Crystal Calorimeters in the Next Decade

Ren-Yuan Zhu

California Institute of Technology

June 9, 2011

Talk given at TIPP 2011, Chicago, Illinois, 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 are also being considered to build sampling calorimeter for applications resolution is less crucial.

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?

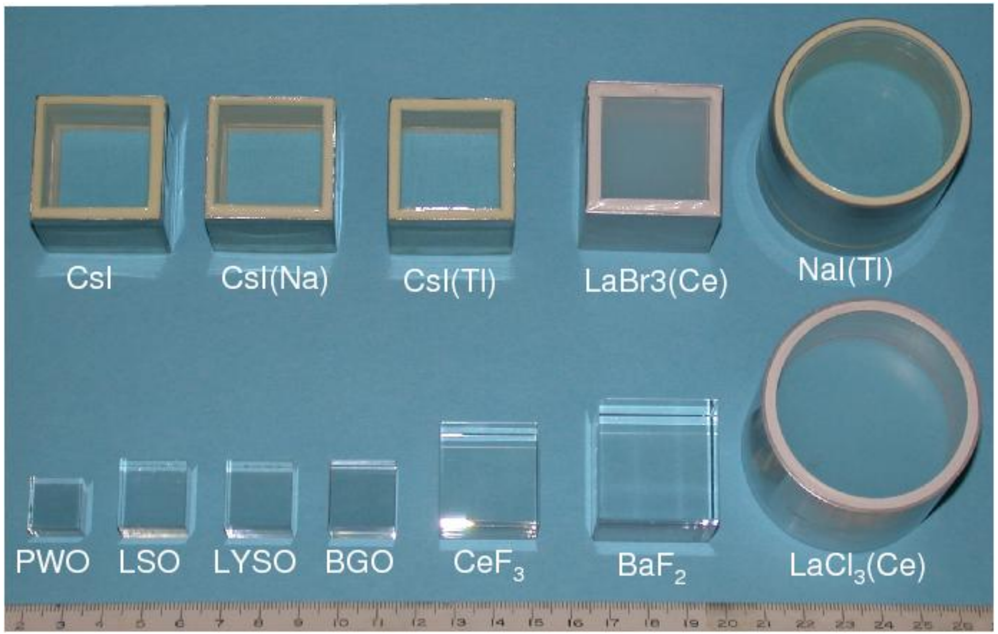
a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

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 (°C)	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] (%/ °C)	-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.

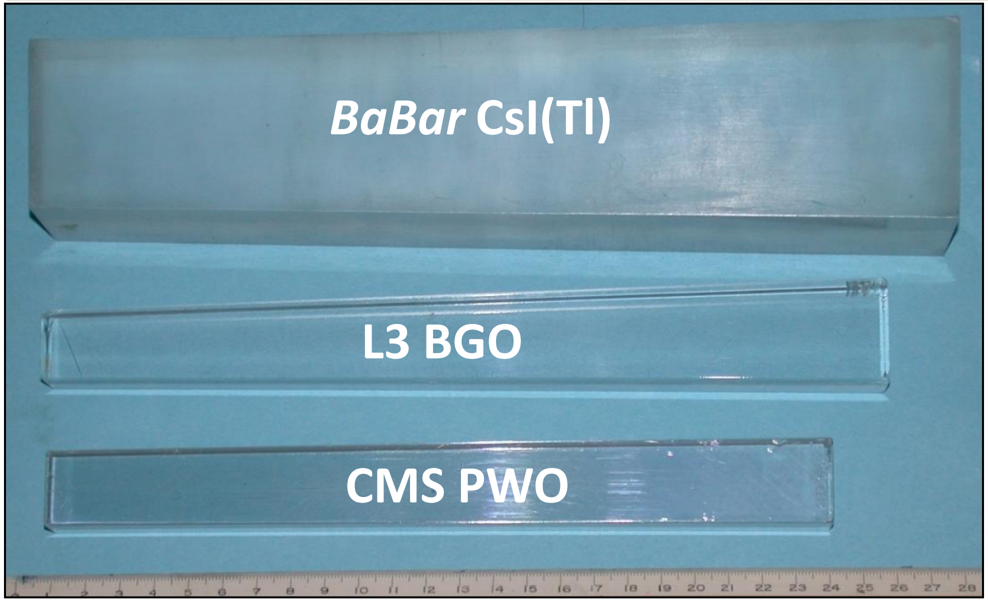
Crystal Density: Radiation Length



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

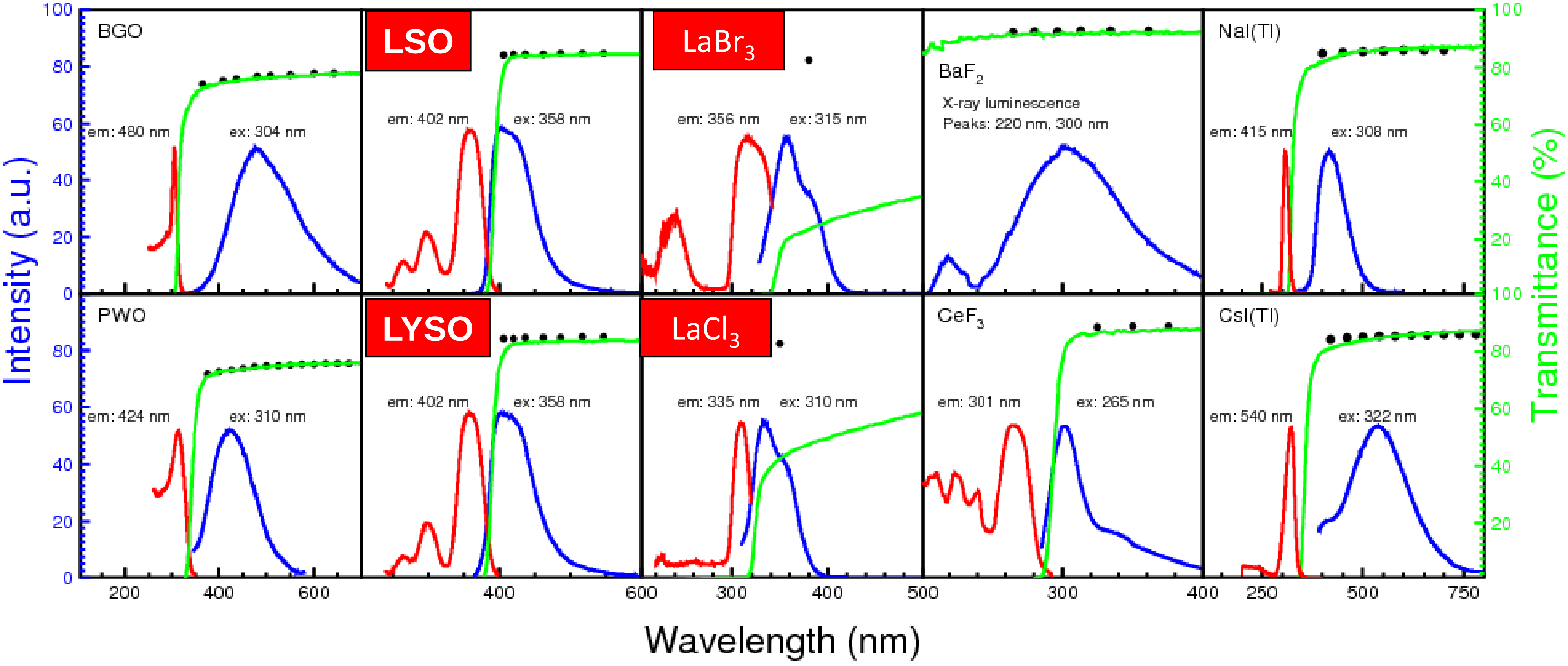
CMS PWO(Y): 25 X_0

Excitation, Emission, Transmission

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

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

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

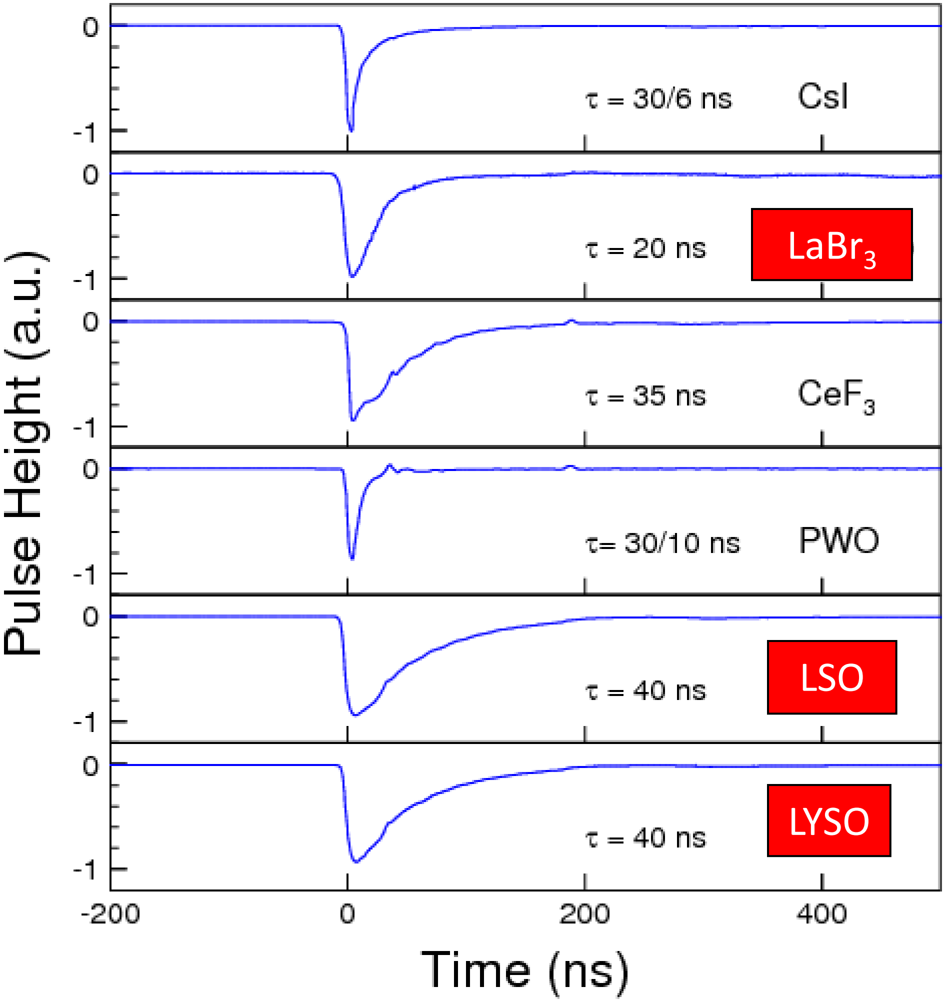


No Self-absorption: BGO, PWO, BaF$_2$, NaI(Tl) and CsI(Tl)

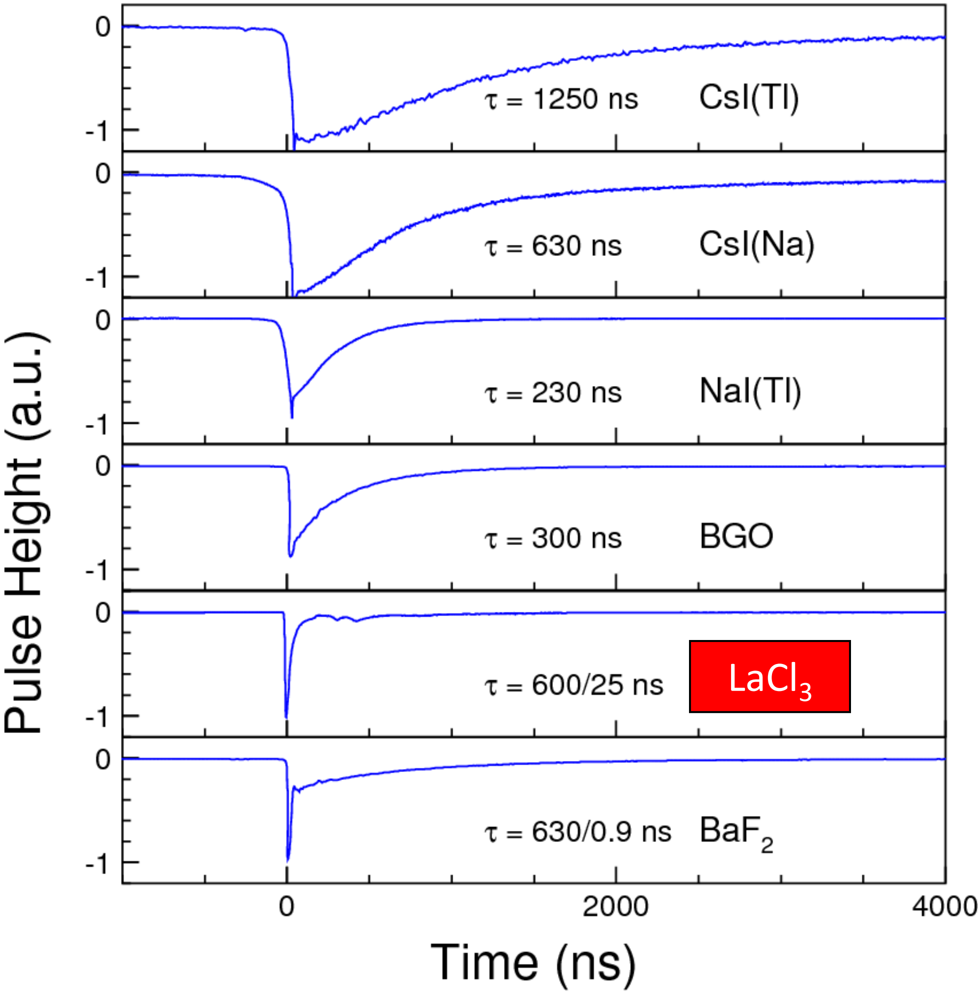
Scintillation Light Decay Time

Recorded with an Agilent 6052A digital scope

Fast Scintillators



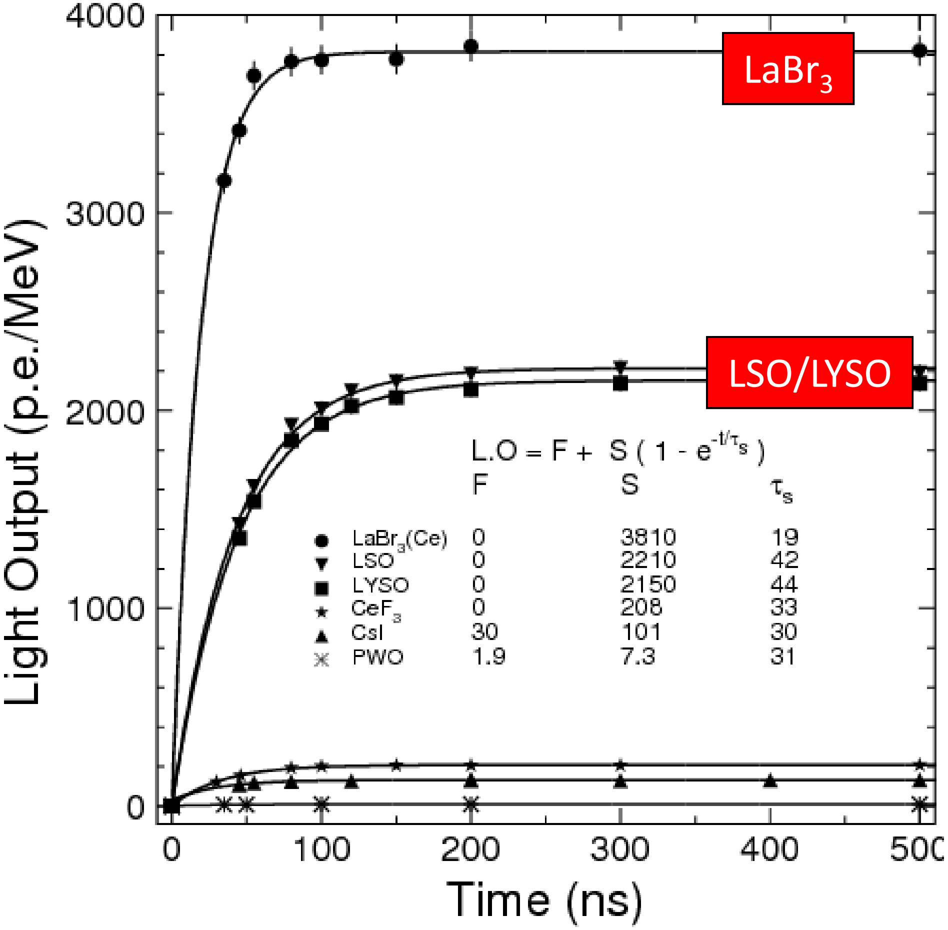
Slow Scintillators



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

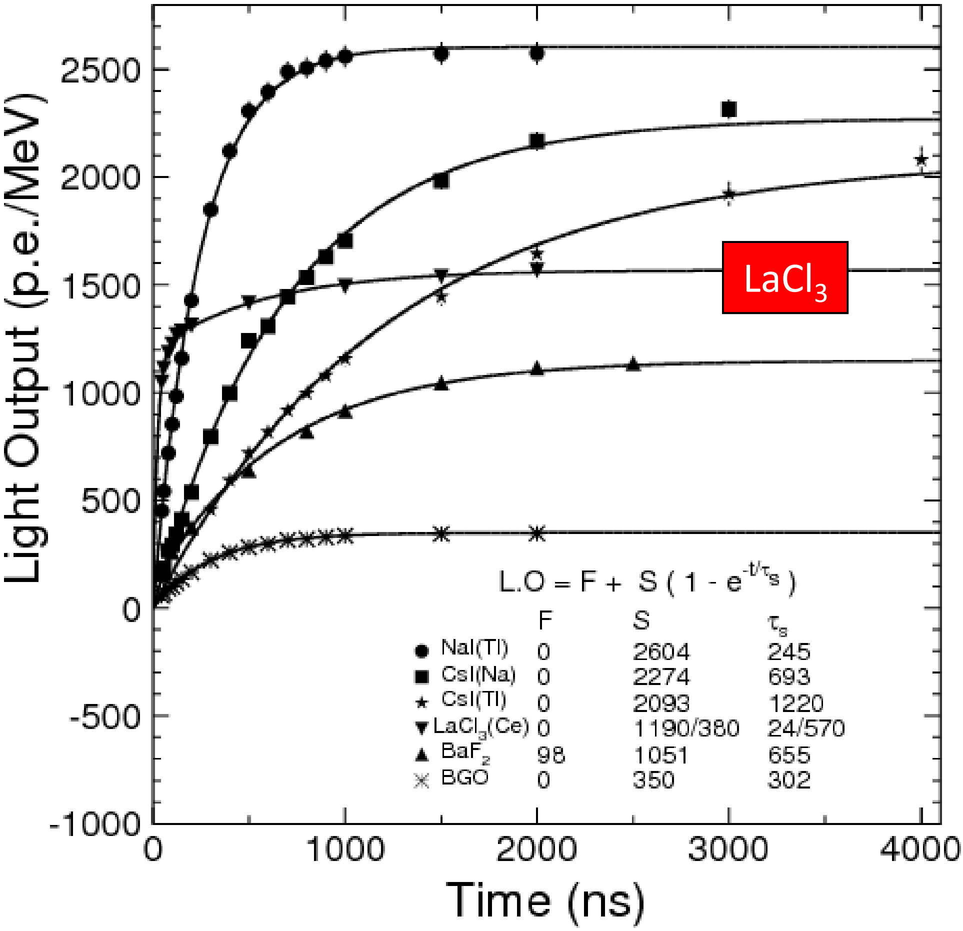
Fast Crystal Scintillators



$L.O = F + S(1 - e^{-t/\tau_s})$

	F	S	τ_s
● LaBr$_3$(Ce)	0	3810	19
▼ LSO	0	2210	42
■ LYSO	0	2150	44
★ CeF$_3$	0	208	33
▲ CsI	30	101	30
✳ PWO	1.9	7.3	31

Slow Crystal Scintillators

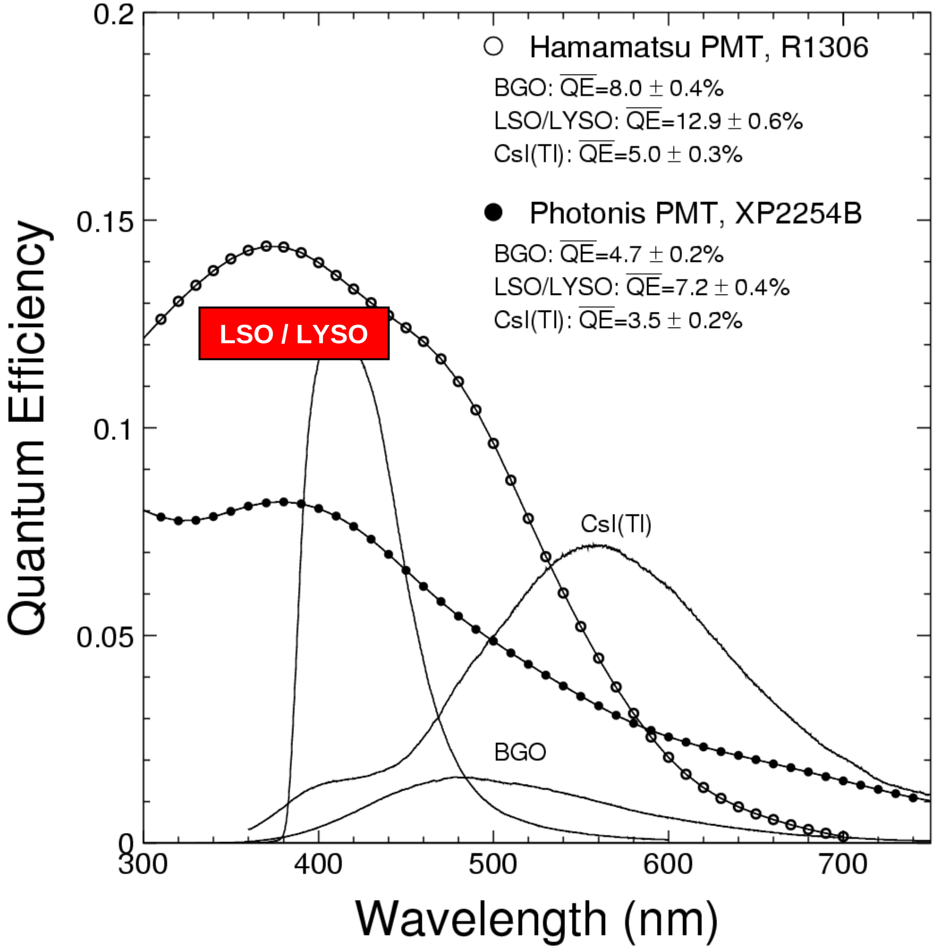


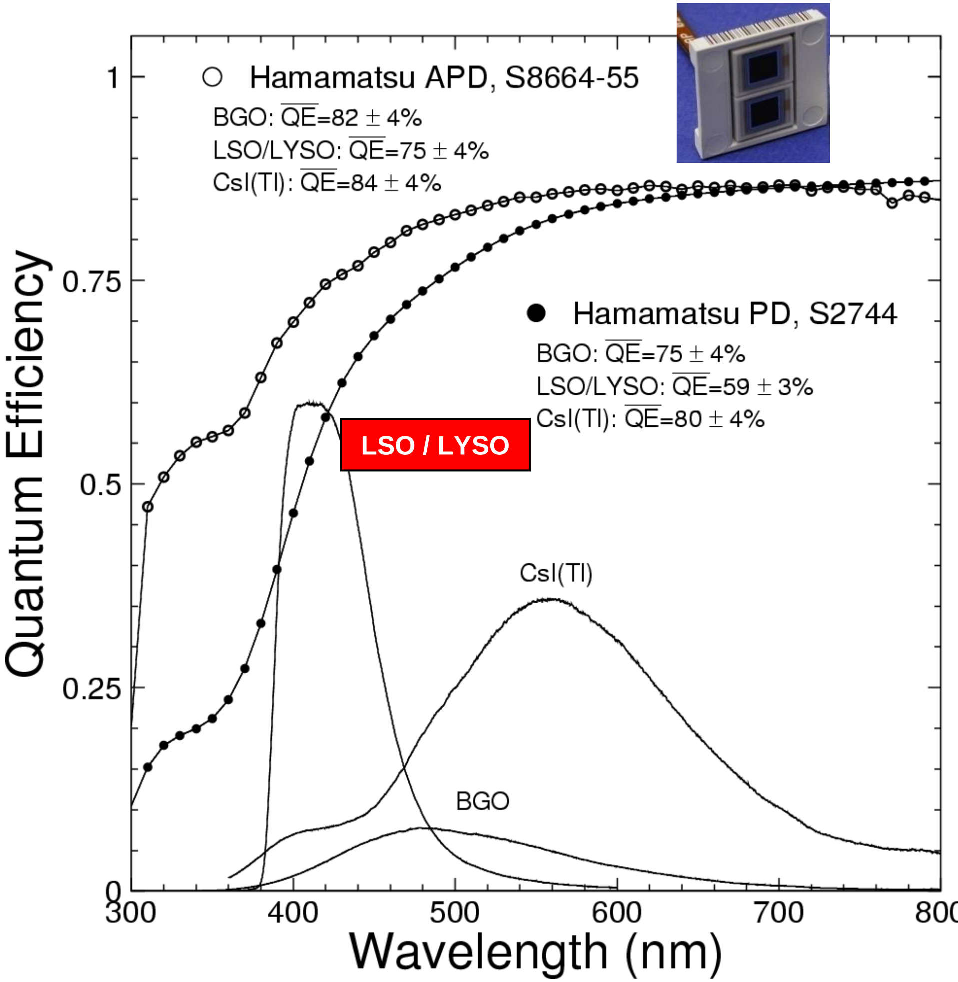
$L.O = F + S(1 - e^{-t/\tau_s})$

	F	S	τ_s
● NaI(Tl)	0	2604	245
■ CsI(Na)	0	2274	693
★ CsI(Tl)	0	2093	1220
▼ LaCl$_3$(Ce)	0	1190/380	24/570
▲ BaF$_2$	98	1051	655
✳ BGO	0	350	302

Emission Weighted QE

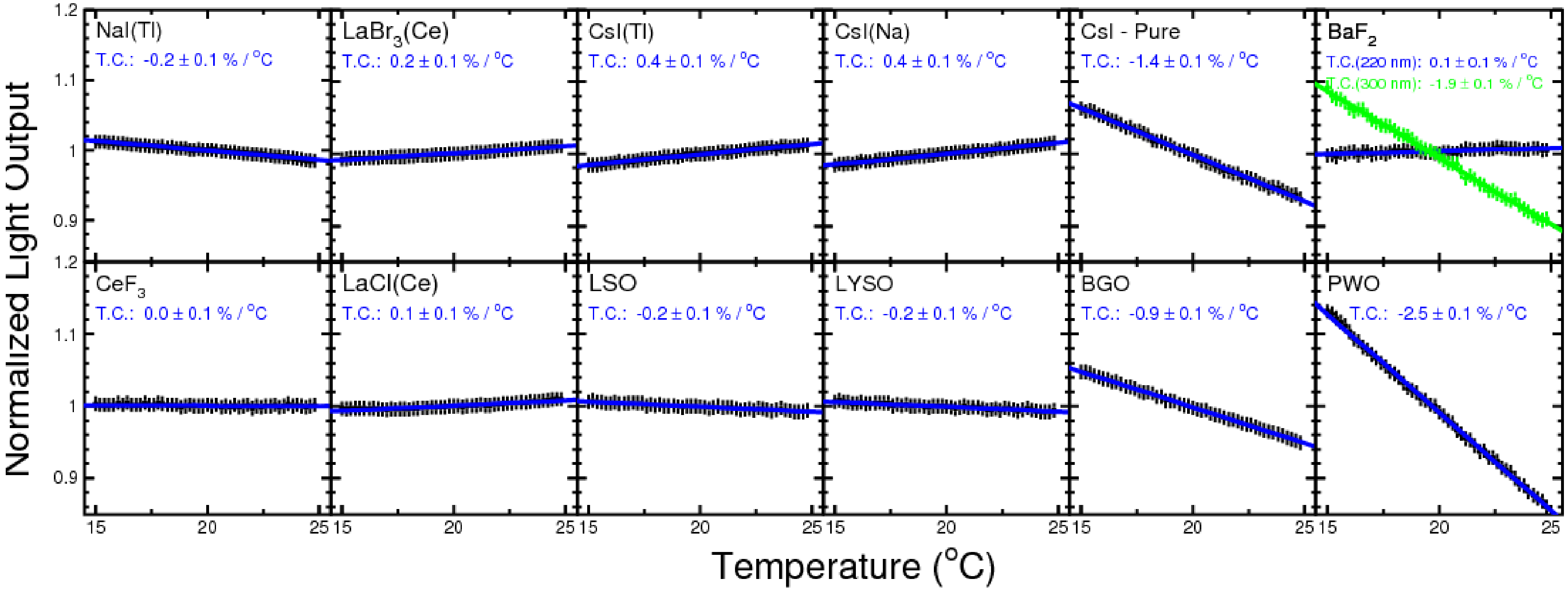
Taking out QE, L.O. of LSO/LYSO is 4/200 times BGO/PWO
Hamamatsu S8664-55 APD has QE 75% for LSO/LYSO





L.O. Temperature Coefficient

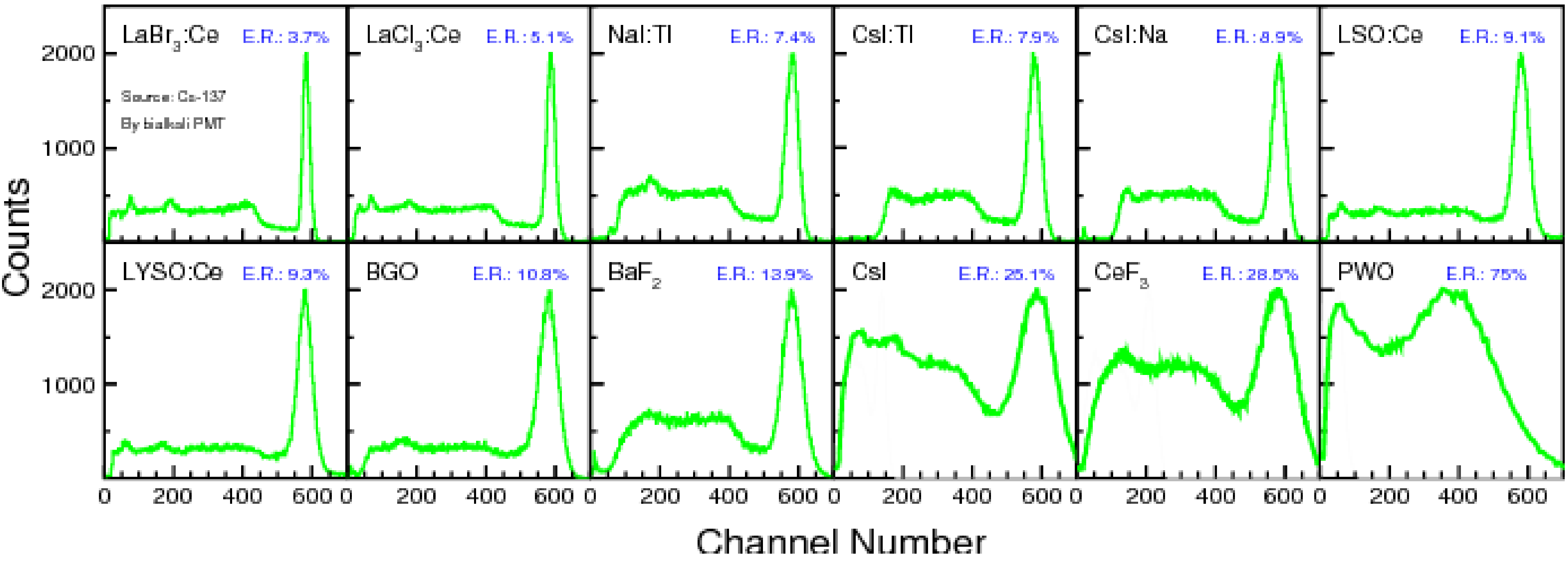
Temperature Range: 15 - 25ºC



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

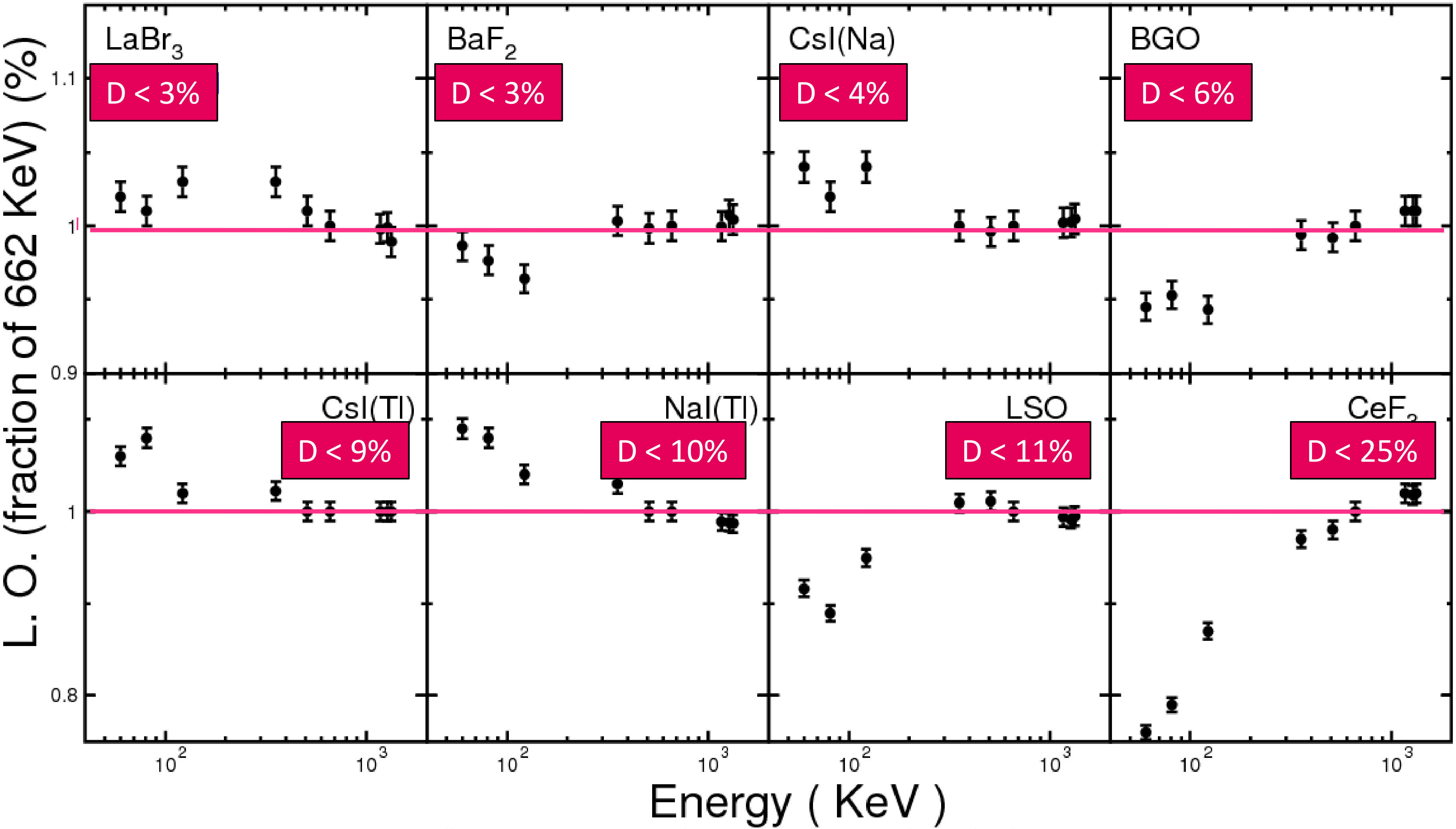


2% resolution and proportionality are important for γ–ray spectroscopy between 10 keV to 2 MeV

Low Energy Non Proportionality

D: deviation from linearity: 60 keV to 1.3 MeV

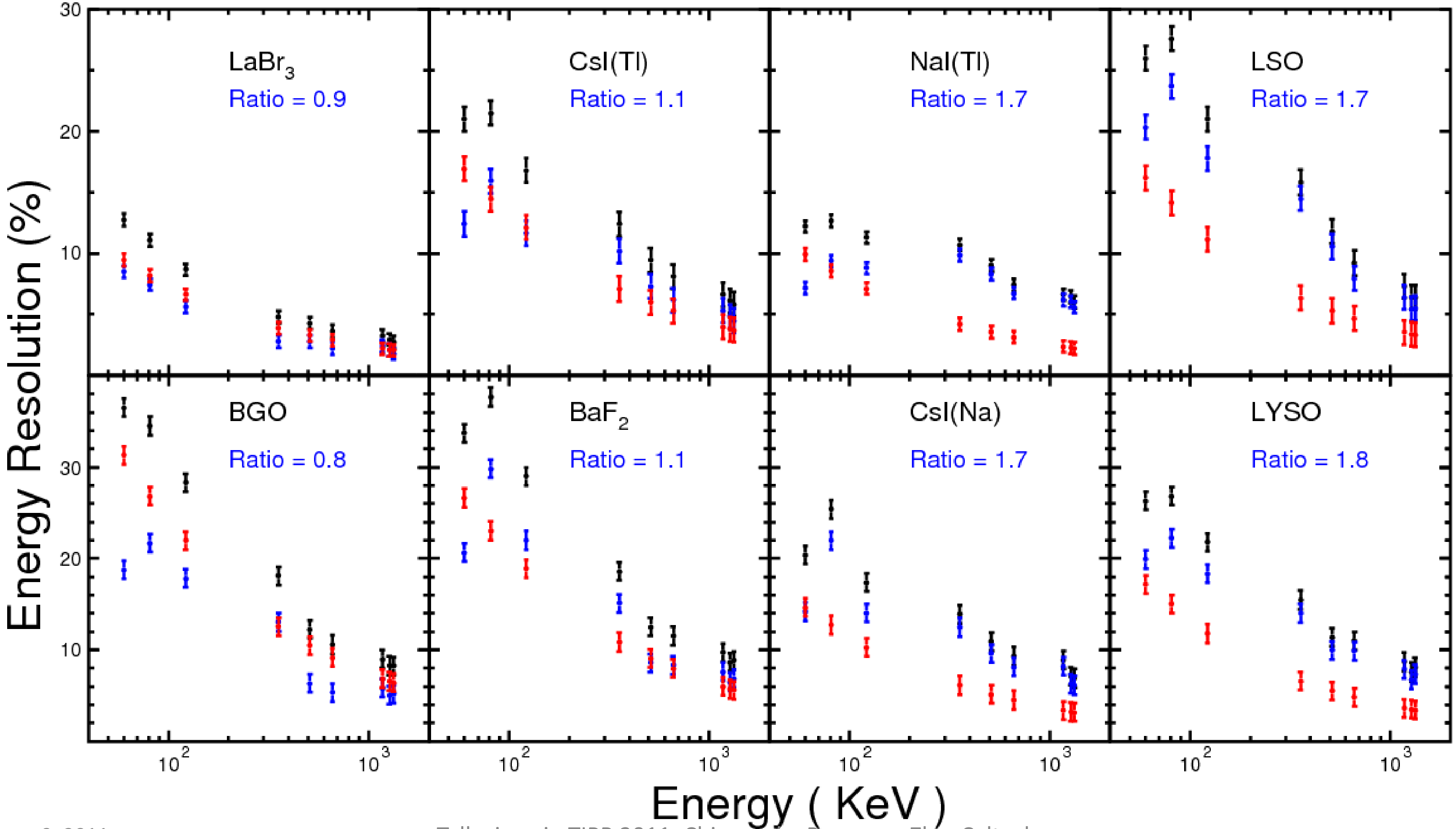
Good Crystals: $LaBr_3$, BaF_2, CsI(Na) and BGO



Statistical & Intrinsic Resolutions

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

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

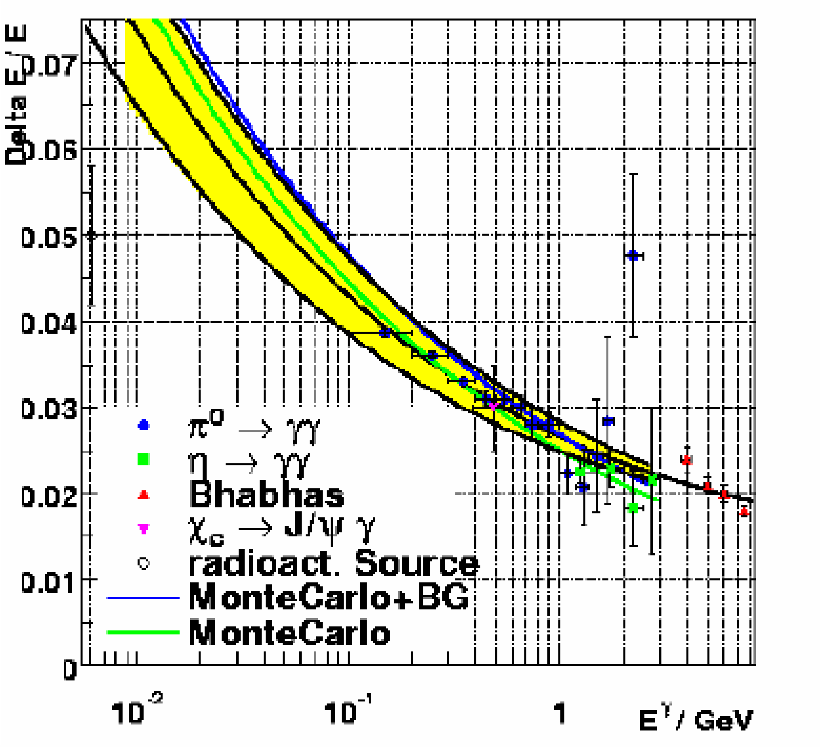
LYSO for Mu2e, Super B and HL-LHC, also a Shashlic

PbF_2, PbFCl, BSO for Homogeneous HCAL

Crystal Calorimeter Resolution

6.6k CsI(Tl)

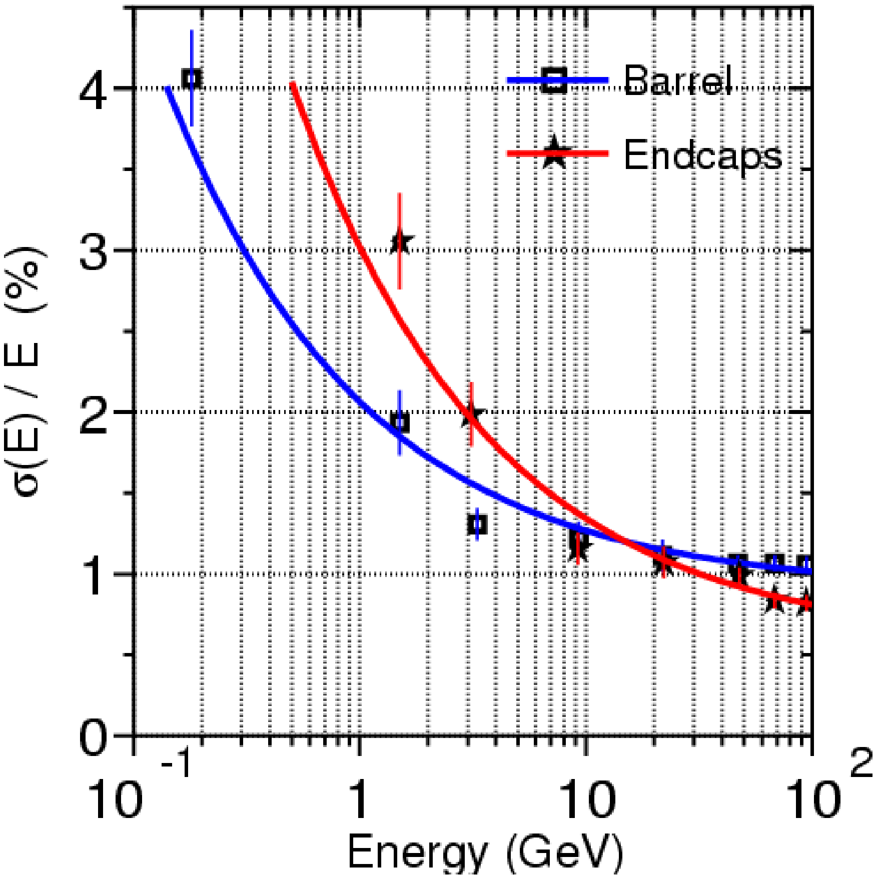
12k BGO



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

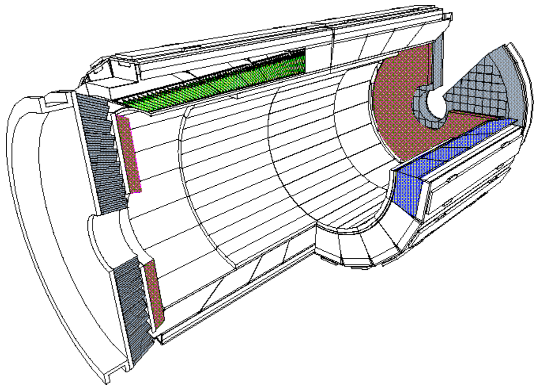
$$\sigma_1 = (2.30 \pm 0.03 \pm 0.3)\%$$

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

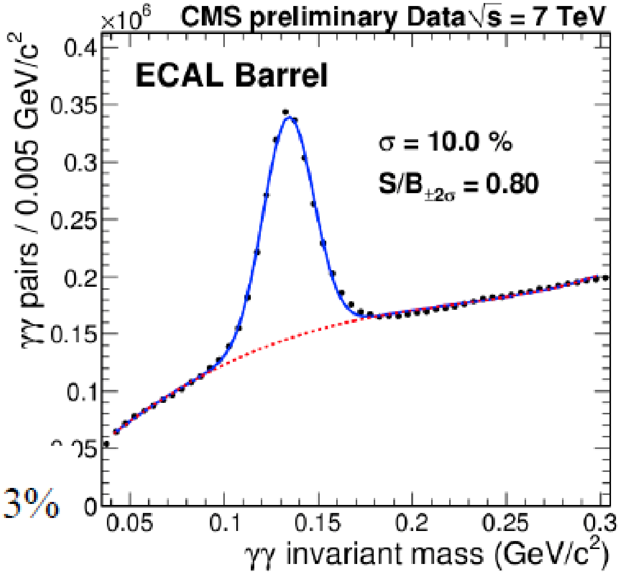


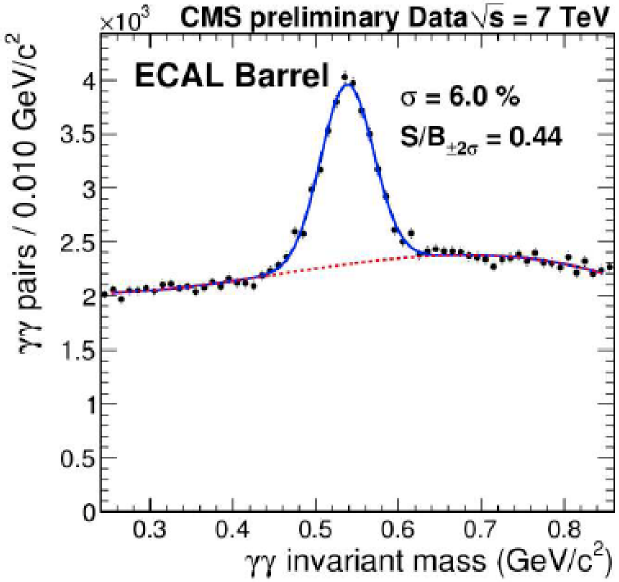
2%/√E + 0.5%

CMS PWO Calorimeter

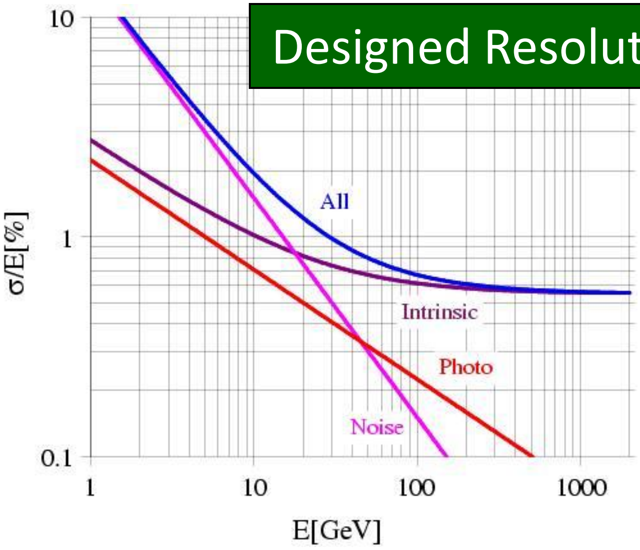


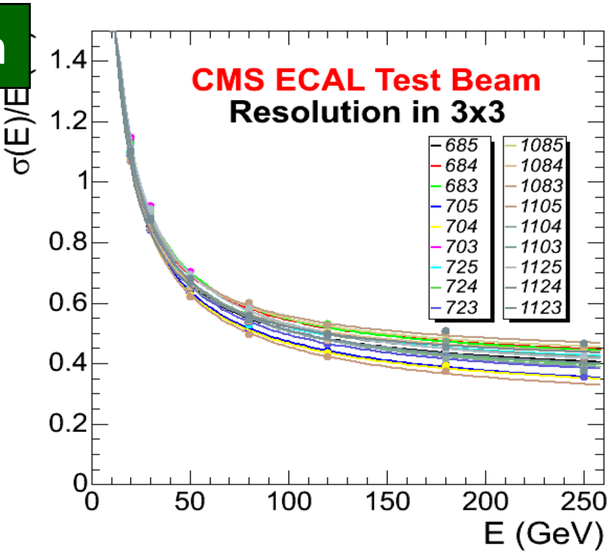
$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E(GeV)}} \oplus \frac{12\%}{E(GeV)} \oplus 0.3\%$$





Designed Resolution





76k PWO

Measured Resolution

σ(E)/E < 1% if E > 25 GeV

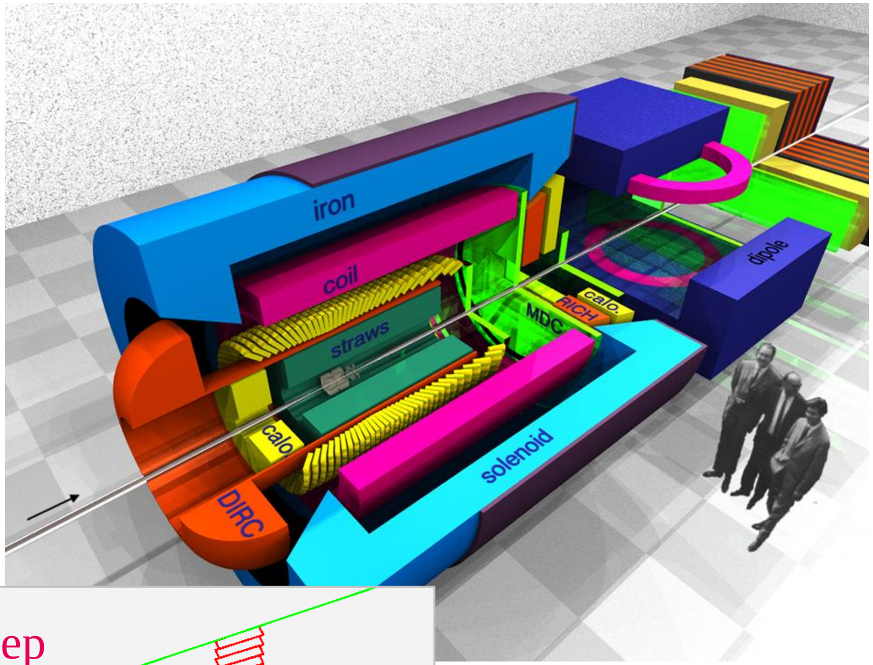
σ(E)/E ~ 0.5% at 120 GeV

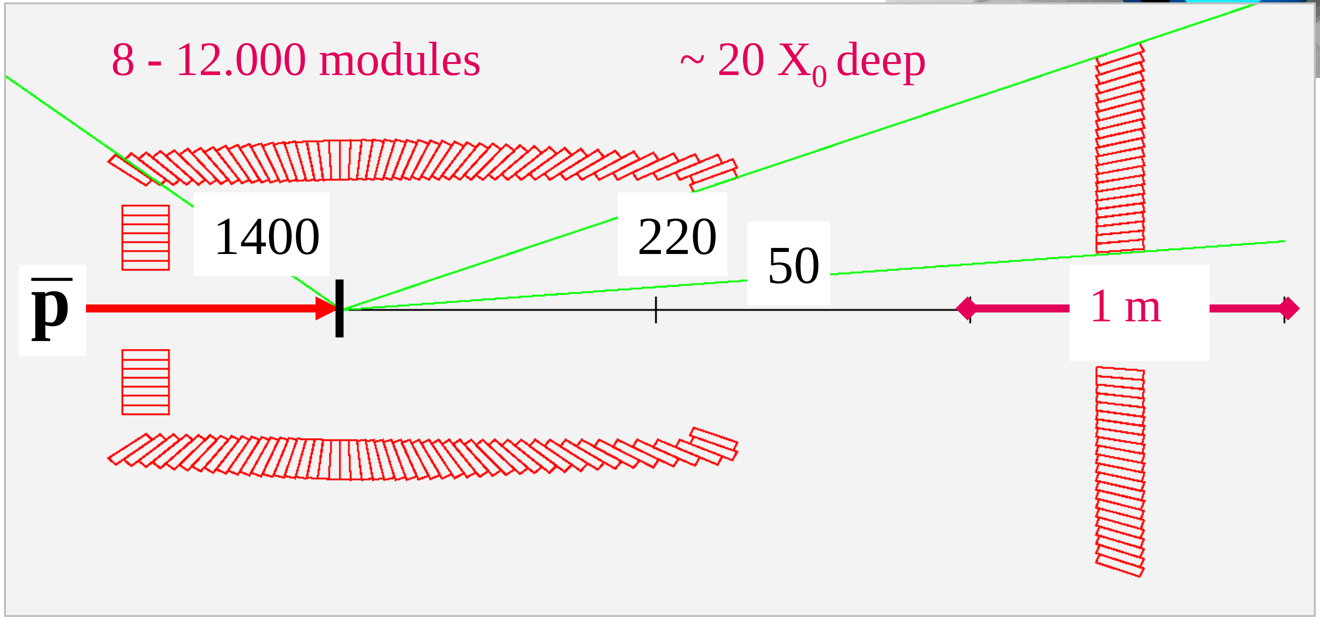
PANDA at GSI, Germany

AntiProton

ANnihilations

at DArmstadt

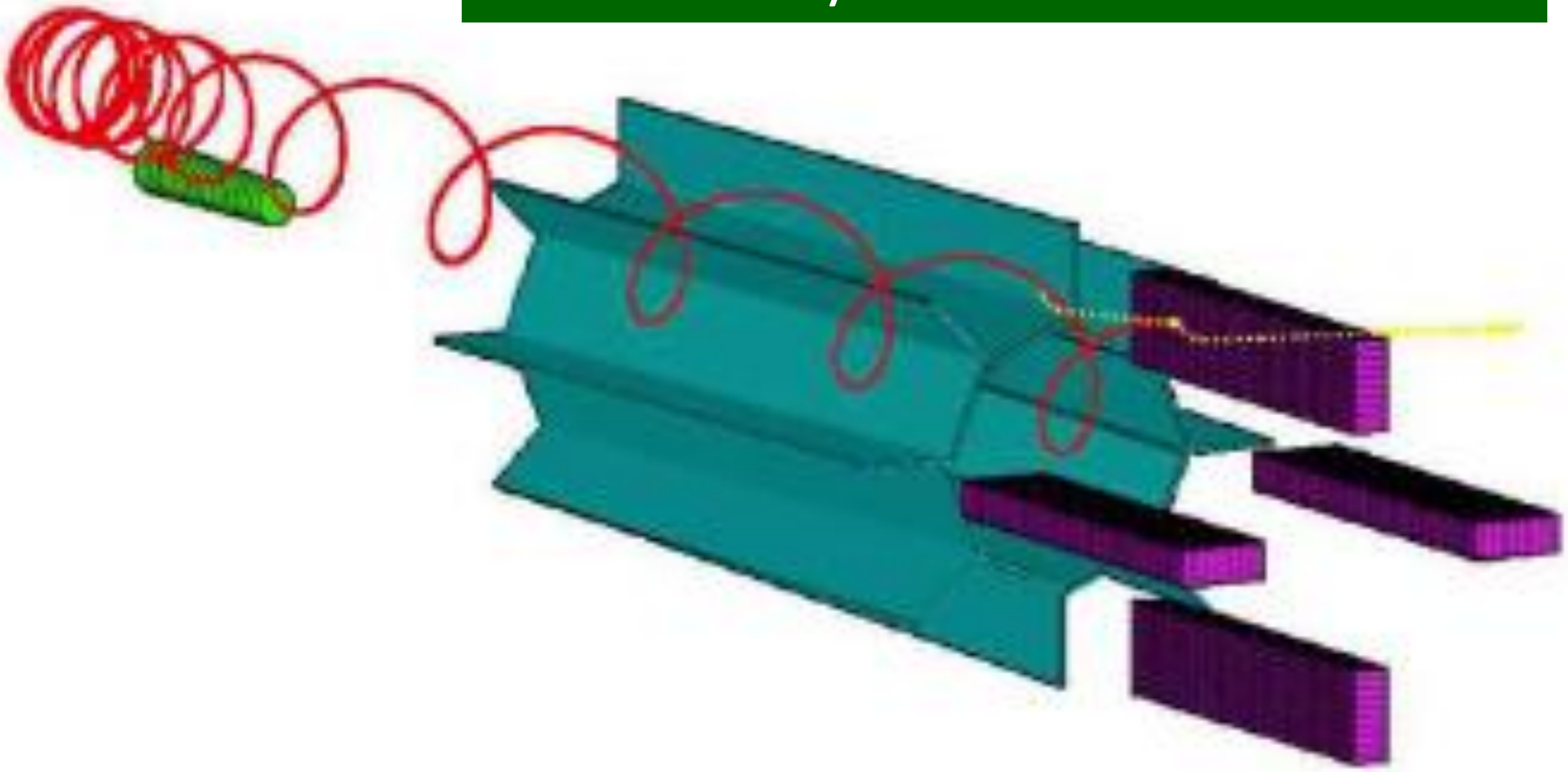




17,000
PWO

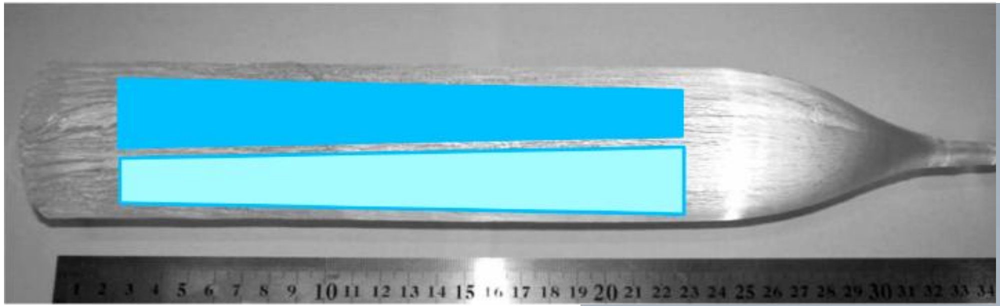
LYSO ECAL for Mu2e

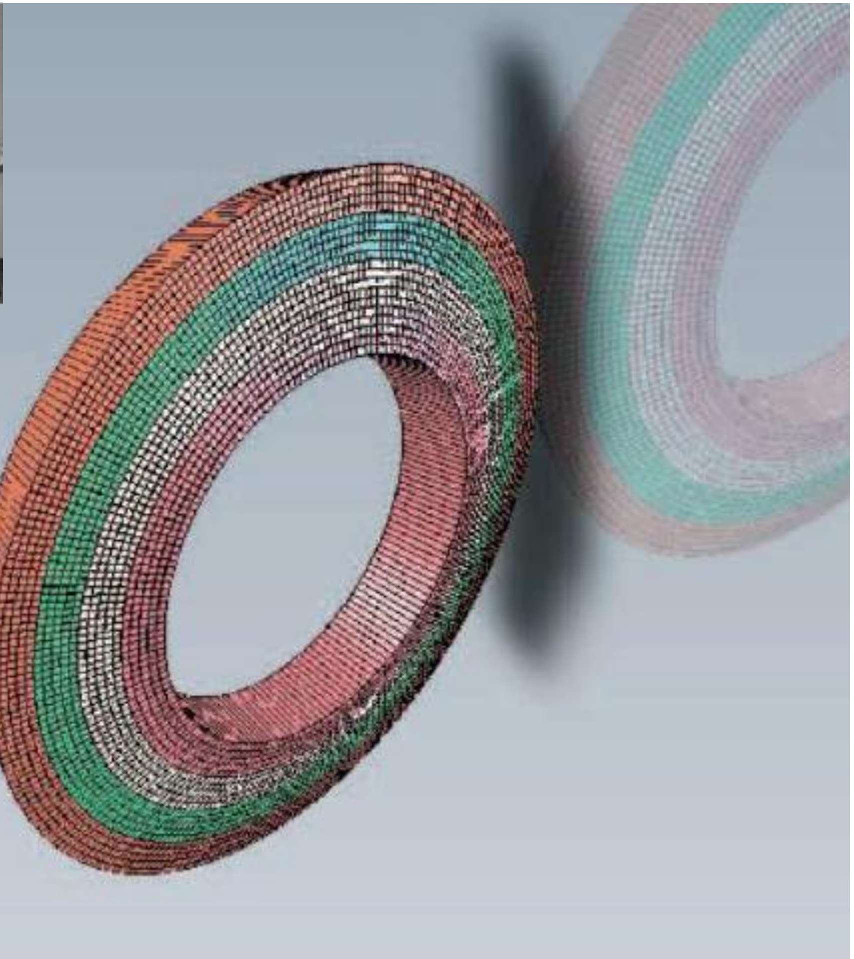
Four-vane calorimeter, comprised of 2400 LYSO crystals of 30 x 30 x 130 mm



LYSO Endcap for SuperB

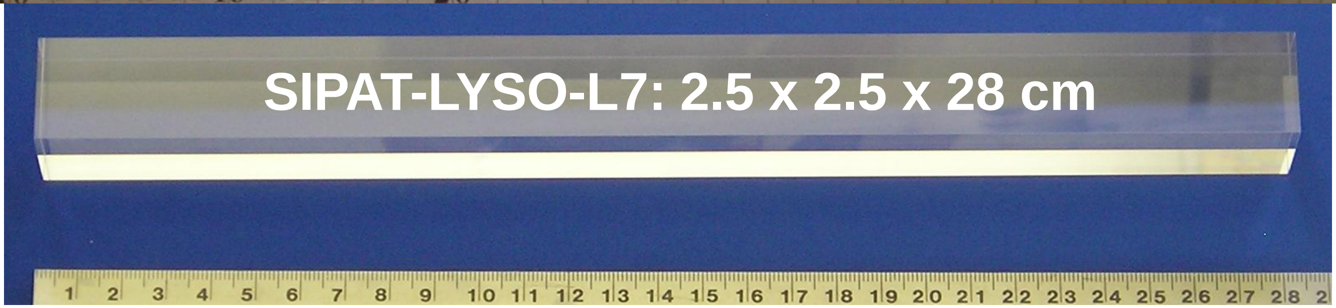
The proposed SuperB ECAL endcap comprising 4400 LYSO crystals in projective geometry





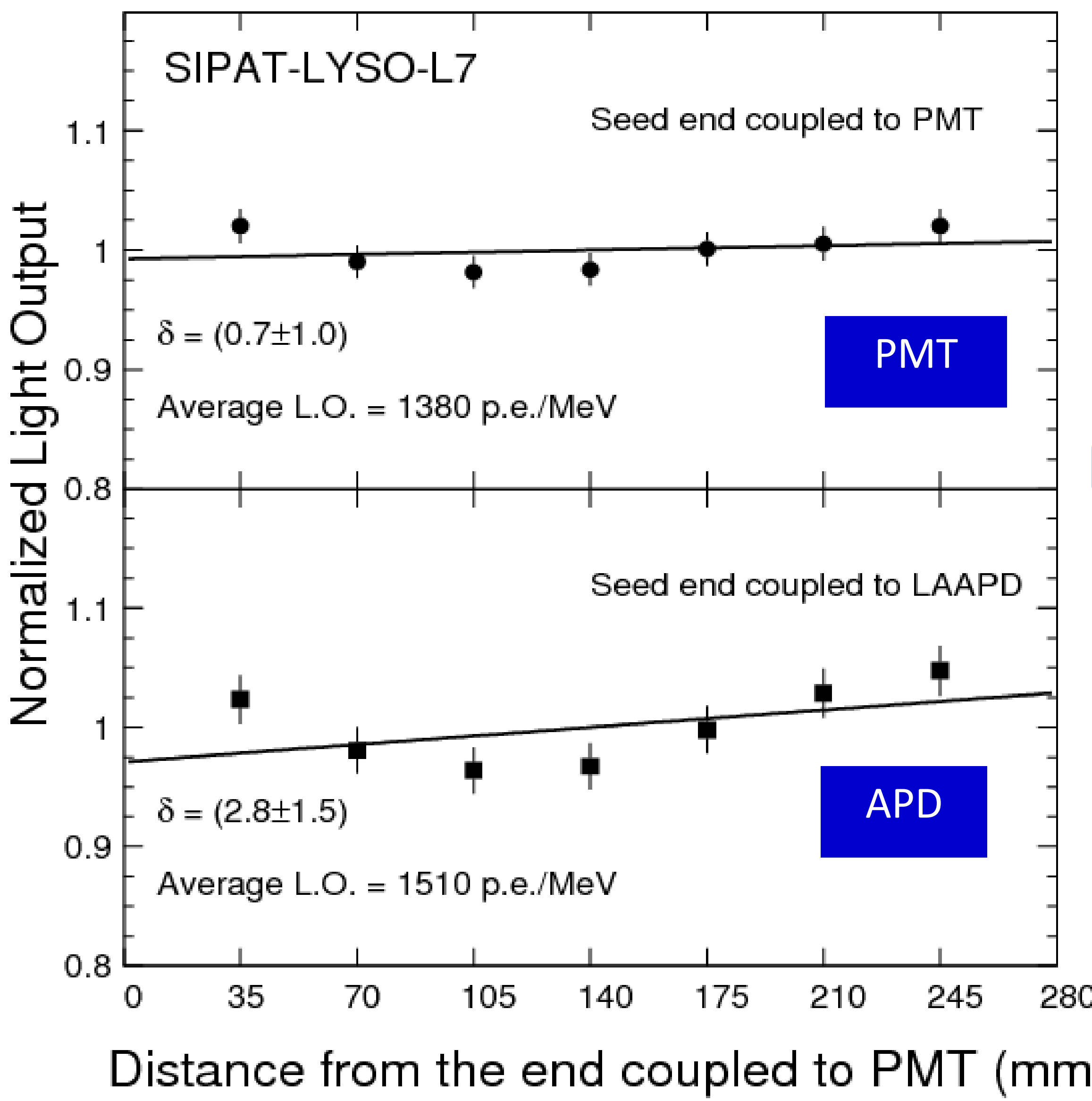
The 1st 28 cm (25 X_0) long LYSO

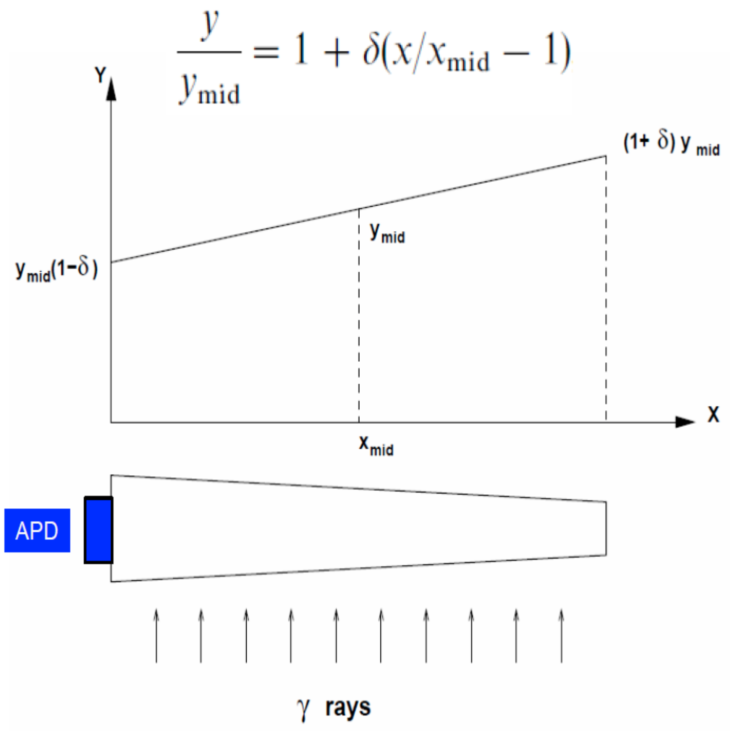

1st 31 cm Ingot grown at SIPAT, Sep,09


SIPAT-LYSO-L7: 2.5 x 2.5 x 28 cm

- A large size ingot of Φ60 x 310 mm was grown at SIPAT in 2009 and a 2.5 x 2.5 x 28 cm LYSO sample was obtained.
- Photo-luminescence, transmission, light output and light response uniformity (LRU) were evaluated.
- Radiation hardness against ^{137}Cs ɣ-rays up to 1 Mrad @ 7.5k rad/h were measured.
- Progress on optical transmittance for large size LYSO will be addressed

L.O. & Response Uniformity

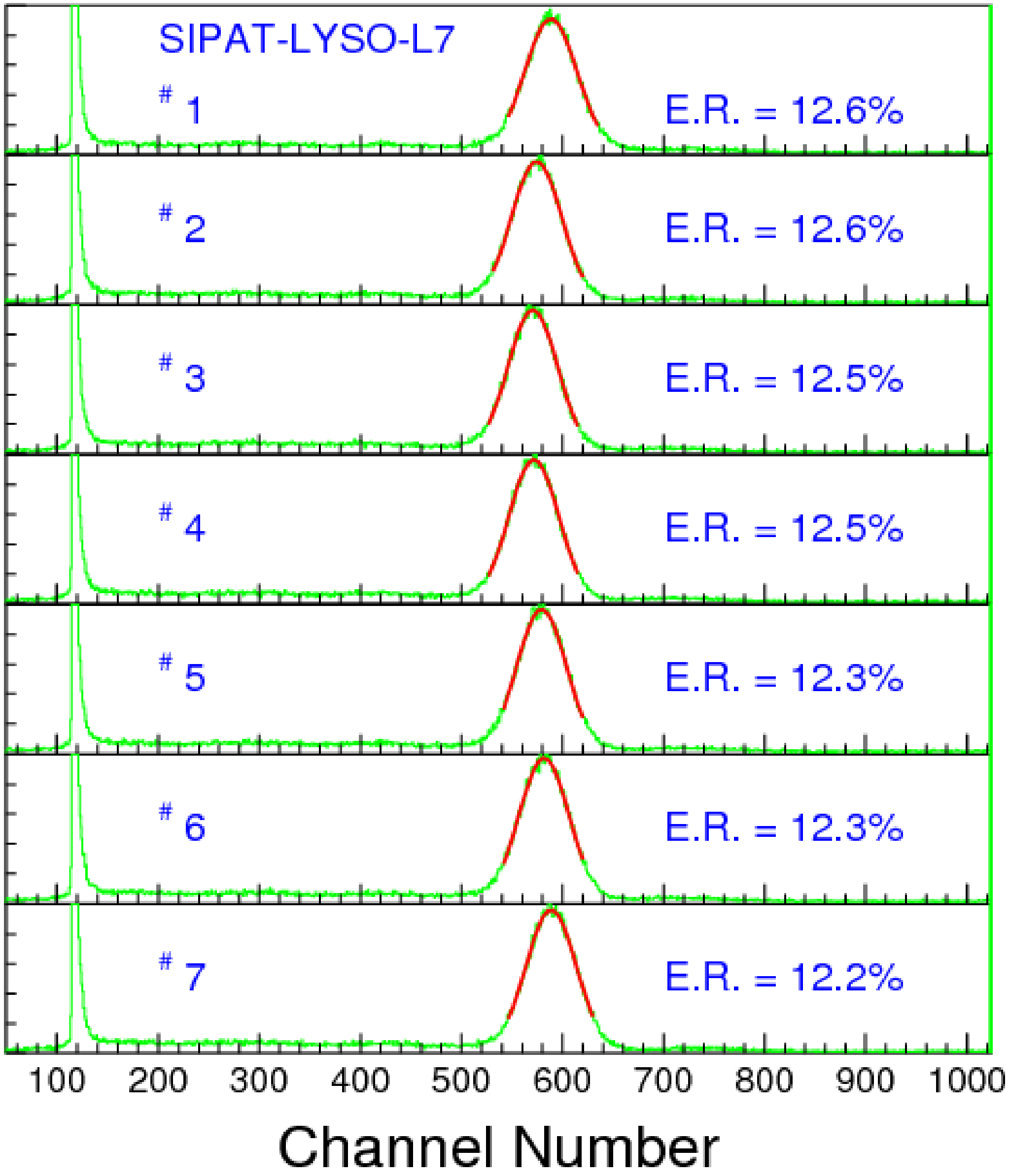




$$\frac{y}{y_{\mathrm{mid}}} = 1 + \delta(x/x_{\mathrm{mid}} - 1)$$

Light response uniformity at a few percents observed for both PMT and APD readouts.

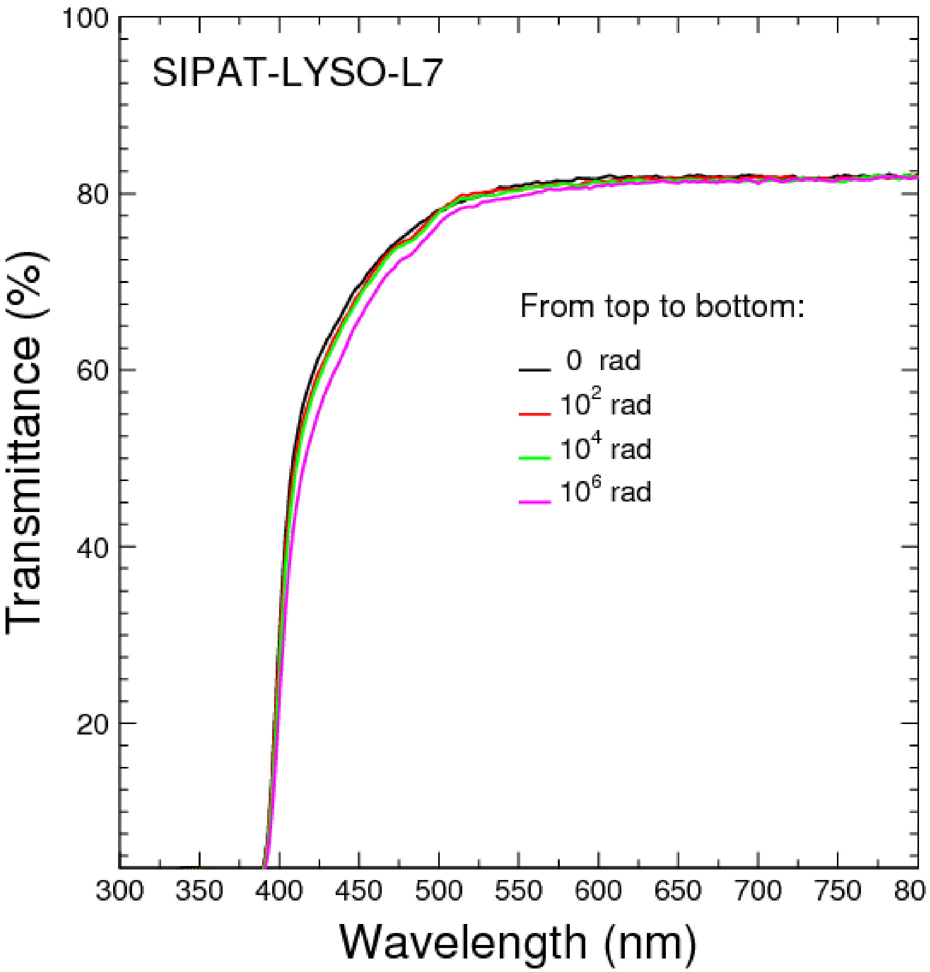
Energy Resolution for 0.511 MeV γ-rays



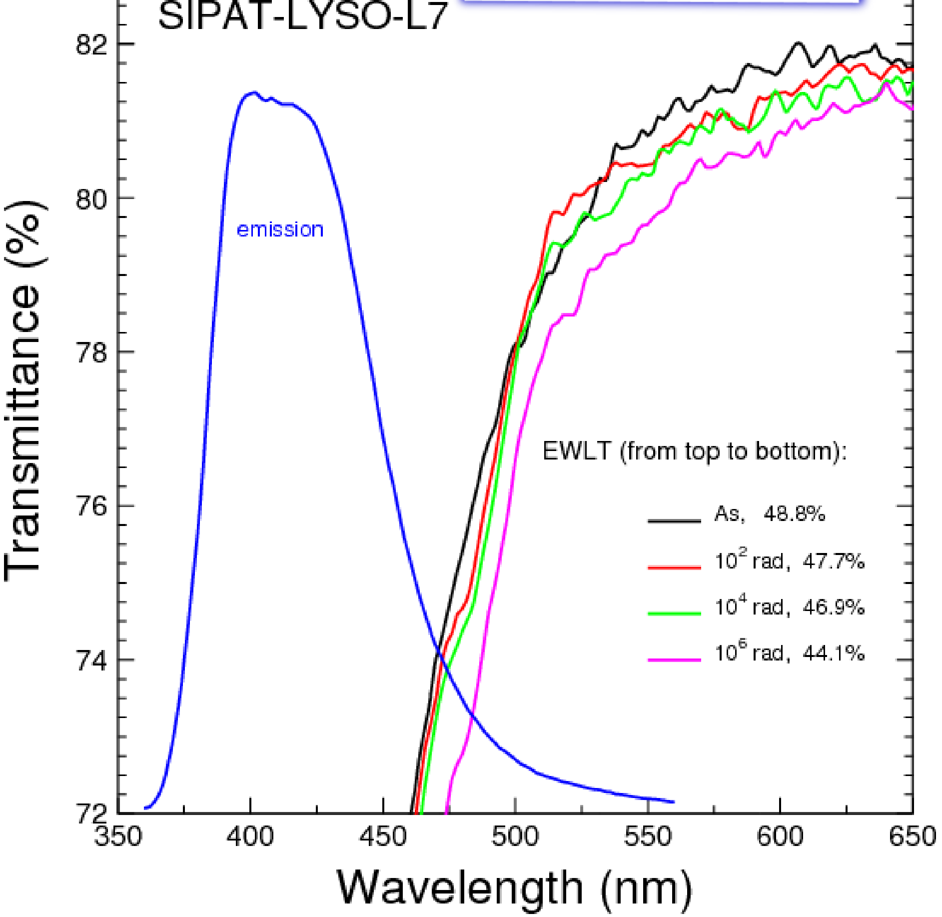
Corresponding FWHM energy resolution at seven points along the crystal was measured by using an R1306 PMT to be 12.4% in average.

ɣ-Ray Induced Damage in LT & EWLT

^{137}Cs ɣ-rays up to 1 Mrad @ 7.5k rad/h: 9.6%

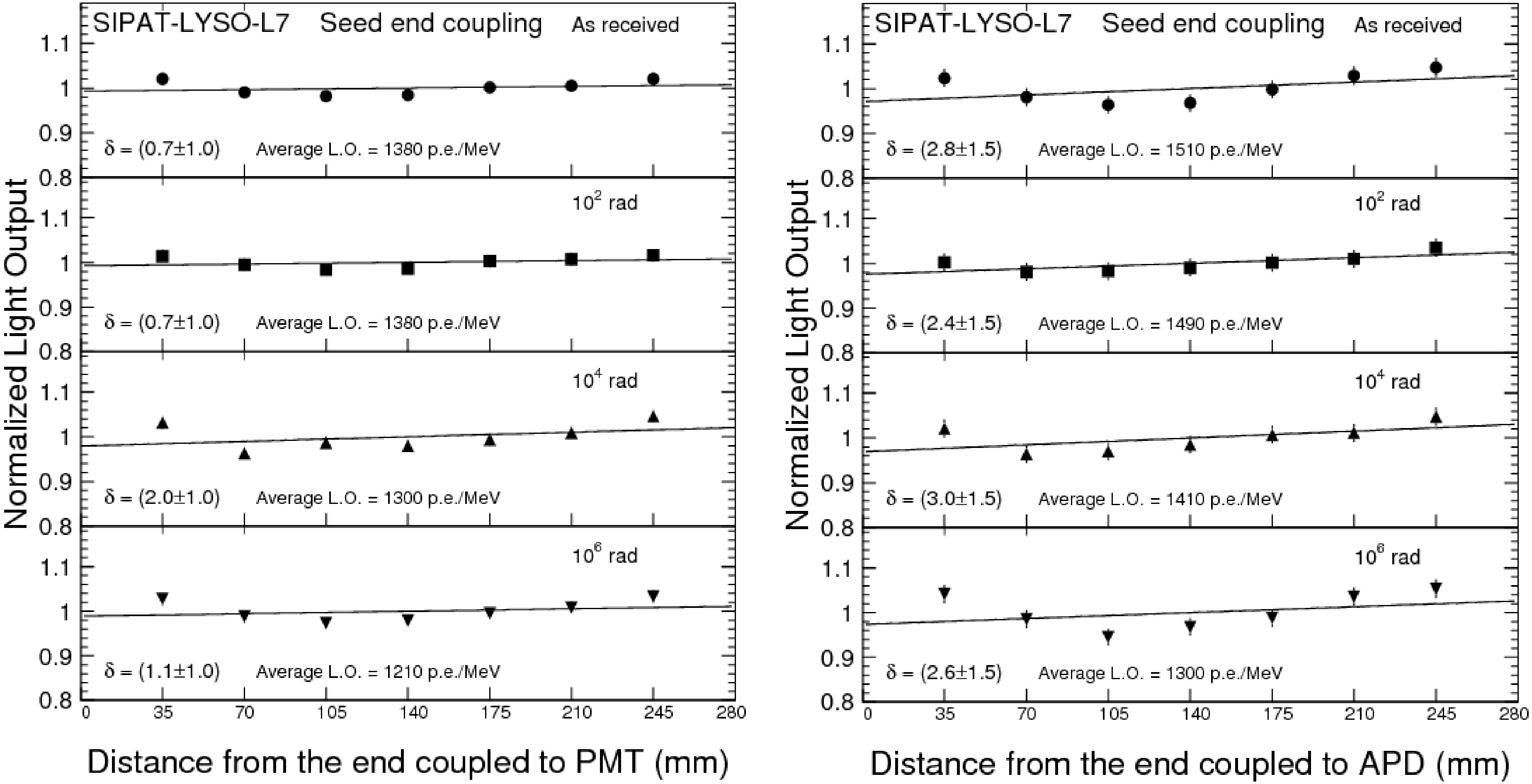


$$EWLT = \frac{\int LT(\lambda)Em(\lambda)d\lambda}{\int Em(\lambda)d\lambda}.$$



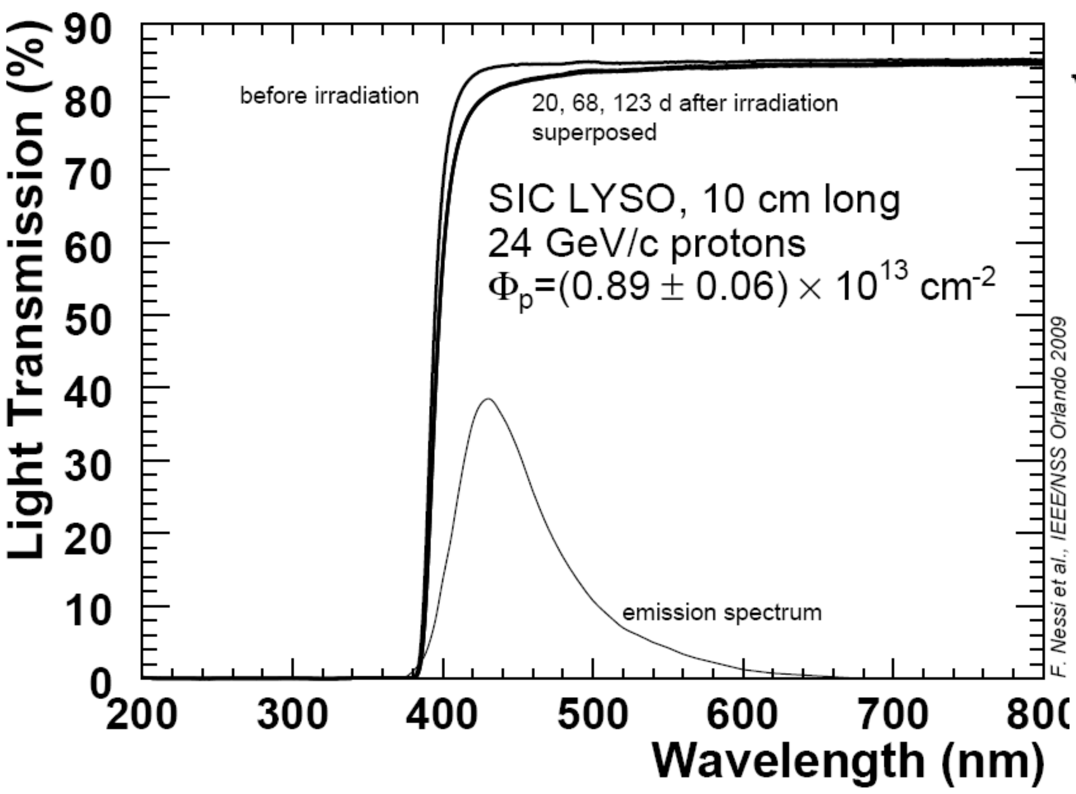
Damage in L.O. and Uniformity

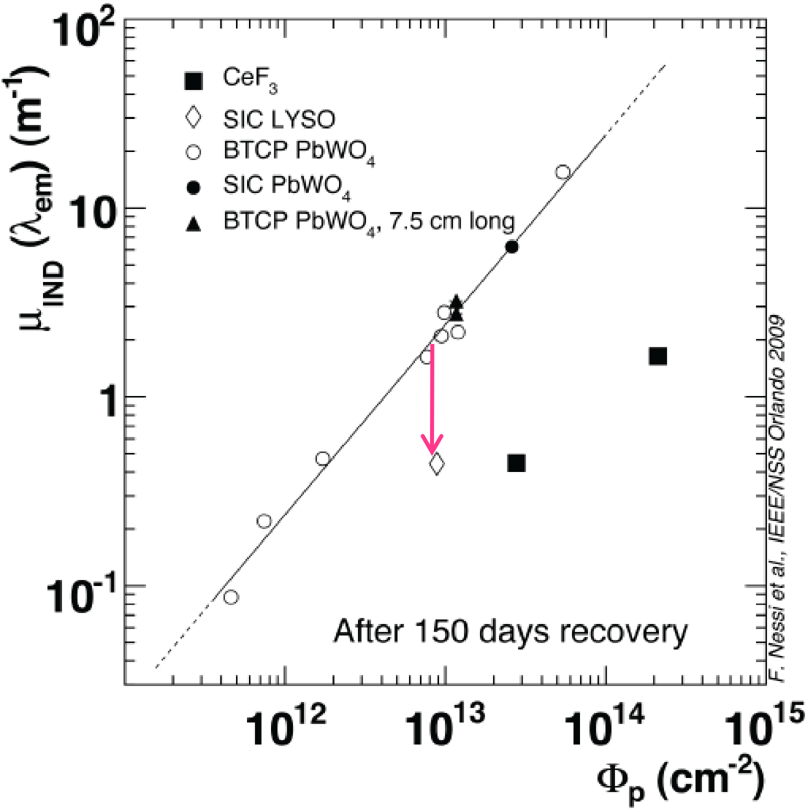
^{137}Cs ɣ-rays up to 1 Mrad @ 7.5k rad/h: 12 ~14%
Light response uniformity is maintained



LYSO is Radiation Hard against Charged Hadrons

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





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

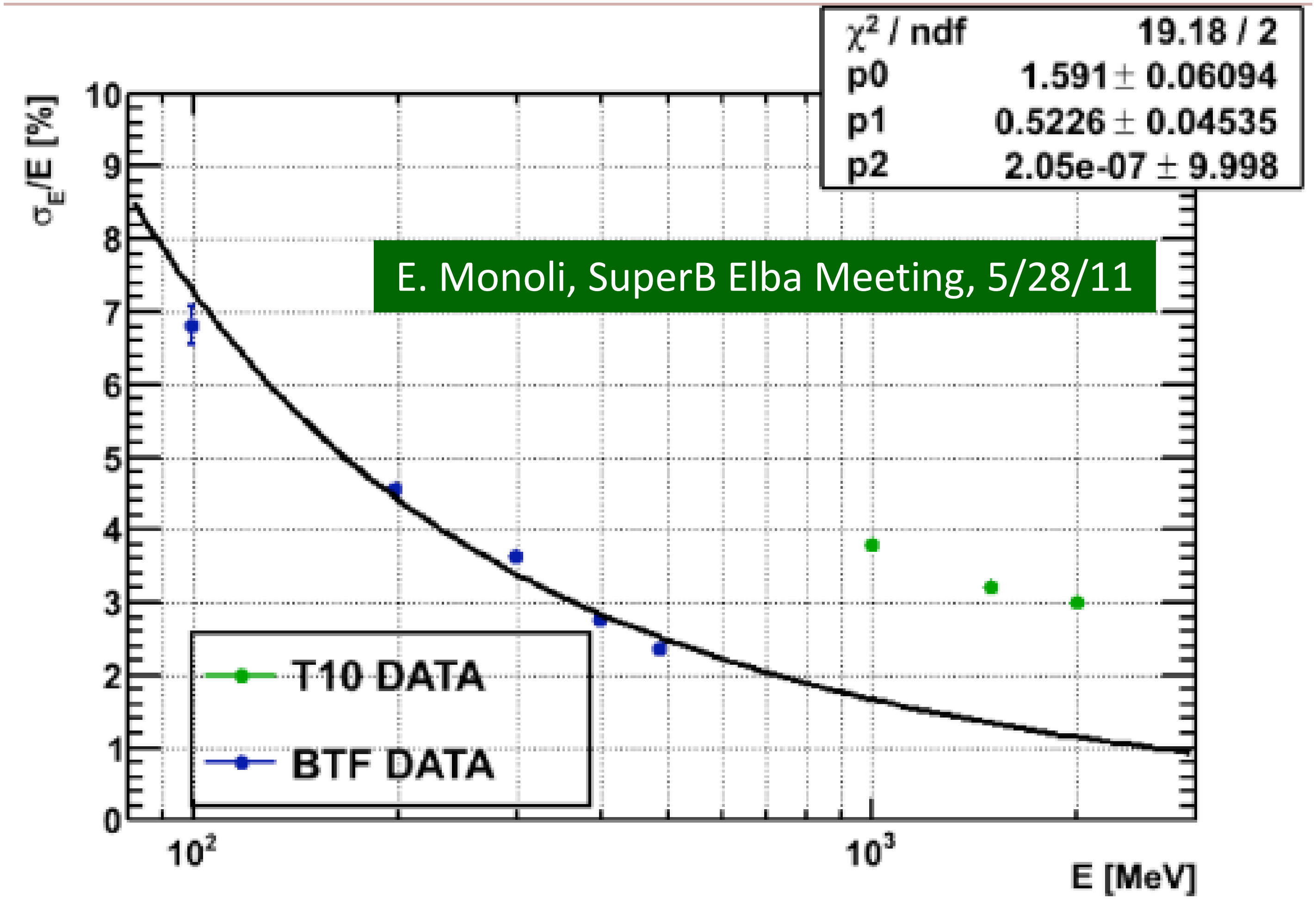
LSO/LYSO ECAL Performance

- 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:

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

SuperB LYSO Test Beam Result

Encouraging resolution measured at BTF, Frascati, with non uniformized LYSO crystals. Another test beam is planned at MAINZ after crystal uniformization

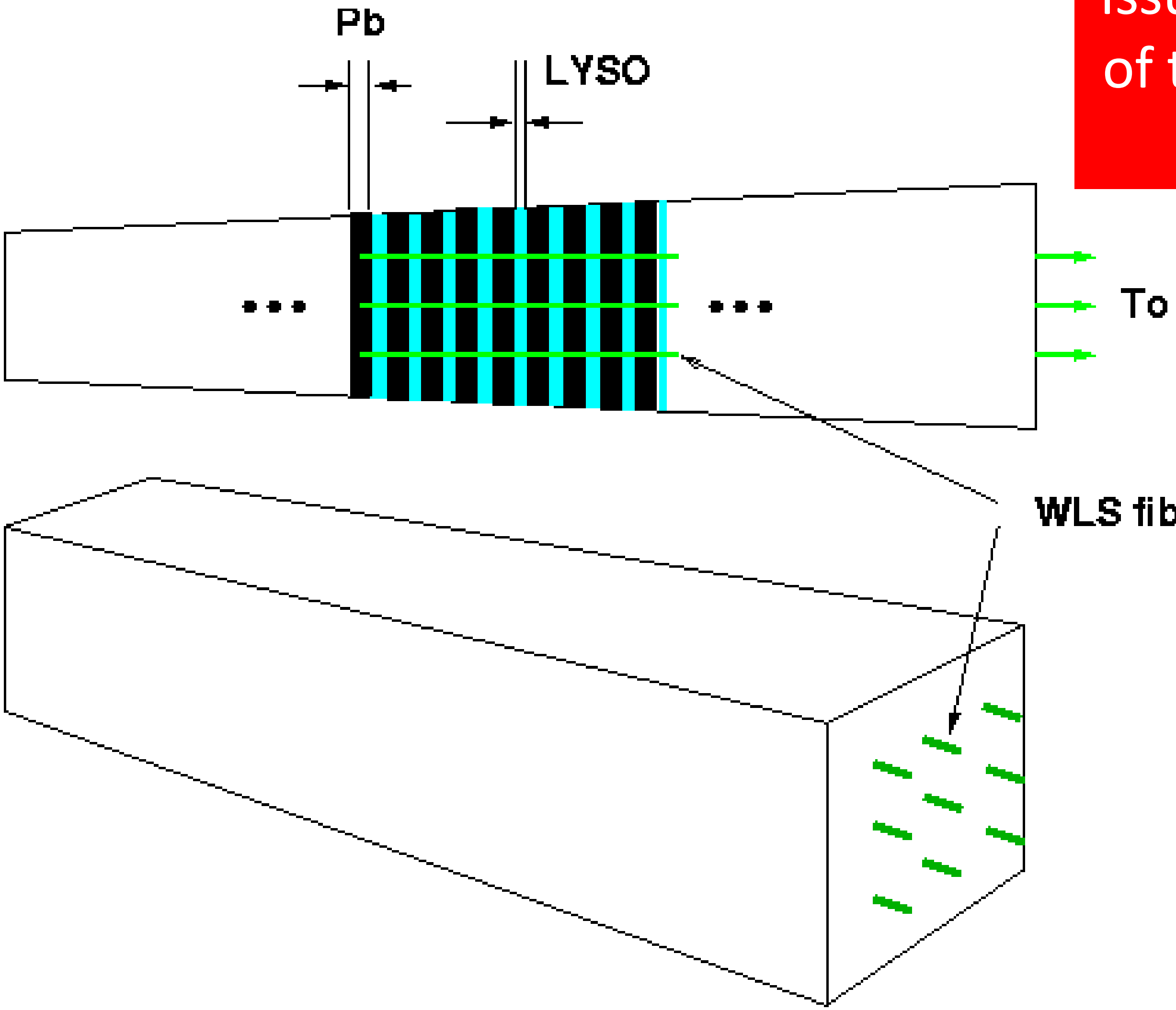


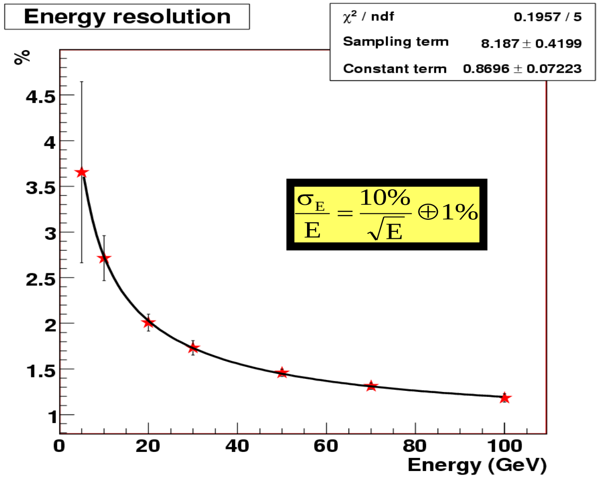
E. Monoli, SuperB Elba Meeting, 5/28/11

An LYSO Shashlic ECAL

R.-Y. Zhu, CMS Forward Calorimetry Meeting at CERN, 6/17/10

Issues: Radiation hardness of the photo-detector and the WLS fiber





Homogeneous Hadron Calorimeter

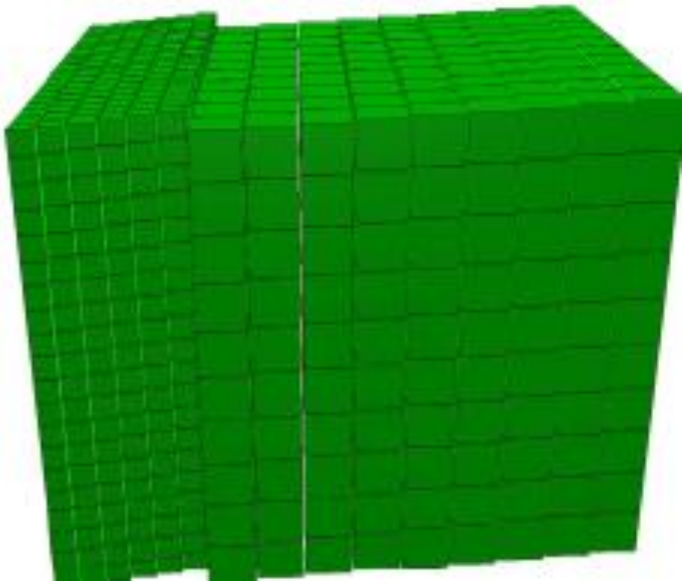
A Fermilab team (A. Para et al.) proposed a total absorption homogeneous HCAL detector concept to achieve good jet mass resolution by measuring both Cherenkov and Scintillation light. It also eliminates the dead materials between classical ECAL and HCAL. This longitudinal segmented crystal HCAL is possible because of the latest development in large area compact readout devices.

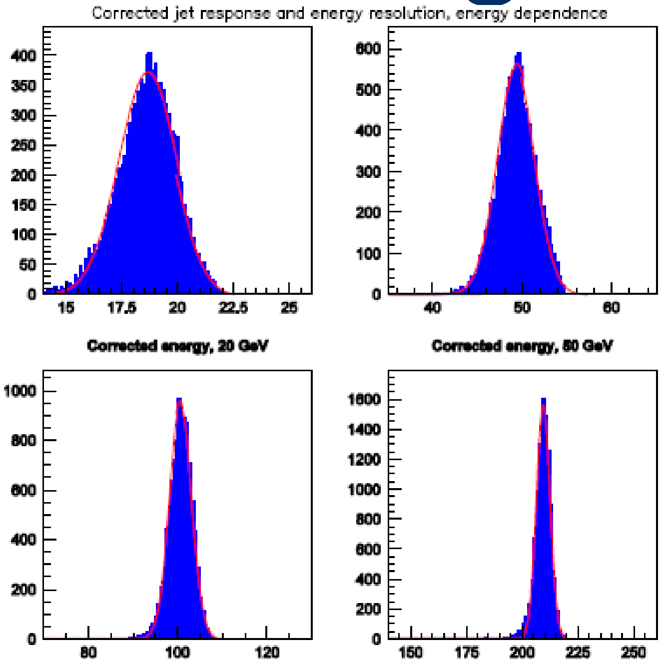
Requirements for the materials to be used for HHCAL:

- Short nuclear interaction length: ~ 20 cm.
- Good UV transmittance: UV cut-off < 350 nm.
- Some scintillation light, not necessary bright and fast.
- Cost-effective material: < \$2/cc for 100 m^3 !
- Radiation hardness is not crucial at the ILC/CLIC.

A series of workshops on material development for HHCAL:
1st 2/19/2008 at SIC, Shanghai, 2nd 5/9/2010 at IHEP, Beijing,
3rd 10/30/2010 at Knoxville, will go with SCINT, CALOR & IEEE NSS.

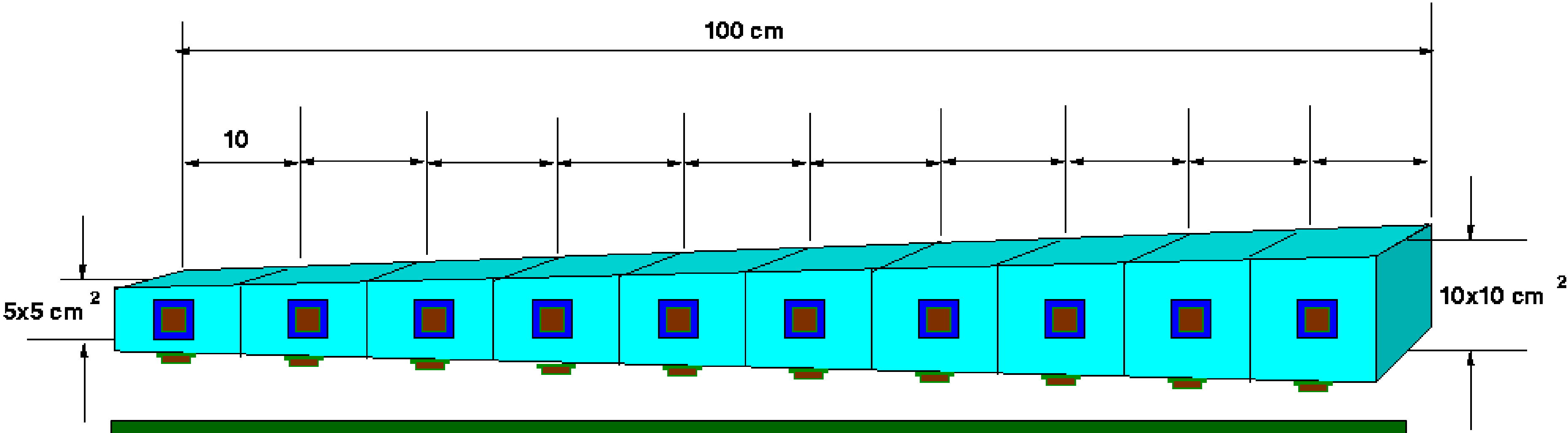
HHCAL Design





Corrected jet response and energy resolution, energy dependence

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, 11/18/08

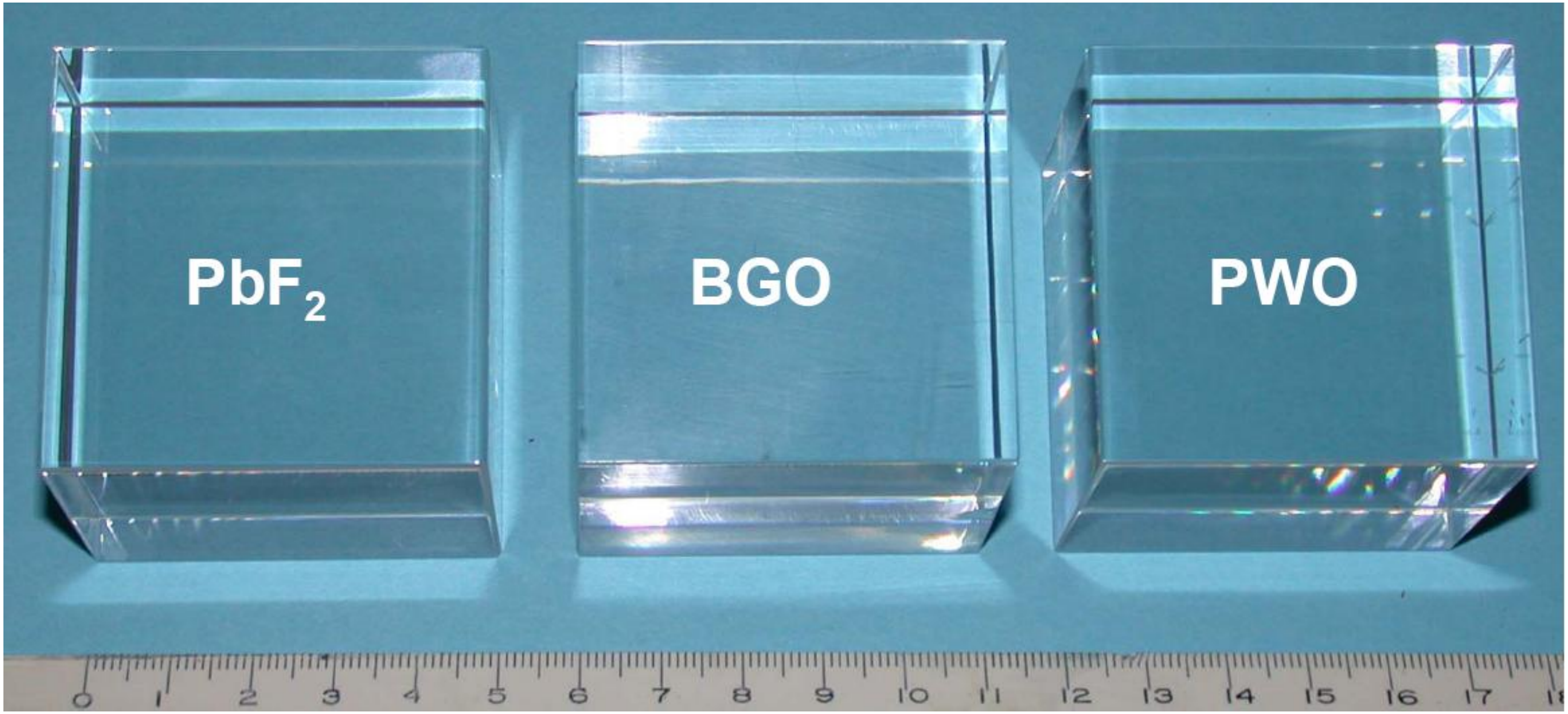
Candidate Crystals for HHCAL

Parameters	$Bi_4Ge_3O_{12}$ (BGO)	$PbWO_4$ (PWO)	PbF_2	PbClF	$Bi_4Si_3O_{12}$ (BSO)
ρ (g/cm^3)	7.13	**8.29**	**7.77**	7.11	6.8?
λ_I (cm)	22.8	**20.7**	**21.0**	24.3	23.1
n @ λ_{max}	2.15	2.20	1.82	2.15	2.06
τ_{decay} (ns)	300	30/10	**?**	30	100
λ_{max} (nm)	480	425/420	**?**	420	470
Cut-off λ (nm)	**310**	350	**250**	**280**	**300**
Light Output (%)	100	1.4/0.37	**?**	17	20
Melting point (°C)	**1050**	**1123**	**842**	**608**	**1030**
Raw Material Cost (%)	100	49	**29**	**29**	47

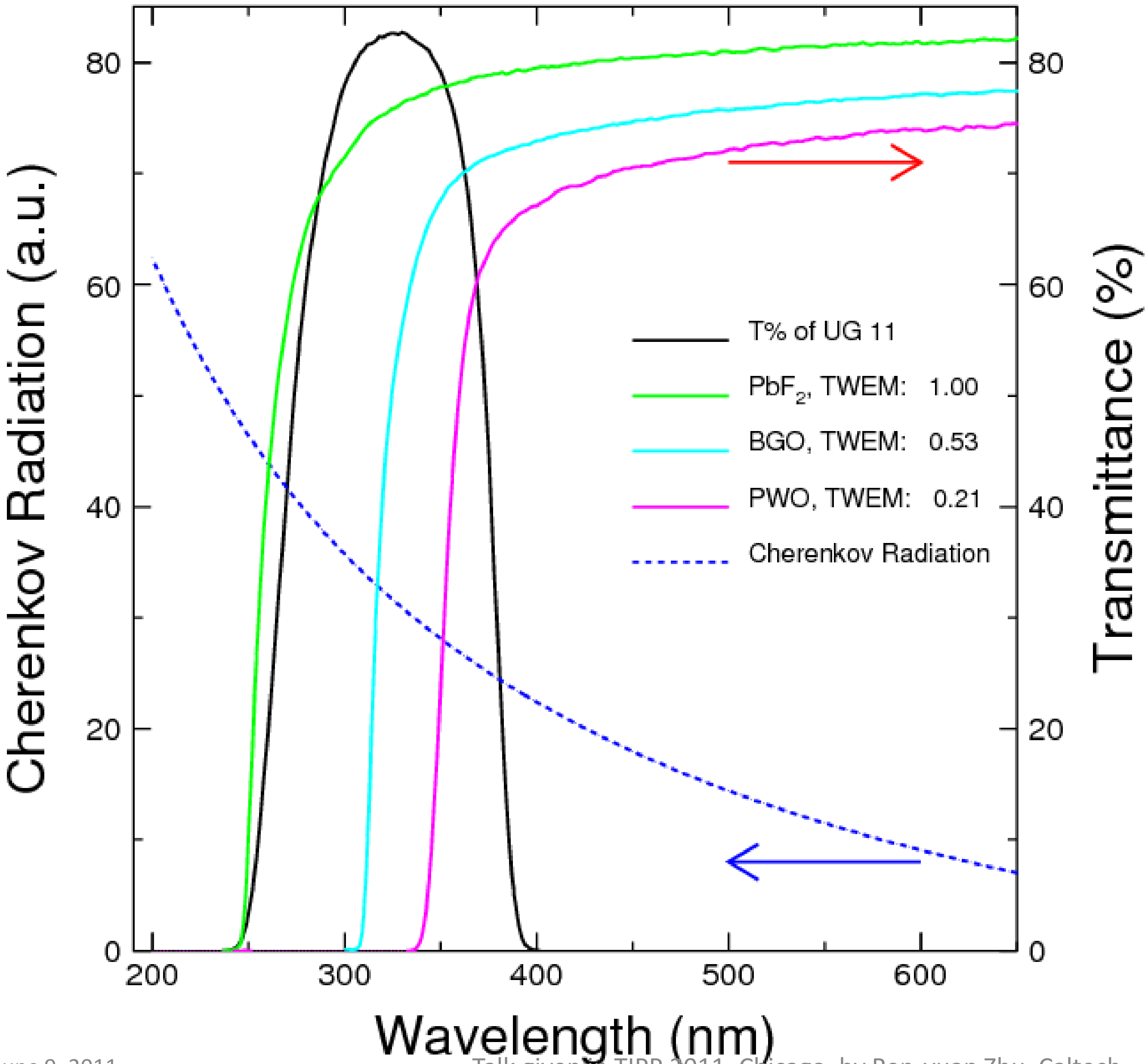
Crystal for Homogeneous HCAL

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

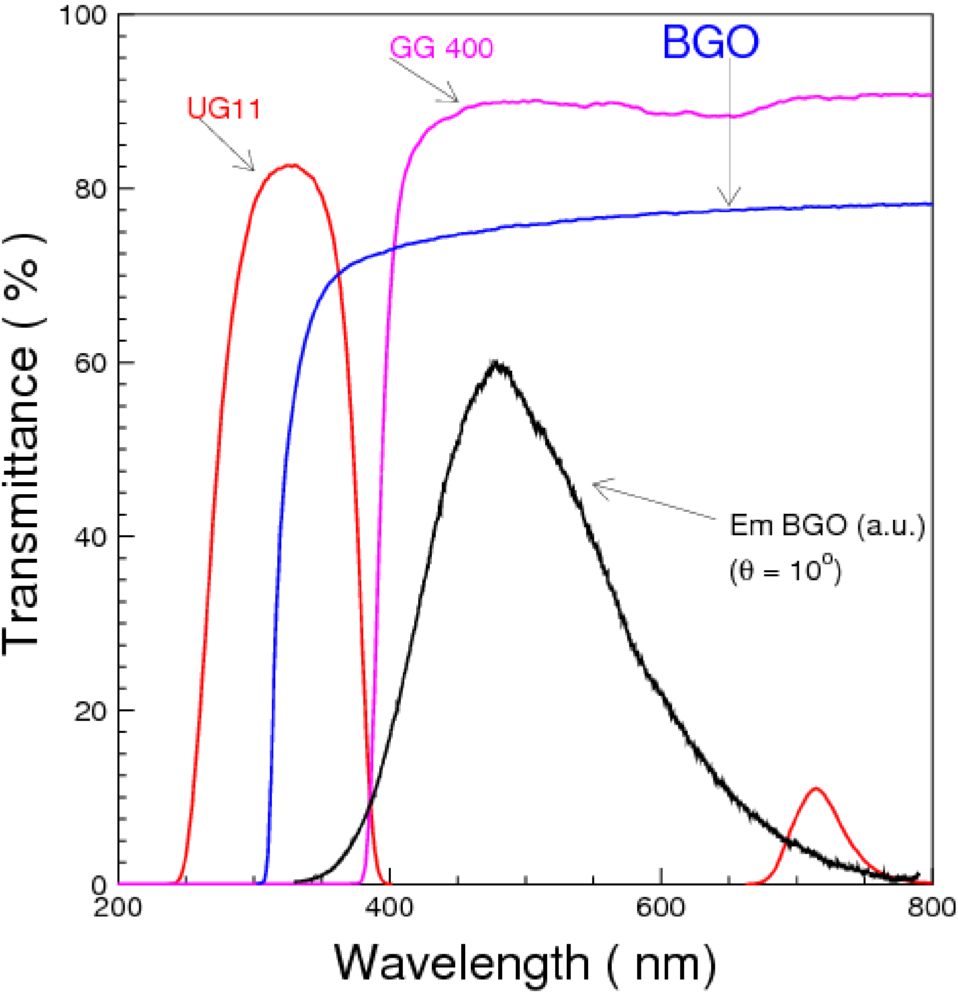


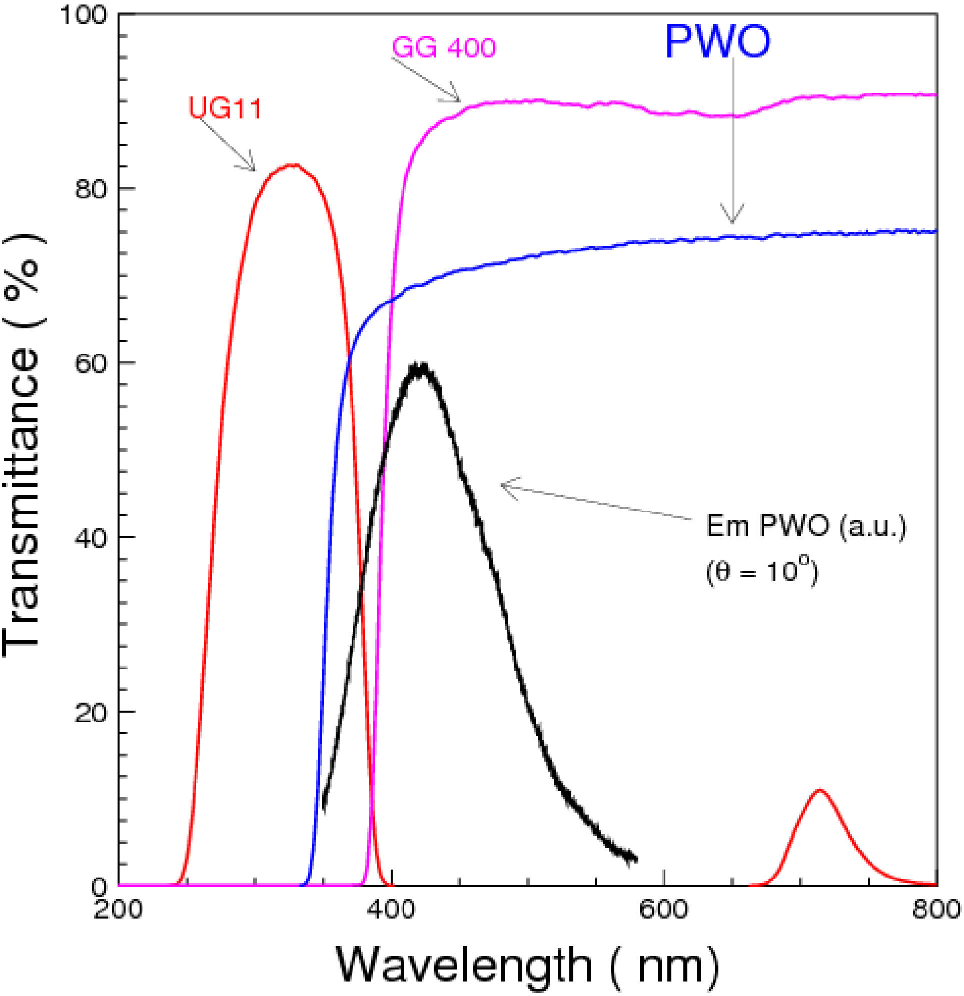
Cherenkov figure of merit

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

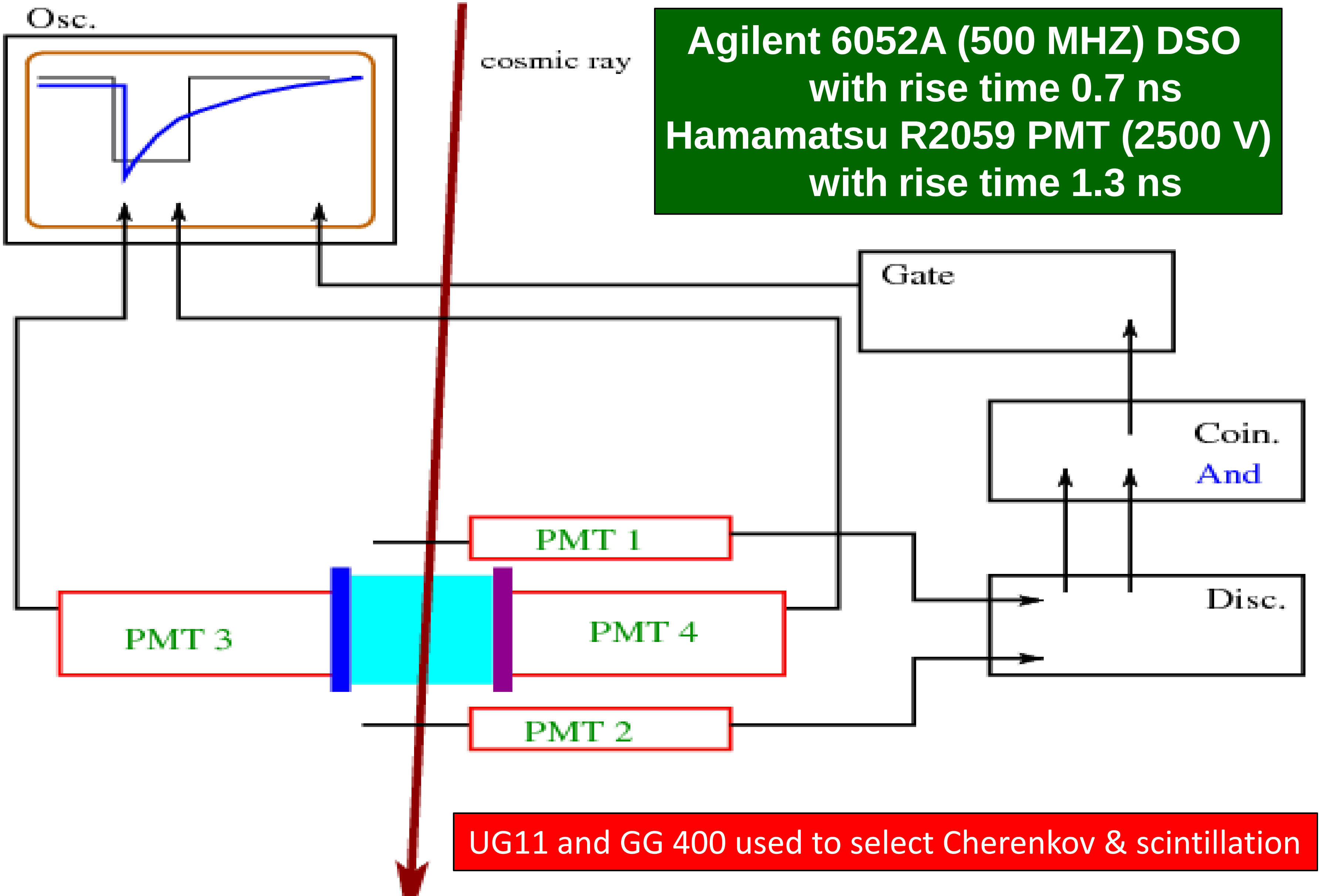
Scintillation Selected with Filters

UG11/GG400 optical filter effectively selects Cherenkov/scintillation light





Cosmic Setup with Dual Readout

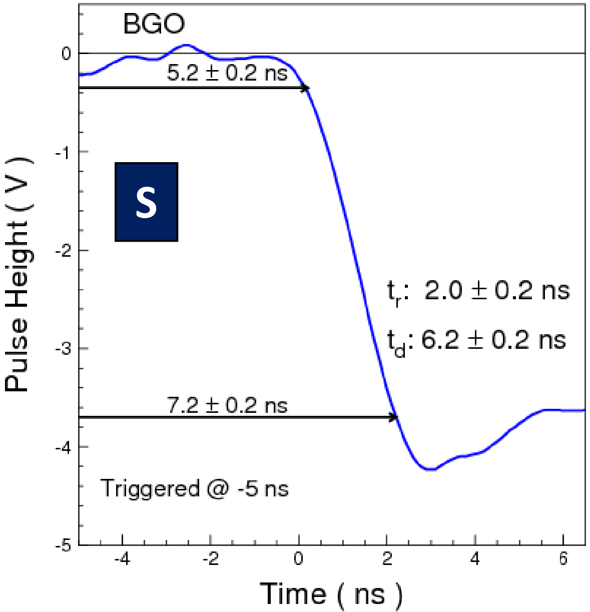


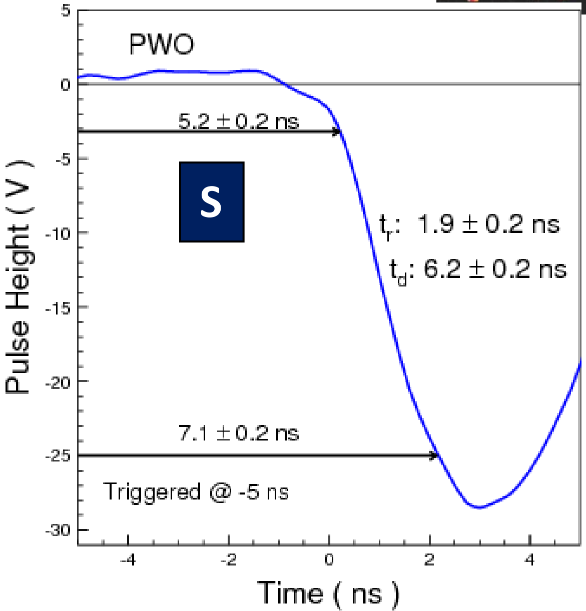
Agilent 6052A (500 MHZ) DSO
with rise time 0.7 ns
Hamamatsu R2059 PMT (2500 V)
with rise time 1.3 ns

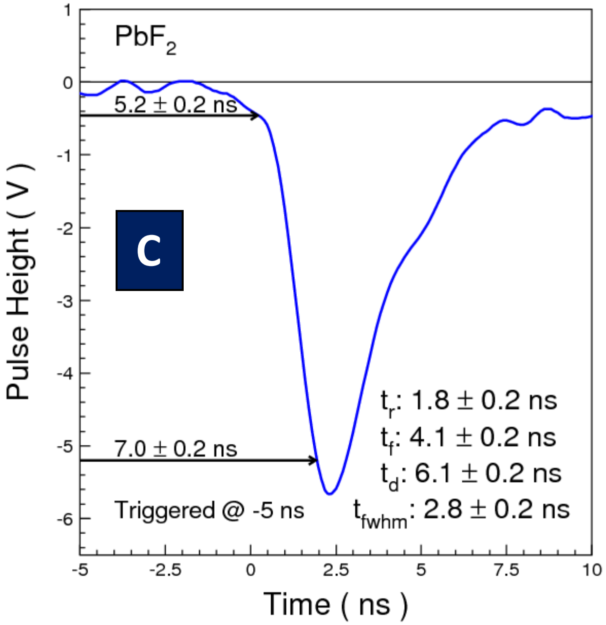
UG11 and GG 400 used to select Cherenkov & scintillation

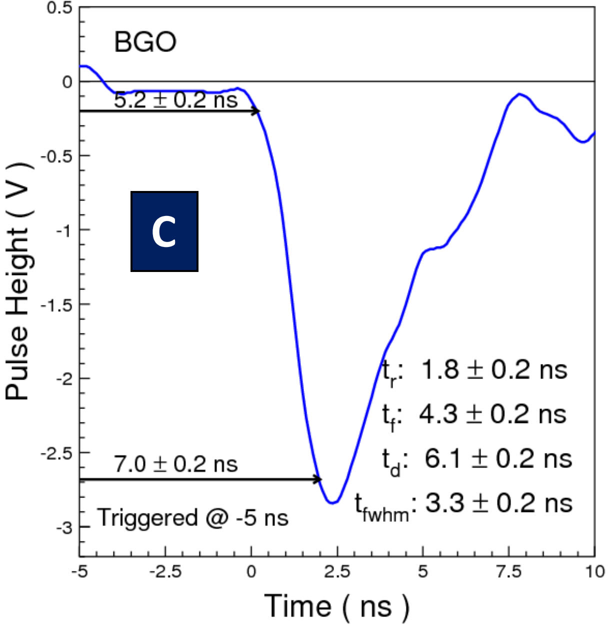
No Discrimination in Front Edge

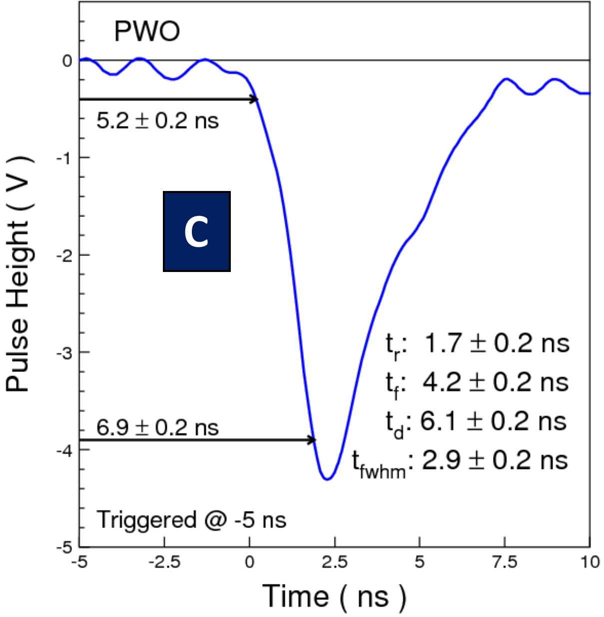
Consistent timing and rise time for all Cherenkov and scintillation light pulses observed.





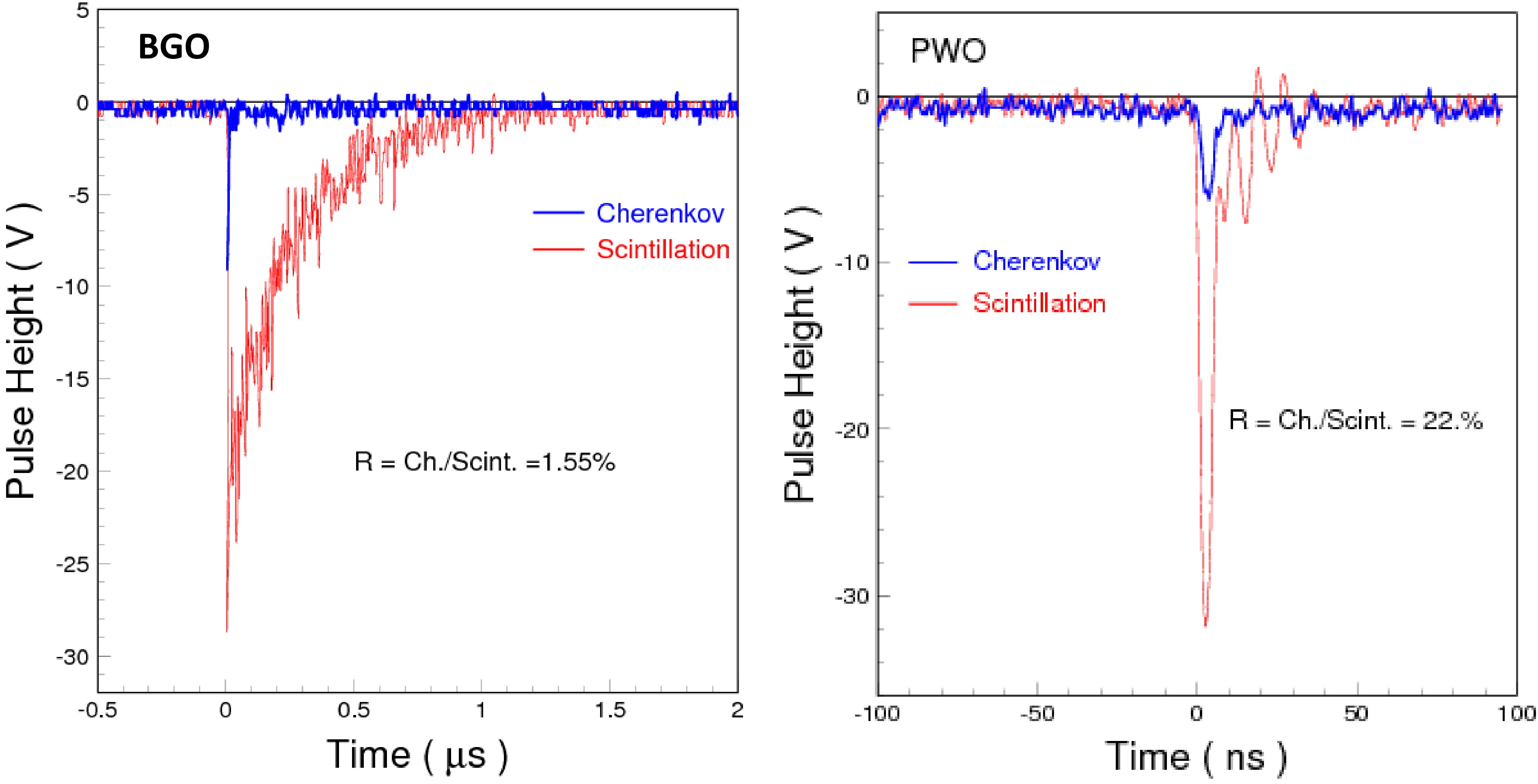






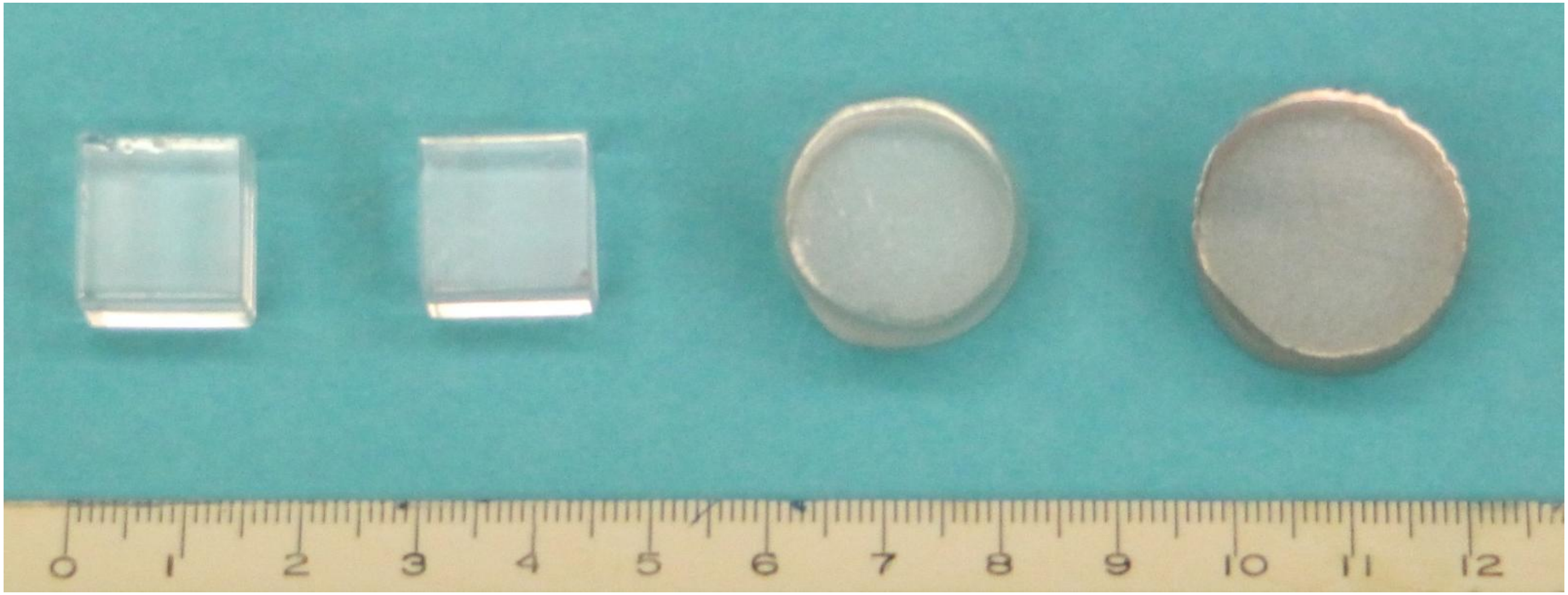
Ratio of Cherenkov/Scintillation

1.6% for BGO and 22% for PWO with UG11/GG400 filter and R2059 PMT, which is configuration dependent.



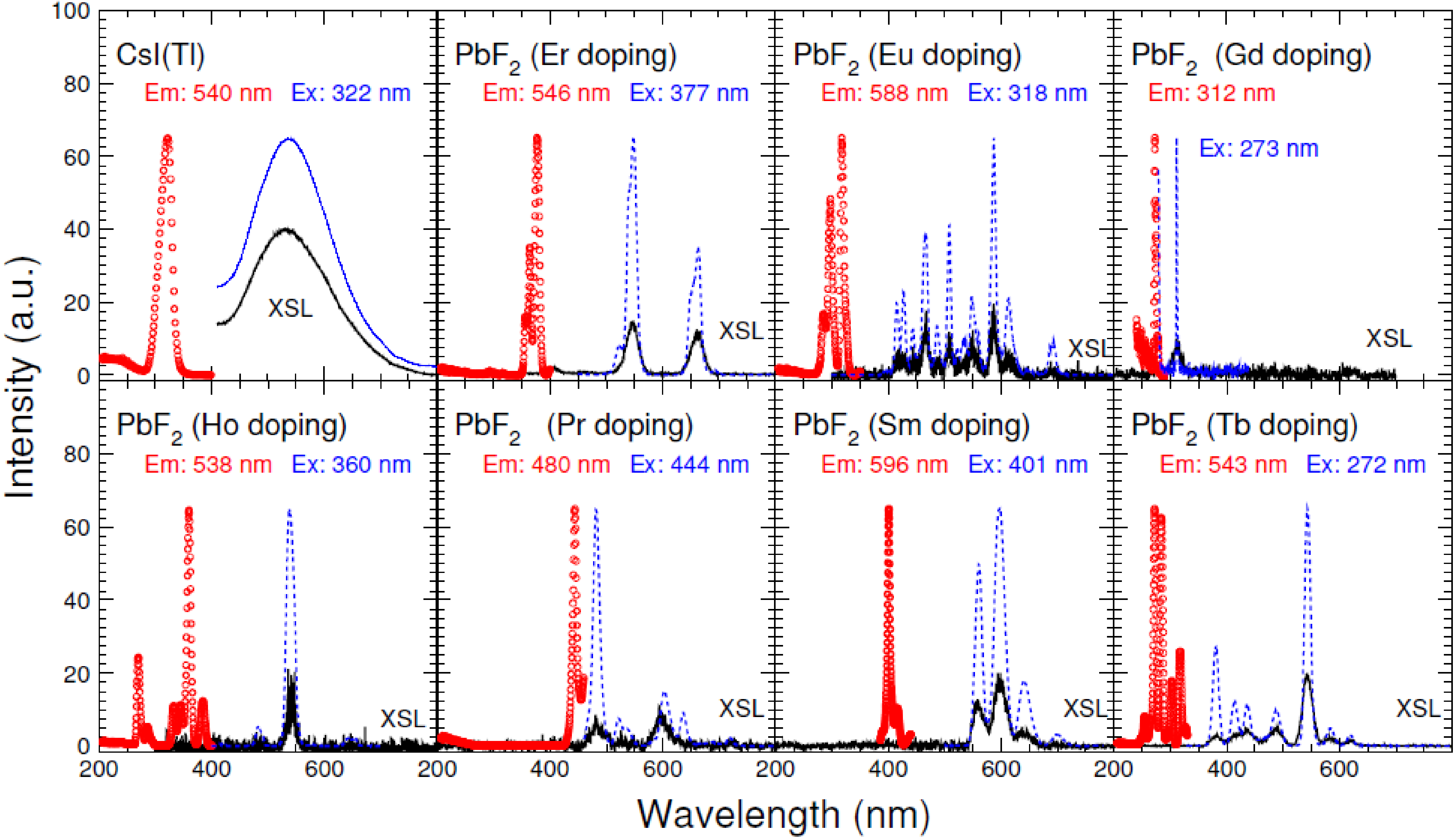
PbF_2 Crystal Samples

- A total of 116 samples with various rare earth doping were grown by vertical Bridgman method at SIC and Scintibow.
- SIC samples: grown in **platinum** crucible, 1.5 X_0 (14 mm) cube.
- Scintibow samples: grown in **graphite** crucible, Φ 22 x 15 mm.



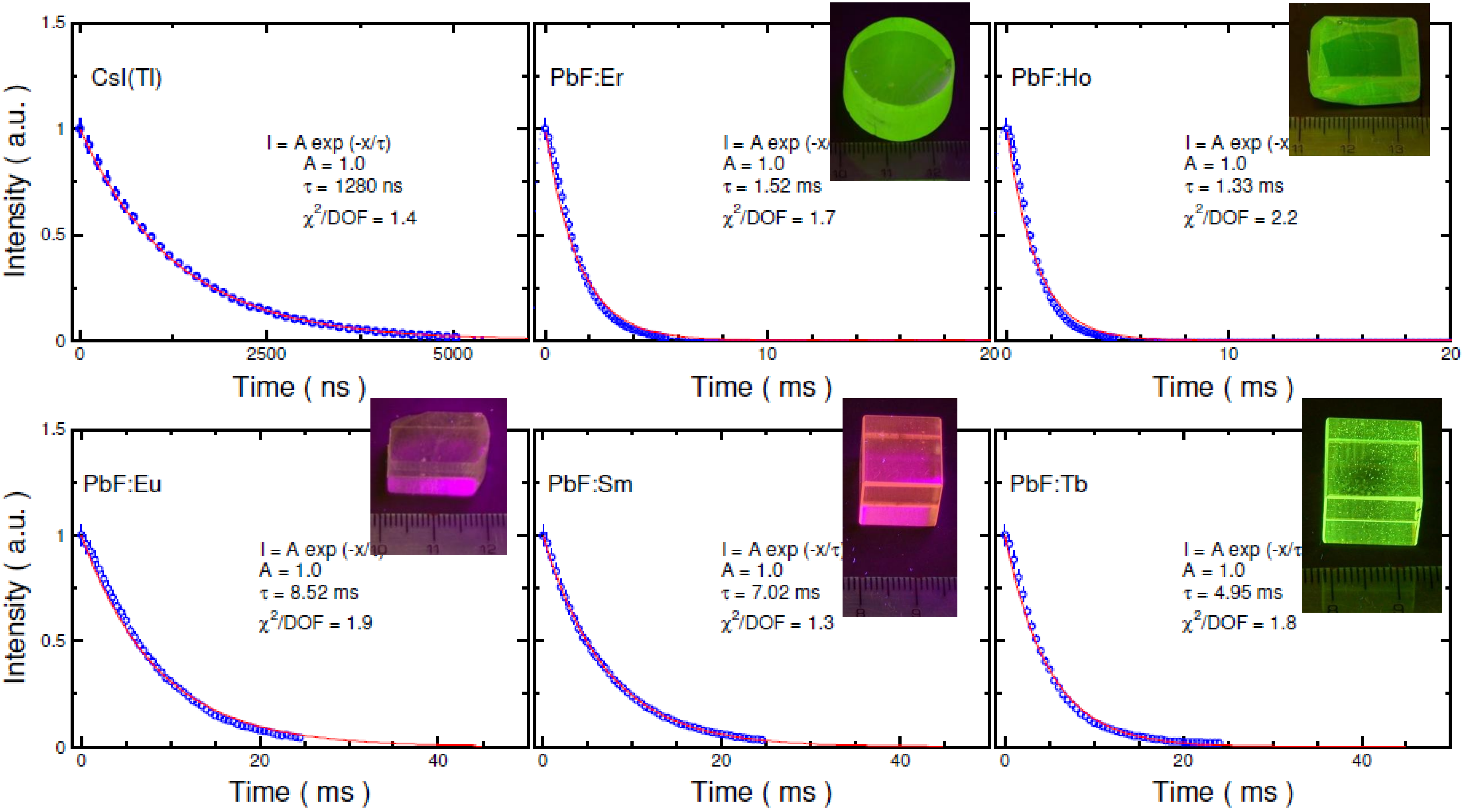
Luminescence Observed in PbF_2

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



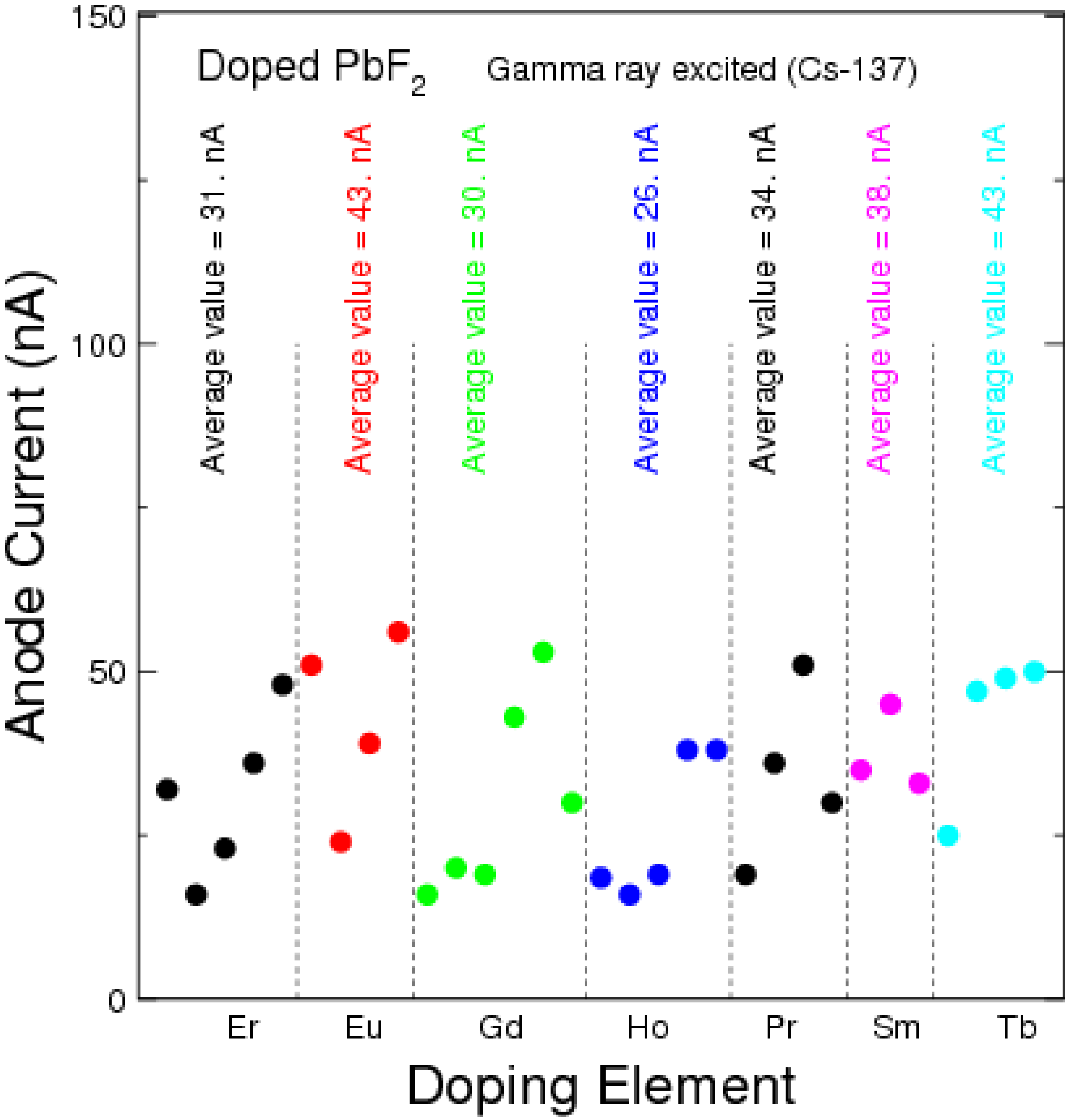
Rare Earth Doped PbF_2

Multi-ms decay time observed, indicating f-f transitions of these rare earth elements which is too slow to be useful.



Anode Current

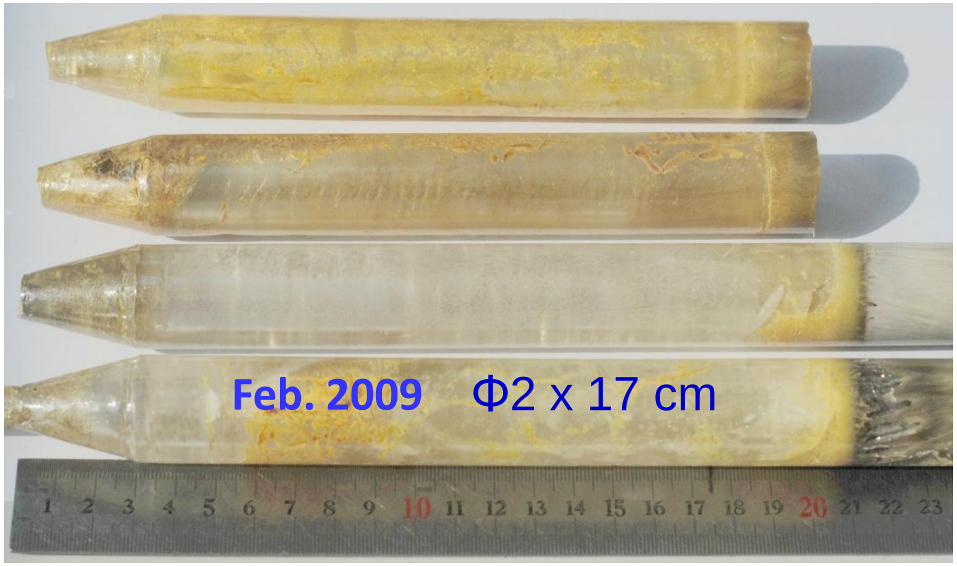
Anode current measured for doped PbF2 samples is at the same level as undoped crystals, indicating weak light.



BSO Crystals

Hu Yuan of SIC: Talk at the 2nd Workshop for HHCAL


Nov. 2008: Φ2.5 x 12 cm


Feb. 2009 Φ2 x 17 cm

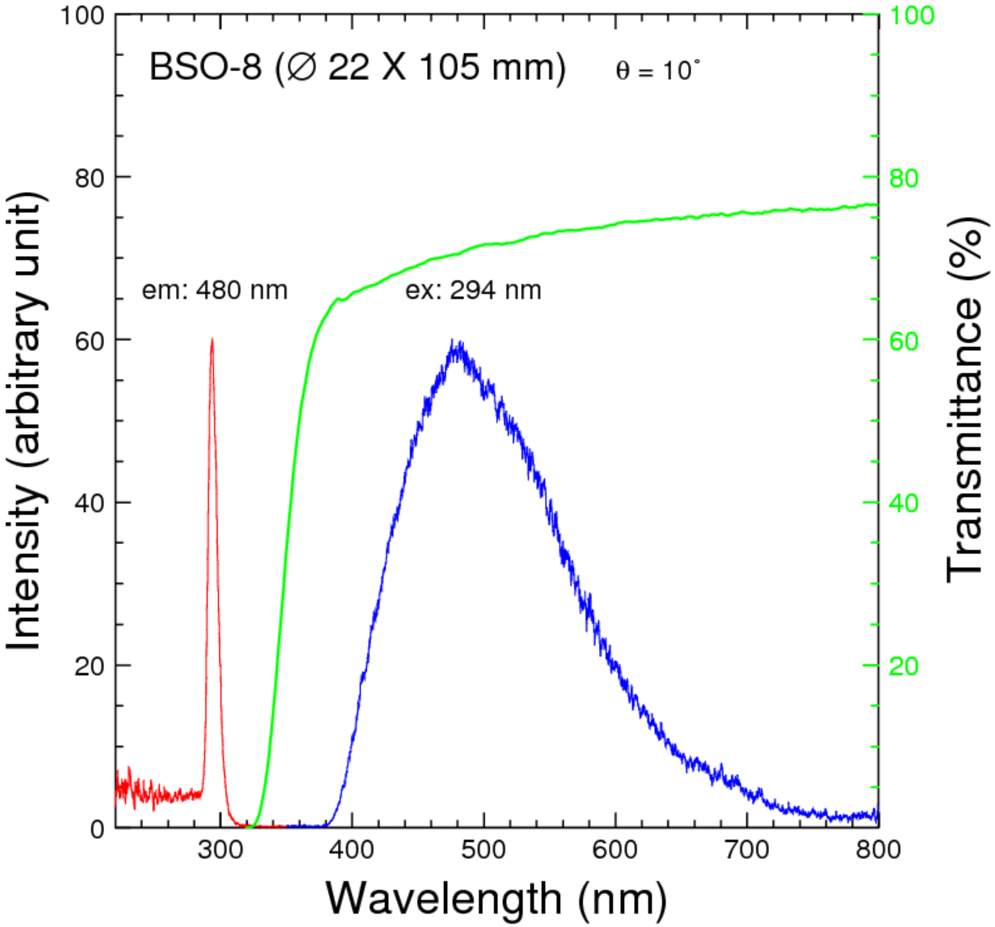

May 2009

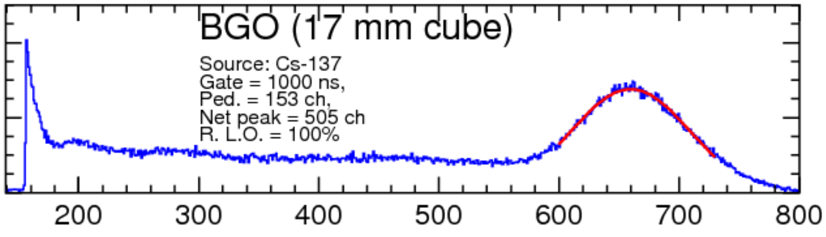
Φ5.5 x 12 cm

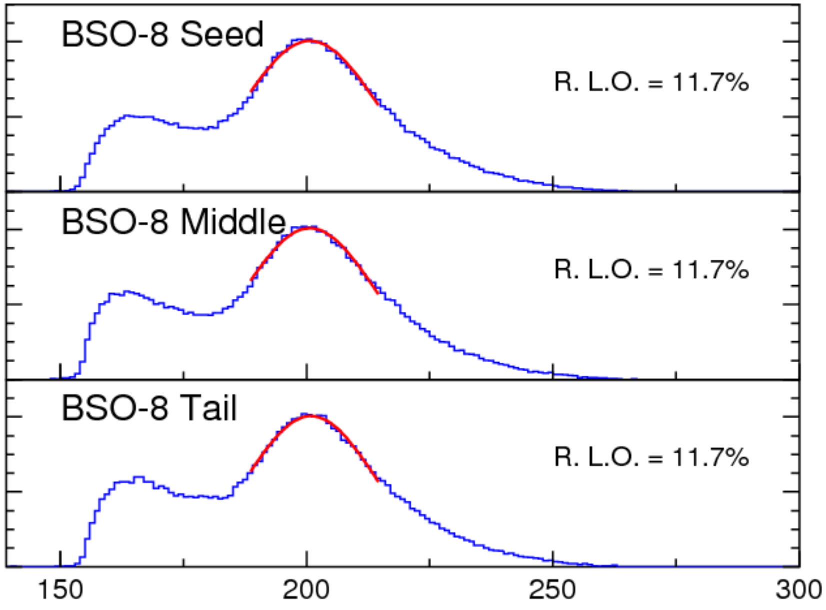

Oct. 2009: 2 x 18 cm

^{137}Cs Spectrum & Decay Kinetics

A Φ22 x 105 mm BSO shows good UV absorption edge and about 12% light output of a BGO cube with decay time 100 ns.

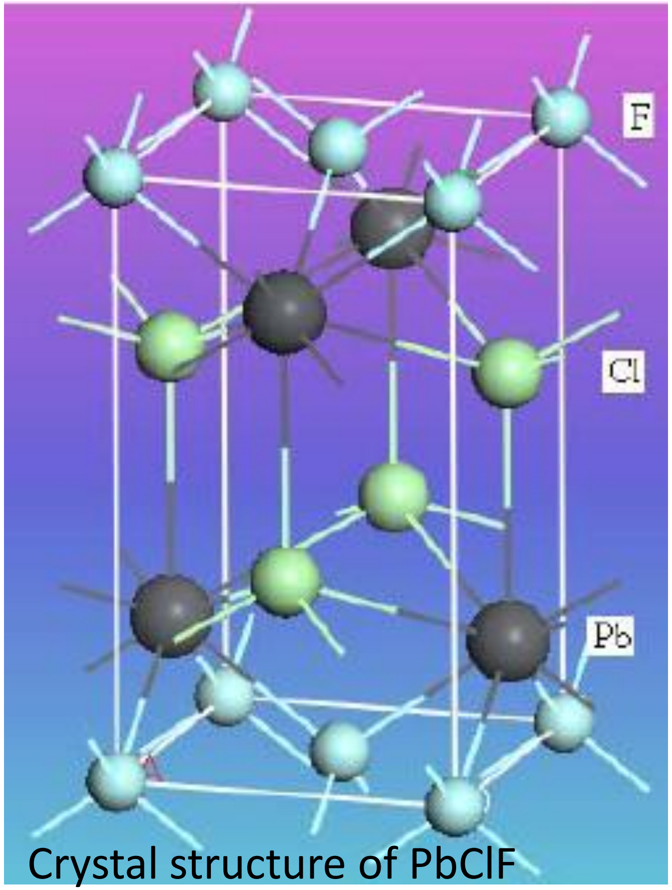






PbClF Crystals

Guohao Ren of SIC: Talk at the 2nd Workshop for HHCAL



Crystal structure of PbClF

D= 7.11g/cm³

Melting point =608°C

Space group=P/4nmm

a=4.10Å;c= 7.22Å

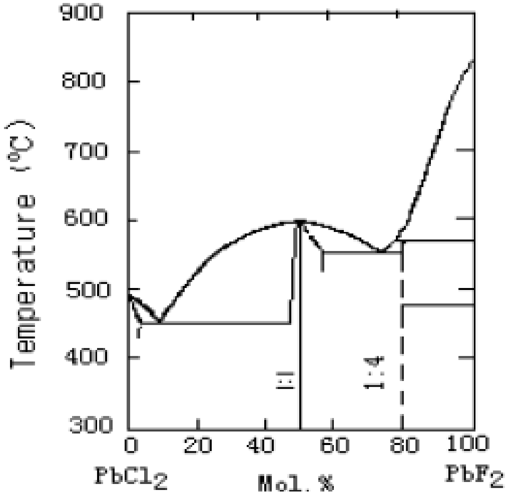
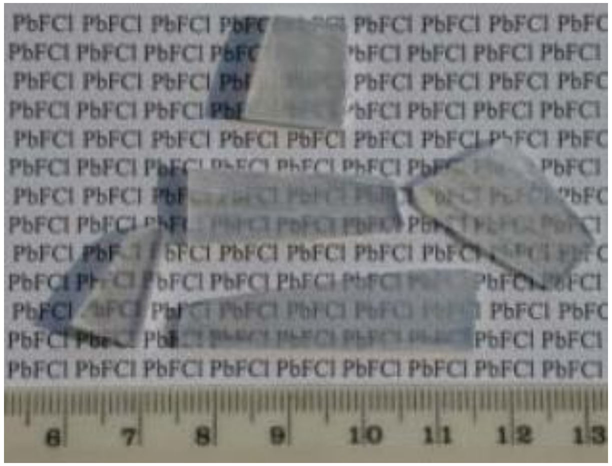
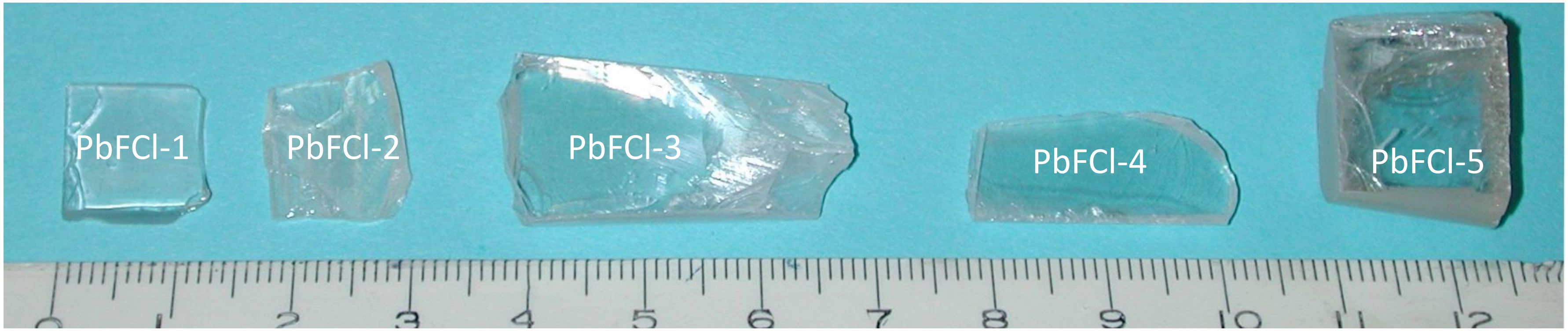


Figure 2.1 Phase relations in $PbCl_2$-PbF_2 system



PbClF Crystal samples grown at SICCAS

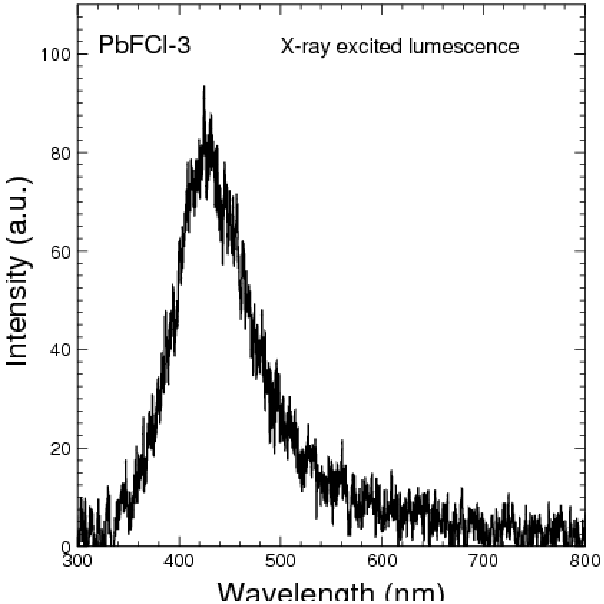
PbFCl Samples

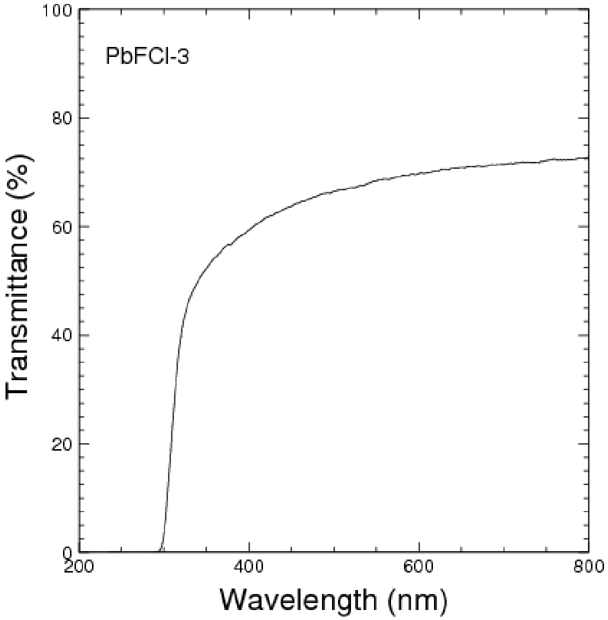


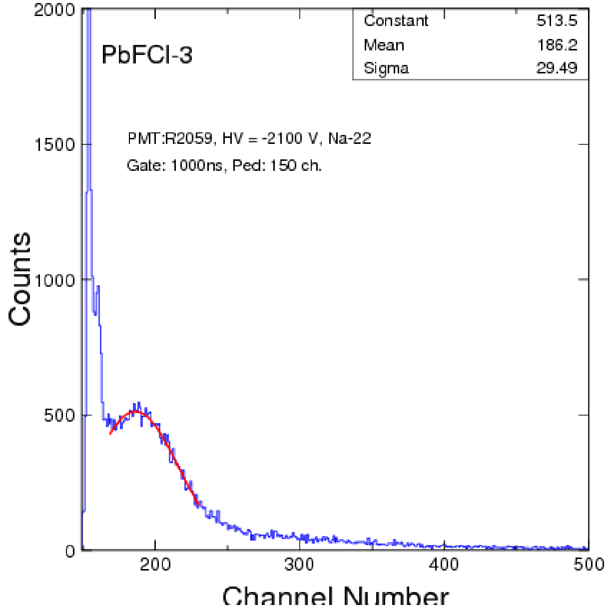
ID	PbFCl-1	PbFCl-2	PbFCl-3	PbFCl-4	PbFCl-5
Doping	--	Na 0.5at%	--	--	
Dimension (mm)	10x10x2	10x10x2	30x10x5	20x10x3	~10x10x9

ID	PWO	PbFCl-1	PbFCl-2	PbFCl-3	PbFCl-4	PbFCl-5
X-luminescence		Peaked @ 420 nm				
L.O. (% PWO)	100	14	64	33	35	31
L.O. (% BGO)	1.8	0.25	1.1	0.59	0.63	0.56

X-Luminescence & Transmittance



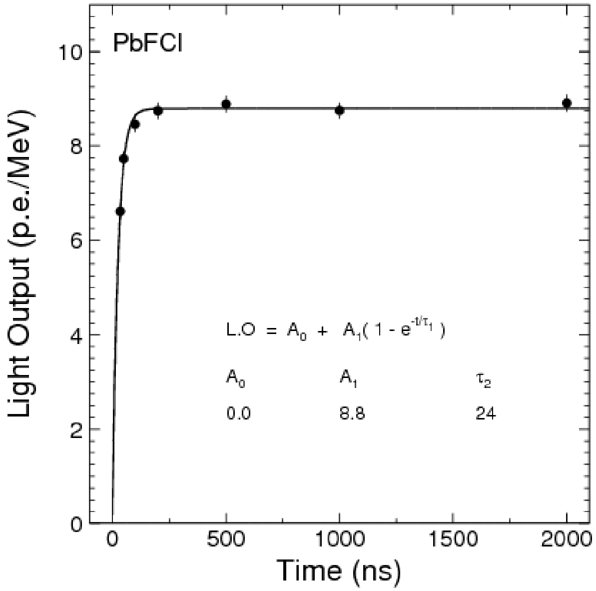




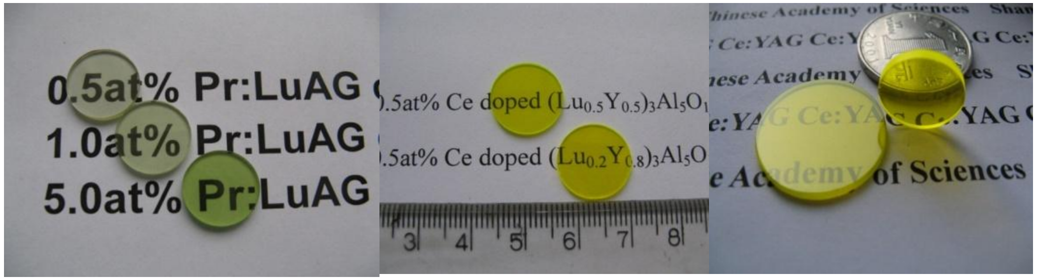
Consistent X-luminescence peaked at 420 nm observed in all PbFCl samples.

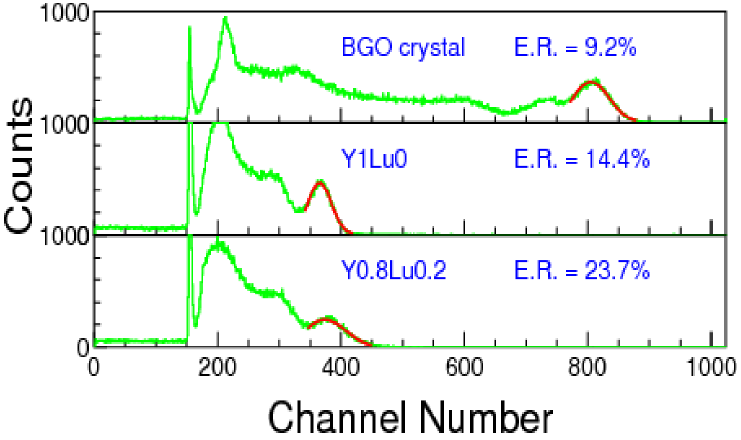
Transmittance cut-off at 300 nm.

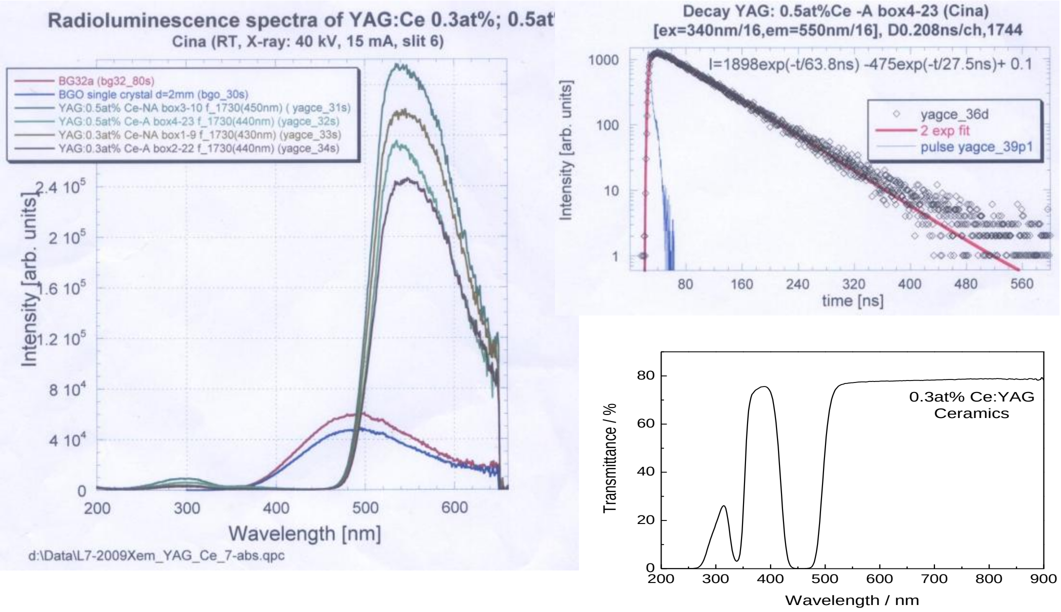
Weak scintillation light with decay time of 24 ns observed in all PbFCl samples.



Scintillating Ceramics at SICCAS





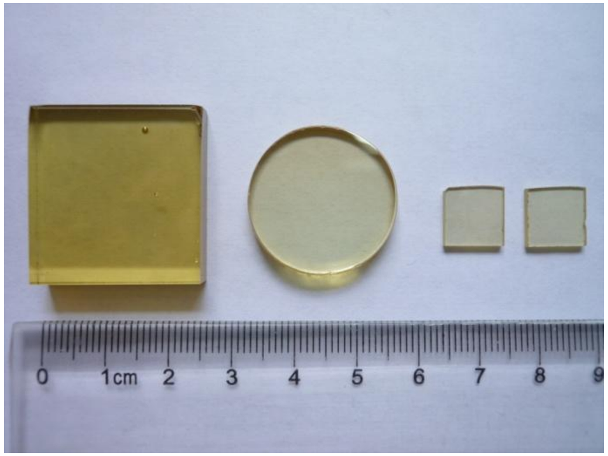


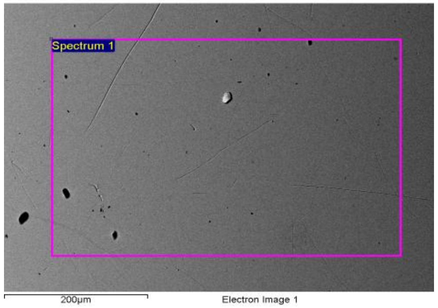
XEL Spectra, Decay curve and Transmittance of YAG based ceramics

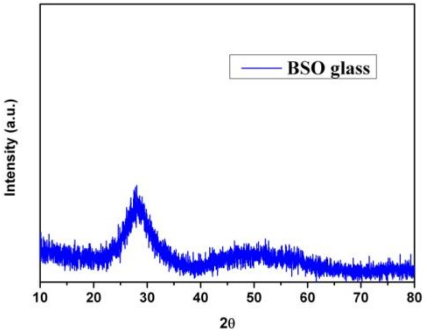
Highly transparent RAG-based scintillation ceramics were prepared and their properties characterized.

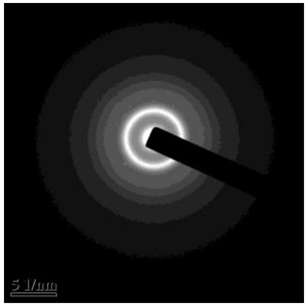
The scintillation properties of these ceramics may be optimized to fit the concept of the HHCAL detector.

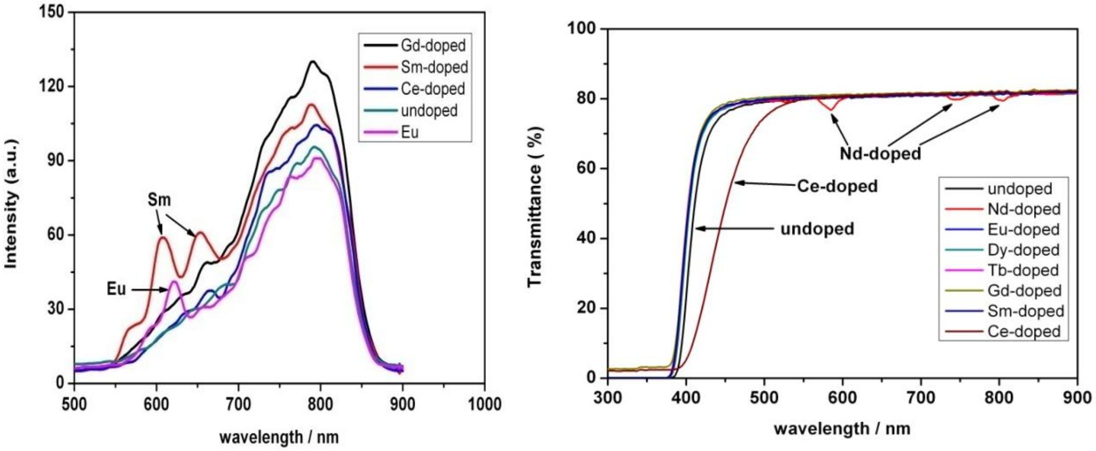
Scintillating BSO Glasses at SICCAS











XEL Spectra and Transmittance of BSO bulk glasses

Highly transparent BSO-based glasses were prepared and their properties characterized.

The scintillation properties of BSO glasses may be modified and optimization are undergoing to fit the concept of the HHCAL detector.

Summary

- Homogeneous crystal ECAL provides good resolutions for e/ɣ measurements. An LSO/LYSO ECAL may provide excellent energy resolution over a large dynamic range down to MeV level.

- Homogeneous hadronic calorimeter (HHCAL) would provide good resolution for hadron and jet measurements. Because of the huge volume needed development of cost-effective UV transparent material is crucial. Our initial investigation indicates that scintillating PbF_2 PbClF and BSO are the best crystal candidates. Scintillating glasses and ceramics are also being considered.

- LSO/LYSO plates have also be proposed for a Shashlic type sampling calorimeter for HL-LHC. Scintillating glasses and ceramics may also fit in this application if radiation hard.

2nd Workshop for the HHCAL

May 9, 2010, Beijing: http://indico.ihep.ac.cn/conferenceTimeTable.py?confId=1470

1) HHCAL and General Requirement:

Gene Fisk, FNAL: "Fermilab's History in the Development of Crystals, Glasses and Si Detector Readout for Calorimetry"
Adam Para, FNAL: "Scintillating Materials for Homogeneous Hadron Calorimetry"
Steve Derenzo, LBL: "Search for Scintillating Glasses and Crystals for Hadron Calorimetry"
Paul Lecoq, CERN: "A CERN Contribution to the Dual Readout Calorimeter Concept"

2) Materials for HHCAL (I) :

Alex Gektin, SCI: "Crystal Development for HHCAL: Physics and Technological Limits"
Liyuan Zhang, Caltech: "Search for Scintillation in Doped Lead Fluoride for the HHCAL Detector Concept"
Guohao Ren, SIC: "Development of Halide Scintillation Crystals for the HHCAL Detector Concept "
Hui Yuan, SIC: "BSO Crystals Development with the Modified Multi-crucible Bridgman Method for the HHCAL Detector Concept"

3) Materials for the HHCAL (II) followed by discussions

Mingrong Zhang, BGRI: "R&D on Scintillation Crystals and Special Glasses at BGRI"
Tiachi Zhao, U Washington/IHEP and Ningbo University: " Study of Dense Scintillating Glass Samples"
Jing Tai Zhao, SIC: "Status of Scintillating Ceramics and Glasses at SIC and Their Potential Applications for the HHCAL Detector Concept"
Richard, Wigmans, Texas Tech University: "Some thoughts about homogeneous dual-readout calorimeters"

3rd Workshop for the HHCAL

October 31, 2010, Knoxville: http://www.nss-mic.org/2010/program/ListProgram.asp?session=HC1,2,3,4

1. A. Para, Prospects for High Resolution Hadron Calorimetry
2. G. Mavromanolakis , Studies on Dual Readout Calorimetry with Meta-Crystals
3. D. Groom, Degradation of resolution in a homogeneous dual readout hadronic calorimeter
4. S. Derenzo, High-Throughput Synthesis and Measurement of Candidate Detector Materials for Homogeneous Hadronic Calorimeters
5. M. Poulain, Fluoride Glasses: State of Art and Prospects
6. I. Dafinei, High Density Fluoride Glasses, Possible Candidates for Homogeneous Hadron Calorimetry
7. P. Hobson, Prospects for Dense Glass Scintillators for Homogeneous Calorimeters
8. G. Dosovitski, Potential of Crystalline, Glass and Ceramic Scintillation Materials for Future Hadron Calorimetry
9. Tianchi Zhao, Study on Dense Scintillating Glasses
10. Jin-tai Zhao, BSO-Based Crystal and Glass Scintillators for Homogeneous Hadronic Calorimeter
11. Guohao Ren, Development of RE-Doped Cubic PbF2 and PbClF Crystals for HHCAL

12, N. Cherepy, Transparent Ceramic Scintillators for Hadron Calorimetry

13. J. Dong, Experimental Study of Large Area GEM
14. H. Frisch, The Development of Large-Area Flat-Panel Photodetectors with Correlated Space and Time Resolution