Crystal Calorimeters in the Next Decade

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October 29, 2009

Invited Paper N43-1, IEEE NSS09, Orlando, Florida, USA

Why Crystal Calorimeter in HEP?

- 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.
- Crystals may also provide a foundation for a homogeneous hadron calorimeter with dual readout of Cherenkov and scintillation light to achieve good resolution for hadrons and jets.

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 (°C)	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] (%/ °C)	-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	KLOE-2 SuperB SLHC?	CMS ALICE PANDA	HHCAL?

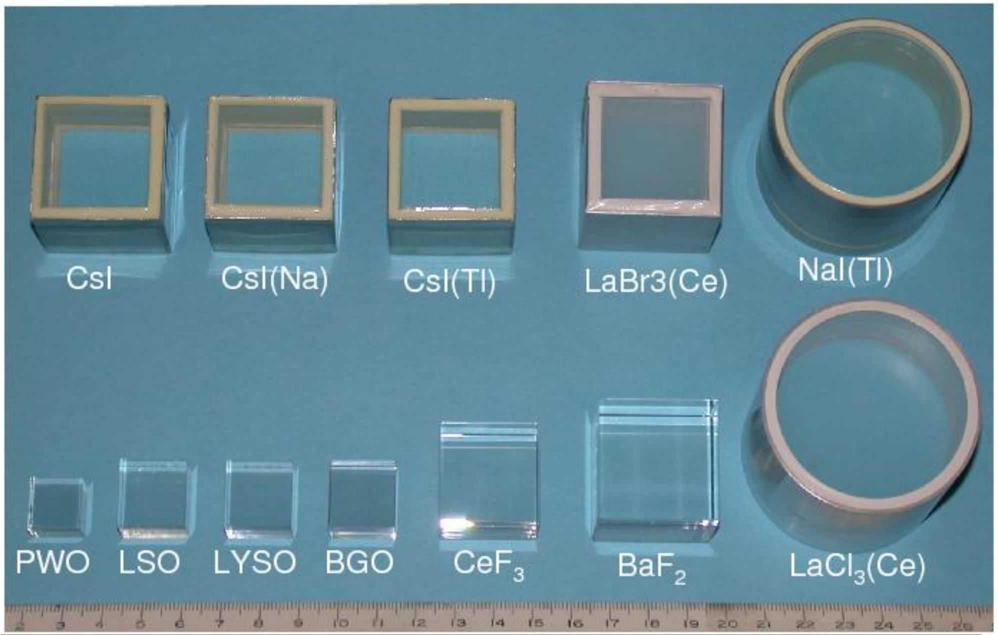
a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

Crystals for Homeland Security

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

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

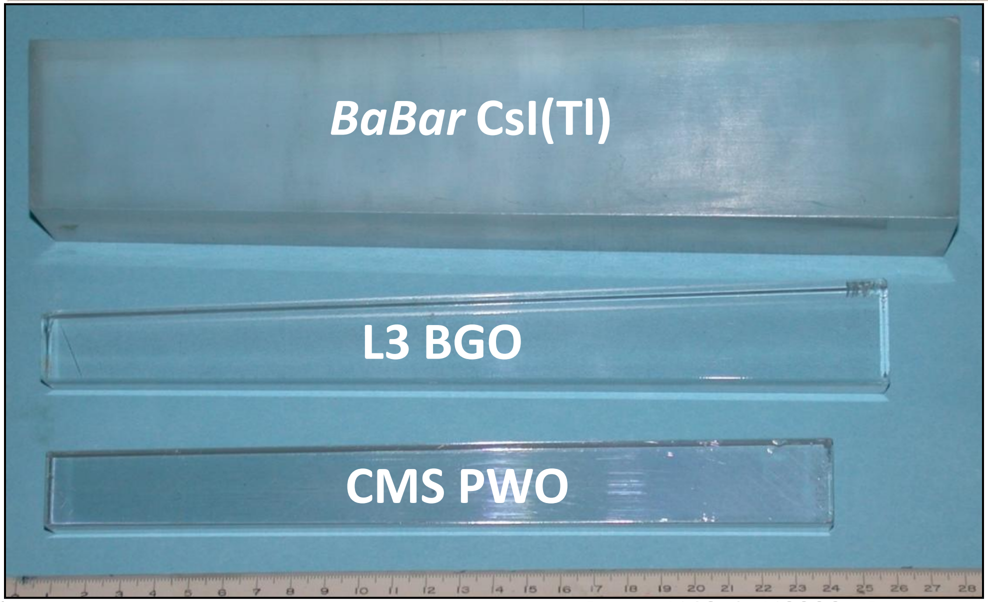
Crystal Density: Radiation Length



1.5 X_0 Cubic Samples:

Hygroscopic: Sealed

Non-hygro: Polished



Full Size Crystals:

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

L3 BGO: 22 X_0

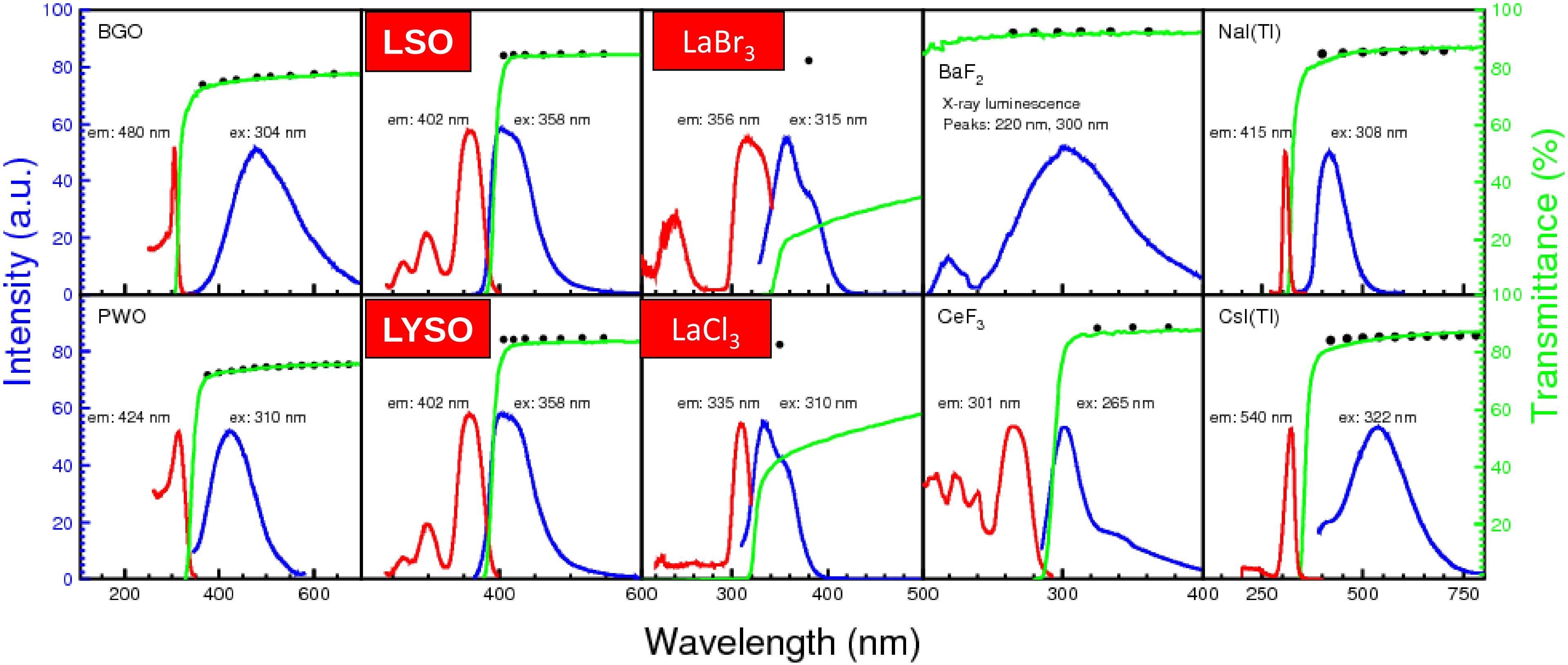
CMS PWO(Y): 25 X_0

Excitation, Emission, Transmission

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

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

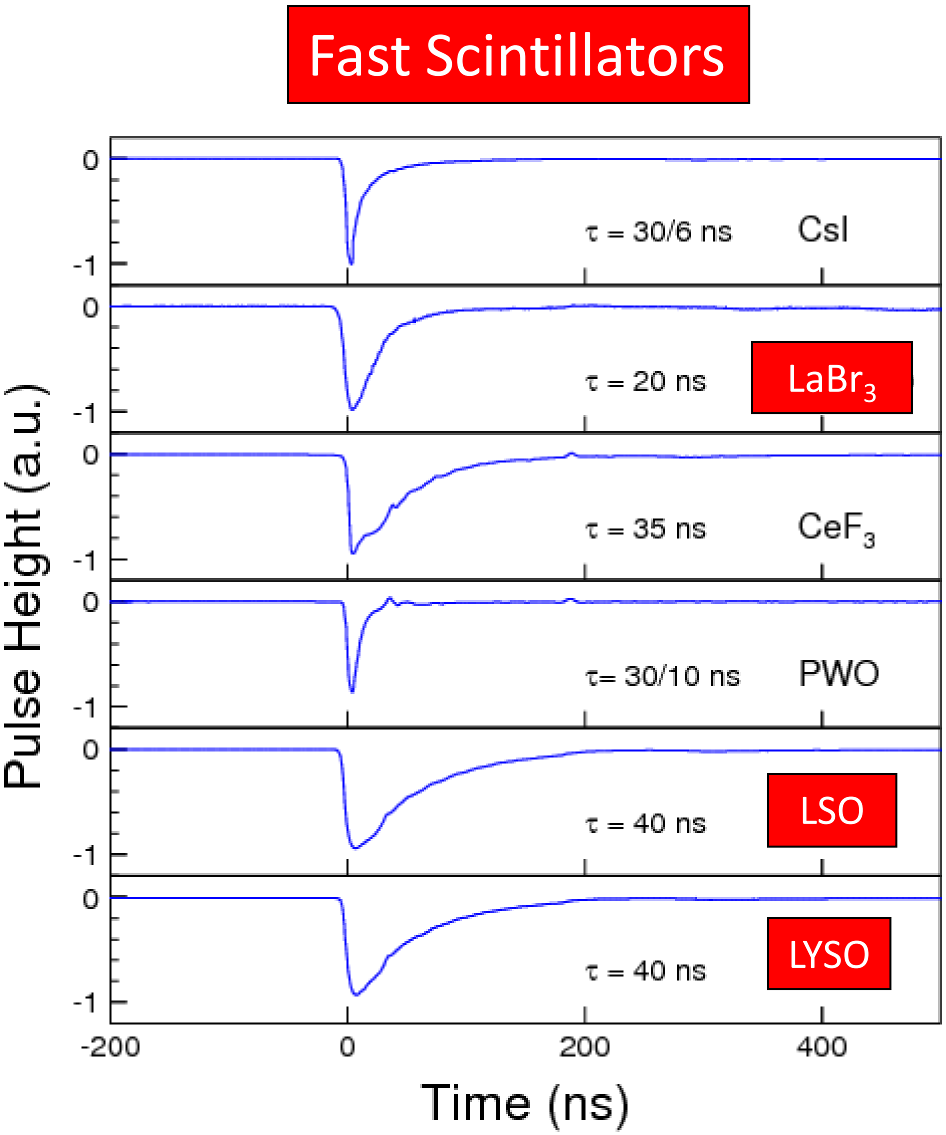
Black Dots: Theoretical limit of transmittance: NIM A333 (1993) 422

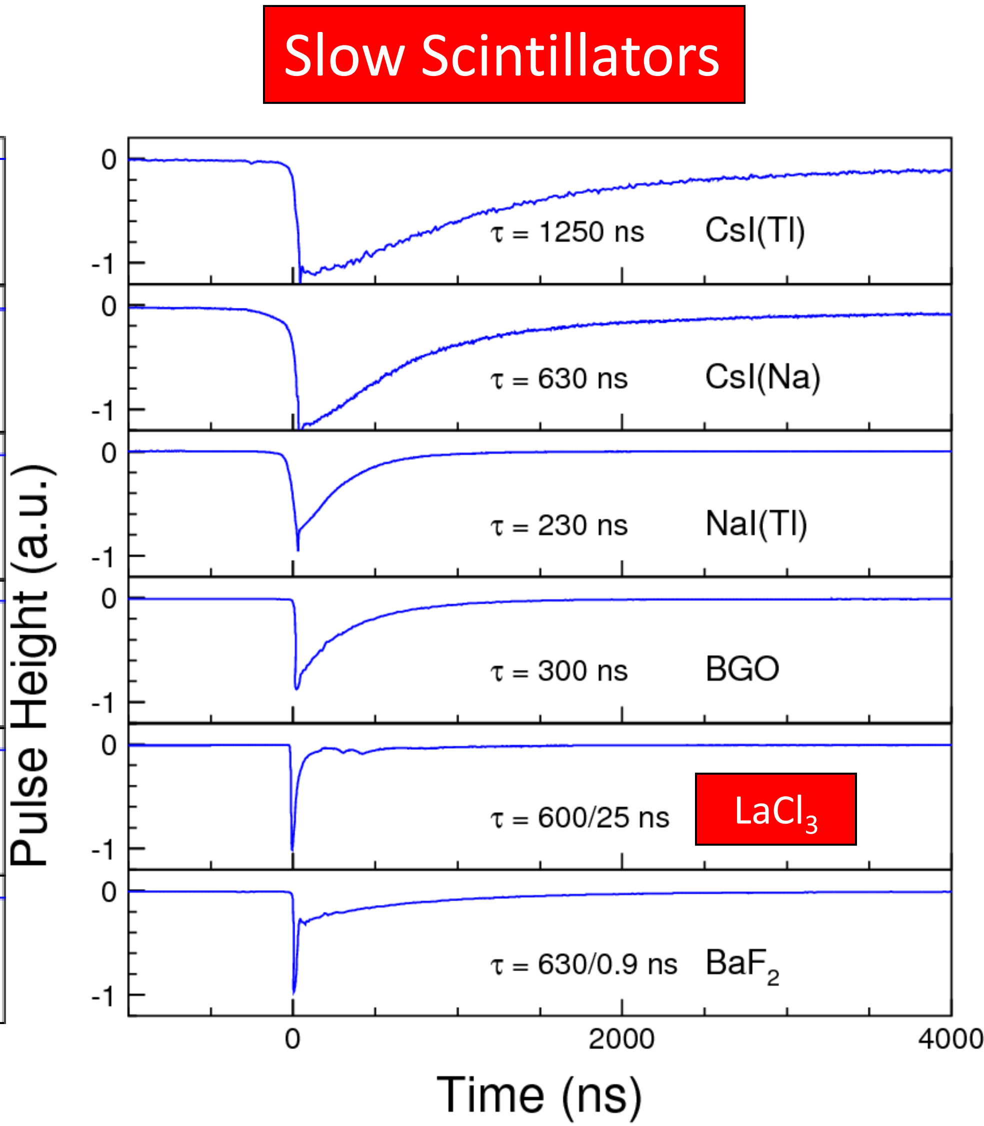


No Self-absorption: BGO, PWO, BaF_2, NaI(Tl) and CsI(Tl)

Scintillation Light Decay Time

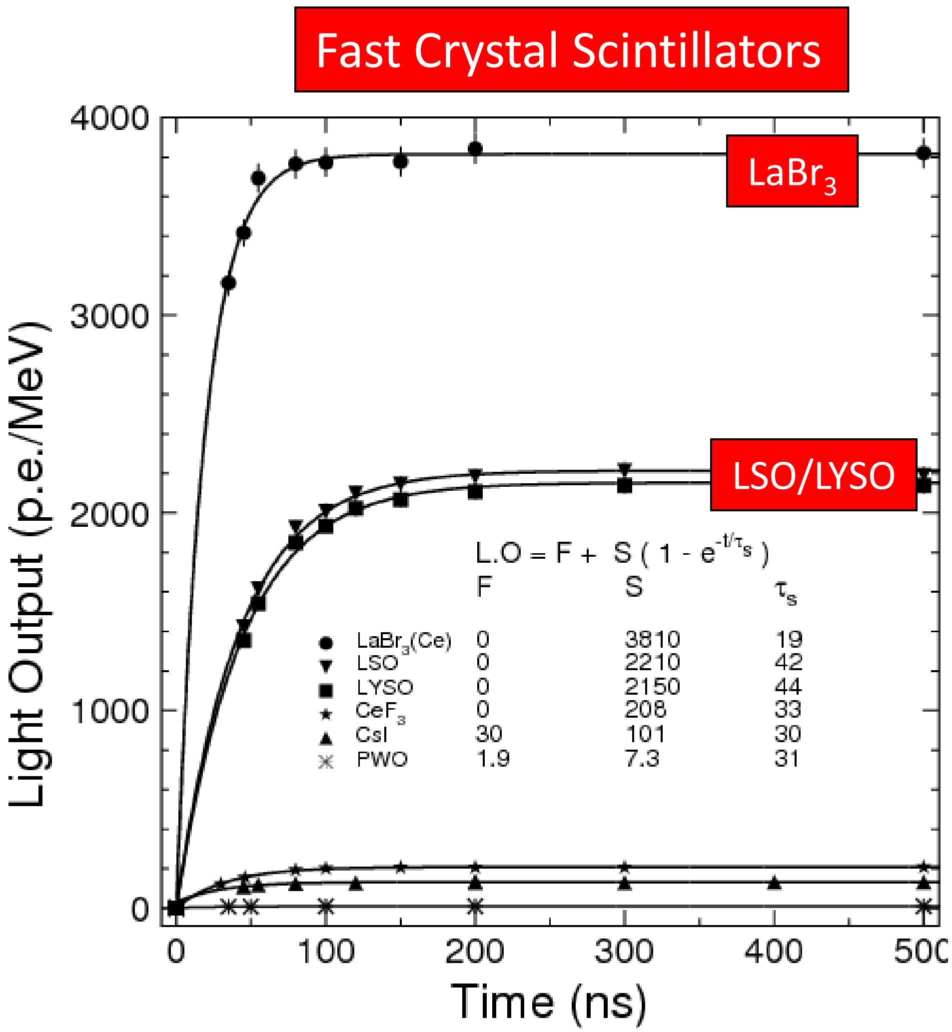
Recorded with an Agilent 6052A digital scope

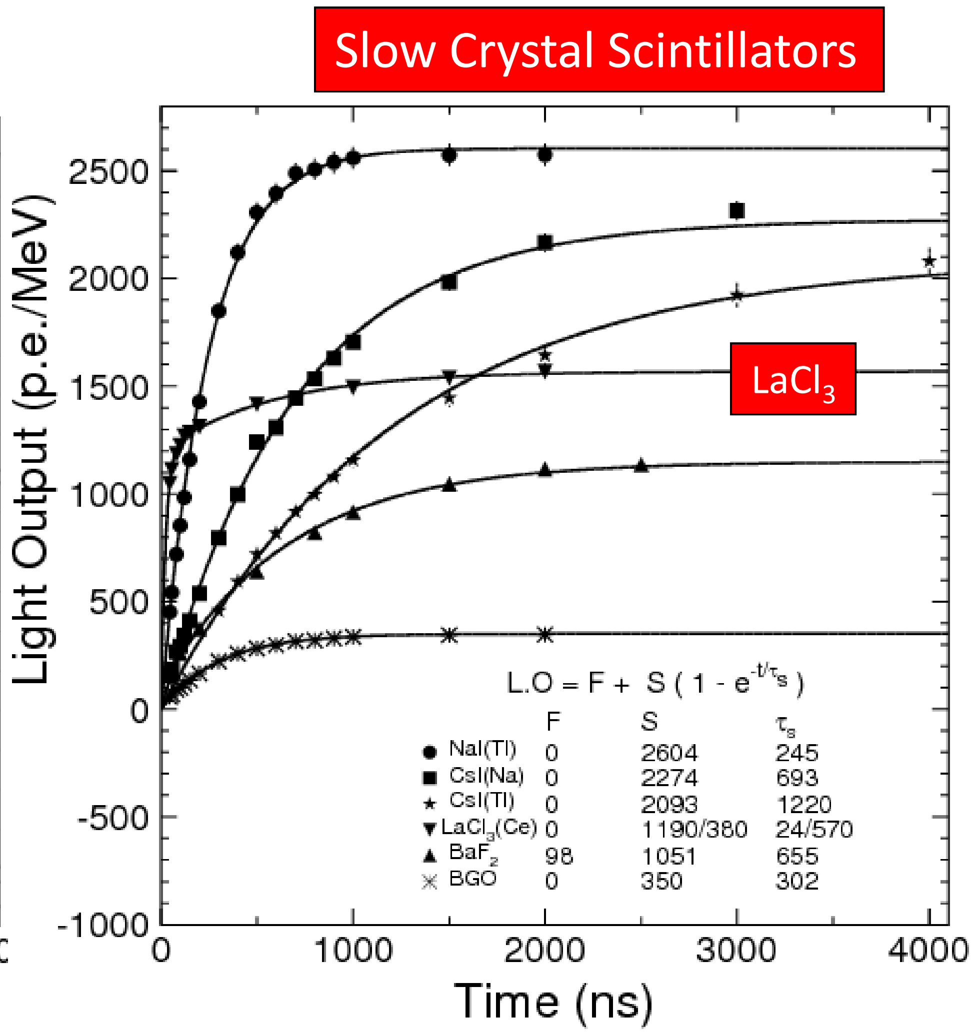




Light Output & Decay Kinetics

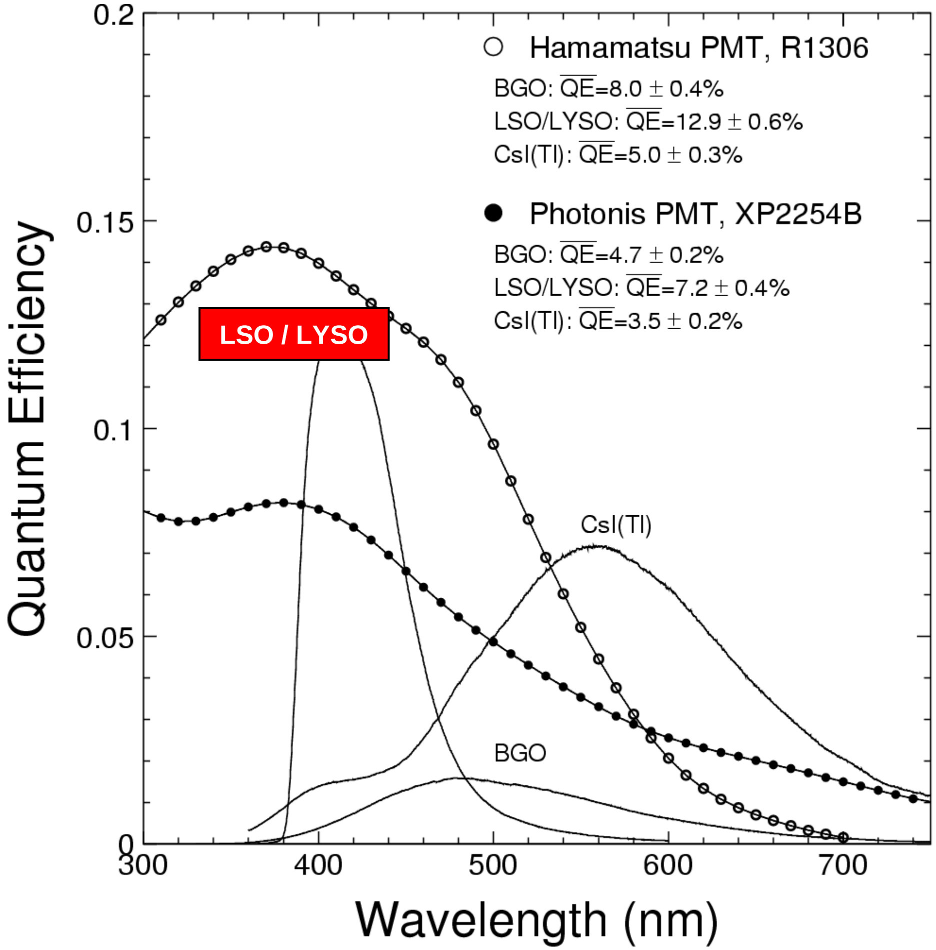
Measured with Philips XP2254B PMT (multi-alkali cathode)
p.e./MeV: LSO/LYSO is 6 & 230 times of BGO & PWO respectively

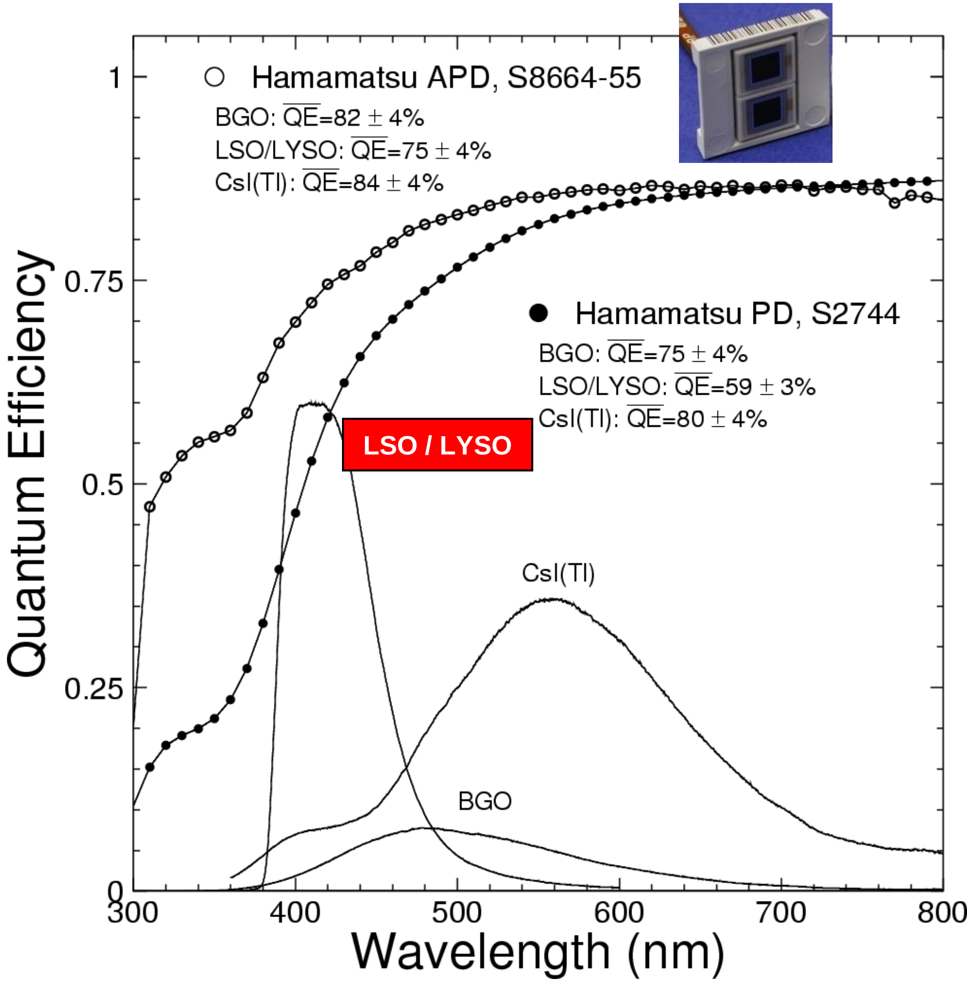




Emission Weighted QE

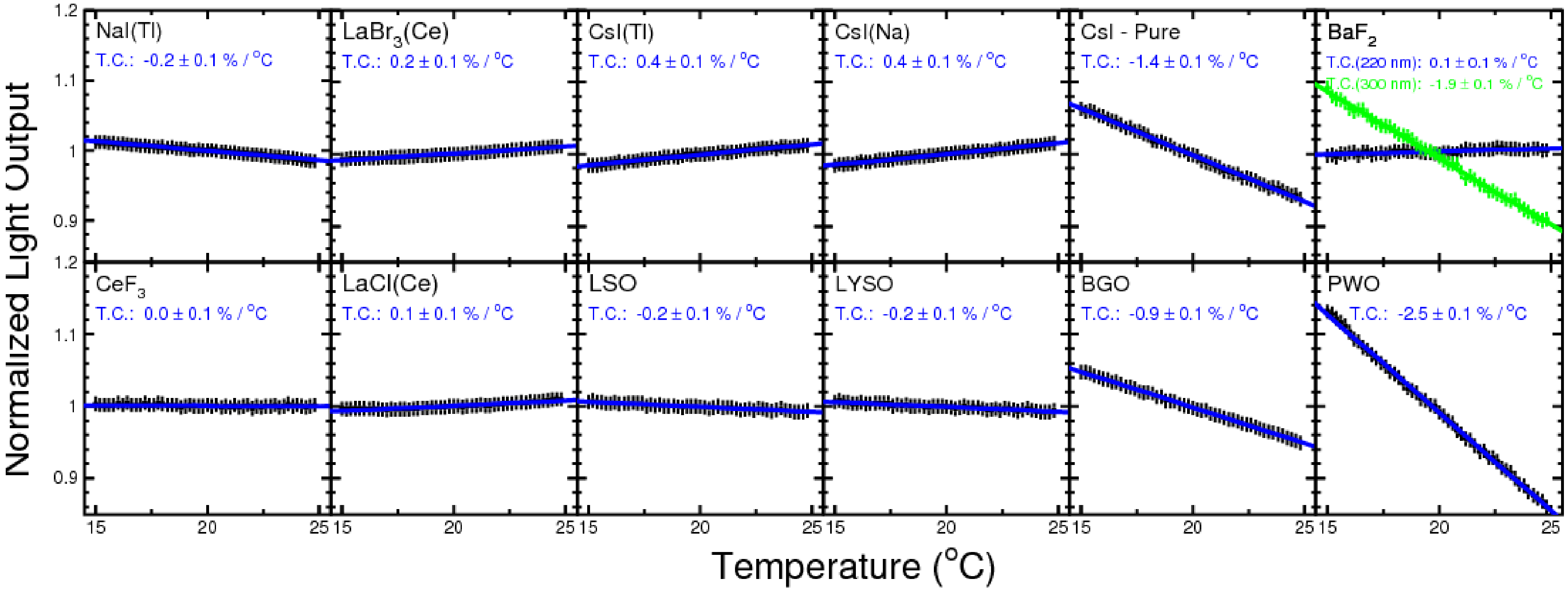
Taking out QE, L.O. of LSO/LYSO is 4/200 times BGO/PWO
Hamamatsu S8664-55 APD has QE 75% for LSO/LYSO





L.O. Temperature Coefficient

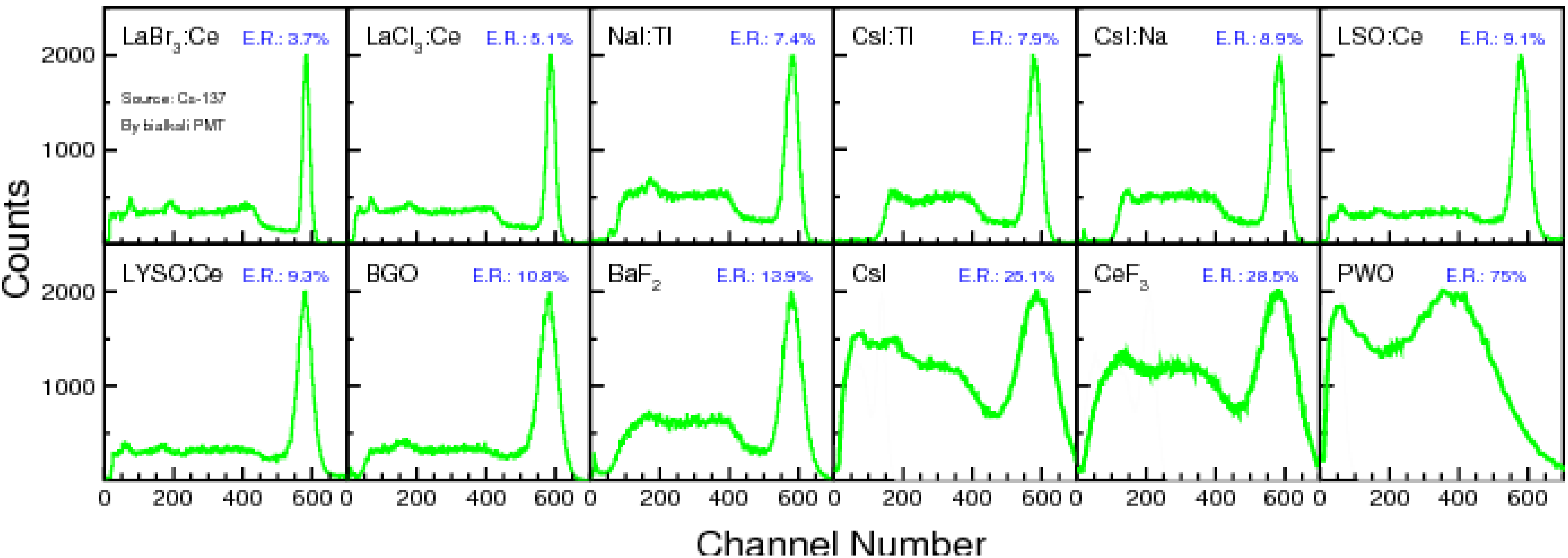
Temperature Range: 15 - 25ºC



Large temperature coefficient: CsI, BGO, BaF_2 and PWO

^{137}Cs FWHM Energy Resolution

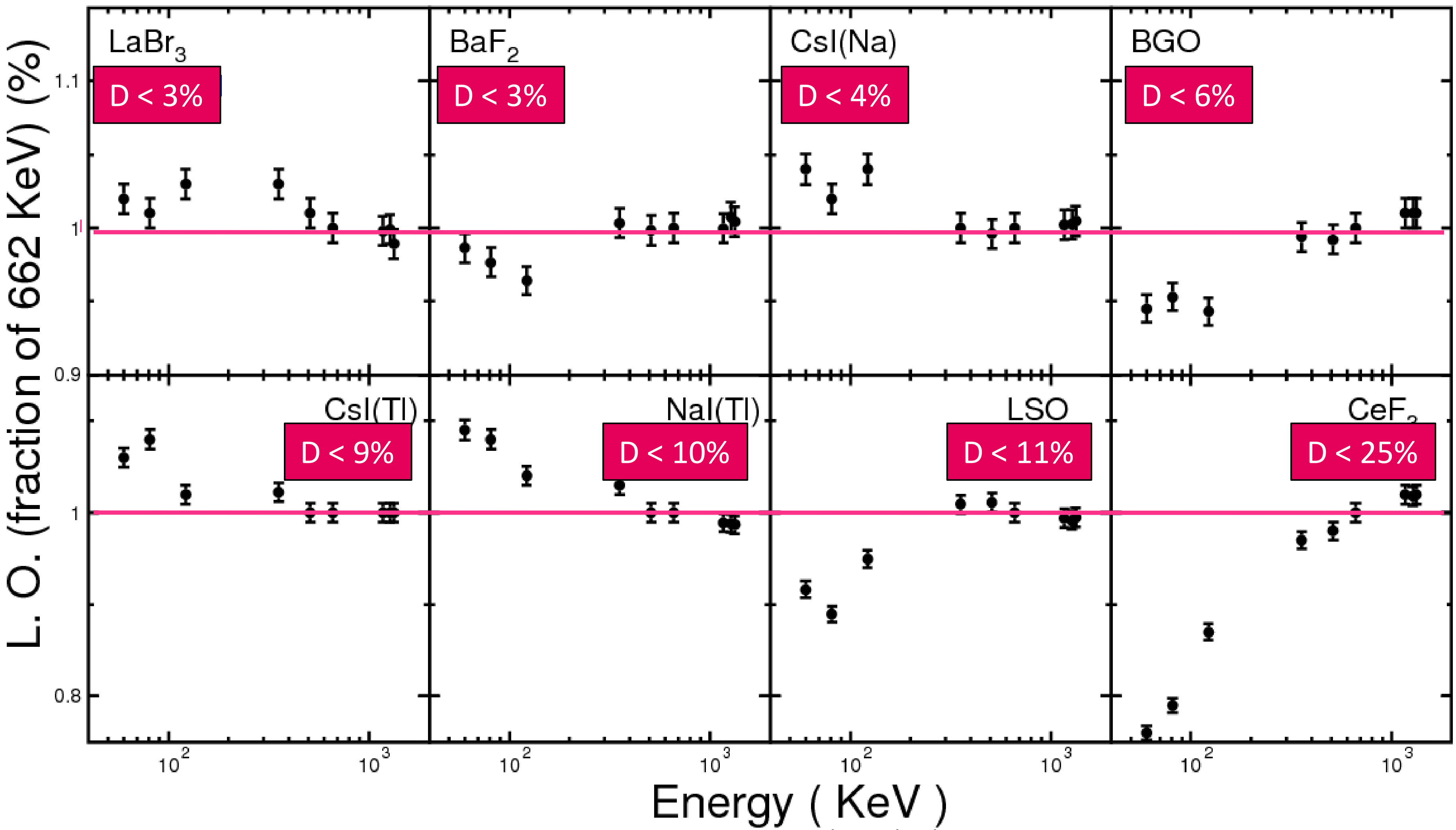
3% to 80% measured with Hamamatsu R1306 PMT with bi-alkali cathode



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

Low Energy Non Proportionality

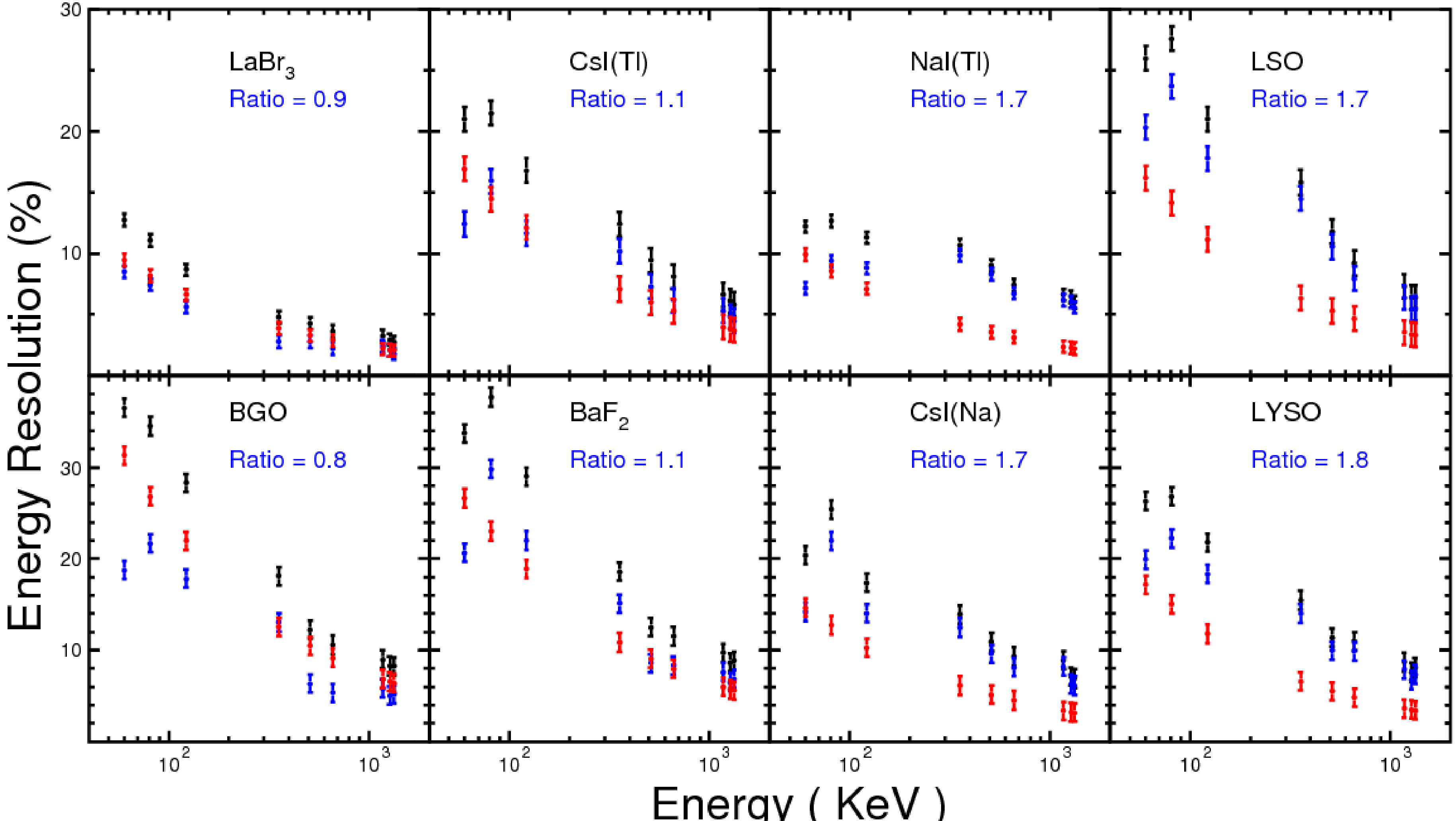
D: deviation from linearity: 60 keV to 1.3 MeV
Good Crystals: $LaBr_3$, BaF_2, CsI(Na) and BGO



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:

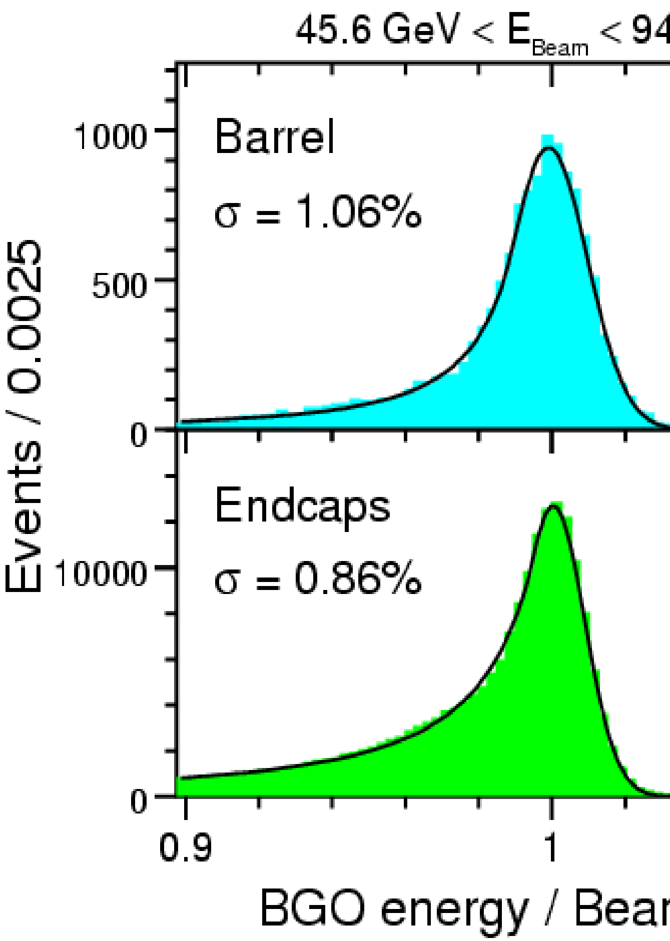
PWO for PANDA at GSI (N32-2)

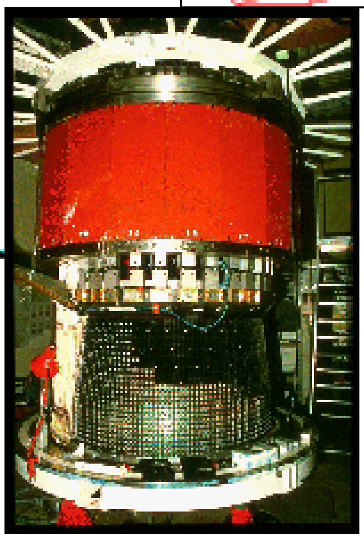
LYSO for a Super B Factory (N43-3), SLHC (N32-3,4,5)

PbF_2, BGO, PWO for Homogeneous HCAL (N40-2)

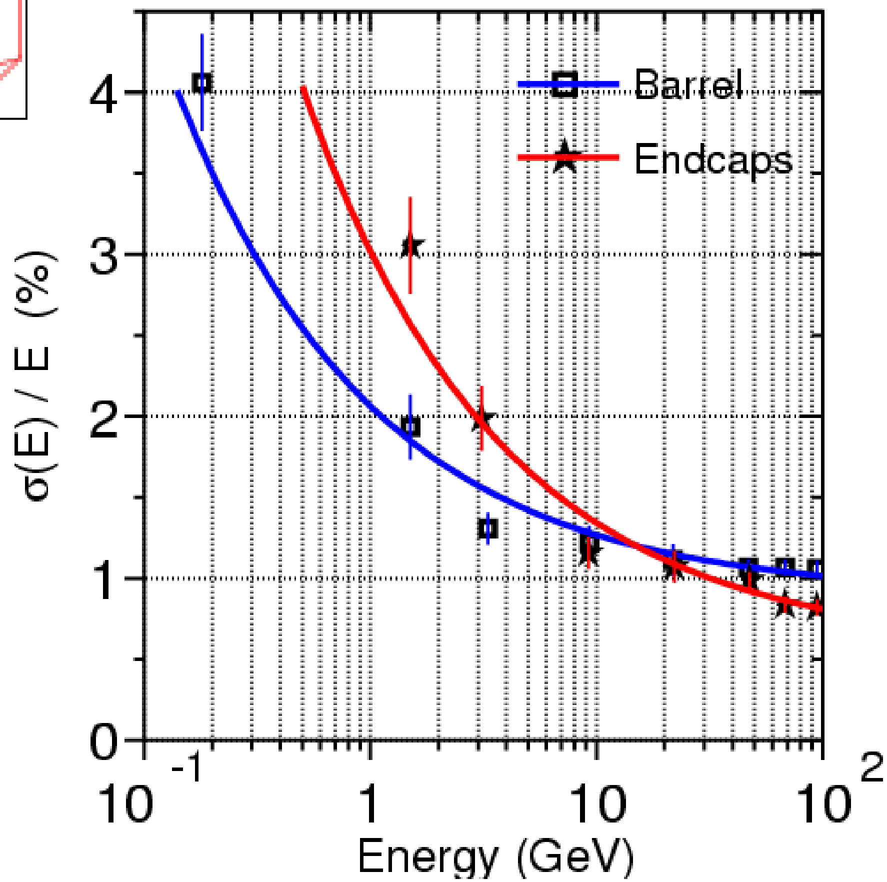
L3 BGO Resolution

Contribution	"Radiative"+Intrinsic	Temperature	Calibration	Overall
Barrel	0.8%	0.5%	0.5%	1.07%
Endcaps	0.6%	0.5%	0.4%	0.88%



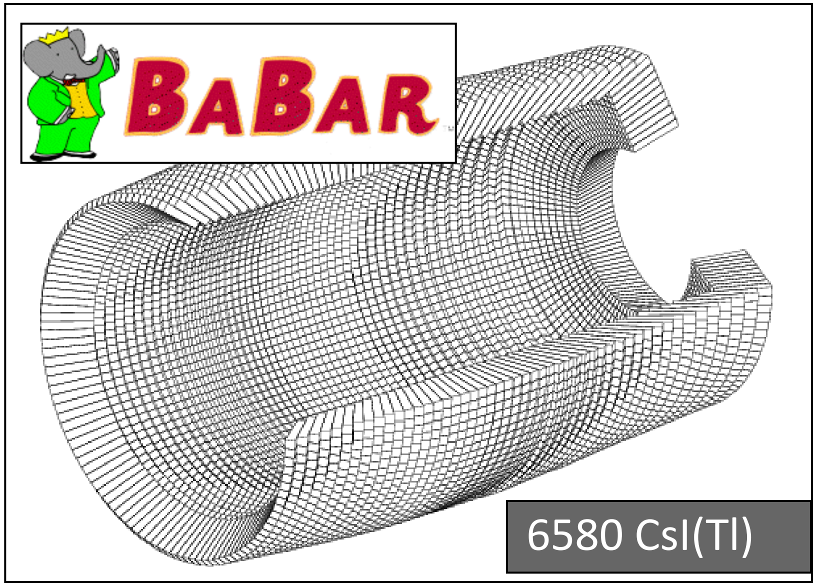


12k BGO



BaBar CsI(Tl) Resolution

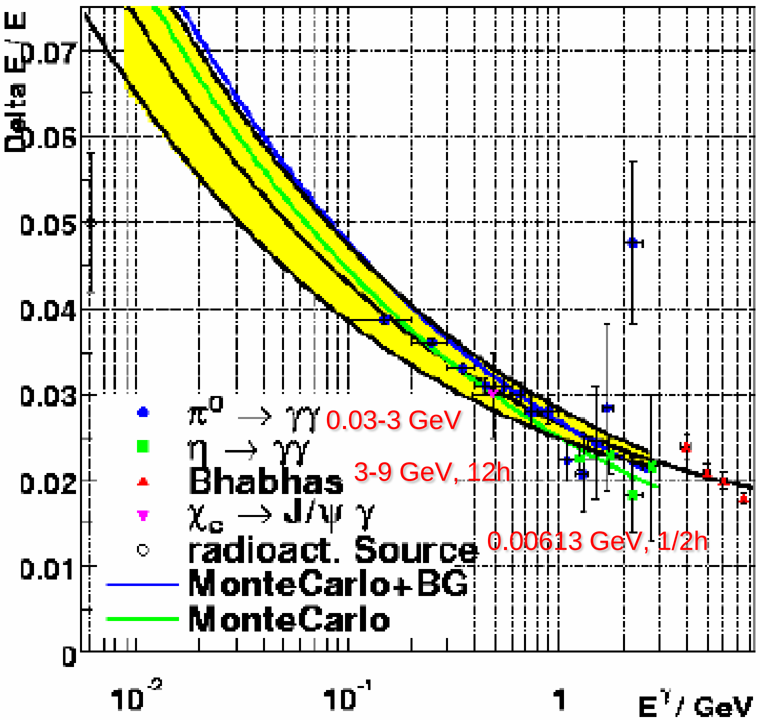
A crystal calorimeter at low energies



Good light yield of CsI(Tl) provides excellent energy resolution at low energies

Energy resolution

M. Kocian, SLAC, CALOR2002

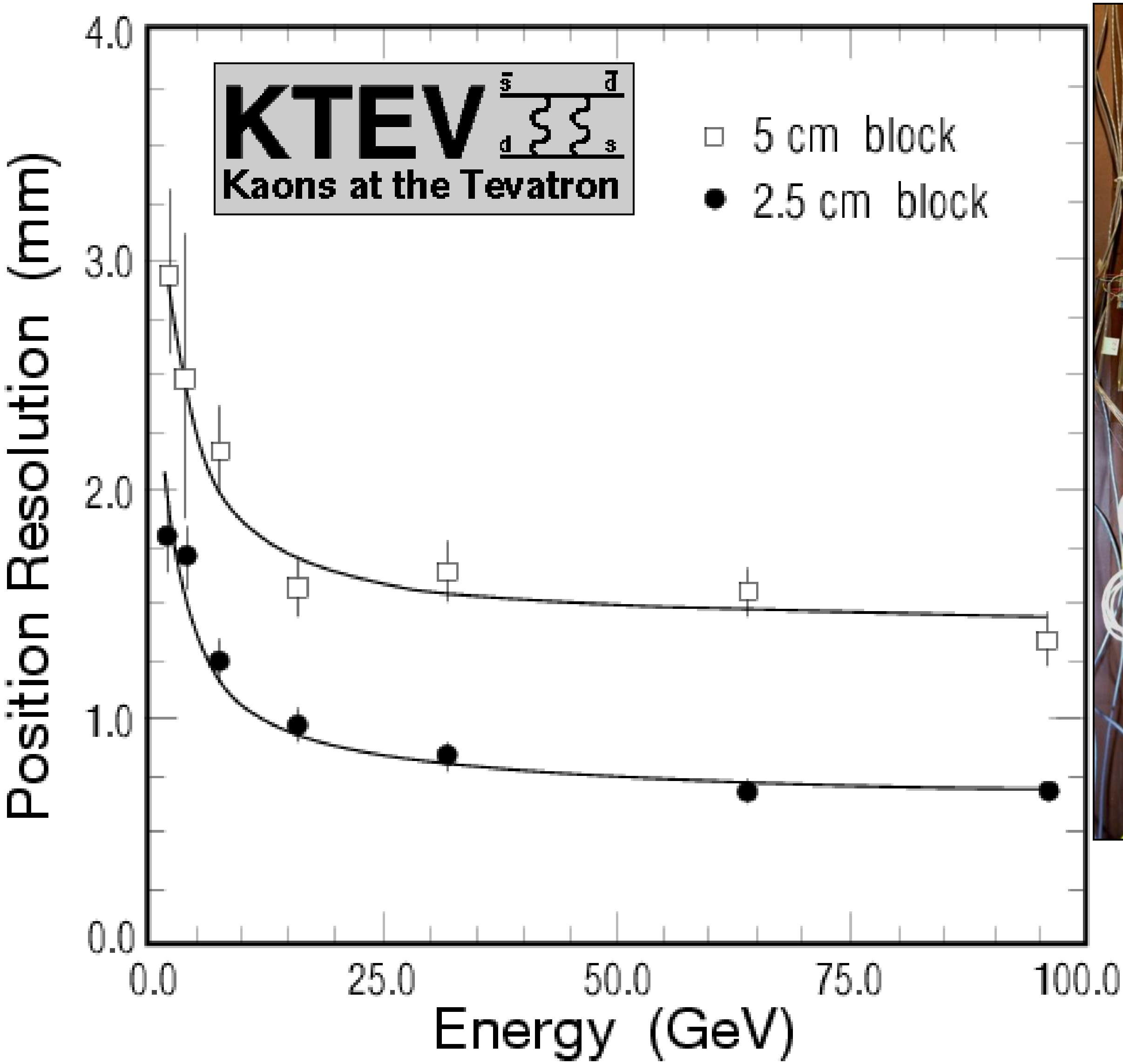


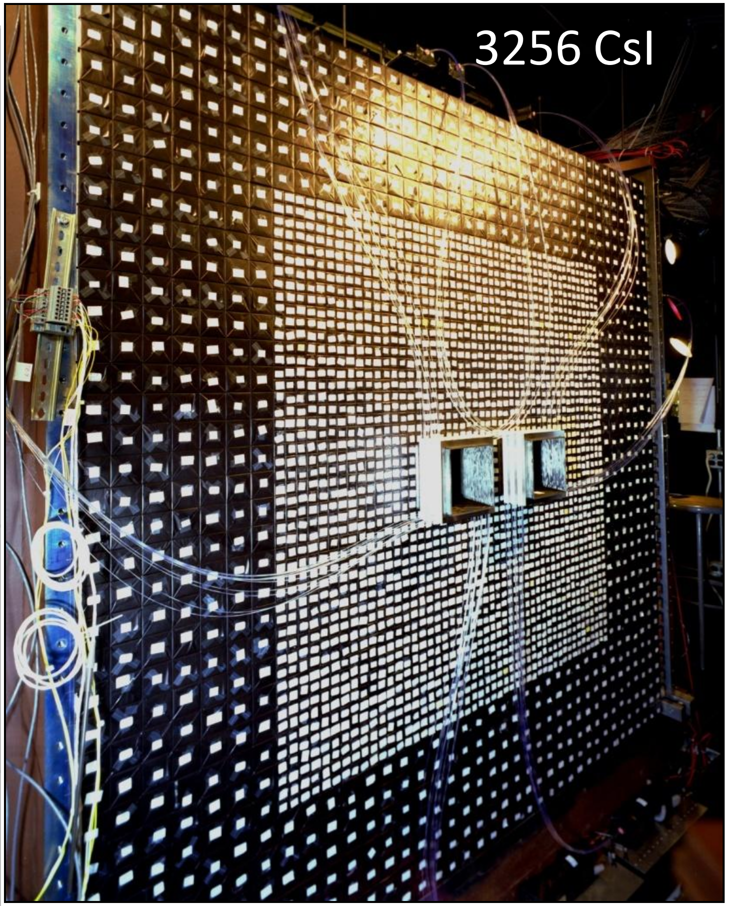
$$\frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt[4]{E}} \oplus \sigma_2$$

$$\sigma_1 = (2.30 \pm 0.03 \pm 0.3)\%$$

$$\sigma_2 = (1.35 \pm 0.08 \pm 0.2)\%$$

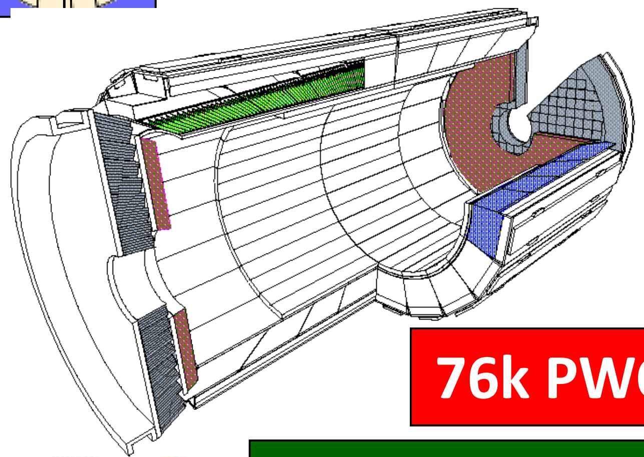
KTeV CsI Position Resolution

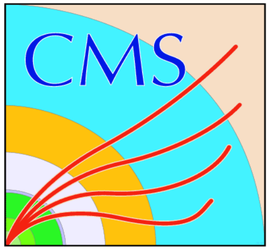




Sub mm position resolution.
L3 BGO & CMS PWO: 0.3 mm.

CMS PWO Resolution

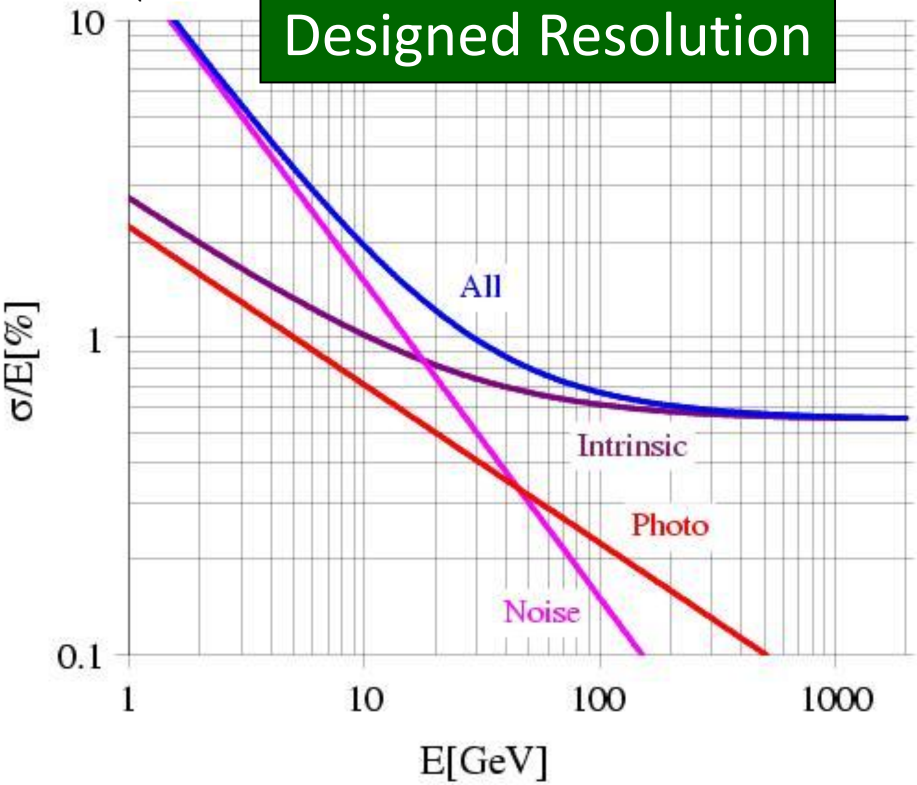


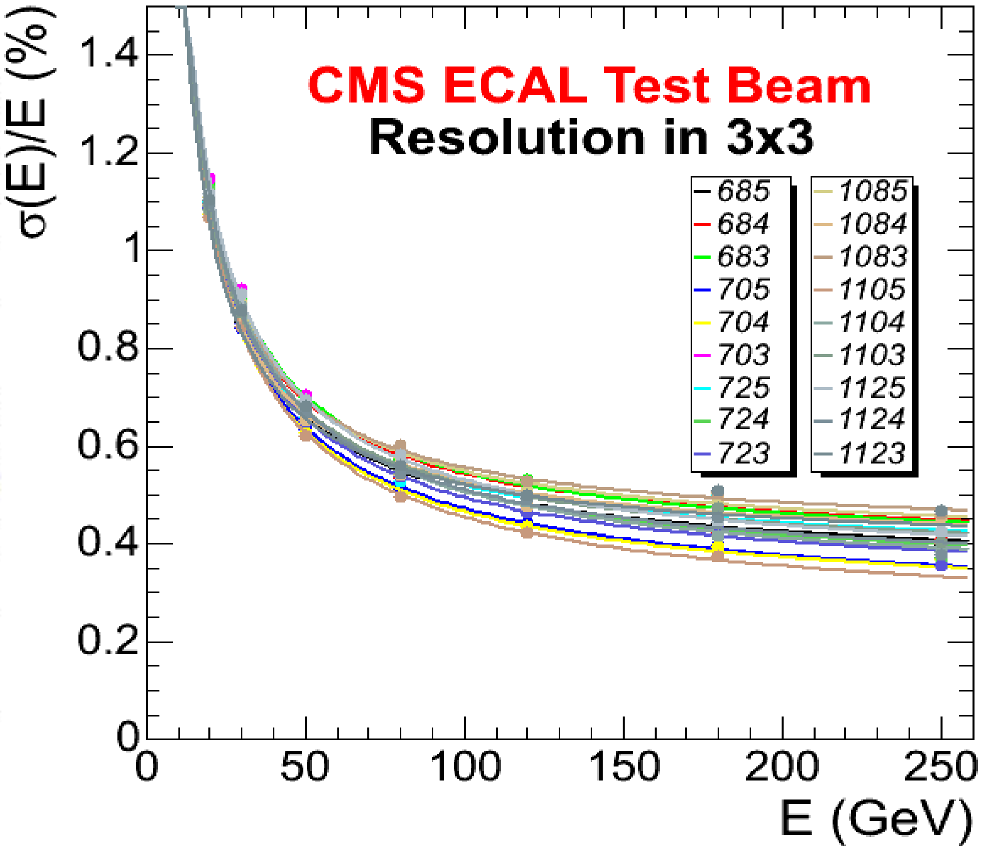


76k PWO, N43-4

Measured Resolution
σ(E)/E < 1% if E > 25 GeV
σ(E)/E ~ 0.5% at 120 GeV

Designed Resolution



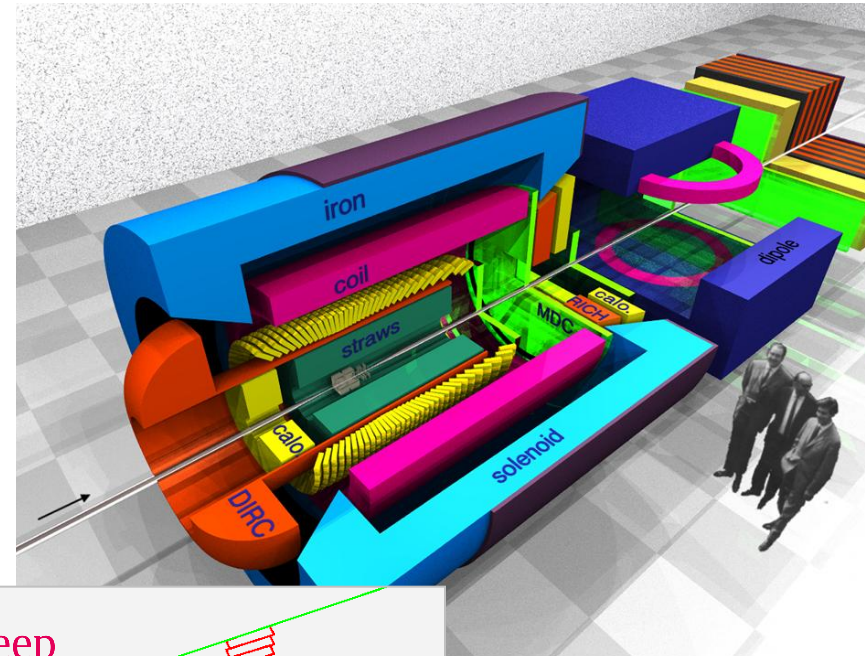


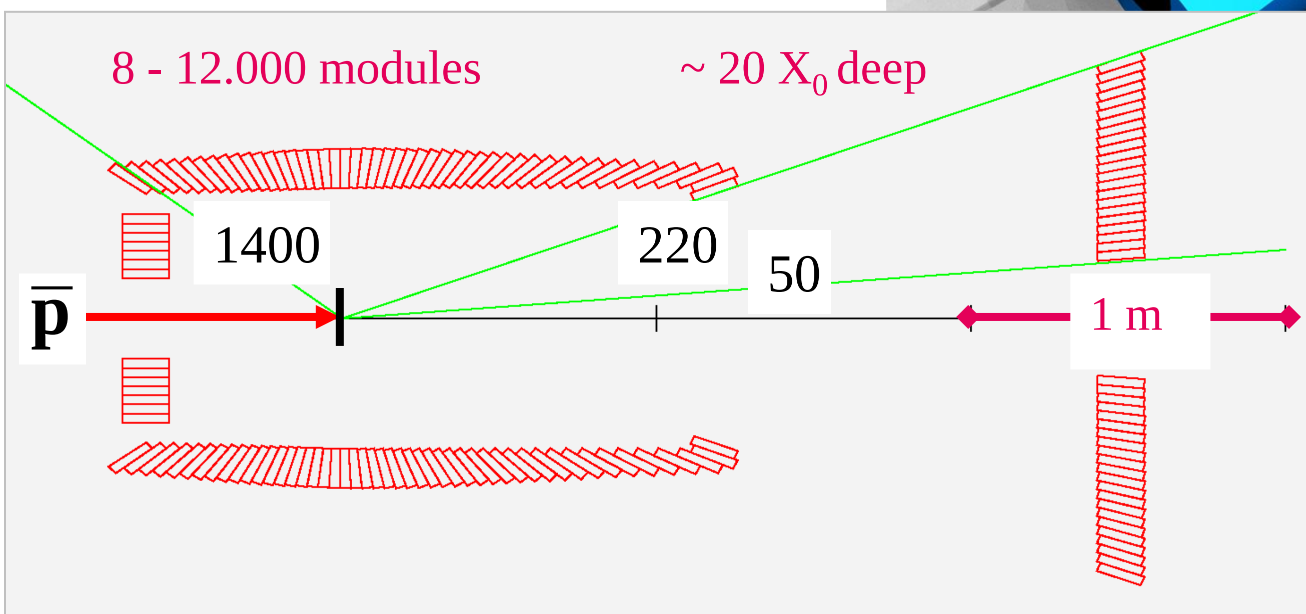
PANDA at GSI, Germany

AntiProton

ANnihilations

at DArmstadt

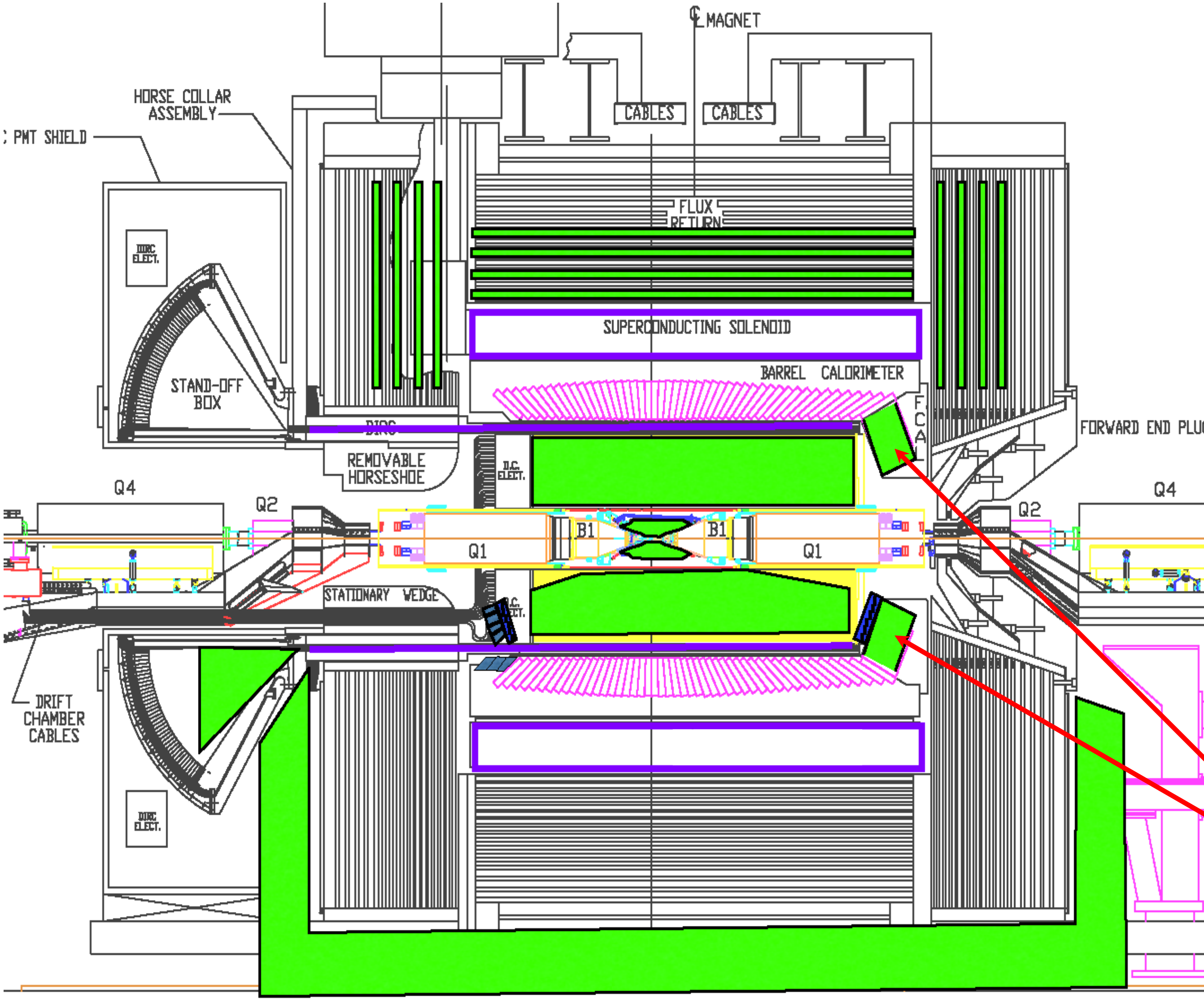




17,000
PWO
N32-2

LYSO Endcap for Super*B*

SuperB Conceptual Design Report, INFN/AE-07/2, March (2007)

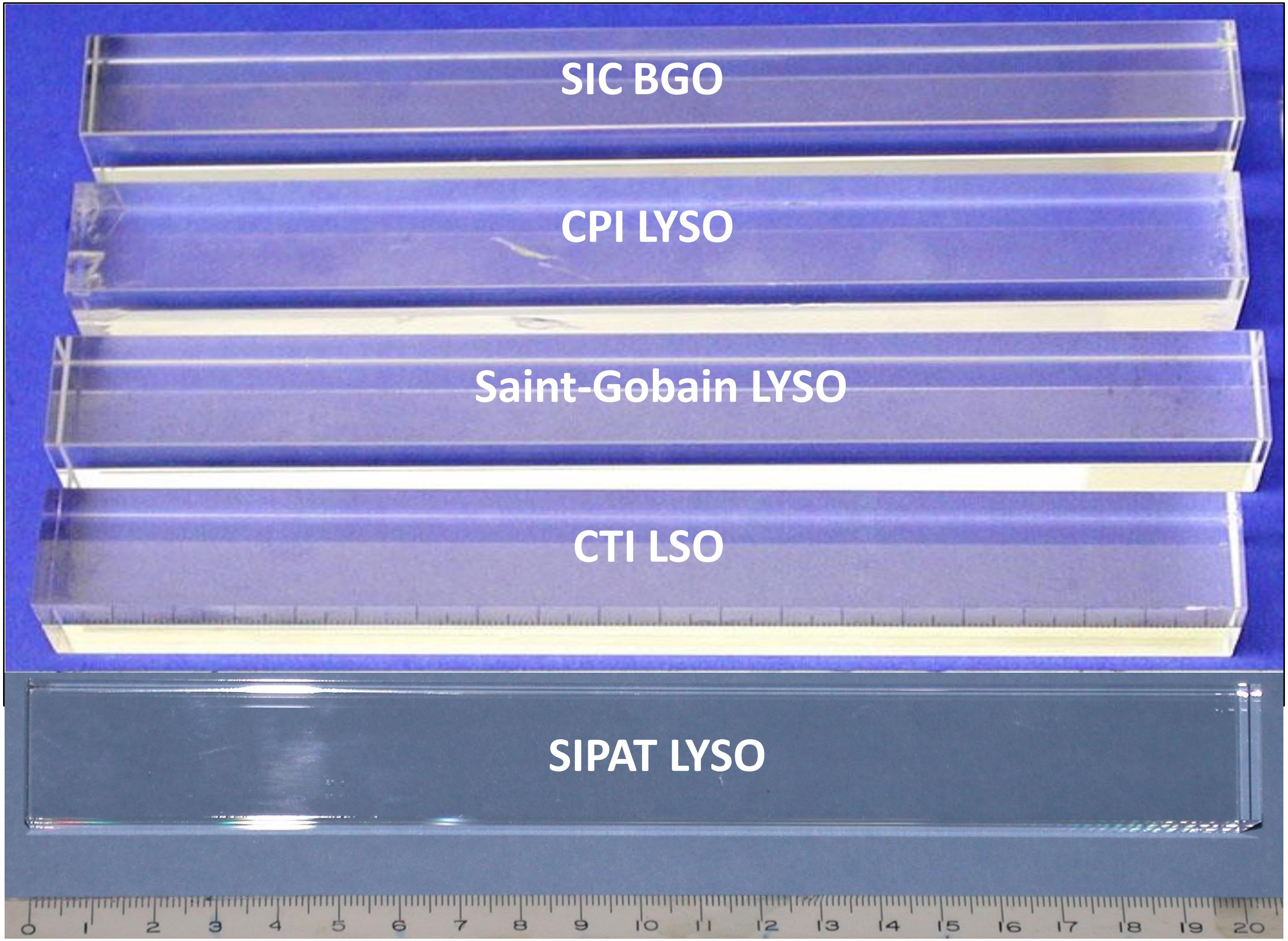


Aiming at 10^{36}/cm^2/s luminosity for rare B decays

Need fast detector with low noise at the endcap

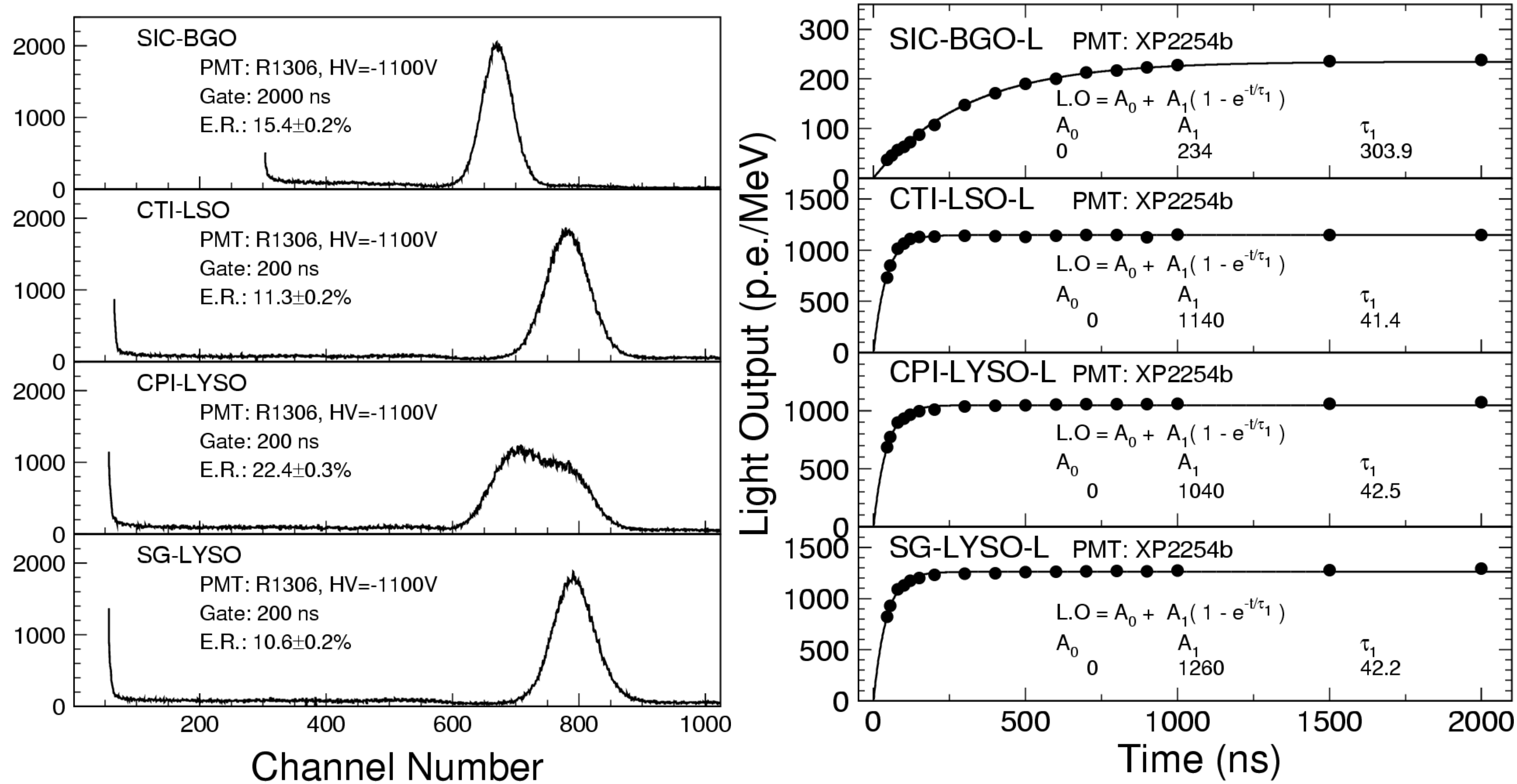
LYSO N43-3

2.5 x 2.5 x 20 cm (18 X_0) Samples



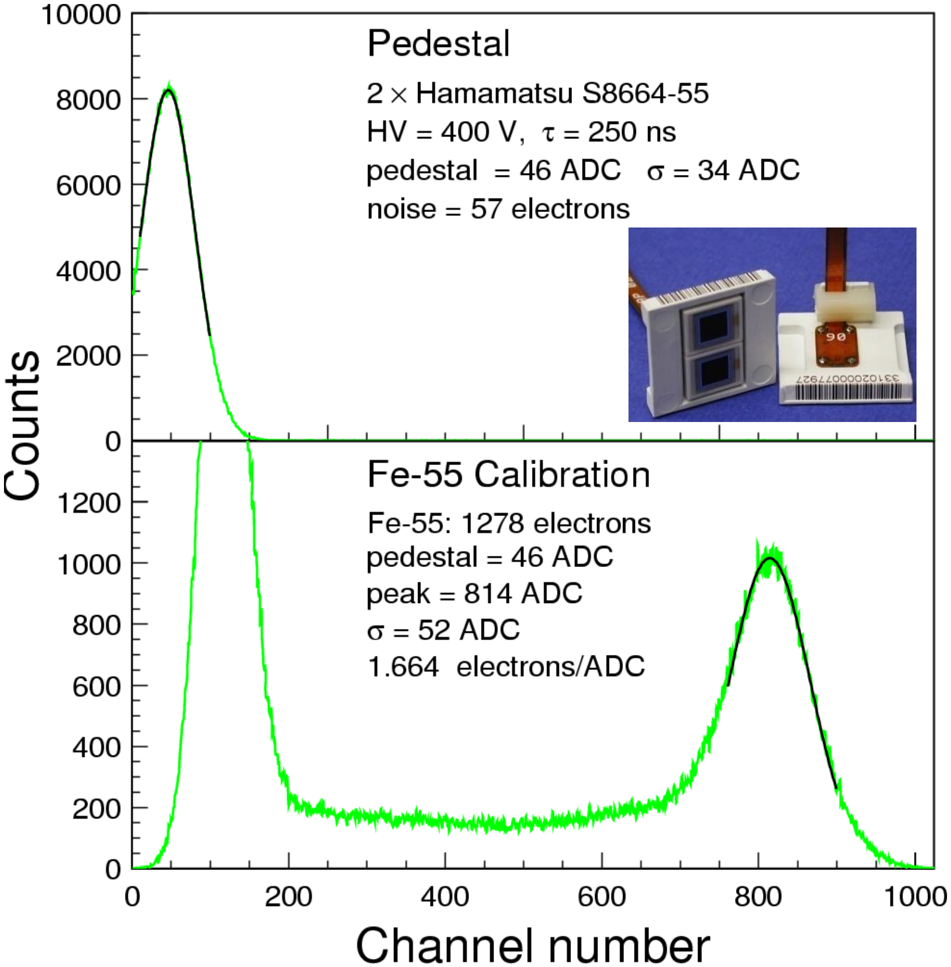
LSO/LYSO with PMT Readout

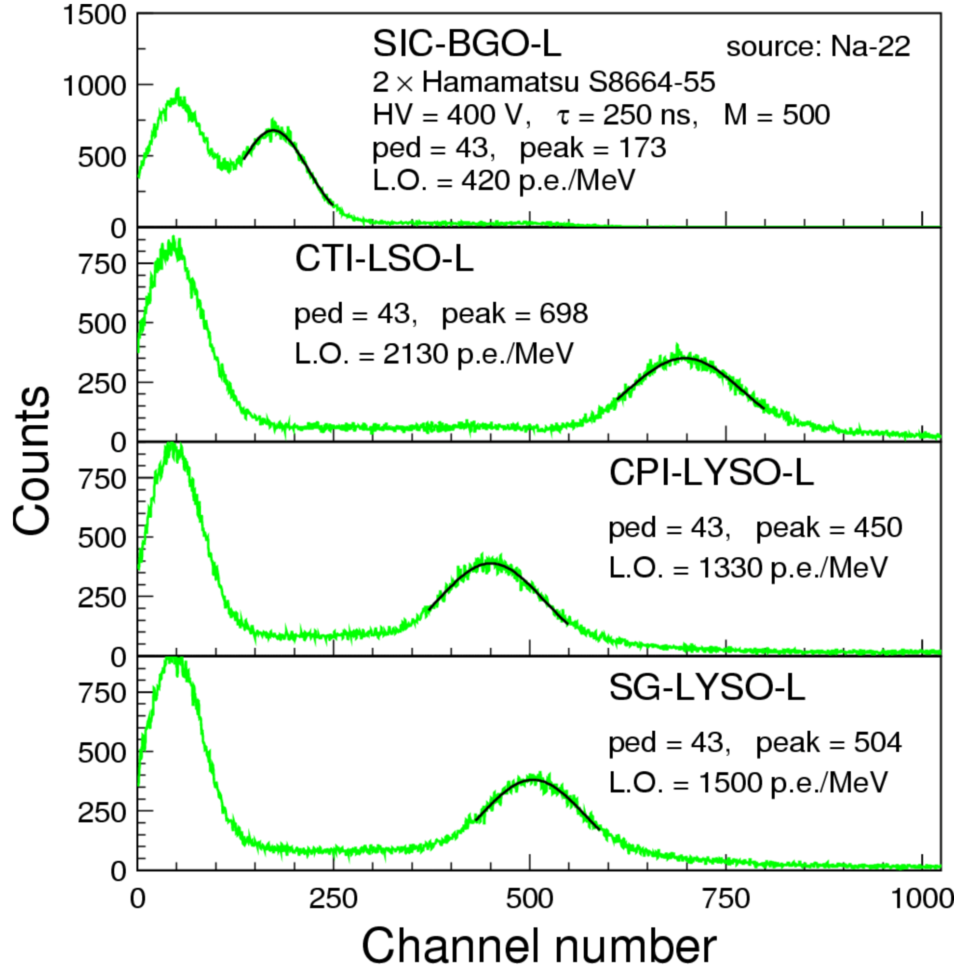
≈10% FWHM resolution for ^{22}Na source (0.51 MeV)
1,200 p.e./MeV, 5/230 times of BGO/PWO



LSO/LYSO with APD Readout

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

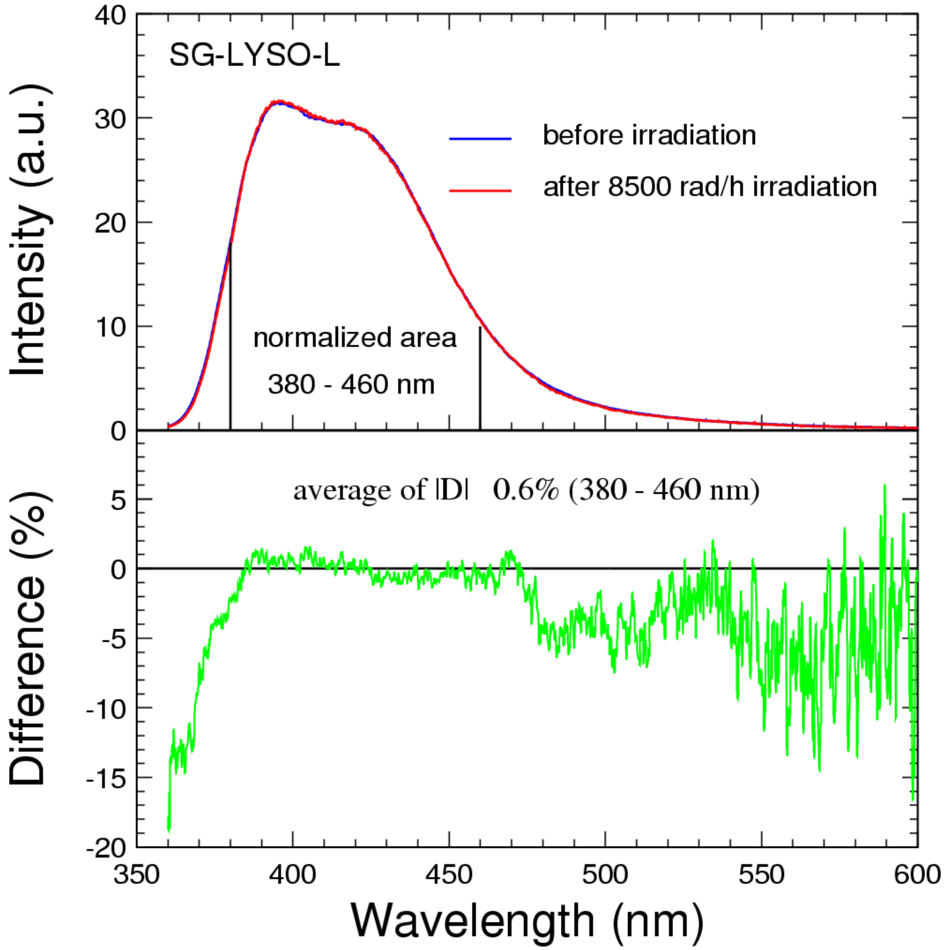


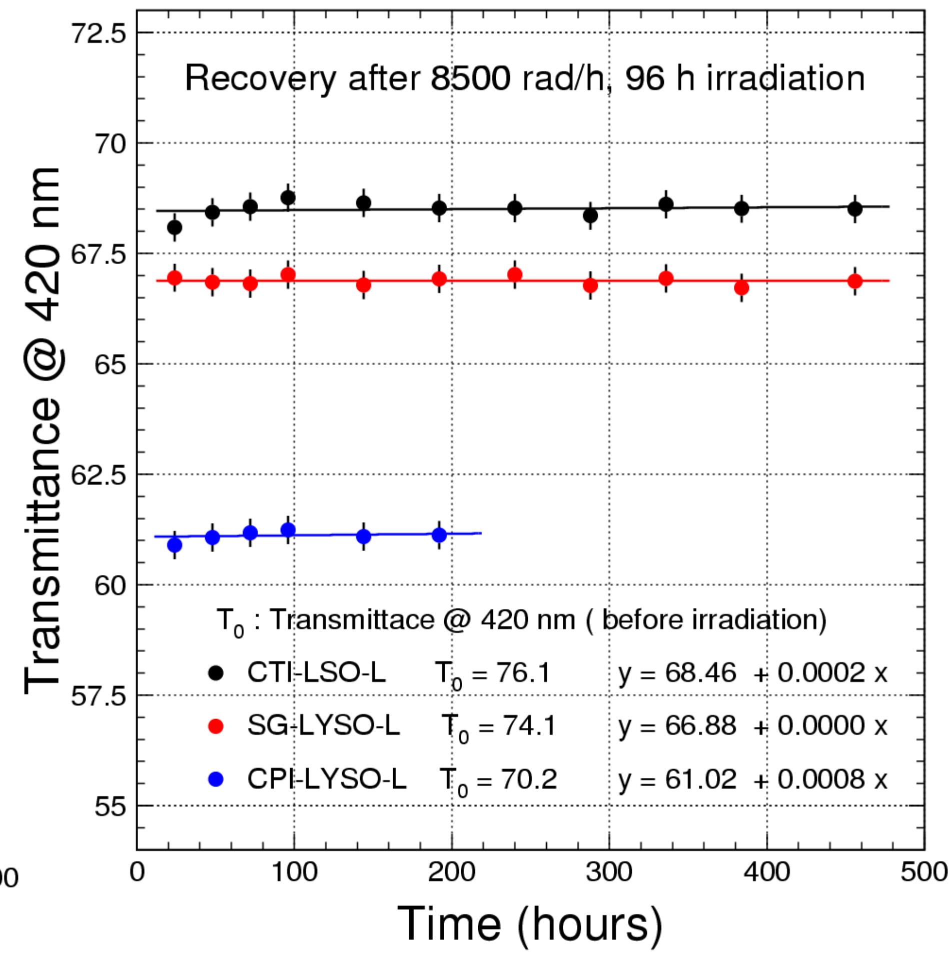


γ-Ray Induced Damage

No damage in Photo-Luminescence

Transmittance recovery slow

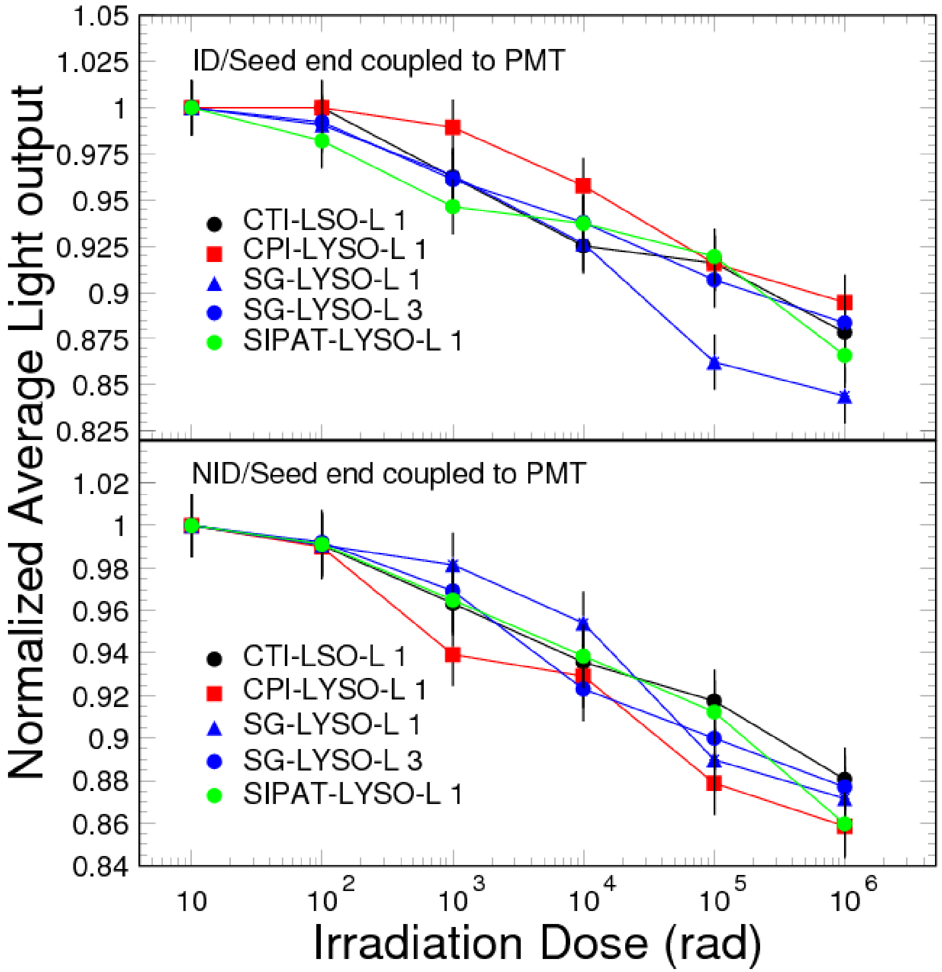




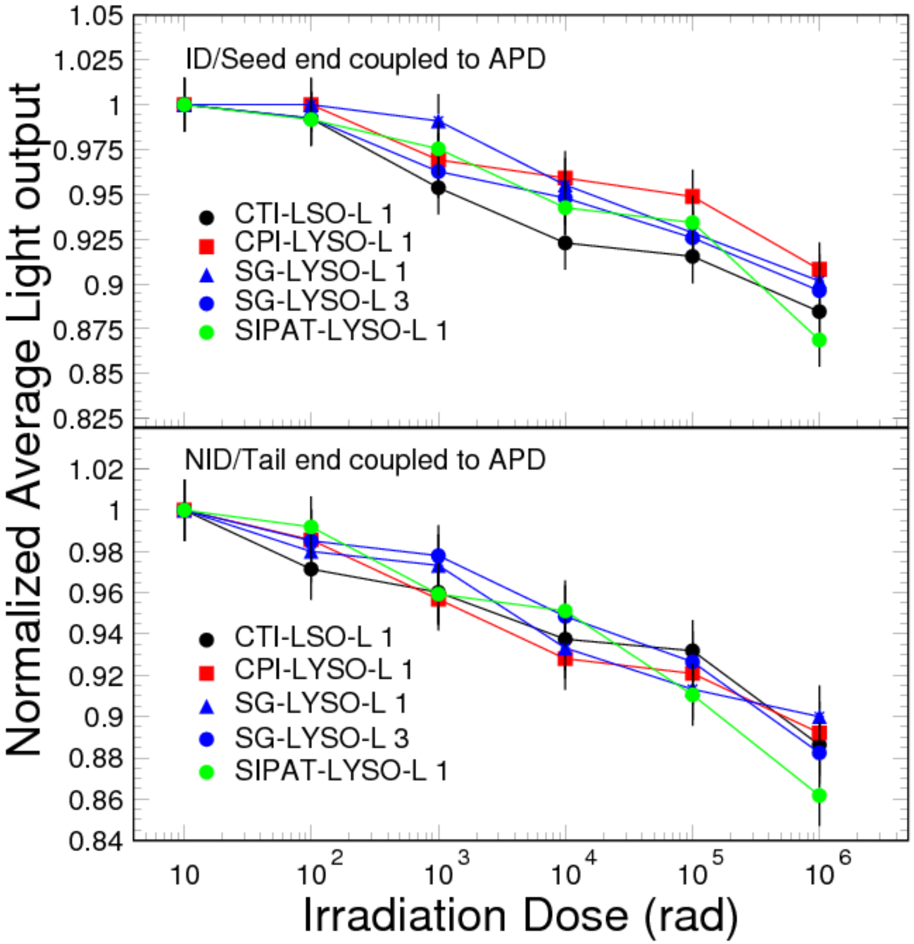
γ-Ray Induced L.O. Damage

All samples show consistent radiation resistance

10% - 15% loss @ 1 Mrad by PMT

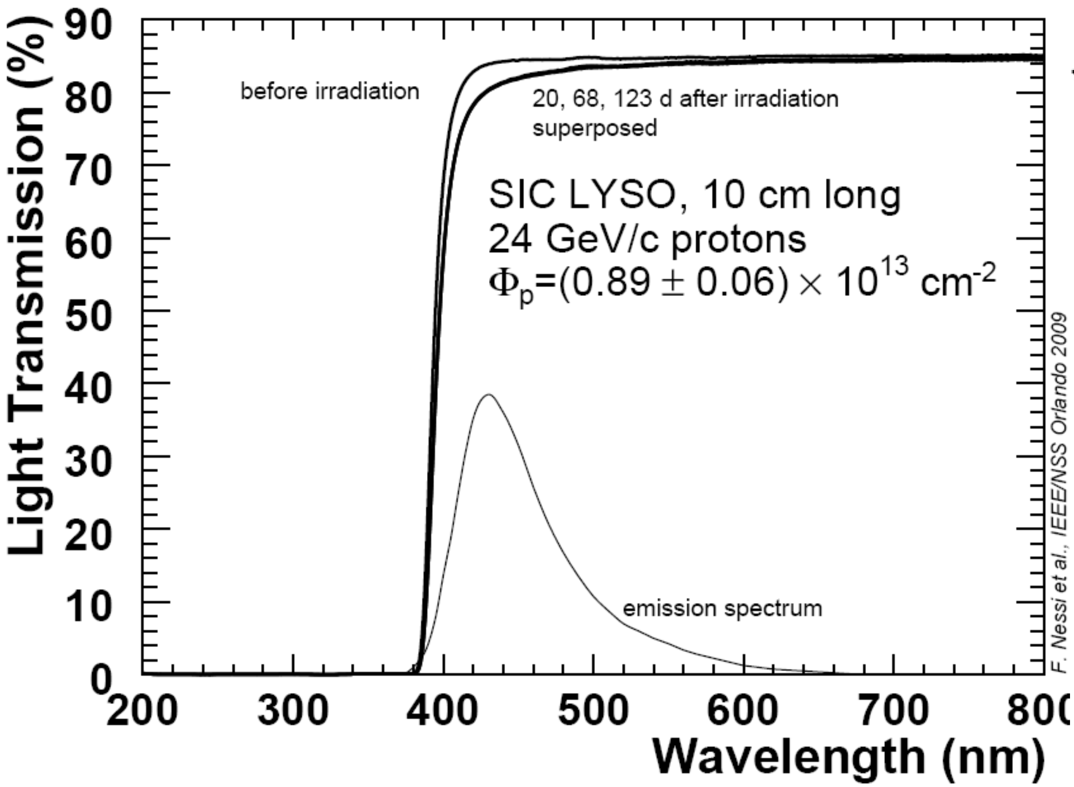


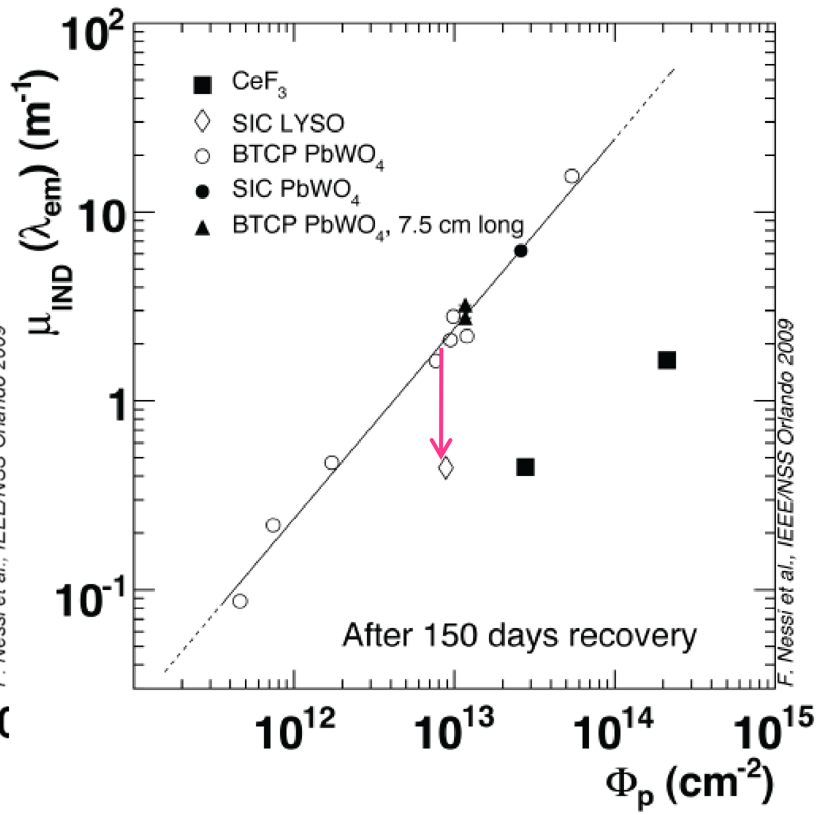
9% - 14% loss @ 1 Mrad by APD



LYSO is Radiation Hard against Charged Hadrons

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





The induced absorption of LYSO is 1/5 of PWO.

LSO/LYSO ECAL Performance

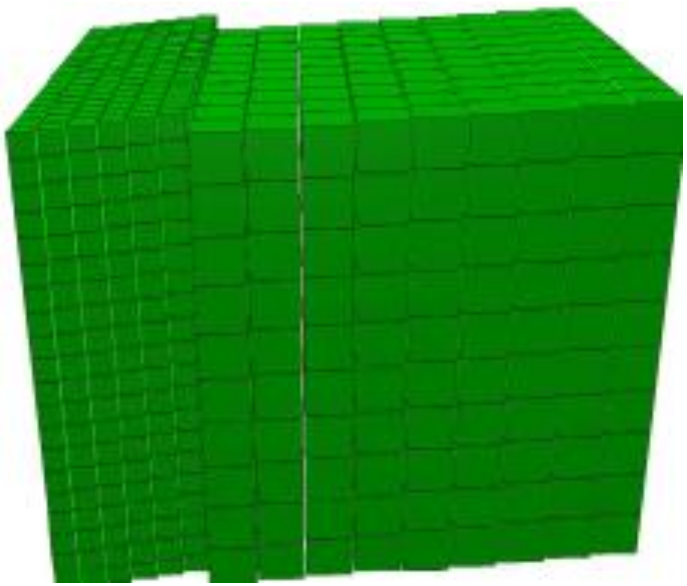
- Less demanding to the environment because of small temperature coefficient.
- Radiation damage is less an issue as compared to other crystals.
- A better energy resolution, $\sigma(E)/E$, at low energies than L3 BGO and CMS PWO because of its high light output and low readout noise:

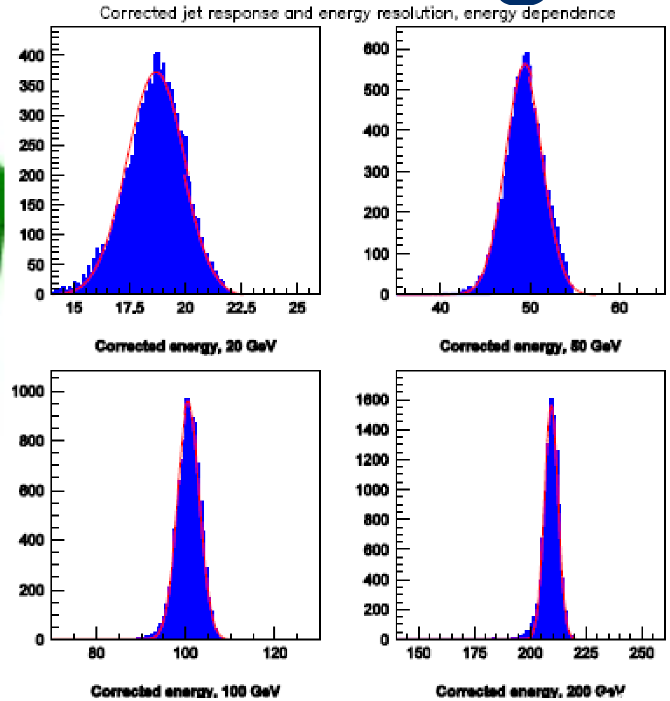
$$2.0\%/\sqrt{E} \oplus 0.5\% \oplus .001/E$$

The Homogeneous HCAL Concept

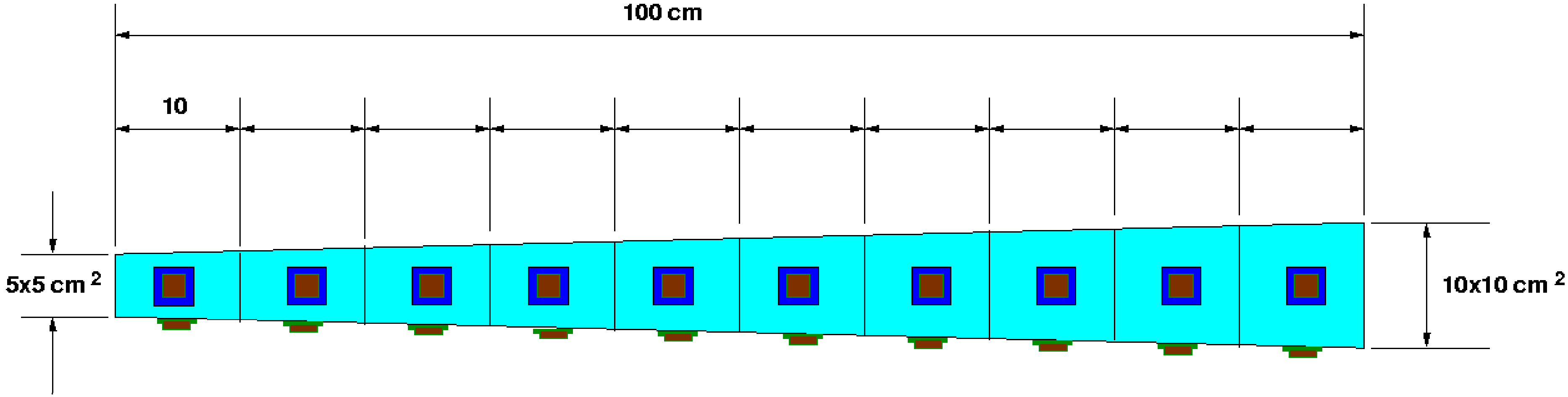
A Fermilab team (A. Para et al.) proposed a total absorption homogeneous HCAL detector concept for the International Linear Collider to achieve good jet mass resolution. It eliminates dead materials between classical ECAL and HCAL. This longitudinal segmented crystal HCAL is possible because of the latest development in compact readout devices, such Si PMT. Readout with both Cherenkov and Scintillation light would further help as demonstrated by the Dream collaboration (R. Wigwams et al.).

HHCAL Design





A. Para, ILCWS08, Chicago: GEANT simulation shows jet energy resolution of about 22%/√E after corrections. This is much better than what has been achieved with PFA.



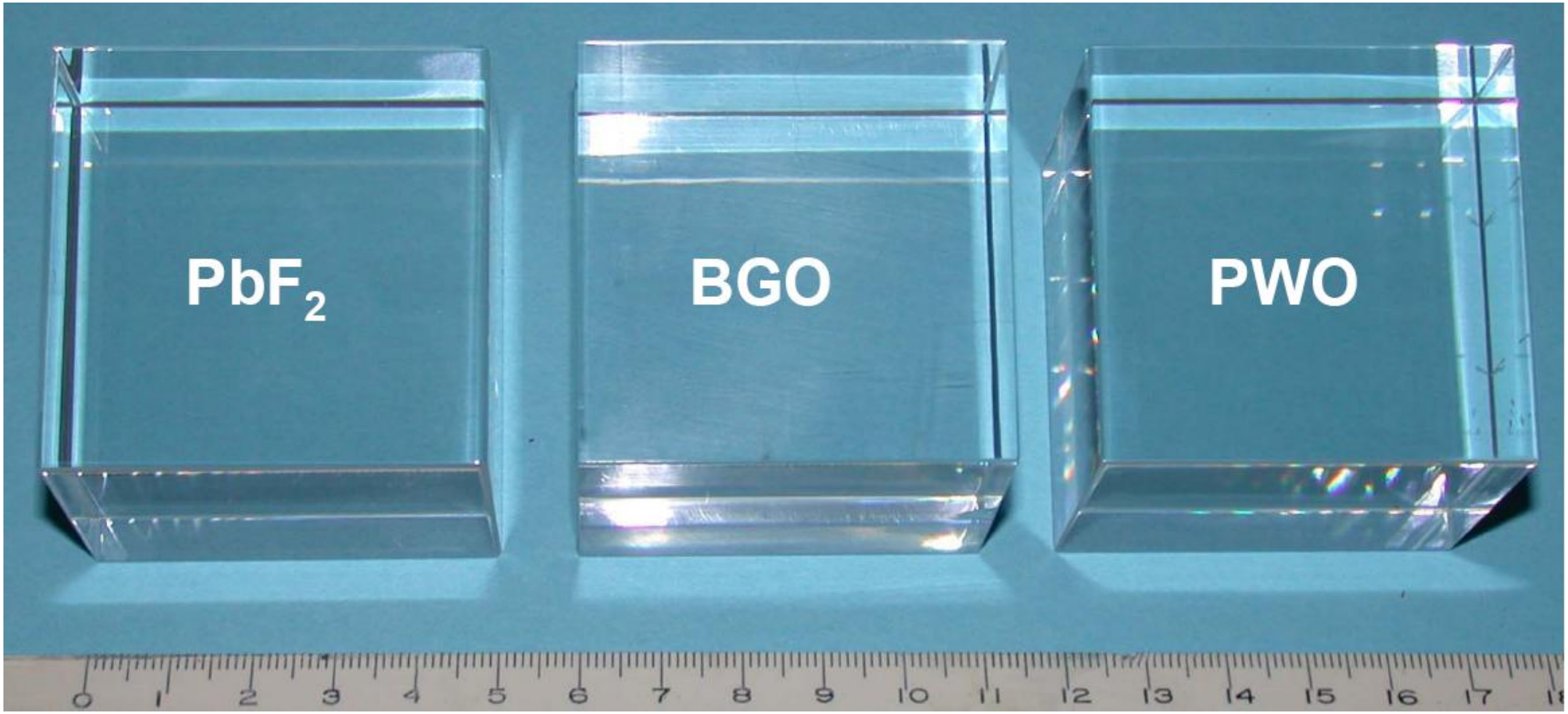
R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry

Comparison of Crystals for TAHCAL

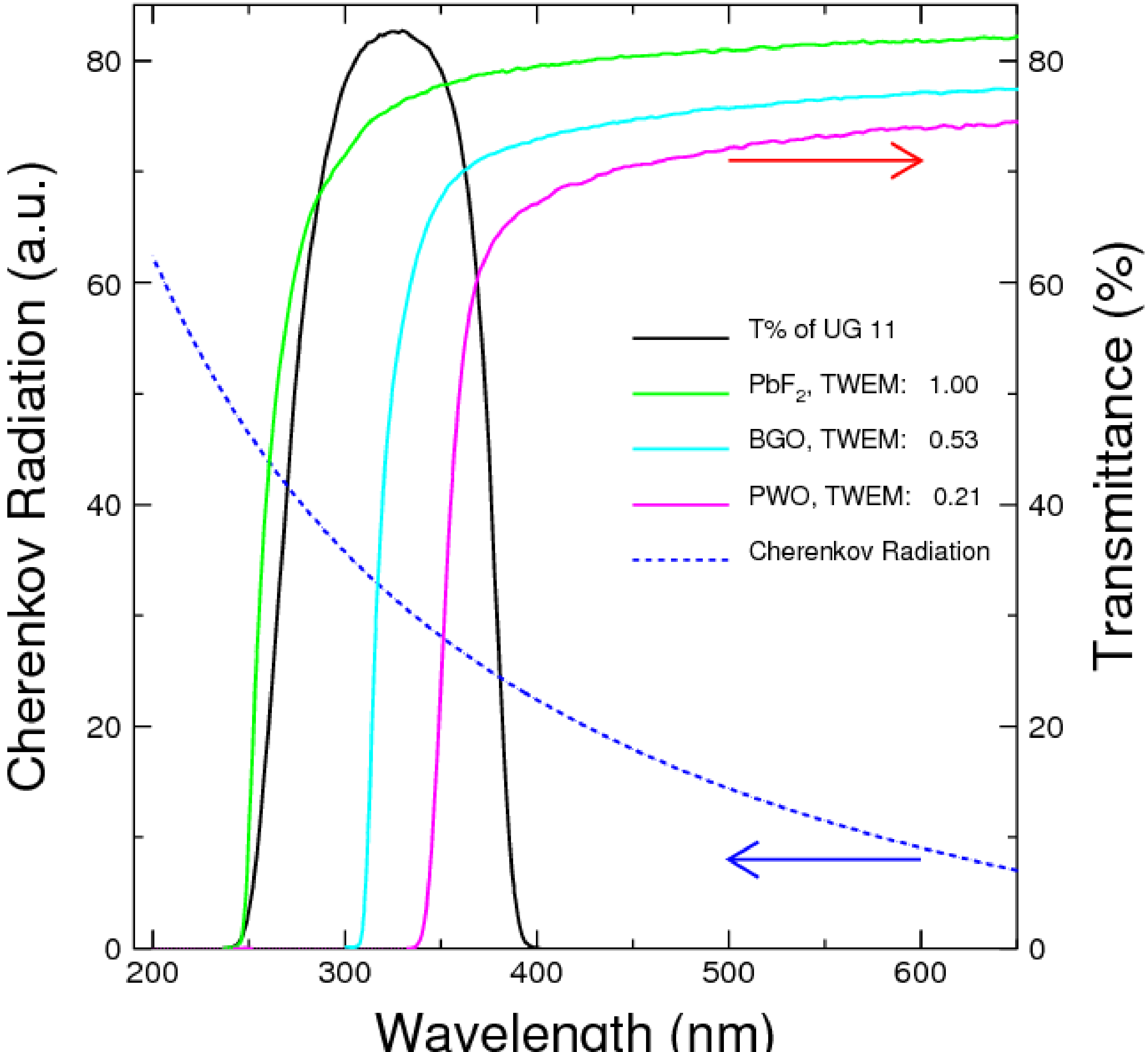
Parameters	$Bi_4Ge_3O_{12}$ (BGO)	$Bi_4Si_3O_{12}$ (BSO)	PbF_2 (PbF)	$PbWO_4$ (PWO)	$NaBi(WO_4)_2$ (NBW)
ρ (g/cm^3)	7.13	6.8?	**7.77**	**8.3**	7.58
λ_I (cm)	22.8	23.1	**21.0**	**20.7**	21.2
n @ λ_{max}	2.15	2.06	1.82	2.2	2.15
τ_{decay} (ns)	300	100	?	10-30 /10-200	?
λ_{max} (nm)	480	470	?	420/512	440
Cut-off λ (nm)	300	295	260	350/400	340
Light Output (%)	100	20	**?**	2	<1
Melting point (°C)	1050	1030	**842**	**1123**	923
Raw Material Cost (%)	100	47	**29**	49	51

Crystal for Homogeneous HCAL

Crystals of high density, good UV transmittance and some scintillation light, not necessary bright and fast, are required.
The volume needed is 70 to 100 m^3: cost-effective material.
Following 2/19/08 workshop at SICCAS, 5 x 5 x 5 cm samples evaluated



Cherenkov Needs UV Transparency

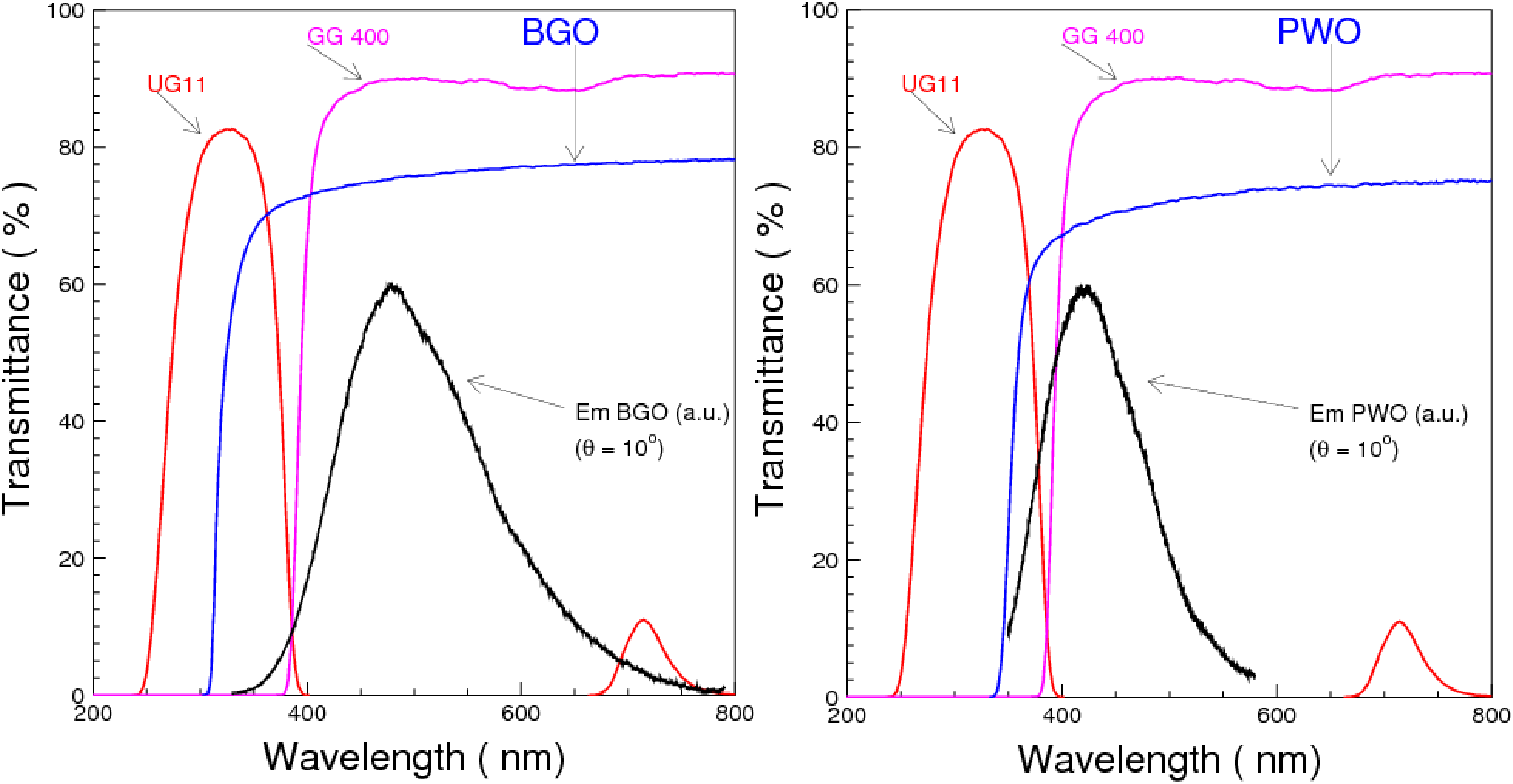


Cherenkov figure of merit

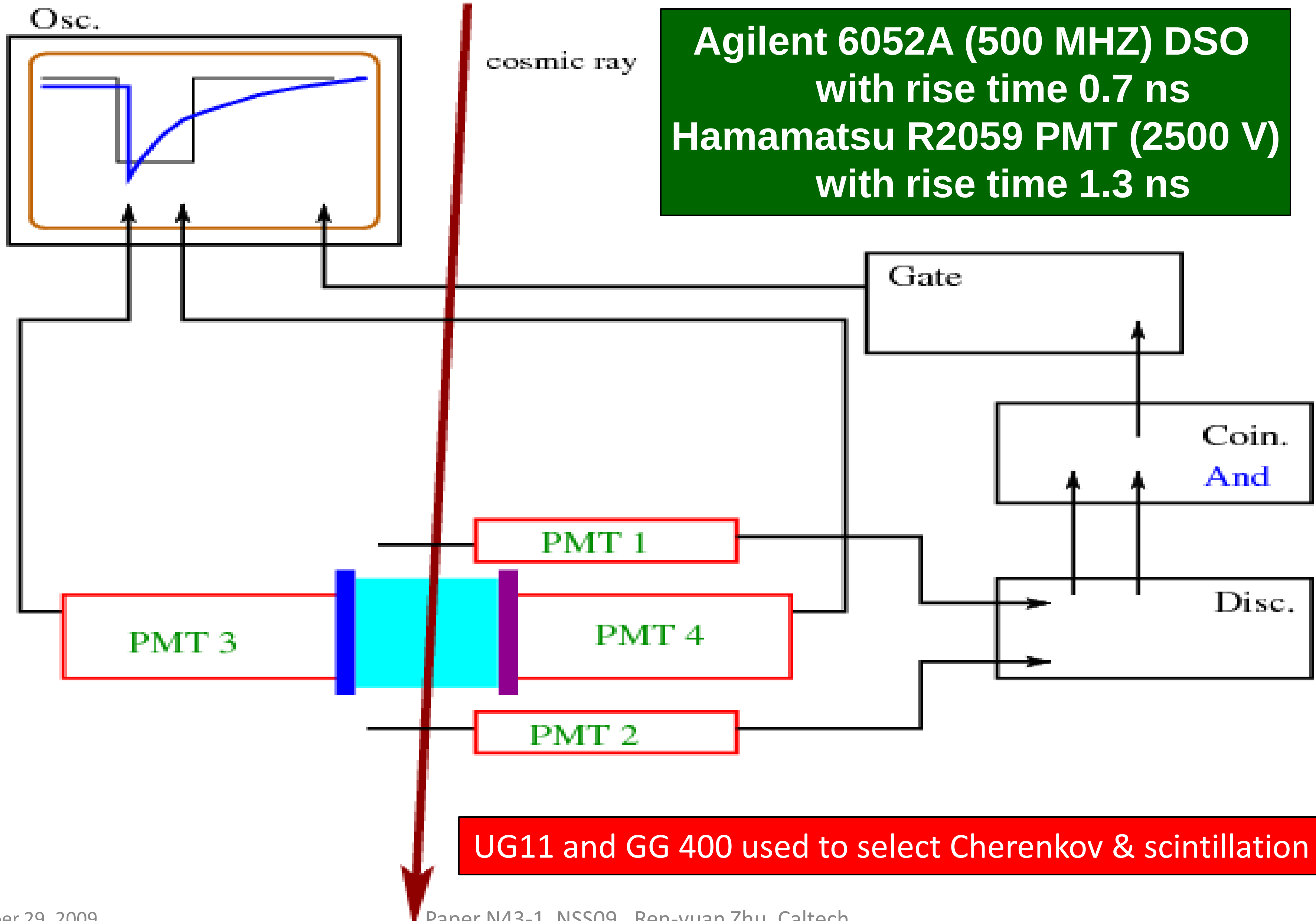
Using UG11 optical filter Cherenkov light can be effectively selected with negligible contamination from scintillation

Scintillation Selected with Filter

GG400 optical filter effectively selects scintillation light with very small contamination from Cherenkov



Cosmic Setup with Dual Readout

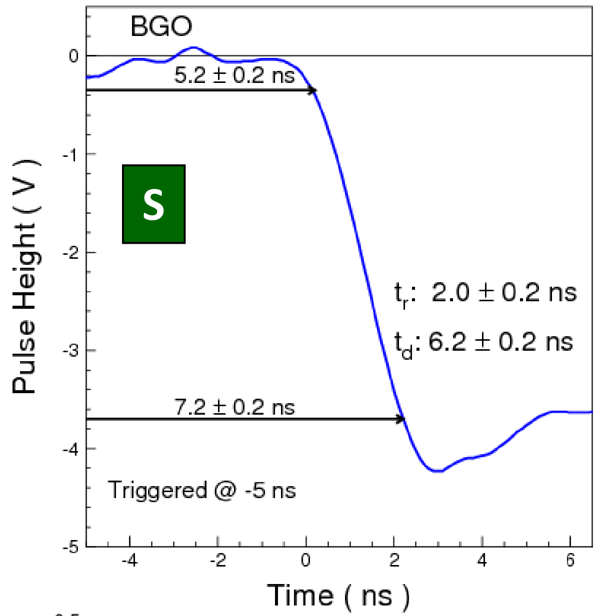


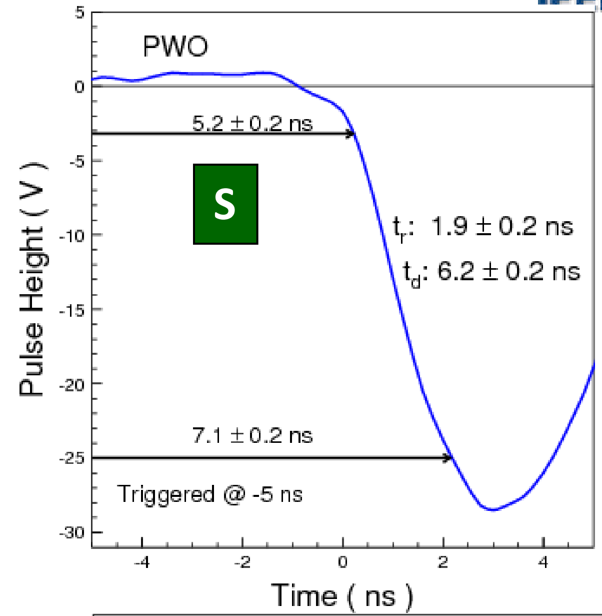
Agilent 6052A (500 MHZ) DSO with rise time 0.7 ns
Hamamatsu R2059 PMT (2500 V) with rise time 1.3 ns

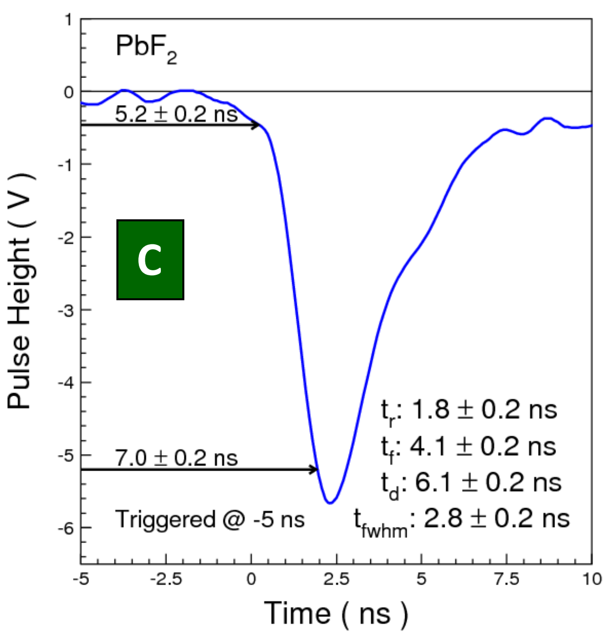
UG11 and GG 400 used to select Cherenkov & scintillation

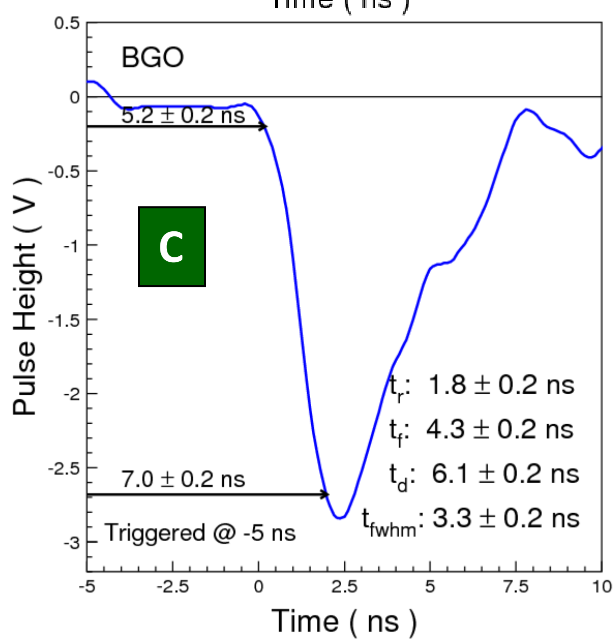
No Discrimination in Front Edge

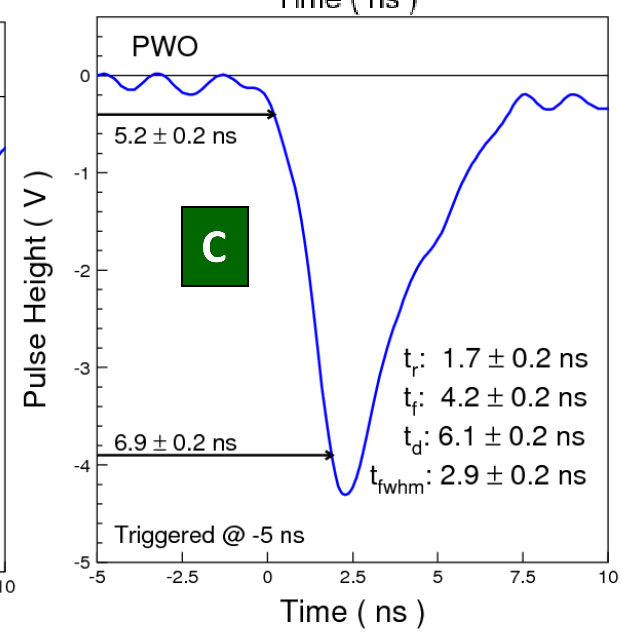
Consistent timing and rise time for all Cherenkov and scintillation light pulses observed.





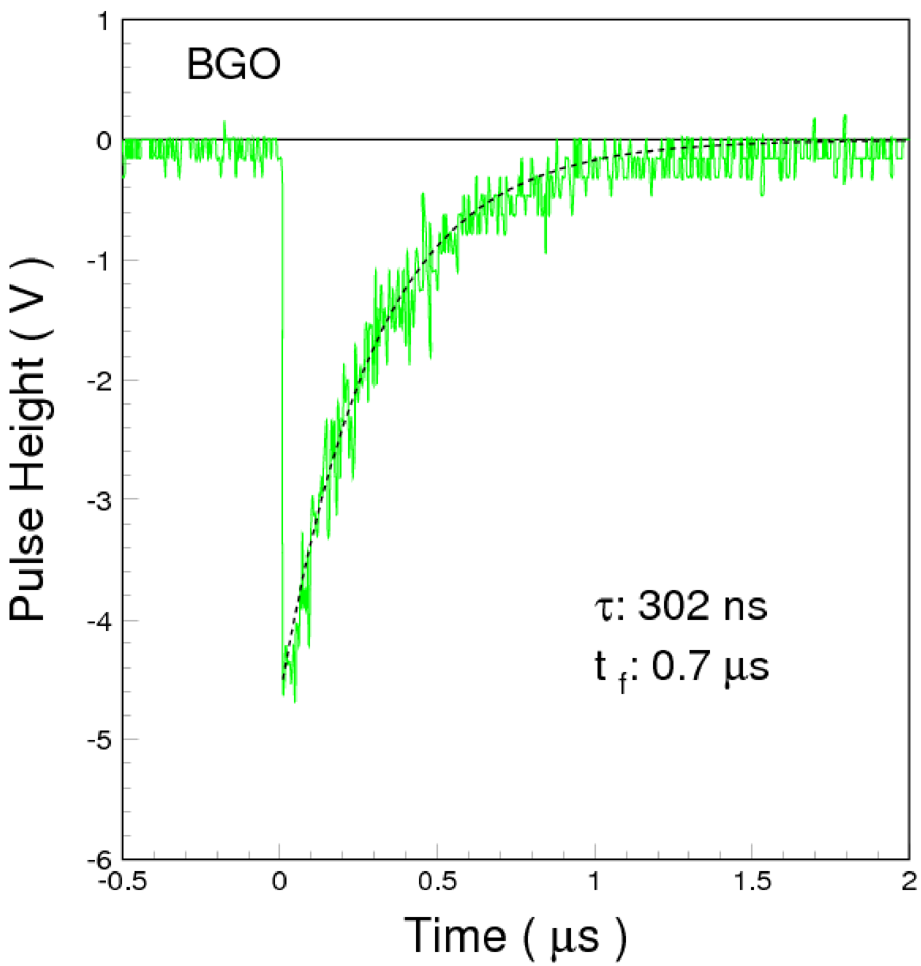


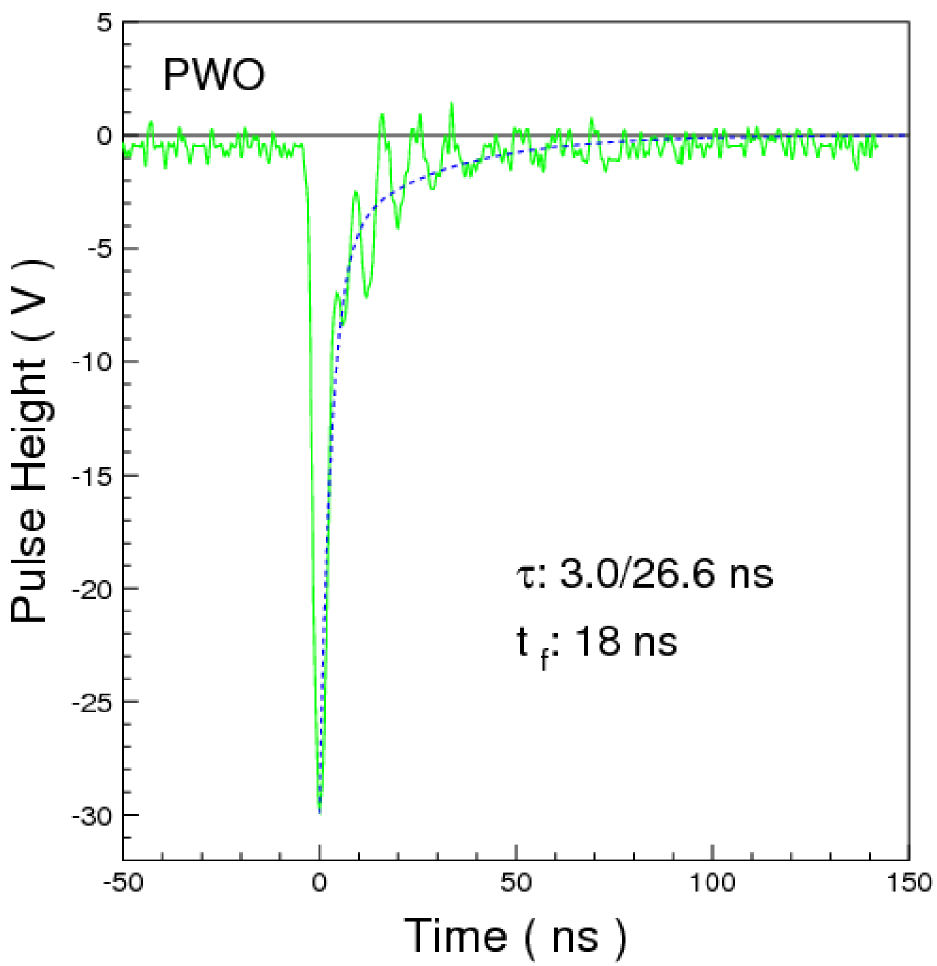




Slow Scintillation Decay May be Used

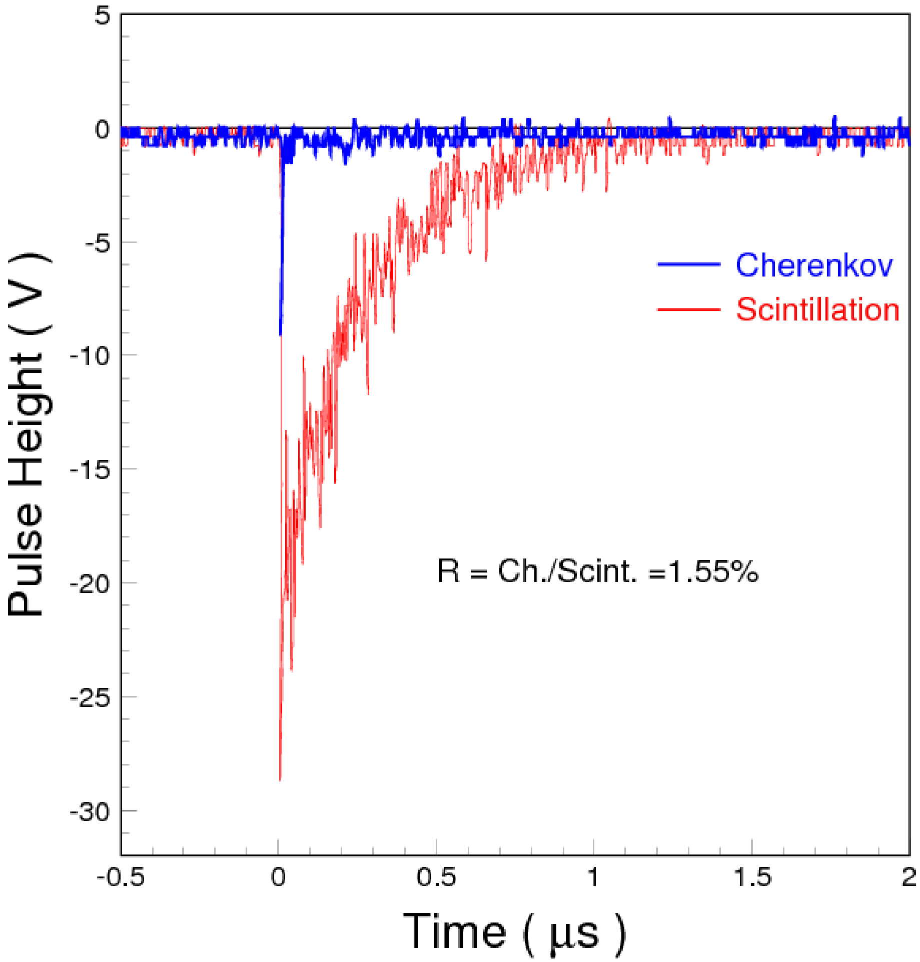
After 15 ns no Cherenkov contamination

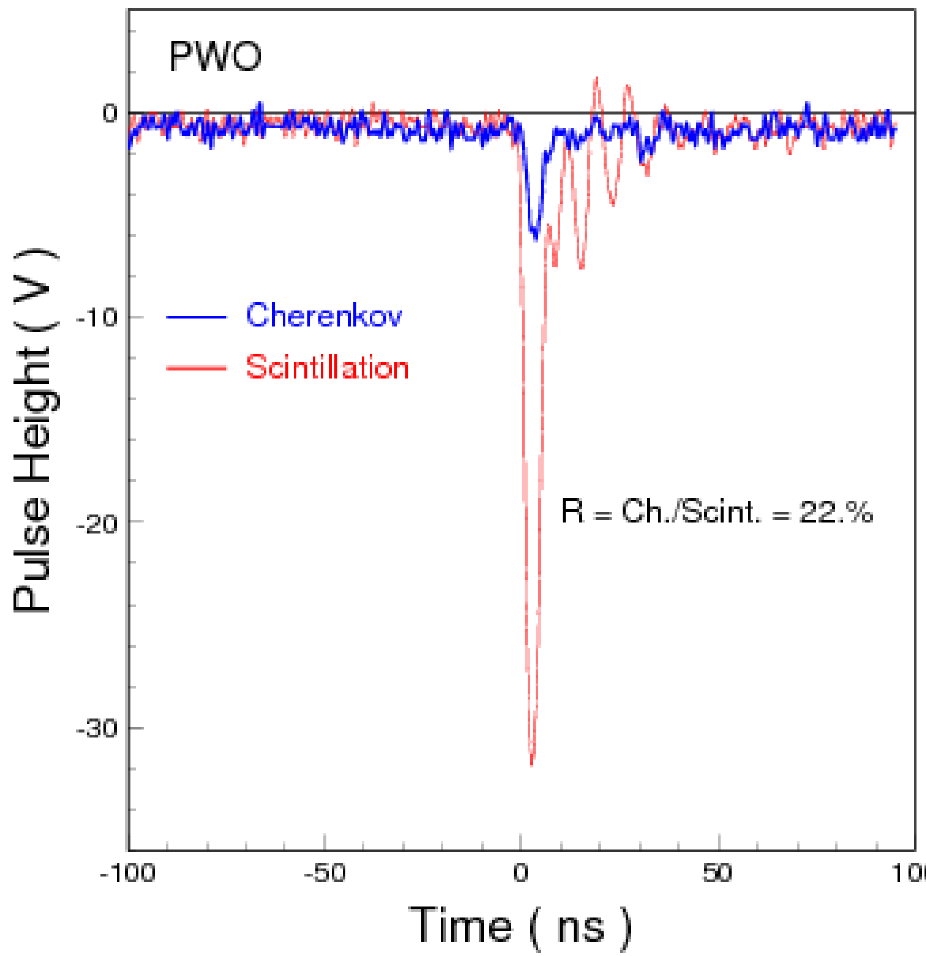




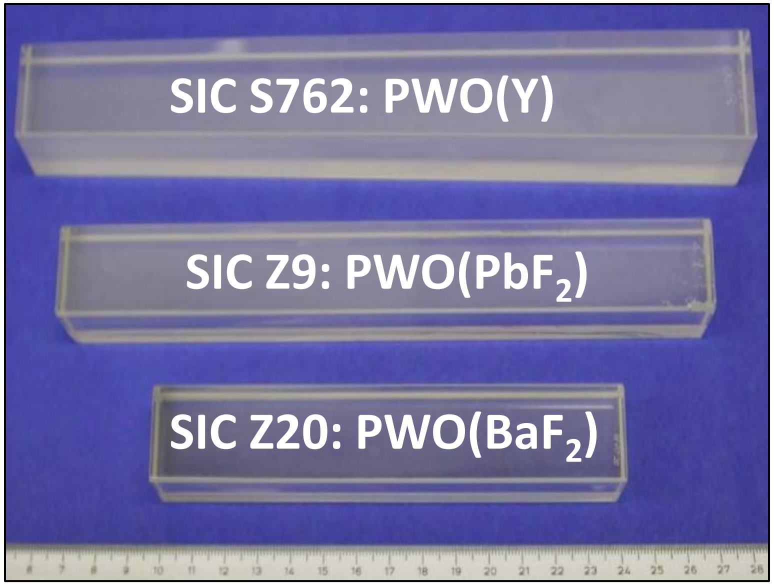
Ratio of Cherenkov/Scintillation

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



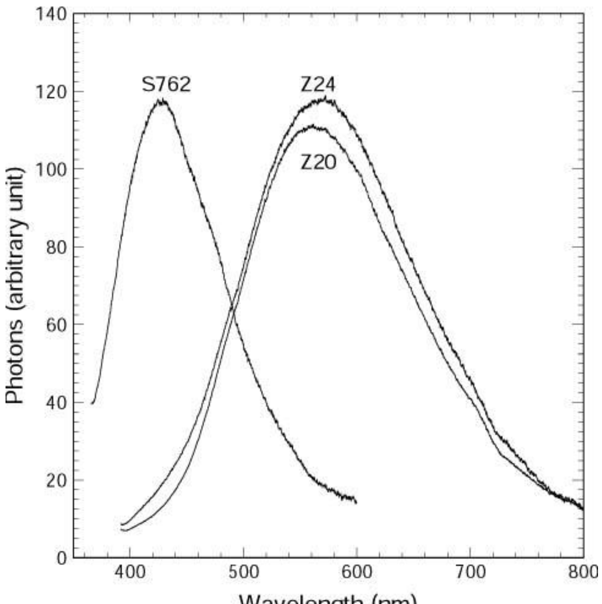


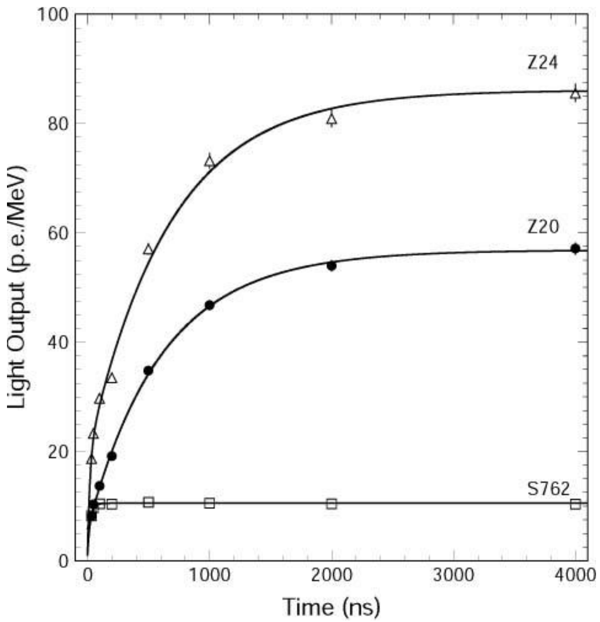
Green Slow Scintillation in PWO

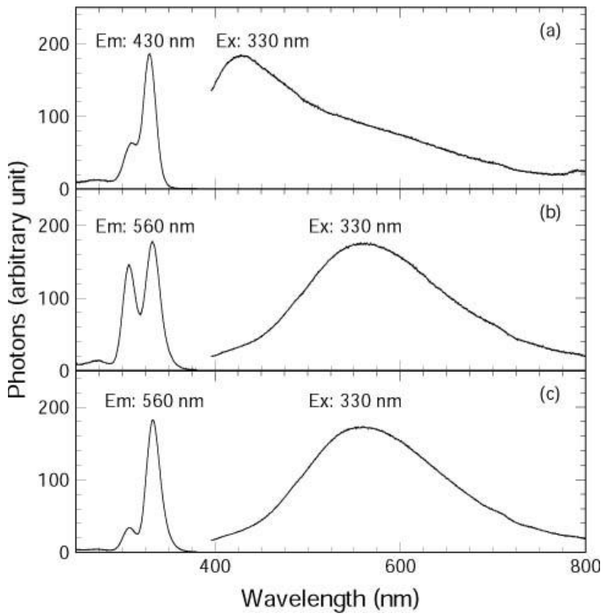


A factor of ten intensity of slow (μs) green scintillation light (560 nm) was observed in PbF_2/BaF_2 doped PWO.

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

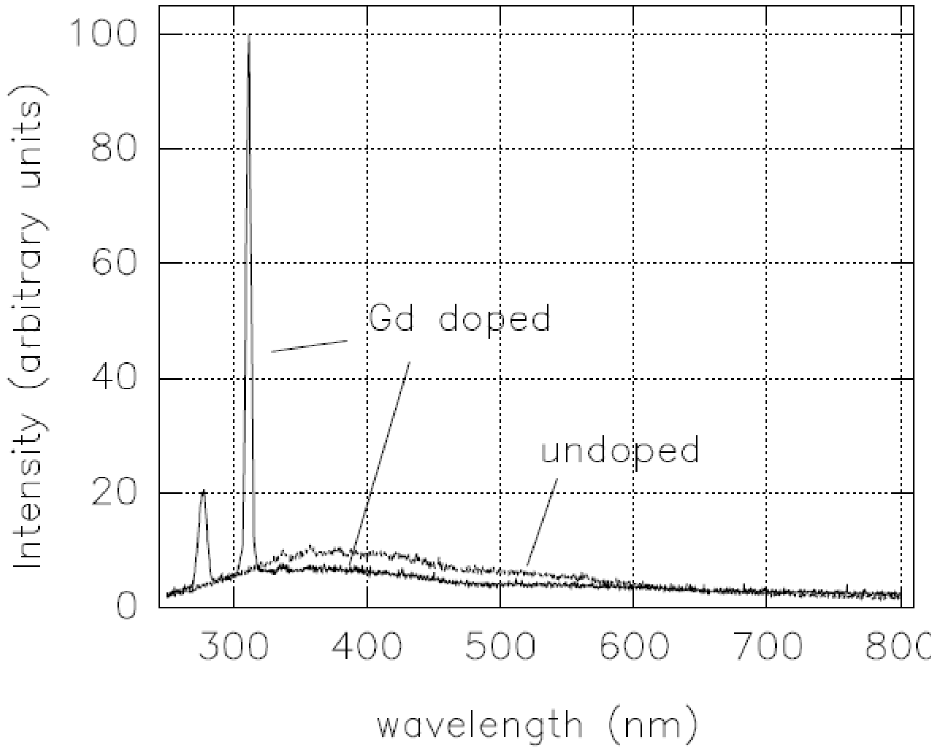




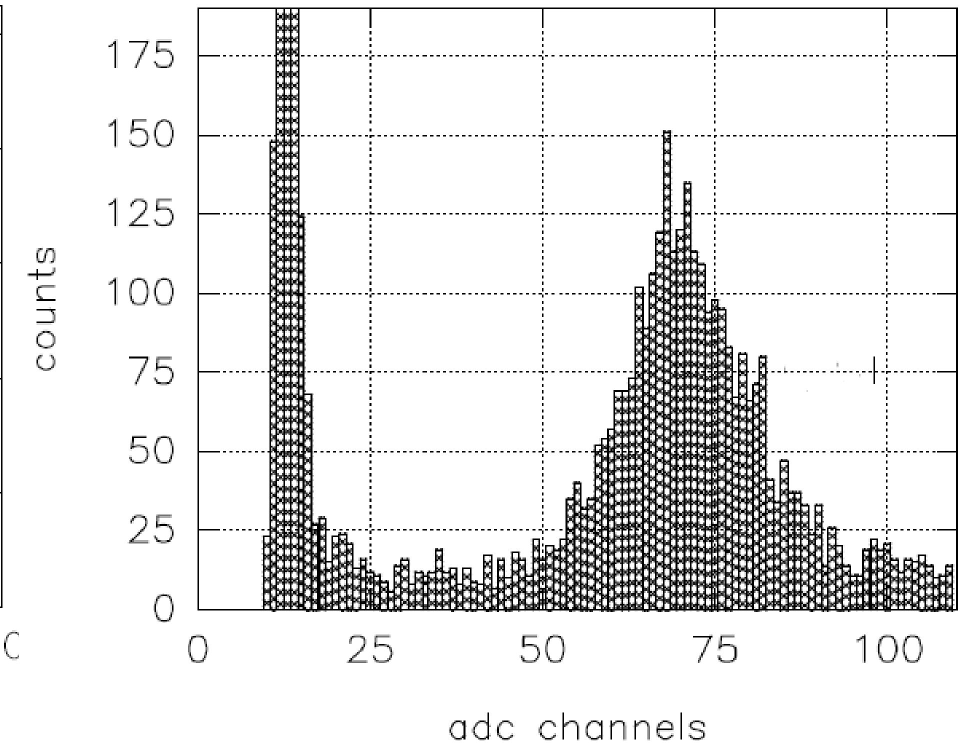


Scintillation was Observed in PbF_2(Gd)

Scintillation of PbF_2(Gd)



PbF_2(Gd) Response to MIP of 1 GeV/c



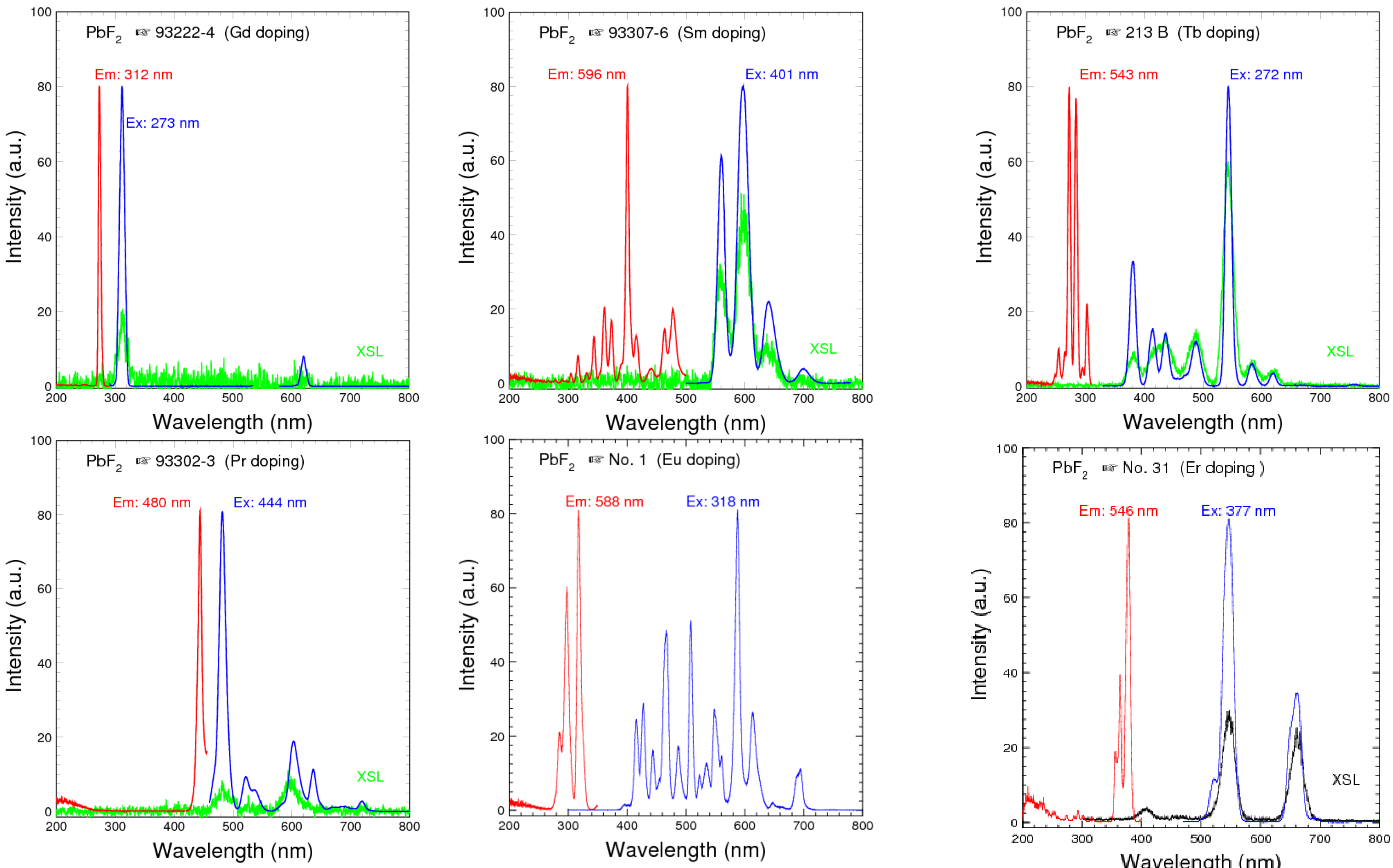
Fast Scintillation of 6.5 p.e./MeV with decay time of less than 10 ns

D. Shen *at al., Jour. Inor. Mater* **Vol. 101** 11 (1995).
C. Woody *et al., IEEE Trans. Nucl. Sci.* ***43*** *(1996) 1303*.

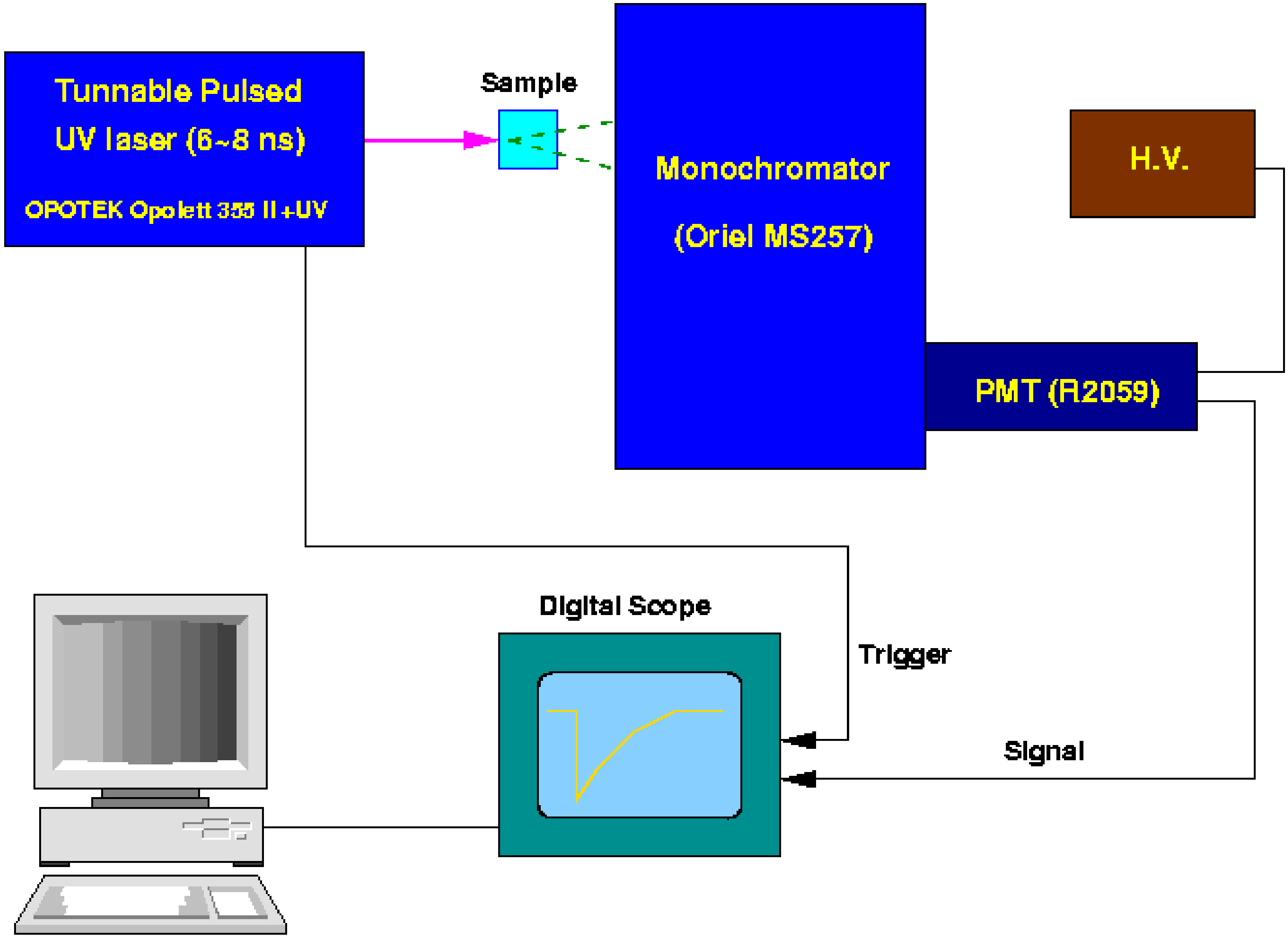
See N40-2

Luminescence Observed in PbF_2

Consistent Photo- and X-luminescence observed in doped PbF_2 samples grown by Prof. Dingzhong Shen of SIC/Scintibow.

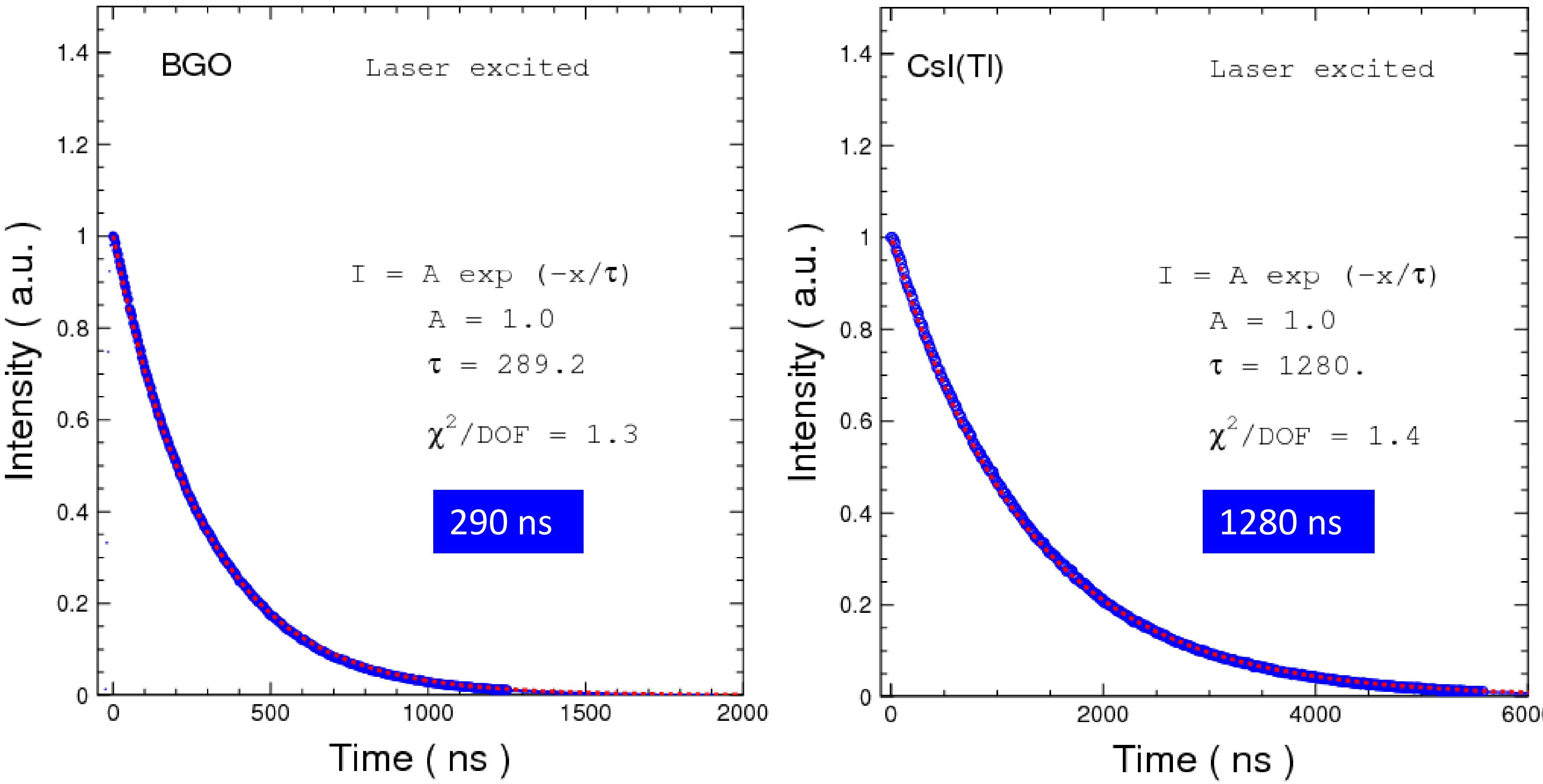


Decay Time Measurement



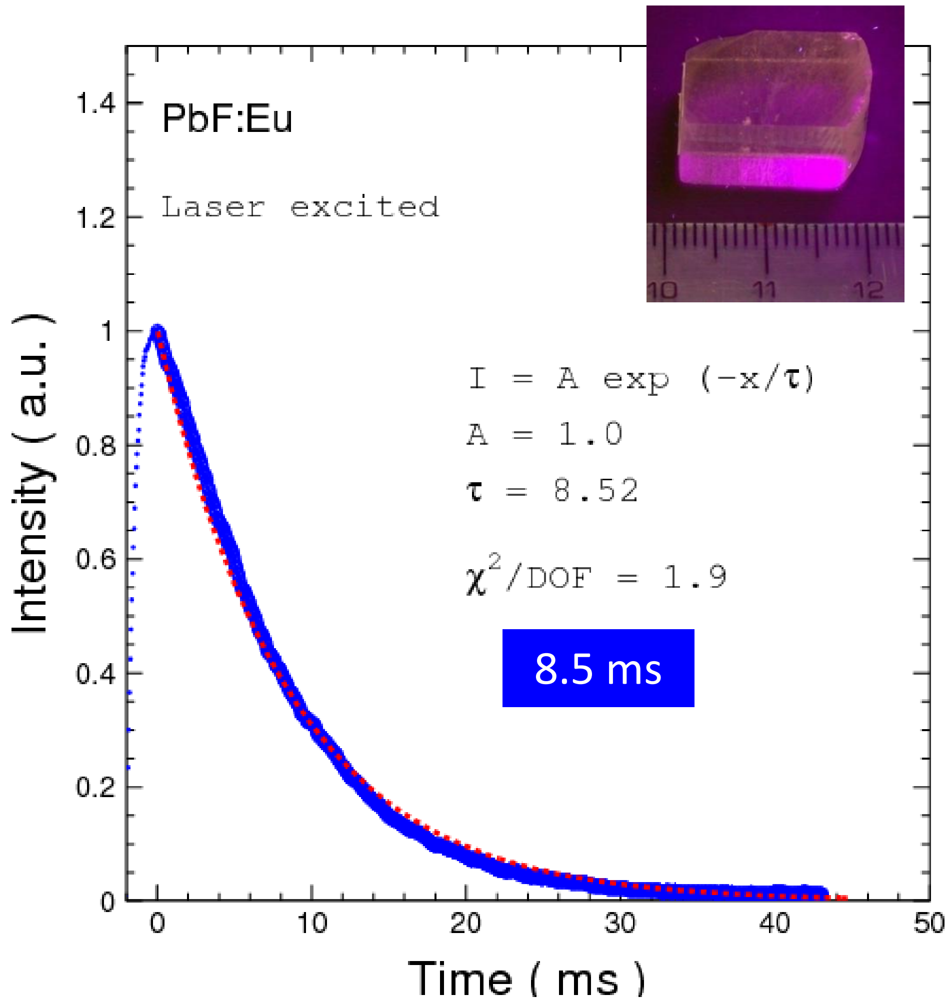
Set-up Verified with BGO & CsI(Tl)

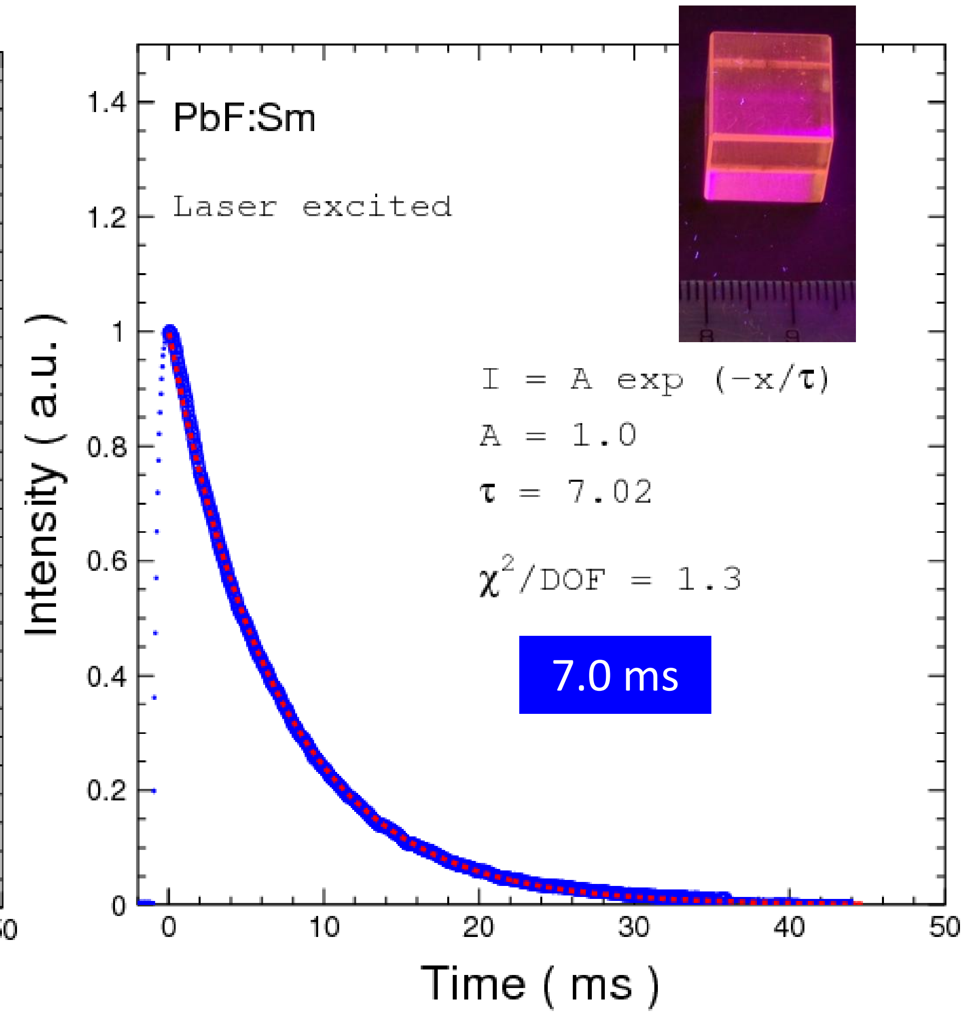
Decay time consists with well known values



Eu and Sm Doped PbF_2

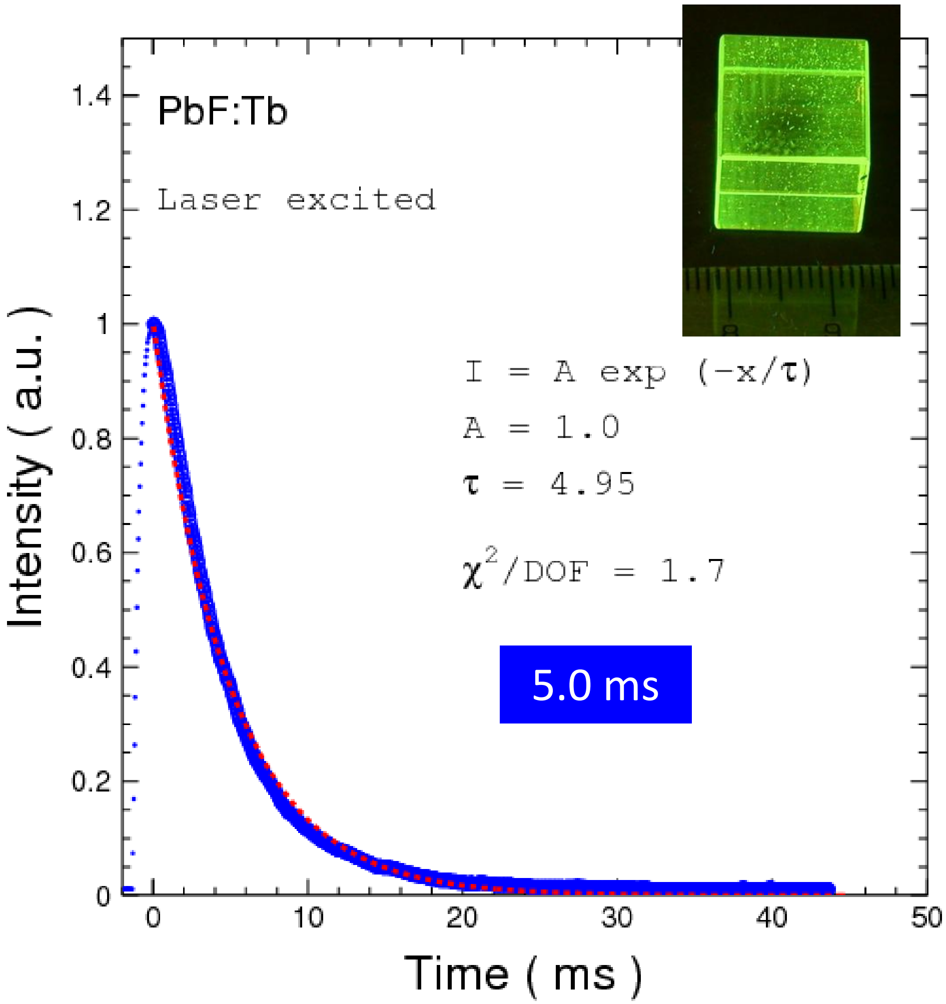
Red emission with multi-ms decay time observed

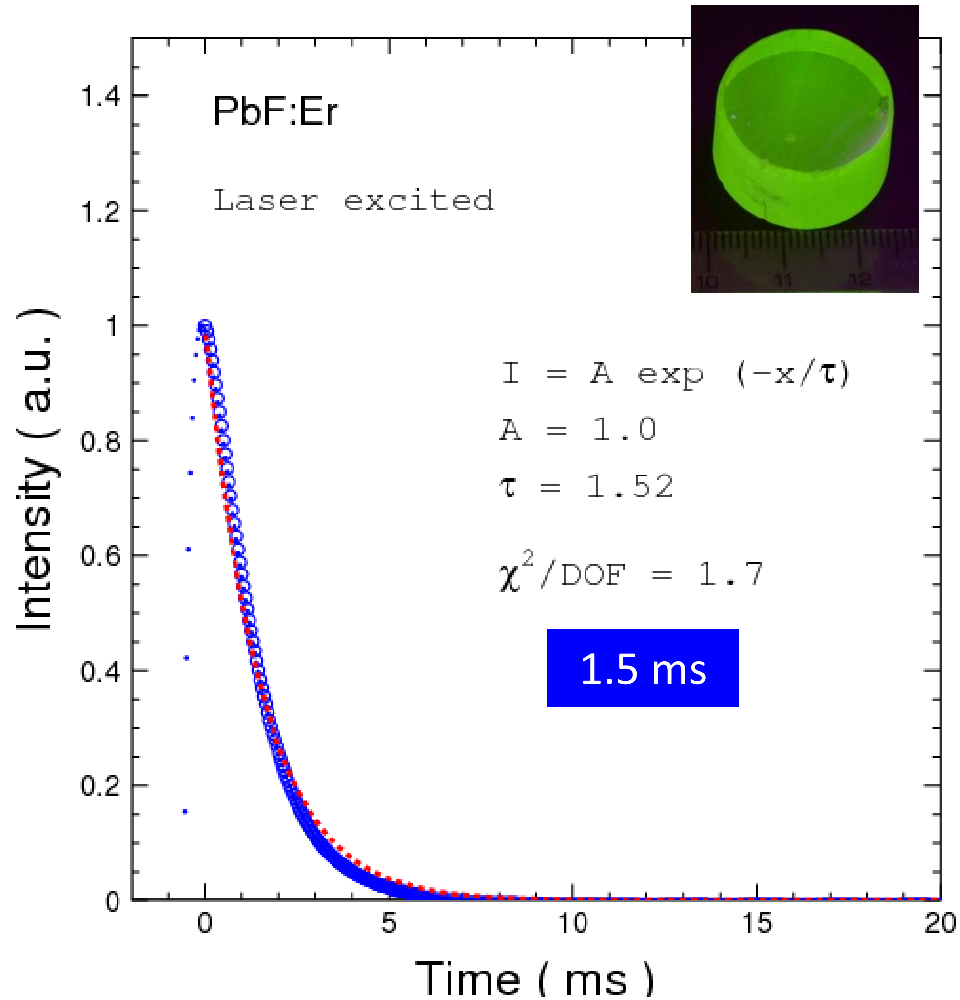




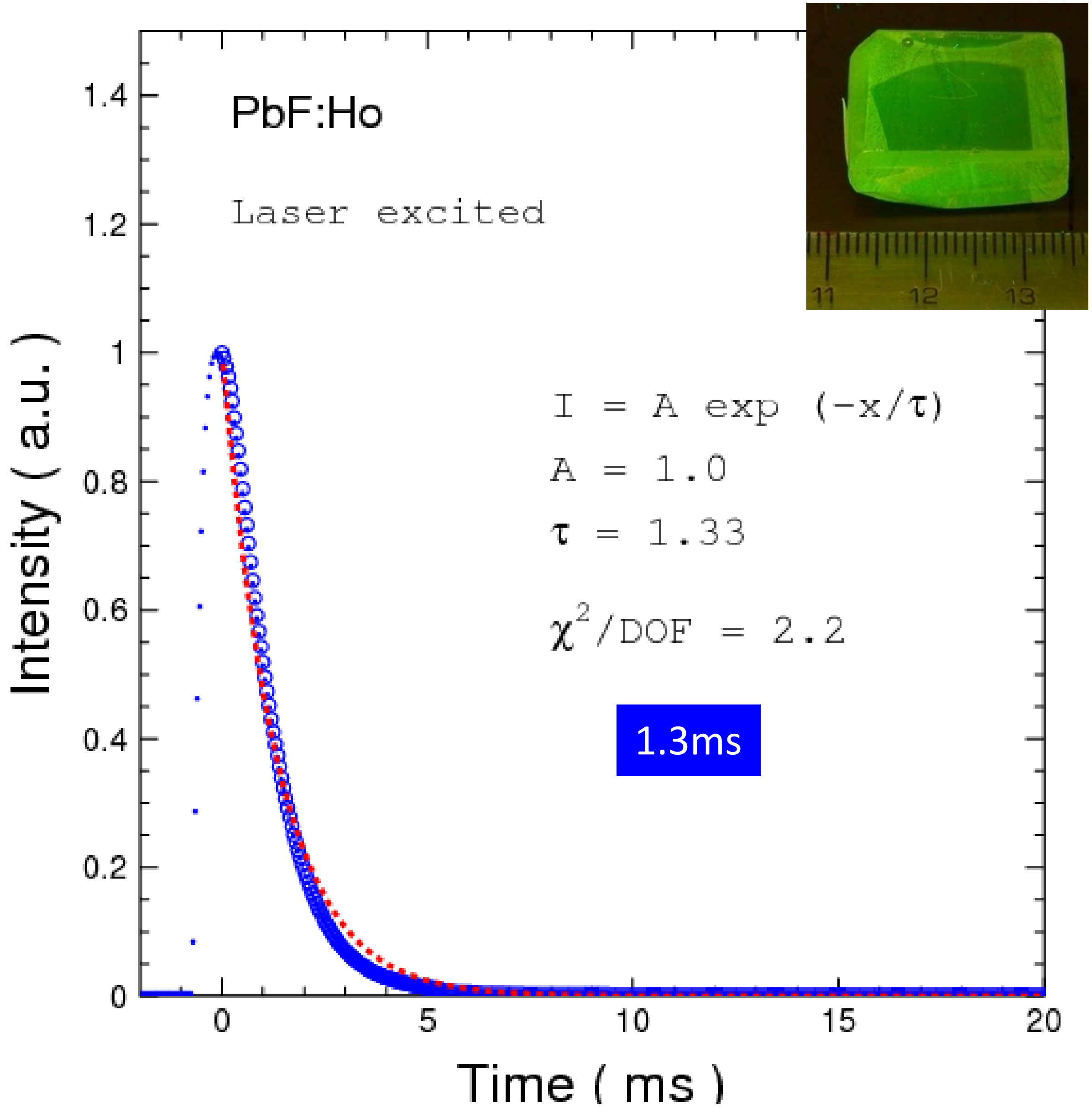
Tb and Er Doped PbF_2

Green emission with ms decay time observed





Ho Doped PbF_2



Summary

- Historically homogeneous crystal electromagnetic calorimeter provides good resolutions for electron and photon measurements. An LSO/LYSO crystal calorimeter may provide excellent energy resolution over a large dynamic range down to MeV level for future HEP and NP experiments.
- The proposed homogeneous hadronic calorimeter (HHCAL) would provide good resolution for hadron and jet measurements. Because of the huge volume needed to construct a HHCAL development of cost-effective UV transparent material is crucial. Our initial investigation indicates that scintillating PbF_2 seems the best choice for this detector concept.