Water-based Liquid Scintillator for Physics Frontiers

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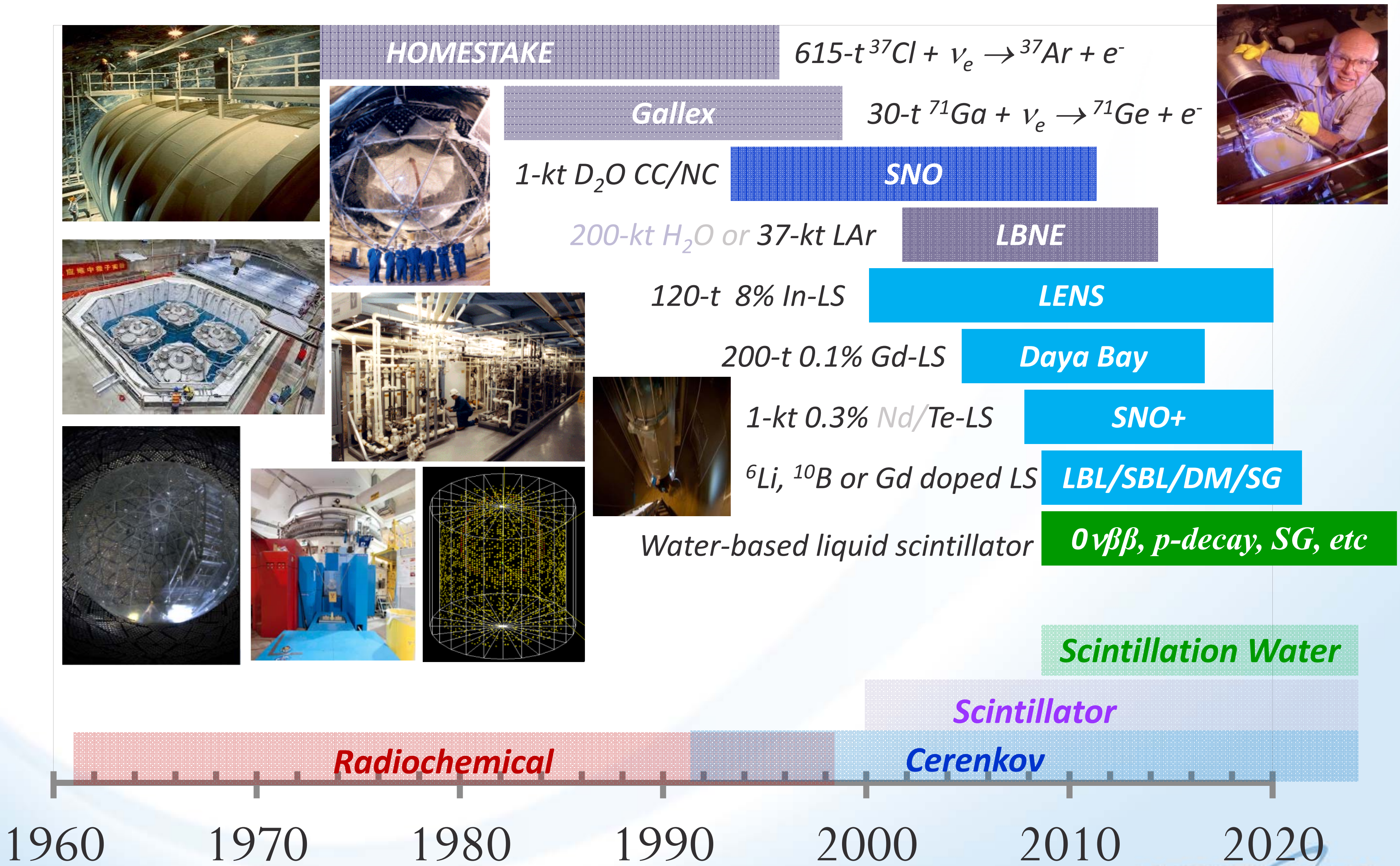
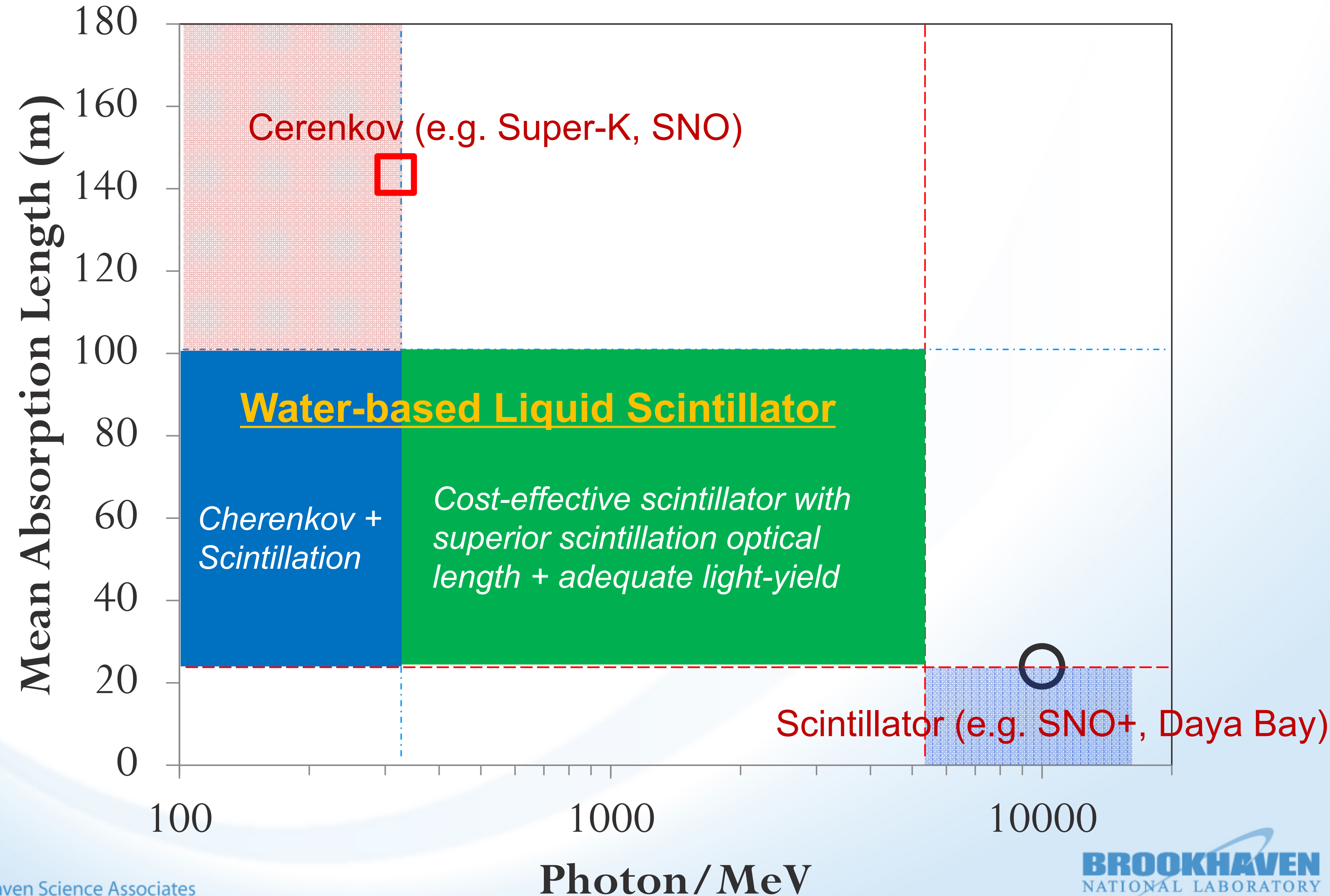


Cherenkov and Scintillation Detectors



Liquid Scintillator for Physics Frontiers

0νββ

Neutrino Mass and Hierarchy

Short Baseline, Reactor, OscSNS, or ν-source

Sterile ν vs. reactor anomaly

Common features between detectors

Nucleon Decay

Liquid Scintillator

(Metal-loaded & Water-based)

Nonproliferation & Medical Imaging

unique requirement for individual detector

Dark Matter

WIMP detection

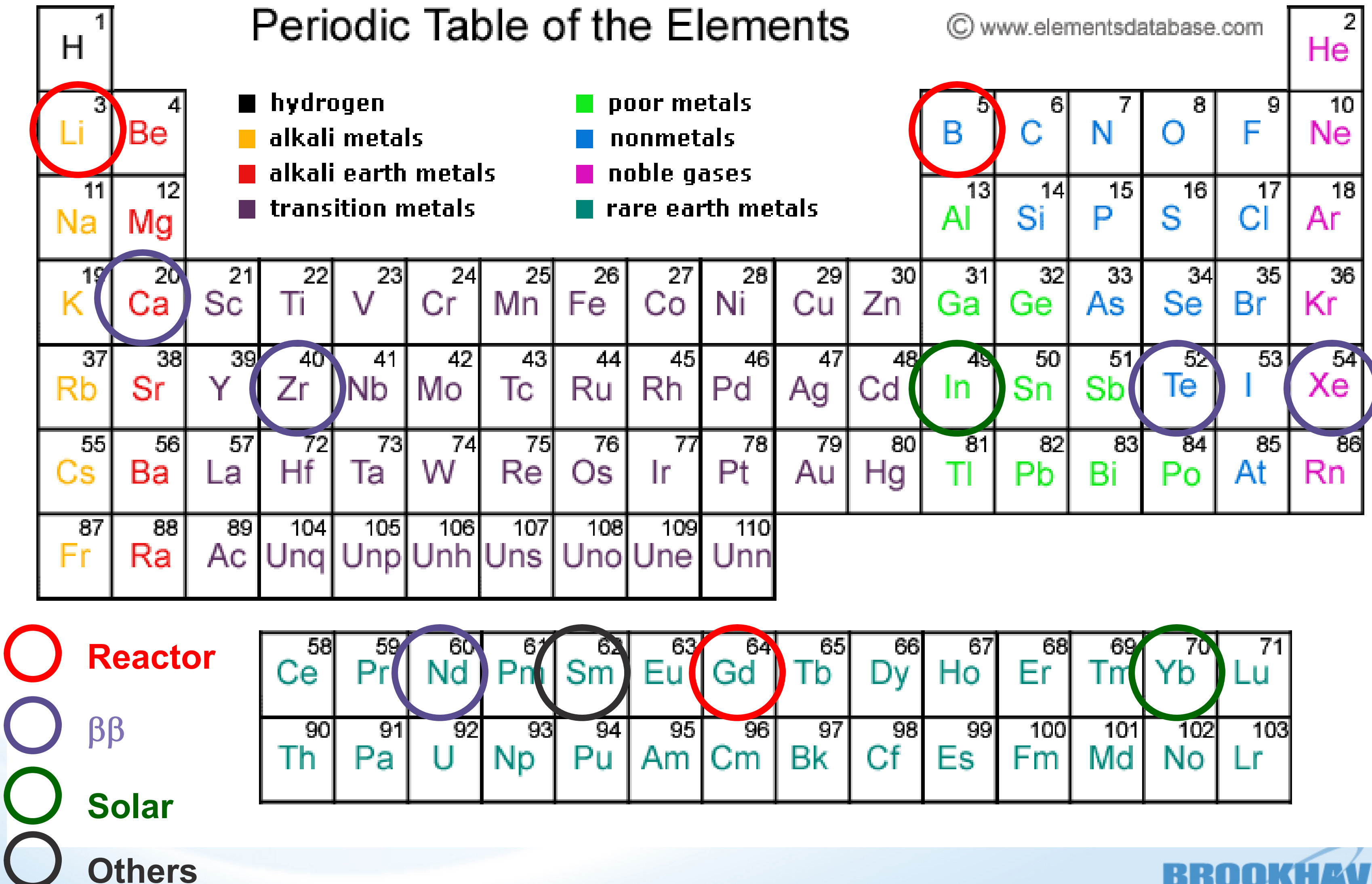
Long Baseline

Neutrino Hierarchy

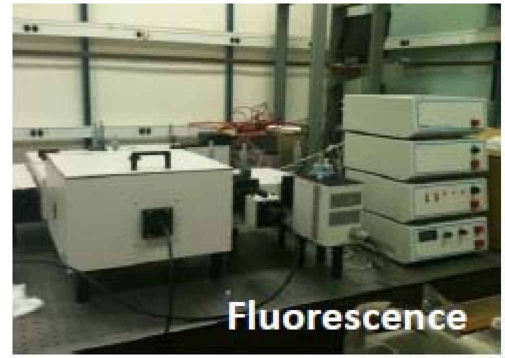
θ_{12}, Δm^2_{21} and Δm^2_{32}

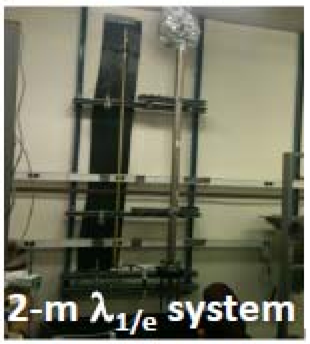
Solar-ν, Geo-ν, etc.

Metal-loaded LS for Neutrino Physics



Liquid Scintillator Development Facility

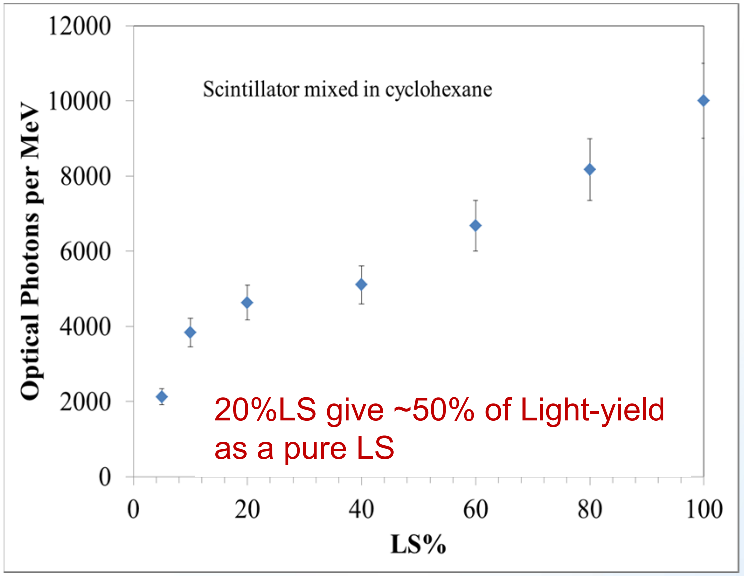


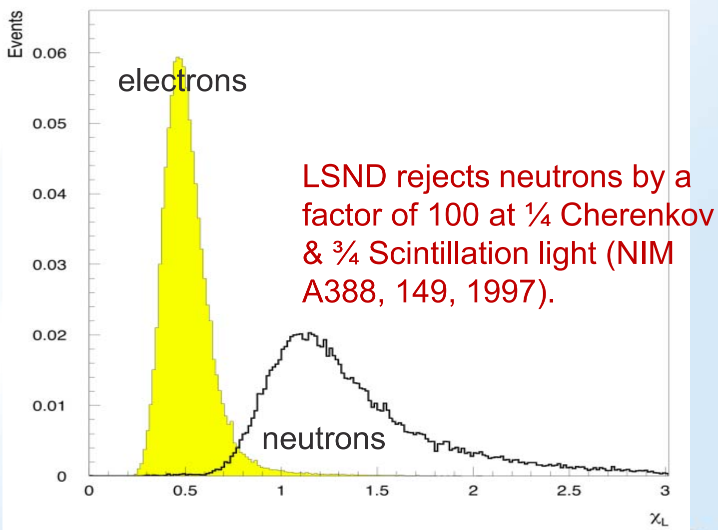


- *A unique facility (since 2002) for Radiochemical, Cerenkov, and Scintillator **(water-based and metal-doped)** detectors for particle physics experiments.*
- *Expertise trained and facility established over years of operations.*
- *$1M facility including XRF, LC-MS, GC-MS, TFVD, FTIR, UV, Fluorescence emission, light-yield coinc. PMT, 2-m system, low bkg. counting, etc. (access to ICP-MS at SBU) for detector R&Ds and prototype tests.*

Water-based Liquid Scintillator

- A cost-effective, new liquid medium utilizing nonlinear light-yield as a function of scintillator % and superior optical property of water for physics below Cerenkov or low-energy neutrino detection.
- 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.
- A new metal-loading technology for different physics applications using scintillator detector.



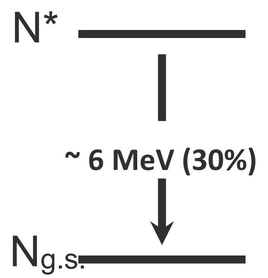


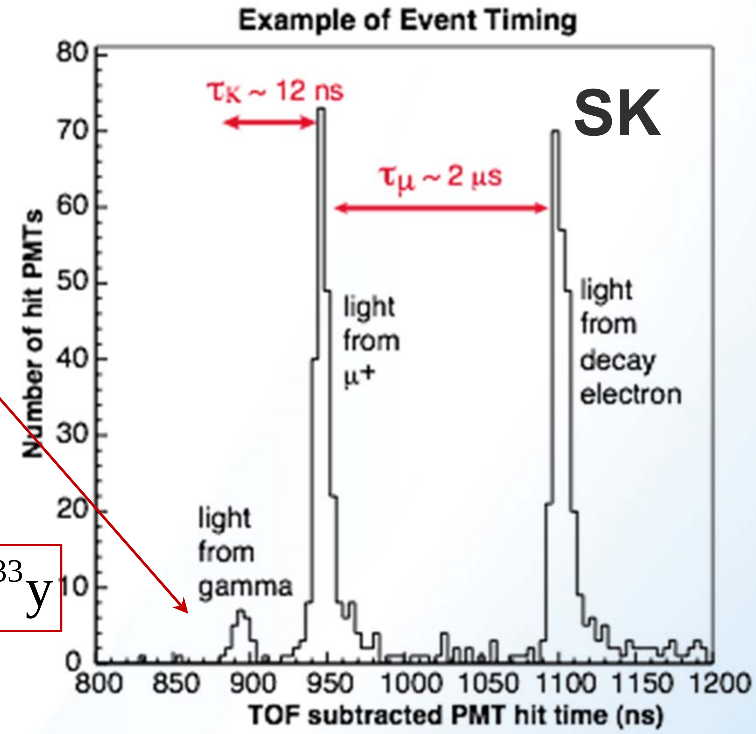
(Motivation) WbLS for Proton Decay

- *A scintillation + Cerenkov detection liquid for proton decay*

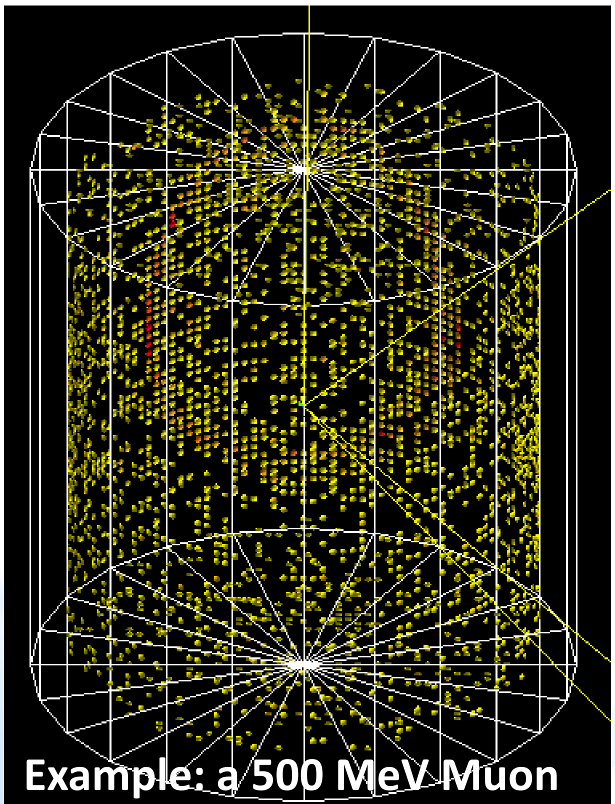
$$p^{+} \rightarrow K^{+}\overline{\nu}$$

- *K^{+} is below Č threshold!*





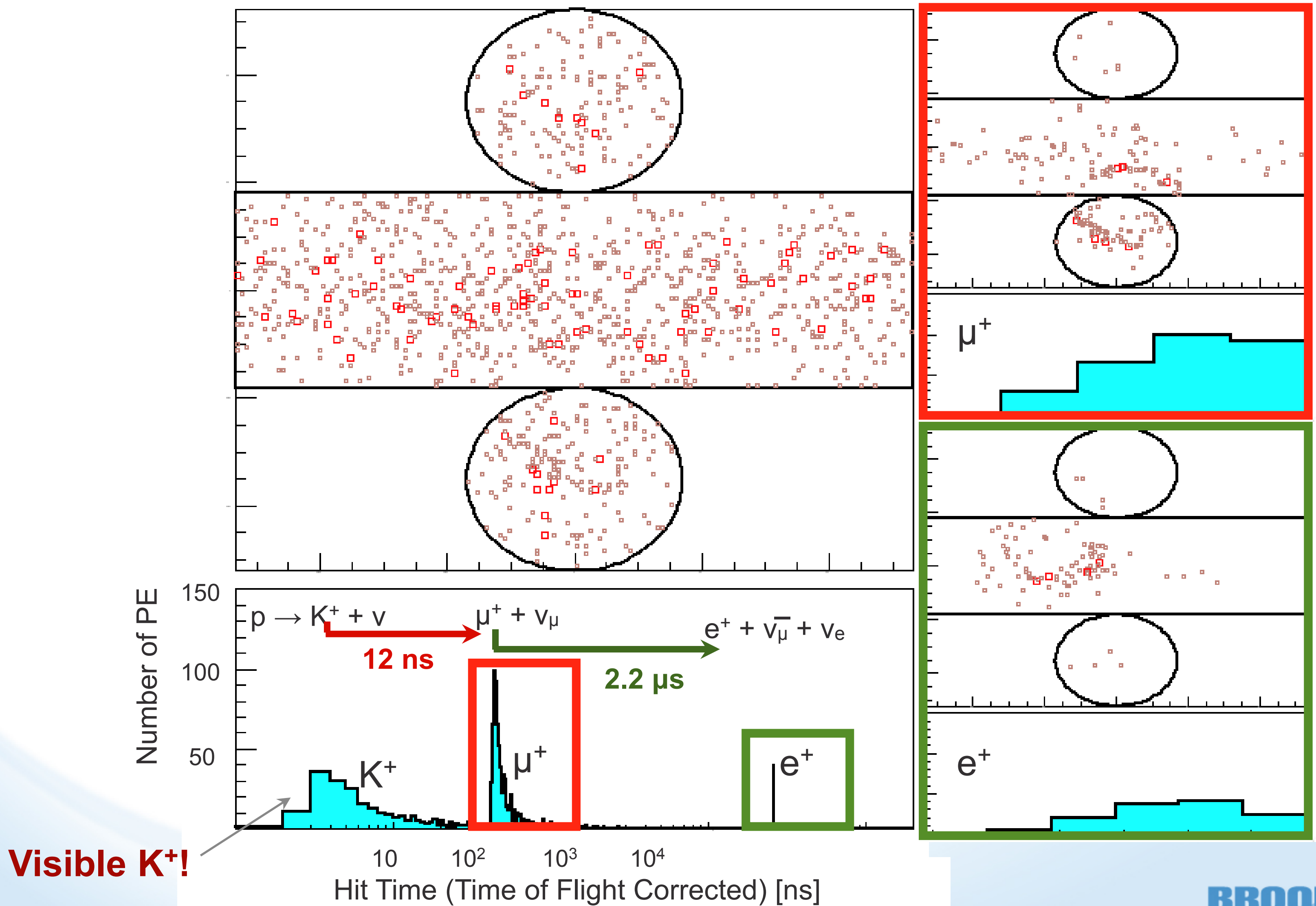
$$\tau(p \rightarrow k^{+}\overline{\nu}) > 2.3\times10^{33}\mathrm{y}$$



- *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 $p^+ \rightarrow k^+ \bar{\nu}$ channel for a WbLS detector

A simulated event with 90 scintillation photons/MeV

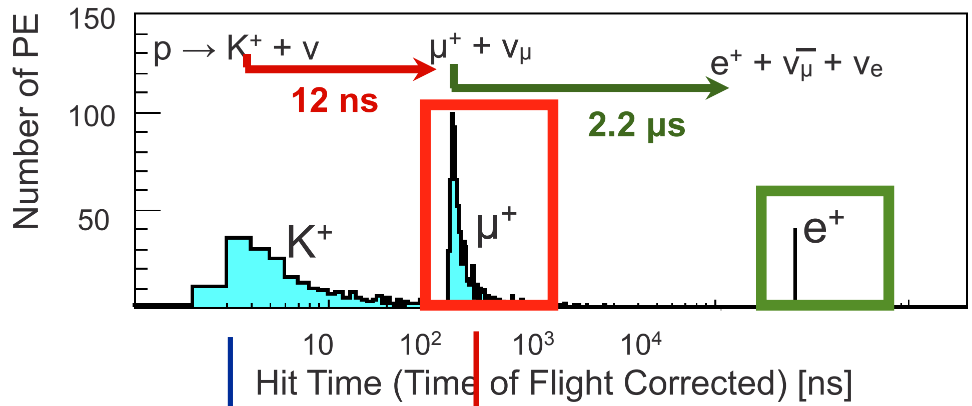


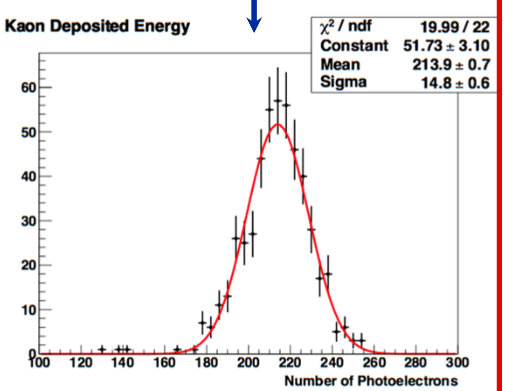
Main background: atmospheric ν_μ

Reduce by:

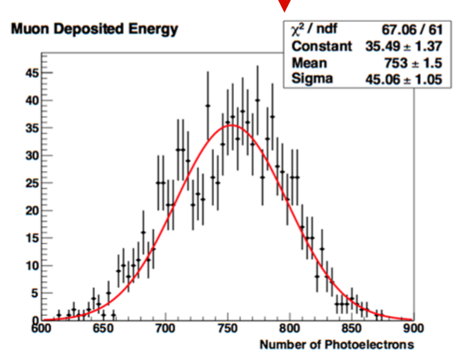
- **Rising-time cut**: define a PSD to distinguish background from signal by rising-time (from 15% to 85% of maximum pulse height) of the pulse shape

- **Reconstructed Kaon energy cut**: by subtracting the reconstructed muon energy

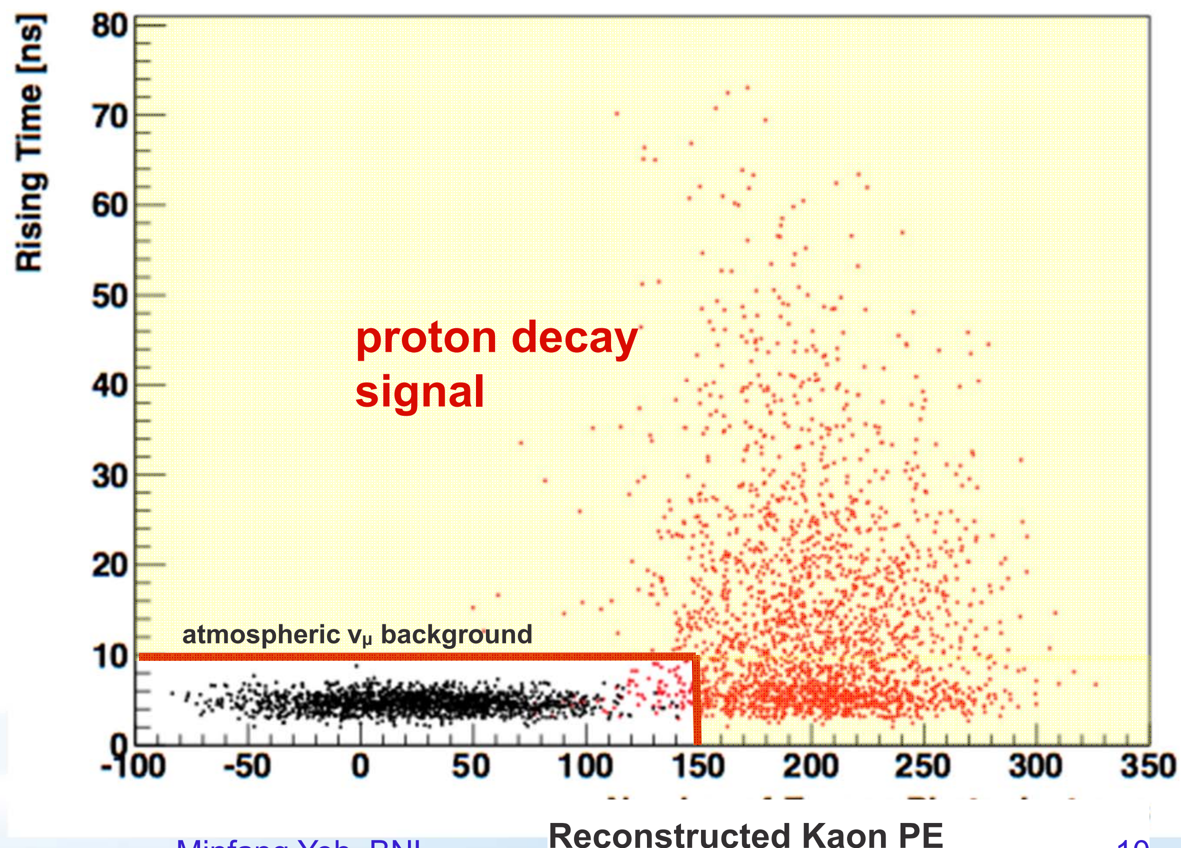




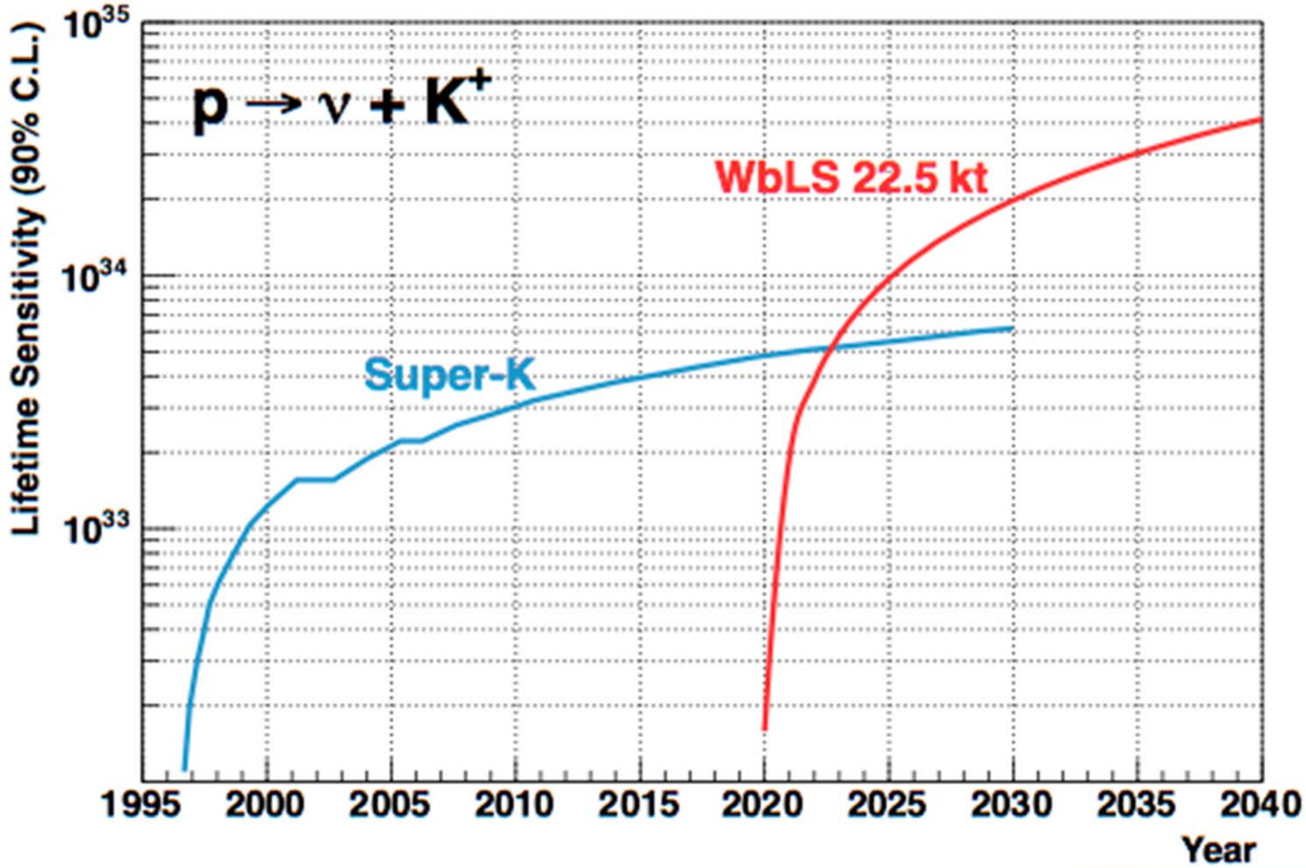
Kaon: 105 MeV -> 213 PE



Muon: 152 MeV -> 753 PE

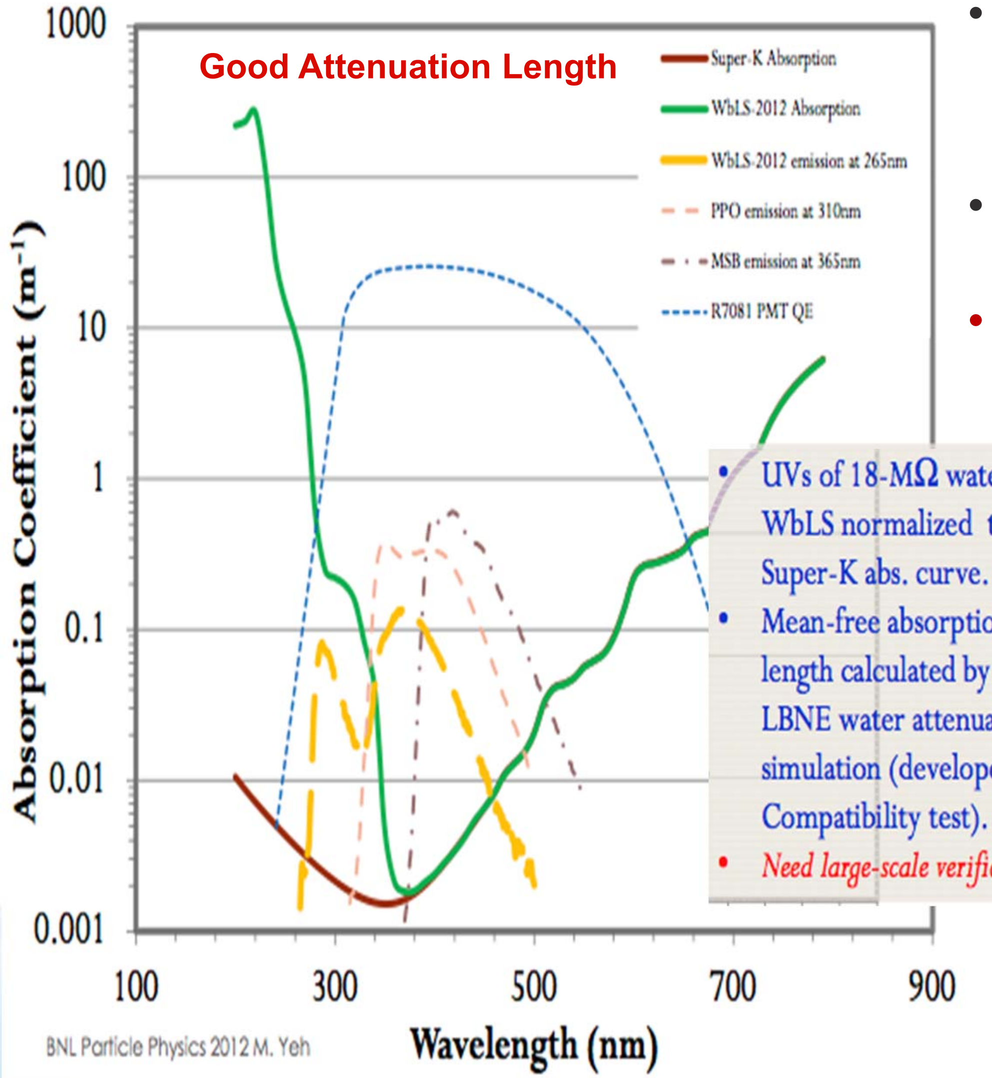


A SK-like WbLS Detector (projected sensitivity)



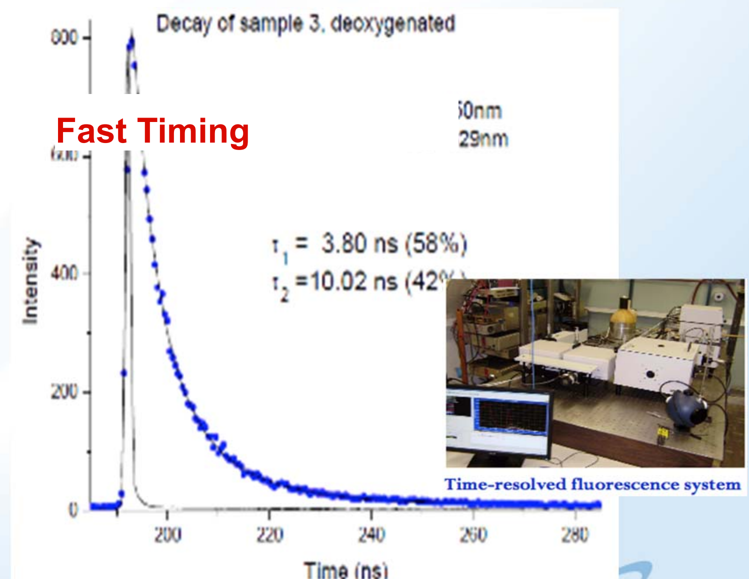
$$\tau(p \to K^+\bar{\nu}) > 2 \times 10^{34}\text{y at 90\% C.L. in 10 years}$$

A fast and transparent 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*

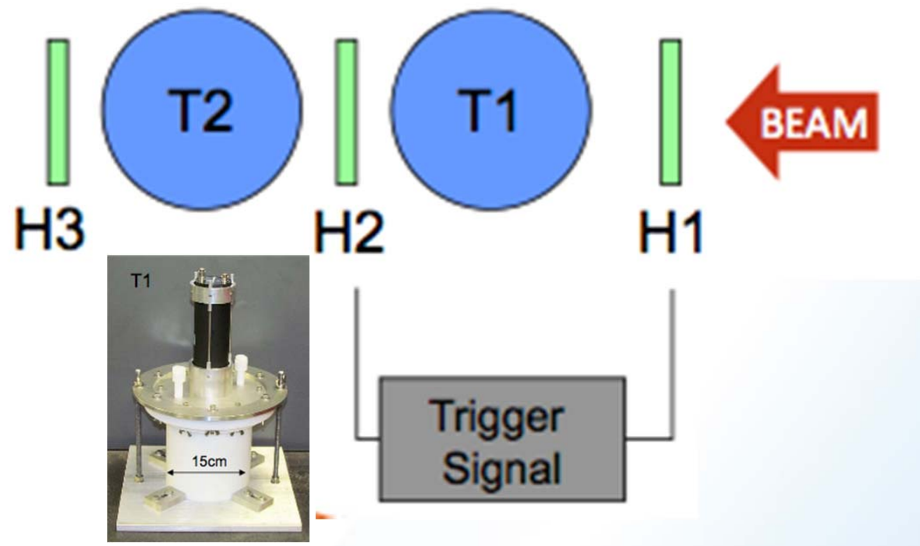
- Started R&D since 2009
  - A clean liquid (at 450nm and above)
  - A fast pulse
  - can load LS in H_2O at as much as 35%
- An ideal detection medium for <u>physics below Cerenkov?</u>
- Investigate light propagation below and above Cerenkov
  - proton beams & sources



Time-resolved fluorescence system

Proton-beam for Scintillation below Cerenkov

WbLS Detectors



3 low Intensity Proton Beams

210 MeV	dE/dx ~ K+ from PDK
475 MeV	Cerenkov threshold
2 GeV	MIP

4 Material Samples

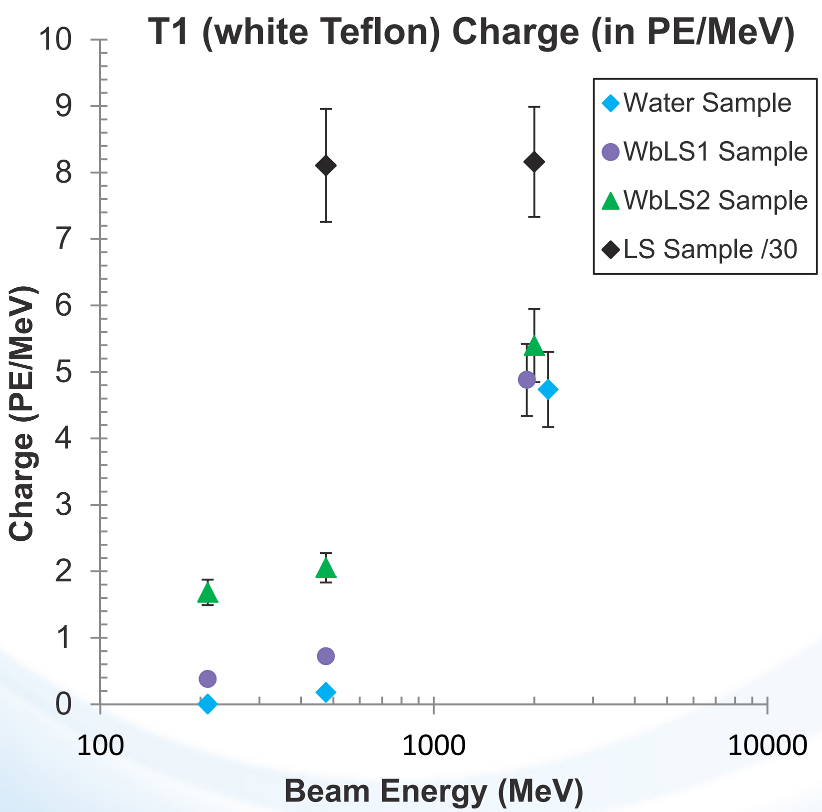
Water	pure water
WbLS 1	0.4% LS
WbLS 2	0.99% LS
LS	pure LS

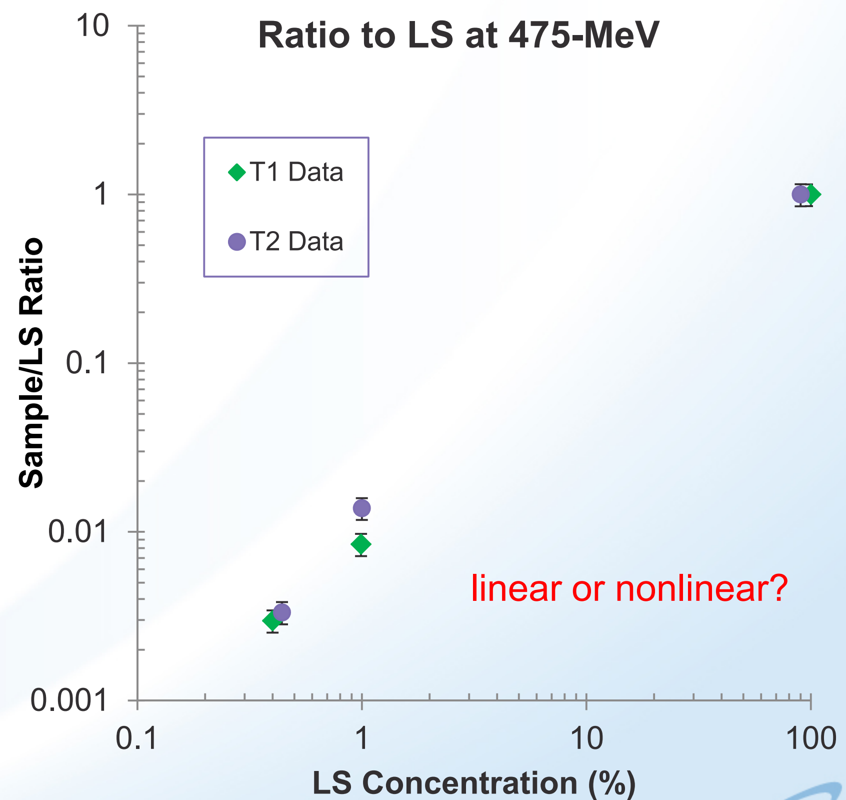
2 Detectors

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

Scintillation below Cerenkov threshold

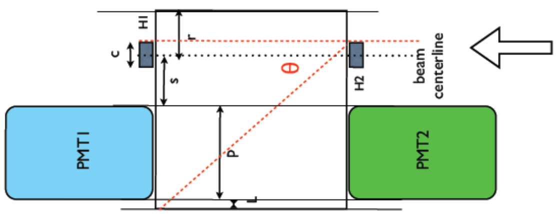
- *Cerenkov dominates at 2GeV while scintillation takes over at 475MeV and below*
- *Minimal Čerenkov contribution at 475MeV – can use the data at this energy for WbLS to LS comparison*
  - *Note that LS sample response is divided by 30 to fit on the same scale*





A New Game of Metal-doped Scintillator

3rd run (475-2000 MeV) in 2013 using same WbLS that was measured 7 months ago



Scintillation/Cerenkov separation

What do we learn from three proton-beam runs:

- showed consistent light-yield compared with previous two runs (**stability**)
- Cerenkov is what we see above Cerenkov threshold
  - only downstream PMT sees the light (Č above threshold) at 2000-MeV
- Scintillation below the threshold
  - both PMTs see the light (Š) at 475- and 2000-MeV
- capable of detecting scintillation and Cerenkov

Q: how to load hydrophilic ions in scintillator? conventional method is difficult!

What physics is WbLS good for?

- tunable light-yield to fit the requirements of various applications
- a new technology of loading metallic ions in scintillator

Current Applications of WbLS

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

PROSPECT (US-SBL)

Common features between detectors

WATCHMAN (nonproliferation, p-decay, etc.)

Liquid Scintillator

(Metal-loaded & Water-based)

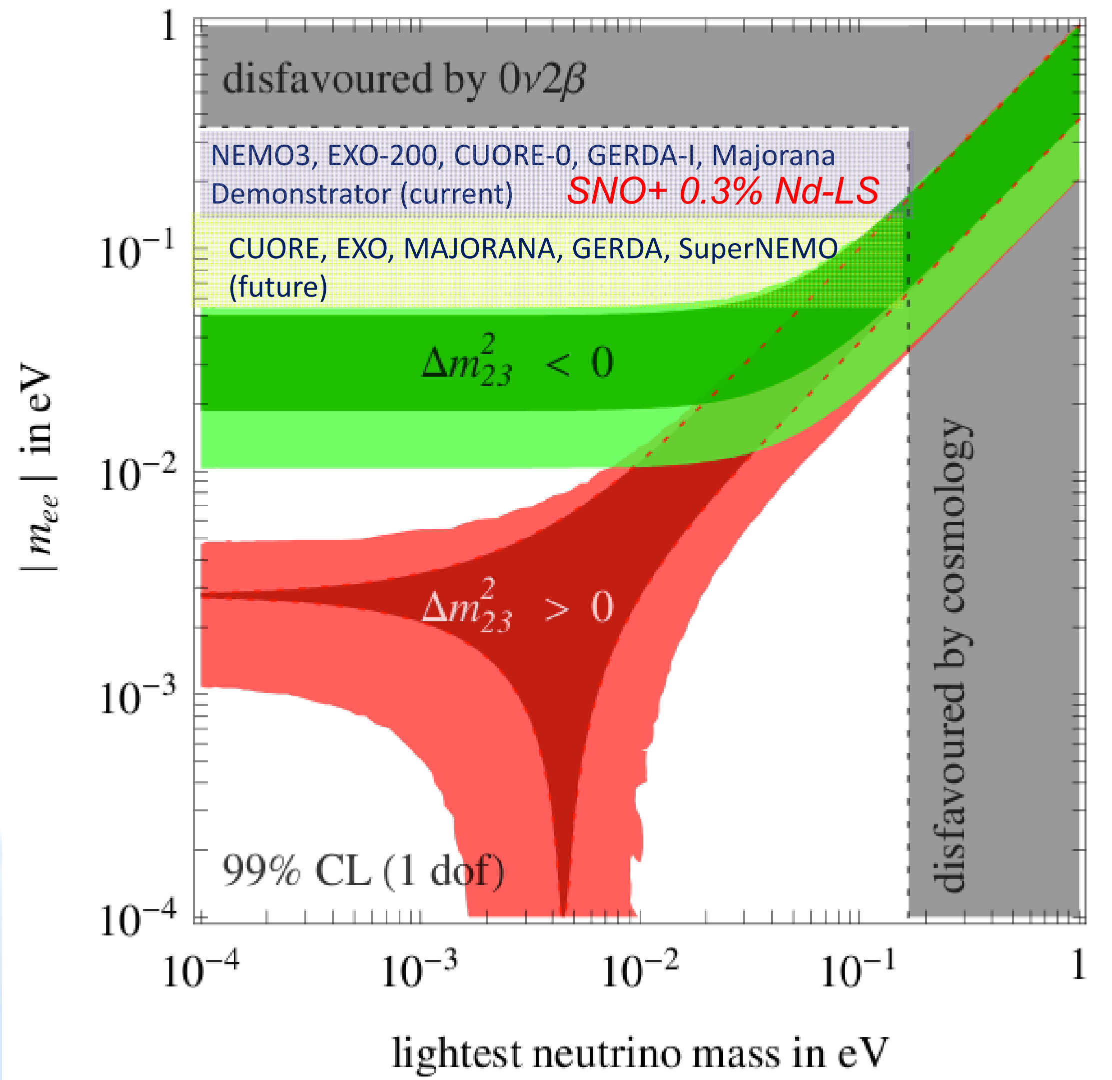
Ion-beam therapy & TOF-PET scan

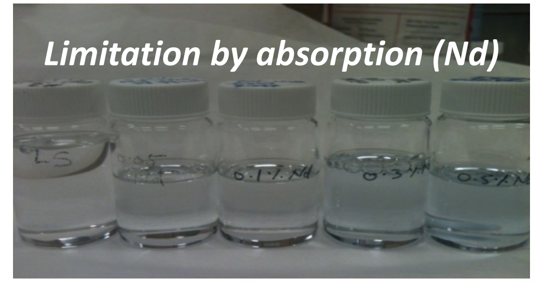
unique requirement for individual detector

Others (under discussion)

T2K (Near detctor)

WbLS App: SNO+ 0νββ



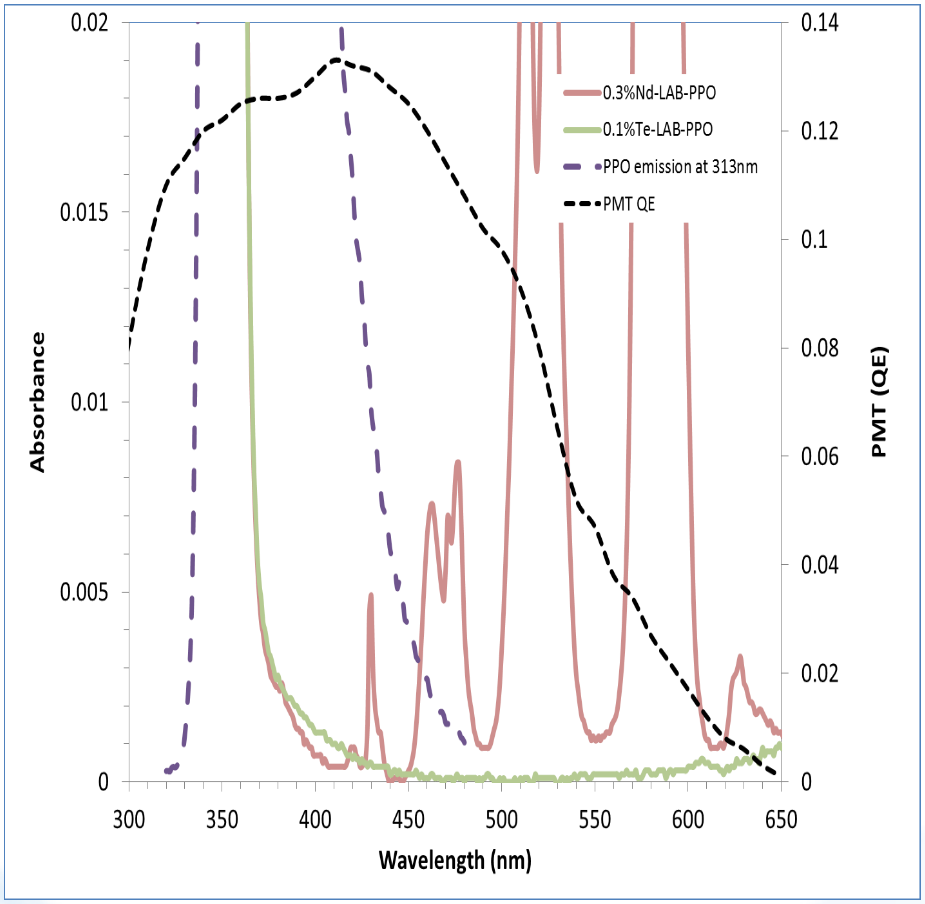


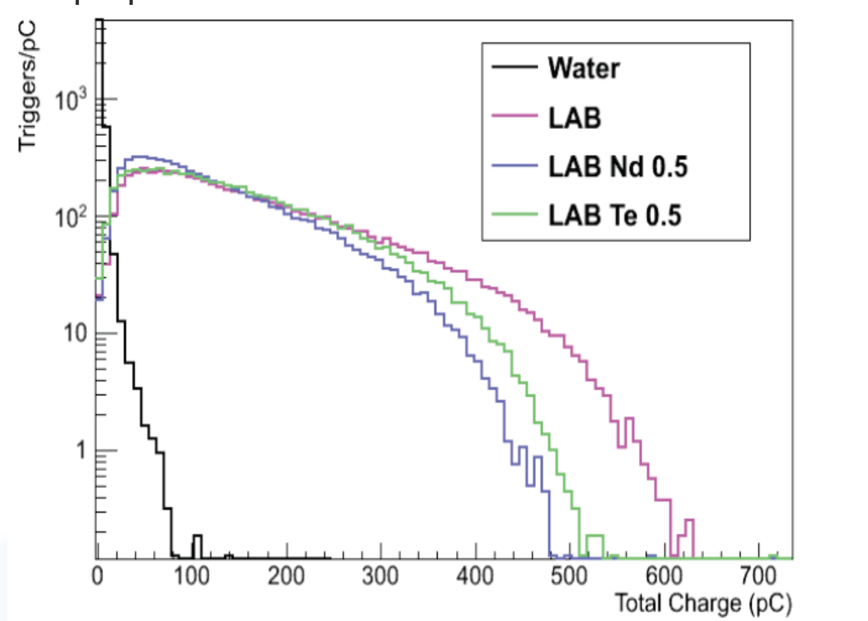
- *limited by optical of Nd-LAB (0.3% is optimized).*
- *always interested in other 0νββ isotopes or enriched ^{150}Nd.*

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

Tellurium enabling in LAB

- Water-based loading technology enabled the loading of tellurium (^{130}Te) in LAB in 2011-2012
- A year (2012-2013) of verification and evaluation by collaboration
- **The new $0\nu\beta\beta$ target for SNO+ (2013)**
- Te-LS has been stable for 1.5 years since preparation

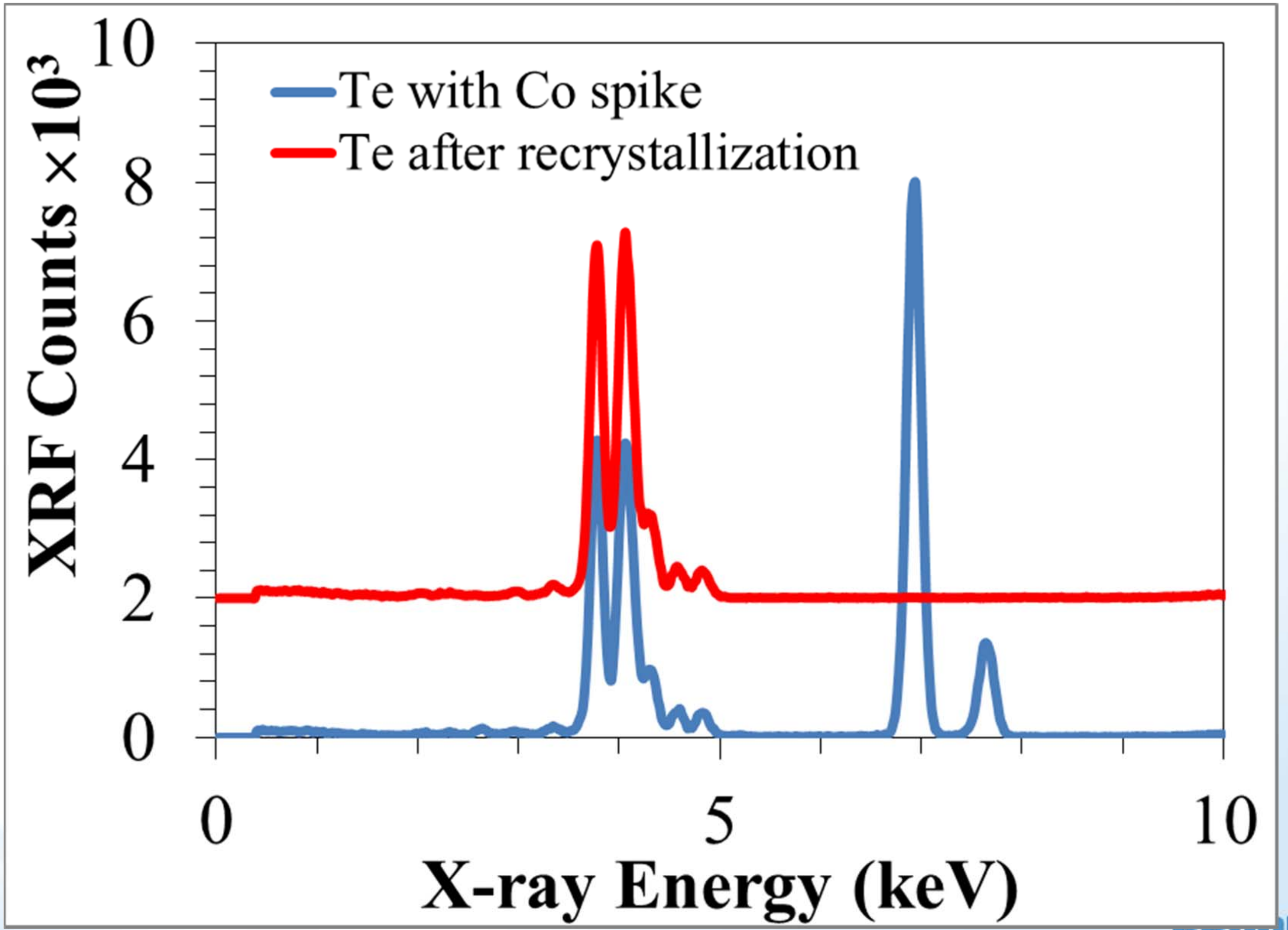




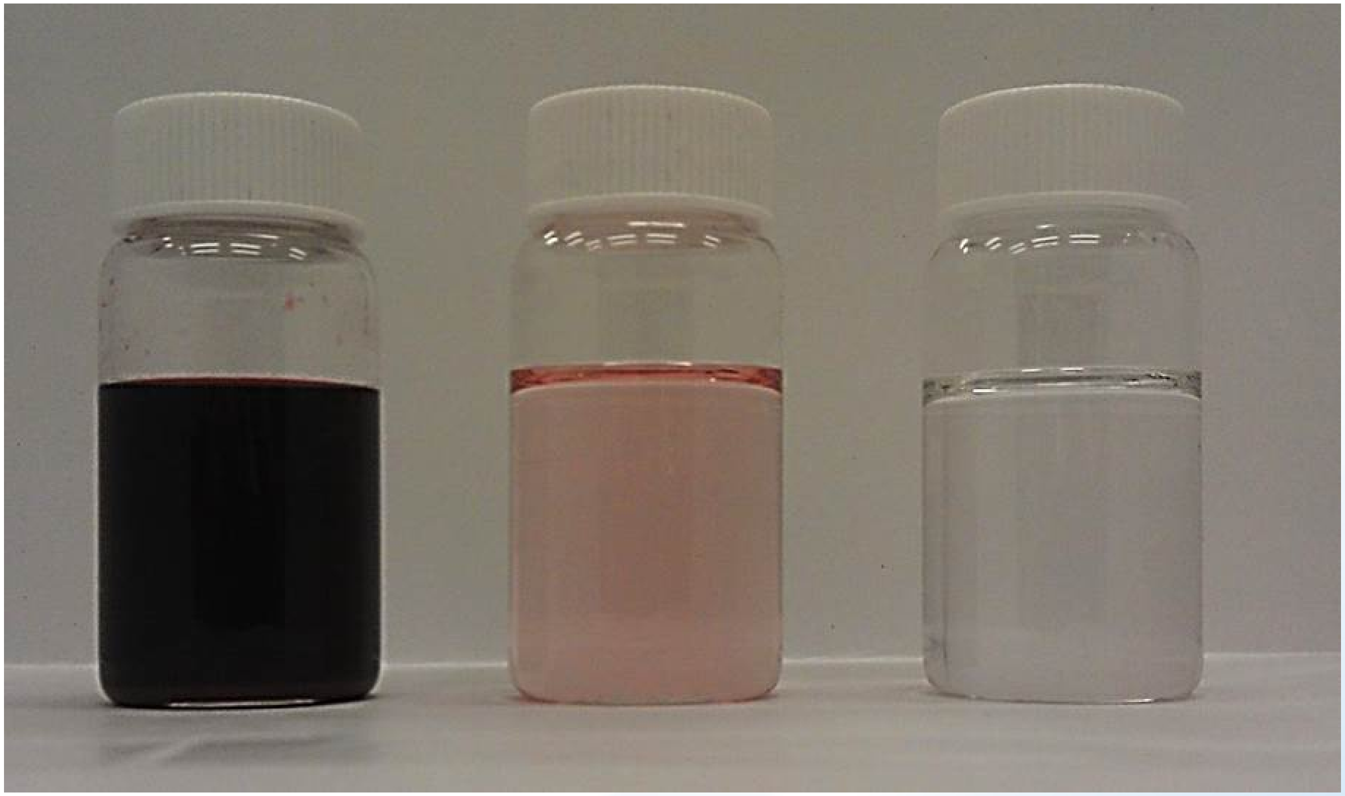
- Compared to Nd-LAB
  - Low absorption in critical region
  - Reasonable intrinsic light yield

Background control is the key
- U/Th and cosmogenic isotopes
- Acid & thermal recrystallizations are developed

Example of purification (Co removal)



Two-Passes Purification (ex. Co)

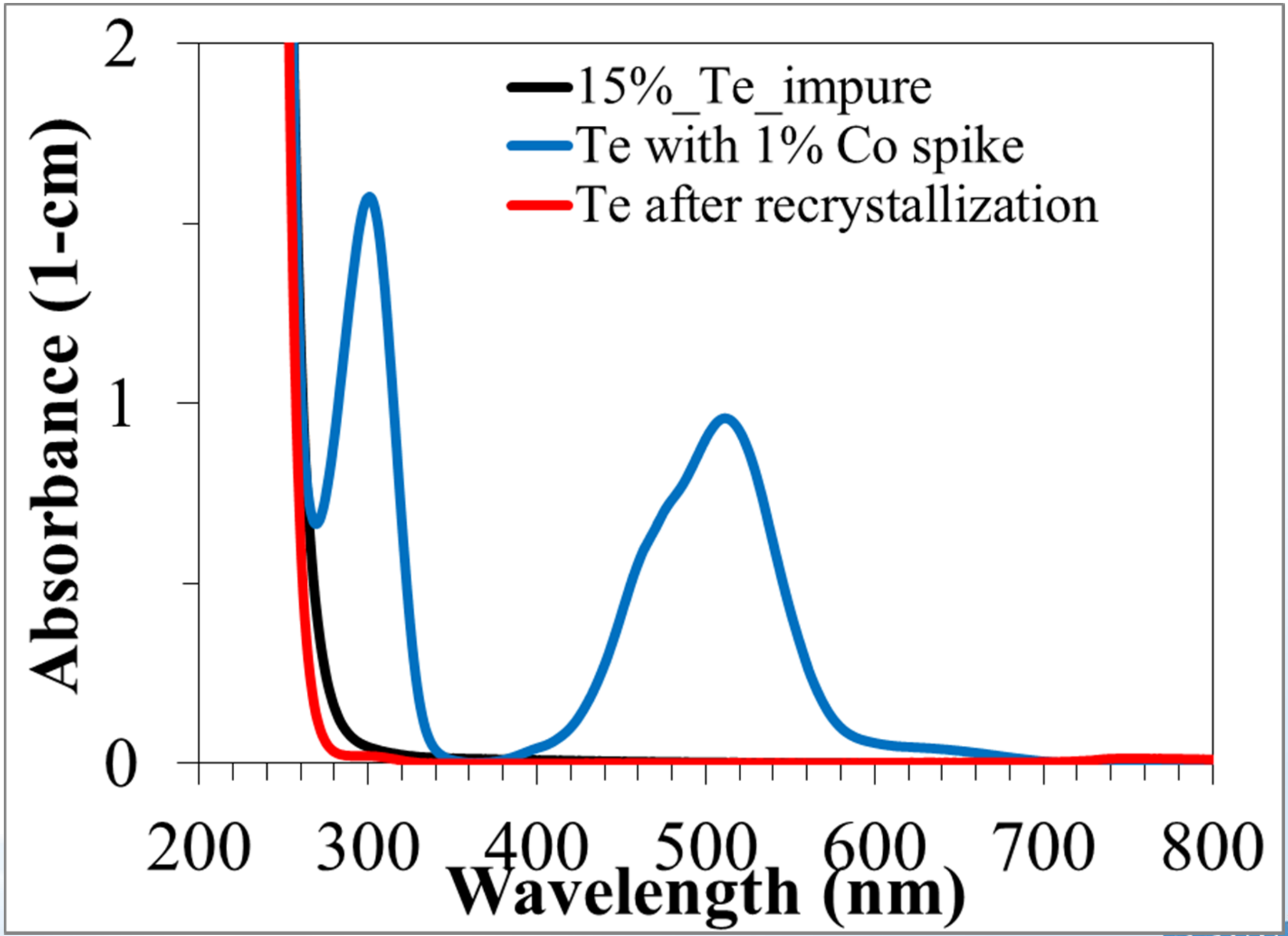


10^6 reduction factor

Table of the Background Isotopes

Isotope	Reducing Factor (spiked)	Non-spiked (before)	Non-spiked (after)	Notes
Sn	$>1.67\times10^2$	20	<20	
Zr	$>2.78\times10^2$	70	<10	Zr-Ti similar chemistry
Ti		40	<10	
Al		<30	<30	
Co	$(1.62\pm0.34)\times10^3$	<10	<10	Co-Fe-Mn similar chemistry
Mn		150	<5	
Fe		40	<30	
Ag	$>2.78\times10^2$	<10	<10	
Y	$>2.78\times10^2$	<10	<10	
Sc	$>1.65\times10^2$	<10	<10	
Sb	$>2.43\times10^2$	30	<20	
^{228}Th	$(3.90\pm0.19)\times10^2$	<0.02	<0.02	
^{224}Ra	$(3.97\pm0.20)\times10^2$	1400	<5	from Ba (analog)
^{212}Pb	$(2.99\pm0.22)\times10^2$	440	<3	from Pb-208
^{212}Bi	$(3.48\pm0.81)\times10^2$	300	<10	from Bi-209
^{238}U	$(3.90\pm0.19)\times10^2$	<0.02	<0.02	

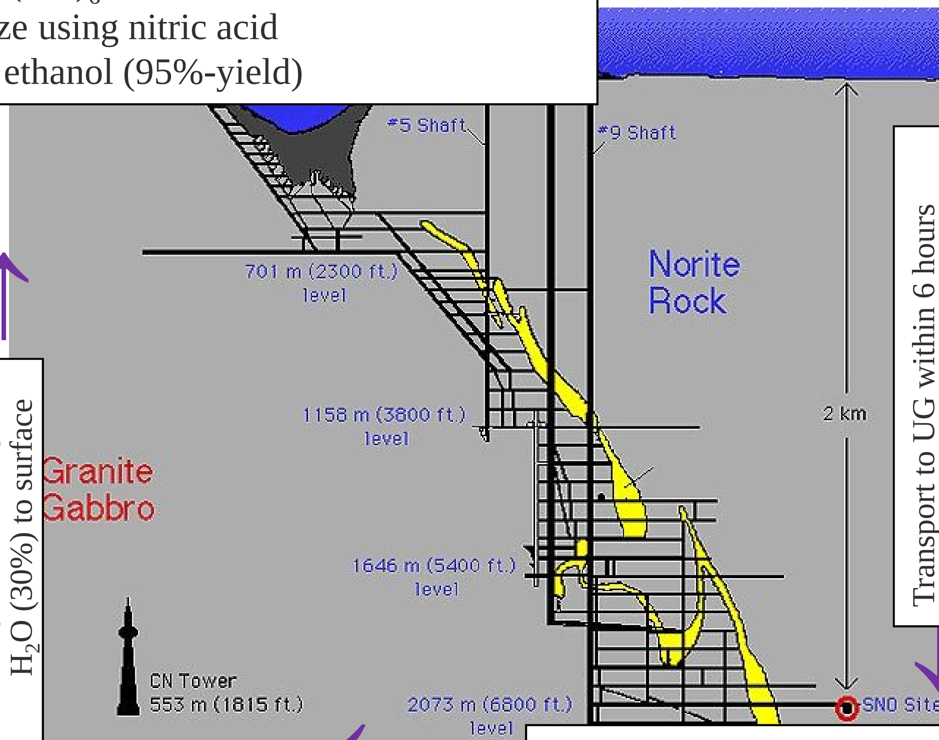
Optical is also improved after purification



Purification Scheme for Te deployment

Surface Facility (Acid-recrystallization/EtOH wash)

- Dissolve $Te(OH)_6$ in water
- Recrystallize using nitric acid
- Rinse with ethanol (95%-yield)



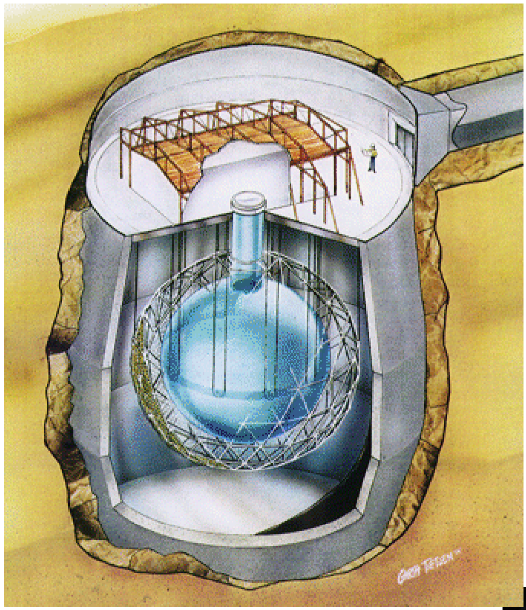
Transport to UG within 6 hours

- Recycle remaining Te-H_2O (30%) to surface

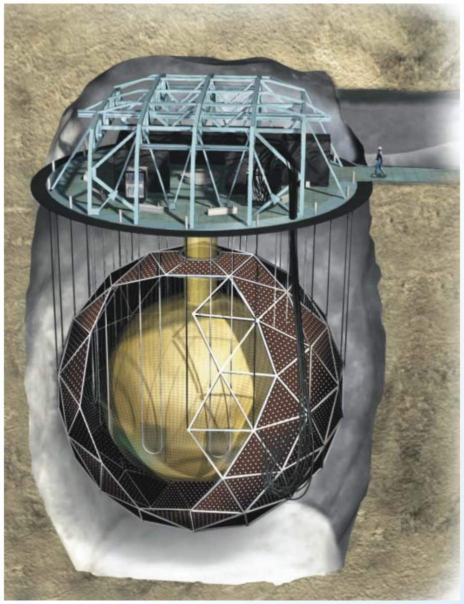
Underground Facility (Thermal-recrystallization)

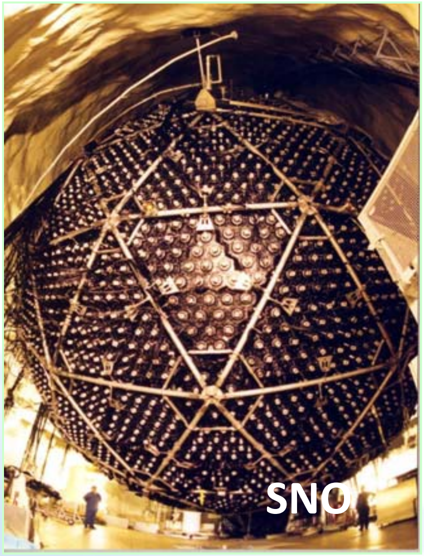
- Dissolve purified $Te(OH)_6$ in 80^{o}C water
- Recrystallize using cold water
- Filter $Te(OH)_6$ refined crystal (70%-yield) for storage; then production

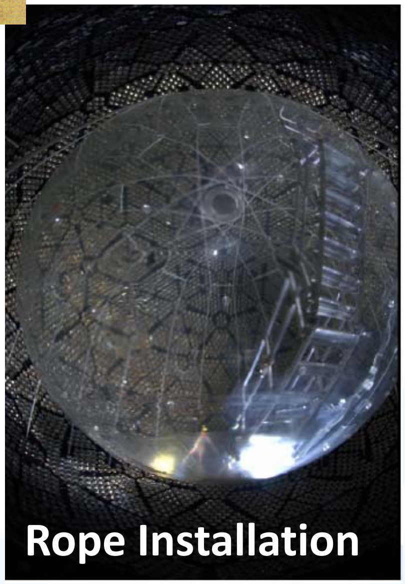
From SNO to SNO+



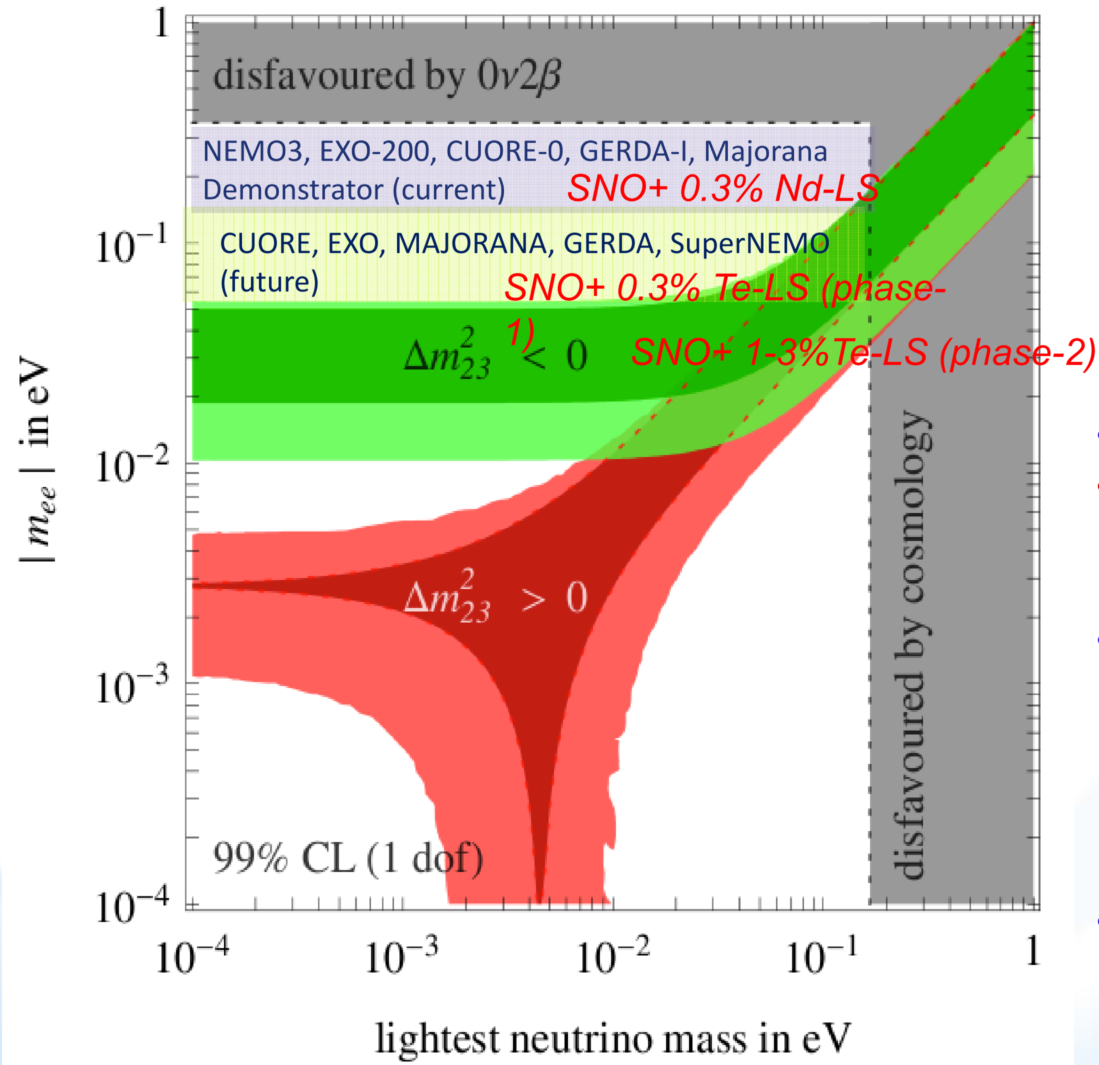
- 800 tons of LAB
- Advantages in size and depth relative to other scintillation detectors
  - resolution not competitive with solid-state detectors; but fixed external bkg (exchangeable)
- Profound physics
  - $0\nu\beta\beta$, solar ν, Geo-ν, Supernova ν
- Progressing…
  - AV cleaned
  - PMT and electronics updated
  - Process and purification installation
  - Water filling
  - …etc

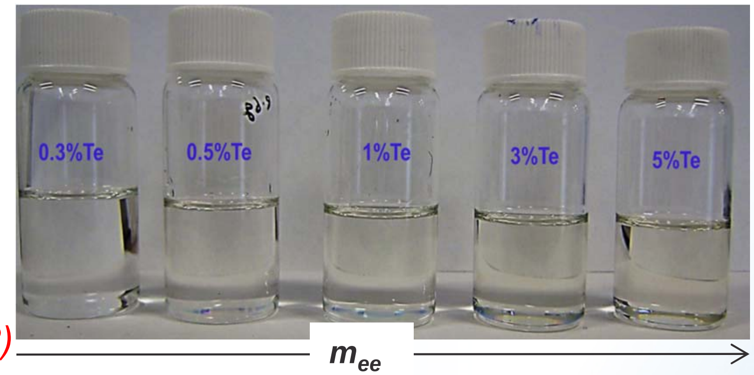






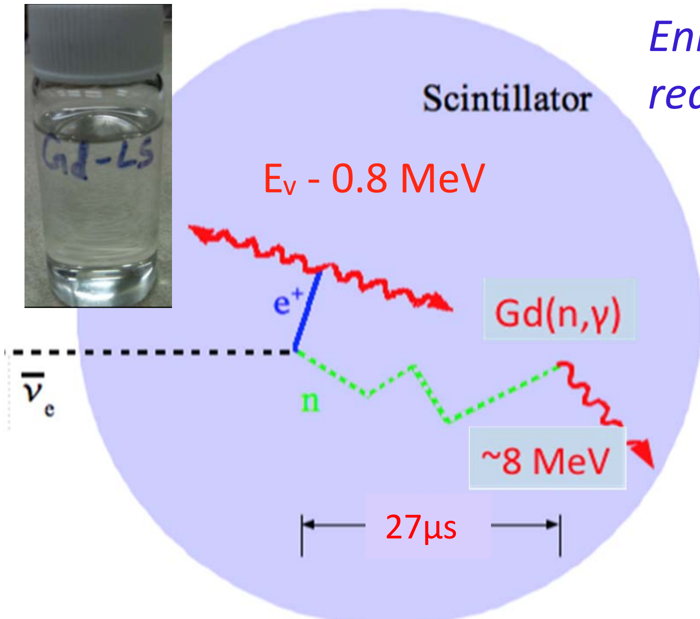
SNO+ 0νββ search is moving…





- 0.3% Te is the baseline
- Scintillator filling in 2015; followed by Te loading and data taking in 2016
- A ton-scale 0νββ detector in the near future
  - loading technique R&D continues
  - 0.6%Te loading is enabling; >1% loading need to optimize the light-yield and optical
- How to reach the discovery region (below 20 meV)?
  - LAB → 0.3% Te-LAB → remove or add more Te → 1~3%Te-LAB

Reactor Neutrino Experiment

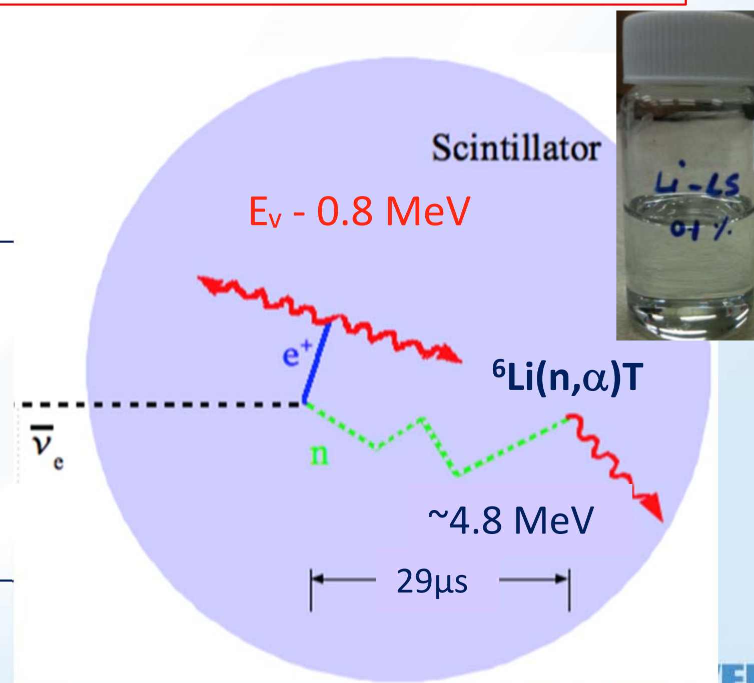


Enhanced measurement of delayed neutron via $\bar{\nu}_e$ IBD reaction by adding:

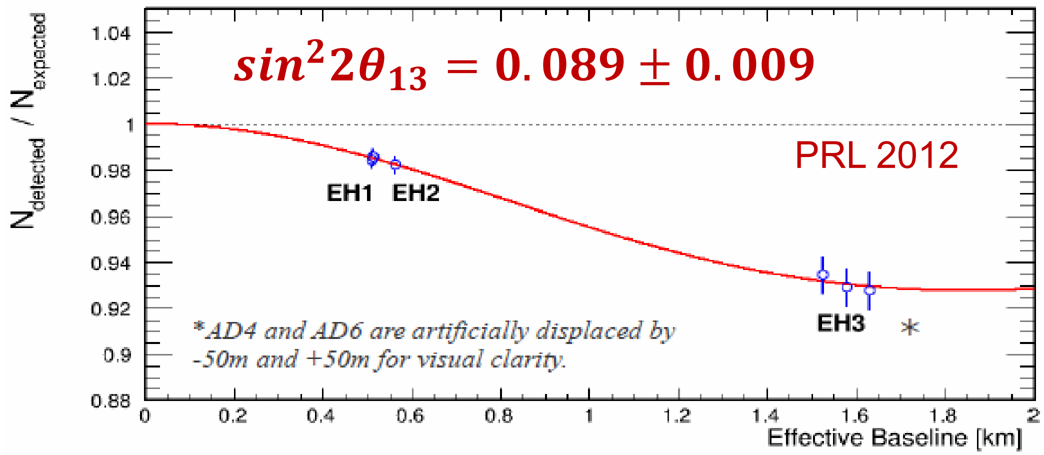
$\mathbf{n_{th} + {}^{A}Gd \rightarrow {}^{A+1}Gd + \gamma's\ (\sigma\sim 55,000\ barn):}$

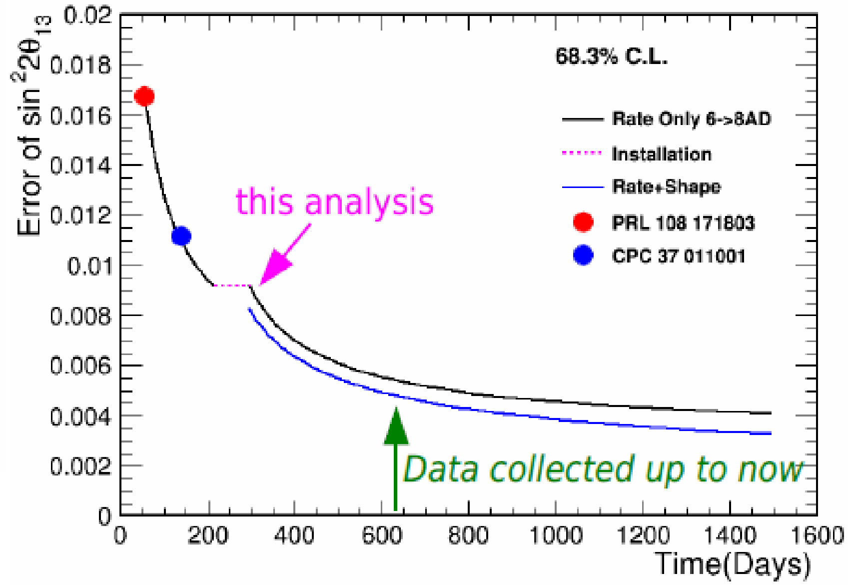
- S% of ~10,000 optical photons /MeV and $\lambda_{1/e}$ at ~20m (need R&D of background rejection).
- Stability demonstrated by Daya Bay experiment.

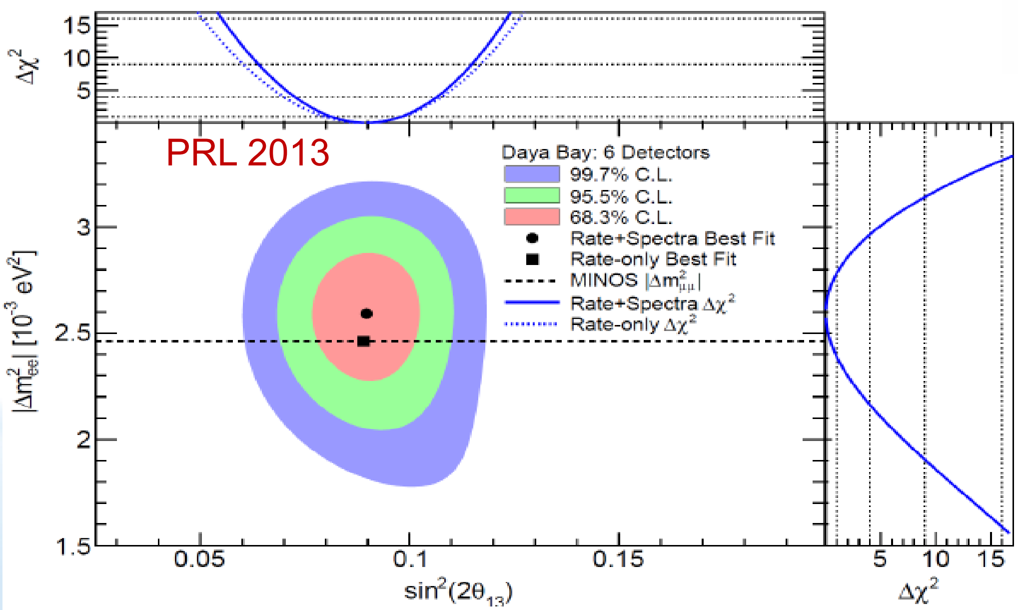
- $\mathbf{n_{th} + {}^{6}Li \rightarrow \alpha + {}^{3}H\ (\sigma\sim 940\ barn):}$
  - S% of ~5,000 optical photons /MeV and $\lambda_{1/e}$ at 2.6m (i.e. Bugey-3).
  - Stability degraded in few months of deployment (**needs R&D's**).



Daya Bay Rate Only & Rate + Shape





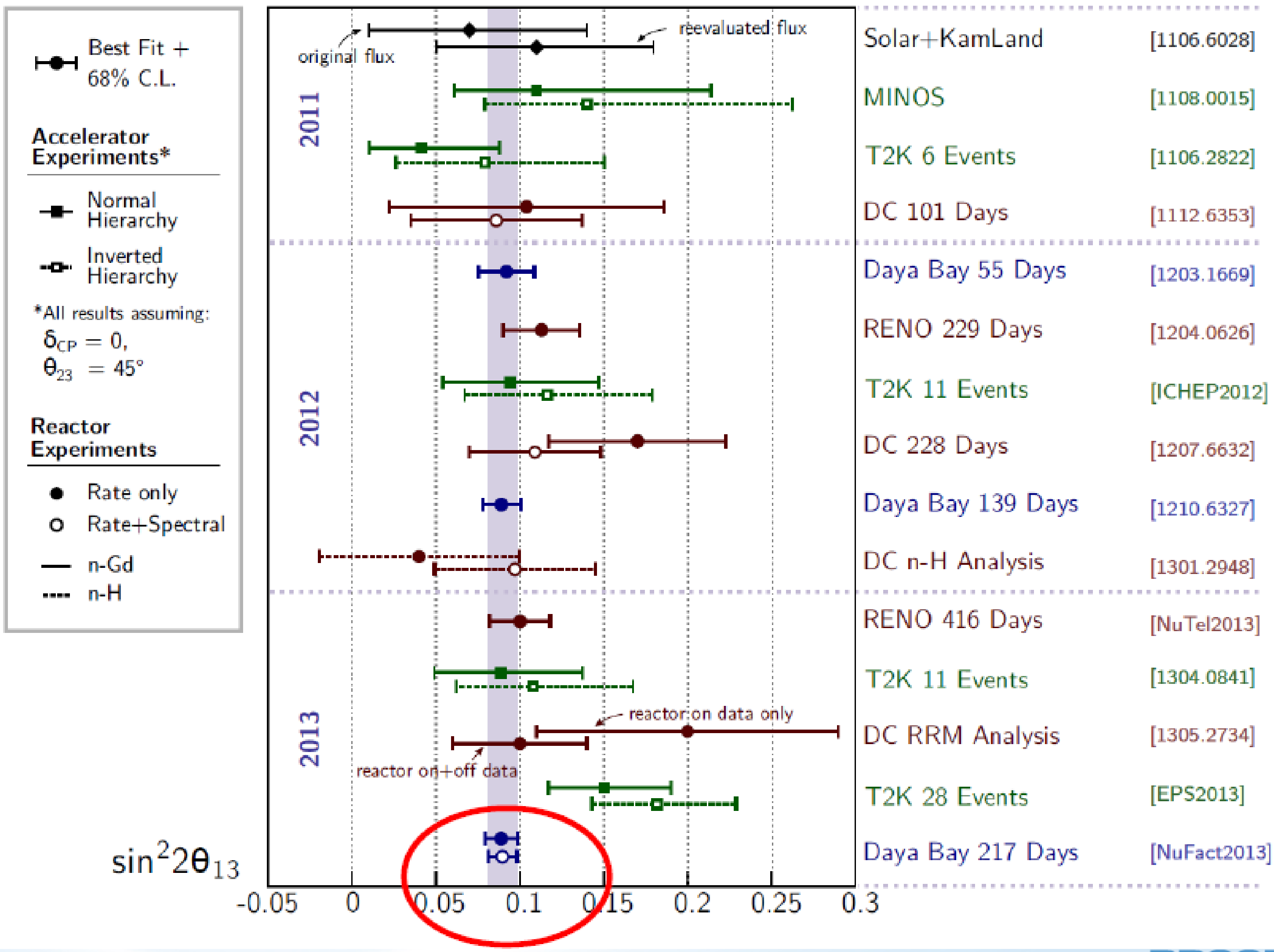


$$sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

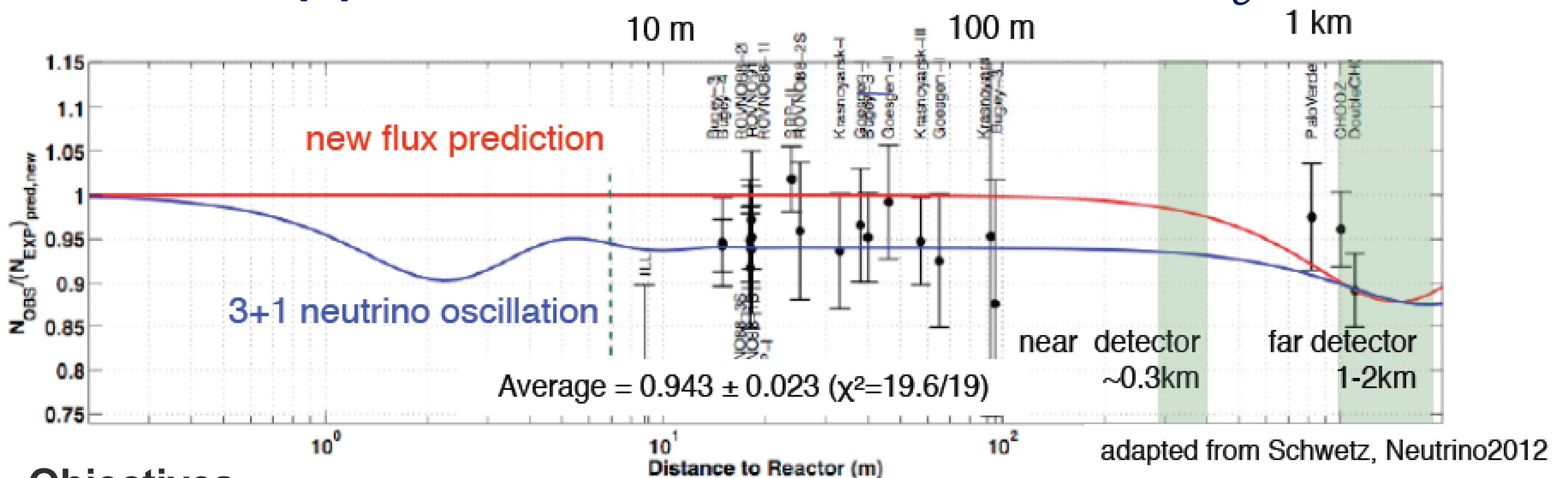
$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3} (eV^2)$$

- strong confirmation of oscillation hypothesis
- consistent with MINOS results
- still statistics dominant (73%)
- **absolute $\overline{\nu}_e$ flux to address anomaly**

Global Comparison of $\sin^2 2\theta_{13}$ Results



WbLS App: Short Baseline Reactor $\bar{\nu}_e$



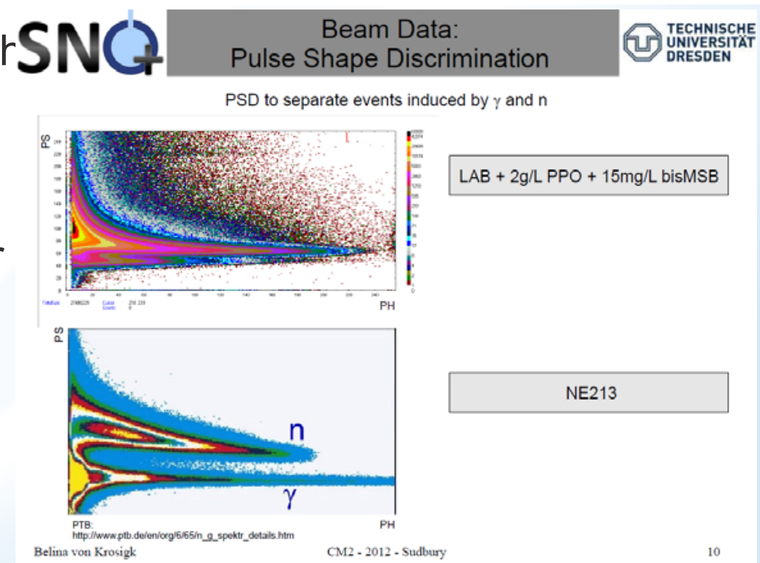
adapted from Schwetz, Neutrino2012

Objectives

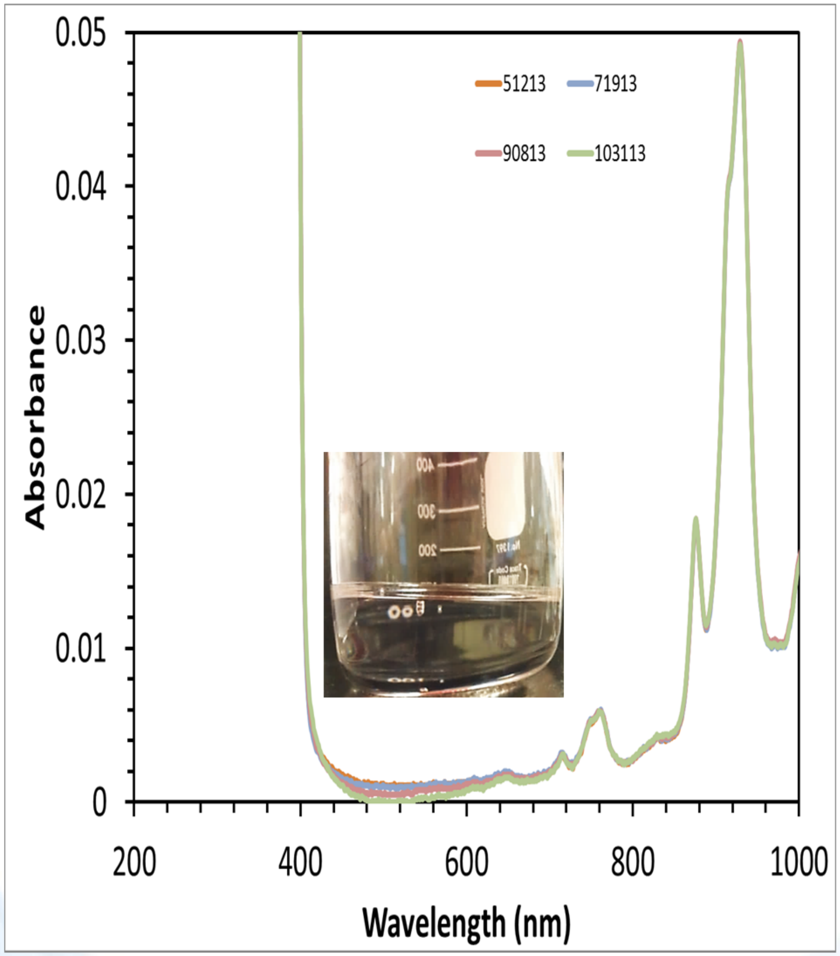
- short-baseline neutrino oscillation search with high sensitivity, probe of new physics
- test of the oscillation region suggested by reactor anomaly and $\bar{\nu}_e$ disappearance channel
- precision measurement of reactor $\bar{\nu}_e$ spectrum for physics and safeguards

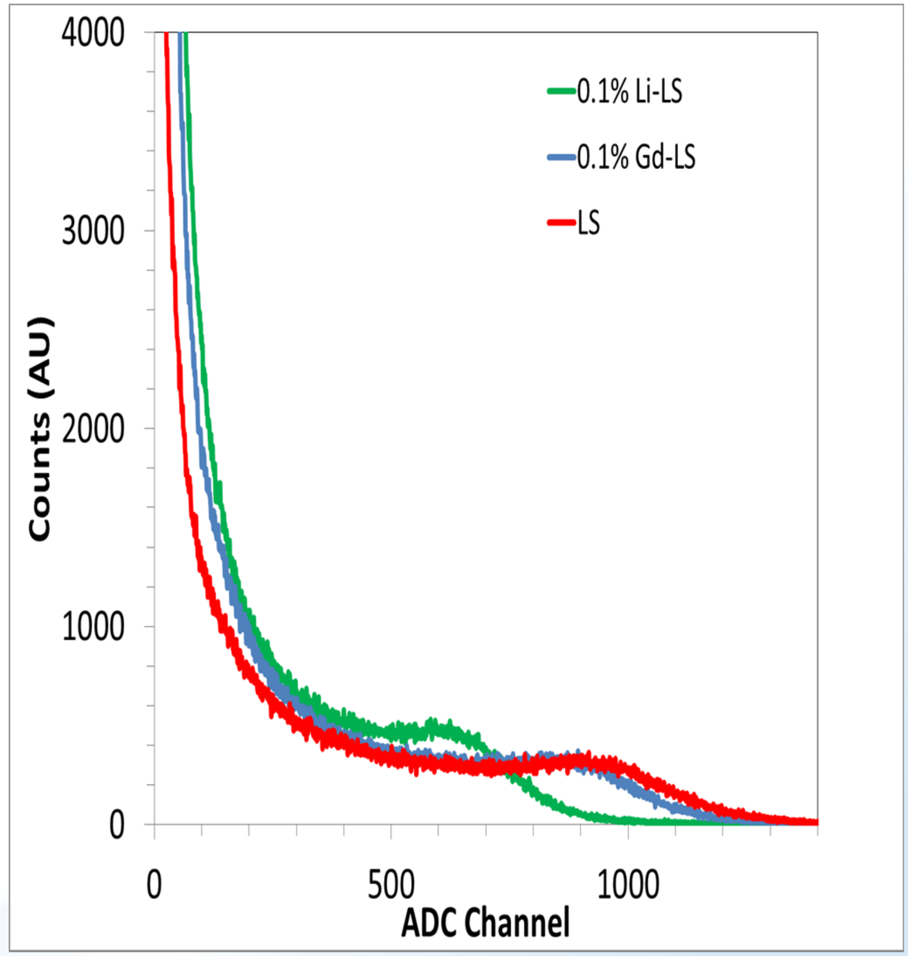
Challenges

- Reactor-related neutron and cosmic-muon shielding and rejection.
- Li-doped LS stability (degraded in few months for Buger-3).



Lithium enabling in LAB

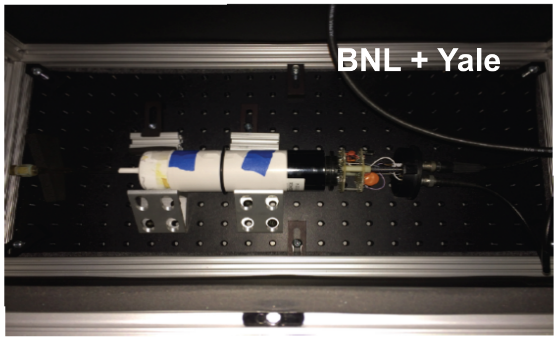


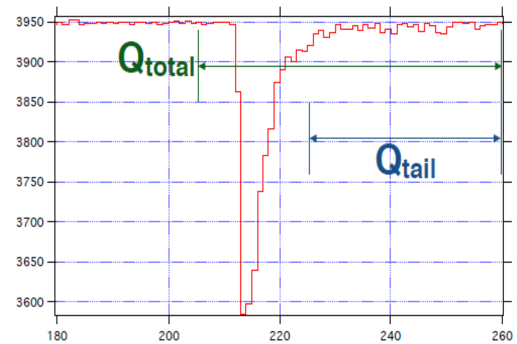


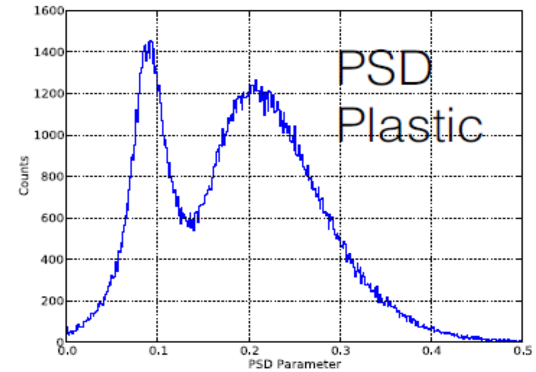
- Li-LS stable over >1 year since preparation
- Optical is better than Bugey-3

- Gd-LS at ~10,000 optical photons per MeV
- Li-LS at ~6,000 optical photons per MeV

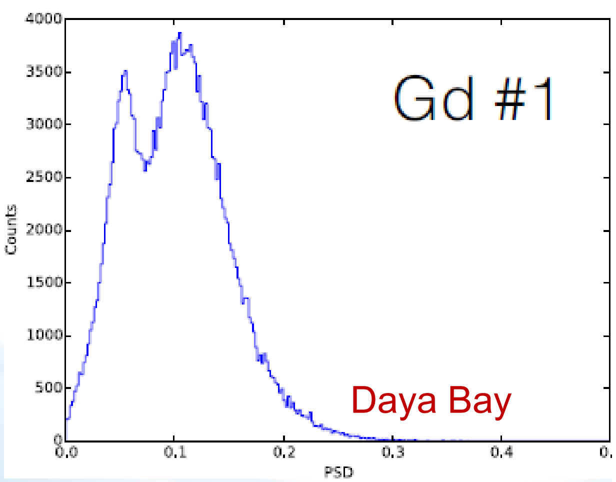
Pulse Shape Discrimination

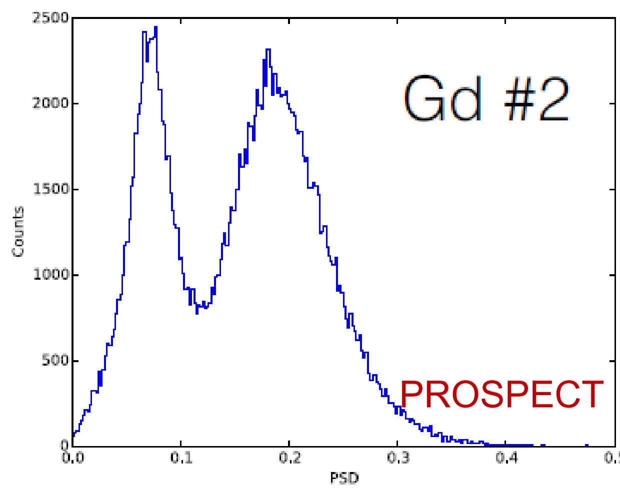






- Initial test for Gd- and Li-doped LS at Yale
- Cf-252 collect mixed γ and n events; triggering on a delayed coincidence between two signatures
- Capture time measurement in progress





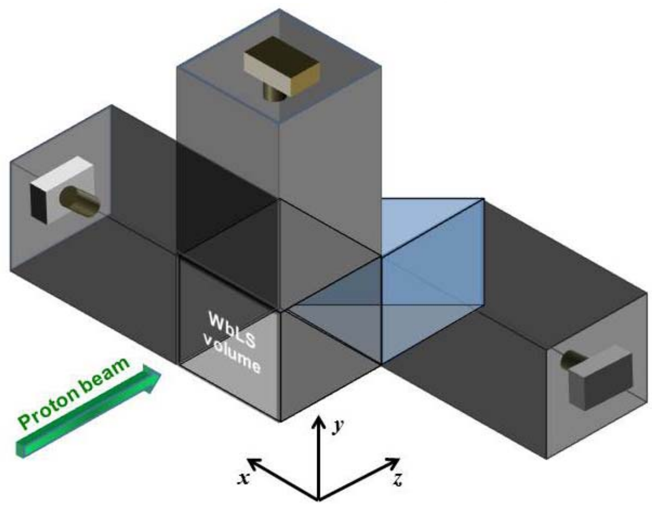
PSD enhancement for 0.1% Gd-doped LS over 6 months; and further improvement can be achieved

PROSPECT

- Development of Gd- and Li-doped LS continues
- Plastics scintillator is another possibility
- Background investigations at three different reactor sites
- Large scale cell test to be deployed for prototyping test (in preparation)

WbLS App: 3-D Imaging for Medical Physics

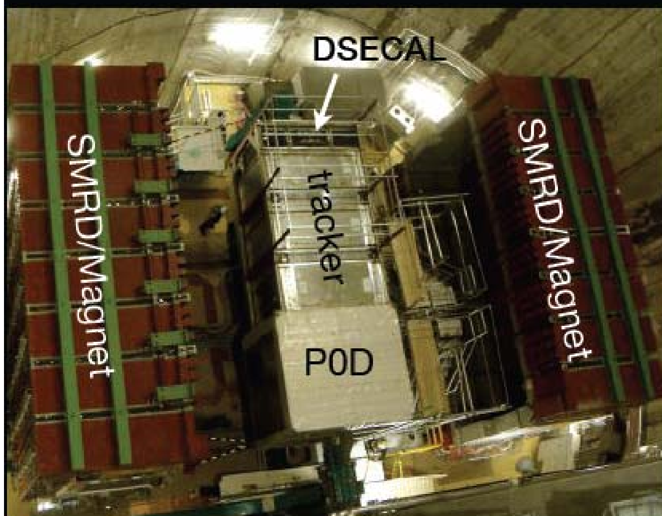
- proton beam therapy enables more precise, delivered radiation dose; especially important for tumors in close proximity to vital healthy organs.
- better match to tissue properties providing a medium more familiar to dosimetrists and medical physicists, who plan treatments in terms of water-equivalent depth.
- Better combustibility and chemical hazard issues with conventional liquid scintillator.
- a much longer attenuation length, and therefore presumably significantly less resolution deterioration from light scattering in the medium.
- less confusion from background Cerenkov light (the proton beam energy itself is well below the Cerenkov threshold, but knock-on electrons can produce some Cerenkov radiation).



The WbLS volume would be viewed (see Fig. 1) by CCD cameras from three orthogonal sides to provide three simultaneous two-dimensional projections of the light generated by the energy deposition of the proton beam stopping in the scintillator.

- SBIR
  - very strong science and technology review in 2013 (luck of IP agreement and patent protection)
  - will resubmit in 2014
- BNL OTCP proposal call

WbLS App: T2K-ND280



Tracker: 3 TPC/2 FGD

FGD: scintillator tracker with ~1x1 cm^2 bars target/H_2O mass with tracking of particles

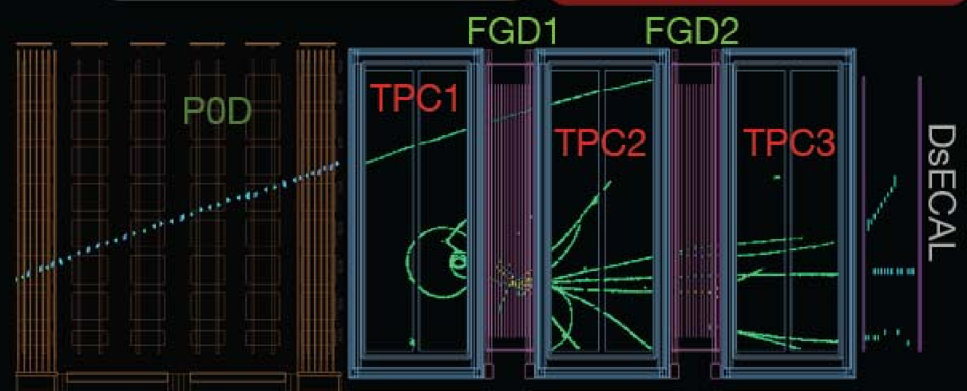
TPC: Precise kinematic reconstruction of tracks with 0.2 T magnetic field
Particle ID for ν_e (~10^3 rejection of μ)

ECAL
Pb/scintillator tracking calorimeter for γ recon e/μ/π identification

SMRD:
scintillator planes instrumenting magnet yoke for μ detection

P0D (π^0 Detector)
scintillator/(brass/Pb) tracker with H_2O bags optimized for photon reconstruction

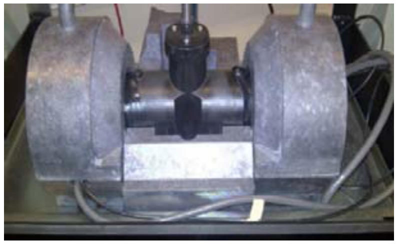
Magnet
Refurbished UA1 magnet provides 0.2 T field

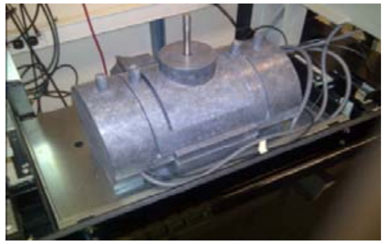


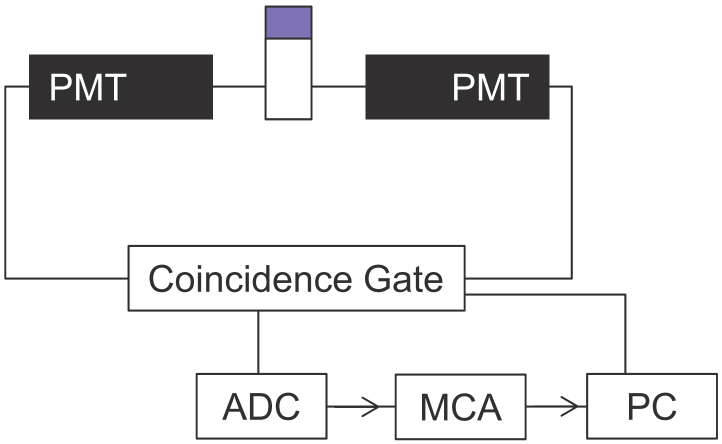
A new water target for T2K ND280

- Since the target for SK where neutrino oscillations are observed is H_2O, near detector measurements on H_2O are also essential
- ND280 currently has two means of measuring H_2O interactions via subtraction analyses; both are **passive** targets
  - P∅D: large scintillator tracking detector with water bags that can be filled/empty
  - FGD: two detectors, one fully active scintillator (~CH) and one alternating active scintillator and passive H_2O modules.
- An **active** H_2O target from WbLS will allow:
  - Improving reconstruction within the scintillator tracking detectors
    - better efficiency/resolution for tracking.
    - better background rejection from pion tagging, etc.
    - better resolution for showers, etc. in π0 reconstruction, etc.
  - vertexing in the water volume, enhancing the need for subtraction, also will help with rejection of external backgrounds
- Heavy water-based liquid scintillator to isolate the scattering of neutron bound in D by D_2O-H_2O subtraction analysis?

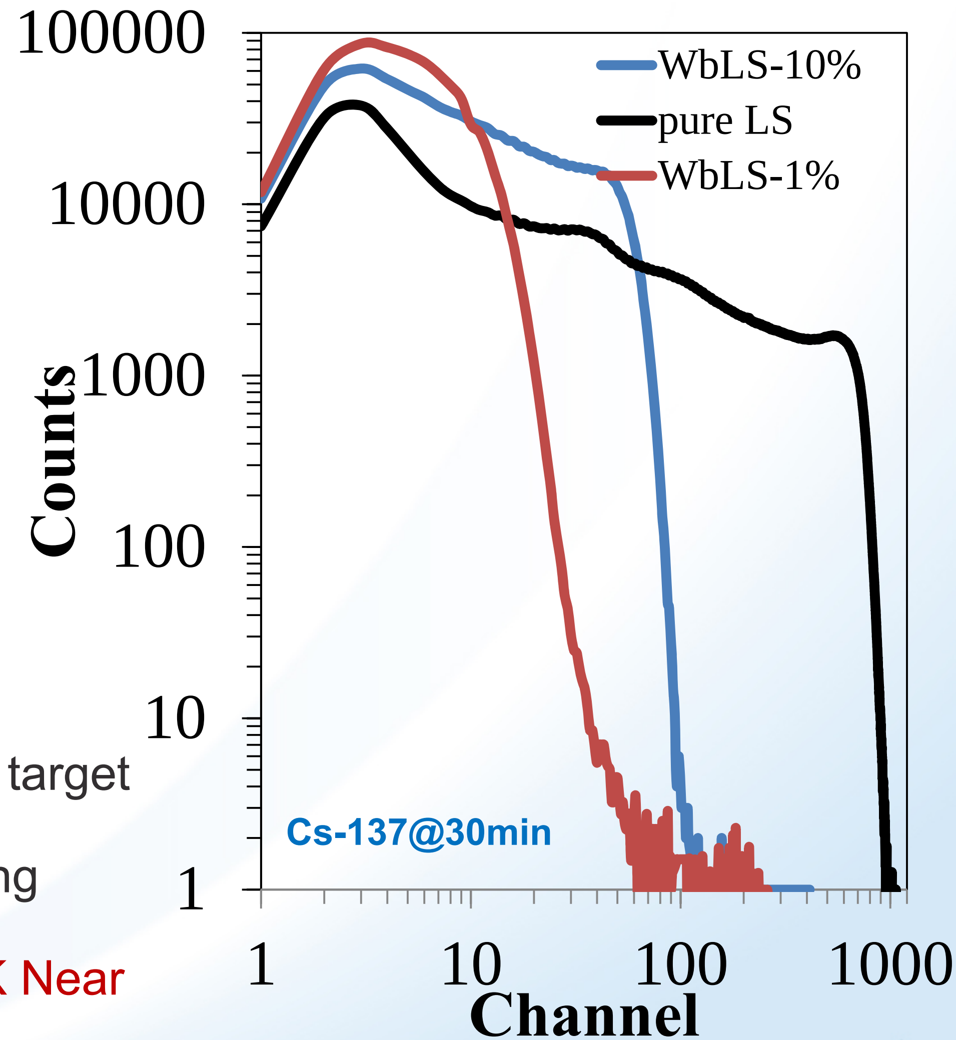
Higher loading (>10%) WbLS for P0D and FGD





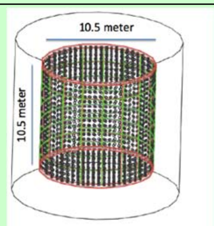
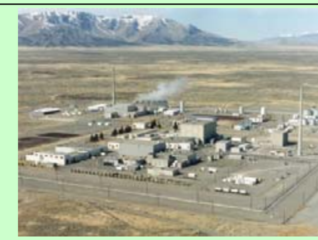


- Optimizing light-yield for ~70% H_2O target
  - First prototype at ~1500 o.p./MeV
- Ongoing material compatibility testing
  - WLS fibers, cell, reflector,…,etc.
- A potential detection medium for HK Near (US-Japan joint R&D)?



WATCHMAN

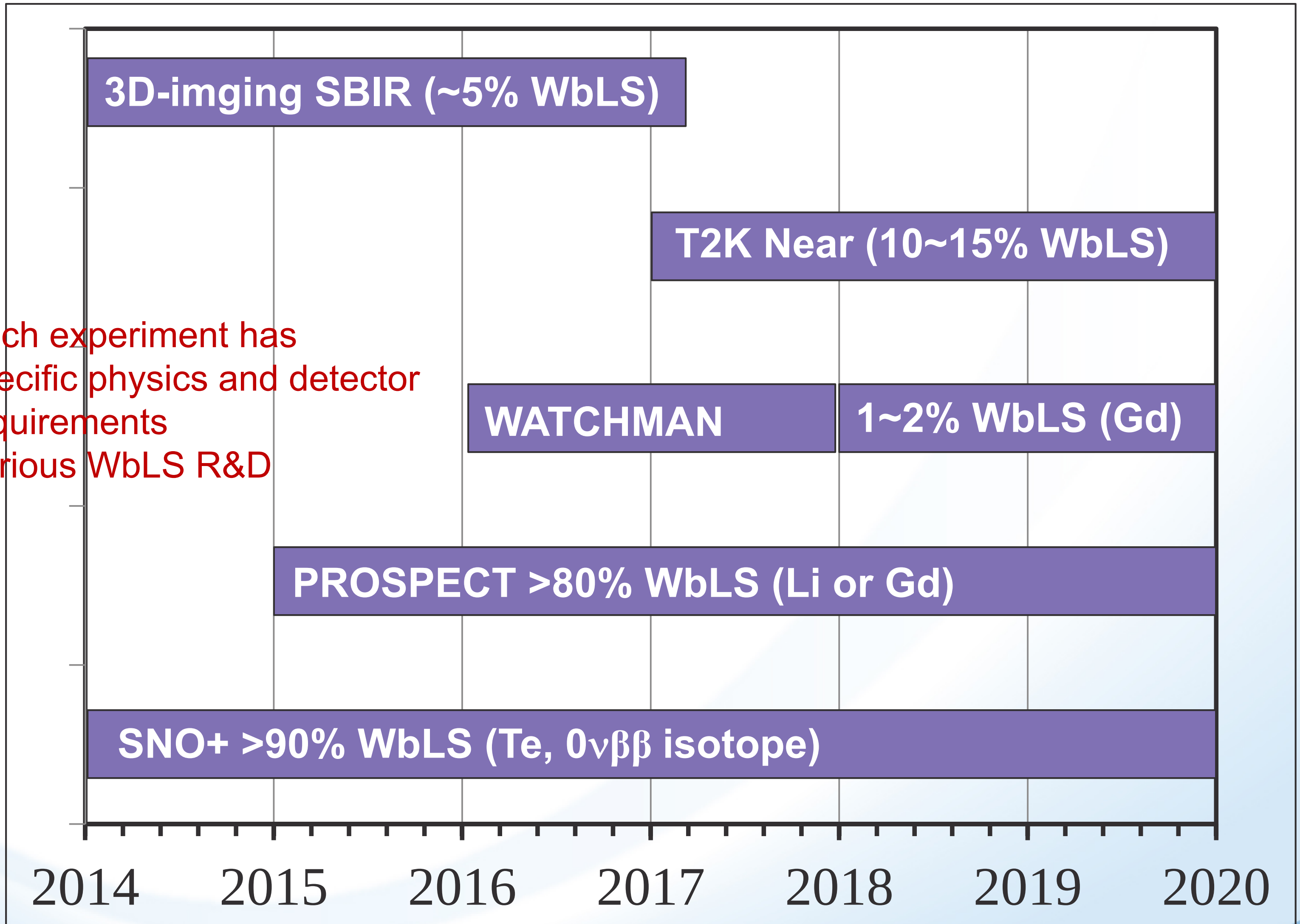
Bernstein 2013

	Preferred	Backup
Reactor Location	PERRY Reactor Perry Ohio	Advanced Test Reactor, Idaho Falls, Idaho
Thermal Power (MWt)	120	3875
		
Detector Location	Morton Salt/IMB mine (!) Paynesville, Ohio	New excavation Idaho National Laboratory
Standoff	13 km - the only reactor in the US at a suitable distance from a deep mine	1 km
Overburden (mwe)	1670	~360
Approval status	Morton Salt has approved installation – assuming cost-neutral and no disruption to mining activities	INL senior management have approved excavation studies – enthusiastic support
Physics potential	Greater physics potential due to greater depth	

WbLS App: WATCHMAN

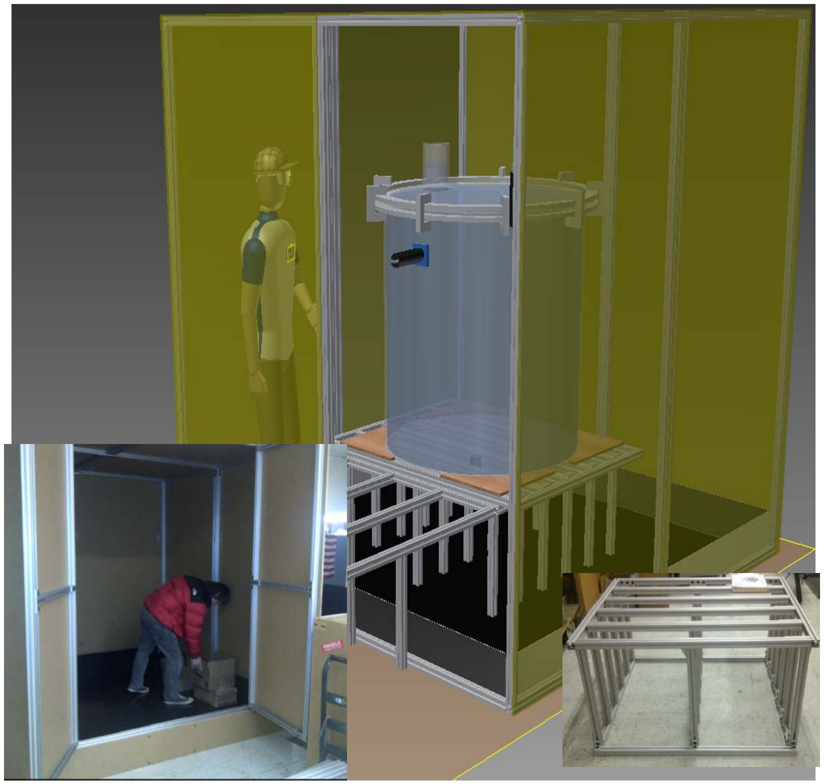
- NA-supported for Phase-I (Gd-water) reactor $\overline{\nu}$ monitoring; seeking inputs from SC-HEP for Phase-II (Gd-WbLS) physics program.
- Enhancement of other physics reaches for supernova, geo-$\overline{\nu}$, sterile neutrino, non-standard interactions, etc. via scintillation mode.
- This $p \rightarrow k^{+}\overline{\nu}$ search can be tried in the WbLS phase (~5 times more efficient for this SUSY mode, equivalent to that expected for LAR TPC's
  - after five years in WbLS phase, WATCHMAN would achieve ~5×10^{32} years using direct K+ detection.
- An input for (future) large Cerenkov detector (SK, HK-near).
- R&D of water circulation system
- Bernstein, Svoboda, and Yeh briefed at DOE in Oct. 2013.

WbLS to Ongoing and Future Experiments…



- Each experiment has specific physics and detector requirements
- Various WbLS R&D

Summary and Onwards



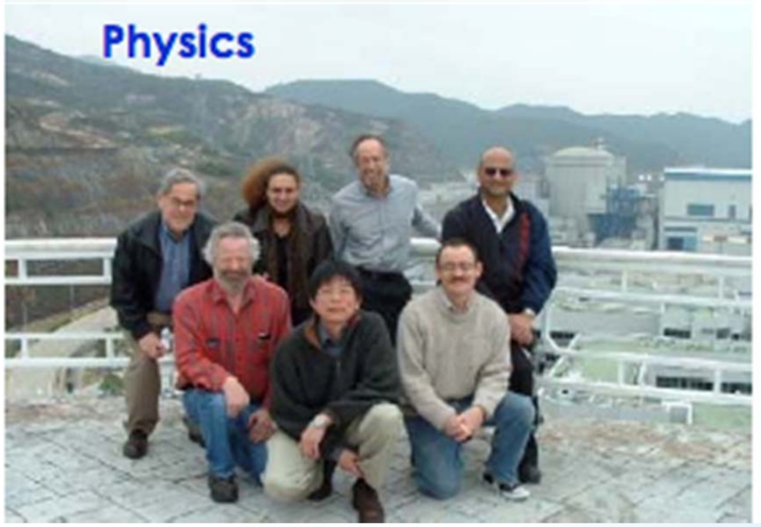
Vessel + Water + Structures -> 1500 kg = 3300 lb Maximum
18 Table Legs @ 2.25 sq in each -> 40.5 sq in total
Gives 183.3 lb per table leg or 81.5 lb per sq in at each leg
This is spread over the shown 43" x 43" (1860 sq in)area

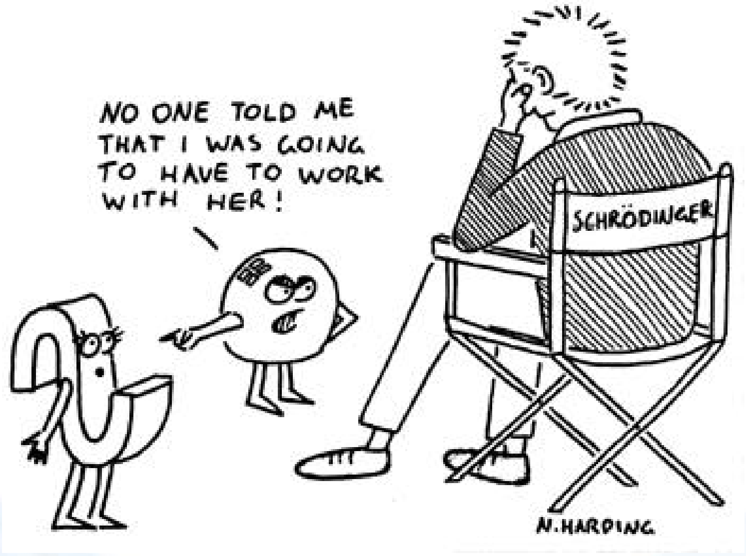
Conceptual design is completed; dark room and supportive structure built; 1-ton acrylic tank ordered; DAQ under development; PMT and electronics ready

- The principal of WbLS has been proven (measured by proton beams and calibration sources)
- Continuing R&D's toward the physics requirements for ongoing and newly proposed experiments (mainly SNO+, PROSPECT, T2K, WATCHMAN) and for medical applications (SBIR + patents)
- **1-ton WbLS prototype**
  - 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 calibration sources
  - **Slow scintillator**
  - **Circulation system test?**

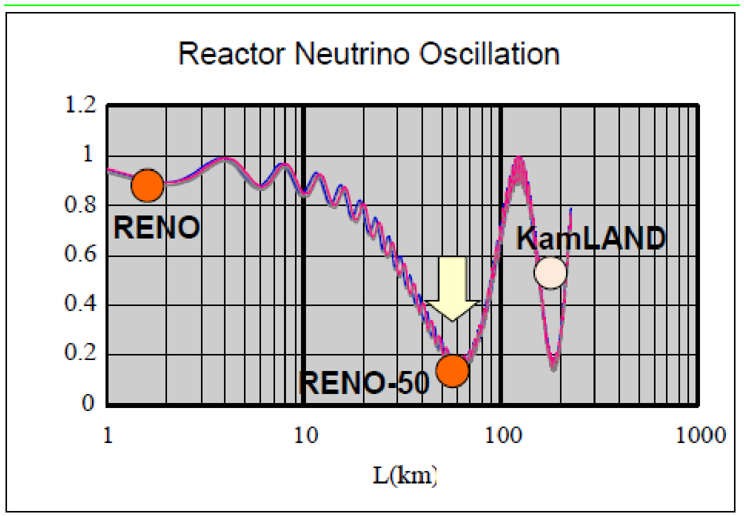
Acknowledgements

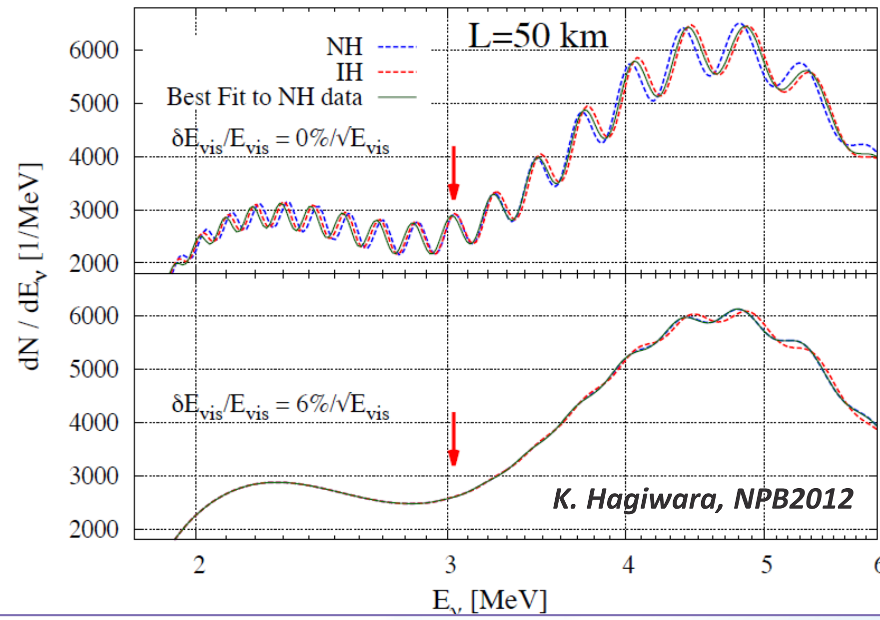
- A great synergetic team at BNL
- Supported by DOE-ONP/OHEP, LDRD

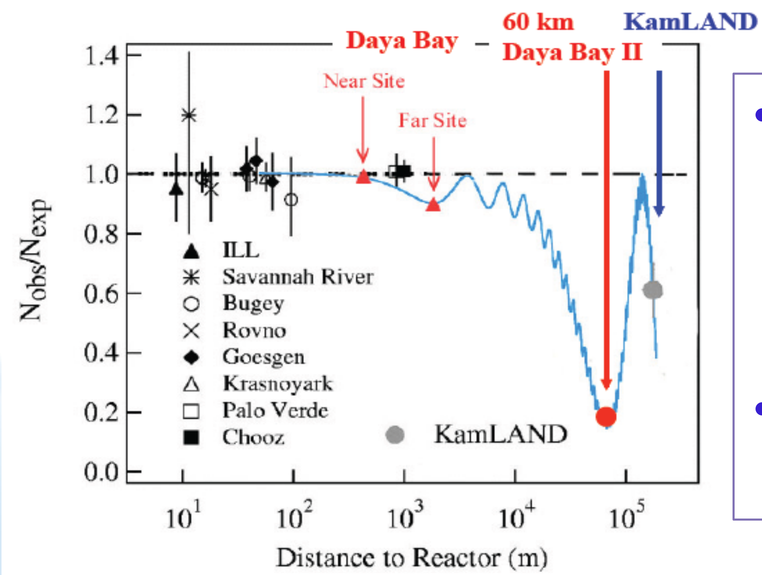




Challenges for Long Baseline Reactor $\bar{\nu}_e$





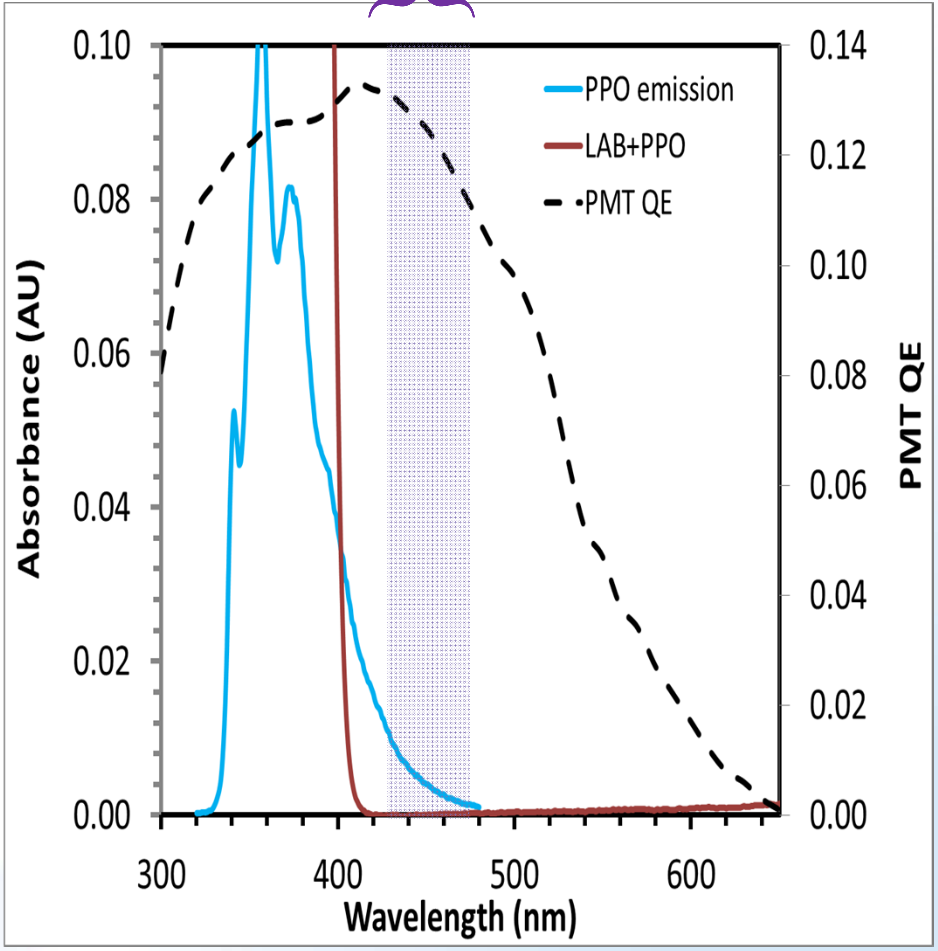


- *better than 3%/ $\sqrt{E}$:*
  - *high QE photo-coverage (LAPPD?)*
  - *$\lambda_{1/e}$ ~ 30m and Š% ~ 15,000 optical photons per MeV*
  - ***No known deployed scintillator can do.***
- *knowing the energy non-linear response to 1%*

Extensive Scintillator R&Ds

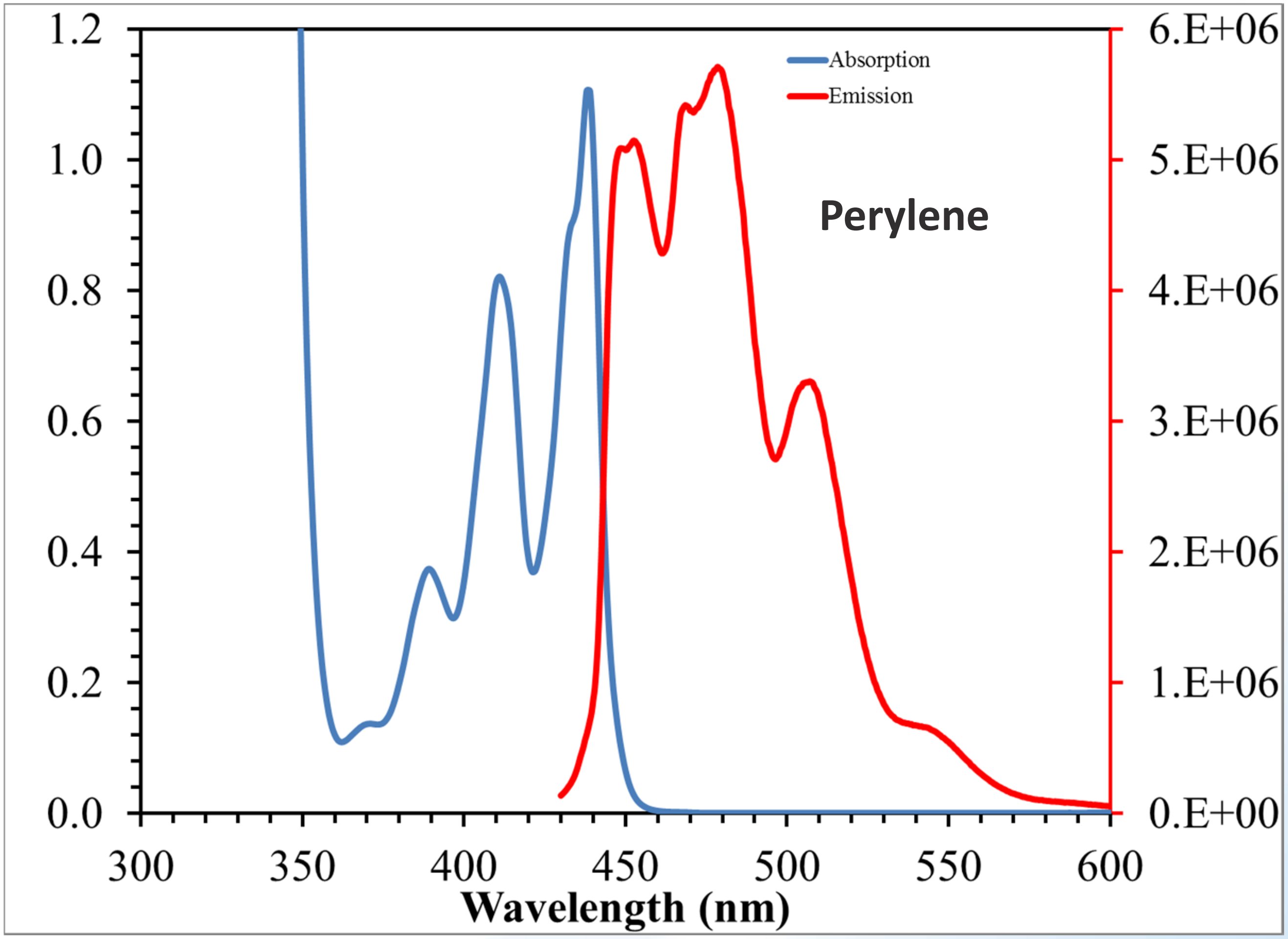
- *A new search for commercially available scintillator (c.f. LAB by SNO+)*
- *Extensive purification of LAB*
  - *Vacuum distillation*
  - *Exchange column*
  - *Still cannot boost up the light*
- *Loading short half-life β^+ or e^- sources in scintillator for energy nonlinearity study*
- *A WbLS of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

Window of opportunity



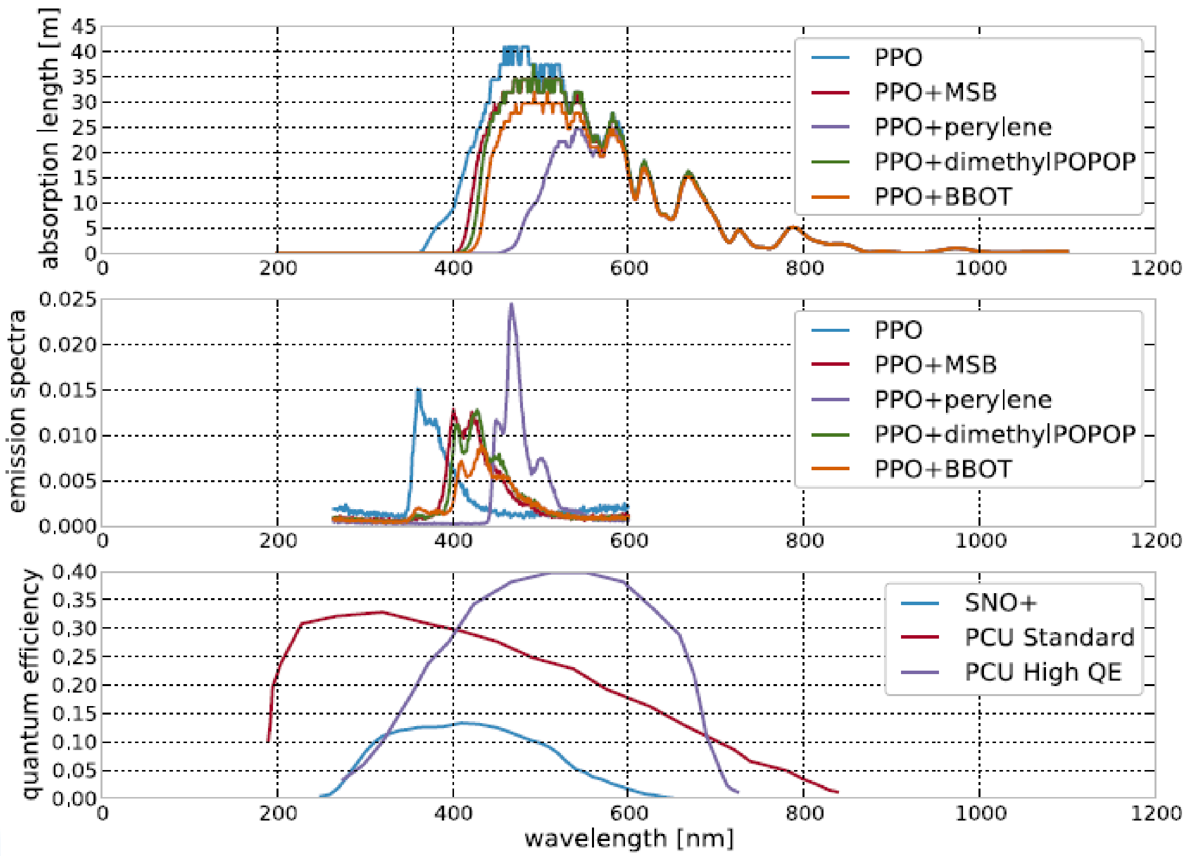
Large Stokes-shift to 440-460nm

Red-shift to Optical Transparent Region



Comparisons of Shifters and PMTs

We look at 5 different shifter combinations, and estimate light yield for 3 different PMTs. We assume a SNO+ geometry (6m radius sphere)



Solvent: LAB PPO: 2 g/L others: 15mg/L	
	Intrinsic Photon Yield
PPO	**1**
PPO + MSB	**0.94**
PPO + perylene	**0.94**
PPO + dimethylPOP	**0.93**
PPO + BBOT	**0.74**

x 10,000 photons/MeV

Red-shift if No Re-emission

Light Yield in PE/MeV, 6 m path length, 100% coverage

	SNO+ PMT	PCU Standard PMT	PCU High QE PMT
PPO	**368**	**978**	**1282**
PPO+MSB	**474**	**1131**	**1565**
PPO+perylene	**198**	**554**	**919**
PPO+dimethylPOP	**455**	**1110**	**1580**
PPO+BBOT	**322**	**794**	**1183**
	PE/MeV	PE/MeV	PE/MeV

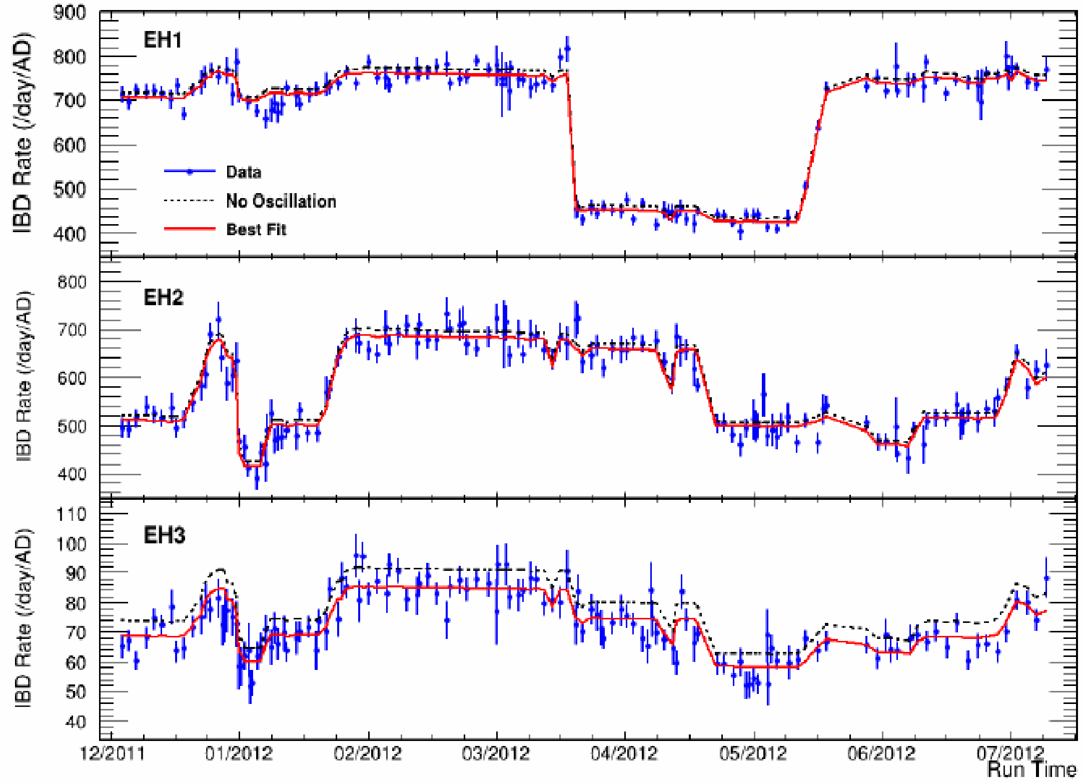
Red-shift if Total Re-emission

Assuming PPO+perylene same absorption as PPO+MSB

	SNO+ PMT	PCU Standard PMT	PCU High QE PMT
PPO	**368**	**978**	**1282**
PPO+MSB	**474**	**1131**	**1565**
PPO+perylene	**783**	**1891**	**2825**
PPO+dimethylPOP	**455**	**1110**	**1580**
PPO+BBOT	**322**	**794**	**1183**
	PE/MeV	PE/MeV	PE/MeV

Challenges of Reactor Safeguard

IBD rate is fully correlated with reactor flux expectations



- *Predicted rate assumes no oscillation*
- *Normalization is determined by fit to data*
- *Absolute normalization is within a few percent of expectations*

A large (portable) cost-effective $\bar{\nu}_e$ detector (i.e. Watchman, Hanohano) to survey geo-ν and monitor nuclear fuel usage.

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 per (ton-yr)*
  - *1-m ^{10}B-loaded scintillator + 4 m water give < 0.1 events per (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 easy to handle).*