Organic Liquid Scintillator Detector Technology

Henoch Wong

Physics 290E – Fall 2016

14 September 2016

Outline

- Introduction
  - What are liquid scintillators?
  - How does it work?
- Properties & Characteristics
  - Why do we use liquid scintillators in detectors?
- Future
  - Where is the technology headed?

Liquid Scintillator 101

INTRODUCTION

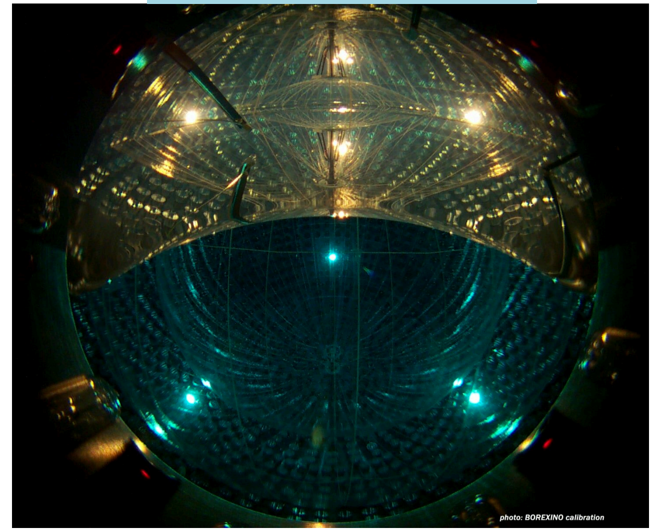
Liquid Scintillator Detectors

1. Particle deposits energy as it travels through liquid scintillator
2. Liquid fluoresces, emitting visible light
3. Light is picked up by photosensors

Current Liquid Scintillator Detectors

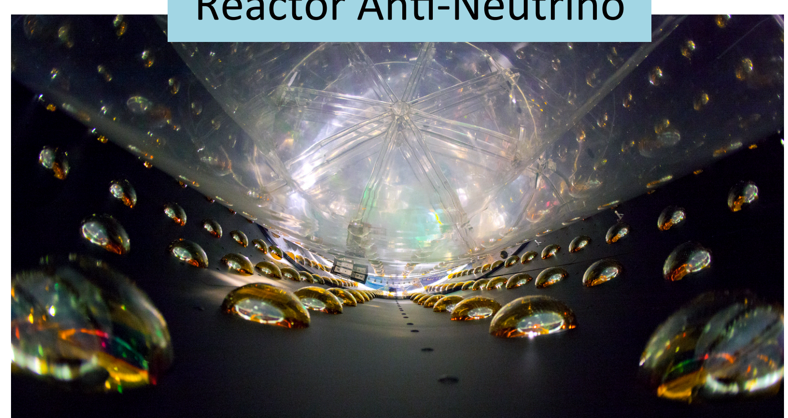
NOvA (USA)
Accelerator Neutrino Beam

Borexino (Italy)
Solar Neutrino



KamLAND-ZEN (Japan)
$^{136}Xe \rightarrow {}^{136}Ba$

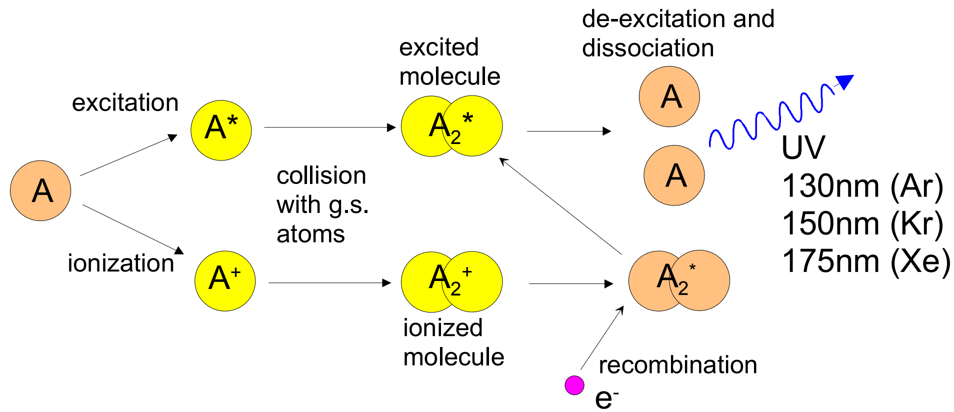
Daya Bay (China)
Reactor Anti-Neutrino



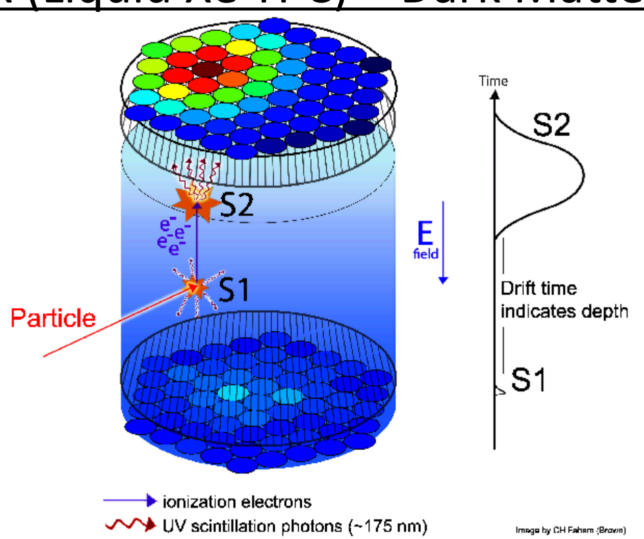
Inorganic Liquid Scintillator

What this talk is not about!

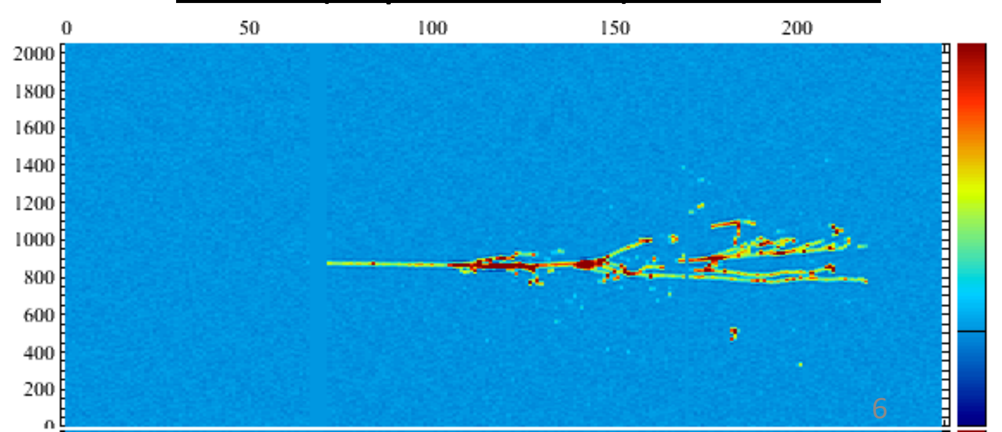
- Liquefied Noble Elements (LAr, LXe, LKr)



LUX (Liquid Xe TPC) – Dark Matter



DUNE (Liquid Ar TPC) – Neutrino

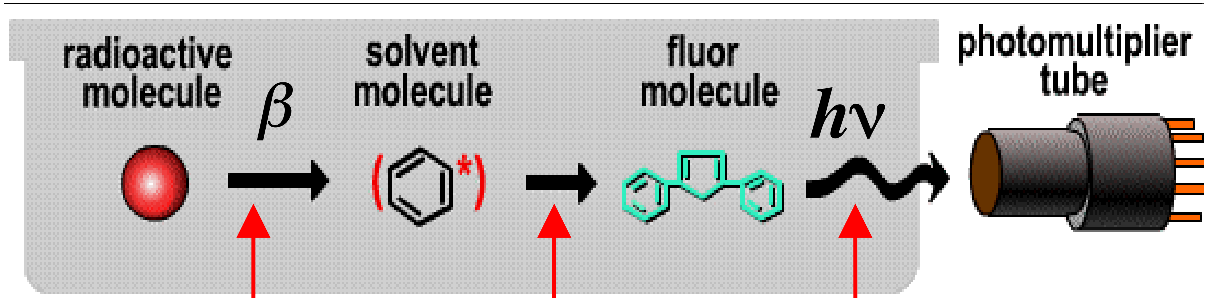


“Cocktail” Recipe

- Liquid Scintillators contains two main ingredients:

1. Solvent
2. Scintillator (Fluor)

Multiple scintillators can be present, with each addition a “Wavelength Shifters”

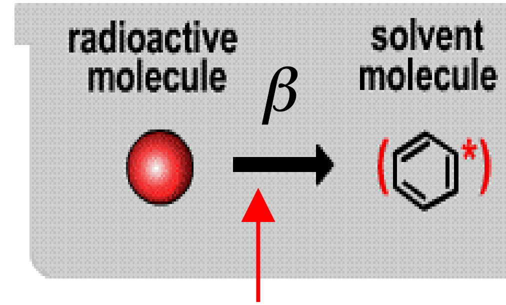


Particle excites solvent

Solvent transfers energy to fluor

Fluor emits visible light

Solvent



- Properties of solvent:
  - Must efficiently absorb deposited energy from particle (aromatic rings with π-electron cloud are excellent)
  - Scintillators (fluors) should be soluble in the solvent

<u>List of Solvents</u>

Solvent	Structure	Relative Pulse Height	Flash-Point (°C)
1,2,4-Trimethylbenzene (Pseudocumene)	CH_3, CH_3, CH_3	112	50
1,4-Dimethylbenzene (P-Xylene)	CH_3, CH_3	110	30
Methylbenzene (Toluene)	CH_3	100	5
Benzene		85	-11
1,4-Dioxane		65	12
Dodecylbenzene Linear Alkyl Benzene (LAB)	$(CH_2)_{11}CH_3$	91	150
1-Phenyl-1-(3,4-dimethylbenzene)ethane (PXE)	CH_3, CH, CH_3, CH_3	114	150
2,6-Di-isopropylnaphthaline (DIPN)	CH_3, CH, CH_3; CH_3, CH, CH_3	114	150

Figure 1. Solvents in liquid scintillation cocktails.

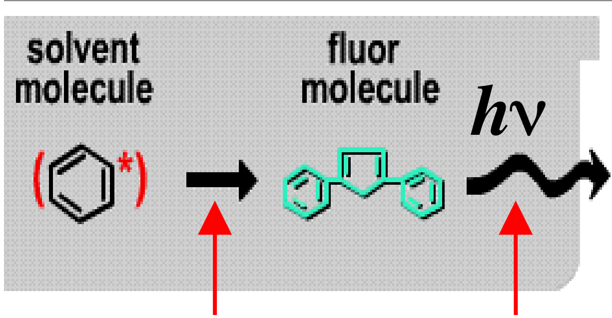
"Classical Cocktails"

- Toxic
- Carcinogenic
- Low Flash Point
- Cowan & Reines used Toluene
- Pseudocumene most popular (Borexino, KamLAND, NOvA)

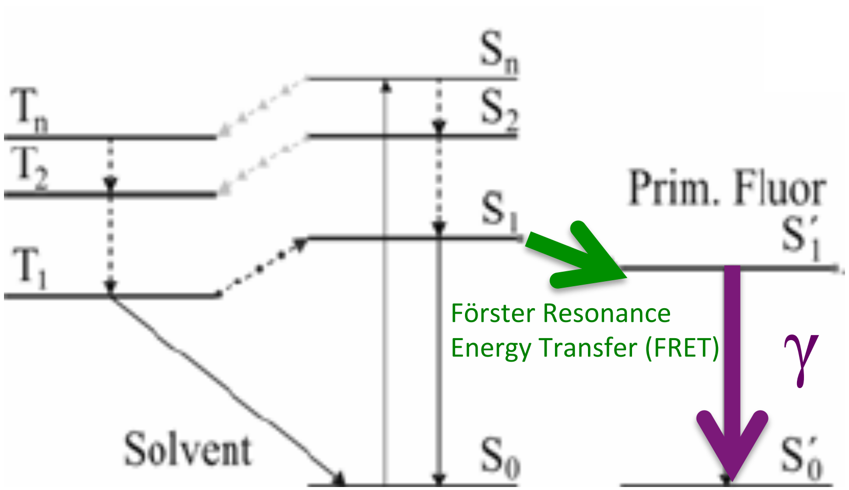
"Safer Cocktails"

- LAB identified as promising solvent by SNO+, now also used by Daya Bay and RENO
- PXE used by Double-CHOOZ

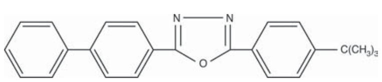
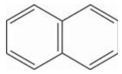
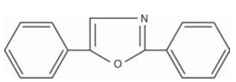
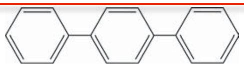
Primary Scintillator



1. The dipole-dipole interaction between the excited solvent and scintillator leads to a radiationless transfer of energy
2. Excited scintillator emits UV light



Primary Scintillators

Scintillator	Structure	Emission Wavelength
Butyl PBD 2-[4-biphenylyl]-5-[4-*tert*-butyl-phenyl]-1,3,4-oxadiazole) **Order No. SFC-20**		363nm
Naphthalene **Order No. SFC-40**		322nm
PPO 2,5-diphenyloxazole **Order No. SFC-10** Most commonly used in experiments		357nm
p-Terphenyl **Order No. SFC-50**		340nm

Secondary Scintillator (Wavelength Shifter)

- Early photomultiplier tubes sensitivity dropped below 400 nm

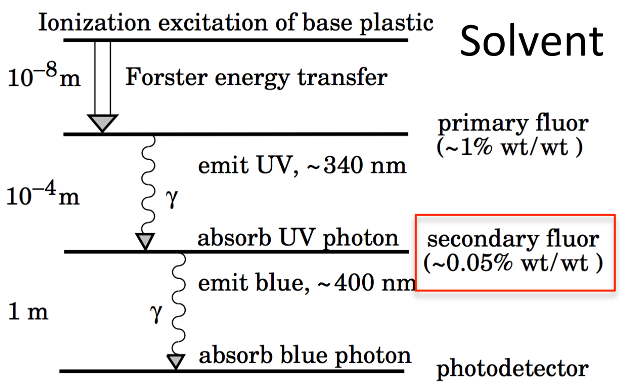
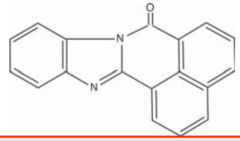
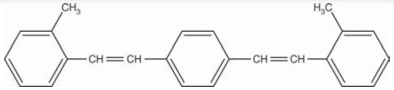
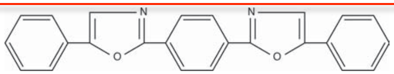
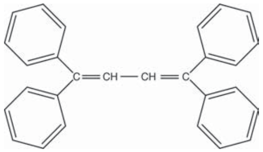


Figure 33.1: Cartoon of scintillation "ladder" depicting the operating mechanism of organic scintillator. Approximate fluor concentrations and energy transfer distances for the separate sub-processes are shown.

Secondary Scintillators

Name	Structure	Wavelength
BBQ (7H-benzimidazo[2,1-a]benz[de]isoquinoline-7-one) **Order No. SFC-13**		477nm
Bis-MSB (1,4-bis[2-methylstyryl]-benzene) **Order No. SFC-90**		420nm Most commonly used in experiments
POPOP (1,4-bis[5-phenyloxazol-2-yl]benzene) **Order No. SFC-60**		410nm
TPB (1,1,4,4-tetraphenyl-1,3-butadiene) **Order No. SFC-15**		455nm

Cowan & Reines (Savannah River Plant) used Dumont 6364 PMT

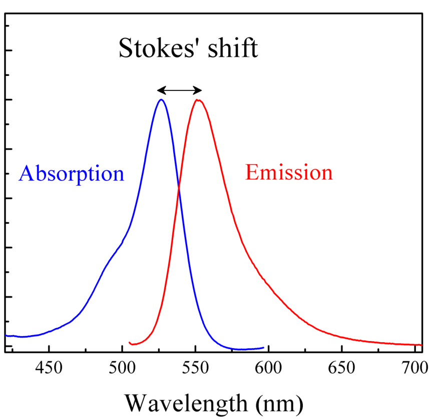
DU MONT TYPE 6363 MULTIPLIER PHOTOTUBE

GENERAL CHARACTERISTICS

Wavelength at maximum response	4400 ± 500	Angstroms
Wavelength at 10% of maximum response on long wavelength side	6125 ± 275	Angstroms
Wavelength at 10% of maximum response on short wavelength side	3250 ± 250	Angstroms

Secondary Scintillator (Wavelength Shifter)

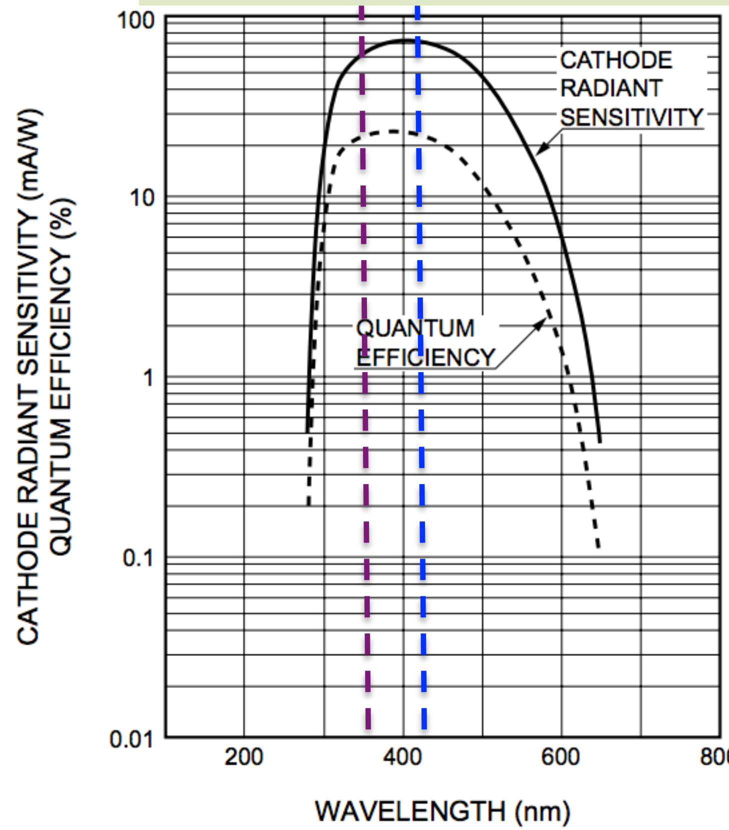
- Modern photomultiplier tubes are capable of detecting UV lights from primary scintillators
- Secondary scintillator are regularly used to improve performance:
  - Solvent more "transparent" to high wavelength light
  - Reduce "self-absorption" (overlap of absorption and emission spectra)



Whitepaper for LENA (10.1016/j.astropartphys.2012.02.011)

Solute	PPO	Bis-MSB
Chemical formula	$C_{15}H_{11}NO$	$C_{24}H_{22}$
Absorption maximum	303 nm	345 nm
Emission maximum	365 nm	420 nm
Stokes' shift:	62 nm	75 nm

Spectral Response
Hamamatsu R5912 PMT
(Daya Bay Experiment)



PPO 357 nm

Bis-MSB 420 nm

Liquid Scintillator for Neutrino experiments

Experiment	LS	Extractant	Fluors/Shifters
Cowan and Reines	Cd-loaded toluene	carboxylate in methanol	αNPO
Palo Verde	40% PC + 60% Mineral oil	carboxylate	4 g/L PPO + 100 mg/L bis-MSB
CHOOZ	50% Norpar-15 (paraffinic liquid) + 50% IPB (isopropylbiphenyl)	hexanol	1 g/L p-TP + bis-MSB
Eljen	Anthracene + PC	n/a	3 g/L PPO + 0.3 g/L POPOP
Bicron	PC or Mix of PC+MO	EHA	unknown
Borexino	PC	n/a	1.5 g/L PPO or p-TP + bis-MSB
MiniBooNE	MO	n/a	n/a
LENS	LAB	carboxylate	3g/L PPO + 15mg/L MSB
Daya Bay	LAB	carboxylate	3g/L PPO + 15mg/L MSB
SNO+	LAB	carboxylate	2g/L PPO
Reno	LAB	carboxylate	3g/L PPO + 15mg/L MSB
Double-CHOOZ	20%PXE + 80%dodecane	b-diketonate	6g/L PPO + 20mg/L MSB
KamLAND	20% PC + 80% dodecane	n/a	1.52 g/L PPO
NOvA	5% PC + 95% MO	n/a	1.2 g/L PPO + 17 mg/L MSB
LENA	PXE/LAB withdodecane	n/a	PPO/MSB or ?

5

From Minfang Yeh (BNL) Talk

https://indico.fnal.gov/getFile.py/access?contribId=18&sessionId=11&resId=2&materialId=slides&confId=3356

Cost / Attenuation Length / Energy Response / Doping

PROPERTIES & CHARACTERISTICS

Particle Data Group: Detector Technology (2015)

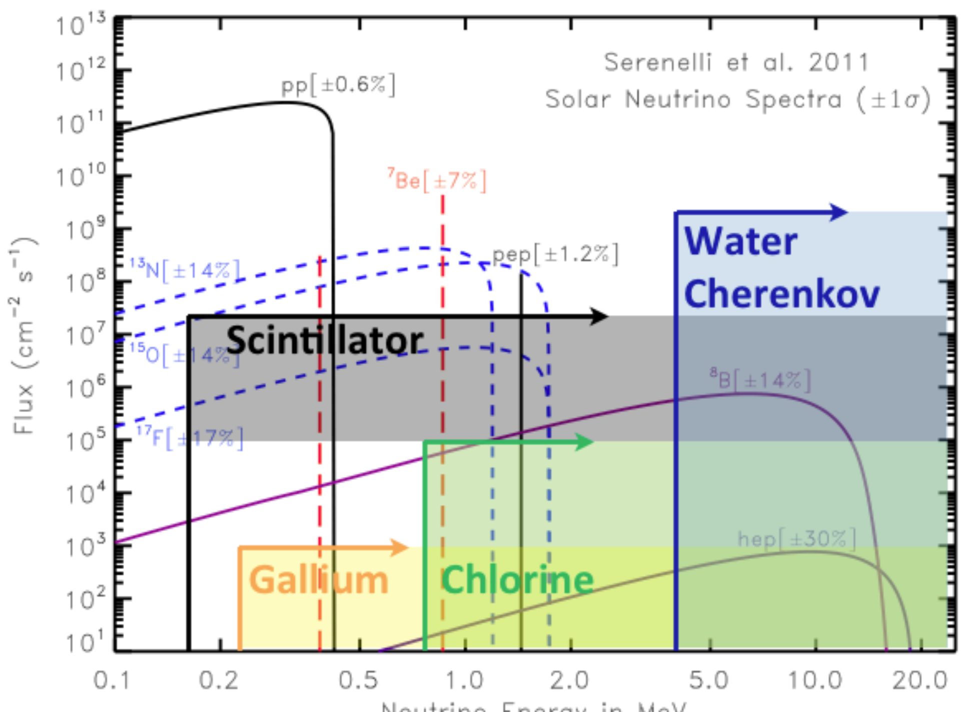
34.3.1.1. *Liquid scintillator detectors:*

Past and current large underground detectors based on hydrocarbon scintillators include LVD, MACRO, Baksan, Borexino, KamLAND and SNO+. Experiments at nuclear reactors include CHOOZ, Double CHOOZ, Daya Bay, and RENO. Organic liquid scintillators (see Sec. 33.3.0) for large detectors are chosen for high light yield and attenuation length, good stability, compatibility with other detector materials, high flash point, low toxicity, appropriate density for mechanical stability, and low cost.

Scintillation detectors have an advantage over water Cherenkov detectors in the lack of Cherenkov threshold and the high light yield. However, scintillation light emission is nearly isotropic, and therefore directional capabilities are relatively weak. Liquid scintillator is especially suitable for detection of low-energy events.

Detector sensitivity to solar neutrino

arXiv:1504.02154 [nucl-ex] - Gabriel



cost of xenon

All Shopping News Images Videos More Search tools

About 688,000 results (0.58 seconds)

$120

Abundance solar system: parts per million by weight, parts per million by moles.
Cost, pure: **$120** per 100g.
Cost, bulk: $ per 100g.
Source: Xenon is a trace gas in Earth's atmosphere.

Xenon - Chemicool
www.chemicool.com/elements/**xenon**.html

About this result • Feedback

Xenon
~$1200 per kg

	Current Experiment	Future Experiments
Dark Matter	XENON100 (165kg) LUX (370kg) PandaX-II (500kg)	XENON1T (3.5 tonne) LZ (7 tonne) PandaX-IV (20 tonne)
$0\nu\beta\beta$	EXO-200 (200kg)	nEXO (5 tonne)

Alibaba.com Global trade starts here.™

Sourcing Solutions | Services & Membership | Help & Community | Selection

Categories | Products | linear alkyl benzene price | Search

Related Searches for linear alkyl benzene price: Super September Purchasing | hot sale linear alkyl benzene sulfonic acid | More...

Related Category

Chemicals

- Organic Acid (662)
- Detergent Raw Materials (412)
- Petroleum Additives (5)

Product Features

Grade Standard

- Agriculture Grade (109)
- Industrial Grade (667)
- Medicine Grade (107)
- Reagent Grade (114)
- See more

Classification

Related Category

Product Features

Sample Order NEW

- Free samples (0)
- Paid samples (0)

Minimum Order: OK

Supplier Features

Supplier by Area

- Africa (1)
- Asia (1153)

Suppliers by Country/Region

- China (Mainland)
- South Africa (1)
- Pakistan (1)

Supplier Types

Home > Chemicals > benzene > benzene price > linear alkyl benzene price > 1,149 Results

LAB
~$1 per kg

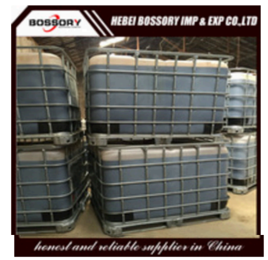
Supplier Location: All Countries & Regions | Supplier Types: Trade Assurance | Gold Supplier | Assessed Supplie

September | Win extra savings between Sept.12-30! | Discount | Promo Price | Free Insp

Minimum Order: | Online

Long-Chain Linear Alkyl Benzene High Base Synthetic Calcium
Hebei Sancolo Chemical Co., Ltd.
2 Metric Tons (Min. Order)
Contact Supplier

Dodecylbenzene Sulfonic Acid/Linear Alkyl Benzene
Henan Innovic Technology Co., Ltd.
US $900-1100 / Metric Ton
3 Metric Tons (Min. Order)
Contact Supplier



Detergent raw material LABSA 96% Linear Alkyl Benzene Sulfonic Acid
Hebei Bossory Import & Export Trade Co....
US $1000-1500 / Ton
5 Tons (Min. Order)
Contact Supplier

Linear Alkyl Benzene Sulphonic Acid/LABSA 96%
Shanghai Sungo Technology&Trade Co., ...
US $1000-1150 / Metric Ton
1 Metric Ton (Min. Order)
Contact Supplier

Detergent Raw Material LABSA 96% / Linear Alkyl Benzene Sulphonic
Shanghai Sungo Technology&Trade Co., ...
US $900-1100 / Metric Ton

linear alkyl benzene price
Linyi Shuaihang Imp. And Exp. Co., Ltd.
US $1400-1600 / Ton

Directly manufacturer of linear alkyl benzene price with SGS/ISO
Zhengzhou Mahaco Commercial Co., Ltd.
US $1050-1150 / Metric Ton

96% LABSA manufacturer Linear Alkyl Benzene Sulfonic Acid/ Linear
Henan Innovic Technology Co., Ltd.
US $900-1100 / Metric Ton

Fisher Scientific
A Thermo Fisher Scientific Brand

Live Chat | Sign Up for Email | Customer Service +1 800-766-7000

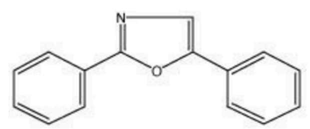
Restock Your Lab with Up to 50% Off

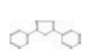
Product Certificates | Safety Data Sheets | Order Status | Special Offers & Programs | Order By Catalog Number

Shop Products | Search by Keyword, Catalog Number, CAS Number | Search | Sign In My Account

Home > Products > Chemicals > Heterocyclic Buildi... > 2,5-Diphenyloxazole, Scintillation Grade 99%, ...

Print | Email





2,5-Diphenyloxazole, Scintillation Grade 99%, ACROS Organics™

$32.99 - $1384.30

Chemical Identifiers

CAS	92-71-7
CAS Min %	98.5
CAS Max %	100.0
Assay Percent Range	99%
Molecular Formula	$C_{15}H_{11}NO$
Formula Weight	221.26g/mol
MDL Number	MFCD00005306
Synonym	PPO
Chemical Name or Material	2, 5-Diphenyloxazole, 99%
Assay	98.5% min.

View More Specs

PPO

~$0.5 per g

Products 4 | Description & Specifications

Catalog Number	Mfr. No.	Quantity	Packaging	Price	Quantity & Availability	
AC117380025 GSA/VA SDS	Acros Organics 117380025	2.5kg	Plastic bucket	Each for $1,384.30	Check Availability	Add to Cart

RESEARCH PRODUCTS INTERNATIONAL

Search

Hello, Sign In
Your Account

$ 0.00
0 items

Biochemicals | Laboratory Equipment | Molecular Biology | Radiation Safety | Scintillation Vials | Specials

bis-MSB [p-bis-(o-methylstyryl)-benzene], Scintillation Grade, 1 Kilogram

Home → Biochemicals → Scintillation Counters → bis-MSB, 1 KG

Price $ 2,950.00

OPTIONS

5 G	25 G	1 KG
$ 49.50	$ 149.50	$ 2950.00

SKU: 111078

Pack Size: 1 KG

Low Stock

Quantity - 1 +

Bis-MSB
~$0.003 per mg

Cost of Liquid Scintillator

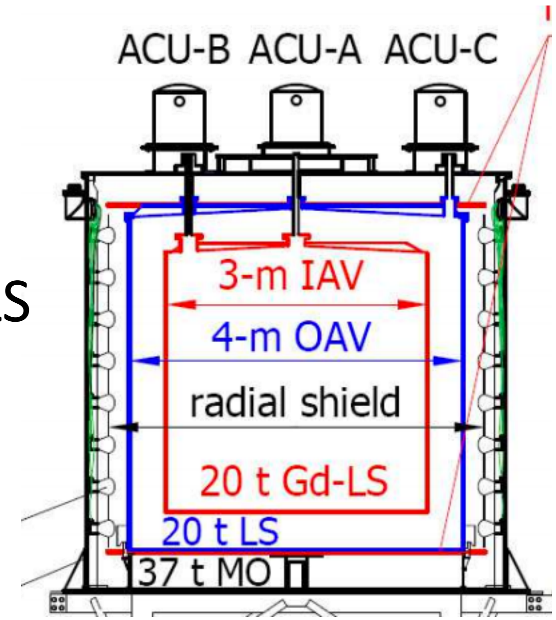
Daya Bay	LAB	carboxylate	3g/L PPO + 15mg/L MSB

- Per kg
  - $1.00 LAB
  - $1.50 PPO
  - $0.05 Bis-MSB

Liquid Scintillator
~$2.5 per kg

Each Daya Bay detector holds 40 tonnes of LS
(20 t Gd-LS + 20 t LS)

~$100k per detector



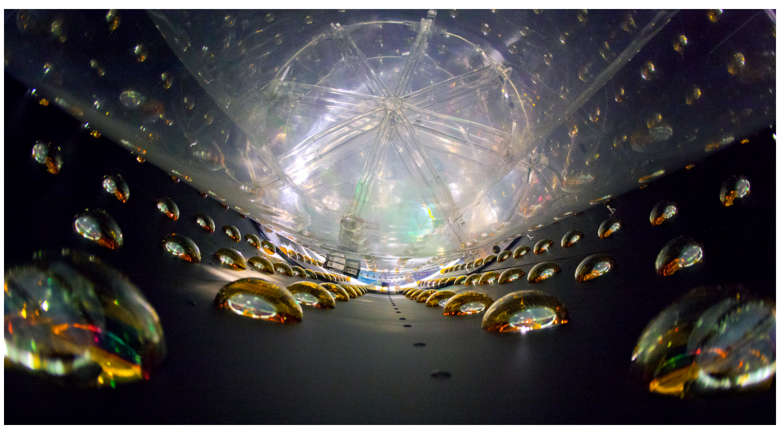
Schematic of Daya Bay antineutrino detector

Attenuation Length

The attenuation length is the distance (λ) where the intensity drops to 1/e (63% probability of absorption)

Probability of light reaching a depth x

$$P(x) = e^{-x/\lambda}$$



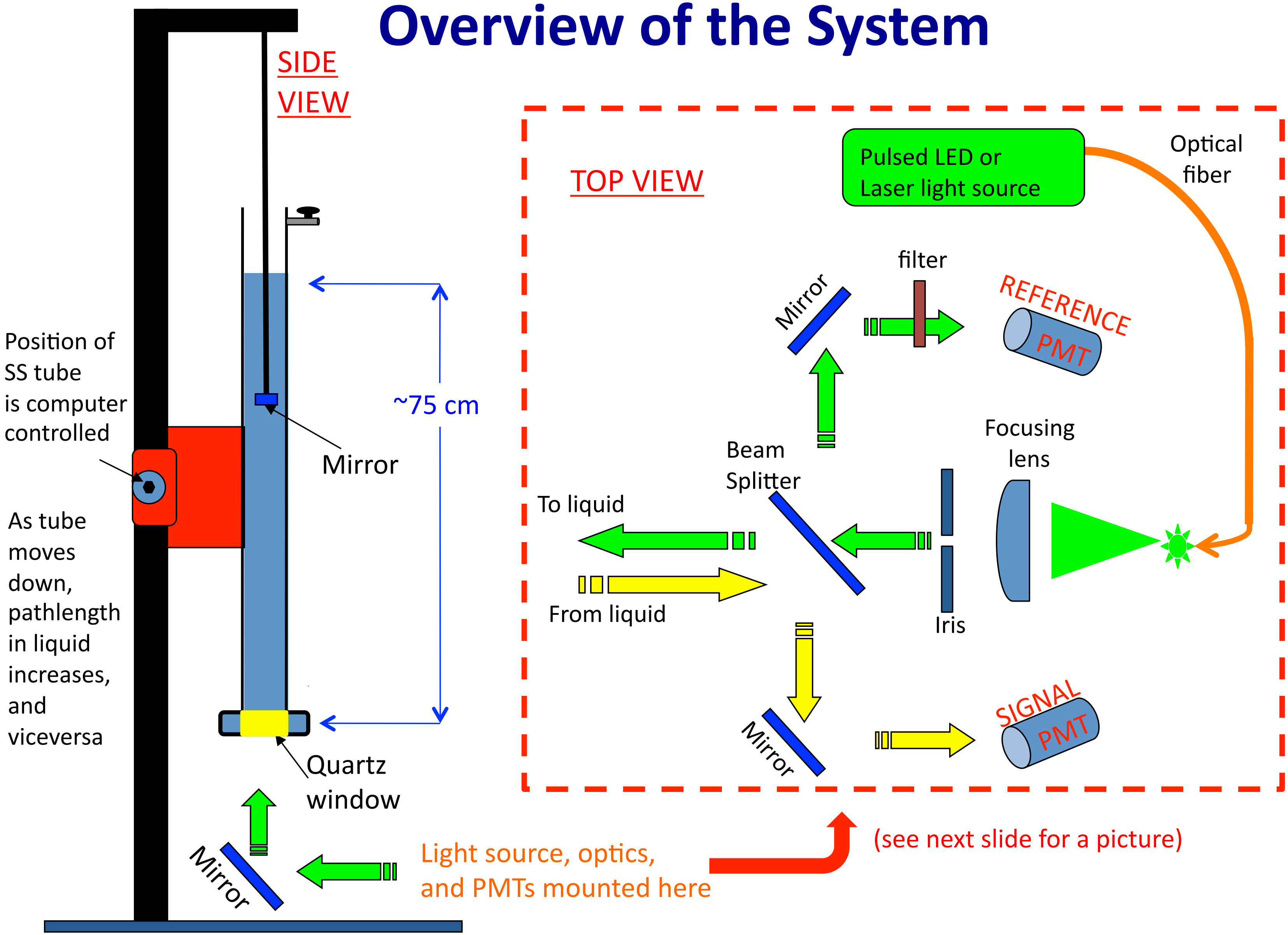
5m height

5m diameter
Daya Bay detector

Want λ large so light can reach PMT unimpeded!

LBNL Attenuation Length Measurement (1)

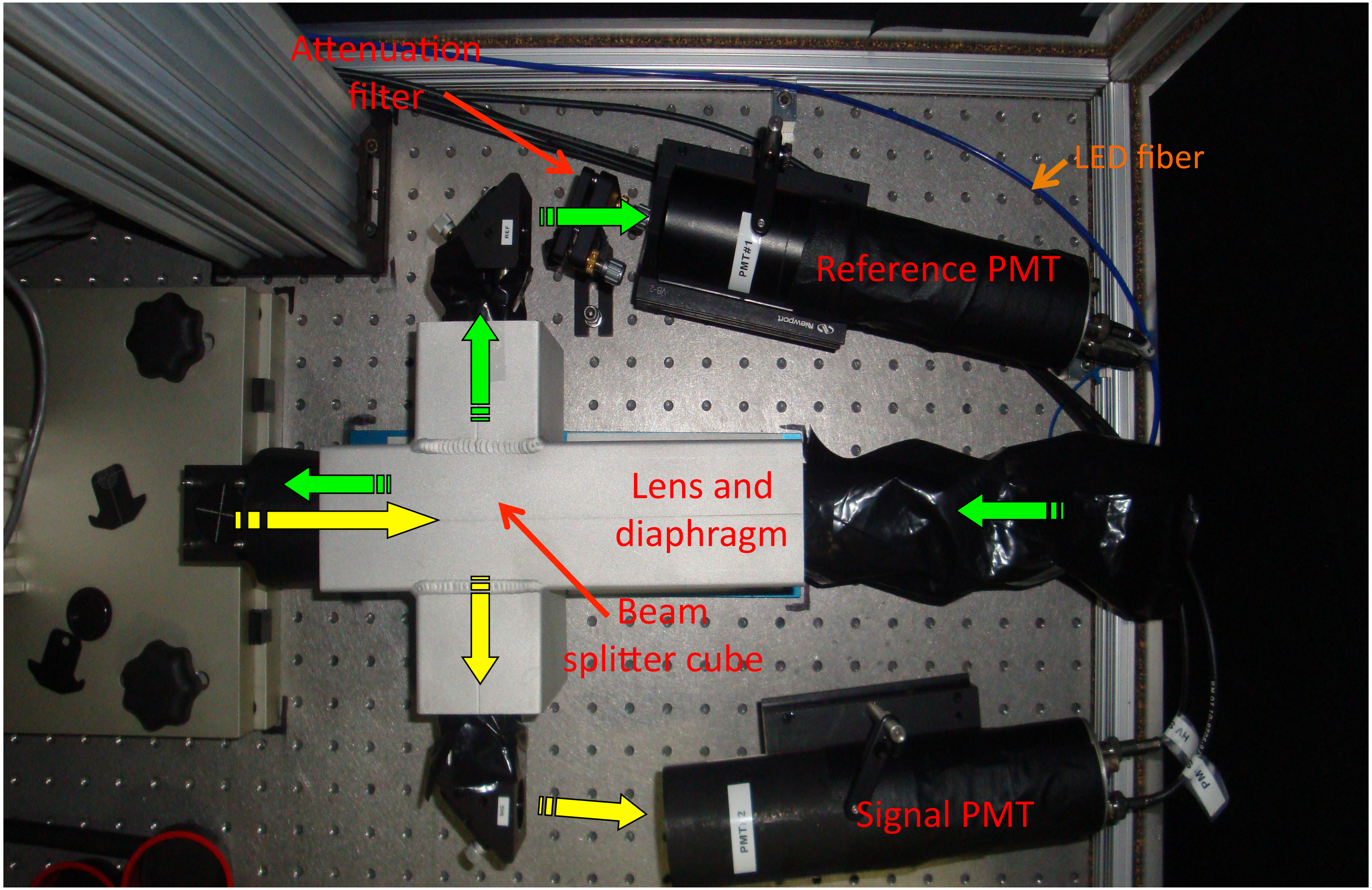
Overview of the System



Cheng-Ju Lin – LBNL Senior Staff Scientist

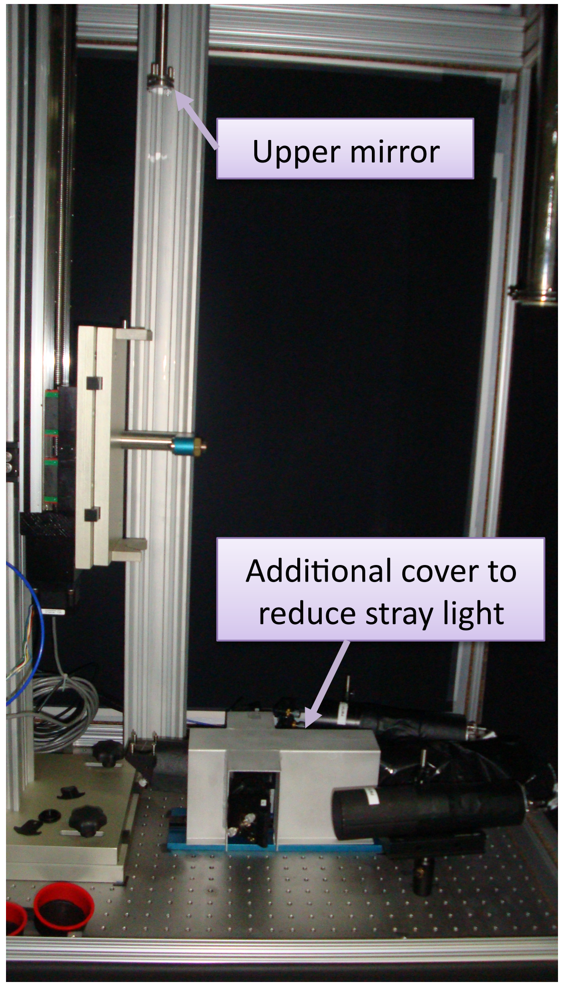
LBNL Attenuation Length Measurement (2)

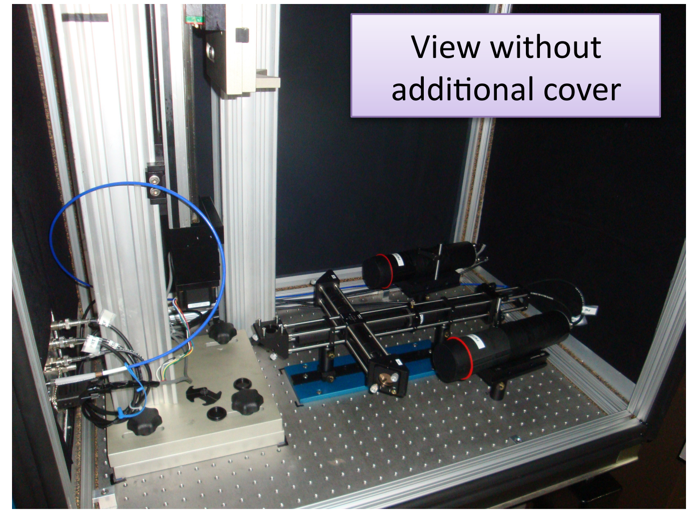
- Top view photograph of the optical system:

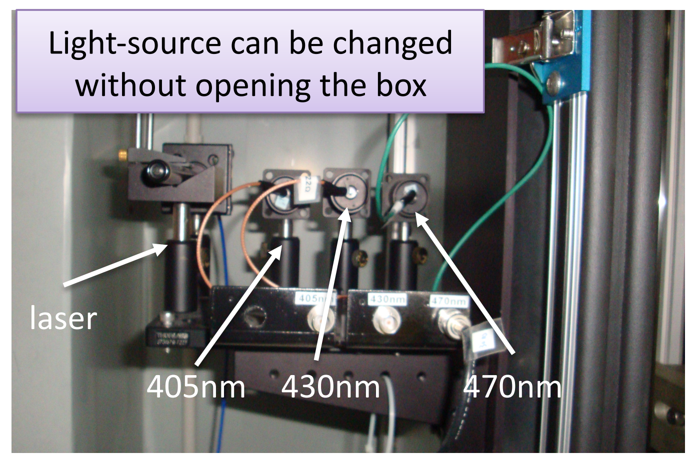


LBNL Attenuation Length Measurement (3)

- More photographs of the system:





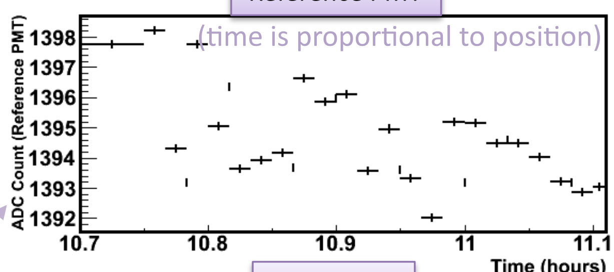


LBNL Attenuation Length Measurement (4)

Basic physics of the system

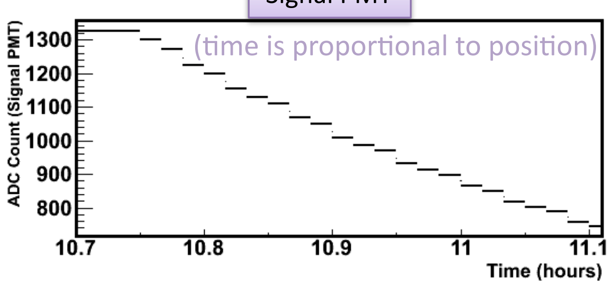
- Overall principle:
  - light beam is sampled before going through the liquid (reference PMT) and after going through the liquid (signal PMT) ⟵ analogous to a long baseline neutrino oscillation experiment!
  - The attenuation length is extracted from the ratio between the signal and reference PMTs as a function of pathlength in the liquid
  - ➢ This way, most systematic effects cancel to first order (namely, all those that are common to the reference and signal measurements)
- Example of a nice attenuation length measurement (**with dirty water**):

Reference PMT

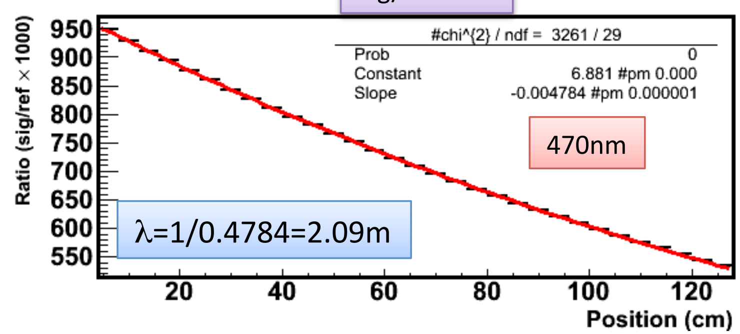


Tube is moved down in 30 discrete steps

Signal PMT



Sig/ref ratio



- ✓ reference is quite stable
- ✓ signal shows a clear trend with pathlength (position)
- ✓ Ratio vs. pathlength gives clear exponential shape, whose slope's inverse yields the attenuation length

Daya Bay LS Attenuation Length

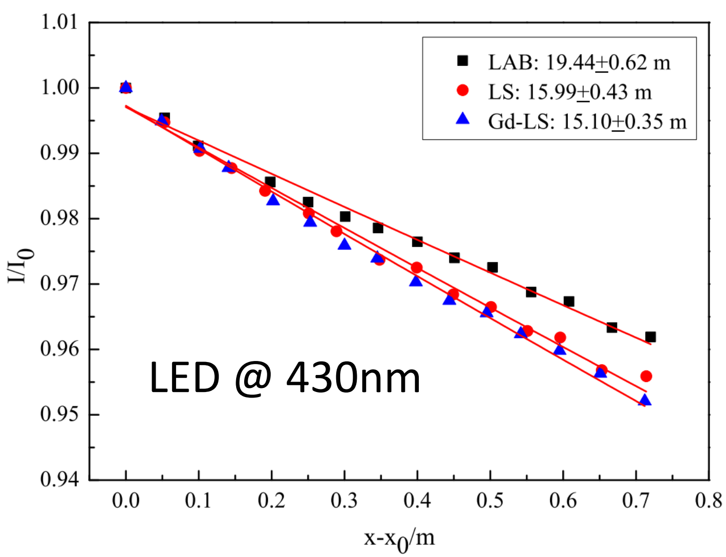
- LBNL measurement:

Preliminary results with <10% uncertainty

LED wavelength	470 nm	430 nm	405 nm
Gd-LS attenuation length	24.5 m	17.0 m	15.3 m

- Beijing Measurement:

Attenuation length measurements of a liquid scintillator with LabVIEW and reliability evaluation of the device
Chinese Physics C, Volume 37, Number 7



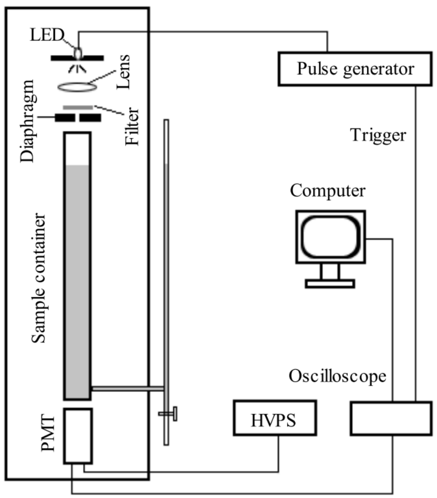
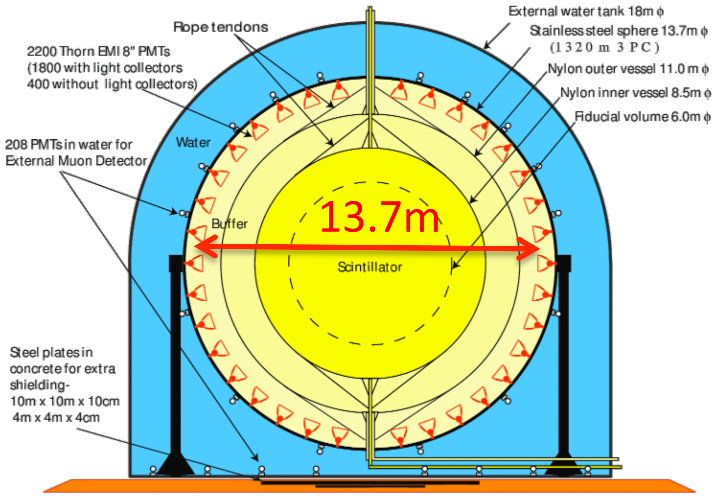


Fig. 1. Experimental set up.

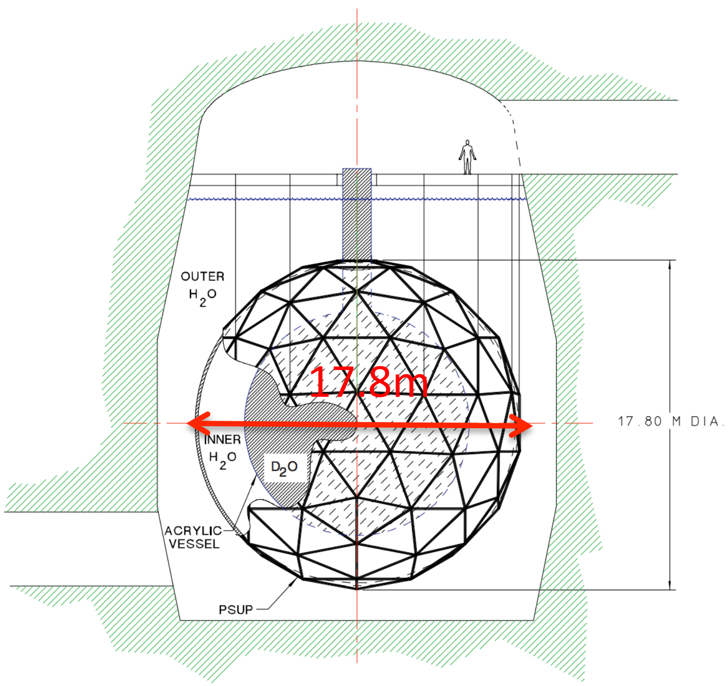
λ(Liquid Scintillator) = ~20m

Size of detectors

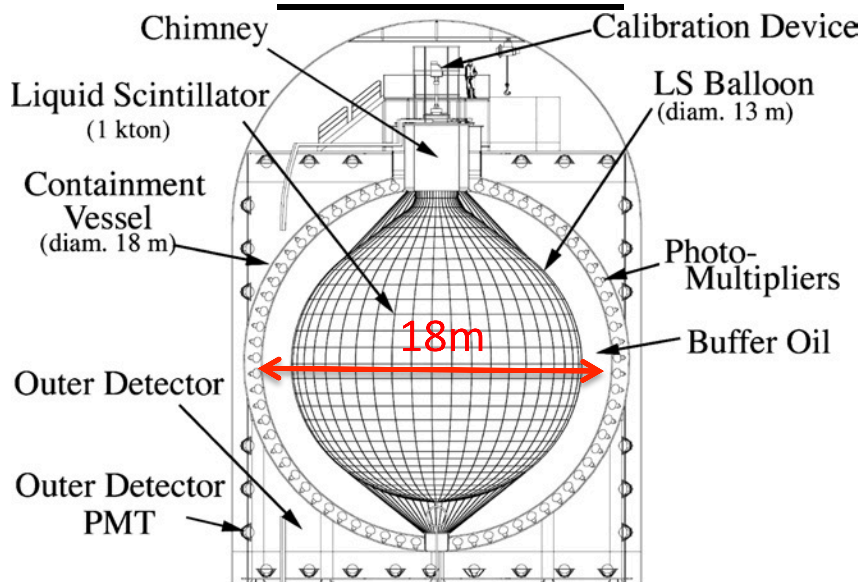
Borexino



SNO+



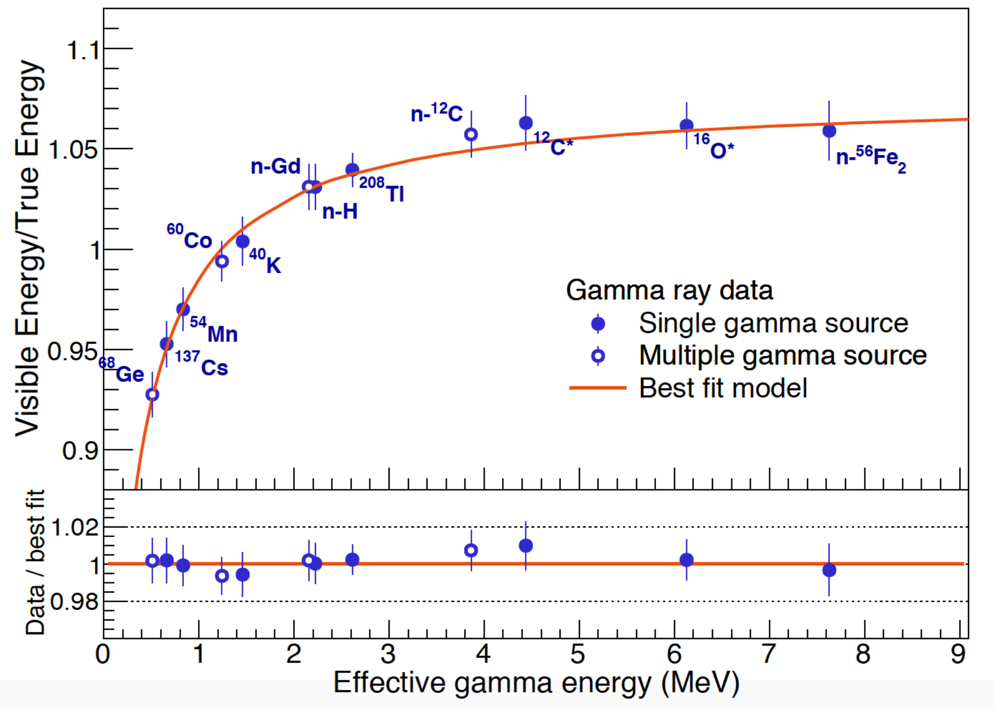
KamLAND



Energy Response of Liquid Scintillators

Is the amount of scintillation proportional to energy deposited into the liquid scintillator?

Daya Bay Detector Radioactive Source Calibration



Liquid scintillator response is non-linear!

Birks' Formula

- J B Birks developed a semi-empirical model:

Light produced should be proportional to ionization of LS

$$\frac{d\mathscr{L}}{dx} = \mathscr{L}_0 \frac{dE/dx}{1 + k_B \, dE/dx}$$

However too much ionization will damage the LS molecules ability to scintillate. Assume damage is also proportional to ionization

L : Luminescence
k_B : Birks' constant
E : Energy deposited
x : Distance traverse in LS

When dE/dx is …

1. Small: $L = L_0 * E_{deposited}$ (Linear Response)
2. Large: $L = L_0/k_B$ * distance (Non-Linear Response)

LBNL LS Energy Response Measurement (1)

Compton Spectrometer

Use gamma Compton scatter to introduce e- into target.

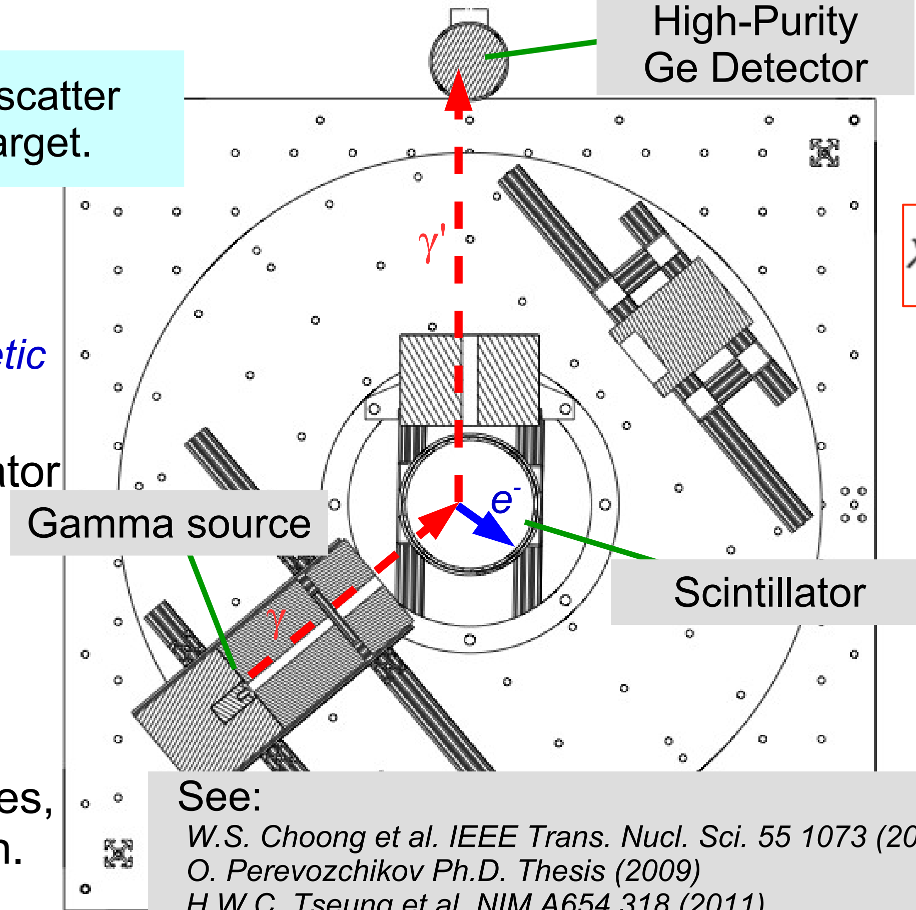
Advantages:

→ 'Tunable' e- energy
Effectively mono-energetic e- source.

→ Generate e- in scintillator bulk.
No bias from e- energy loss or shadowing.

Disadvantages:

→ Requires relatively intense gamma sources, and careful collimation.



Compton Scattering

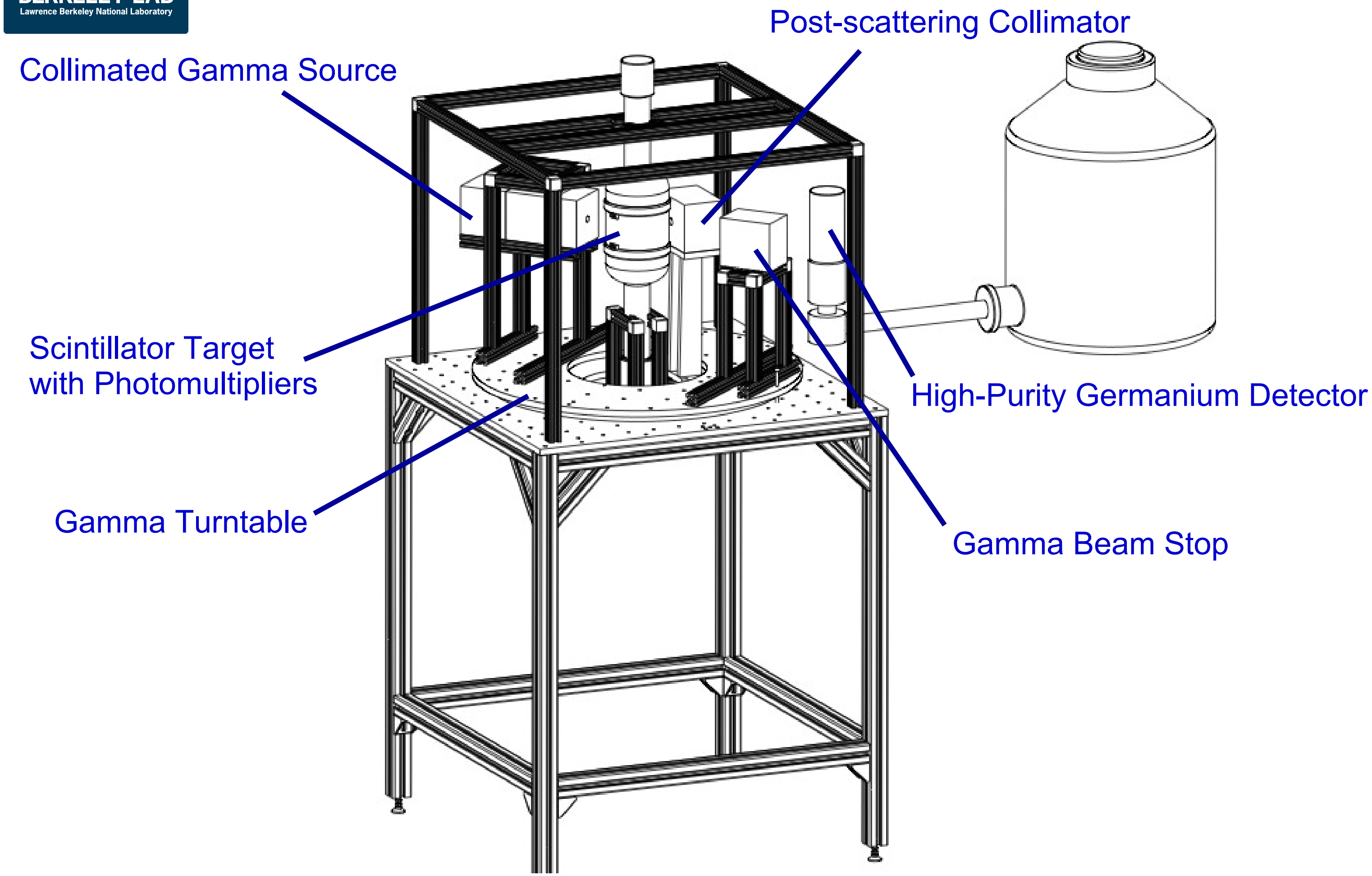
$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta),$$

See:
W.S. Choong et al. IEEE Trans. Nucl. Sci. 55 1073 (2008)
O. Perevozchikov Ph.D. Thesis (2009)
H.W.C. Tseung et al. NIM A654 318 (2011)
F.H. Zhang et al. arXiv:1403.3257

Dan Dwyer – LBNL Staff Scientist
Christian Dorfer – Exchange Undergraduate

LBNL LS Energy Response Measurement (2)

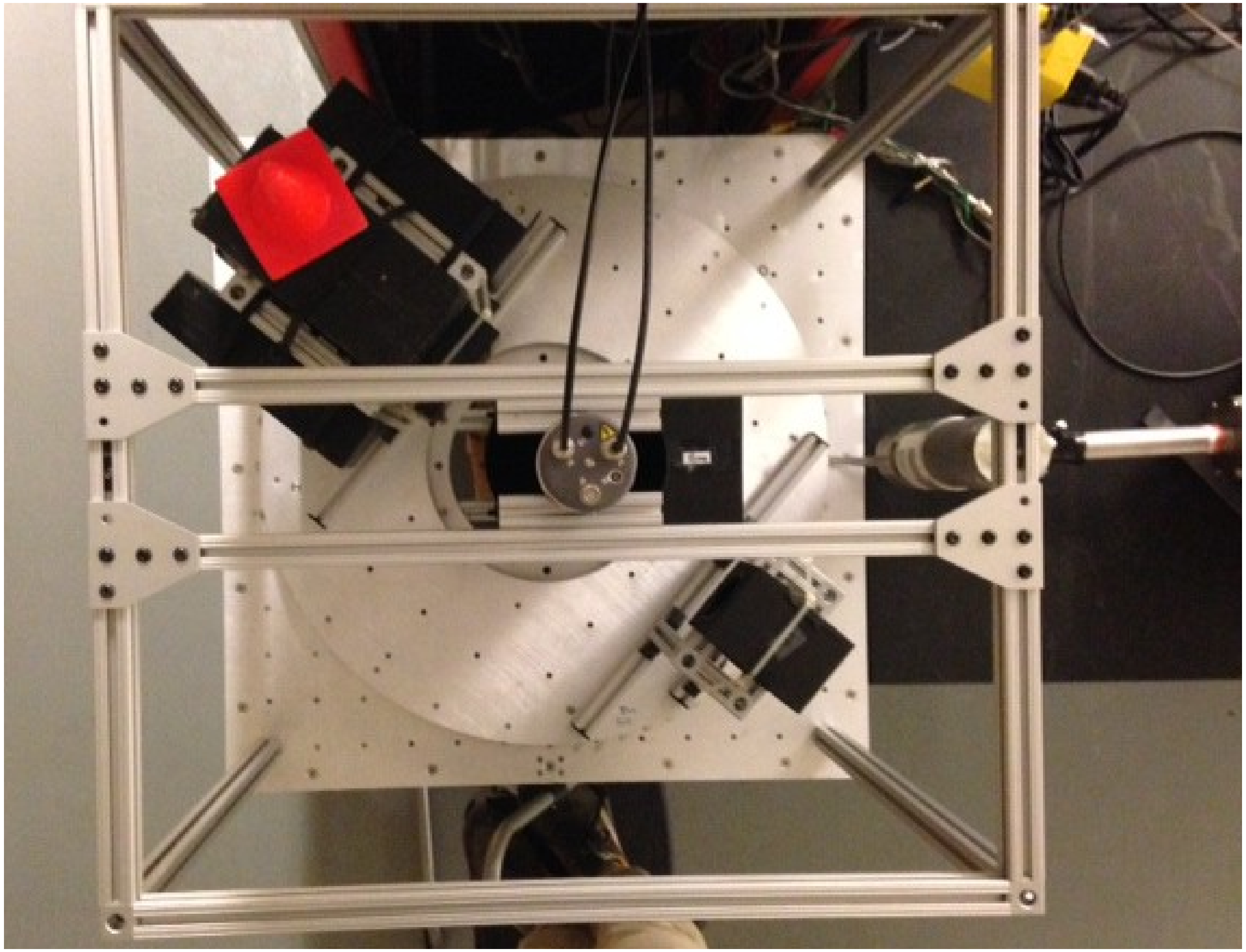
System Layout



LBNL LS Energy Response Measurement (3)

In Real Life...

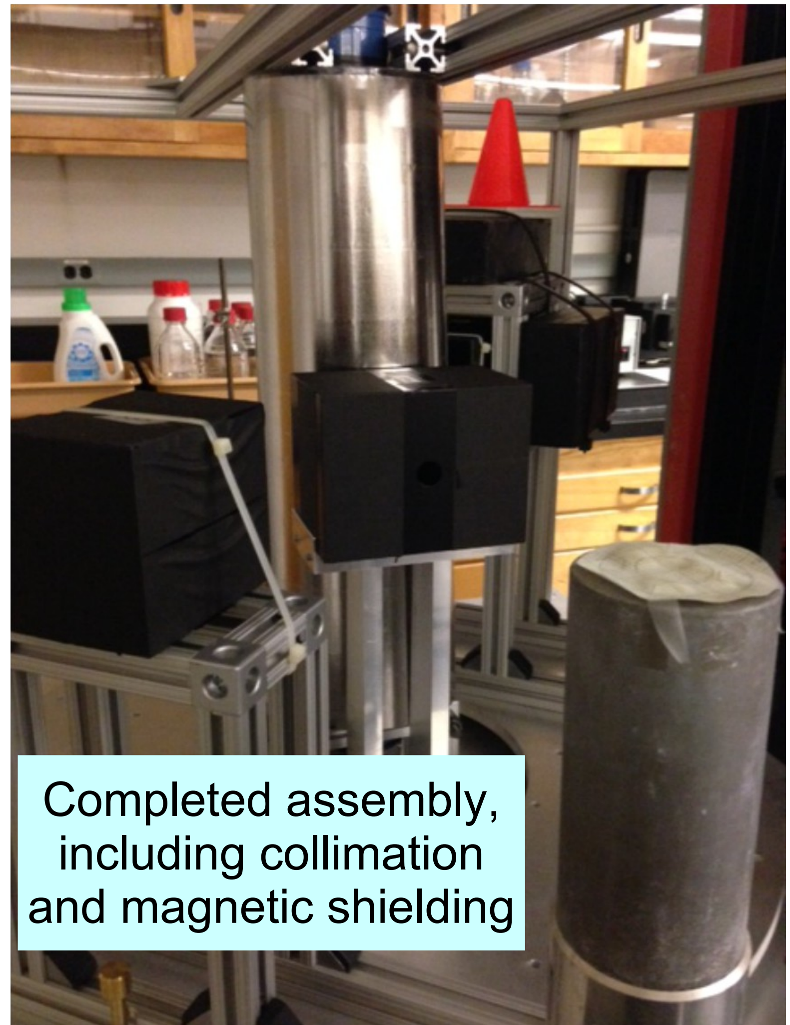
View from above of complete system, at 40° scattering angle



LBNL LS Energy Response Measurement (4)

In Real Life...

Target mounted in gamma turntable

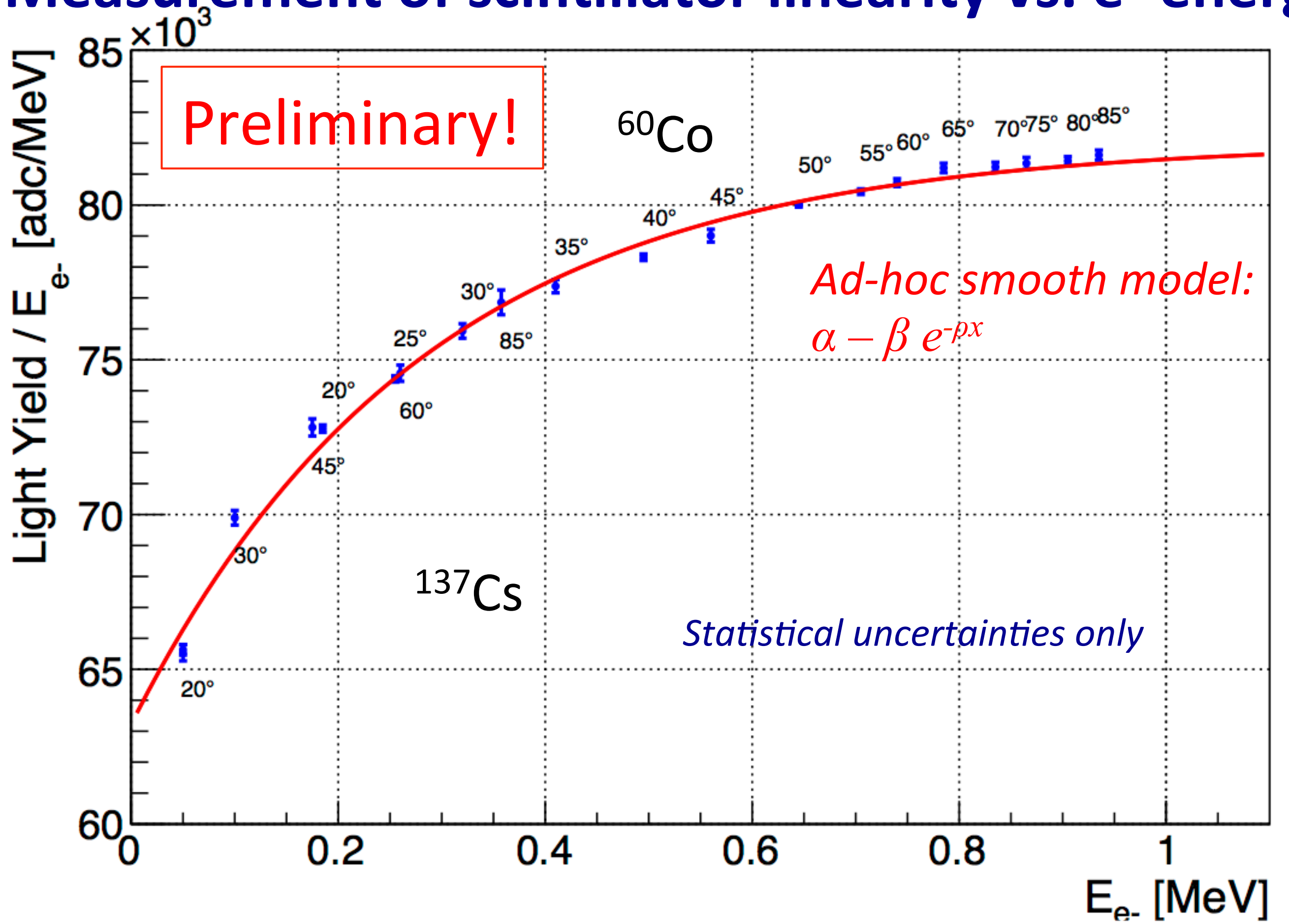


Completed assembly, including collimation and magnetic shielding

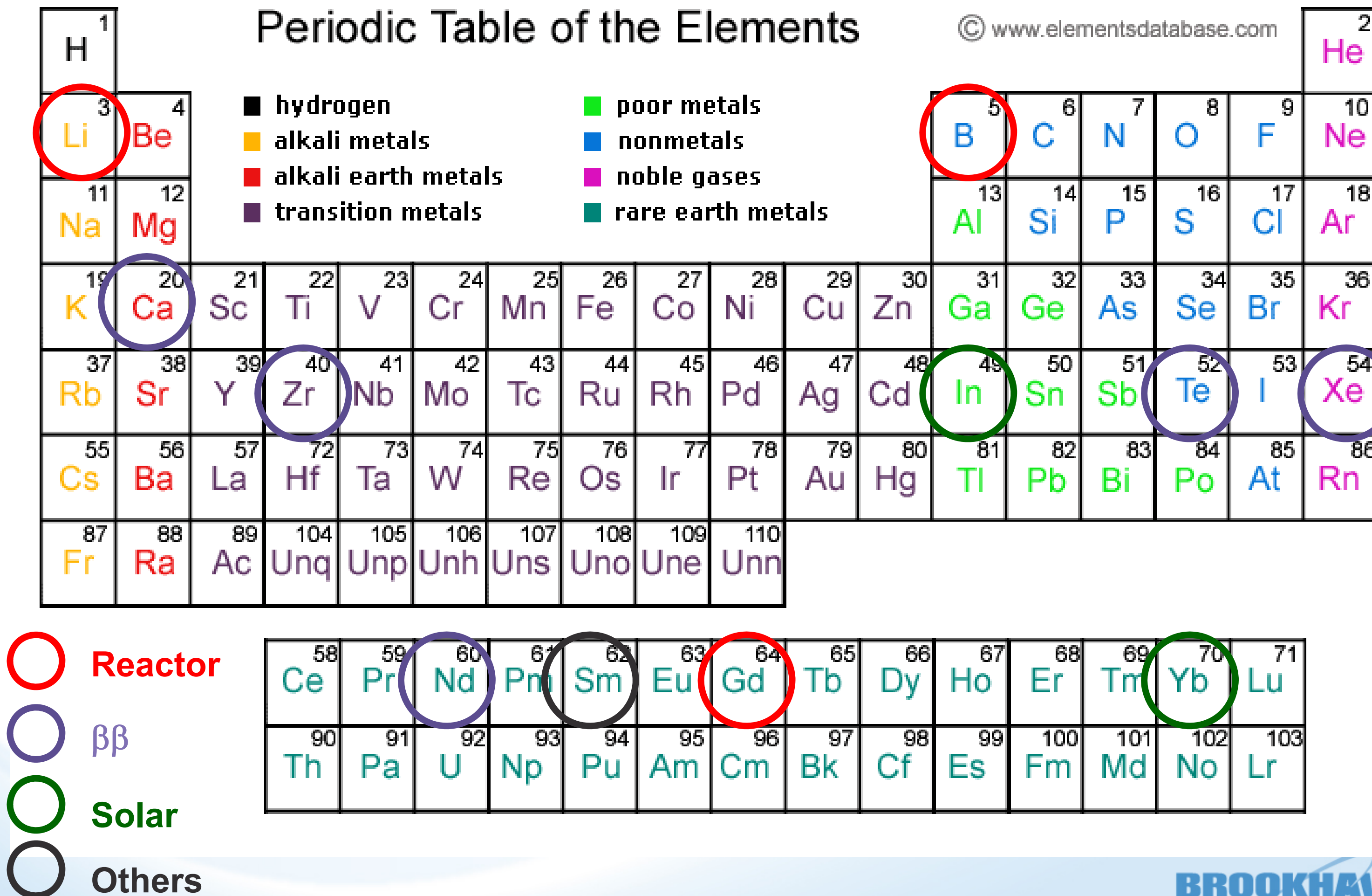
LBNL LS Energy Response Results

Scintillation Linearity

Measurement of scintillator linearity vs. e- energy



Metal-loaded LS for Neutrino Physics



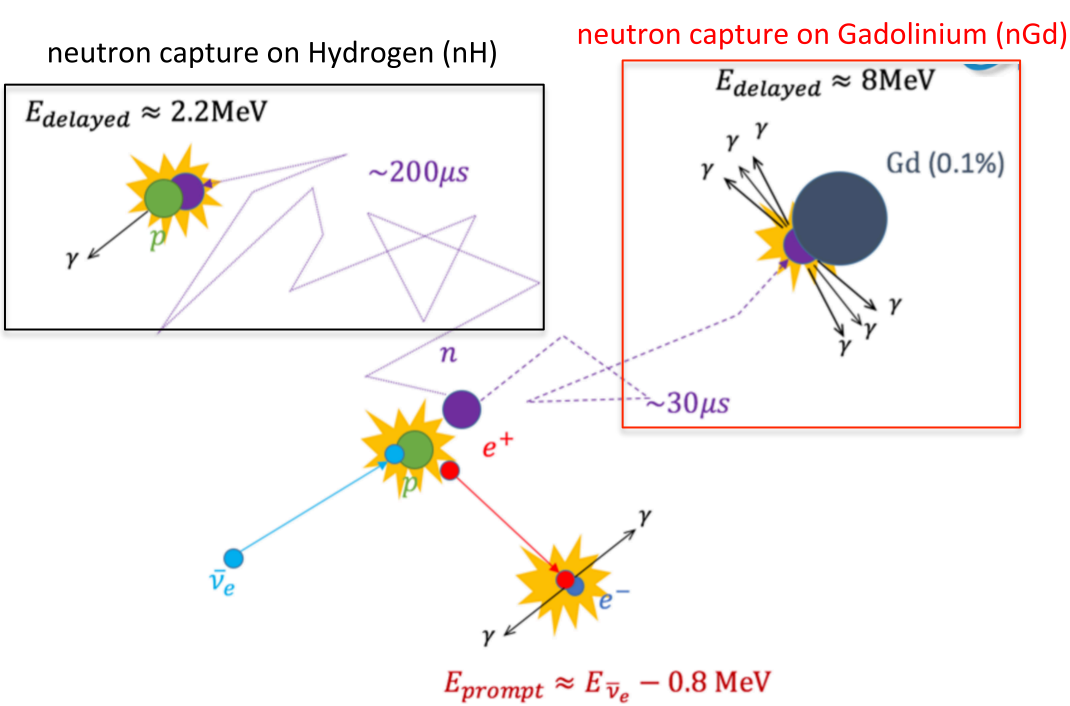
From Minfang Yeh (BNL) Talk

https://p25ext.lanl.gov/seminar_files/Minfang_Yeh_040114.pdf

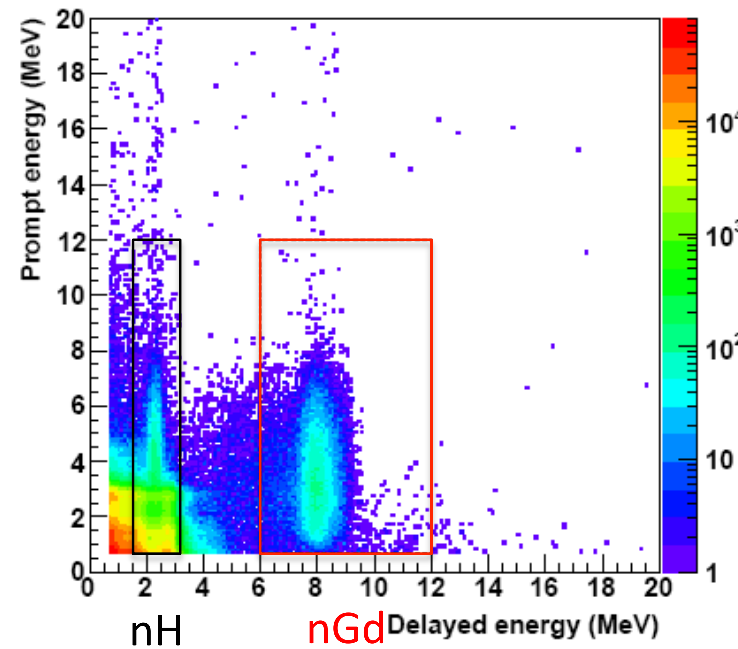
Doping for Reactor Neutrinos Experiments

- Daya Bay, Double-CHOOZ, RENO are doped with Gadolinium (Gd)
- Electron Anti-Neutrino detected by the inverse beta decay (IBD):

Illustration of IBD event



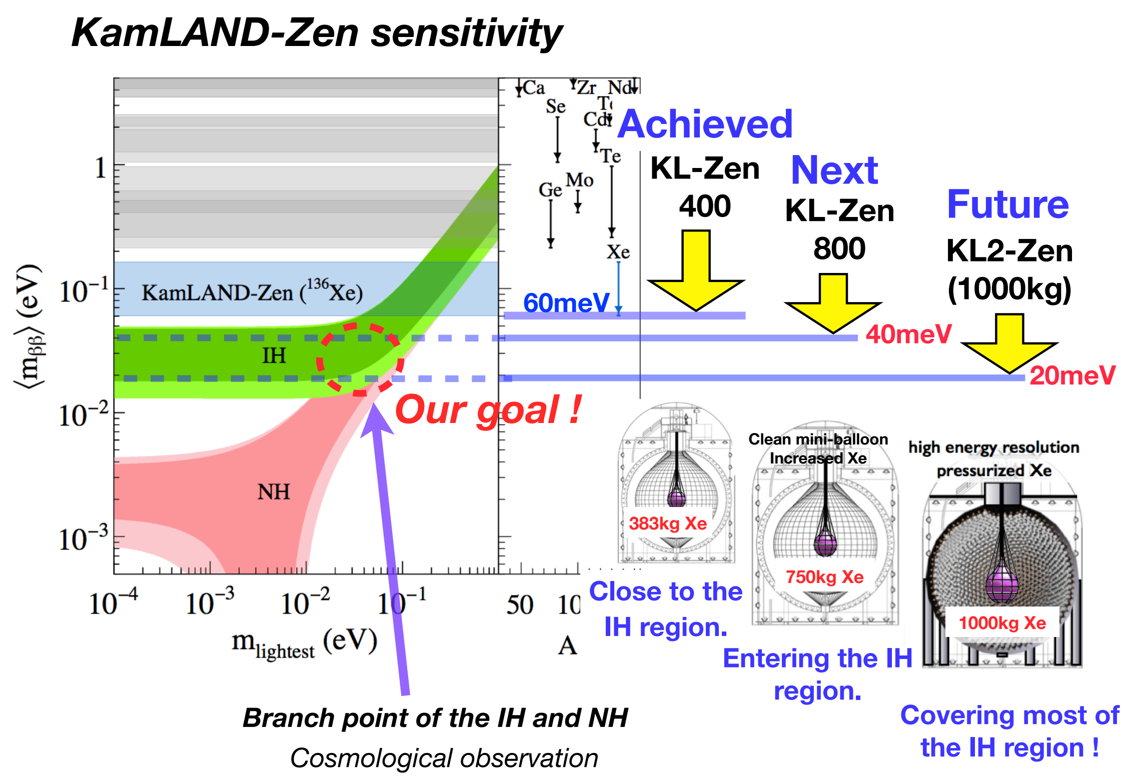
Daya Bay IBD selection



Doping for 0νββ experiments

- KamLAND (Reactor Neutrino) and SNO (Solar Neutrino) detectors have been repurposed to search for 0νββ
  - KamLAND-ZEN (^{136}Xe)
  - SNO+ (^{130}Te)

KamLAND-Zen talk (Neutrino 2016)



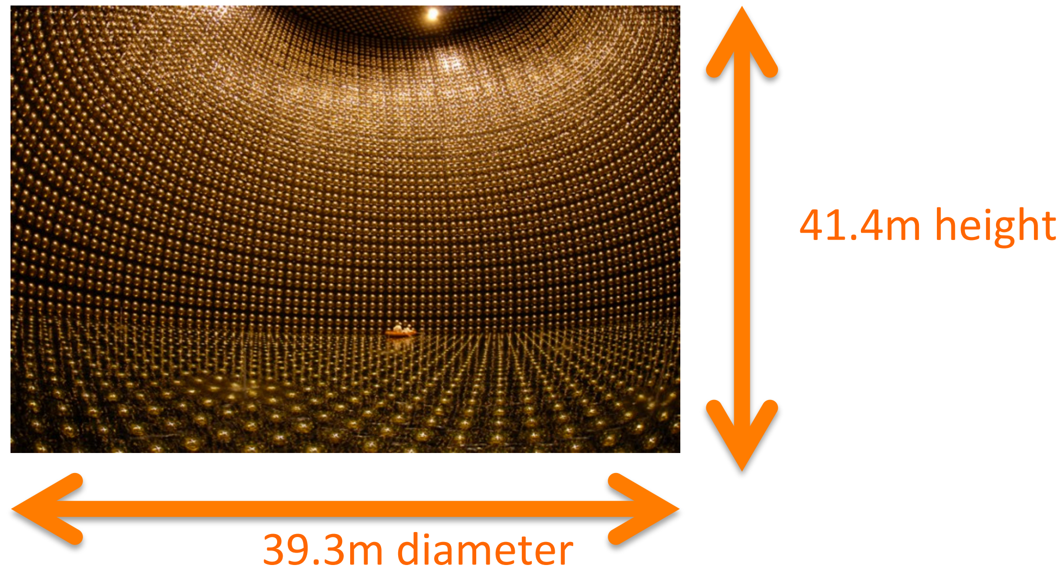
Towards a Water-Based Liquid Scintillator

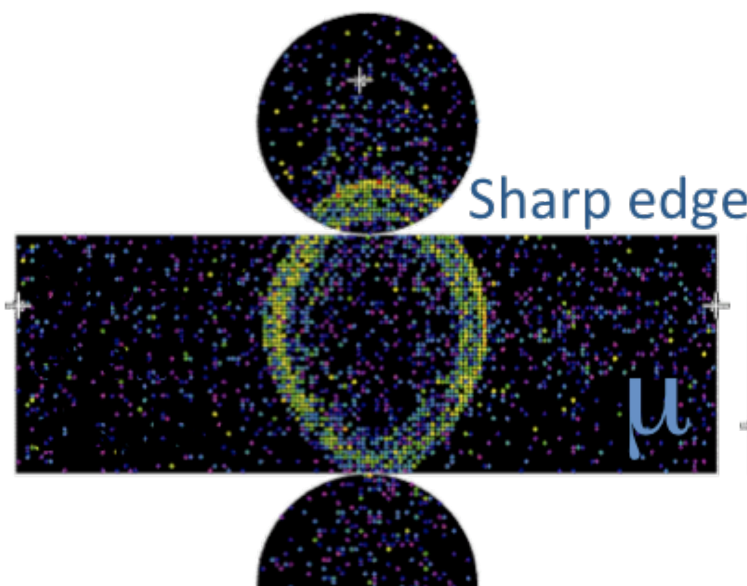
FUTURE

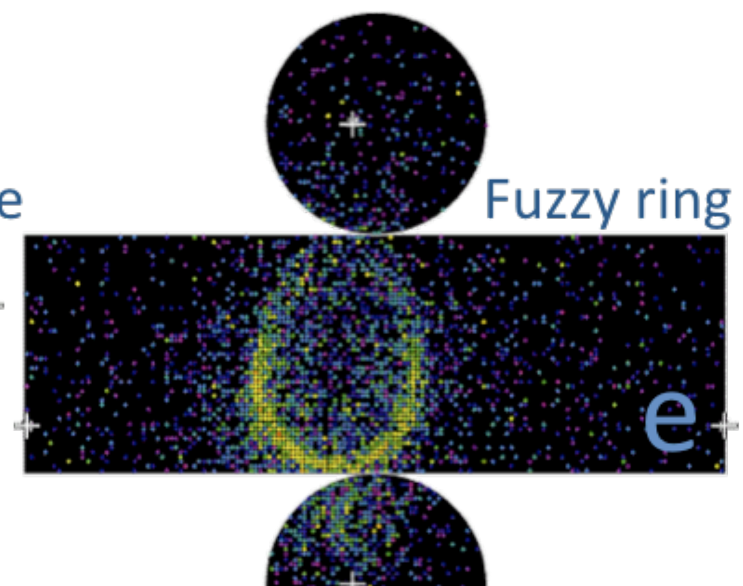
Water Cherenkov

What this talk is not about!

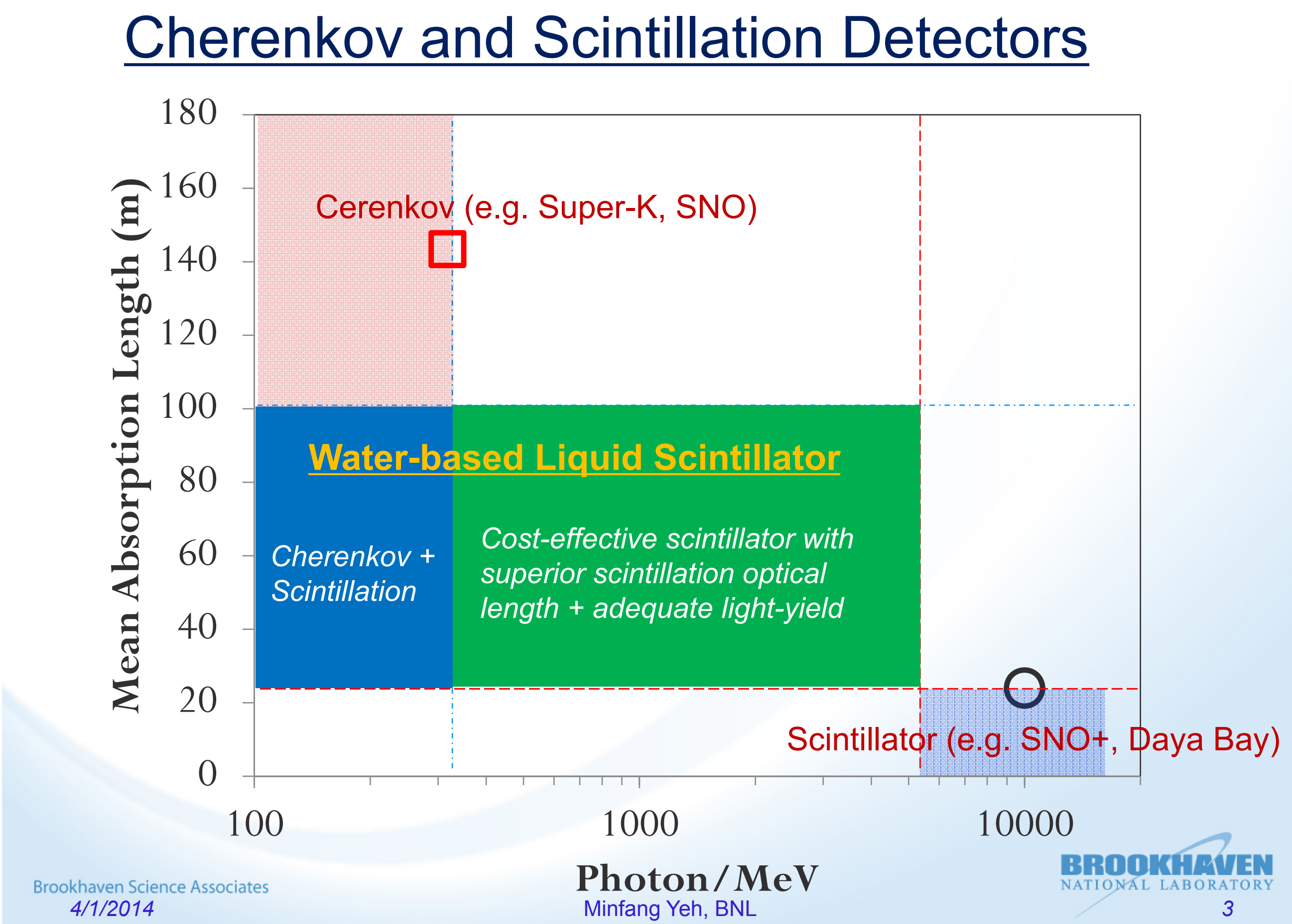
Super-Kamiokande







Water-based Liquid Scintillator



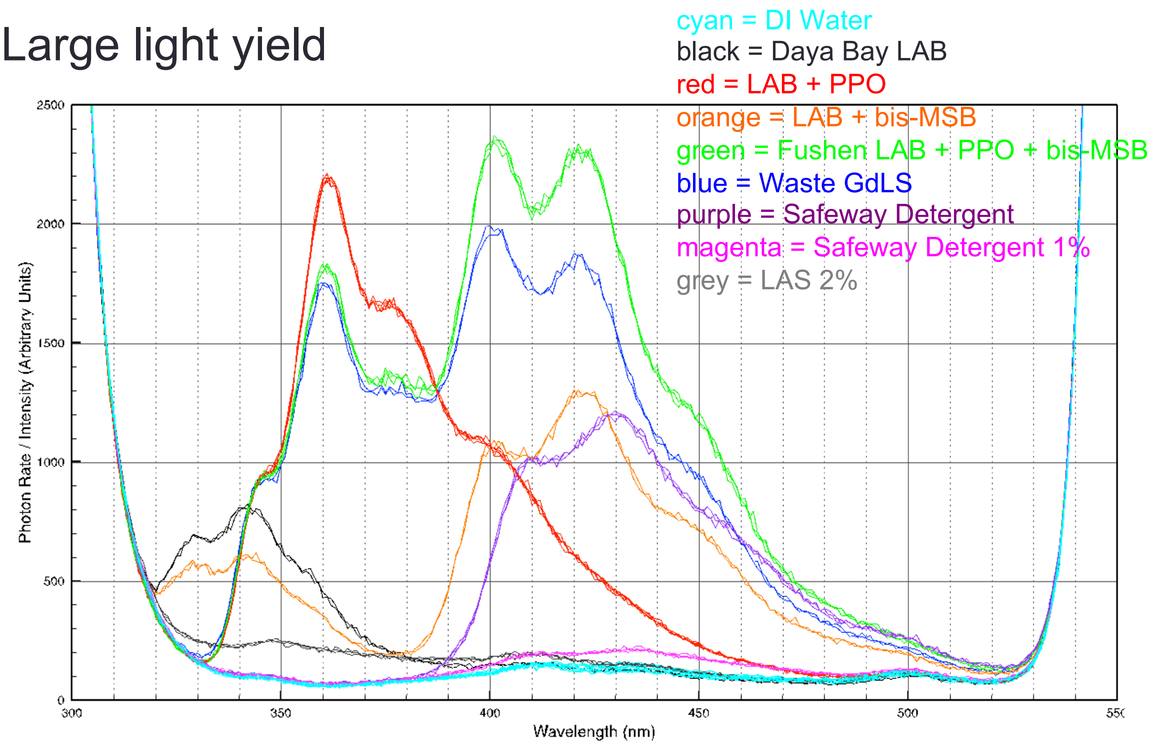
From Minfang Yeh (BNL) Talk

https://p25ext.lanl.gov/seminar_files/Minfang_Yeh_040114.pdf

LBNL Daya Bay research on WbLS

- Group is hard at work on WbLS!
- Unfortunately most of the work is

2) Large light yield



Undergraduates
Sean Hooten
Lauren Capelluto
Peter Dotti