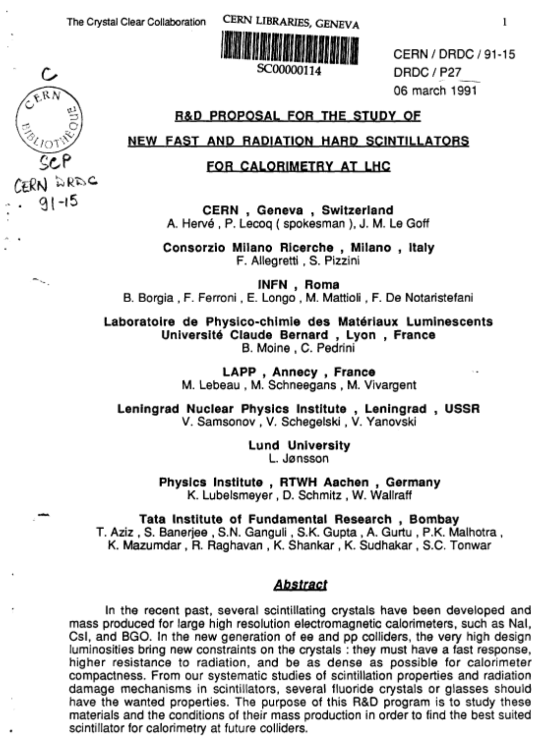
R&D ACTIVITIES ON SCINTILLATORS IN CRYSTAL CLEAR COLLABORATION (RD18)

E. Auffray, *CERN, EP-CMX*
Crystal Clear Collaboration Spokesperson

History of RD18
Crystal Clear collaboration

- Initiated @CERN in 1990 by P. Lecoq
- Approved in April 1991 by DRDC @ CERN for R&D for future LHC detectors
- **Initial Aim:** Develop scintillating materials suitable for use at the future LHC collider.



CERN / DRDC / 91-15
DRDC / P27
06 march 1991

R&D PROPOSAL FOR THE STUDY OF
NEW FAST AND RADIATION HARD SCINTILLATORS
FOR CALORIMETRY AT LHC

CERN , Geneva , Switzerland
A. Hervé , P. Lecoq (spokesman), J. M. Le Goff

Consorzio Milano Ricerche , Milano , Italy
F. Allegretti , S. Pizzini

INFN , Roma
B. Borgia , F. Ferroni , E. Longo , M. Mattioli , F. De Notaristefani

Laboratoire de Physico-chimie des Matériaux Luminescents
Université Claude Bernard , Lyon , France
B. Moine , C. Pedrini

LAPP , Annecy , France
M. Lebeau , M. Schneegans , M. Vivargent

Leningrad Nuclear Physics Institute , Leningrad , USSR
V. Samsonov , V. Schegelski , V. Yanovski

Lund University
L. Jønsson

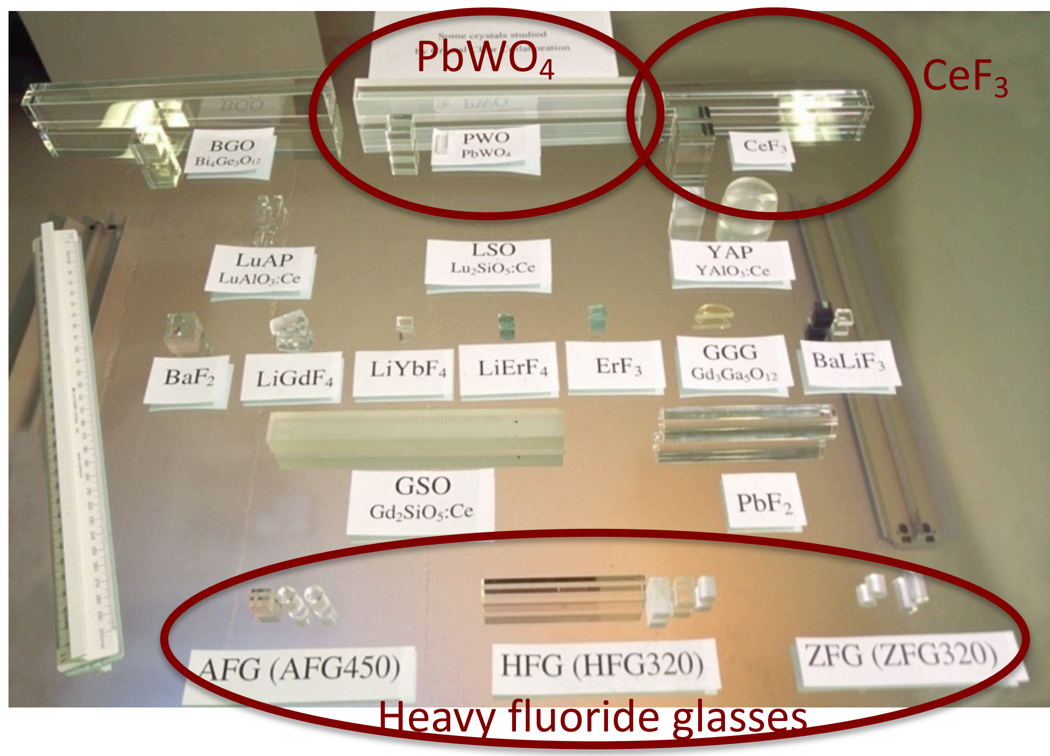
Physics Institute , RTWH Aachen , Germany
K. Lubelsmeyer , D. Schmitz , W. Wallraff

Tata Institute of Fundamental Research , Bombay
T. Aziz , S. Banerjee , S.N. Ganguli , S.K. Gupta , A. Gurtu , P.K. Malhotra ,
K. Mazumdar , R. Raghavan , K. Shankar , K. Sudhakar , S.C. Tonwar

Abstract

In the recent past, several scintillating crystals have been developed and mass produced for large high resolution electromagnetic calorimeters, such as NaI, CsI, and BGO. In the new generation of ee and pp colliders, the very high design luminosities bring new constraints on the crystals : they must have a fast response, higher resistance to radiation, and be as dense as possible for calorimeter compactness. From our systematic studies of scintillation properties and radiation damage mechanisms in scintillators, several fluoride crystals or glasses should have the wanted properties. The purpose of this R&D program is to study these materials and the conditions of their mass production in order to find the best suited scintillator for calorimetry at future colliders.

After 4 years of extensive studies of several crystals



Choice of PWO crystal

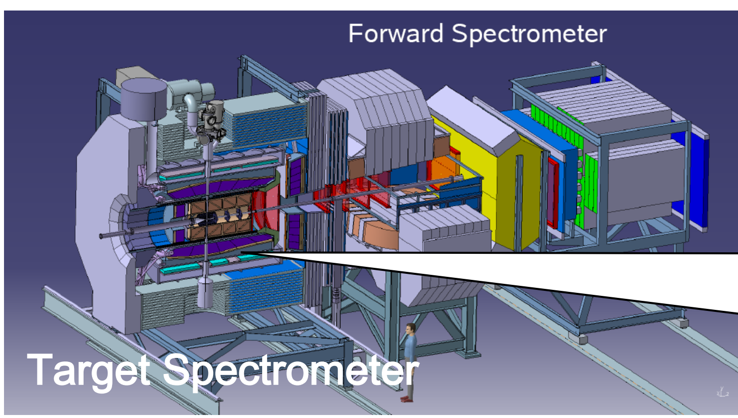
for 2 LHC experiments in 1994

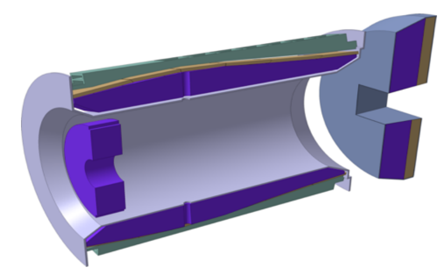
ALICE :17920 crystals (18 cm)

CMS

75848 crystals (23/22cm)

Later for Panda at Fair (GSI) :





15164 crystals (20cm)

Today: after 30 years

CCC: 31 institutes all over the world, mainly in Europe

In last years involved in many European projects:
EndoTOFPET, PICOSEC_MCNet, TICAL, AIDA2020, ASCIMAT, Intelum, FAST, ATTRACT,
Recently: AIDAnova, IPR CNRS project : ScintLab

Broad expertise

Scintillators

Crystal growth

Photo-detection

Electronics

Detector design and implementation

Today main CCC activities:

- Generic R&D on inorganic scintillators:
  - ➢ Scintillation mechanism, timing properties, radiation hardness
  - ➢ Novel crystal production technologies (eg: calorimeter concepts based on fibers)
  - ➢ Multifunctional scintillator systems
- Generic R&D activities on photo-detectors
- Several applications (focus on HEP and medical imaging)
- Bring together the scintillator community since 1992:

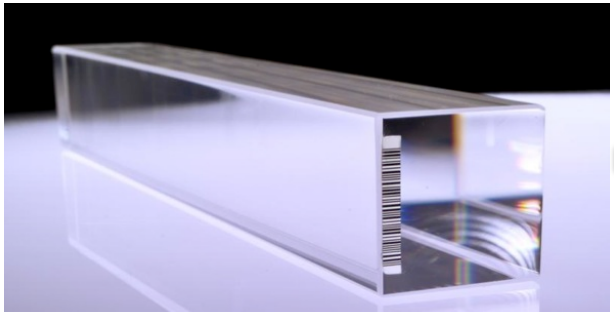
SCINT Conferences and Schools

Development of crystal fibers allows for flexibility in the calorimeter design

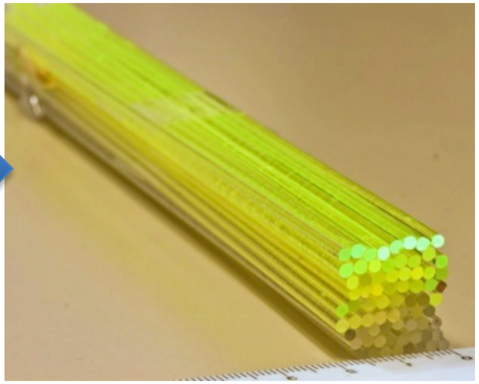
Homogeneous calorimeter

=> Requires large volume of fibers with high density

From bulk crystal



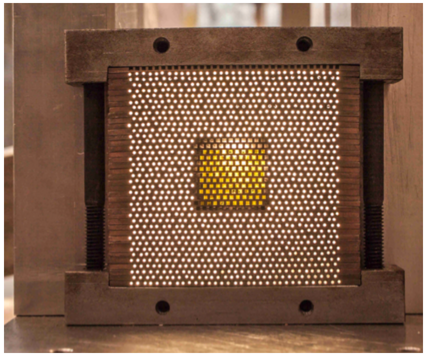
To bloc of fibers



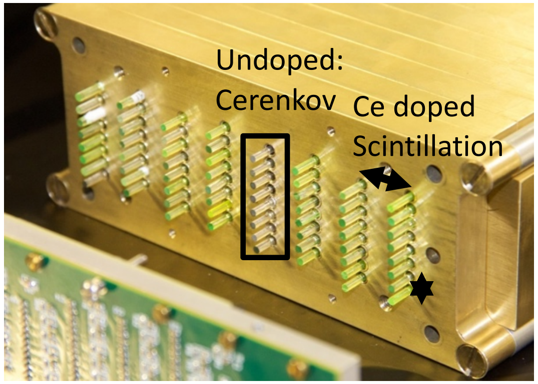
Sampling calorimeter

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

Pointing Fibers : SPACAL



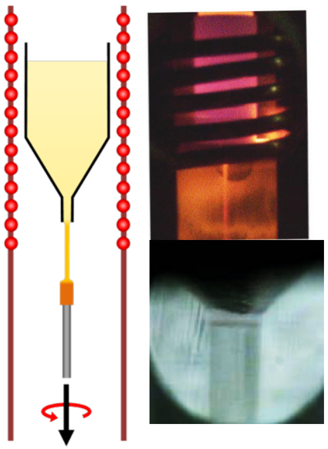
Layers of crystal fibers



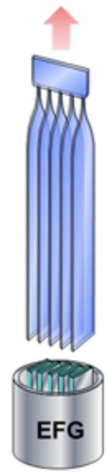
Could be multifunctional: mixed type of fibers
Cerenkov + scintillation +neutrons sensitive
Could play on sampling fraction

Crystal fiber production

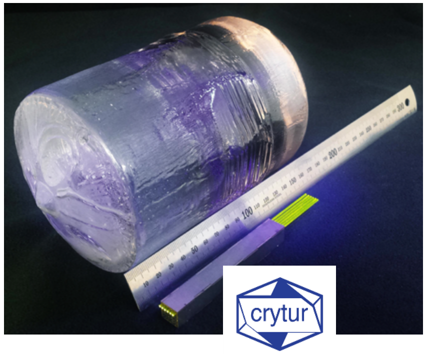
Micropulling down technique

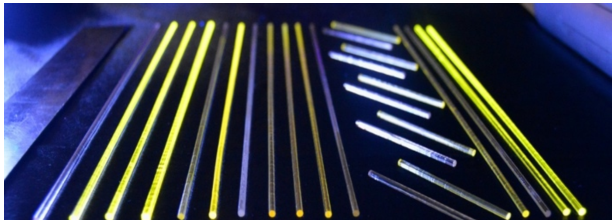


EFG

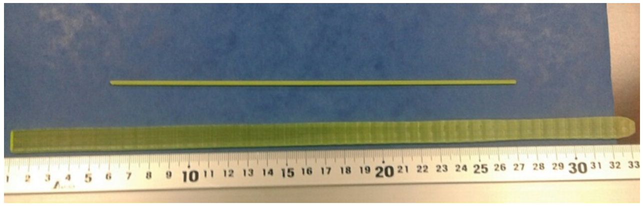


Czochralski method
Cut from large ingot

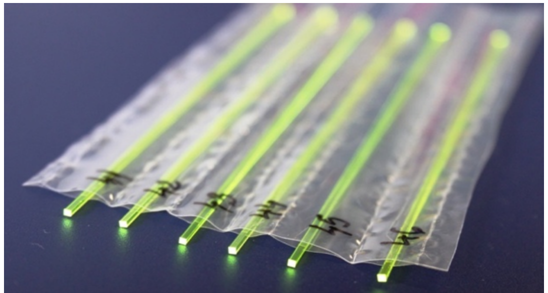




Several types of Fibers from ILM; Lyon



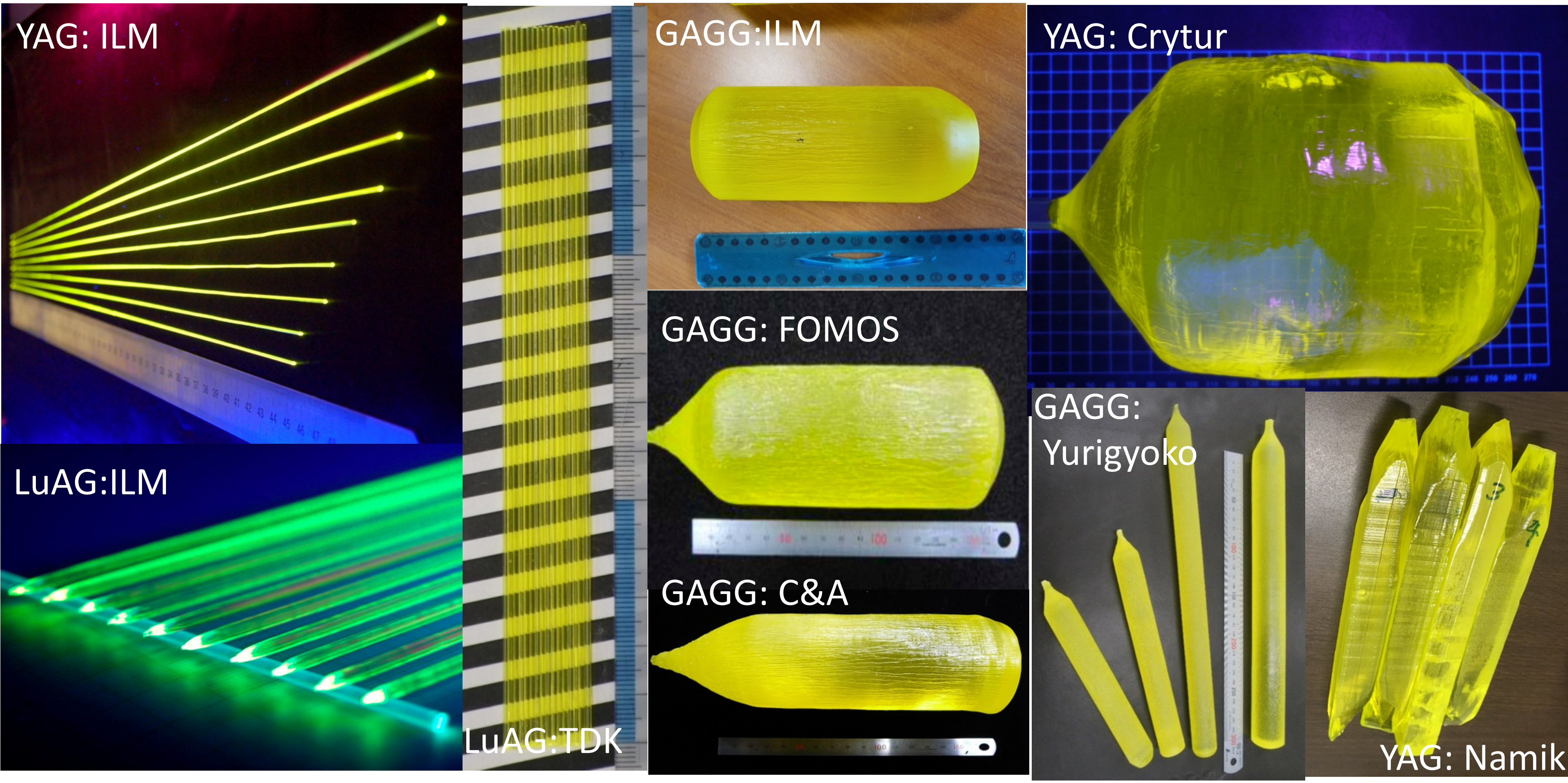
EFG-grown plate & fiber of LuAG:Ce from Adamant Namiki Co , Japan



Square fibers 1x1x10mm^3

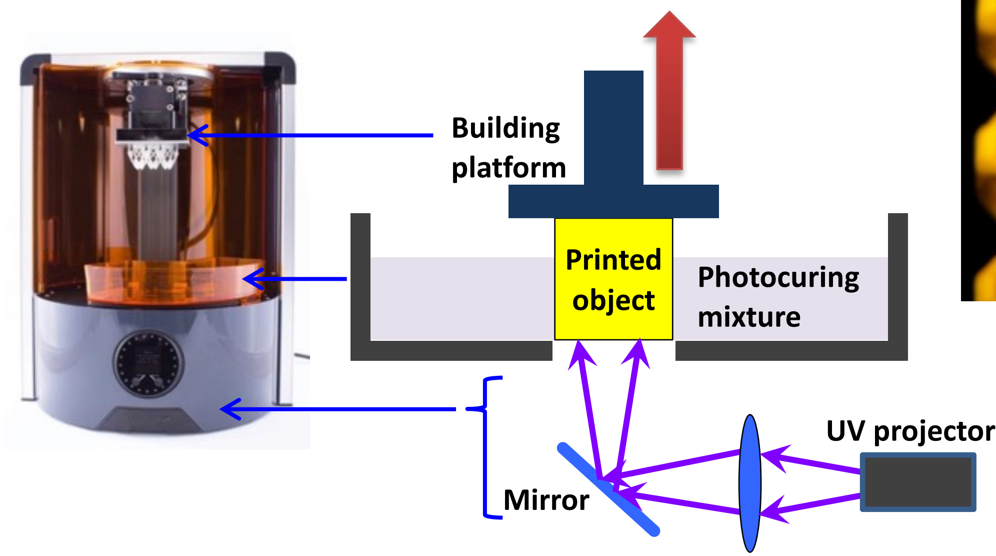
⇒ Feasibility study: in an ANR project INFHINI (ILM Lyon, CERN) and Intelum project (European Rise grant 644260) with 16 Partners (many from CCC) from 12 different countries: 11 academia and 5 companies

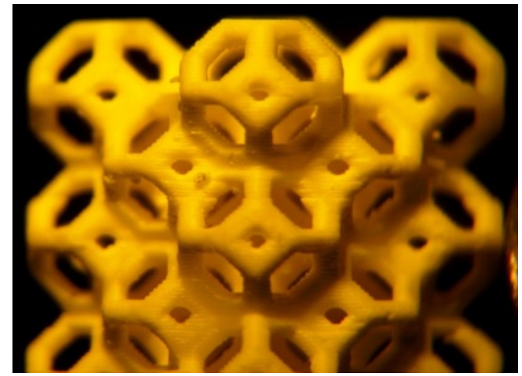
Garnet production

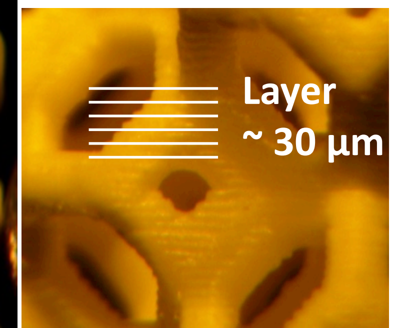


New production method: 3D printing

A way to design detector with unconventional shape

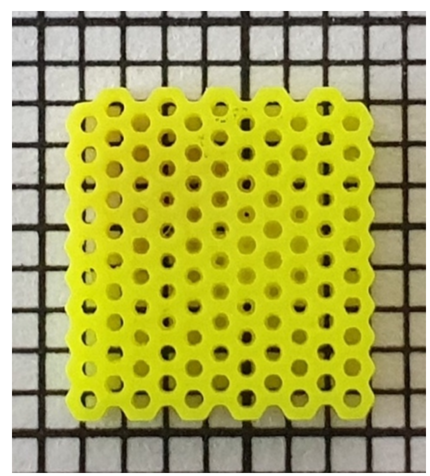






YAG

Printing is done layer-by-layer
Voxel size is ~50 x 50 x 10-50 µm



YAGG

Hole ⌀<400 µm

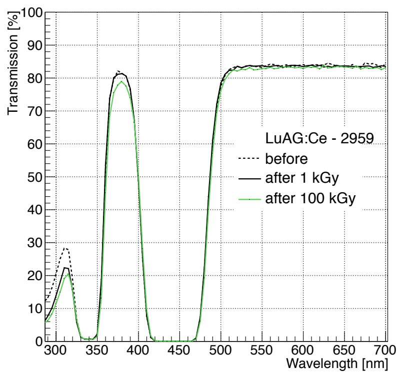
Courtesy of G. Dossovitky, Kurchatov Institute

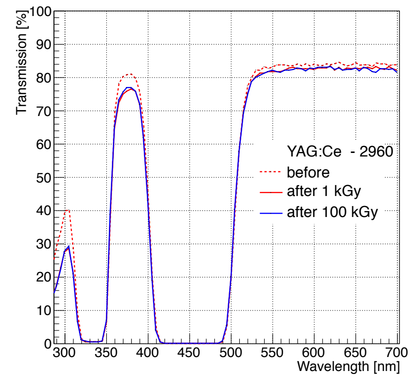
Radiation hardness of garnet scintillators

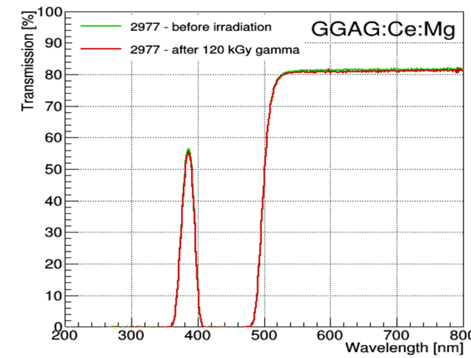
Very Good radiation tolerance under gamma & proton radiations

LuAG | YAG | GAGG

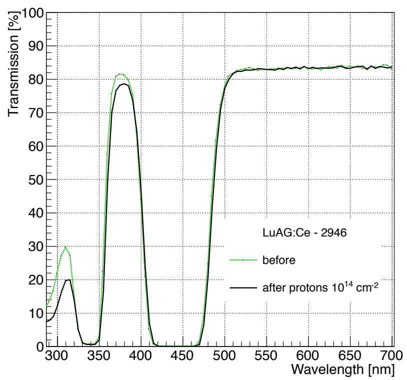
Gamma

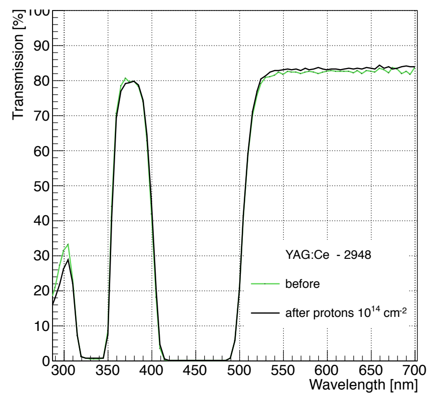


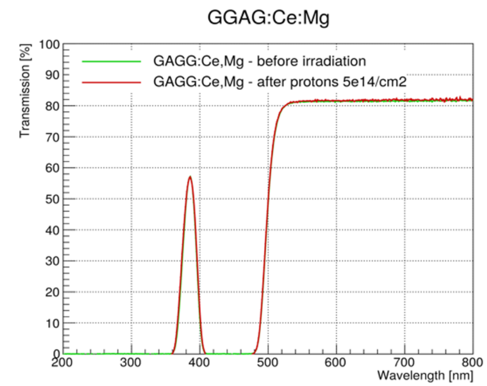




protons



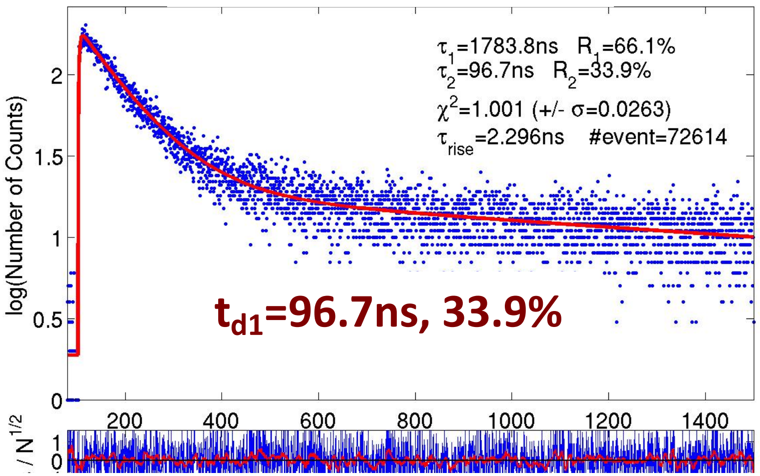




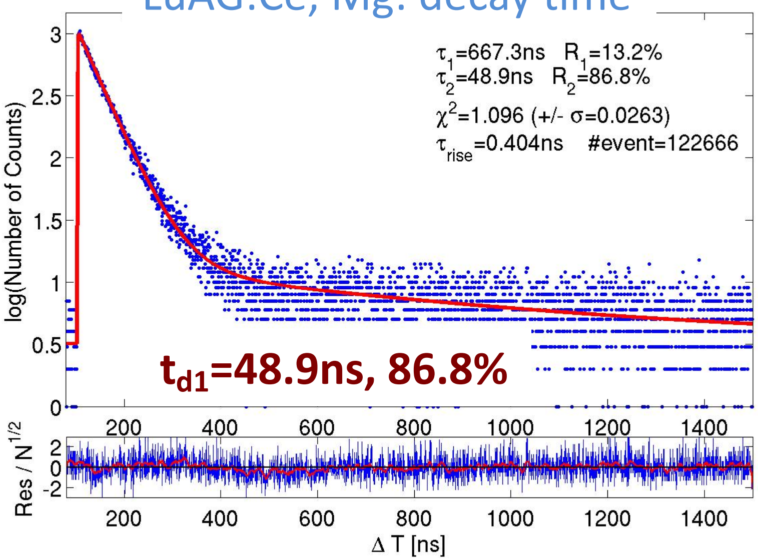
M. T. Lucchini, et al.,, IEEE Transactions on Nuclear Science (2016), 63, 2
E. Auffray, et al, Rad. Phys.Chem. (2019), 164, 108365
V. Alenkov, et a., NIM A (2019), 916, 418 226{229

Improvement of timing properties in garnet crystals

LuAG:Ce: decay time



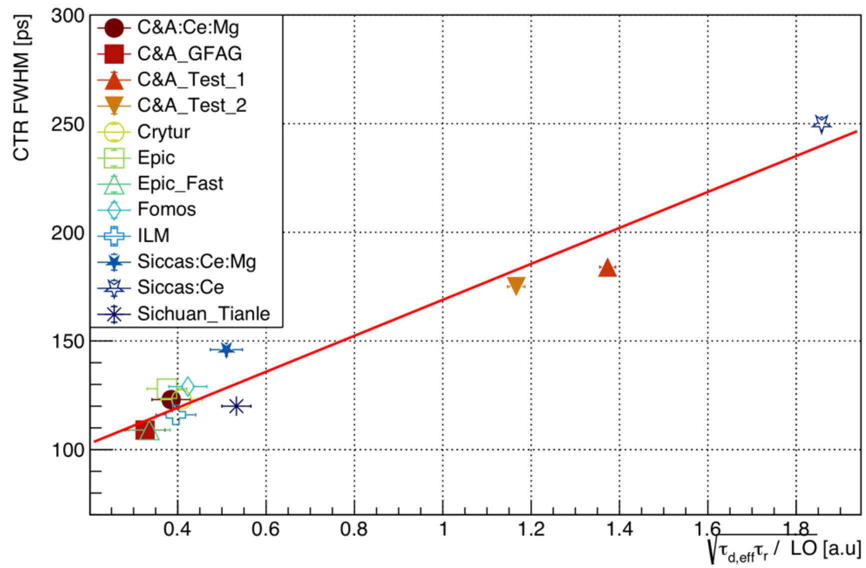
LuAG:Ce, Mg: decay time



S. Gundacker et al., *Phys*. Med. Biol. 61 (2016) 2802–2837

S. Gundacker et al, NIMA A 891 (2018) 42–52

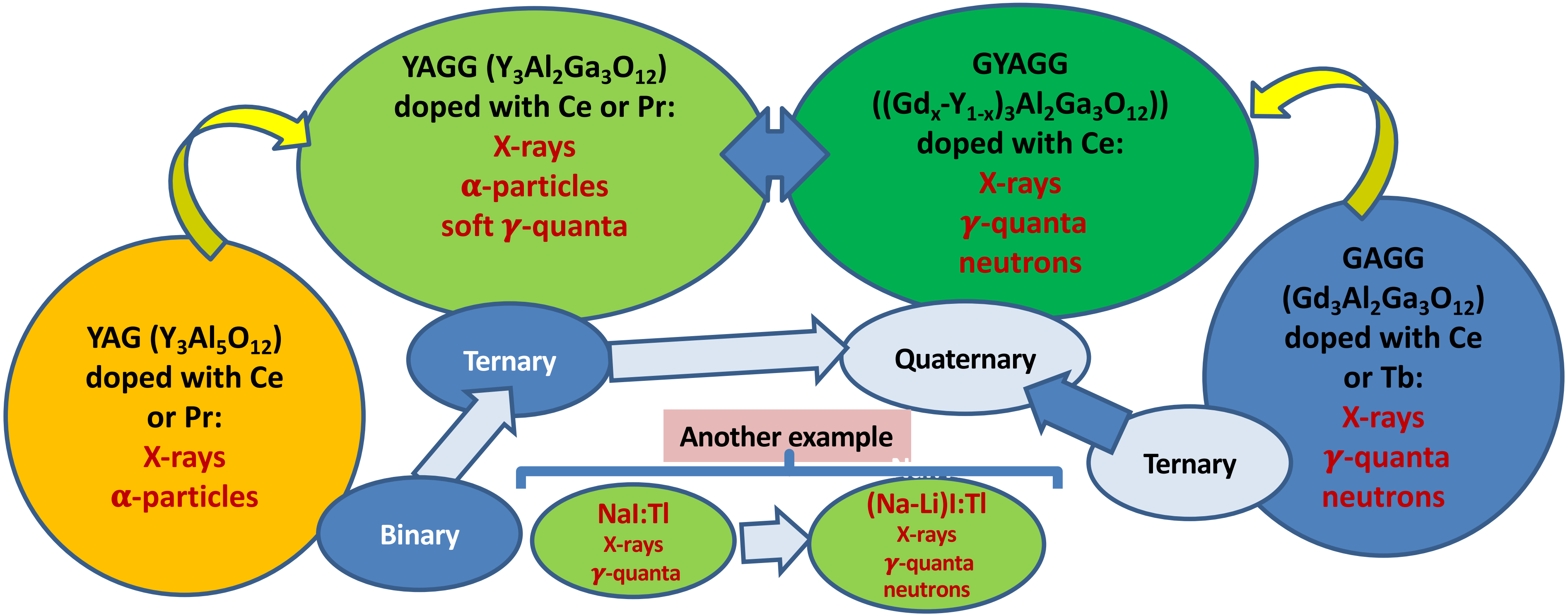
Time resolution @ 511 KeV versus photon density of various GAGG samples from various producers



M. Lucchini et al, NIM A Volume 816 (2016), pp 176–183,
L. Martinazzoli et al., NIM A, *Volume 1000, (2021), 165231*

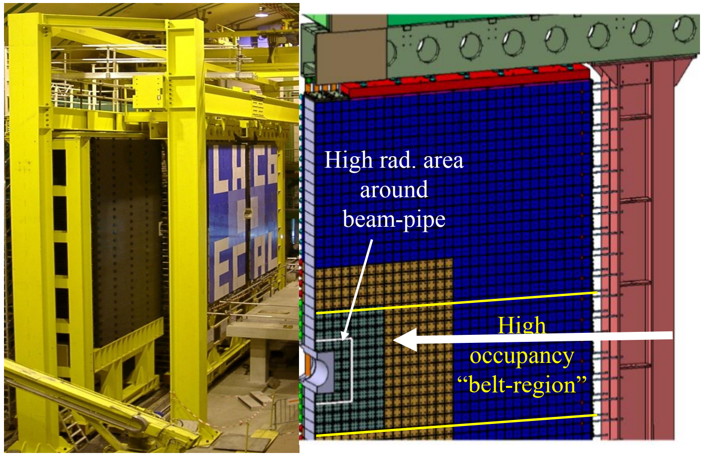
Concept of multipurpose scintillation materials

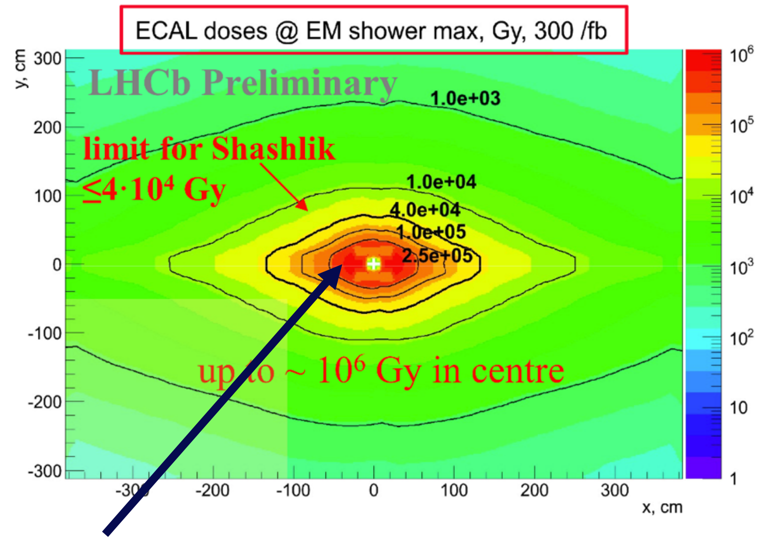
Possibility with garnet material to modify crystal composition
=> the detection of different kinds of the ionizing radiation



Courtesy M. Korzhik, RINP,

Potential use of Crystal fibers for LHCb upgrade phase II

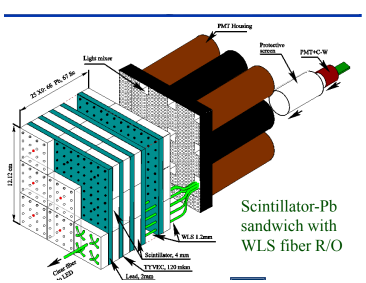


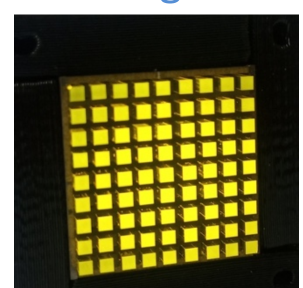


Shashlik ("skewer") technology:

- 4mm thick plastic scintillating tiles (white)
- 2mm thick Pb tiles (blue)
- WLS bers running through the tiles

High radiation level in central Part
Need to replace shashlik in central part by a radiation hard and dense material
=> Crystals.
=>R&D on SPACAL design with garnet fibers





See for instance L. Martinazolli, IEEE NS (2020), 67, 6, 1003-1008, doi:432 10.1109/TNS.2020.2975570
M. Pizzichemi, CHEF 2019. https://indico.cern.ch/event/818783/contributions/3598444/attachments/1950327/3237342/CHEF2019_Spacal_RD.pdf

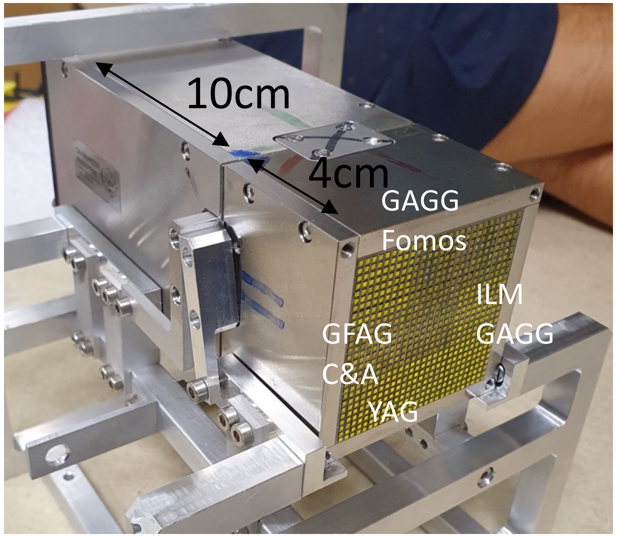
SPACAL R&D with garnet fibers & Tungsten

In frame of EP-RD WG3 calorimetry and in collaboration with LHCb:

Aim:

- Sustain radiation doses of up to ~1MGy & ≤$6 \cdot 10^{15}$cm^{-2} for 1MeV neq/cm^2 at 300 fb^{-1}
- Increase granularity
- Energy resolution of order $\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\%$
- Very fast timing component of few $\vartheta(10)$ ps for pile-up mitigation

SPACAL Prototype with various garnet fibers
tested in DESY Nov20220

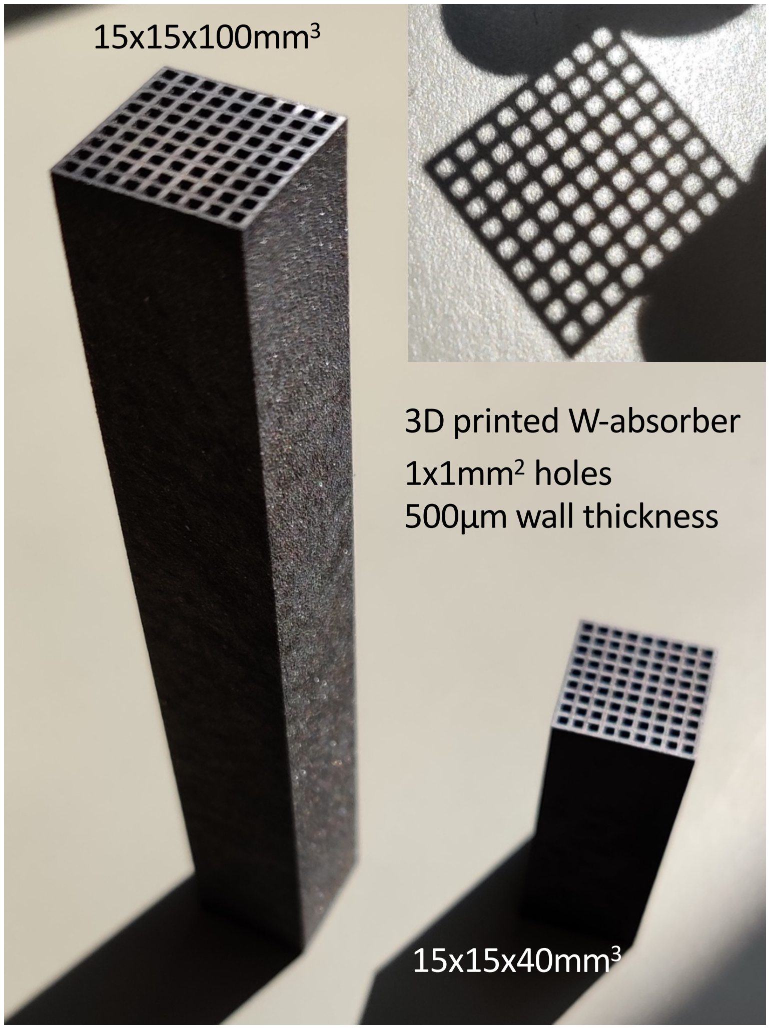


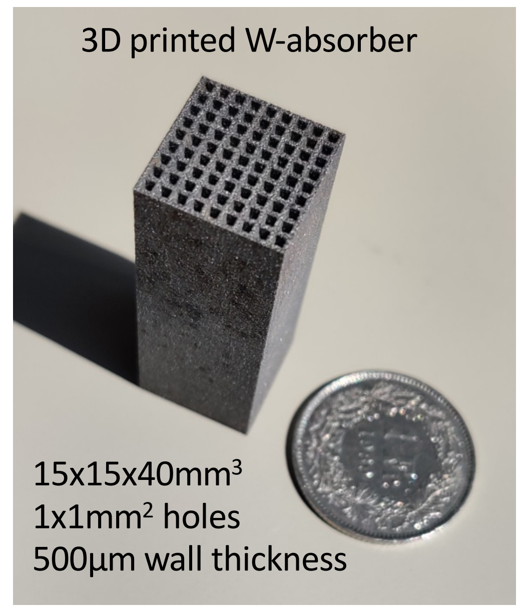
9-cells of 1.5x1.5cm^2 with
GAGG an YAG fibers in W-absorber

Analysis on going: preliminary results very encouraging

Development of 3D printing W

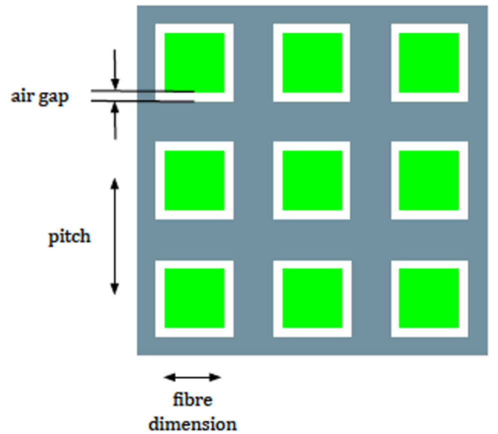
3d printing W absorber developed for SPACAL R&D in frame of EP R&D and LHCb



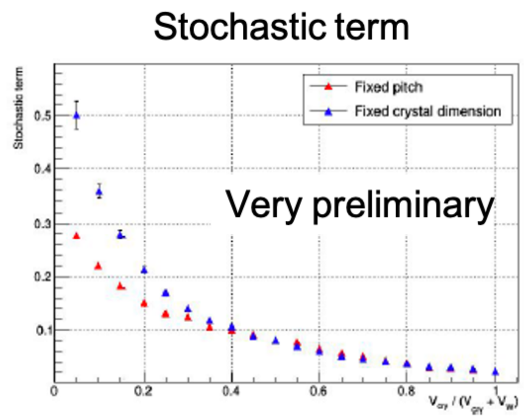


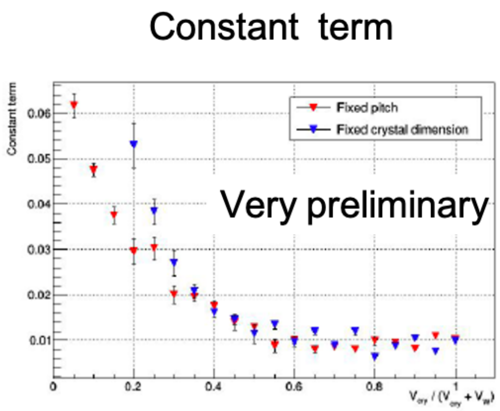
Flexibility of SPACAL geometry

Study with:
Pitch fixed at 1.67 mm, crystal dimension variable;
Pitch variable, crystal dimension fixed at 1.00 mm.



GAGG fibers/W absorber

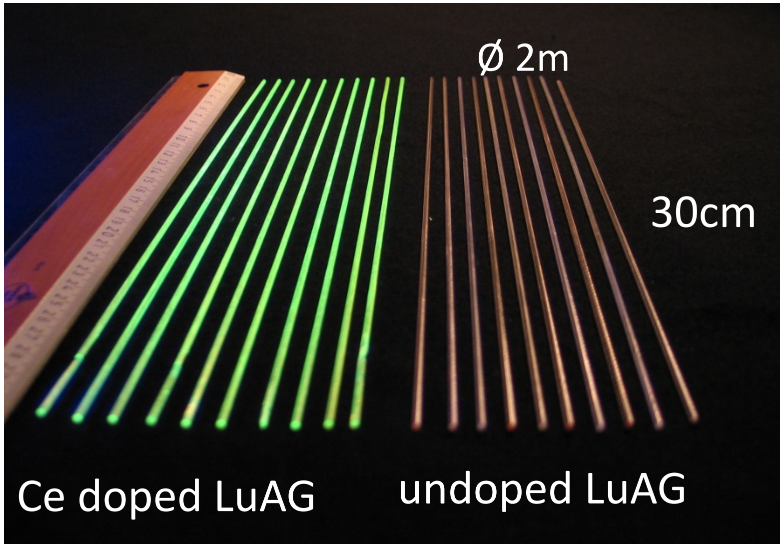




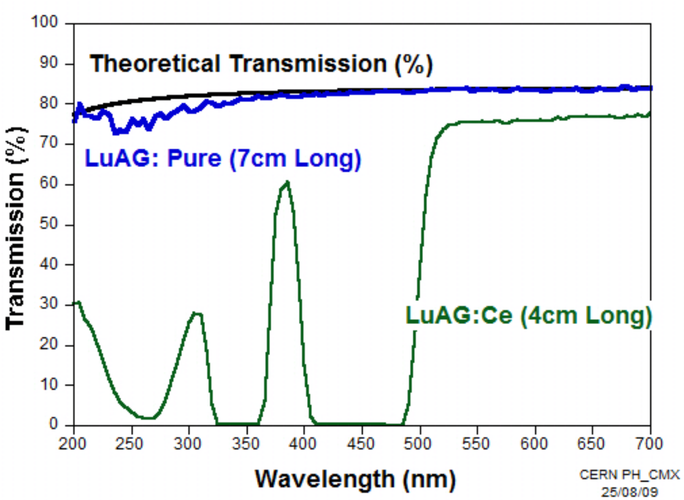
R. Cala, M. Pizzichemi, E. Auffray preliminary results

Optimisation of sampling fraction => optimisation of energy resolution

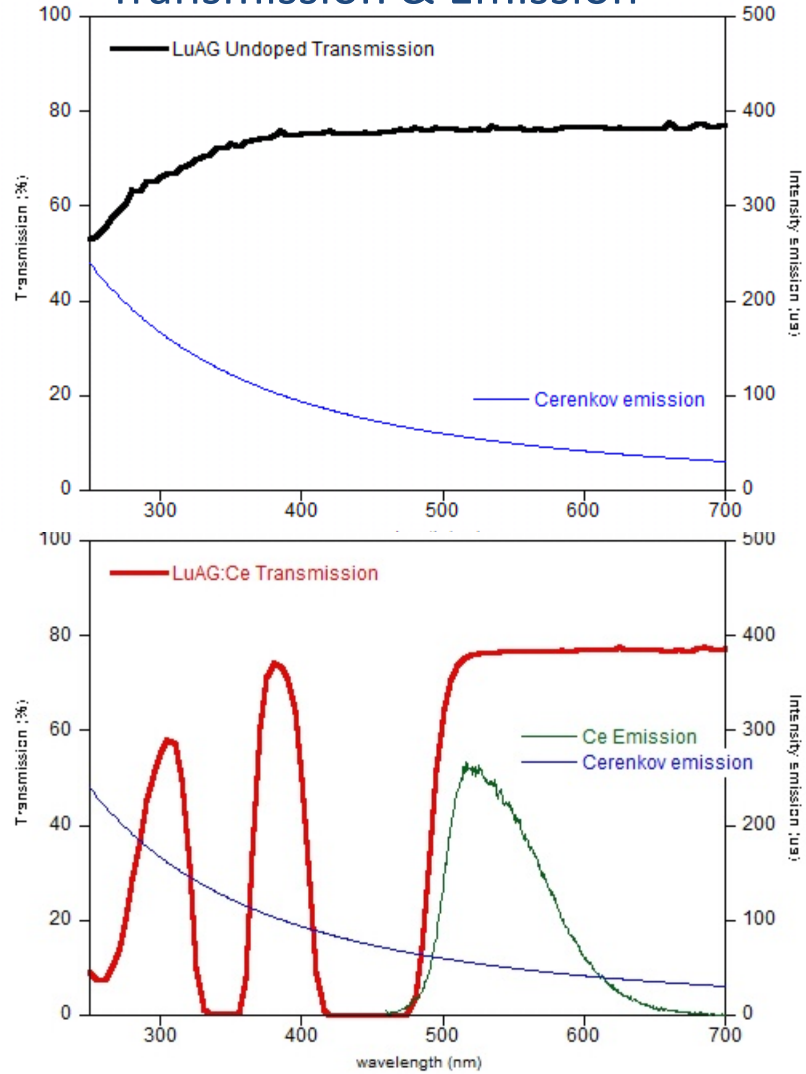
Dual readout with crystal fibers



Fibercryst (spin of from ILM), France

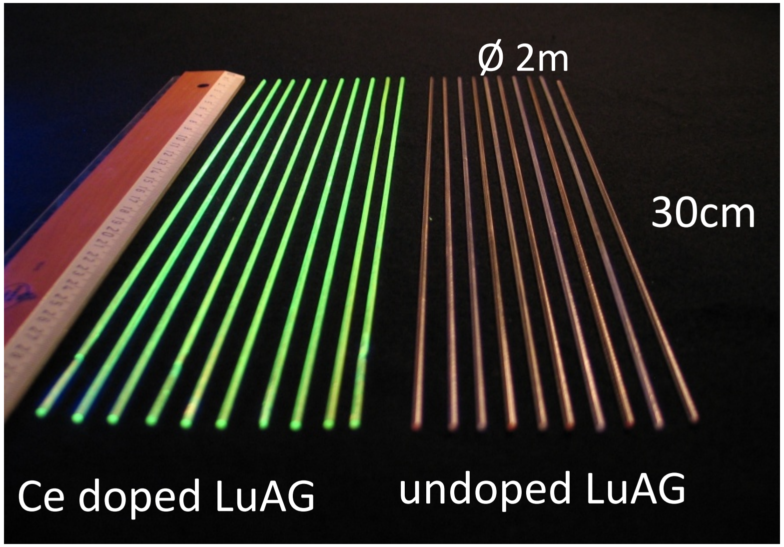


Transmission & Emission

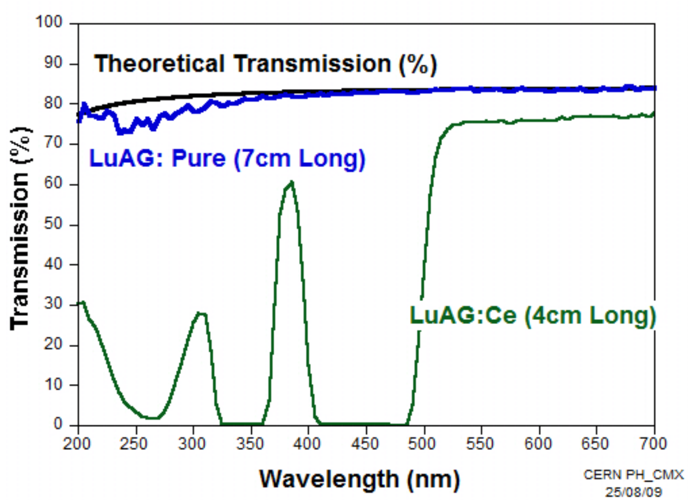


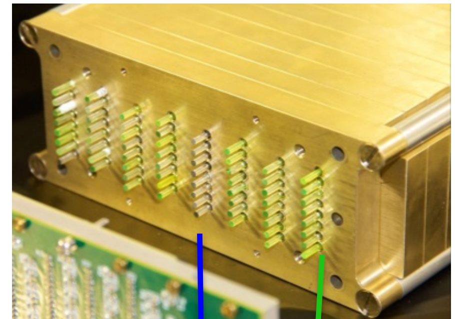
Measured on sample of 2x2x8mm from A. Petrosyan

Dual readout with crystal fibers



Fibercryst (spin of from ILM), France

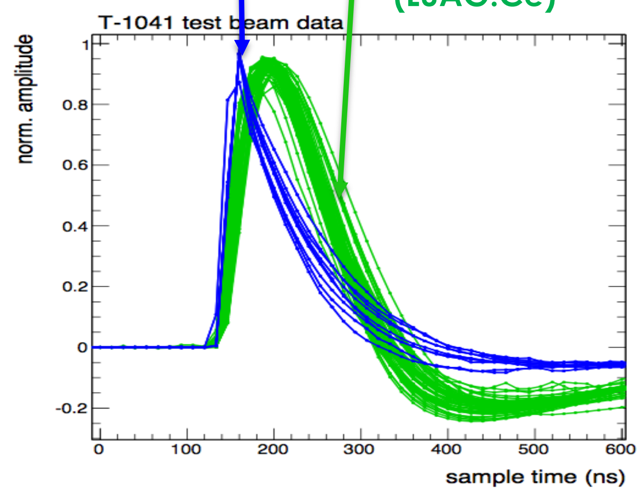




Beam

Cerenkov (LuAG)

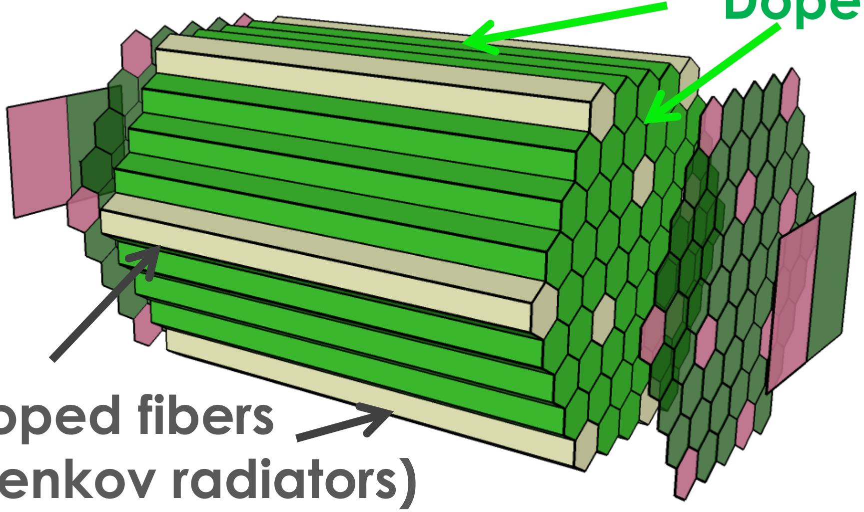
Scintillation (LuAG:Ce)

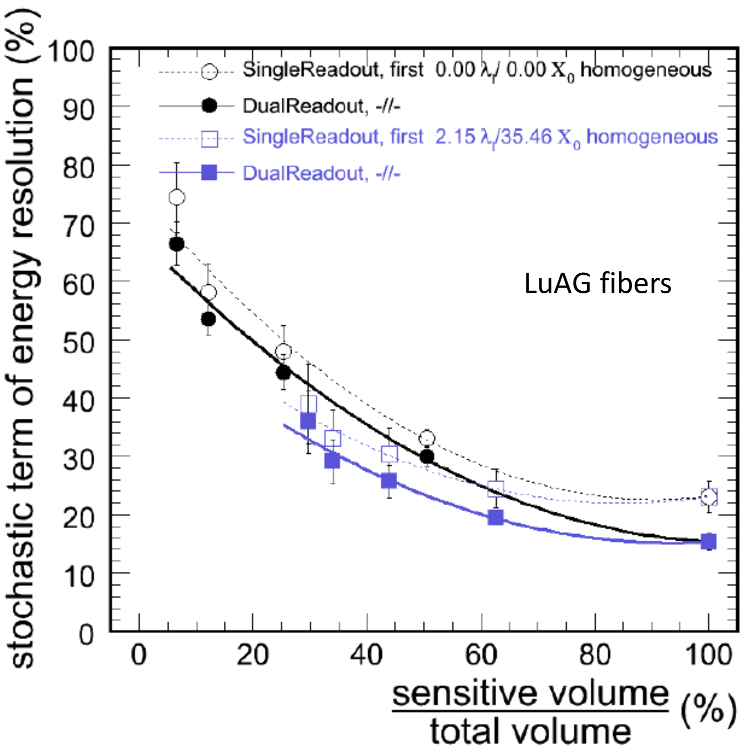


Good separation of Scintillation & Cerenkov

K. Pauwels et al., JINST428 (2013), 8, P09019
A. Benaglia *et al*, JINST 11(5) 05004 (2016)

Crystal fibers for homogeneous calorimetry





Full Homogenous Calorimeters show excellent energy resolution !

$$\left[\frac{\sigma_E}{E}\right]_{Stochastic} = \frac{22\%}{\sqrt{E}} \rightarrow \frac{15\%}{\sqrt{E}}$$

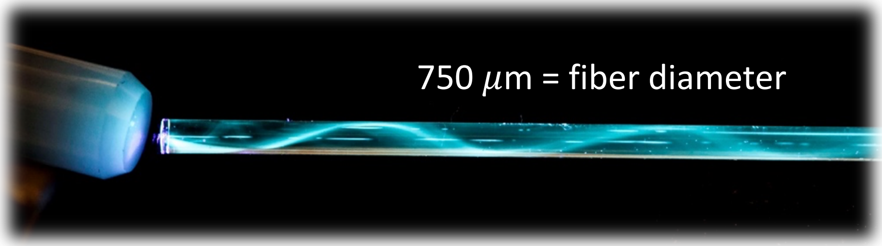
Single readout → *Dual readout*

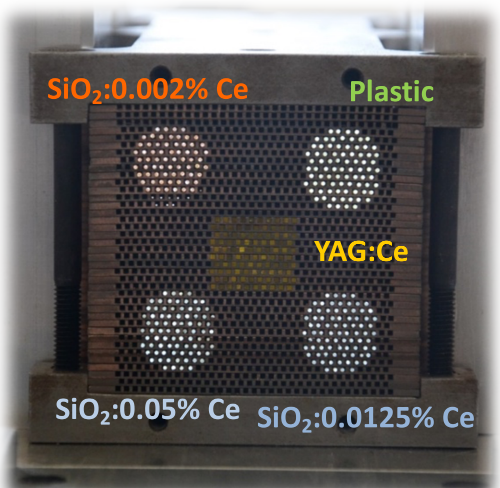
For pions !

P. Lecoq ,CALOR 2008 [J PHYS 160 (2009) p12016]
G. Mavromanolakis et al. CALOR 2010 + JINST 6 p10012 (2011)

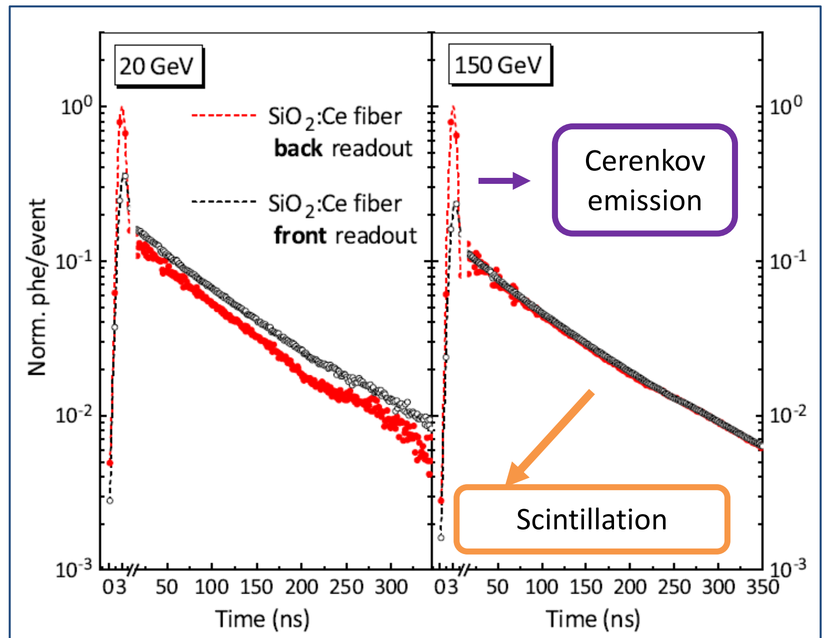
Silica doped fibers

SiO2:Ce **fibers** Milano/Polymicro





Dual read-out of Cherenkov and scintillation light simultaneously with the same SiO_2:Ce fiber



F. Cova et al., Phys. Rev. Appl. 11 (2), 024036 (2019)

Cerenkov emission

2 types of materials:

- Pure Cerenkov as PbF_2, undoped heavy materials (eg LuAG):

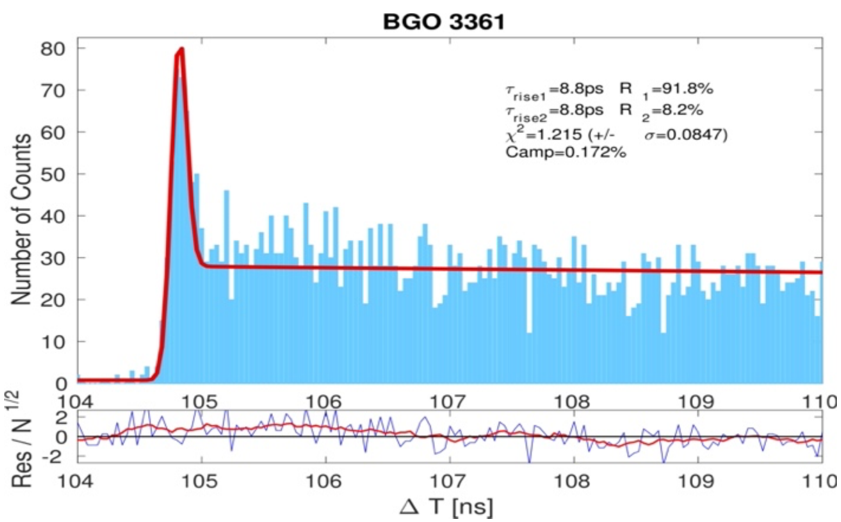
"A Cerenkov EM-calorimeter for CMS, using PbF_2 crytals" proposed by J. L. Faure, 1992

- Cerenkov + Scintillation:
    - heavy scintillator: eg PWO, BGO, BSO, LuAG:Ce, Pr
    - Light scintillator: Silica doped materials

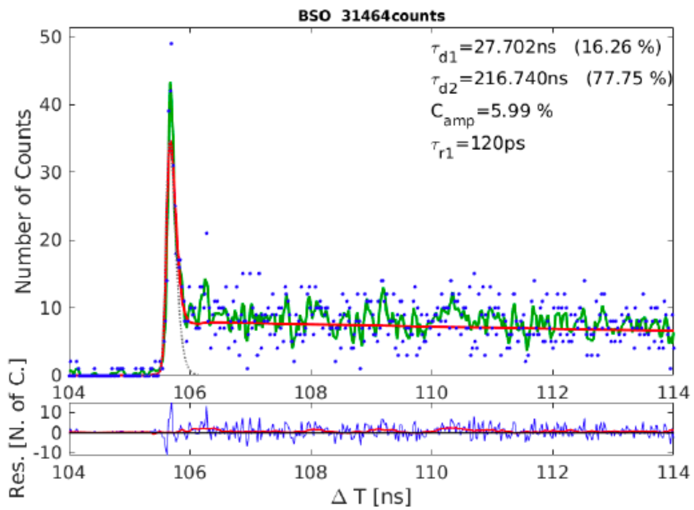
  => dual readout with same material by separation emission wavelength or pulse shape

Cerenkov/scintillation signal in intrinsic scintillating crystal

Rise time measurements of BGO & BSO excited with 511KeV => Cerenkov signal clearly visible



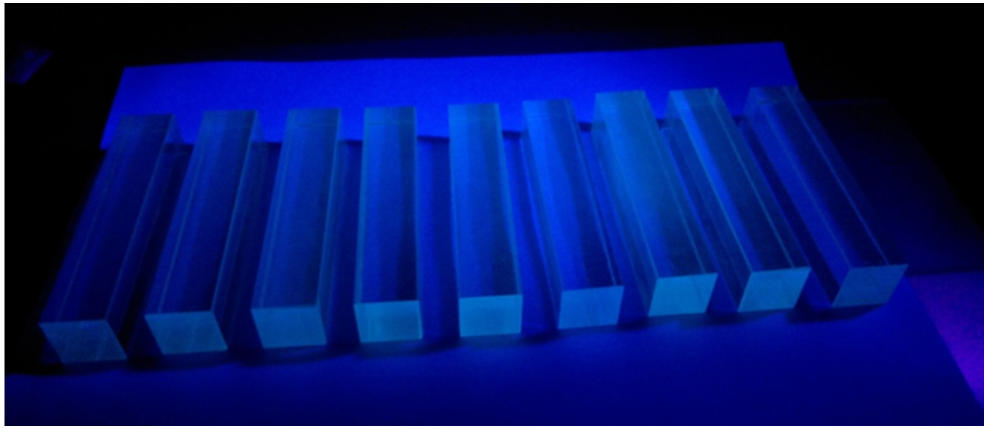
S. Gundacker et al 2019 Phys. Med. Biol. 64 055012

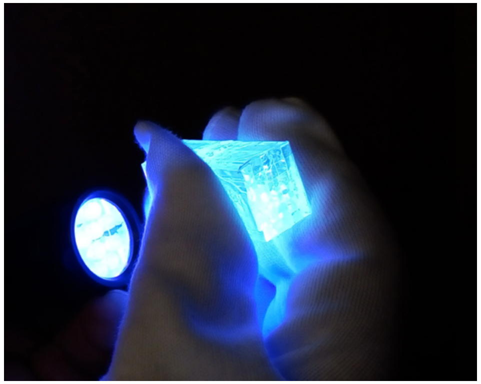


R. Cala et al., CERN CCC group preliminary results

Development of Barium Silica glasses: DSB

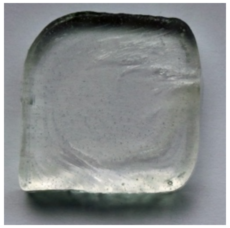
R&D started in RINP Minsk

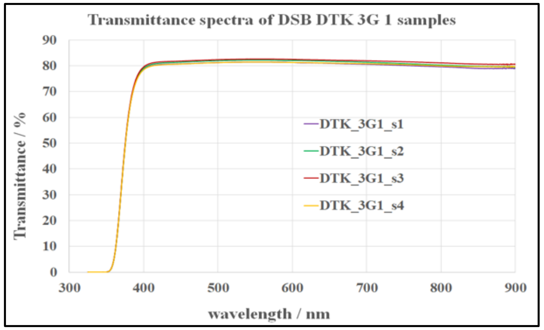




first prototype detecting module made of rectangular fibres.

Industrial development via ScintiGlass Attract project with Preciosa Company



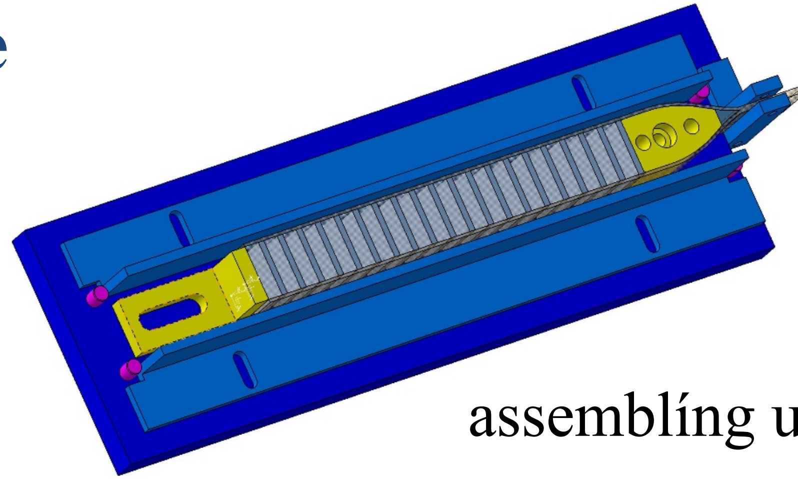


V. Dormenev et al, Presented at IEEE/NSSMIC2020
V. Dorenev Attract web site

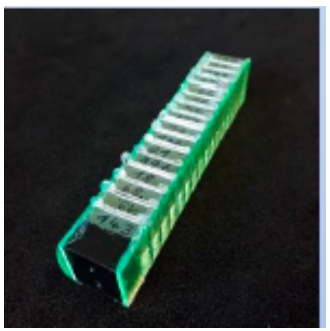
Future Design concept

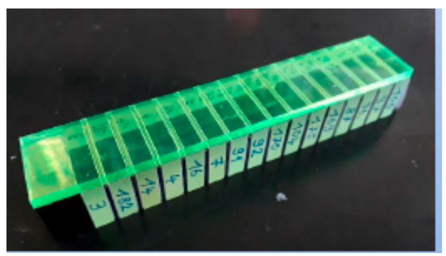
DSB/Pb sampling module

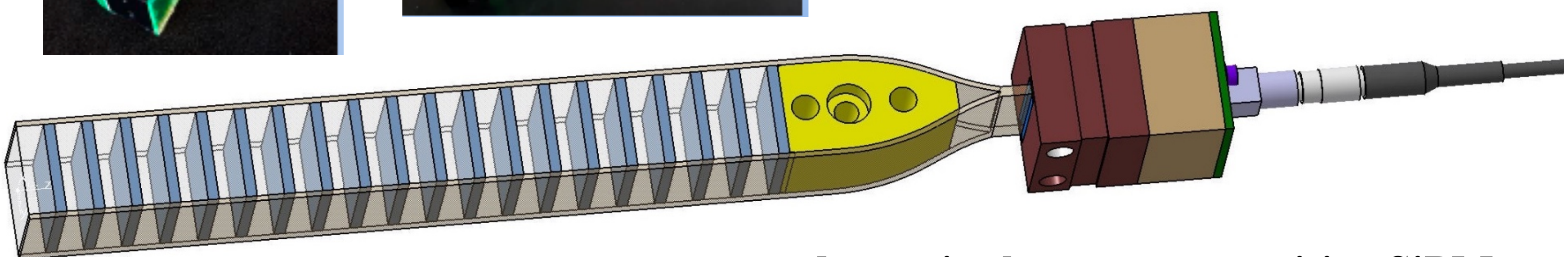
DSB:Ce	$20x17x5mm^3$
Pb	$20x20x1mm^3$
WLS	EJ-280-10
	$20x1.5mm^2$



assemblíng unit







read-out via three green sensitive SiPMs

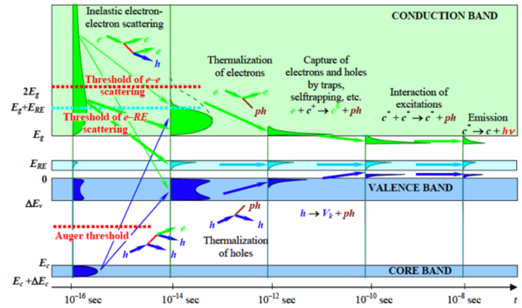
V. Dormenev et al, Presented at IEEE/NSSMIC2020
V. Dorenev Attract web site

ATTRACT

R&D on ultrafast scintillators: light mechanisms and light transport & collection

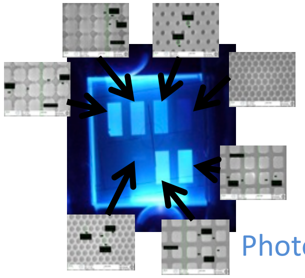
- **Study of various emission types:**
  - Excitonic emission (STE, excitations of anion complexes)
  - Emission of activators (Ce, Pr, …)
  - **Crossluminescence**
  - **Quantum confinement driven luminescence**
  - **Hot intraband luminescence (HIL)**
  - **Cerenkov radiation**

Slow → Ultra fast



- **Study of Light transport and collection**
  - R&D on innovative ways to transport the light
  - R&D on increase light collection

work on going surface treatment, photonic crystals, light guide

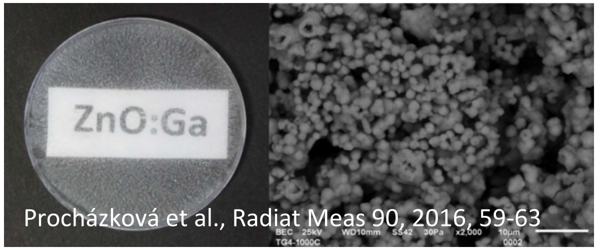


Photonic crystals

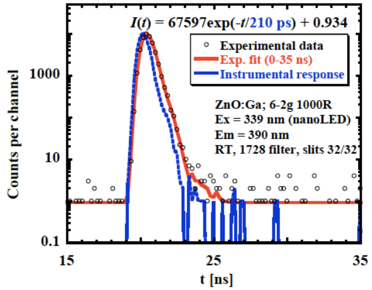
⇒ Multifunctional heterostructure concept

- Eg Combined bulk material with nanomaterial

ZnO:Ga nanopowders embedded in a thin layer of SiO_2

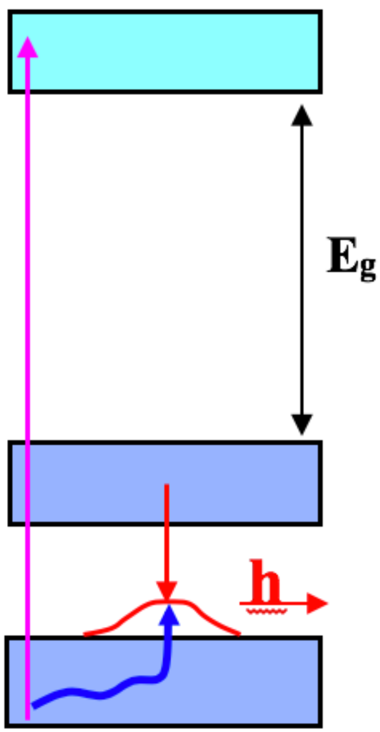


Procházková et al., Radiat Meas 90, 2016, 59-63



Crossluminescence

Radiative transition between the core- and valence bands.



Many Materials available

Compilation of CL data at 293 K

BaF$_2$ →

	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]

C.W.E. Van eijk Journal of Luminescence60&OI 1994! 9~694!

Very fast emission < 2ns but emission < 400nm

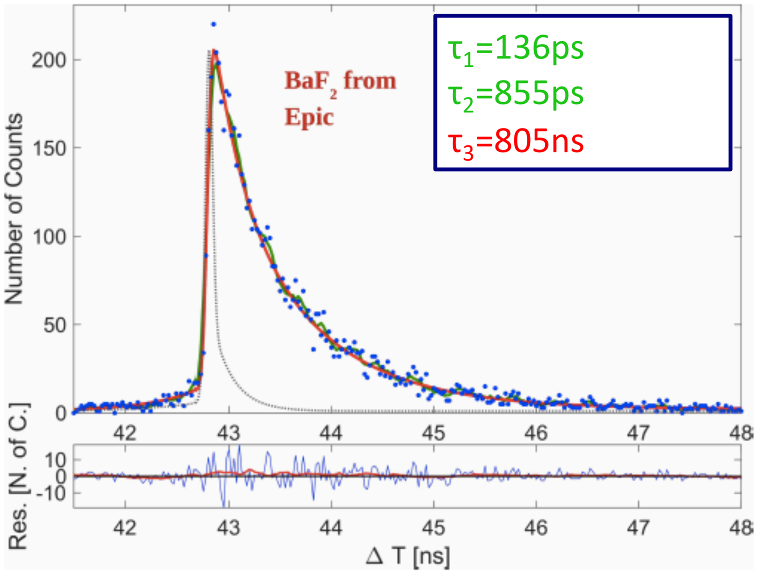
BaF_2 was proposed in 90's for ECAL in L* @SSC, L3P @LHC

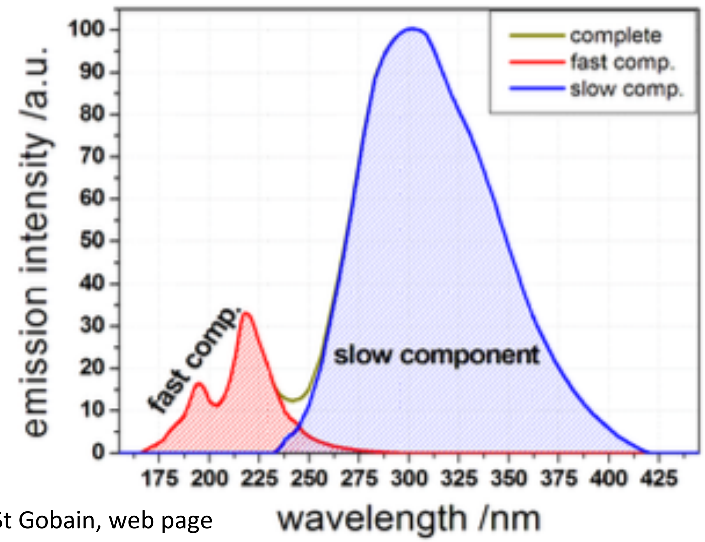
L* Collaboration, Letter of Intent to the SSC Laboratory: https://lss.fnal.gov/archive/other/ssc/sscl-sr-1154.pdf

R. Zhu, NIMA A 340 (1994) 442-457

Crossluminescence in BaF_2

Sub ns emission but in UV &additional slow component





St Gobain, web page

R&D on going on:

- VUV photodetector
- Optical coupling
- Reduction of slow component
- Search for material with crossluminescence toward visible

R. Pots et all Front. Phys. | doi: 10.3389/fphy.2020.592875

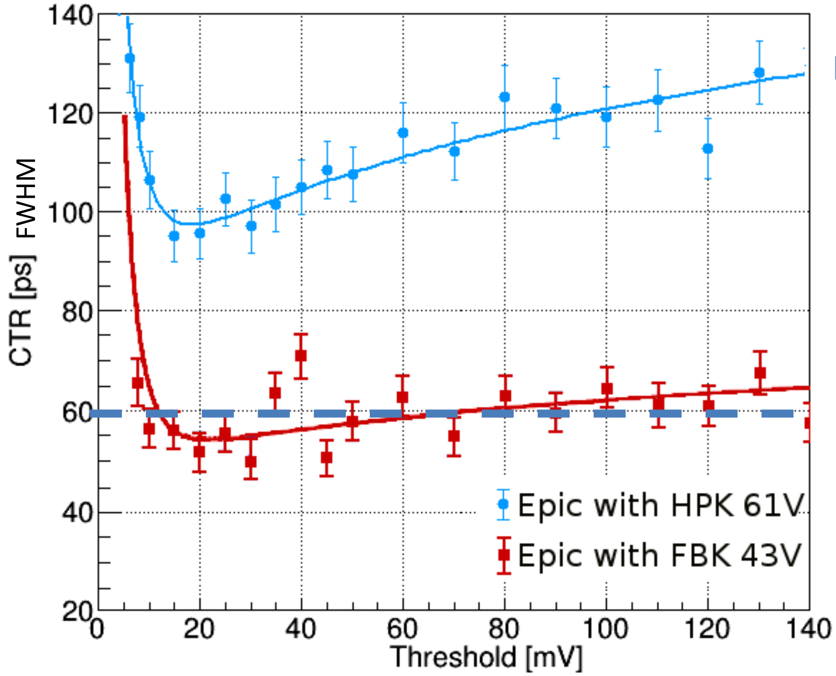
S. Gundacker et al., 2021 Phys. Med. Biol. in press https://doi.org/10.1088/1361-6560/abf476

Improvement of UV photodetection

Development on going on VUV SiPM both in Hamatmasu: HPK S13370-CN & FBK NUV HD (eg: for nEXO experiment (Xe liquid @175nm)*)

⇒ PDE about 20%

Time resolution measured @CERN with BaF_2 ($2x2x3mm^3$) pixels @511keV



HPK S13370-CN

Better SPTR & PDE

FBK VUV HD

LSO:Ce,Ca $2x2x3mm^3$
with optical coupling,PDE 59%

PDE: 15-20%
No optical coupling

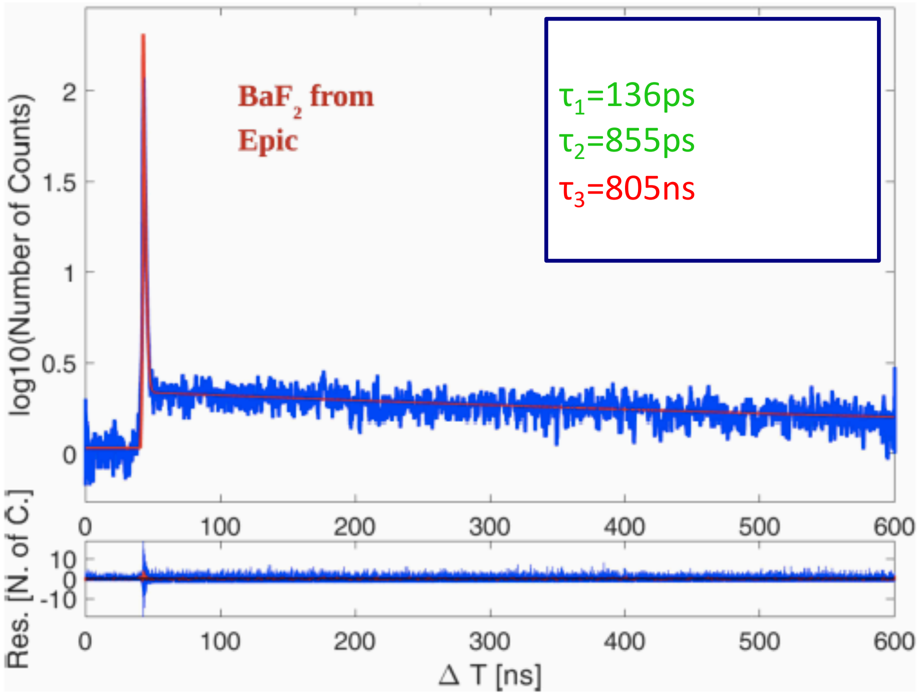
Further improvement of PDE in UV and optical coupling may improve time resolution

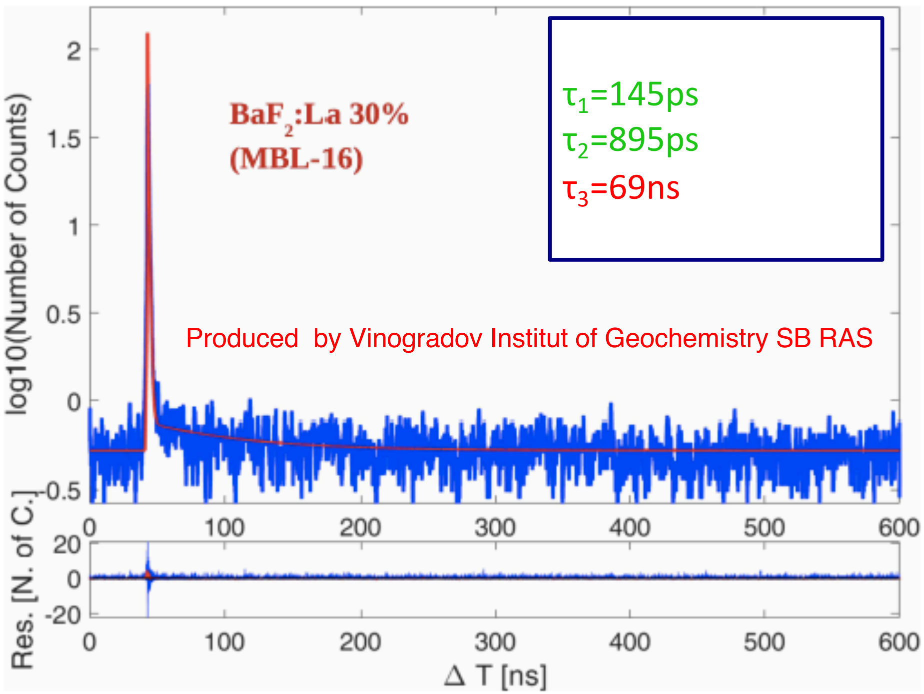
* A. Jamil et al., in IEEE TNS, vol. 65, no. 11, pp. 2823-2833, 2018, doi: 10.1109/TNS.2018.2875668.

R. Pots et al, Front. Phys. | doi: 10.3389/fphy.2020.592875
S. Gundacker et al., 2021 Phys. Med. Biol. in press https://doi.org/10.1088/1361-6560/abf476

Suppression of slow component with various doping

Example with La doping

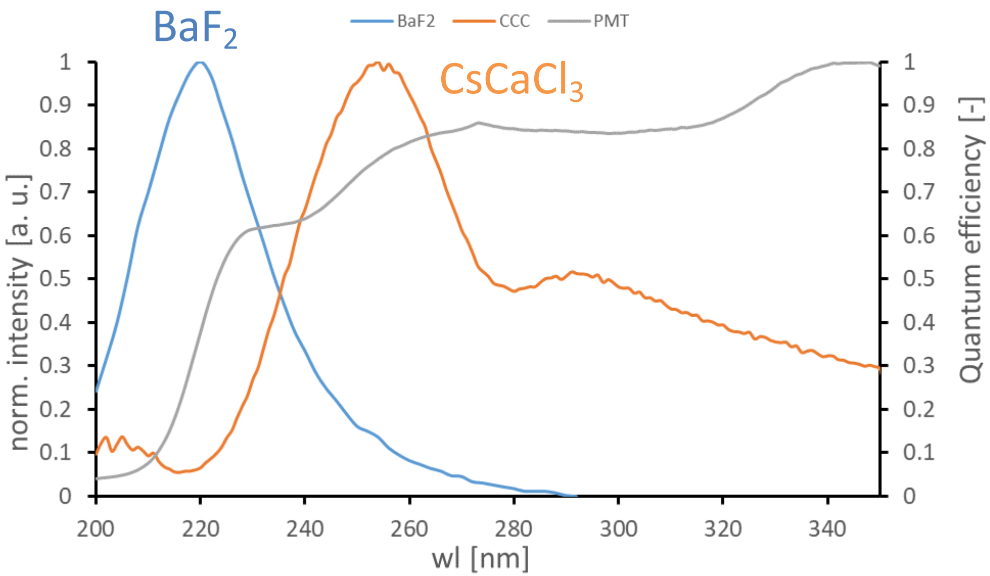




S. Gundacker et al., 2021 Phys. Med. Biol. in press https://doi.org/10.1088/1361-6560/abf476

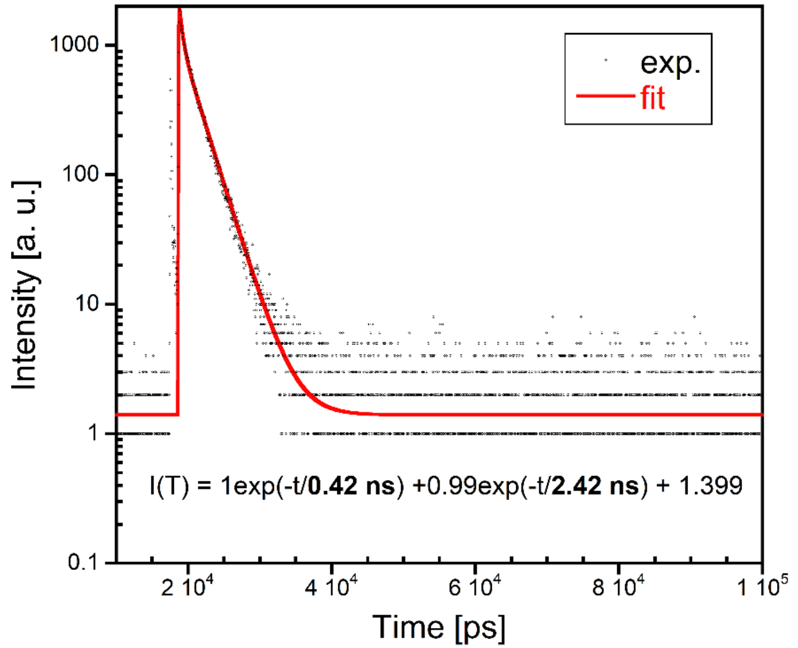
Development cross luminescence material more in UV visible region

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

Deacy spectra



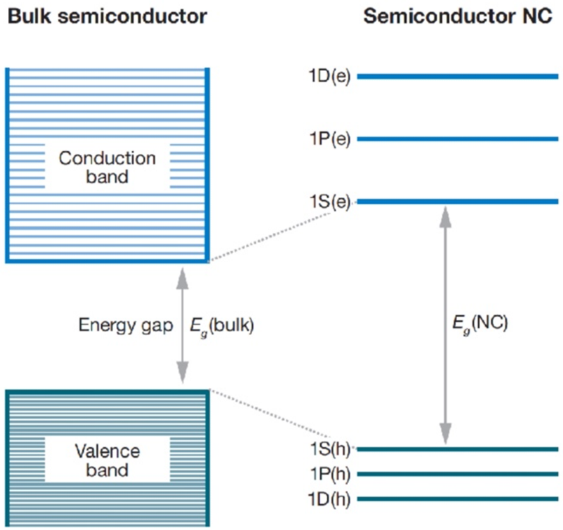
Courtesy V. Vanecek, M. Nikl, FZU Prague

Emission @ 260nm
2 fast decay time 0.42ns, 2.42ns

Fyzikální ústav Akademie věd České republiky

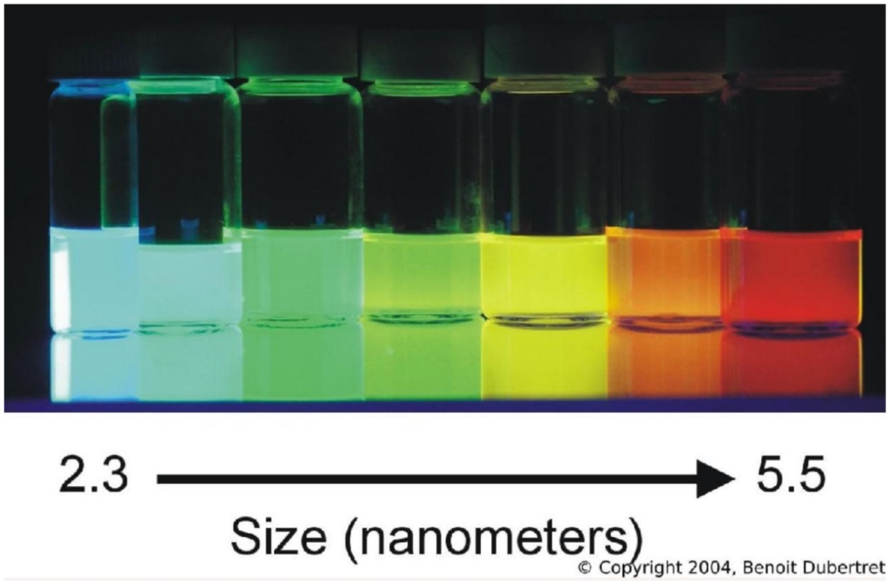
Quantum confinement

$a \sim \lambda_B \longrightarrow QUANTUM\ CONFINEMENT$



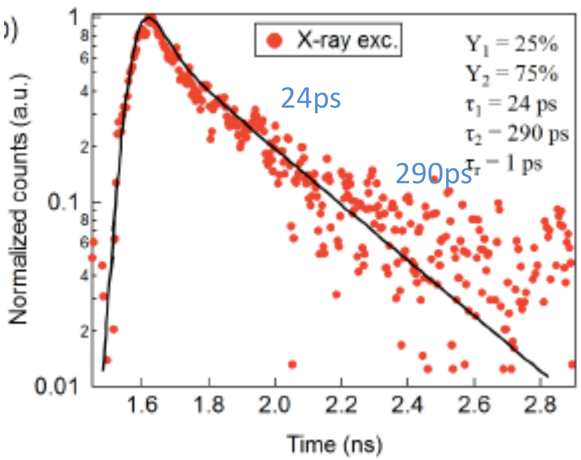
V. Klimov, *Annu. Rev. Phys. Chem,* 58, pp. 635-73, 2007.

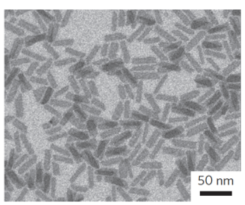
Size dependent optoelectronic-properties



Some examples of scintillating nanomaterials with subns emission

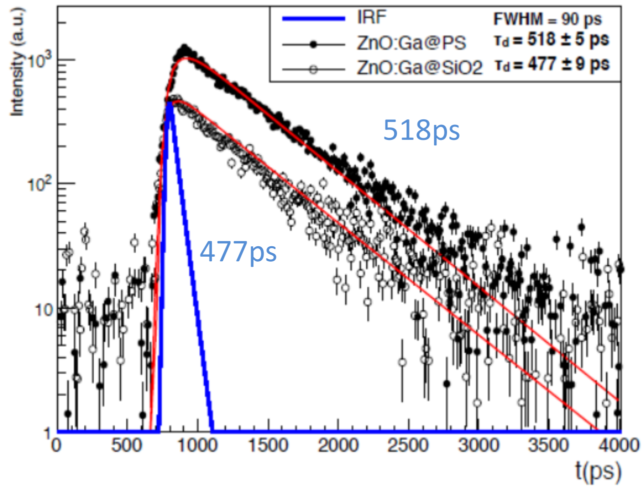
CdSe nanoplatelet,

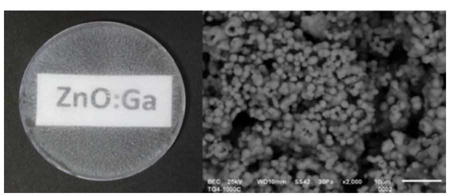




J. Grim et al., *Nature Nanotechnology*, **9**,2014, 891–895
R. Martinez Turtos et al., 2016 JINST_11 (10) P10015

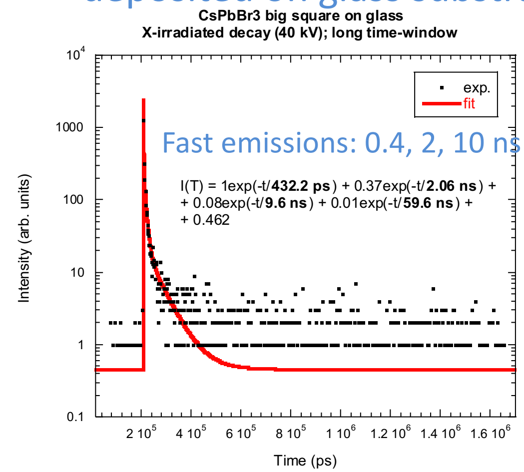
ZnO:Ga embedded in SiO_2 or polystyrene

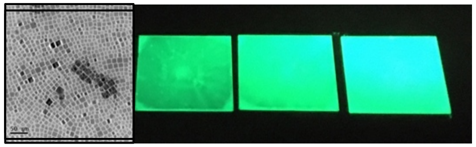




Procházková et al., Radiat Meas 90, 2016, 59-63
R. Turtos Phys. Status Solidi RRL 10, No. 11, 843–847 (2016)

$CsPbBr_3$ thin films deposited on glass substrate

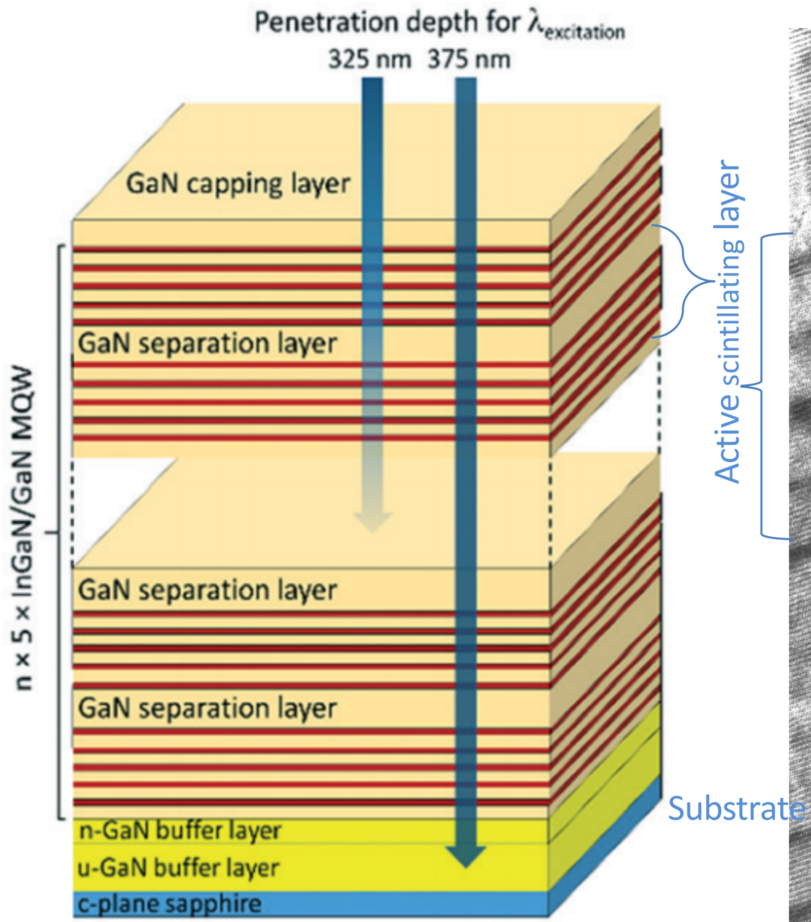


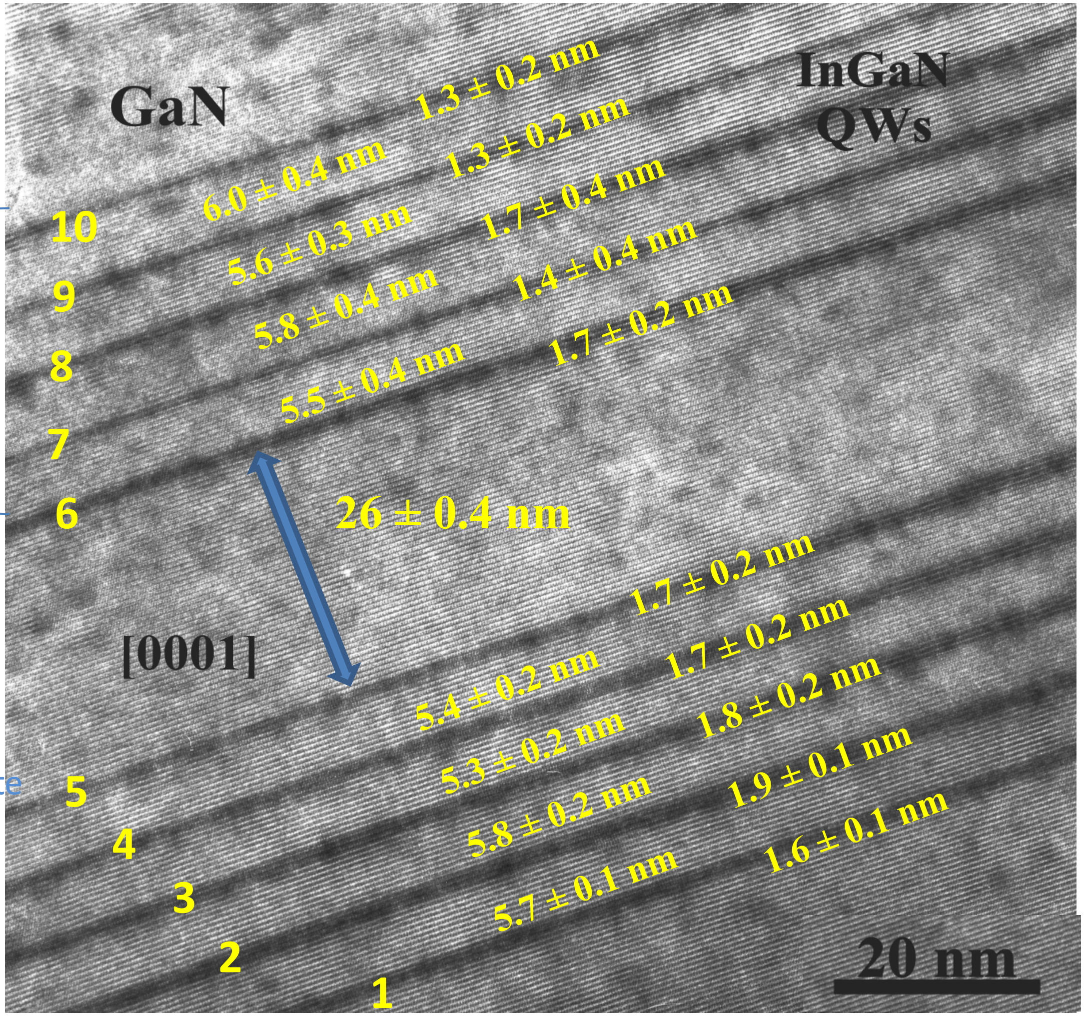


Courtesy V. Čuba, K. Děcká, A. Suchá CTU, Prague

InGaN/GaN heterostructure: Multiple Quantum Wells (MQW)

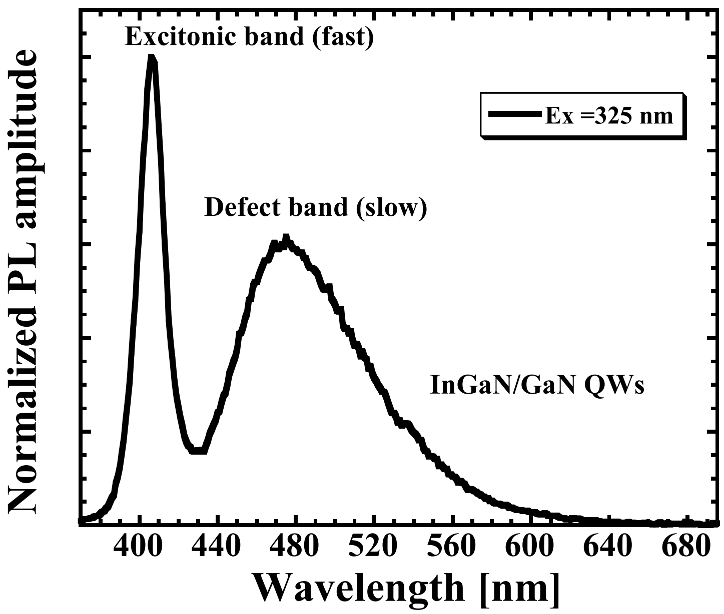
Picture from A. Hospodkova

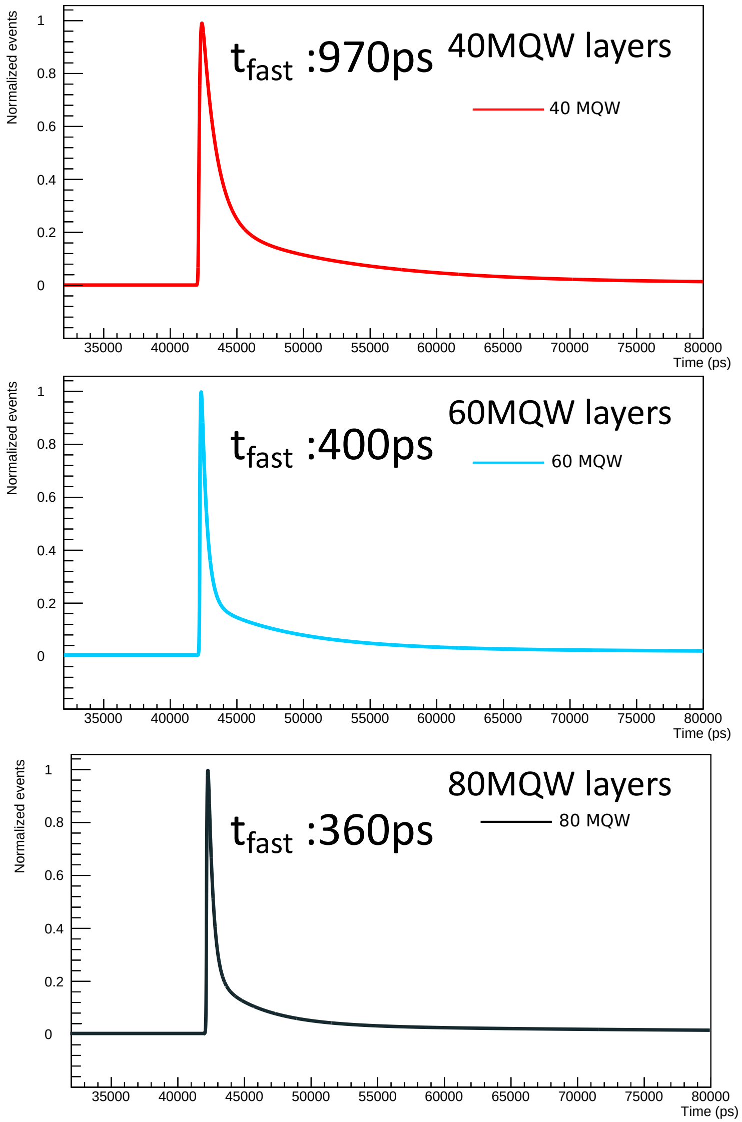




T. Hubacek, CrystEngComm, 2019, 21, 356

InGaN/GaN heterostructure: Multiple Quantum Wells (MQW)

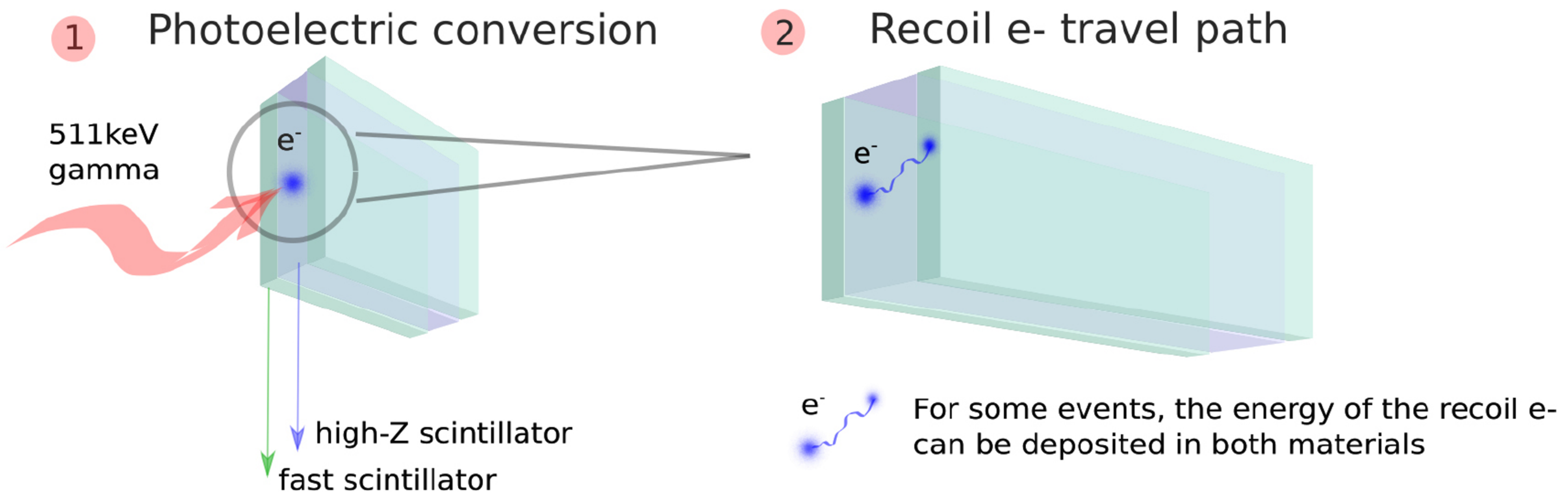




Preliminary, measured @cern Lab27

Heterostructure concept

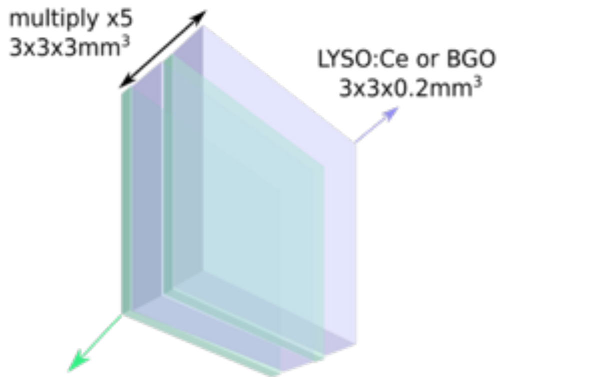
Combine scintillators with high light yield, high stopping power & material with prompt emission



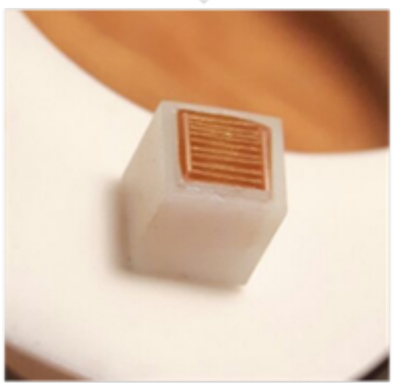
Energy sharing among multiple layers of standard and fast scintillators

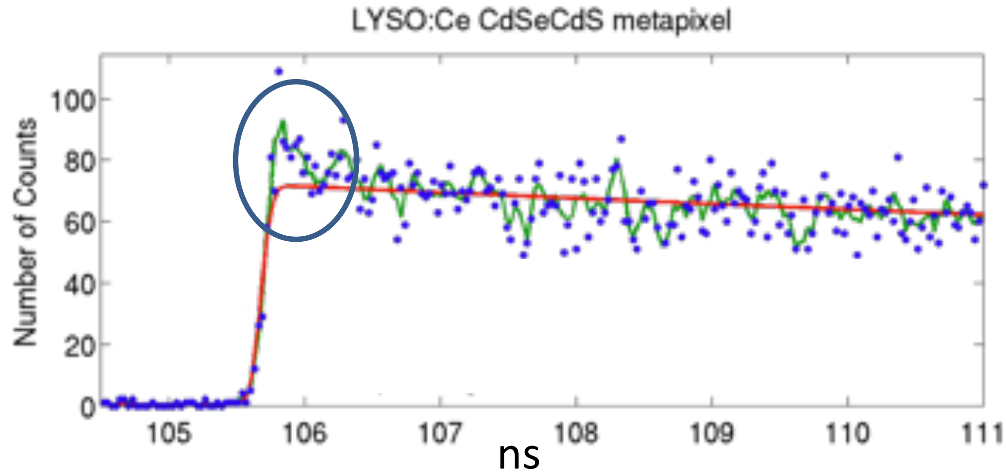
R. M. Turtos et al, Phys. Med. Biol. 64 (2019) 185018, https://doi.org/10.1088/1361-6560/ab18b3

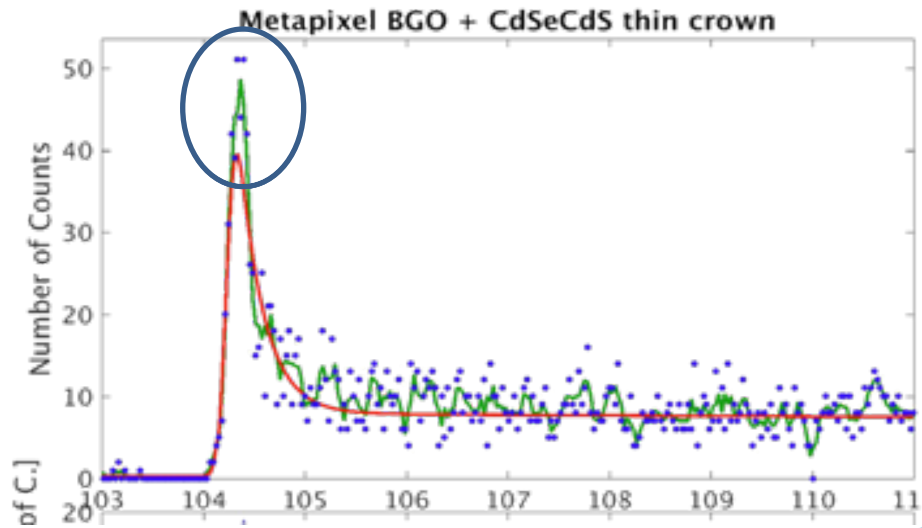
First attempt of heterostructure realized in our group



CdSe/CdS core crown nanoplatelets (CC NPLs) drop-casted film
Effective deposited mass equivalent to 20μm







R. M. Turtos et al, Phys. Med. Biol. 64 (2019) 185018, https://doi.org/10.1088/1361-6560/ab18b3

Conclusion

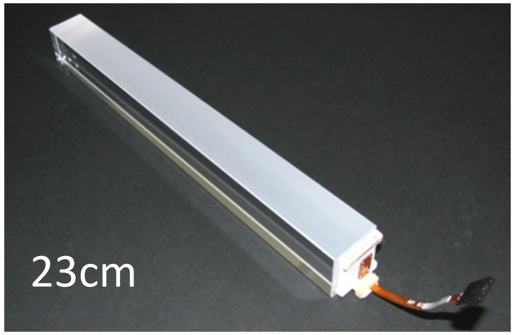
- Many new emerging technologies exist in the field of scintillators, which open new perspectives for new innovative scintillating detector concepts with high granularity & high time resolution

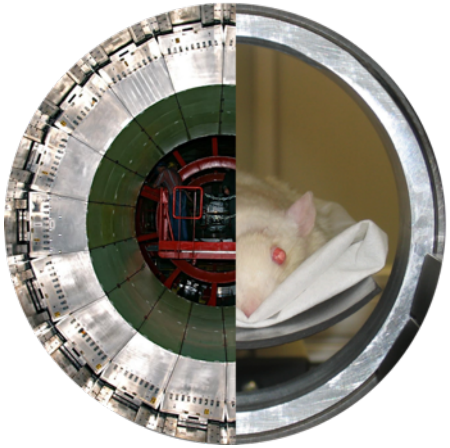
- The Crystal Clear Collaboration (RD18) provides access to a huge expertise in light based detectors developed over the last 30 years through a wide international network of experts in different fields

- Development on scintillators, photodetectors, electronics for HEP has impact on many applications
  - ⇒ Strong cross fertilization between HEP and applied physics (eg medical and industrial apps).
  - ⇒ HEP can widely benefit from synergy effects achieved in common R&D projects carried out with research partners active in fields outside HEP

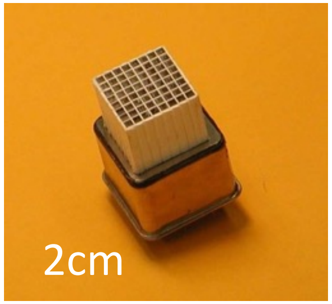
Synergy with other applications
Case of medical applications: PET

ECAL in CMS experiment





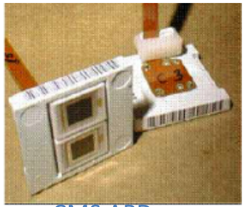
PET scanner



ClearPET module

In CCC, since 1995 development of several PET prototypes
with particular focus on timing during last years

Example of cross fertilization between HEP to Health:



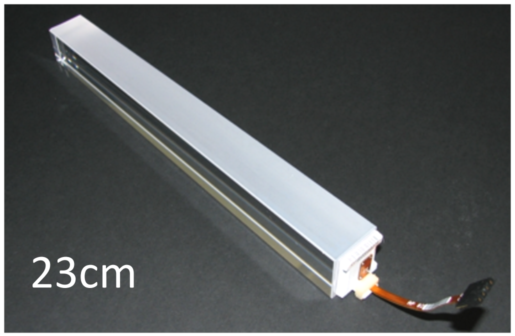
CMS APD

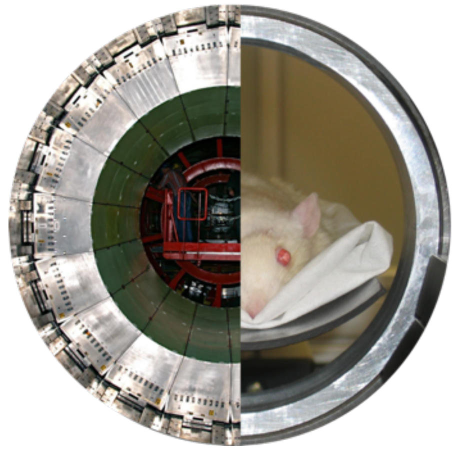
ClearPEM:
Used APD developed for CMS ECAL

HEP → Health

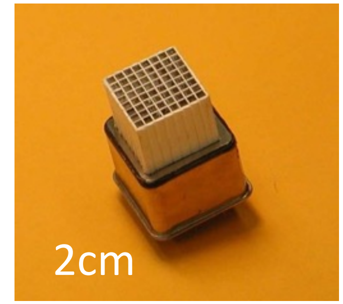
Synergy with other applications
Case of medical applications: PET

ECAL in CMS experiment





PET scanner



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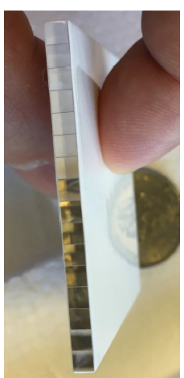

Crystal array CMS BTL

ClearPEM:
Used APD developed for CMS ECAL

Future CMS barrel timing layer: LYSO/SiPM and
electronic developed first for EndoTOFPET