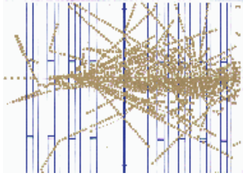


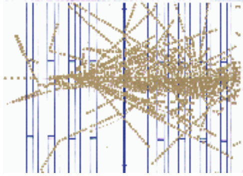
Precision Crystal Calorimetry in High Energy Physics

Ren-Yuan Zhu

California Institute of Technology

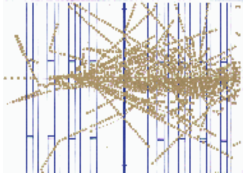
August 13, 2008

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 of Cherenkov and scintillation light.

Physics with Crystal Calorimeters (I)



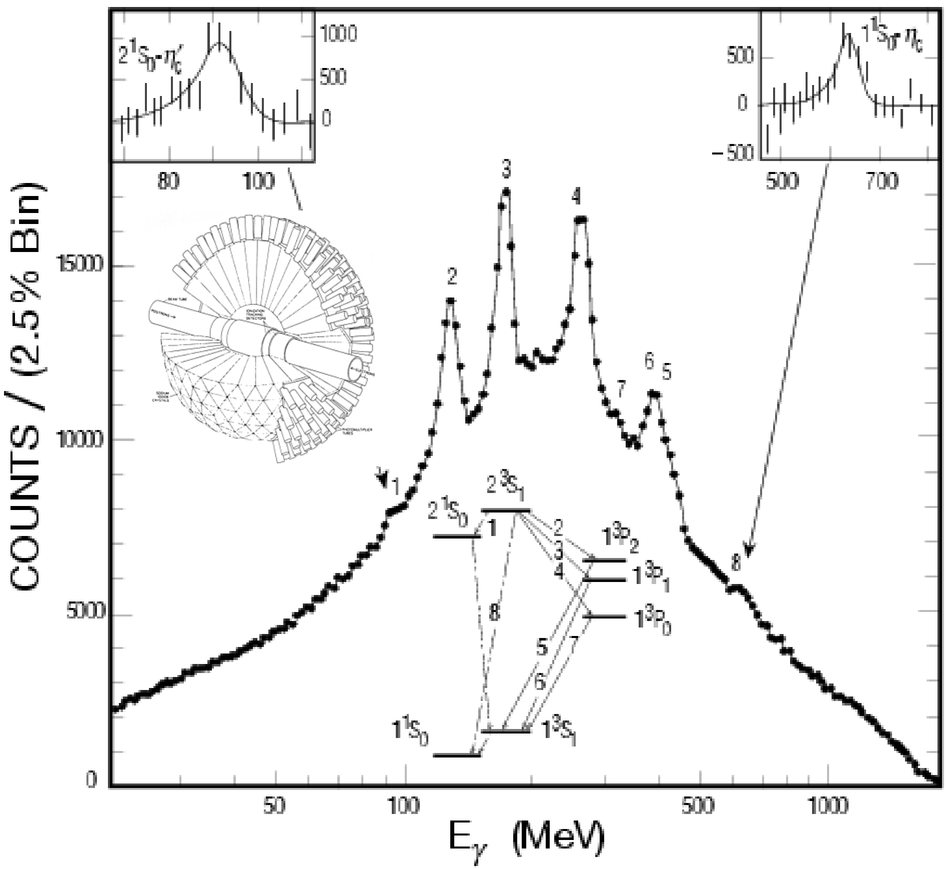
Charmonium system observed by CB through Inclusive photons

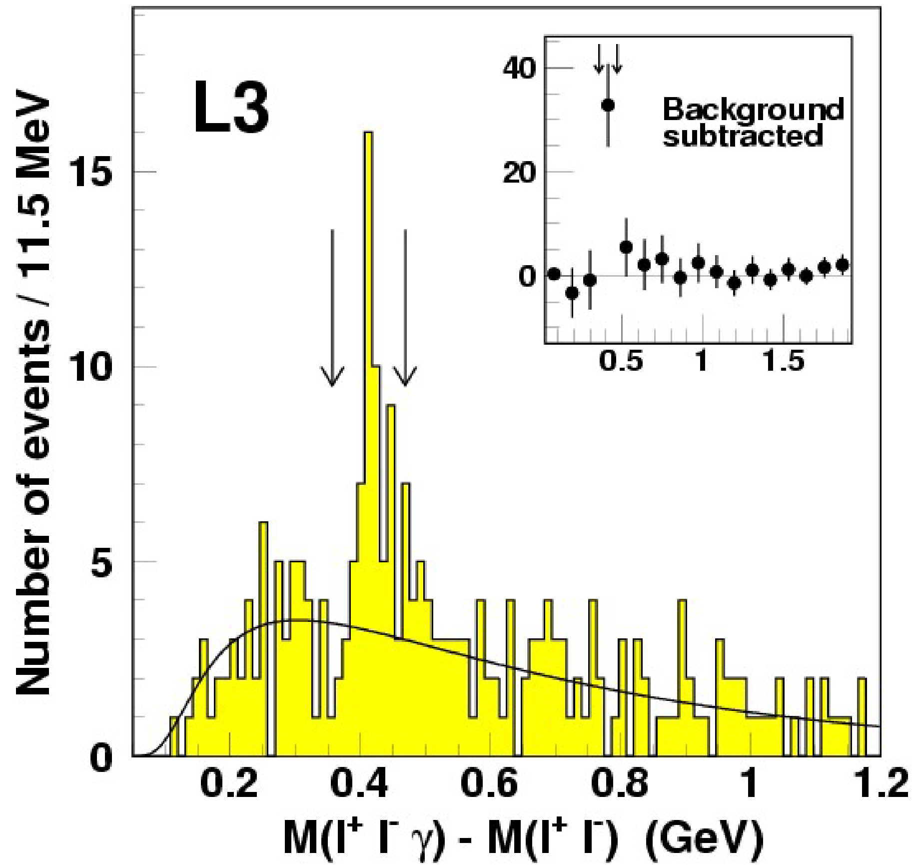
Charmed Meson in Z Decay

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

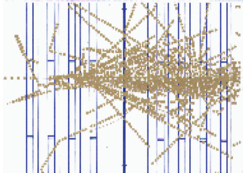
CB NaI(Tl)

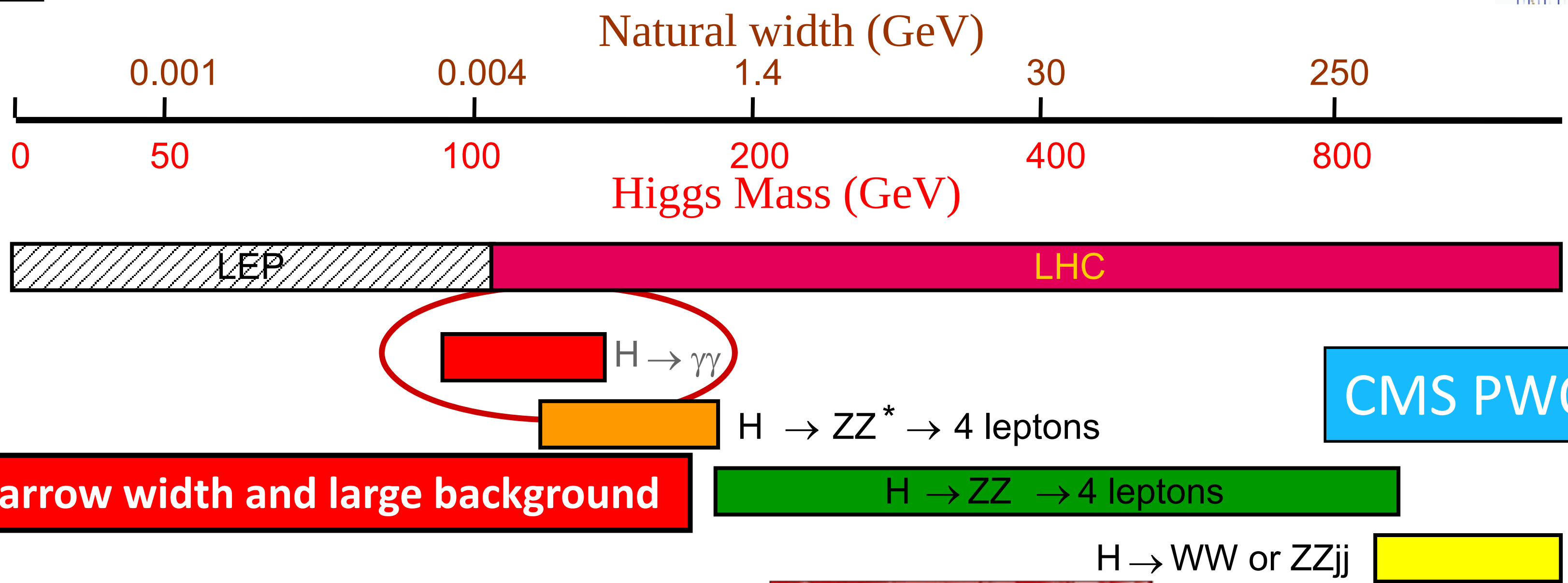
L3 BGO





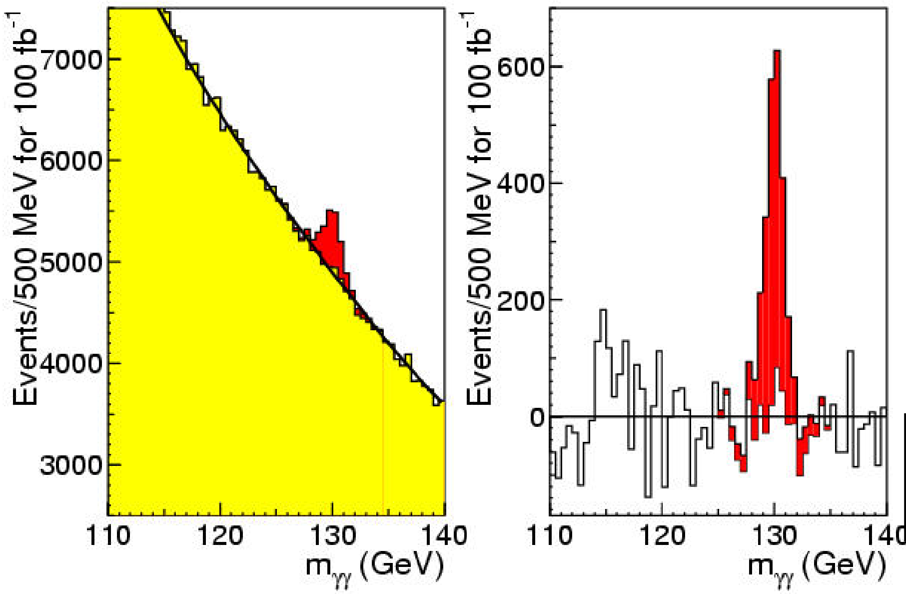
H→γγ Search Needs Precision ECAL

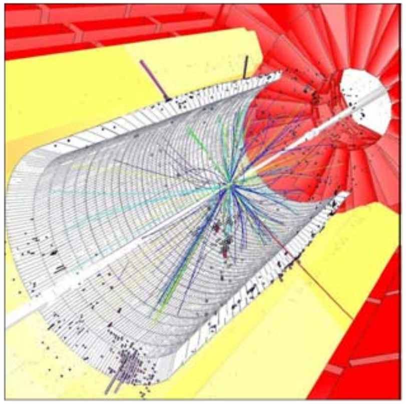


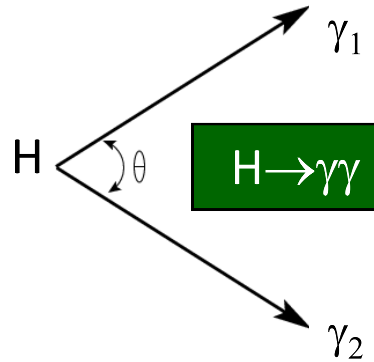


CMS PWO

Narrow width and large background





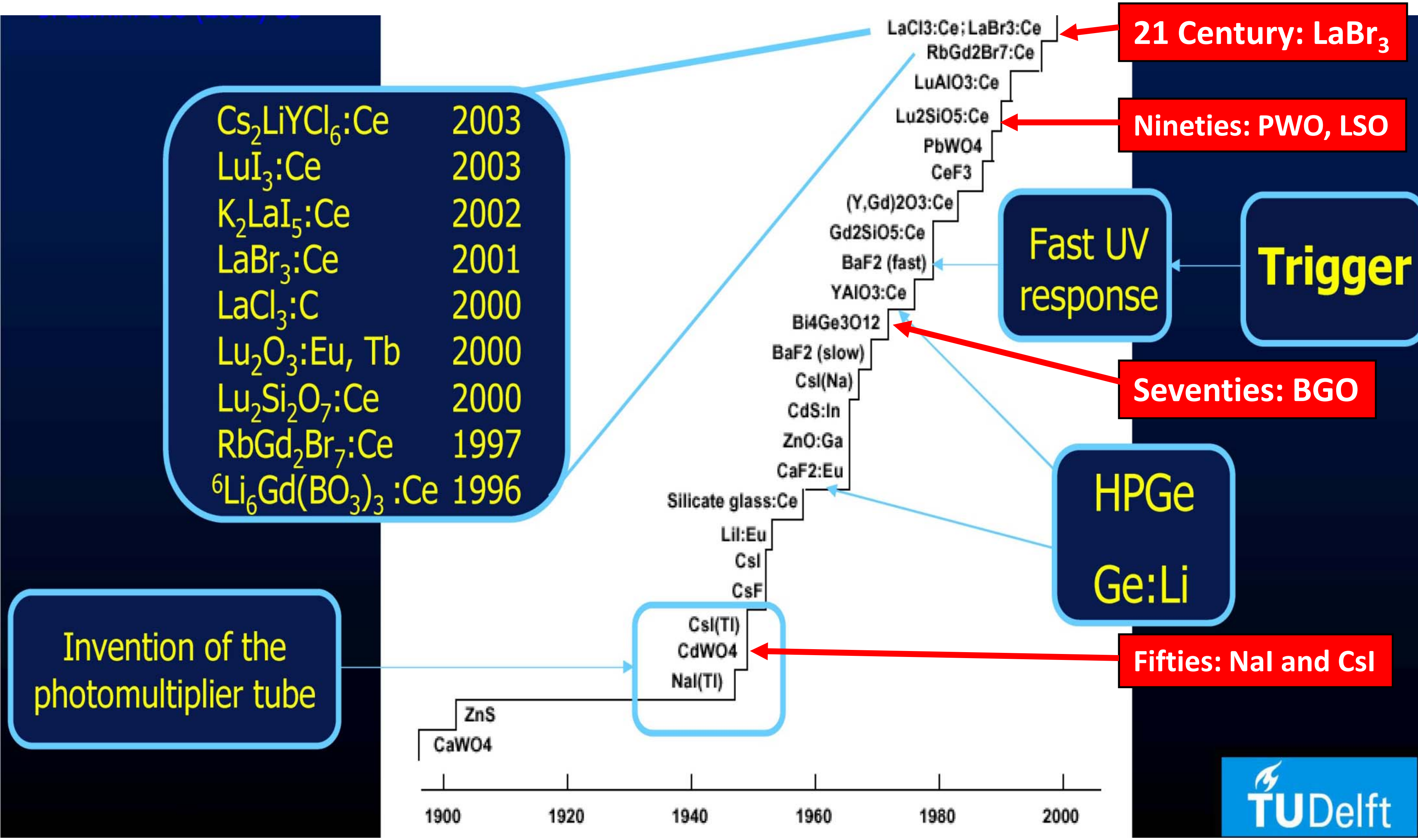


H→γγ at LHC

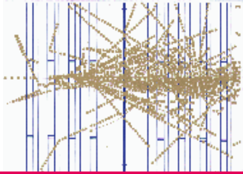
$\sigma m / m = 0.5\ [\sigma E_1/E_1 \oplus \sigma E_2/E_2 \oplus \sigma\theta/\tan(\theta/2)]$,
where $\sigma E / E = a/\sqrt{E} \oplus b \oplus c/E$ and E in GeV

History of Crystal Development

M.J. Weber, J. Lumin. 100 (2002) 35



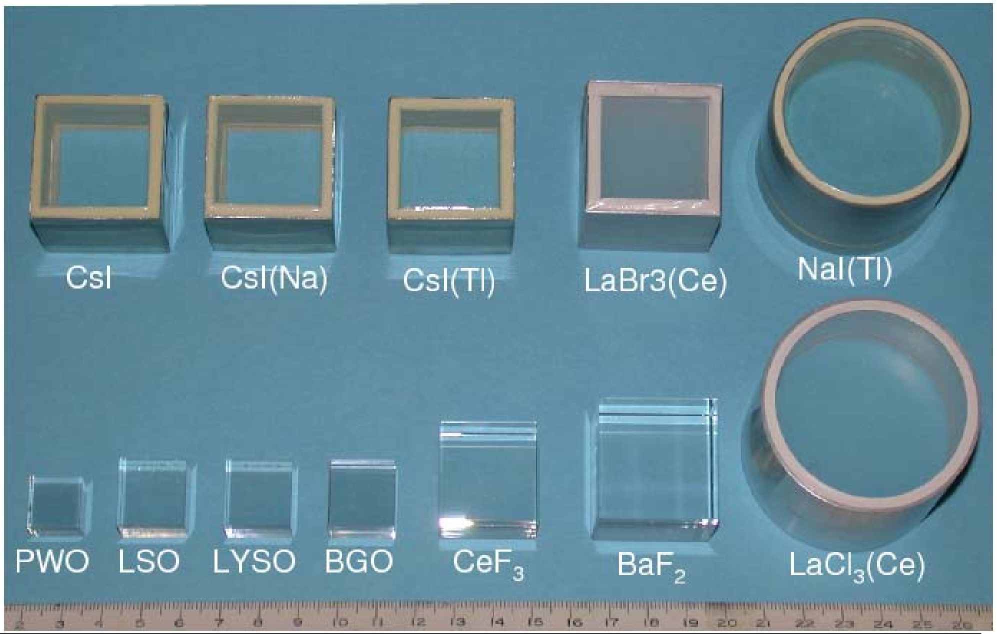
Crystals for HEP Calorimeters



Crystal	NaI(Tl)	CsI(Tl)	CsI(Na)	CsI	BaF_2	CeF_3	BGO	PWO(Y)	LSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.51	4.89	6.16	7.13	8.3	7.40
Melting Point (ºC)	651	621	621	621	1280	1460	1050	1123	2050
Radiation Length (cm)	2.59	1.86	1.86	1.86	2.03	1.70	1.12	0.89	1.14
Molière Radius (cm)	4.13	3.57	3.57	3.57	3.10	2.41	2.23	2.00	2.07
Interaction Length (cm)	42.9	39.3	39.3	39.3	30.7	23.2	22.8	20.7	20.9
Refractive Index [a]	1.85	1.79	1.95	1.95	1.50	1.62	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	300 220	340 300	480	425 420	402
Decay Time [b] (ns)	245	1220	690	30 6	650 0.9	30	300	30 10	40
Light Yield [b,c] (%)	100	165	88	3.6 1.1	36 4.1	7.3	21	0.3 0.1	85
d(LY)/dT [b] (%/ ºC)	-0.2	0.4	0.4	-1.4	-1.9 0.1	0	-0.9	-2.5	-0.2
Experiment	Crystal Ball	BaBar BELLE BES III	-	KTeV	(L*) (GEM) TAPS	-	L3 BELLE	CMS ALICE PANDA	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: Sealed

Non-hygro: Polished

Full Size Crystals:

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

L3 BGO: 22 X_0

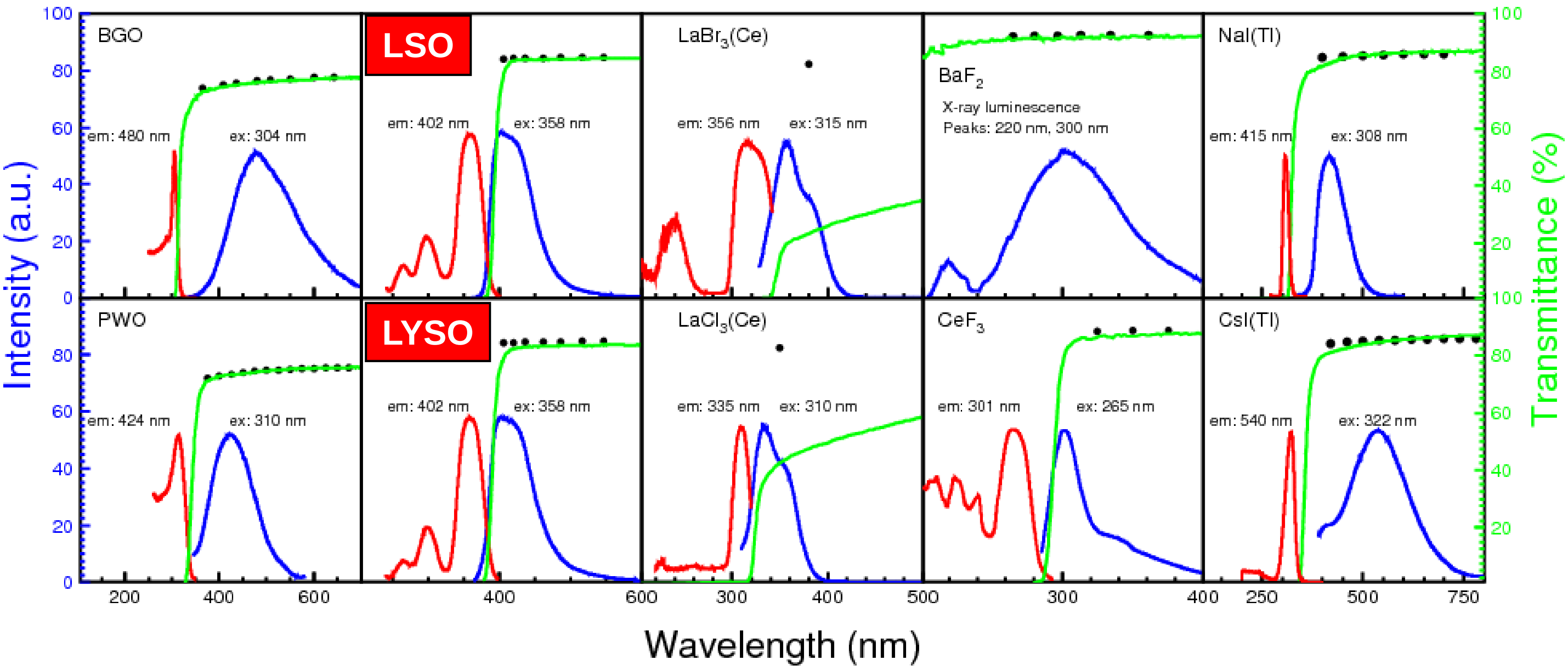
CMS PWO(Y): 25 X_0

Excitation, Emission, Transmission

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

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

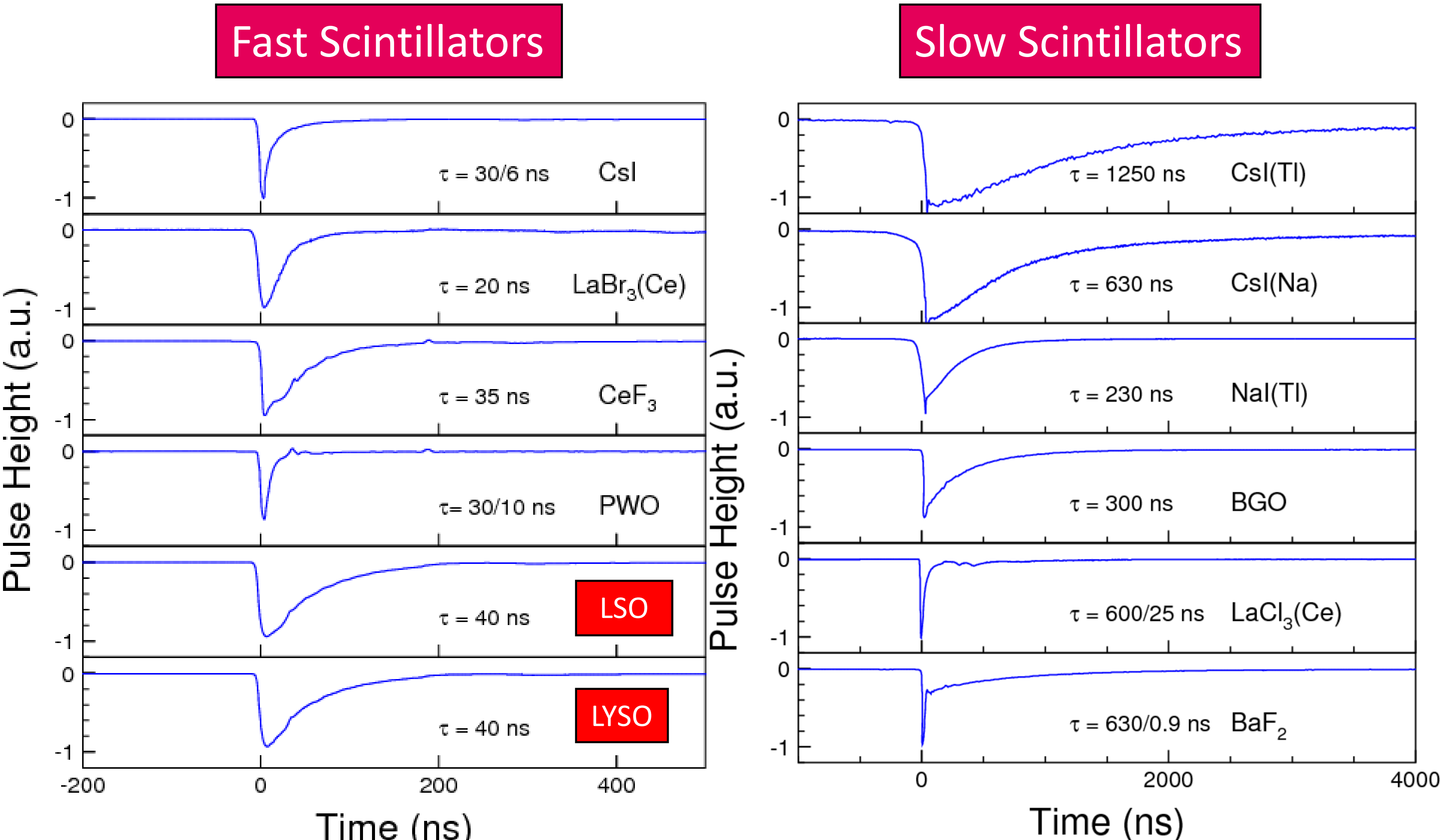
Black Dots: Theoretical limit of transmittance: NIM A333 (1993) 422



No Self-absorption: BGO, PWO, BaF_2, NaI(Tl) and CsI(Tl)

Scintillation Light Decay Time

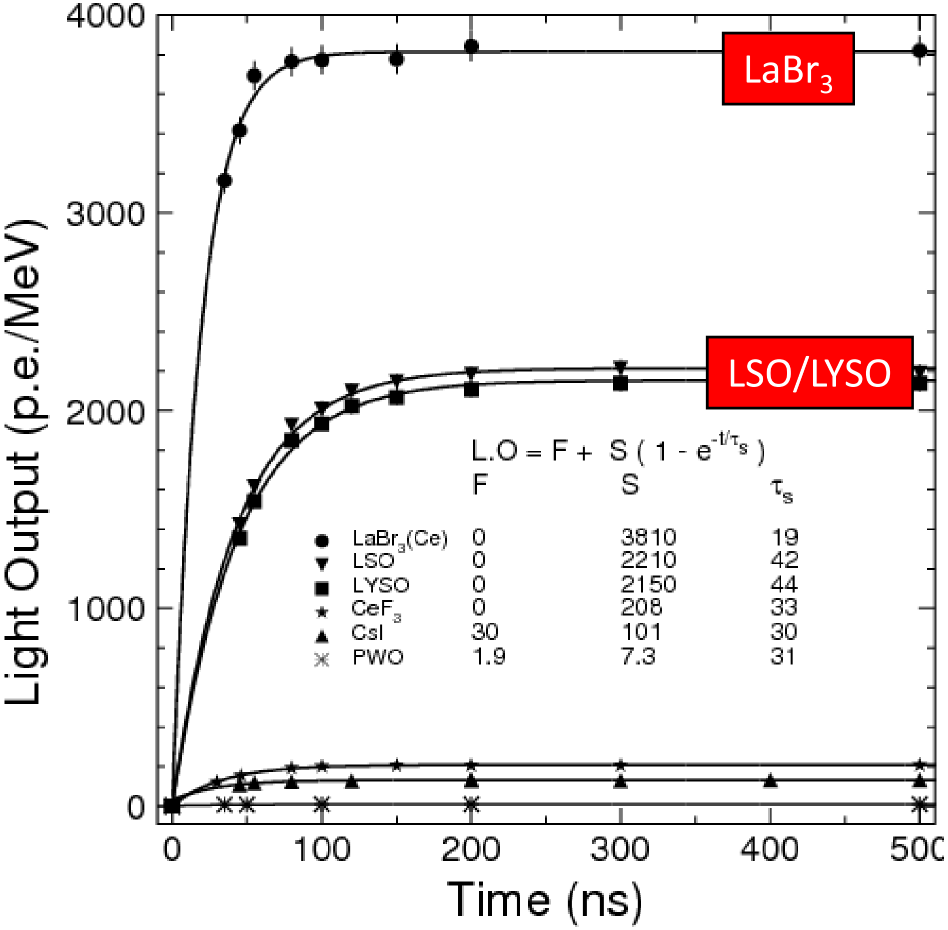
Recorded with an Agilent 6052A digital scope



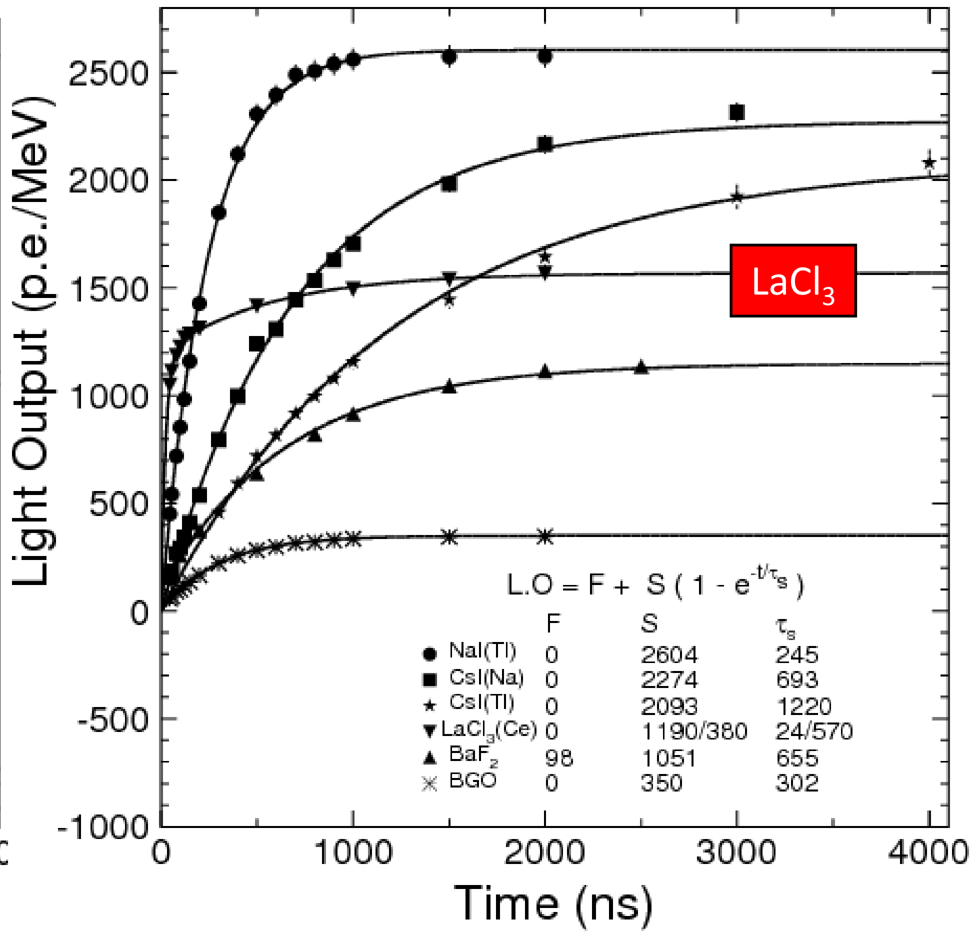
Light Output & Decay Kinetics

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

Fast Crystal Scintillators

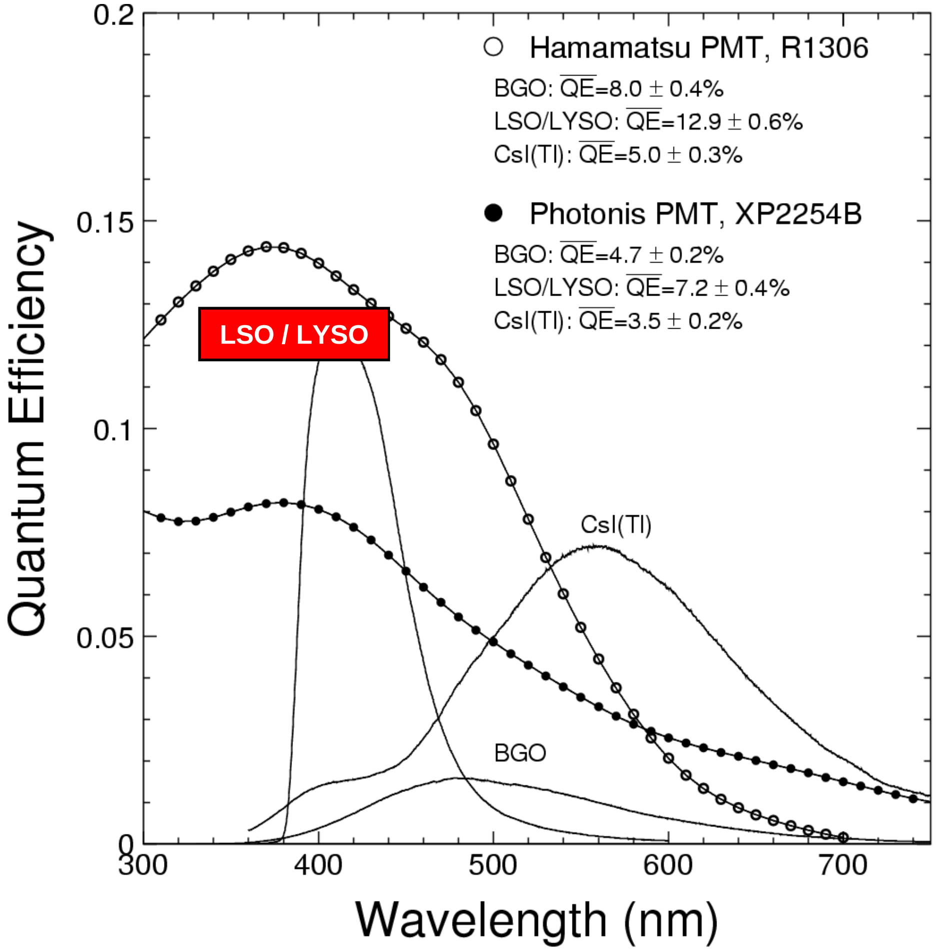


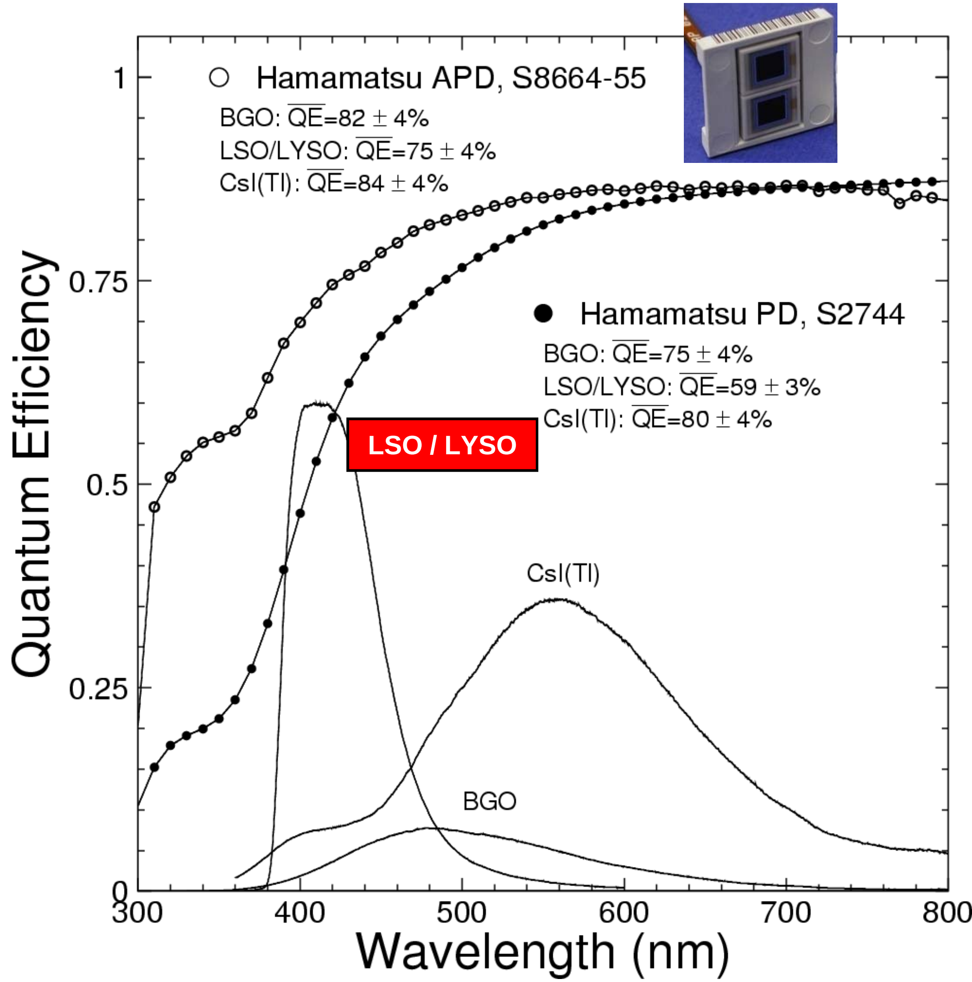
Slow Crystal Scintillators



Emission Weighted QE

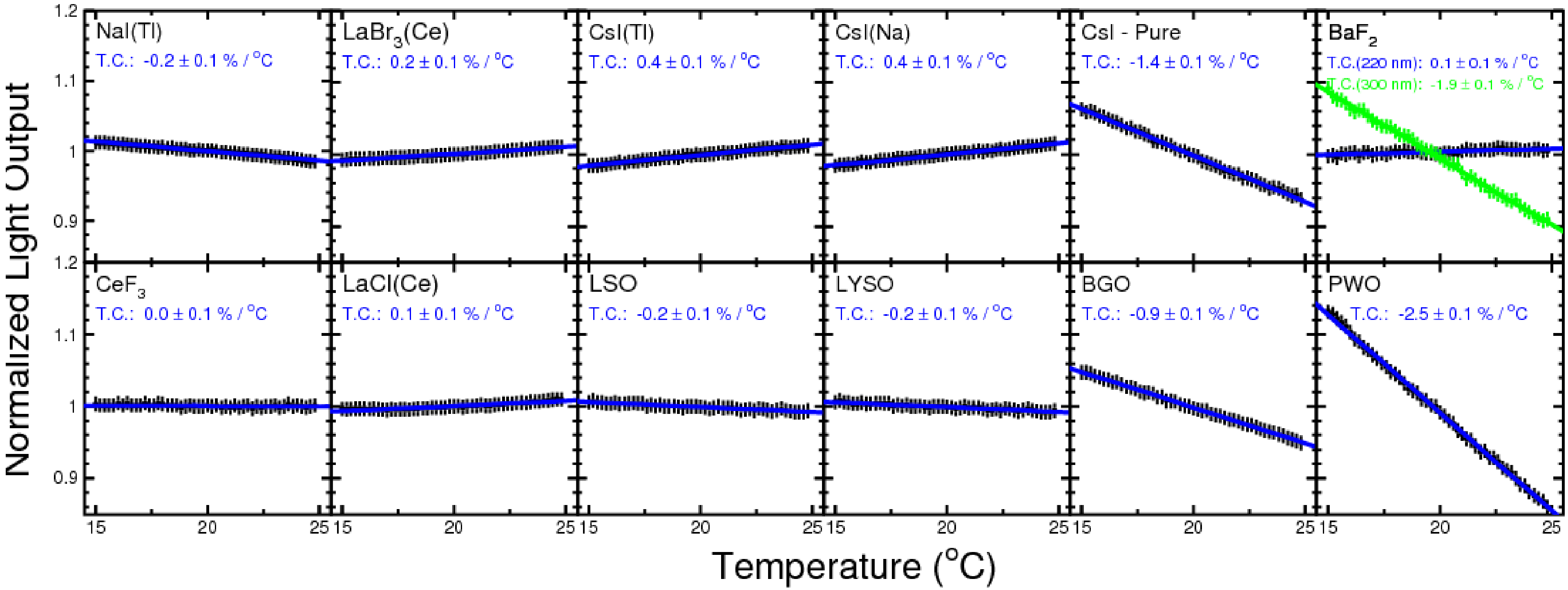
Taking out QE, L.O. of LSO/LYSO is 4/200 times BGO/PWO
Hamamatsu S8664-55 APD has QE 75% for LSO/LYSO





L.O. Temperature Coefficient

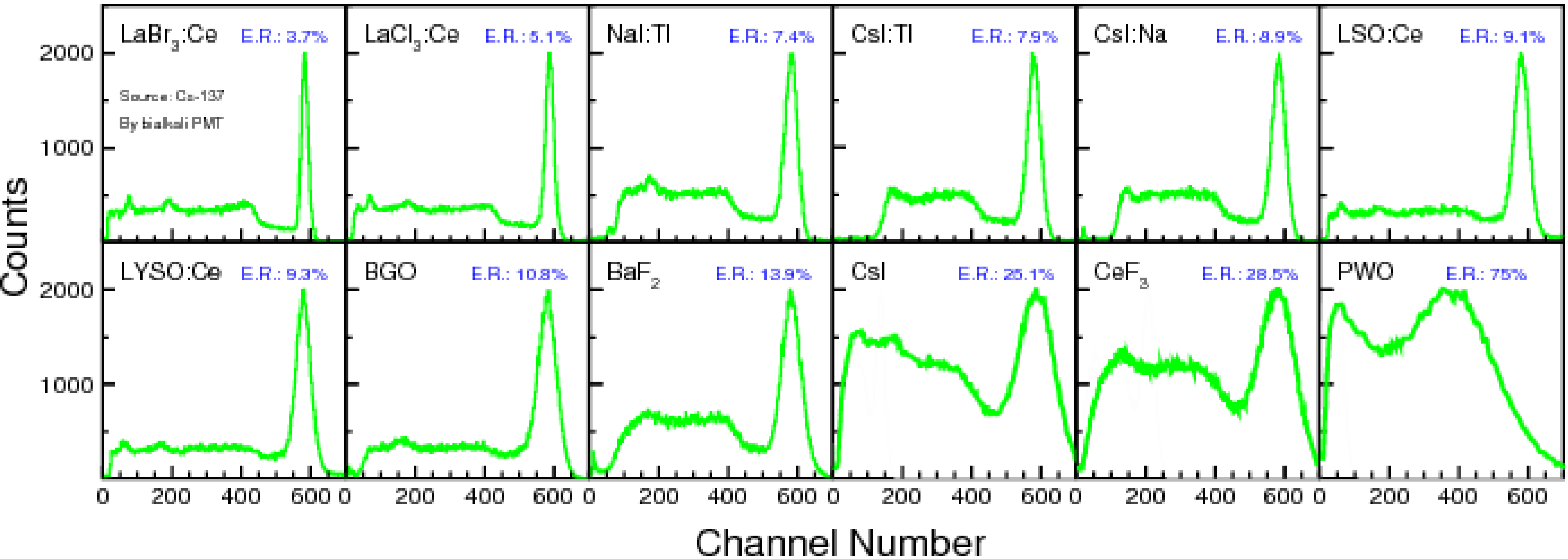
Temperature Range: 15 - 25ºC



Large temperature coefficient: CsI, BGO, BaF_2 and PWO

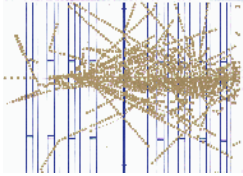
^{137}Cs FWHM Energy Resolution

3% to 80% measured with Hamamatsu R1306 PMT with bi-alkali cathode



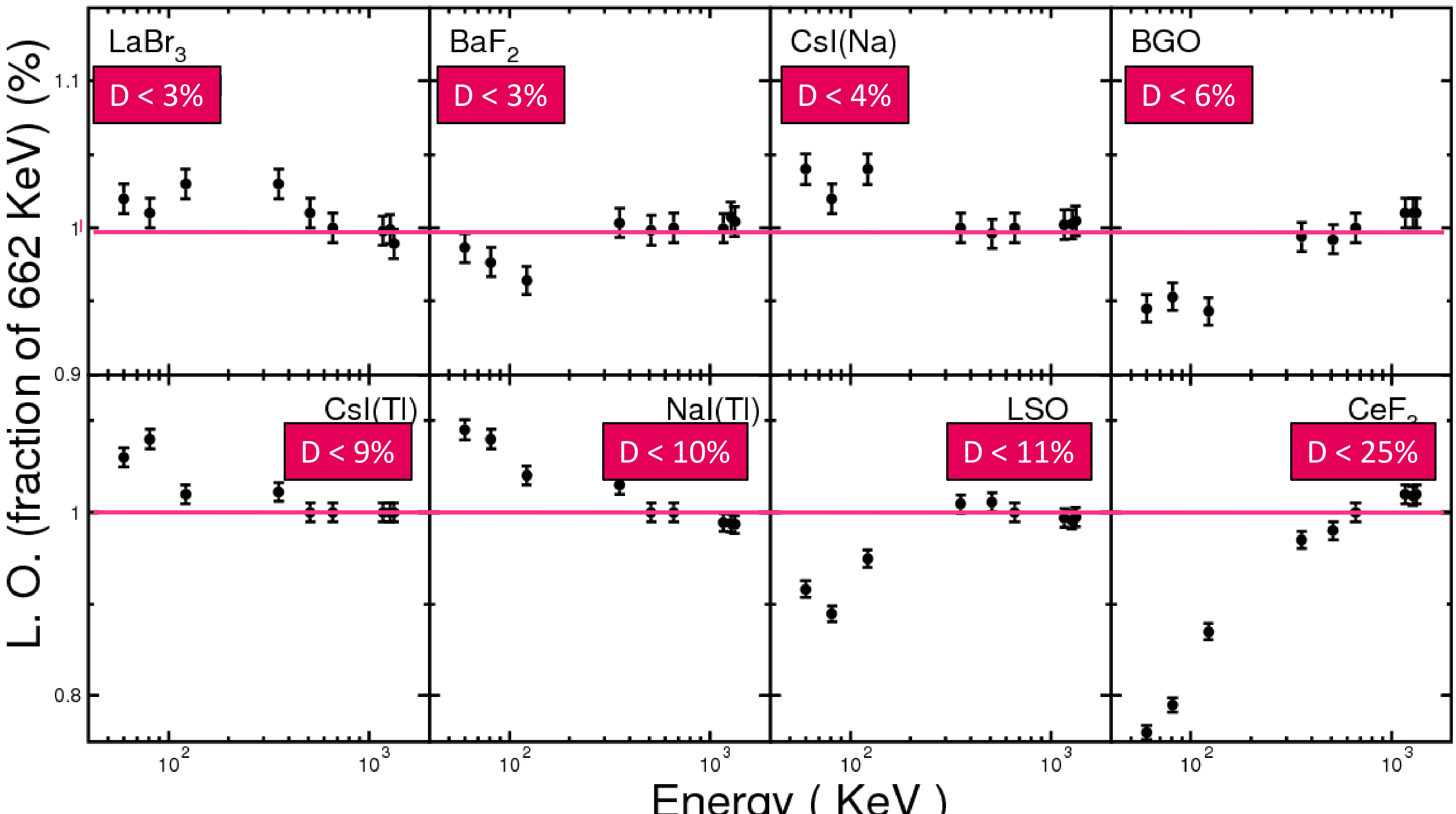
2% resolution and proportionality are important for γ–ray spectroscopy between 10 keV to 2 MeV

Low Energy Non Proportionality

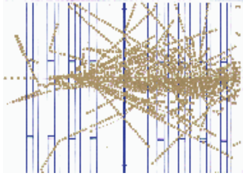


D: deviation from linearity: 60 keV to 1.3 MeV

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



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

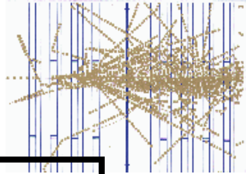
Future crystal calorimeters in HEP:

PWO for PANDA at GSI

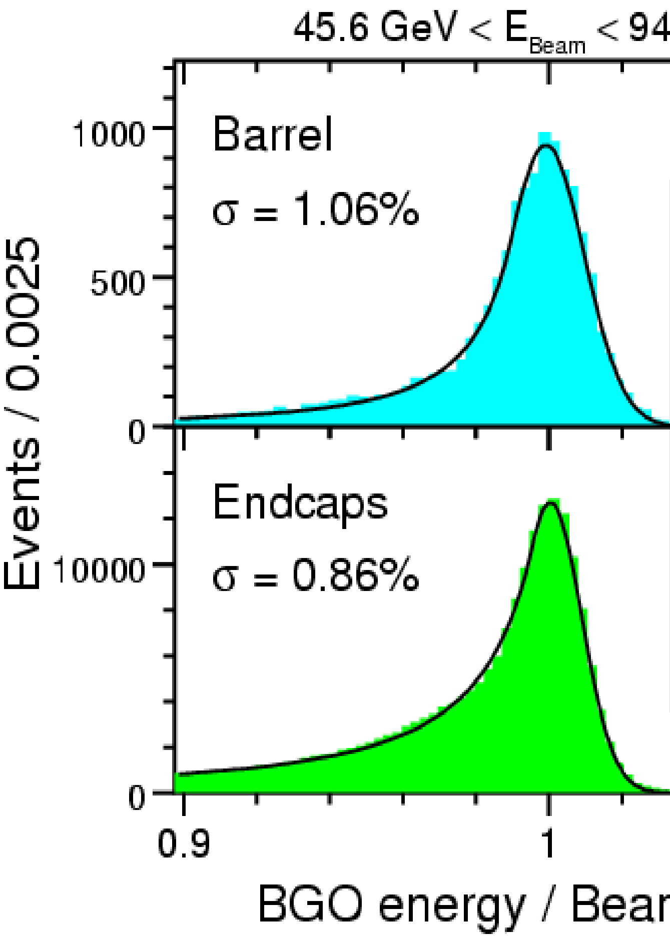
LYSO for a Super B Factory

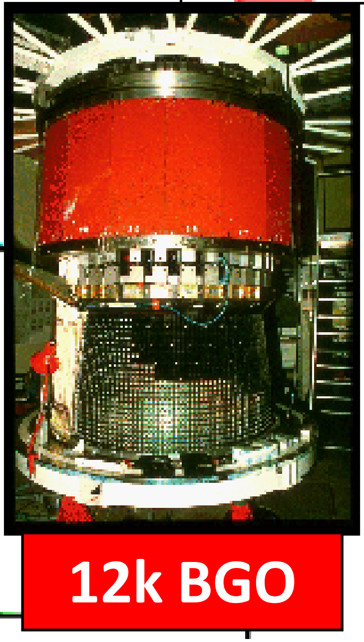
PbF_2, BGO, PWO for Homogeneous HCAL

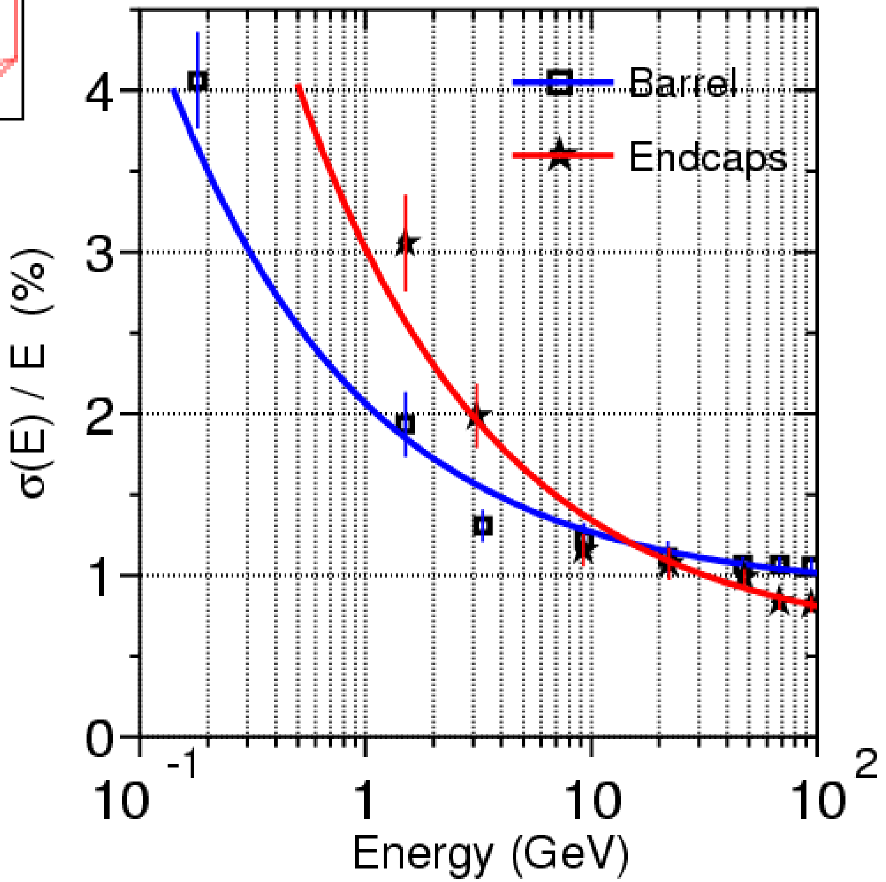
L3 BGO Resolution



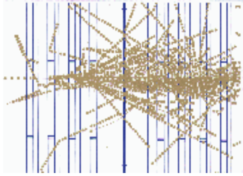
Contribution	"Radiative"+Intrinsic	Temperature	Calibration	Overall
Barrel	0.8%	0.5%	0.5%	1.07%
Endcaps	0.6%	0.5%	0.4%	0.88%



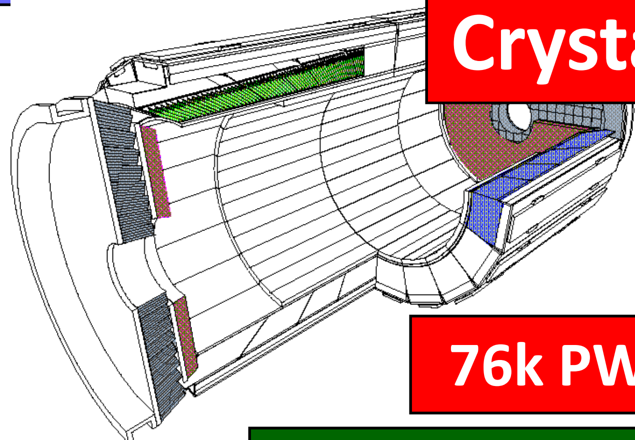




CMS PWO Resolution



Crystal Radiation Damage?



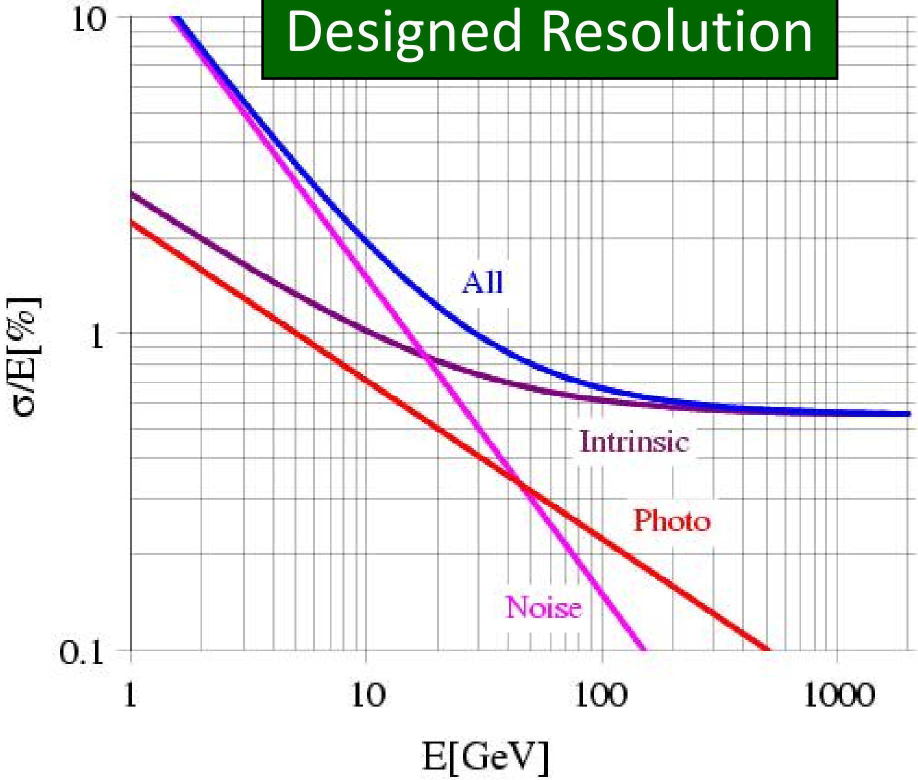
76k PWO

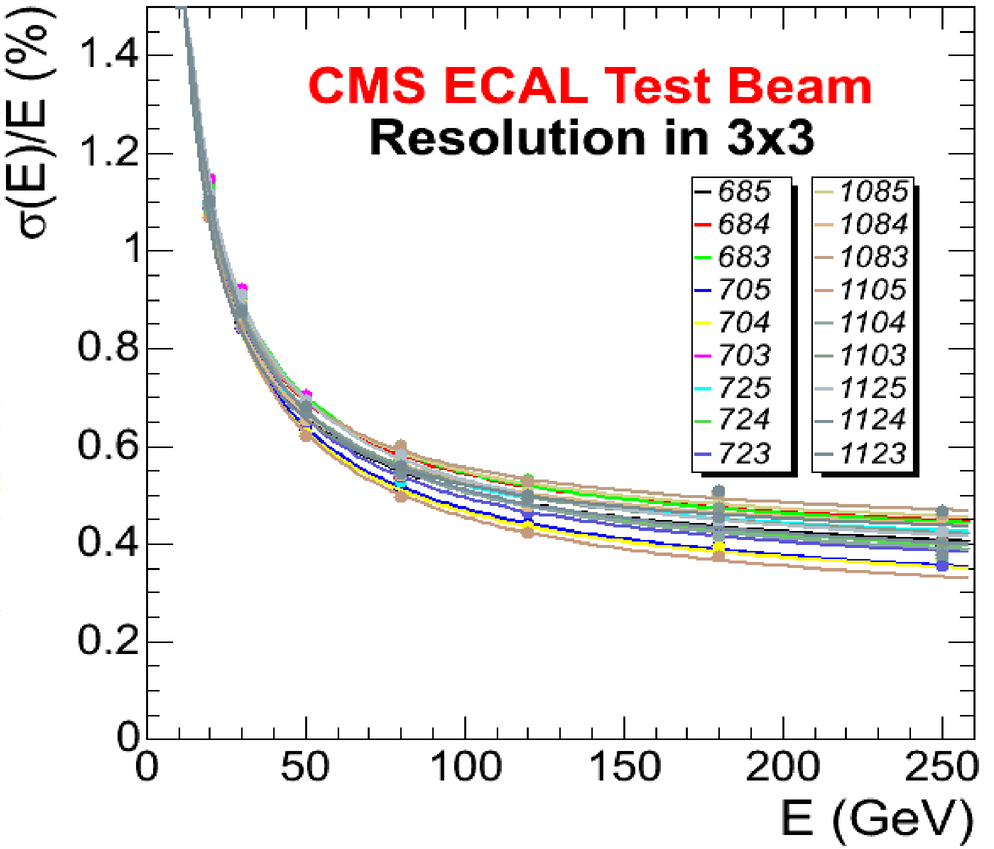
Measured Resolution

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

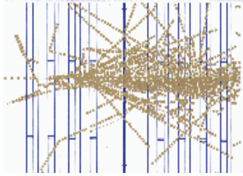
$\sigma(E)/E \sim 0.5\%$ at 120 GeV

Designed Resolution



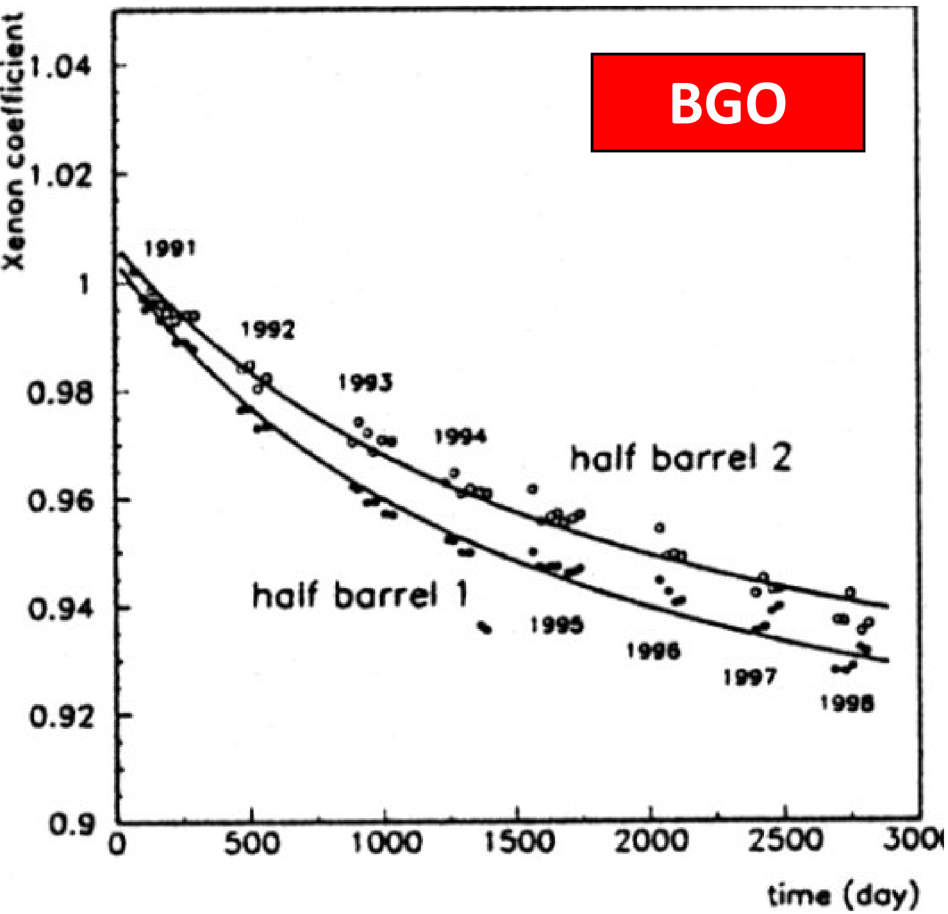


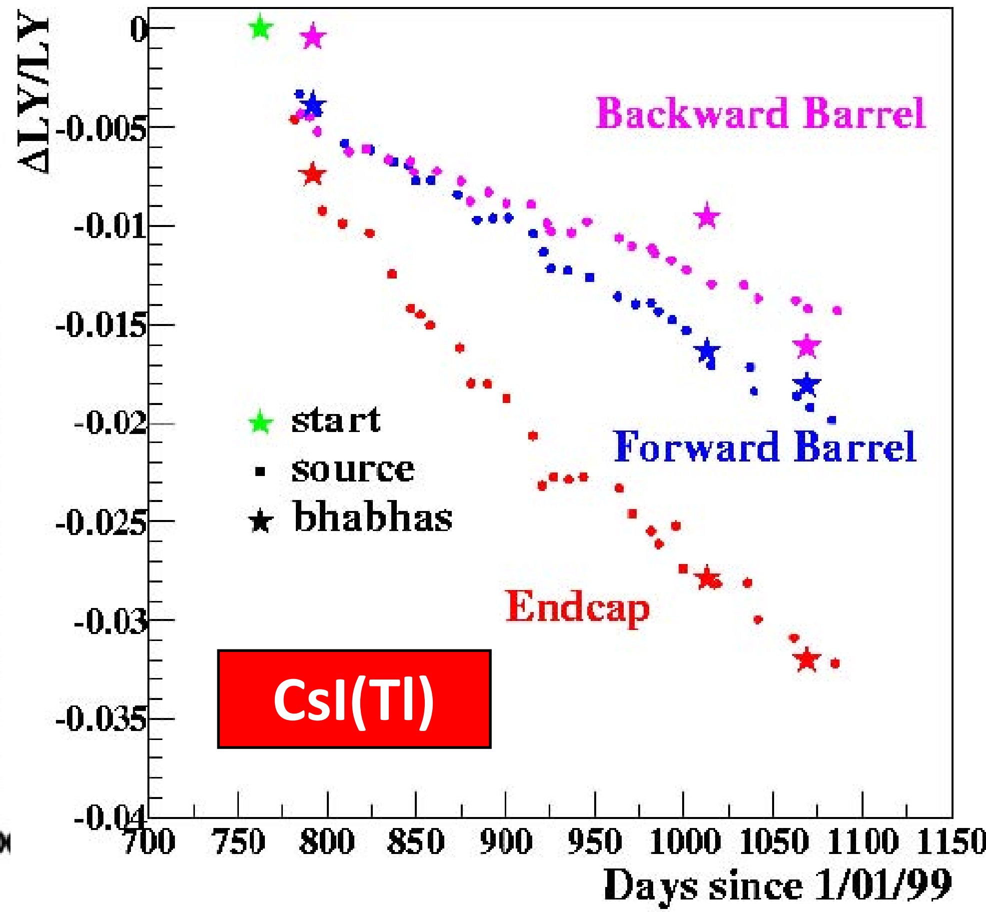
Crystal Degradation *in situ*



L3 BGO degrades 6 – 7% in 7 years

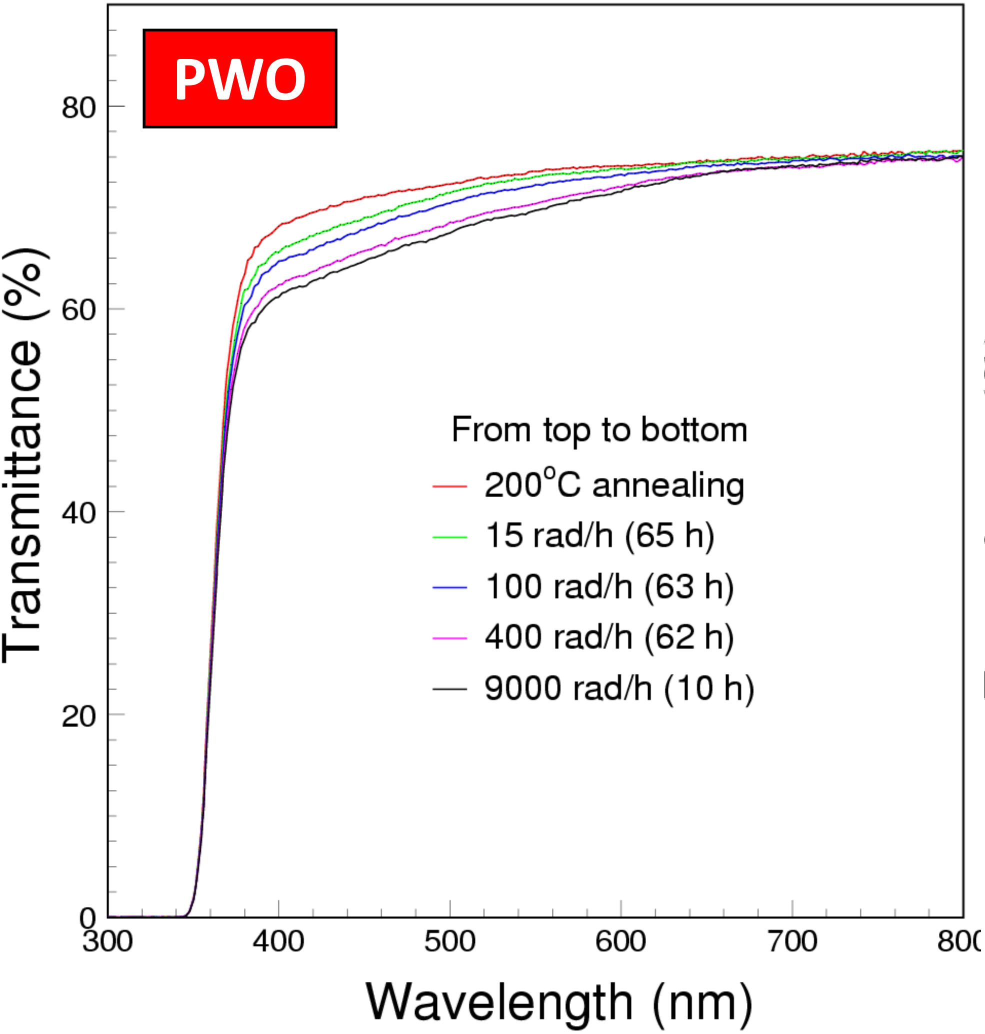
***BaBar* CsI(Tl): 1 - 3 % per year**

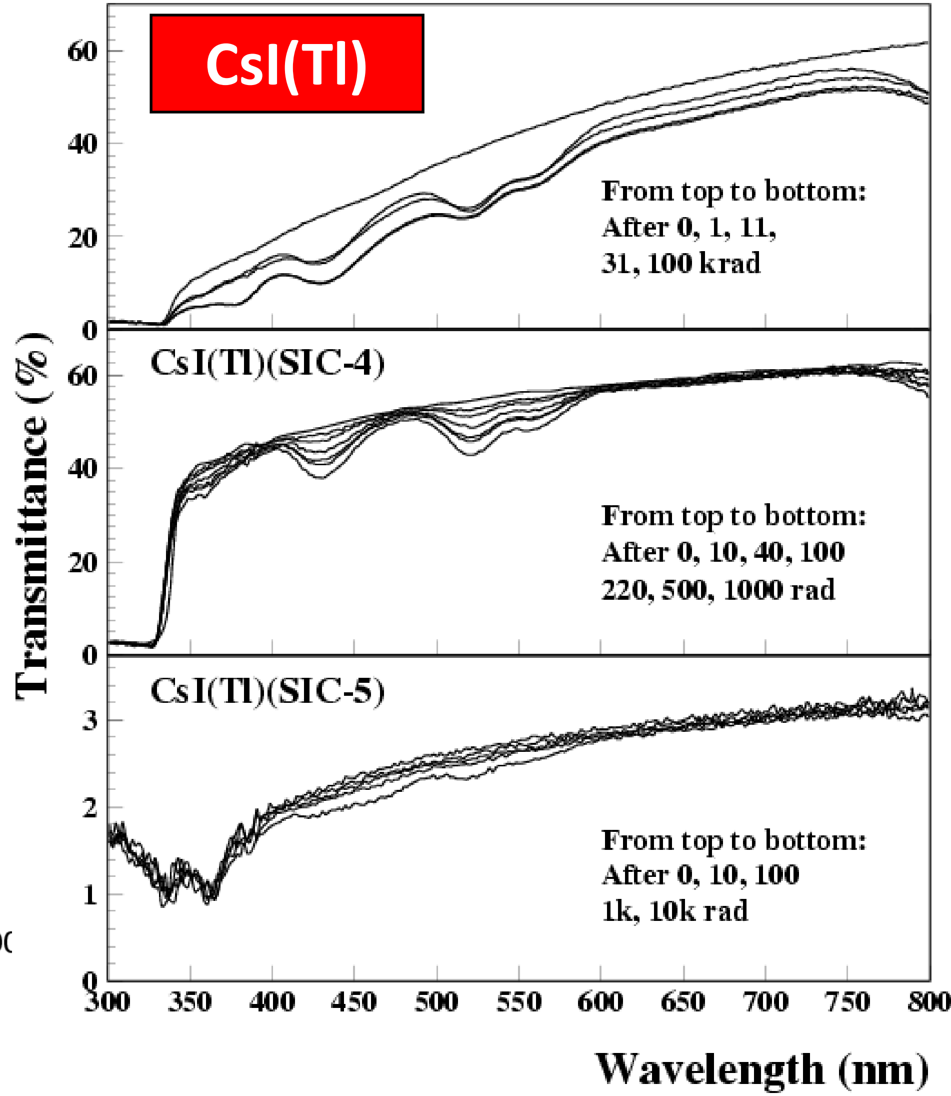


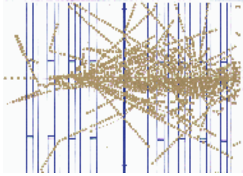


Radiation Induced Absorption

Measured with Hitachi U-3210 Photospectrometer







Dose Rate Dependence

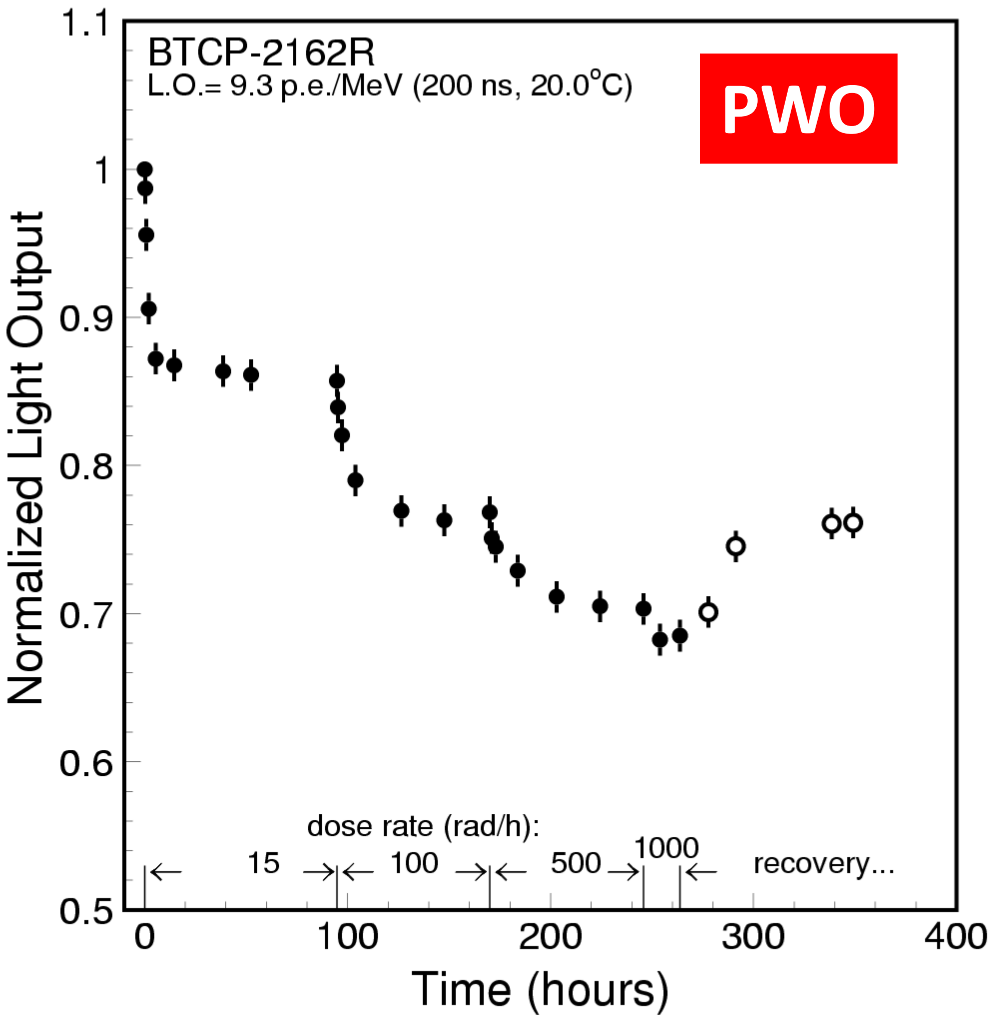
IEEE Trans. Nucl. Sci., Vol. 44 (1997) 468-476

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

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

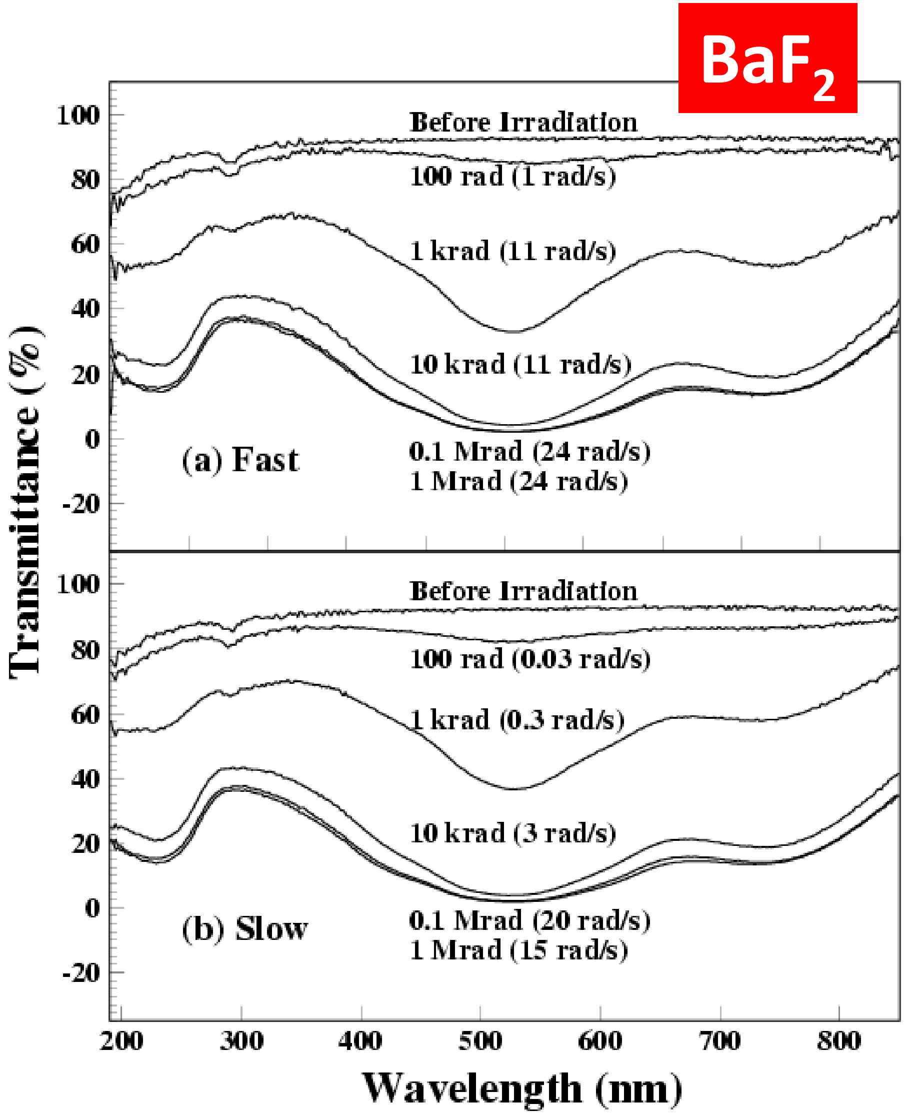
- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of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

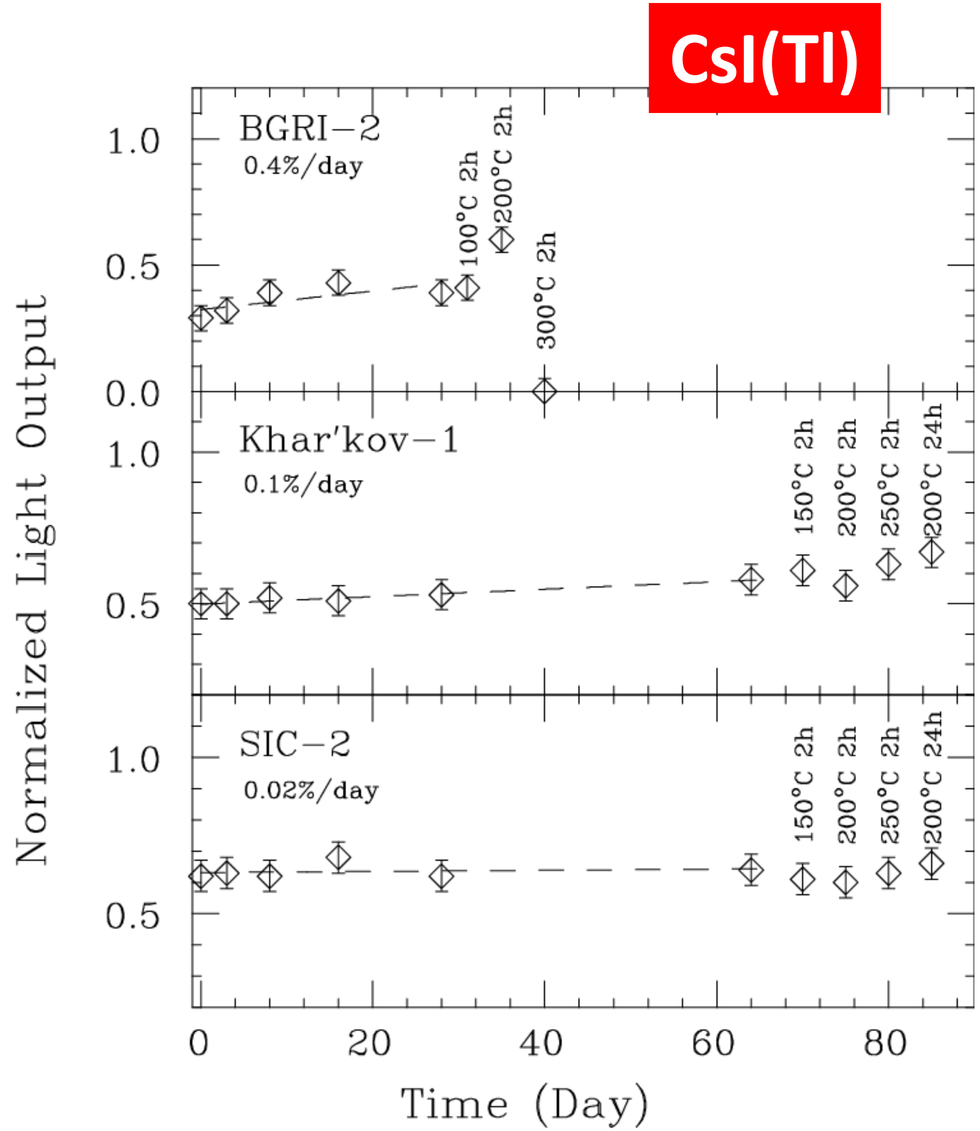
$$D_{eq} = \sum_{i=1}^{n}\frac{b_i R D_i^{all}}{a_i + b_i R}$$



No Dose Rate Dependence

No recovery: no dose rate dependence





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

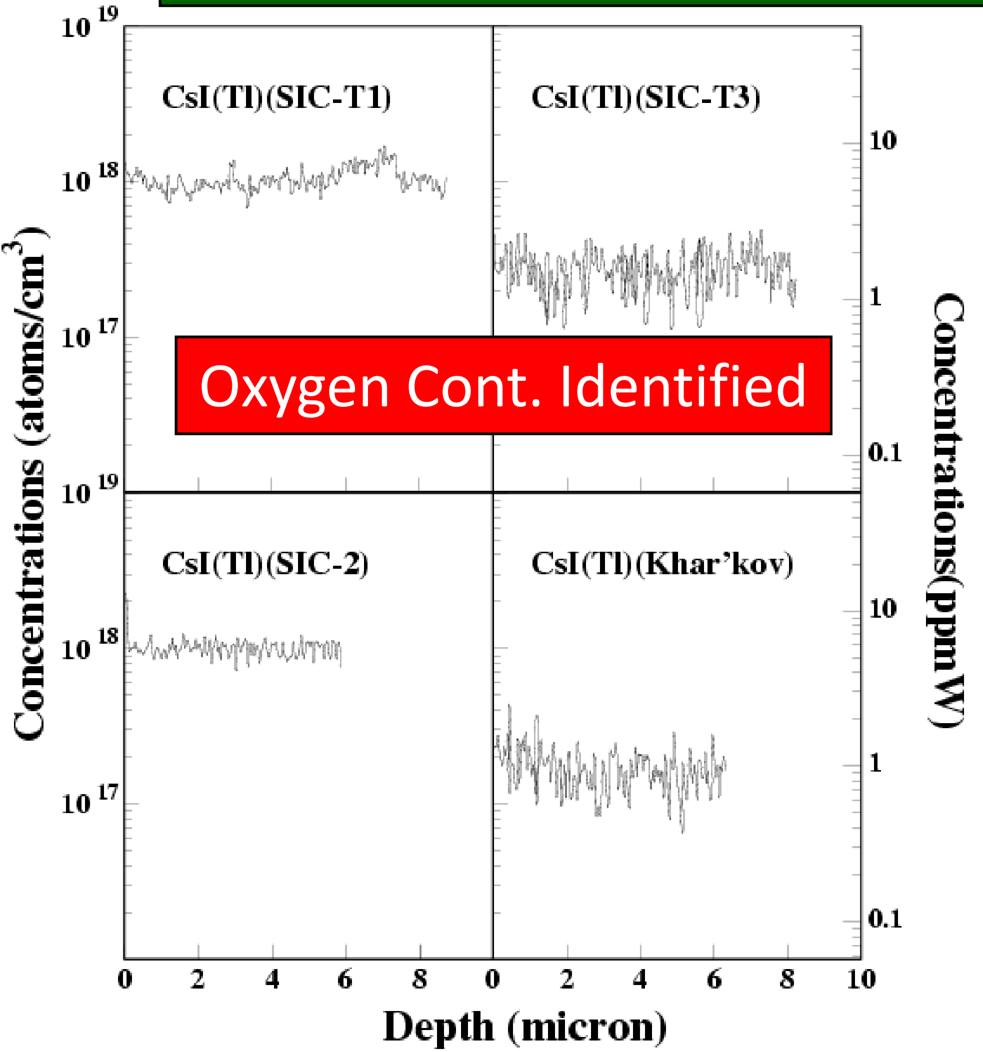
CsI(Tl) Damage Mechanism

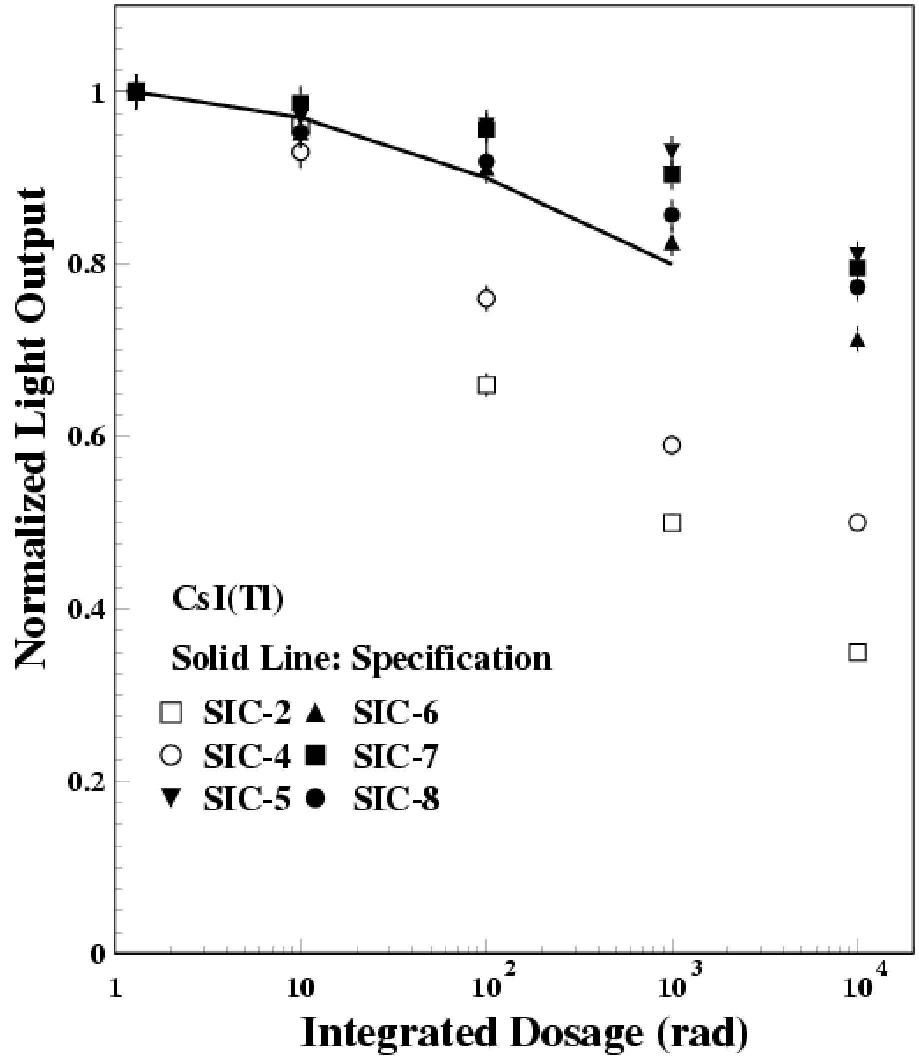
Nucl. Instr. And Meth. A340 (1994) 442

- **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).

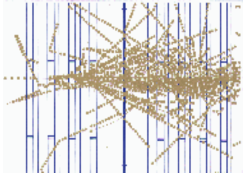
SIMS Study & CsI(Tl) Improvement

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





PWO Radiation Damage Mechanism

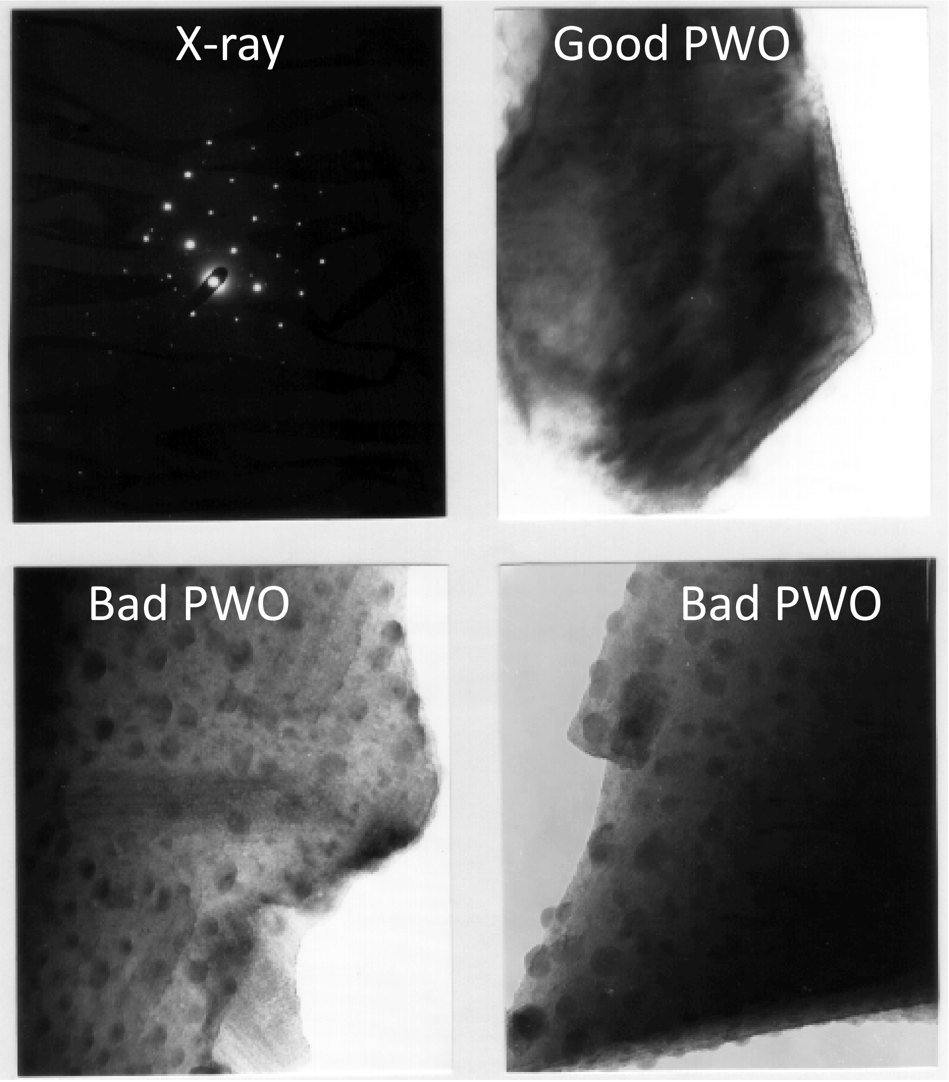


Nucl. Instr. And Meth. A413 (1998) 297

- 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

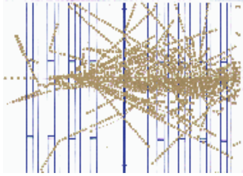
Element	Black Spot	Peripheral	$Matrix_1$	$Matrix_2$
O	1.5	15.8	60.8	63.2
W	50.8	44.3	19.6	18.4
Pb	47.7	39.9	19.6	18.4

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

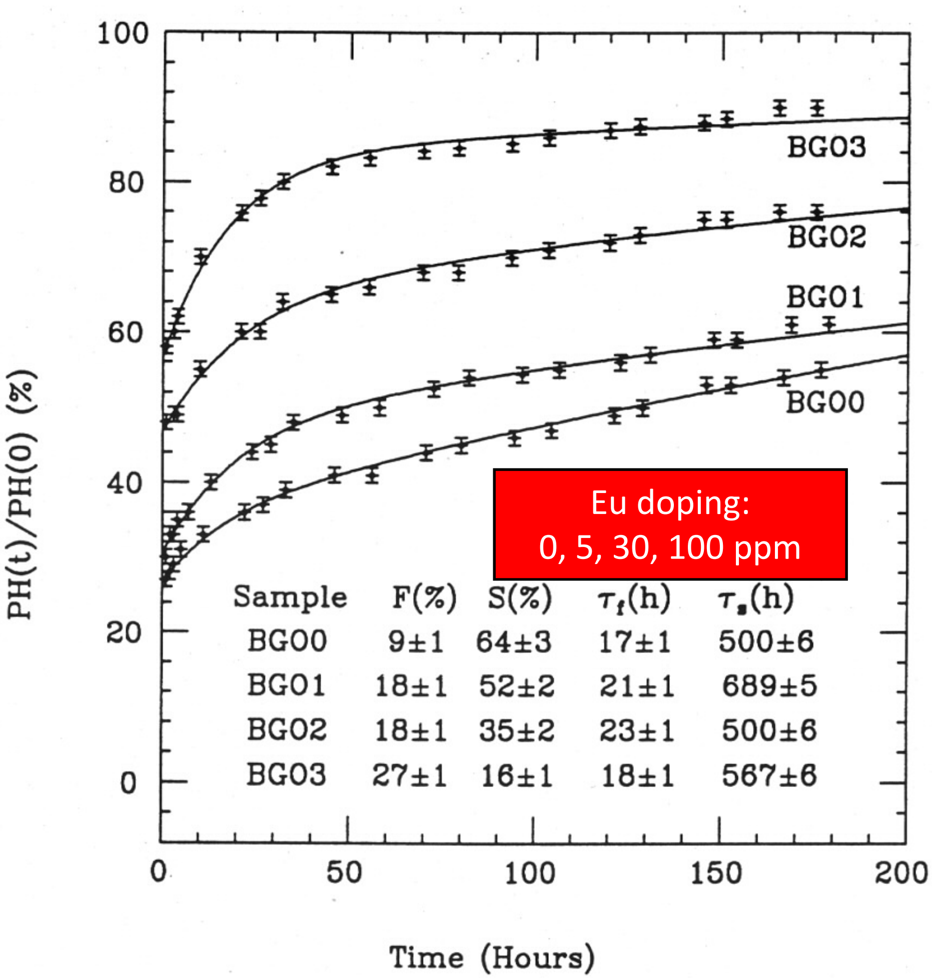
Oxygen Vacancies Identified

BGO/PWO Quality Improvement



Nucl. Instr. and Meth. A302 (1991)

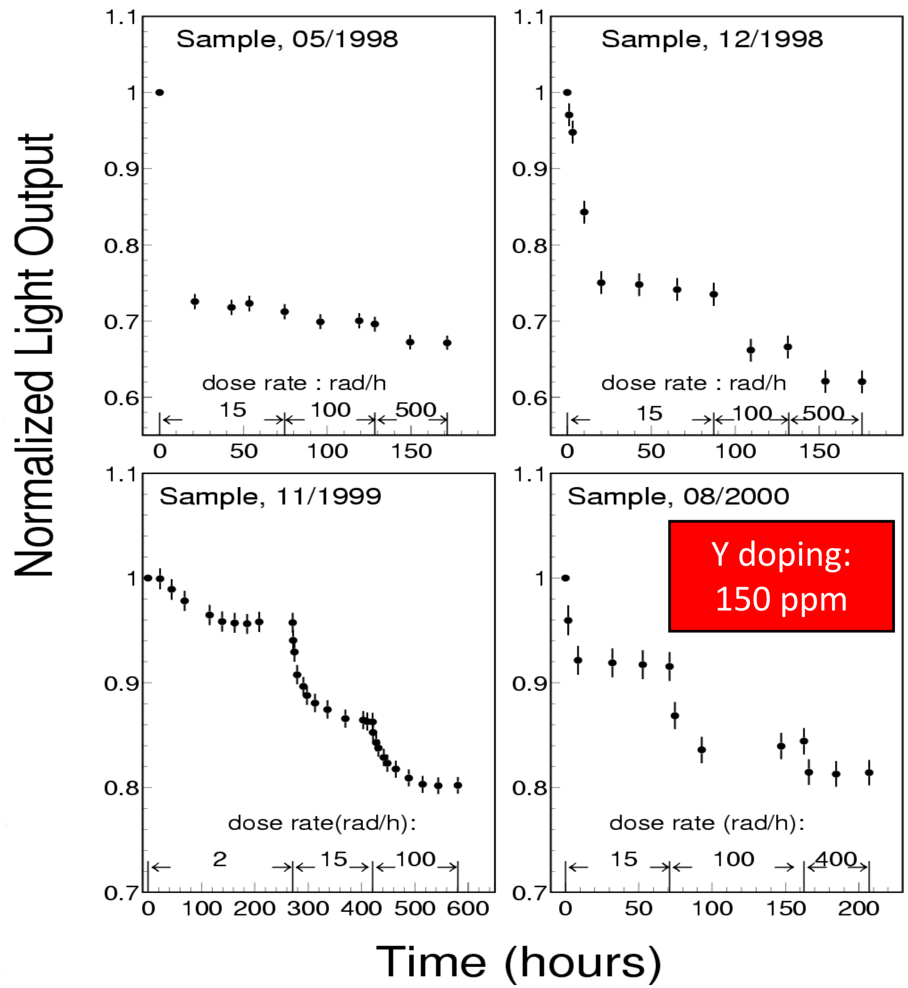
BGO damage recovery after 2.5 krad



Eu doping:
0, 5, 30, 100 ppm

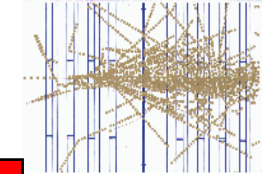
Nucl. Instr. and Meth. A480 (2002) 470

PWO damage at different dose rate

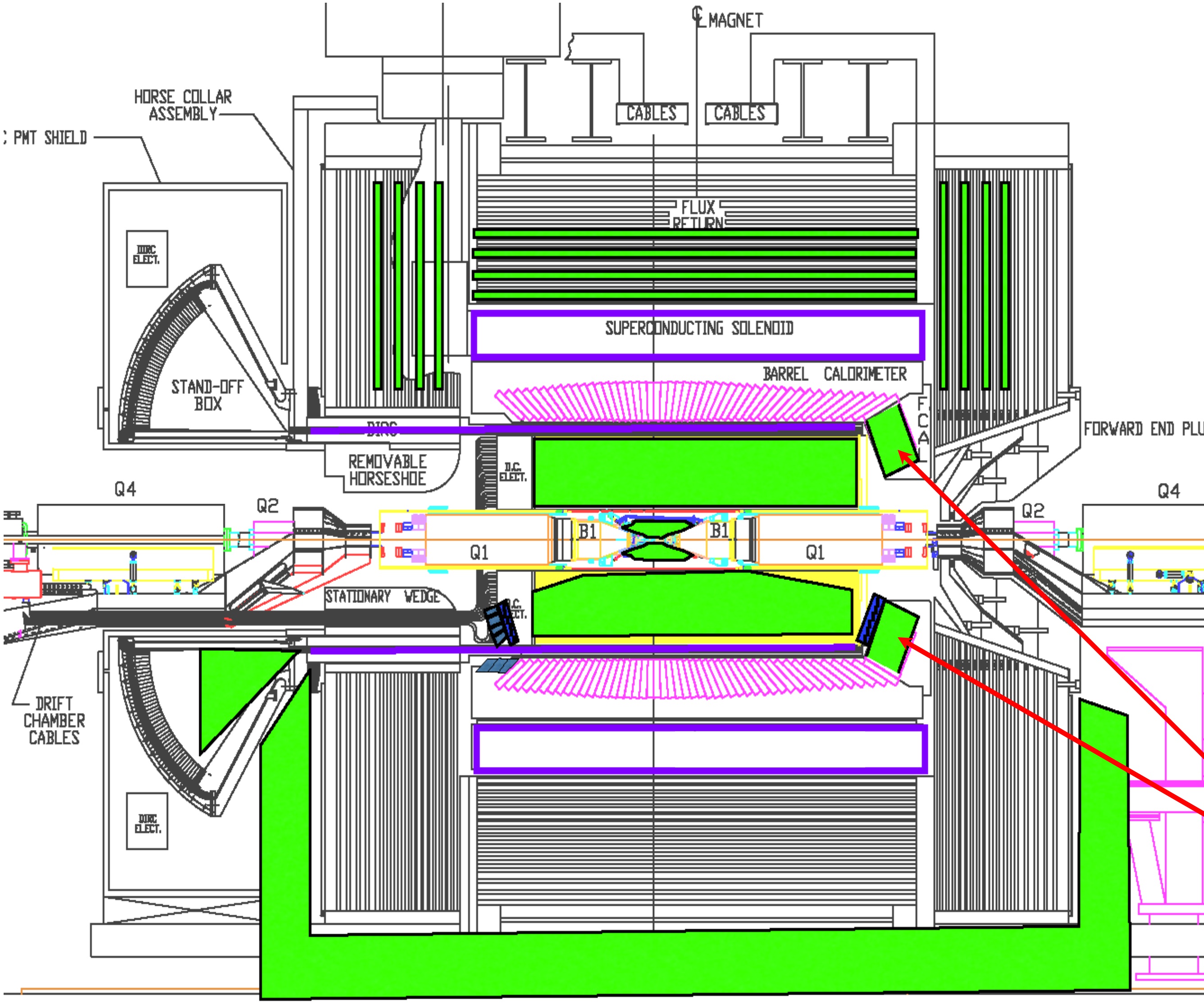


Y doping:
150 ppm

LYSO Endcap for Super*B*



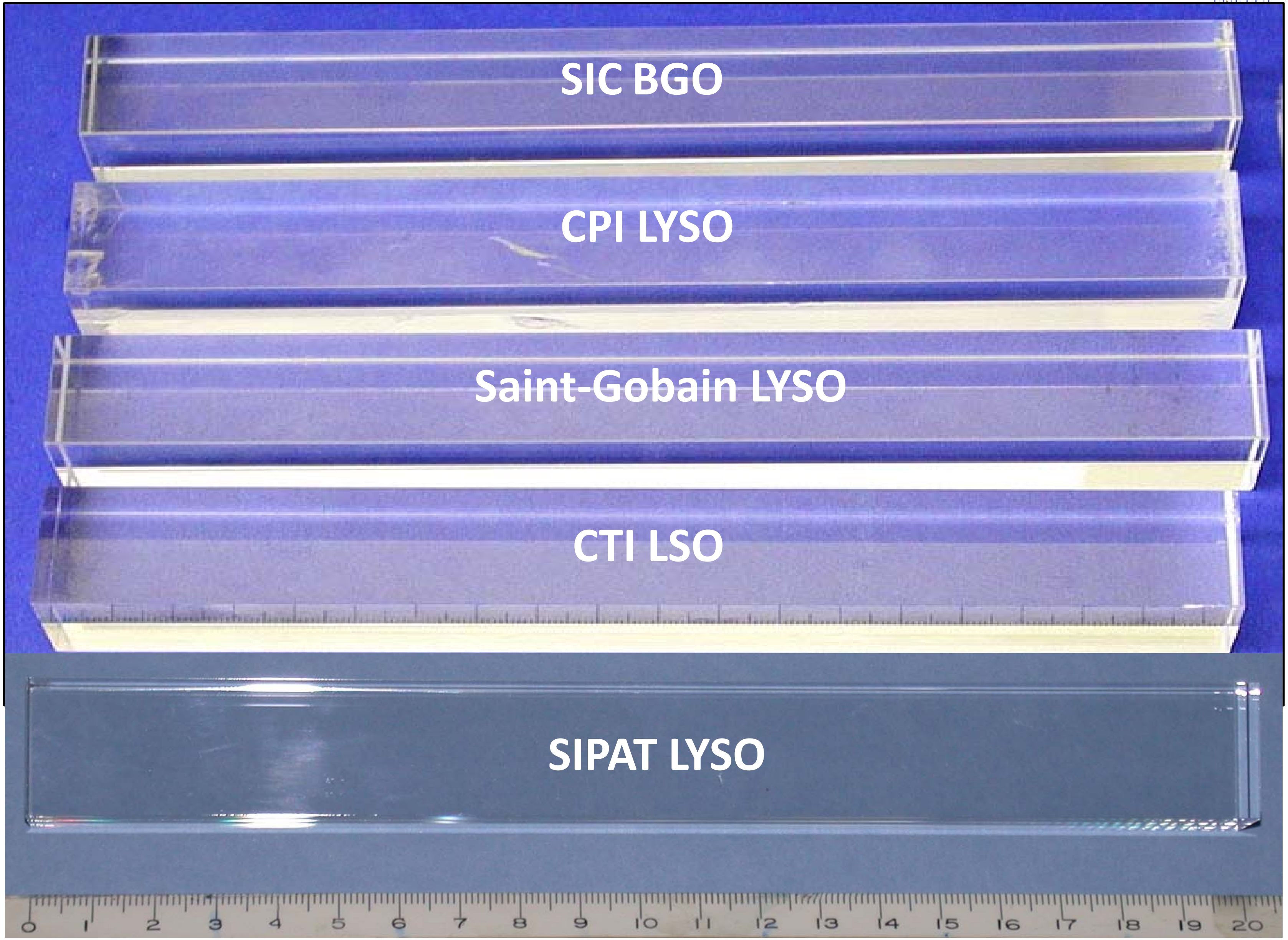
SuperB Conceptual Design Report, INFN/AE-07/2, March (2007)



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

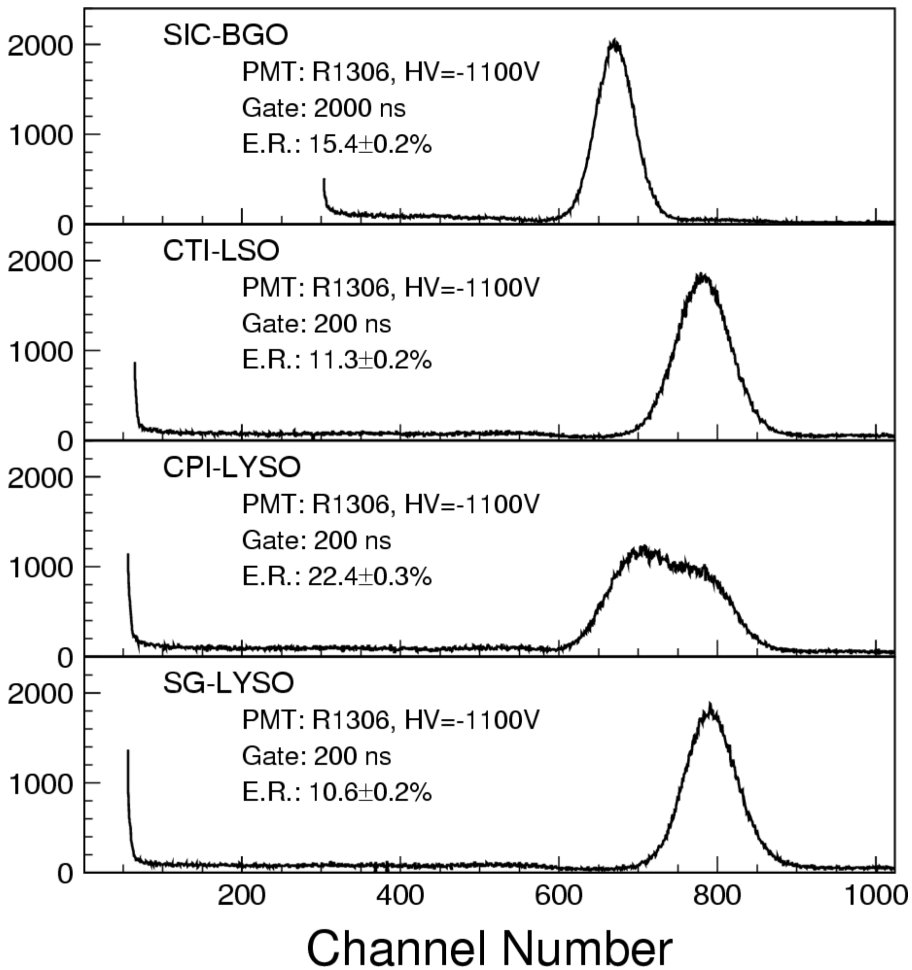
Need fast detector with low noise at the endcap

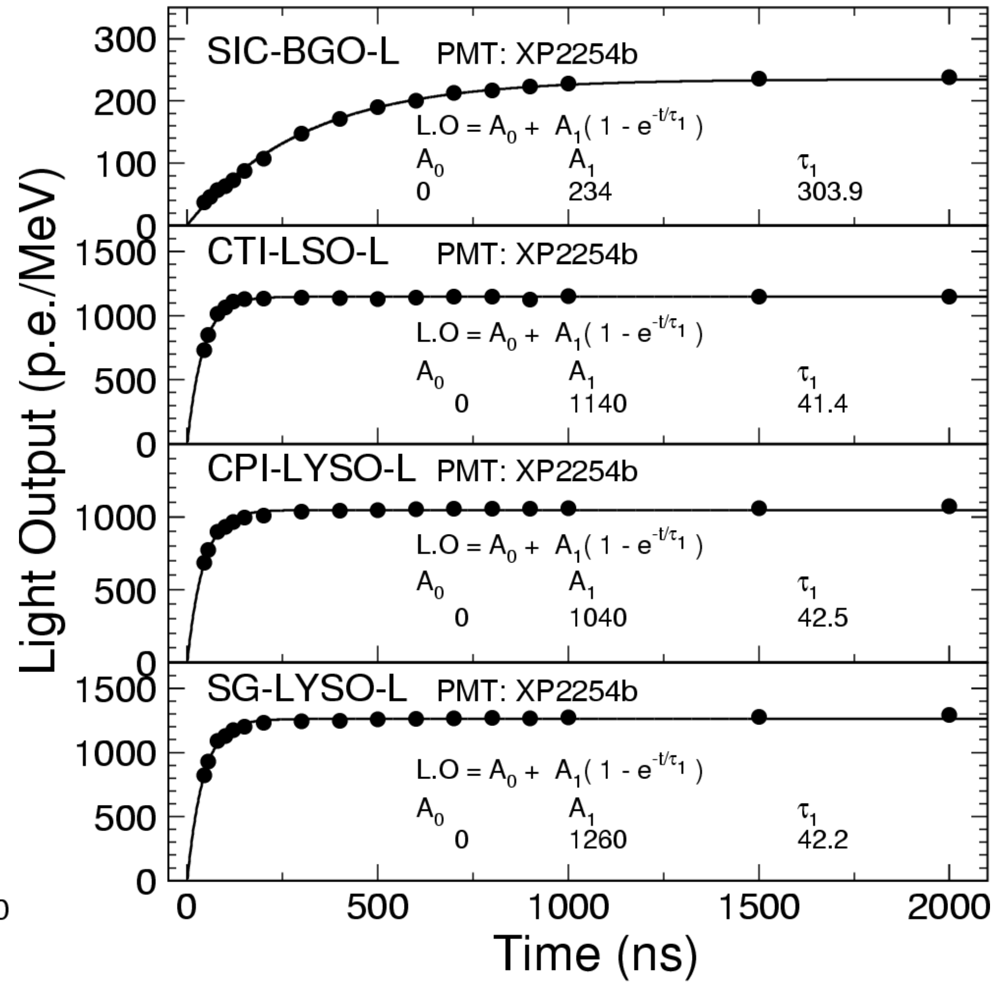
2.5 x 2.5 x 20 cm (18 X_0) Samples

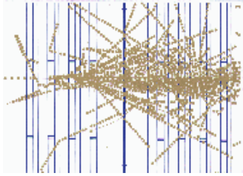


LSO/LYSO with PMT Readout

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

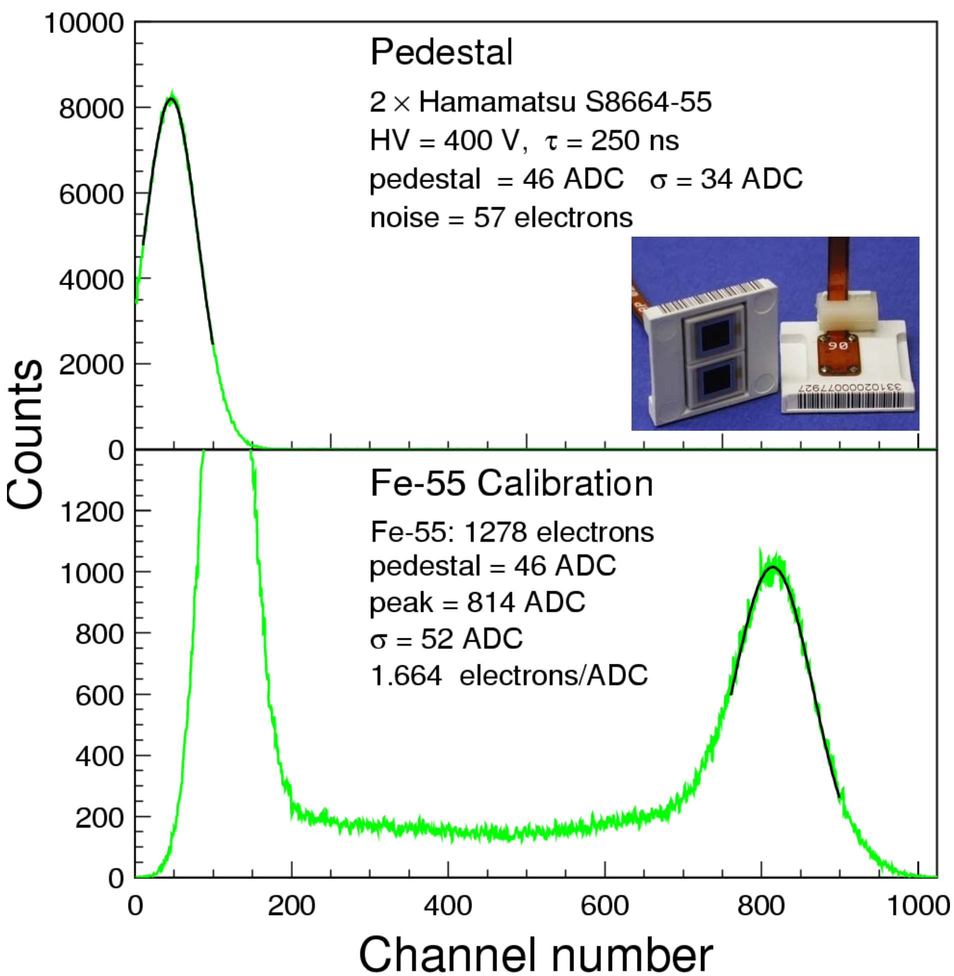


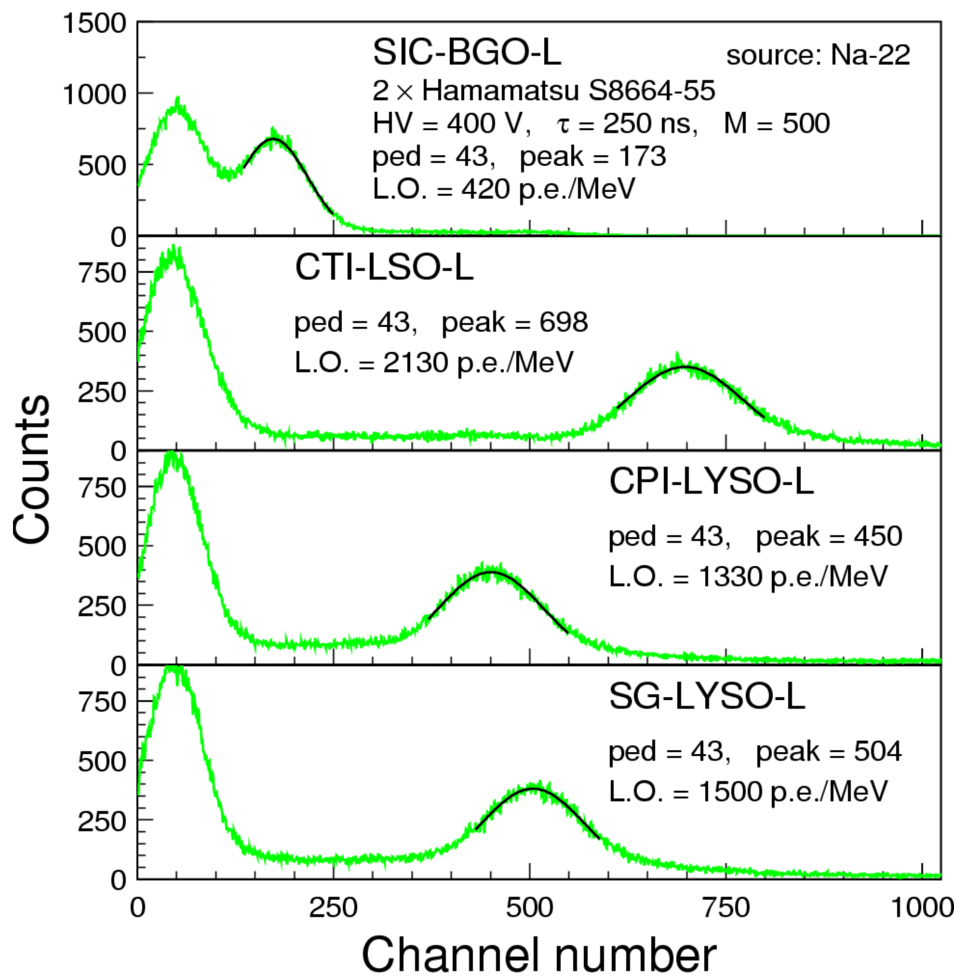




LSO/LYSO with APD Readout

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

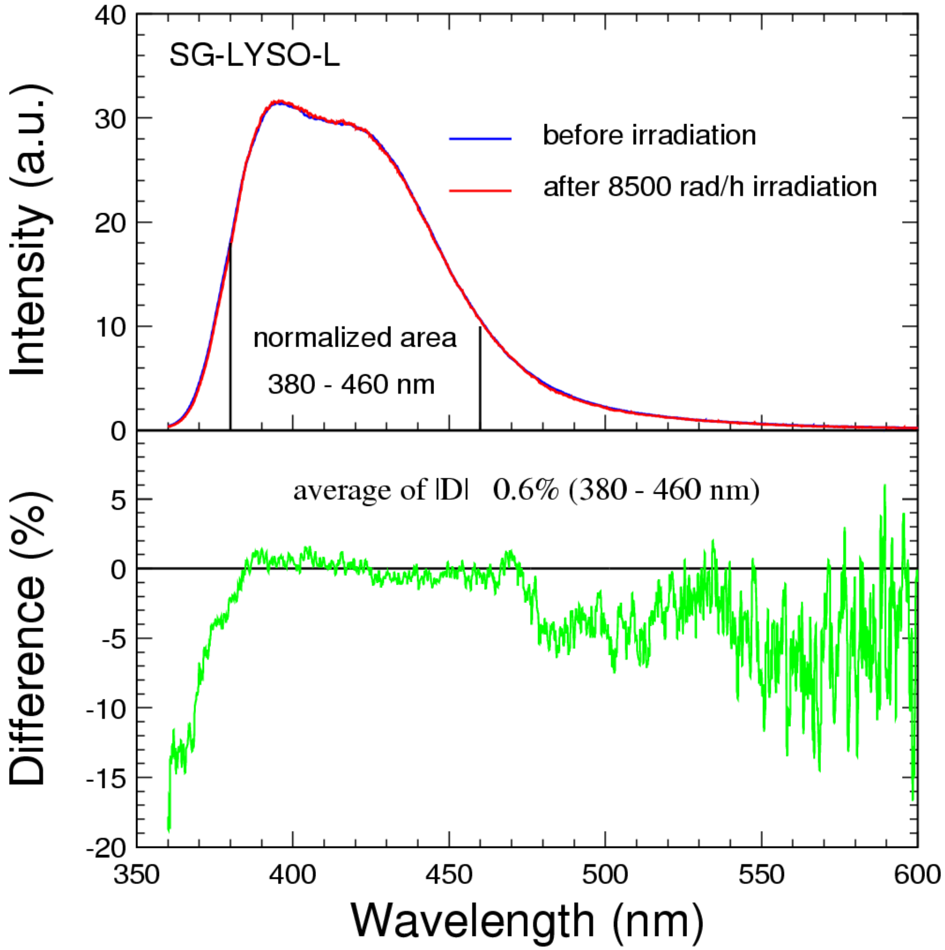


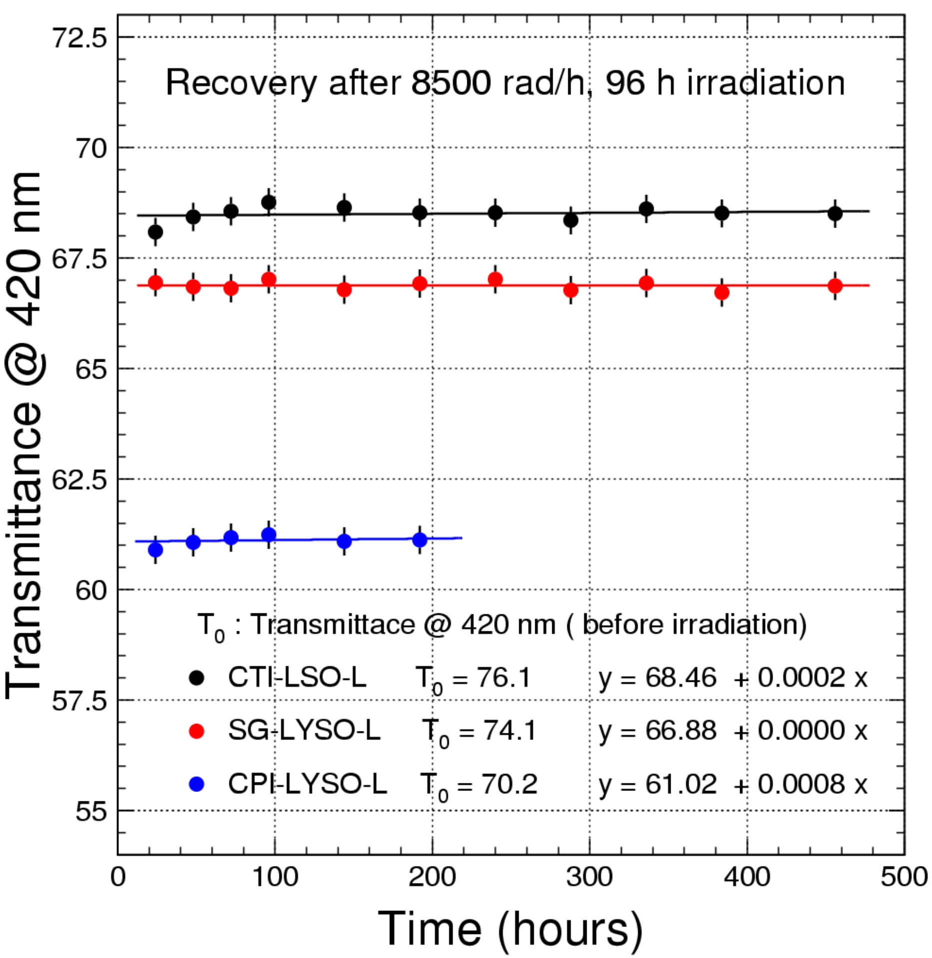


γ-Ray Induced Damage

No damage in Photo-Luminescence

Transmittance recovery slow



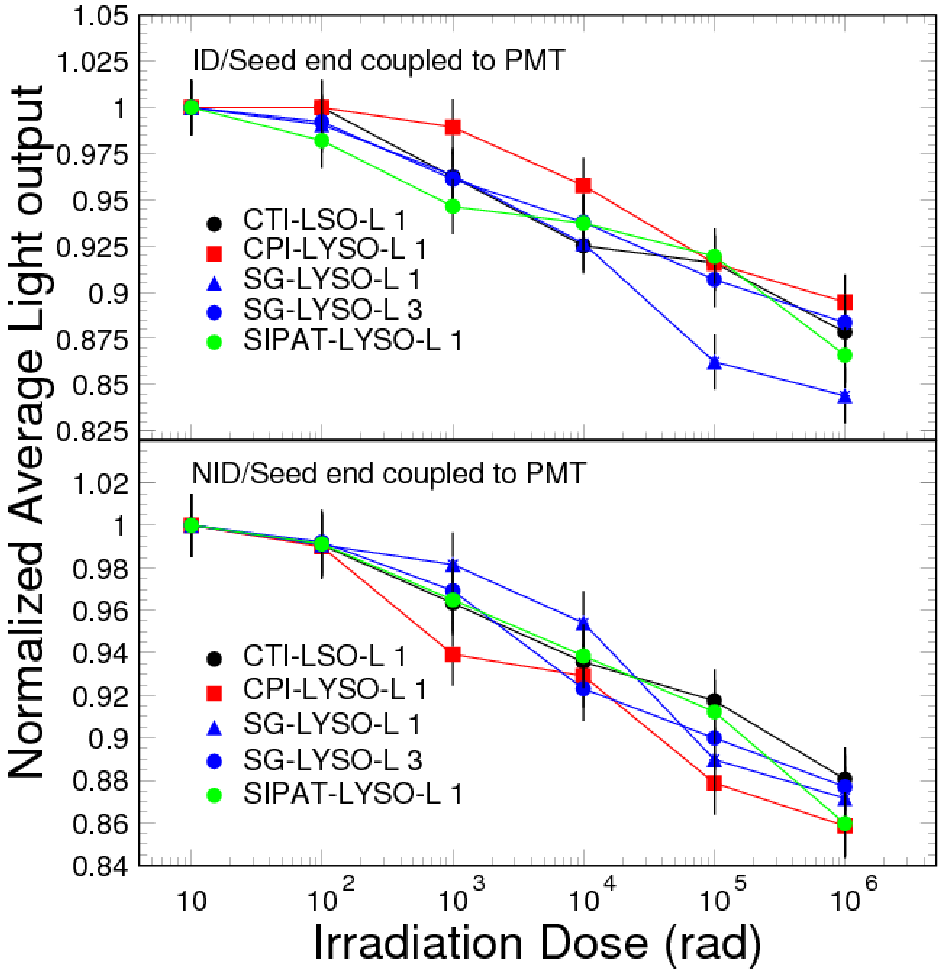


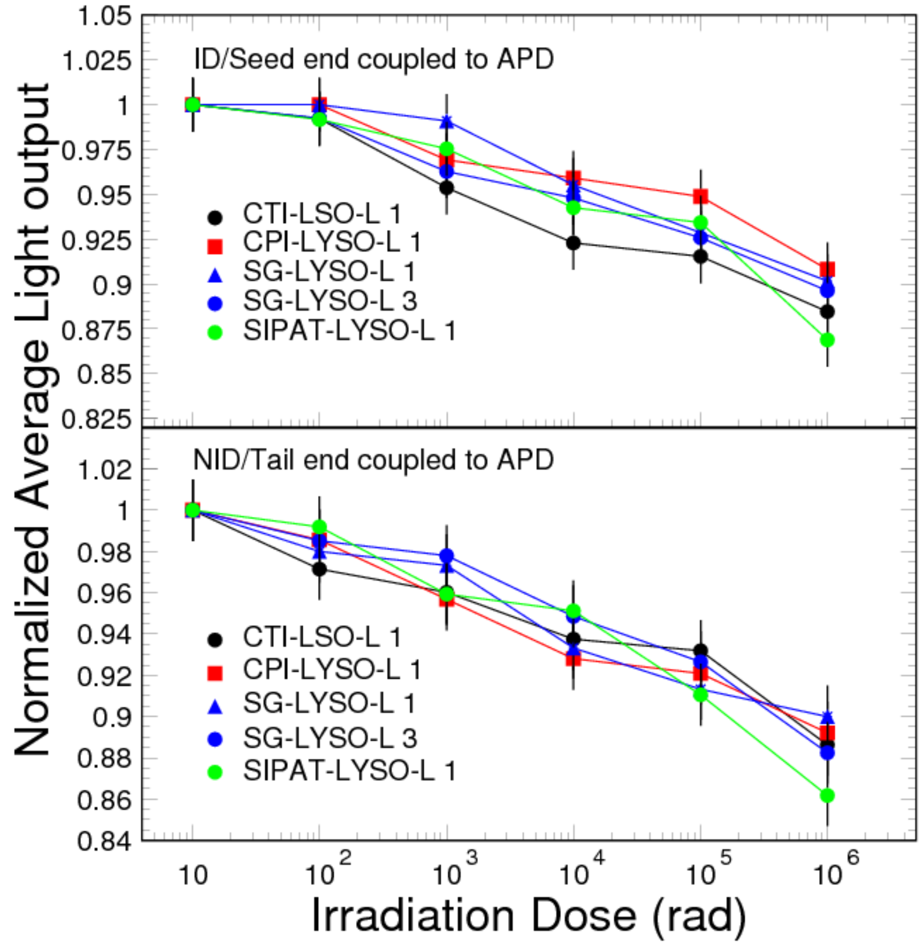
γ-Ray Induced L.O. Damage

All samples show consistent radiation resistance

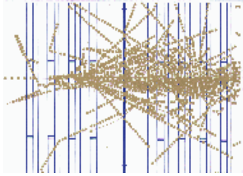
10% - 15% loss @ 1 Mrad by PMT

9% - 14% loss @ 1 Mrad by APD



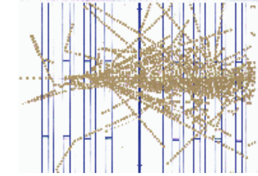


LSO/LYSO ECAL Performance

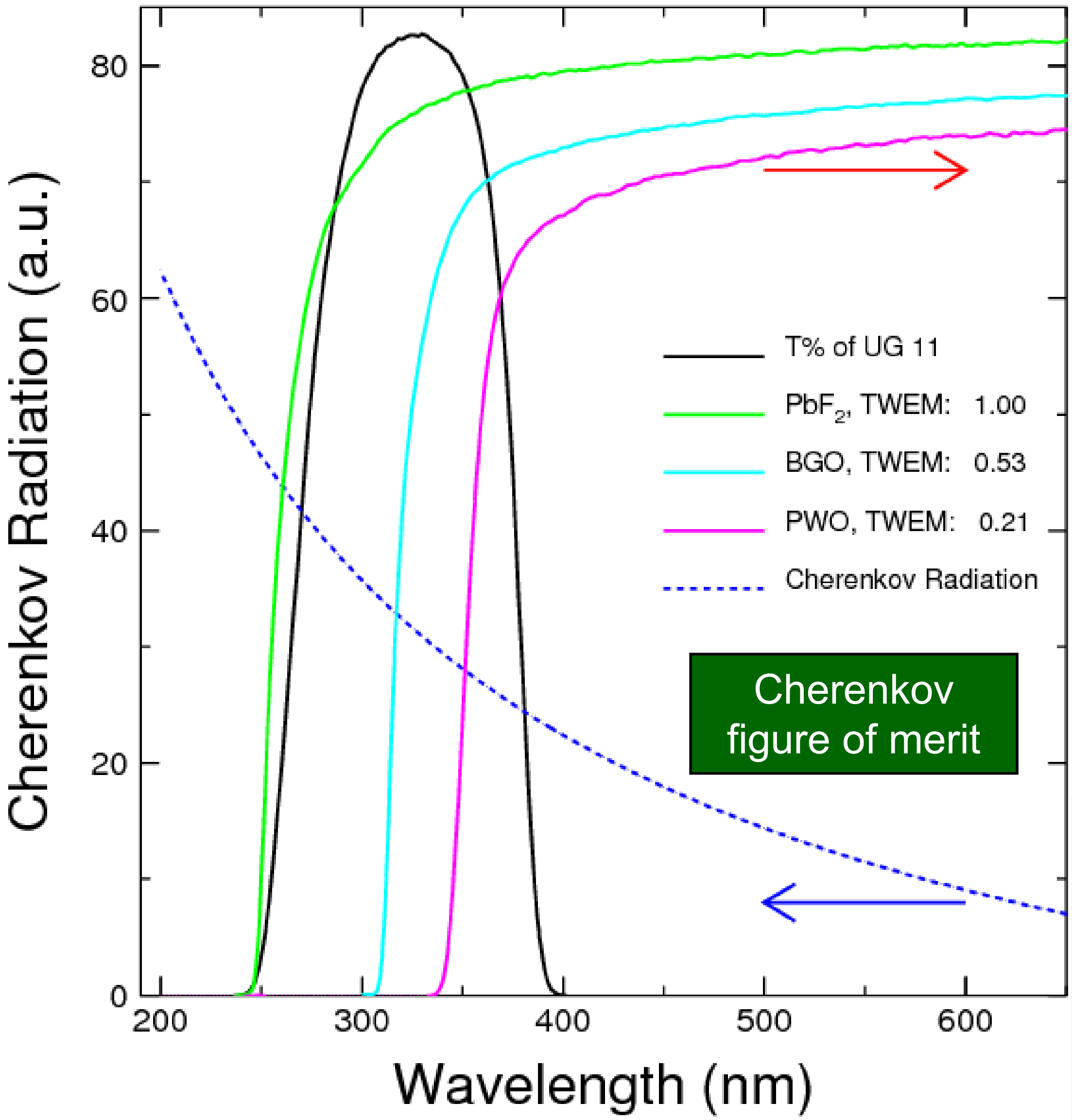


- Less demanding to the environment because of small temperature coefficient.
- Radiation damage is less an issue as compared to other crystals.
- A better energy resolution, $\sigma(E)/E$, at low energies than L3 BGO and CMS PWO because of its high light output and low readout noise:

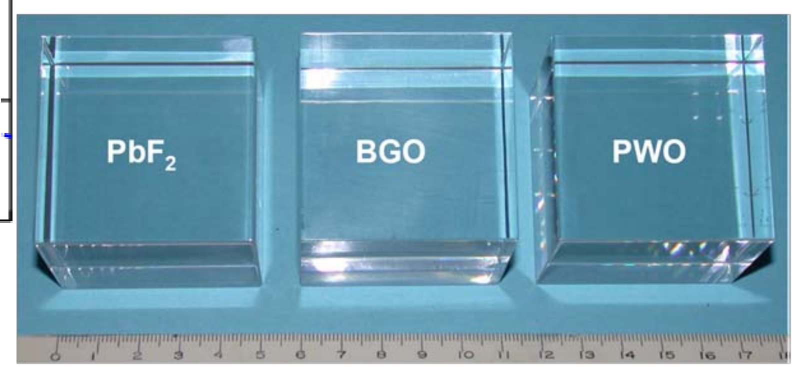
$$2.0\% / \sqrt{E} \oplus 0.5\% \oplus .001/E$$



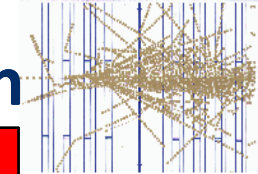
Homogeneous HCAL



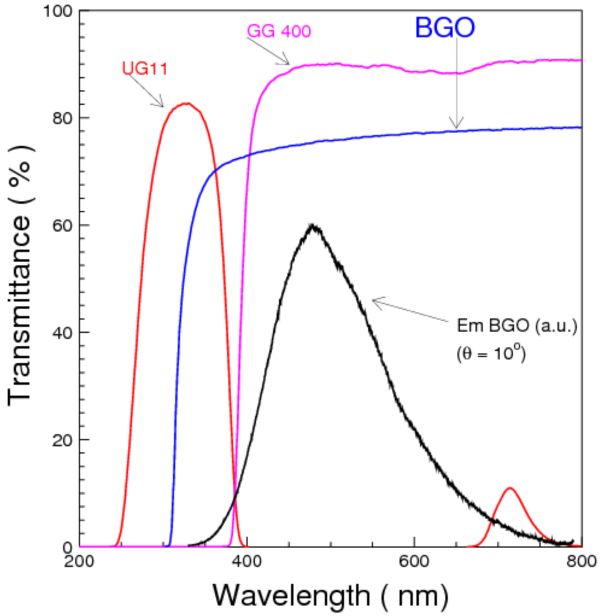
Measure both Cherenkov and scintillation light independently to achieve the best hadronic energy resolution by compensation.

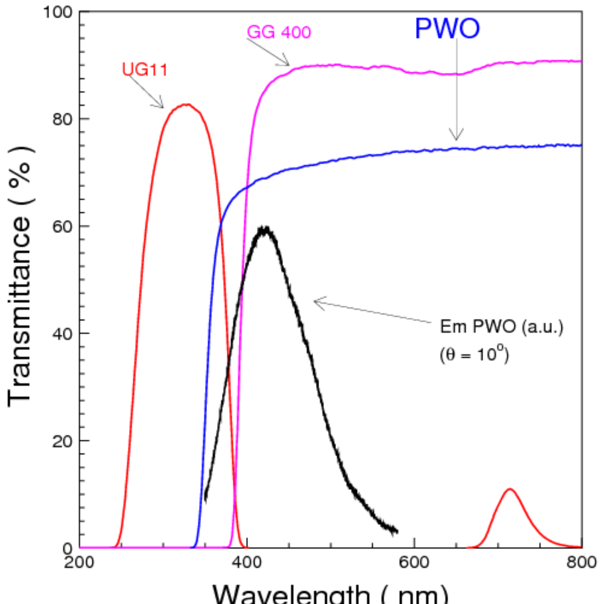


Spectral Separation of Cherenkov & Scintillation

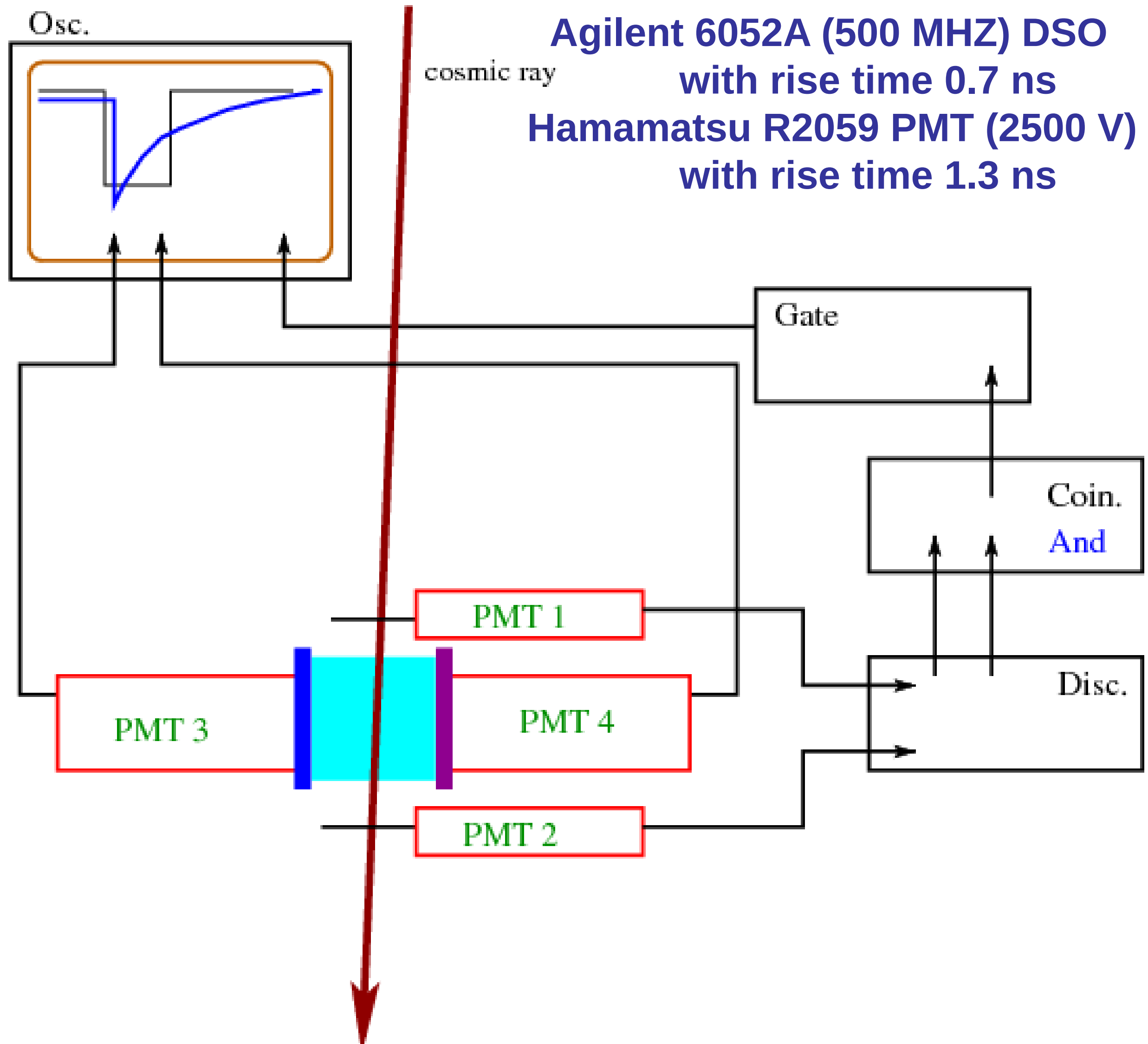


Filters UG11 and GG 400 are effective



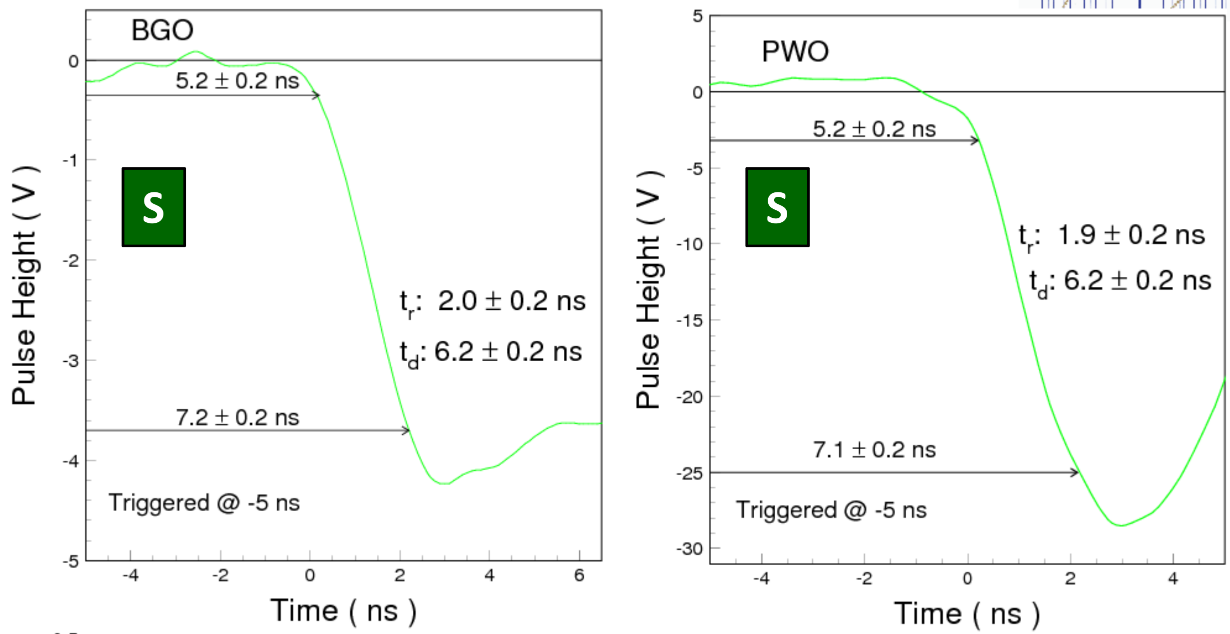


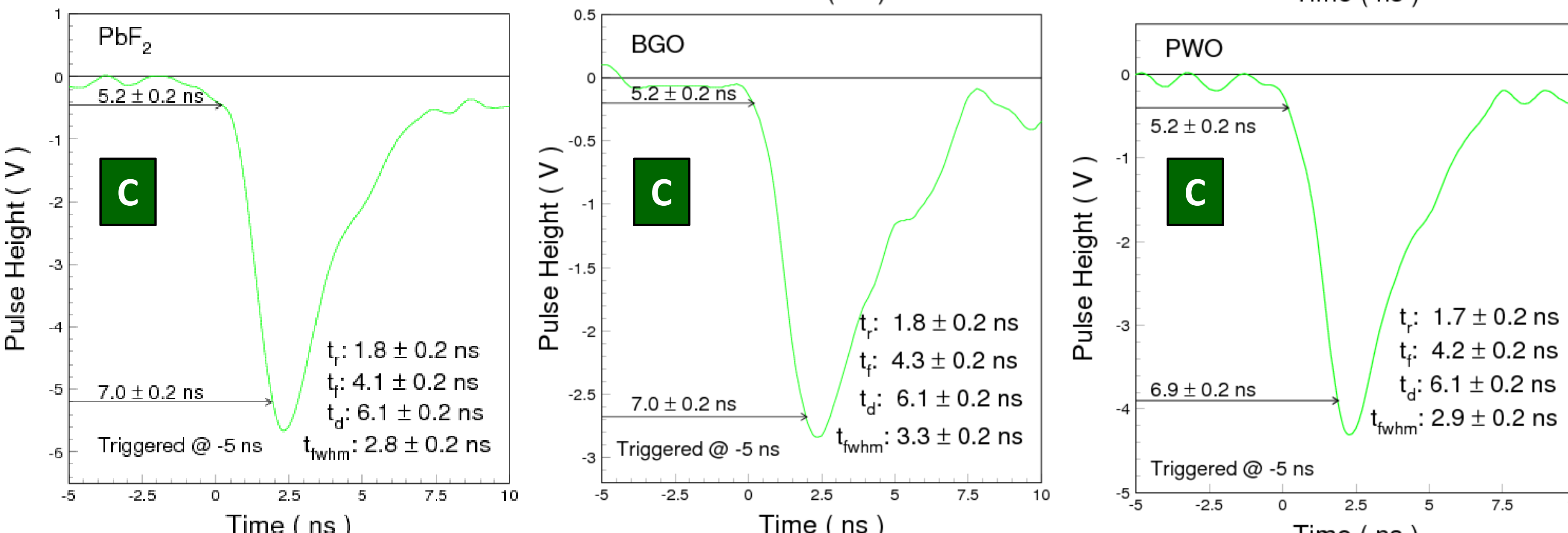
Agilent 6052A (500 MHZ) DSO with rise time 0.7 ns
Hamamatsu R2059 PMT (2500 V) with rise time 1.3 ns



Pulse Shape Separation?

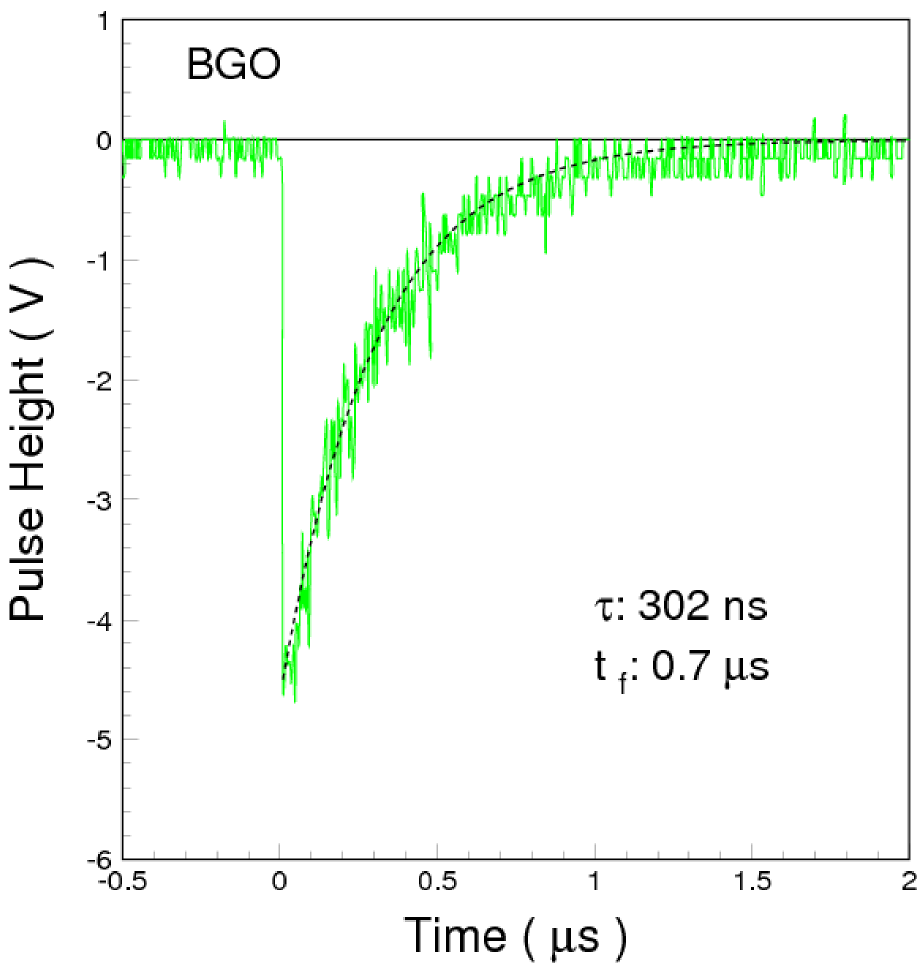
Consistent timing and rise time for all Cherenkov and scintillation light pulses.

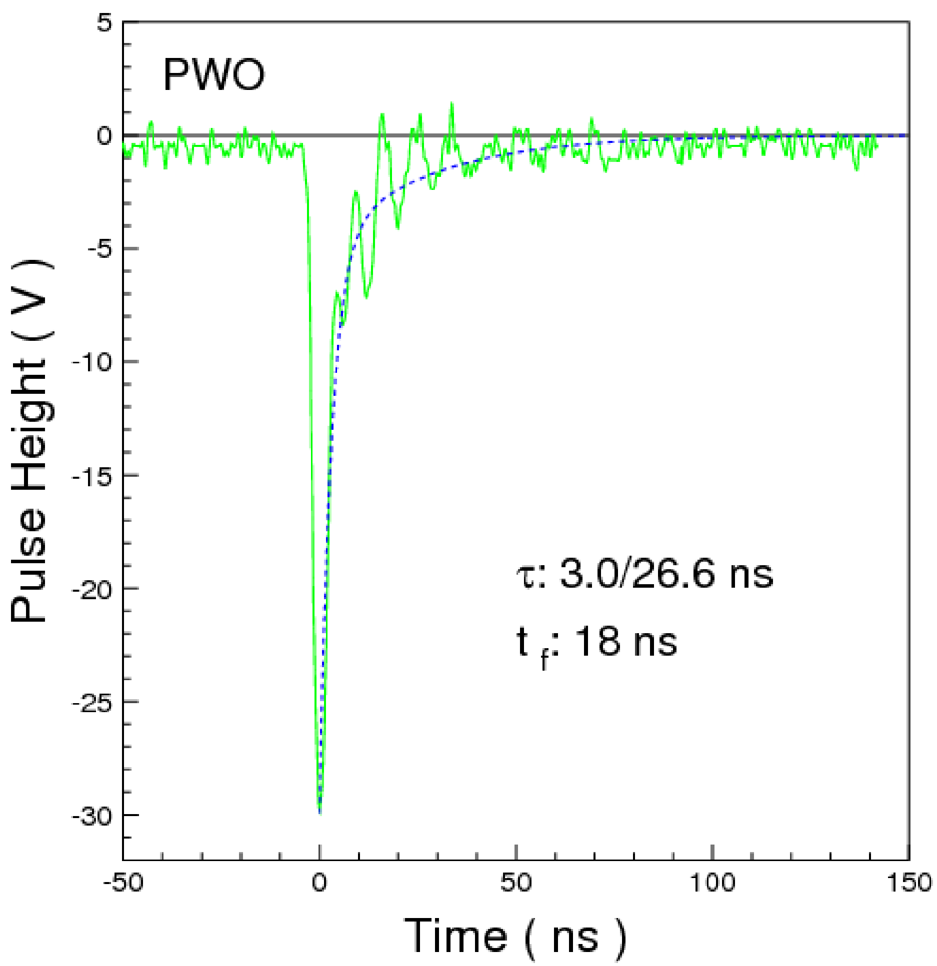




Pulse Shape Separation

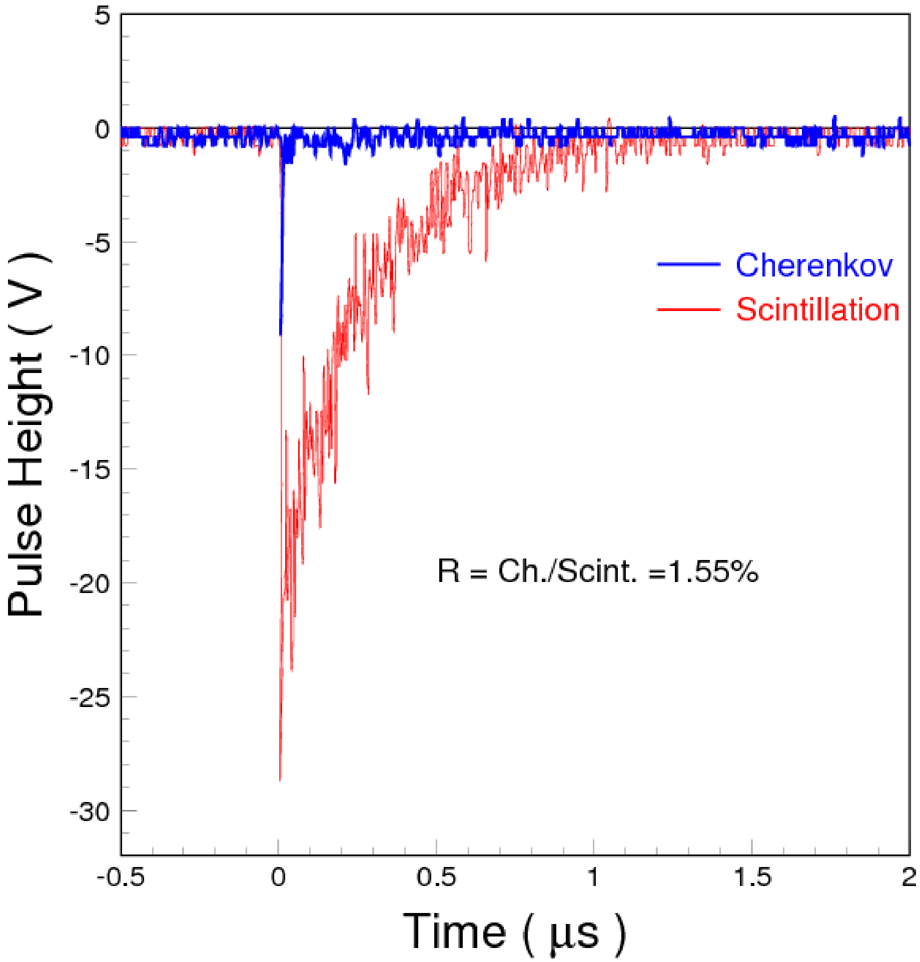
The slow scintillation decay may be useful

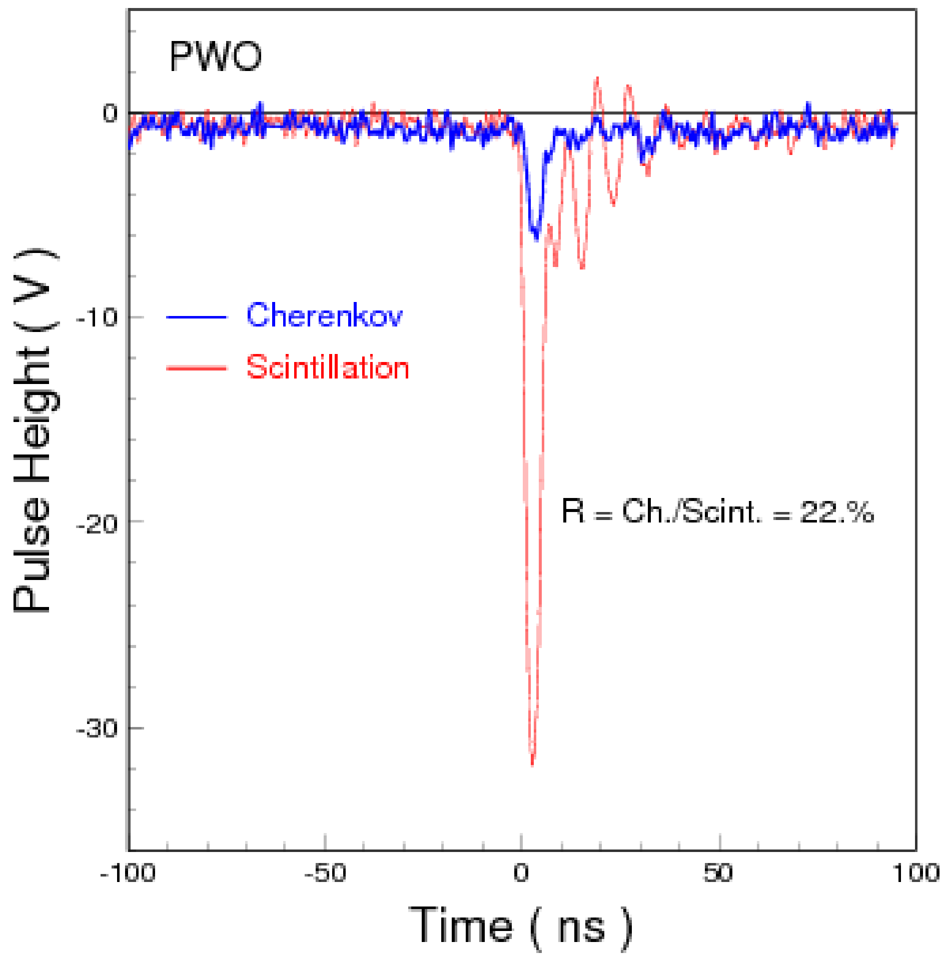




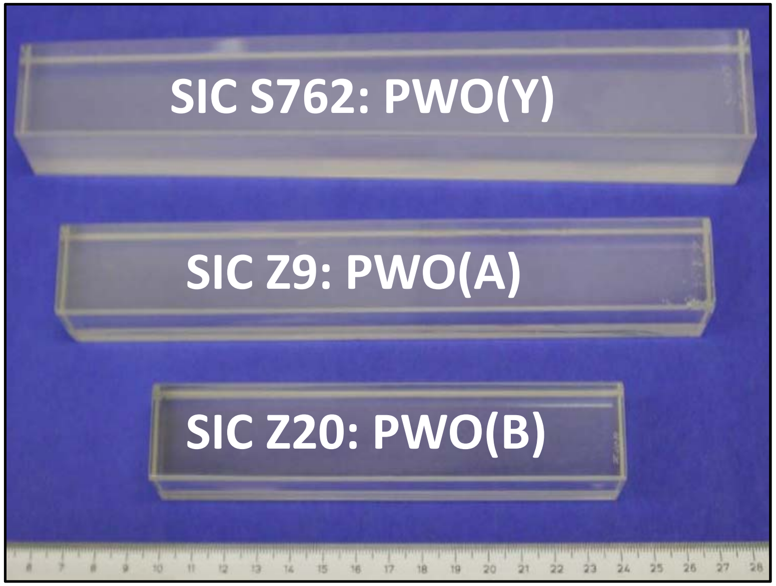
Ratio of Cherenkov/Scintillation

1.6% for BGO and 22% for PWO with UG11/GG400 filter and R2059 PMT



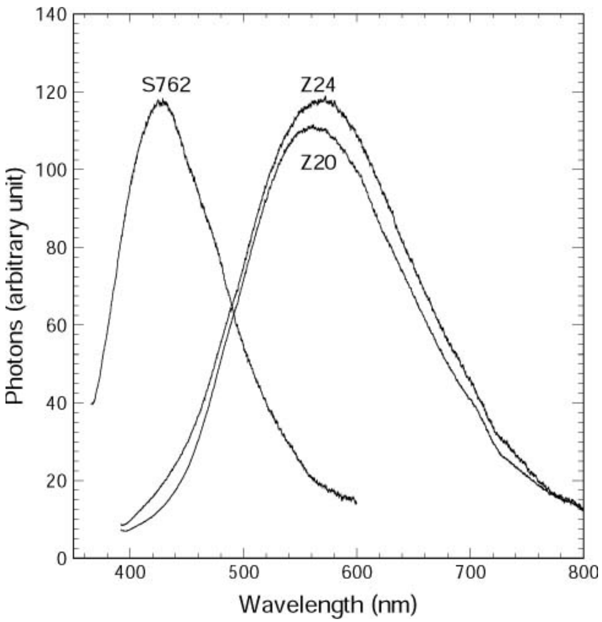


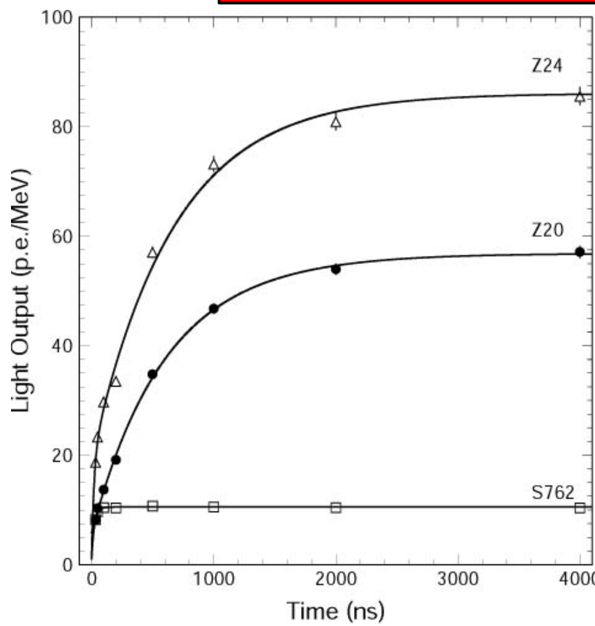
Green Slow Scintillation in PWO

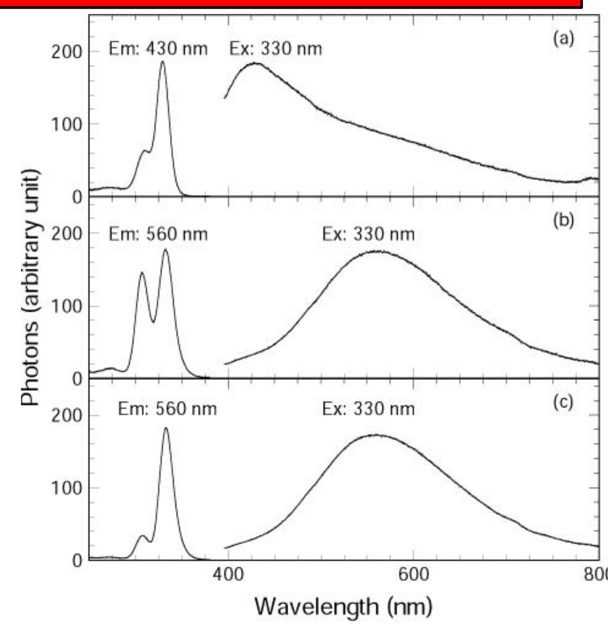


A factor of ten intensity of slow green scintillation (560 nm) was observed by selective doping in PWO: useful for dual readout

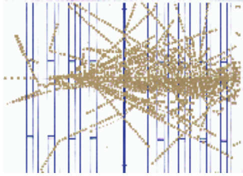
R.H. Mao at al., in Calor2000 proceedings

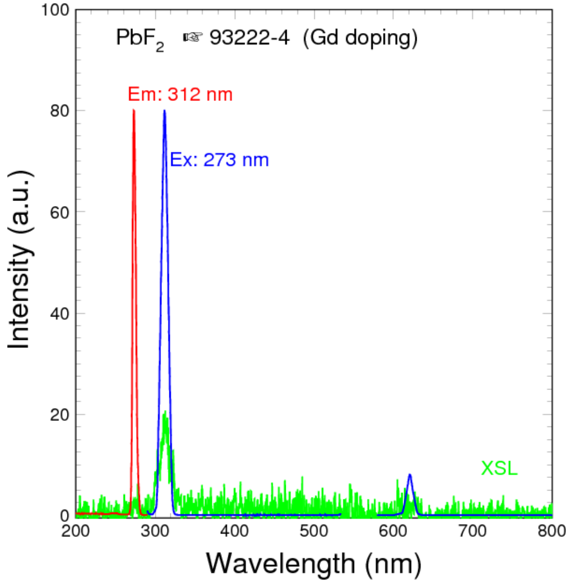


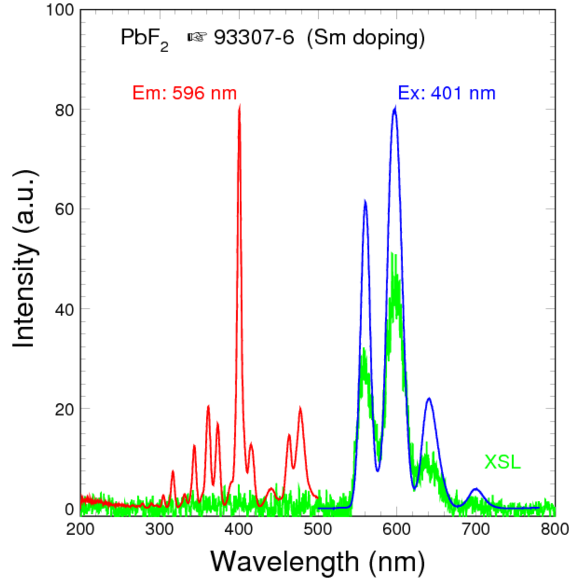


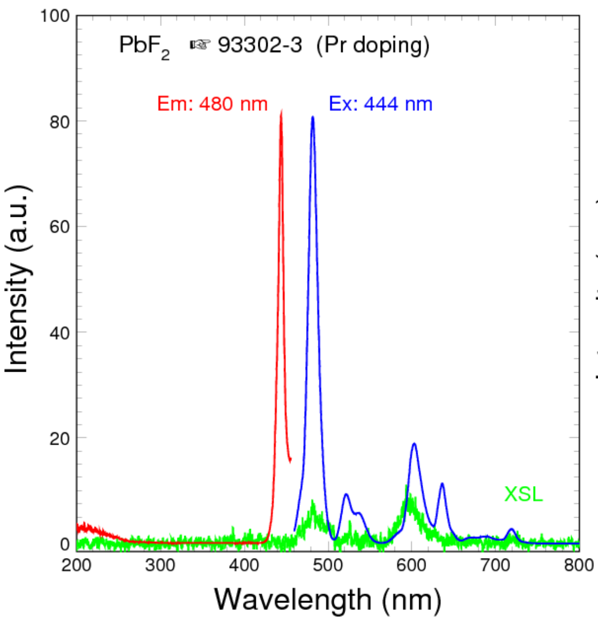


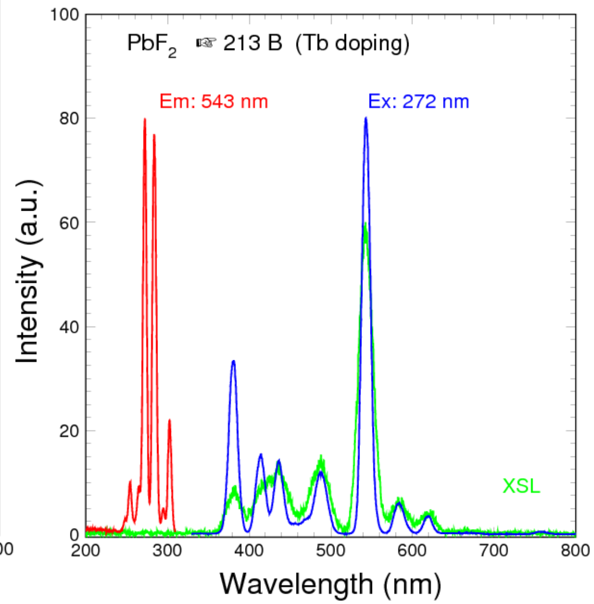
Scintillation Observed in PbF_2







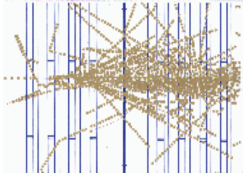




Some rear earth doping seems introducing scintillation, but not at the level can be measured by source.

Investigation is continuing aiming at developing cost effective crystals for dual readout.

Summary



- **Precision crystal calorimeter 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 provides excellent energy resolution over a large dynamic range down to MeV level for future HEP and NP experiments.**
- **Because of the expected huge volume needed development of cost-effective UV transparent material, such as doped PbF_2, is crucial for the homogeneous HCAL concept.**