

# Liquid Scintillator Timing Property



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*a passion for discovery*



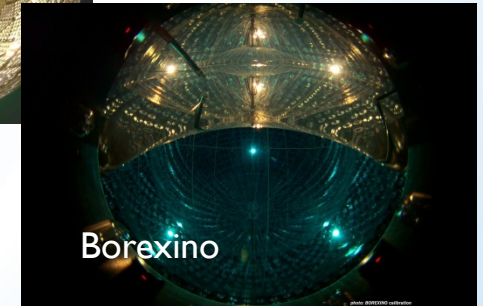
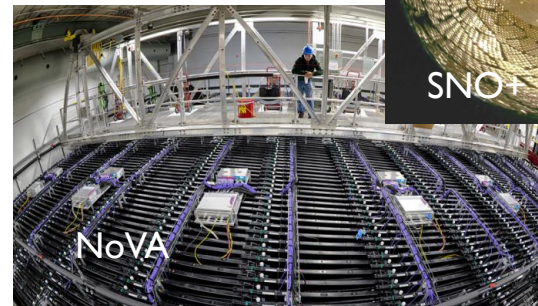
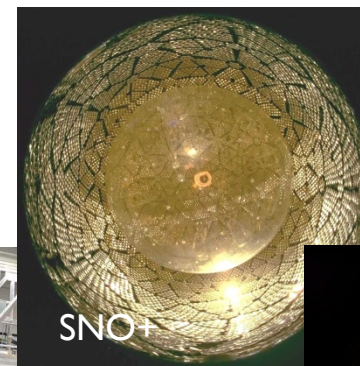
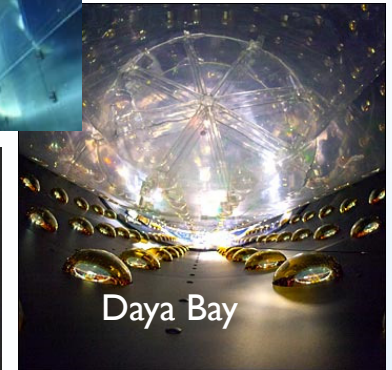
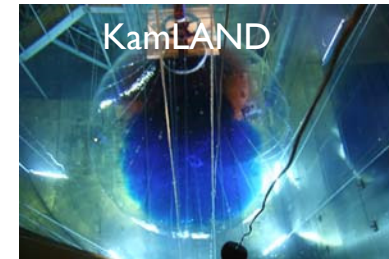
U.S. DEPARTMENT OF  
**ENERGY**

Office of  
Science

MIT workshop, Dec 15, 2015

# Main Neutrino Interactions in Scintillator

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



- Excellent detection medium for neutrinos in MeV range
- Different LS combinations to meet the needs of various physics
- Profound physics applications in Solar-, Geo-, Reactor-, Supernova-Neutrinos, Neutrino Oscillation, Proton Decay

# Isotope-doped Liquid Scintillator

## for Neutrino Physics and Other Applications

Periodic Table of the Elements © www.elementsdatabase.com

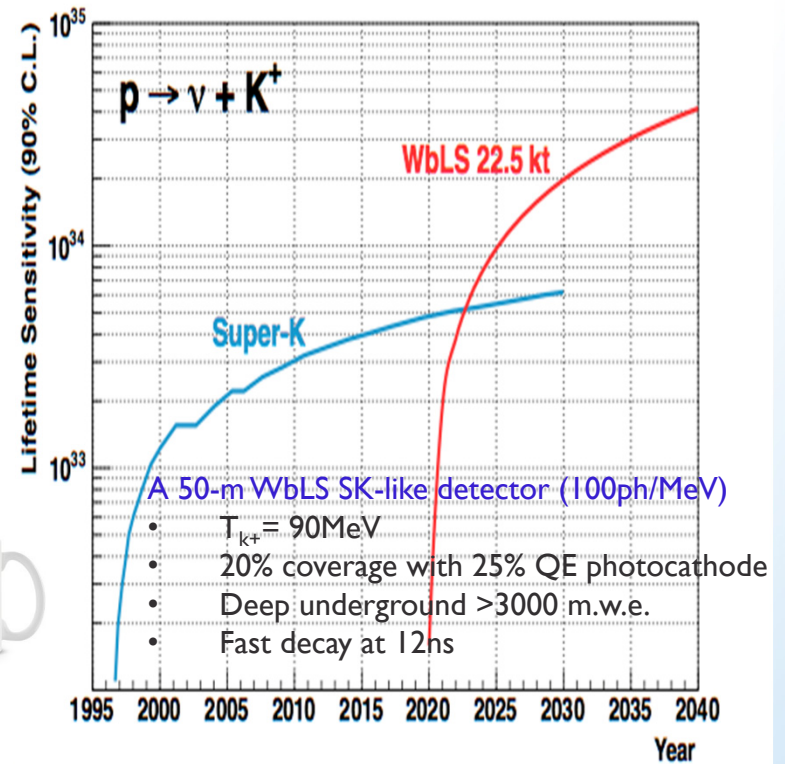
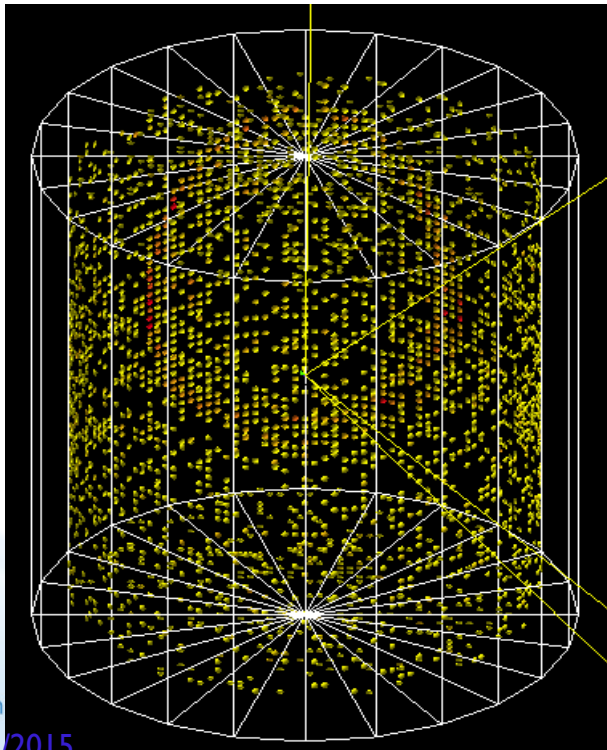
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

- Reactor
- $\beta\beta$
- Solar
- Others

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

# Water-based Liquid Scintillator

- A new detection medium, bridging scintillator and water
- Tunable scintillation light from ~pure water to ~organic
- A novel technology for loading various isotopes
- Cherenkov transition
  - $\lambda$  overlaps with scintillator energy-transfers will be absorbed and re-emitted to give isotropic light.
  - $\lambda$  emits at  $>400\text{nm}$  will propagate through the detector (directionality).



- A New metal-doped technology using water-base Liquid Scintillator principal (e.g. PROSPECT, SNO+, beam-therapy, calorimetry etc.)
  - Suitable for ~most metallic ions
  - less-selective isotope loading

# Liquid Scintillator Physics

$0\nu\beta\beta$   
(e.g. SNO+, KamLAND-Zen)

Reactor  $\nu$   
(e.g. Daya Bay, PROSPECT,  
JUNO)

Other  
Applications  
(e.g. Nonproliferation,  
source  $\nu$ , LZ)

Common features  
between detectors

**Liquid Scintillator**  
**(Metal-loaded & Water-based)**

Ion-beam therapy  
&  
TOF-PET scan

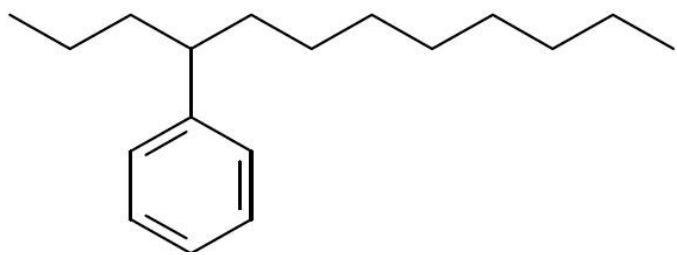
unique requirement for  
individual detector

Solar & Geo  $\nu$   
(e.g. LENS, Borexino,  
KamLAND)

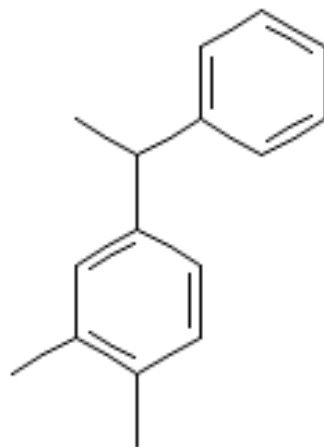
Accelerator Physics  
(e.g. NO $\nu$ A, T2K, SNS, J-  
PARC-E56)

# Common Liquid Scintillators

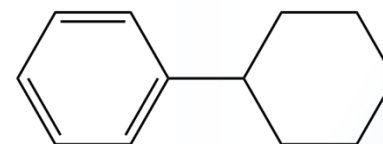
- Stability, light-yield and optical transparency
- High flashpoint (PXE>DIN>LAB>PCH>PC) and low toxicity
- **Most slow decay at tens of ns**
- New generation scintillation water



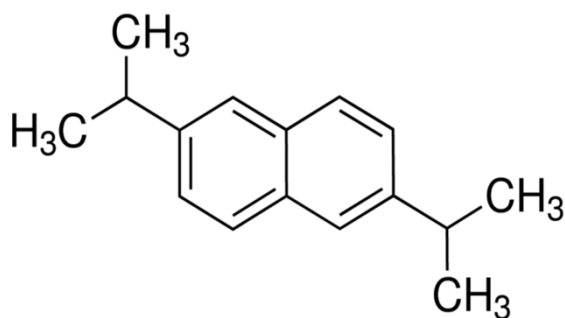
Linear alkylbenzene (LAB)



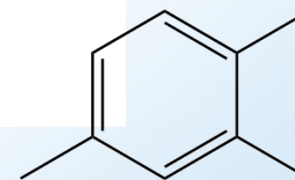
1-phenyl-1-xylyl-ethane (PXE)



Cyclohexylbenzene (PCH)



Di-isopropylnaphthalene (DIN)



1,2,4-trimethylbenzene (PC)

# Common fluors and shifters

Table III-8  
Properties of a few primary solutes


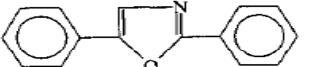
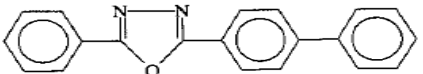
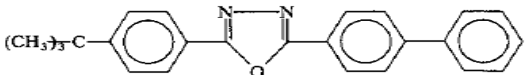

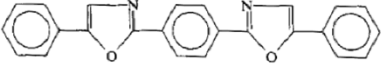
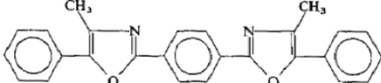
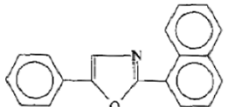
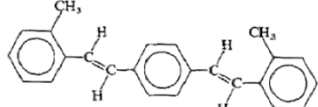
Solute	Peak fluorescence (nm)	Decay time, $\tau$ (nsec)	Quantum yield, $\Phi$	Solubility in toluene (g/liter) at room temperature	Optimum solute concentration (g/liter)
<i>p</i> -Terphenyl 	342	1.0	0.77	5	5
PPO 	375	1.4	0.83	400	3-7
PBD 	375	1.0	0.69	12	8-10
Butyl-PBD 	385	1.0	0.69	130	12
Naphthalene 	334	96.0	0.19	250	"

Table III-17  
Some commonly used secondary solutes

Compound	Abbreviation	Concentration (g/liter)	Average wavelength (nm)
	POPOP	0.05-0.2	415
	M.-POPOP	0.1-0.5	427
	$\alpha$ -NPO	0.05-0.2	400
	bis-MSB	1.5	425

D.L. Horrocks, Applications of Liquid Scintillation Counting, Academic Press 1974

- Match the best absorption and emission overlaps between the scintillation solvent, fluors and shifters for non-radiative transitions
- **Most fluors and shifters are fast decay at few ns (but not limited to)**

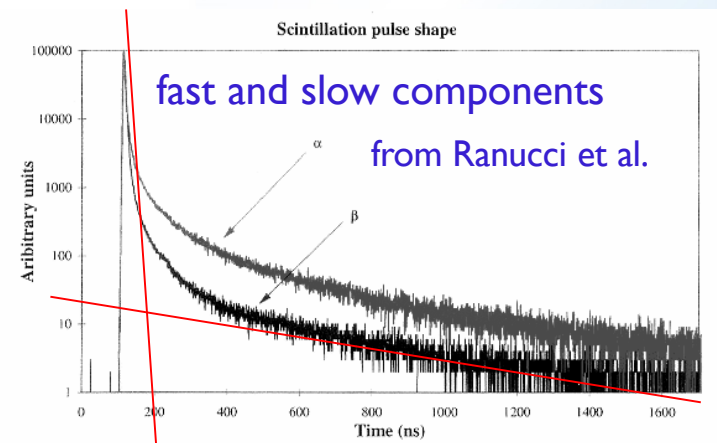
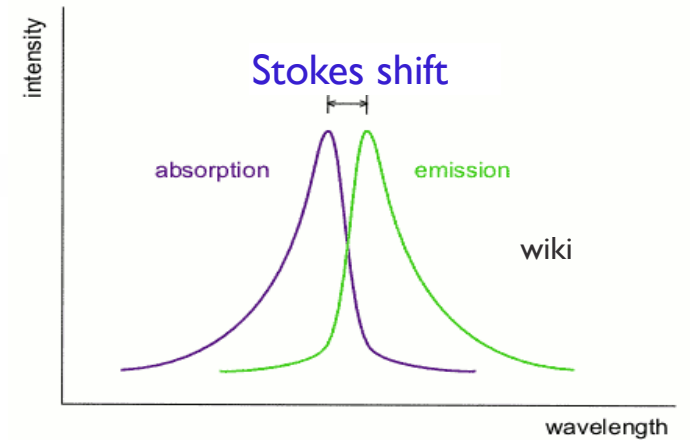
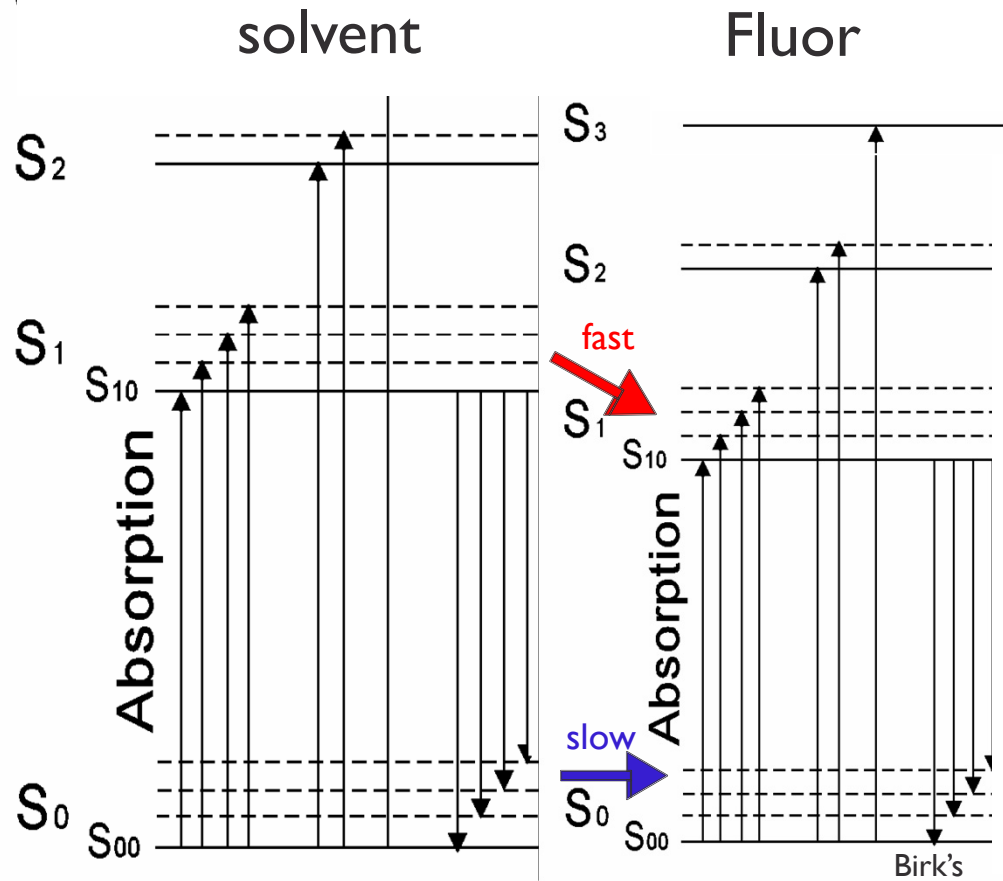
# Combination of Scintillator Cocktail

**Table 1.** Fluorescence quantum yield of aromatic molecules used in liquid scintillators. All samples were diluted in cyclohexane and measured at room temperature inside a 1 cm fluorescence cell (for DPA, BPO, PBD and butly-PBD the yields determined in the 4 mm cell were used). Besides the range of excitation wavelengths used to determine the quantum yields the wavelengths of the absorption and emission peaks are quoted.

Molecule	concentration	exc. range [nm]	Quantum yield	abs. max.	em. max.
bis-MSB	$1.6 \cdot 10^{-6}$ M	300–380	$0.863 \pm 0.043$	345 nm	418 nm
PPO	$2.3 \cdot 10^{-6}$ M	290–330	$0.842 \pm 0.042$	303 nm	358 nm
Anthracene	$1.1 \cdot 10^{-5}$ M	300–370	$0.323 \pm 0.021$	357 nm	400 nm
DPA	$1.5 \cdot 10^{-6}$ M	350–380	$0.91 \pm 0.05$	373 nm	407 nm
BPO	$1.7 \cdot 10^{-6}$ M	320–350	$0.91 \pm 0.05$	320 nm	384 nm
PBD	$1.7 \cdot 10^{-6}$ M	300–320	$0.84 \pm 0.05$	302 nm	358 nm
butyl-PBD	$1.4 \cdot 10^{-6}$ M	300–320	$0.89 \pm 0.05$	302 nm	361 nm
POPOP	$1.4 \cdot 10^{-6}$ M	350–380	$0.90 \pm 0.05$	360 nm	411 nm
o-PXE	$1.2 \cdot 10^{-4}$ M	260–280	$0.33 \pm 0.03$	269 nm	290 nm
PC	$8.3 \cdot 10^{-5}$ M	250–270	$0.41 \pm 0.04$	267 nm	290 nm
LAB	$4.1 \cdot 10^{-4}$ M	250–270	$0.20 \pm 0.02$	260 nm	284 nm
DIN	$4.7 \cdot 10^{-5}$ M	250–270	$0.32 \pm 0.03$	279 nm	338 nm

C. Buck, B. Gramlich and S. Wagner, JINST10 P09007 (2015)

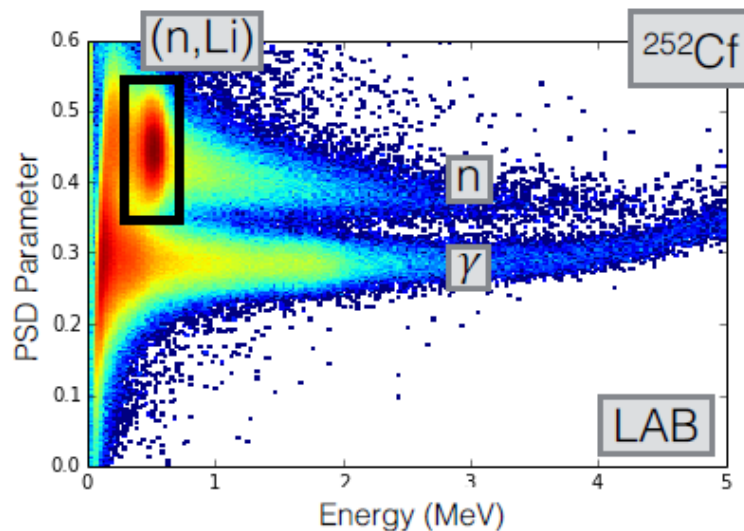
# Scintillation Mechanism



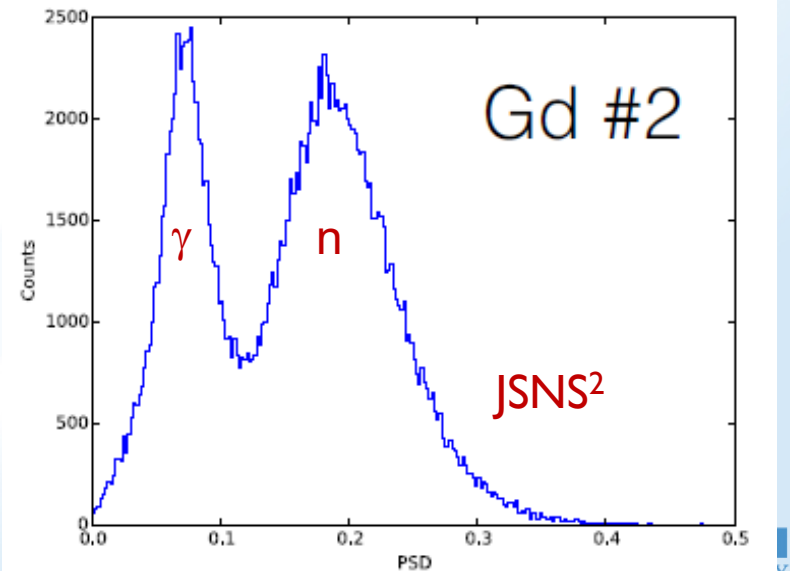
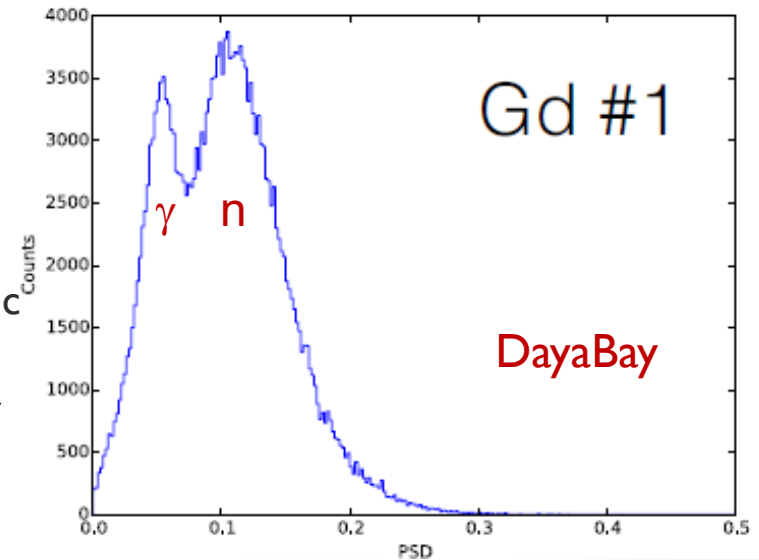
- Stokes shift, timing structure, density and  $Z$  are the key parameters that determine the responses of detector

# Pulse Shape Discrimination

- A muon veto alone cannot reduce the cosmo/accelerator background for a surface detector; **Need PSD to distinguish proton recoils from electron-like events**
  - 2D-PSD to distinguish IBD events from cosmogenic fast neutrons and ambient-related gammas
- LAB-based scintillator doesn't have good n- $\gamma$  separation; DIN or other "pseudo" toluene scintillators enables an enhanced PSD capability

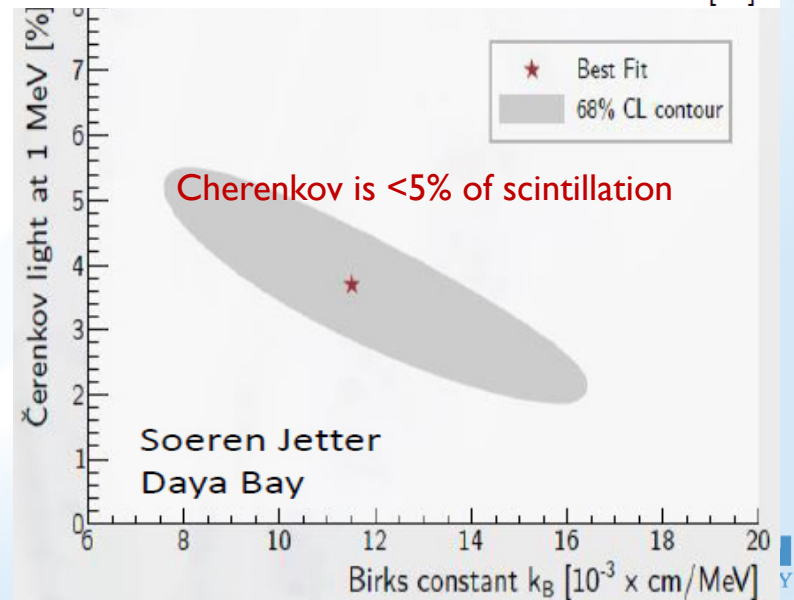
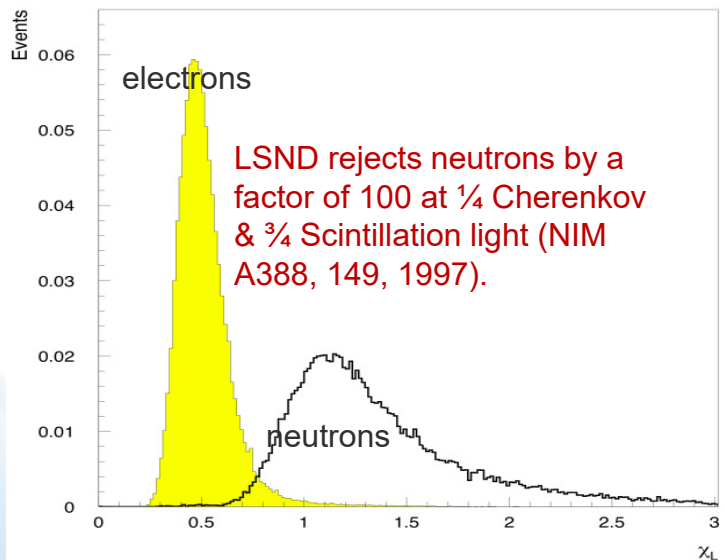
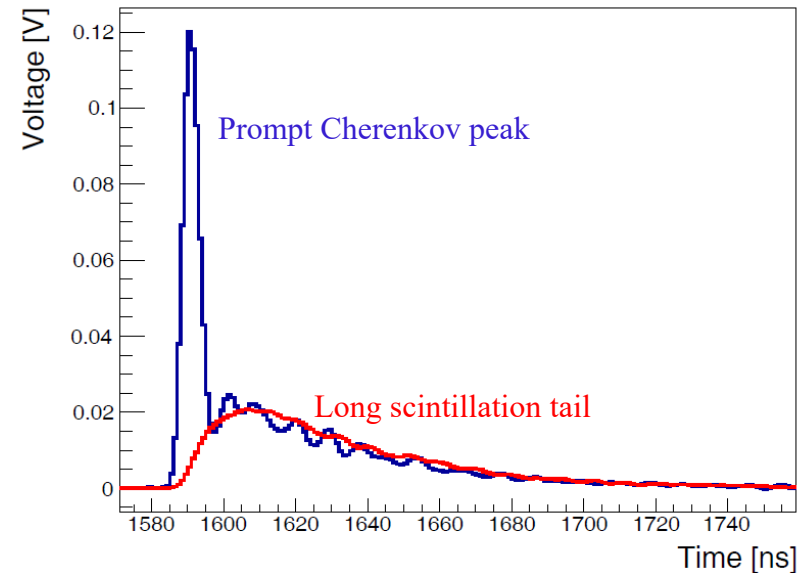


PROSPECT



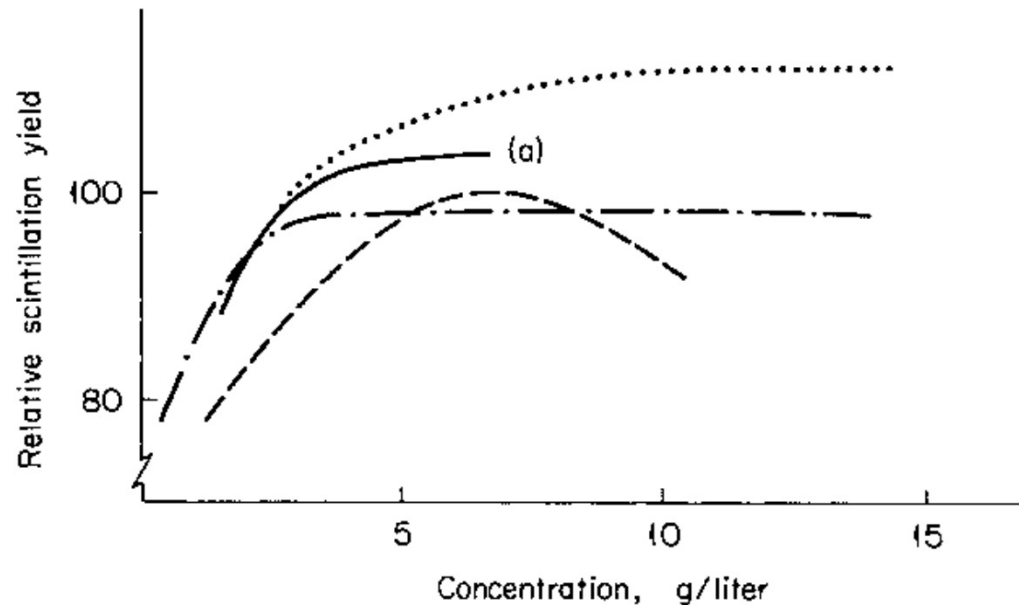
# Cherenkov/Scintillation Separation

- Separation of Cherenkov from scintillation allows directional cut for particle ID, great impacts for future particle-physics experiments
  - Fast photosensors/electronics
  - Ratio of scintillation light in Cherenkov
  - Slow scintillation time



# Fluor Effect

- Decay time is a function of type and concentration of fluor/shifter (before saturation)
- Once the FRET mechanism are completed, adding more fluors reduces the light yield due to color and collision quenching



**Fig. III-5.** Concentration dependency of the scintillation yield. (a) Solubility limit of *p*-terphenyl; — — — PPO; . . . . *t*-butyl-PBD; — — — *p*-terphenyl; · — · — · TMQP.

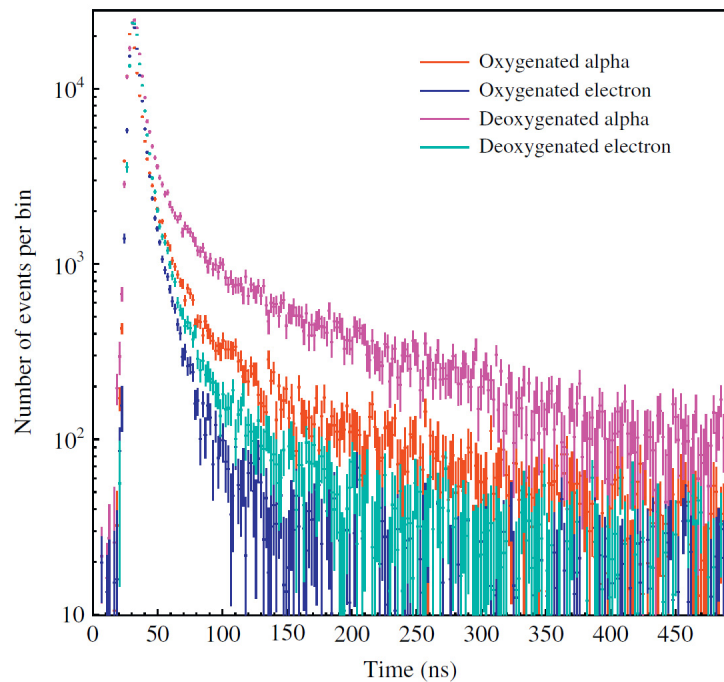
D.L. Horrocks, Applications of Liquid Scintillation Counting, Academic Press 1974

# Quenching Effect

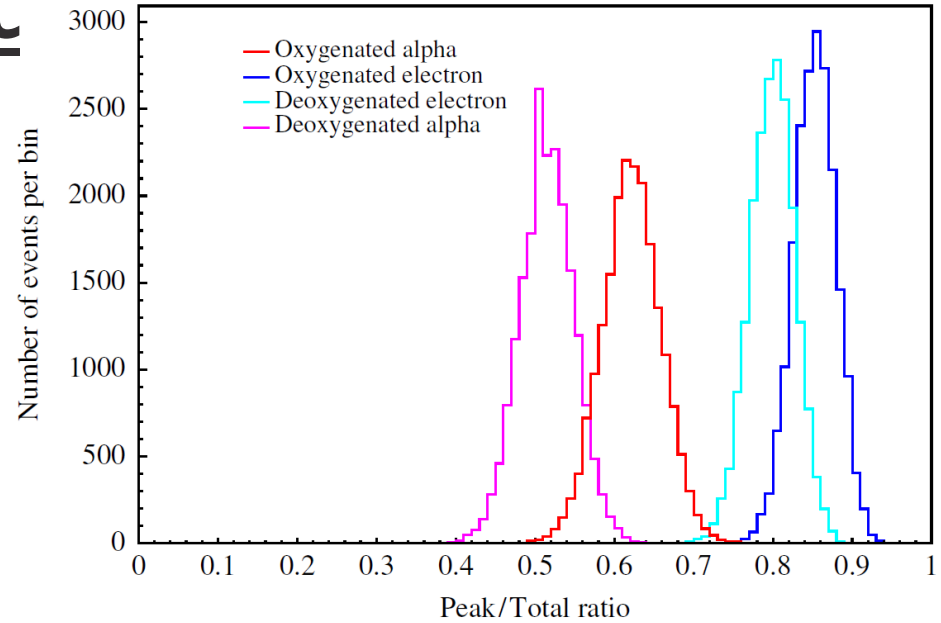
**Table 1**

Summary of timing results for the alpha and electron timing profile fits. Tot errors are given.

	Oxygenated $\alpha$	Oxygenated $e^-$	Deoxygenated $\alpha$	Deoxygenated $e^-$
$t_1$ (ns)	$4.4 \pm 0.2$	$4.3 \pm 0.3$	$3.2 \pm 0.2$	$4.6 \pm 0.3$
$t_2$ (ns)	$20 \pm 1$	$16 \pm 1$	$18 \pm 1$	$18 \pm 1$
$t_3$ (ns)	$178 \pm 10$	$166 \pm 11$	$190 \pm 10$	$156 \pm 9$
$A_1$	$520 \pm 6$	$768 \pm 12$	$794 \pm 7$	$753 \pm 14$
$A_2$	$59 \pm 3$	$59 \pm 4$	$53 \pm 3$	$61 \pm 3$
$A_3$	$3.3 \pm 0.1$	$0.8 \pm 0.1$	$12.6 \pm 0.2$	$2.2 \pm 0.1$
$R_1$ (%)	55	75	44	71
$R_2$ (%)	28	22	16	22
$R_3$ (%)	17	3	41	7



**Fig. 2.** Alpha and electron timing profiles for oxygenated and deoxygenated samples of LAB + 2 g/L PPO.



**Fig. 3.** Peak to total distributions for excitations due to electrons and alpha particles in oxygenated and deoxygenated LAB + 2 g/L PPO.

Oxygen quenching slows the decay time, gives better PSD; but reduces the light-yield (as much as ~15% less)

H.M. O’Keeffe , E.O’Sullivan, M.C.Chen, NIM A 640 (2011) 119–122

# Quenching Parameters

**Table 4** Quenching parameter  $kB$  for protons and  $\alpha$ -particles in LAB based scintillator resulting from simultaneous neutron beam measurements. Also given are the total  $1\sigma$  uncertainties. The proton quenching results are taken from [1]. In this reference,  $C$  is  $< 5 \times 10^{-7} \text{ cm}^2/\text{MeV}^2$  for the first and  $< 1 \times 10^{-7} \text{ cm}^2/\text{MeV}^2$  for the second scintillator sample at 95% C.L. and consistent with zero.

Particle	$kB$ [cm/MeV]
LAB + 2 g/l PPO + 15 mg/l bis-MSB	
Proton	$0.0097 \pm 0.0002$
$\alpha$ -particle	$0.0076 \pm 0.0003$
LAB + 3 g/l PPO + 15 mg/l bis-MSB	
Proton	$0.0098 \pm 0.0003$
$\alpha$ -particle	$0.0071 \pm 0.0003$

Variation of decay time depends on the incident particle

B. von Krosigk et al:arXiv:1510.00458, submitted to JINST

# Metal-doped effect

Gd concentration	o-Ps fraction	lifetime (ns)
No Gd	$0.544 \pm 0.008$	$3.05 \pm 0.03$
0.01%	$0.554 \pm 0.008$	$3.07 \pm 0.03$
0.05%	$0.540 \pm 0.008$	$3.05 \pm 0.03$
0.08%	$0.537 \pm 0.008$	$3.04 \pm 0.03$
0.1%	$0.529 \pm 0.008$	$3.09 \pm 0.03$
0.45%	$0.406 \pm 0.008$	$3.02 \pm 0.03$

TABLE I. Results for the o-Ps formation and mean lifetime in Gd doped LAB samples.

Nd concentration	o-Ps fraction	lifetime (ns)
No Nd	$0.537 \pm 0.013$	$3.15 \pm 0.04$
0.05%	$0.527 \pm 0.013$	$3.11 \pm 0.04$
0.1%	$0.494 \pm 0.013$	$3.17 \pm 0.04$
0.3%	$0.460 \pm 0.013$	$3.15 \pm 0.04$
0.5%	$0.402 \pm 0.013$	$3.15 \pm 0.04$

TABLE II. Results for the o-Ps formation and mean lifetime in Nd doped LAB samples.

## Doped metal affects the o-Ps fraction; but not its lifetime

- G. Consolati, D. Franco, S. Hans, C. Jollet, A. Meregaglia, S. Perasso, A. Tonazzo, and M. Yeh, PRC 88, 065502 (2013)
- S. Perasso, a, 1 G. Consolati, b D. Franco, a C. Jollet, c A. Meregaglia, c A. Tonazzo and M. Yeh, JINST, v9, March 2014

TABLE III. Results for the o-Ps formation fraction and mean lifetime in Li doped LAB samples, and in the same samples without Li (same water concentration).

Li [%]	Concentration of		$f$	$\tau_3$ [ns]
	water [%]	surfactant [%]		
0.01	0.24	29.93	$0.363 \pm 0.011$	$2.92 \pm 0.04$
0.05	0.97	29.68	$0.353 \pm 0.010$	$2.84 \pm 0.03$
0.1	1.99	29.39	$0.346 \pm 0.011$	$2.90 \pm 0.03$
0.35	6.7	28.02	$0.323 \pm 0.010$	$2.90 \pm 0.03$
0	0.24	29.93	$0.380 \pm 0.011$	$2.92 \pm 0.04$
0	0.97	29.71	$0.367 \pm 0.010$	$2.84 \pm 0.03$
0	1.99	29.42	$0.351 \pm 0.011$	$2.90 \pm 0.03$
0	6.7	28.12	$0.344 \pm 0.010$	$2.90 \pm 0.03$

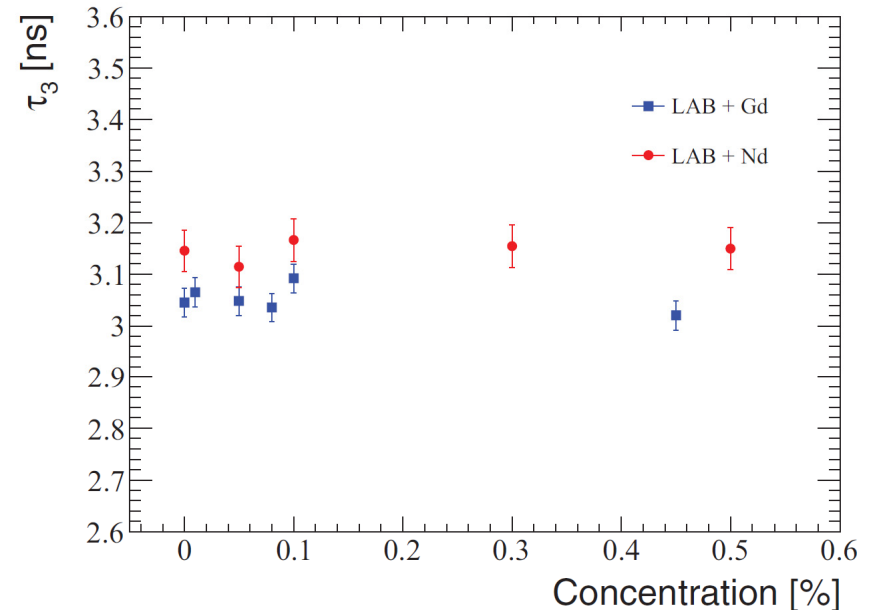


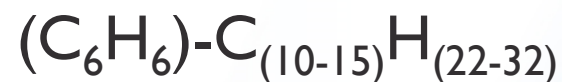
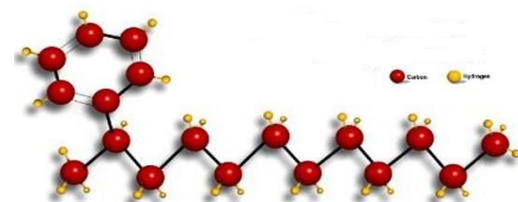
FIG. 2. (Color online) Results for the o-Ps lifetime for Gd (blue squares) and Nd (red circles) dopers in LAB as a function of the doper concentration.

# Experiment of Chev/Scin Separation

Table III-6

Fluorescence properties of solvents used in liquid scintillation counting

	Absorption $\lambda$ (nm)	Emission $\lambda$ (nm)	Quantum yield	Decay time (nsec)	Internal conversion $S_3 \rightarrow S_1$
Benzene	255	283	0.06	29	0.45
Toluene	263	285	0.14	34	0.76
<i>p</i> -Xylene	266	291	0.34	30	1.00
1,2,4-TMB	270	293	0.33	27.2	1.00
<i>p</i> -Dioxane (neat)	185	247	0.03	2.1	—
<i>p</i> -Dioxane + H <sub>2</sub> O (5%)	185	325	0.01 <sub>3</sub>	—	—
1-Methylnaphthalene	280	338	0.21	67	—
2-Ethyl-naphthalene	280	330	0.26	50	—
<i>m</i> -Xylene	265	289	0.14	30.8	—
<i>o</i> -Xylene	265	289	0.16	32.2	—
Anisole methoxybenzene	270	296	0.26	27.4	—



chemically and environmentally friendly; not flammable, merely combustible (Class IIIB), Flash Point – 250-280° F (120-140 C); Density 0.86 gm/cm<sup>3</sup>

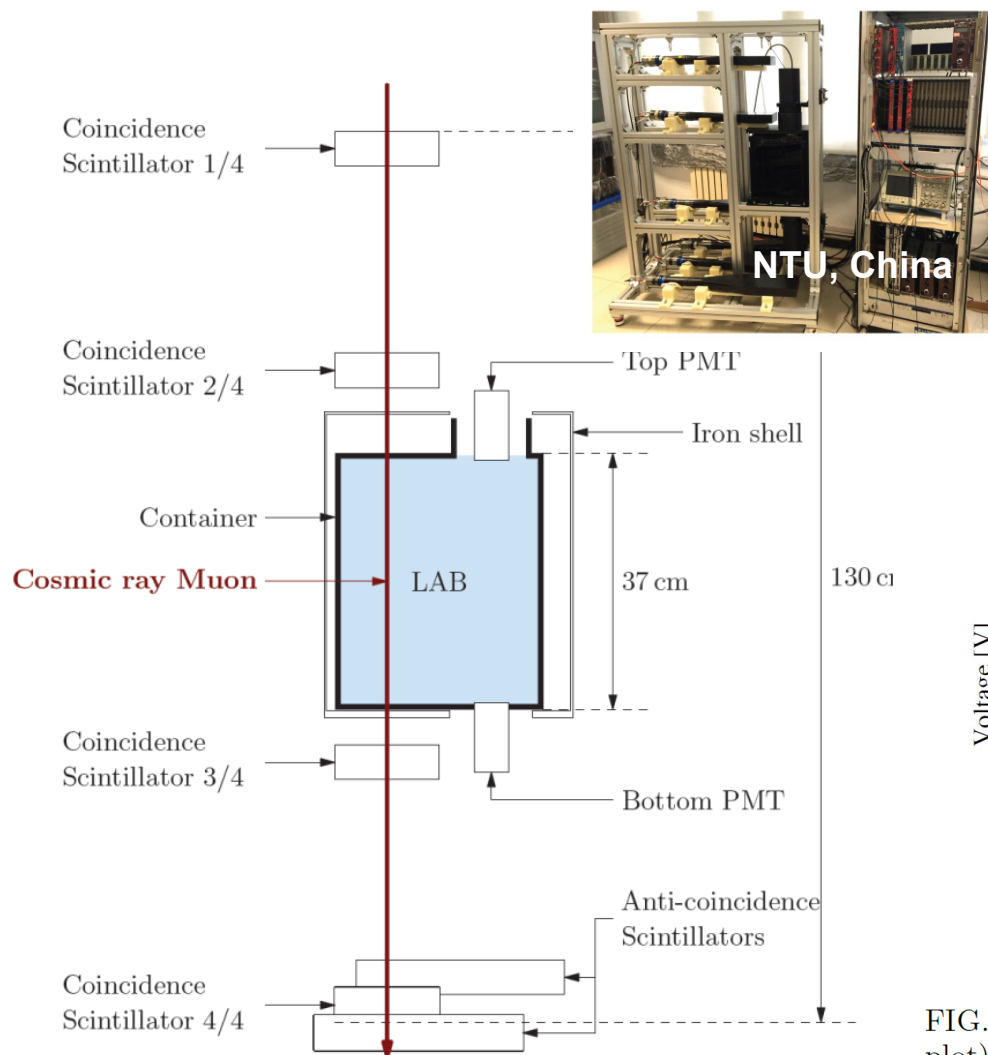


Cepas at Spain

D.L. Horrocks, Applications of Liquid Scintillation Counting, Academic Press 1974

- Scintillator solvents are relatively slow decay
- LAB is the current favor of several ongoing for future-planned experiments
- Good base solvent to test the Cherenkov and scintillation separation with partial scintillation light and slow decay time

# Demonstration of Chev/Scin Separation



M. Li, Z. Guo, M. Yeh, Z. Wang, S. Chen: arXiv:1511.09339v1

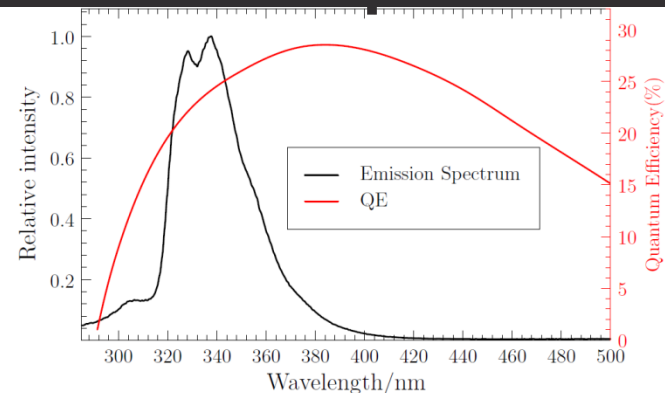


FIG. 7: The emission spectrum of linear alkyl benzene and the quantum efficiency of the PMT's in the related range.

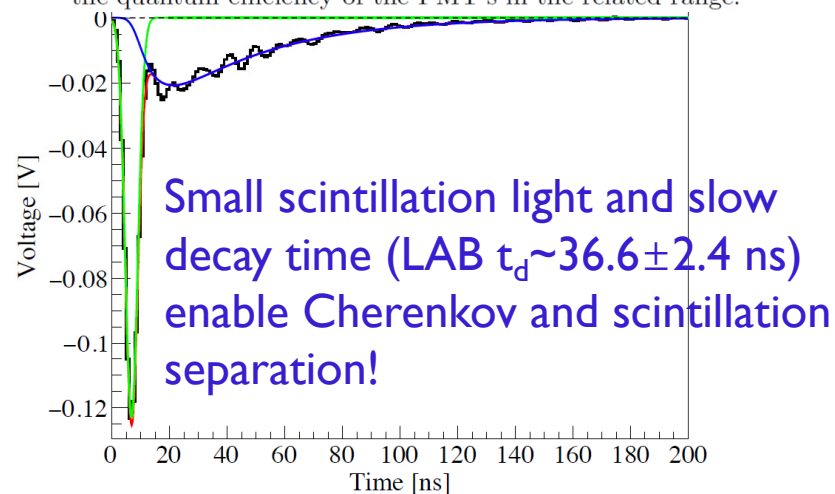


FIG. 9: Time profile of the scintillation light on the top (upper plot) and bottom (lower plot) PMT's and their fit results, where the green is for the Cherenkov component, the blue for the scintillation component, and the red for their sum.

# Summary/Futures

- Scintillator directionality is the key parameter for future scintillator experiments
- Cherenkov and scintillation separation can be achieved by controlling scintillator doping (LAB~36ns).
- Optimizing maximum scintillation light while still enabling the Chev/Scin separation
  - **Fast (ps) photo-detector and electronics**
  - Slow the scintillation time further:
    - Benzocarbazole derivatives (20~30ns),
    - Anthracene derivatives (30-40ns), anthrene derivatives (30 ~60ns), benzofluorene (~65ns), 2-phenyl naphthalene (~114ns), etc.
- Test light-yield, timing and PSD of scintillation cocktail with various types and concentrations of fluor and shifter
- I-ton Water-based Liquid Scintillator prototype
  - Direct measurement of Cherenkov from scintillation
  - Timing and Quenching measurements

