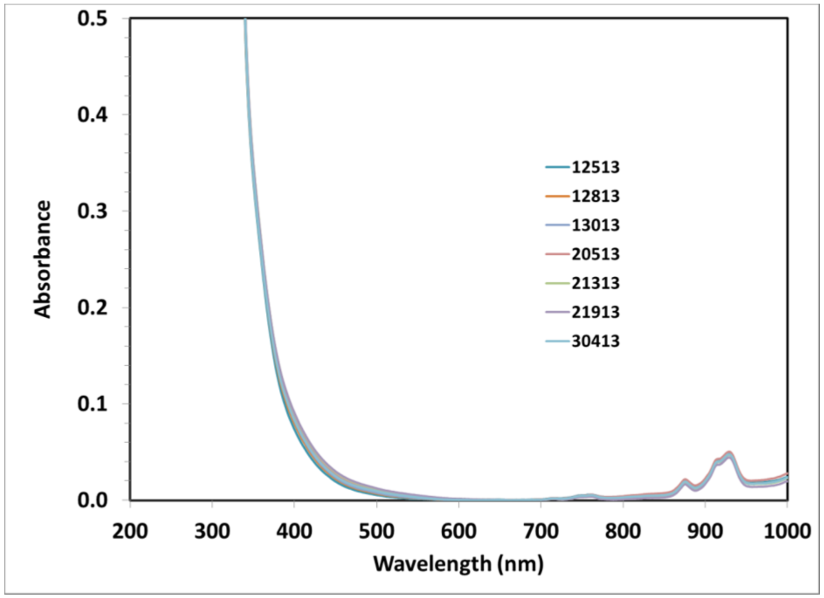
$\mathbf{n_{th} + {}^{A}Gd \rightarrow {}^{A+1}Gd + \gamma's\ (\sigma \sim 55,000\ barn)}$:

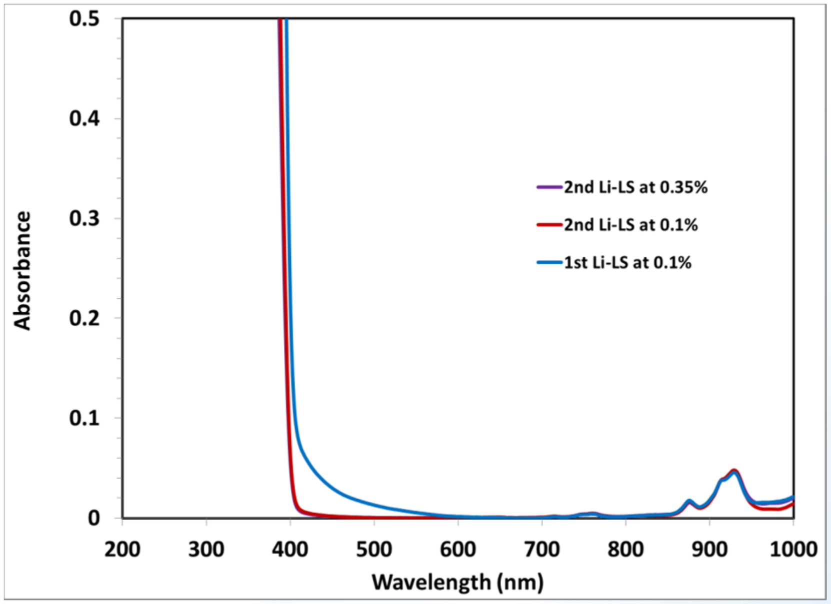
- S% of ~10,000 optical photons /MeV and $\lambda_{1/e}$ at ~20m (need R&D of background rejection).
- Stability of 3 years demonstrated by Daya Bay experiment.

- **$\mathbf{n_{th} + {}^{6}Li \rightarrow \alpha + {}^{3}H\ (\sigma \sim 940\ barn)}$:**
  - S% of ~5,000 optical photons /MeV and $\lambda_{1/e}$ at 2.6m (i.e. Bugey-3).
  - Stability degraded in few months of deployment (**<u>needs R&D's</u>**).



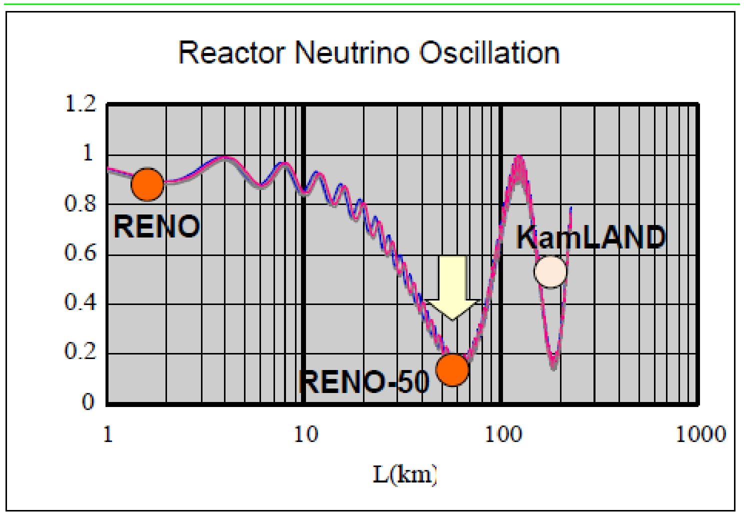
WbLS loading application:
A stable Li-doped LS for SBL (another WbLS detector)

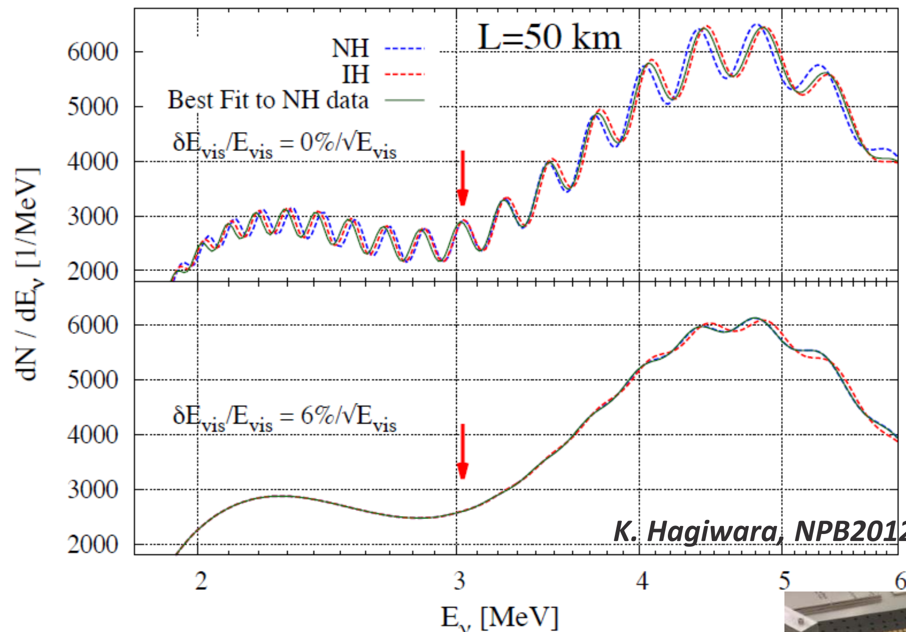


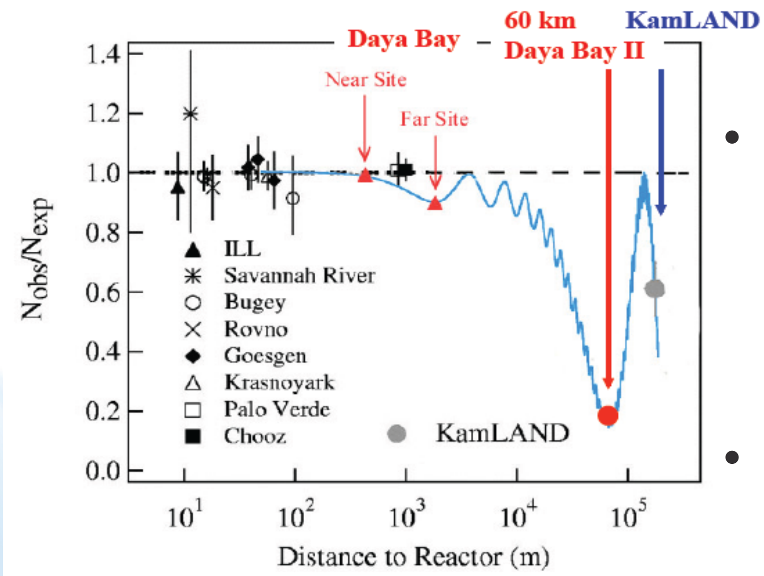


- *^{6}Li-LS stability:*
  - *1st formula of ^{6}Li-doped LS has been stable over 6 months since preparation.*
  - *2nd formula of ^{6}Li-doped LS improves the UV significantly.*
- *Gd-LS PSD: A new scintillator?*
- *Segmented scintillator deployment for reactor background measurement.*

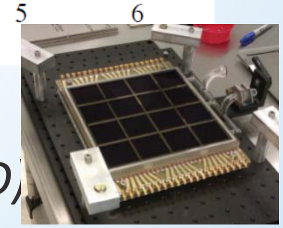
Challenges for Long Baseline Reactor $\bar{\nu}_e$





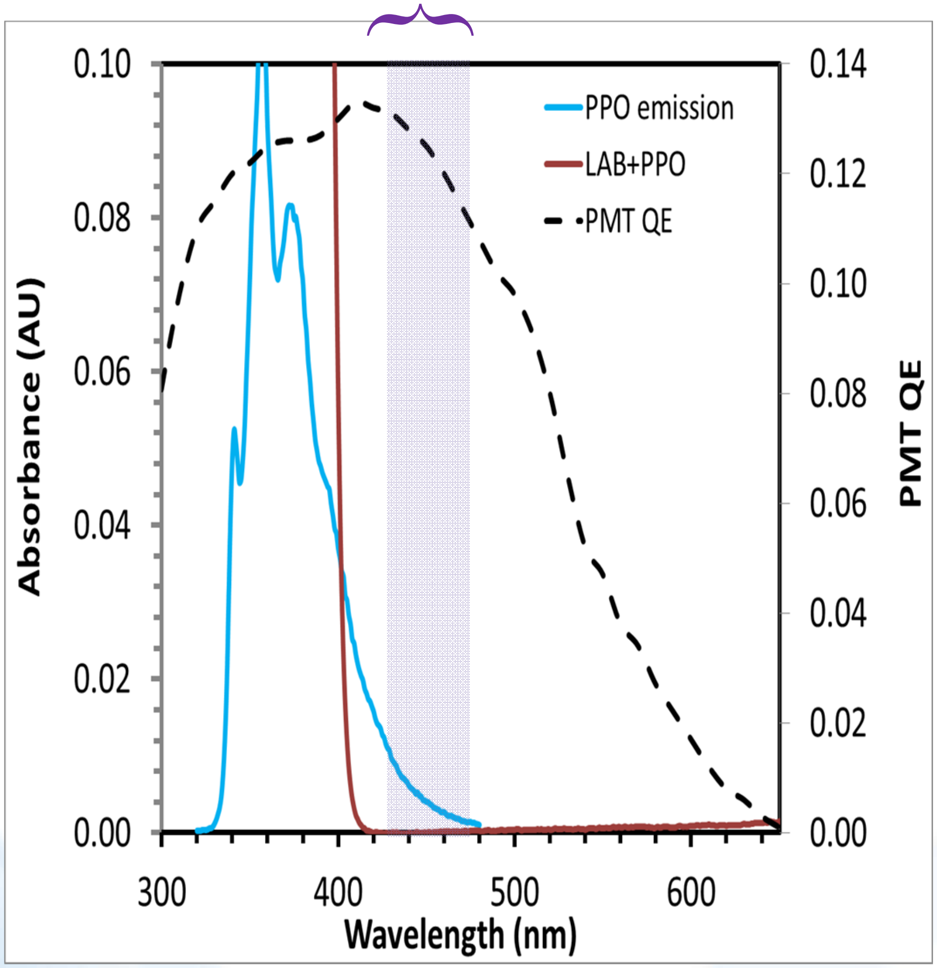


- *< 3% / √E:*
  - *High QE photo-coverage (LAPPD)*
  - *$\lambda_{1/e}$ ~ 30m and Š% ~ 15,000 o.p./MeV*
  - *No known deployed scintillator can do.*
- *Energy non-linear response to 1%*



Extensive Scintillator R&Ds

Window of opportunity

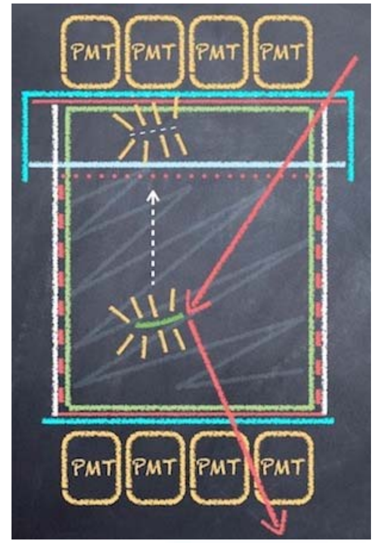


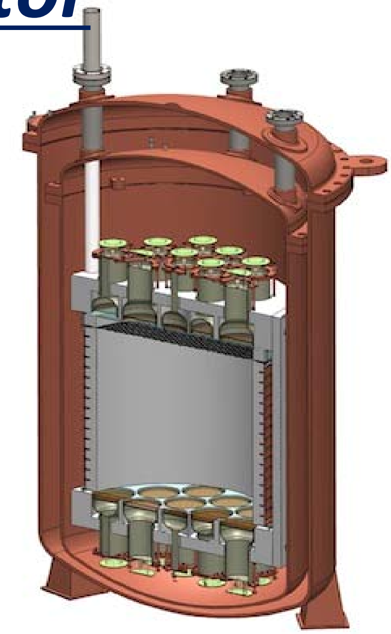
Large Stokes-shift to 440-460nm

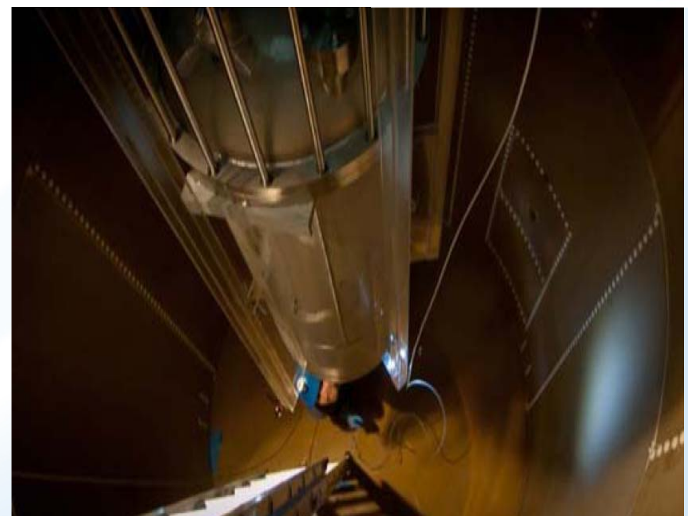
- *Lunch for a new search of a new scintillator (c.f. LAB by SNO+)*
- *Extensive purification of LAB*
    - *Vacuum distillation*
    - *Exchange column*
    - *Still cannot boost up the light*
- ***Flour/shifter optimization could be the key.***
- *Loading short half-life β^+ or β^- sources in scintillator for energy nonlinearity study*
- *Can WbLS help?*
    - *$\lambda_{1/e}$ >30m with loading of inorganic scintillator?*

Challenges for Dark Matter Detector

- *Radiogenic and Cosmogenic single-scattered neutrons (major backgrounds).*
- *Passive vs. Active shielding (F. Calaprice):*
  - *40-cm polyethylene + 20-cm Pb + 15-cm Steel give ~3,000 background events/(ton-yr)*
  - *1-m ^{10}B-loaded scintillator + 4 m water give < 0.1 events/(ton-yr)*
- *How to control the radiogenic background*
  - *Ultra clean Gd-, ^{6}Li- or ^{10}B-doped scintillator*
  - *(0.1Hz) of U/Th (ppt level) are required*
  - *TMB-loaded LS is not stable*







Summary

- *Profound frontier physics programs for scintillation detector:*
  - *Intensity frontiers (LBL, SNO+, SBL, etc.)*
  - *Cosmic frontiers of DM veto (LZ, DarkSide)*
- *Water-based liquid scintillator is ready for a proton-decay experiment*
  - *a whitepaper submitted for Snowmass; current communication with T2K, nonproliferation, etc.*
  - *Ton-scale demonstrator for Cerenkov & Scintillation separation*
  - *Low-energy reactor neutrino*
- *Water-based loading technology opens a new door for future scintillation detectors.*
  - *A future ton-scale $0\nu\beta\beta$ (with slow scintillation, β/γ separation) detector.*
  - *SBL, calibration, etc…*

BNL synergetic activity