THEIA Scintillator Development

Minfang Yeh

Neutrino and Nuclear Chemistry

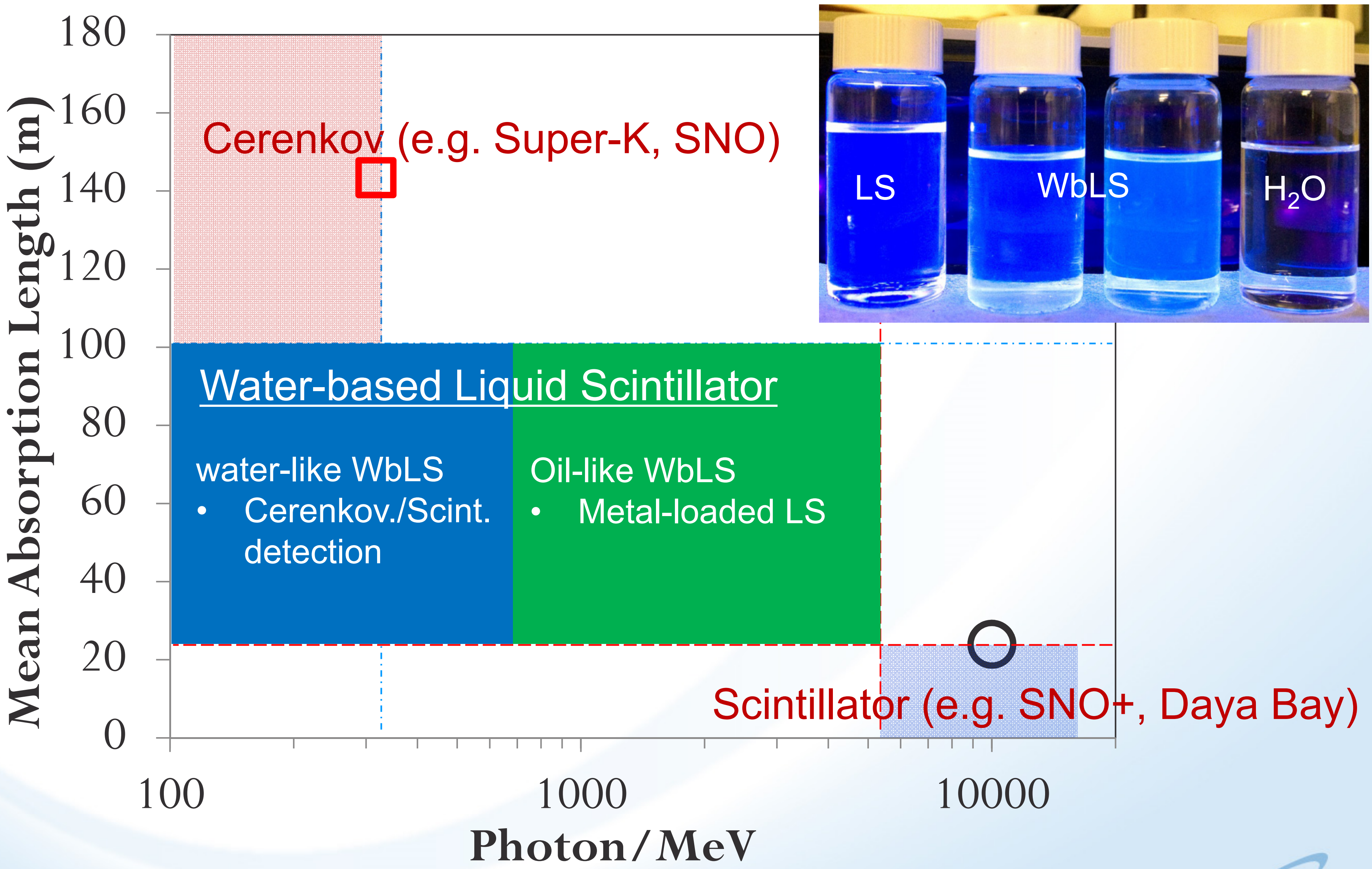
BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

FroST Workshop, DESY, Germany 03/2017

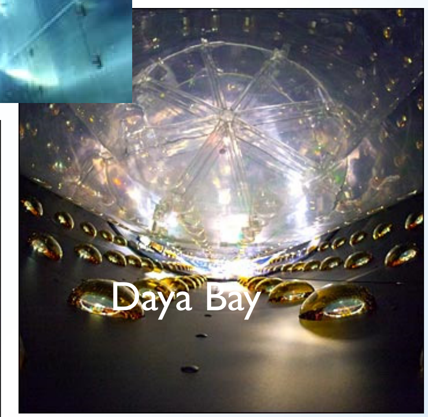
Office of Science U.S. DEPARTMENT OF ENERGY

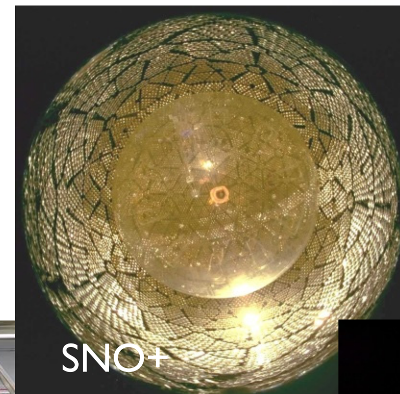
If you always do what you always did, you will always get what you always got. ***-Albert Einstein***

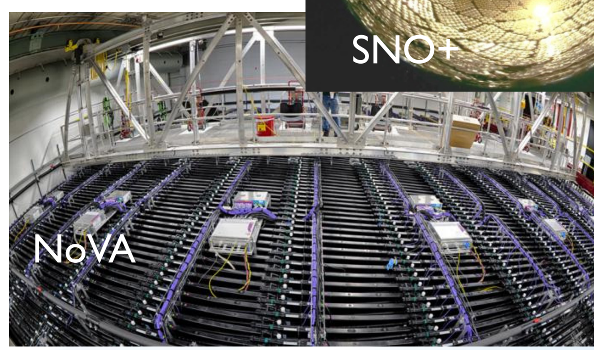


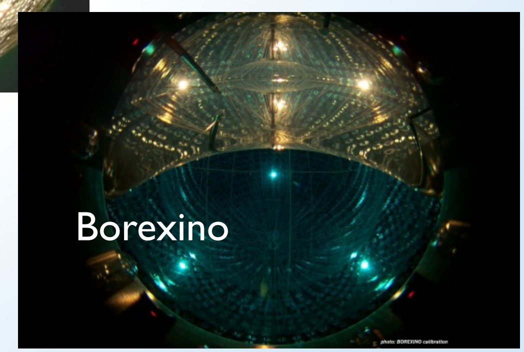
Neutrino Interactions in Scintillator

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



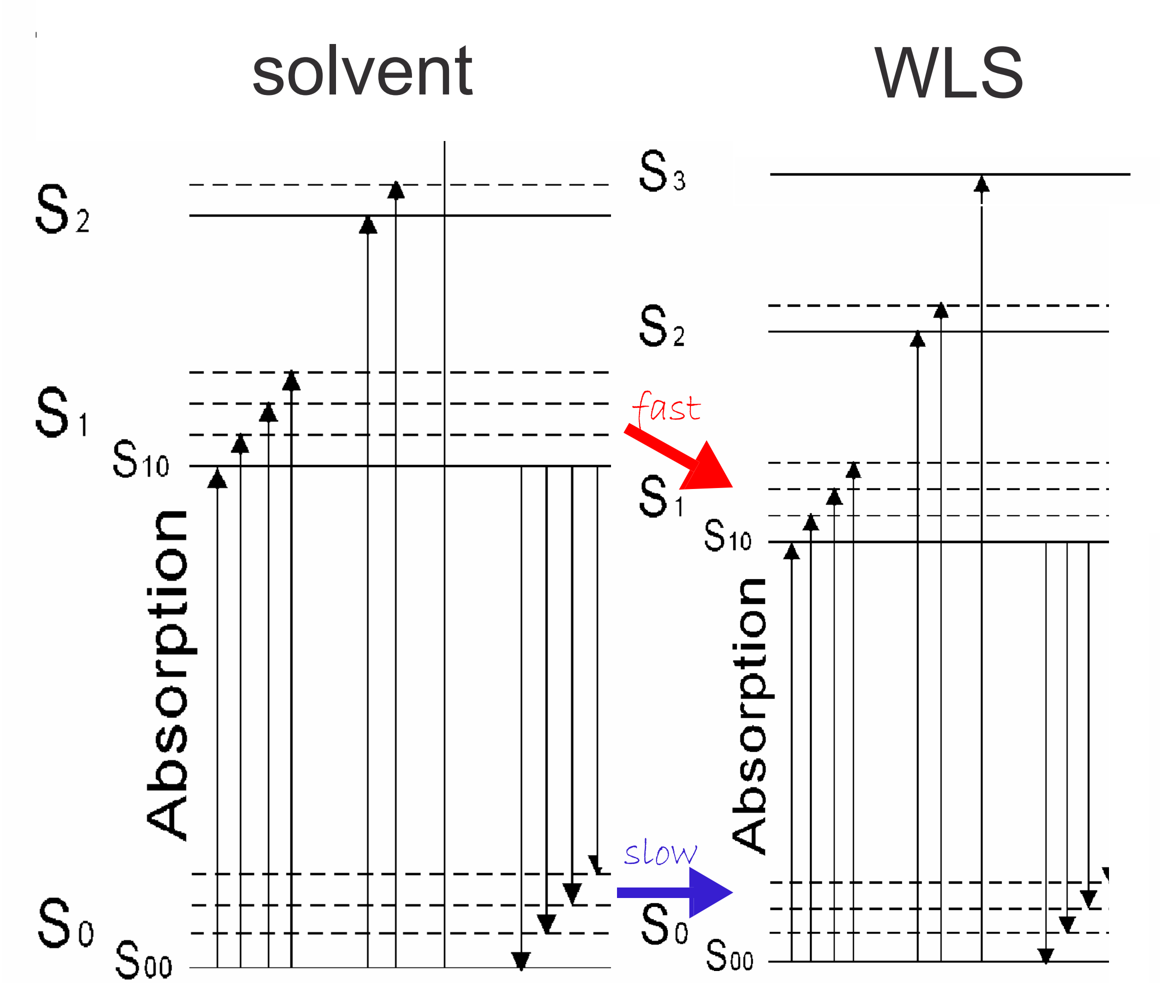




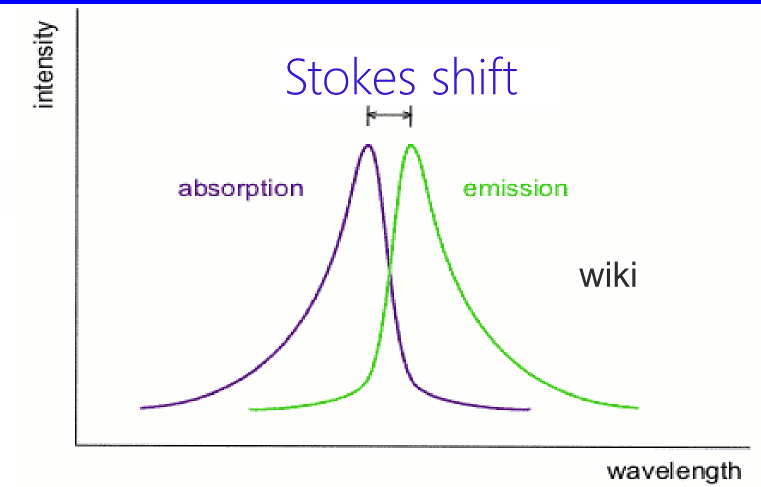


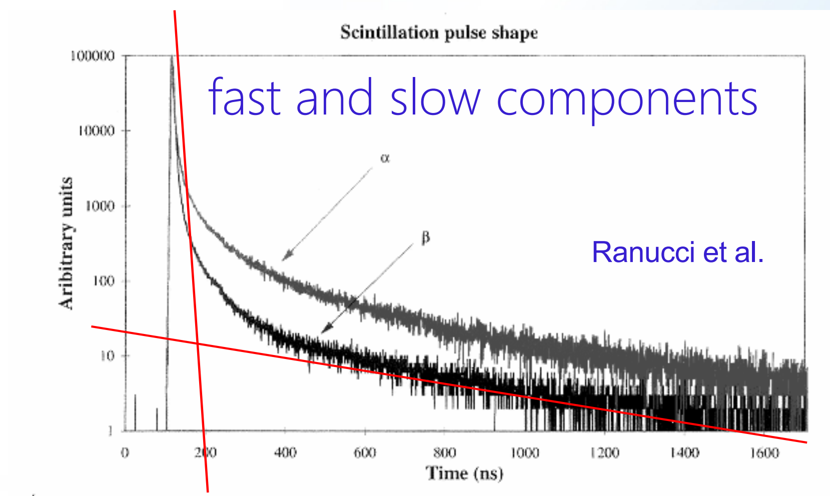
An excellent detection medium for neutrinos in MeV range

Scintillation Mechanism



Birk's Mechanism





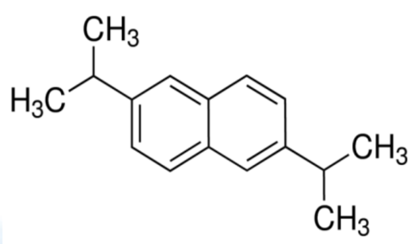
WbLS follows the same scintillation transition mechanism with quenching from water

Liquid Scintillators

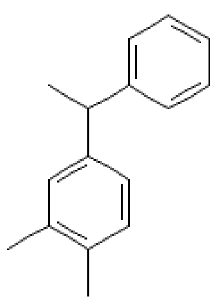
Table 1: Density, flash point and the wavelengths of the optical absorption/emission peaks (dissolved in cyclohexane) for several solvent candidates are shown.

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

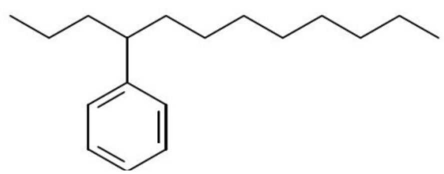
Molecule	chemical formula	density [kg/l]	flash point	abs. max.	em. max.
PC	C_9H_{12}	0.88	48°C	267 nm	290 nm
toluene	C_7H_8	0.87	4°C	262 nm	290 nm
anisole	C_7H_8O	0.99	43°C	271 nm	293 nm
LAB	–	0.87	∼ 140°C	260 nm	284 nm
DIN	$C_{16}H_{20}$	0.96	> 140°C	279 nm	338 nm
o-PXE	$C_{16}H_{18}$	0.99	167°C	269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

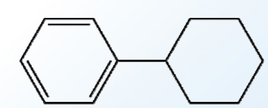


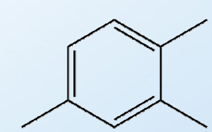
Di-isopropylnaphthalene (DIN)



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

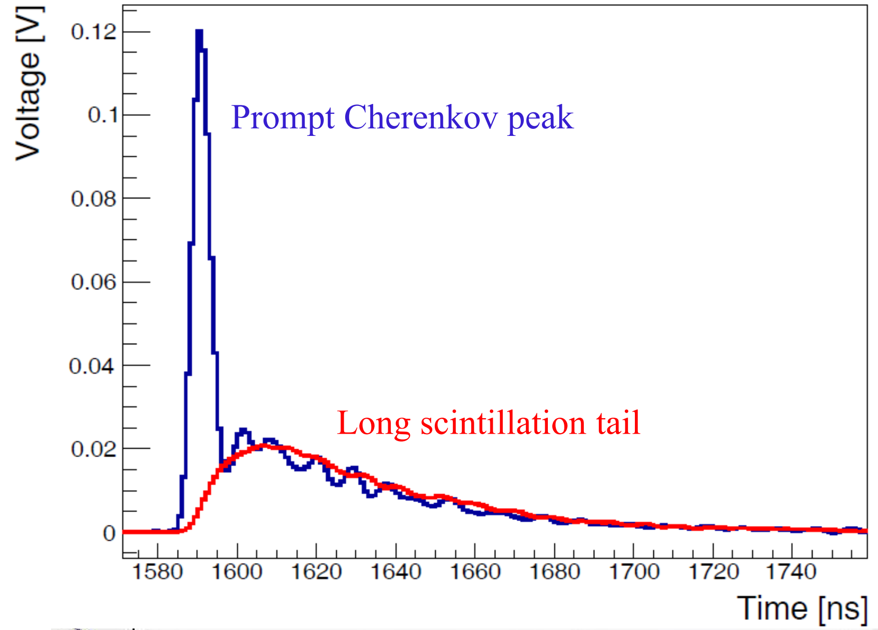

Linear alkylbenzene (LAB)

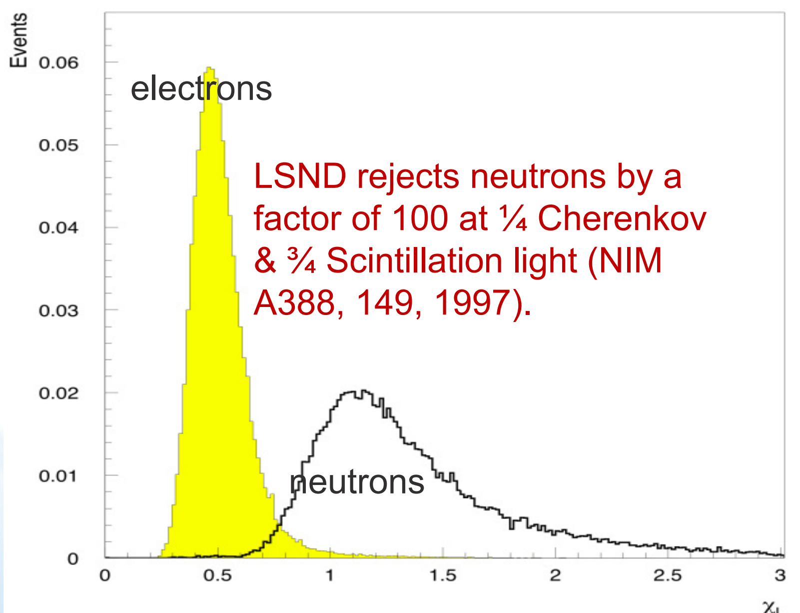

Cyclohexylbenzene (PCH)

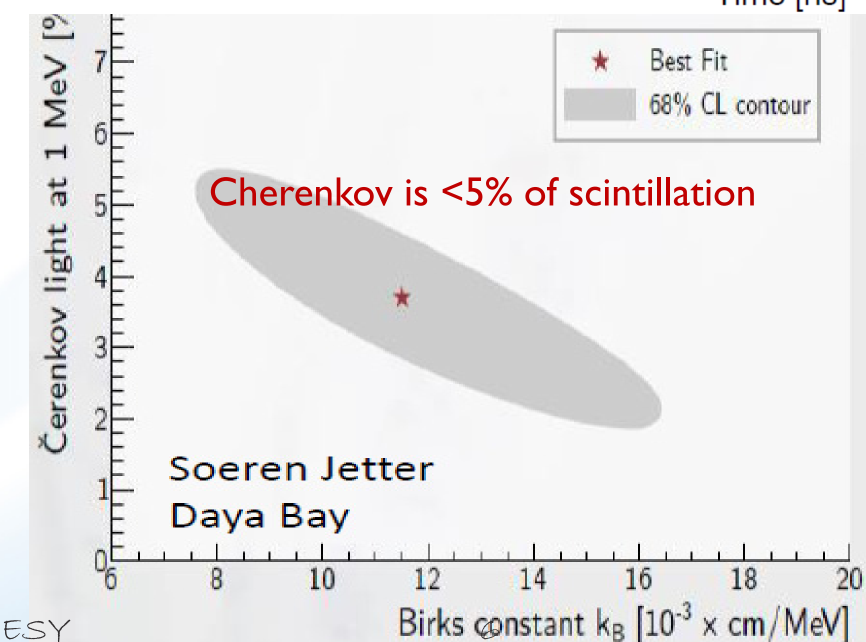

1,2,4-trimethylbenzene (PC)

Cherenkov/Scintillation Separation

- Separation of Cherenkov from scintillation allows directional cut for particle ID
  - Fast photosensors/electronics (LAPPD)
  - Ratio of scintillation light in Cherenkov
  - Slow scintillation decay time with max. fluorescence





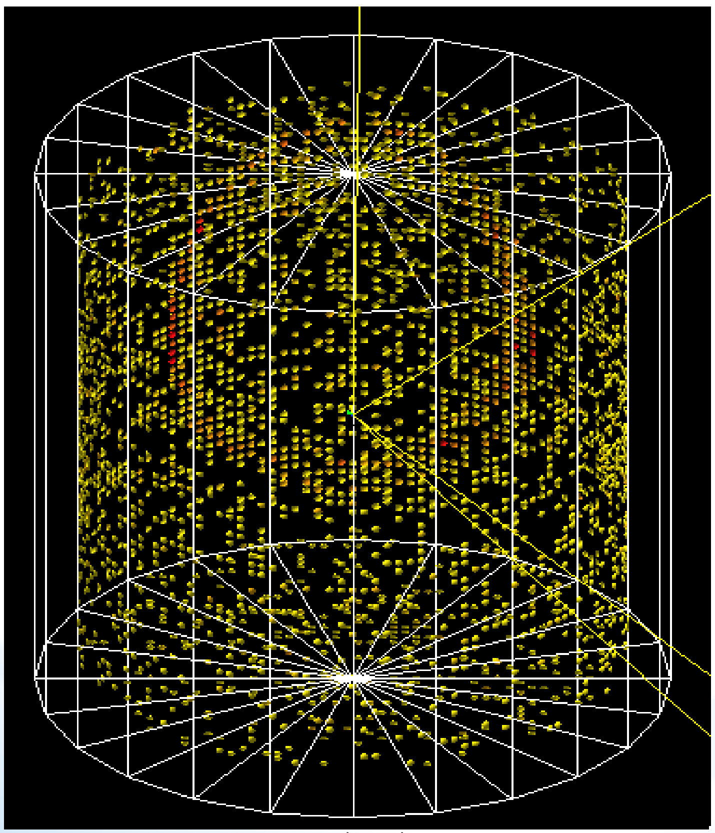


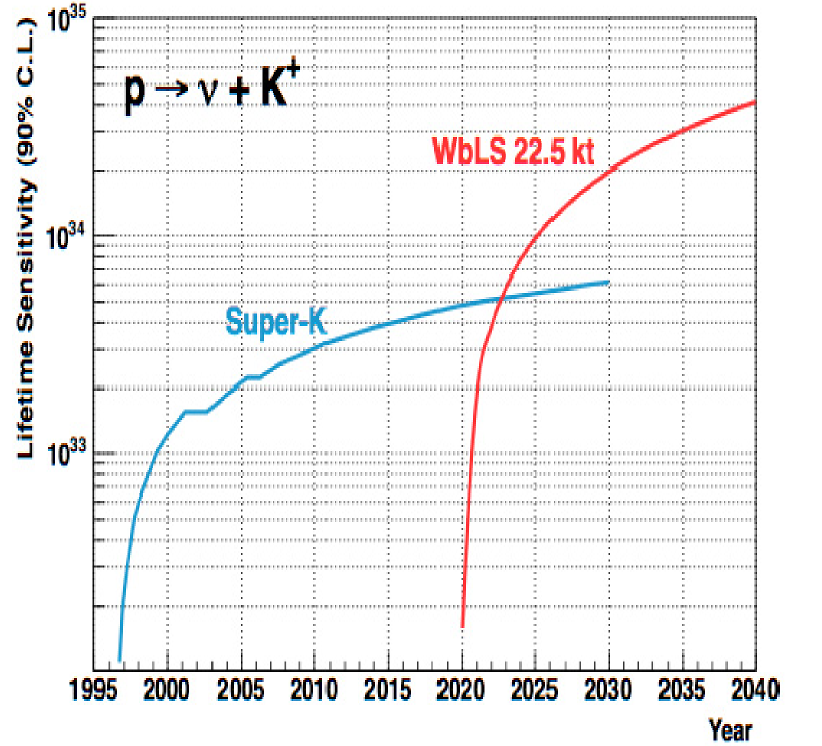
THEIA LS Selection
optimization of C/S separation

- Fast timing with limited light yield
  - R&D on Jinping 1-ton prototype
- Slow timing with max light yield
  - Neutrinoless double-beta decay experiment (i.e. SNO+)
- Scintillation-enhanced Cherenkov detector (WbLS)
  - Low-scintillator-doped, cost-effective, water-based scintillator
  - Metal-doped capability

Water-based Liquid Scintillator

- Motivated by proton decay with physics below E_{Chev} and scintillation addition in WCD
- A novel scintillation liquid ranging from ~pure water to ~pure organic





A 50-m WbLS SK-like detector (100ph/MeV)

- T_{k+}= 90MeV
- 20% coverage with 25% QE photocathode
- Deep underground >3000 m.w.e.
- Fast decay at 12ns

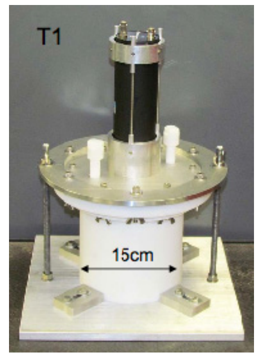
WbLS Principals

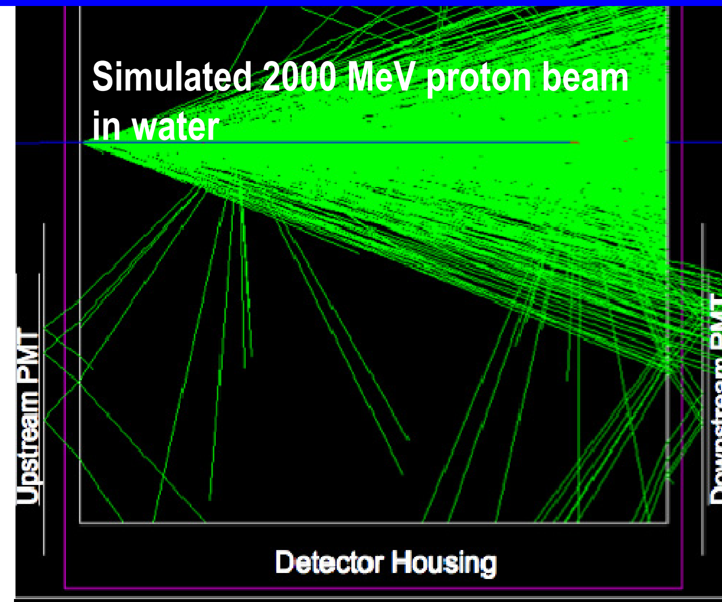
- Adjustable scintillation light yield from 1 to 15% LS added to water for physics of interest
- Long attenuation length (LS~20m, water ~100m, (1%)WbLS~30m)
- Particle identification/reconstruction:
  - Directional (Cerenkov) and isotropic (Scintillation) light
  - Timing of prompt Cerenkov and scintillation light
  - Energy measurement via calorimetry (scint.) and Cerenkov threshold
- Low-cost: (1%) WbLS using LAB (linear alkylbenzene) derivatives as LS ~ $(30+$H_2O$)/ton
- Environmentally and chemically friendly
- Enables dissolution of lipophobic but hydrophilic metals

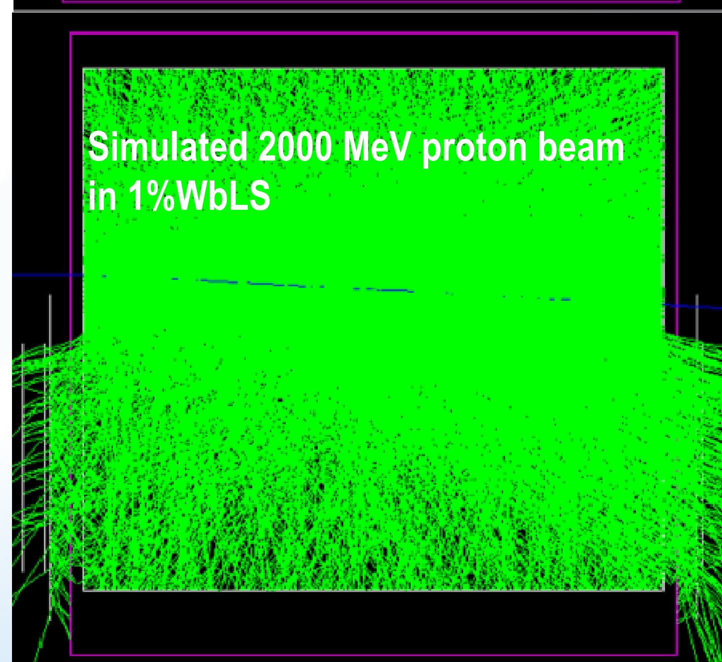
Cherenkov

- λ <400nm overlaps with scintillator energy-transfers will be converted to scintillation isotropic light.
- λ emits at >400nm will propagate unabsorbed (directionality).

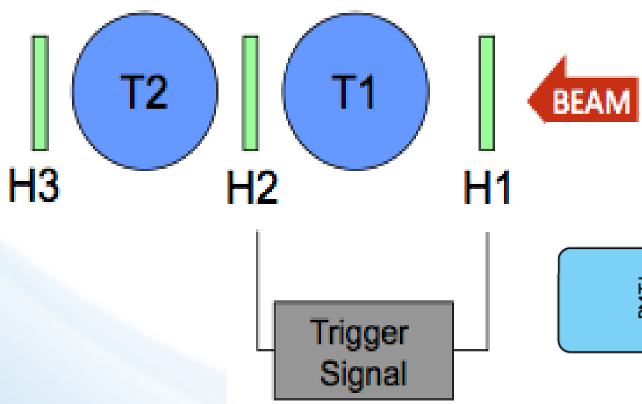
WbLS Proton-beam Measurements



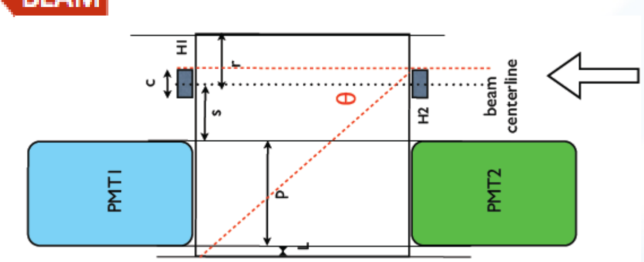




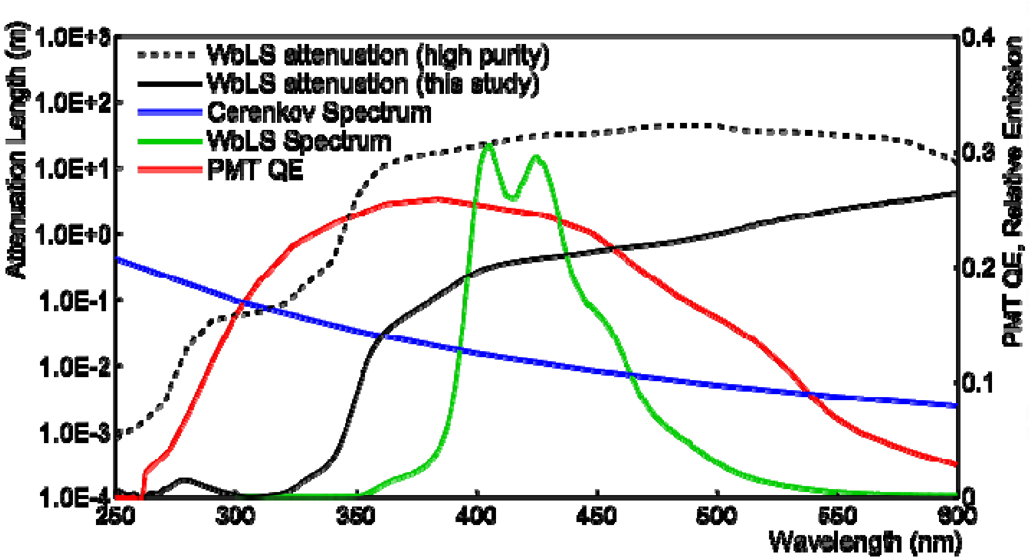
WbLS Detectors

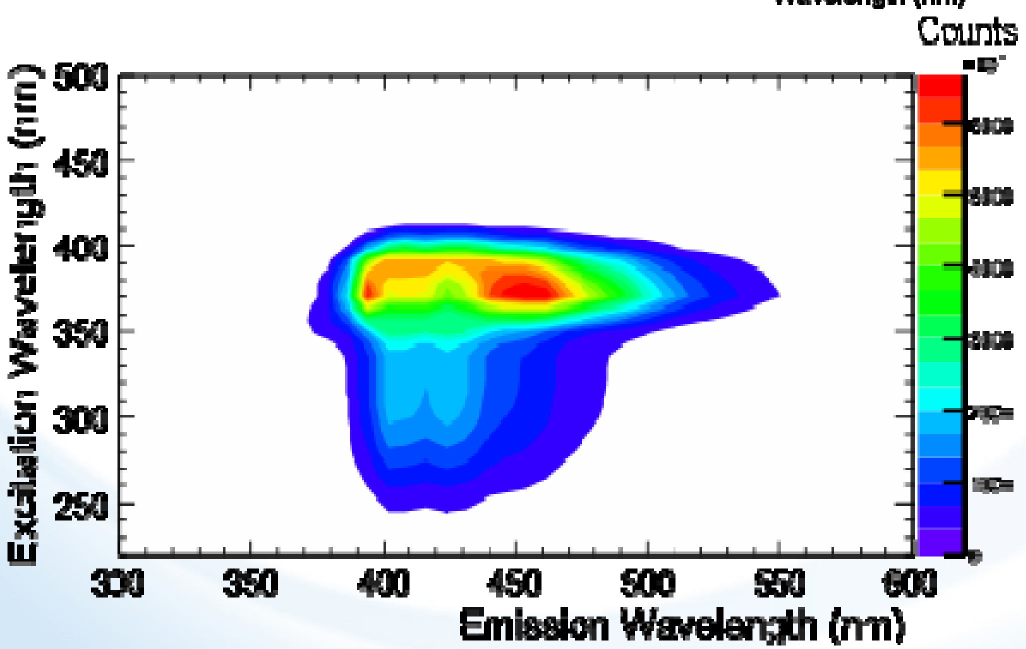


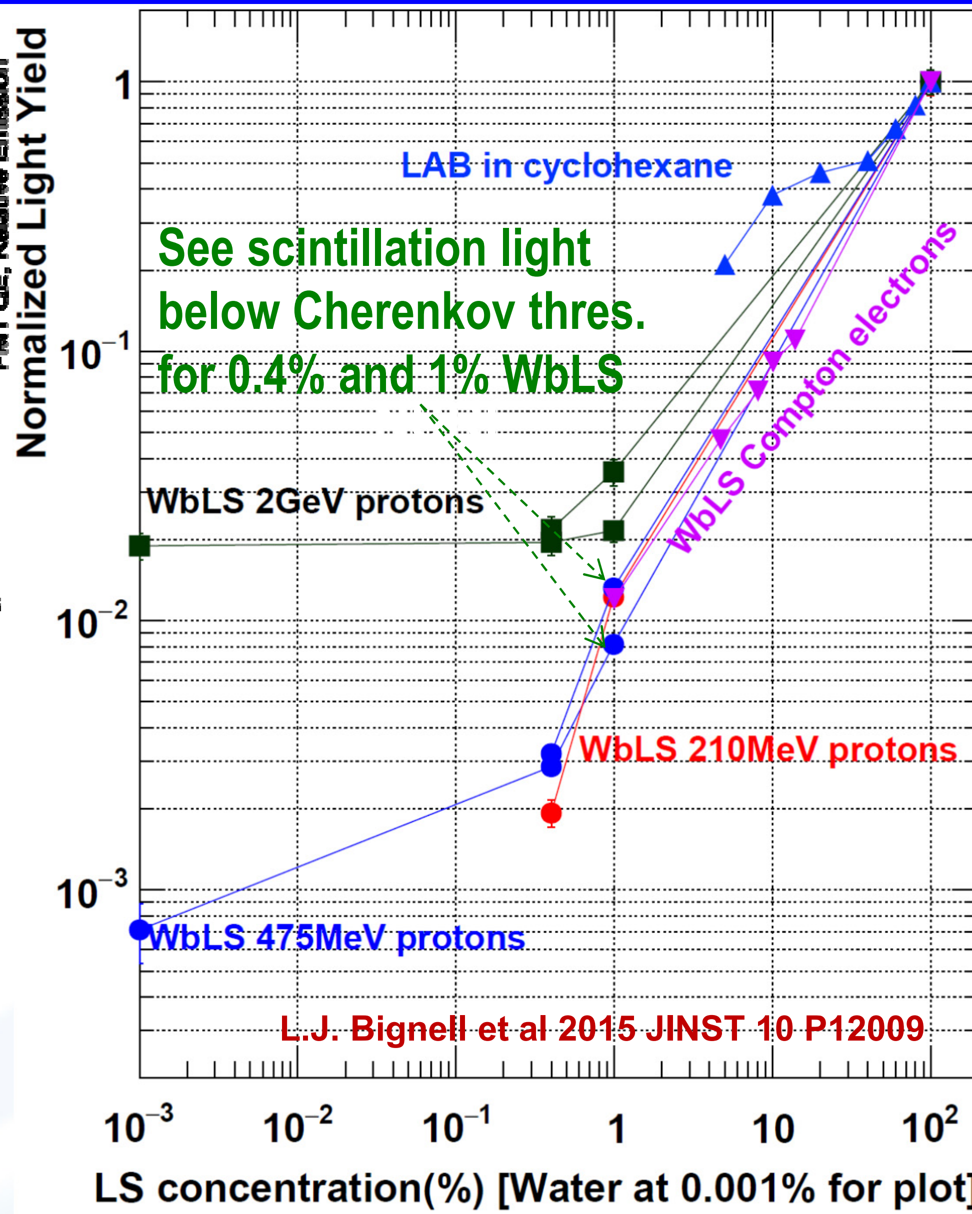
E_p = 210, 475, 2000 MeV



1% WbLS Property







WbLS Light-Yield and Quenching

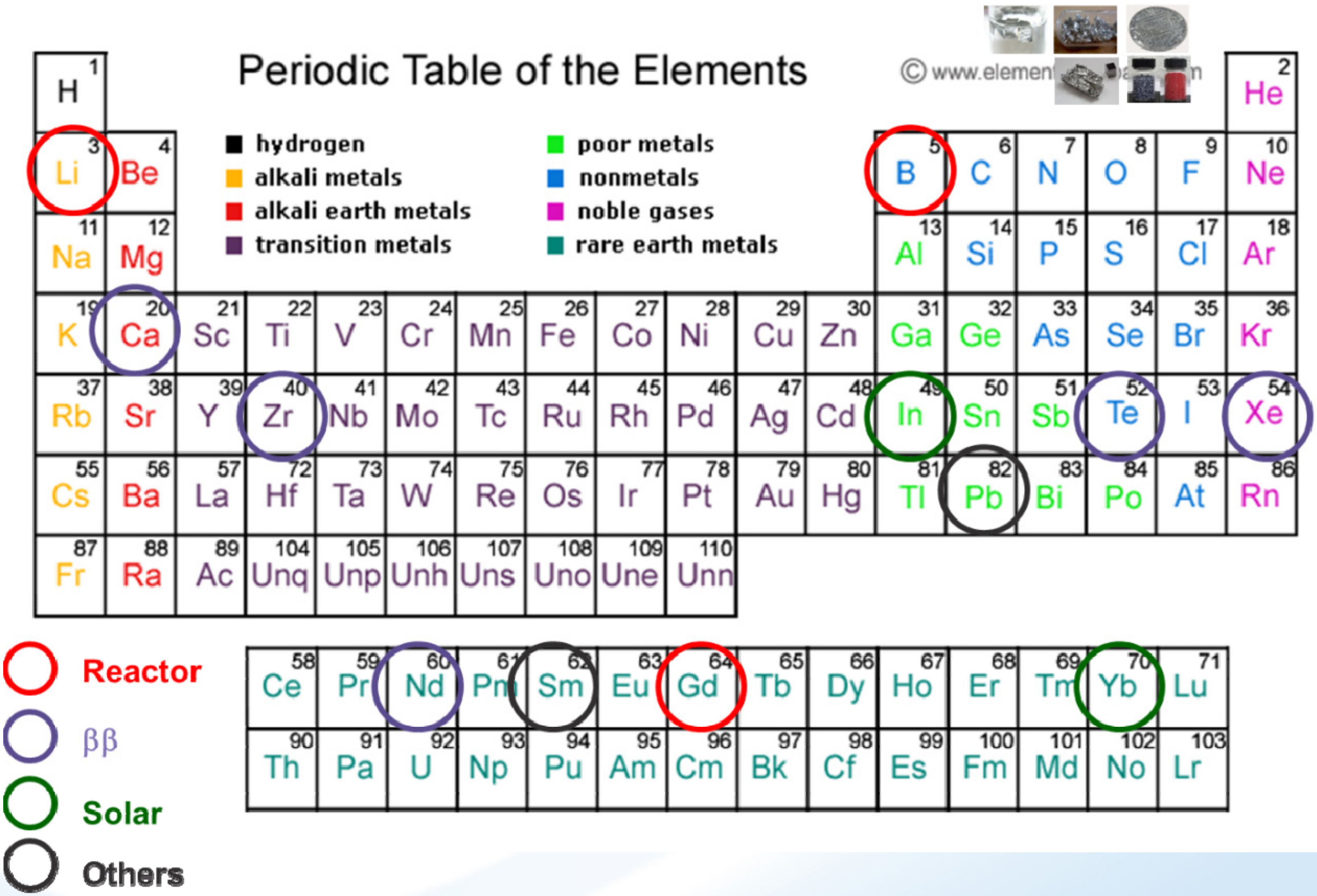
Material	Light yield (photons/MeV)	kB (mm/MeV)
0.4%WbLS	19.9±2.3	0.70±0.14
1%WbLS	109±11	0.44±0.05
LS	9156±917	0.07±0.01

L.J. Bignell et al 2015 JINST 10 P12009

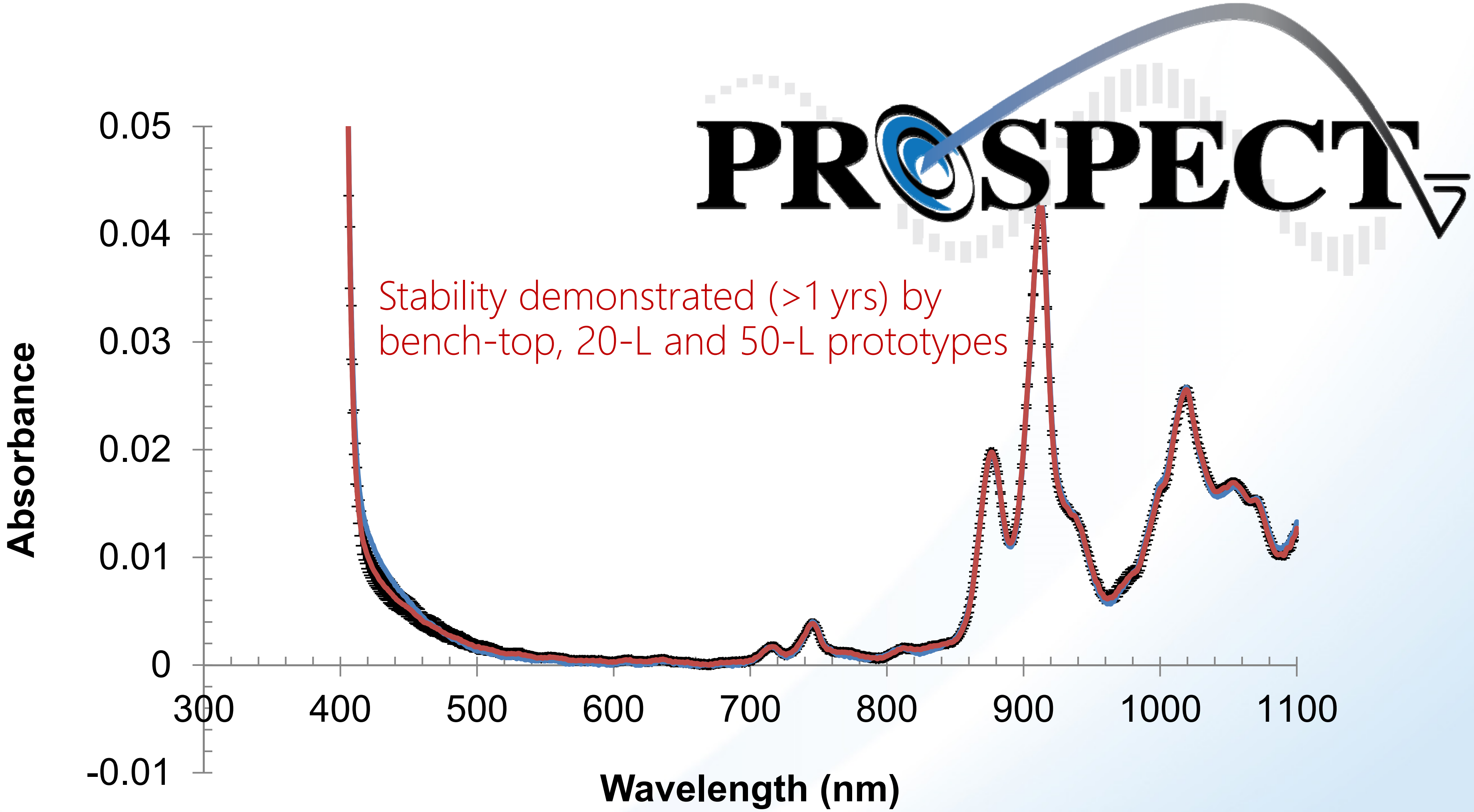
$$\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}.$$

- 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?

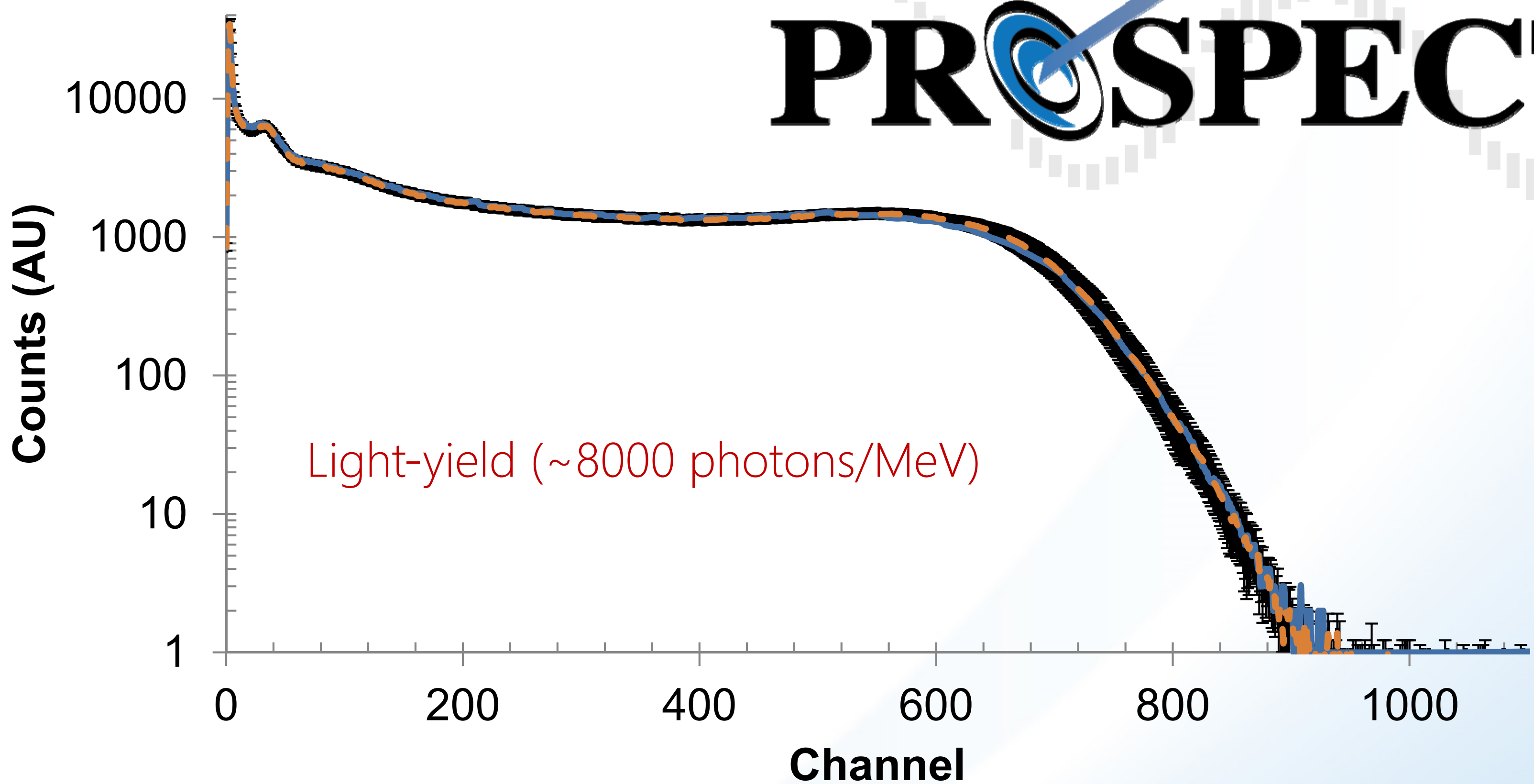
Metal-doped Liquid Scintillator



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

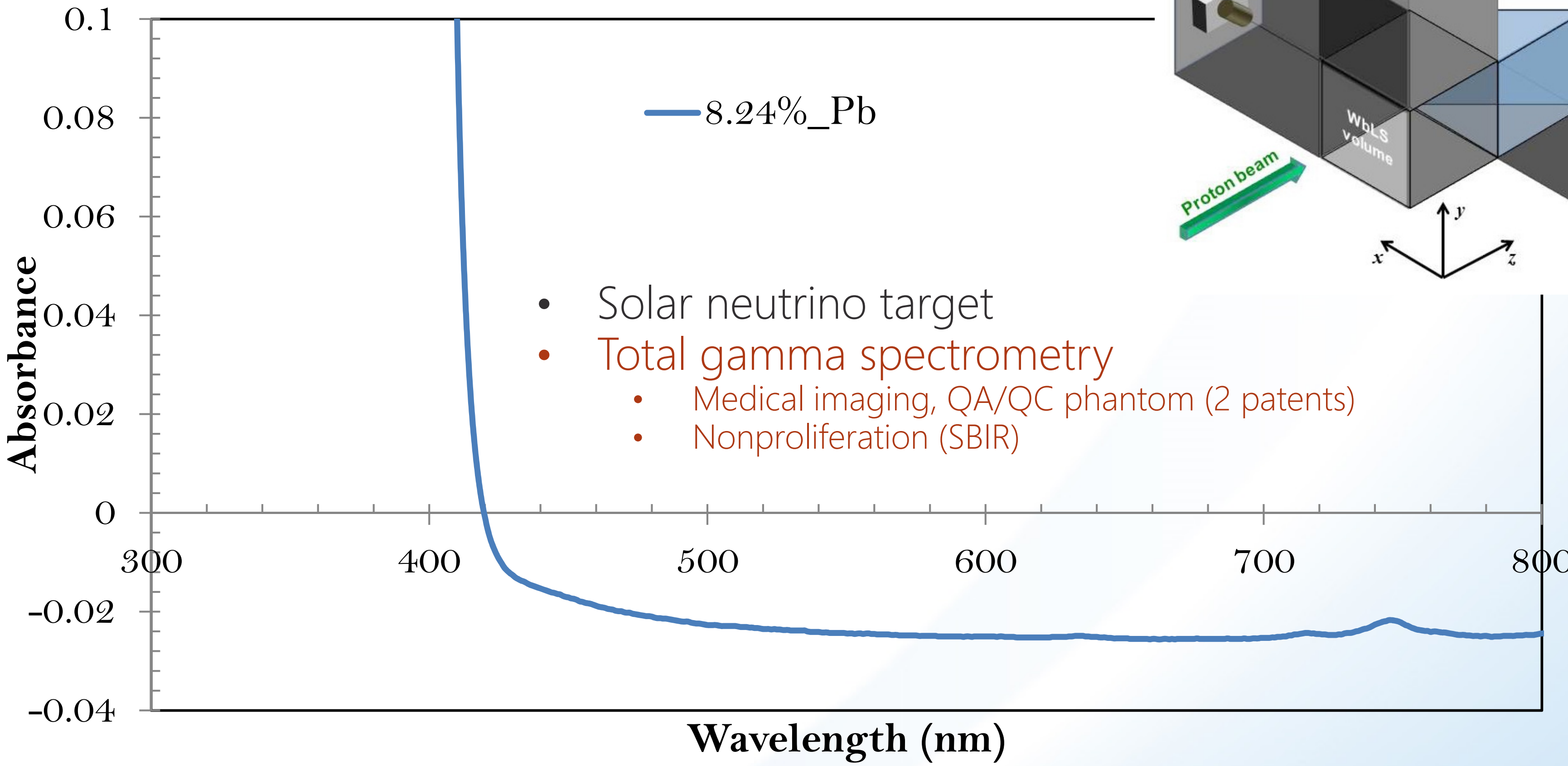


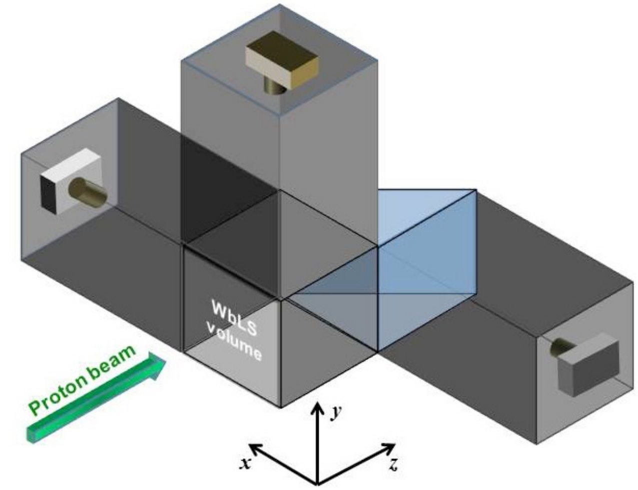
Ex. 0.1% ^{6}Li-doped LS)



Production of 5 tons is underway at BNL; aiming to start data taking in late 2017

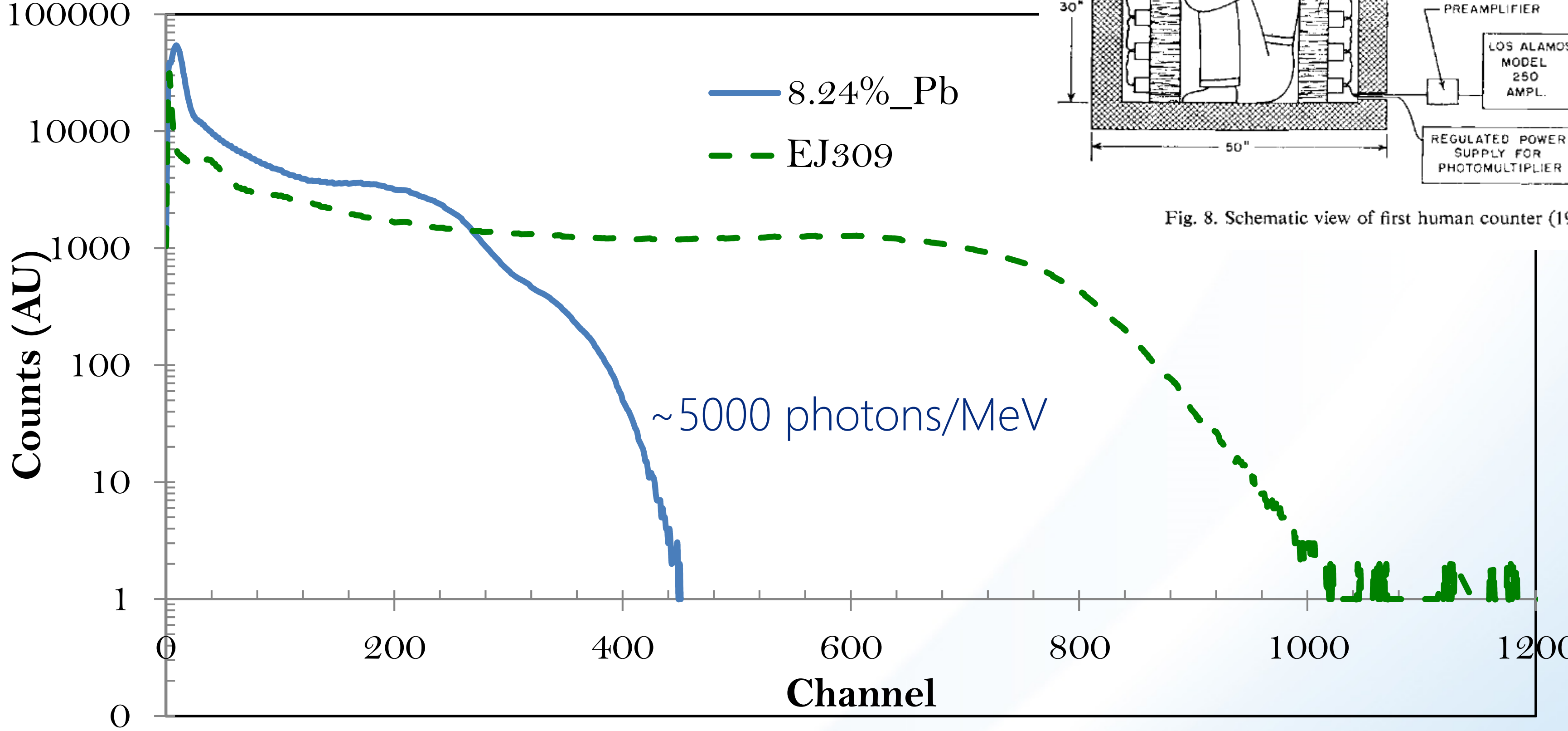
Ex. 8.24% Pb-doped LS





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

Ex. 8.24% Pb-doped LS



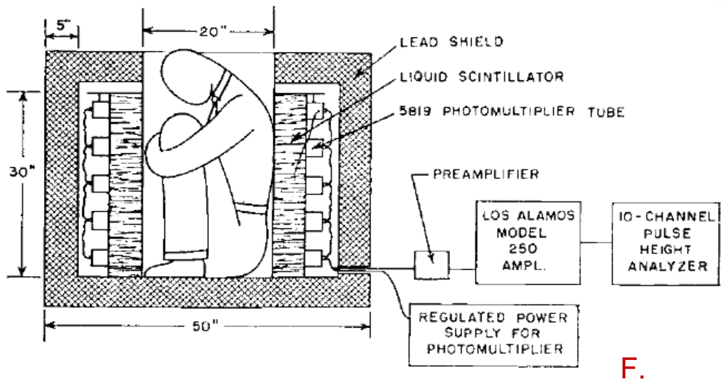


Fig. 8. Schematic view of first human counter (1953).

F. Reines

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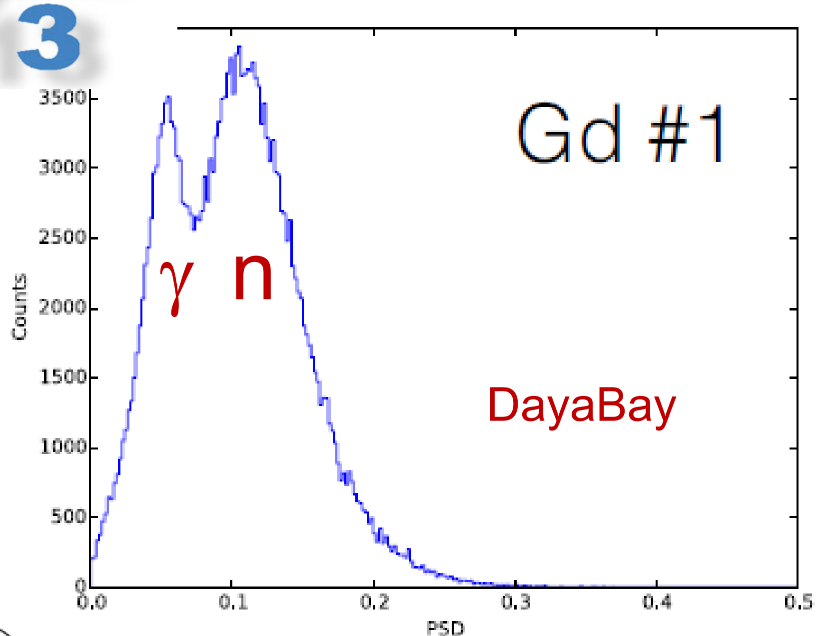
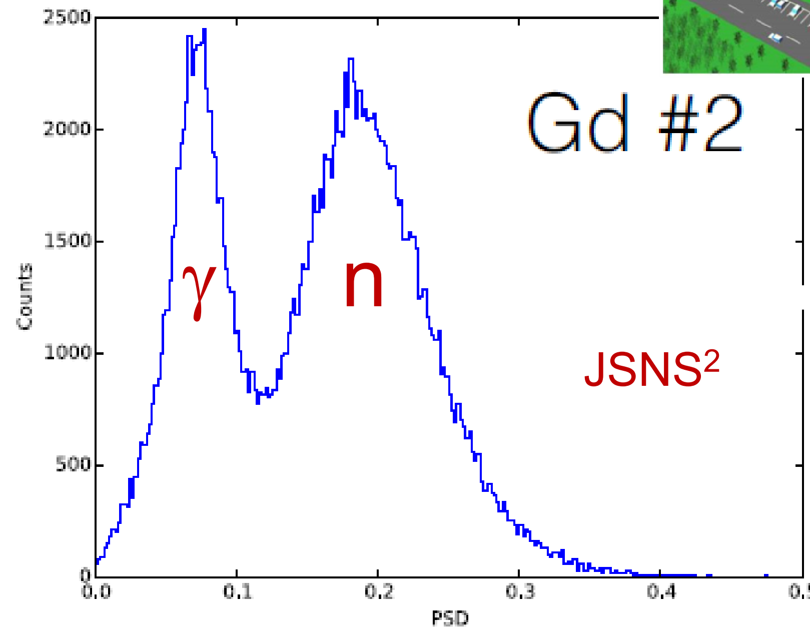
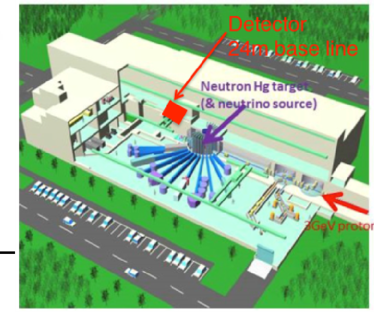
Ex. 0.1 wt% Gd-LS

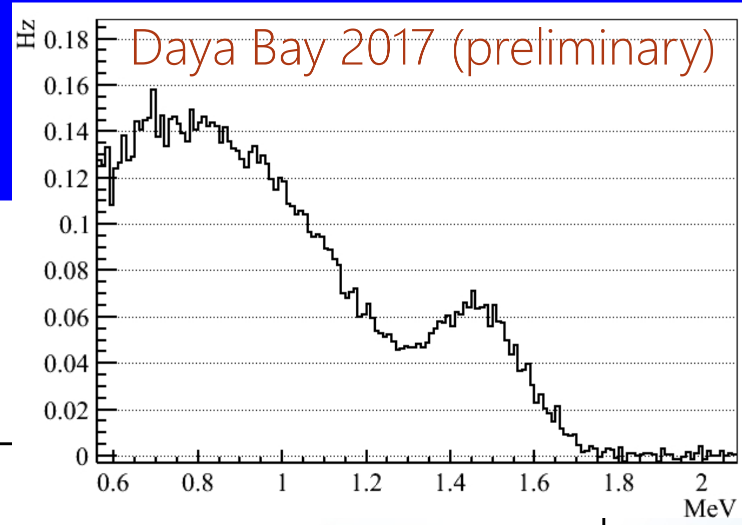


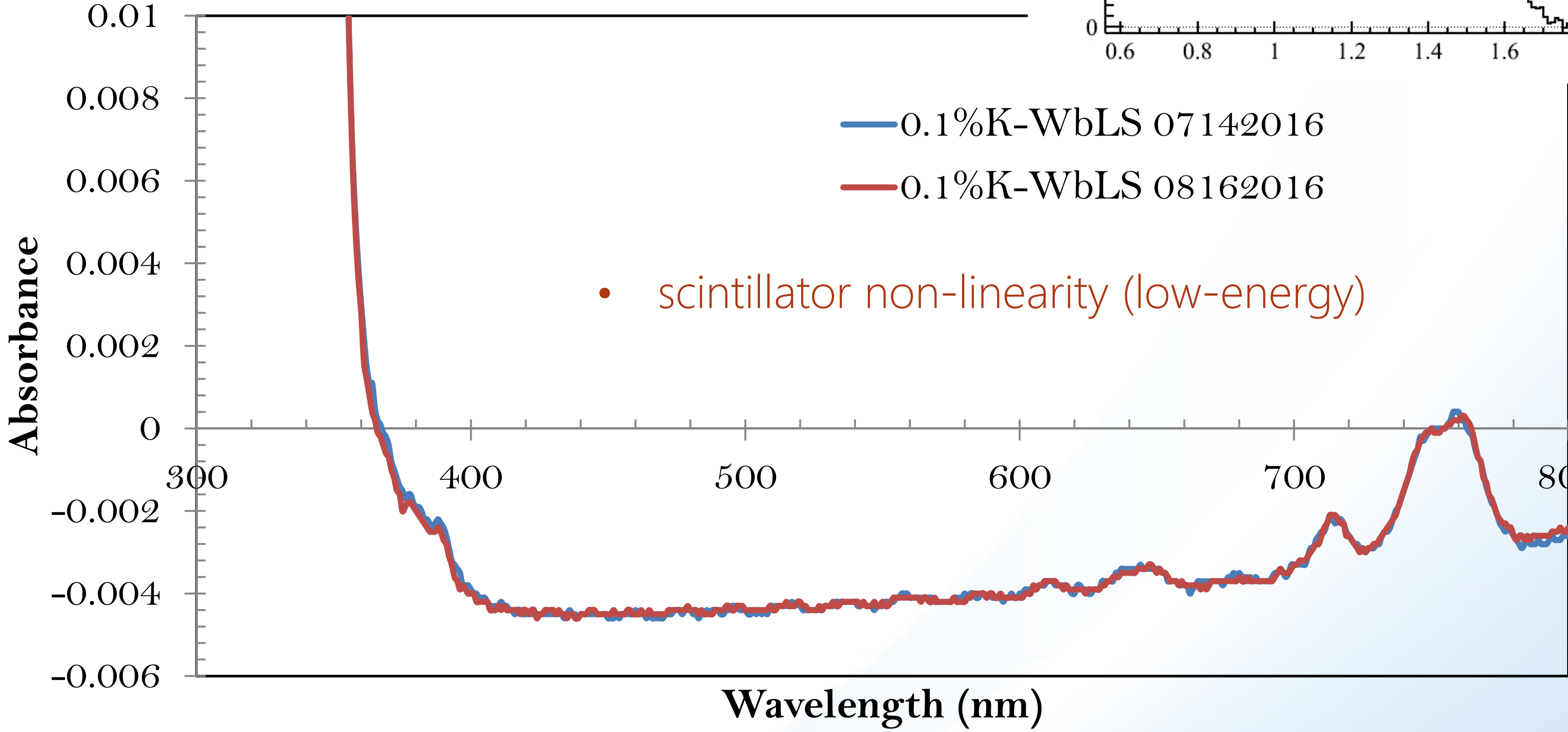




- 0.1% wt% Gd-doped LS (demonstrated by Daya Bay)
- Radiopure (LZ)
- PSD-improved and Cherenkov separation for detector operated on surface close to reactor/beam facility (JSNS² or other accelerator physics experiment)

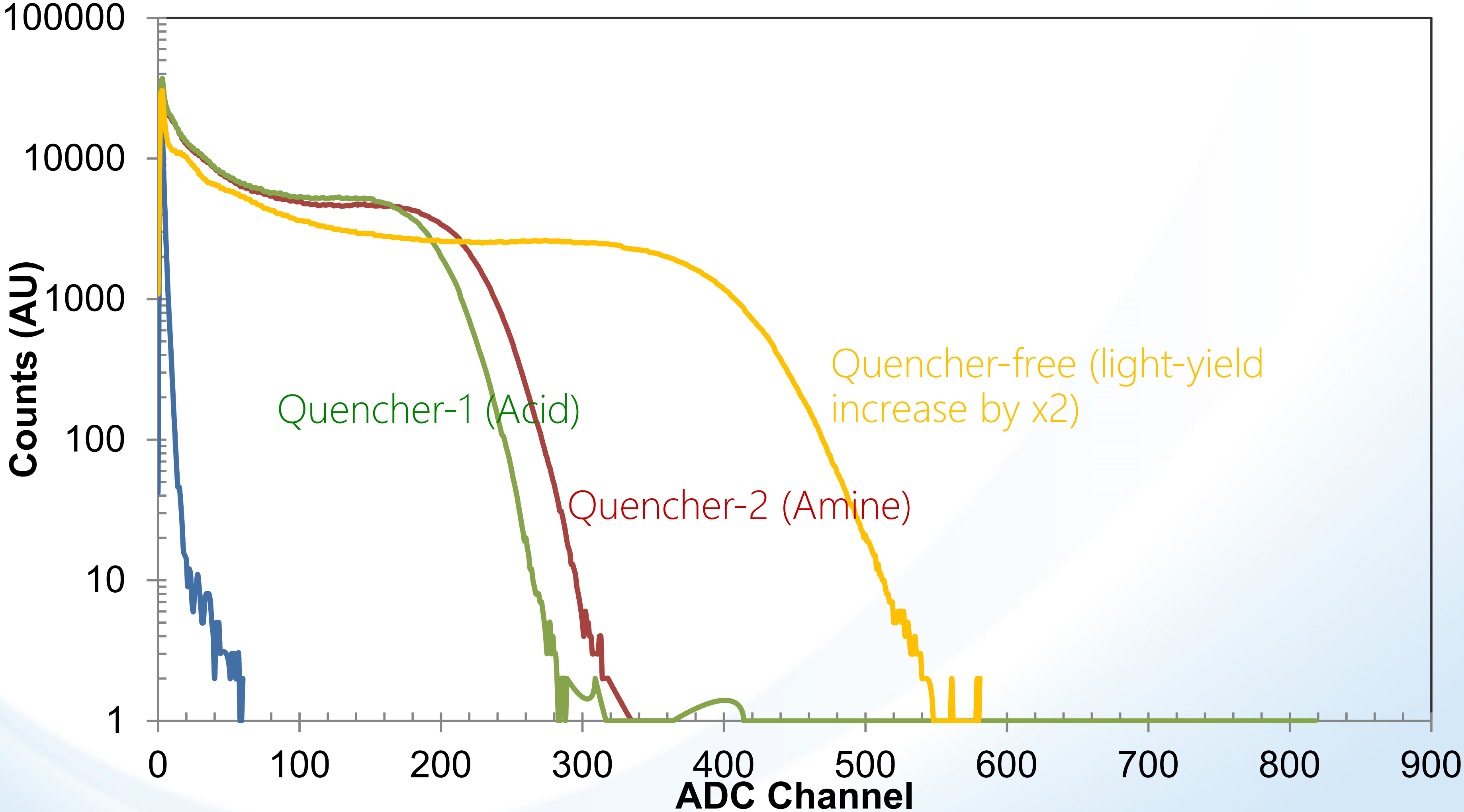
Ex. 0.1% K-doped LS



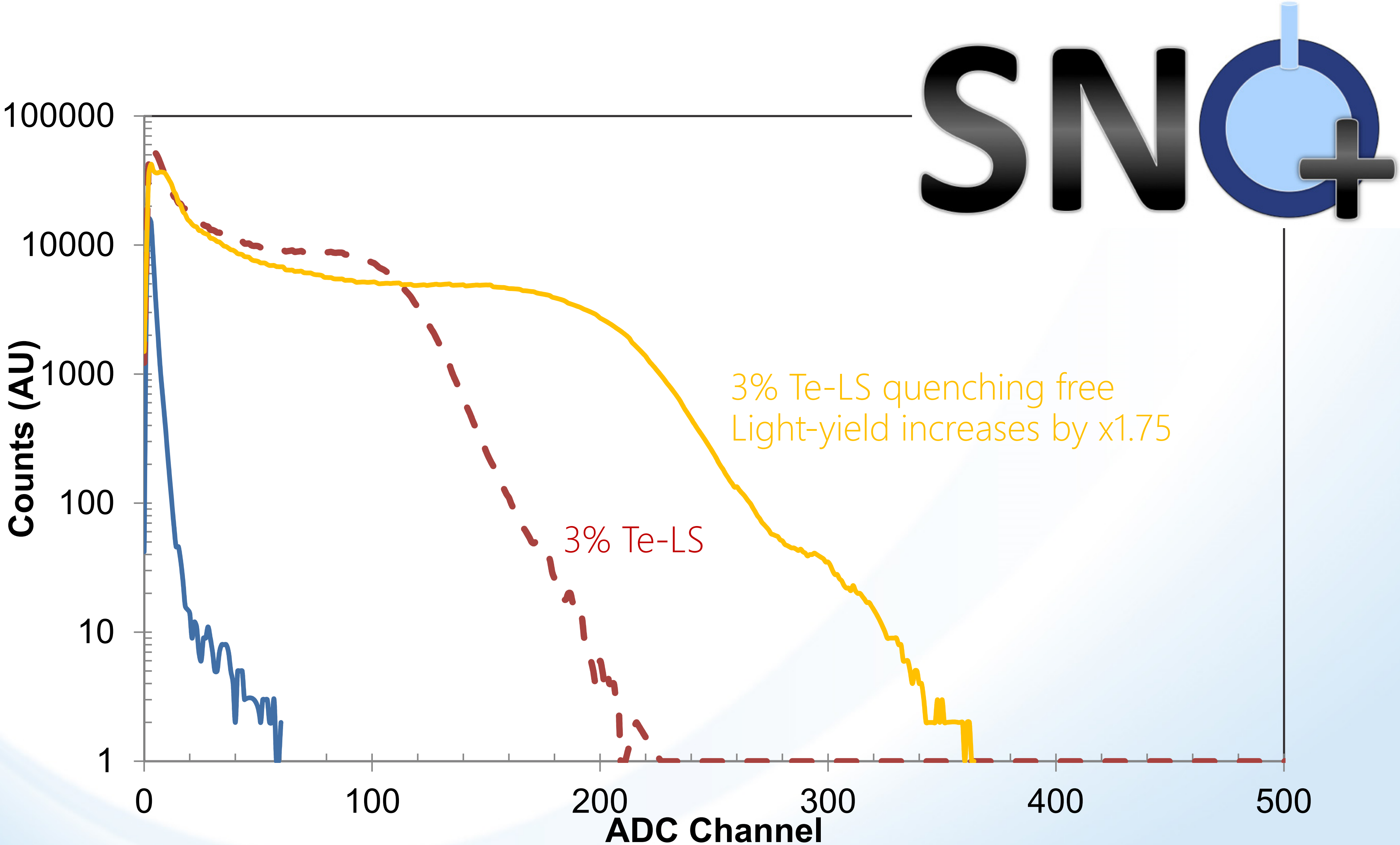


- scintillator non-linearity (low-energy)

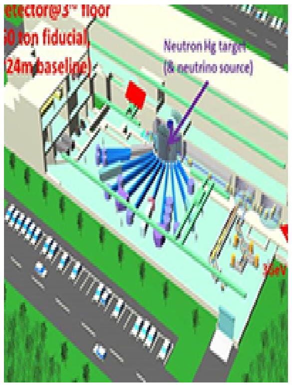
Kill Quenching (ex. LS)



Kill Quenching (ex. Metal-doped LS)



WbLS Near Plan



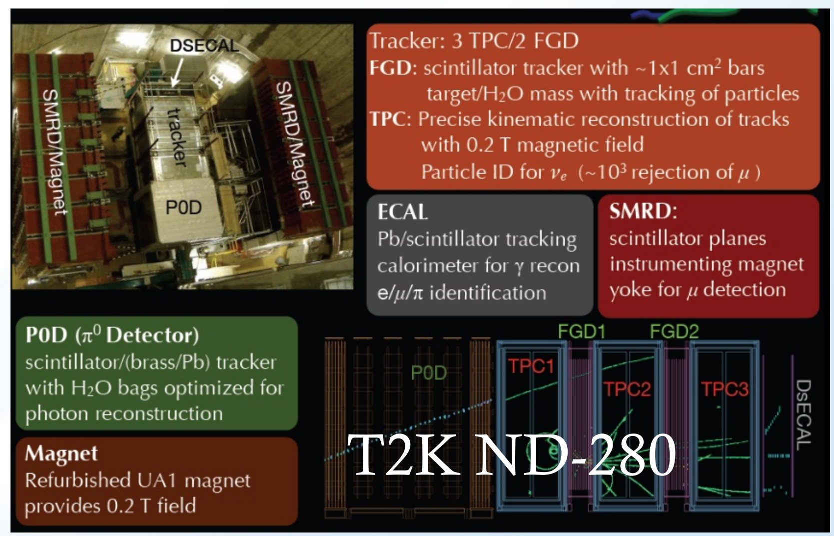
JSNS^2 (J-PARC E56) 実験

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

NP-supported

HEP-project



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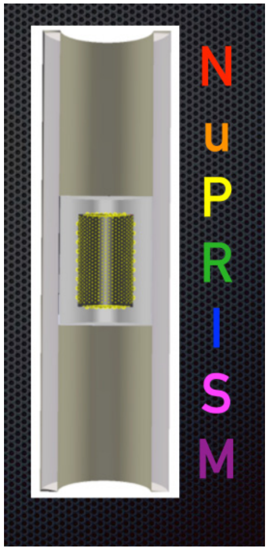
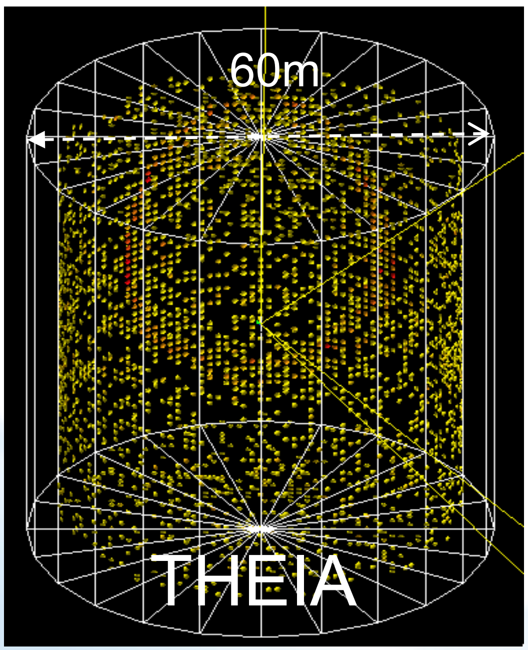
A large Water Cherenkov Detector (THEIA)

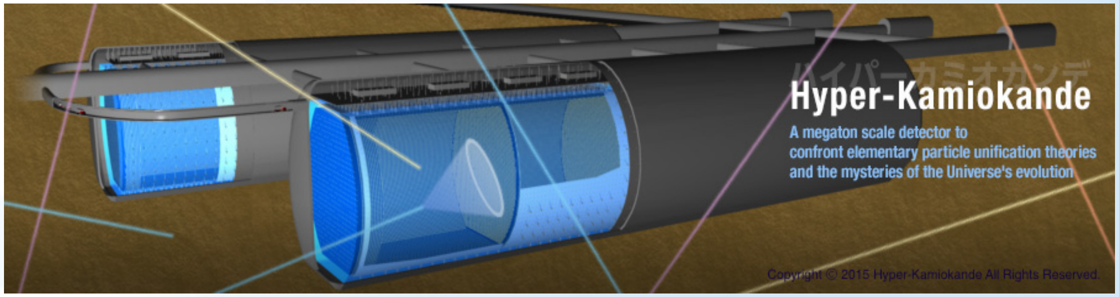
THEIA Proto-Collaboration

- 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

ANNIE
Accelerator Neutrino Neutron Interaction Experiment





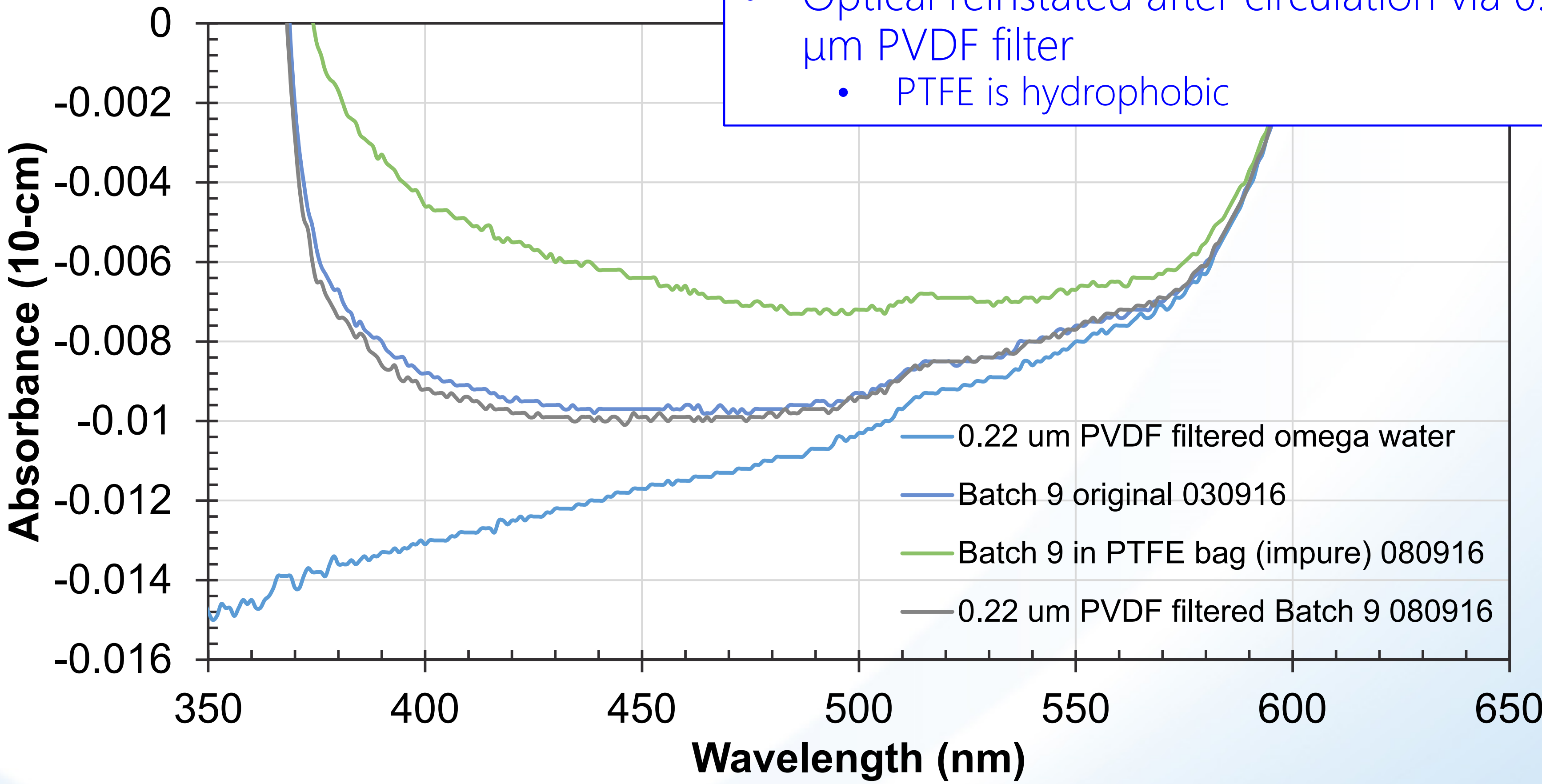


WbLS Challenges and Development

- 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



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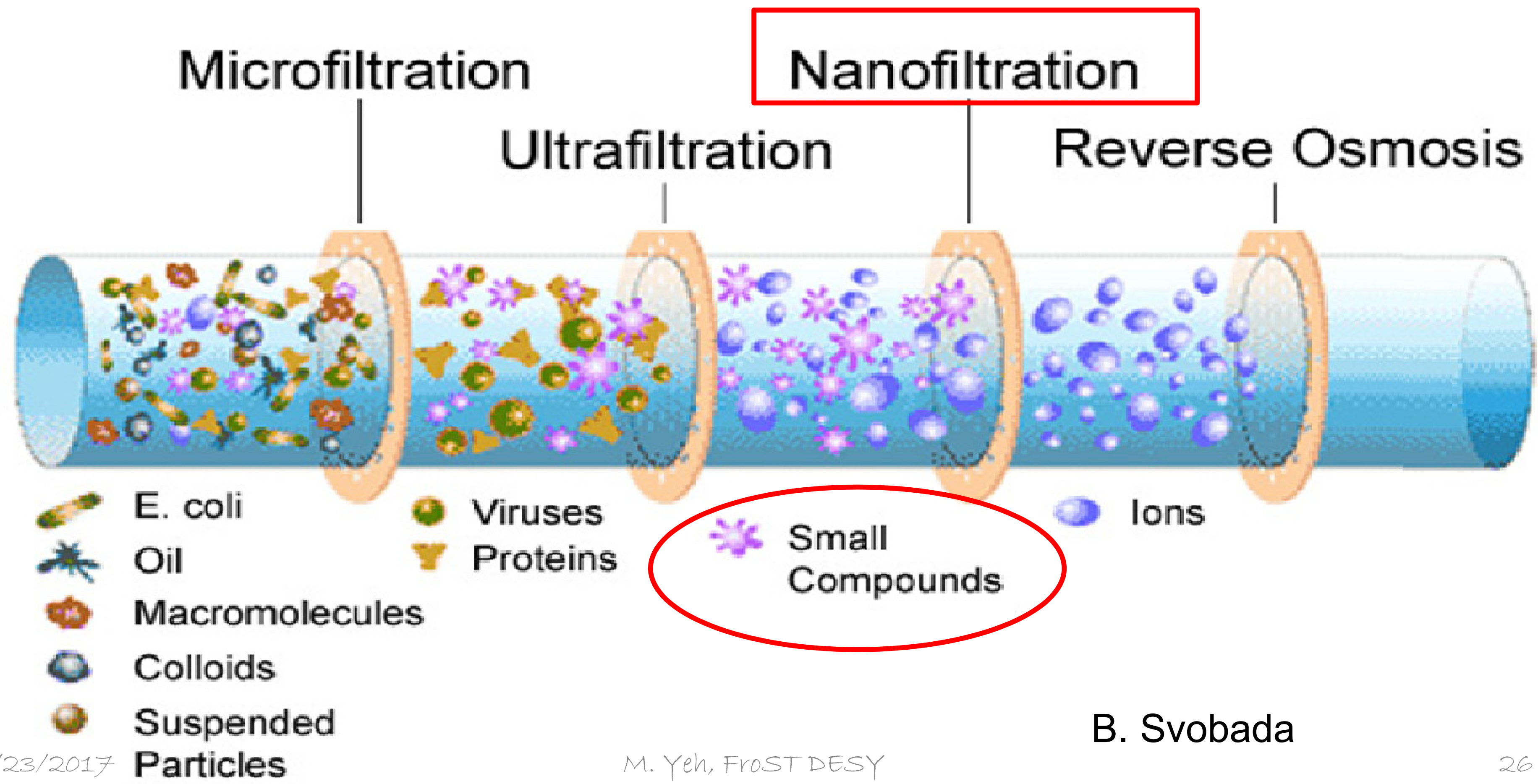
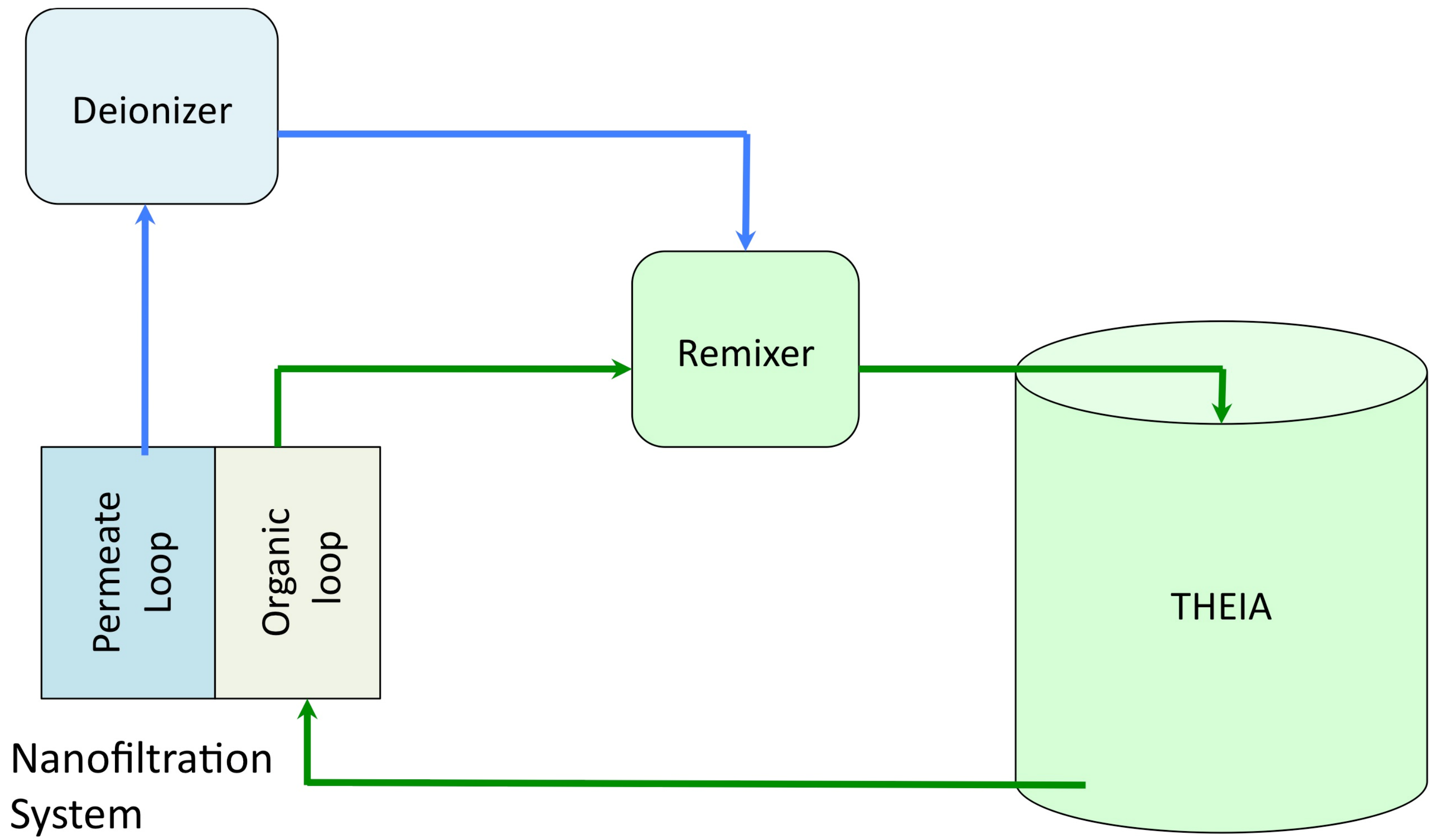
Contaminants such as iron ions degrade optical transparen of water detectors so they need to be constantly purified.

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

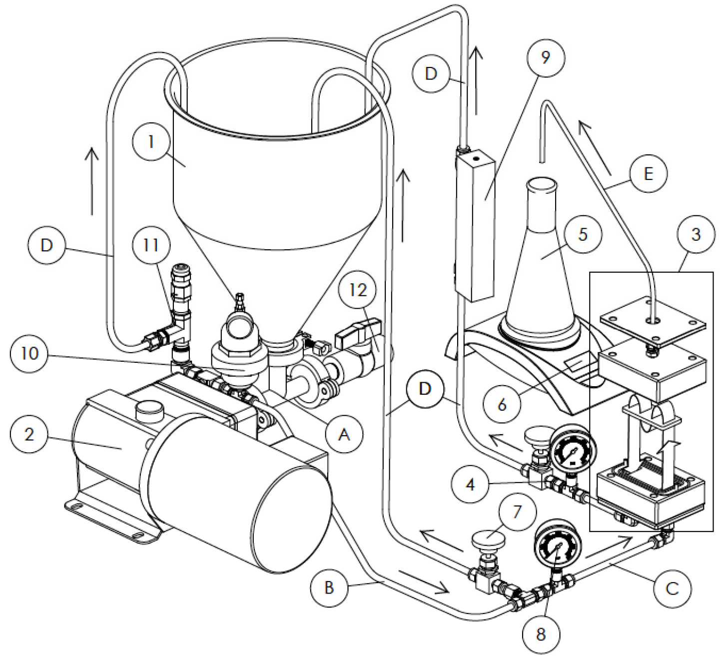
B. Svobada

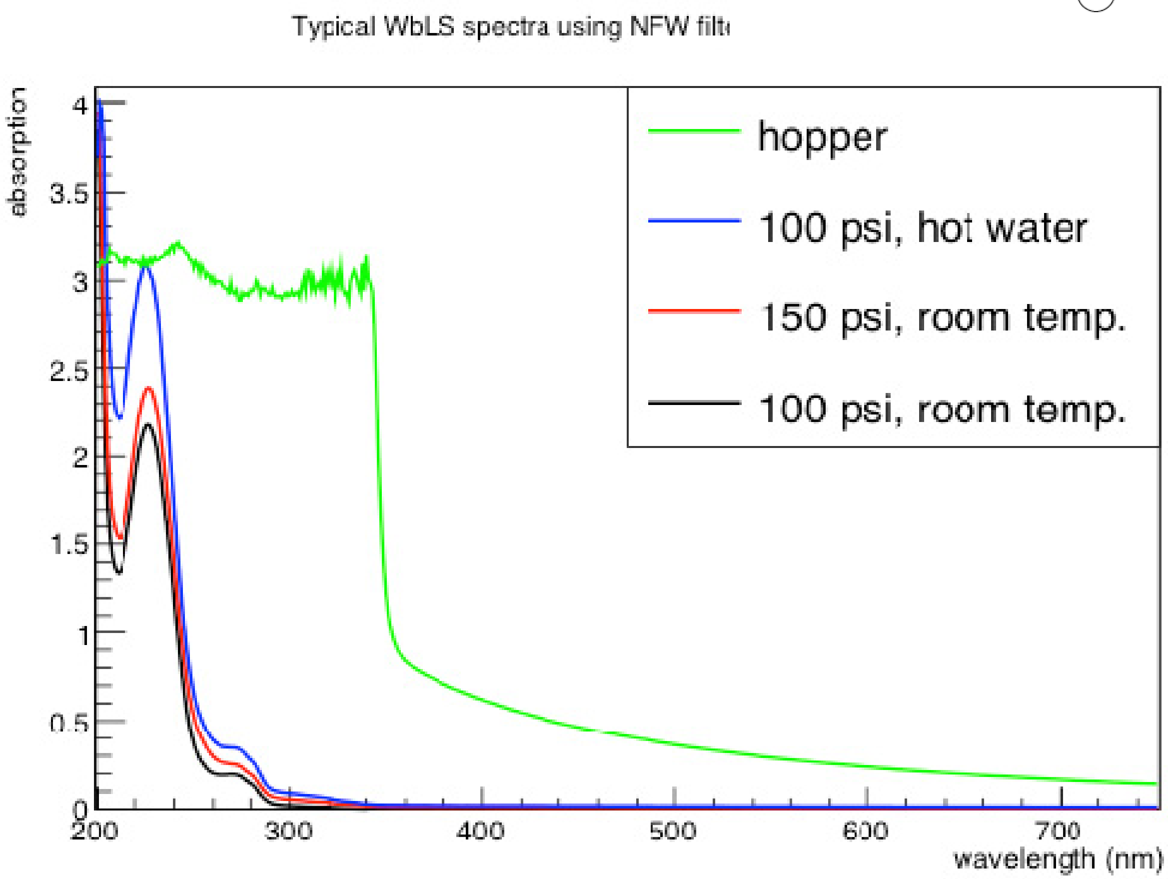
...but there are many considerations

- 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





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:

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

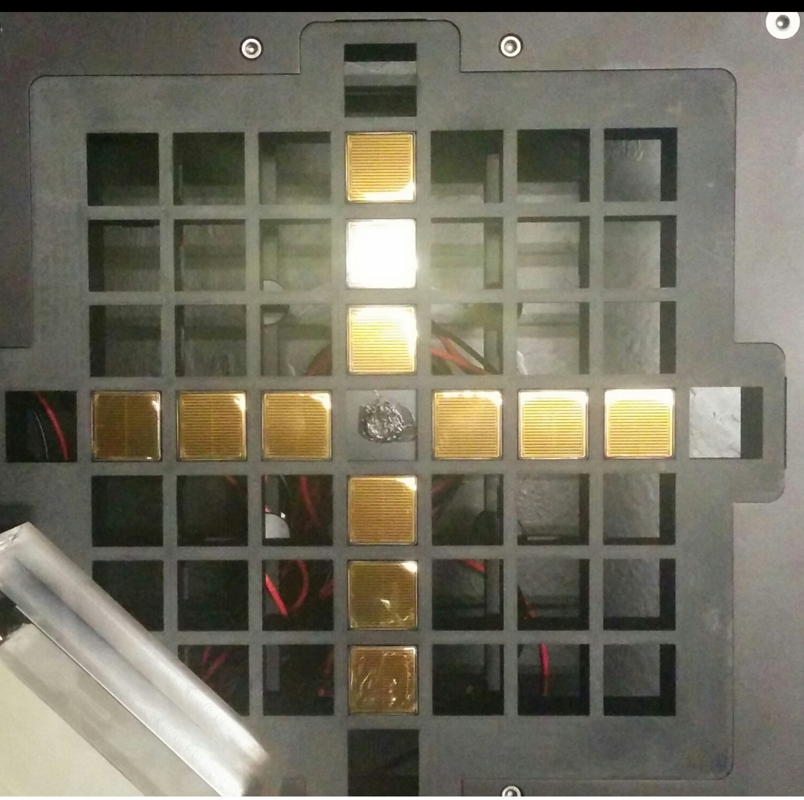
CHErenkov-Scintillation Separation

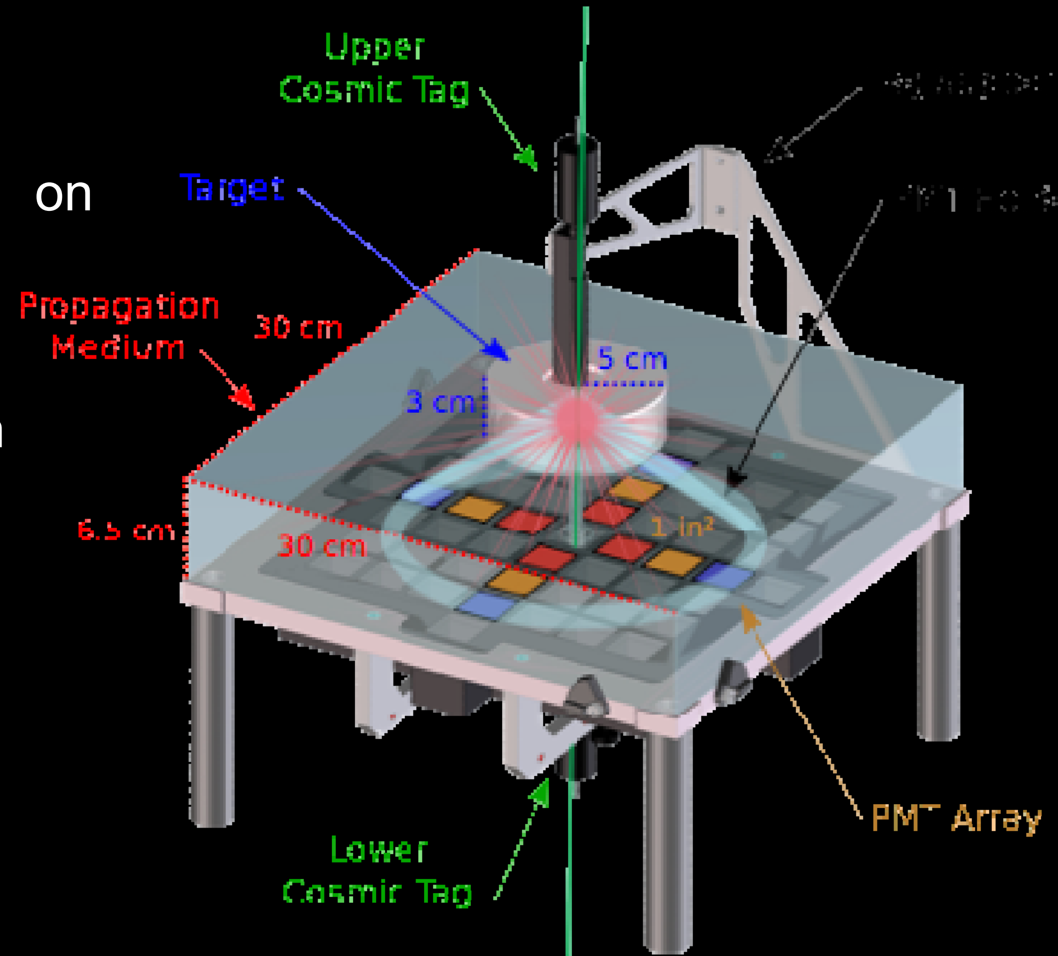
Select vertical cosmic muon events

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)

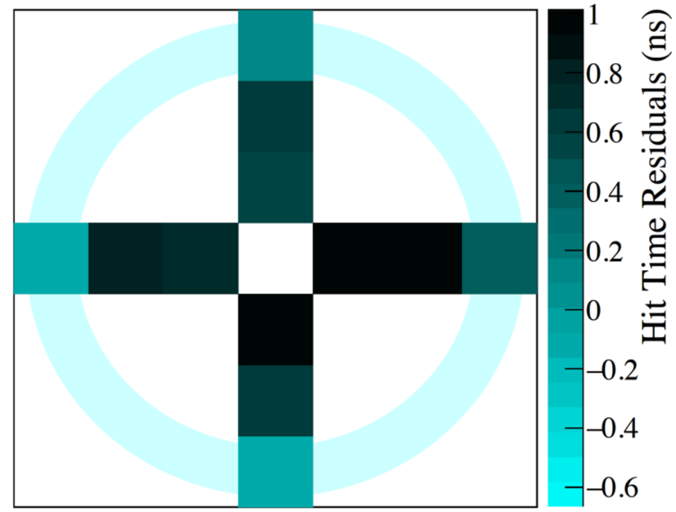
CHESS:
CHErenkov-Scintillation Separation

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

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

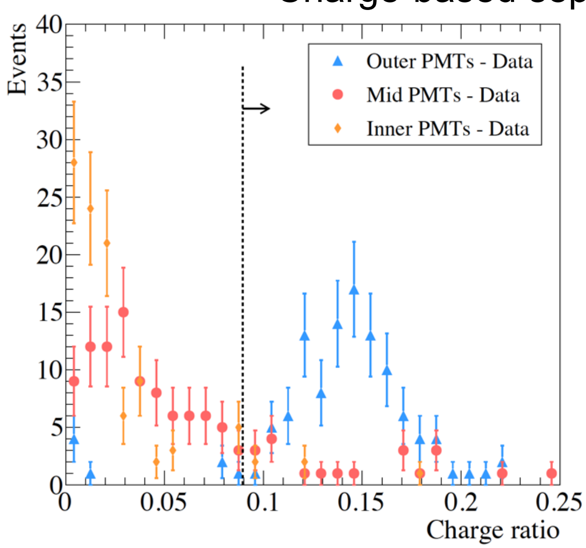
See dedicated talks at DNP, FROST (Oct '16)

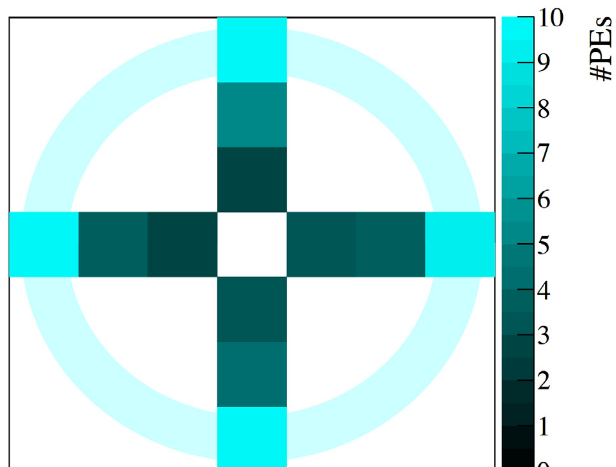
	LAB Time-based	LAB Charge-based	LAB/PPO Time-based	LAB/PPO Charge-based
Cherenkov detection efficiency	83 ± 3 %	96 ± 2 %	70 ± 3 %	63 ± 8 %
Scintillation contamination	11 ± 1 %	6 ± 3 %	36 ± 5 %	38 ± 4 %

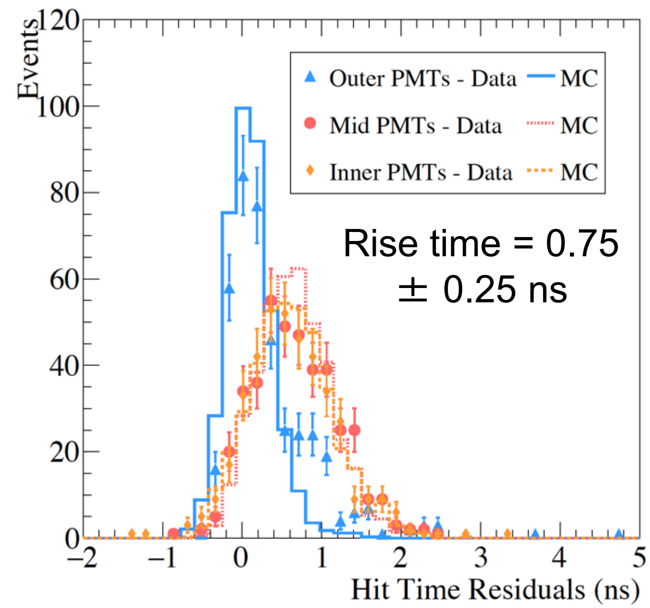


Time-based separation in LAB/PPO

Charge-based separation in pure LAB



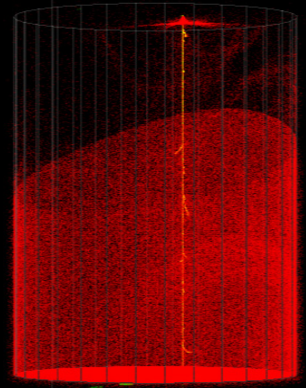




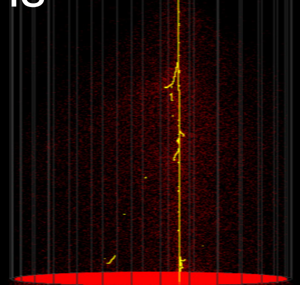
Full simulation includes detailed geometry, DAQ effects (TTS, pulse shapes, electronics noise…)

1000 liter WbLS Demonstrator

No black barrier

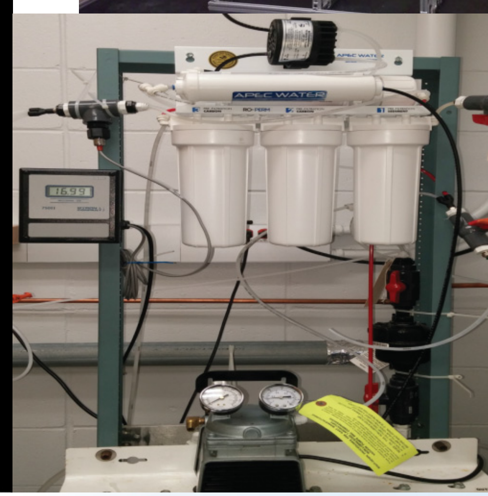


Simulated cosmic muon in water. Red points are absorbed & reflected photons

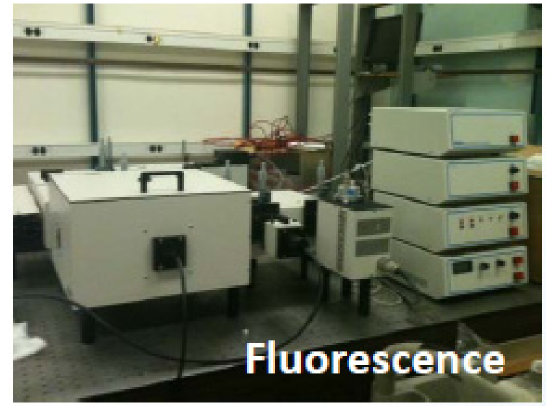


With black barrier

- 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



Liquid Scintillator development facility



- An existing facility for **water-based and metal-doped liquid scintillator** <u>Detector R&D</u> for particle physics applications.
- Operating since 2009: DayaBay, SNO+, LZ, PROSPECT, T2K-ND, JSNS^2
- Instrumentation including XRF, LC-MS, GC-MS, TFVD, FTIR, UV, Fluorescence emission, light-yield coincident PMT, 2-m system, low bkg. Counting...etc. (access to ICP-MS at SBU and other facilities)
- A ton-scale liquid production facility is under construction (only at US Res. Inst.)

Ton-scale Scintillator Facility

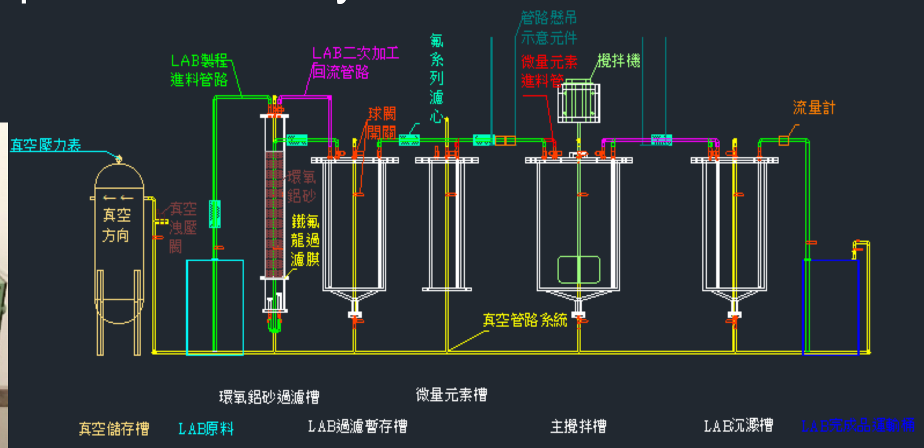
- From bench-top to ton-scale: A unique ton per batch production facility at BNL in 2017 (LZ)
- Available for other scintillator experiments in 2019

Liquid storage warehouse

90L

Storage capacity of ~30 tons of scintillator with built-in containment

Scheme for ton-scale production from purification to synthesis



ton/batch

Summary

- Metal-doped (oil)-base liquid scintillators (using WbLS technology) are well demonstrated by reactor and double-beta decay experiments.
- The principal of (metal-doped) water-based liquid scintillator has been proven; continuing the R&D toward a large-scale deployment (currently at 1-ton scale), stability, online circulation, compatibility, etc.
- Cherenkov separation from scintillator light is a key feature for future (water or oil) based liquid scintillator detector
- Define a physics program to guide the development of scintillator for THEIA