LSO/LYSO Crystal Development

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Why Crystal Calorimeter

- Enhance physics discovery potential since photons and electrons are fundamental particles for the standard model physics and 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 energy resolution.

Physics with Crystal Calorimeters

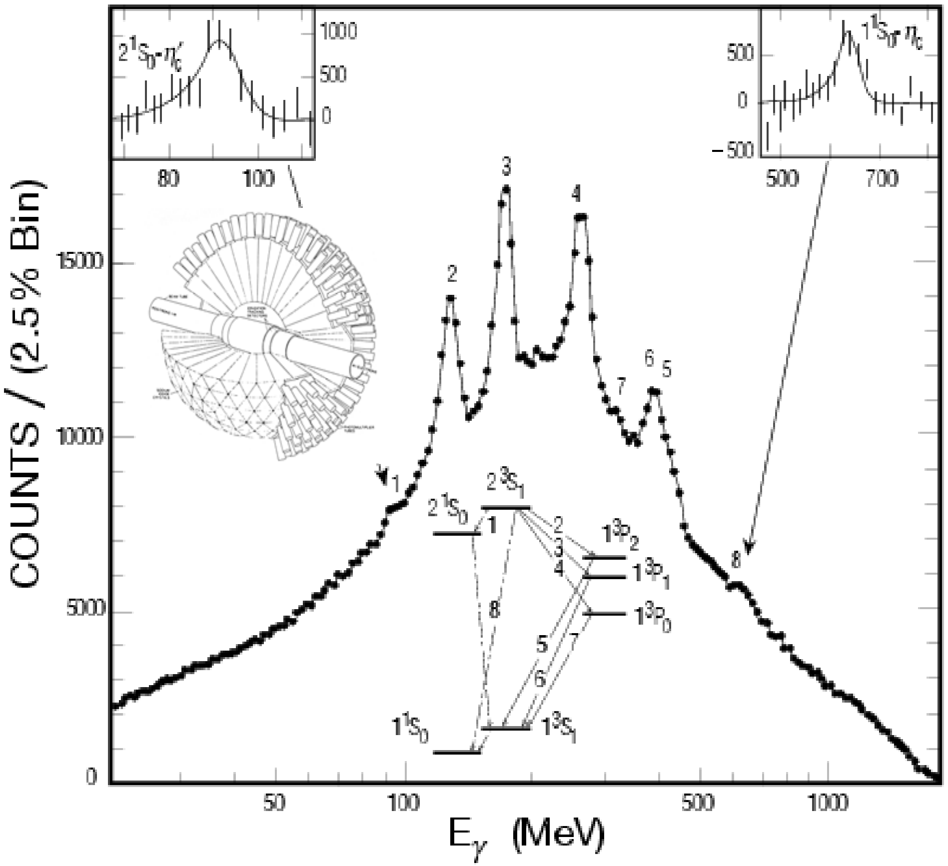
Charmonium system observed by CB through Inclusive photons

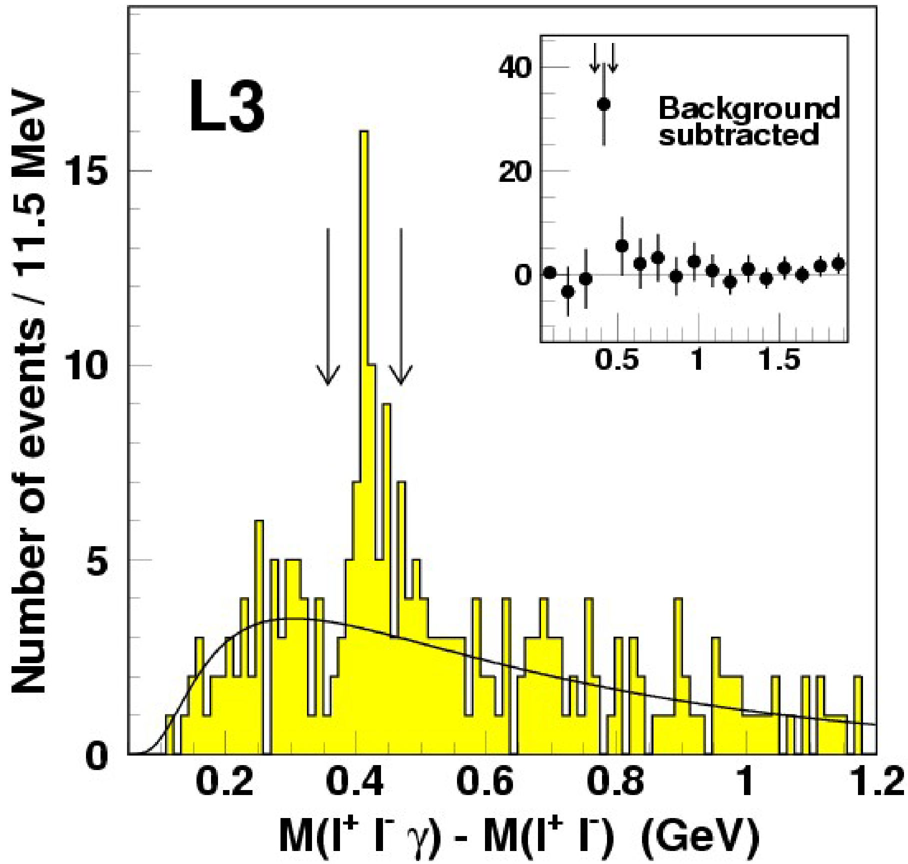
Charmed Meson in Z Decay

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

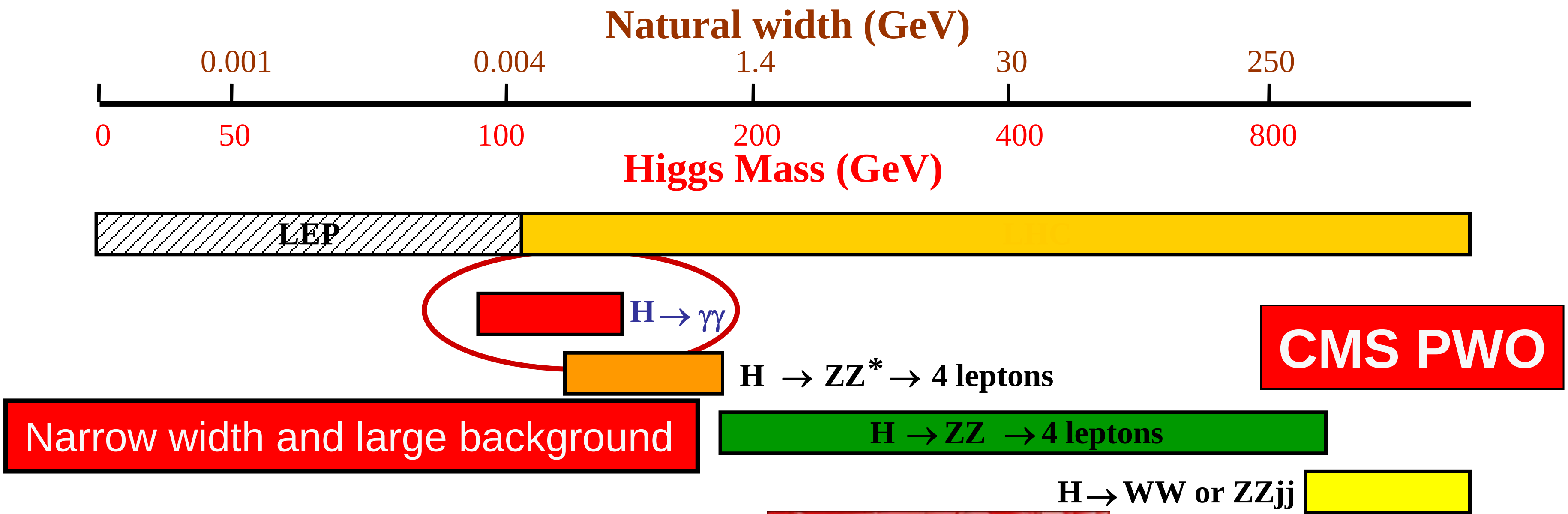
CB NaI(Tl)

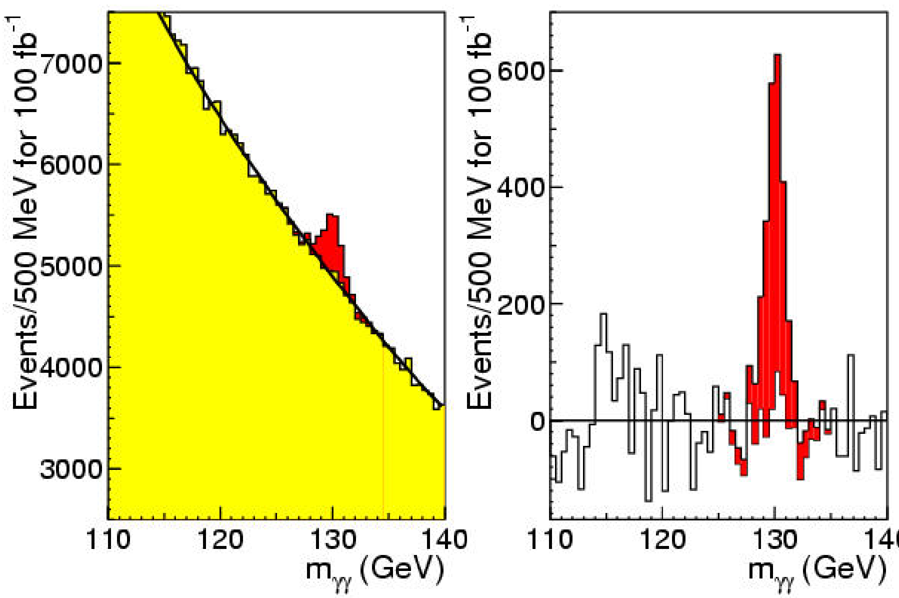
L3 BGO

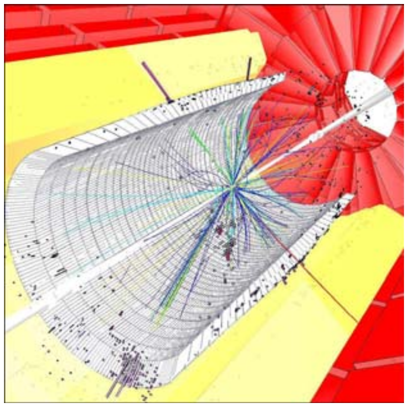


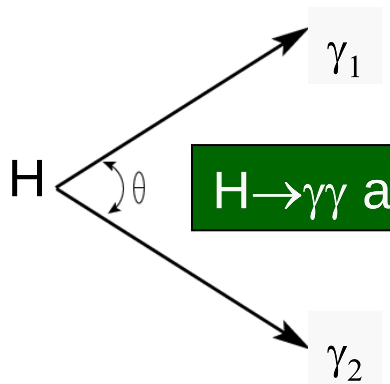


H→γγ Search Needs Precision ECAL





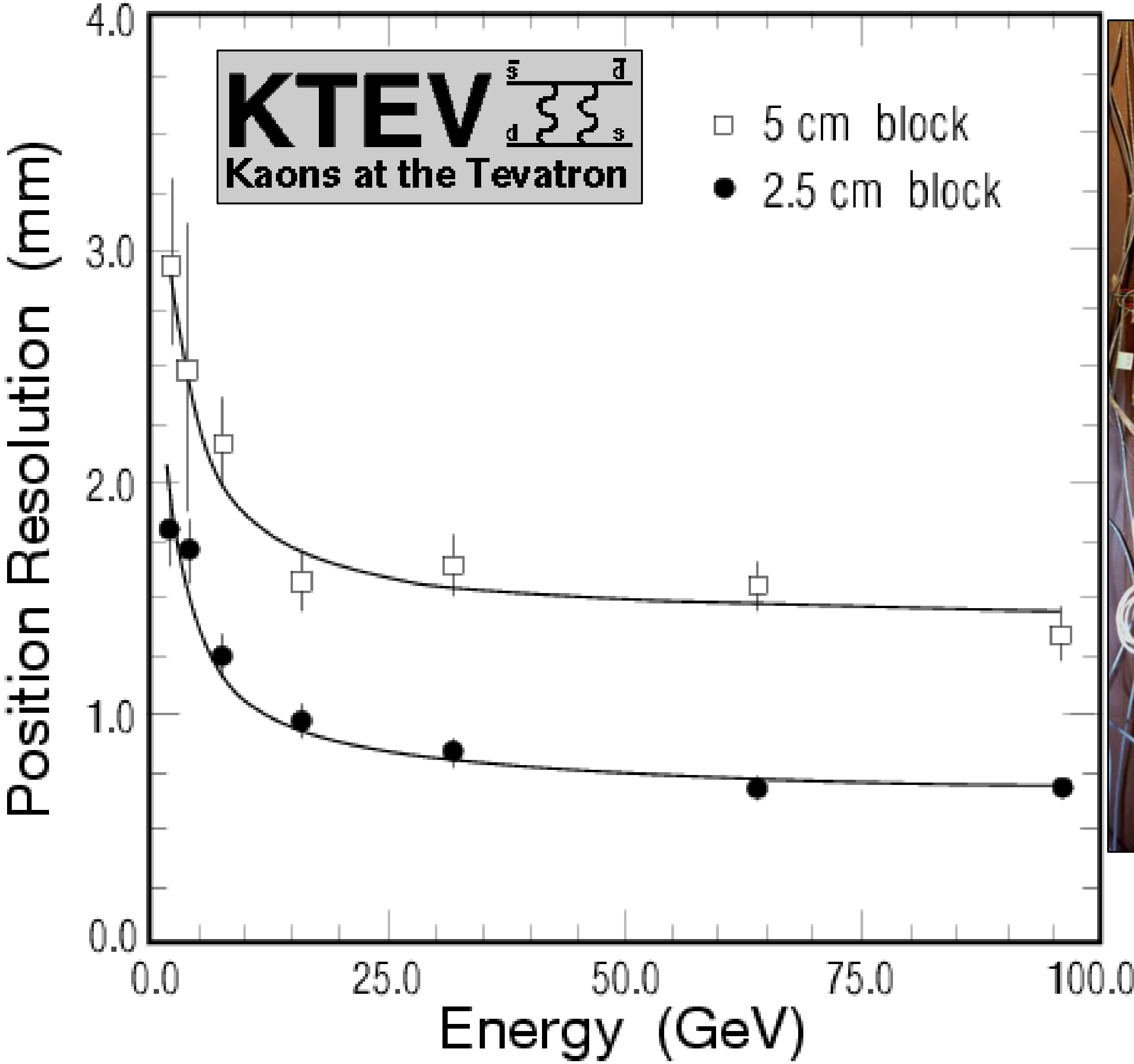


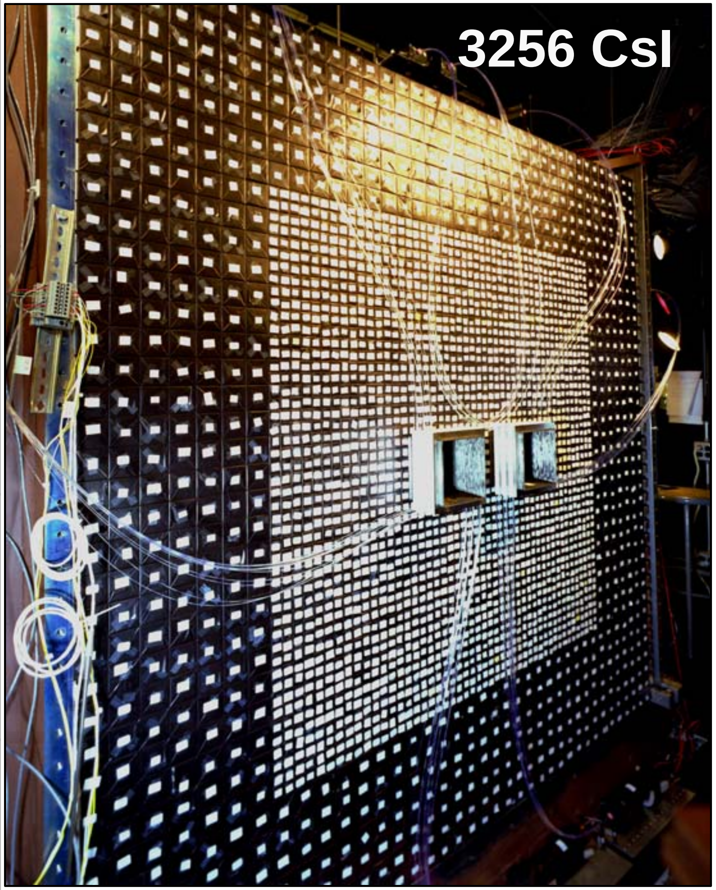


H→γγ at LHC

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

KTeV CsI Position Resolution

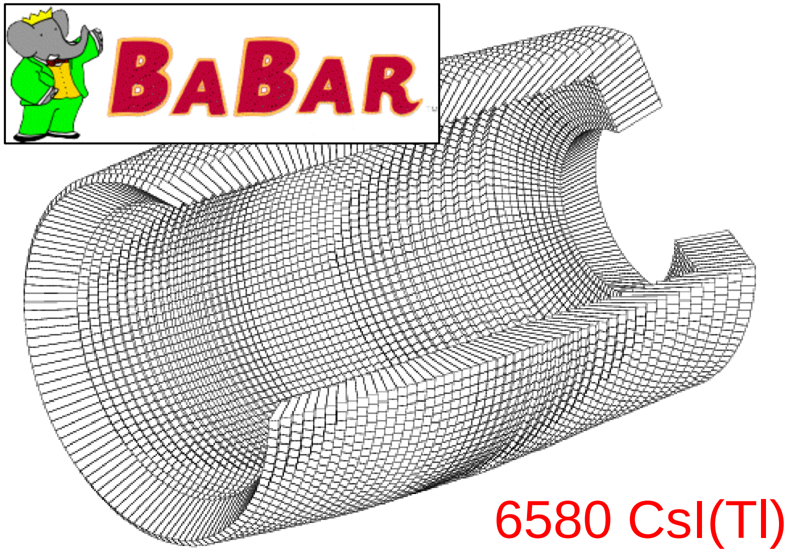




$\sigma x = 3/\sqrt{E} \oplus 0.3$ mm for L3 BGO & CMS PWO

BaBar CsI(Tl) Energy Resolution

BaBar CsI(Tl)

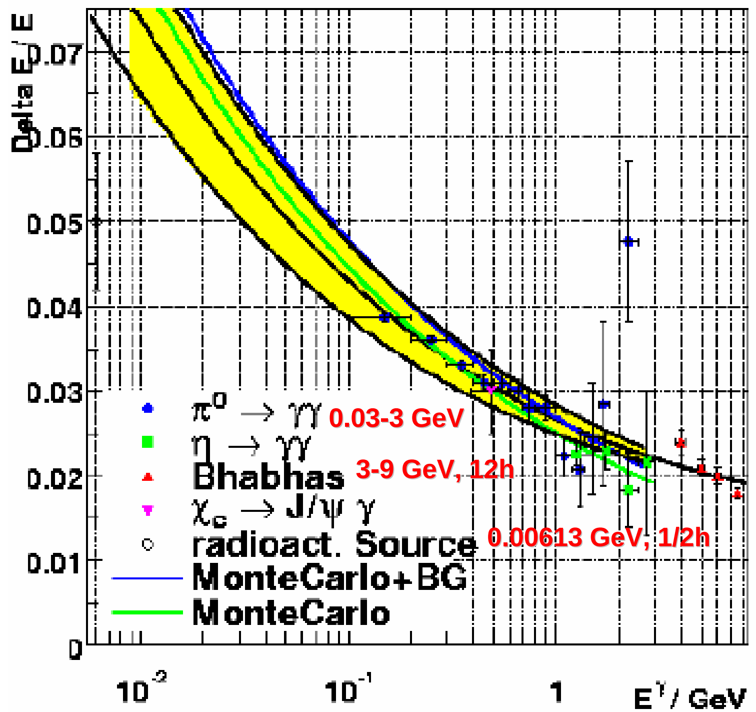


6580 CsI(Tl)

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

Energy resolution

M. Kocian, SLAC, CALOR2002



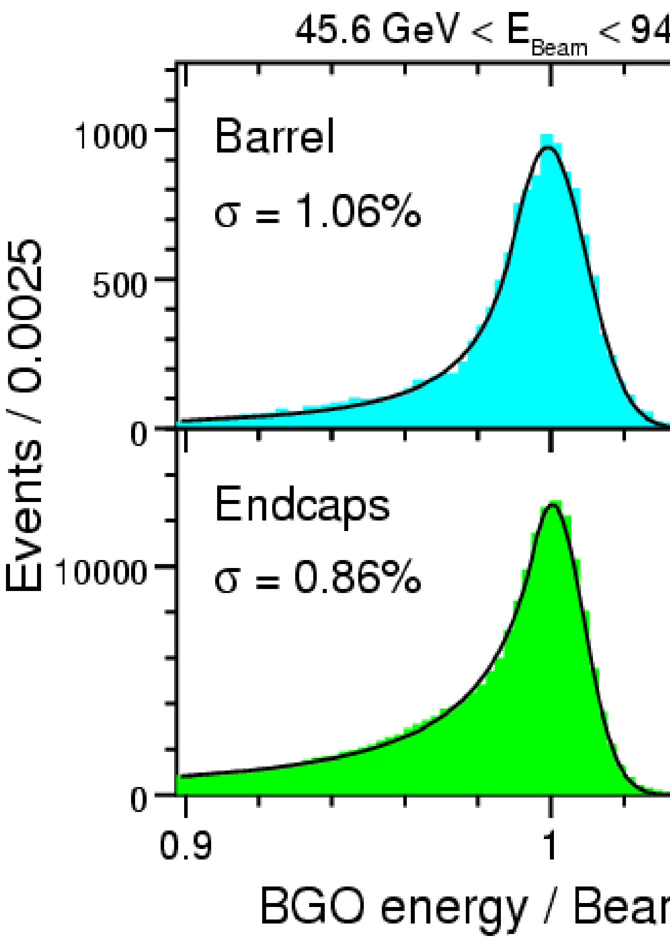
$$\frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt[4]{E}} \oplus \sigma_2$$

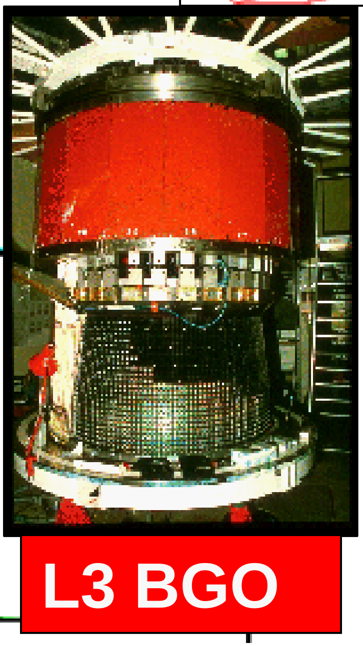
$$\sigma_1 = (2.30 \pm 0.03 \pm 0.3)\%$$

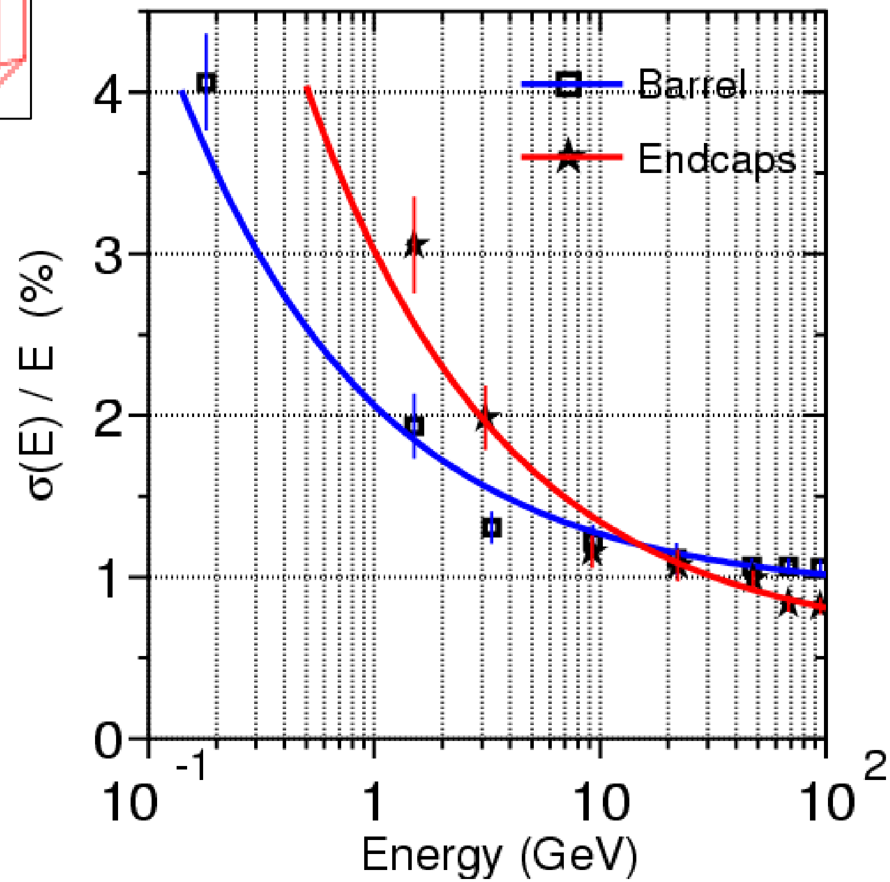
$$\sigma_2 = (1.35 \pm 0.08 \pm 0.2)\%$$

L3 BGO Energy Resolution

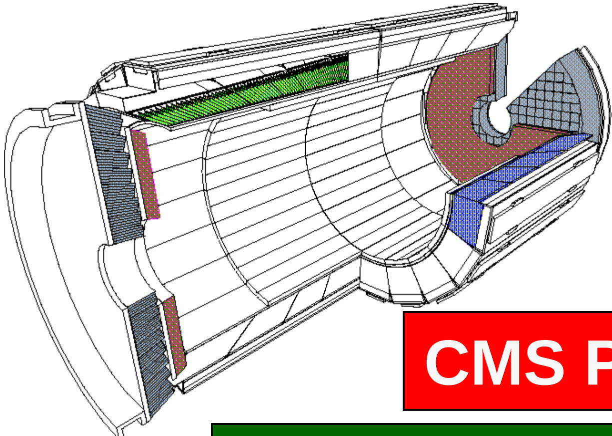
Contribution	“Radiative”+Intrinsic	Temperature	Calibration	Overall
Barrel	0.8%	0.5%	0.5%	1.07%
Endcaps	0.6%	0.5%	0.4%	0.88%







CMS PWO Energy Resolution



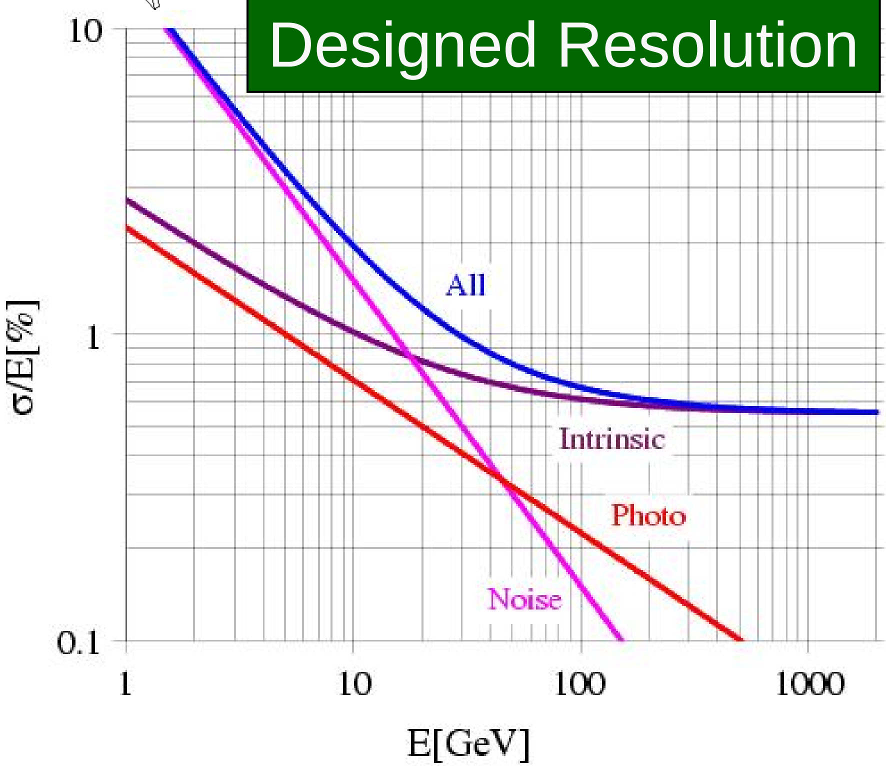
Measured Resolution

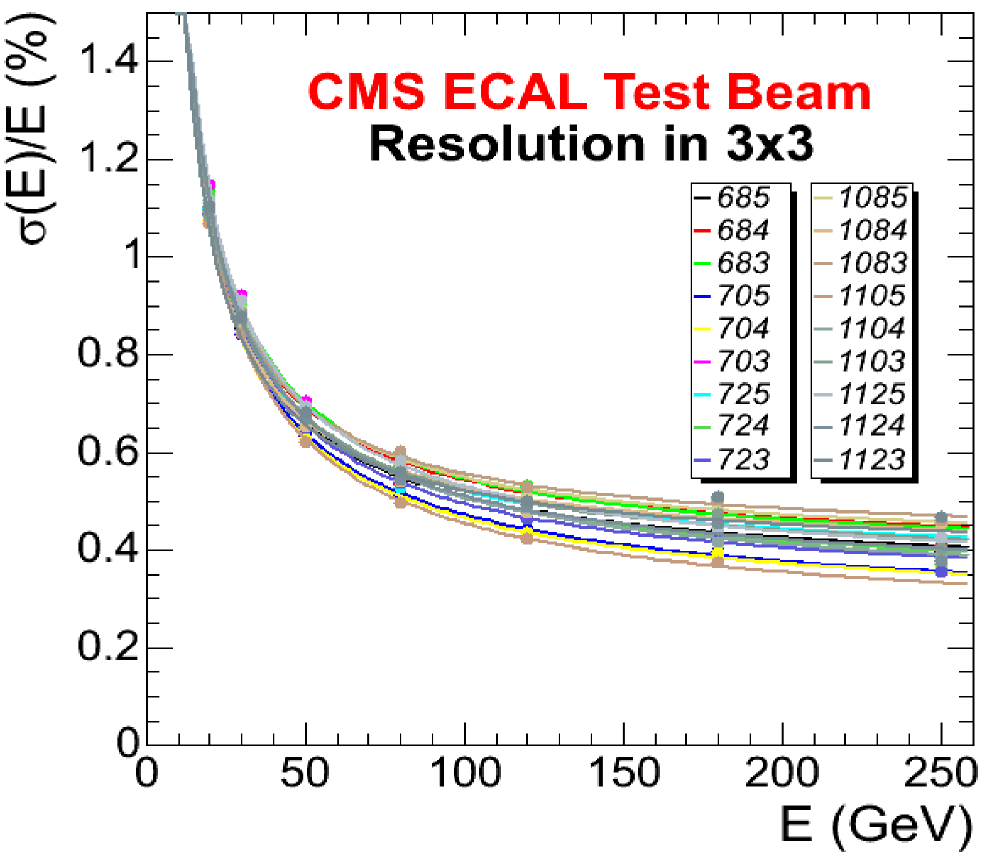
$\sigma(E)/E < 1\%$ if $E > 25$ GeV

$\sigma(E)/E \sim 0.5\%$ at 120 GeV

CMS PWO

Designed Resolution



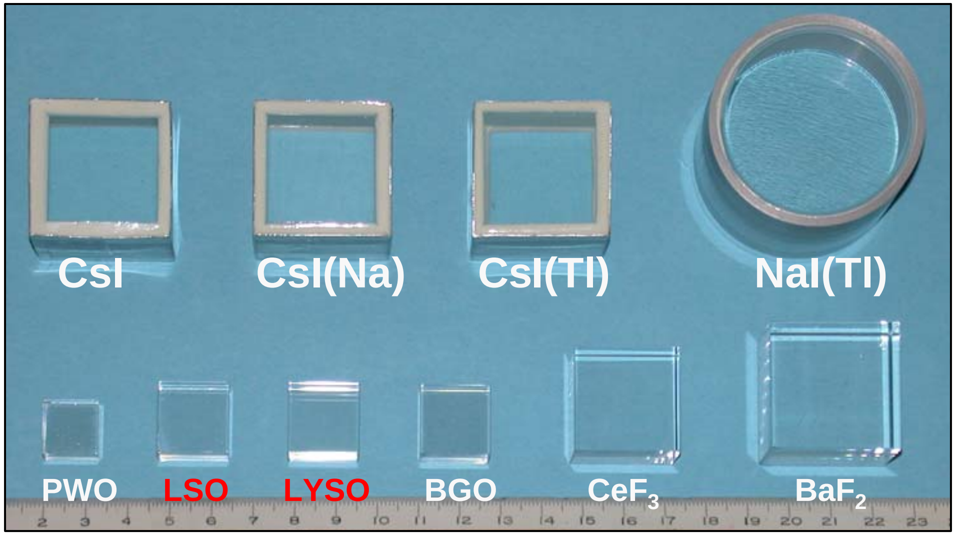


Bright Fast Dense LSO Crystal

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 (ºC)	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	1.62	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] (%/ ºC)	-0.2	0.4	0.4	-1.4	0	-1.9 0.1	-0.9	-2.5	-0.2

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

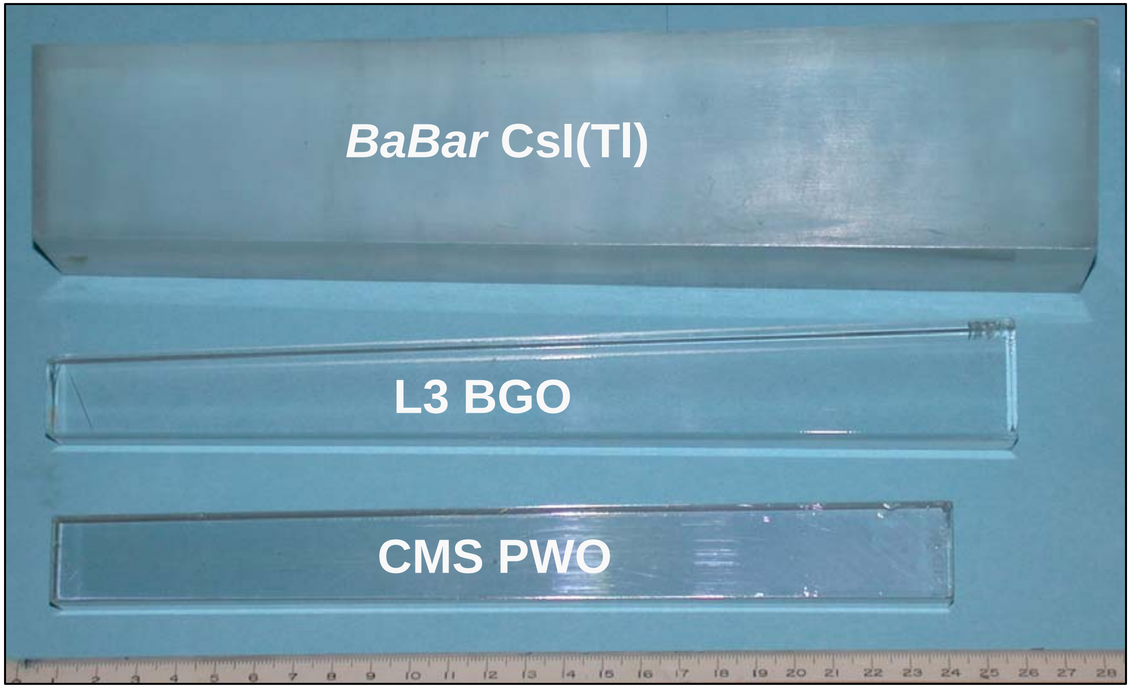
Crystal Density: Radiation Length



1.5 X_0 Cubic Samples:

Hygroscopic Halides

Non-hygroscopic



Full Size Crystals:

BaBar CsI(Tl): 16 X_0

L3 BGO: 22 X_0

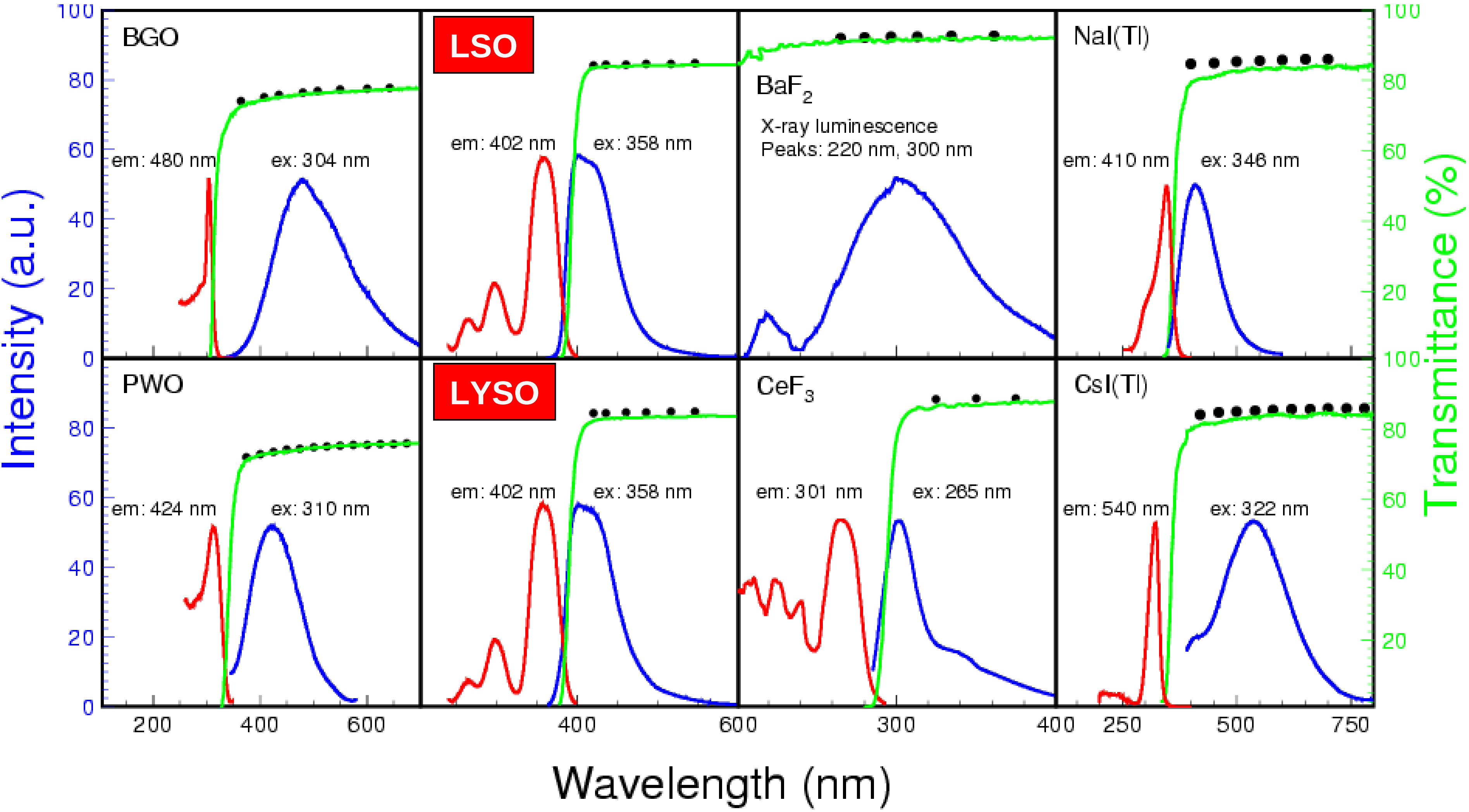
CMS PWO(Y): 25 X_0

Excitation, Emission, Transmission

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

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

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

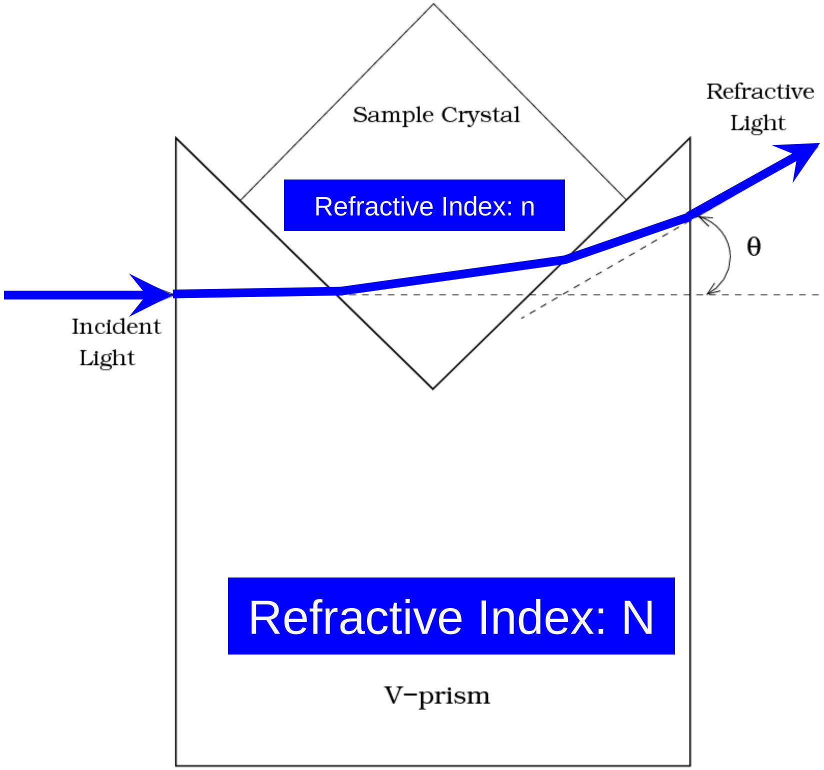


LSO/LYSO Refractive Index

Wavelength dependent measurement by a V-prism

- Cubic sample placed inside a V-prism
- Incident light shooting perpendicularly to one side of the prism
- The refractive index is calculated according to the following the equation:

$$n = \left(N^2 + \sin\theta\sqrt{N^2 - \sin^2\theta} \right)^{\frac{1}{2}}$$

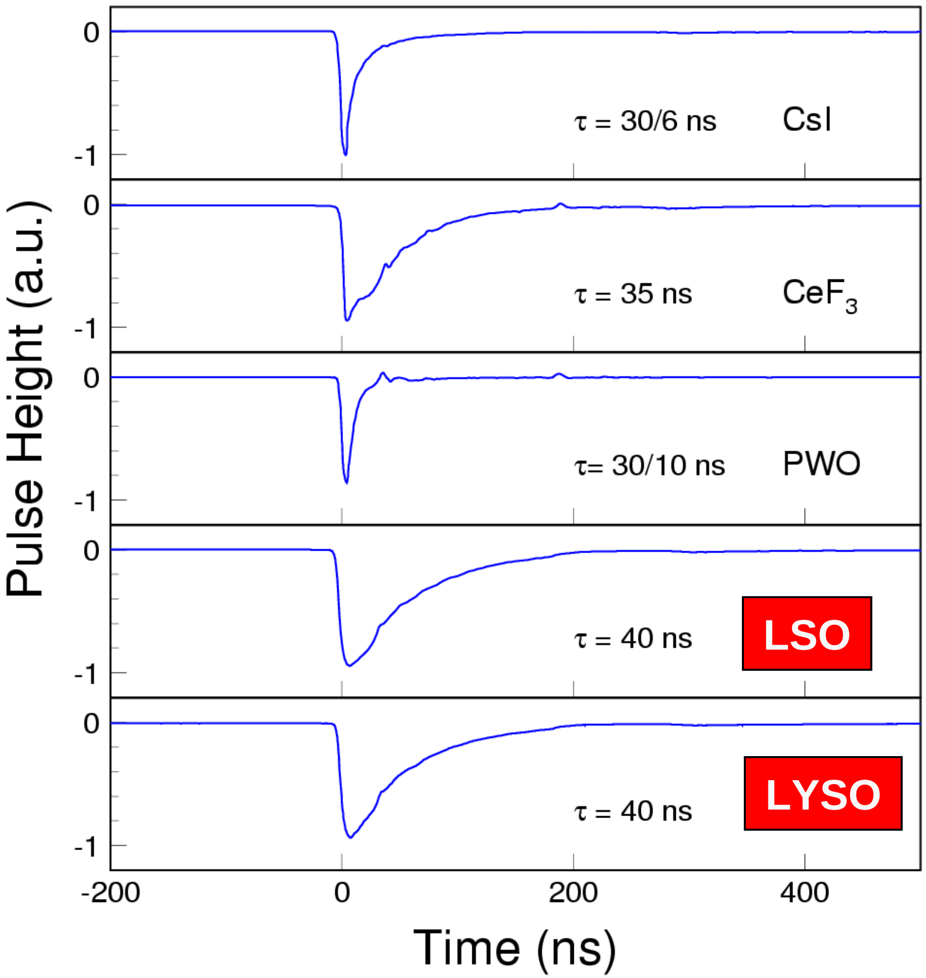


λ (nm)	405	420	436	461	486	516	546
R. I.	1.833	1.827	1.822	1.818	1.813	1.810	1.806

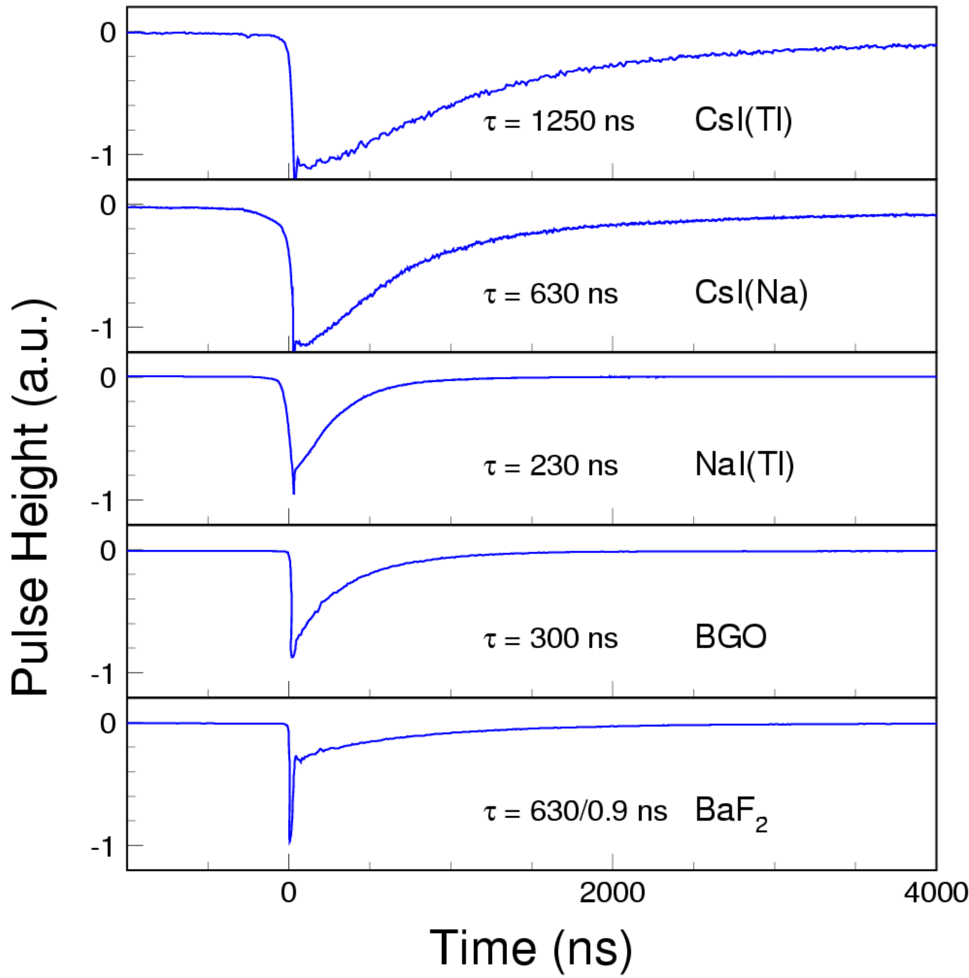
Scintillation Light Decay Time

Recorded with an Agilent 6052A digital scope

Fast Scintillators



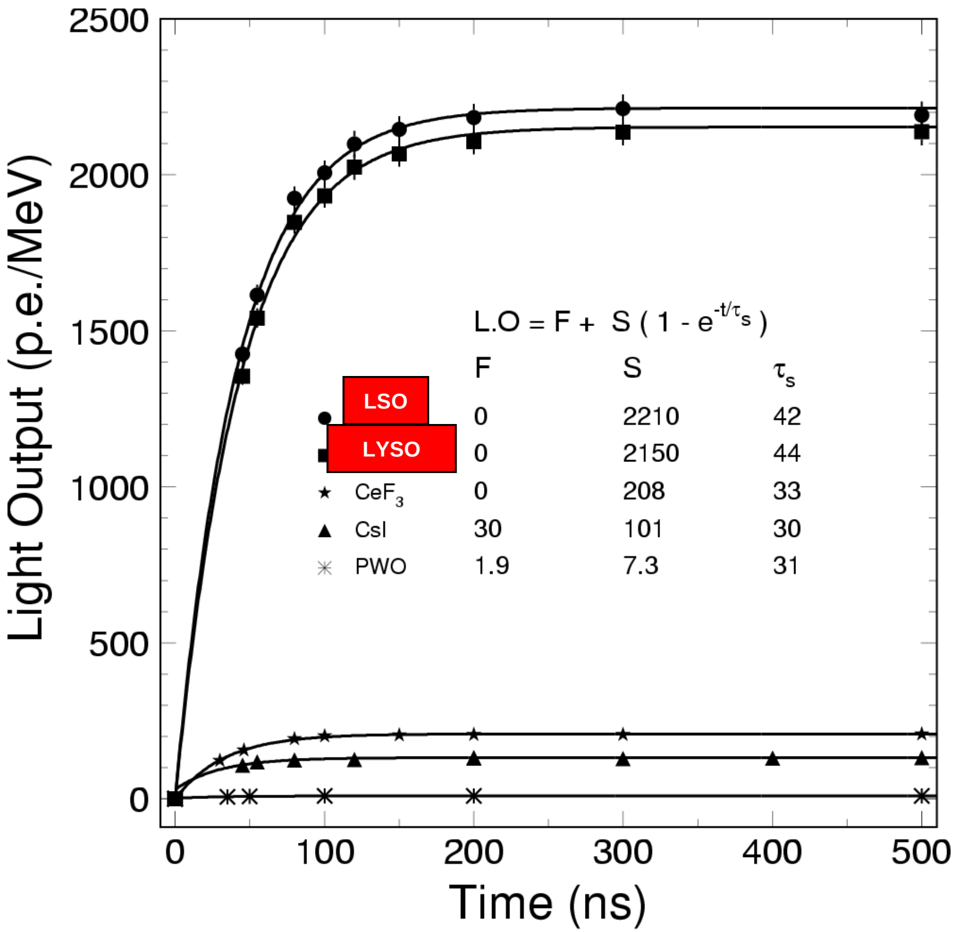
Slow Scintillators



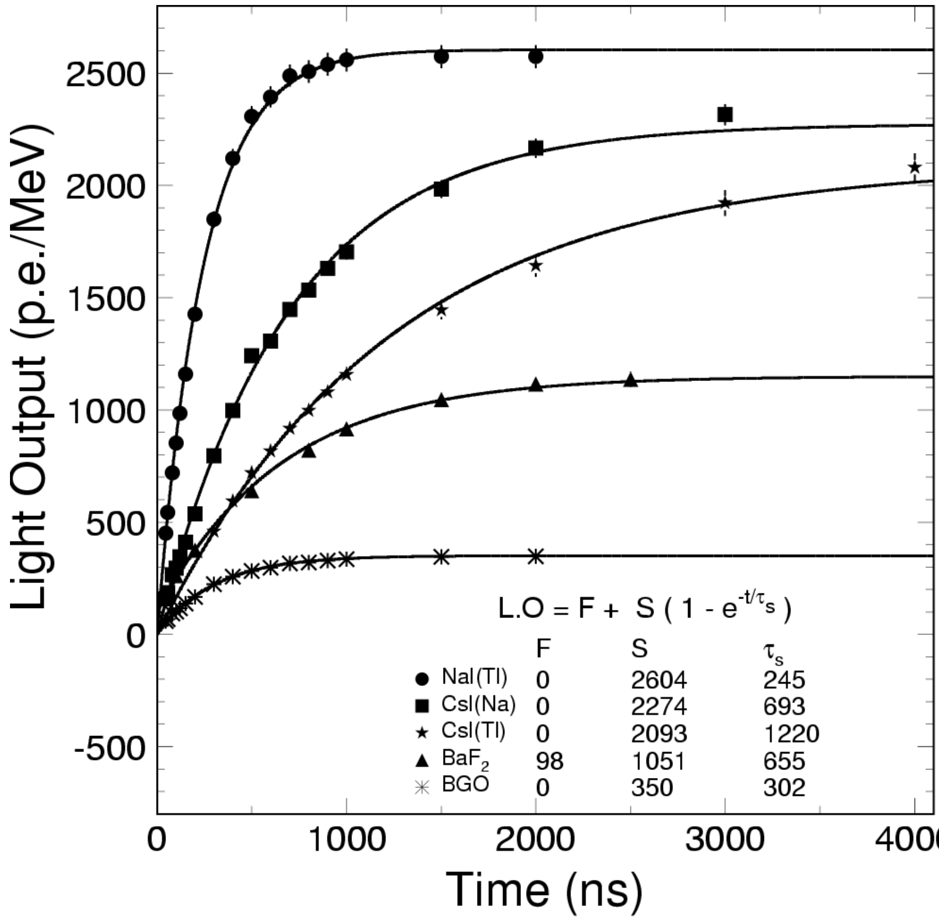
Light Output & Decay Kinetics

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

Fast Scintillators

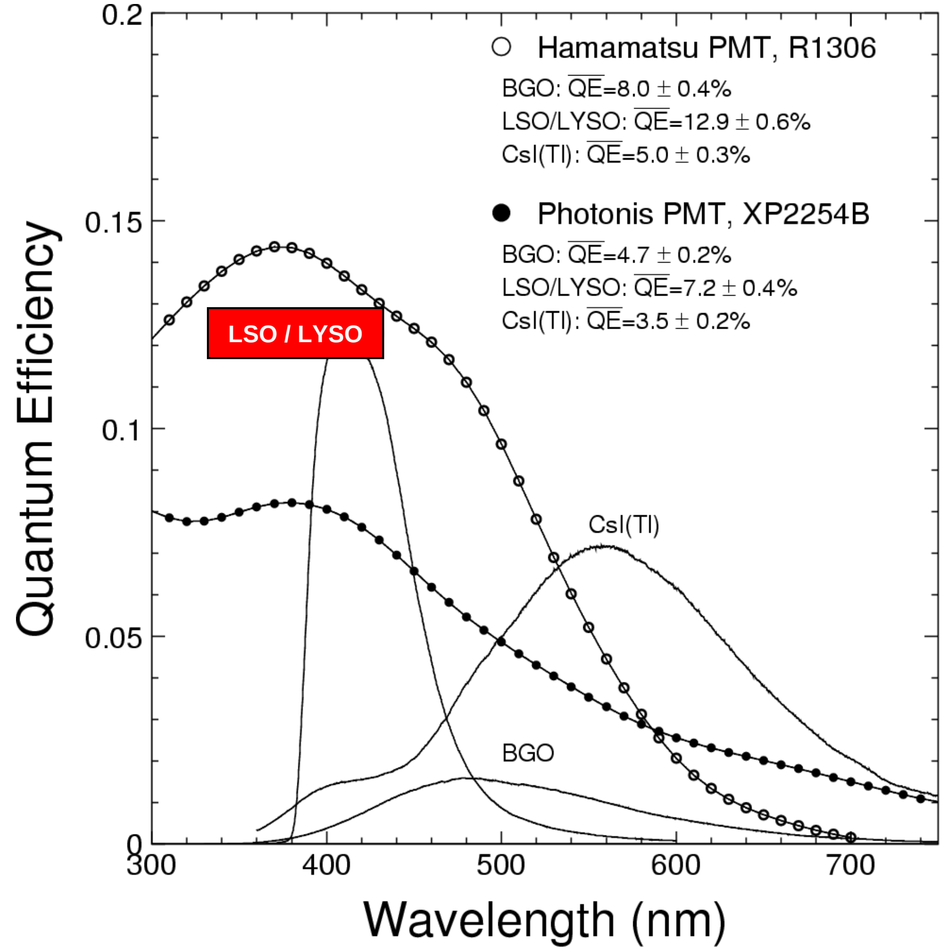


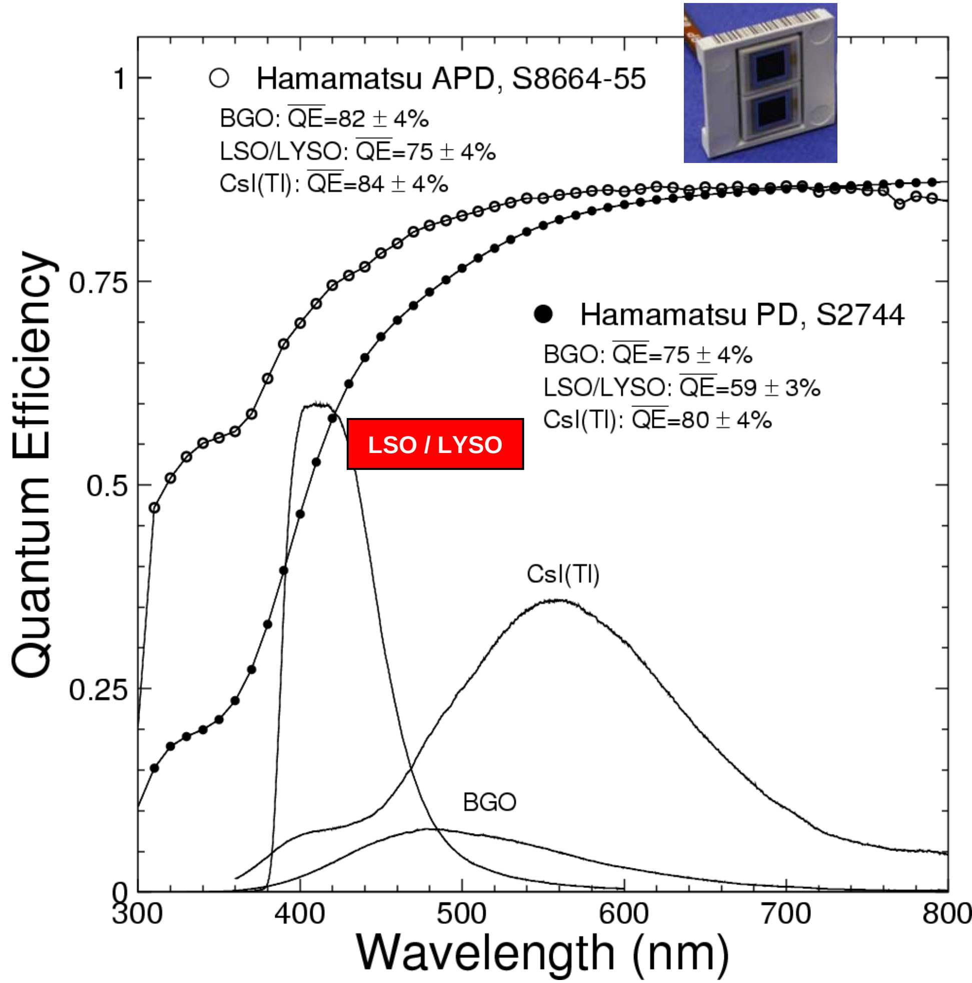
Slow Scintillators



Emission Weighted Quantum Efficiency

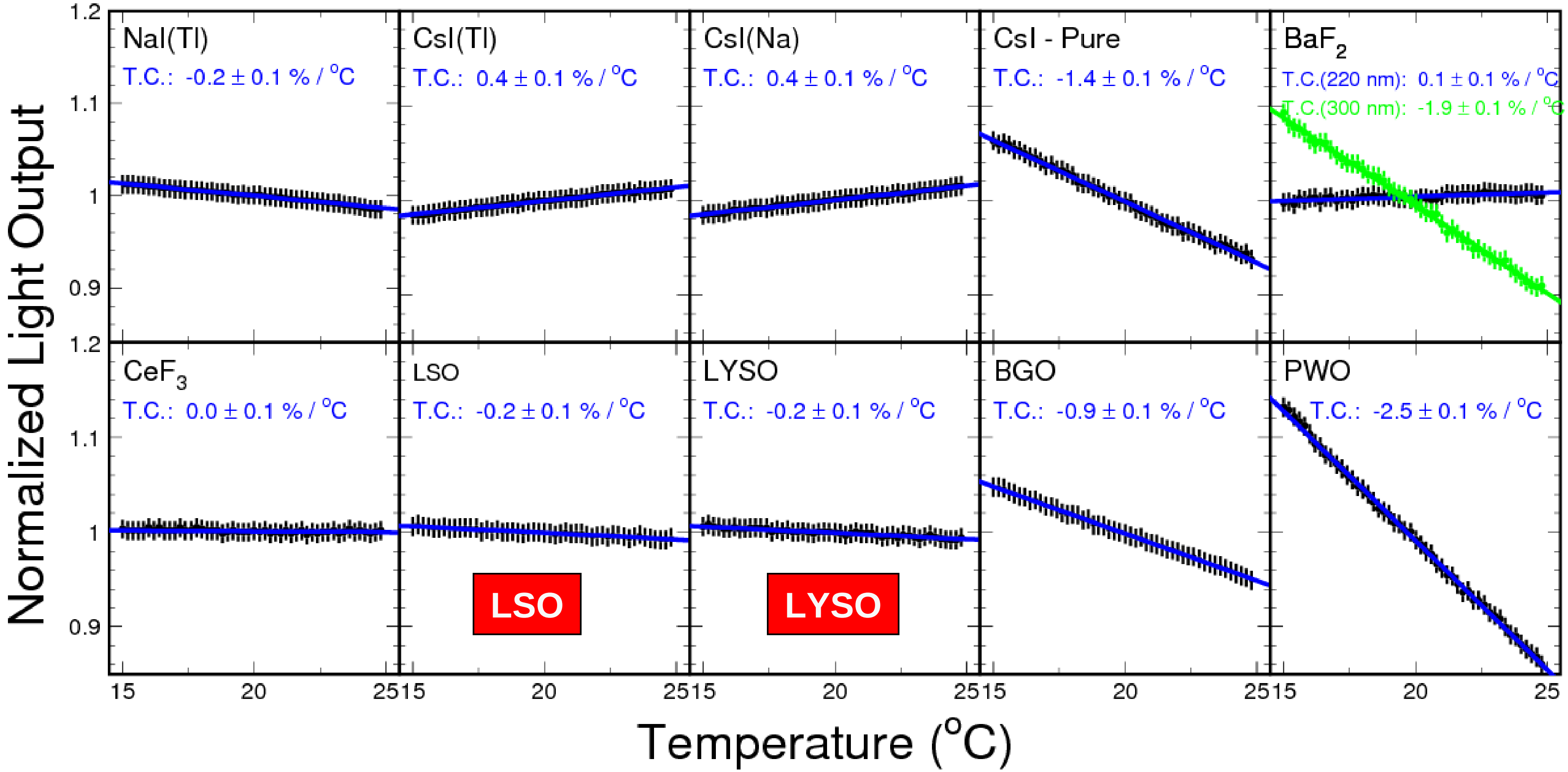
Taking out QE, L.O. of LSO/LYSO is 4/200 times BGO/PWO
Hamamatsu S8664-55 APD has QE 75% for LSO/LYSO





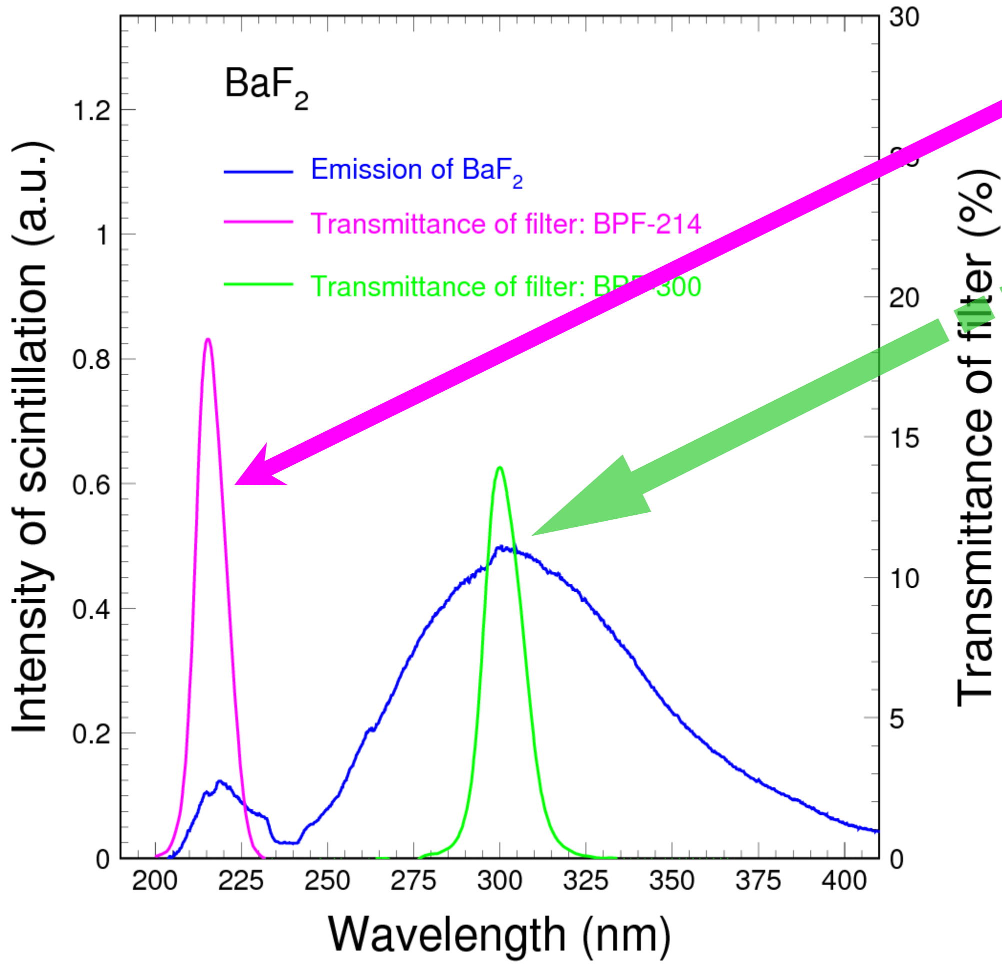
Light Output Temperature Coefficient

Temperature Range: 15ºC ~ 25ºC



BaF_2: Fast and Slow Components

Two filters used to select scintillation component



Transmittance for filter BPF-214 (fast component)

Transmittance for filter BPF-300 (slow component)

- Scintillation of BaF_2 has two components: the fast one peaked at 220 nm while the slow one peaked at 300 nm.
- Special band pass filters were used to measure the light output temperature coefficients for individual component.

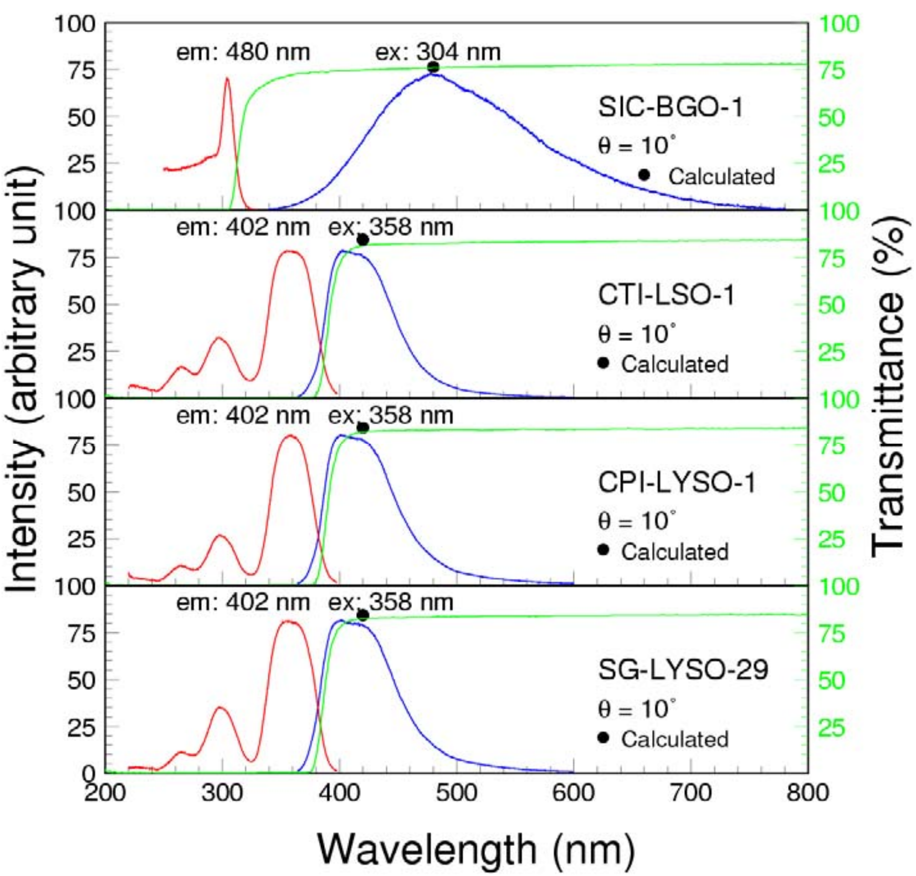
Comparison of BGO, LSO & LYSO

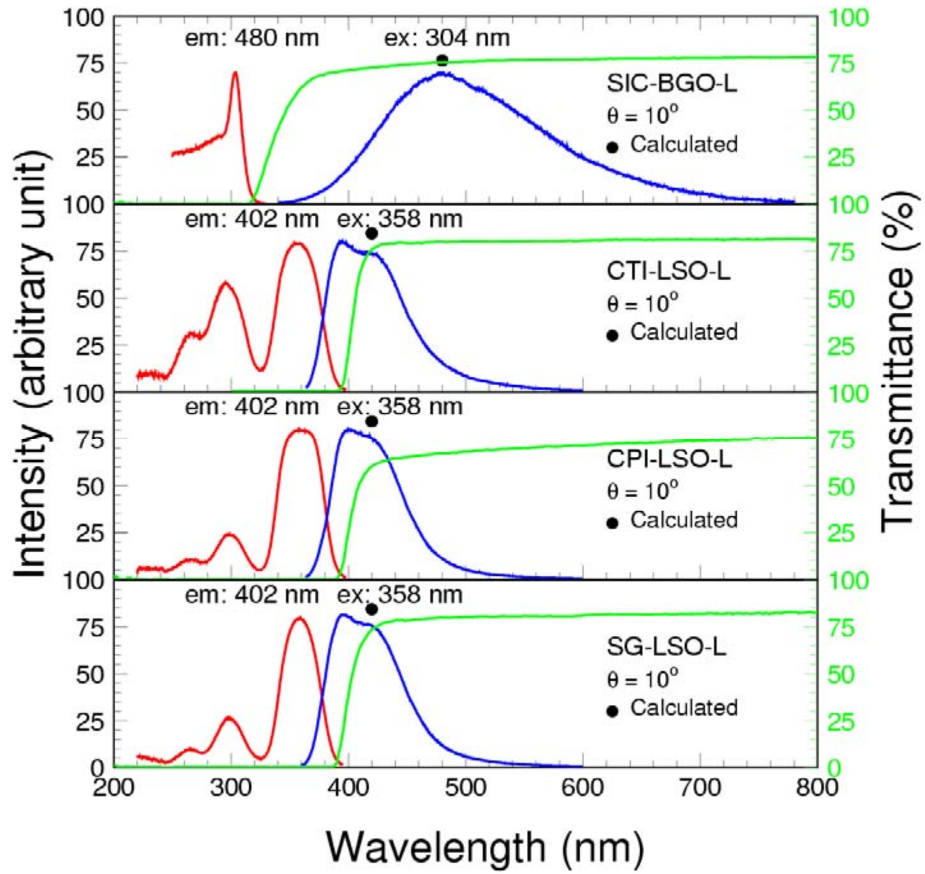
2.5 x 2.5 x 20 cm (18 X_0) Bar

Excitation, Emission, Transmission

Identical transmittance, emission & excitation spectra
Part of emitted light may be self-absorbed in long samples

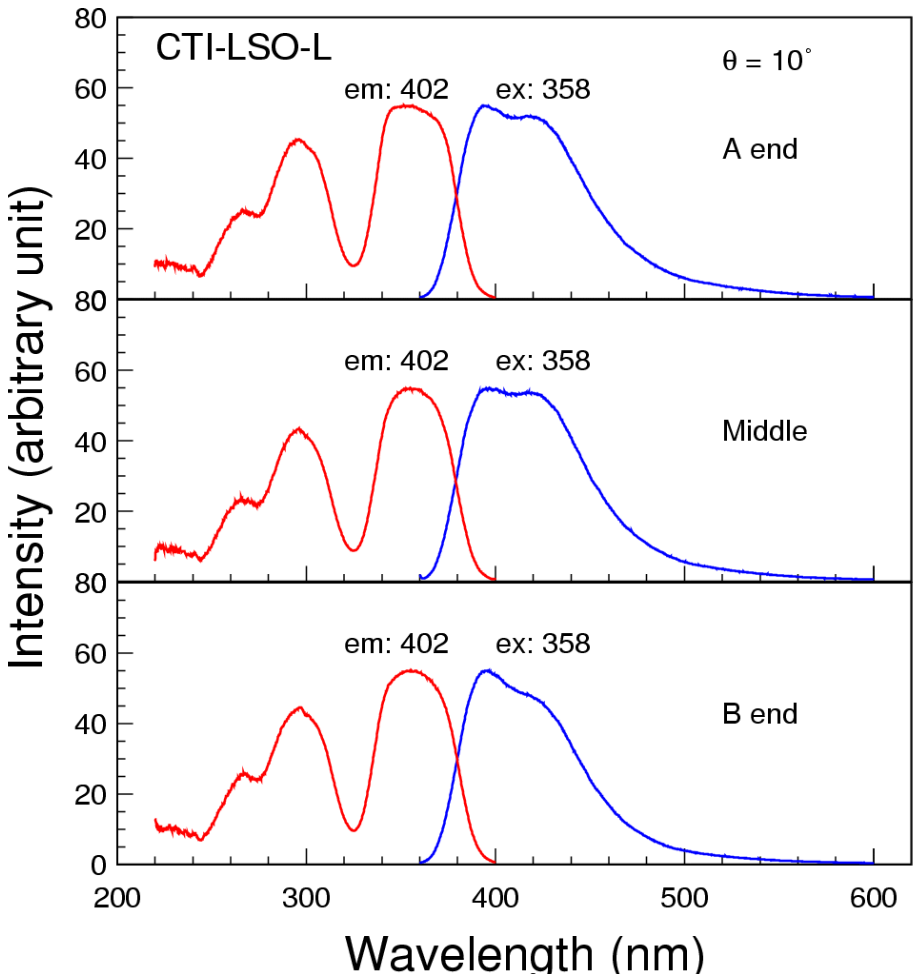
1.7 cm Cube	2.5 x 2.5 x 20 cm Bar

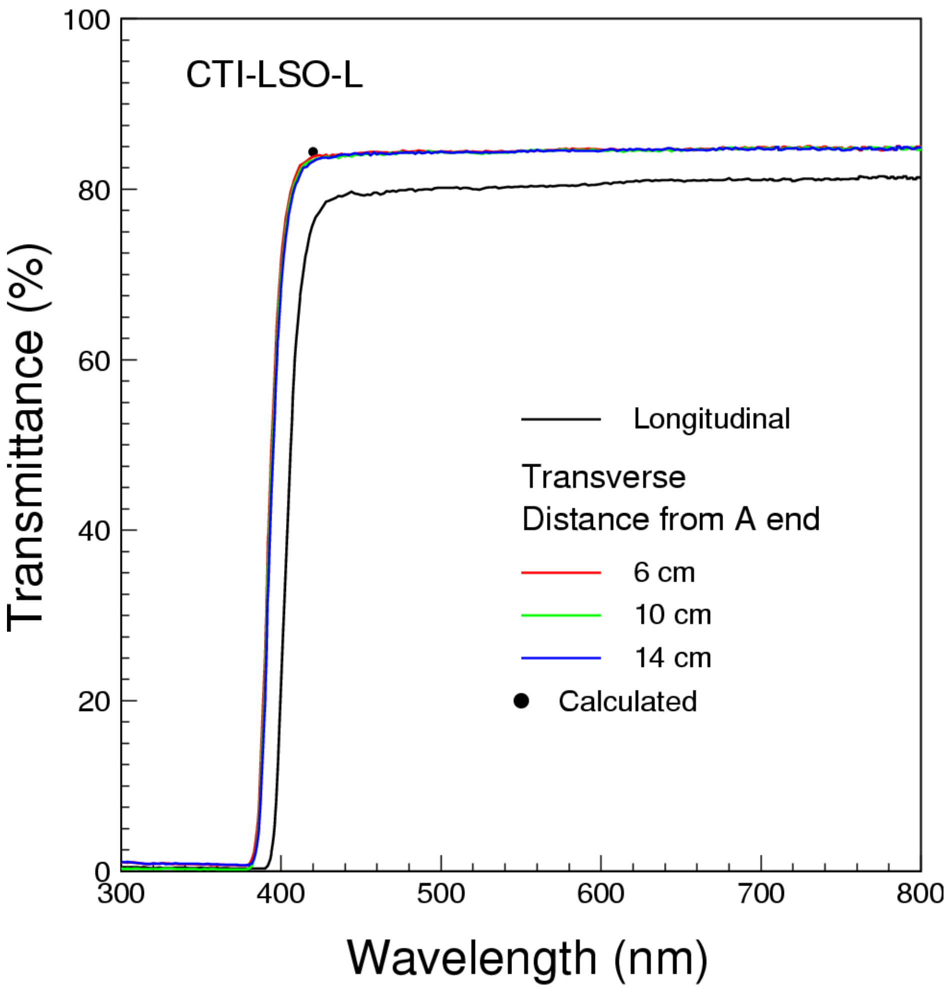




CTI LSO: Longitudinal Uniformity

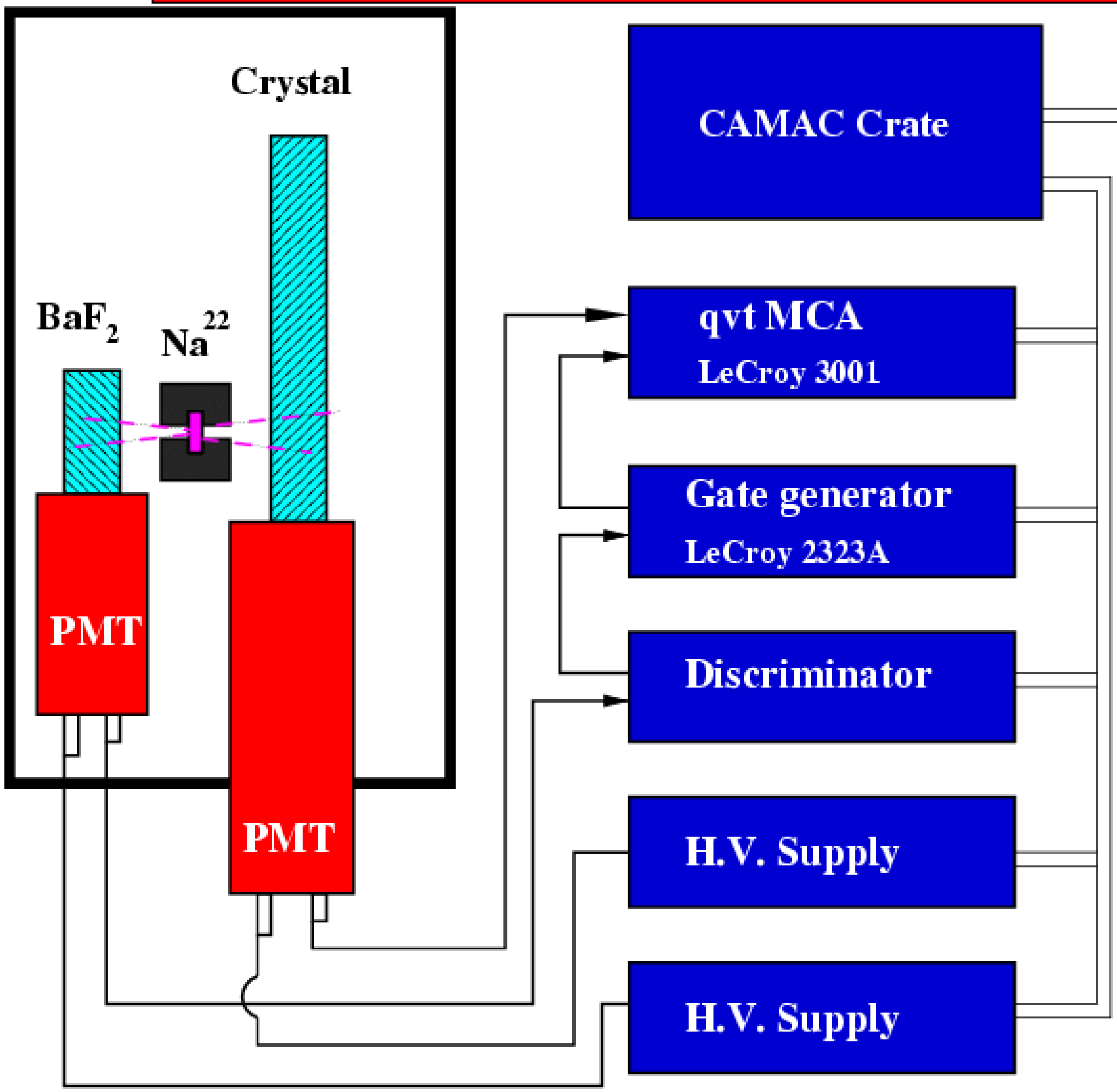
No longitudinal variation in optical properties
Transverse transmittance approaches theoretical limit

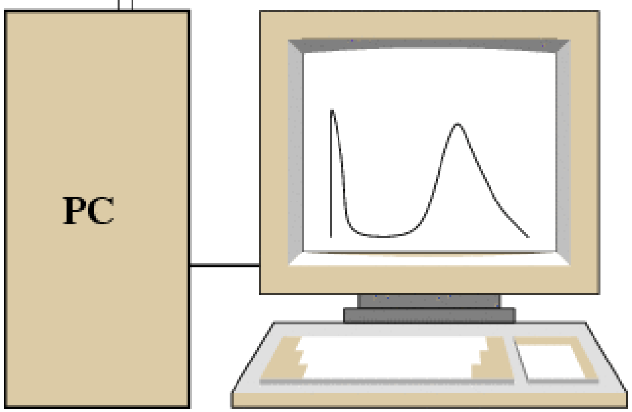


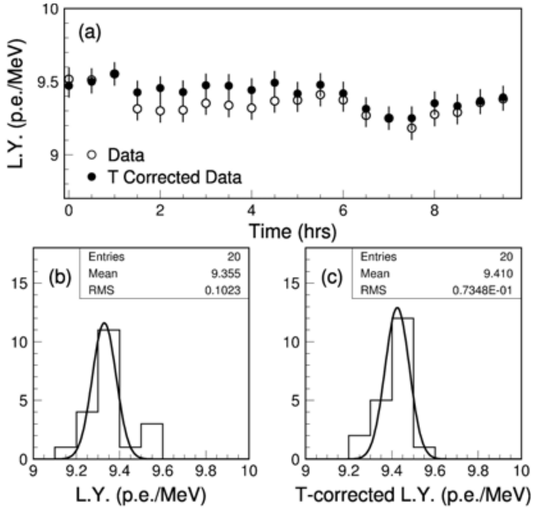


PMT Based Readout with Coincidence

Systematic error with repeated mounts & measurements: < 1%





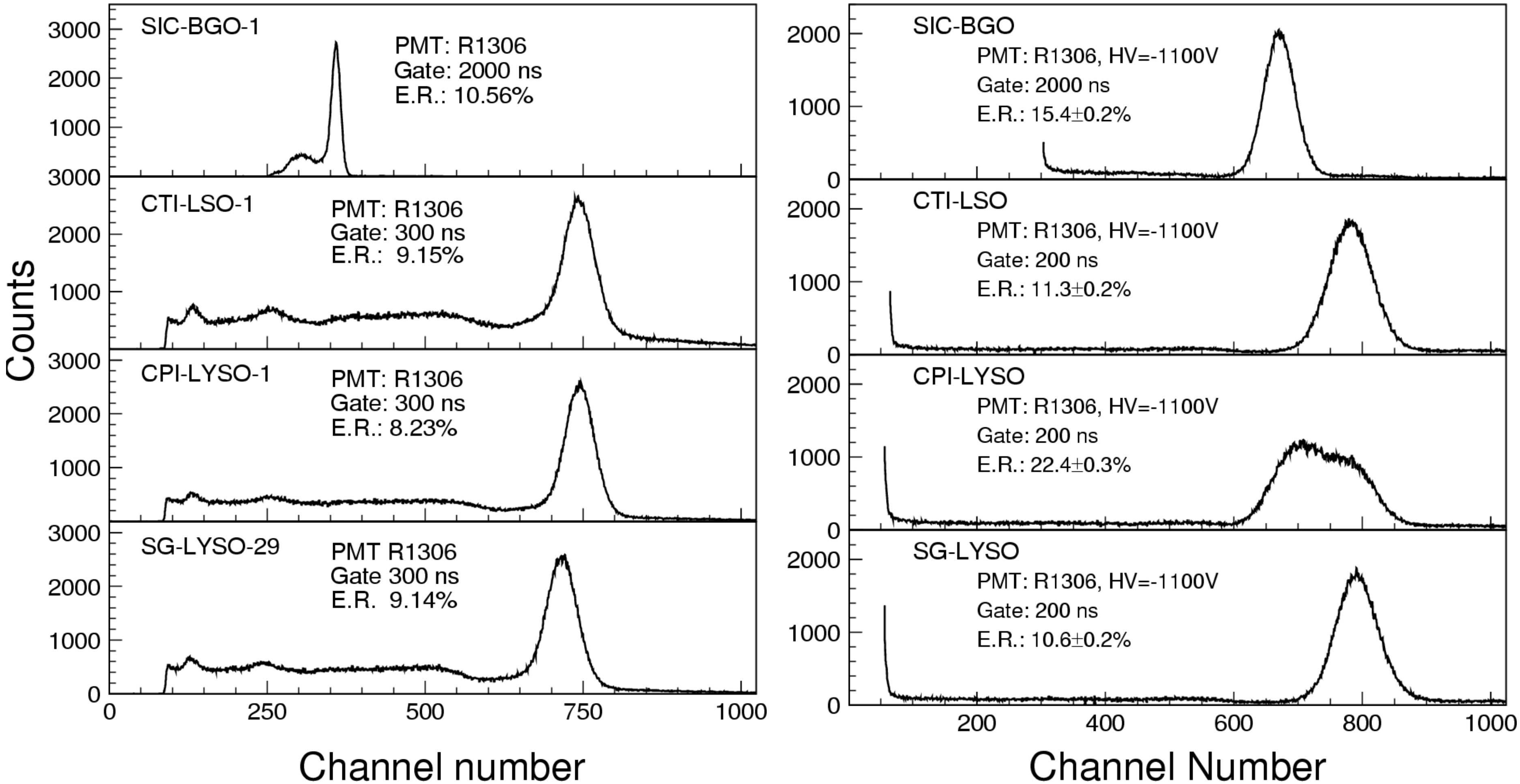


LSO/LYSO Resolution with PMT

~10% FWHM resolution for ^{22}Na source (0.51 MeV)

1.7 cm Cube

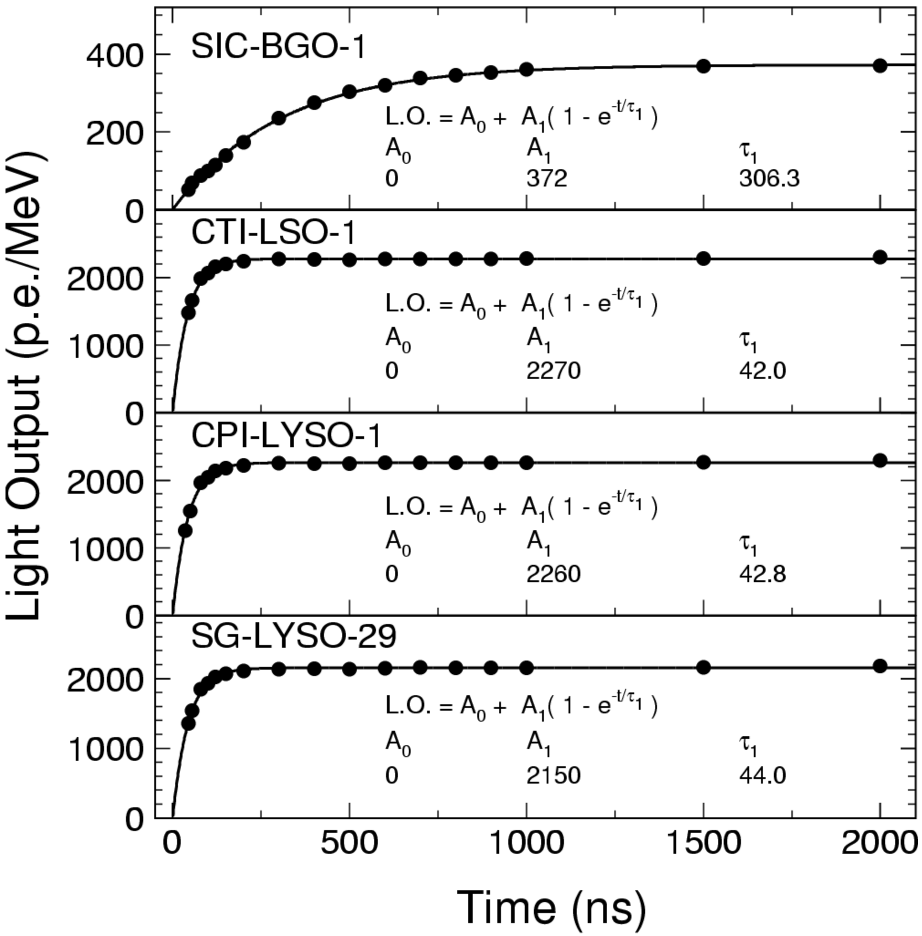
2.5 x 2.5 x 20 cm Bar

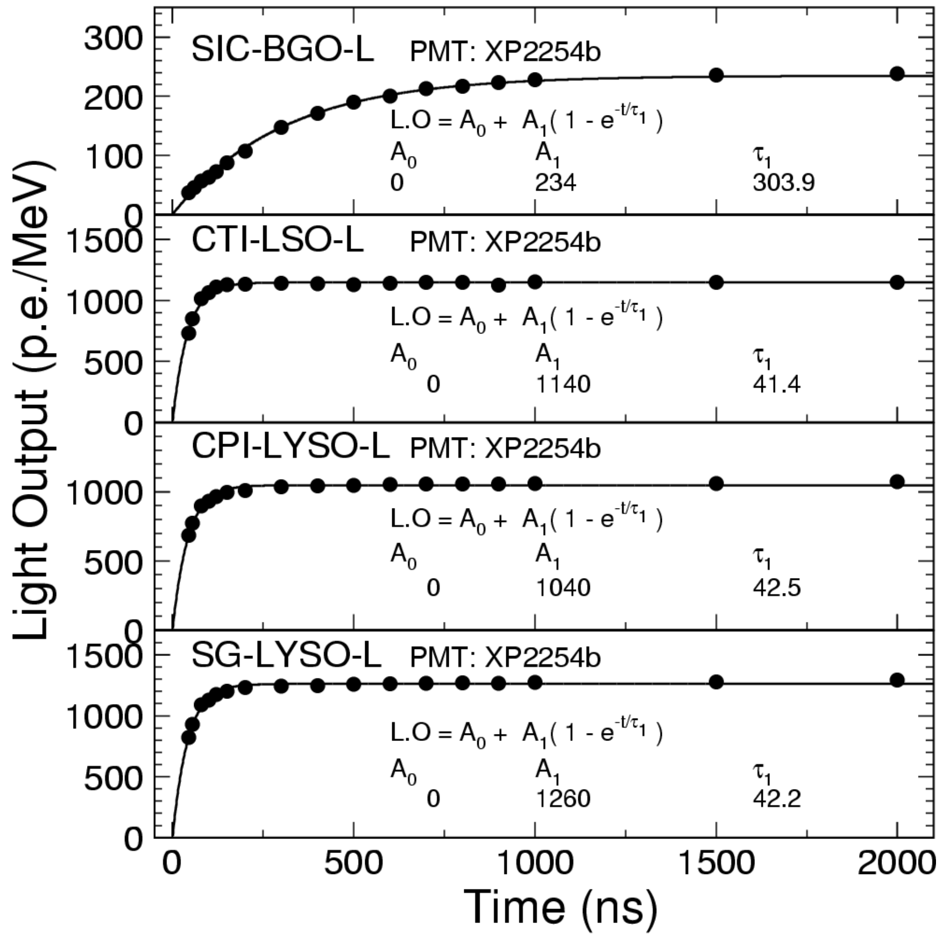


LSO/LYSO Light Output with PMT

1,200 p.e./MeV, 5/230 times of BGO/PWO

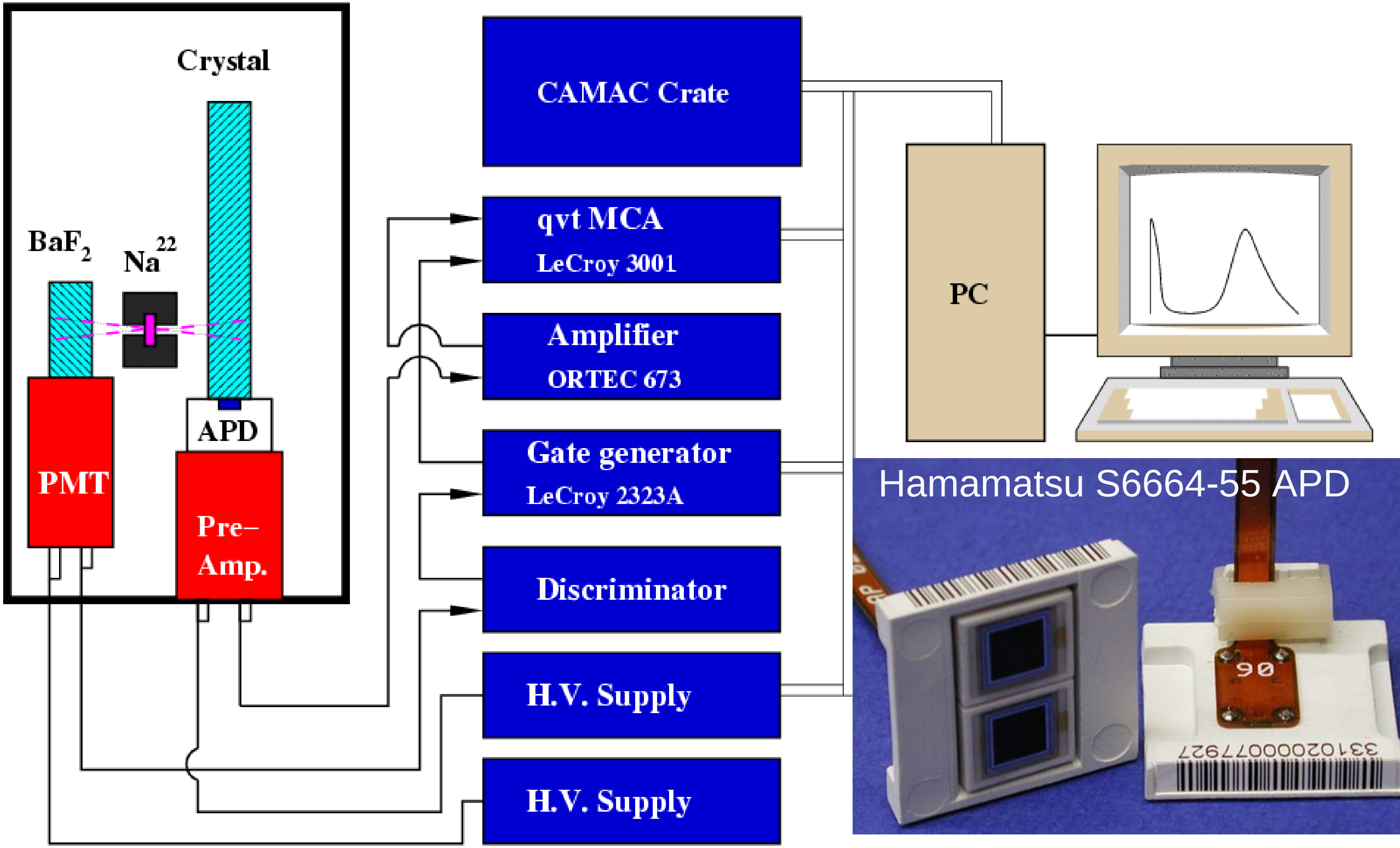
1.7 cm Cube	2.5 x 2.5 x 20 cm Bar





APD Based Readout with Coincidence

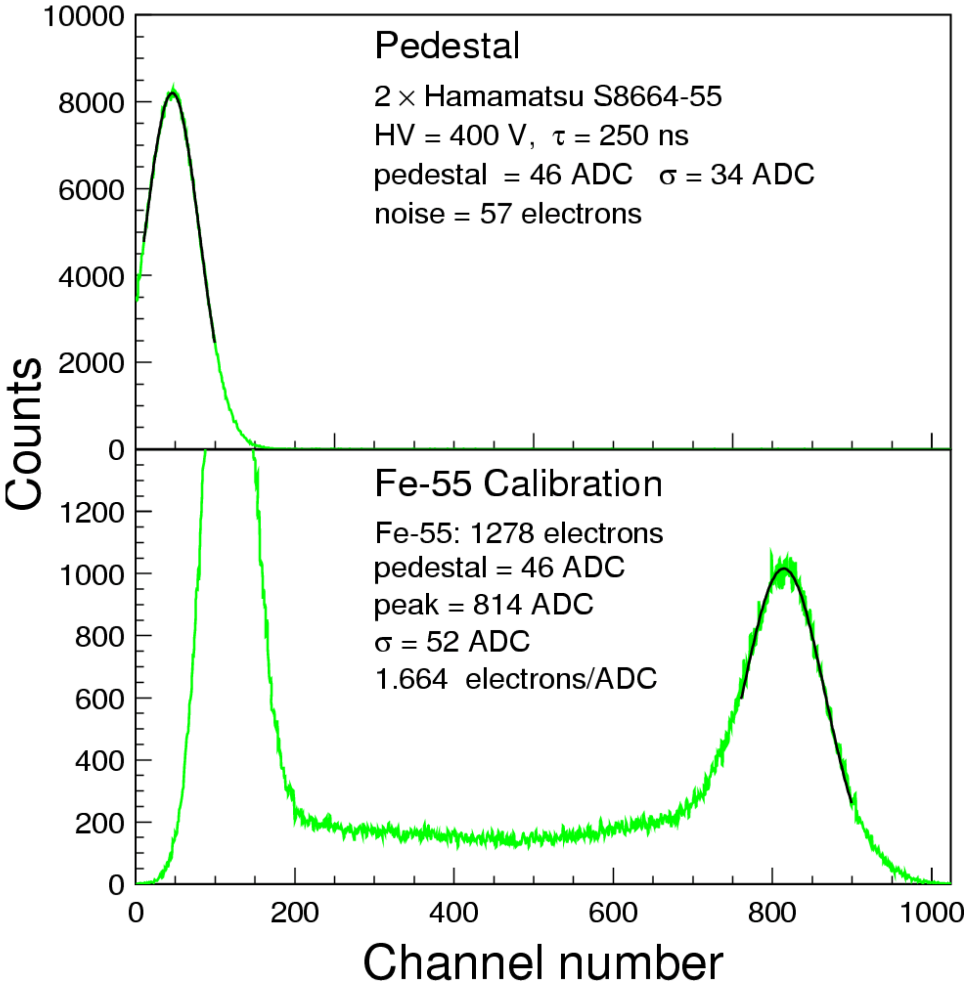
Two Hamamatsu S6664-55 APD, Canberra 2003 BT preamplifier and ORTEC 673 shaping amplifier with shaping time 250 ns

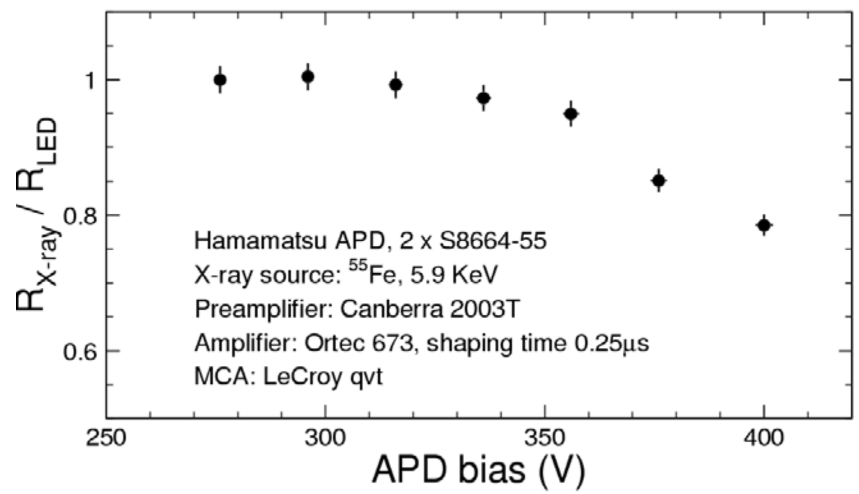


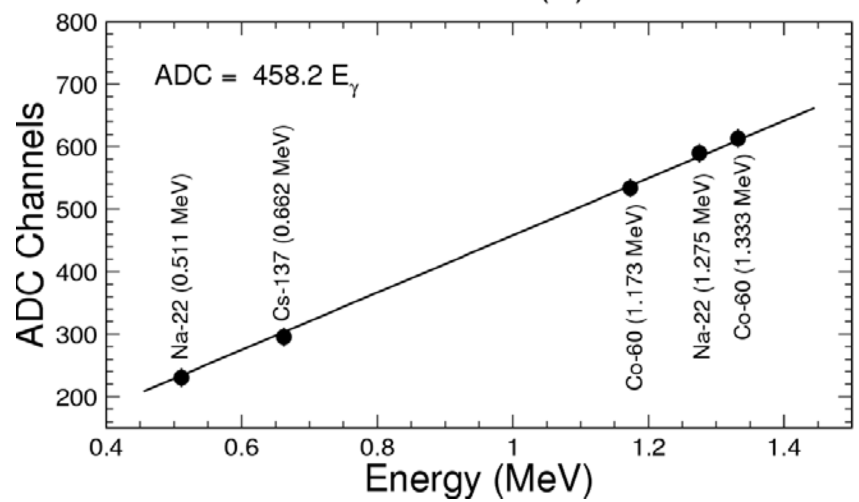
Hamamatsu S6664-55 APD

Calibration of the APD Readout

Pedestal: 34 ADC, corresponding to 57 electrons
Corrections for 5.9 keV X-ray: 78%; Good linearity



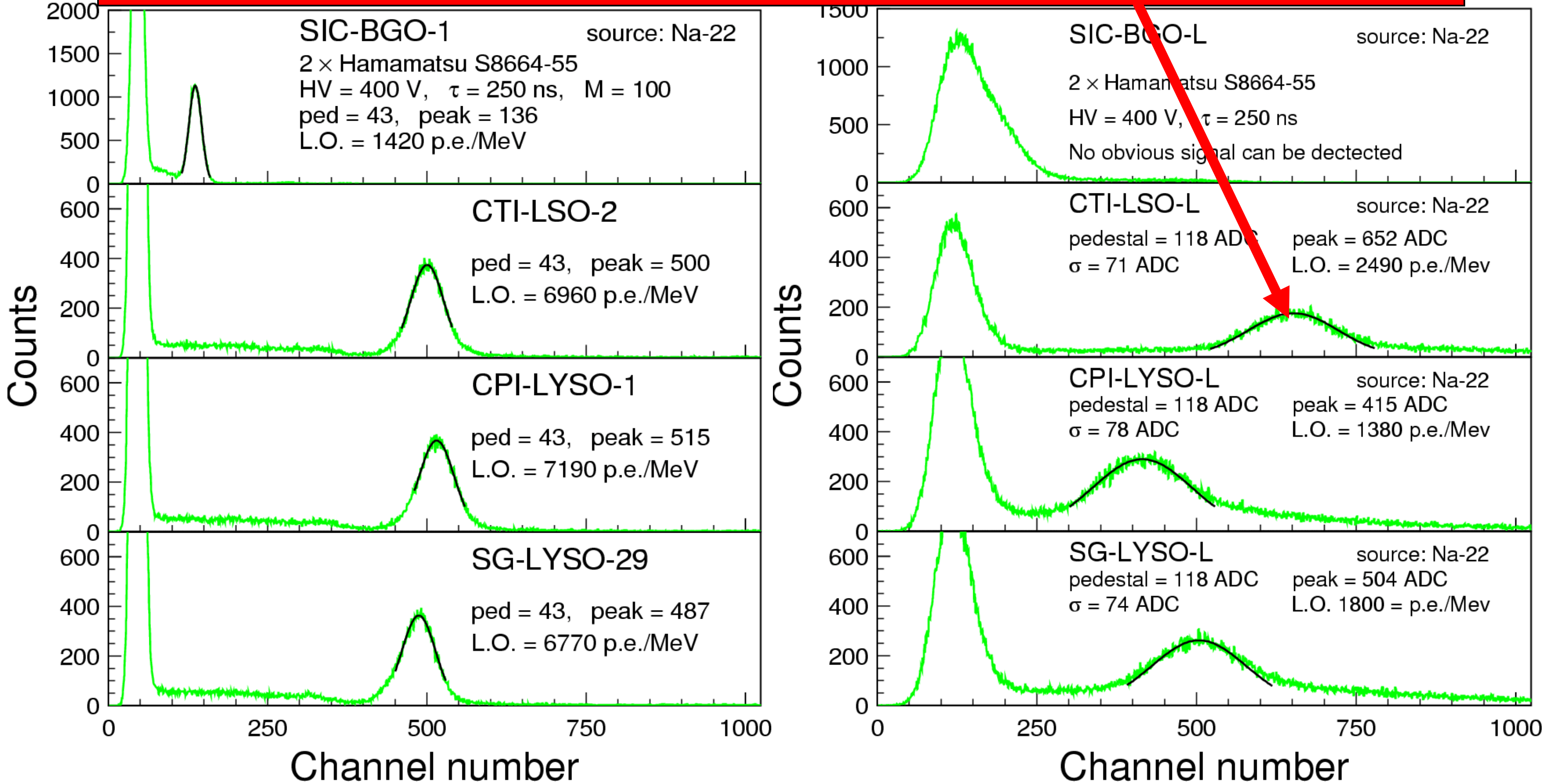




LSO/LYSO Light Output with APD

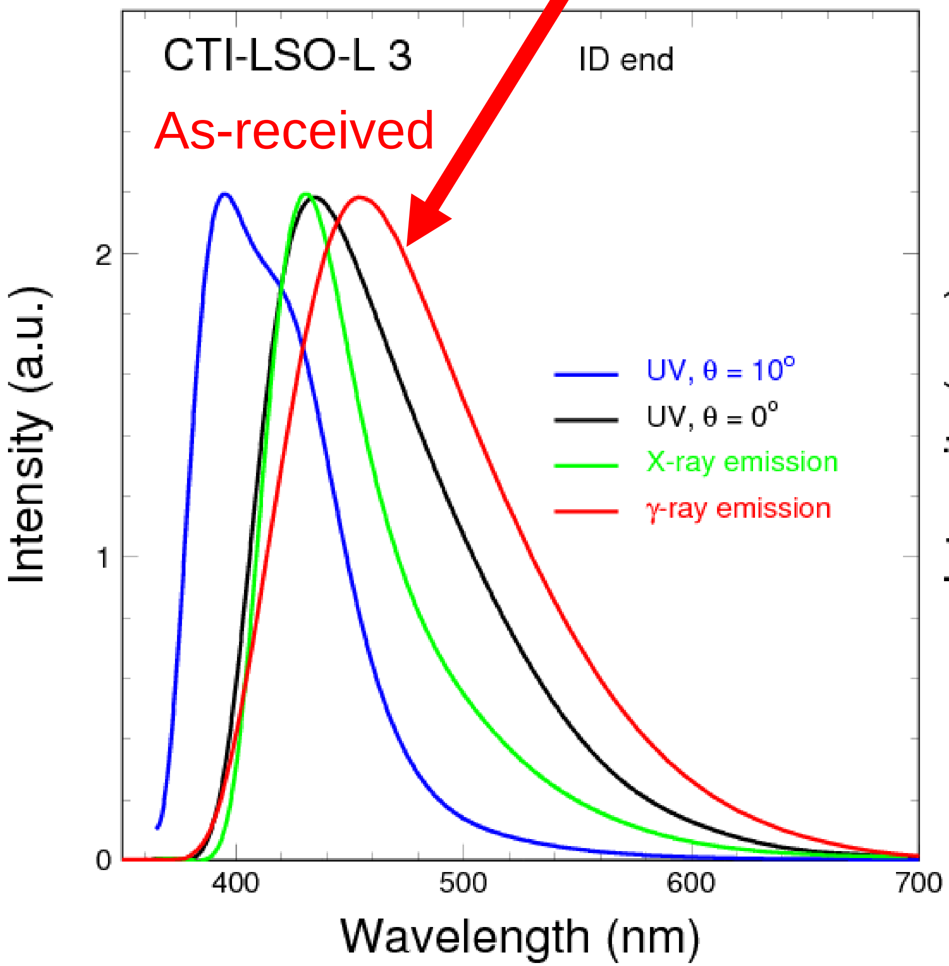
1,500 p.e./MeV, 4/200 times of BGO/PWO, Noise < 40 keV

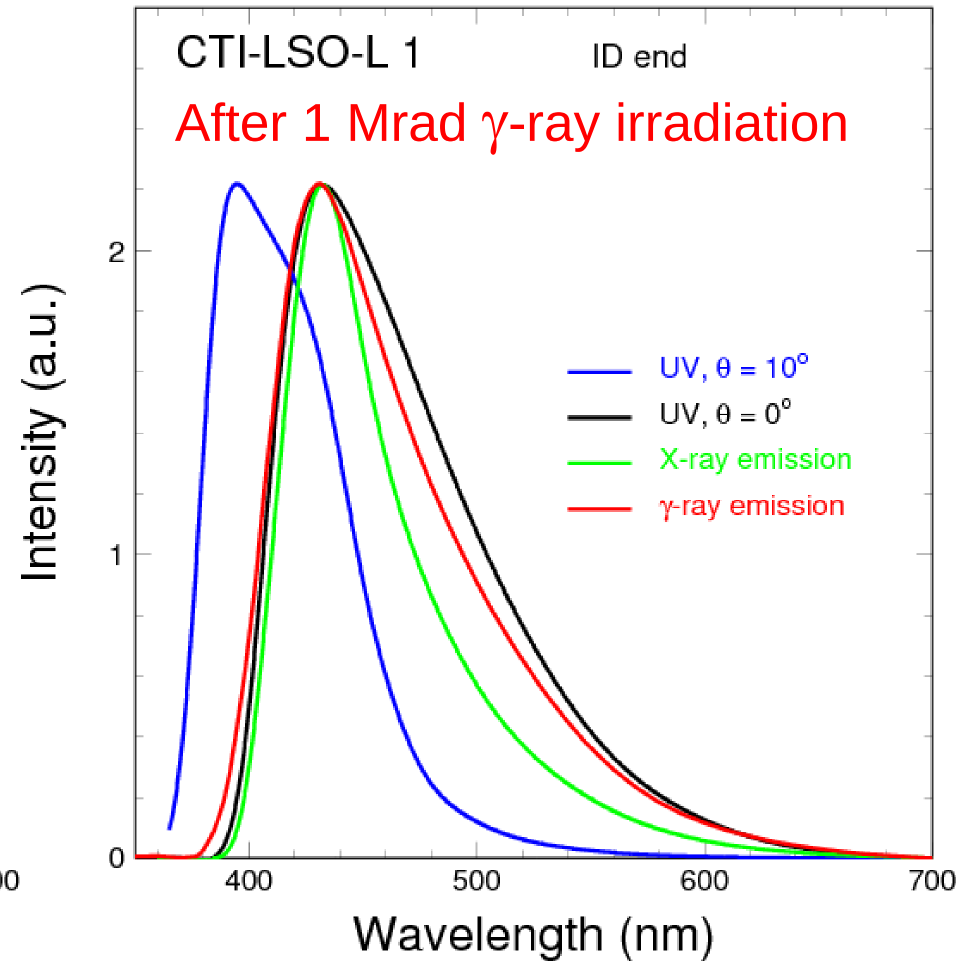
Discrepancy reported in NSS05: LSO has more light output, which disappeared after irradiation to 1 Mrad and thermal annealing.



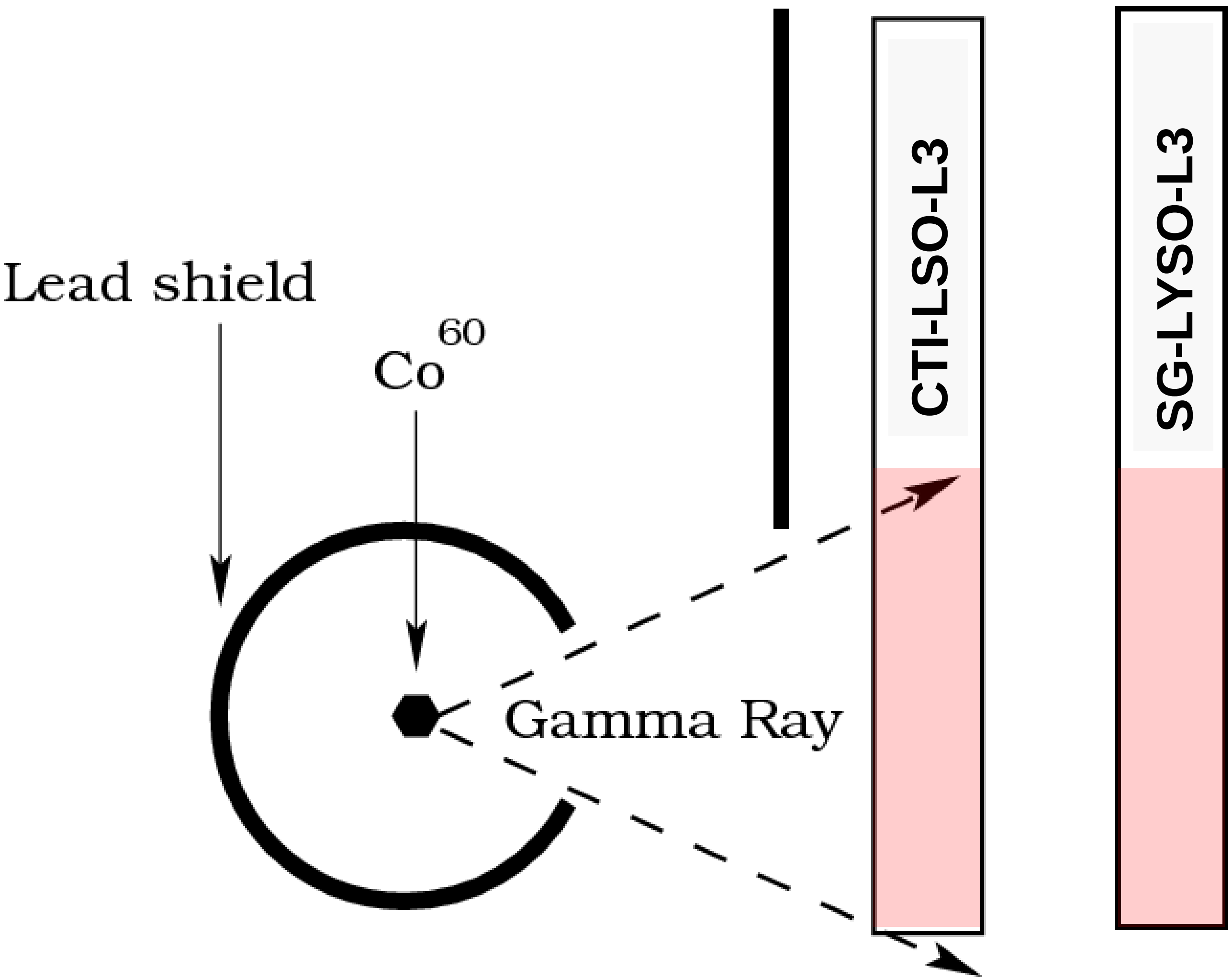
LSO Emission Spectra

All emission spectra are similar to that of LYSO, except that γ-ray excited emission has a “red shift”, which disappeared after irradiations with γ-ray.





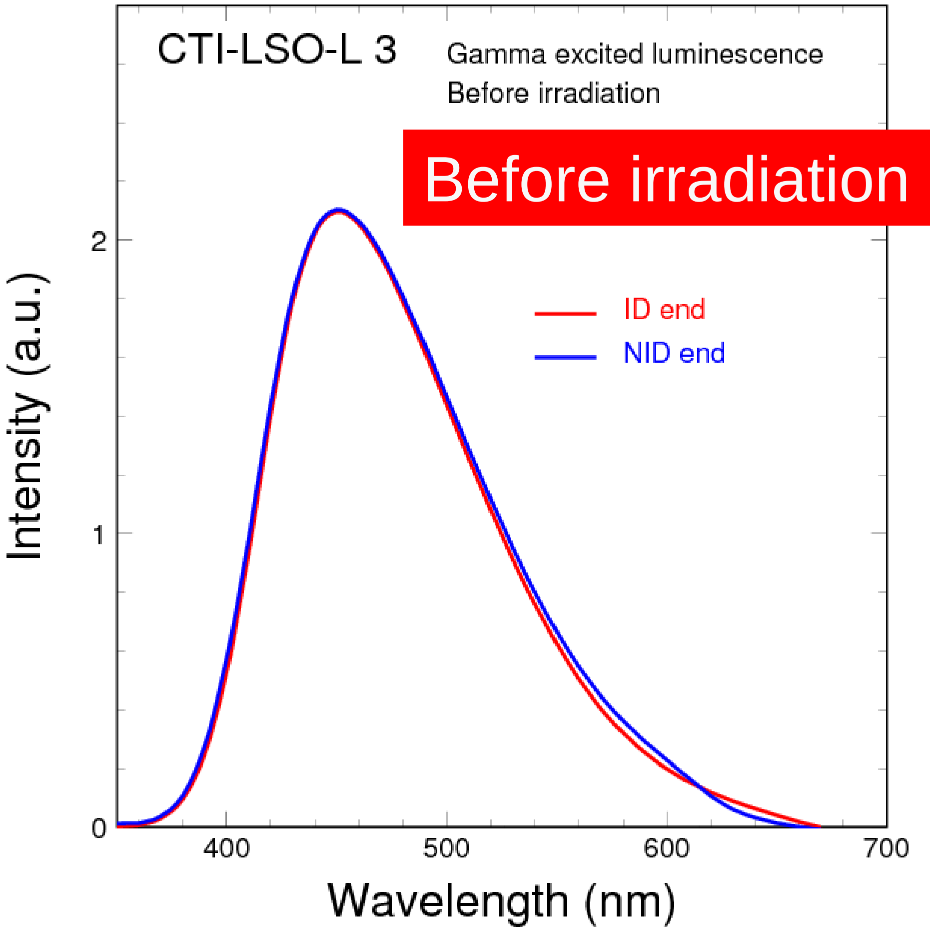
γ-Ray Irradiation on Sample's ID End

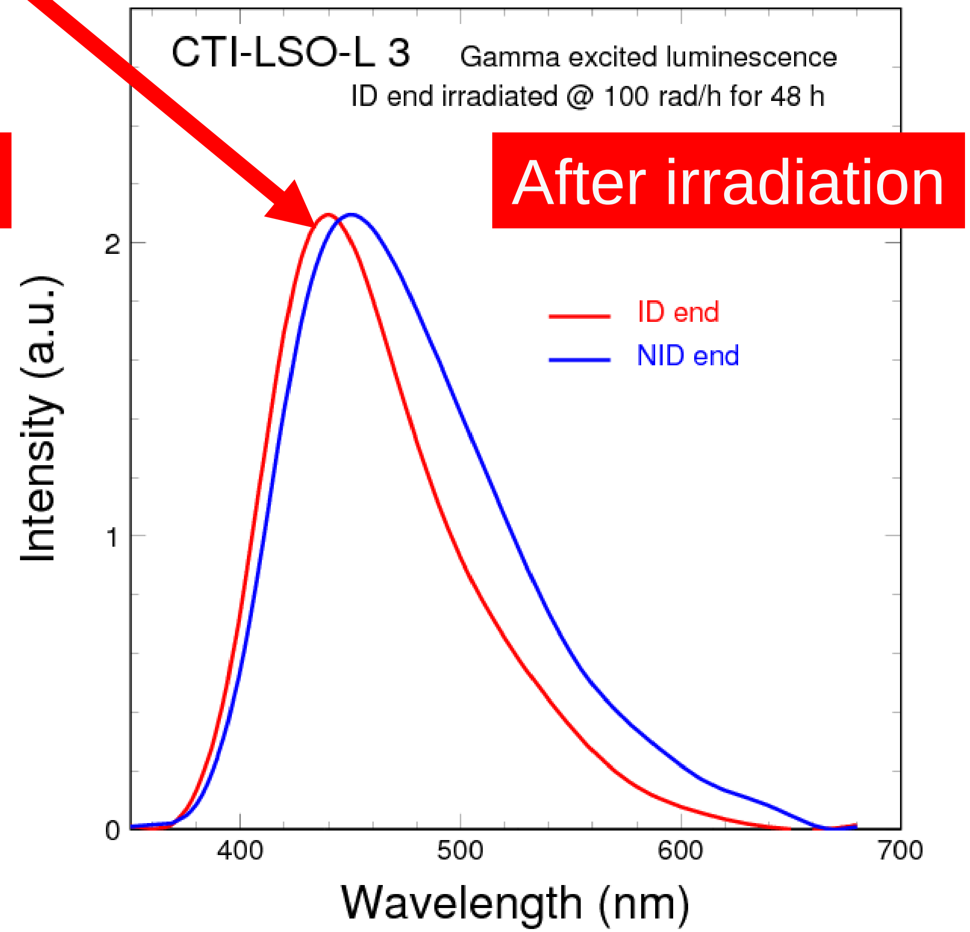


ID End received
~5,000 rad

LSO: γ -Ray Excited Emission Spectra

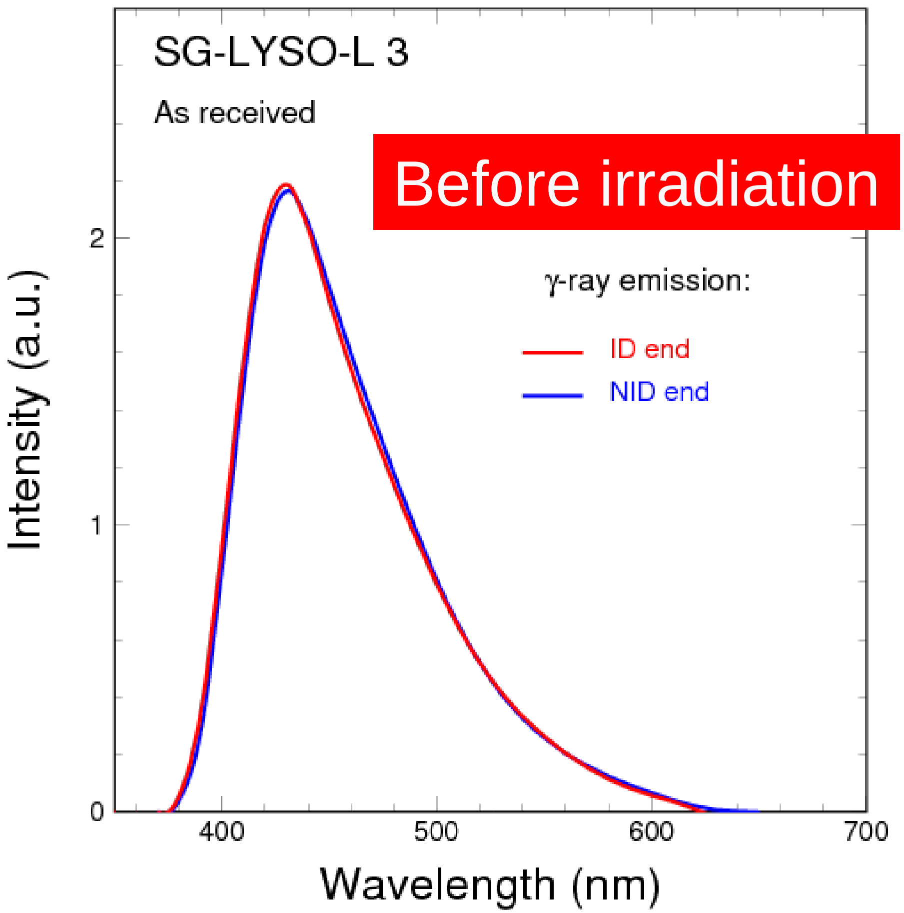
The emission peak of sample's irradiated ID end has a ~15 nm "blue" shift

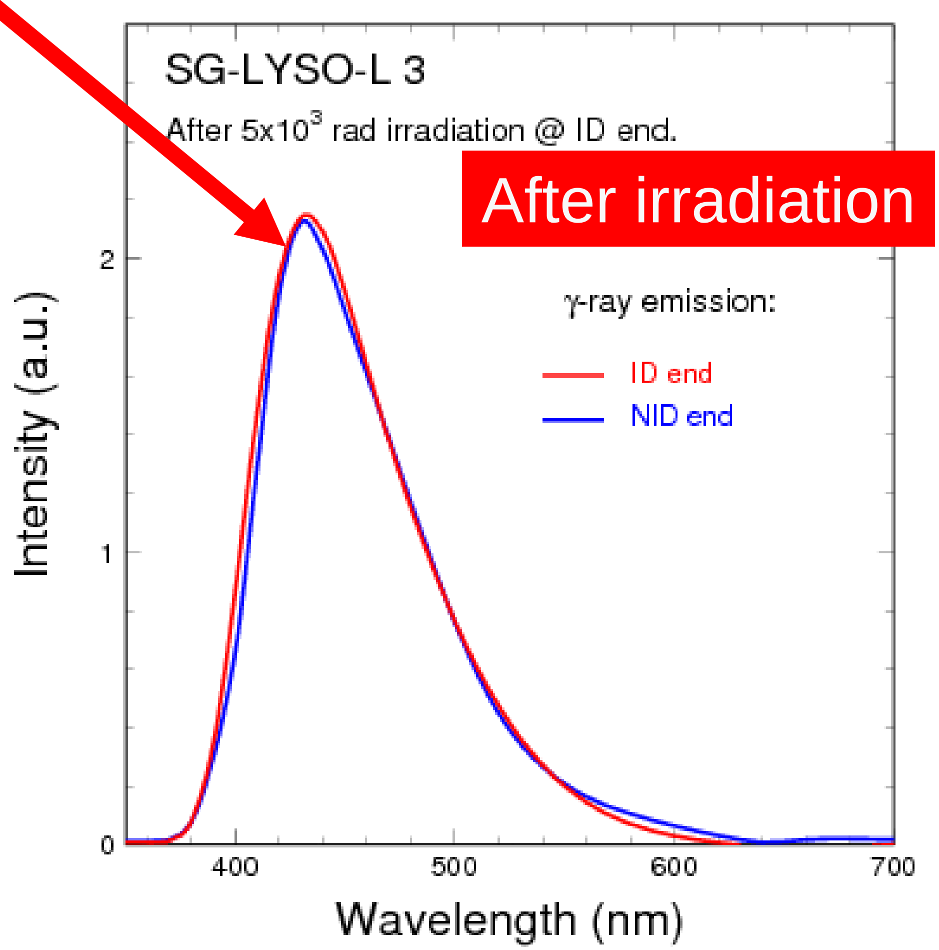




LYSO: γ -Ray Excited Emission Spectra

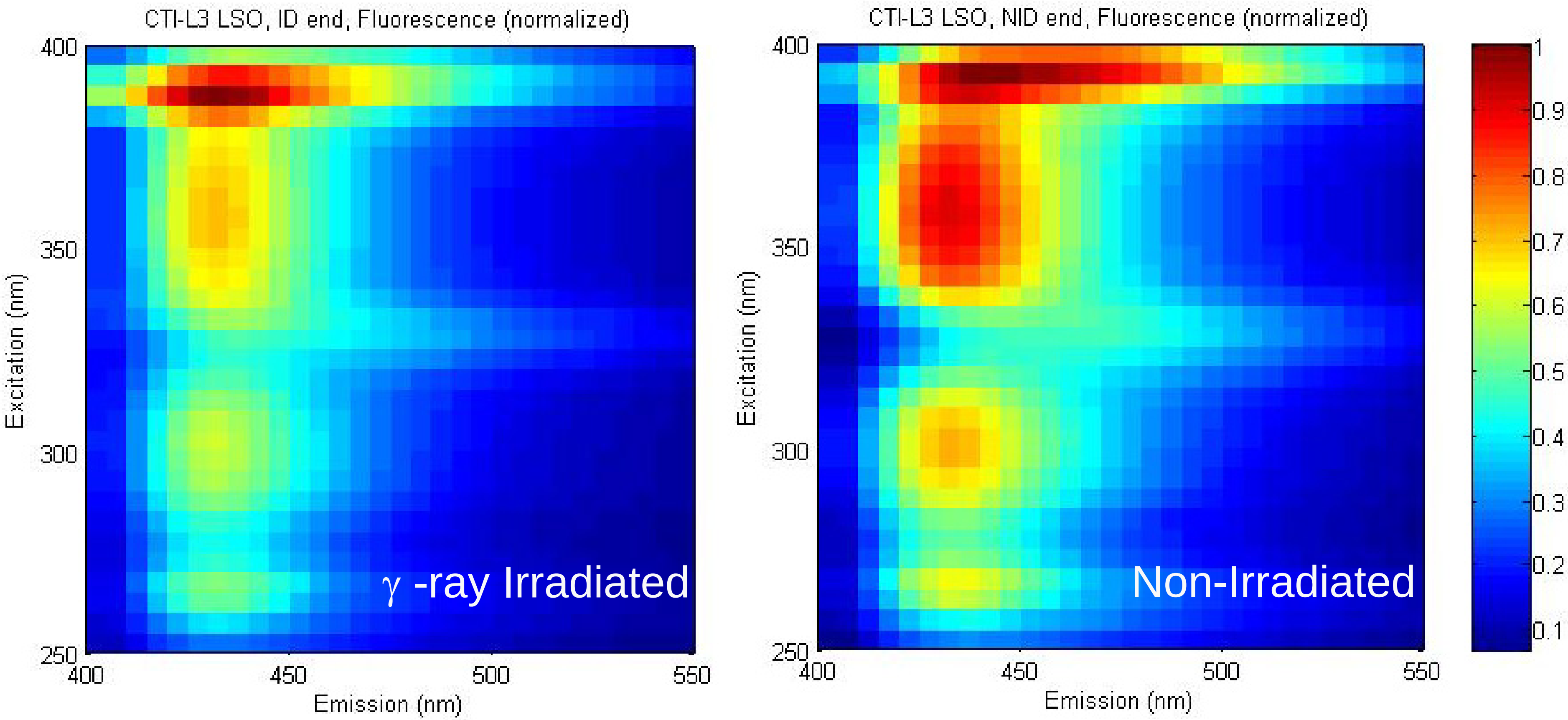
The emission peak of sample's ID (irradiated) end has NO "blue" shift





UV Excited Emission Spectra of Two Halves of the LSO Sample

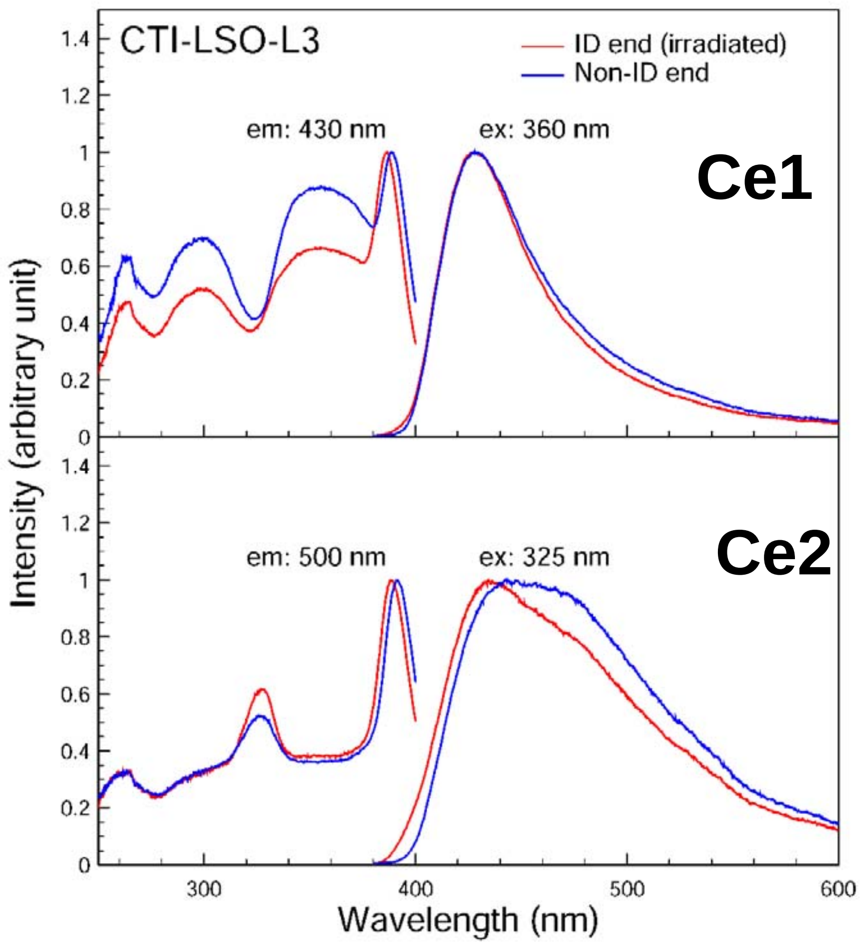
The γ -ray irradiated half shows less long wavelength emission when excited at 325 nm and 380 nm.

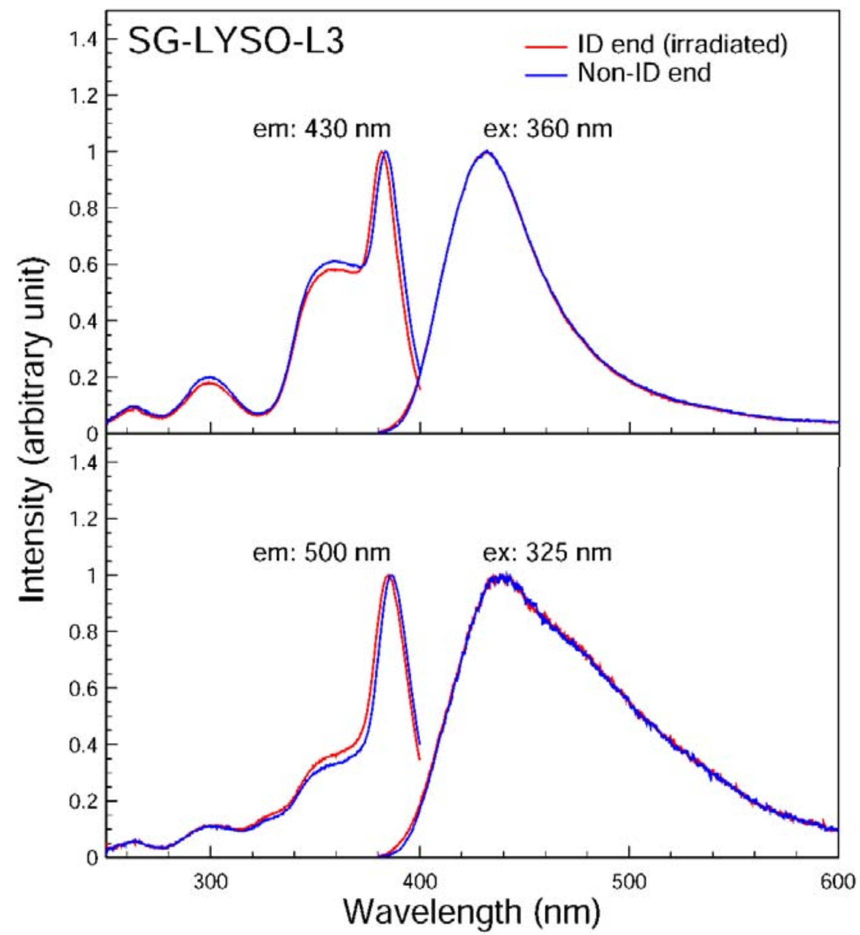


Ce^{3+} Luminescence Centers in LSO

J.D. Naud et. al., IEEE Trans. Nuclear Sci., Vol.43, p1324, June 1996

Ce1: two regular Lu^{3+} crystallographic sites, ex: 360 nm, em: 430 nm
Ce2: irregular sites, proposed “interstitial site”, ex: 325 nm, em: 500 nm

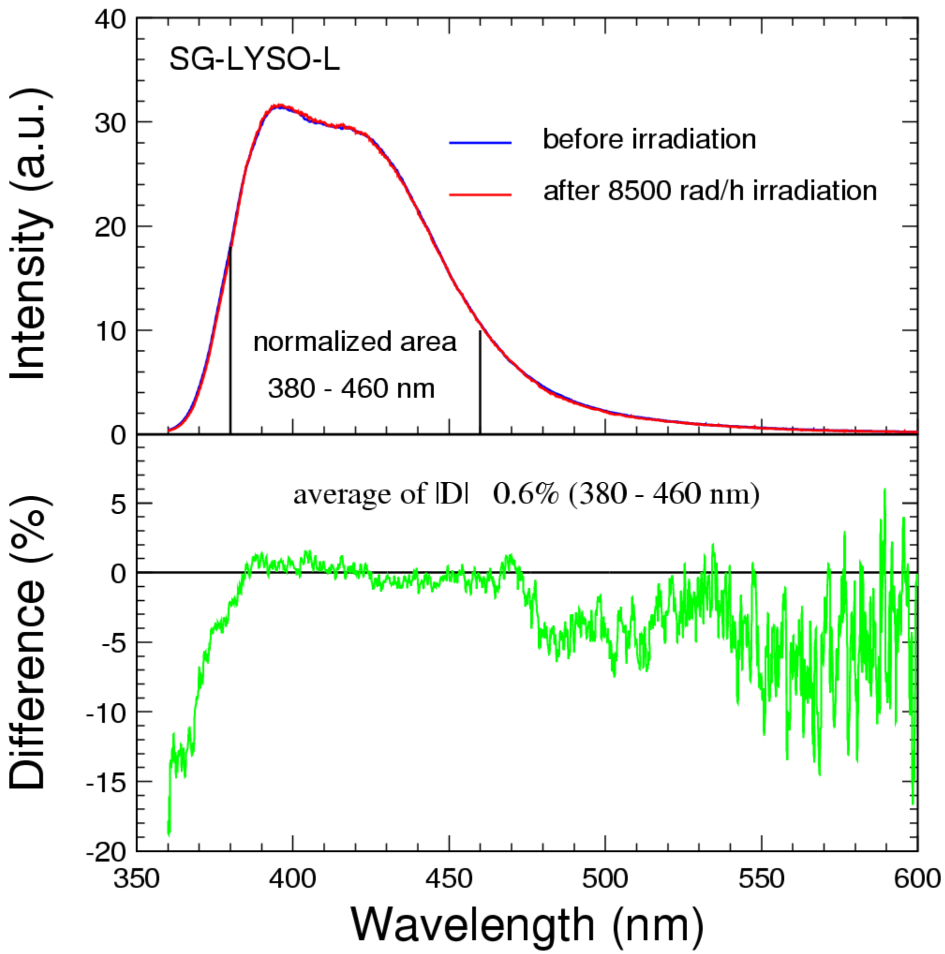


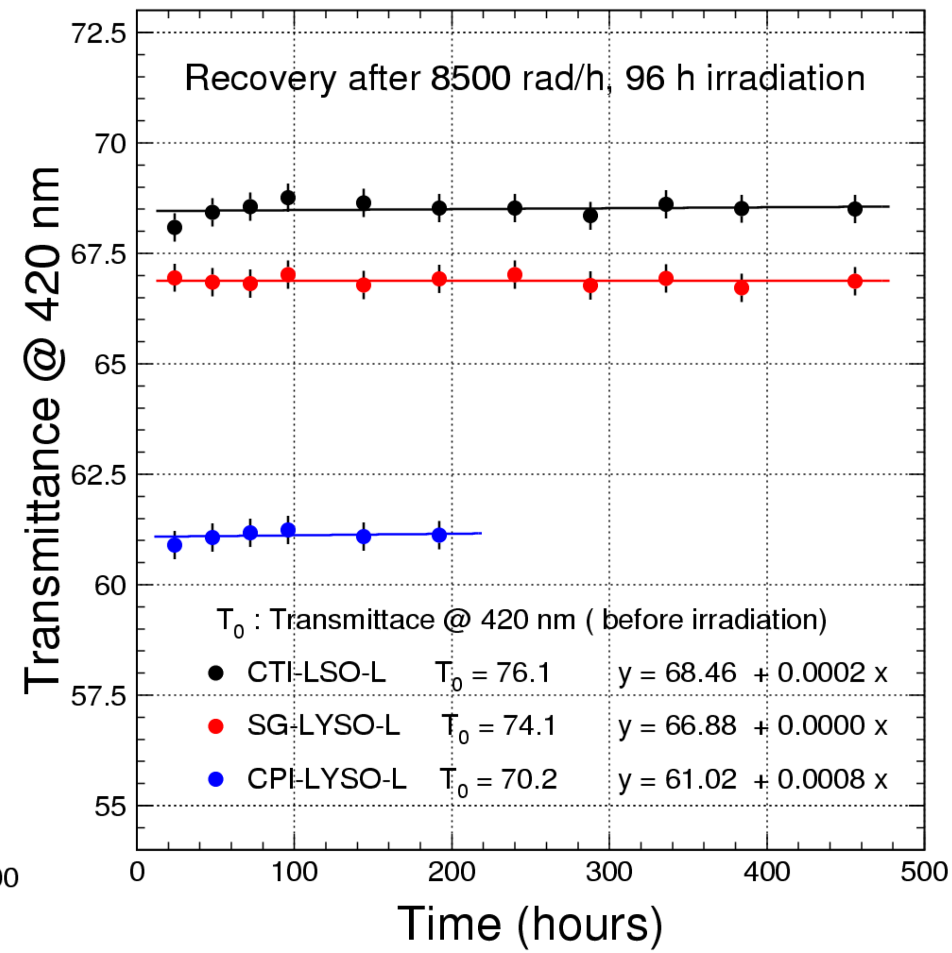


γ-Rays Induced Damage in LSO/LYSO

No damage in Photo-Luminescence

LT recovery very slow

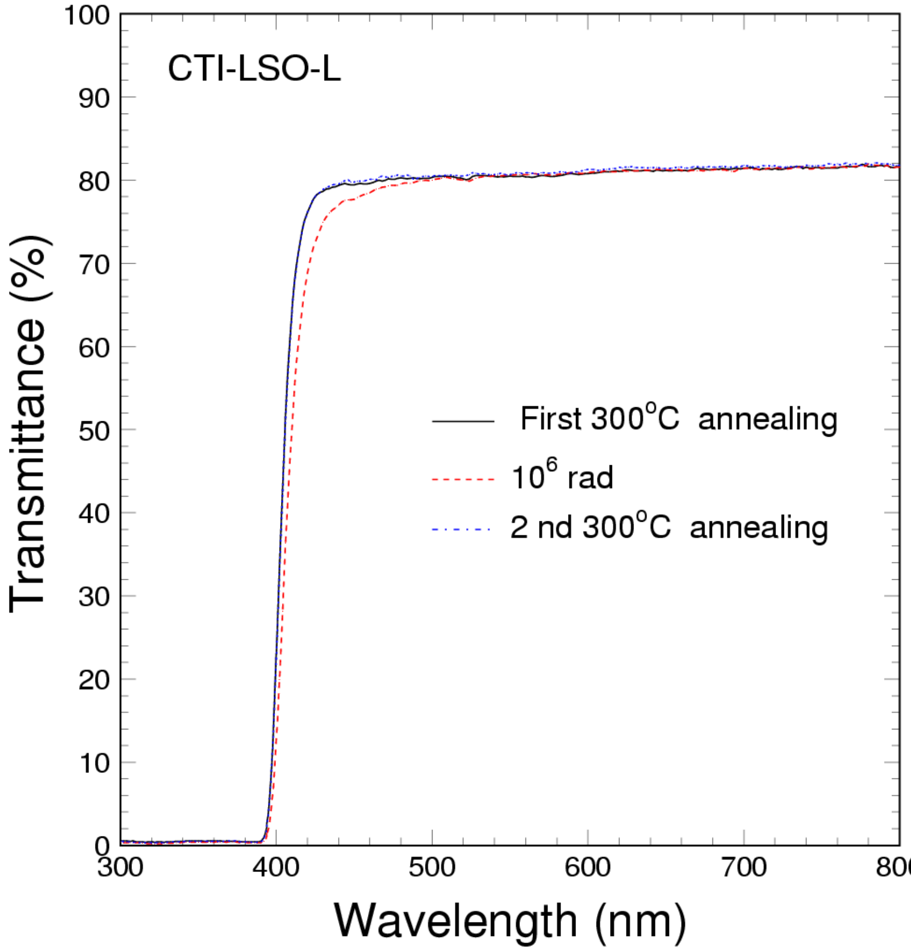


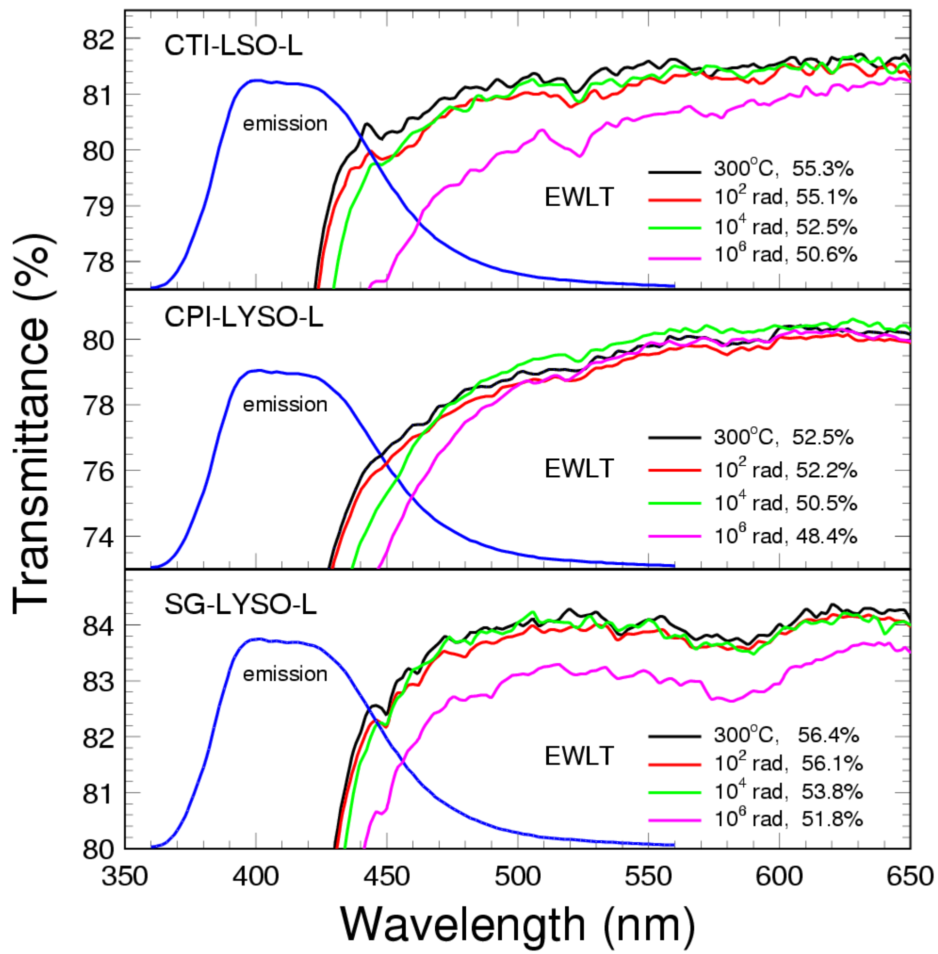


Transmittance Damage

300ºC thermal annealing effective

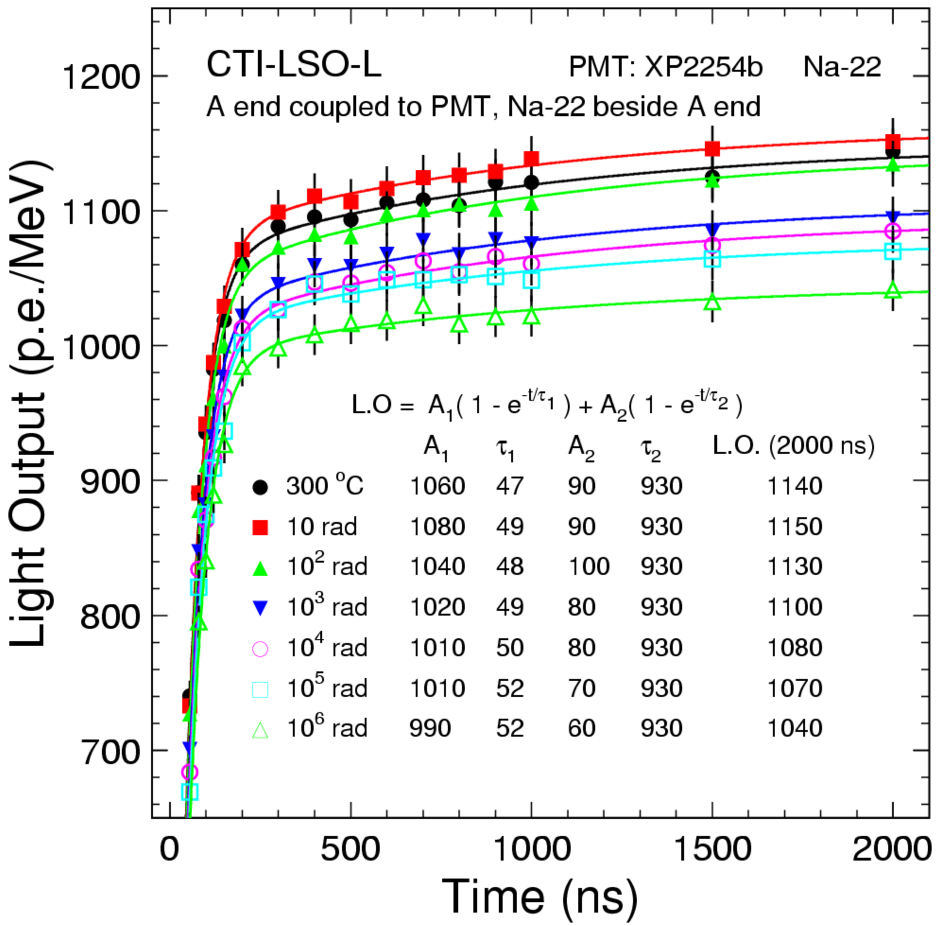
LT damage: 8% @ 1 Mrad

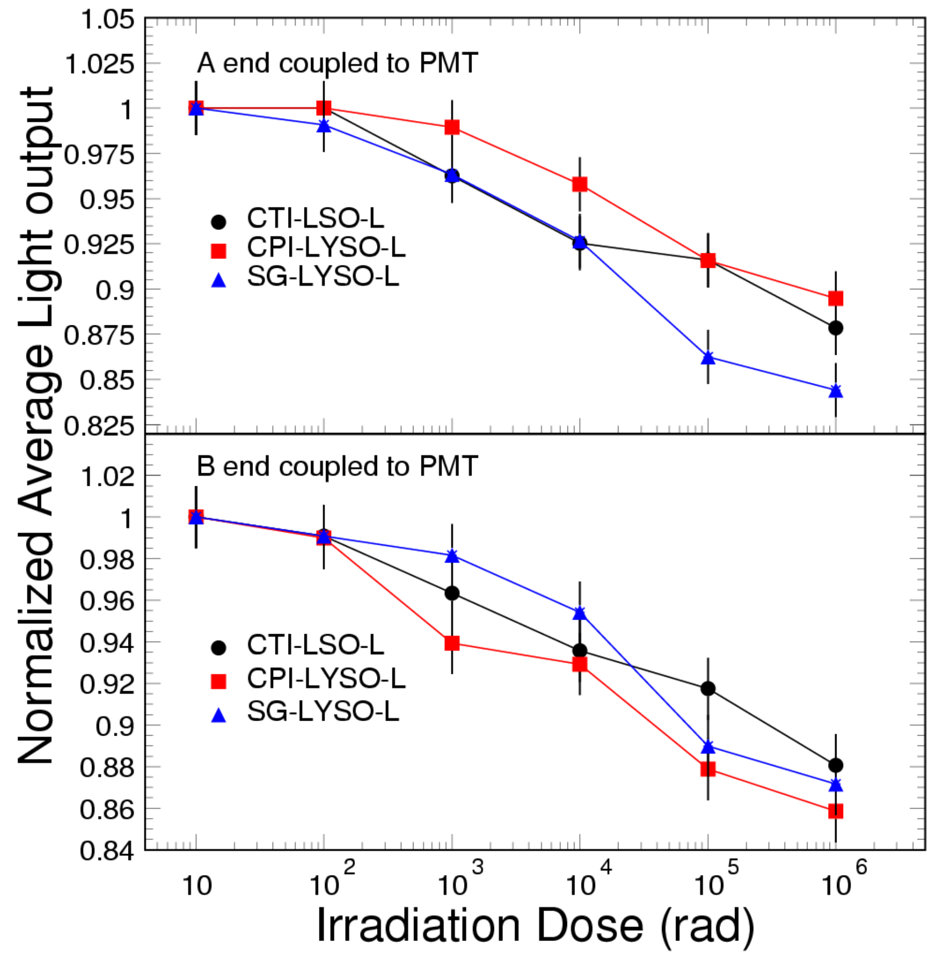




Light Output Damage with PMT

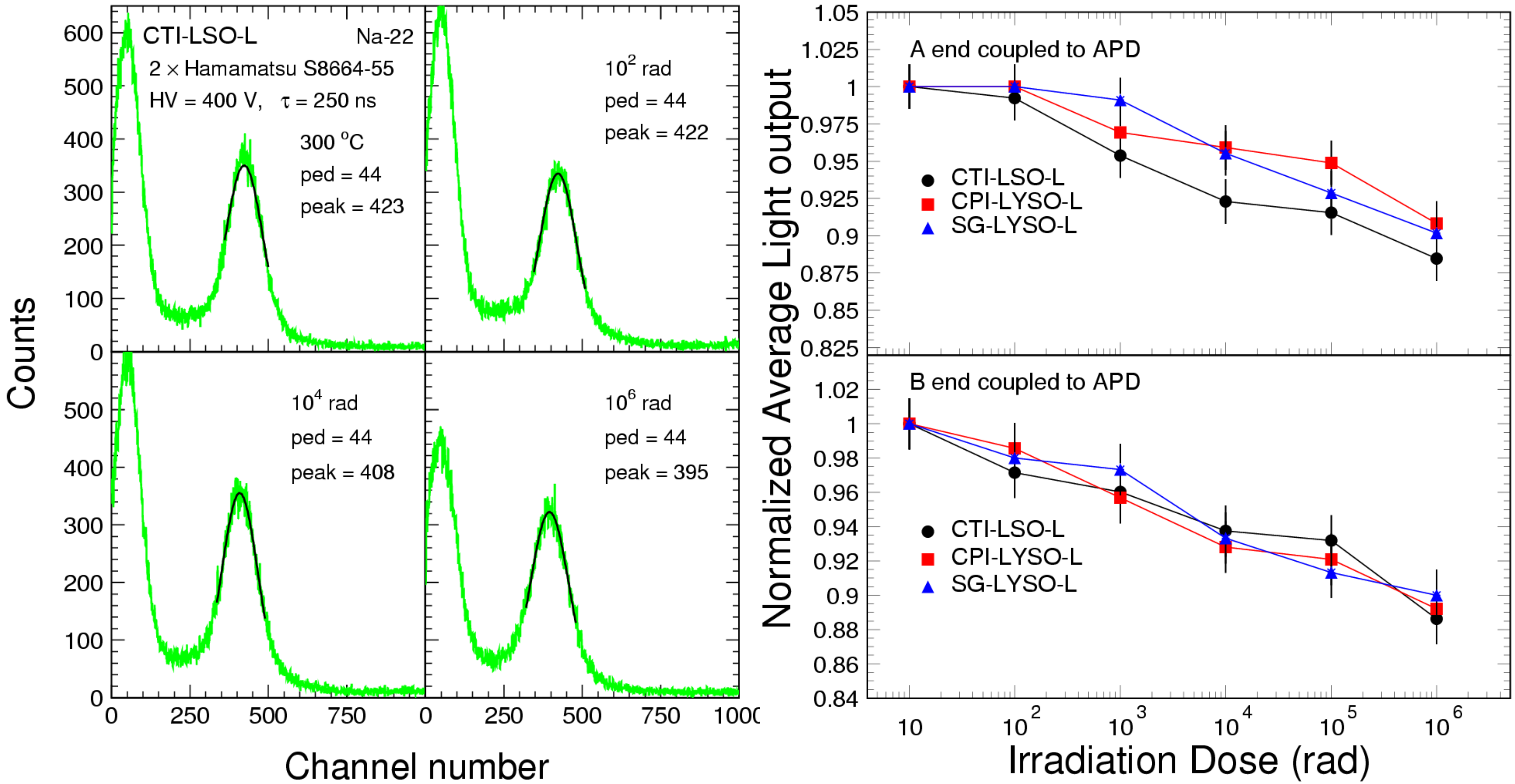
Light output loss: about 12% to 14% @ 1 Mrad





Light Output Damage with APD

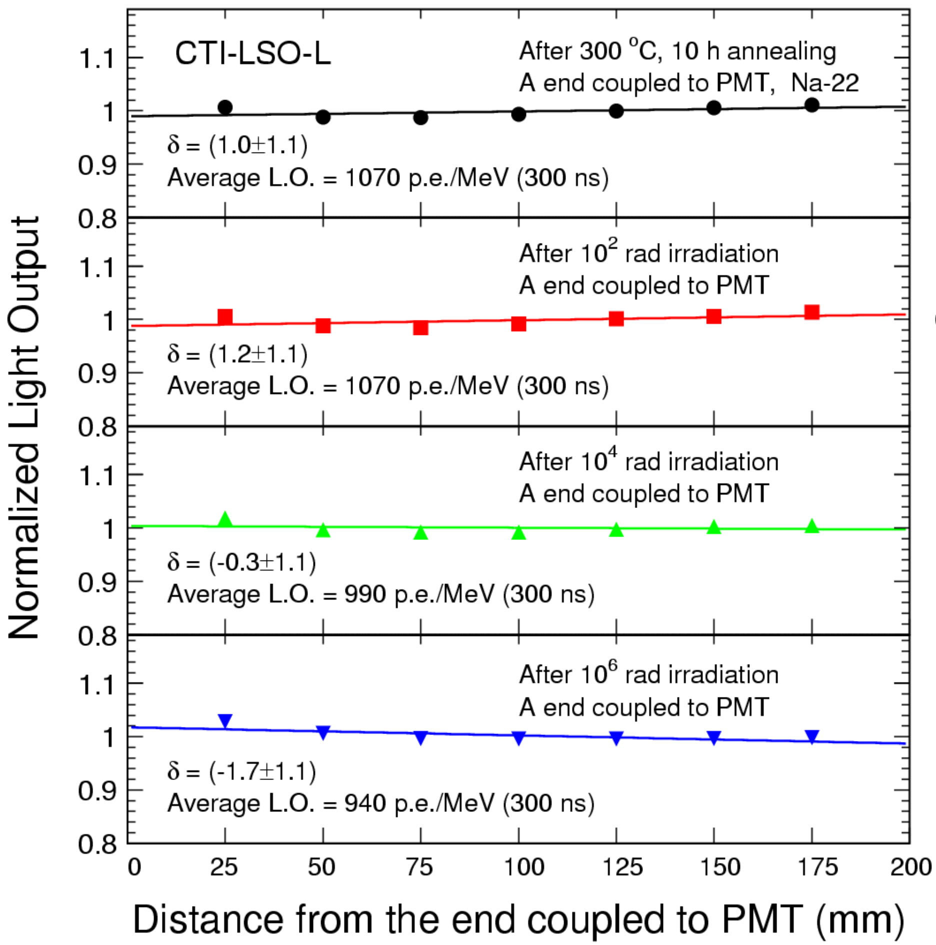
Light output loss: about 10% to 12% @ 1 Mrad



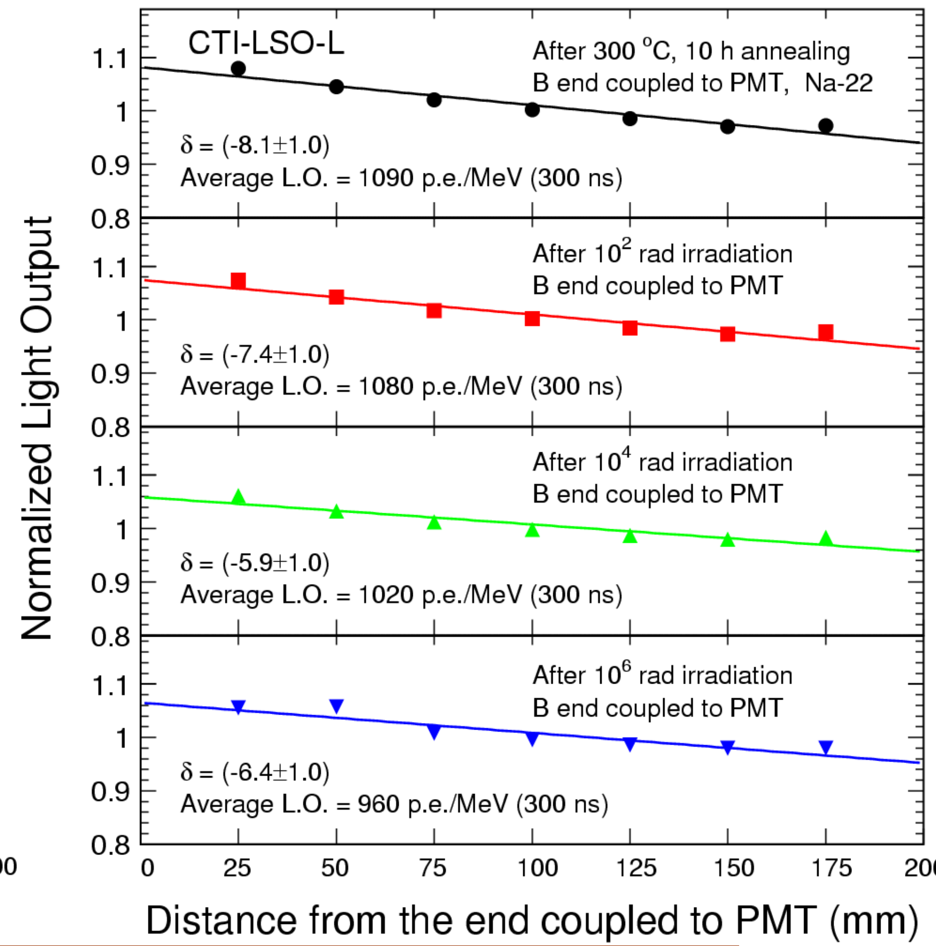
LRU Damage with PMT

Uniformity depends on end coupled to the PMT
No damage in the light response uniformity

A end Coupling



B end Coupling

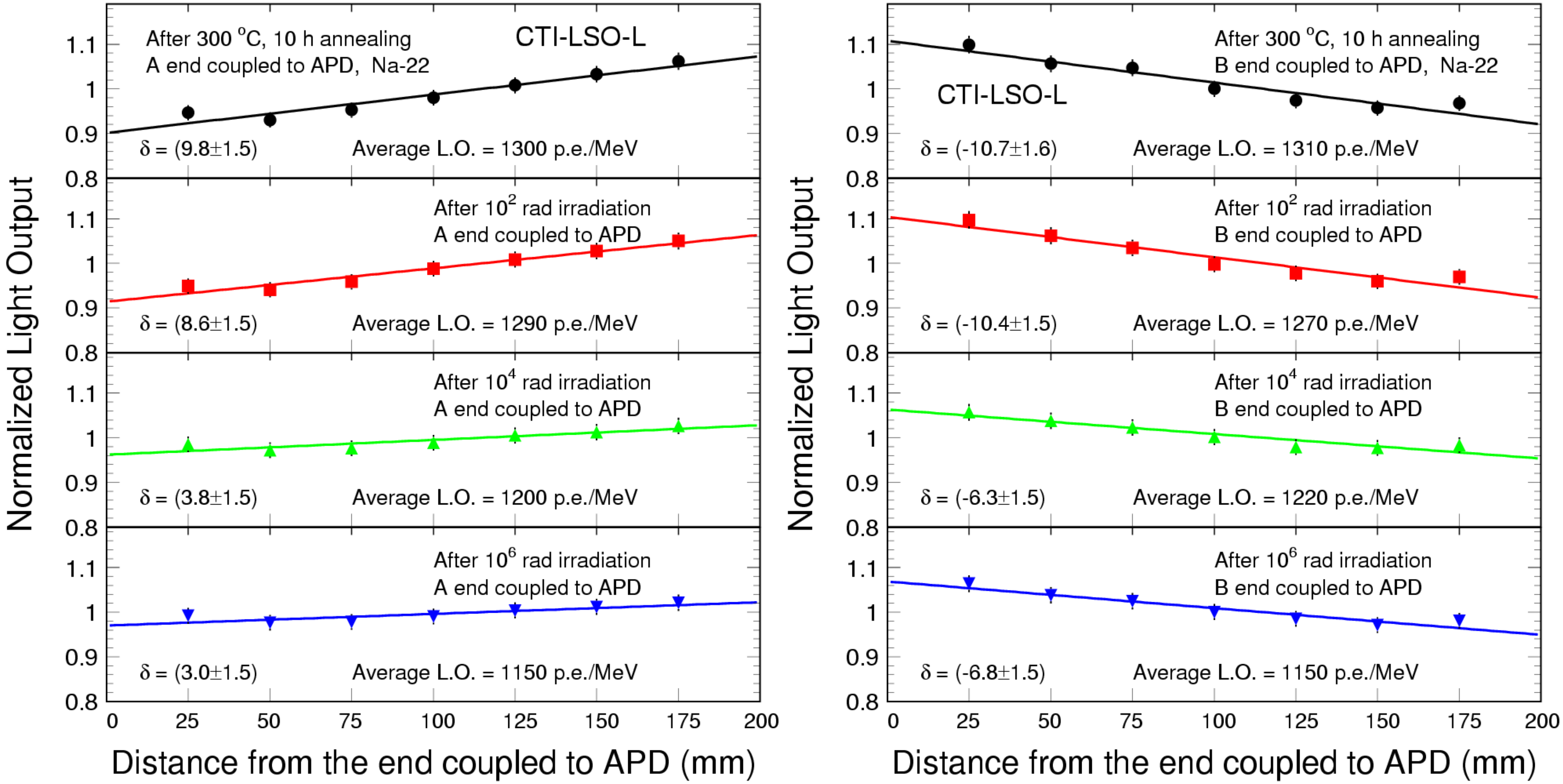


LRU Damage with APD

Uniformity depends on end coupled to the APD
Some change in the light response uniformity

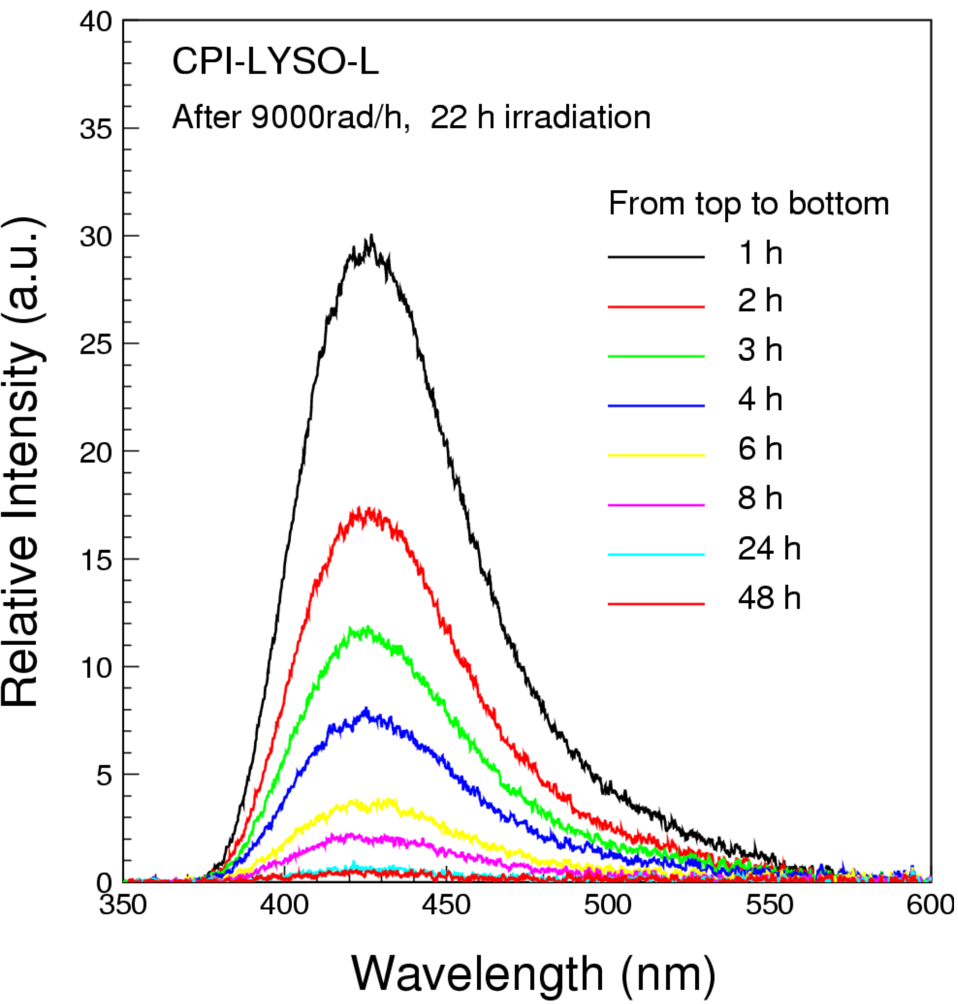
A end Coupling

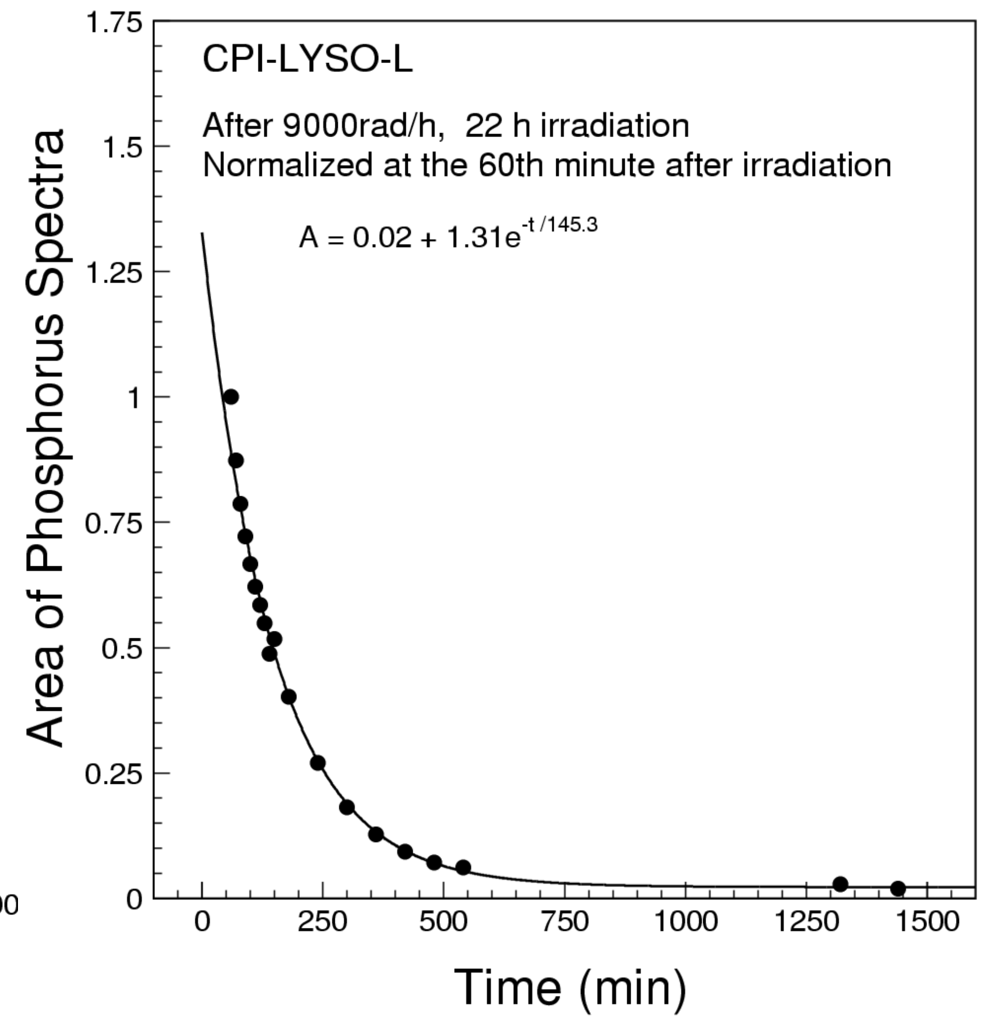
B end Coupling



Radiation Induced Phosphorescence

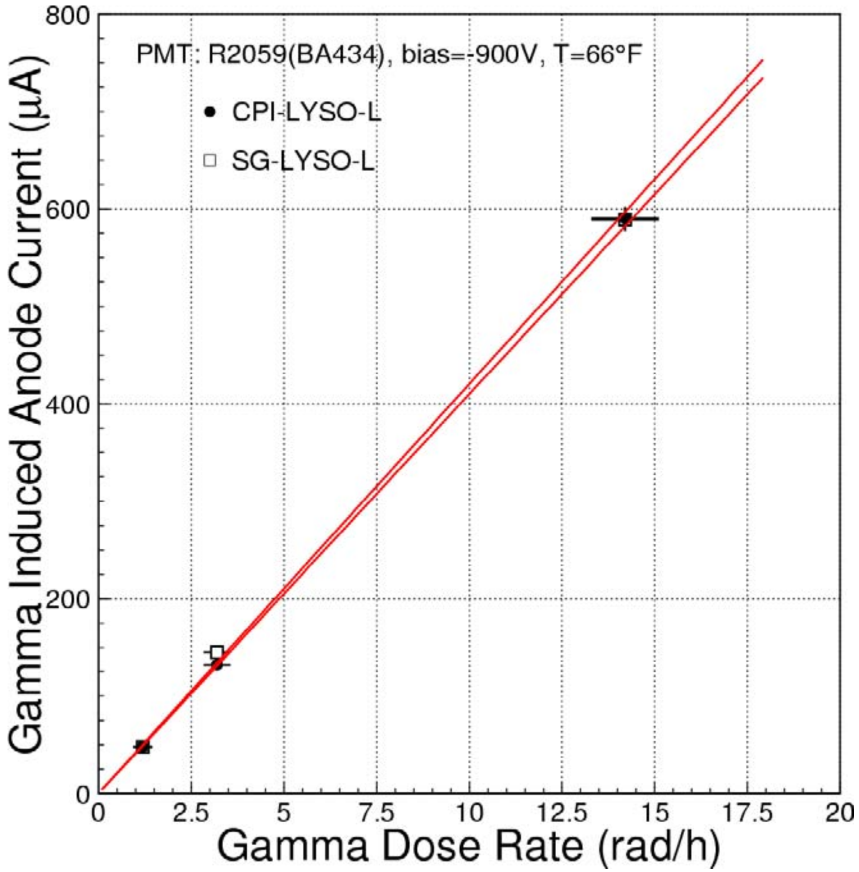
Phosphorescence peaked at 430 nm with decay time constant of 2.5 h observed





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.	σ 15 rad/h MeV	σ 500 rad/h 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).

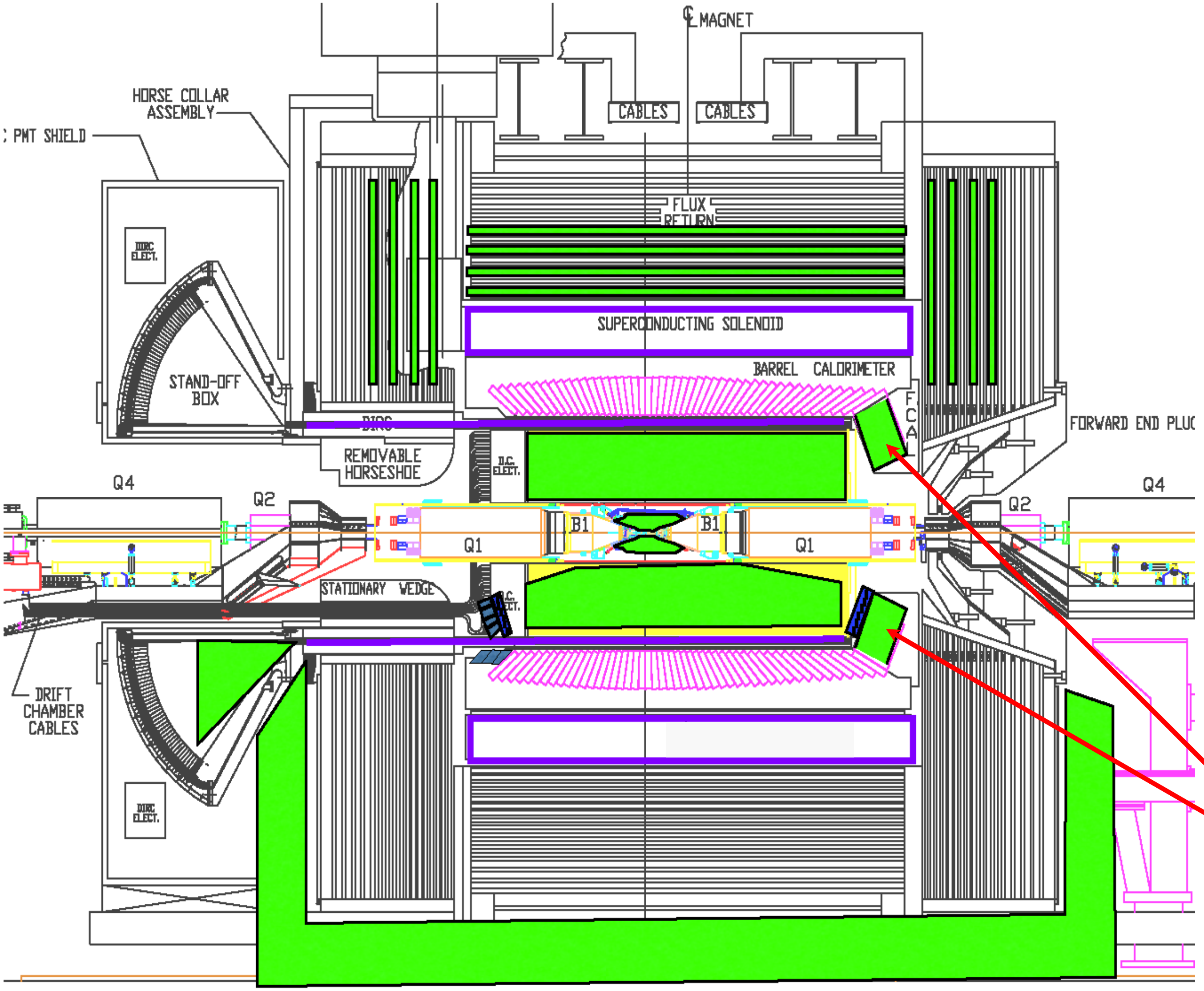
LSO/LYSO ECAL Performance

- 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, σ(E)/E, at low energies than L3 BGO and CMS PWO because of its high light output and low readout noise:

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

LYSO Development 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 endcap

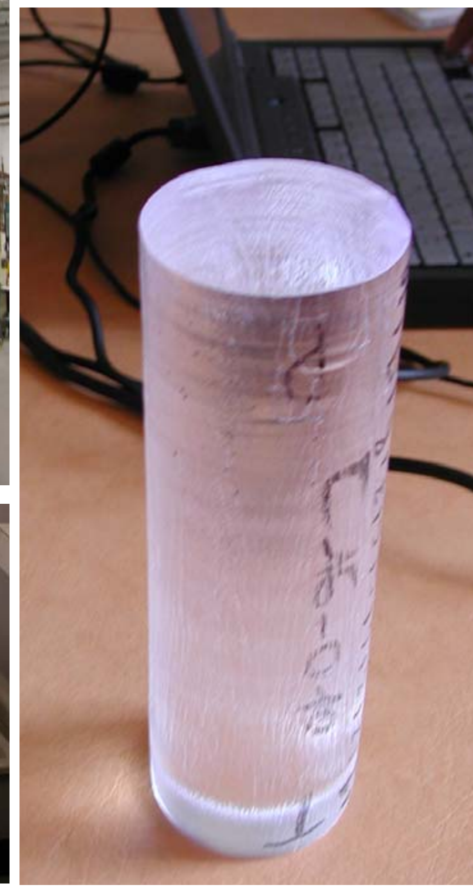
LSO/LYSO

LSO/LYSO Mass Production

CTI: LSO

CPI: LYSO

Saint-Gobain LYSO



Additional Capability: SIPAT @ Sichuan, China

Six LSO & LYSO Samples

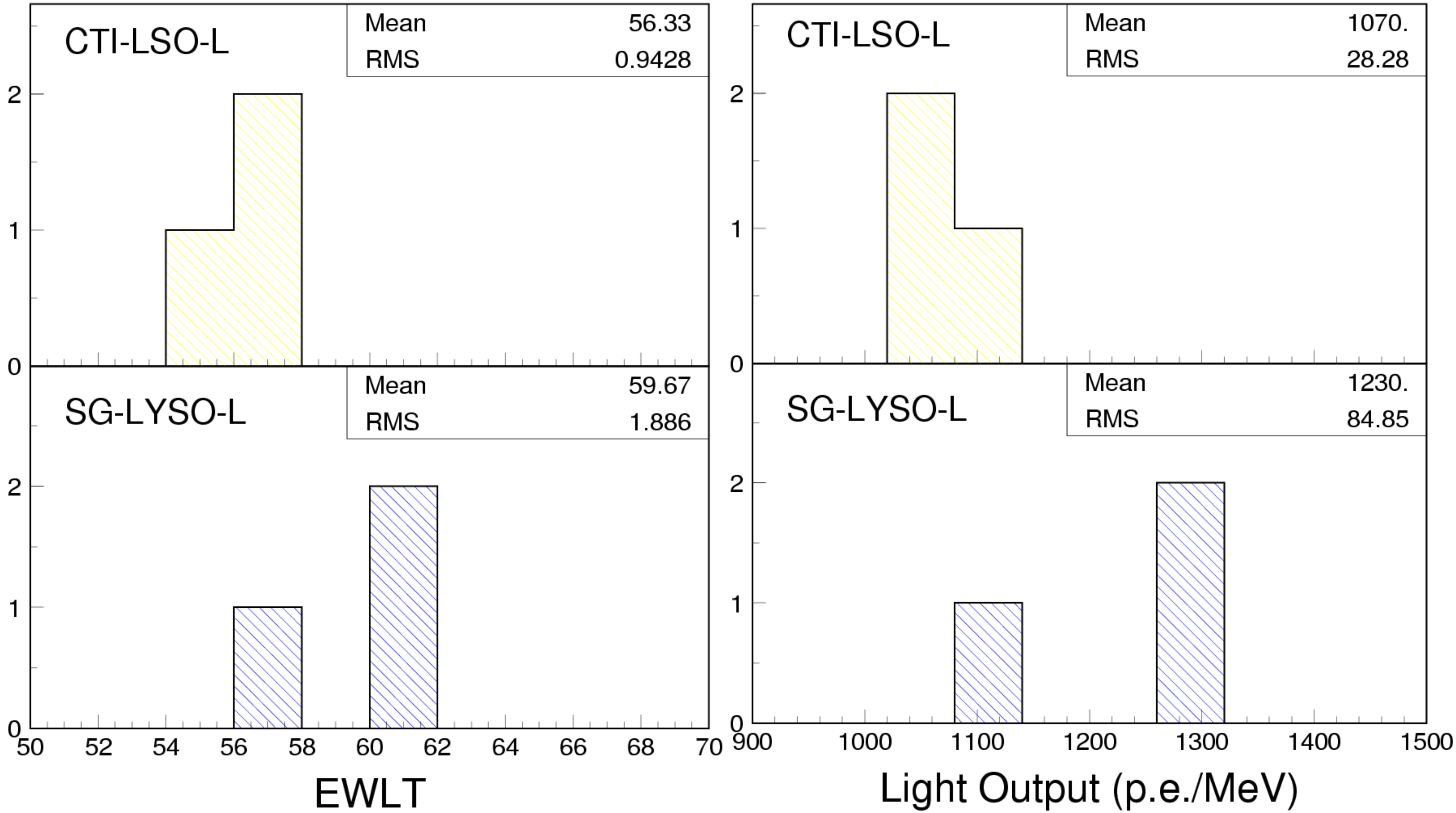
2.5 x 2.5 x 20 cm (18 X_0) Bar

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 R&D Building

SIPAT: Furnace & R&D Issues

- Raw material:

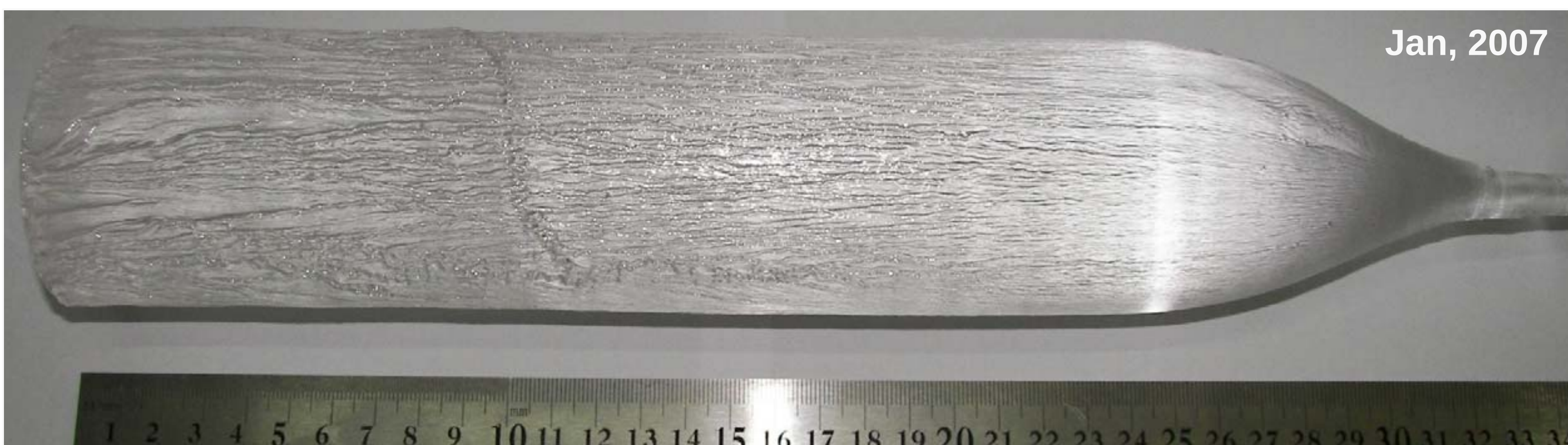
  Lu_2O_3: 99.995%

  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

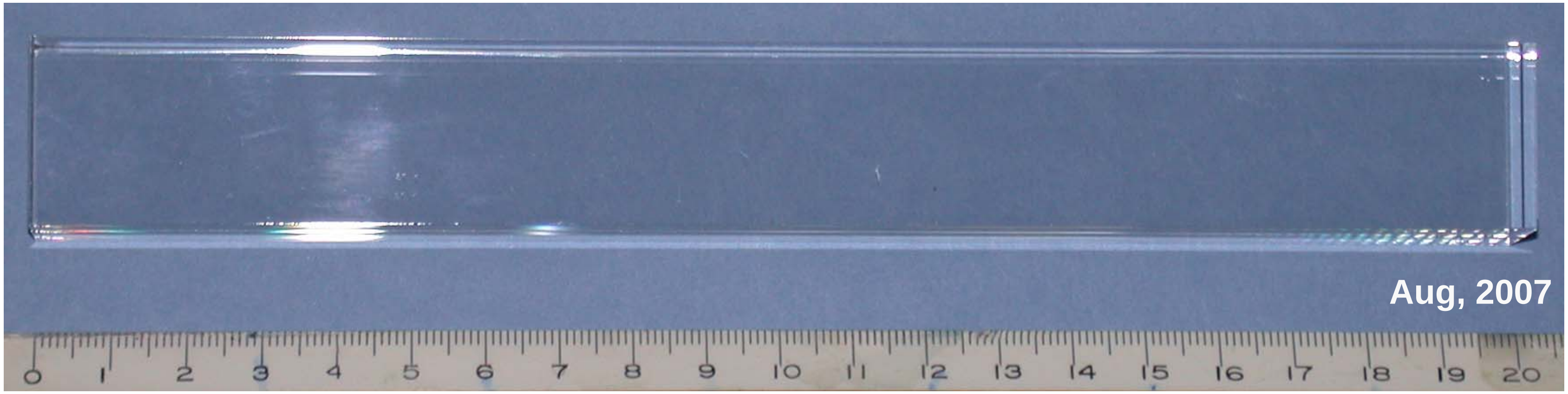
Started 2001, invested >$1M, Significant Progress in last year



SIPAT Ø 60 x 250 mm LYSO Boles

SIPAT Czochralski Furnaces

First SIPAT LYSO Sample for HEP

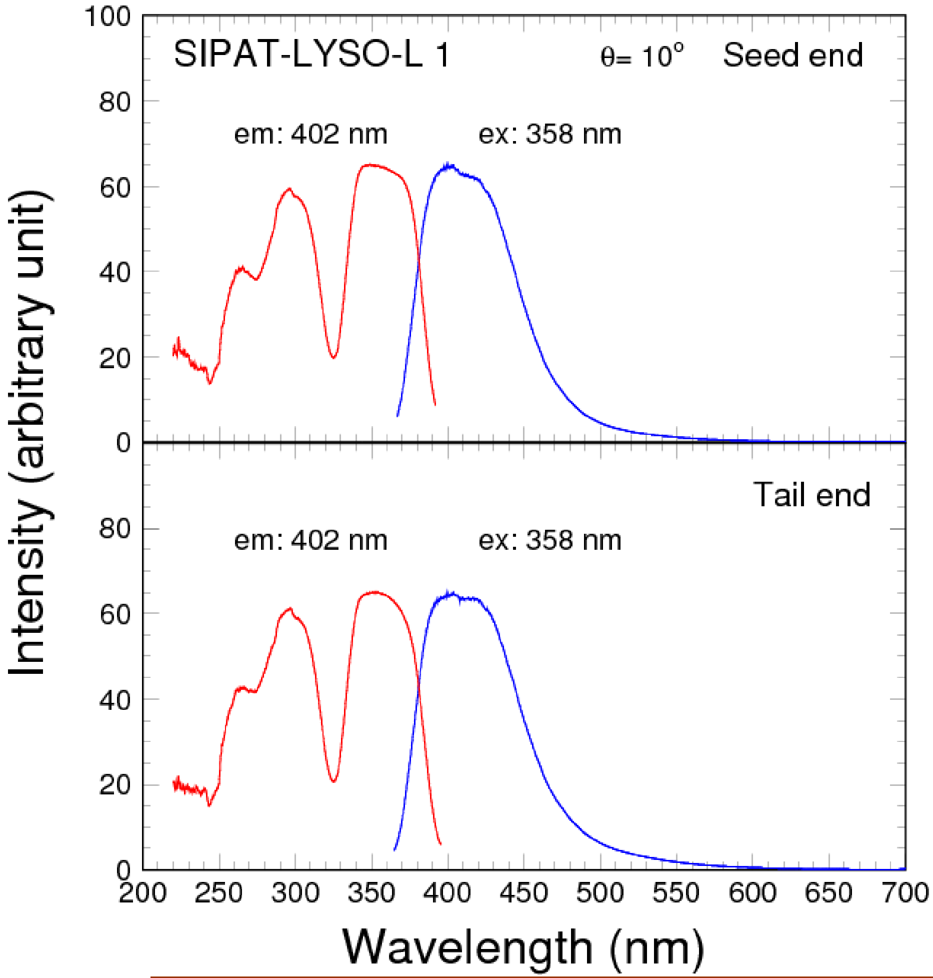


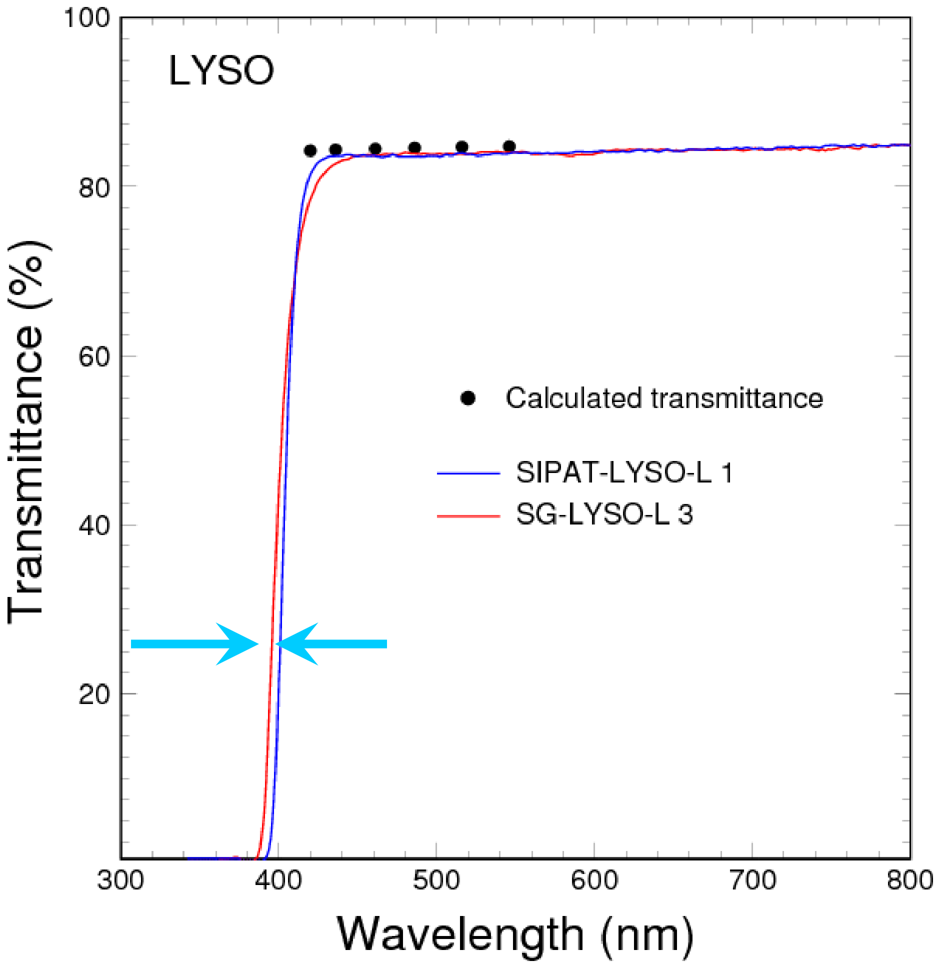
- Received in the middle of August with dimension of 25 x 25 x 200 mm and good visual inspection.
- It was first annealed at 300°C for 10 hours and with its initial optical and scintillation properties measured.
- Together with SG-L3, two samples were irradiated with integrated doses of 10, 10^2, 10^3, 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

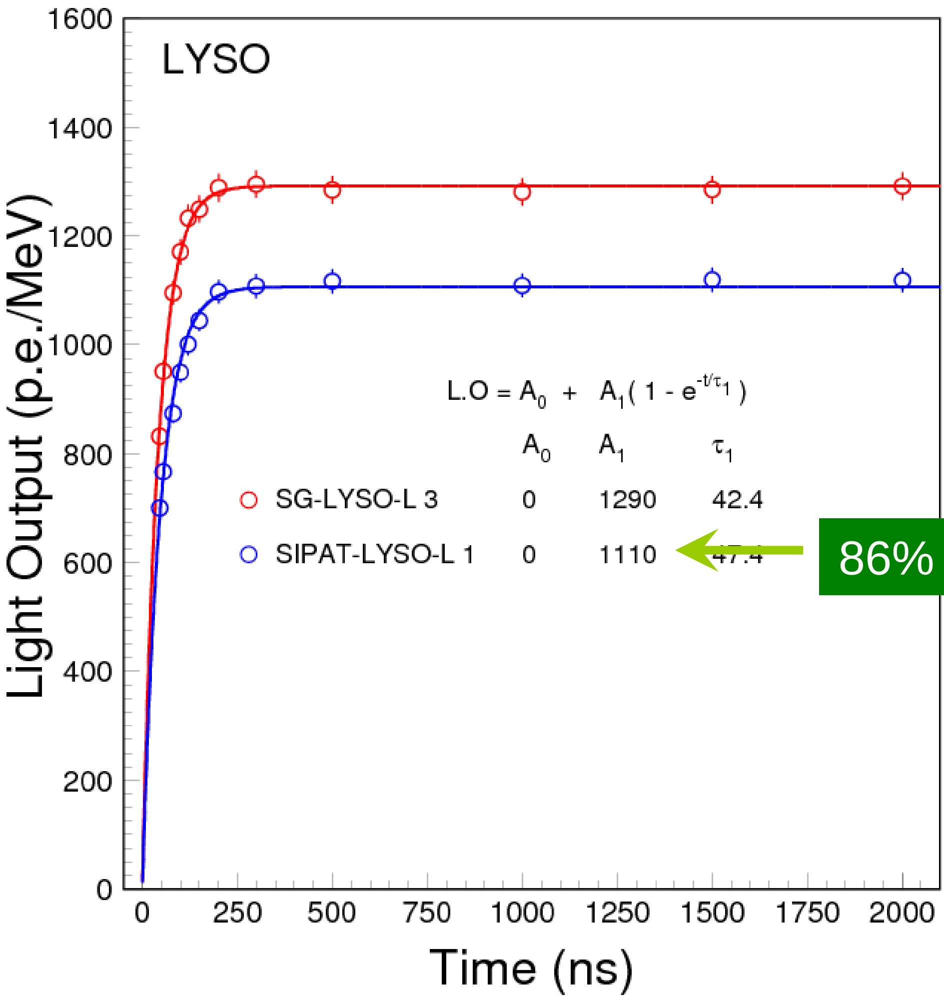
The cutoff of SG-L3 has ~5 nm blue shift compared to SIAPT-L1

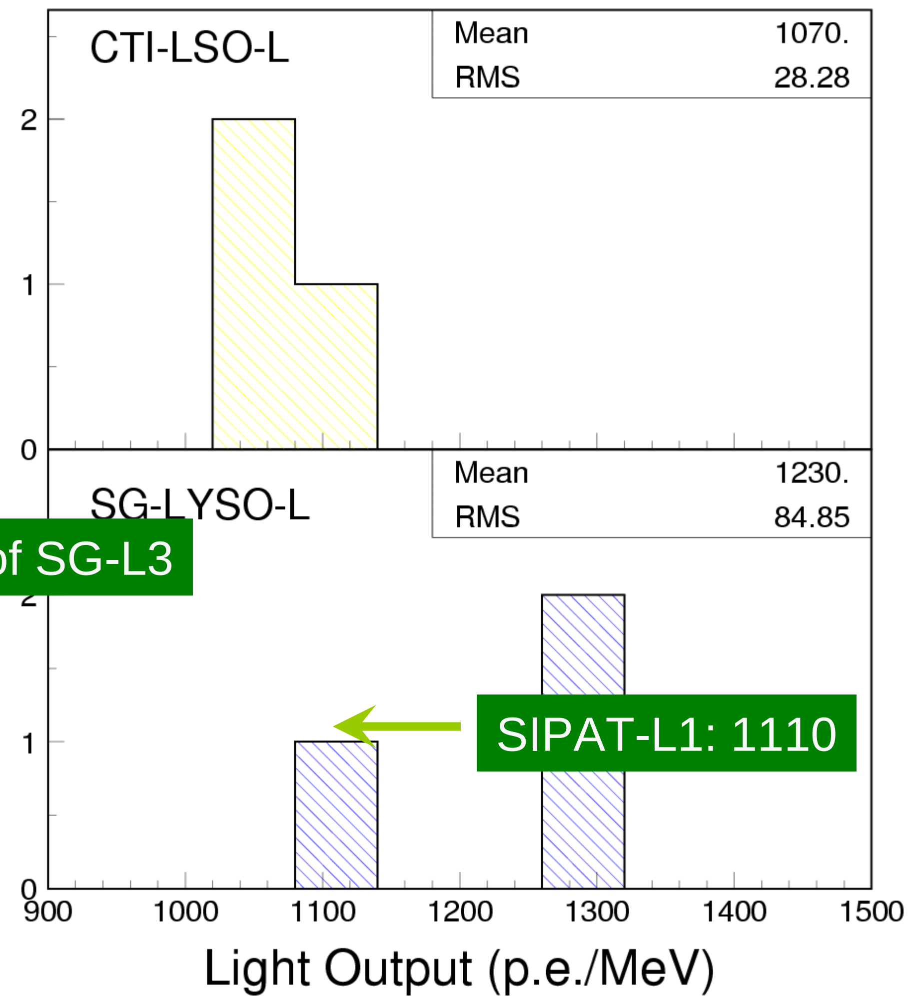




Light Output & Decay Kinetics

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

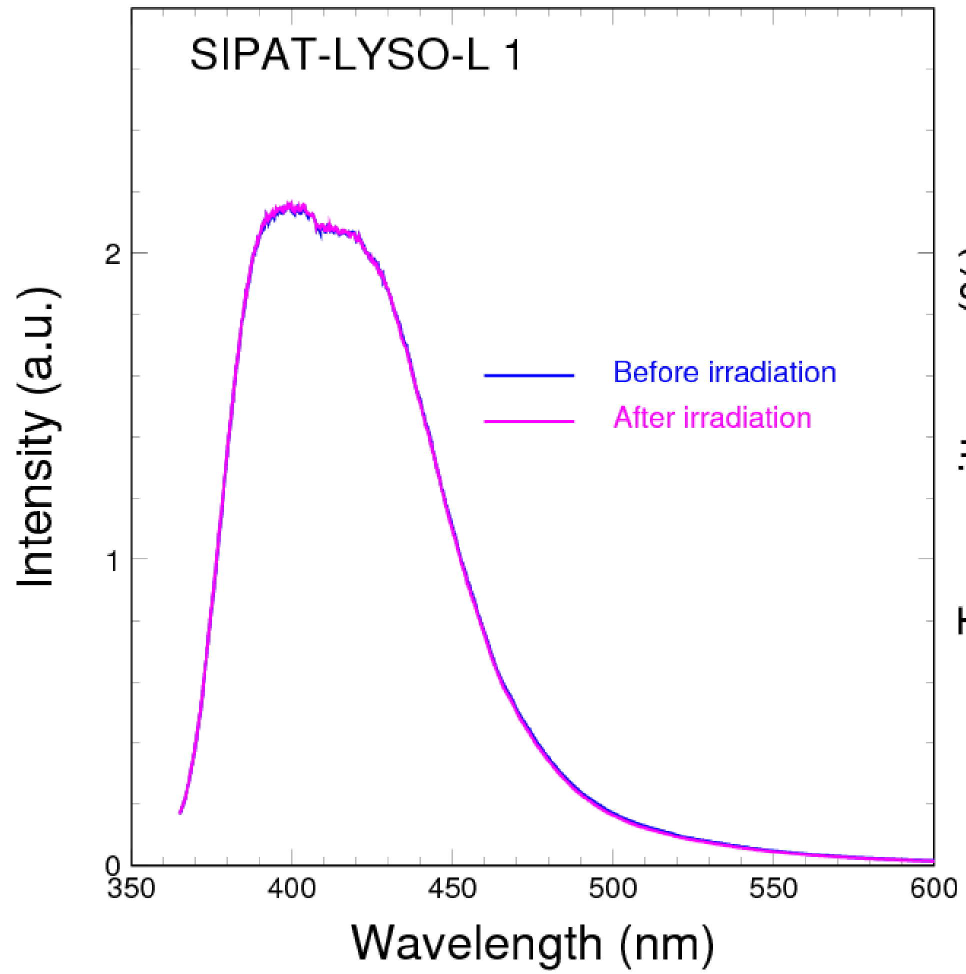


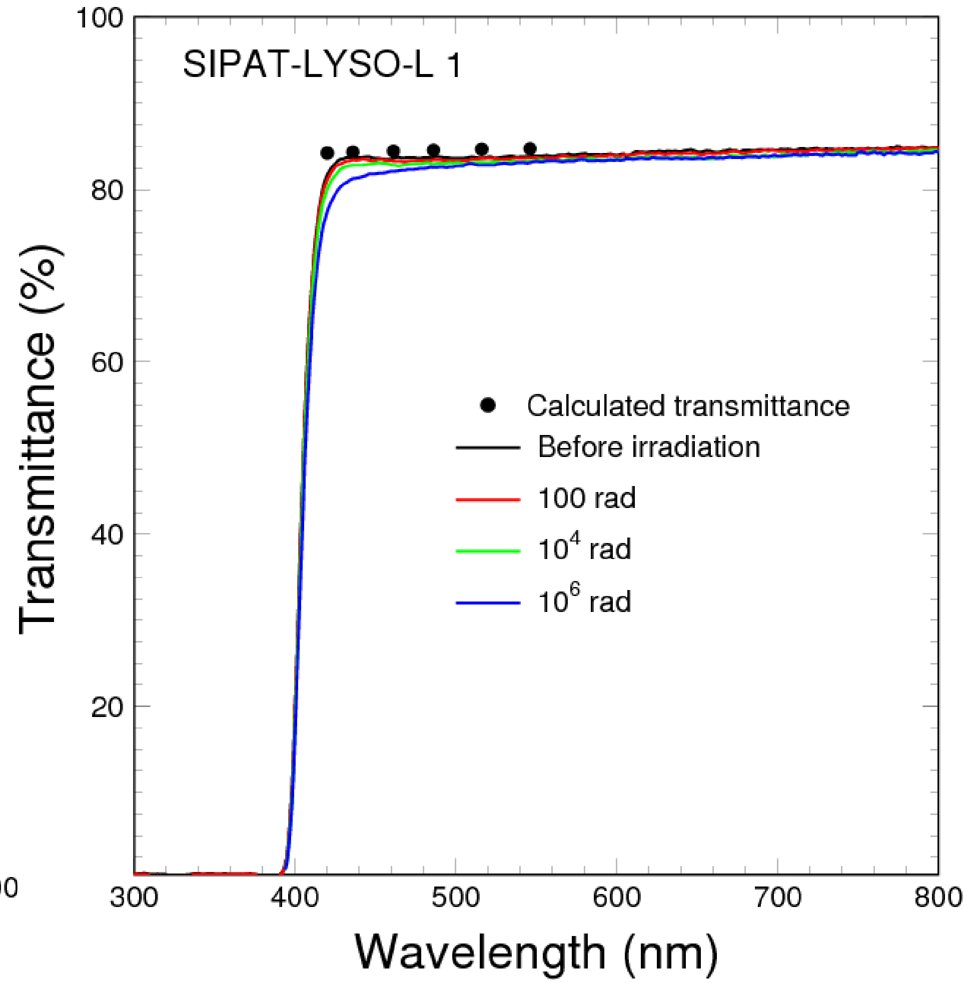


γ-Ray Induced Radiation Damage

Scintillation spectrum not affected by irradiation

~8% damage @ 420 nm after 10^6 rad irradiation



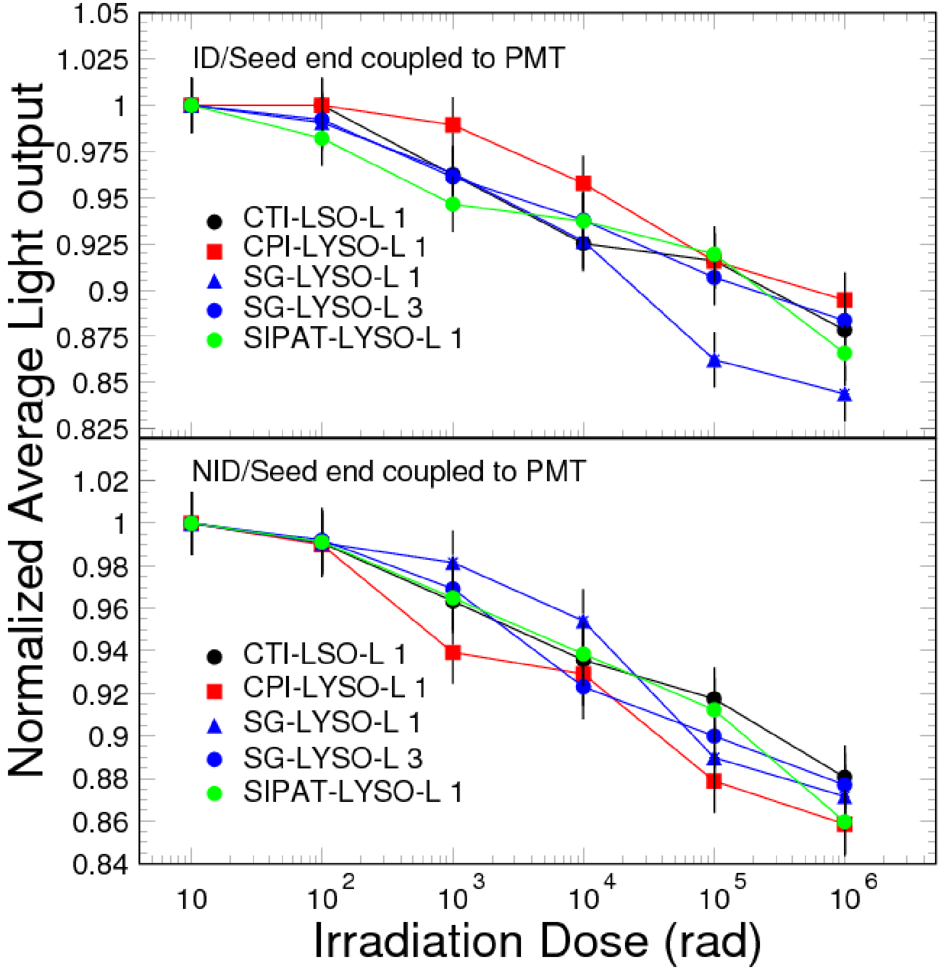


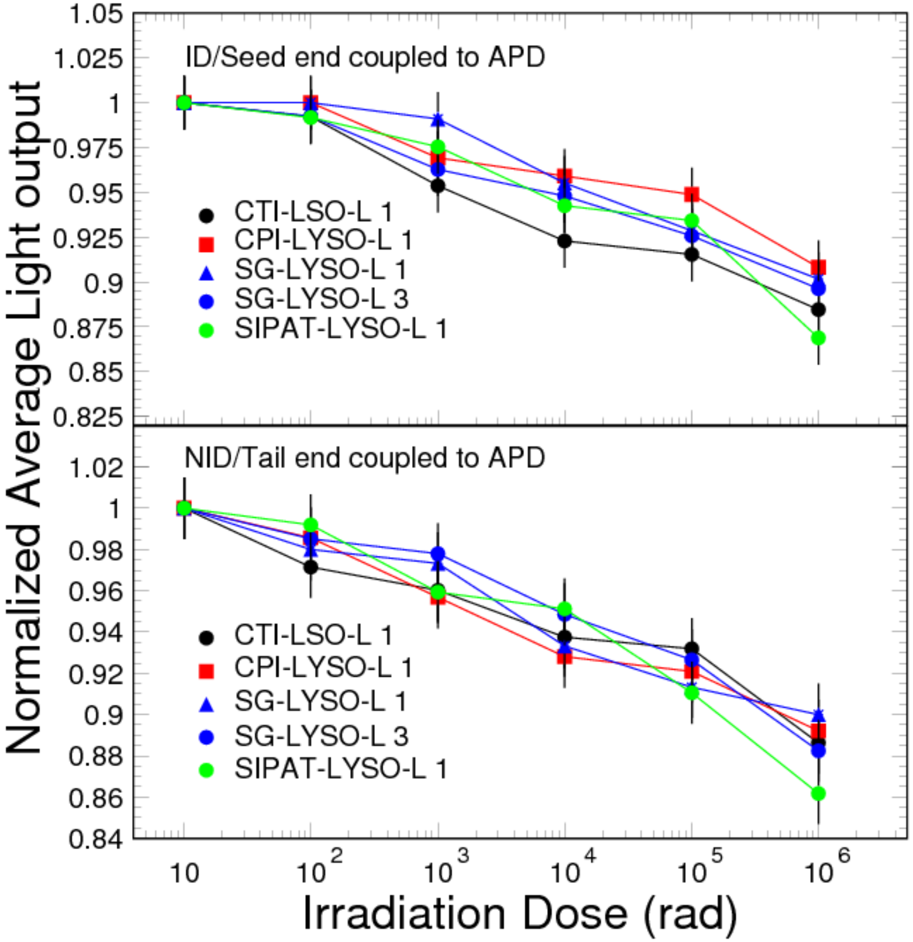
Comparison of L.O. Damage

All samples show consistent radiation resistance

10% - 15% loss by PMT

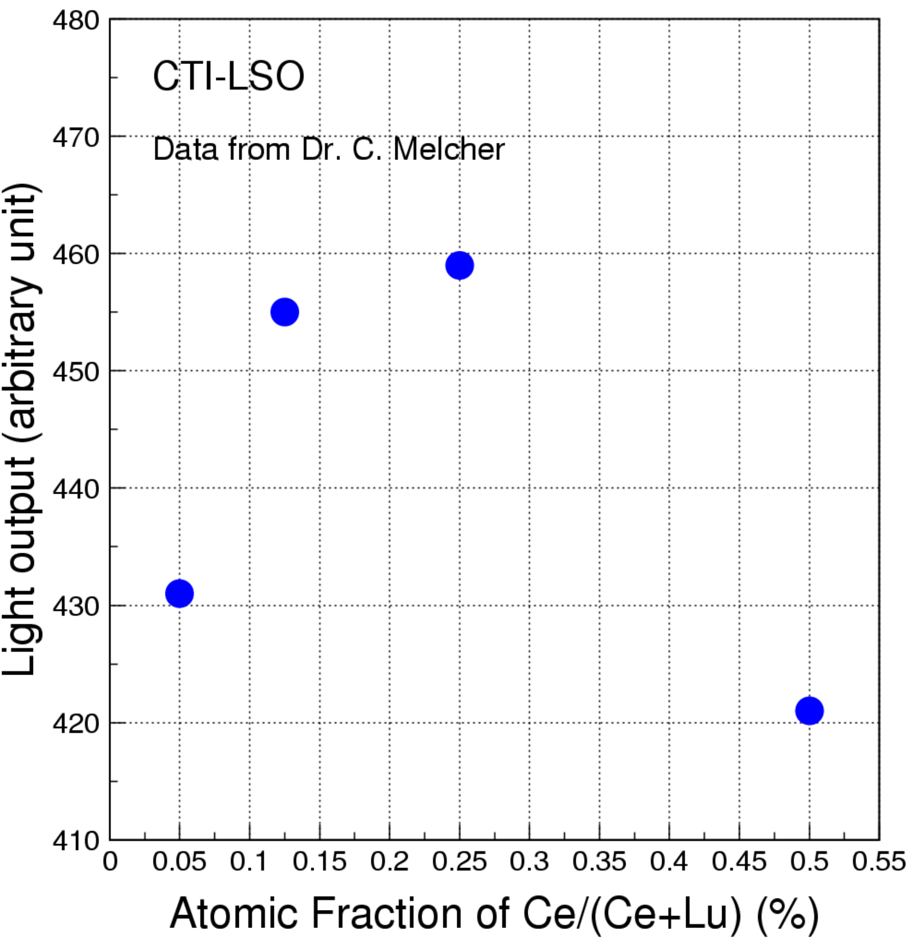
9% - 14% loss by APD

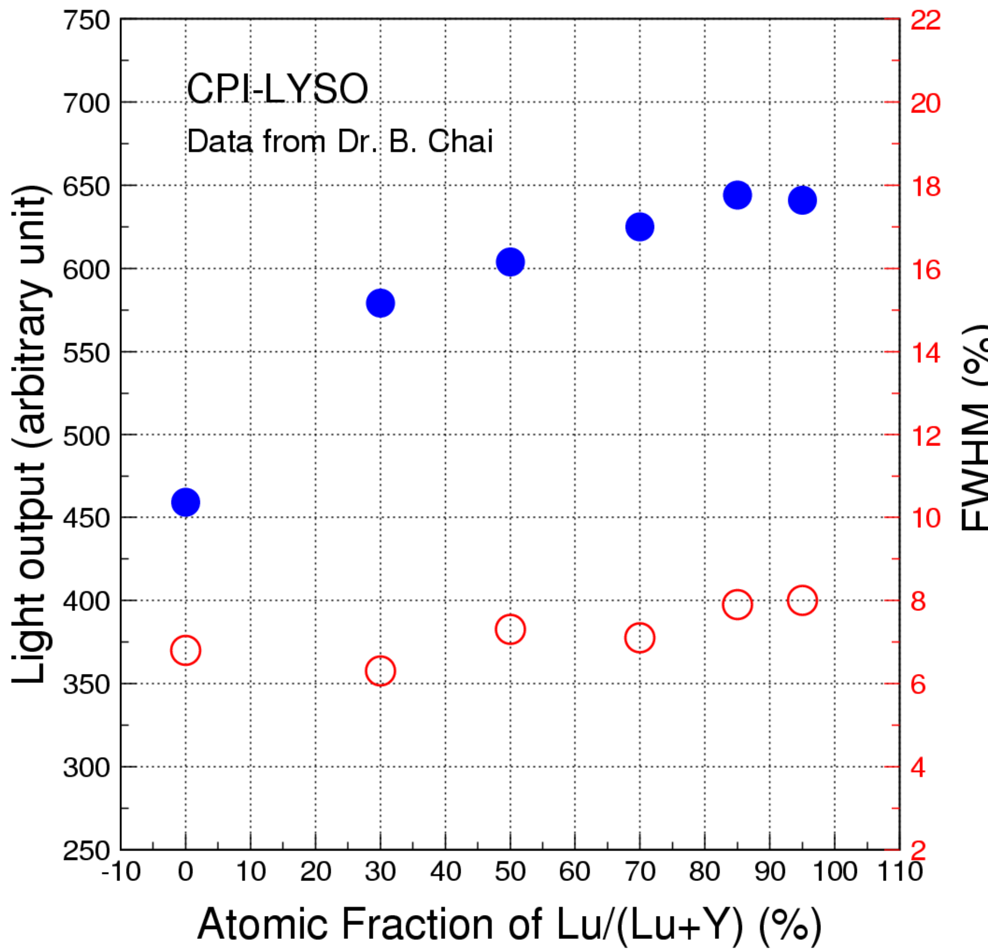




Possible Origin of Non Uniformity

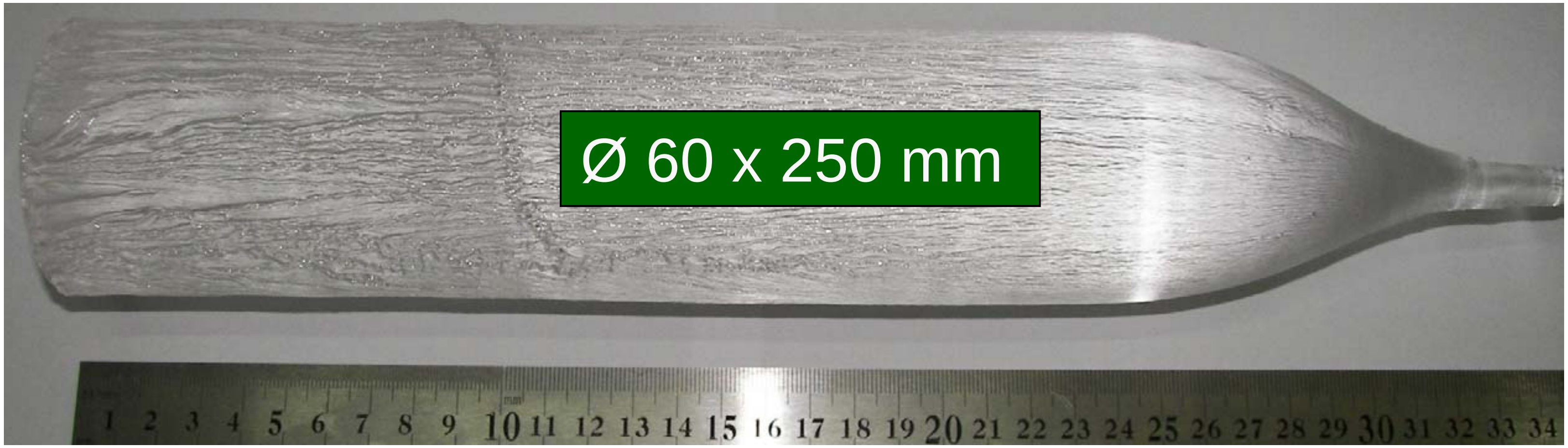
C. Melcher: LO in LSO is a function of Ce concentration
B. Chai: LO in LYSO is a function of Yttrium fraction



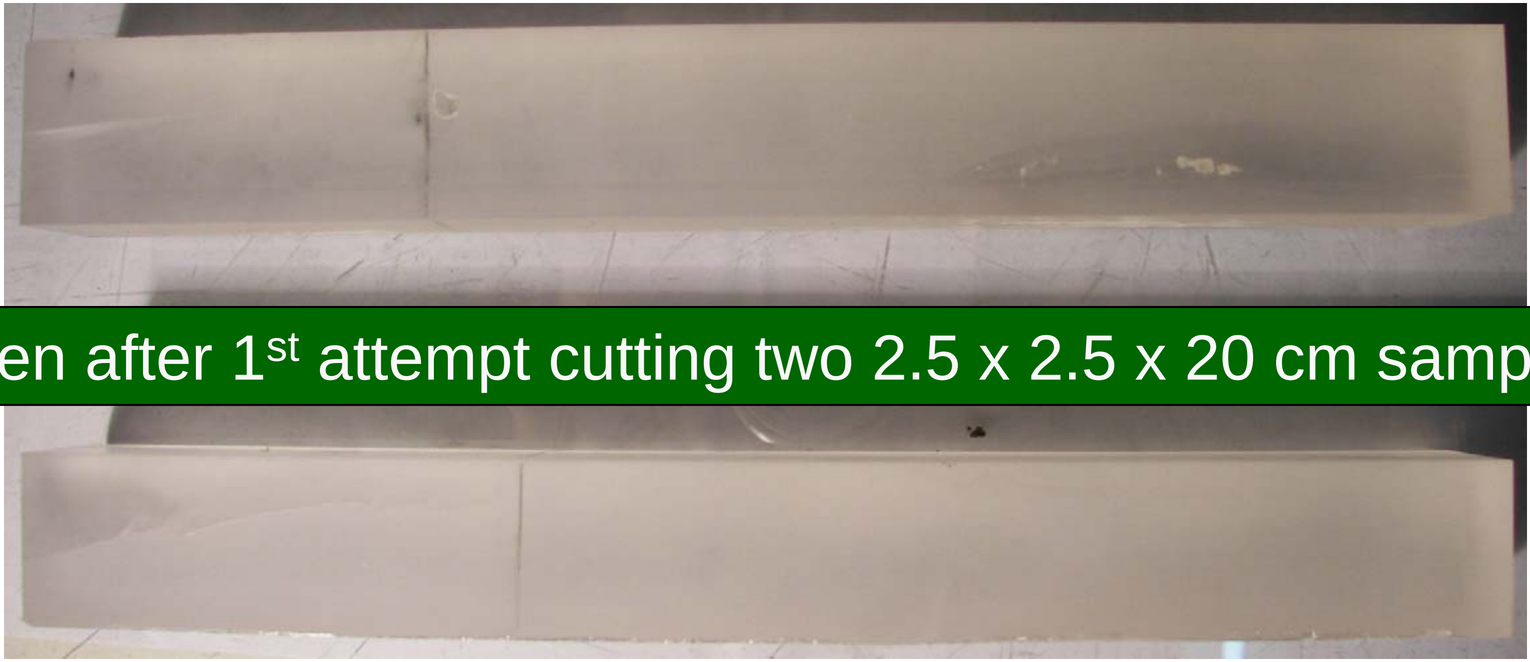


First SIPAT LYSO Bole for HEP

R&D aiming at producing crystals for HEP experiments

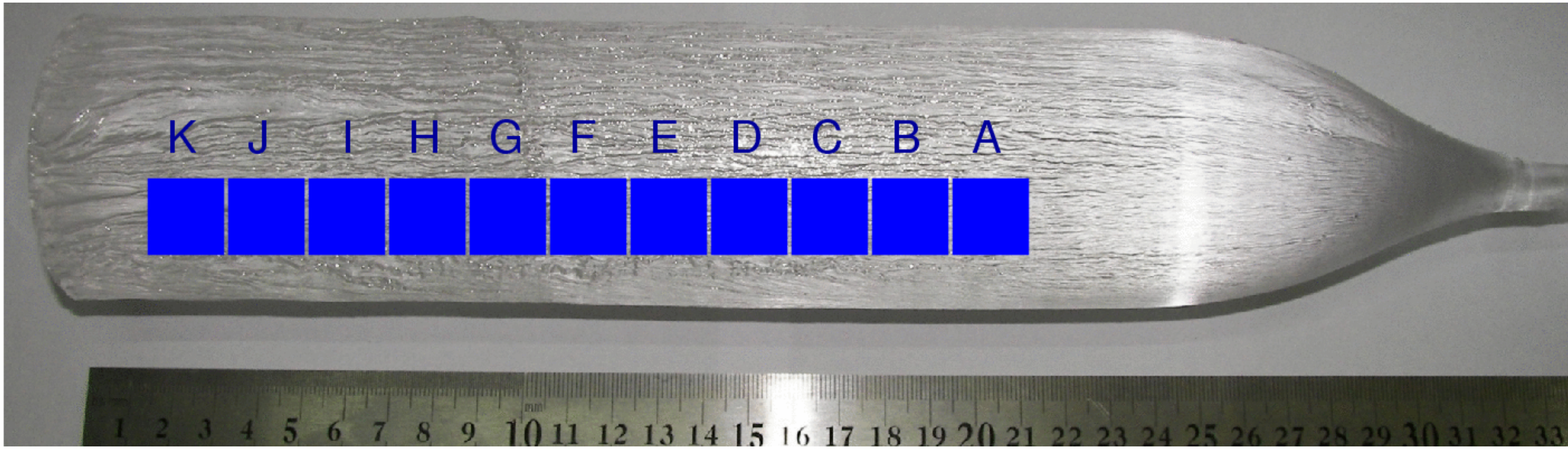


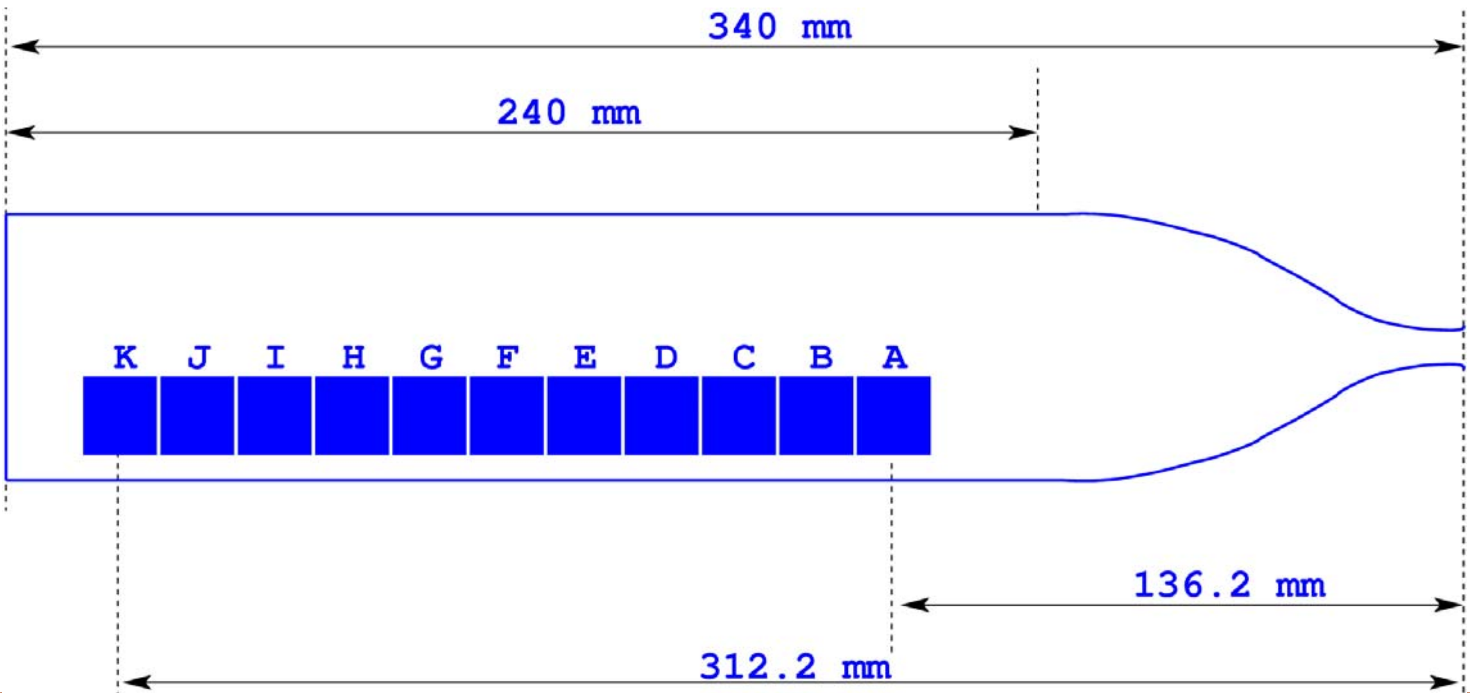
Ø 60 x 250 mm



Broken after 1st attempt cutting two 2.5 x 2.5 x 20 cm samples

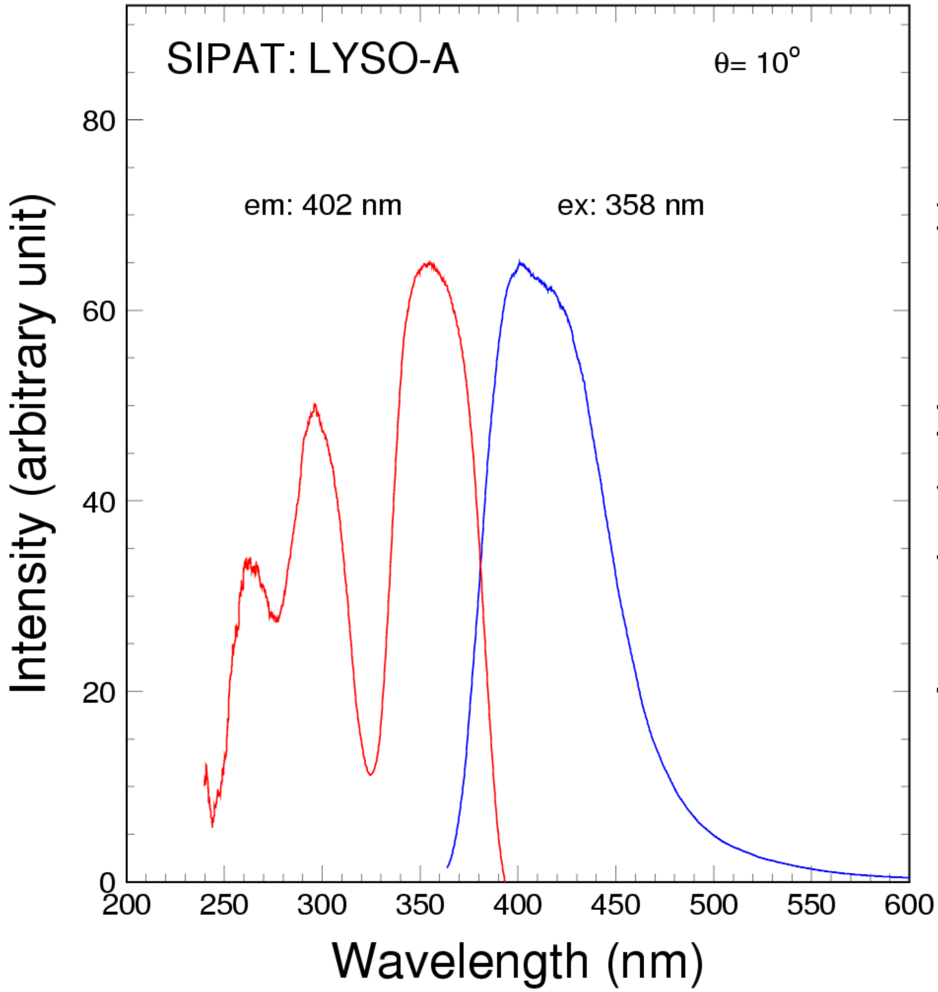
11 Samples from the 1st Ingot

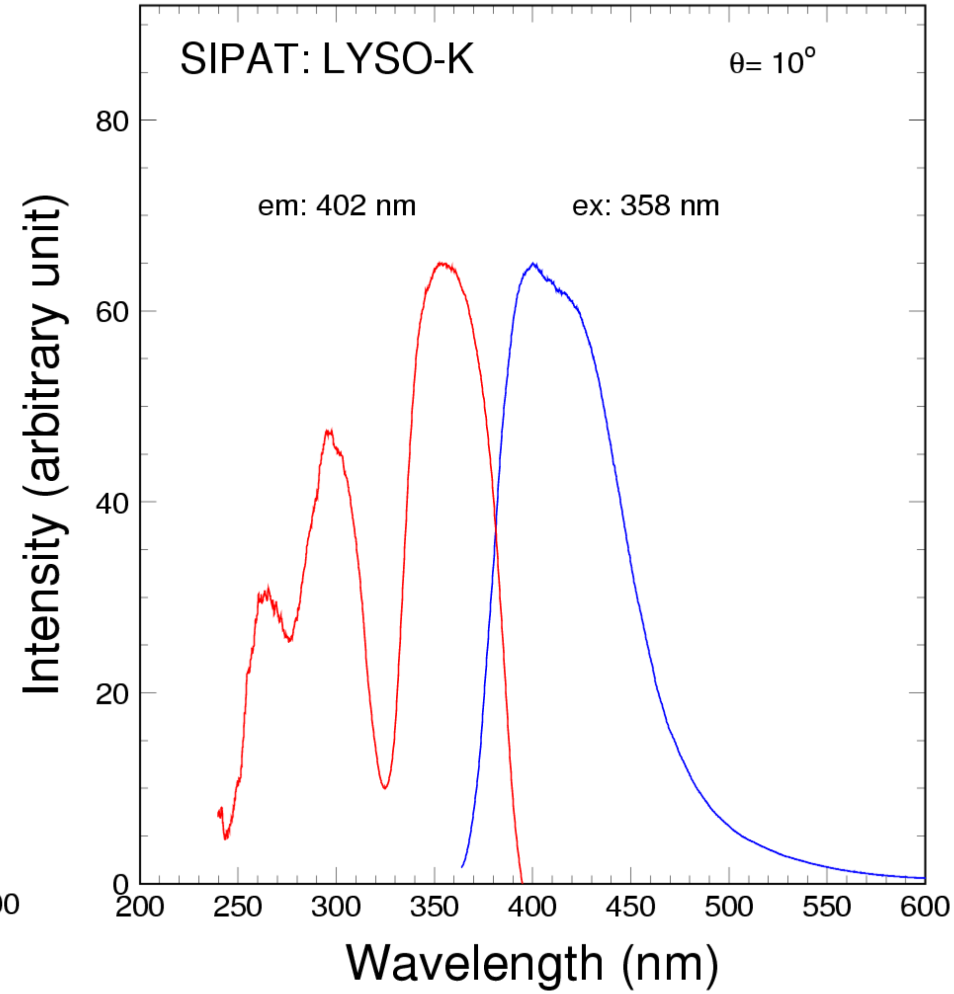




Excitation & Photo-Luminescence

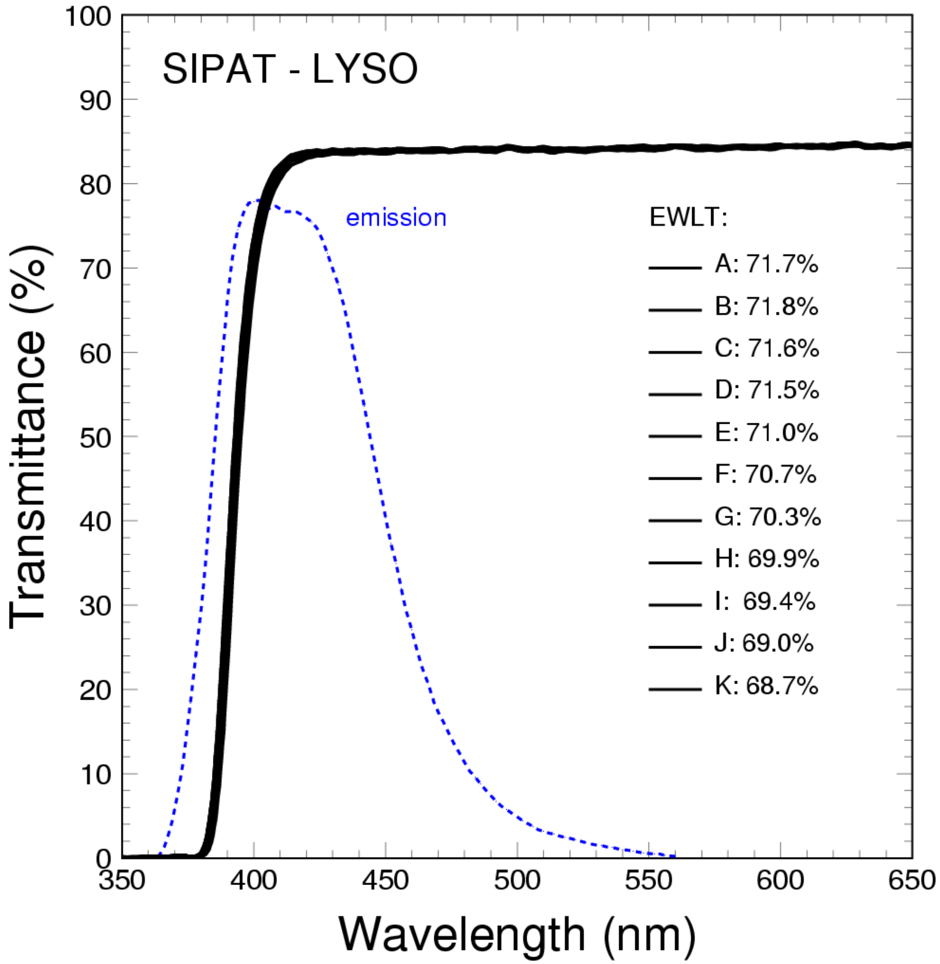
No variation in excitation and emission

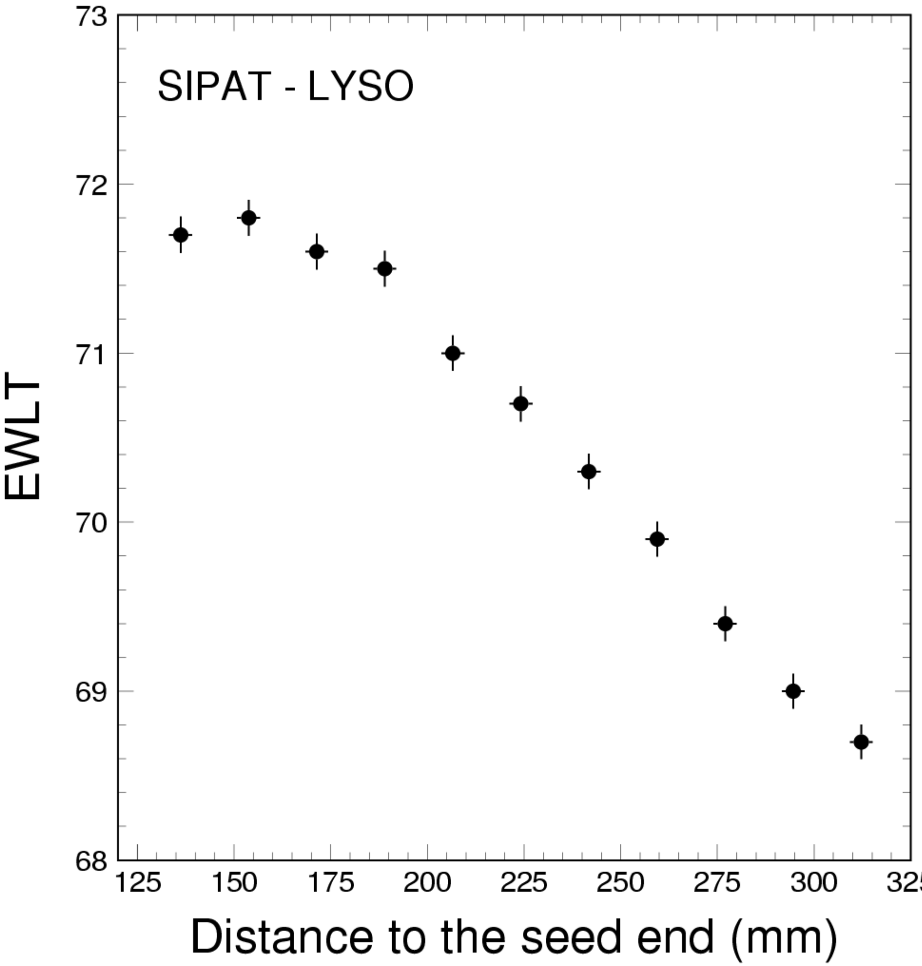




Transmittance

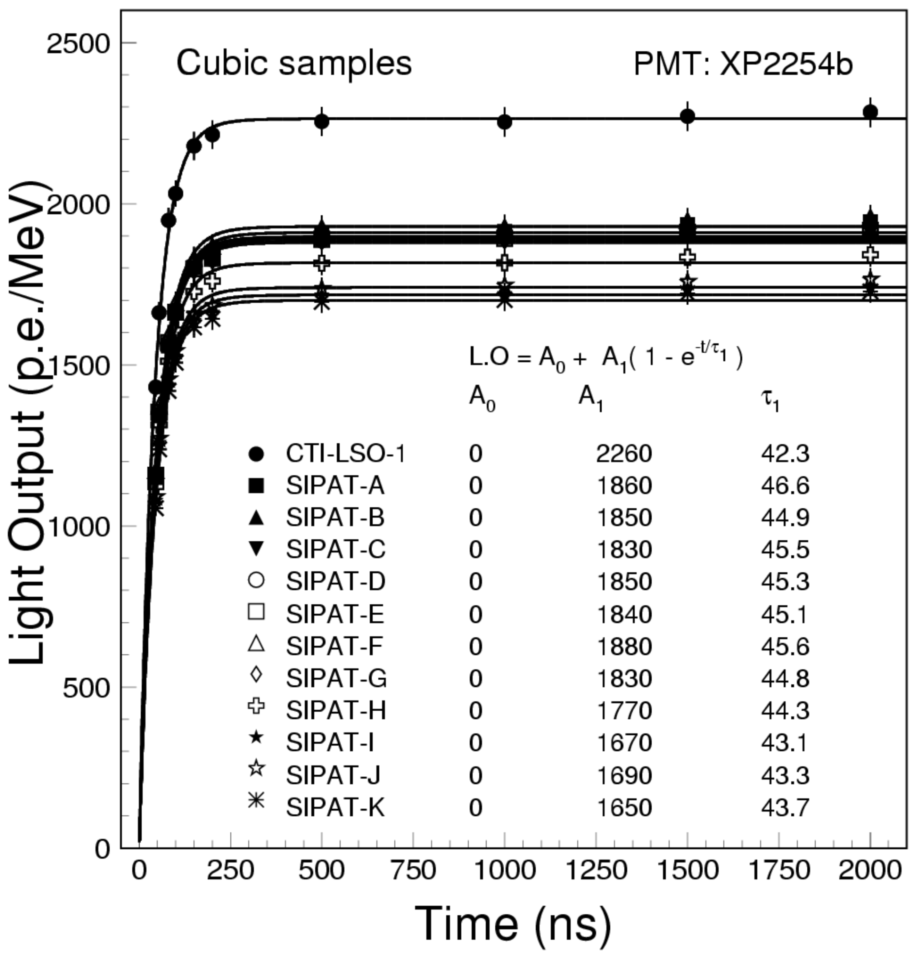
Transmittance degrades after 5 cm from the seed

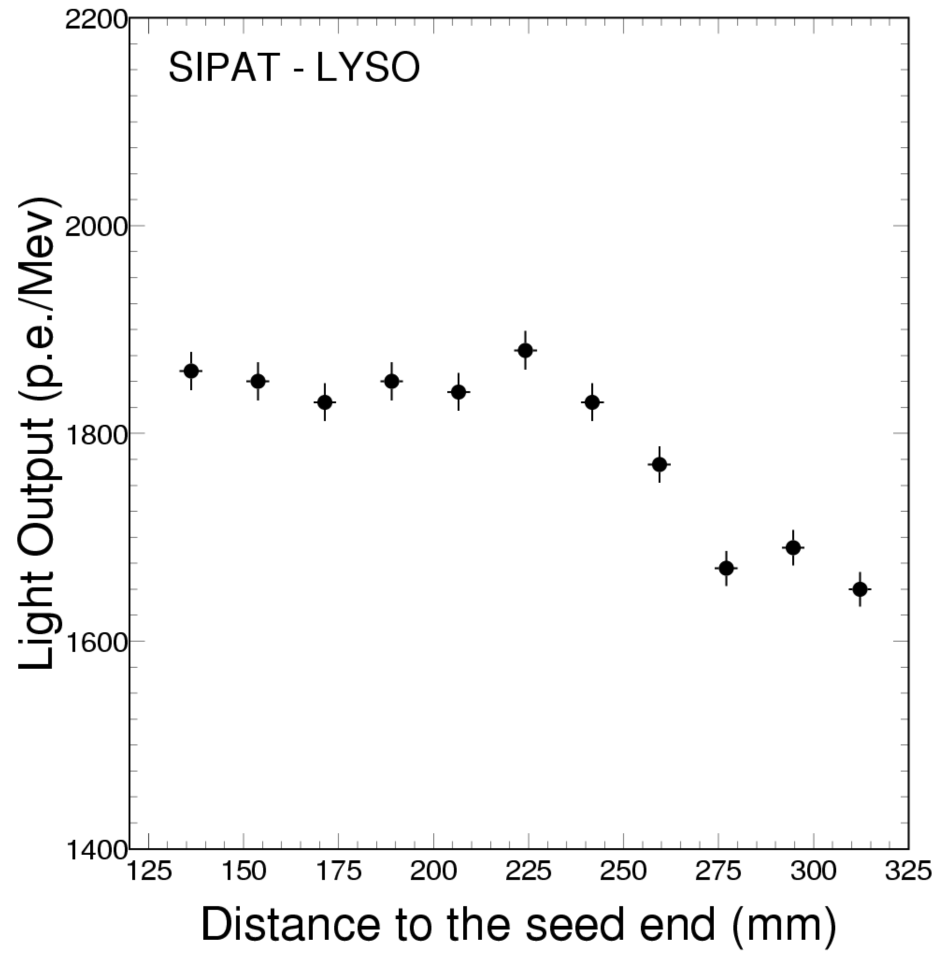




Light Output

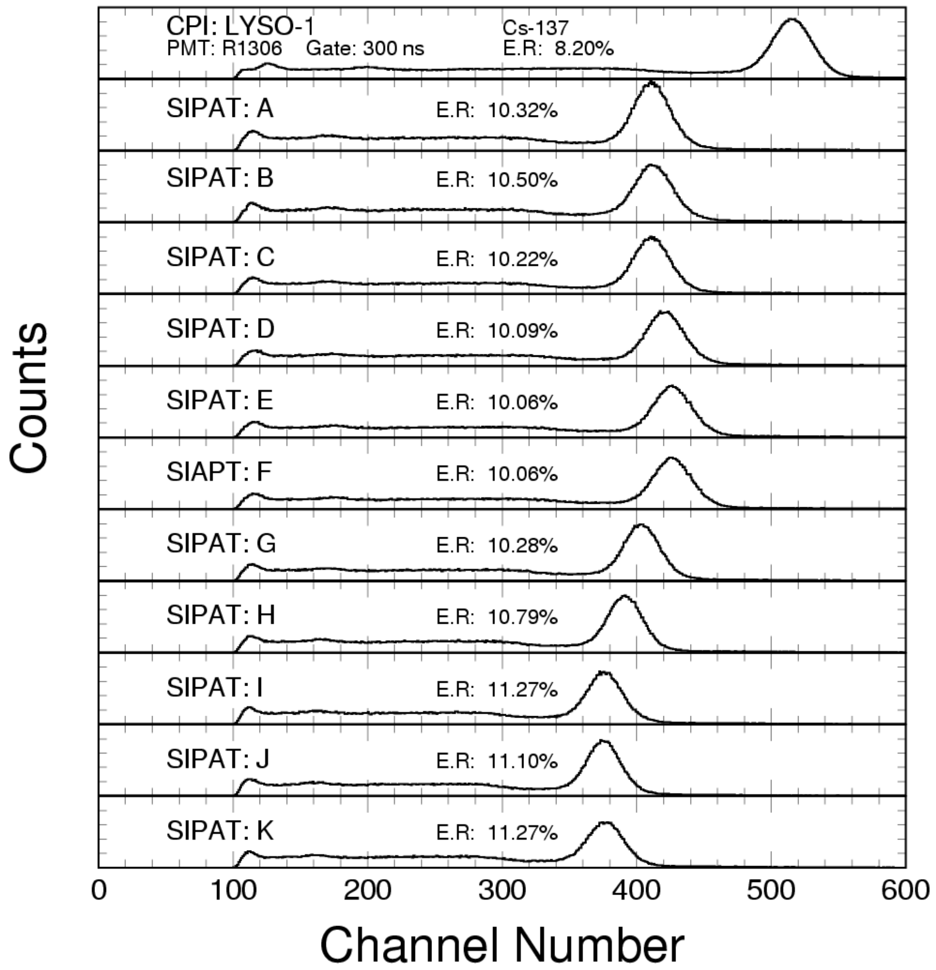
Light output degrades after 10 cm from the seed

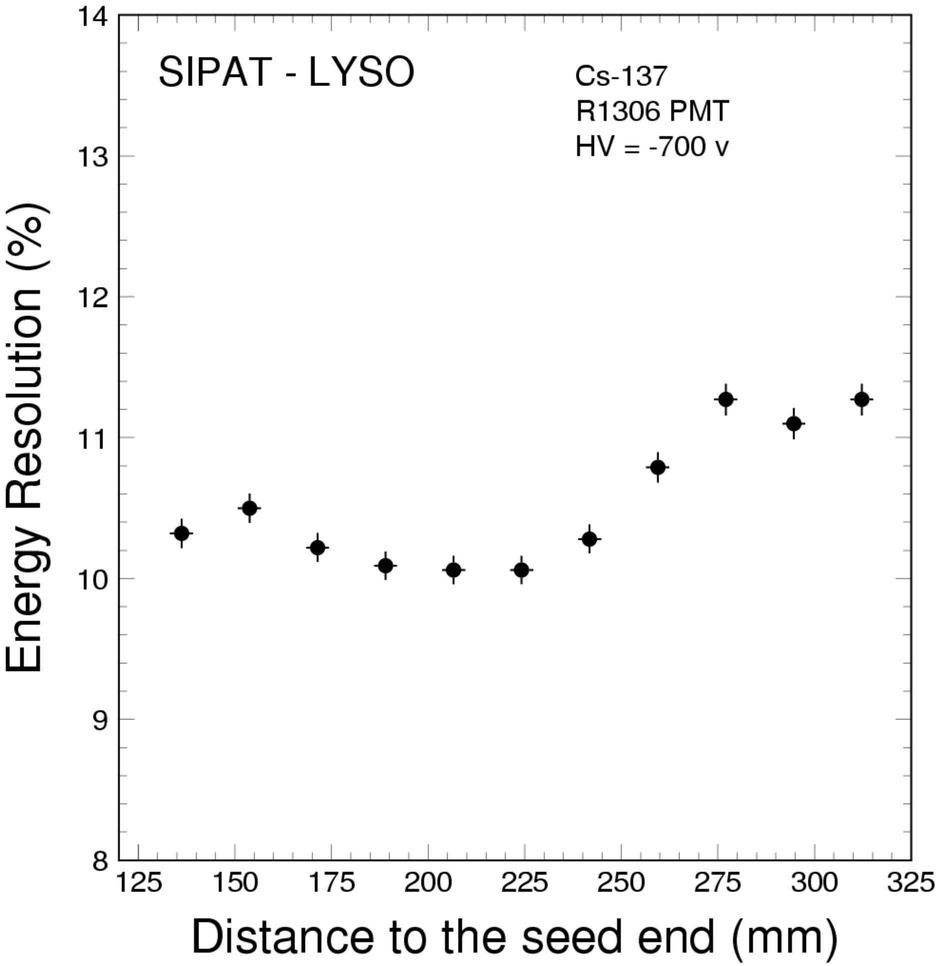




Energy Resolution

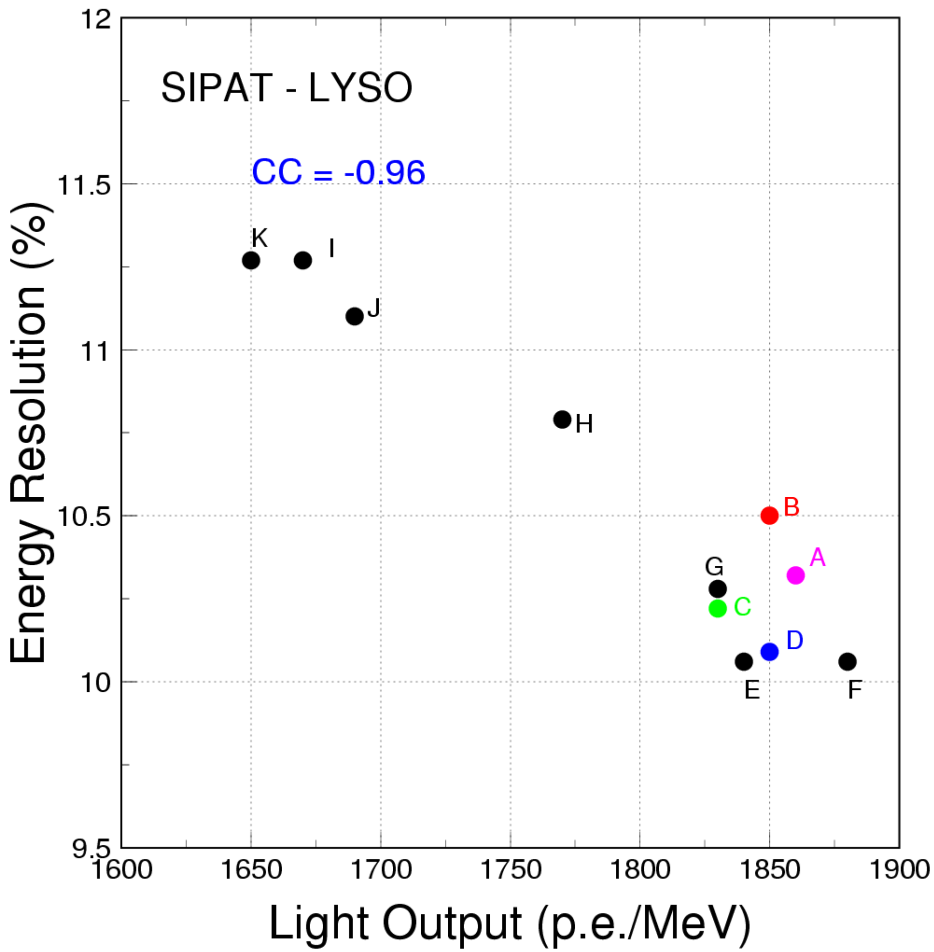
Resolution degrades after 10 cm from the seed

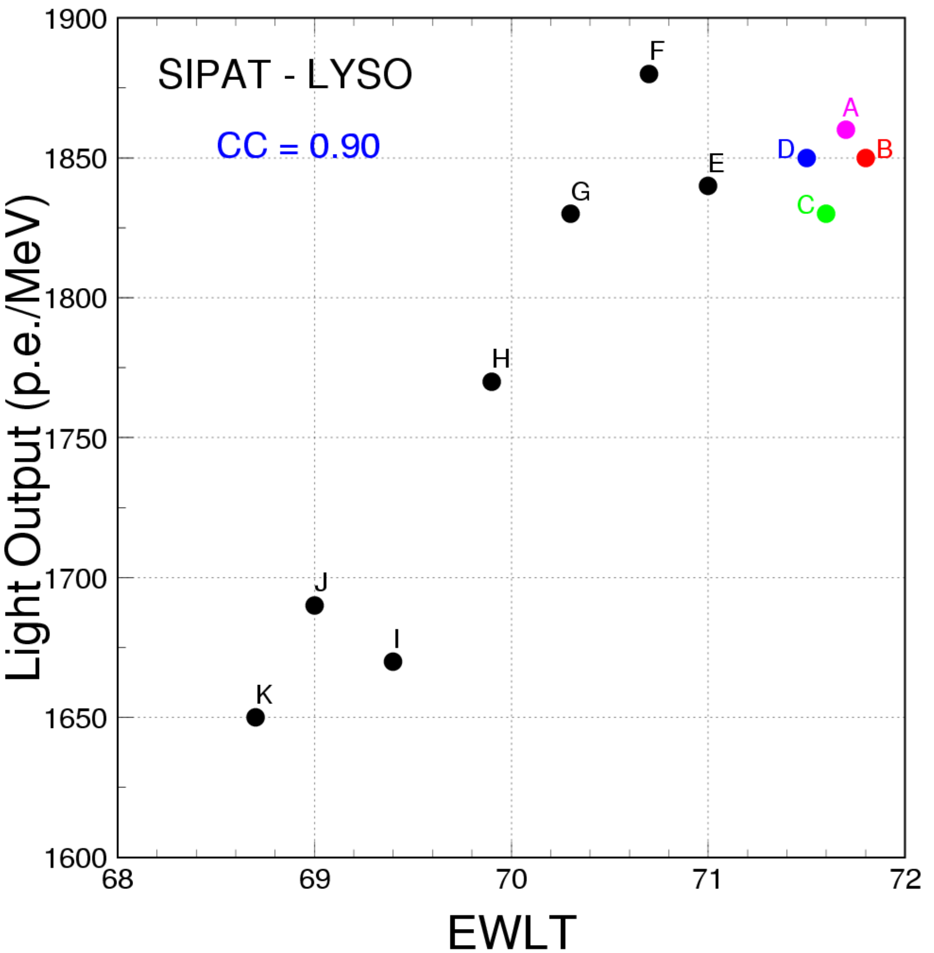




Excellent Correlations

Between light output and resolution/transmittance



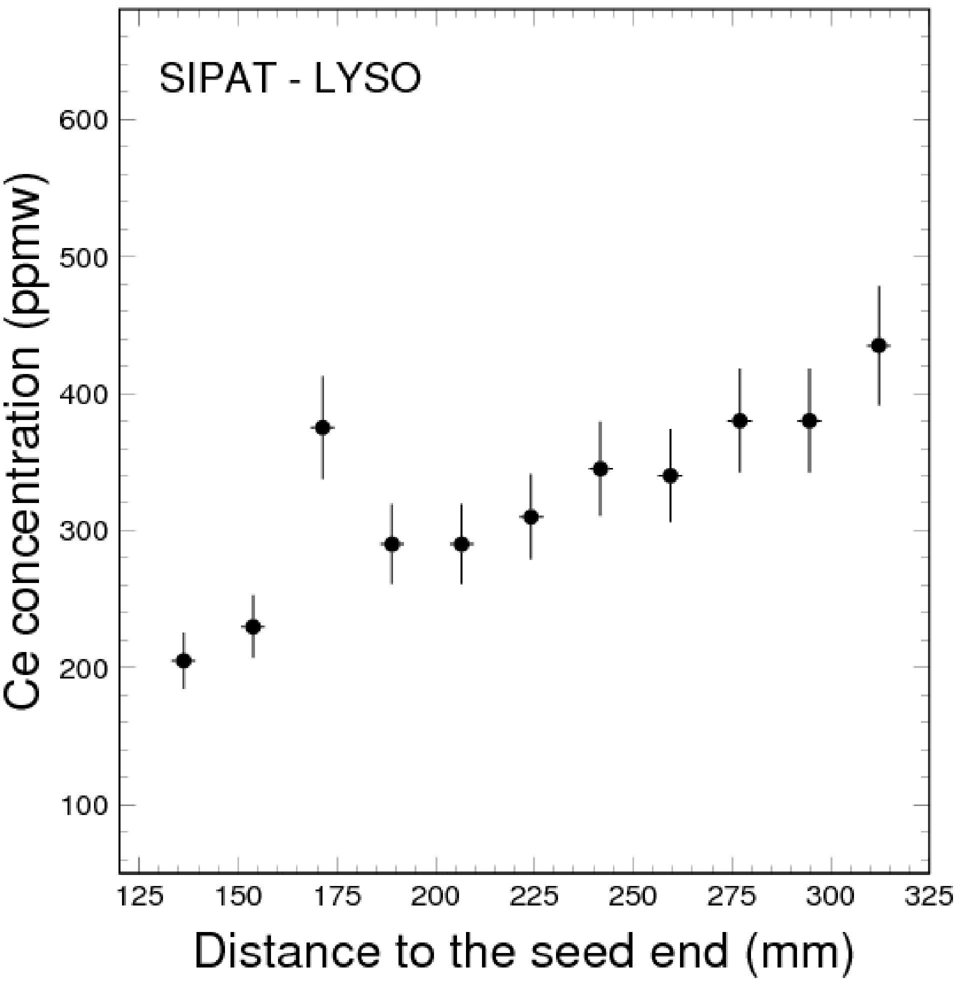


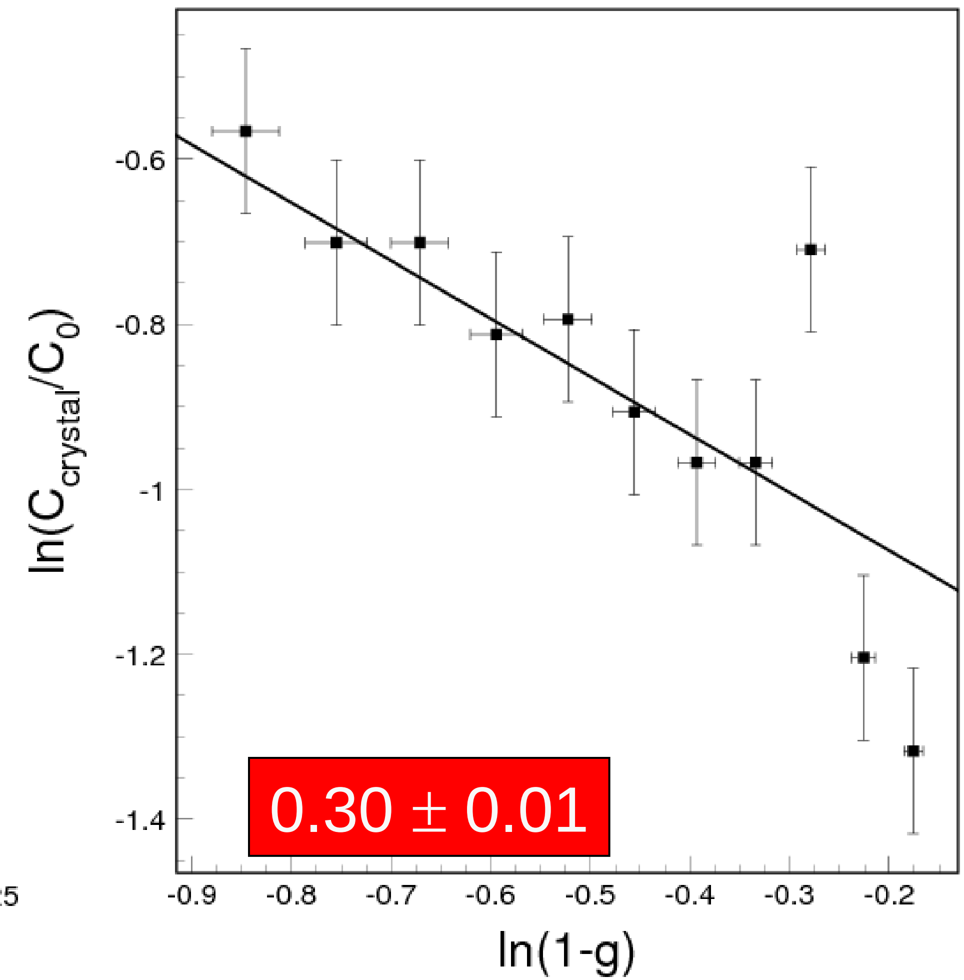
Ce & Y Concentrations by GDMS

ID	Ce (ppmw)	Y (W%)
SIAPT-A	205	1.11
SIAPT-B	230	1.05
SIAPT-C	375	1.42
SIAPT-D	290	1.32
SIAPT-E	290	1.09
SIAPT-F	310	1.33
SIAPT-G	345	1.43
SIAPT-H	340	1.28
SIAPT-I	380	1.33
SIAPT-J	380	1.24
SIAPT-K	435	1.45

Cerium Segregation in LSO

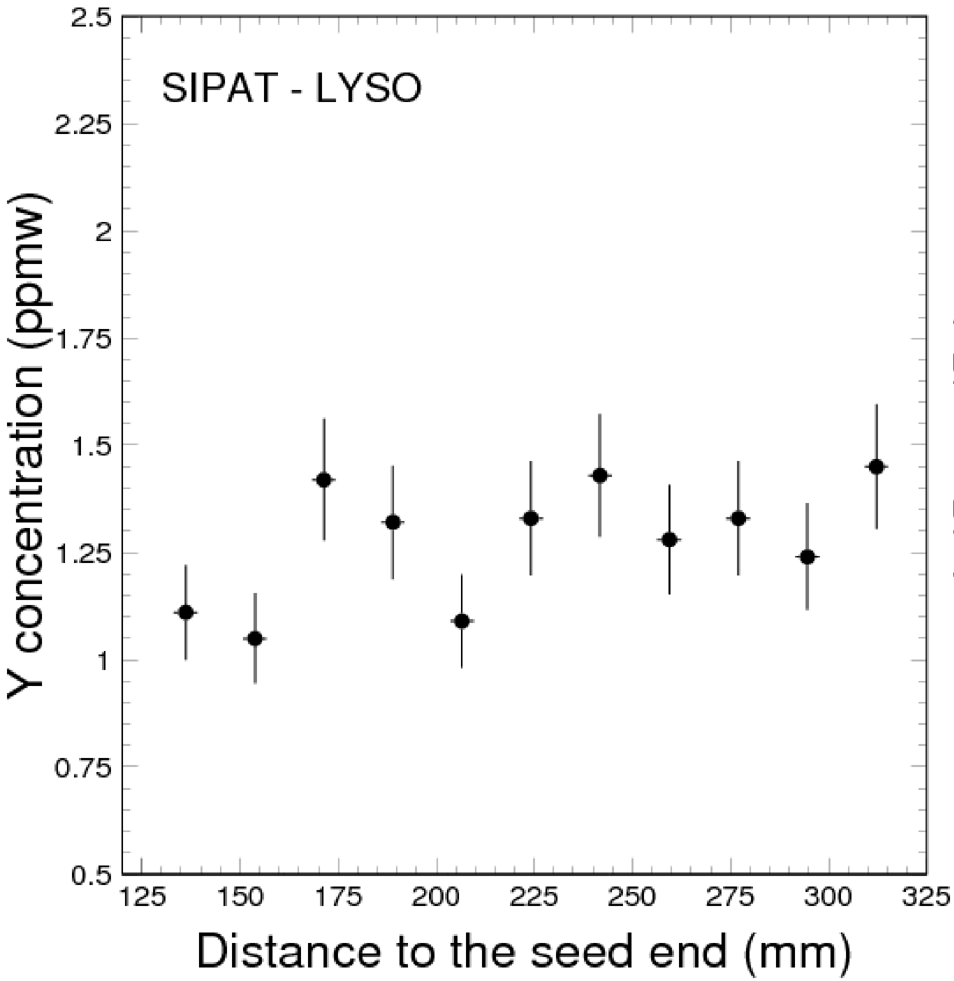
Ce is not easy to enter LSO lattice.
It may be important to make it uniform.

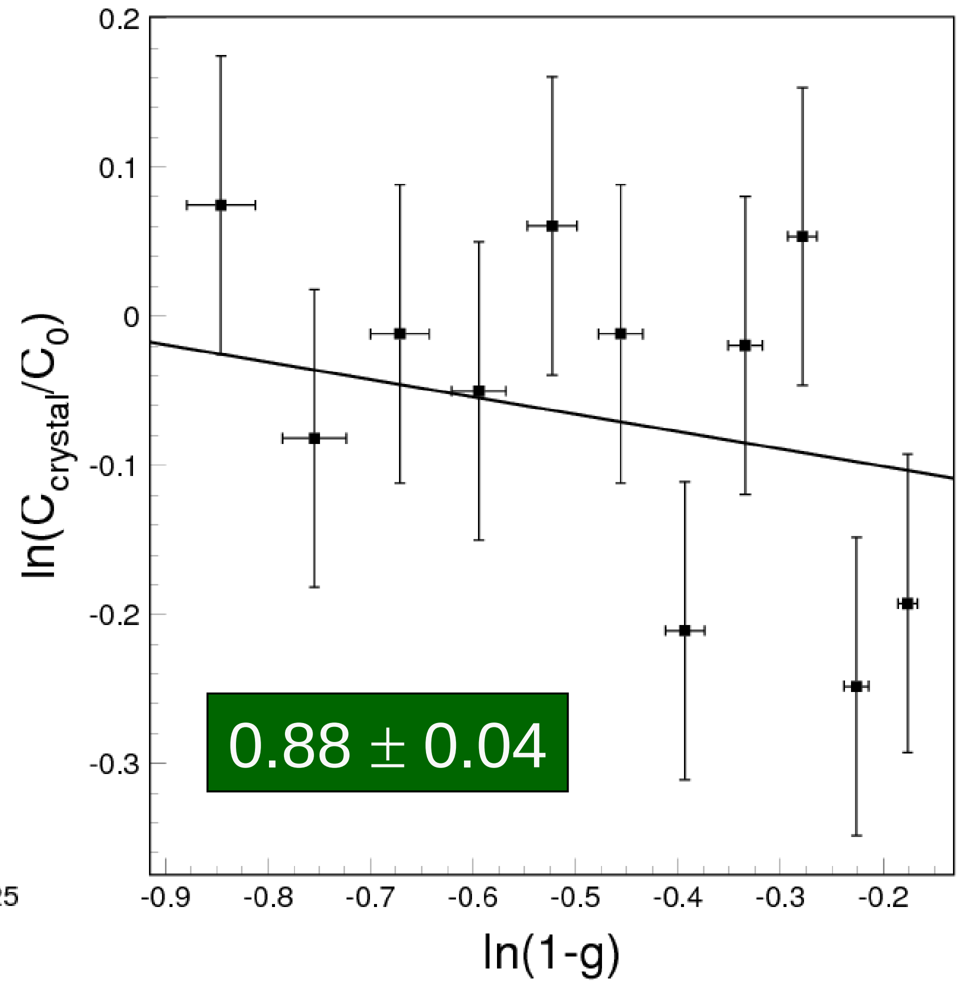




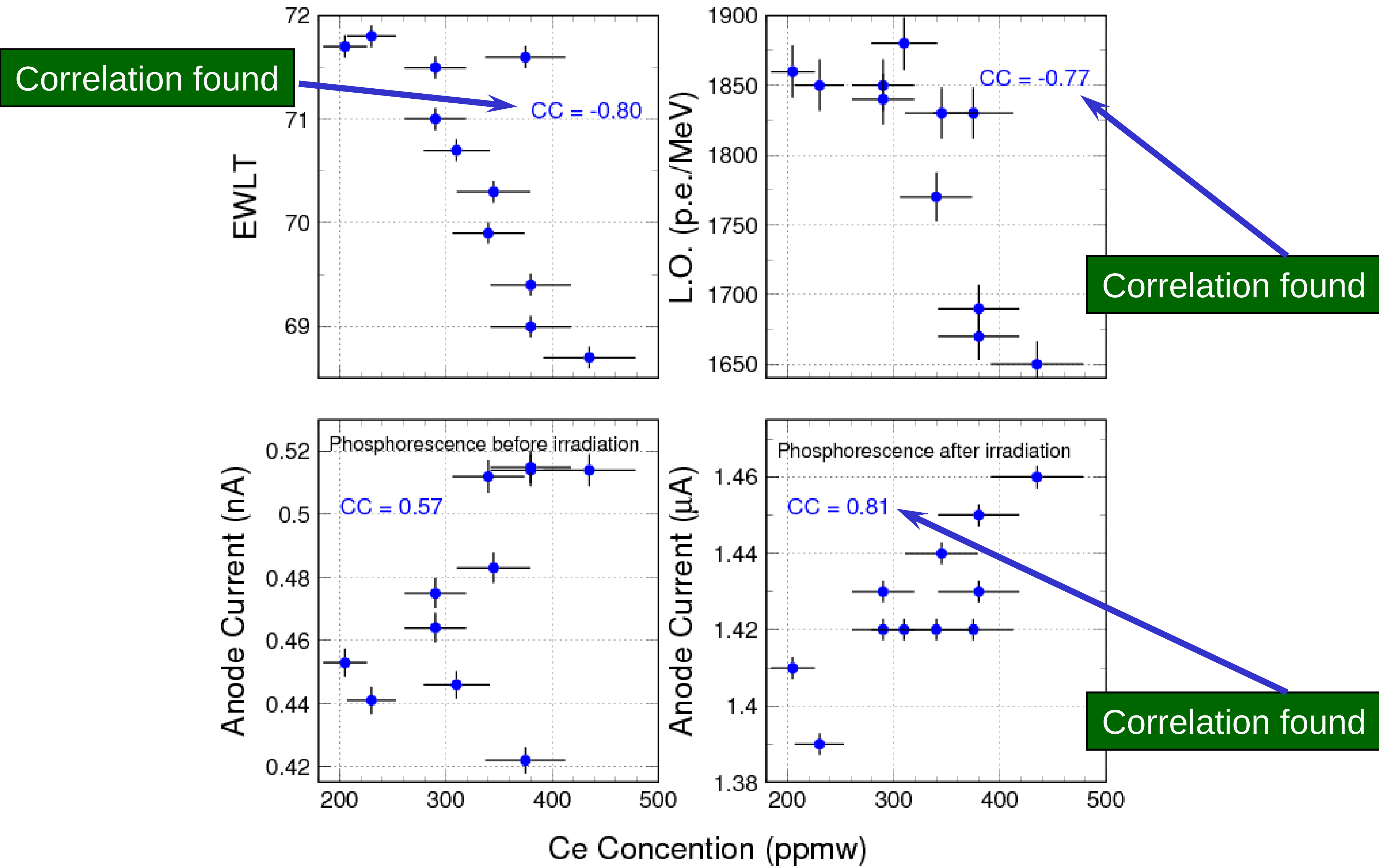
Yttrium Segregation in LSO

Yttrium is more uniform in LSO.
Its distribution seems not a concern.





Correlation: Ce and EWLT/L.O./Phors.



Summary

- LSO/LYSO crystals are a good candidate for future precision crystal calorimeters.
- Progress has been made in understanding LSO and LYSO crystals.
- Development of cost effective LYSO crystals for SuperB experiments is being pursued.
- Thanks to the DOE ADR program for supporting this work.