Water-based Liquid Scintillator (WbLS) Technology

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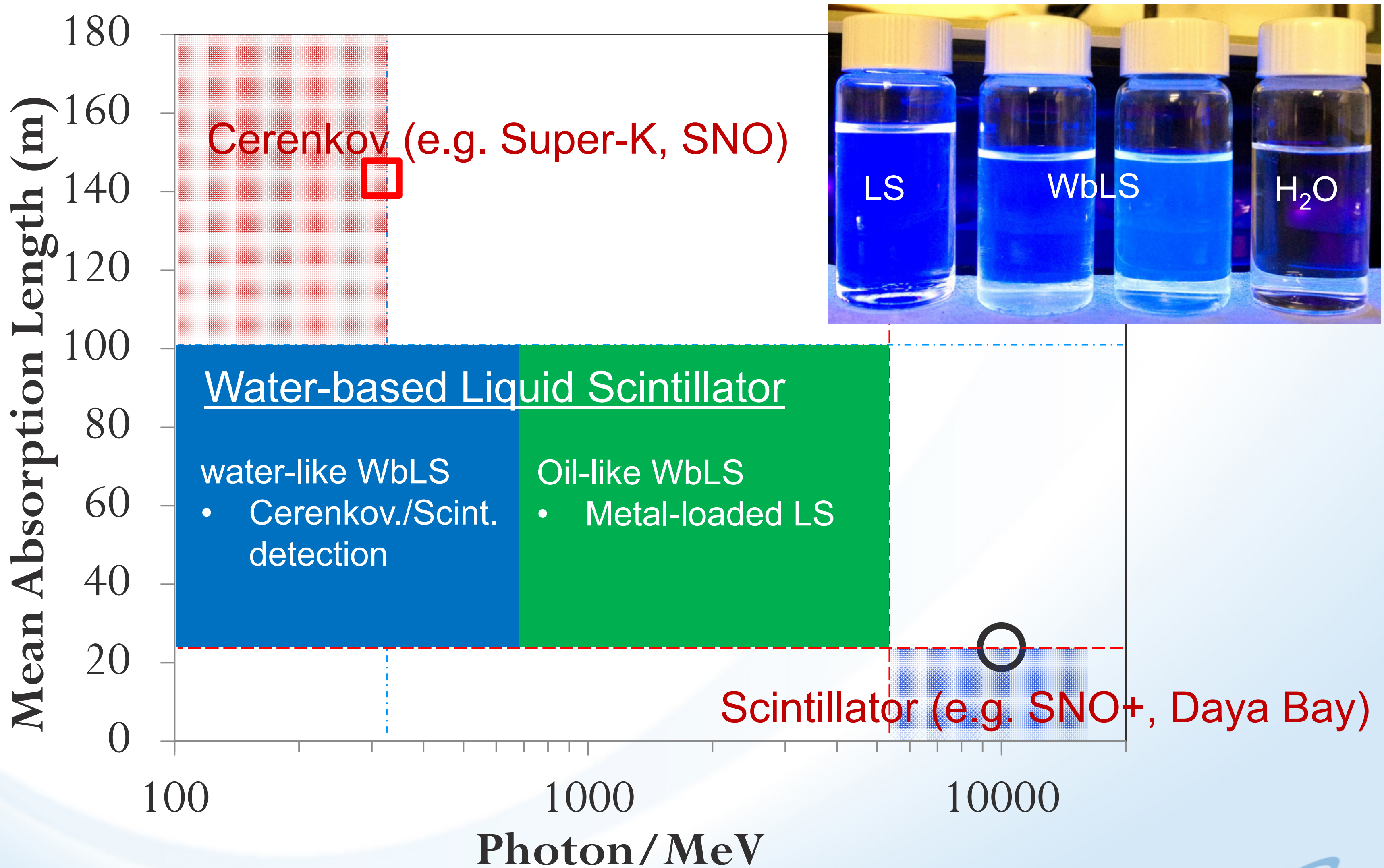
Neutrino and Nuclear Chemistry

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

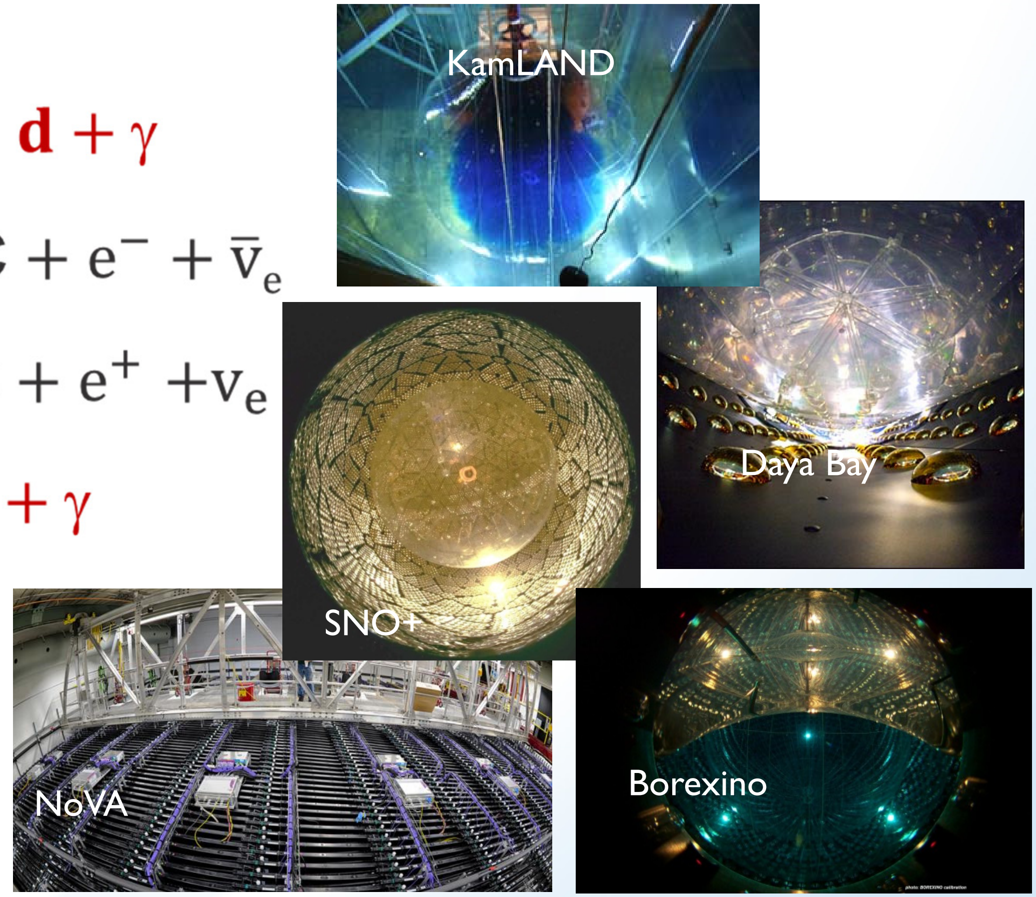
NNN2016, IHEP, Beijing, Nov. 2016

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



Neutrino Interactions in Scintillator

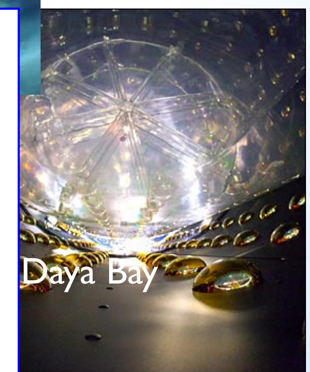
- $\bar{\nu}_e + p \rightarrow n + e^+;\ n + p \rightarrow d + \gamma$
- $\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B \rightarrow {}^{12}C + e^- + \bar{\nu}_e$
- $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N \rightarrow {}^{12}C + e^+ + \nu_e$
- $\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^* \rightarrow {}^{12}C + \gamma$
- $\nu_x + e^- \rightarrow \nu_x + e^-$
- $\nu_x + p \rightarrow \nu_x + p$

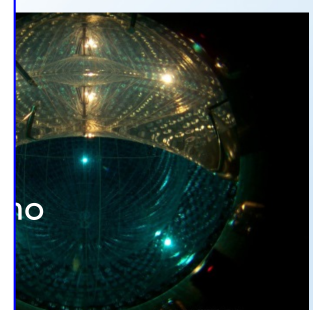


An excellent detection medium for neutrinos in MeV range

Neutrino Interactions in Scintillator

- $\bar{\nu}_e + p \rightarrow n + e^+; \; n + p \rightarrow d + \gamma$
- $\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B \rightarrow {}^{12}C +$
- $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N \rightarrow {}^{12}C +$
- $\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^* \rightarrow {}^{12}C +$
- $\nu_x + e^- \rightarrow \nu_x + e^-$
- $\nu_x + p \rightarrow \nu_x + p$





Scintillator Applications

Proton decay

0νββ

Solar neutrinos (w ^{7}Li loading)

Geo-neutrinos

Supernova neutrinos

Diffuse SN background neutrinos

long baseline neutrino physics (w accelerator neutrino source)

Sterile neutrinos (w neutrino source)

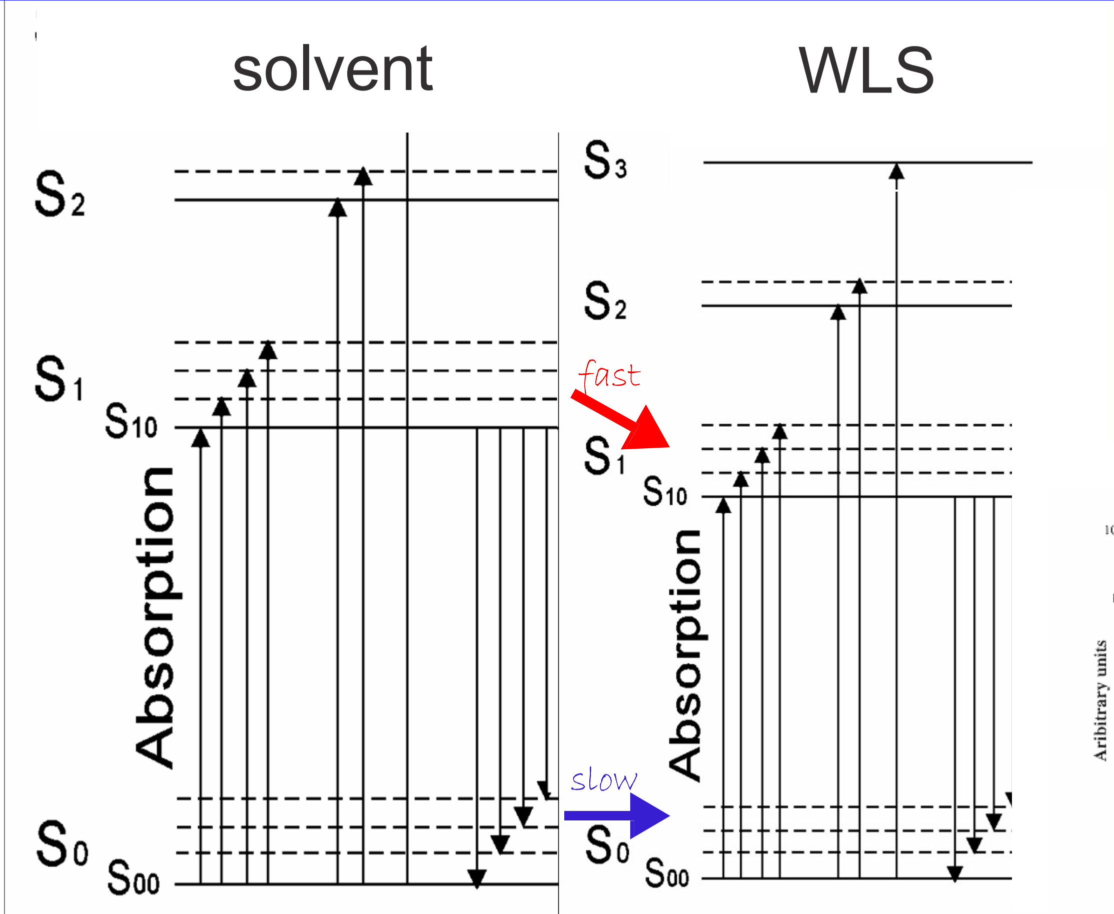
Ion-beam therapy imaging

TOF-PET

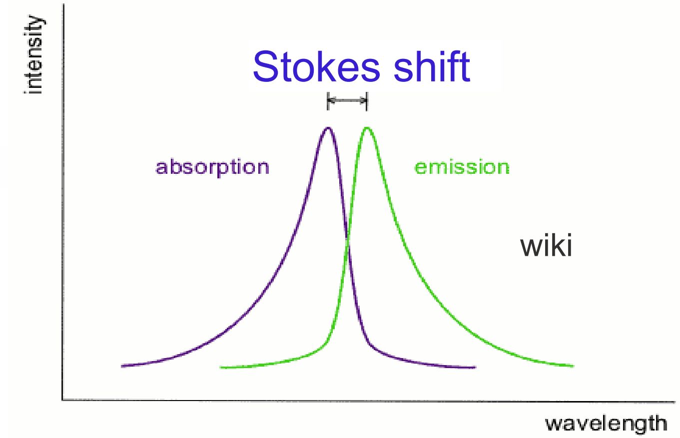
Some details in arXiv:1409.5864

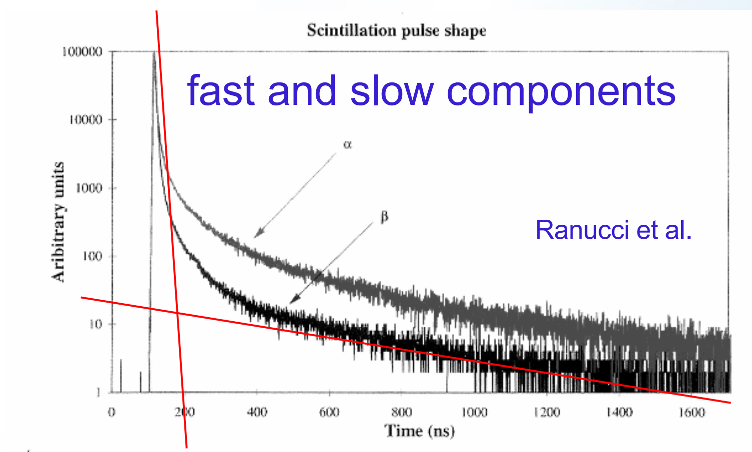
An excellent detection mediu ange

Scintillation Mechanism



Birk's Mechanism

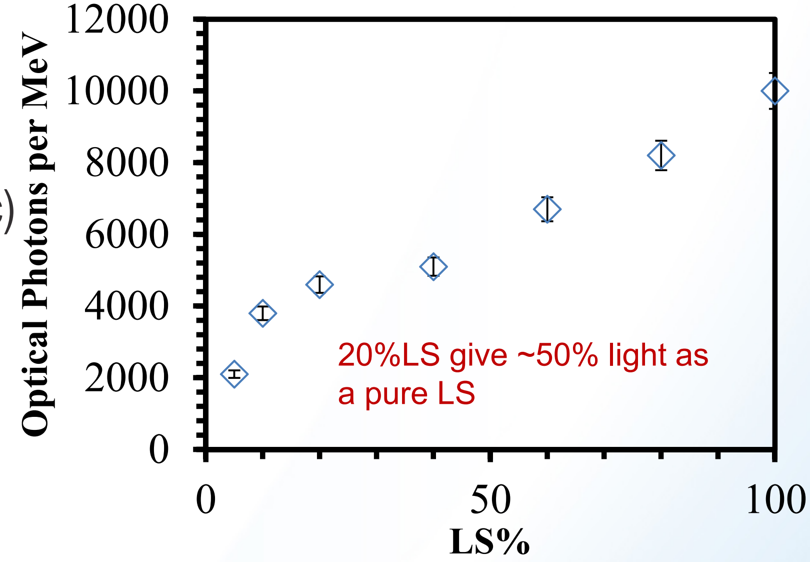


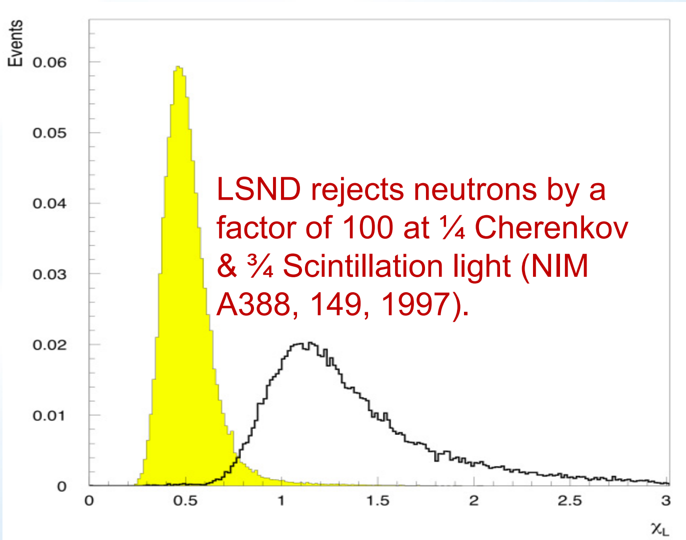


WbLS follows the same scintillation transition mechanism with quenching from water

Water-based Liquid Scintillator

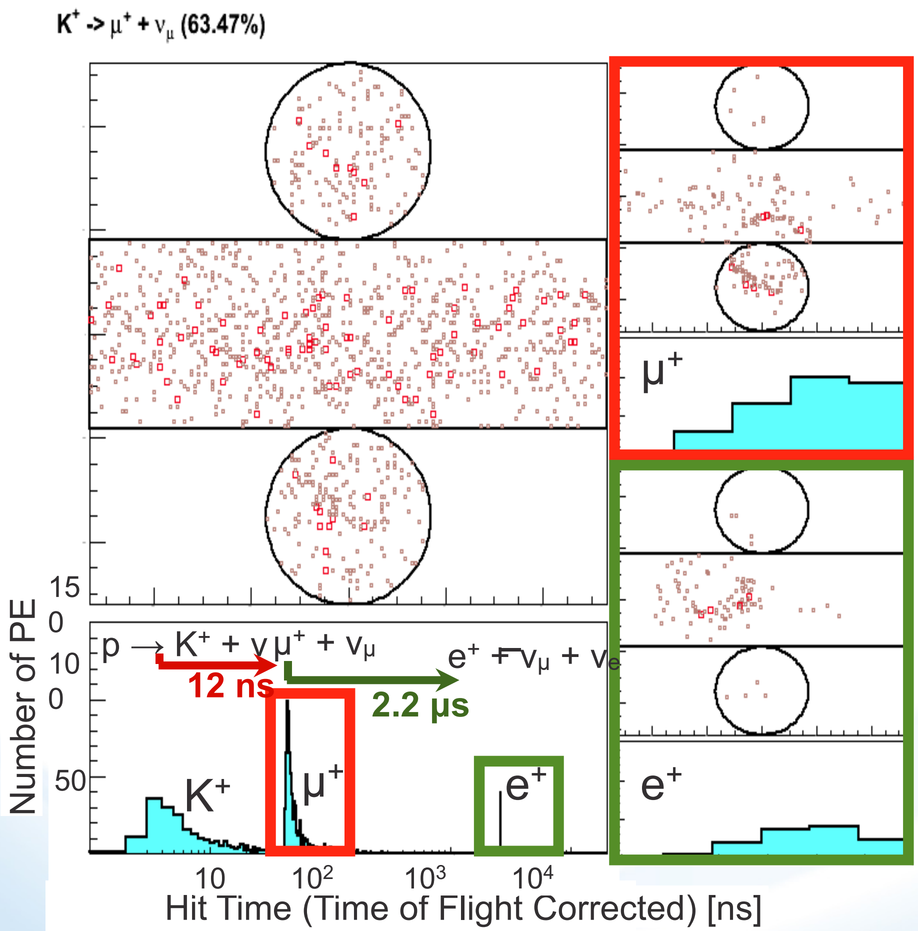
- **A novel scintillation liquid ranging from pure organic to pure water**
  - Cherenkov (directional) and scintillation (isotropic)
    - Energy measurement below Cherenkov threshold ($p \rightarrow K^{+}\bar{\nu}$)
  - Particle identification
    - Timing separation of fast Cherenkov from slow scintillation
  - Adjustable scintillation light yield (0%~15% LS)
  - Long attenuation length
  - Cost effective (~$30/ton) compared to LS ($3k/ton)
  - Environmental for confined space or close to accelerator facility)
- **A new metal loading technology to hydrophobic elements: Te, Li, K, Pb,…,etc.**

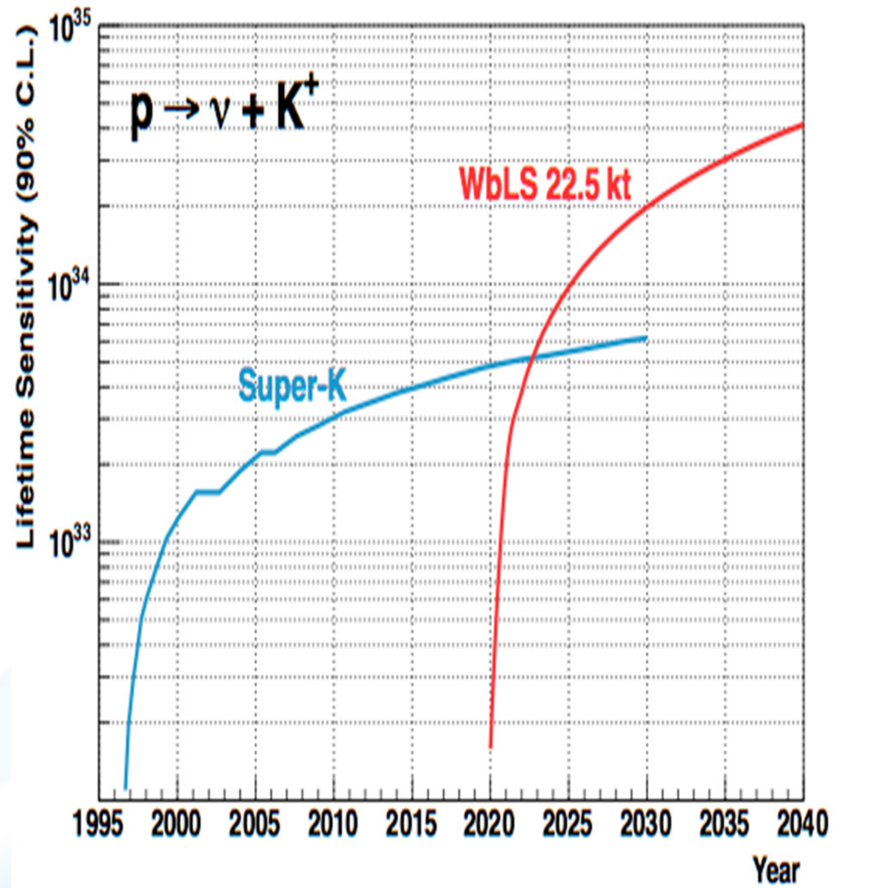




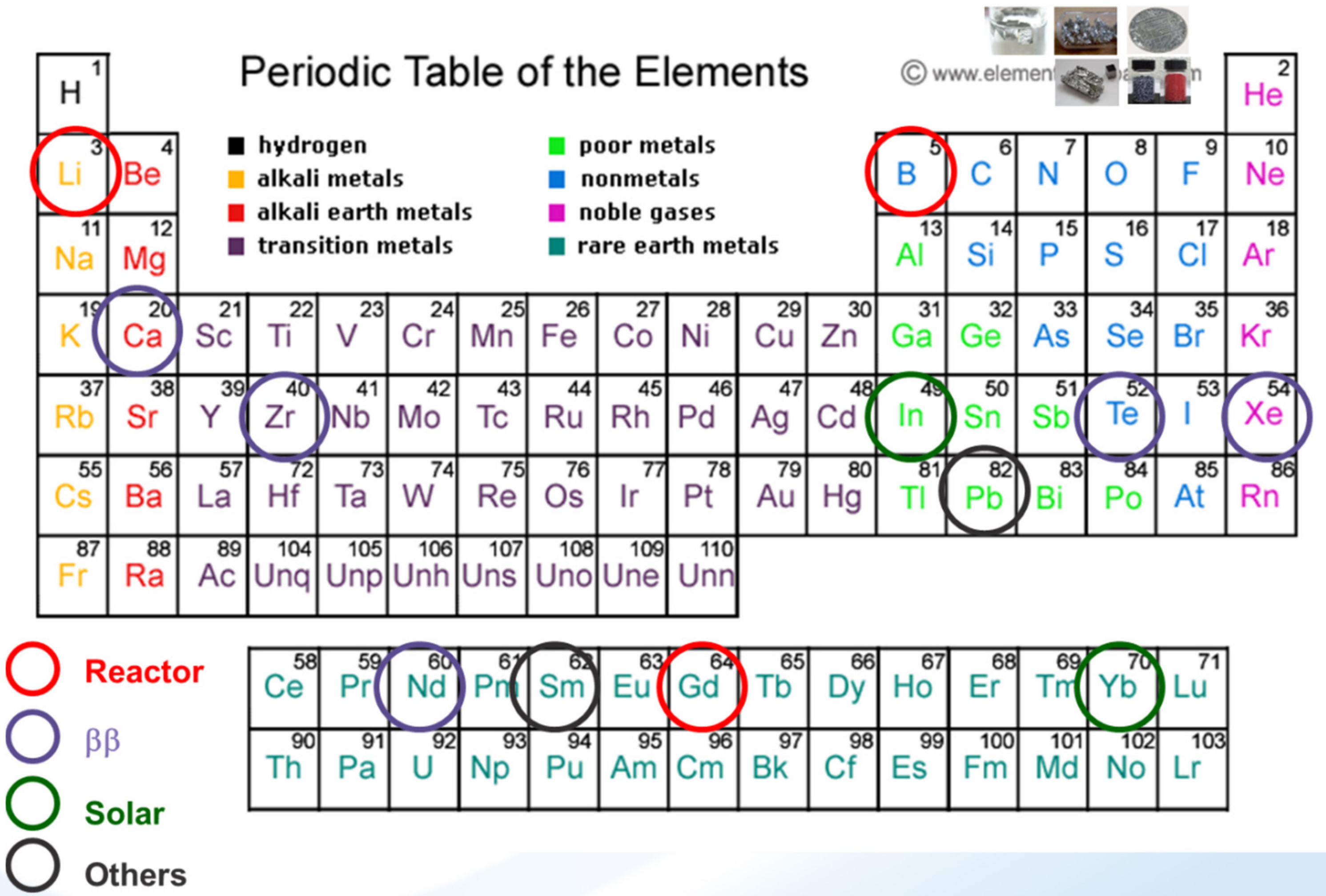
WbLS Physics below Cherenkov

- A simulated event with 90 photons/MeV in a SK detector for ($p \rightarrow K^+ \bar{\nu}$) mode
- An order of magnitude improvement over the current SK sensitivity

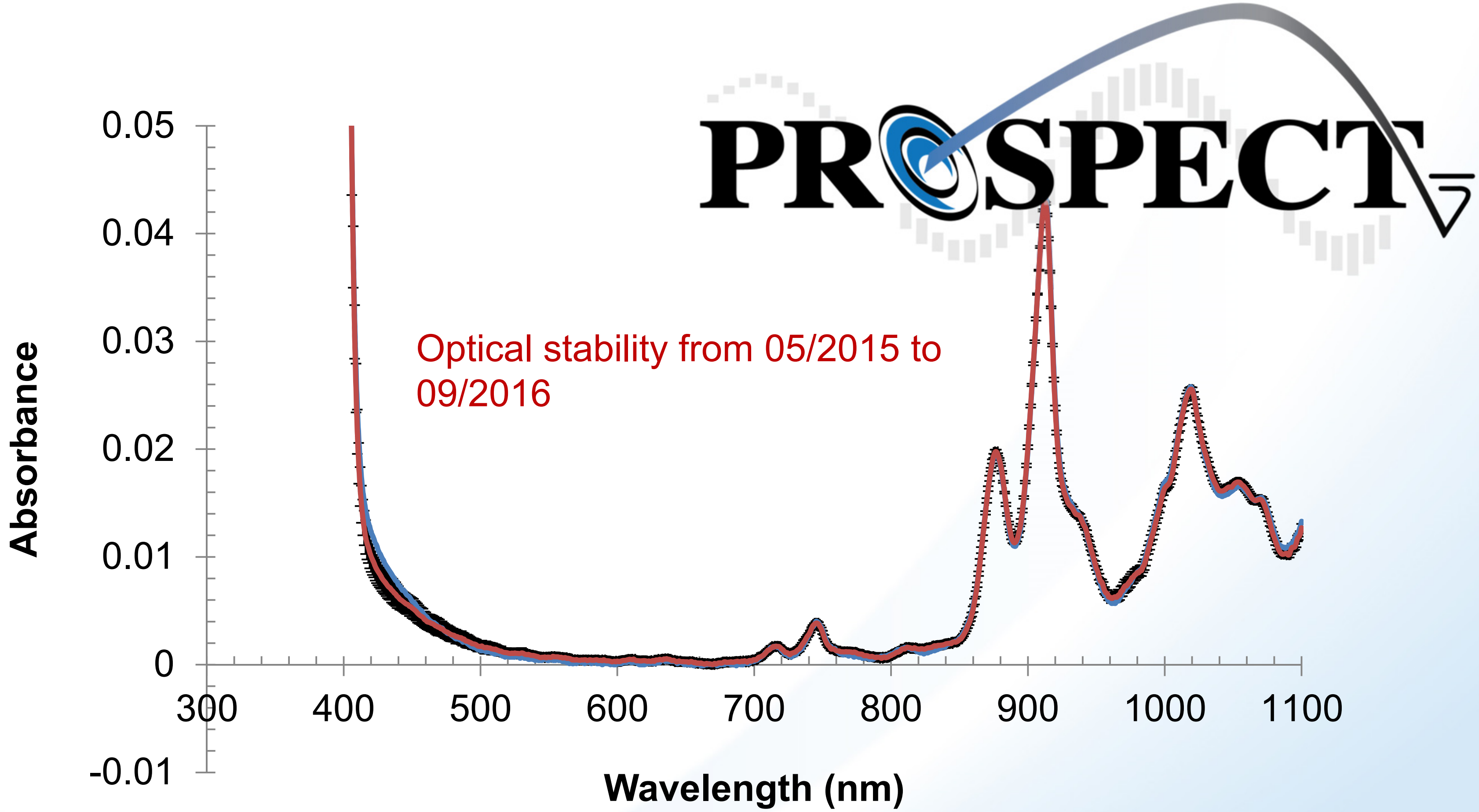




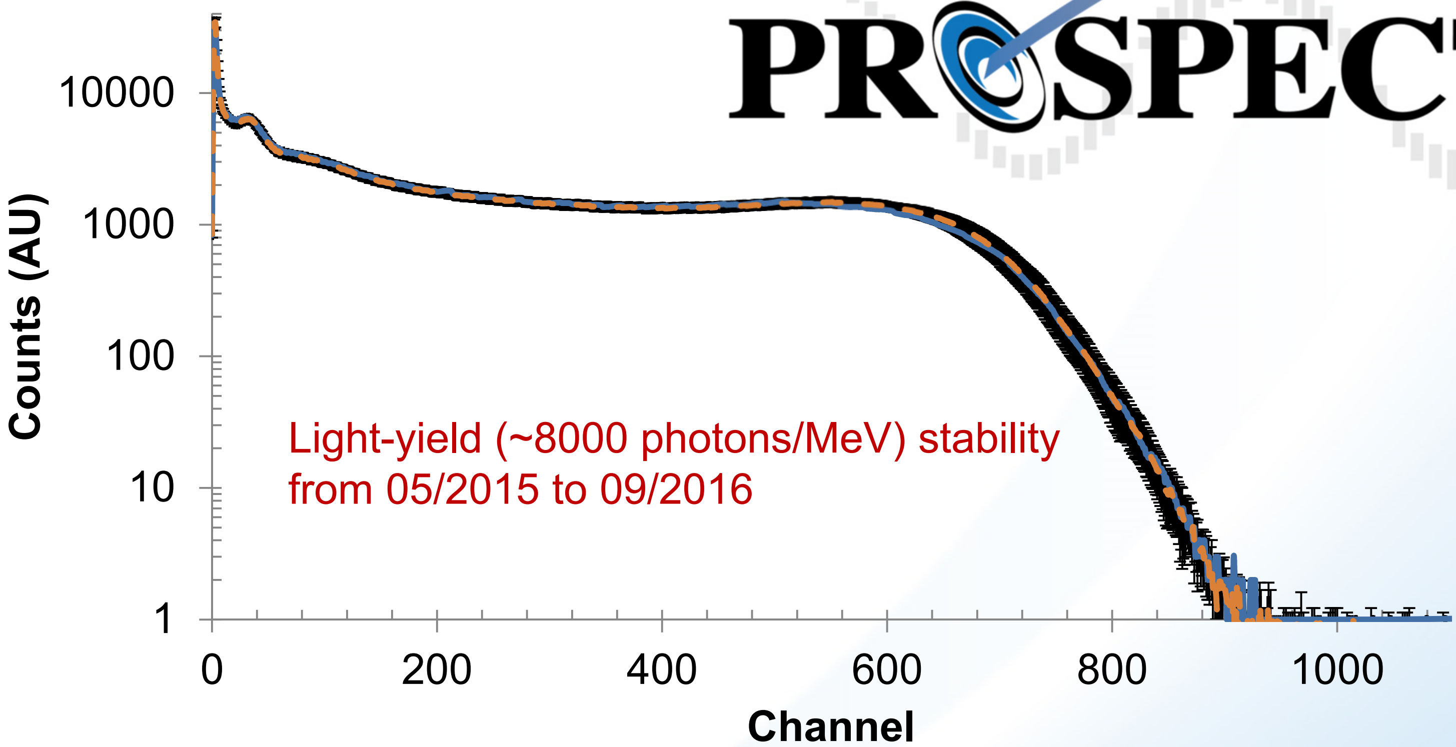
Metal-doped Liquid Scintillator



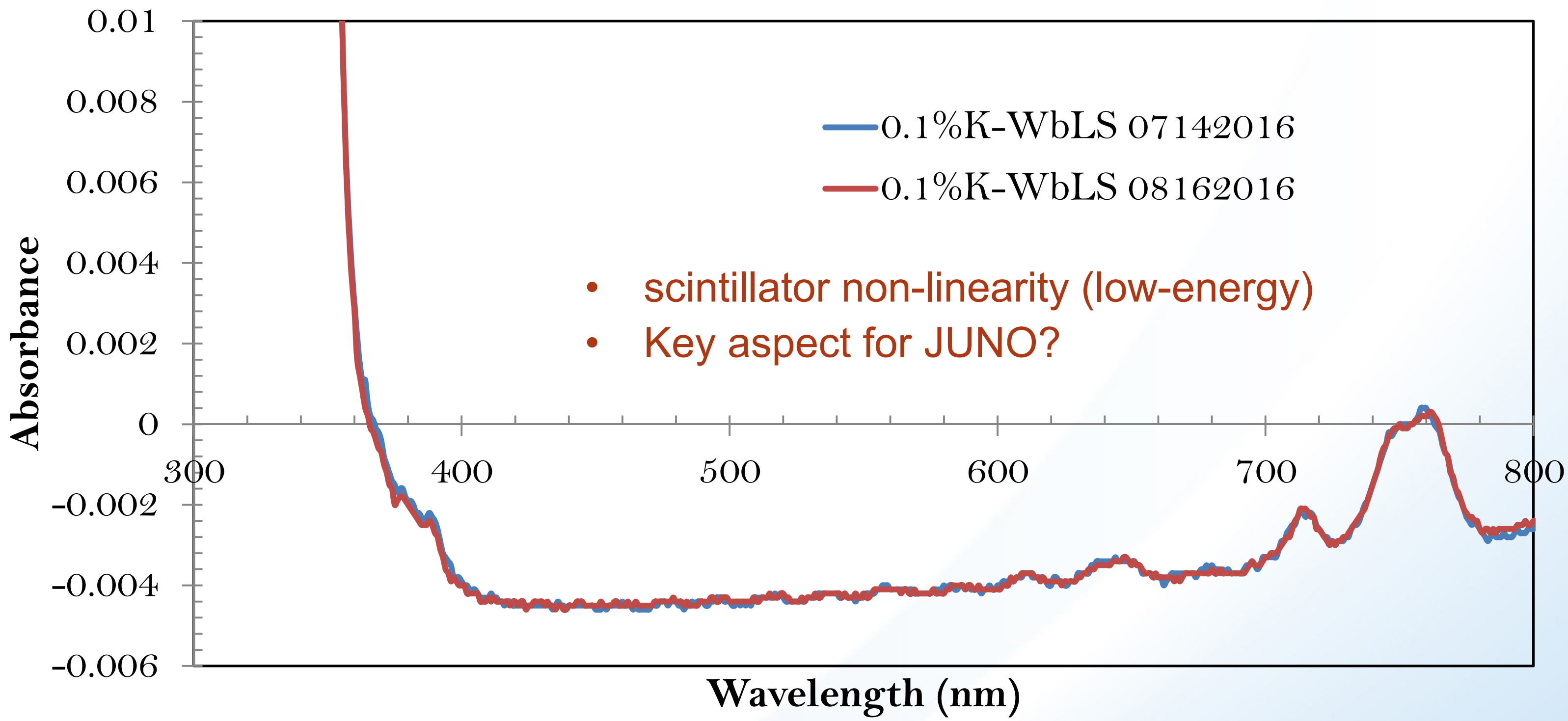
Ex. 0.1% ^{6}Li-doped LS



Ex. 0.1% ^{6}Li-doped LS)

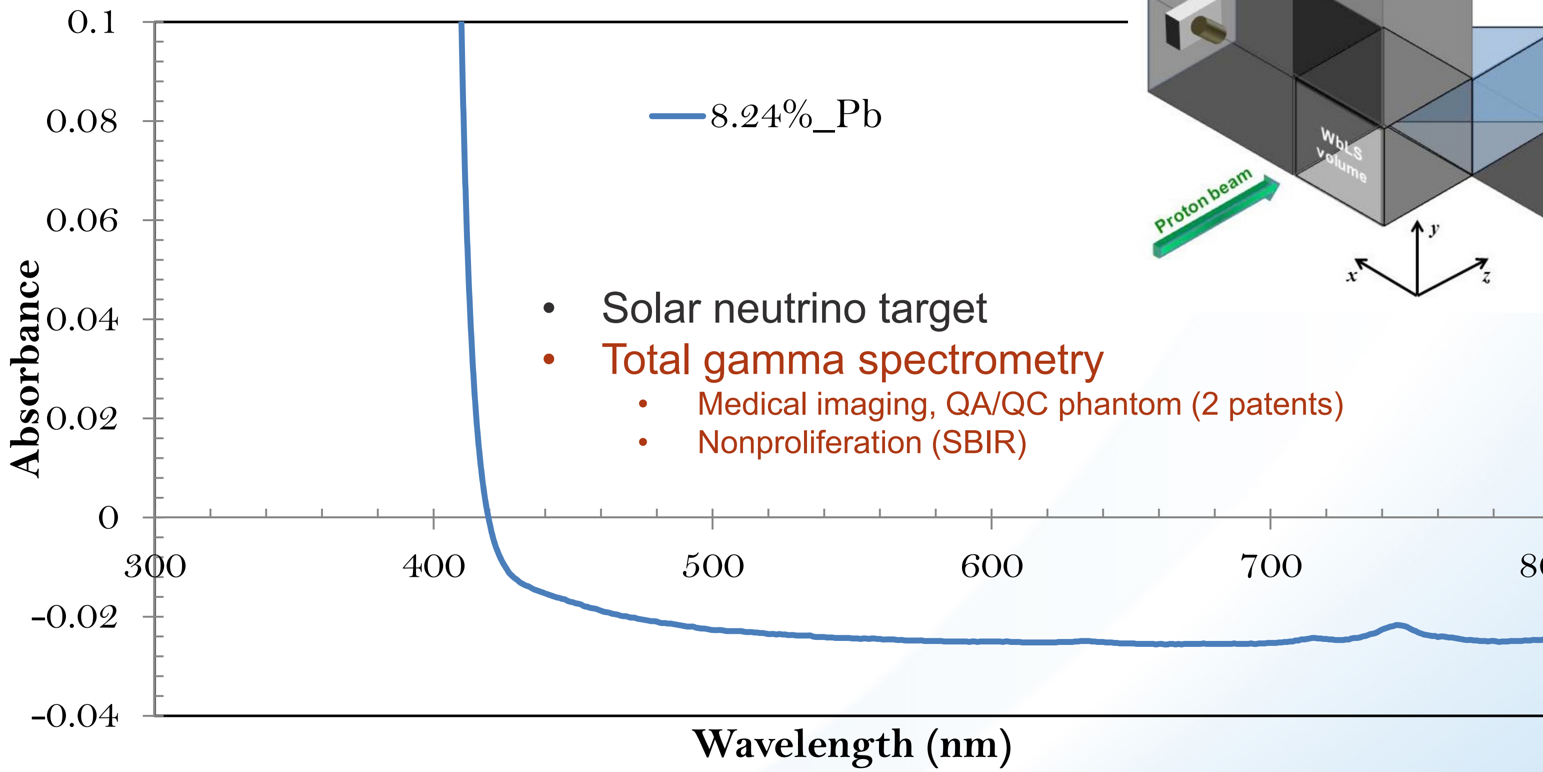


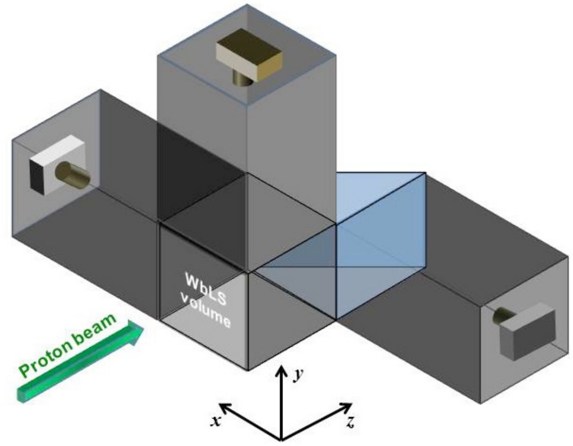
Ex. 0.1% K-doped LS



- scintillator non-linearity (low-energy)
- Key aspect for JUNO?

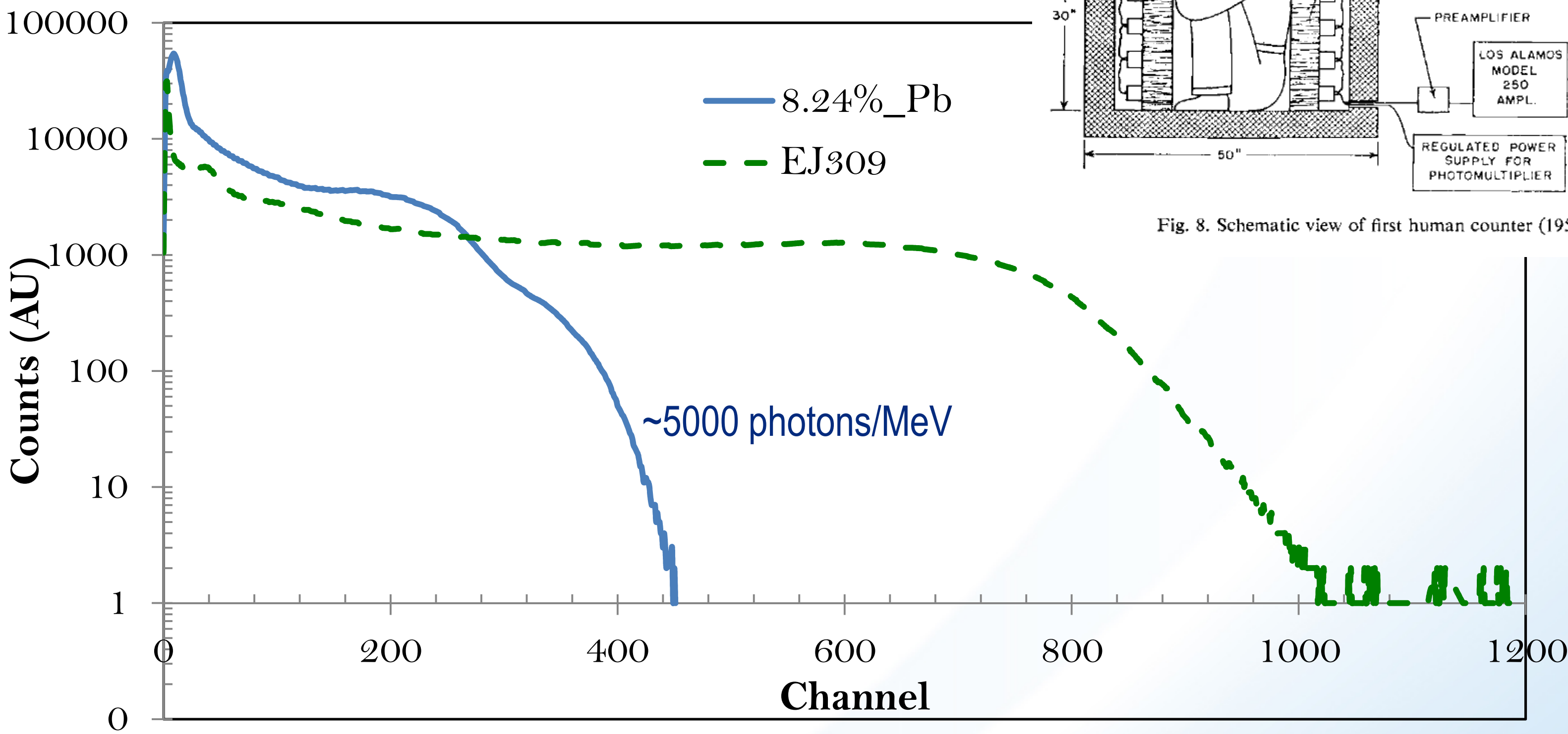
Ex. 8.24% Pb-doped LS





- Solar neutrino target
- Total gamma spectrometry
  - Medical imaging, QA/QC phantom (2 patents)
  - Nonproliferation (SBIR)

Ex. 8.24% Pb-doped LS



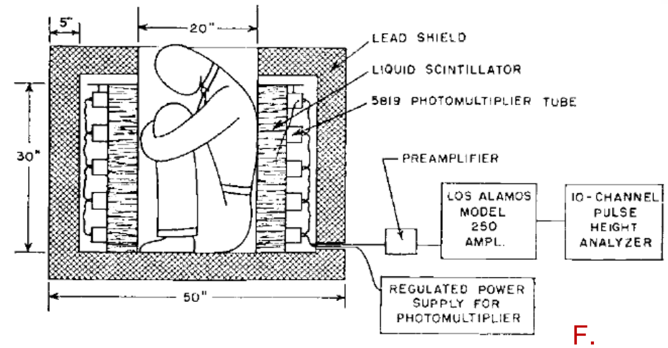
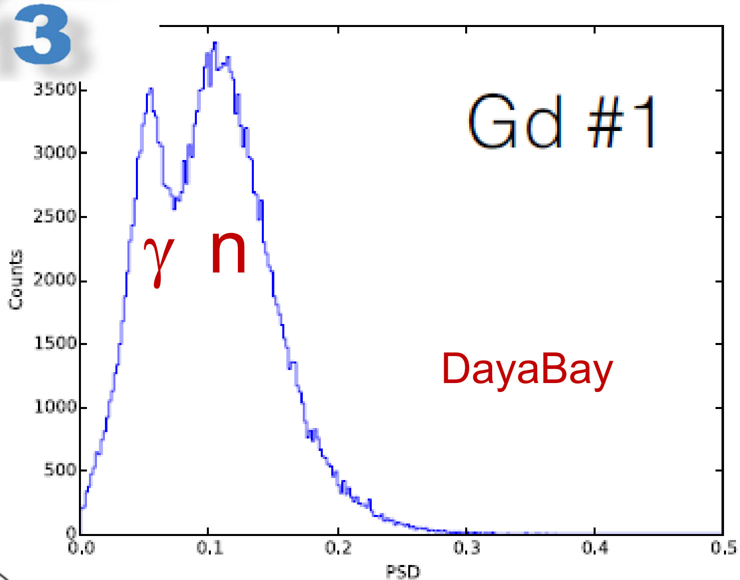
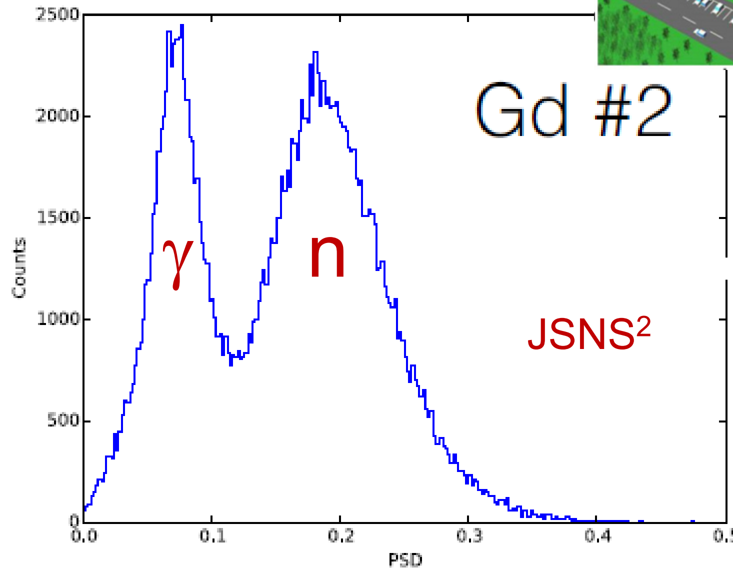
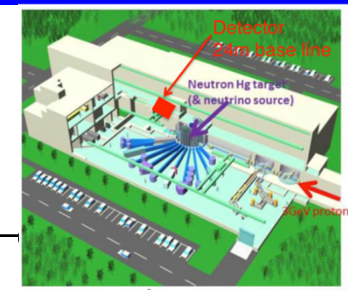


Fig. 8. Schematic view of first human counter (1953). F. Reines

Ex. 0.1 wt% Gd-LS

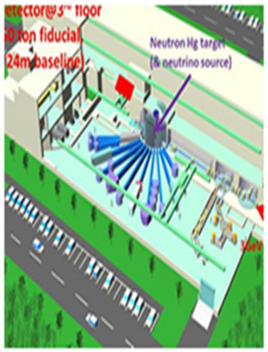






- 0.1% wt% Gd-doped LS (demonstrated by Daya Bay)
- Radiopure (LZ)
- PSD-improved and Cherenkov separation for detector operated on surface close to reactor/beam facility (JSNS^2 or other accelerator physics experiment)

WbLS Near Plan



JSNS² (J-PARC E56) 実験

J-PARC 物質生命科学研究施設(MLF)の水銀標的にて大量に発生するニュートリノを用いて、現在までの標準模型で記述されない（弱い相互作用を行わない）ステライルニュートリノに関する振動現象を探索します。（2013年9月に正式に実験を提案しました。）

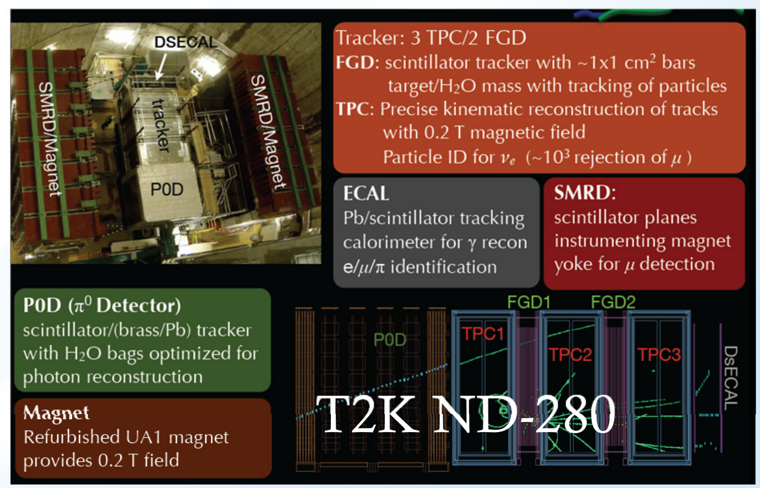
PROSPECT

LZ

HEP-project

SNO+

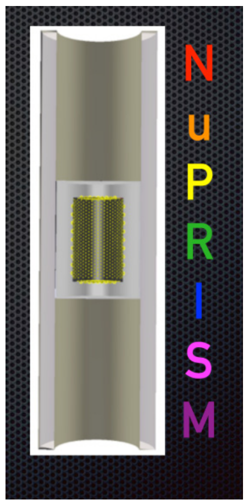
NP-supported

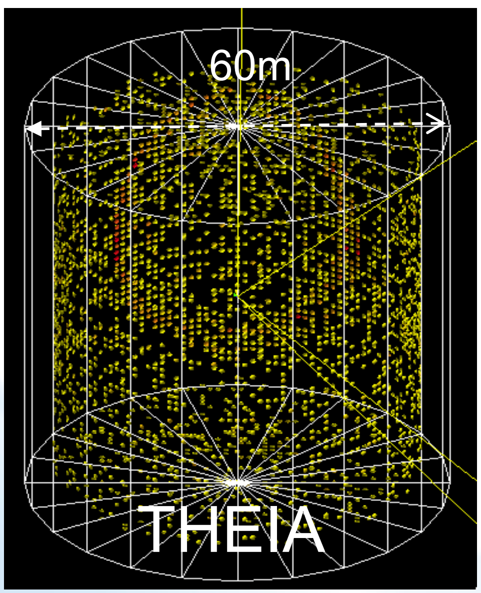


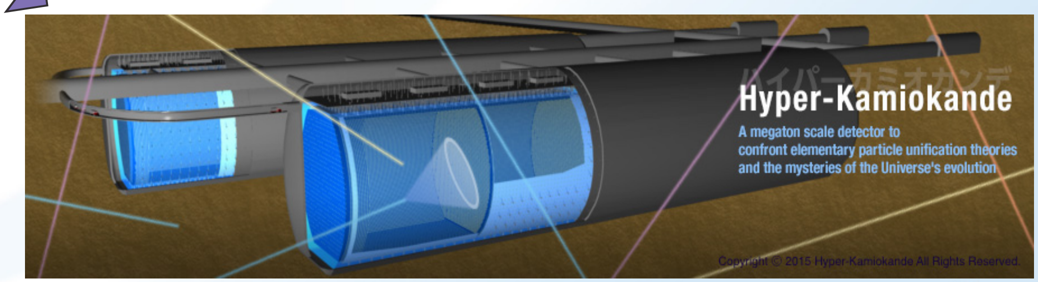
A large Water Cherenkov Detector (THEIA)

THEIA Proto-Collaboration

ANNIE
Accelerator Neutrino Neutron Interaction Experiment

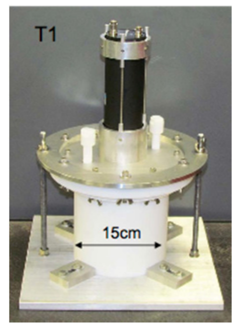


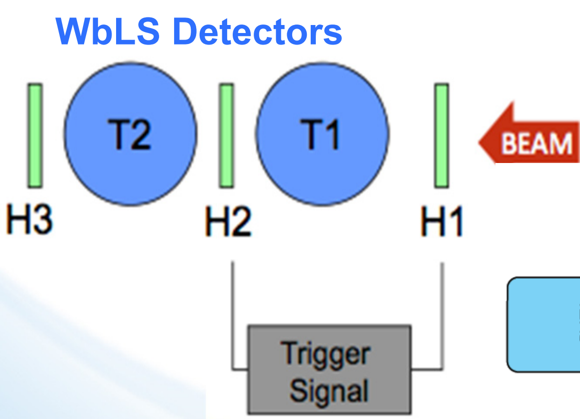




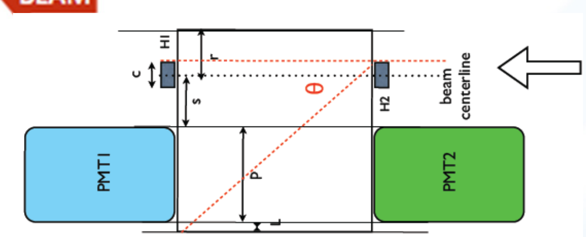
- Kick-off meeting, LBNL in 2015
- two THEIA workshops (FroST) at FNAL and JGU Mainz in 2016
- Multi-physics Program
  - Long-baseline physics (mass hierarchy, CP violation)
  - Neutrinoless double beta decay
  - Solar neutrinos (solar metallicity, luminosity)
  - Supernova burst neutrinos & DSNB
  - Geo-neutrinos
  - Nucleon decay
  - Source-based sterile searches

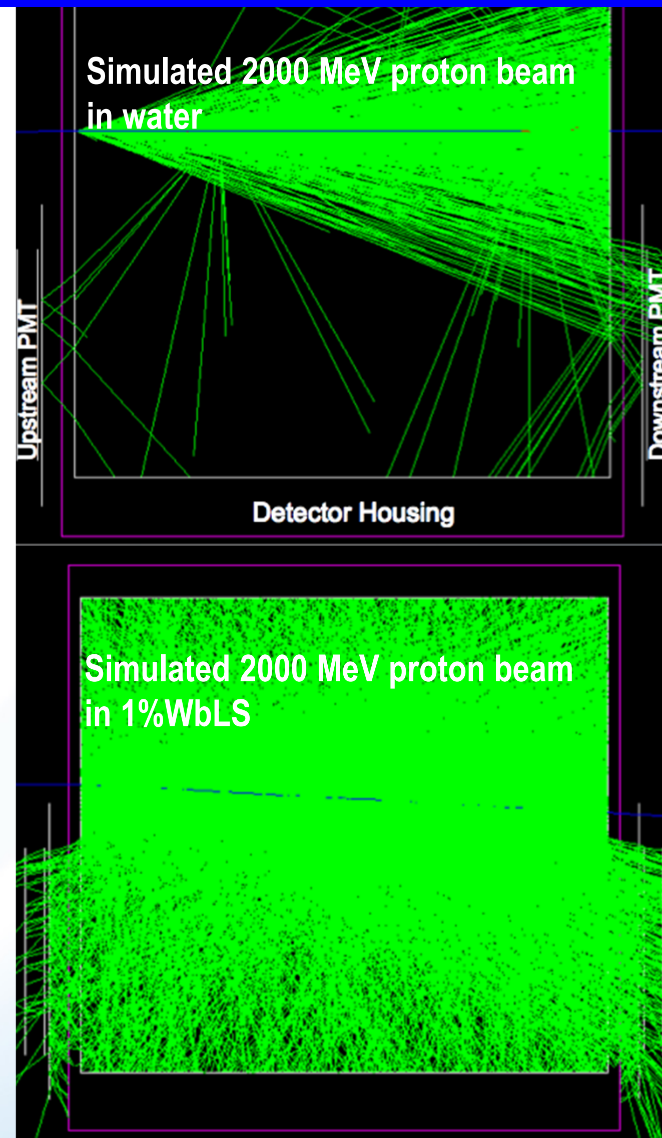
WbLS Proton-beam Measurements



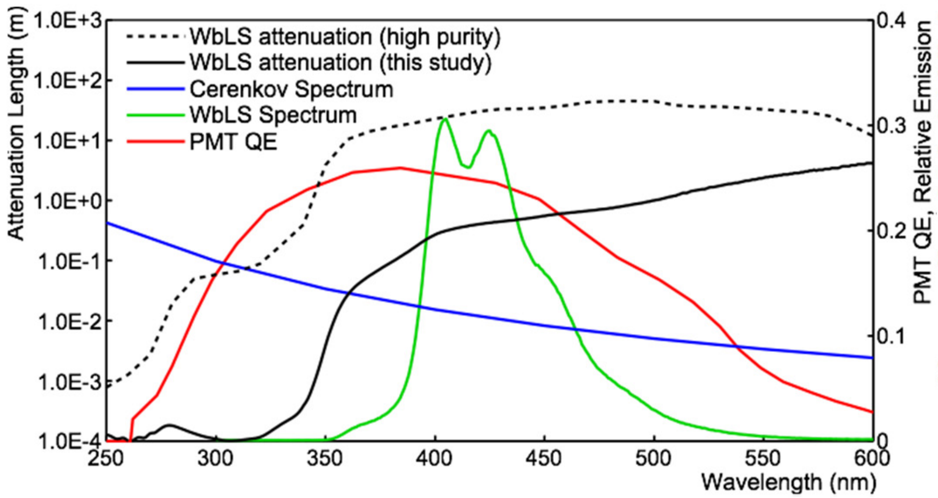


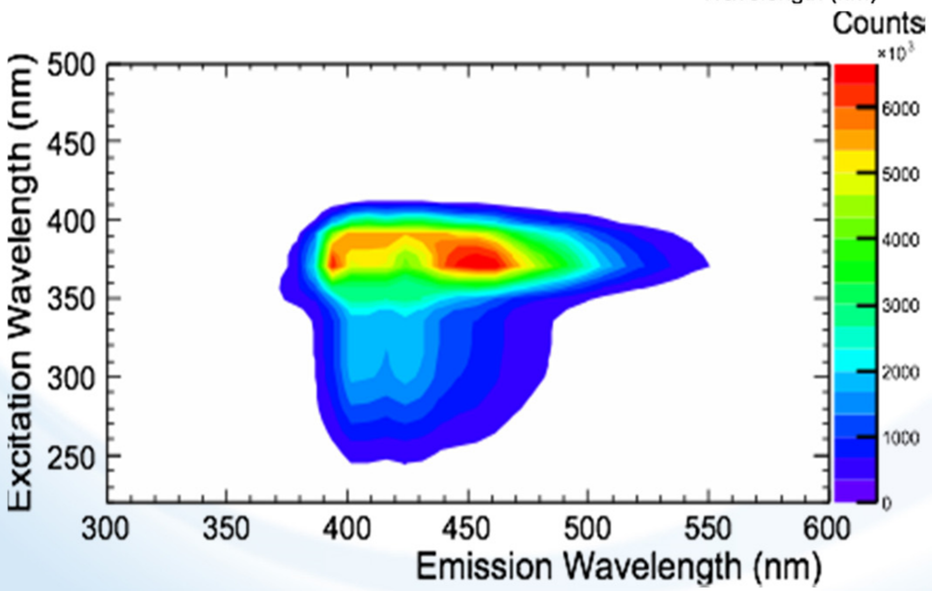
E_p = 210, 475, 2000 MeV

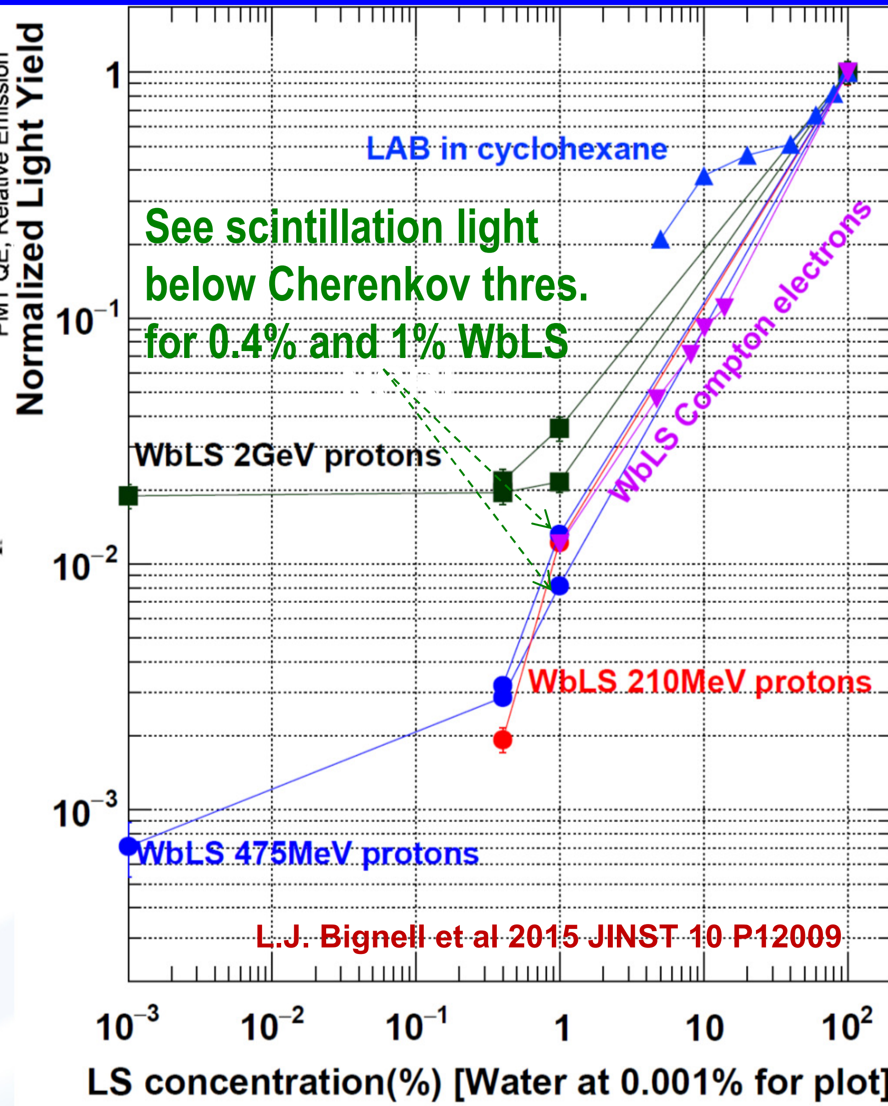




1% WbLS Property







WbLS Light-Yield and Quenching

Material	Light yield (photons/MeV)	kB (mm/MeV)
0.4%WbLS	19.9±2.3	0.70±0.14
1%WbLS	109±11	0.44±0.05
LS	9156±917	0.07±0.01

L.J. Bignell et al 2015 JINST 10 P12009

$$\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}.$$

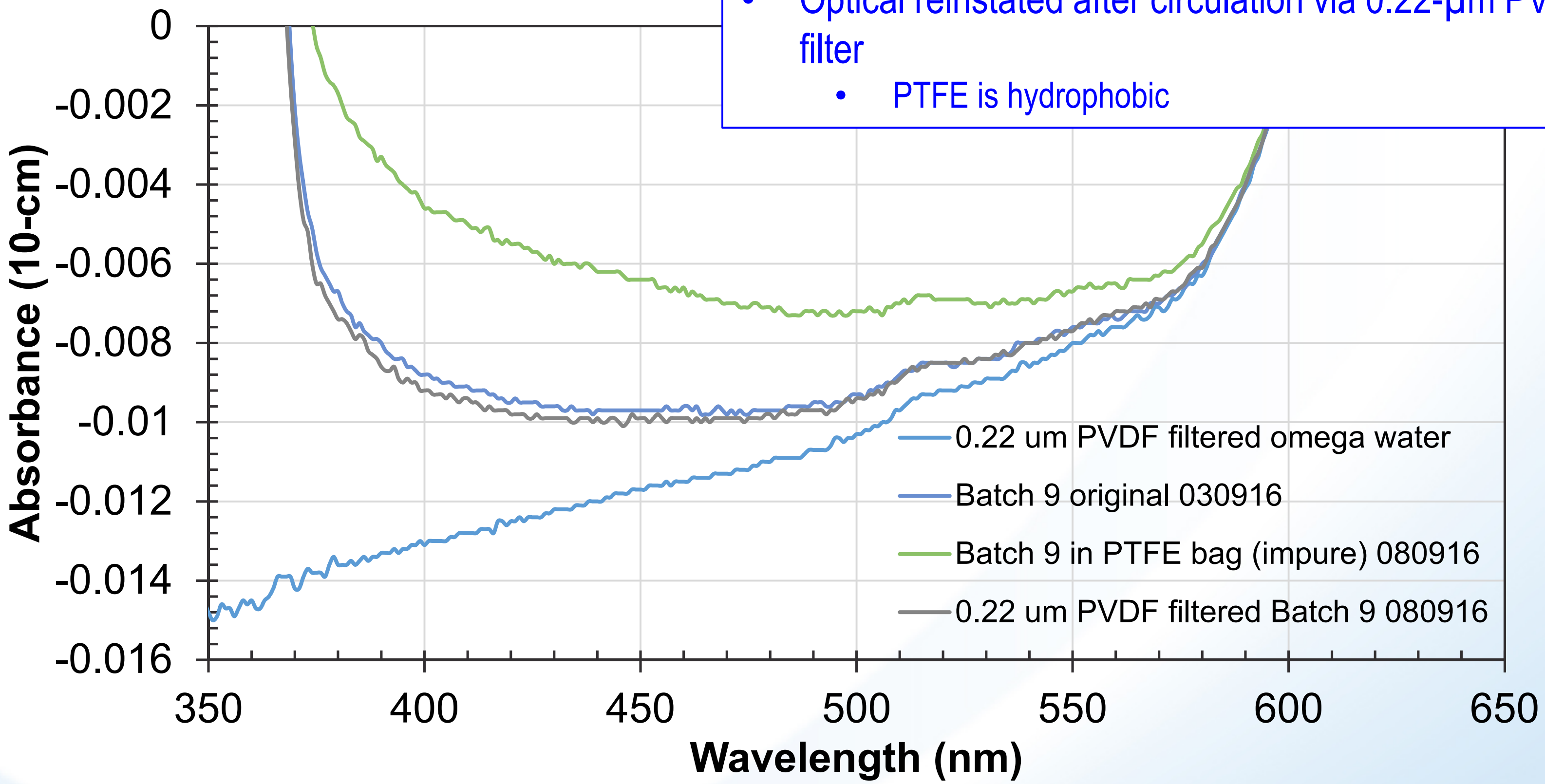
- LS light yield and kB consistent with other measurements in literature for LS and plastic scintillator (0.09<kB<0.19 mm/MeV)
- Light yield of 1% WbLS is ~1% of LS (expect more in pure scintillator)
- kB of WbLS significantly larger than LS.
  - Due to presence of surfactant and/or water?

WbLS Challenges and Development

- *The optical property is dominated by Rayleigh scattering (absorption length is >60m)*
  - A (ionic/non-ionic) mixing system?
  - Further reduce the organic, but maintain the L.Y. by reducing quenching
- *WbLS is stable >1.5 ys; but material leaching could still affect the optical property*
  - Online circulation to separate and purify the organic and aqueous phases respectively (Nano-filtration)
- *Demonstration of Cherenkov & scintillation separation*
  - CHESS at UC Berkeley
  - Tsinghua demonstrator
  - BNL 1-ton demonstrator

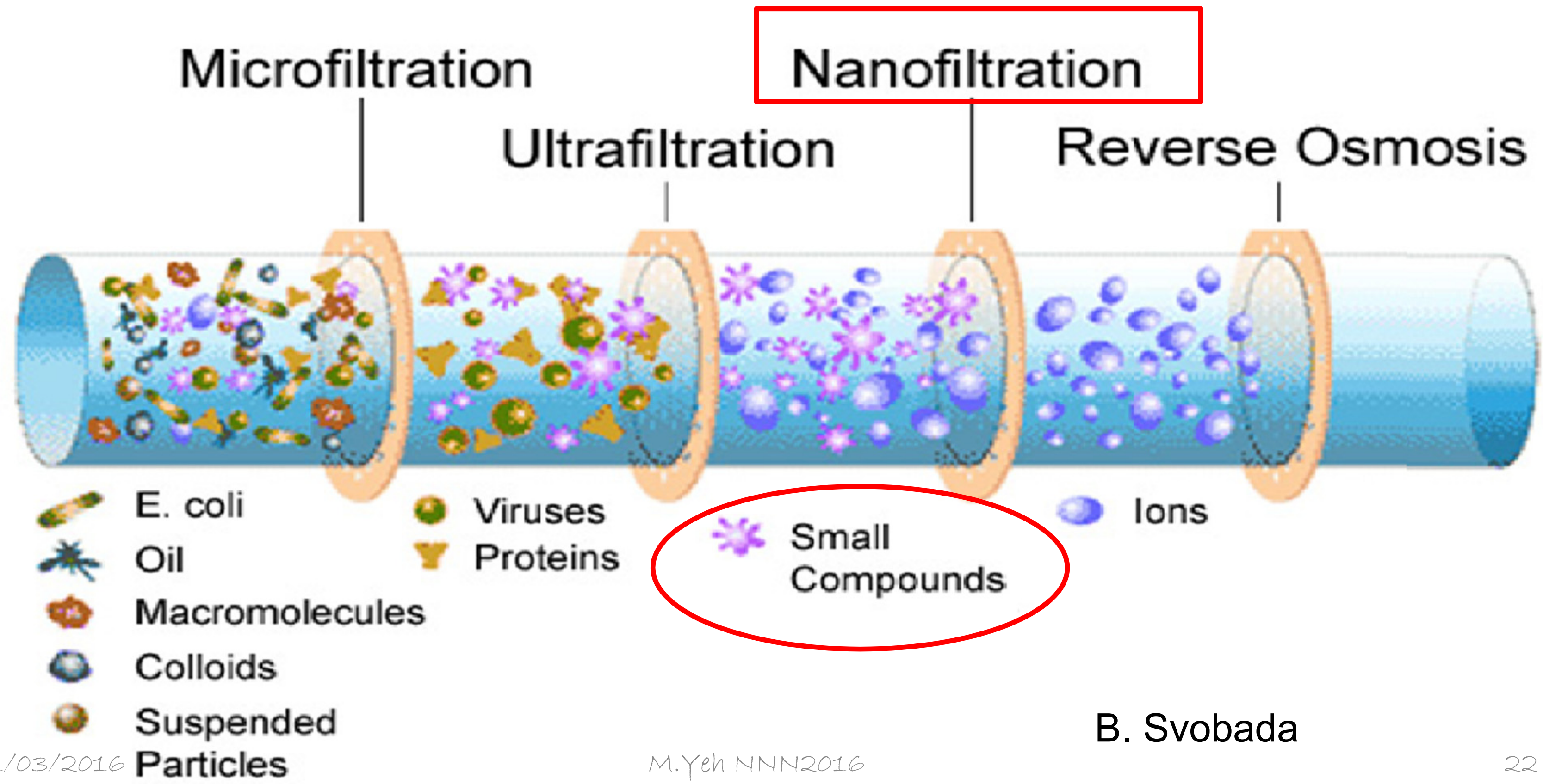
Online Circulation with Filtration

- 1% WbLS in a PTFE lined drum
  - PTFE is not pure (leaching)
- Optical reinstated after circulation via 0.22-µm PVDF filter
  - PTFE is hydrophobic



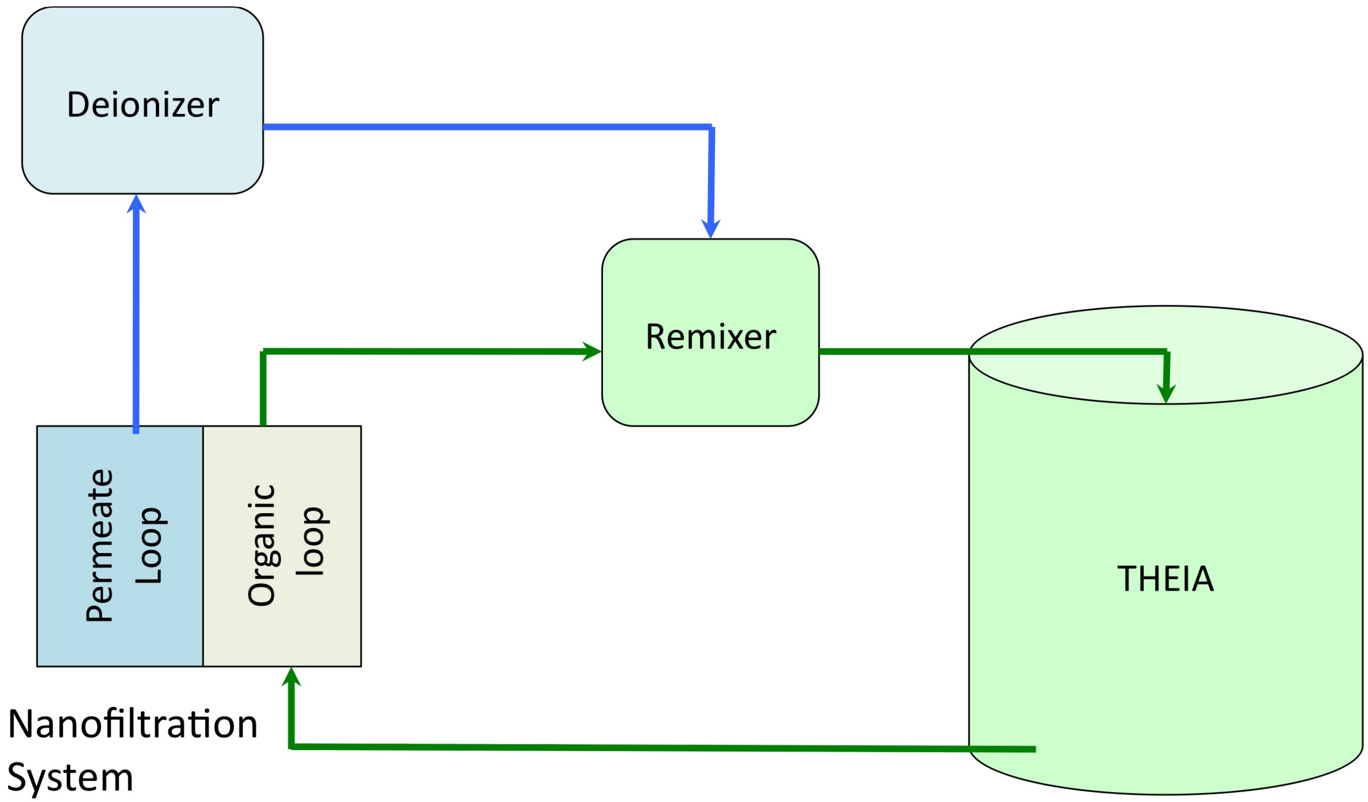
Contaminants such as iron ions degrade optical transparen of water detectors so they need to be constantly purified.

How to do this for WbLS where the organic compounds need to stay in solution?



B. Svobada

One could try and separate the organic and water stream, purify the water stream, then remix.



THEIA recirculation concept

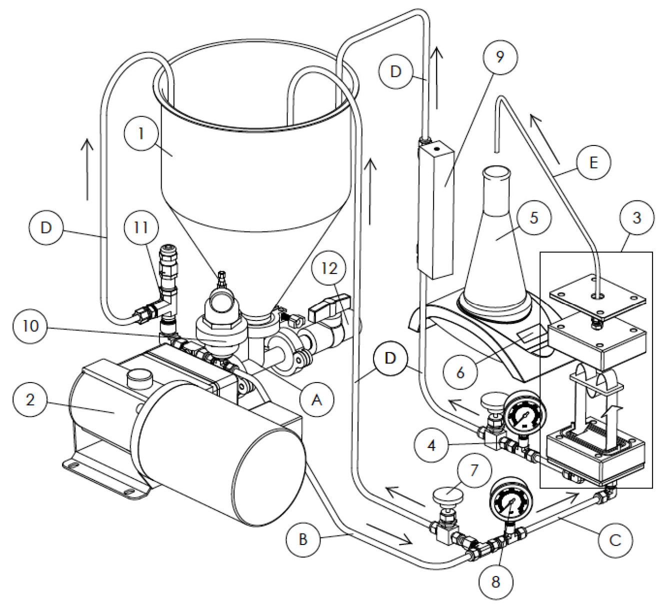
B. Svobada

...but there are many considerations

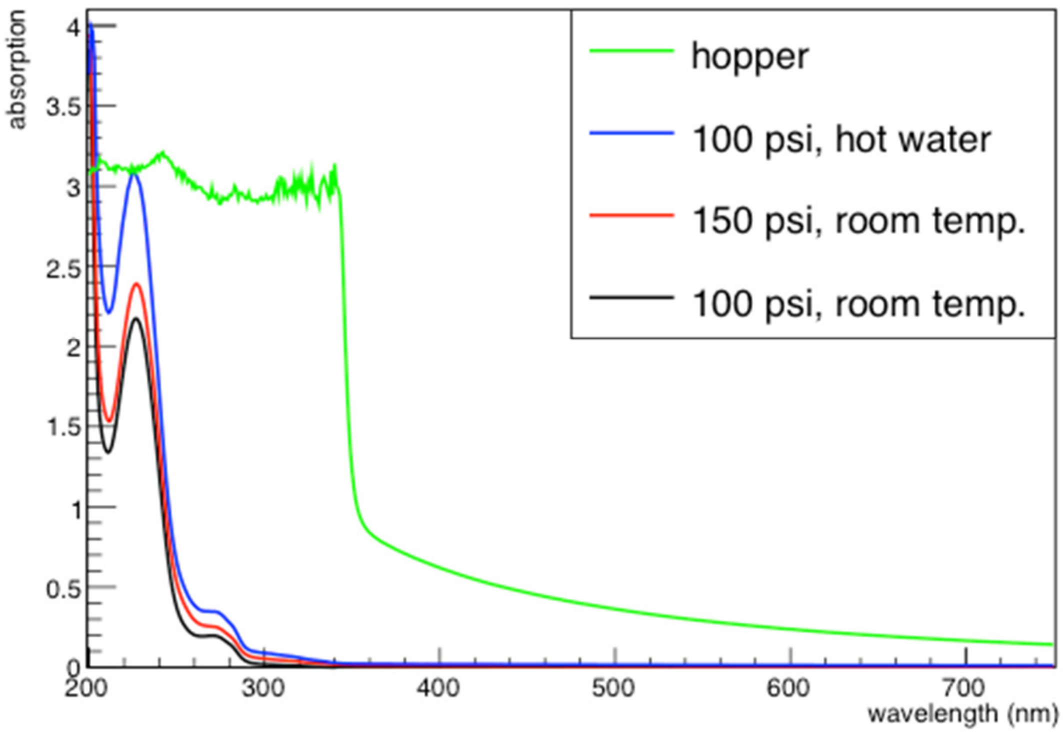
- Identification of appropriate Molecular Weight CutOff (MWCO) hydrophilic materials
- Concentration saturation effects
- Surface charge effects (polar molecules can be attached to filters and create an electric field that opposes flow)
- Surface fouling
- Remixing in such a way as to retain light yield

B. Svobada

Sterlitech CF042
Nanofiltration Unit
Modified at
UC Davis for a permeate
loop to overcome CP
and for handling viscous
LS compared to water



Typical WbLS spectra using NFW filt



Recent success in separating out the active WbLS components at a level >99% with flow rates high enough to be used in THEIA

B. Svobada

CHESS:
CHErenkov-Scintillation Separation

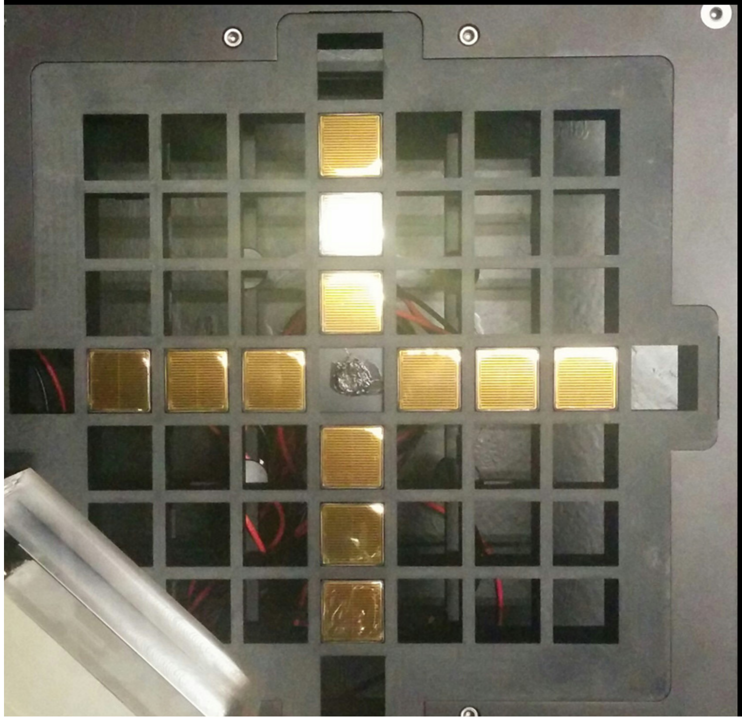
Orebi Gann research group
Supported by LBNL LDRD (FY ’15-16

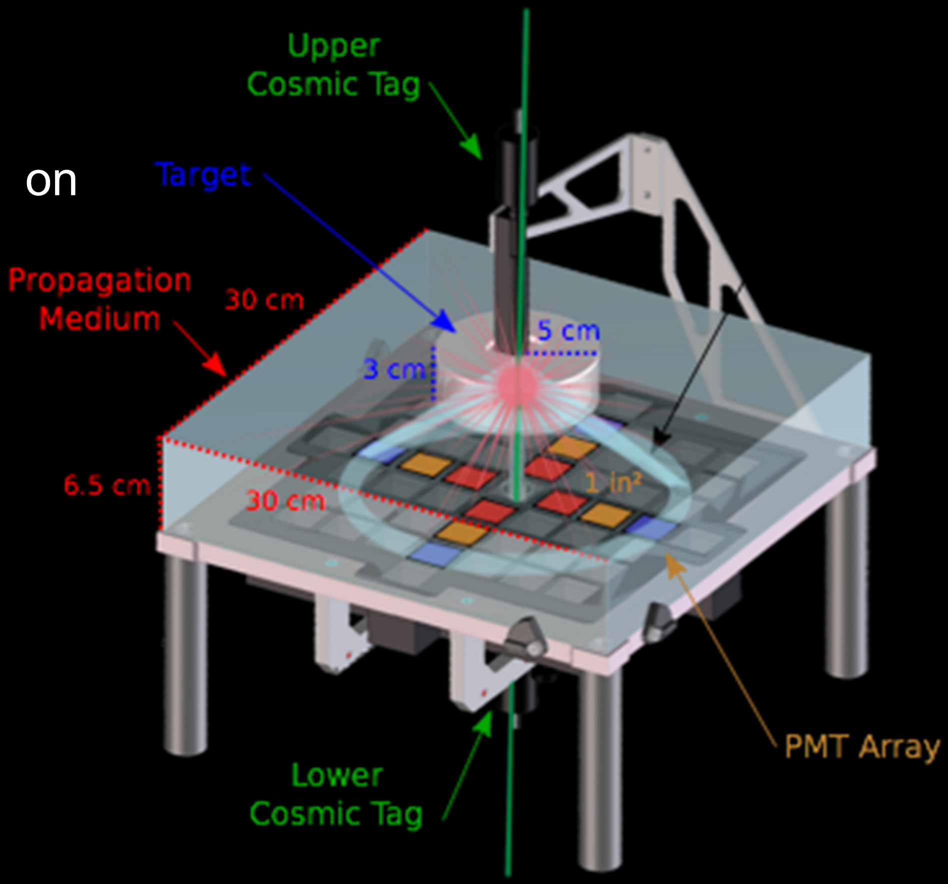
Select vertical cosmic muon events

Image Cherenkov ring in Q and T on fast-PMT array

Detector resolution: 338±12 ps

Allows charge- and time-based separation





12 1-inch H11934 PMTs (300ps FWHM, 42% QE)
CAEN V1742 (5GHz)
675 samples (135ns window)
CAEN V1730 (500MHz)

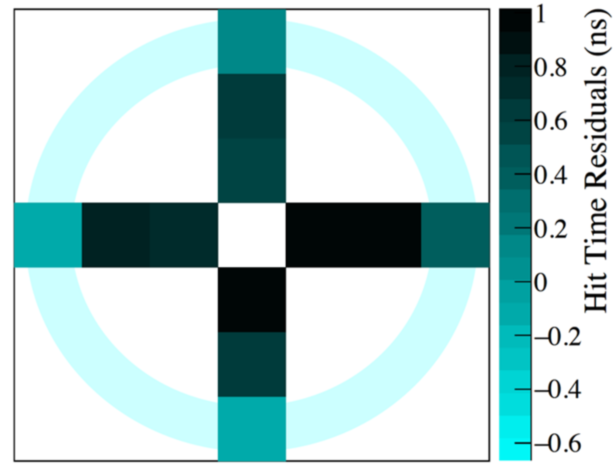
CHESS: CHErenkov-Scintillation Separation

Orebi Gann research group
Supported by LBNL LDRD (FY ’15-16

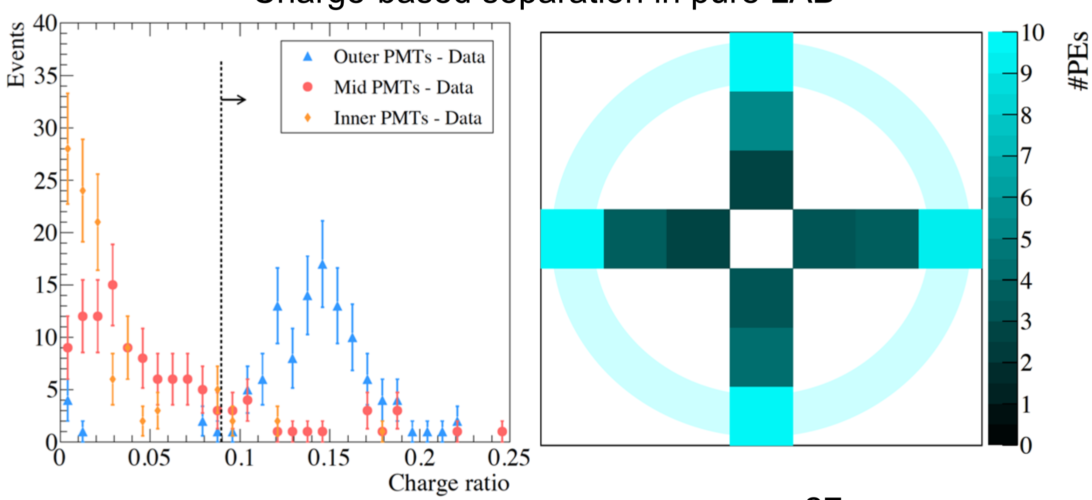
arXiv:1610.02011, arXiv: 1610.XXXXX
Submitted to PRC, PRL

	LAB Time-based	LAB Charge-based	LAB/PPO Time-based	LAB/PPO Charge-based
Cherenkov detection efficiency	83 ± 3 %	96 ± 2 %	70 ± 3 %	63 ± 8 %
Scintillation contamination	11 ± 1 %	6 ± 3 %	36 ± 5 %	38 ± 4 %

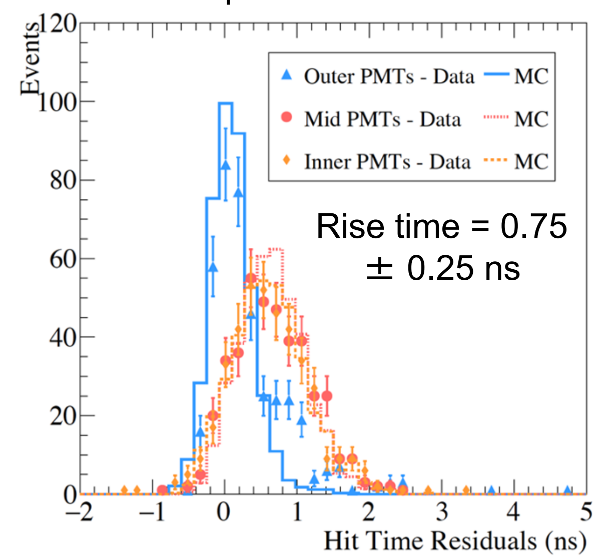
See dedicated talks at DNP, FROST (Oct ’16)



Charge-based separation in pure LAB

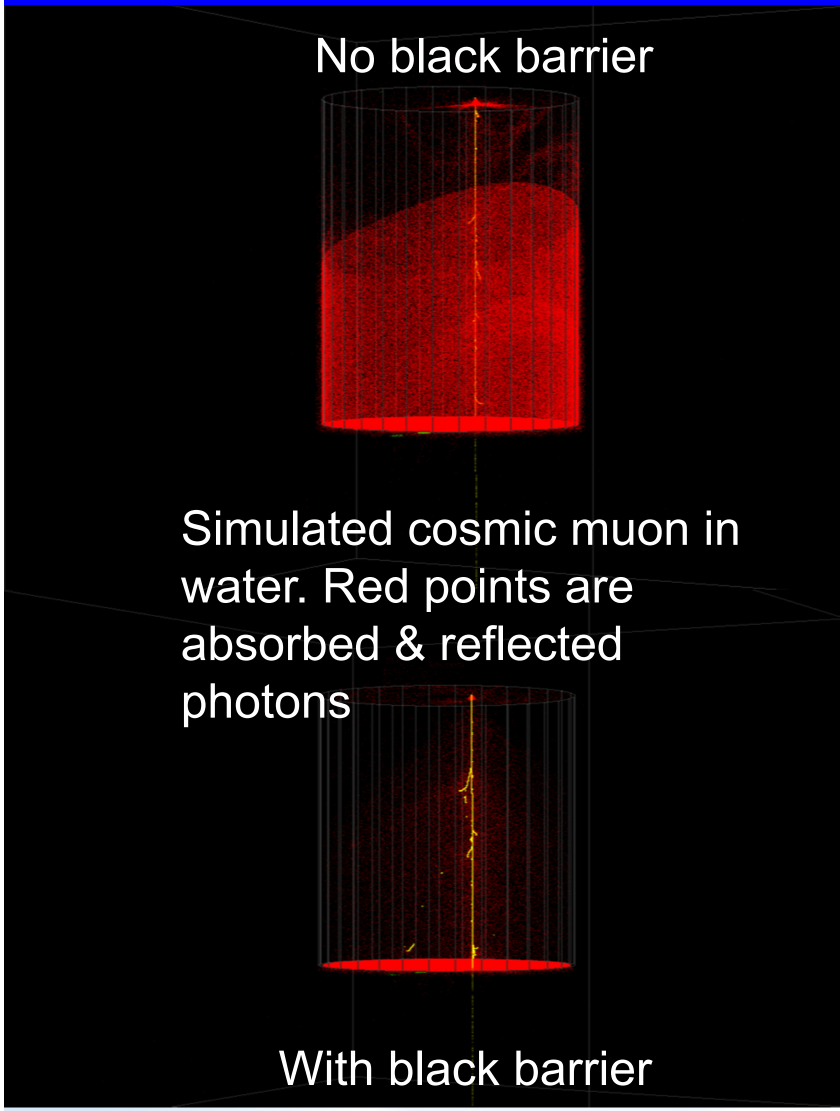


Time-based separation in LAB/PPO

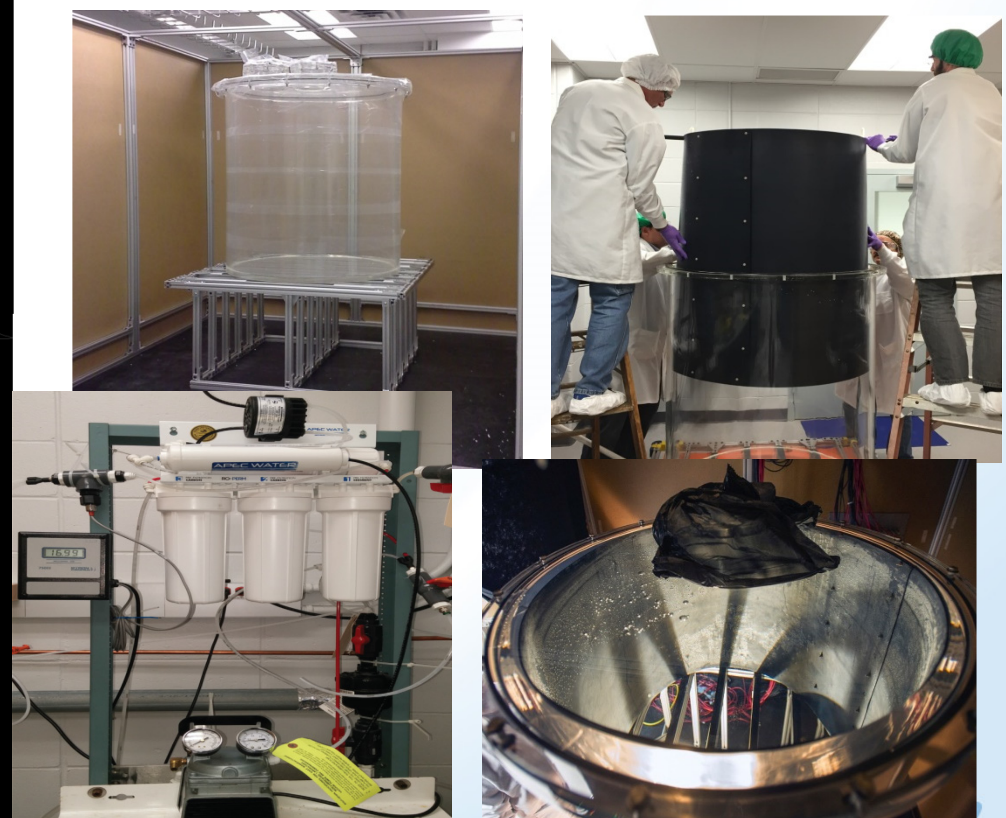


Full simulation includes detailed geometry, DAQ effects (TTS, pulse shapes, electronics noise…)

1000 liter WbLS Demonstrator

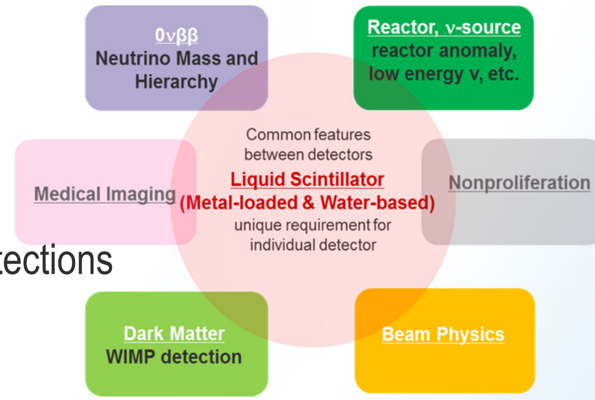


- Cherenkov separation as a function of %WbLS
- Installations of Teflon-barrier, water system, degas, LN_2 system, PMTs/electronics, DAQ
- Filled with water; followed by WbLS in 01/2017



Summary

- Scintillator maintains as a main-stream detection medium for neutrino detections
  - (Daya Bay), JUNO, LZ, JSNS^2, etc.



- Water-based liquid scintillator is
  - an ideal liquid for $p \to K^+\bar{\nu}$ by scintillation and Cherenkov detections
    - Physics below Cherenkov
  - A cost-effect and physics-rich option to future large water Cherenkov detector (THEIA)
    - HK? 2nd detector for DUNE?
    - Upgrades to any Gd-water detector (SK or WATCHMAN)
  - A new step for metal-loaded nuclear and particle physics experiment
    - 0νββ (SNO+), short-baseline neutrinos (PROSPECT), accelerator neutrinos, nonproliferation, medical imaging