LSO/LYSO Crystals for Future High Energy Physics Experiments

Ren-yuan Zhu

California Institute of Technology

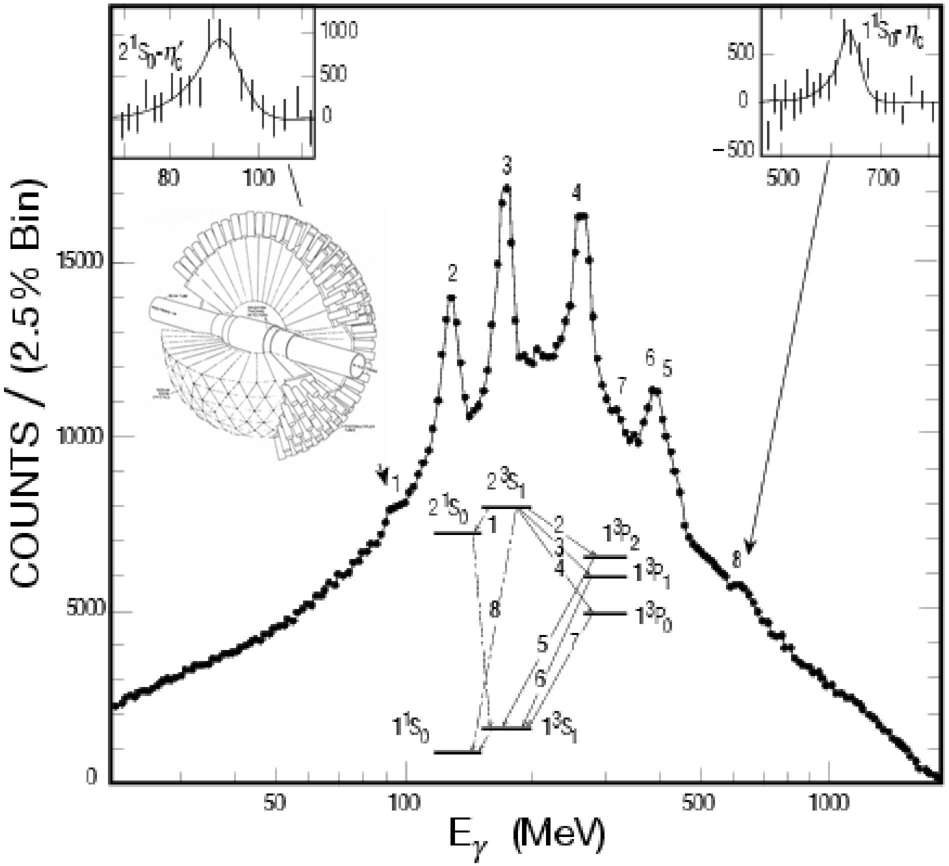
Why Crystal Calorimeter

- 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

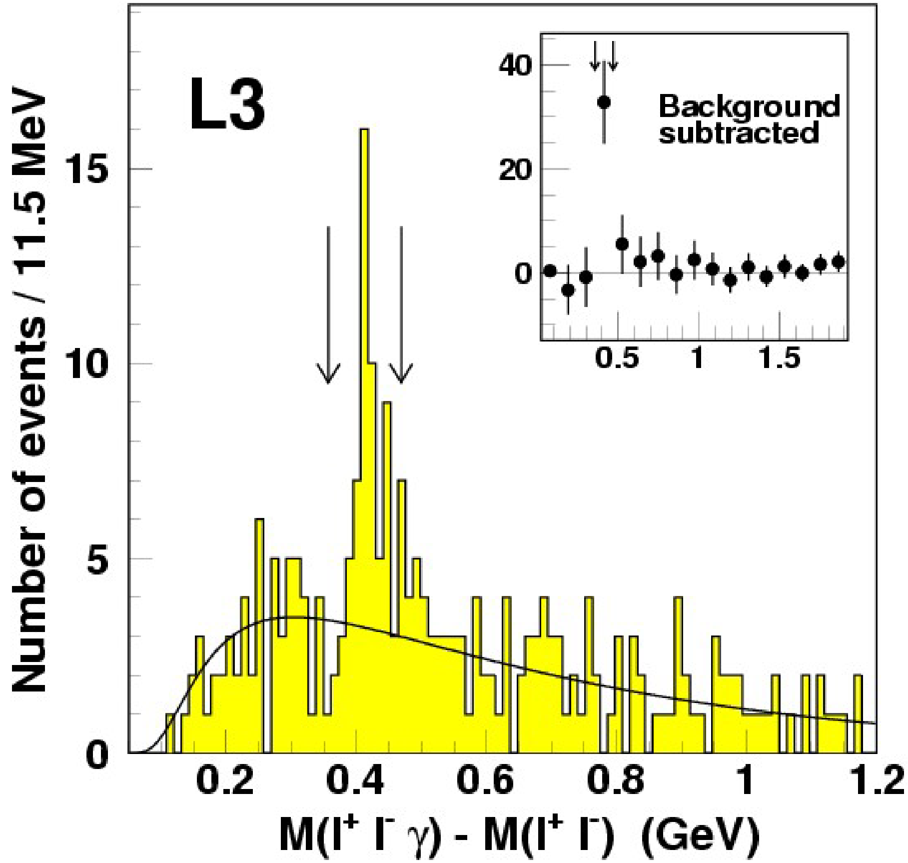
CB NaI(Tl)



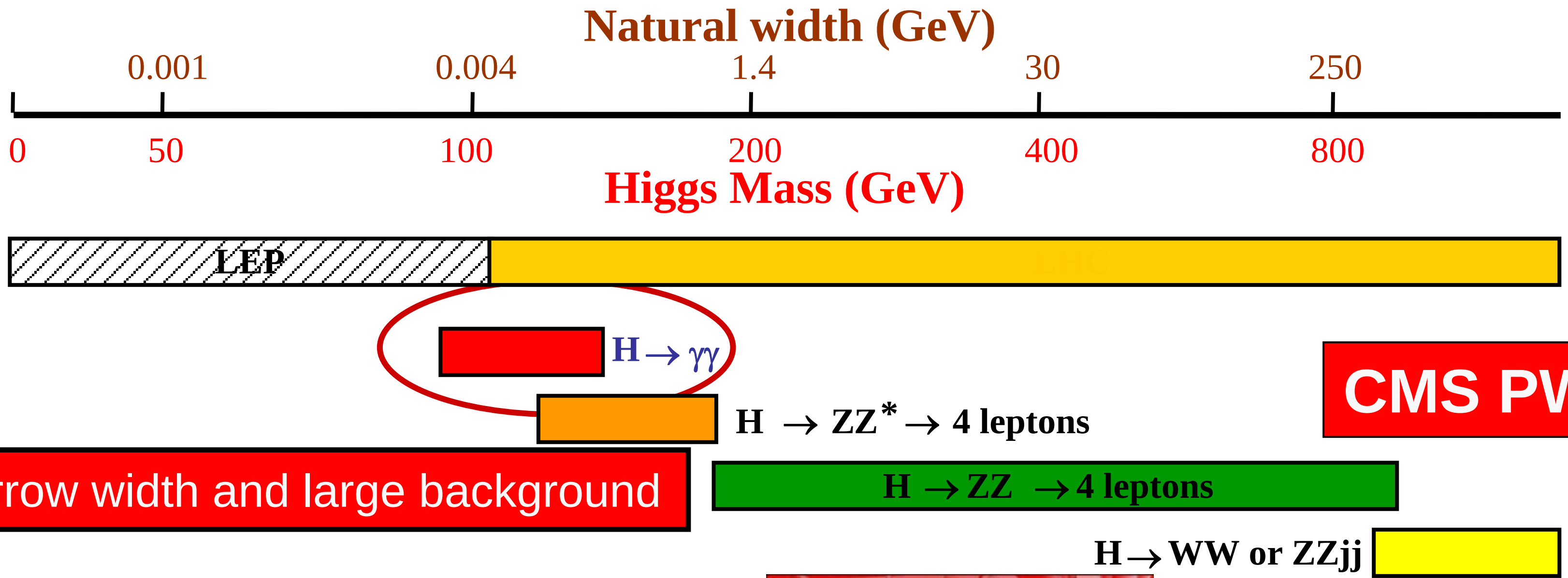
Charmed Meson in Z Decay

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

L3 BGO

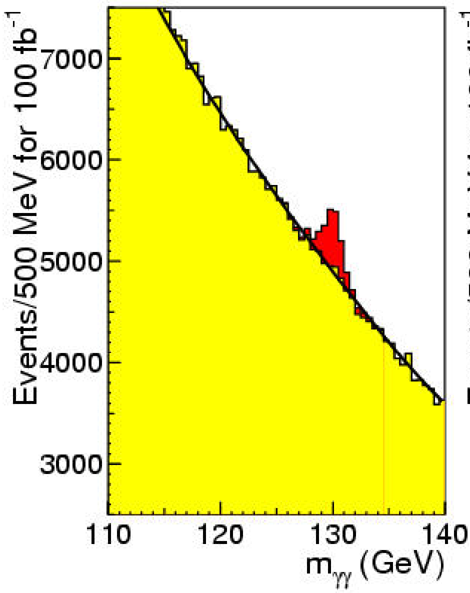


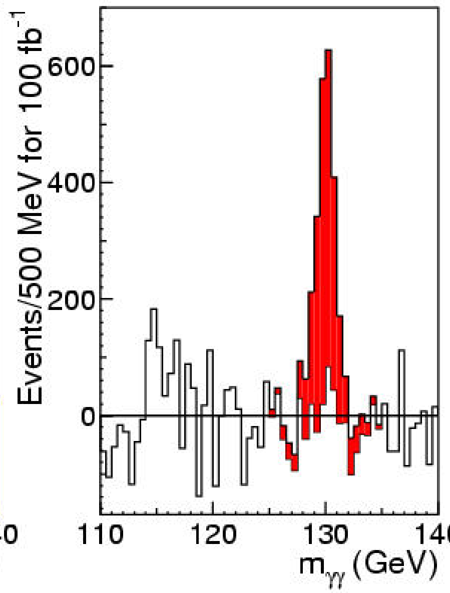
H→γγ Search Needs Precision ECAL

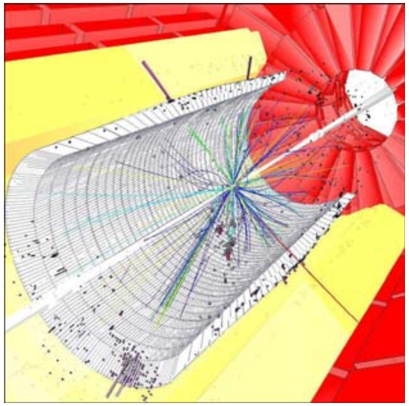


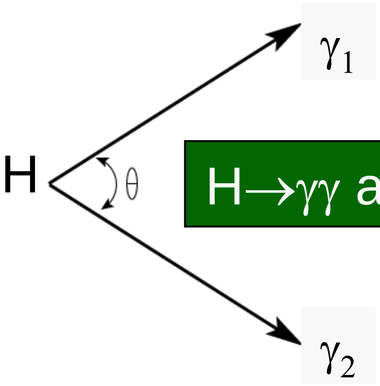
CMS PWO

Narrow width and large background





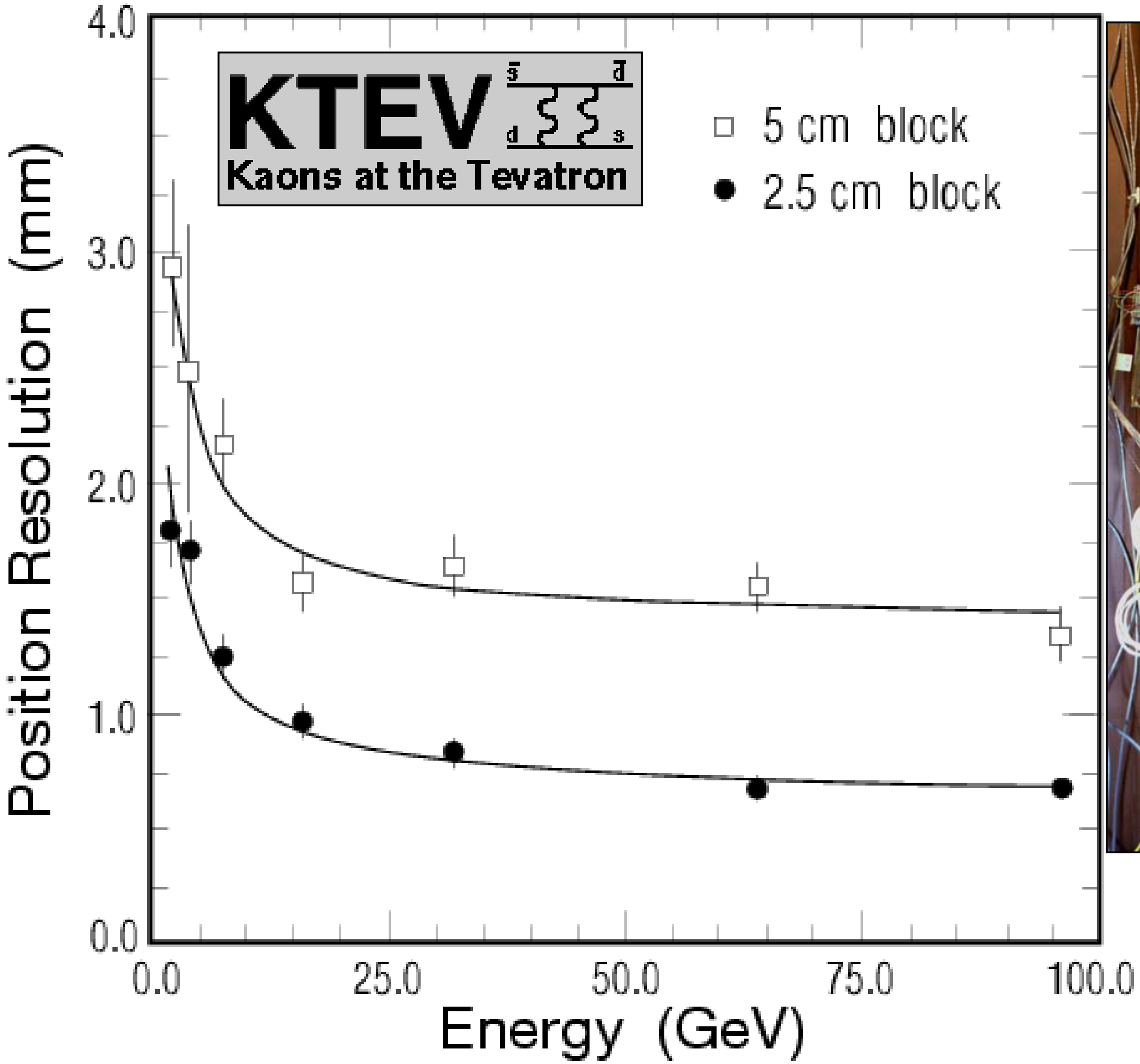


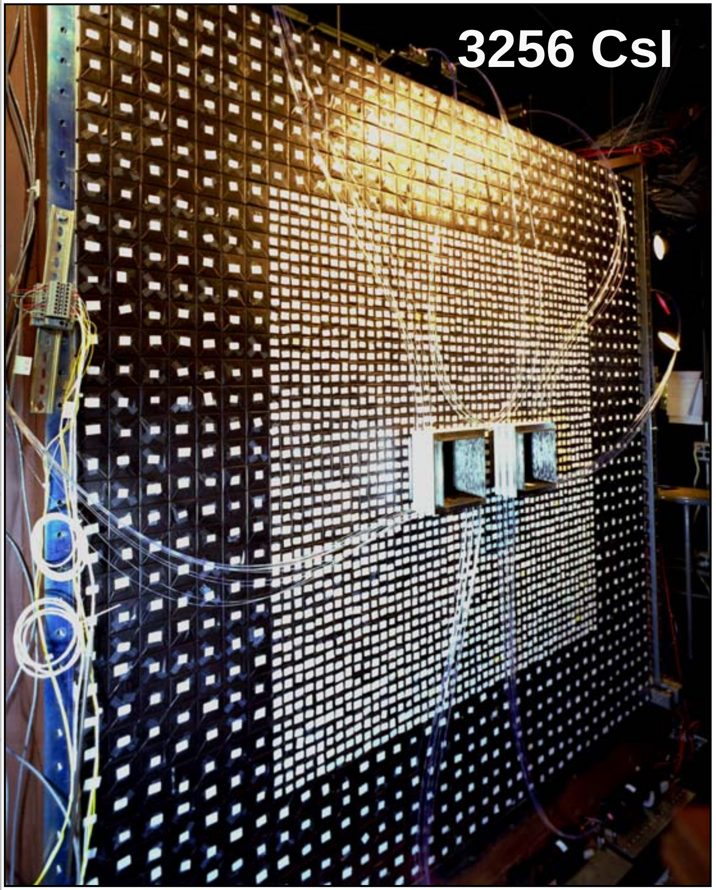


H→γγ at LHC

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

KTeV CsI Position Resolution

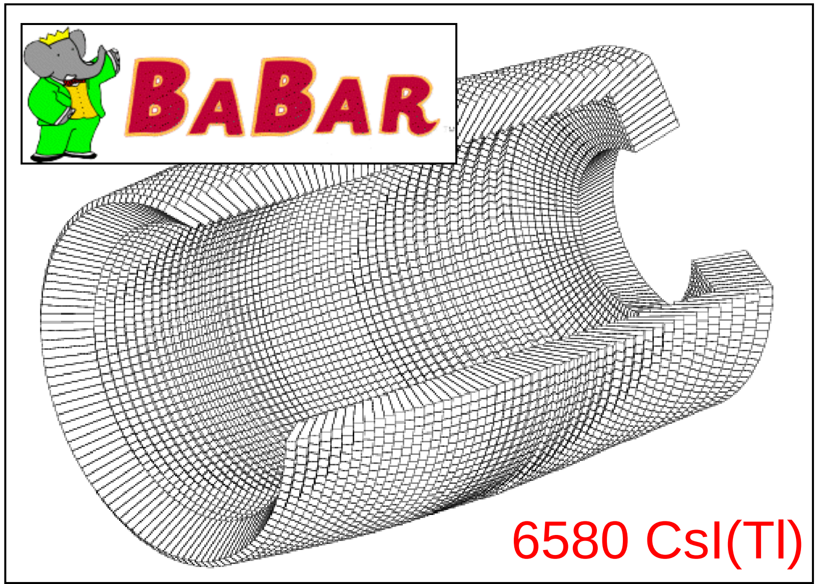




σx = 3 /√ E ⊕ 0.3 mm for L3 BGO & CMS PWO

BaBar CsI(Tl) Energy Resolution

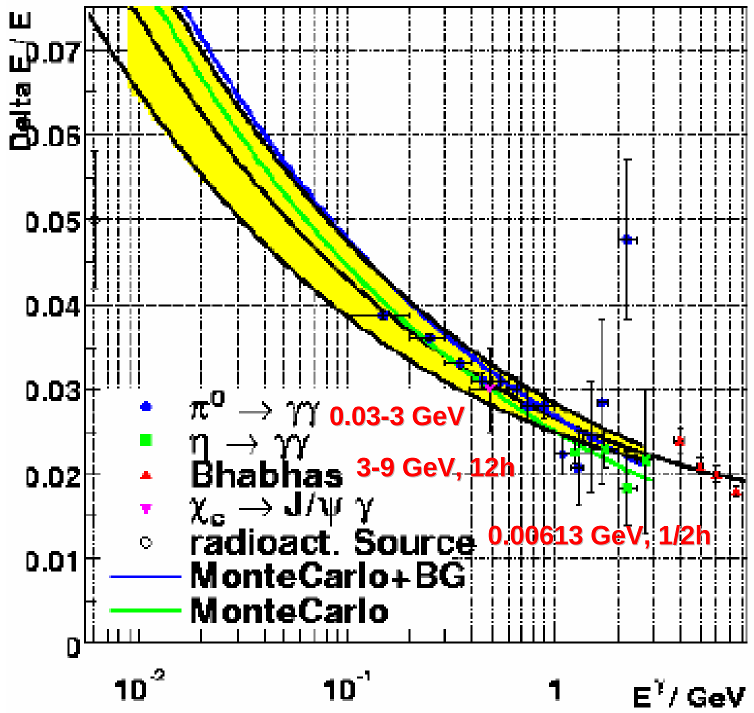
BaBar CsI(Tl)



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

Energy resolution

M. Kocian, SLAC, CALOR2002



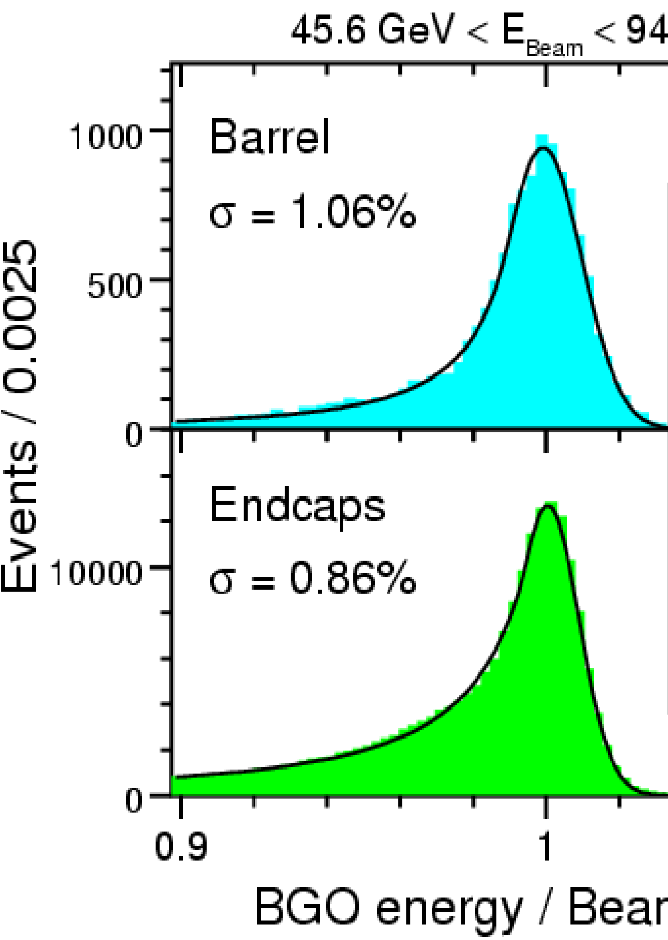
$$\frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt[4]{E}} \oplus \sigma_2$$

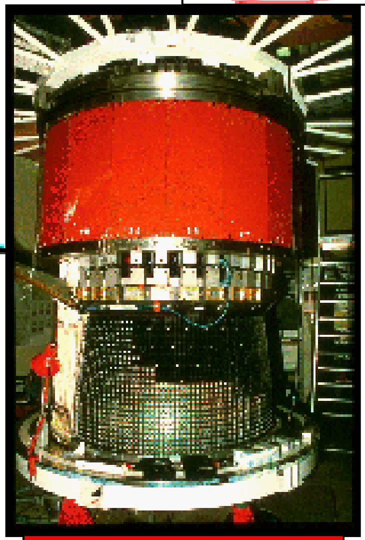
$$\sigma_1 = (2.30 \pm 0.03 \pm 0.3)\%$$

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

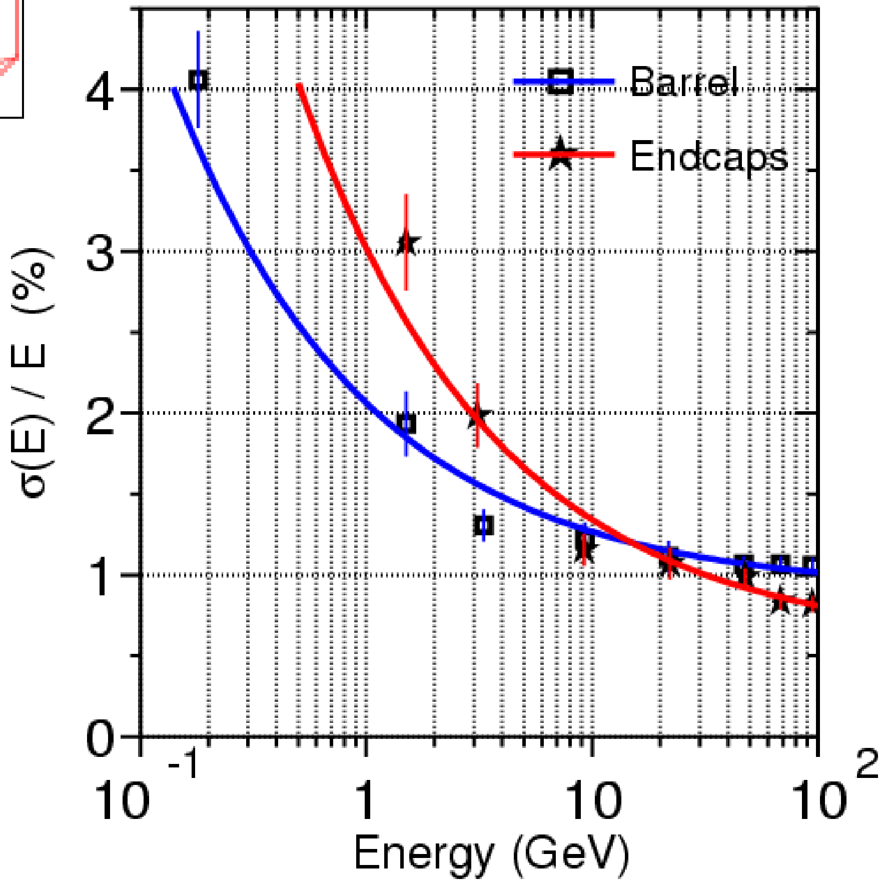
L3 BGO Energy Resolution

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

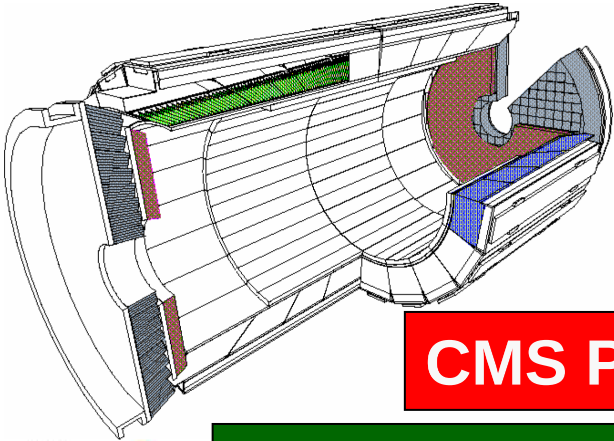




L3 BGO



CMS PWO Energy Resolution



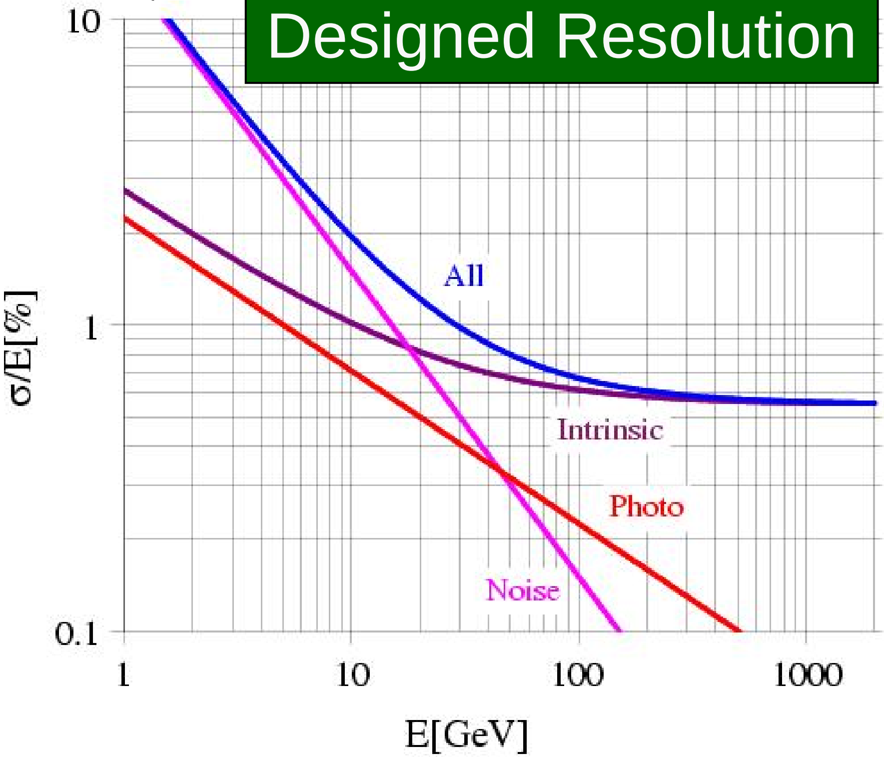
Measured Resolution

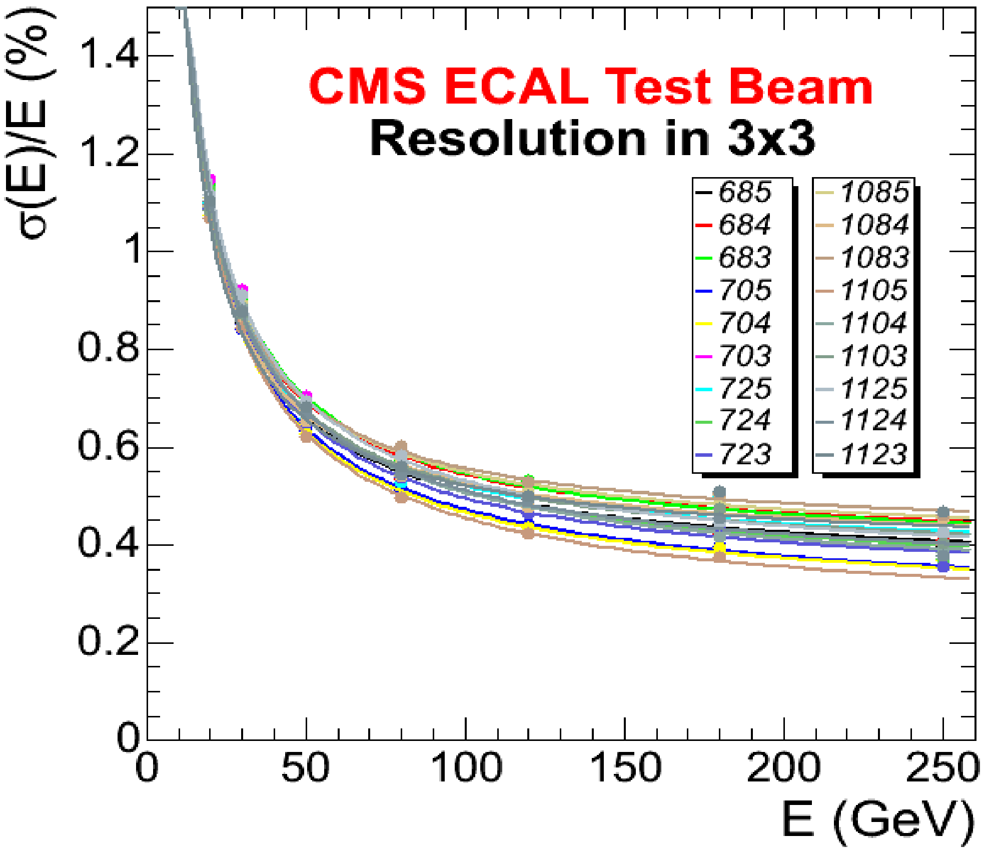
$\sigma(E)/E < 1\%$ if $E > 25$ GeV

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

CMS PWO

Designed Resolution



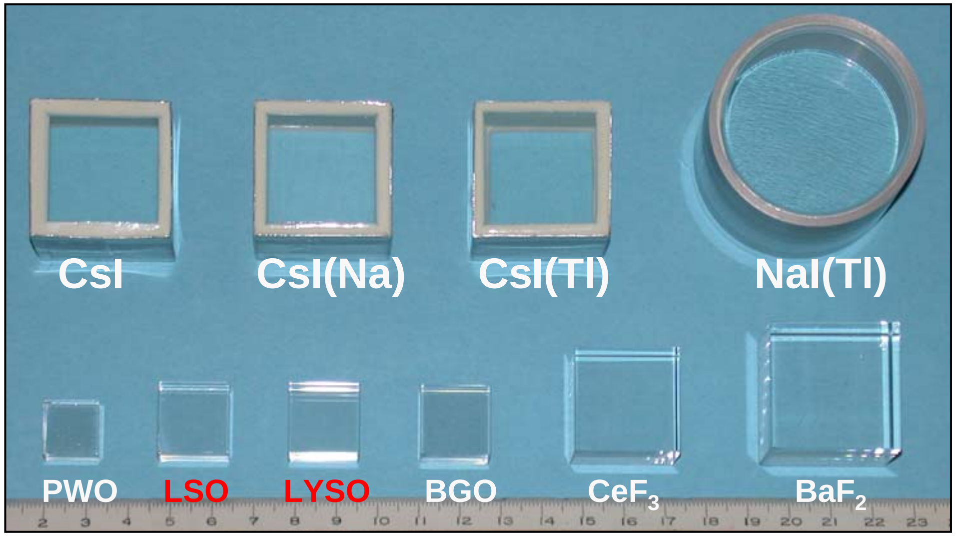


Mass Produced Crystals

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	PWO(Y)	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	550	420 310	300 220	480	425 420	402	440
Decay Time [b] (ns)	245	1220	30 6	650 0.9	300	30 10	40	60
Light Yield [b,c] (%)	100	165	3.6 1.1	36 4.1	21	0.3 .083	85	30
d(LY)/dT [b] (%/ ºC)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-2.5	-0.2	-0.1
Experiment	Crystal Ball	CLEO BaBar BELLE BES III	KTeV	TAPS (L*) (GEM)	L3 BELLE	CMS ALICE PrimEx PANDA	Super B?	-

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

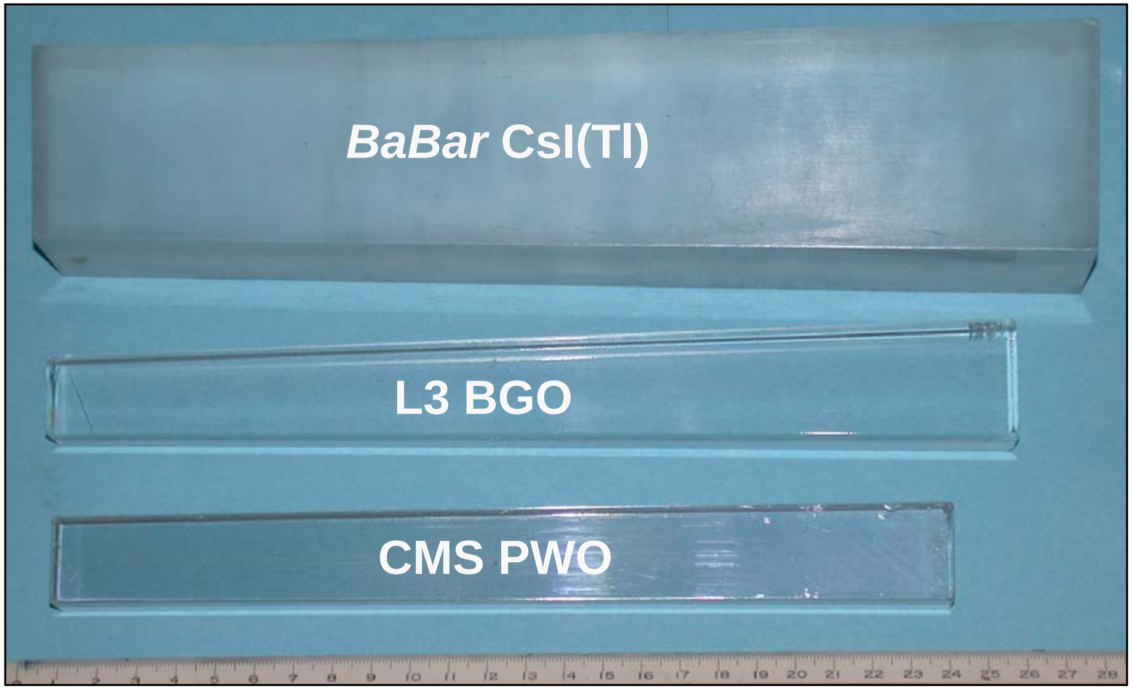
Crystal Density: Radiation Length



1.5 X_0 Cubic Samples:

Hygroscopic Halides

Non-hygroscopic



Full Size Crystals:

BaBar CsI(Tl): 16 X_0

L3 BGO: 22 X_0

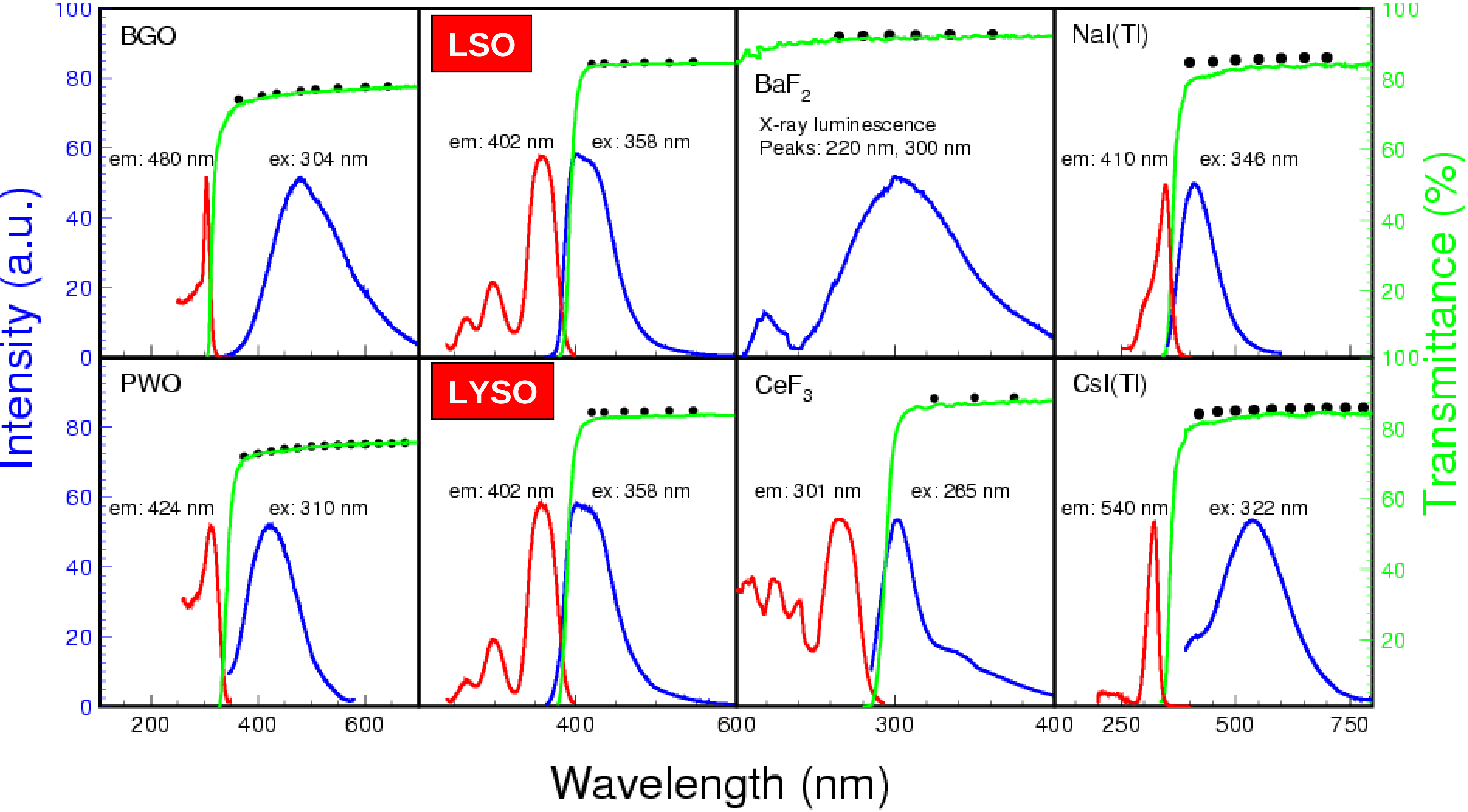
CMS PWO(Y): 25 X_0

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

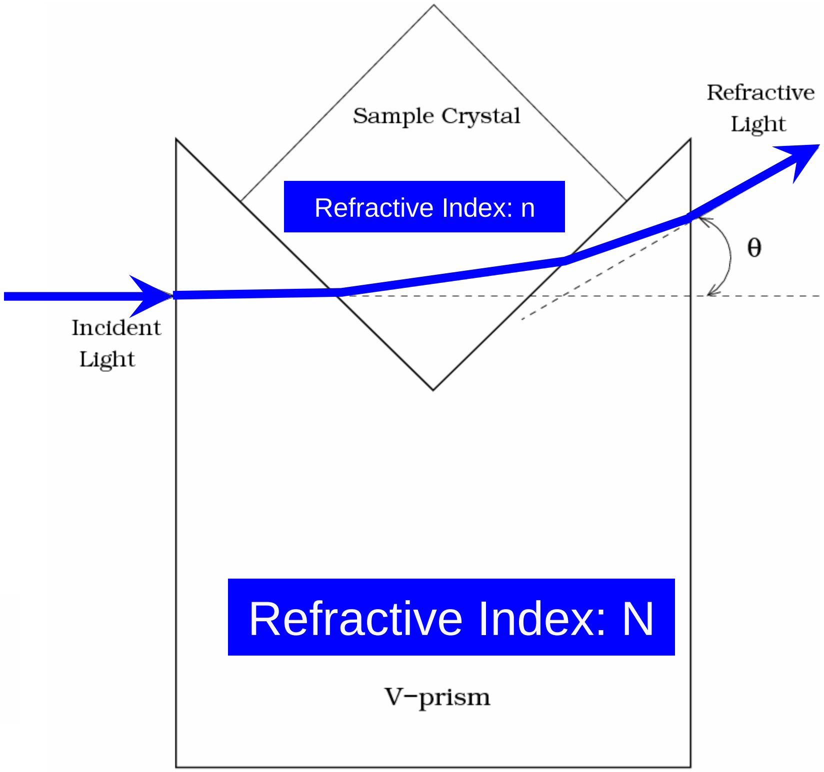


LSO/LYSO Refractive Index

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:

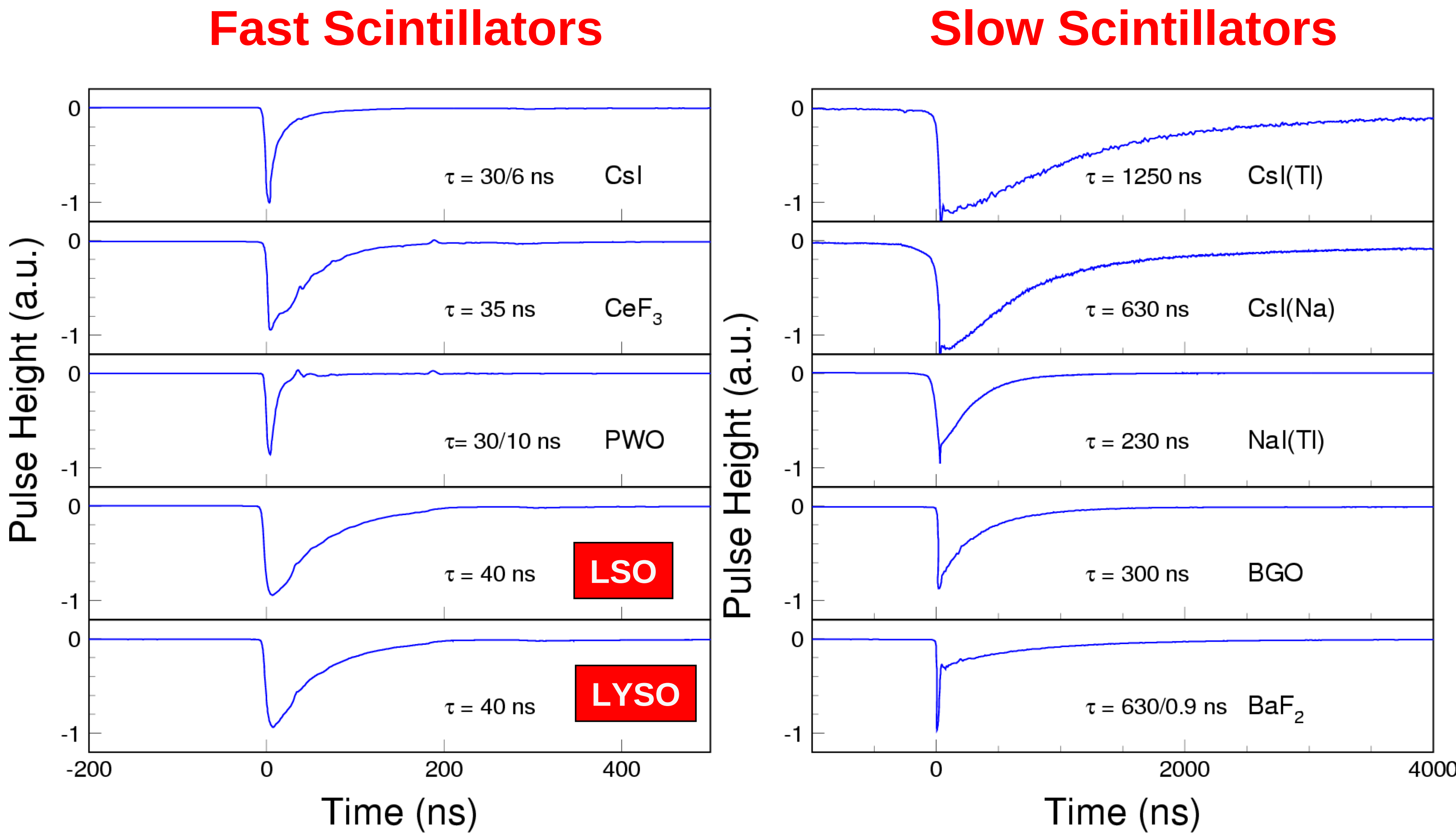
$$n = \left(N^2 + \sin\theta \sqrt{N^2 - \sin^2\theta} \right)^{\frac{1}{2}}$$



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

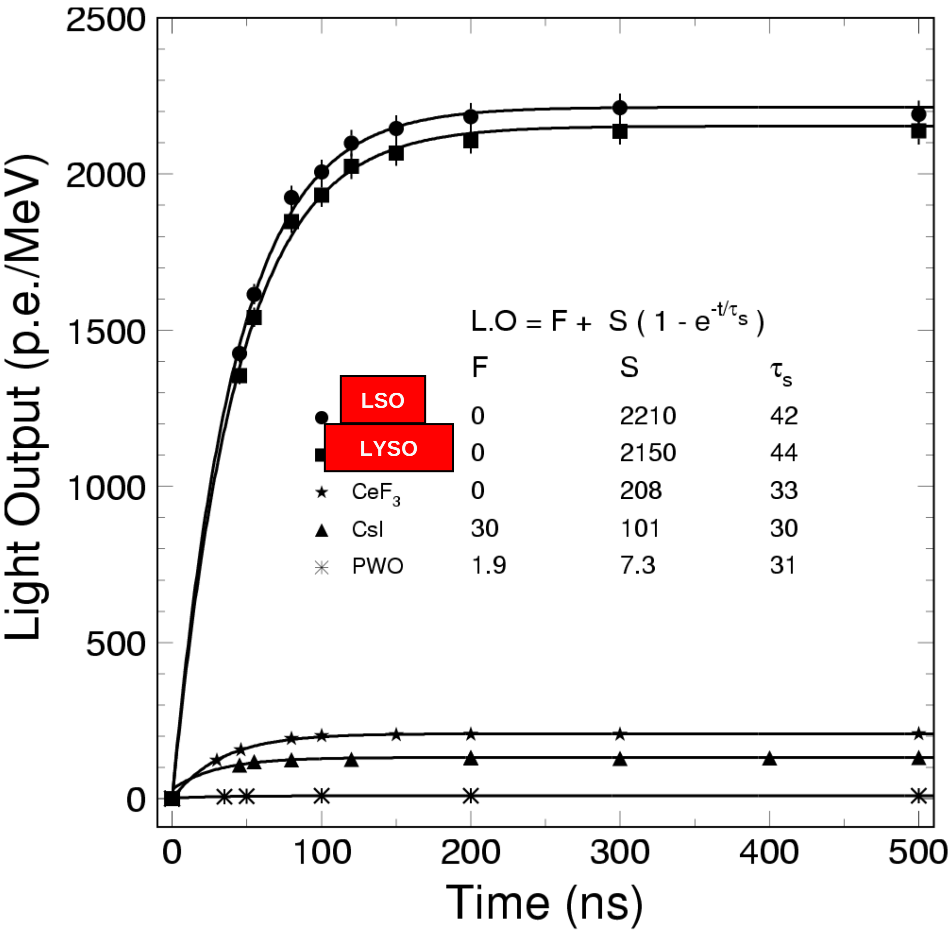
Recorded with an Agilent 6052A digital scope



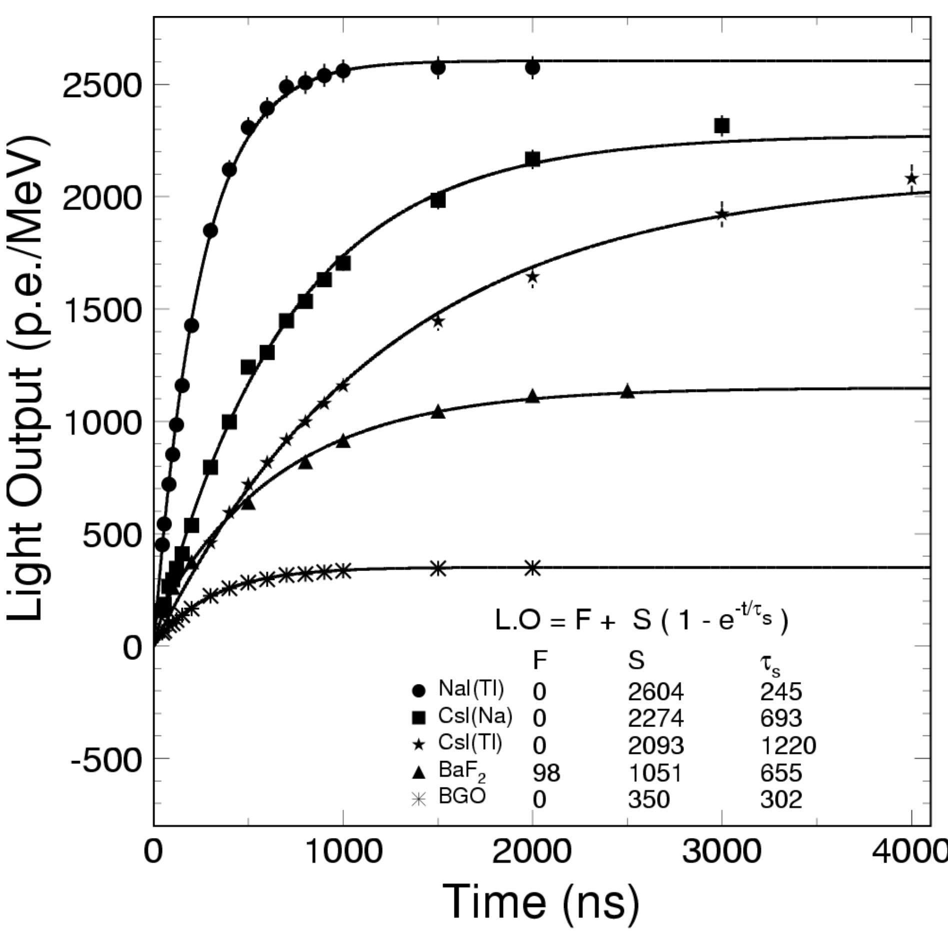
Light Output & Decay Kinetics

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

Fast Scintillators

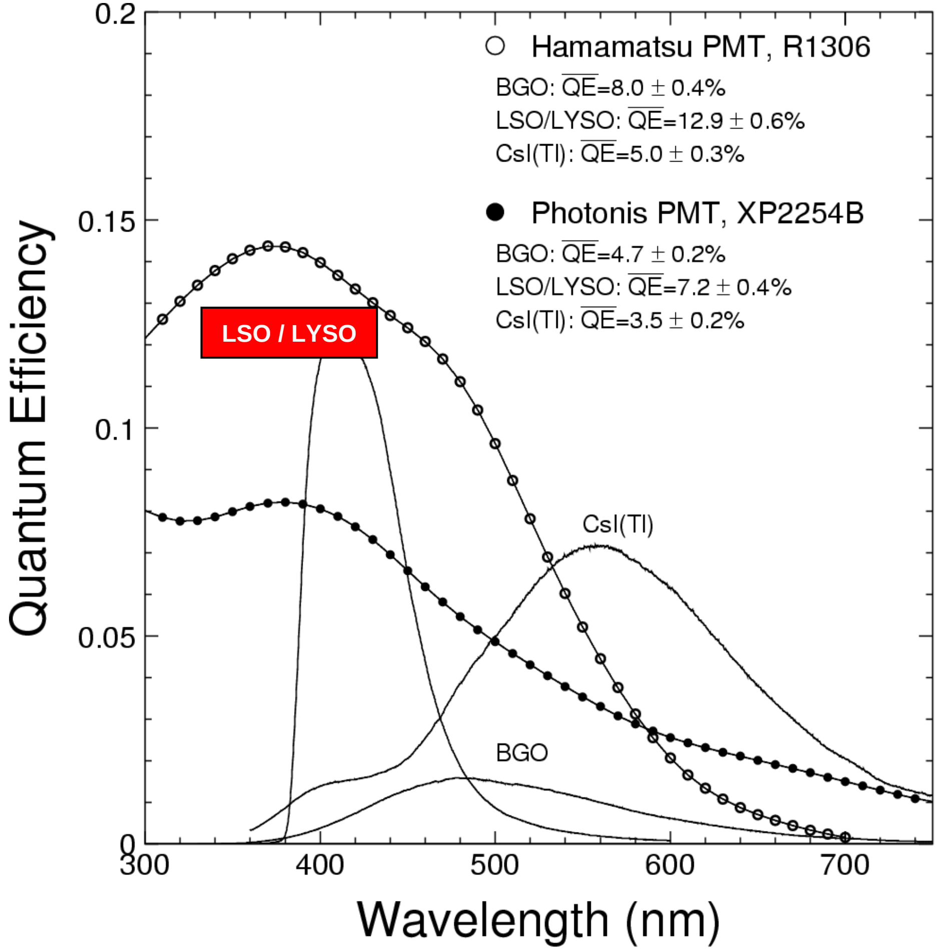


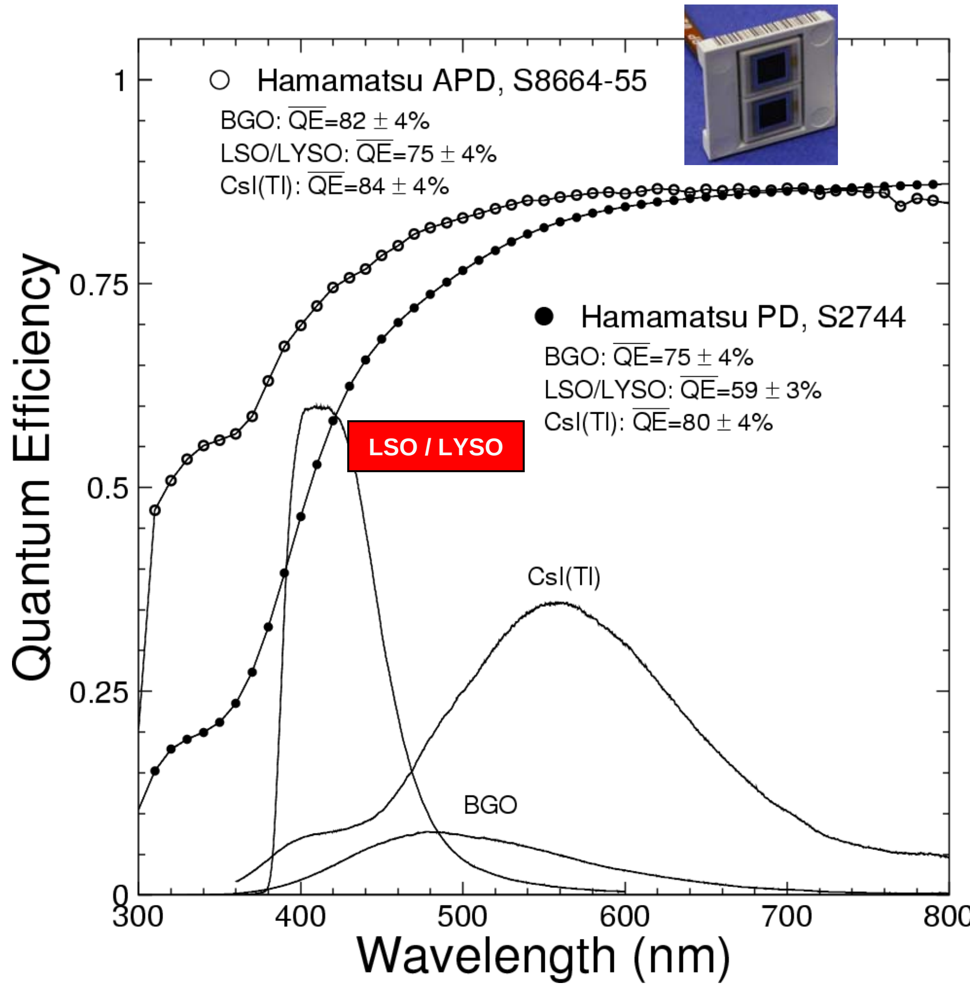
Slow Scintillators



Emission Weighted Quantum Efficiency

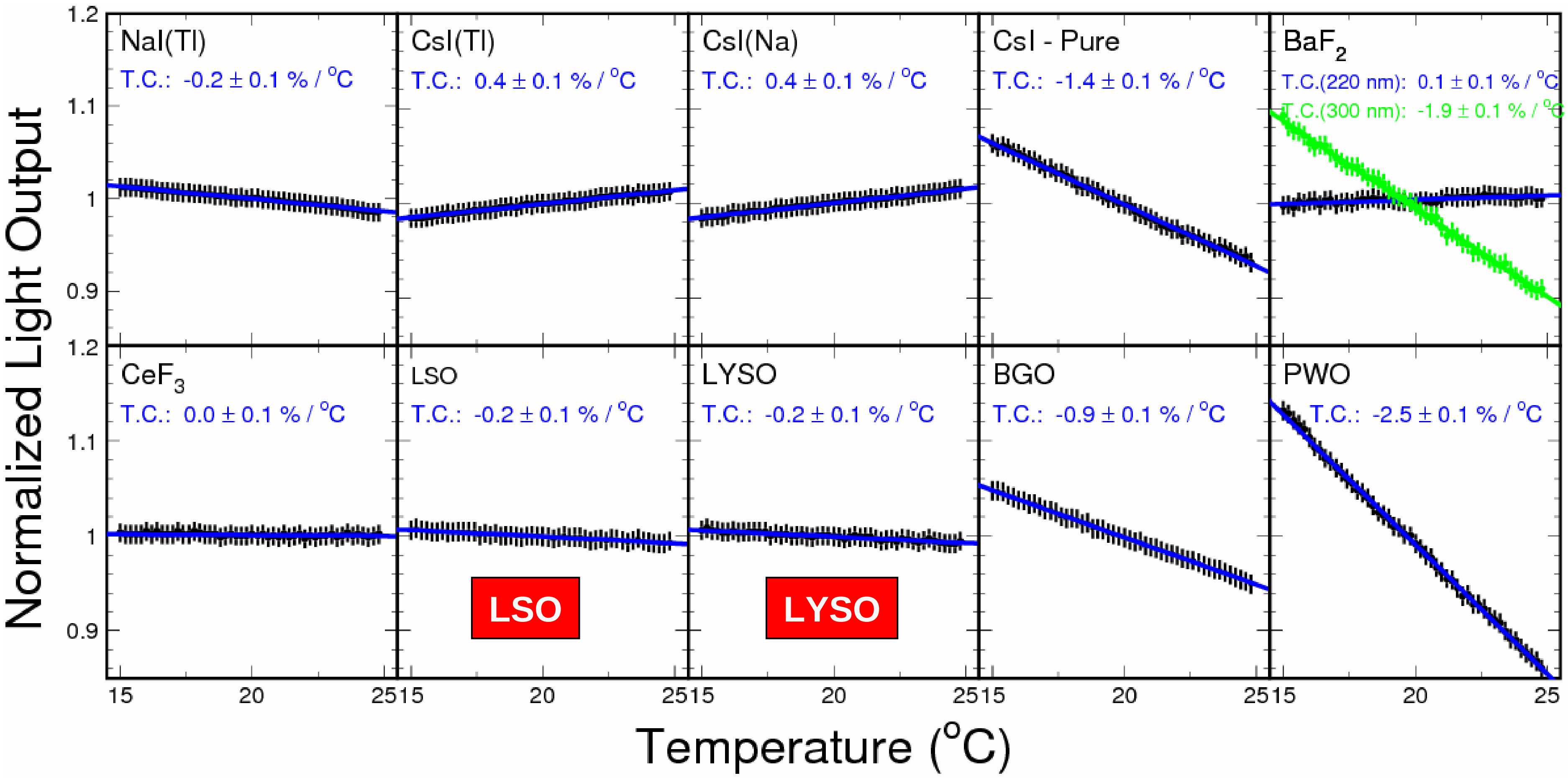
Taking out QE, L.O. of LSO/LYSO is 4/200 times BGO/PWO
Hamamatsu S8664-55 APD has QE 75% for LSO/LYSO





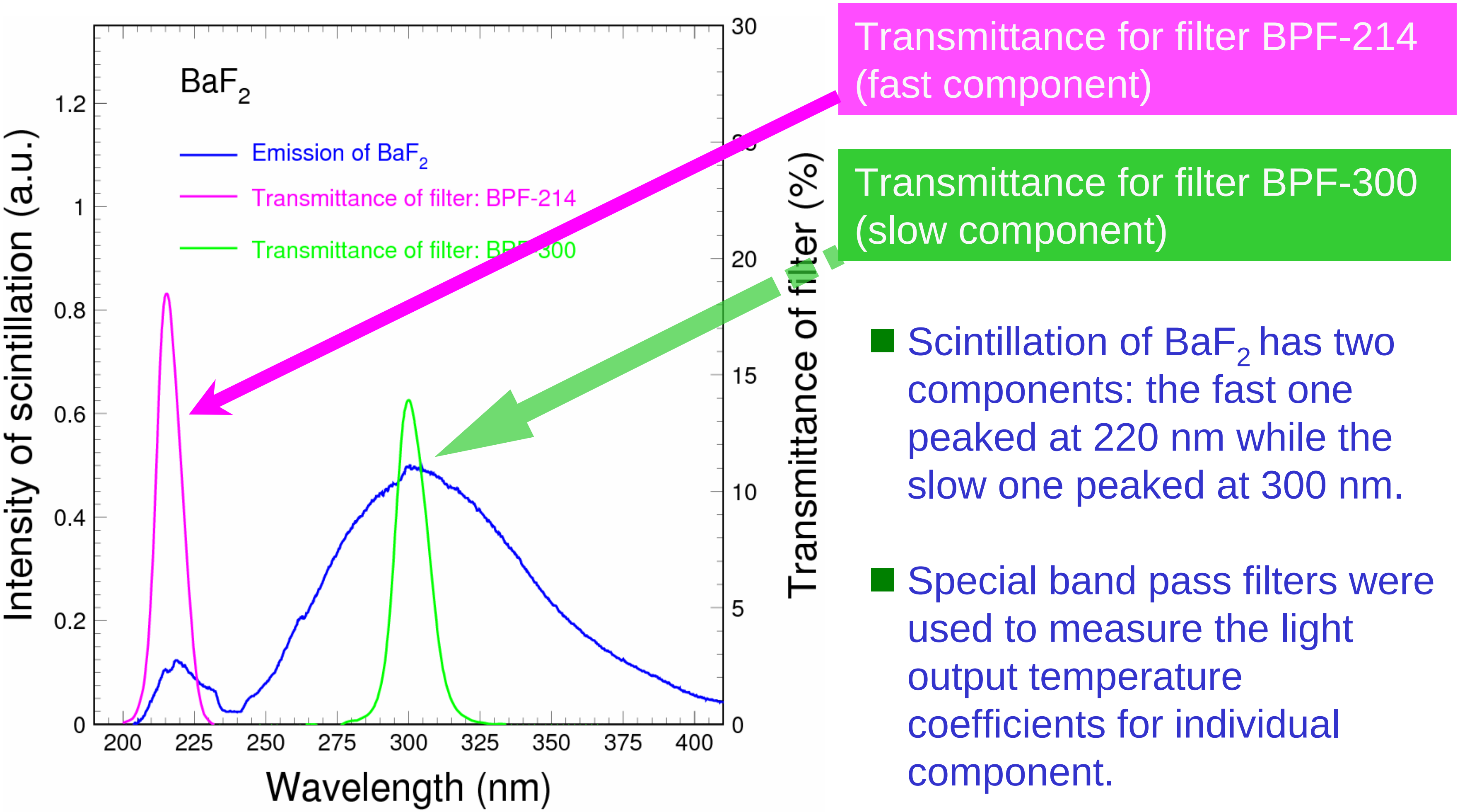
Light Output Temperature Coefficient

Temperature Range: 15ºC ~ 25ºC



BaF_2: Fast and Slow Components

Two filters used to select scintillation component



- 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.

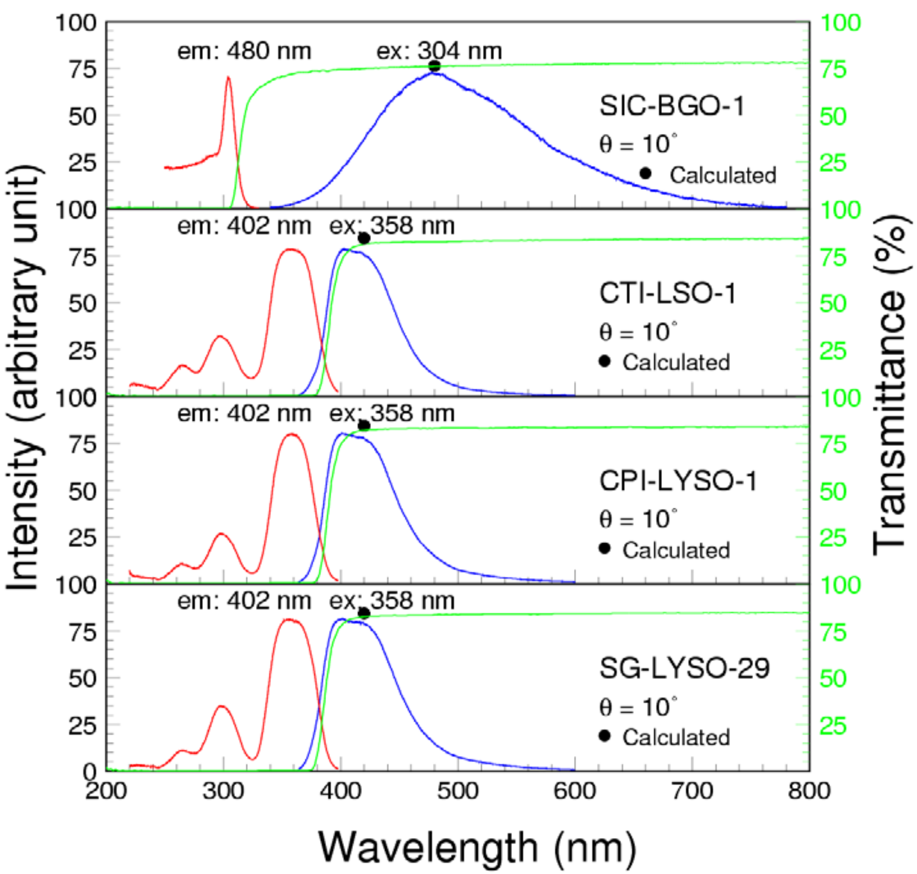
BGO, LSO & LYSO Samples

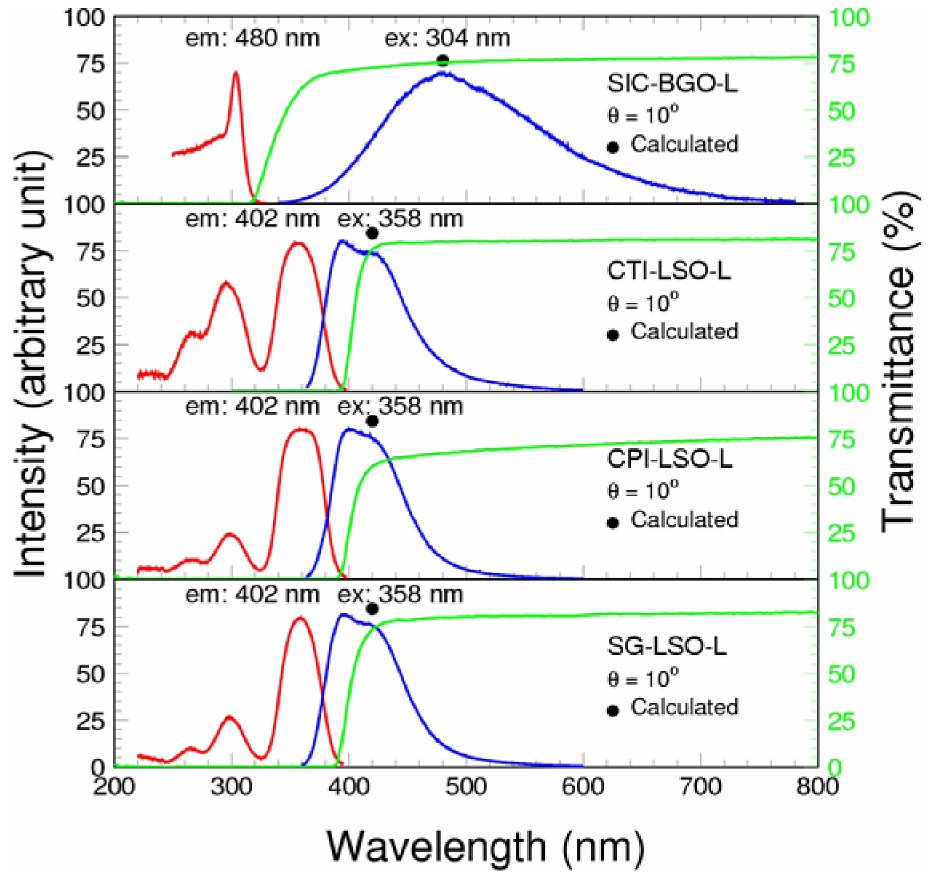
2.5 x 2.5 x 20 cm (18 X_0) Bar

Excitation, Emission, Transmission

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

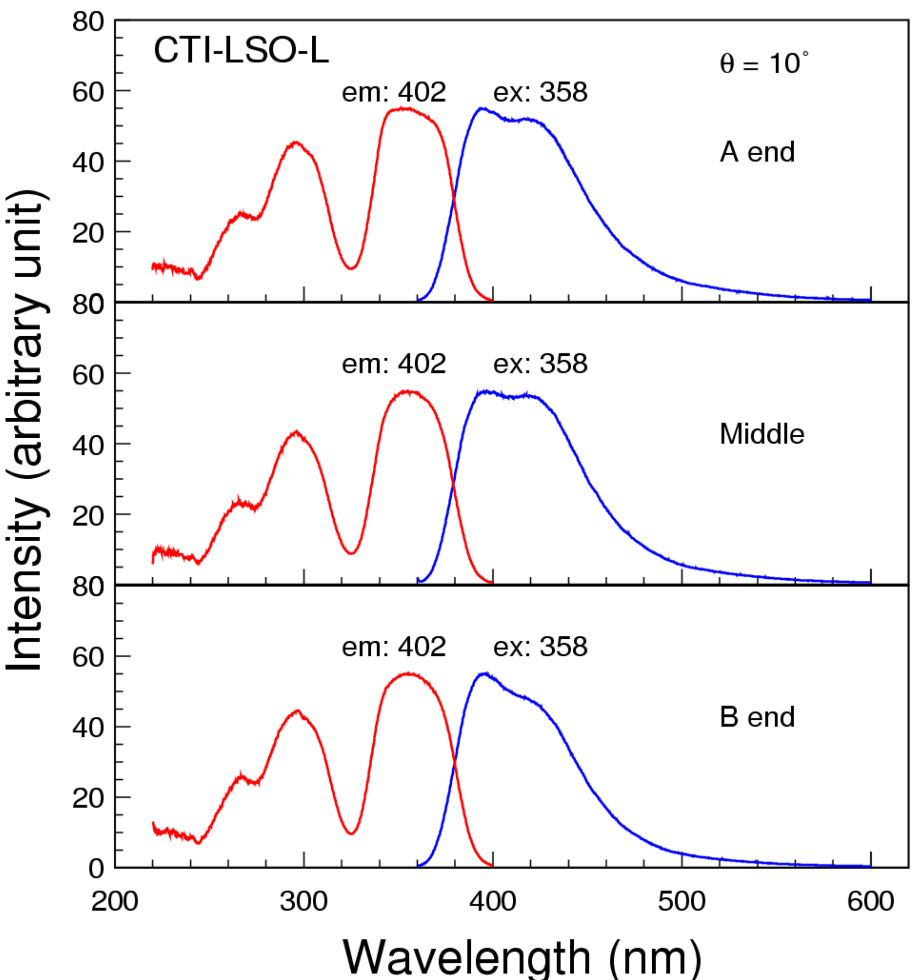
1.7 cm Cube | **2.5 x 2.5 x 20 cm Bar**

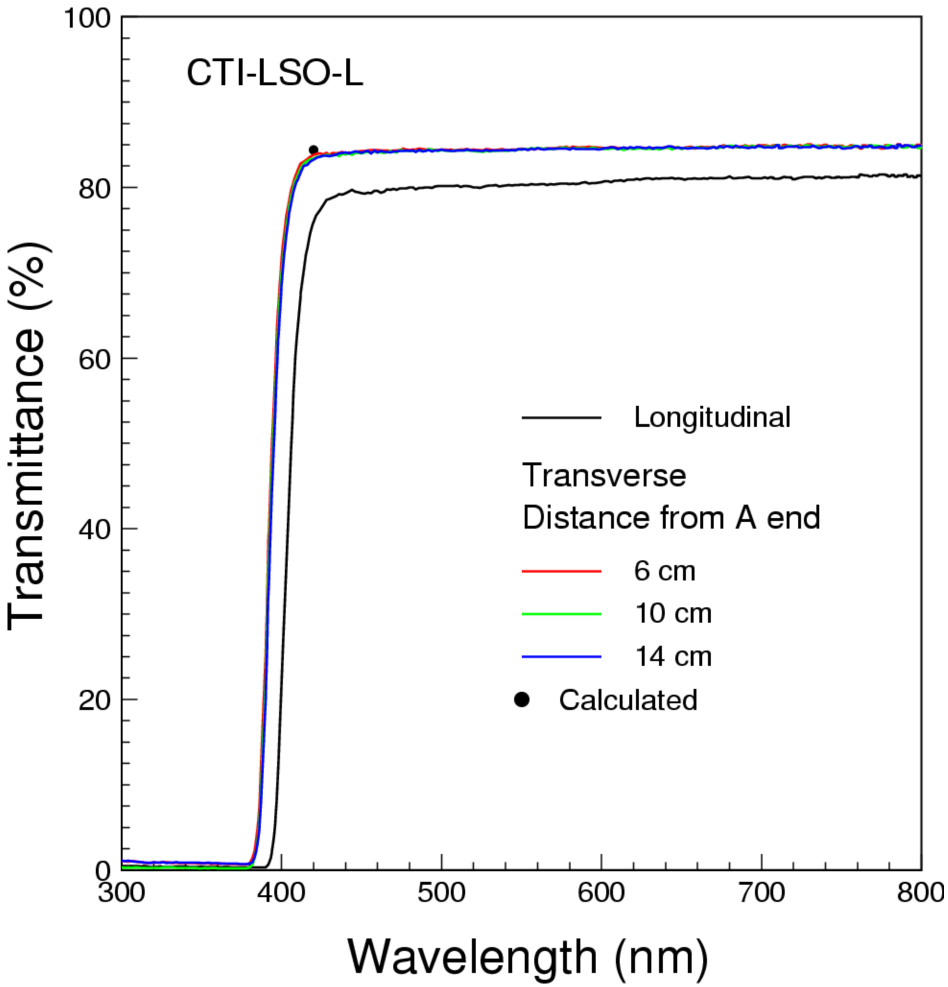




CTI LSO: Longitudinal Uniformity

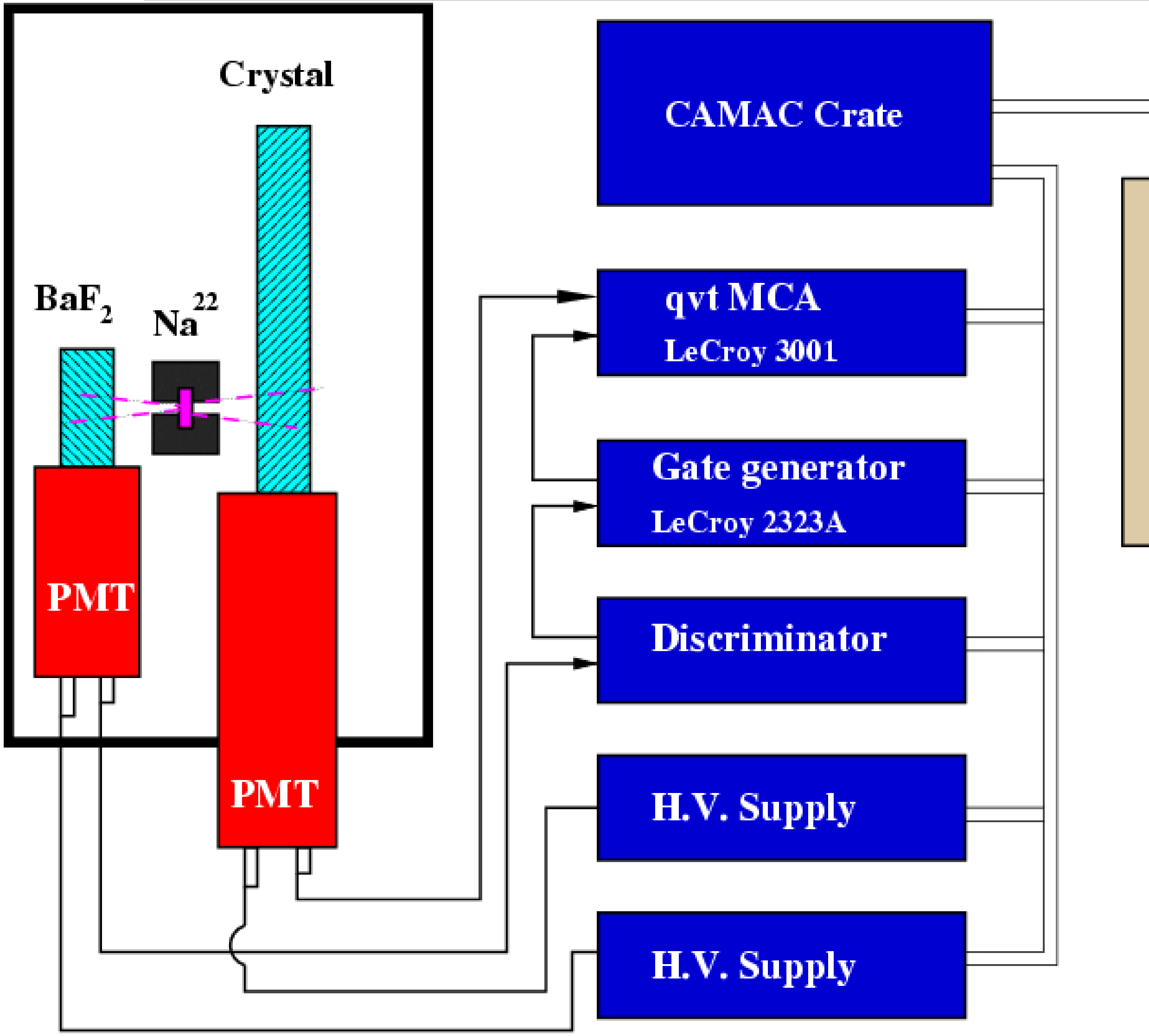
No longitudinal variation in optical properties
Transverse transmittance approaches theoretical limit

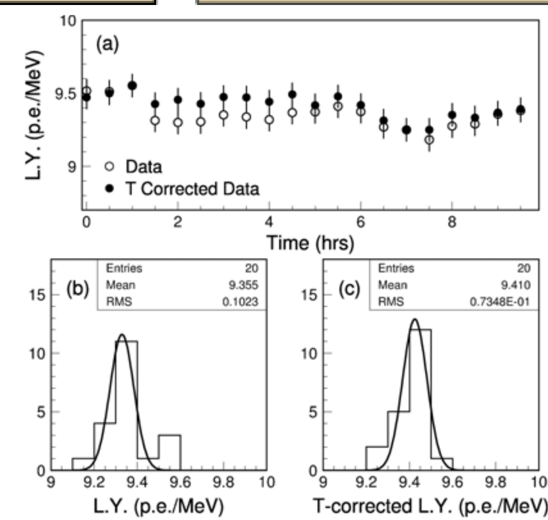




PMT Based Readout with Coincidence

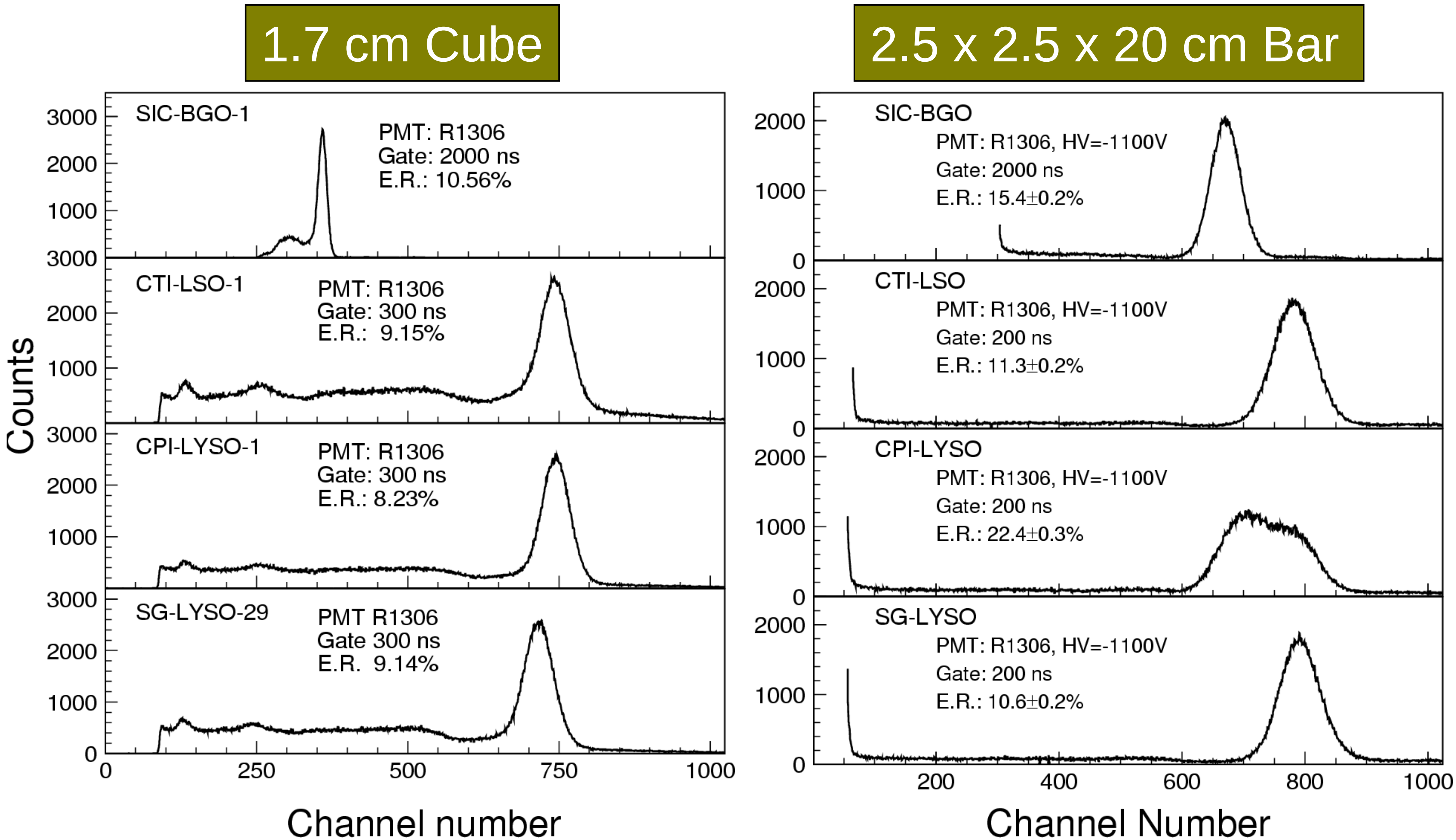
Systematic error with repeated mounts & measurements: < 1%





LSO/LYSO Resolution with PMT

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

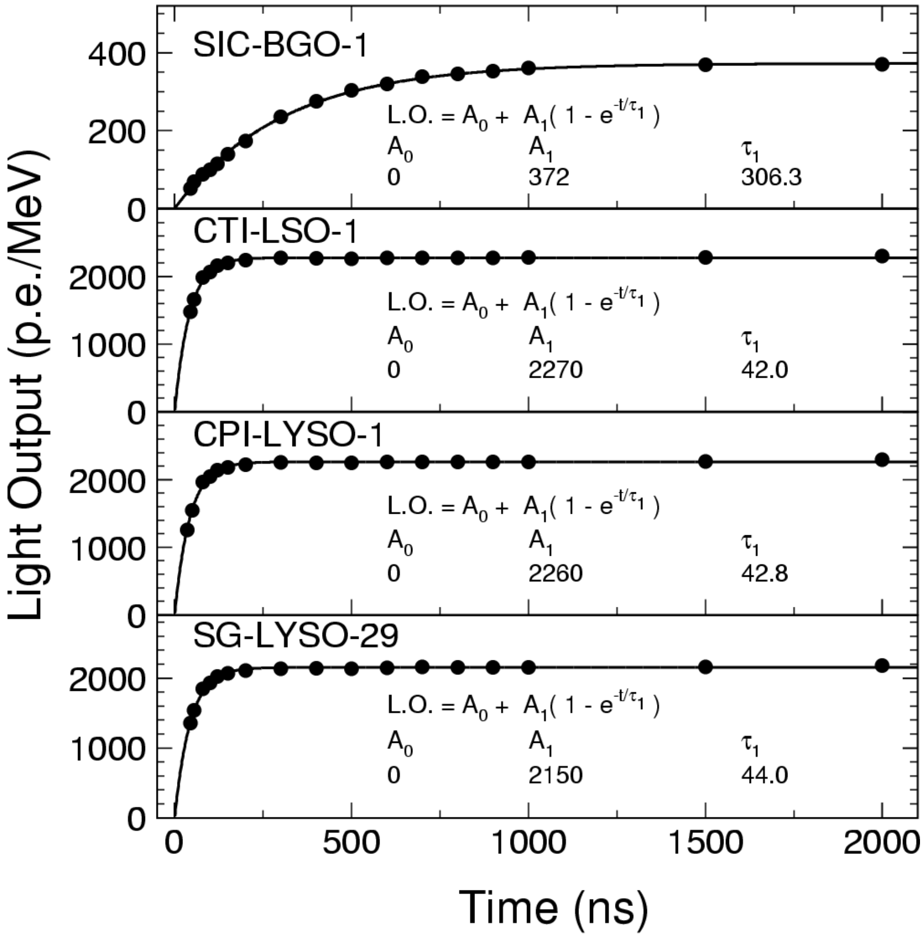


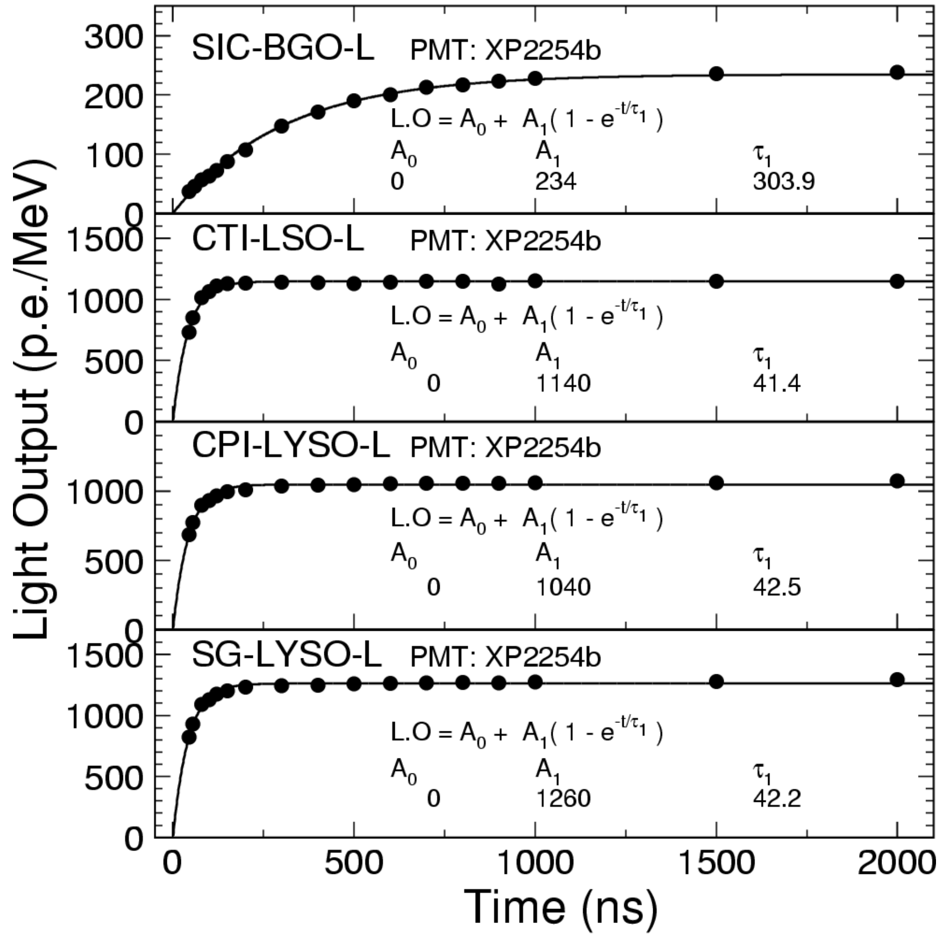
LSO/LYSO Light Output with PMT

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

1.7 cm Cube

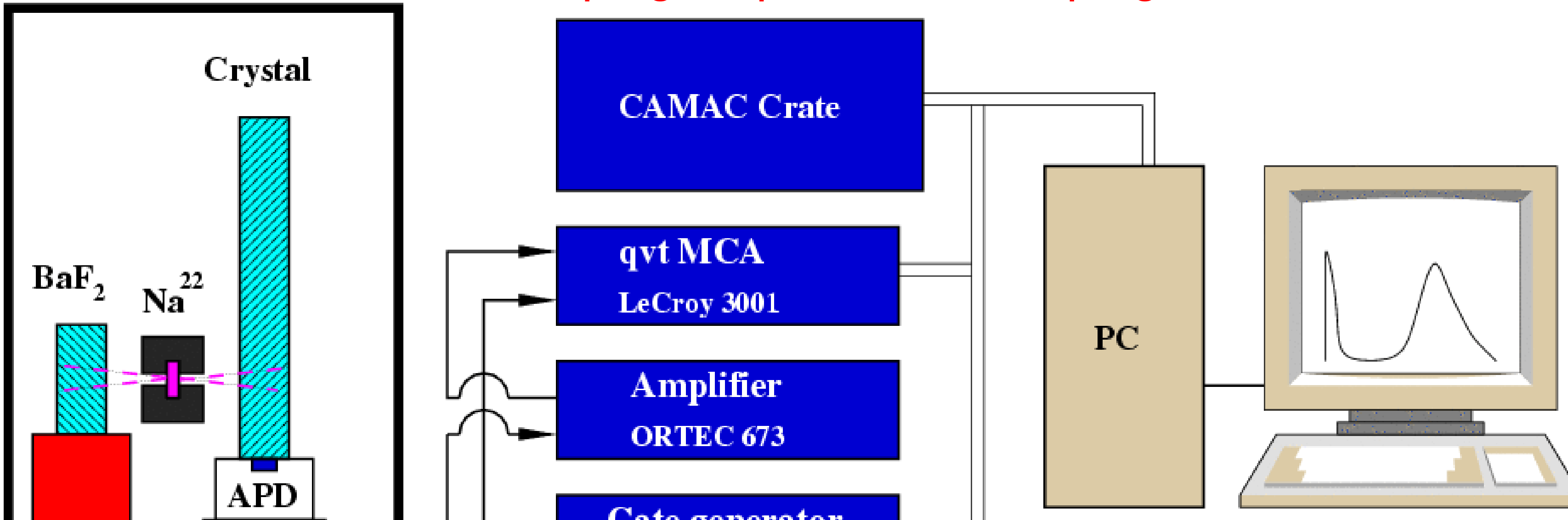
2.5 x 2.5 x 20 cm Bar

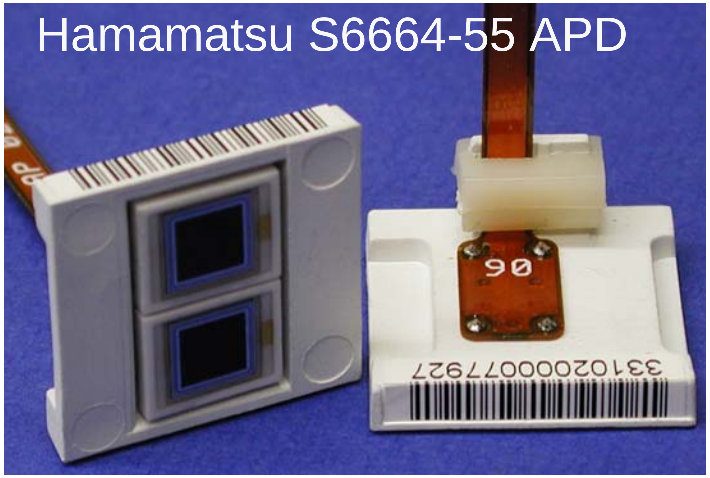




APD Based Readout with Coincidence

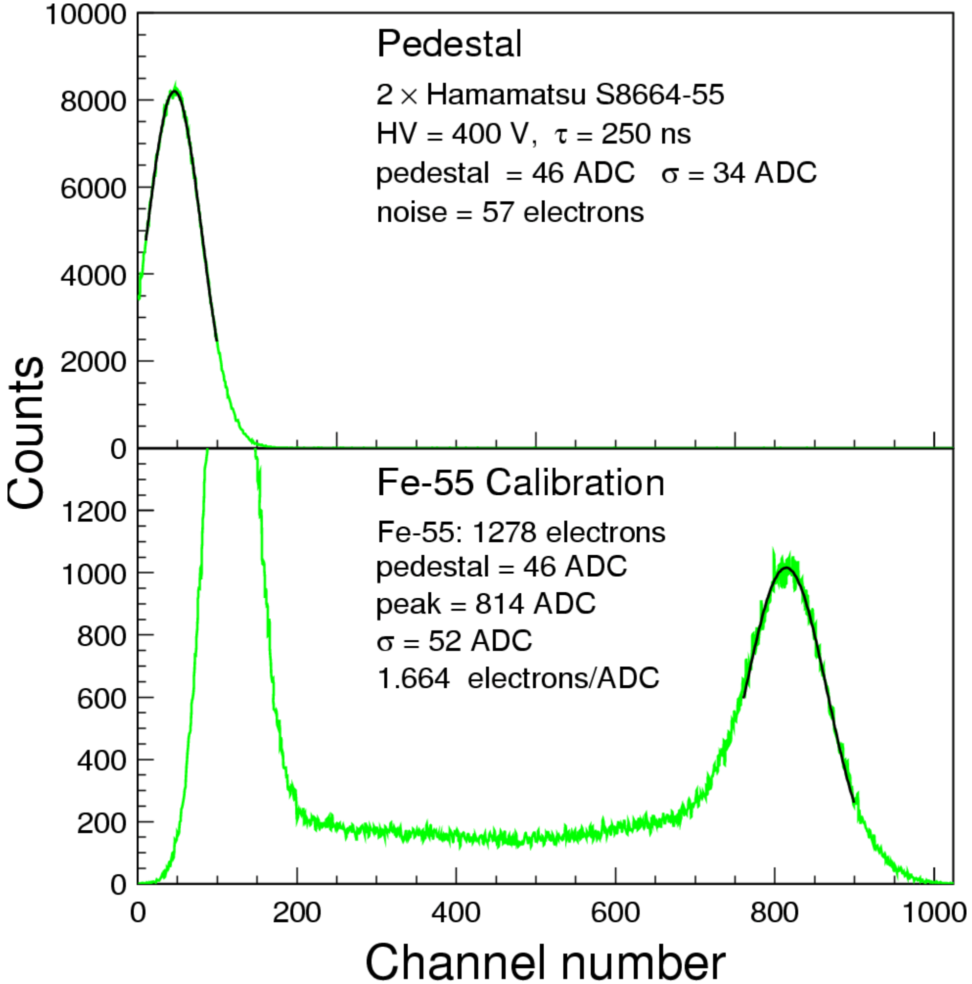
Two Hamamatsu S6664-55 APD, Canberra 2003 BT preamplifier and ORTEC 673 shaping amplifier with shaping time 250 ns

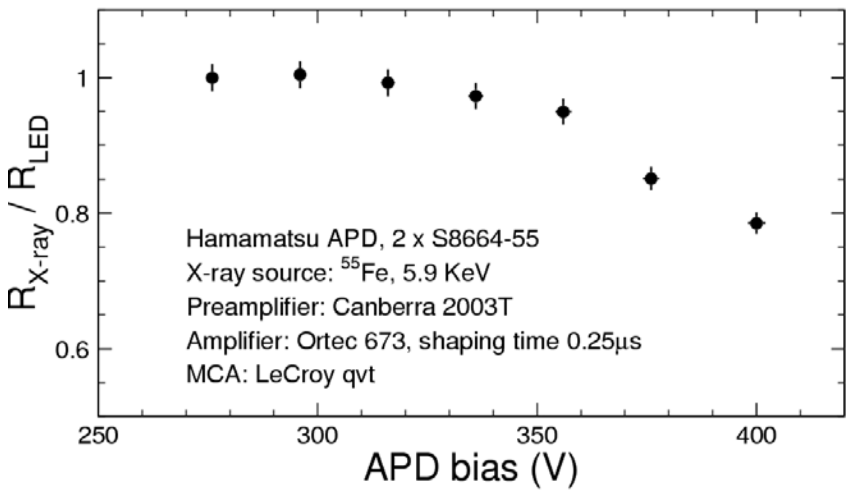


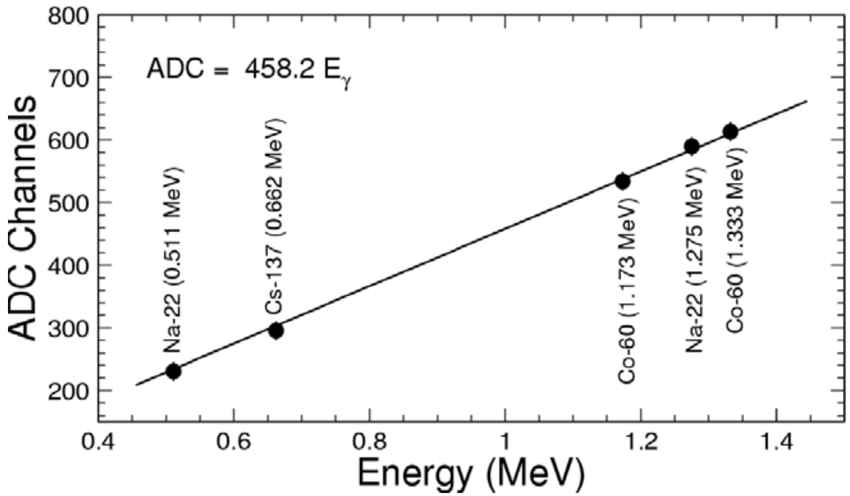


Calibration of the APD Readout

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



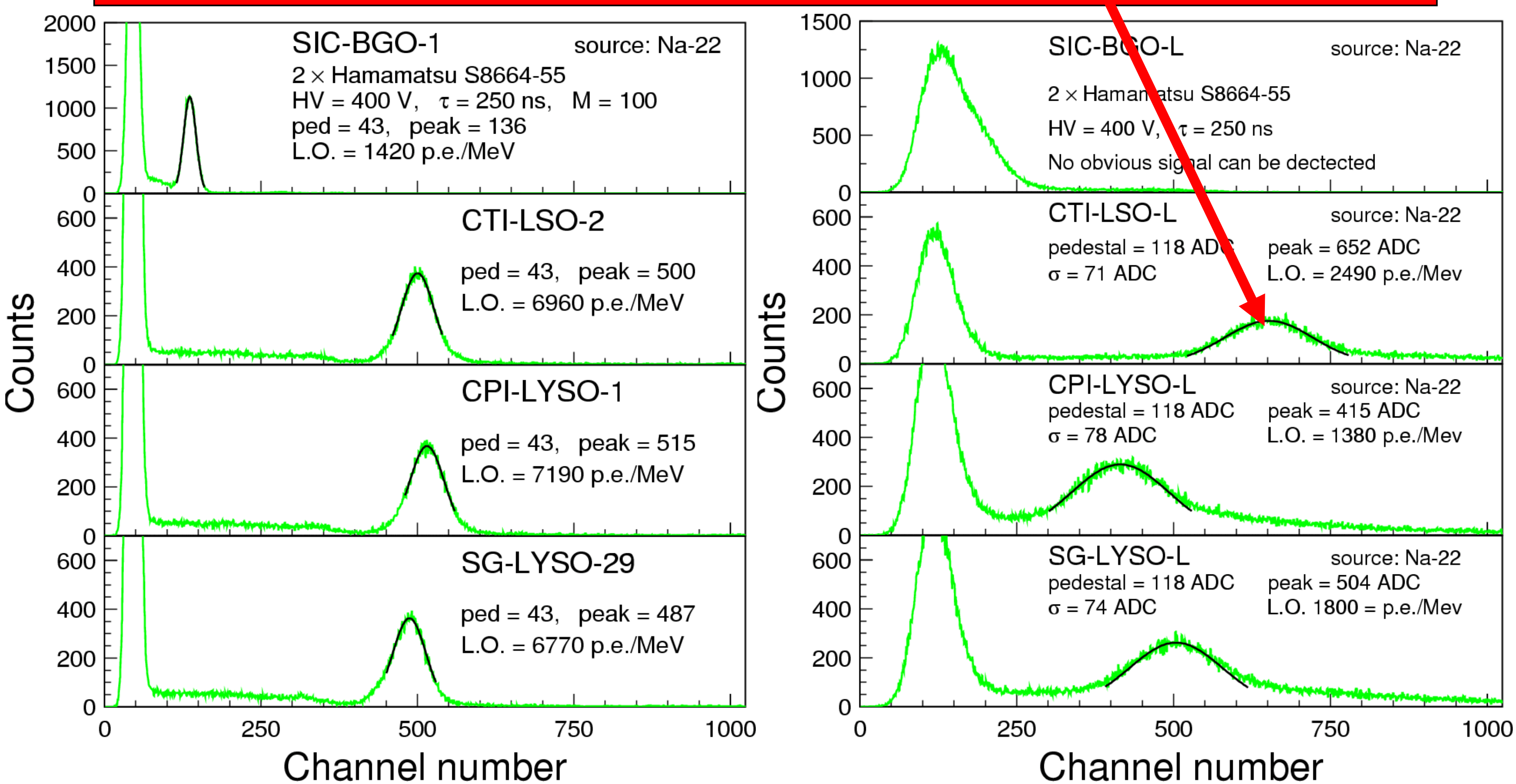




LSO/LYSO Light Output with APD

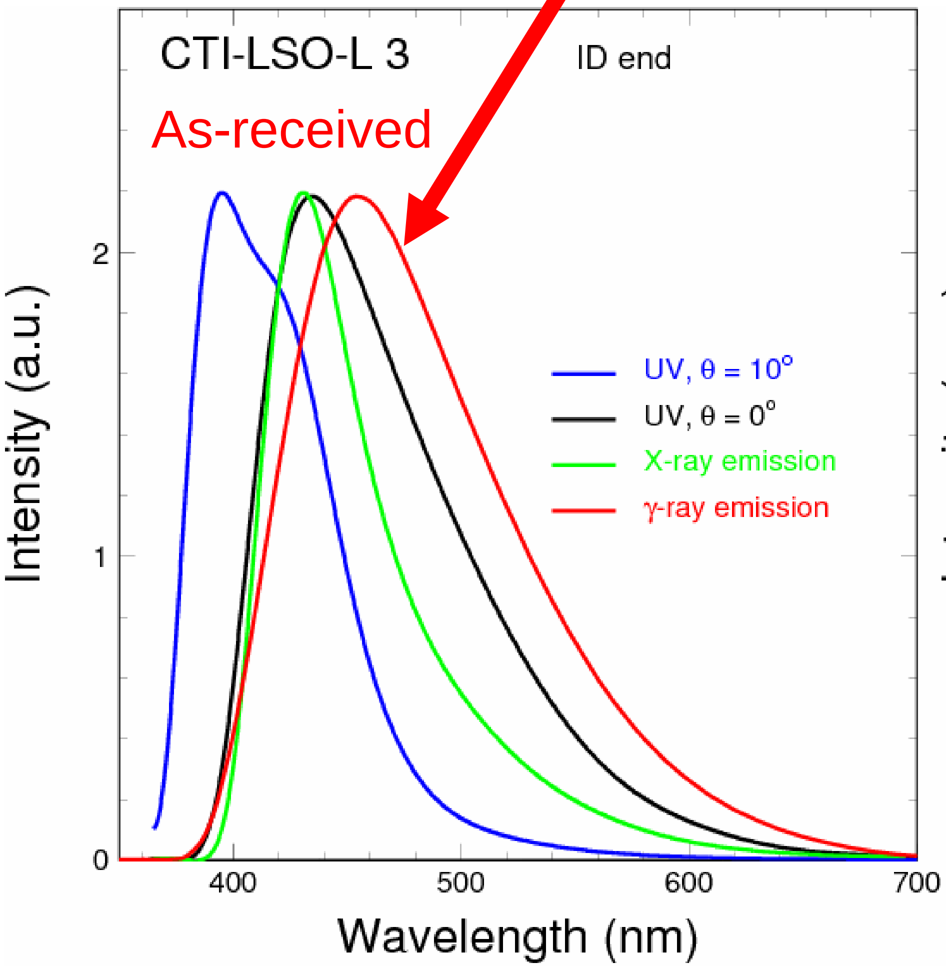
1,500 p.e./MeV, 4/200 times of BGO/PWO, Noise < 40 keV

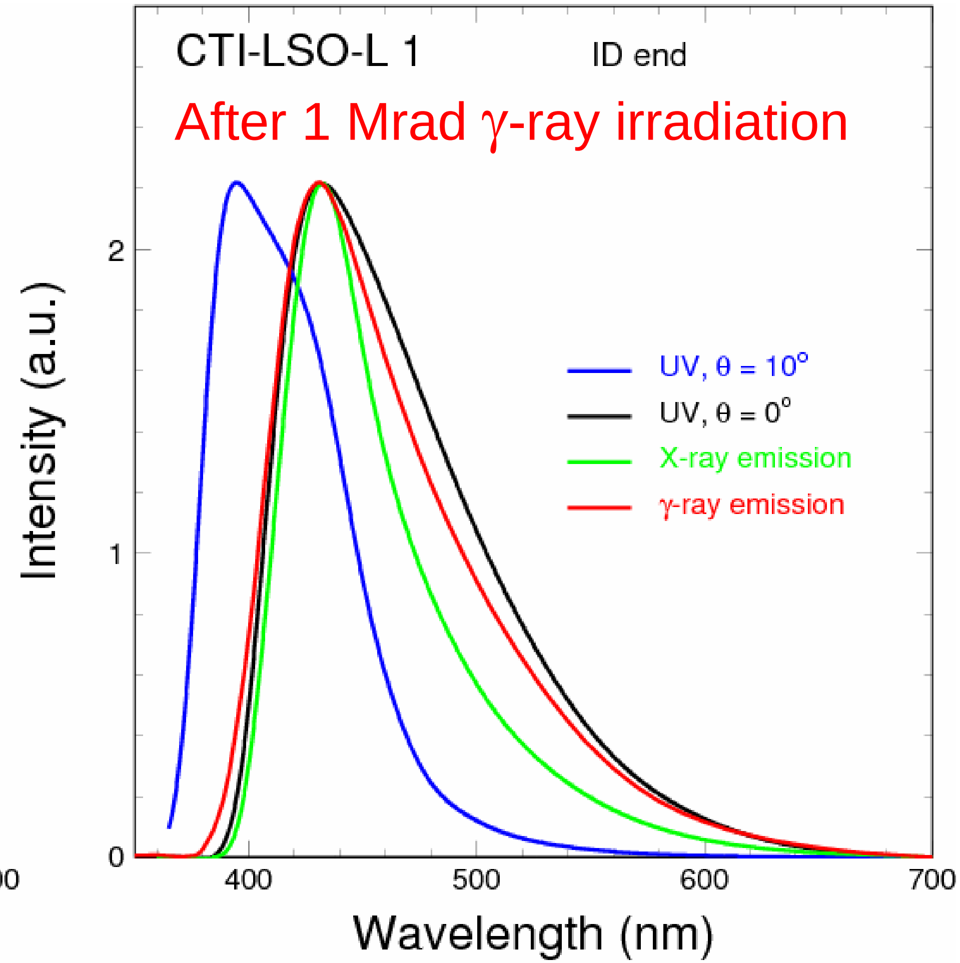
A discrepancy reported @ Puerto Rico: LSO has more light output, which disappeared after irradiation to 1 Mrad and thermal annealing.



LSO Emission Spectra

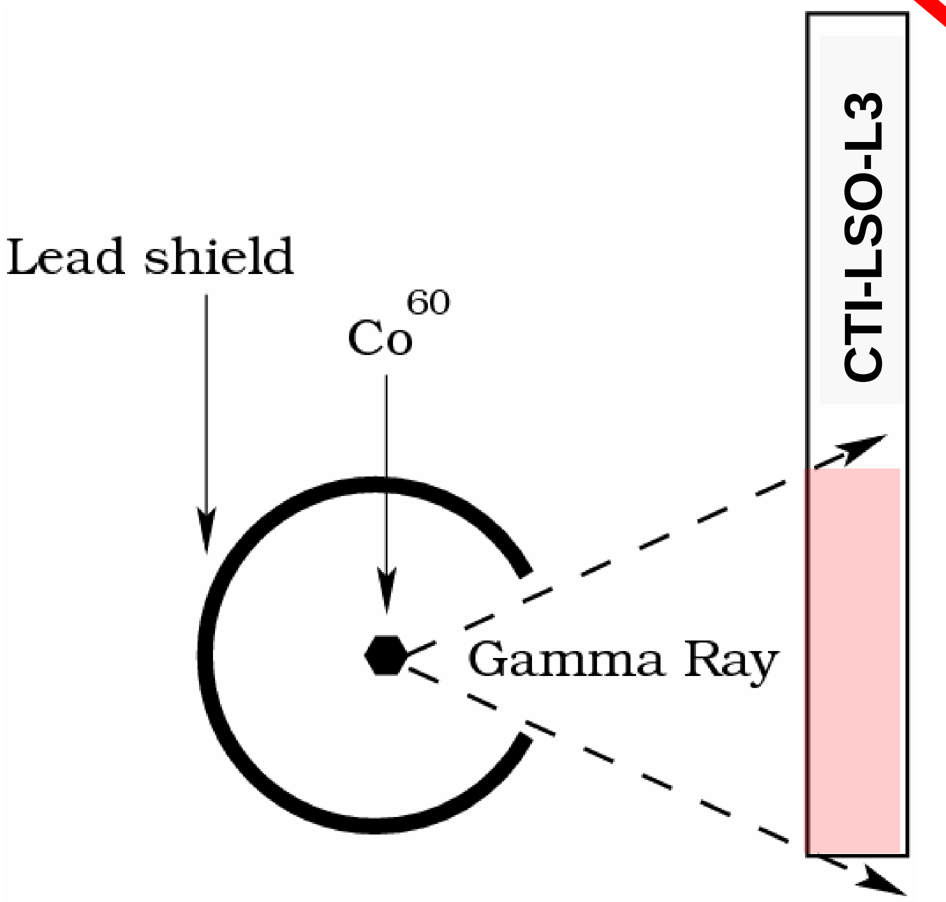
All emission spectra are similar to that of LYSO, except that γ-ray excited emission has a “red shift”, which disappeared after irradiations with γ-ray.

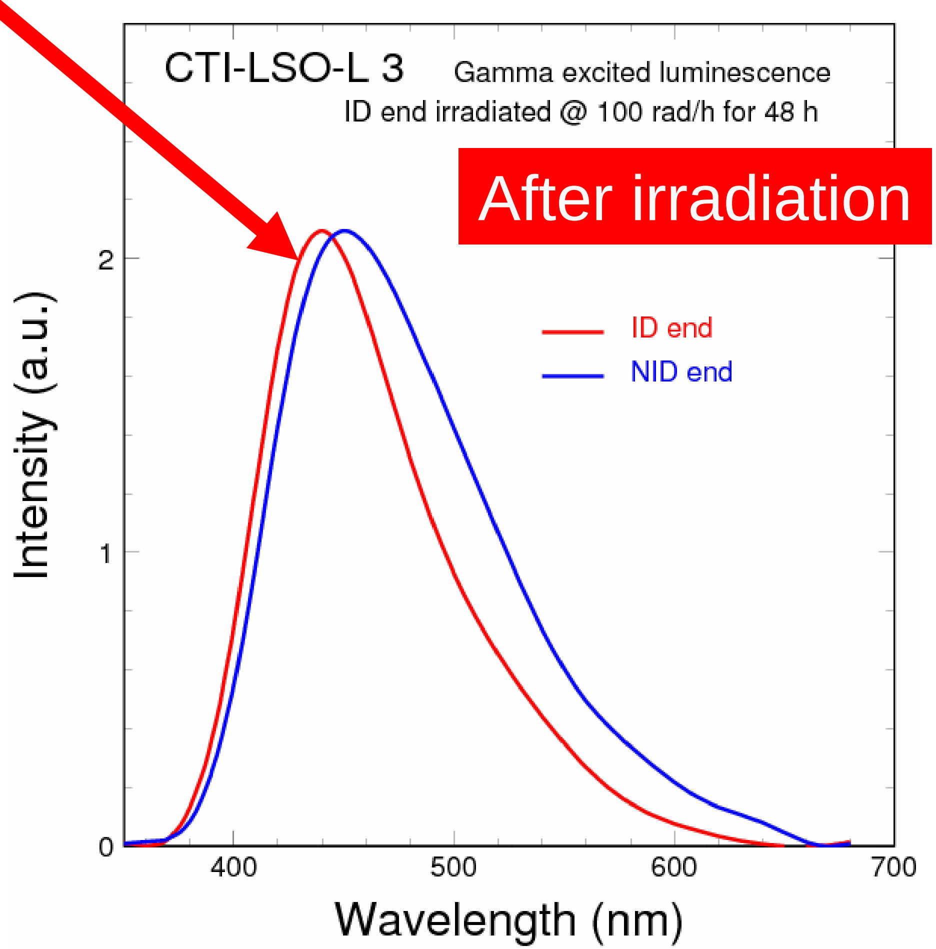




LSO Radio-Luminescence Spectra

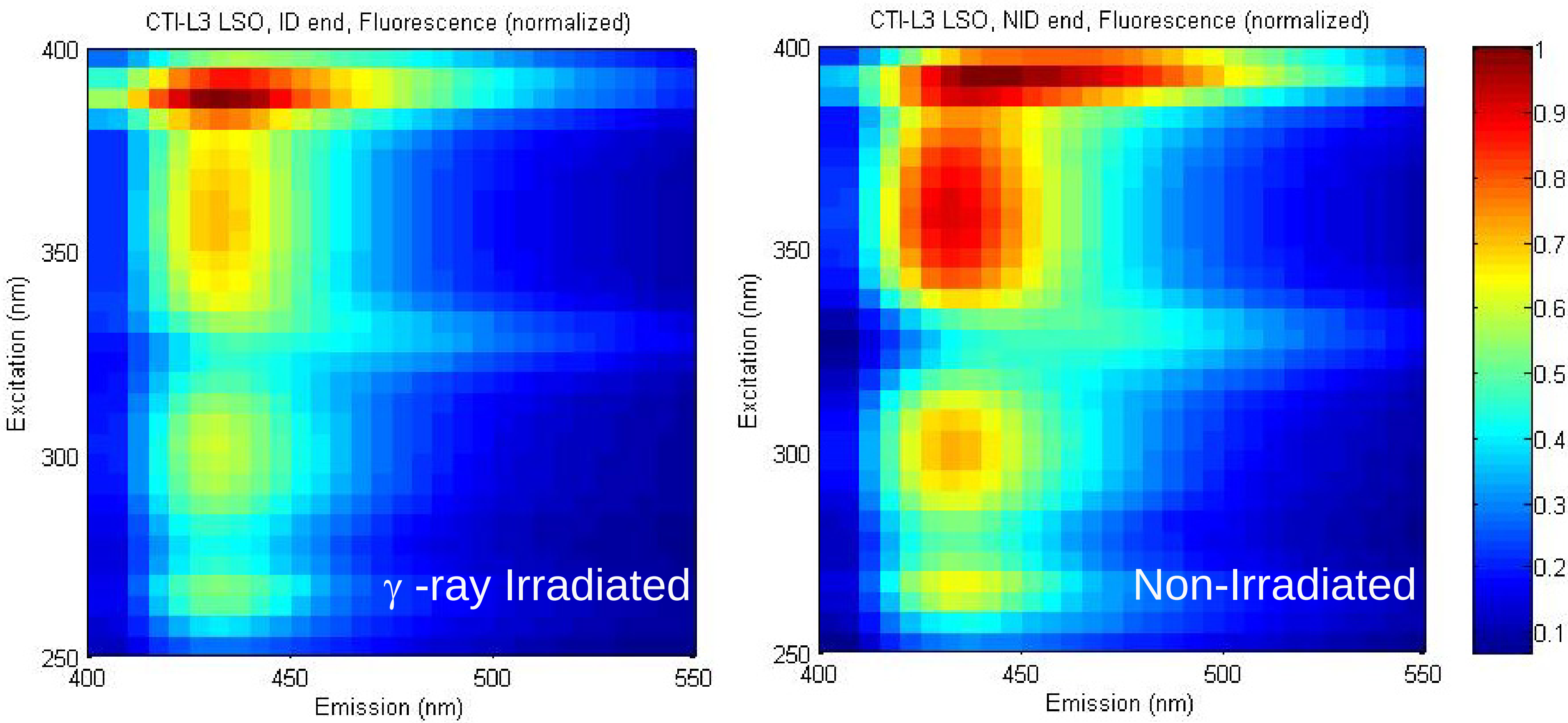
The emission peak of the irradiated half has a ~20 nm "blue" shift





UV Excited Emission Spectra of Two Halves of the LSO Sample

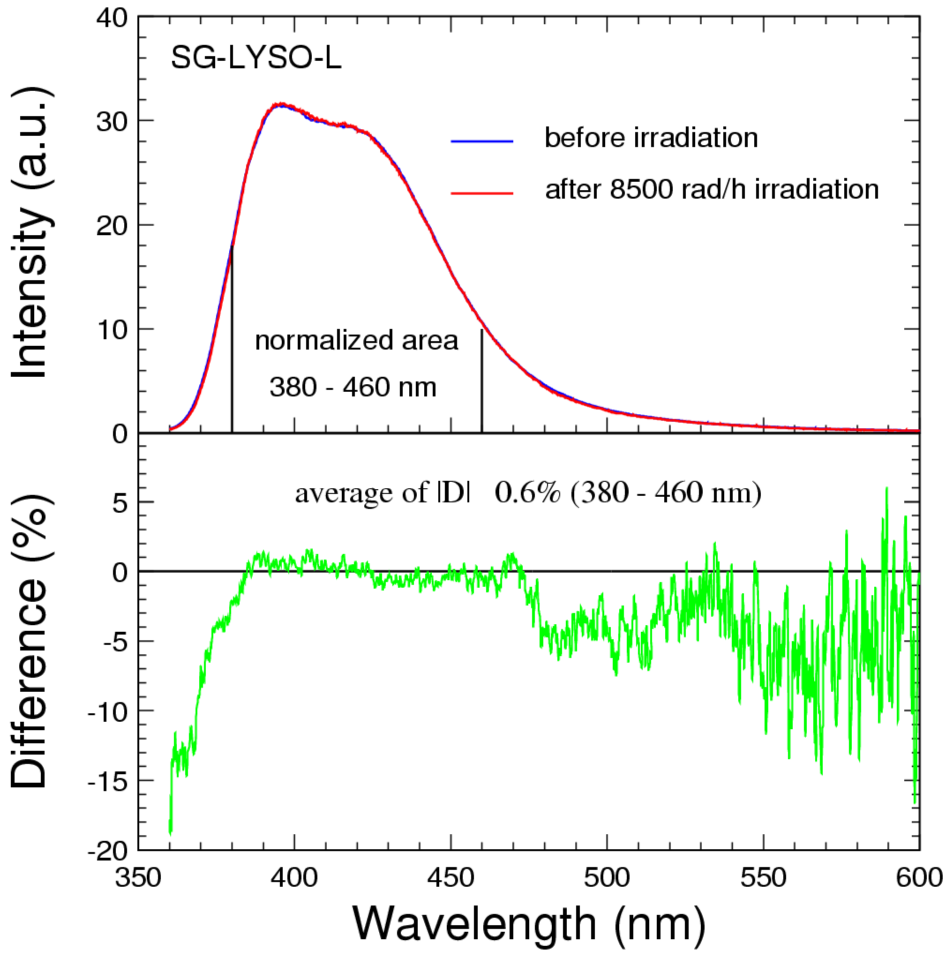
The γ -ray irradiated half shows less long wavelength emission when excited at 325 nm and 380 nm.

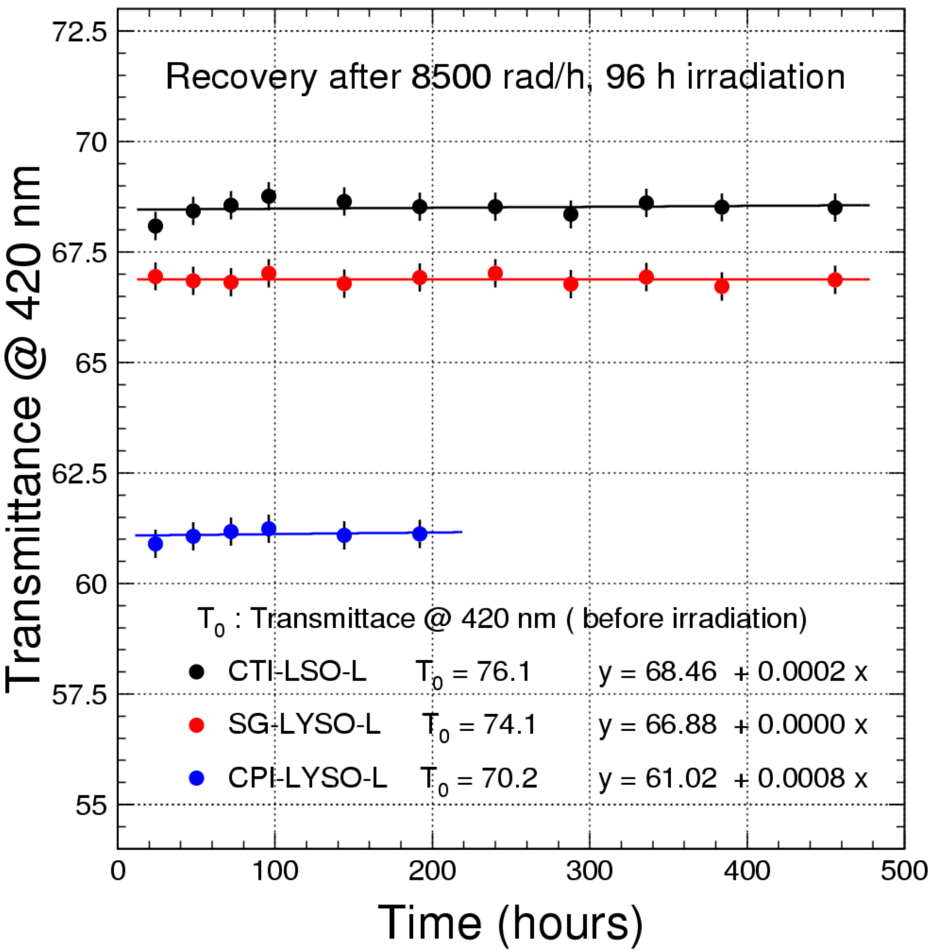


γ-Rays Induced Damage in LSO/LYSO

No damage in Photo-Luminescence

LT recovery very slow

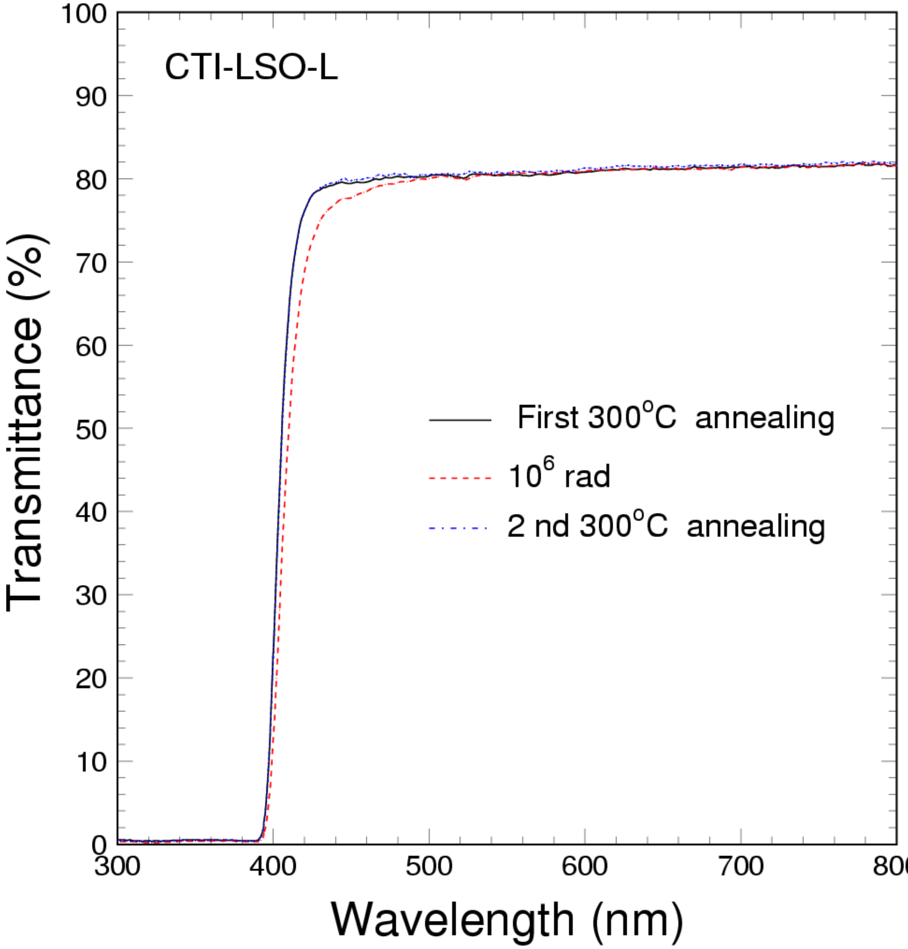


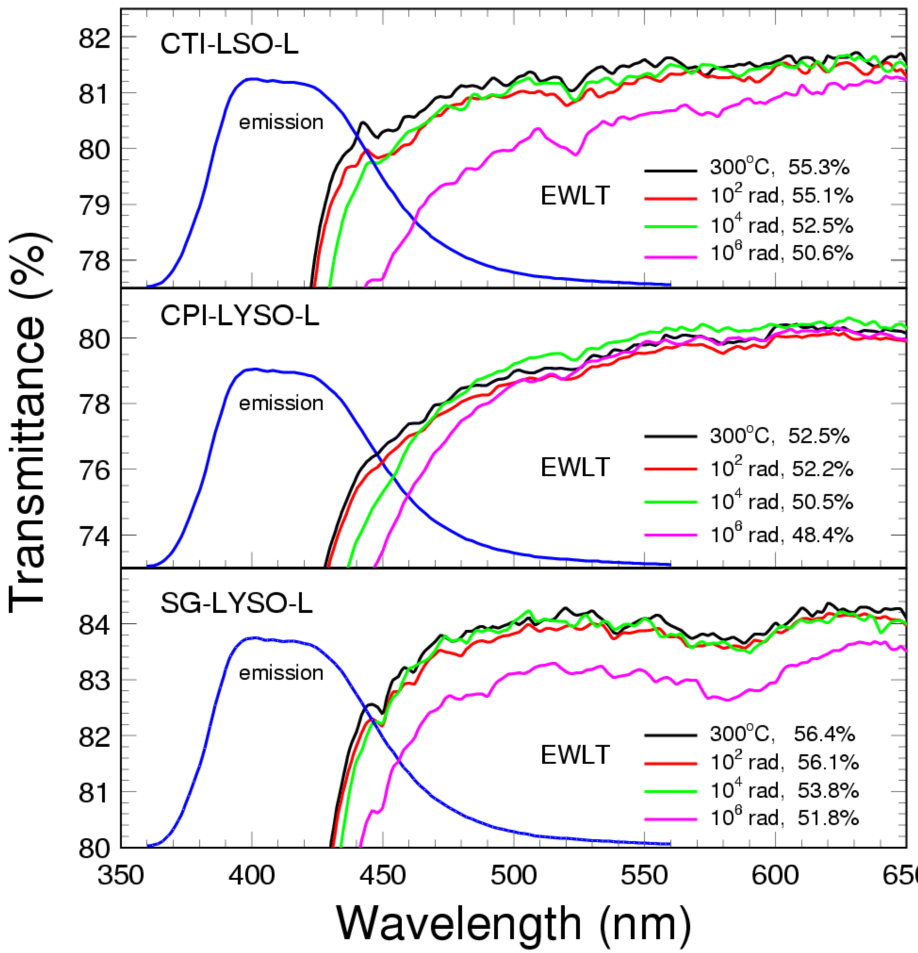


Transmittance Damage

300°C thermal annealing effective

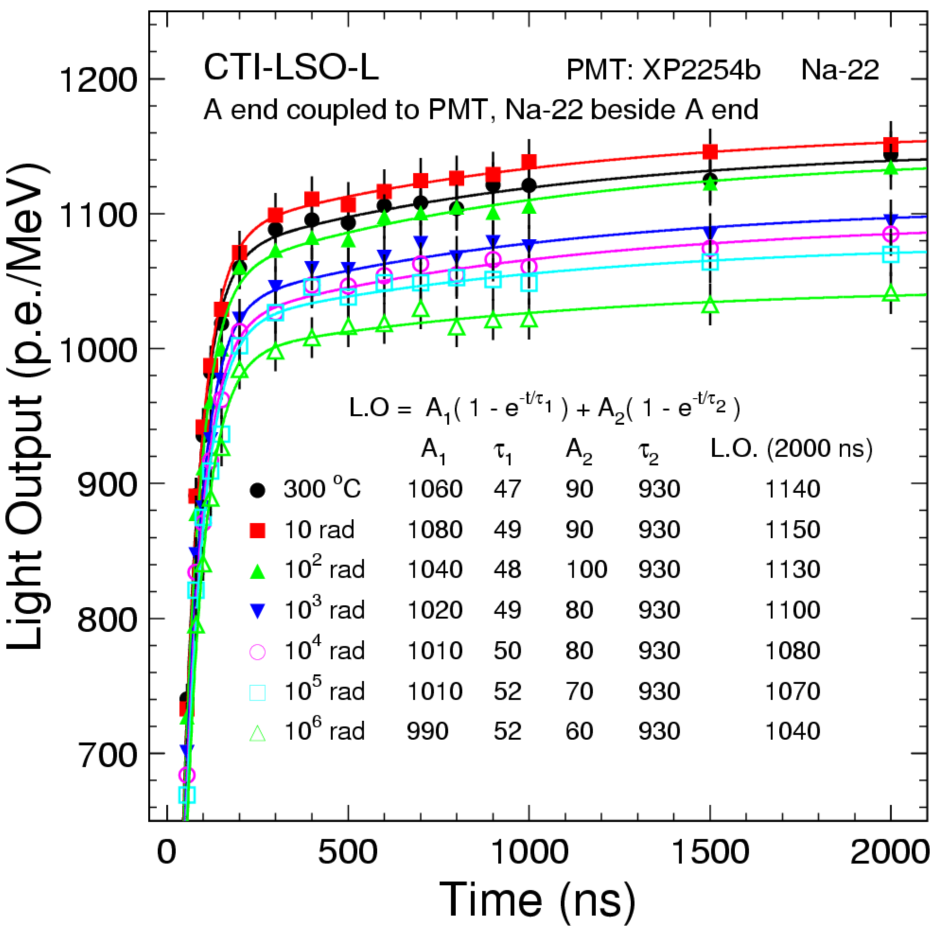
LT damage: 8% @ 1 Mrad



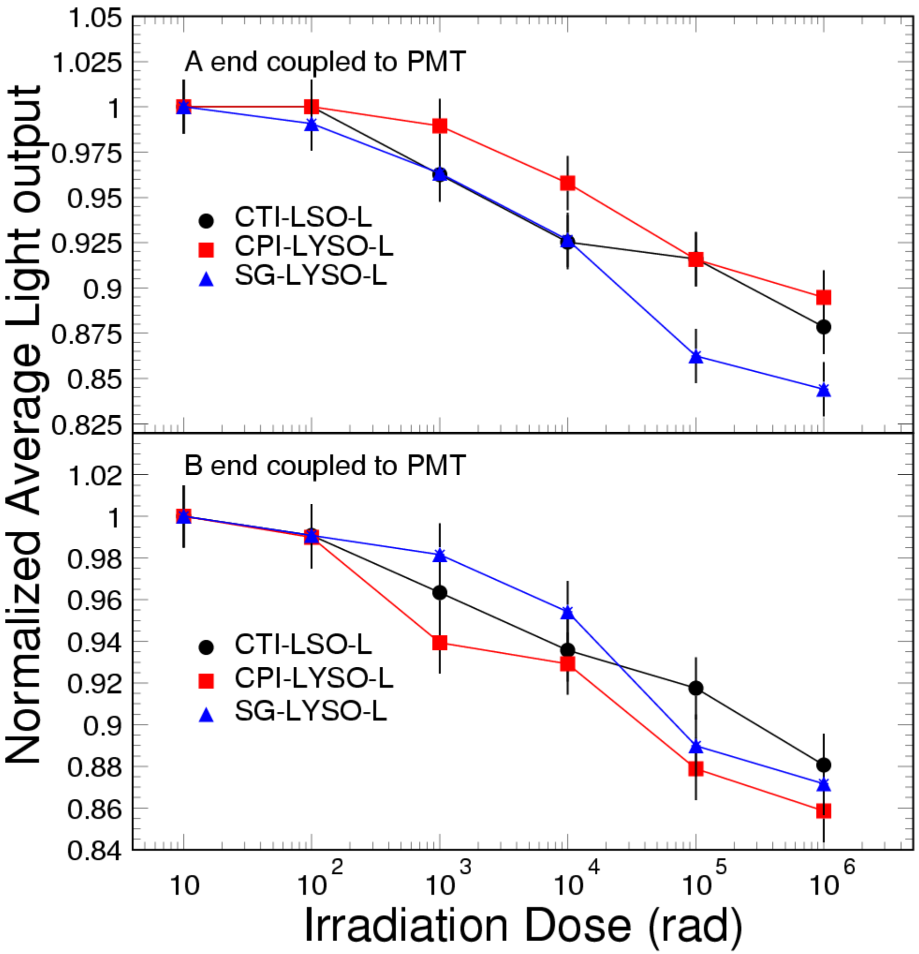


Light Output Damage with PMT

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

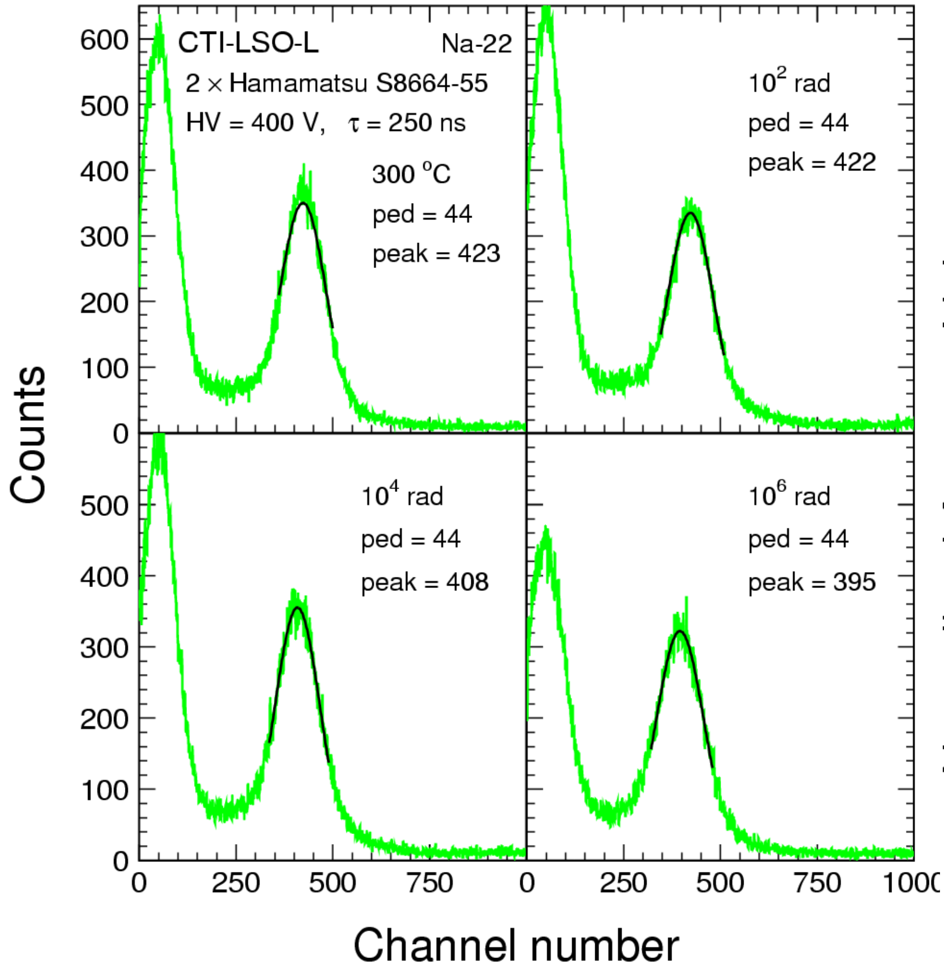


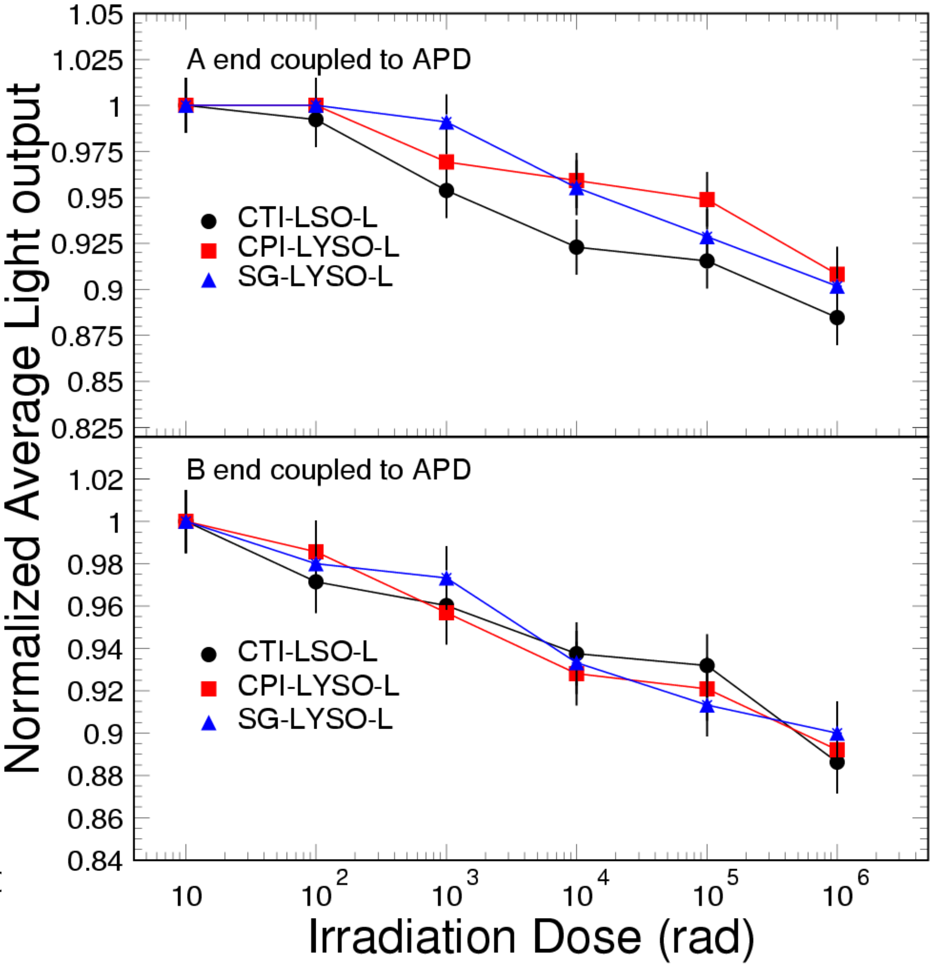
	A_1	τ_1	A_2	τ_2	L.O. (2000 ns)
300 °C	1060	47	90	930	1140
10 rad	1080	49	90	930	1150
10^2 rad	1040	48	100	930	1130
10^3 rad	1020	49	80	930	1100
10^4 rad	1010	50	80	930	1080
10^5 rad	1010	52	70	930	1070
10^6 rad	990	52	60	930	1040



Light Output Damage with APD

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

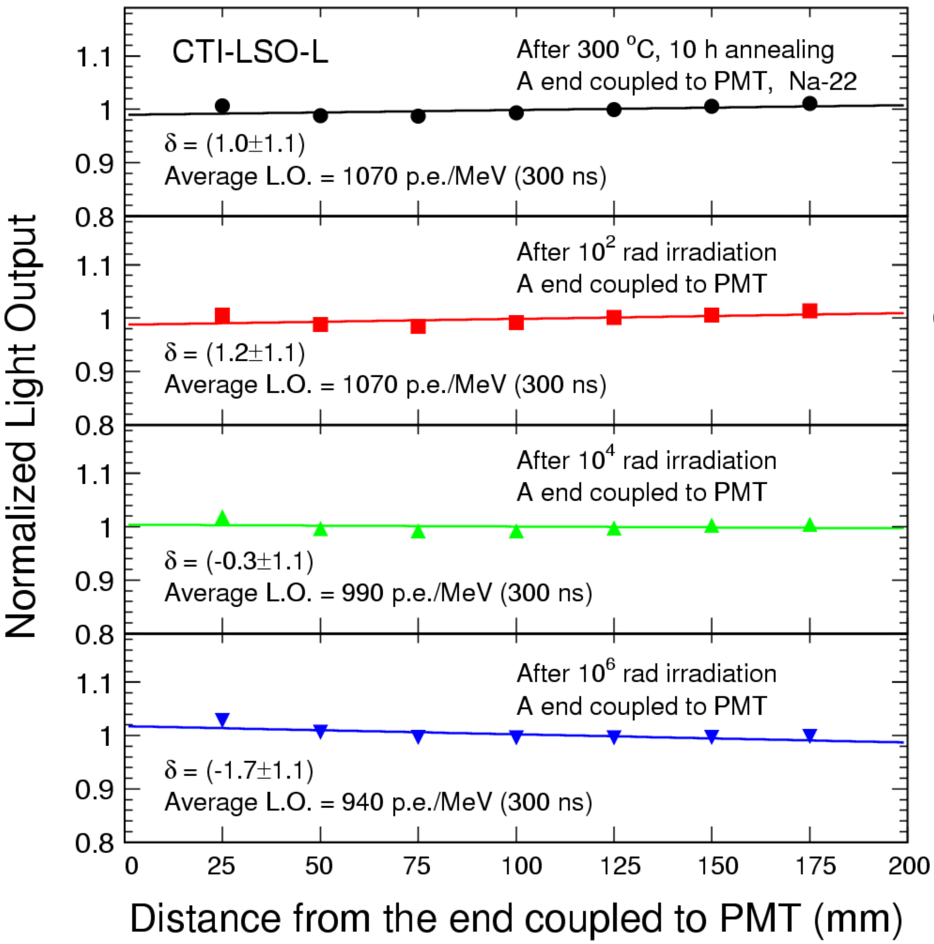




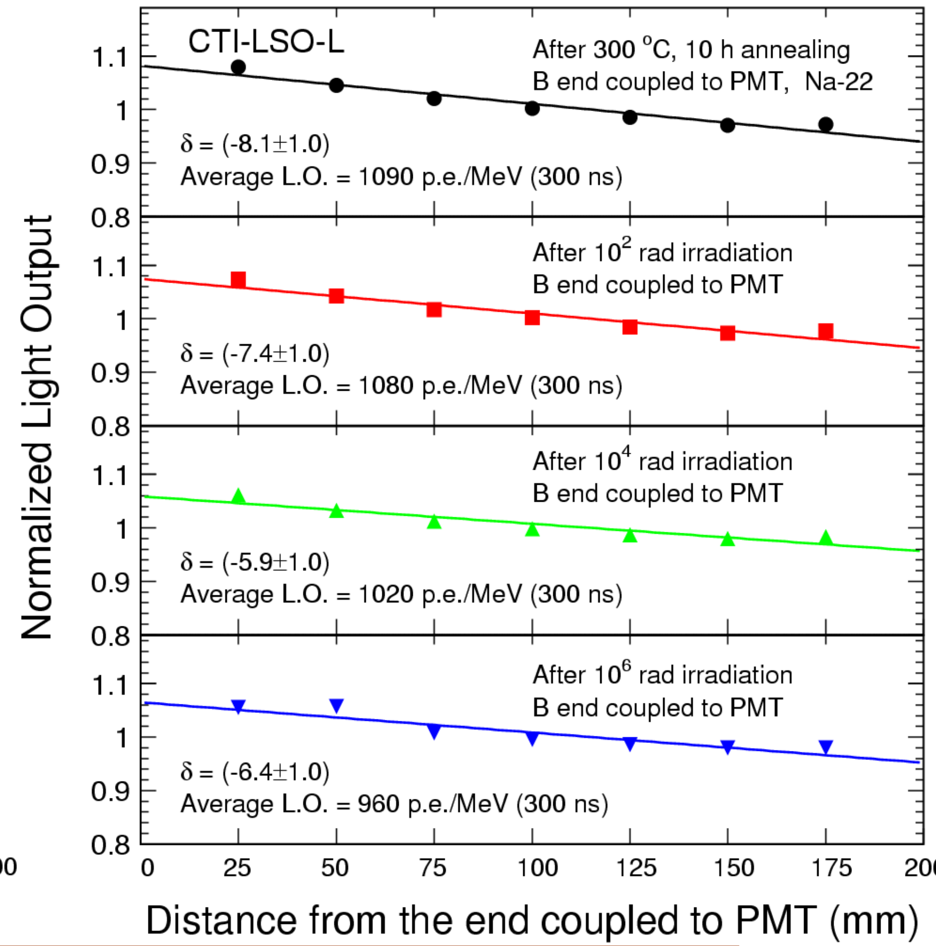
LRU Damage with PMT

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

A end Coupling



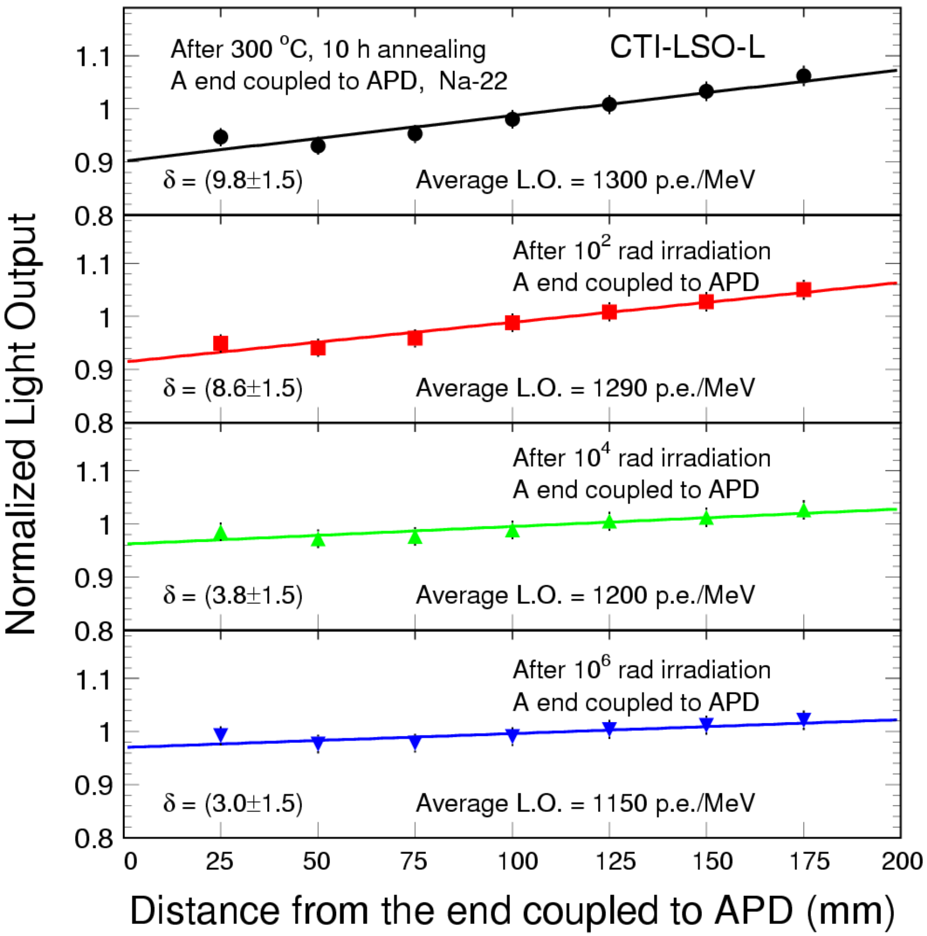
B end Coupling

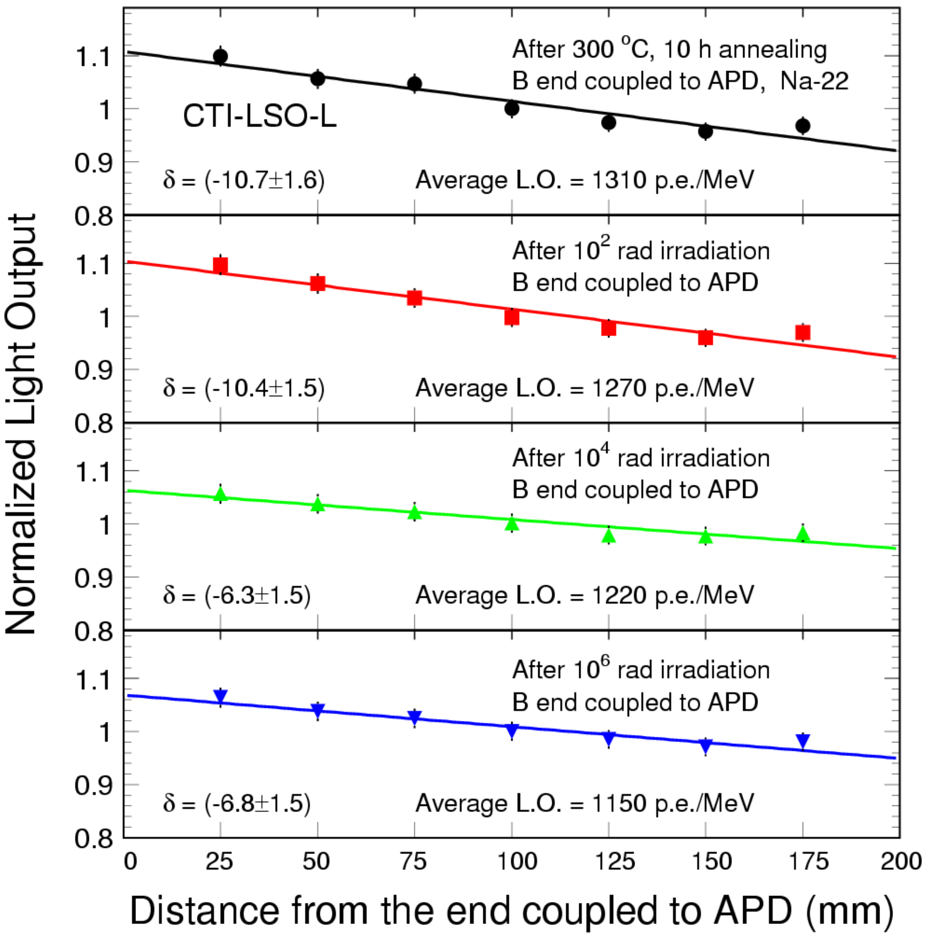


LRU Damage with APD

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

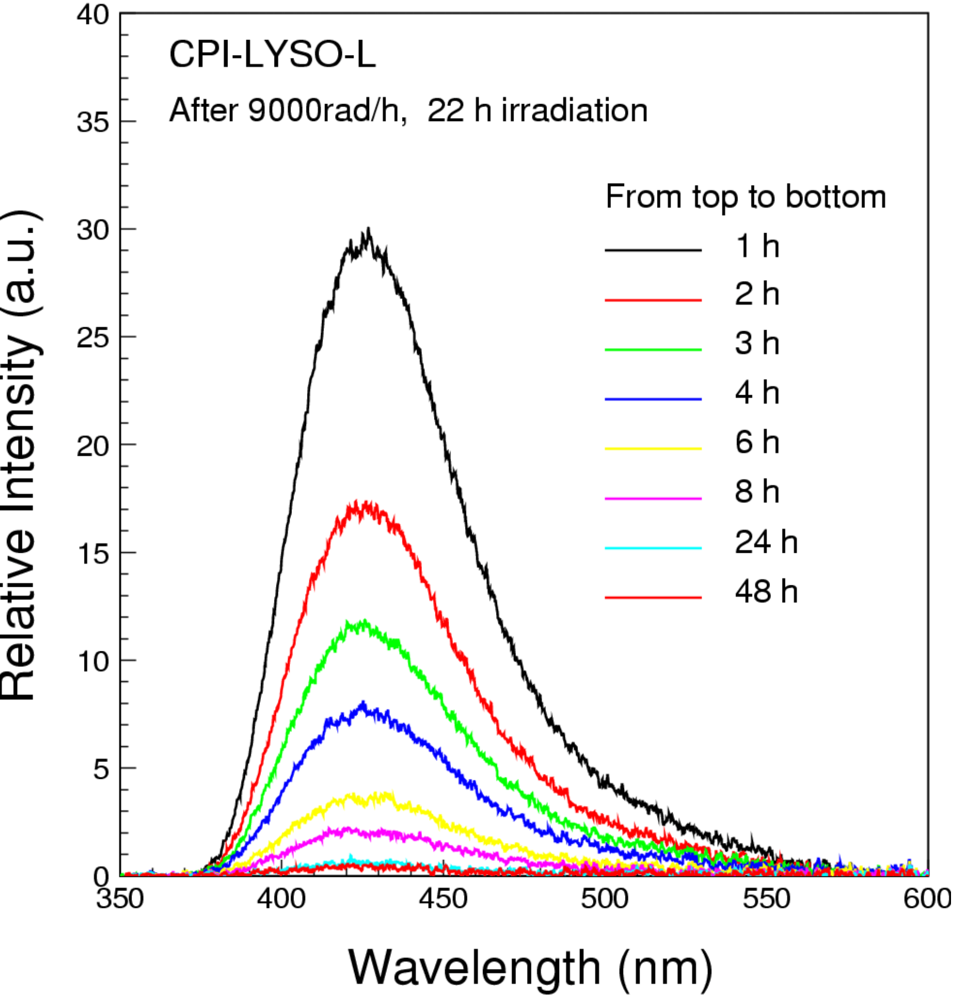
A end Coupling | B end Coupling

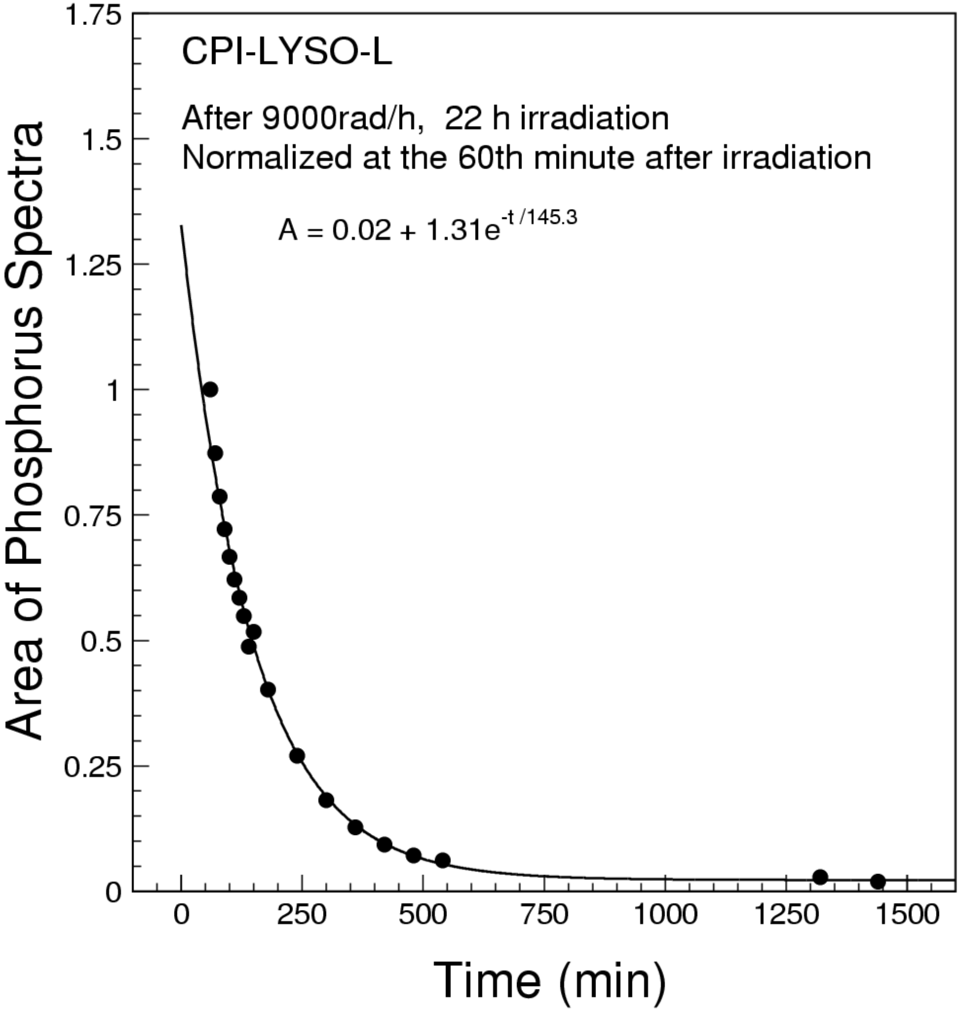




Radiation Induced Phosphorescence

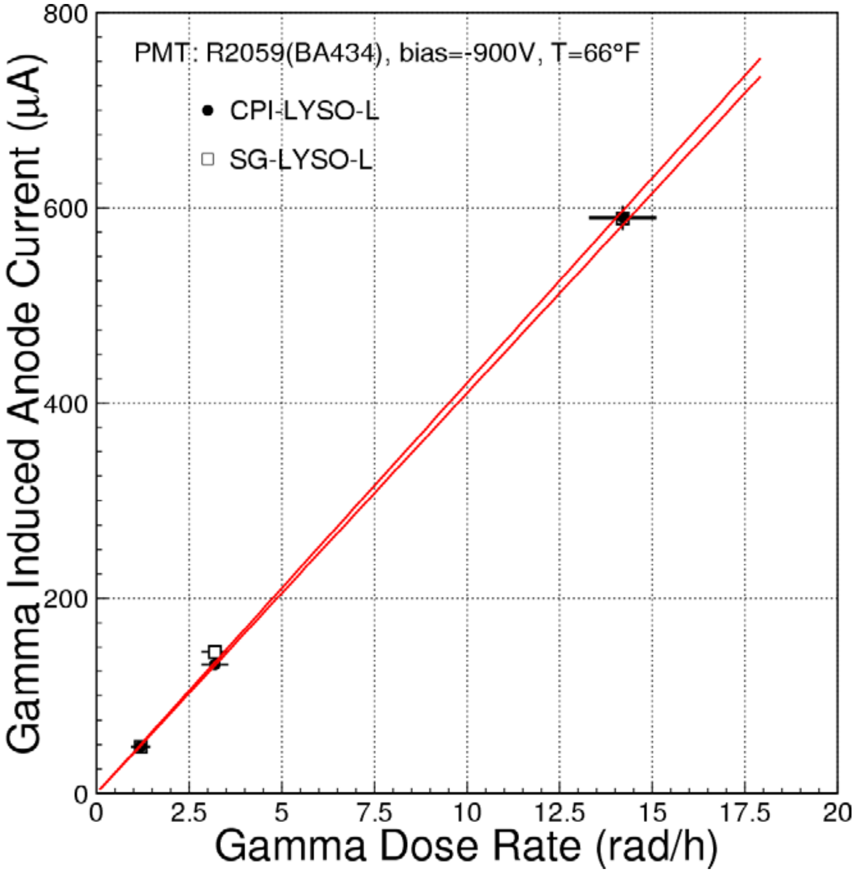
Phosphorescence peaked at 430 nm with decay time constant of 2.5 h observed





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.	$\sigma_{15\ rad/h}$ 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).

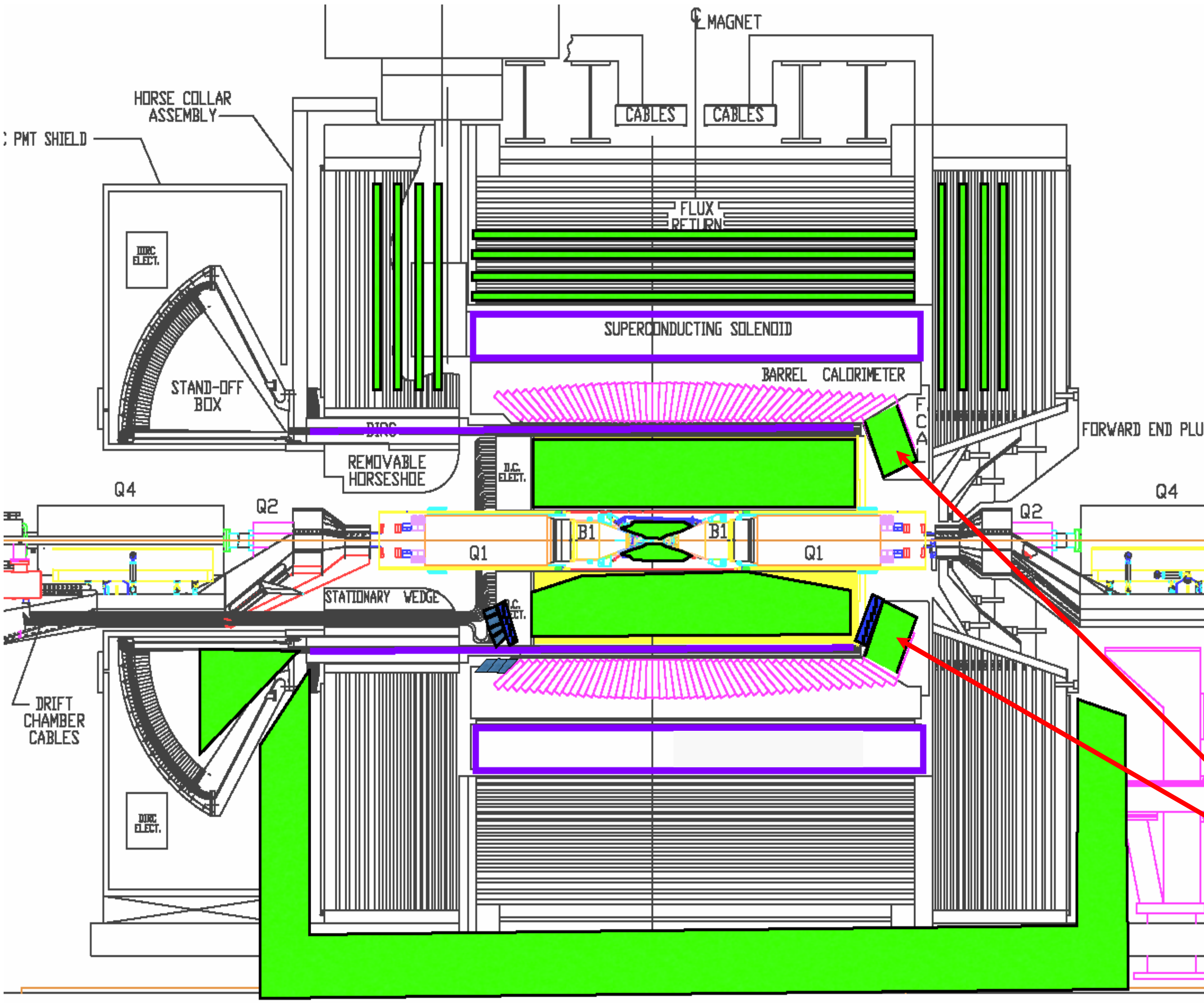
LSO/LYSO ECAL Performance

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

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

BABAR upgrade 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

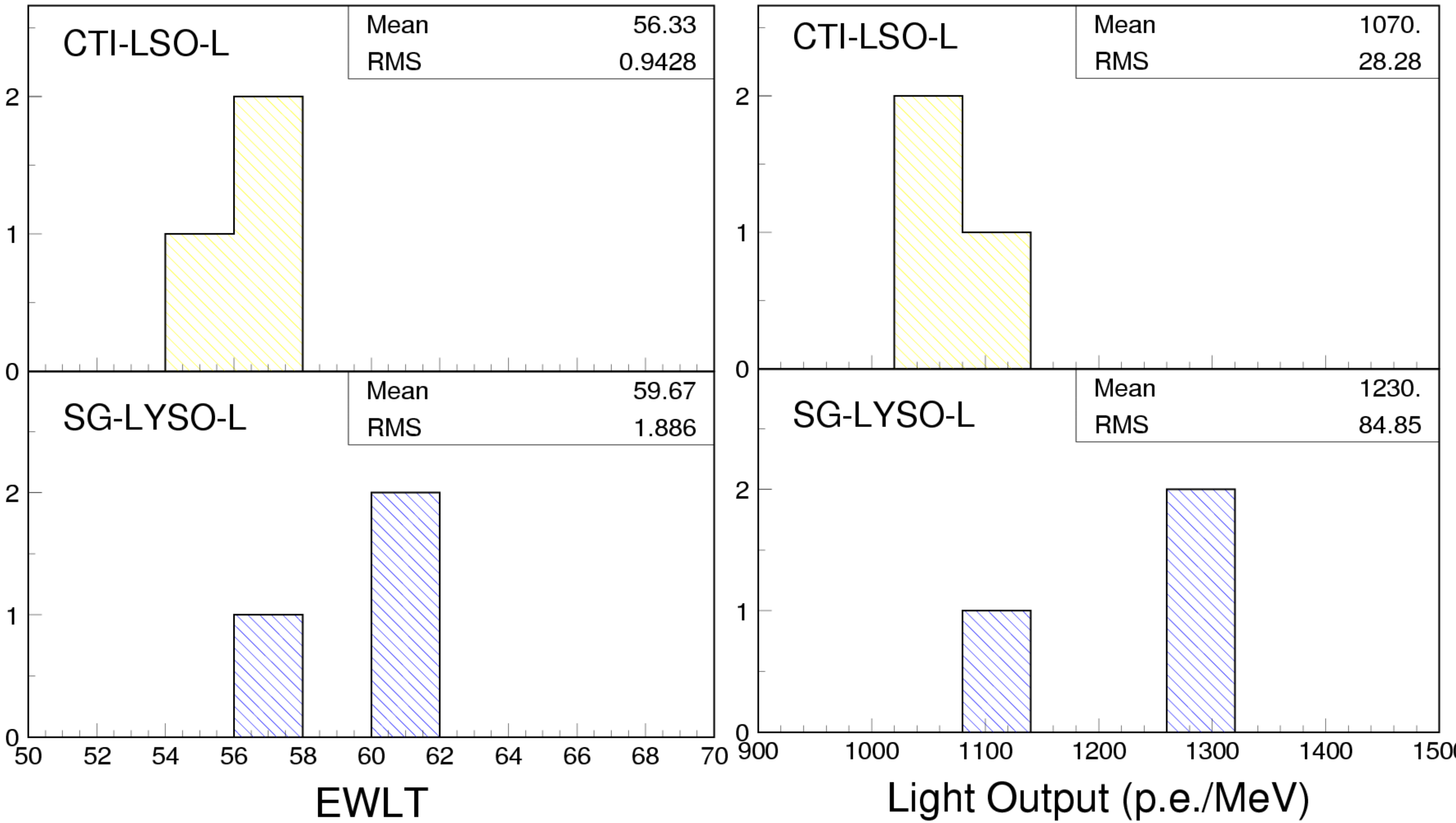
2.5 x 2.5 x 20 cm (18 X_0) Bar

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:

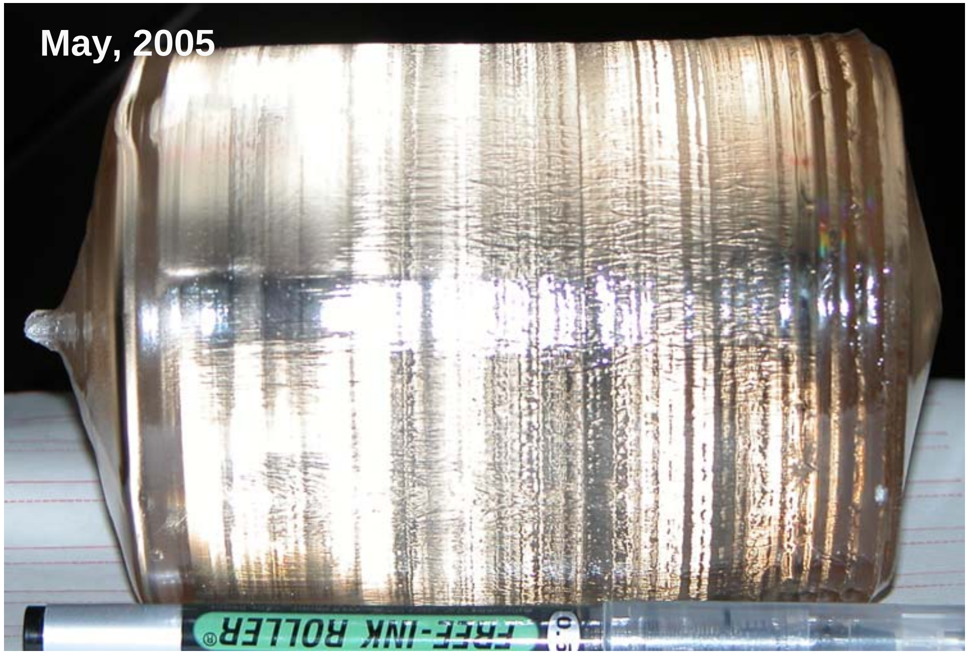
  Lu_2O_3: 99.995%

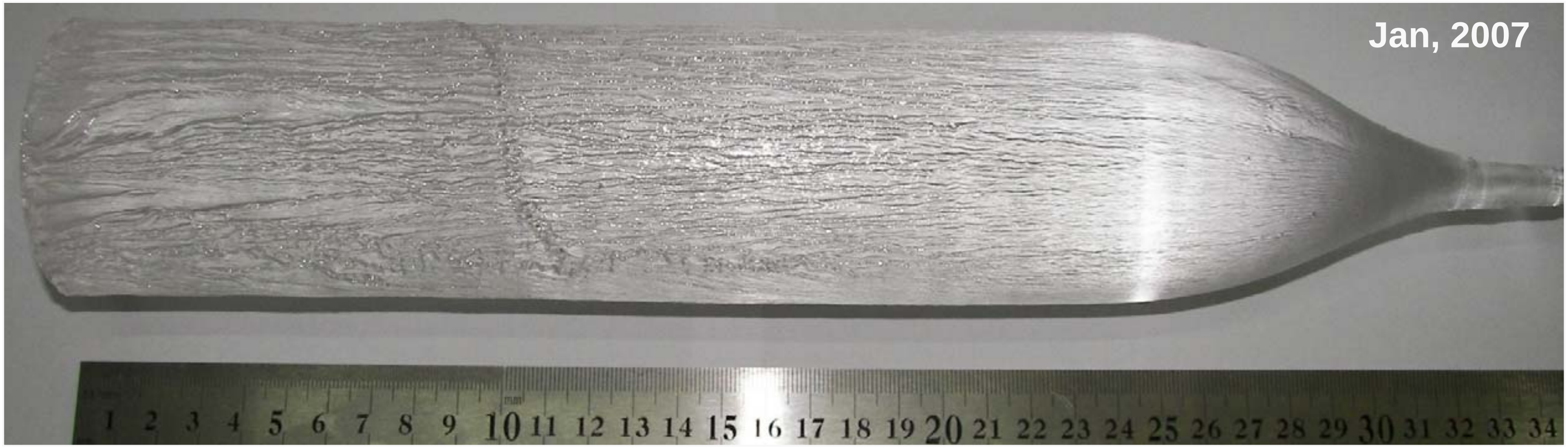
  SO_2: 99.999%

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

SIPAT Progress in LSO/LYSO Growth

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

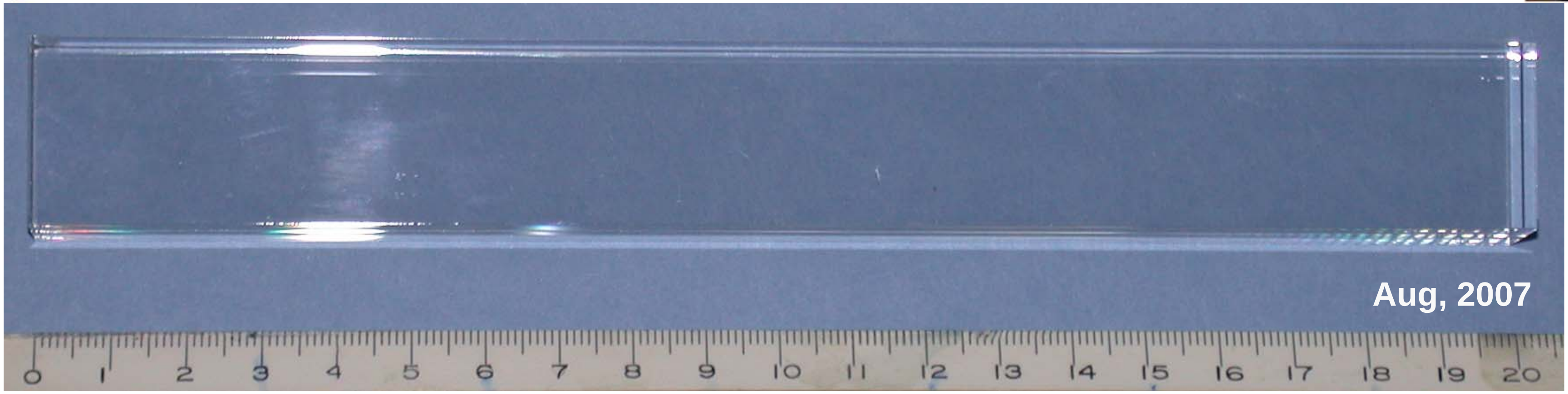




SIPAT Ø 60 x 250 mm LYSO Boles

SIPAT Czochralski Furnaces

First SIPAT LYSO Sample for HEP

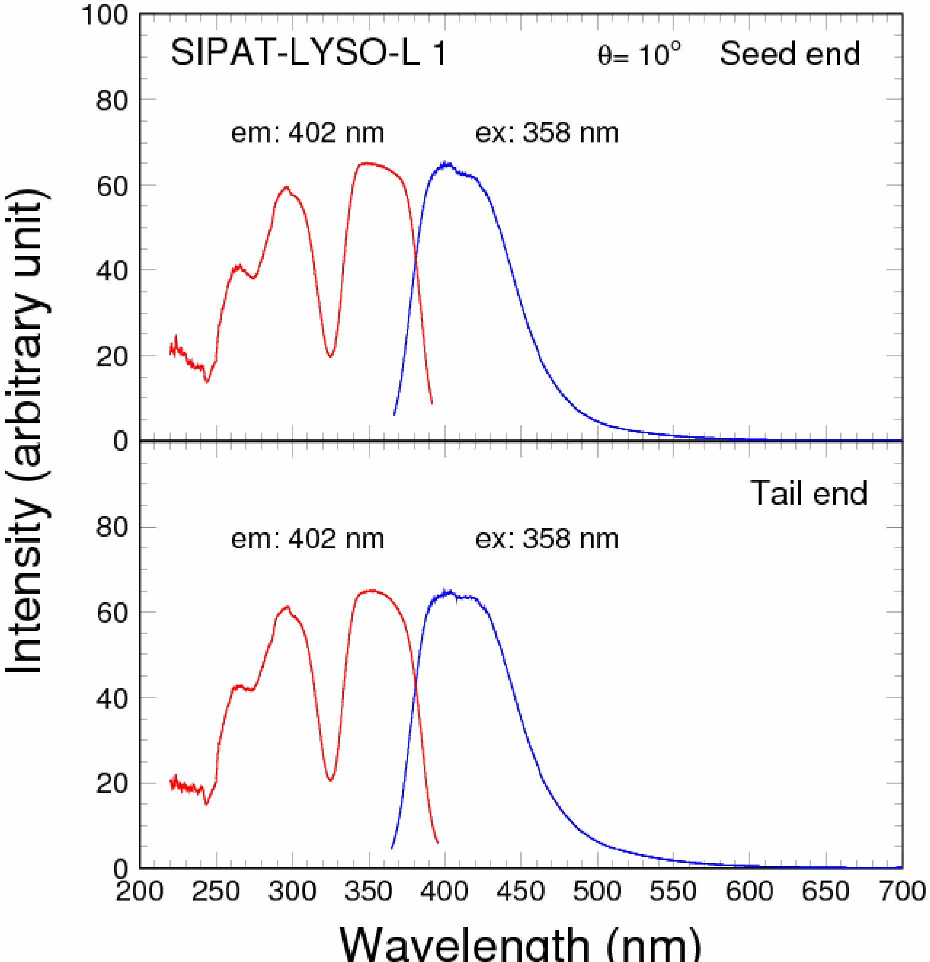


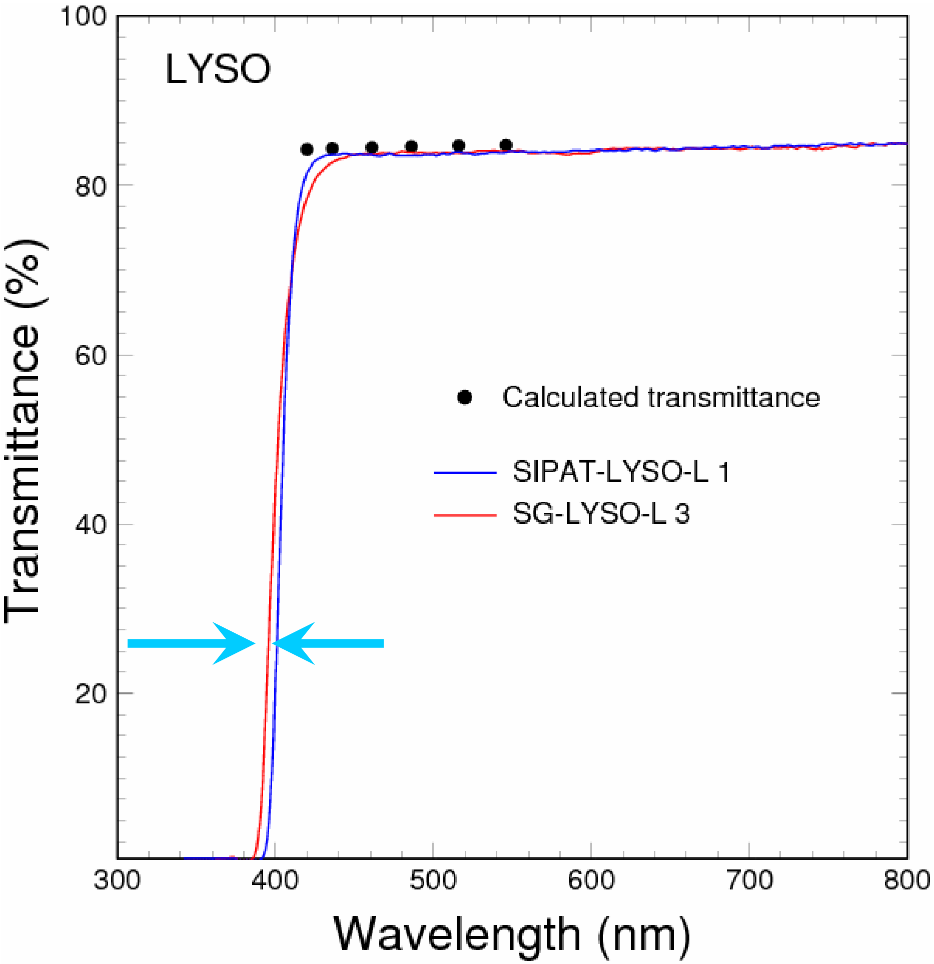
- Received in the middle of August with dimension of 25 x 25 x 200 mm and good visual inspection.
- It was first annealed at $300^{o}C$ for 10 hours and with its initial optical and scintillation properties measured.
- Together with SG-L3, two samples were irradiated with integrated doses of 10, 10^2,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

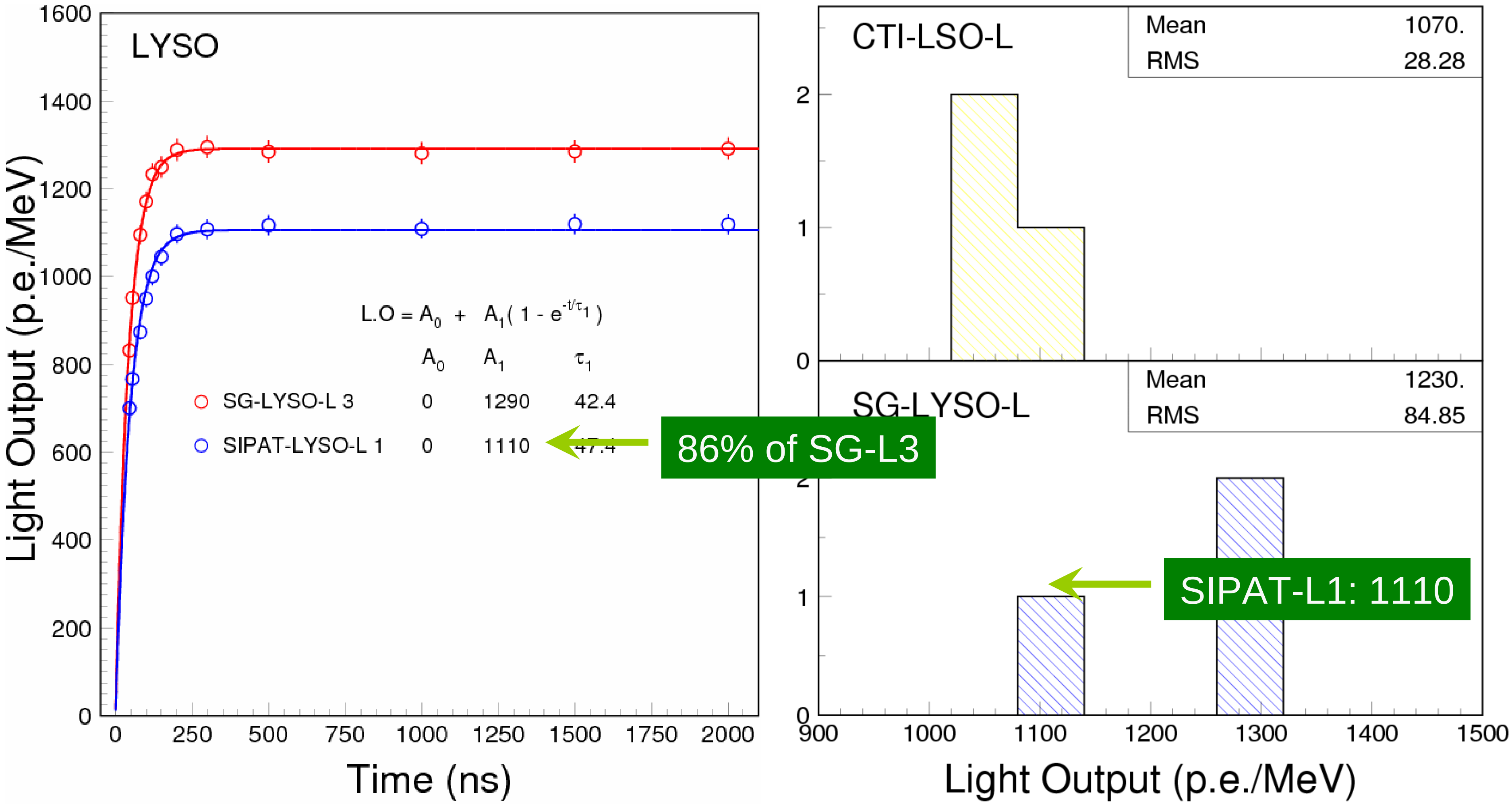
The cutoff of SG-L3 has ~5 nm blue shift compared to SIAPT-L1





Light Output & Decay Kinetics

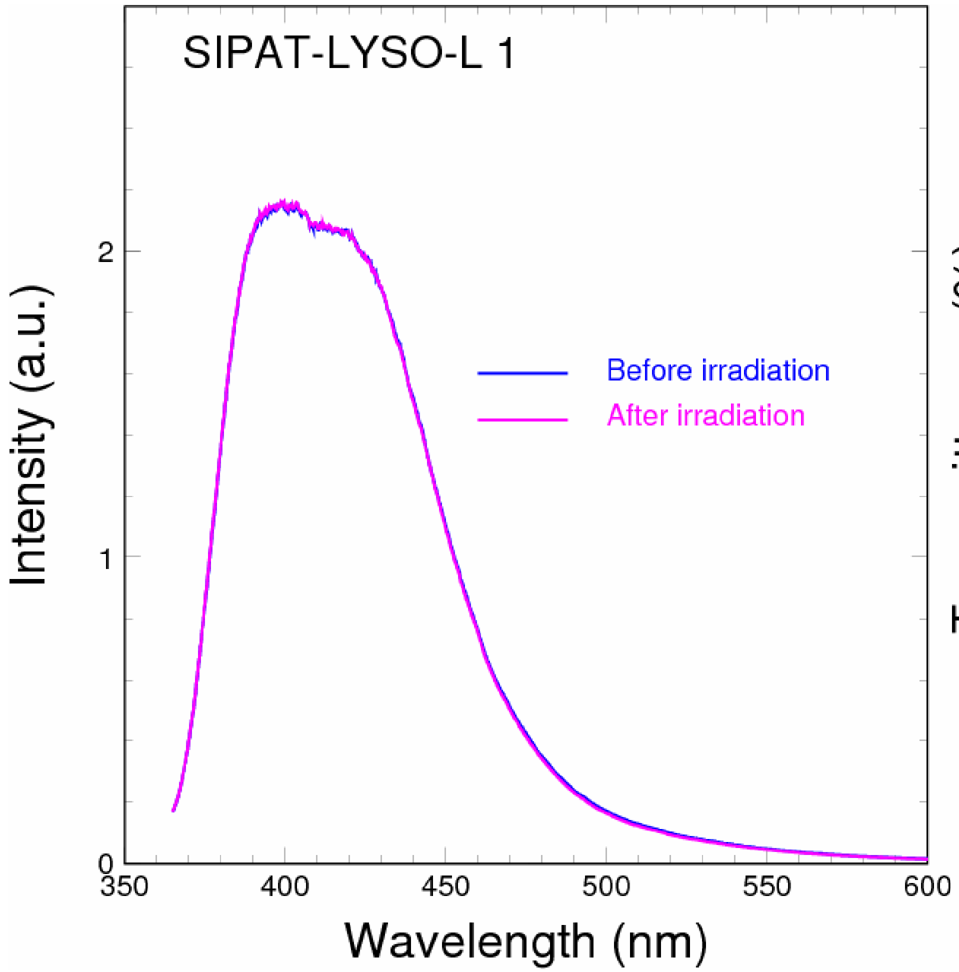
Compatible with the first batch large size samples from CTI and Saint-Gobain, and is 86% of the 'best' samples

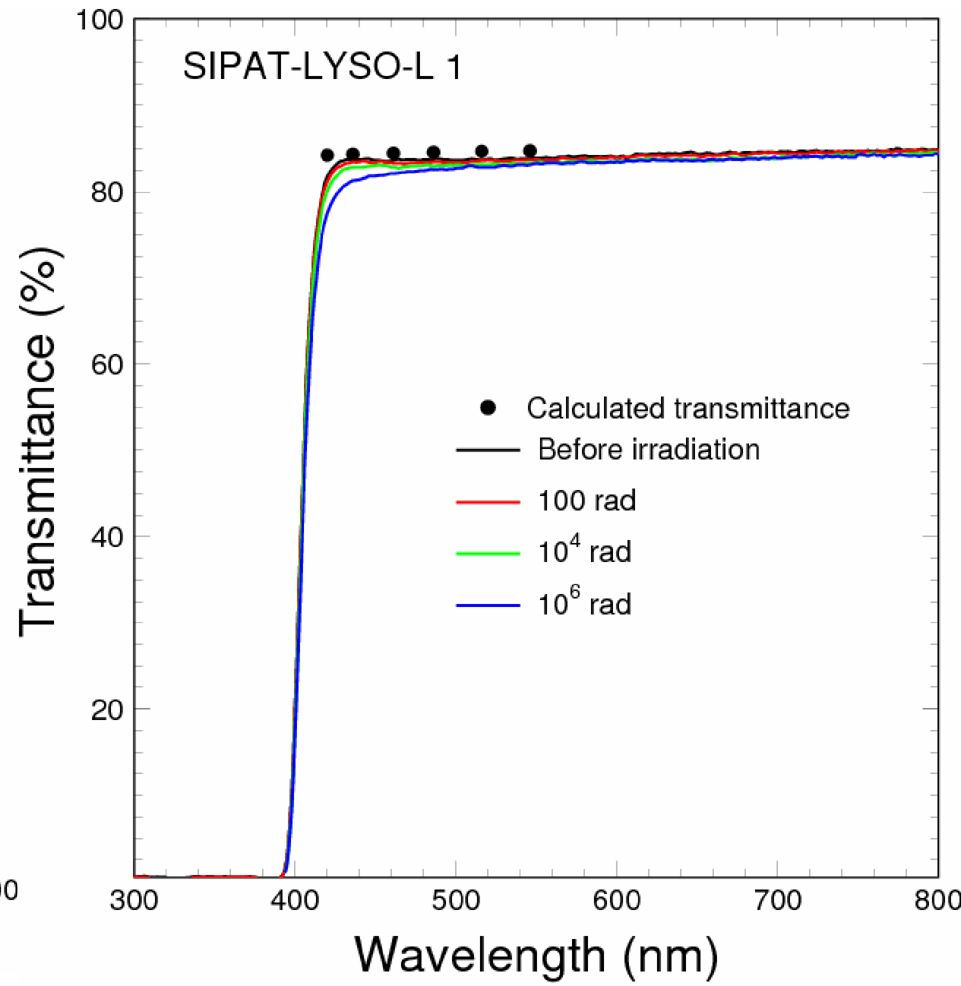


γ-Ray Induced Radiation Damage

Scintillation spectrum not affected by irradiation

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

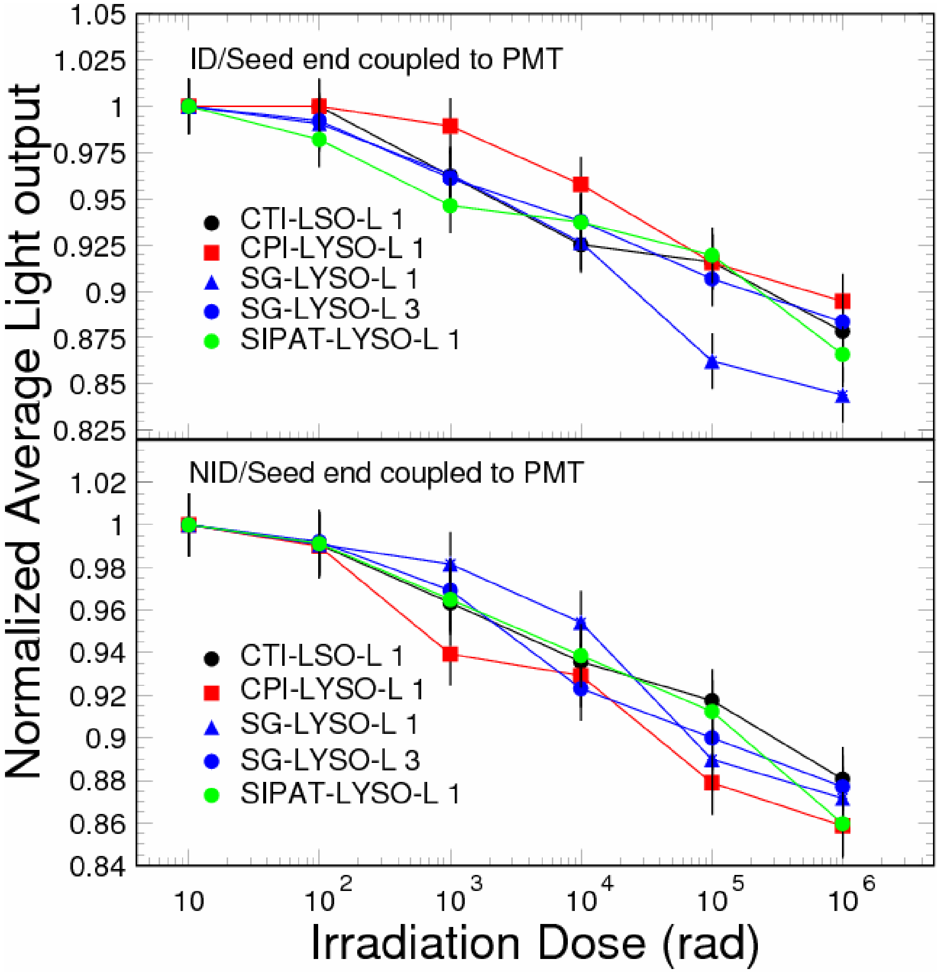


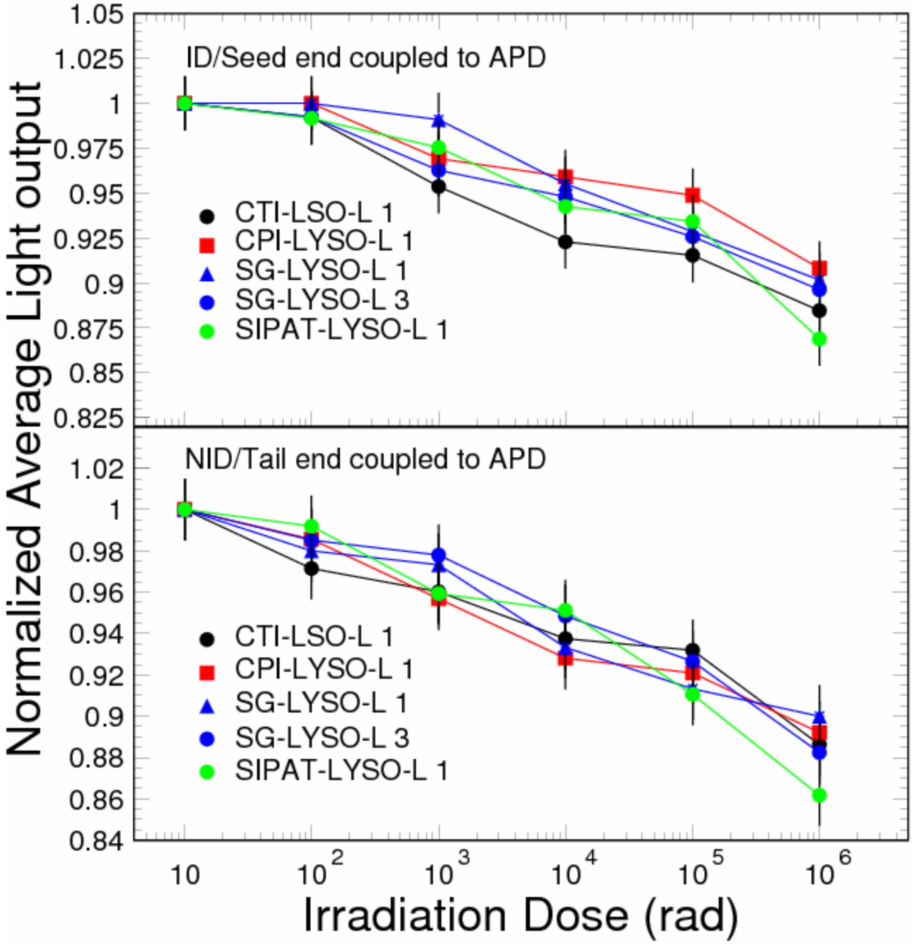


Comparison of L.O. Damage

10% - 15% loss by PMT

9% - 14% loss by APD





Summary

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