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

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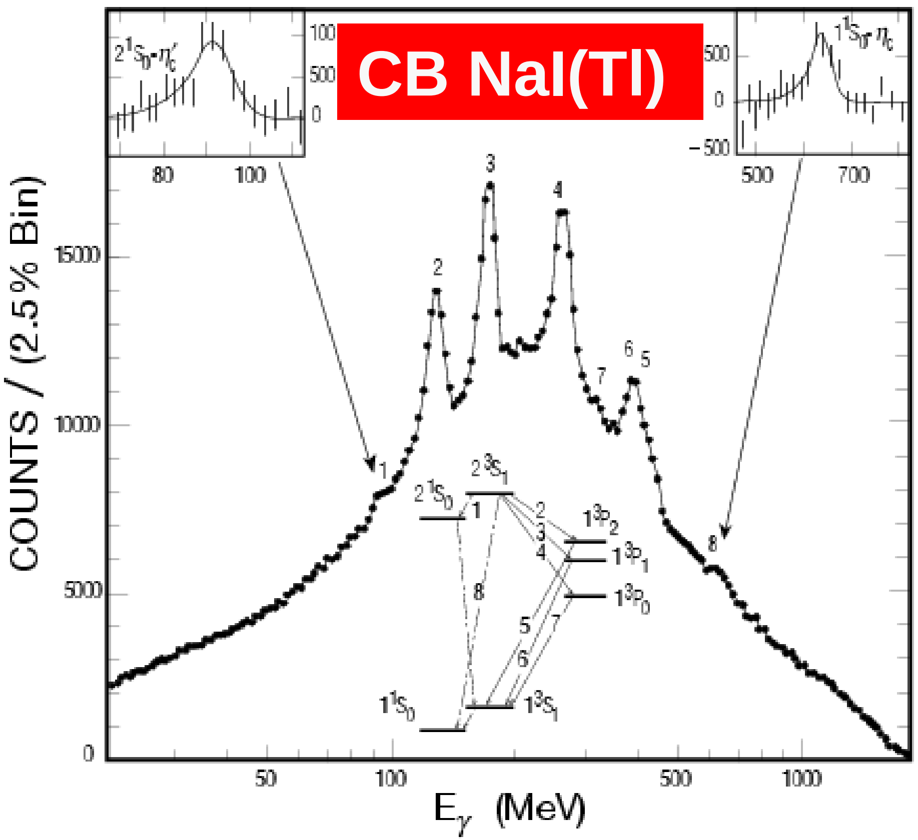
Why a Crystal Calorimeter

- Photons and electrons are fundamental particles in the SM and for new physics.
- Performance of a crystal calorimeter is well understood:
  - The best possible energy resolution, good position and photon angular resolution;
  - Good e/photon identification and reconstruction efficiency;
  - Good missing energy resolutions;
  - Good jet mass resolution.
- Precision e/γ: physics discovery potential.

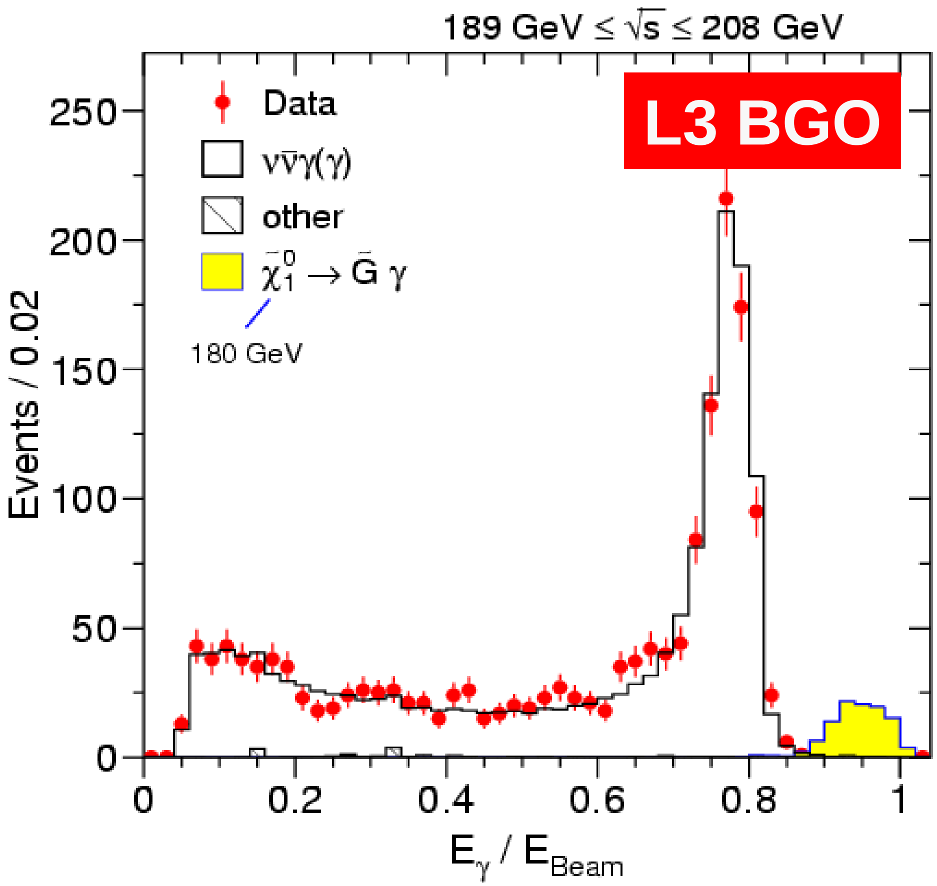
Physics with Crystal ECAL

Charmonium System Observed Through Inclusive Photons



SUSY Breaking with Gravitino

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



Single & Multi-Photons Physics

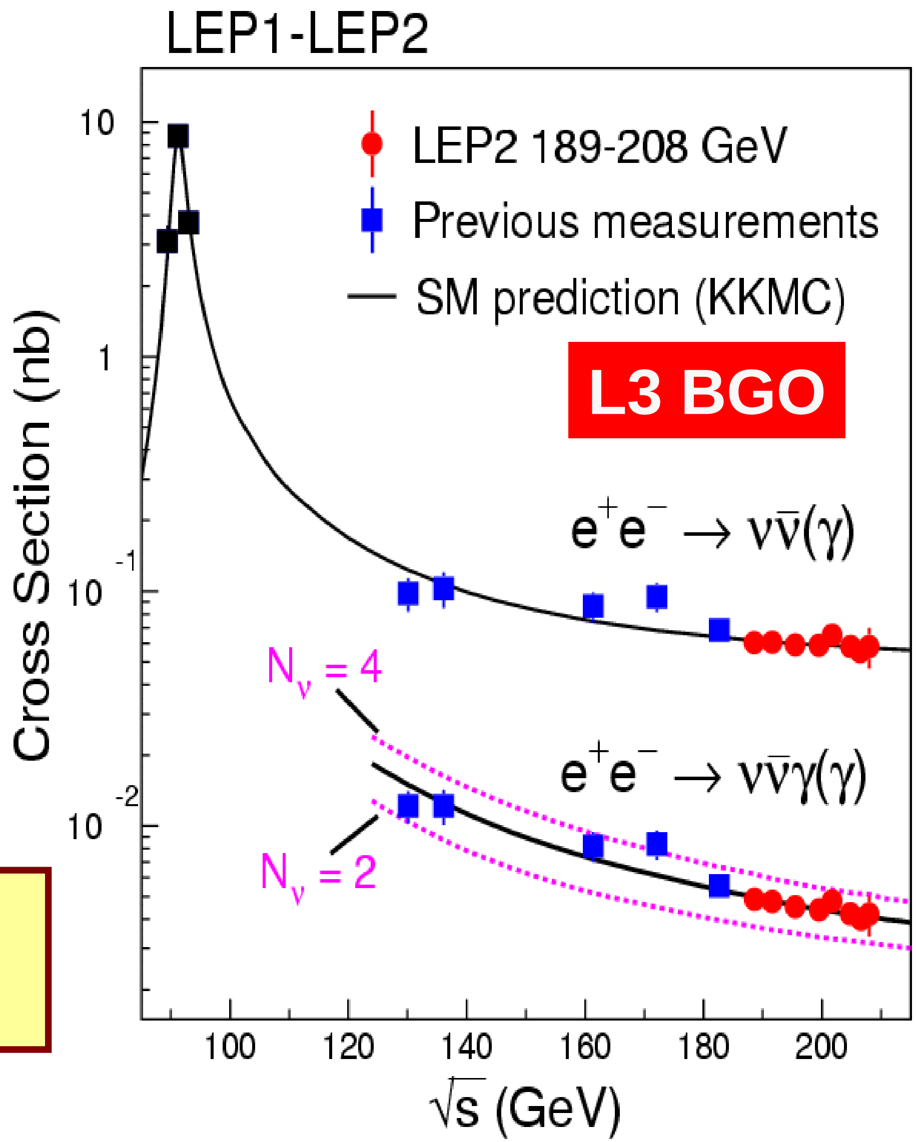
L3 BGO was the best ECAL at LEP
Efficiency ~ 73%
Purity ~ 99%:
Precision: 0.5% (RFQ calibration)
Best sensitivity at LEP

Physics Topics Include:

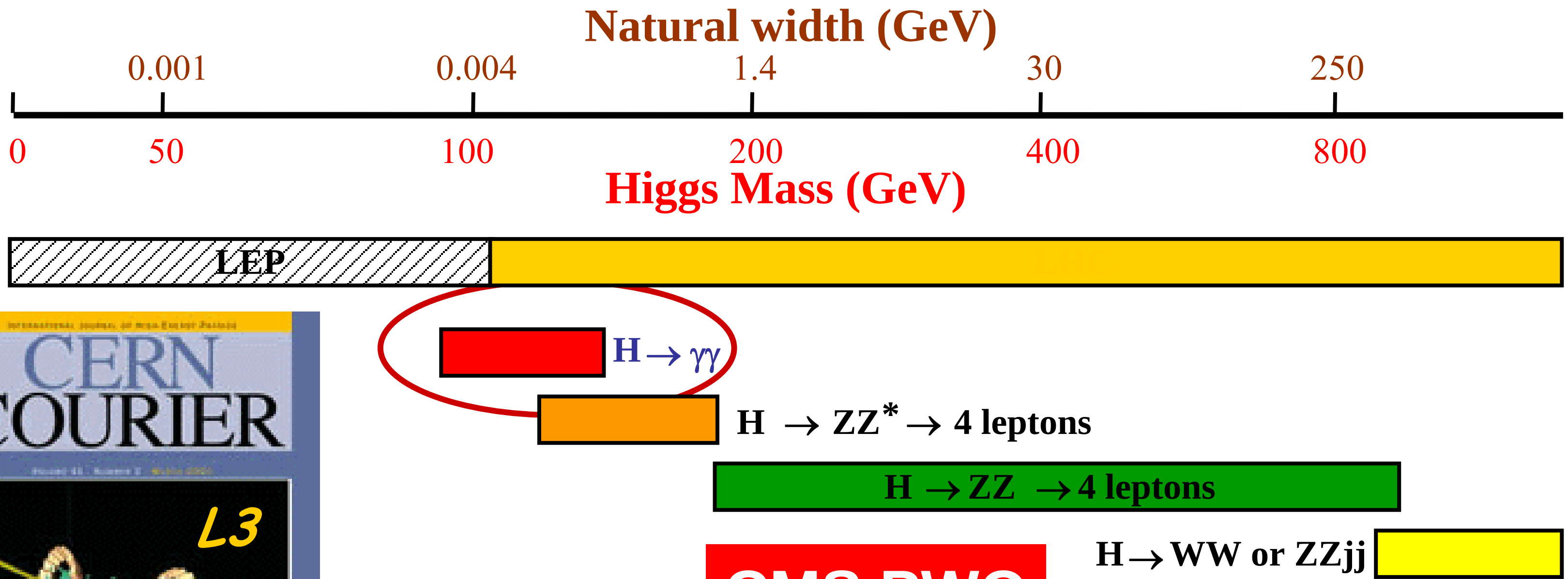
- ❒ Neutrino Production (SM)
- ❒ Extra Dimensions and SUSY
- ❒ Additional light neutrino flavors
- ❒ Anomalous gauge couplings through γ-W and γ-Z vertices

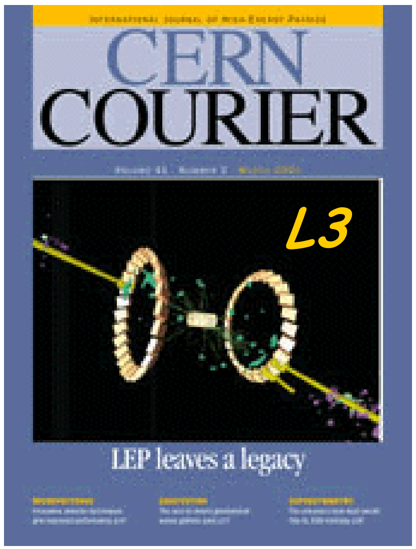
Number of neutrino species
$N_\nu = 2.98 \pm 0.06$

More precise than PDG'04

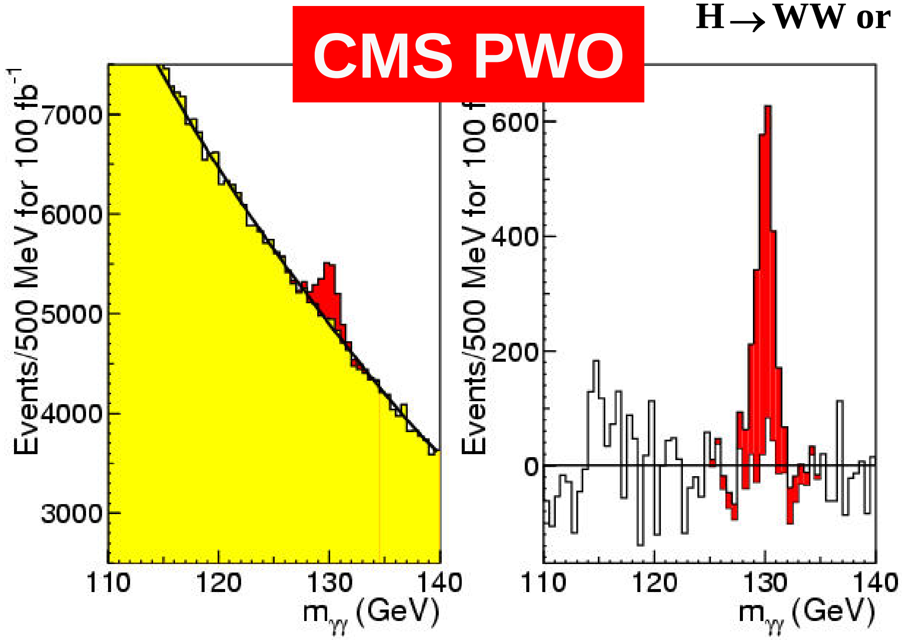


Higgs Hunt at LHC





LEP observed an excess of events around 115 GeV



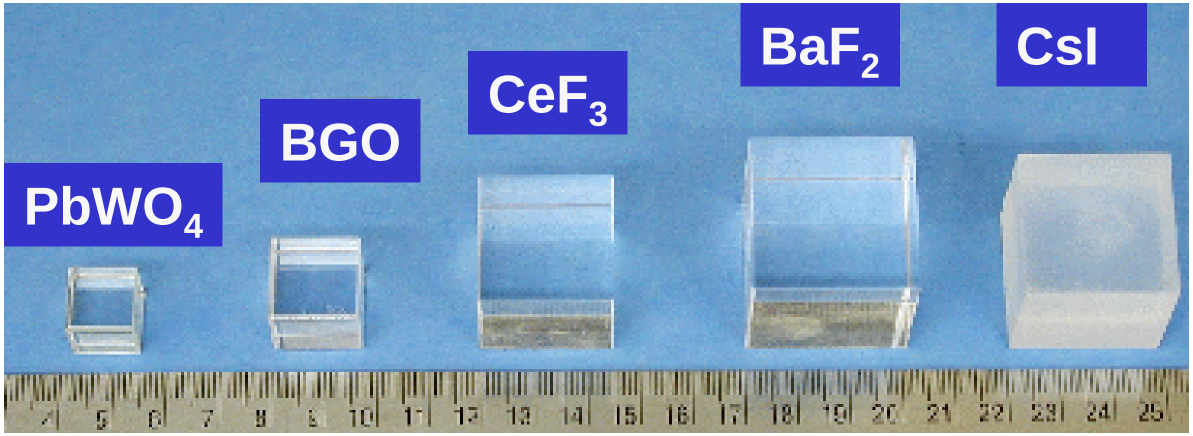
H → γγ signal in CMS ECAL @ design resolution

Mass Produced Crystals

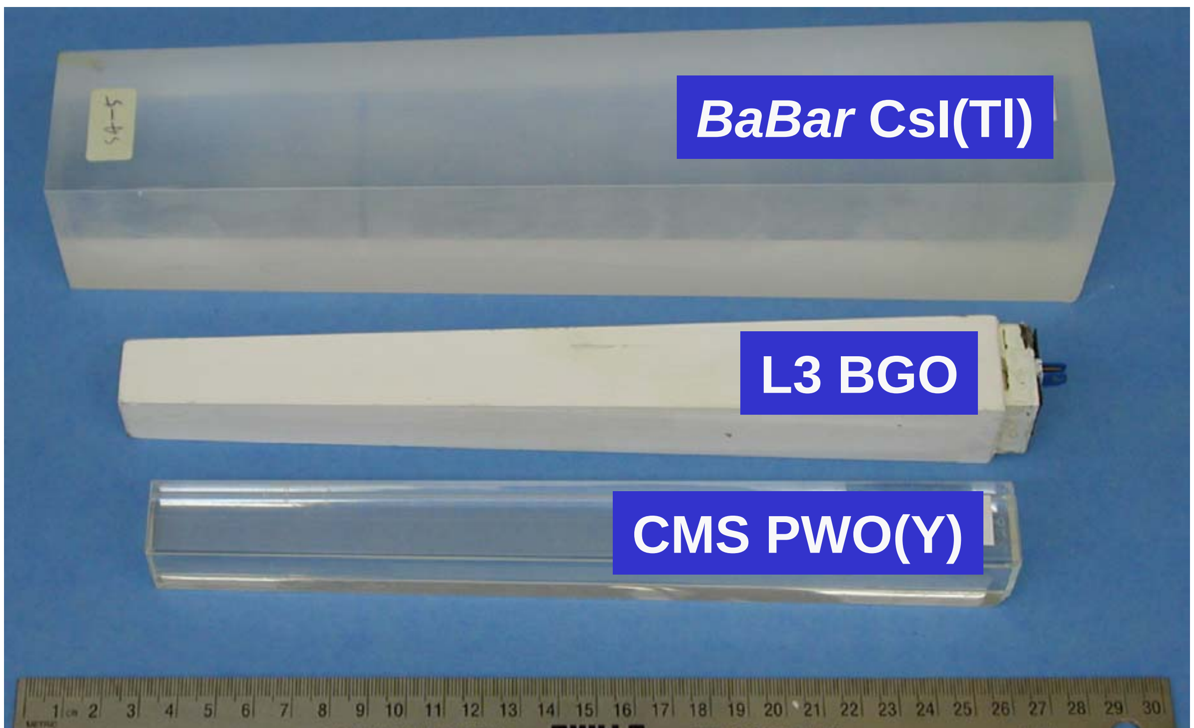
Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	$PbWO_4$	LSO(Ce)	GSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	8.3	7.40	6.71
Melting Point (ºC)	651	621	621	1280	1050	1123	2050	1950
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	0.89	1.14	1.38
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.00	2.07	2.23
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.7	20.9	22.2
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	2.20	1.82	1.85
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	560	420 310	300 220	480	560 420	420	440
Decay Time [b] (ns)	230	1300	35 6	630 0.9	300	50 10	40	60
Light Yield [b,c] (%)	100	45	5.6 2.3	21 2.7	13	0.1 0.6	75	30
d(LY)/dT [b] (%/ ºC)	~0	0.3	-0.6	-2 ~0	-1.6	-1.9	~0	-0.1
Experiment	Crystal Ball	CLEO BaBar BELLE BES III	KTeV	TAPS (L*) (GEM)	L3 BELLE PANDA?	CMS ALICE PANDA? (BTeV)…	-	-

a. at peak of emission; b. up/low row: slow/fast component; c. measured by PMT of bi-alkali cathode.

Crystal Density: Radiation Length



1.5 X_0 Cubic



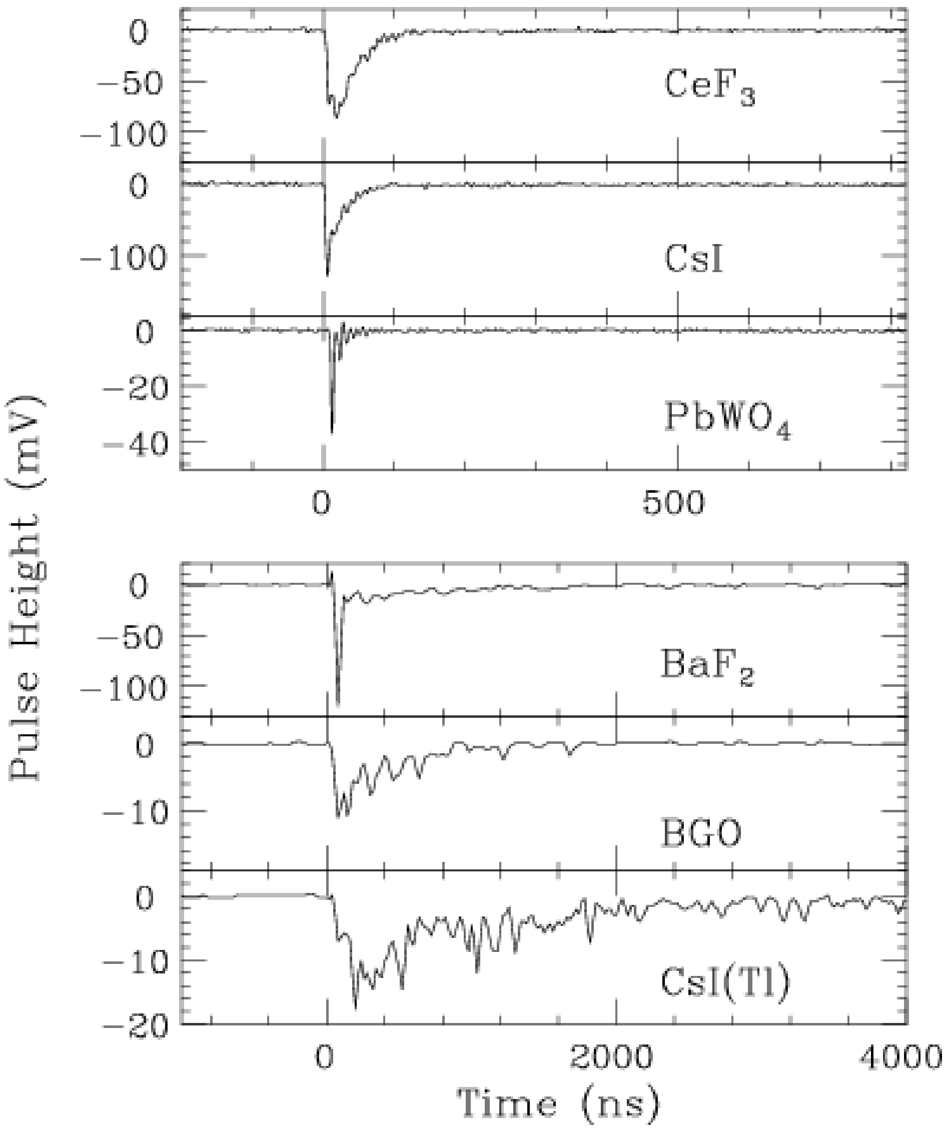
Full Size Samples

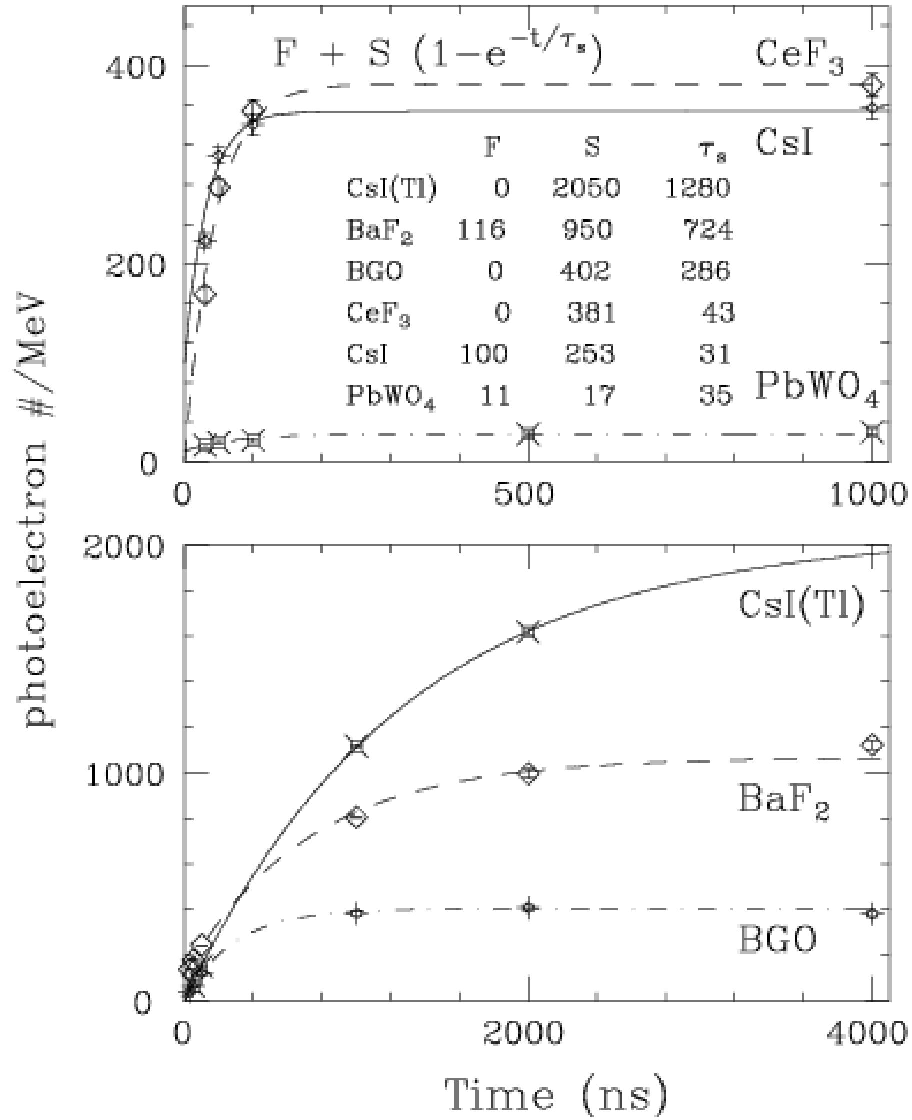
***BaBar* CsI(Tl): 16 X_0**

L3 BGO: 22 X_0

CMS PWO(Y): 25 X_0

Scintillation Speed: Decay Time





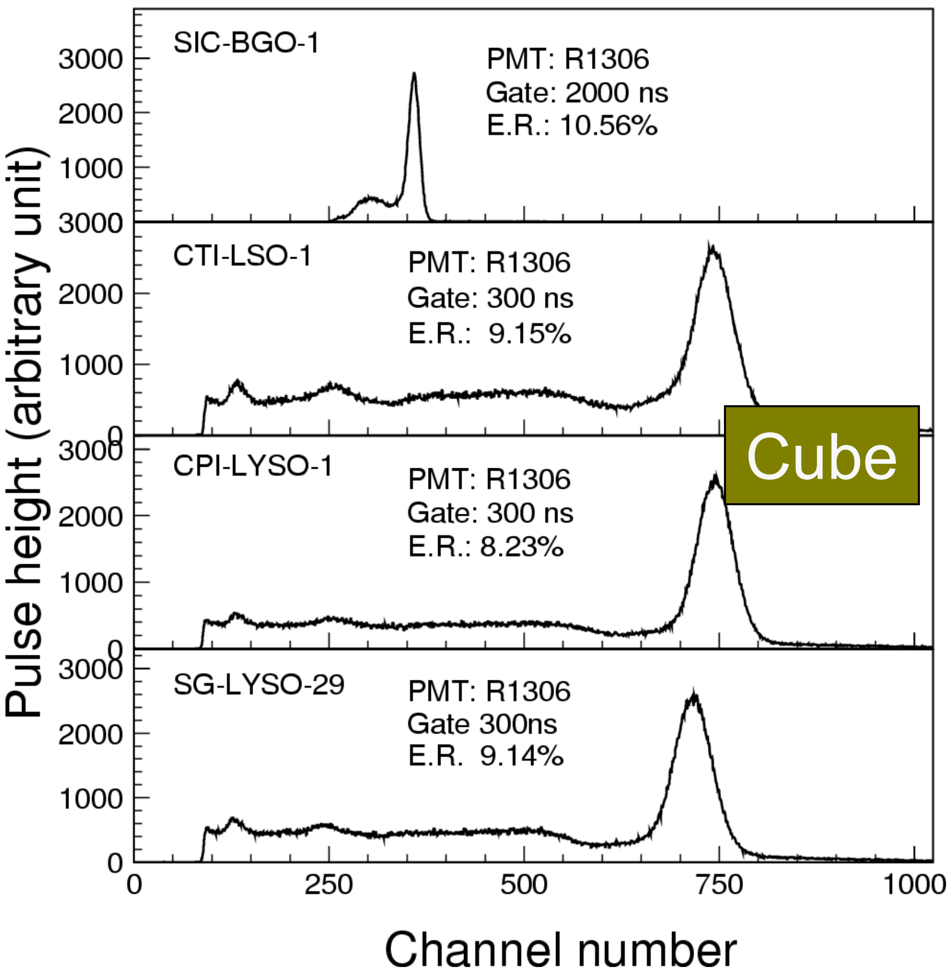
BGO, LSO & LYSO Samples

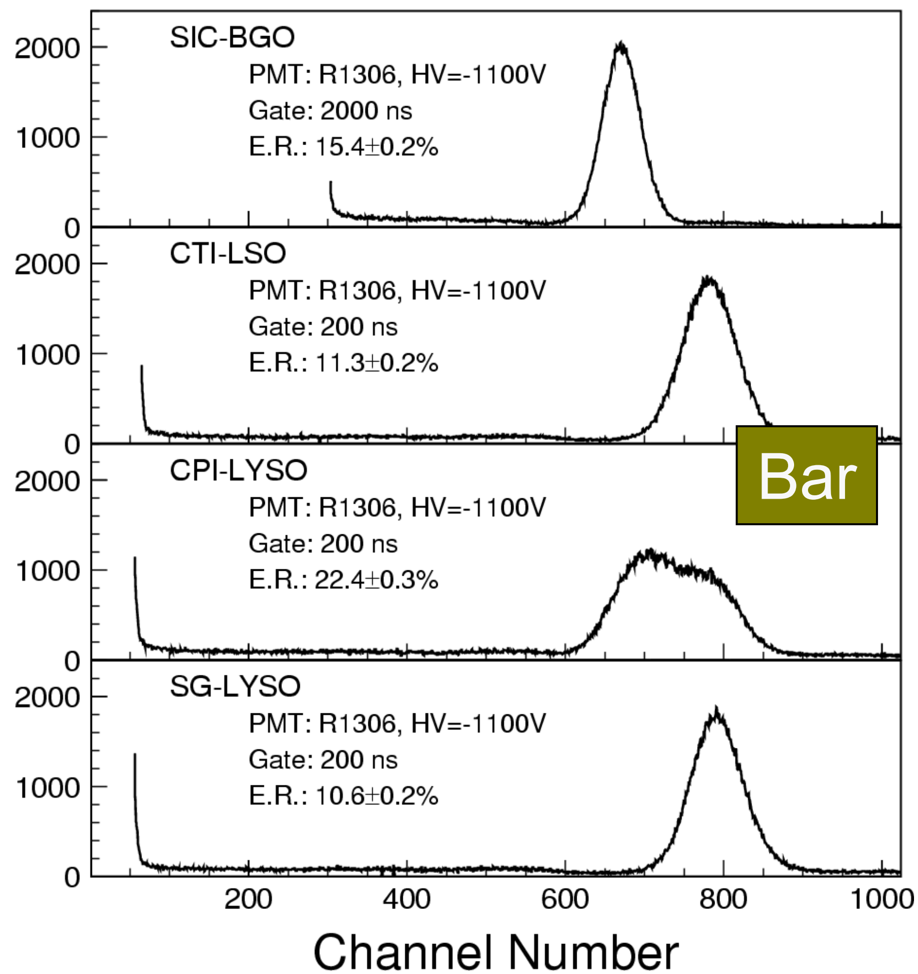
Cube: 1.7 X1.7 x 1.7 cm (1.5 X_0)
Bar: 2.5 x 2.5 x 20 cm (18 X_0)

^{137}Cs & ^{22}Na Pulse Height Spectra

Cube and bar samples have 8% and 10% FWHM resolution respectively for ^{137}Cs (0.66 MeV) and ^{22}Na source (0.51 MeV)

CPI LYSO bar has double peak because of poor annealing



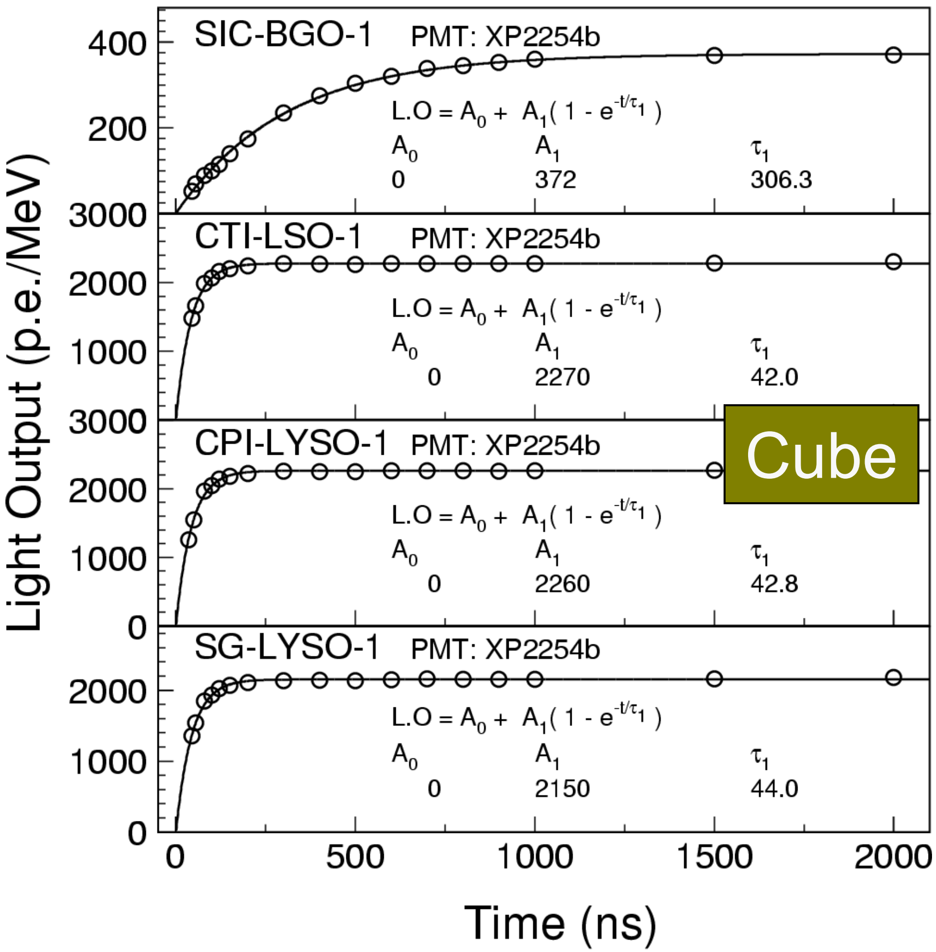


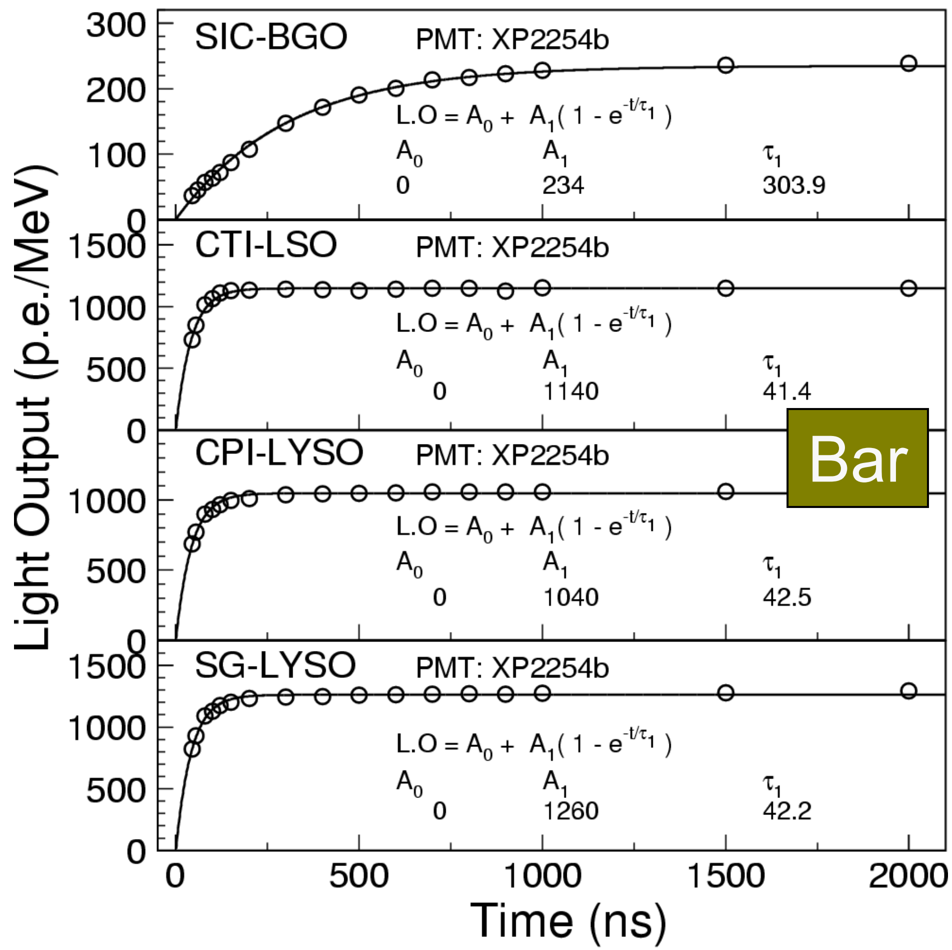
Light Output & Decay Time

LSO/LYSO Light yield: a factor of 6/100 of BGO/PWO

Bar sample has ~50% light of the cube sample

LSO/LYSO decay time: 42 ns compared to 300 ns of BGO

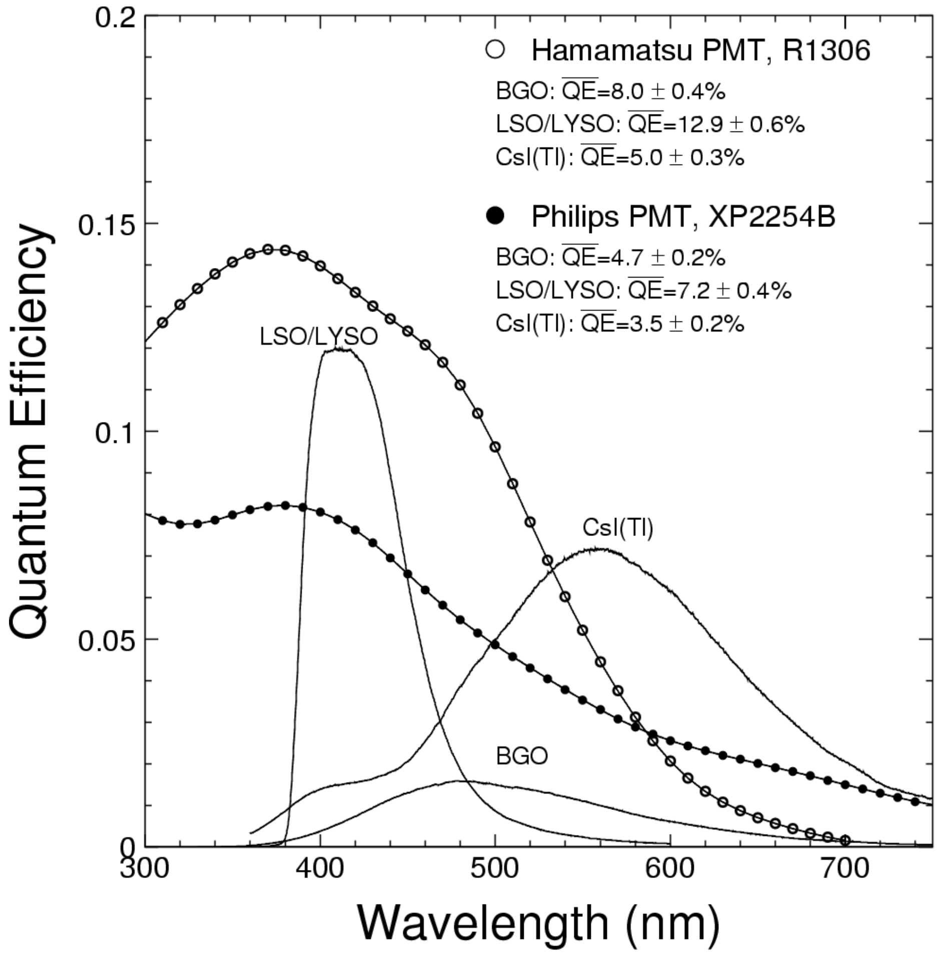


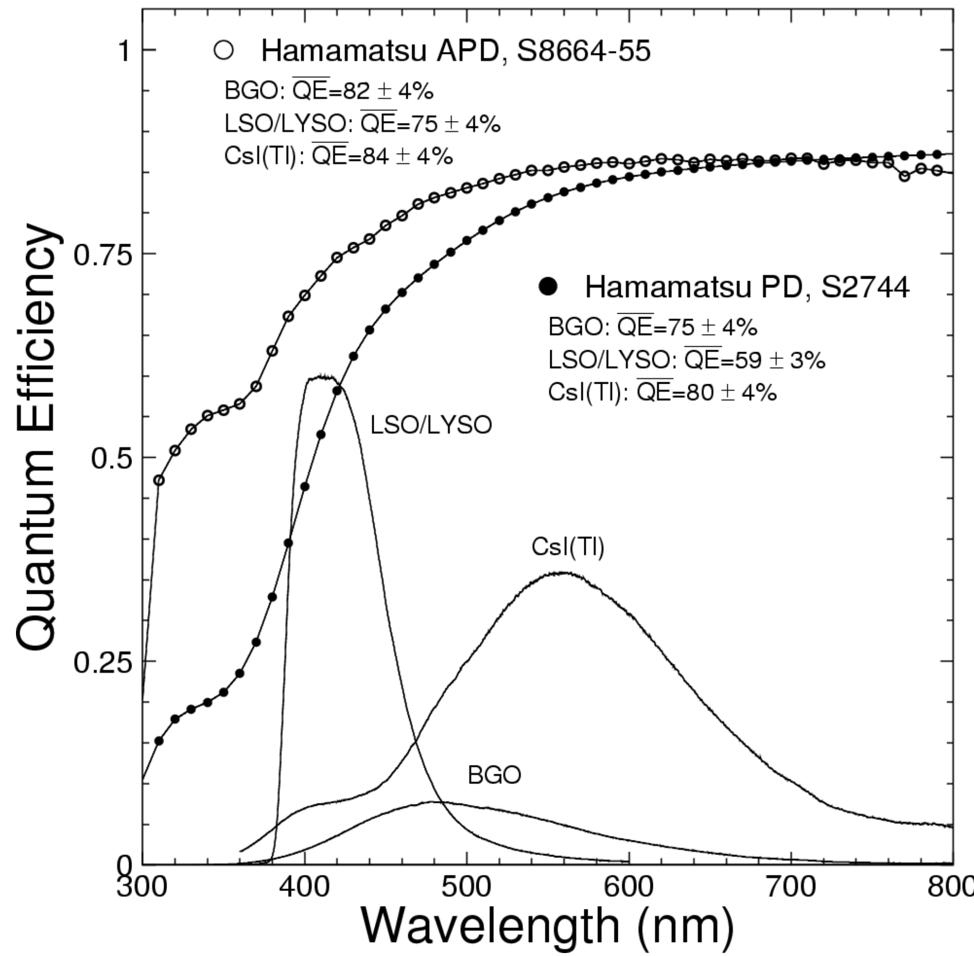


Emission Weighted Q.E.

Taking out PMT QE, LO of LSO/LYSO is 4 times BGO

Hamamatsu S8664-55 APD has QE 75% for LSO/LYSO



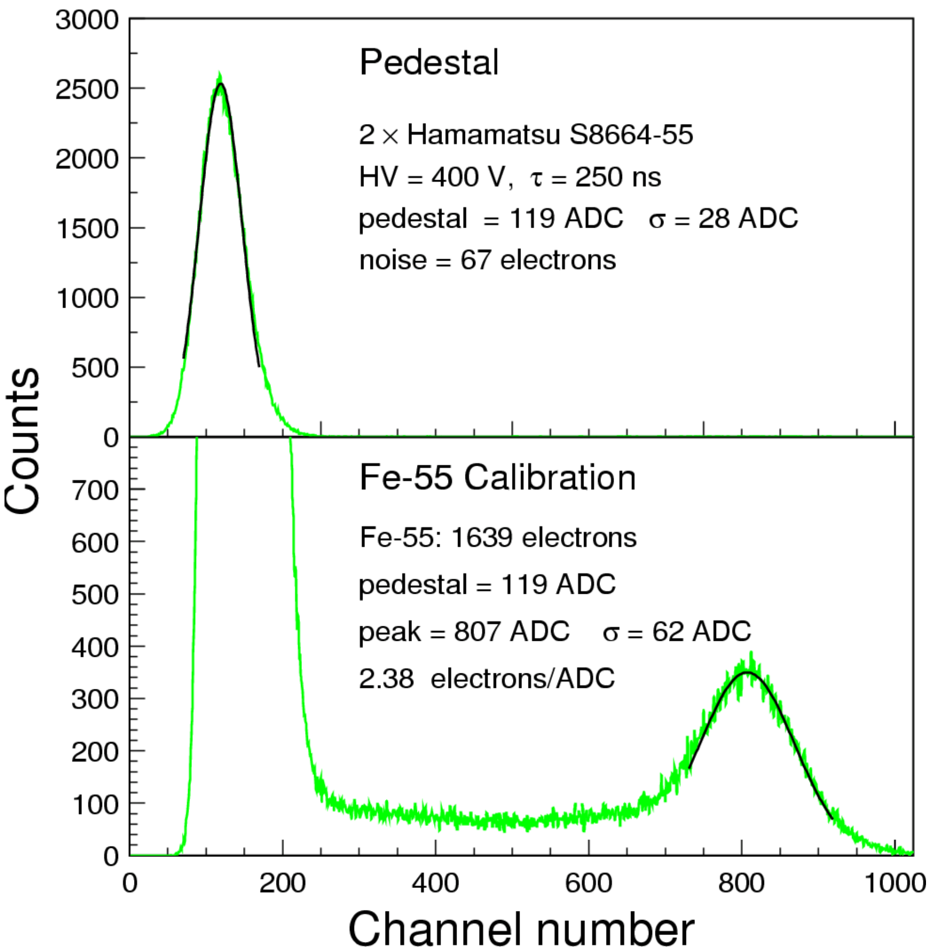


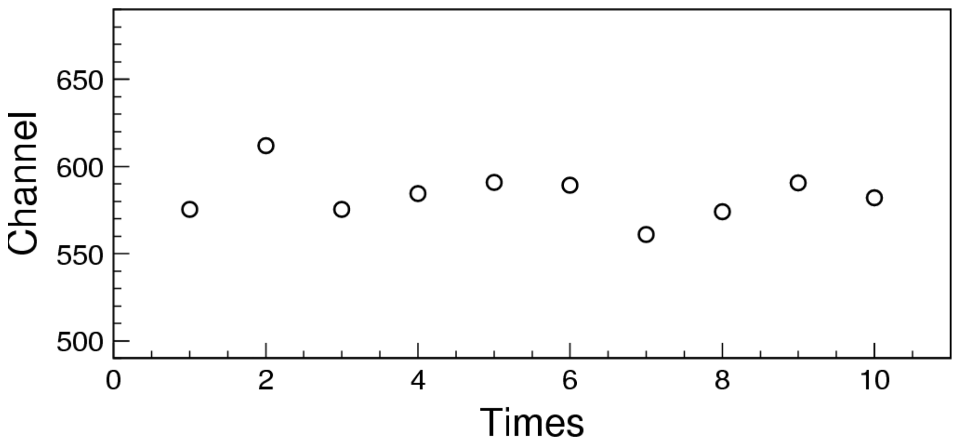
APD Readout Calibration

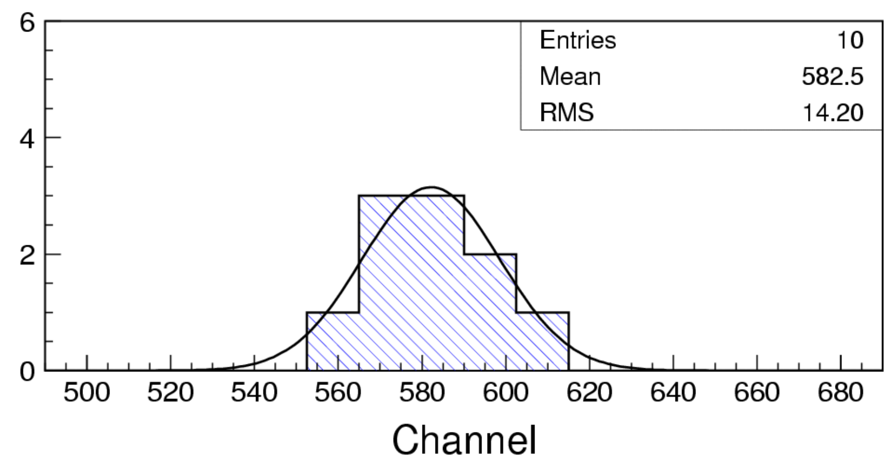
Calibration: 2.38 e/ADC for 2 Hamamatsu S8644-55 APD

Systematic error with repeated mountings & measurements: **2.4%**

Noise: 67 electrons, or ~30 keV for LSO/LYSO bar samples

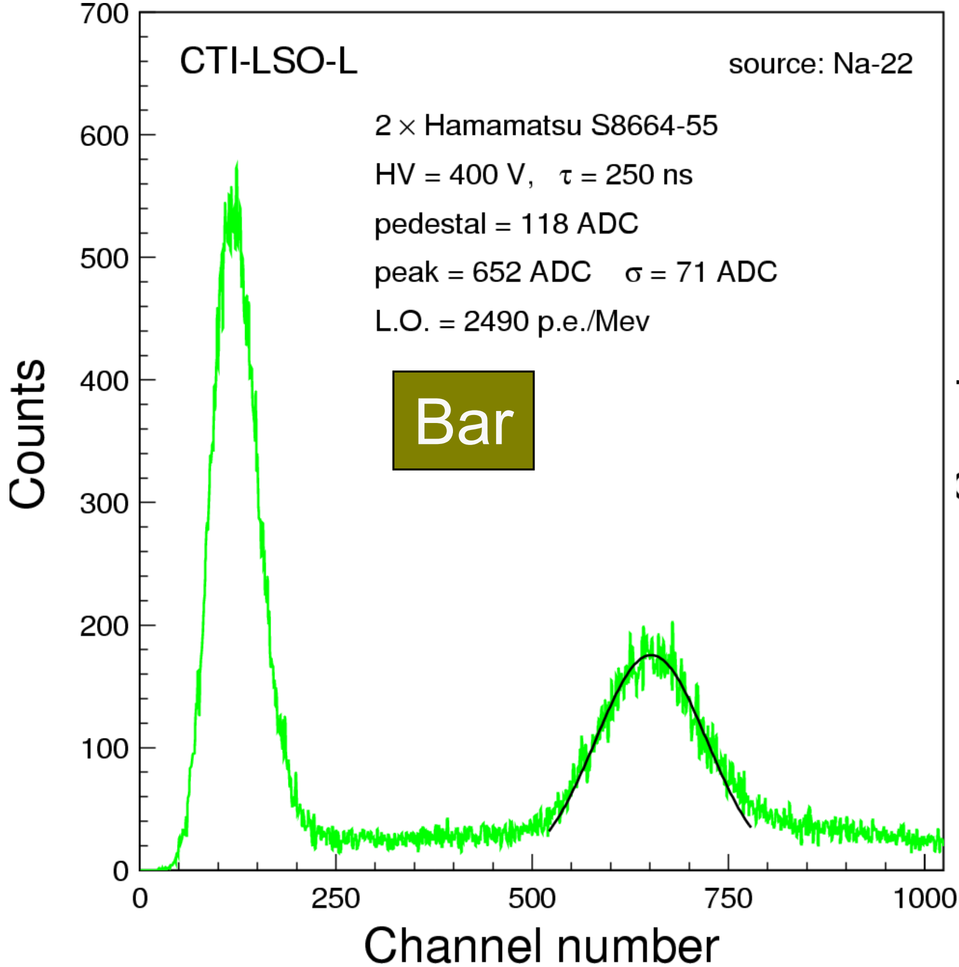


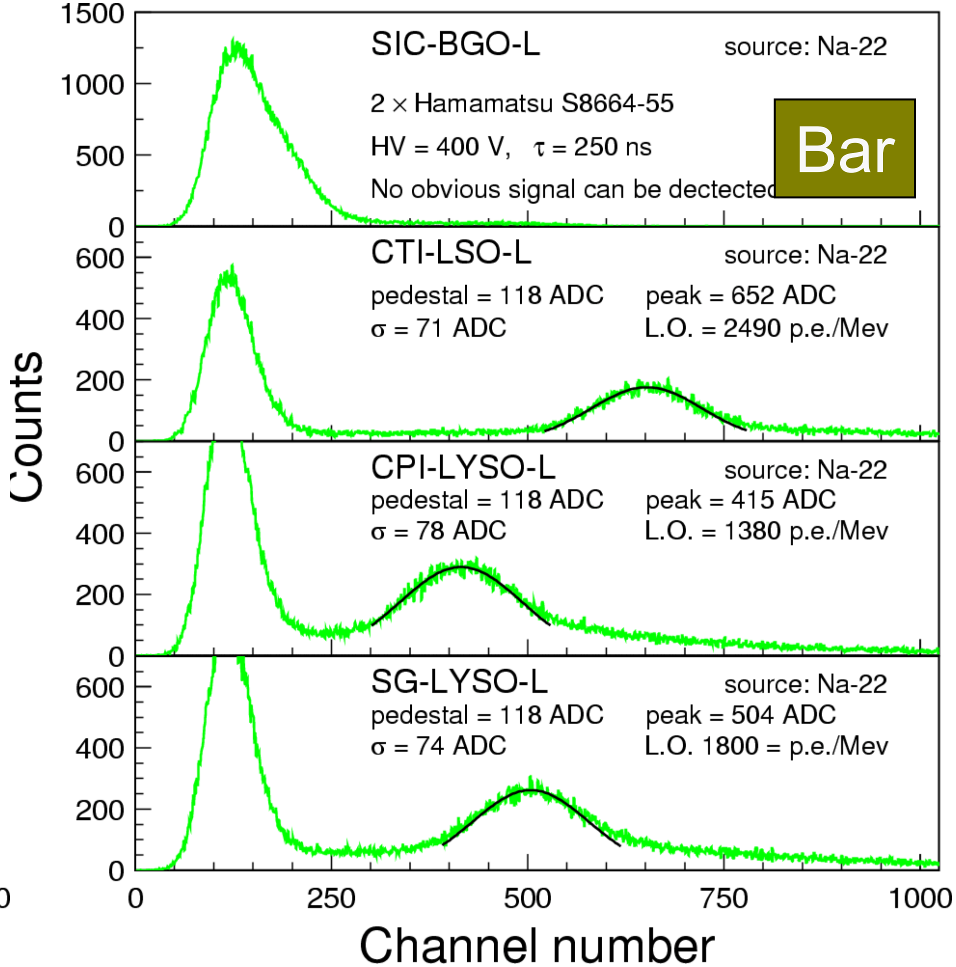




Pulse Height & Light Yield with APDs

Na-22 annihilation peak (510 keV) well measured
CTI LSO sample has significantly higher LO





Crystal Calorimeters in HEP

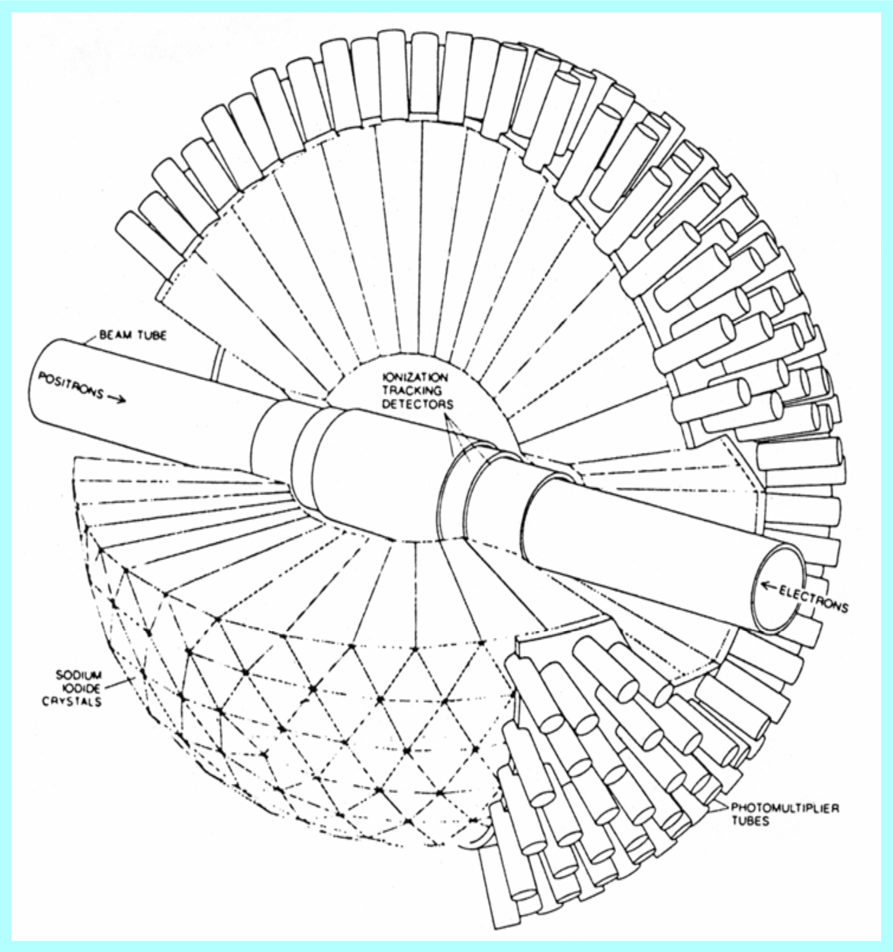
Date	75-85	80-00	80-00	80-00	90-10	94-10	94-10	95-20
Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	LEAR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	-	0.5	1.5	1.5	-	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	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

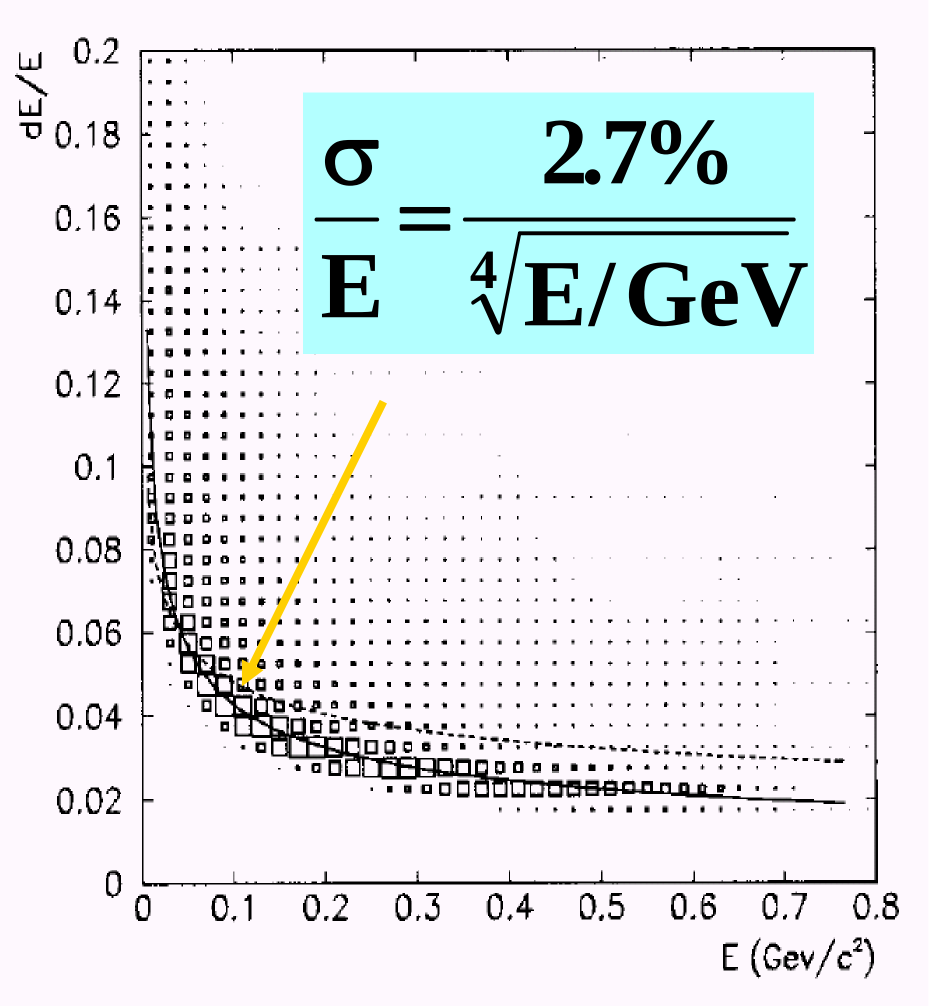
Future crystal calorimeters in HEP:

PANDA at GSI: PWO or BGO?

LSO/LYSO for the ILC and Super *BaBar*?

Crystal Ball Na(Tl) Resolution



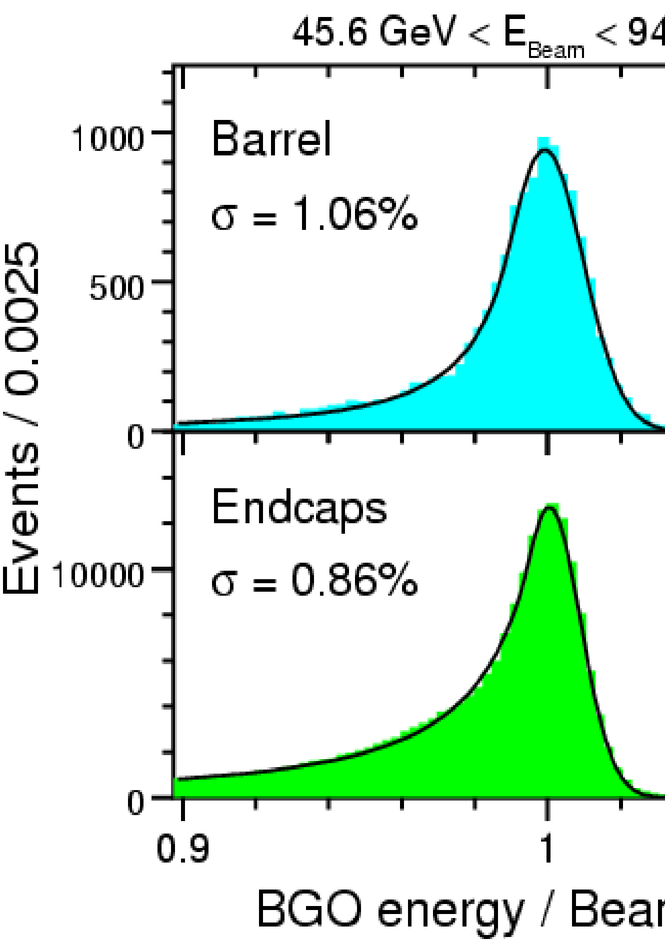


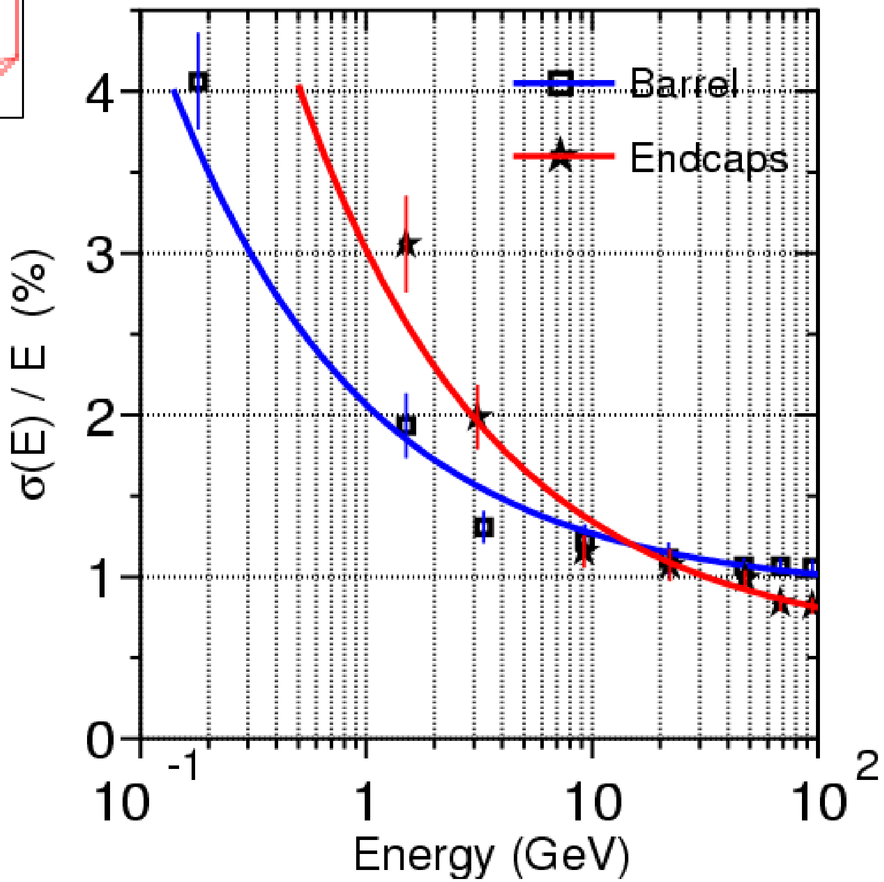
$$\frac{\sigma}{E} = \frac{2.7\%}{\sqrt[4]{E/\mathrm{GeV}}}$$

- 672 crystals cover 93% of solid angle
- Energy Resolution: 3.5% @ 300 MeV and 2.6% @ 1 GeV

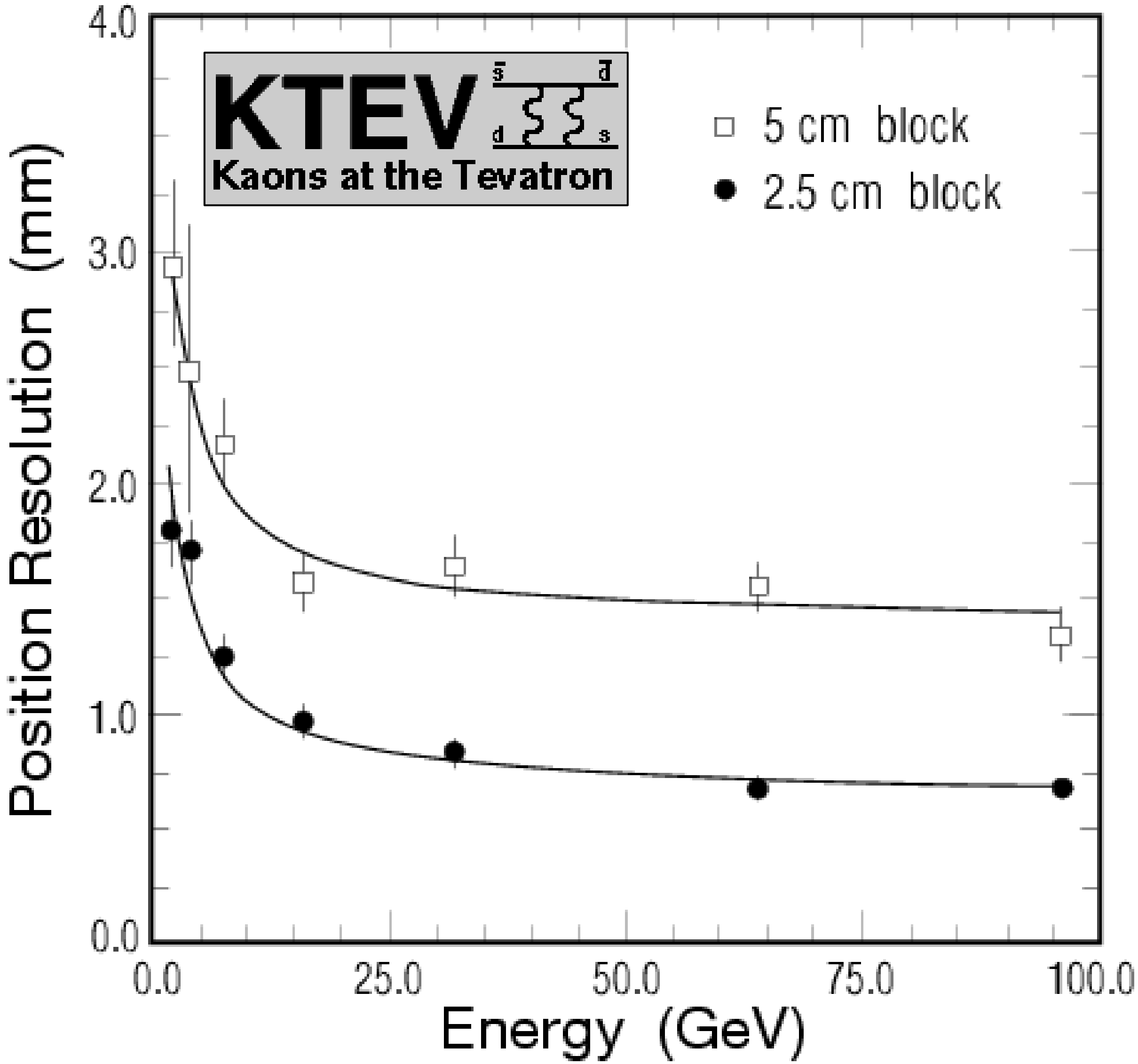
L3 BGO Resolution

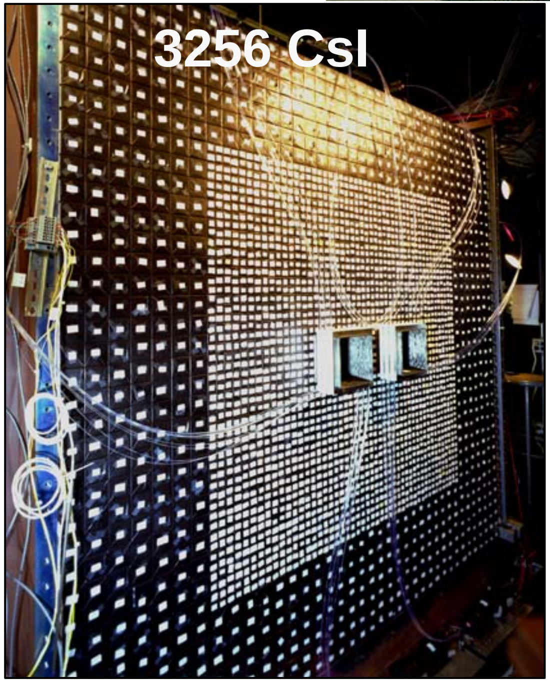
Contribution	"Radiative"+Intrinsic	Temperature	Calibration	Overall
Barrel	0.8%	0.5%	0.5%	1.07%
Endcaps	0.6%	0.5%	0.4%	0.88%





KTeV CsI Position Resolution



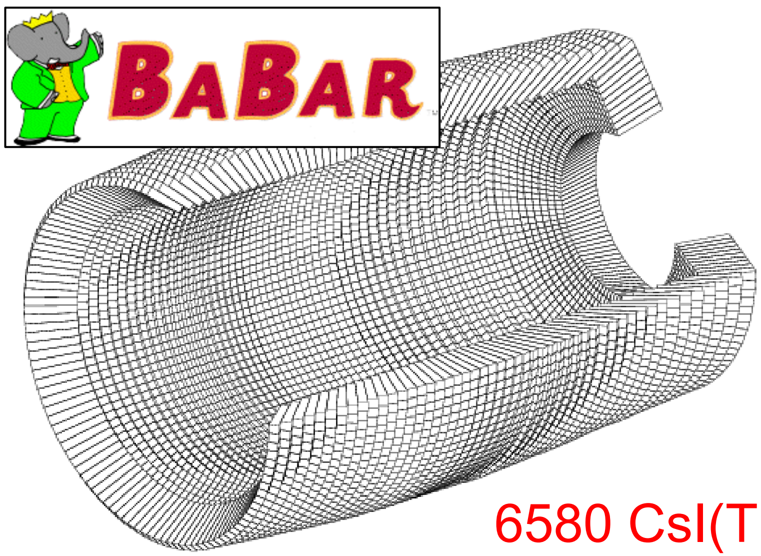


Sub mm position resolution at high energies.

L3 BGO & CMS PWO: 0.3 mm.

BaBar CsI(Tl) Resolution

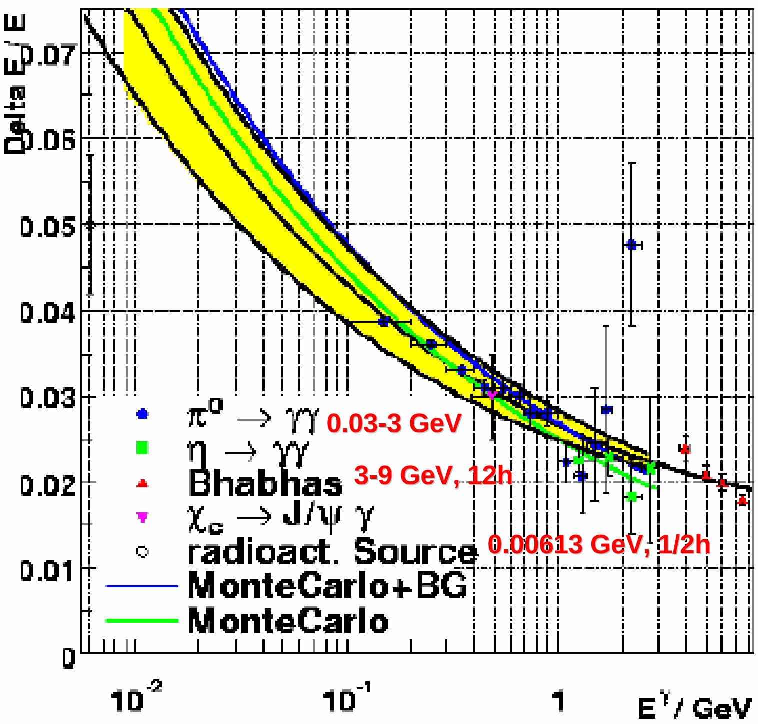
A crystal calorimeter at low energies



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

Energy resolution

M. Kocian, SLAC, CALOR2002



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

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

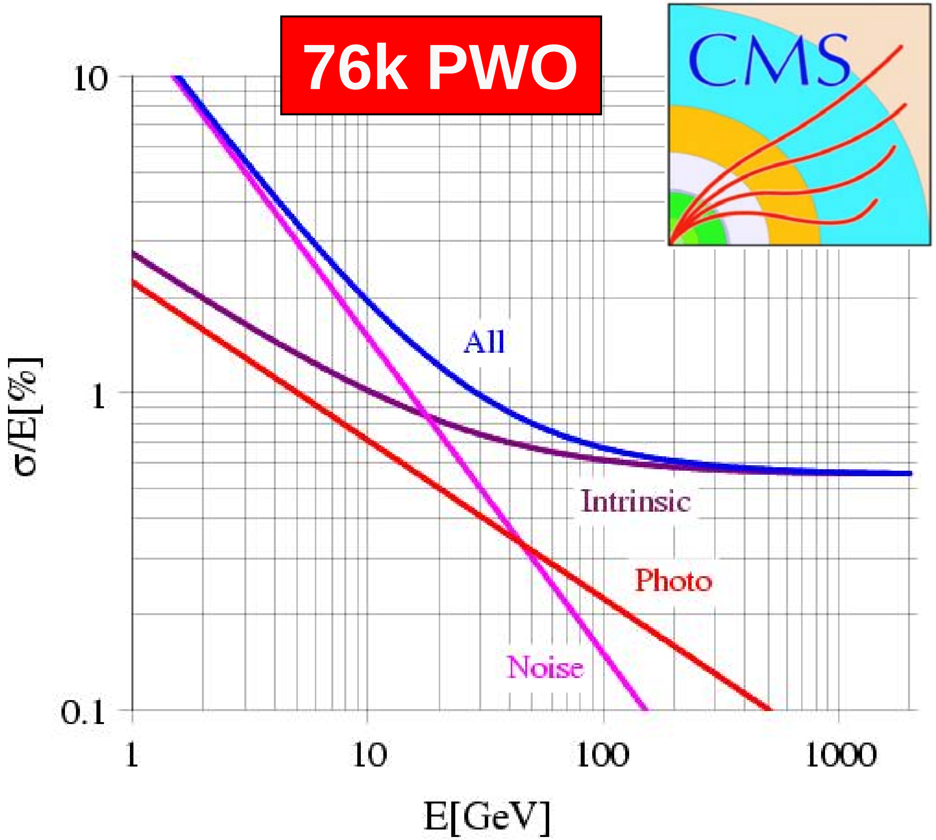
$$\sigma_2 = (1.35 \pm 0.08 \pm 0.2)\%$$

PWO Crystal ECAL Resolution

Aging and Radiation Damage?

Designed Resolution

76k PWO

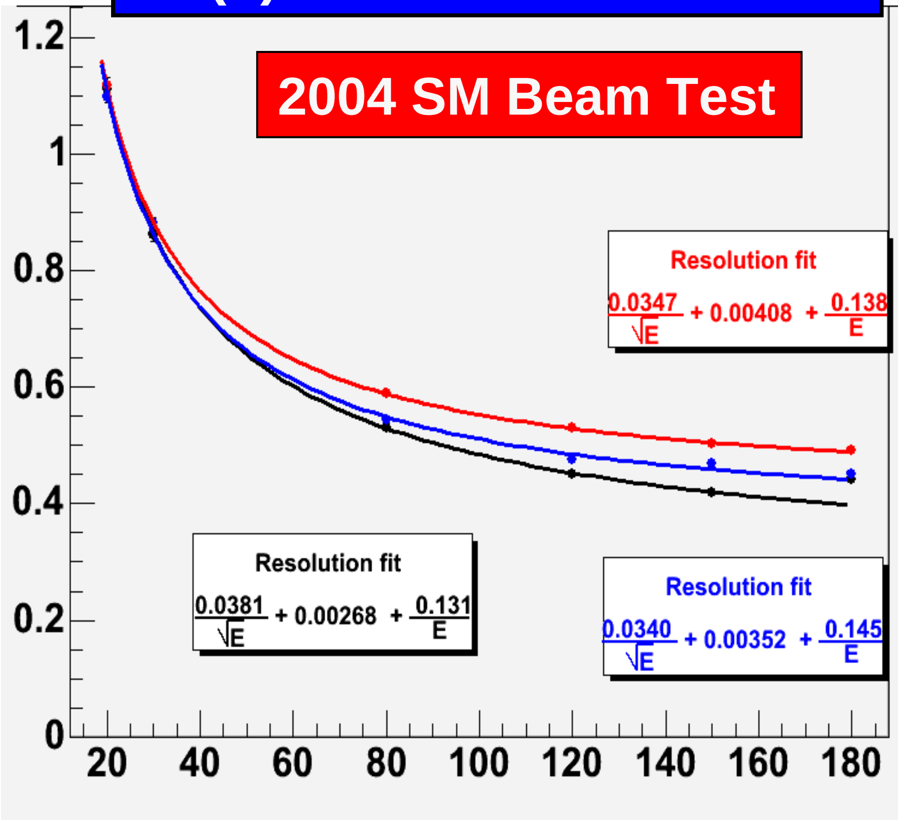


Measured Resolution

σ(E)/E < 1% if E > 25 GeV

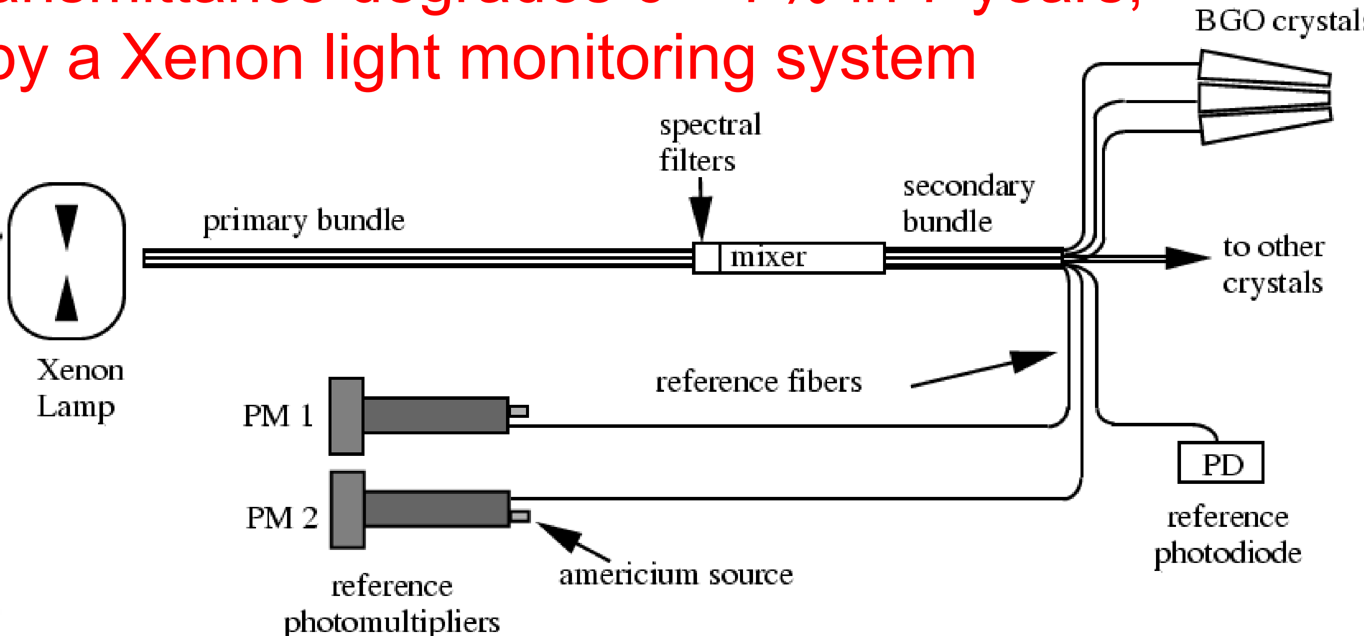
σ(E)/E ~ 0.5% at 120 GeV

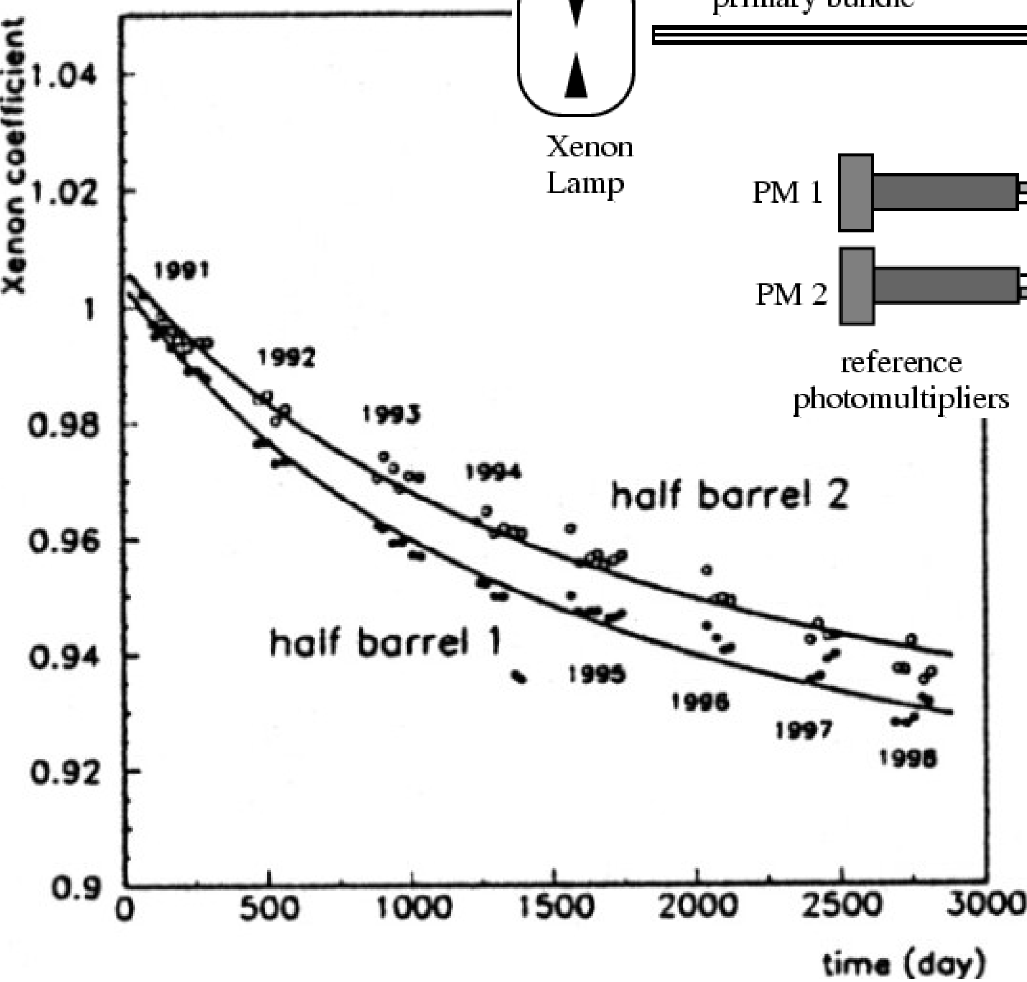
2004 SM Beam Test



BGO Degradation *in situ*

L3: BGO transmittance degrades 6 – 7% in 7 years, measured by a Xenon light monitoring system





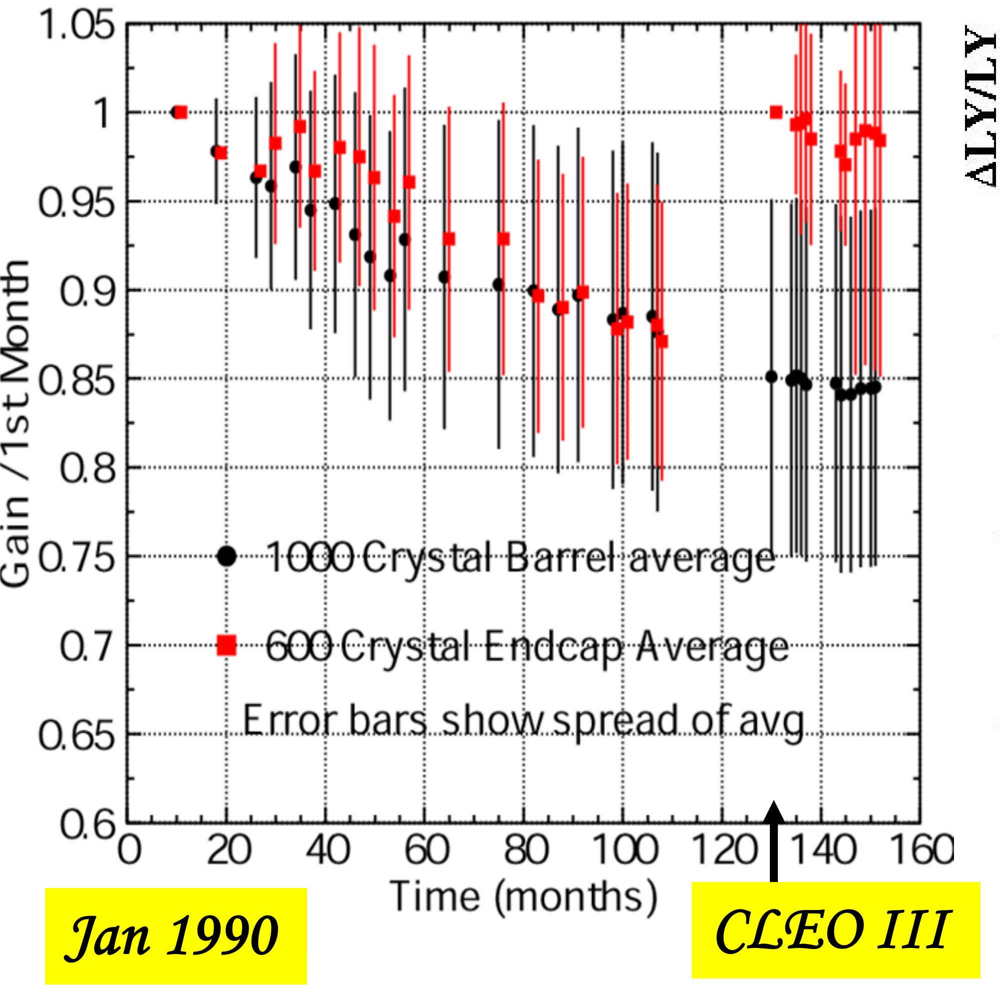
-pulsed light from Hamamatsu L2453 Xenon lamps;

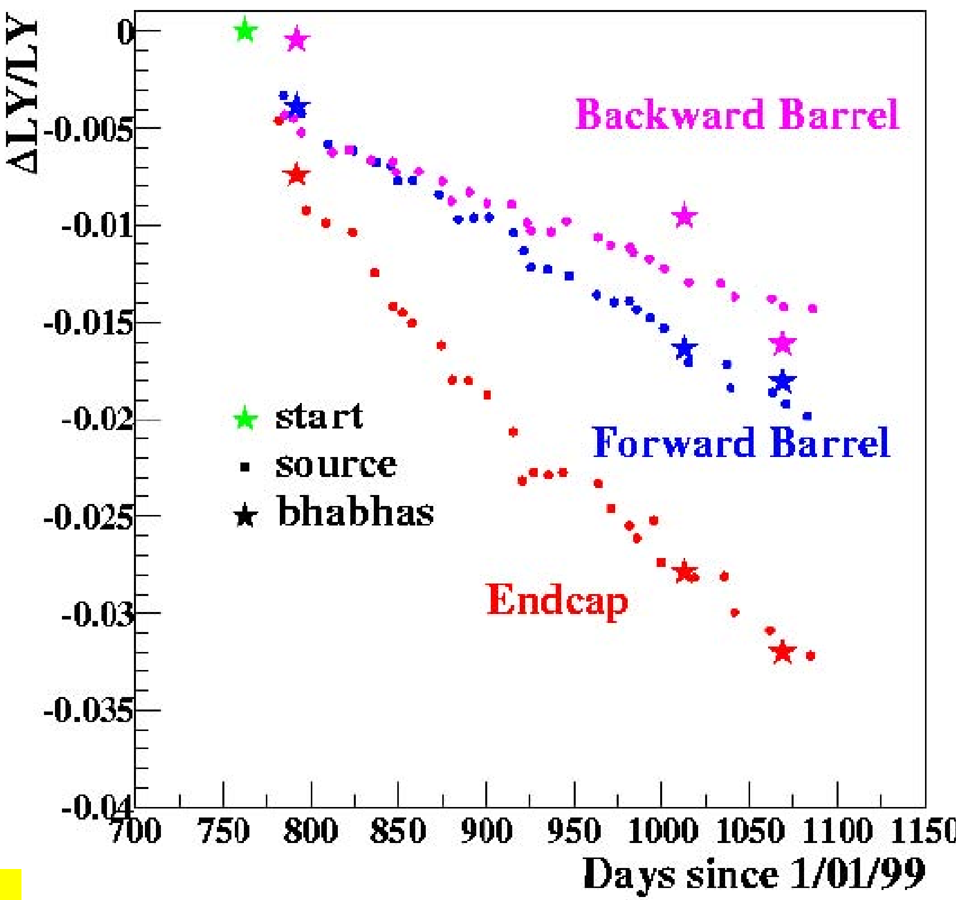
- two fibers per crystal crystal;

- response normalized to reference photo detectors.

CsI(Tl) Degradation *in situ*

CLEO: ~15 % over 12 years *BaBar* : 1 - 3 % per year





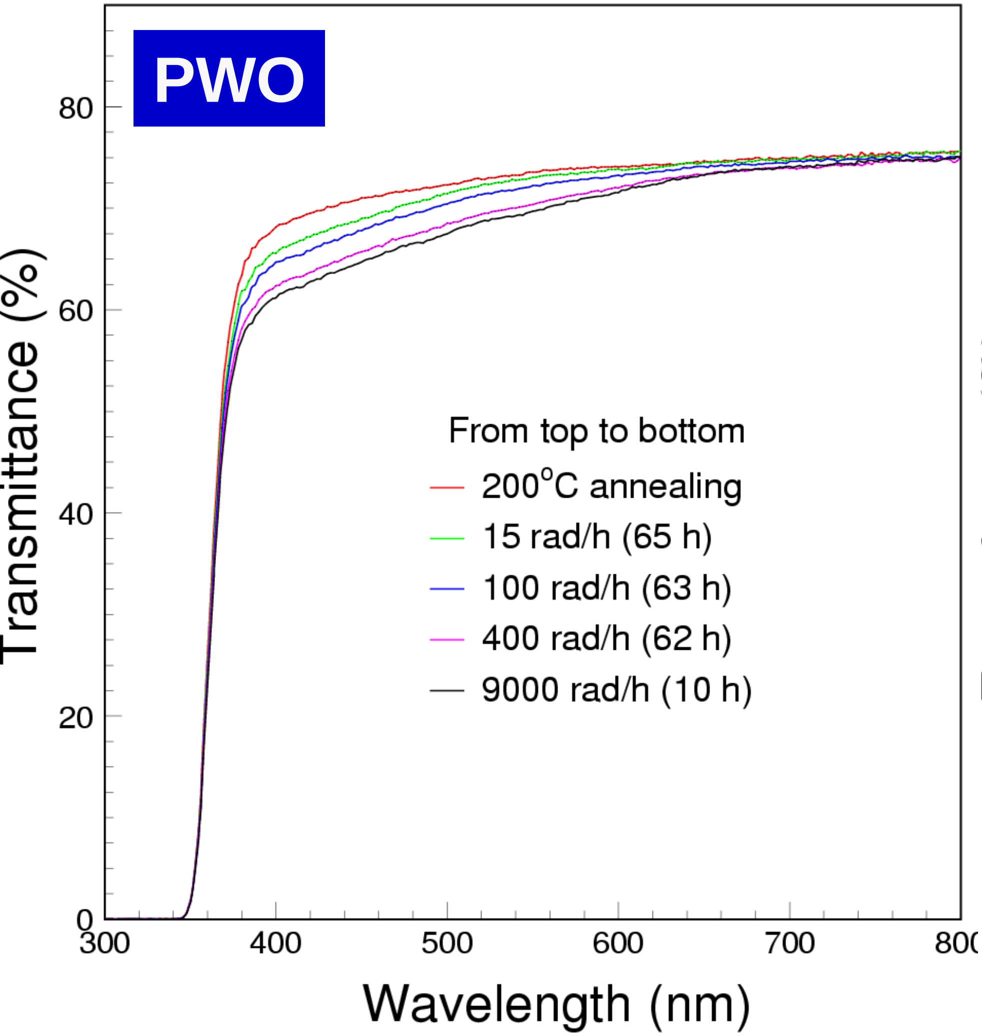
Possible Effects of Radiation Damage

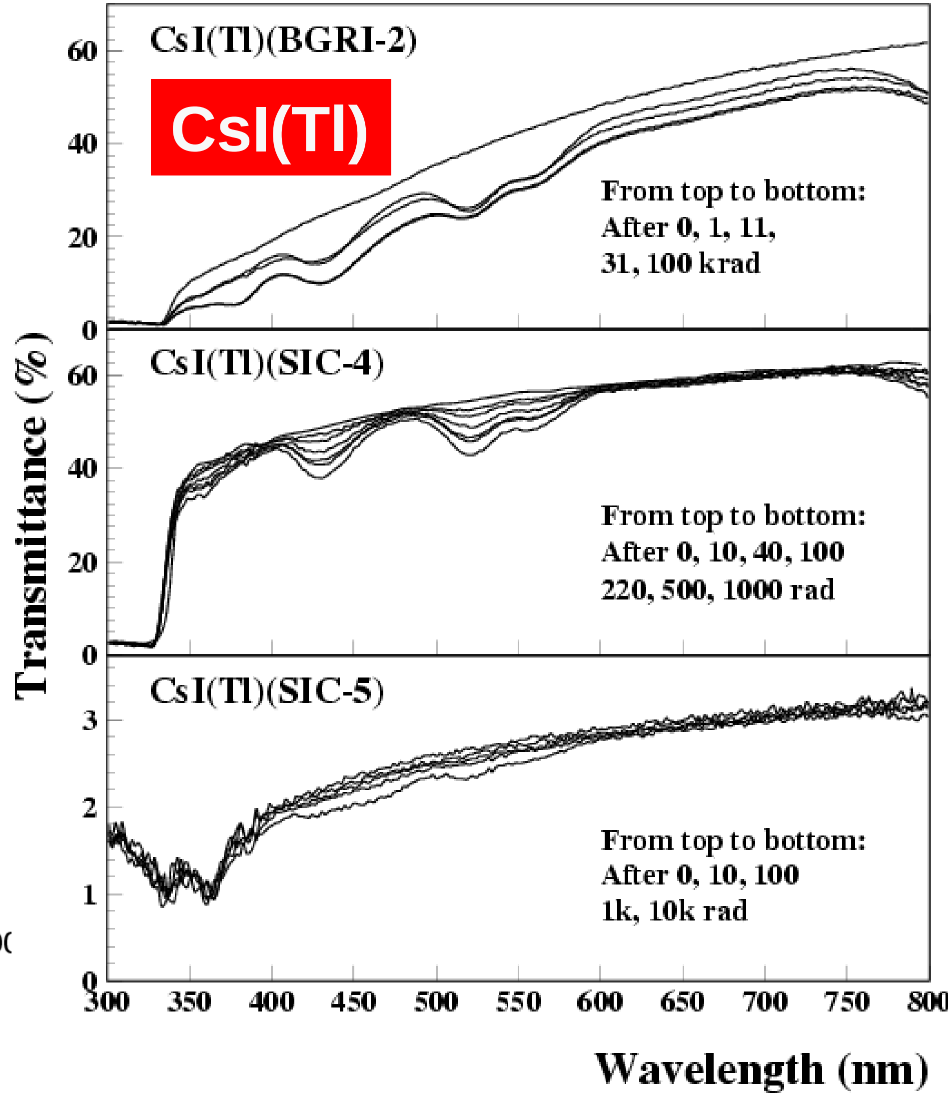
- Induced absorption caused by color center formation:
  - reduced light attenuation length and thus light output, and maybe
  - degraded of light response uniformity (LRU).
- Induced phosphorescence:
  - increase readout noise.
- Reduced scintillation light yield:
  - reduce light output and degrade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



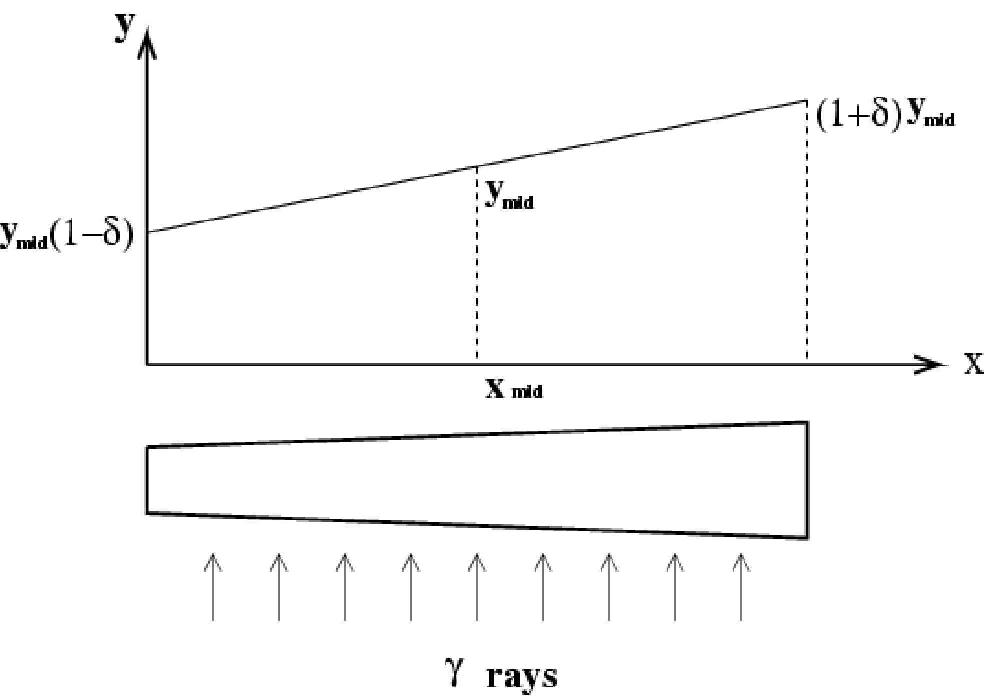


Light Response Uniformity (LRU)

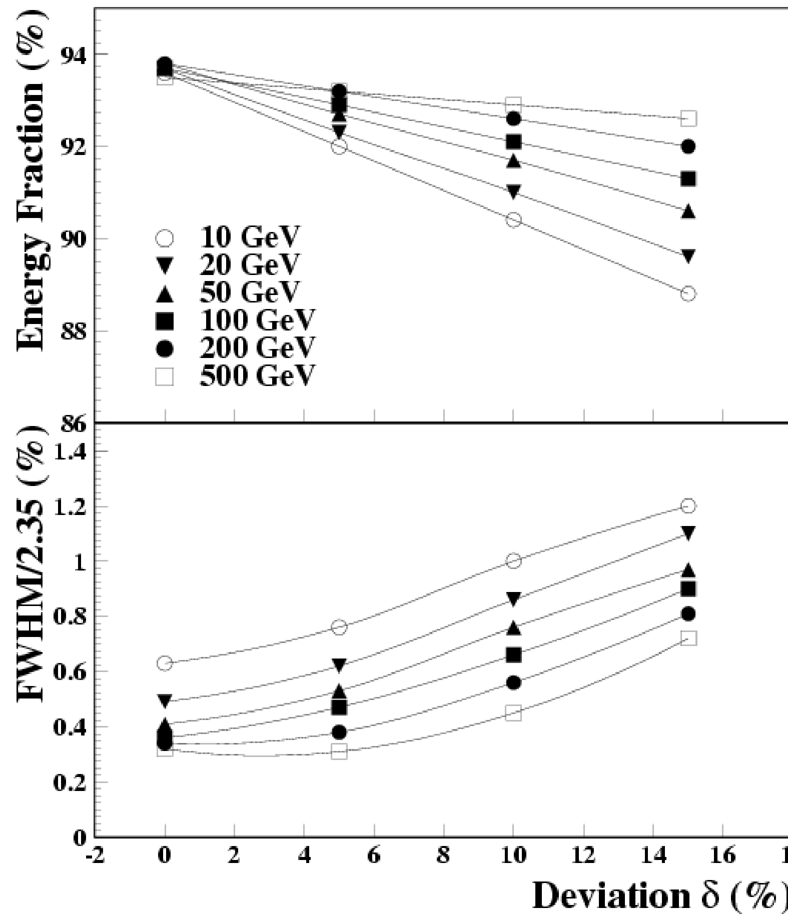
Nucl. Instr. And Meth. A340 (1994) 442

Definition

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



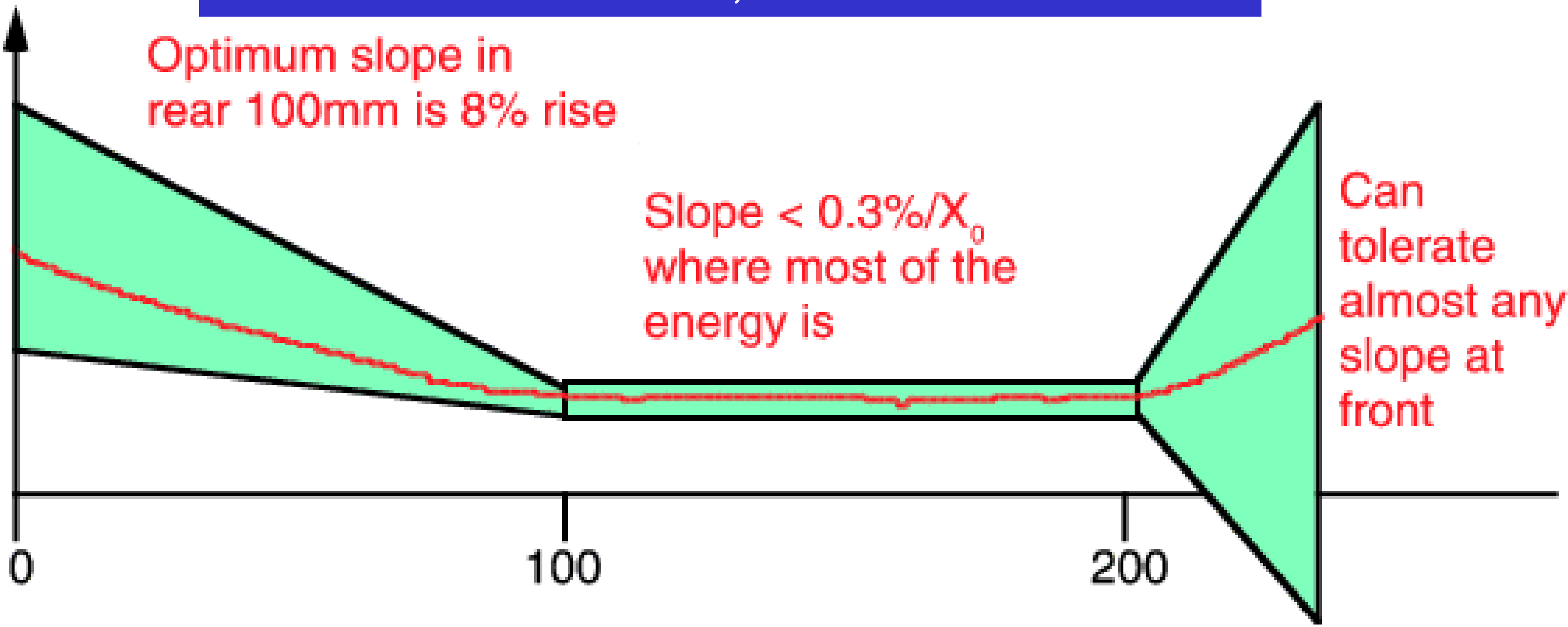
GEANT Simulation

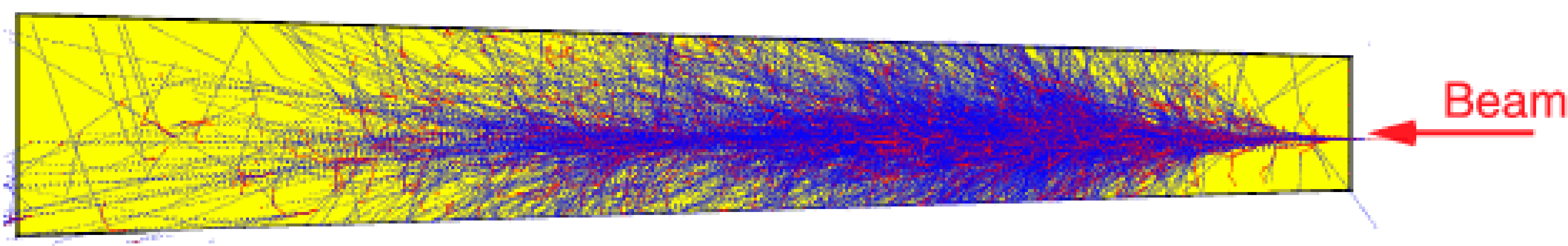


Resolution degradation is not recoverable if LRU is damaged

CMS Specification to the LRU

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





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

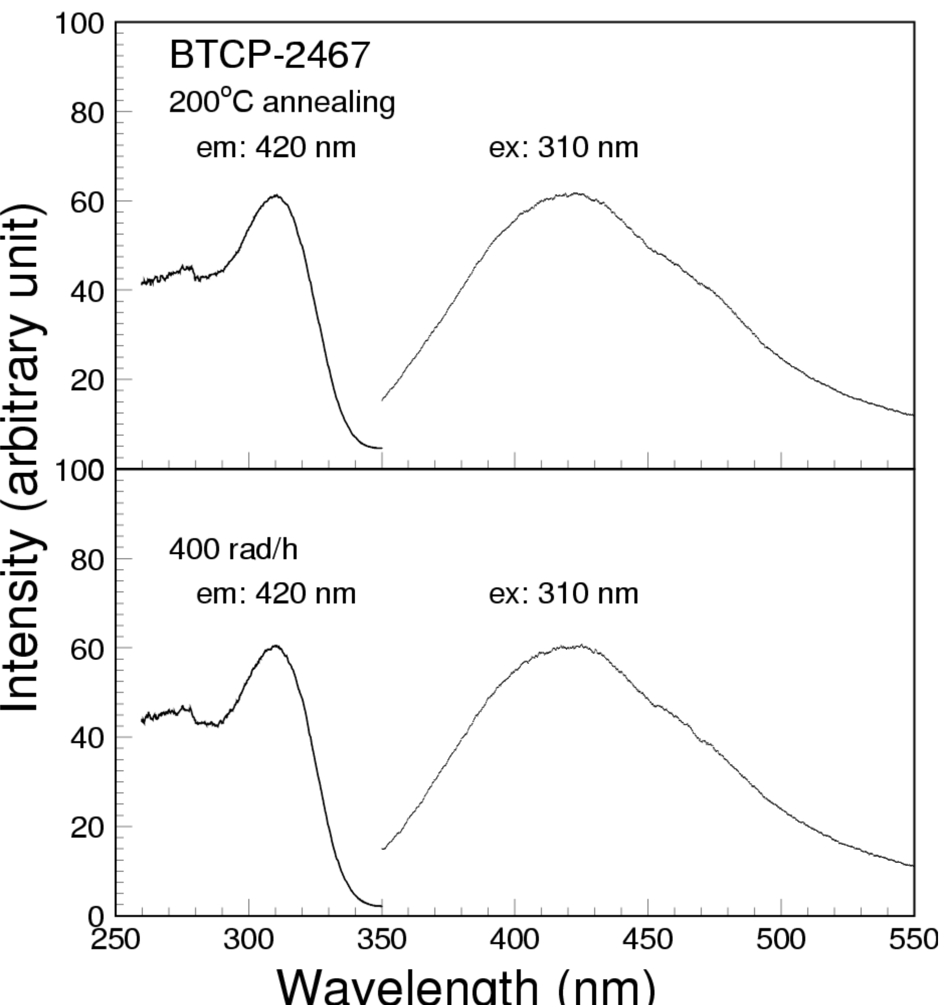
Light collection efficiency, fit to a linear function of distance to the small end of the crystal, was determined with two parameters: the light collection efficiency at the middle of the crystal and the uniformity.

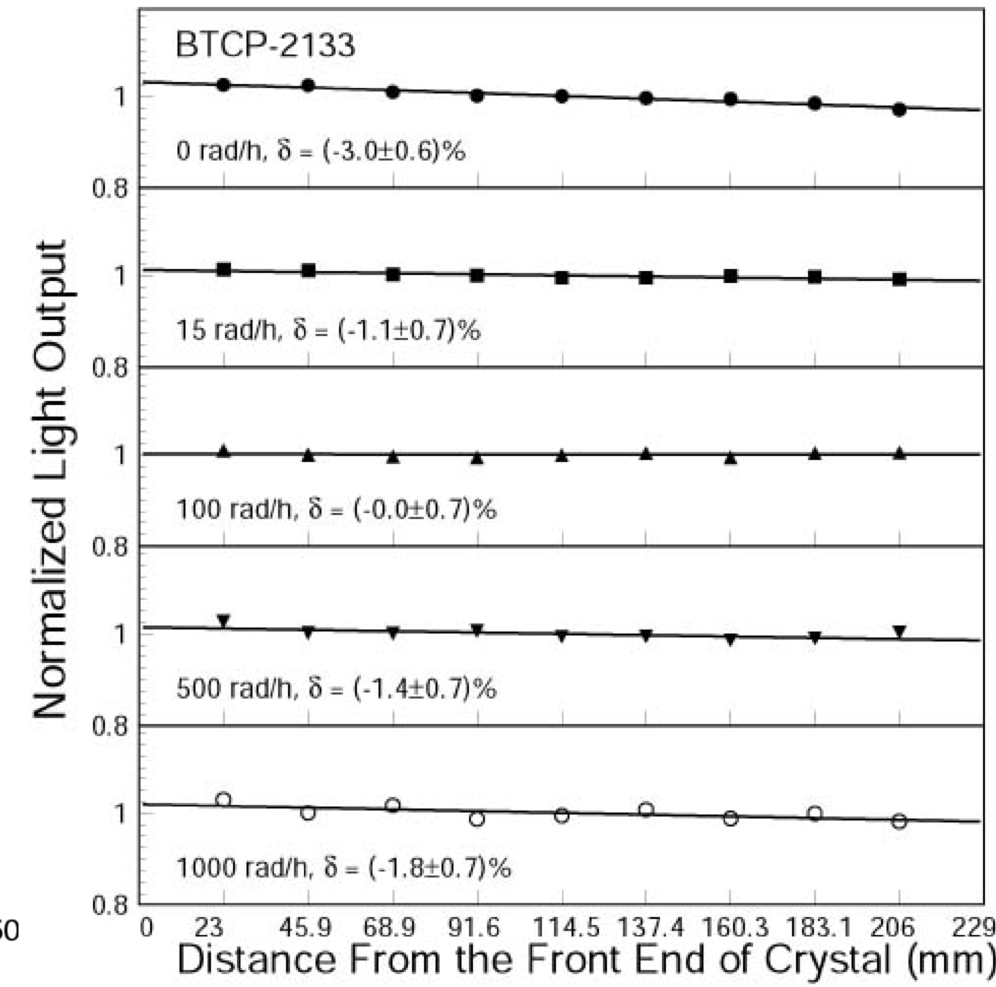
LAL (cm)	20	40	60	80	200
Large Area Photo Detector, covering 100% back face					
η_m (%)	9.5±.2	15.7±.4	19.2±.5	21.6±.6	26.9±.7
δ (%)	23±1	-4.6±.8	-11±1	-15±1	-15±1
ϕ5 mm Photo Detector, covering 3.7% back face					
η_m (%)	.38±.04	.74±.08	1.1±.1	1.4±.2	3.0±.3
δ (%)	23±4	–3.5±4	-12±4	-16±4	-17±3
$\frac{\eta_m(\phi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

PWO Radiation Damage

No damage in scintillation mechanism

No damage in resolution if light attenuation length > 1 m





Dose Rate Dependence

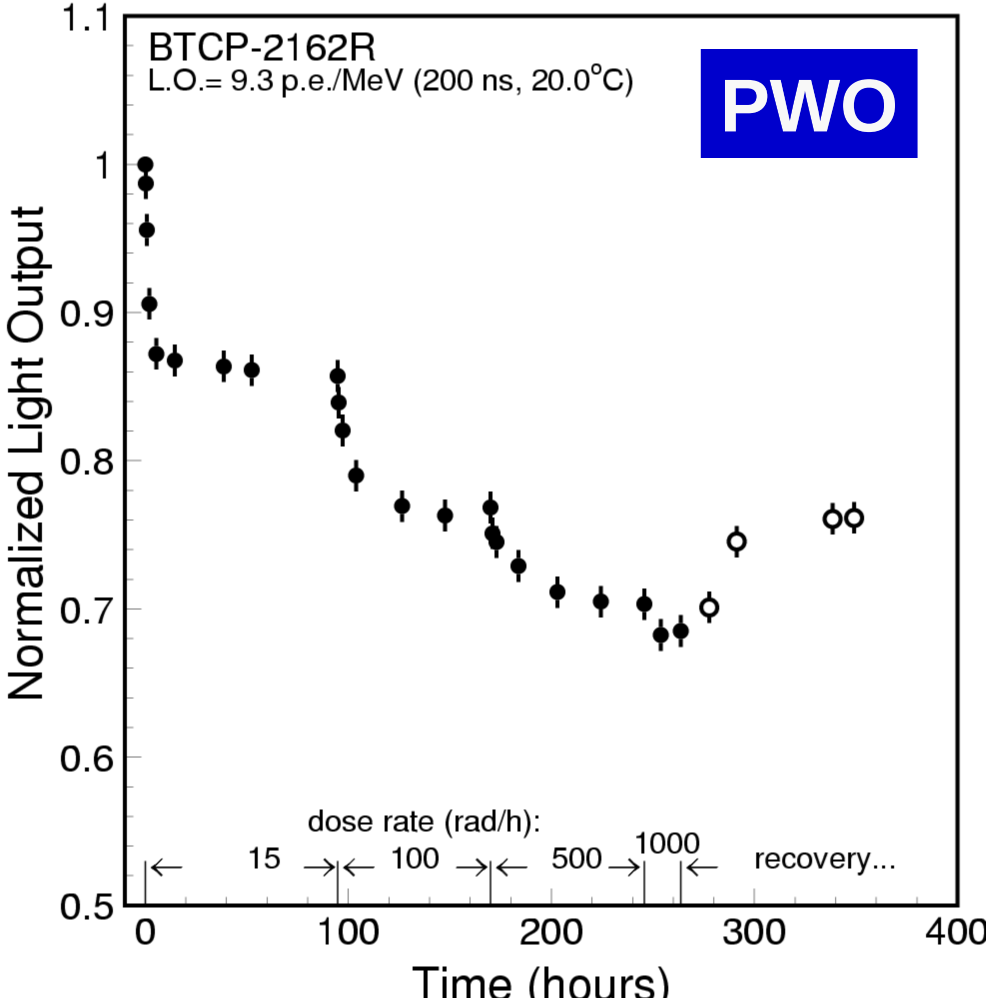
IEEE Trans. Nucl. Sci., Vol. 44 (1997) 468-476

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

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

- 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.

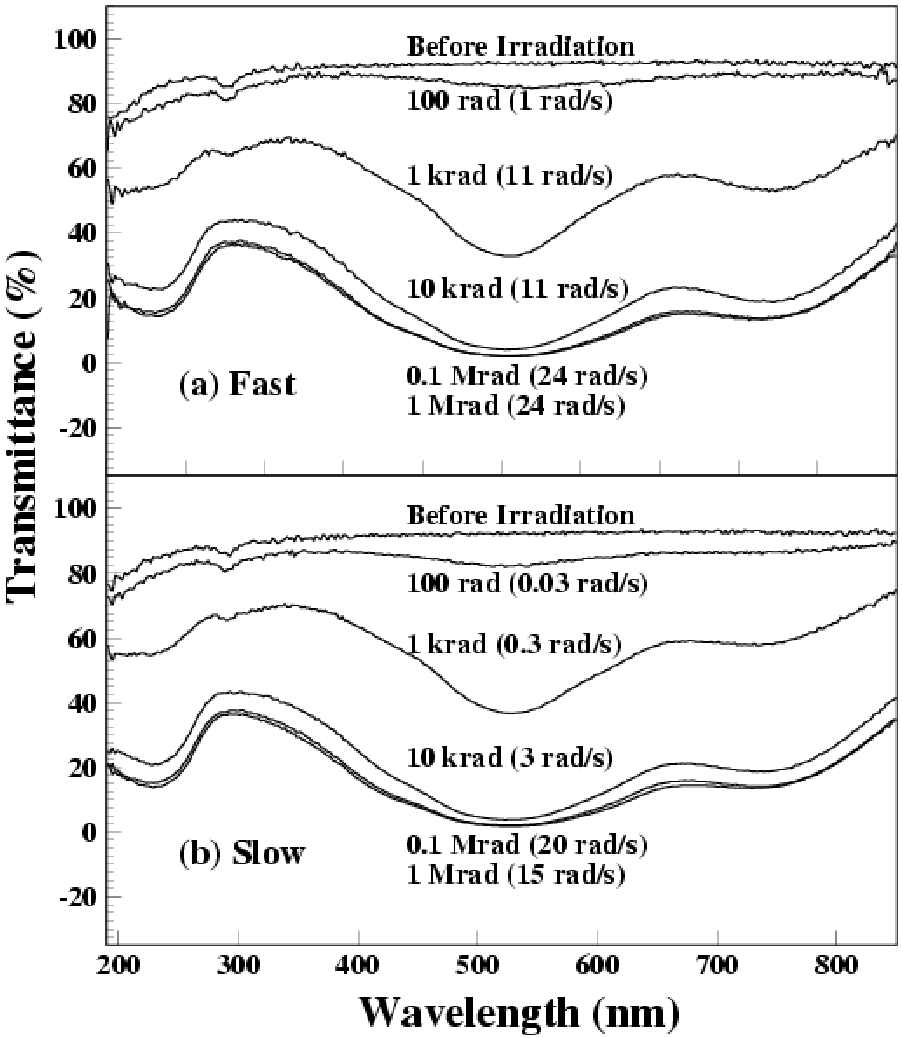
$$D_{eq} = \sum_{i=1}^{n} \frac{b_i R D_i^{all}}{a_i + b_i R}$$



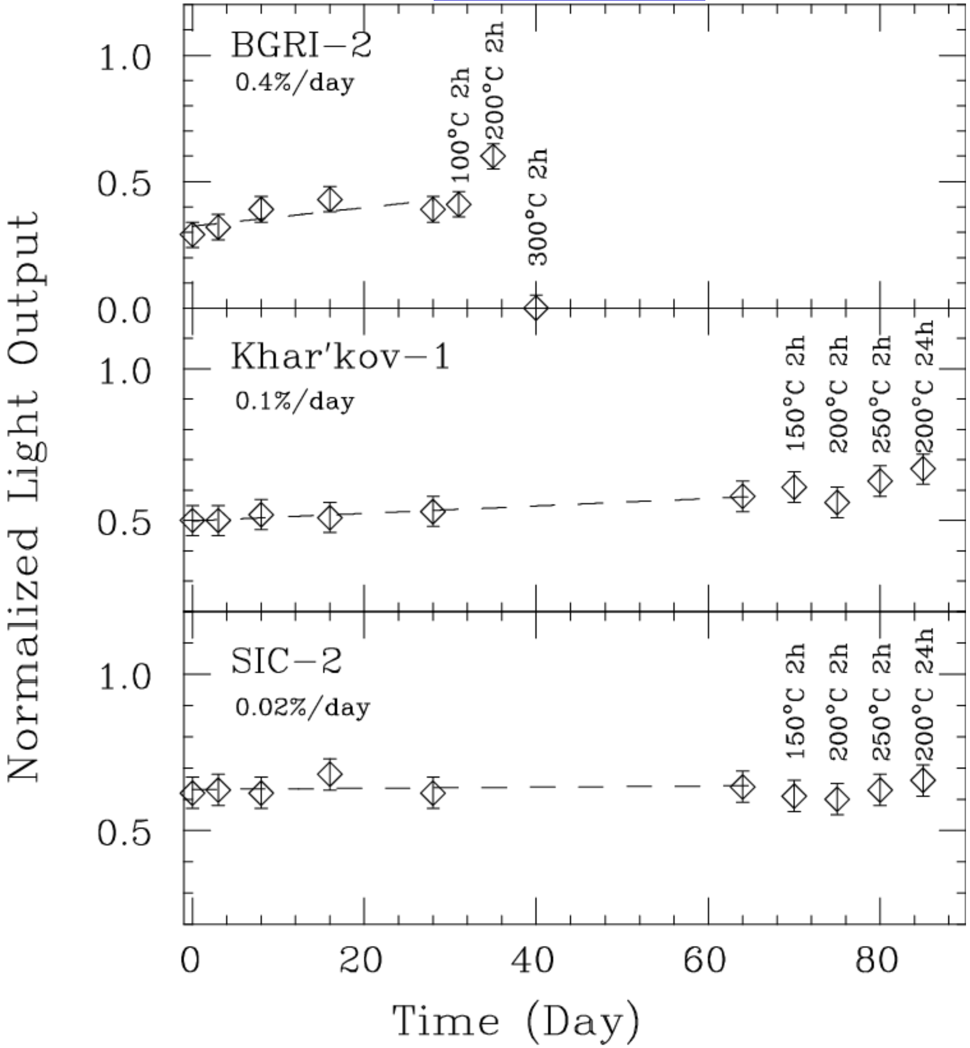
No Dose Rate Dependence

No/slow recovery: no/less dose rate dependence

BaF_2



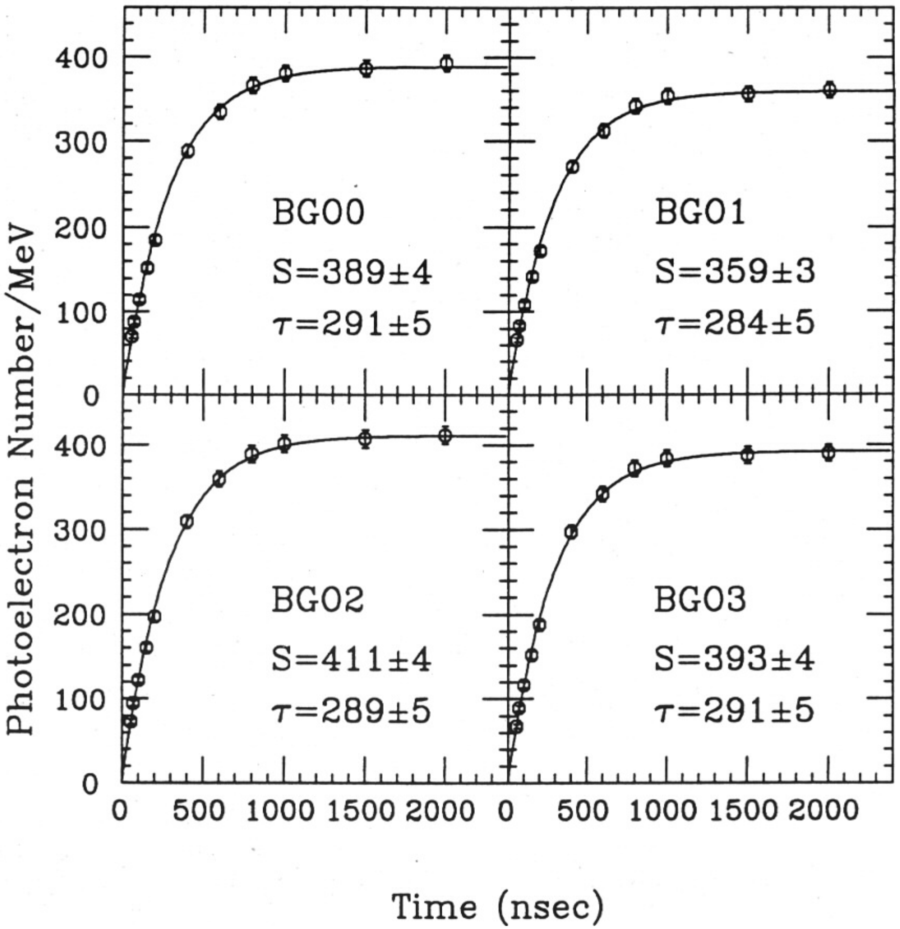
CsI(Tl)



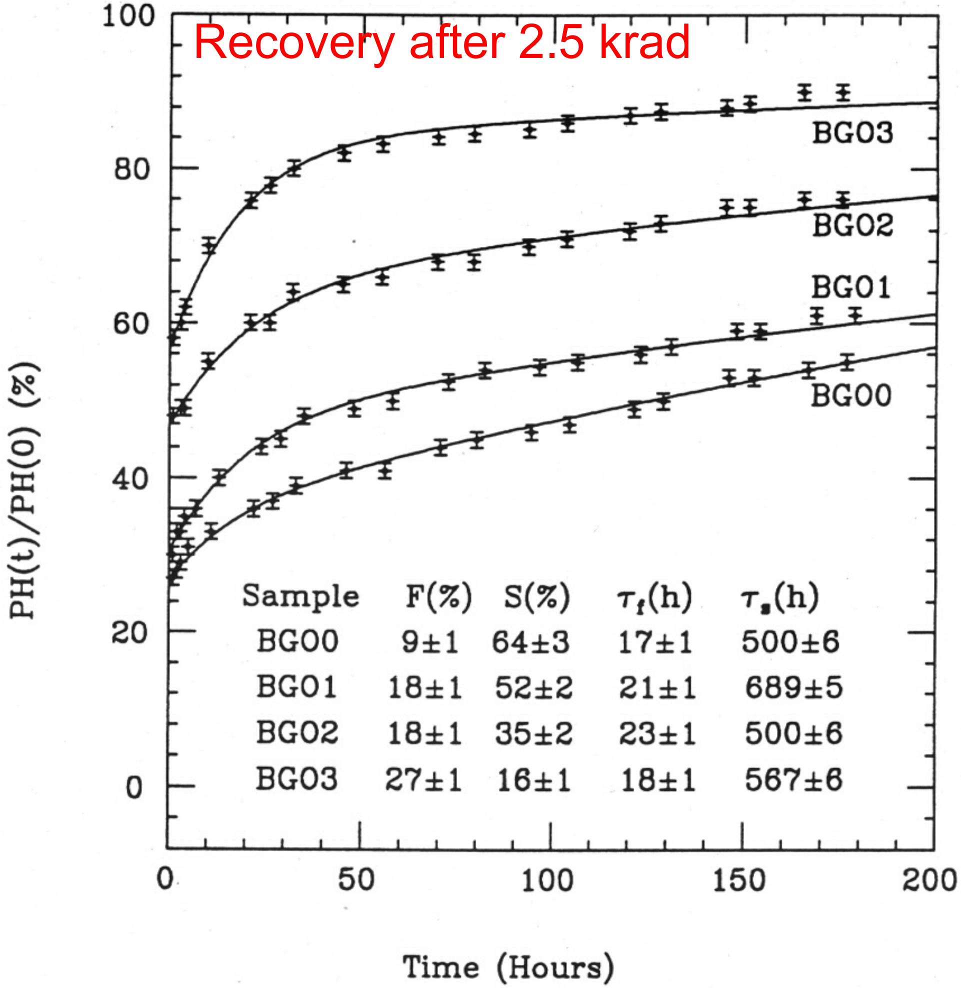
BGO Quality Improvement

Nucl. Instr. and Meth. A302 (1991) 69.

No change in decay time
by Eu doping: 0, 5, 30, 100 ppm



Recovery after 2.5 krad



Significant Improvement in
radiation hardness by Eu doping

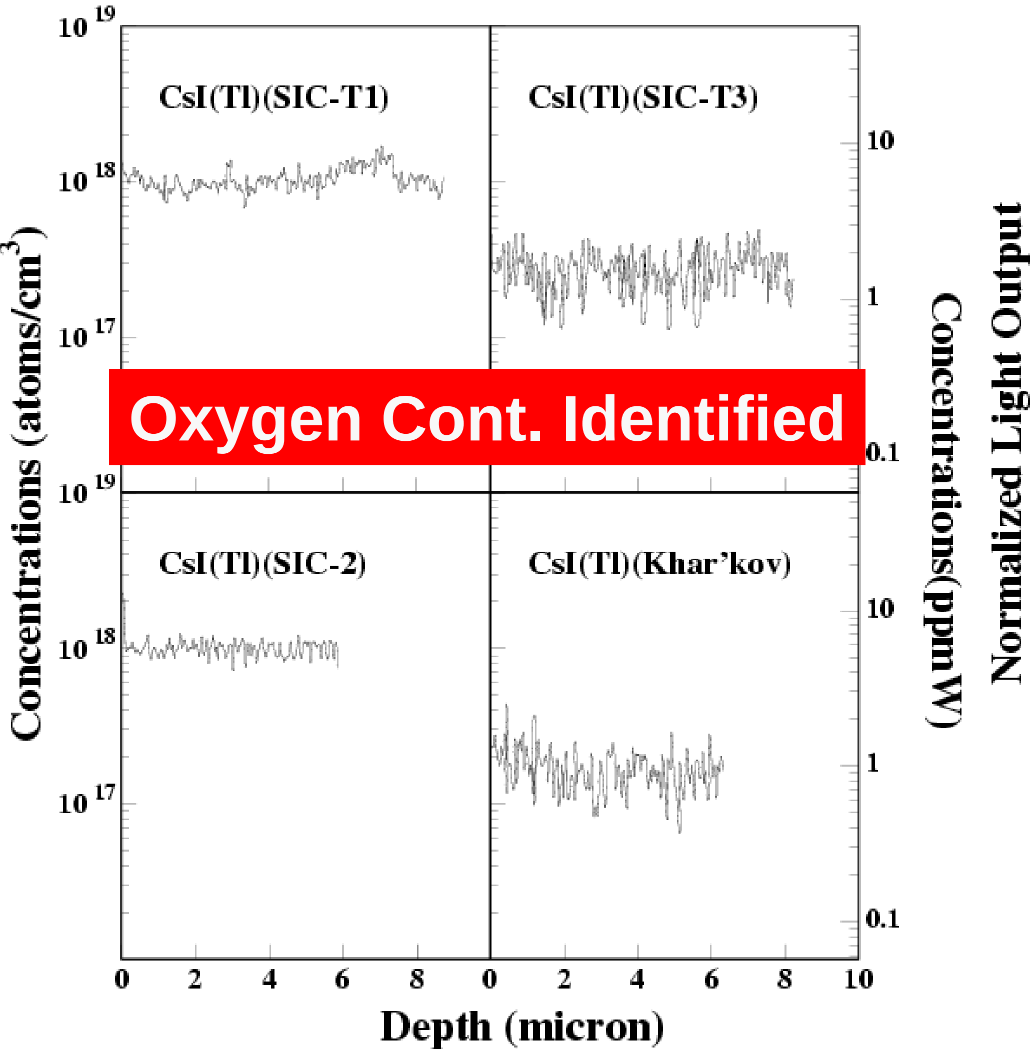
CsI(Tl) Damage Mechanism

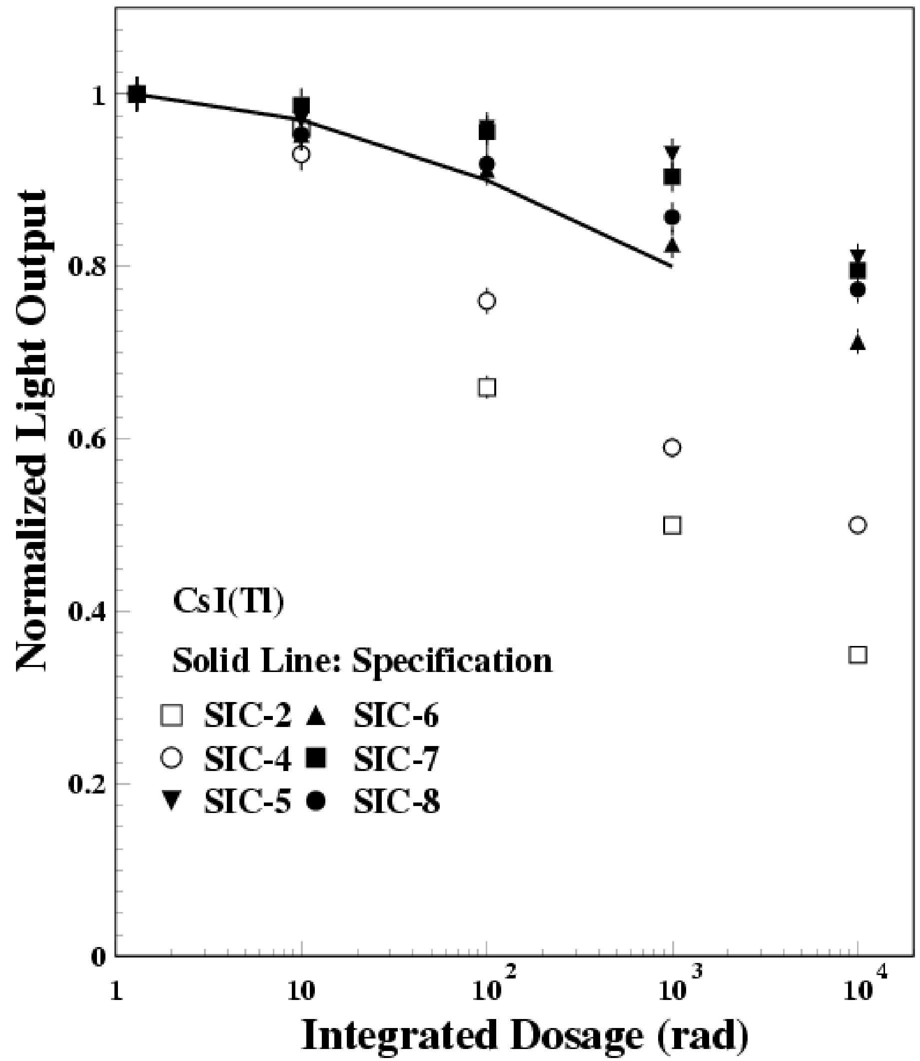
Nucl. Instr. And Meth. A340 (1994) 442

- 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

SIMS at Charles Evans & Associates revealed depth profile of oxygen contamination; Oxygen control improves CsI(Tl) quality





PWO Radiation Damage Mechanism

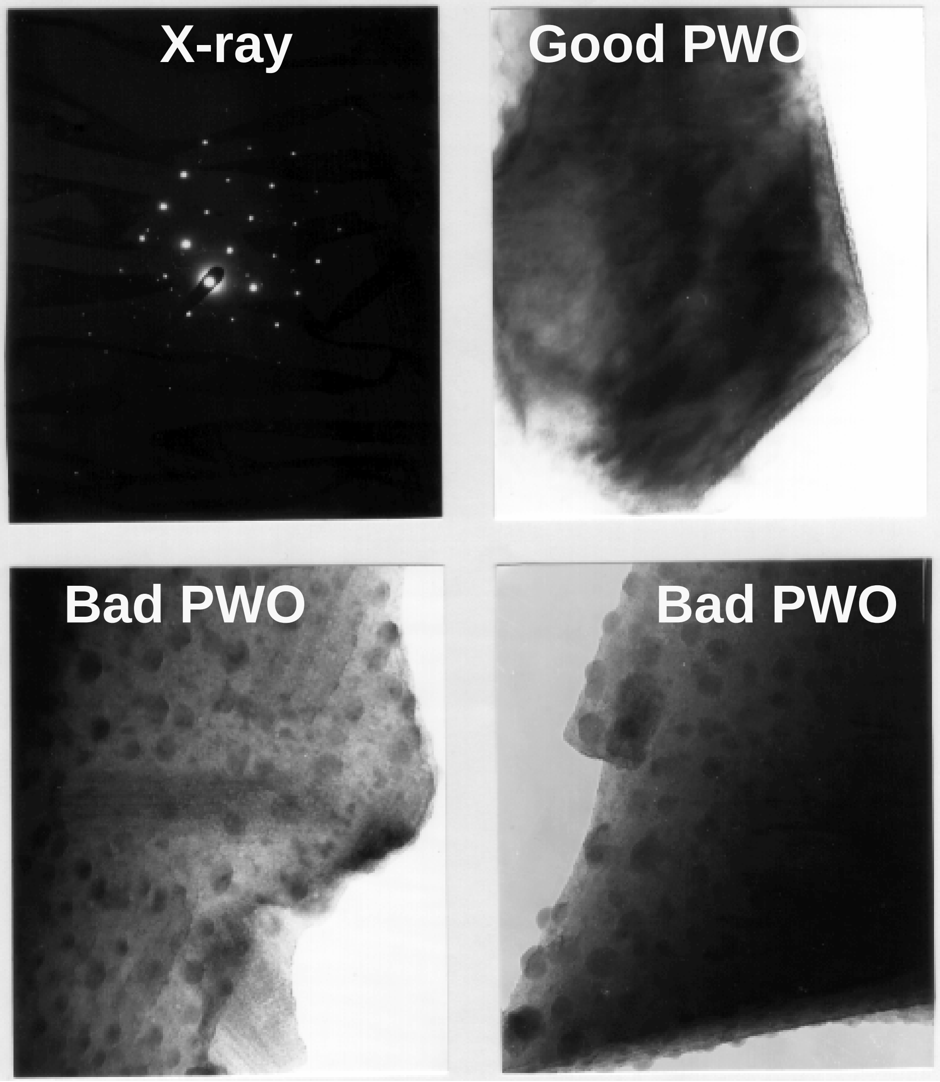
Nucl. Instr. And Meth. A413 (1998) 297

- 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

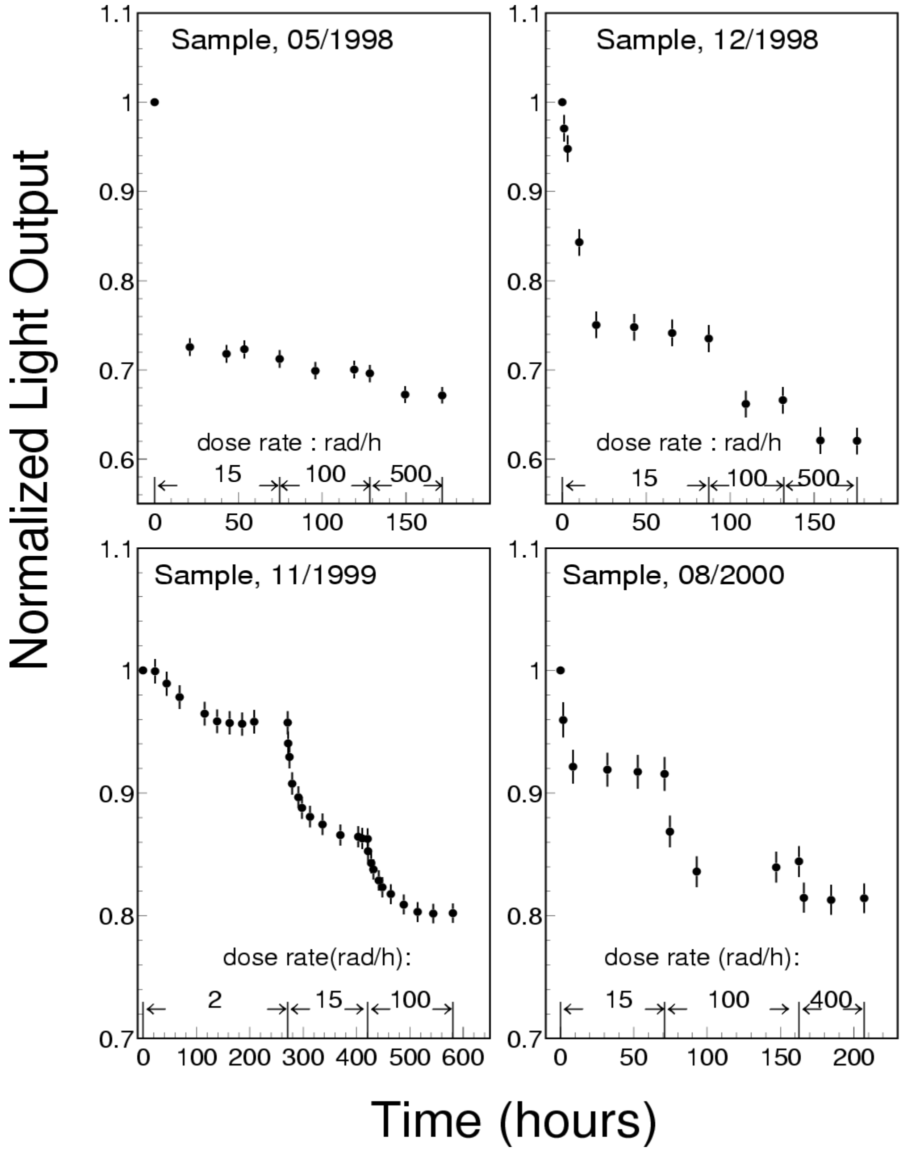
The Same Sample after Oxygen Compensation

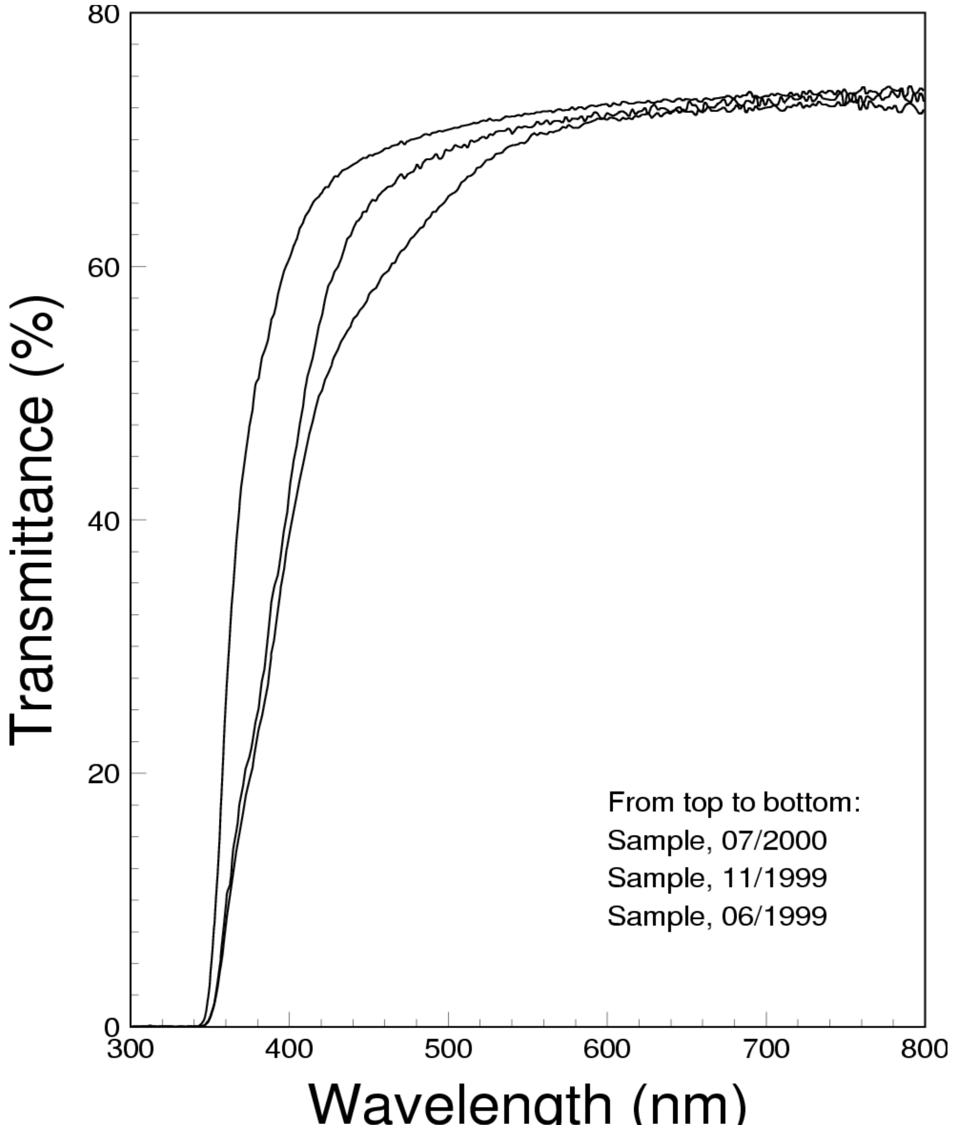
Element	Point$_1$	Point$_2$	Point$_3$	Point$_4$
O	59.0	66.4	57.4	66.7
W	21.0	16.5	21.3	16.8
Pb	20.0	17.1	21.3	16.5

Oxygen Vacancies Identified

PWO Quality Improvement

during mass production at Shanghai Institute of Ceramics

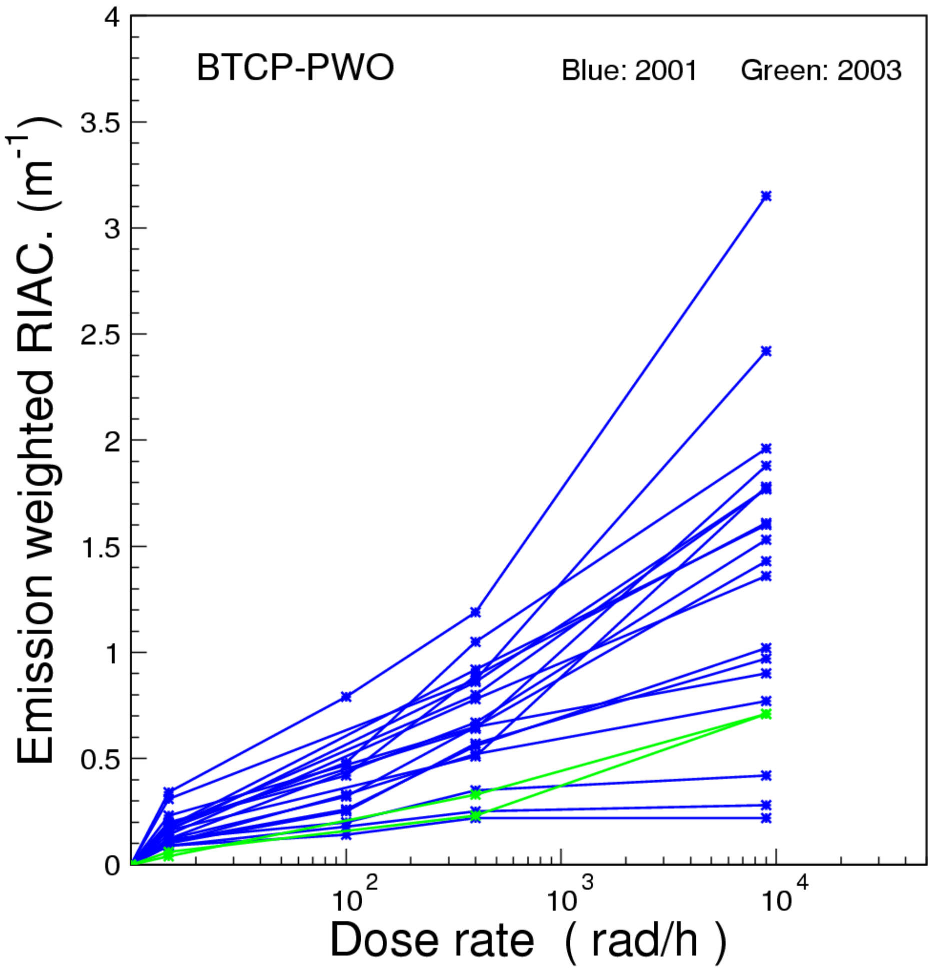


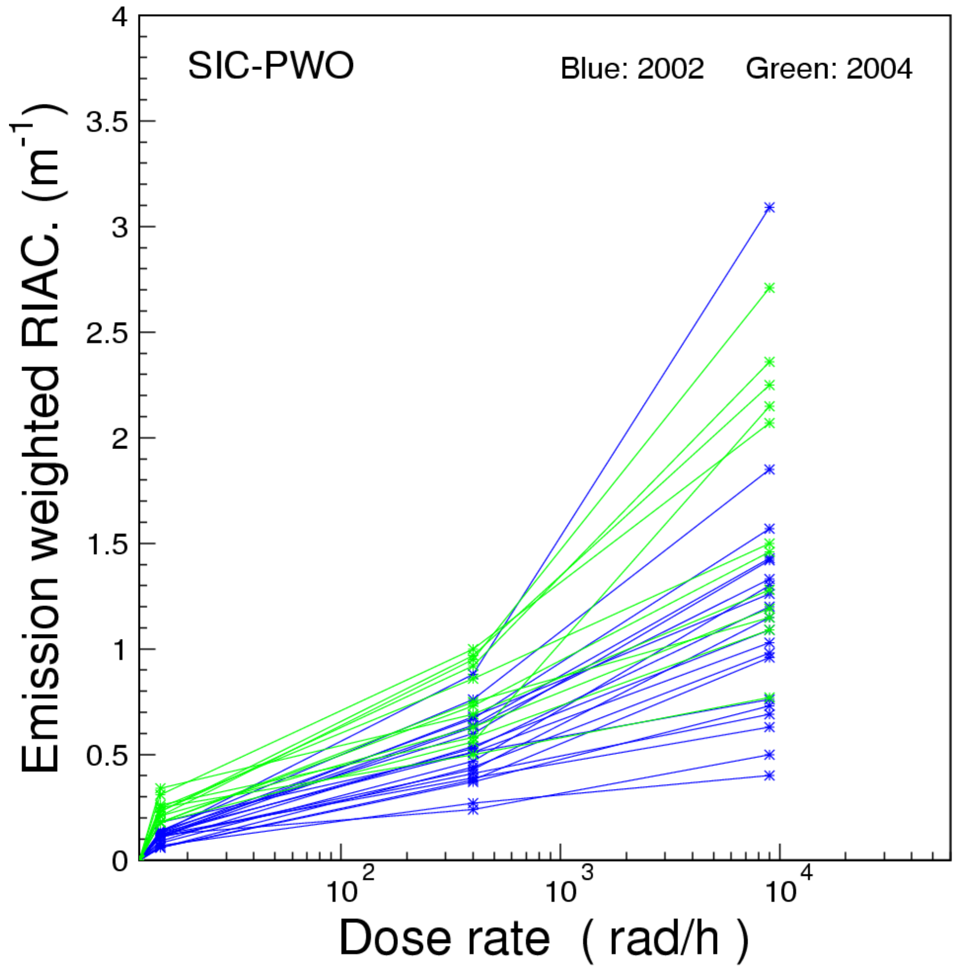


Mass Produced PWO Crystals

All samples: EWRIAC < 1 m^{-1} up to 400 rad/h

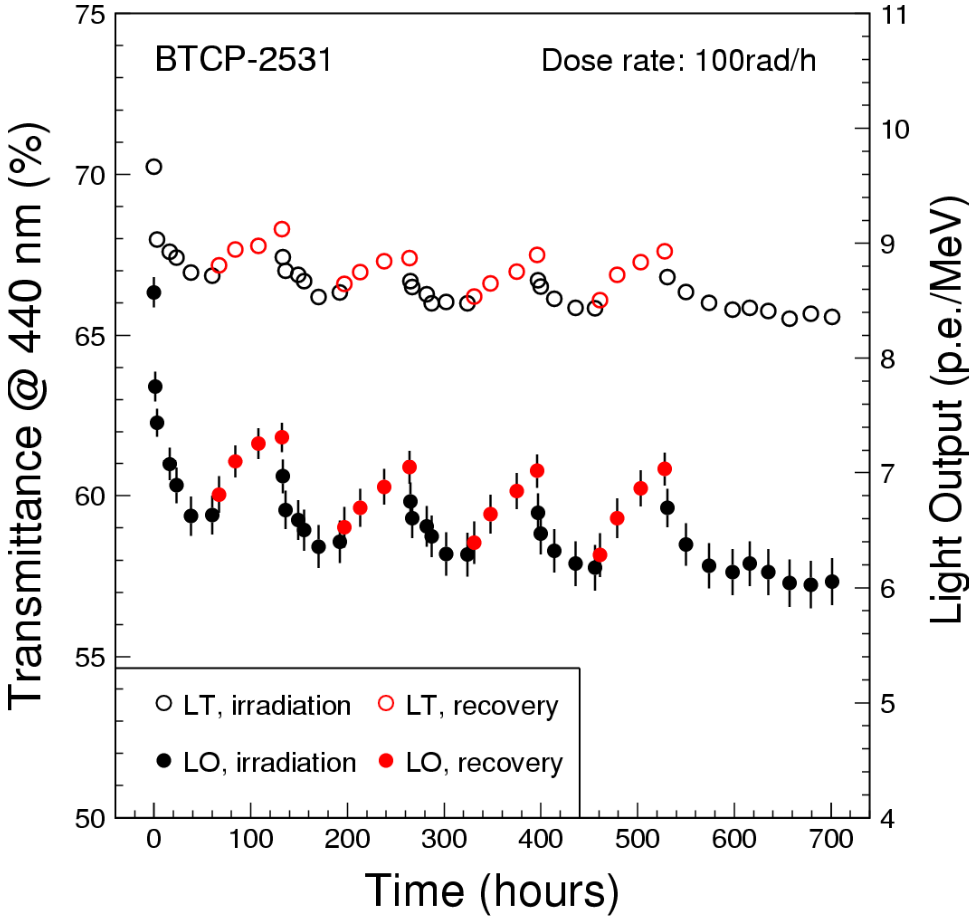
Rigorous QC required to qualify endcap crystals for SLHC

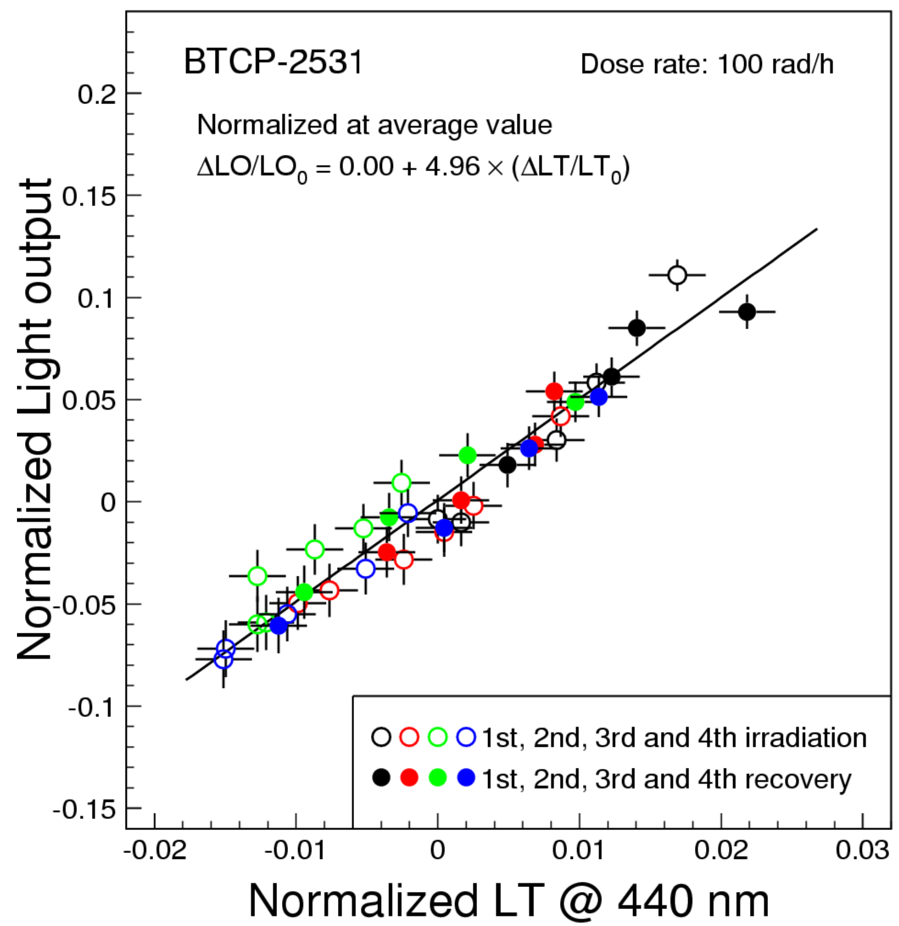




δLO/LO versus δLT/LT @ 100 rad/h

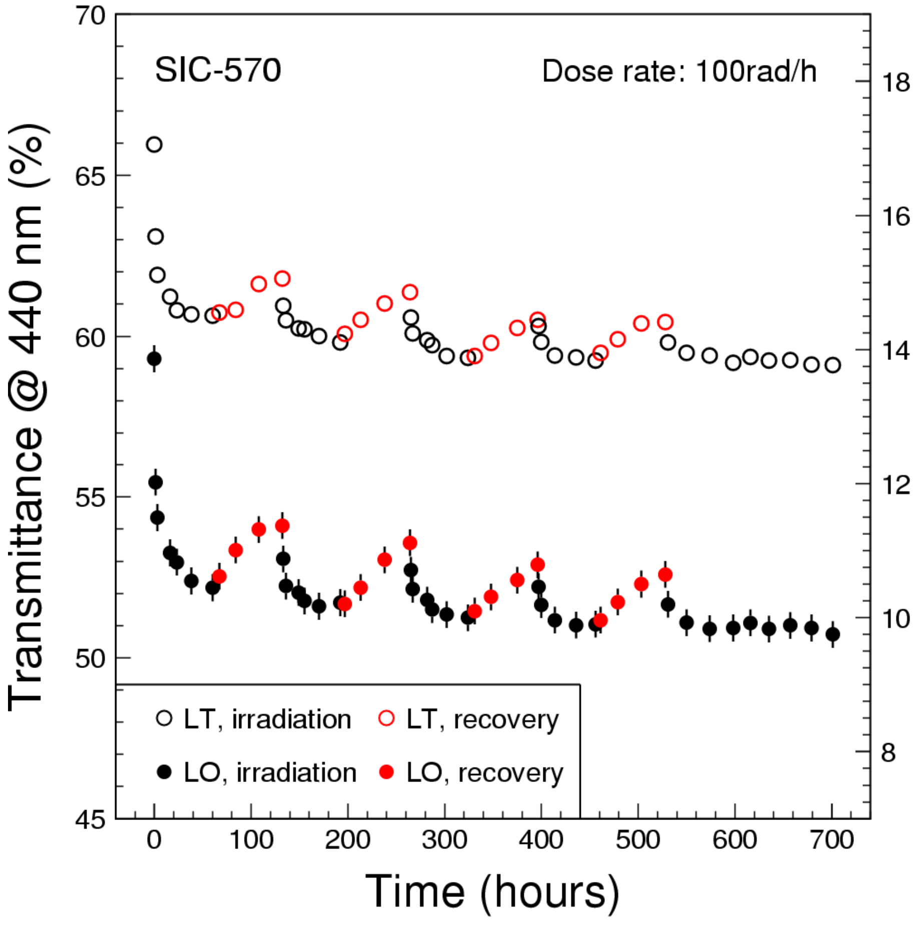
Strong correlation: Slope = 4.96

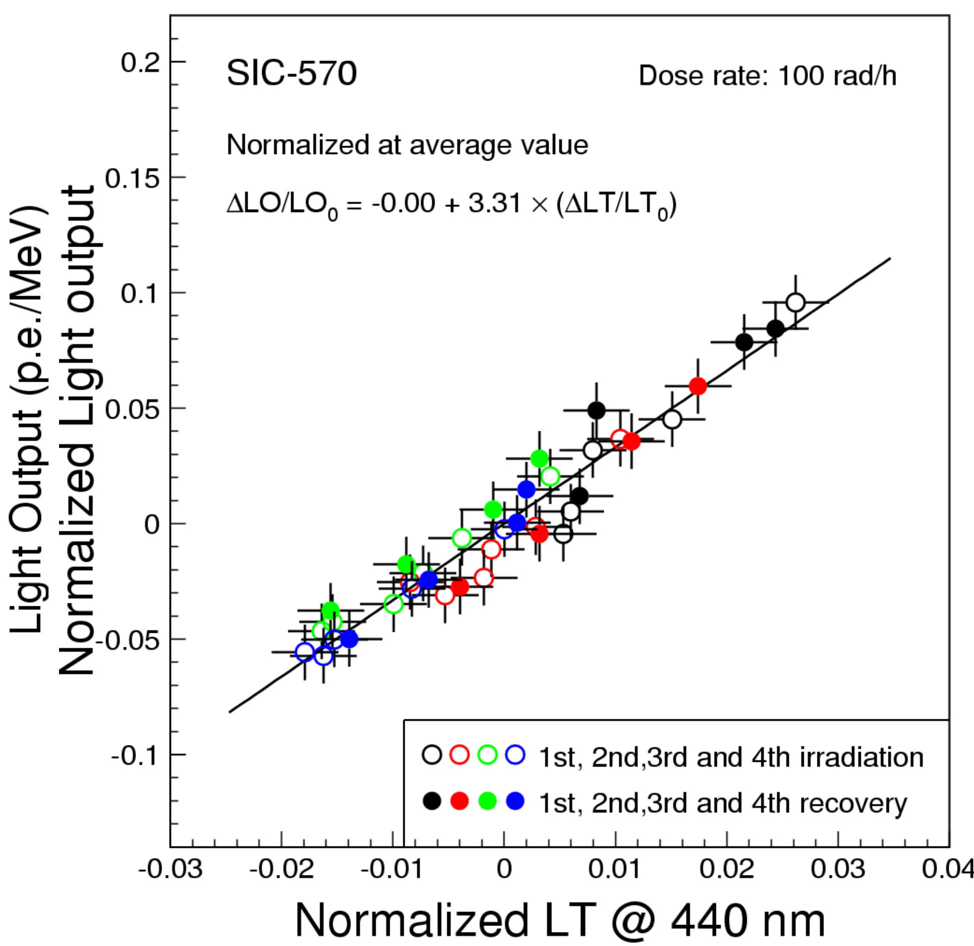




δLO/LO versus δLT/LT @ 100 rad/h

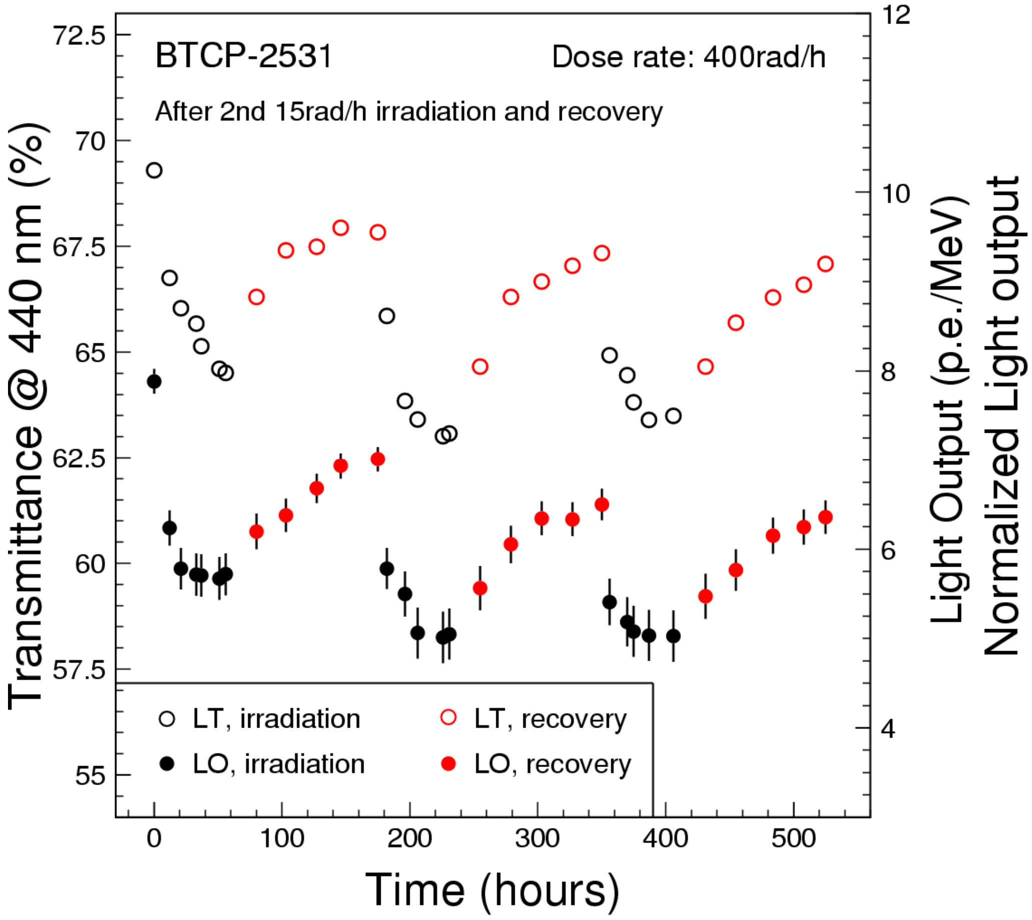
Strong correlation: Slope = 3.31

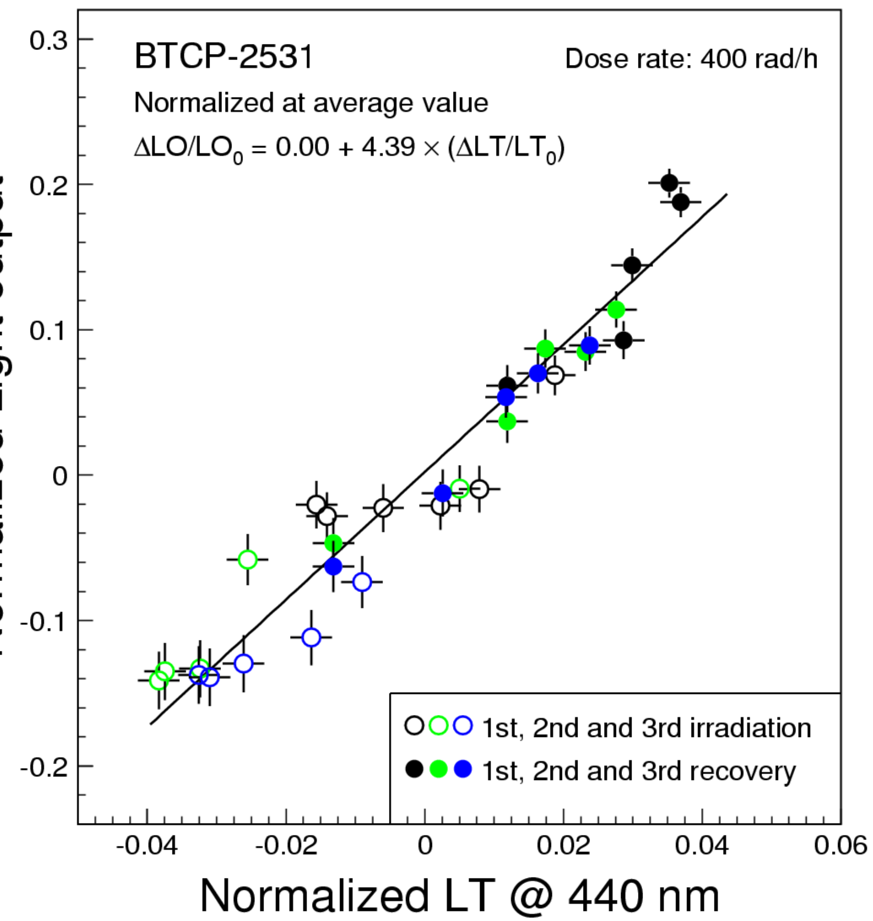




δLO/LO versus δLT/LT @ 400 rad/h

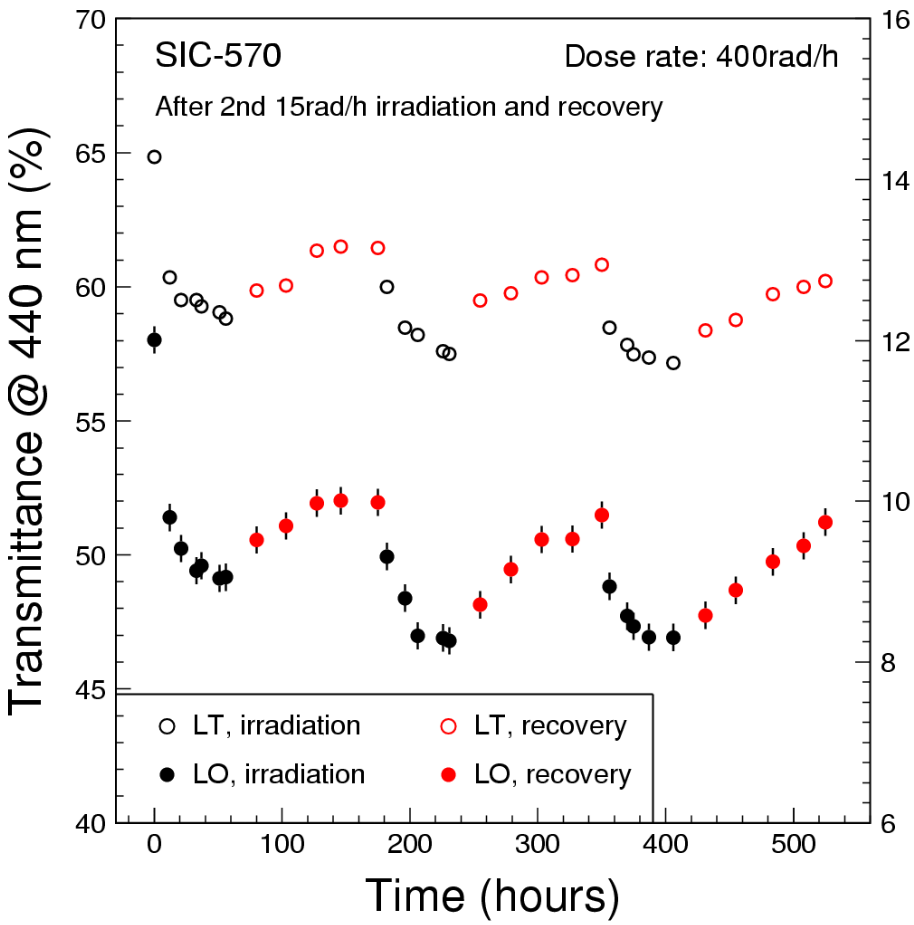
Strong correlation: Slope = 4.39

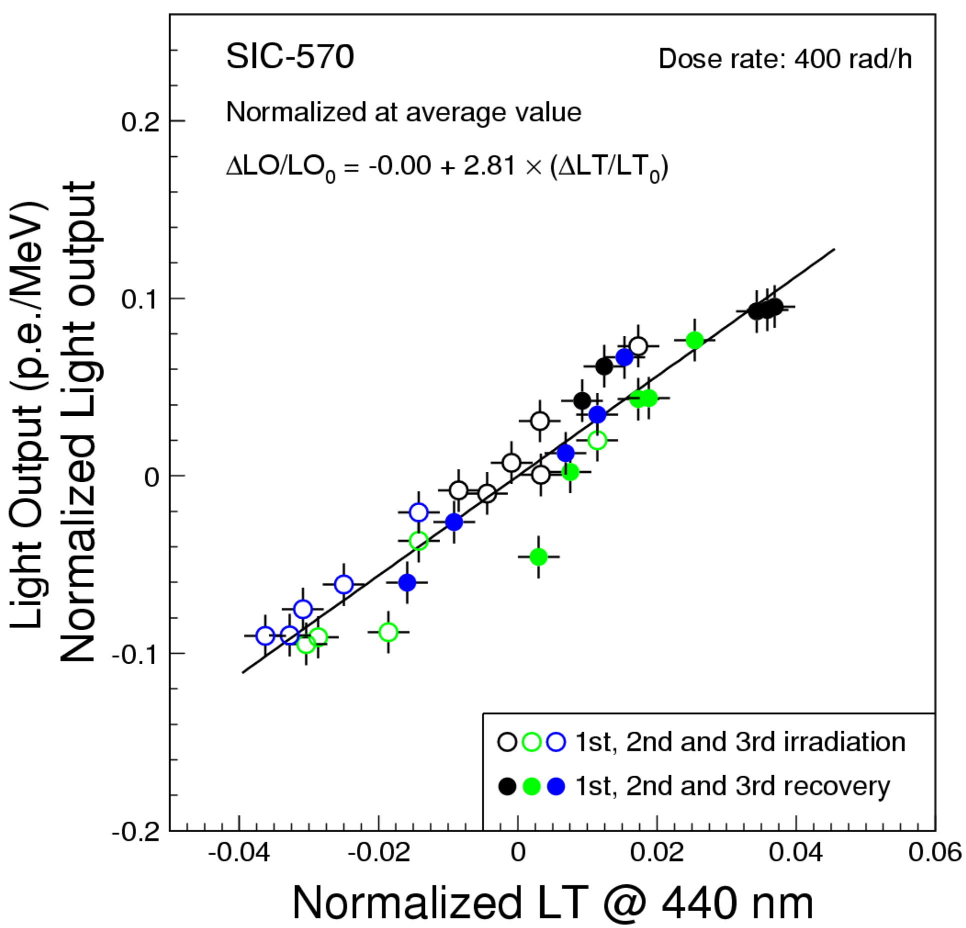




δLO/LO versus δLT/LT @ 400 rad/h

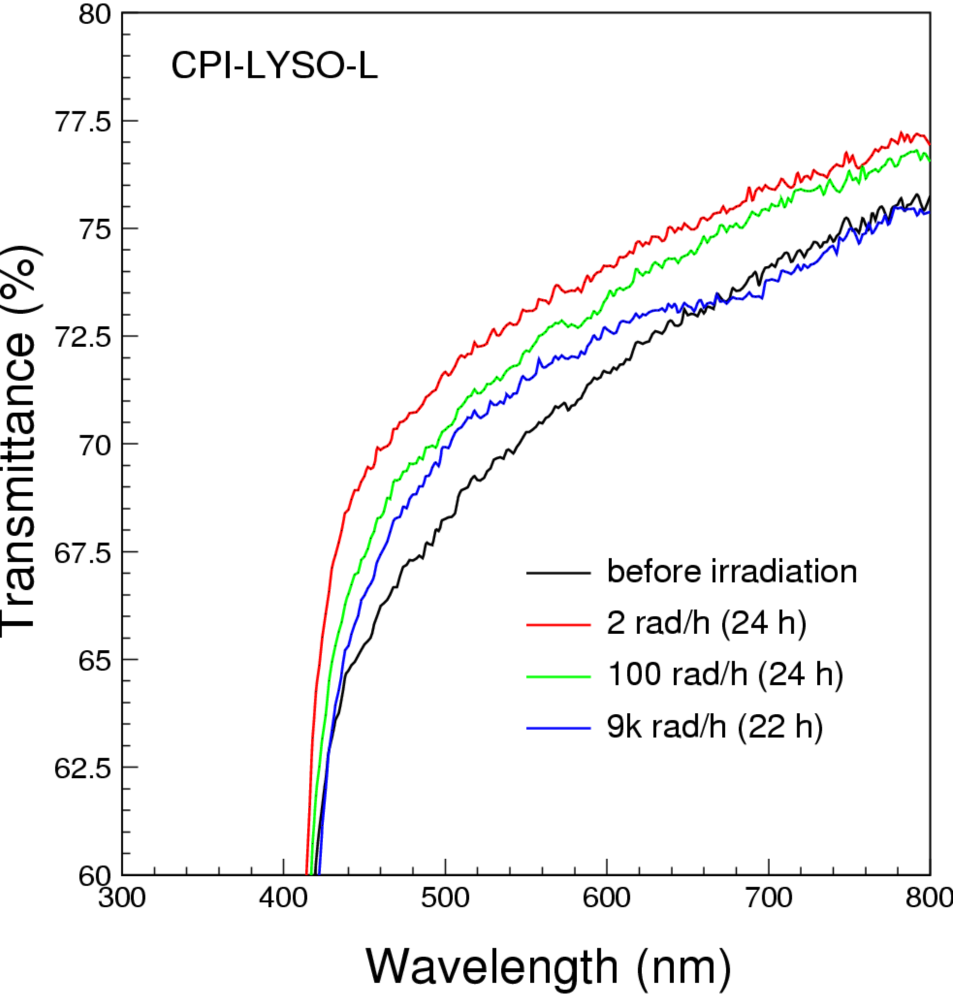
Strong correlation: Slope = 2.81

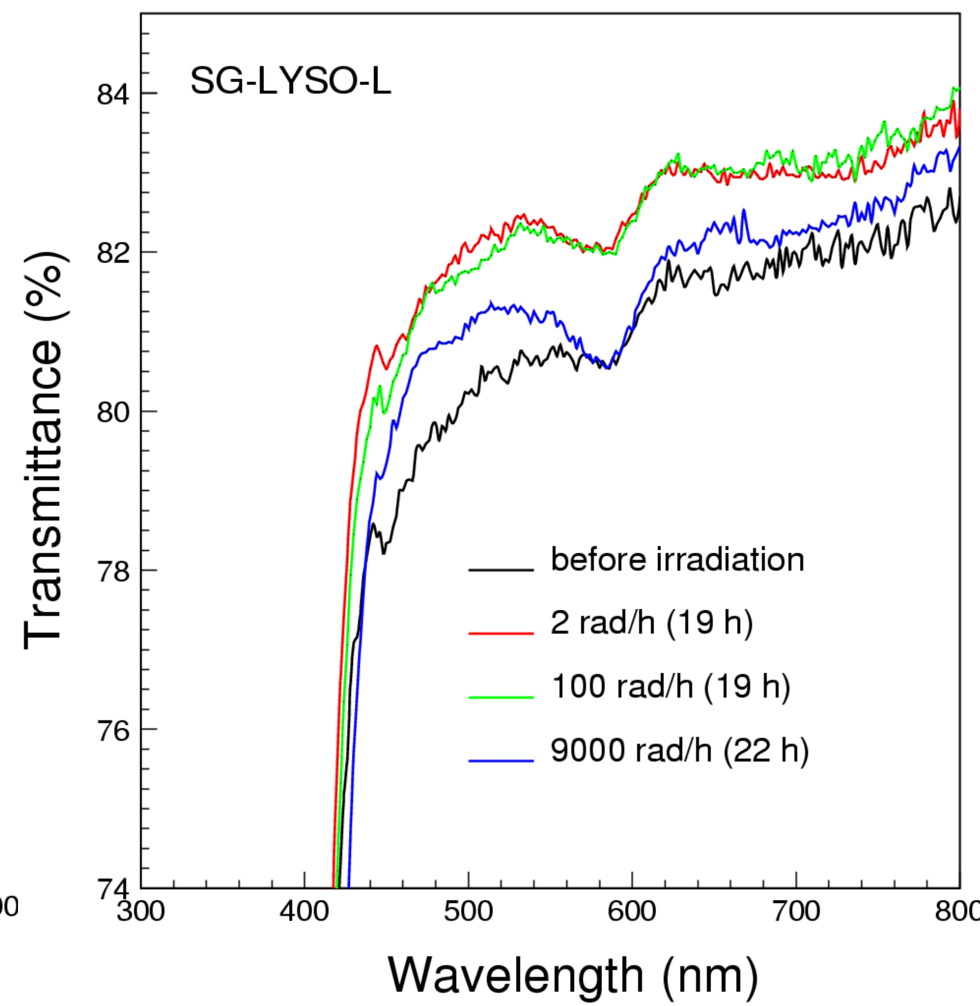




LYSO Transmittance Damage

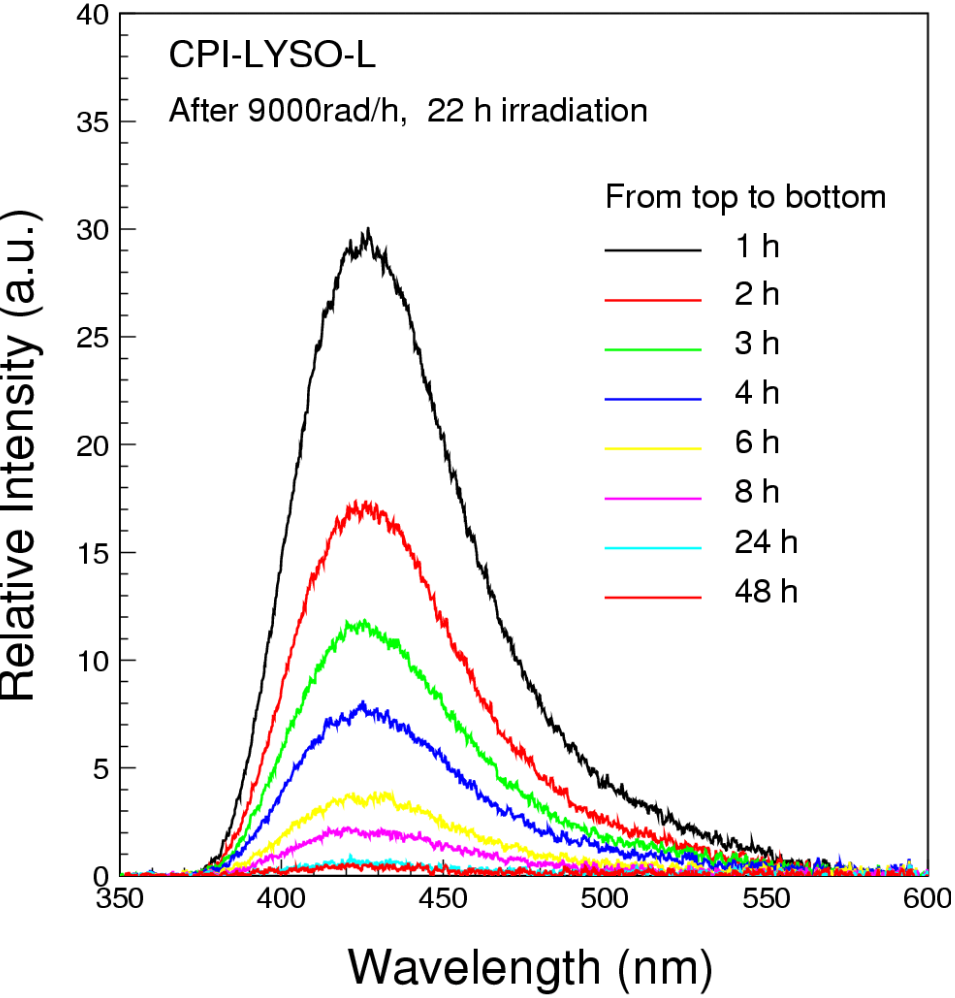
LT @ 430 nm shows 6 and 3% increase under 2 rad/h, followed by 6 and 5% degradation under 9 krad/h for CPI and SG samples respectively

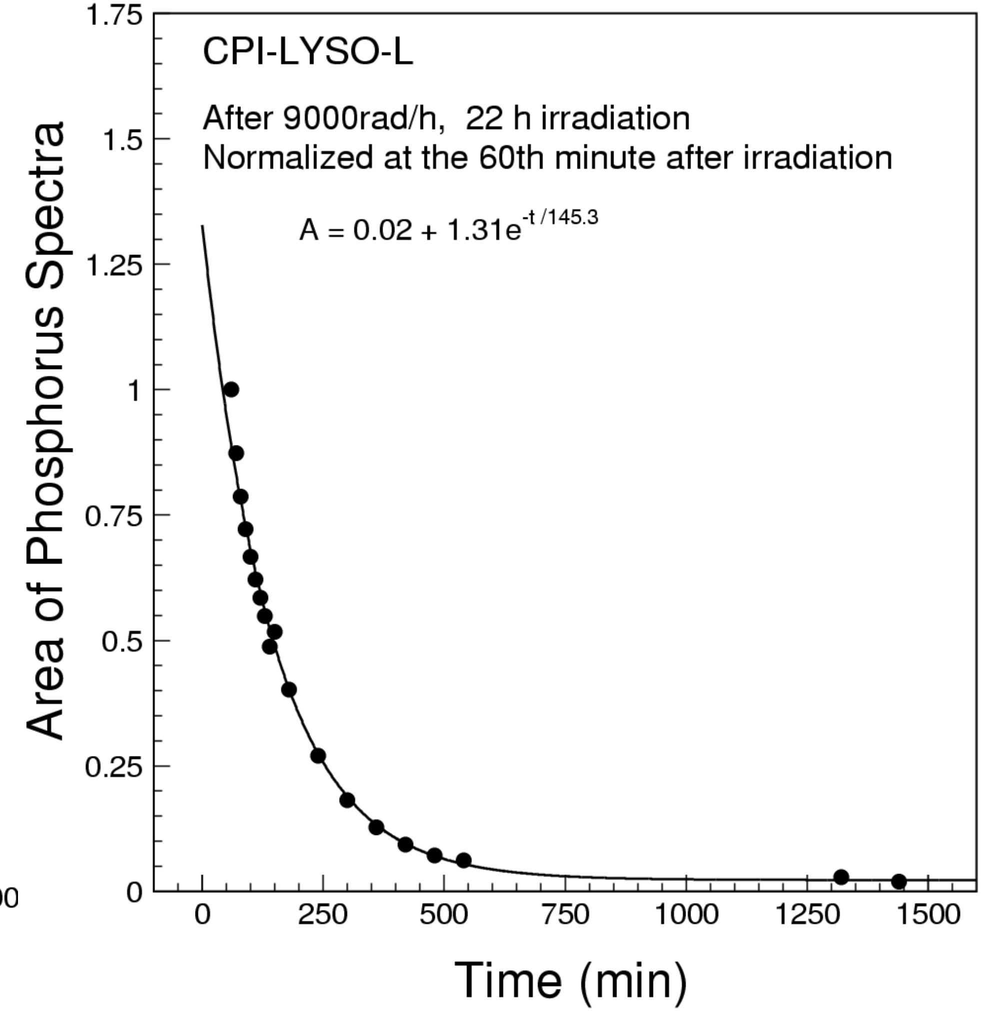




Radiation Induced Phosphorescence

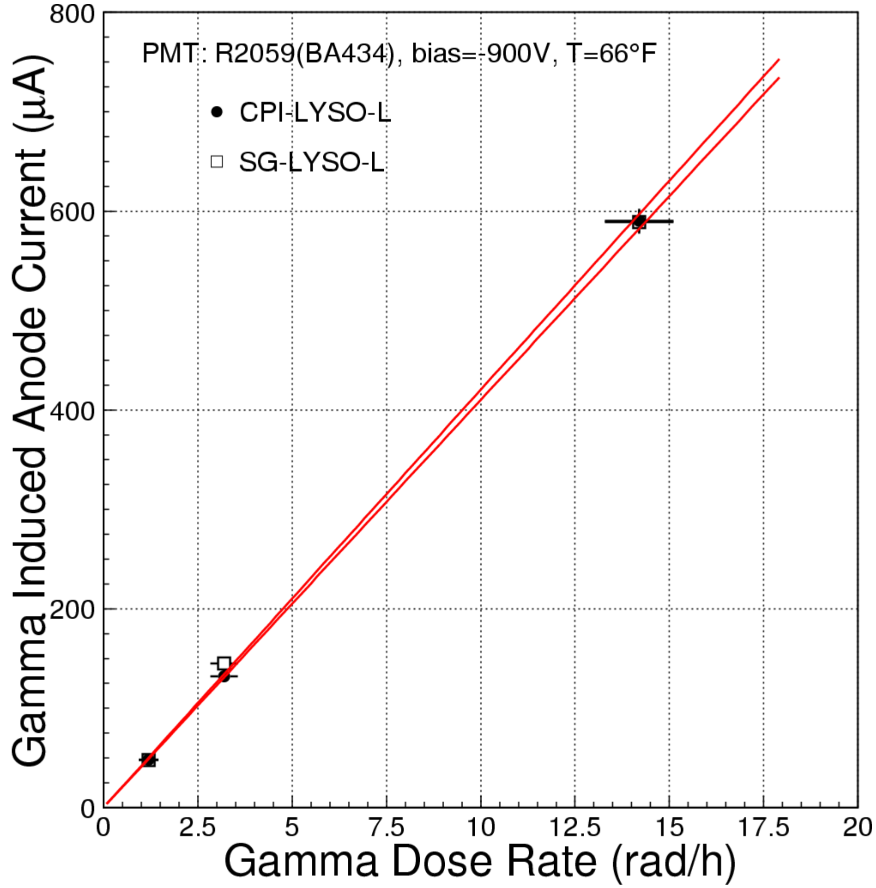
Phosphorescence peaked at 430 nm with decay time constant of 2.5 h observed





γ–ray Induced Readout Noise

Sample ID	L.Y. p.e./MeV	F μ A/rad/h	$Q_{15\ rad/h}$ p.e.	$Q_{500\ rad/h}$ p.e.	$\sigma_{15\ rad/h}$ MeV	$\sigma_{500\ rad/h}$ MeV
CPI	1,480	41	6.98×10^4	2.33×10^6	0.18	1.03
SG	1,580	42	7.15×10^4	2.38×10^6	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).

LSO/LYSO ECAL Performance

- Less demanding to the environment because of small temperature coefficient.
- Radiation damage is less an issue as compared to the CMS PWO ECAL.
- 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:

$$2.0\%/\sqrt{E} \oplus 0.5\% \oplus .002/E$$

Summary

- Precision crystal calorimetry has been an important part of HEP detector. It, however faces a challenge: radiation damage.
- Progress has been made in understanding crystal radiation damage.
- Quality of mass produced crystals can be improved through rigurous R&D.
- An LSO/LYSO crystal calorimeter will provide excellent energy resolution over a large dynamic range down to MeV level.