Crystal Scintillators & Time Resolution

Ren-Yuan Zhu

California Institute of Technology

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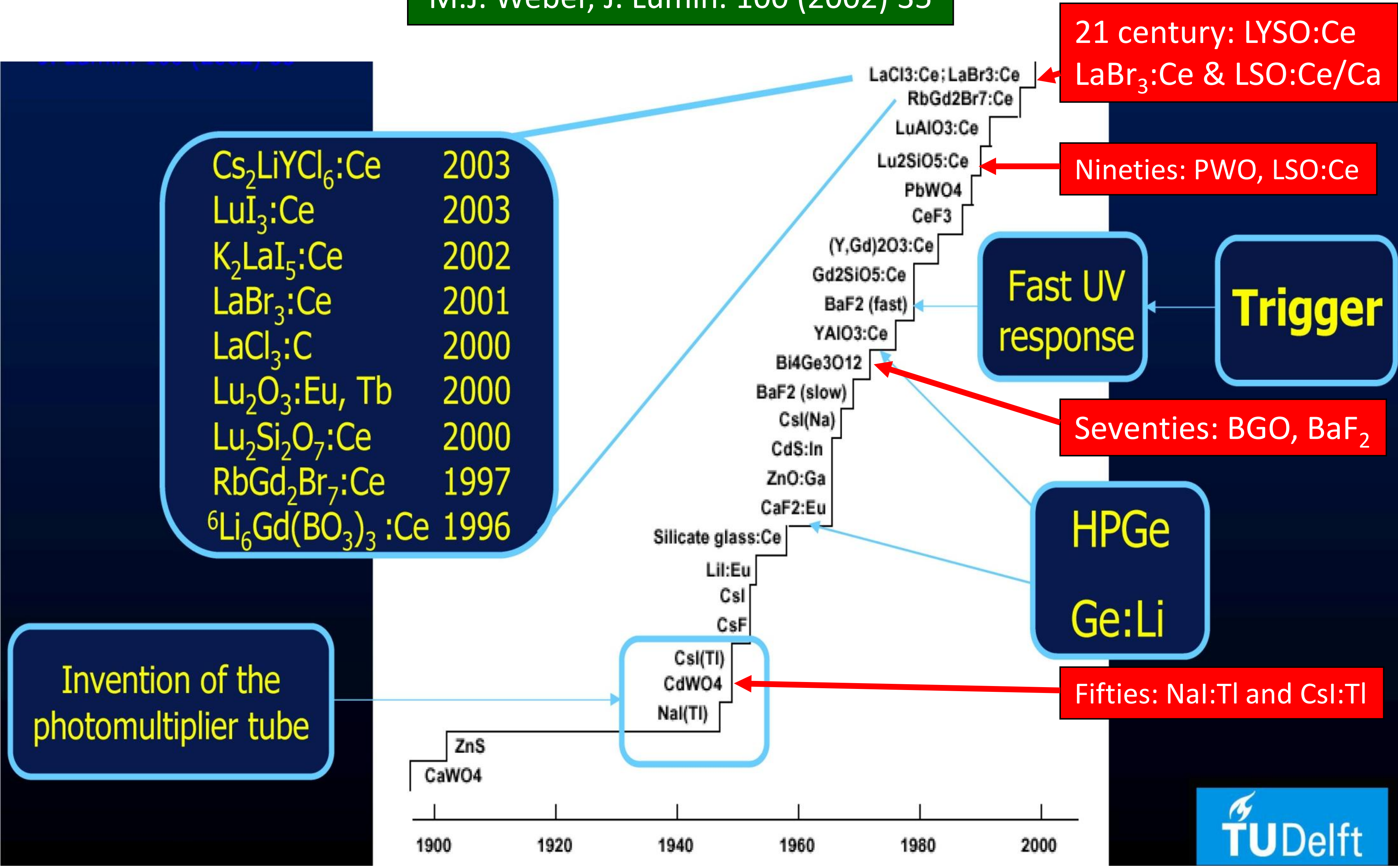
History of Scintillating Crystals

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



Crystals for HEP Calorimeters

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LSO(Ce)	PWO	PbF_2
Density (g/cm³)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (°C)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	420 310	300 220	480	402	425 420	?
Decay Time [b] (ns)	245	1220	30 6	650 0.9	300	40	30 10	?
Light Yield [b,c] (%)	100	165	3.6 1.1	36 4.1	21	85	0.3 0.1	?
d(LY)/dT [b] (%/ °C)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	?
Experiment	Crystal Ball	BaBar BELLE BES III	KTeV	TAPS (L*) (GEM)	L3 BELLE	Mu2e SuperB SLHC?	CMS ALICE PANDA	A4 HHCAL?

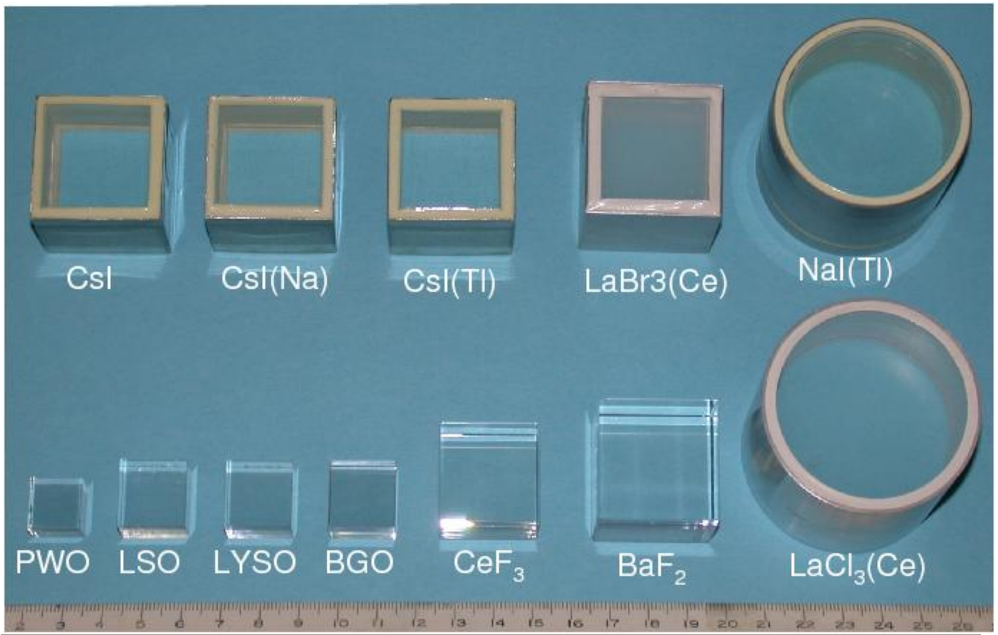
a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

Crystals for Homeland Security

Crystal	NaI(Tl)	CsI(Tl)	CsI(Na)	$LaCl_3$(Ce)	SrI_2 (Eu)	$LaBr_3$(Ce)
Density (g/cm^3)	3.67	4.51	4.51	3.86	4.59	5.29
Melting Point (ºC)	651	621	621	859	538	788
Radiation Length (cm)	2.59	1.86	1.86	2.81	1.95	1.88
Molière Radius (cm)	4.13	3.57	3.57	3.71	3.40	2.85
Interaction Length (cm)	42.9	39.3	39.3	37.6	37.0	30.4
Refractive Index [a]	1.85	1.79	1.95	1.9	?	1.9
Hygroscopicity	Yes	Slight	Slight	Yes	Yes	Yes
Luminescence [b] (nm) (at peak)	410	550	420	335	435	356
Decay Time [b] (ns)	245	1220	690	570 24	1100	20
Light Yield [b,c] (%)	100	165	88	13 42	221	130
d(LY)/dT [b] (%/ ºC)	-0.2	0.4	0.4	0.1	?	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 Cube Samples:

Hygroscopic: Sealed

Non-hygro: Polished

Full Size Crystals:

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

L3 BGO: 22 X_0

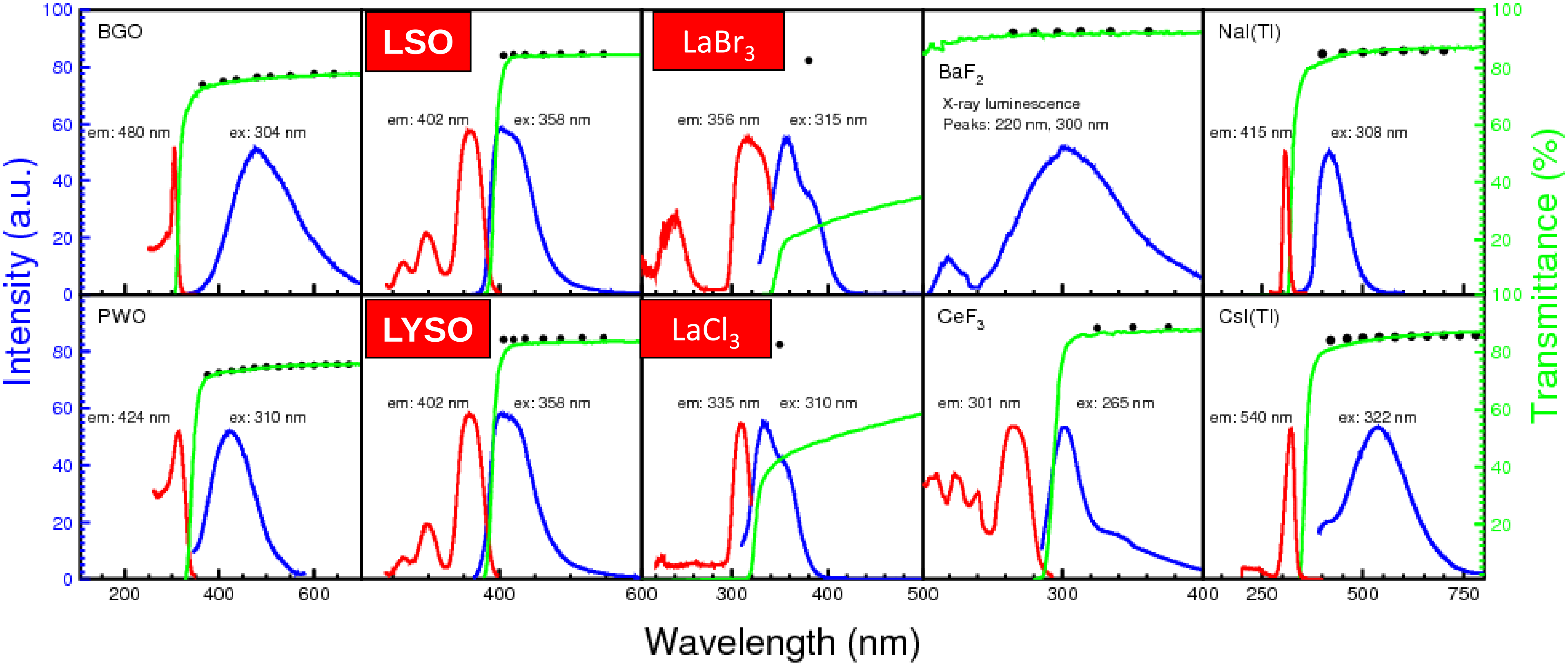
CMS PWO(Y): 25 X_0

Excitation, Emission, Transmission

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

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

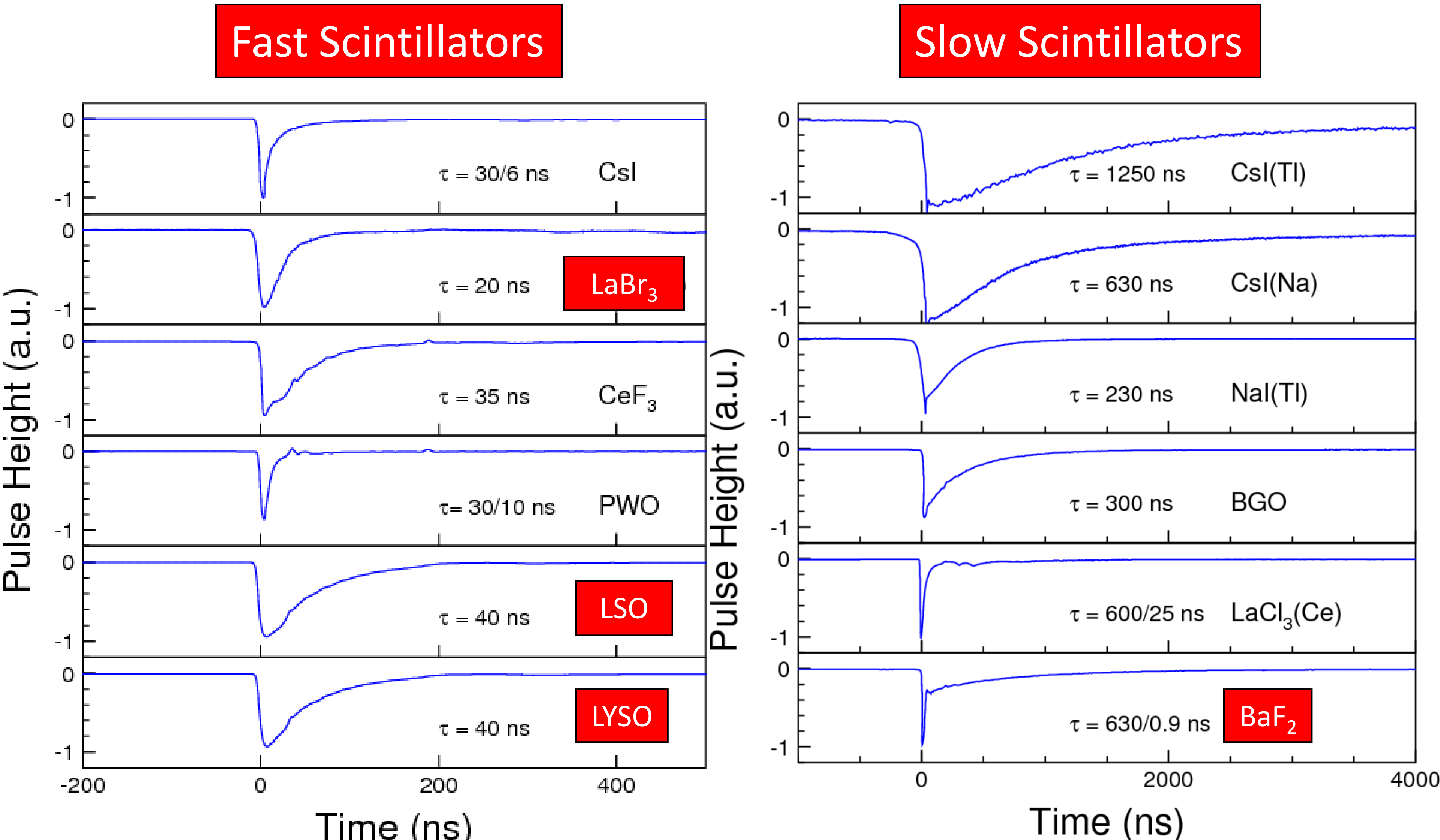
Black Dots: Theoretical limit of transmittance: NIM A333 (1993) 422



Poor transmittance indicates scattering centers: $LaBr_3$ and La Cl_3

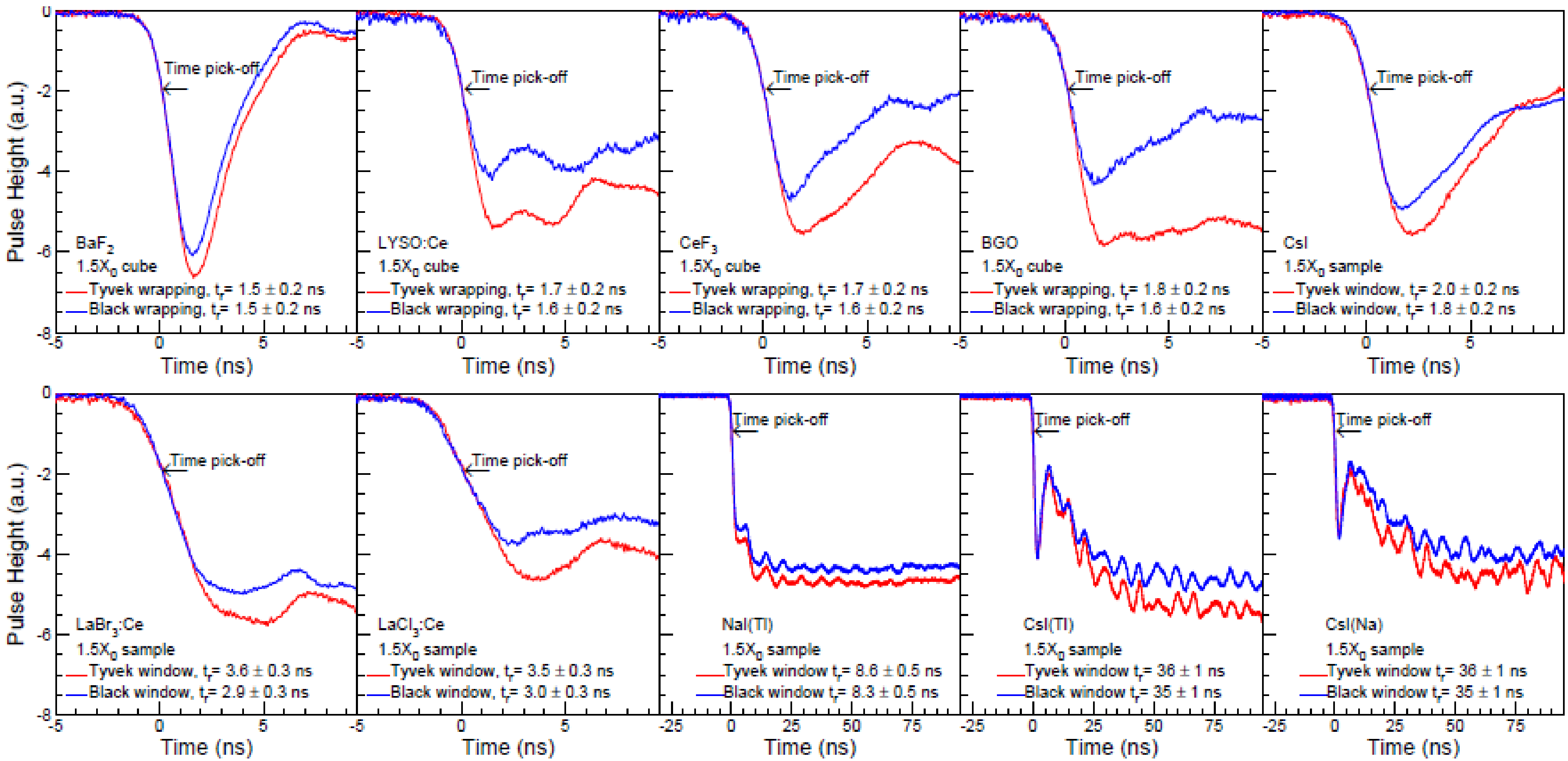
Scintillation Light Decay Time

Recorded with an Agilent 6052A digital scope



Rising Time for 1.5 X_0 Samples

Agilent MSO9254A (2.5 GHz) DSO with 0.14 ns rise time
Hamamatsu R2059 PMT (2500 V) with rise time 1.3 ns

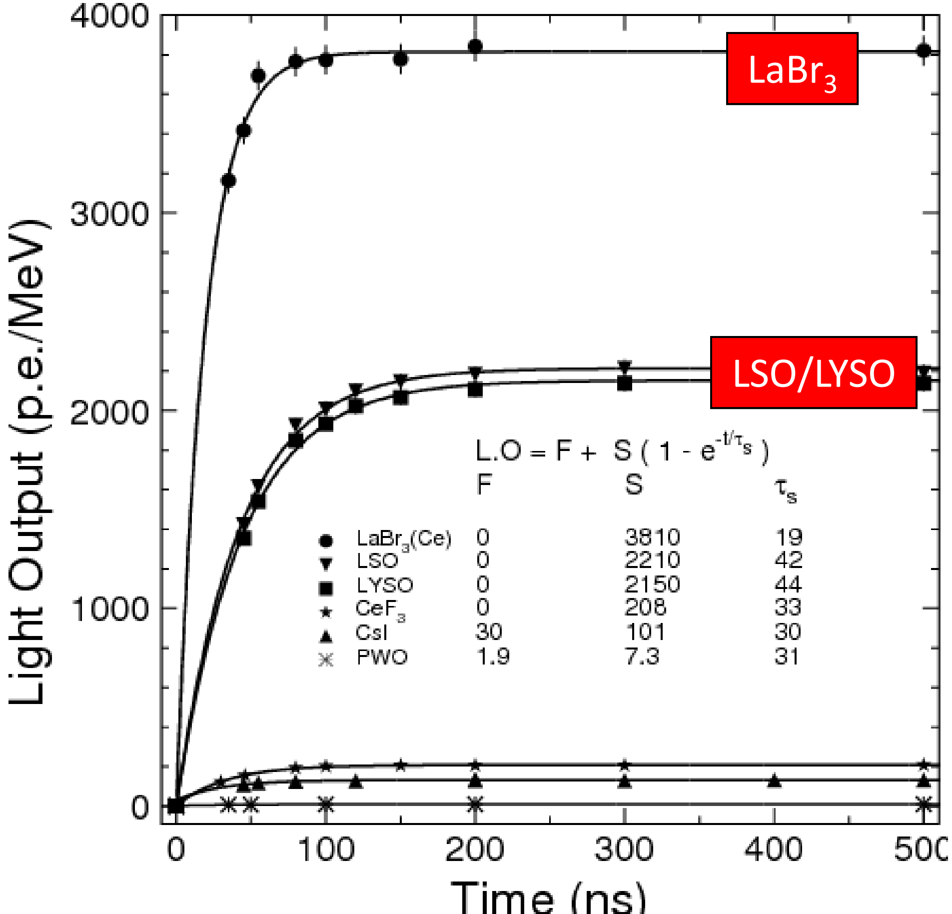


Measured rising time is dominated by photo-detector response, and is affected by light propagation in crystal.

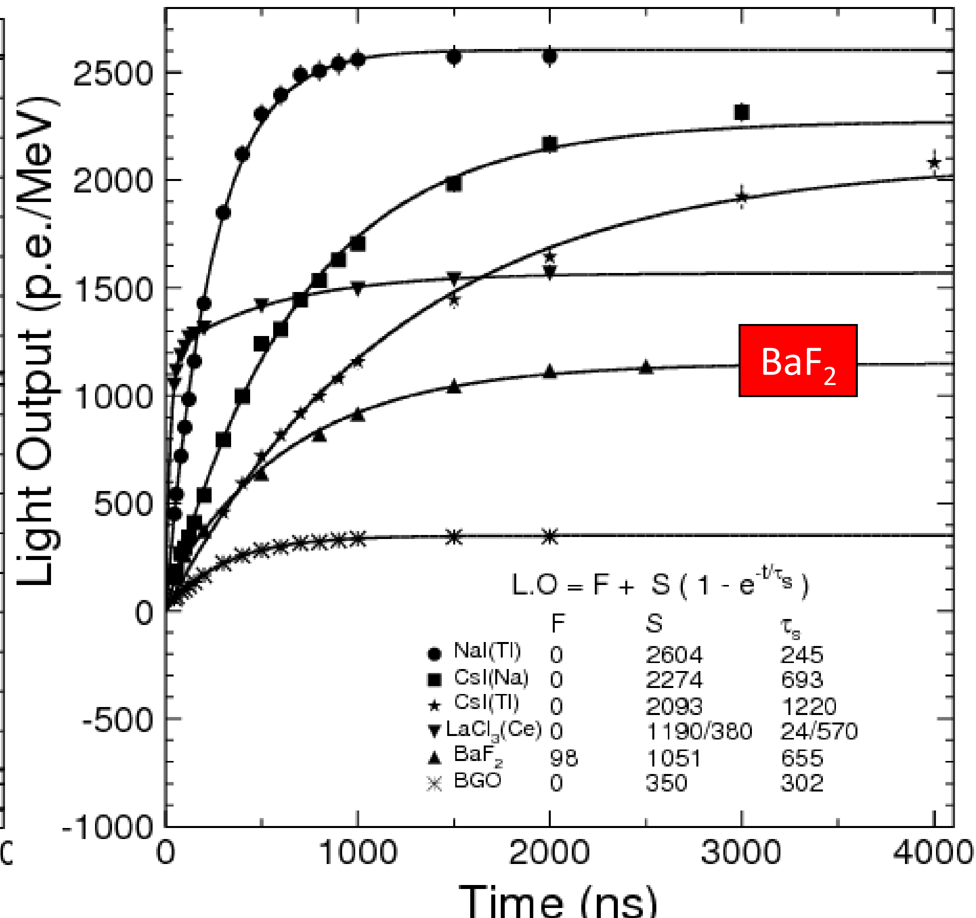
Light Output & Decay Kinetics

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

Fast Crystal Scintillators

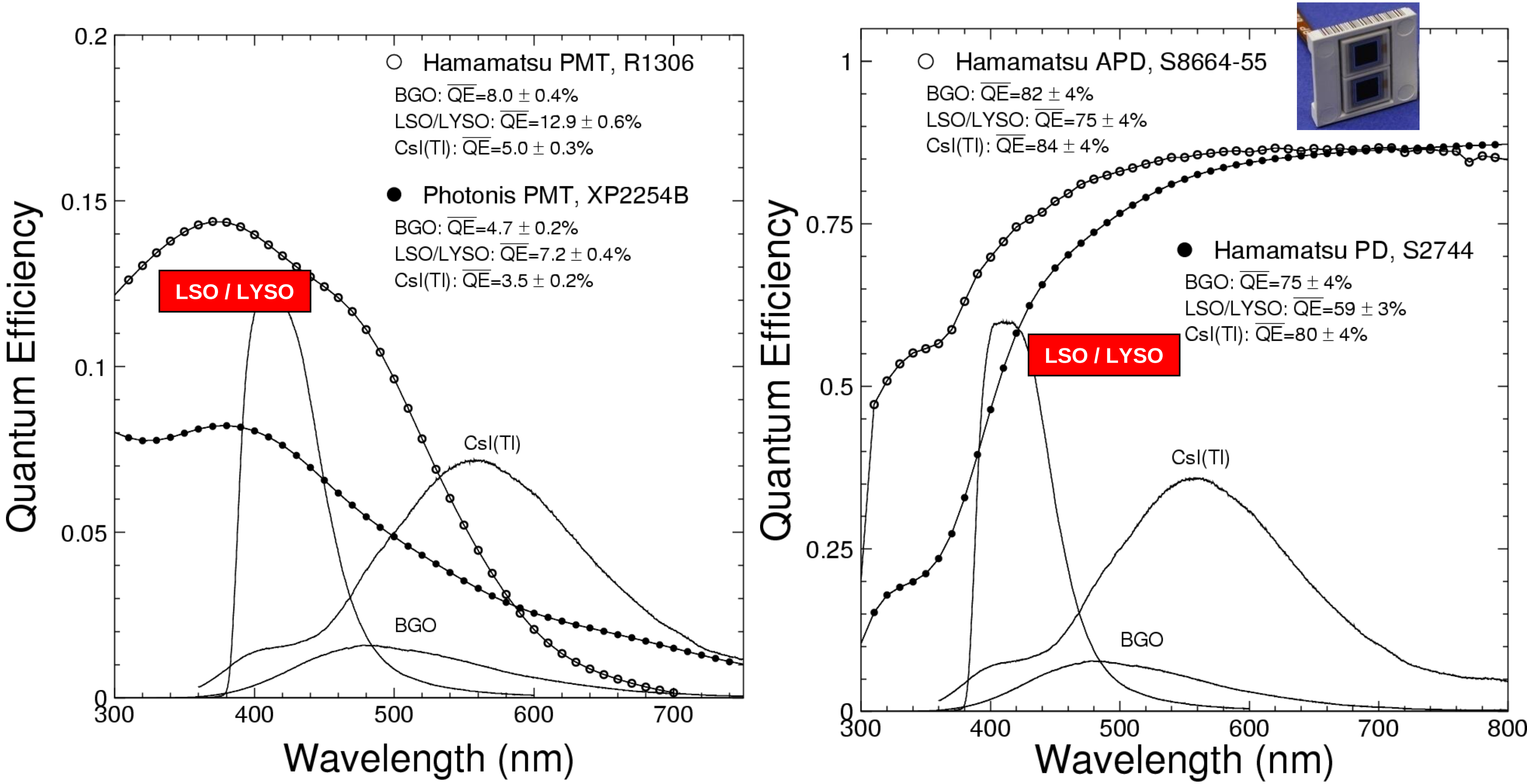


Slow Crystal Scintillators



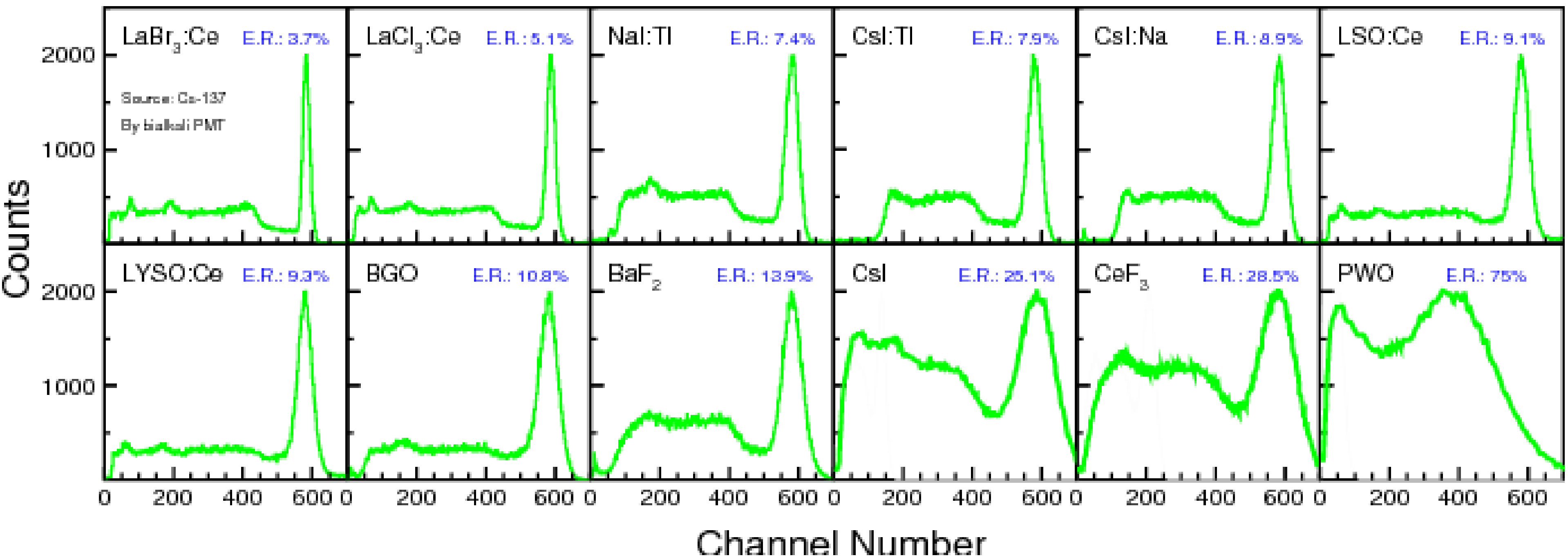
Emission Weighted QE

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



^{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

Time Resolution

For TOF PET it is defined as the minimum time interval required to separate two subsequent photon events, it is the FWHM of the time difference distribution. For a detector with finite signal to noise ratio and transit time jitter it can be written as

$$\sigma_{time}^2 \approx \left(\frac{\sigma_{noise}}{\frac{dV}{dt}}\right)^2 + \sigma_{TTS}^2$$

where both the signal slope (dV/dt) at the point of time pick-off and the jitter contribute. A fast and bright crystal scintillator combined with a photo-detector with high gain, fast response and small jitter are important for TOF PET.

TOF resolution in HEP is usually defined as the rms for single particles. Its numerical value is 3.3 times smaller than TOF PET.

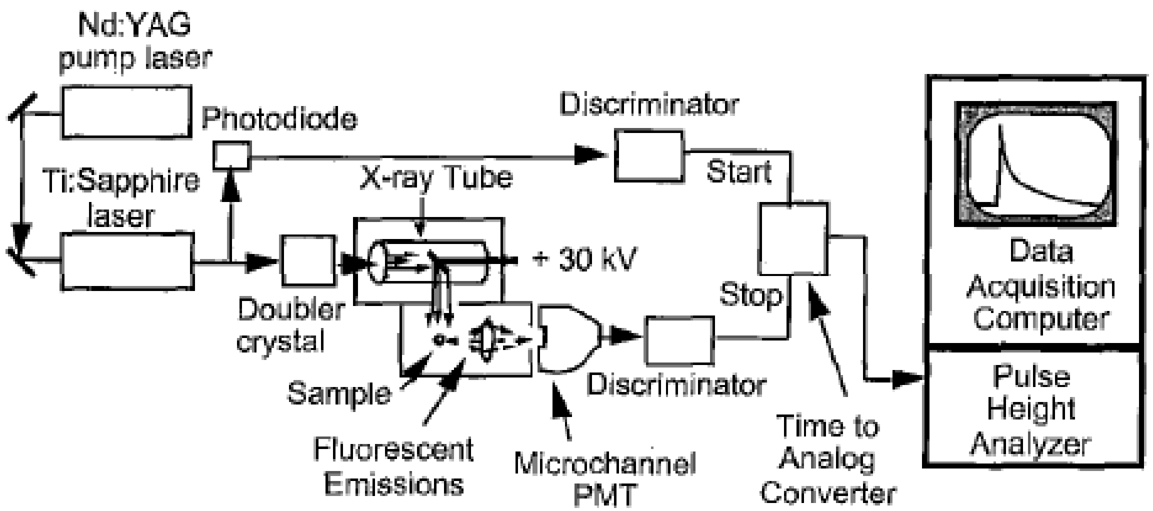
Optimization of Time Resolution

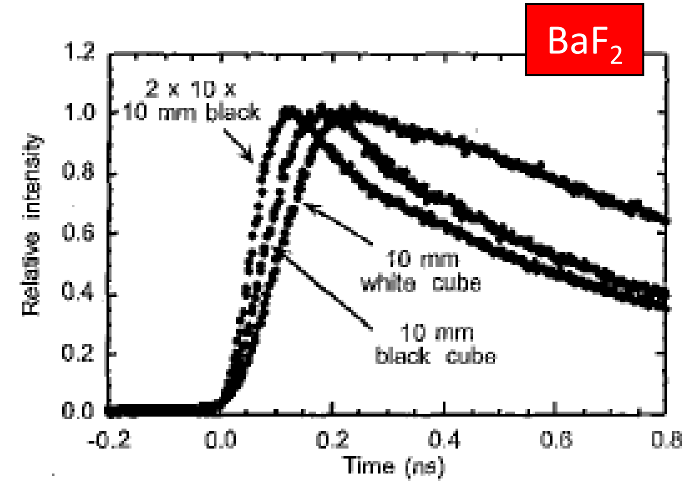
- The intrinsic rising time of fast crystals is 30 ps. Most measured time resolutions are dominated by instrumentational effects, such as photo-detector responses and light propagations inside crystals.

- Optimization of time resolution:
  - Fast crystal scintillators: with fast rise time & maximum photo-electron numbers in the 1st ns.
  - Quantum efficiency of photo-detectors matches scintillation emission peak.
  - Select appropriate pick off time to maximize dV/dt and minimize jitters.

A Measurement of Rising time

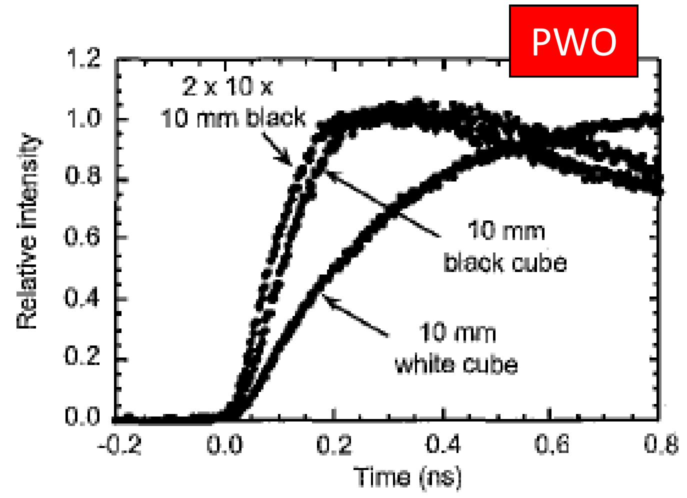
S. Derenzo et al., IEEE TNS 47 (2000) 860-864





Excitation: 60 ps FWHM x-ray pulse
Detector: MCP with 45 ps response

Effects of light propagation inside the samples are noticed: difference between small and large size samples and different wrappings.



Crystal Scintillation Rising Time

S. Derenzo et al., IEEE TNS 47 (2000) 860-864

Sample	Form*	Supplier**	τ_r (ps)†	τ_d (ns)††
BaF_2	2 x 10 x 10 mm	Harshaw	0 (calibration)	0.12(2%), 0.78(12%) + longer
BaF_2	powder	Aesar, Inc.	< 30	0.18(2%), 0.88(8%) + longer
BC-422	2 x 10 x 20 mm	Bicron	< 30	1.1(59%), 2.3(29%) + longer
$Bi_4Ge_3O_{12}$	3 x 3 x 30 mm	Harshaw	30 ±30	5.8(1%), 28(4%) + longer
CaF_2:Eu	2 x 30 x 30 mm	Bicron	40±30	slow decay components
CeF_3	2 x 10 x 10 mm	Optovac	30 ±30	several decay components
CdS:Te	2 x 5 x 10 mm	Peter Trower	80 ±30	several decay components
$CdWO_4$	2 x 10 x 10 mm	Harshaw	< 30	13(1%) + longer
CsI	2 x 10 x 10 mm	Bicron	30±30	several decay components
CsI:Tl	10 x 10 x 10 mm	Optovac	9,500(66%), 41,000(34%)§	long decay
Lu_2SiO_5:Ce	3 x 3 x 30 mm	CTI	30 ±30 (88%), 350±70(12%)	7(1%), 38.8(99%)
$PbWO_4$	2 x 10 x 10 mm	FSU	60 ±30	several decay components
$YAlO_3$:Ce	10 x 10 x 10 mm	Peter Trower	240±50	26(90%), 67(10%),
ZnO:Ga	powder	Westinghouse	< 30	0.36(35%), 0.82(65%)

* All samples (except powders) roughened and painted black on five sides

** Bicron Chemical, Solon, Ohio; FSU = Former Soviet Union; CTI, Inc. Knoxville. TN; Optovac, Inc., North Brookfield, MA.

† Best fit rise time using x-ray tube calibration of 60 ps fwhm shown in Figure 4.

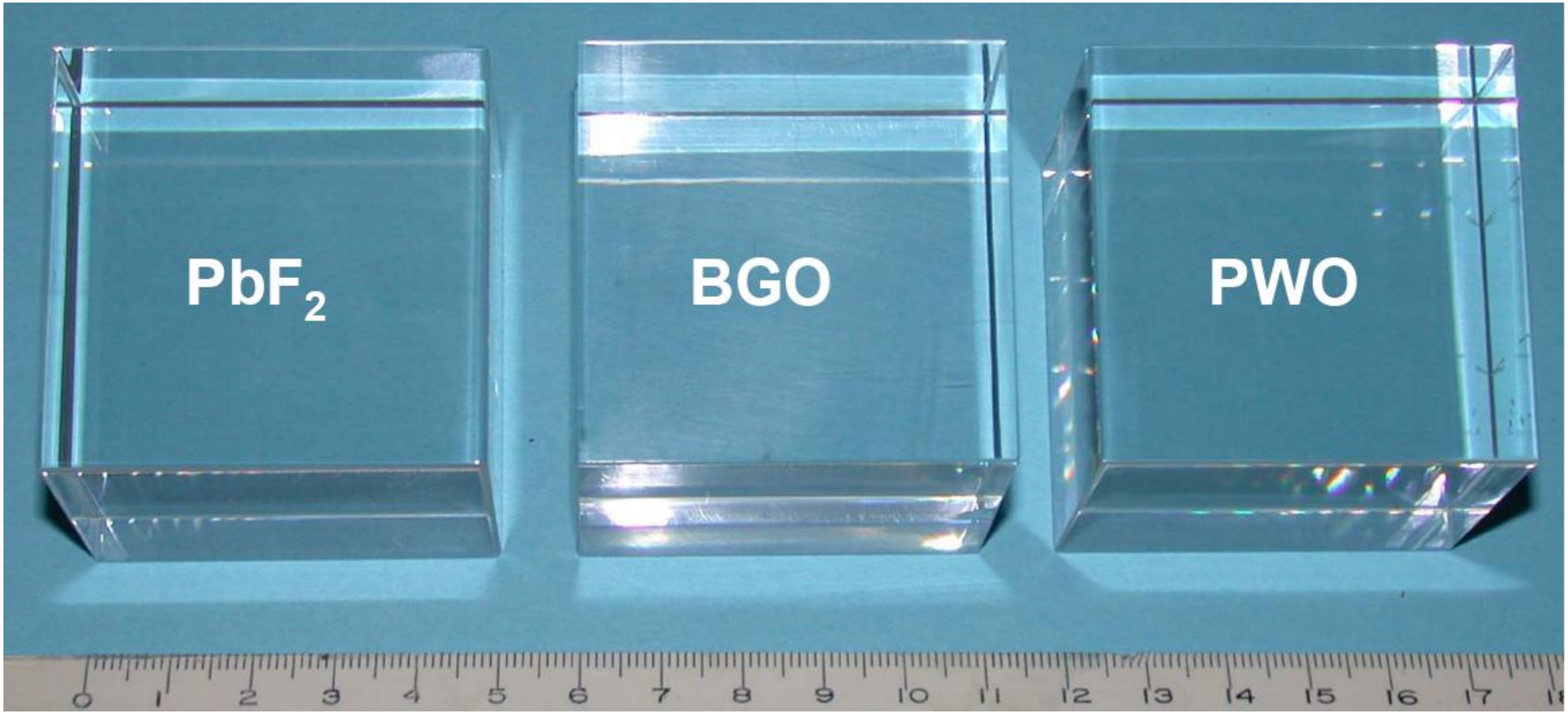
†† Decay times may vary from sample to sample.

§ Rise time is temperature dependent. See Ref. [9].

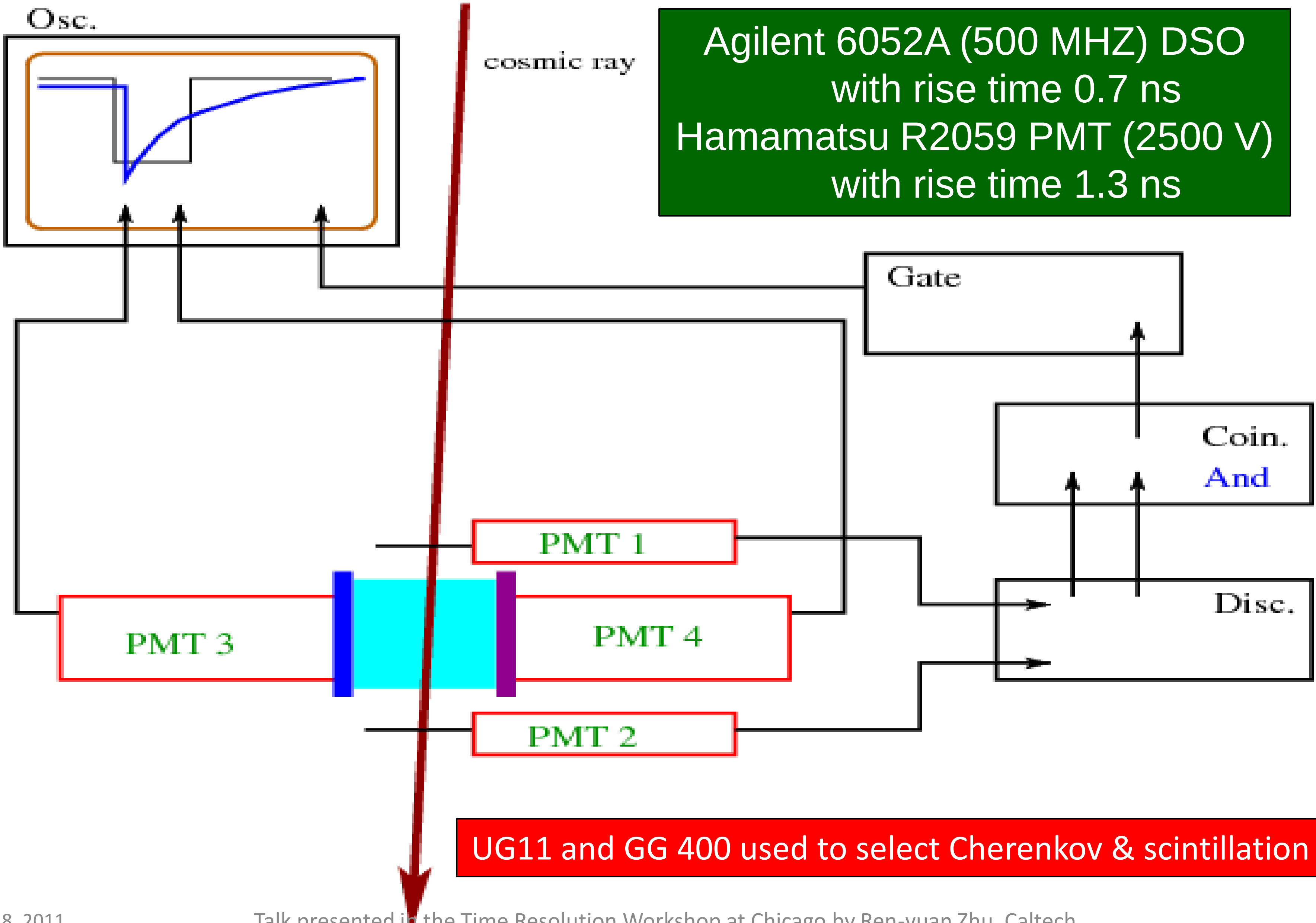
Scintillation rising time is about 30 ps or less for BaF_2, BGO and CeF_3

Crystal for Homogeneous HCAL

Crystals of high density, good UV transmittance and some scintillation light, not necessary bright and fast, are required. The volume needed is 70 to 100 m^3: cost-effective material.
Following 2/19/08 workshop at SICCAS, 5 x 5 x 5 cm samples evaluated



Cosmic Setup with Dual Readout

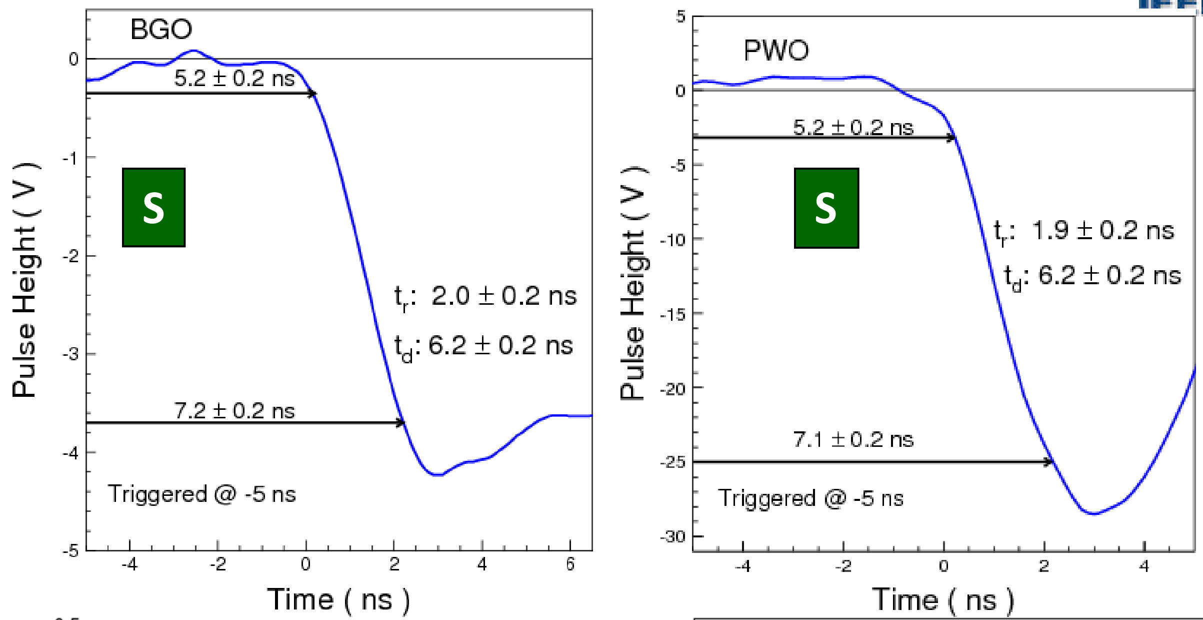


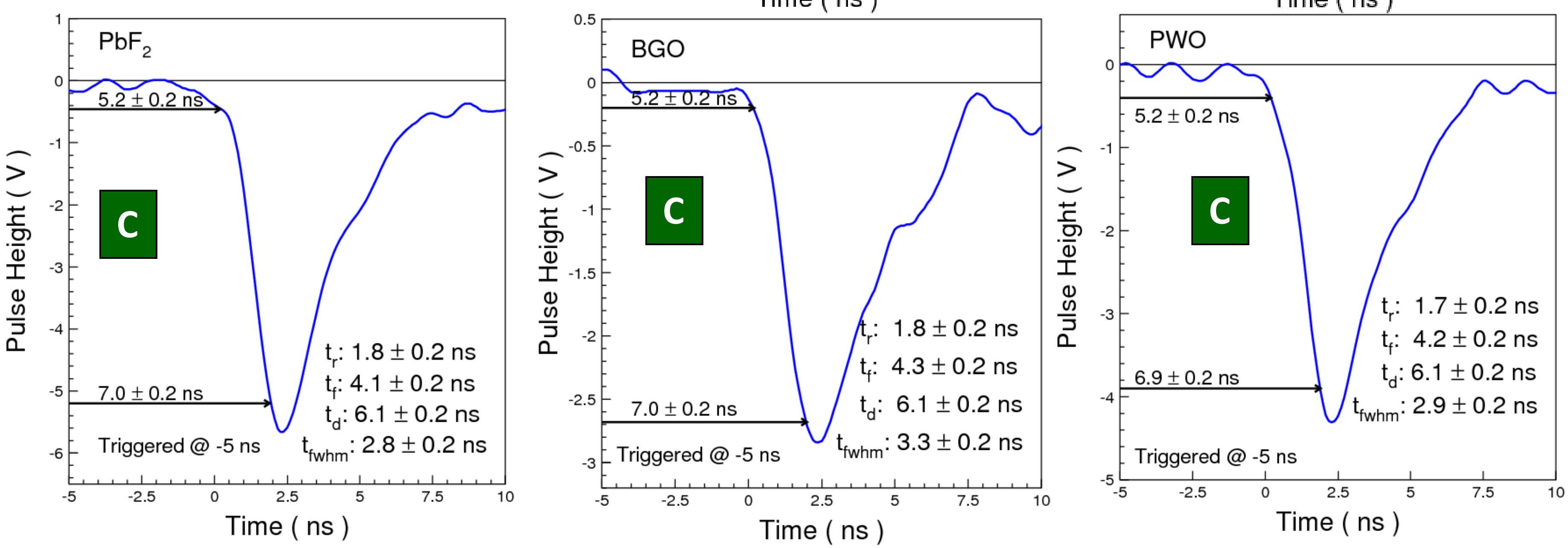
Agilent 6052A (500 MHZ) DSO
with rise time 0.7 ns
Hamamatsu R2059 PMT (2500 V)
with rise time 1.3 ns

UG11 and GG 400 used to select Cherenkov & scintillation

No Discrimination in Front Edge

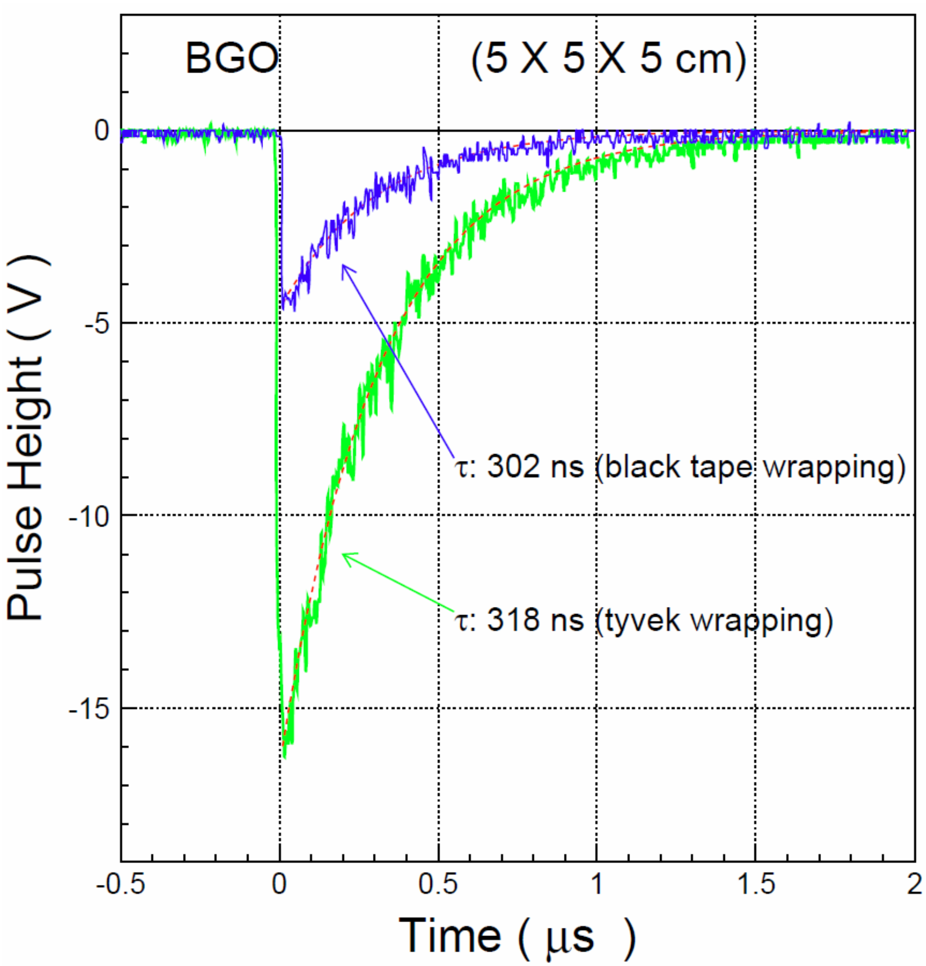
Consistent timing and rise time for all Cherenkov and scintillation light pulses with crystals wrapped black.

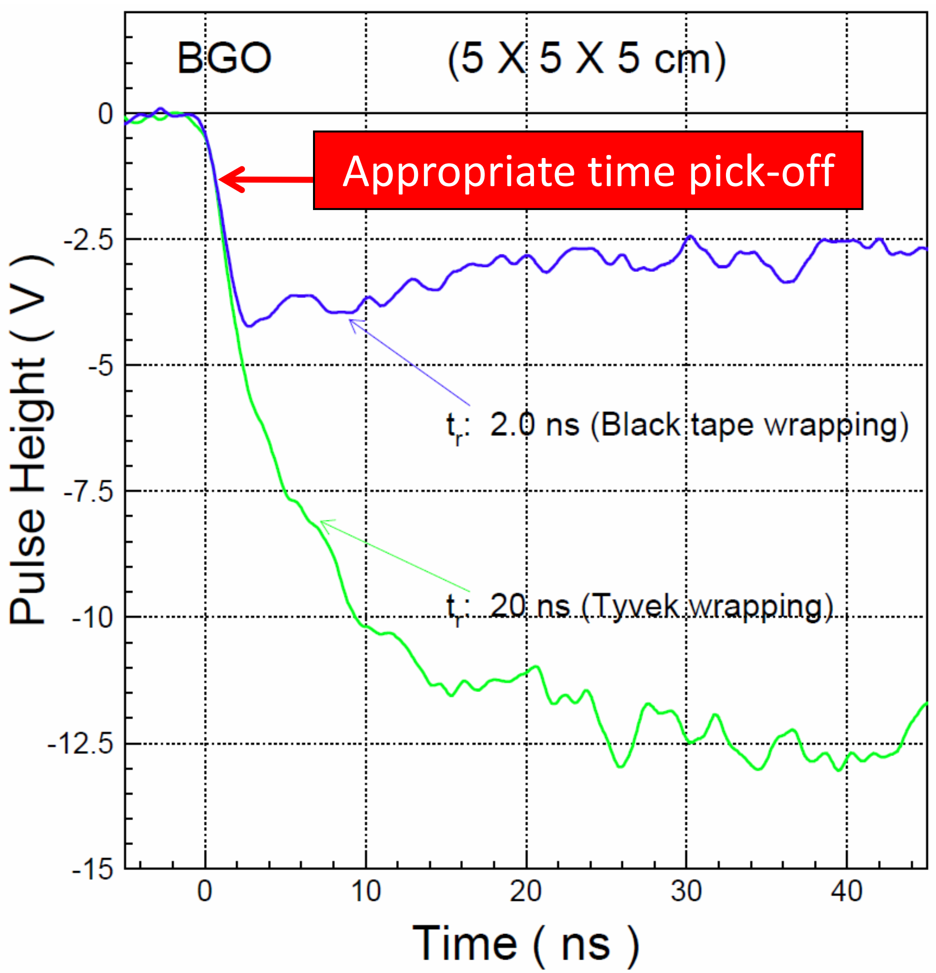




Effect of Light Propagation

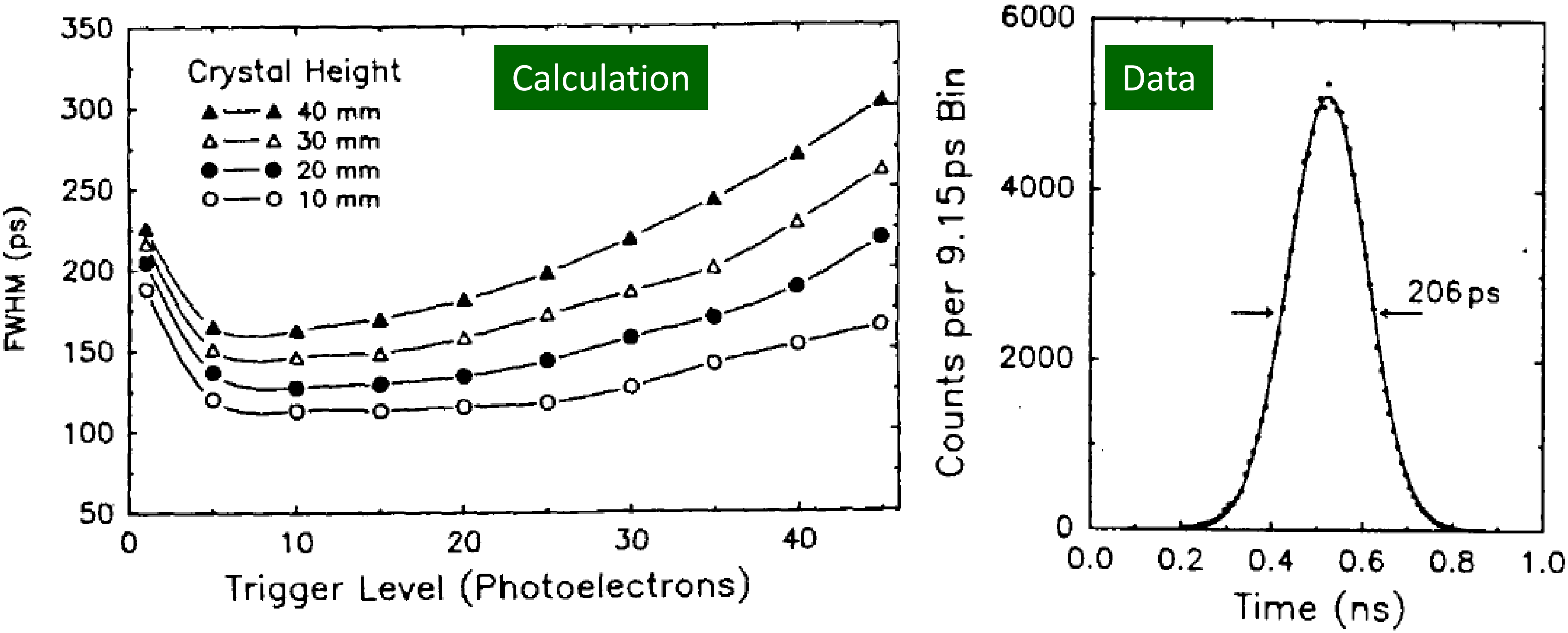
Reflectors increase light output, but slow down rising time
Appropriate choice of time pick-off may avoid this effect





Effect of Time Pick-Off

S. Ziegler et al., IEEE TNS 37 (1990) 574-579
Time resolution may be optimized by appropriate trigger threshold



200 ps FWHM, or 60 ps σ_{single}, measured with BaF_2 & Hamamatsu R3377 PMT readout: a factor of three better than commercial system

Figure of Merit for Crystals

FoM is calculated as the LY in 1st ns obtained by using light output and decay time data measured for 1.5 X_0 crystal samples.

Crystal Scintillators	Relative LY (%)	A_1 (%)	τ_1 (ns)	A_2 (%)	τ_2 (ns)	Total LO (p.e./MeV, XP2254B)	LO in 1ns (p.e./MeV, XP2254B)	LO in 0.1ns (p.e./MeV, XP2254B)	LY in 0.1ns (photons/MeV)
BaF_2	40.1	91	650	9	0.9	1149	71.0	11.0	136.6
LSO:Ca,Ce	94	100	30			2400	78.7	8.0	110.9
LSO/LYSO:Ce	85	100	40			2180	53.8	5.4	75.3
CeF_3	7.3	100	30			208	6.8	0.7	8.6
BGO	21	100	300			350	1.2	0.1	2.5
PWO	0.377	80	30	20	10	9.2	0.42	0.04	0.4
$LaBr_3$:Ce	130	100	20			3810	185.8	19.0	229.9
$LaCl_3$:Ce	55	24	570	76	24	1570	49.36	5.03	62.5
NaI:Tl	100	100	245			2604	10.6	1.1	14.5
CsI	4.7	77	30	23	6	131	7.9	0.8	10.6
CsI:Tl	165	100	1220			2093	1.7	0.2	4.8
CsI:Na	88	100	690			2274	3.3	0.3	4.5

The best crystal scintillator for time resolution is BaF_2 and LSO: Ce/Ca and LYSO. $LaBr_3$ is a material with high potential.

TOF with LSO & LYSO Crystals

100 ps achieved with LYSO & LSO:Ce/Ca with MCP & G-APD readout.

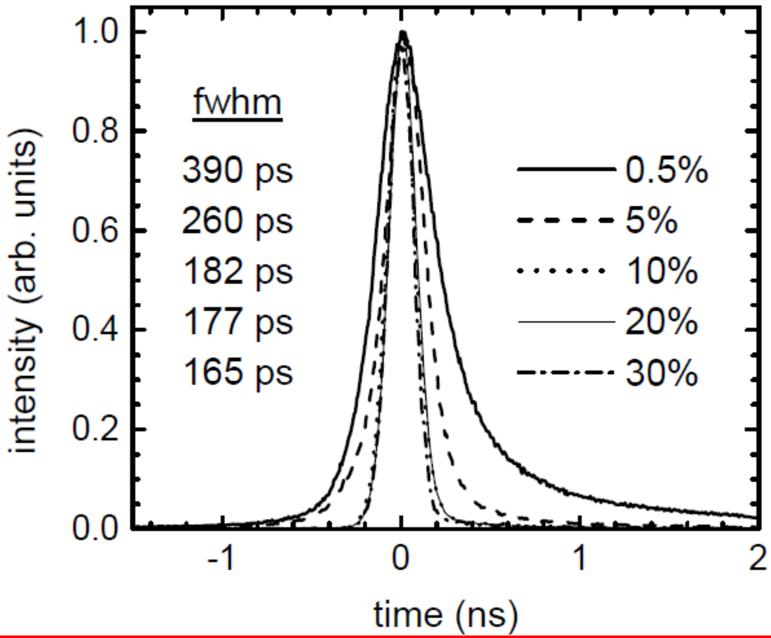
Test	Crystal	Detector	Particle	σ_{single}
Fermilab	LYSO 3 x 3 x 7 mm	G-APD 3 mm^2	^{60}Co: γ's	110 ps
PISA	LSO:Ce/Ca 3 x 3 x 10 mm	G-APD 3 mm^2	^{22}Na: γ's	107 ps
SLAC	LYSO 17 mm Cube	MCP	CRT: μ's	109/159 ps
SLAC	Scintillator 17 mm Cube	G-APD	CRT: μ's	136 ps
SLAC	LYSO 17 mm Cube	G-APD	CRT: μ's	140 ps
SLAC	LYSO 2.5 x 2.5 x 20 cm	G-APD	CRT: μ's	220 ps

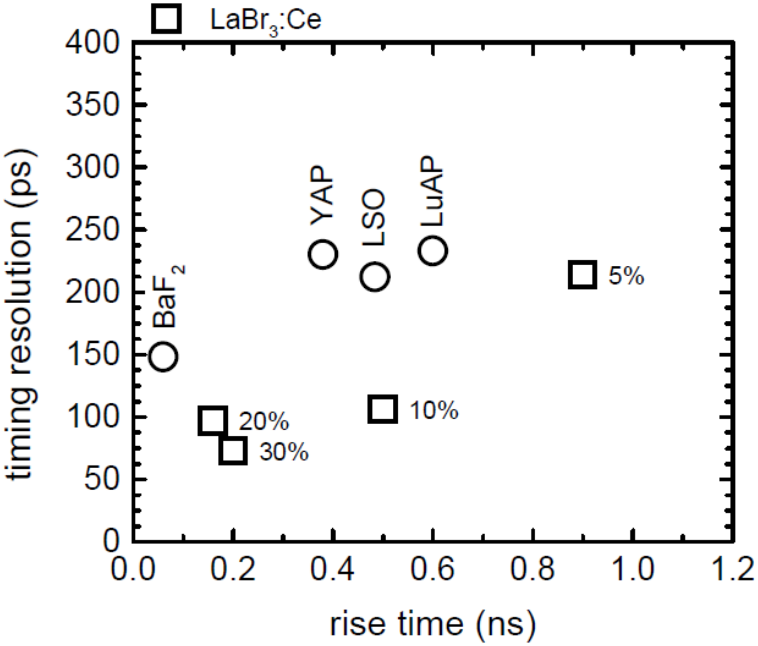
100 ps corresponds to 330 ps for TOF-PET

Time Resolution of $LaBr_3$

J. Glodo et al., IEEE TNS 52 (2005) 1805-1808

Ce^{3+} Contr. %	Light Output %	Decay / Rise Times (intensity) ns/ns (%)	Effective Rise Time, ns	Timing Resolution FWHM (ps)	$LaBr_3$:Ce (ps)	$\sqrt{(\tau / N)}$ (ps)
0.5	97	19/15 (56%), 15.2/2 (28%), 55 (16%)	9.4	390	361	83
5.0	100	15/0.38 (70%), 15/2.2 (27%), 55 (3%)	0.93	260	214	62
10.0	94	16.5/0.5 (89%), 4.5/0.5 (5%), 55 (6%)	0.5	182	106	67
20.0	92	17.5/0.16 (89%), 4.5/0.15 (5%), 55 (6%)	0.16	177	97	70
30.0	93	18/0.2 (91%), 2.5/0.2 (4%), 55 (6%)	0.20	165	73	70





Time resolution achievable: 100 ps for TOF-PET with MCP readout.

Summary

- Most fast crystals have a rising time at a level of 30 ps. Laboratory measurements of TR are often dominated by the response time of photo-detectors and readout electronics, and also affected by light propagation.
- Time resolution of a scintillator based system can be optimized by choosing (1) bright and fast scintillators, (2) fast photo-detector with high gain and low jitter and (3) appropriate time pick off or trigger threshold.
- Photo-electron # in the 1st ns can be seen as a figure of merit for time resolution of crystals with fast rise time.
- The achievable FWHM time resolution for TOF PET is about 100 ps by $LaBr_3$, and 200 and 300 ps respectively for non-hygroscopic crystals BaF_2 and LSO/LYSO.