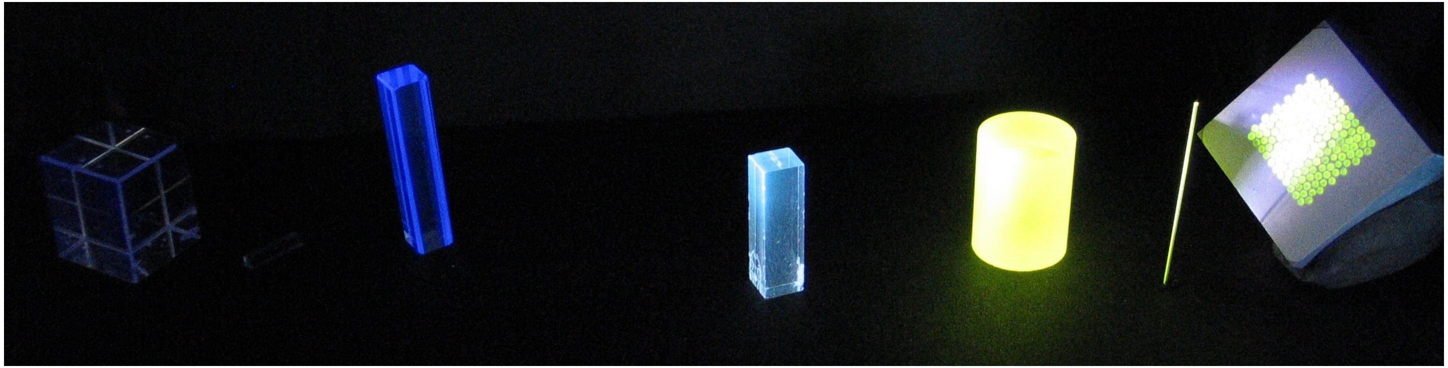
RECENT DEVELOPMENTS IN THE FIELD OF SCINTILLATORS FOR FAST RADIATION DETECTORS

E. Auffray, *CERN, EP-CMX*

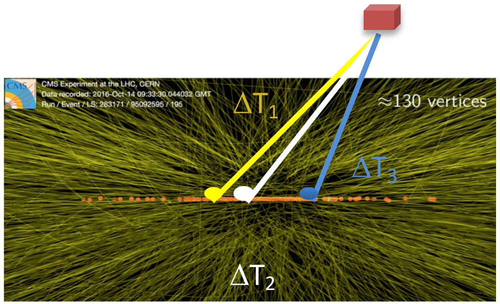


Request for fast timing detectors

In HEP :

High rate @ high luminosity accelerators;
 >140 collision events per bunch crossing at *High Luminosity-LHC;*
 → Pileup mitigation via TOF requires TOF resolution < 50 ps.

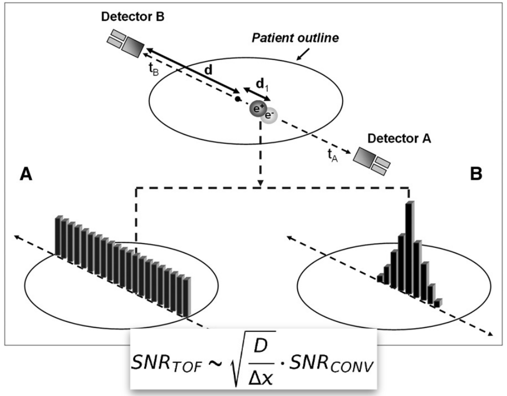
ParticLle identification



In medical imaging

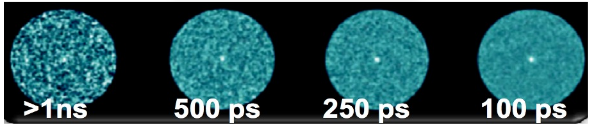
In Positron Emission Tomograph: Time of flight PET

→ Better image quality for same acquisition time
→ Faster exam
→ Simplify reconstruction
→ Help for limited field of view



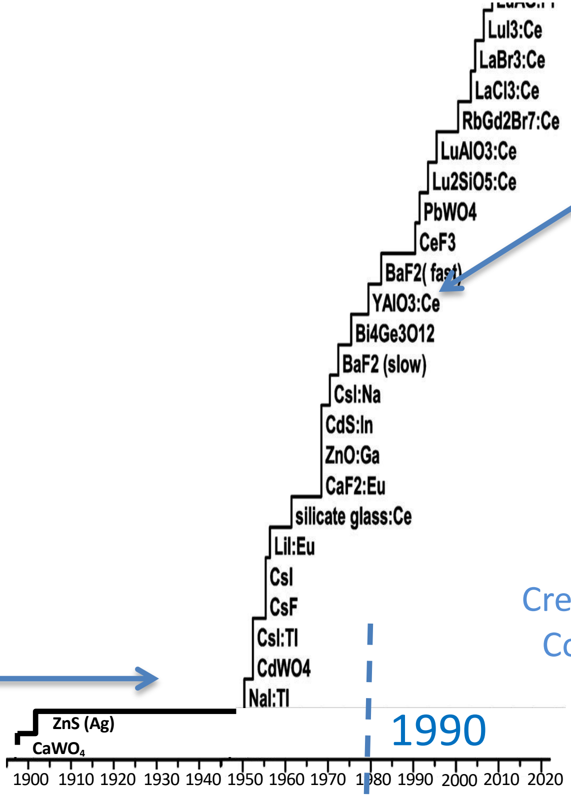
In Computed tomograph: TOF CT

→ Reduce scattered photons contribution



=> Need to push the limit of time resolution of detectors

120 years of inorganic scintillators



1990: Request for scintillators for LHC
Start of SCINT community

1940:
Invention of the photomultiplier tube

Birth of Scintillator community

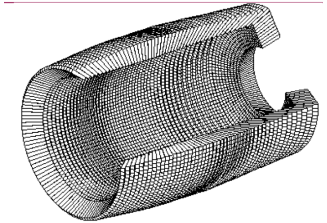
Creation of Crystal Clear Collaboration in 1991

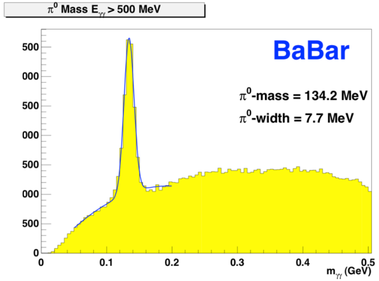
First Scint conference in 1992

P. Dorenbos, Optical Materials: X 1 (2019) 100021, https://doi.org/10.1016/j.omx.2019.100021

120 years of inorganic scintillators

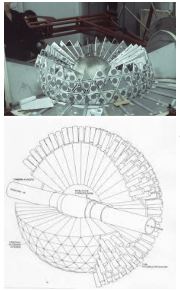
6580 CsI:Tl crystals:Babar @SLAC, 1999

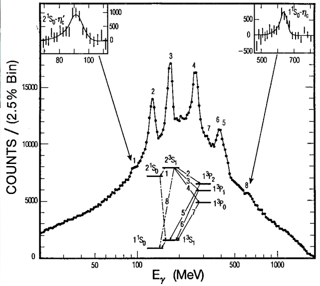


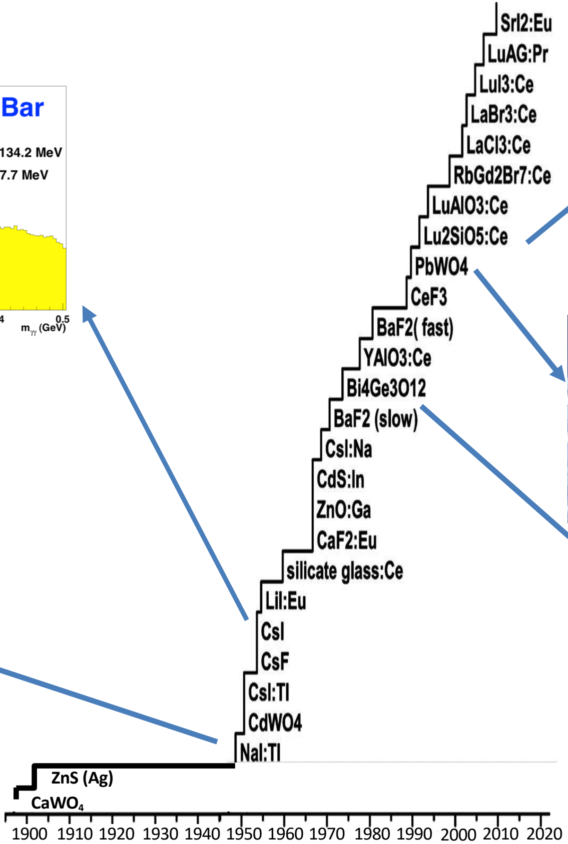


642 NaI (Tl): Crystal Ball @SLAC, 1979

Charmonium spectra



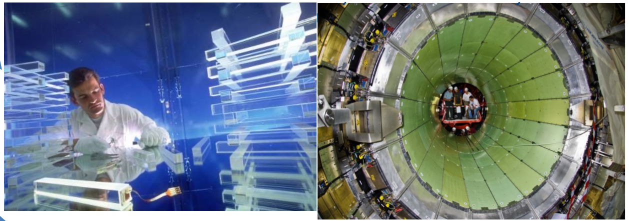




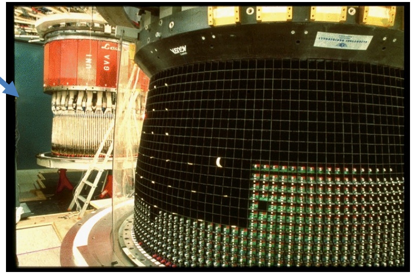
P.Dorenbos,, 10.1109/TNS.2009.2031140

~ 166000 LYSO: CMS Barrel timing layer (2026

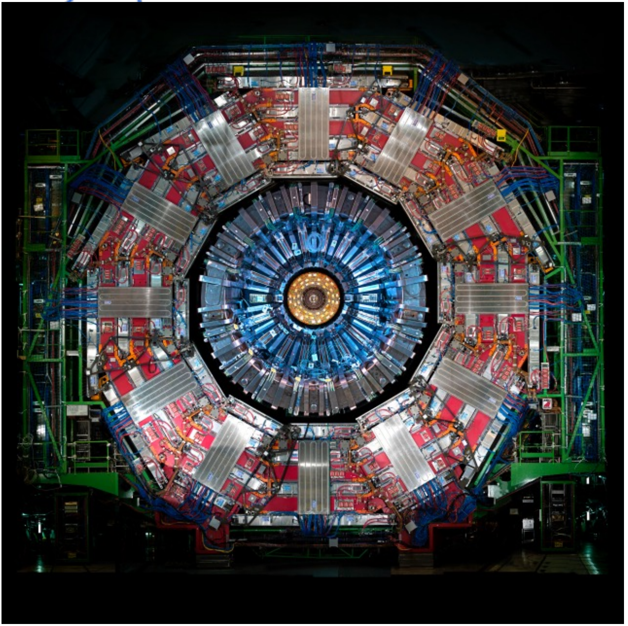
75848 PWO: CMS calorimeter @LHC 2008

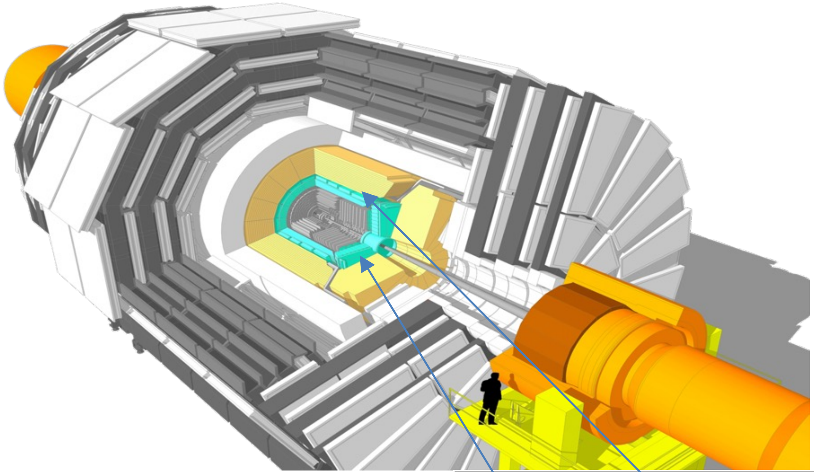


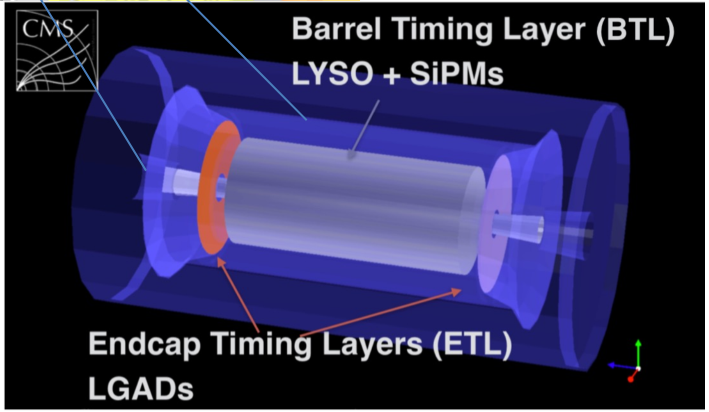
10752 BGO: L3 calorimeter @LEP 1989



CMS Barrel timing layer (BTL)

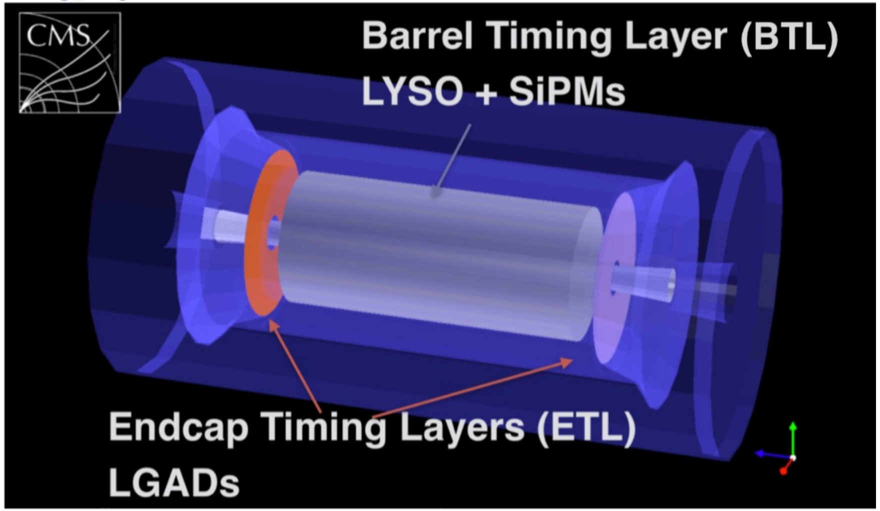


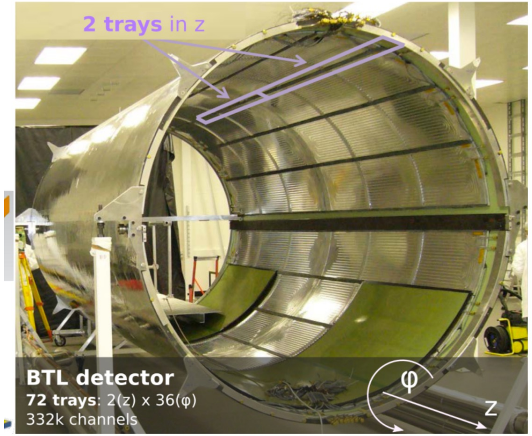




Between tracker and ECAL
Introduction of timing layer
With mip sensitivity with time resolution of 30-50ps
See talks this morning

CMS Barrel timing layer (BTL)





short fibres (3*3*57mmm^3)

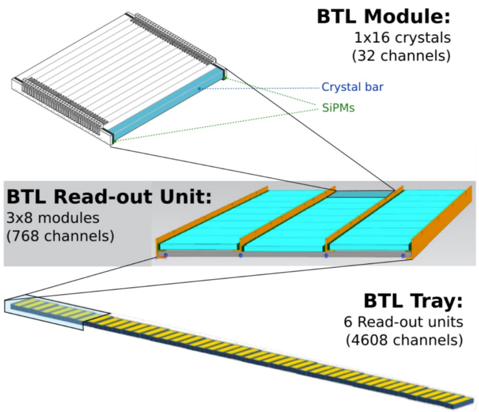
LYSO crystals with dual-end SiPM readout

Basic unit: 16x1 array of crystals (~ 3 x 3 x 57 mm^3)

Coverage: Iηl<1.45, surface ~38 m2; 332k channels

Nominal fluence: **1.9x10^{14} neq/cm^2** (3000 fb-1)

Target 30ps time resolution in barrel

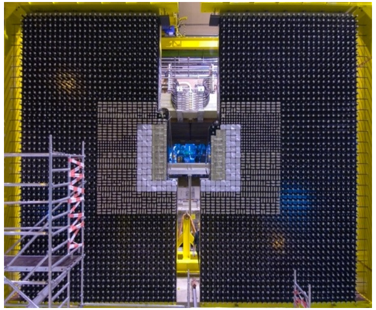


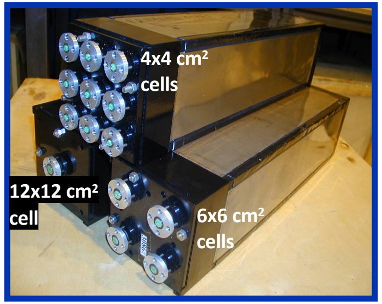
See talks this morning

The Upgrade phase II of the LHCb ECAL

Current LHCb ECAL:

- Optimised for π^0 and γ reconstruction in the few GeV to 100 GeV region at 2 x 10^{32} $cm^{-2}s^{-1}$
- Radiation hard up to 40 kGy
- Shashlik technology: 4x4 / 6x6 / 12x12 cm^2 cell size
- Energy resolution: $\sigma(E) / E \approx 10\% / \sqrt{E} \oplus 1\%$
- Large array (8 x 7 m^2) with 3312 modules and 6016 channels

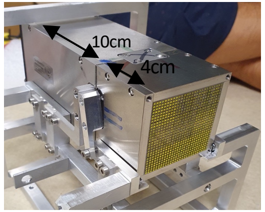




Requirements for the Upgrade II: operation at L = 1-2 x 10^{34} $cm^{-2}s^{-1}$

- Sustain radiation doses up to 1 MGy and ≤ $6{\cdot}10^{15}cm^{-2}$ for 1MeV neq/cm^2 at 300 fb^{-1}
- Keep at least current energy resolution
- Pile-up mitigation crucial
  - ✓ **Timing capabilities with O(10) ps precision**, preferably directly in the calorimeter modules
  - ✓ Increased granularity in the central region with denser absorber
- Respect outer dimensions of the current modules: 12x12 cm^2

SPACAL W/GAGG prototype test at DESY2020/2021



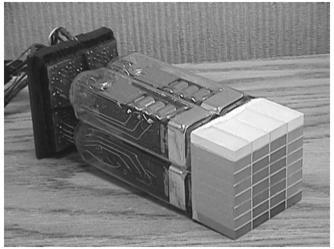
9-cells of 1.5x1.5cm^2 GAGG & YAG fibres in W-absorber

⇒Possible solution SPACAL for central part : W/Garnet (GAGG) or W/plastic fibres

See talks: Tuesday afternoon D. Breton & Wednesday morning

120 years of inorganic scintillators

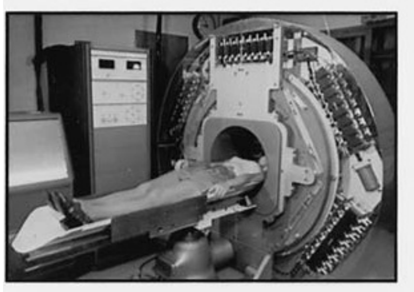
4096 BGO: ECAT 931 1987

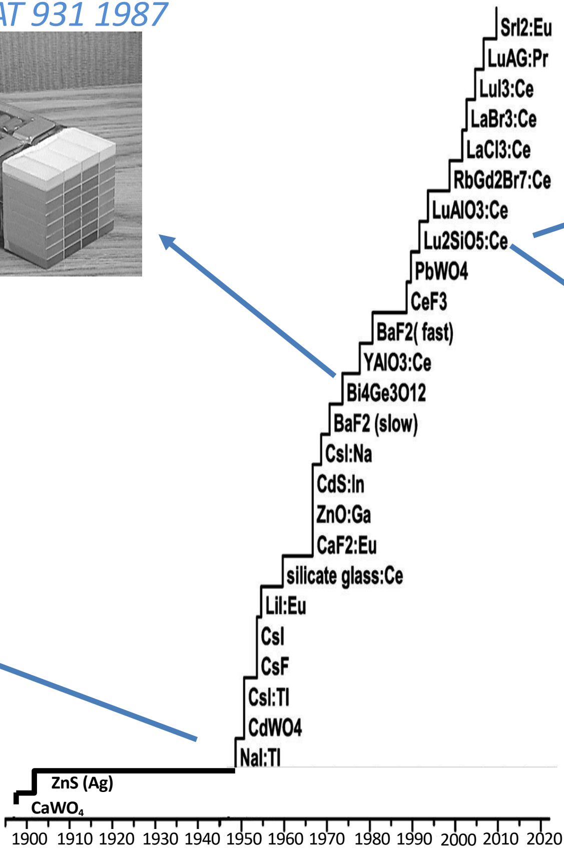


2018 LSO: TOF PET Biograph Siemens

24 NaI (Tl): PETII, 1973

48 NaI (Tl): PETIII, 1974





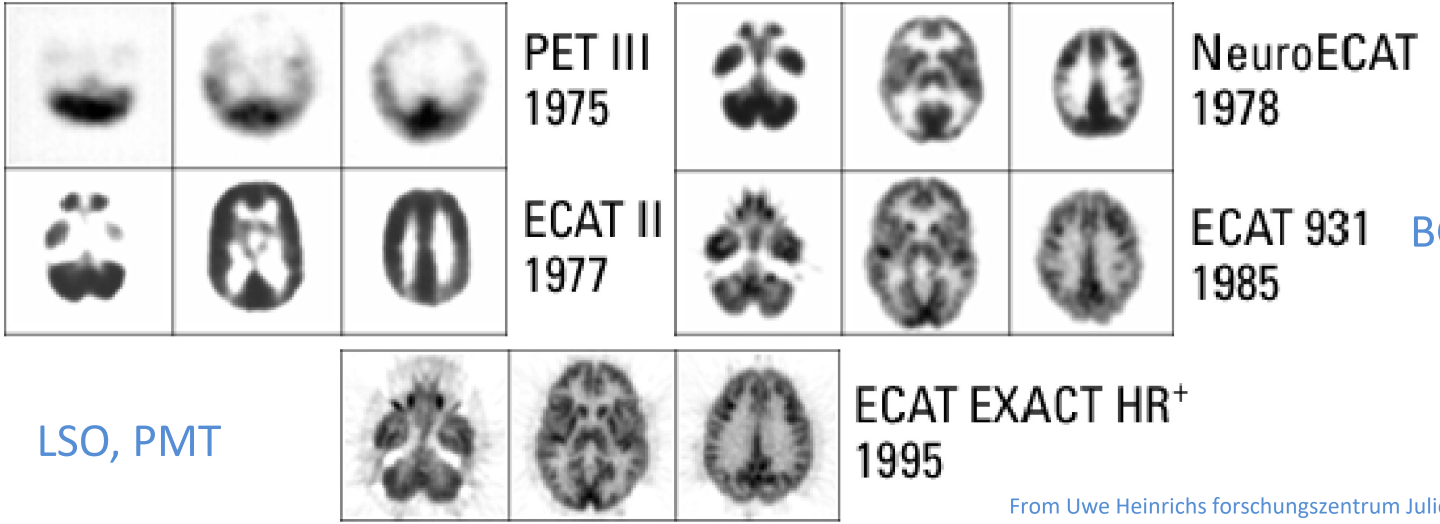
P.Dorenbos,, 10.1109/TNS.2009.2031140

1995 LSO: ECAT EXACT HR+

Evolution of PET Images

Brain images from various PET from CTI/Siemens

NaI, PMT



BGO, PMT

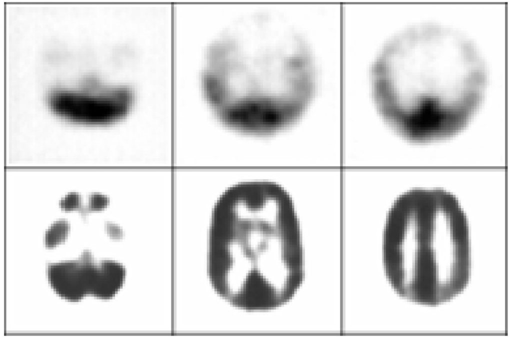
LSO, PMT

From Uwe Heinrichs forschungszentrum Julich

Evolution of PET Images

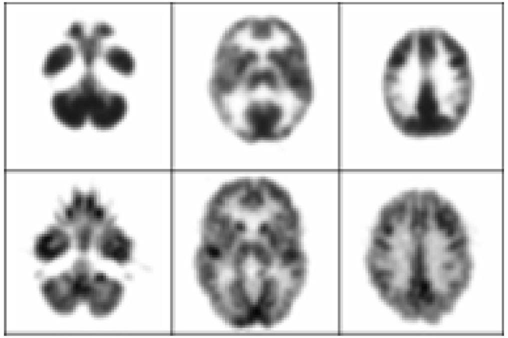
Brain images from various PET from CTI/Siemens

NaI, PMT



PET III
1975

ECAT II
1977

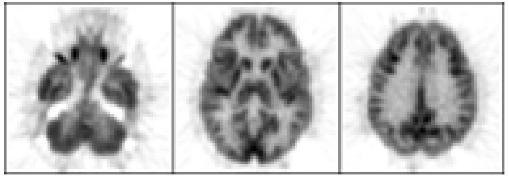


NeuroECAT
1978

ECAT 931
1985

BGO, PMT

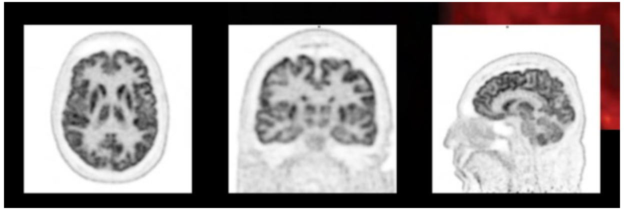
LSO, PMT



ECAT EXACT HR+
1995

From Uwe Heinrichs forschungszentrum Julich

Biograph vision from SIEMENS Healthcare 2018

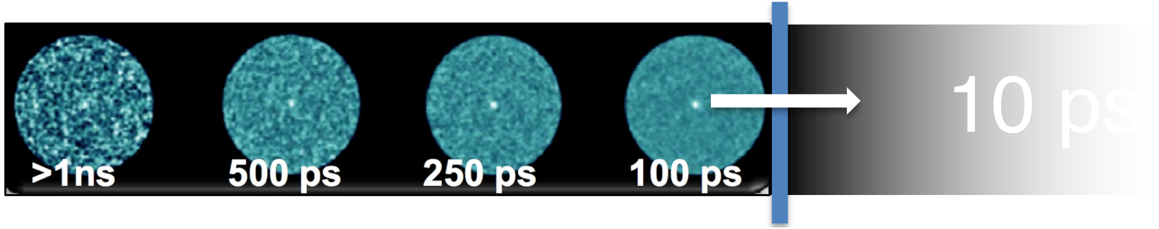


Data courtesy of Centre Hospitalier Universitaire Vaudois, Lausanne, Switzerland

LSO, SiPM, TOF-PET/CT (215ps)

From SIEMENS Healthcare web page

New TOF-PET frontier :10ps



Time resolution	1ns	500ps	250ps	100ps	10ps
Spatial resolution on LOR	15cm	7.5	3.75	1.5cm	**1.5mm**

10ps: Spatial localization directly from TOF (1.5 mm)

- Sharp improvement in SNR
- Less dose to the patient
- More accurate dynamic studies
- No need for full angular coverage

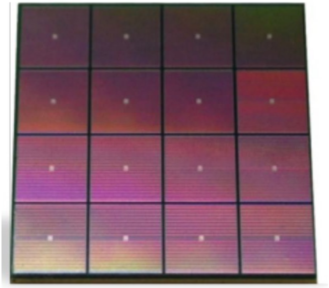
See P. lecoq's talk today

The full detection chain impacts timing properties

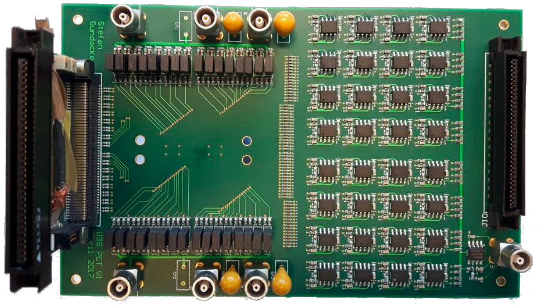
Light production & transport

γ

Light detection



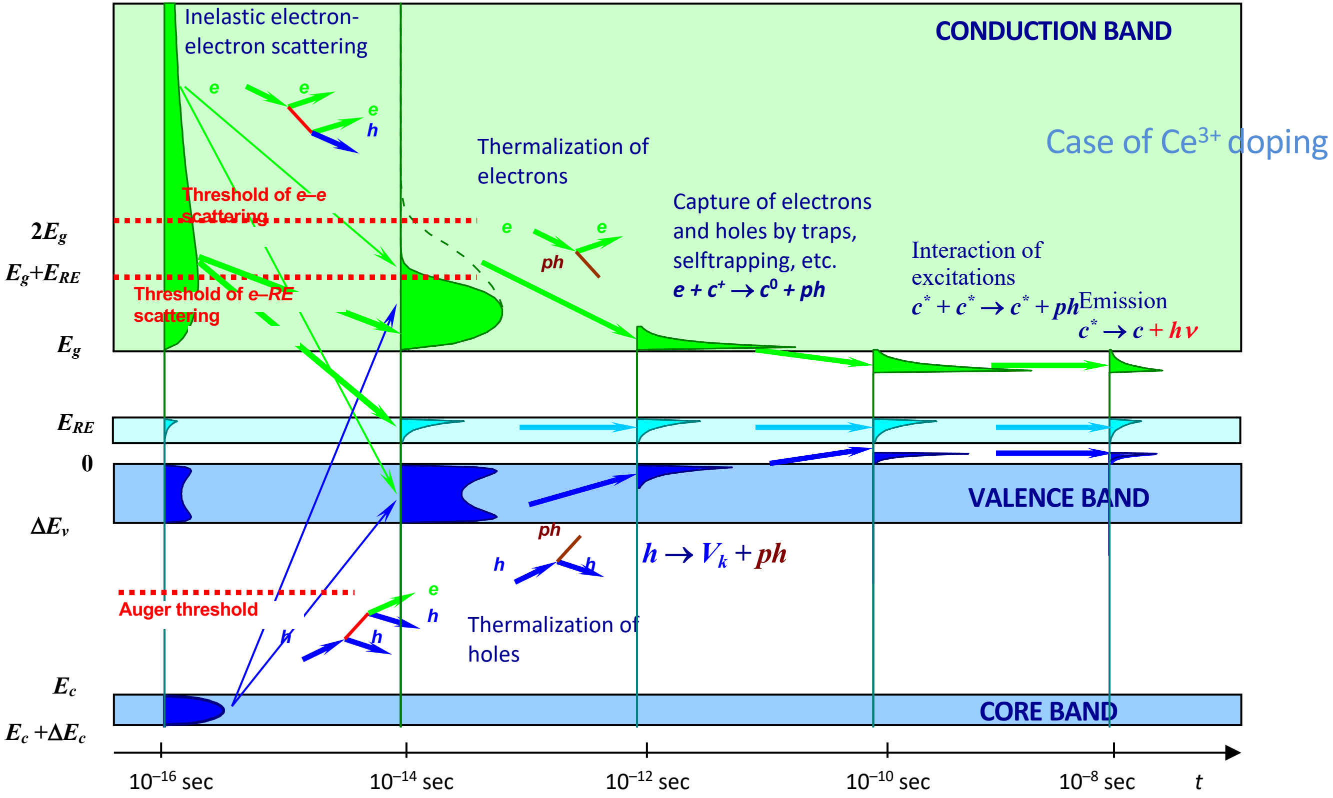
Electronic readout



Many developments ongoing on scintillators

Scintillation: a complex process chain

From eh pair creation to light emission



A. Vasiliev, Proceedings of The SCINT99 conference, Moscow, Faculty of Physics, Moscow State University, 2000, p. 43-52

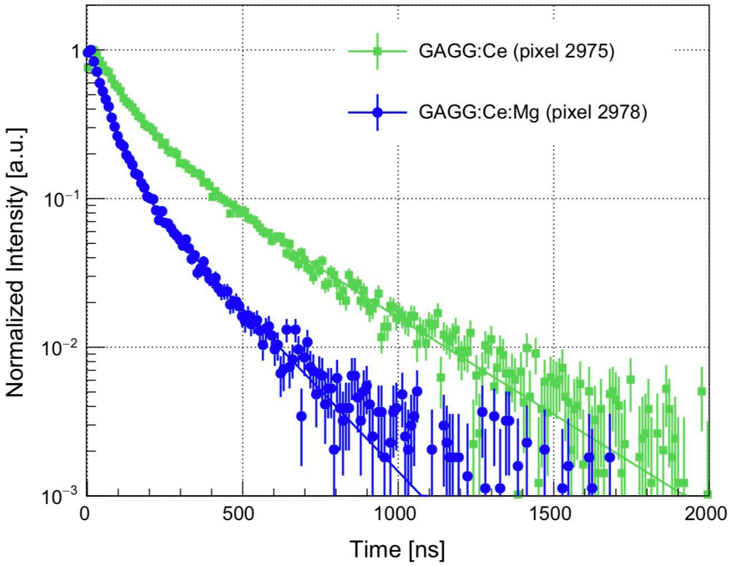
Various possibilities for fast emission process

- Excitonic emission (STE, excitations of anion complexes)
- Emission of activators (Ce, Pr, …) Codoping:
- **Cherenkov radiation**
- **Crossluminescence**
- **Hot intraband luminescence (HIL)**
- **Quantum confinement driven luminescence:**

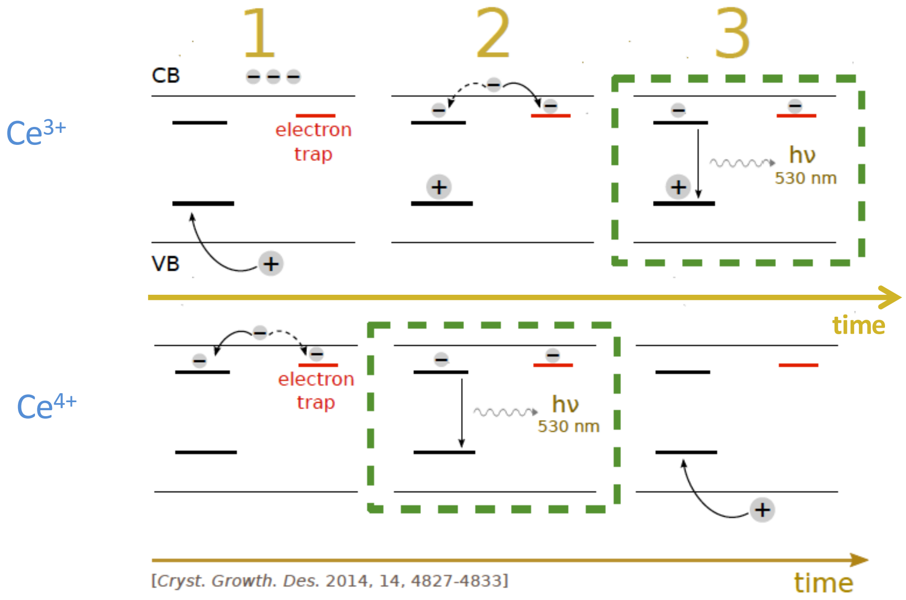
Slow

Ultra fast

Engineering scintillator example of codoping Ce, Mg in garnet



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



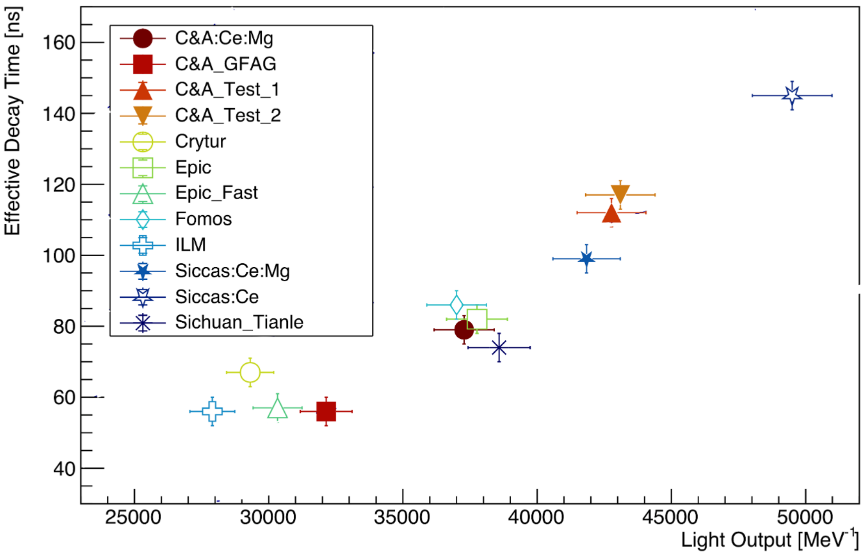
Mg2+ increase Ce^{4+} centers which can directly compete with any electron trap for electron capture in the first instants of scintillator mechanism => Expected faster decay time and lower slow component

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

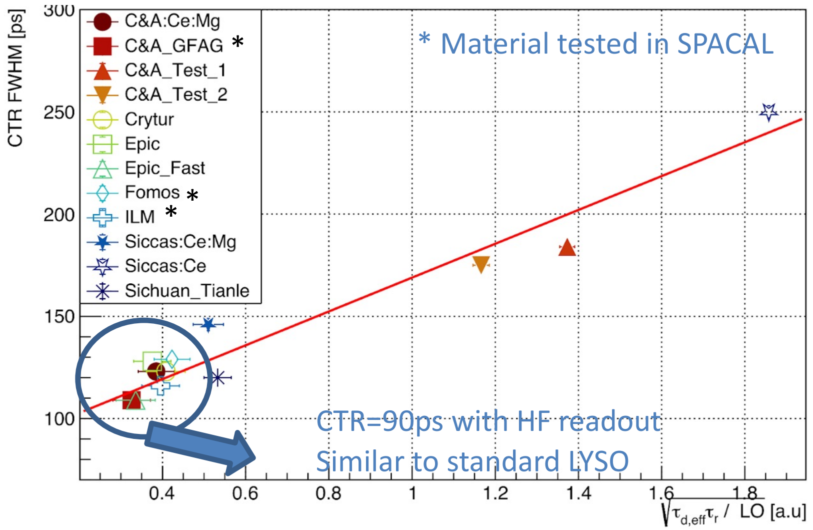
M. Nikl, A. Yoshikawa, Adv. Optical Mater. 2015, 3, 463–481
M. Nikl et al. Cryst. Growth Des. 2014 , 14 , 4827 .

GAGG: Tunable properties with composition

Effective decay time versus Light output



Coincidence time resolution (CTR) versus photon density



Photon time density:

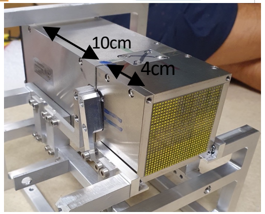
$$\frac{LO}{t_{d\ eff}}$$

CTR inversely proportional to the photon time-density:

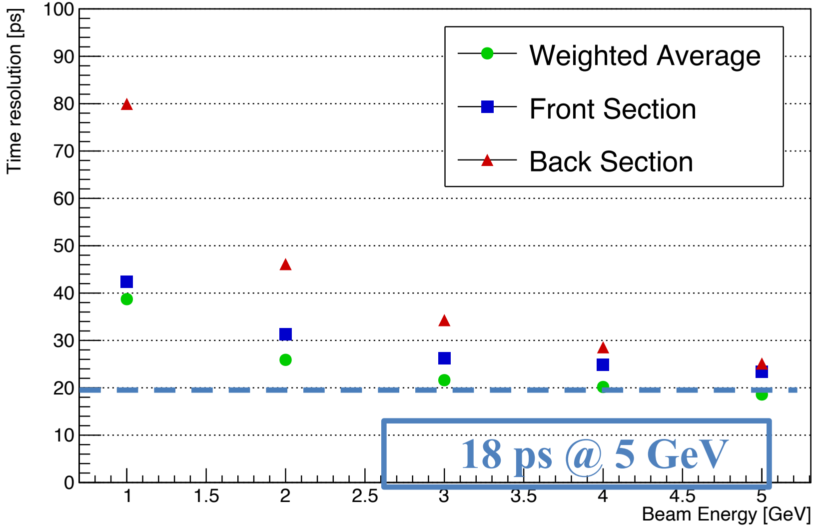
Candidate for central part of LHCb phase II calorimeter

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

GAGG performance in SPACAL prototype

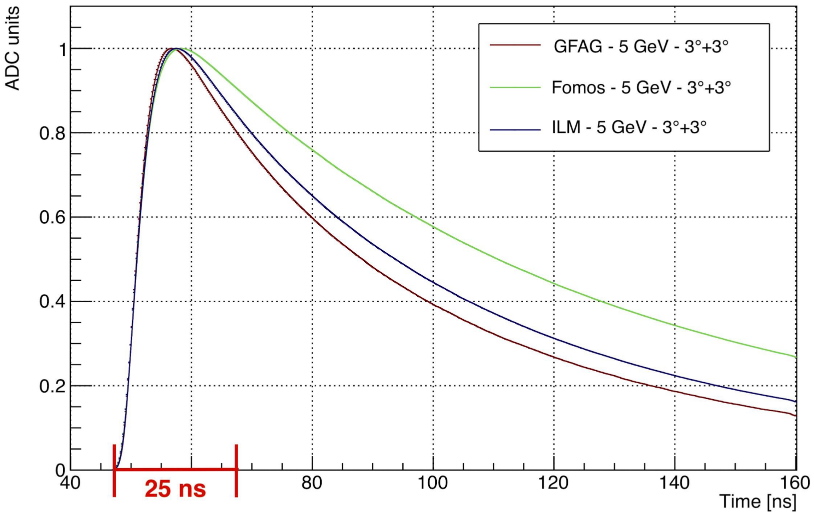


Time resolution GFAG cell @ incident angle of 3o + 3o
(DESY 2020 , R7600-20)



Excellent timing performance in TB

Pulse shape comaparison

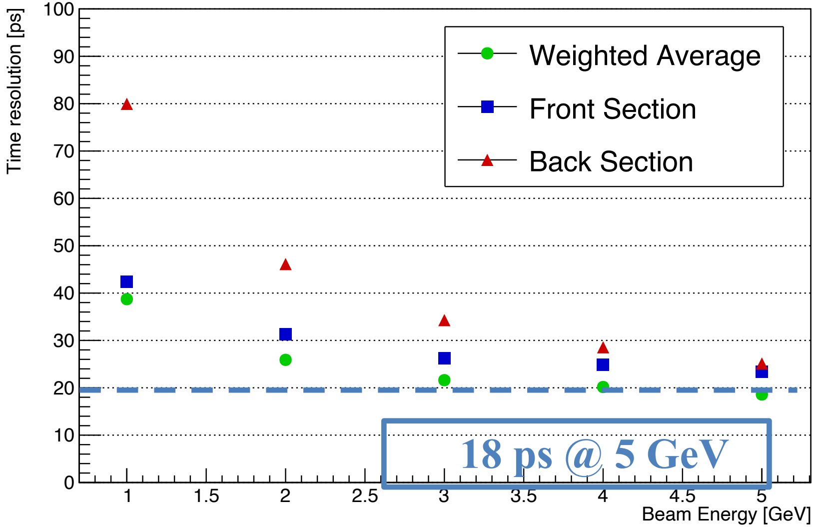


But what will be the impact of pulse shape at HL-LHC ?

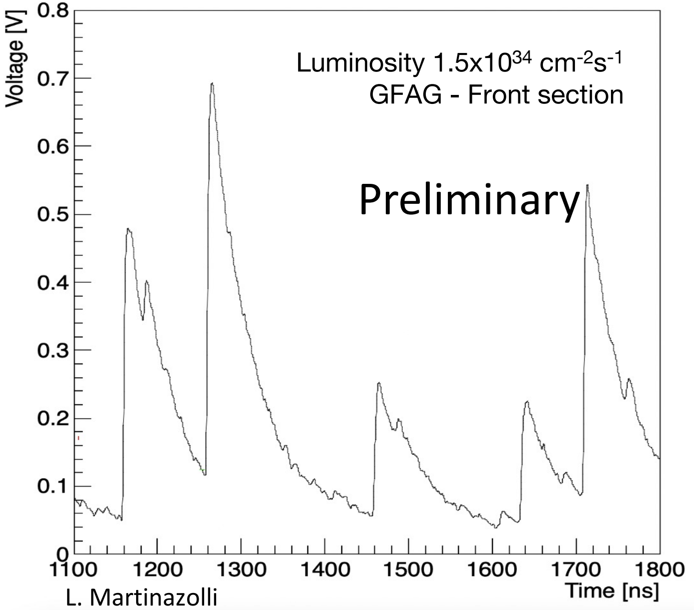
L. Ann, NIMA, 1045 (2022) 167629 arXiv:2205.02500

GAGG performance in SPACAL prototype

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



SPACAL Signal Simulated



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

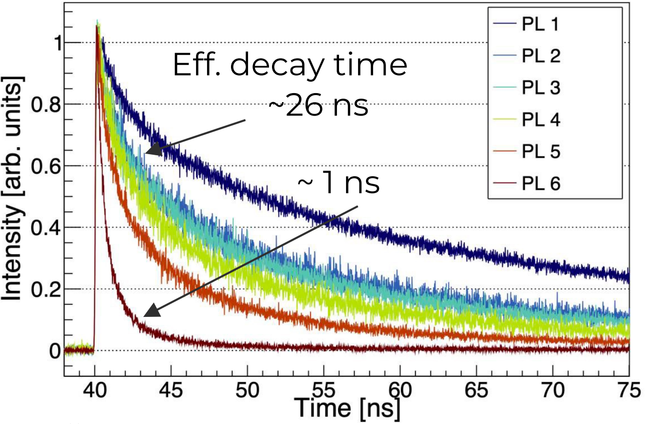
⇒ **Need to suppress slow component and shorten the main decay component to avoid pulses from different interaction to pile up**
⇒ **But maintain time resolution**

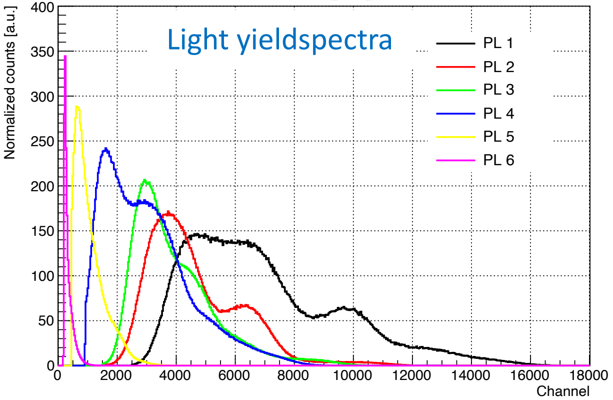
L. Ann, NIMA, 1045 (2022) 167629 arXiv:2205.02500

Further acceleration of the emission

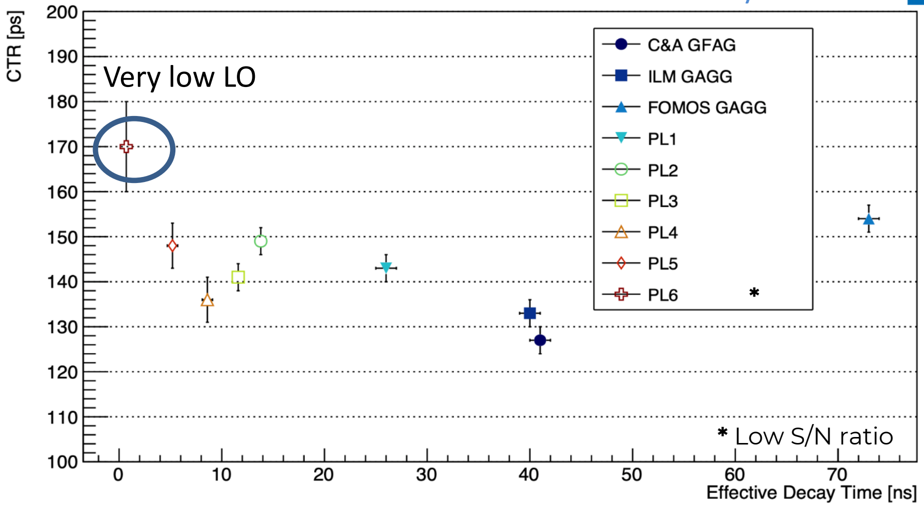
Heavy codoping Ce^{3+}/Mg^{2+}

Scintillation decay - Pulsed X-Rays





Coincidence time resolution vs effective decay time

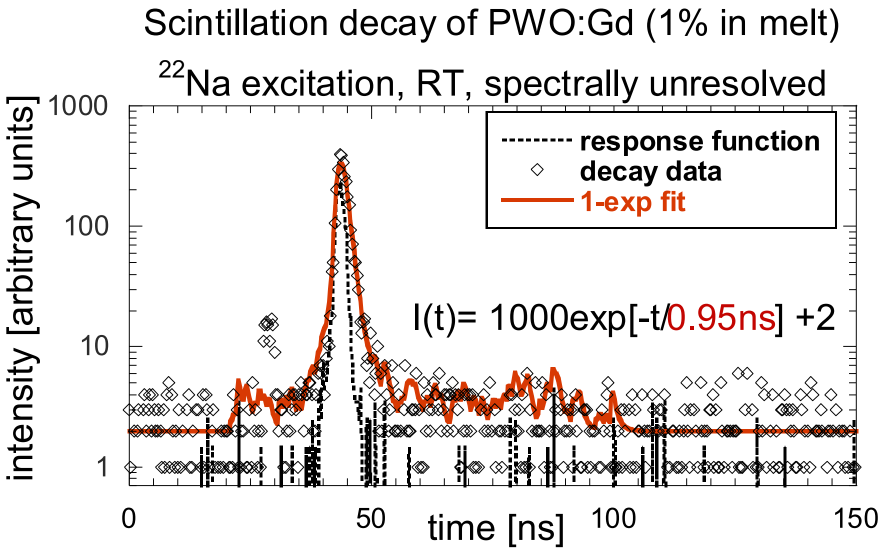


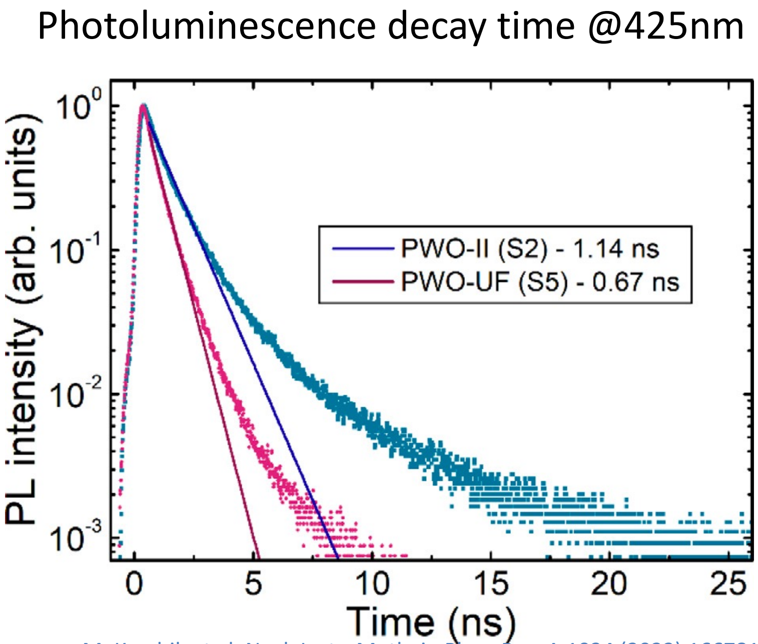
No major loss of time resolution!
Decay time decrease compensated the Light output reduction
=> the same photon time-density

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

Towards very fast PWO

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





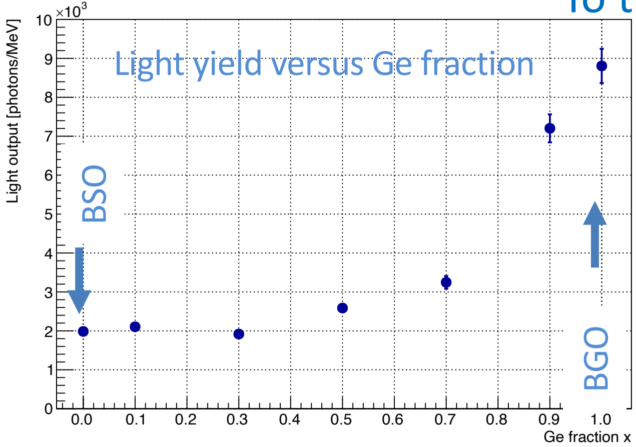
M. Nikl et al, J.Cryst. Growth **229**, 312-315 (2001)
M. Nikl, et al, Radiation Measurements **33**, 705-708 (2001)
M. Kobayashi, et al: Nucl. Instr. Meth. in Phys. Res. A **459**, 482-493 (2001)

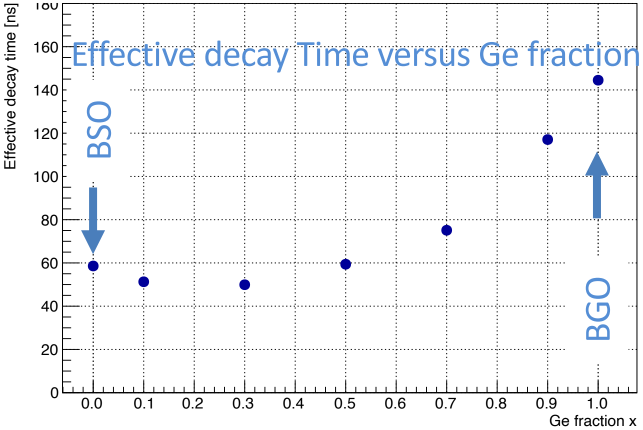
M. Korzhik et al, Nucl. Instr. Meth. in Phys. Res. A 1034 (2022) 166781

Candidate for KLEVER &CRILIN calorimeter

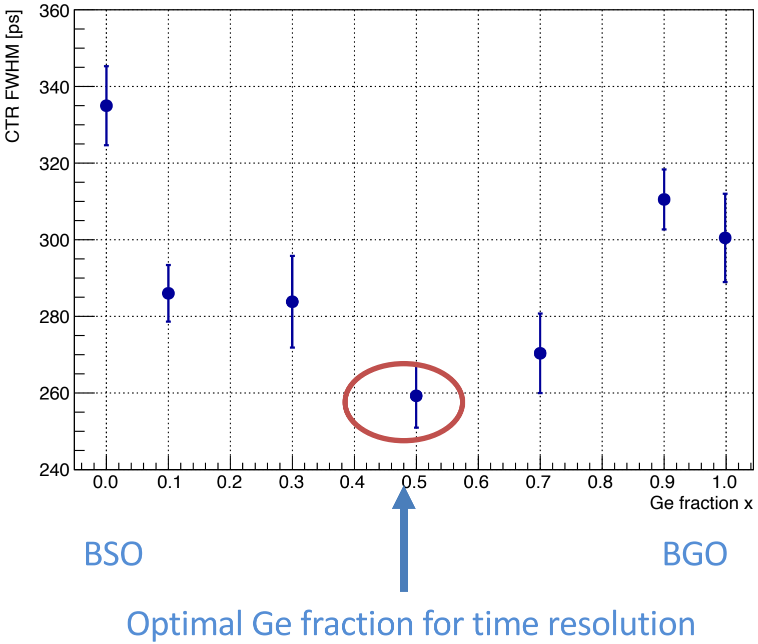
Mixed Material: BGO-BSO ($Bi_4(Ge_xSi_{1-x})_3O_{12}$)

To tune the material properties



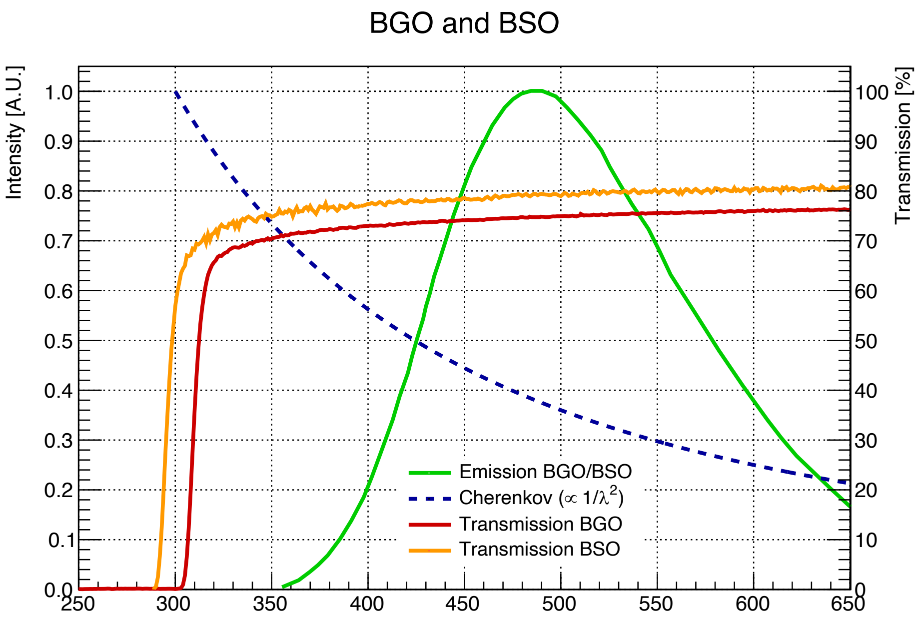


Coincidence time resolution @511Kev versus Ge fraction

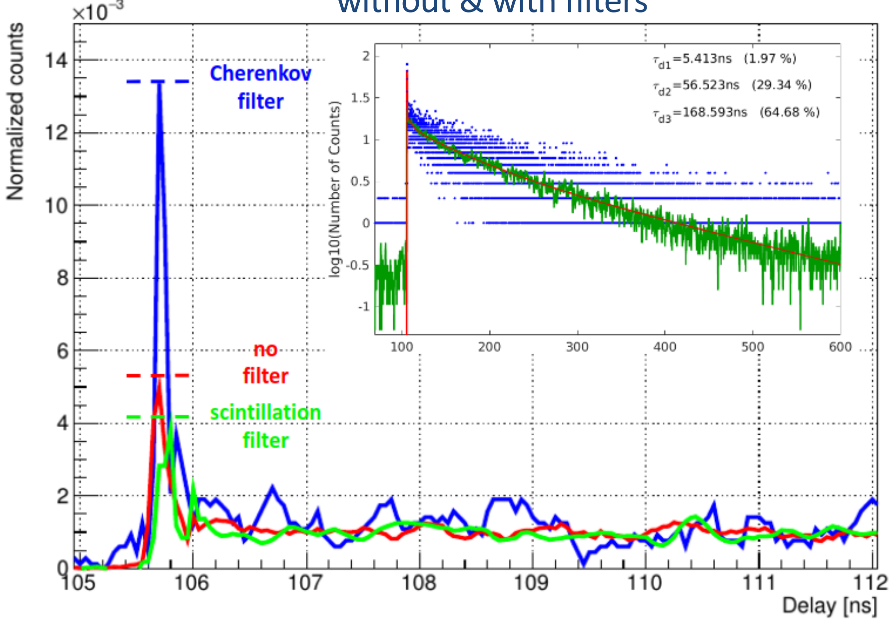


R. Cala et al, NIMA, A 1032 (2022) 166527

Exploitation of Cherenkov/scintillation in intrinsic scintillating crystals



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



⇒ Possibility to separate Cerenkov from scintillation with filters and/or pulse discrimination

BSO (or mixed BGSO) is faster than BGO and has higher LY than PWO

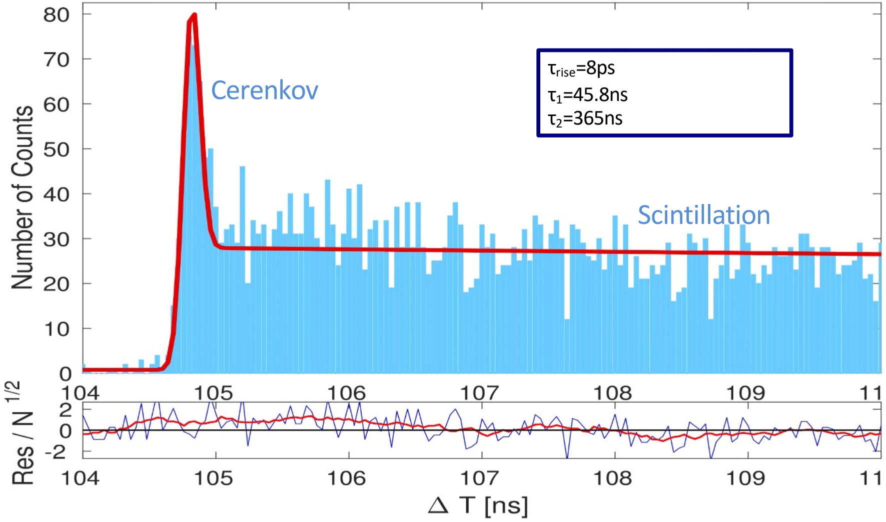
⇒ Promising candidate for dual readout homogenous calorimeter

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

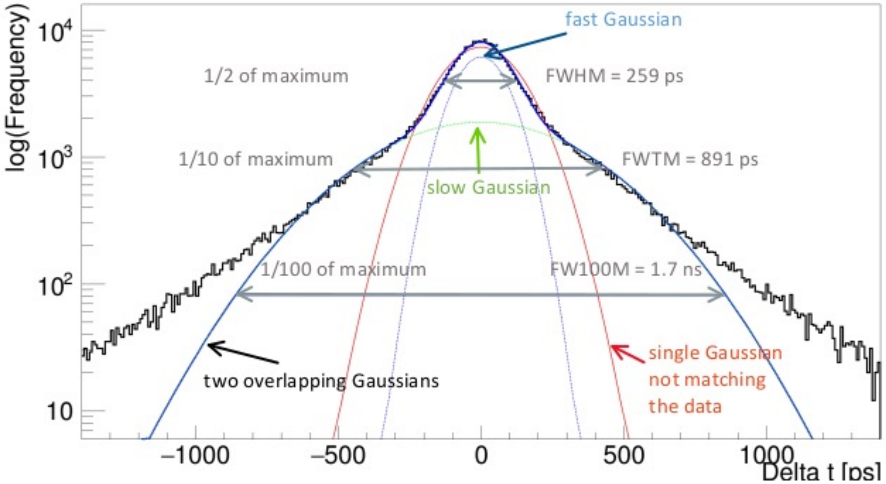
Cherenkov exploitation to improve time resolution

Example of BGO

Decay time spectra with 511KeV

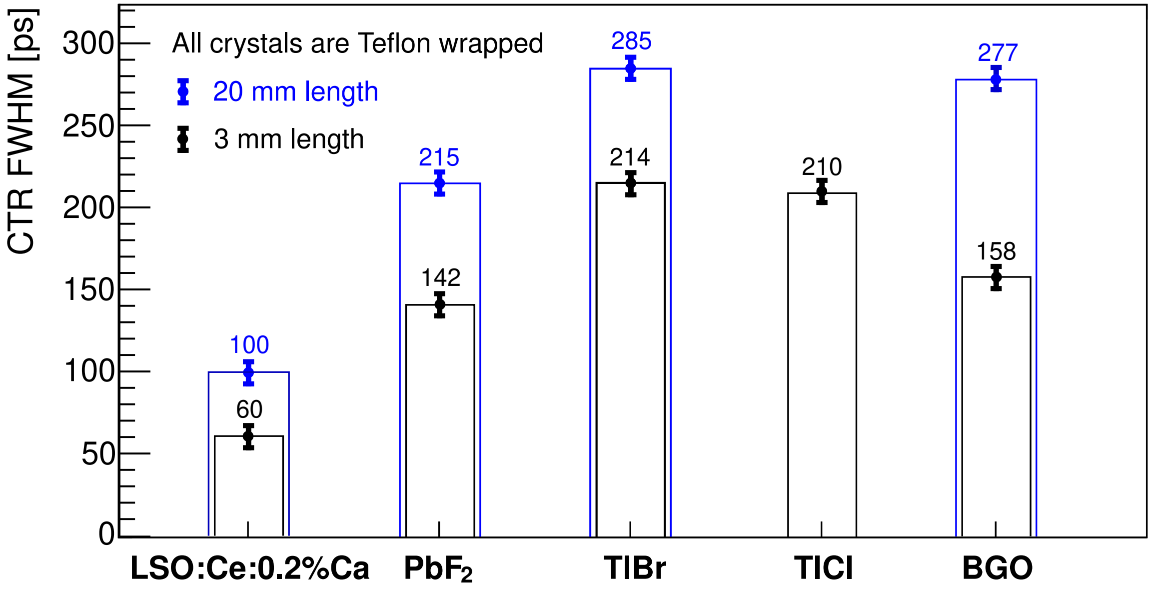


Coincidence time resolution @ 511KeV



S. Gundacker et al. (2019) Phys. Med. Biol. 64 055012
N. Kratochwil et al (2020), Phys. Med. Biol. 65 115004
N Kratochwil et al (2020) IEEE TRPMS 2020.3030483

Cherenkov exploitation to improve time resolution

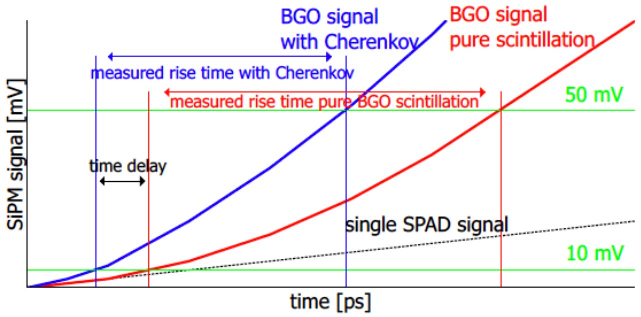


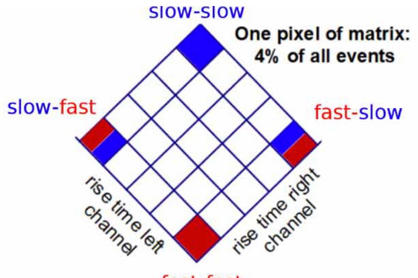
S. Gundacker et al, Phys. Med. Biol. 65 (2020) 025001 (LSO& BGO)
N. Kratochwil et al 2021 Phys. Med. Biol. 66 195001 (PbF_2)
G. Terragni et al., Front. Phys. 2022 10:785627., (TlCl& TlBr)

PbF2: candidate for Klever & CRILIN calorimeter

Cherenkov exploitation to improve time resolution
Further Improvement

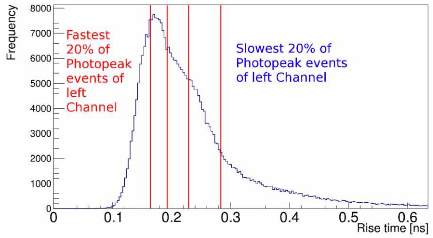
Variation of rise time with Cherenkov events

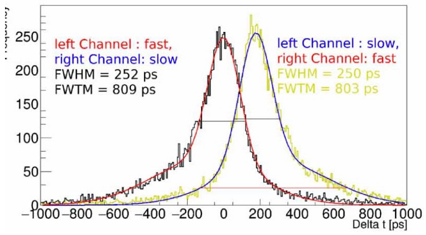


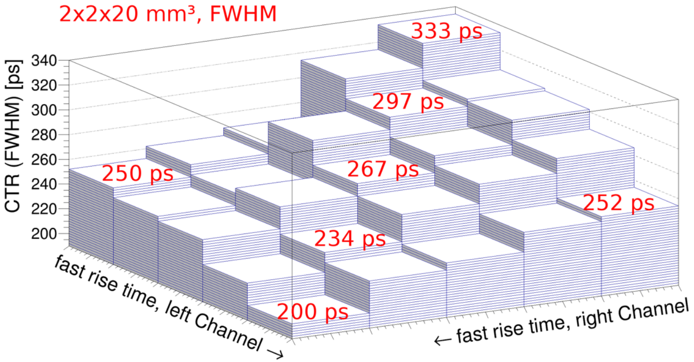


N. Kratochwil et al (2020), Phys. Med. Biol. 65 115004
N Kratochwil et al (2020) IEEE TRPMS 2020.3030483

Classification of events with rise time



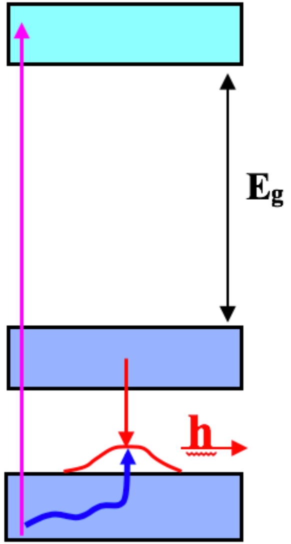




For fastest events CTR of 200ps !

Crossluminescence material

Radiative transition between the core- and valence bands.



Many possible materials

Compilation of CL data at 293 K

C.W.E. Van Eijk J of lum., Vol 6061, 1994936-941

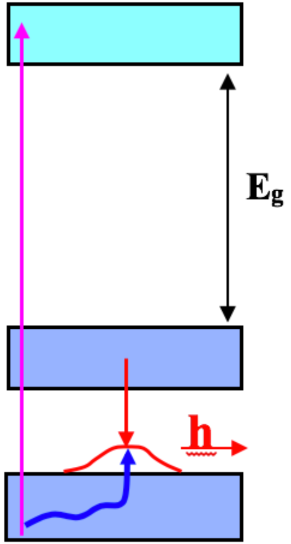
	E(C – V) (eV)	E(G) (eV)	Theoretical	Observed (eV)	λ (nm)	Light yield (photons/MeV)	τ (ns)	Density (g/cm^3)	References
KF	7.5–10.5	10.7	+	7.5–8.5	156	--		2.5	[13, 18]
KCl	10–13	8.4	–						
KBr	10–13	7.4	–						
KI	9.5–14	6.0	–	STE					
RbF	0–7.5	10.3	+	3–6	203, 234	1700	1.3	3.6	[11–14, 18]
RbCl	4–9	8.2	+	5.5–7.5	190	1		2.8	[12]
RbBr	6.7–9.5	7.4	/						
RbI	5–10	6.1	/	STE					
CsF	0–4.5	9.9	+	2.5–4	390	2000	2.9	4.1	[6, 11, 14]
CsCl	1–5	8.3	+	4–5.5	240, 270	900	0.9	4.0	[6, 14, 15, 17, 18]
CsBr	4–6	7.3	+	4.5–6.5	250	20	0.07	4.4	[6, 14, 15, 18]
CsI	0–7	6.2	/	–/STE					
CaF_2	12.5–17.3	12.6	–	–/STE					[1]
SrF_2	8.4–12.8	11.1	/	–/STE					[1]
BaF_2	4.4–7.8	10.5	+	5–7	195, 220	1400	0.8	4.9	[1, 3, 4, 9]
$K_xRb_{1-x}F$				5–6/8					[13, 18]
$KMgF_3$				6–9	140–190	1400	1.3	3.2	[7–10]
$KCaF_3$				6–9	140–190	1400	<2	3.0	[10]
KYF_4					170	1000	1.9	3.6	[9, 16]
K_2YF_5				5.5–8.5	170	300	1.3	3.1	[8, 9]
$KLuF_4$				5.5–8.5	170–200	~200	1.3	5.2	[8, 9, 16]
KLu_2F_7				5.5–8.5	165	~200	<2	7.5	[8]
K_2SiF_6				5–9	140–250				[21]
$CsCaCl_3$					250, 305	1400	~1	2.9	[10, 17, 19]
$CsSrCl_3$					260, 300		~1		[19, 21]
$LiBaF_3$					190, 230	1400	0.8	5.2	[10]
$BaMgF_4$					190, 220	1000		4.5	[21]
BaY_2F_8				4–7.5			0.9	5.0	[20]
K_2LiGaF_6				5–9	140–250				[21]
K_2NaAlF_6				5–9	140–250				[21]

Very fast emission < 2ns but UV emission

Crossluminescence material

Radiative transition between the core- and valence bands.

Many possible materials



BaF_2 →

Compilation of CL data at 293 K

C.W.E. Van Eijk J of lum., Vol 6061, 1994936-941

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KBr	10–13	7.4	−						
KI	9.5–14	6.0	−	STE					
RbF	0–7.5	10.3	+	3–6	203, 234	1700	1.3	3.6	[11–14, 18]
RbCl	4–9	8.2	+	5.5–7.5	190	1		2.8	[12]
RbBr	6.7–9.5	7.4	?						
RbI	5–10	6.1	?	STE					
CsF	0–4.5	9.9	+	2.5–4	390	2000	2.9	4.1	[6, 11, 14]
CsCl	1–5	8.3	+	4–5.5	240, 270	900	0.9	4.0	[6, 14, 15, 17, 18]
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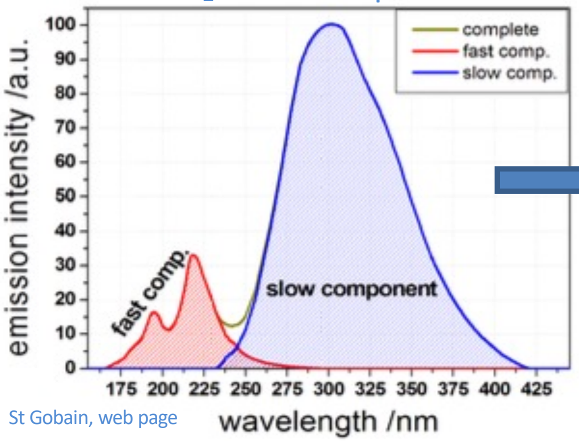
K_2NaAlF_6				5–9	140–250				[21]

Very fast emission < 2ns but UV emission

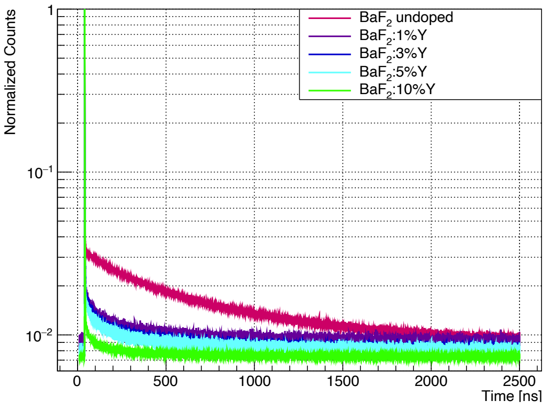
Suppression of slow component in BaF_2

BaF_2 emisison spectra

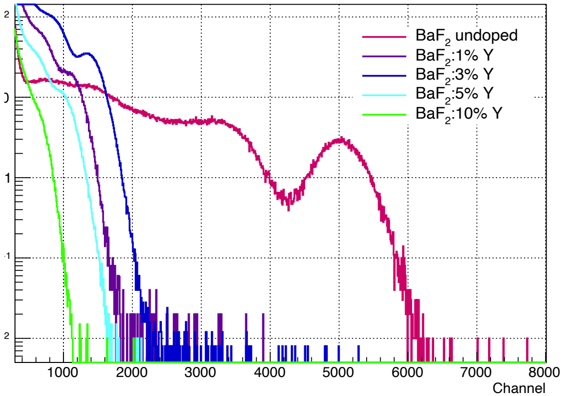


St Gobain, web page

Decay time spectra



LY spectra



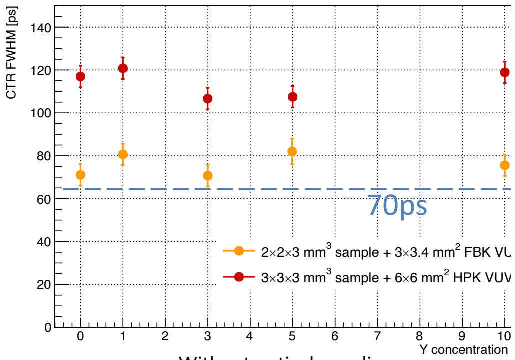
Sub ns emission but in UV & additional slow component

R&D to suppress the slow component by doping

⇒No change in short decay

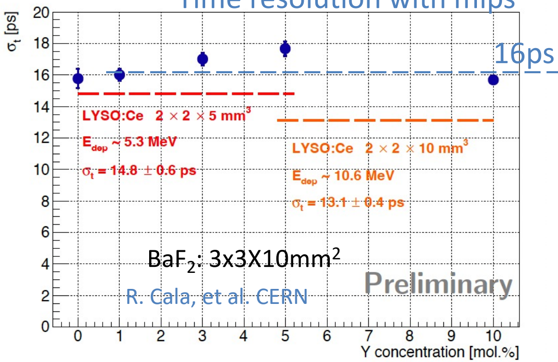
⇒No impact on CTR

CTR



Without optical coupling

Time resolution with mips

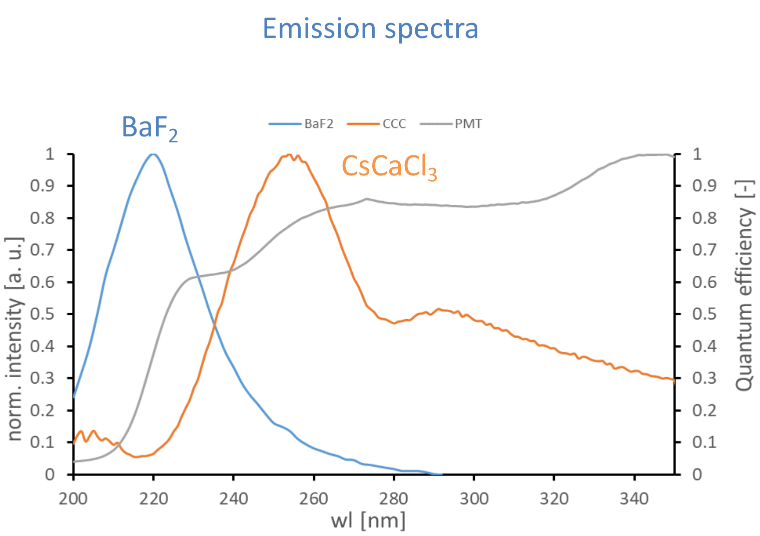


See talk R. Cala' Tuesday

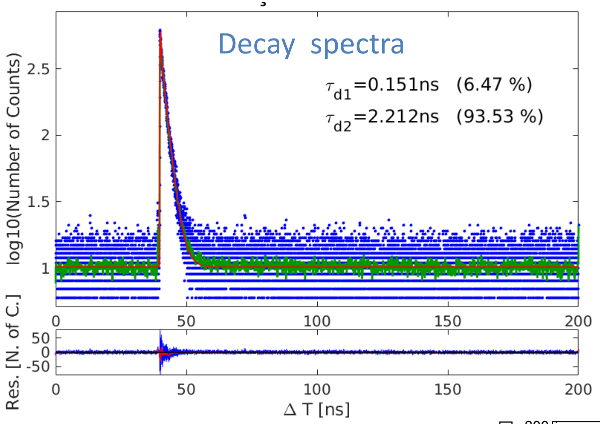
J. Chen, et al., IEEE Trans. Nucl. Sci., vol. 65, no. 8, pp. 2147-2151, 2018.

S. Gundacker et al., Phys. Med. Biol. 66 (2021) 114002

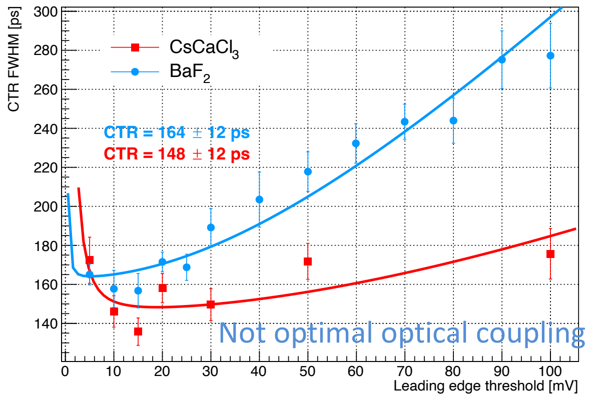
Development of cross luminescence material more in UV visible region



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



CTR



$CsCaCl_3$:2 emissions @ 260nm & 290nm

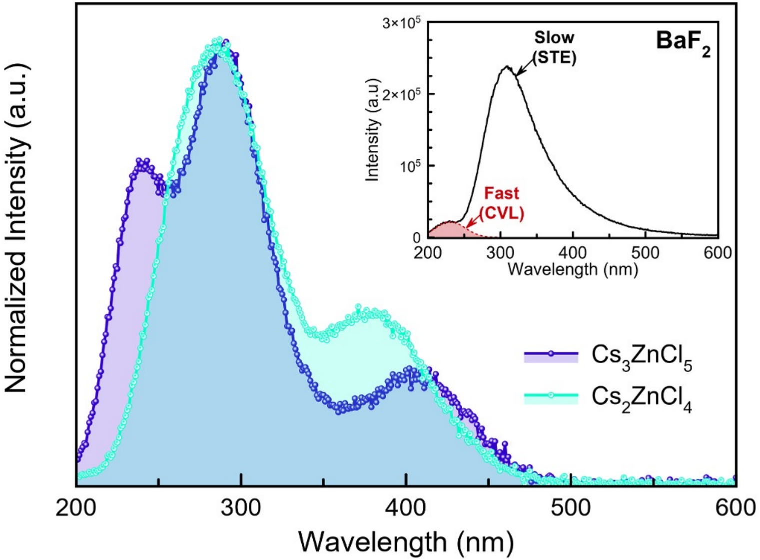
2 fast decay times: 0.15ns, 2.2ns

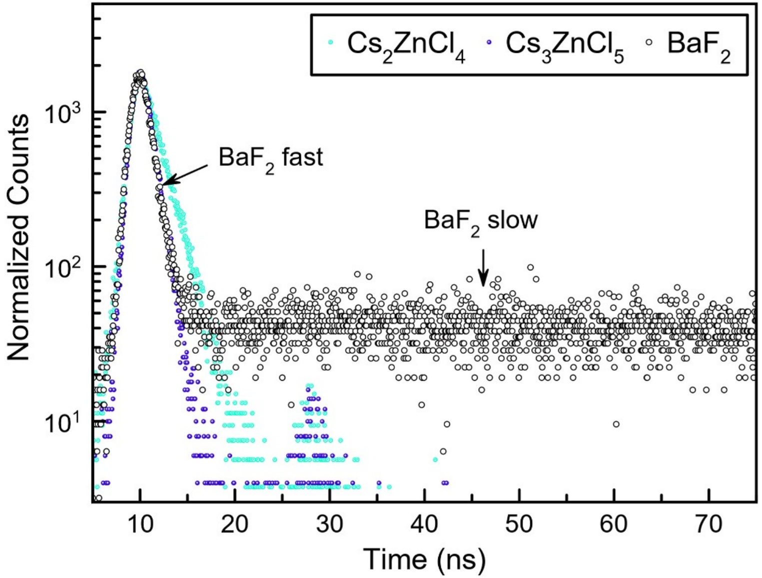
Same CTR than BaF_2

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

FZU Fyzikální ústav Akademie věd České republiky

Development of cross luminescence material more in UV visible region

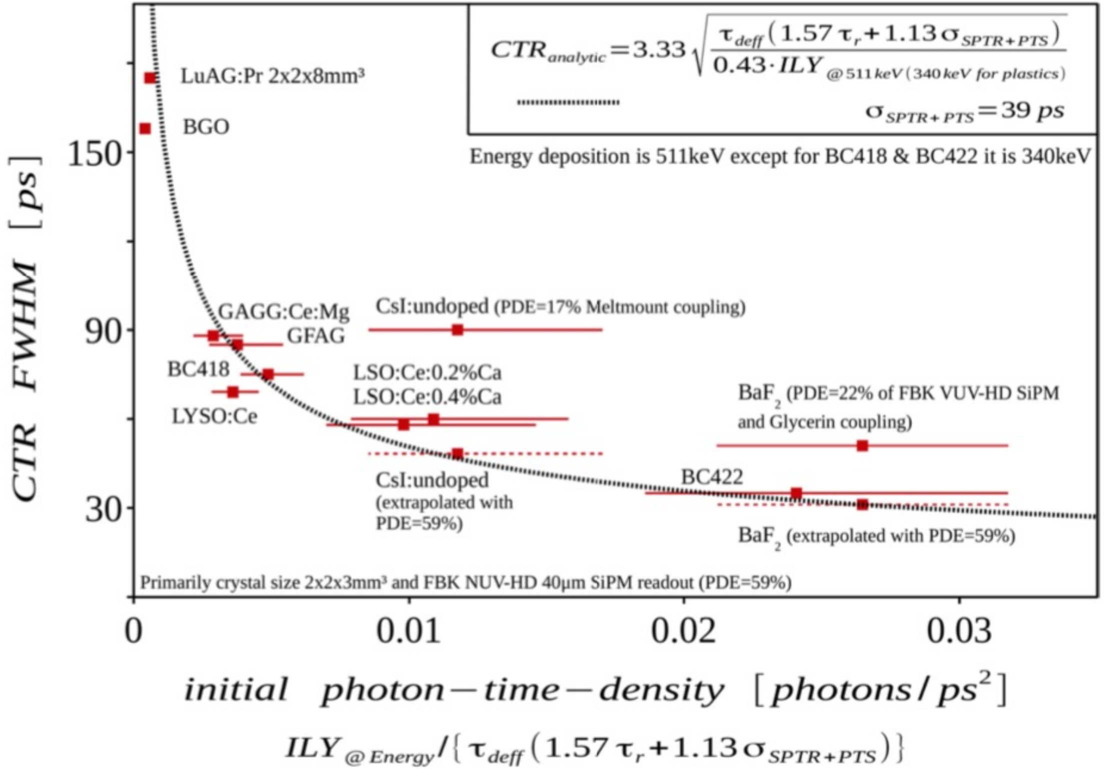




Daniel Rutstrom et al, Optical Materials 133 (2022) 112912

CTR @511 keV for several scintillators

Typical crystal size 2x2x3mm^3



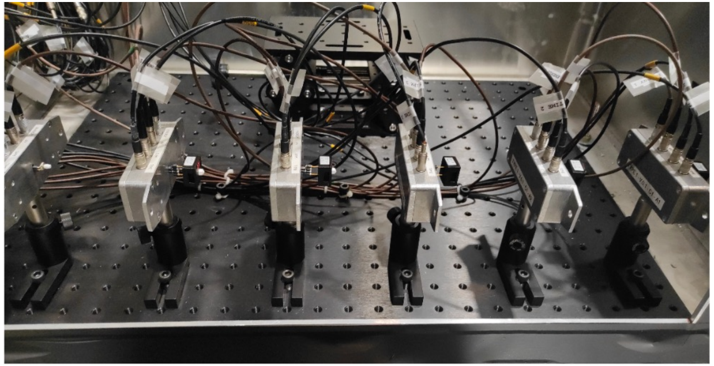
Analytic CTR expression
S. Vinogradov,
NIMA 912 (2018) 149-153

S. Gundacker et al. Phys. Med. Biol. 65 (2020) 025001

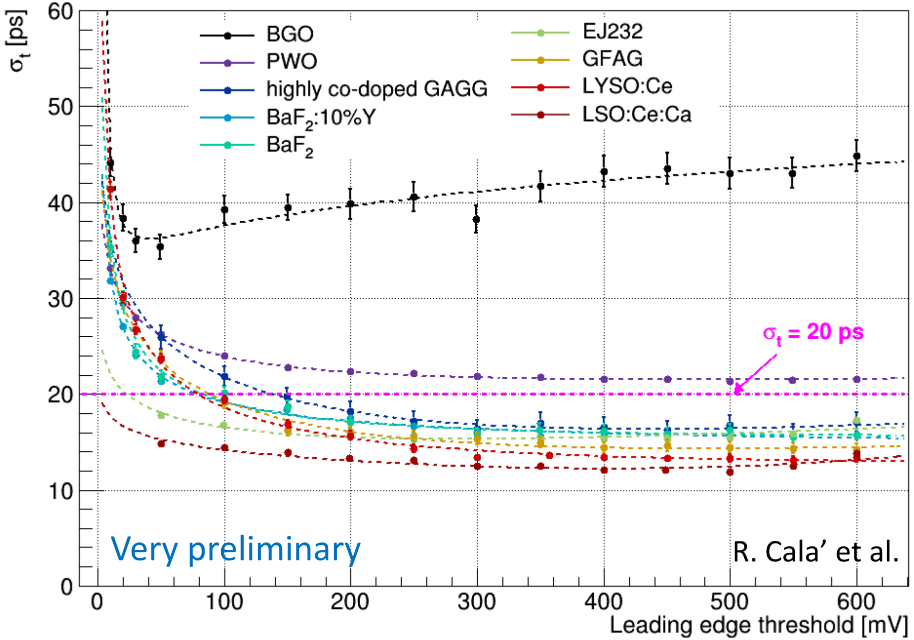
Time resolution of several scintillators under mips

Test conditions :

- Scintillator length 10mm except EJ232 (3mm)
- Crystals Teflon wrapped and Meltmount coupled to SiPM
- SiPM used HPK S13360-3050PE SiPMs (except for LSO:Ce:Ca (FBK NUV-HD)
- Readout with HF amplifier



Very promising results



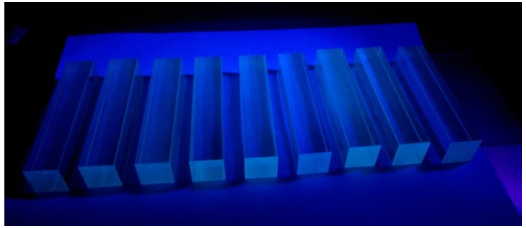
See talk R. Cala' Tuesday

Development on Scintillating Glasses

- Scintillating glasses were considered in the 90's for LHC but were not sufficiently radiation tolerant*

  *See for instance E. Auffray *et al, NIM A* **380** (1996) 524-536; P R Hobson *et al* Journal of Non-Crystalline Solids 213-214 (1997) 147-151, S F Shaukat *et al* Journal of Non-Crystalline Solids 244 (1999) 197-204, CMS note)
- 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

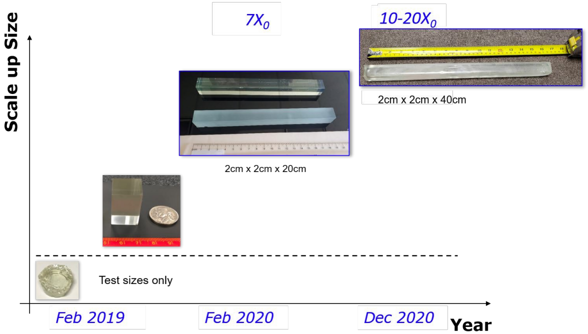


Industrial development via ScintiGlass: Attract project with Preciosa Company

ATTRACT

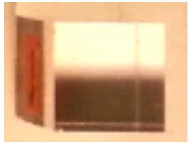
V. Dormenev et al, NIMA, 1015, 2022, 165762

EIC R&D: eRD105 (SciGlass)



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

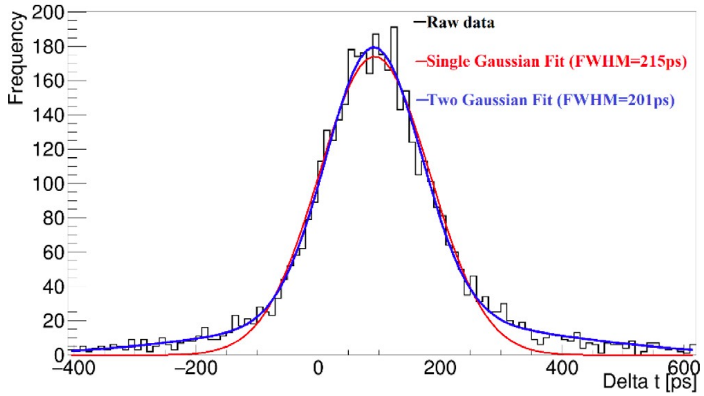
Fluorophosphate glasses From AFO company



Potential of scintillating glasses for fast timing

DSB Glasses

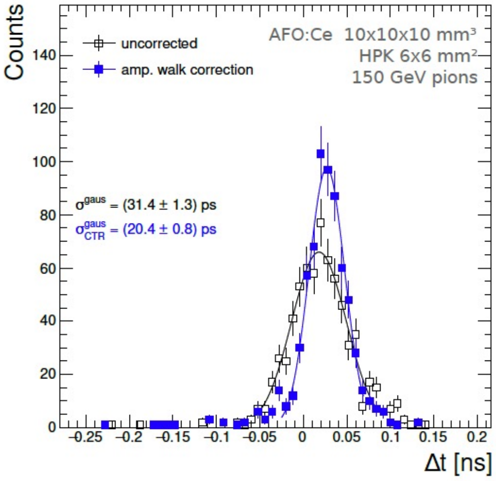
Coincidence time resolution @ 511Kev



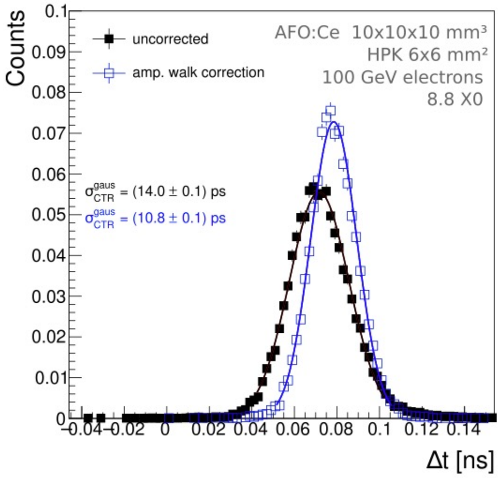
V. Dormenev et al, NIMA, 1015, 2022, 165762

AFO Glasses

Timing resolution with mip



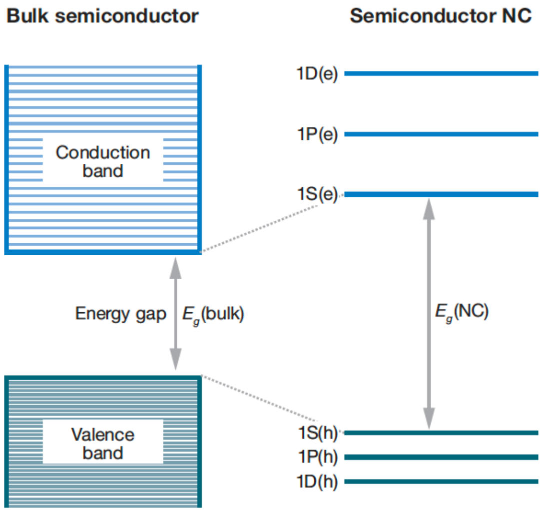
Timing resolution at shower max 100GeV electrons



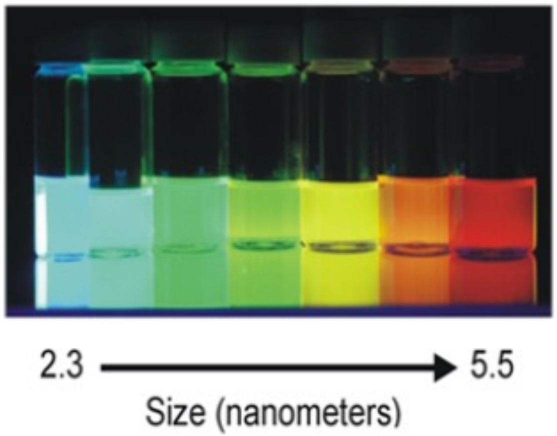
M. Lucchini et al., NIMA A 1051 (2023) 168214

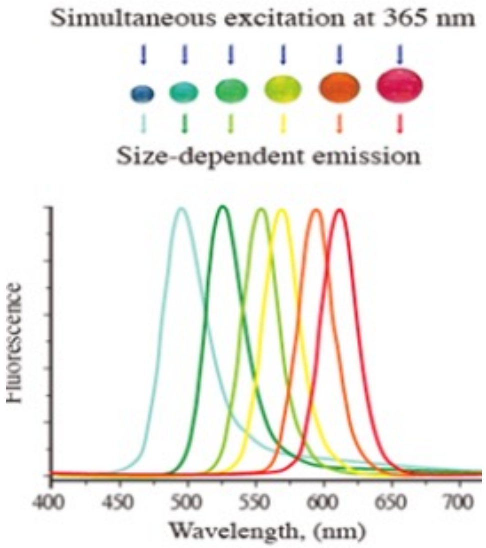
From Bulk to Nanomaterial: Quantum Confinement

Same crystal lattice but nanometer-sized crystal particle



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



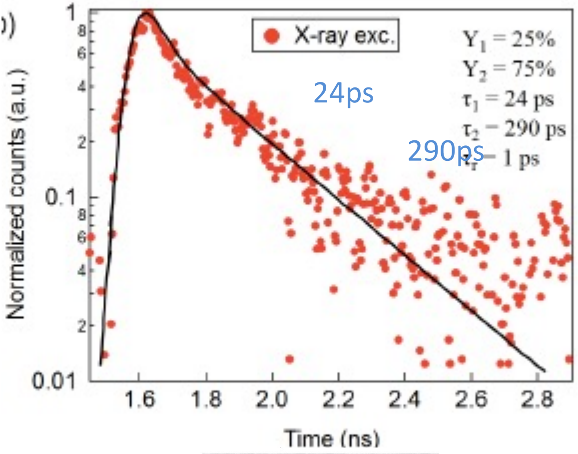


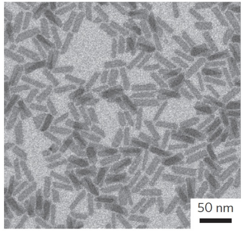
from Benoit Dubertret and Hideki Ooba

With decreasing crystal size
From “continous band” to quantized energy levels

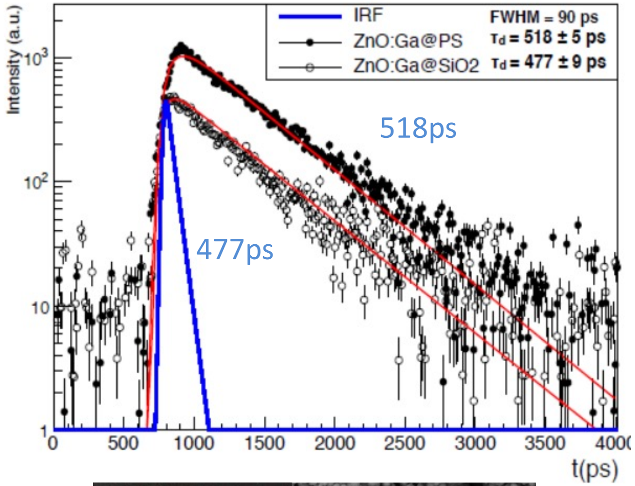
Subns emission with nanomaterials

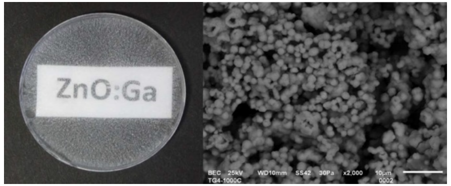
CdSe nanoplatelet,



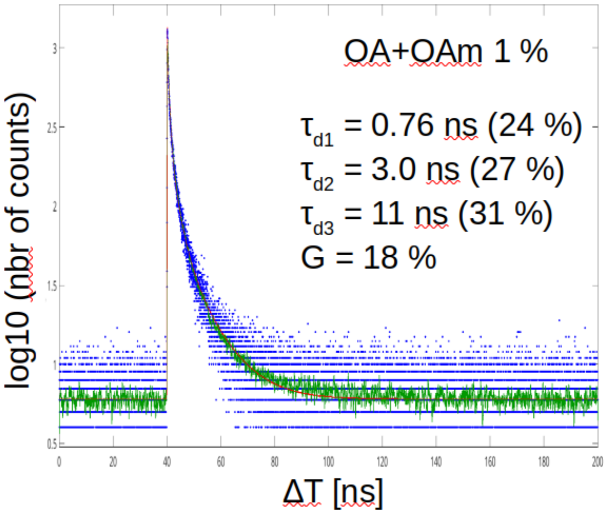


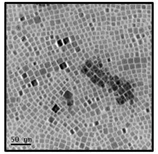
ZnO:Ga embedded in SiO_2 or polystyrene





$CsPbBr_3$ embedded in polystyrene



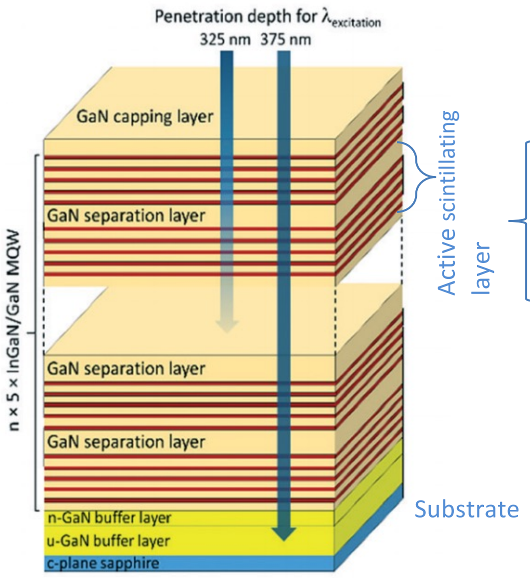


J. Grim et al., *Nature Nanotechnology*, **9**,2014, 891–895
R. Martinez Turtos et al., 2016 JINST 11 (10) P10015

Procházková et al., Radiat Meas 90, 2016, 59-63
R. Turtos Phys. Status Solidi RRL 10, No. 11, 843–847 (2016)

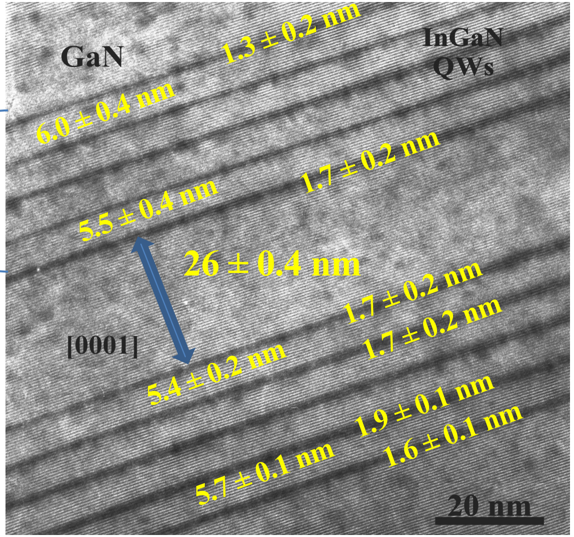
K. Děcká et al. Journal of Material Chemistry C 10(35):12,836–12,843.

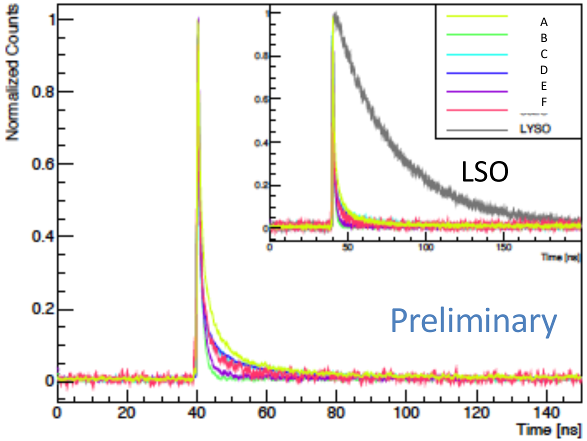
InGaN/GaN heterostructure: Multiple Quantum Wells



T. Hubacek, CrystEngComm, 2019, 21, 356

Picture from A. Hospodkova



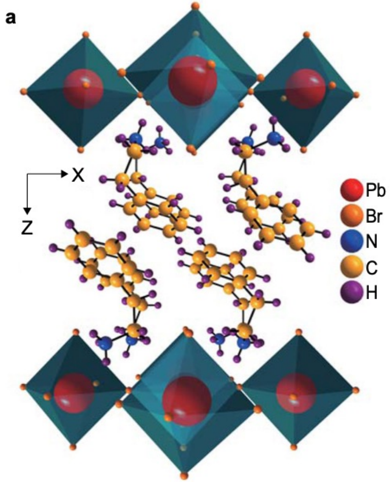


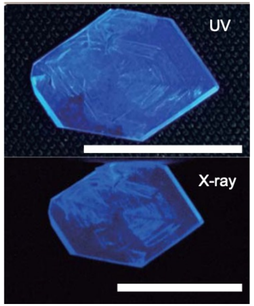
F.Pagano, et al, CERN &FZU

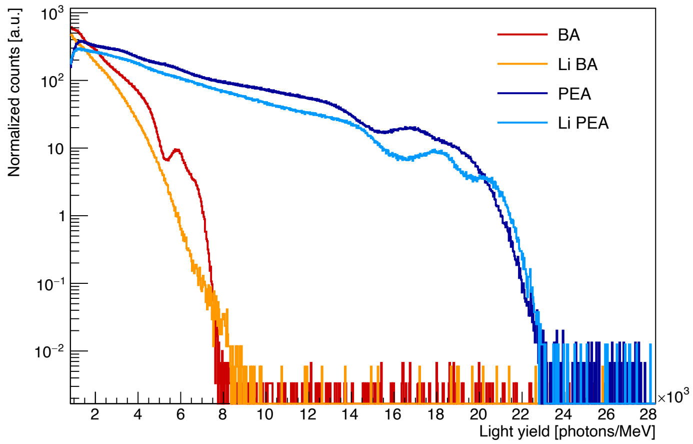
Sub-ns fast emisison

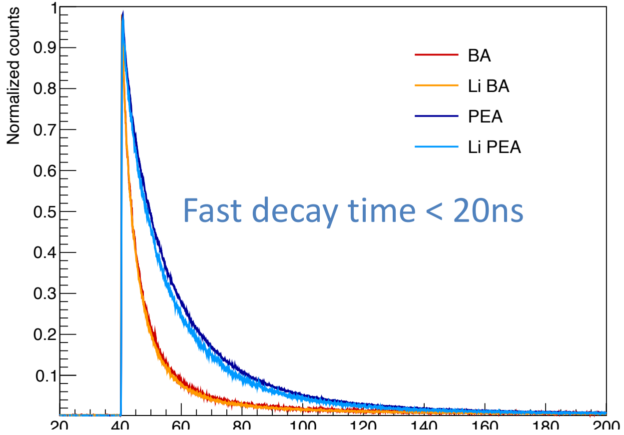
Two dimensional hybrid perovskites

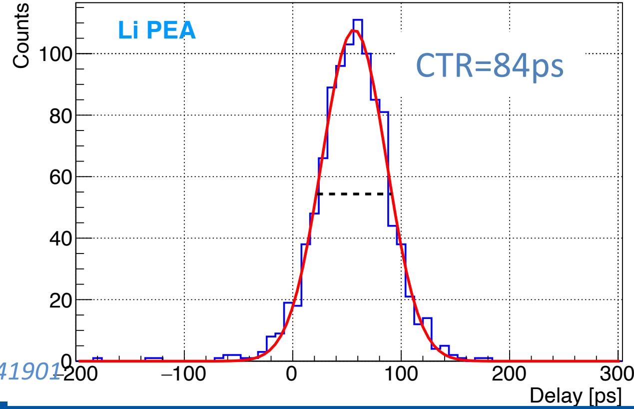
An organic-inorganic hybrid structure.









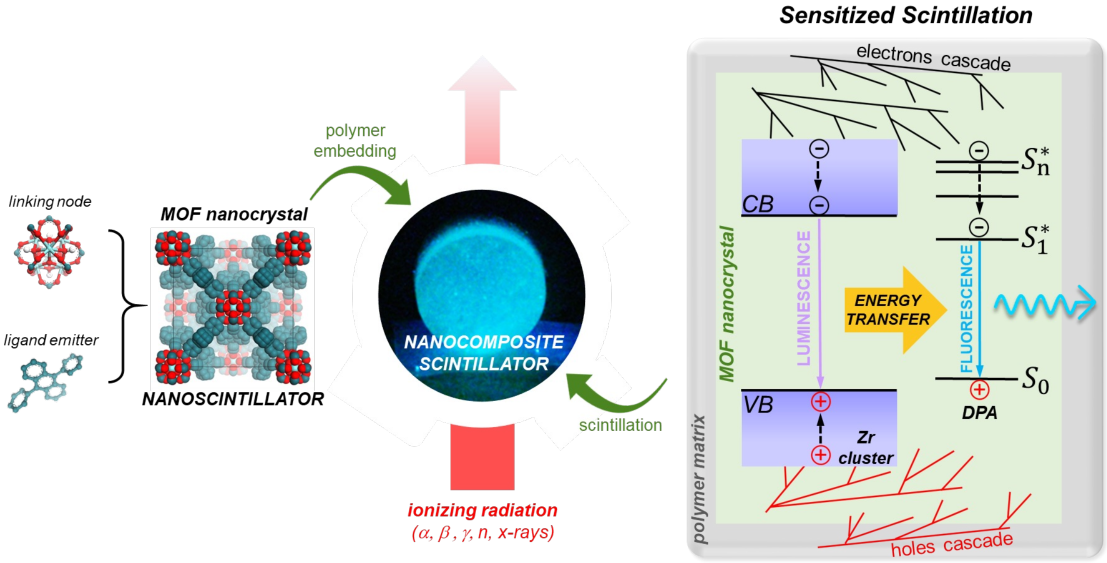


Relative high light output
20000ph/MeV for PEA type

A. Xie et al, Chem. Mater. 2020, 32, 8530–8539

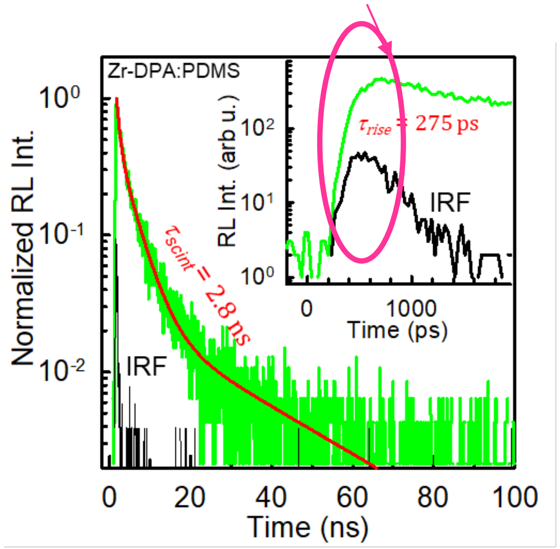
R. Cala et al, Appl. Phys. Lett. 120 (2022) 241901

Composite fast scintillators based on high-Z fluorescent metal–organic framework (MOF) nanocrystals



Rise time limited by the instrumental response function

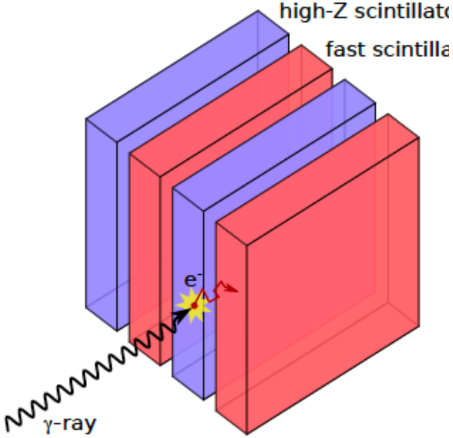
REAL τ_{rise} *<< 300 ps*

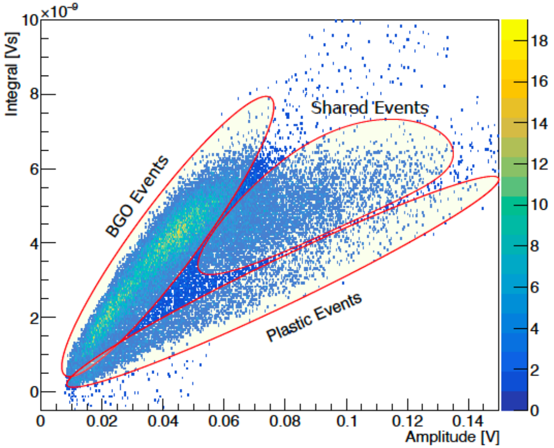


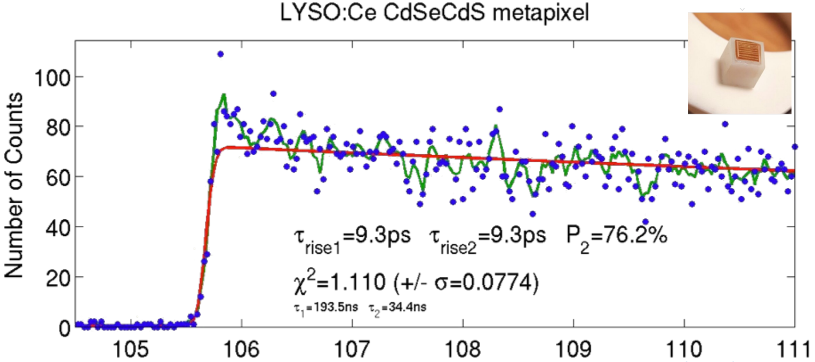
J. Perego, et al. Nat. Photonics (2021). https://doi.org/10.1038/s41566-021-00769-z

Heterostructure Concept

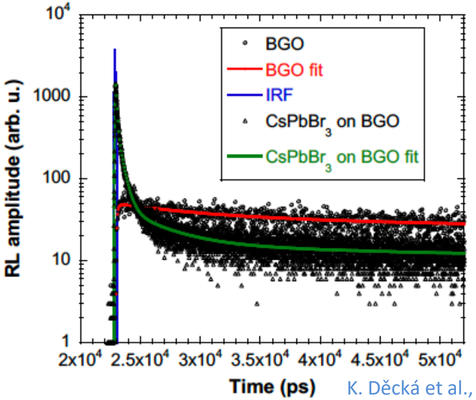
Combine scintillators with high light yield, high stopping power with prompt emission material







R. M. Turtos et al, Phys. Med. Biol. 64 (2019) 85018



BGO

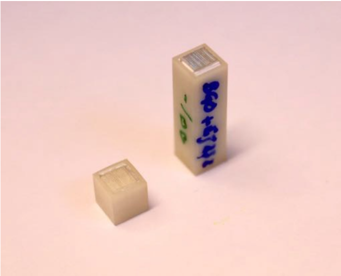
BGO+ $CsPbBr_3$

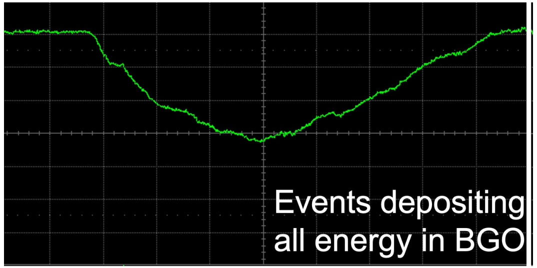
K. Děcká et al., Nanomaterials 2022, 12, 14.

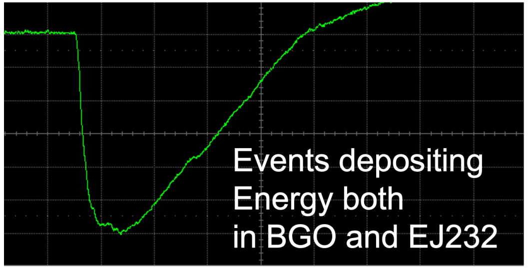
=> Energy sharing between bulk and fast emitter

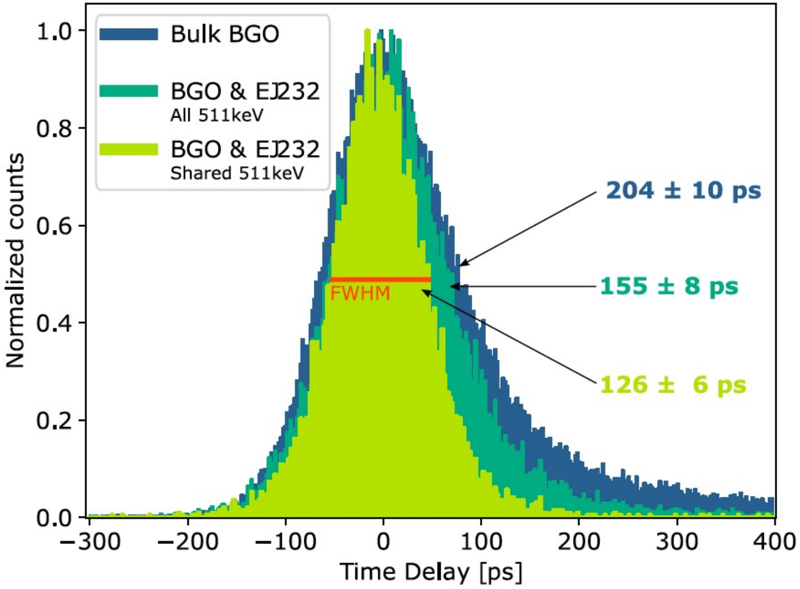
Concept proposed in the frame of ERC TICAL (GA 338953 PI: P.Lecoq)
R. M. Turtos et al, Phys. Med. Biol. 64 (2019) 85018
F. Pagano et al, 2022, 2022 Phys. Med. Biol. 67 135010

Heterostructure proof of concept with BGO and Plastic







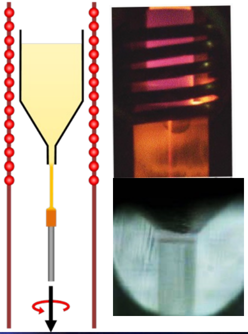


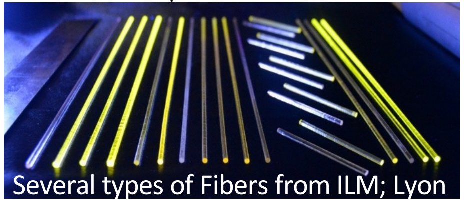
F. Pagano et al 2022 Phys. Med. Biol. 67 135010

Work supported by CERN KT medical applications budget

Future detector concept: Benefit from new developments

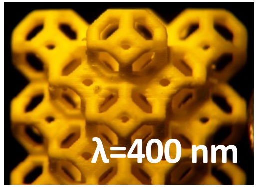
Micropulling down technique

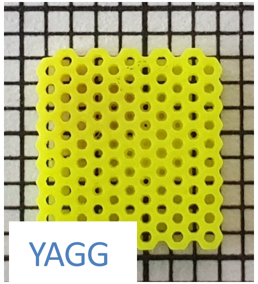




3D printing

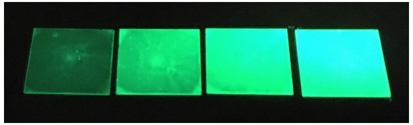
YAG





Courtesy of G. Dossovitky, Kurchatov Institute

$CsPbBr_3$ Nano crystals thin films deposited on glass substrate

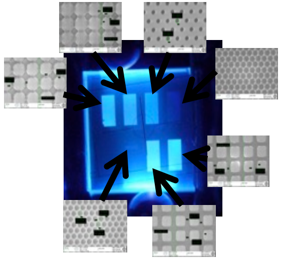


Courtesy V. Čuba, K. Děčká, CTU, Prague

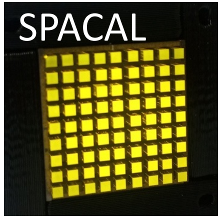
$CsPbBr_3$ Nano crystals embedded in polystyrene

K. Děčká et al., Journal of Materials Chemistry C 10(35):12,836–12,843.

Photonic Crystals



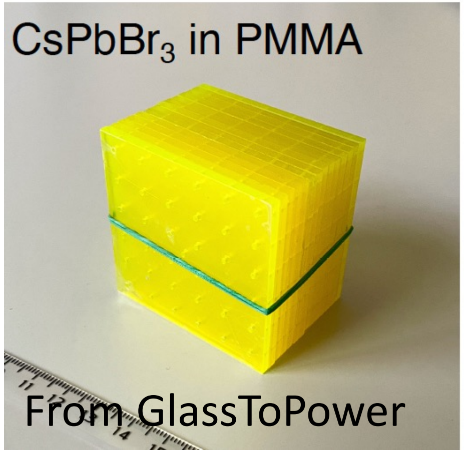
A. Knapitsch et al. IEEE TNS, VOL. 63, 2016
M. Salomini et al., Crystals 2018, 8(2), 78;

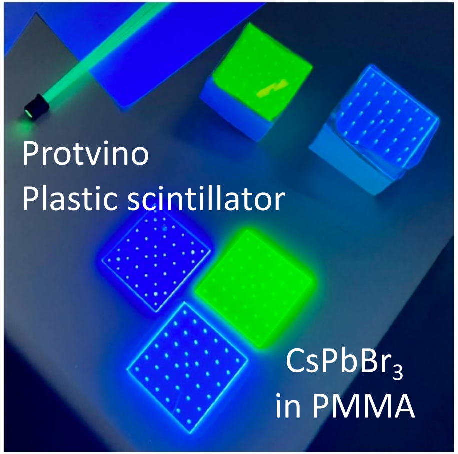


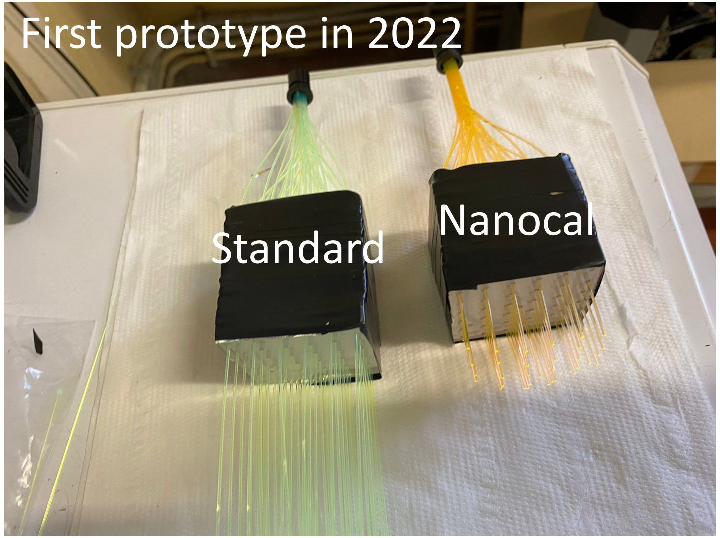
Development in CERN EP R&D

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% CsPbBr3
Kuraray Y-11(200) fibers	Kuraray O-2(100) fibers

From M. Moulson Aidainnova WP13 20.12.2022

First test beam performed in October 2022 in H2

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

Conclusion

Many approaches in the scintillation field have been explored for fast timing and need R&D to be pursued:

- Develop bright and fast scintillator:
  - Search for new material
  - Band gap engineering
- Exploit better: cross luminescence and Cherenkov emission
  - Request for better UV sensitive photodetector and optical glue
- Research of for fast nanomaterials with bright sub-ns light emission based on quantum confinement

Together with new developments in:

- Production methods
- Photonic crystals, plasmonic effect to manipulate and enhance the light output

=> Open perspectives for innovative concepts of future detectors with multi-functionalities

Acknowledgment

Many thanks to
my Crystal Clear team at CERN
my colleagues from Crystal Clear Collaboration
and all SCINT community

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