Precision Crystal Calorimeters in High Energy Physics: Past, Present and Future

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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.

Physics with Crystal Calorimeters (I)

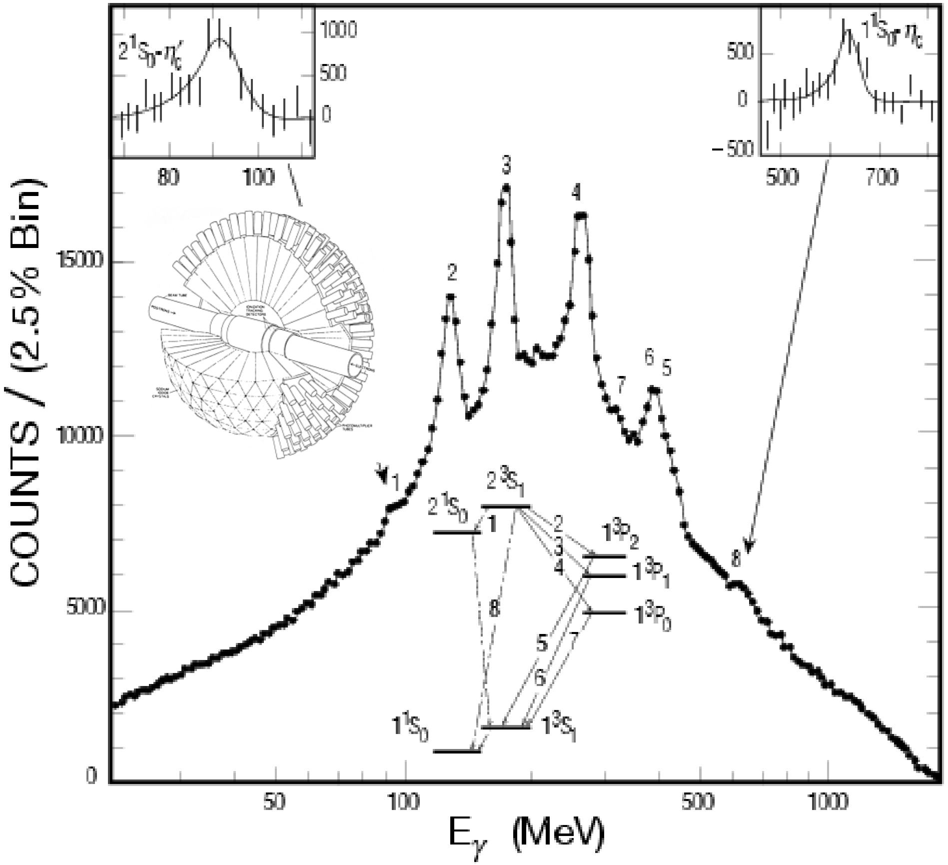
Charmonium system observed by CB through Inclusive photons

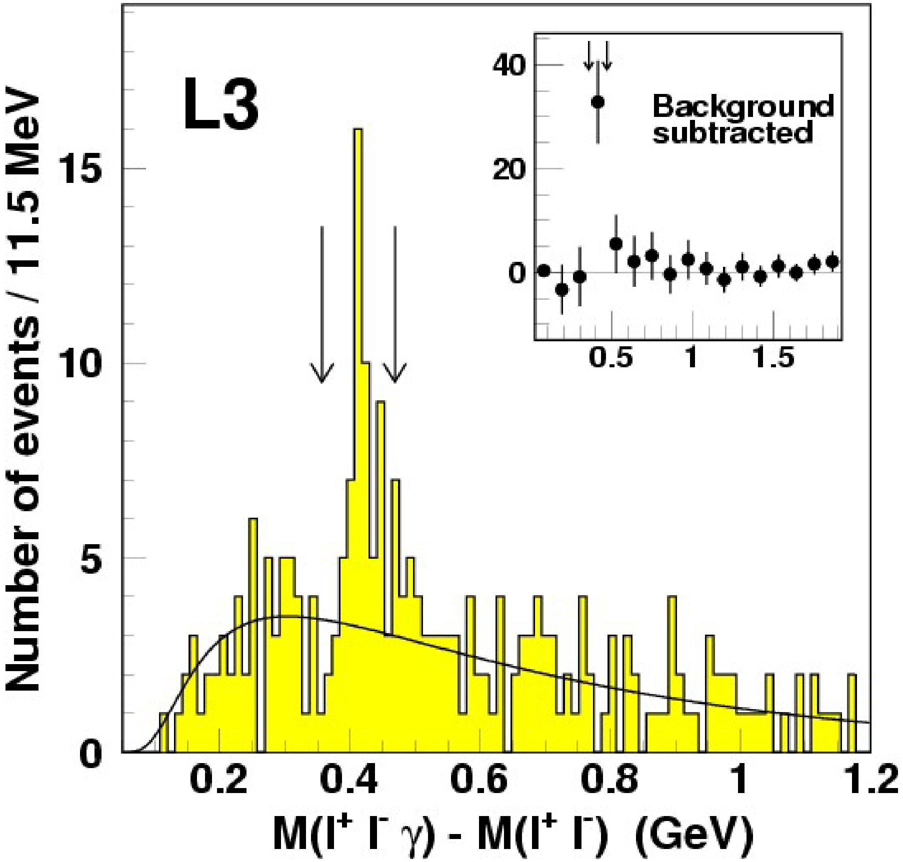
Charmed Meson in Z Decay

$$\chi_{c1} \rightarrow J/\psi\gamma$$

CB NaI(Tl)

L3 BGO

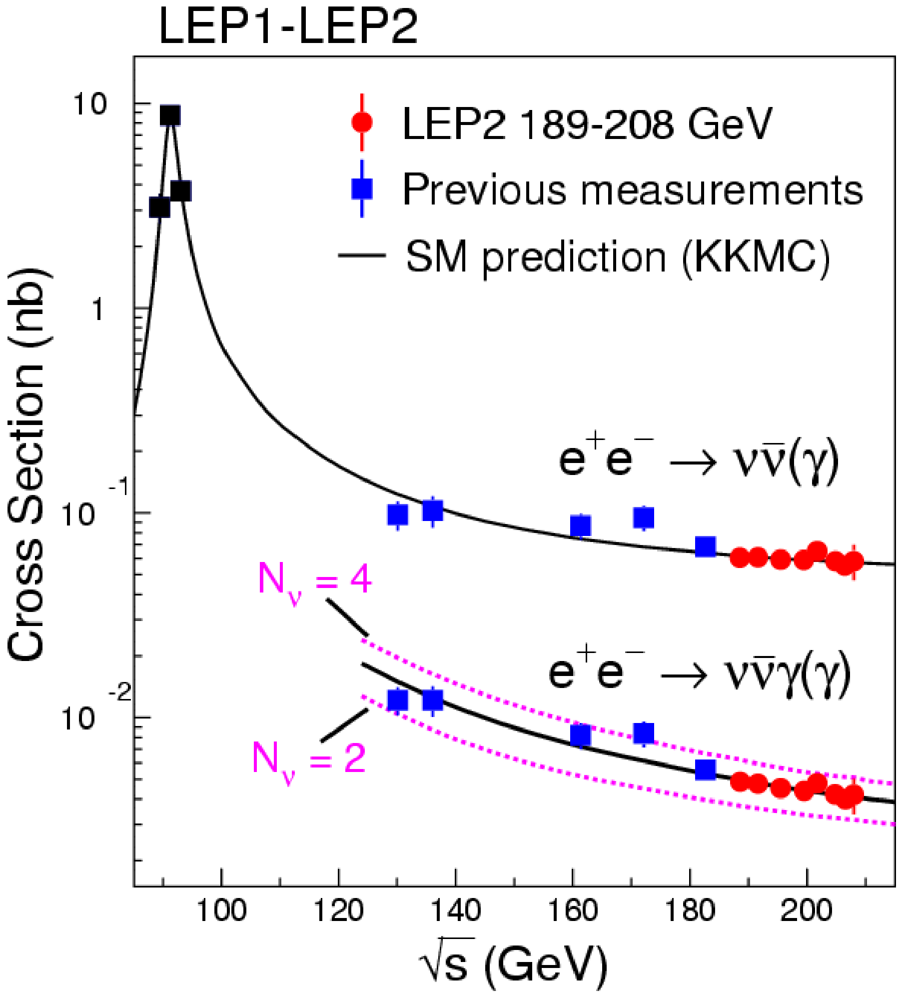




Physics with Crystal Calorimeters (II)

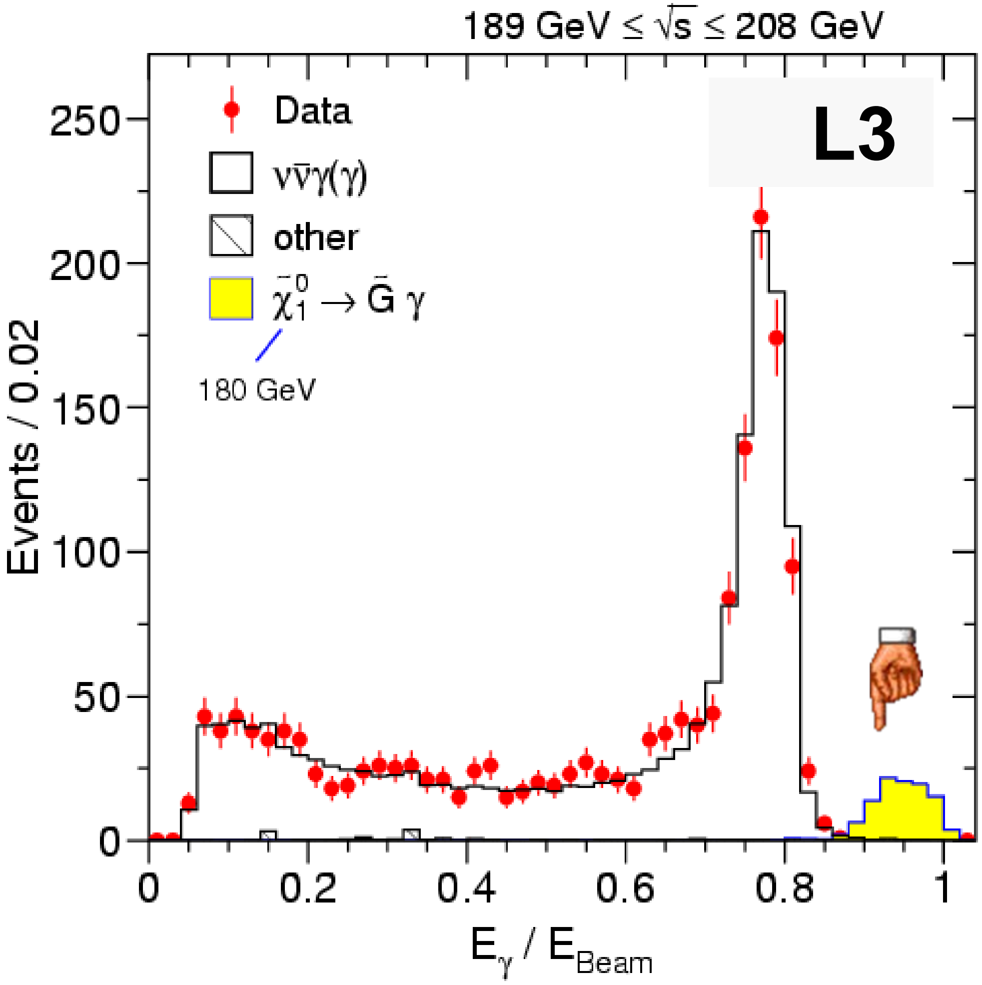
Neutrino Counting in Z Decay

$N_\nu = 2.98 \pm 0.06$

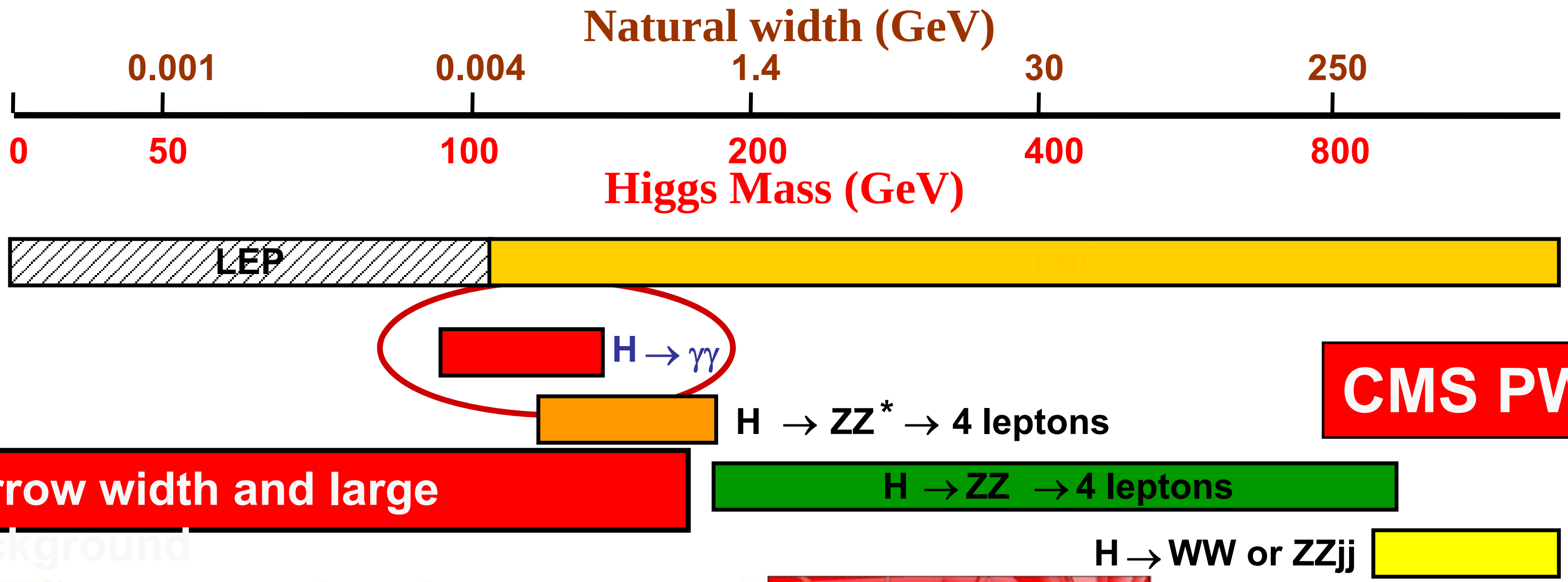


SUSY Breaking with Gravitino

$$e^+e^- \rightarrow \tilde{G}\tilde{\chi}_1^0 \rightarrow \tilde{G}\tilde{G}\gamma$$

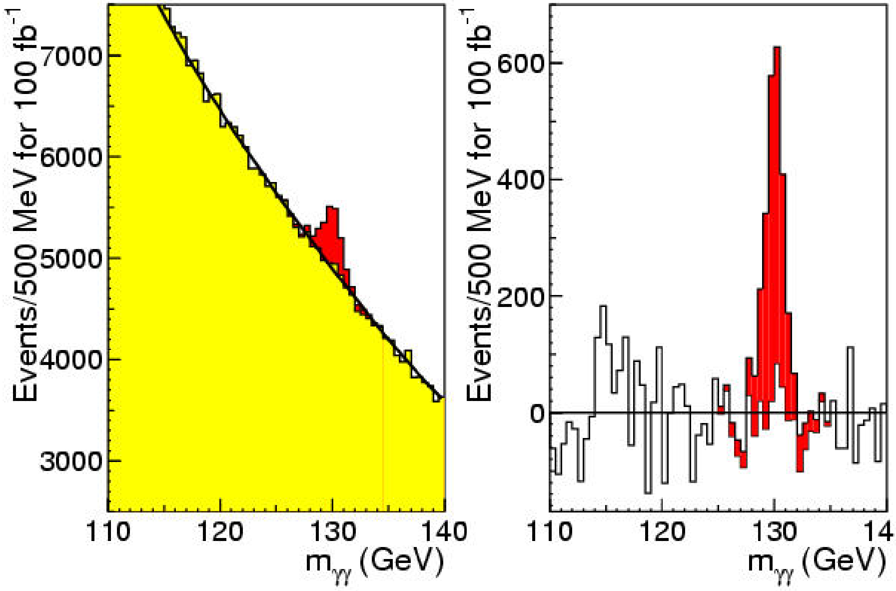


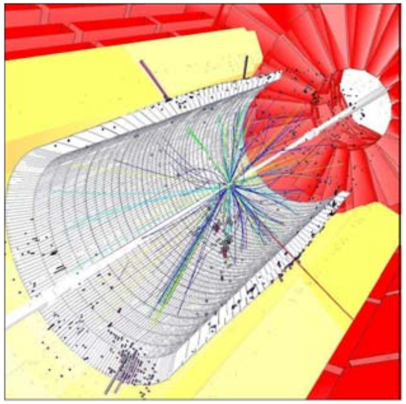
H→γγ Search Needs Precision ECAL

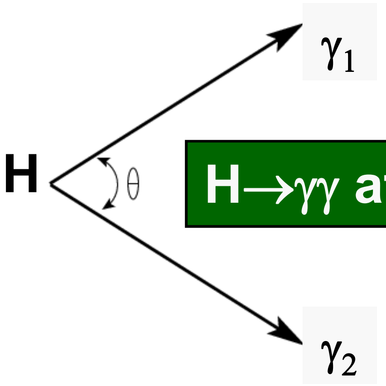


CMS PWO

Narrow width and large background





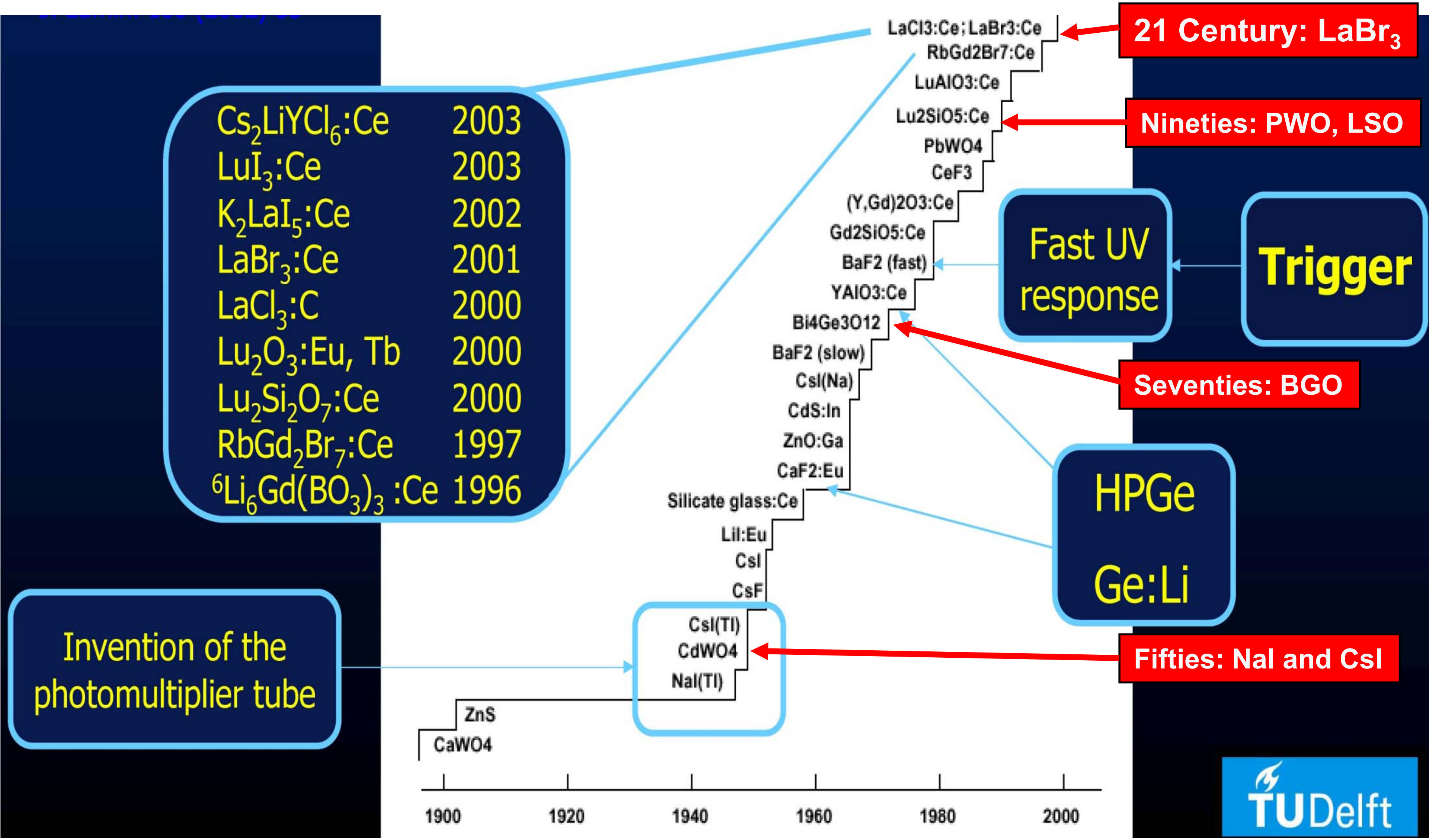


H→γγ at LHC

$\sigma m / m = 0.5\, [\sigma E_1/E_1 \oplus \sigma E_2/E_2 \oplus \sigma\theta/\tan(\theta/2)]$, where $\sigma E / E = a/\sqrt{E} \oplus b \oplus c/E$ and E in GeV

History of Crystal Development

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

Seventies: BGO

Fifties: NaI and CsI

Fast UV response

Trigger

HPGe

Ge:Li

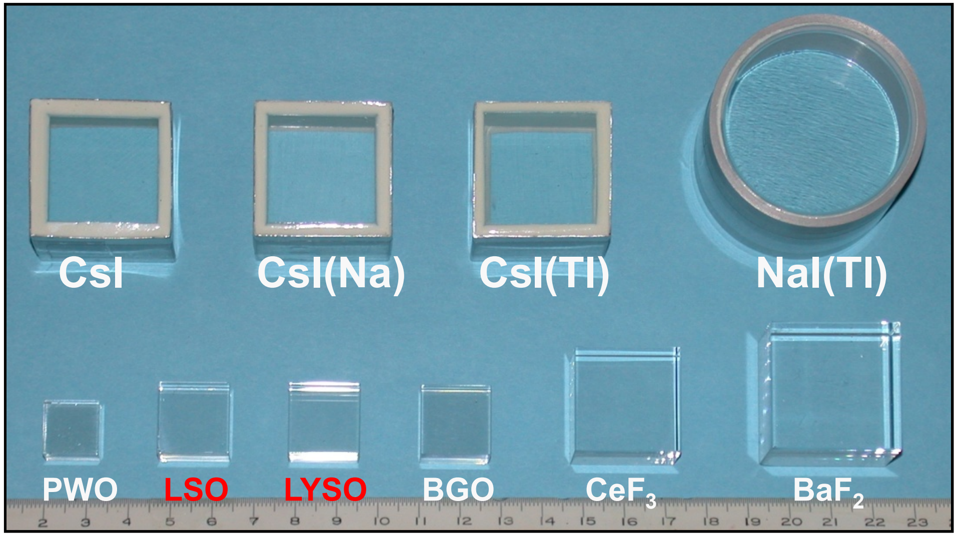
Invention of the photomultiplier tube

Mass-Produced Crystal Scintillators

Crystal	NaI(Tl)	CsI(Tl)	CsI(Na)	CsI	CeF_3	BaF_2	BGO	PWO(Y)	LSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.51	6.16	4.89	7.13	8.3	7.40
Melting Point (°C)	651	621	621	621	1460	1280	1050	1123	2050
Radiation Length (cm)	2.59	1.86	1.86	1.86	1.65	2.03	1.12	0.89	1.14
Molière Radius (cm)	4.13	3.57	3.57	3.57	3.38	3.10	2.23	2.00	2.07
Interaction Length (cm)	42.9	39.3	39.3	39.3	23.17	30.7	22.8	20.7	20.9
Refractive Index [a]	1.85	1.79	1.95	1.95	1.62	1.50	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	340 300	300 220	480	425 420	402
Decay Time [b] (ns)	245	1220	690	30 6	30	650 0.9	300	30 10	40
Light Yield [b,c] (%)	100	165	88	3.6 1.1	7.3	36 4.1	21	0.3 0.1	85
d(LY)/dT [b] (%/ °C)	-0.2	0.4	0.4	-1.4	0	-1.9 0.1	-0.9	-2.5	-0.2
Experiment	Crystal Ball	BaBar BELLE BES III	-	KTeV	-	(L*) (GEM) TAPS	L3 BELLE	CMS ALICE PrimEx	SuperB

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

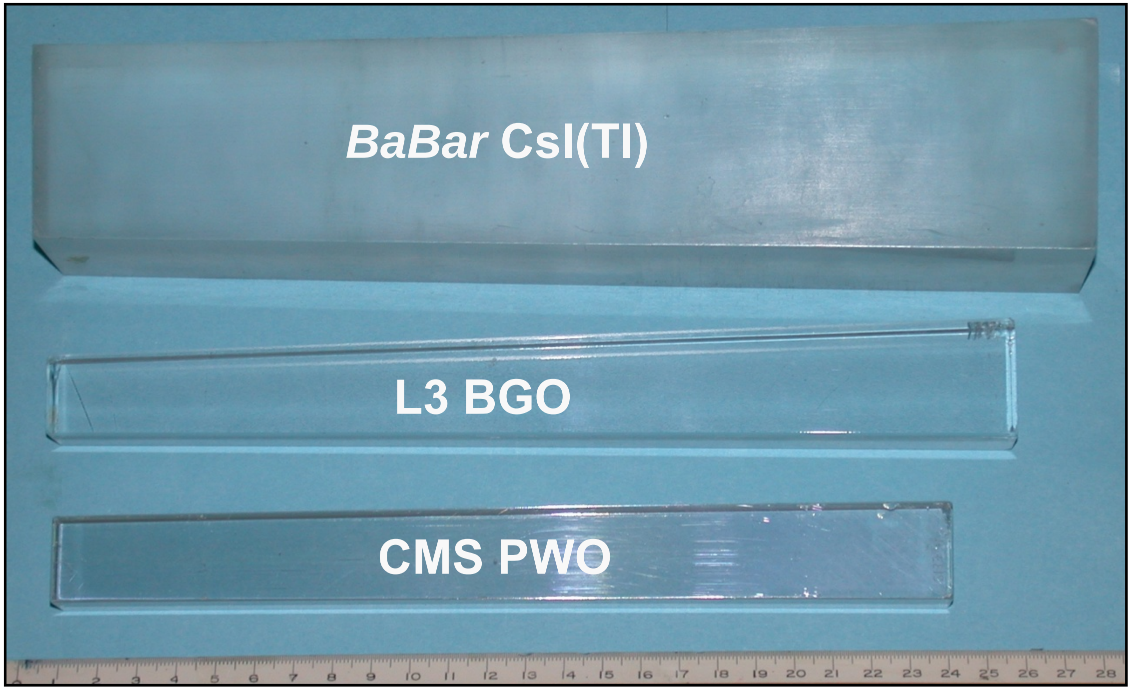
Crystal Density: Radiation Length



1.5 X_0 Cubic Samples:

Hygroscopic Halides

Non-hygroscopic



Full Size Crystals:

BaBar CsI(Tl): 16 X_0

L3 BGO: 22 X_0

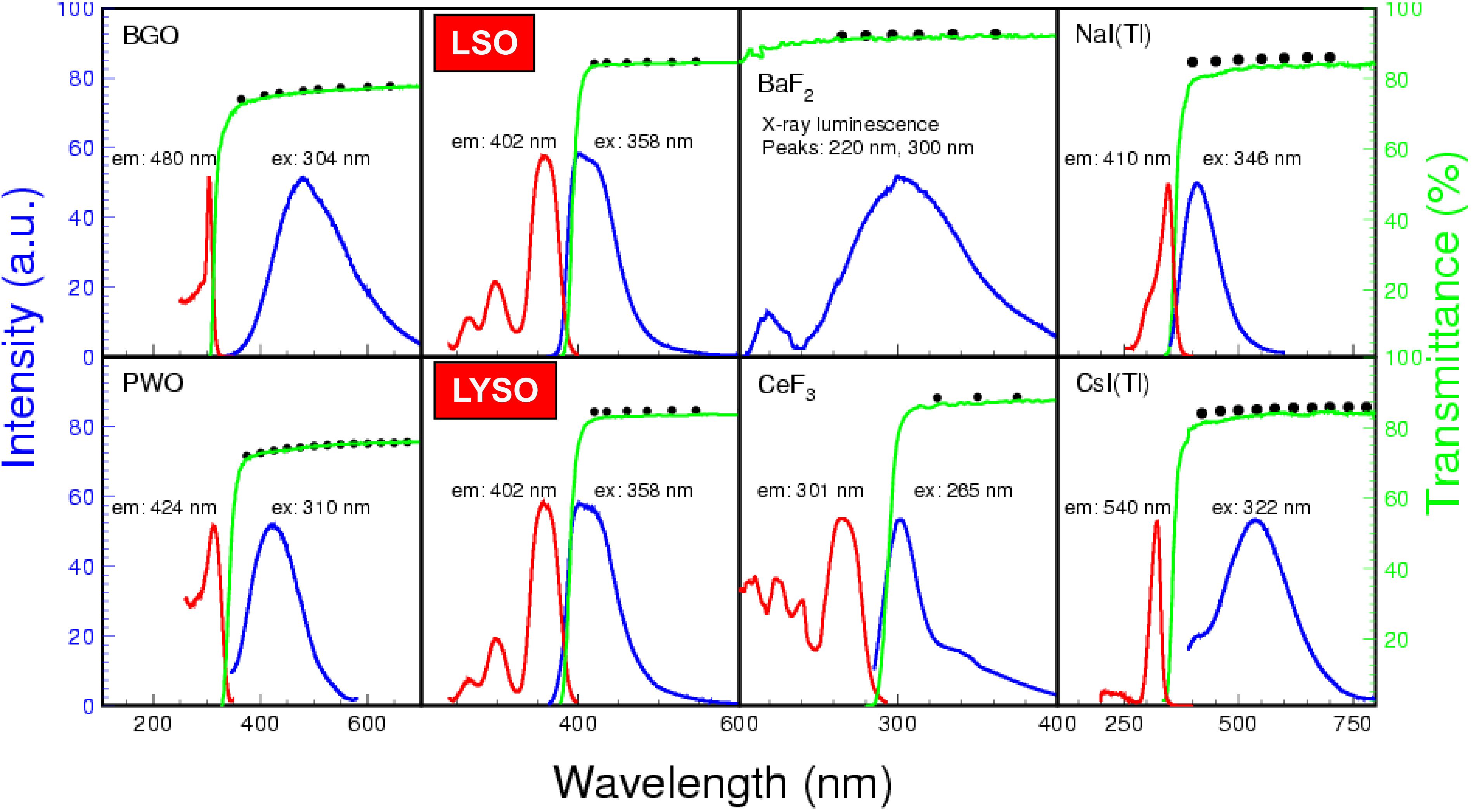
CMS PWO(Y): 25 X_0

Excitation, Emission, Transmission

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

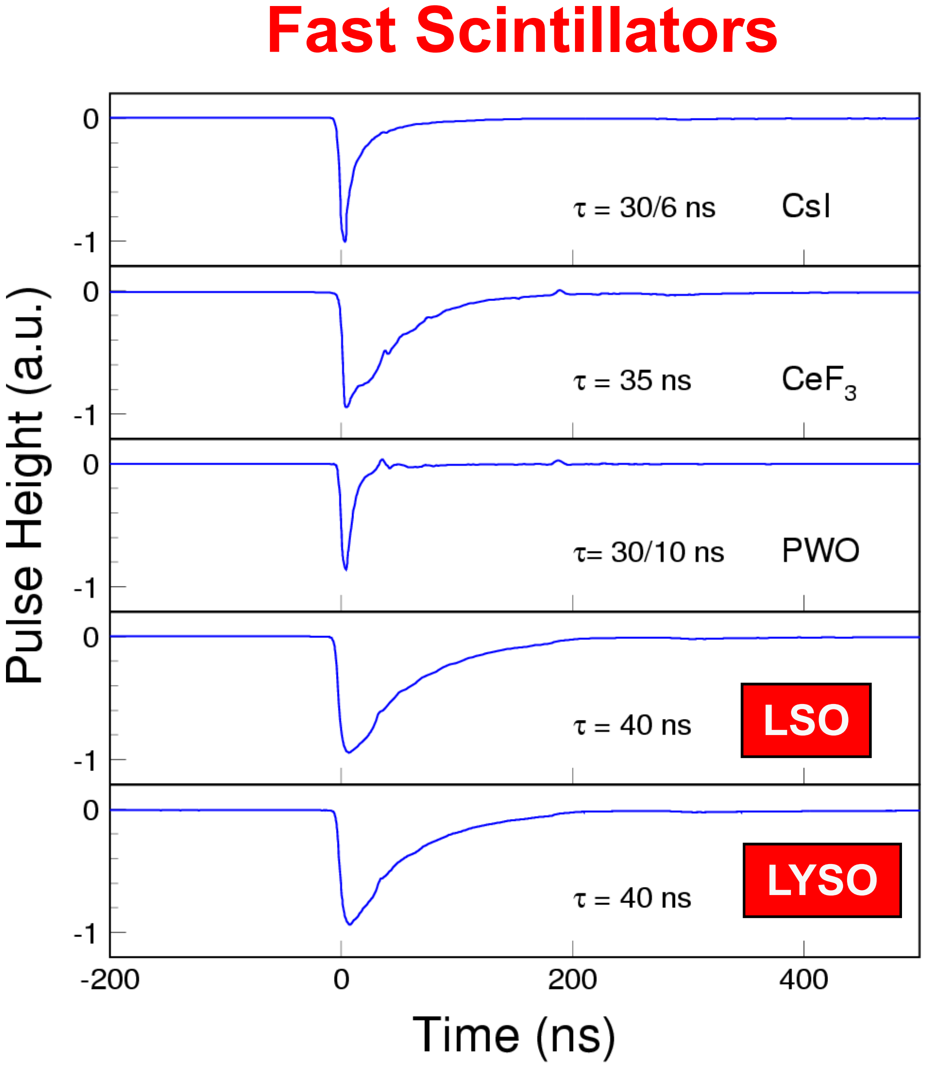
$R = \frac{(n_{crystal}-n_{air})^2}{(n_{crystal}+n_{air})^2}$.

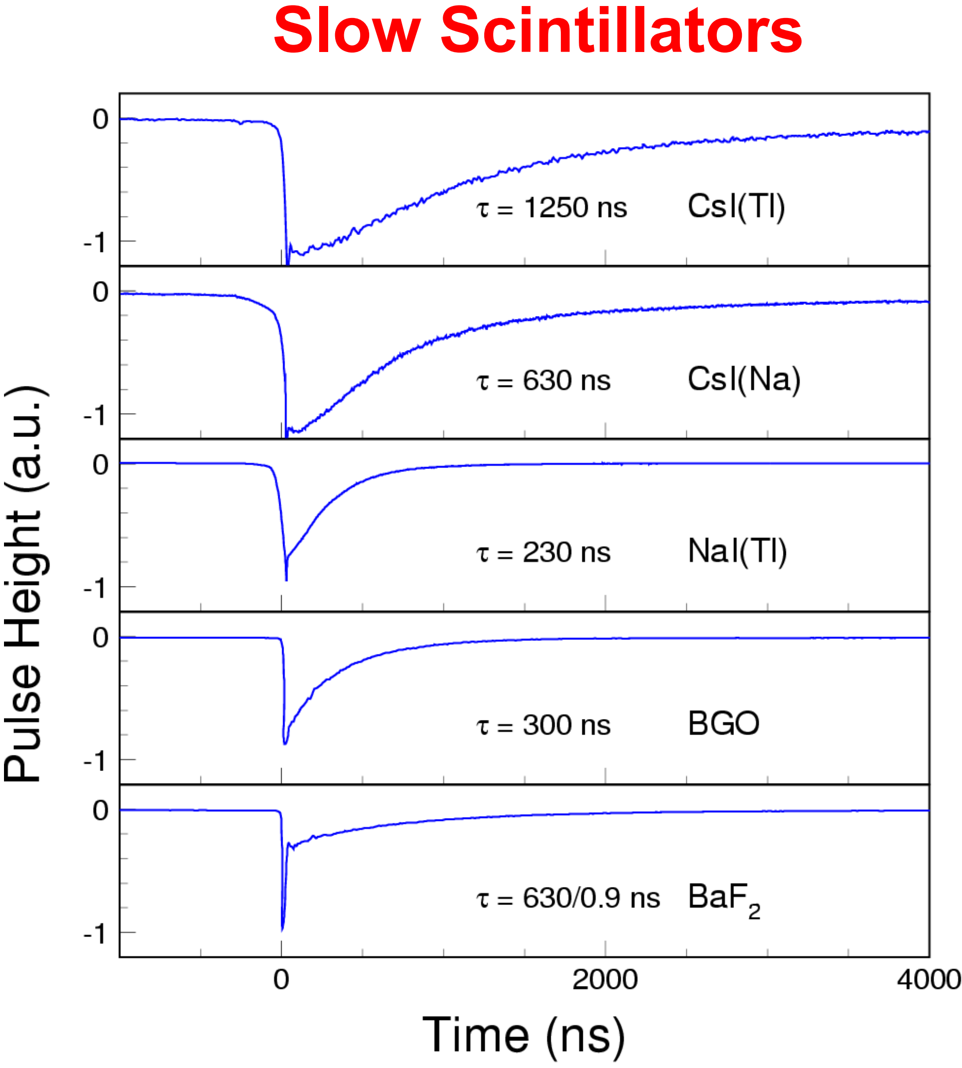
Black Dots: Theoretical limit of transmittance: NIM A333 (1993) 422



Scintillation Light Decay Time

Recorded with an Agilent 6052A digital scope

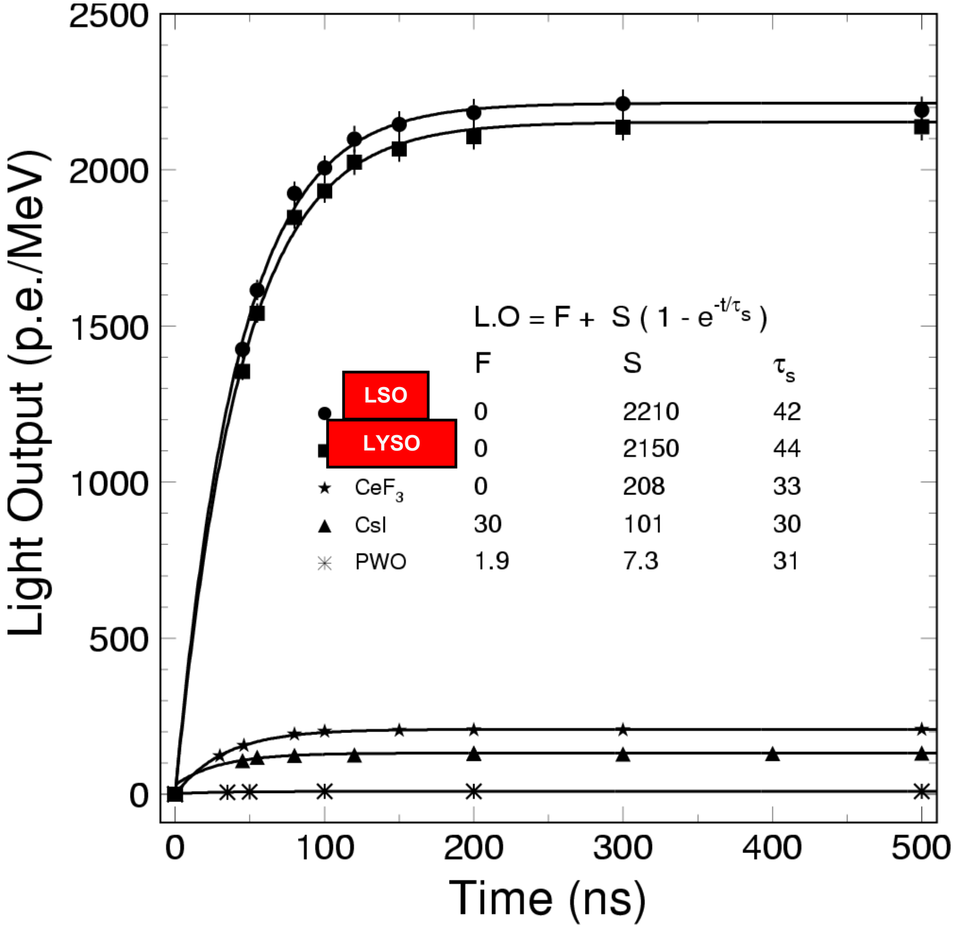




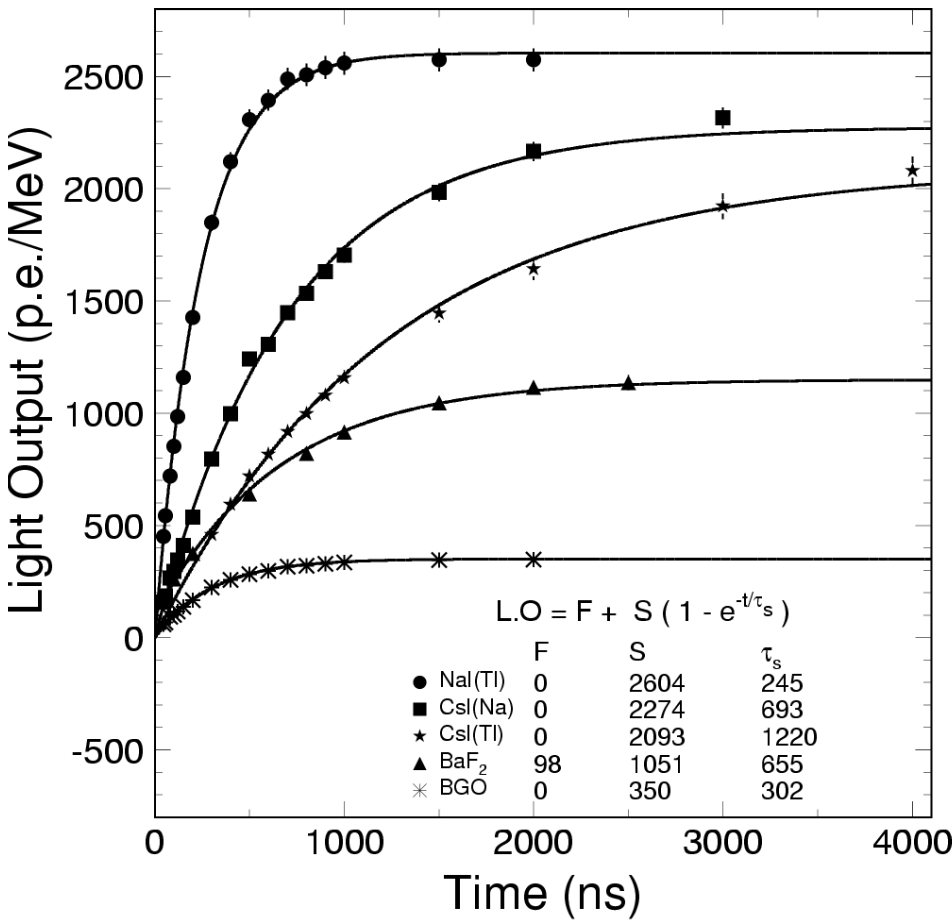
Light Output & Decay Kinetics

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

Fast Scintillators

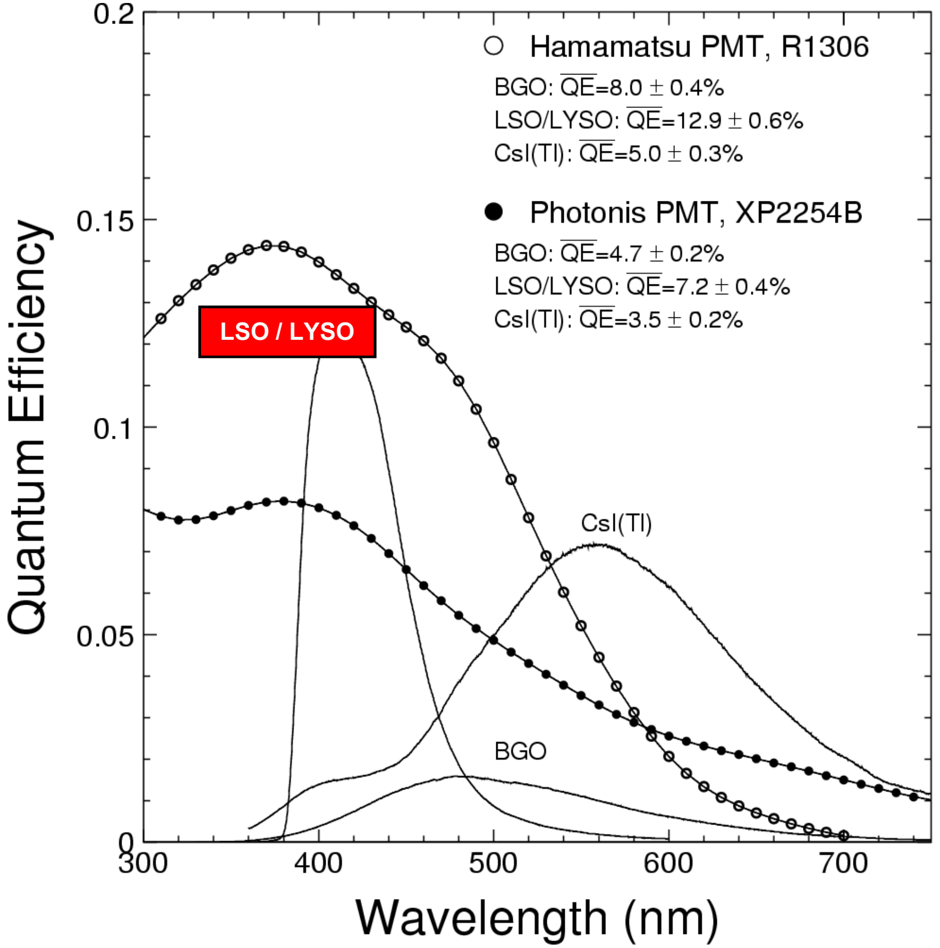


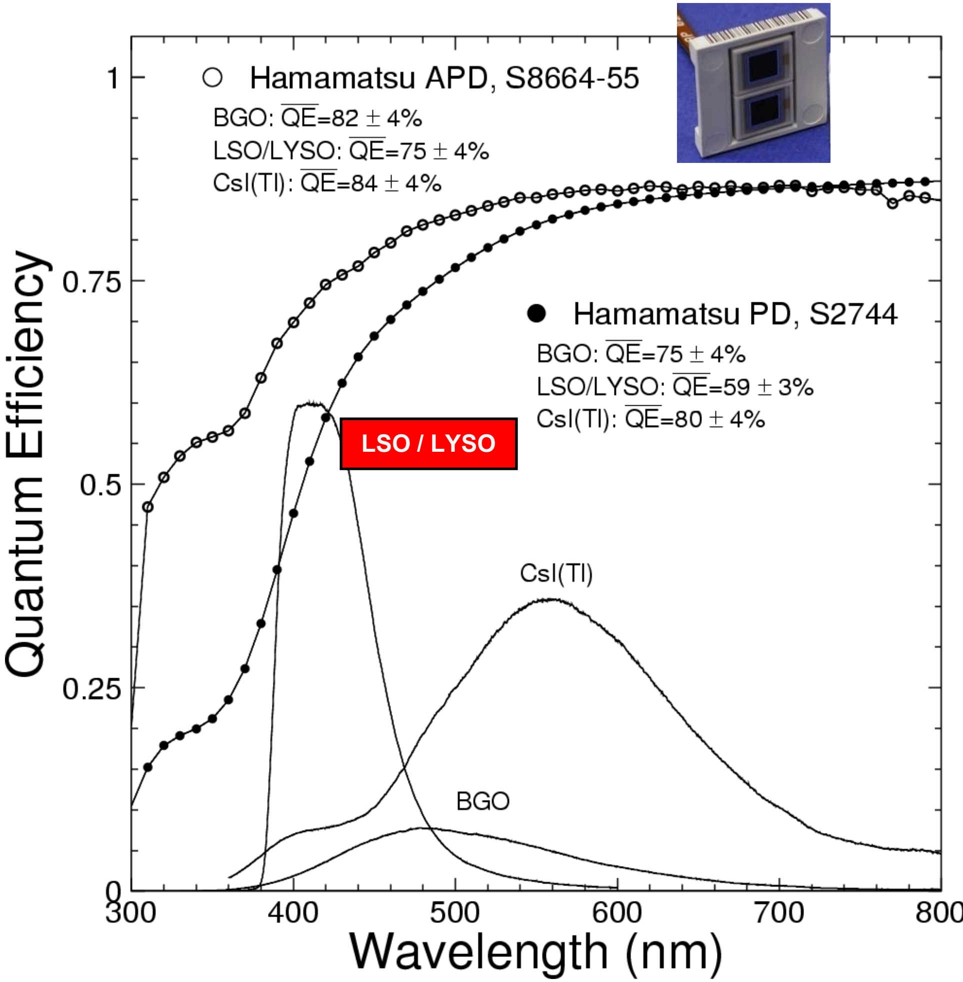
Slow Scintillators



Emission Weighted Quantum Efficiency

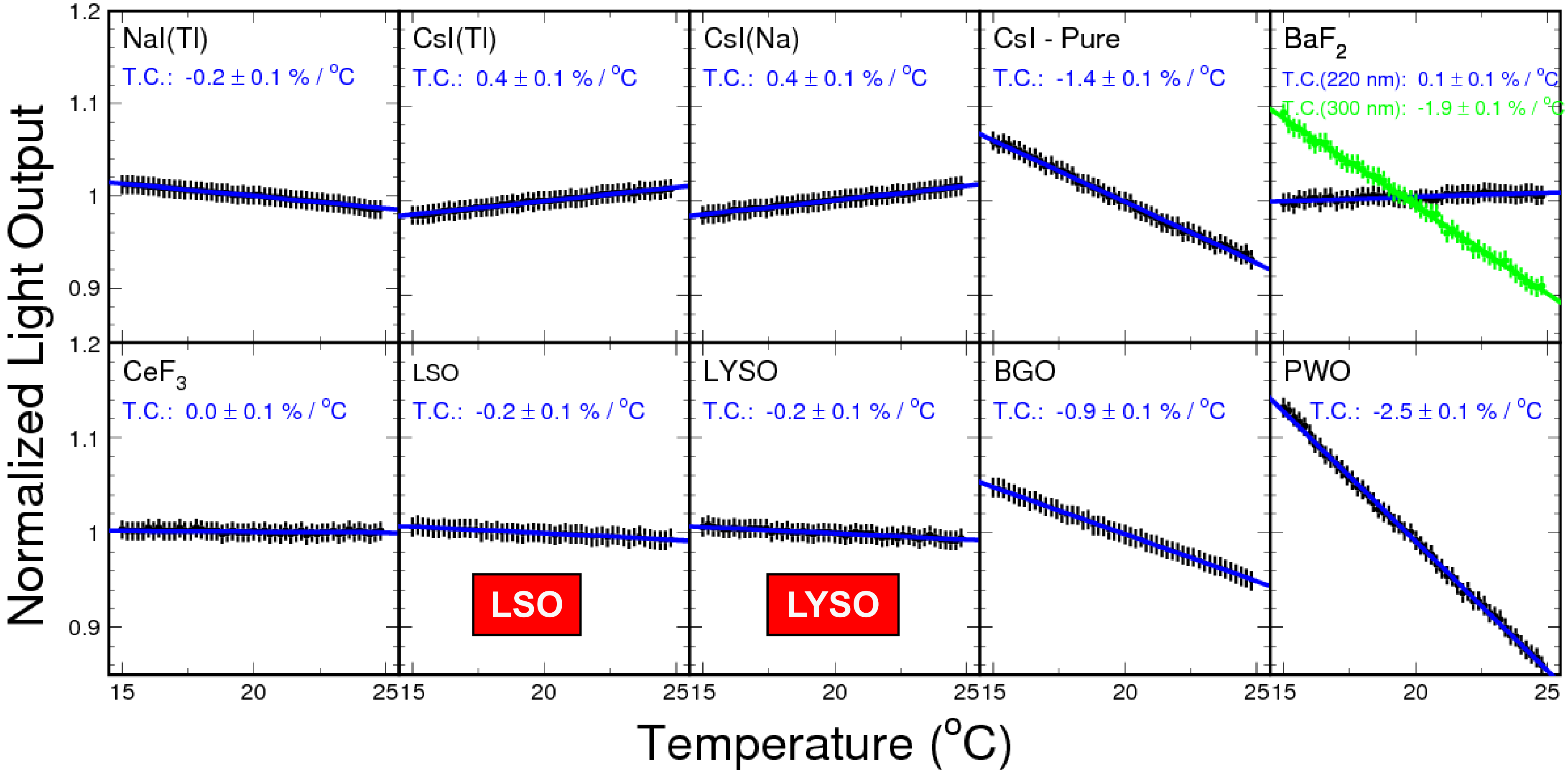
Taking out QE, L.O. of LSO/LYSO is 4/200 times BGO/PWO
Hamamatsu S8664-55 APD has QE 75% for LSO/LYSO





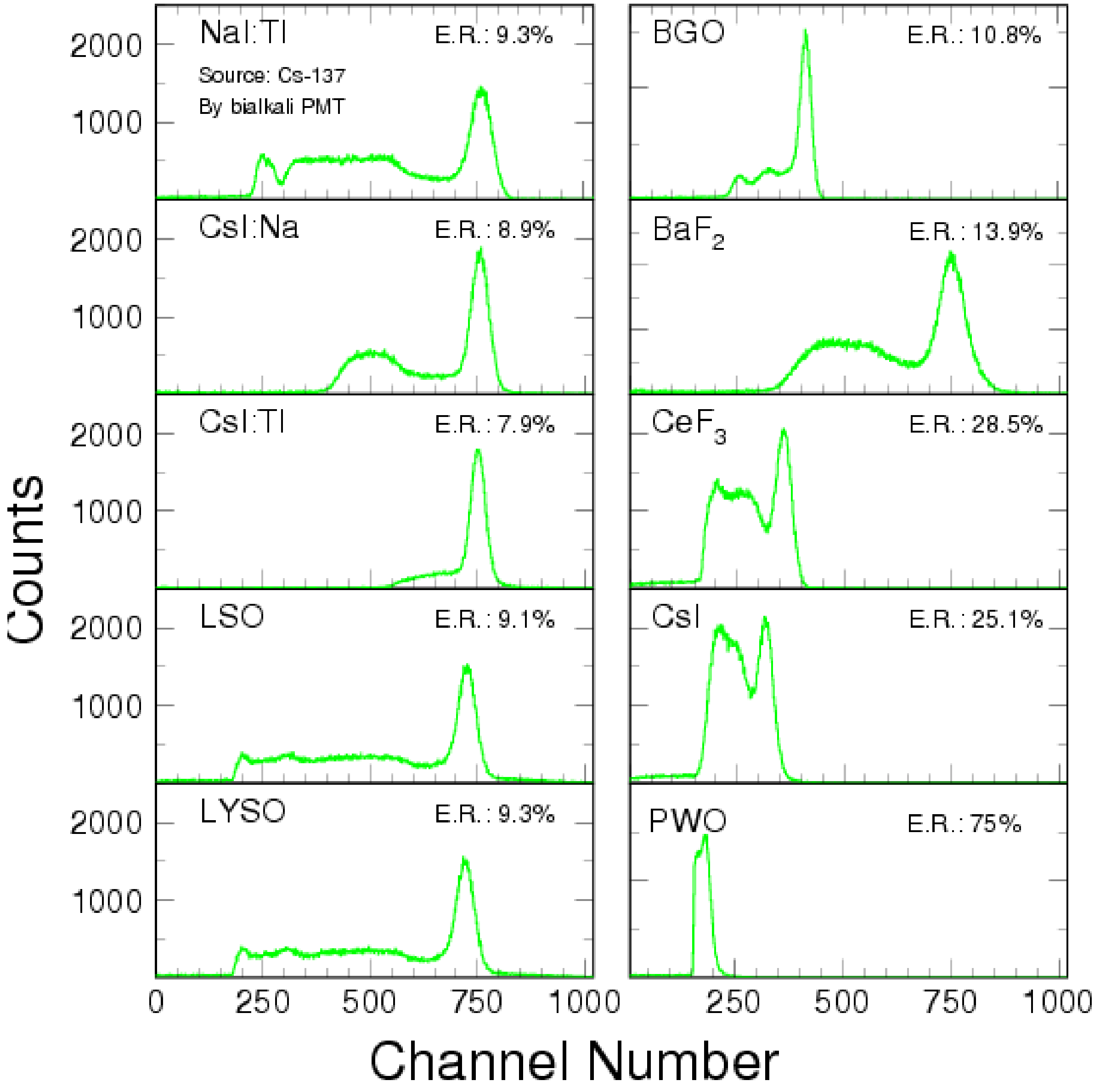
Light Output Temperature Coefficient

Temperature Range: 15ºC ~ 25ºC



^{137}Cs γ-ray Resolution at 10%

Measured with Hamamatsu R1306 PMT with Bi-alkali Cathode

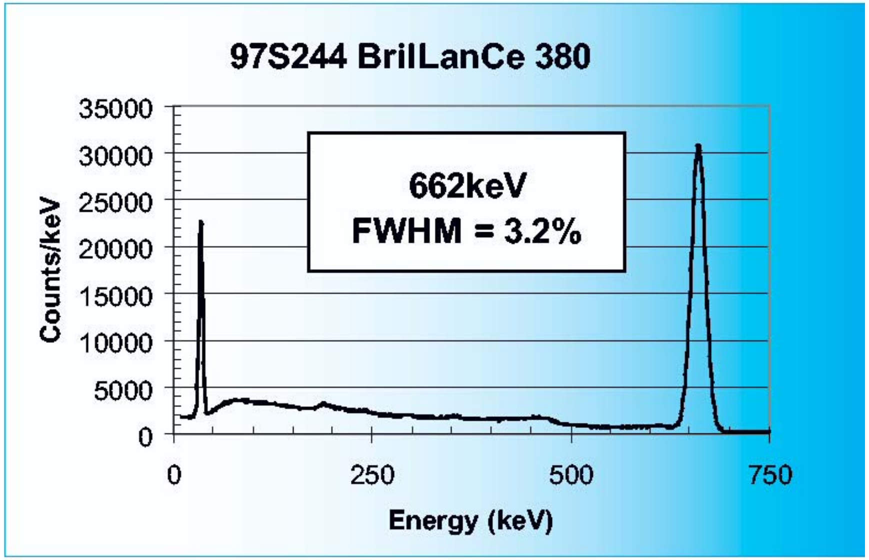


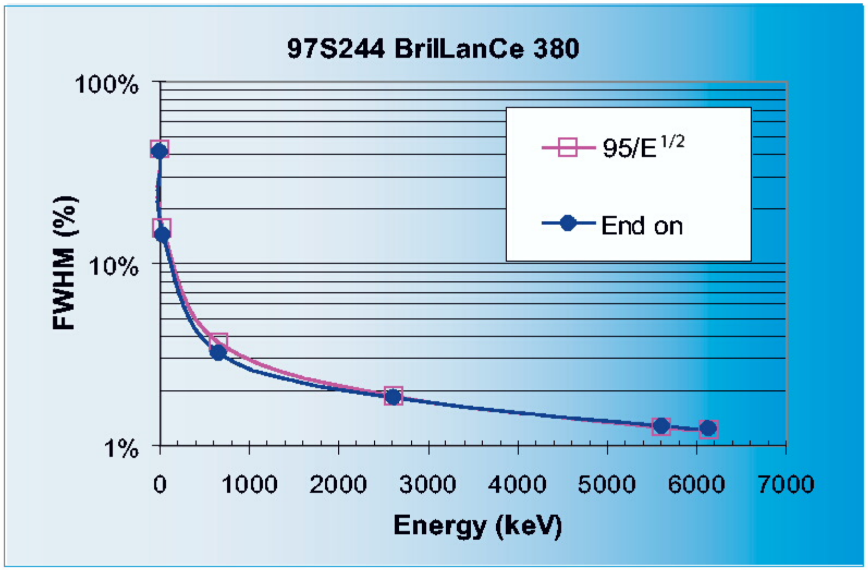
Saint-Gobain Φ4” × 10” $LaBr_3$ Detector

The best energy resolution for γ-ray spectroscopy

Currently expansive: ~$200/cc

Potential low cost in future, so may replace NaI(Tl) for H.S…





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

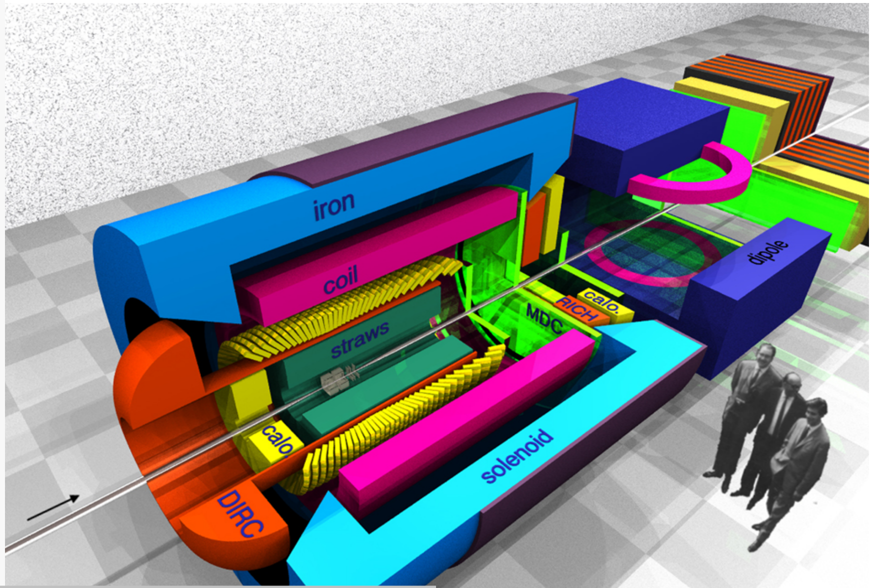
BGO, PbF2, PWO for Homogeneous HCAL

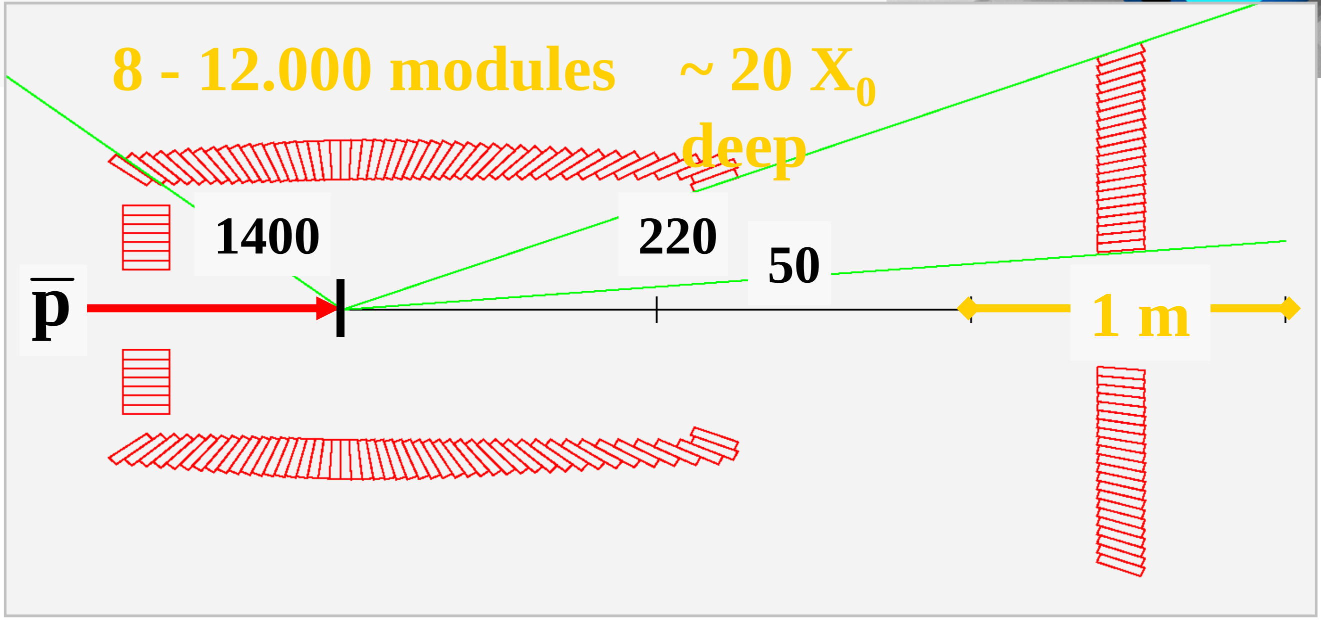
PANDA at GSI, Germany

AntiProton

ANnihilations

at DArmstadt

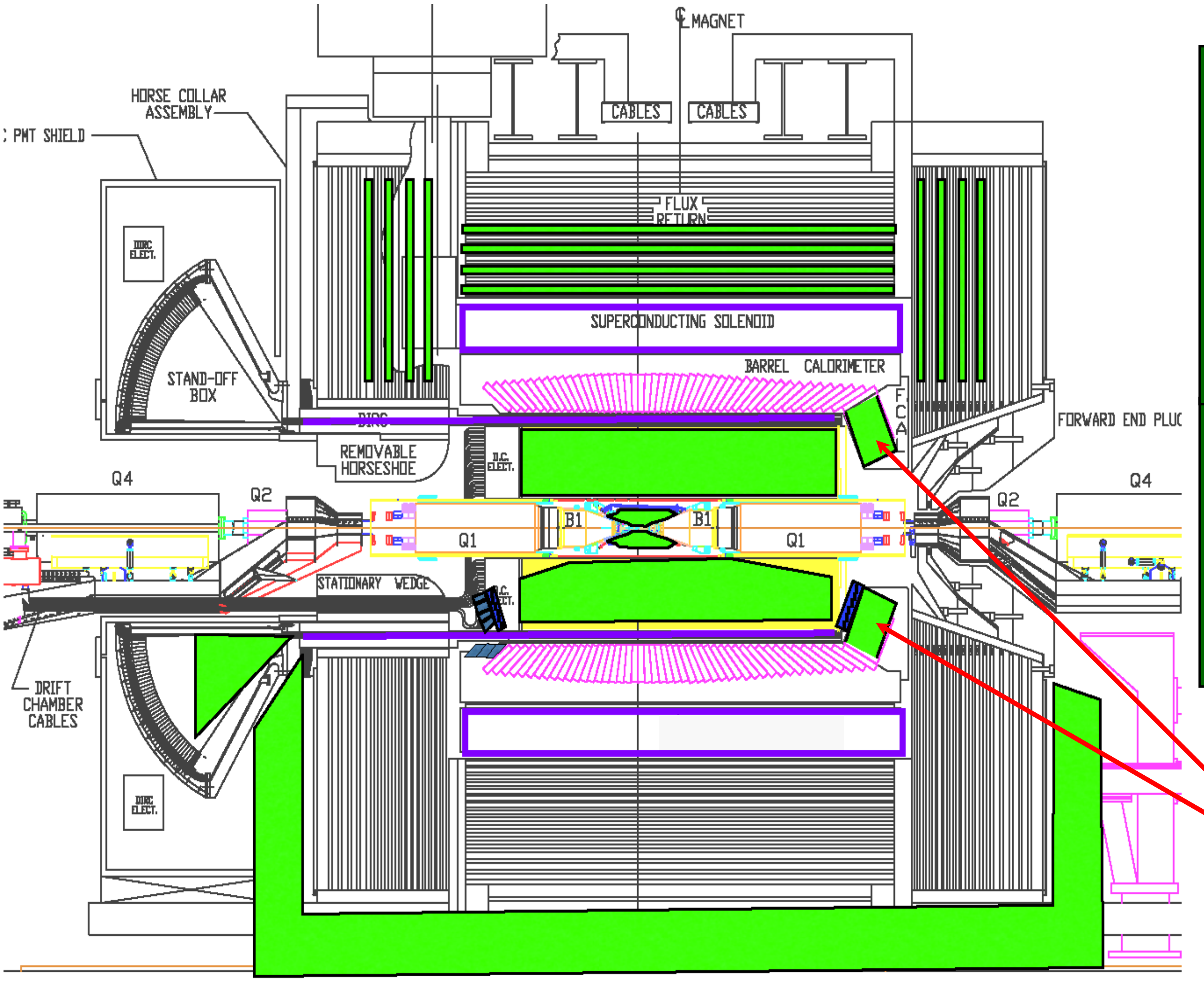




10,000 PWO

LYSO Endcap for Super*B*

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

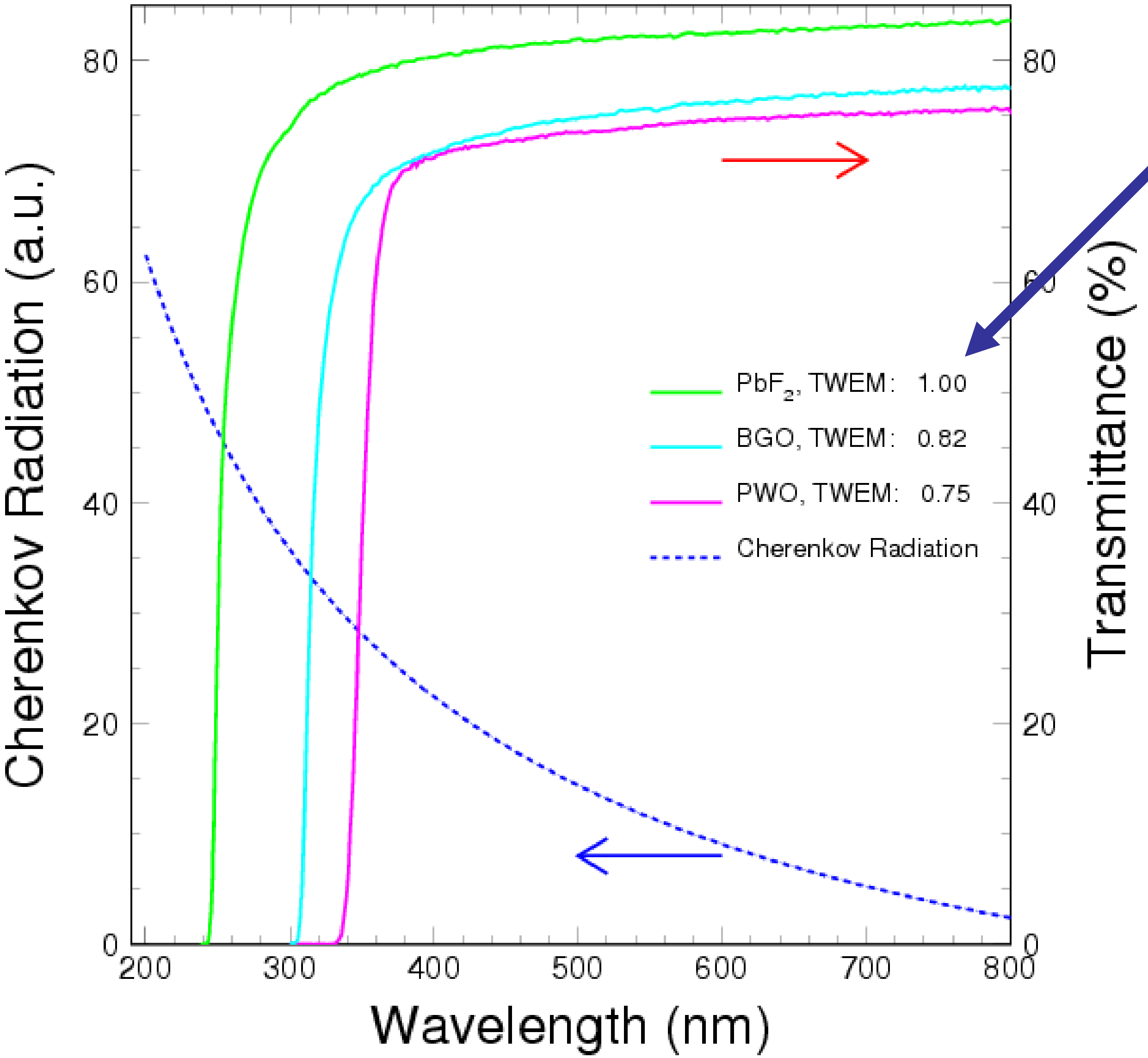


Aiming at 10^{36}/cm^2/s luminosity for rare B decays

Need fast detector with low noise at the endcap

LYSO

Homogeneous HCAL for ILC

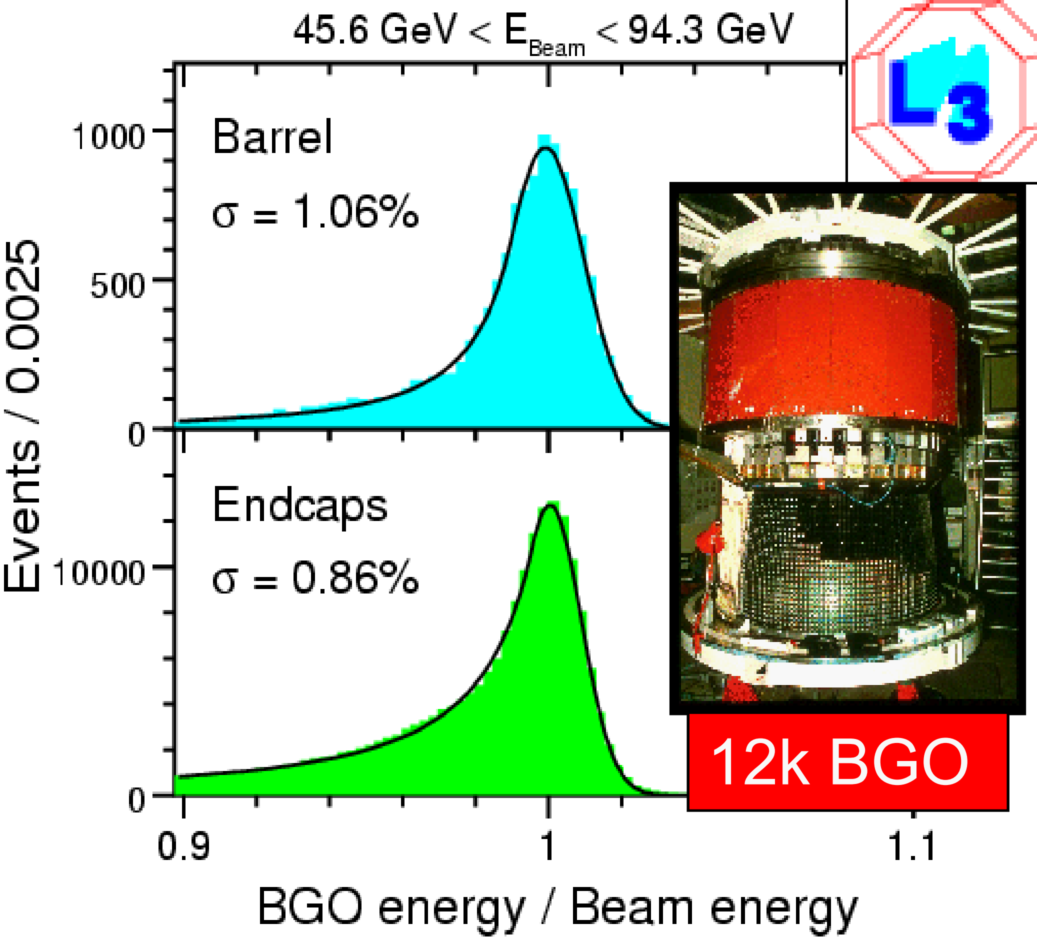


Cherenkov figure of merit

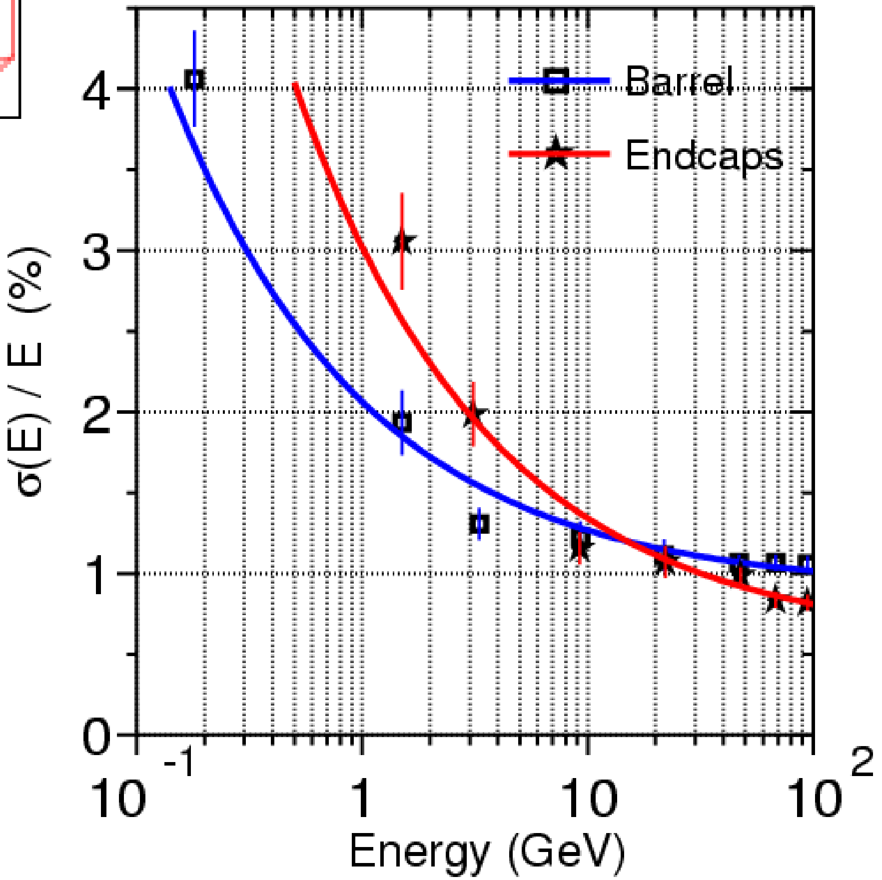
Measure both Cherenkov and scintillation light to achieve the best hadronic energy resolution.

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%

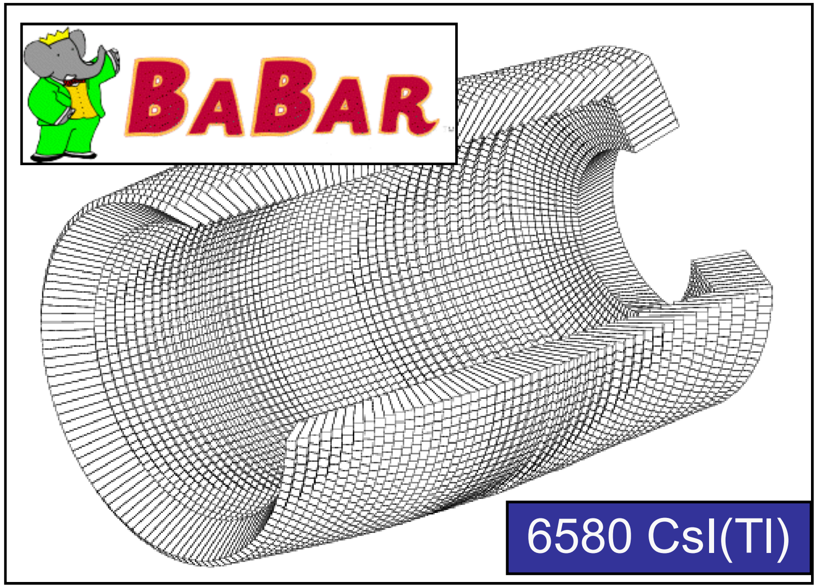


12k BGO



BaBar CsI(Tl) Resolution

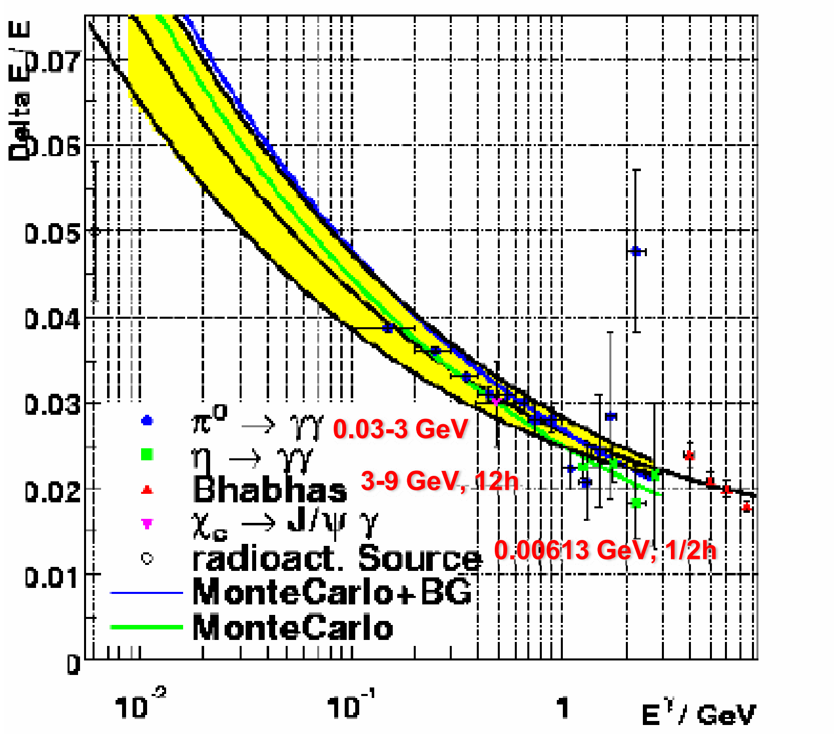
A crystal calorimeter at low energies



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

Energy resolution

M. Kocian, SLAC, CALOR2002

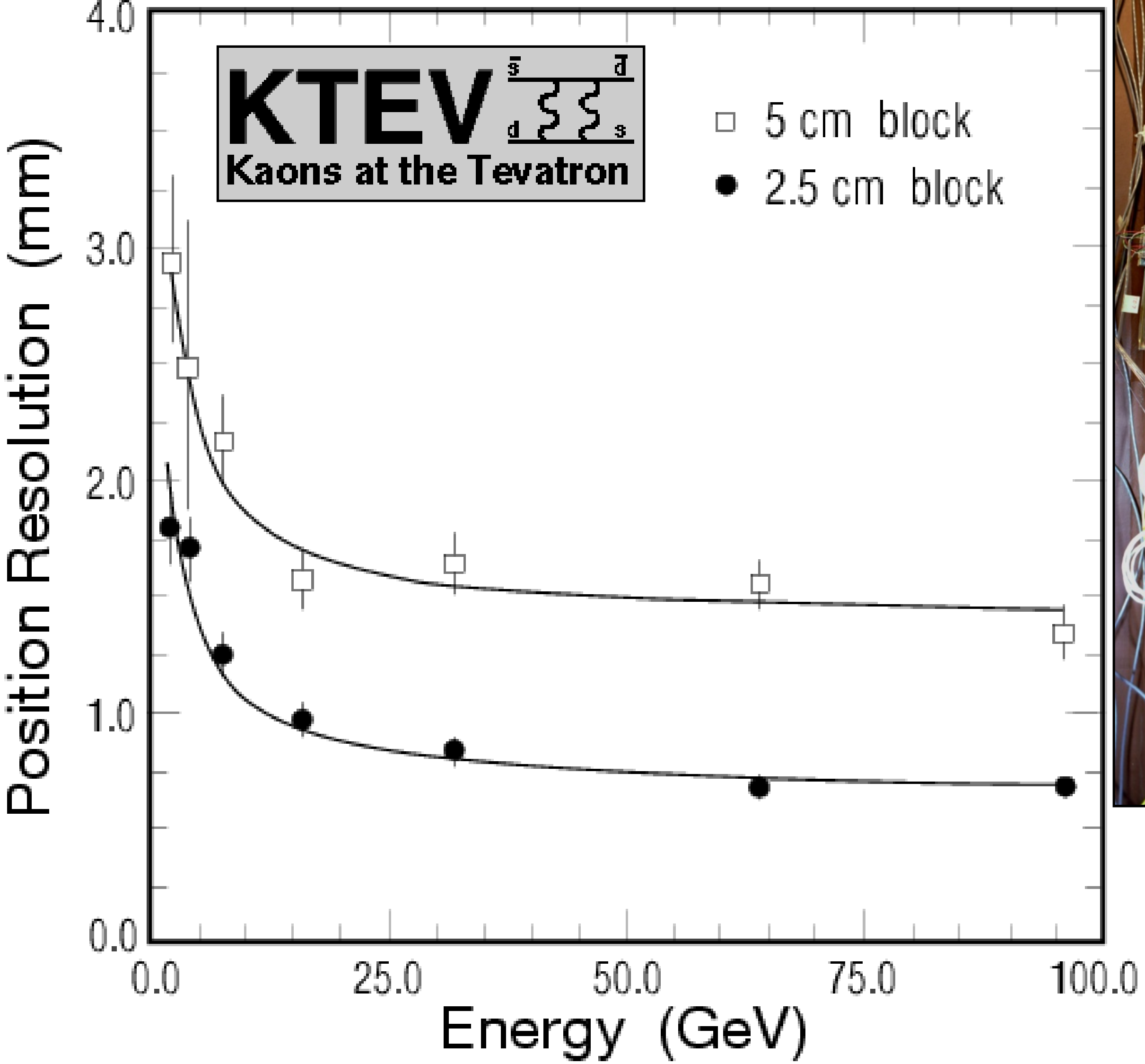


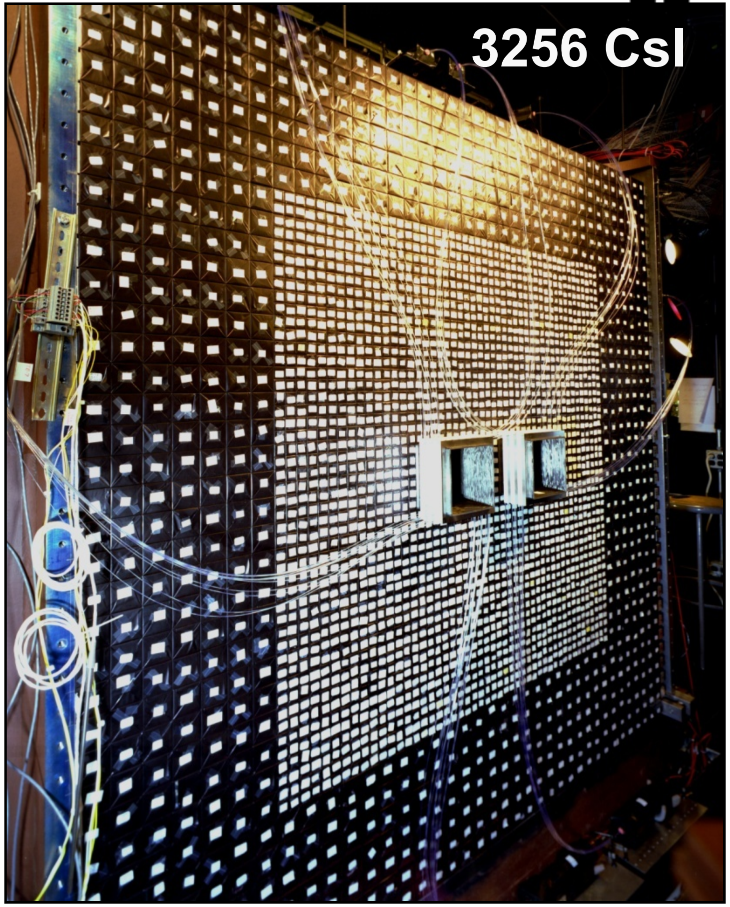
$$\frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt[4]{E}} \oplus \sigma_2$$

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

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

KTeV CsI Position Resolution

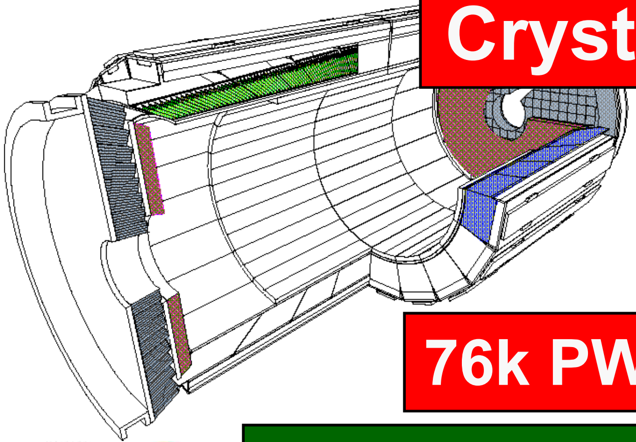




Sub mm position resolution.
L3 BGO & CMS PWO: 0.3 mm.

CMS PWO Resolution

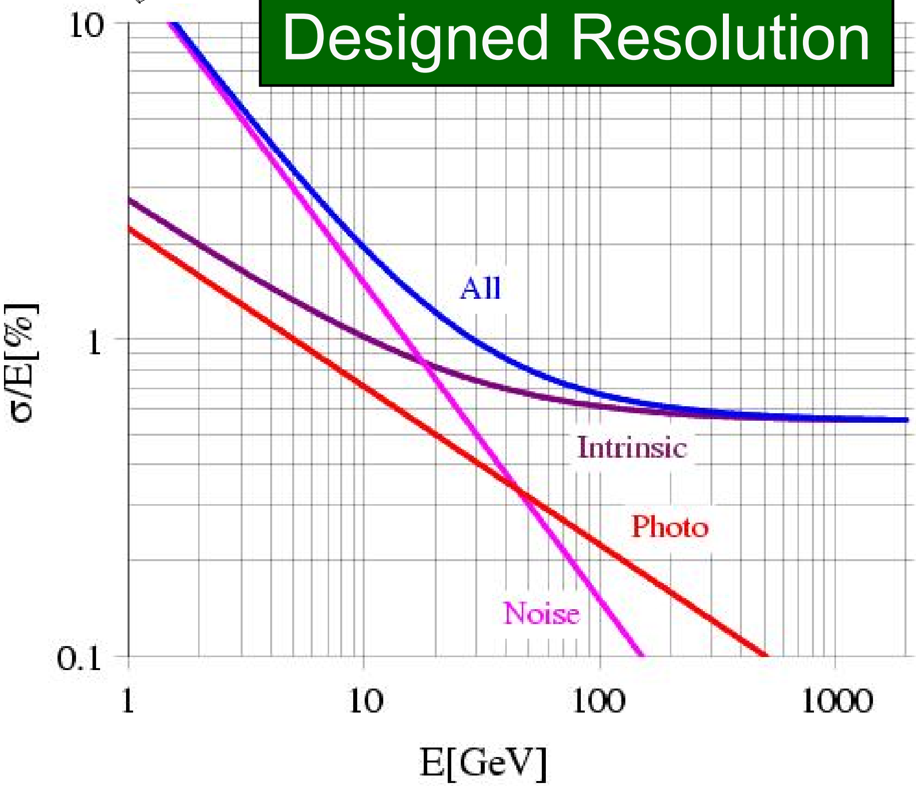
Crystal Radiation Damage?

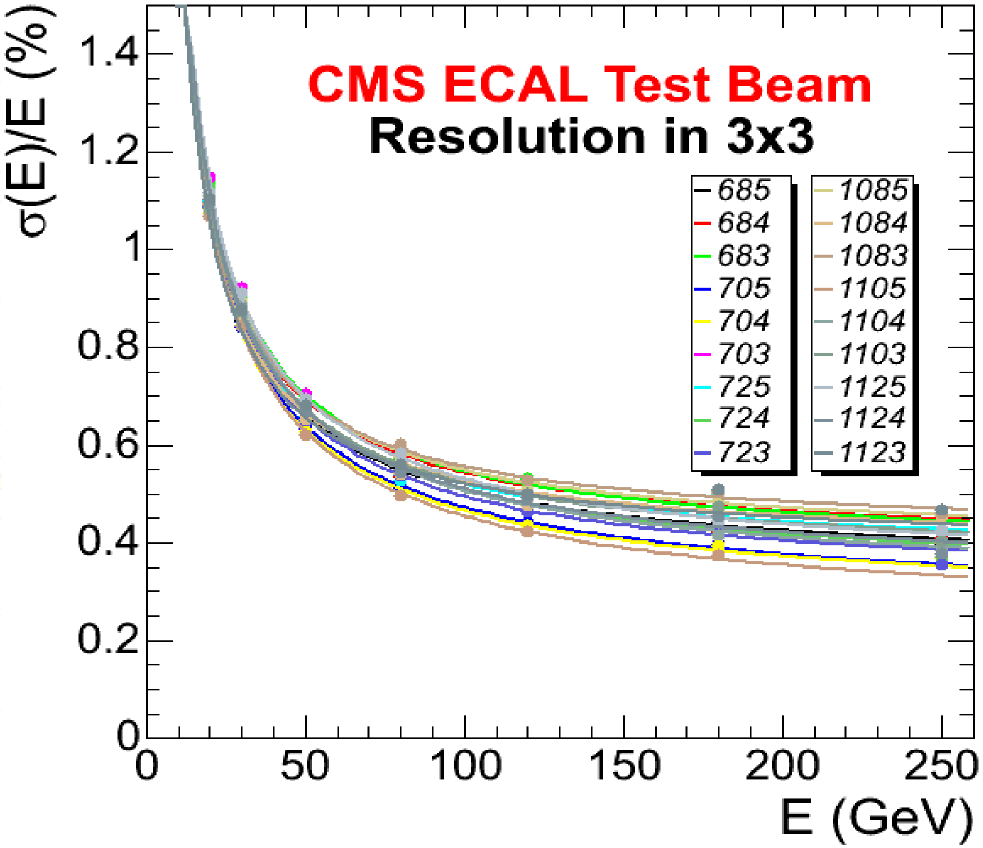


76k PWO

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

Designed Resolution

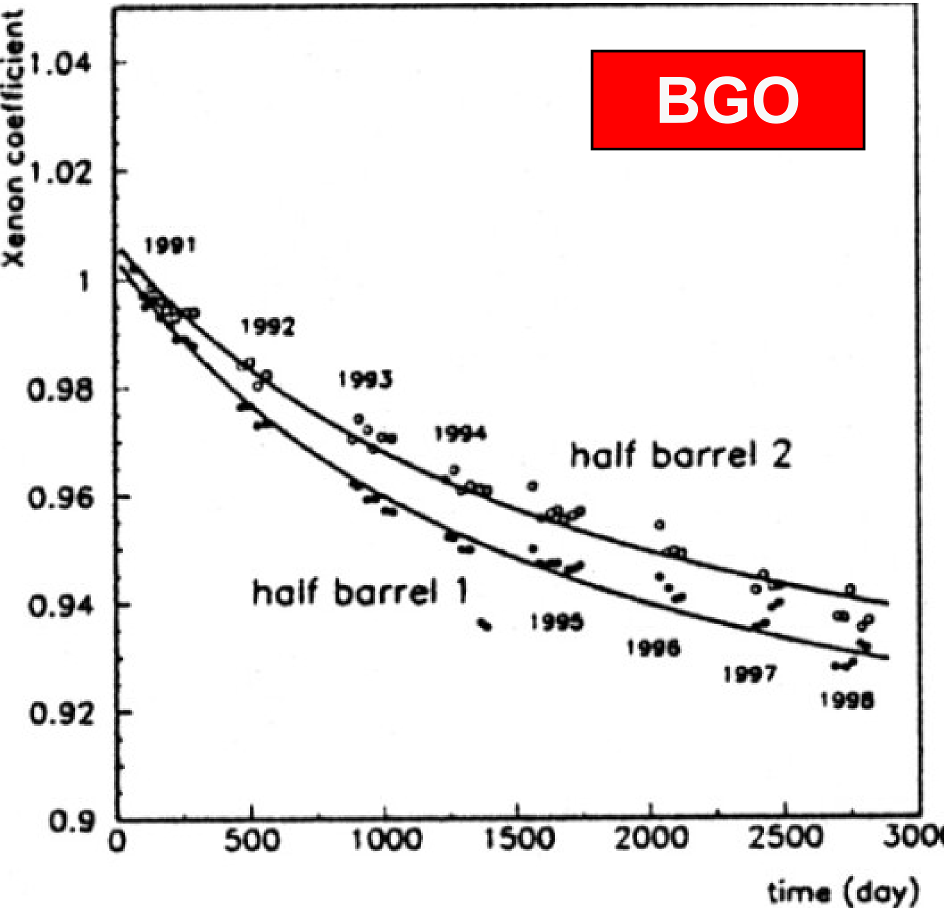


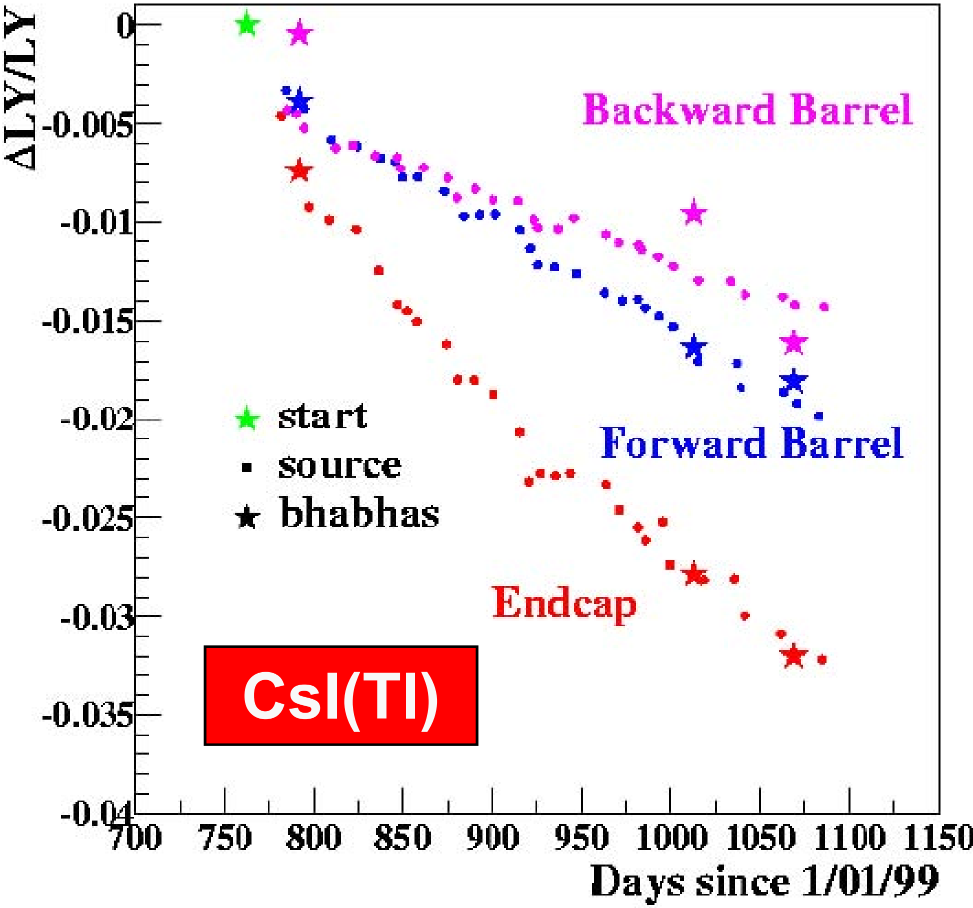


Crystal Degradation *in situ*

L3 BGO degrades 6 – 7% in 7 years

***BaBar* CsI(Tl): 1 - 3 % per year**





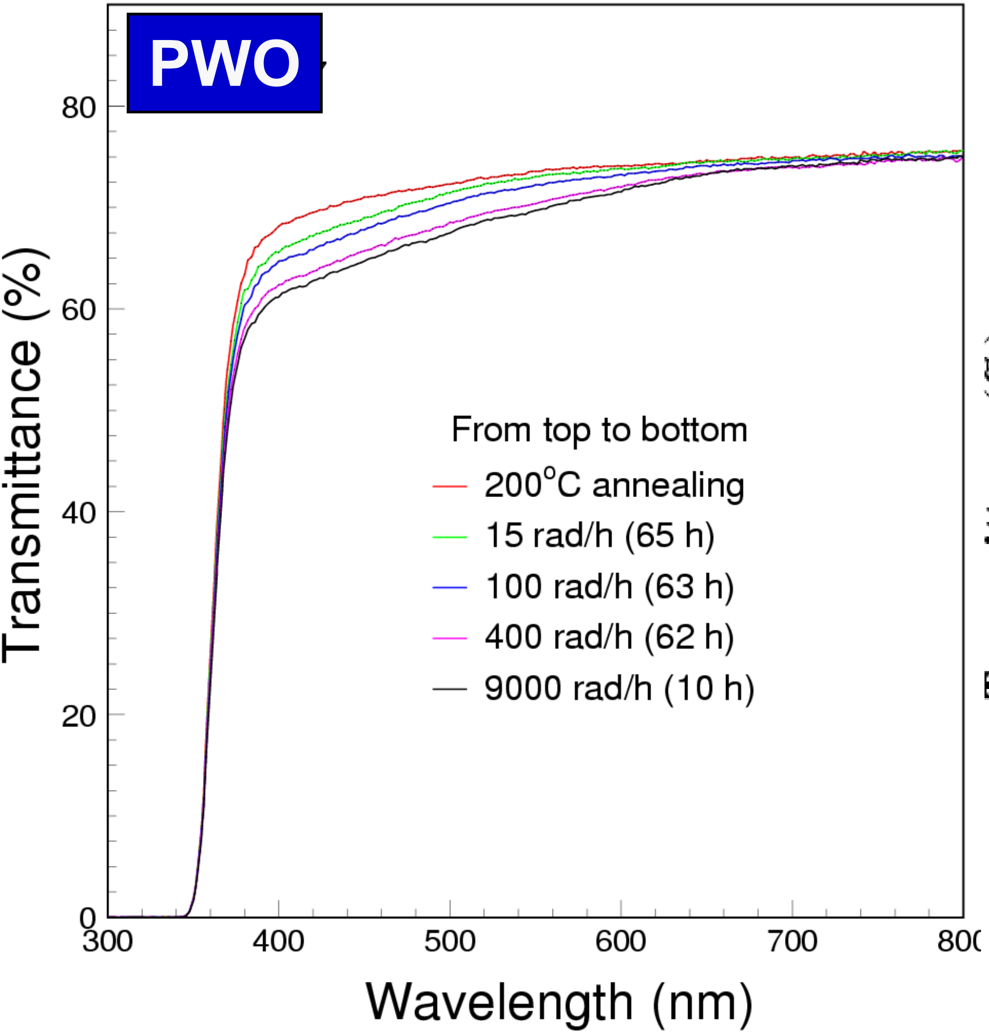
Radiation Damage Effects

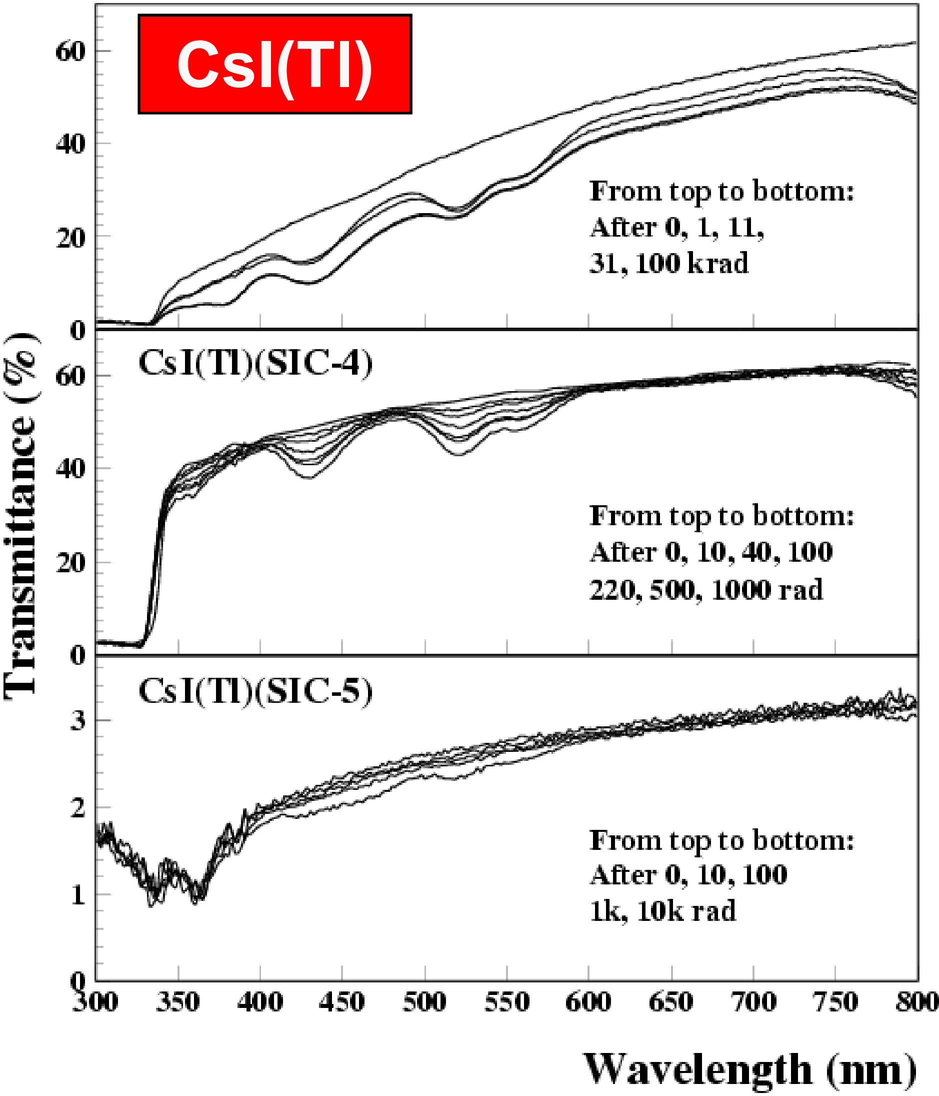
- Induced absorption caused by color center formation:
  - reduced light attenuation length and thus light output, and maybe
  - degraded of light response uniformity (LRU).
- Induced phosphorescence:
  - increase readout noise.
- Reduced scintillation light yield:
  - reduce light output and degrade light response uniformity.

Item	CsI(Tl)	CsI	BaF_2	BGO	$PbWO_4$
Color Centers	Yes	Yes	Yes	Yes	Yes
Fluorescence	Yes	Yes	Yes	Yes	Yes
Scintillation	No	No	No	No	No
Recover @RT	Slow	Slow	No	Yes	Yes
Dose Rate Dependence	No	No	No	Yes	Yes
Thermall Annealing	No/Yes	No/Yes	Yes	Yes	Yes
Optical Bleaching	No/Yes	No/Yes	Yes	Yes	Yes

Radiation Induced Absorption

Measured with Hitachi U-3210 Photospectrometer

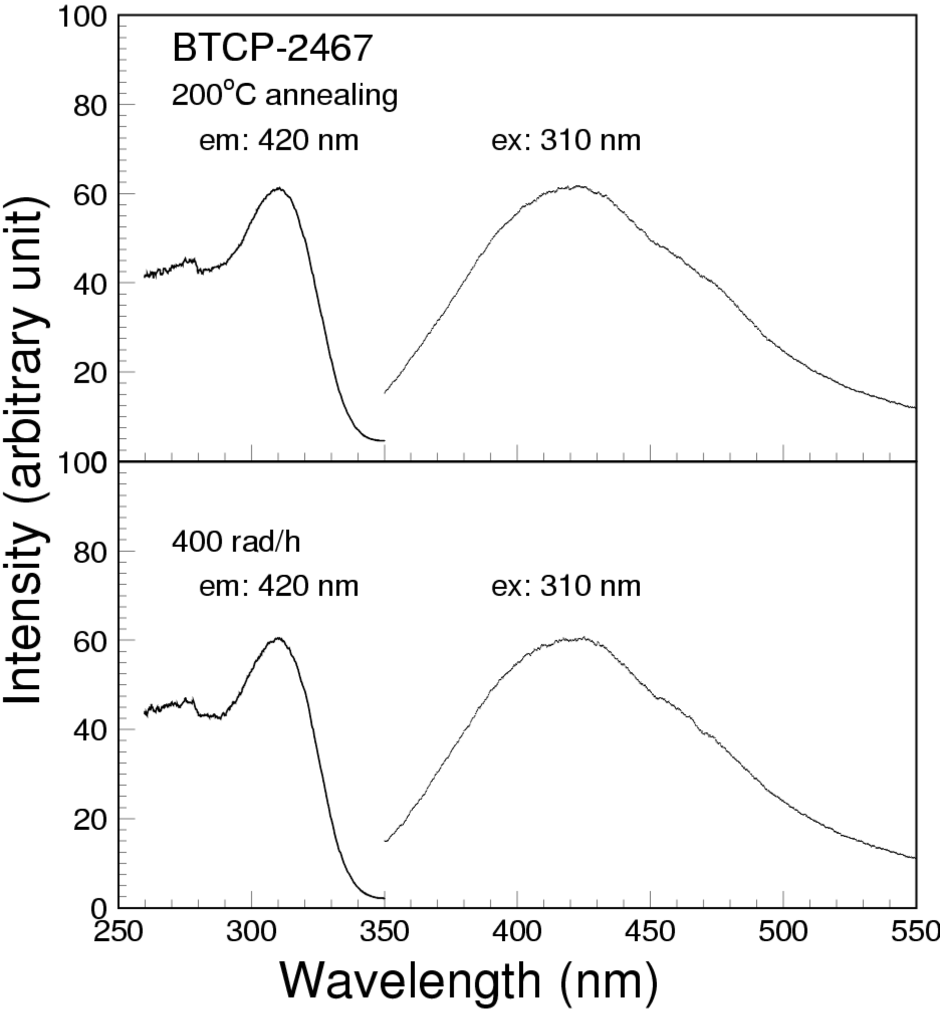


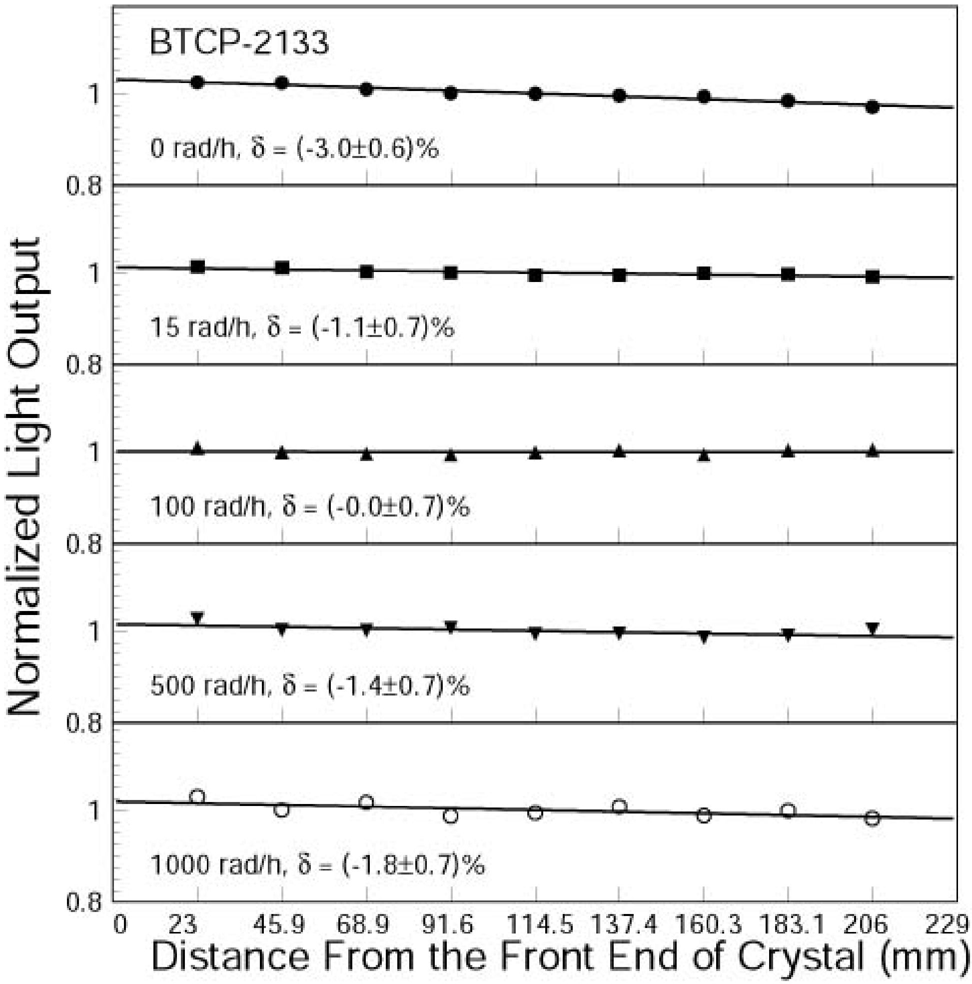


PWO Radiation Damage

No damage in scintillation mechanism

No damage in resolution if light attenuation length > 1 m



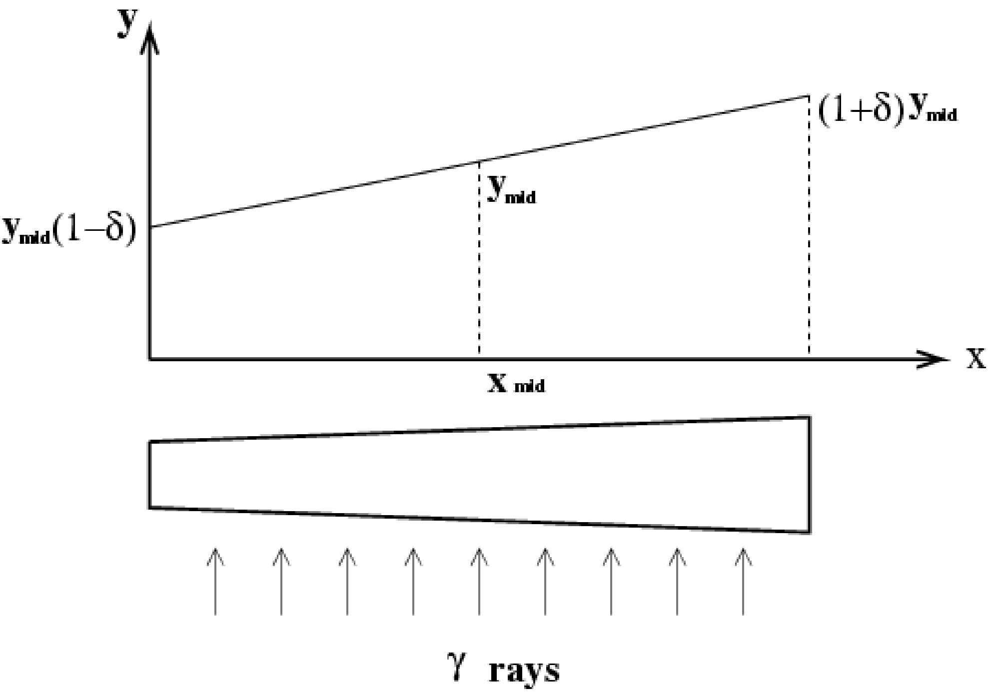


Light Response Uniformity (LRU)

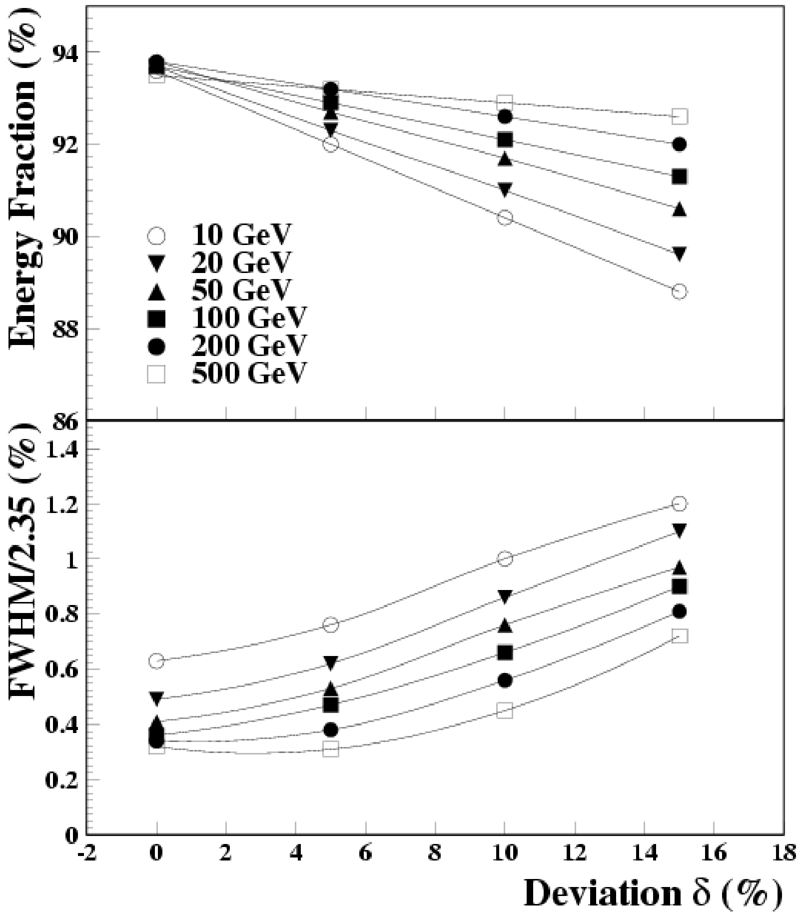
Nucl. Instr. And Meth. A340 (1994) 442

Definition

$$Y = Y_{mid}\,[1 + \delta(x/x_{mid} - 1)]$$



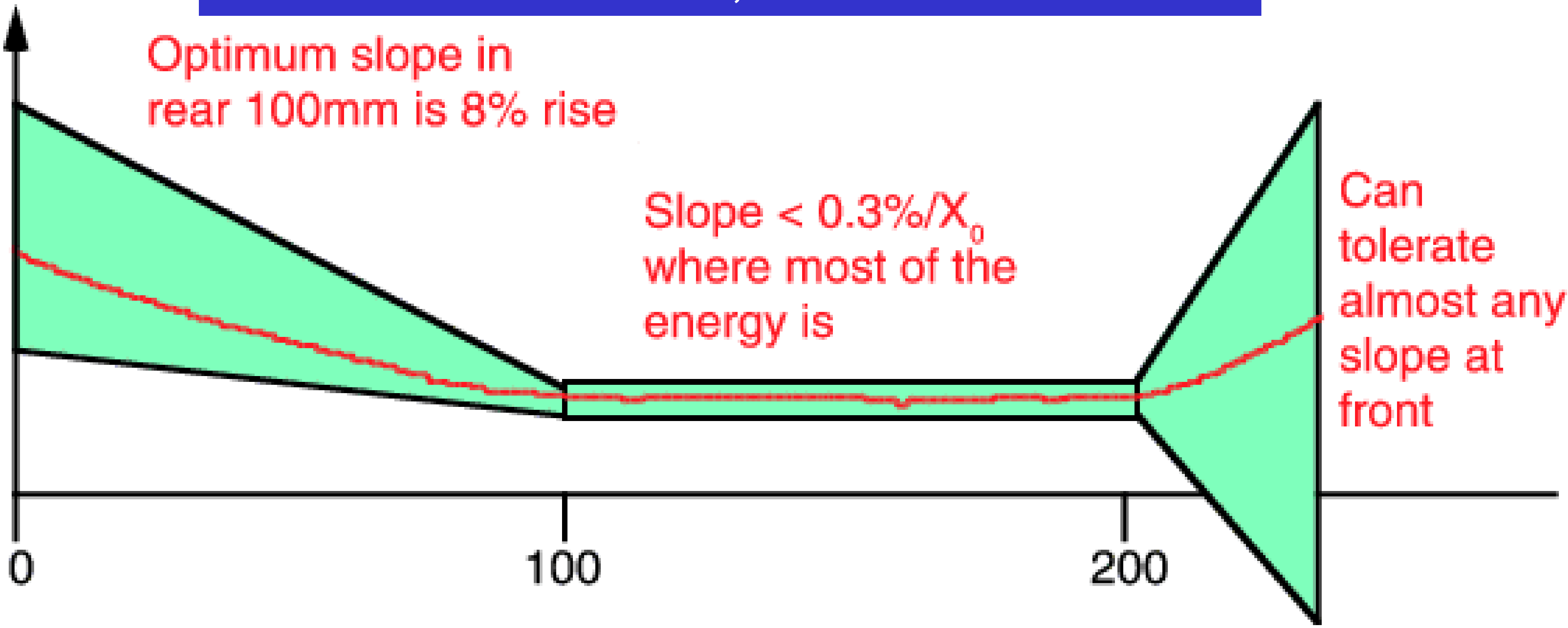
GEANT Simulation



Resolution degradation is not recoverable if LRU is damaged

CMS Specification to the LRU

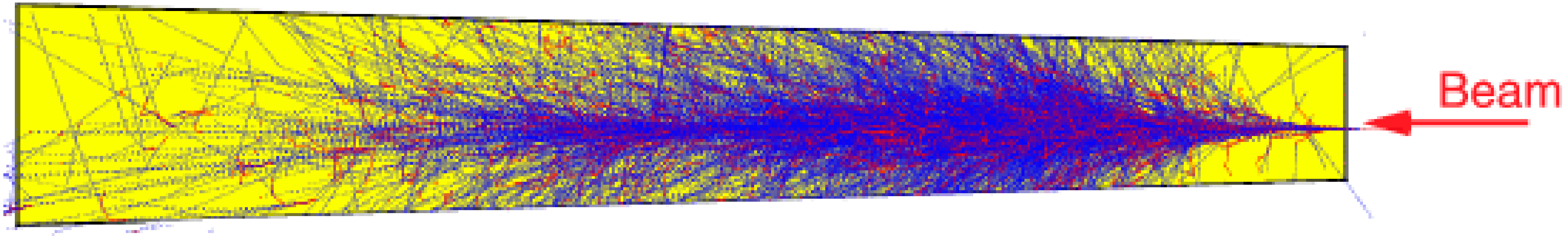
D. Graham & C. Seez, CMS Note 1996-002



Optimum slope in rear 100mm is 8% rise

Slope < 0.3%/X_0 where most of the energy is

Can tolerate almost any slope at front



LAL affects LRU

Nucl. Instr. And Meth. A413 (1998) 297

Ray-Tracing simulation for CMS PWO crystals shows no change in LRU if LAL is longer than 3.5 crystal length

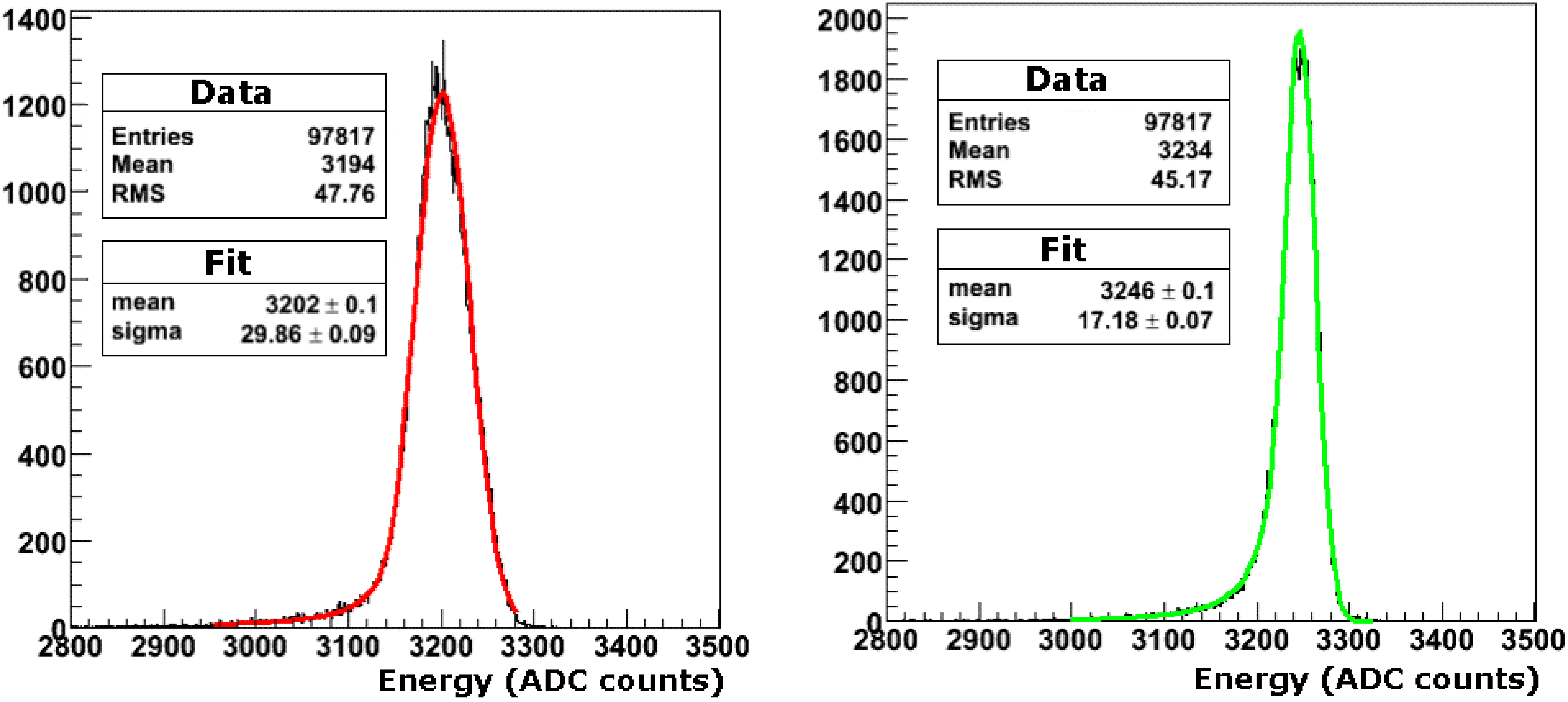
Light collection efficiency, fit to a linear function of distance to the small end of the crystal, was determined with two parameters: the light collection efficiency at the middle of the crystal and the uniformity.

LAL (cm)	20	40	60	80	200
Large Area Photo Detector, covering 100% back face					
η_m (%)	9.5±.2	15.7±.4	19.2±.5	21.6±.6	26.9±.7
δ (%)	23±1	-4.6±.8	-11±1	-15±1	-15±1
ϕ5 mm Photo Detector, covering 3.7% back face					
η_m (%)	.38±.04	.74±.08	1.1±.1	1.4±.2	3.0±.3
δ (%)	23±4	–3.5±4	-12±4	-16±4	-17±3
$\frac{\eta_m(\phi 5mm)}{\eta_m(Full)}$ (%)	4.0	4.7	5.7	6.5	11

Laser Monitoring is Effective

IEEE Trans. Nucl. Sci. vol. 55 (2008) 637-643

120 GeV electrons reconstructed by 3x3 crystal matrix



SM	Crystal	Res before	Res after
22	168	0.93%	0.53%

Dose Rate Dependence

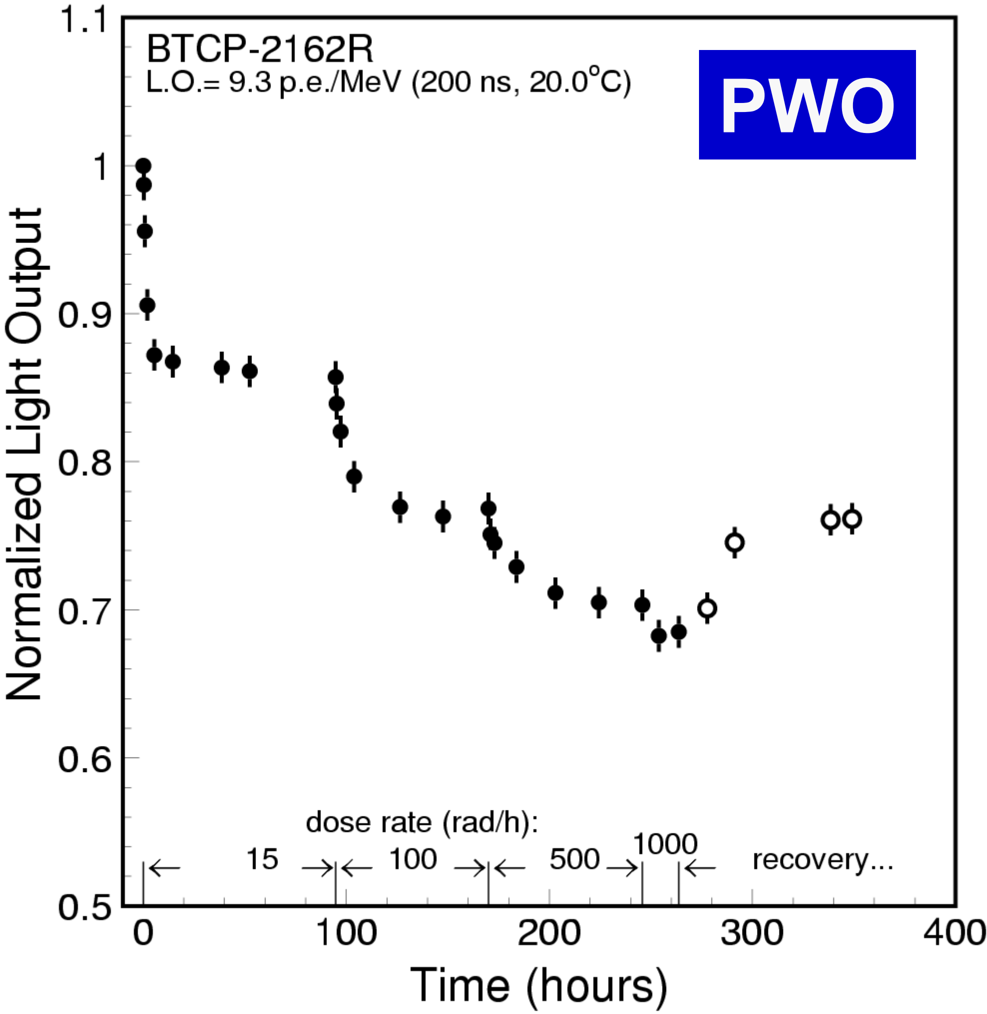
IEEE Trans. Nucl. Sci., Vol. 44 (1997) 468-476

$$dD = \sum_{i=1}^{n}\{-a_i D_i dt + (D_i^{all} - D_i)\, b_i R dt\}$$

$$D = \sum_{i=1}^{n}\{\frac{b_i R D_i^{all}}{a_i + b_i R}\,[1 - e^{-(a_i+b_iR)t}] + D_i^0 e^{-(a_i+b_iR)t}\}$$

- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of kRad/hr.

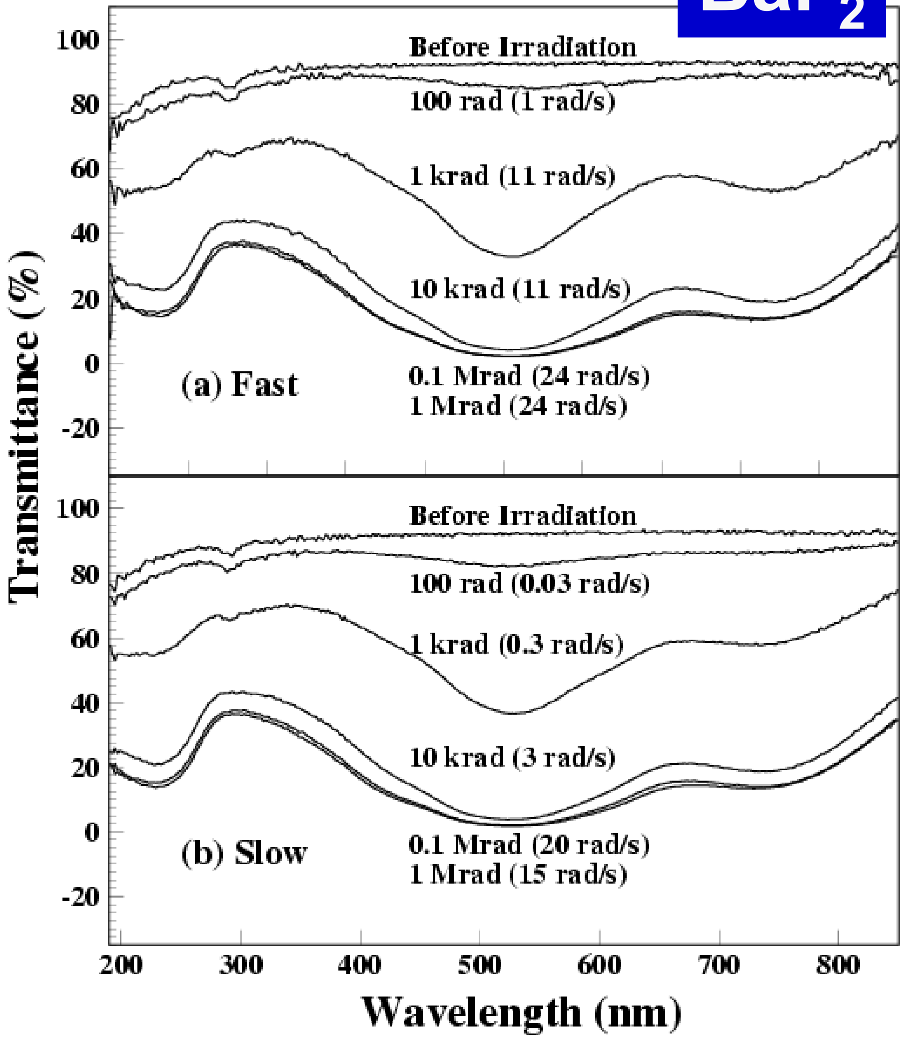
$$D_{eq} = \sum_{i=1}^{n}\frac{b_i R D_i^{all}}{a_i + b_i R}$$



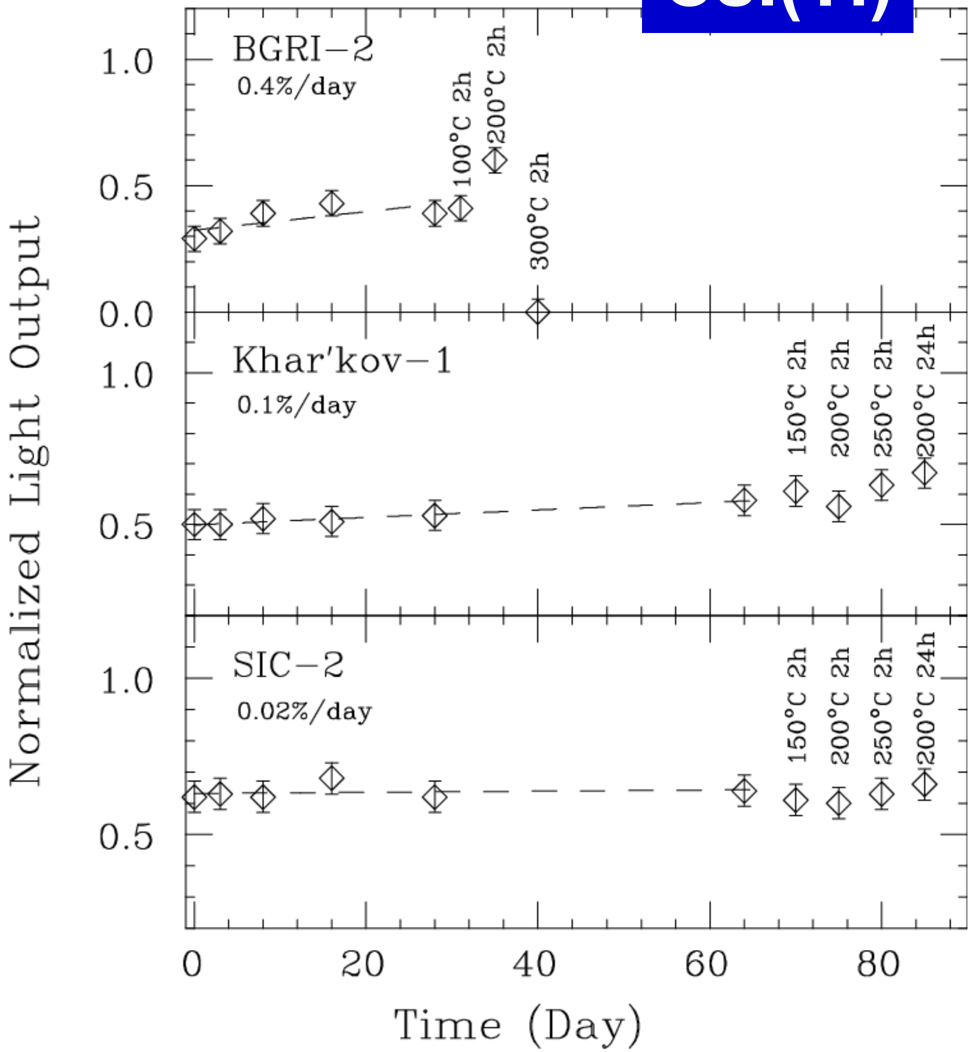
No Dose Rate Dependence

No recovery: no dose rate dependence

BaF_2



CsI(Tl)



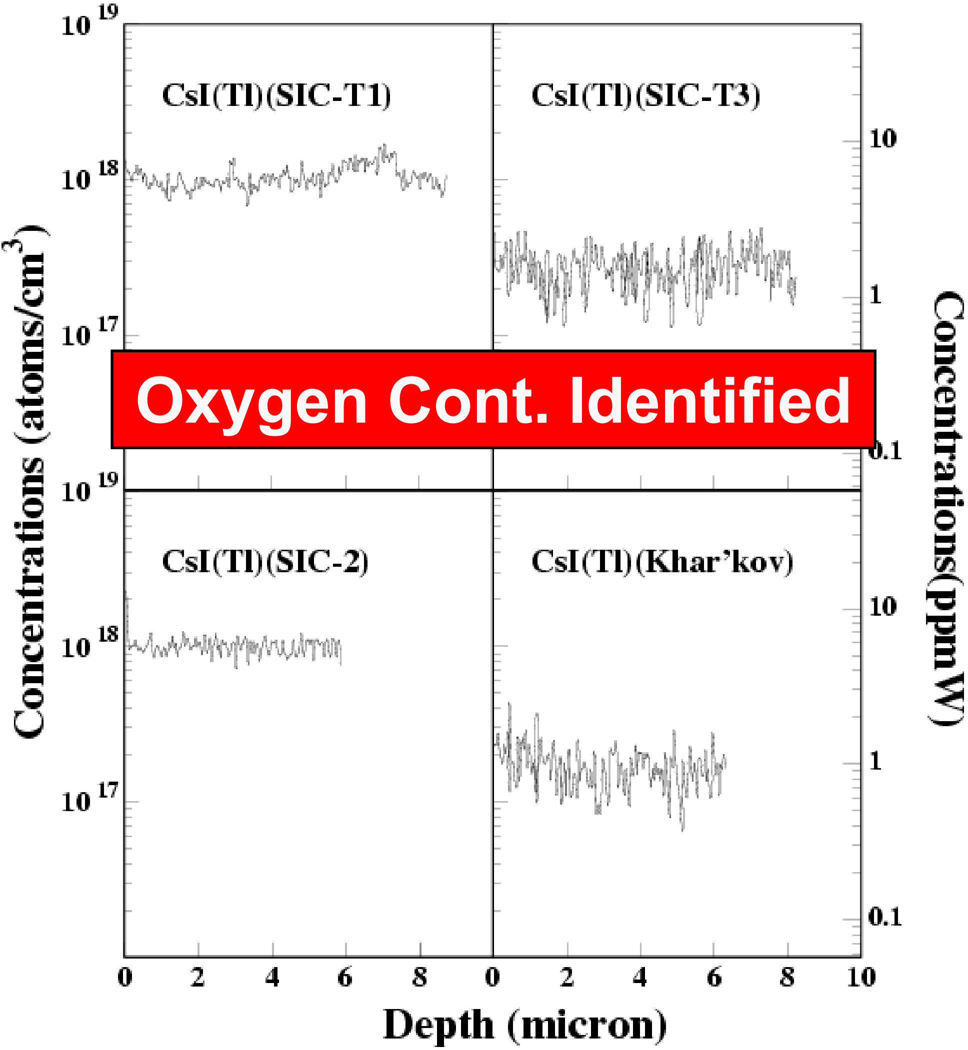
CsI(Tl) Damage Mechanism

Nucl. Instr. And Meth. A340 (1994) 442

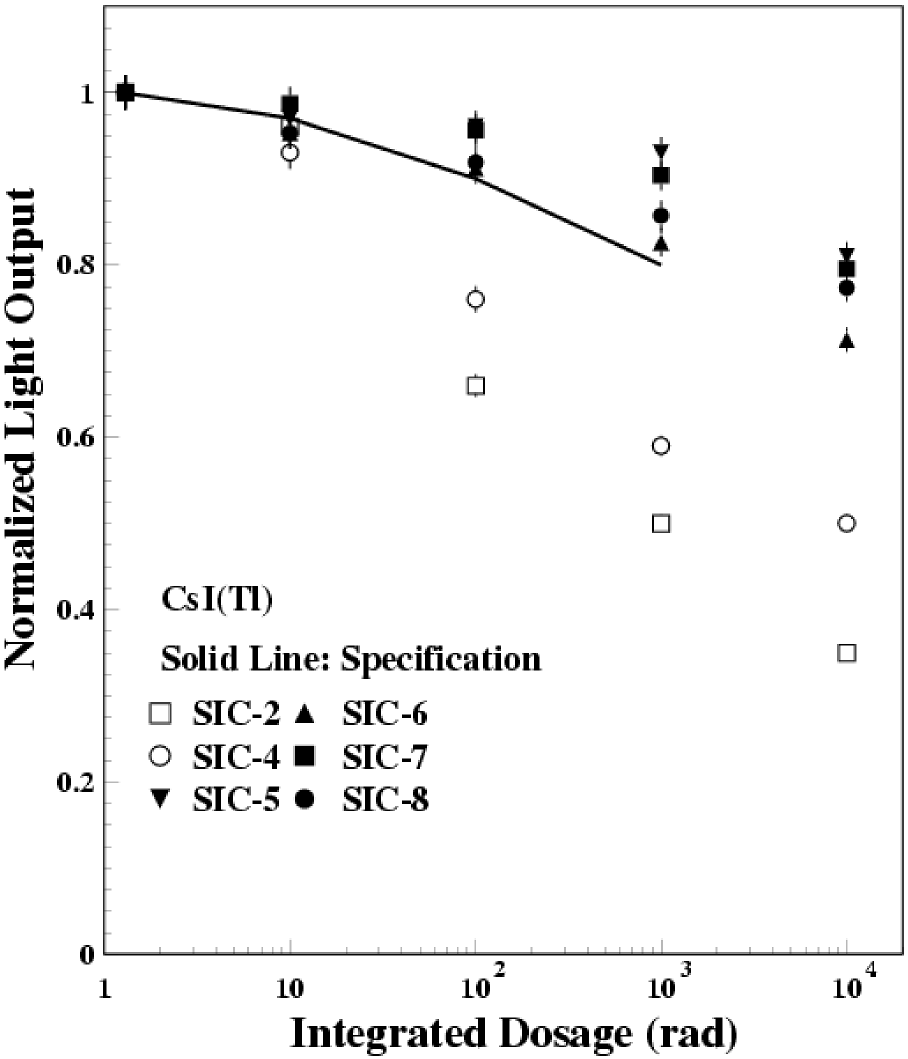
- **Oxygen Contamination** is known to cause radiation damage for other alkali halide scintillators. In BaF_2, for example, hydroxyl (OH^-) may be introduced into crystal through a hydrolysis process, and latter decomposed to interstitial and substitutional centers by radiation through a radiolysis process: $H_i^0 + O_s^-$ or $H_s^- + O_i^0$, where subscript i and s refer to interstitial and substitutional centers respectively.
- Possible means for trace oxygen identification:
  - **Secondary Ionization Mass Spectroscopy (SIMS);**
  - Gas Fusion (LEGO); and
  - Energy Dispersive x-Ray (EDX).

SIMS Study & CsI(Tl) Improvement

Secondary Ion Mass Spectroscopy revealed depth profile of oxygen contamination; Oxygen control improves CsI(Tl) quality



Oxygen Cont. Identified



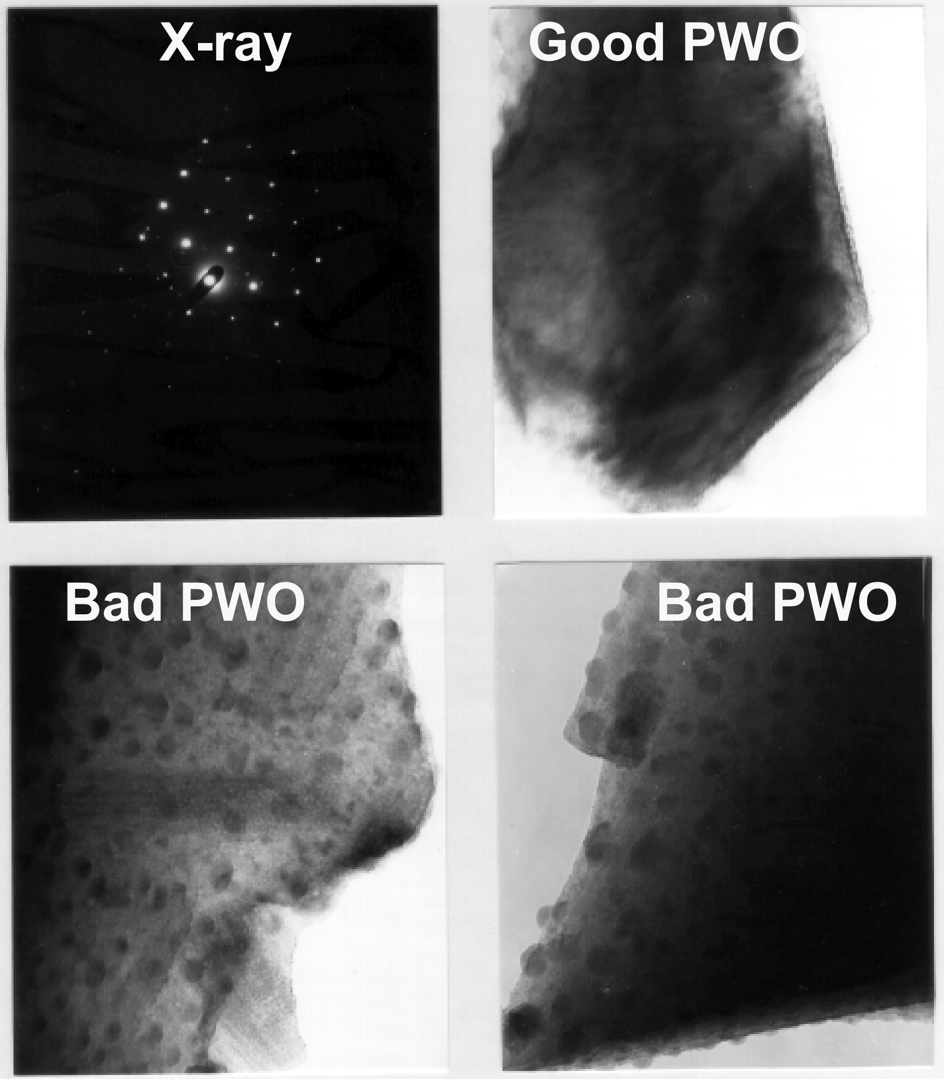
PWO Radiation Damage Mechanism

Nucl. Instr. And Meth. A413 (1998) 297

- Crystal defects, such as **Oxygen Vacancies**, are known to cause radiation damage for other oxide scintillators. In BGO, for example, three common radiation induced absorption bands at 2.3, 3.0 and 3.8 eV were found in a series of 24 doped samples, indicating defect-related color centers.
- Possible means for oxygen vacancy identification:
  - Electron Paramagnetic Resonance (ESR) and Electron-Nuclear Double Resonance (ENDOR);
  - **Transmission Electron Microscopy (TEM)/Energy Dispersion Spectrometry (EDS);** and
  - A pragmatic way: Oxygen Compensation by Post-Growing Annealing in Oxygen Rich Atmosphere.

TEM/EDS Study on PWO Crystals

TOPCON-002B scope, 200 kV, 10 uA, 5 to10 nm black spots identified
JEOL JEM-2010 scope and Link ISIS EDS localized Stoichiometry Analysis



Atomic Fraction (%) in $PbWO_4$

As Grown Sample

Element	Black Spot	Peripheral	$Matrix_1$	$Matrix_2$
O	1.5	15.8	60.8	63.2
W	50.8	44.3	19.6	18.4
Pb	47.7	39.9	19.6	18.4

The Same Sample after Oxygen Compensation

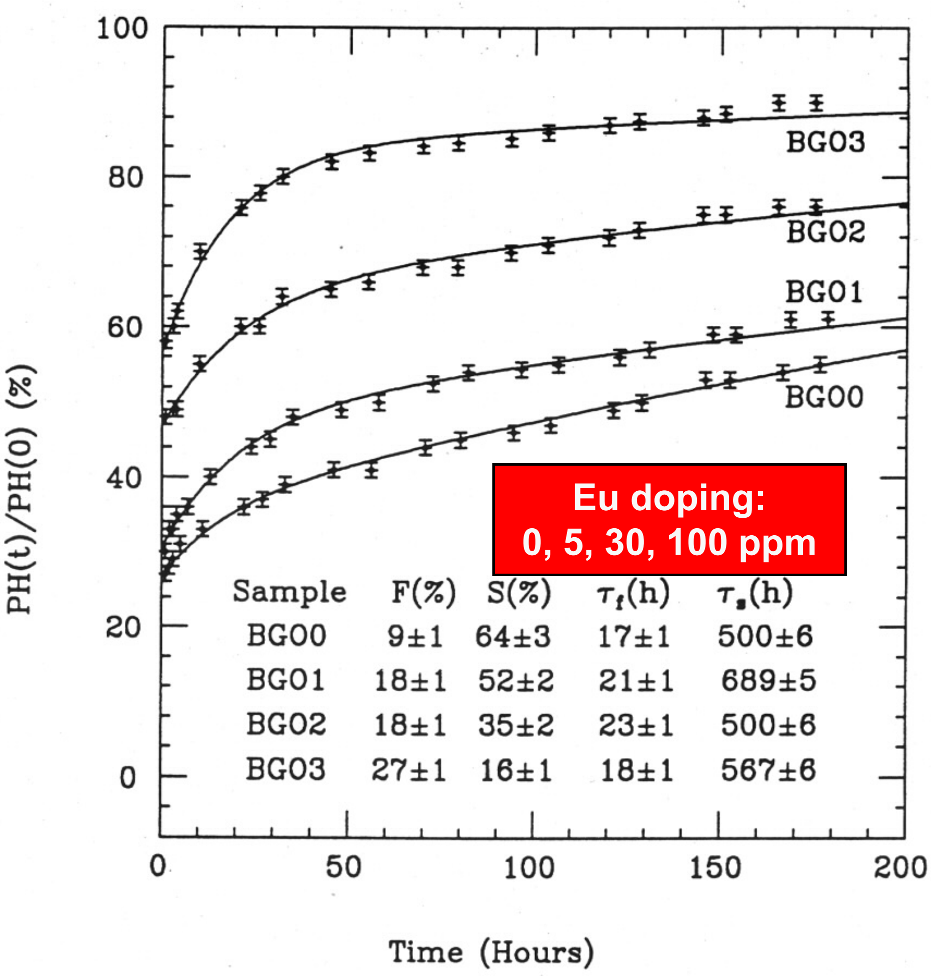
Element	$Point_1$	$Point_2$	$Point_3$	$Point_4$
O	59.0	66.4	57.4	66.7
W	21.0	16.5	21.3	16.8
Pb	20.0	17.1	21.3	16.5

Oxygen Vacancies Identified

BGO/PWO Quality Improvement

Nucl. Instr. and Meth. A302 (1991)

BGO damage recovery after 2.5 krad

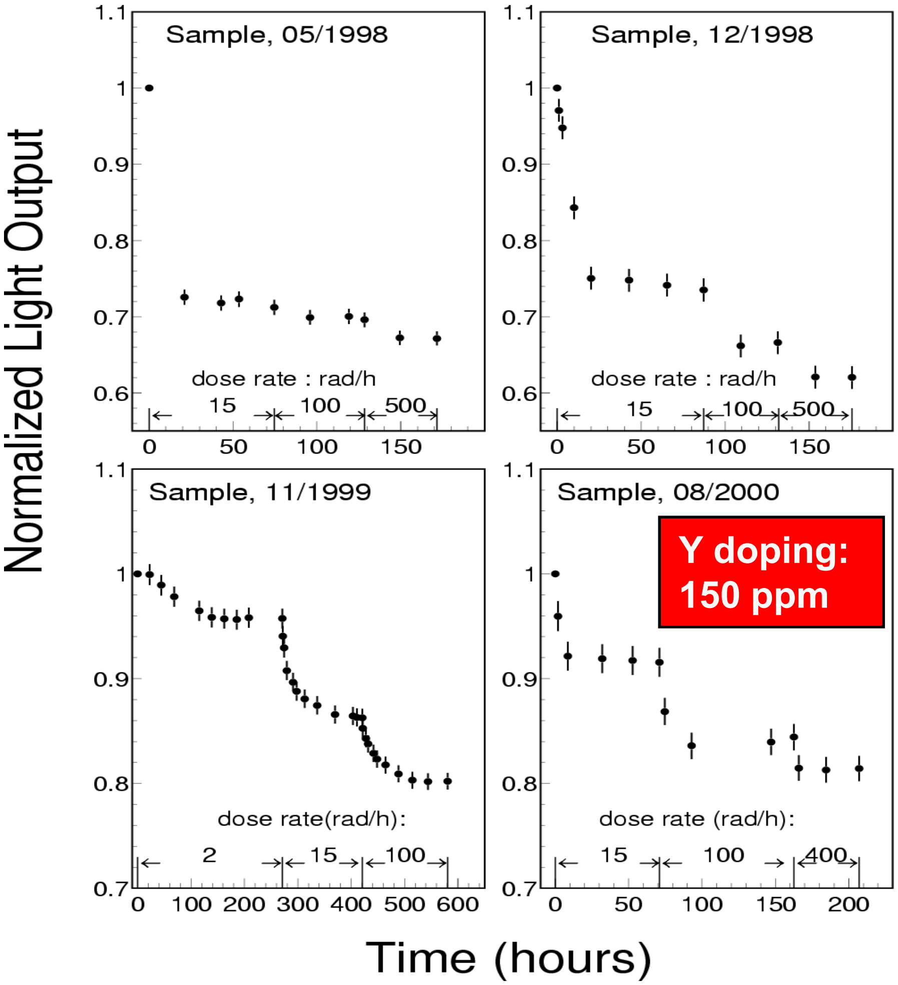


Sample	F(%)	S(%)	τ_f(h)	τ_s(h)
BGO0	9±1	64±3	17±1	500±6
BGO1	18±1	52±2	21±1	689±5
BGO2	18±1	35±2	23±1	500±6
BGO3	27±1	16±1	18±1	567±6

Eu doping:
0, 5, 30, 100 ppm

Nucl. Instr. and Meth. A480 (2002) 470

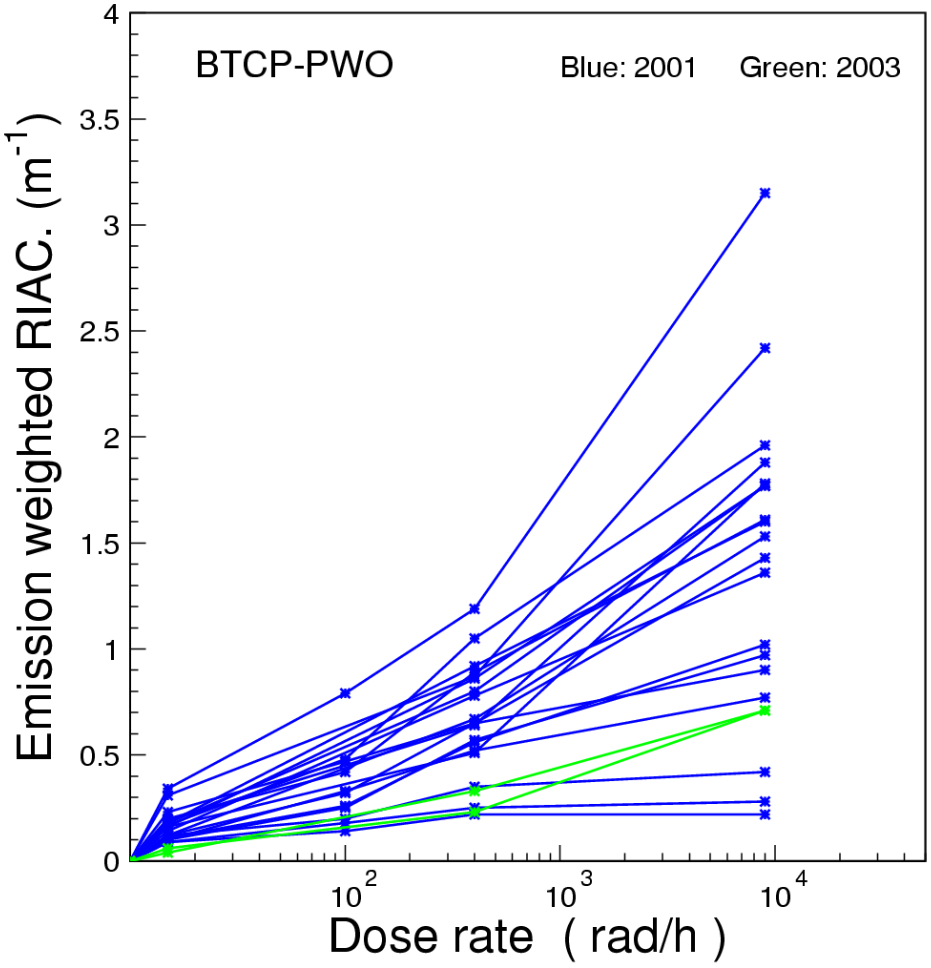
PWO damage at different dose rate

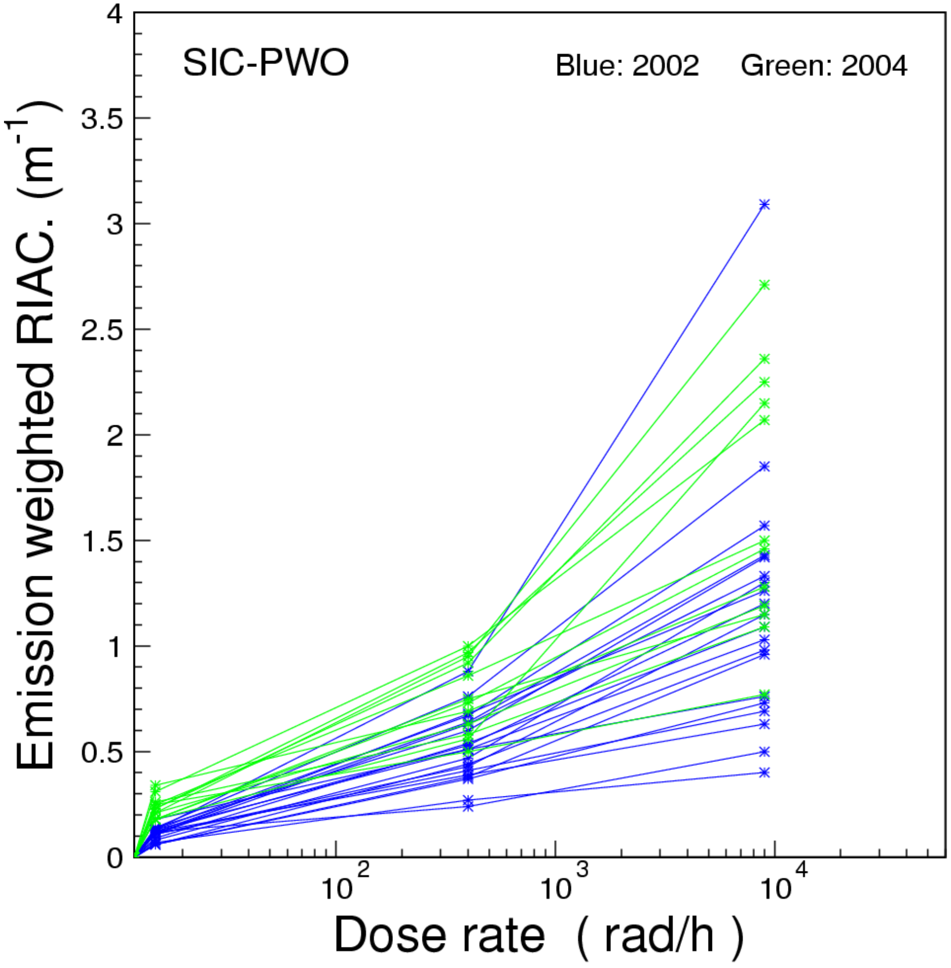


Y doping:
150 ppm

Mass Produced PWO Crystals

All samples: EWRIAC < 1 m^{-1} up to 400 rad/h
Rigorous QC required to qualify CMS endcap crystals





LSO/LYSO Mass Production

CTI: LSO

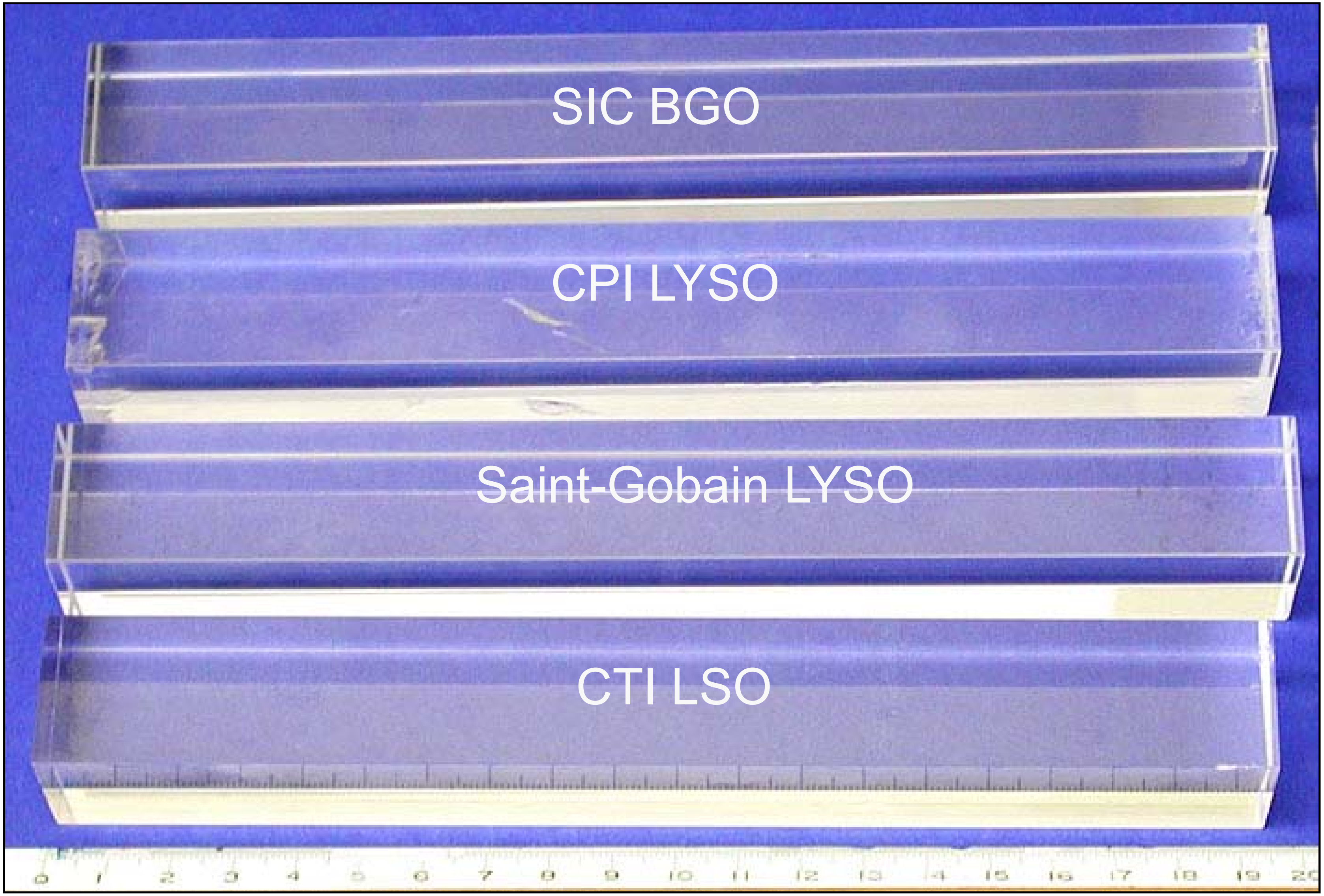
CPI: LYSO

Saint-Gobain LYSO

Additional Capability: SIPAT @ Sichuan, China

BGO, LSO & LYSO Samples

2.5 x 2.5 x 20 cm (18 X_0)


SIC BGO

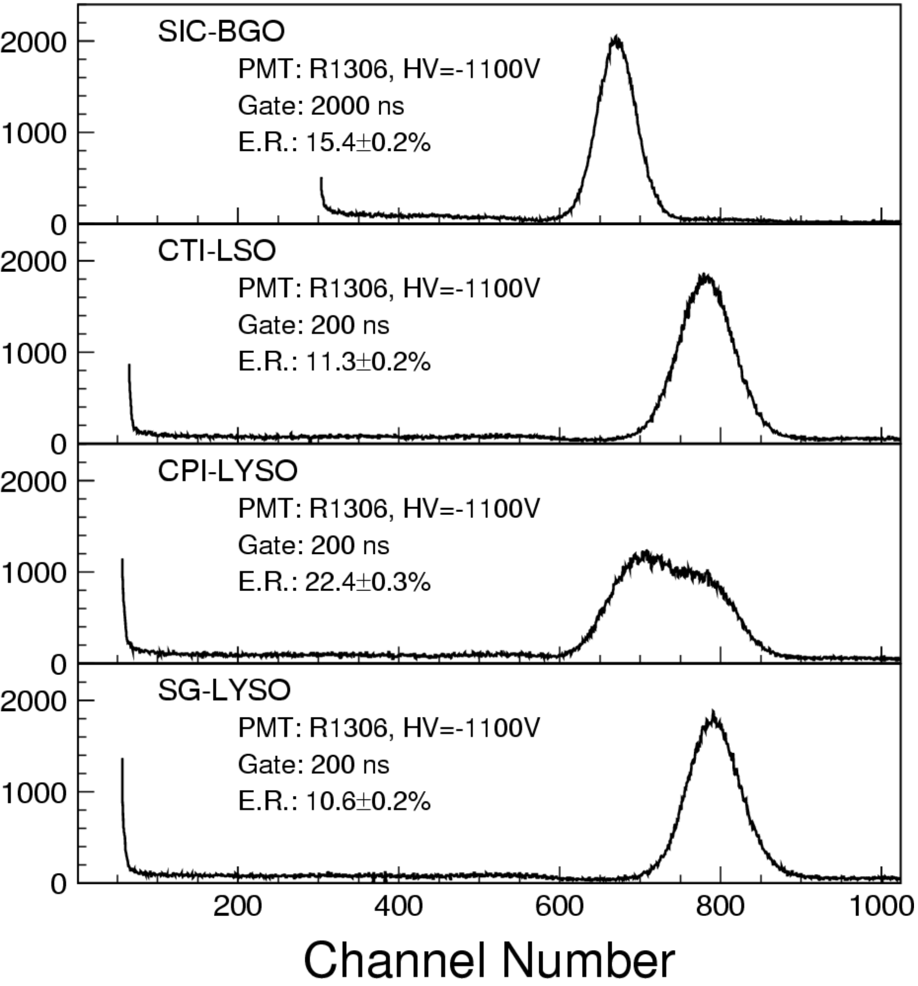
CPI LYSO

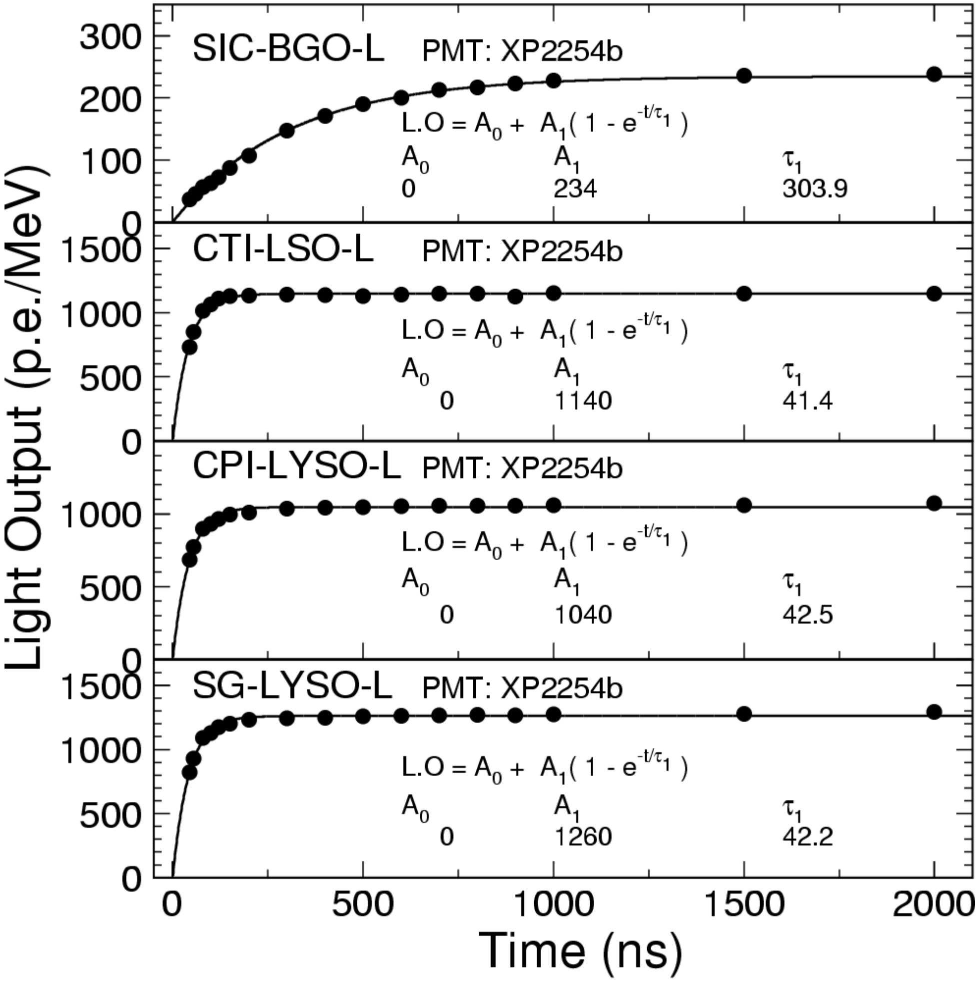
Saint-Gobain LYSO

CTI LSO

LSO/LYSO with PMT Readout

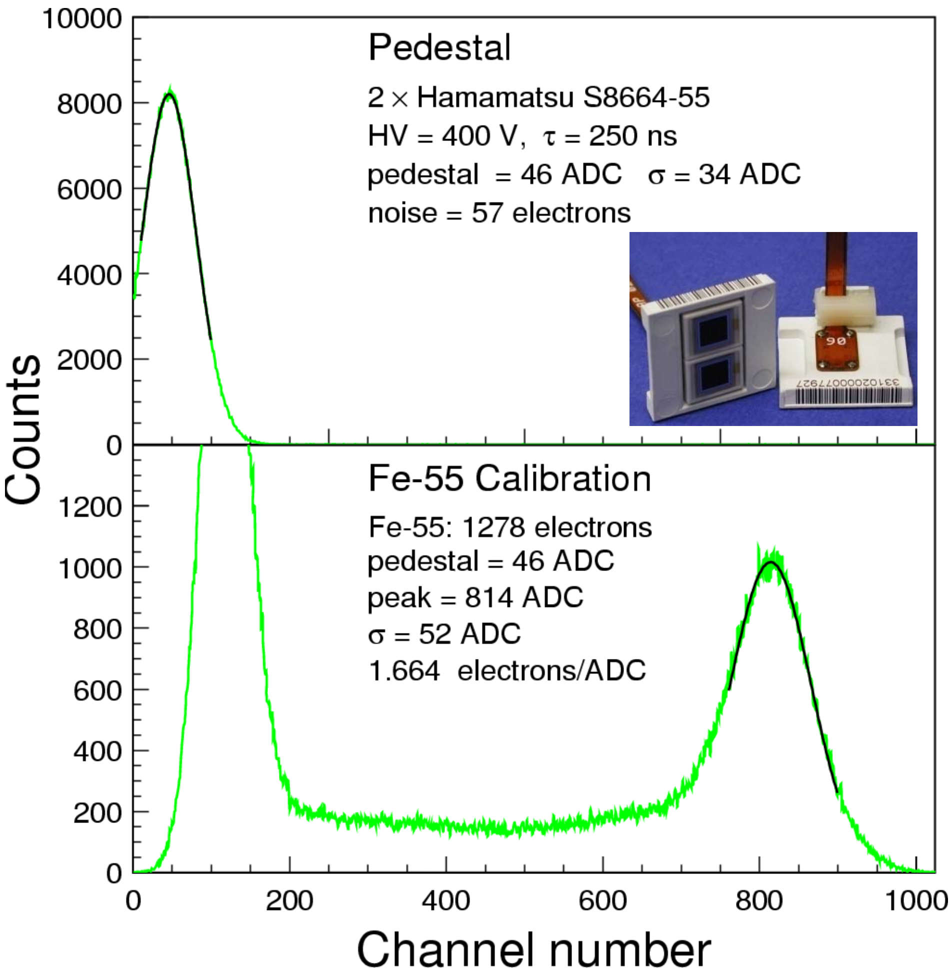
~10% FWHM resolution for ^{22}Na source (0.51 MeV)
1,200 p.e./MeV, 5/230 times of BGO/PWO

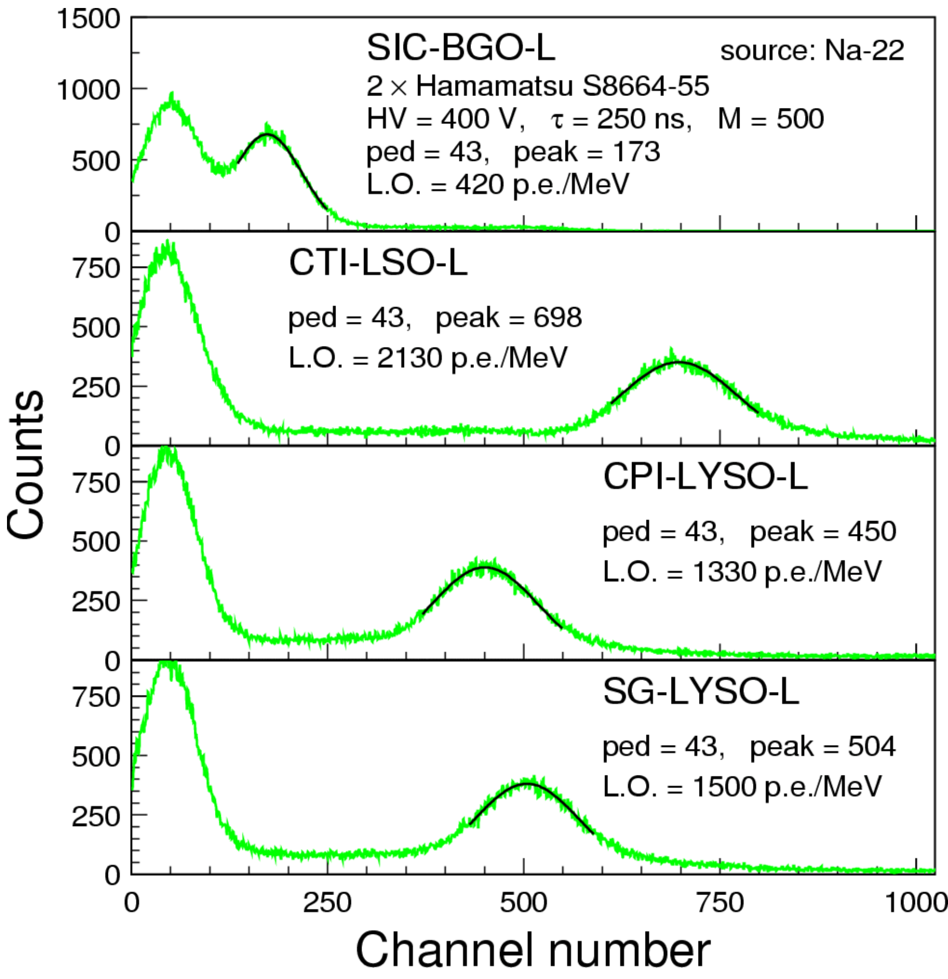




LSO/LYSO with APD Readout

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

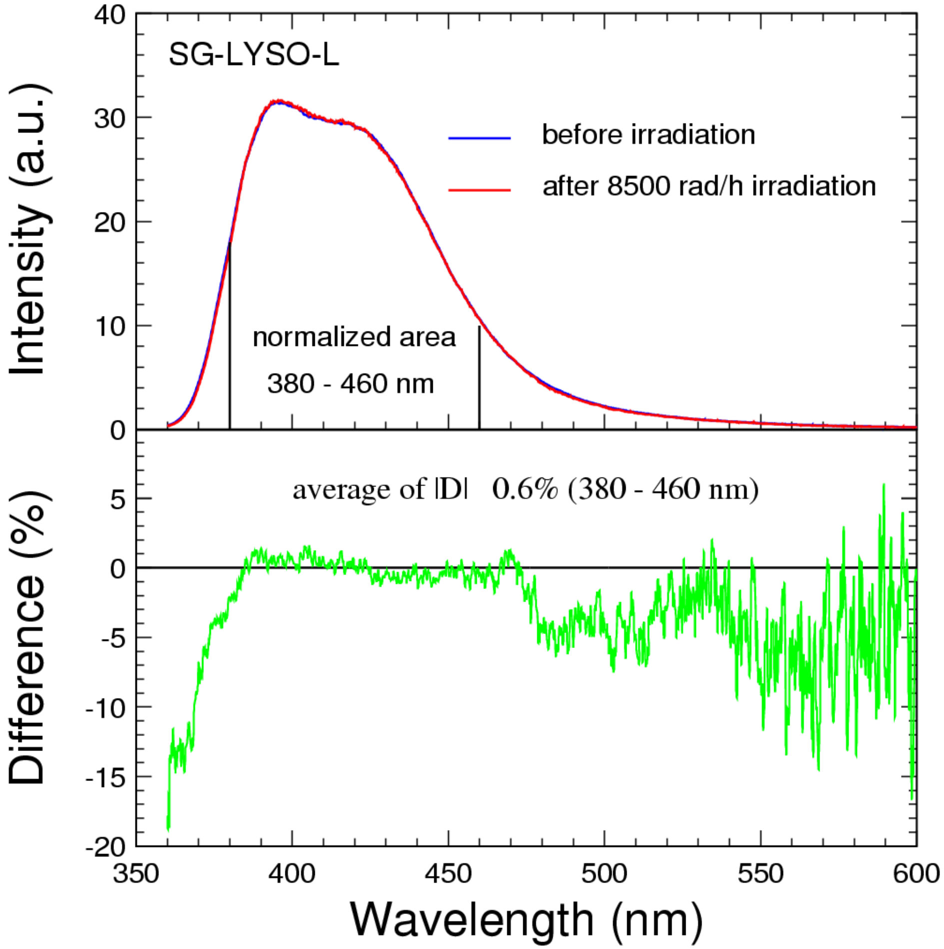


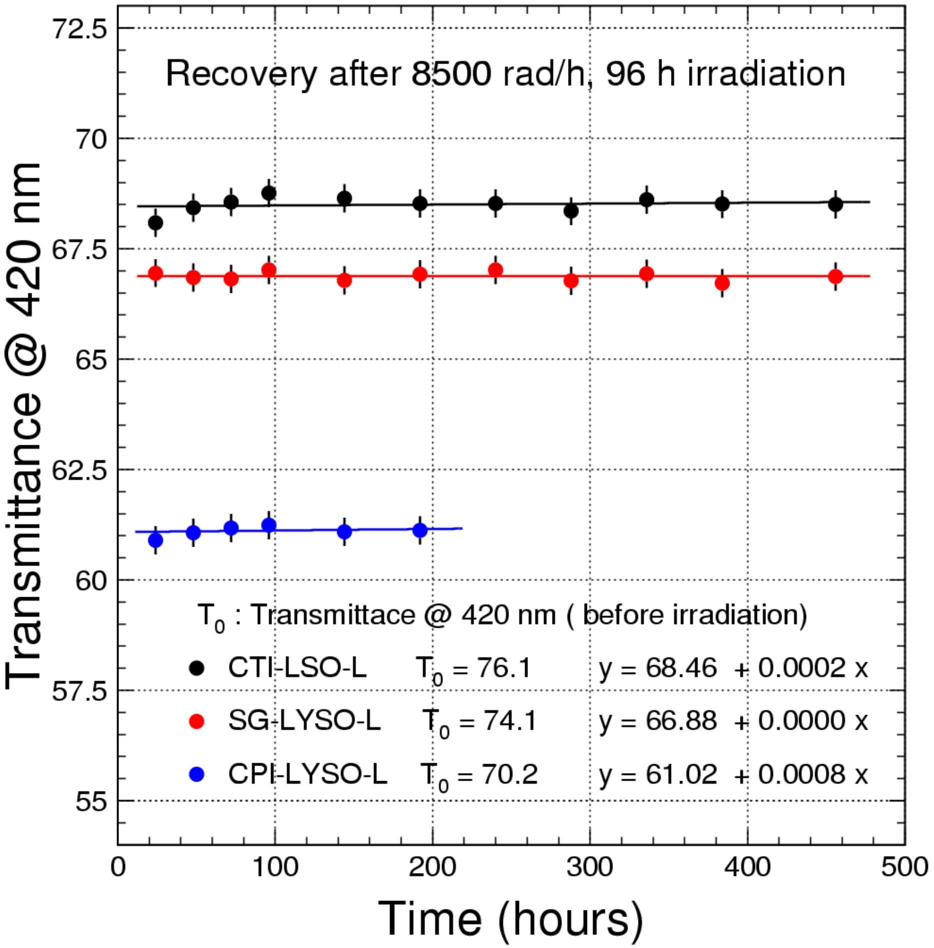


γ-Rays Induced Damage

No damage in Photo-Luminescence

Transmittance recovery slow

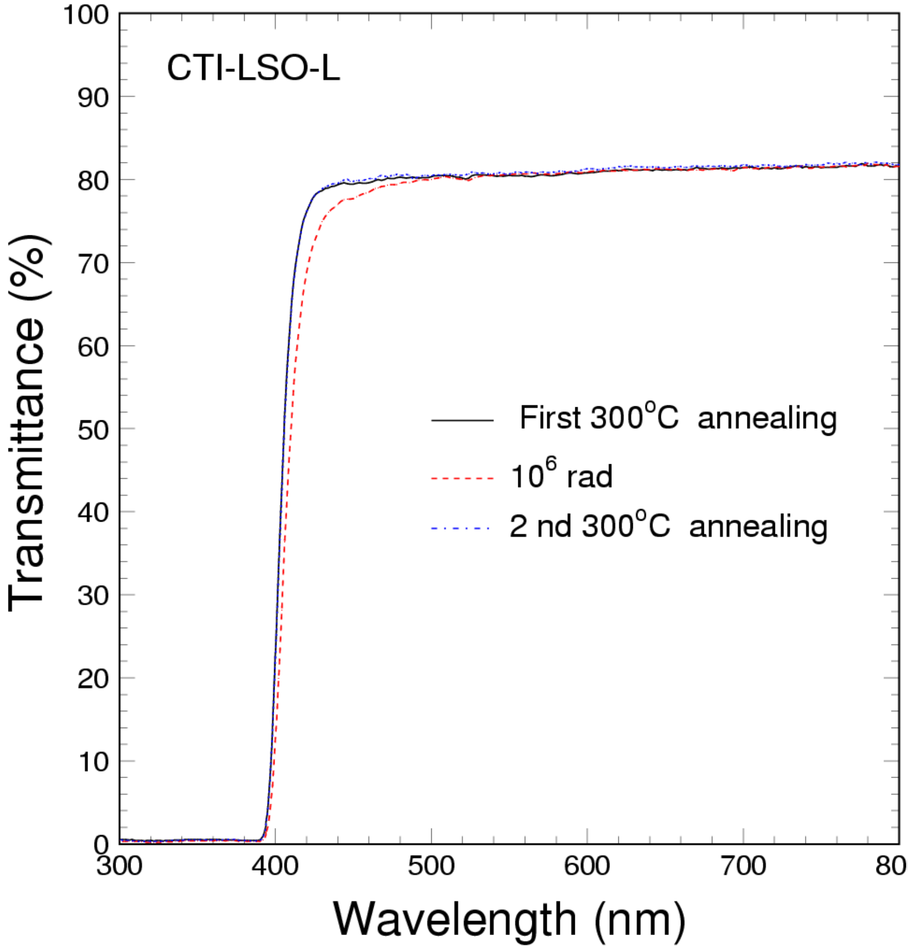


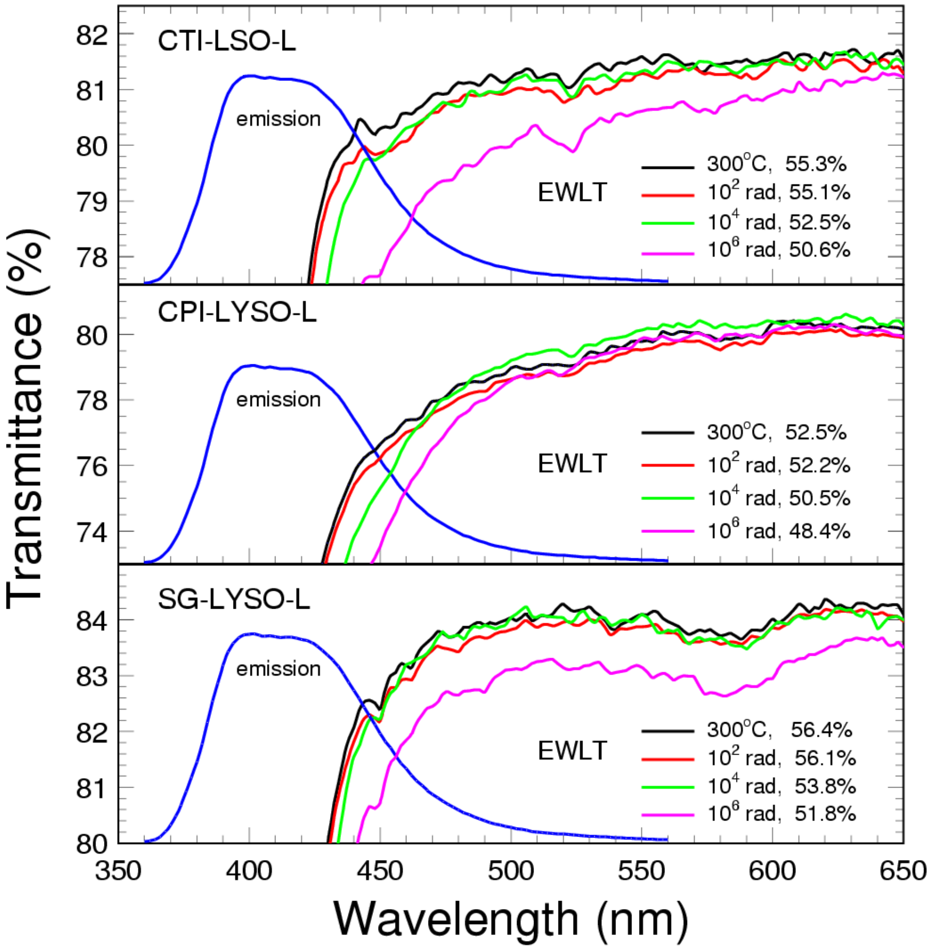


γ-Rays Induced Transmittance Damage

300°C thermal annealing effective

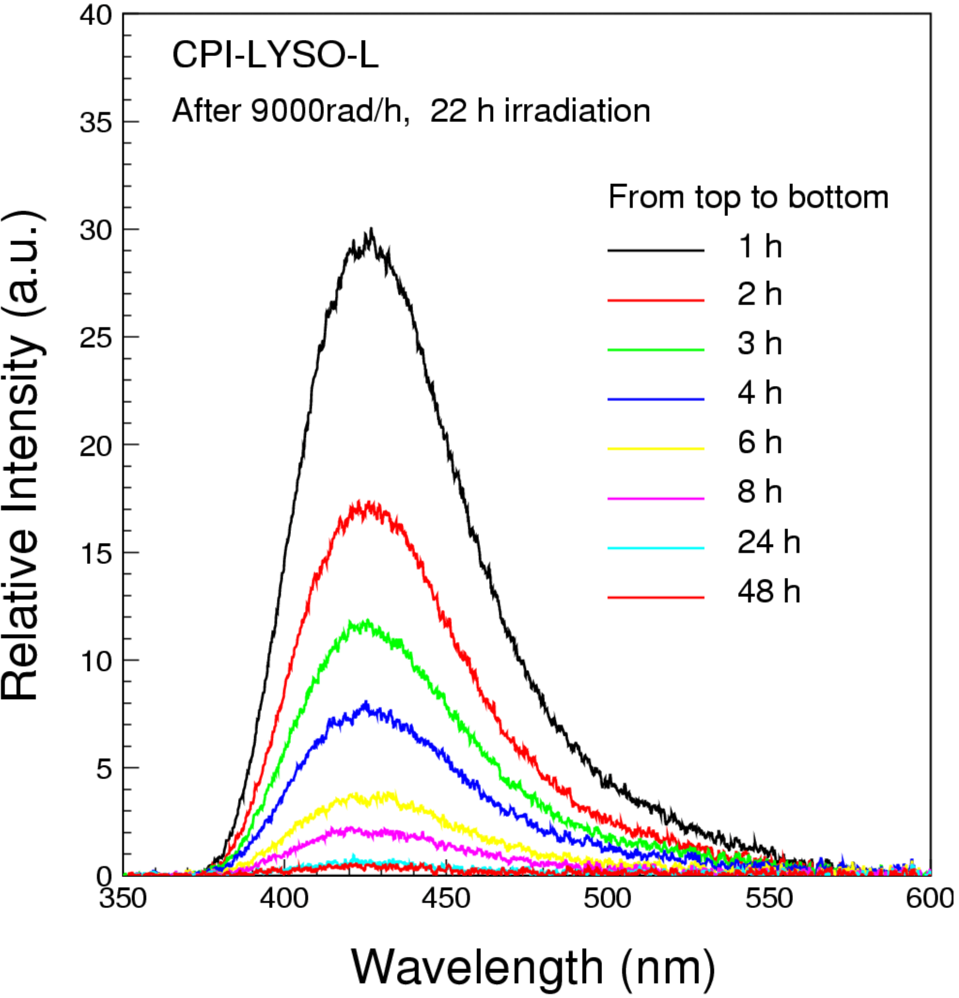
LT damage: 8% @ 1 Mrad

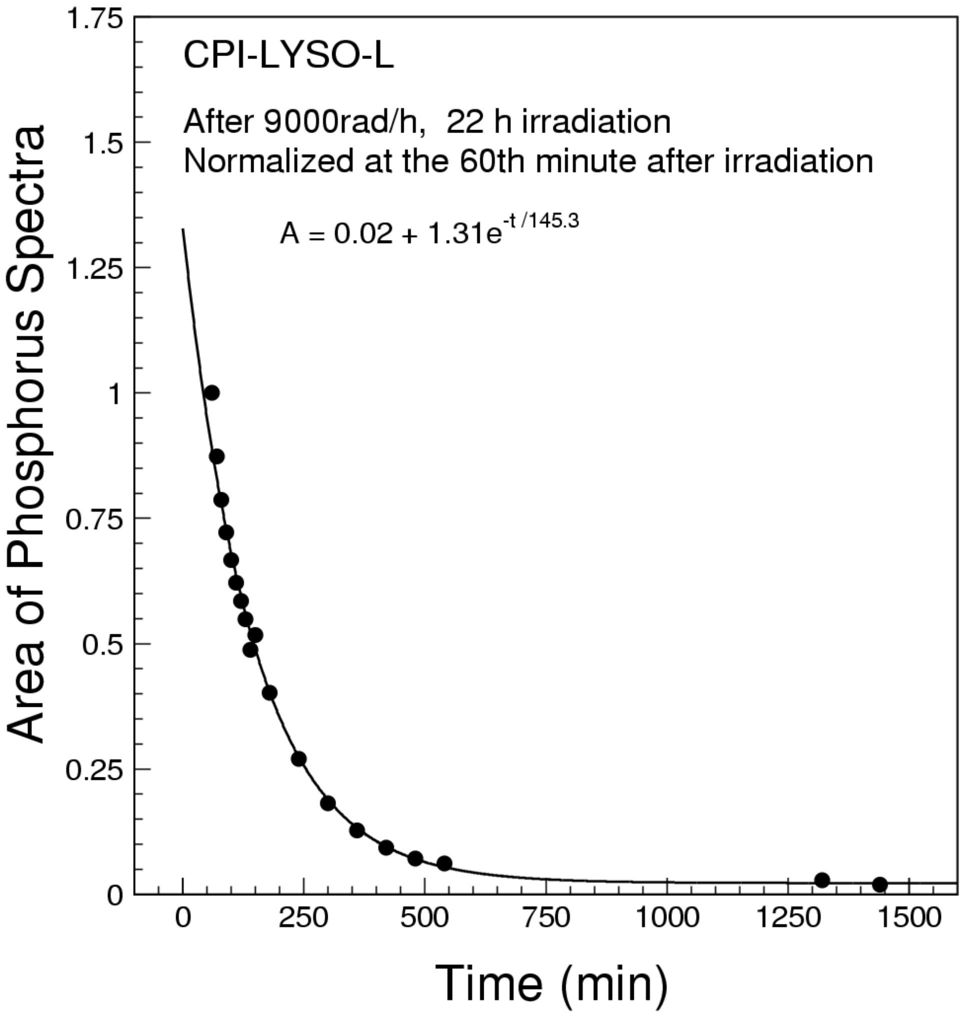




γ–ray Induced Phosphorescence

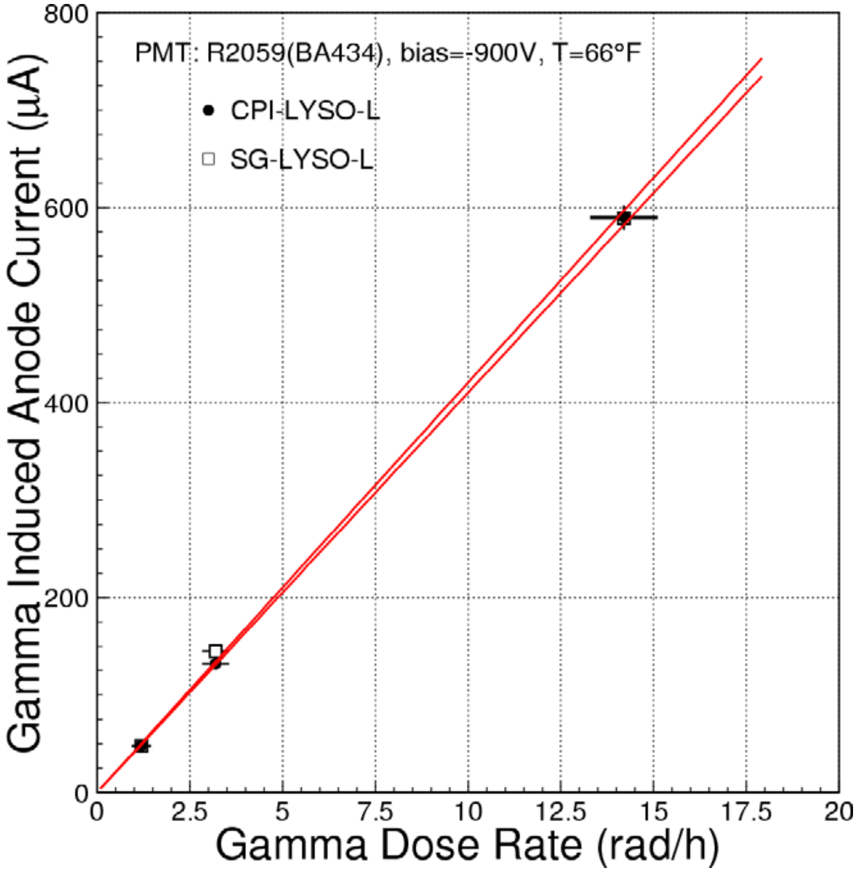
Phosphorescence peaked at 430 nm with decay time constant of 2.5 h observed





γ–ray Induced Readout Noise

Sample	L.Y.	F	$Q_{15\ \mathrm{rad/h}}$	$Q_{500\ \mathrm{rad/h}}$	$\sigma_{15\ \mathrm{rad/h}}$	$\sigma_{500\ \mathrm{rad/h}}$
ID	p.e./MeV	µA/rad/h	p.e.	p.e.	MeV	MeV
CPI	1,480	41	6.98x10^{4}	2.33x10^{6}	0.18	1.03
SG	1,580	42	7.15x10^{4}	2.38x10^{6}	0.17	0.97



γ–ray induced PMT anode current can be converted to the photoelectron numbers (Q) integrated in 100 ns gate. Its statistical fluctuation contributes to the readout noise (σ): 0.2 & 1 MeV @ 15 & 500 rad/h.

Six LSO & LYSO Samples

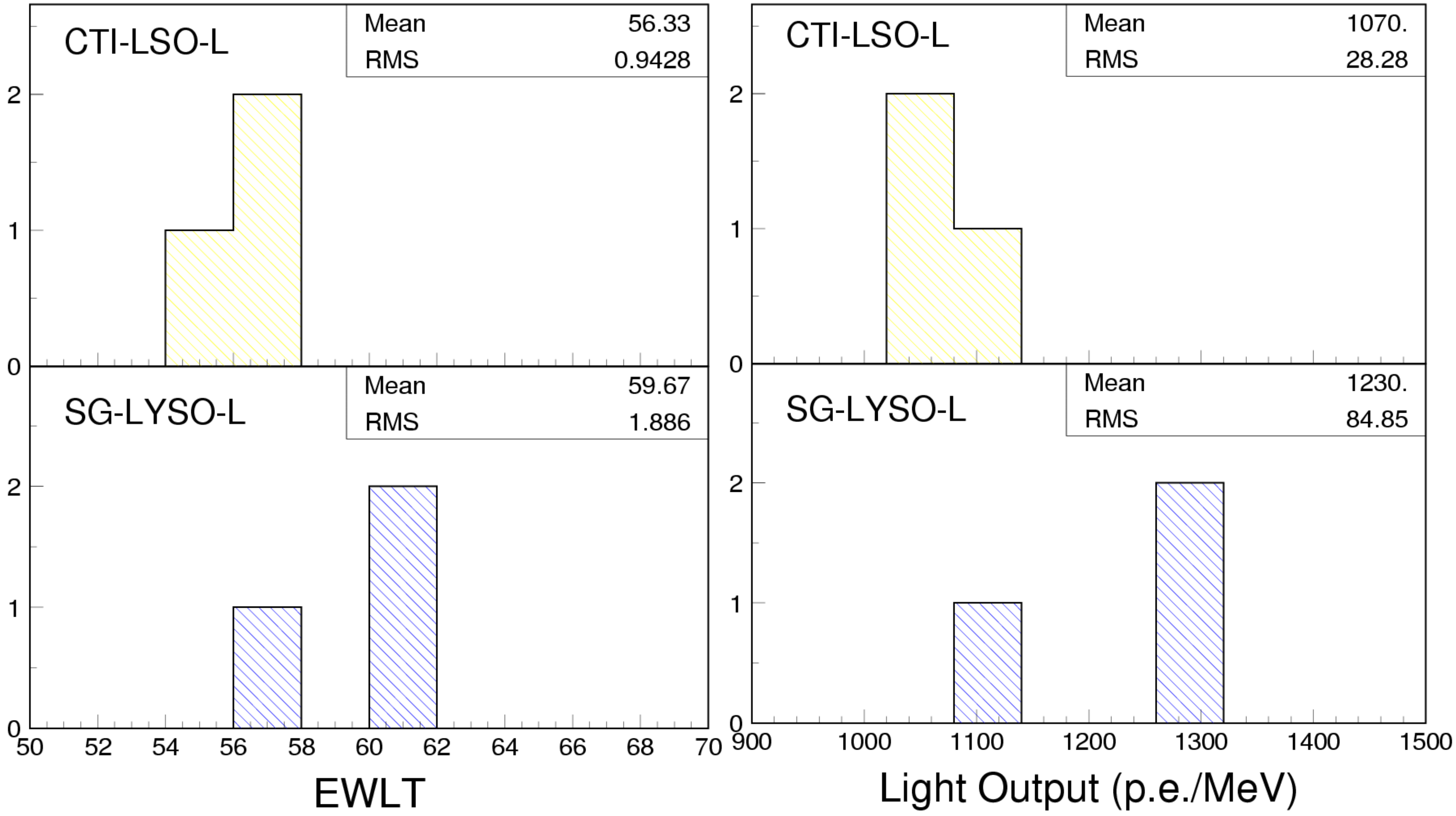
2.5 x 2.5 x 20 cm (18 X_0) Bar

Three CTI LSO samples are provided by Chuck Melcher.

Three LYSO samples are purchased from Saint-Gobain.

Statistical Comparison

Recent LYSO crystals are better than LSO



Sichuan Institute of Piezoelectric and Acousto-optic Technology (SIPAT)

China Electronics Technology Corporation (CETC)
No. 26 Research Institute, www.sipat.com

SIPAT: Furnace & R&D Issues

- Raw material:

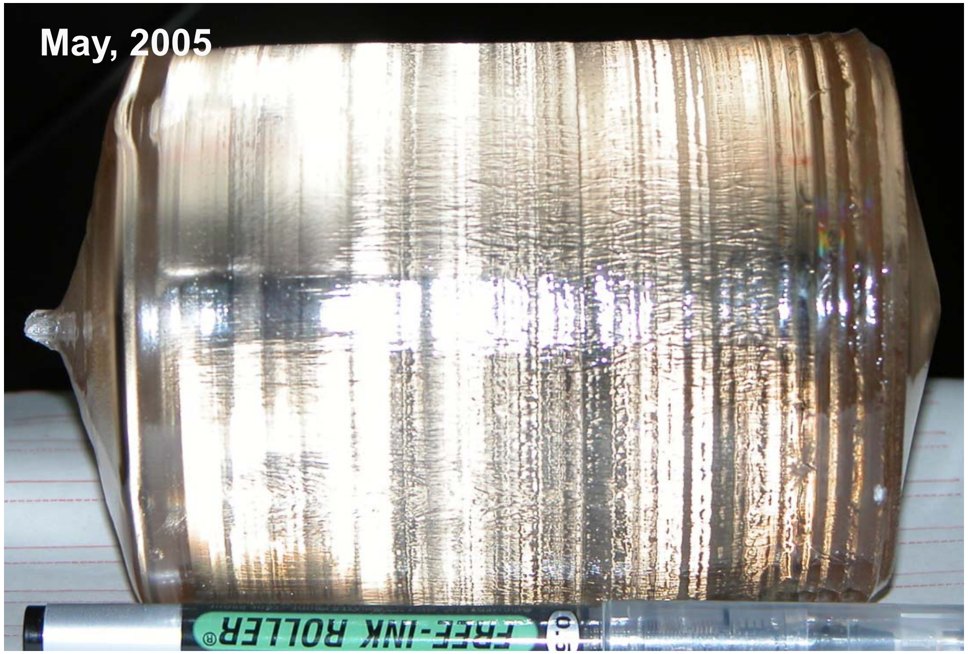
  Lu_2O_3: 99.995%

  SO_2: 99.999%

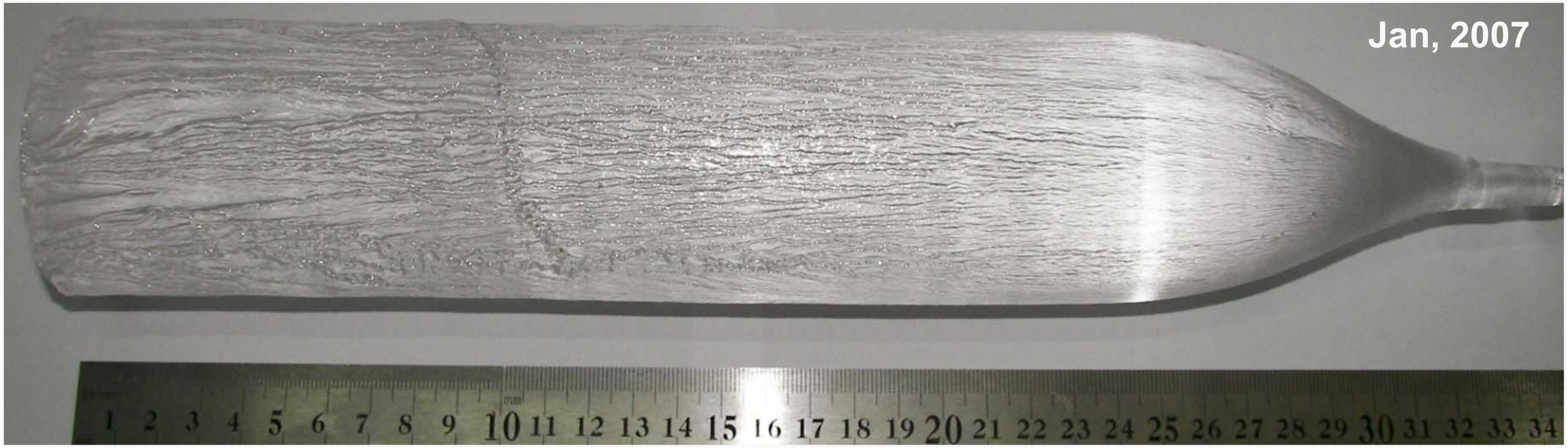
- Stoichiometry
- Temperature Gradient
- Growth Parameter Optimization
- Thermal Annealing
- Iridium Crucible Maintenance
- Power Supply Stability
- Chilled Water Stability

LYSO Growth Progress at SIPAT

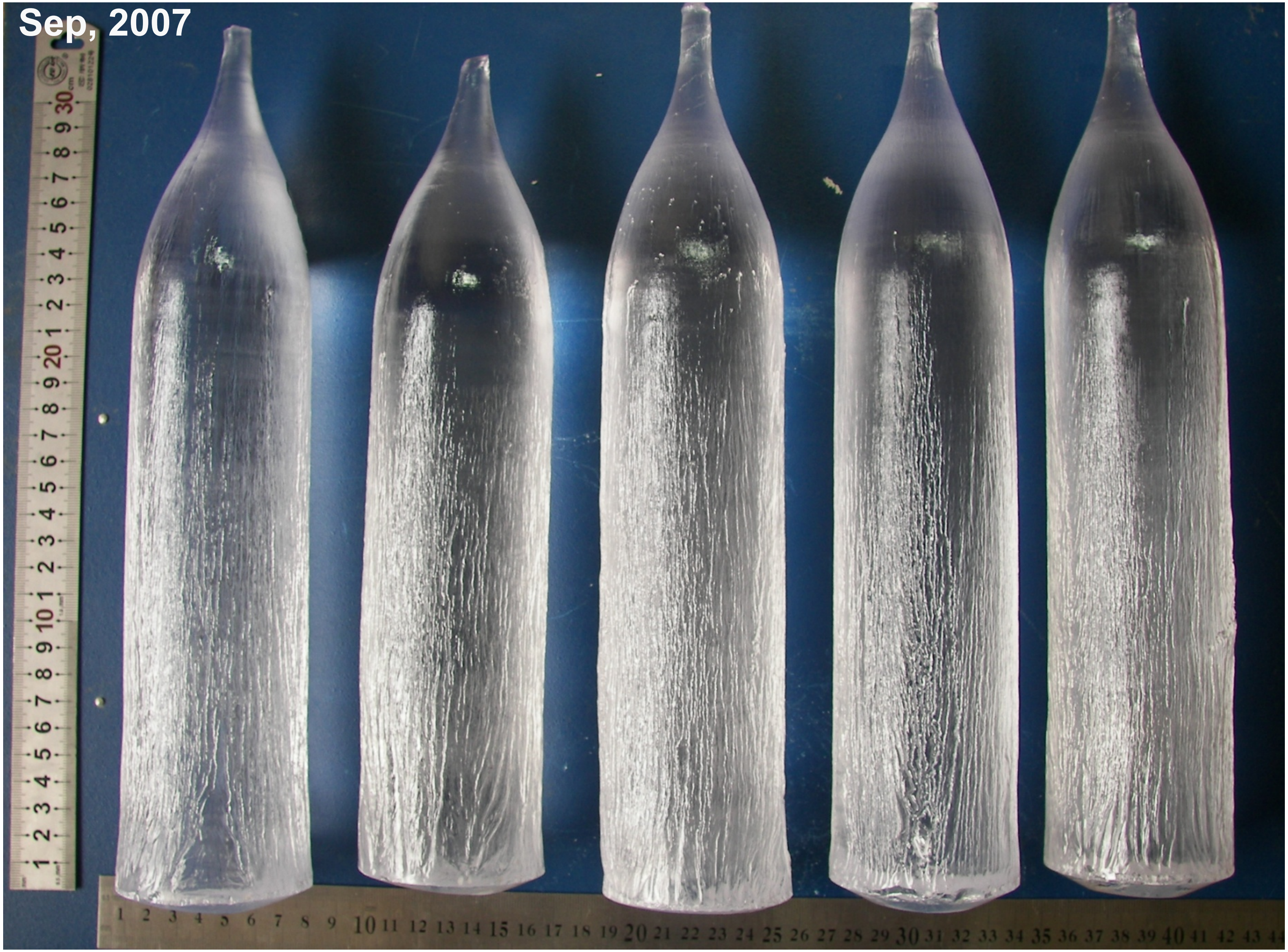
Started 2001 with Significant Progress in the last year


May, 2005


Sep, 2006


Jan, 2007

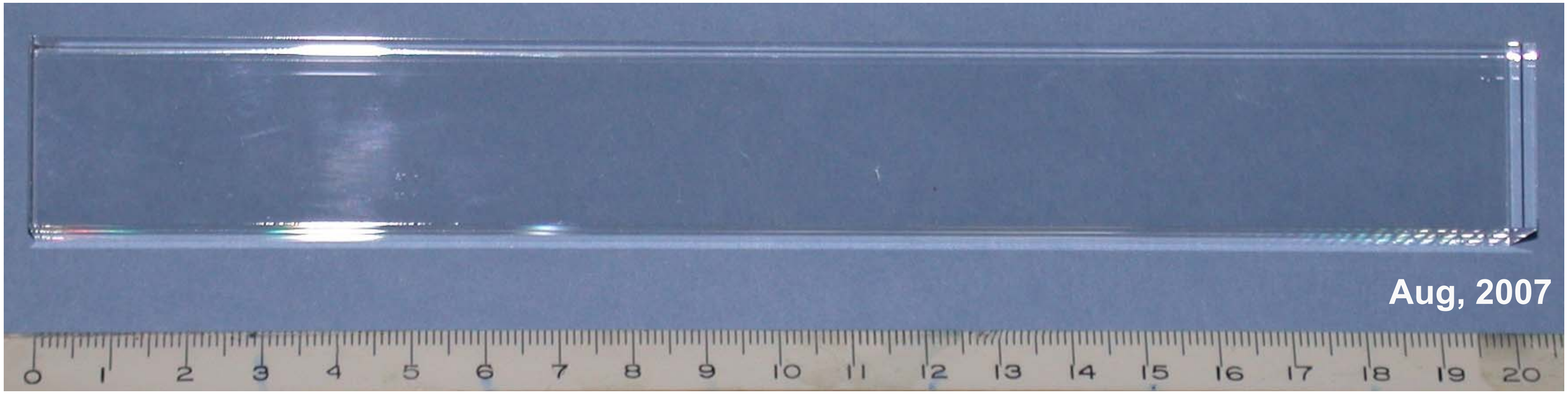
SIPAT Ø 60 x 250 mm LYSO Ingots



Sep, 2007

SIPAT Czochralski Furnaces

First SIPAT LYSO Sample for HEP

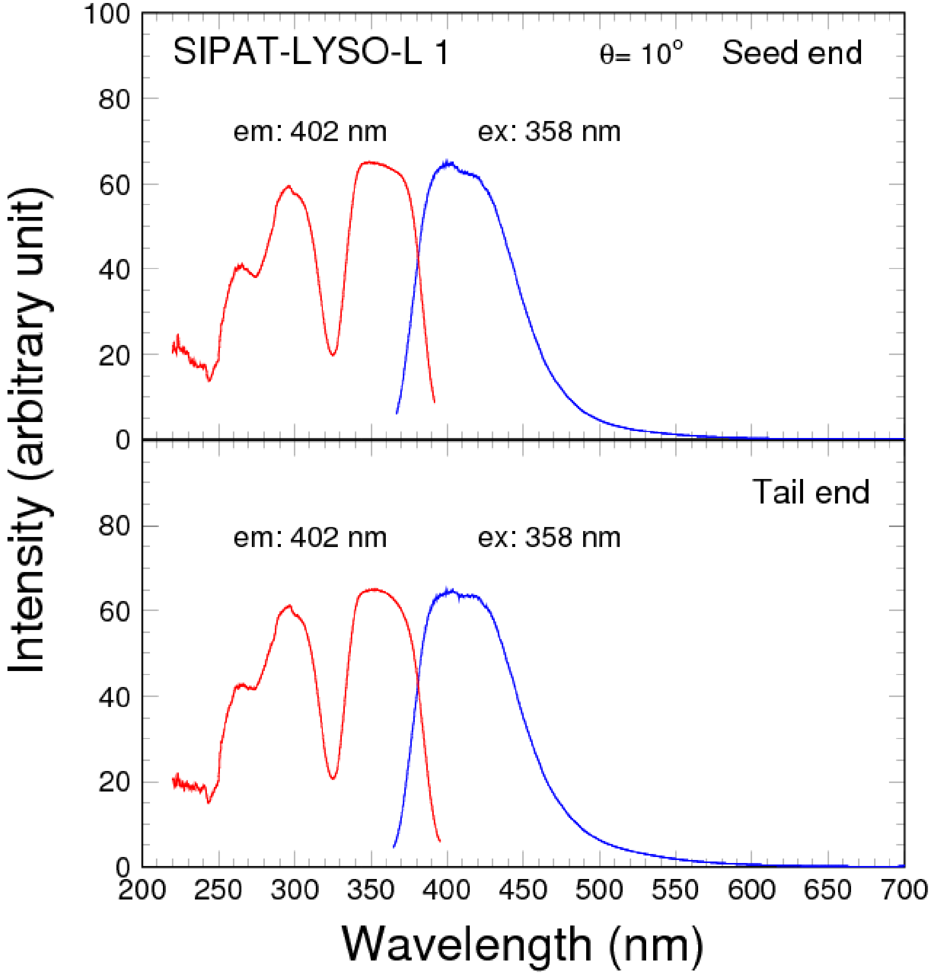


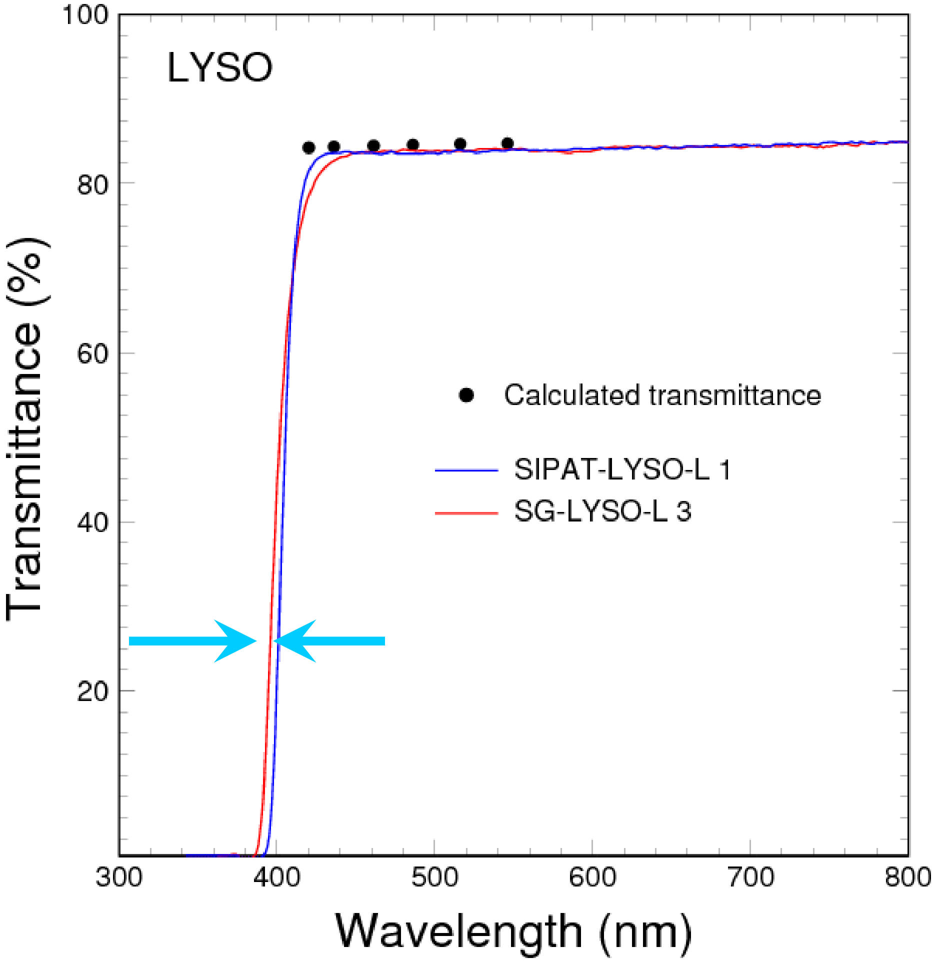
- Received in the middle of August with dimension of 25 x 25 x 200 mm and good visual inspection.
- It was first annealed at 300ºC for 10 hours and with its initial optical and scintillation properties measured.
- Together with SG-L3, two samples were irradiated with integrated doses of 10, 10^2, 10^3, 10^4 10^5 and 10^6.
- Samples were kept in dark after irradiation for 48 hours before optical and scintillation property measurement.
- Damage to transmittance, light output and uniformity are compared with samples from CTI, CPI and Saint-Gobain.

Initial Optical Properties

Excitation: emission @ 402 nm Emission: excitation @ 358 nm

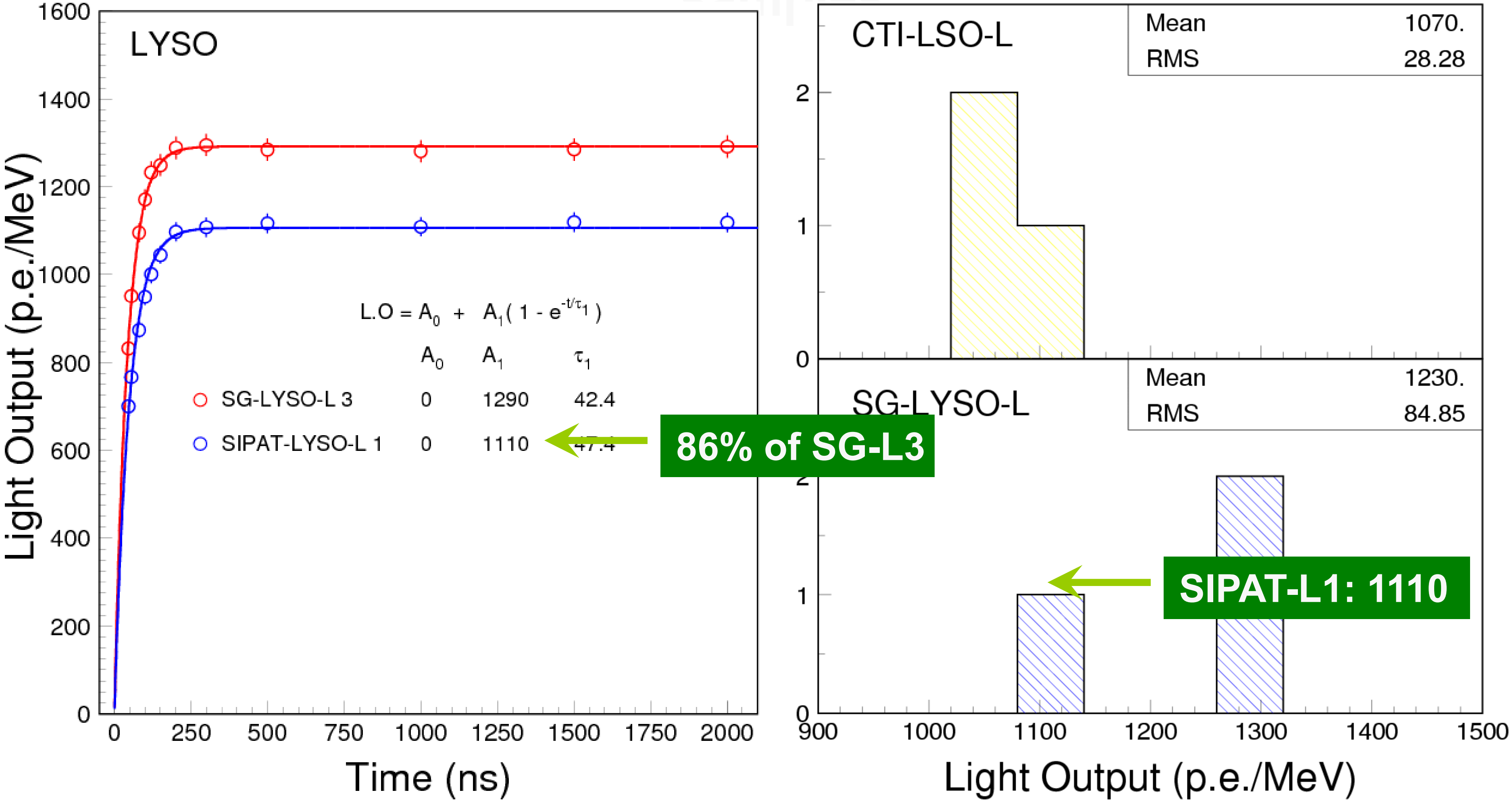
The cutoff of SG-L3 has ~5 nm blue shift compared to SIAPT-L1





Light Output & Decay Kinetics

Compatible with the first batch large size samples from CTI and Saint-Gobain, and is 86% of the 'best'



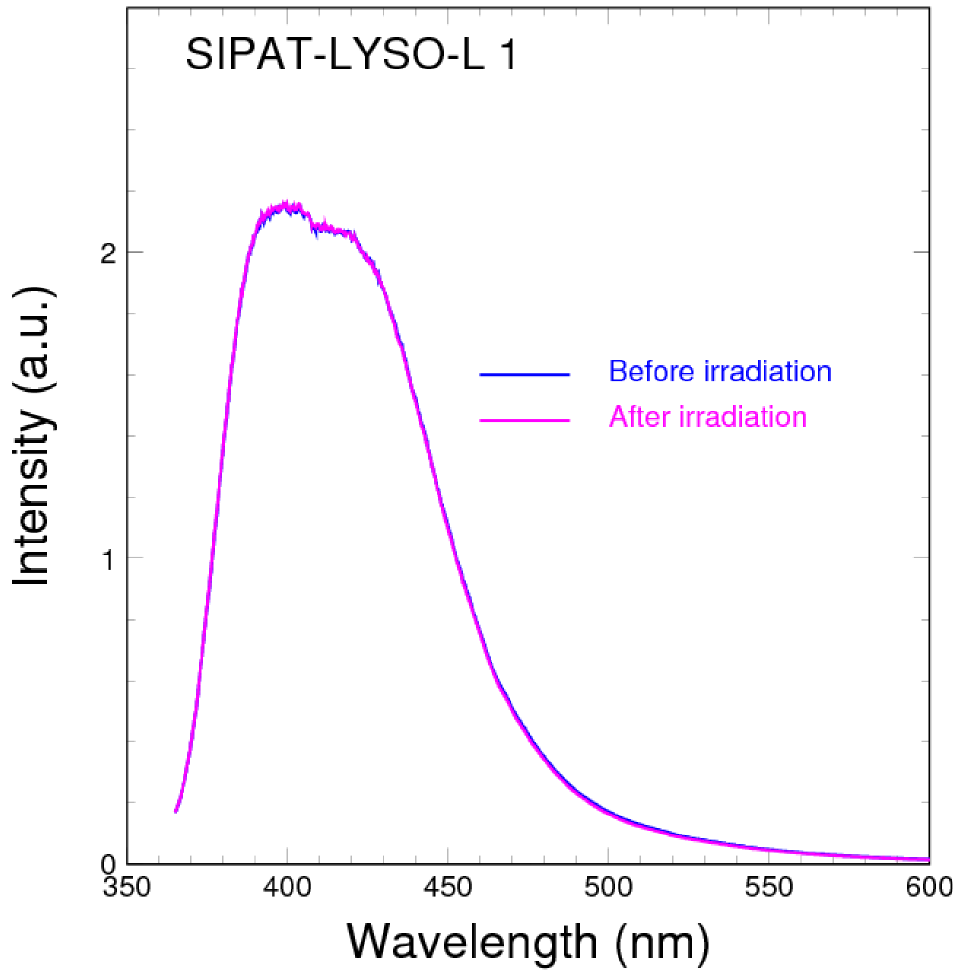
86% of SG-L3

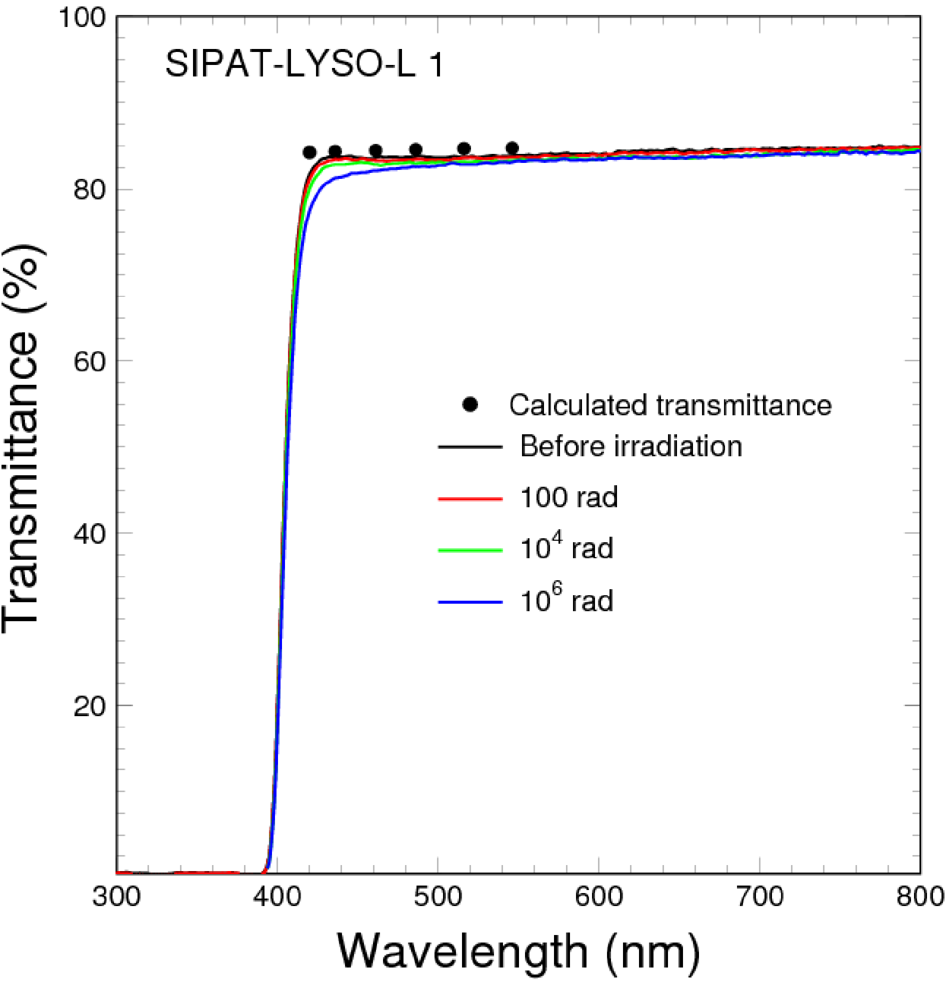
SIPAT-L1: 1110

γ-Ray Induced Radiation Damage

Scintillation spectrum not affected by irradiation

~8% damage @ 420 nm after 106 rad irradiation

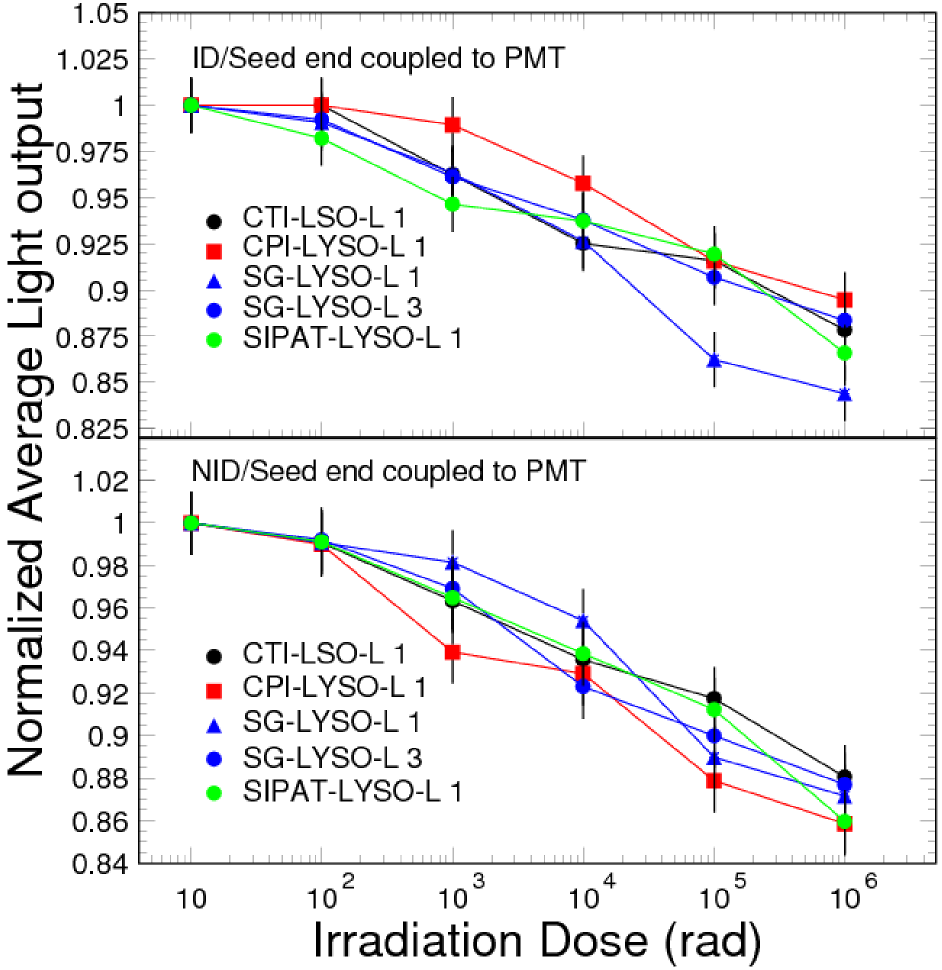




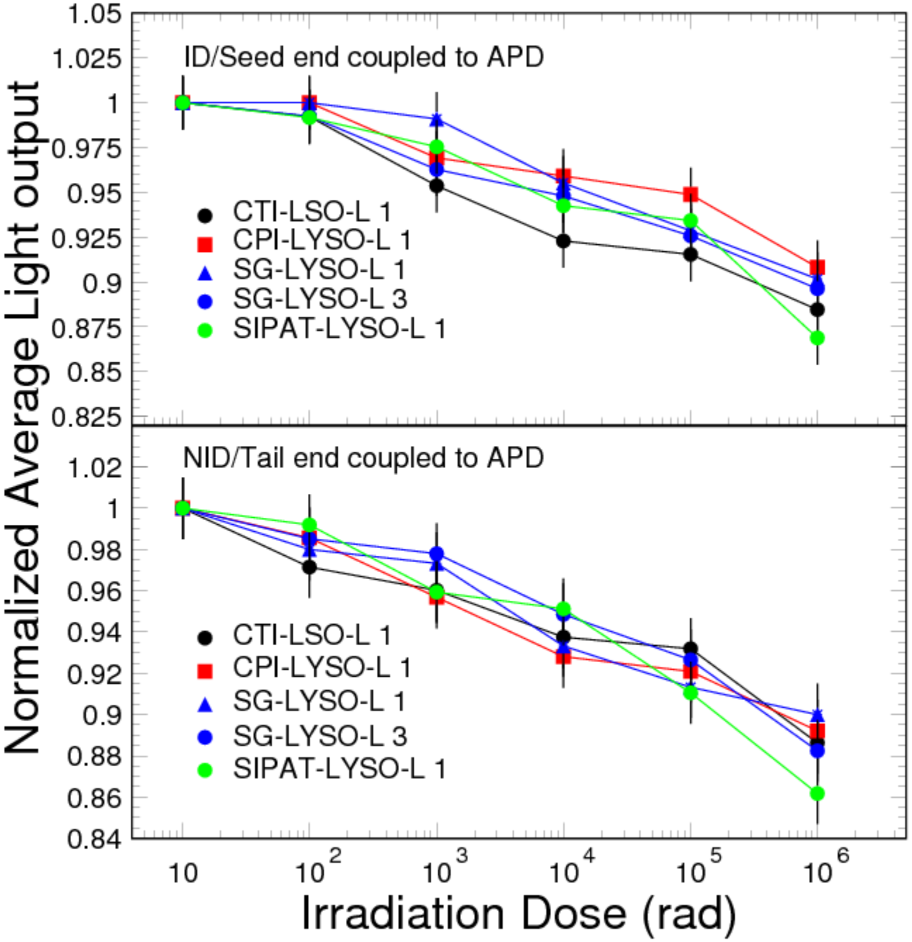
Comparison of L.O. Damage

All samples show consistent radiation resistance

10% - 15% loss by PMT



9% - 14% loss 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:

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

Summary

- Because of total absorption, 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.
- Progress has been made in understanding crystal radiation damage and improving qualities of mass produced crystals.
- An LSO/LYSO crystal calorimeter will provide excellent energy resolution over a large dynamic range down to MeV level for future HEP and NP experiments.
- Development of cost-effective materials is crucial for the homogeneous HCAL concept.