BNL Material Development

Minfang Yeh

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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)

Nonproliferation
(e.g. AIT-WATCHMAN)

Common features between detectors

Liquid Scintillator
(Metal-loaded & Water-based)

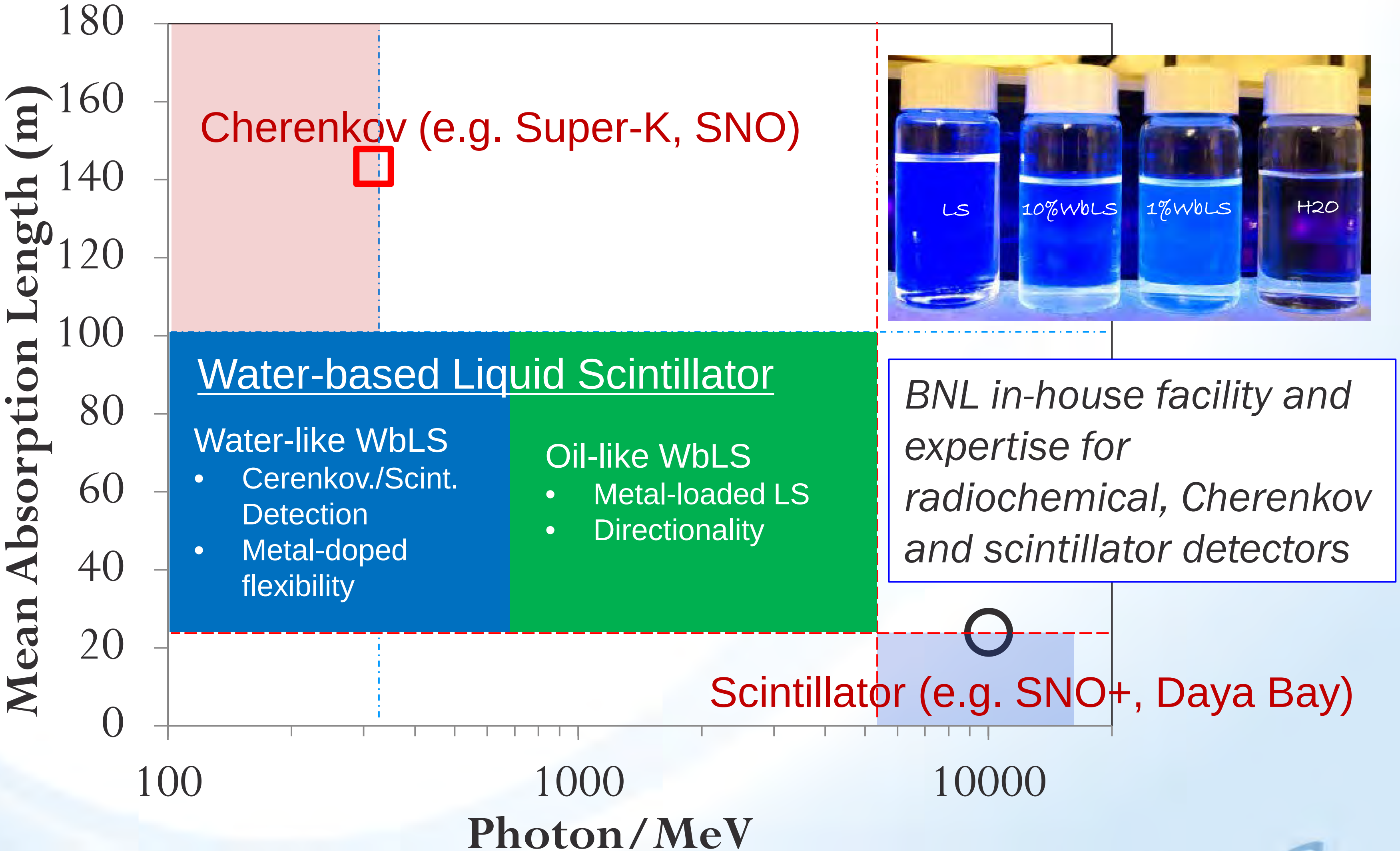
unique requirement for individual detector

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

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

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

If you always do what you always did, you will always get what you always got. ***-Albert Einstein***



BNL Scintillator R&D's

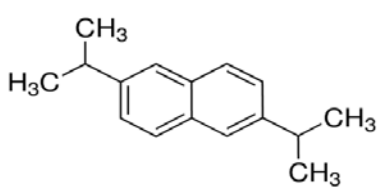
- Pure Liquid Scintillator (LS)
  - Stability, transparency, photon-yield, PSD
  - Scalability, Capability for purification/synthesis, Compatibility (and *Directionality*?)
- Metal-doped Liquid Scintillator (M-doped LS)
  - Extend physics reaches for scintillator detectors
- Water-based Liquid Scintillator (WbLS)
  - Cost-effective approach for large-scale detector
  - Directional scintillation water probing physics below Cherenkov threshold

Liquid Scintillator Development

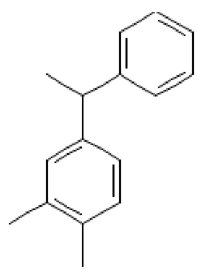
Table 1: Density, flash point and the wavelengths of the optical absorption/emission peaks (dissolved in cyclohexane) for several solvent candidates are shown.

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

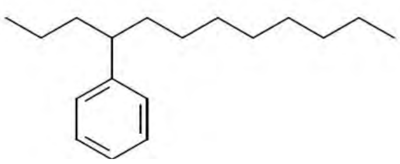
Molecule	chemical formula	density [kg/l]	flash point	abs. max.	em. max.
PC	C_9H_{12}	0.88	48°C	267 nm	290 nm
toluene	C_7H_8	0.87	4°C	262 nm	290 nm
anisole	C_7H_8O	0.99	43°C	271 nm	293 nm
LAB	–	0.87	$\sim$ 140°C	260 nm	284 nm
DIN	$C_{16}H_{20}$	0.96	> 140°C	279 nm	338 nm
o-PXE	$C_{16}H_{18}$	0.99	167°C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



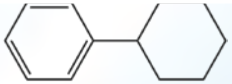
Di-isopropylnaphthalene (DIN)



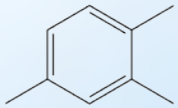
1-phenyl-1-xylyl-ethane (PXE)



Linear alkylbenzene (LAB)



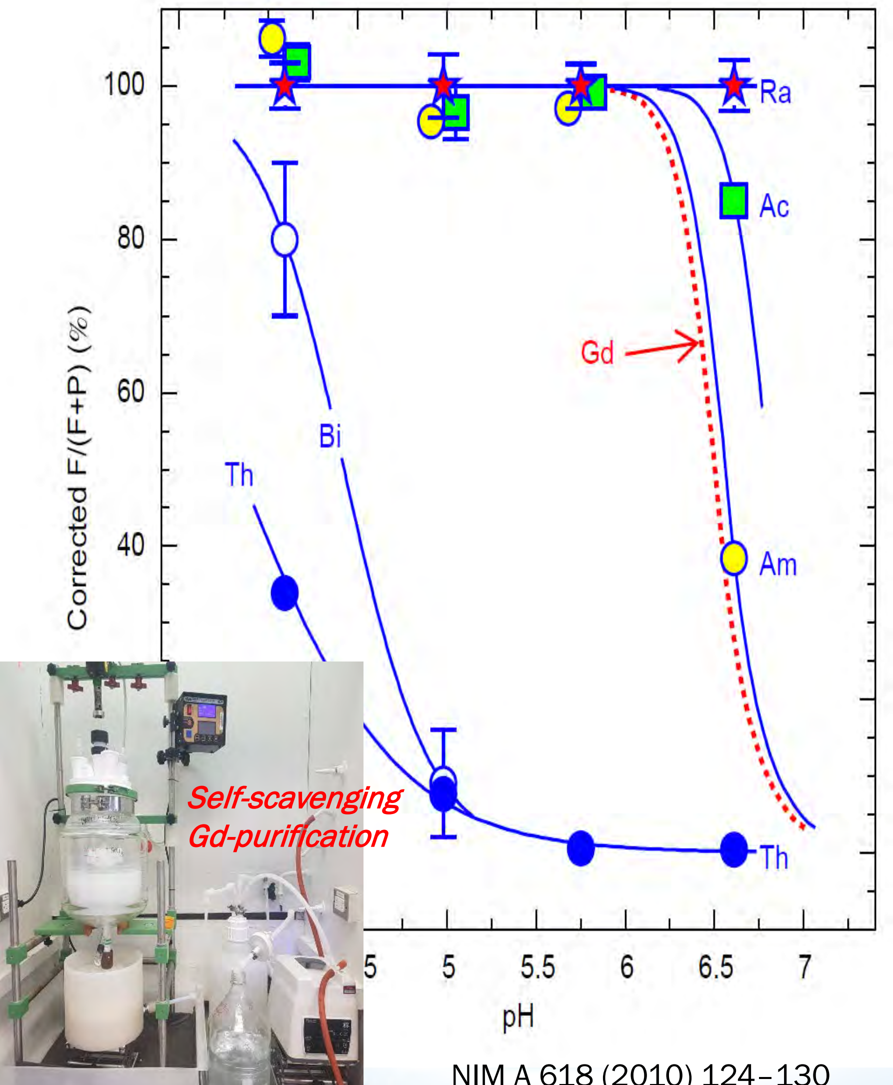
Cyclohexylbenzene (PCH)



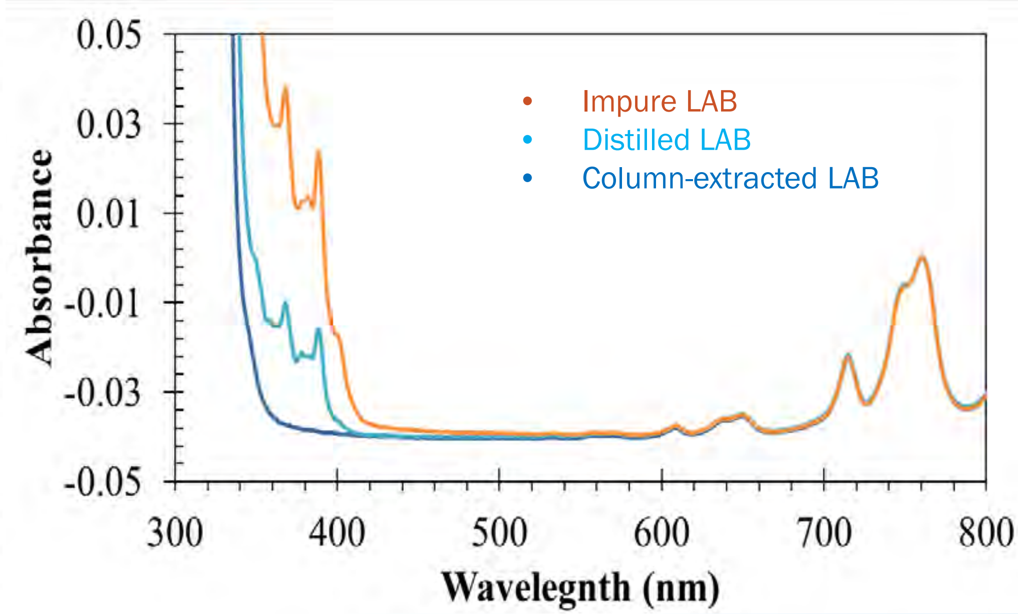
1,2,4-trimethylbenzene (PC)

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

Purification Development



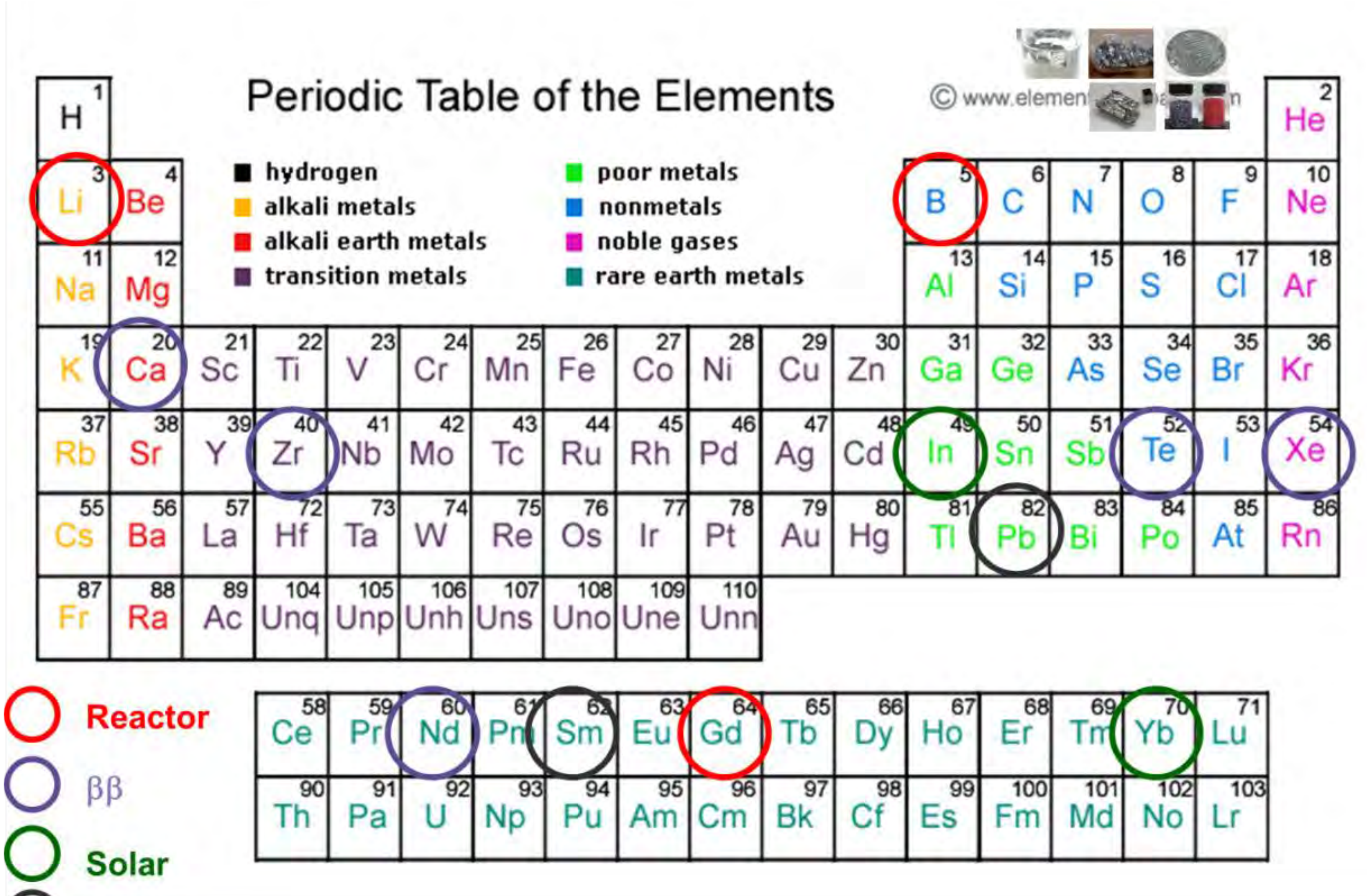
NIM A 618 (2010) 124–130



Ton-scale Liquid Production Facility

Currently dedicated to LZ; available for other experiments in 2020

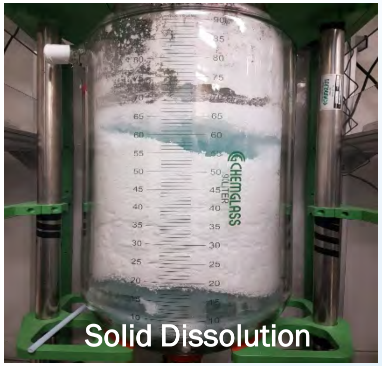
Metal-doped Liquid Scintillator



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

Metal-loading Techniques

- Organometallic complexes (multi-step, water-exclude)
  - Require a 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)

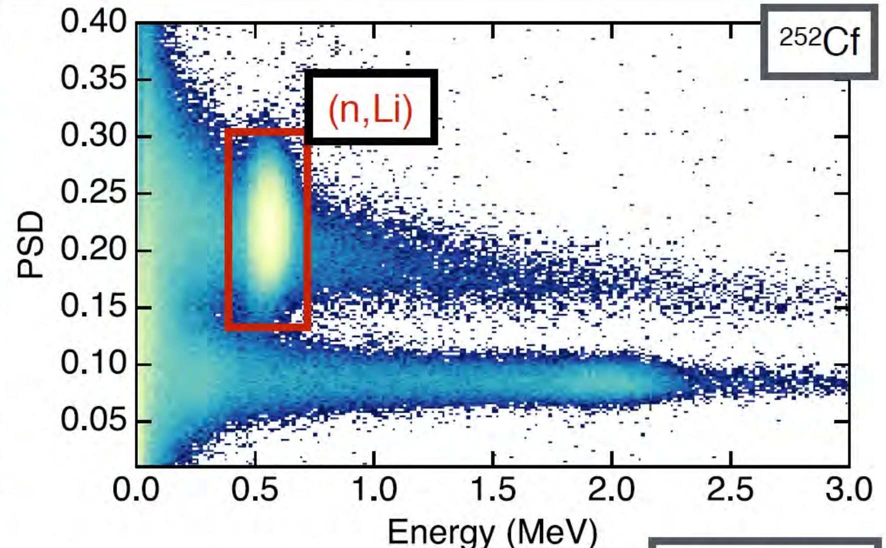


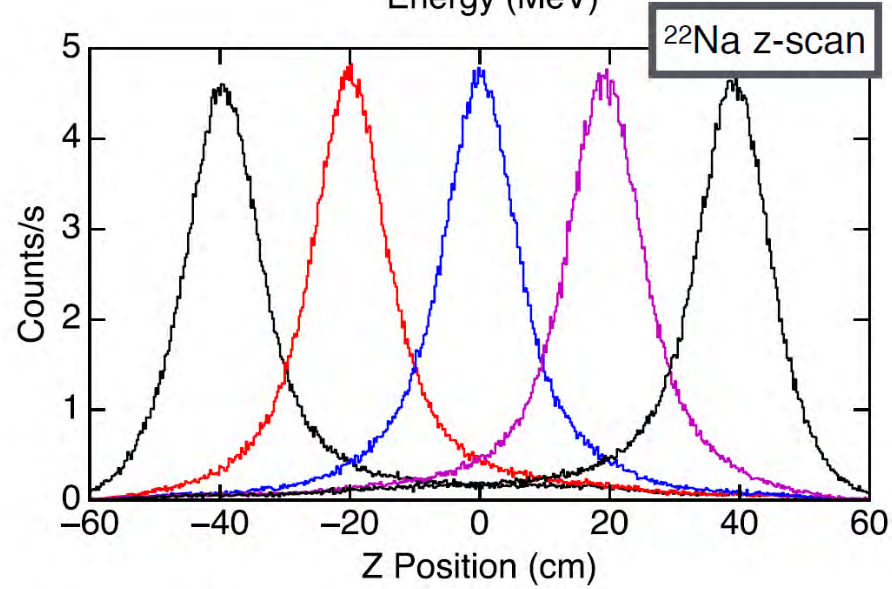
Solid Dissolution

Solvent Extraction

Ex. ^{6}Li-doped LS (Criteria from PROSPECT prototype)

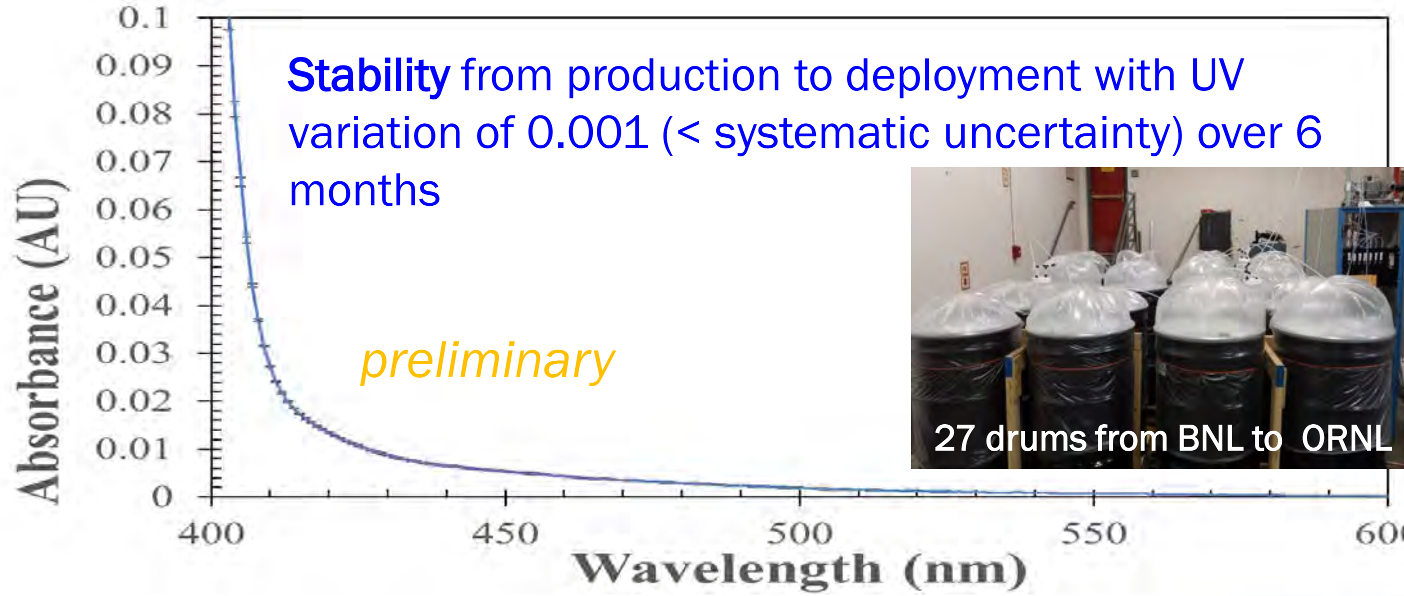
- In operation since March 2016, near continuous data-collection
- Measured light collection with ^{6}LiLS: >550PE/MeV
  - **5% energy resolution at 1MeV**
- Measured PSD Figure of Merit: 1.25 at (n,Li) capture
  - **>99.9% background rejection**
- Double-ended readout
  - Position reconstruction along cell length



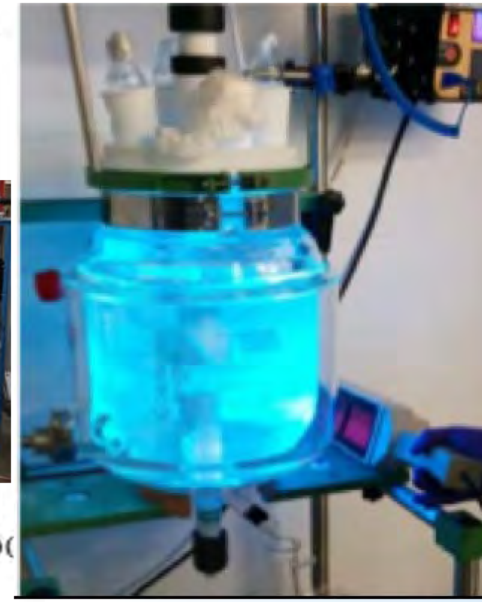


Scalability (~5 tons in 6 months)

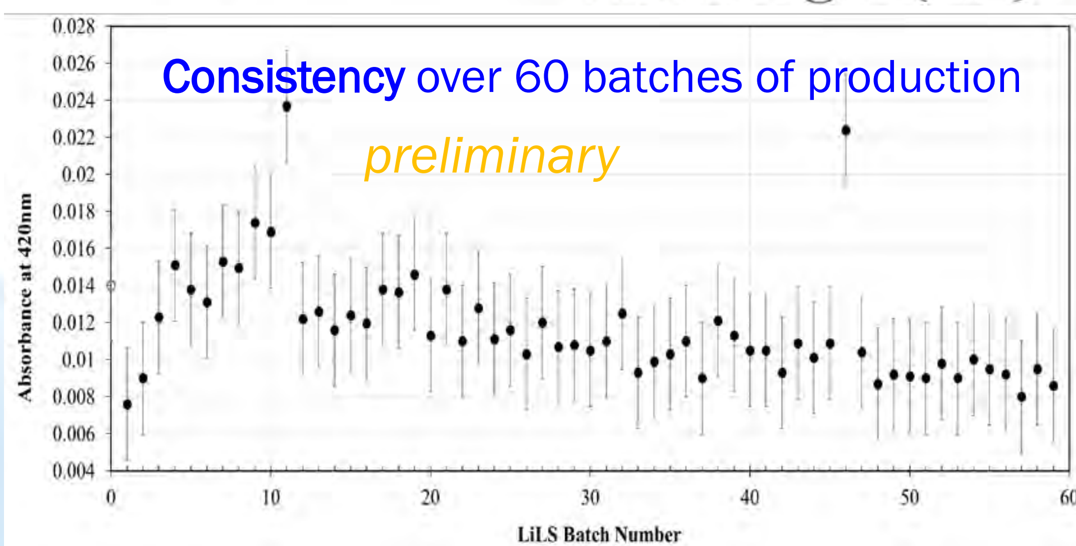
Stability from production to deployment with UV variation of 0.001 (< systematic uncertainty) over 6 months



27 drums from BNL to ORNL

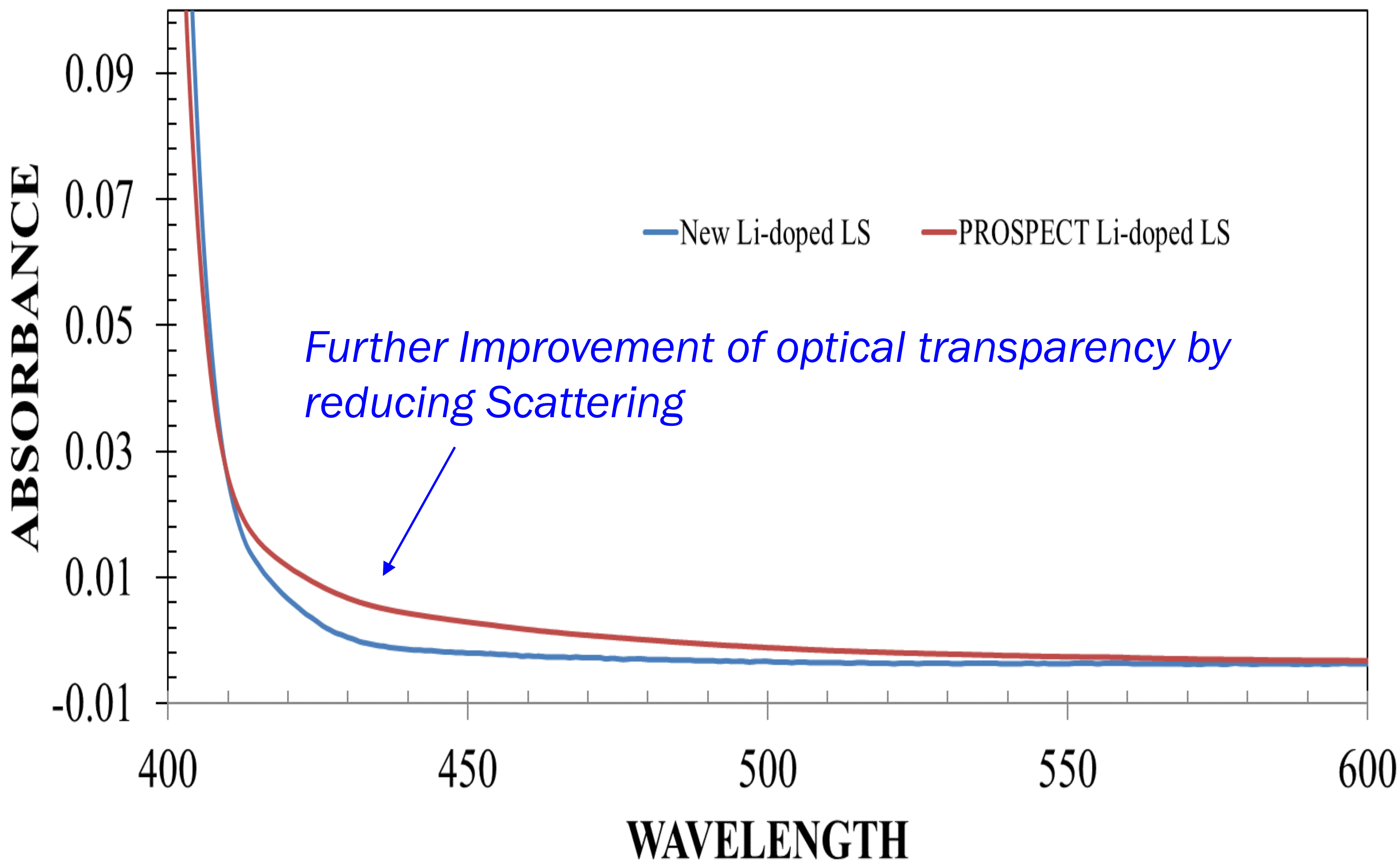


Consistency over 60 batches of production



Production at BNL

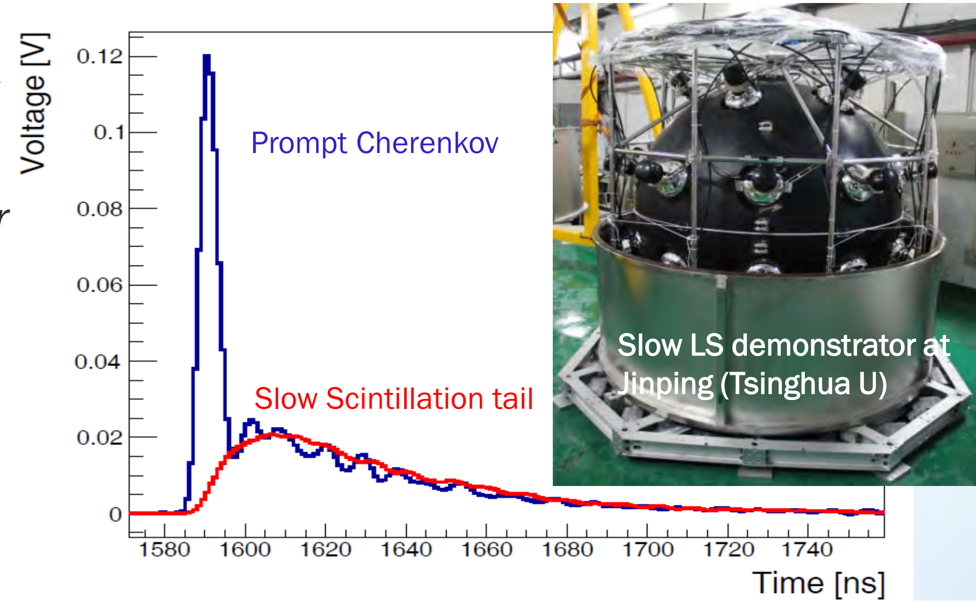
2nd Generation Li-doped LS

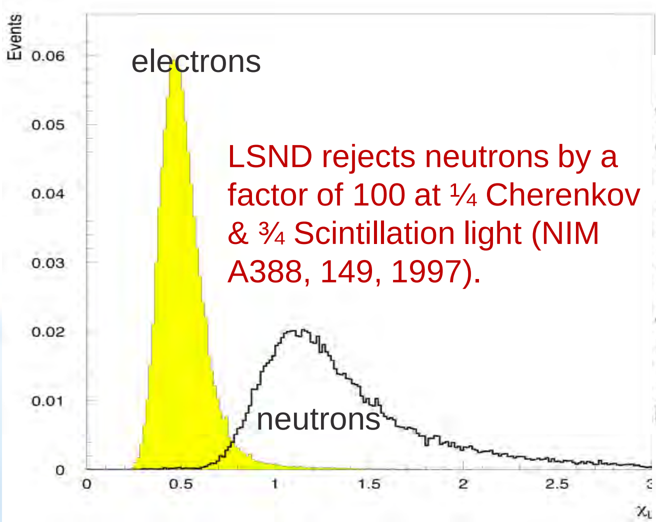


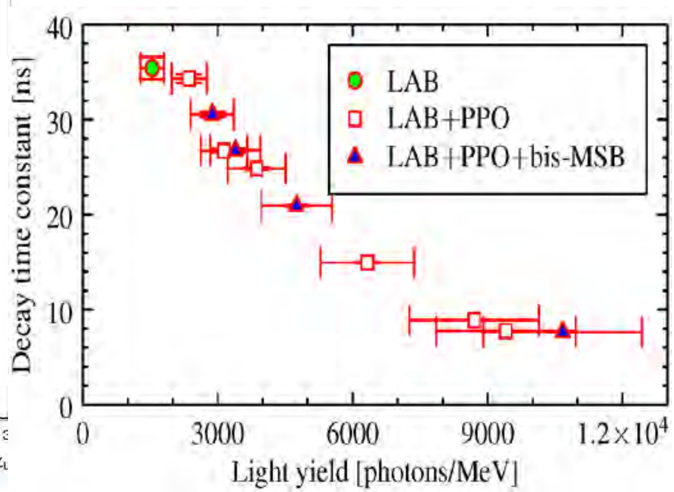
Directional Liquid Scintillator

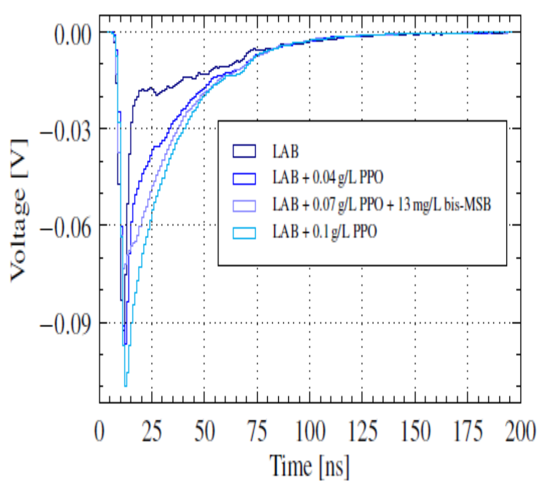
*A Cherenkov-visible Scintillation Liquid is the **key** to future LS detectors:*

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



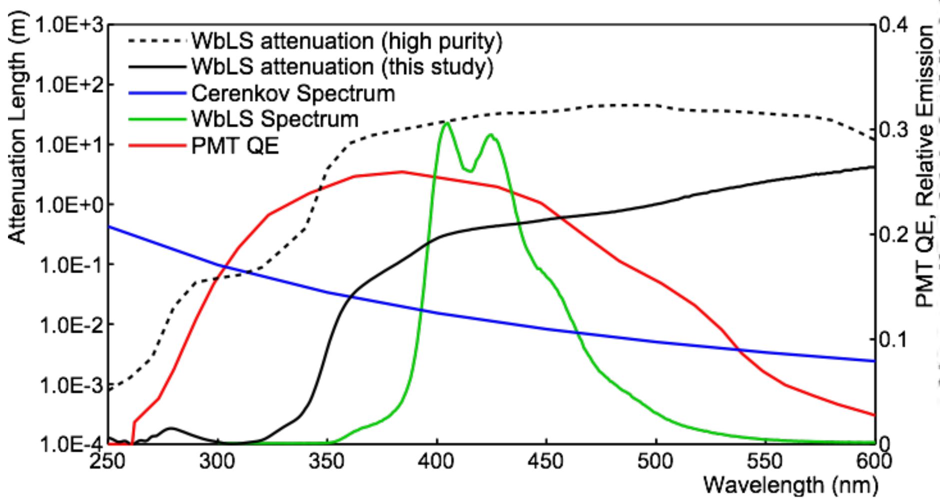


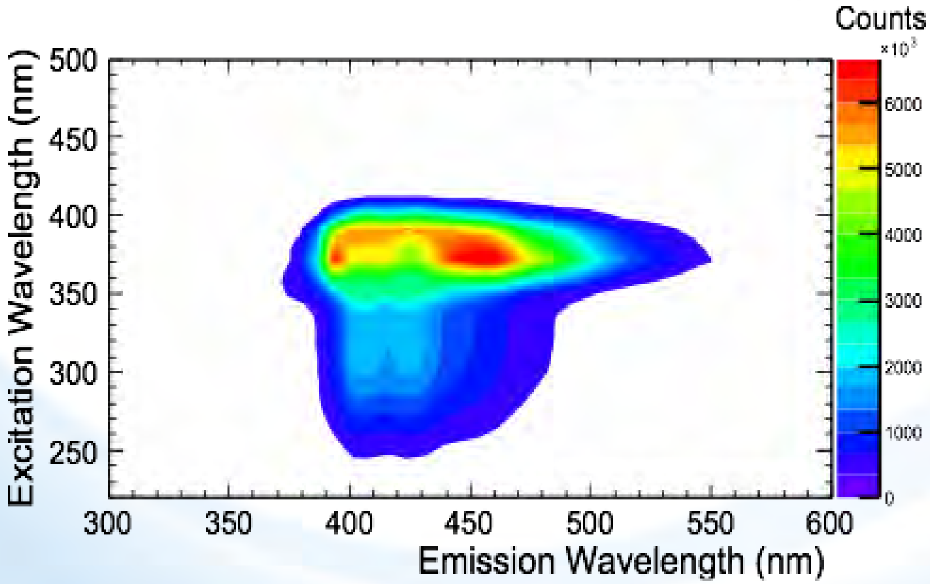


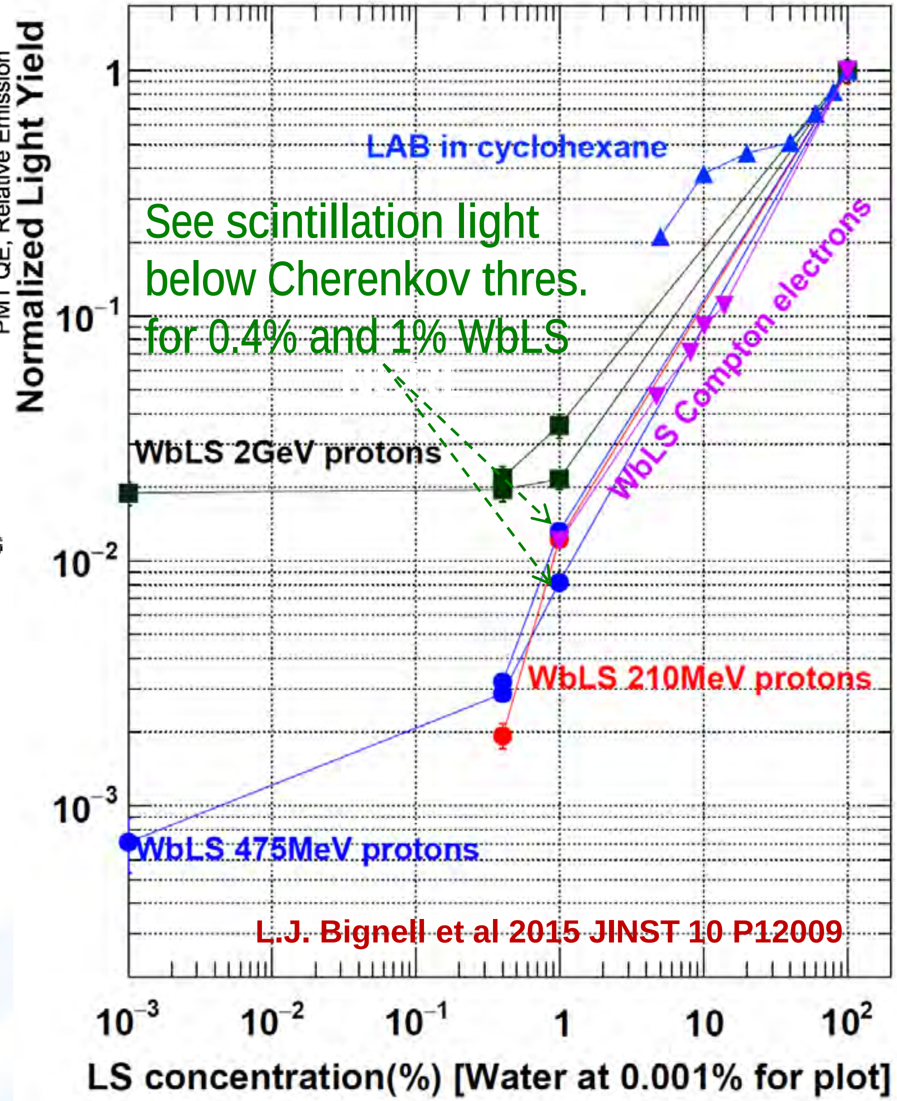


NIM. A830, 303 (2016) and J. Astroparticle Phys (submitted)

WbLS today: 1% WbLS Properties capable of detection below Cherenkov







Advanced Instrumentation Testbed (AIT)-WATCHMAN

Standoff for finding small reactors within days to months

>10¹ km → >10² km → ~10³ km

Detector Size

$$$

~10² ton

WATCHBOY, MARS, EGADS (complete)

~10³ ton

WATCHMAN

~10⁶ ton

Megaton-scale Gd-doped or water based scintillator

>~10⁶ 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 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**

Sequential WbLS Deployment

In-situ WbLS deployment by direct injection of scintillator to water detector; followed by circulation mixing

Summary

WbLS Detector (liters)

100,000,000 — **2??**: THEIA

2025+: WATCHMAN

3,500,000 — **2019+**: ANNIE

27,000

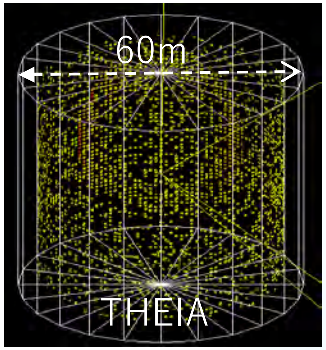
1,000

100

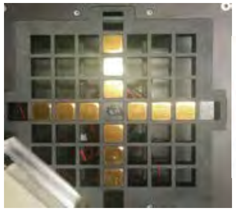
10

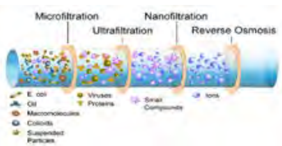
1

0.1

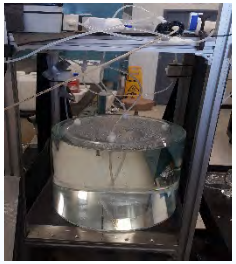


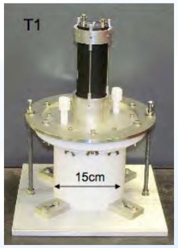
2018 –: circulation, S/C separation, scale-up product, material compatibility





2016 –: optimization, purification, characterization





2012 –: survey, formulation, characterization