IFMP WORKSHOP IN IONIAN UNIVERSITY, CORFU, GREECE

Friday 10/11/2017 9:30

CHALLENGES IN TOFPET

Paul Lecoq

CERN, Geneva, Switzerland

The future generation of radiation detectors is more and more demanding on timing performance for a wide range of applications, such as time of flight (TOF) techniques for PET cameras and particle identification in nuclear physics and high energy physics detectors, precise event time tagging in high luminosity accelerators and a number of photonic applications based on single photon detection. A target of 10ps coincidence time resolution in TOFPET scanners would introduce a paradigm shift in PET imaging. Besides resulting in on-line image formation, the localisation of annihilation events directly from their TOF provides ultimate use of the dose delivered to the patient to get the best Signal to Noise Ratio into the resulting image and offers a potential reduction of the scan duration and a direct access to the image during the scan itself. Reconstructionless TOF-PET also reduces efficiently undesired effects inherent to the PET detection, namely randoms and scatters when appropriately correlated to energy discrimination, hence contributing to reduce dose, scan duration and possibly scan cost while using very short-lived positron emitting isotopes.

The time resolution of a scintillator-based detector is directly driven by the density of photoelectrons generated in the photodetector at the detection threshold. At the scintillator level it is related to the intrinsic light yield, the pulse shape (rise time and decay time) and the light transport from the gamma-ray conversion point to the photodetector. When aiming at 10ps time resolution fluctuations in the thermalization and relaxation time of hot electrons and holes generated by the interaction of ionization radiation with the crystal become important. These processes last for up to a few tens of ps and are followed by a complex trapping-detrapping process, Poole-Frenkel effect, Auger ionization of traps and electron-hole recombination, which can last for a few ns with very large fluctuations.

This talk will review the different processes at work and evaluate if some of the transient phenomena taking place during the fast thermalization phase can be exploited to extract a time tag with a precision in the few ps range.

Some considerations will also be given on the possibility to exploit quantum confinement for the production of ultrafast spontaneous or stimulated emission in semi-conductors. A particularly promising route toward ultrafast emission comes in the form of 2D CdSe nanosheets. This system is characterized by confinement in only one dimension and free electron and hole motion in the plane, which contributes to a giant oscillator strength transition and ultrafast radiative emission rates. Further, CdSe nanosheets have ultralow thresholds for stimulated emission, with a lifetime of less than 1 picosecond.

The light transport in the crystal is also an important source of time jitter. In particular light bouncing within the scintillator must be reduced as much as possible as it spreads the arrival time of photons on the photodetector and strongly reduces the light output by increasing the effect of light absorption within the crystal. It concerns typically about 70% of the photons generated in currently used scintillators.

A possible solution to overcome these problems is to improve the light extraction efficiency at the first hit of the photons on the crystal/photodetector coupling face by means of photonic crystals (PhCs) specifically designed to couple light propagation modes inside and outside the crystal at the limit of the total reflection angle.

The 10ps Time-of-Flight PET challenge: Myth or reality?

Paul Lecoq
CERN, Geneva

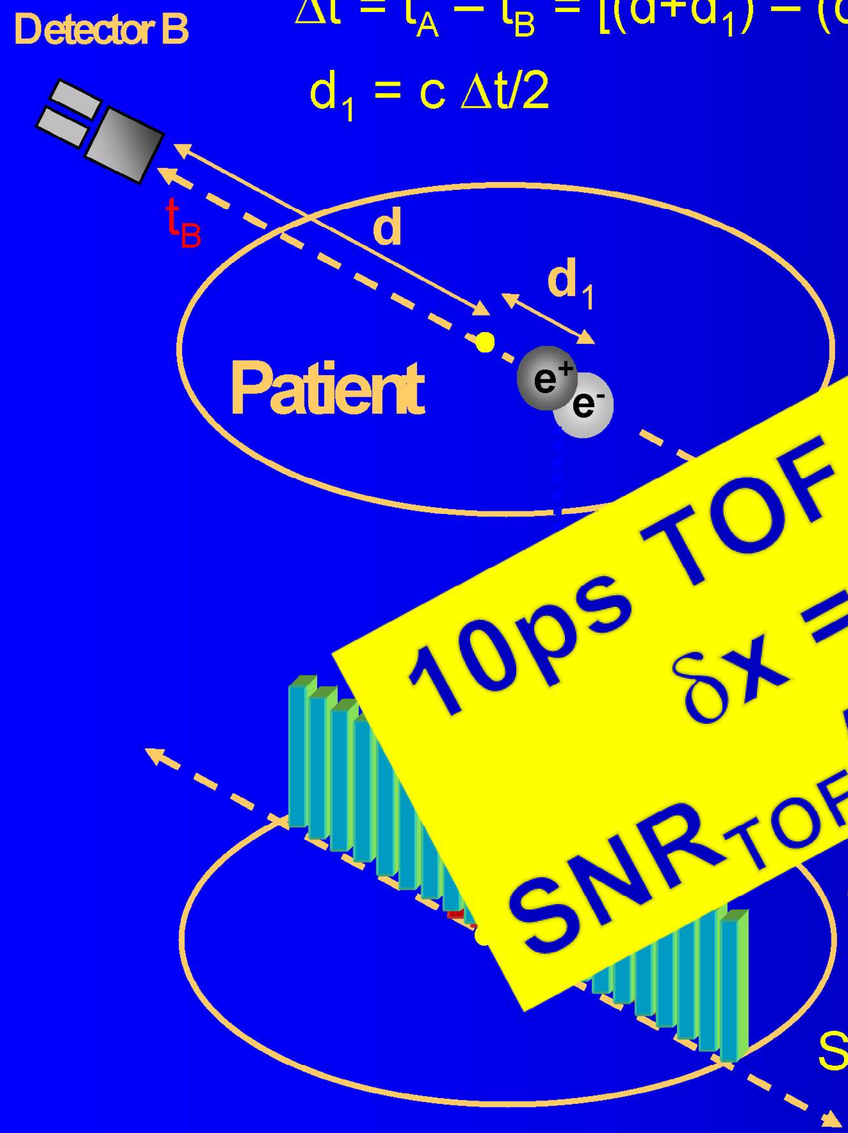
This work and presentation are made in the frame of the ERC Advanced Grant Agreement N°338953–TICAL

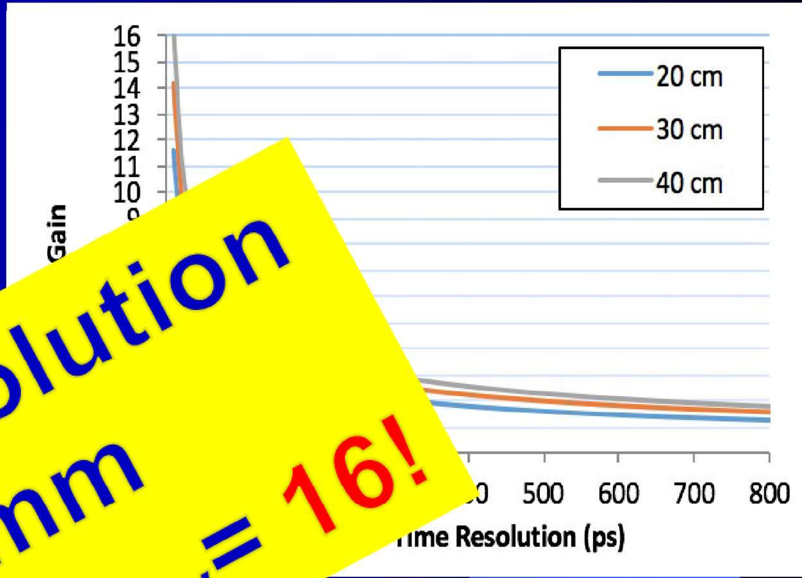
European Research Council
Executive Agency

Time of Flight PET

$\Delta t = t_A - t_B = [(d+d_1) - (d-d_1)]/c$

$d_1 = c\,\Delta t/2$





10ps TOF resolution

δx = 1.5mm

SNR_{TOF}/SNR_{CONV} = 16!

$_{F} = \sqrt{(2D/cDt)} \cdot SNR_{conv}$

	δt (ps)	δx (cm)	SNR *
	10	0.15	16
	100	1.5	5.2
	300	4.5	3.0
State-of-the-art	500	7.5	2.3

** SNR gain for 40 cm phantom*

Why 10ps TOFPET?

- TOF for direct 3D information
  - Requires 10ps TOF resolution for 1.5mm resolution along LOR
- Allows limited angle tomography without artifacts
- > 15-fold improvement in S/N ratio, even more with high random rate
  - Equivalent potential in dose reduction (0.5mSv/scan)
    - Annual natural background: 2.4mSv
    - Return flight Paris SFO: 0.11mSv
  - Allows longer longitudinal studies per injection
  - Reduce the cost of radiotracer production infrastructures
- Less sensitive to incorrect attenuation correction and normalization
  - Less stringent requirements on CT: cost, dose reduction)
  - Reduce problems of not direct attenuation measurement in PET/MR
- Open PET to new categories of patients (children, fœtus)

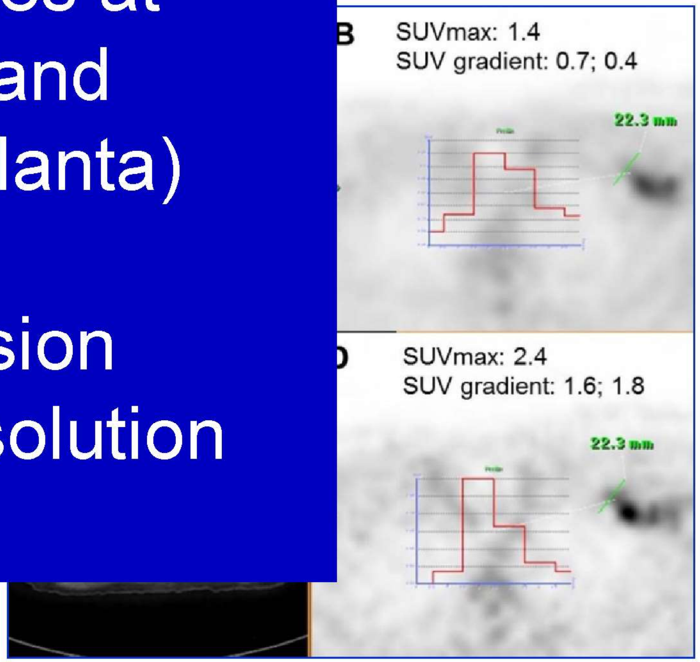
State-of-the-art TOFPET

2013: Vereos PET/CT

PHILI

- Digital SiPM photodetectors
- ...with crystals
- ...ltiplexing
- ...ld-of-view: 57.6 cm

Paramete		
LYSO dete		
Resolution		
Sensitivity		
Peak NECR		
	@ 17 kBq/ml	@ 50 kBq/ml
Timing	585 ps	325 ps
Axial FOV	18.0 cm	16.4 cm



Nguyen et al, JNM 2015

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Breaking News (Oct 2017)

Siemens announces at EANM (Vienna) and IEEE NSS/MIC (Atlanta)

The Biograph Vision
With 249ps CTR resolution

TOFPET in the context of PET/MRI

Pets and MR

- The reconstruction of quantitative PET images requires accurate correction for attenuation of 511 kev gamma rays.
- The half value layer thickness for a 511 keV gamma ray in tissue is about 7 cm.
- An accurate correction method is required to avoid image distortions and artefacts and to permit accurate regional quantification for quantitative dynamic studies.
- Transmission images can only be acquired with limited statistics due to limited countrate of the PET system (TOF can improve this).
- Using TOF information it becomes possible to separate emission from transmission data if the distance from emission to the transmission source is sufficiently large.

State-of-the-art TOFPET

STIC 3 ASIC

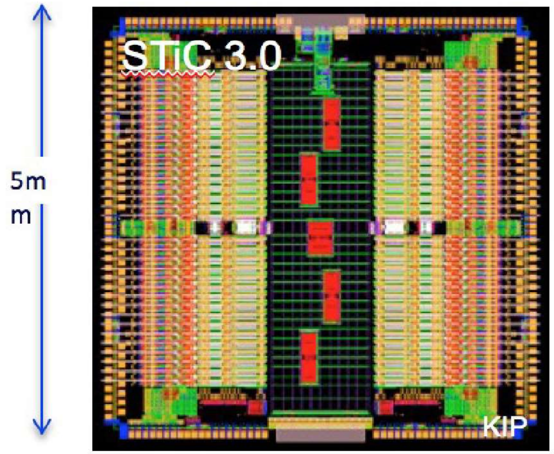
PICOSEC

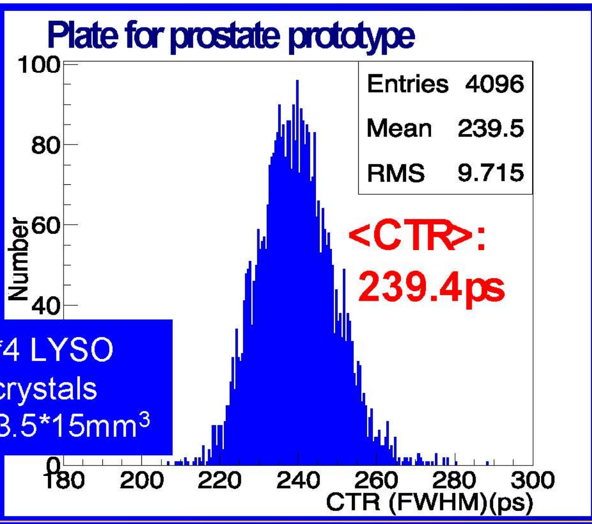
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

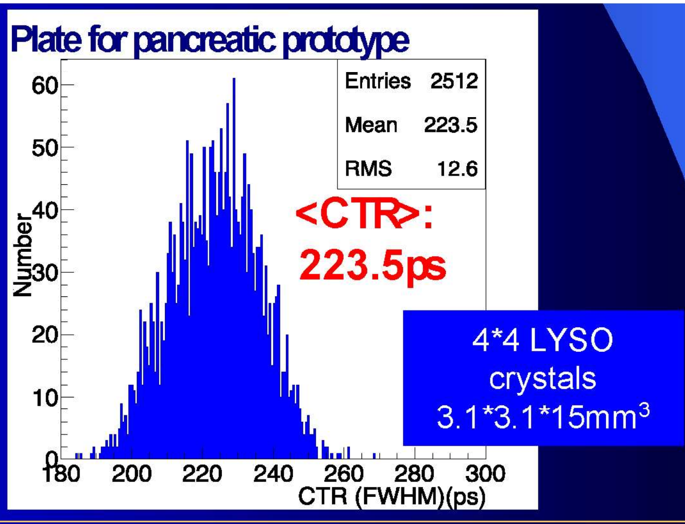
ENDO TOFPET US
Endoscopic TOFPET & Ultrasound

STIC 3.0 (Developed by Heidelberg)

- UMC CMOS 180 nm
- High resolution time measurement
- Linear Time-over-Threshold energy measurement
- Analog Frontend + Digital TDC + Digital readout
- Single-ended / Differential input
- 64-channels



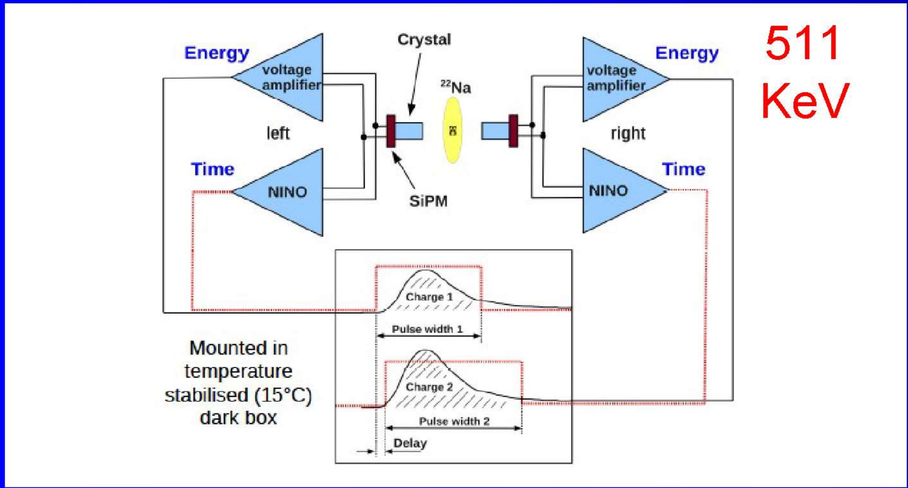


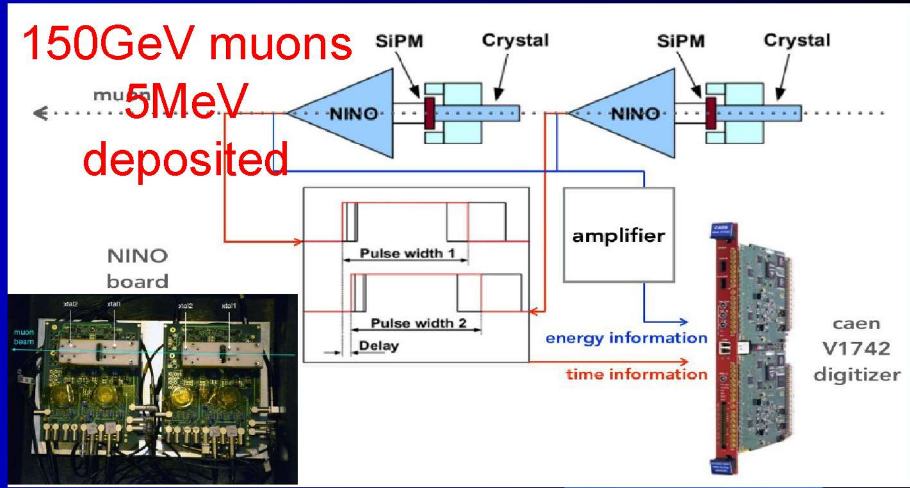


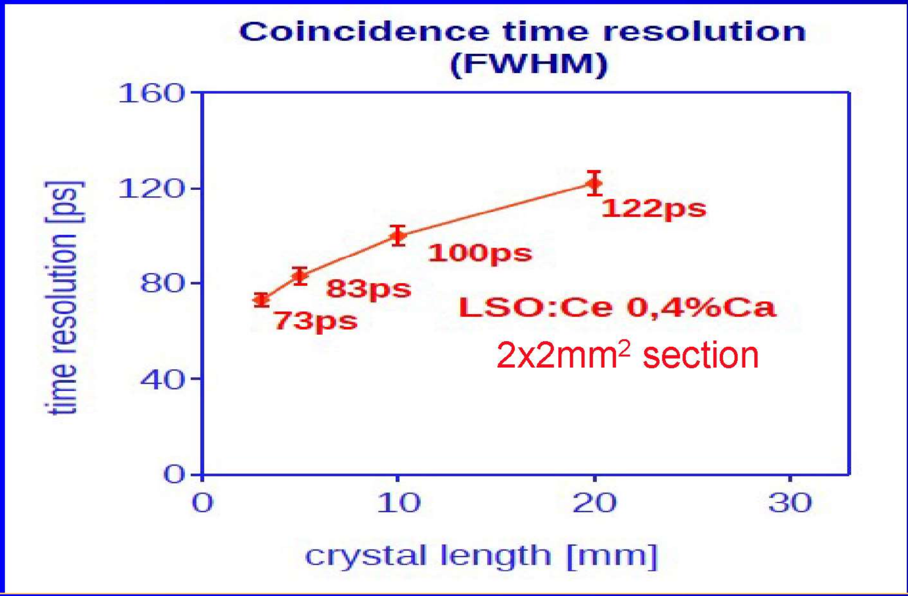
Recent developments: timing results at CERN

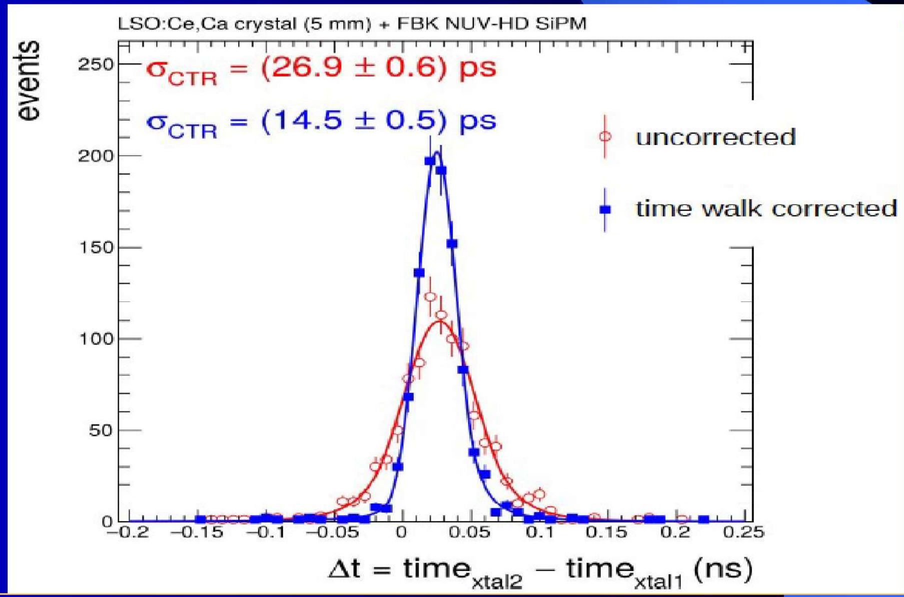
LSO:Ce, 0.4%Ca, melmount coupled to 3x3mm^2 NUV SiPM from FBK, 55%PDE

S. Gundacker et al., CERN







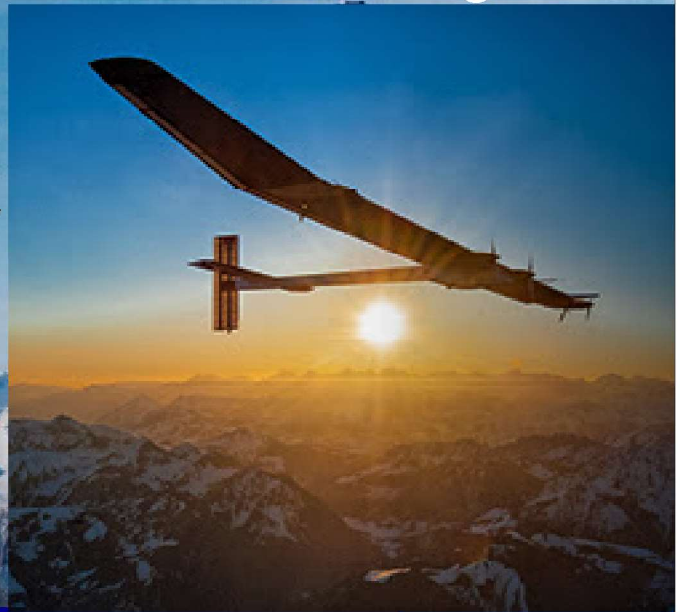


The 10ps challenge

1992: FAI raised a challenge for the first balloon circumnavigation

March 1999: Breitling Orbiter III circumnavigate the globe in 19 days 1 hour 49 minutes and won the Budweiser Cup

July 2016: Solar Impulse closed the loop of the Round-the-World without fuel attempt

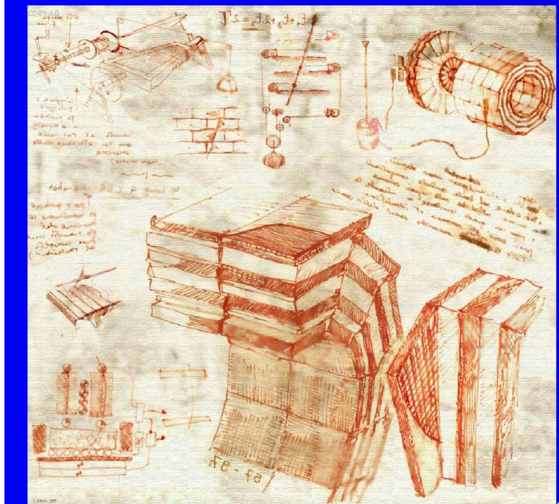


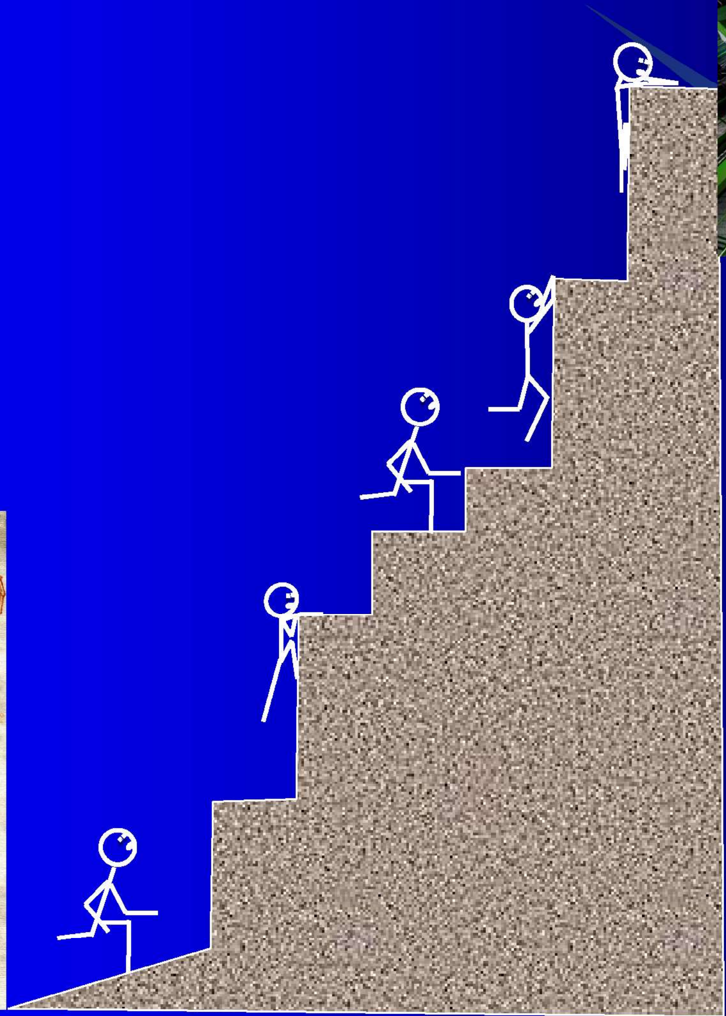
This is a clear-cut case to shed light on TOF-PET with CTR < 10 ps FWHM and raise a challenge on reconstructionless positron tomography

Courtesy of C. Morel, CPPM

From Myth to Reality

1990

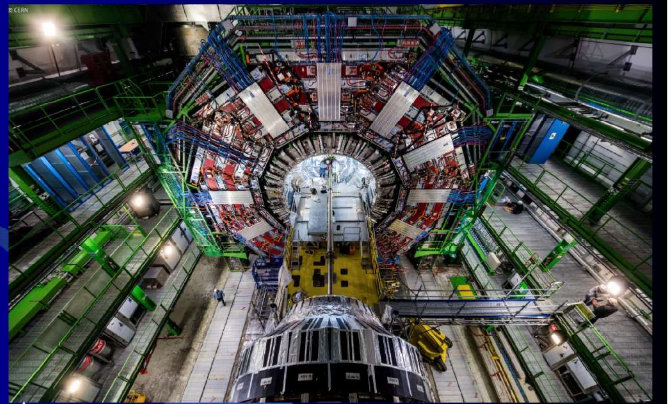




Every step was an enabling technology, which needed to be developped from TRL1 to TRL9

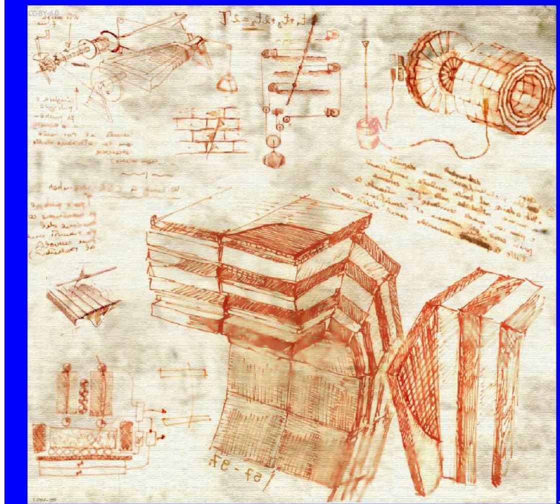
From Myth to Reality

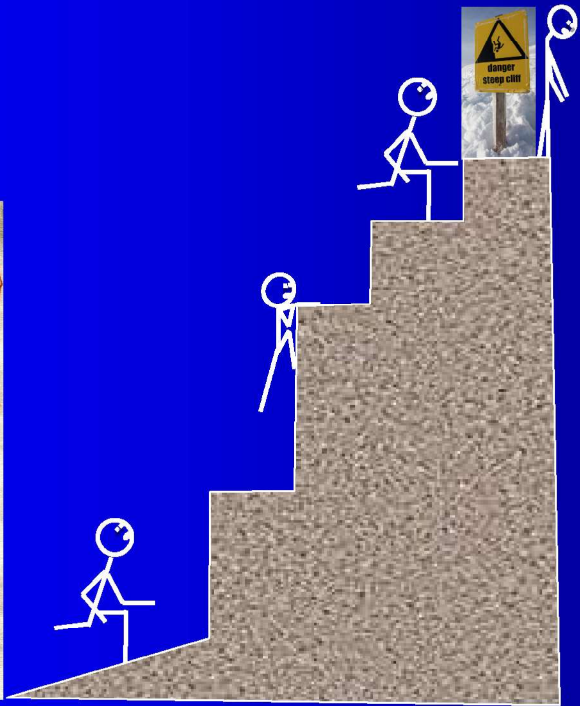
Only impossible
if there is a
physical barrier



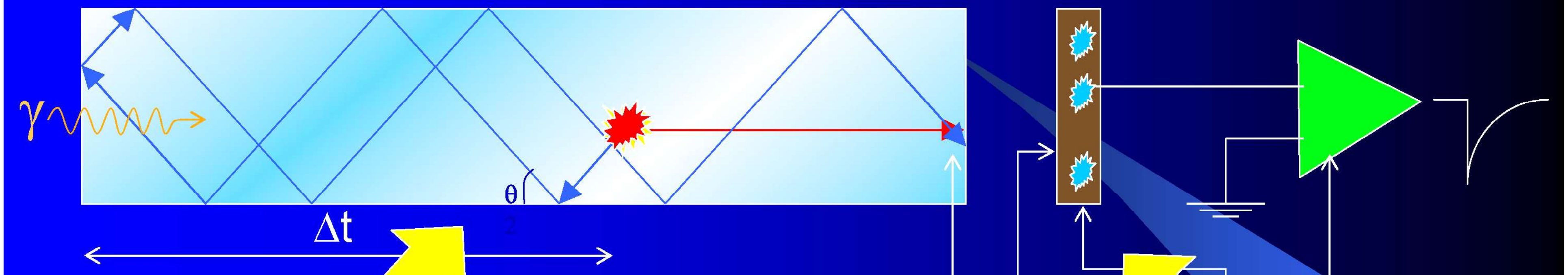
$$\Delta E . \Delta t \geq \hbar$$

1990





The detection chain



$t_{kth\ pe}$ = Δ + $t_{k'\ ph}$ + $t_{transit}$ + t_{SPTR} + t_{TDC}

	Scintillation process	Transit time jitter	Single photon	TDC

Light generation
Light transport

Photoconversion

Random deletion 1
Absorption
Self-absorption

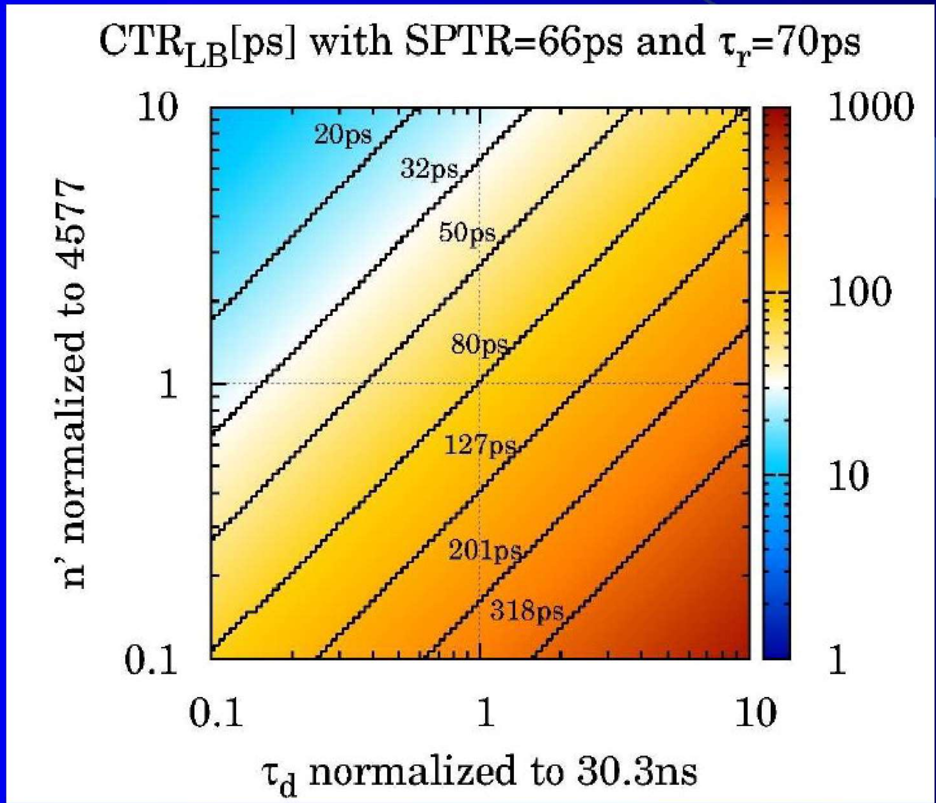
Random deletion 2
SiPM PDE

Unwanted pulses 1
DCR, cross talk
Afterpulses

Unwanted pulses 2
DCR

Parameters of interest to improve timing resolution

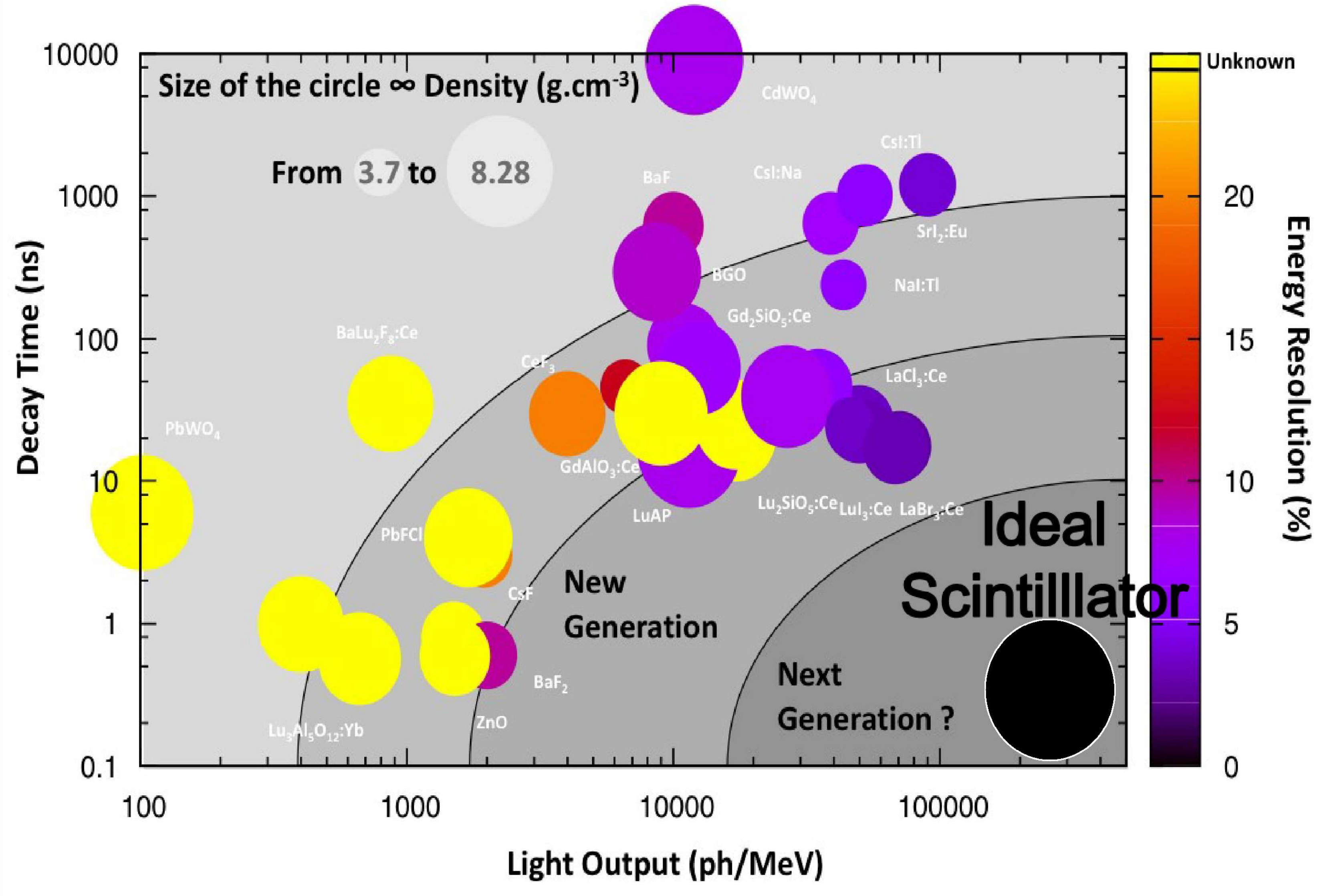
511KeV - Parameters for LSO: Ce and Hamamatsu S10931-050P MPPC



CTR improves like
SQRT (photon time density)

S Gundacker, CERN-THESIS-2014-034 - 210 p.

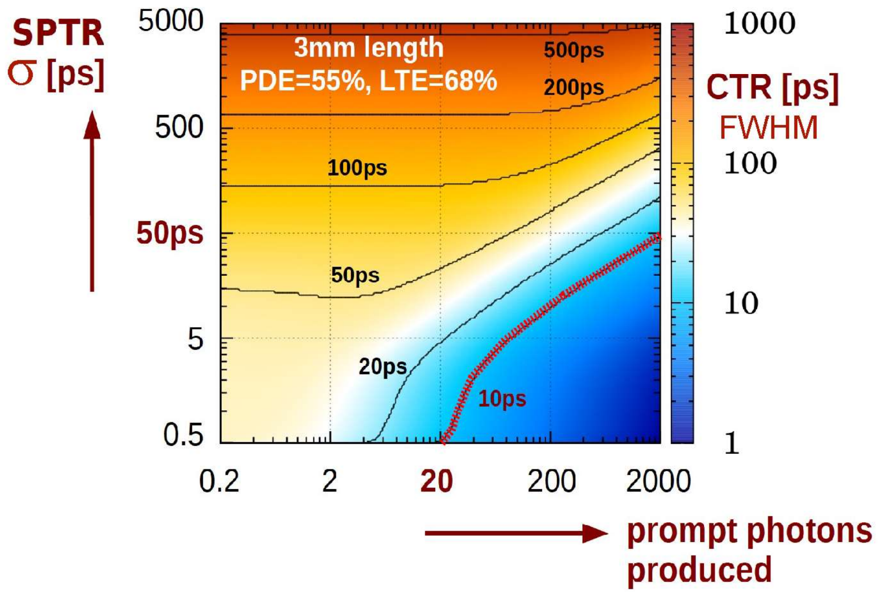
Classification of scintillators



Prompt photons to boost the timing resolution

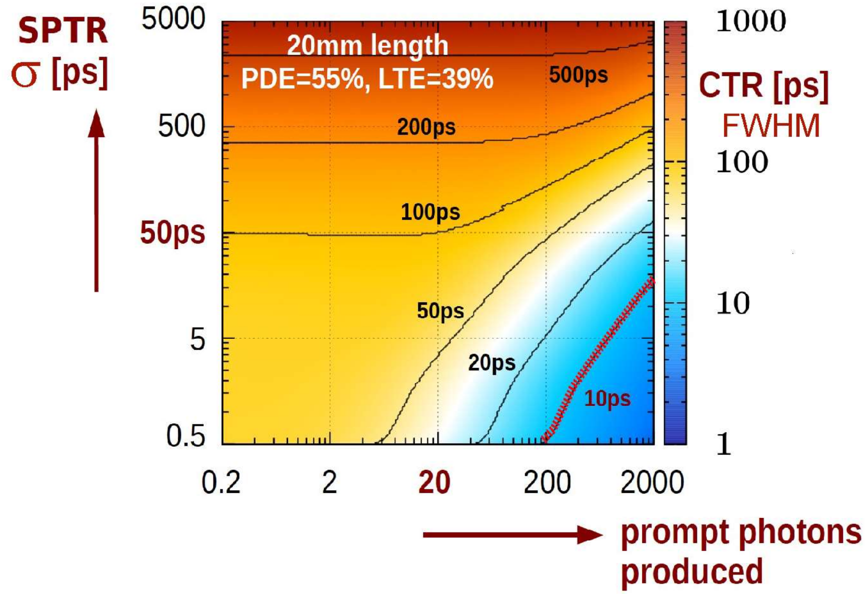
Parameters for LSO: Ce, Ca and Hamamatsu S10931-050P MPPC

Length 3mm



τ_{d1}=33ns (94%), τ_{d1}=8ns (6%), τ_r=21ps and Light Yield=32kph/MeV

Length 20mm



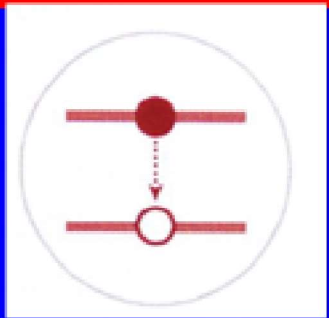
τ_{d1}=33ns (94%), τ_{d1}=8ns (6%), τ_r=21ps and Light Yield=32kph/MeV

S Gundacker, CERN-THESIS-2014-034 - 210 p.

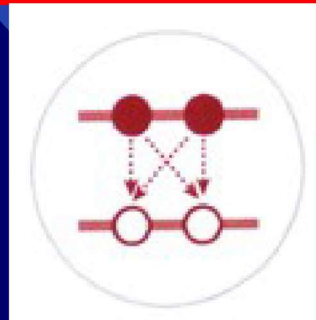
Possible sources of prompt photons (< 1ns)

Ce3+ Activator: 5d-4f
Ca^{2+} & Mg^{2+} co-doping
$\tau_r \sim 20$ ps $\tau_d > 16$ ns

Excitons
stable at 300 K



Bi-excitons
Multi-excitons
stables at 300 K



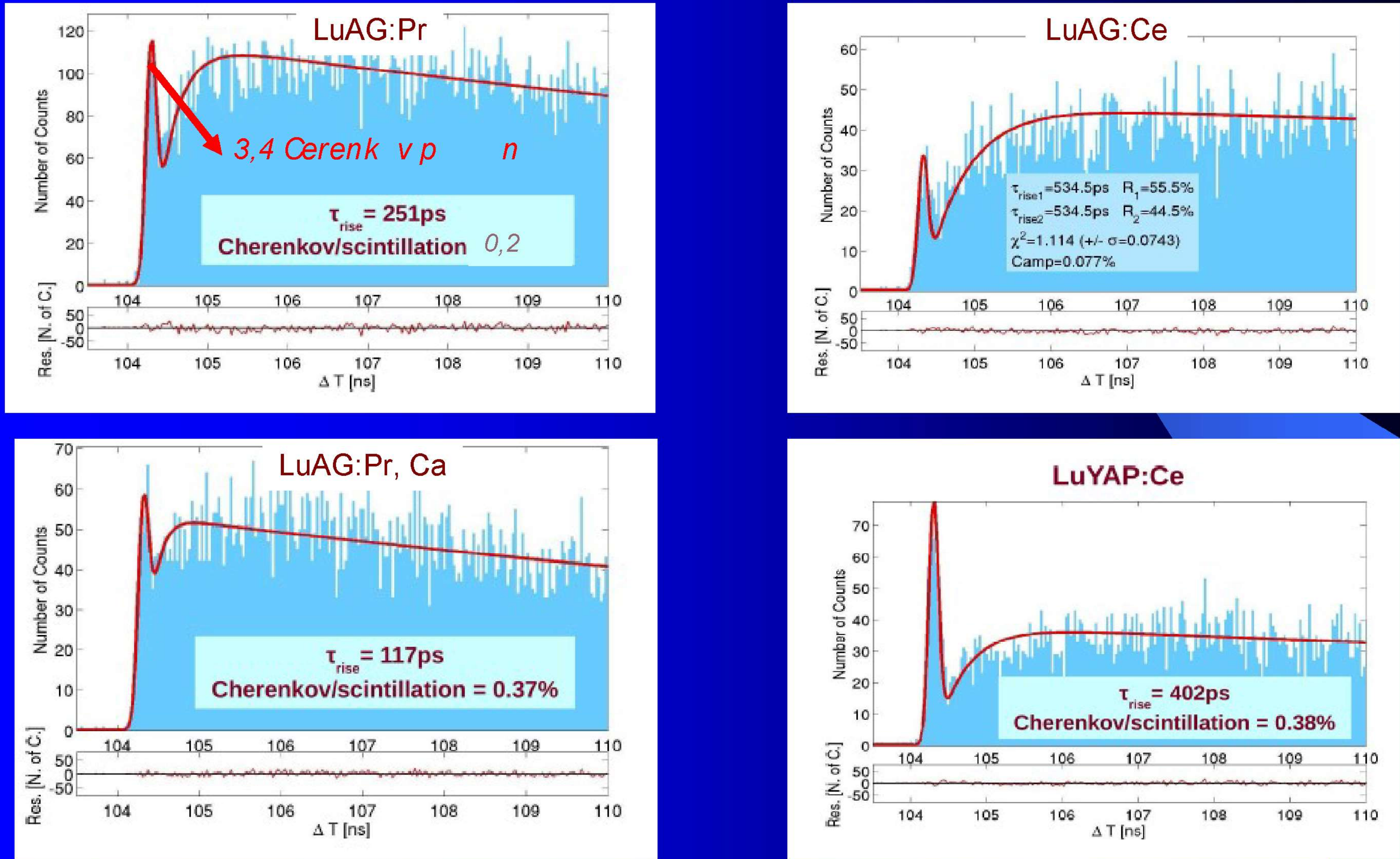
$$\frac{1}{\tau} = \frac{4e^2}{3\hbar c^3}\,\omega_{21}^3\,\left|\vec{r}_{21}\right|^2$$

Cross Luminescence
<300 nm - <1ns

Hot Intraband Luminescence
0.1 - 10 ps

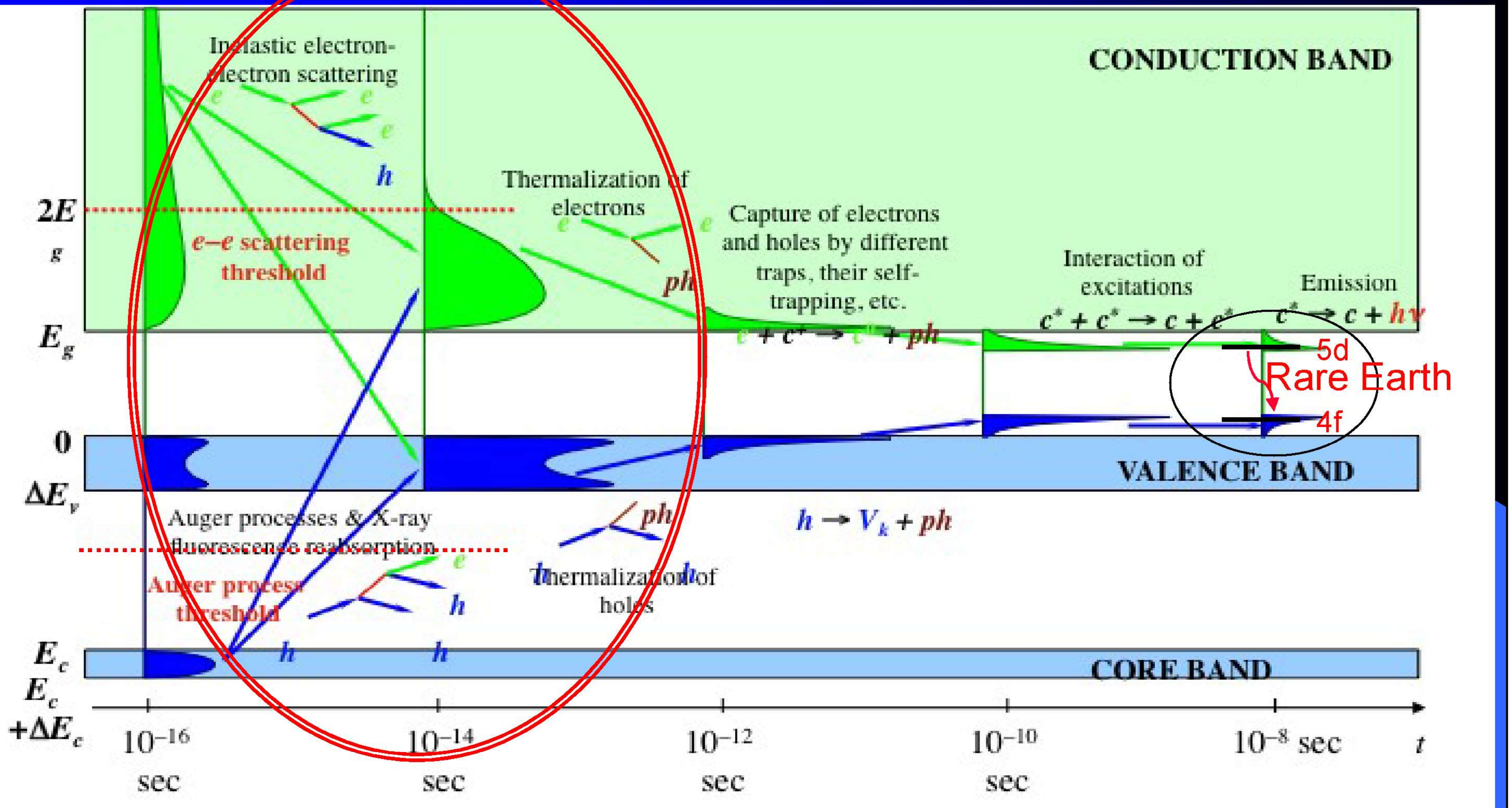
Cerenkov
$\tau \sim 0$ ps

Cerenkov contribution



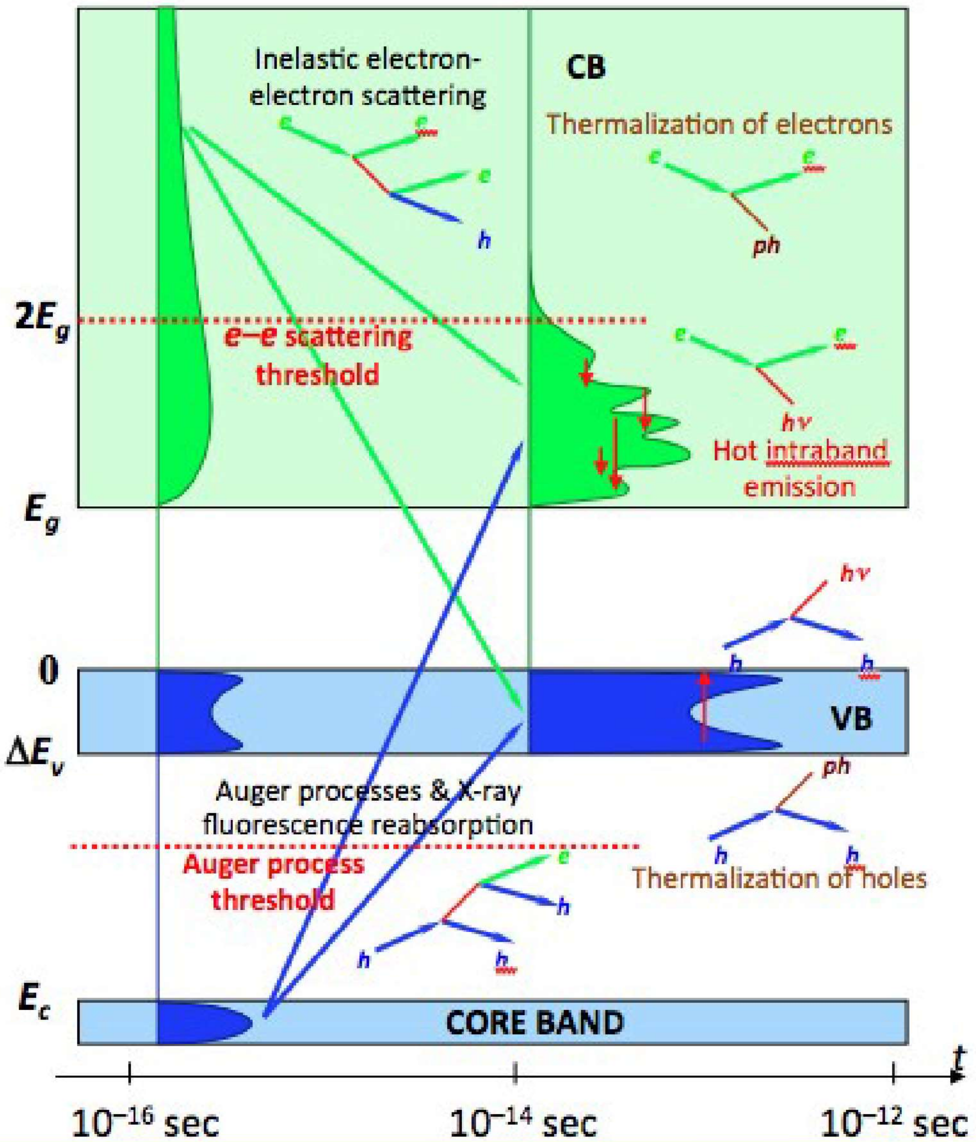
S. Gundacker, E. Auffray, K. Pauwels, and P. Lecoq, Phys. Med. Biol. , vol. 61, pp. 2802–2837, 2016.

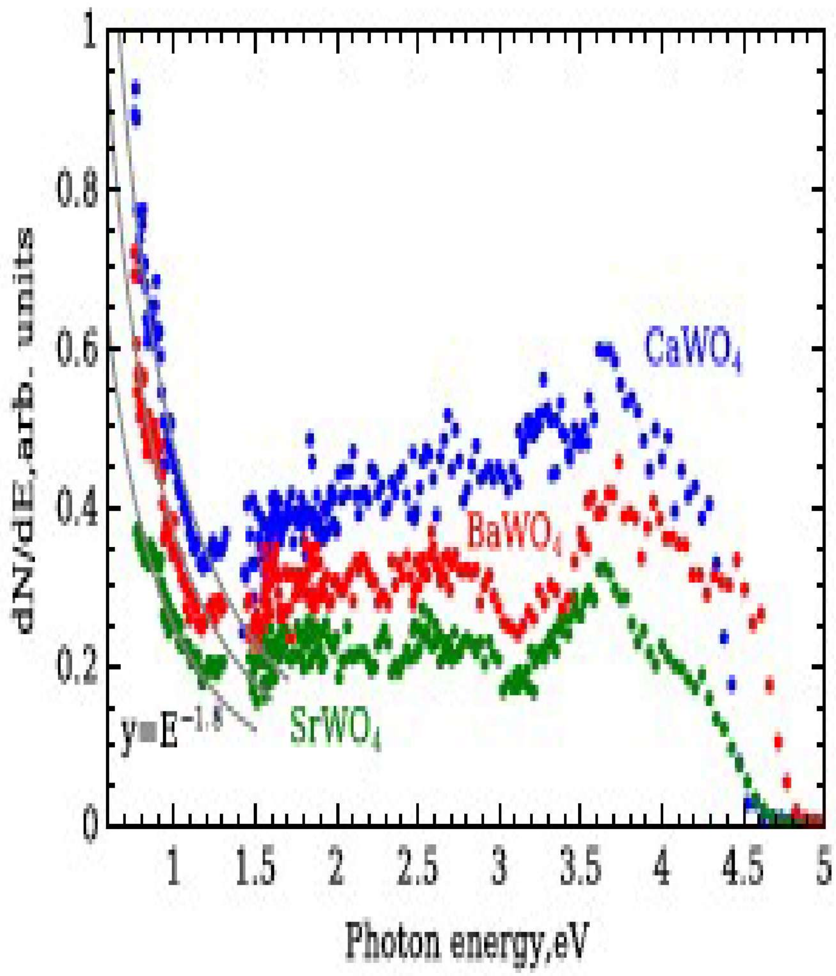
Light generation



A. Vasil'ev, SCINT2001 proceedings, NIMA 486 (2002) 367

Hot intraband luminescence





Quantum dots spontaneous emission

Decay time is driven by the electric dipole moment between the e cited and fundamental states

$$_{n} = \frac{1}{t_{n}} \quad \frac{n}{l^{3}} \left(\frac{n^{2} + 2}{3} \right)^{2} \quad \left| \langle \quad | m | i \rangle \right|^{2}$$

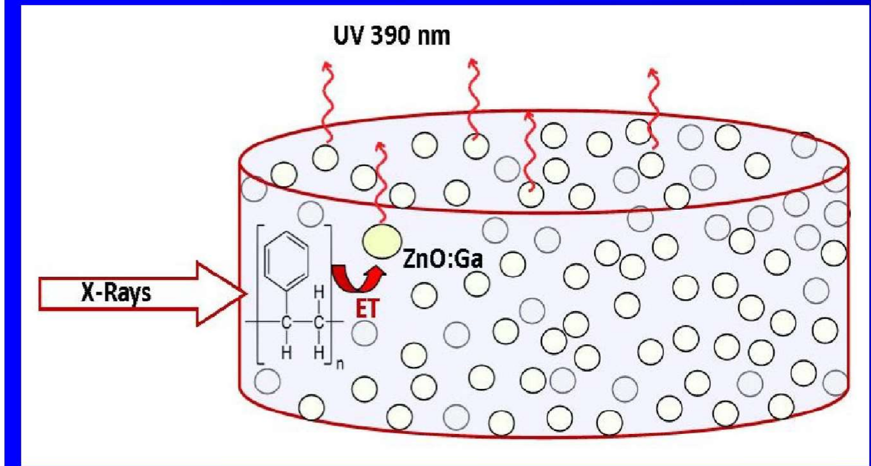
E citon confinement in quantum wells leads to efficient and sub-ns luminescence

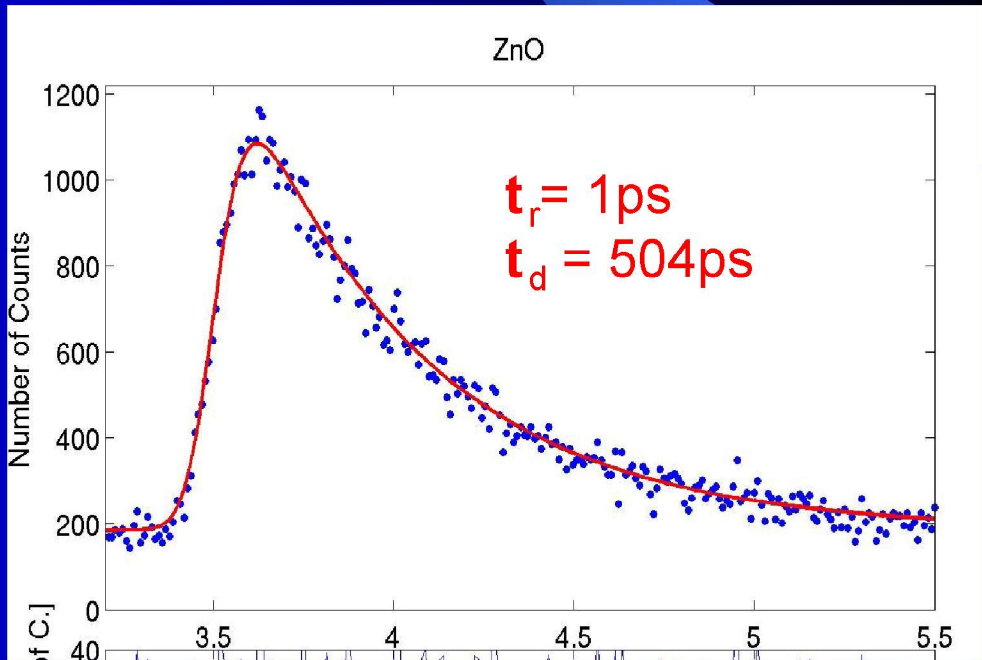
Properly designed quantum dot-based heterostructures can produce coherent phasing of dipoles over many unit cells and achieve   iant Oscillator Strength (OS)

nO:Ga polystyrene composite scintillator

ighly luminescent nO: a nano crystals 0-100nm

– Prepared by a photochemical method
– Embedded in a polystyrene sheet 10 weigth



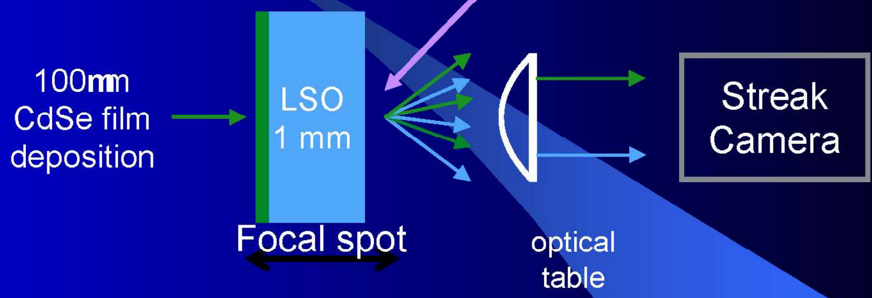


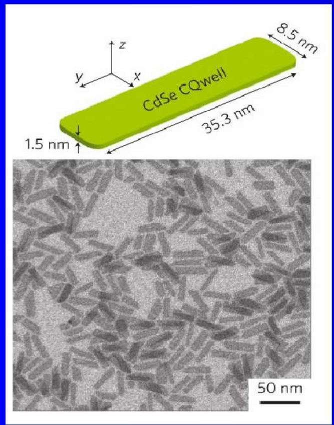
GOS in 1D quantum confined systems

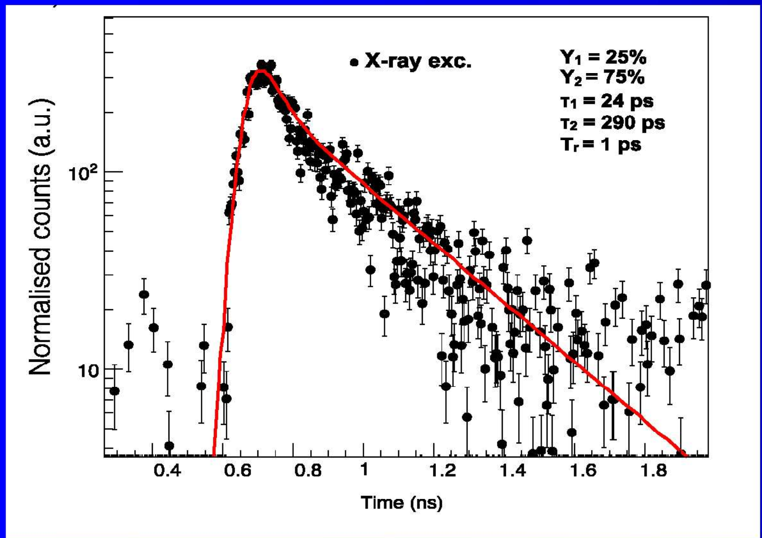
S plate 1mm thick

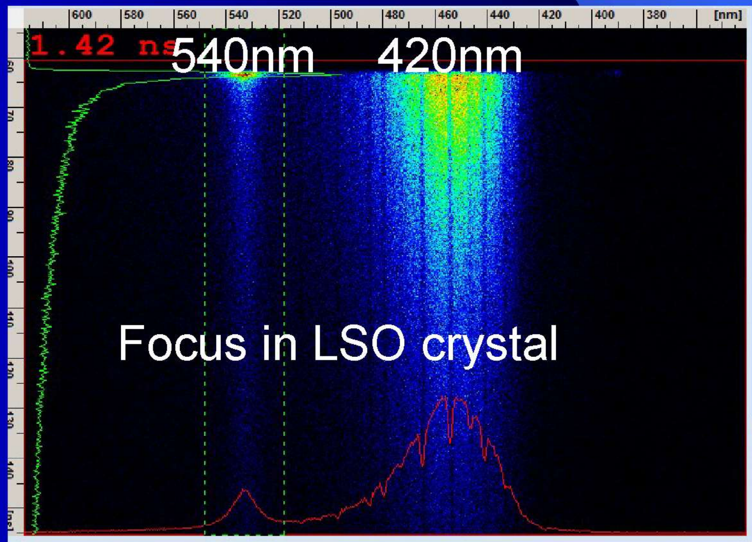
CdSe nanoplate film 100mm thick

372 nm laser

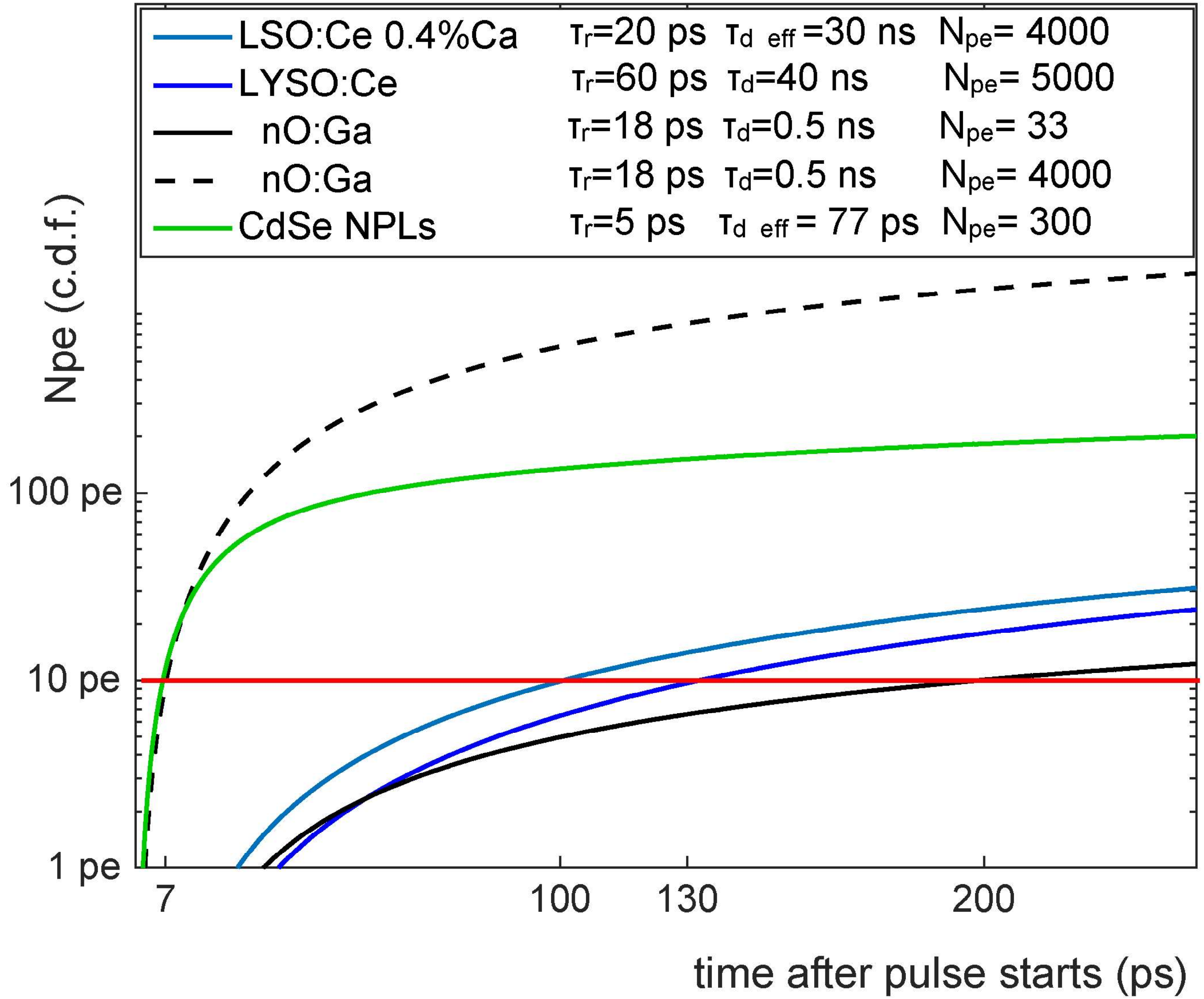






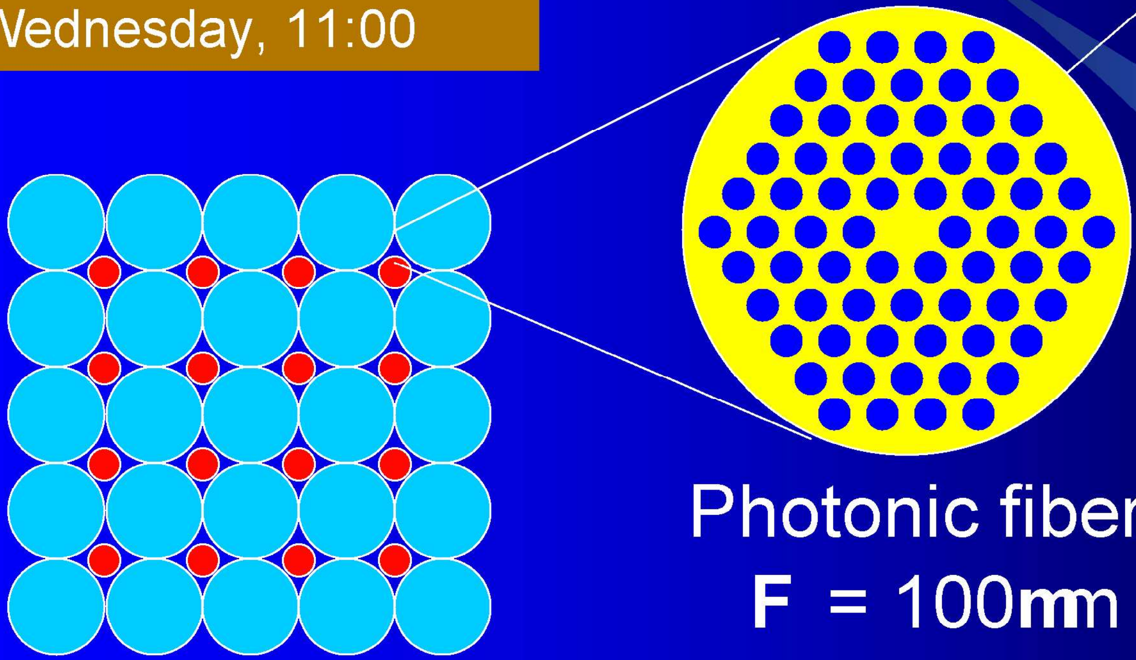


Time profile of pe generation for bulk and nano-crystals



Meta-X- Detector Block for Low Energy Applications

More by R. Martine Turtos
Wednesday, 11:00



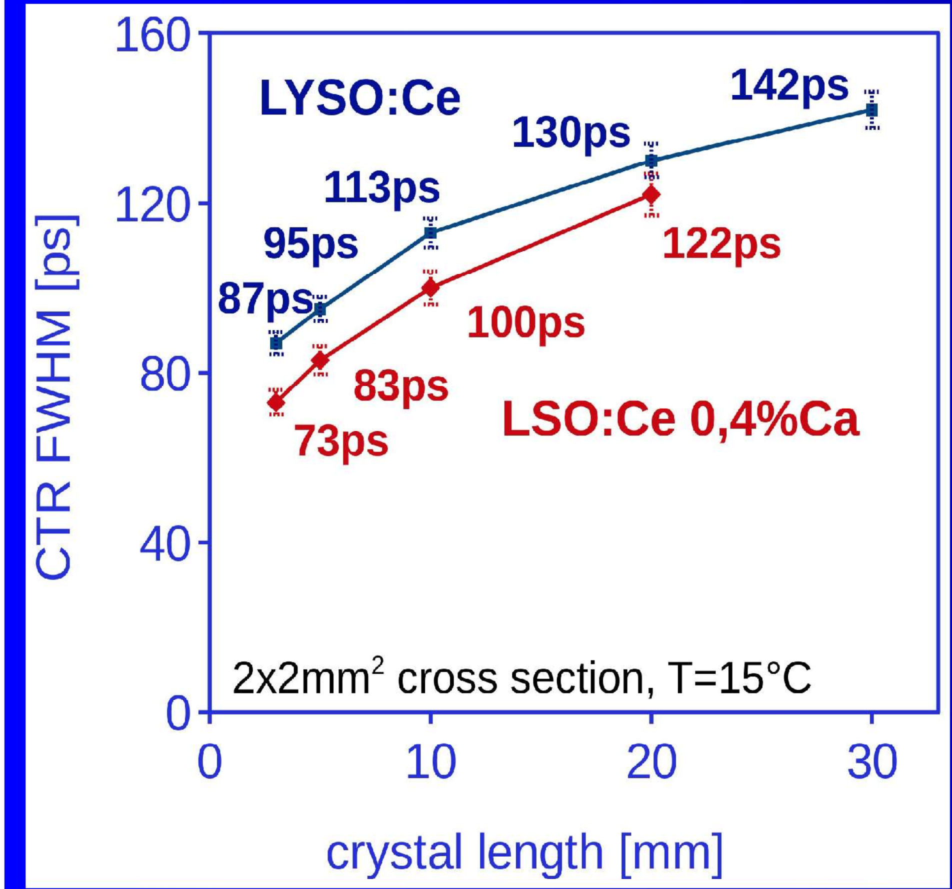
Quantum dot loaded polymer with a gradient of QD radius along the fibre

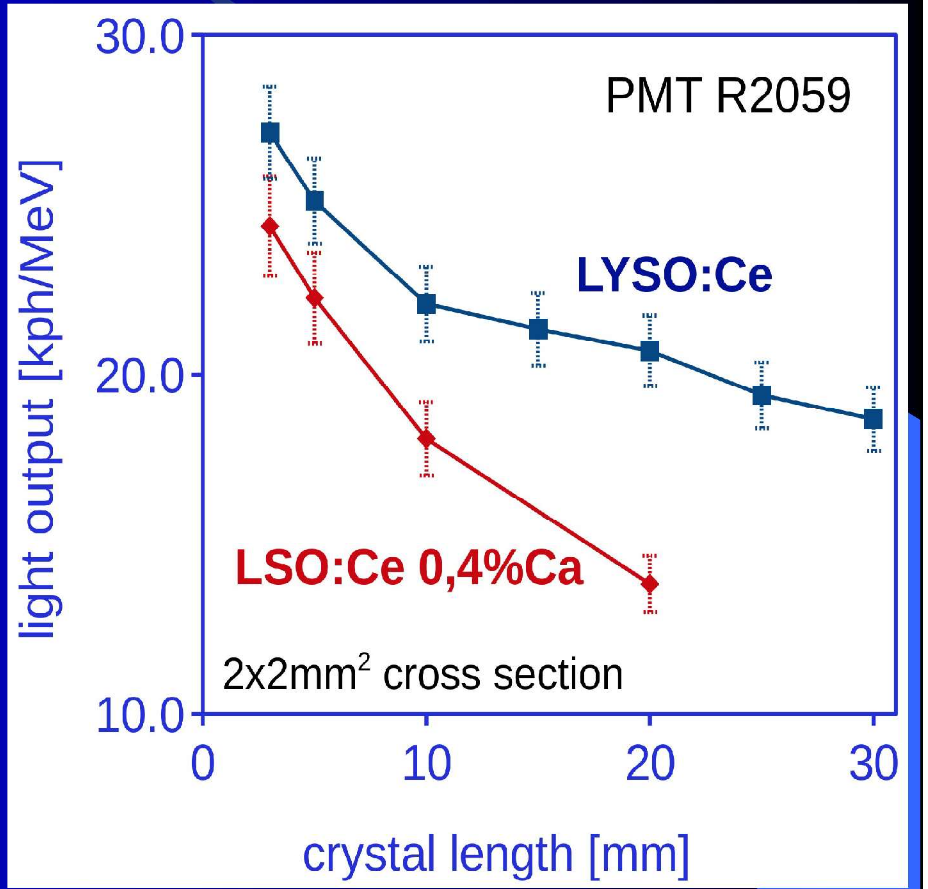
Photonic fibers
F = 100mm

Heavy scintillating fibers
(LuAG, LSO)
F = 500mm

Influence of crystal length on timing resolution

Measured with FBK NUV-HD (25 m SPAD si e, 4x4mm^2 device si e)
2x2mm^2 crystal cross section, T=15 C





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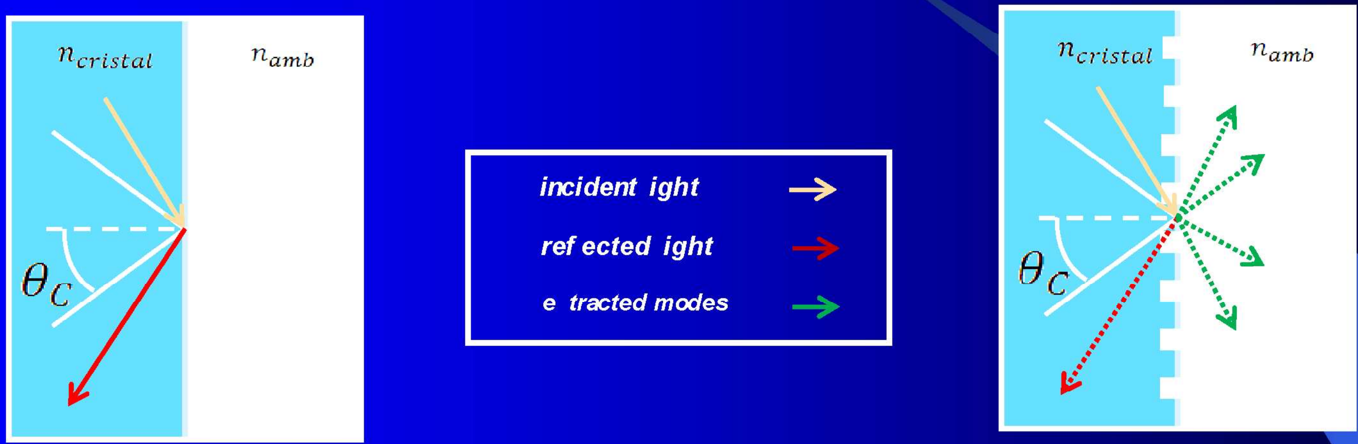
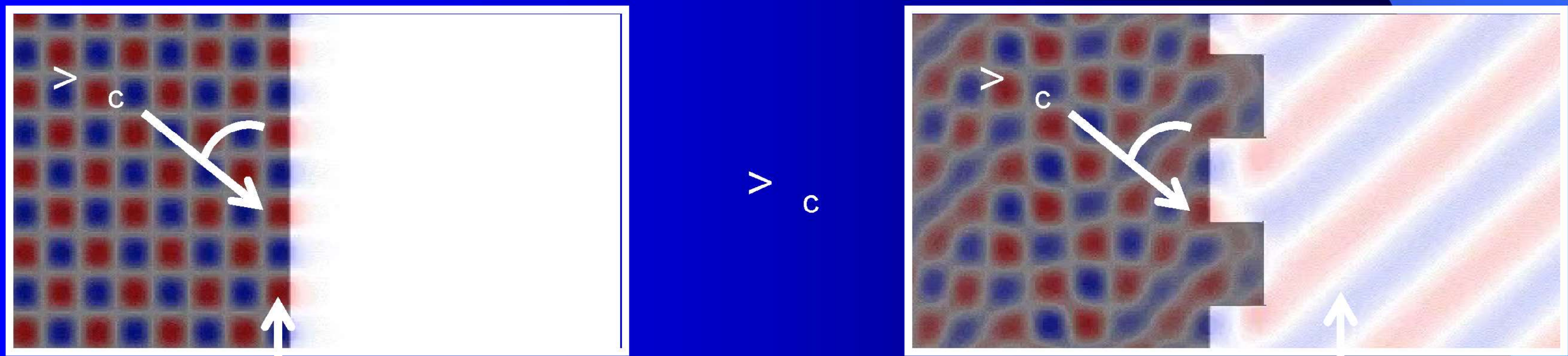
Photonic Crystal: principle of work

Diffracted modes interfere constructively in the PhC-grating and are therefore able to escape the crystal

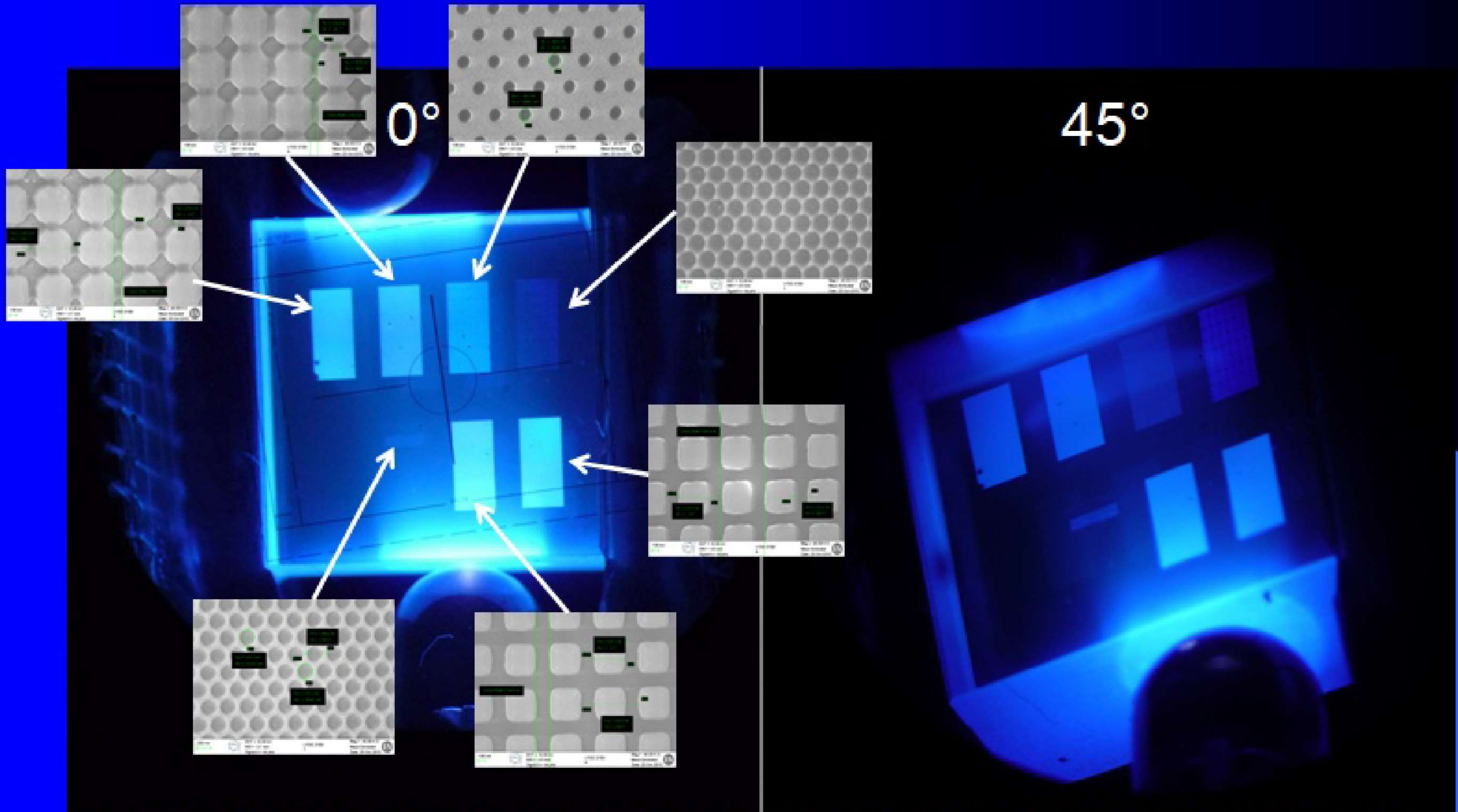




Total Reflection at the interface

Extracted Mode

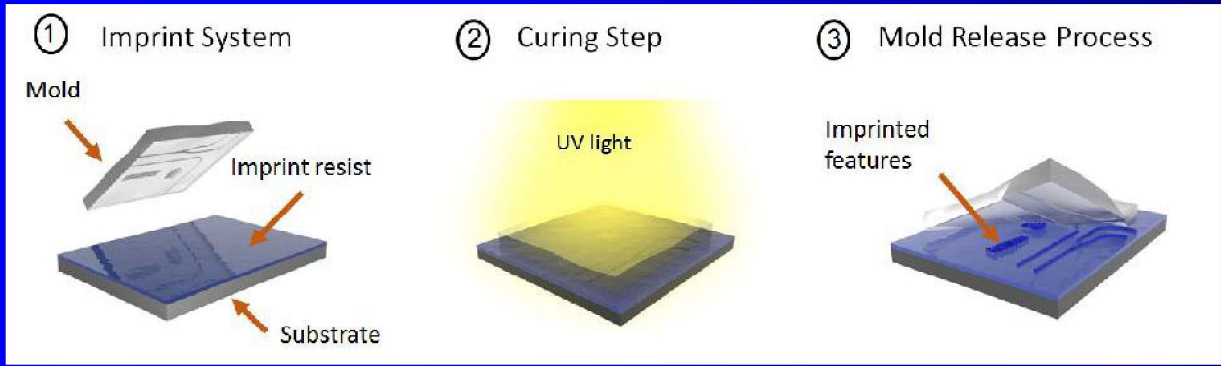
Photonic crystals

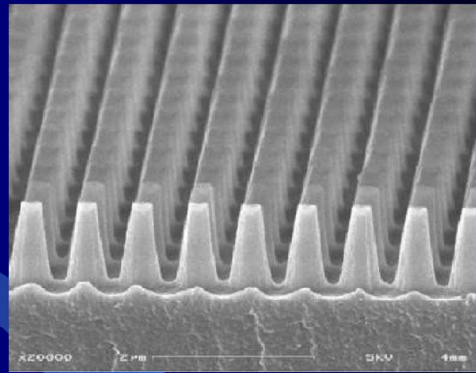


A. Knapitsch et al, "Photonic crystals: A novel approach to enhance the light output of scintillation based detectors, NIM A268, pp.385-388, 2011

LY and energy resolution gain

CERN, RMD, MIT, Abeam Technologies





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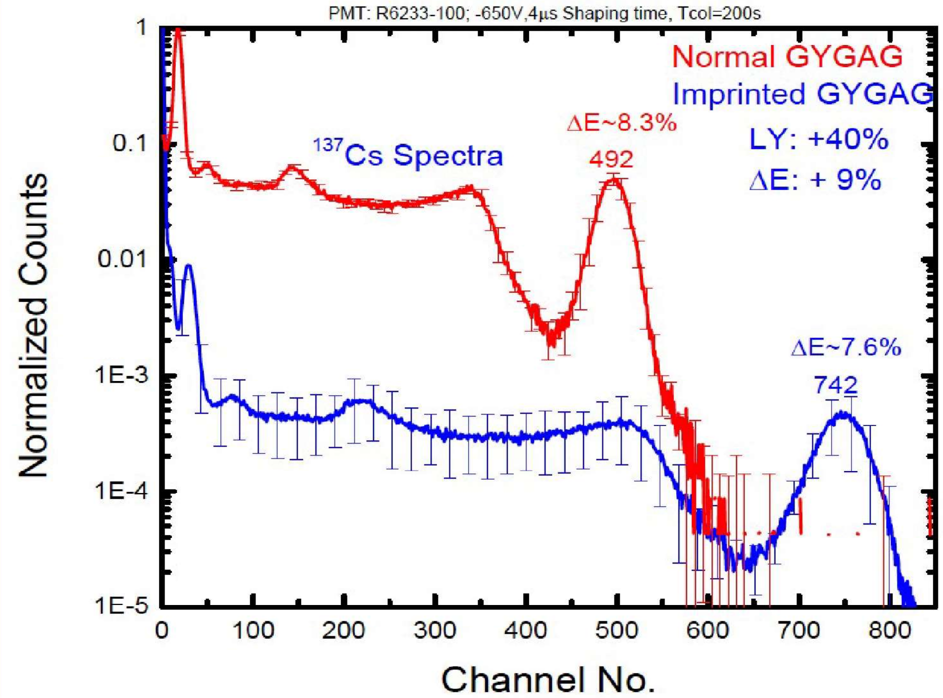
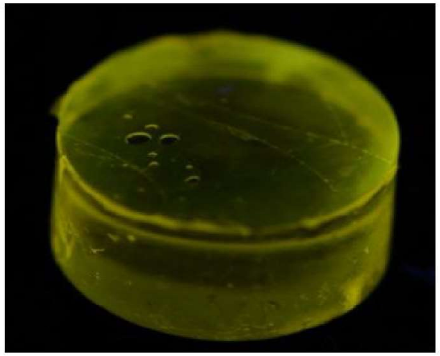


Custom Polymer	RI	Gain in LY	Gain in Energy Resolution
CP5	1.88	40%	9%
CP2	1.82	33%	3.6%



TurboPET MAMMI

NAPA Technologies, ONCOVISION, CERN, HCUV, UT Troyes

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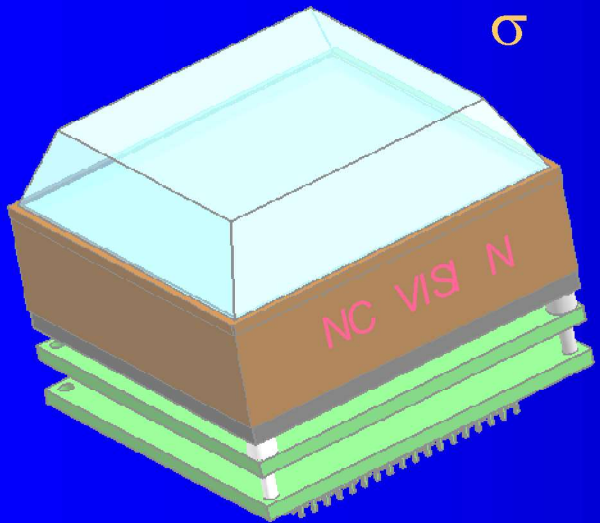
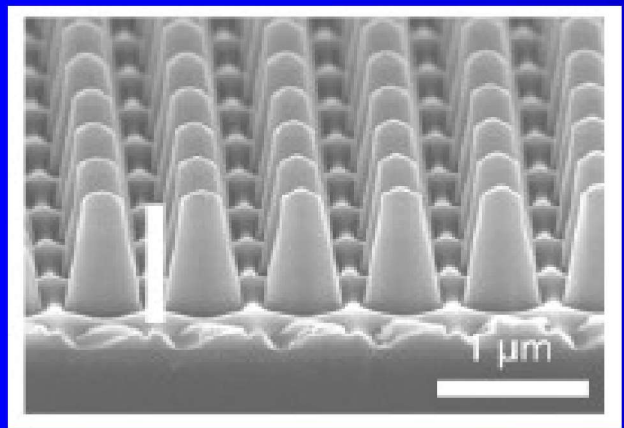
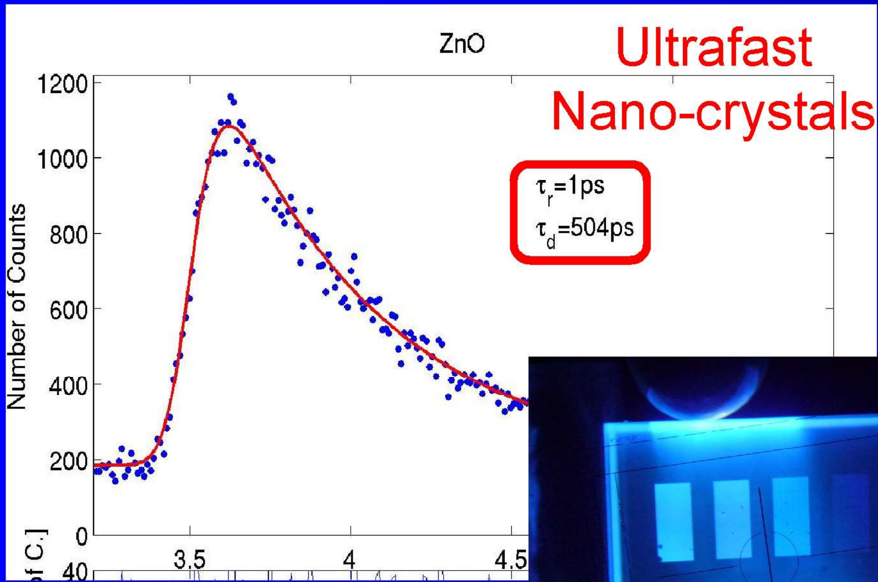
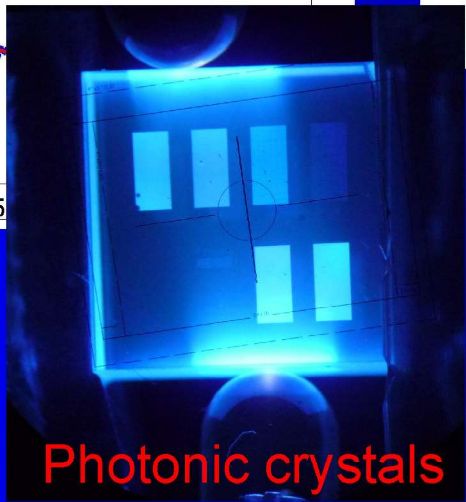


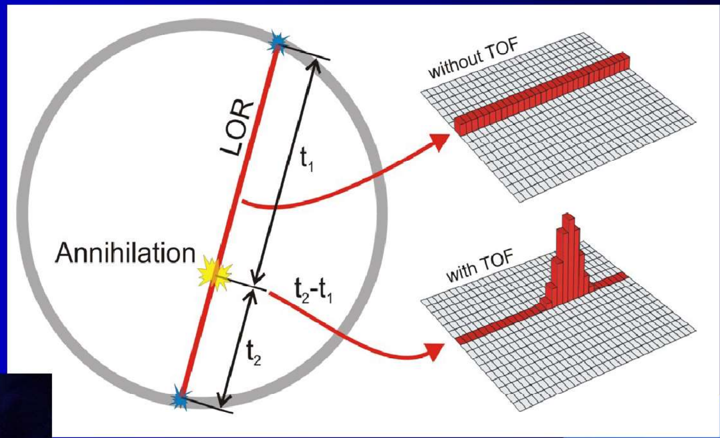


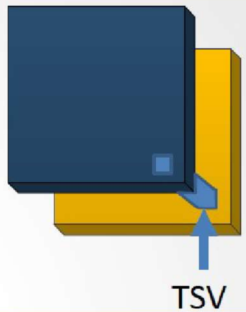
Fast sintillation timing: the way to reconstructionless TOFPET

Ultrafast Nano-crystals









Digital 3D SiPM

- High fill factor - PDE
- Electronic flexibility
- Heterogeneous technologies
- The only way to eliminate the SPAD to TDC timing skew in the Single Photon Timing Resolution

erc TICAL

Fast Advanced Scintillator Timing

cost TD1401 EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY FAST

Conclusion - 1

"Impossible" is not a French word *(Napoléon)*

Conclusion - 2)

inspired by Maurizio Conti, Siemens (MEDAMI 2017, Sardinia)

- . . . looking forward to a 10 ps TOF PET!

OR

  - eagerly anticipating a 10 ps TOF PET!
  - eagerly/impatiently awaiting a 10 ps TOF PET!
  - anticipating with pleasure a 10 ps TOF PET!
  - hoping for a 10 ps TOF PET!
  - drooling/slobbering in anticipation of a 10 ps TOF PET!
  - envisioning with pleasure/delight/joy a 10 ps TOF PET!
  - confidently awaiting a 10 ps TOF PET!

Conclusion

- Standard scintillation mechanisms are unlikely to give access to the 10ps range
- A number of transient phenomena could generate sub-ns measurable signals
- Photonic crystals improve scintillator timing resolution by two means:
  - increasing the light output decreasing photostatistics jitter
  - redistributing the light in the fastest propagation modes in the crystal
- New generation SiPM
  - Requires significant improvement on SPTR for low energy deposition

The dream of the fast timing imager

Implies   mm resolution along PET LOR

Requires   10ps timing resolution

1mSv PET exposure   1 flight Paris-SF

CT Transaxials