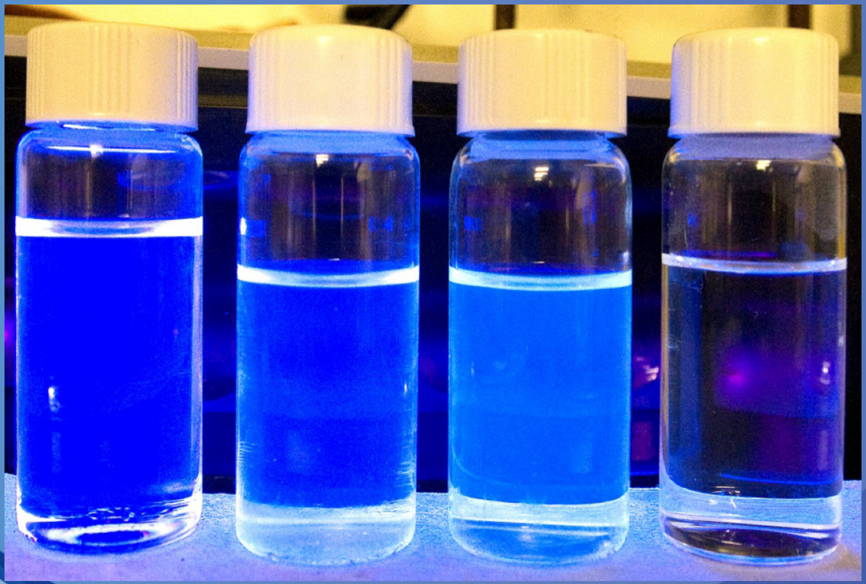
Radiopure Metal-doped Liquid Scintillators



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BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

LRT, U. Washington, Seattle, Mar. 18-20, 2015

Liquid Scintillator Physics

0νββ
(e.g. SNO+, KamLAND-Zen)

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

Safeguard and Dark Matter
(e.g. WATCHMAN, LZ)

Common features between detectors

Liquid Scintillator
(Metal-loaded & Water-based)

unique requirement for individual detector

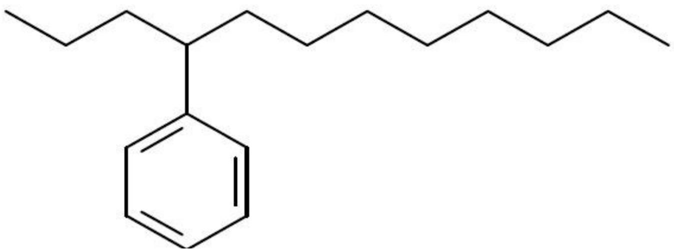
Ion-beam therapy
TOF-PET scan

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

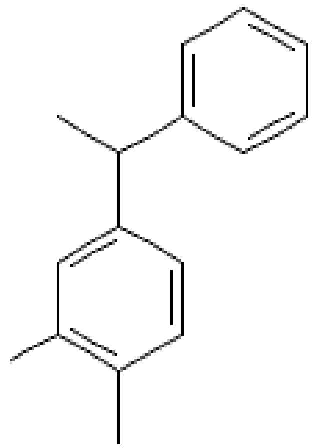
Accelerator Physics
(e.g. NOνA, T2K, SNS, J-PARC-E56)

Liquid Scintillators

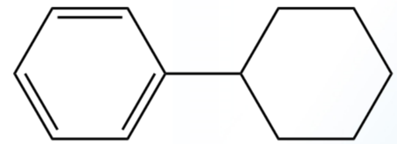
- Detector defined by Stokes Shift, timing structure, Z and density
- High flashpoint (PXE>DIN>LAB>PCH>PC) and low toxicity
  - LAB, first identified by SNO+, is the current selection for several scintillator exp't
- New generation Water-based Liquid Scintillation



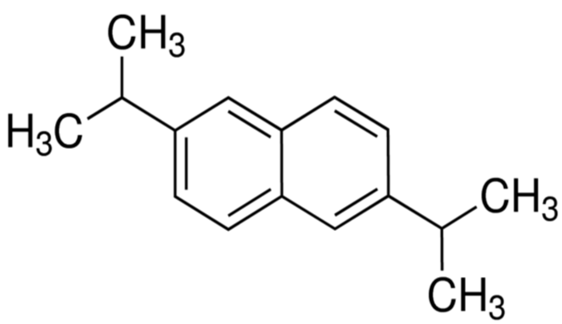
Linear alkylbenzene (LAB)



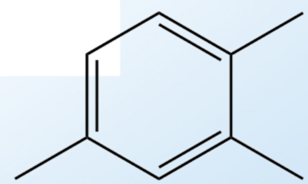
1-phenyl-1-xylyl-ethane (PXE)



Cyclohexylbenzene (PCH)



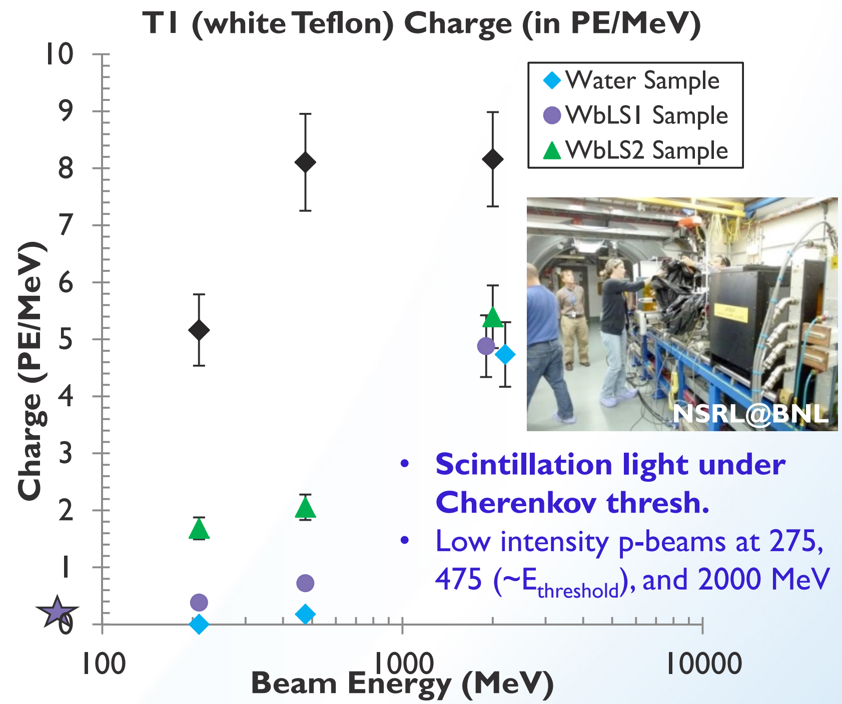
Di-isopropylnaphthalene (DIN)



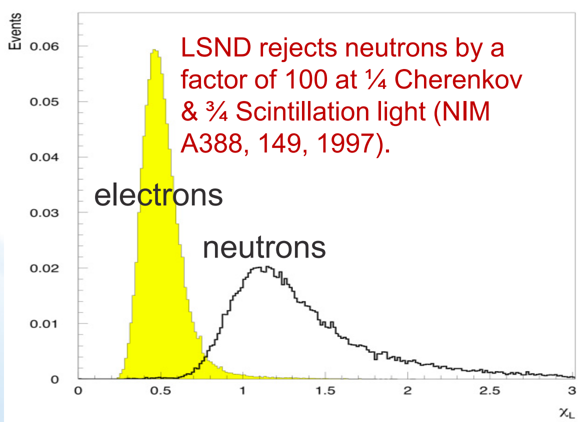
1,2,4-trimethylbenzene (PC)

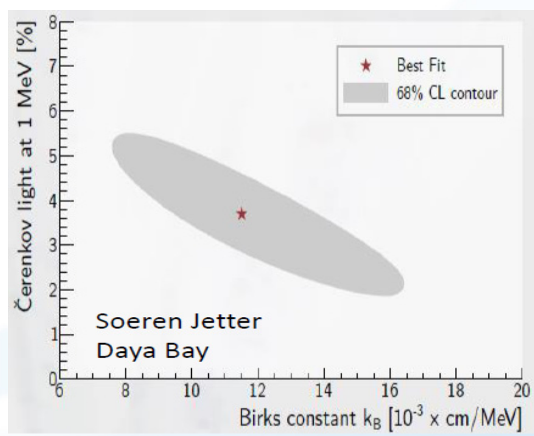
Water-based Liquid Scintillator

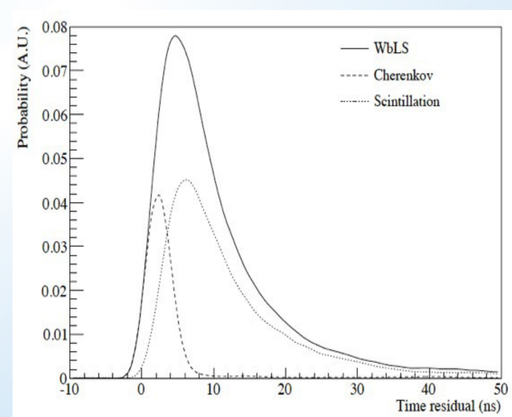
- A new detection liquid bridging scintillator and water with tunable scintillation light from ~pure water to ~organic:
  - Water-like WbLS: A scintillation water with Cherenkov and Scintillation detections (i.e. proton decay)
  - Oil-like WbLS: A novel technology for loading various isotopes in scintillator
- Cherenkov radiation
  - λ overlaps with scintillator will be absorbed and re-emitted to give isotropic light, λ >400nm will propagate through the detector (directionality).



- **Scintillation light under Cherenkov thresh.**
- Low intensity p-beams at 275, 475 (~$E_{threshold}$), and 2000 MeV



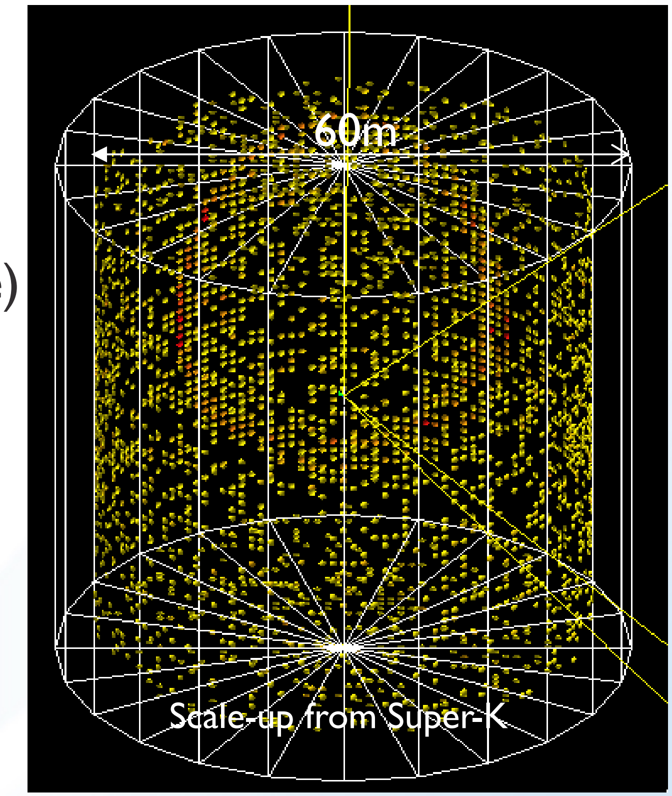




THEIA

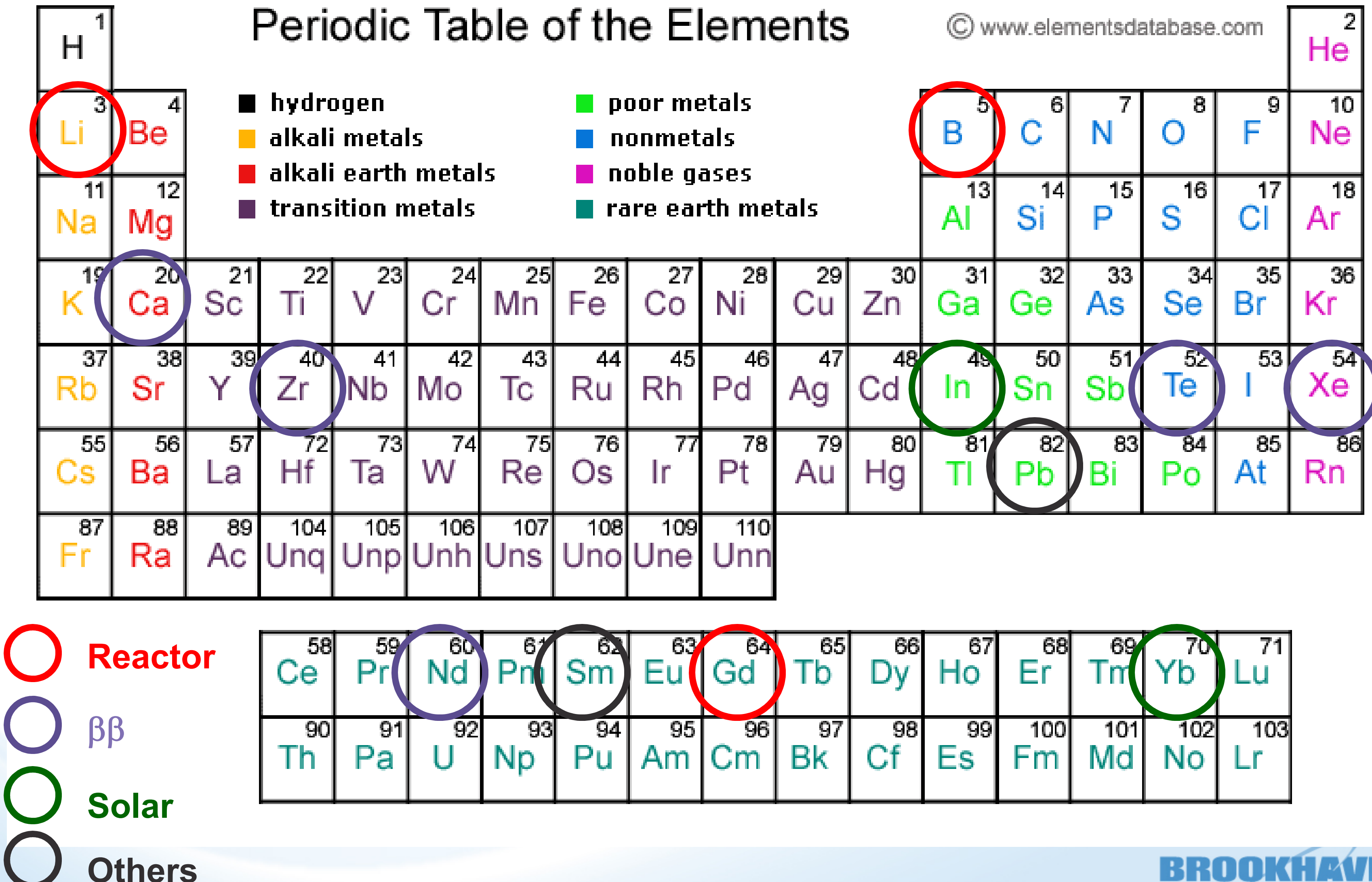
Advanced Scintillation Detector Concept: ASDC

- First Workshop in 2014
- 50-100 kton WbLS target
- High coverage with ultra-fast, high efficiency photon sensors
- Deep underground (e.g. 4800 mwe Homestake)
- 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



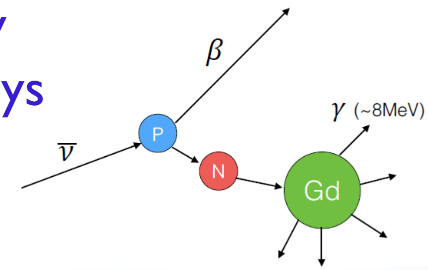
- Concept paper - arXiv:1409.5864: 50
- WATCHMAN is the next large water Cherenkov detector

Metal-doped Liquid Scintillator
for Neutrino Physics and Other Applications

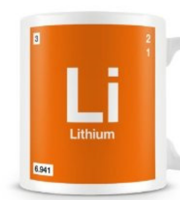


Manufacture of M-LS

- Solubility, light-yield, optical transmission, and radiopurity (naturally occupied and cosmogenic isotopes) are the keys

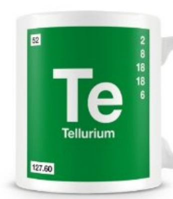


1. Oragnometallic-extraction in scintillator has been successfully applied to reactor $\bar{\nu}_e$ detection (e.g. Daya Bay)
   - *Require a mixing ligand to bring inorganic metallic ions into organic liquid scintillator*
   - *Additional discrimination for radioactive isotopes*
   - *difficult for hydrophilic isotopes*

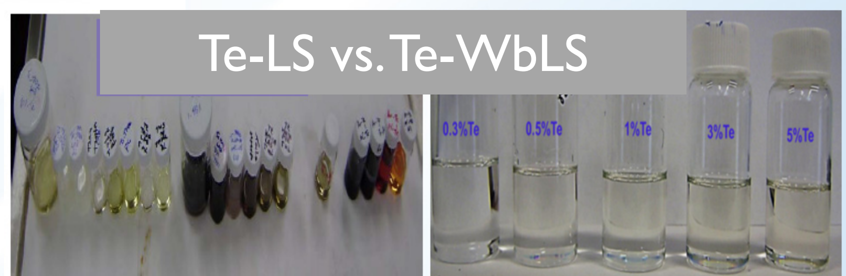


Lithium-doped scintillator detector
- Solar neutrino (^{7}Li, 92.5% abundance)
- Reactor antineutrino (^{6}Li, 7.6% abundance)

2. A New metal-doped technology using water-base Liquid Scintillator principal (e.g. PROSPECT, SNO+, etc.)
   - *Suitable for ~most metallic ions*
   - *less-selective isotope loading→ Require extensive purification for radiopurity*



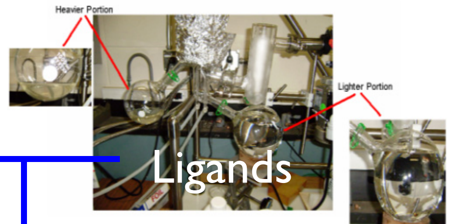
Tellurium-doped scintillator detector
- Double-beta decay isotope (^{130}Te, 34% abundance)
- Future ton-scale 0νββ



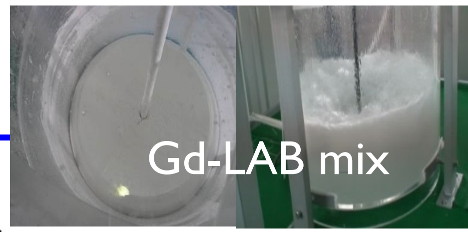
Lead-doped scintillator calorimeter
- Solar neutrino
- Total-absorption radiation detector (Medical)

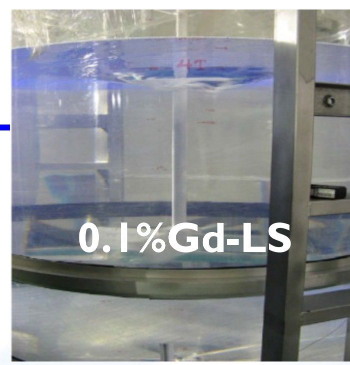
M-LS by Organometallic Loading

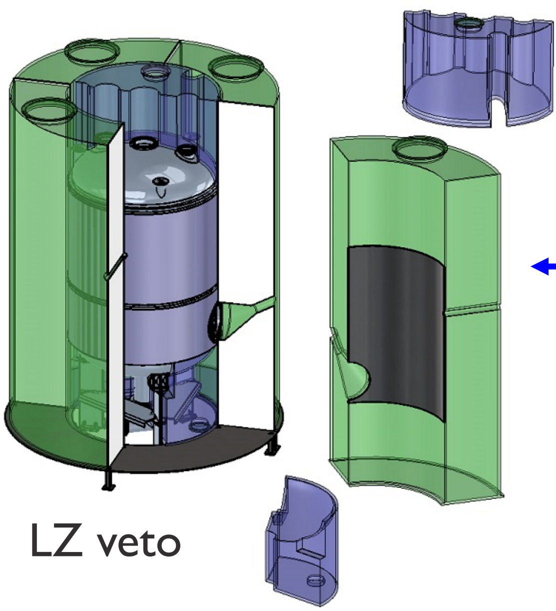
- Method well developed and demonstrated by reactor experiments (e.g. Daya Bay, RENO, and D-Chooz)
- LZ veto with higher radiopurity requirement



Additional radioisotope removal

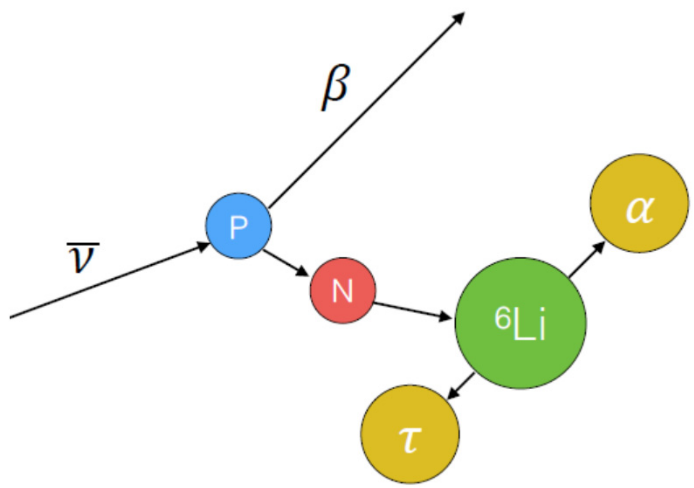




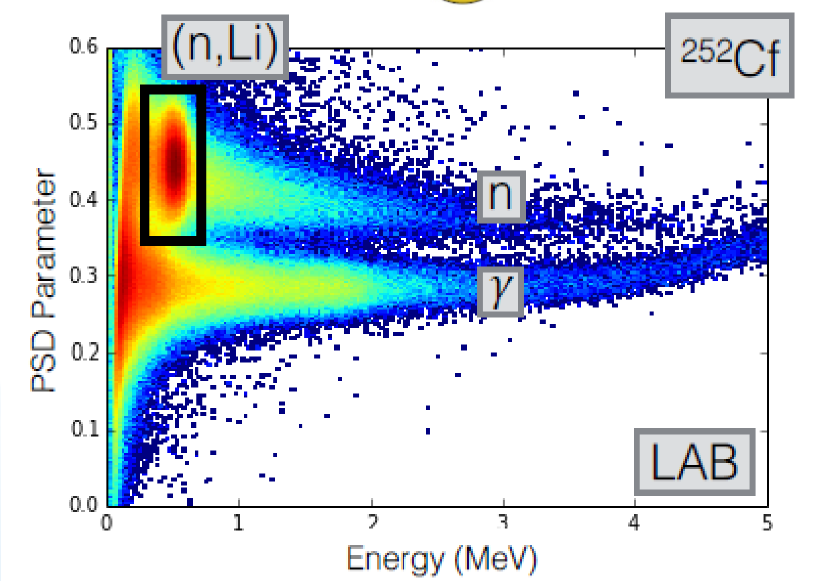


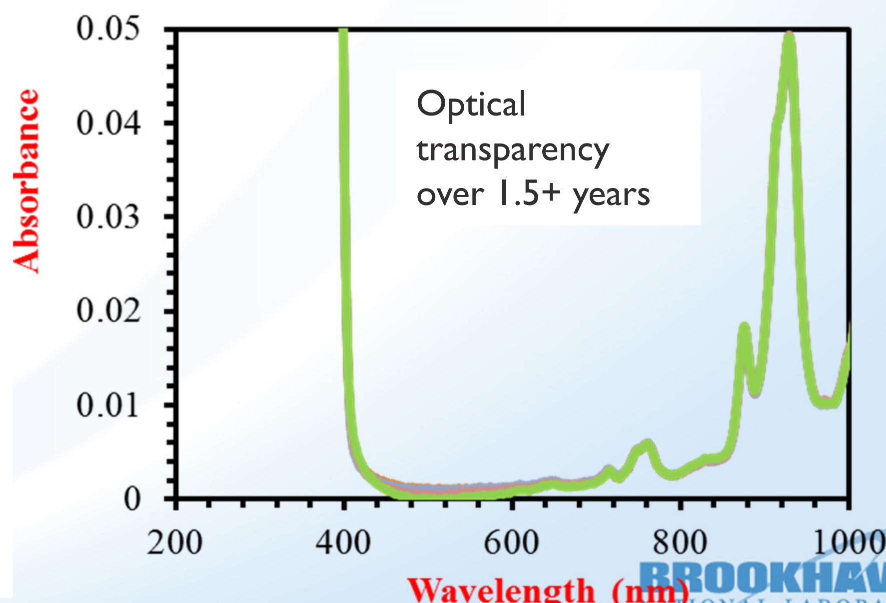
LZ veto

M-LS by WbLS Loading



- Require surface chemistry
- Ex. of Li-doped WbLS with enhanced light-yield, optical better and PSD that has been stable over 1.5 years
- Several applications in short baseline (PROSPECT), 0νββ (Te-LS, SNO+), medical, and other applications



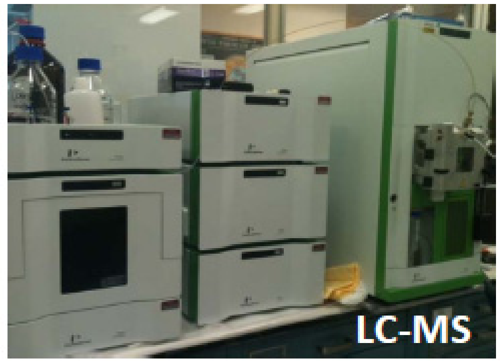


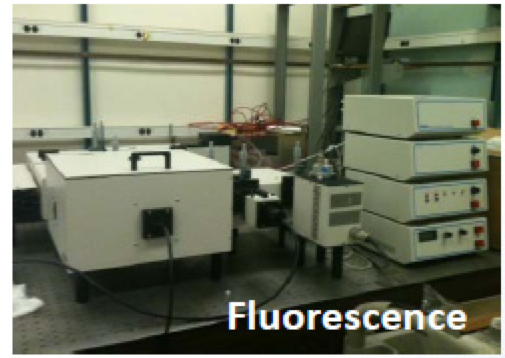
Purification Method for M-LS

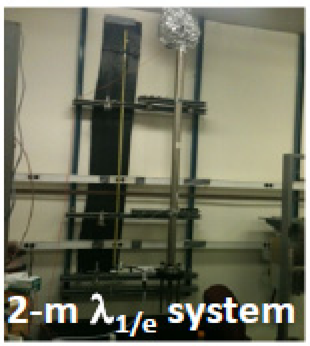
Component	Purification
Scintillator	• Vacuum Distillation • Column separation • Nanofiltration+
Complexing Ligand	• Vacuum distillation • Column separation
Metallic Compound	• Recrystallization • Self-scavenging • Column Separation
Fluor	• Solvent Washing • Recrystallization
Wavelength Shifter	• negligible

+demonstrated for Gd-H2O by M.Vagins; further application for scintillator purification (UC Davis)
*Vendor selection and QA/QC are important

Assay and Assessment
BNL Liquid Scintillator Development Facility



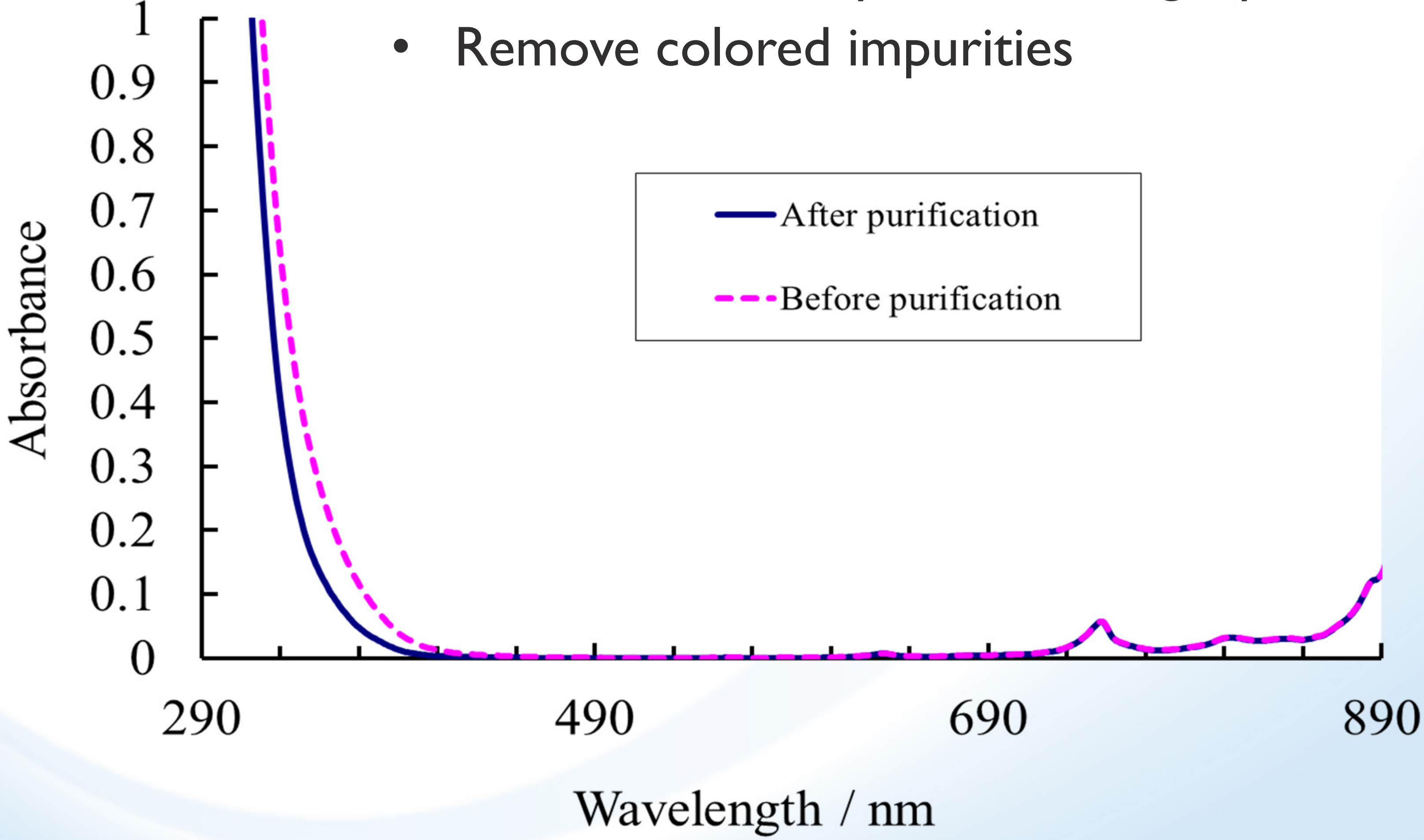




- A unique development facility (since 2002) for Radiochemical, Cherenkov, and Scintillator (water-based and metal-doped) detectors for particle physics expt's
- Readiness equipment for sample preparation and pre-screening

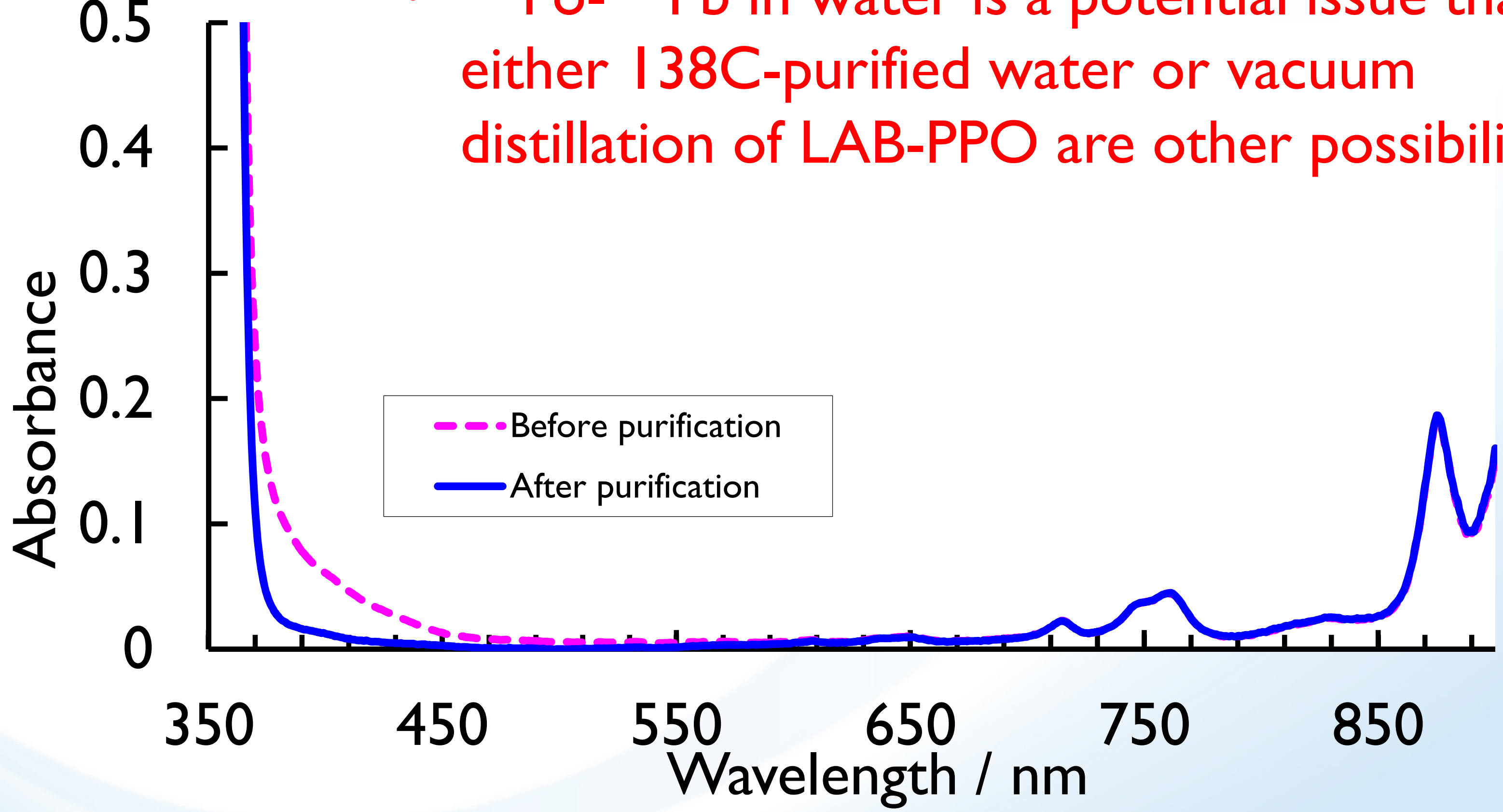
Vacuum Distillation (TMHA)

- >95% of metal impurities in single pass
- Remove colored impurities



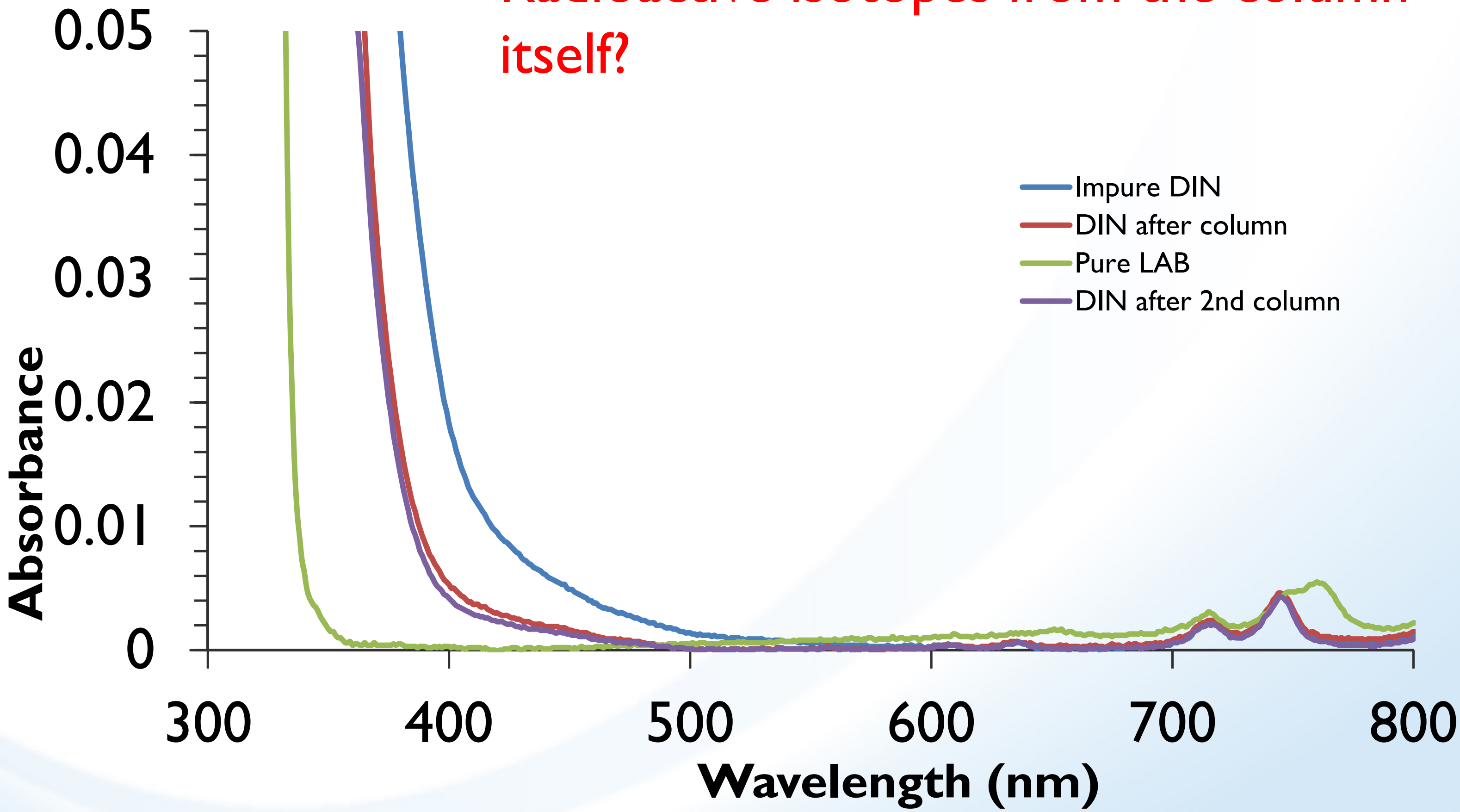
H2O Extract. + Recrystal. (PPO)

- ~100% U/Th isotopes left in supernatant
- ^{210}Po-^{210}Pb in water is a potential issue that either 138C-purified water or vacuum distillation of LAB-PPO are other possibilities



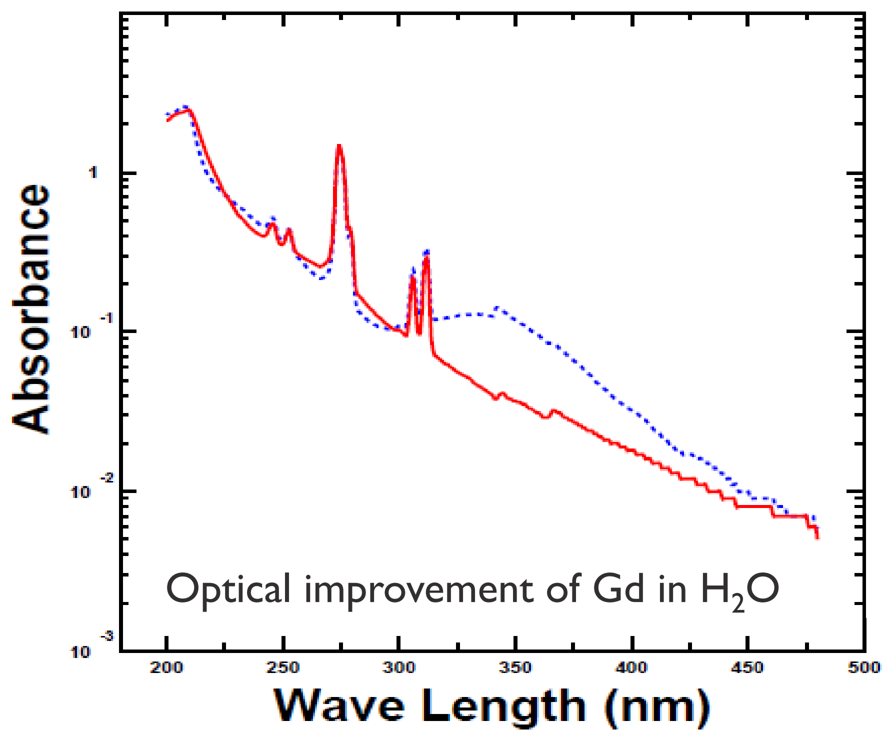
Column Separation (Scintillator)

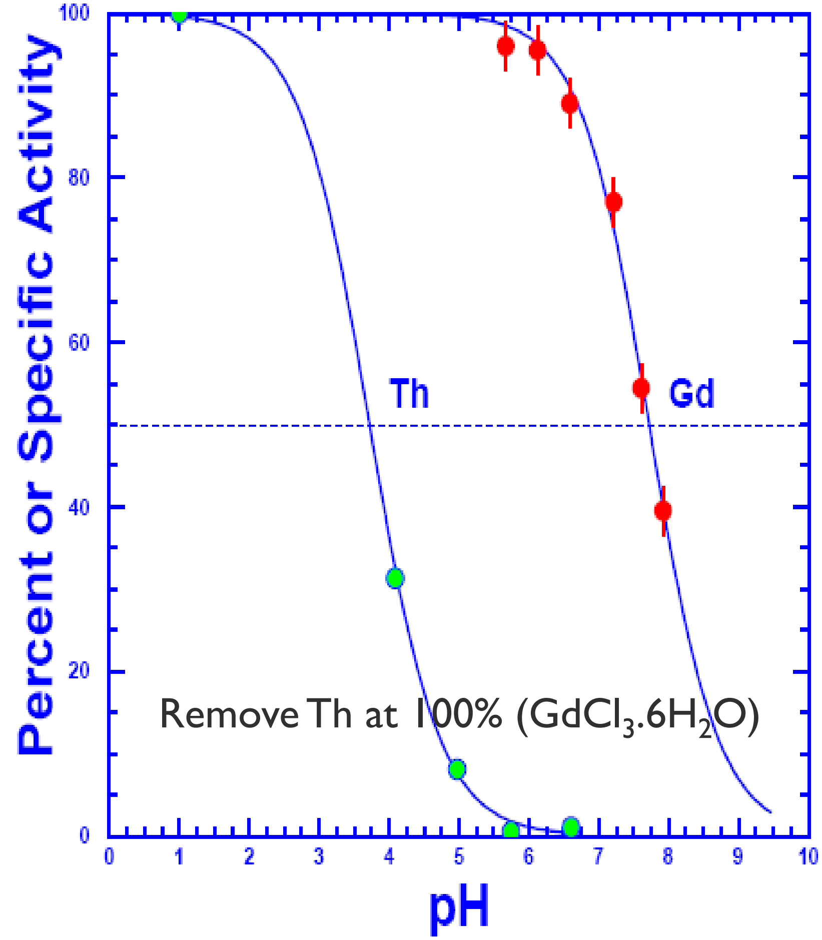
- 50-90% U/Th removal with large errors
- Radioactive isotopes from the column itself?



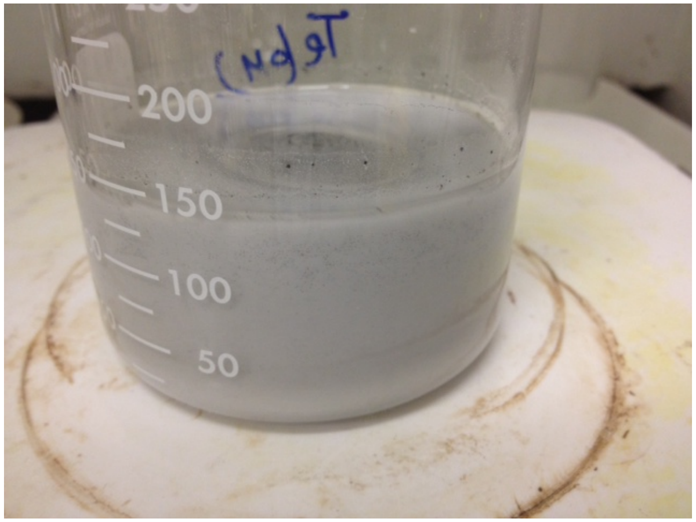
Self-scavenging (Gd)

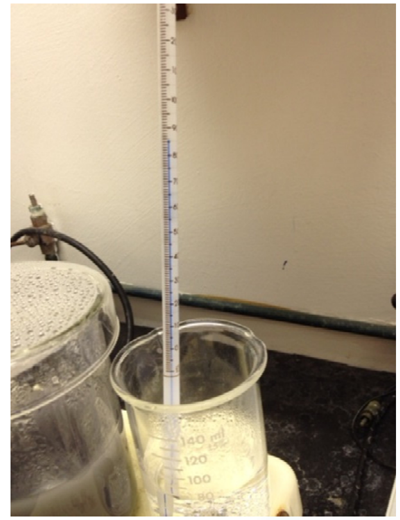
- Take advantages of low solubility constants of U/Th
- pH adjustments followed by fine-particle filtration

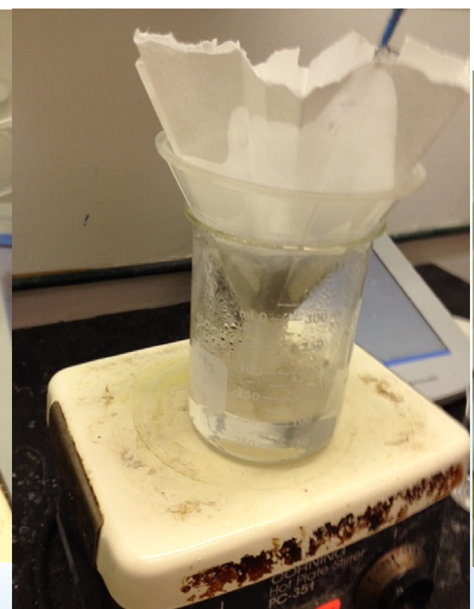




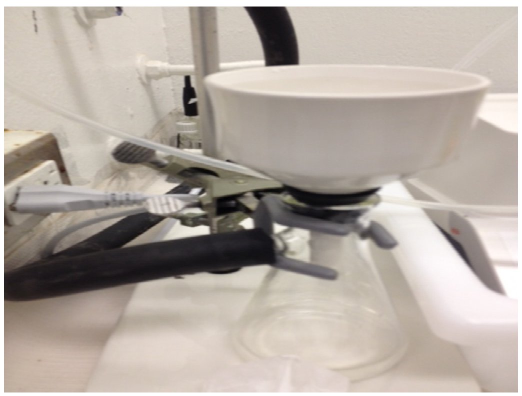
Recrystallization (Te)



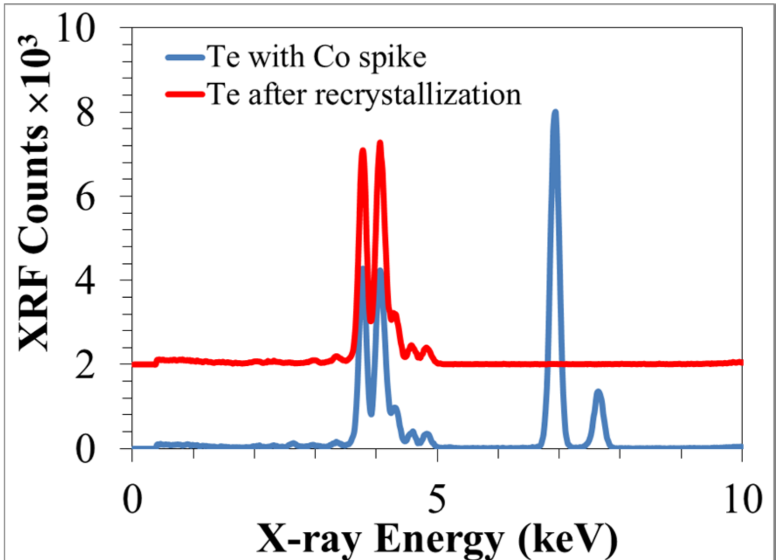


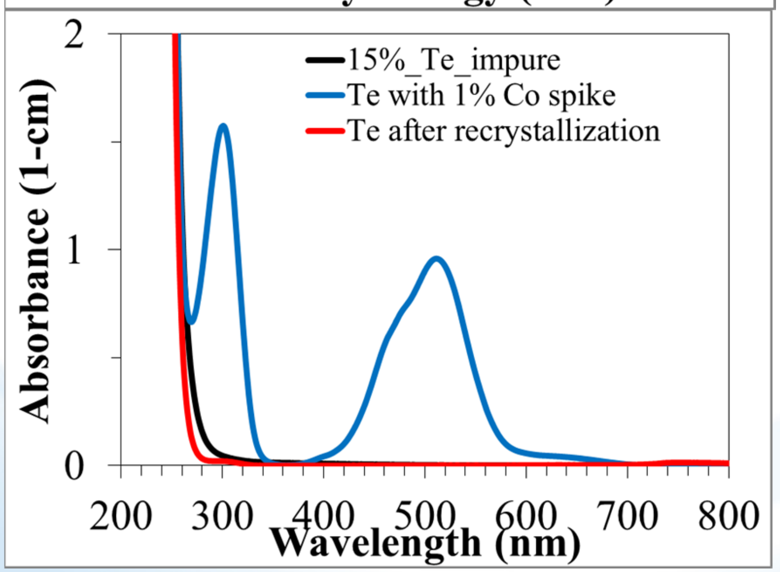


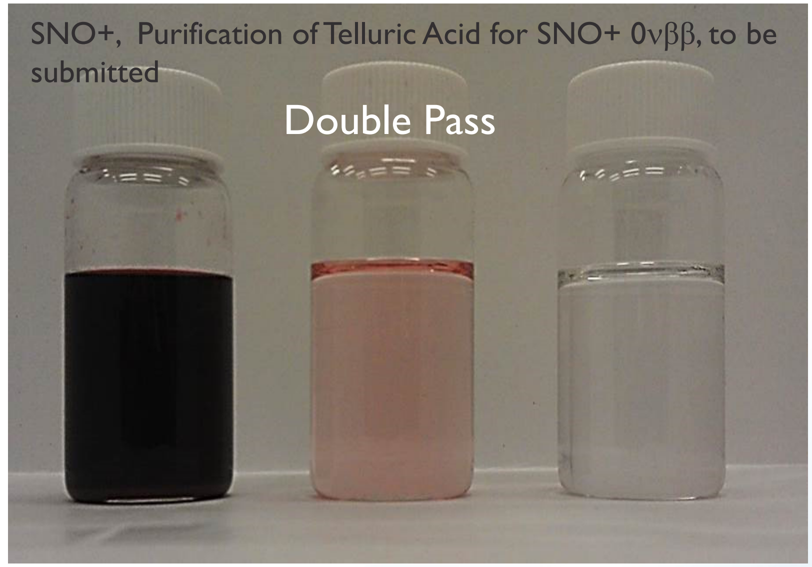
Recrystallization (Te) cont'd



Ex. of Co removal from Te







SNO+, Purification of Telluric Acid for SNO+ $0\nu\beta\beta$, to be submitted

- SNO+ will conduct double-pass acid-recrystallization on surface and single-pass thermal-recrystallization at underground to achieve 10^4 radioactive reduction (Laura Sequi talk)
- First $Te(OH)_6$ batch stored underground at SNOLAB

Table of Reduction Factor

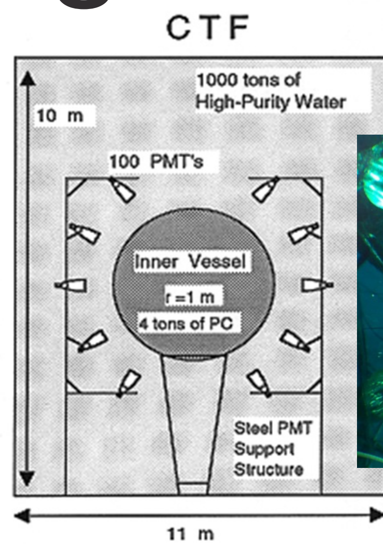
Isotope	Spiked	ICP-MS (ppt)	
	Trace Analysis	Before Puri	After Puri
Sn	$>1.67\times10^2$	20	<20
Zr	$>2.78\times10^2$	70	<10
Co	$(1.62\pm0.34)\times10^3$	<10	<10
Ag	$>2.78\times10^2$	<10	<10
Y	$>2.78\times10^2$	<10	<10
Sc	$>1.65\times10^2$	<10	<10
Sb	$>2.43\times10^2$	30	<20
^{228}Th	$(3.90\pm0.19)\times10^2$	<0.02	<0.02
^{224}Ra	$(3.97\pm0.20)\times10^2$	1400	<5
^{212}Pb	$(2.99\pm0.22)\times10^2$	440	<3
^{212}Bi	$(3.48\pm0.81)\times10^2$	300	<10
^{238}U	$(3.90\pm0.19)\times10^2$	<0.02	<0.02

SNO+, Purification of Telluric Acid for SNO+ $0\nu\beta\beta$, to be submitted

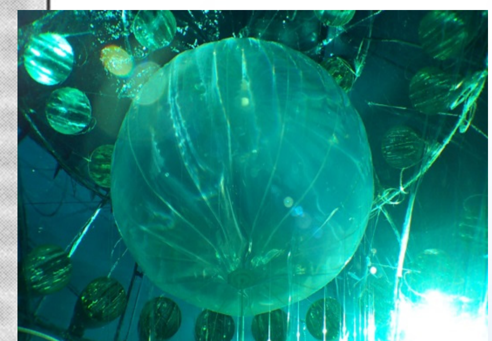
- Reduction effect verified by direct measurement of targeted isotopes in Te compound before and after purification
- Need to improve the detection sensitivity

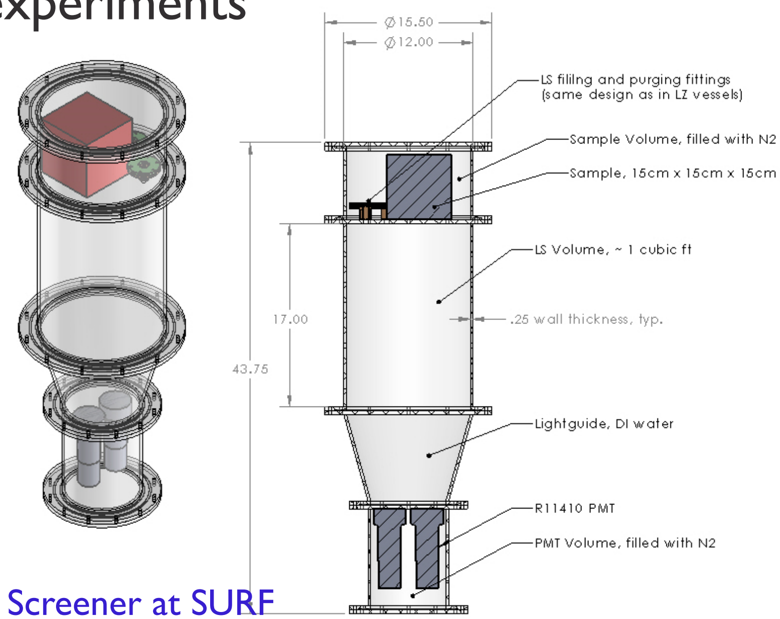
Low-bkg. Screening Facility

- Borexino has demonstrated the most clean scintillator in all experiments, U/Th <10^{-17} g/g
- Great interests and needs for US community and participated experiments

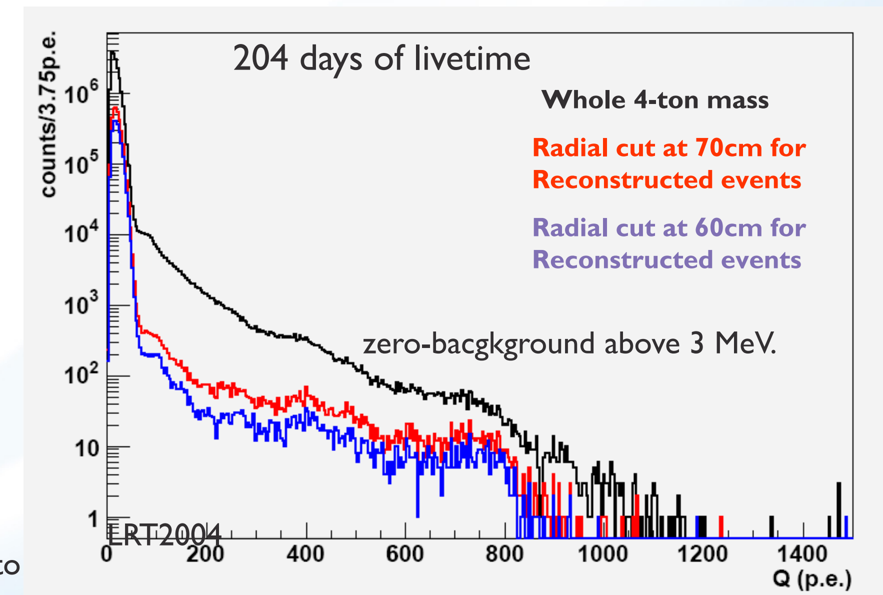


4-t Counting-Test Facility at LNGS





LZ Screener at SURF



•1/1000 Mass of LZ veto detector suspended in the water tank next to LUX support stand, aiming to assess tens of mBq activity of scintillator

Summary

- Liquid scintillator continues to play a key role for present and future nuclear and particle physics experiments
- The radiopurity of metal-doped liquid scintillator depends on the physics of interest; and their purifications have to be applied before preparation (methods defined and demonstrated)
- Purification, clean deployment, and careful material selection are the keys to achieve the sensitivity of requirements
- Developments of pre-concentration, sample-digestion, and/or low-counting facility (e.g. CTF) are important to improve the detection limit