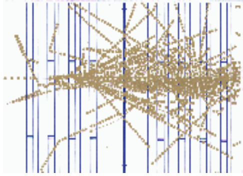


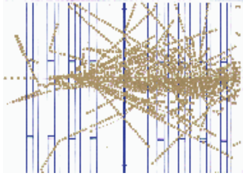
Crystal Calorimeters in the Next Decade

Ren-Yuan Zhu

California Institute of Technology

May 26, 2008

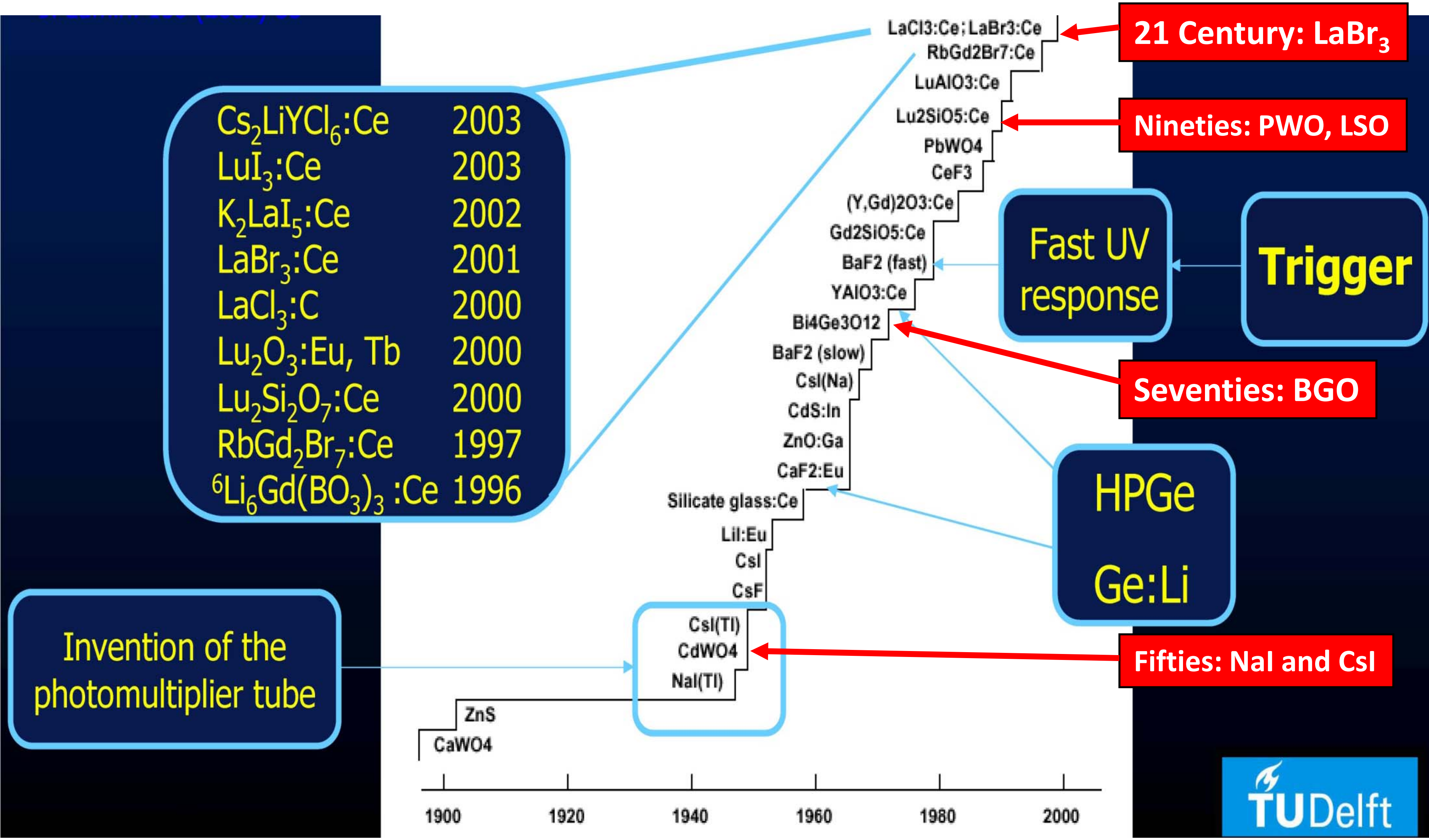
Why Crystal Calorimeter?



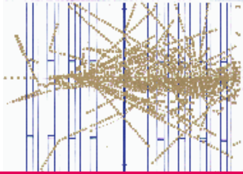
- Photons and electrons are fundamental particles. Precision e/γ enhance physics discovery potential.
- Crystal calorimeter performance in e/γ measurements is well understood:
  - The best possible energy resolution;
  - Good position resolution;
  - Good e/ γ identification and reconstruction efficiency.
- Crystals may also provide a foundation for homogeneous hadron calorimeter with dual readout of Cherenkov and scintillation light.

History of Crystal Development

M.J. Weber, J. Lumin. 100 (2002) 35



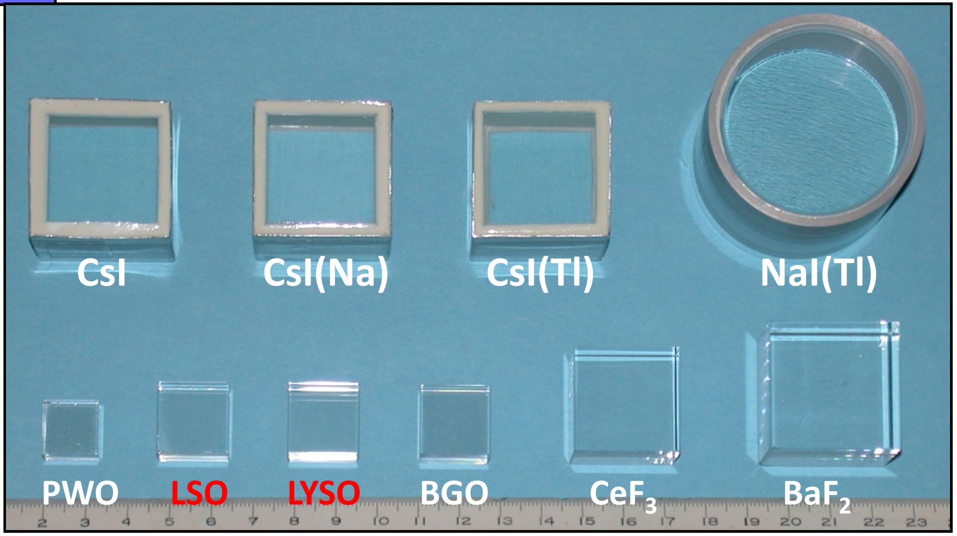
Crystals for HEP Calorimeters



Crystal	NaI(Tl)	CsI(Tl)	CsI(Na)	CsI	BaF_2	CeF_3	BGO	PWO(Y)	LSO(Ce)
Density (g/cm³)	3.67	4.51	4.51	4.51	4.89	6.16	7.13	8.3	7.40
Melting Point (°C)	651	621	621	621	1280	1460	1050	1123	2050
Radiation Length (cm)	2.59	1.86	1.86	1.86	2.03	1.70	1.12	0.89	1.14
Molière Radius (cm)	4.13	3.57	3.57	3.57	3.10	2.41	2.23	2.00	2.07
Interaction Length (cm)	42.9	39.3	39.3	39.3	30.7	23.2	22.8	20.7	20.9
Refractive Index [a]	1.85	1.79	1.95	1.95	1.50	1.62	2.15	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	420	420 310	300 220	340 300	480	425 420	402
Decay Time [b] (ns)	245	1220	690	30 6	650 0.9	30	300	30 10	40
Light Yield [b,c] (%)	100	165	88	3.6 1.1	36 4.1	7.3	21	0.3 0.1	85
d(LY)/dT [b] (%/ °C)	-0.2	0.4	0.4	-1.4	-1.9 0.1	0	-0.9	-2.5	-0.2
Experiment	Crystal Ball	BaBar BELLE BES III	-	KTeV	(L*) (GEM) TAPS	-	L3 BELLE	CMS ALICE PANDA	SuperB

a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

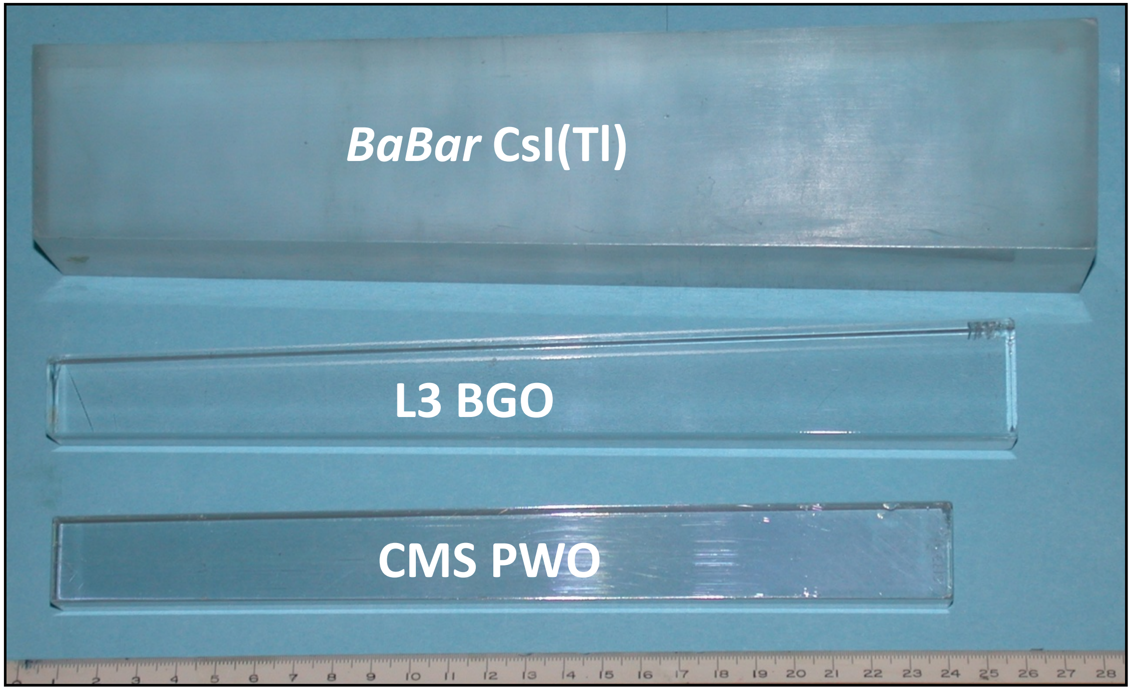
Crystal Density: Radiation Length



1.5 X_0 Cubic Samples:

Hygroscopic Halides

Non-hygroscopic



Full Size Crystals:

***BaBar* CsI(Tl): 16 X_0**

L3 BGO: 22 X_0

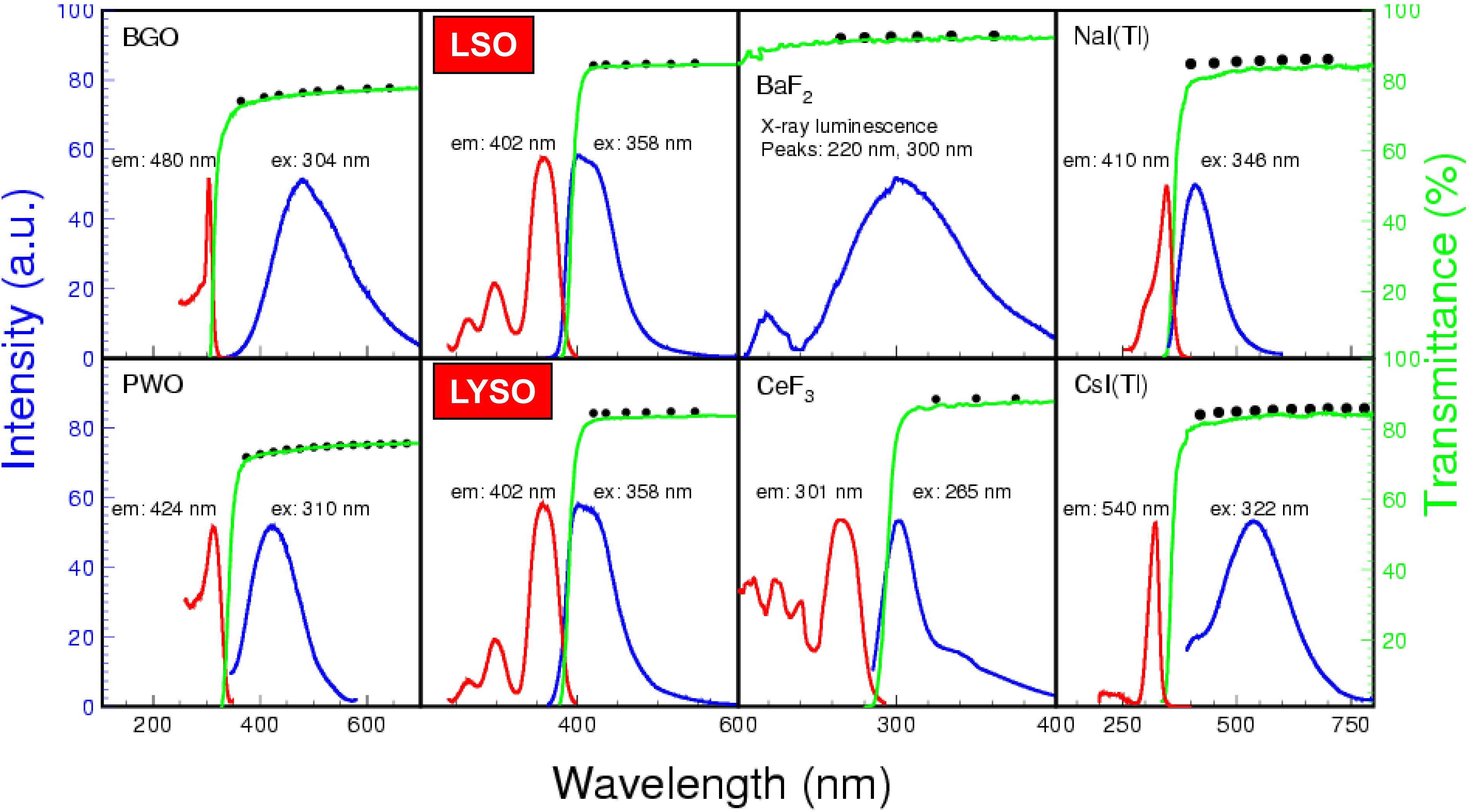
CMS PWO(Y): 25 X_0

Excitation, Emission, Transmission

$$T_s = (1-R)^2 + R^2(1-R)^2 + \ldots = (1-R)/(1+R), \text{ with}$$

$$R = \frac{(n_{crystal} - n_{air})^2}{(n_{crystal} + n_{air})^2}.$$

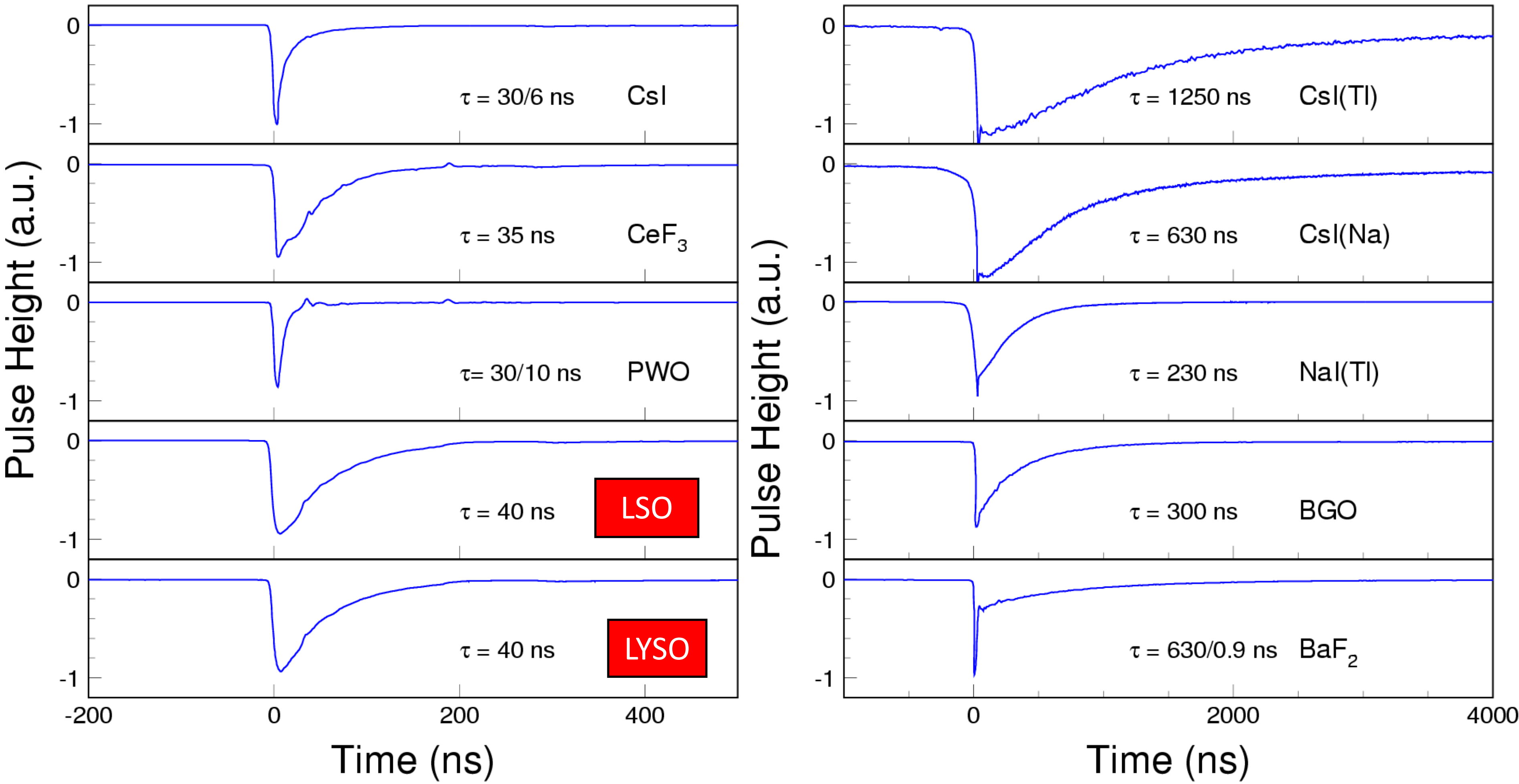
Black Dots: Theoretical limit of transmittance: NIM A333 (1993) 422



Scintillation Light Decay Time

Recorded with an Agilent 6052A digital scope

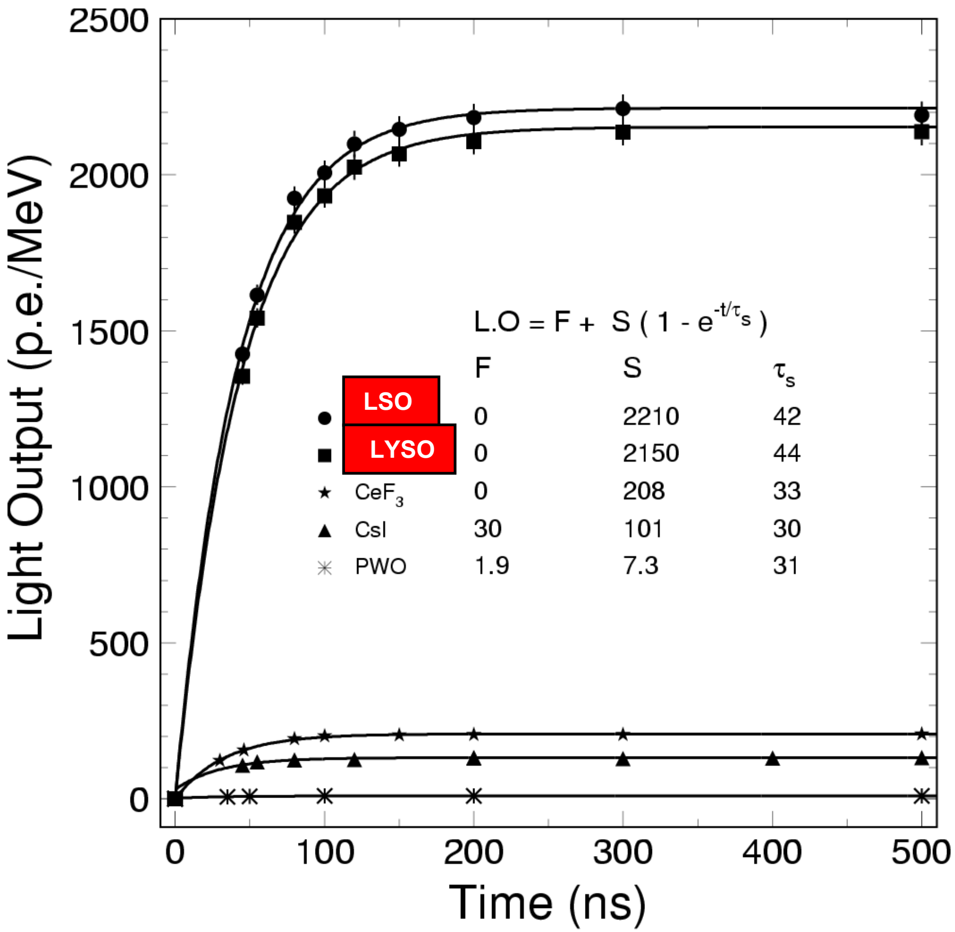
Fast Scintillators | **Slow Scintillators**



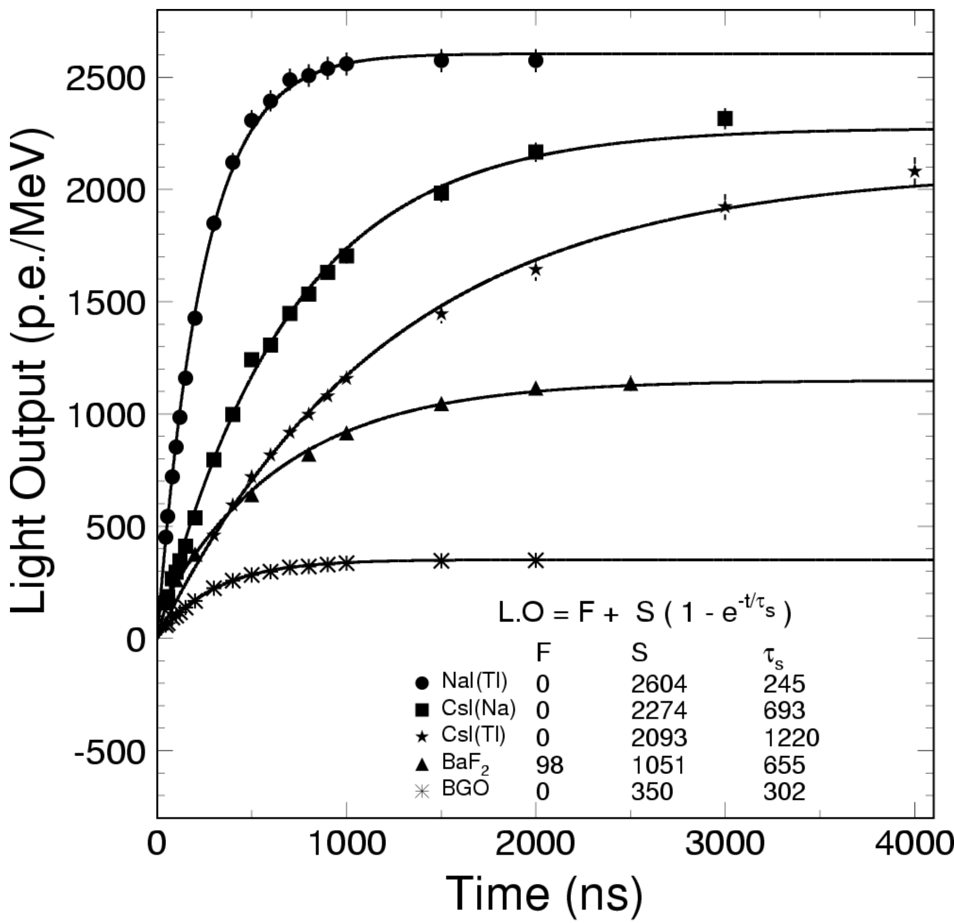
Light Output & Decay Kinetics

Measured with Philips XP2254B PMT (multi-alkali cathode)
p.e./MeV: LSO/LYSO is 6 & 230 times of BGO & PWO respectively

Fast Crystal Scintillators

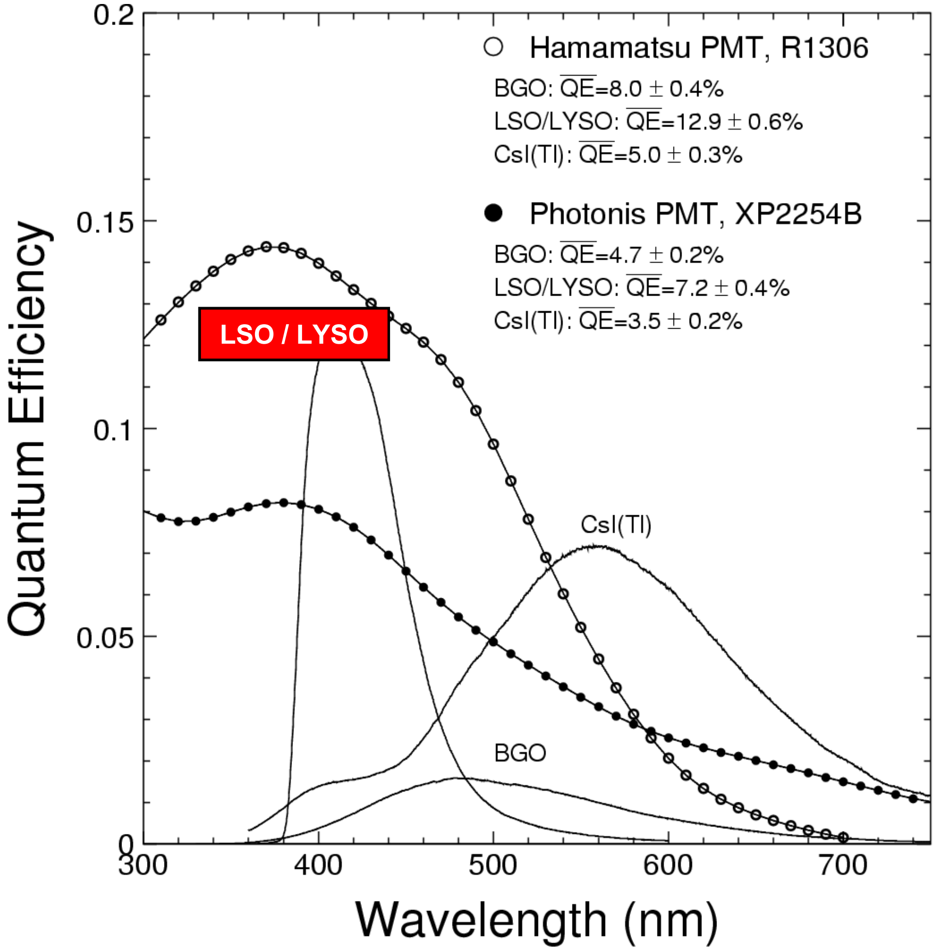


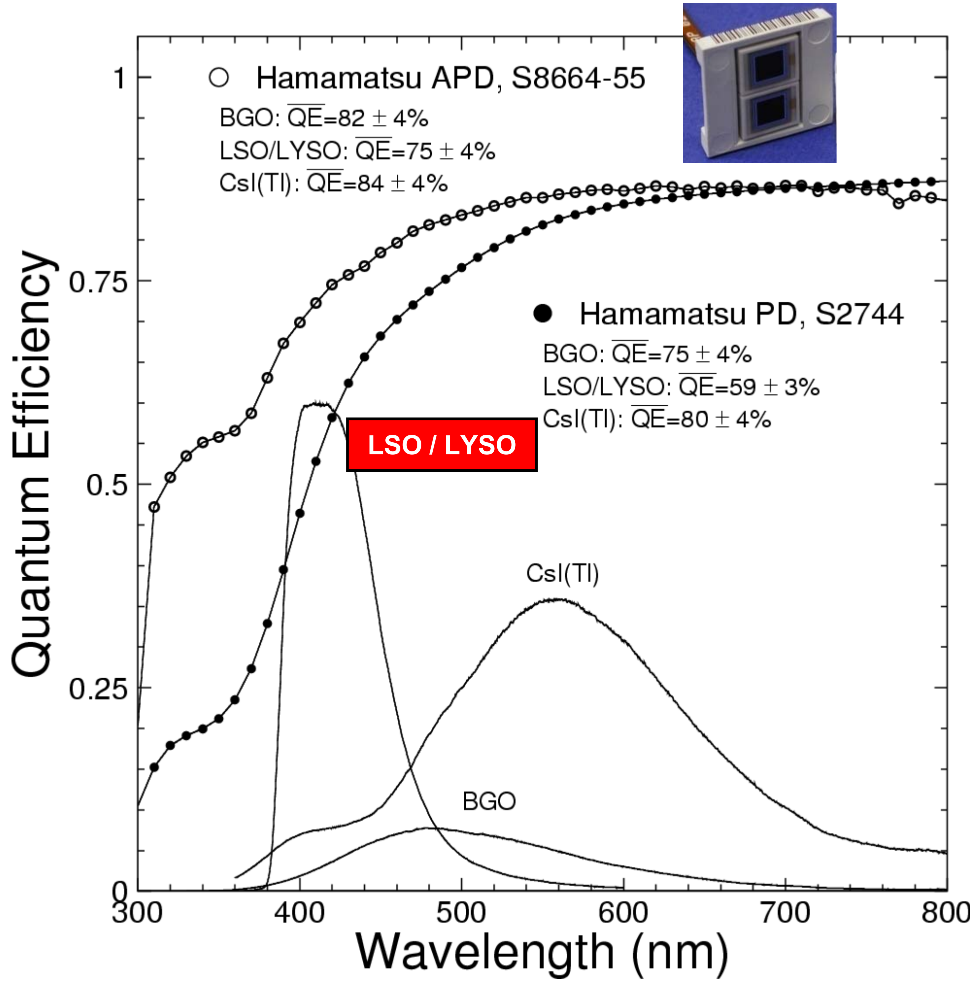
Slow Crystal Scintillators



Emission Weighted QE

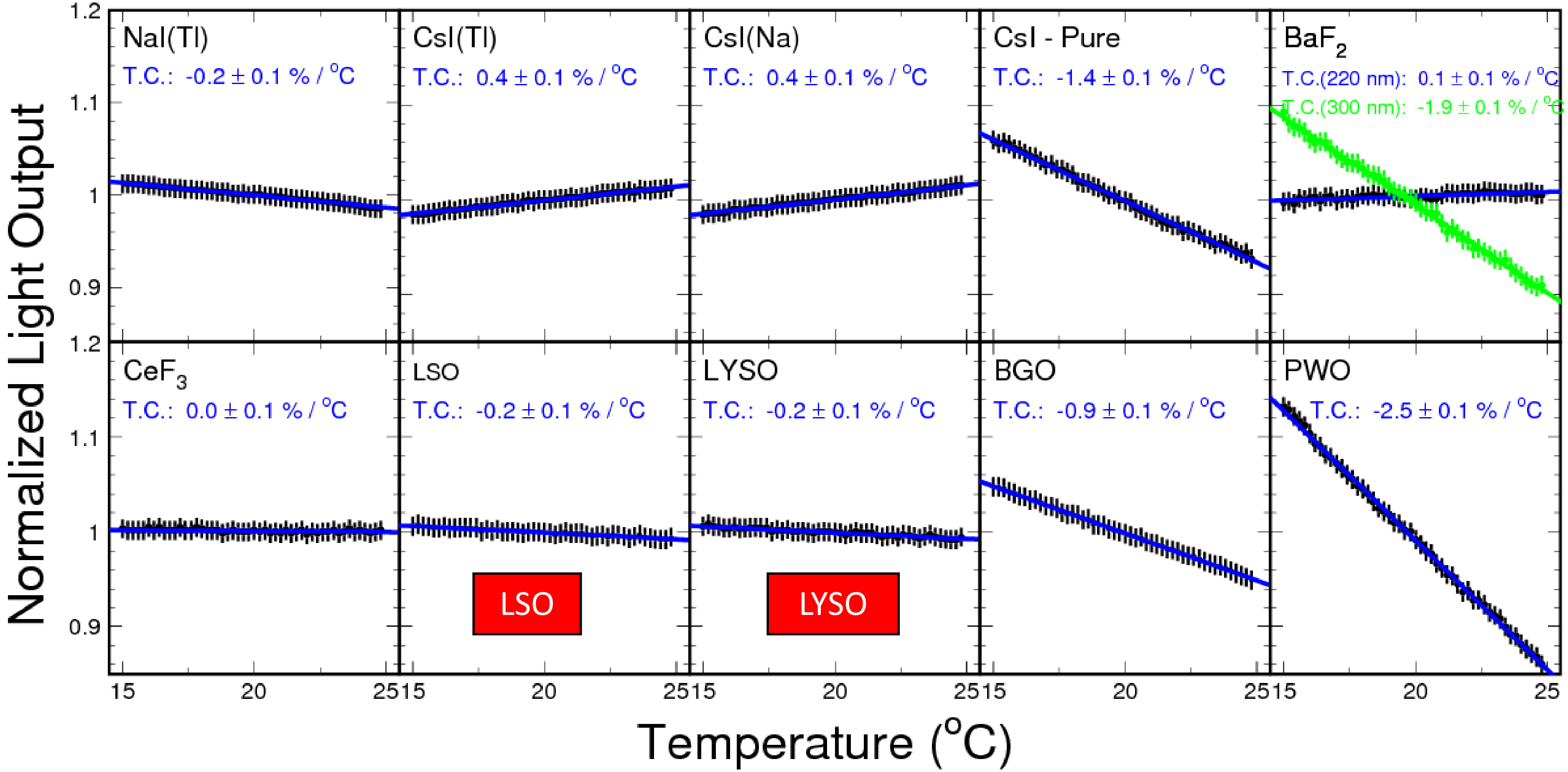
Taking out QE, L.O. of LSO/LYSO is 4/200 times BGO/PWO
Hamamatsu S8664-55 APD has QE 75% for LSO/LYSO





L.O. Temperature Coefficient

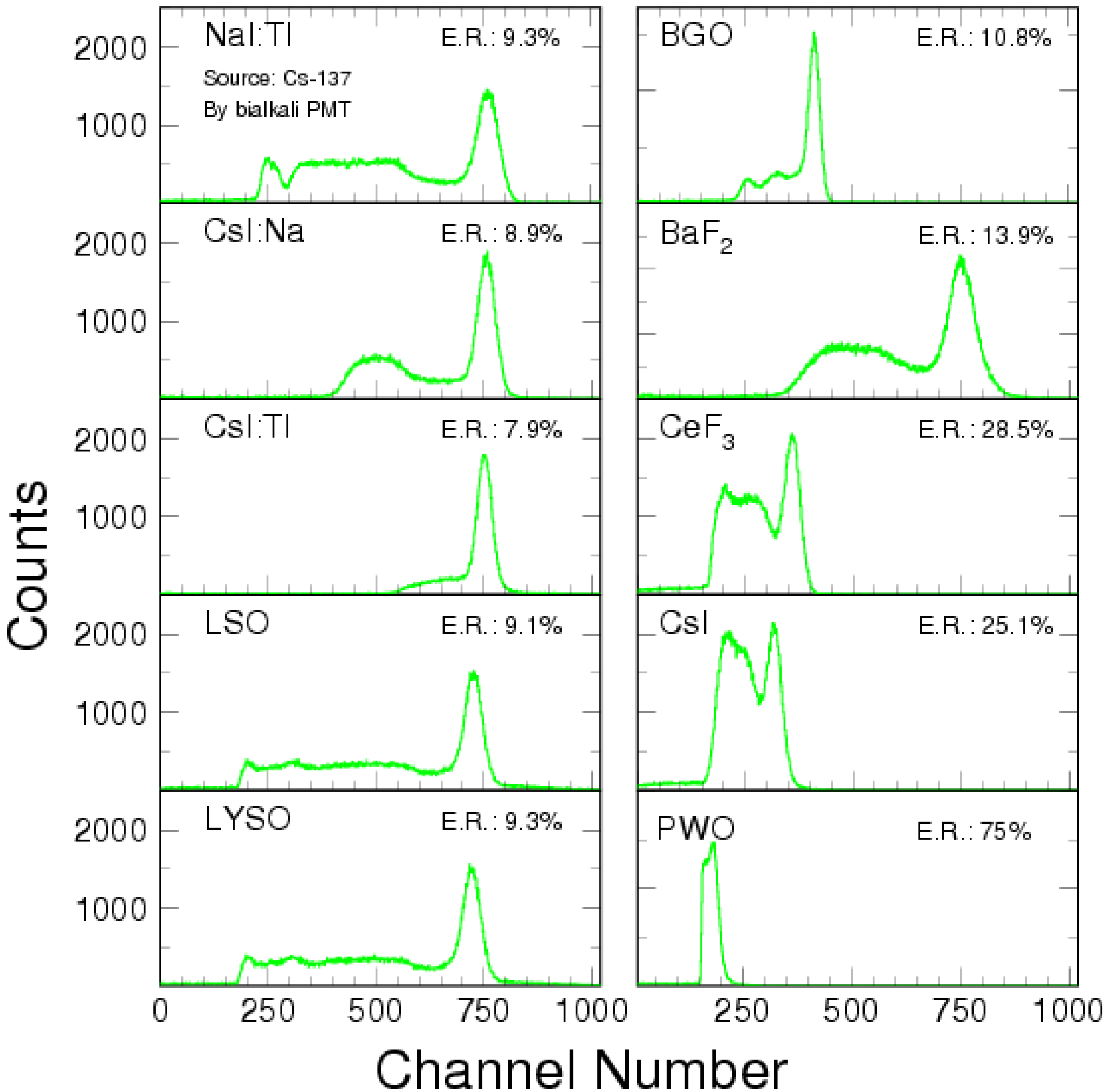
Temperature Range: 15 - 25ºC



^{137}Cs FWHM Energy Resolution

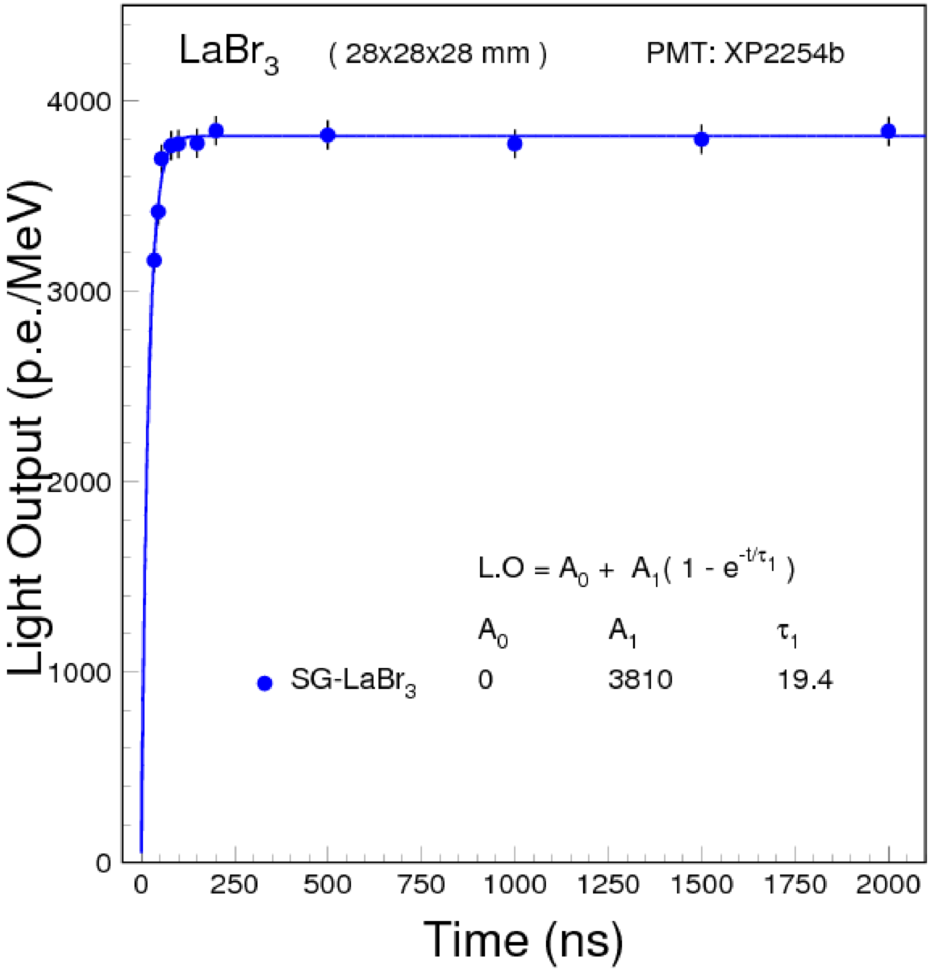
8% to 80% measured with Hamamatsu R1306 PMT with bi-alkali cathode

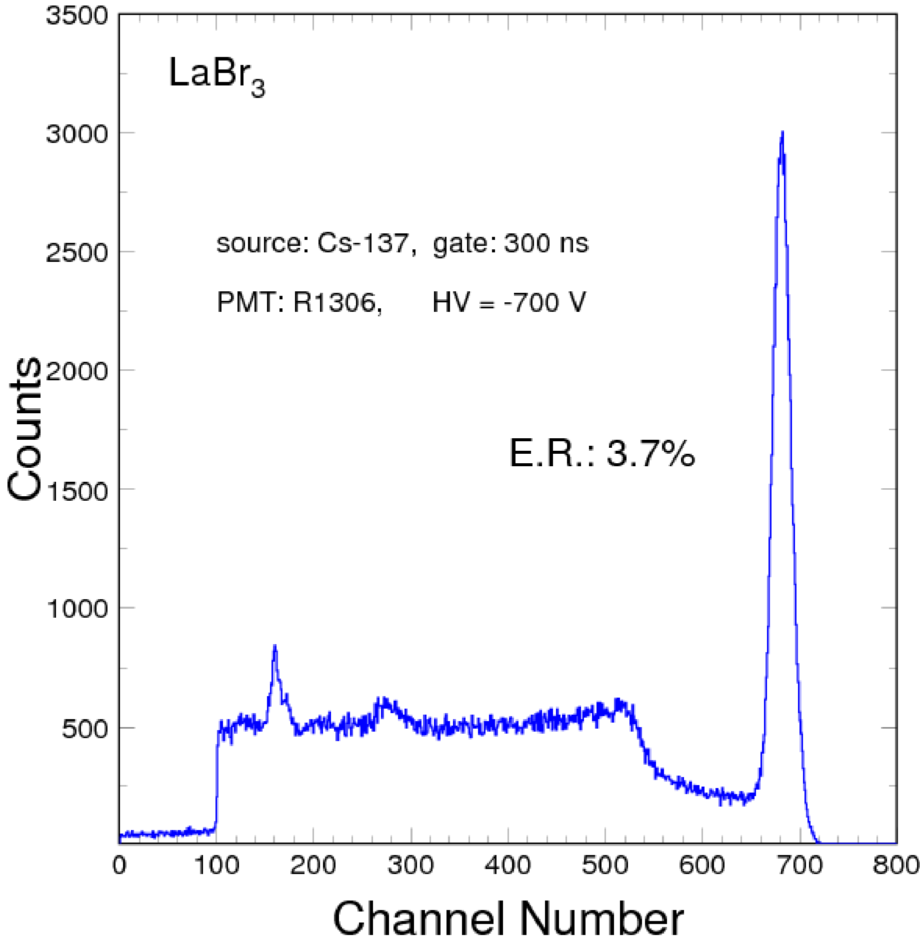
2% resolution and proportionality are important for the homeland security application for γ–ray spectroscopy between 10 keV to 2 MeV



$LaBr_3$ for Homeland Security

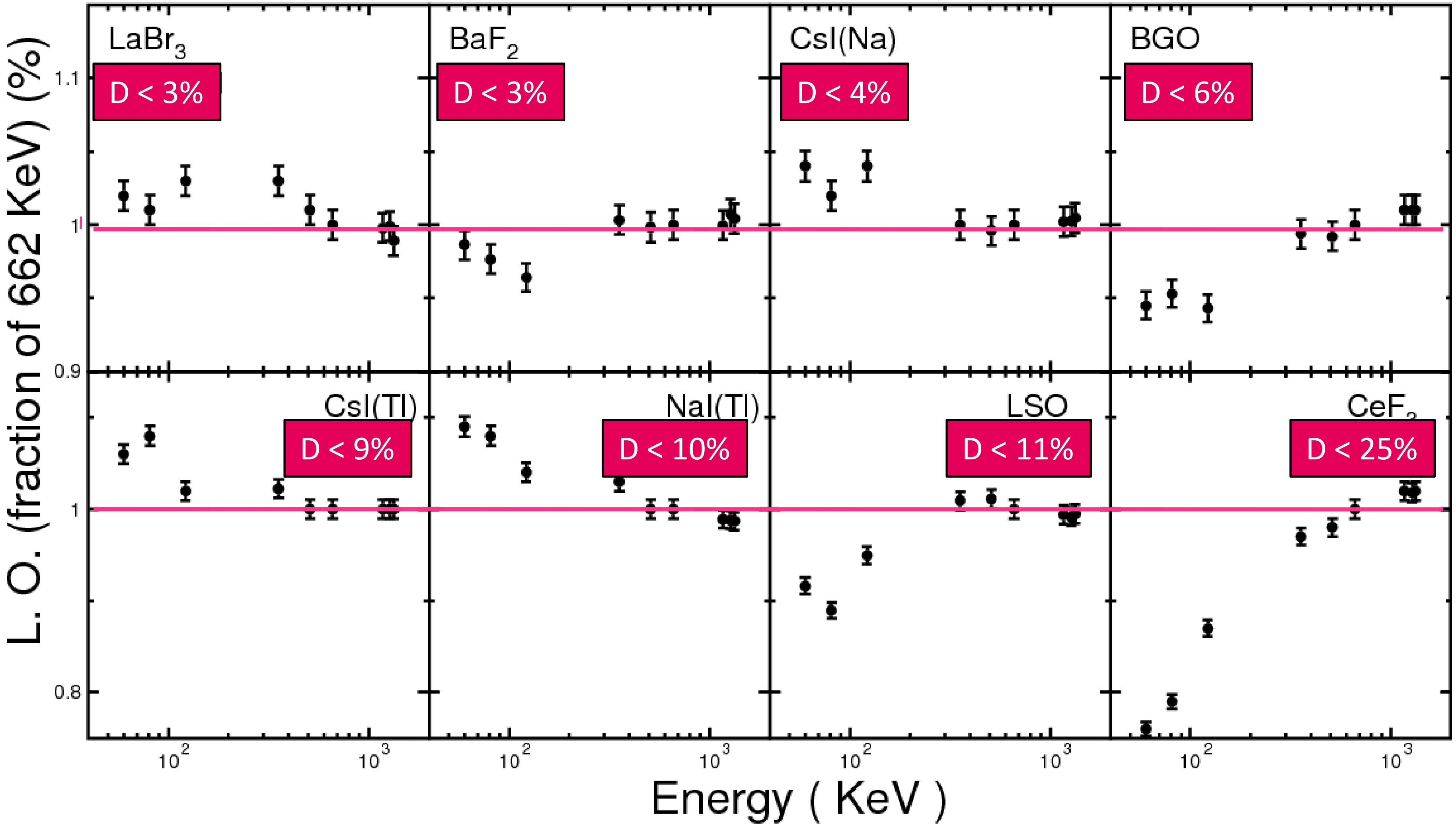
Fast decay time: 20 ns as compared to LSO: 40 ns
High light yield 3,810 p.e./MeV as compared to LSO: 2,200 p.e./MeV
Excellent energy resolution ≈3% as compared to ≈9% of LYSO





Low Energy Non Proportionality

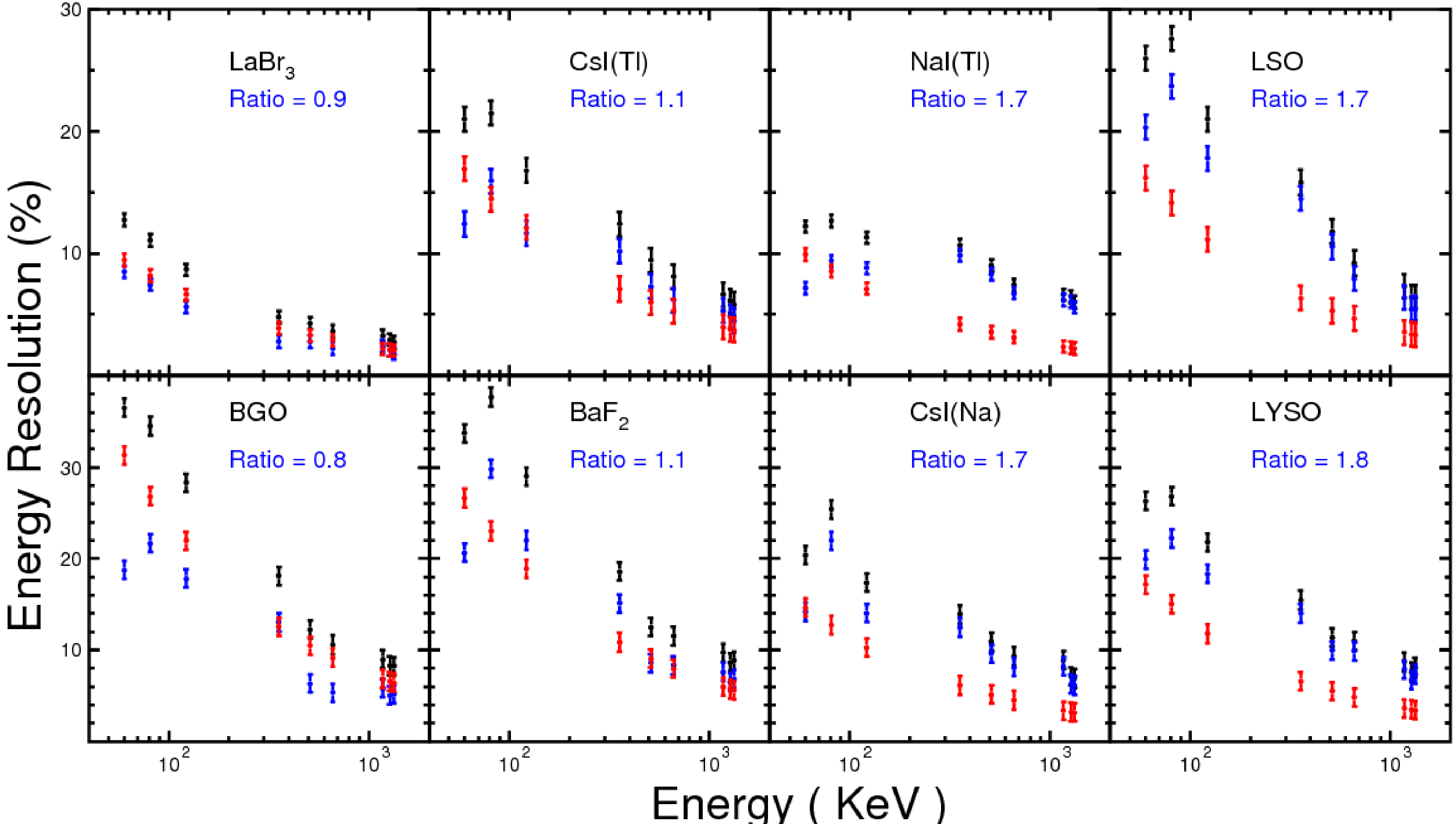
D: deviation from linearity: 60 keV to 1.3 MeV
Good Crystals: $LaBr_3$, BaF_2, CsI(Na) and BGO



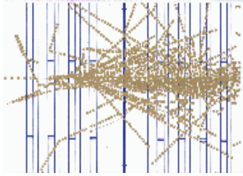
Statistical & Intrinsic Resolutions

$\sigma^2 = \sigma^2_{intrinsic} + \sigma^2_{statistical}$, ratio = $\sigma_{intrinsic} / \sigma_{statistical}$

Good crystals: BGO and $LaBr_3$



Crystal Calorimeters in HEP



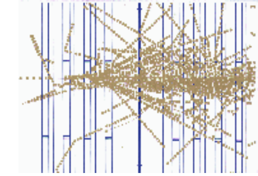
Date	75-85	80-00	80-00	80-00	90-10	94-10	94-10	95-20
Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	LEAR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	-	0.5	1.5	1.5	-	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	1.0	0.27	-	1.0	1.25	1.29
Number of Crystals	672	11,400	7,800	1,400	3,300	6,580	8,800	76,000
Crystal Depth (X_0)	16	22	16	16	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	1	1.5	7	1	2	5.9	9.5	11
Light Output (p.e./MeV)	350	1,400	5,000	2,000	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	WS[a]+Si PD	PMT	Si PD	Si PD	APD[a]
Gain of Photosensor	Large	1	1	1	4,000	1	1	50
σ_N/Channel (MeV)	0.05	0.8	0.5	0.2	small	0.15	0.2	40
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^4	10^5

Future crystal calorimeters in HEP:

PWO for PANDA at GSI

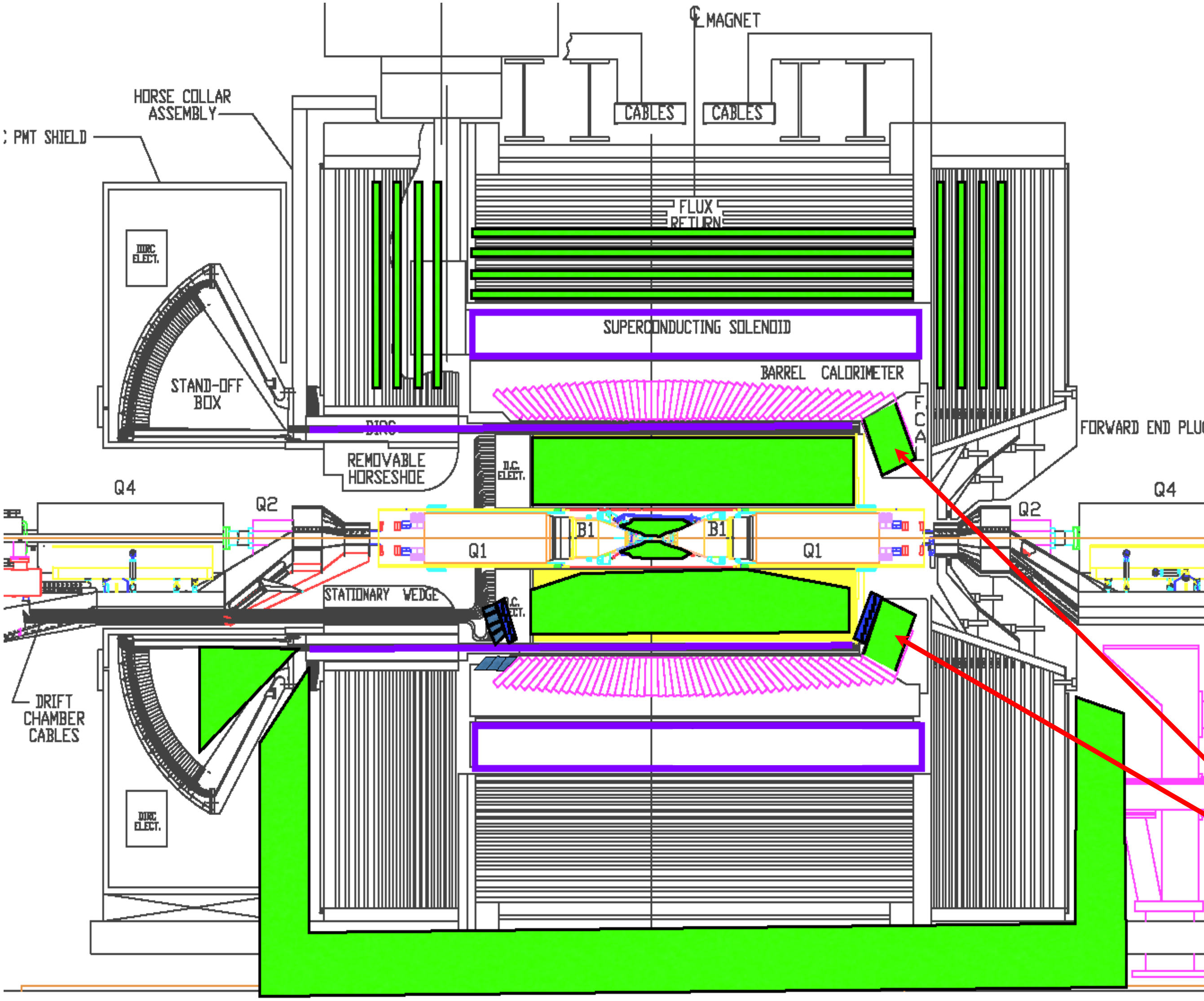
LYSO for a Super B Factory

PbF_2, BGO, PWO for Homogeneous HCAL



LYSO Endcap for Super*B*

David Hitlin The Super*B* Project N01-3 IEEE NSS 2007

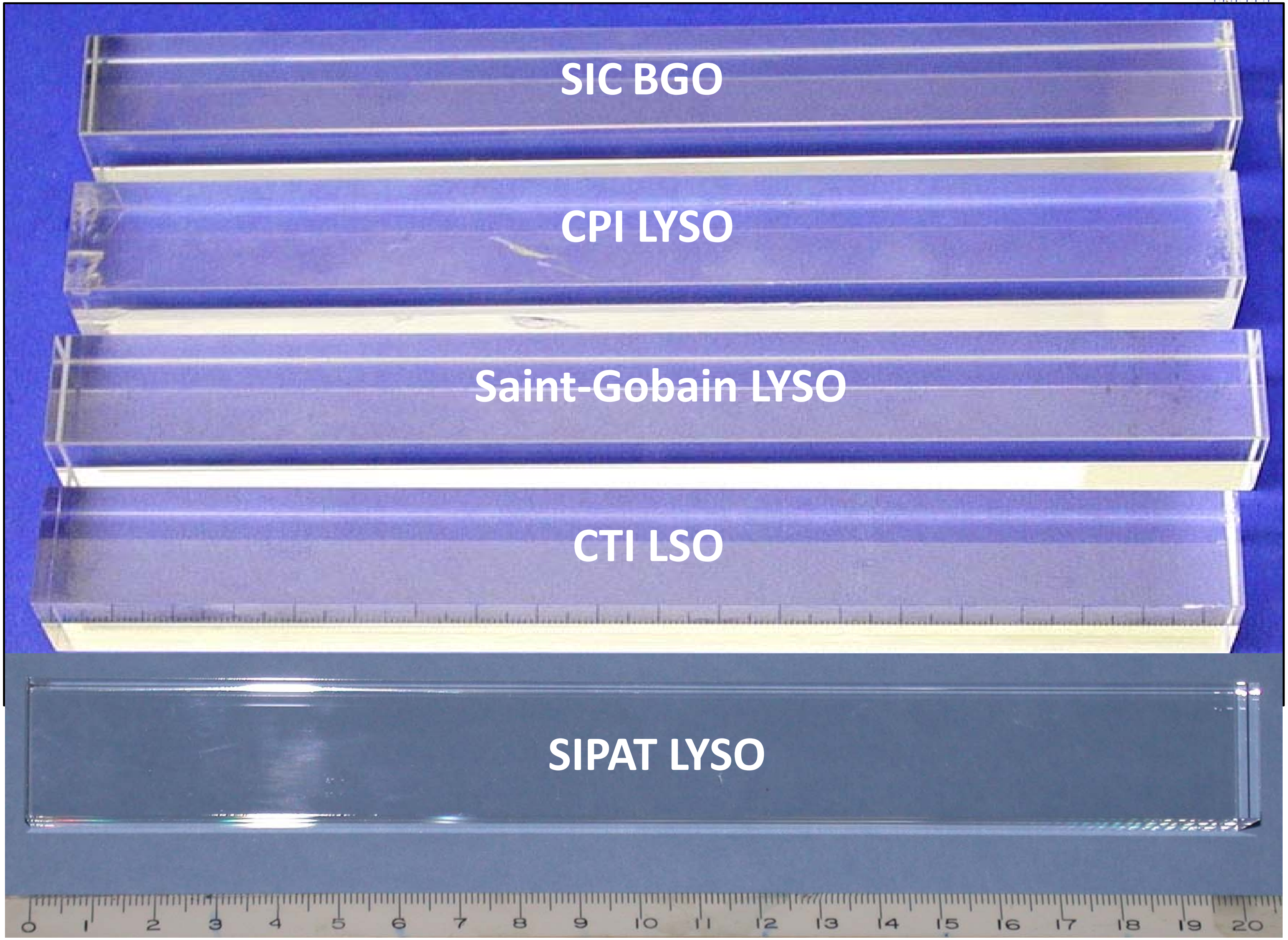


Aiming at 10^{36}/cm^2/s luminosity for rare B decays

Need fast detector with low noise at the endcap

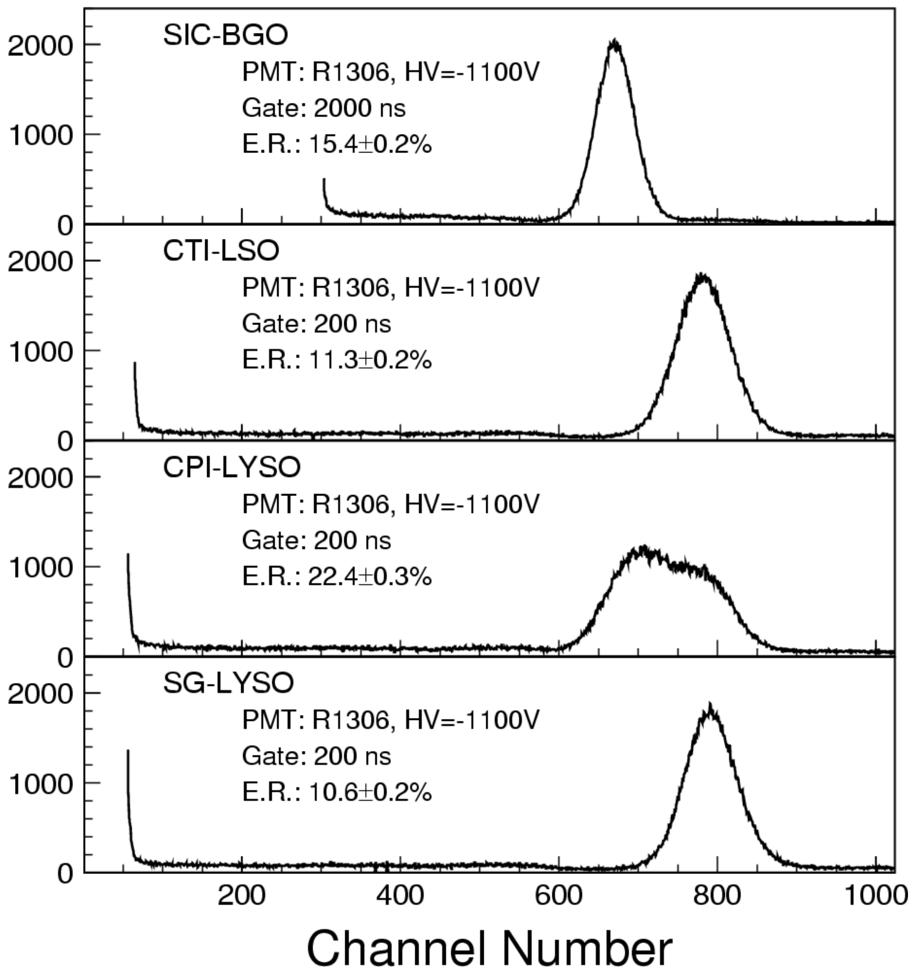
LYSO

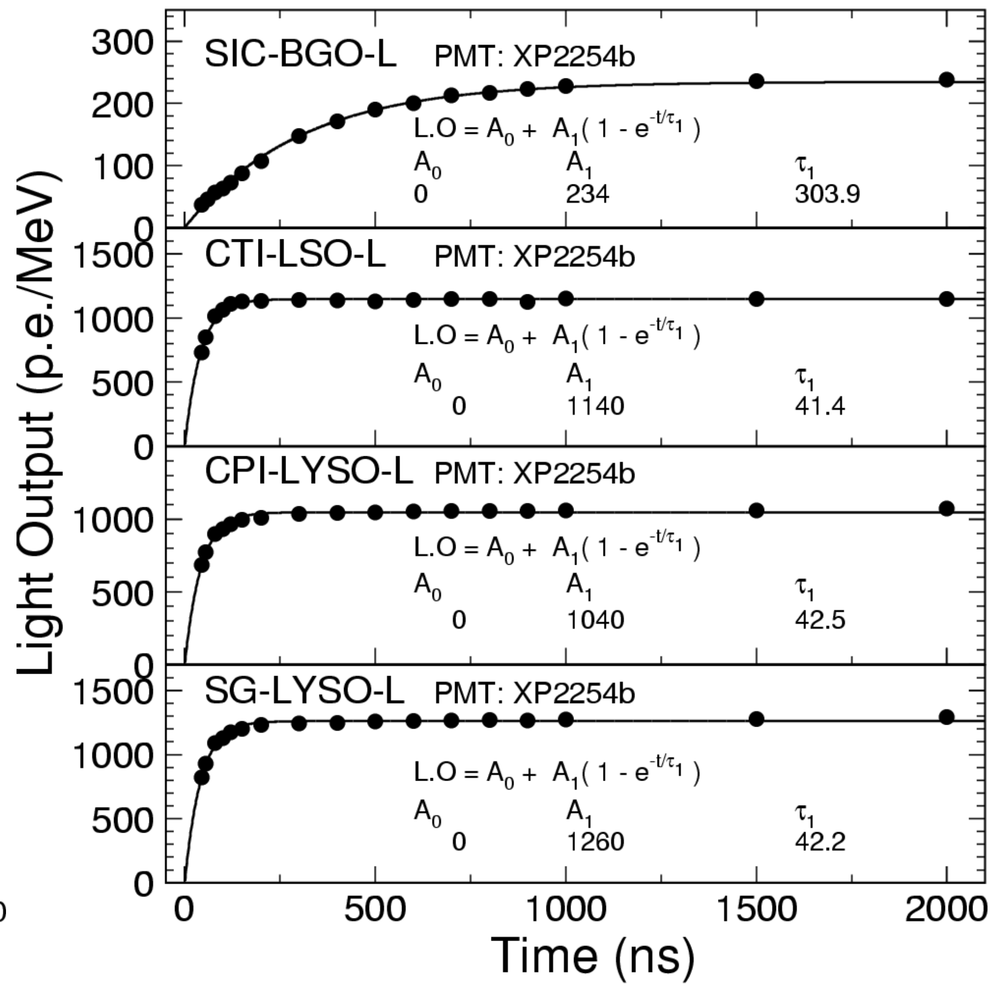
2.5 x 2.5 x 20 cm (18 X_0) Samples



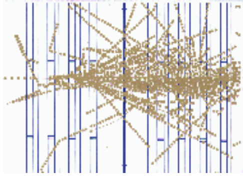
LSO/LYSO with PMT Readout

≈10% FWHM resolution for ^{22}Na source (0.51 MeV)
1,200 p.e./MeV, 5/230 times of BGO/PWO

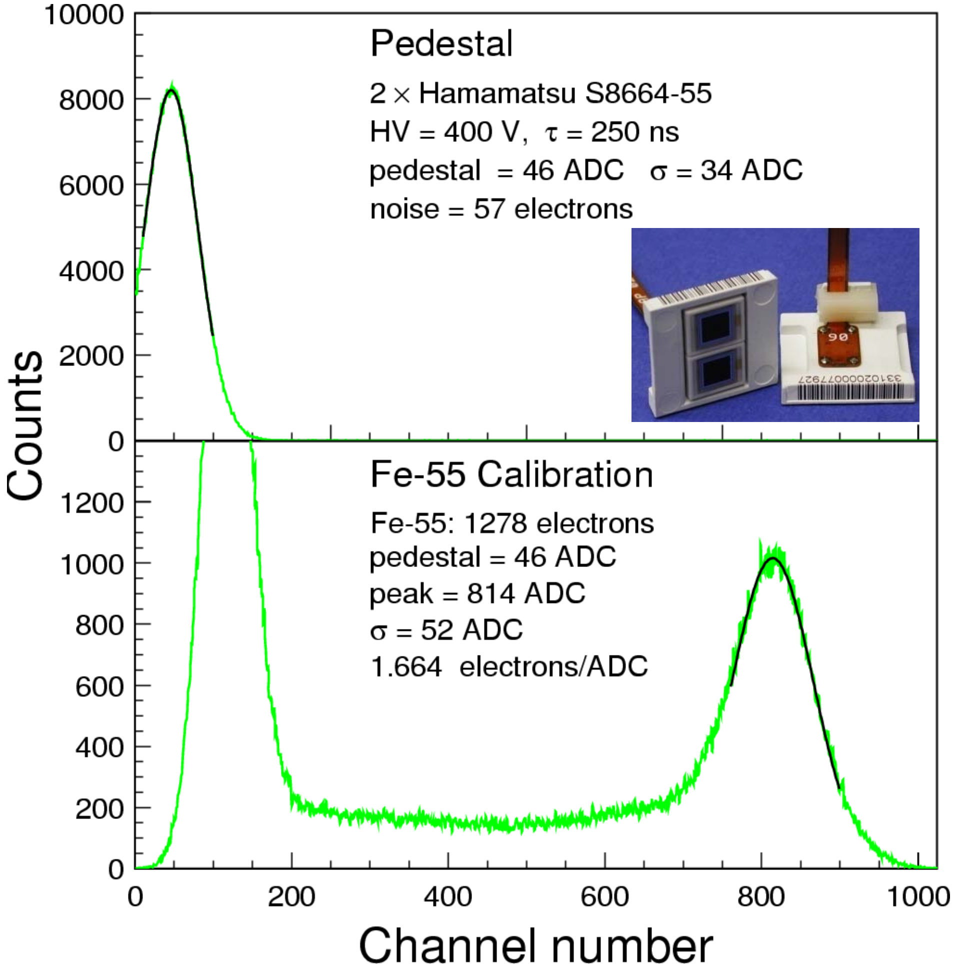


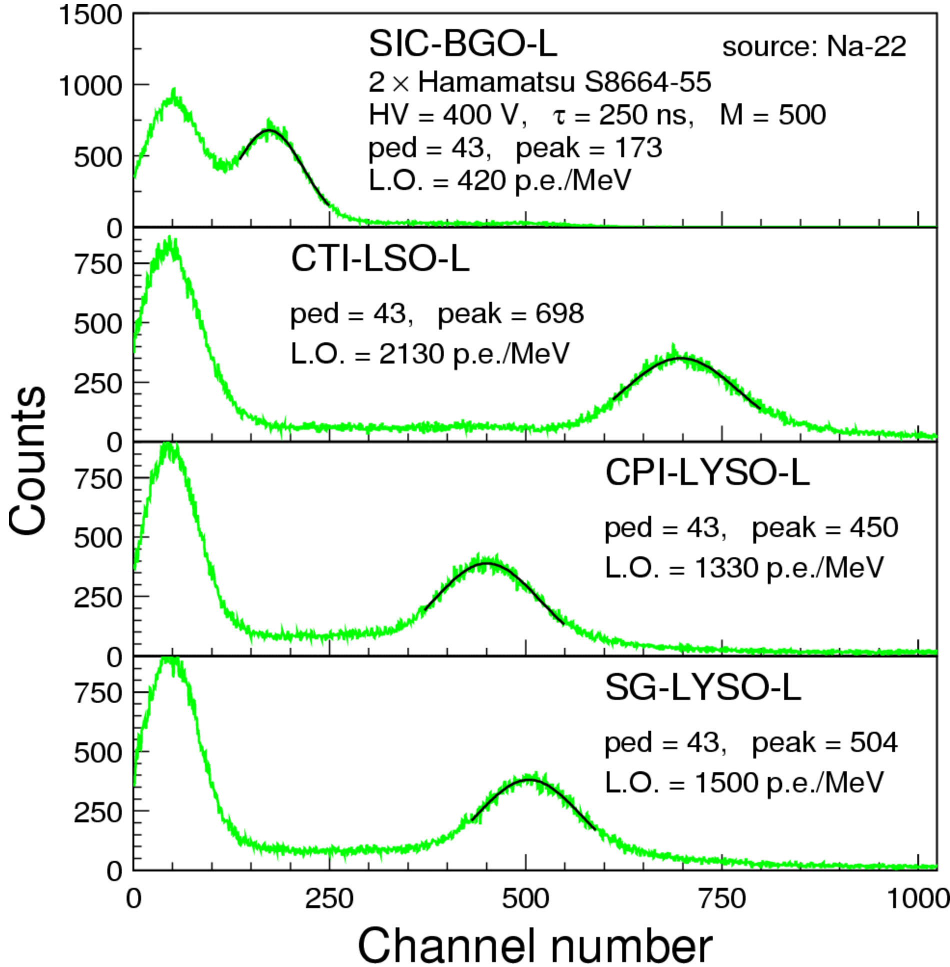


LSO/LYSO with APD Readout



L.O.: 1,500 p.e./MeV, 4/200 times of BGO/PWO
Readout Noise: < 40 keV

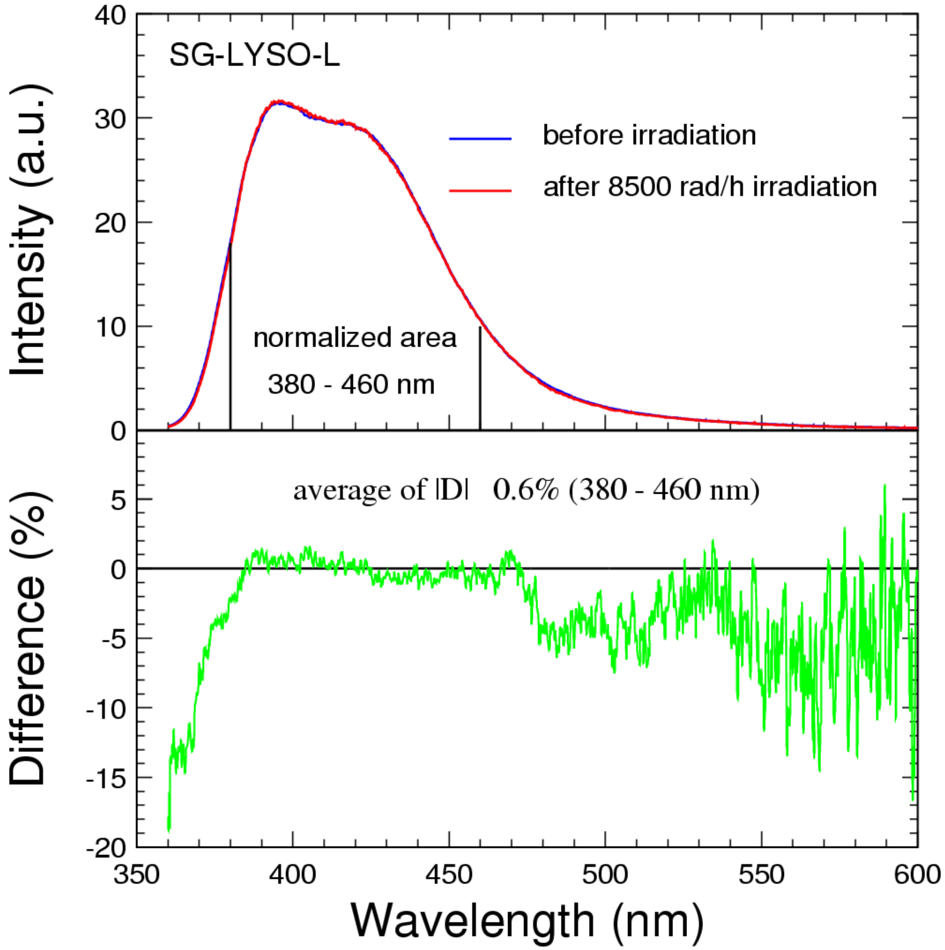


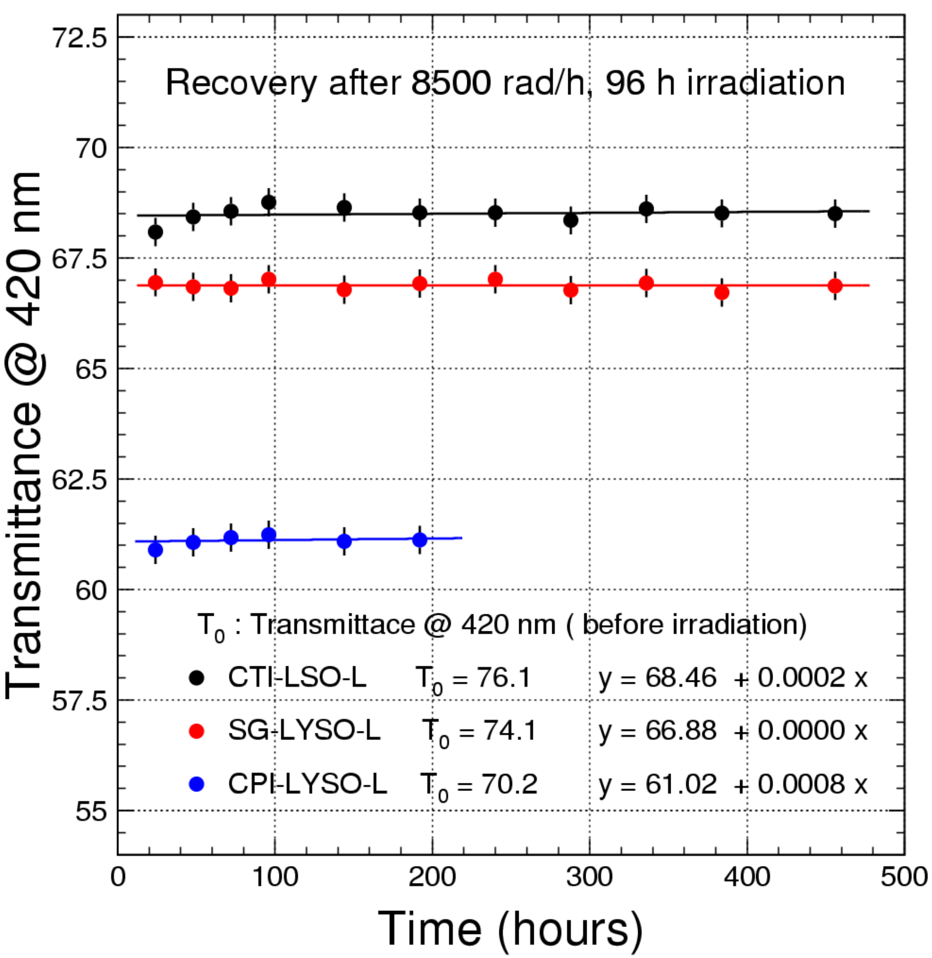


γ-Ray Induced Damage

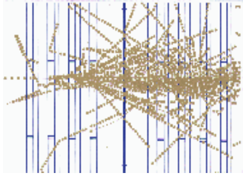
No damage in Photo-Luminescence

Transmittance recovery slow





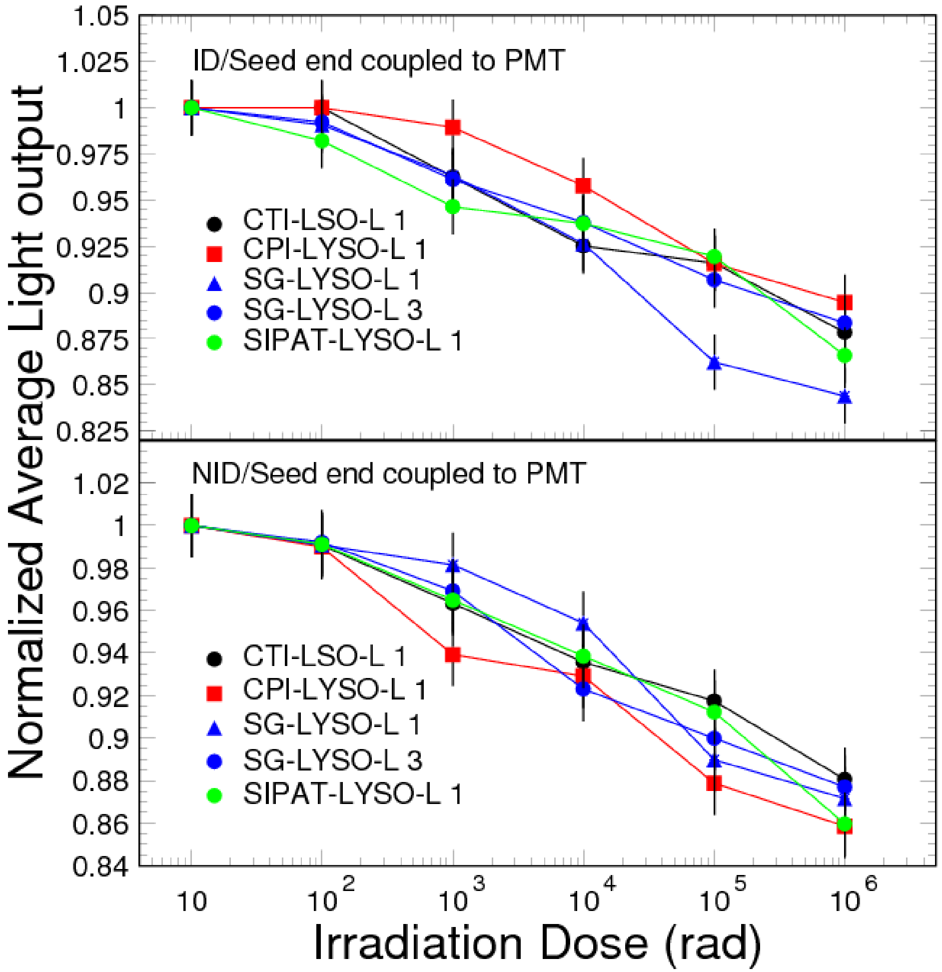
γ-Ray Induced L.O. Damage

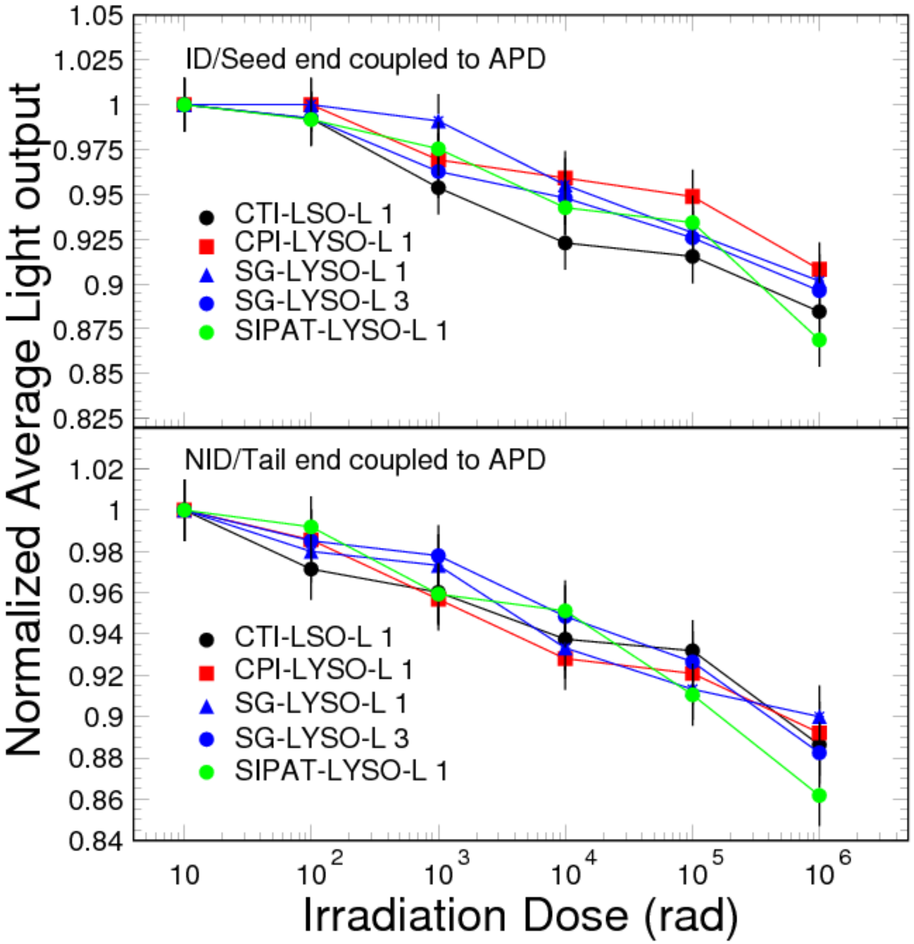


All samples show consistent radiation resistance

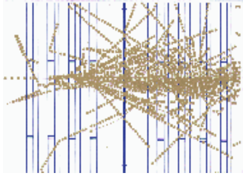
10% - 15% loss @ 1 Mrad by PMT

9% - 14% loss @ 1 Mrad by APD





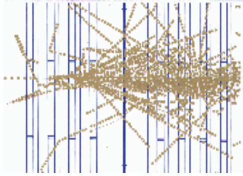
LSO/LYSO ECAL Performance

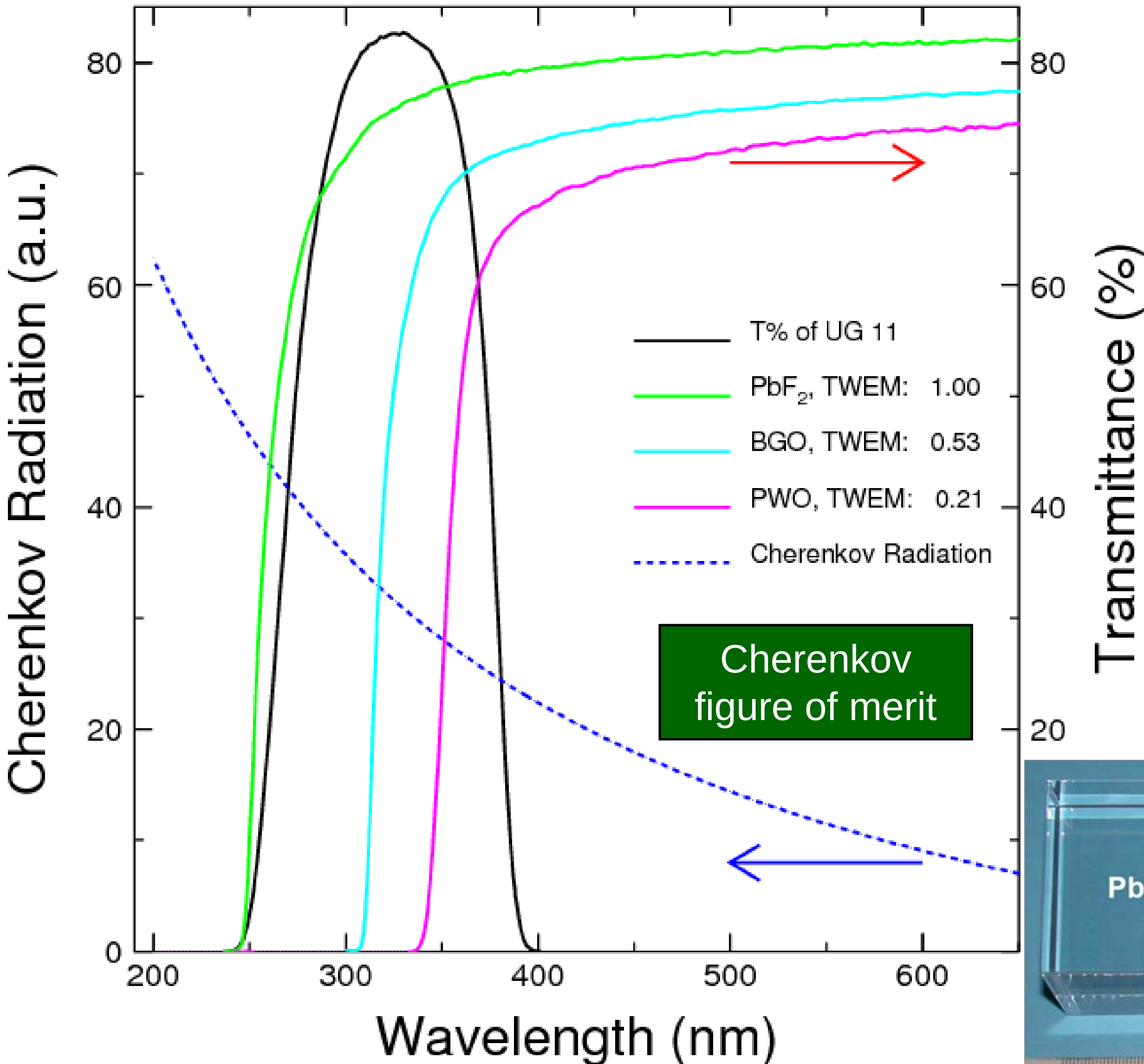


- Less demanding to the environment because of small temperature coefficient.
- Radiation damage is less an issue as compared to other crystals.
- A better energy resolution, $\sigma(E)/E$, at low energies than L3 BGO and CMS PWO because of its high light output and low readout noise:

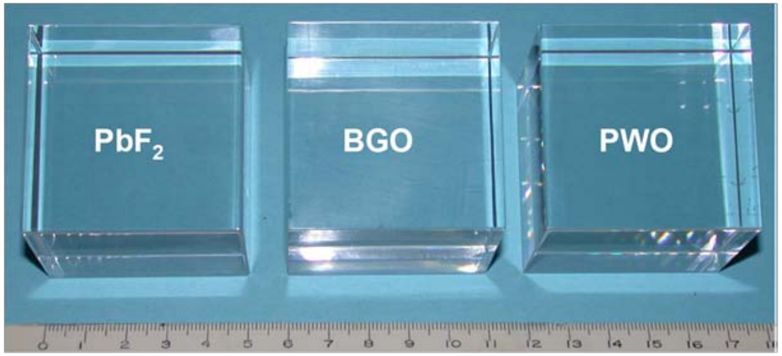
$$2.0\%/\sqrt{E} \oplus 0.5\% \oplus .001/E$$

Homogeneous HCAL

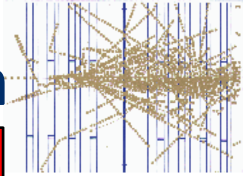




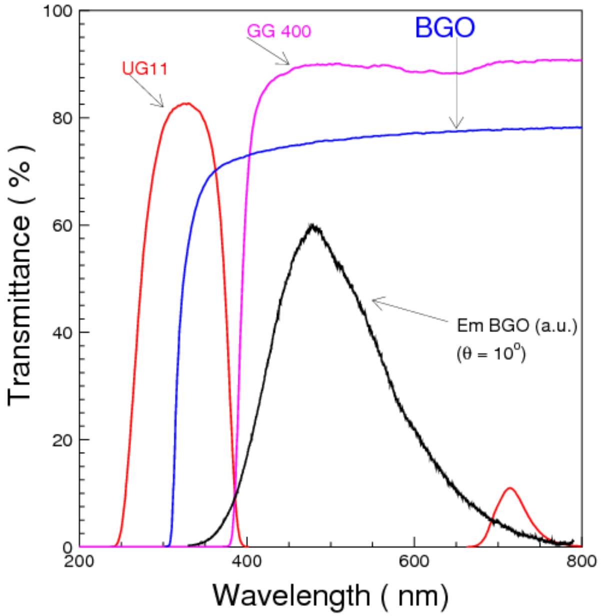
Measure both Cherenkov and scintillation light independently to achieve the best hadronic energy resolution by compensation.

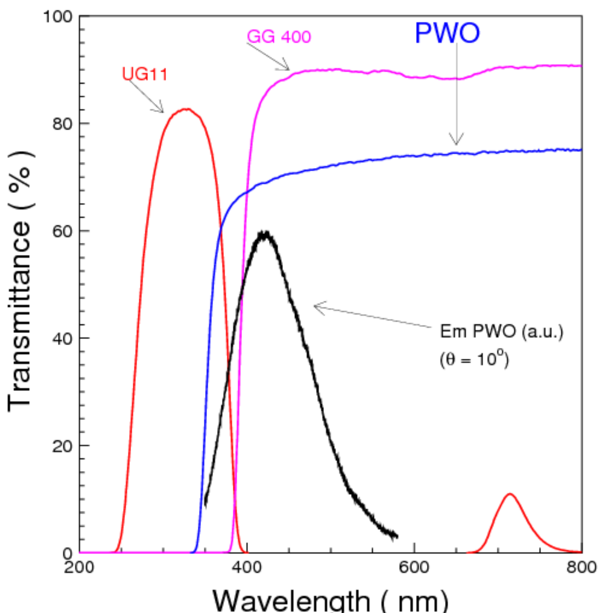


Spectral Separation of Cherenkov & Scintillation



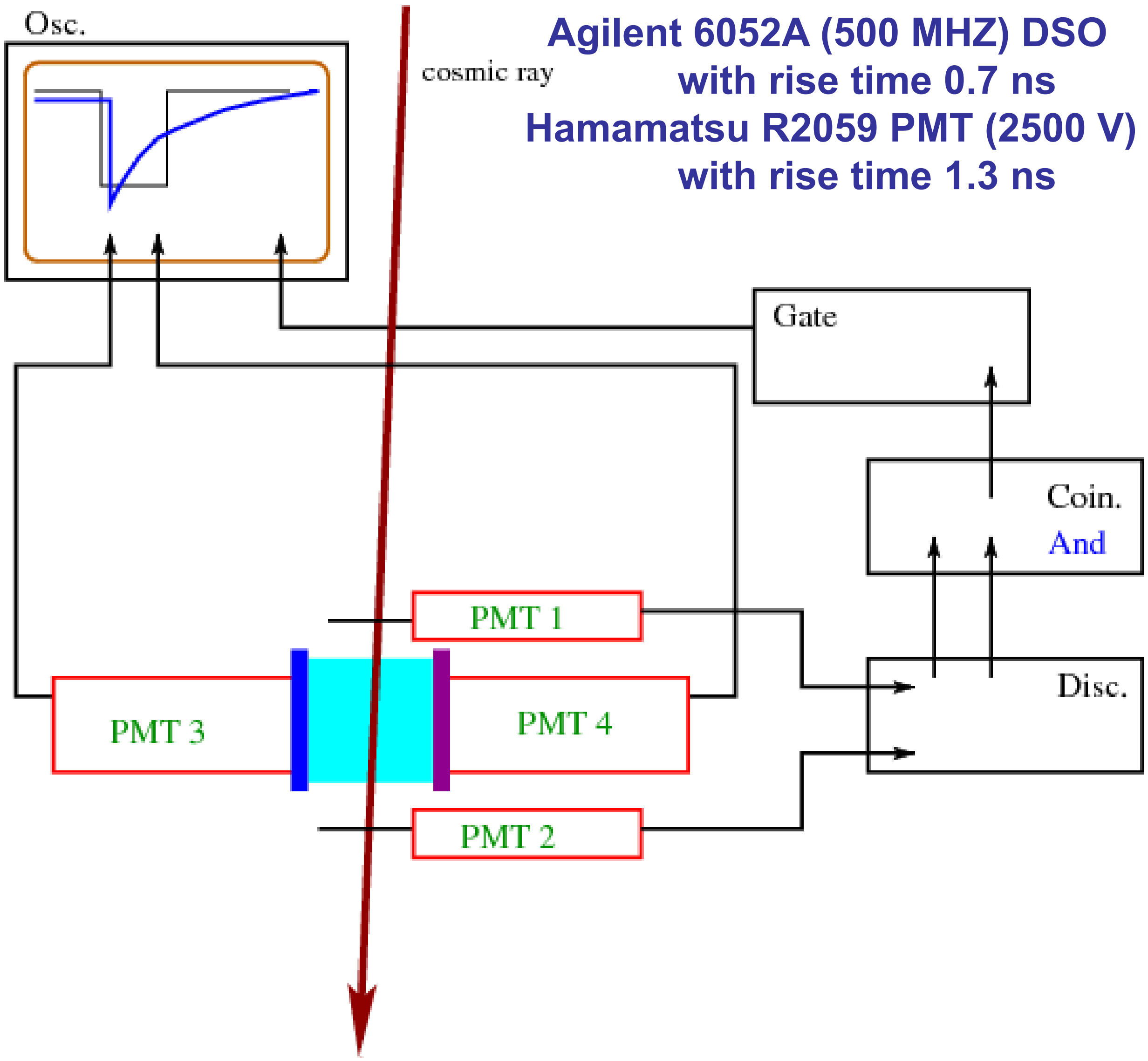
Filters UG11 and GG 400 are effective



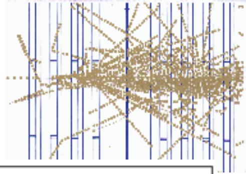


Agilent 6052A (500 MHZ) DSO with rise time 0.7 ns

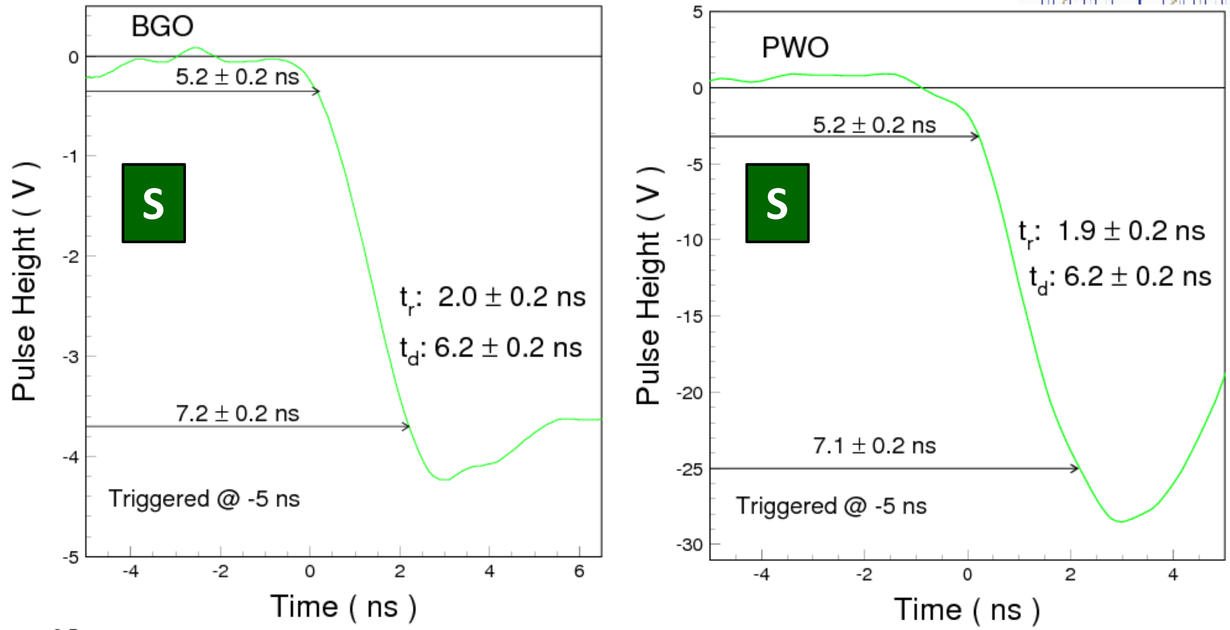
Hamamatsu R2059 PMT (2500 V) with rise time 1.3 ns

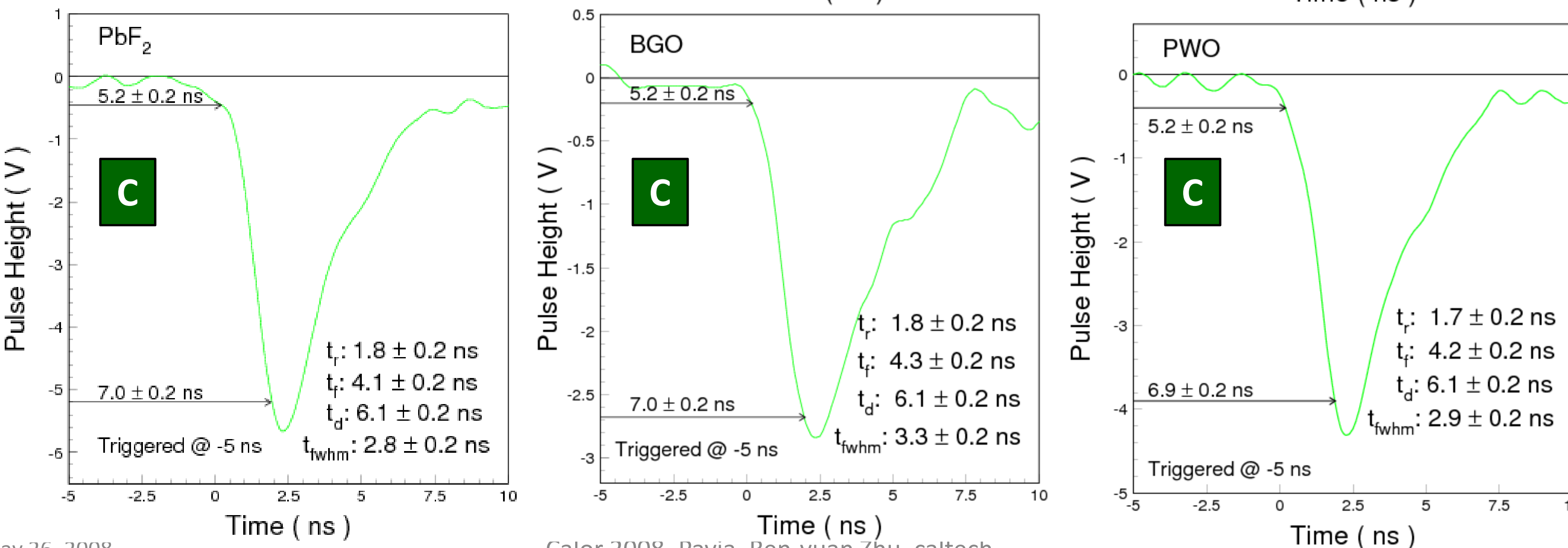


Pulse Shape Separation?



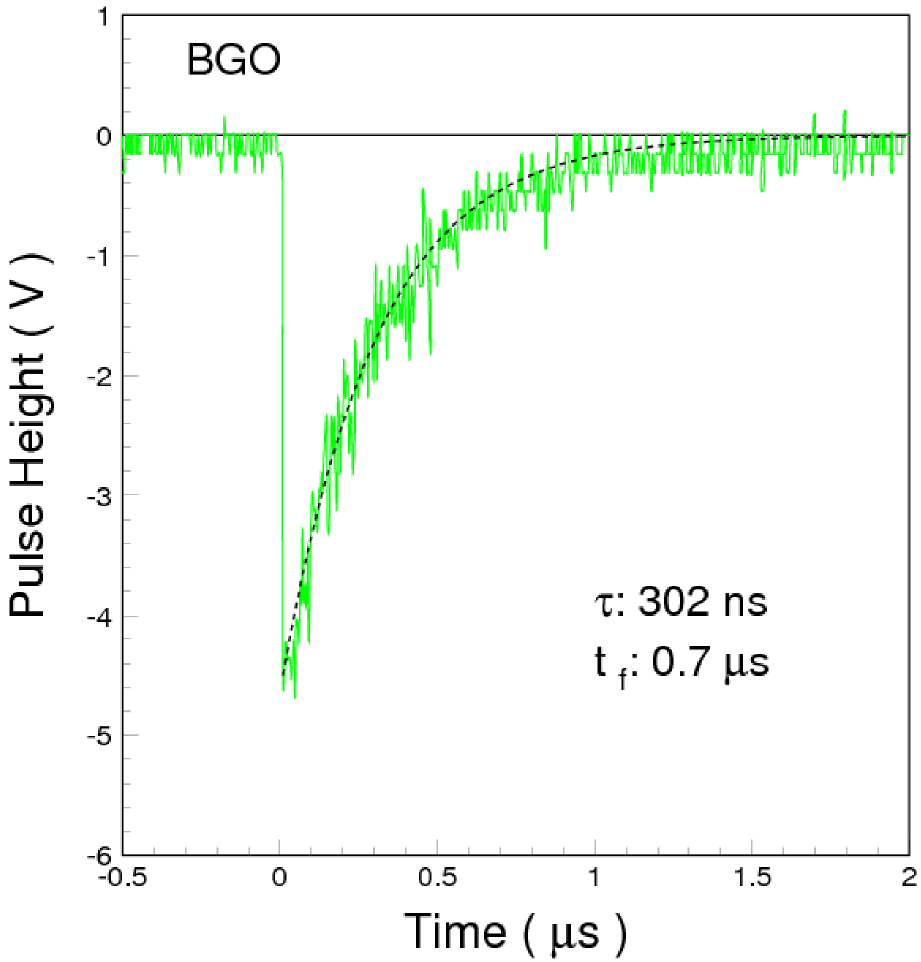
Consistent timing and rise time for all Cherenkov and scintillation light pulses.

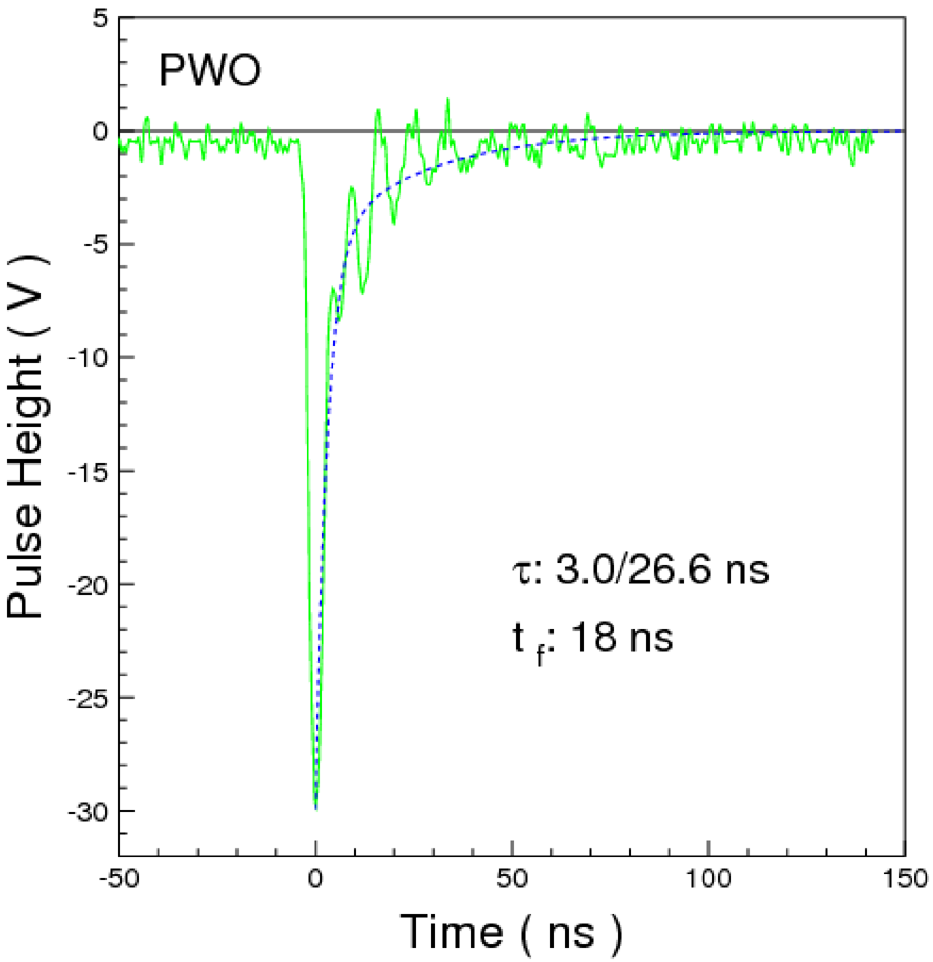




Pulse Shape Separation

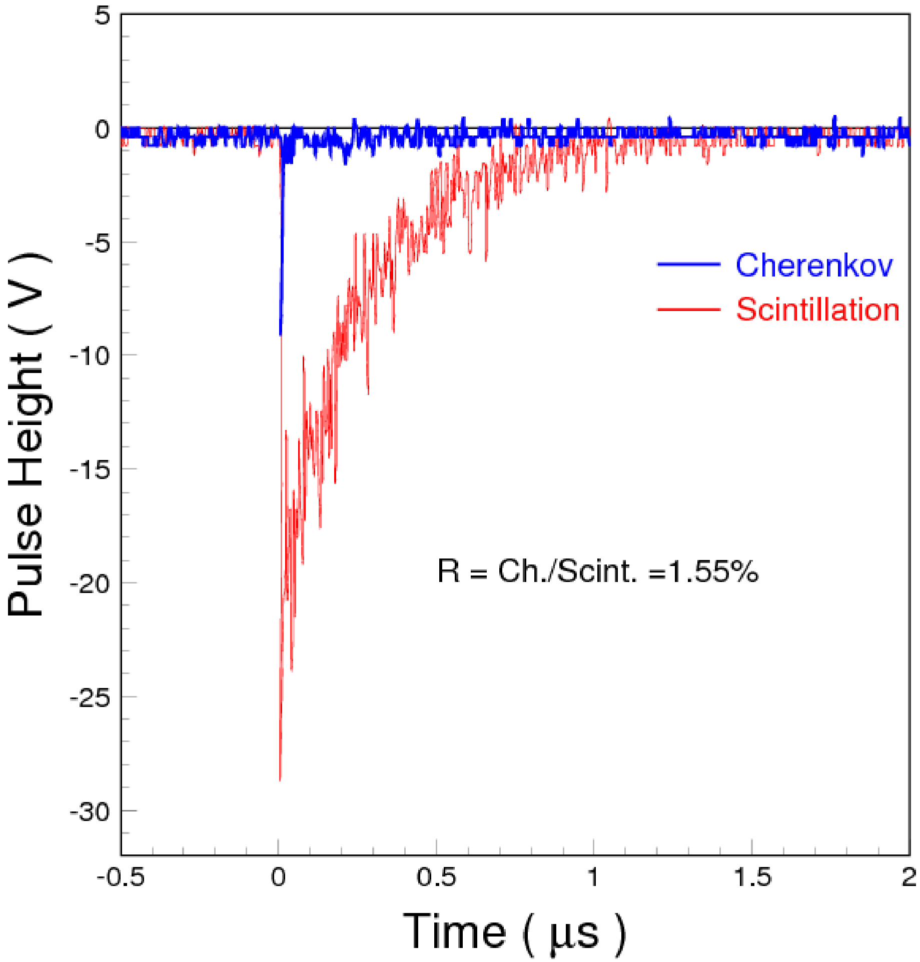
The slow scintillation decay may be useful

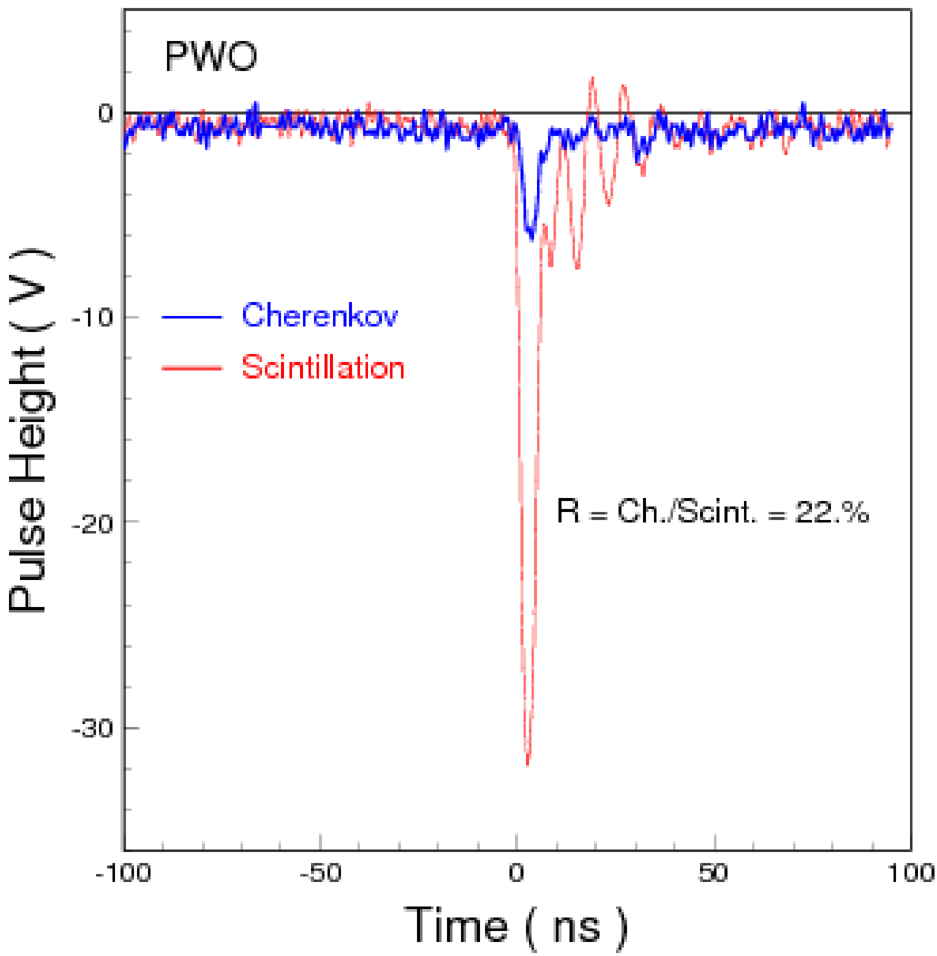




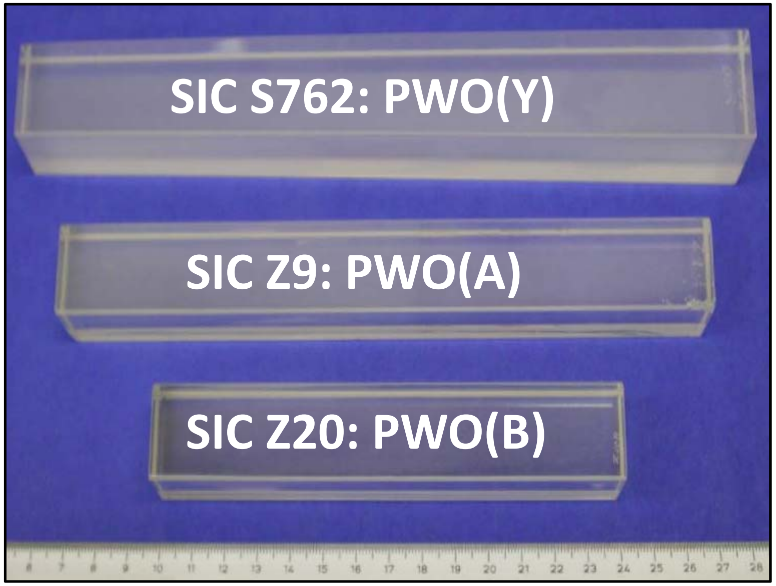
Ratio of Cherenkov/Scintillation

1.6% for BGO and 22% for PWO with UG11/GG400 filter and R2059 PMT



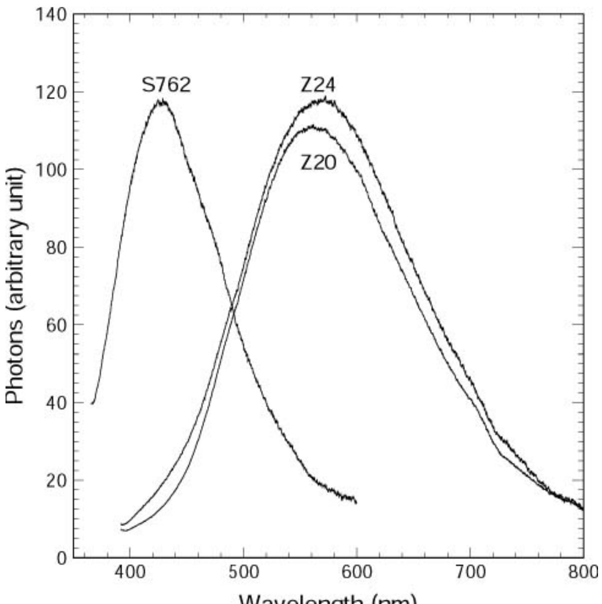


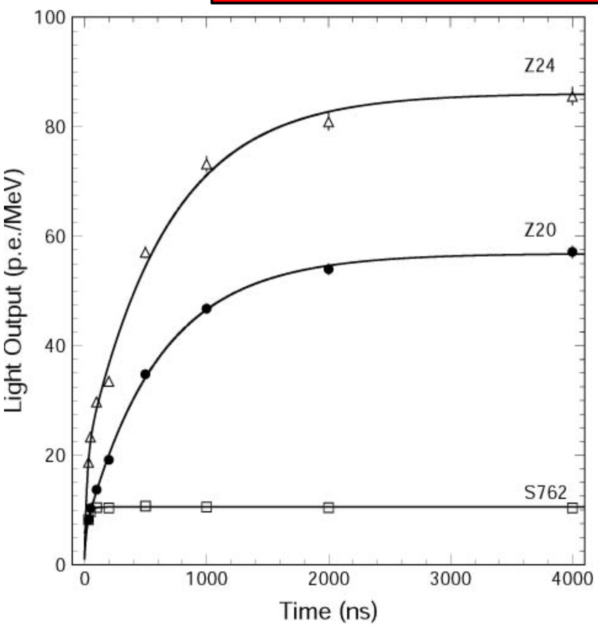
Green Slow Scintillation in PWO

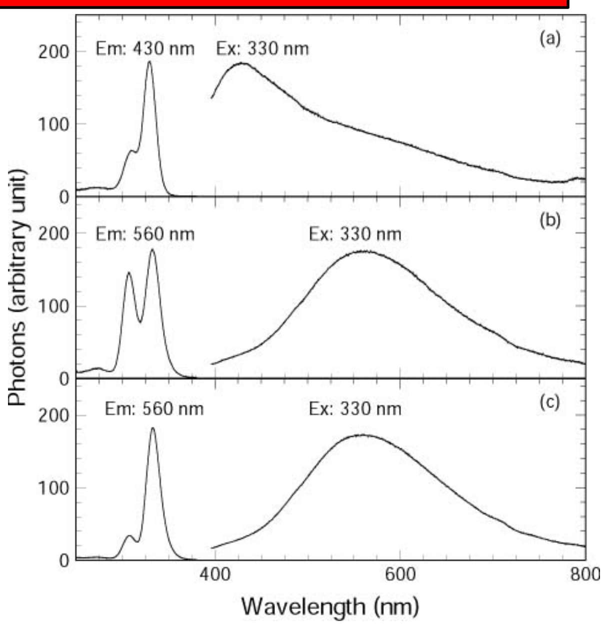


A factor of ten intensity of slow green scintillation (560 nm) was observed by selective doping in PWO: useful for dual readout

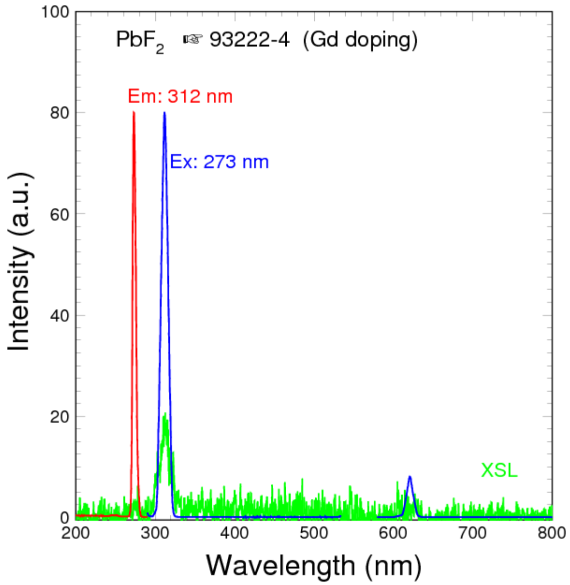
R.H. Mao at al., in Calor2000 proceedings

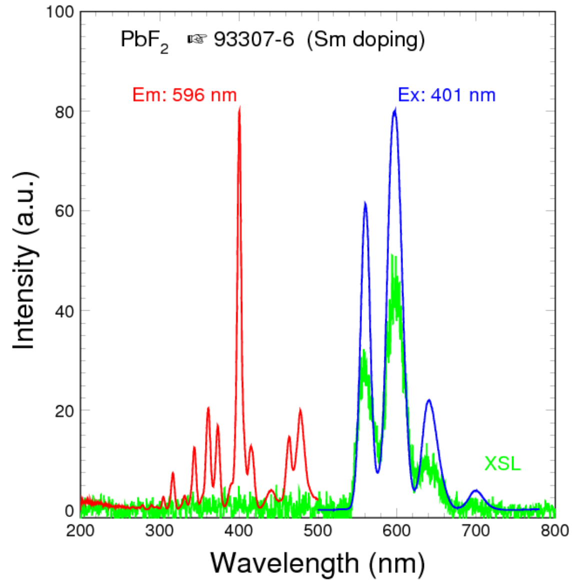


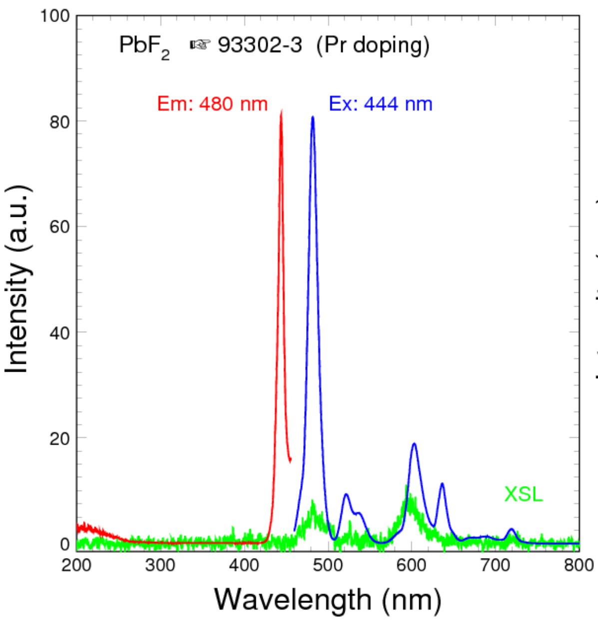


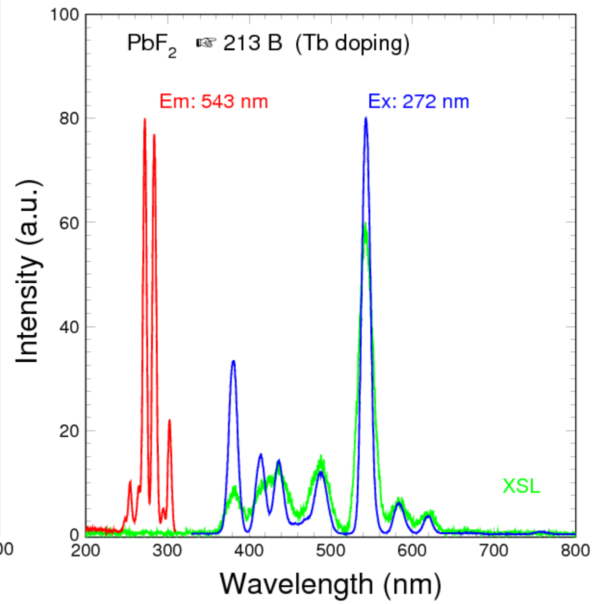


Scintillation Observed in PbF_2





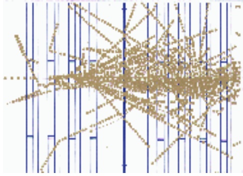




Some rear earth doping seems introducing scintillation, but not at the level can be measured by source.

Investigation is continuing aiming at developing cost effective crystals for dual readout.

Summary



- Precision crystal calorimetry provides the best possible energy and position resolutions for electrons and photons as well as good e/γ identification and reconstruction efficiencies.
- An LSO/LYSO crystal calorimeter provides excellent energy resolution over a large dynamic range down to MeV level for future HEP and NP experiments.
- Because of the expected huge volume needed development of cost-effective UV transparent material, such as doped PbF_2, is crucial for the homogeneous HCAL concept.