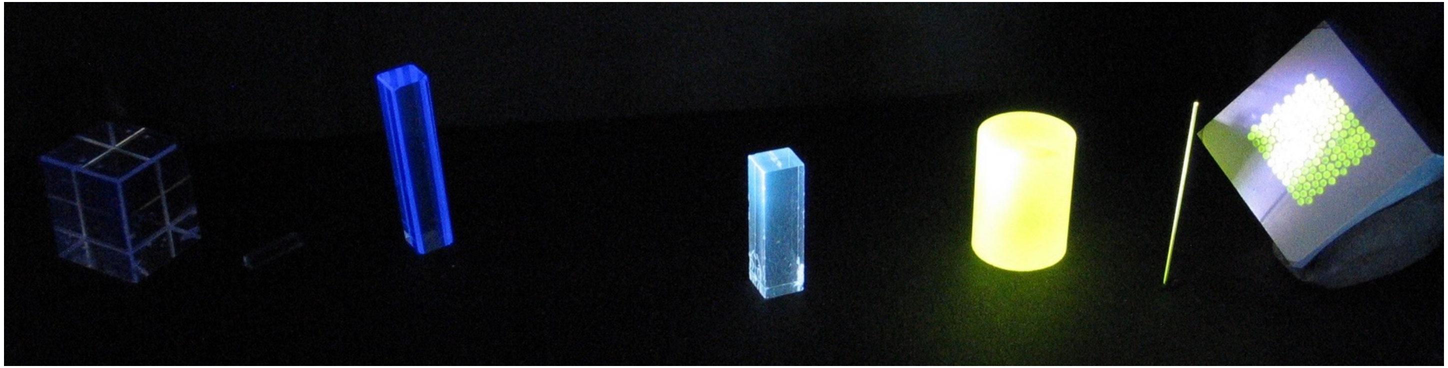
SCINTILLATOR FOR FUTURE CALORIMETERS

CEPC WORKSHOP 8-11 APRIL 2024

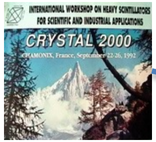
E. Auffray, *CERN, EP-CMX*



120 years of inorganic scintillators

1990: Request for scintillators for LHC
Birth of SCINT community

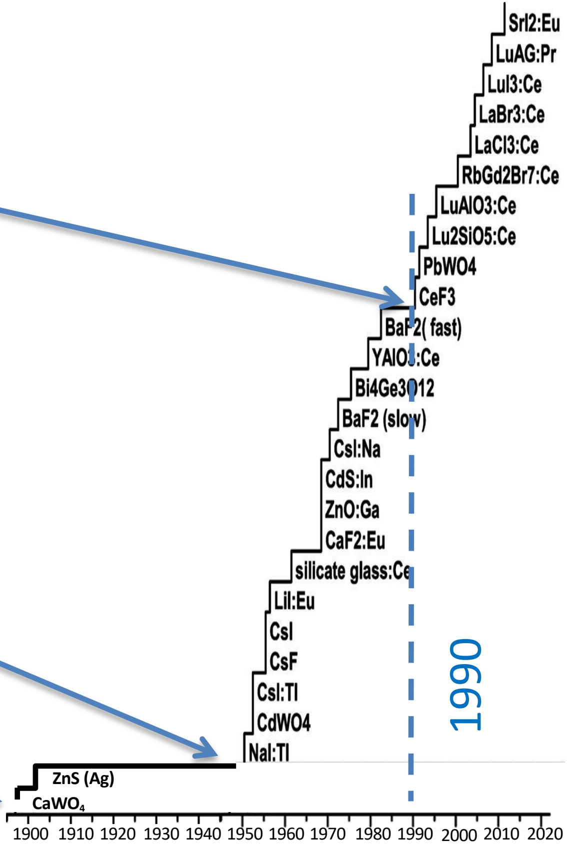
1991



1992
1st Scint conference

1930-1940:
Invention of the photomultiplier tube

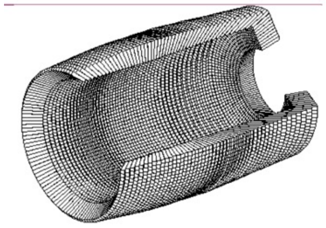
1896:
CaW04 used by Roentgen

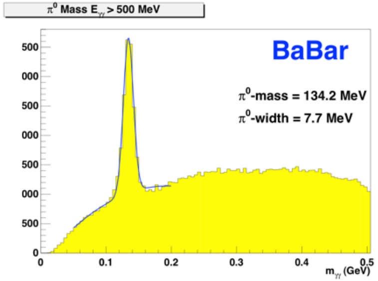


P. Dorenbos, Optical Materials: X 1 (2019) 100021,

Inorganic scintillators largely used in HEP

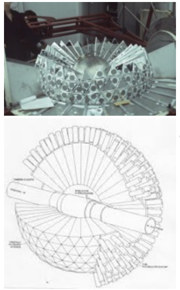
6580 CsI:Tl crystals:Babar @SLAC, 1999

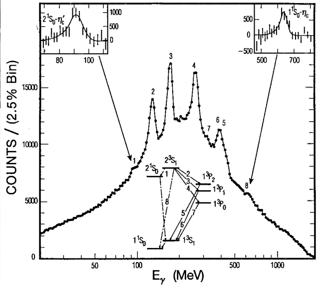


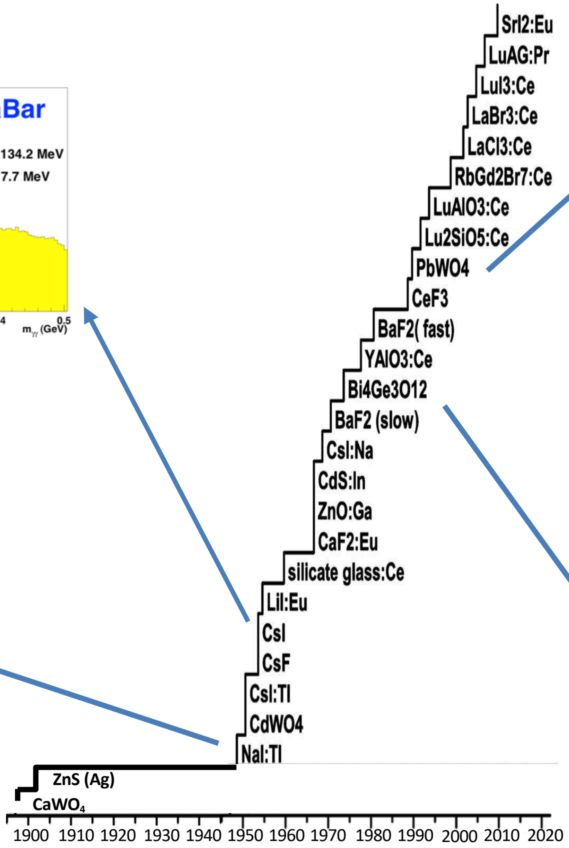


642 NaI (Tl): Crystal Ball @SLAC, 1979

Charmonium spectra

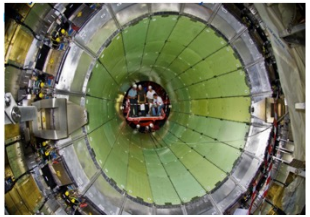




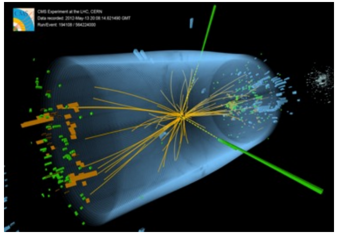


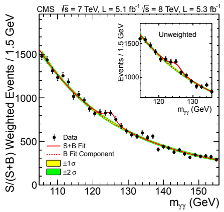
P.Dorenbos,, 10.1109/TNS.2009.2031140

75848 PWO: CMS calorimeter @LHC 2008

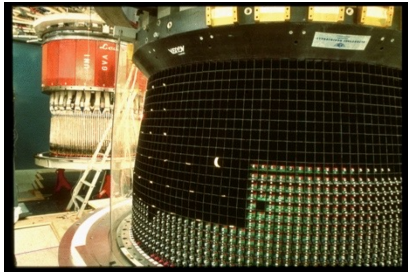


Higgs discovery in 2012

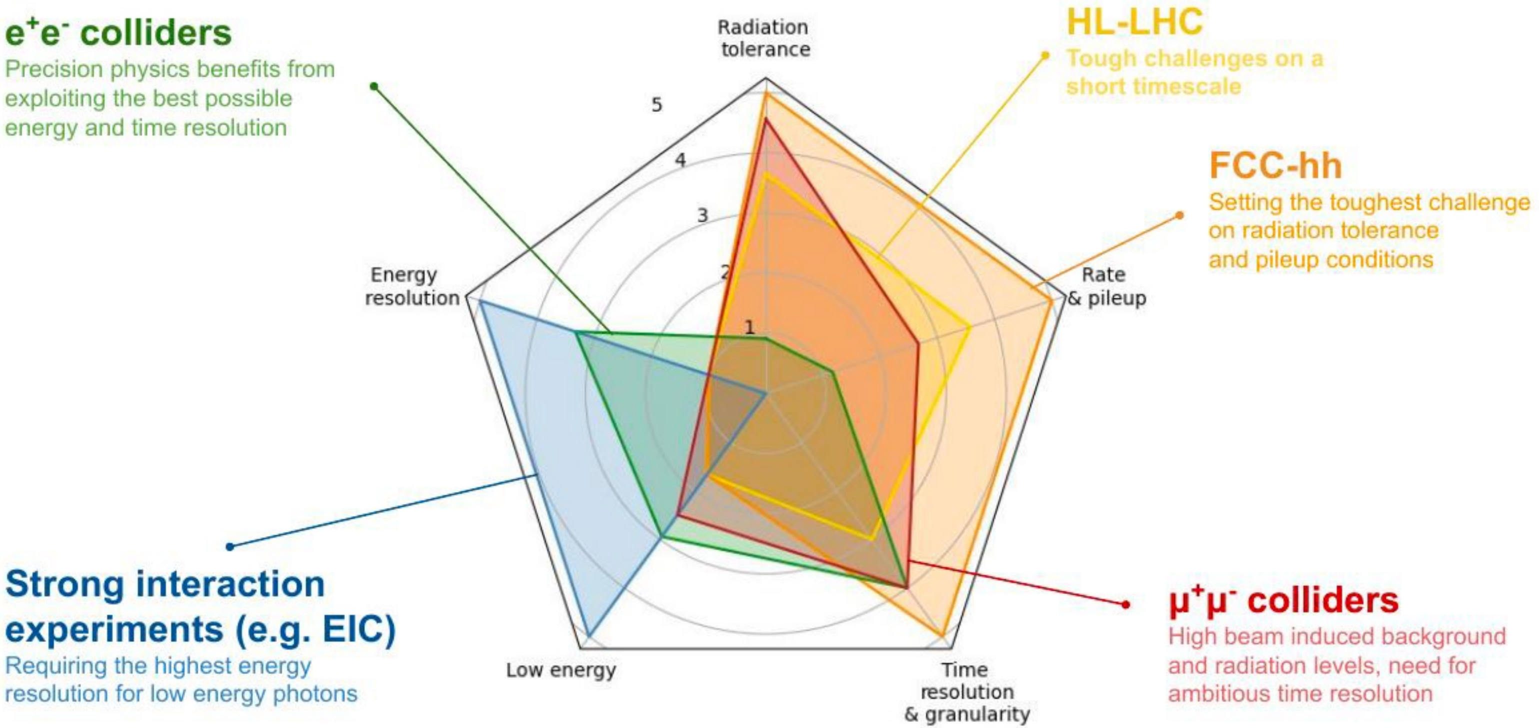




10752 BGO: L3 calorimeter @LEP 1989



A large variety of future detectors with different requirements

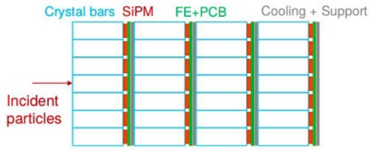


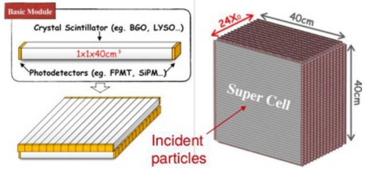
M.T. Lucchini, Scint2022 conference

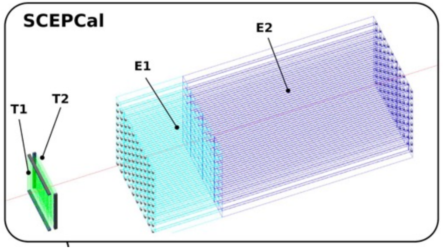
A large variety of proposals with inorganic scintillators

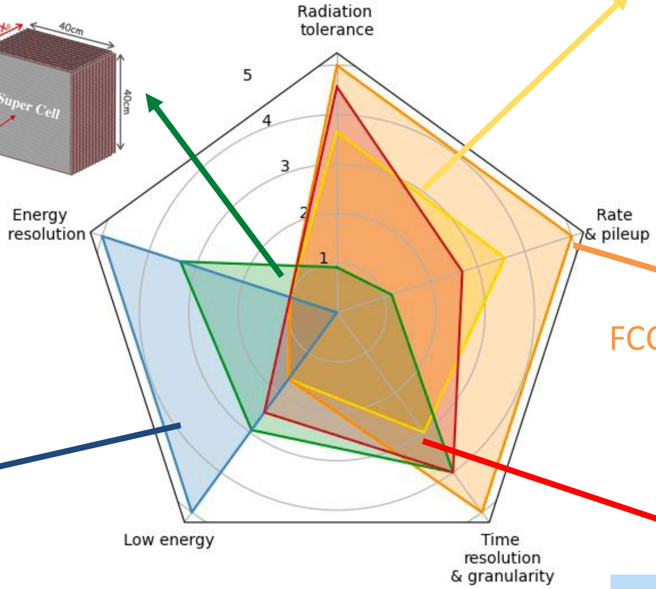
e^-e^+ colliders

HGCAL



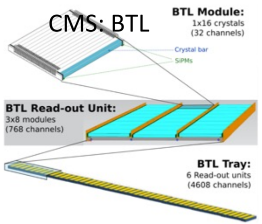




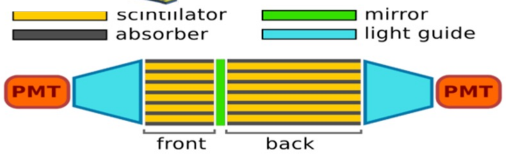


HL-LHC

CMS: BTL

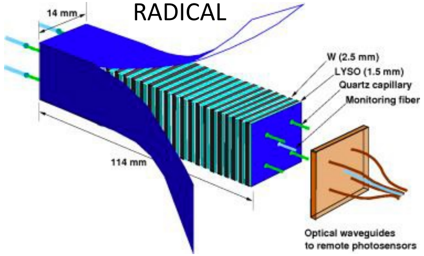


LHCb : SPACAL

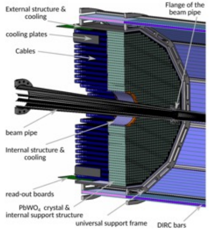


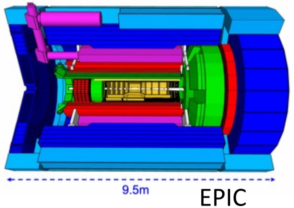
FCC-hh

RADICAL



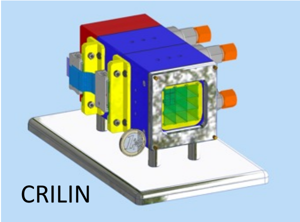
Strong interaction experiments (eg EIC)





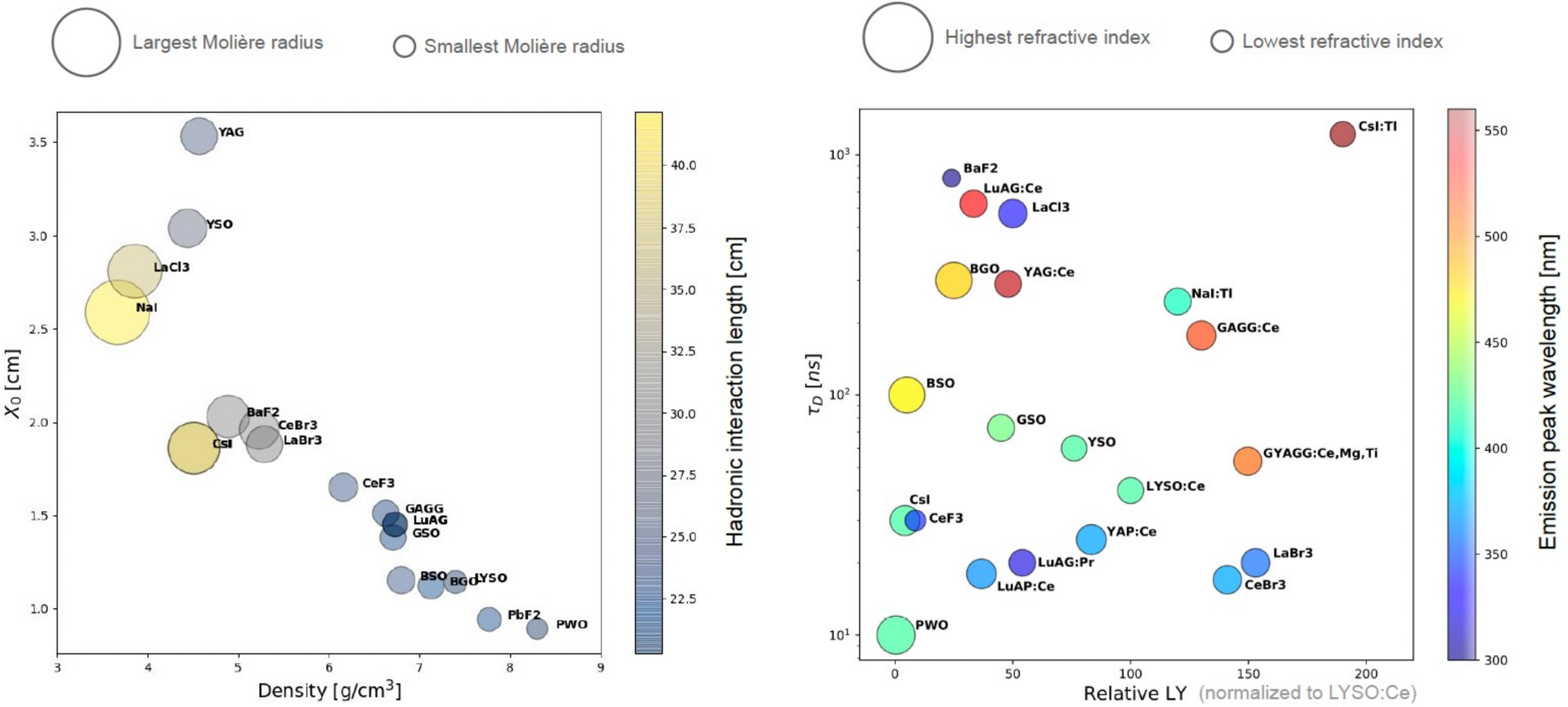
EPIC

$\mu^-\mu^+$ colliders



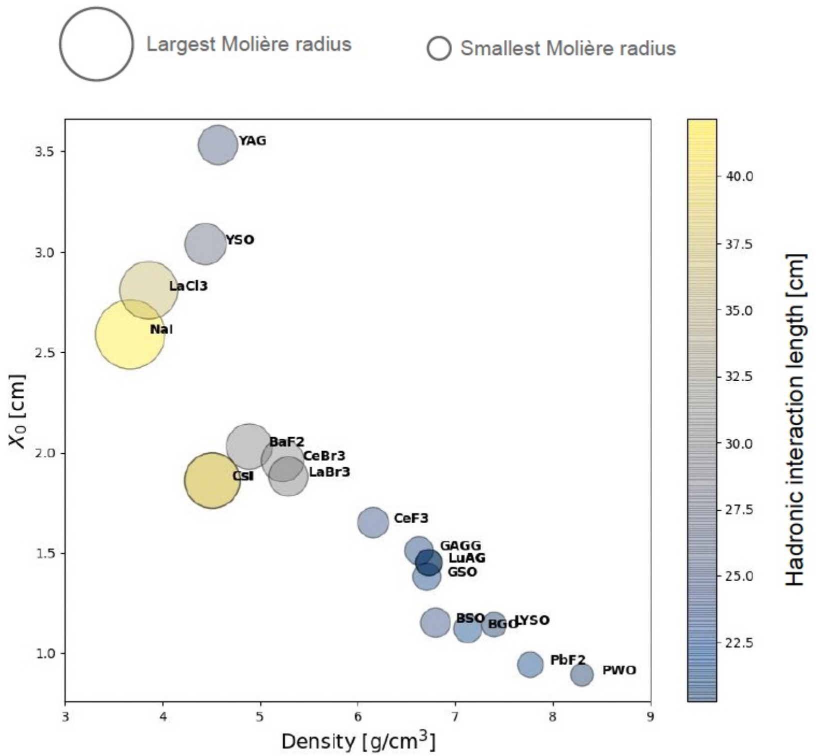
A large variety of scintillating materials is available

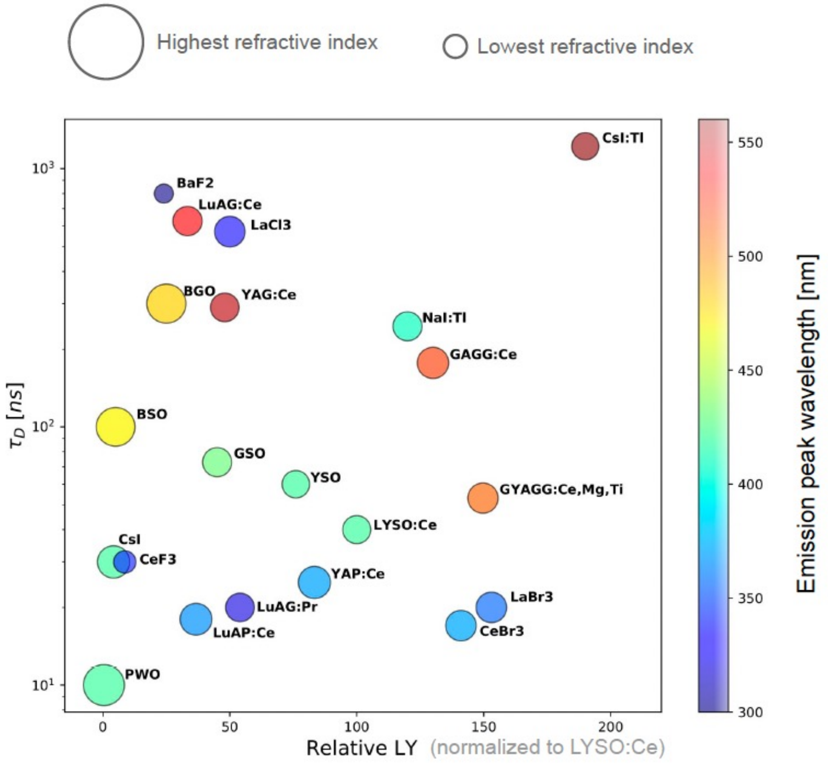
Which one to choose?



M.T. Lucchini, Scint2022 conference

Which one to choose?





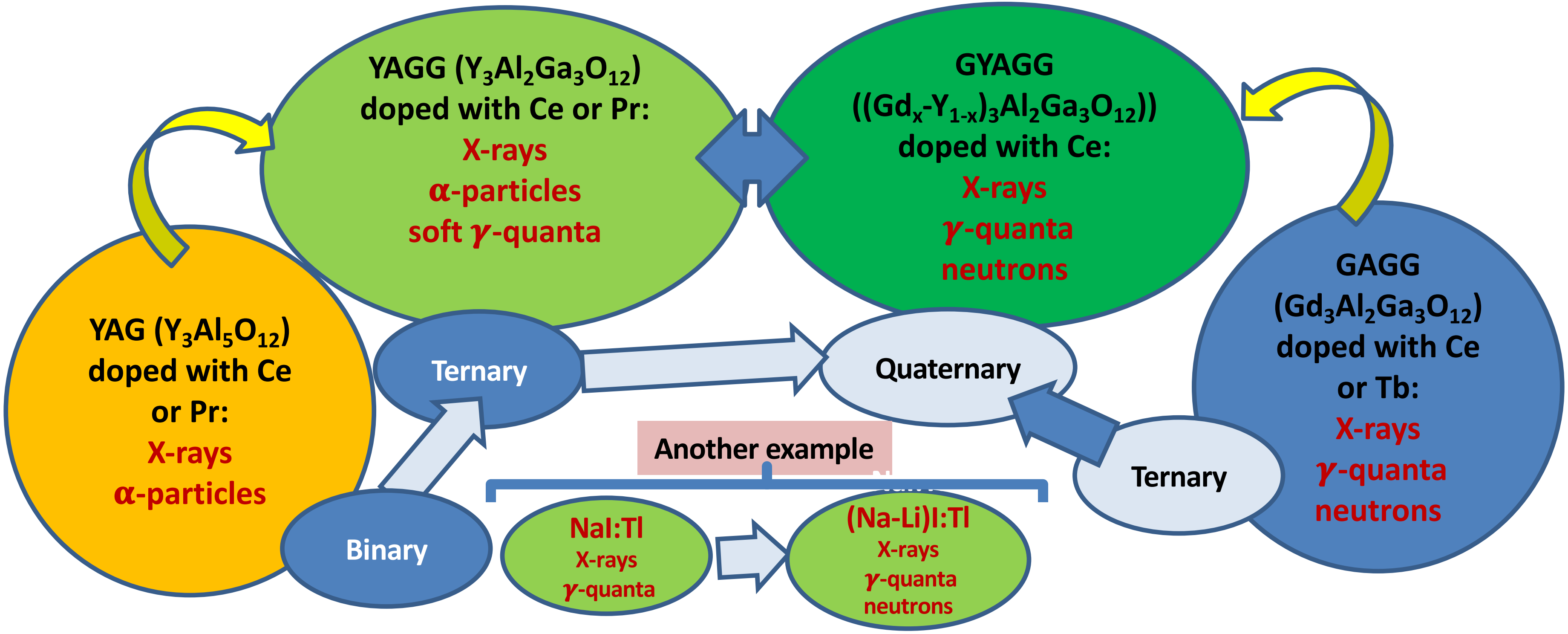
M.T. Lucchini, Scint2022 conference

What is the Ideal one?

Possibility to engineer existing scintillators ?

Possibility to modify crystal composition to tune the properties

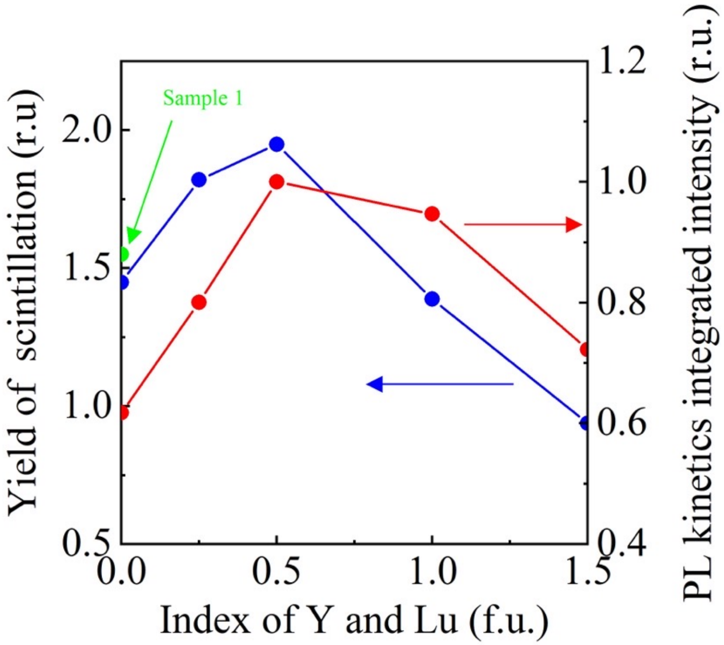
eg Mixed materials: concept of multipurpose scintillation materials

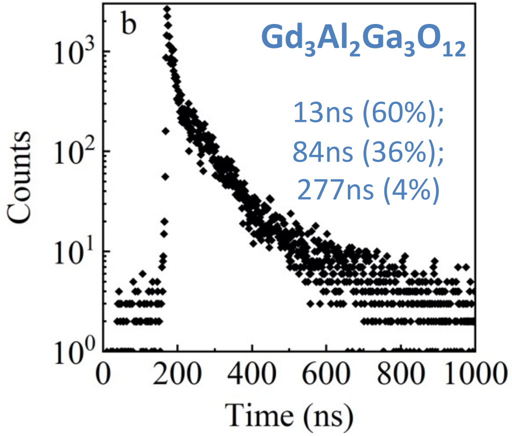


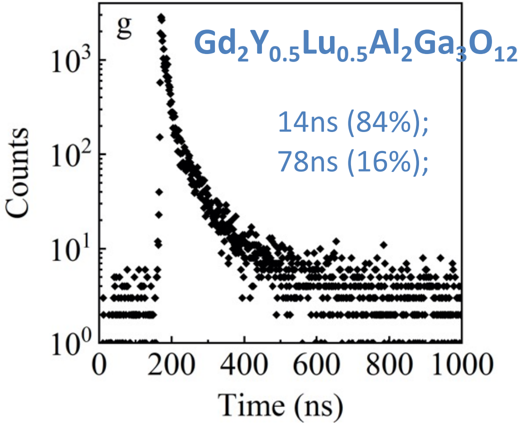
Courtesy M. Korzhik, RINP, Minsk

$(Gd,Y,Lu)_3Al_2Ga_3O_{12}$:Ce, Mg

Light Yield and photoluminescence

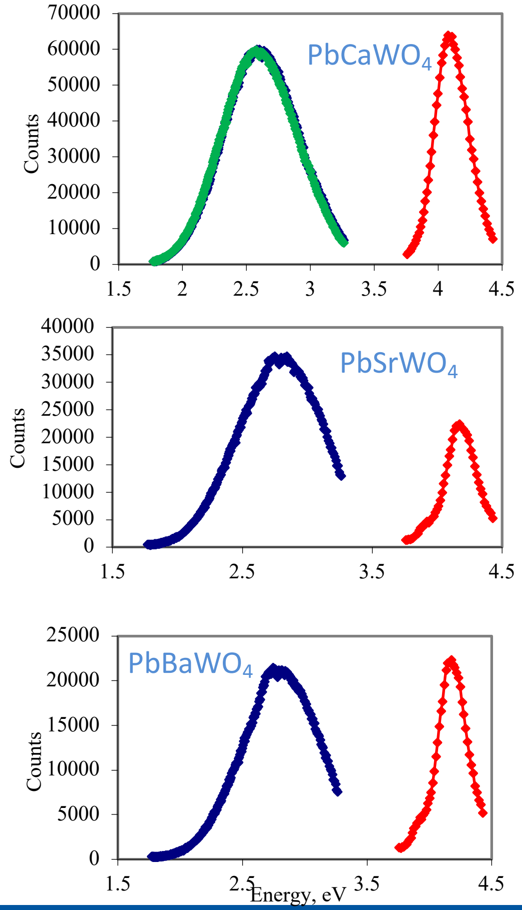


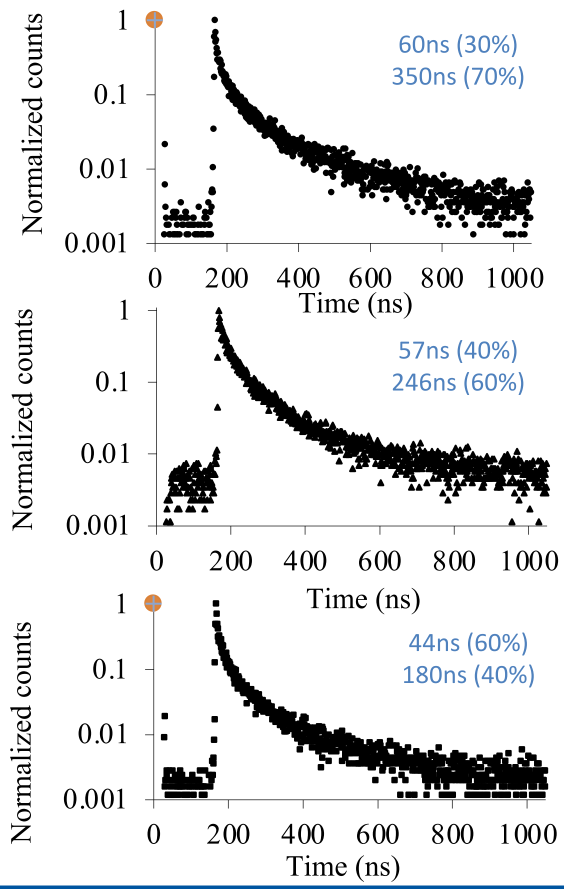




D. Kuznetsova et al., Journal of Applied Physics, 2022; 132 (20): 203104.

New mixed tungstate (Pb,Ca,Sr,Ba)WO_4





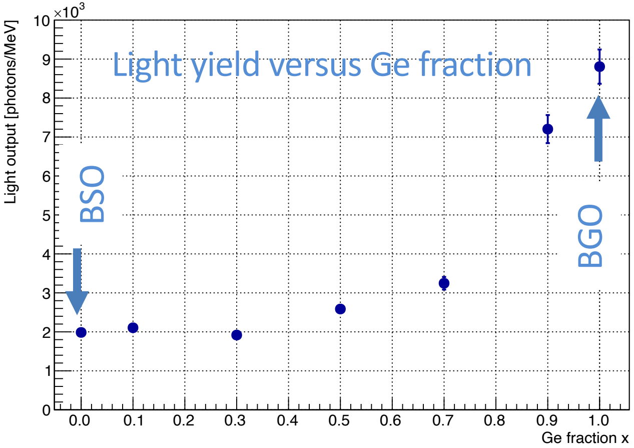
Courtesy M. Korzhik, RINP, Minsk

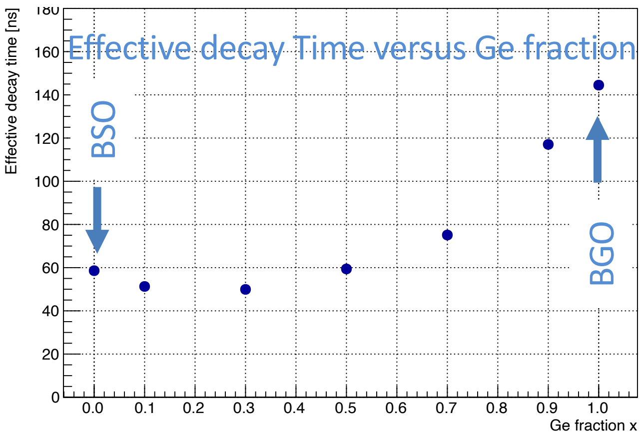
Mixed tungstate properties

Compound	$PbWO_4$	$CaWO_4$	$SrWO_4$	$BaWO_4$	$(Pb, Ca)WO_4$ (PCWO)	$(Pb, Sr)WO_4$ (PSWO)	$(Pb, Ba)WO_4$ (PBWO)
Density, g/cm^3	8.28	6.12	6.03	6.38	7.20	7.15	7.33
Effective charge, Z_{eff}	76	66	64	65	72	71	71
Photo-absorption coefficient at 511 keV, cm^{-1}	0.485	0.222	0.197	0.223	0.359	0.340	0.350
Radiation length Xo, cm	0.89	1.49	1.50	1.33	1.11	1.11	1.07
Moliere radius R_M, cm	1.91	2.28	2.40	2.36	2.09	2.12	2.11
LY, ph/MeV (γ-quanta)	200	14400	1200	>100	7000	8700	5500
Parameters of the scintillation kinetics, ns (%)	1.8(60) 6(40)	8200	522	>10	60(30) 350(70)	57(40) 246(60)	44(60) 180(40)
*Effective decay constant, ns					263	170	90

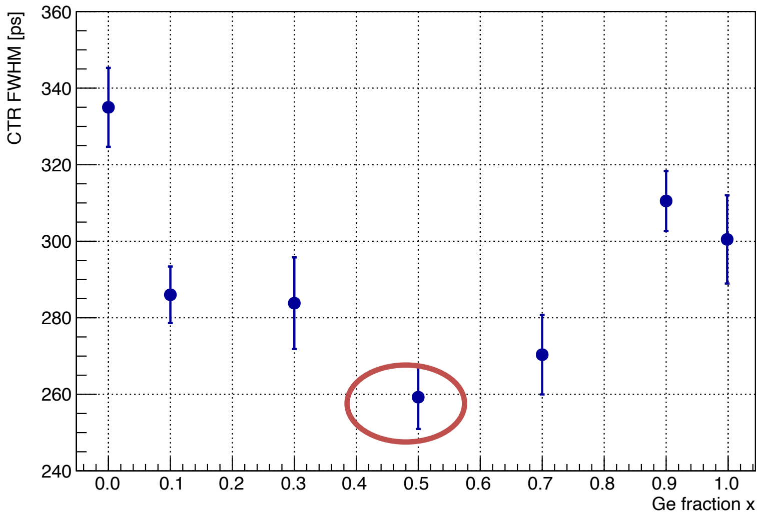
Courtesy M. Korzhik, RINP, Minsk

Mixed Material: BGO-BSO ($Bi_4(Ge_xSi_{1-x})_3O_{12}$)





Coincidence time resolution @511Kev versus Ge fraction



BSO BGO

Optimal Ge fraction for time resolution

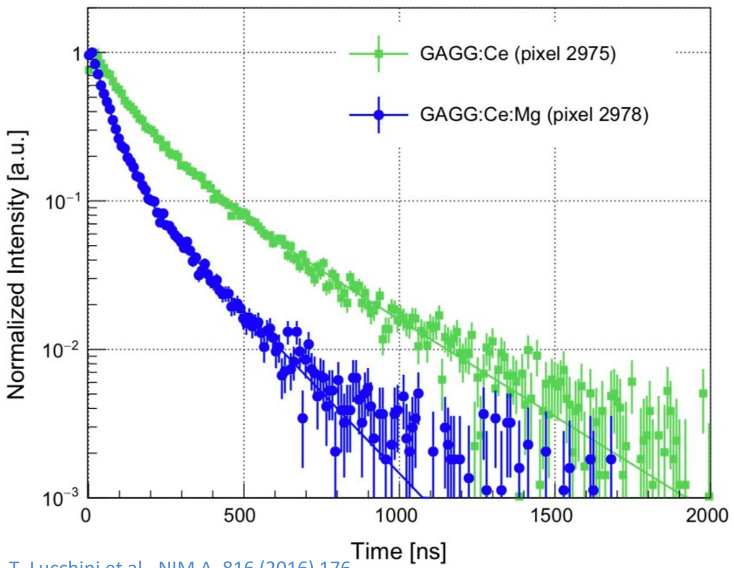
R&D on production on going

Could be a candidate for future homogenous EM calorimeter

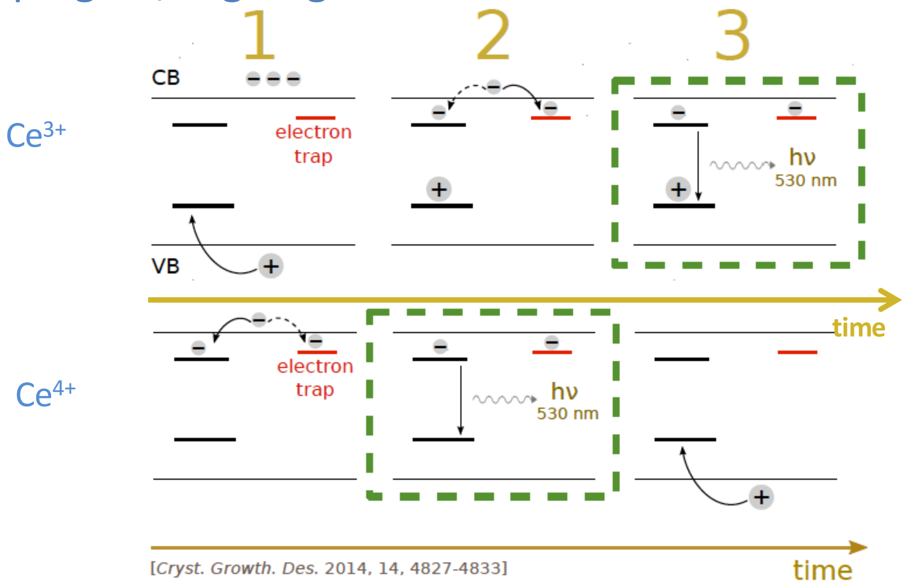
R. Cala et al, NIMA, A 1032 (2022) 166527

Playing with the doping

Example of Codoping Ce, Mg of garnets



M. T. Lucchini et al., NIM A, 816 (2016) 176



Faster decay time with codoping Ce^{3+}/Mg^{2+}

Mg^{2+} increase Ce^{4+} centers which can directly compete with any electron trap for electron capture in the first instants of scintillator mechanism

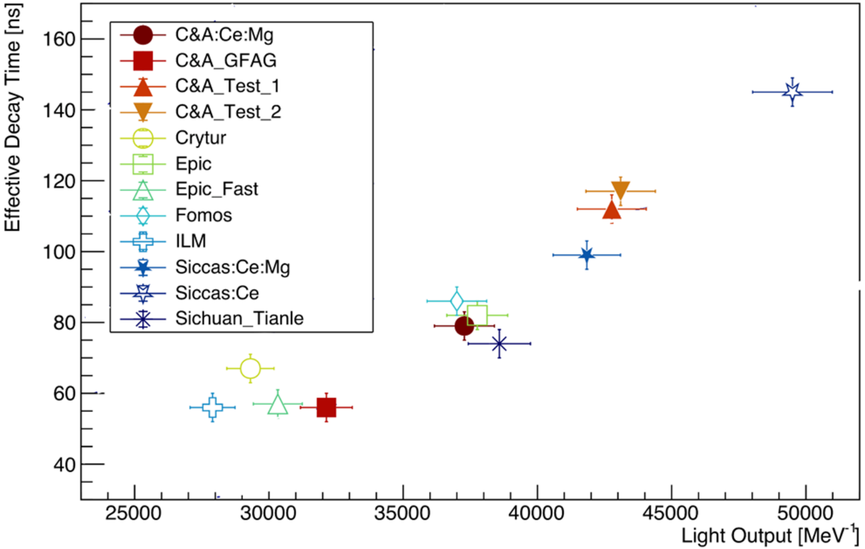
=> Expected faster decay time and lower slow component

M. Nikl, A. Yoshikawa, Adv. Optical Mater. 2015, 3, 463–481
M. Nikl et al. Cryst. Growth Des. 2014 , 14 , 4827 .

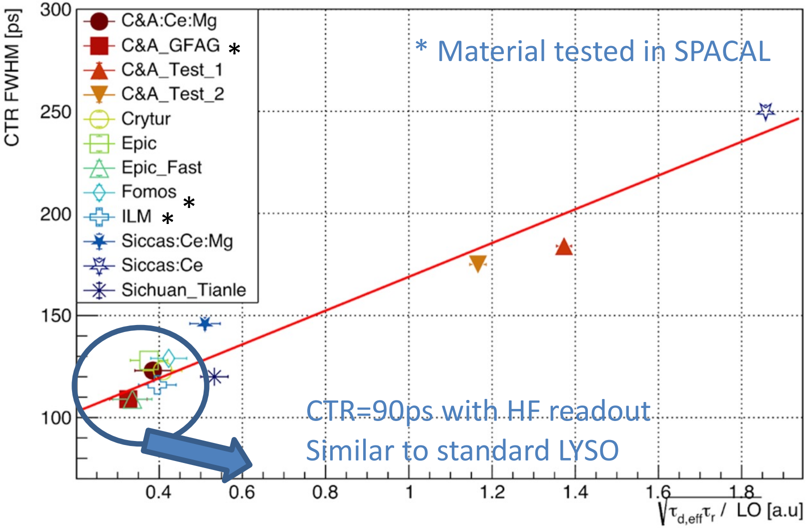
GAGG ($Gd_3Al_2Ga_3O_{12}$): Tunable properties with composition

EP R&D

Effective decay time versus Light output



Coincidence time resolution (CTR) versus photon density



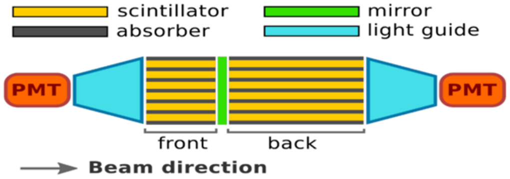
Correlation between Light output and decay time

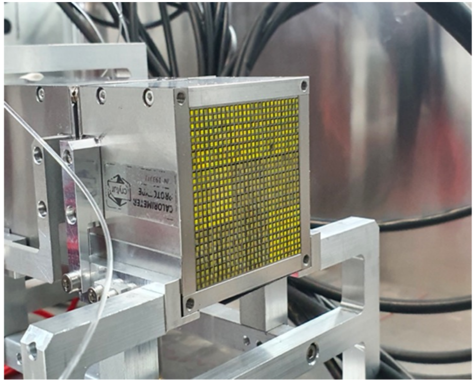
CTR inversely proportional to the photon time-density ($\frac{LO}{t_{d\,eff}}$):

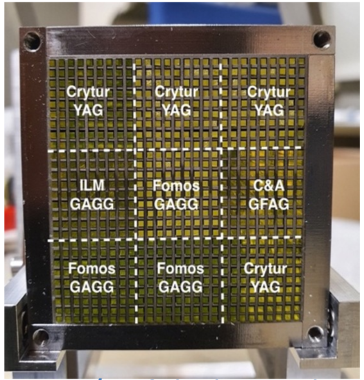
Candidate for central part of LHCb phase II calorimeter

L. Martinazzoli et al., NIM A, 2021, 165231

Spaghetti calorimeter concept with W and garnet crystal fibres

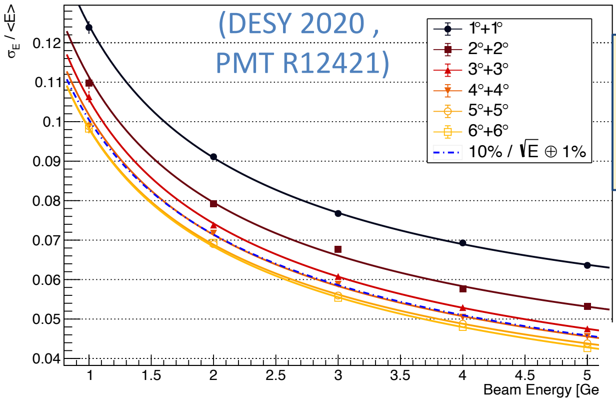






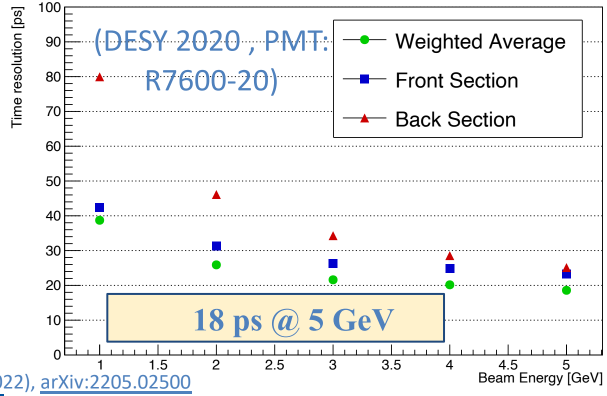
- **Pure tungsten** absorber with 19 g/cm³ holes with
- **Crystal garnet scintillators**
- 9 cells, each 1.5 x 1.5 cm² ($R_M \approx 1.45$ cm)
- Longitudinal section at the shower maximum
- 4 + 10 cm long split (7+18 X_0), pitch 1.7mm
- Reflective mirror between sections

Energy resolution versus incident angles



Energy resolution at 3° + 3°:
- Sampling term: 10.2% ± 0.1
- Constant term:1.2% ± 0.3

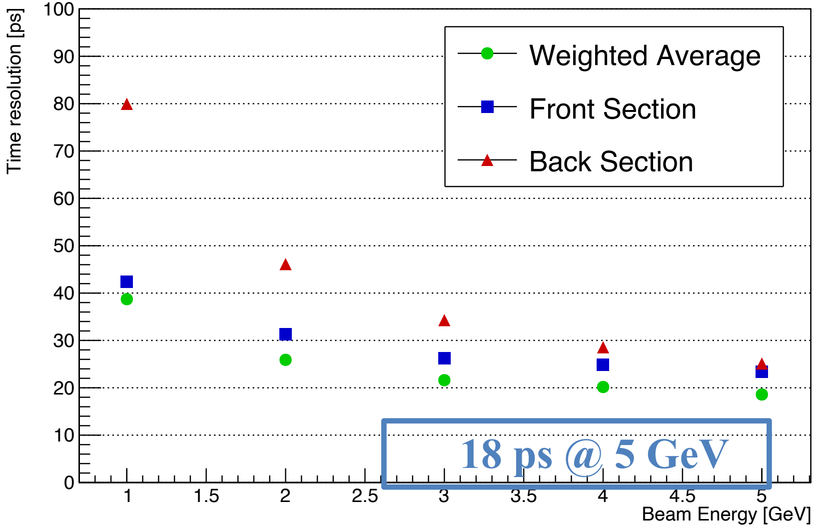
Time resolution GFAG cell @ incident angle of 3° + 3°



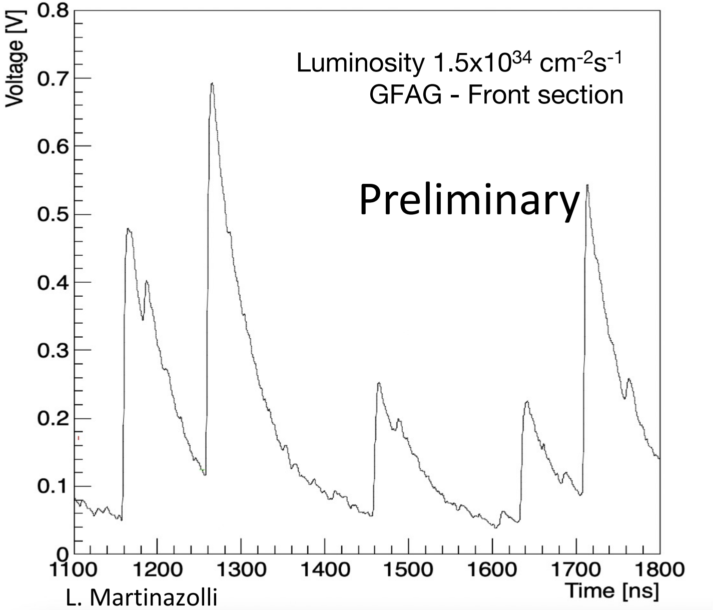
L. Ann, NIM A 1045, 167629 (2022), arXiv:2205.02500

Performance in SPACAL

Time resolution GFAG cell @ incident angle of 3° + 3° (DESY 2020 , R7600-20)



SPACAL Signal Simulated



Excellent timing performance in TB
But what will be the impact of pulse shape at HL-LHC ?

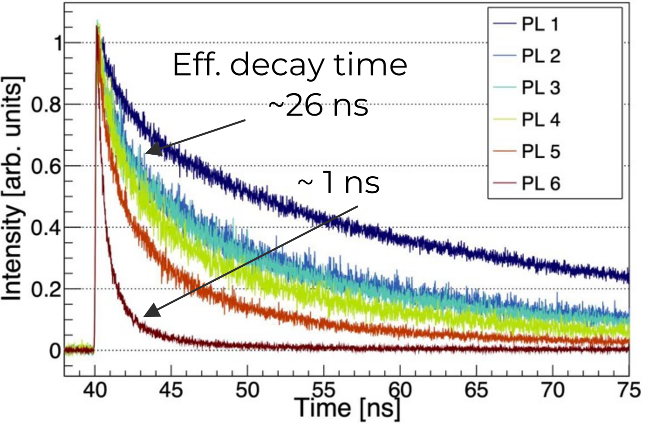
⇒ **Need to suppress slow component and shorten the main decay component to avoid pulses from different interaction to pile up**
⇒ **But maintain time resolution**

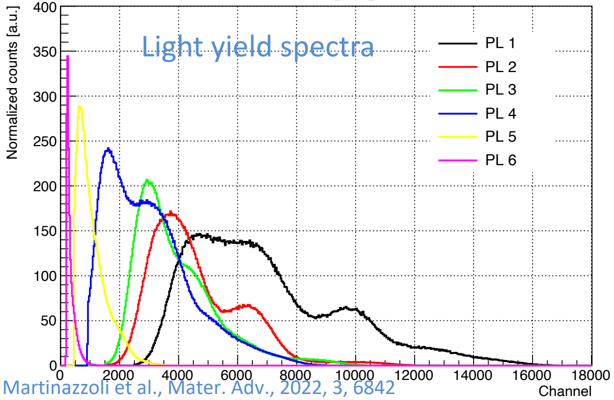
L. Ann, NIMA, 1045 (2022) 167629 arXiv:2205.02500

Acceleration of GAGG emission

Heavy co-doping Ce^{3+}/Mg^{2+}

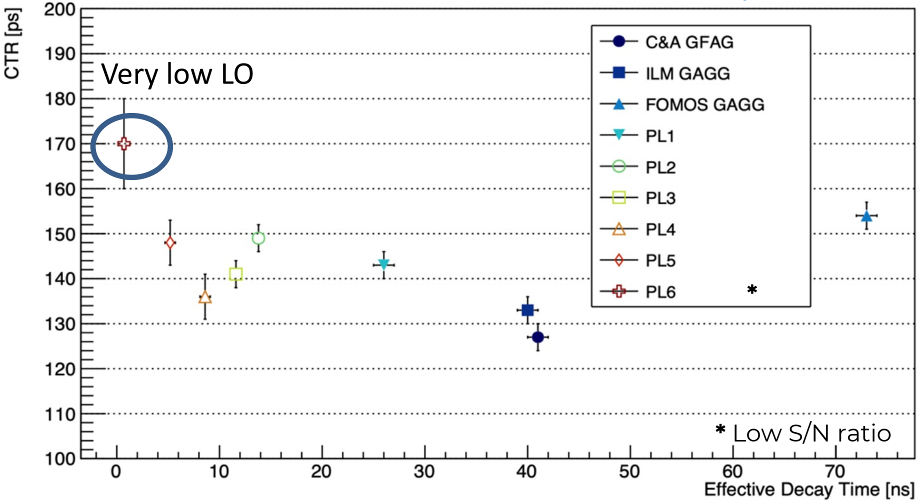
Scintillation decay - Pulsed X-Rays





L. Martinazzoli et al., Mater. Adv., 2022, 3, 6842

Coincidence time resolution vs effective decay time



No major loss of time resolution!
Decay time decrease compensated the Light output reduction
=> the same photon time-density

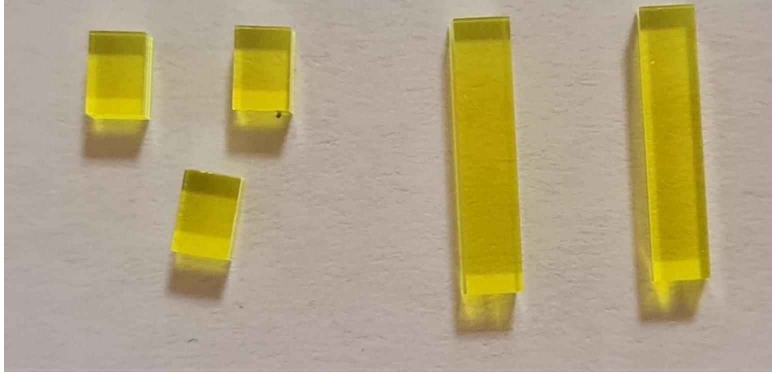
R&D on going in different groups to define optimal composition and production

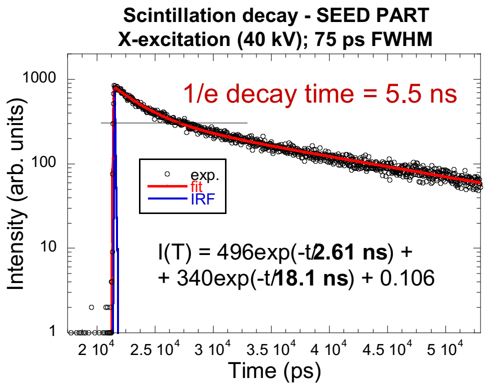
Acceleration of GAGG emission

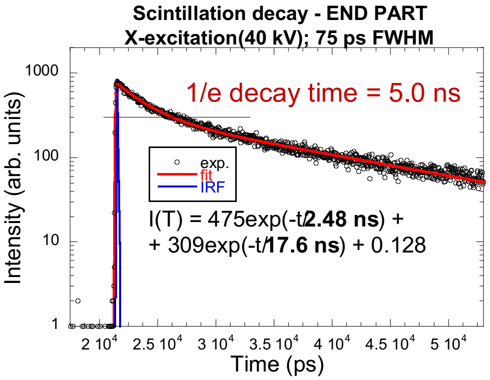
Heavy co-doping Ce^{3+}/Mg^{2+}

First results obtained by Crytur Company

Produced by Crytur, Czochralsky Method





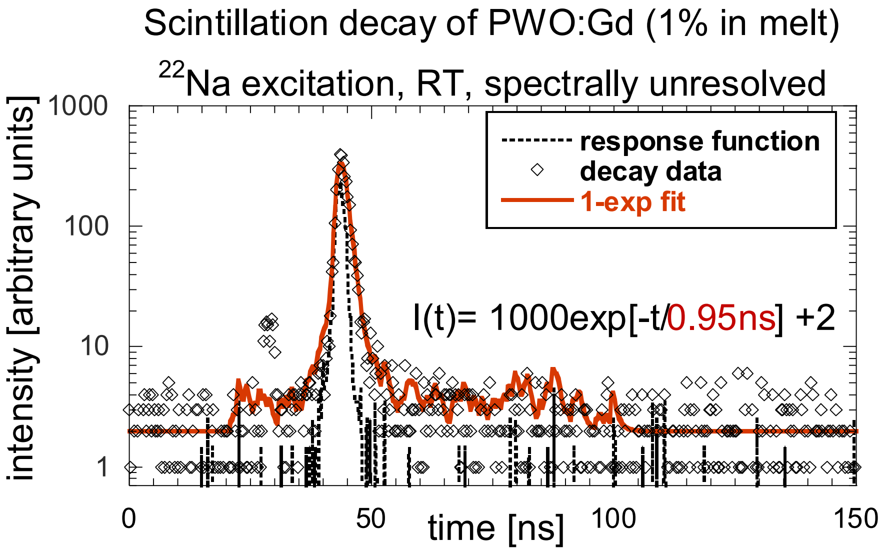


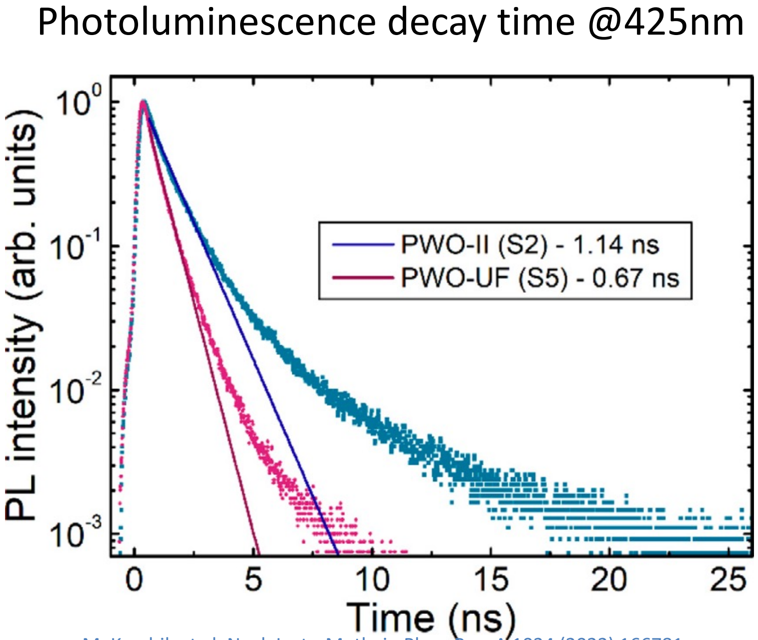
Measured by FZU, M. Nikl

No slow component, decay time below 10ns!

Towards very fast PWO by doping

Many developments on PWO to decrease decay time toward sub ns domain with heavy doping:





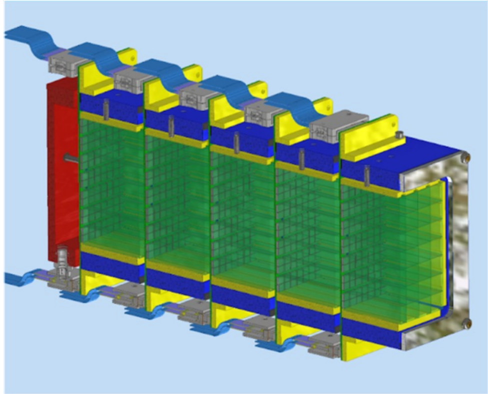
M. Nikl et al, J.Cryst. Growth **229**, 312-315 (2001)
M. Nikl, et al, Radiation Measurements **33**, 705-708 (2001)
M. Kobayashi, et al: Nucl. Instr. Meth. in Phys. Res. A **459**, 482-493 (2001)

M. Korzhik et al, Nucl. Instr. Meth. in Phys. Res. A 1034 (2022) 166781

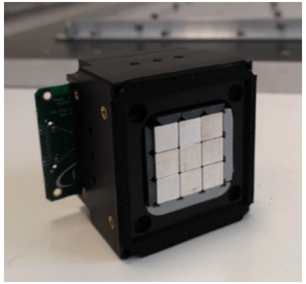
Candidate for KLEVER &CRILIN calorimeter

CRILIN calorimeter concept

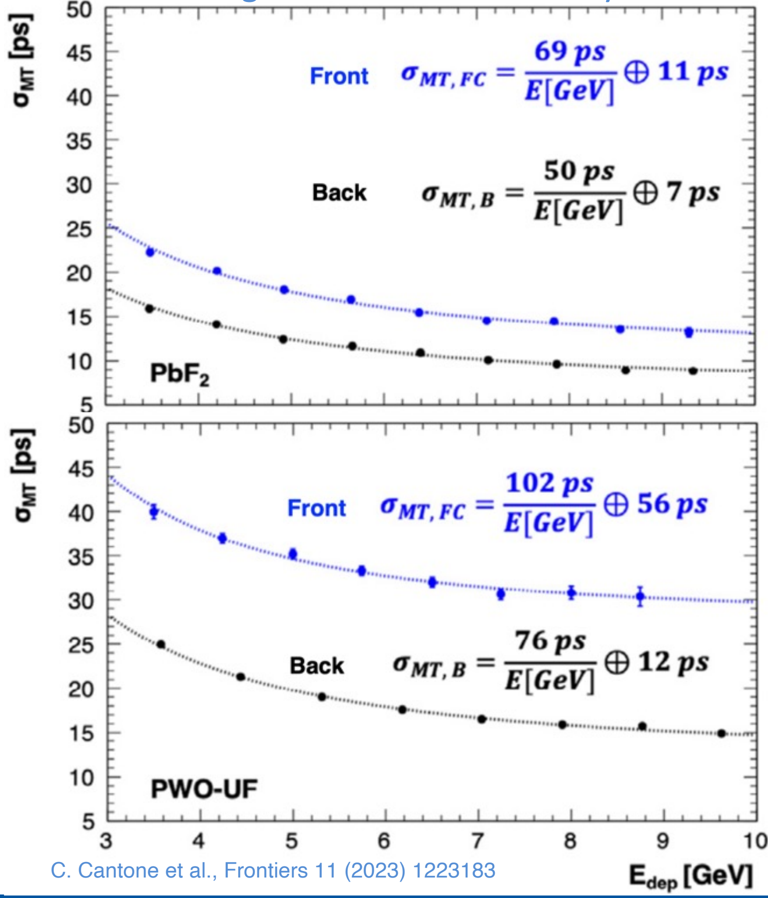
Crystal Calorimeter with Longitudinal Information



5 layers of 40mm³ of high-*Z*, ultra-fast crystals (22 X_o): PbF2 or **PWO-UF**
UV-extended SiPM readout.



Time resolution obtained with single 10 × 10 × 40 mm² crystals

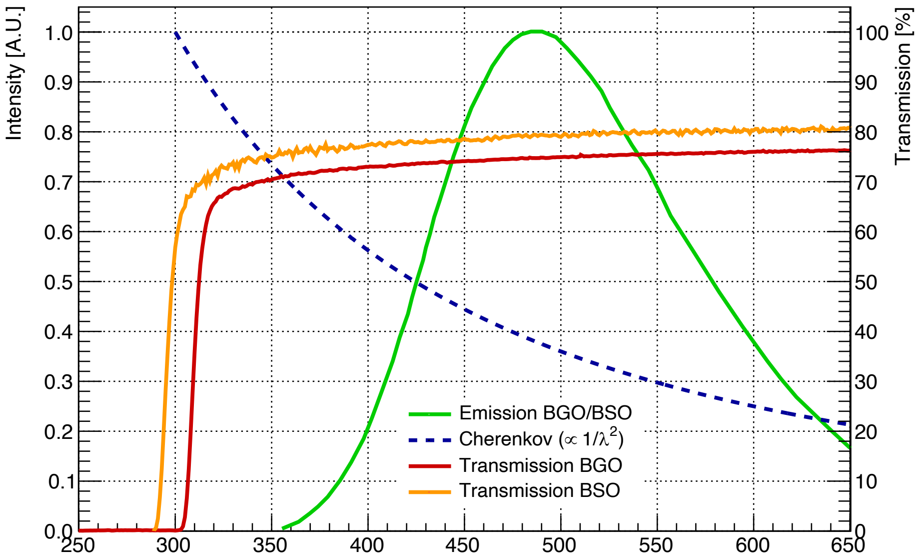


C. Cantone et al., Frontiers 11 (2023) 1223183

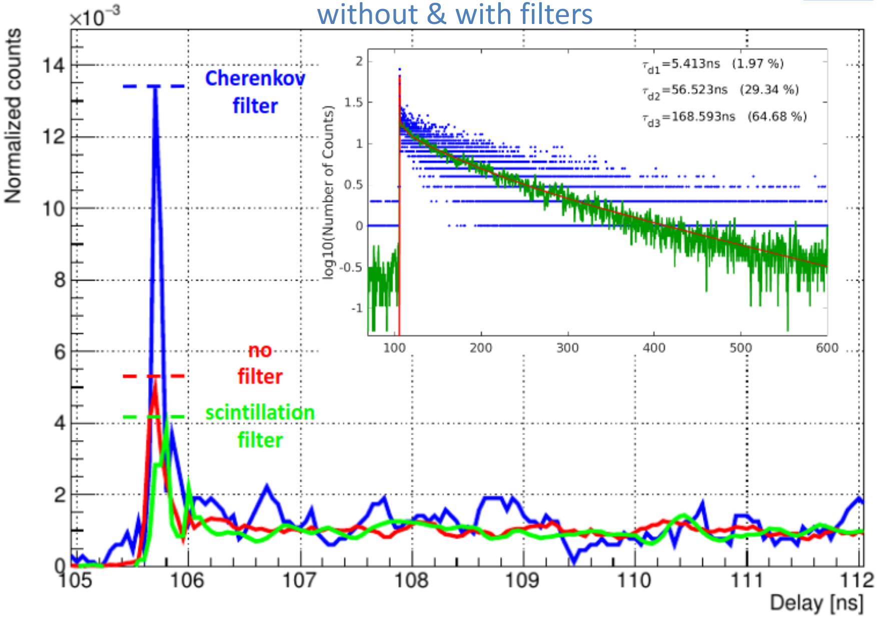
EXPLOITATION OF FAST EMISSION PROCESSES

Exploitation of Cherenkov/scintillation in intrinsic scintillating crystals

BGO and BSO transmission spectra



Decay time spectra of BSO under 511 keV excitation without & with filters

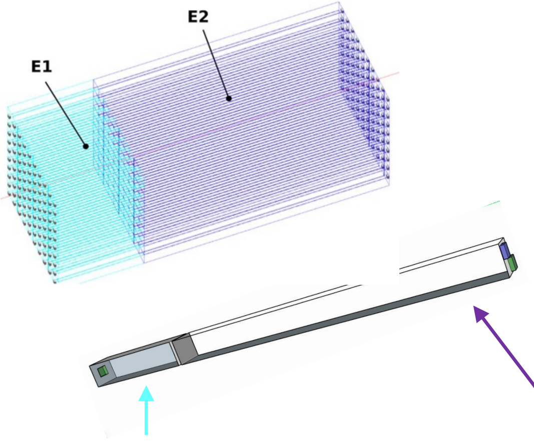


R. Cala et al, NIMA 1032, 2022, 166527

R&D on going:
to study dual readout (Cherenkov/scintillation) in bulk inorganic crystals
To optimise the readout separation Cherenkov & scintillation with filters and/or pulse discrimination

Maximum information calorimeter concept (MAXICC)

Dual readout on bulk scintillators

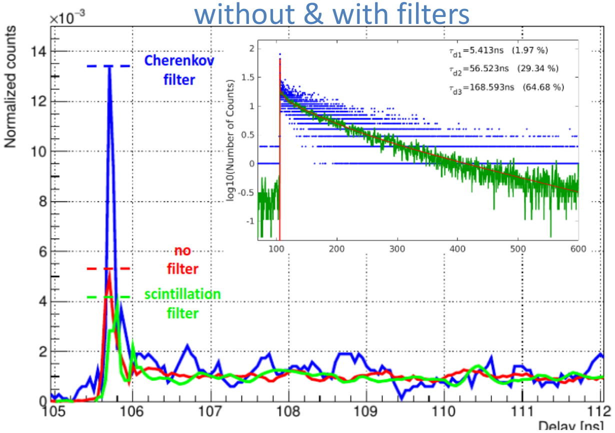


Front crystal ECAL segment:
Single 5x5 mm² SiPM per crystal optimized for scintillation light detection (10 µm cell size)

Rear crystal ECAL segment:
Two 4x4 mm² SiPMs with optical filters optimized for scintillation (10 µm cell size) and Cherenkov (40 µm cell size) detection

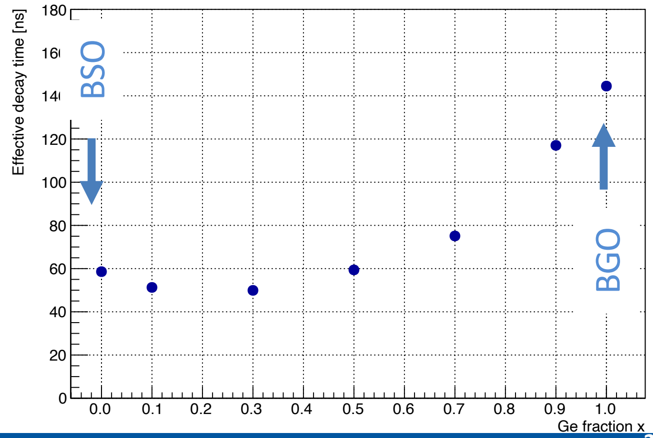
Ourtesy M. Lucchini

Decay time spectra of BSO under 511 keV excitation without & with filters



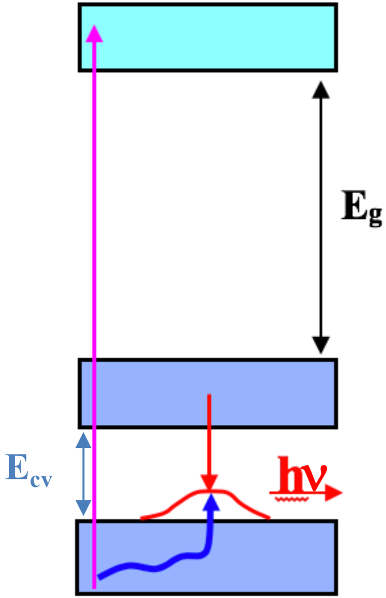
BSO (or mixed BGSO) crystal: faster than BGO, higher LY than PWO, better transmission
May be a good candidate for MAXICC

Effective decay Time versus Ge fraction



Crossluminescence material

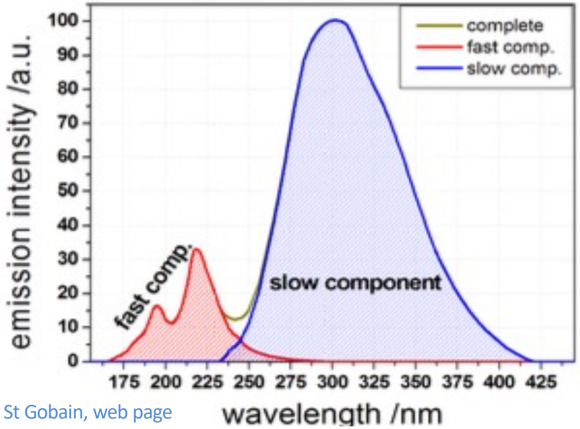
Radiative transition between the core- and valence bands.



$E_{cv} < E_g$

Very fast emission < 2ns
but generaly in UV emission

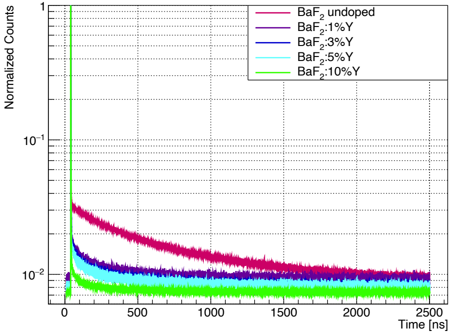
BaF_2 emisison spectra



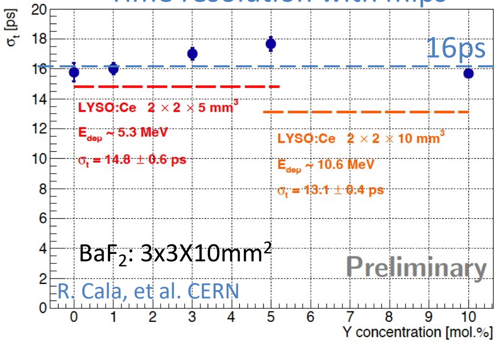
St Gobain, web page

R&D to **suppress the slow component in BaF_2 by doping**
⇒ No change in short decay
⇒ No impact on time resolution

Decay time spectra



Time resolution with mips

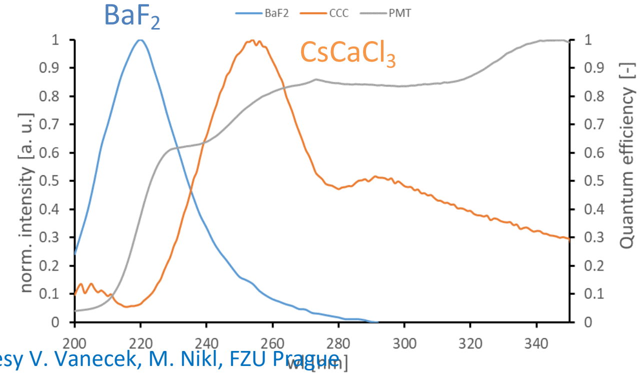


J. Chen, et al., IEEE Trans. Nucl. Sci., vol. 65, no. 8, pp. 2147-2151, 2018.
R. Cala et al, SCINT2022 conference SantaFe Sept2022

Crossluminescence Recent Developments

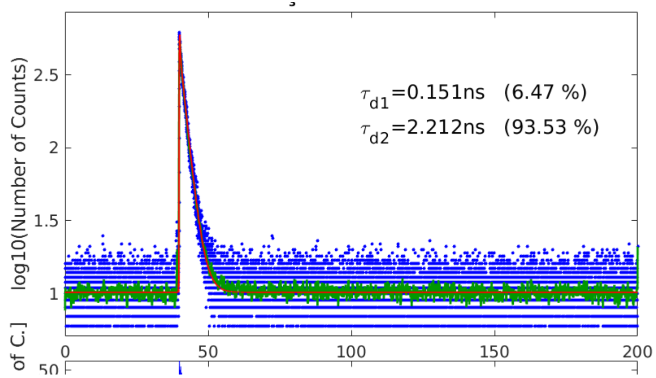
R&D **to shift the emission towards Visible**

Emission spectra



Courtesy V. Vanecek, M. Nikl, FZU Prague

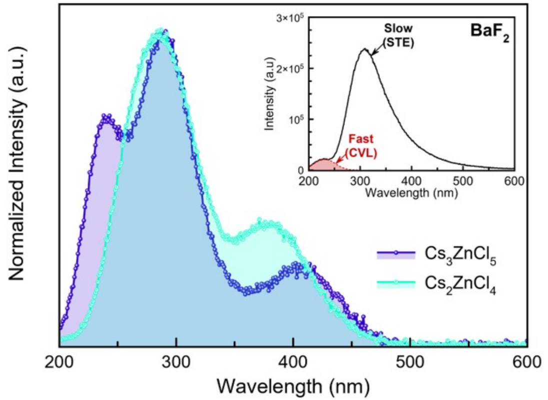
Data for BaF_2 from M. Laval et al. , NIM Phys. Res., 206 (1983) 169–176

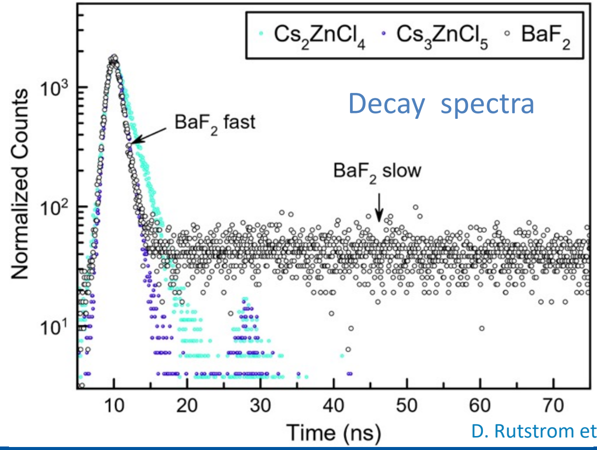


D. Rutstrom et al, Optical Materials 133 (2022) 112912

V. Vanecek et al., Optical Materials X 12 (2021) 100103

Emission spectra



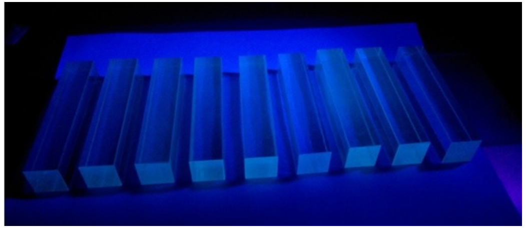


D. Rutstrom et al, Optical Materials 133 (2022) 112912

Development on Scintillating Glasses

- Since some years new developments on glasses within different projects (eg ATTRACT project, EIC R&D)
  - Oxyde and Fluoro glasses
    - Attempt to increase the density and the radiation hardness
    - Progress in production scale

Exemple DSB Glasses Intelum

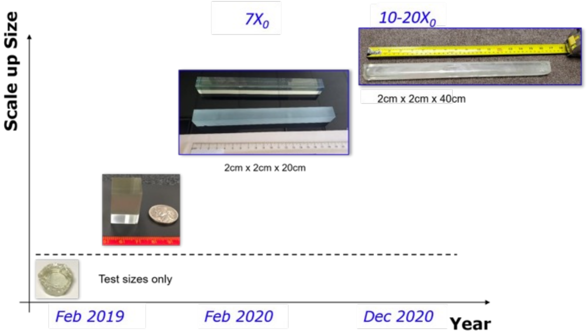


Industrial development via ScintiGlass: Attract project with Preciosa Company

ATTRACT

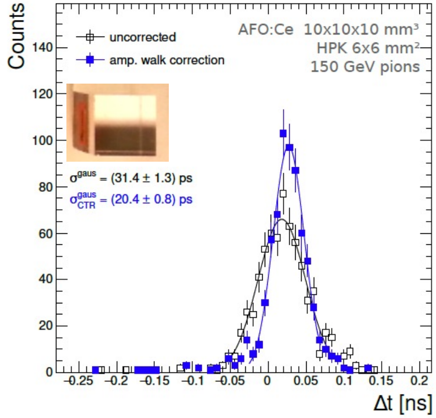
V. Dormenv et al, NIMA, 1015, 2022, 165762

EIC R&D: eRD105 (SciGlass)



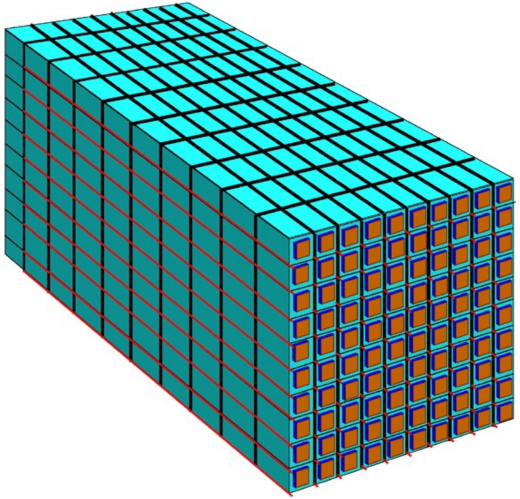
From T. Horn, CERN EP R&D, Nov21

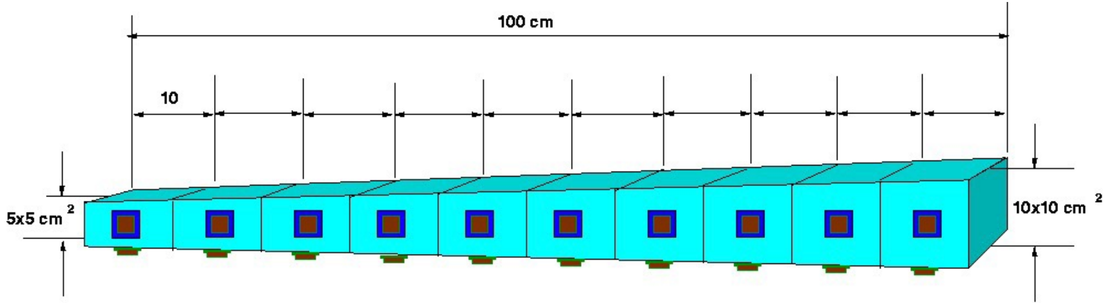
Fluorophosphate AFO glasses
Timing resolution with mip



M. Lucchini et al., arXiv:2212.03368, submitted to NIMA

Homogenous Hadronic calorimeter concept





Total absorption :

- no sampling fluctuations or other sampling–related contributions
- Separate measurement of Scintillation light (S) and Čherenkov light (C) in the same device.

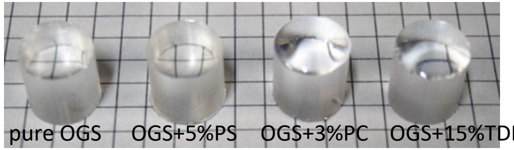
With low cost high density scintillating crystals or **glasses**

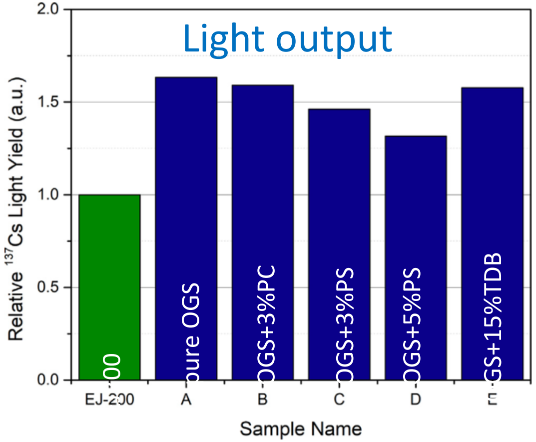
M. Marteau et al. CPAD2021,

See talk today Sen Qian

R&D for Organic Scintillators

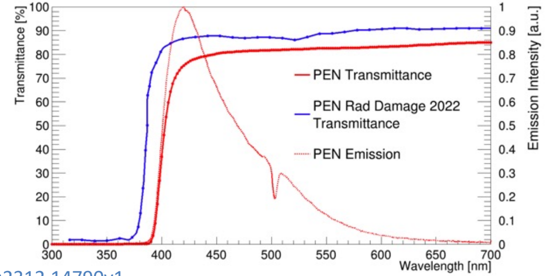
Organic glasses developed in Sendai National lab





From L. Q Nguyen et al., NIMA 1036 (2022) 166835

Polyethylene Naphtalate(PEN)

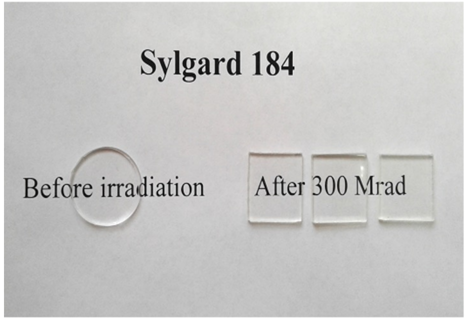


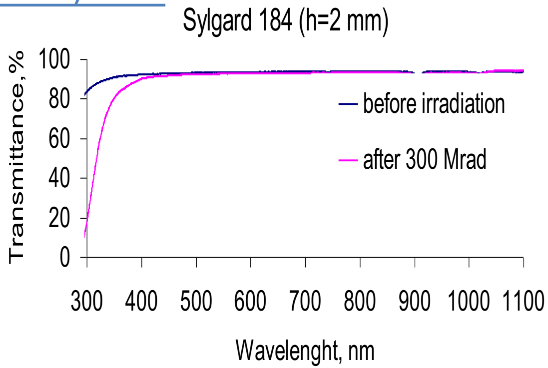
P. Conde Muino et al. , arXiv:2312.14790v1

Polysiloxane materials

Irradiation with electrons (E_0 = 8.3 MeV) up to 300 MRad dose

ISMA (Kharkiv) tests



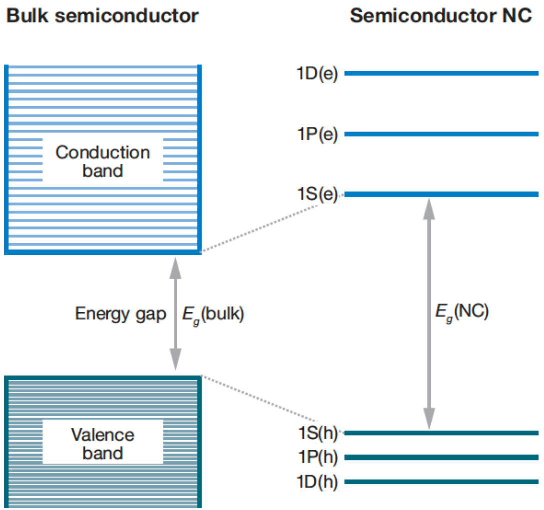


See aA. Boyarintsev NIMA 930, 2019, 180–184
A. Quaranta et al. NIM B, 268, Issue 19, 2010, Pages 3155-3159

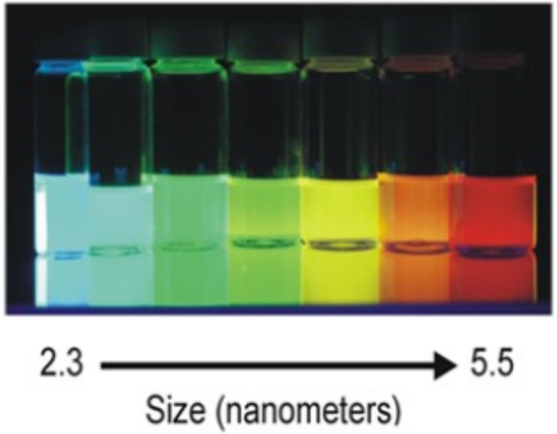
Courtesy A Boyarintsev, ISMA, Kharkiv

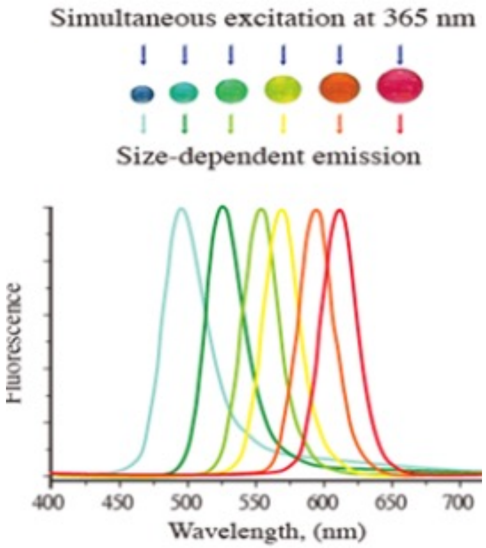
From Bulk to Nanomaterial: Quantum Confinement

Same crystal lattice but nanometer-sized crystal particle



V. Klimov Annu Rev. Phys. Chem. 58 (2007) 535-573



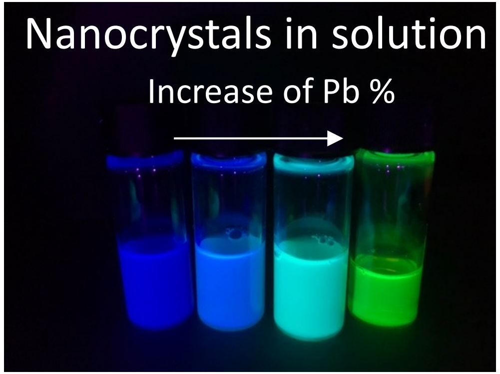


from Benoit Dubertret and Hideki Ooba

With decreasing crystal size
From "continous band" to quantized energy levels

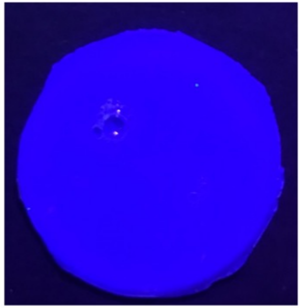
CsPb(Cl/Br)$_3$ Scintillating nanocomposite

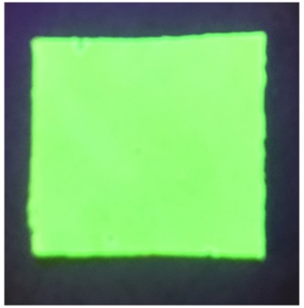
Tunable emission

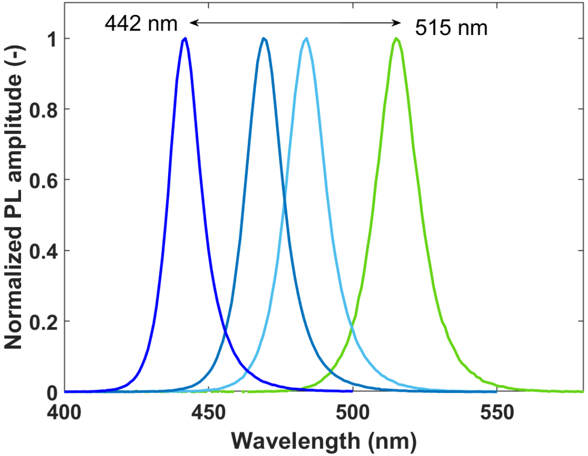


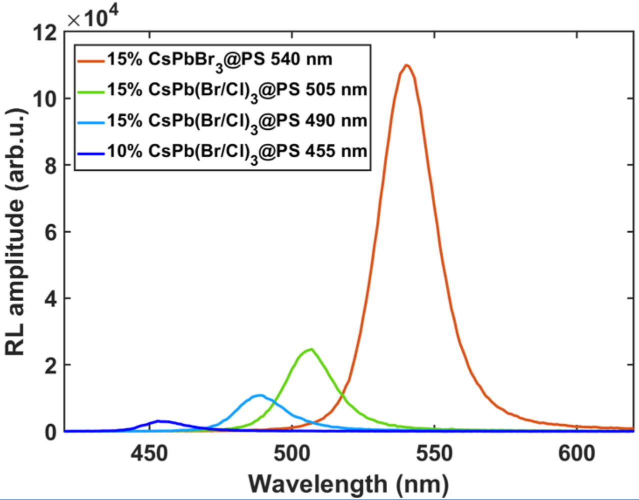
Polymerisation

Nanocrystals embedded in polymer





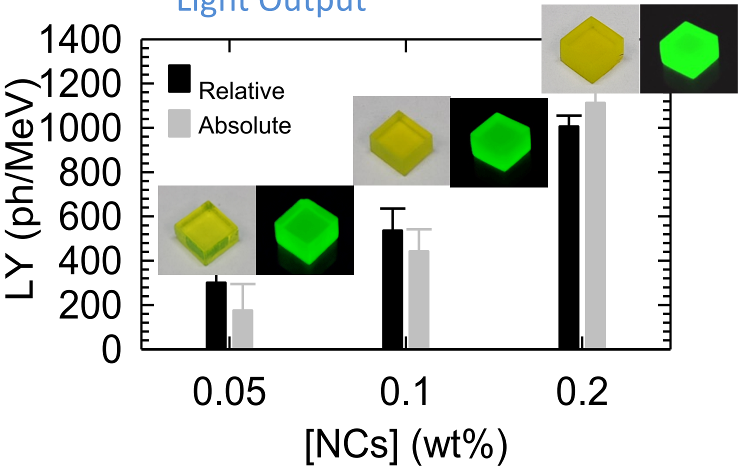




Courtesy J. Kral, CTU, Prague

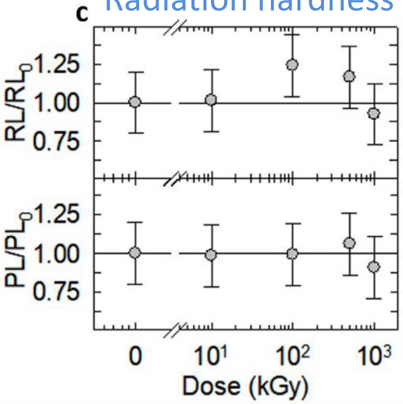
$CsPbBr_3$ Scintillating nanocomposite

Light Output

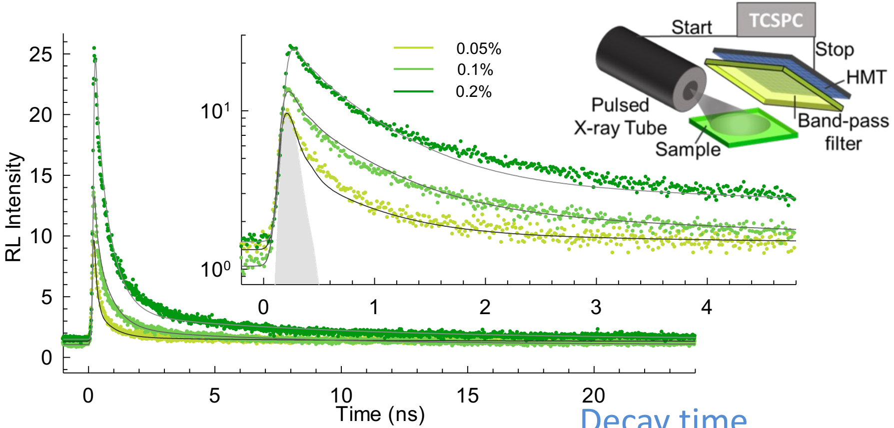


No degradation up to 1 MGy

Radiation hardness



Decay spectra



Decay time

[NC] (wt %)	Prompt	t_1		t_2	
	R_P	R_1	ns	R_2	ns
0.05	0.30	0.37	0.61	0.33	22
0.1	0.32	0.21	0.62	0.47	8.7
0.2	0.34	0.22	0.60	0.44	6.8

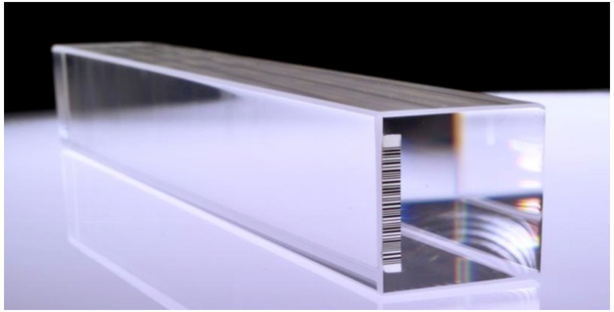
Very fast emission

A. Erroi et al, *ACS Energy Lett.* 2023, 8, 3883–3894

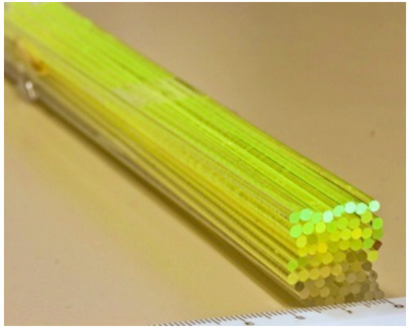
INNOVATIVE CONCEPTS

Fibres allow flexibility in detector design

From bulk crystal



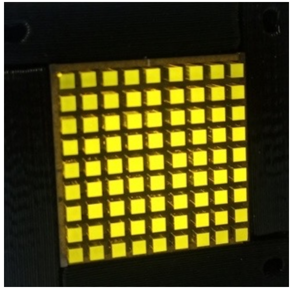
To bloc of fibres



Homogeneous calorimeter

=> Requires large volume of fibres with high density

To SPACAL



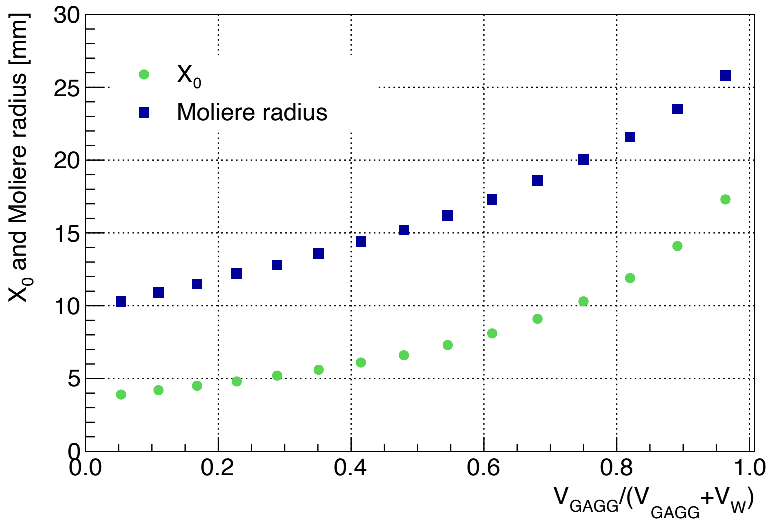
Sampling calorimeter

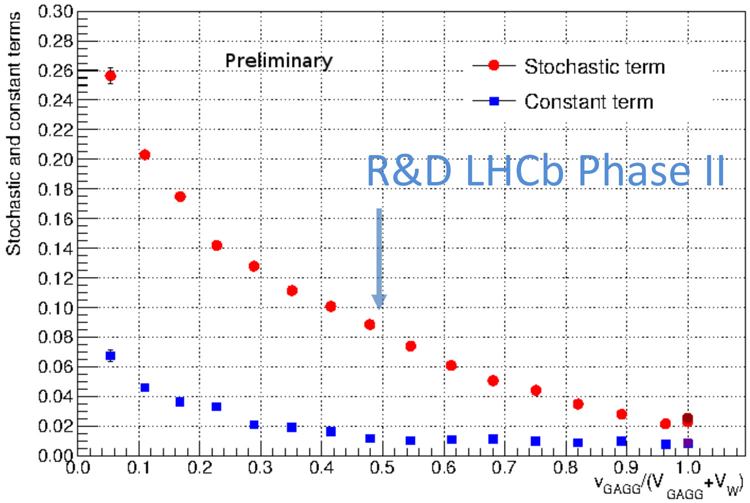
⇒ requires less fibres, possibility to use materials with lower density

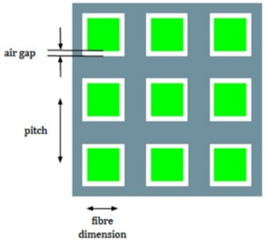
Could be multifunctional: mixed type of fibres
Cherenkov + scintillation +neutrons sensitive
Could play on sampling fraction

Tuning of detector performance with SPACAL

Study for :Pitch fixed at 1.67 mm, fibre size variable;







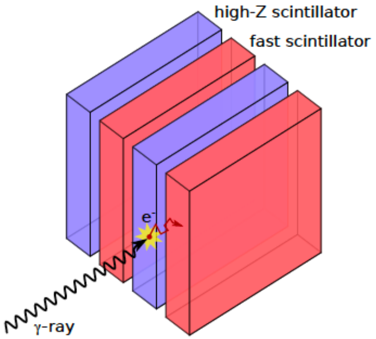
GAGG fibers/W absorber

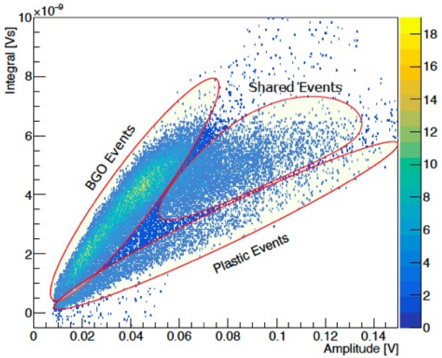
Modification of Moliere radius and X_0
=> optimisation of granularity

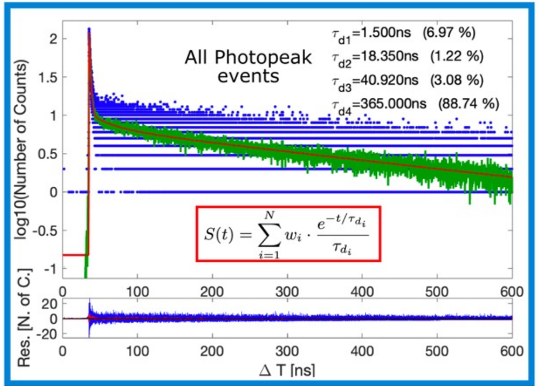
Optimisation of sampling fraction
⇒ optimisation of energy resolution

Heterostructure Concept

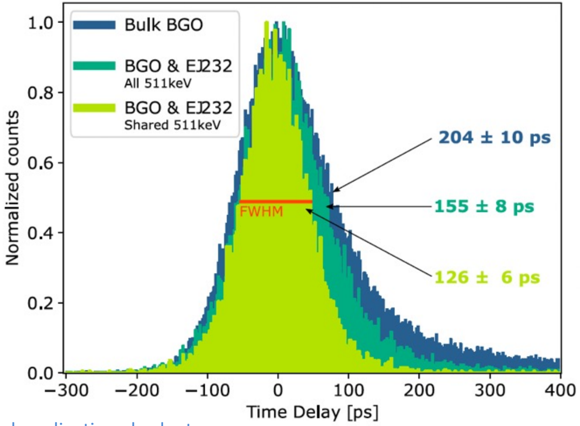
Combine scintillators with high light yield, high stopping power with prompt emission material







F. Pagano et al, IEEE NSS/MIC2022, IEEE TNS, 70, 12 (2023) 2630-2637



=> Energy sharing between bulk and fast emitter

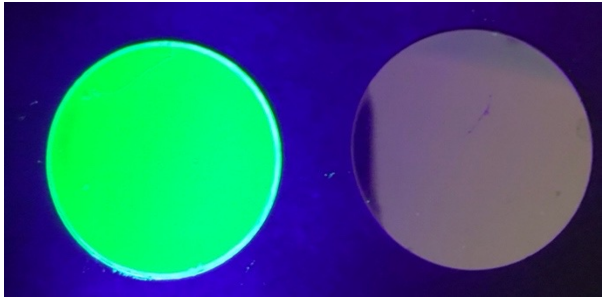
Concept proposed in the frame of ERC TICAL (GA 338953 PI: P.Lecoq)
R. M. Turtos et al, Phys. Med. Biol. 64 (2019) 85018
F. Pagano et al, 2022, 2022 Phys. Med. Biol. 67 135010

Work supported by CERN KT medical applications budget

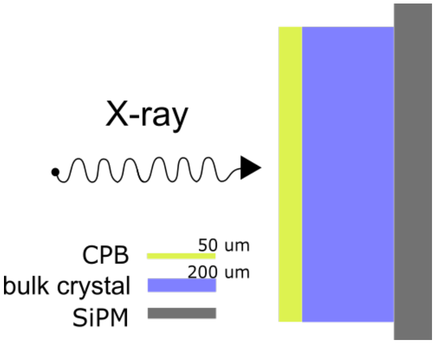
F. Pagano et al 2022 Phys. Med. Biol. 67 135010

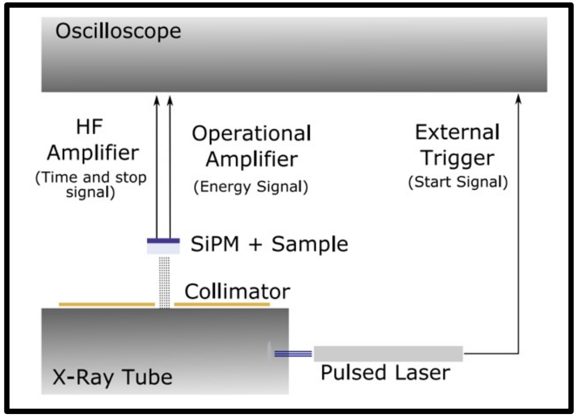
Timing performance of $CsPbBr_3$ nanocrystal layer on bulk GAGG

Thin layer of $CsPbBr_3$ NC on bulk scintillators



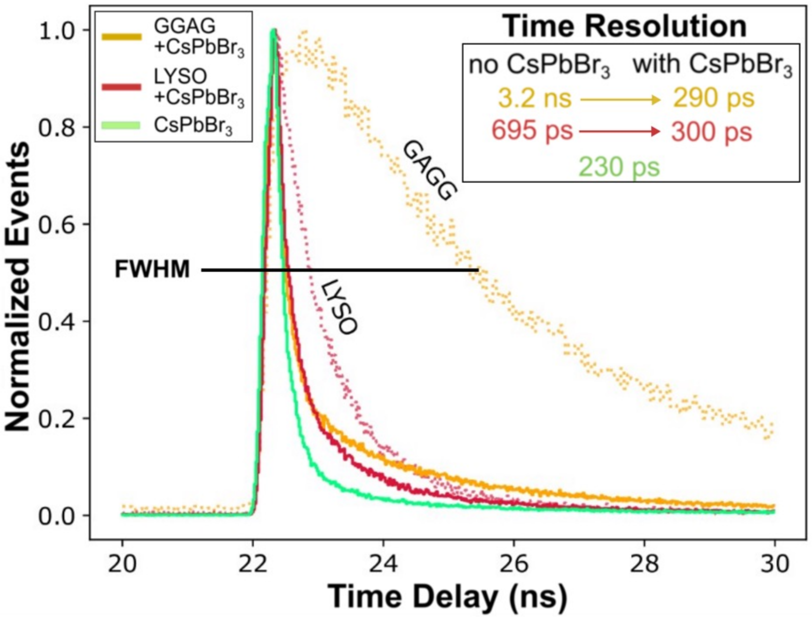
Detector time resolution (DTR) measurements





F. Pagano et al., Frontiers in Physics (vol10)

Detector time resolution with pulsed Xray source



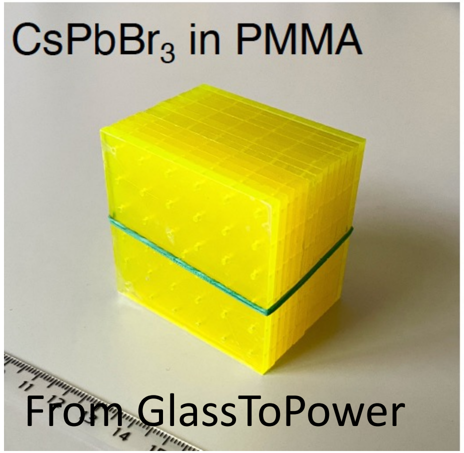
Significant improvements in timing performance under X-ray excitation with nanocrystal layer

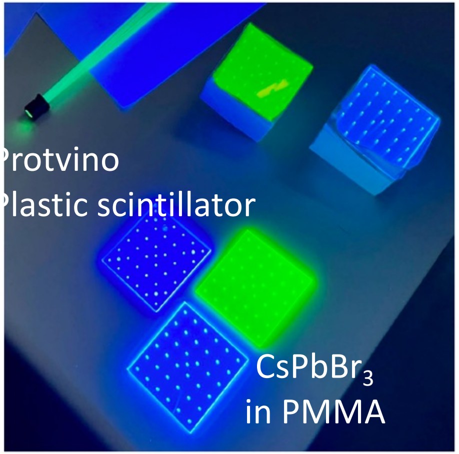
Work supported by CERN KT medical applications budget

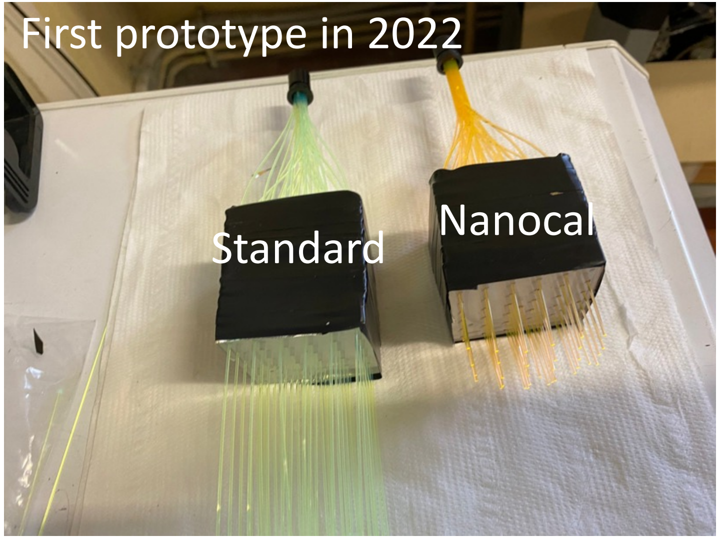
F. Pagano et al., Adv. Mater. Interfaces2024,11, 2300659

First Attempt to use Nanomaterial in HEP
Nanocal Bluesky Aidainnova project

Build a Shashlik module with $CsPbBr_3$ nanomaterial embedded in PMMA





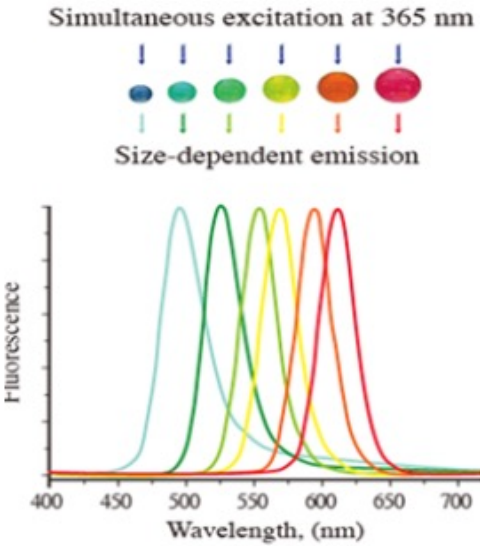


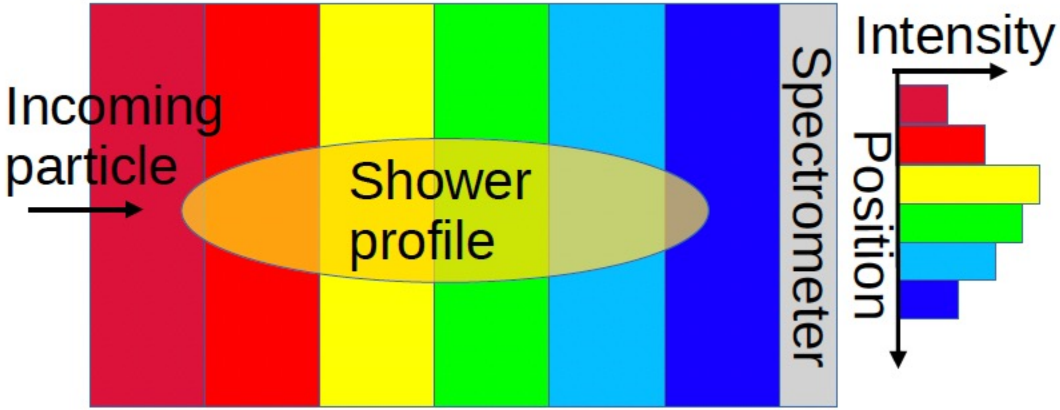
Protvino scintillator	NanoCal scintillator
Polystyrene	PMMA
1.5% PTP/0.04% POPOP	0.2% $CsPbBr_3$
Kuraray Y-11(200) fibers	Kuraray O-2(100) fibers

From M. Moulson Aidainnova WP13 20.12.2022

See EP newsletter Nov 22
M. Moulson presentation Aidainnova WP13 20.12.2022

Chromatic calorimeter concept with nanomaterial scintillator





Longitudinal Shower development information

M. Doser et al, 2022, Front. Phys. 10:887738.

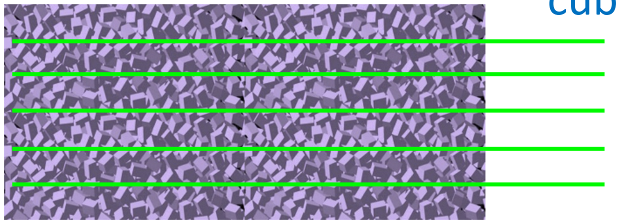
Grainita Project

Inspired by LiquidO technique for neutrino detector
(A. Cabrera et al. LiquidO Commun Phys 4, 273 (2021))

Concept: dispersed sub-millimetric grains heavy material ($ZnWO_4$) in dense liquid CH_2I_2 readout with wavelength shifter

$ZnWO_4$ (From ISMA Ukraine):

- LY= 10kph/MeV
- Density 7.62
- Index n=2.1
- τ = 20 μs
- λ_{max} = 480 nm
- grain size : 0.5 mm - 1 mm



GEANT4 simulation for $ZnWO_4$ + CH_2I_2 cubes (random position) 1mm cubes:

$$\frac{\sigma_E}{E} \sim \frac{2\%}{\sqrt{E}}$$

Current Status

- Proof of principle demonstrated with a small test bench
  - (average light path in $ZnWO_4$ + propanol ~ 17 cm)
- Tests of various WLS fibers from Kuraray on-going
- 16-channels prototype (~ 200 g $ZnWO_4$) under design
- Cosmic rays test bench under design

Courtesy M.H. Schune, IJCLab, Orsay, France
on Behalf of Grainita project, see more:
https://indico.in2p3.fr/event/27968/timetable/#20221121.detailed

Conclusion

The field of scintillation is constantly evolving since more than century

Much progress in the understanding of scintillators has been made since the 1990s

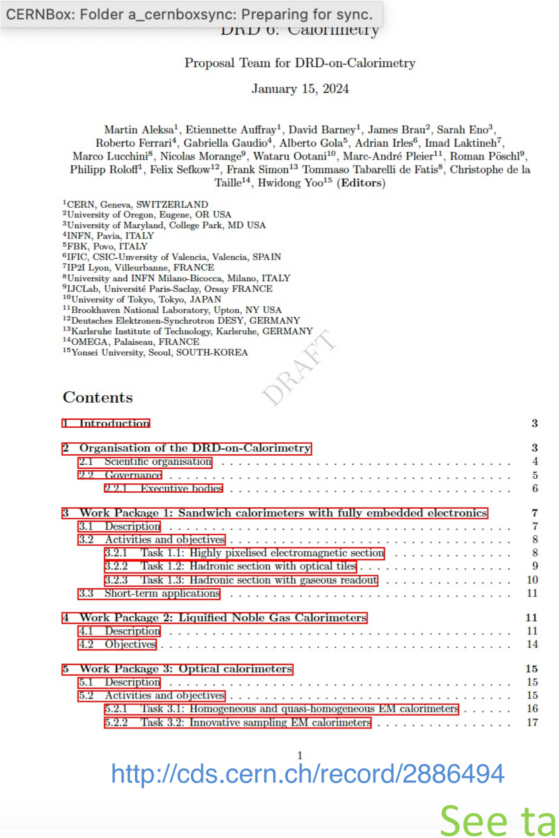
The availability of new technologies and methods has enabled a much better understanding of the processes behind

The research on fast emission processes has been strongly fostered by an increasing demand for fast timing detectors

=> New perspectives for innovative concepts of detectors based on scintillating material with multi-functionalities (eg. Cherenkov/scintillation) for next generation of radiation detectors

ECFA detector Roadmap

=> New collaboration on calorimetry since Jan 2024 (DRD6)



CERNBox: Folder a_cernboxsync: Preparing for sync.

DRD 6: Calorimetry

Proposal Team for DRD-on-Calorimetry

January 15, 2024

Martin Aleksa[1], Etiennette Auffray[1], David Barney[1], James Brau[2], Sarah Eno[3], Roberto Ferrari[4], Gabriella Gaudio[4], Alberto Gola[5], Adrian Irles[6], Imad Laktineh[7], Marco Lucchini[8], Nicolas Morange[9], Wataru Ootani[10], Marc-André Pleier[11], Roman Pöschl[9], Philipp Roloff[1], Felix Sefkow[12], Frank Simon[13] Tommaso Tabarelli de Fatis[8], Christophe de la Taille[14], Hwidong Yoo[15] (Editors)

[1]CERN, Geneva, SWITZERLAND
[2]University of Oregon, Eugene, OR USA
[3]University of Maryland, College Park, MD USA
[4]INFN, Pavia, ITALY
[5]FBK, Povo, ITALY
[6]IFIC, CSIC-Unversity of Valencia, Valencia, SPAIN
[7]IP2I Lyon, Villeurbanne, FRANCE
[8]University and INFN Milano-Bicocca, Milano, ITALY
[9]IJCLab, Université Paris-Saclay, Orsay FRANCE
[10]University of Tokyo, Tokyo, JAPAN
[11]Brookhaven National Laboratory, Upton, NY USA
[12]Deutsches Elektronen-Synchrotron DESY, GERMANY
[13]Karlsruhe Institute of Technology, Karlsruhe, GERMANY
[14]OMEGA, Palaiseau, FRANCE
[15]Yonsei University, Seoul, SOUTH-KOREA

DRAFT

Contents

1

http://cds.cern.ch/record/2886494

See talk Roberto today

ECFA DRD6 collaboration on calorimetry

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[15]Yonsei University, Seoul, SOUTH-KOREA

WP3 Optical calorimeter

Project	Scintillator/WLS	Photodetector	DRDTs	Target
Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters				
HGCCAL	BGO, LYSO	SiPMs	6.1, 6.2	e^+e^-
MAXICC	PWO, BGO, BSO	SiPMs	6.1, 6.2	e^+e^-
Crilin	PbF_2, PWO-UF	SiPMs	6.2, 6.3	$\mu^+\mu^-$
Task 3.2: Innovative Sampling EM calorimeters				
GRAiNITA	$ZnWO_4$, BGO	SiPMs	6.1, 6.2	e^+e^-
SpaCal	GAGG, organic	MCP-PMTs,SiPMs	6.1, 6.3	e^+e^-/hh
RADiCAL	LYSO, LuAG	SiPMs	6.1, 6.2, 6.3	e^+e^-/hh
Task 3.3: (EM+)Hadronic sampling calorimeters				
DRCal	PMMA, plastic	SiPMs, MCP	6.2	e^+e^-
TileCal	PEN, PET	SiPMs	6.2, 6.3	e^+e^-/hh
Task 3.4: Materials				
ScintCal	-	-	6.1, 6.2, 6.3	$e^+e^-/\mu^+\mu^-$/hh
CryoDBD Cal	TeO, ZnSe, LiMoO NaMoO, ZnMoO	n.a.	-	DBD experiments

Subtask on scintillator R&D for future calorimeter

See talk Roberto today

Acknowledgment

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and various European projects:

ENDO TOFPET US Endoscopic TOFPET & Ultrasound
TICAL
AIDA 2020
AIDA innova
ATTRACT
Unicorn
THE PICOSEC MC-NET PROJECT
Intelum
ASCIMAT
FAST Fast Advanced Scintillator Timing
TWISMA

Garnet crystal fibres, Courtesy K. Lebbou, ILM, Lyon, France