New Crystal Development for Project X Calorimetry

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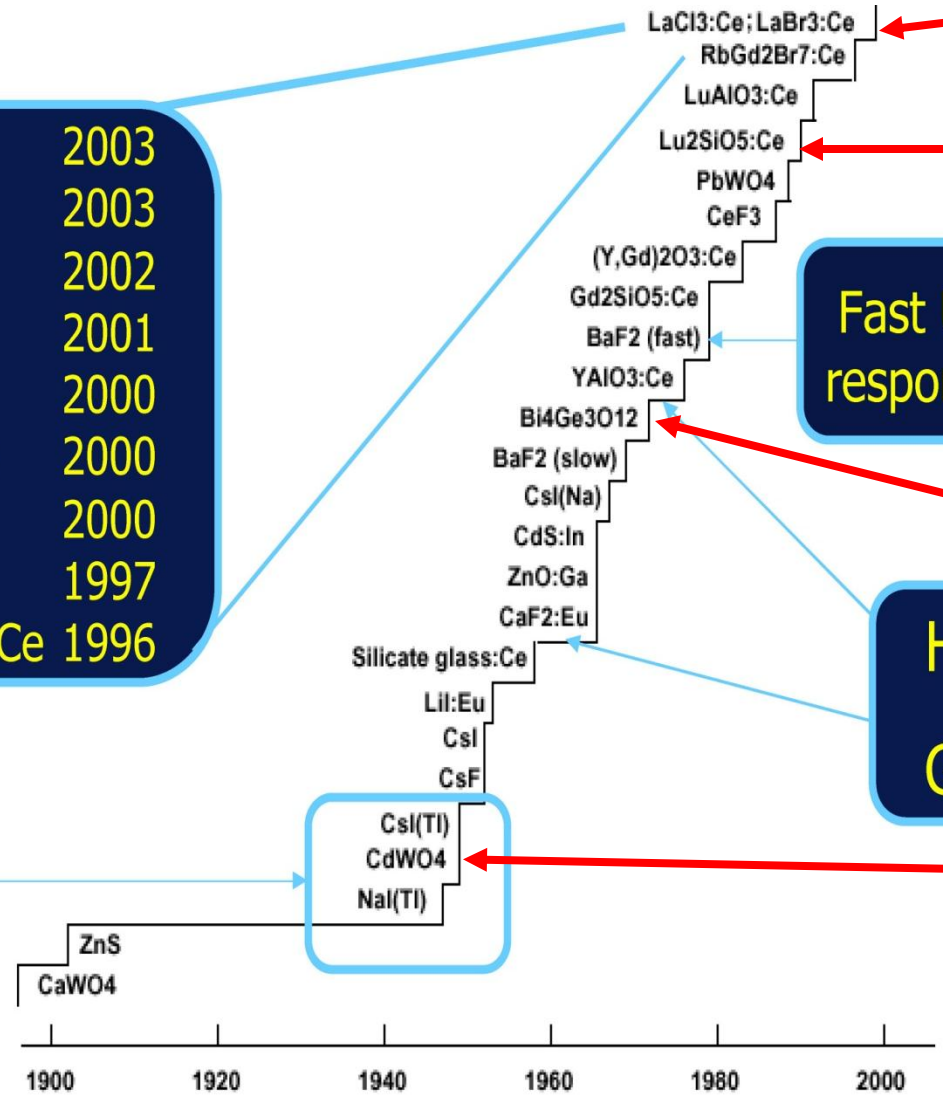
Why Crystal Calorimeter?

- **Photons and electrons are fundamental particles. Precision e/γ measurements enhance physics discovery potential.**
- **Performance of homogeneous crystal calorimeter in e/γ measurements is well understood:**
  - **The best possible energy resolution;**
  - **Good position resolution;**
  - **Good e/ γ identification and reconstruction efficiency.**
- **Requirements for project X calorimetry:**
  - **Very fast: for good time resolution and high rate;**
  - **Very blight: relatively low energy;**
  - **High density: for position resolution;**
  - **Good radiation hardness.**

History of Scintillating Crystals

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

Cs_2LiYCl_6:Ce	2003
LuI_3:Ce	2003
K_2LaI_5:Ce	2002
$LaBr_3$:Ce	2001
$LaCl_3$:C	2000
Lu_2O_3:Eu, Tb	2000
$Lu_2Si_2O_7$:Ce	2000
$RbGd_2Br_7$:Ce	1997
$^6Li_6Gd(BO_3)_3$:Ce	1996



21 Century: $LaBr_3$

Nineties: PWO, LSO

Fast UV response

Trigger

Seventies: BGO

HPGe

Ge:Li

Fifties: NaI and CsI

Invention of the photomultiplier tube

Crystals for HEP Calorimeters

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (ºC)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	420 310	300 220	480	402	425 420	?
Decay Time [b] (ns)	245	1220	30 6	650 0.9	300	40	30 10	?
Light Yield [b,c] (%)	100	165	3.6 1.1	36 4.1	21	85	0.3 0.1	?
d(LY)/dT [b] (%/ ºC)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	?
Experiment	Crystal Ball	BaBar BELLE BES III	KTeV	(L*) (GEM) TAPS	L3 BELLE	Mu2e SuperB HL-LHC?	CMS ALICE PANDA	HHCAL?

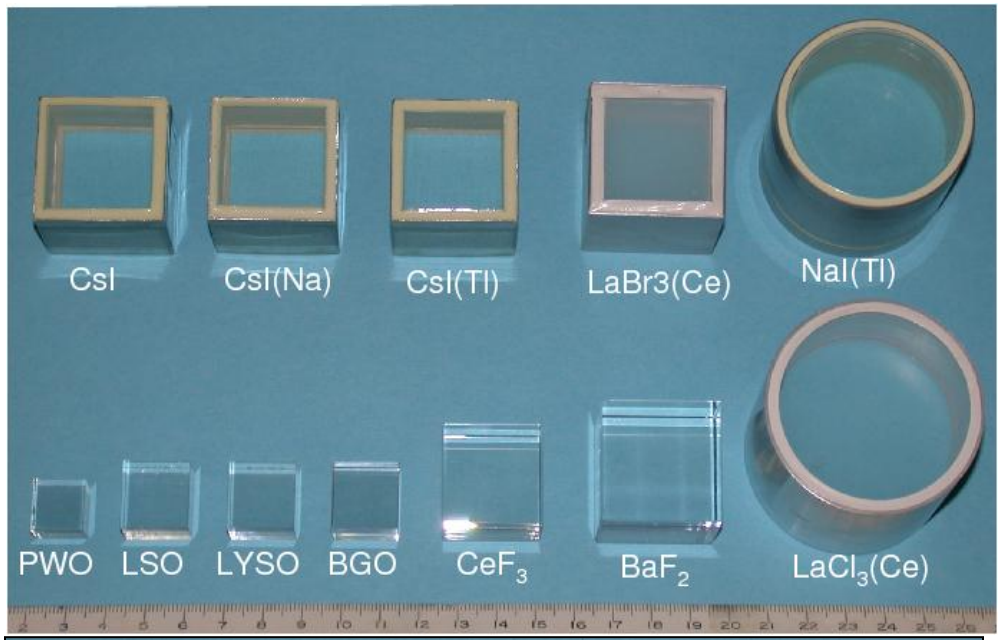
a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

Crystals for Homeland Security

Crystal	NaI(Tl)	CsI(Tl)	CsI(Na)	$LaCl_3$(Ce)	SrI_2 (Eu)	$LaBr_3$(Ce)	$CeBr_3$
Density (g/cm^3)	3.67	4.51	4.51	3.86	4.59	5.29	5.10
Melting Point (ºC)	651	621	621	859	538	788	722
Radiation Length (cm)	2.59	1.86	1.86	2.81	1.95	1.88	1.96
Molière Radius (cm)	4.13	3.57	3.57	3.71	3.40	2.85	2.97
Interaction Length (cm)	42.9	39.3	39.3	37.6	37.0	30.4	31.5
Refractive Index [a]	1.85	1.79	1.95	1.9	?	1.9	2.3
Hygroscopicity	Yes	Slight	Slight	Yes	Yes	Yes	Yes
Luminescence [b] (nm) (at peak)	410	550	420	335	435	356	371
Decay Time [b] (ns)	245	1220	690	570 24	1100	20	17
Light Yield [b,c] (%)	100	165	88	13 42	221	130	122
d(LY)/dT [b] (%/ ºC)	-0.2	0.4	0.4	0.1	?	0.2	-0.1

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

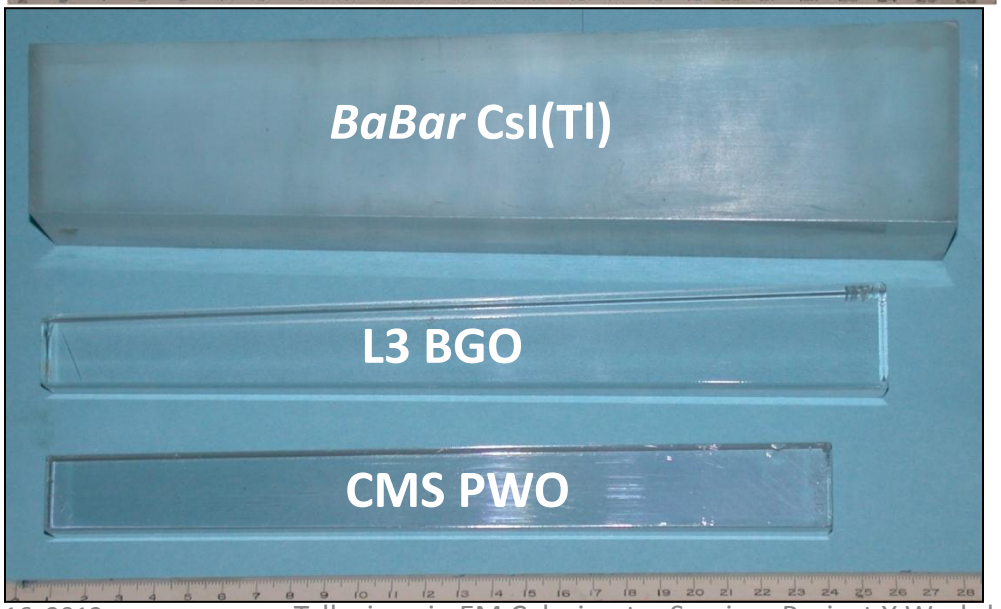
Crystals Measured at Caltech



1.5 X_0 Cubic Samples:

Hygroscopic: Sealed

Non-hygro: Polished



Full Size Crystals:

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

L3 BGO: 22 X_0

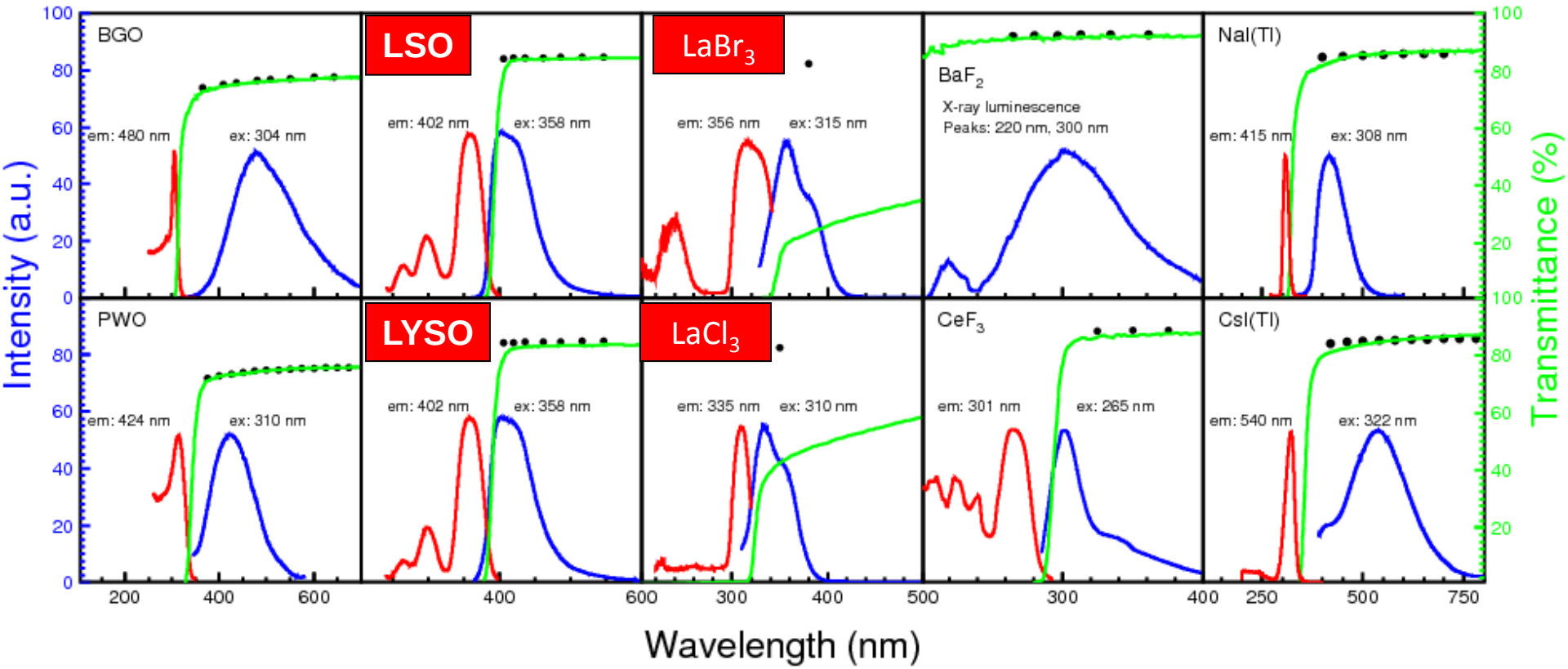
CMS PWO(Y): 25 X_0

Excitation, Emission, Transmission

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

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

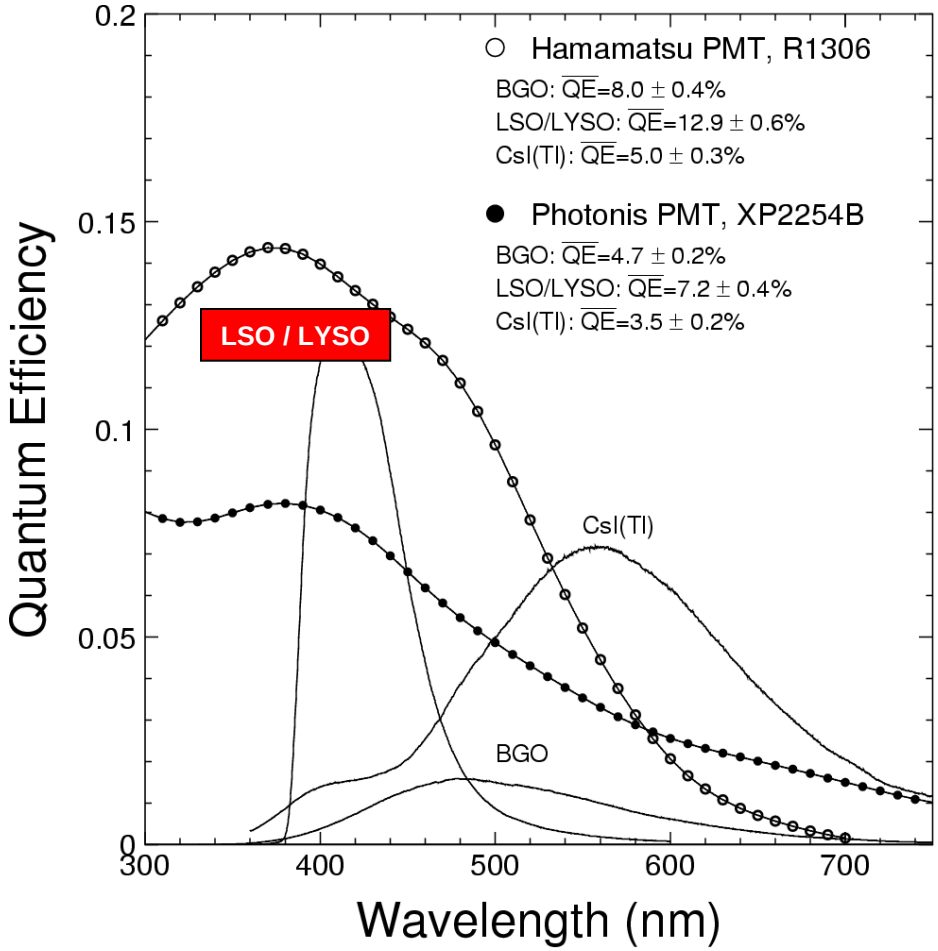
Black Dots: Theoretical limit of transmittance: NIM A333 (1993) 422

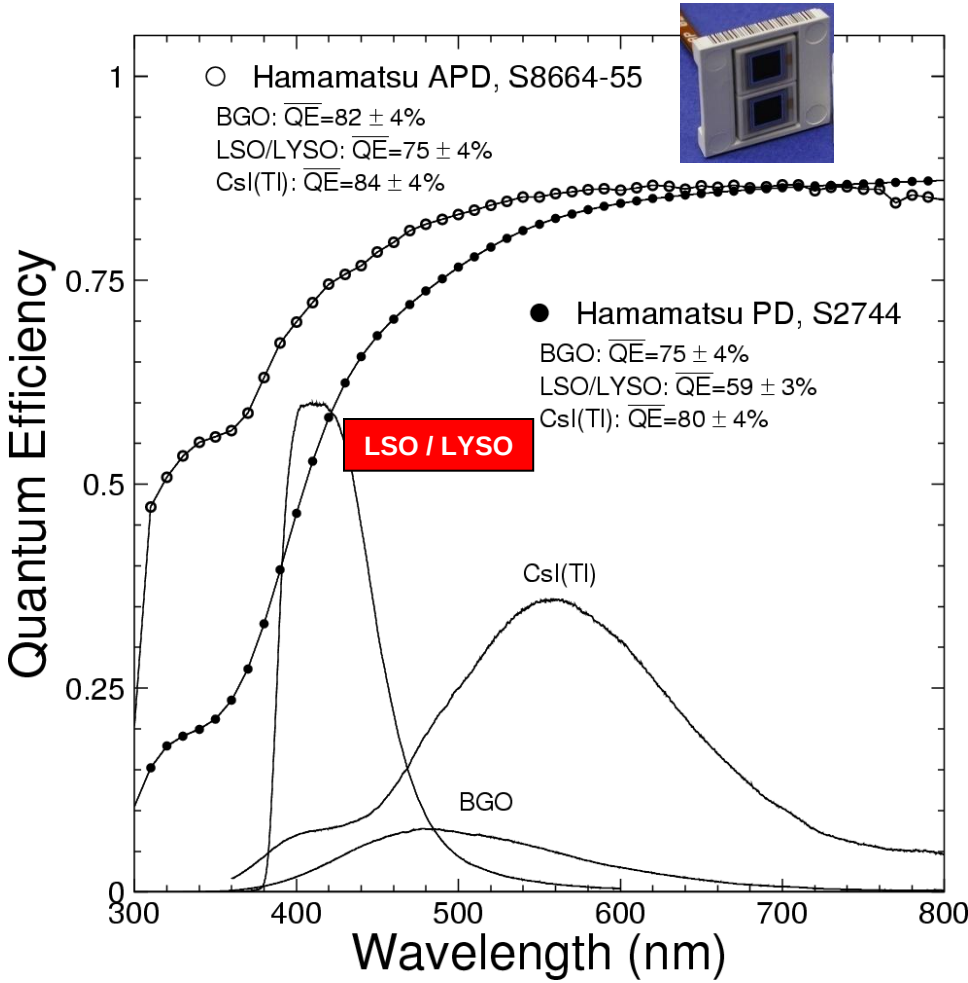


No Self-absorption: BGO, PWO, BaF_2, NaI(Tl) and CsI(Tl)

Emission Weighted QE

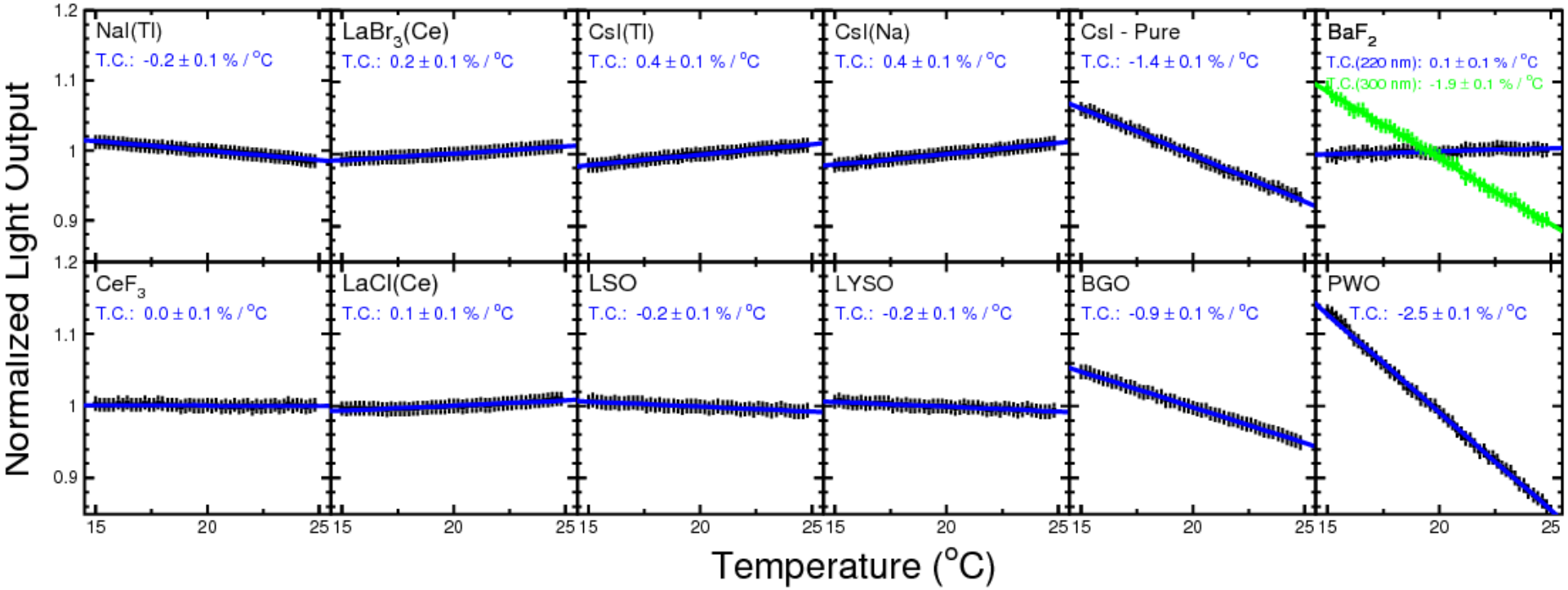
Taking out QE, L.O. of LSO/LYSO is 4/200 times BGO/PWO
Hamamatsu S8664-55 APD has QE 75% for LSO/LYSO





L.O. Temperature Coefficient

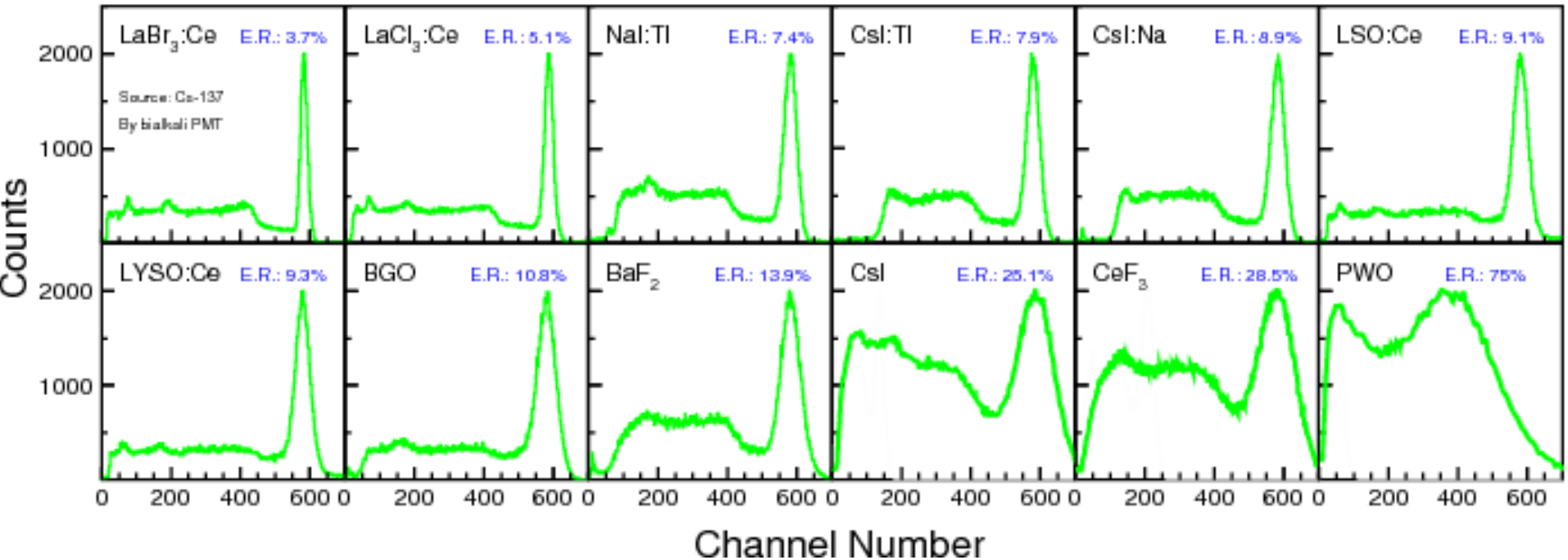
Temperature Range: 15 - 25ºC



Large temperature coefficient: CsI, BGO, BaF_2 and PWO

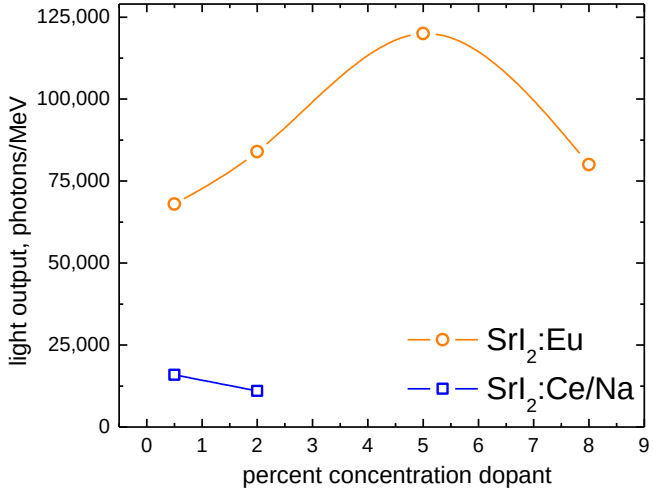
^{137}Cs FWHM Energy Resolution

3% to 80% measured with Hamamatsu R1306 PMT with bi-alkali cathode

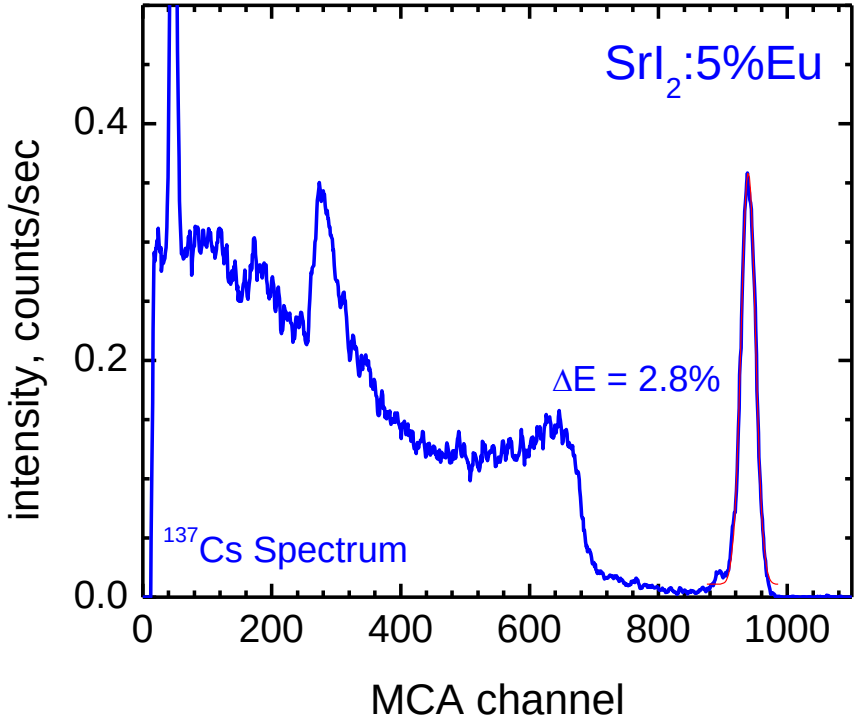


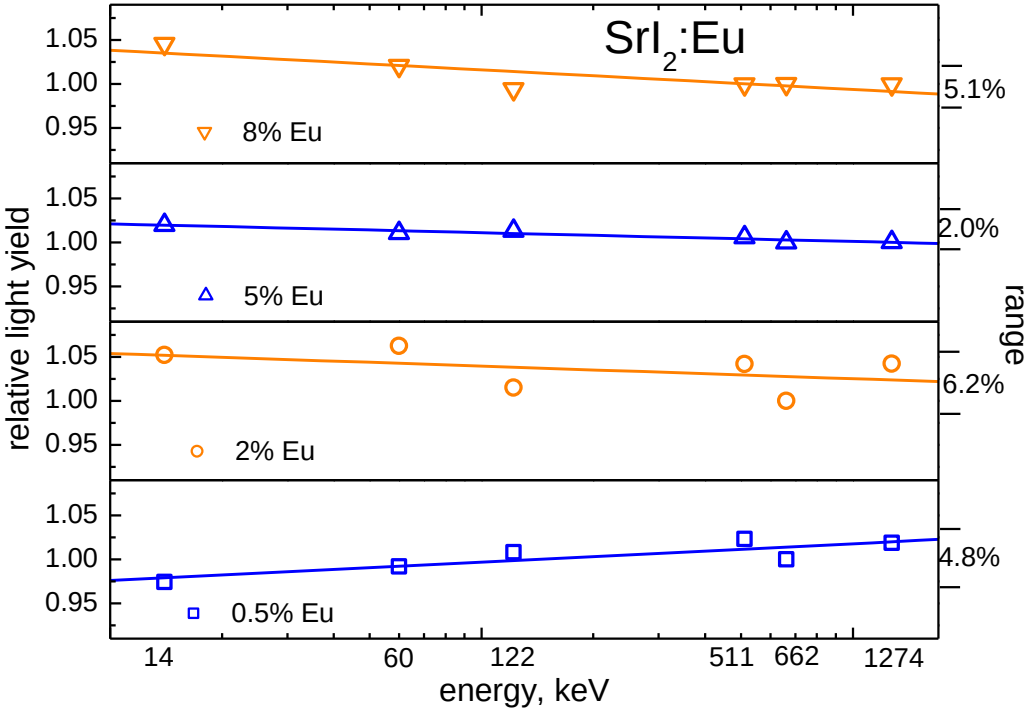
2% resolution and proportionality are important for γ–ray spectroscopy between 10 keV to 2 MeV

SrI_2(Eu) Development



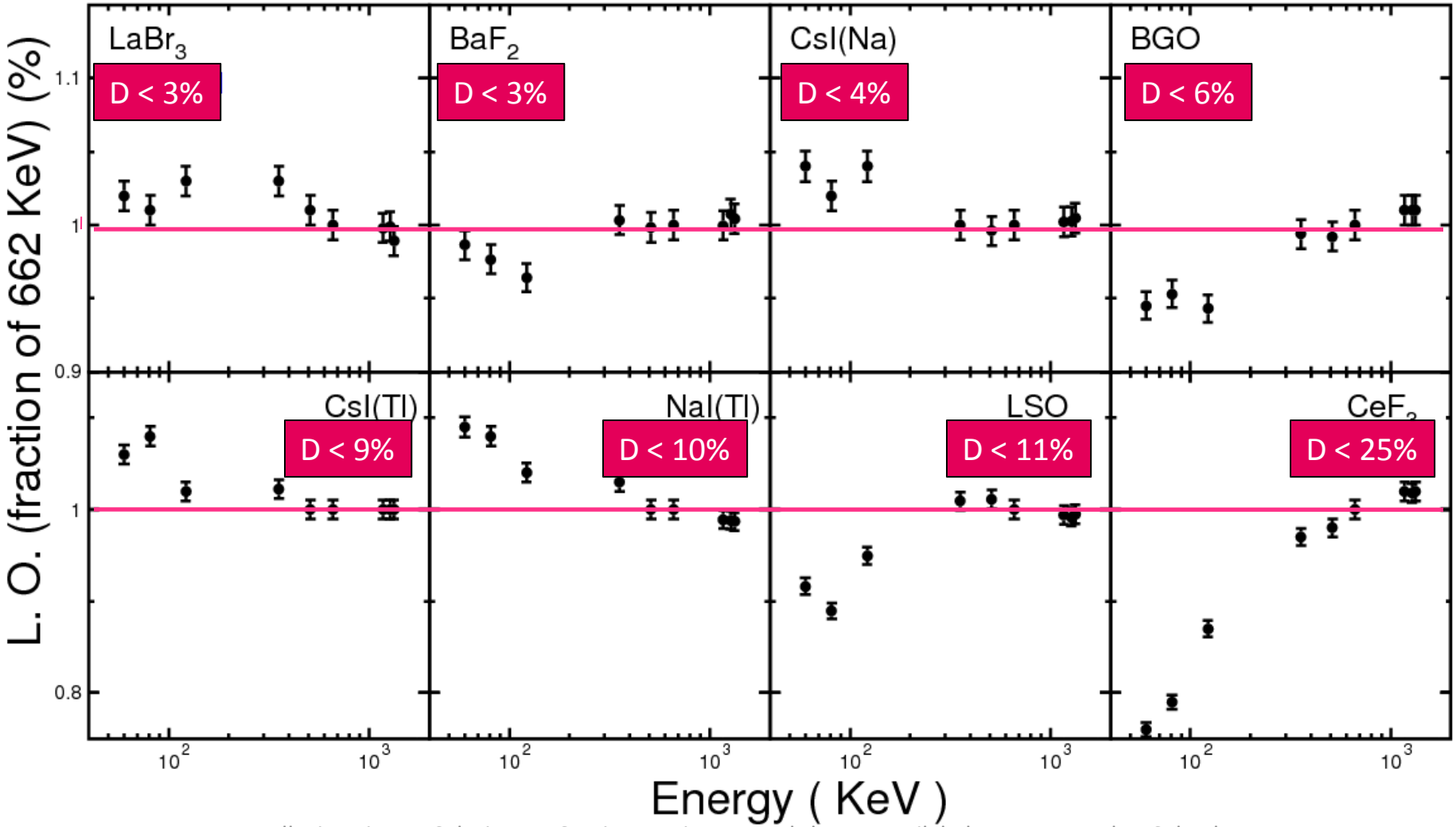
C. Wilson, RMD
ϕ10 X 24 mm ingot
Best Eu doping at 5%
Energy resolution (< 3%)
Linearity (~2%)
Patent (1968) expired





Low Energy Non Proportionality

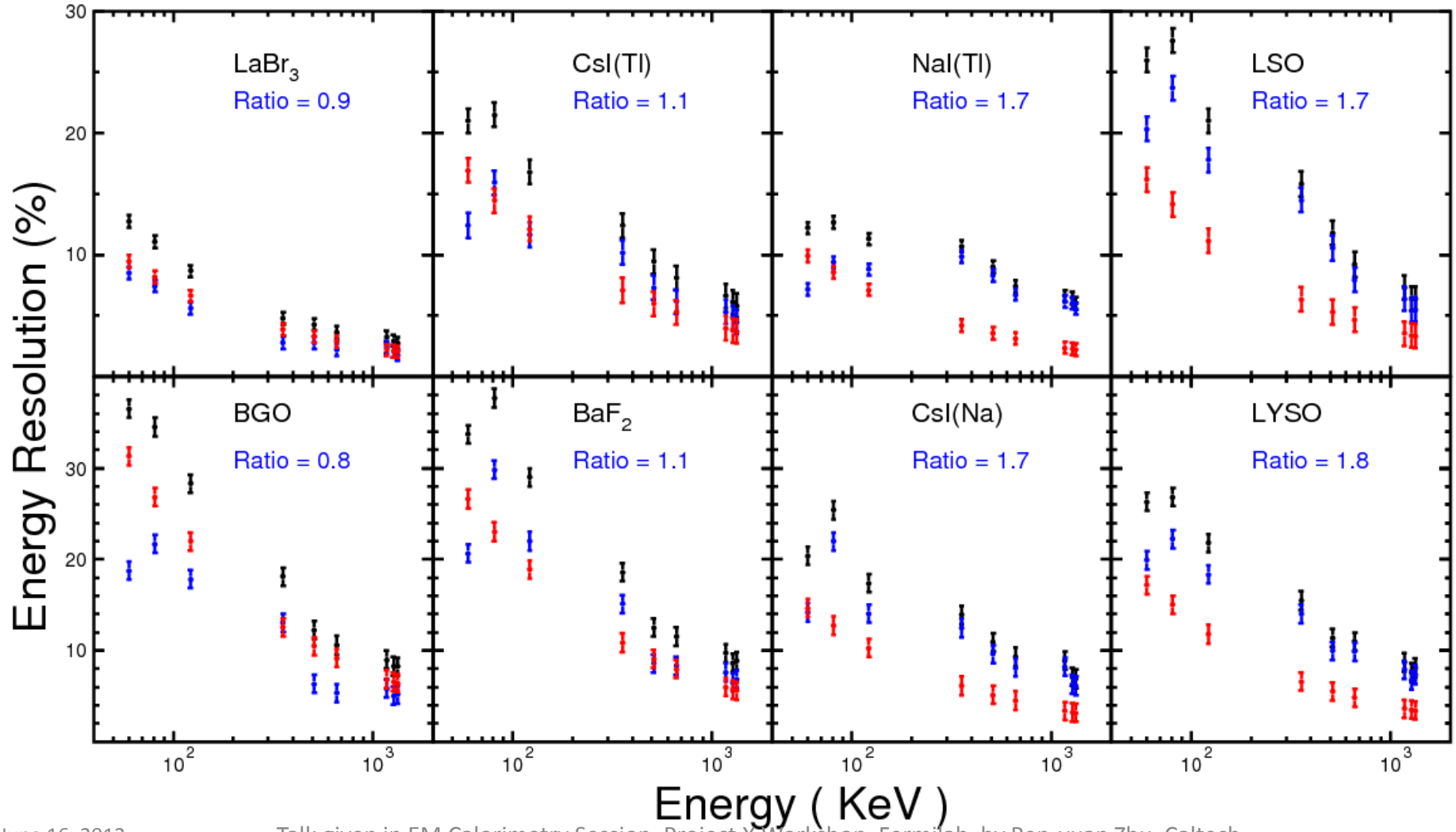
D: deviation from linearity: 60 keV to 1.3 MeV
Good Crystals: $LaBr_3$, BaF_2, CsI(Na) and BGO



Statistical & Intrinsic Resolutions

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

Good crystals: BGO and $LaBr_3$

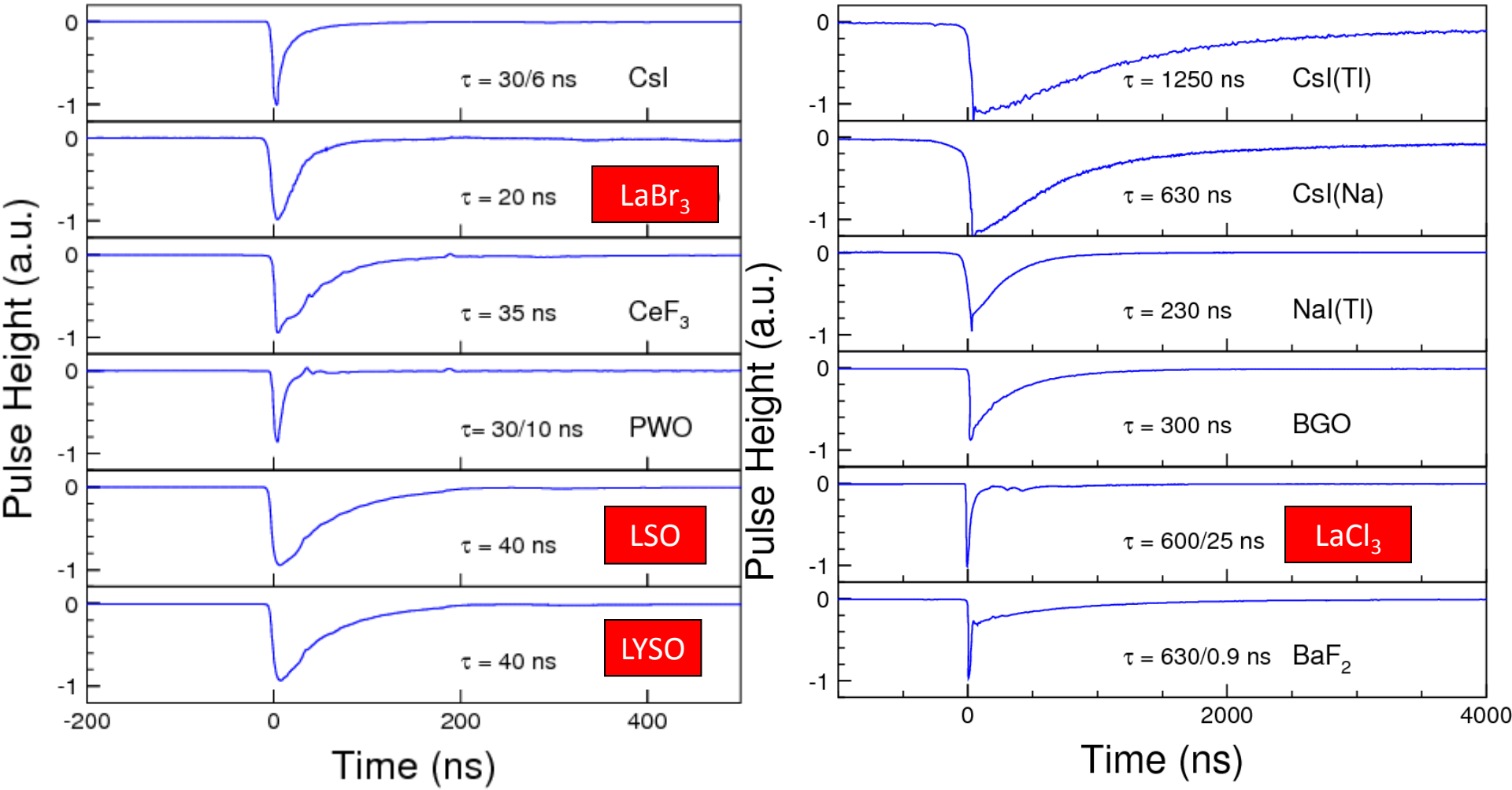


Scintillation Light Decay Time

Recorded with an Agilent 6052A digital scope

Fast Scintillators

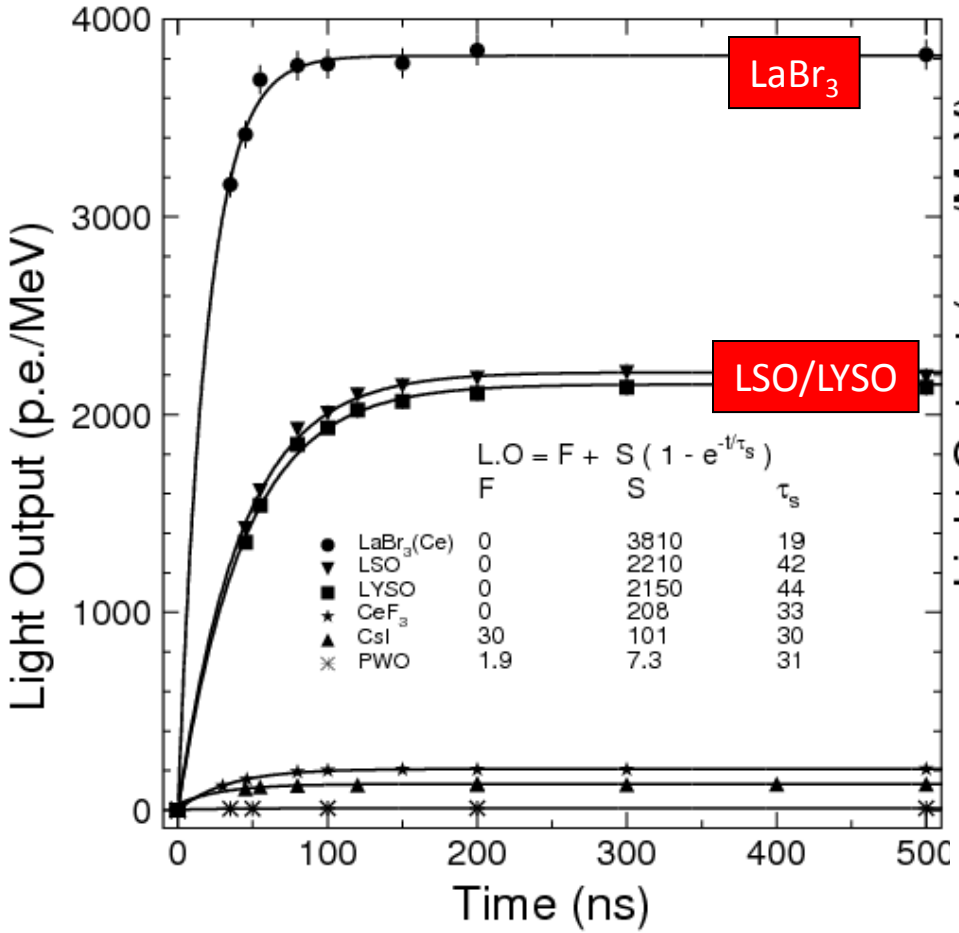
Slow Scintillators



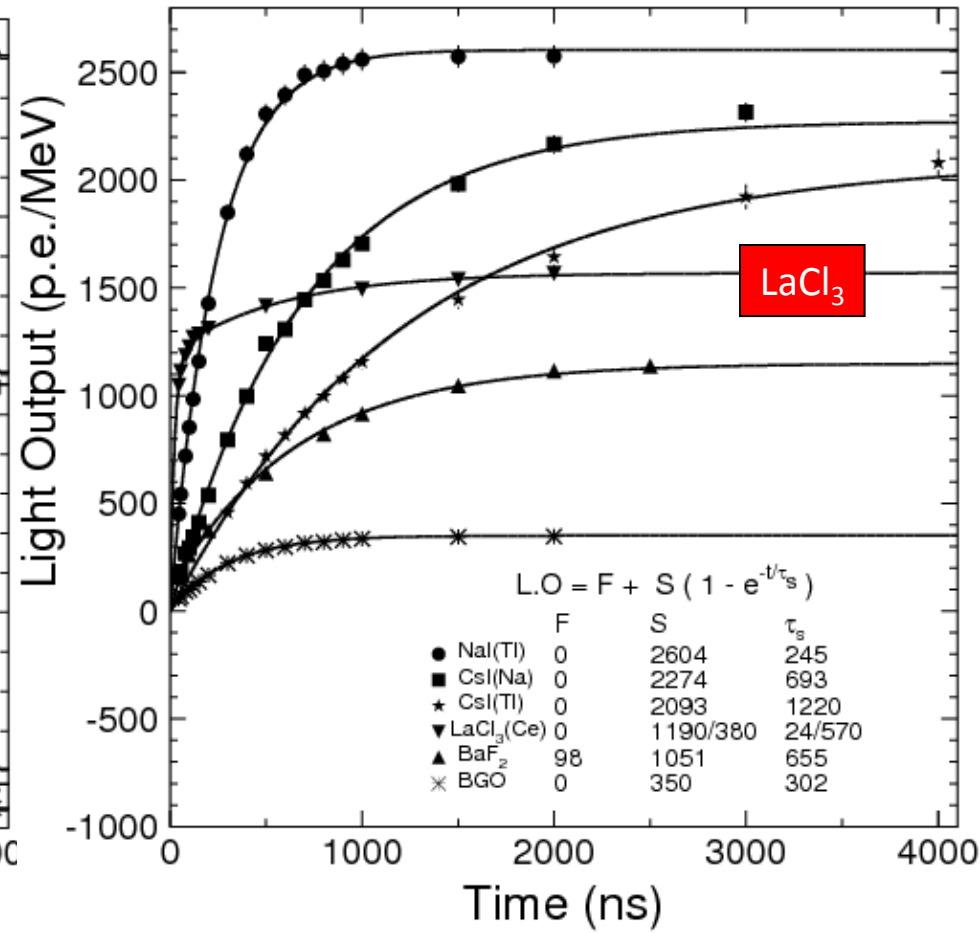
Light Output & Decay Kinetics

Measured with Philips XP2254B PMT (multi-alkali cathode)
$LaBr_3$, $LaCl_3$ and LSO/LYSO are blight and fast crystals

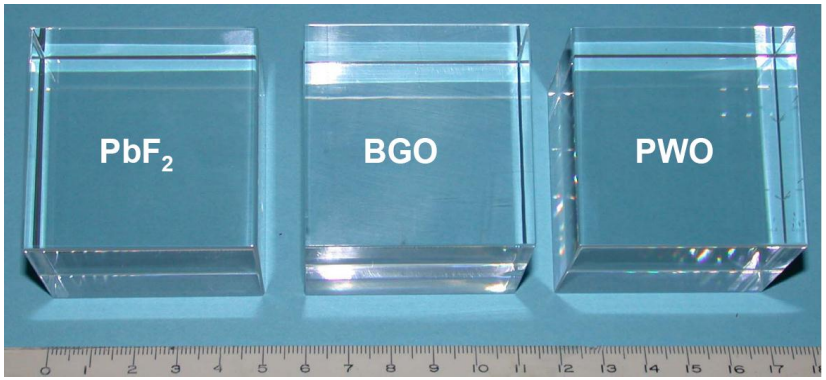
Fast Crystal Scintillators

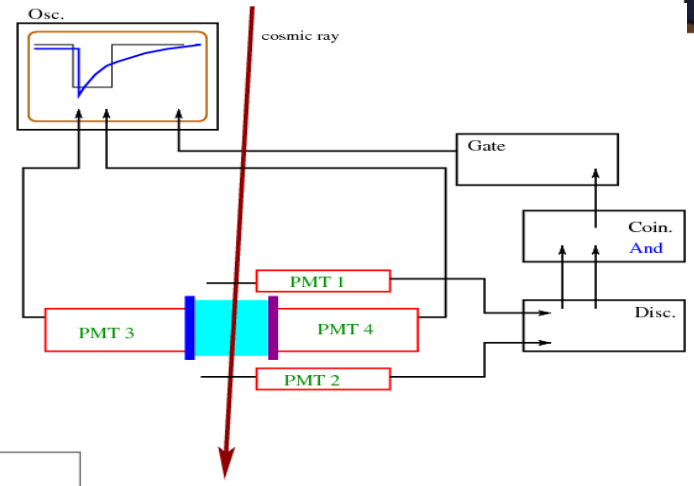


Slow Crystal Scintillators

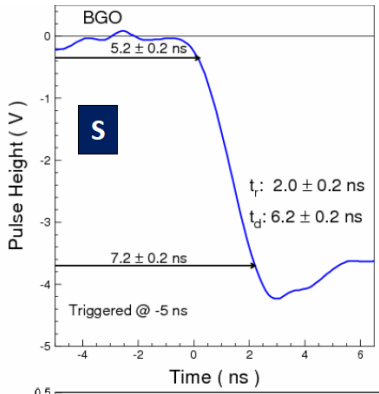


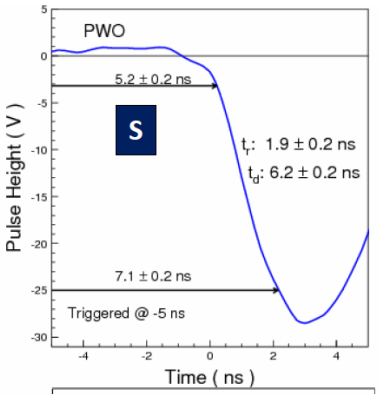
Rising Time of Cherenkov & Scintillation

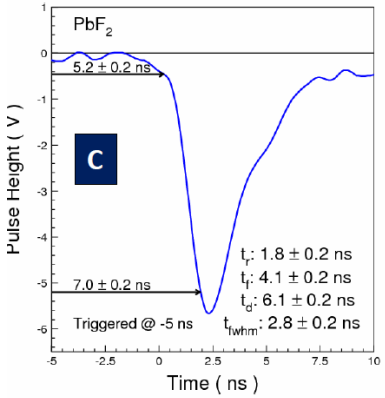


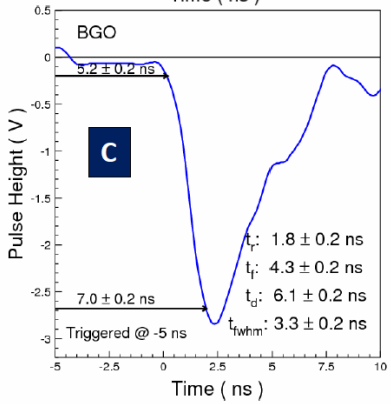


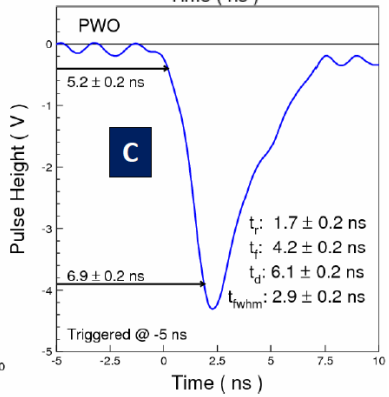
Consistent timing and rise time for all Cherenkov and scintillation light pulses observed.

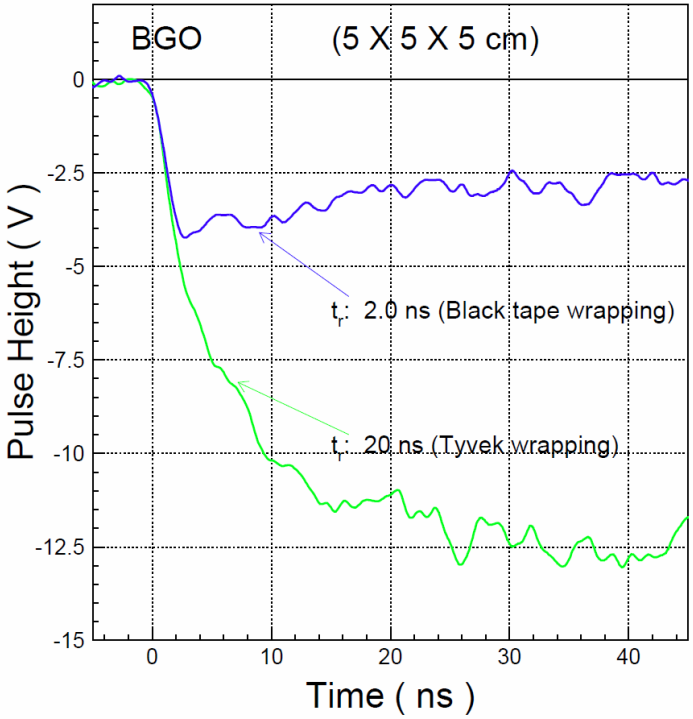






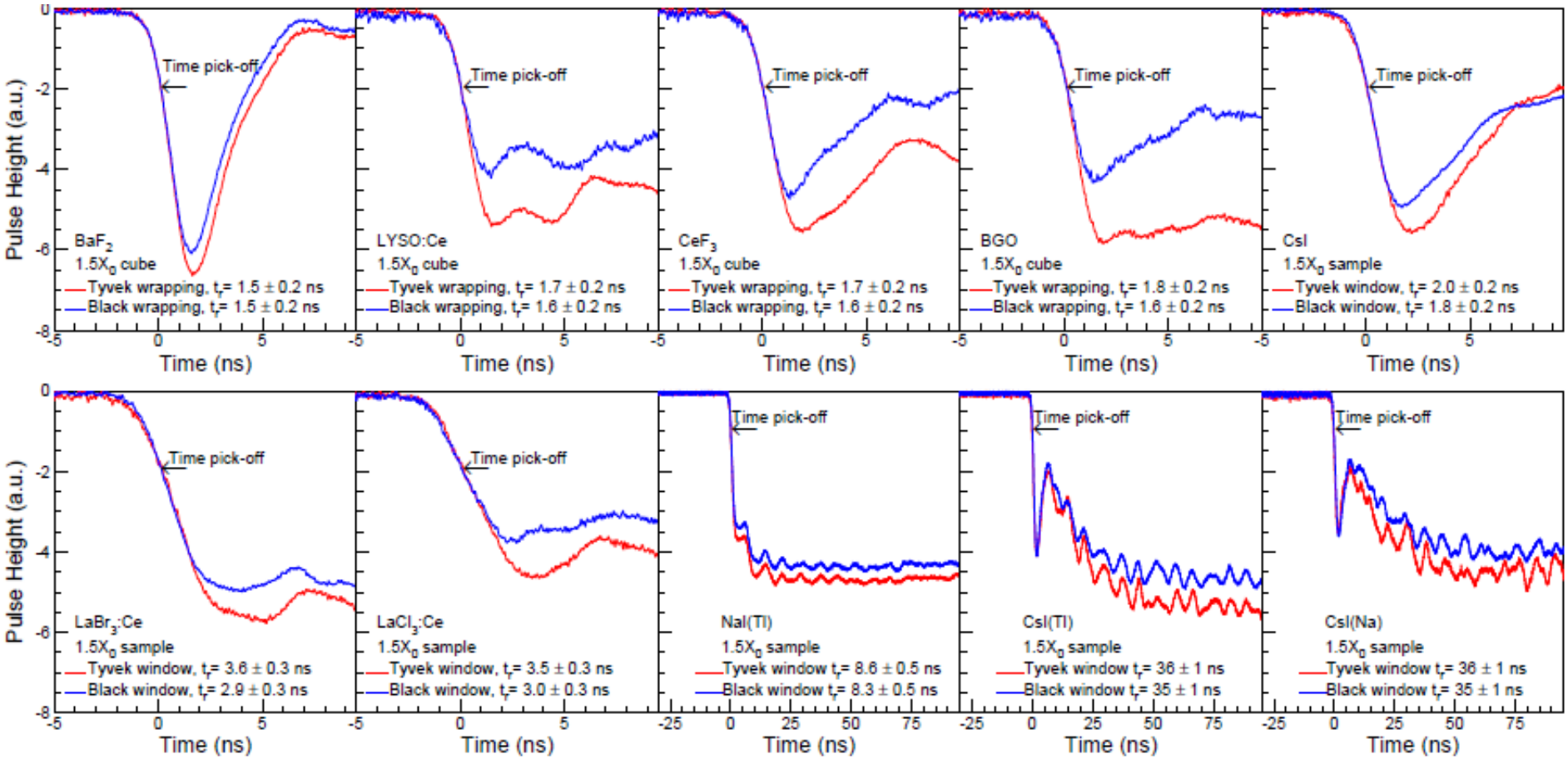






Rising Time for 1.5 X_0 Samples

Reported in the time resolution workshop at U. Chicago: Agilent MSO9254A (2.5 GHz) DSO with 0.14 ns rise time Hamamatsu R2059 PMT (2500 V) with rise time 1.3 ns



Measured rising time is dominated by photo-detector response, and is affected by light propagation in crystal.

Figure of Merit for Crystals

FoM is calculated as the LY in 1st ns obtained by using light output and decay time data measured for 1.5 X_0 crystal samples.

Crystal Scintillators	Relative LY (%)	A_1 (%)	τ_1 (ns)	A_2 (%)	τ_2 (ns)	Total LO (p.e./MeV, XP2254B)	LO in 1ns (p.e./MeV, XP2254B)	LO in 0.1ns (p.e./MeV, XP2254B)	LY in 0.1ns (photons/MeV)
BaF_2	40.1	91	650	9	0.9	1149	71.0	11.0	136.6
LSO:Ca,Ce	94	100	30			2400	78.7	8.0	110.9
LSO/LYSO:Ce	85	100	40			2180	53.8	5.4	75.3
CeF_3	7.3	100	30			208	6.8	0.7	8.6
BGO	21	100	300			350	1.2	0.1	2.5
PWO	0.377	80	30	20	10	9.2	0.42	0.04	0.4
$LaBr_3$:Ce	130	100	20			3810	185.8	19.0	229.9
$LaCl_3$:Ce	55	24	570	76	24	1570	49.36	5.03	62.5
NaI:Tl	100	100	245			2604	10.6	1.1	14.5
CsI	4.7	77	30	23	6	131	7.9	0.8	10.6
CsI:Tl	165	100	1220			2093	1.7	0.2	4.8
CsI:Na	88	100	690			2274	3.3	0.3	4.5

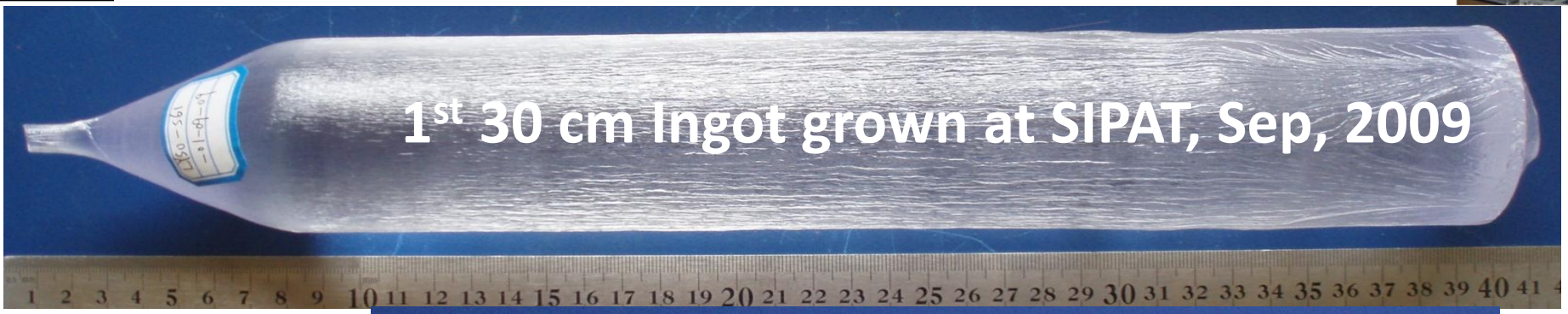
The best crystal scintillator for time resolution is BaF_2 and LSO: Ce/Ca and LYSO. $LaBr_3$ is a material with high potential.

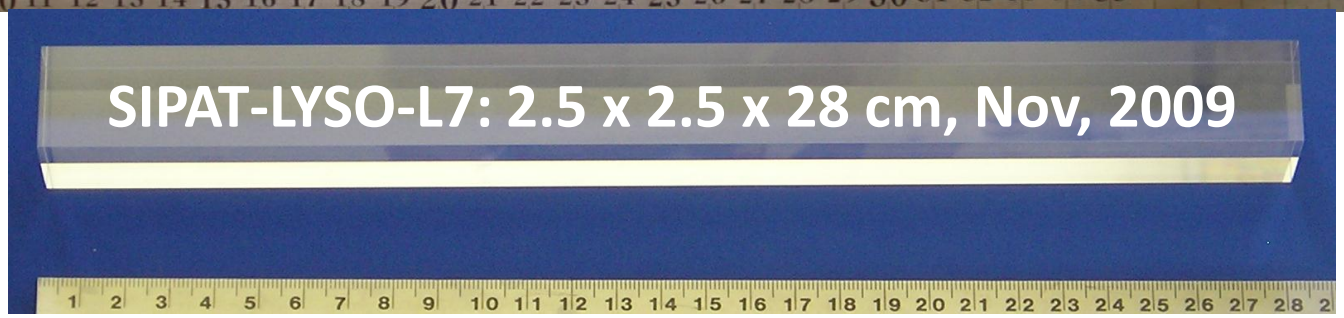
Summary of Fast Crystals

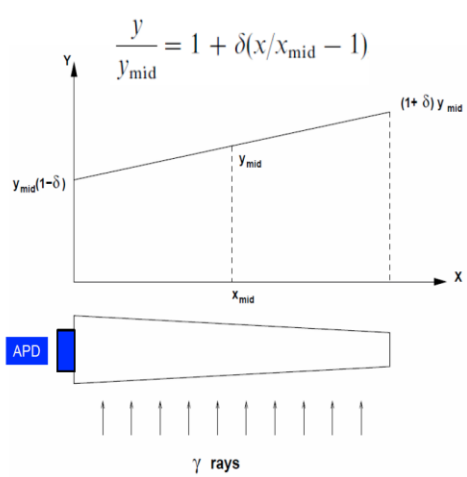
	LSO/LYSO	YSO	GSO	BaF_2	CsI	CeF_3	$CeBr_3$	$LaBr_3$	$LaCl_3$
Density (g/cm^3)	7.40	4.54	6.71	4.89	4.51	6.16	5.10	5.29	3.86
Radiation Length (cm)	1.14	3.04	1.38	2.03	1.86	1.70	1.96	1.88	2.81
Molière Radius (cm)	2.07	2.87	2.23	3.10	3.57	2.41	2.97	2.85	3.71
Interaction Length (cm)	20.9	27.3	22.2	30.7	39.3	23.2	31.5	30.4	37.6
Z value	64.8	33.3	57.9	51.6	54.0	50.8	45.6	45.6	47.3
dE/dX (MeV/cm)	9.55	6.70	8.88	6.52	5.56	8.42	6.65	6.90	5.27
Emission Peak[a] (nm)	420	420	430	300 220	420 310	340 300	371	356	335
Refractive Index[b]	1.82	1.80	1.85	1.50	1.95	1.62	2.3	1.9	1.9
Relative Light Yield[a,c]	100	40		42 4.8	4.2 1.3	8.6	144	153	15 49
Decay Time[a] (ns)	40	70	65	650 0.9	30 6	30	17	20	570 24
d(LY)/dT[d] (%/°C)	-0.2	-0.3	-0.7	-1.9 0.1	-1.4	~0	-0.1	0.2	0.1

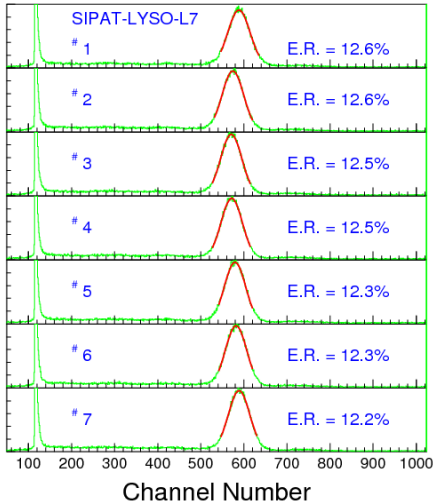
a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. Relative light yield normalized to the light yield of LSO
d. At room temperature (20°C)

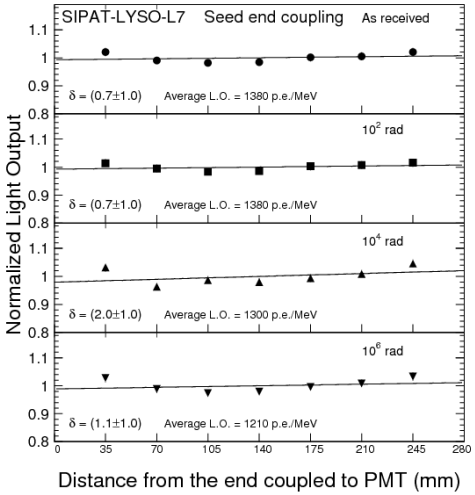
First 28 cm long LYSO Sample

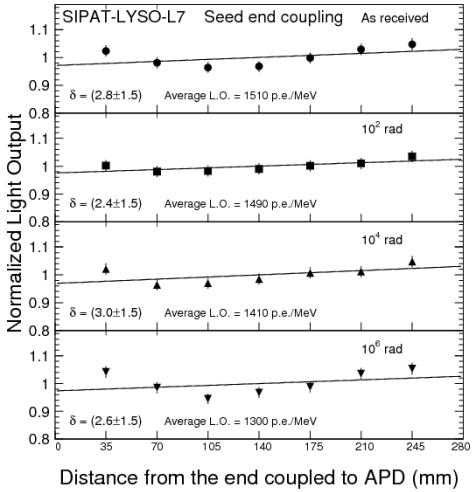










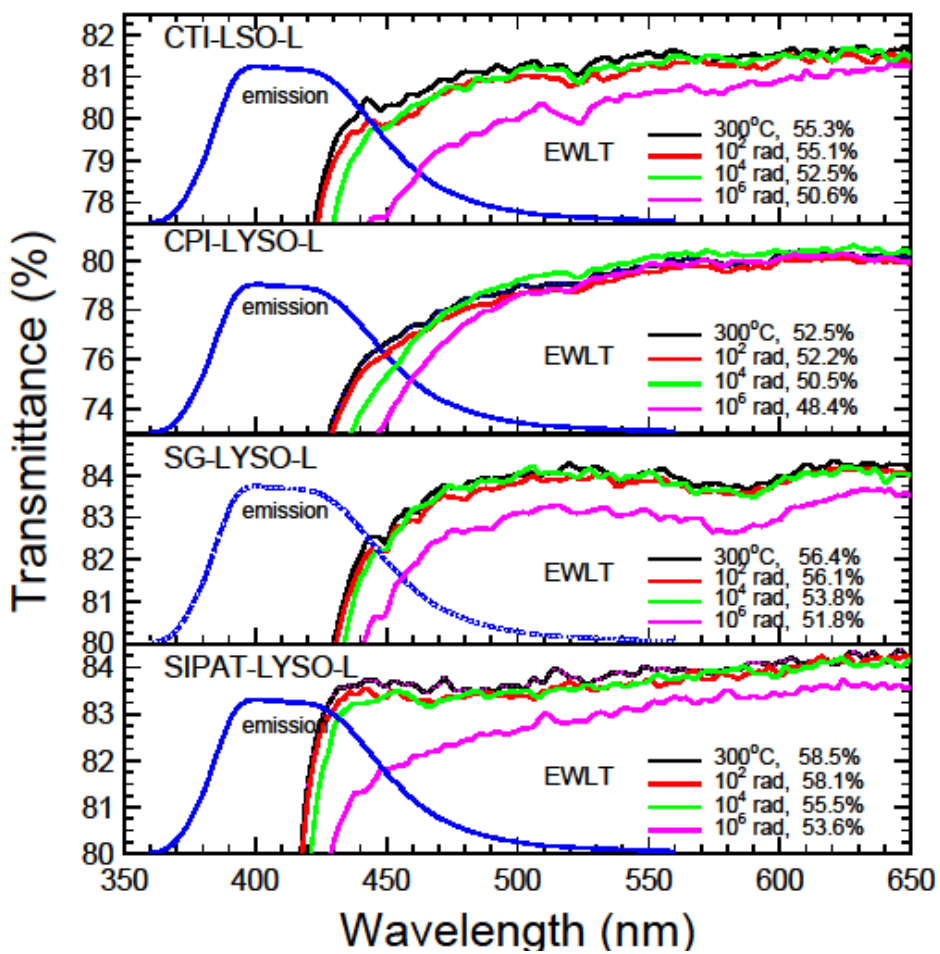


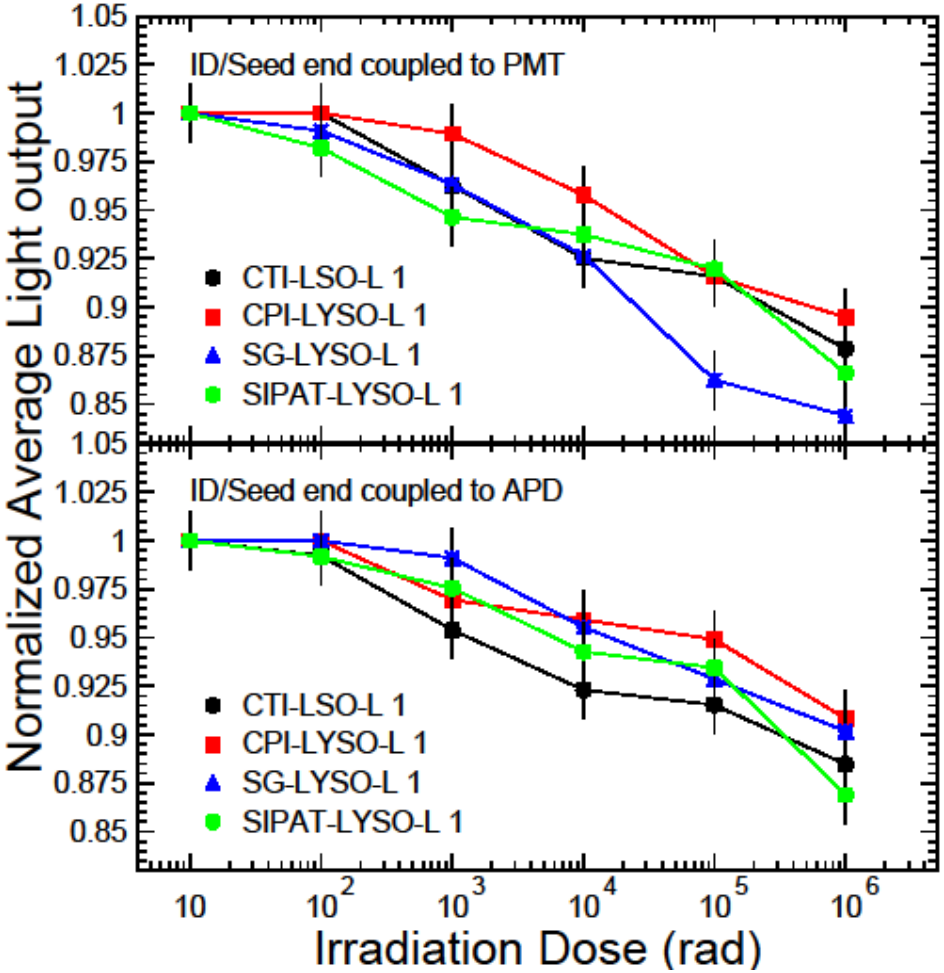
20 cm Long LSO/LYSO under γ-Rays

Consistent radiation hardness better than other crystals

EWLT damage: 8% @ 1 Mrad

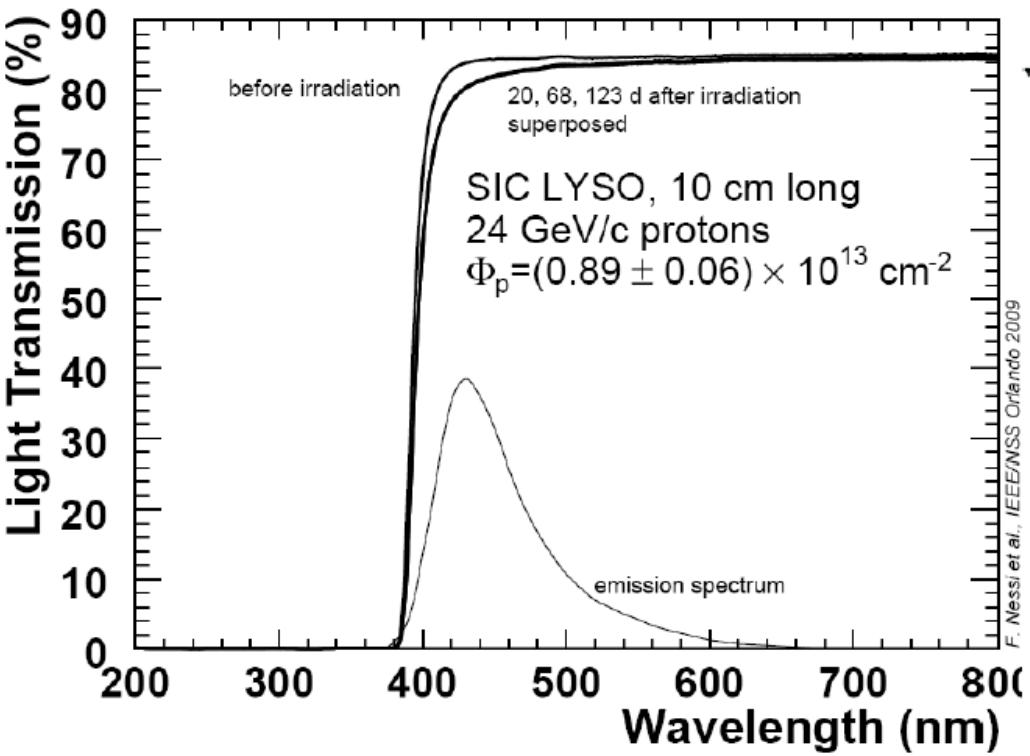
10% - 15% loss by PMT & APD

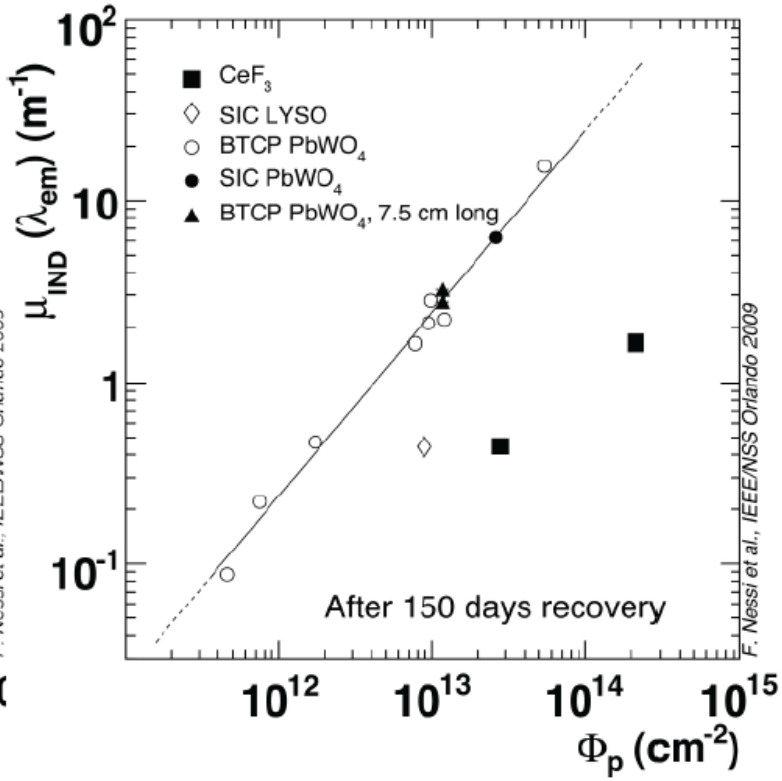




Protons: >100 times better than PWO

G. Dissertori, D. Luckey, P. Lecomte, Francesca Nessi-Tedaldi, F. Pauss, Paper N32-3@NSS09, Orlando.





After 10^{13} neutrons/cm^2 the induced absorption of LYSO is five times less than that of PWO. See talk by Guenther Dissertori in this workshop.

Summary

- Blight crystals are **Eu:SrI_2, Ce:$LaBr_3$, $CeBr_3$, Ce:$LaCl_3$ and LSO/LYSO.**
- Fast crystals are available in three groups:
  - A traditional group not very blight: **BaF_2, pure CsI and CeF_3**.
  - A hygroscopic group with patent: **Ce:$LaBr_3$, Ce:$LaCl_3$ and $CeBr_3$.**
  - An expansive group: **LSO/LYSO/YSO and GSO**.
- A R&D program is needed to develop cost effective crystals for the project X, including crystal characterization, radiation hardness study, quality improvement and cost analysis.