Liquid Scintillator R&D

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BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Scintillator Physics

0νββ
(e.g. SNO+, KamLAND-Zen)

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

Common features between detectors

Nonproliferation
(e.g. AIT-WATCHMAN)

Liquid Scintillator
(Metal-loaded & Water-based)

Medical Physics
(e.g. 3D-imaging for Ion-beam therapy & TOF-PET)

unique requirement for individual detector

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

Dark Matter & Accelerator Physics
(e.g. LZ, JSNS2)

Liquid Scintillator Development

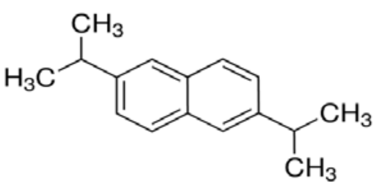
- Search for new scintillation medium with Scalability, Stability, Compatibility and Photon-yield
- Cleaner and Brighter (Purification)
  - Colored contaminant (Optical Transparency)
  - Radioactive contaminant (U/Th/Ra)
- Metallic-ion loadable (M-doped LS)
- Pulse-shape discrimination
  - Background rejection
- Directionality
  - Particle ID and background rejection
  - Water-based Liquid Scintillator (WbLS) and Slow liquid scintillator

Conventional Liquid Scintillator (Scalable to multi-tons)

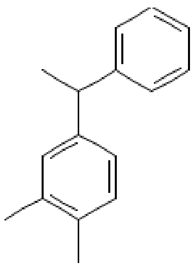
Table 1: Density, flash point and the wavelengths of the optical absorption/emission peaks (dissolved in cyclohexane) for several solvent candidates are shown.

C. Buck and M. Yeh, J. Phys. G (2016)

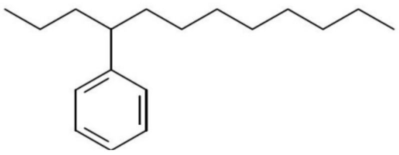
Molecule	chemical formula	density [kg/l]	flash point	abs. max.	em. max.
PC	C_9H_{12}	0.88	48°C	267 nm	290 nm
toluene	C_7H_8	0.87	4°C	262 nm	290 nm
anisole	C_7H_8O	0.99	43°C	271 nm	293 nm
LAB	–	0.87	$\sim$ 140°C	260 nm	284 nm
DIN	$C_{16}H_{20}$	0.96	$>$ 140°C	279 nm	338 nm
o-PXE	$C_{16}H_{18}$	0.99	167°C	269 nm	290 nm
n-dodecane	$C_{12}H_{26}$	0.75	71°C	–	–
mineral oil	–	0.82 – 0.88	$>$ 130°C	–	–



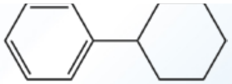
Di-isopropylnaphthalene (DIN)



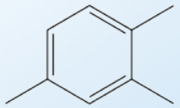
1-phenyl-1-xylyl-ethane (PXE)



Linear alkylbenzene (LAB)



Cyclohexylbenzene (PCH)



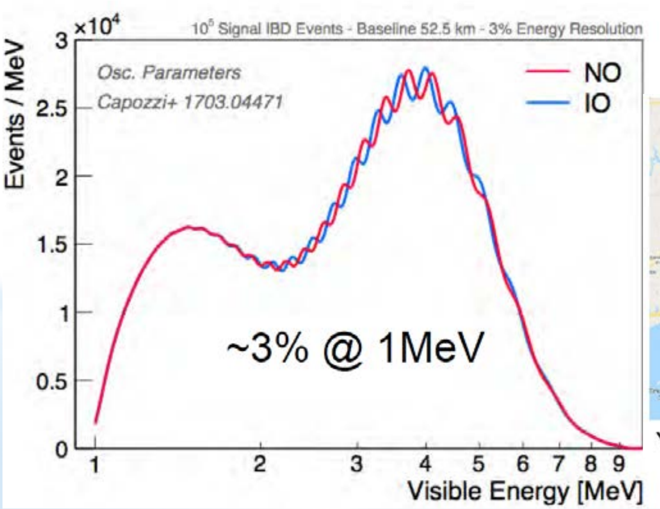
1,2,4-trimethylbenzene (PC)

Liquid scintillator today is safer and more environmental friendly with better compatibility

Brighter and Cleaner

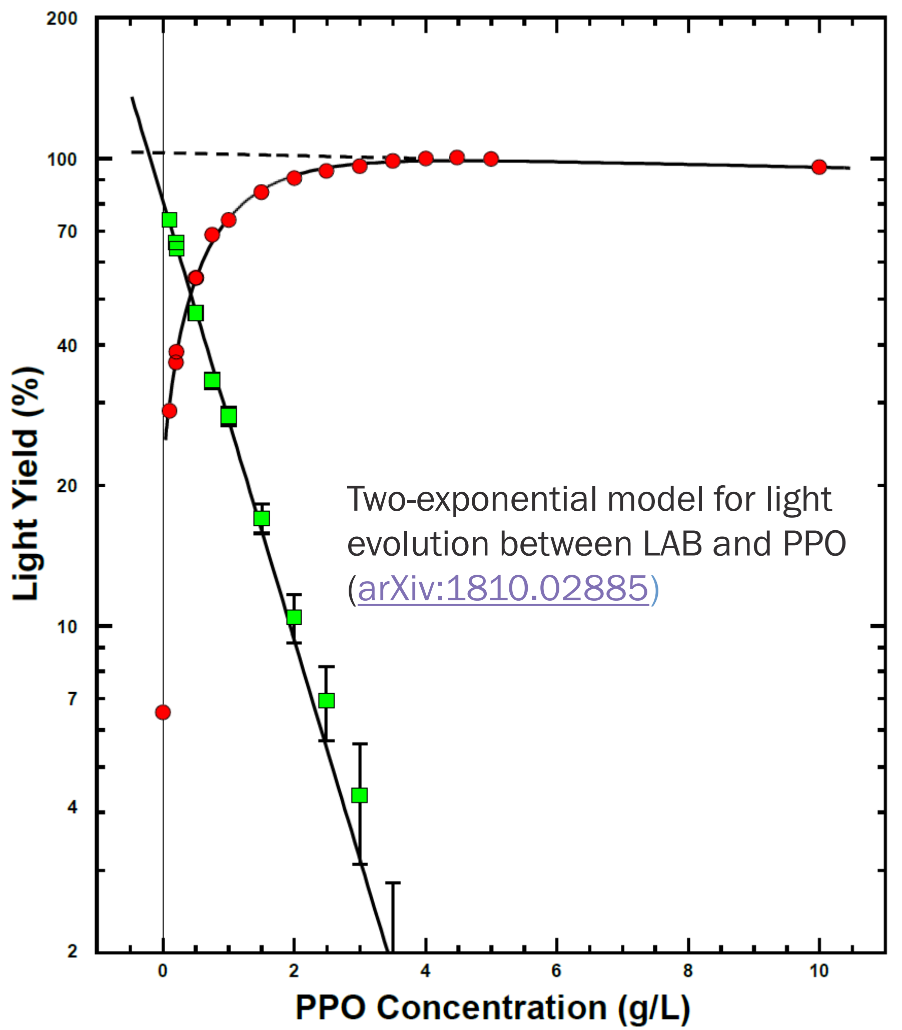
	KamLAND	BOREXINO	Daya Bay	PROSPECT	JUNO
Scintillator	PC/n-dodecane	PC	LAB	EJ309 (DIN)	LAB
Fluor/WLS	PPO	PPO	PPO/bis-MSB	PPO/bis-MSB	PPO(+bis-MSB)
Mass (ton)	1000	300	20	4	20000
PE/MeV (exp./req.)	250	500	160	795	1200
Energy Resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$7.5\%/\sqrt{E}$	$4.5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Energy Scale	2%	1%	1.5%	<1%	<1%

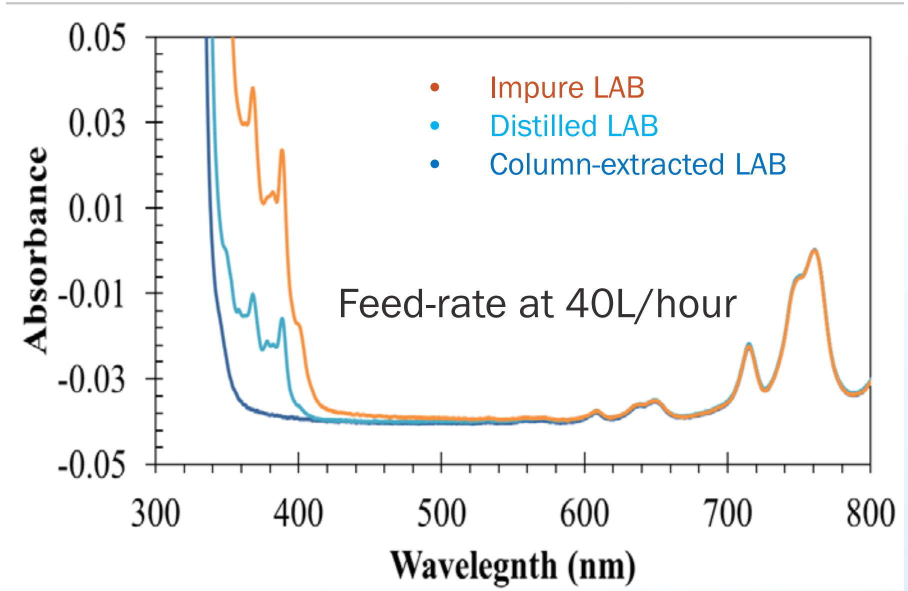
C. Buck and M. Yeh, J. Phys. G (2016) and W. Wang, AAP2018



- JUNO LS detector has very challenging performance goals in energy resolution and scale uncertainty
  - High light-yield and superior optical transparency (purification)
  - Sophistic energy calibration (non-linearity)
  - High photocathode coverage ($$$)

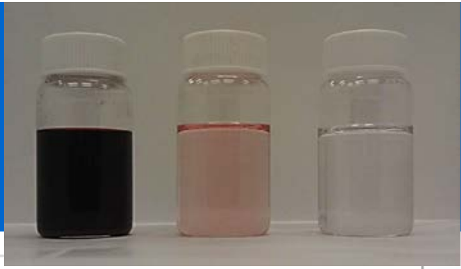
Purification (LS)

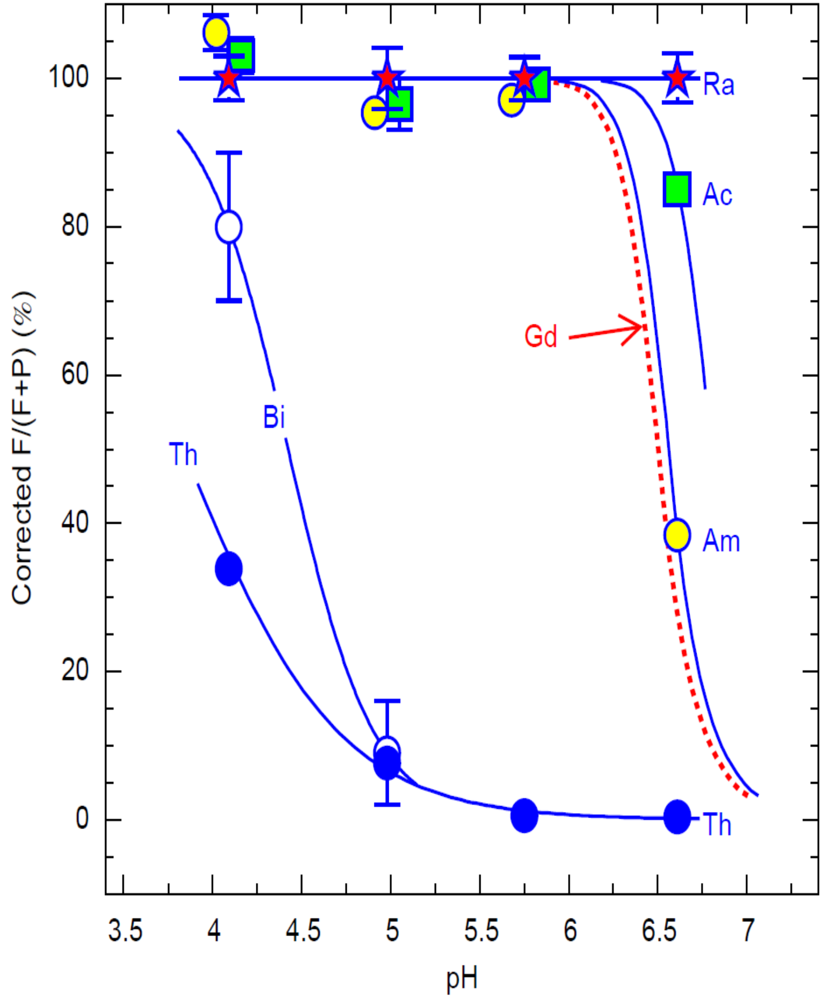




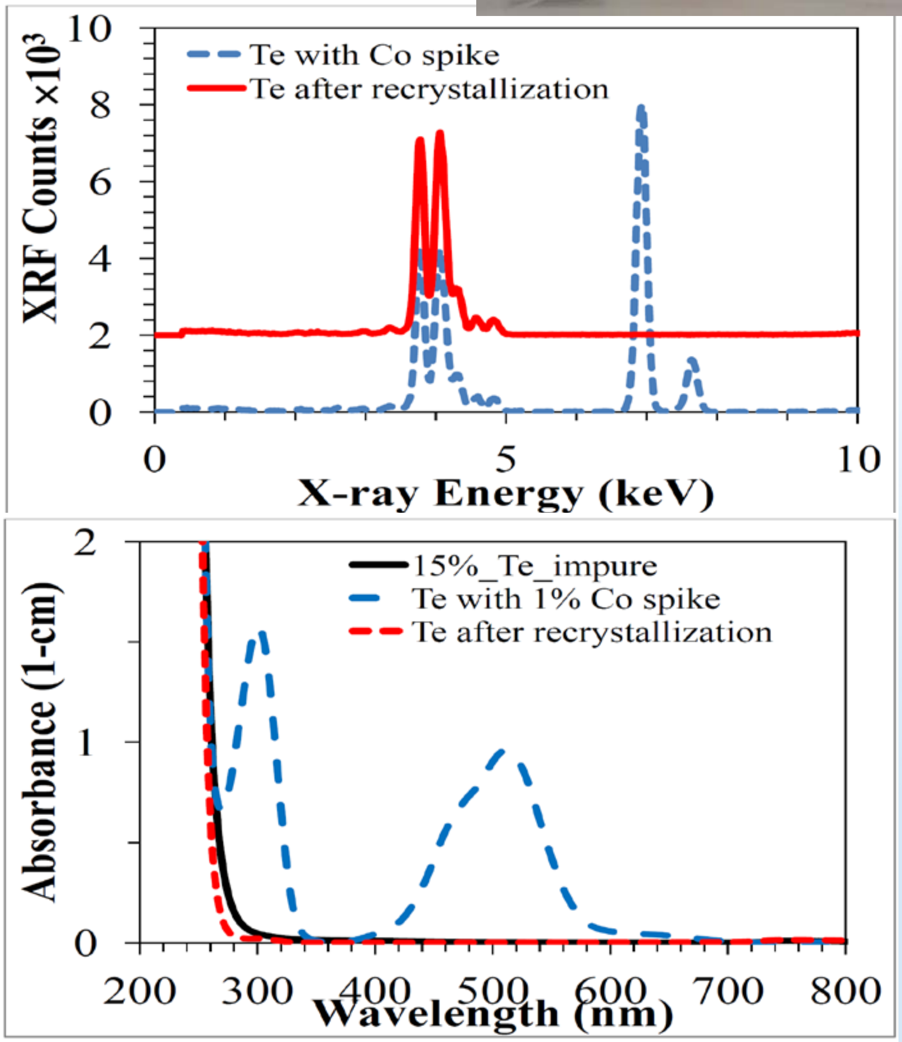
- Column-extraction gives better optical purification (but resin-saturation is problematic; regeneration)
- Once scintillator transition is completed, adding more fluors doesn't improve light-yield (self-absorption)

Purification (M-doped LS)



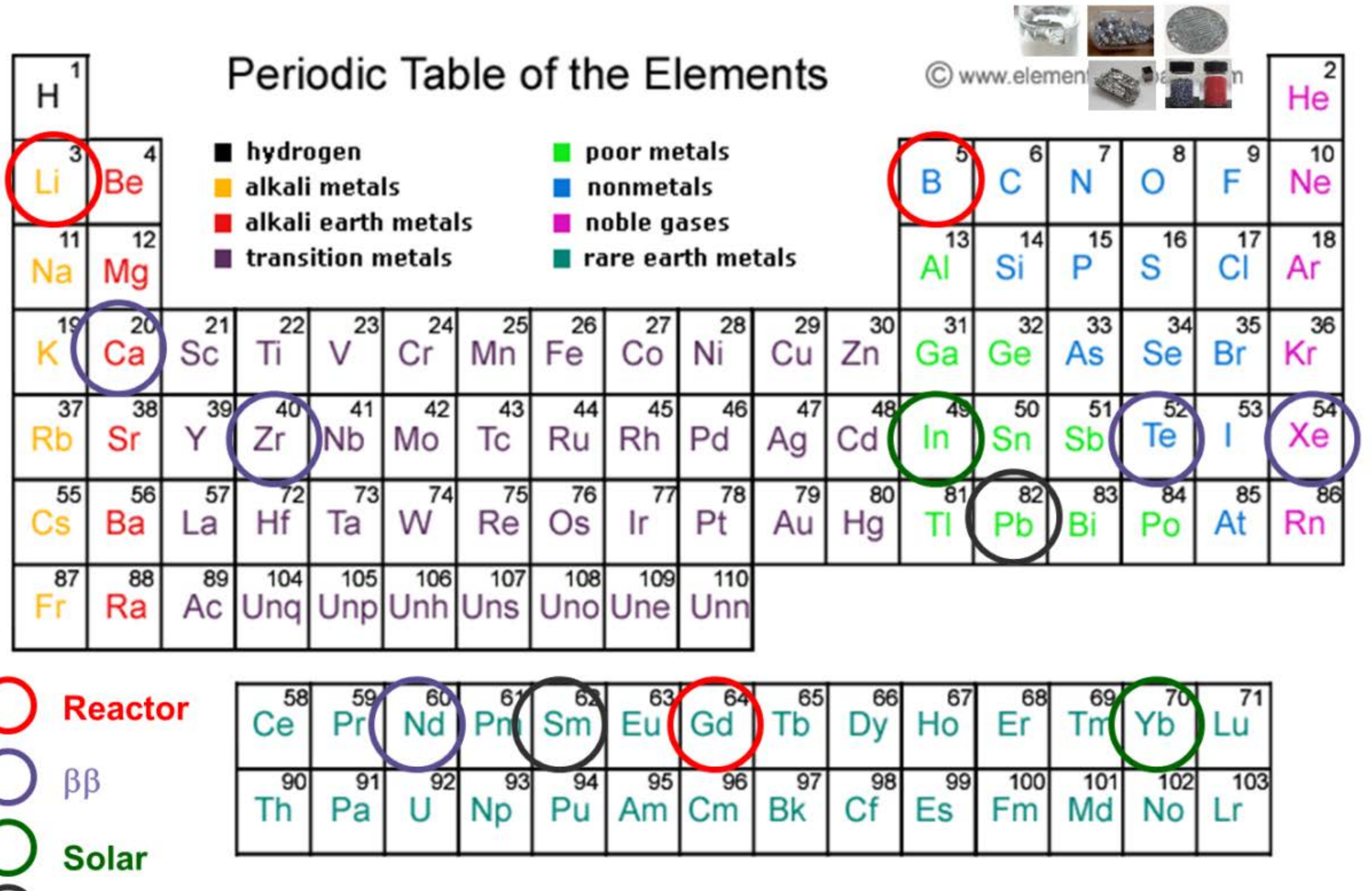


Gd self-scavenging, NIMA 618 (2010) 124-130



Te-recrystallization, NIMA 795 (2015) 132-139

Metal-loading Capability in Liquid Scintillator



Reactor

ββ

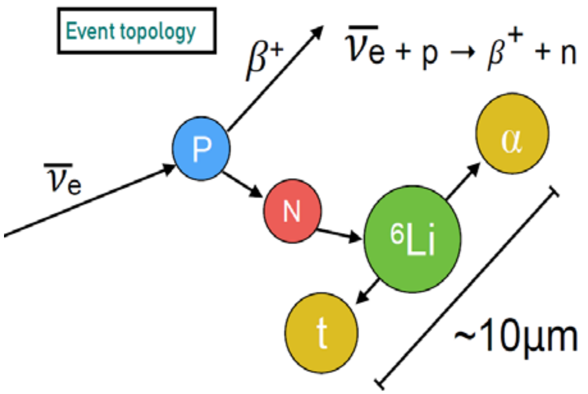
Solar

Others (e.g. ~8.4%Pb-loaded LS, 2.8%Mo-doped LS)

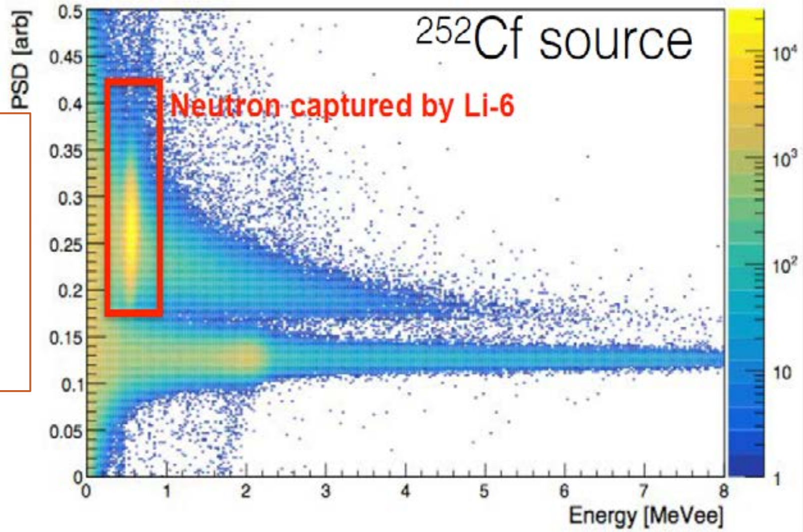
Metal-loading Techniques

- Organometallic complexes (multi-step, water-exclude)
  - Complexing ligand
    - carboxylic acid
      - From C_2 to C_{12} as early development by LENS (In-LS and Yb-LS)
      - C_6 for Gd-doped PC; C_9 for Gd-doped LAB
      - e.g. Palo Verde, Daya Bay, RENO
    - β-diketone (BDK)
      - Early development also in the context of LENS
      - 2,4-pentanedione (Hacac) and 2,2,6,6-Tetramethylheptane-3,5-dione (Hthd)
      - e.g. Double-Chooz, Nucifer
  - Solvent Extraction vs. Solid Dissolution
  - Not effective for hydrophilic elements
- Direct mixing (one-step, water-include)
  - Surfactant chemistry
  - Water-based mixing (e.g. PROSPECT)

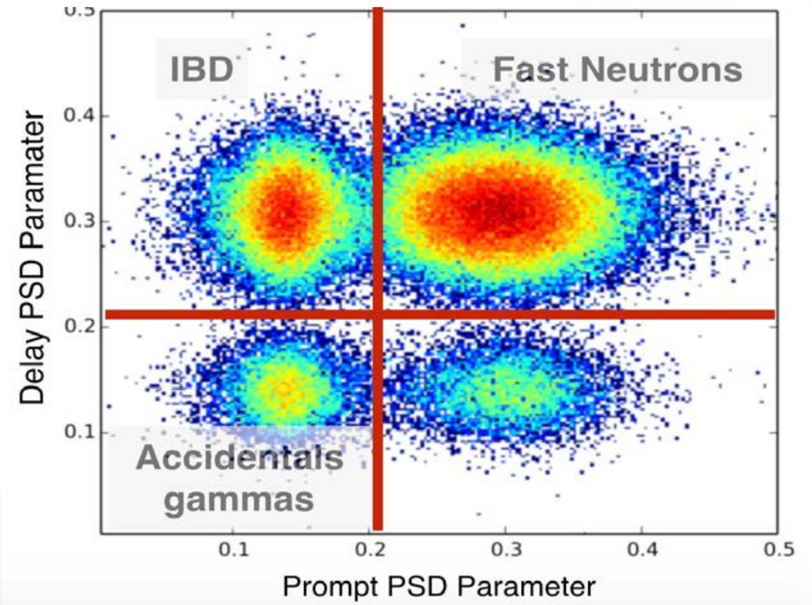
A "Surface" antineutrino detector



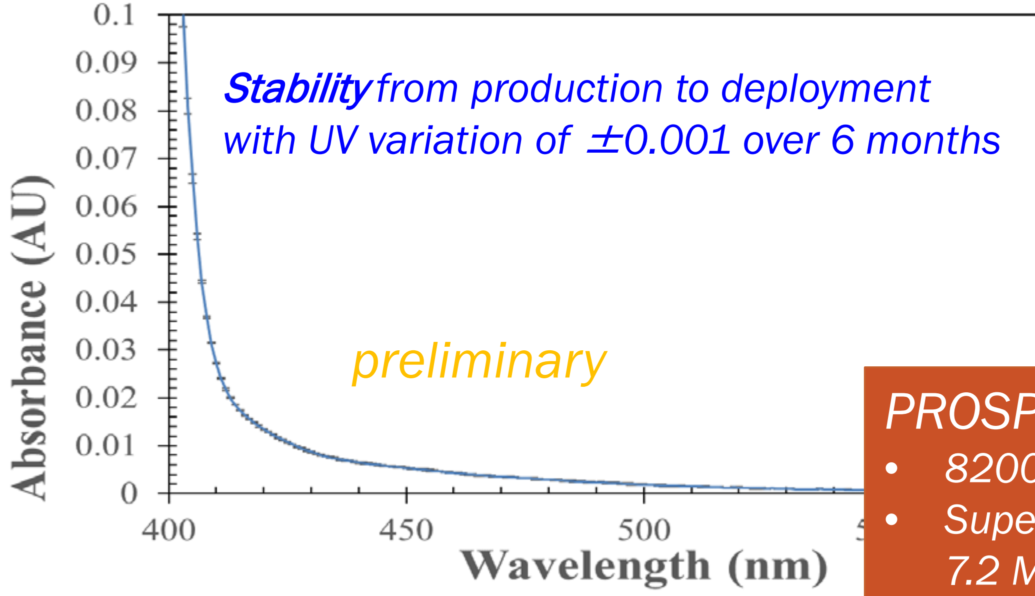
e-like prompt + n-captured delay coincidence + PSD to reject background



localization in a compact and segmented detector



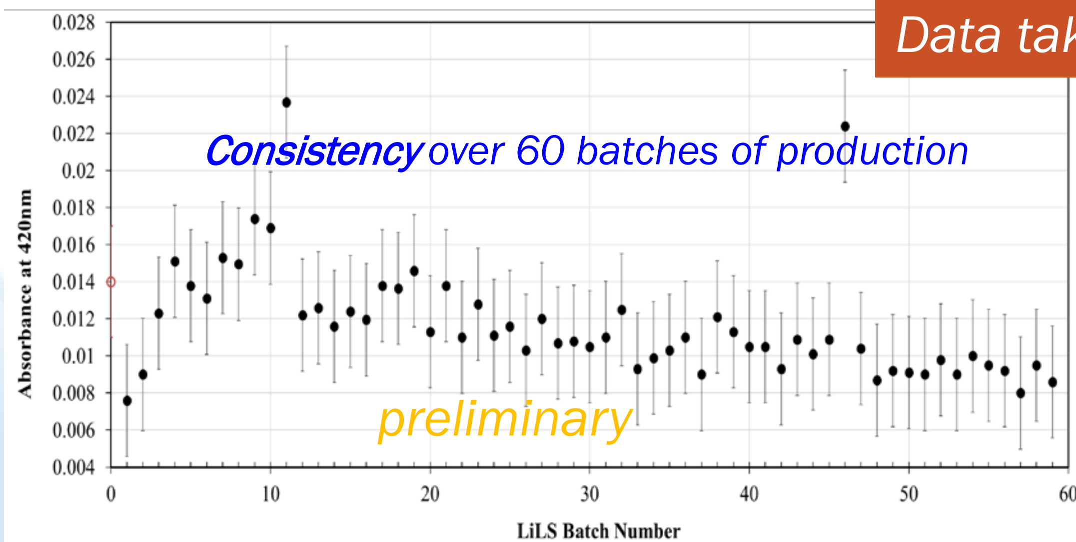
^{6}Li-LS (scalable with high stability)

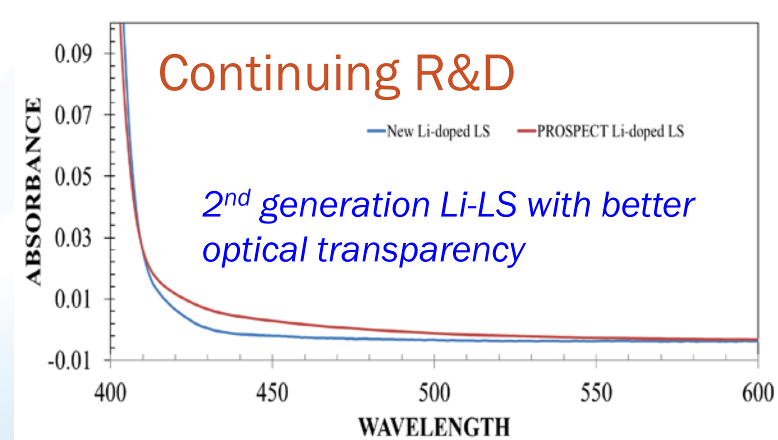


PROSPECT Li-LS detector

- 8200 ph/MeV (795 pe/MeV)
- Superior S/B at surface 1.7/1 (0.8-7.2 MeV)

Data taking since March 2018

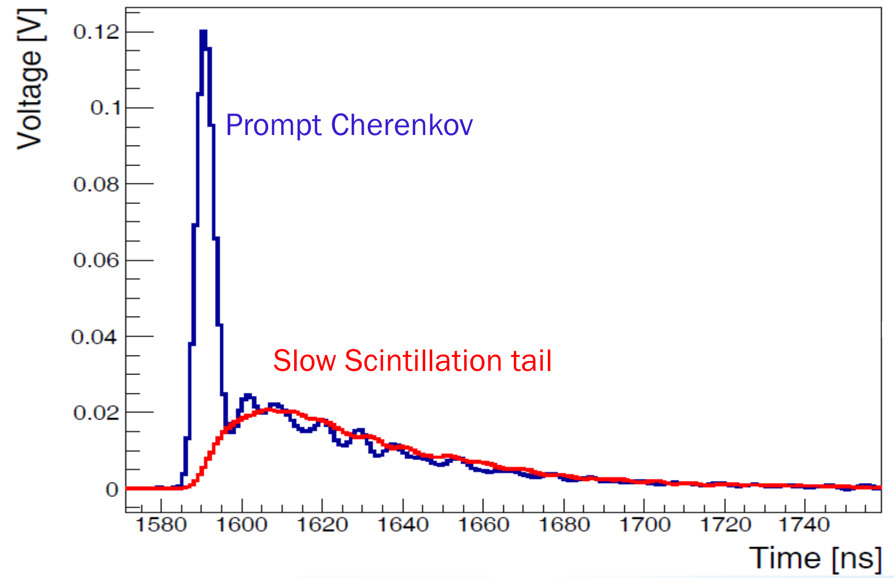


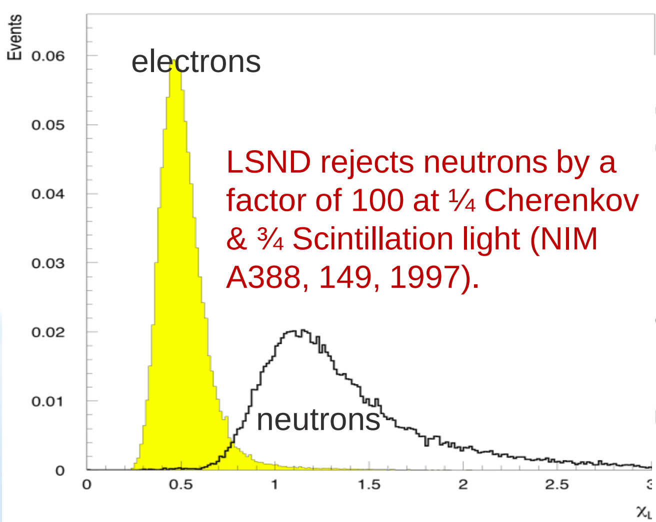


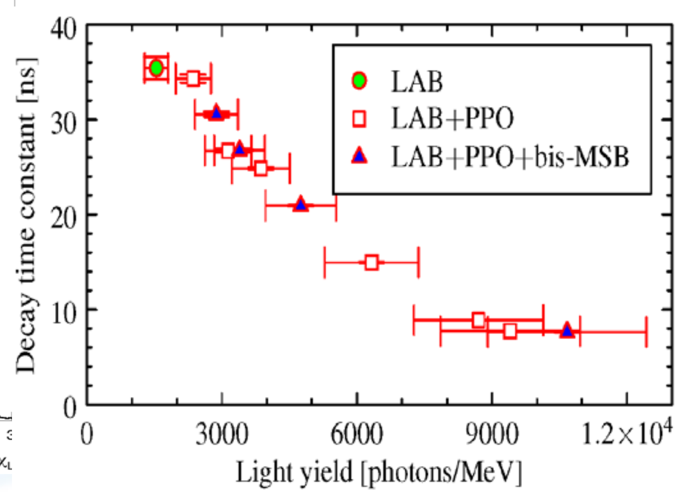
Directional Liquid Scintillator

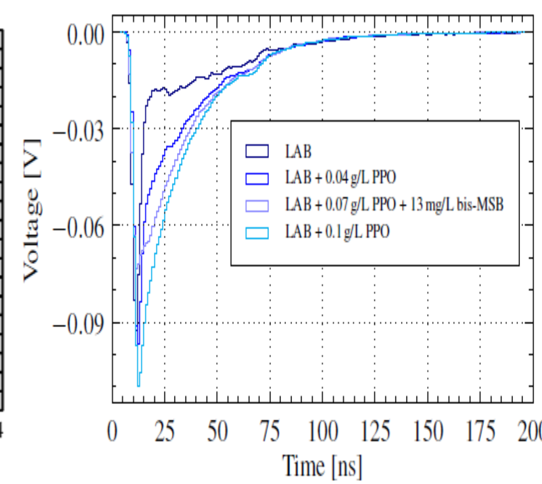
*A Cherenkov-visible Scintillation Liquid is the **key** to future LS detectors:*

- *Oil-based scintillator: **reducing** scintillation light or **slowing** scintillation decay-time to allow Cherenkov imaging*
- ***Water-based Liquid Scintillator (WbLS)***
- *Fast photosensors/electronics (LAPPD)*
- *Liquid Scintillator Imaging*



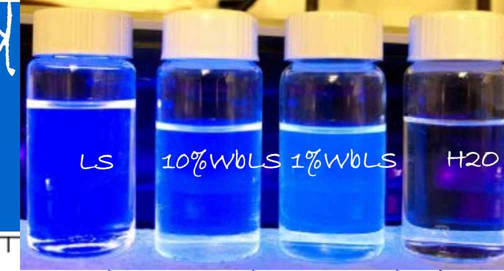


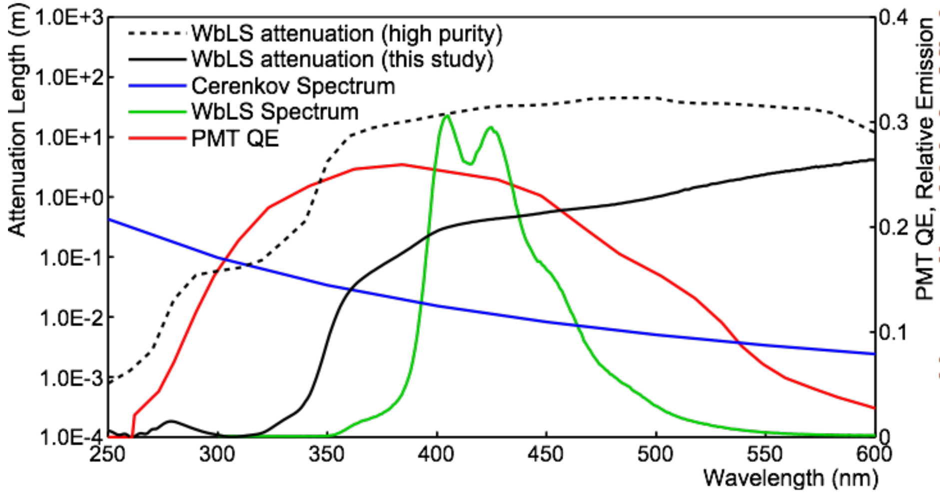


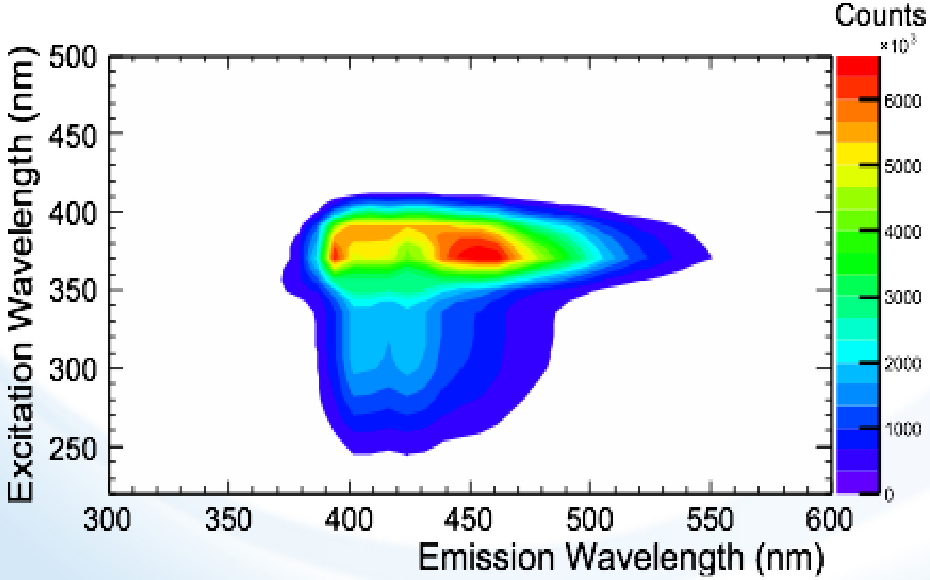


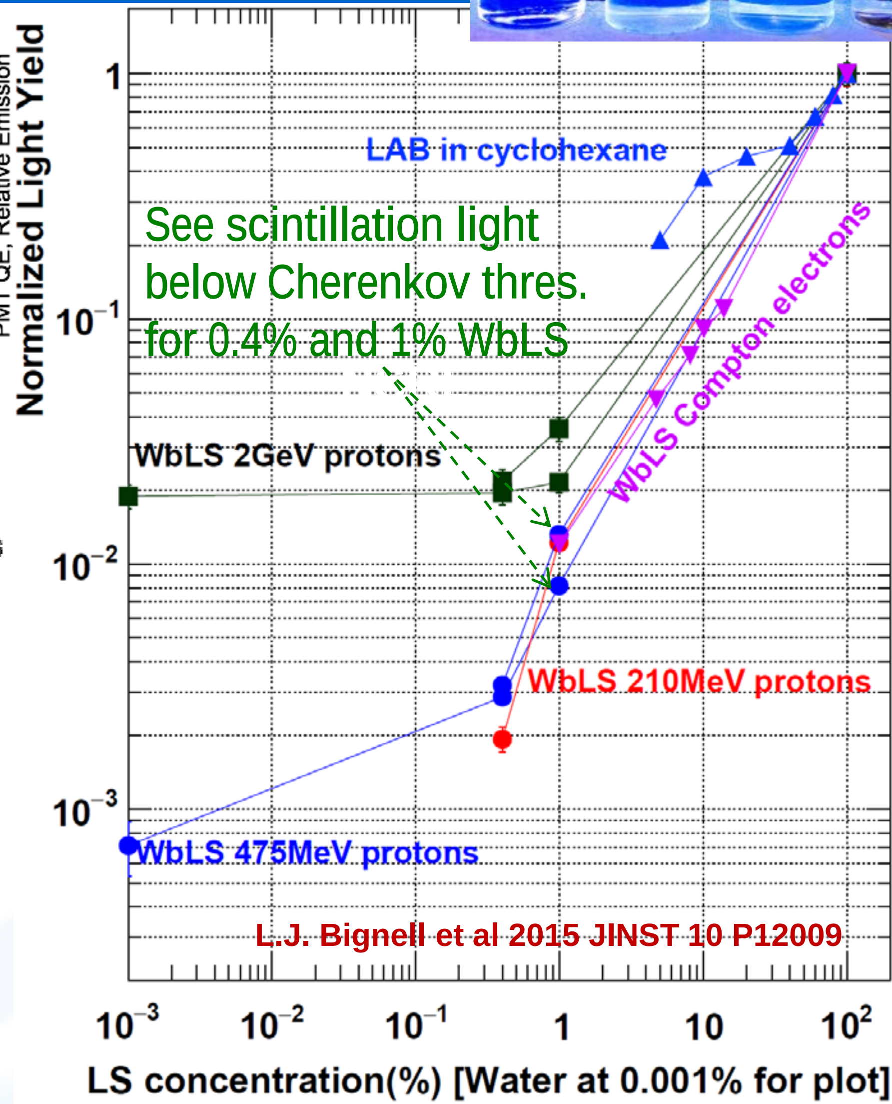
NIM. A830, 303 (2016) and J. Astroparticle Phys (submitted)

WbLS: low-energy threshold with Cherenkov Imaging







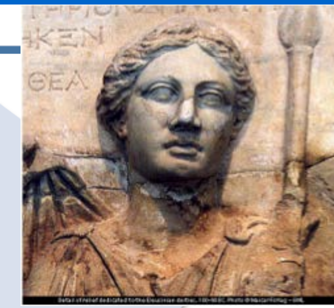


Advanced Instrumentation Testbed (AIT)-WATCHMAN

See WATCHMAN talk by Chris Mauger

Standoff for finding small reactors within days to months

>10^1 km → >10^2 km → ~10^3 km



Size~$$$

~10^2 ton
WATCHBOY, MARS, EGADS (complete)

~10^3 ton
WATCHMAN

~10^6 ton
Megaton-scale Gd-doped or water based scintillator

>~10^6 ton
Megaton-scale detector with directionality

WbLS AIT-detector

- Cost-effective for Megaton detector
  - At LS~$3k per ton, 1% WbLS ~ $30M (+Water)
- Fundamentals known from previous DUNE WD design and other scintillator expt's
- Yet R&D's for ***feasibility*** and ***scalability*** need to be demonstrated

A. Bernstein

2012-2017 activities → **~6 year, 30 M$ lifecycle (decision in 2017)** → **Long-term vision**

WbLS Evolution

See THEIA talks by Gabriel and THEIA/WbLS poster by Vincent

Size (liters)

100,000,000 — **20??**: THEIA

3,500,000 — **2025+**: WATCHMAN

27,000 — **2019+**: ANNIE

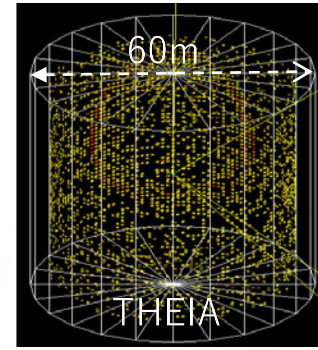
1,000 — **2018 –** : circulation, S/C separation, scale-up product, material compatibility

100

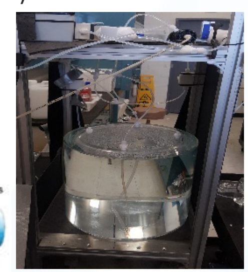
10

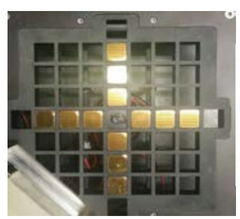
1

0.1

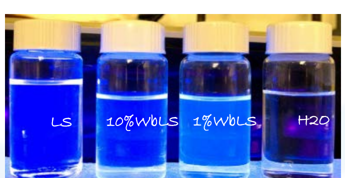


2016 –: optimization, purification, characterization

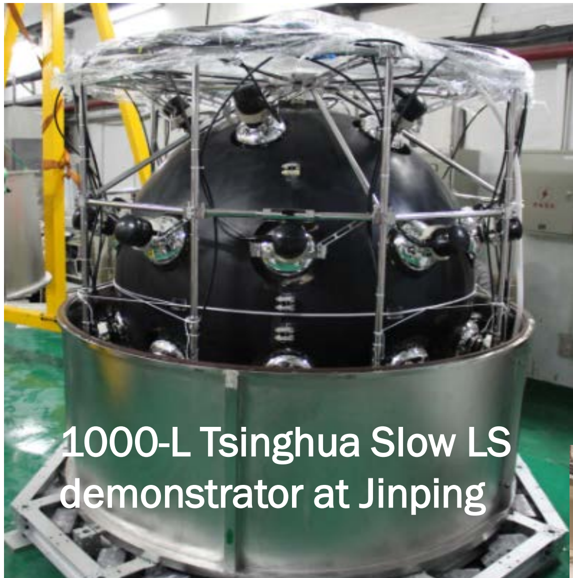


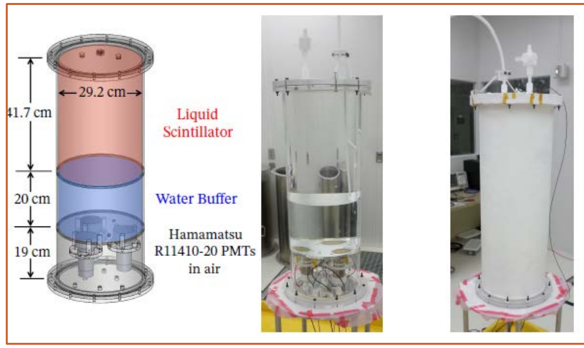


2012 – : survey, formulation, characterization

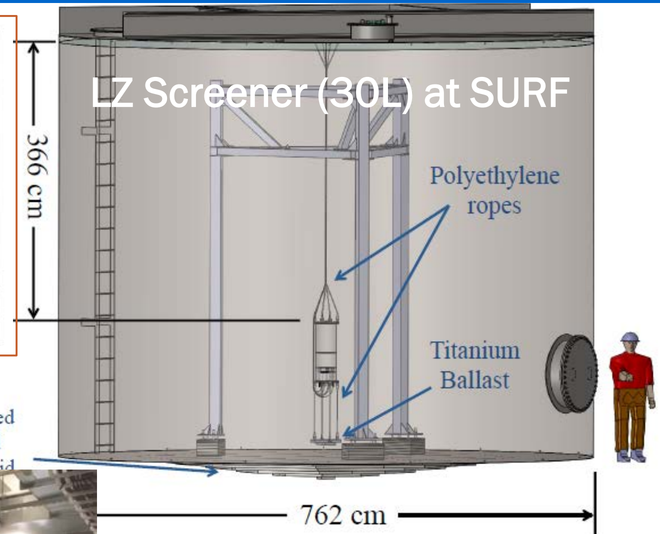


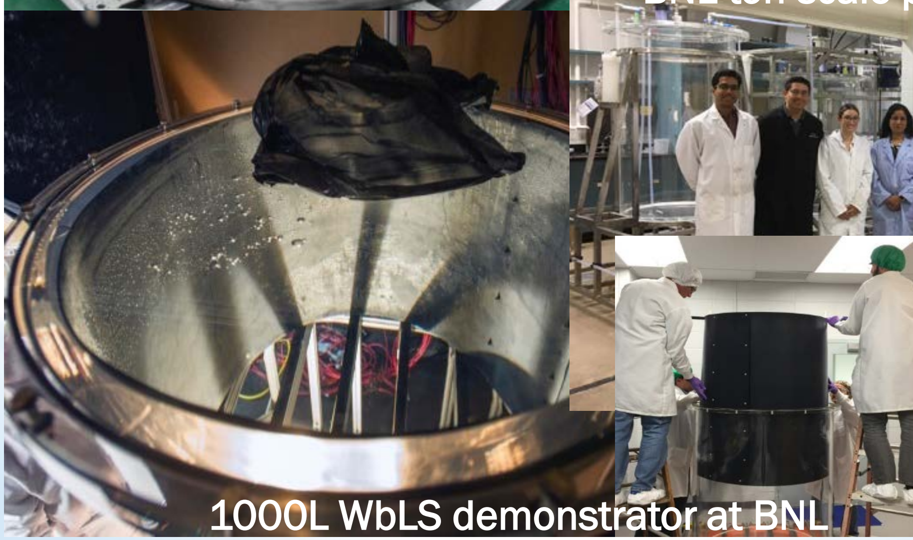
Large Instrumentation Development (few selected examples; see posters)





Sensitivity of ^{14}C at ~10^{-17}





Summary

- Many progress has been made over the past decade
  - A safer (f.p.) and environment-friendly scintillator with better compatibility
  - Improved metal-loading technologies to expand physics reach and extend stability
- Purification enables ultraclean (metal-doped) scintillator detectors
  - Remove colored and radioactive impurities
  - LZ 0.1%Gd-LS outer detector with U/Th < 1ppt
  - Large-scale characterization and purification facility development
- A surface-operable scintillator detector has strong implication in safeguard and nonproliferation
  - Compact with superior S/B ratio
  - PROSPECT 6Li-LS
- Future massive water-Cherenkov scintillation detector is reachable
  - Low-energy threshold with Cherenkov directionality of WbLS (cost-effective)
  - AIT-WATCHMAN and THEIA