Materials for Calorimetry

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arXiv: 2203.07154

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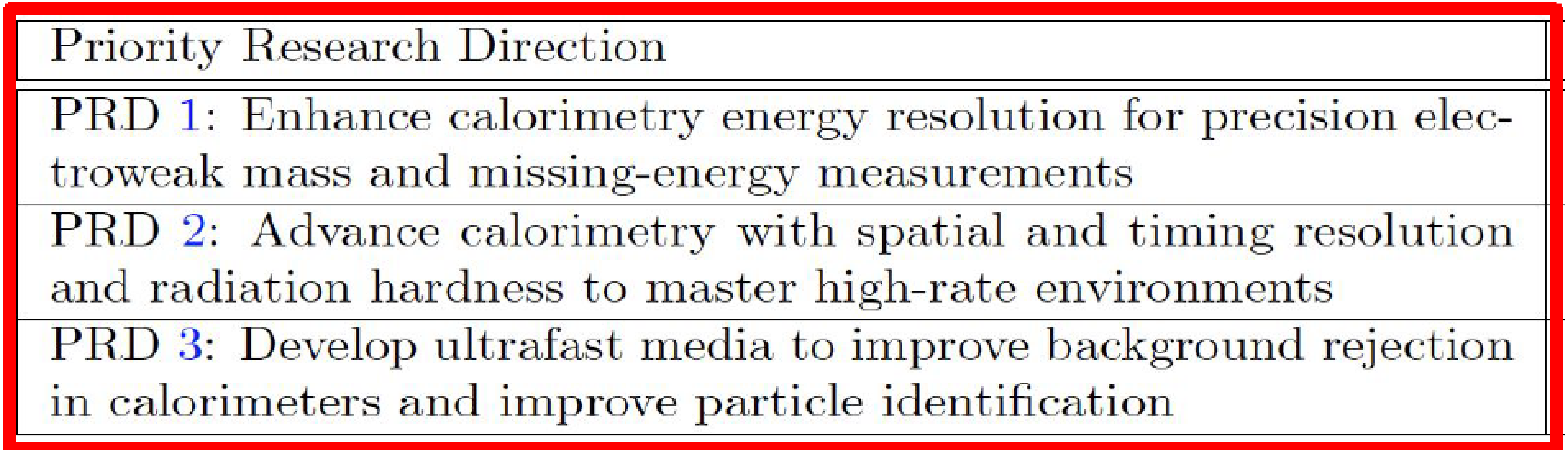
2019 DOE Basic Research Needs Study on Instrumentation for Calorimetry



Priority Research Direction
PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements
PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments
PRD 3: Develop ultrafast media to improve background rejection in calorimeters and improve particle identification

arXiv: 2203.07154 summarizes community response to the PRD
Fast/ultrafast, radiation hard and cost-effective active materials

Inorganic Scintillators

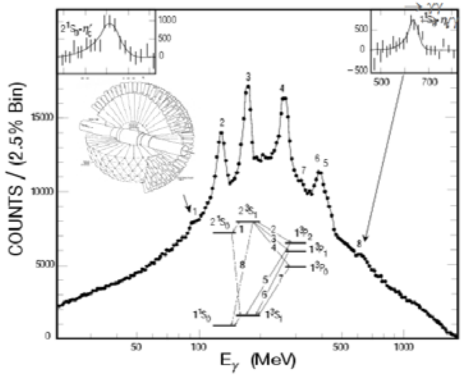
- **Precision photons and electrons enhance physics discovery potential.**
- **Crystal performance is well understood:**
  - **The best possible energy resolution and position resolution;**
  - **Good e/γ identification and reconstruction efficiency;**
  - **Excellent jet mass resolution with dual readout,: C/S or F/S gate.**
- **Challenges at future HEP Experiments:**
  - **Fast and radiation hard scintillators for the HL-LHC and FCC-hh;**
  - **Ultrafast scintillators to break ps timing barrier & Mu2e-II ECAL;**
  - **Cost-effective crystals for the proposed Higgs factory.**
- **Inorganic scintillators at Caltech Crystal Lab:**
  - **Radiation hard LYSO:Ce and BaF_2 crystals, and LuAG:Ce ceramics;**
  - **Ultrafast BaF_2:Y, Cs_2ZnCl_4 and Ga_2O_3 crystals, and Lu_2O_3 ceramics;**
  - **BGO, BSO & PWO crystals, and heavy scintillating glasses.**

arXiv:2203.06731/06788

Crystal ECAL Physics

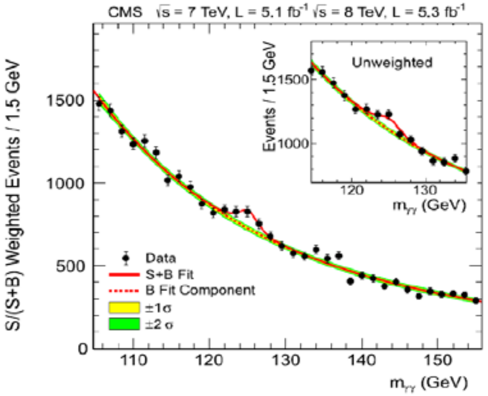
Charmonium system observed by CB through Inclusive photons

CB NaI(Tl)



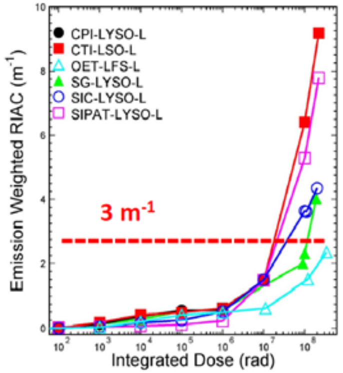
Higgs -> γγ by CMS through reconstructing photon pairs

CMS PWO

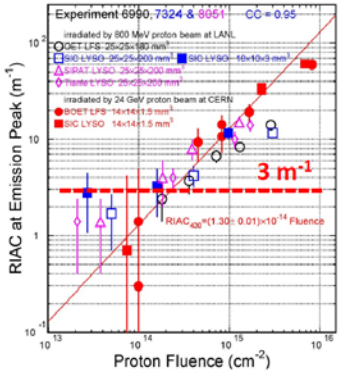


LYSO:Ce Crystals for CMS BTL

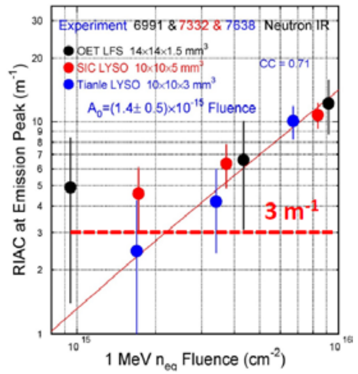
NIM A **824** (2016) 726-728



IEEE TNS **64** (2017) 665-672 , **65** (2018) 1018-1024



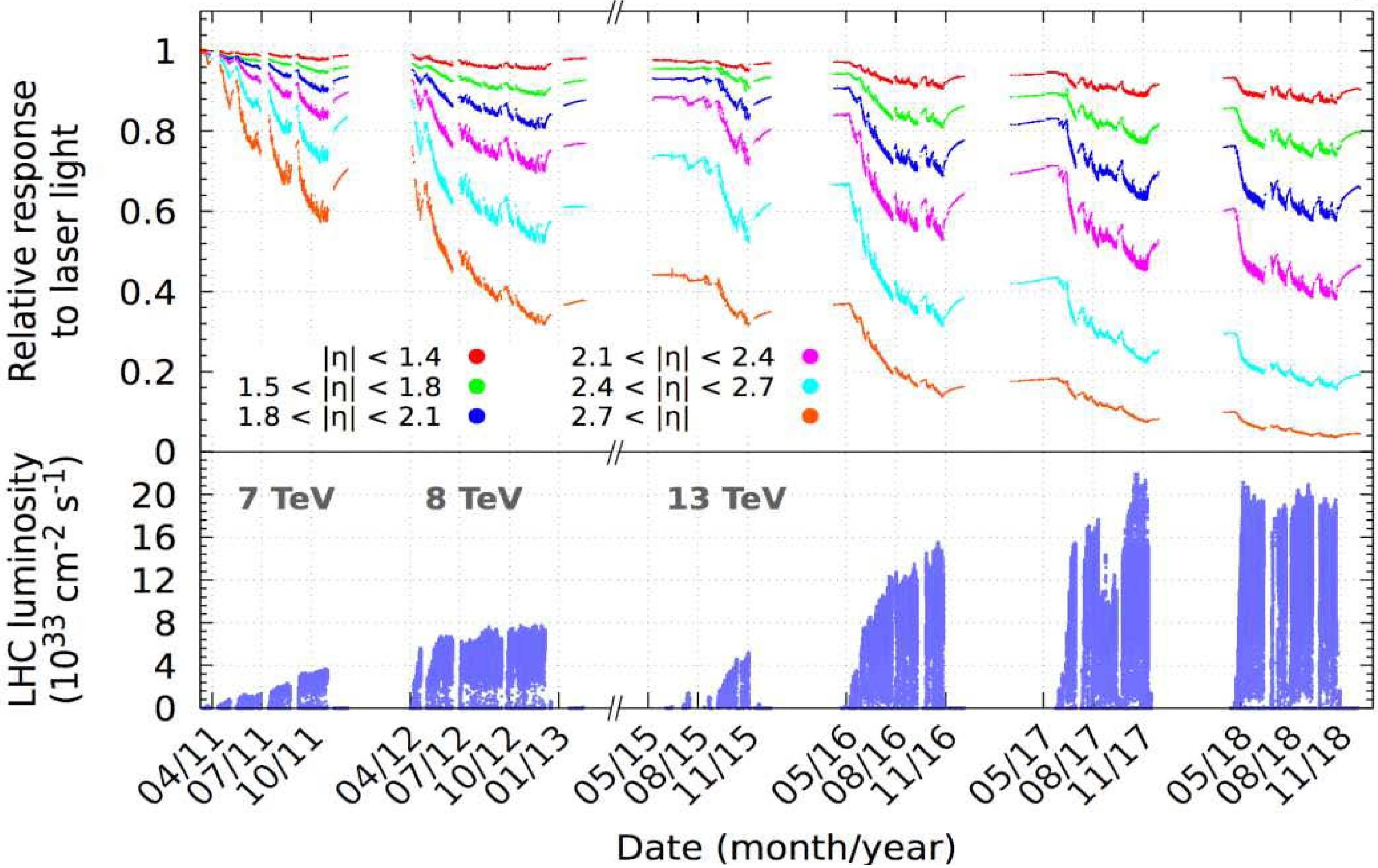
IEEE TNS **67** (2020) 1086-1092



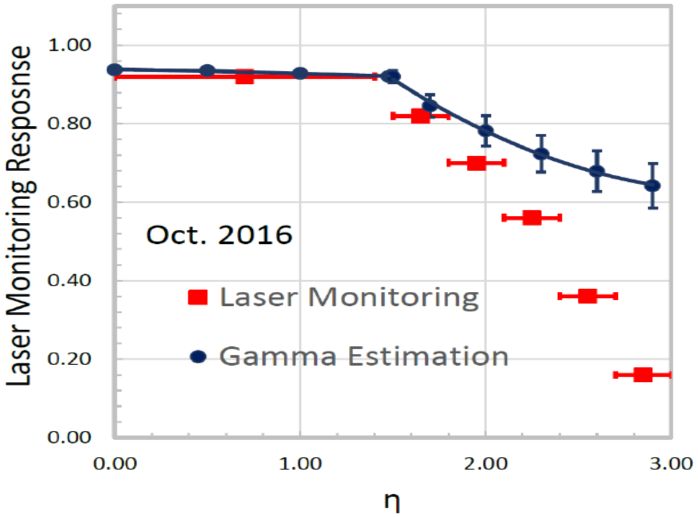
Crystals damaged by both proton and neutron. Damage by proton is larger than that from neutrons because of ionization energy loss in addition to displacement and nuclear breakup

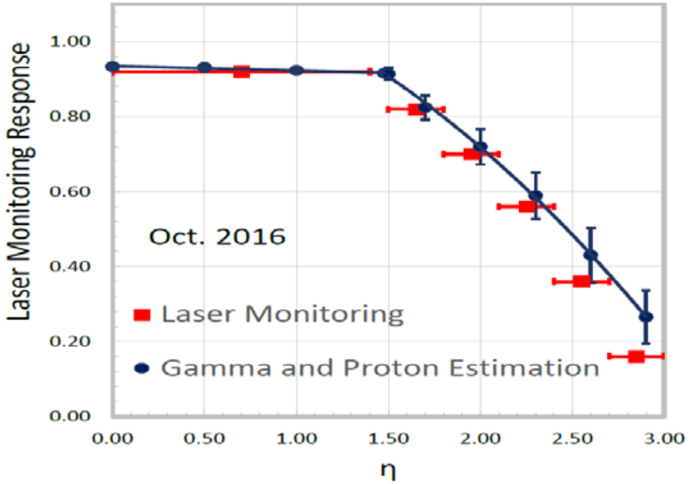
Challenge: Radiation Damage at LHC

F. Ferri, Calor 2022, https://indico.cern.ch/event/847884/timetable/#20220515



http://www.hep.caltech.edu/~zhu/talks/ryz_161028_PWO_mon.pdf

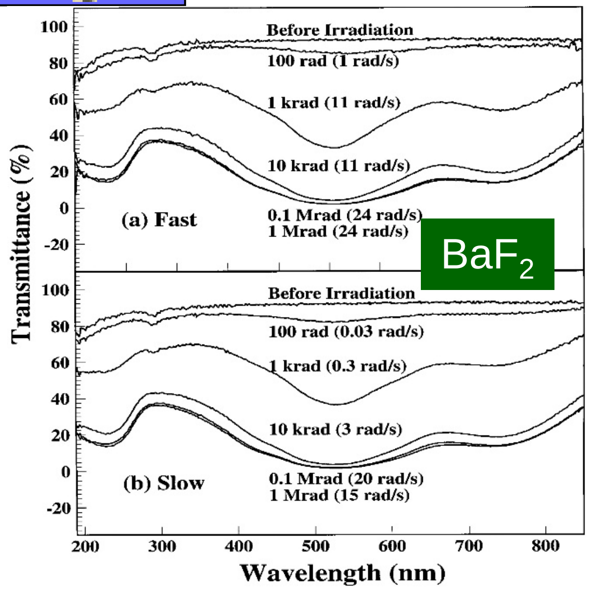


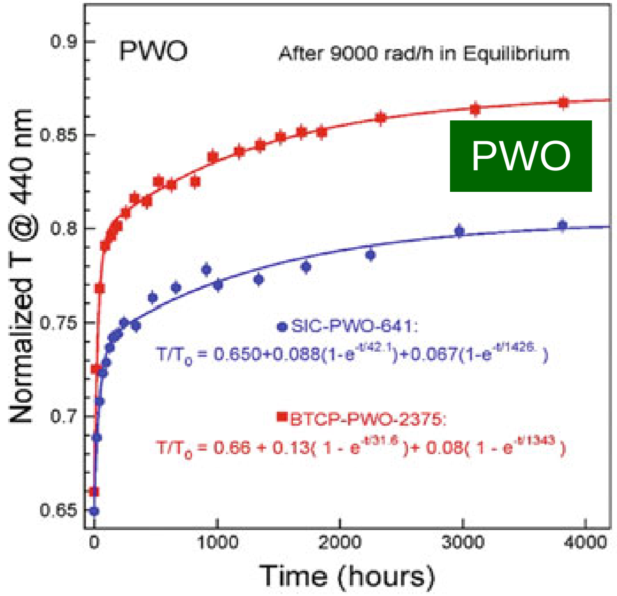


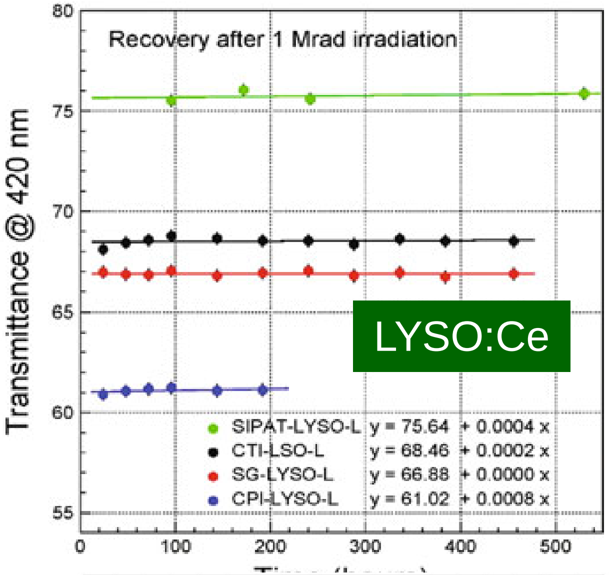
Use materials with monotonic damage: BaF_2, CsI, LYSO:Ce, LuAG:Ce

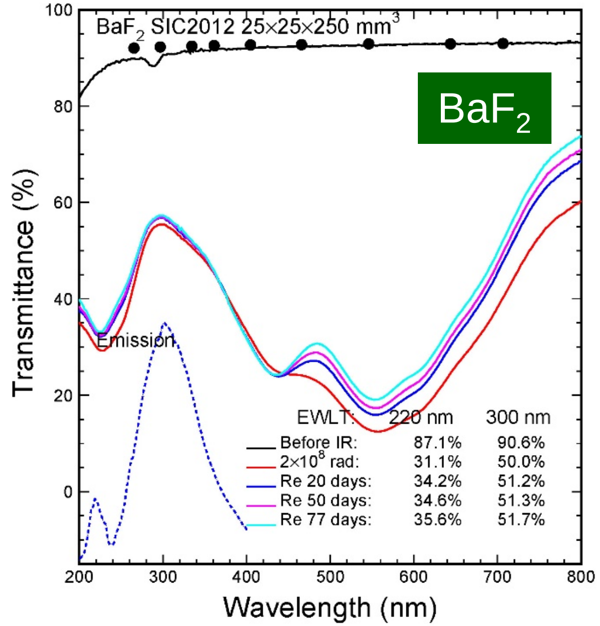
Neutron damage?

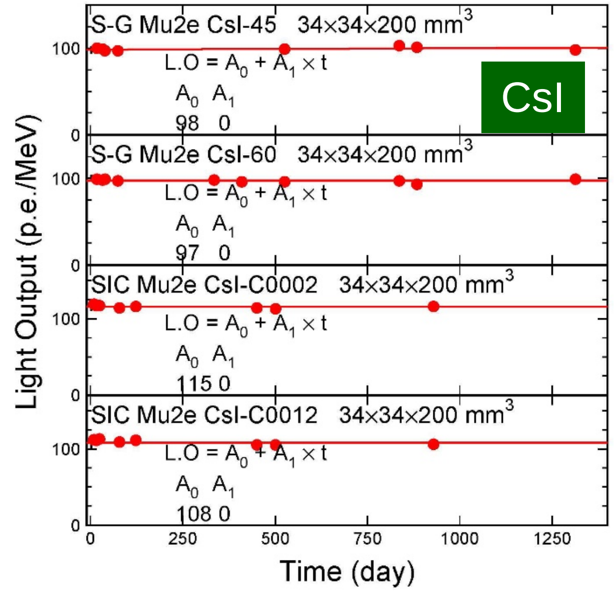
Use Materials with no Damage Recovery

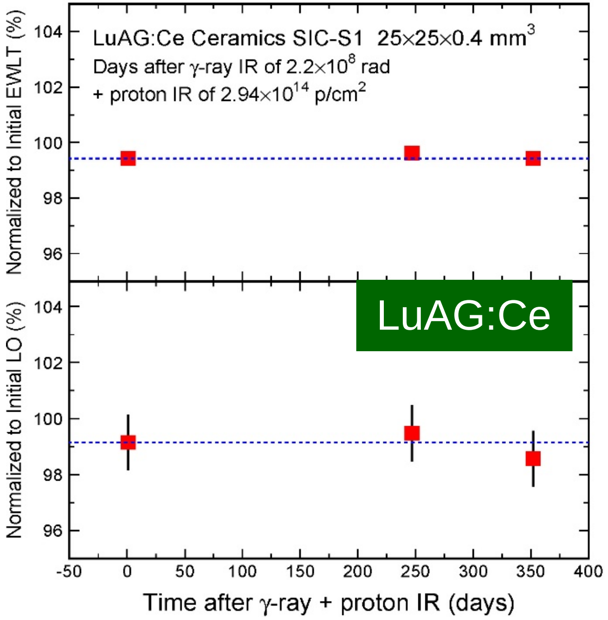












Damage in PWO recovers at room temperature, requiring frequent calibration/monitoring

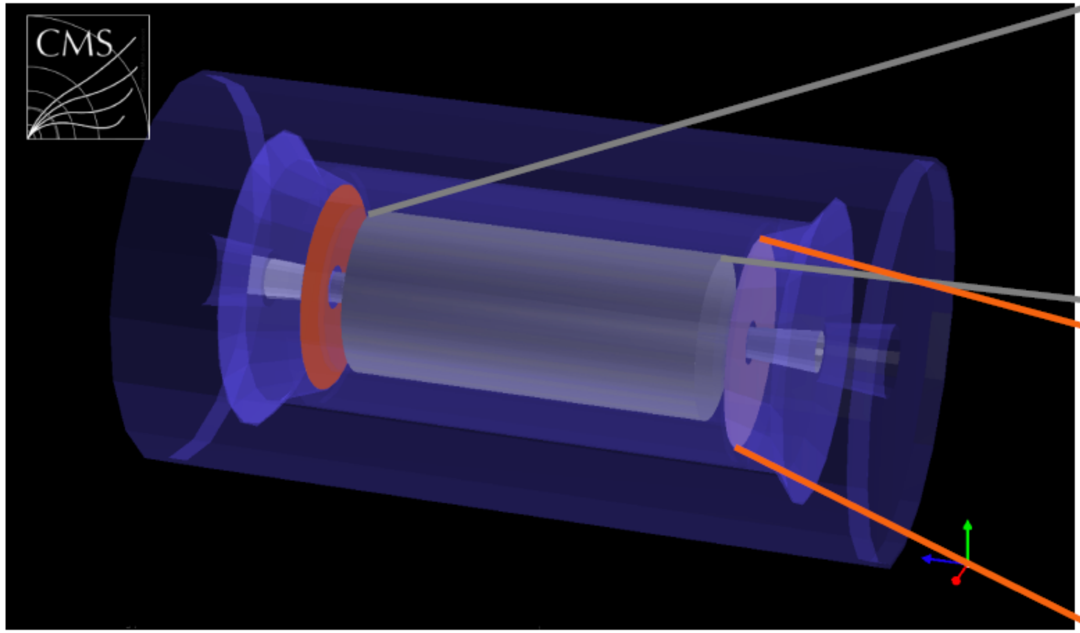
No recovery in BaF_2, CsI and LYSO:Ce crystals, and LuAG:Ce ceramics, indicating dose-rate independent damage.

LYSO:Ce for CMS Barrel Timing Layer

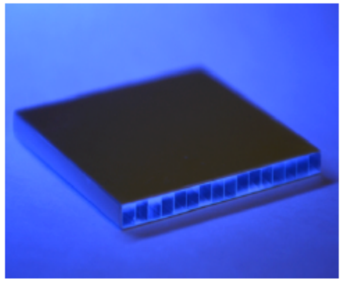
MTD performance goal: 30-40 ps at the start degrading to < 60 ps at 3000 fb^{-1}

Barrel Timing Layer: arrays of LYSO crystal bars connected to SiPMs at both ends and readout by TOFHIR

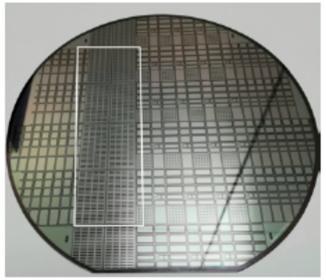
Ultrafast inorganic scintillators would help to break the pico-second time barrier



BTL: LYSO bars + SiPM read-out
- ▻ TK / ECAL interface ~ 45 mm thick
- ▻ $|\eta| < 1.45$ and $p_T > 0.7$ GeV
- ▻ Active area ~ 38 m^2 ; 332k channels
- ▻ Fluence at 3 ab^{-1}: 2×10^{14} n_{eq}/cm^2

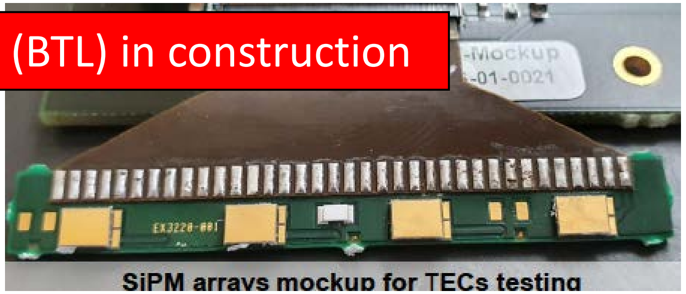


ETL: Si with internal gain (LGAD)
- ▻ On the HGC nose ~ 65 mm thick
- ▻ $1.6 < |\eta| < 3.0$
- ▻ Active area ~ 14 m^2; ~ 8.5M channels
- ▻ Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2



LYSO + SiPM with Thermal Electric Cooler (TEC) for CMS Barrel Timing Layer (BTL) in construction

SiPM array prototypes from FBK

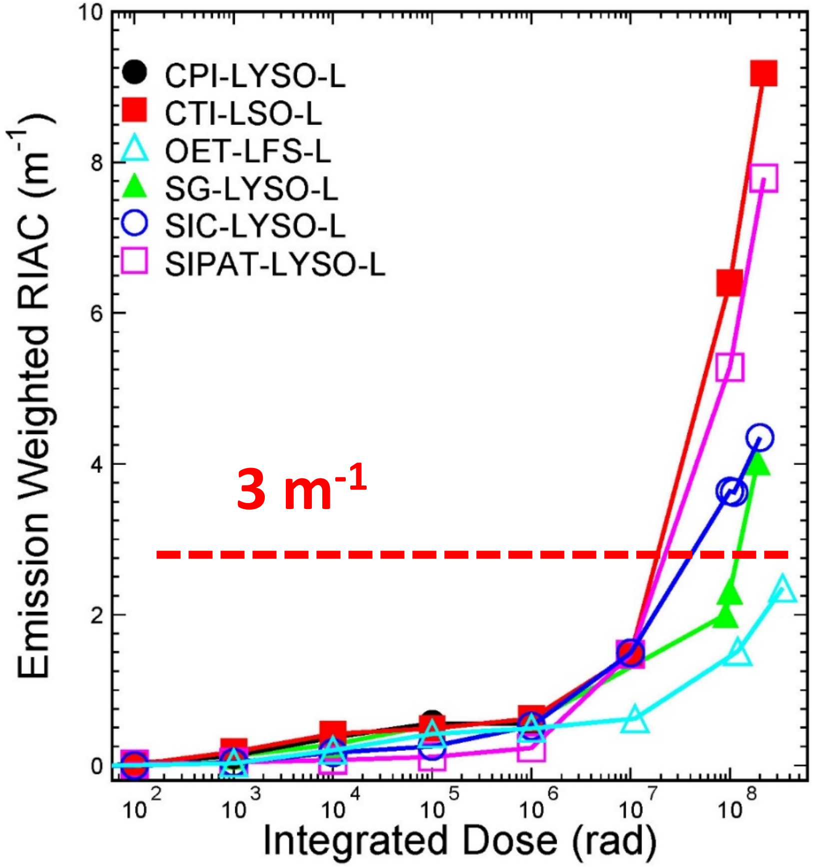


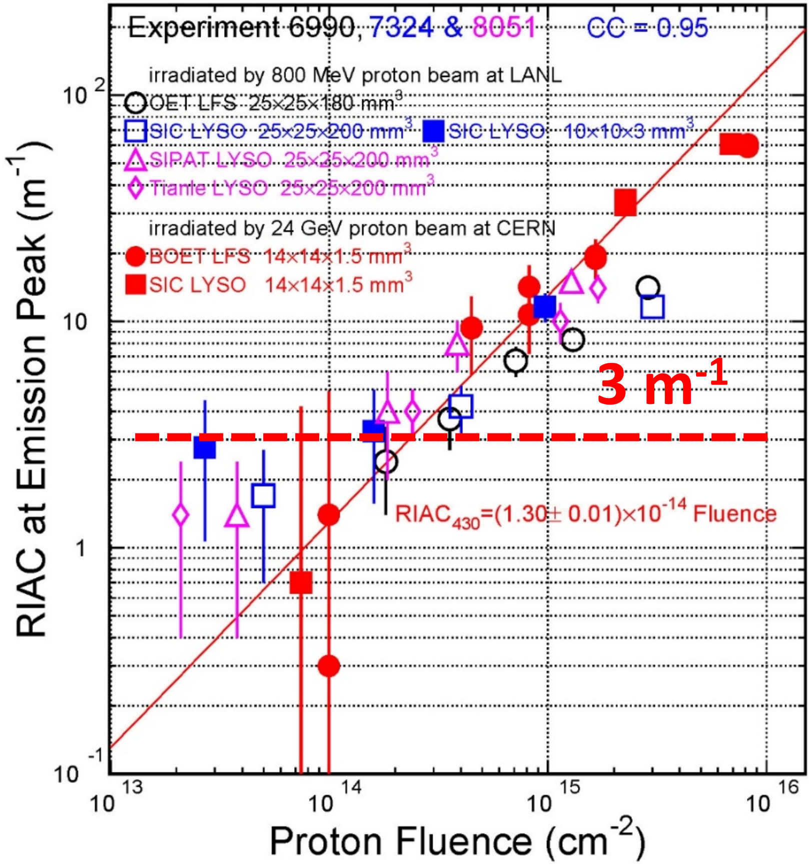
SiPM arrays mockup for TECs testing

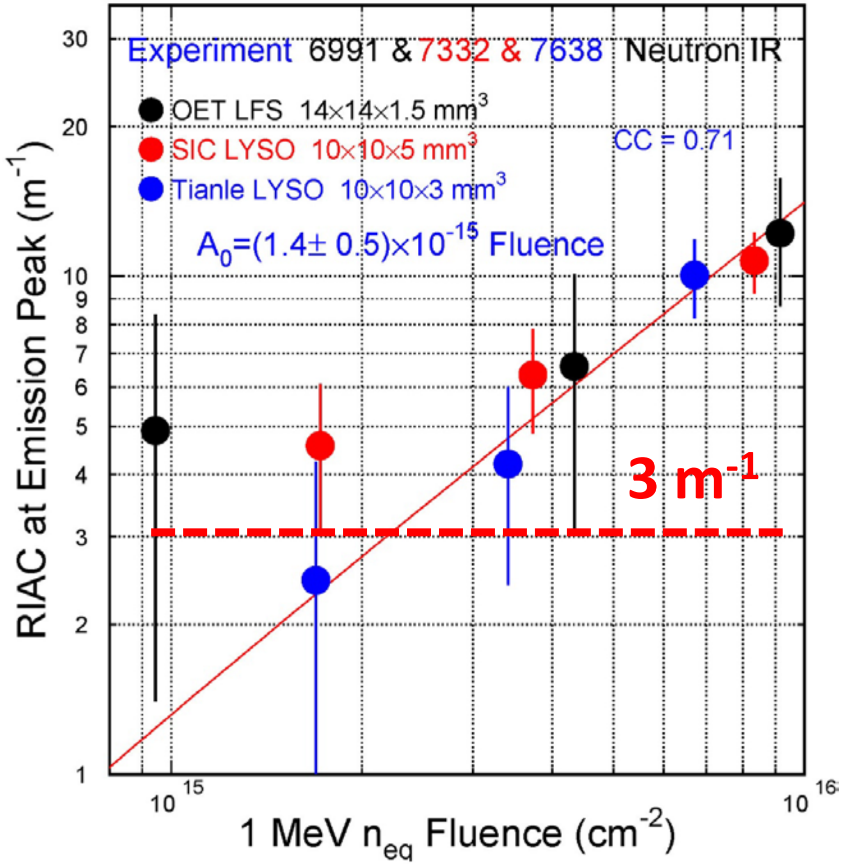
LYSO Radiation Hardness

IEEE TNS 63 (2016) 612-619,

CMS LYSO spec: RIAC < 3 m^{-1} after 4.8 Mrad, 2.5 x 10^{13} p/cm^2 and 3.2 x 10^{14} n_{eq}/cm^2







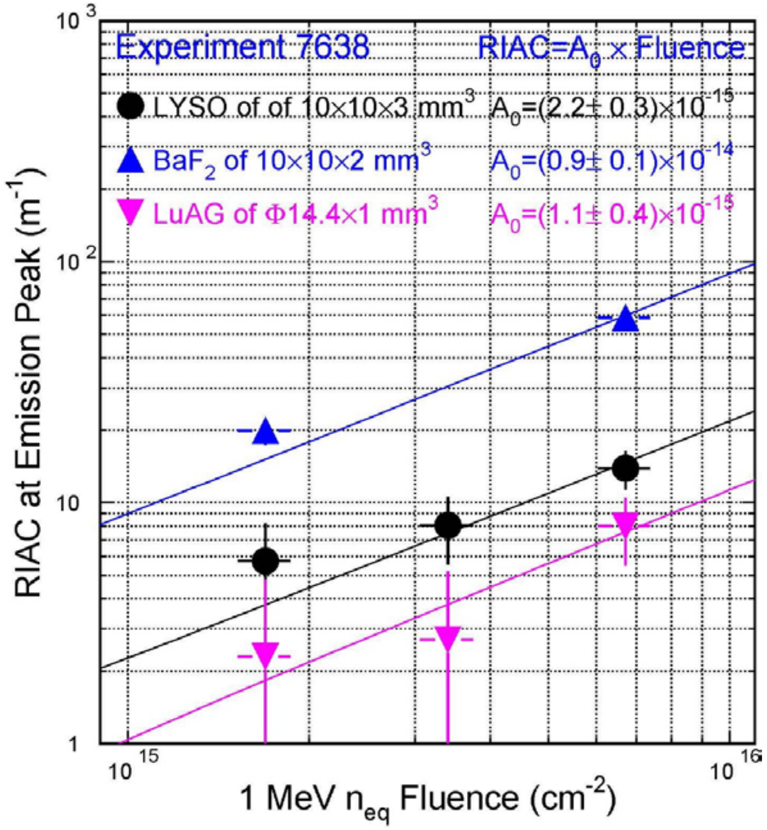
Damage induced by protons is larger than that from neutrons

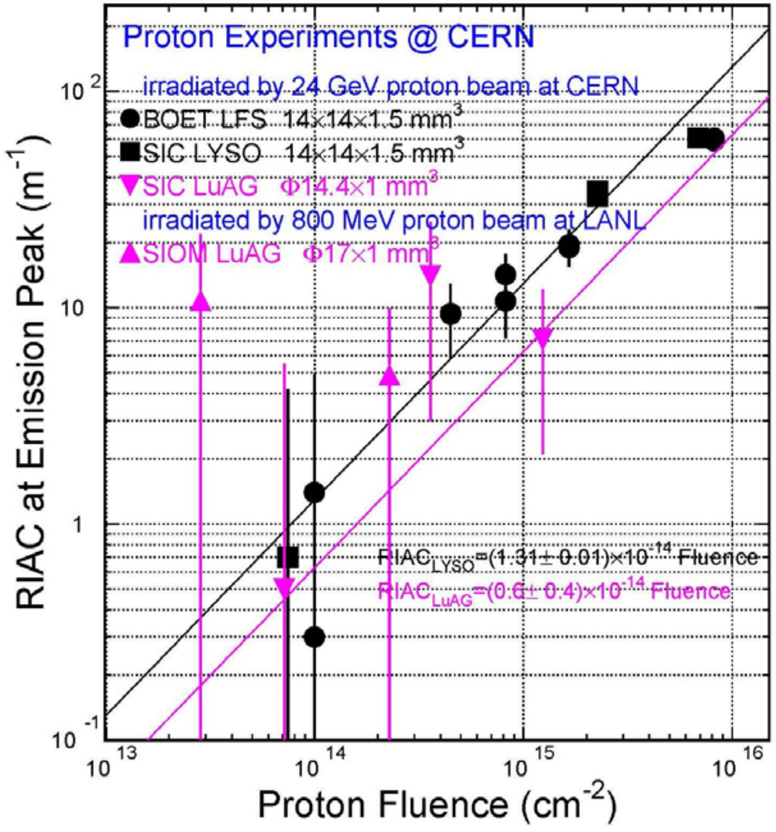
Due to ionization energy loss in addition to displacement and nuclear breakup

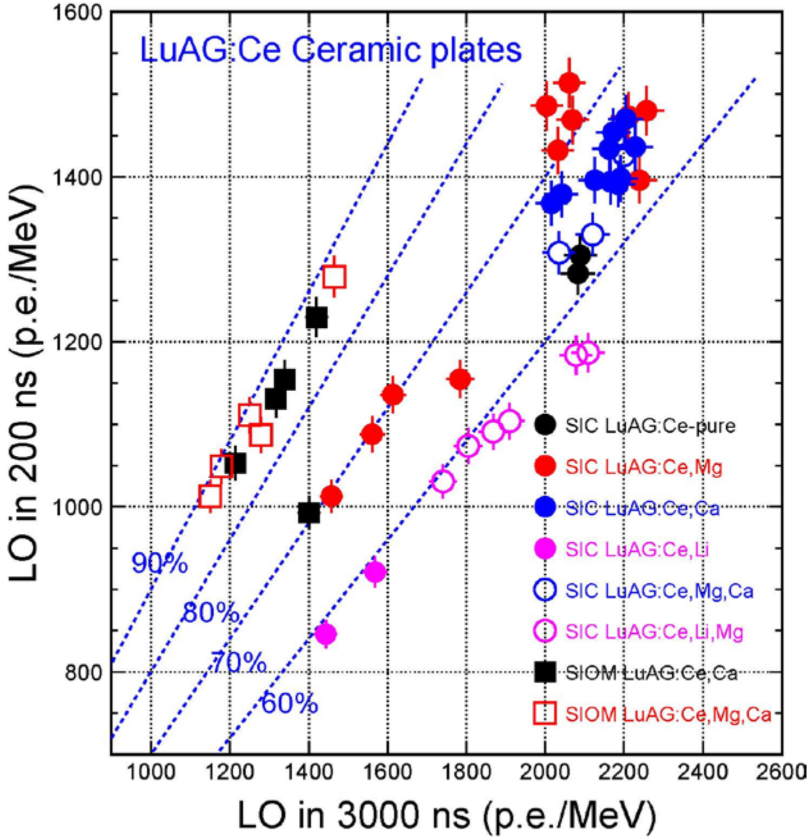
LuAG:Ce Ceramics Radiation Hardness

IEEE TNS 69 (2022) 181-186

LuAG:Ce ceramics show a factor of two smaller RIAC values than LYSO:Ce up to 6.7×10^{15} n_{eq}/cm^2 and 1.2×10^{15} p/cm^2, promising for FCC-hh

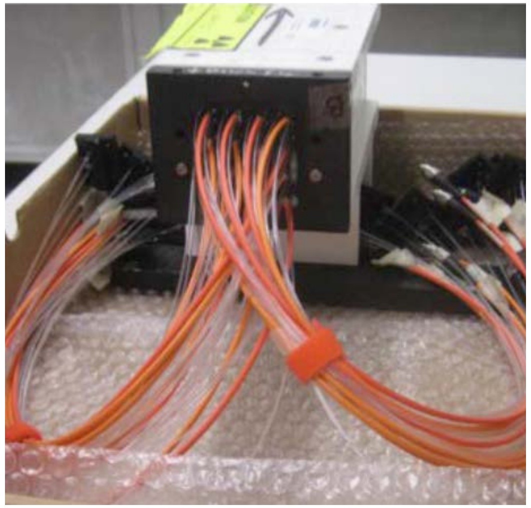


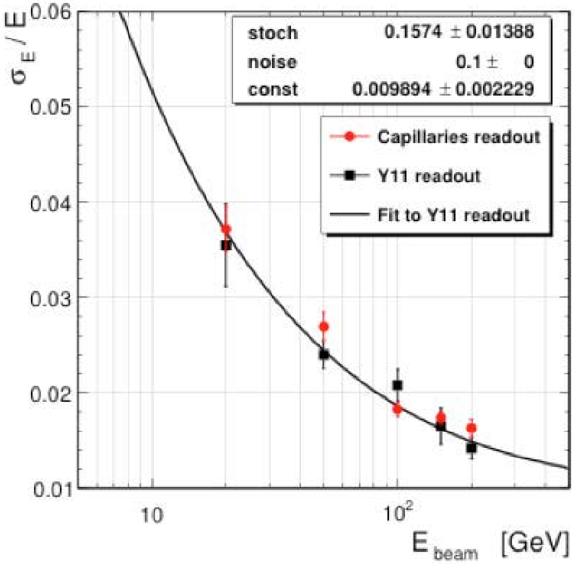




R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

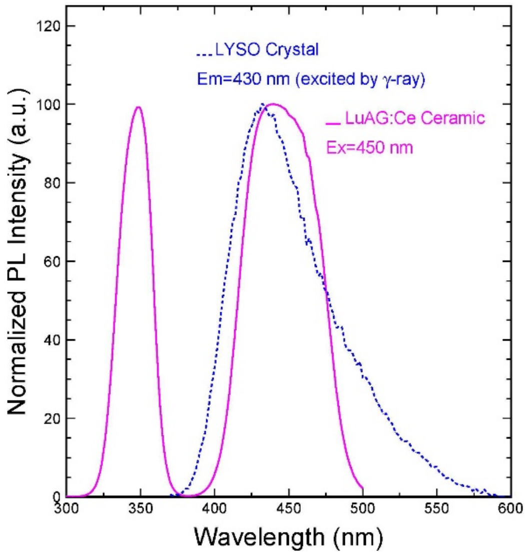
RADiCAL: LYSO/LuAG Shashlik CAL

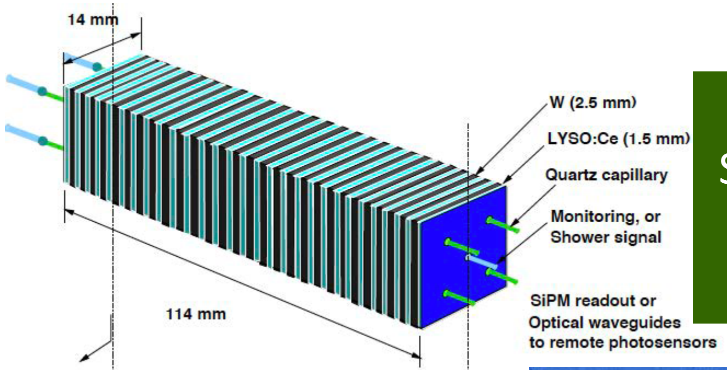




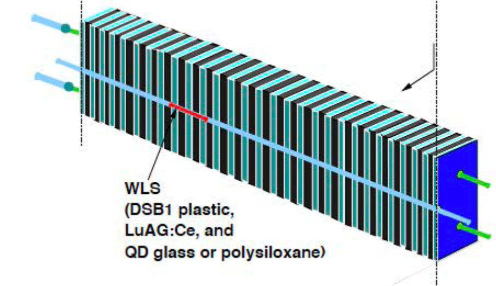
arXiv: 2203.12806

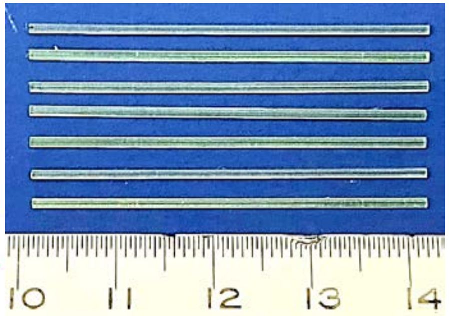
RADiation hard **CAL**orimetry
Reducing light path length to mitigate radiation damage effect
Using radiation hard materials: LuAG:Ce ceramics excitation matches LYSO:Ce emission

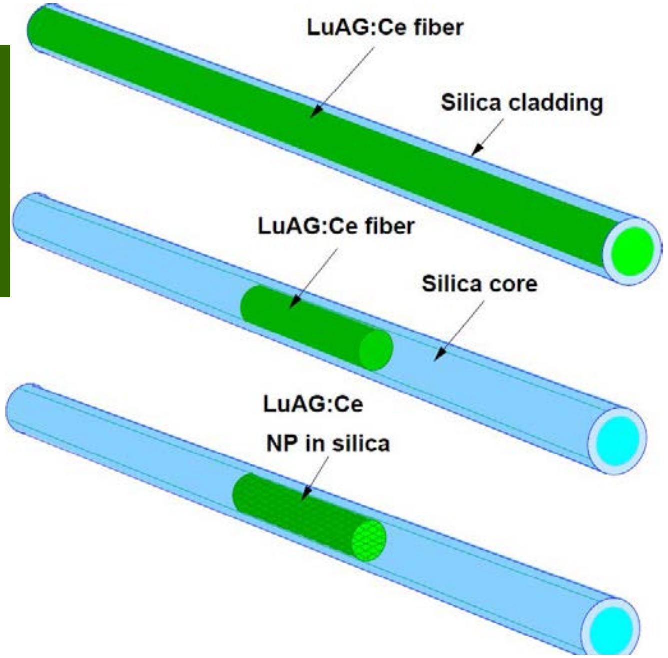


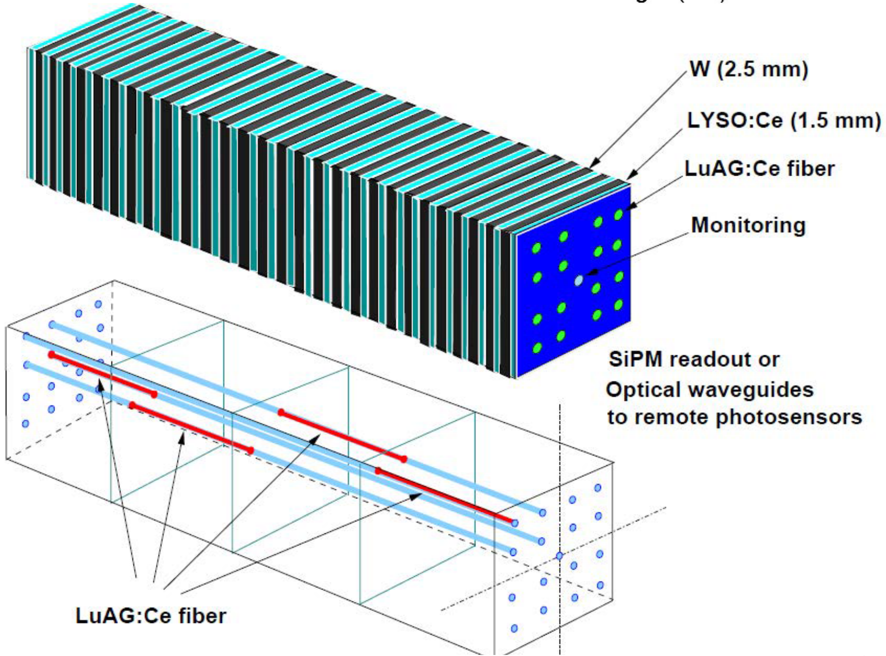


Φ1x40 mm
SIC LuAG:Ce ceramic
LHPG fibers





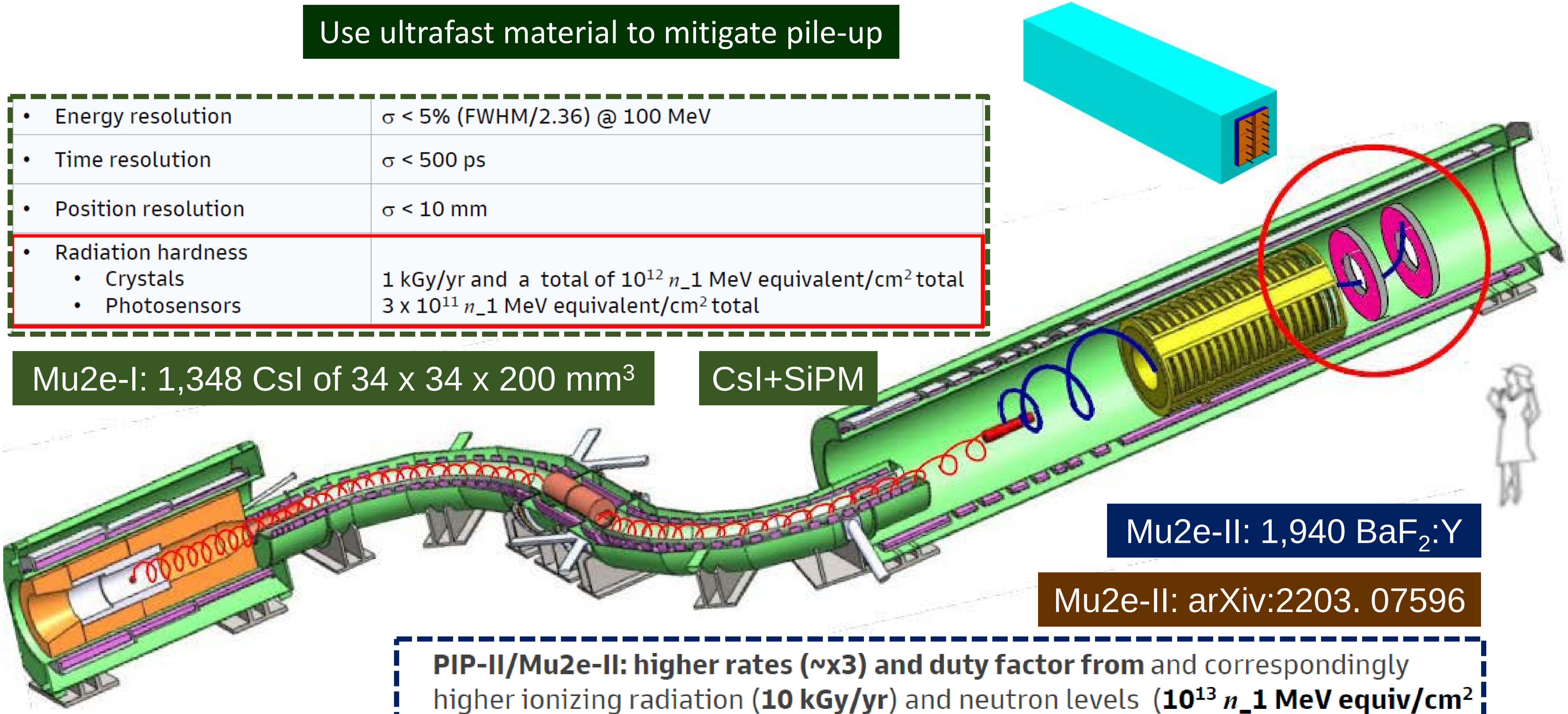




Mu2e-II BaF$_2$:Y Calorimeter

Use ultrafast material to mitigate pile-up

• Energy resolution	$\sigma < 5\%$ (FWHM/2.36) @ 100 MeV
• Time resolution	$\sigma < 500$ ps
• Position resolution	$\sigma < 10$ mm
• Radiation hardness • Crystals • Photosensors	 1 kGy/yr and a total of 10^{12} n_1 MeV equivalent/cm^2 total 3 x 10^{11} n_1 MeV equivalent/cm^2 total



Mu2e-I: 1,348 CsI of 34 x 34 x 200 mm^3

CsI+SiPM

Mu2e-II: 1,940 BaF$_2$:Y

Mu2e-II: arXiv:2203. 07596

PIP-II/Mu2e-II: higher rates (~x3) and duty factor from and correspondingly higher ionizing radiation (**10 kGy/yr**) and neutron levels (**10^{13} n_1 MeV equiv/cm^2 total**), which are particularly important at the inner radius of disk 1

Fast and Ultrafast Inorganic Scintillators

Snowmass 2022 White Paper: https://doi.org/10.48550/arXiv.2203.06788

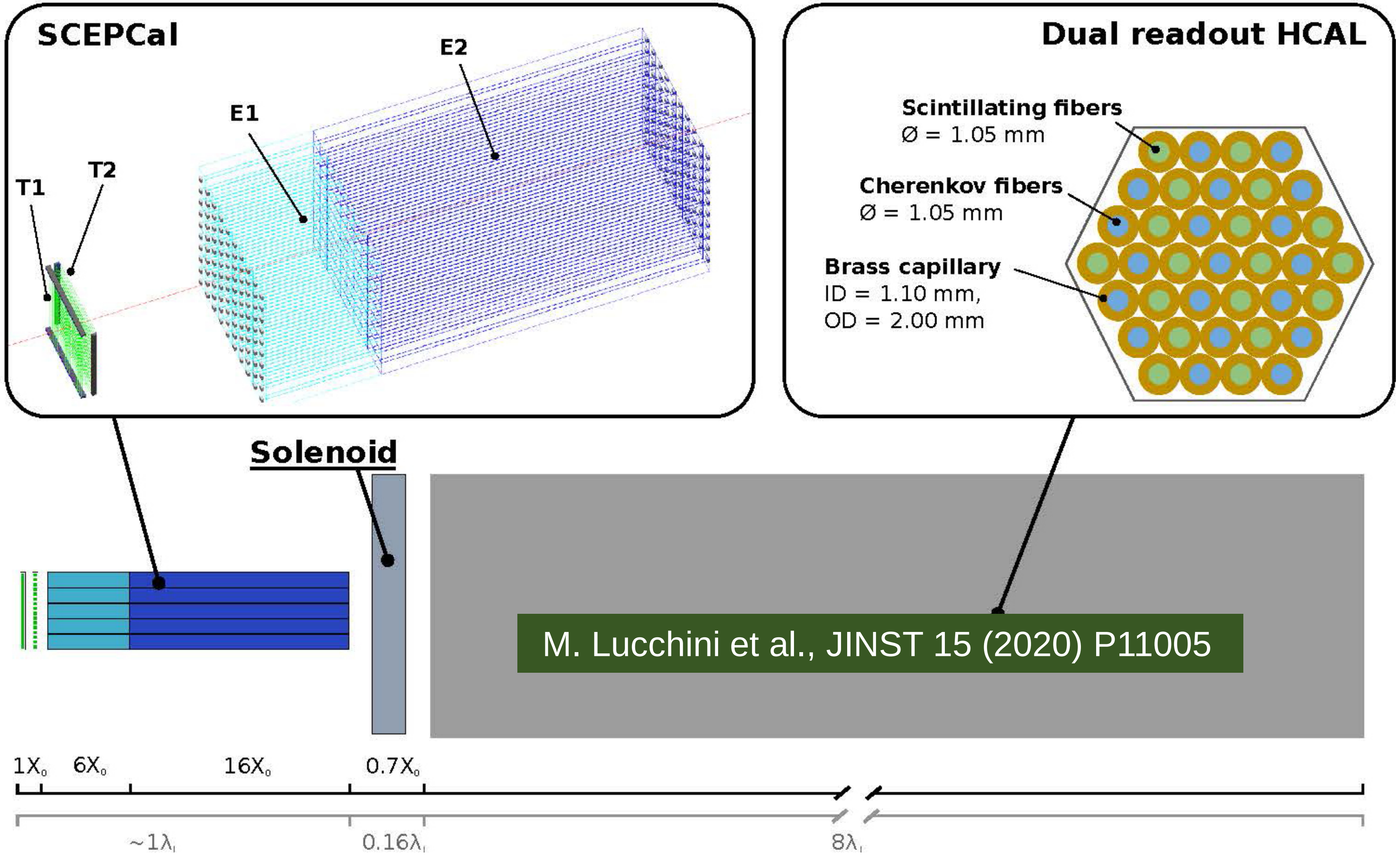
	BaF_2	BaF_2:Y	ZnO:Ga	YAP:Yb	YAG:Yb	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	5.67	5.35	4.56	5.94	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	1975	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	2.77	3.53	2.51	1.14	1.45	2.77	1.63	1.37	3.10
R_M (cm)	3.1	3.1	2.28	2.4	2.76	2.20	2.07	2.15	2.4	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	22.2	22.4	25.2	20.9	20.9	20.6	22.4	21.5	19.5	27.8
Z_{eff}	51.6	51.6	27.7	31.9	30	28.1	64.8	60.3	31.9	51.8	58.6	33.3
dE/dX (MeV/cm)	6.52	6.52	8.42	8.05	7.01	8.82	9.55	9.22	8.05	8.96	9.82	6.57
λ_{peak} [a] (nm)	300 220	300 220	380	350	350	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.1	1.96	1.87	1.97	1.82	1.84	1.96	1.92	1.94	1.78
Normalized Light Yield[a,c]	42 4.8	1.7 4.8	6.6[d]	0.19[d]	0.36[d]	6.5 0.5	100	35[e] 48[e]	9 32	115	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	2,000[d]	57[d]	110[d]	2,100	30,000	25,000[e]	12,000	34,400	10,000	24,000
Decay time[a] (ns)	600 0.5	600 0.5	<1	1.5	4	148 6	40	820 50	191 25	53	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	610[d]	28[d]	24[d]	43	740	240	391	640	125	318
LY in 1st ns/Total LY	9.2%	60%	31%	49%	22%	2.0%	2.5%	1.0%	3.3%	1.9%	1.3%	1.3%
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.407	0.314	0.439	0.394	0.185	0.251	0.314	0.319	0.214	0.334

[a] top/bottom row: slow/fast component; [b] at the emission peak; [c] normalized to LYSO:Ce; [d] excited by alpha particles;
[e] ceramic with 0.3 Mg at% co-doping; [f] density for composition $Lu_{0.7}Y_{0.3}AlO_3$:Ce

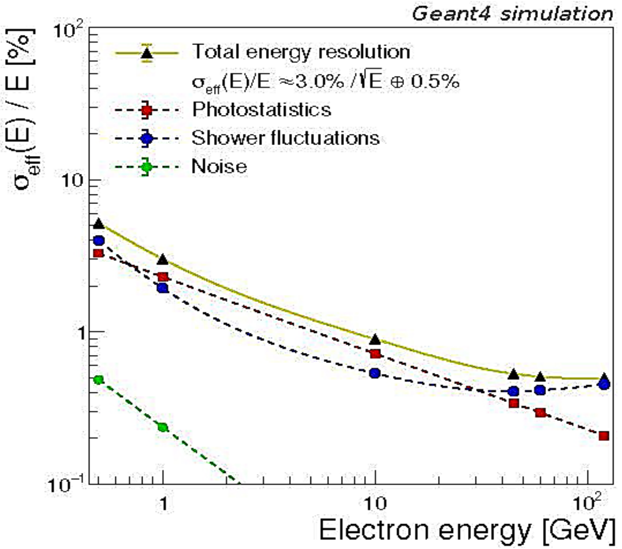
CalVision: A Longitudinally Segmented Crystal ECAL

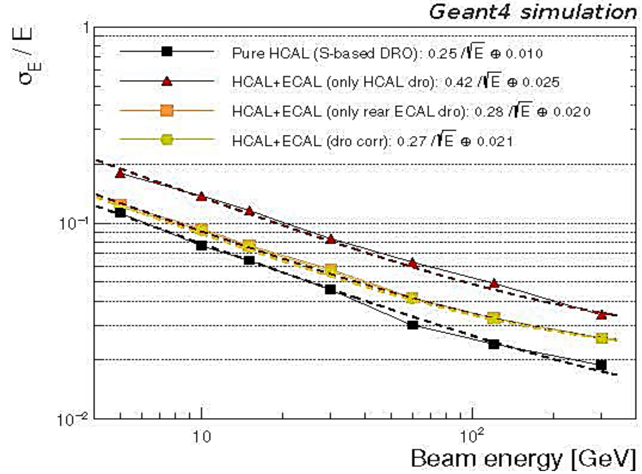
arXiv: 2203.04312, see the DR session for details

Followed by the IDEA DR HCAL, aiming at both EM and jet resolution

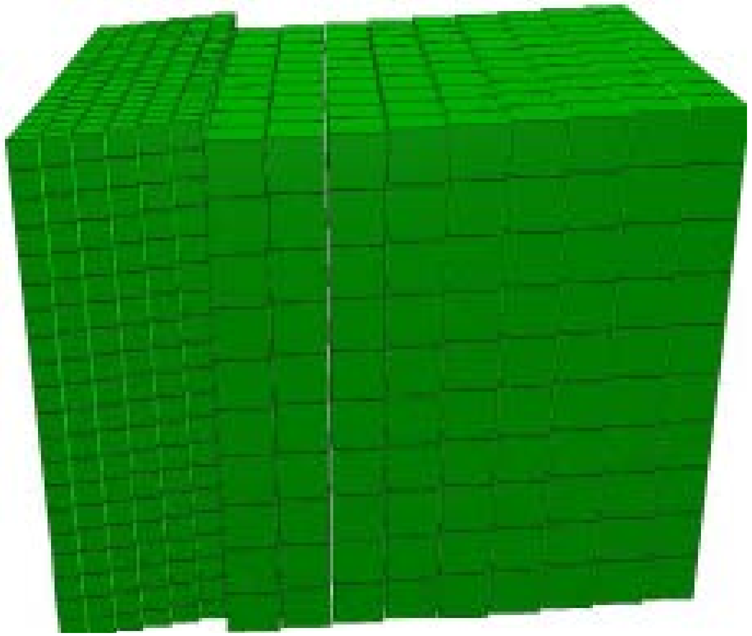


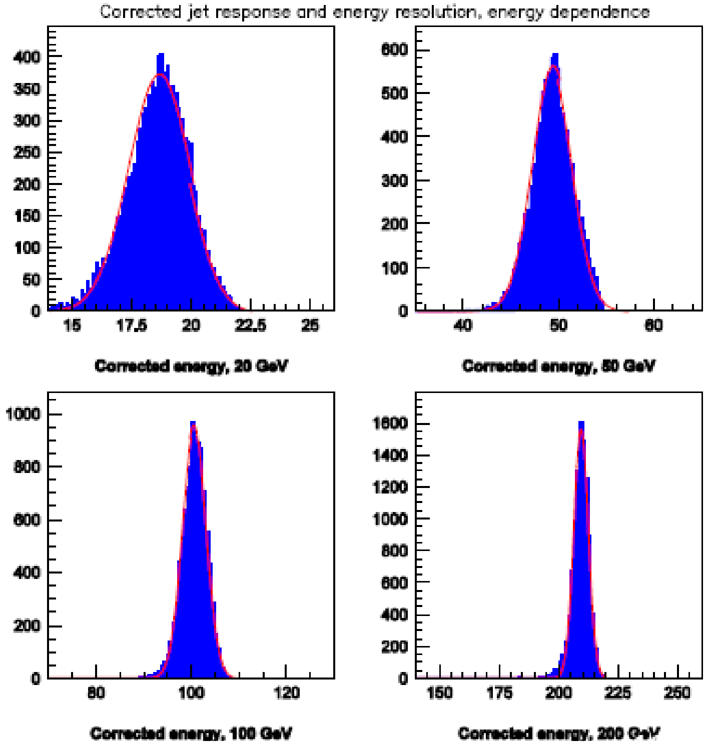
M. Lucchini et al., JINST 15 (2020) P11005



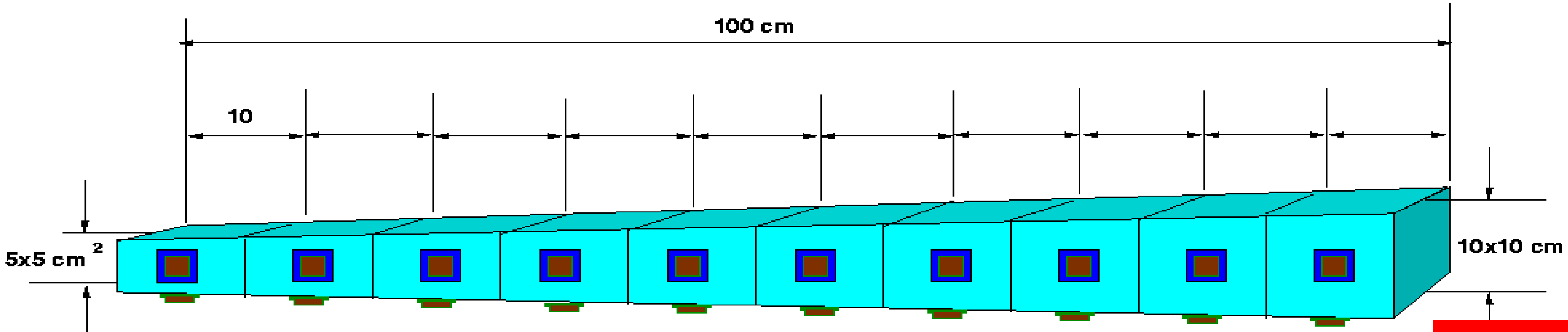


The HHCAL Concept

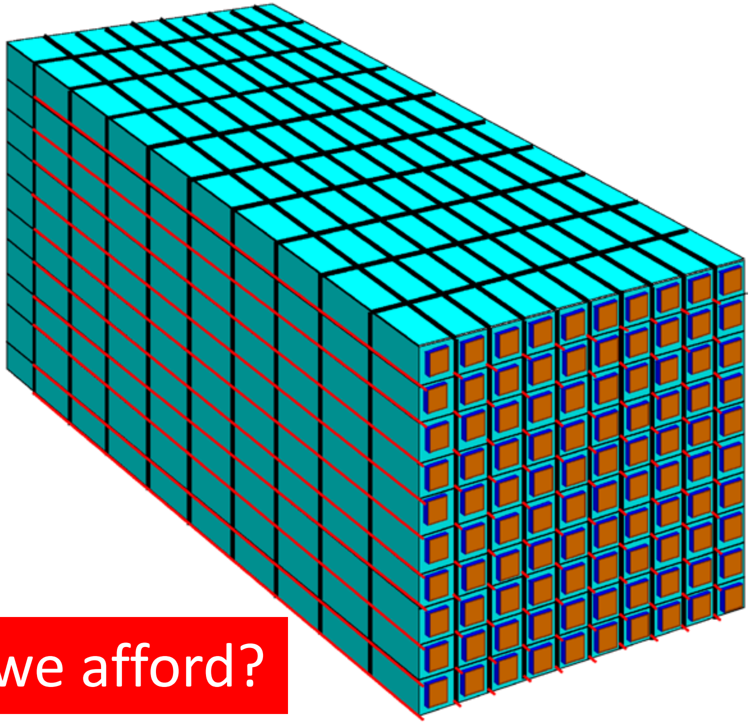




A. Para, H. Wenzel and S. McGill in Callor2012 Proceedings and A. Benaglia *et al.*, IEEE TNS **63** (2016) 574-579: a jet energy resolution at a level of 20%/√E by HHCAL with dual readout of S/C or dual gate.
M. Demarteau, 2021 CPAD Workshop



R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry



Can we afford?

Inorganic Scintillators for HHCAL

Snowmass 2022 White Paper: https://doi.org/10.48550/arXiv.2203.06788

	BGO	BSO	PWO	PbF_2	PbFCl	Sapphire:Ti	AFO Glass	$BaO{\cdot}2SiO_2$ Glass[1]	HFG Glass[2]
Density (g/cm^3)	7.13	6.8	8.3	7.77	7.11	3.98	4.6	3.8	5.95
Melting point (℃)	1050	1030	1123	824	608	2040	980[3]	1420[4]	570
X_0 (cm)	1.12	1.15	0.89	0.94	1.05	7.02	2.96	3.36	1.74
R_M (cm)	2.23	2.33	2.00	2.18	2.33	2.88	2.89	3.52	2.45
λ_I (cm)	22.7	23.4	20.7	22.4	24.3	24.2	26.4	32.8	23.2
Z_{eff} value	72.9	75.3	74.5	77.4	75.8	11.2	42.8	44.4	56.9
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68	6.75	6.84	5.56	8.24
Emission Peak[a] (nm)	480	470	425 420	\	420	300 750	365	425	325
Refractive Index[b]	2.15	2.68	2.20	1.82	2.15	1.76	\	\	1.50
Relative Light Output by PMT[a,c]	100	20	1.6 0.4	\	2.0	0.2 0.9	2.6	5.0 4.0	3.3 6.1
LY (ph/MeV)[d]	35,000	1,500	130	\	150	7,900	450	3,150	150
Decay Time[a] (ns)	300	100	30 10	\	3	300 3200	40	180 30	25 8
d(LY)/dT (%/°C)[d]	-0.9	?	-2.5	\	?	?	?	-0.04	-0.37
Cost ($/cc)	6.0	7.0	7.5	6.0	?	0.6	?	?	?

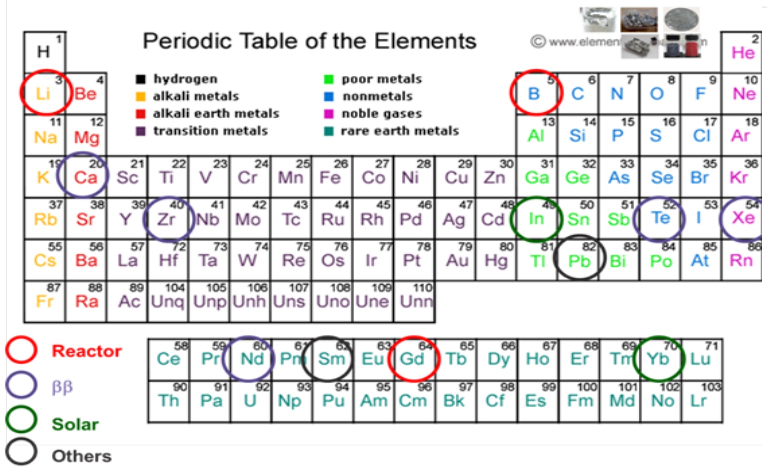
a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. Relative light yield normalized to the light yield of BGO
d. At room temperature (20°C) with PMT QE taken out.

Low density crystals/glasses

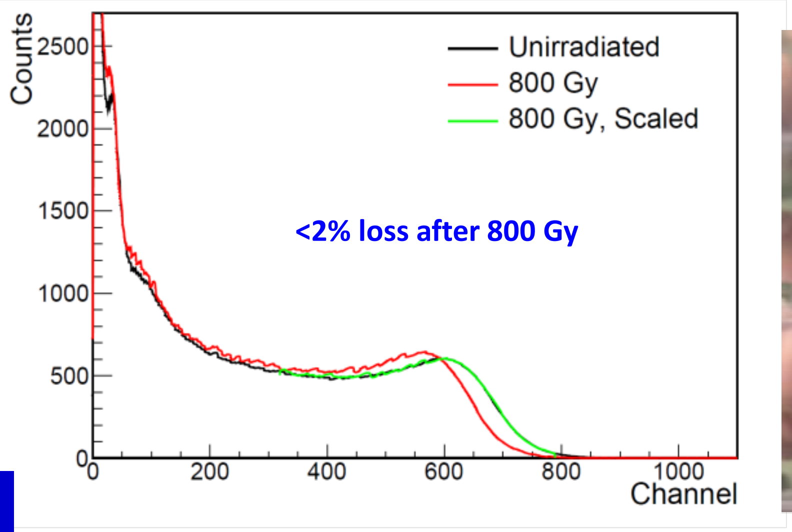
Organic, Liquid and Water-based Scintillators

- Plastic scintillator has modest cost ($10s/kg) and scale-up accessibility
  - Polyvinyltoluene (PVT) and polystyrene (PS) are the base resins for fabrication
  - New resins under development; 3D-printing can be employed to further reduce cost and labor request.
  - A new thermoplastics acrylic scintillator to load scintillators and high-Z elements directly into acrylic monomers is under investigation; a multilayer acrylic detector coupling with SiPMs could provide excellent position and energy reconstruction.
- Liquid scintillator has low cost ($1s/kg), fast timing (sub-ns) and adequate light-yield (10^3 ~ 10^4 ph/MeV)
  - New scintillator solvents enhance performance and improved chemical stability and compatibility with most plastics polymers have been developed for the neutrino frontier over the past decade.
  - Low density required loading high-Z elements at high mass fraction (capability~10%)
- Water-based Liquid Scintillator is novel for high-energy Cherenkov and low-energy scintillation detection
  - Bridging organic and water with long optical transparency (10s m) and more environmentally friend, enabling a broad physics program across a dynamic range from hundreds of keV to many GeV.
  - Low density required loading high Z elements (even more capable up to 30% and still has appreciable scintillation yield)
  - A 30T demonstrator is under construction at BNL to explore engineering parameters and scale-up performance of a kiloton-scale detector for next-generation particle physics experiments.

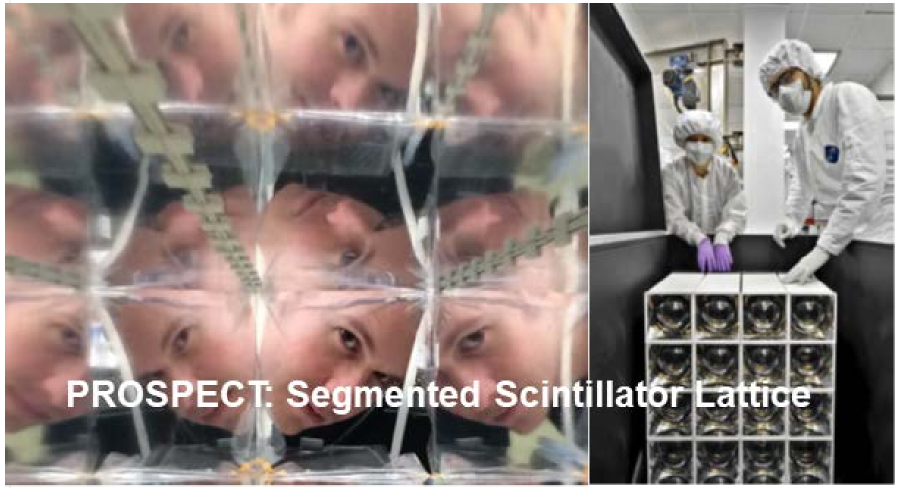
Scintillator Comparison



Metal-doped Liquid Scintillators up to kton scale demonstrate the feasibility of high-Z doping



<2% loss after 800 Gy



PROSPECT: Segmented Scintillator Lattice

Organic Glass Scintillator (OGS) at SNL (P. Feng)

LY ~ >15,000 γ/MeV

2”x2”

Materials (noble gas not included)	LY (ph/MeV)	Cost$^+$ (per kg)	Decay Time (ns)	Comments
Inorganic Scintillators	140 – 63,000	\$1k-\$5k	Sub to 1,000s	High density, easy deployment, low optical, scale-up challenge for large volume application, e.g. HHCAL; RADiCAL uses WLS*
Organic Scintillator Plastics	1,000s	\$10s	1s	Medium density, easy deployment, m-optical, scale-up challenge (3D-print?), WLS*
(High Z-doped, 1s%) Organic Liquid Scintillator	9,000-14,000	\$1s	Sub	~10m-optical, low density (mitigated by high-Z?), large volume; WLS-doped
(High Z-doped, 10s%) Water-based Liquid Scintillator	1,000s	<\$1s	Sub	~10m-optical, low density (mitigated by high-Z?), environmentally-friendly, large volume, WLS-doped

- WLS (fibers) bridging emission to photosensor are required for plastics; direct coupling (no WLS) used by crystal calorimetry

\+ See slide 27 of http://www.hep.caltech.edu/~zhu/talks/ryz_210316_EIC_Crystal_CAL.pdf, for mass-produced crystal cost per cc.

Wavelength Shifter (WLS)

- WLS forms optical “bridges”:
  - Connect scintillation light emission from crystal, ceramic or organic scintillators to photosensors
    - Located proximately (or directly) within a detector region if the photosensors are radiation tolerant to the levels needed
    - Remotely - with fiberoptic connection - as needed for radiation protection of the photosensors.

- WLS are spectrally matched to a given scintillator and photosensor:
  - WLS Excited by the scintillation emission
  - WLS Emit at a longer wavelength that is accessible to photosensors.
  - Can be placed strategically to provide selective measurements.

- WLS in capillary or fiber/filament form are particularly effective in EM calorimetry:
  - Energy Measurement
  - Fast-timing Measurement
  - Precision spatial measurement of shower position
  - All of the above are potentially possible in ultracompact EM Calorimetry Modules (example RADiCAL)
  - These structures have the potential for application in challenging radiation environments, e.g. FCC-hh.

WLS R&D for RADiCAL

Scintillator material	Scintillator Emission Wavelength	Wavelength Shifters	WLS Emission Wavelengths	Photosensor Possibilities
LYSO:Ce	425nm	DSB1	495nm	SiPM, GaInP, new
LYSO:Ce	425nm	LuAG:Ce	520nm	SiPM, GaInP, new
LYSO:Ce	425nm	Direct - No WLS		SiPM, new
LuAG:Ce	520nm	Quantum Dots	560-580nm	SiPM, GaInP, new
LuAG:Pr	310nm	pTP TPB Flavenols	360nm 460nm 530-560nm	SiPM, GaInP, new
LuAG:Pr	310nm	Direct - No WLS		SiC
CeF_3	330mm	pTP TPB Flavenols	360nm 460nm 560nm	SiPM, GaInP, new
CeF_3	330nm	Direct - No WLS		SiC
BaF_2:Y	220nm	Direct – No WLS		Diamond

Summary

Future calorimetry requires fast, radiation hard and cost-effective material.

Radiation-hard LYSO:Ce crystals and LuAG:Ce ceramics are proposed for an ultra-compact **RADiCAL** concept.

A BaF_2:Y ultrafast crystal calorimeter is proposed for Mu2e-II.

A segmented crystal ECAL with dual readout followed by the IDEA HCAL is proposed by **CalVision** for both EM and jet resolution for the Higgs factory.

Homogeneous HCAL (**HHCAL**) promises the best jet mass resolution by total absorption. A critical issue is cost-effective mass-produced inorganic scintillator.

Organic, liquid and water-based scintillators are very cost-effective, but have low density.

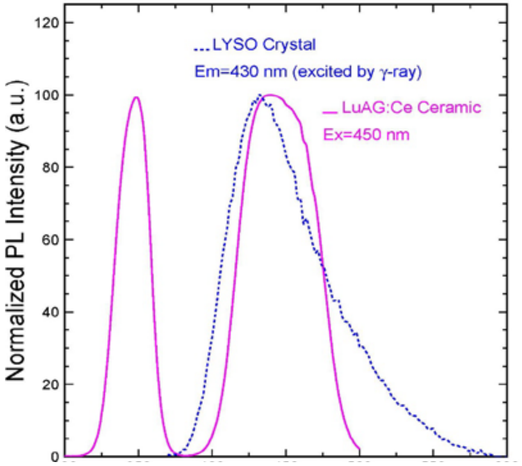
RADiCAL has a plan for novel WLS.

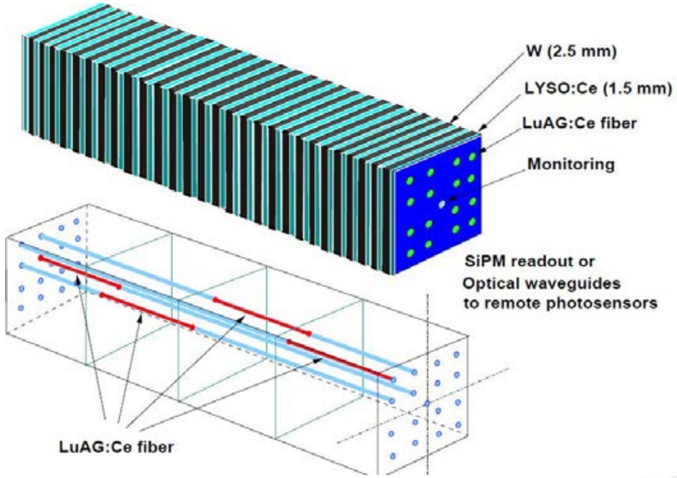
Novel materials are needed for all these calorimeter concepts

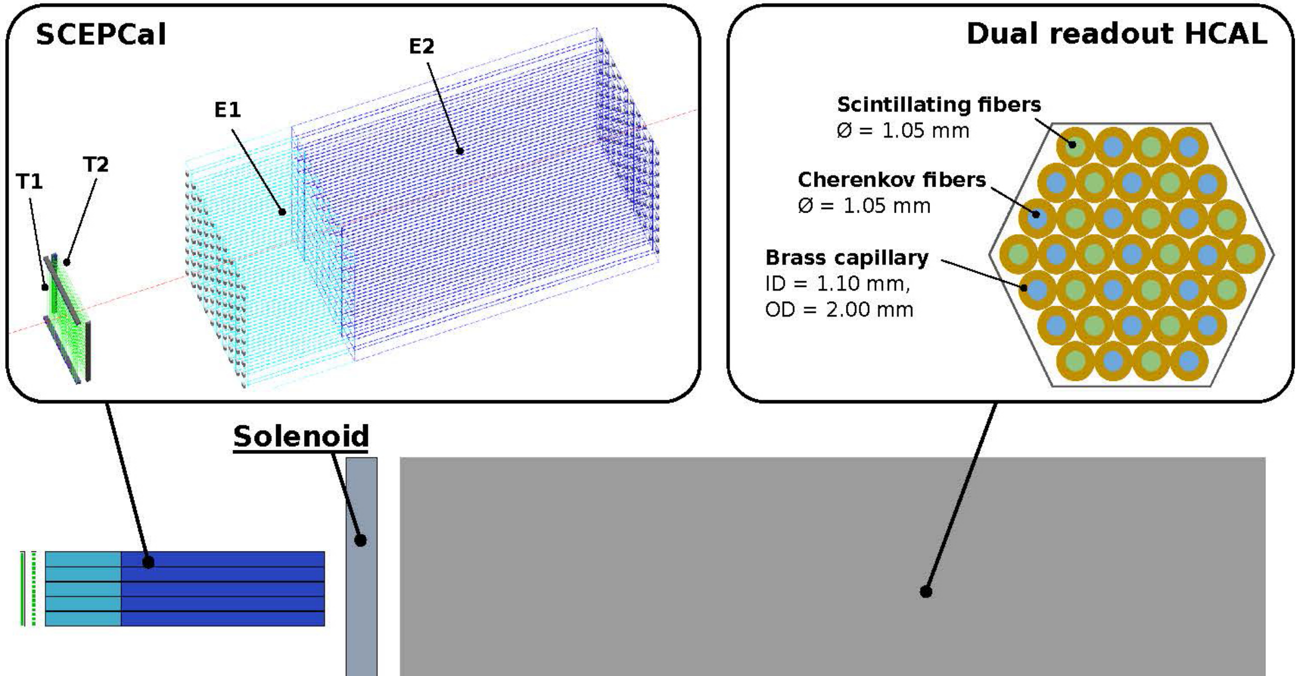
Acknowledgements: DOE HEP Award DE-SC0011925DE-SC0017810, DEAC02-98CH10886

Snowmass White Papers

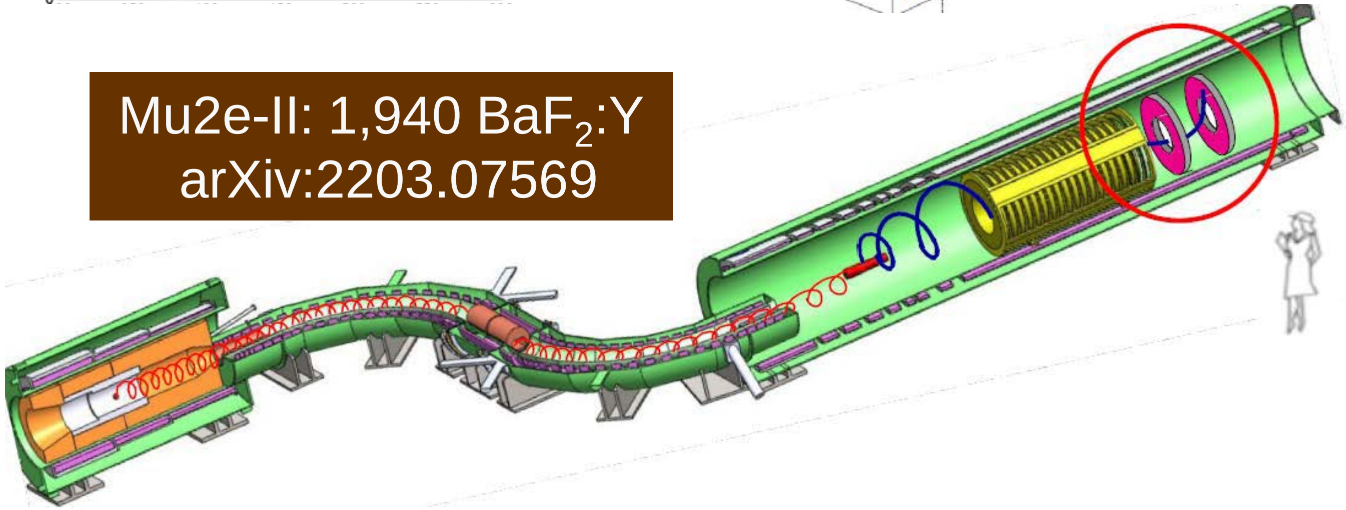
RADiCAL: **RAD**iation hard **i**nnovative **CAL**orimetry
LYSO:Ce crystals and LuAG:Ce ceramics
arXiv: 2203.12806







Mu2e-II: 1,940 BaF_2:Y
arXiv:2203.07569



CalVision: A Longitudinally segmented crystal ECAL (BGO, BSO, PWO and glasses) followed by IDEA DR HCAL
arXiv:2203.04312

Mass-Produced Crystal Cost (Mar 2019)

http://www.hep.caltech.edu/~zhu/talks/ryz_210316_EIC_Crystal_CAL.pdf

Item	Size (R_MxR_Mx25 X_0)	1 m^3	10 m^3	100 m^3	Scaled to X_0
BGO	22.3×22.3×280 mm	$8/cc	$7/cc	$6/cc	1.23
BaF_2:Y	31.0×31.0×507.5 cm	$12/cc	$11/cc	$10/cc	2.28
LYSO:Ce	20.7x20.7x285 mm	$36/cc	$34/cc	$32/cc	1.28
PWO	20x20x223 mm	$9/cc	$8/cc	$7.5/cc	1.00
BSO	22x22x274 mm	$8.5/cc	$7.5/cc	$7.0/cc	1.29
CsI	35.7x35.7x465 mm	$4.6/cc	$4.3/cc	$4.0/cc	2.09

CMS MTD: Expected Radiation

CMS BTL/EMEC: 4.8/68 Mrad, $2.5\times10^{13}/2.1\times10^{14}$ p/cm^2 & $3.2\times10^{14}/2.4\times10^{15}$ n_{eq}/cm^2

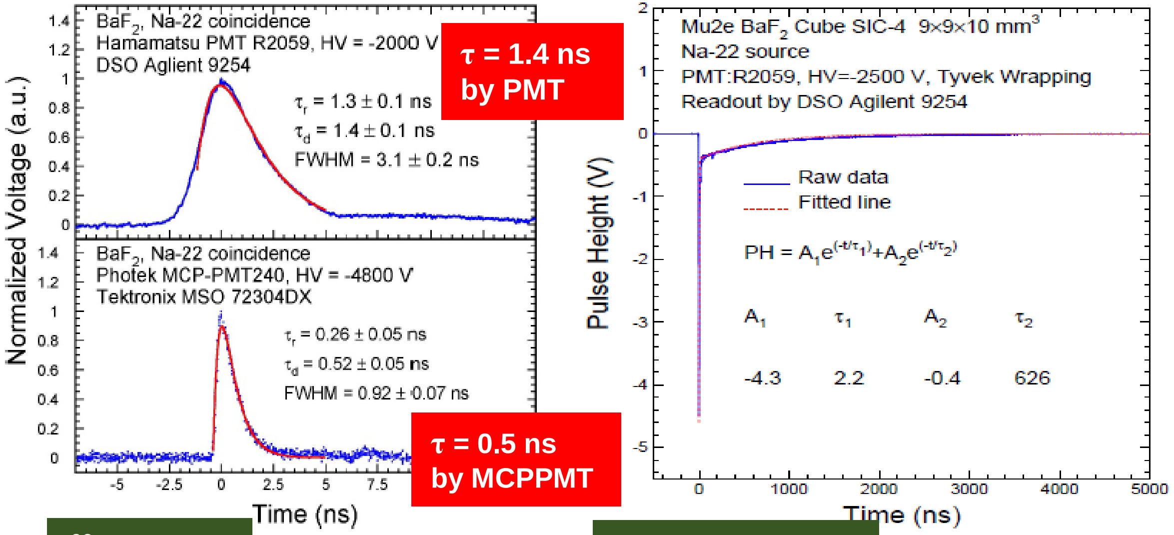
CMS MTD	η	n_{eq} (cm^{-2})	n_{eq} Flux (cm^{-2}s^{-1})	Proton (cm^{-2})	p Flux (cm^{-2}s^{-1})	Dose (Mrad)	Dose rate (rad/h)
Barrel	0.00	2.5E+14	2.8E+06	2.2E+13	2.4E+05	2.7	108
Barrel	1.15	2.7E+14	3.0E+06	2.4E+13	2.6E+05	3.8	150
Barrel	**1.45**	**2.9E+14**	**3.2E+06**	**2.5E+13**	**2.8E+05**	**4.8**	**192**
Endcap	1.60	2.3E+14	2.5E+06	2.0E+13	2.2E+05	2.9	114
Endcap	2.00	4.5E+14	5.0E+06	3.9E+13	4.4E+05	7.5	300
Endcap	2.50	1.1E+15	1.3E+07	9.9E+13	1.1E+06	26	1020
Endcap	**3.00**	**2.4E+15**	**2.7E+07**	**2.1E+14**	**2.3E+06**	**68**	**2700**

Much higher at FCC-hh: up to 0.1/500 Grad and $3\times10^{16}/5\times10^{18}$ n_{eq}/cm^2 at EMEC/EMF

M. Aleksa *et al.*, Calorimeters for the FCC-hh CERN-FCCPHYS-2019-0003, Dec 23, 2019

Ultrafast and Radiation Hard BaF$_2$

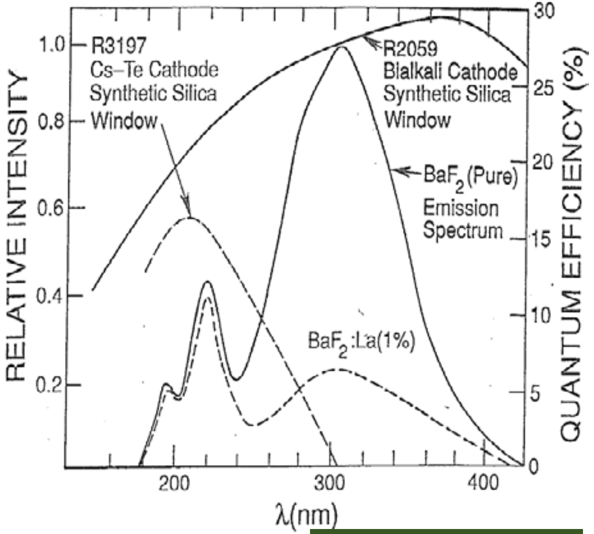
IEEE TNS NS 67, NO. 6 (2020) 1014-1019



τ = 1.4 ns by PMT

τ = 0.5 ns by MCPPMT

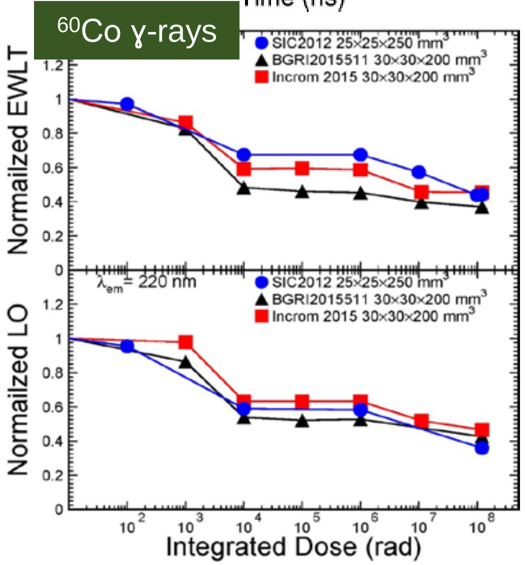
NIMA 340 (1994) 442-457



BaF$_2$ has an ultrafast scintillation component @ 220 nm with **0.5 ns** decay time and a much larger slow component @ 300 nm with 600 ns decay time.

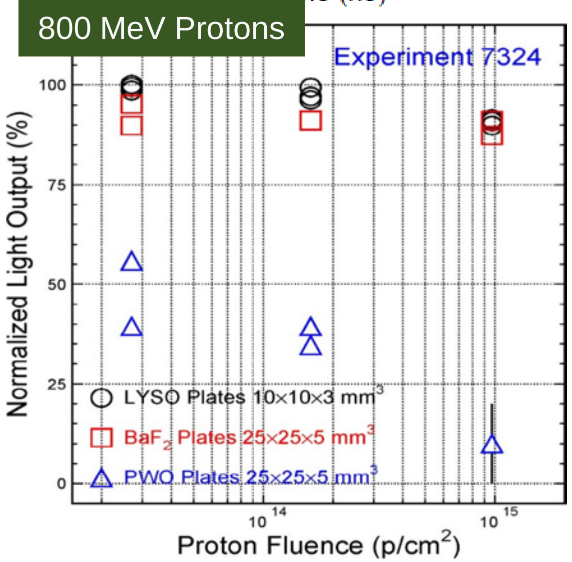
Slow suppression may be achieved by rare earth doping, and/or solar-blind photo-detectors

^{60}Co ɣ-rays



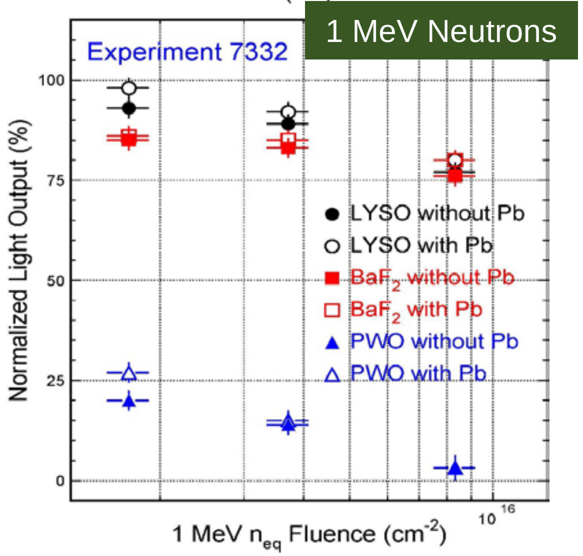
IEEE TNS **63** (2016) 612-619

800 MeV Protons



IEEE TNS **65** (2018) 1086-1092

1 MeV Neutrons



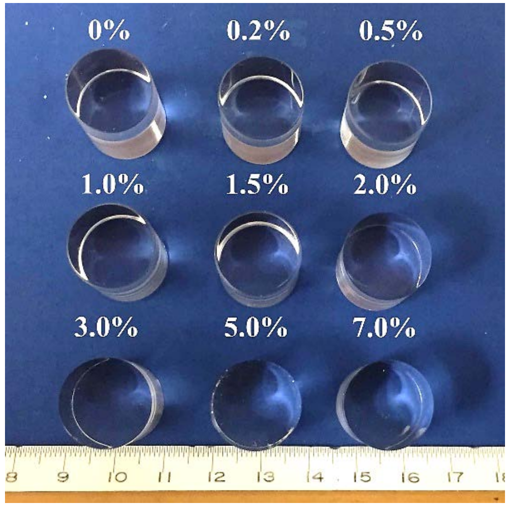
IEEE TNS **67** (2020) 1018-1024

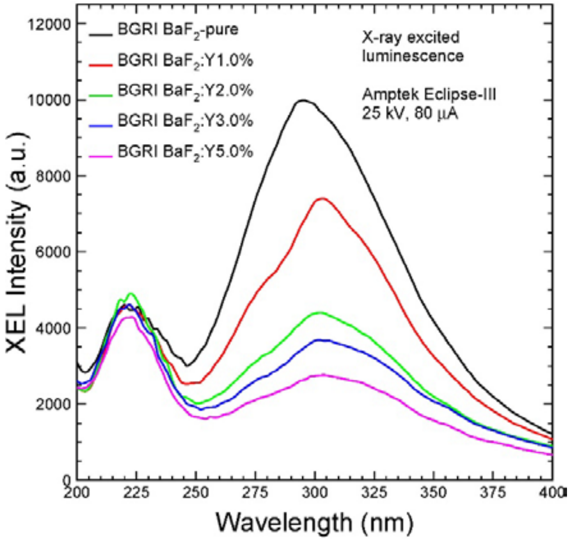
BaF$_2$ shows saturated damage from 10 krad to 100 Mrad, indicating good radiation resistance against ɣ-rays

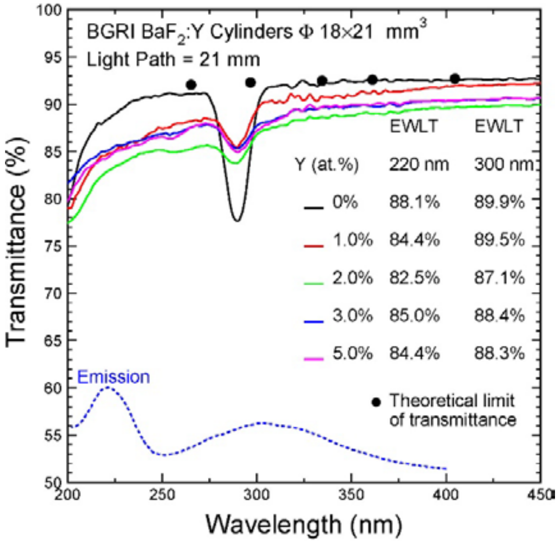
BaF$_2$ also survives after proton irradiation up to 9.7×10^{14} p/cm^2, and neutron irradiation up to 8.3×10^{15} n_{eq}/cm^2

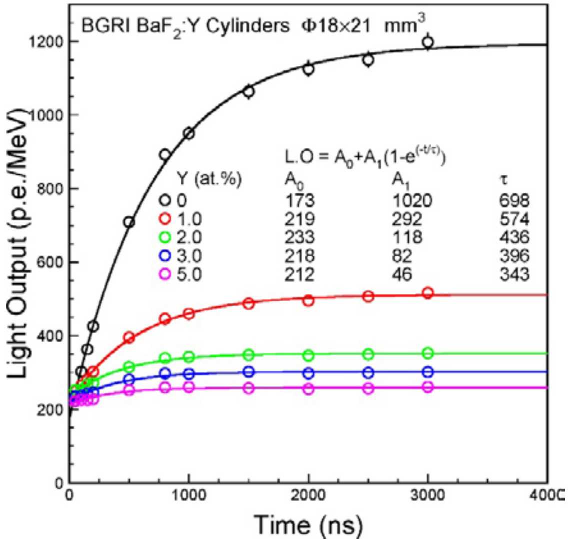
BaF$_2$:Y for Ultrafast Calorimetry

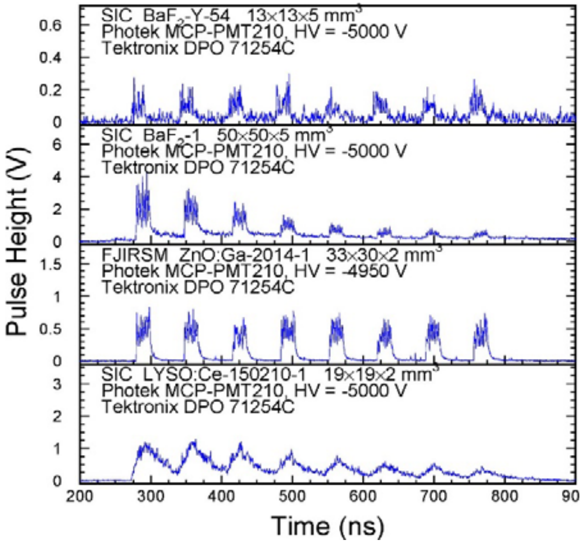
Increased F/S ratio observed in BGRI BaF$_2$:Y crystals: Proc. SPIE 10392 (2017)

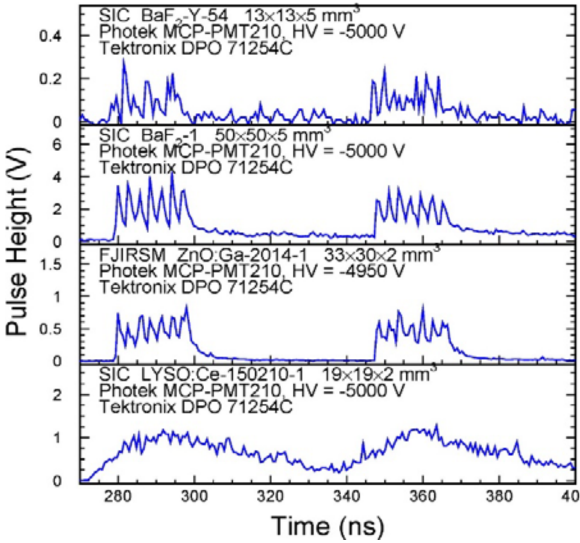


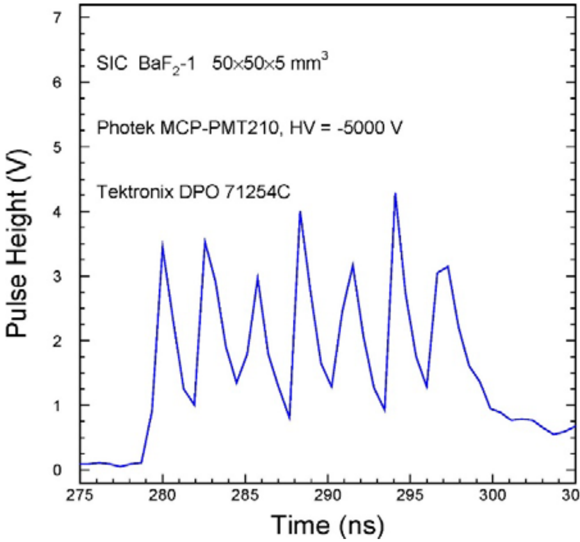






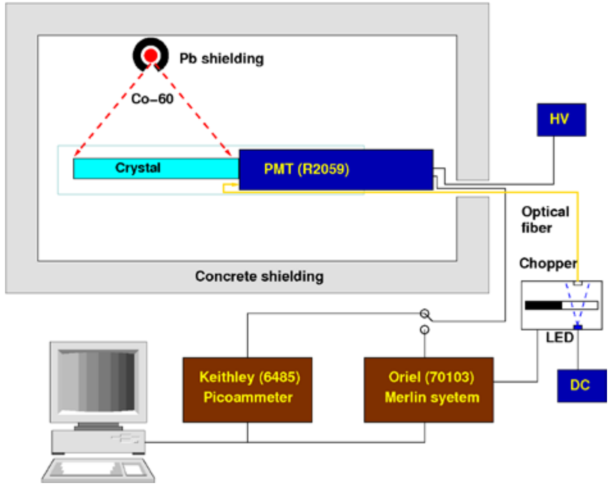






X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF$_2$:Y and BaF$_2$ crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

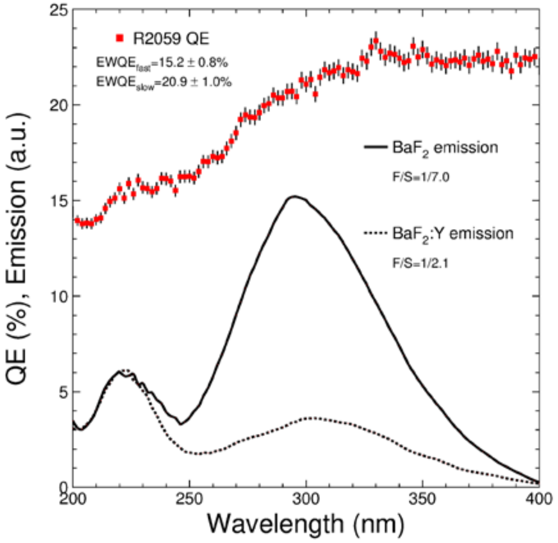
Gamma-ray Induced Readout Noise RIN:γ

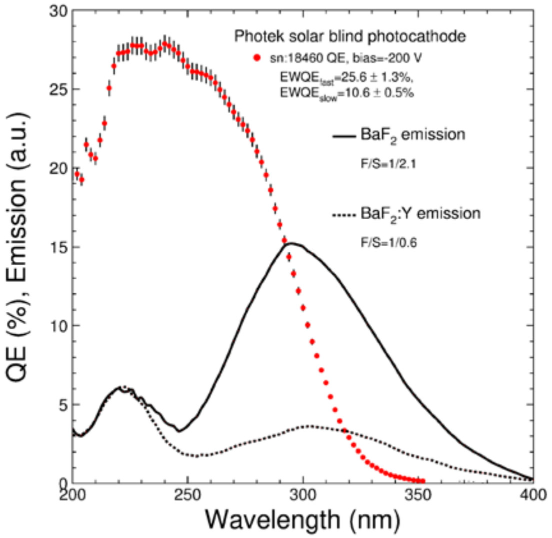


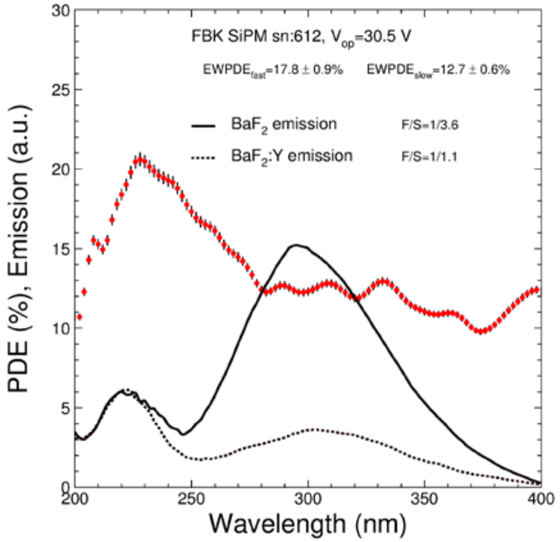
BaF$_2$ crystals wrapped by Tyvek with an air gap coupling to a Hamamatsu PMT R2059, were irradiated by Co-60 with dose rates of 2 and 23 rad/h

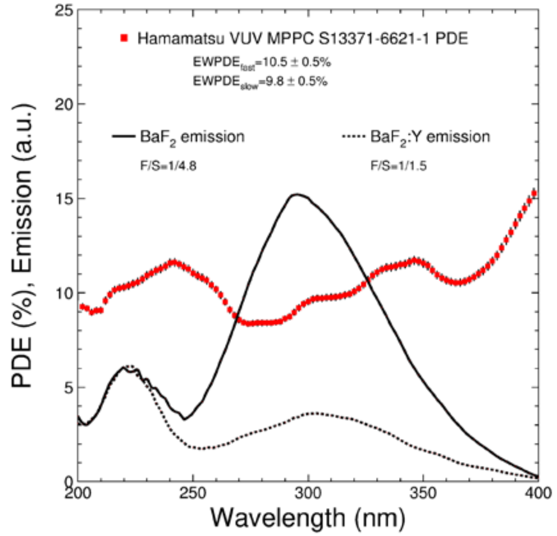
$$F = \frac{\dfrac{Photocurrent}{Charge_{electron} \times Gain_{SiPM}}}{Dose\ rate_{\gamma-ray}\ or\ Flux_{neutron}} \qquad \sigma = \frac{\sqrt{Q}}{LO}\ \text{(MeV)}$$

QE/PDE of four VUV photodetectors for BaF$_2$ and BaF$_2$:Y, IEEE TNS **69** (2022) 958-964









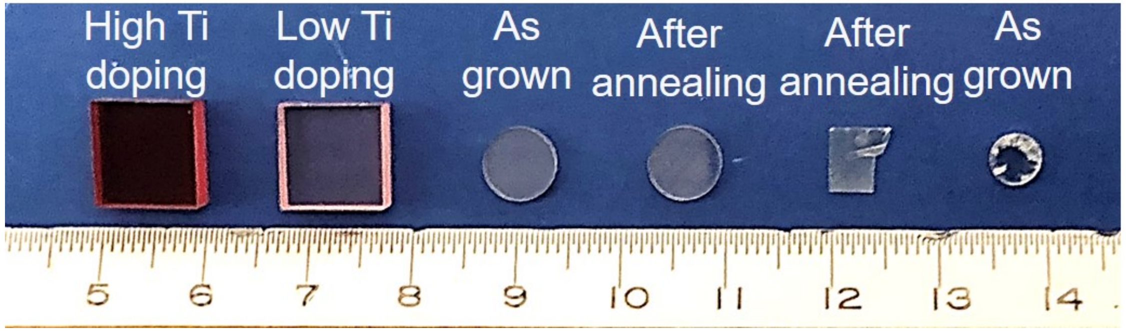
Cost-Effective Sapphire Crystals for HHCAL

Large sapphire crystal of 400-450 kg

Prof. Xu Jun of Tongji University: Sapphire crystals by Kyropoulos (KY) technology A producer can grow 1,000 tons ingots annually with 400 to 450 kg/ingot Cost of mass-produced Sapphire crystals including processing: less than $1/cc

	Weight (kg)	Size (cm)	Unit Price	Comment
ingot boule	400	Φ50×55	US$12000/pc	for undoped
cutting/polishing	4	1×1×1	**~US$0.6/cc**	for undoped

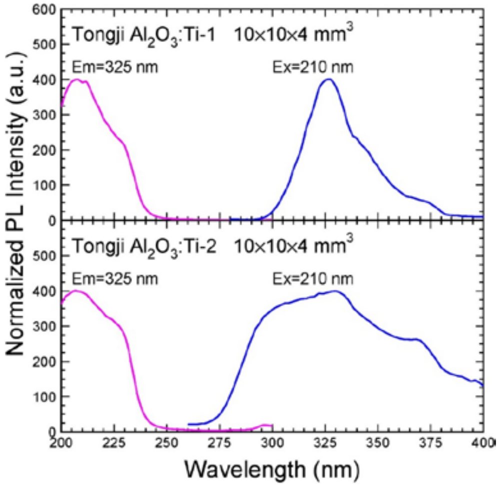
Sapphire:Ti Emission and Transmittance



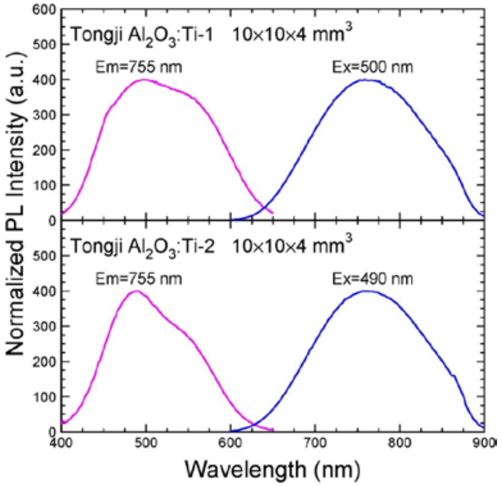
A weak emission at 325 nm with 150 ns decay time
A strong emission at 755 nm with 3 μs decay time

ID	Dimension (mm³)	#	Polishing
Tongji Al_2O_3:Ti-1,2	**10×10×4**	**2**	**Two faces**
Tongji Al_2O_3:C-1,2	Φ7×1	2	Two faces
Tongji Lu_2O_3:Yb	6.4×4.8×0.4	1	Two faces
Tongji $LuScO_3$:Yb	Φ4.8×1.3	1	Two faces

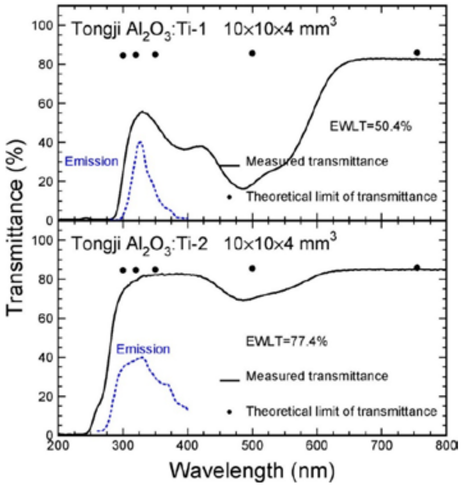
Fast @325 nm



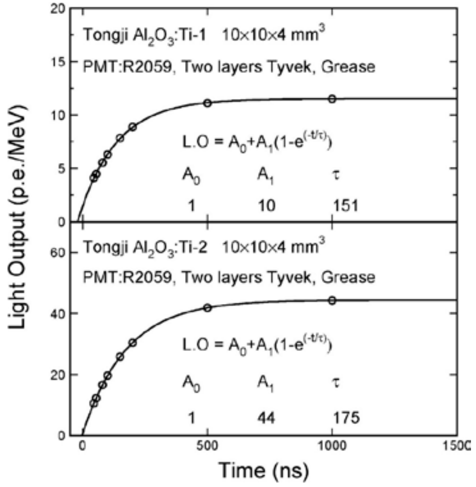
Slow @755 nm



EWLT for Fast & Slow



Fast = 162 ns



Slow = 3.2 μs