# Recent Progress on Fast Inorganic Scintillators for Future HEP Experiments


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# Fast & Radiation Hard Scintillators

- Supported by the DOE ADR program we are developing fast and radiation hard scintillators to face the challenge for future HEP experiments at the energy and intensity frontiers.
- LYSO:Ce, $BaF_2$ and LuAG:Ce will survive the radiation environment expected at HL-LHC with 3000 $fb^{-1}$. LYSO is proposed for a MIP timing detector for CMS upgrade:
  - Absorbed dose: up to 100 Mrad,
  - Charged hadron fluence: up to $6\times10^{14}$ p/cm$^2$,
  - Fast neutron fluence: up to $3\times10^{15}$ n/cm$^2$.
- Ultra-fast scintillators with excellent radiation hardness is also needed to face the challenge of unprecedented event rate expected at future HEP experiments at the intensity frontier, such as Mu2e-II, and the GHz X-ray imaging for the proposed Marie project at Los Alamos. Y:$BaF_2$ with a sub-ns FWHM pulse width and a suppressed slow scintillation component is a leading candidate for both applications.

# Bright & Fast Scintillators: LYSO & $BaF_2$

| Crystal | NaI(Tl) | CsI(Tl) | CsI | $BaF_2$ | BGO | LYSO(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 (ºC) | 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)<br>(at peak) | 410 | 550 | 310 | 300<br>220 | 480 | 402 | 425<br>420 | ? |
| Decay Time [b] (ns) | 245 | 1220 | 26 | 650<br>0.9 | 300 | 40 | 30<br>10 | ? |
| Light Yield [b,c] (%) | 100 | 165 | 4.7 | 36<br>4.1 | 21 | 85 | 0.3<br>0.1 | ? |
| d(LY)/dT [b] (%/ ºC) | -0.2 | 0.4 | -1.4 | -1.9<br>0.1 | -0.9 | -0.2 | -2.5 | ? |
| Experiment | Crystal Ball | BaBar<br>BELLE<br>BES-III | KTeV<br>S.BELLE<br>Mu2e-I | (GEM)<br>TAPS<br>Mu2e-II | L3<br>BELLE<br>HHCAL? | COMET &<br>CMS (Mu2e<br>& SperB) | CMS<br>ALICE<br>PANDA | A4<br>g-2<br>HHCAL |

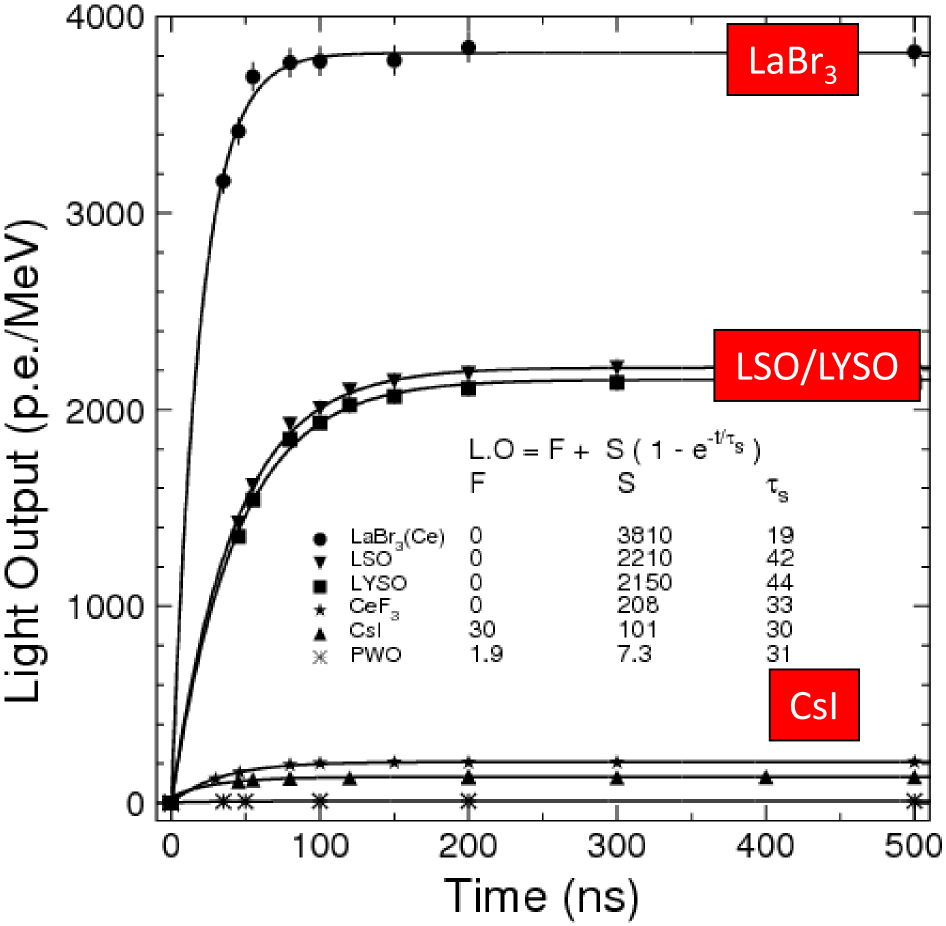
a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

# Light Output & Decay Kinetics

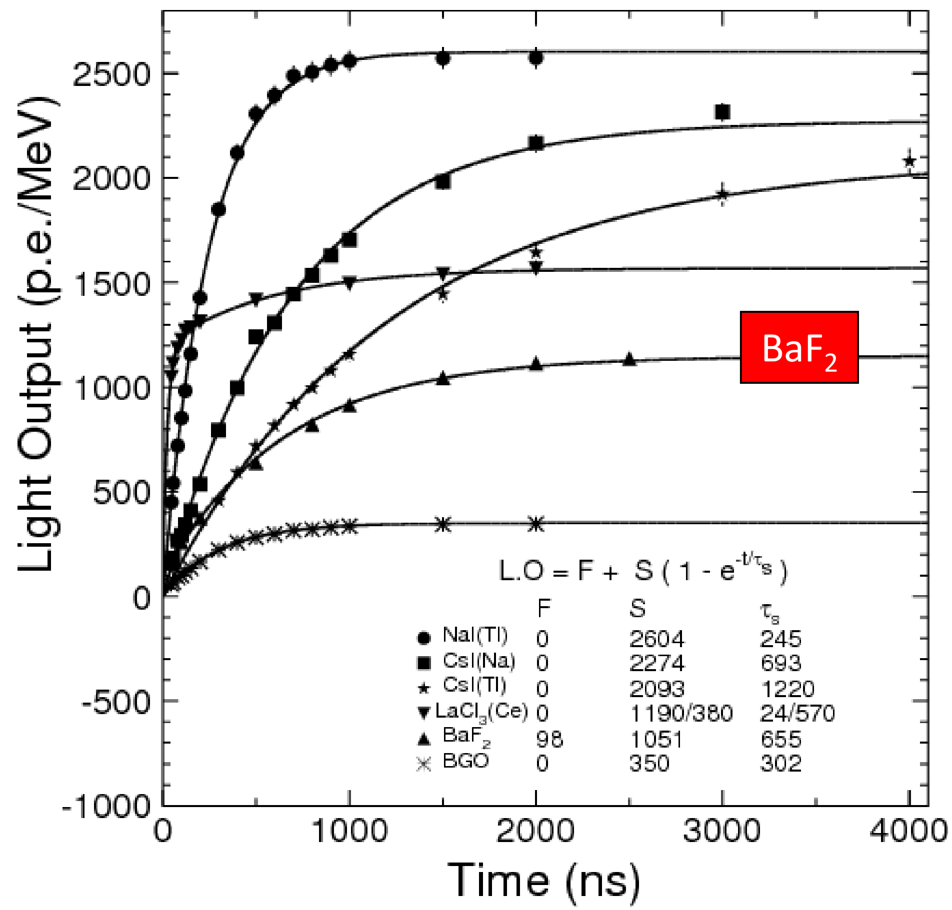
Measured with Philips XP2254B PMT (multi-alkali cathode)

p.e./MeV: LSO/LYSO is 6 & 230 times of BGO & PWO respectively

## Fast Crystal Scintillators

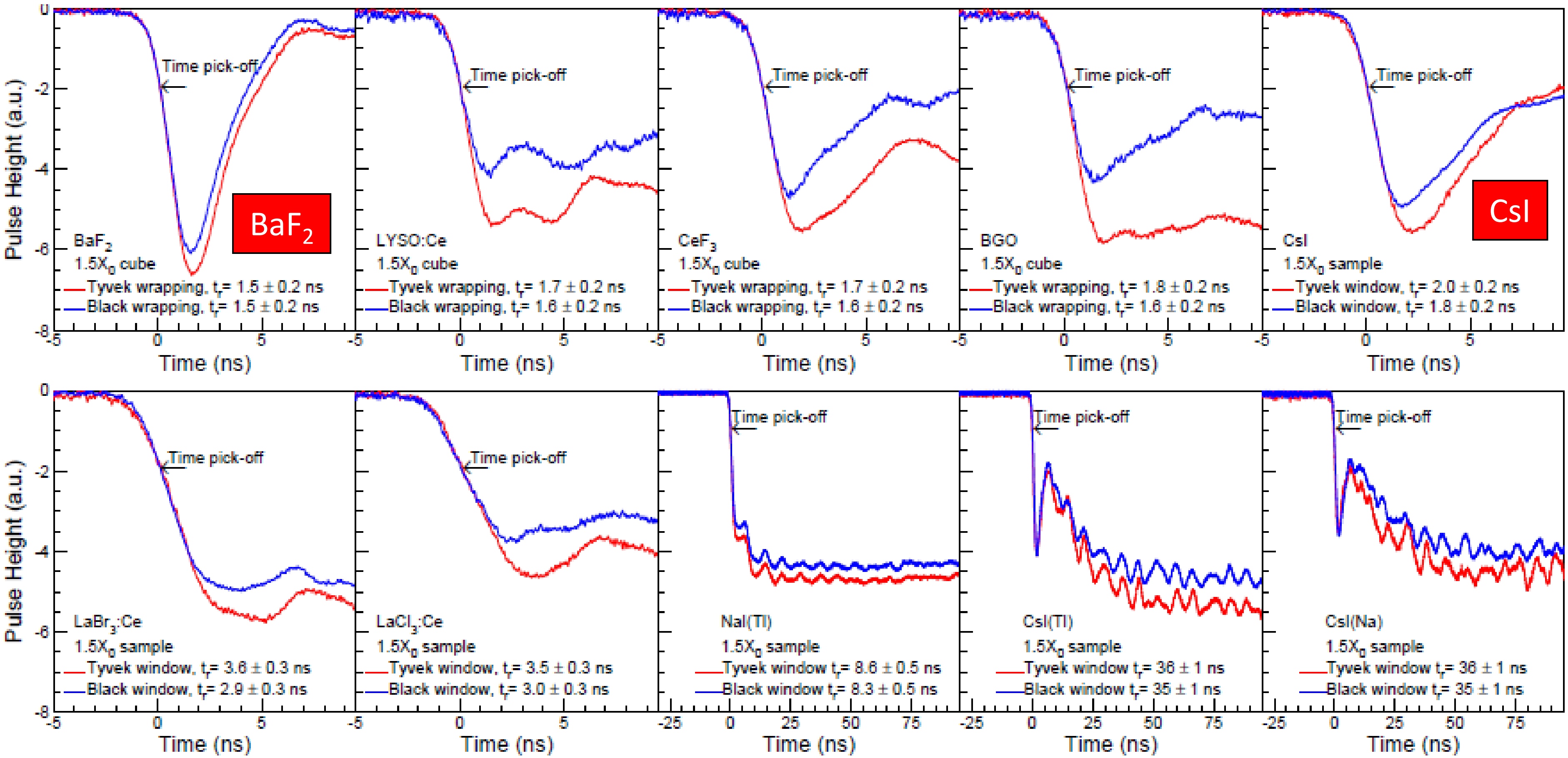



## Slow Crystal Scintillators



# Fast Signals with 1.5 $X_0$ Samples

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




The 3 ns width of $BaF_2$ pulse may be further reduced by faster photodetector
LYSO, $LaBr_3$ & $CeBr_3$ have tail, which would cause pile-up for GHz readout

# Fast Inorganic Scintillators for HEP

| | LYSO:Ce | LSO:Ce, Ca[1] | LuAG:Ce [2] | LuAG:Pr[3] | GGAG:Ce[4,5] | CsI | $BaF_2$[6] | $BaF_2$:Y | $CeBr_3$ | $LaBr_3$:Ce[7] |
|---|---|---|---|---|---|---|---|---|---|---|
| Density (g/cm$^3$) | 7.4 | 7.4 | 6.76 | 6.76 | 6.5 | 4.51 | 4.89 | 4.89 | 5.23 | 5.29 |
| Melting points (°C) | 2050 | 2050 | 2060 | 2060 | 1850[d] | 621 | 1280 | 1280 | 722 | 783 |
| $X_0$ (cm) | 1.14 | 1.14 | 1.45 | 1.45 | 1.63 | 1.86 | 2.03 | 2.03 | 1.96 | 1.88 |
| $R_M$ (cm) | 2.07 | 2.07 | 2.15 | 2.15 | 2.20 | 3.57 | 3.1 | 3.1 | 2.97 | 2.85 |
| $\lambda_I$ (cm) | 20.9 | 20.9 | 20.6 | 20.6 | 21.5 | 39.3 | 30.7 | 30.7 | 31.5 | 30.4 |
| $Z_{eff}$ | 64.8 | 64.8 | 60.3 | 60.3 | 51.8 | 54.0 | 51.6 | 51.6 | 45.6 | 45.6 |
| dE/dX (MeV/cm) | 9.55 | 9.55 | 9.22 | 9.22 | 8.96 | 5.56 | 6.52 | 6.52 | 6.65 | 6.90 |
| $\lambda_{peak}$[a] (nm) | 420 | 420 | 520 | 310 | 540 | 310 | 300<br>220 | 300<br>220 | 371 | 360 |
| PL Emission Peak (nm) | 402 | 402 | 500 | 308 | 540 | 310 | 300<br>220 | 300<br>220 | 350 | 360 |
| PL Excitation Peak (nm) | 358 | 358 | 450 | 275 | 445 | 256 | <200 | <200 | 330 | 295 |
| Absorption Edge (nm) | 170 | 170 | 160 | 160 | 190 | 200 | 140 | 140 | n.r. | 220 |
| Refractive Index[b] | 1.82 | 1.82 | 1.84 | 1.84 | 1.92 | 1.95 | 1.50 | 1.50 | 1.9 | 1.9 |
| Normalized Light Yield[a,c] | 100 | 116[e] | 35[f]<br>48[f] | 44<br>41 | 40<br>75 | 4.2<br>1.3 | 42<br>5.0 | 1.7<br>5.0 | 99 | 153 |
| Total Light yield (ph/MeV) | 30,000 | 34,800[e] | 25,000[f] | 25,800 | 34,700 | 1,700 | 13,000 | 2,100 | 30,000 | 46,000 |
| Decay time[a] (ns) | 40 | 31[e] | 981[f]<br>64[f] | 1208<br>26 | 319<br>101 | 30<br>6 | 600<br>0.6 | 600<br>0.6 | 17 | 20 |
| Light Yield in 1$^{st}$ ns (photons/MeV) | 740 | 950 | 240 | 520 | 260 | 100 | 1200 | 1200 | 1,700 | 2,200 |
| Issues | | | | | neutron x-section | Slightly hygroscopic | Slow component | DUV PD | hygroscopic | |

# Fast Inorganic Scintillators (II)

**a. Top line: slow component, bottom line: fast component;**

**b. At the wavelength of the emission maximum;**

**c. Excited by Gamma rays;**

**d. For $Gd_3Ga_3Al_2O_{12}$:Ce**

**e. For 0.4 at% Ca co-doping**

**f. Ceramic with 0.3 Mg at% co-doping**


[1] Spurrier, et al., *IEEE T. Nucl. Sci.* 2008,55 (3): 1178-1182

[2] Liu, et al., *Adv. Opt. Mater.* 2016, 4(5): 731–739

[3] Hu, et al., *Phys. Rev. Applied* 2016, 6: 064026

[4] Lucchini, et al., *NIM A* 2016, 816: 176-183

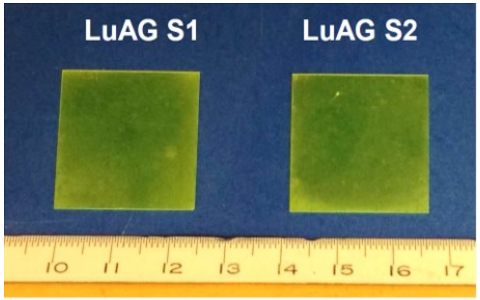
[5] Meng, et al., *Mat. Sci. Eng. B-Solid* 2015, 193: 20-26

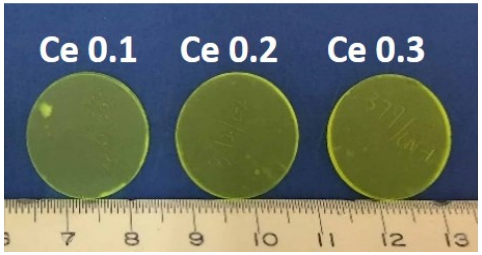
[6] Diehl, et al., *J. Phys. Conf. Ser* 2015, 587: 012044

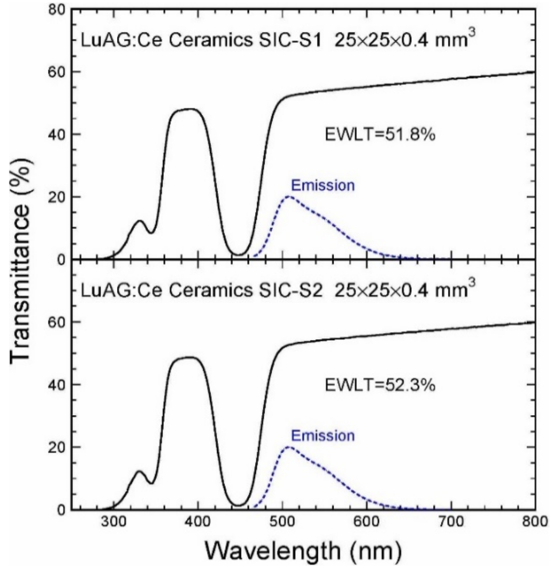
[7] Pustovarov, et al., Tech. Phys. Lett. 2012, 784-788

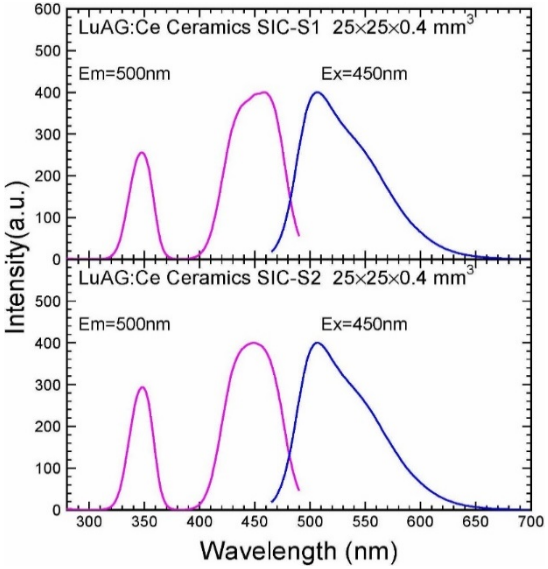
# LuAG:Ce Ceramic Samples

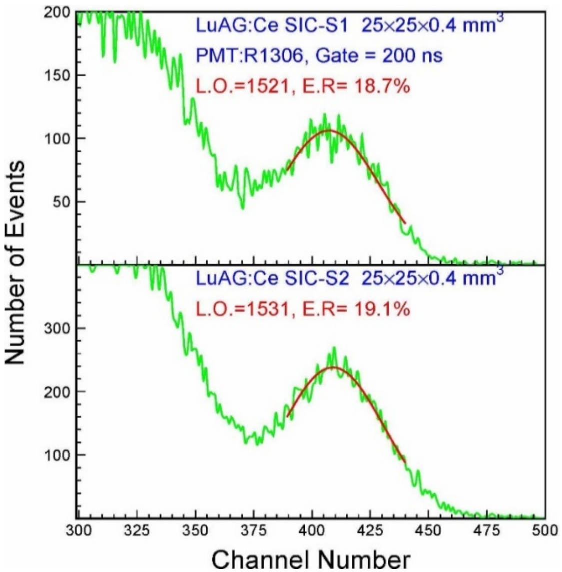
Presented in NSS2017, will be published in IEEE TNS NS

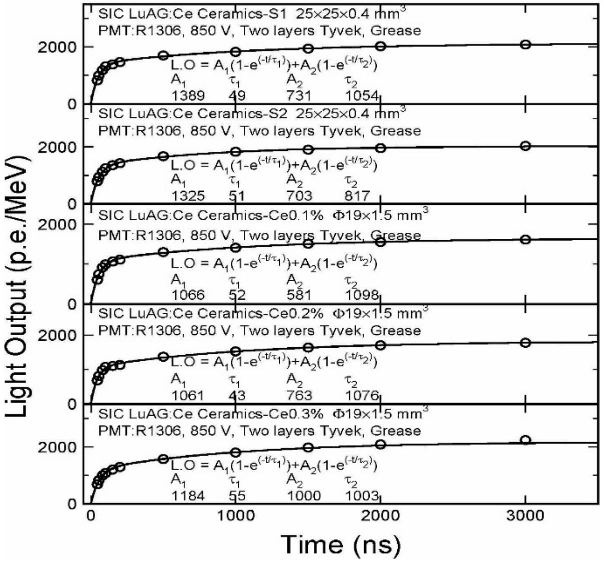


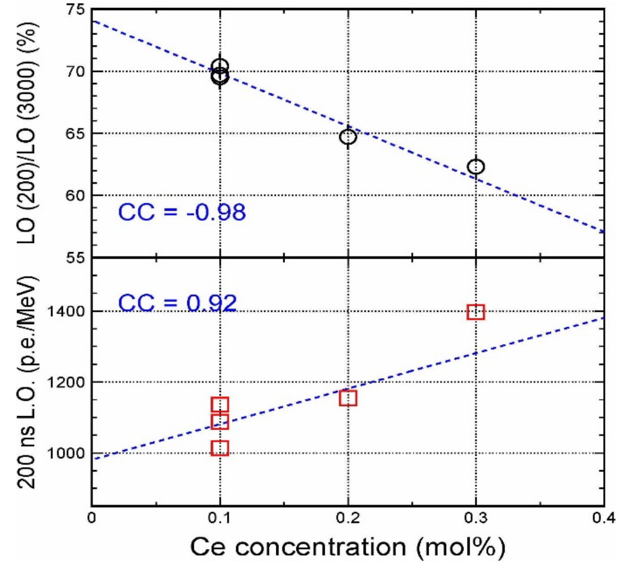



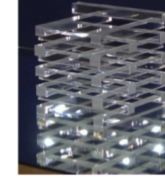



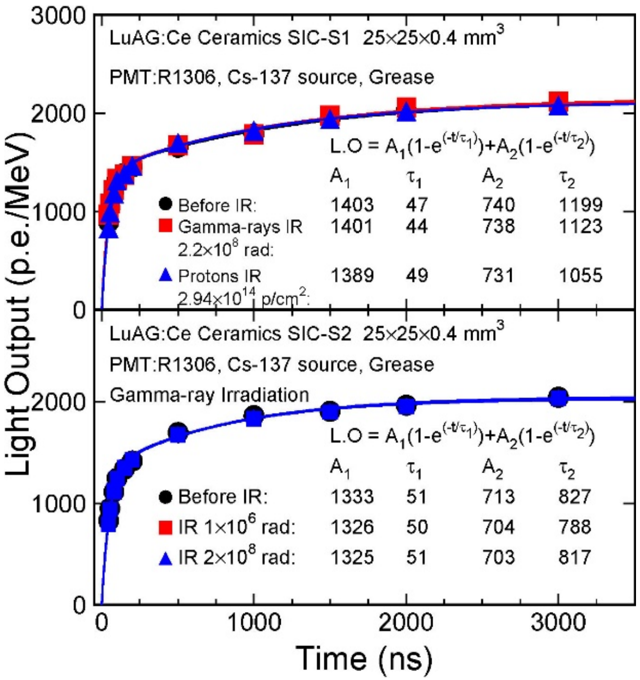



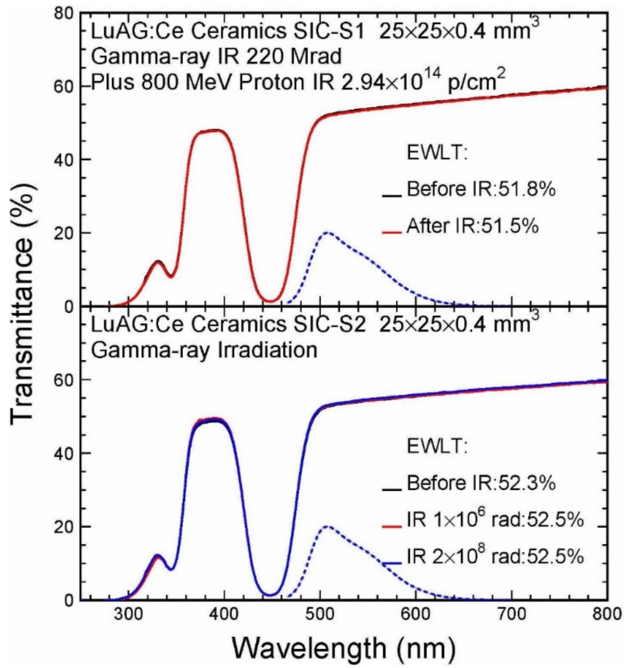



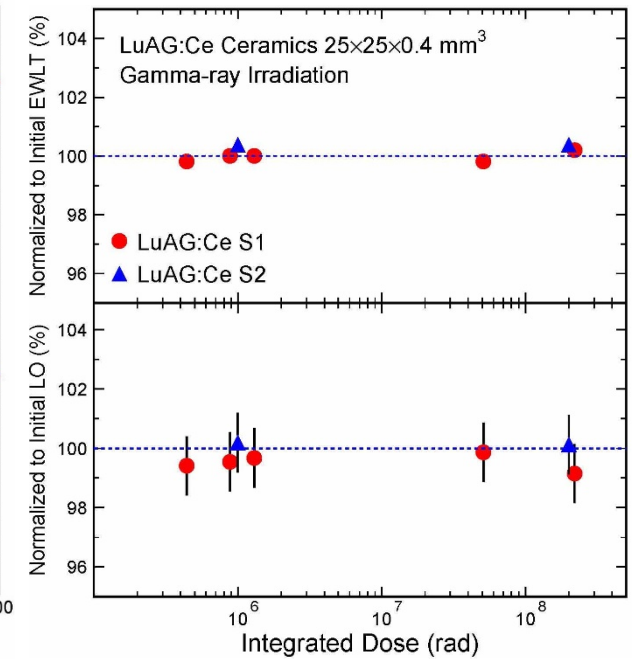
# Excellent Radiation Hardness



No damage observed in both transmittance and light output after 220 Mrad ionization dose and $3 \times 10^{14}$ p/cm$^2$ of 800 MeV

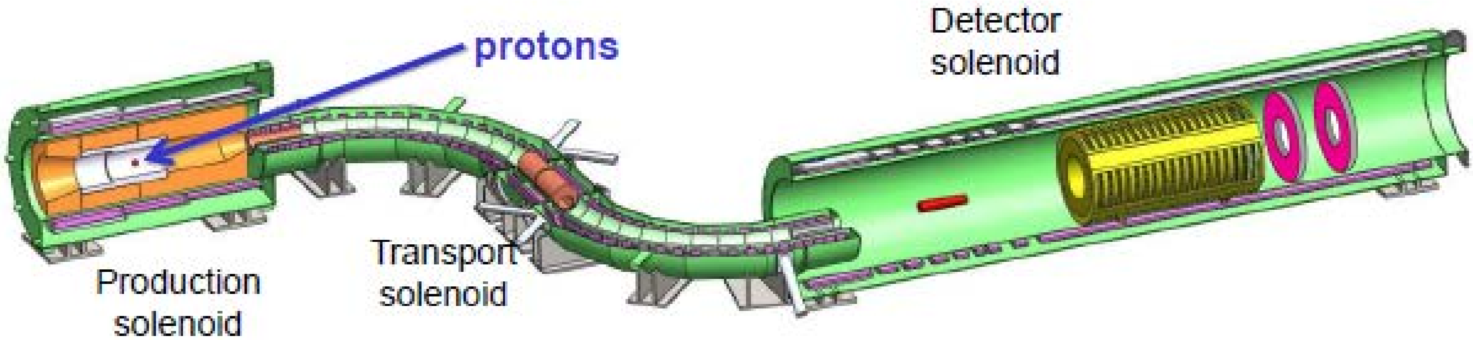



Very promising for a scintillating ceramics based calorimeter
Presented in NSS2017 will be published in IEEE TNS NS

# Mu2e Specifications for Undoped CsI



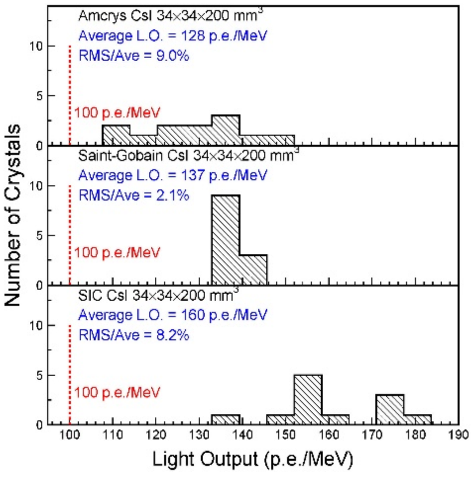

- ❑ Crystal lateral dimension: ±100 μ, length: ±100 μ.
- ❑ Scintillation properties at seven points along the crystal wrapped by two layers of Tyvek paper of 150 μm for alternative end coupled to a bi-alkali PMT with an air gap. Light output and FWHM resolution are the average of seven points with 200 ns integration time. The light response uniformity is the rms of seven points. F/T is measured at the point of 2.5 cm to the PMT.
  - ❑ Light output (LO): > **100 p.e./MeV** with 200 ns gate, will be compared to reference for cross-calibration;
  - ❑ FWHM Energy resolution: **< 45%** for Na-22 peak;
  - ❑ Light response uniformity (LRU, rms of seven points): **< 5%**;
  - ❑ Fast (200 ns)/Total (3000 ns) Ratio: **> 75%**.
- ❑ Radiation related spec::
  - ❑ Normalized LO **after 10/100 krad: > 85/60%;**
  - ❑ Radiation Induced noise **@ 1.8 rad/h: < 0.6 MeV**.

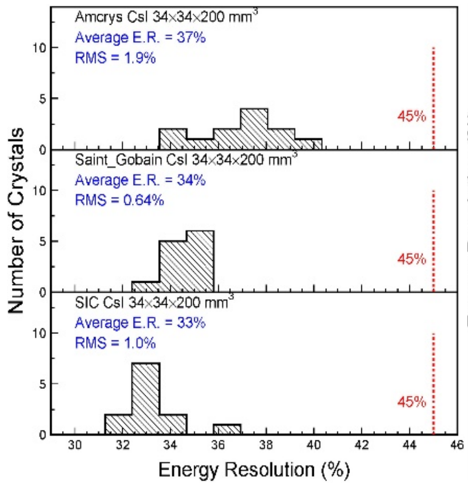
# Mu2e Preproduction CsI

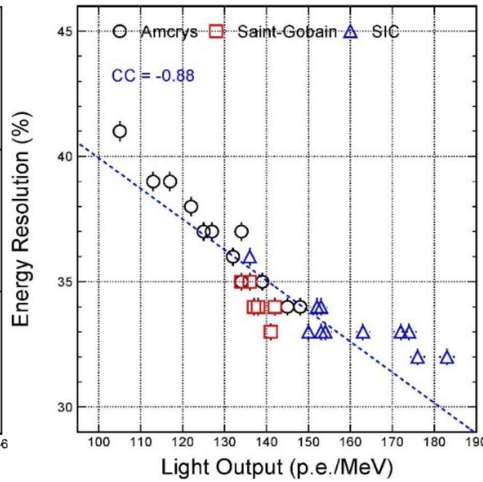
A total of 72 crystals from Amcrys, Saint-Gobain and SICCAS has been measured at Caltech and LNF

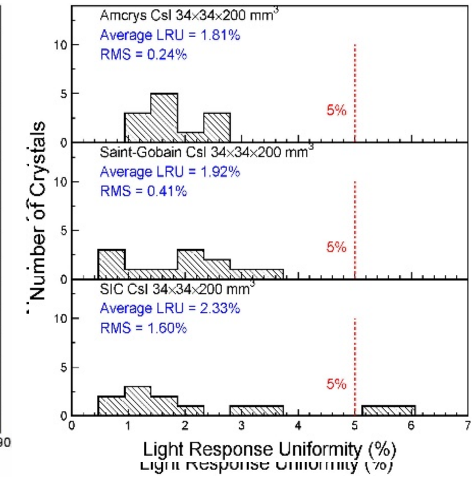
# Quality of Pre-Production CsI

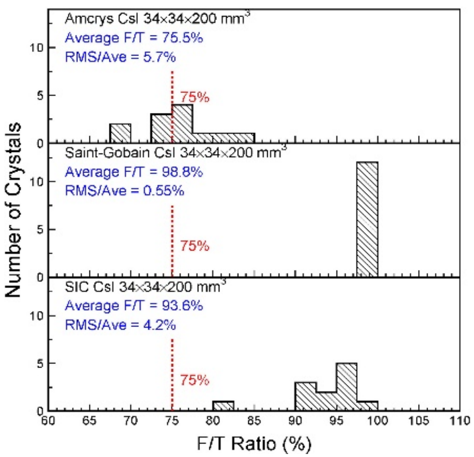
Presented in SCINT2017, will be published in IEEE TNS NS

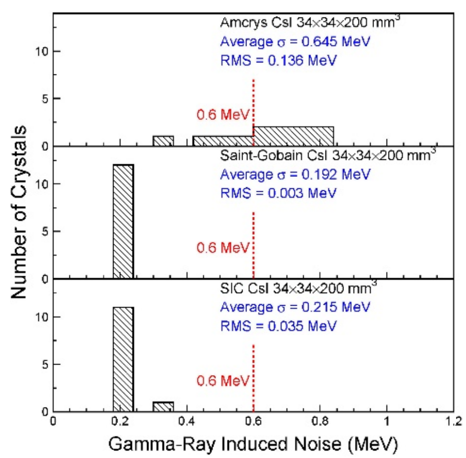


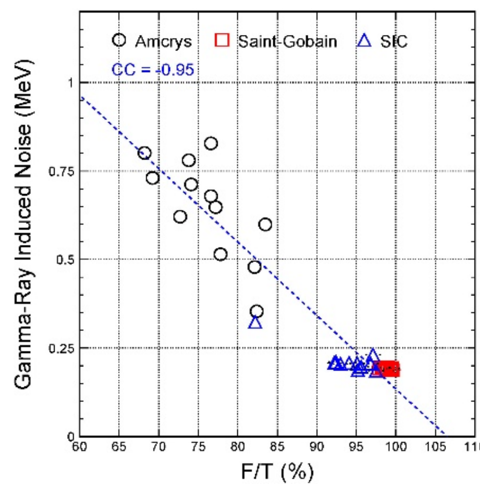



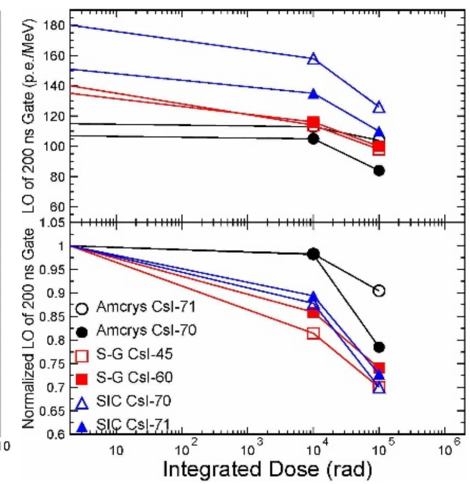



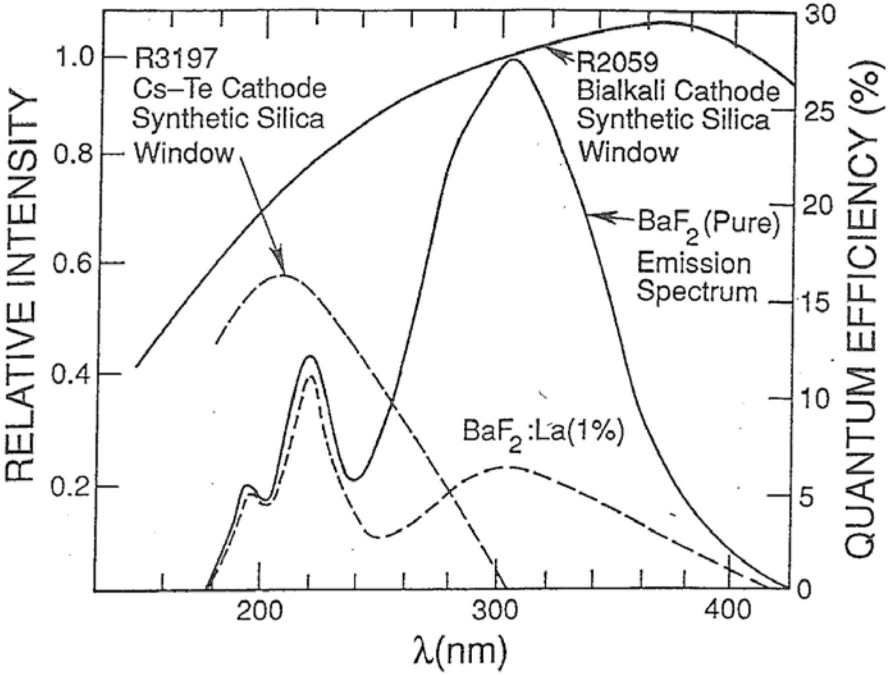

Most preproduction crystals satisfy specifications, except a few crystals from SICCAS fail the LRU spec and about half Amcrys crystals fail the F/T ratio and RIN

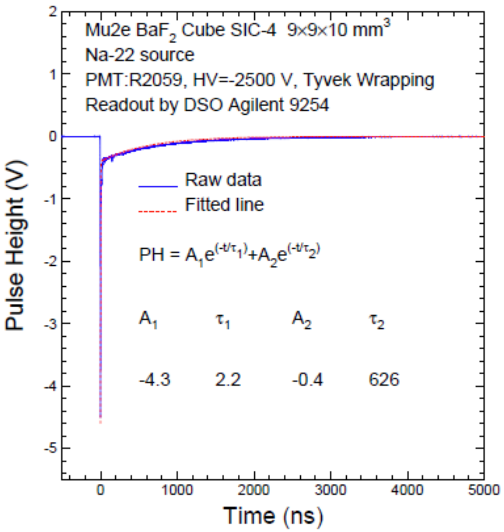
# Fast and Slow Light from $BaF_2$

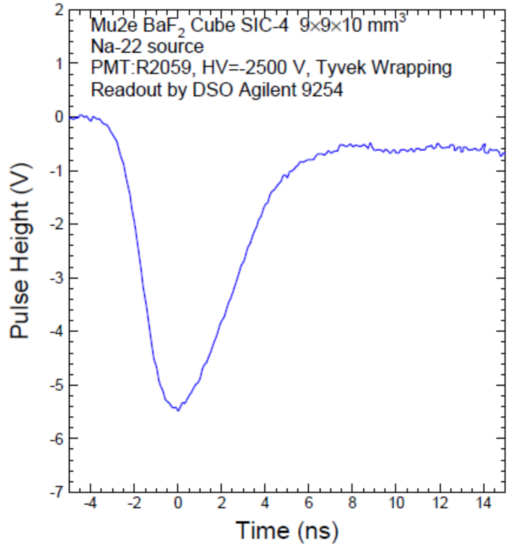
A radiation level exceeding 100 krad is expected at the proposed Mu2e-II, so $BaF_2$ is being considered.

The amount of light in the fast component of $BaF_2$ at 220 nm with sub-ns decay time is similar to CsI.

Spectroscopic selection of fast component may be realized by solar blind photocathode and/or selective doping.



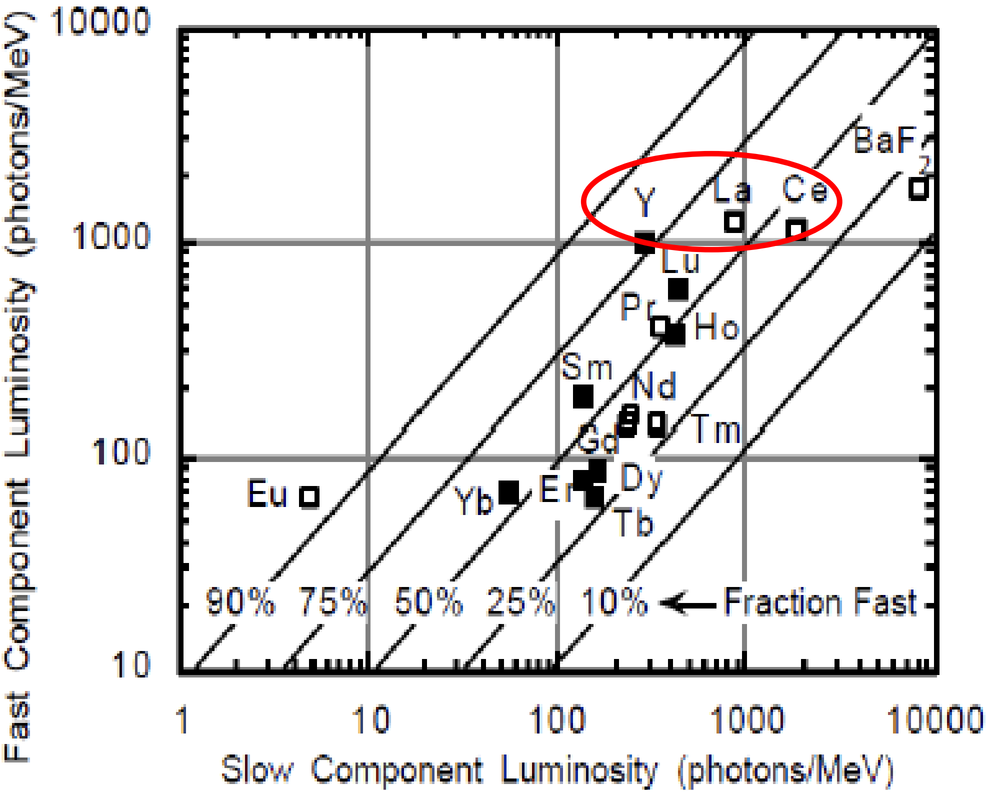



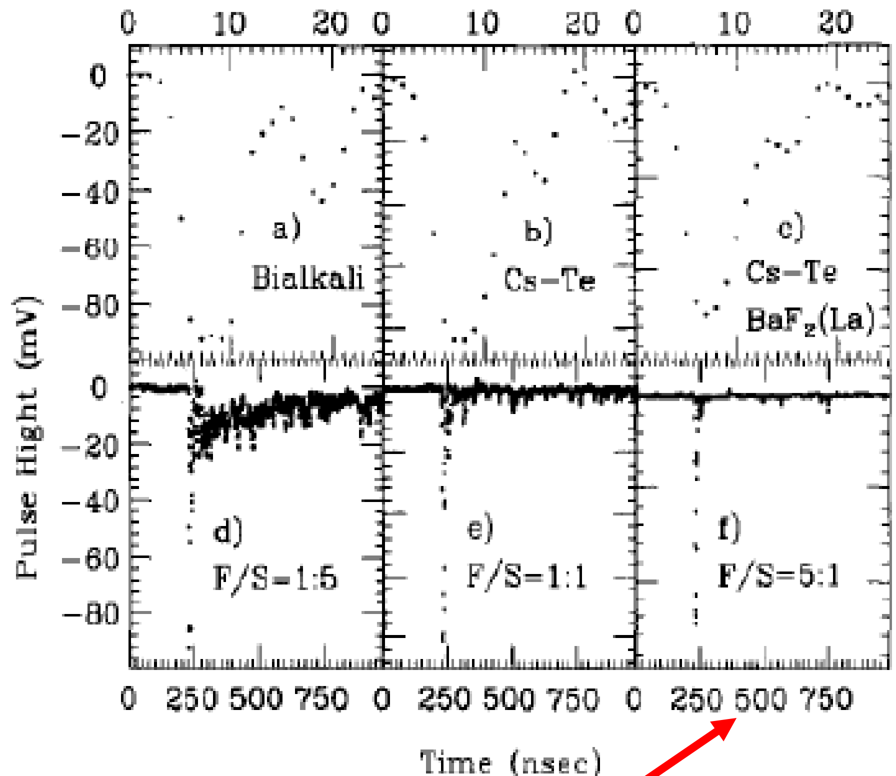



# Slow Suppression: Doping & Readout

**Slow component may be suppressed by RE doping: Y, La and Ce**

B.P. SOBOLEV et al., "SUPPRESSION OF BaF2 SLOW COMPONENT OF X-RAY LUMINESCENCE IN NON-STOICHIOMETRIC Ba0.9R0.1F2 CRYSTALS (R=RARE EARTH ELEMENT)," *Proceedings of The Material Research Society: Scintillator and Phosphor Materials*, pp. 277-283, 1994.

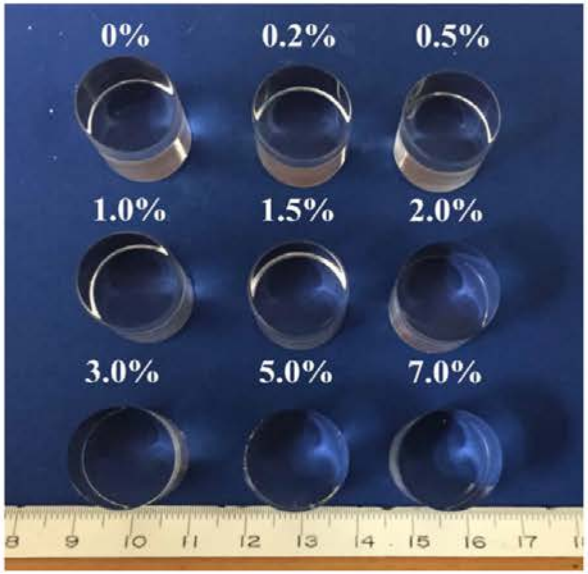


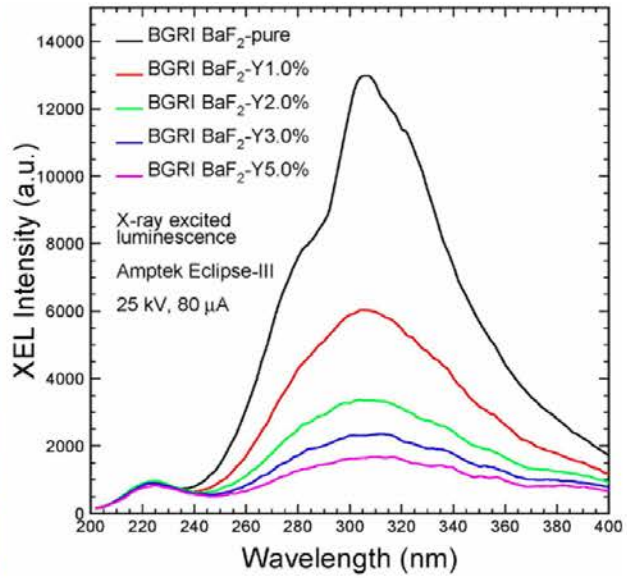



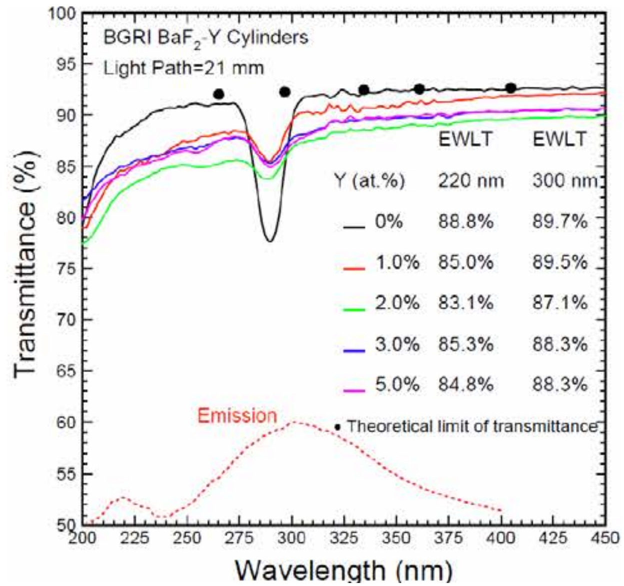

**Solar-blind cathode (Cs-Te) + La doping achieved F/S = 5/1**

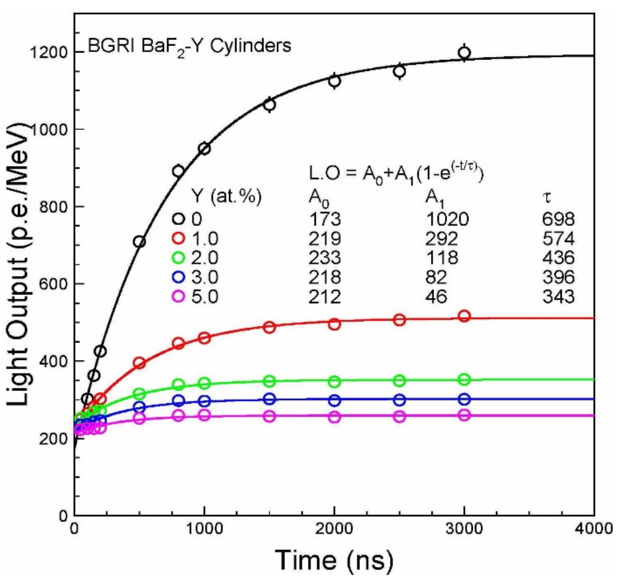
# Yttrium Doped $BaF_2$ for Mu2e-II

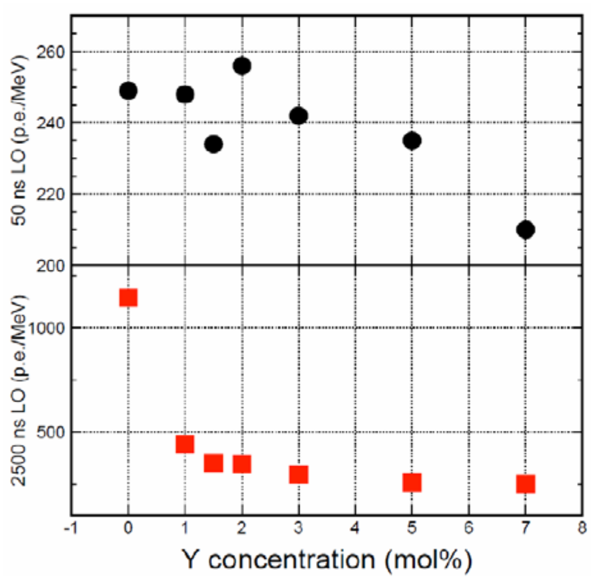
## F/S ratio from 1/5 to 5/1 , presented in TIPP 2017 Beijing

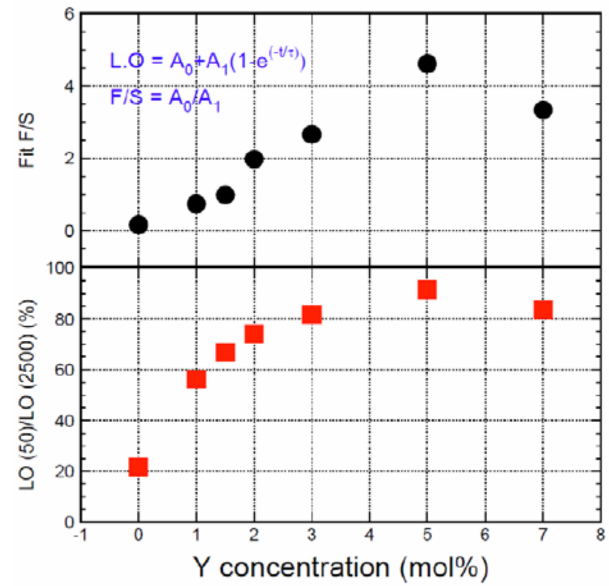


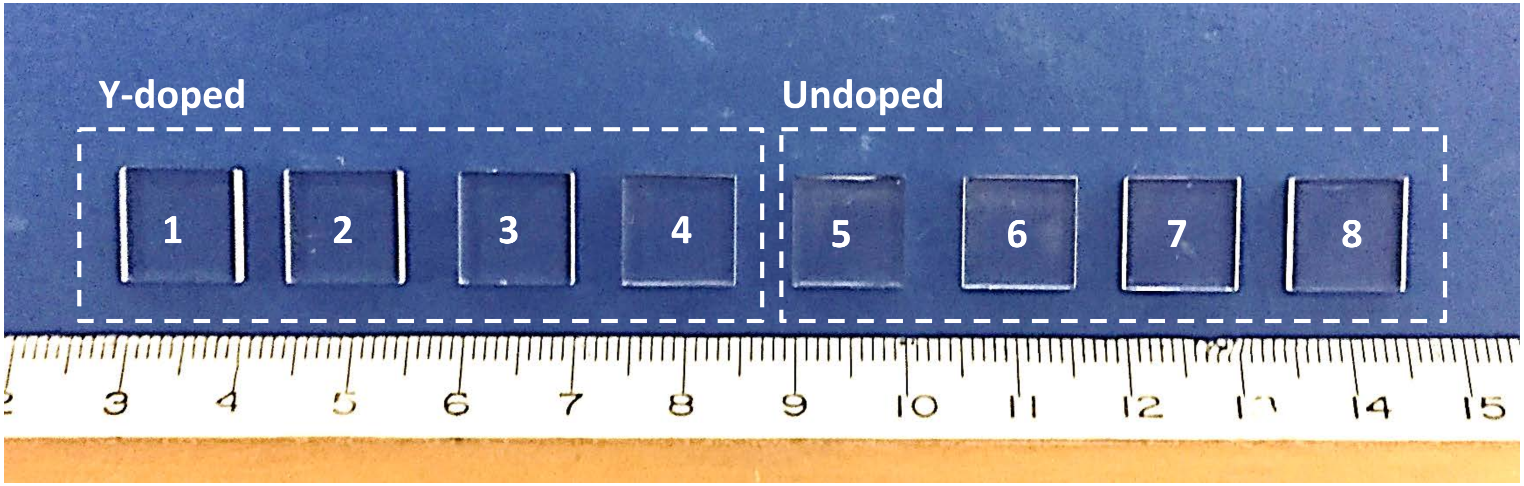



# Eight $BaF_2$ Plates from BGRI



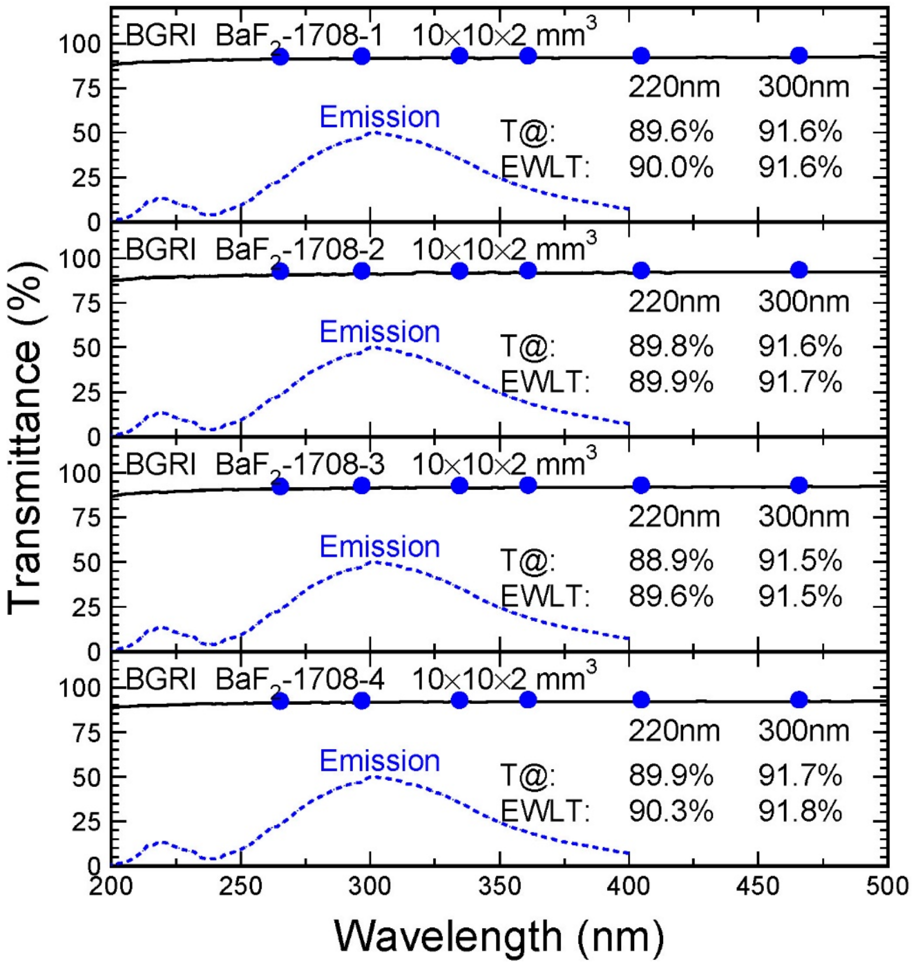

| ID | Dimension ($mm^3$) | Polishing |
|---|---|---|
| BGRI Y-doped $BaF_2$-1708-1,4 | 10x10x2 | Double faces |
| BGRI Undoped $BaF_2$-1708-5,8 | 10x10x2 | Double faces |
| All samples received in August 31, 2017 | | |

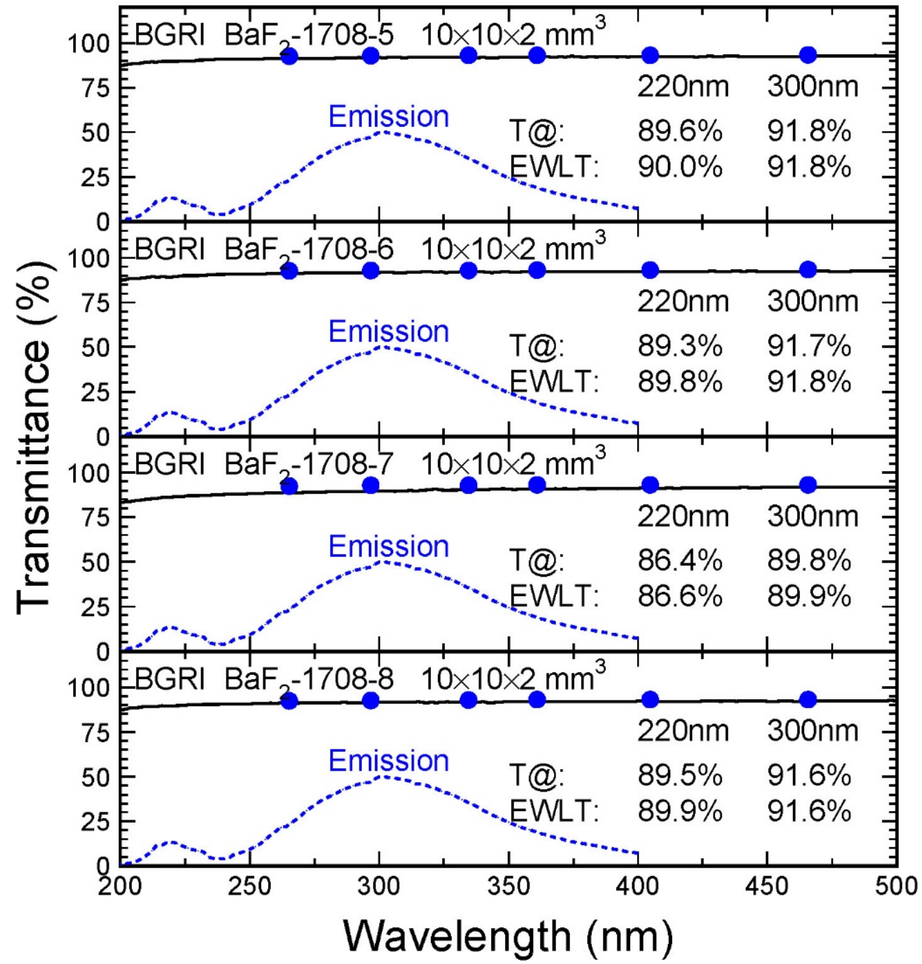
## Experiments

- Properties measured at room temperature : PHS, LO & Decay kinetics

# Transmittance: Y:$BaF_2$ and $BaF_2$

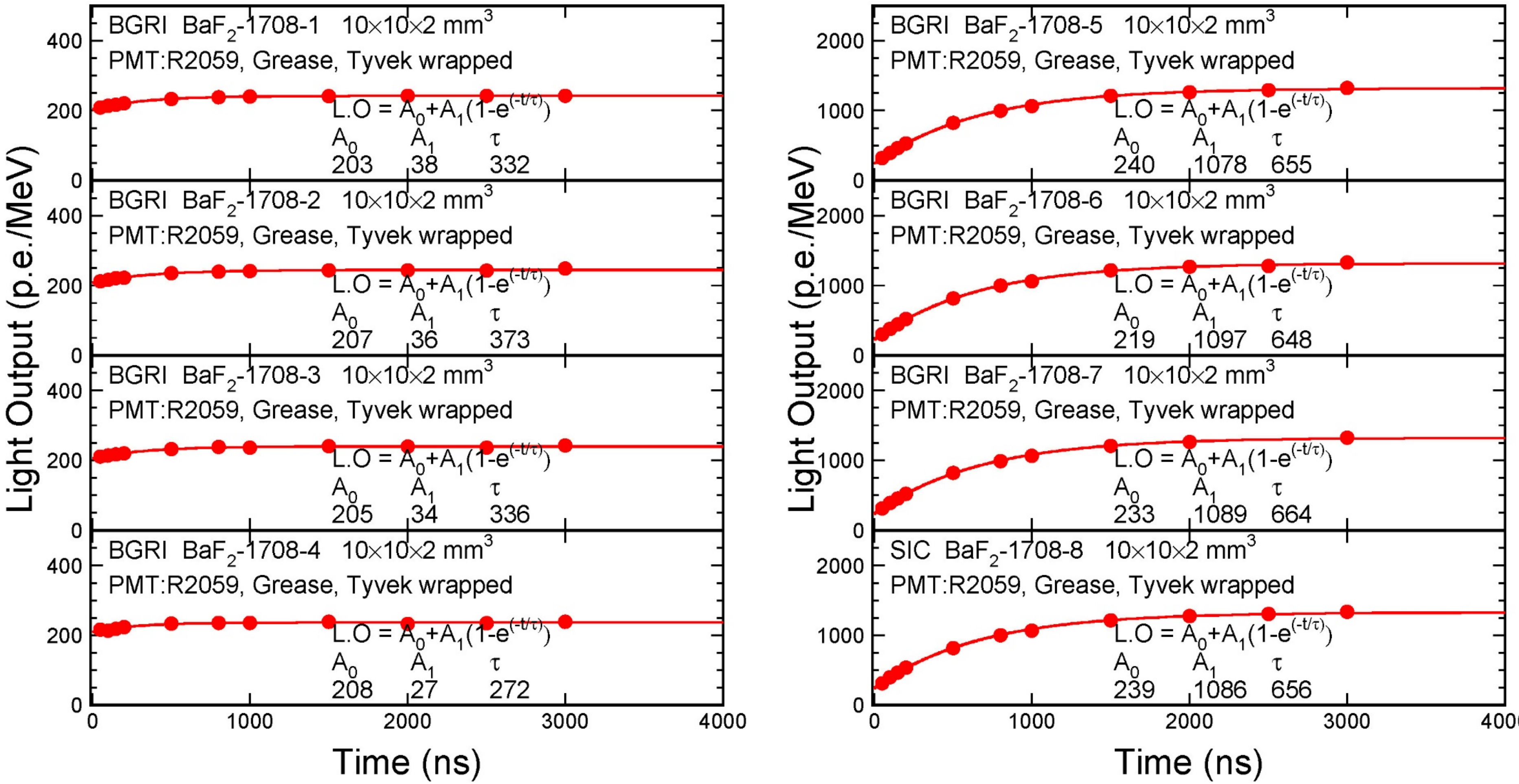
Good transparency for both fast and slow scintillation



# Light Output: Y:$BaF_2$ and $BaF_2$

F/S ratio increased from 0.21 to 6 .2, presented in NSS2017

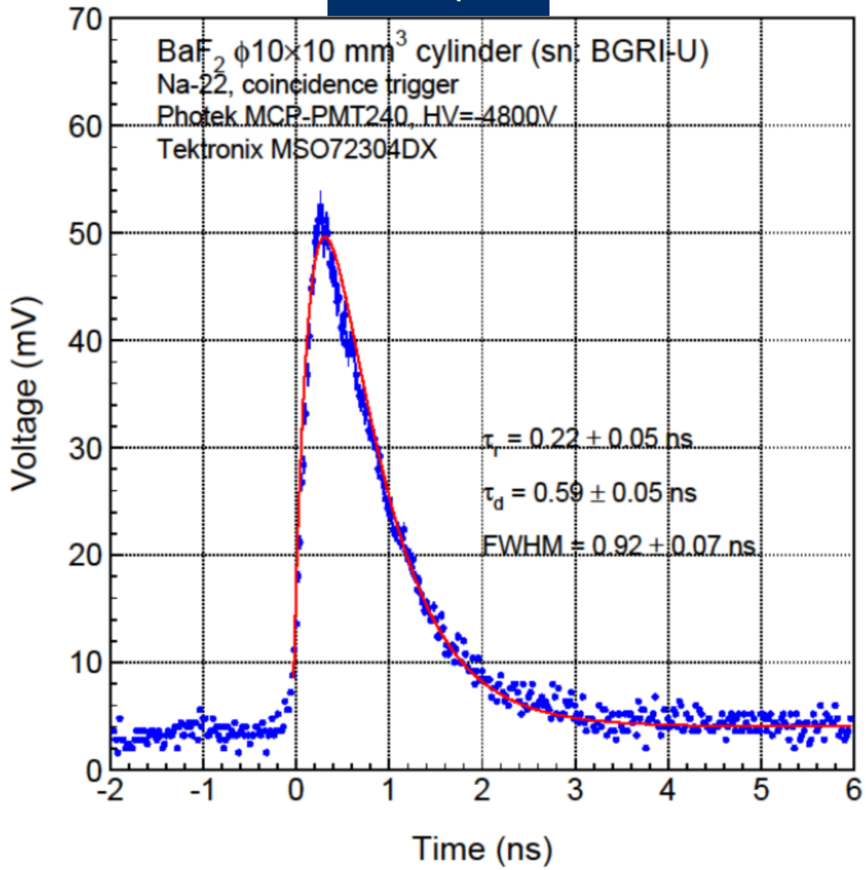



Being irradiation up to 200 Mrad and $2x10^{15}$ n/cm$^2$ at the East Port of LANSCE

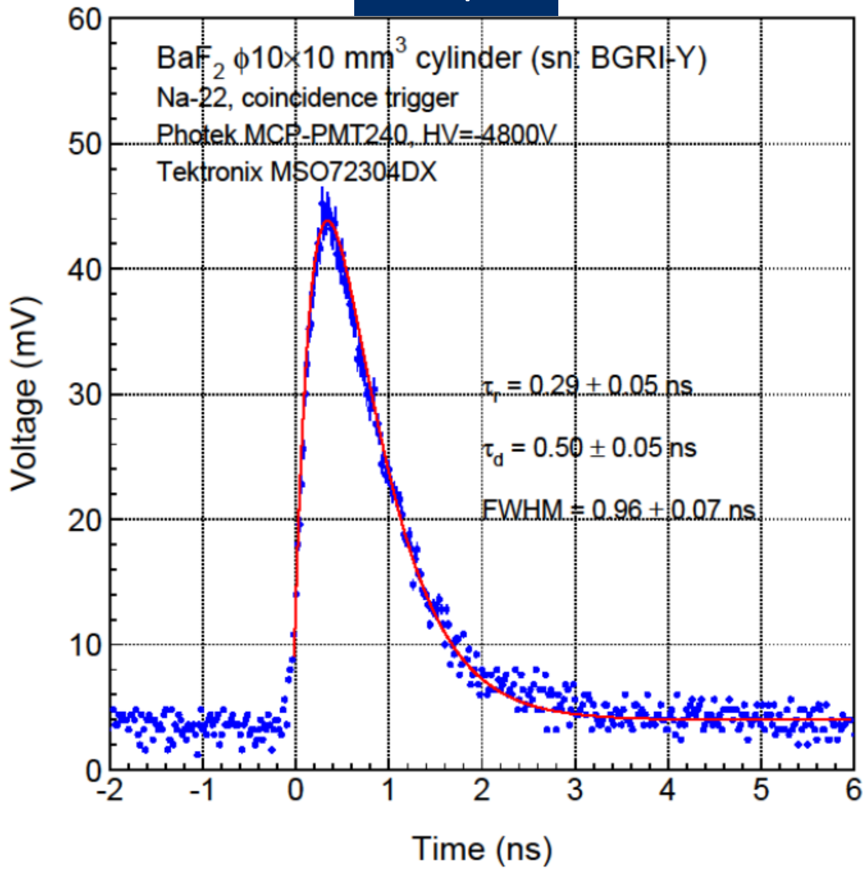
# Pulse Shape: $BaF_2$ Cylinders

BGRI $BaF_2$ cylinders of $\Phi 10\times 10\ cm^3$ shows γ-ray response: 0.26/0.55/0.94 ns of rising/decay/FWHM width

Undoped

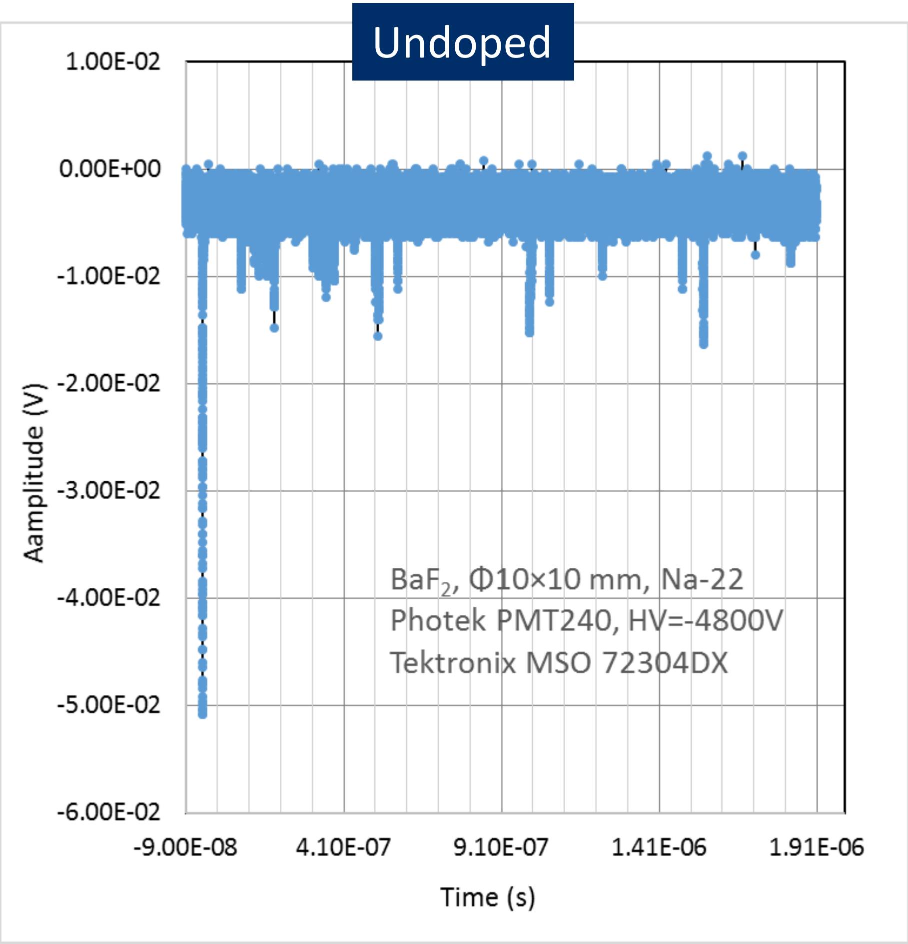


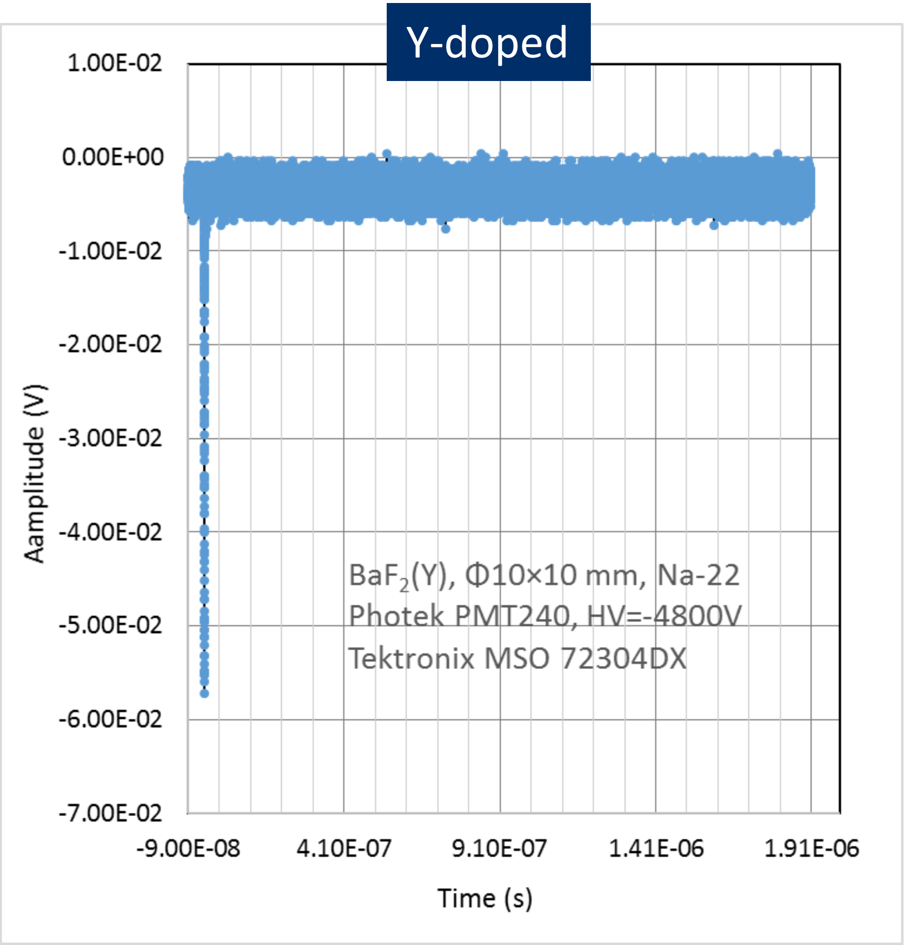

Y-doped



# Tail Reduced in BGRI $BaF_2$:Y

Slow component tail observed in 2 µs in BaF2, not BaF2:Y



# Summary of $BaF_2$ Cylinders

Consistent pulse shape observed between $PbF_2$ and $BaF_2$, indicating that the decay time of the fast component in $BaF_2$ less than 0.6 ns, faster than literature

| Samples | Dimensions | Excitation | Rise time (ns) | Decay time (ns) | FWHM (ns) |
|---|---|---|---|---|---|
| MCP-PMT240* | Φ40 mm | Laser pulse | 0.185 | N/A | 1.36 |
| PbF | 50×50×50 $mm^3$ | Cosmic-ray | 0.18±0.05 | 0.61±0.05 | 0.88±0.07 |
| SIC-U | Φ10×10 $mm^3$ | Cosmic-ray | 0.26±0.05 | 0.52±0.05 | 0.92±0.07 |
| SIC-Y | Φ10×10 $mm^3$ | Cosmic-ray | 0.26±0.05 | 0.57±0.05 | 0.98±0.07 |
| BGRI-U | Φ10×10 $mm^3$ | Na-22 (511KeV) | 0.22±0.05 | 0.59±0.05 | 0.92±0.07 |
| BGRI-Y | Φ10×10 $mm^3$ | Na-22 (511KeV) | 0.29±0.05 | 0.50±0.05 | 0.96±0.07 |

*From test report of the Photek PMT240 MCPT.

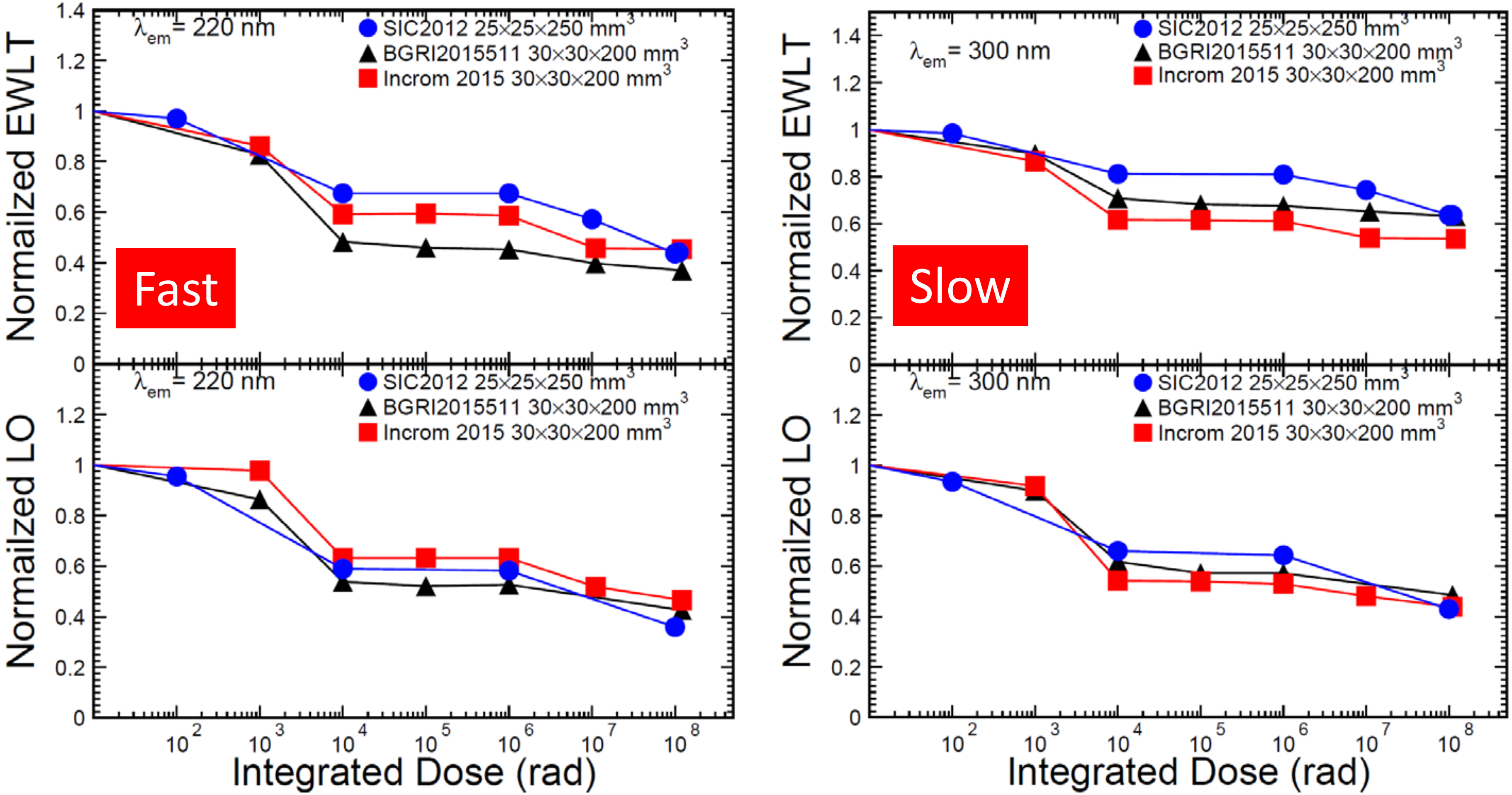
# BGRI/Incrom/SIC $BaF_2$ Samples




| ID | Vendor | Dimension (mm³) | Polishing |
|---|---|---|---|
| SIC 1-20 | SICCAS | 30x30x250 | Six faces |
| BGRI-2015 D, E, 511 | BGRI | 30x30x200 | Six faces |
| Russo 2, 3 | Incrom | 30x30x200 | Six faces |

# $BaF_2$: Normalized EWLT and LO

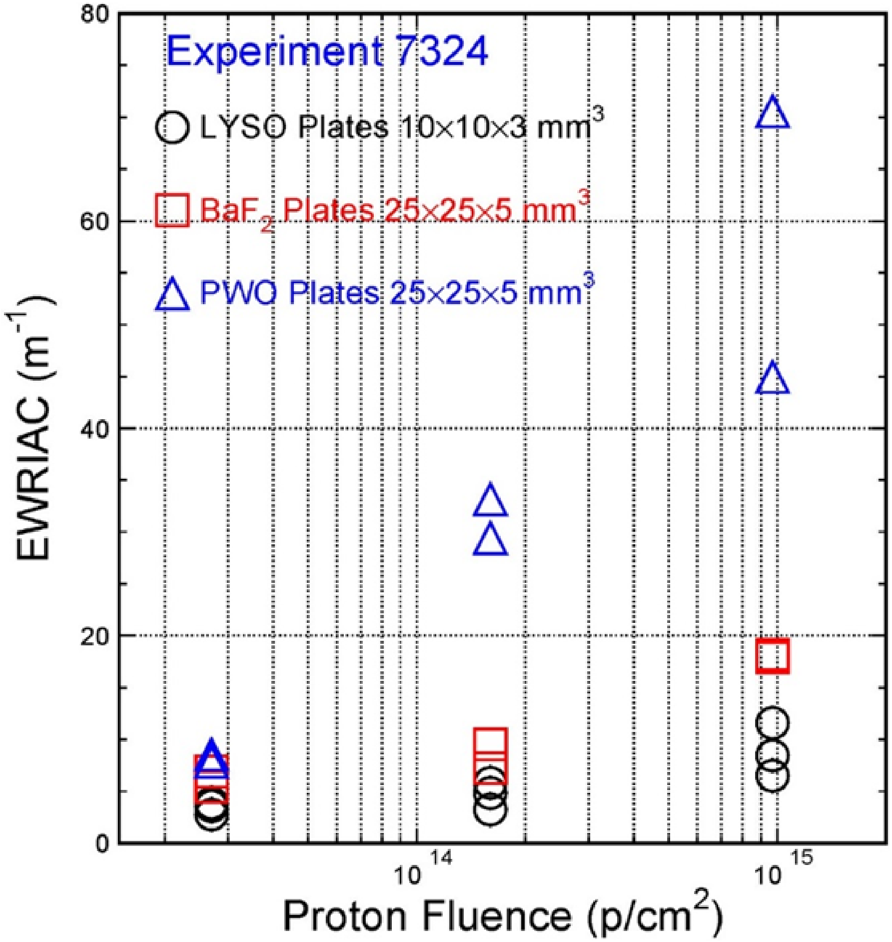
Consistent damage in crystals from three vendors

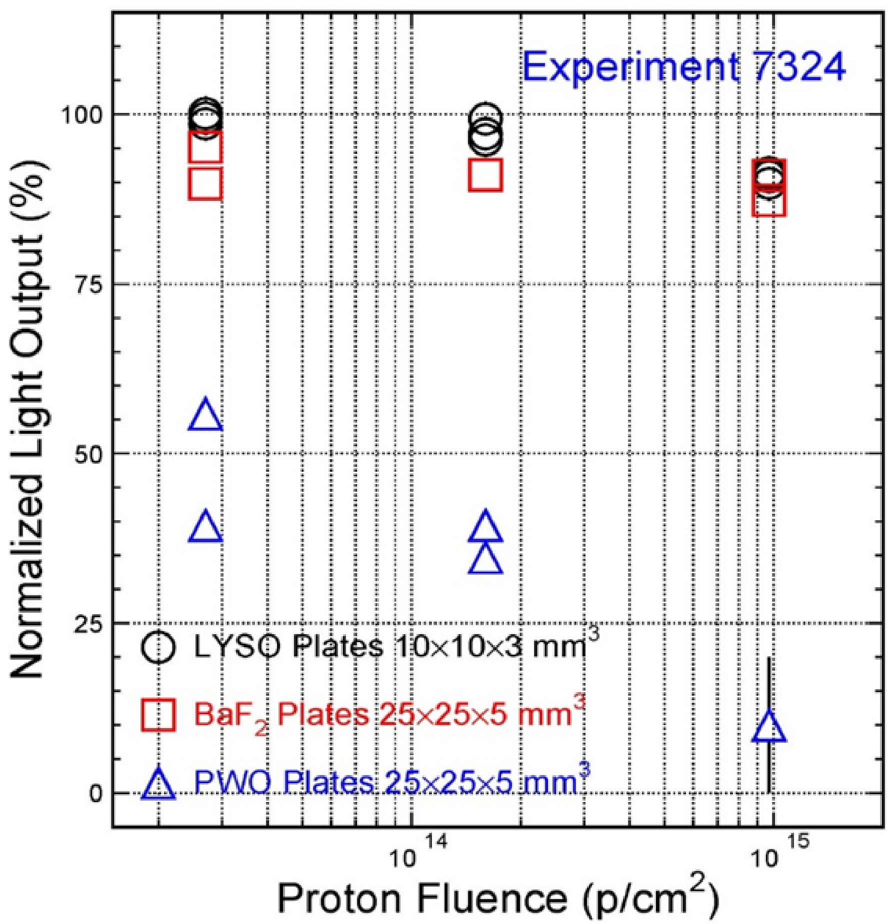



Remaining light output after 120 Mrad: 40%/45% for the fast/slow component

# RIAC & LO Vs. Proton Fluence

Excellent radiation hardness of LYSO and $BaF_2$ up to $10^{15}$ p/cm$^2$



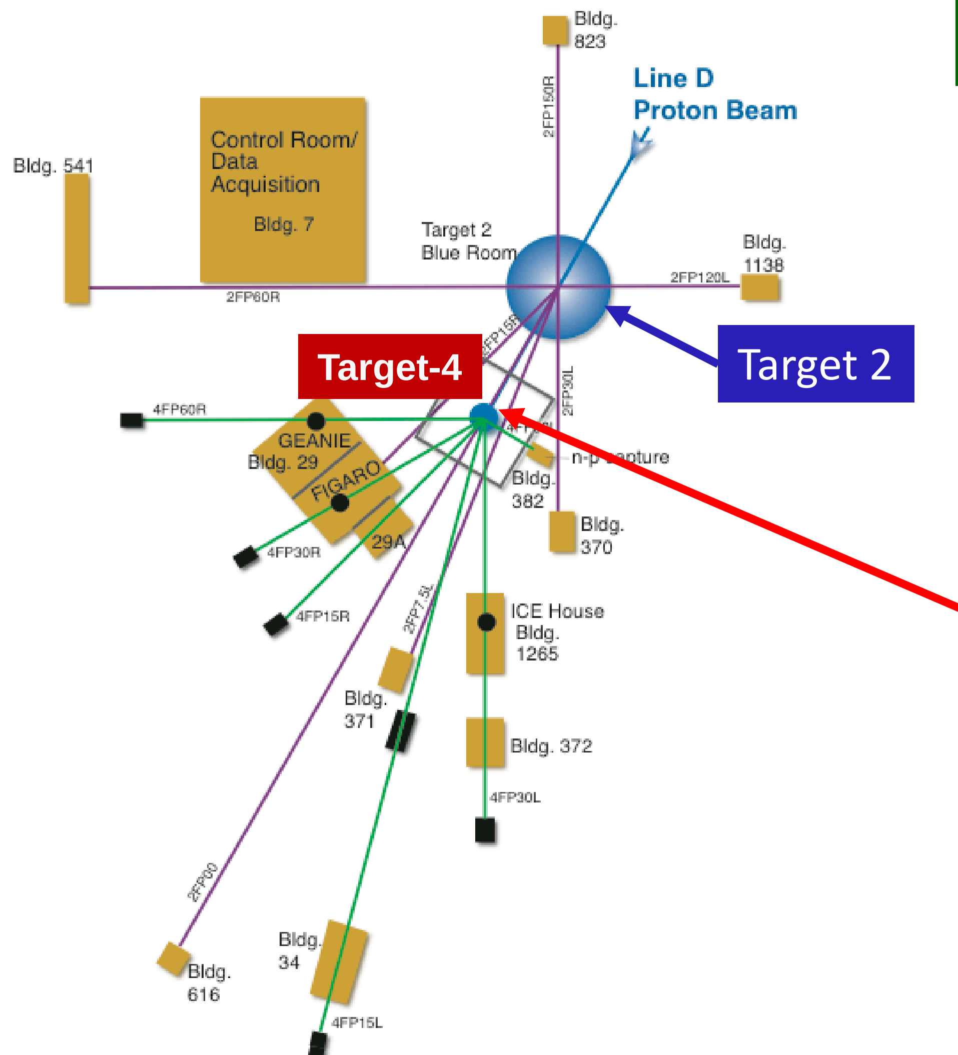



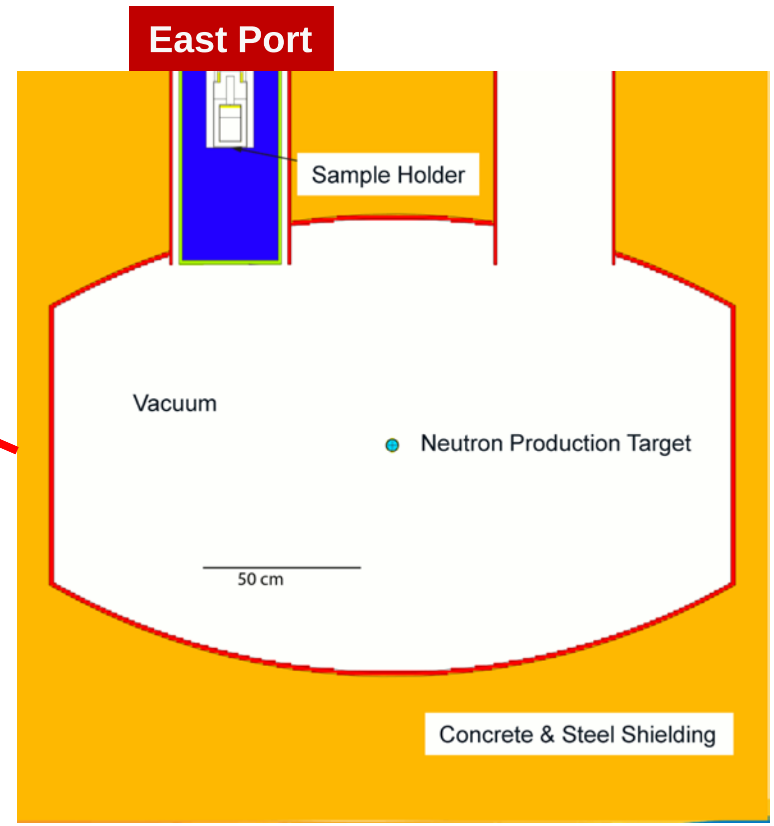

Presented in SCINT 2017, will be published in IEEE TNS NS

# Neutron Irradiation Test at LANL

**Los Alamos Neutron Science Center (LANSCE)**

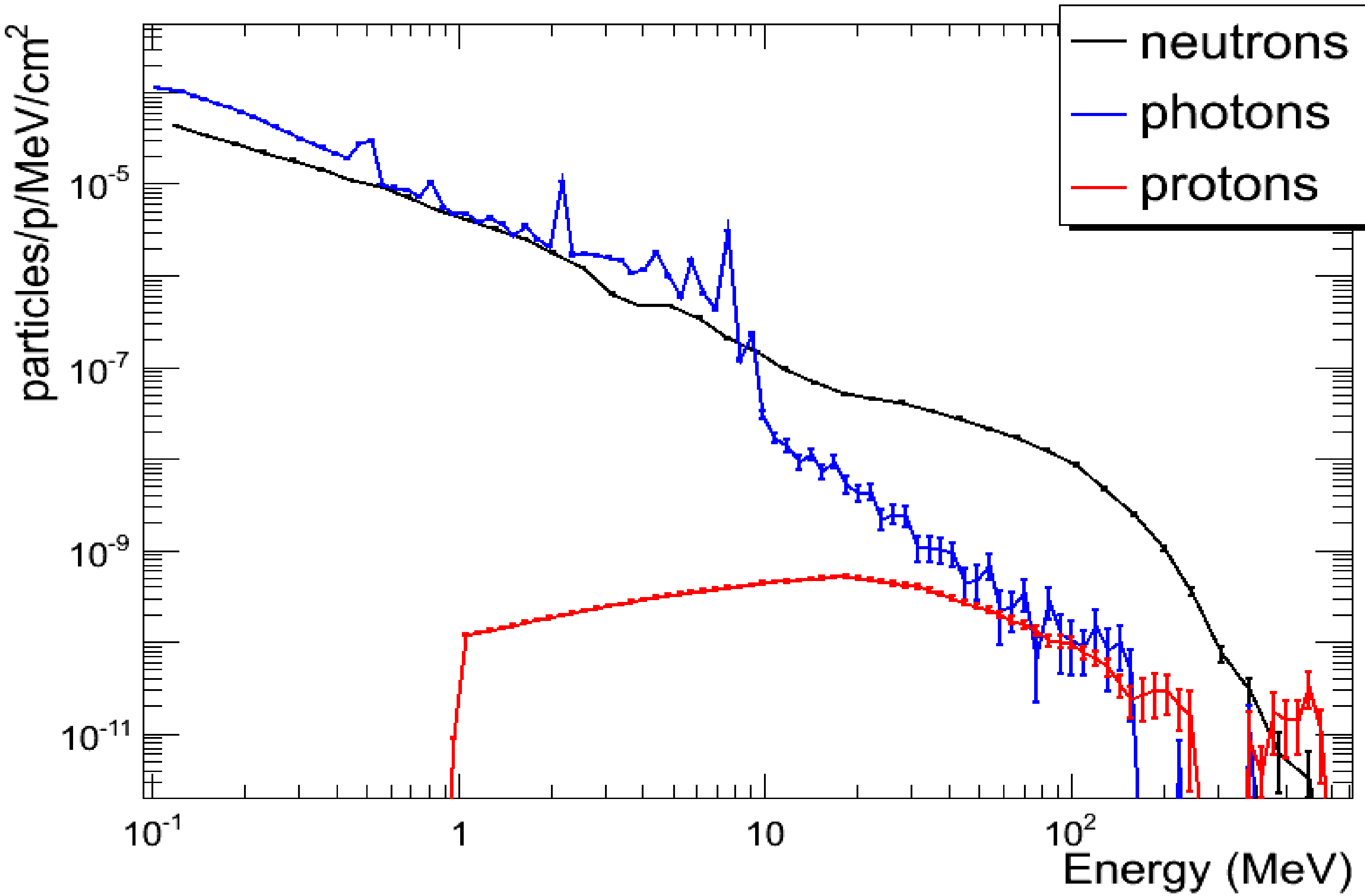
Samples are placed at the Target-4 East Port, about 1.2 m away from the neutron production target.



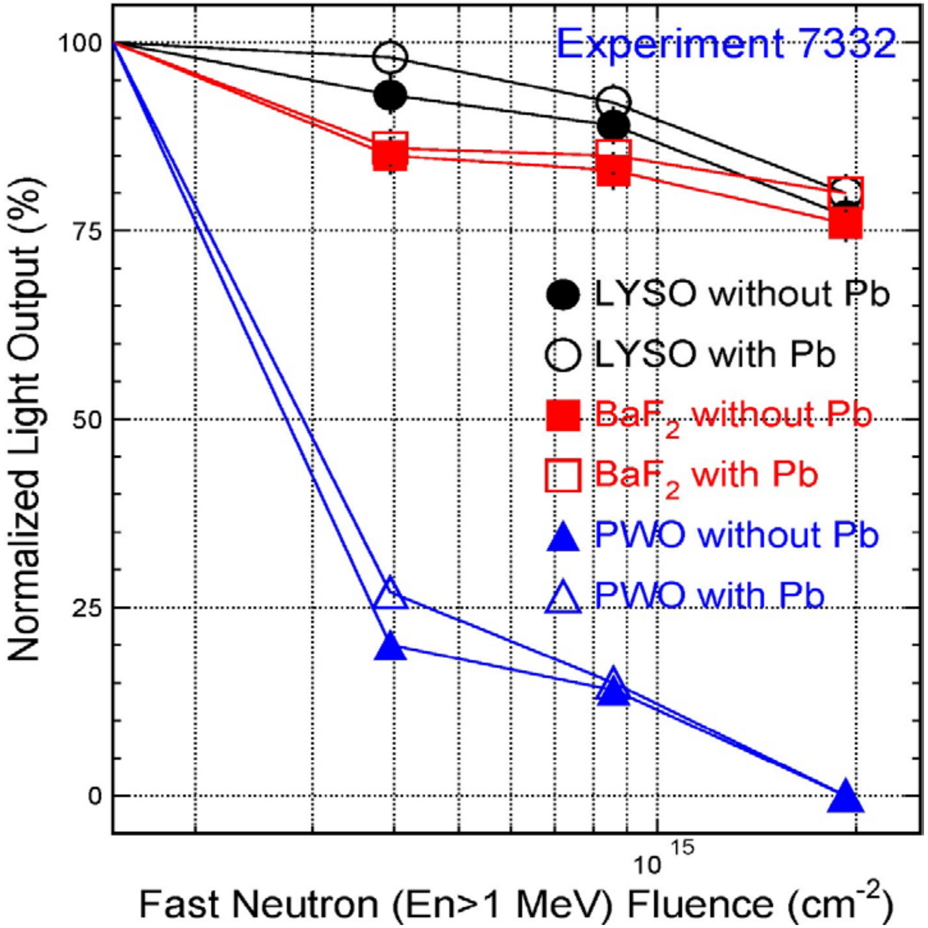
# Neutrons/Photons/Protons Fluxes

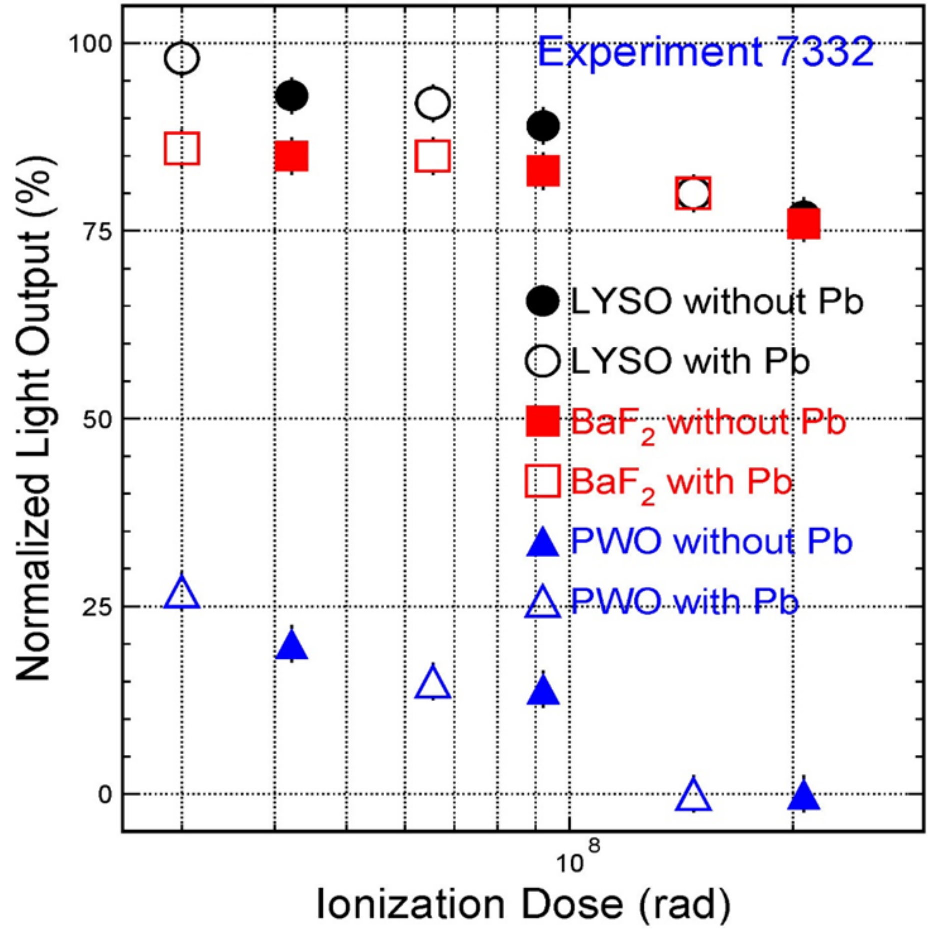
Neutrons/Photons/Protons fluxes are calculated by using MCNPX (Monte Carlo N-Particle eXtended). Plotted spectra are tallied in the largest sample volume (averaging)



# LO Vs. Fast Neutron Fluence And Ionization Dose from γ-Rays

Robust LYSO and $BaF_2$: up to 200 Mrad and 2 x $10^{15}$ n/$cm^2$
No neutron specific damage in LYSO, $BaF_2$ & PWO

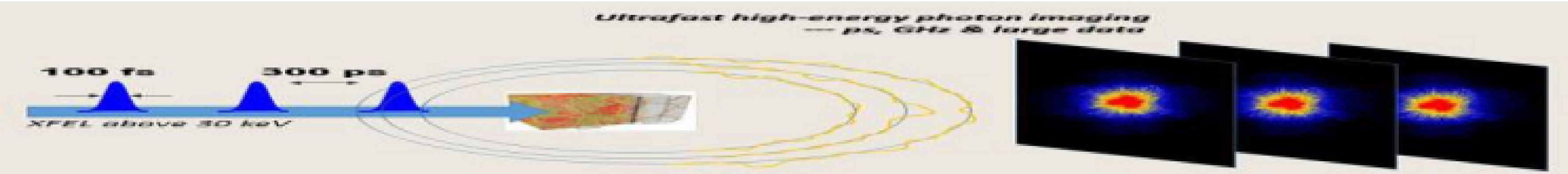



Presented in NSS2017, will be published in IEEE TNS NS

# Sensor for GHz Hard X-Ray Imaging

LANL Report LA-UR-17-22085 (2017)




**High-Energy and Ultrafast X-Ray Imaging Technologies and Applications**

*Organizers: Peter Denes, Sol Gruner, Michael Stevens & Zhehui (Jeff) Wang[1]*
*(**Location/Time**: Santa Fe, NM, USA /Aug 2-3, 2016)*

The goals of this workshop are to gather the leading experts in the related fields, to prioritize tasks for ultrafast hard X-ray imaging detector technology development and applications in the next 5 to 10 years, see Table 1, and to establish the foundations for near-term R&D collaborations.

Los Alamos National Laboratory Report LA-UR-17-22085 (2017).
[3] Z. Wang, C. W. Barnes

Table I. High-energy photon imagers for MaRIE XFEL

| Performance | Type I imager | Type II imager |
|---|---|---|
| X-ray energy | 30 keV | 42-126 keV |
| Frame-rate/inter-frame time | 0.5 GHz/2 ns | 3 GHz / 300 ps |
| Number of frames | 10 | 10 - 30 |
| X-ray detection efficiency | above 50% | above 80% |
| Pixel size/pitch | ≤ 300 μm | < 300 μm |
| Dynamic range | $10^3$ X-ray photons | ≥ $10^4$ X-ray photons |
| Pixel format | 64 x 64 (scalable to 1 Mpix) | 1 Mpix |

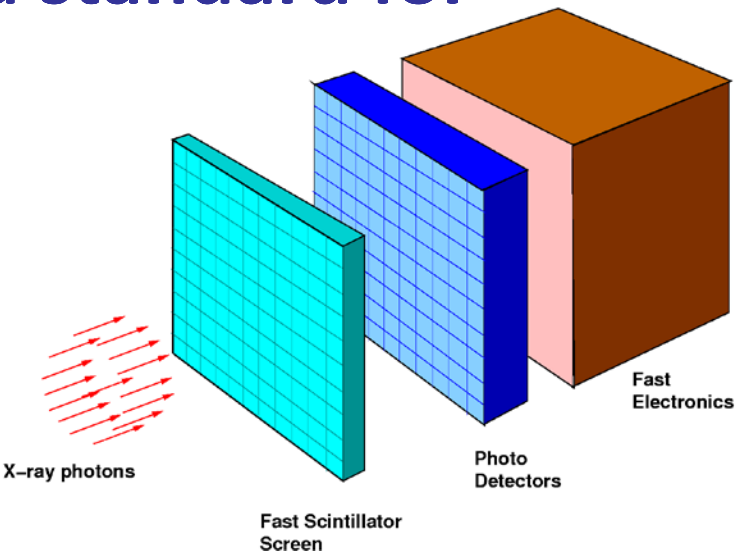
2 ns and 300 ps inter-frame time requires very fast sensor

# Why Crystal Scintillator?

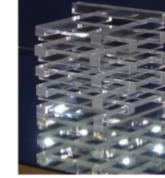
LANL Report LA-UR-17-22085 (2017)

- **Detection efficiency for hard X-ray requires bulk detector.**
- **Scintillation light provides fast signal.**
- **Pixelized crystal detector is a standard for medical industry.**
- **A total absorption concept:**
  - Pixelized fast scintillator screen;
  - Pixelized fast photodetector;
  - Fast electronics readout.
- **Challenges:**

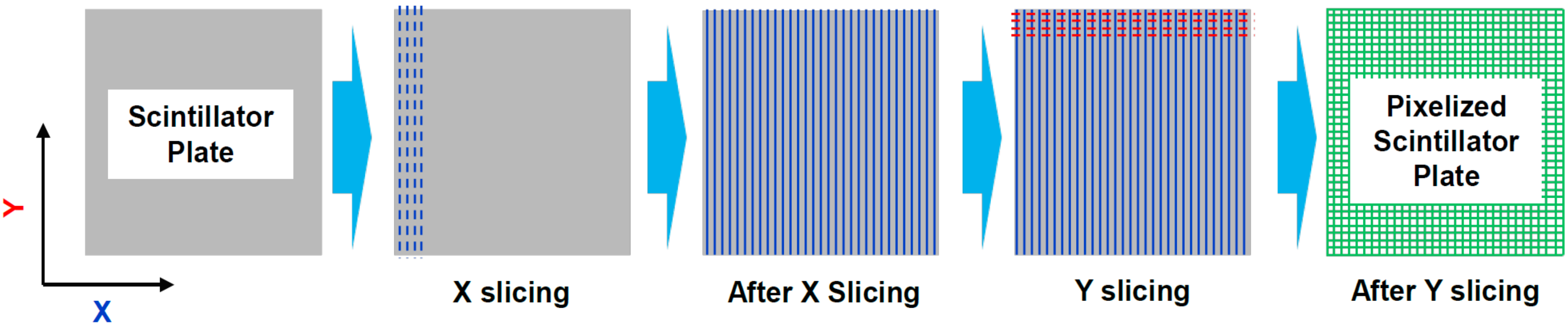
**Ultra-fast crystals, photodetectors and readout.**



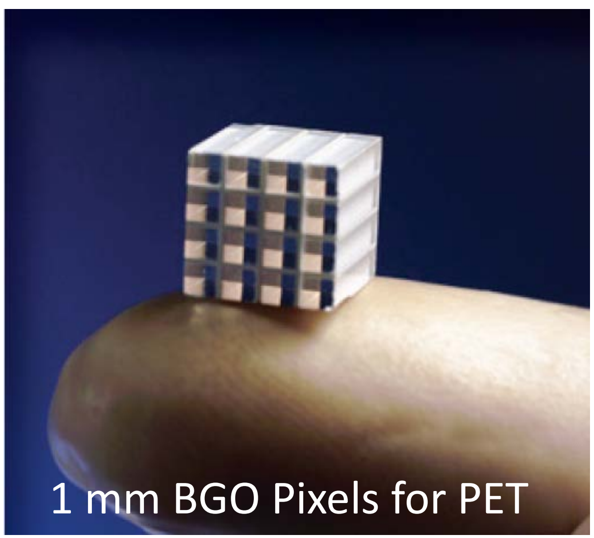
# Pixelized Crystal Detectors



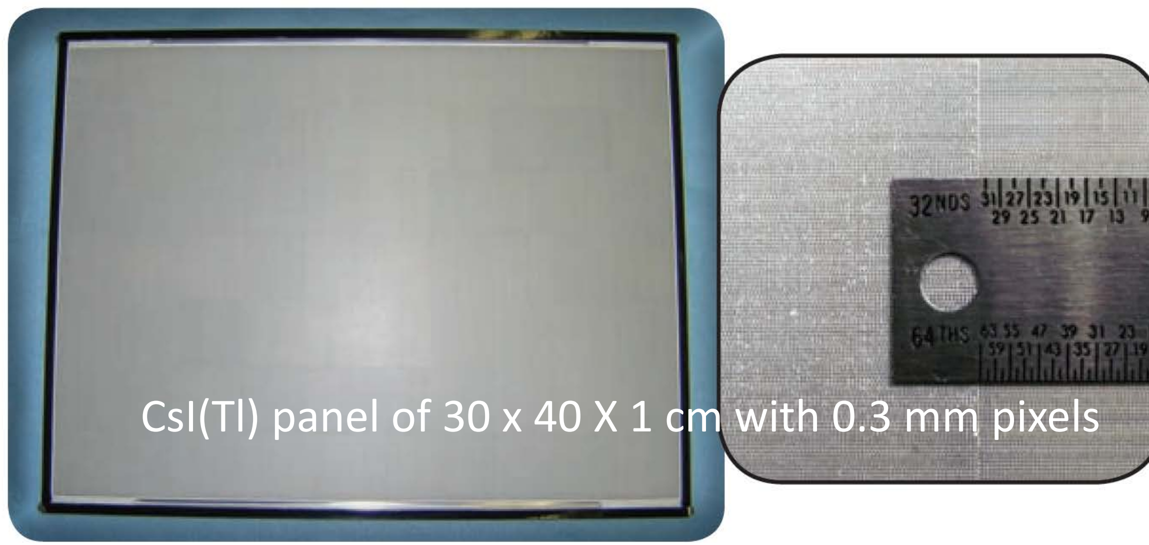
**Crystal panels of 300 μ pitch may be fabricated by classical mechanical processing**




A Schematic showing pixelized scintillator plate processing



1 mm BGO Pixels for PET



CsI(Tl) panel of 30 x 40 X 1 cm with 0.3 mm pixels

**Laser slicing, micropore or not pixelized provide better coverage**

# Candidate Scintillators for Marie

Proc. of SPIE 10392 (2017)

| | LYSO (:Ce) | YSO:Ce | ZnO:Ga | $BaF_2$ | $BaF_2$:Y | YAP:Ce | YAP:Yb | YAG:Yb | LuAG:Ce | $LaBr_3$ (:Ce) |
|---|---|---|---|---|---|---|---|---|---|---|
| Density ($g/cm^3$) | 7.4 | 4.44 | 5.67 | 4.89 | 4.89 | 5.35 | 5.35 | 4.56 | 6.76 | 5.29 |
| Melting points ($^oC$) | 2050 | 2070 | 1975 | 1280 | 1280 | 1870 | 1870 | 1940 | 2060 | 783 |
| $X_0$ (cm) | 1.14 | 3.10 | 2.51 | 2.03 | 2.03 | 2.77 | 2.77 | 3.53 | 1.45 | 1.88 |
| $R_M$ (cm) | 2.07 | 2.93 | 2.28 | 3.1 | 3.1 | 2.4 | 2.4 | 2.76 | 2.15 | 2.85 |
| $\lambda_I$ (cm) | 20.9 | 27.8 | 22.2 | 30.7 | 30.7 | 22.4 | 22.4 | 25.2 | 20.6 | 30.4 |
| $Z_{eff}$ | 64.8 | 33.3 | 27.7 | 51.6 | 51.6 | 31.9 | 31.9 | 30 | 60.3 | 45.6 |
| dE/dX (MeV/cm) | 9.55 | 6.57 | 8.42 | 6.52 | 6.52 | 8.05 | 8.05 | 7.01 | 9.22 | 6.90 |
| $\lambda_{peak}$ [a] (nm) | 420 | 420 | 389 | 300<br>220 | 300<br>220 | 370 | 350 | 350 | 520 | 360 |
| Refractive Index[b] | 1.82 | 1.78 | 2.1 | 1.50 | 1.50 | 1.96 | 1.96 | 1.87 | 1.84 | 1.9 |
| Normalized Light Yield[a,c] | 100 | 80 | 6.6[e] | 42<br>4.8 | 1.7<br>4.8 | 9<br>32 | 0.19[e] | 0.36[e] | 35[f]<br>48[f] | 153 |
| Total Light yield (ph/MeV) | 30,000 | 24,000 | 2,000[e] | 13,000 | 2,000 | 12,000 | 57[e] | 110[e] | 25,000[f] | 46,000 |
| Decay time[a] (ns) | 40 | 75 | <1 | 600<br>0.6 | 600<br>0.6 | 191<br>25 | 1.5 | 4 | 981[f]<br>64[f] | 20 |
| Light Yield in 1st ns (photons/MeV) | 740 | 318 | 610[e] | 1200 | 1200 | 391 | 28[e] | 24[e] | 240 | 2,200 |
| 40 keV Att. Length (1/e, mm) | 0.185 | 0.334 | 0.407 | 0.106 | 0.106 | 0.314 | 0.314 | 0.439 | 0.251 | 0.131 |

[1] Spurrier, et al., *IEEE T. Nucl. Sci.* 2008,55 (3): 1178-1182.

a. Top line: slow component, bottom line: fast component;

b. At the wavelength of the emission maximum;

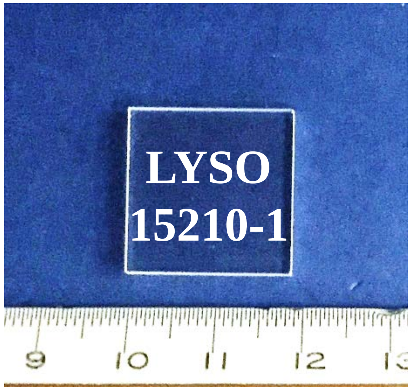
c. Excited by Gamma rays;

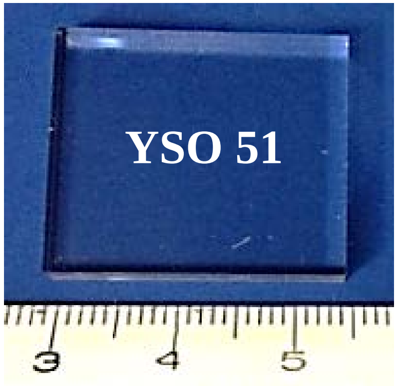
d. For 0.4 at% Ca co-doping;

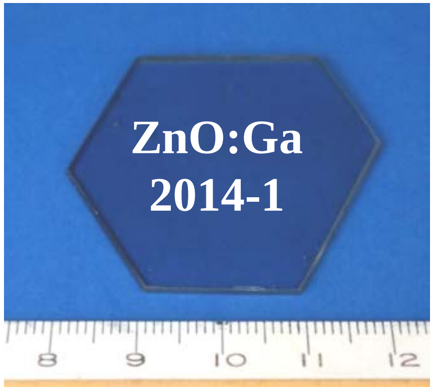
e. Excited by Alpha particles.

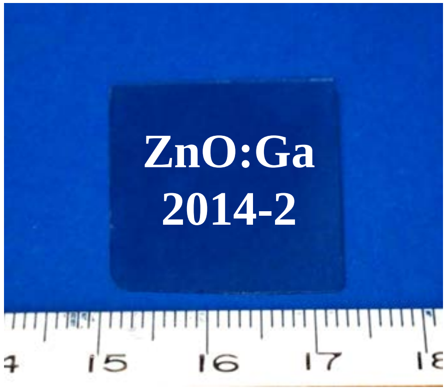
f. Ceramic with 0.3 Mg at% co-doping

# LYSO and ZnO:Ga Samples




| Crystal | Vendor | ID | Dimension (mm$^3$) |
|---|---|---|---|
| LYSO:Ce | SIC | 150210-1 | 19x19×2 |
| YSO:Ce | SIC | 51 | 25×25×5 |
| ZnO:Ga | FJIRSM | 2014-1 | 33×30×2 |
| ZnO:Ga | FJIRSM | 2014-2 | 22×22×0.3 |

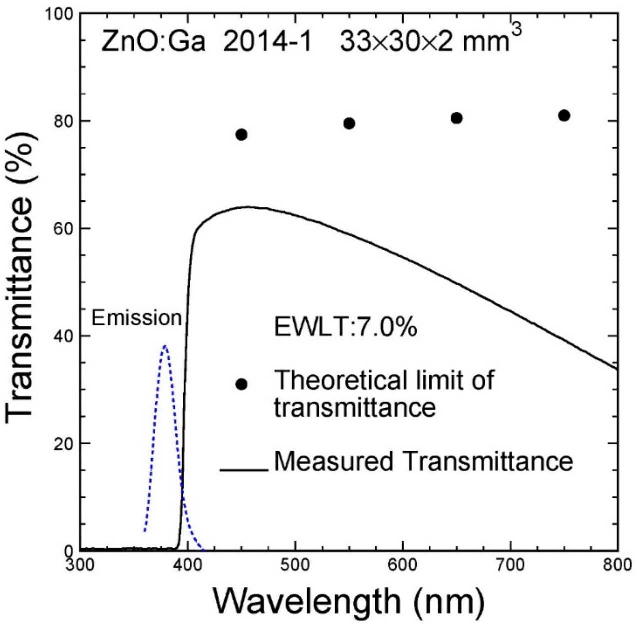
## Experiments

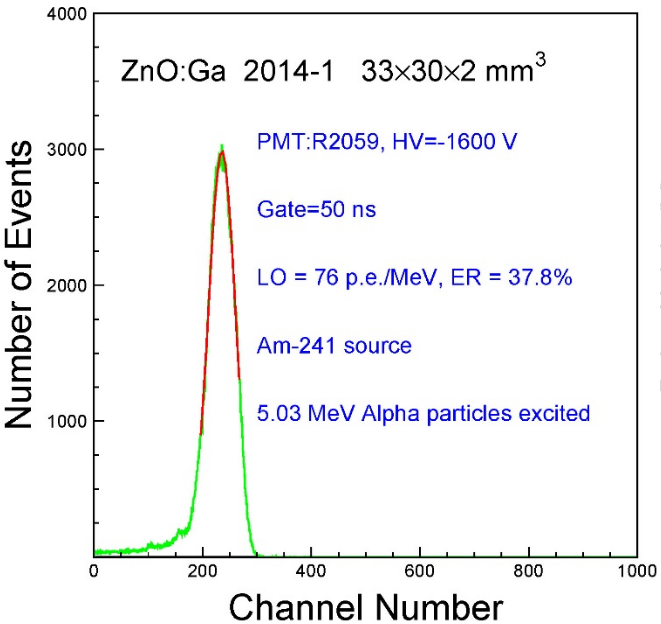
- Properties measured at room temperature : PL & Decay, Transmittance, PHS, LO & Decay kinetics

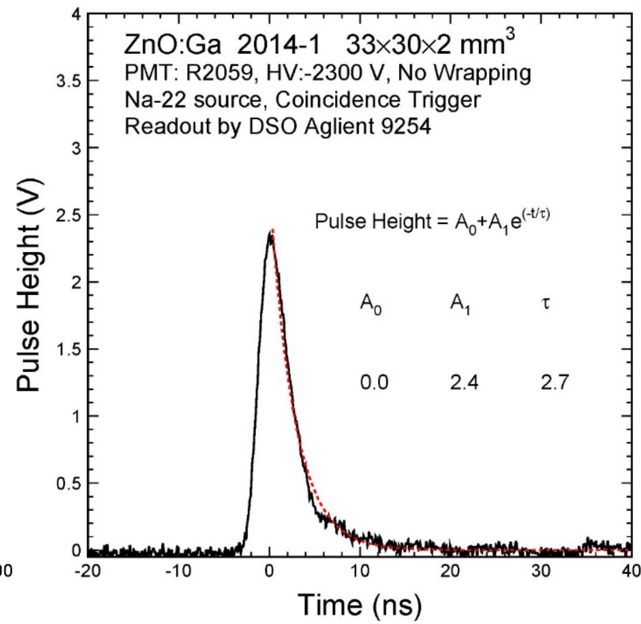
# FJIRSM 2mm ZnO:Ga-2014-1

✓ **Very short decay time**

× **Low EWLT and LO due to severe self absorption**



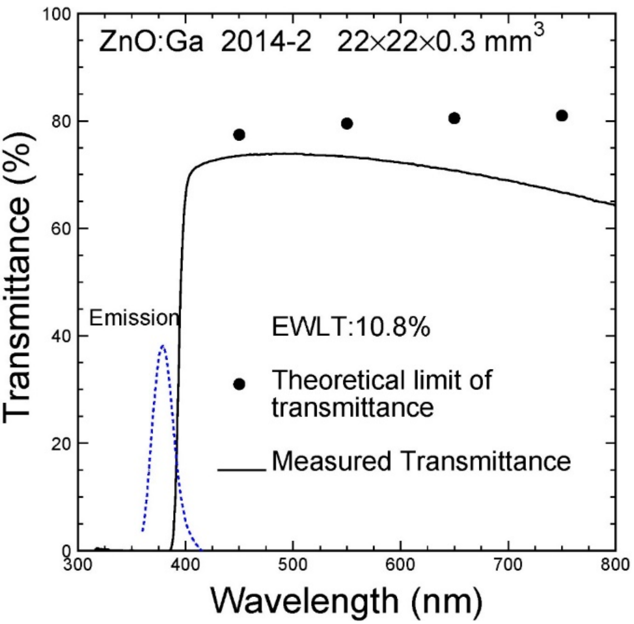



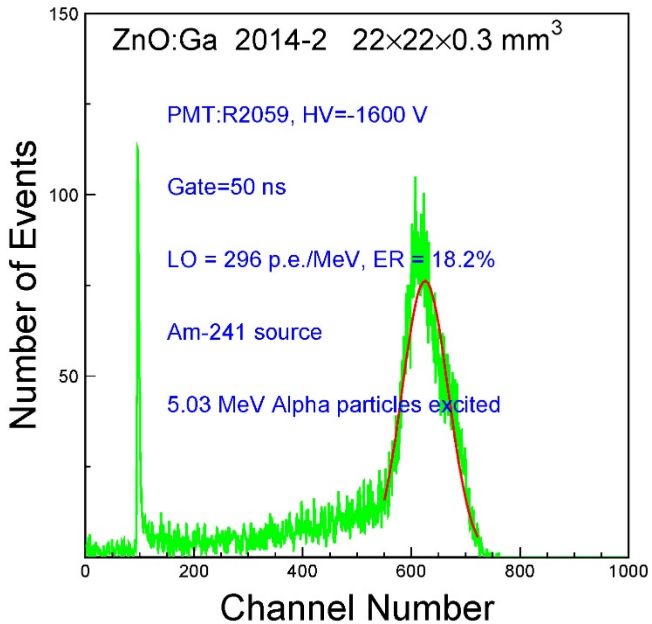



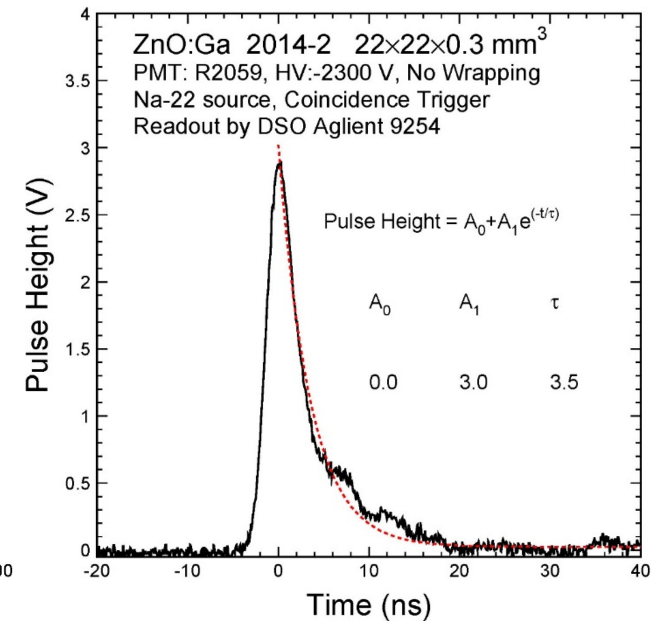

| ID | Dimension | EWLT (%) | ER (%) | 50 ns LO (p.e./MeV) | Primary Decay Time (ns) |
|---|---|---|---|---|---|
| FJIRSM ZnO:Ga-2014-1 | 33×30×2 | 7.0 | 37.8 | 76 (α) | 2.7 |

# FJIRSM 0.3 mm ZnO:Ga-2014-2

- × Reduced self absorption due to 0.3 mm thickness
- × May pursue QD, NP or thin film based solution



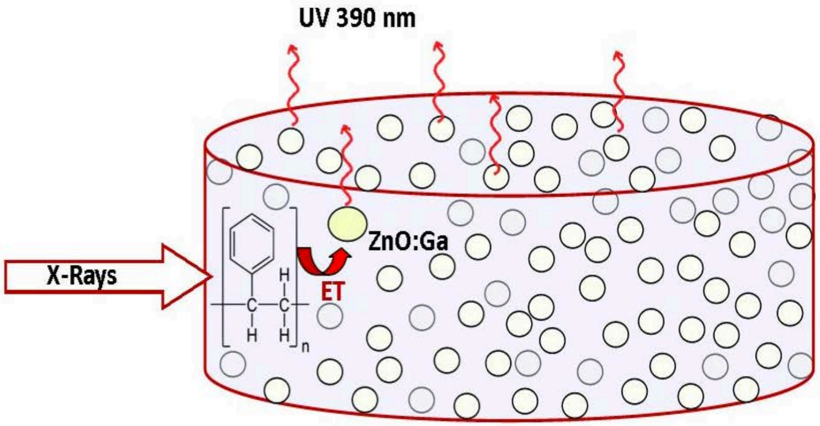



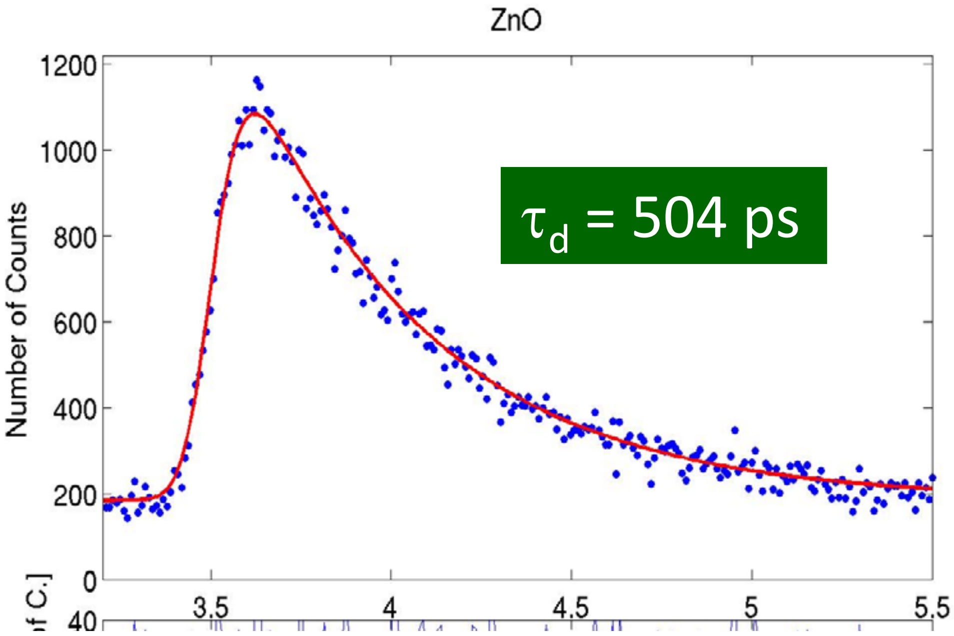

| ID | Dimension | EWLT (%) | ER (%) | 50 ns LO (p.e./MeV) | Primary Decay Time (ns) |
|---|---|---|---|---|---|
| FJIRSM ZnO:Ga-2014-2 | 22×22×0.3 | 10.8 | 18.2 | 296 (α) | 3.5 |

# ZnO:Ga Polystyrene Composite

P. Lecoq, Talk in the Picosecond workshop, Kansas City, 15-18 September, 2016

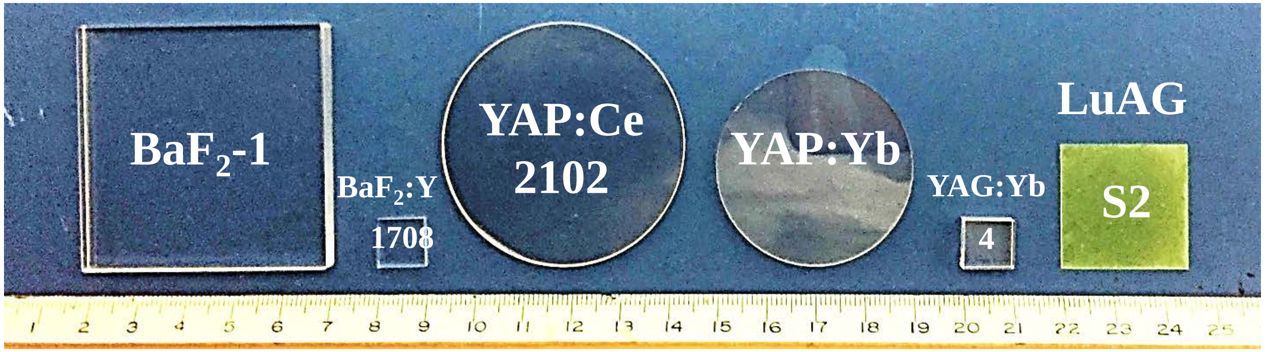
- Highly luminescent ZnO:Ga nano crystals 80-100nm
  - Prepared by a photochemical method
  - Embedded in a polystyrene sheet 10%weigth




$\tau_d$ = 504 ps

# $BaF_2$ and Other Samples




| Crystal | Vendor | ID | Dimension (mm³) |
|---|---|---|---|
| $BaF_2$ | SIC | 1 | 50×50×5 |
| $BaF_2$:Y | BGRI | 1708 | 10×10×2 |
| YAP:Ce | Dongjun | 2102 | Φ50×2 |
| YAP:Yb | Dongjun | 2-2 | Φ40×2 |
| YAG:Yb | Dongjun | 4 | 10×10×5 |
| LuAG:Ce | SIC | S2 | 25×25×0.4 |

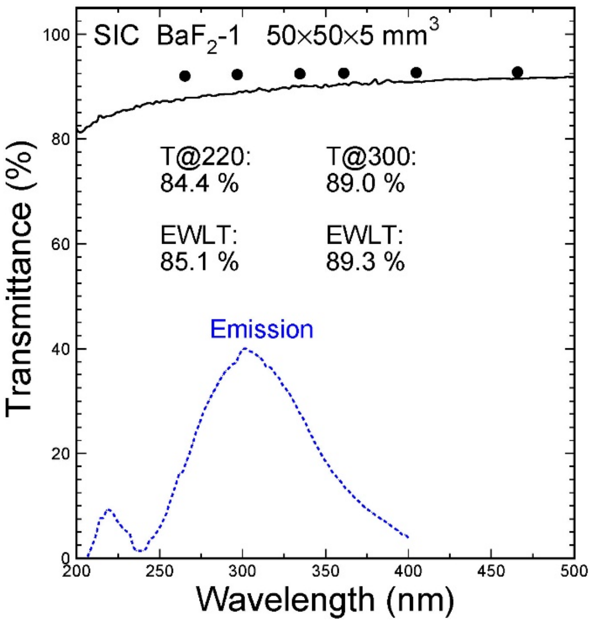
## Experiments

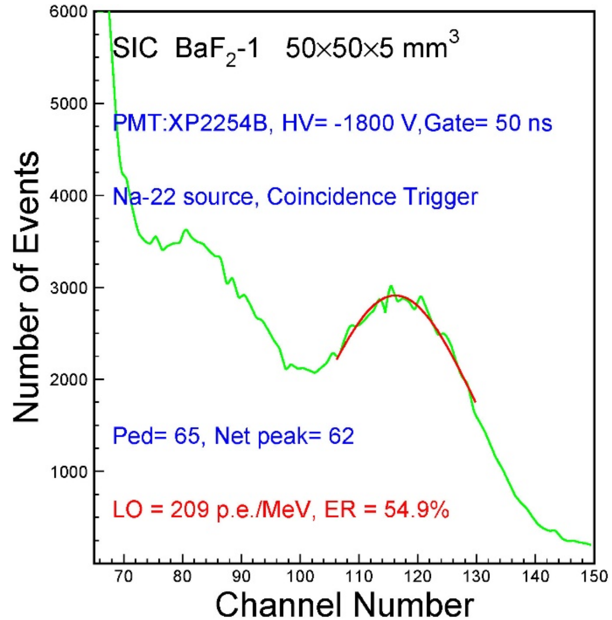
- Properties measured at room temperature : PL & Decay, Transmittance, PHS, LO & Decay kinetics

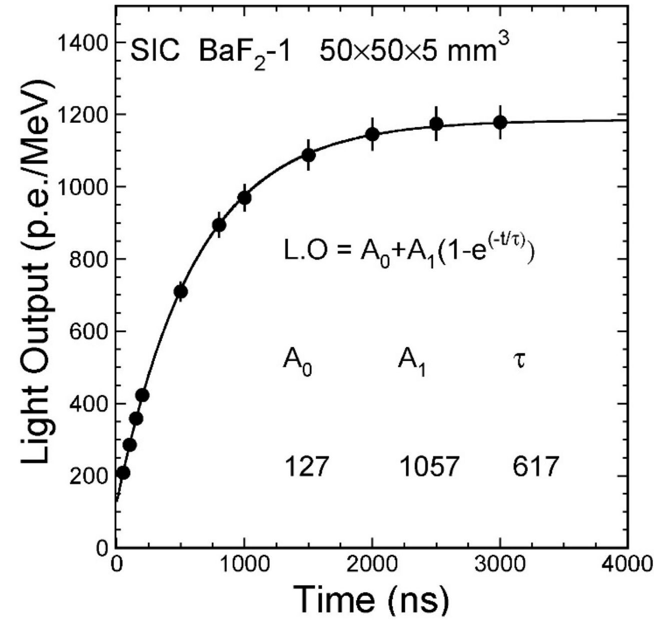
# SIC $BaF_2$-1

✓ **The highest LY in 1st ns among all non-hygroscopic scintillators**

× **~600 ns slow component may be suppressed by Y doping**




| ID | Dimension | EWLT (%) | ER (%) | 50 ns LO (p.e./MeV) | Primary Decay Time (ns) |
|---|---|---|---|---|---|
| SIC $BaF_2$-1 | 50×50×5 | 85.1 | 54.9 | 209 | 0.6 |

# Use Thin Layer Scintillators

Proc. of SPIE 0504 (2015)

A multilayer high QE photocathode coated thin fast scintillators concept was proposed for GHz hard X-ray imaging:

- Spatial resolution determined layer thickness,
- Overall efficiency defined layer number,
- Maximized conversion of scintillation photon to p.e.,
- Magnetic field extraction of p.e. and image preserving,
- Off-beam p.e. multiplication,
- On-board charge storages.

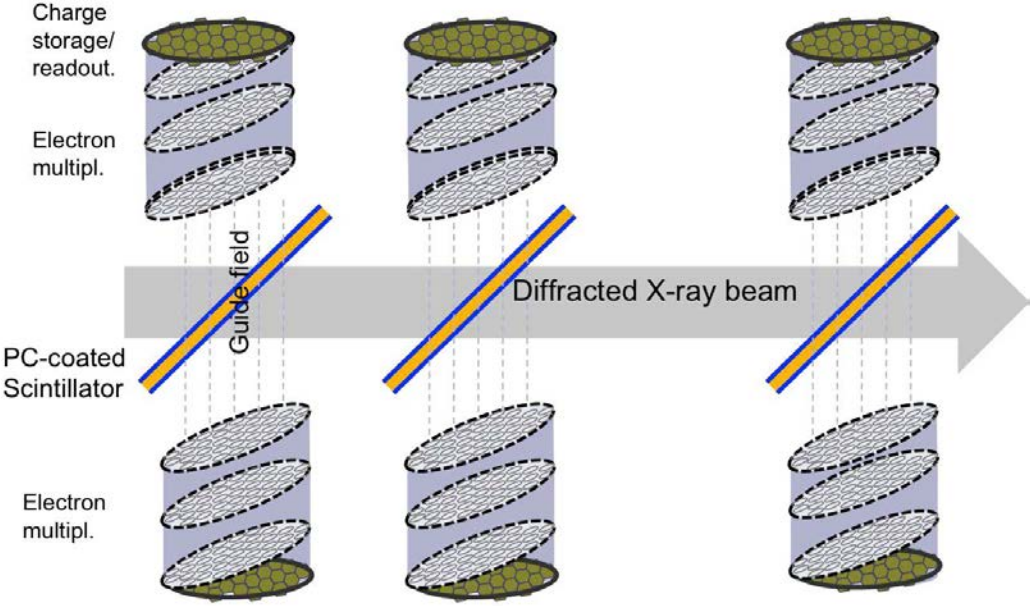



**Figure 6.** A multi-layer detector architecture for efficient and fast imaging of diffracted X rays. A guide magnetic field perpendicular to the X-ray direction guide the photoelectrons to amplification and storage. The magnetic field also preserves the image contrast due to X-ray absorption at the scintillator location.

# Ag/Au-ZnO Core-Shell Nano Particles

Nature Scientific **Reports** | 5:14004 | DOI: 10.1038/srep14004

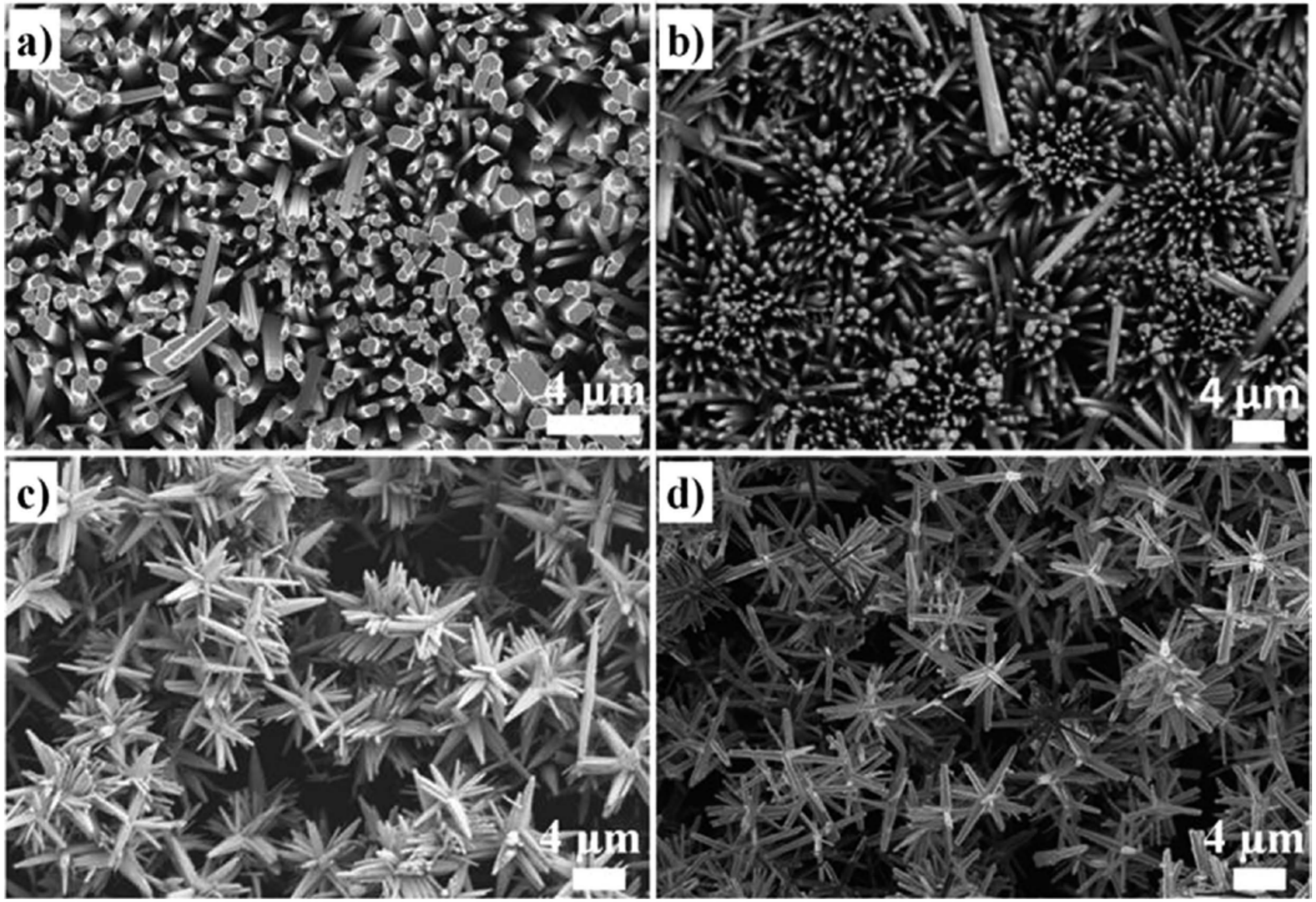
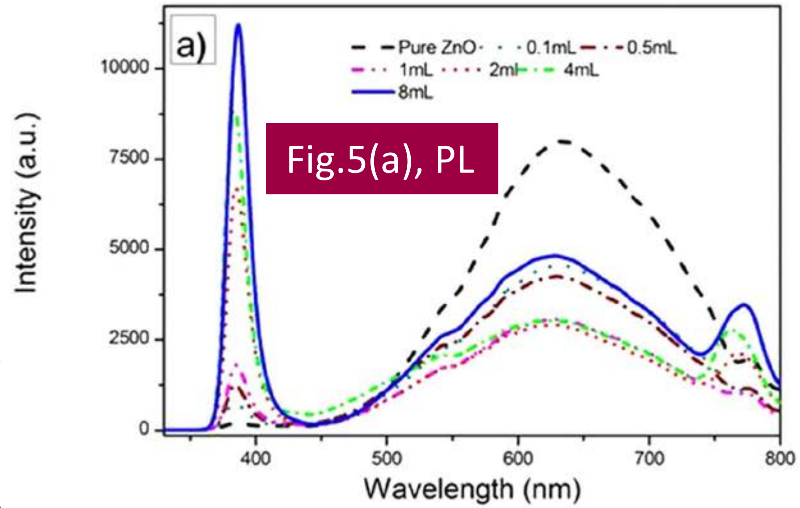


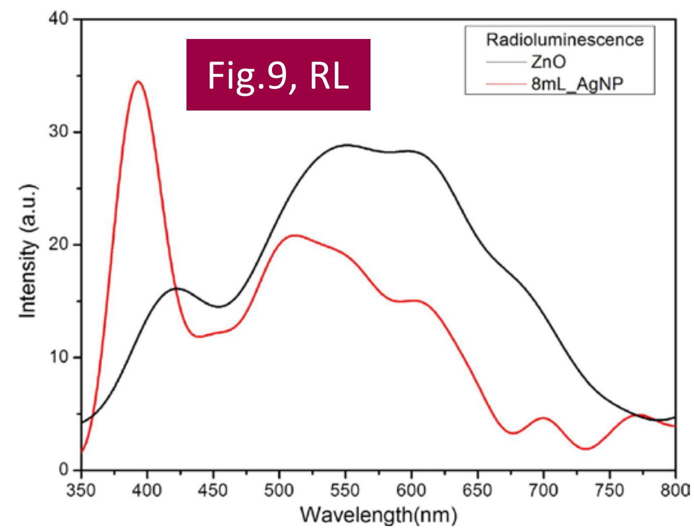

**Figure 2.** SEM images for ZnO samples without nanoparticles (**a**), with 2 mL_AgNP (**b**), 8 mL_AgNP (**c**), and 8 mL_AuNP (**d**) illustrating the change in shape of the particles. The particles in the lower two micrographs are referred to as "star" or "thistle" shaped in the text.

# Enhanced UV Emission in Ag/Au-ZnO

Nature Scientific **Reports** | 5:14004 | DOI: 10.1038/srep14004

- Enhancement of ZnO near-band-edge (UV) emission centered at 385 nm was reported in PL and RL of Ag/Au-ZnO core shell nanoparticles.
- The enhanced luminescence and the decreased free exciton lifetime suggest a plasmon-coupled-emission mechanism.
- This suggests that plasmon-coupled luminescence can be employed for the development of improved scintillators.



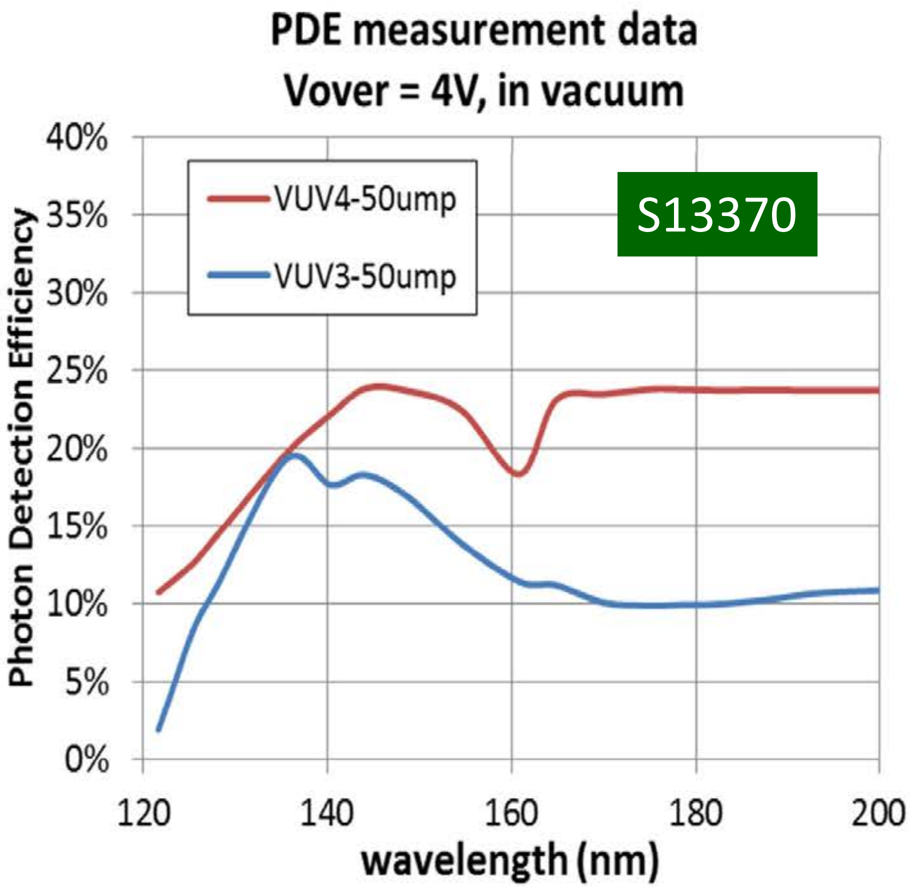



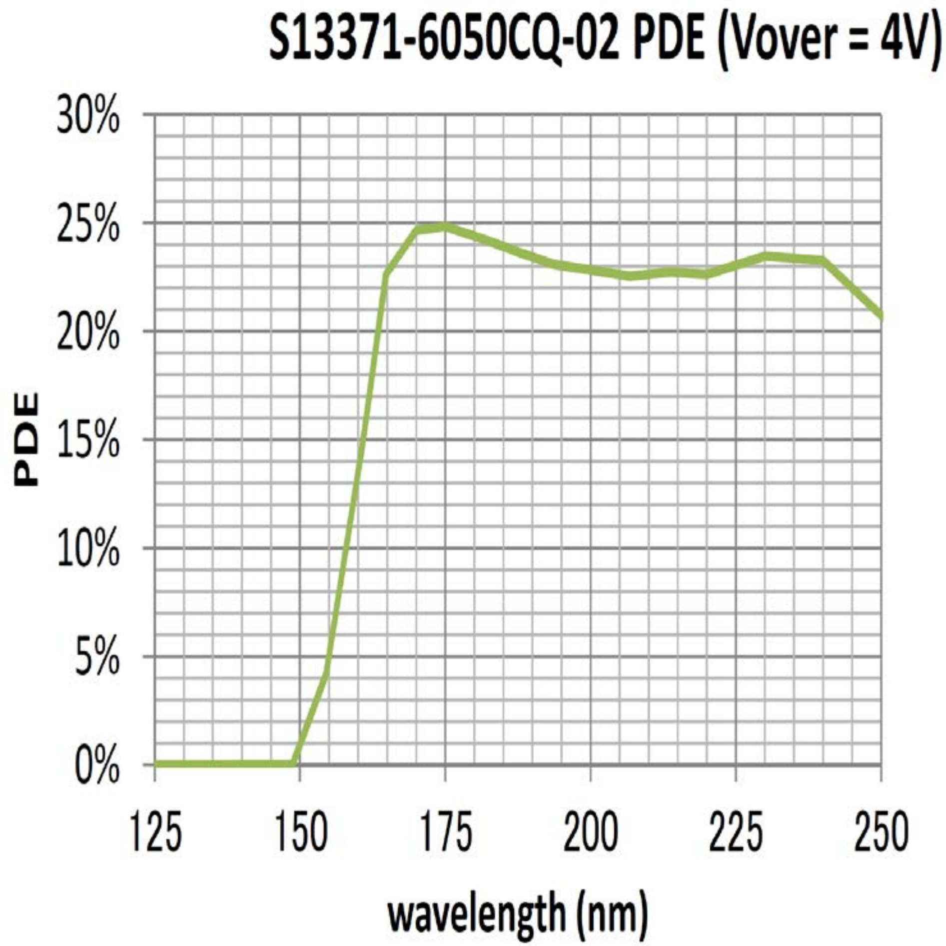
# Summary: HEP Experiments

- LYSO, $BaF_2$ crystals and LuAG ceramics show an excellent radiation hardness beyond 100 Mrad, 1 x $10^{15}$ p/cm$^2$ and 2 x $10^{15}$ n/cm$^2$. They promise a very fast and robust detector in a severe radiation environment, such as the HL-LHC.
- Commercially available undoped $BaF_2$ crystals provide sufficient fast light with sub-ns FWHM pulse width. Yttrium doping in $BaF_2$ crystals increases its F/S ratio from 1/5 to 6/1 while maintaining the intensity of its sub-ns fast component. The slow contamination at this level is already less than commercially available undoped CsI, so is promising for Mu2e-II and GHz X-ray imaging.
- Results of the experiments 6991 and 7332 at LANL show fast neutrons up to 2 x $10^{15}$ n/cm$^2$ do not damage LYSO, $BaF_2$ and PWO crystals, confirming early observation at Saclay reactor.
- Our plan is to investigate LYSO:Ce,Ca crystals, LuAG:Ce and LuAG:Pr ceramics and try to develop Y:$BaF_2$ crystals for future HEP experiments. Will also pay an attention to photodetector with DUV response: LAPPD, Si or diamond based solid state detectors.

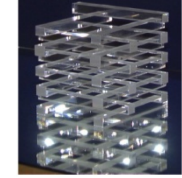
# Hamamatsu S13371-6050CQ-02

SiPM with VUV response is available: QE = 22% at 220 nm



# Diamond Photodetector



In addition to SiPM with VUV response

E. Monroy, F. Omnes and F. Calle,"Wide-bandgap semiconductor ultraviolet photodetectors, IOPscience 2003 Semicond. Sci. Technol. 18 R33

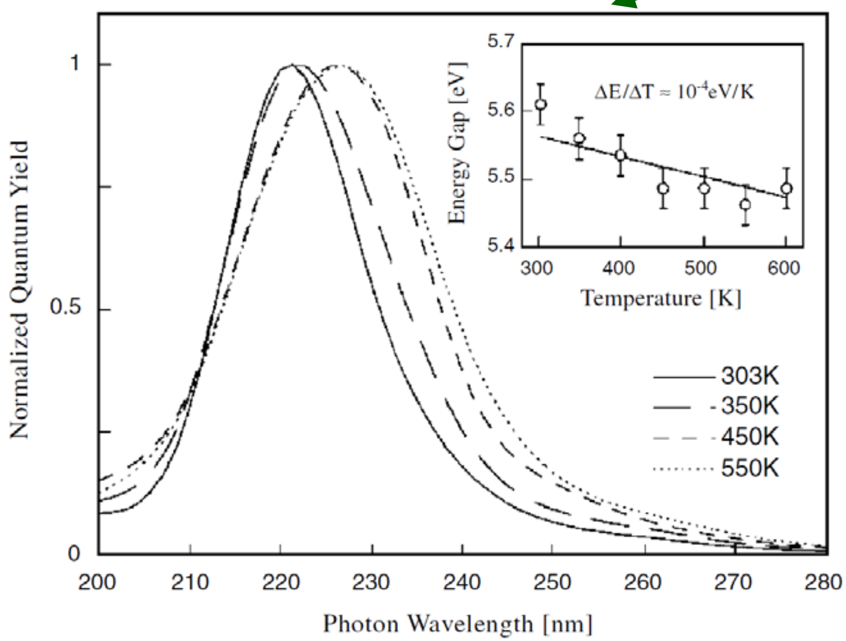



**Figure 6.** Quantum efficiency of diamond photoconductors at different temperatures and Arrhenius plot of the peak value (inset). (From [Sal00].)

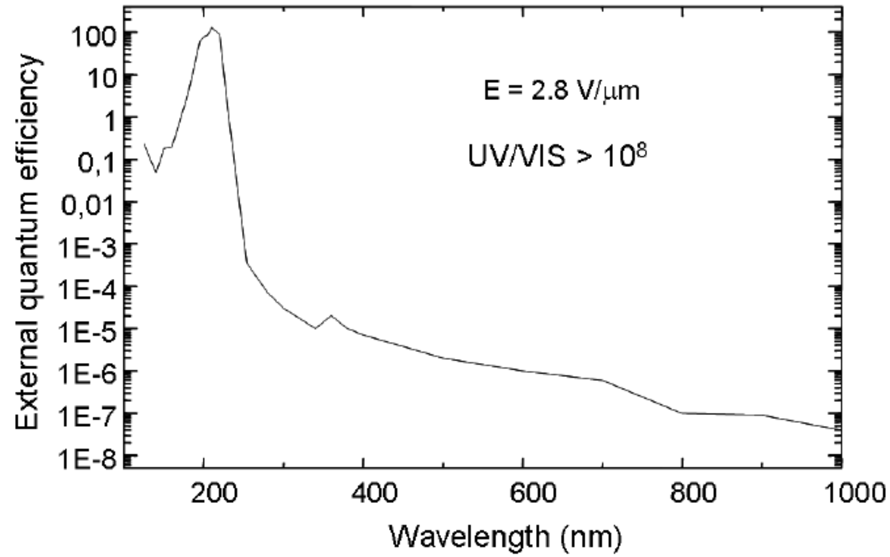



**Fig. 4.** External quantum efficiency extended to visible and near infrared wavelength regions. The

E. Pace and A. De Sio, "Innovative diamond photo-detectors for UV astrophysics", Mem. S.A.It. Suppl. Vol. 14, 84 (2010)

# Summary: GHz Imaging

- GHz hard X-ray imaging for the proposed Marie project presents an unprecedented challenge to the speed and radiation hardness of the inorganic scintillators.
- $BaF_2$ crystals provide sufficient fast light with a sub-ns FWHM pulse width and an excellent radiation hardness beyond 100 Mrad and 1 x $10^{15}$ h/cm$^2$. With its slow component effectively suppressed by yttrium doping Y:$BaF_2$ promises a fast and robust front imager.
- Bulk ZnO:Ga crystals suffer from serious self-absorption. Enhanced UV emission observed in Ag/Au ZnO core-shell nano particles hints a thin film based approach.
- Our plan is to investigate along both lines: Y:$BaF_2$ crystals, and ZnO QD/NP based thin film for the Marie project with a close collaboration between the NP, HEP and material science community.