Comparing BSO and BGO with different surface finishes as cost-effective, hybrid scintillation/ Cherenkov detectors for TOF-PET

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European Commission

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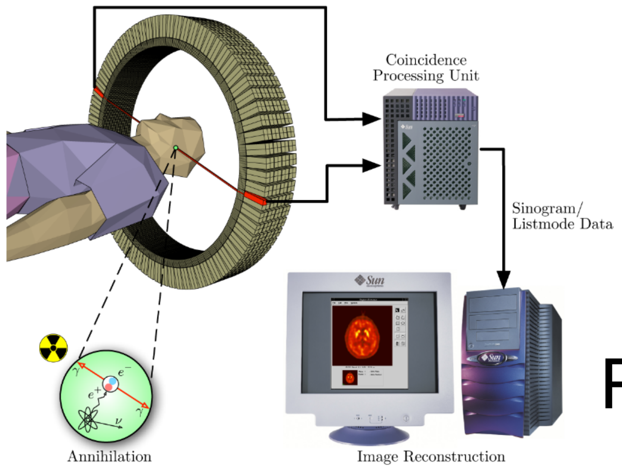
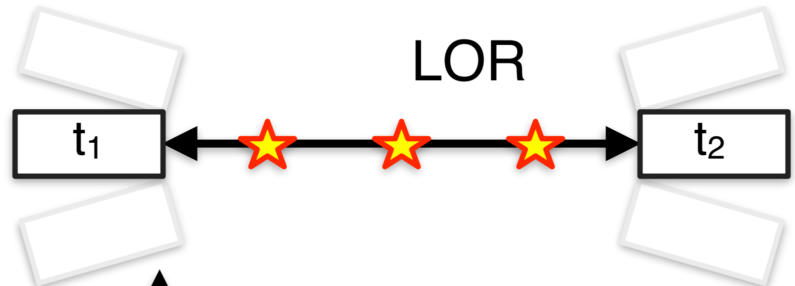
European Union funding
for Research & Innovation

TU Delft

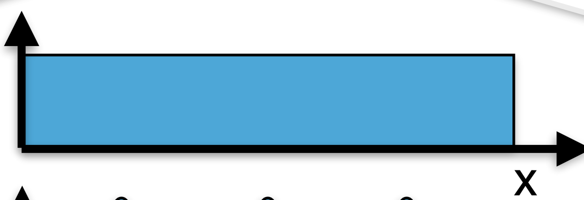
Motivation: TOF-PET

Wikimedia commons, http://en.wikipedia.org/wiki/Positron_emission_tomography

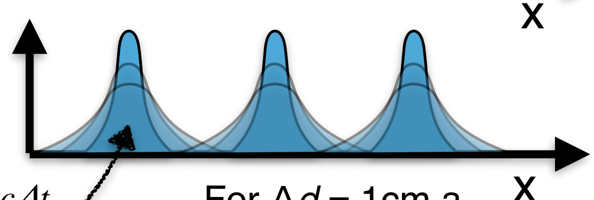




PET annihilation probability



TOF-PET annihilation probability



$$\Delta d = \frac{c\Delta t}{2}$$

For Δd = 1cm a Δt of 66 ps is required!

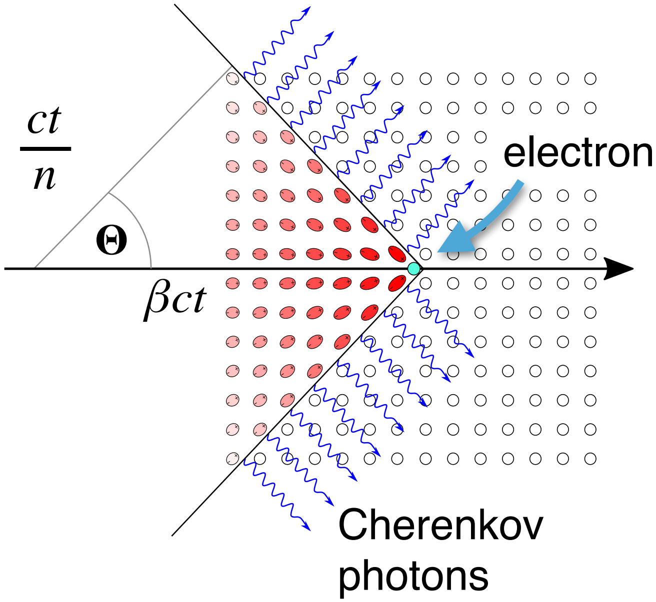
Time resolution (ns)	Δx (cm)	TOF NEC gain	TOF SNR gain
0.1	1.5	26.7	5.2
0.3	4.5	8.9	3.0
0.6	9.0	4.4	2.1
1.2	18.0	2.2	1.5
2.7	40.0	1.0	1.0

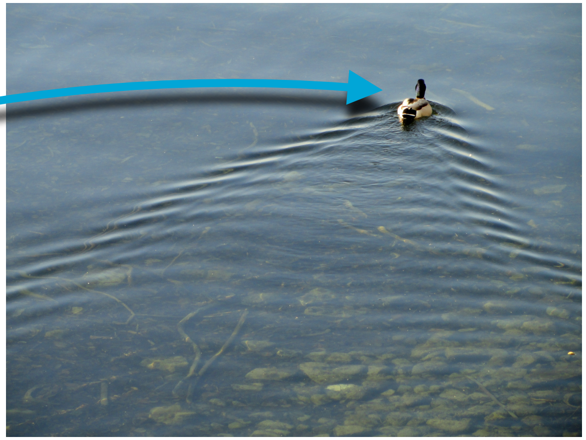
Conti 2011

- **State-of-the-art:**
  - Systems: CRT 300 ps to 400 ps FWHM (LSO:Ce based)
  - Preclinical systems: 200 ps to 250 ps FWHM (LSO:Ce based)
  - Lab: 70 ps to 80 ps FWHM (Ca codoped LSO:Ce, 3x3x5mm^3)

Cost-efficient timing - Ultra-fast processes

The Cherenkov effect

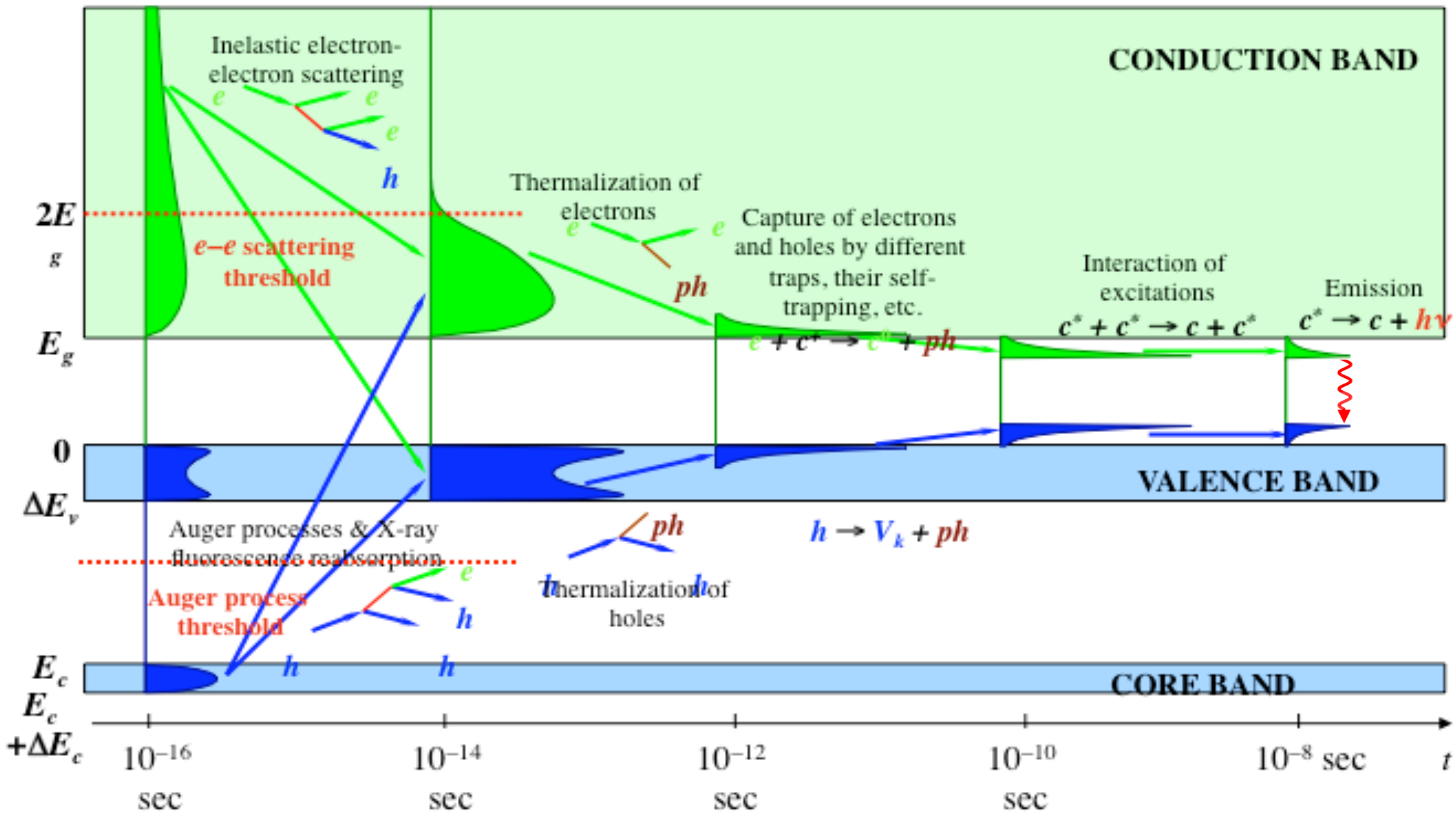




- Photons emitted almost **instantaneously (< 10 ps)**
- Emission increases towards **blue/UV** (prop $1/\boldsymbol{\lambda}^2$)
- Emission increases with increasing refractive index
- Only **a few Cherenkov photons** are emitted at **511 keV** (10-20 photons)

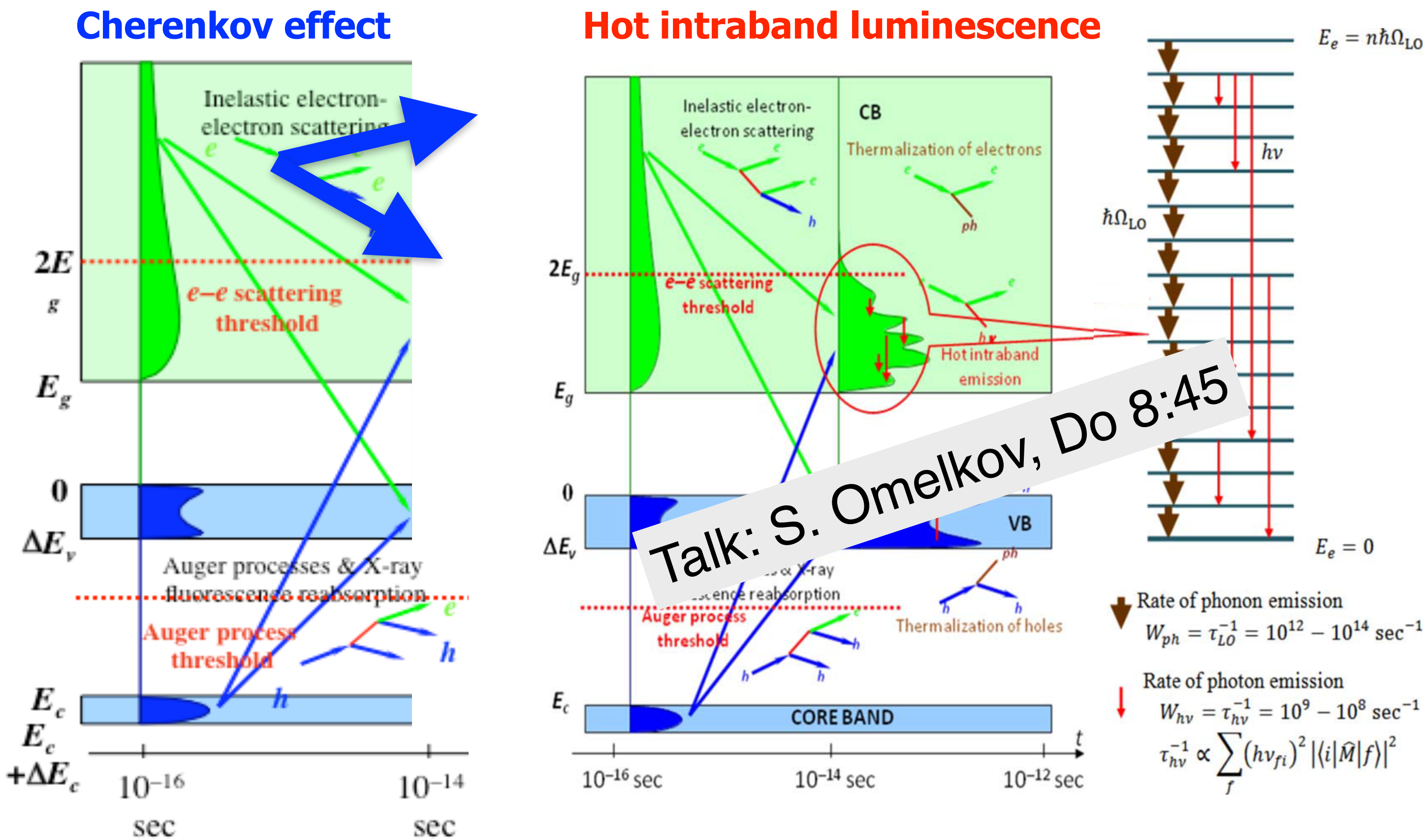
$$\frac{\mathrm{d}N^2}{\mathrm{d}x\mathrm{d}\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{n(\lambda)^2\beta^2}\right)$$

Annihilation photon induced Cherenkov emission



Based on: Vasil'ev, SCINT99

Annihilation photon induced Cherenkov emission



Based on: Vasil'ev, SCINT99

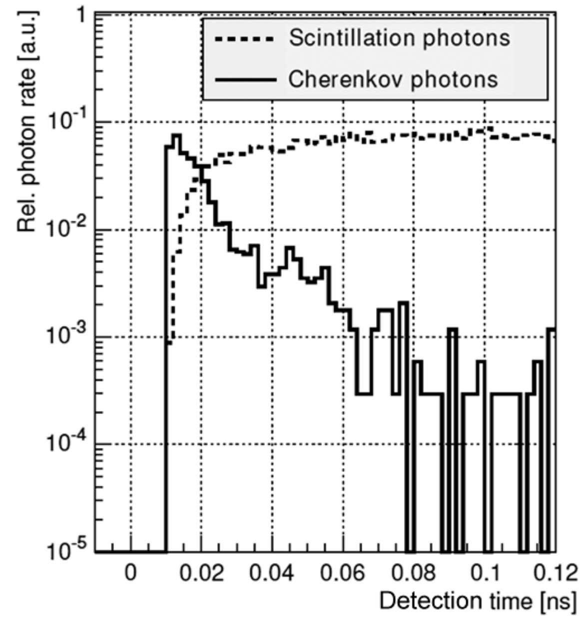
Investigating materials

Problem: How to discriminate photoelectric events from Compton scattering?

A1: Energy after Compton scattering is not sufficient for Cherenkov emission - *pure Cherenkov radiator* ($\beta_{thr} > 1/n$)

A2: Use of combined scintillation and Cherenkov emission - *hybrid Cherenkov radiator / scintillator*

LSO:Ce



- Simulation study using Geant4
- Figure of merit: ratio of Cherenkov/scintillation emission in first 100 ps
- **LSO:Ce, LuAG:Ce, BGO, PbWO, Pb-glass**

Ratio Cherenkov/scintillation photon yield

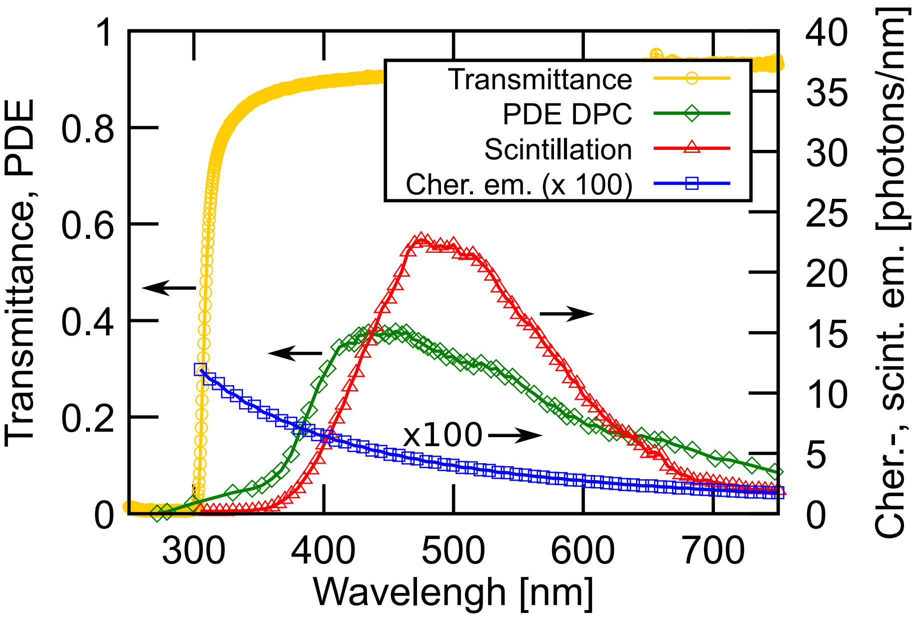
Material	< 25 ps	< 100 ps
LSO:Ce	1.78	0.16
LuAG:Ce	41.5	3.4
BGO	364	28
PWO	134	21

Brunner et al., IEEE TNS 61-1 (2014)

Comparing LSO:Ce with BGO/BSO

BGO/BSO compared to LSO:Ce
- *higher stopping power*
- *higher photo-fraction*
- *no intrinsic radiation*
- *is inexpensive*

BSO compared to BGO
- *improved detection rate cap.*
- *is inexpensive*



	Lu_2SiO_5:Ce	$Bi_4Ge_3O_{12}$	$Bi_4Si_3O_{12}$
Refractive index (@420nm)	1.83[a]	2.2[b]	2.06 (480 nm)[c]
Light yield [phot x MeV^{-1}]	30000[d]	8200[e]	1200[f]
Scint. rise time [ps]	69[g]	30[h], 50[p]	< 50 ps[r]
Decay time [ns]	40[g]	300 + fast[h,i,j]	100 + fast[c]
Density [g x cm^{-3}]	7.4[d]	7.13[m]	6.8[c]
Z_{eff}	66[n]	75.2[e]	74.4[l]
Photo fraction	0.31[o]	0.41[o]	0.43[o]
intrinsic radiation	yes	no	no

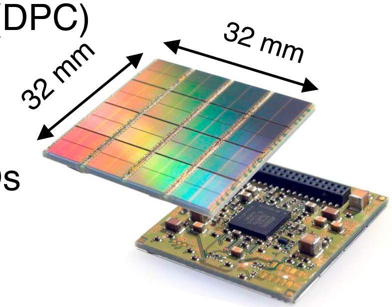
a) Spurrier 2008
b) Williams 1996
c) Ishii 2008
d) Humm 2003
e) Holl 1988
f) Shulgin 1991
g) Gundacker 2016
h) Derenzo 2000
i) Moszynski 1981
j) Wolszczak 2014
k) Kobayashi 1983
l) Harada 2002
m) Weber 1973
n) Welcher 1995
o) NIST XCOM
p) Brunner 2017
r) this work

A simple, digital SiPM based setup for high precision TCSPC on scintillators using e+/e- annihilation photons

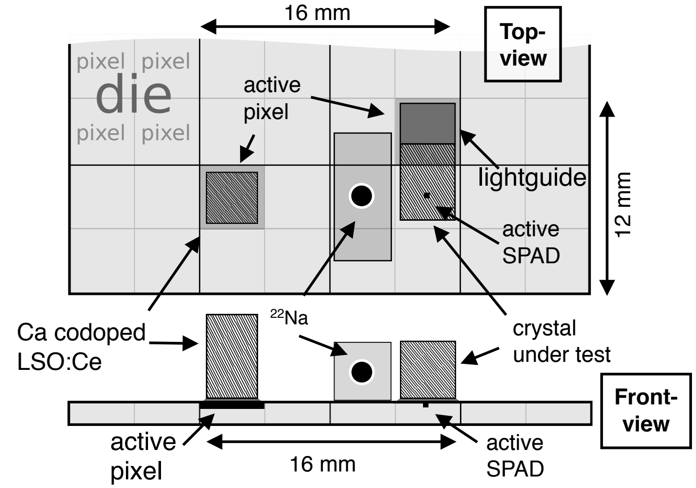
Motivation: Measure **rise time of scintillators including Cherenkov emission ➔** need 511keV for excitation (^{22}Na).

Detector: Philips Digital Photon Counter (DPC)

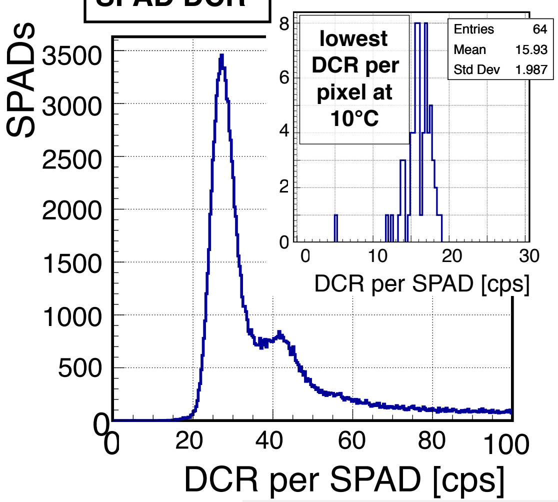
- 16 DPC dies → 16 timestamps
- 64 DPC pixels → 64 photon counts
- 3200 SPADs per pixel → > 200 kSPADs
- **each SPAD individually addressable**



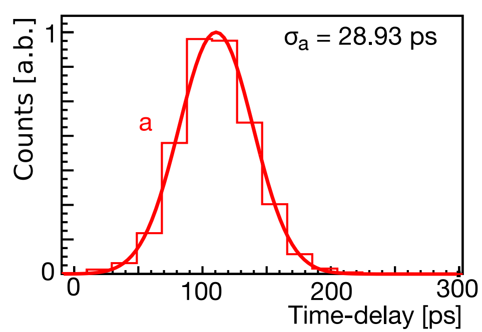
Time correlated single photon counting - setup



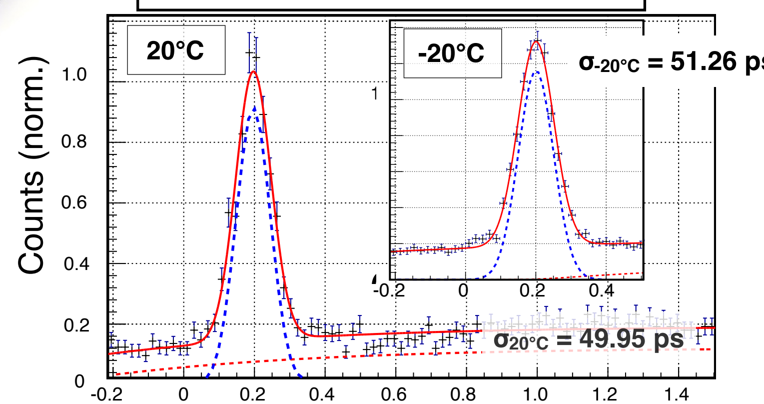
SPAD DCR

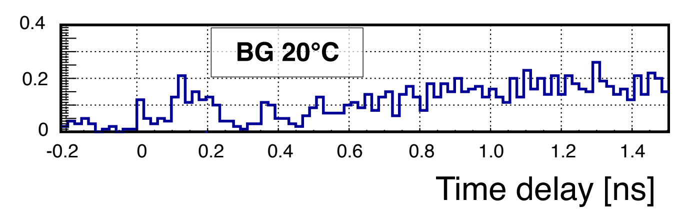


DPC SPAD SPRT 48 ps FWHM



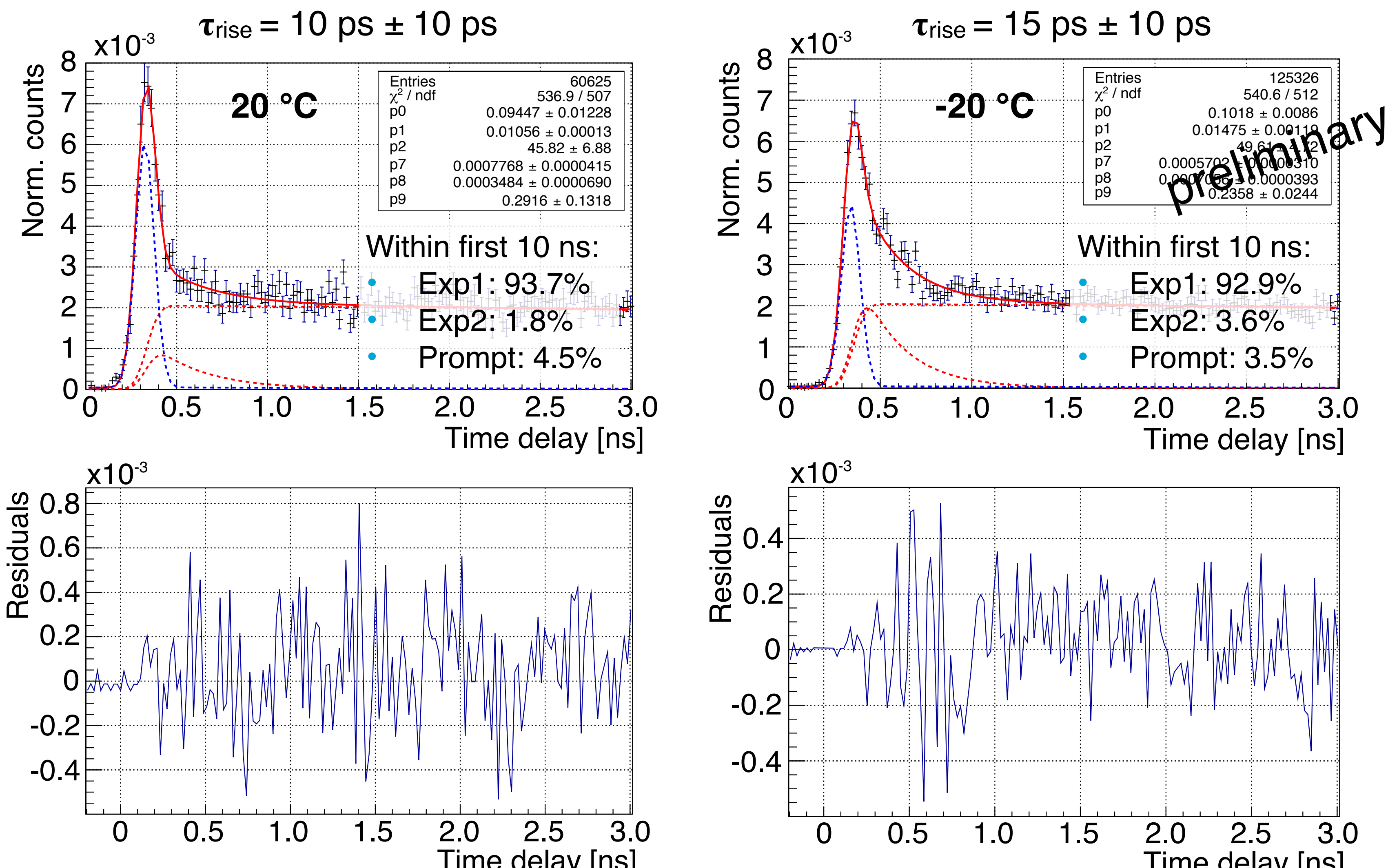
System TR - impulse response function using undated LuAG (Cherenkov only)





S. E. Brunner **The SPAD with the lowest DCR is selected for the TCSPC measurements.**

BGO: 511 keV excited luminescence spectra



$$p_{t_e}(t|\theta) = \sum_{i=1}^{N} \frac{\rho_i}{\tau_{d,i}-\tau_{r,i}} \left(e^{-\frac{t-\theta}{\tau_{d,i}}} - e^{-\frac{t-\theta}{\tau_{r,i}}}\right)\cdot\Theta(t-\theta)+\delta_C(t-\theta).$$

$$f_{te}(t|\Theta) = p_{te}(t|\Theta) * IRF(t)$$

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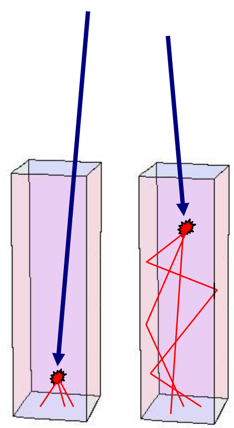
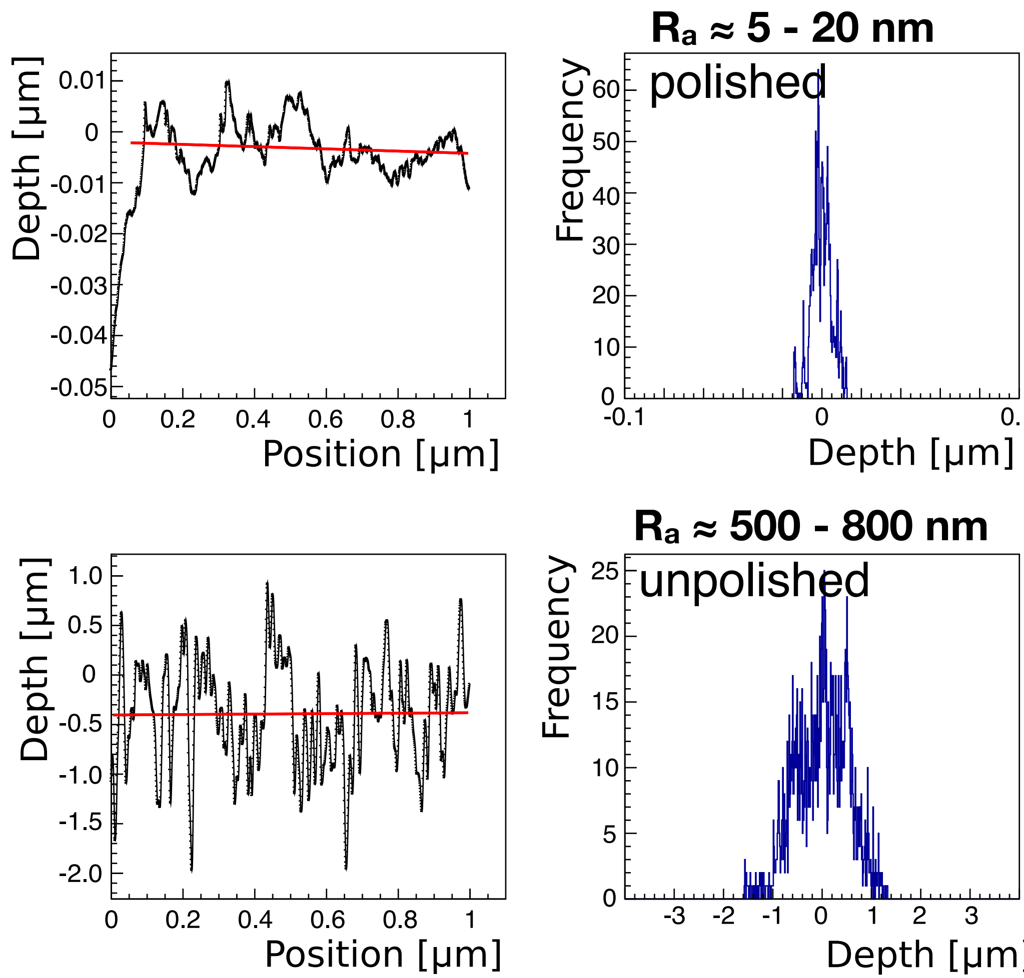
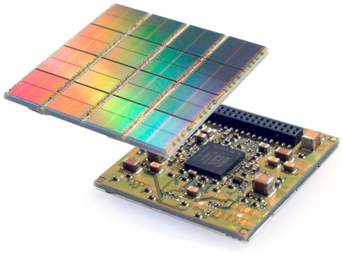
Adding the surface roughness as parameter to the timing measurements

- Photon transport time jitter is factor influencing the timing
- Few photons emitted → majority is reflected at surface
- Investigate timing of BGO and BSO with different surface roughness
- Roughness R_a measured using a profileometer
- R_a is rms along 1 µm

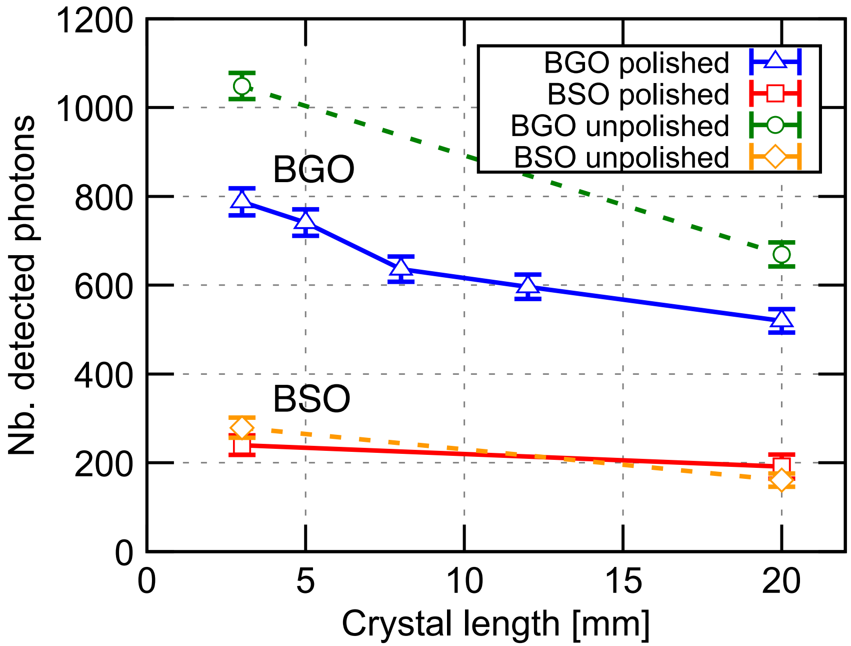




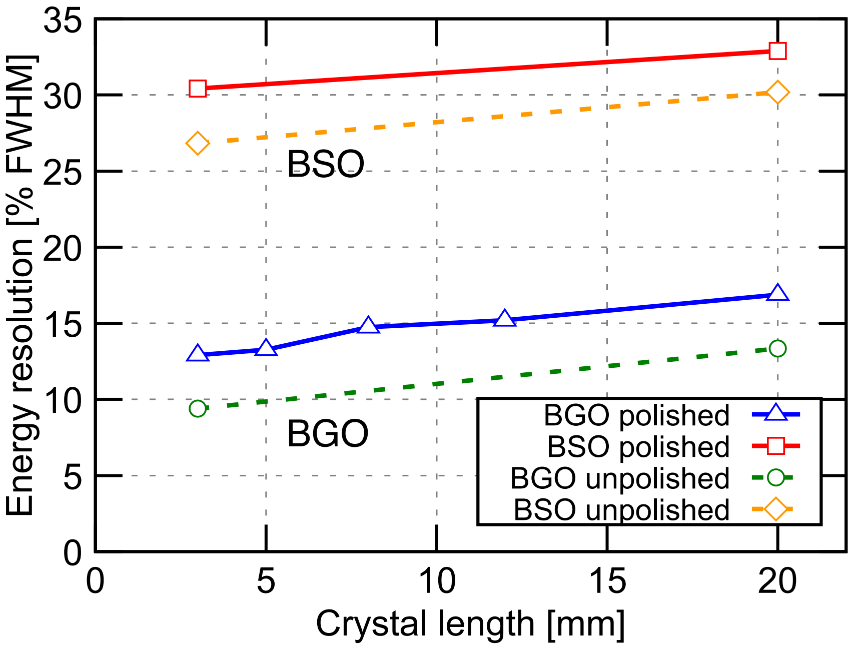
Energy resolution and photon detection yield of BGO/BSO at



Photon detection yield

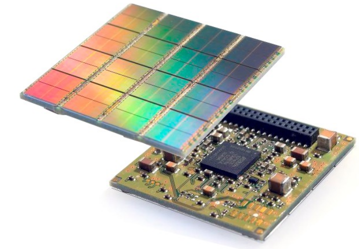


Energy resolution

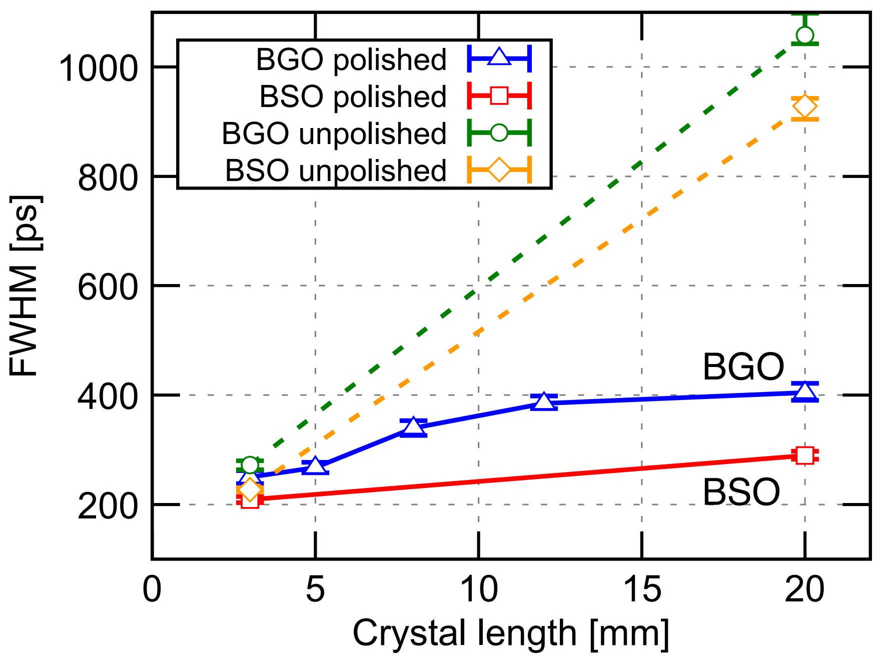


coincidence setup using ^{22}Na (511keV); cross section 3 mm x 3 mm; +20°C; Teflon wrapping; attached to digital photon counter; BC630 grease

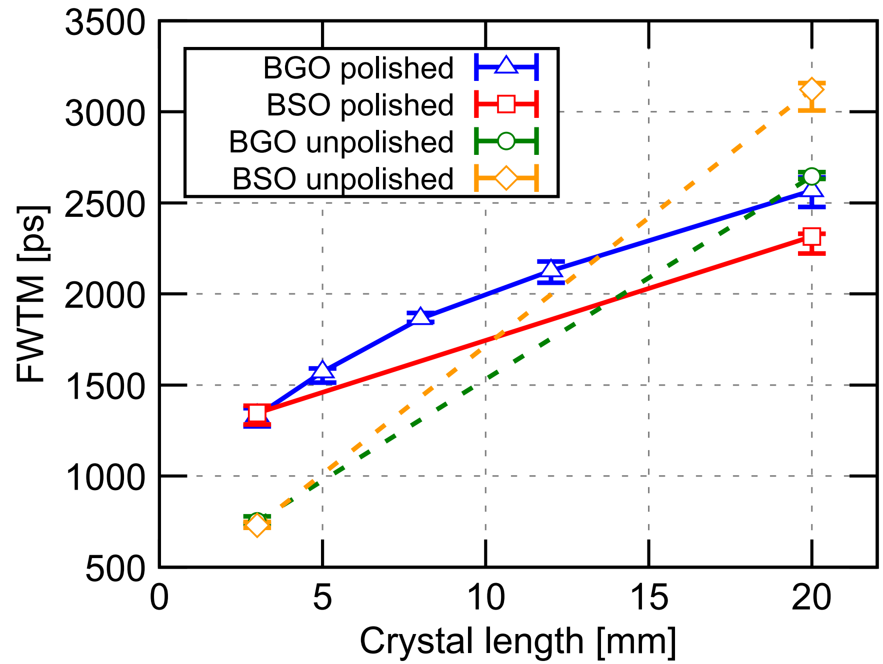
Coincidence timing with BGO and BSO



FWHM

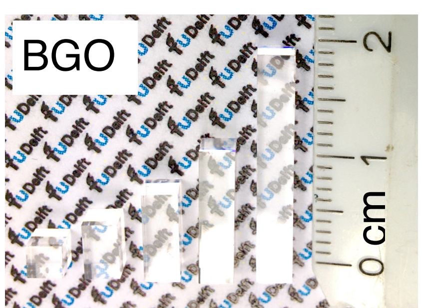


FWTM

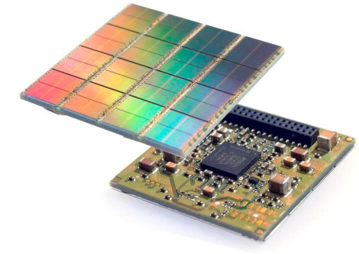


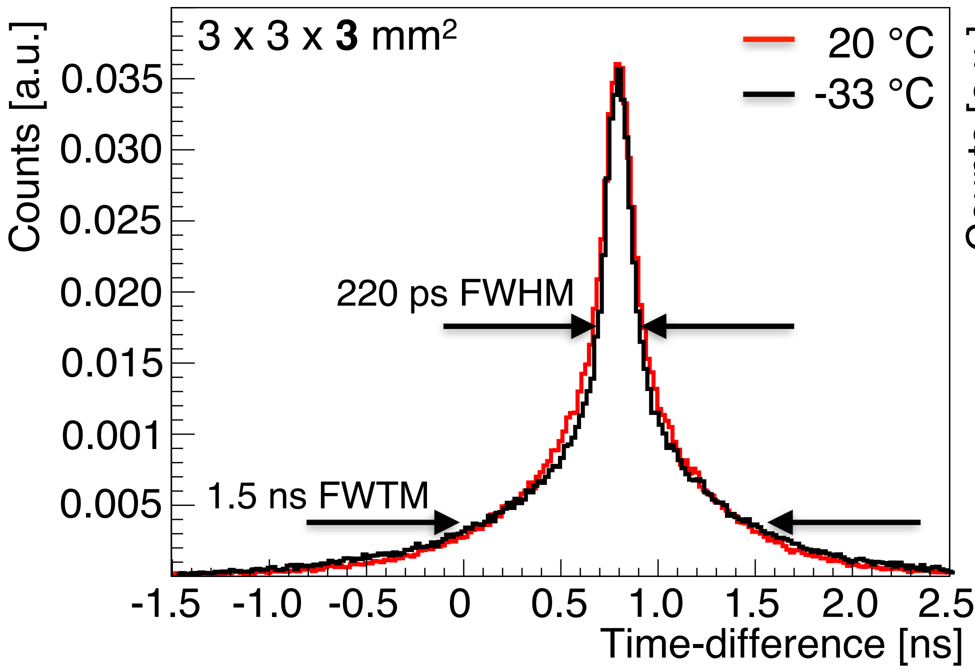
Timing performance of **BGO** and **BSO** almost similar although $LY_{BSO} : LY_{BGO} \approx 1 : 8$; $\tau_{decay\text{-}BSO} : \tau_{decay\text{-}BGO} \approx 1 : 3$!

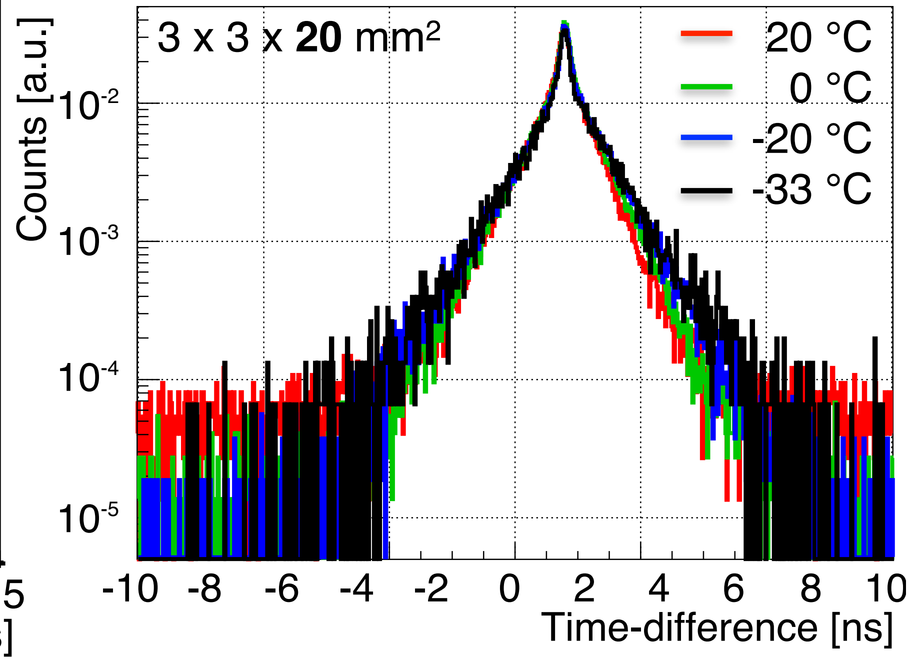
coincidence setup using ^{22}Na; cross section 3 mm x 3 mm; +20°C; Teflon wrapping; attached to digital photon counter; BC630 grease



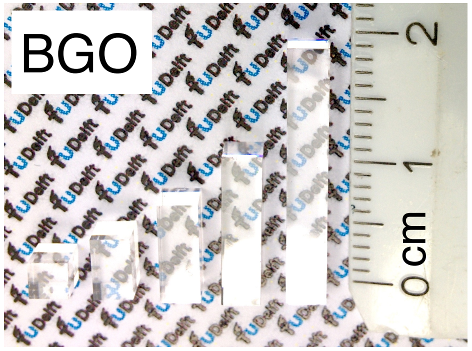
Coincidence Resolving Time





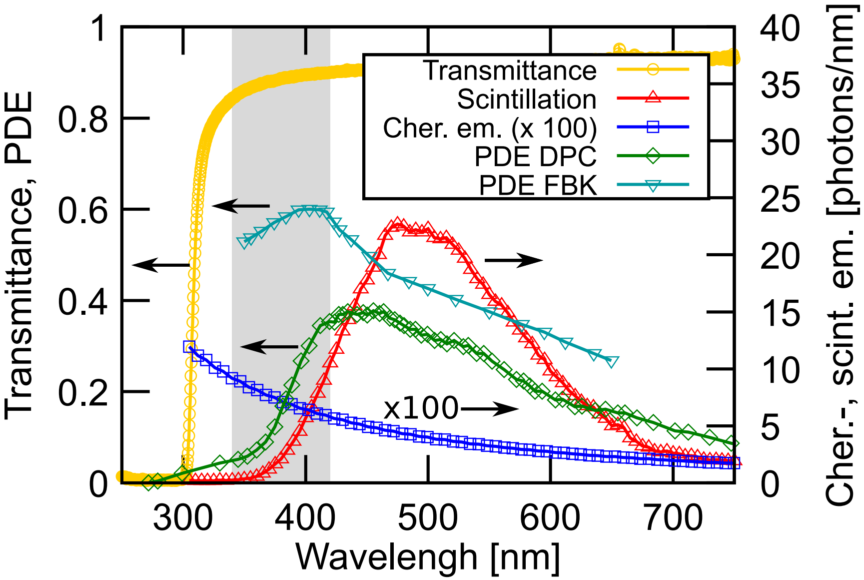


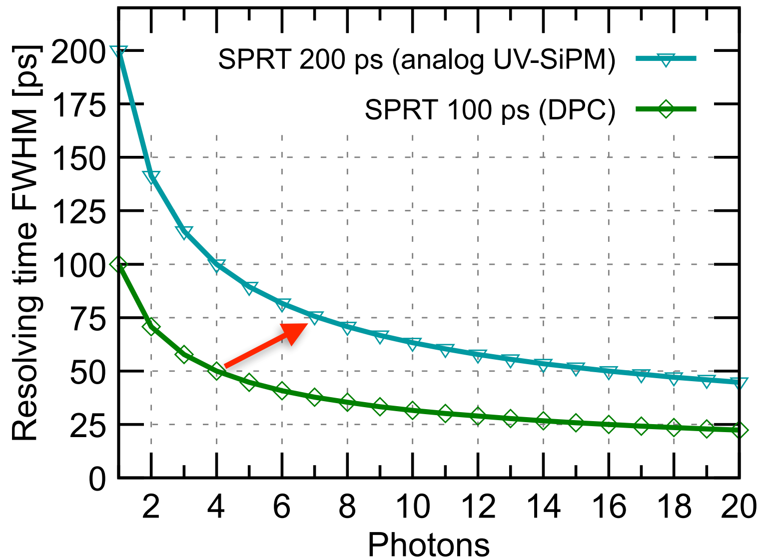
Crystal cross section 3 x 3 mm²; surface polished; wrapped in Teflon; opt. coupler BC630; 2 Philips DPCs in coincidence with ^{22}Na source



Comparison analog - digital SiPM with BGO/BSO

	size [mm³]	CRT FWHM [ps]
analog[1]	2 x 2 x 3	267
digital[2]	3 x 3 x 3	250
analog[1]	3 x 3 x 20	562
digital[2]	3 x 3 x 20	404

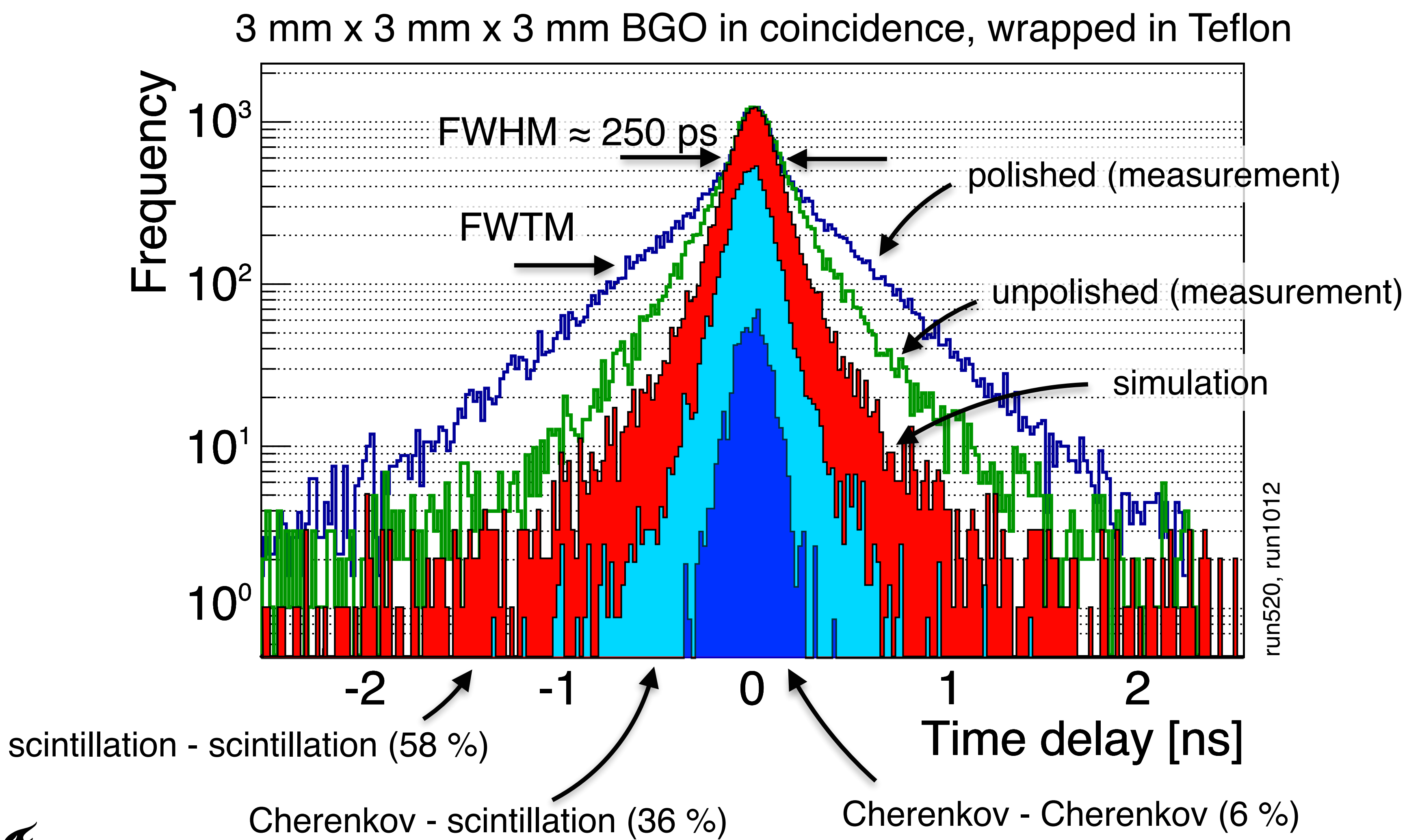




- UV-sensitive analog SiPM is inferior. Why?
  - SPRT?
  - PDE?
  - First photon time-pickoff?
- Need better understanding!

[1]Kwon et al., PMB 61 (2016)
[2]Brunner, Schaart, PMB 62-11 (2017)
[3]Nemallapudi et al., JINST 11 (2016)
[4]Brunner et al., JINST 11 (2016)

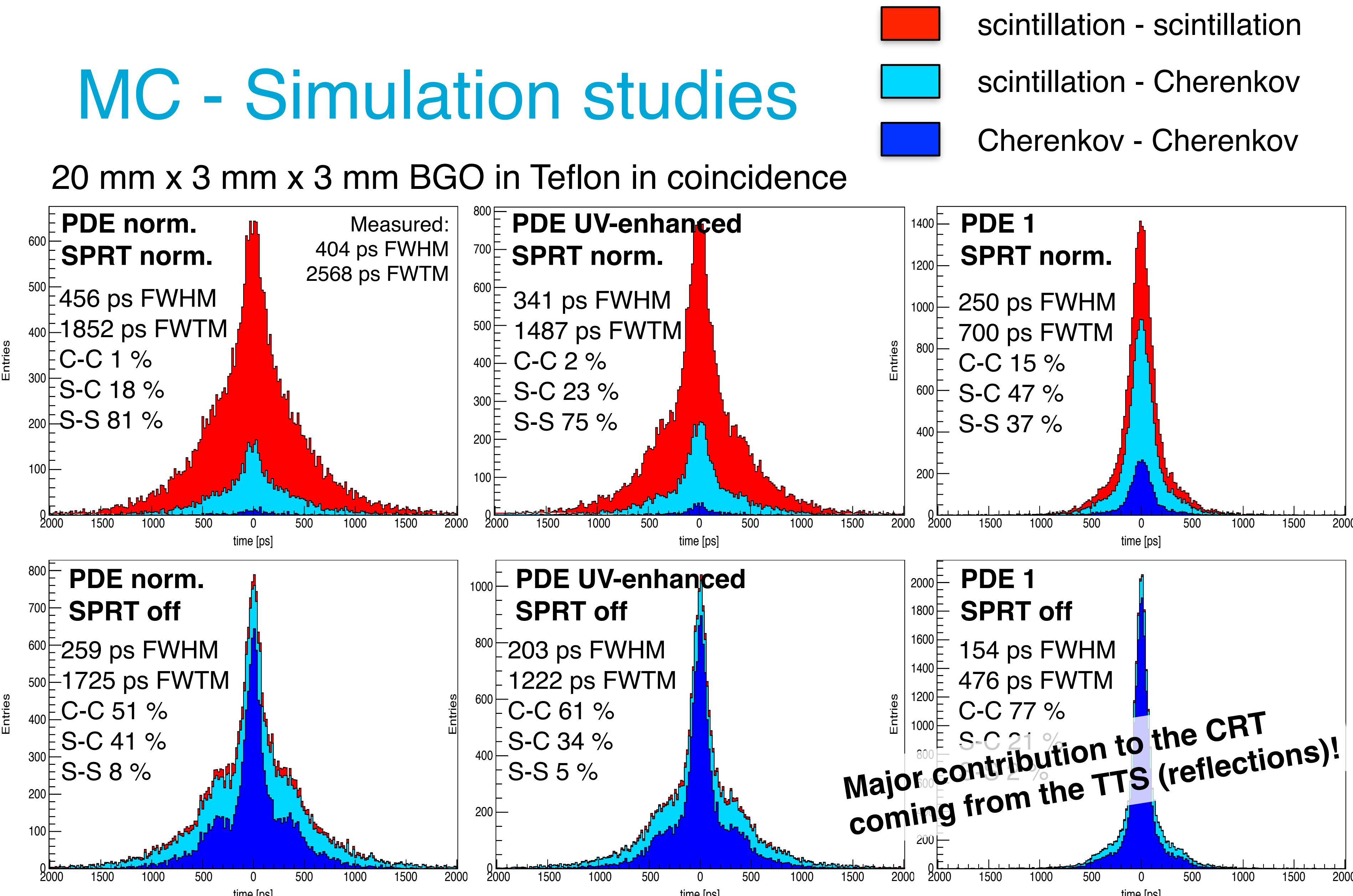
MC - Simulation vs measurement



geant4-10-02-patch-01, Physics List: stdEM_opt4

MC - Simulation studies

20 mm x 3 mm x 3 mm BGO in Teflon in coincidence



PDE norm. acc. DPC datasheet, 5% SPADs off; UV-enhanced: PDE = 0.4 (270 - 400nm), 5% SPADs off; PDE 1 (270 - 600nm), 5% SPADs off; SPRT norm: σ_{SPRT} = 51 ps

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Summary & Conclusion

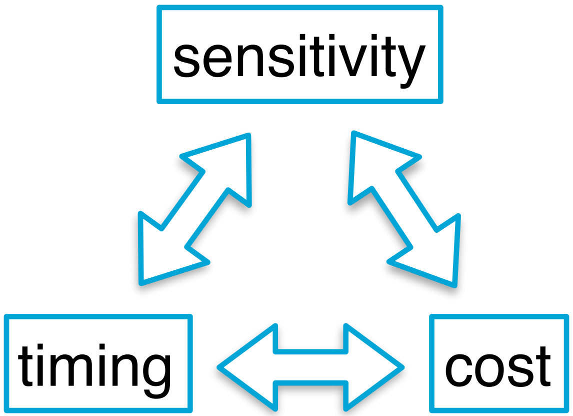
- Timing performance of **BGO** and **BSO** almost similar although $LY_{BSO}:LY_{BGO} = 1:8$; $\tau_{decay\text{-}BGO}:\tau_{decay\text{-}BGO} \approx 1:3$

➡ **Cherenkov (prompt) photons** enable **timing** with **BGO/ BSO**

➡ **200 ps FWHM and 750 ps FWTM achieved with BSO**

- **Energy discrimination** from simultaneously detected **scintillation** photons

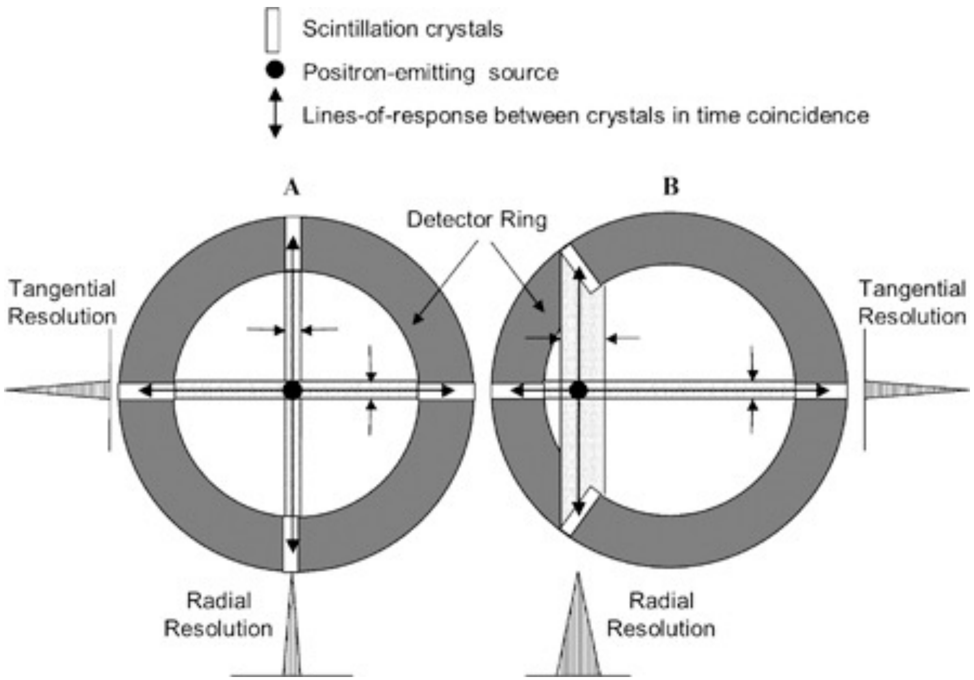
➡ **Timing** can be **improved** by **surface optimisation**



- **BGO/BSO** are inferior to **L(X)SO:Ce** in terms of timing, but provide
  - better stopping power
  - higher photo-fraction
    - ➡ **higher sensitivity**
  - no intrinsic radiation (important for monolithic scintillation det.)
  - are **cost-effective**

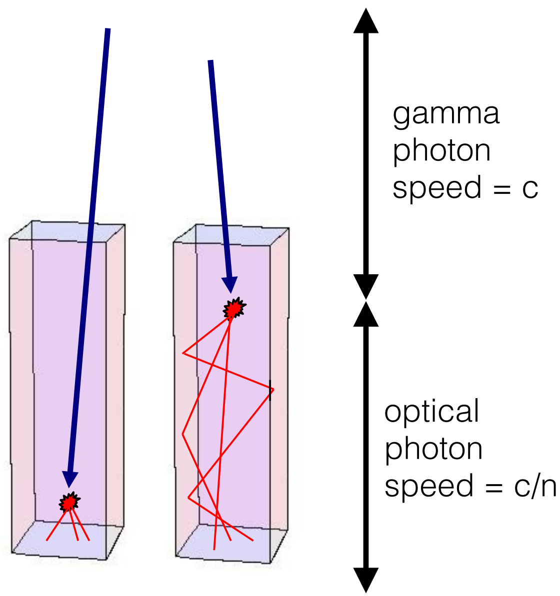
Questions?

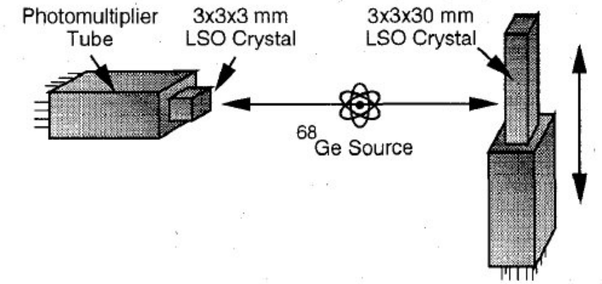
Problem of Depth-of-Interaction I

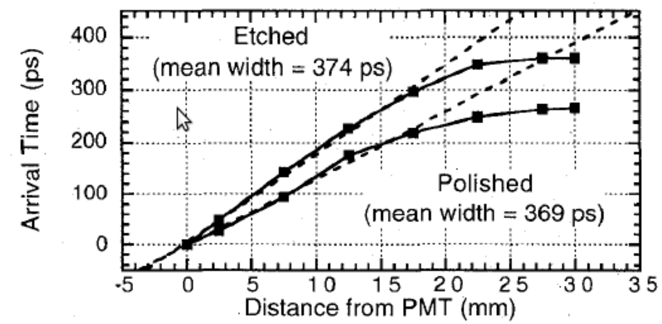


Pomper, 2010

Problem of Depth-of-Interaction II



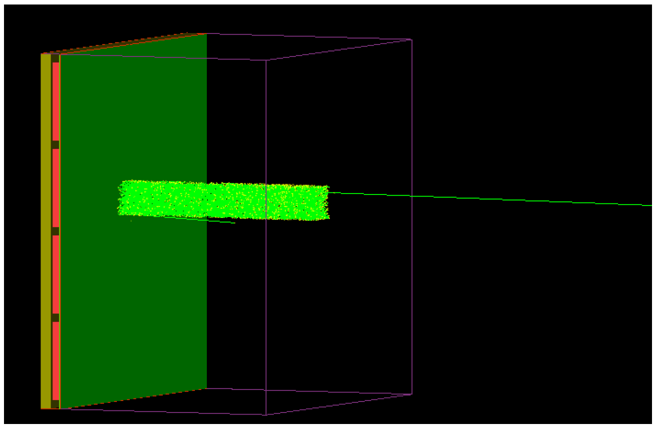


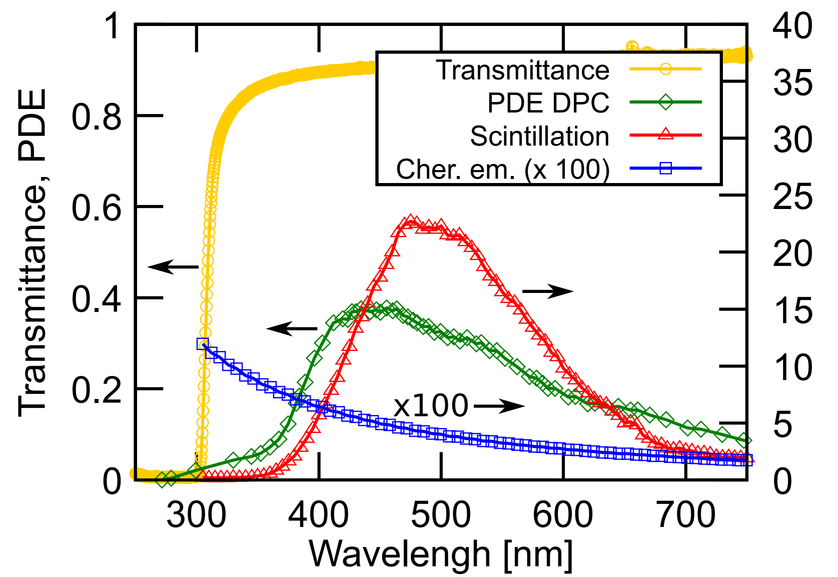


Moses & Derenzo, 1999

Depth of interaction (DOI)
- deteriorates time resolution
- deteriorates spatial resolution

MC - simulation details and parameters



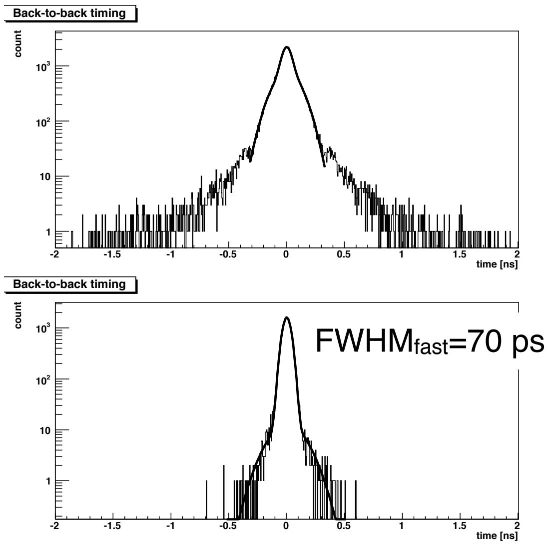


- Geant4: version geant4-10-02-patch-01 (26-February-2016), Physics List: stdEM_opt4
- 2 crystals in coincidence with 511 keV photon gun (random direction, 2 photons back-to-back)
- cross section 3 mm x 3 mm (wrapped in Teflon; coupled with grease; Quartz cover glass and opt. glue included)
- LY_{BGO}: 8200 phot/MeV; τ_{rise} = 50 ps; τ_{decay1} = 60 ns; τ_{decay1} = 300 ns; scint-ratio 1:10
- PDE according to Philips data sheet + 5 % of SPADs deactivated (randomly)
- measured σ_{SPRT} = 51 ps [1]
- Measured transmittance and emission spectrum used
- crystal surface using LUTs [2]: SetType(dielectric_LUT); SetModel(LUT); SetFinish(polishedteflonair)

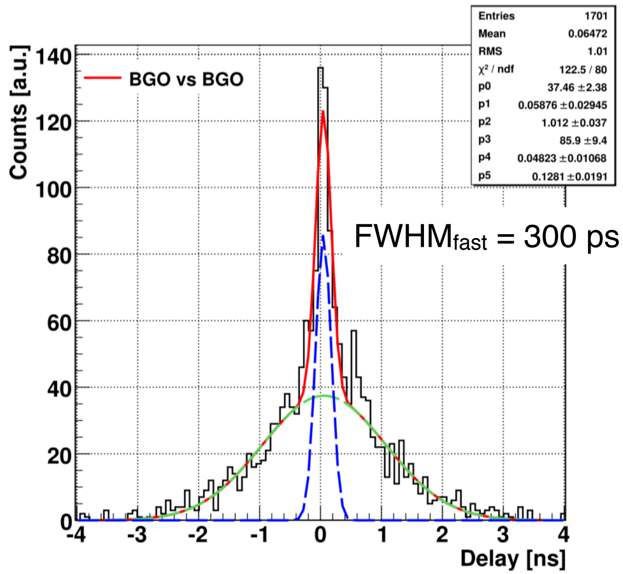
[1] S. E. Brunner et al., "A comprehensive characterization of the time resolution of the Philips Digital Photon Counter," J. Instrum., vol. 11, no. 11, pp. P11004–P11004, Nov. 2016.
[2] J. Allison al., "Recent developments in GEANT4," Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 835, pp. 186–225, 2016.

State-of-the-art CRT with Cherenkov emission

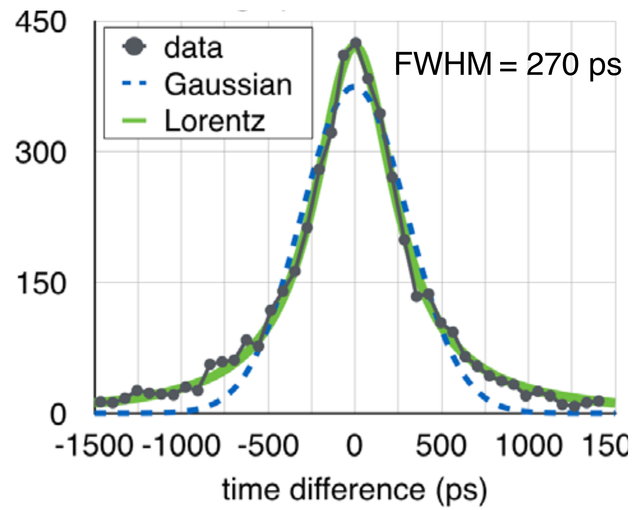
Dolenec 2011, PbF_2



Brunner 2014, BGO



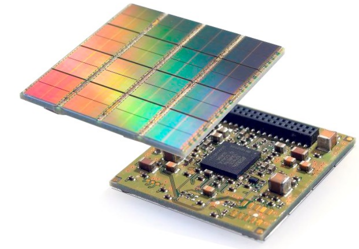
Kwon 2016, BGO

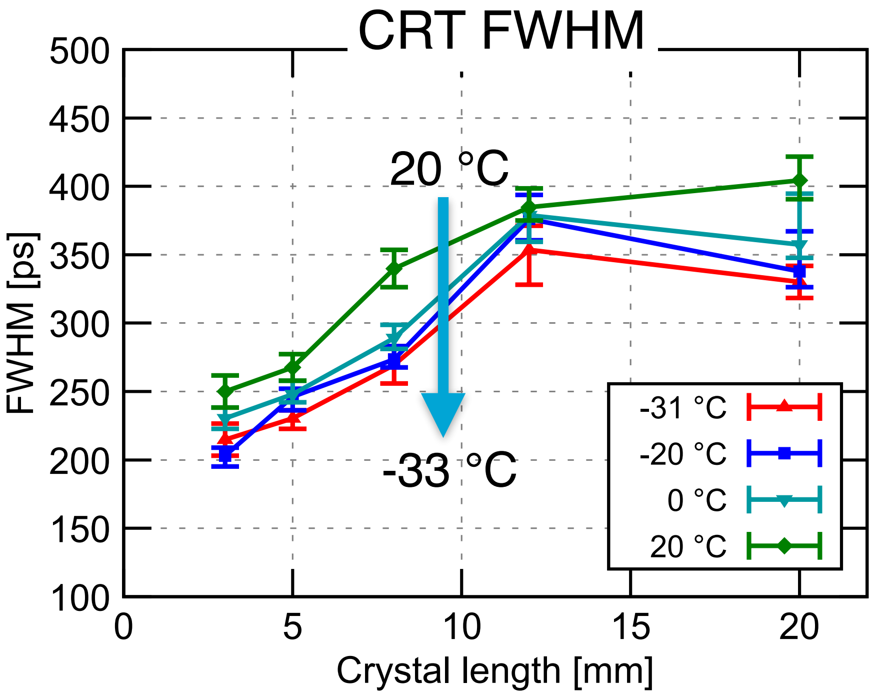


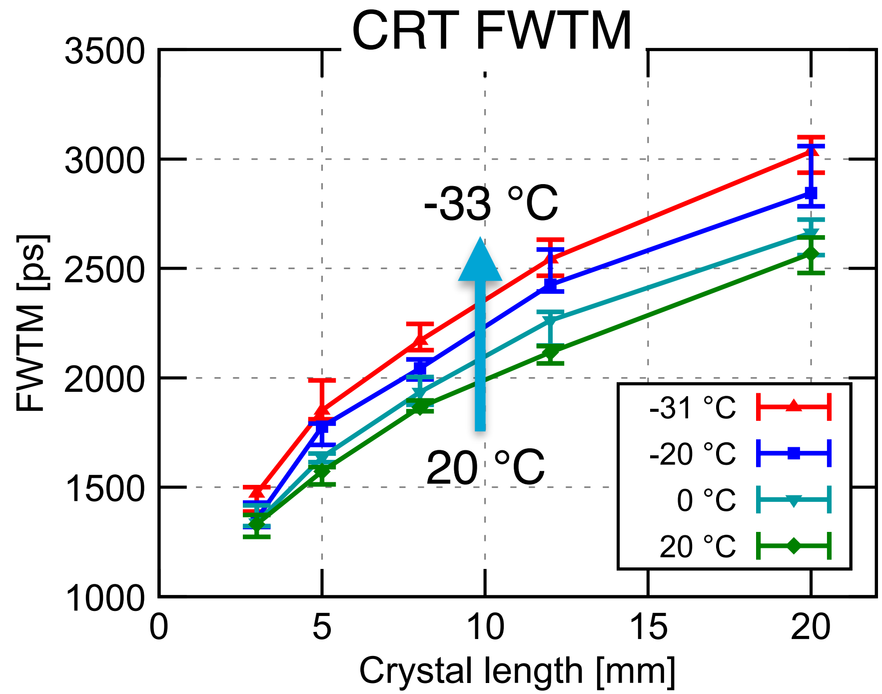
- 2010: **250 ps** FWHM, Lecoq, Brunner et al. IEEE TNS 57 (2010), LuAG & PMTs
- 2011: **70 ps** FWHM, Dolenec, Korpar, Krizan et al., NIM A654 (2011); PbF_2 & MCP-PMTs
- 2014: **300 ps** FWHM, Brunner, PhD thesis (2014) TU Vienna*; BGO & dSiPM
- 2016: **297 ps** FWHM; Dolenec Korpar Krizan et al., IEEE TNS 61 (2016); PbF_2 & aSiPM
- 2016: **270 ps** FWHM; Kwon et al., PMB 61 (2016); BGO & aSiPM
- 2017: **200 ps** FWHM; Brunner et al., PMB 62-11 (2017); BGO & dSiPM

*see http://katalog.ub.tuwien.ac.at/AC11996520

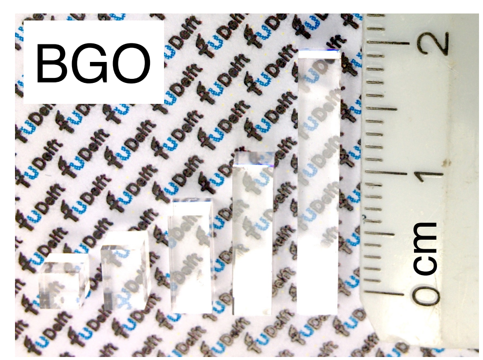
BGO & Digital Photon Counter: Coincidence Resolving Time





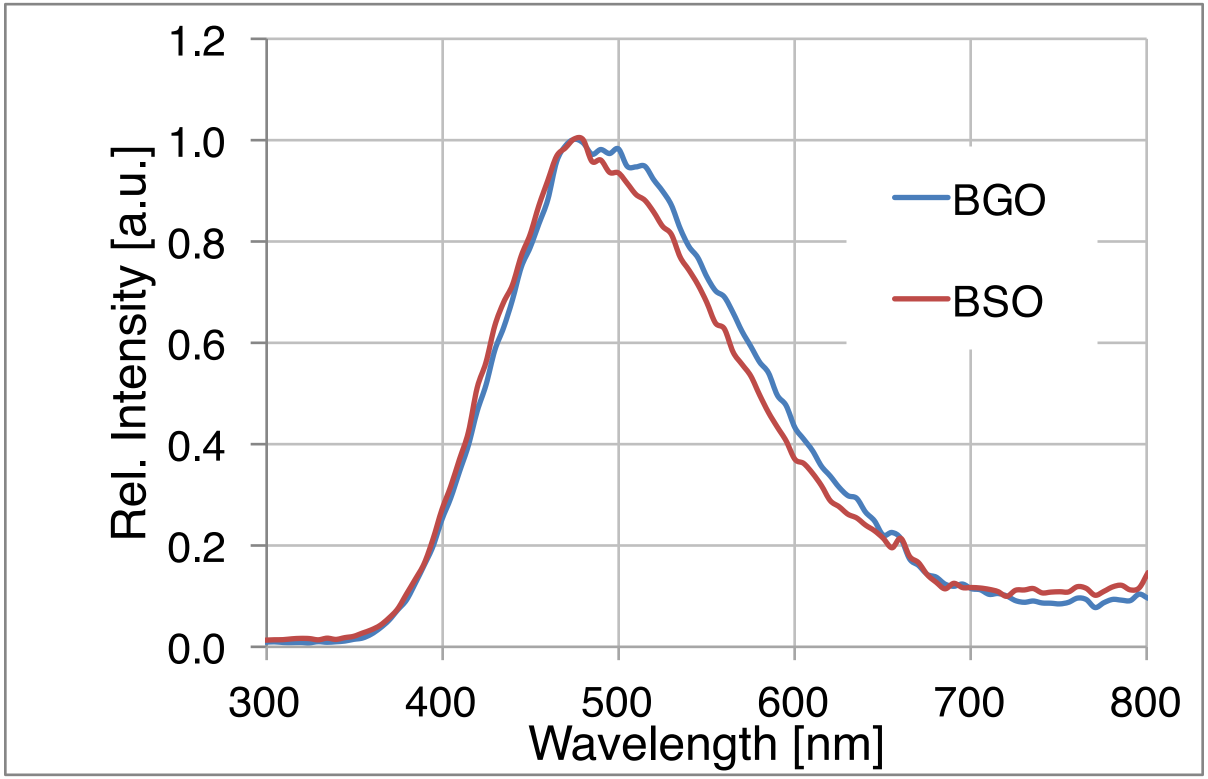


Crystal cross section 3 x 3 mm^2
Crystal lengths: **3 mm, 5 mm, 8 mm, 12 mm, 20 mm**
2 Philips DPCs in coincidence with ^{22}Na source



Brunner, Schaart, Phys. Med Biol., 62-11 (2017)

BGO/BSO photoluminescence spectra



- X-ray excitation 35 kV (current 10 mA)
- Czerny–Turner monochromator (Action Motion Corporation, model vm504)
- PMT: Hamamatsu R943-02
- corrected for PMT sensitivity

Data analysis