Water-based Liquid Scintillator

Minfang Yeh

Neutrino and Nuclear Chemistry, Brookhaven National Laboratory

AAP-2014, Paris, Dec. 15-16, 2014

BROOKHAVEN NATIONAL LABORATORY

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Liquid Scintillator Physics

0νββ
(e.g. SNO+, KamLAND-Zen)

Reactor ν
(e.g. Daya Bay, PROSPECT, JUNO)

Other Applications
(e.g. Nonproliferation, source -ν, DM)

Common features between detectors

Liquid Scintillator
(Metal-loaded & Water-based)

unique requirement for individual detector

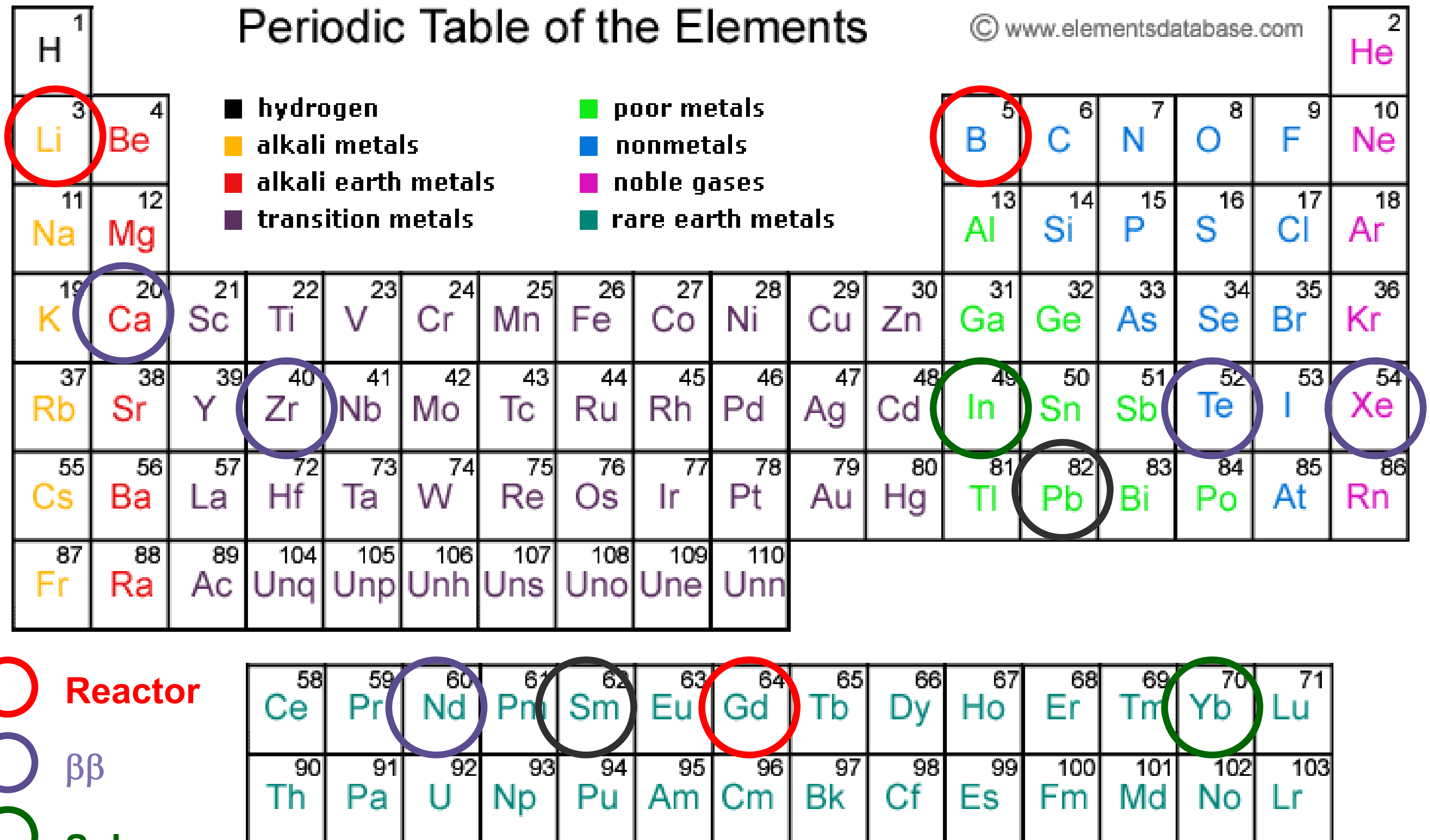
Ion-beam therapy & TOF-PET scan

Solar & Geo ν
(e.g. LENS, Borexino, KamLAND)

Accelerator Physics
(e.g. NOνA, T2K, SNS, MLF)

Isotope-doped Liquid Scintillator

for Neutrino Physics and Other Applications



Reactor

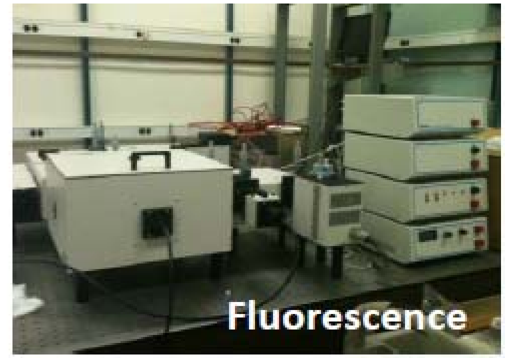
ββ

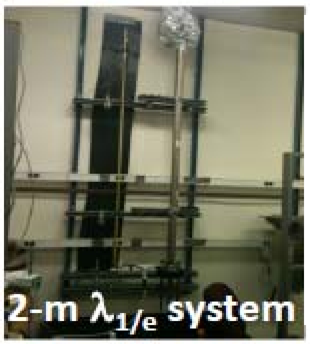
Solar

Others

Some are tougher than others!

BNL-Liquid Scintillator Development Facility

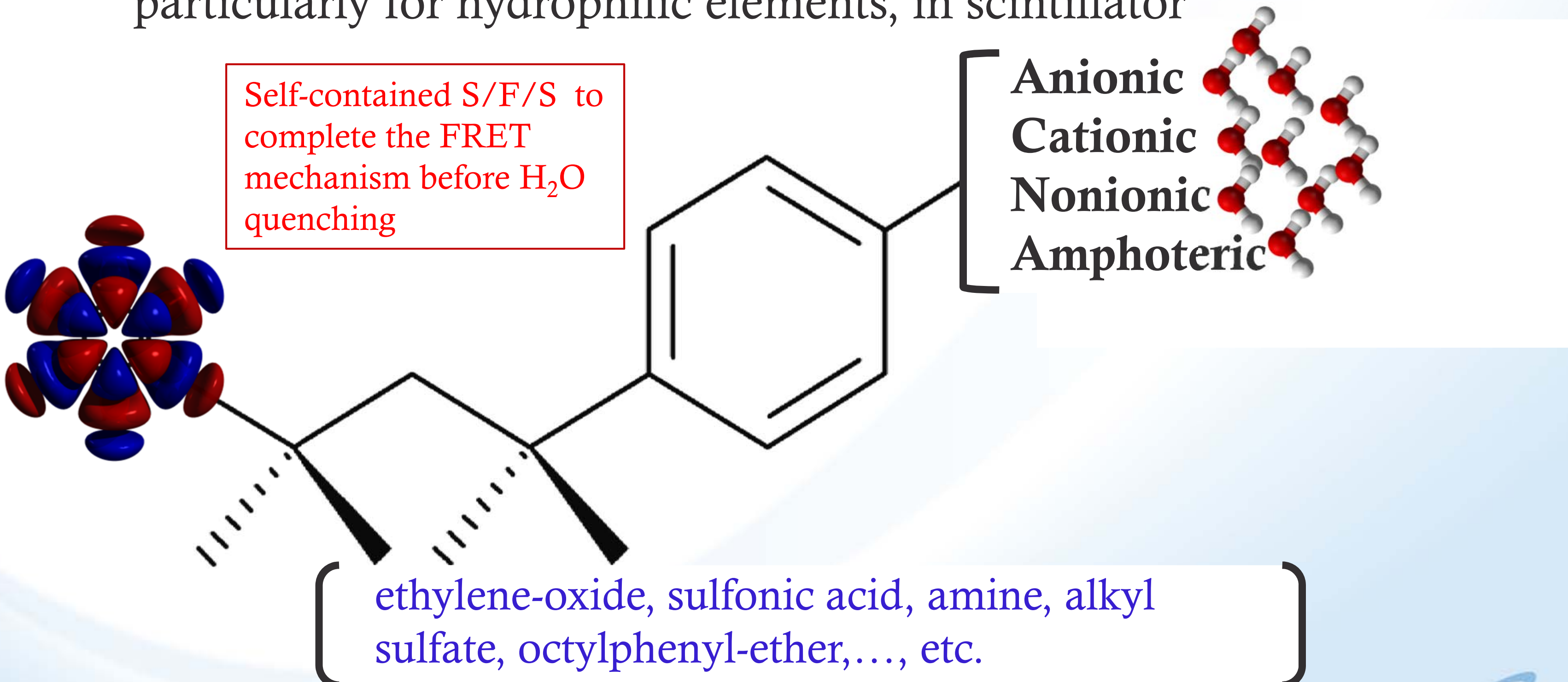




- A unique development facility (since 2002) for Radiochemical, Cherenkov, and Scintillator **(water-based and metal-doped)** detectors for particle physics experiments.
- **(LENS), Daya Bay, SNO+, PROSPECT, LZ, WATCHMAN, ASDC(?)**

Water-based Liquid Scintillator

- Tunable scintillation light from ~pure water to ~organic (LAB, PC, DIN, PXE, PCH, EJ309):
  - **Water-like** WbLS: A cost-effective scintillation water with Cherenkov and Scintillation detection
  - **Oil-like** WbLS: A novel technology for loading various isotopes, particularly for hydrophilic elements, in scintillator



Oil-like WbLS (Isotope Loading)

- Conventional method has been successfully applied to reactor $\bar{\nu}_e$ detection (e.g. Gd-LS)
  - mixing ligands are mostly quencher
  - difficult for hydrophilic isotopes
- WbLS provides a new method of doping hydrophilic metallic isotopes in scintillator

Lithium-doped scintillator detector

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

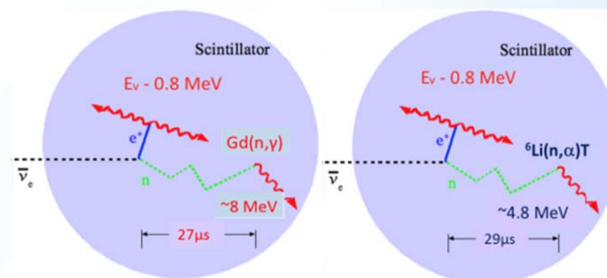
Tellurium-doped scintillator detector

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

Lead-doped scintillator calorimeter

- Solar neutrino
- Total-absorption radiation detector

Neutron Tagging



8-MeV γ's (Gd) vs. α,T (^{6}Li)

Solar Neutrino Targets

$^{115}In + \nu_e \rightarrow {}^{115}Sn + e^- + (\tau = 4.76\ \mu s)\ 2\ \gamma$ (LENS)

- High nature abundance at 95.7%
- Low Q value at 114-keV, sensitive to >95% pp continuum
- Triple coincidence allows tagging of ν_e event
- 6-8% loading with conventional organometallic technology

$^{208}Pb + \nu_e \rightarrow {}^{208}Bi^* + e^-$ & $^{208}Pb + \nu_x \rightarrow {}^{208}Pb^* + \nu_x$ (HALO)

- Abundance at 52.4%
- Bursts of neutrons via CC and NC
- Neutron detection by IBD reaction using scintillator (^{208}Pb is a double magic nuclei)
- Targeting 10% ^{nat}Pb using WbLS (aligned with medical applications)

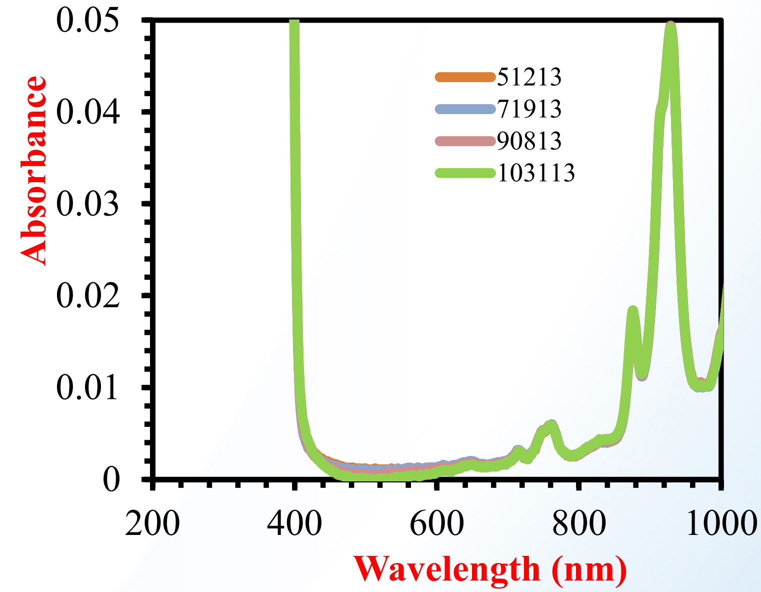
$^{7}Li + \nu_e \rightarrow {}^{7}Be + e^-$

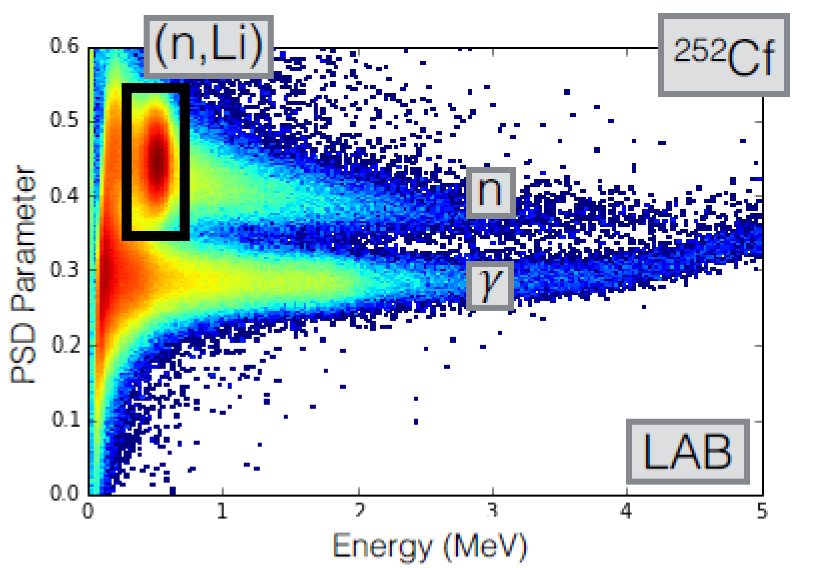
- group state (E_{thresh} = 0.861 MeV) and first excited state (E_{thresh} = 1.339 MeV)
- High abundance at 92.5%
- Conventional organometallic loading is not stable (e.g. Bugey-3)
- 1~3% loading using WbLS (aligned with short-baseline reactor experiments)

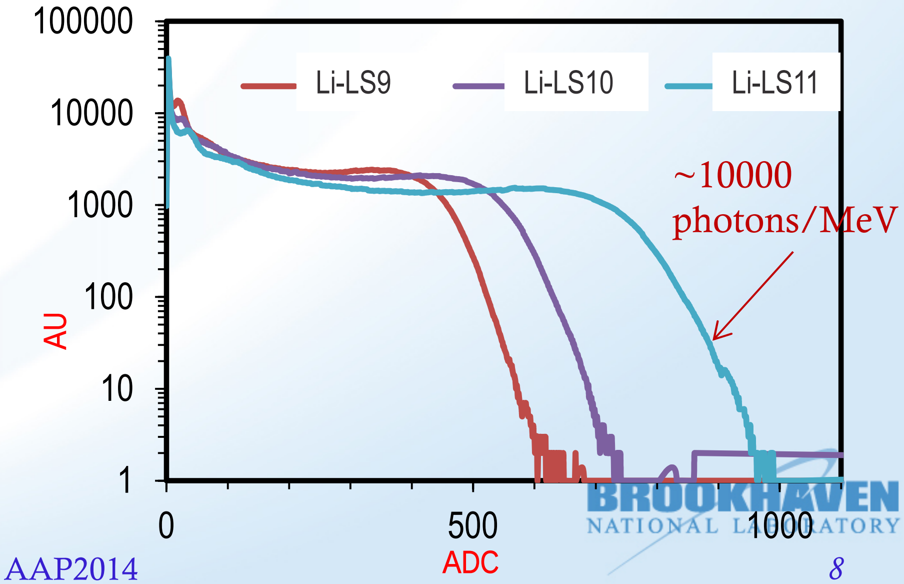
Few others: ^{11}B, ^{35}Cl, ^{31}P,…, etc.

^{6}Li-WbLS (PROSPECT)

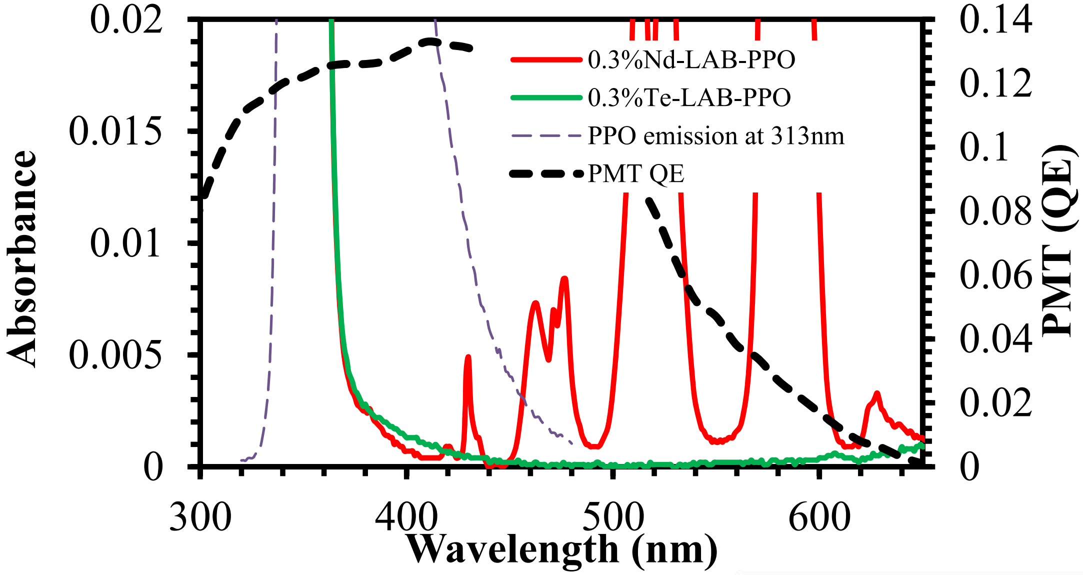
- A Li-doped LS that has been stable over 1.5 years (light-yield and optical better than commercial product) for PROSPECT
  - Gd-LS also performed well (but 8-MeV γ's)
  - Background investigations (20-L) at the selected reactor site
  - Plan to start full-scale 2-ton ND in 2015
- 2D-PSD to distinguish IBD events from
  - Cosmogenic fast neutrons
  - Reactor-related gammas
- Continue R&D for higher loading at ~0.15%

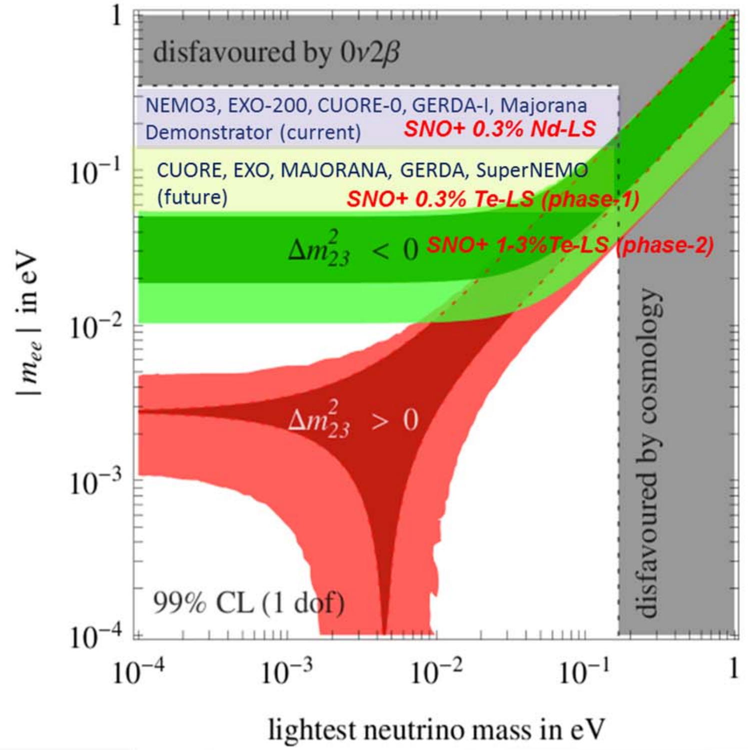


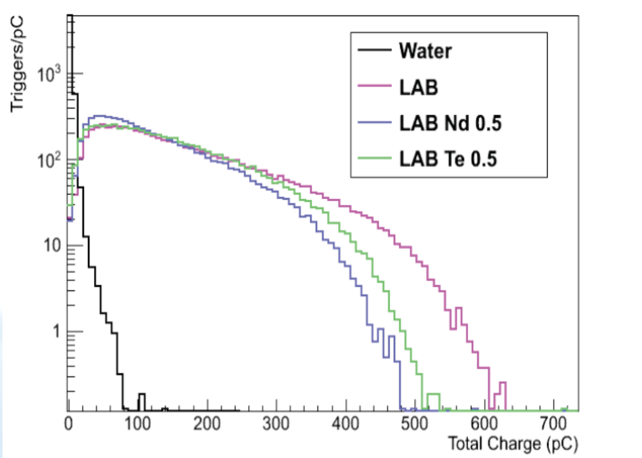




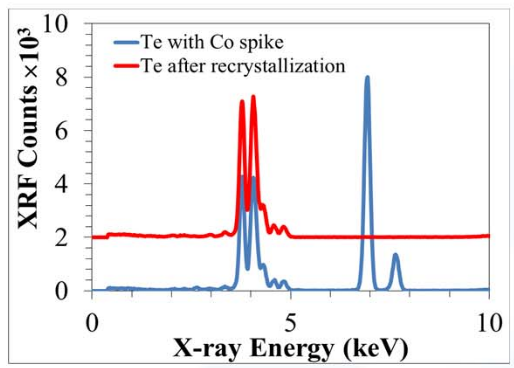
Te-WbLS (SNO+)

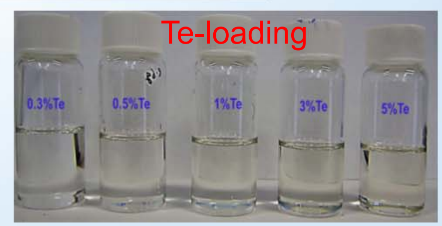






better light-yield and optical than Nd-LS

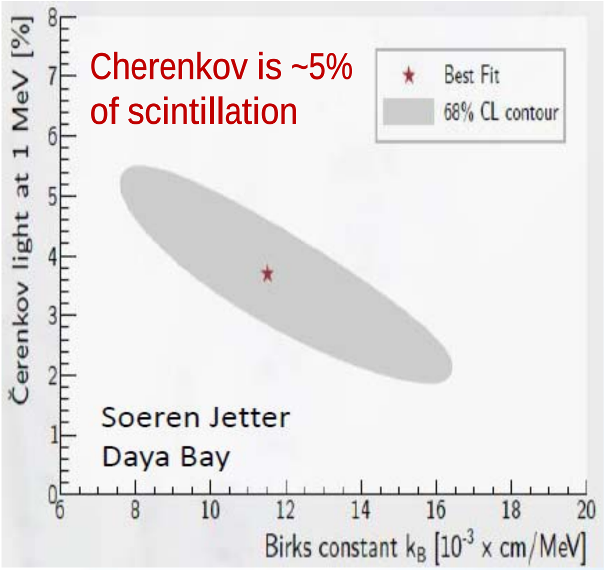


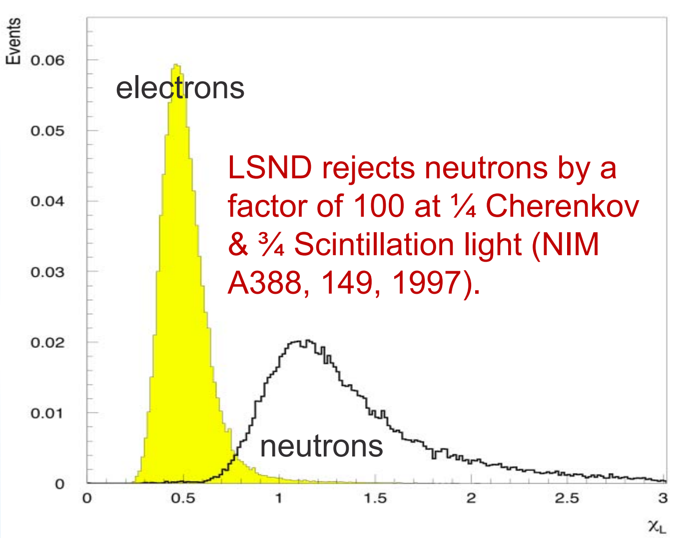


- 0.3% Te is the baseline (phase-I)
- Higher loading (3%) and background controls (purification) of Te-LS are the keys to a future ton-scale $0\nu\beta\beta$ experiment (phase-II)

Water-Like WbLS

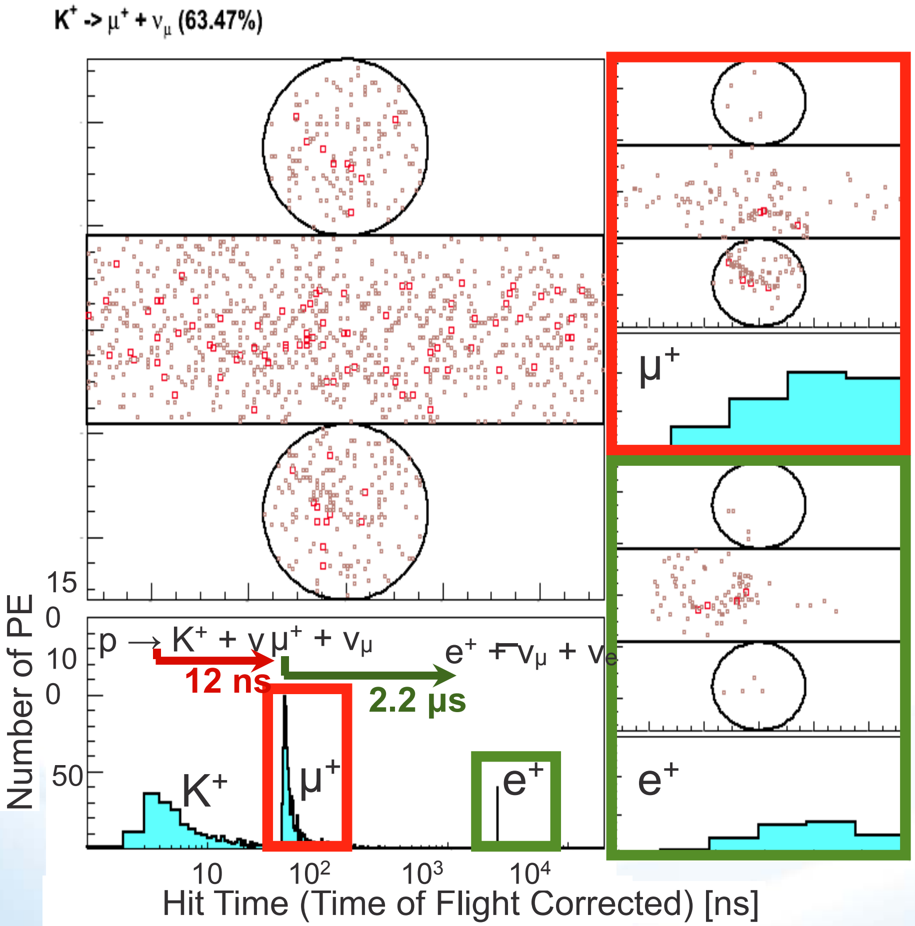
- A new liquid medium utilizing nonlinear light-yield as a function of scintillator % and superior optical property of water for physics below Cerenkov (e.g. **nucleon decay**) or low-energy neutrino detection
- Cherenkov transition
  - λ overlaps with scintillator energy-transfers will be absorbed and 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)
- Cost-effective and environmentally friendly for **a large scintillation Cherenkov detector**

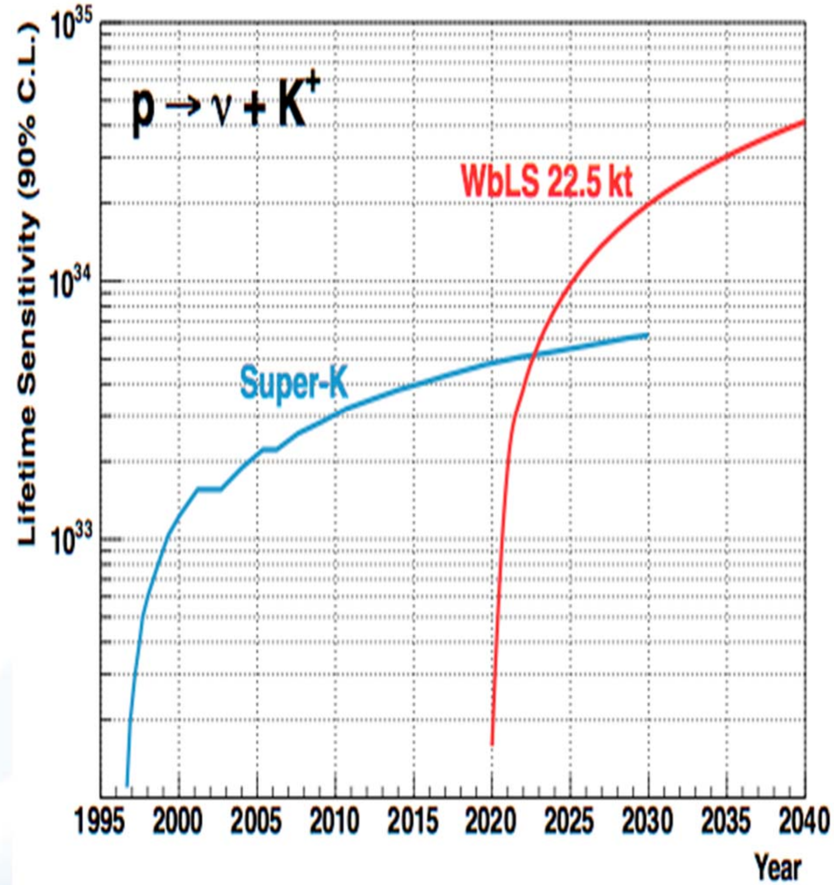




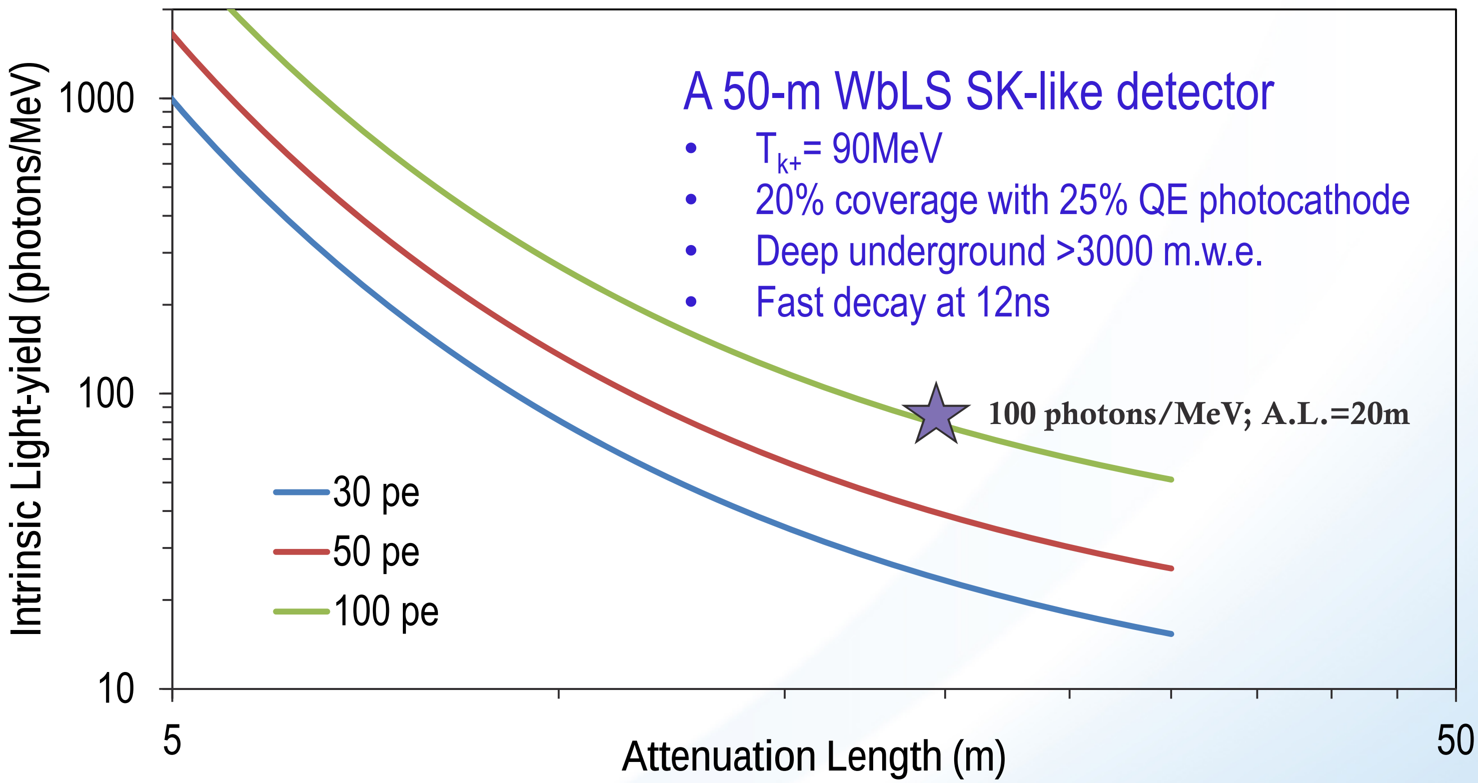
WbLS for Proton Decay

- 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)

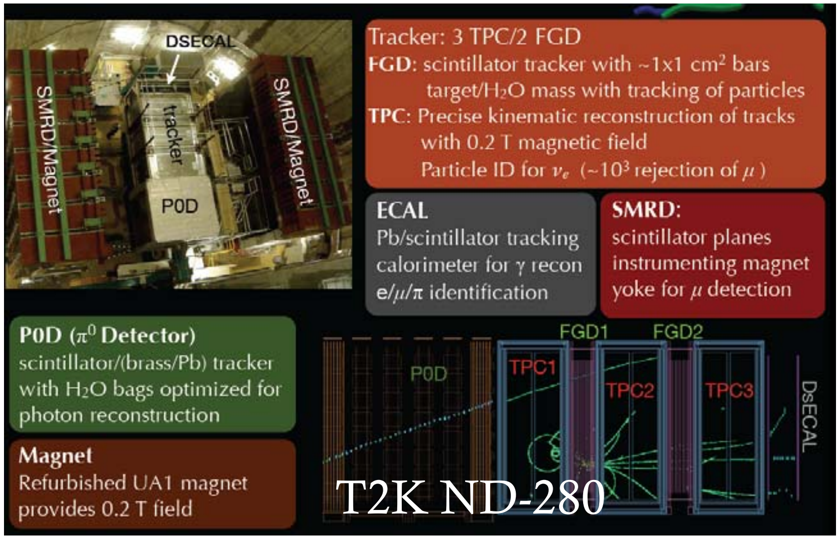


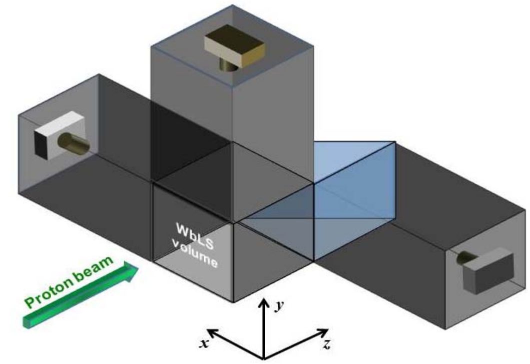


WbLS S% vs. A.L. for $p \rightarrow k^{+}\bar{v}$

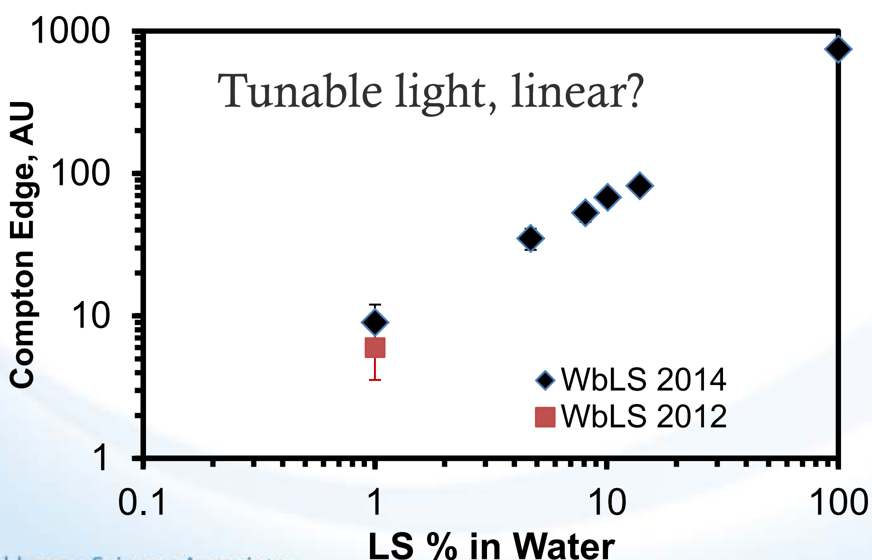


Water-likeWbLS Physics (now)



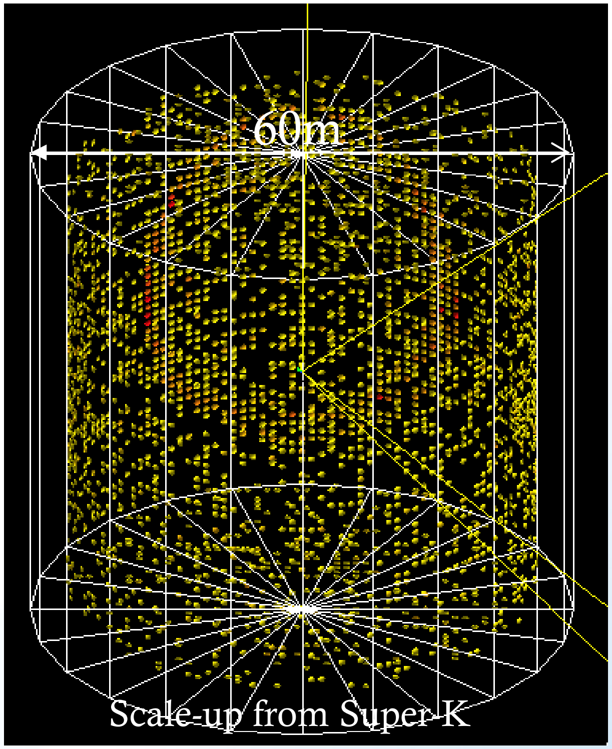


- 3-D medical Imaging and TOF-PET (10% Gd- or Pb-WbLS)



Advanced Scintillation Detector Concept (ASDC)- WbLS future

- 50-100 kton WbLS target
- High coverage with ultra-fast, high efficiency photon sensors
- Deep underground (e.g. 4800 mwe Homestake mine, SD)
- Complementary program to proposed LAr detector at LBNF (P5, Scenario-C) with comprehensive low-energy program
  - Long-baseline physics (mass hierarchy, CP violation)
  - Neutrinoless double beta decay
  - Solar neutrinos (solar metallicity, luminosity)
  - Supernova burst neutrinos & DSNB
  - Geo-neutrinos
  - Nucleon decay
  - Source-based sterile searches



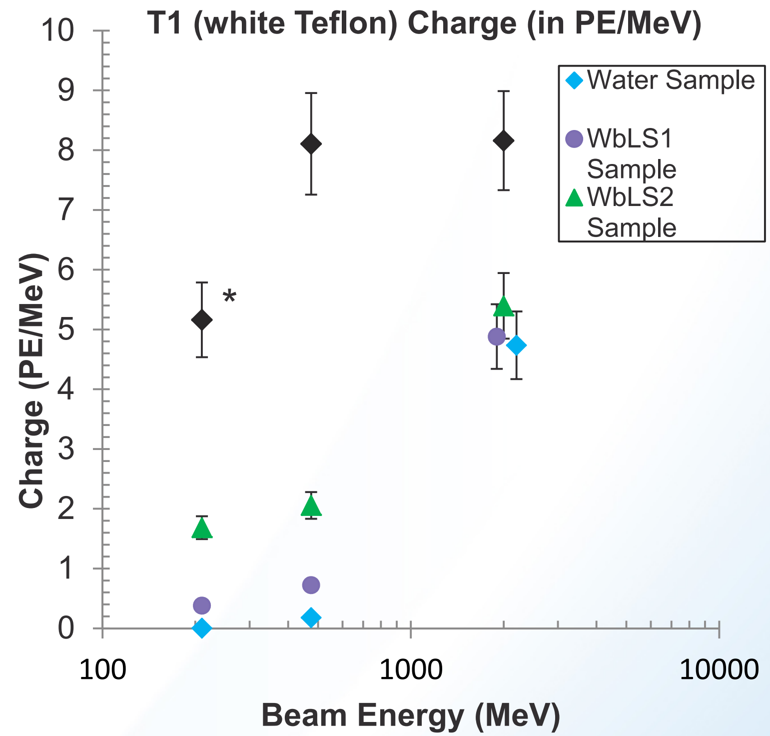
- Concept paper - arXiv:1409.5864: 50 authors (potential PIs), 23 institutions
- Large international community with interest and experience; **New participation welcome**

Concepts to be demonstrated

- Stability of Cocktail
- Scintillation light below Cherenkov
- Cherenkov/scintillation separation
  - WbLS cocktail tuning
  - Slow timing
- Cherenkov light yield
  - Cherenkov light below 400nm being transferred
- Attenuation length
  - Bench-top scale demonstrated; need long arm measurement
- Reconstruction & particle ID
  - Background rejection
- Isotope loading
  - $0\nu\beta\beta$, solar, n tagging

Sci. light below Che. thresh.

Low-intensity Proton-beam 3 runs



3 low Intensity Proton Beams

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

4 Material Samples

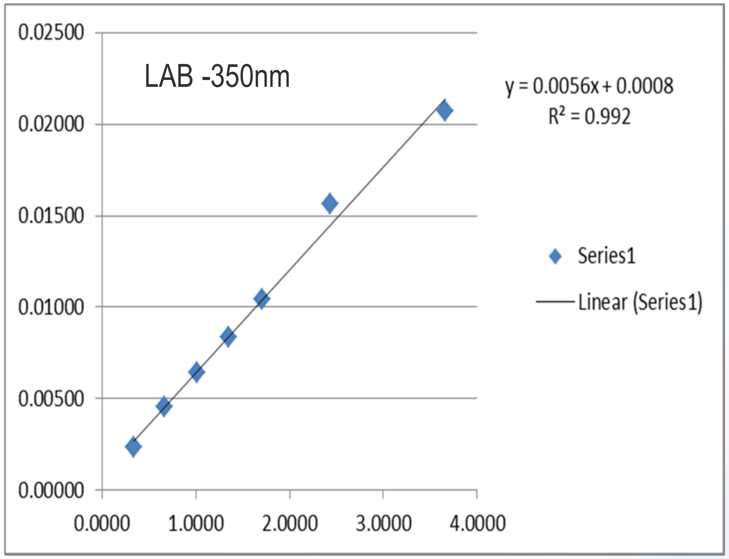
Water	pure water
WbLS 1	0.4% LS
WbLS 2	0.99% LS
LS	pure LS

2 Detectors

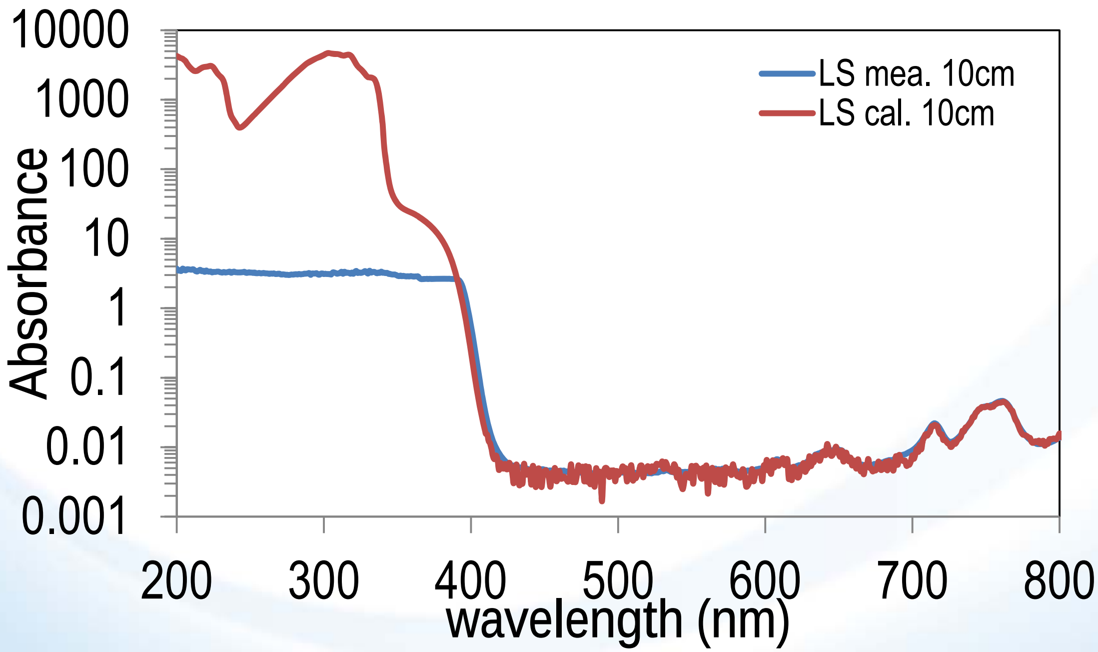
Tub 1	PTFE (highly reflective white Teflon)
Tub 2	Aluminum coated with black Teflon

Attenuation length:
Optical Model

- Extinction coefficient (scattering + absorption)
  - 2-m system to verify the extinction length
  - UV spectrometer (10-1 to mitigate Fresnel reflection) to measure molar extinction coefficient of each component of WbLS



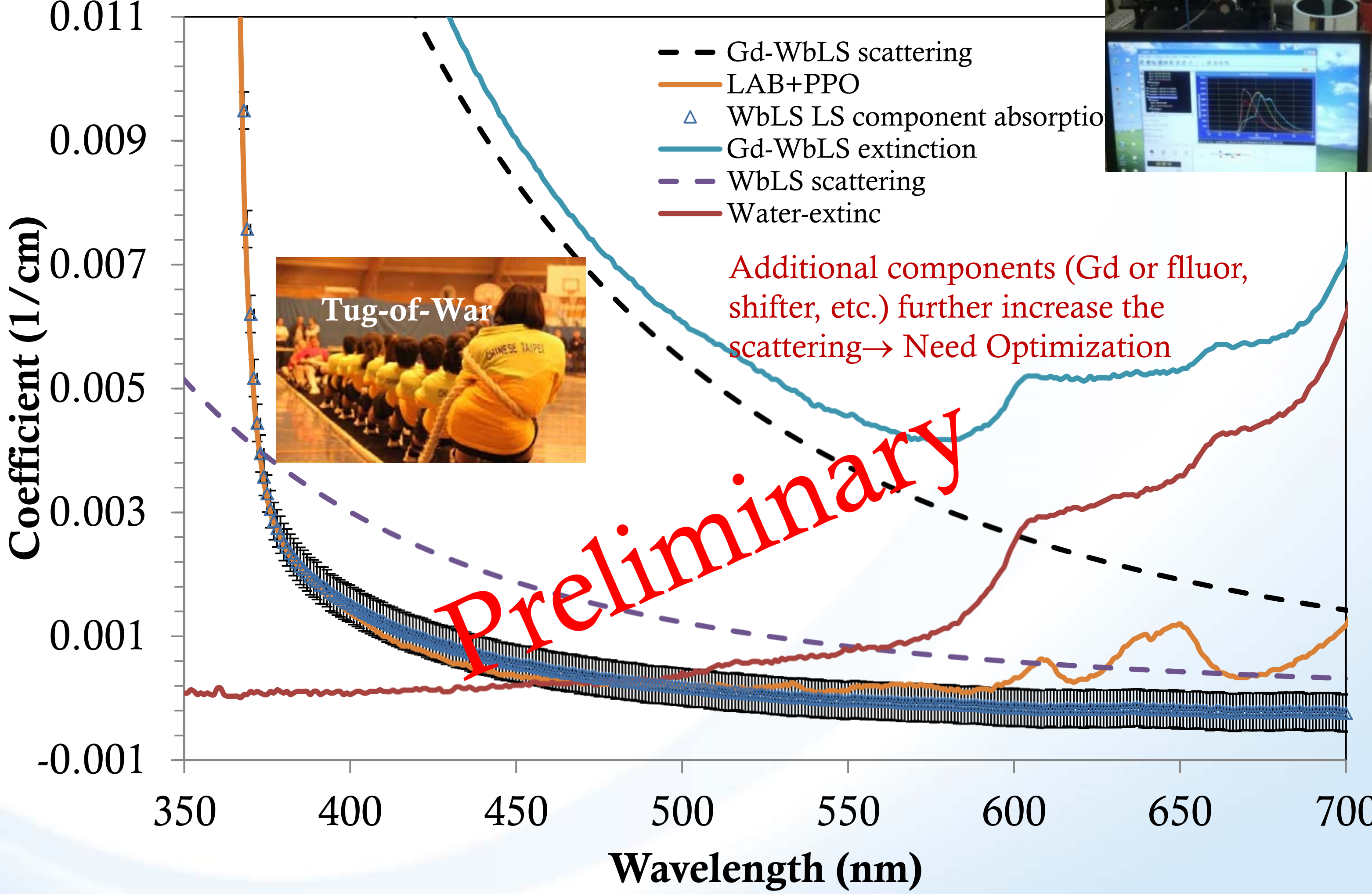
$$A = (\varepsilon_1 c_1 + \varepsilon_2 c_2 + \varepsilon_3 c_3 + \ldots) \times \lambda$$

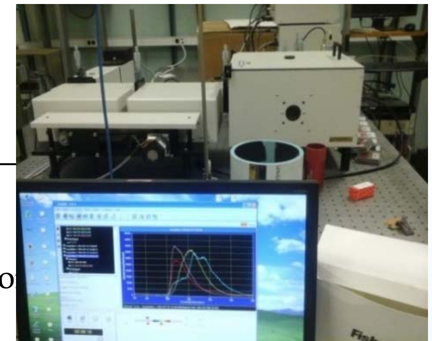


- Absorption is predictable
- Scattering is complicated
  - Rayleigh, Mie, …, etc
- Optical model successfully predicts the attenuation length of LAB + PPO + bis-MSB (verified by 2m system)

Scattering needs improvement

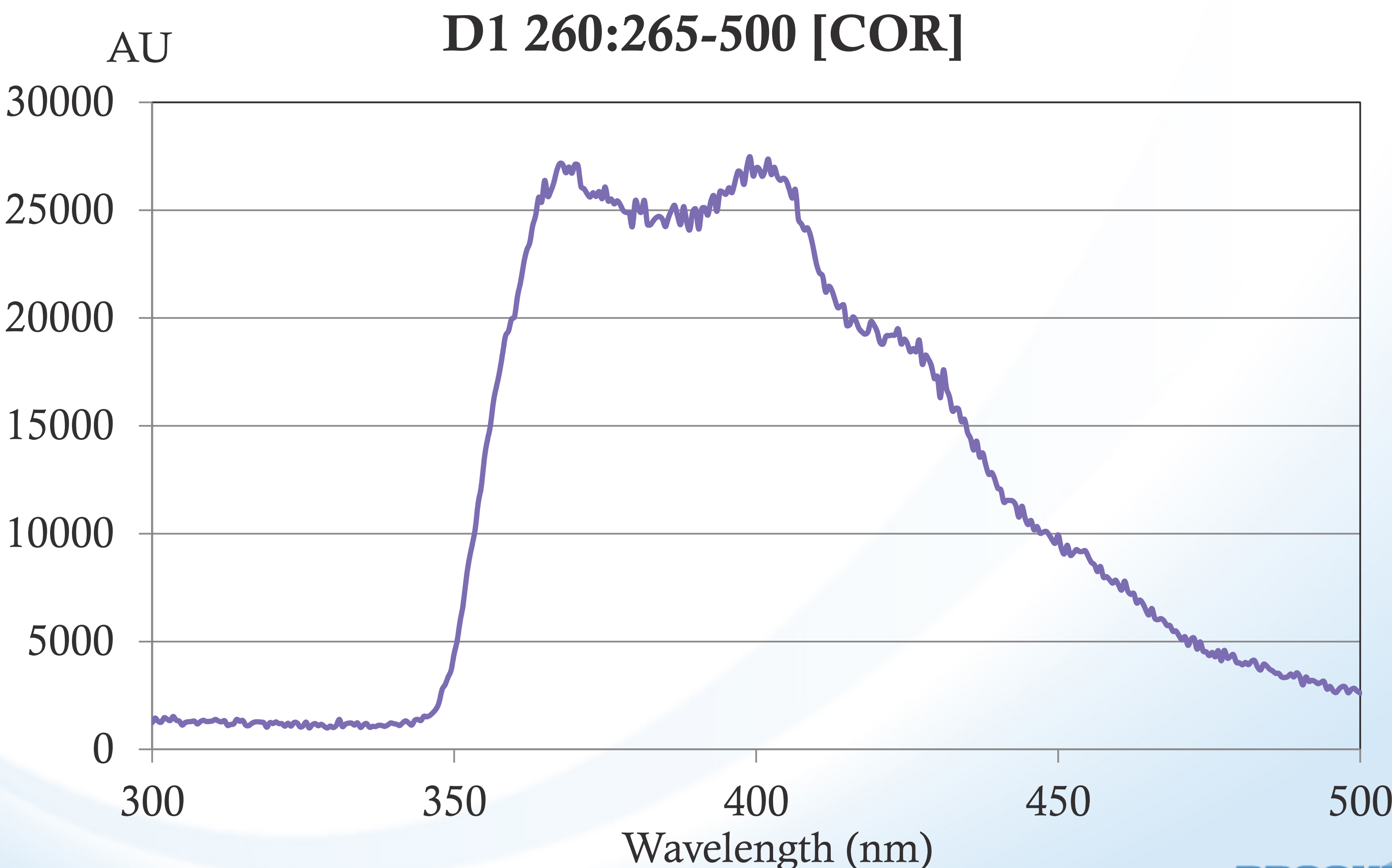
Work-in-Progress





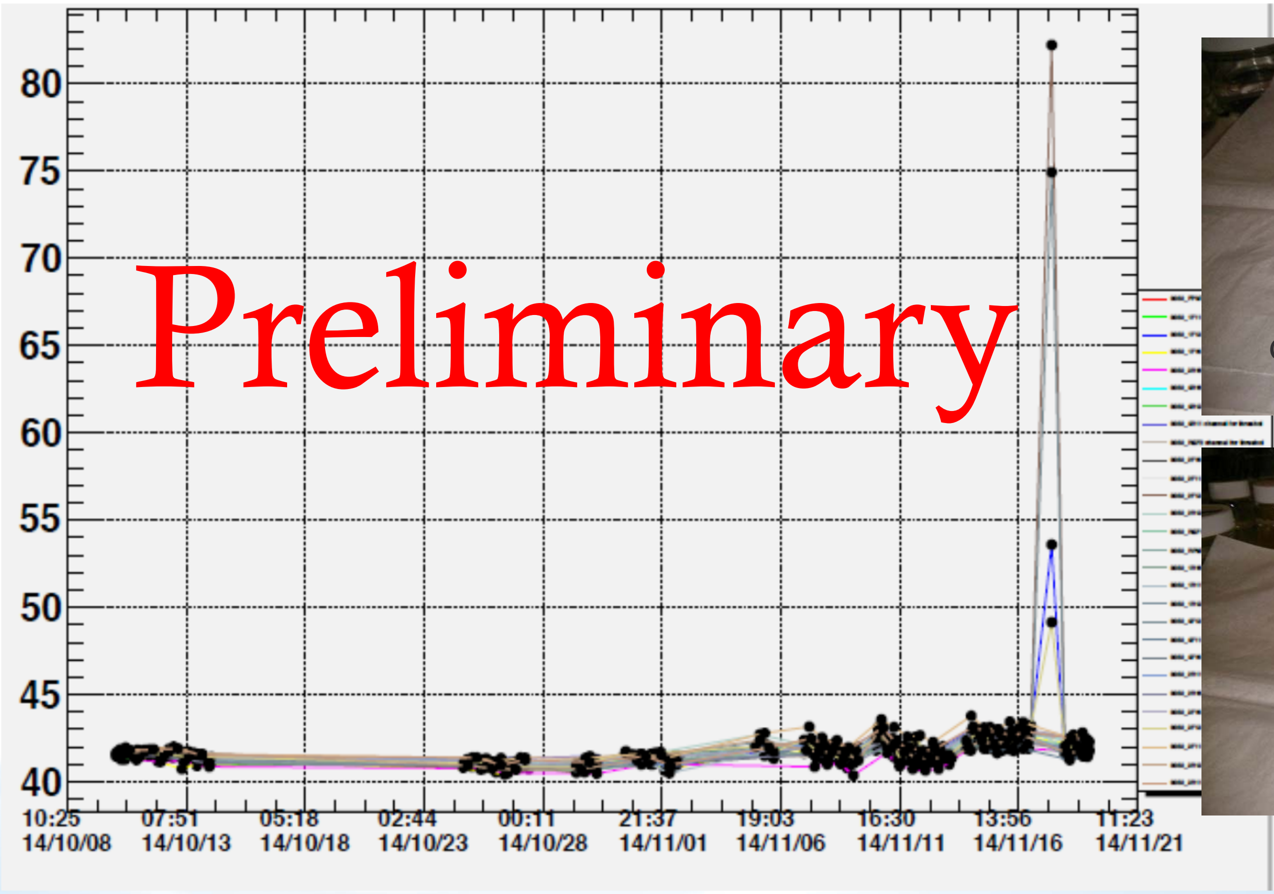
WbLS at ~100 photons/MeV

Emission by $\lambda_{ext.}$=260nm

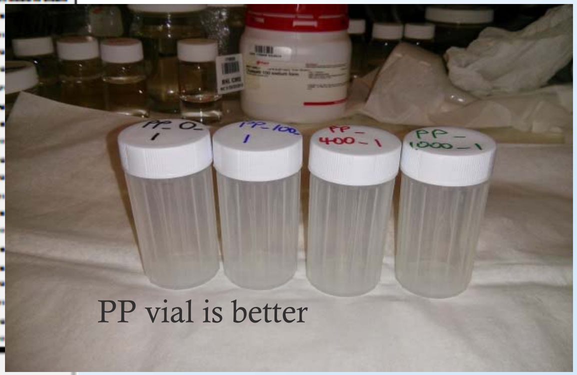


Radiation Hardness

No observable light-yield loss of 5%WbLS up to 1000Gy using NSRL proton beam and CERF Gamma sources



Glass vial damaged by radiation



PP vial is better

Circulation of WbLS

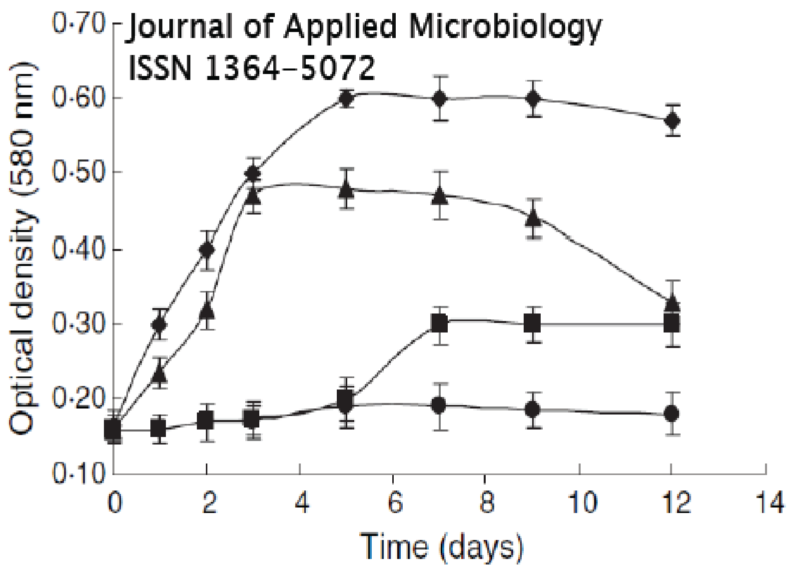


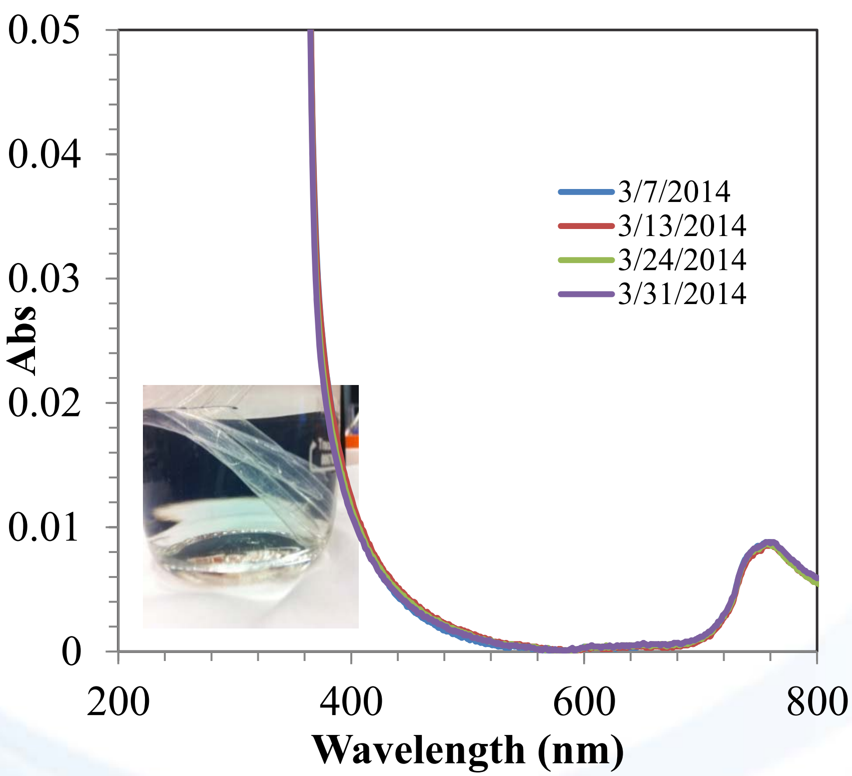
Figure 5 Time-course analysis of consortium growth at different linear alkylbenzene sulfonate concentrations (in mg l^{-1}): (◆) 10; (▲) 20; (■), 50; and (●) 100. Values are means ± standard deviations for three replicates.

- extensive studies by environmental researches in academia and industry

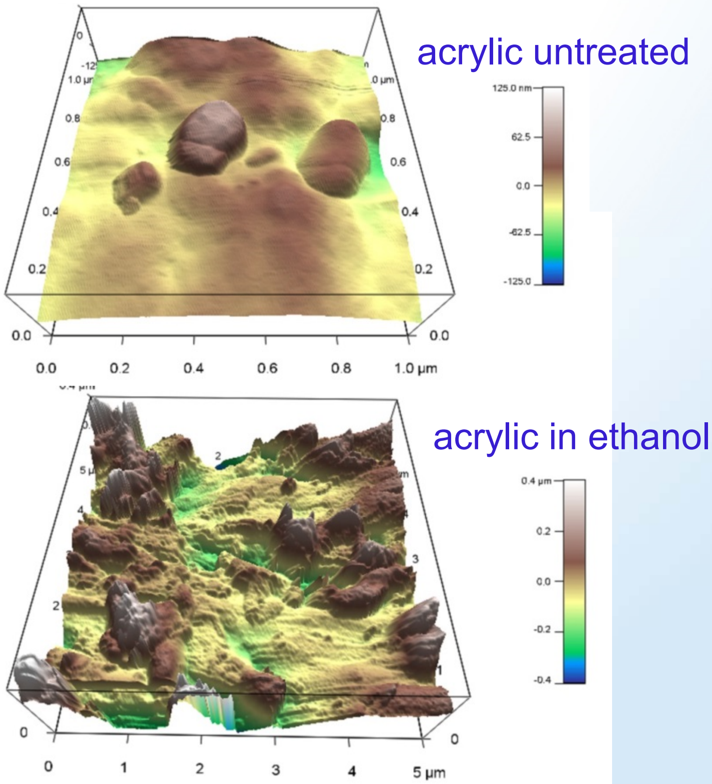
- Biodegradable?
  - Surfactant degradation only occurs at <50mg/L.
  - Surfactant at 100mg/L or higher completely inhibits bacteria growth
- 1% WbLS is 10^5 mg/L
- Stable in acrylic, PP, some polycarbonate, etc.
- Oil-like WbLS doesn't require circulation (e.g. Daya Bay, SNO+, PROSPECT)
- Water-like WbLS might not need circulation with careful selection of vessel and materials-in-contact
  - Passing 0.1 micron filter
  - Radon daughters?
- Ongoing test with bacteria testing kit

Material Compatibility

- 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)

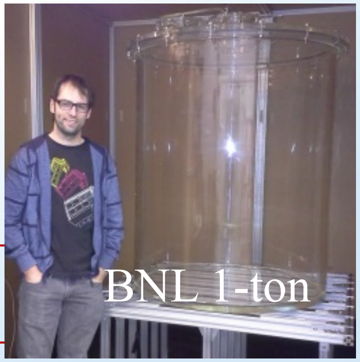


Atomic force microscopy (**AFM**) high-resolution scanning

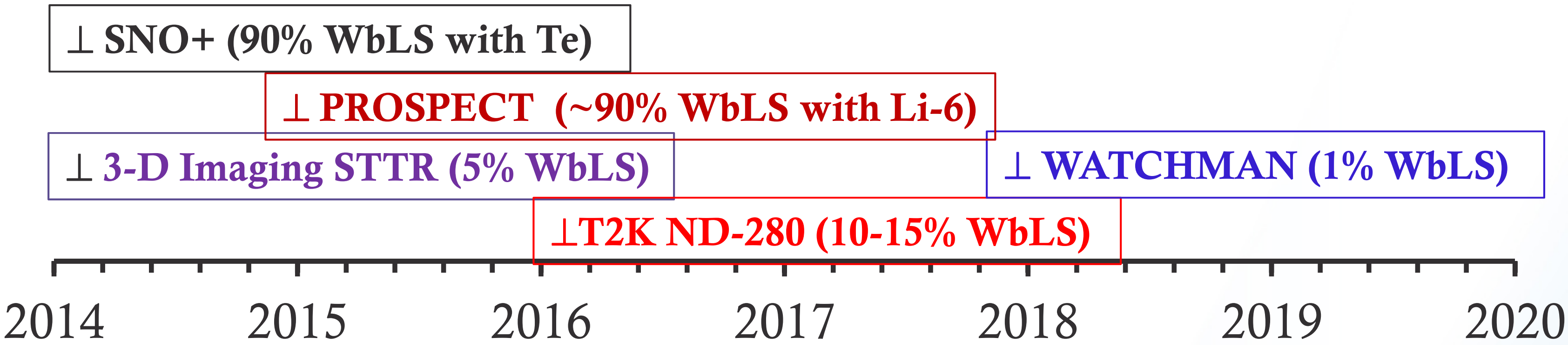
Concepts (to be) demonstrated

- Stability of Cocktail √
- Scintillation light below Cherenkov √
- Cherenkov/scintillation separation ?
  - WbLS cocktail tuning √
  - Slow timing √
- Cherenkov light yield ?
  - Cherenkov light below 400nm being transferred
- Attenuation length ?
  - Bench-top scale demonstrated; need long arm measurement
- Reconstruction & particle ID ?
  - Background rejection
- Isotope loading √
  - $0\nu\beta\beta$, solar, n tagging

Demonstrators are under construction



Conclusions



- Principals of WbLS detection and isotope loading have been proven; applied to several ongoing and/or newly proposed experiments already.
- The developments of a large WbLS detector with fast timing and Cherenkov and Scintillation separation (ASDC) for multi-physics searches are ongoing.

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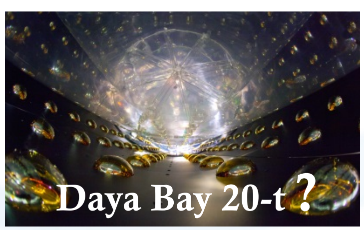

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