Water-based Liquid Scintillator & Isotope Loading

Minfang Yeh

Brookhaven National Laboratory

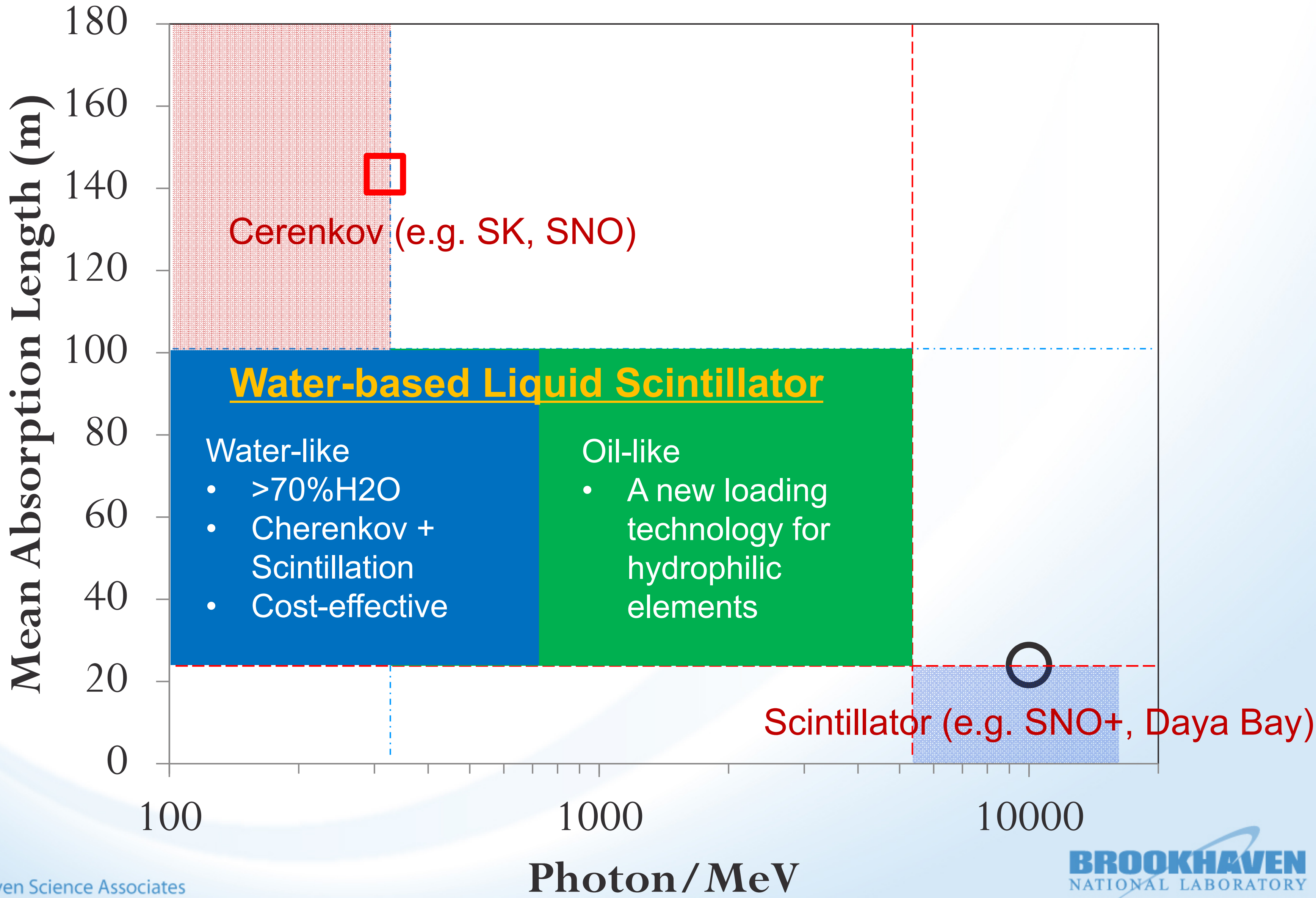
HK Meeting, Vancouver, July 2014

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

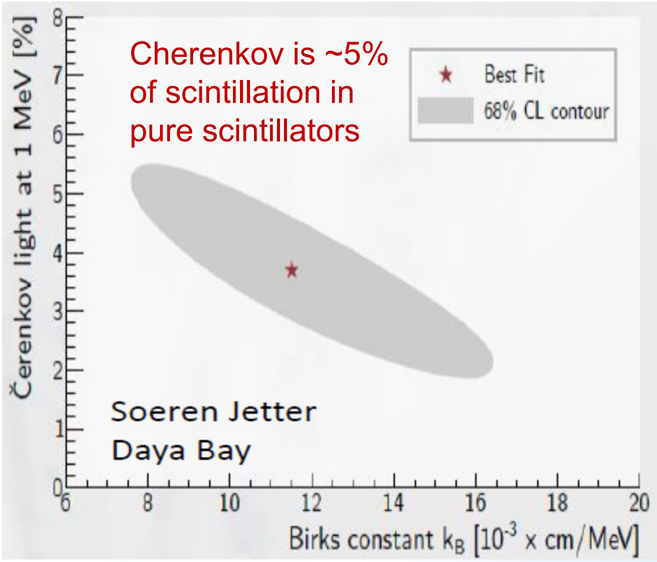
U.S. DEPARTMENT OF ENERGY | Office of Science

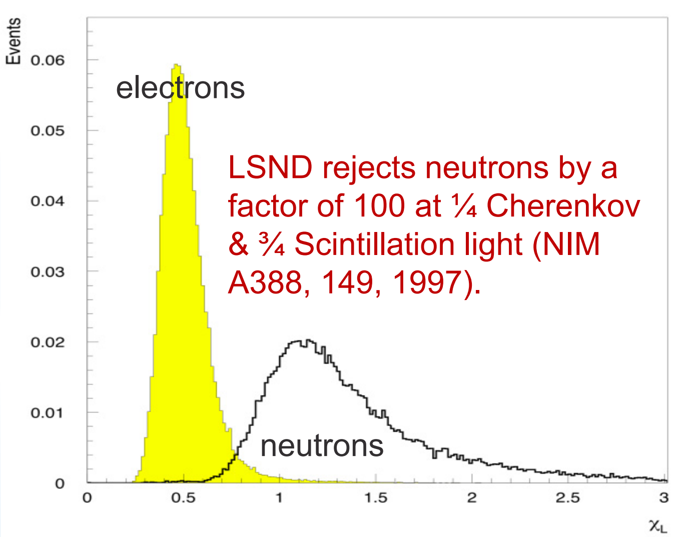
An Advance Scintillator Detector



Water-based Liquid Scintillator

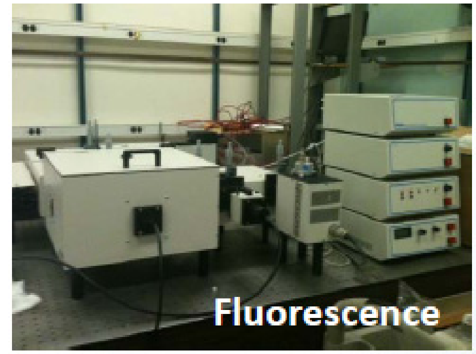
- A new liquid medium utilizing nonlinear light-yield as a function of scintillator % and superior optical property of water for
  - physics below Cerenkov, low-energy neutrino detection, rare-event physics
  - Cherenkov + scintillation detection
  - Tunable scintillator doping
- Cherenkov transition
  - λ overlaps with scintillator energy-transfers will be absorbed and re-emitted to give isotropic light.
  - λ emits at >400nm will propagate through the detector (directionality).
- PID using timing cut and energy reconstruction to separate the directional Cherenkov (fast) and isotropic scintillation (slow, controllable)
- Environmentally and chemically friendly
  - Cost-effective (~$100/ton for 1% loading)





Liquid Scintillator Development Facility

Synergic activity between Chem. and Phys. Divisions: M. Yeh, D. Jaffe, S. Hans, L. Hu, R. Rosero, B. Viren, E. Worcester, C. Zhang, L. Bignell



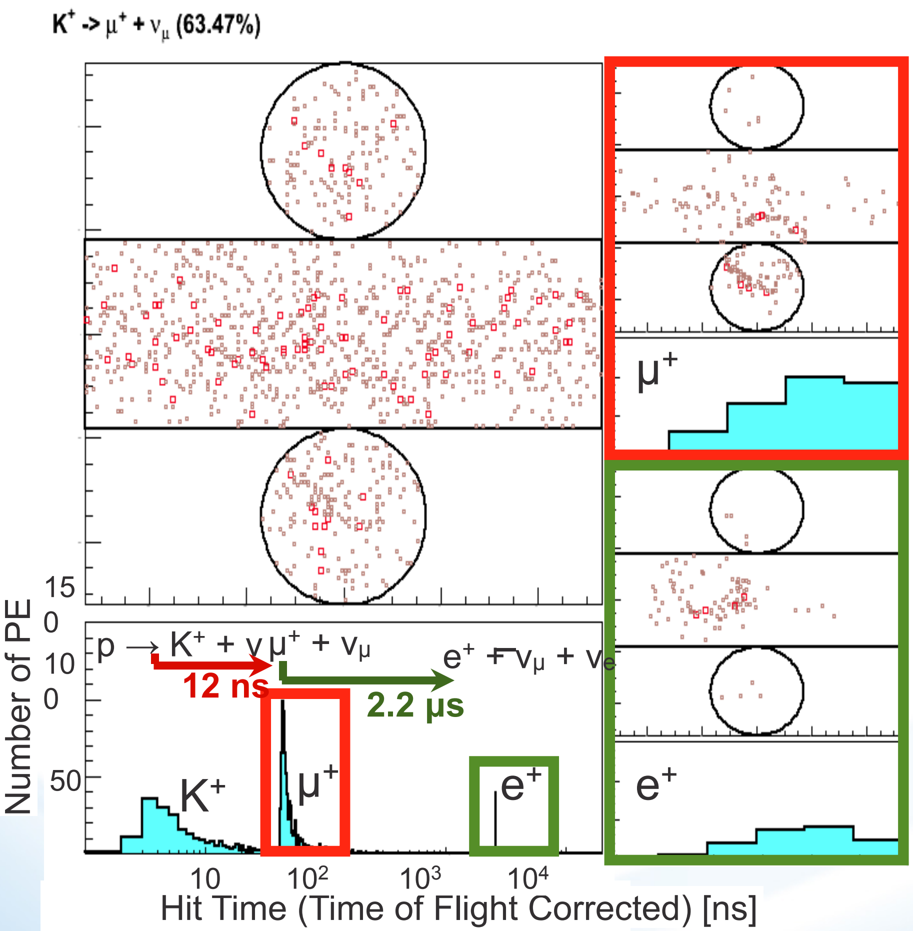
- A unique facility for Radiochemical, Cerenkov, and Scintillator **(water-based and metal-doped)** Detector R&D for particle physics Applications.
- ~$1M instrumentation including XRF, LC-MS, GC-MS, TFVD, FTIR, UV, Fluorescence emission, light-yield coincident PMT, 2-m system, low bkg. counting, etc. (access to ICP-MS at SBU and other facilities)

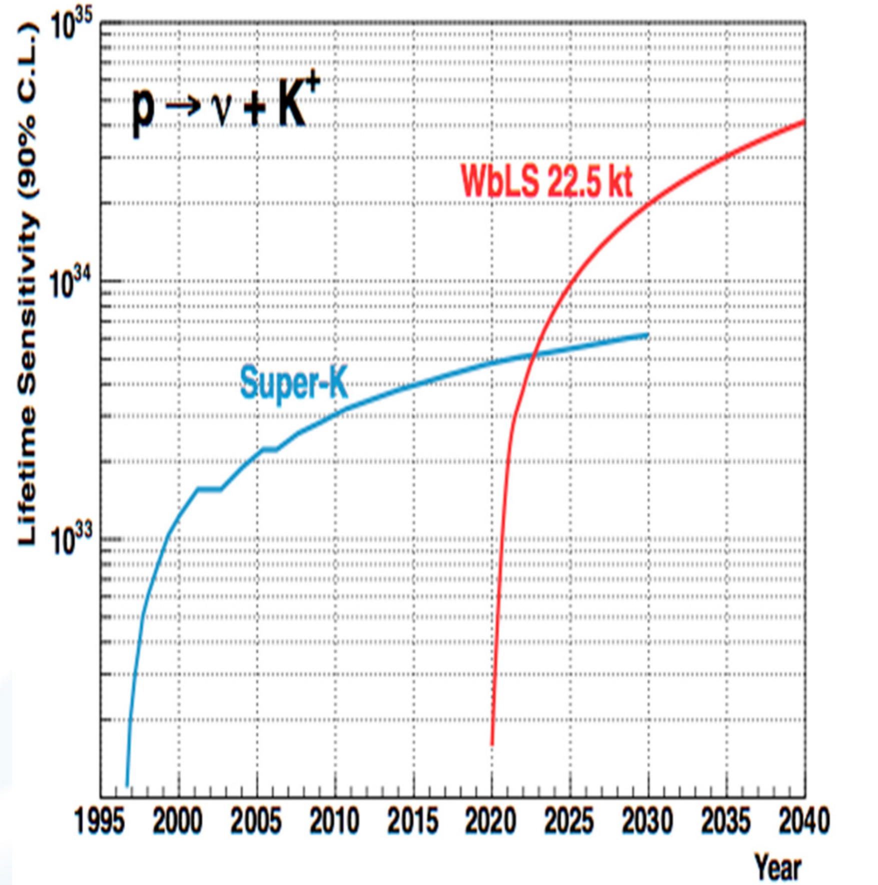
- Proof-of-Principal
  - Simulations
  - Development of water-based scintillator formulas
  - Development a new isotope loading technology
  - Testing of scintillation below Cherenkov threshold

FY13

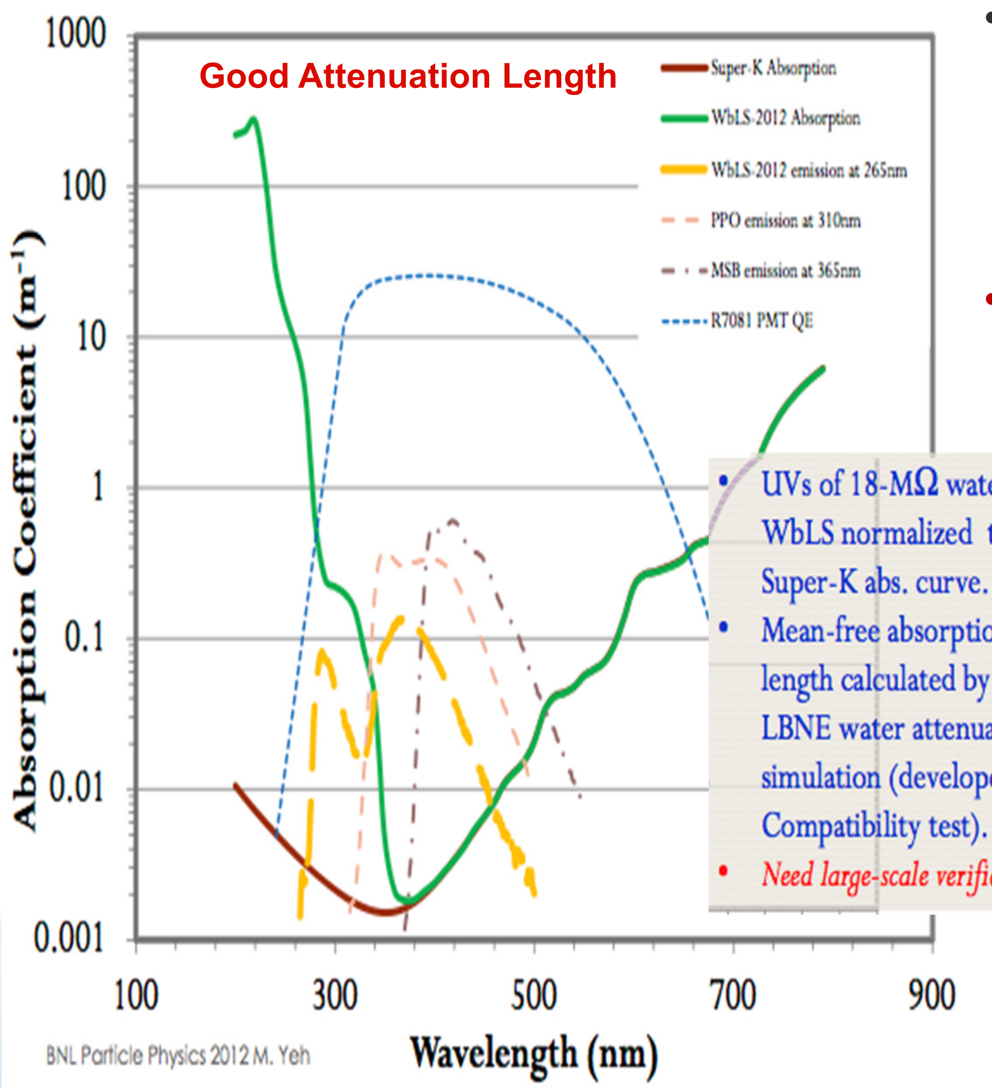
WbLS Cherenkov & Scintillation Simulation

- **Proton decay** remains to be one of the top challenges
- A simulated event with 90 scintillation photons/MeV in a SK detector for $p \rightarrow k^{+}\bar{\nu}$
- An order of magnitude improvement over the current SK sensitivity (2.3×10^{33} yrs)



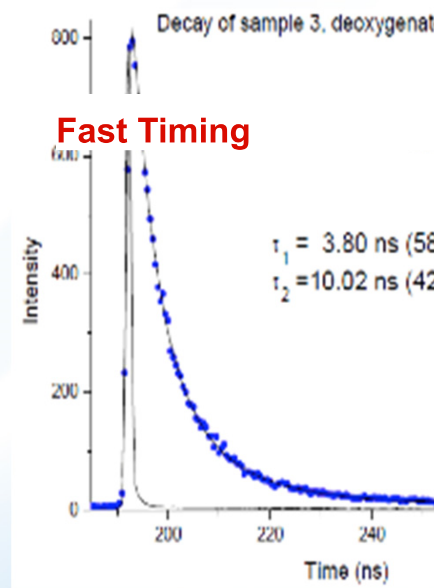


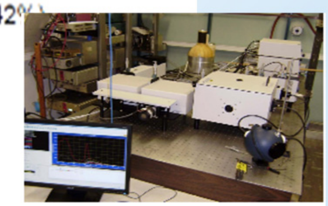
Proof-of-Concept (1% WbLS)



- 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*

- Started R&D since 2009
  - A clean liquid (at 450nm and above); **need 10^4 optical purification (fine-tune the formula for practical use)**
  - A fast pulse
  - can load as much as 35% of LS
- Investigate light propagation below and above Cerenkov
  - proton beams & sources

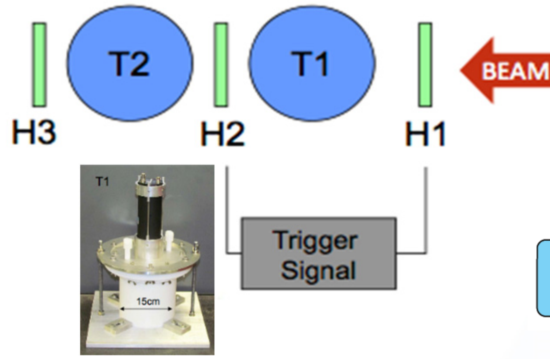


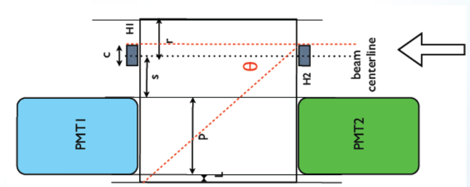


Time-resolved fluorescence system

Proton-beam Measurements at BNL

WbLS Detectors





- Two NSRL runs from 2012-2013
  - Same sample; different geometries
  - Cherenkov at higher energy and scintillation below Č threshold

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

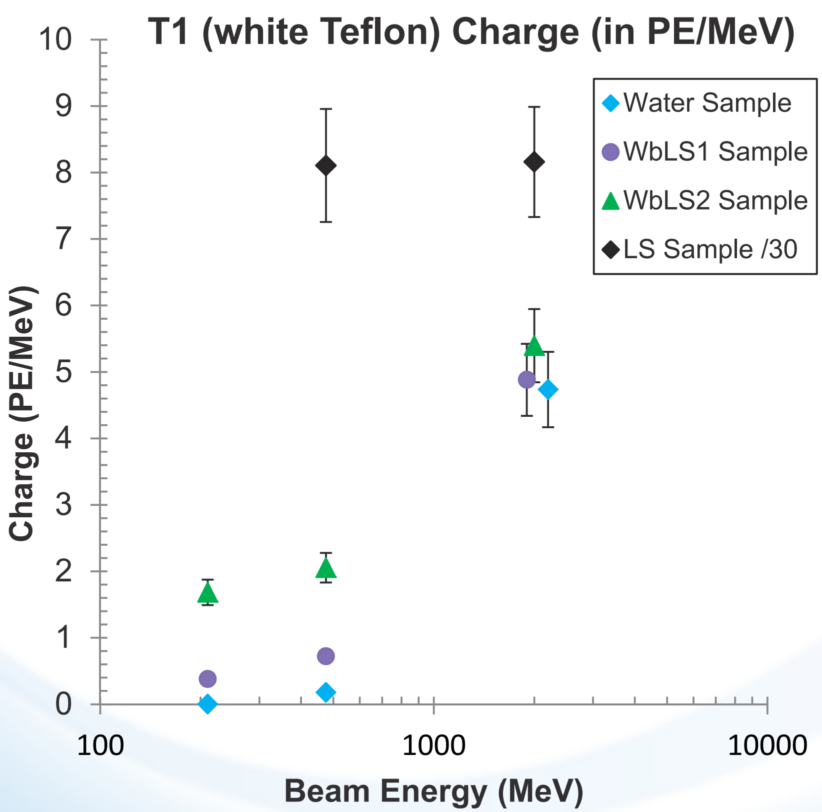
2 Detectors

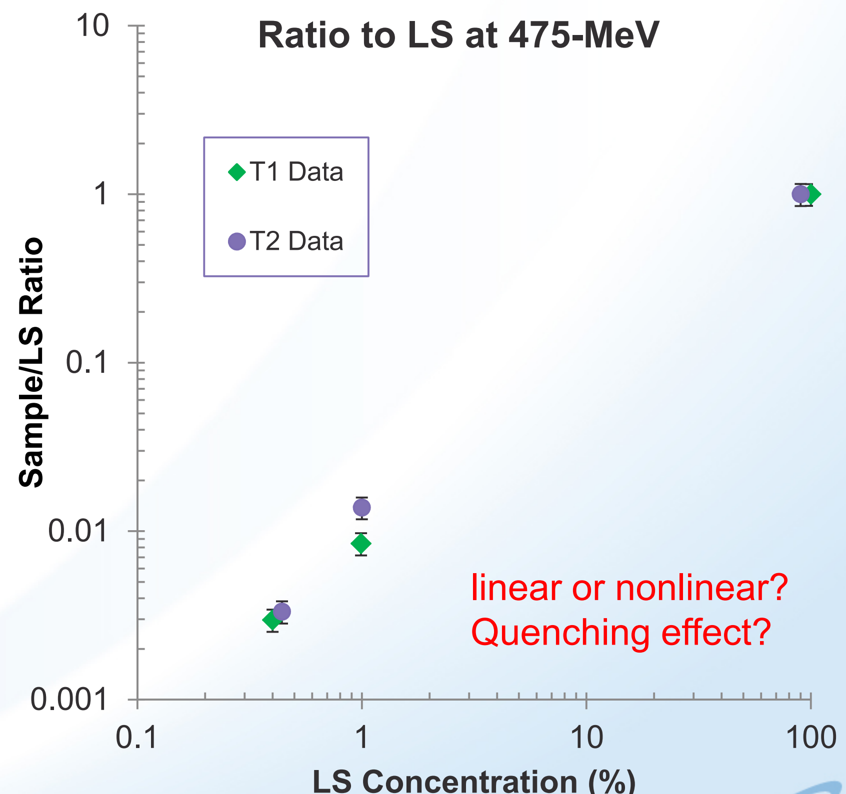
Tub 1	PTFE (highly reflective white Teflon)
Tub 2	Aluminum coated with black Teflon

Scintillation below Cherenkov threshold

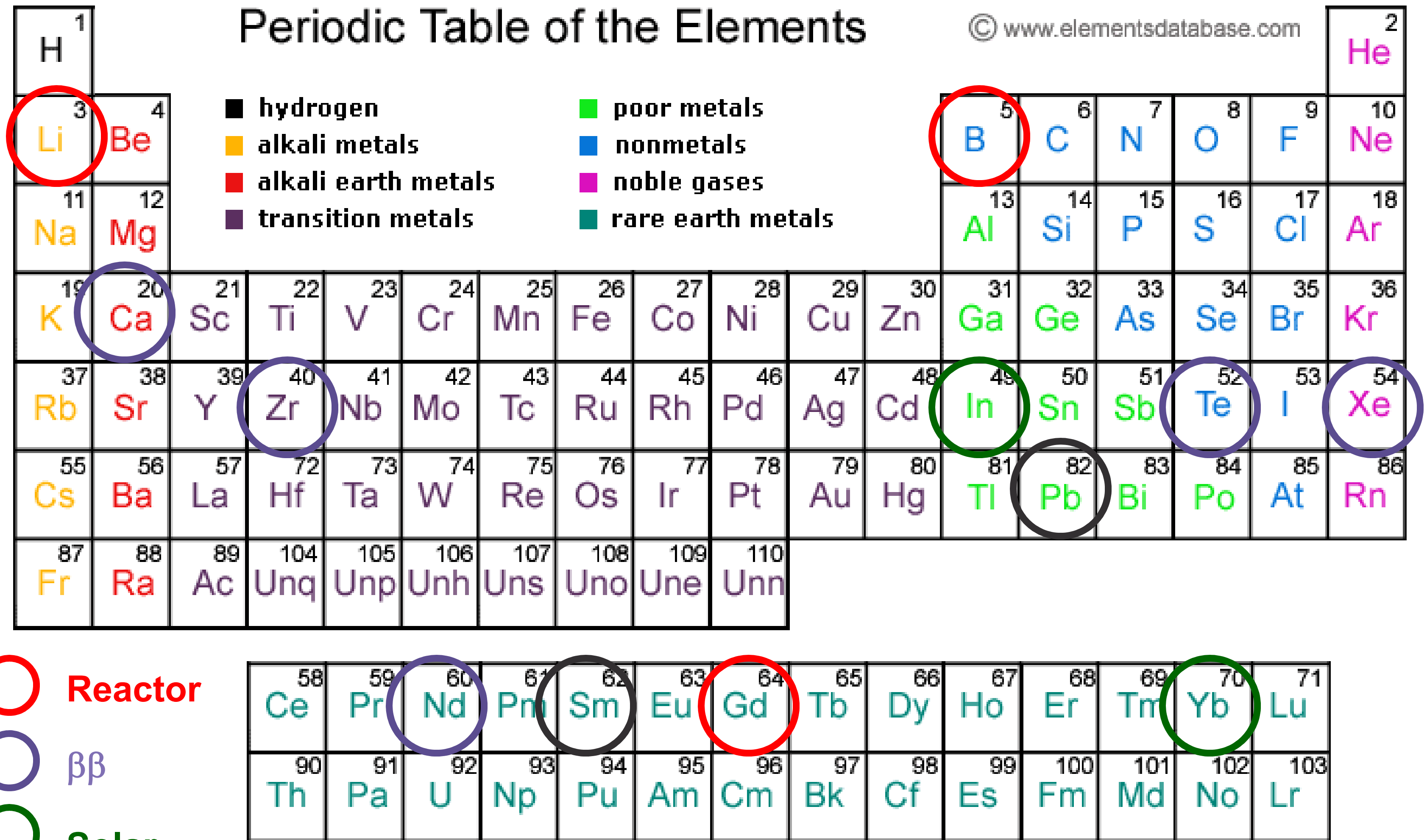
- Cherenkov dominates at 2GeV while scintillation takes over at 475MeV and below
- Principle of detection below Cherenkov threshold is proven

LS response is divided by 30





Metal-doped LS for Neutrino Physics



Reactor

ββ

Solar

Others

hydrophilic elements are difficult!

Metal-doped Water-based LS

- Conventional loading method using organic complexing ligands has been successfully applied to reactor $\bar{\nu}_e$ detection (e.g. Gd-LS)
  - –OH group is a known quencher
  - Loading hydrophilic elements in scintillator is a challenge
- WbLS enables a new metal-doped technology

Lithium-doped scintillator detector

- Reactor antineutrino (^{6}Li, 7.6% abundance)
- Solar neutrino (^{7}Li, 92.5% abundance)

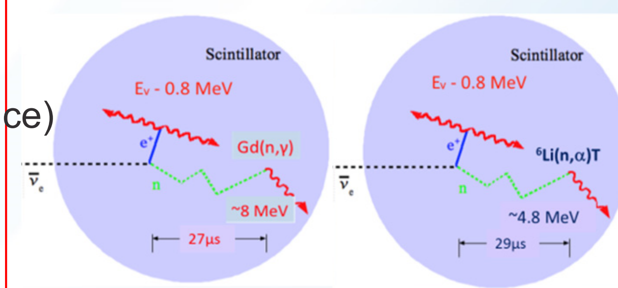
Tellurium-doped scintillator detector

- Double-beta decay isotope (^{130}Te, 34% abundance)
- Future ton-scale $0\nu\beta\beta$
- ONP-support

Lead-doped scintillator calorimeter

- Total-absorption radiation detector
- Solar neutrino

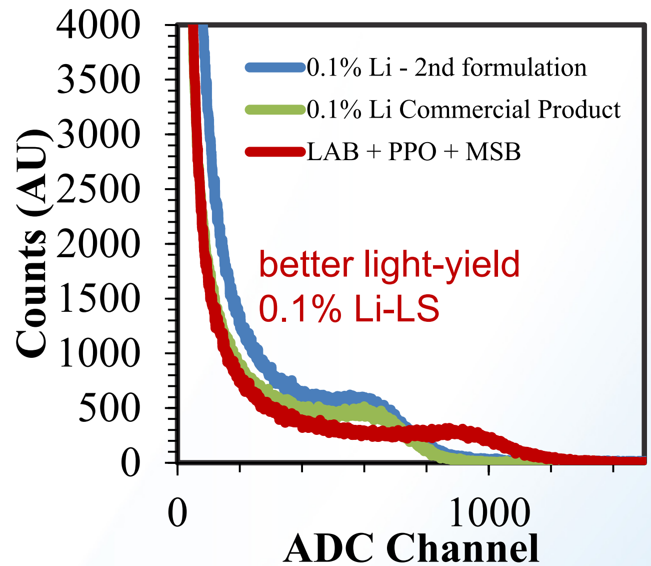
Neutron Tagging

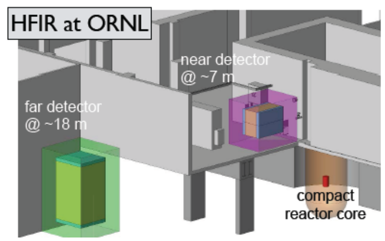


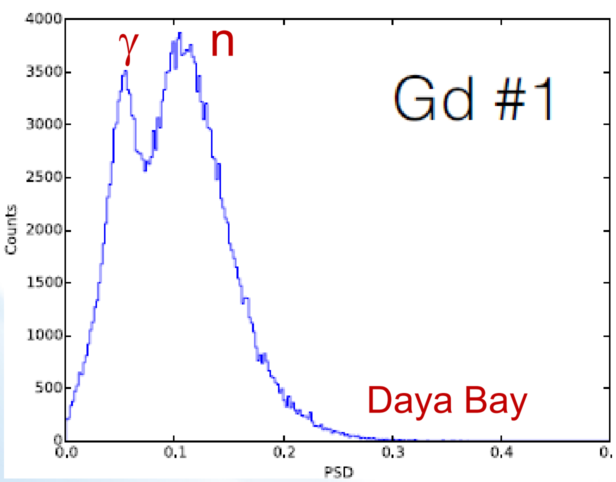
8-MeV γ's (Gd) vs. α,T (^{6}Li)

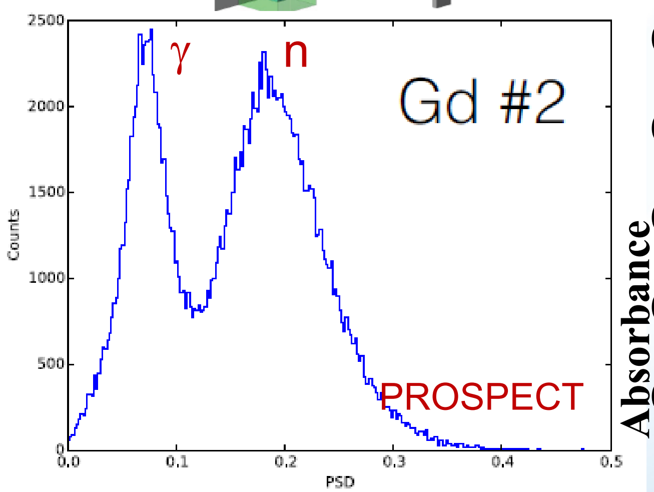
^{6}Li-WbLS and Gd-LS (PROSPECT)

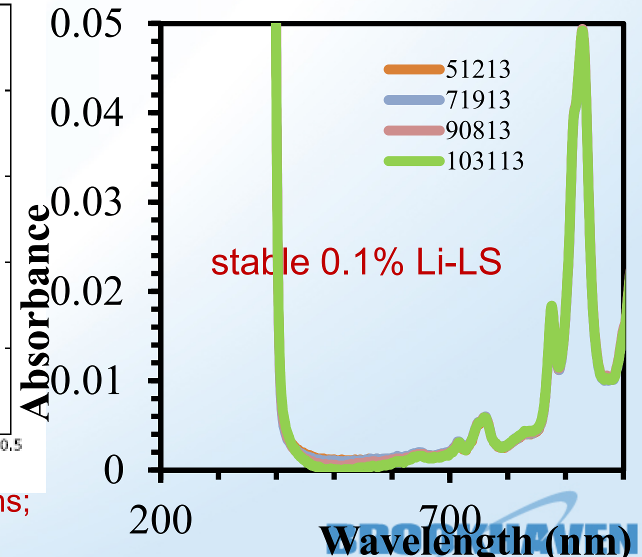
- Development and production of ^{6}Li- or Gd-doped LS with high pulse shape discrimination ability
  - ^{6}Li-LS stable over 1.5 years (light-yield and optical better than commercial product)
  - Improve PSD of Gd-LS (applicable to ^{6}Li-LS)
- Current progress
  - Background investigations at NIST, ORNL and INL
  - A large Gd-LS cell prototyping test
  - Plastics scintillator R&D
- Goals
  - Phase-I 2m^{3} Near detector
  - Phase-II 10m^{3} Far detector





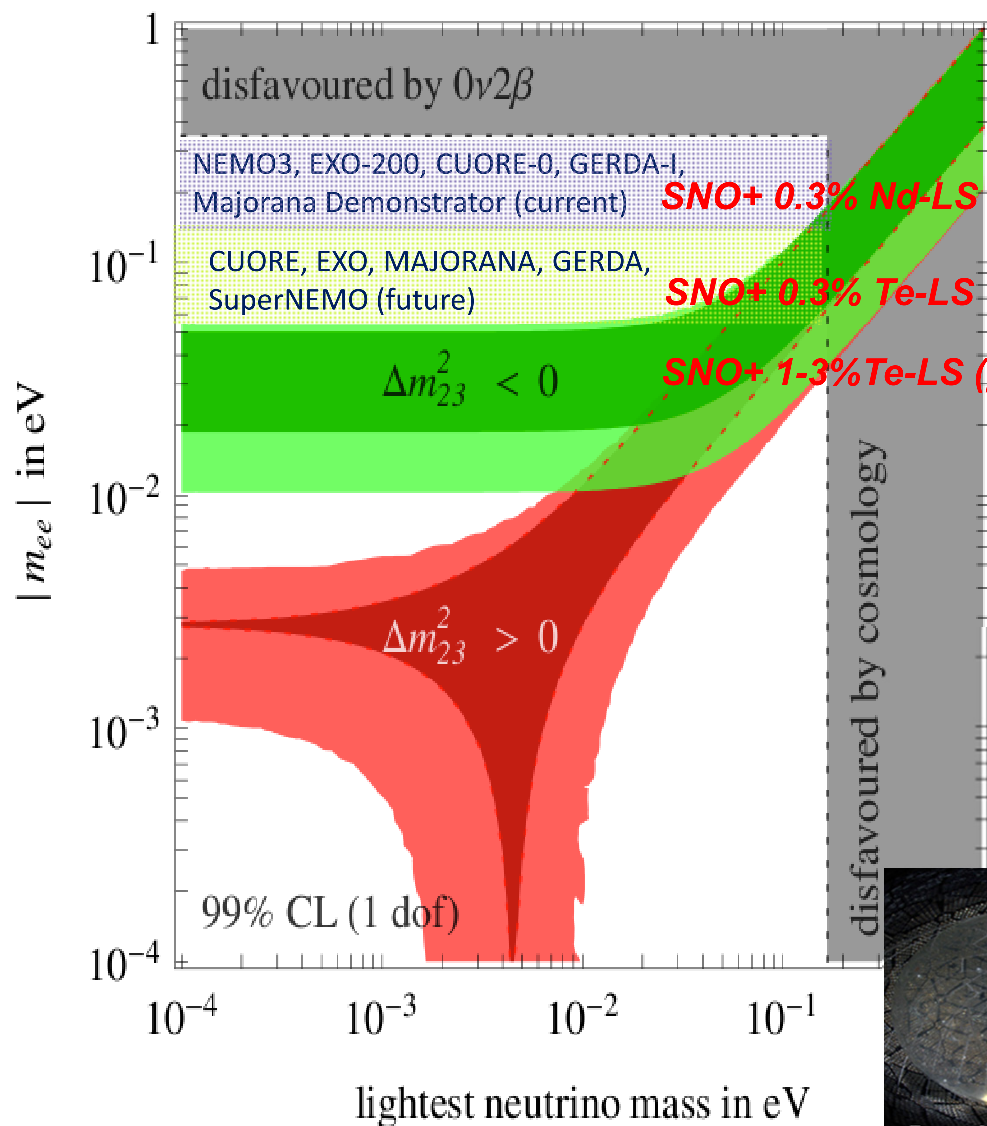


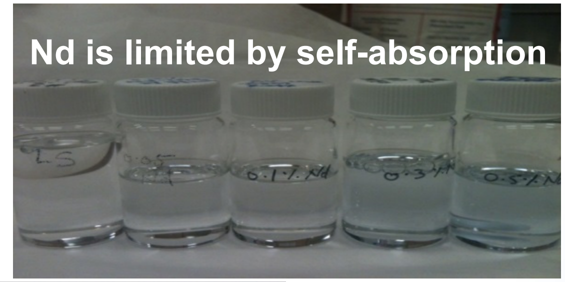


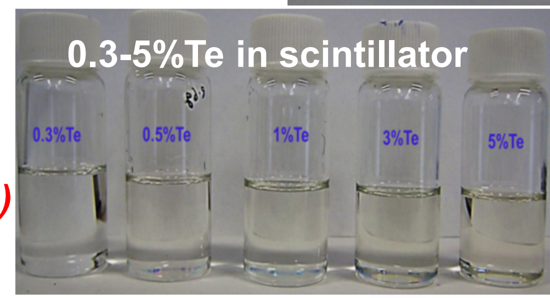


PSD enhancement for 0.1% Gd-doped LS (compatible with plastics) over 6 months; and further improvement can be achieved

Te-WbLS for SNO+ 0νββ

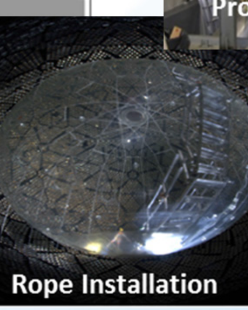


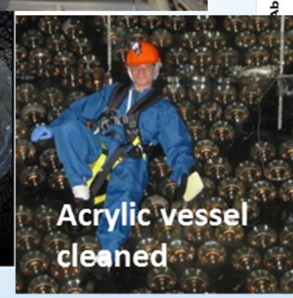


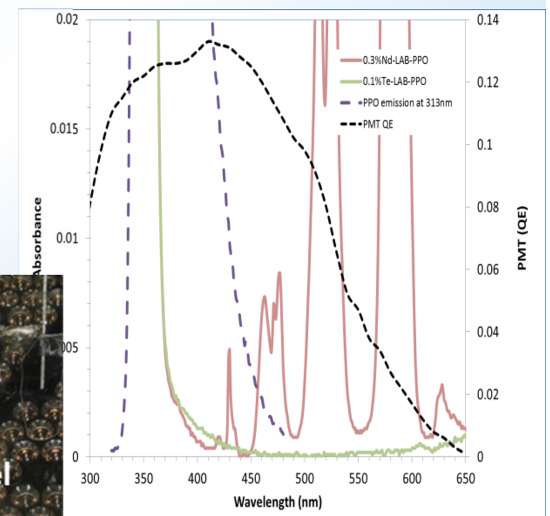


Te is optically cleaner with better light-yield

- 0.3% Te is the new baseline
- Scintillator filling in 2015; followed by Te-loading and data taking in 2016
- **A future ton-scale 0νββ detector**







- Applications to particle & nuclear physics experiments
  - PROSPECT
  - SNO+
  - LZ Dark Matter
  - Medical imaging
- Feasibility of A large Water-based Liquid Scintillator detector
  - (Inter)national WbLS working group
  - 1-t prototype
  - WATCHMAN
  - Neutrino beam physics (T2K, LBNE or HK)

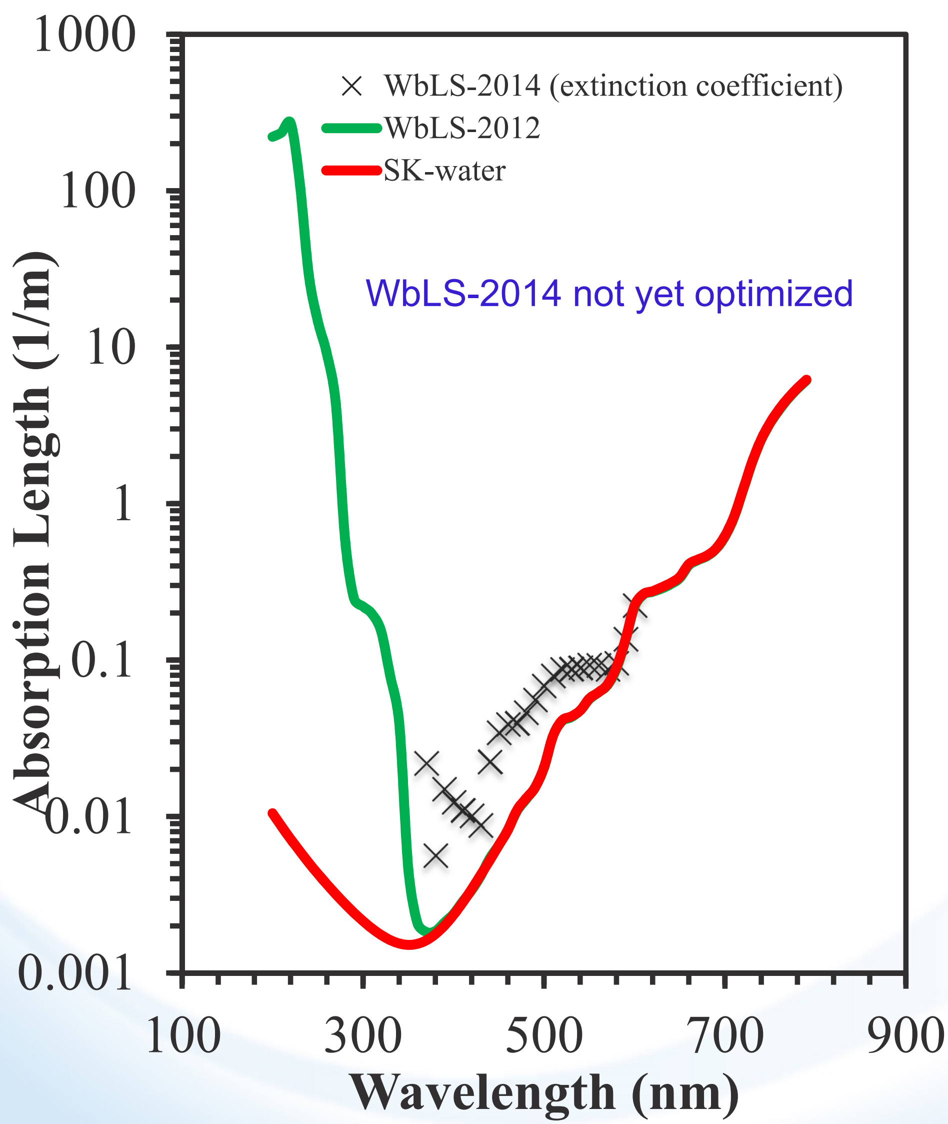
FY14 Onwards

A Large WbLS Detector

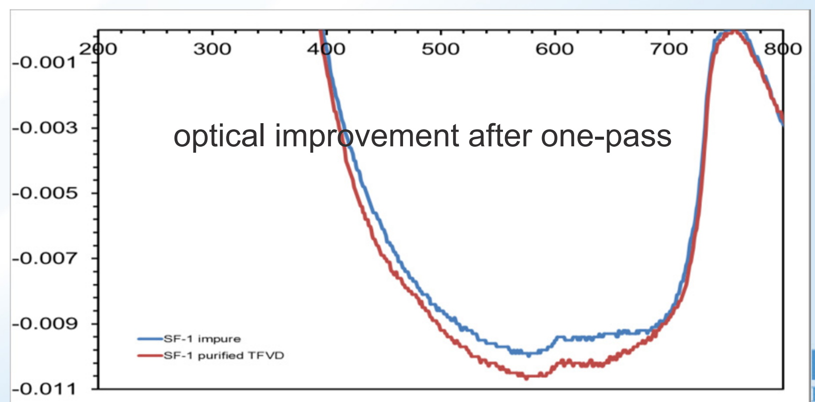
- A WbLS-LBNE workshop was held at LBNL in June: http://underground.physics.berkeley.edu/WbLS/slides/
  - Great interests from science community
    - BNL, LBNL/UCBerkeley, UPenn, UCDavis, UCIrvine, UChicago, UPrinceton, UCLA, UHawaii, SNL
  - Potential physics reaches by a WbLS detector
  - complementarity of an additional WbLS detector to LBNE-LAr detector
  - A technical or white paper is under discussion
- A US-WbLS working group is formed to:
  - coordinate future R&D plans
  - interact with WATCHMAN
- An international Workshop is under consideration

"the U.S. to host a large water Cherenkov neutrino detector, as one of three additional high-priority activities, to complement the LBNF liquid argon detector, unifying the global long-baseline neutrino community to take full advantage of the world's highest intensity neutrino beam. The placement of the water and liquid argon detectors would be optimized for complementarity. This approach would be an excellent example of global cooperation and planning" – P5 (scenario C)

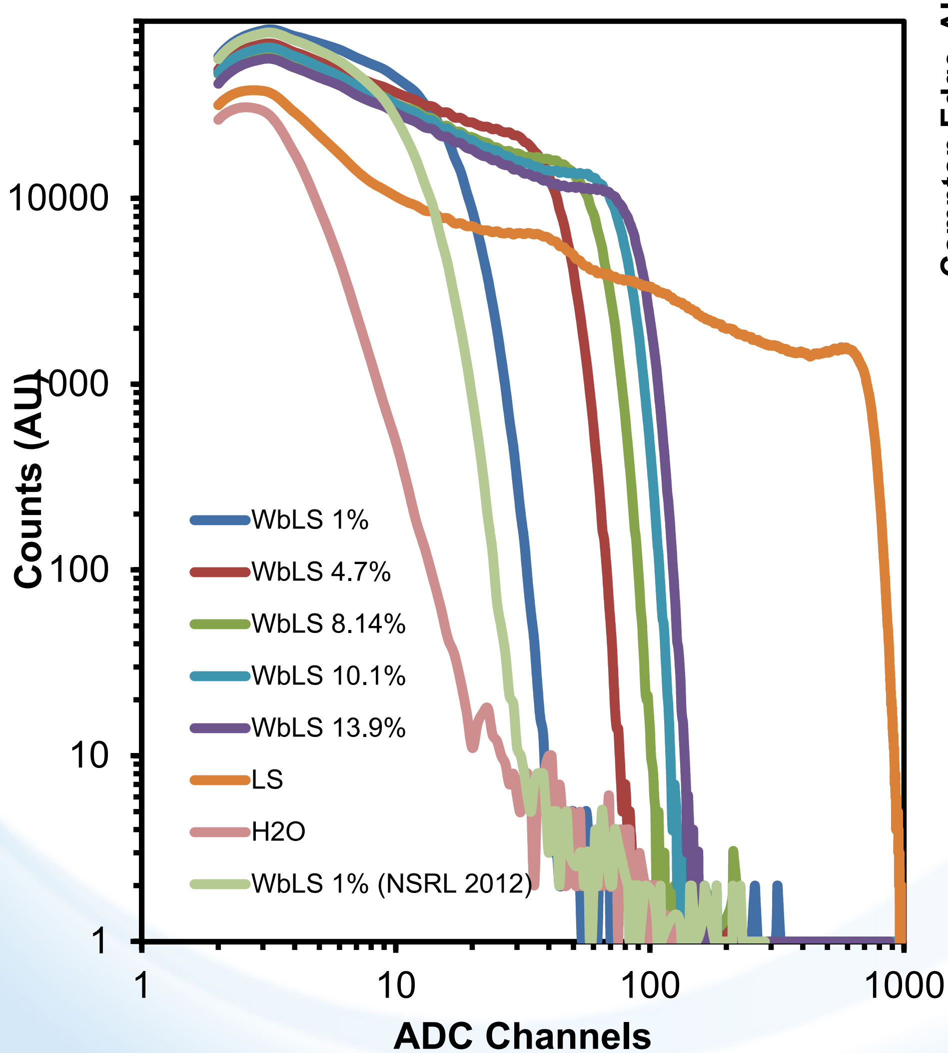
1% WbLS-2014

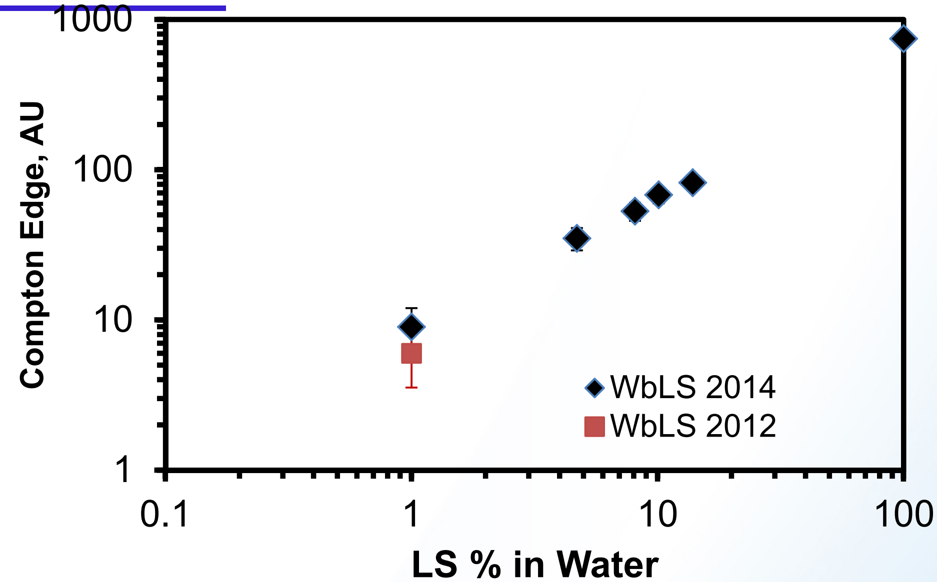


- The WbLS-2012 needs 10^4 optical purification
  - relying on the vendor for a cleaner starting material
  - Multi-step technologies proven; but high cost and labor-consuming
- The WbLS-2014
  - New chemical components
  - Non-purified and includes scattering; need to measure its effect
  - extinction coefficients calculated from each component (successfully predict LS)
  - $\varepsilon_{total} = \varepsilon_{organic} + \varepsilon_{water}$
  - $\varepsilon_{organic} \sim \varepsilon_{water}$ of 0.0046 (m^{-1}) at 430nm
  - Region of 300-400nm dominated by flour/shifter; purification is needed



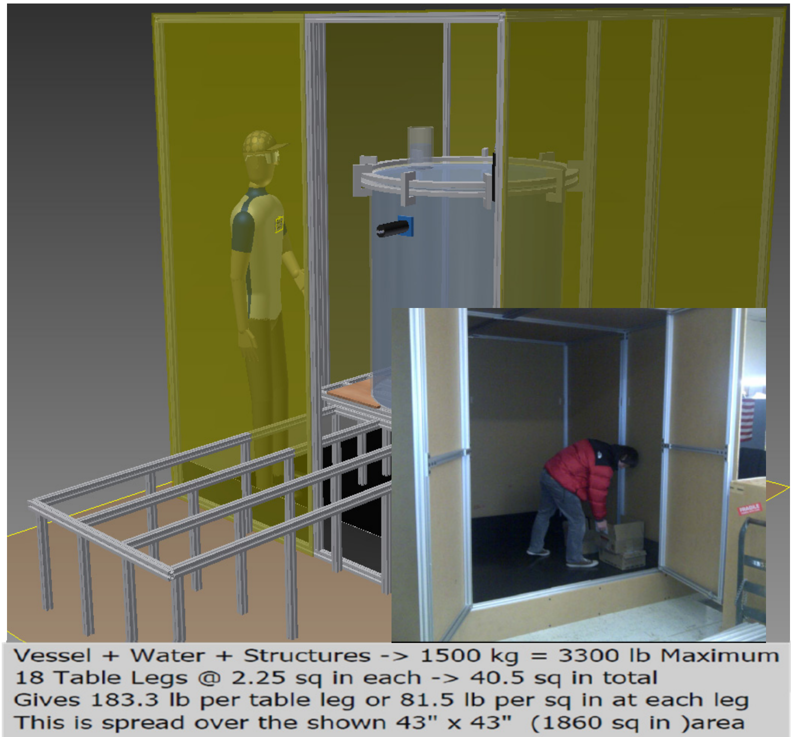
1% WbLS-2014 cont'd

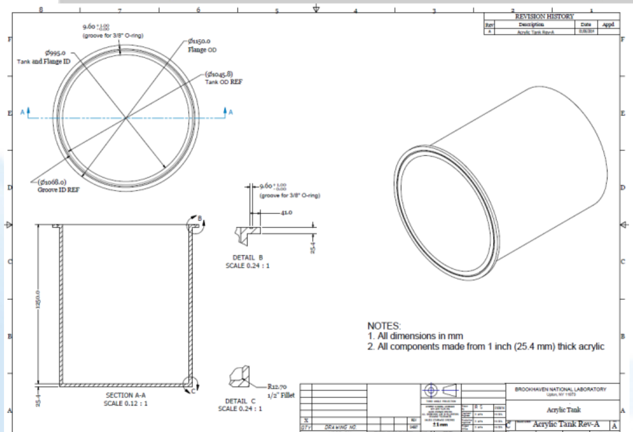


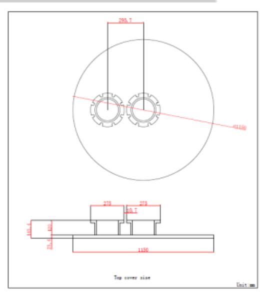


- WbLS light-yield as a function of LS% loading
  - Higher light-yield at the cost of optical transmission
- Linear correlation between light-yield and LS% (up to ~15%)
  - Behave differently compared with pure scintillator
- WbLS-2014 has ~25% more light-yield than WbLS-2012

A 1-ton WbLS Prototype

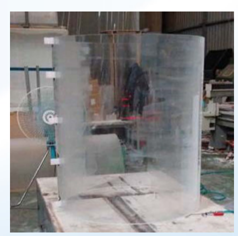






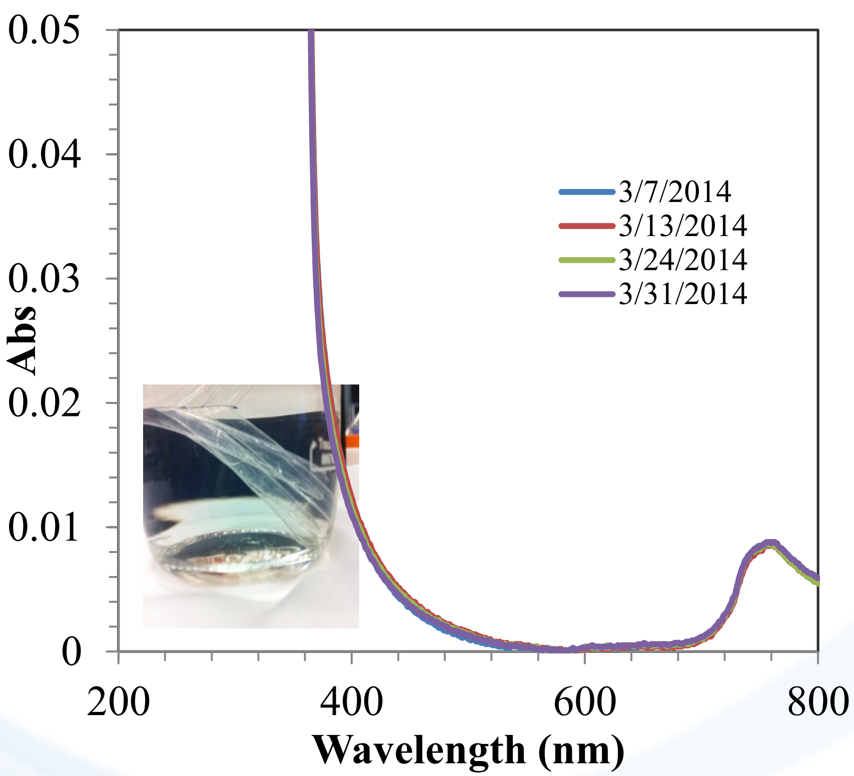
Under construction; will be ready in Sept. 2014

- Test WbLS in different formulas
- Feasibility at 1-ton performance scale (followed by a 20-ton Daya Bay AD in 2017? E. Worcester)
- **Prototyping studies of**
  - Optical and scattering measurements
  - Light-propagation over 1-m path-length;
  - Direct Cherenkov & scintillation separation using cosmic muon and calibrated sources
  - Testing of loading + unloading
  - Development of e^+ sources for nonlinearity
  - ***Slow scintillator for better C/S separation?***
- Assembly in 2014 and start 1-ton liquid production in 2015



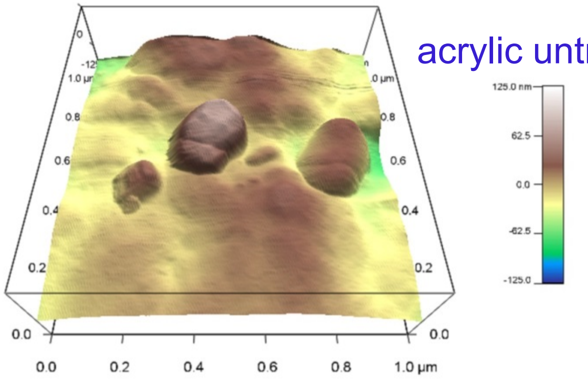
Material Compatibility in WbLS

- A well-equipped compatibility program at BNL
  - serving to several experiments (SNO, SNO+, Daya Bay, PROSPECT, LBNE-water, T2K)
  - High s/V ratio (or elevated temp) to speed up the test
  - Impact of material to liquid (UV, XRF, 2-m attenuation system)
  - Impact of liquid to material (AFM and FTIR-microscope)

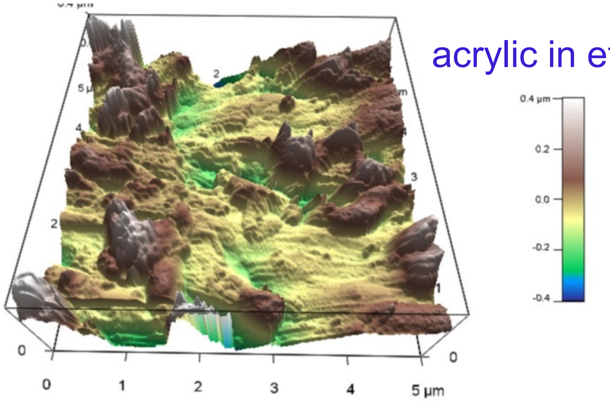


10% WbLS optically stable for acrylic, PP, PFA (other materials in preparation)

acrylic untreated



acrylic in ethanol

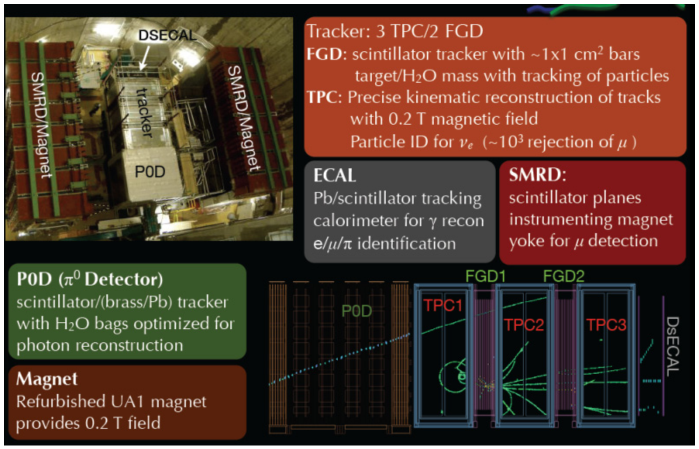


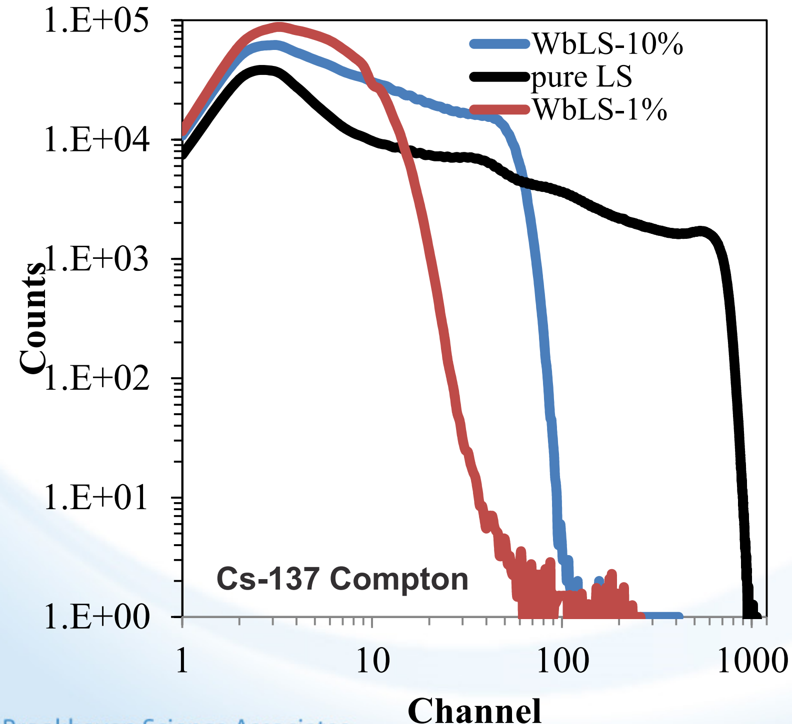
Atomic force microscopy (**AFM)** high-resolution scanning

WATCHMAN

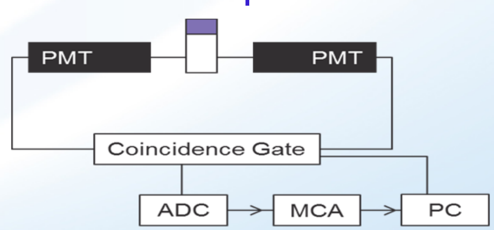
- Phase-I (Gd-water)
  - Remote reactor $\bar{\nu}_e$ monitoring
  - A 3.5-kT Cherenkov detector at IMB site
    - 13km from Perry reactor at 1670 mwe
  - Start construction in 2016 upon approval (NA review in May 2014)
- Seeking inputs from SC-HEP for Phase-II physics
  - A platform to test WbLS with LAPPD
- Physics enhancements by WbLS
  - supernova, geo- $\bar{\nu}_e$, and other non-standard interactions
  - proton decay $(\mathrm{p} \rightarrow \mathrm{k}^{+}\bar{\nu}_e)$
- Current discussions between WATCHMAN and WbLS-working Group for R&D collaborations
- R&D proposals to be submitted
  - Material compatibility program, long-arm attenuation length system, large circulation system, etc.

Neutrino Beam Physics





- Scintillation Water for T2K-ND280
  - A WbLS detector for ν-flux monitoring and H_2O cross-section measurements by replacing the passive FGD and P∅D targets with an active scintillation water
  - Maximize scintillation at ~70% H2O target
  - US-Japan detector R&D (start 07/2014)
  - Material compatibility at BNL; prototype testing at CSU and TRIUMF/UBC
  - *Heavy water-based Liquid Scintillator?*
- A scintillation Cherenkov detector for long baseline neutrino oscillation (e.g. LBNE or T2HK)
  - Adequate scintillation light not to degrade the Cherenkov imaging (>90%H2O)
  - Complement to LBNE-LAr detector



WbLS in Applications

SNO+ ($0\nu\beta\beta$)

PROSPECT (US-SBL)

Common features between detectors

WATCHMAN (nonproliferation, p-decay, etc.)

Liquid Scintillator

(Metal-loaded & Water-based)

3-D Imaging for p-therapy (SBIR)

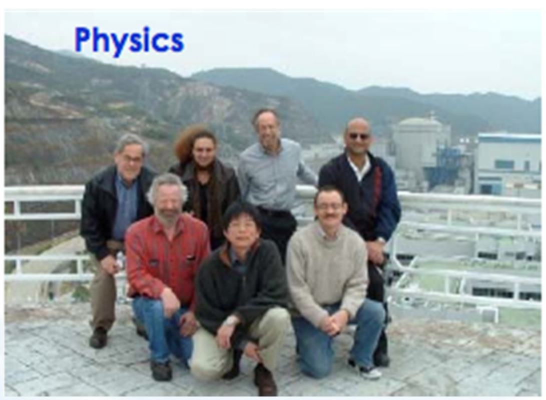
unique requirement for individual detector

Others (LZ, calibration, etc.)

ν-beam physics (T2K, HK, LBNE)

Summary

- Scintillator detector could contribute three of the five particle physics "Science Drivers" identified by the current P5
- WbLS detection and isotope loading are proven; great interests (with potential experiments) from science community
  - US-WbLS working group
  - International collaborators: Queen's, Oxford, KEK, UBC, UTH-CN
- A large WbLS detector for particle physics with implications to nuclear physics and other applications
  - PROSPECT, T2K, WATCHMAN (and LZ)
  - Potential for a future ton-scale $0\nu\beta\beta$ detector (NSAC)



DOE-ONP/OHEP
BNL-LDRD/TM