Studies on the Cherenkov Effect for Improved Time Resolution of TOF-PET using digital SiPM

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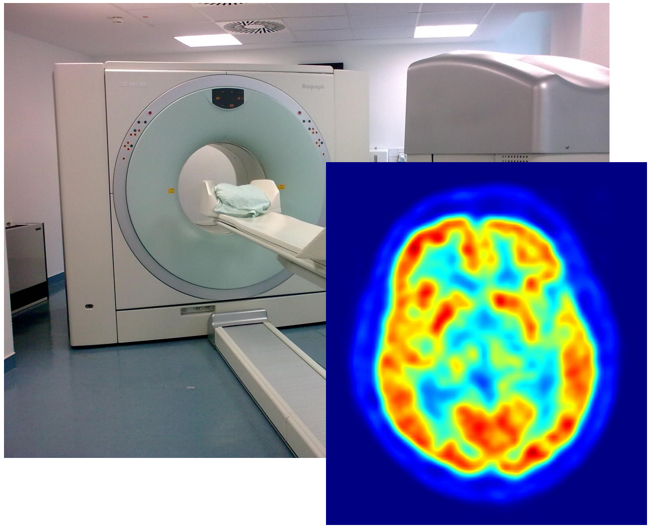
Outline

- **Motivation**: time-of-flight positron emission tomography
- **Fast photon detection:** digital **SiPM**
- Factors influencing the **time resolution of scintillators**
- Improving the time resolution of scintillators using the **Cherenkov effect**
  - **Simulation** investigations
  - **Proof of principle** measurements
  - Comparing Cherenkov radiators scintillators

Motivation

Fast particle/gamma detection is applied in many research fields:

- Material research (positron annihilation life time spectroscopy)
- Particle ID (time of flight detectors in high energy physics)
- ...

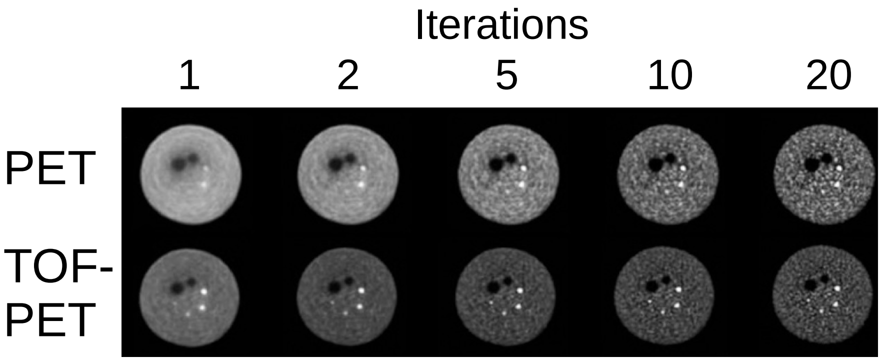


Ref. :http://de.wikipedia.org/wiki/ Positronen-Emissions-Tomographie

Main motivation:

Time-of-Flight Positron Emission Tomography (TOF-PET)

- TOF for PET allows to decrease the SNR of reconstructed PET pictures
- Dependent on the time resolution of the PET detectors

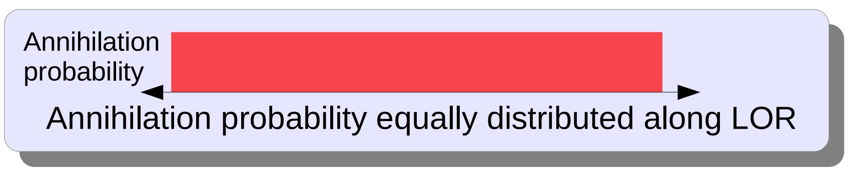


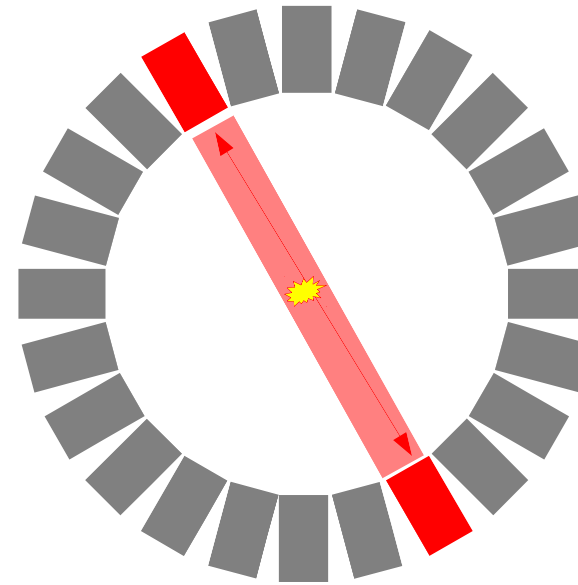
Karp et al., JNM, 49-3 (2008) pp.462-470

Positron Emission Tomography

PET

- Radiotracer (e.g. sugar + e^+ emitter) injected into patient
- Tracer accumulates at region of interest (e.g. metabolic tissue)
- e^+ annihilates with e^- of tissue
- Emission of two annihilation photon with 511keV at rel. angle of 180°
- The two photons are detected by a ring of detectors (within coinc. time window)
- A LOR is drawn between the responding detectors
- Statistics → Image reconstruction





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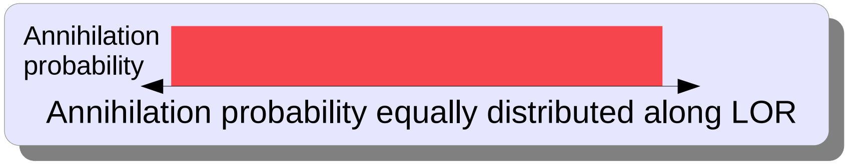

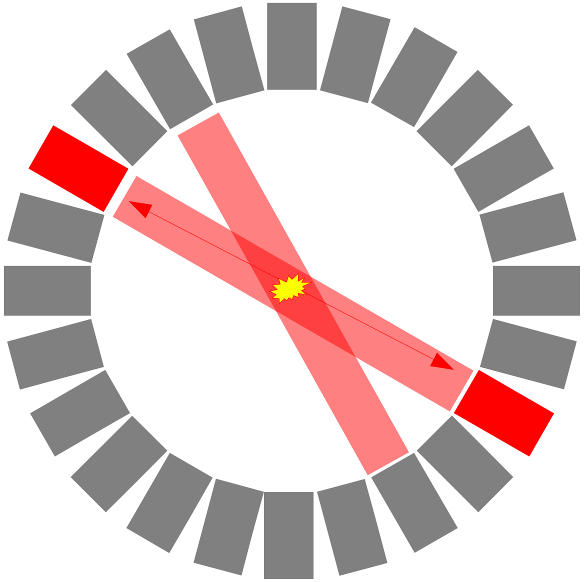

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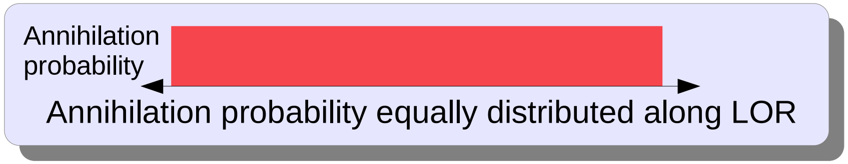

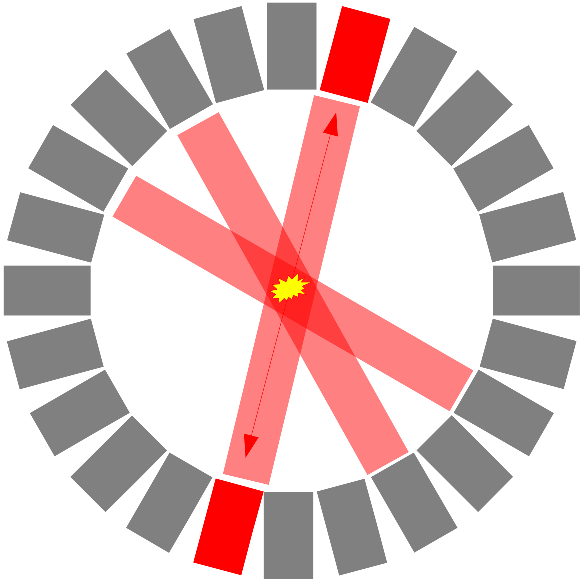

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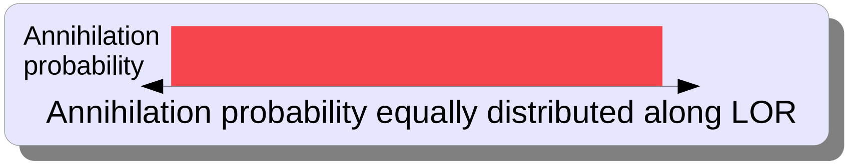

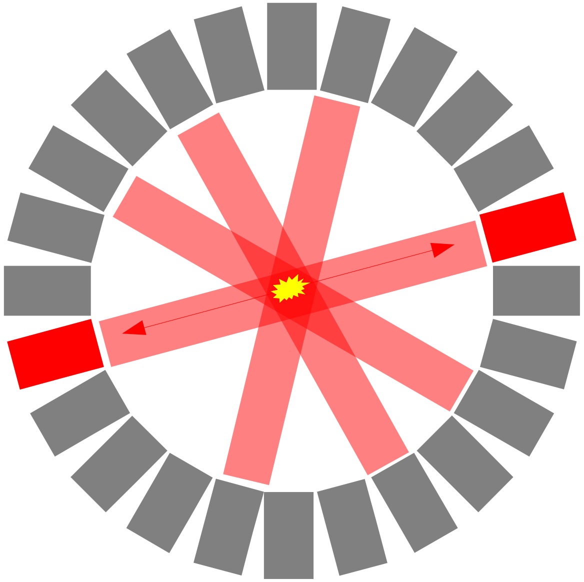

Time-of-flight PET

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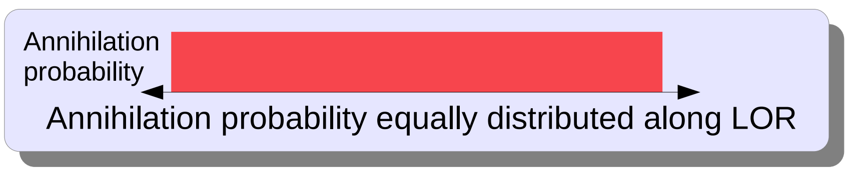
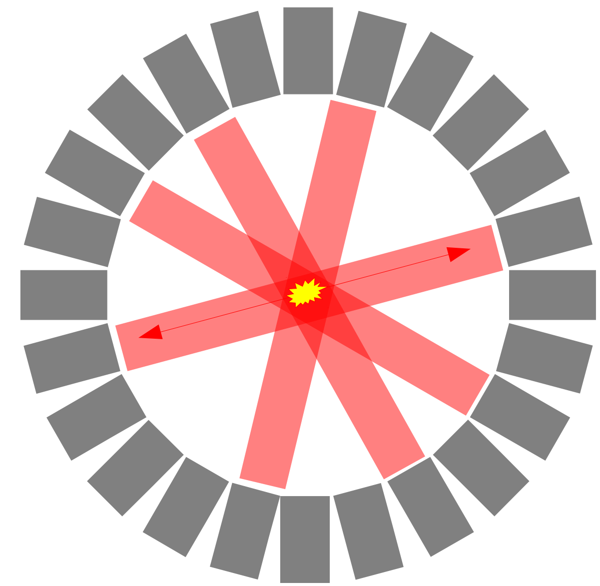
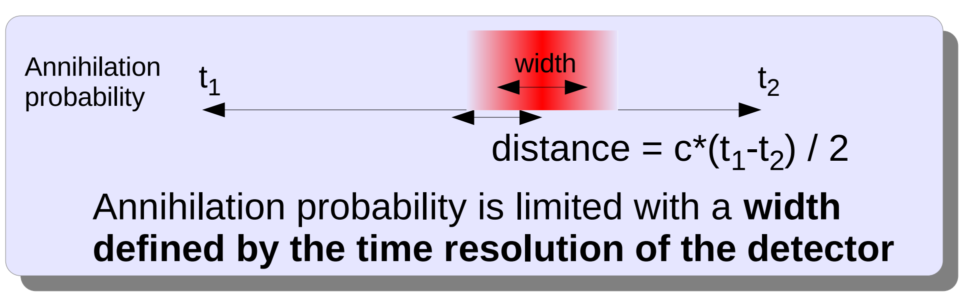
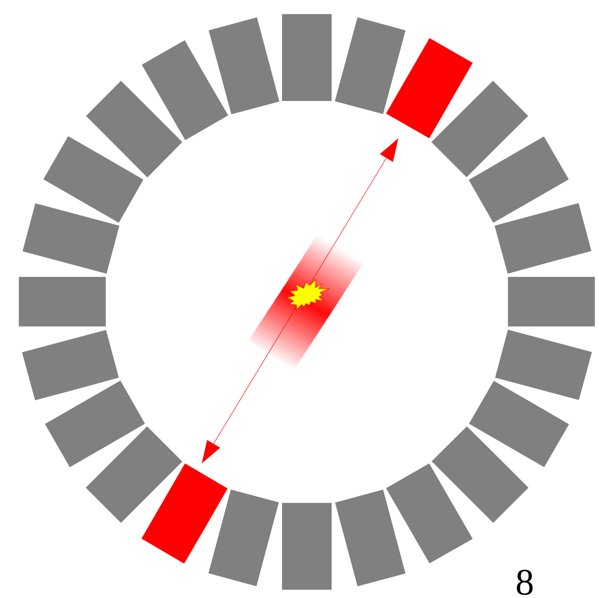




TOF–PET

- arrival **time** of the 511keV photons is **measured**,
- LOR between responding detectors with a probability distribution
  - → **Less artefacts**
  - → **Improved SNR**





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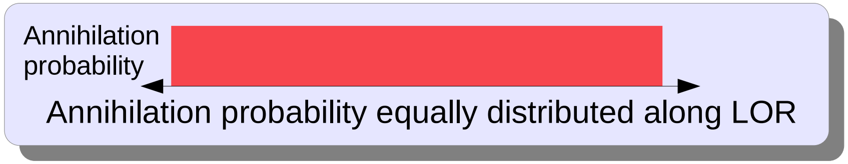

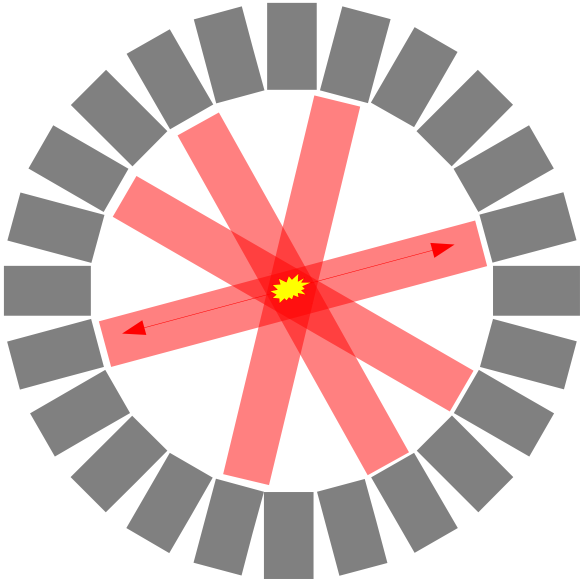

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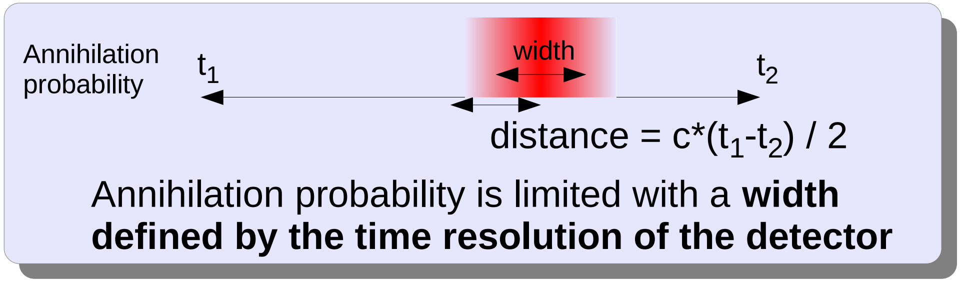

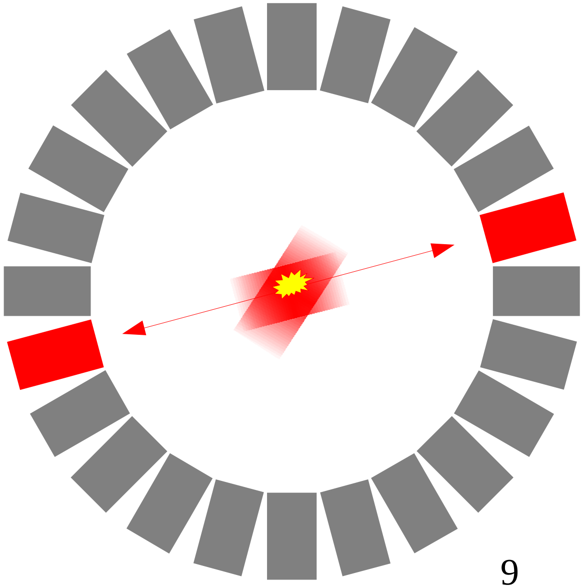

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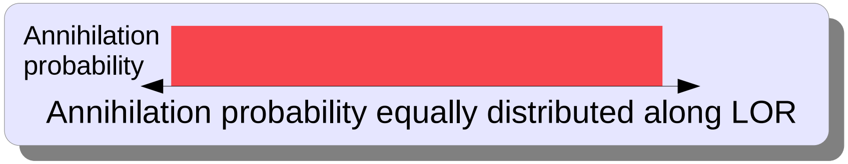

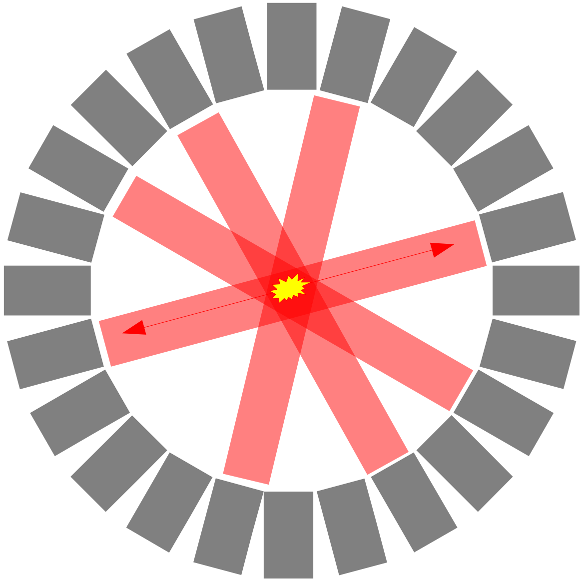

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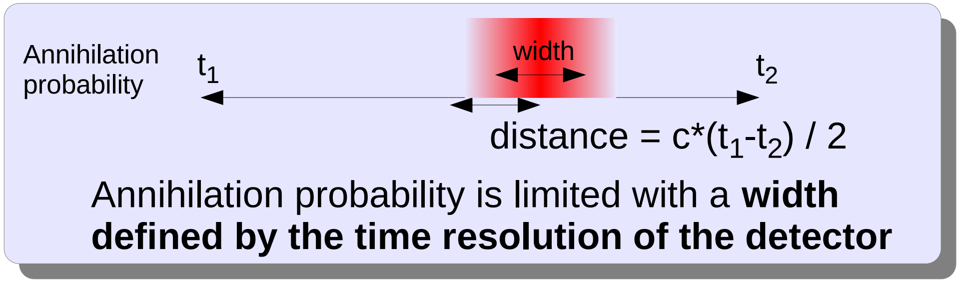

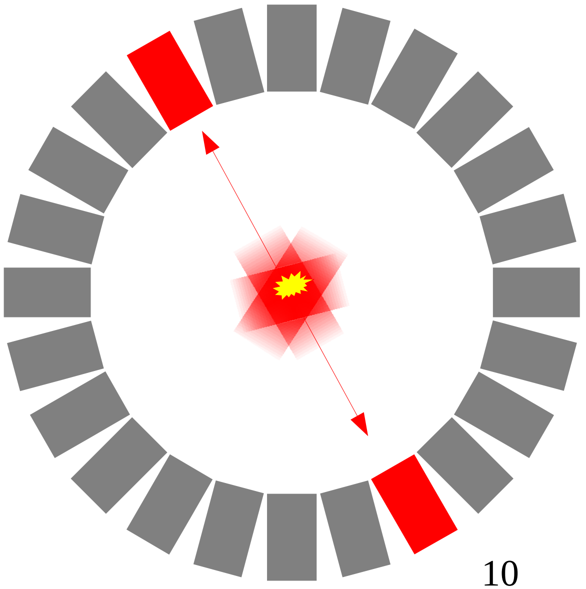

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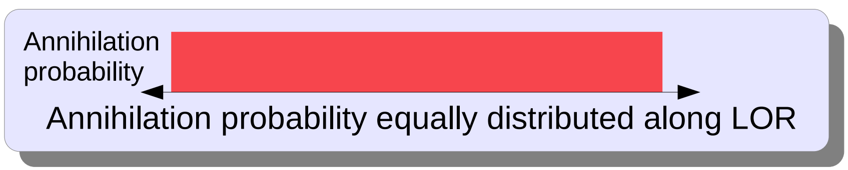

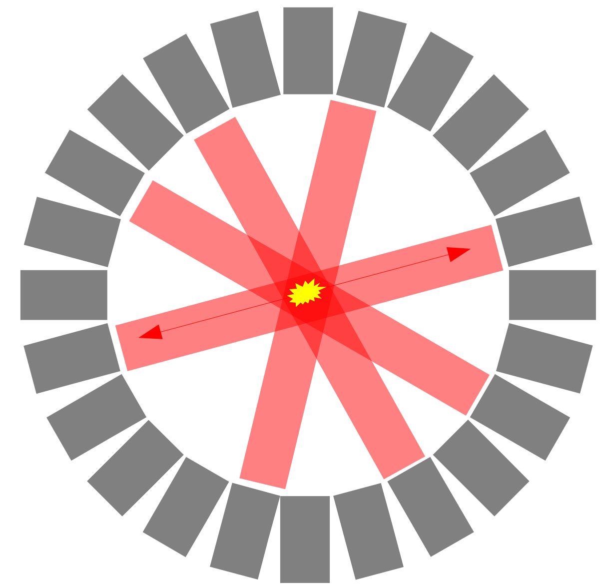

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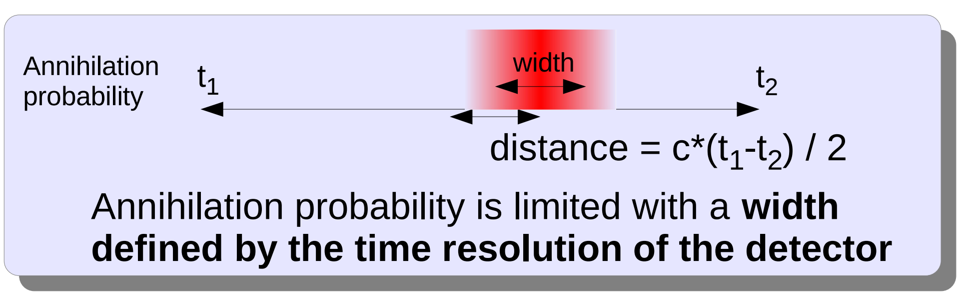
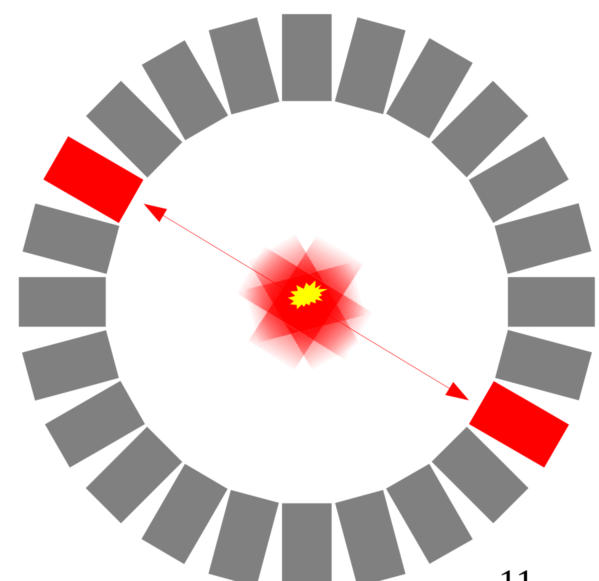
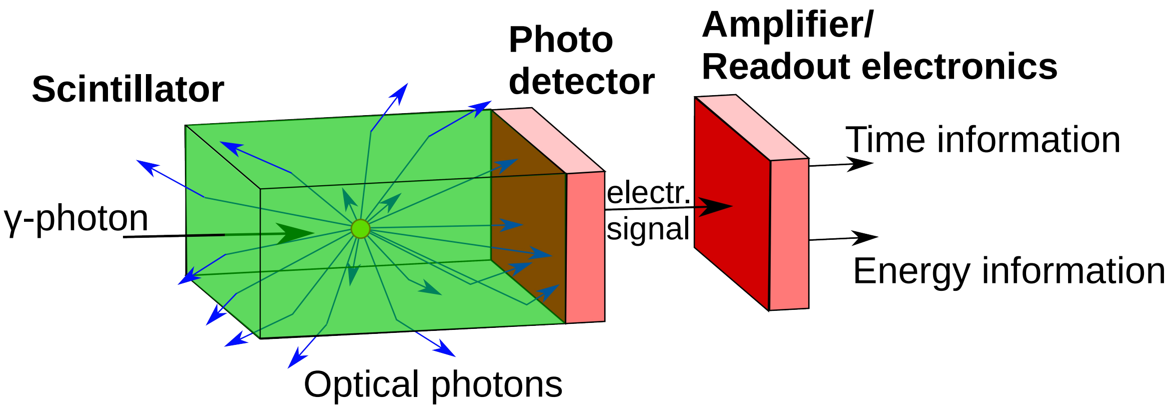




Scintillation based gamma/particle detection

A scintillation detector consists of 3 major parts:

- **Scintillator:** Converting energy of particle/γ-photon into optical photons
- **Photo detector:** Converts optical photons into electric signal
- **Amplifier/Readout electronics:** Amplifies the signal and digitizes it



Every part is adding time spread to the total time resolution.

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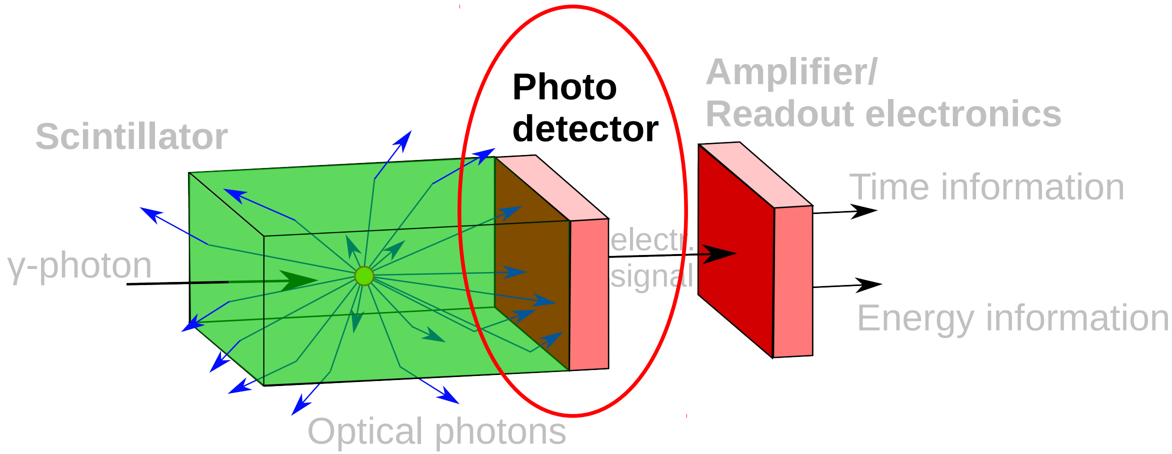

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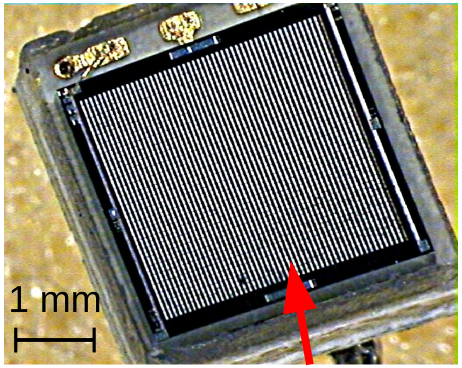
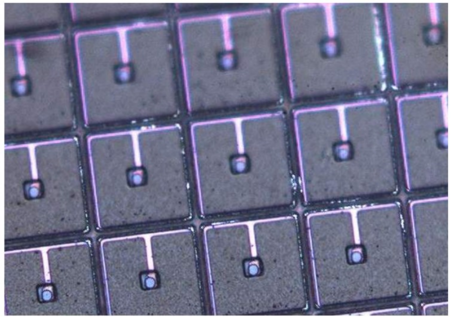
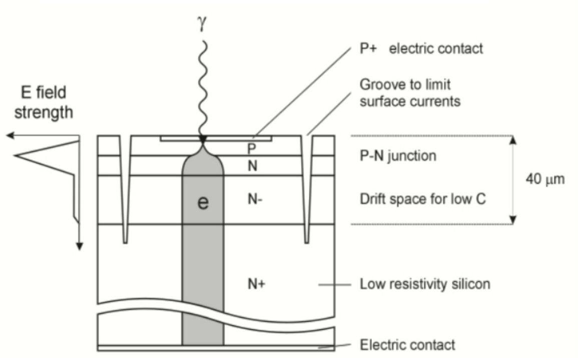
The silicon photomultiplier

- Solid state detector based on silicon
- Array of miniature avalanche photo diodes driven in Geiger mode
- Sensitive area a few mm² (typically 3x3mm²)
- High gain (~ 10^6) → detection of single photons
- Very fast, insensitive to magnetic fields, high PDE, compact, robust, cheap, low power consumption
- Well suited detectors for many kinds of detectors in HEP and nuclear imaging (PET)
- Drawbacks: high dark count rate (100 kHz/mm²), crosstalk, after pulses, temperature sensitivity



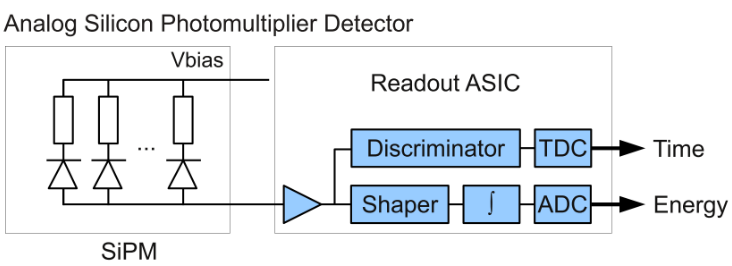
50 x 50 cells

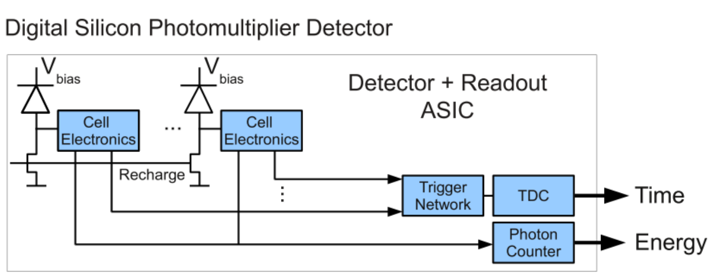




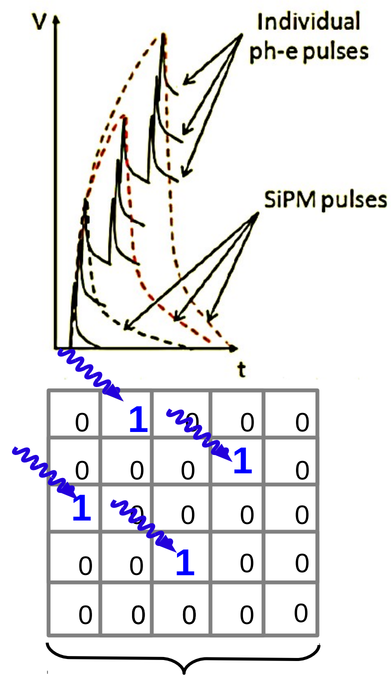
Ref: Renker et al., JINST 4 (2009) P04004

The analogue vs. the digital SiPM





Ref.: Frach, JINST 7 (2012) C01112



Photon number
+ time of the first photon

- SiPM is an analogue device
- Provides quasi digital information about the number of detected photons

Analogue SiPM:

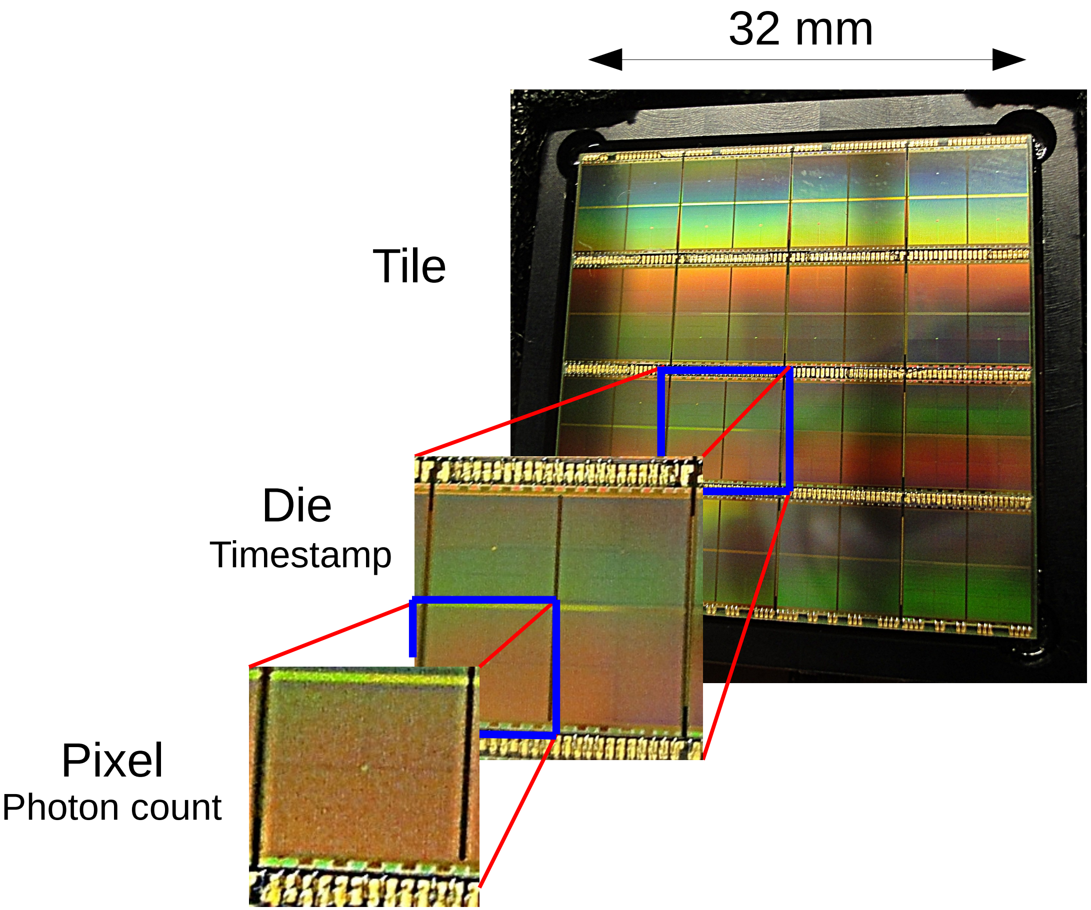
- Signal is the analogue sum of the single cells

Digital SiPM:

- Each SPAD connected to logic electronics
- Signal is the digital sum of fired SPADs
- **Advantages:** Electronics as close as possible at the SPADs (**fast, accurate**), control of single SPADs (**reduction of darkcounts**)

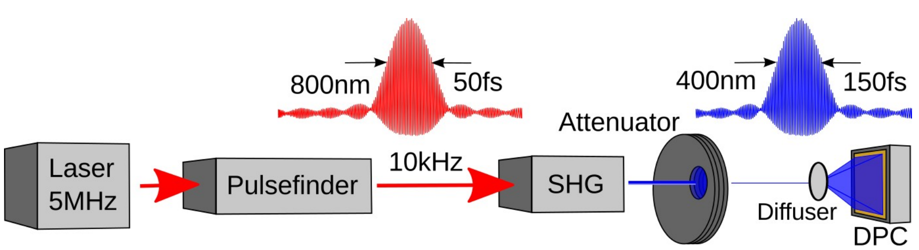
The Philips Digital Photon Counter (DPC)

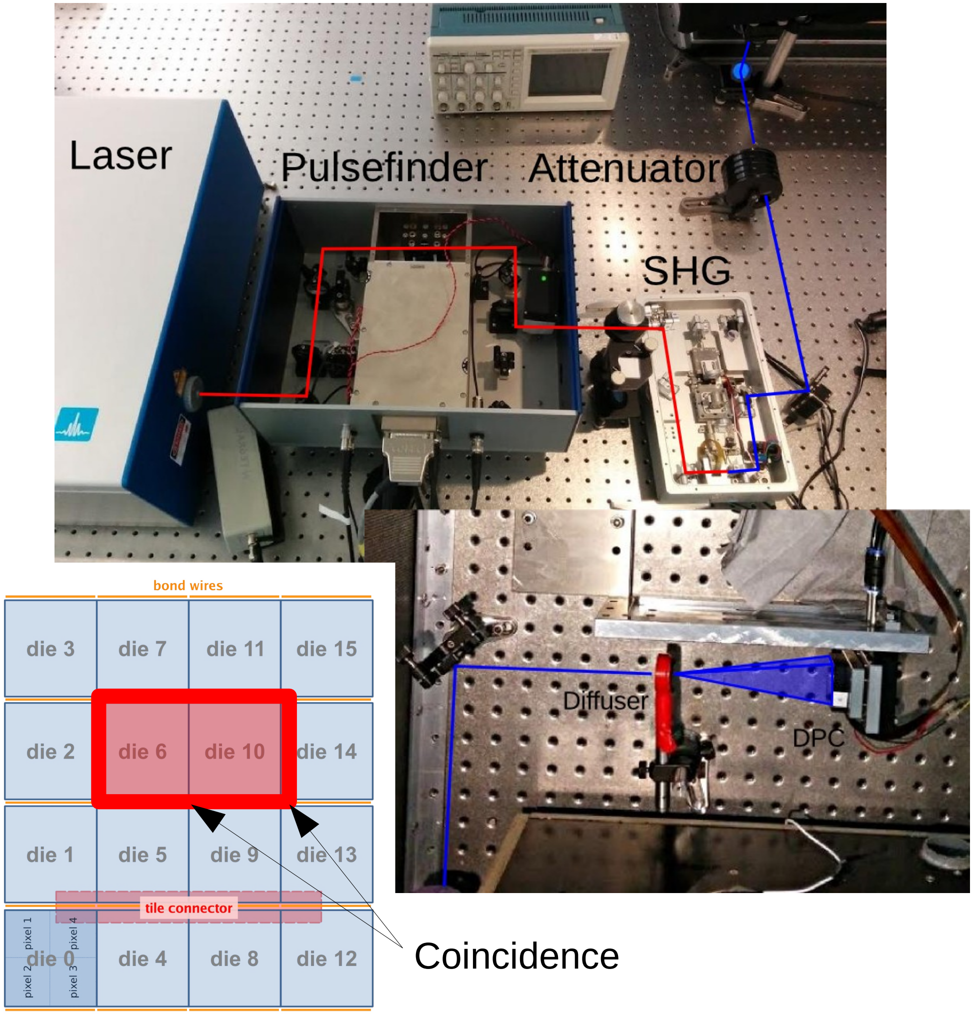
- DPC consists of 16 dies (~3x3cm²)
- Each die consists of 4 pixels
- Each pixel consists of 3200/6400 microcells
- Each cell can be turned on/off individually
- One time stamp per die
- One photon count per pixel
- 16 timestamps / 64 photon counts



Time resolution of the digital SiPM: setup

- Femtosecond laser
- Laser at detector: λ = 400nm, Δt = 150fs, rep. rate = 10kHz
- 1 DPC tile, two pixels/dies in coincidence
- Trigger level: 1 photon
- At low photon levels: no validation, no intergration
- Two dies or pixels activated, give timestamp ***t*** and number of triggers ***n***
- The time resolution was determined by calculating the **standard deviation** of t_1-t_2 dependent on *n*



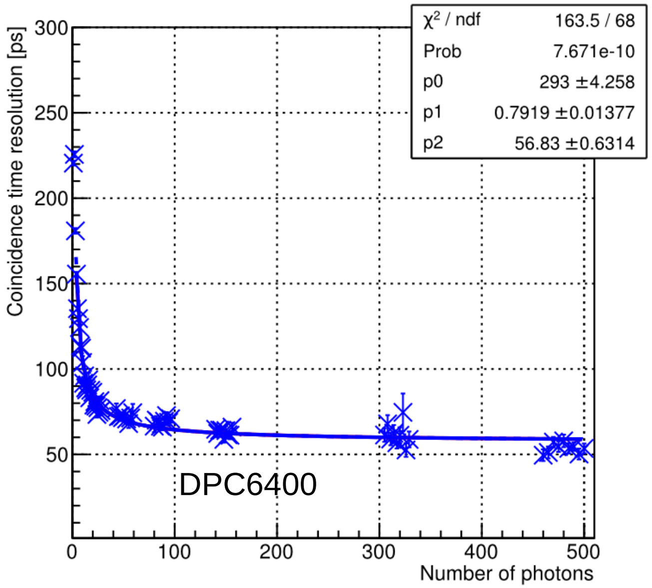


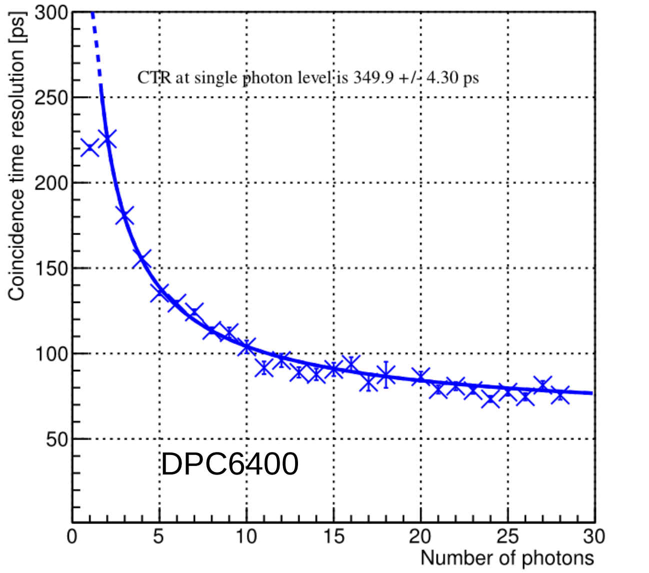
Time resolution of the digital SiPM: Results

Single photon **coincidence** time resolution

DPC	Active cells	T [°C]	Laser rate [kHz]	Inact. cells [%]	SPCTR [ps] FWHM	System (coinc.) [ps]
3200	die	0	10	0	265 ± 8.4	67 ± 2.7
3200	die	0	10	20	238 ± 4.3	60 ± 1.2
3200	die	0	10	50	216 ± 3.3	64 ± 0.8
3200	die	10	10	20	361 ± 17.7	66 ± 0.9
3200	pixel	10	10	20	143 ± 3.9	22 ± 3.4
3200	pixel	20	10	20	160 ± 4.9	20 ± 4.4
6400	die	0	10	20	350 ± 4.3	57 ± 0.6

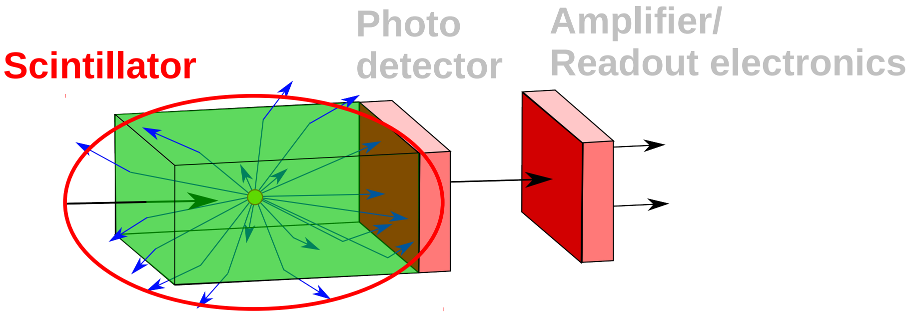
Ref.: S.E. Brunner, PhD thesis, Vienna UT (2014)





Time resolution prop. $1/n^p$ (expected by simulation).
Drop of SPCTR when approaching single photon level.

Factors influencing the time resolution of scintillators
&
Improvement by the Cherenkov effect



The Cherenkov effect

- Dielectric material
- Charged particle
- Faster than the speed of light in the medium
- Constructive interference of electromagnetic pulses by polarisation of the atomic dipoles
- Cherenkov emission angle θ

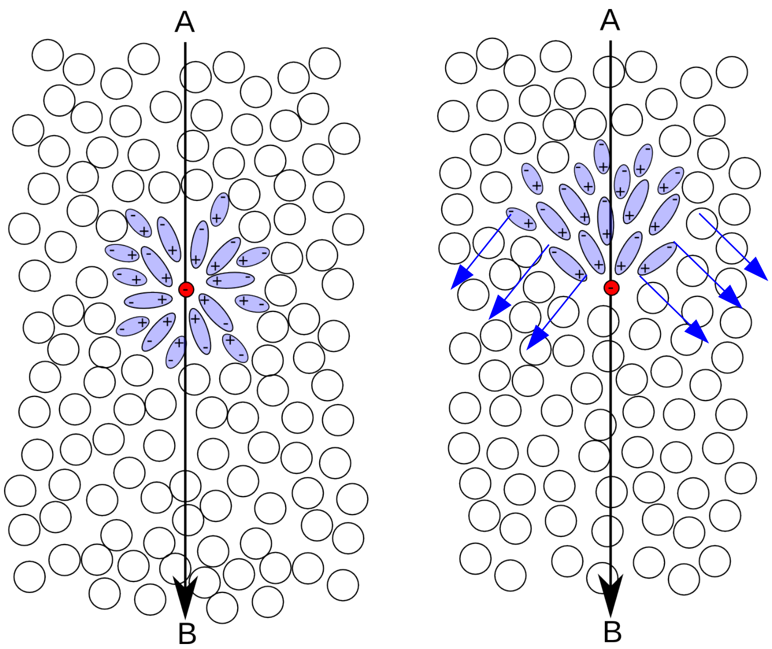
$$\cos\theta = \frac{1}{\beta n}$$

- Number of emitted Cherenkov photons

$$\frac{dN^2}{dx d\lambda} = \frac{2\pi z^2 \alpha}{\lambda^2} \cdot \left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

- Emission spectrum (Frank-Tamm)

$N(\lambda) \sim 1/\lambda^2$

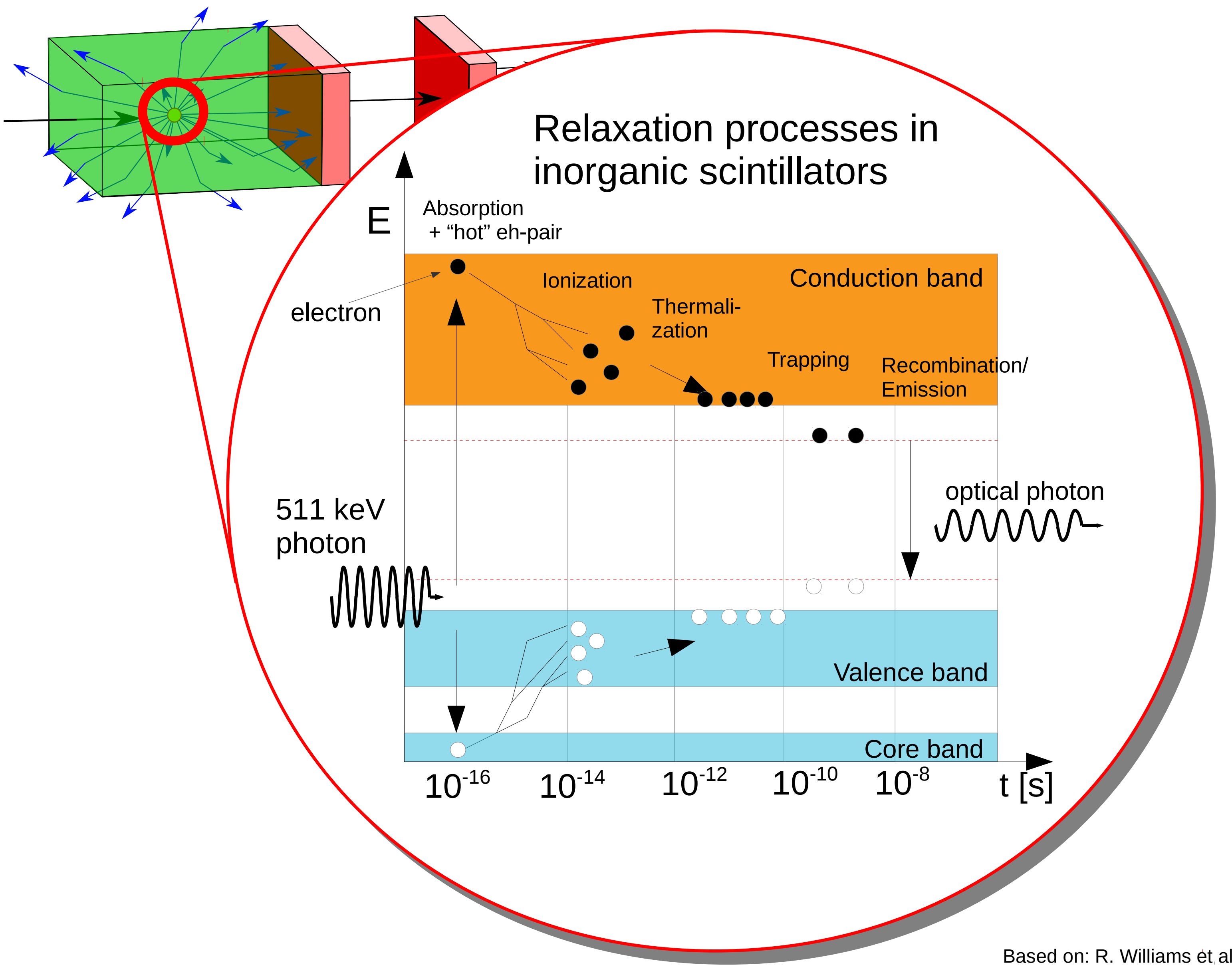


Slower than the speed of light v < c/n

Faster than the speed of light v > c/n

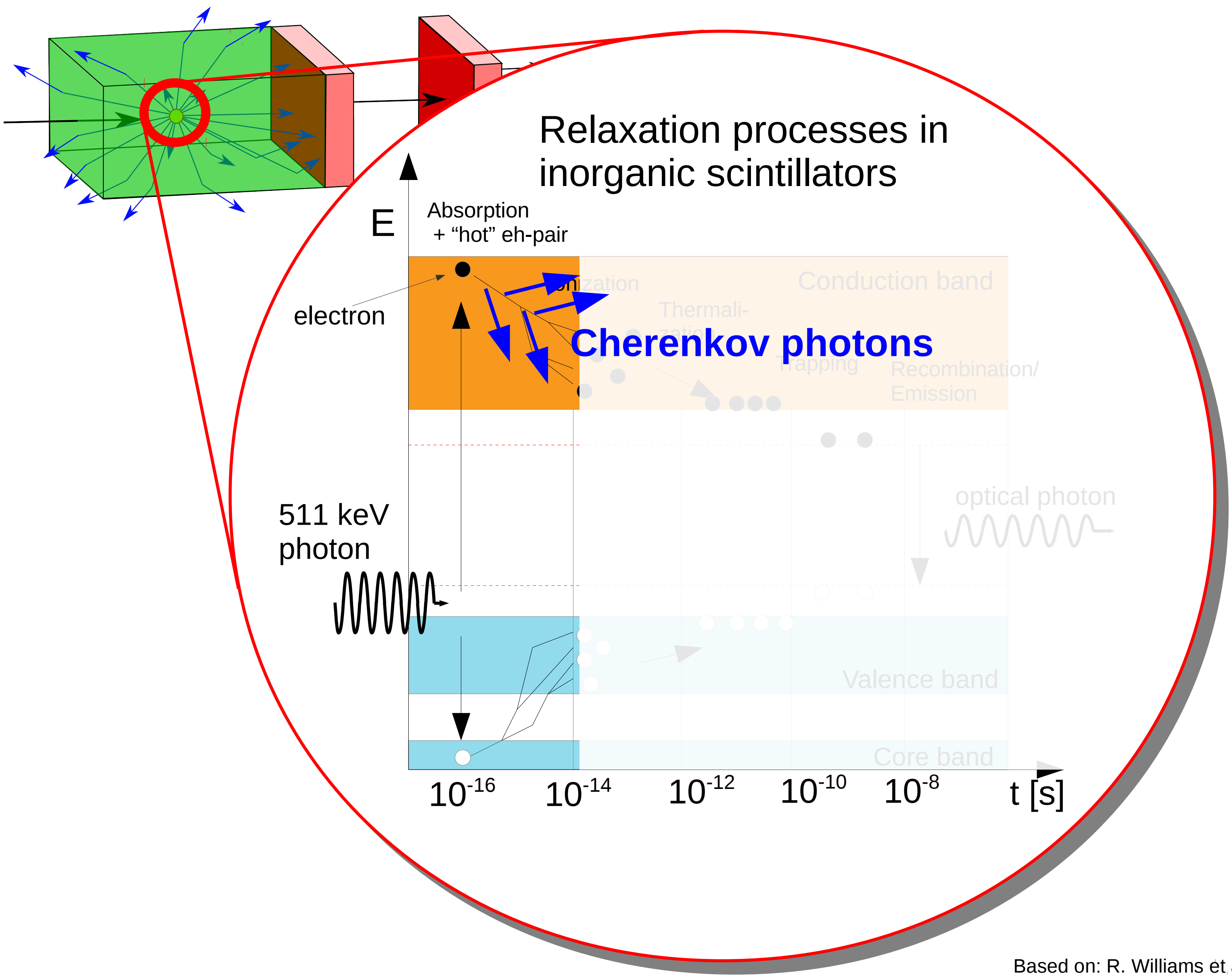
Cherenkov photon emission

Gamma-photons and the Cherenkov effect



Based on: R. Williams et al., Rad. Meas. 33 (2001) p. 497.

Gamma-photons and the Cherenkov effect



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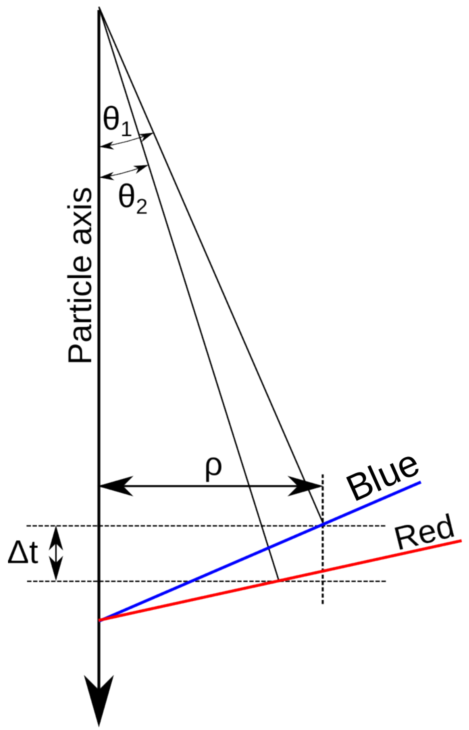
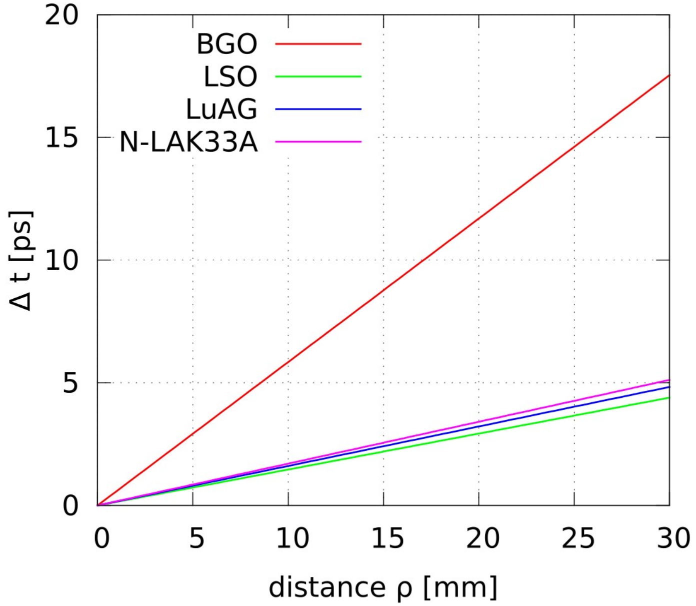
Time precision of the Cherenkov effect

Cherenkov photons are emitted almost instantaneously.



- Influence of **electron propagation** inside the material:
  - Electron range ~ 200-300µm, velocity ≥ $\beta_t = 1/n$
  - time spread ~ **1-2 ps**
- **Dispersion**: Angle of Cherenkov emission is dependent on the wavelength, $\mathbf{\cos\theta = 1/\beta n(\lambda)}$



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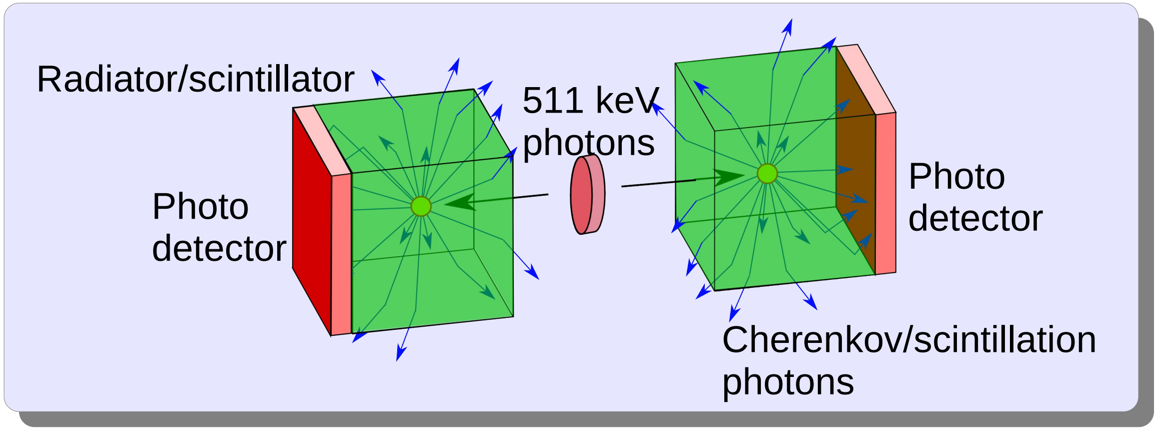
Investigating the Cherenkov effect for gamma detection: simulation environment

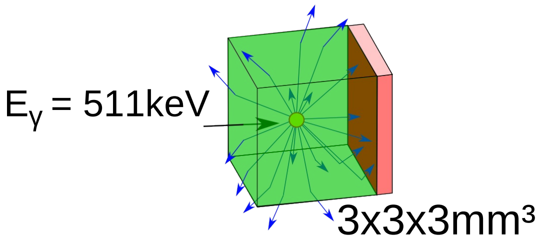
- Monte Carlo simulations using Geant4 (v9.4.p3, Livermore libraries)
- Basic setup: **scintillator** attached to a **generic photo detector** (TR=0, QE=1)
- Size scintillator: $3x3x3mm^3$, photo detector $3x3mm^2$
- Perfectly polished surface, no wrapping, surrounded by air
- Comparing various materials (high density, high n):
  - **pure Cherenkov radiators:** N-LAK33A/B, N-FK5, N-LASF31A, P-SF68, LuAG
  - **hybrid materials:** LuAG:Ce, LSO:Ce, BGO, PWO



Cherenkov photon yield for 511keV annihilation photons (simulation)

Material	Luminescence type*	Density [g/cm³]	n	Cutoff wavel. [nm]	Created photons (avrg.)	Detected photons (avrg.) [3x3x3mm³]
N-LAK33A	Cherenkov	4.22	1.77	300	22.4	13.7
N-LAK33B	Cherenkov	4.22	1.77	280	24.9	14.5
N-FK5	Cherenkov	2.45	1.5	260	26.1	14.6
N-LASF31A	Cherenkov	5.51	1.91	310	19.6	**12.1**
P-SF68	Cherenkov	6.19	2.07	400	12.8	8.4
LuAG pure	Cherenkov	6.73	1.84	180	32	**10.6**
LuAG:Ce	hybrid	6.73	1.84	250	24.3	**7.2**
LSO:Ce	hybrid	7.4	1.82	390	13.8	1.1
BGO	hybrid	7.13	2.15	310	32.8	**4.6**
PWO	hybrid	8.28	2.2	340	22.6	3.8

Ref.: S. E. Brunner, PhD thesis, Vienna UT (2014)
*Cherenkov: photon emission via the Cherenkov effect
Hybrid: simultaneous photon emission via the Cherenkov effect and scintillation



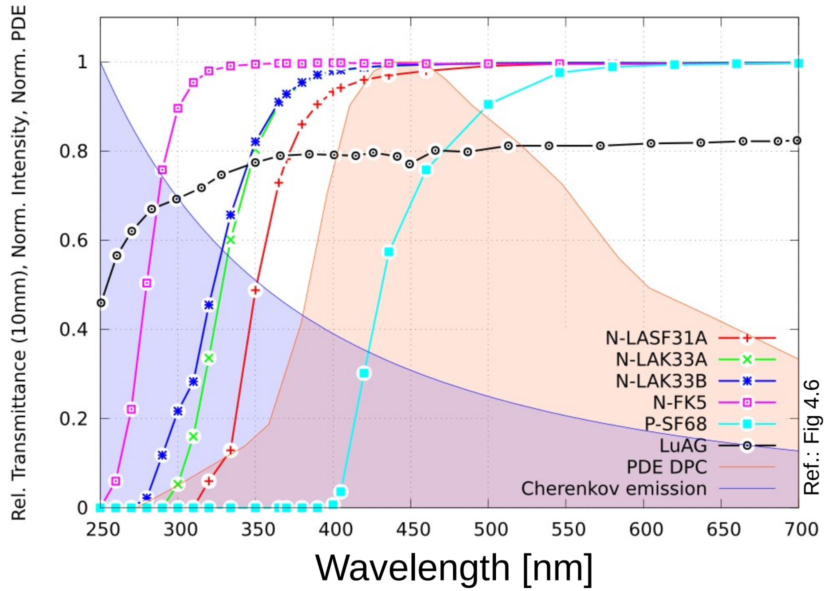
Factors influencing the Cherenkov photon yield

Cherenkov photon yield

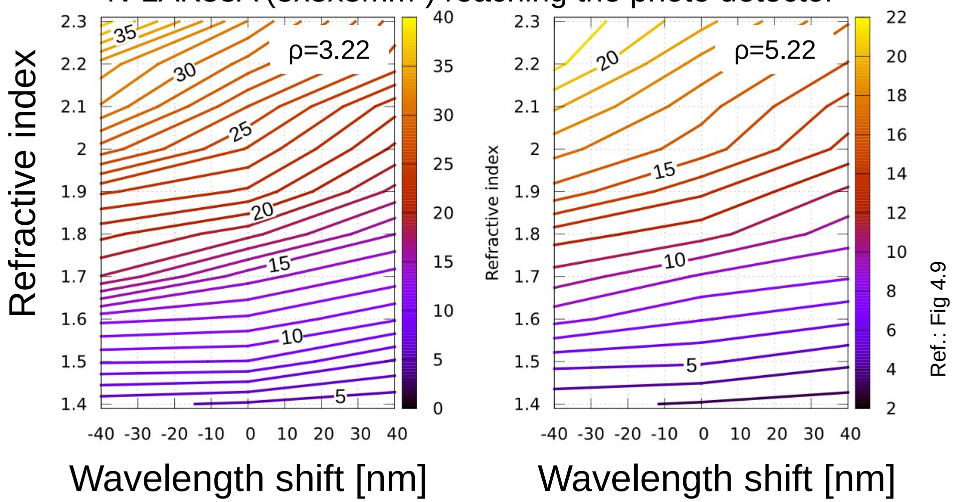
$$\frac{dN^2}{dx\,d\lambda} = \frac{2\pi z^2 \alpha}{\lambda^2} \cdot \left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

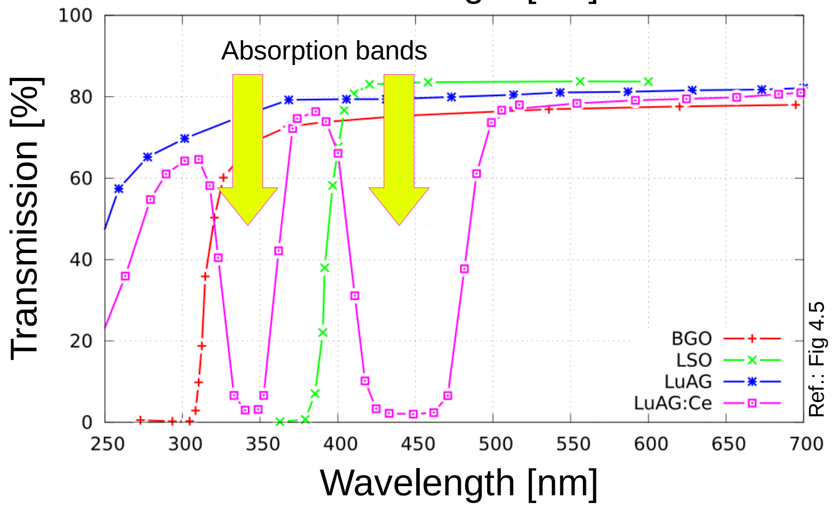
Dependent on

- Transmission
- Refractive index
- Density (electron range)



Simulated number of Cherenkov photons in
N-LAK33A (3x3x3mm³) reaching the photo detector



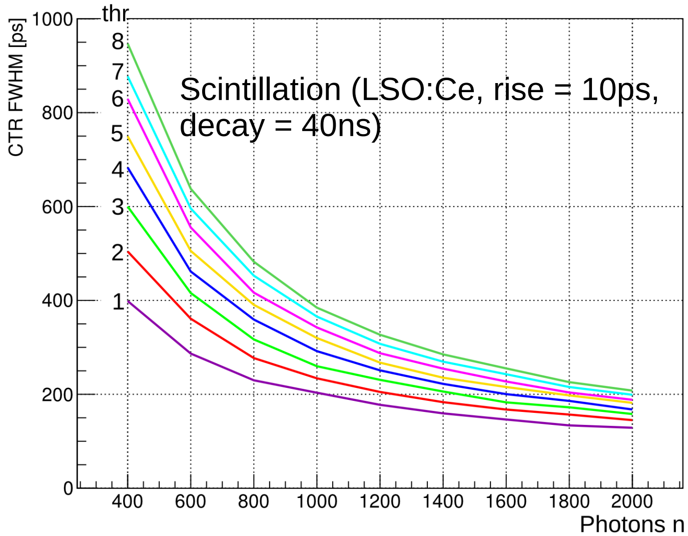


Ref.: S. E. Brunner, PhD thesis, Vienna UT (2014)

Comparing factors influencing the time resolution of scintillators and Cherenkov radiators

- **Photon statistics** (rise & decay time, light yield)
- **Depth of interaction** (crystal dimension, density)
- **Photon propagation** (crystal dimension, transmission)

Influence of photon statistics



- **Simulation** using a double exponential function for scintillation photon emission after gamma absorption at θ

$$f(x|\theta) = \begin{cases} \sum_i \frac{P_i}{\tau_{d,i} - \tau_{r,i}} \left[e^{-\frac{x-\theta}{\tau_{d,i}}} - e^{-\frac{x-\theta}{\tau_{r,i}}} \right], & \text{for} \quad x \geq \theta \\ 0, & \text{else} \end{cases}$$

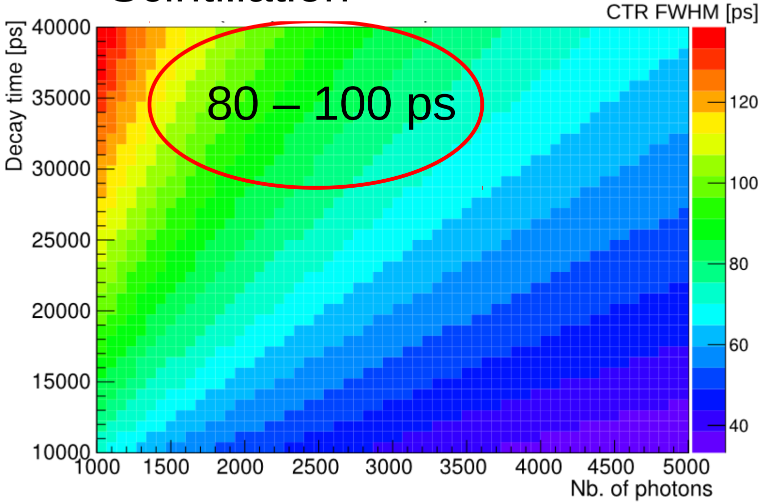
The time resolution improves with **increasing number of photons** and **decreasing threshold**
(first photon provides the best time resolution if rise time is short)

- **Analytical approach:** improved version of estimation of approach by Post & Schiff, Lynch, Wright:

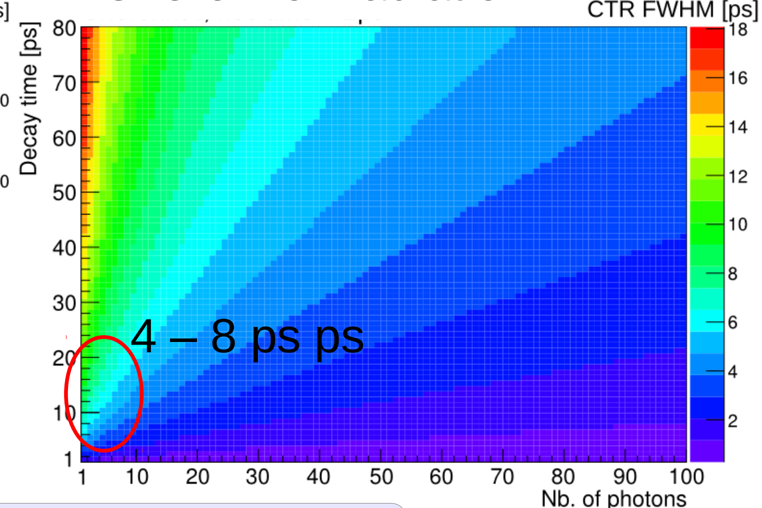
$$P(Q,t) = \frac{f(t)^Q \, e^{-f(t)}}{Q!}$$

$$W(Q,t) \cdot dt = P_{Q-1}(t) \cdot \frac{df}{dt} dt$$

Scintillation



Cherenkov radiation

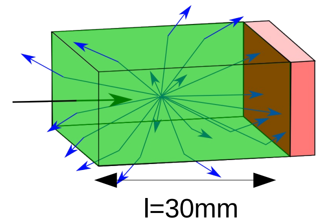


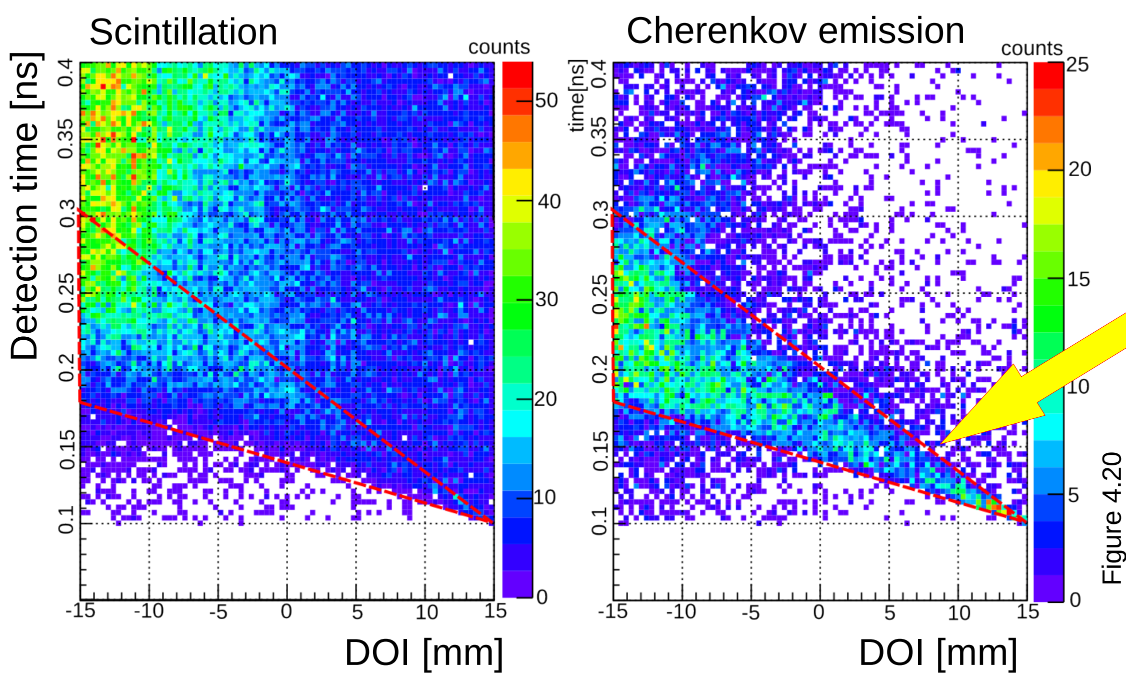
The time resolution improves for **shorter rise-** and **decay times** and **increasing light yield. Cherenkov emission** provides much **better intrinsic time resolution** than fast state-of-the-art scintillators.

Influence of DOI and photon propagation

- Simulation, LSO:Ce 3x3x30mm³

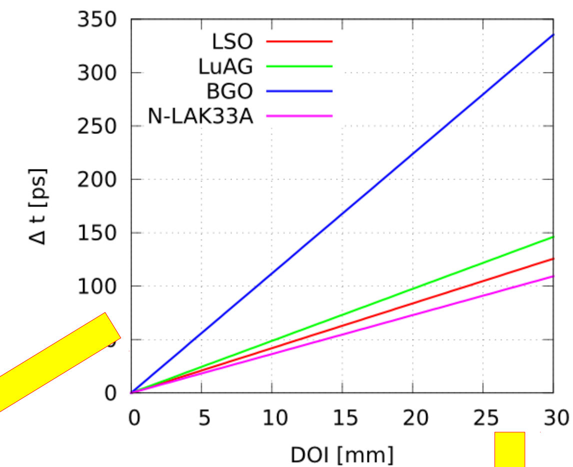
Compare **photon arrival times at detector** of scintillation and Cherenkov emission



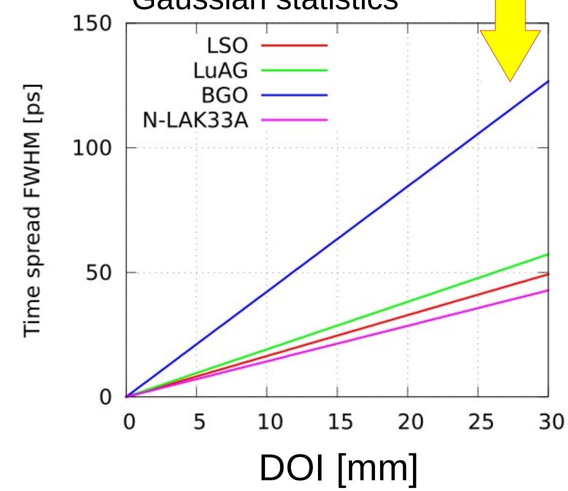


Maximum possible time spread

$$\Delta t = t_{\max} - t_{\min} = DOI \cdot \frac{n_{\mathrm{cr}}}{c} \left(\frac{n_{\mathrm{cr}}^2}{n_{\mathrm{det}}^2} - 1 \right)$$



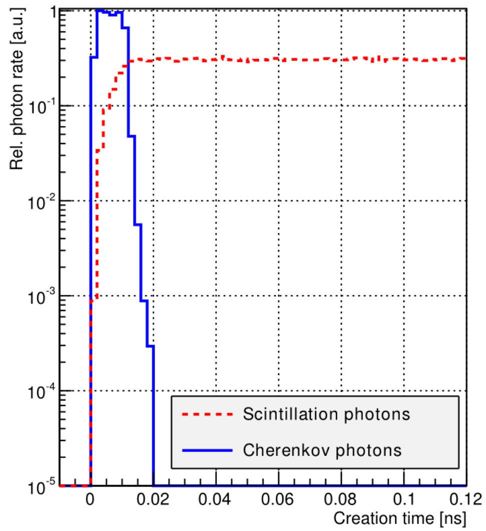
Time spread assuming Gaussian statistics



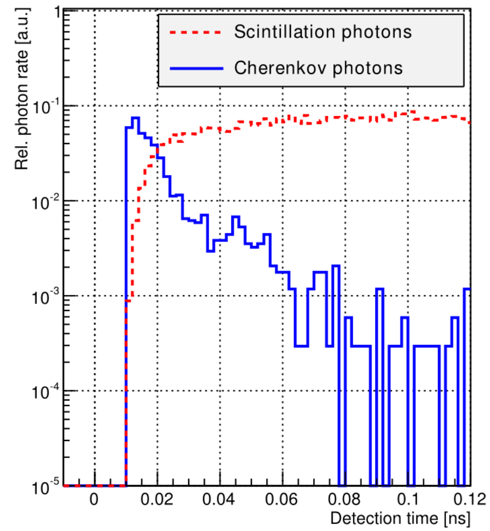
Influence of DOI and photon propagation can be reduced by shortening the crystals (efficiency for γ-detection decreases).

Comparing creation and arrival times of scintillation and Cherenkov photons

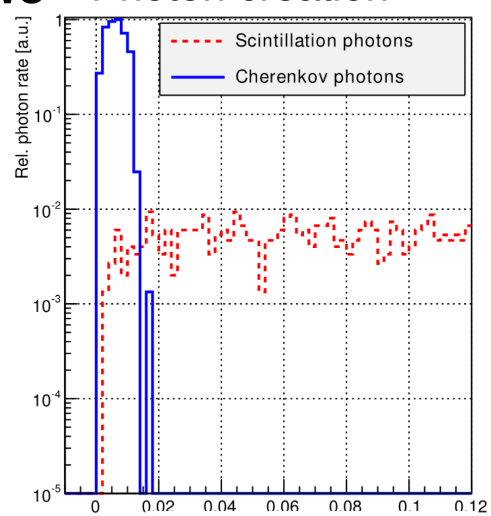
LSO:Ce Photon creation



Photon detection

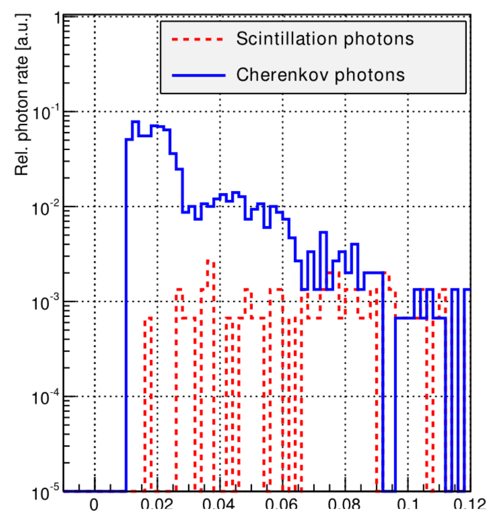


PWO Photon creation



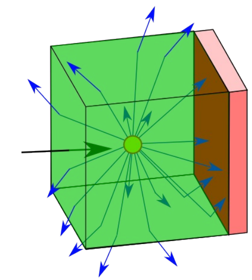
Creation time [ns]

Photon detection



Detection time [ns]

- Cube with 3x3x3mm³



- Calculating “yield ratio” within time window
- Yield ratio = $\frac{n_{Cherenkov}}{n_{scintillation}}$

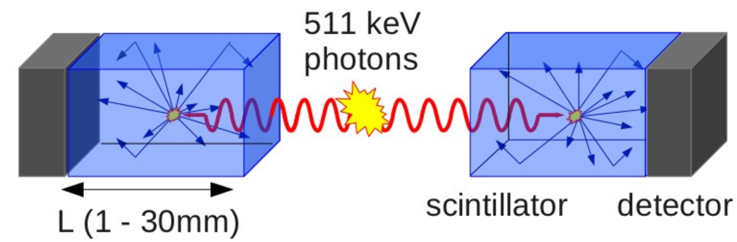
	created		detected	
	<25ps	<100ps	<25ps	<100ps
LSO:Ce	1.77	0.34	1.78	0.16
LuAG:Ce	11.5	2.1	41.5	3.4
BGO	122	24.2	**364**	**28**
PWO	86	16.6	134	21

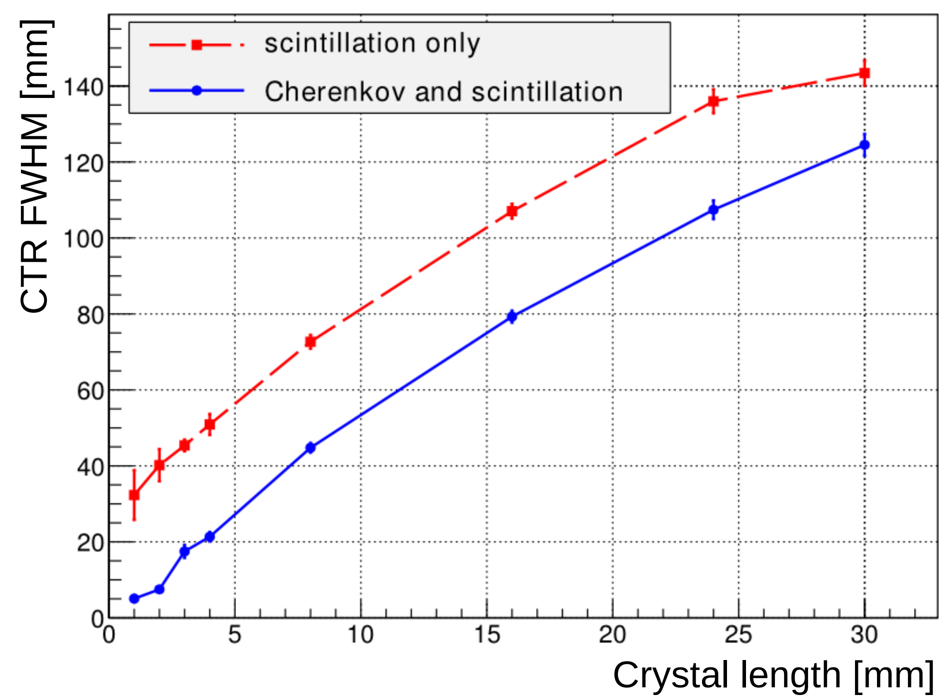
Ref.: Brunner et al., IEEE Trans. Nucl. Sci. 61 (2014) p. 443

Impact of the Cherenkov effect on the coincidence time resolution

- Simulation of a coincidence setup
- LSO:Ce, length *l* = 1-30mm
- Determination of the coincidence time resolution with and without the Cherenkov effect
- On average 1-2 Cherenkov photons were detected in each crystal per event
- Cherenkov photons clearly **improve** the **CTR** for all crystal lengths
- Influence of **crystal length** (DOI + photon propagation) on the CTR is visible

Improvement of the CTR due to Cherenkov emission ↔ **fast time constants**.
Improvement of the CTR with decreasing crystal length ↔ **DOI & photon propagation**.





S. E. Brunner et al. NIM A 732 (2013) p. 560

Improving the time resolution of scintillators using the Cherenkov effect: proof of principle measurements

The Cherenkov effect for annihilation photon detection: setup

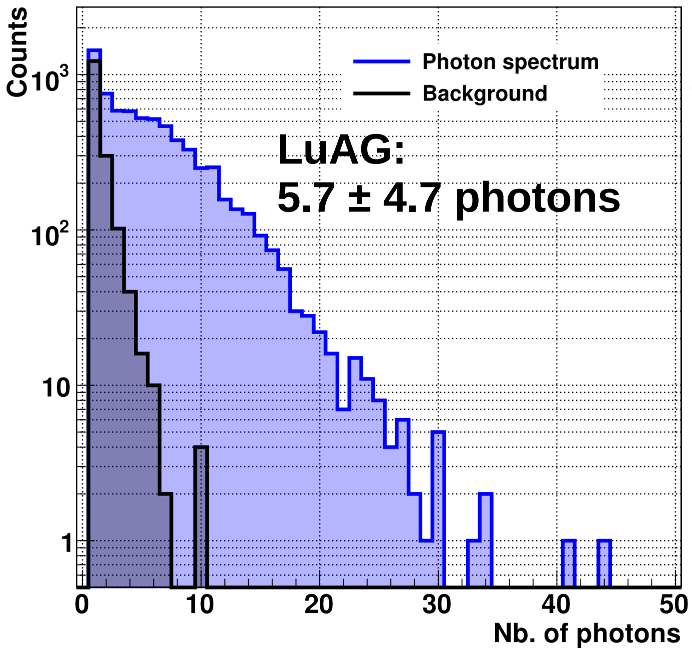
- Coincidence setup using ^{22}Na
- Photo detectors: Philips DPC3200
- Temp.: -18°C, 10% cells off
- **LSO:Ce** (3x3x3mm³) as **reference** detector
- **Cherenkov radiator** (3x3x8mm³) for investigations
- Surface: polished, no wrapping

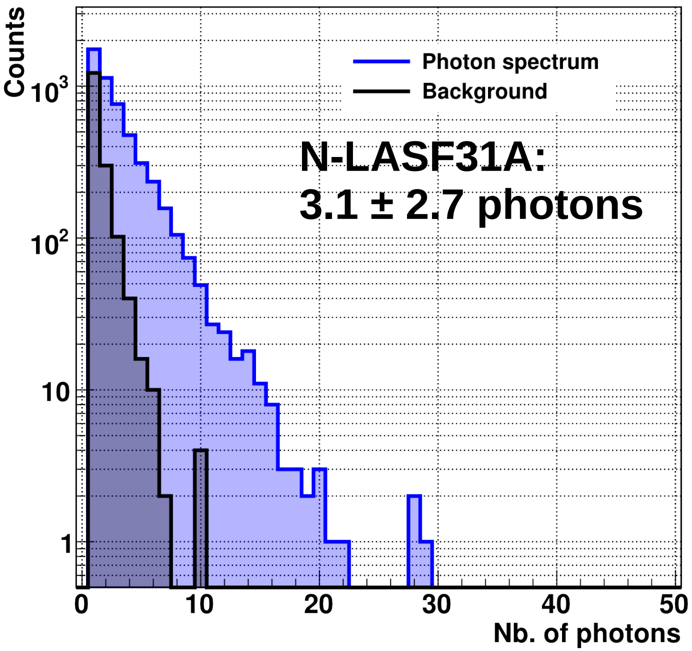
Materials

♦ **Pure** Cherenkov radiators (Cherenkov emission only):
LuAG, N-LASF31A

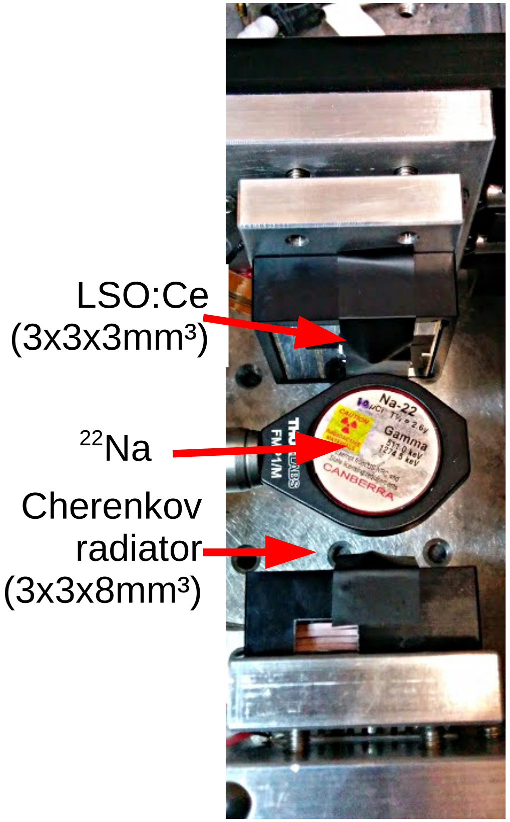
♦ **Hybrid** materials (Cherenkov emission and scintillation occur):
LuAG:Ce, BGO

Proof of principle measurement: Cherenkov photon yield



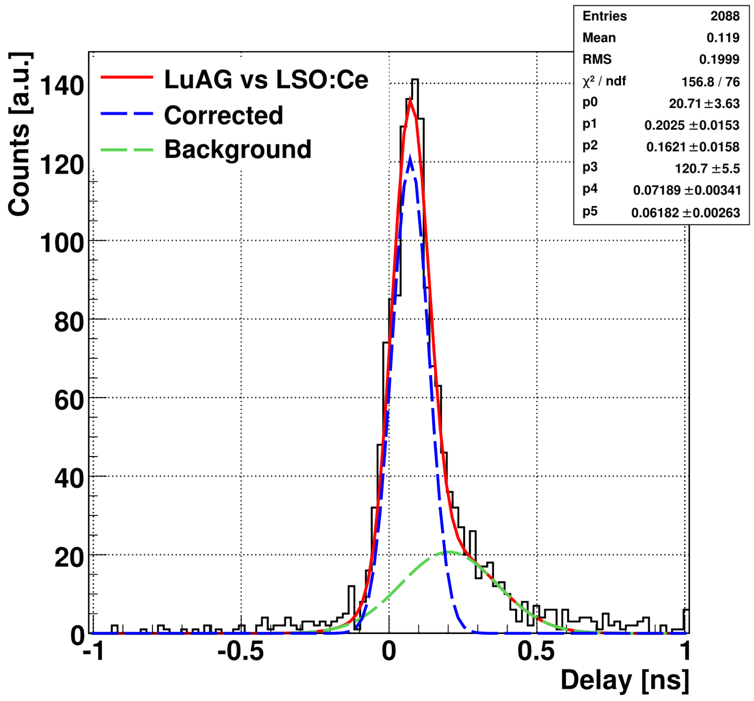


Ref.:S. E. Brunner, PhD thesis, Vienna UT (2014)

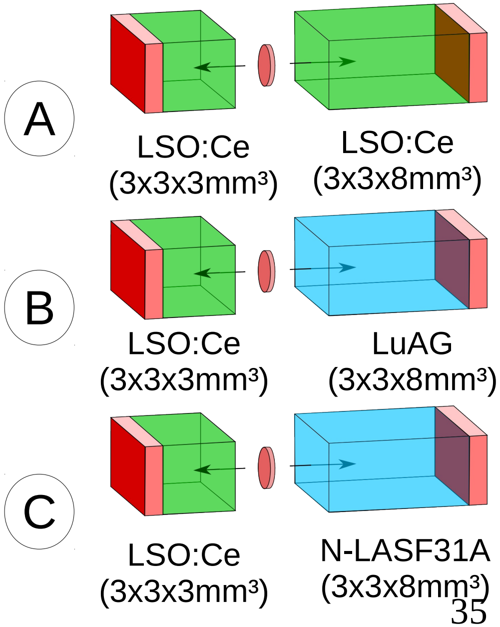


- Temp. -18°C, inhibited cells 10%
- Crystal sizes: 3x3x8mm³, polished, no wrapping
- Cut on photoelectric absorption of annihilation photons at reference detector

Proof of principle measurements: Time resolution with pure Cherenkov radiators

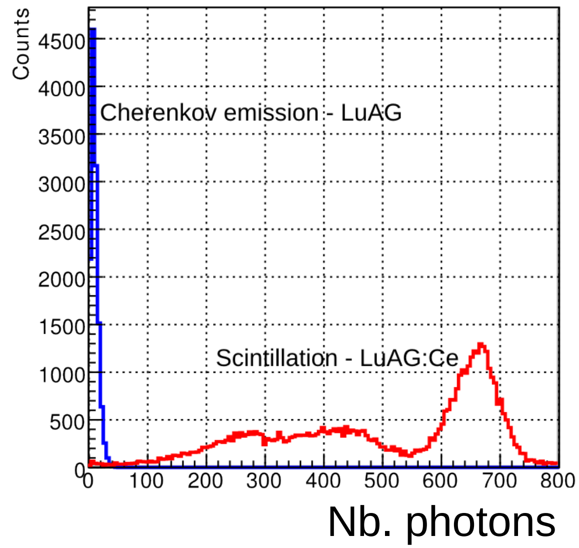


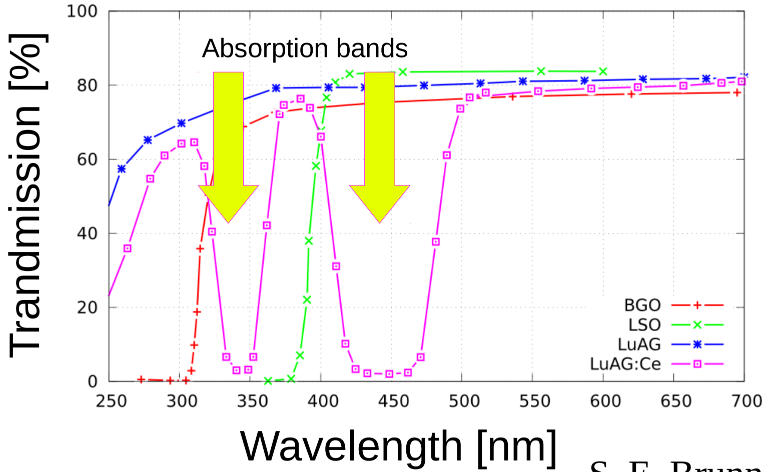
Crystal 1	Crystal 2	Length 1 [mm]	Length 2 [mm]	Thr 2 [photons]	Setup	CTR [ps]
LSO:Ce	LSO:Ce	3	8	photo-p.	A	192 ± 4
LSO:Ce	LuAG	3	8	6	B	**146 ± 16**
LSO:Ce	LuAG	3	8	4-6	B	**145 ± 6**
LSO:Ce	N-LASF31A	3	8	6	C	**178 ± 16**

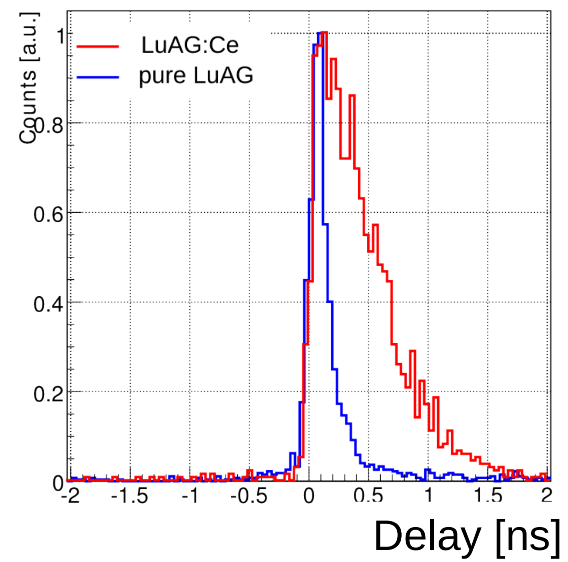


Time resolution with hybrid scintillators

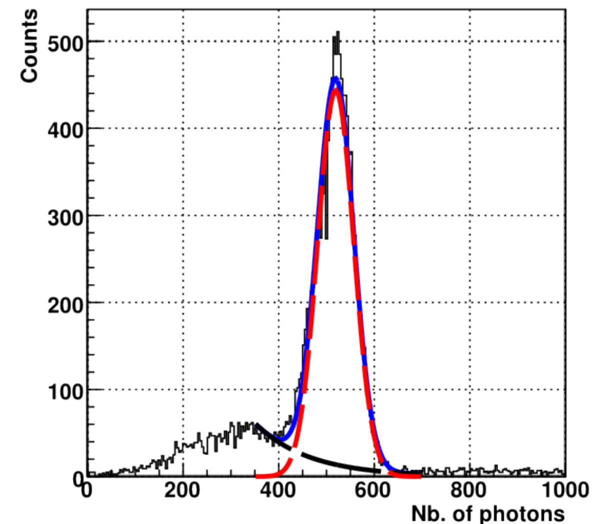
- Undoped LuAG shows only Cherenkov emission
- Ce doped LuAG shows **Cherenkov emission and scintillation**
- Cherenkov emission is fast → **good time resolution**
- Scintillation provides high light output →**good energy resolution** (necessary for rejecting scattered events in PET)
- A **hybrid material** offers **both** advantages
- **Challenge:** in undoped LuAG Cherenkov photons can be detected in doped LuAG:Ce many Cherenkov photons get absorbed → better material: **BGO**







Time resolution using hybrid Cherenkov radiators

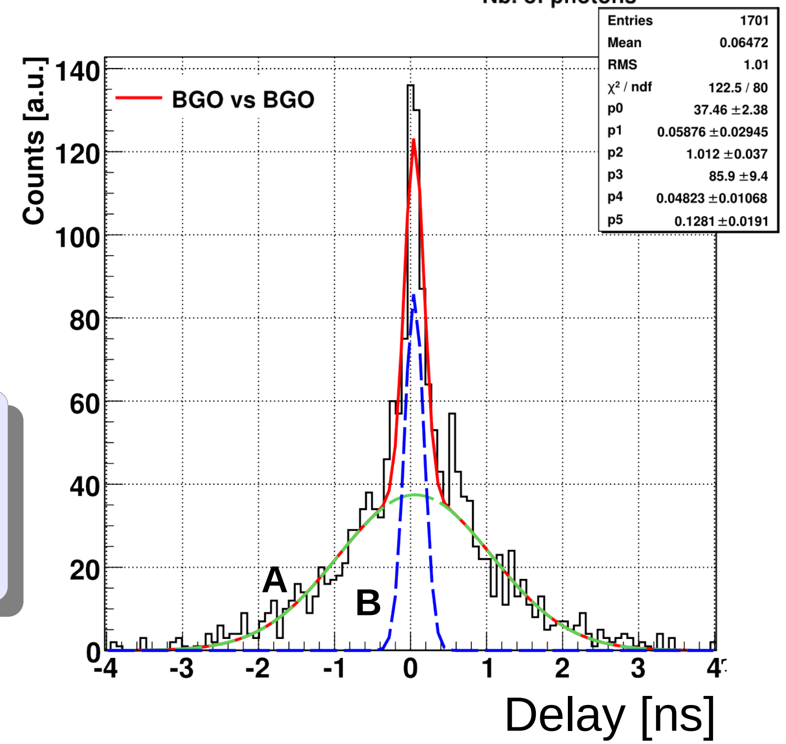


- Two BGO crystals 3x3x8mm³ in coincidence
- Philips DPC3200
- Surfaces polished, wrapped in Teflon,
- Trigger on first arriving photon
- Two components visible:

Component A (76%): CTR = 2.38ns FWHM
Component B (24%): **CTR = 301ps FWHM**

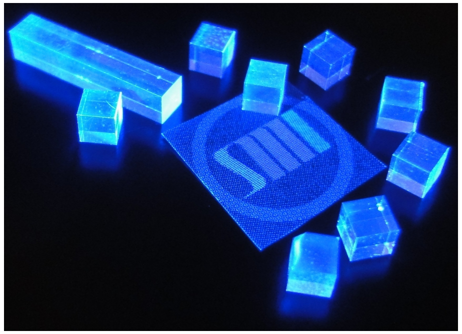
- Best ever measured CTR with BGO
  (according to Moses, NIM A 580 (2007) p.919)
- LSO:Ce with the same size: 240ps FWHM

Cherenkov emission improves the CTR also in scintillators. The **DPC** is the **optimum detector** for Cherenkov photon detection in hybrid materials, because it allows to trigger on the first arriving photon.



S. E. Brunner

The Cherenkov effect for gamma detection: potential and outlook

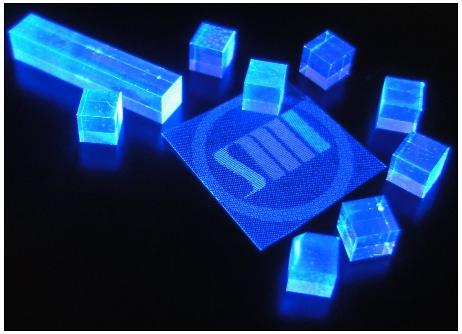


- **Cherenkov photons** were **detected** for γ-photons with 511keV in Cherenkov radiators and hybrid scintillators using digital SiPM
- The **time resolution** could be **improved** when compared with a fast scintillator (LSO:Ce)
- **Detecting Cherenkov photons in hybrid** scintillators could solve problem of energy determination while improving the TR
- **Challenge**: Cherenkov photon yield is very low

Outlook

- Detection of Cherenkov radiation with two (pure) Cherenkov radiators in **coincidence** (first tests are promising)
- Investigations of **new materials** for increasing the Cherenkov photon yield

The Cherenkov effect for gamma detection: potential and outlook



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- **Detecting Cherenkov photons in hybrid** scintillators could solve problem of energy determination while improving the TR
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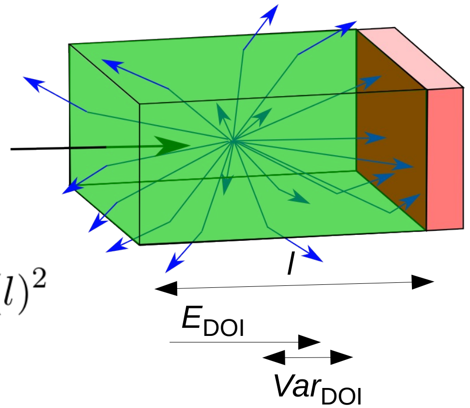
Outlook

- Detection of Cherenkov radiation with two (pure) Cherenkov radiators in **coincidence** (first tests are promising)
- Investigations of **new materials** for increasing the Cherenkov photon yield

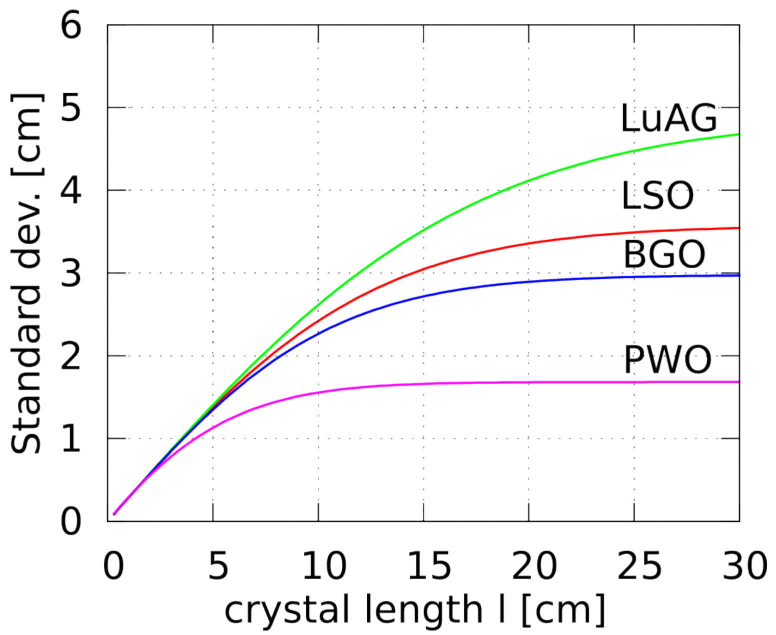
Thank you!

Influence of the DOI

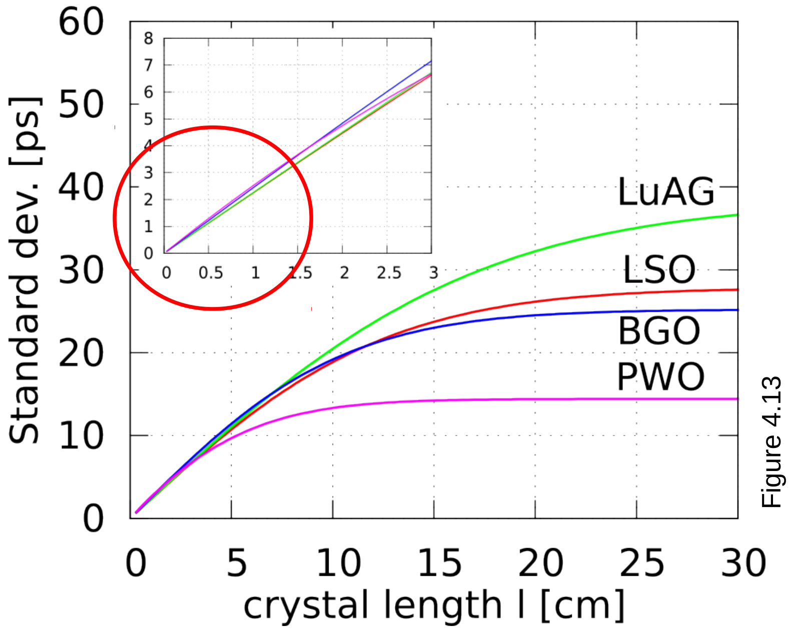
- Analytical approach
- Calculating expectation value of γ-interaction inside a scintillator with a length *l*



$$E_{\mathrm{DOI}} = \frac{N(l)}{\mu}\left(1 - \mathrm{e}^{-\mu l}\,(1+\mu l)\right) \qquad Var_{\mathrm{DOI}} = \frac{1}{\mu}\left(2E(l) - l^2\mathrm{e}^{-\mu l}\right) - E(l)^2$$

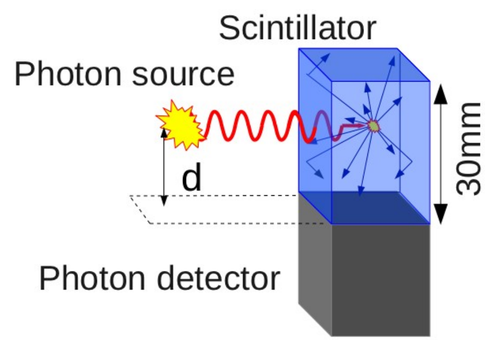


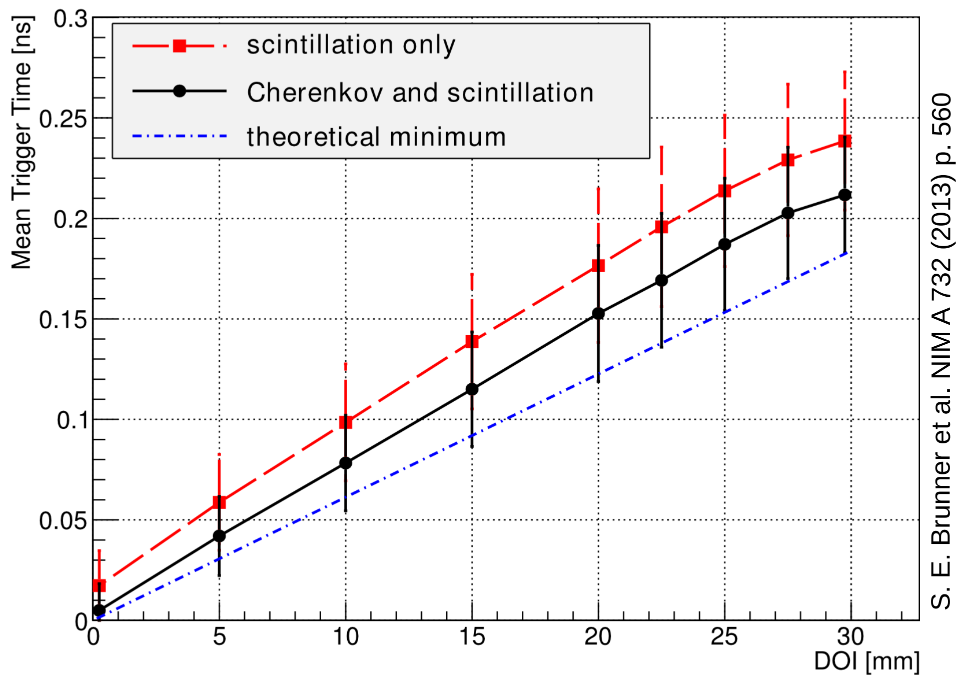
$\sigma(t = xn/c)$



Photon detection times

- Simulating photon arrival times at photo detector for LSO:Ce (3x3x30mm³)
- Shoot γ-source from the side
- Variating distance of γ-source relative to photo detector





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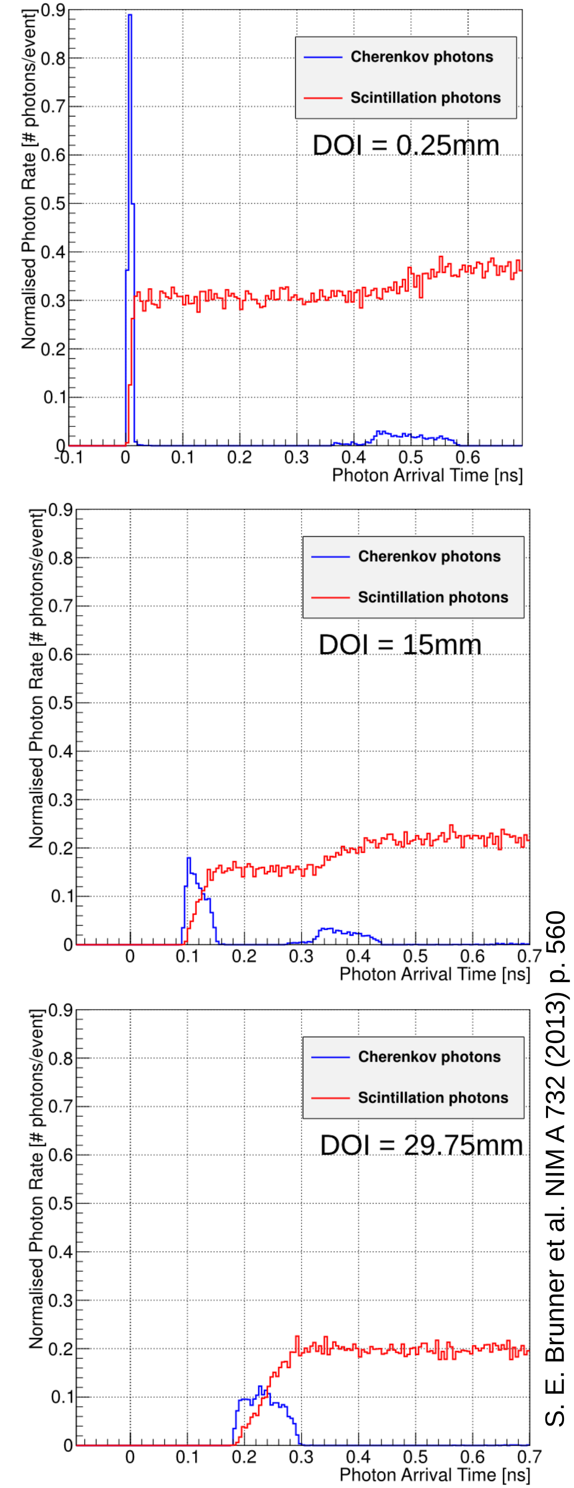
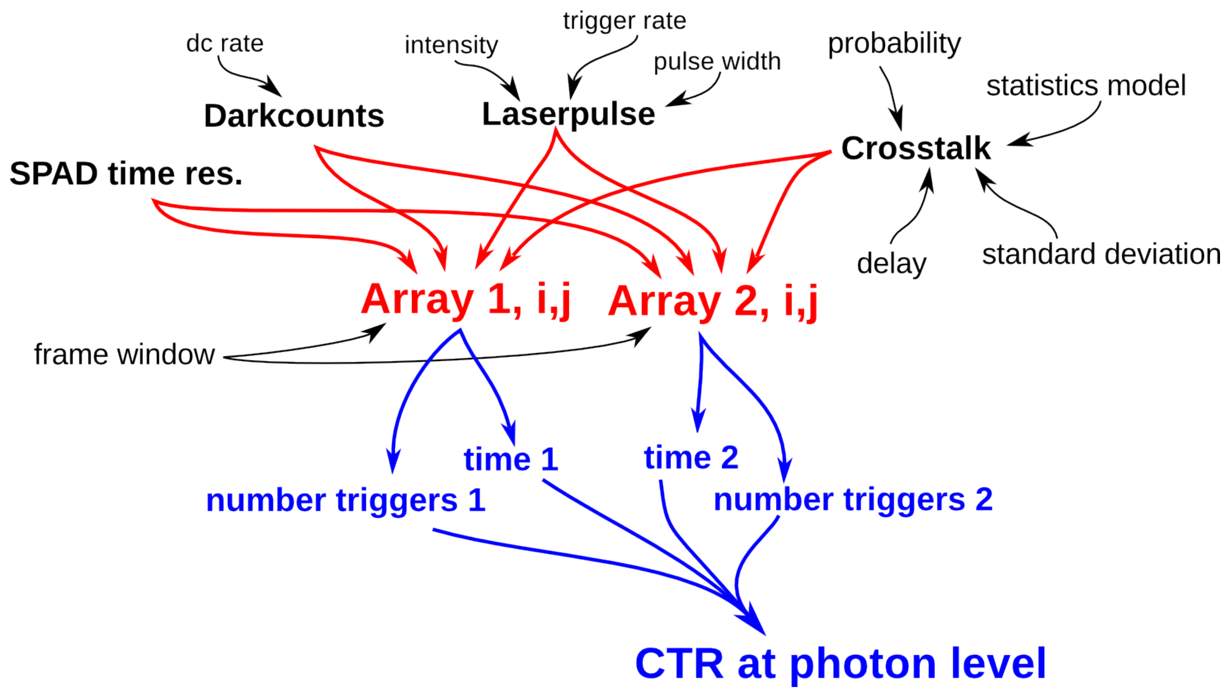


Time resolution of the digital SiPM: simulation



- MC simulation using ROOT
- Structure based on the Philips DPC
- Two arrays representing the SPADs of two pixels/dies
- Laserpulse is triggering cells
- The arrays give back the time of the first trigger and the number of triggers per array

  → **time resolution**

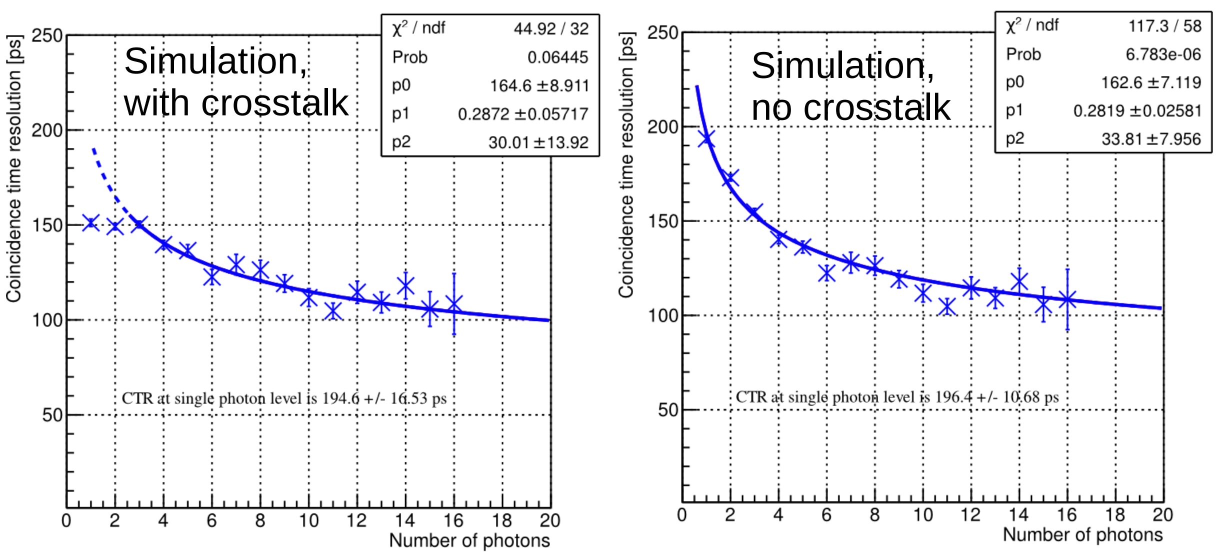
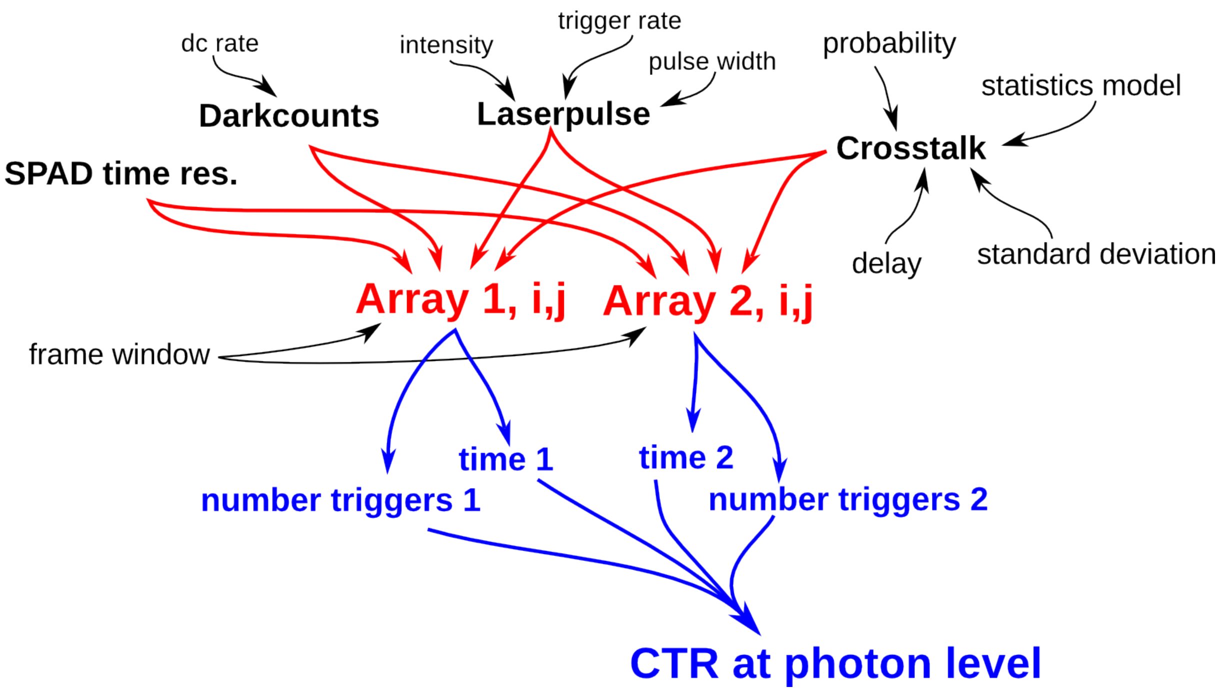


Figure 3.21

Time resolution of the digital SiPM: simulation



- MC simulation using ROOT
- Structure based on the Philips DPC
- Two arrays representing the SPADs of two pixels/dies
- Laserpulse is triggering cells
- The arrays give back the time of the first trigger and the number of triggers per array

  → **time resolution**

Setup was adjusted according to outcomes of the simulation.
Artefacts at low photon levels vanished.

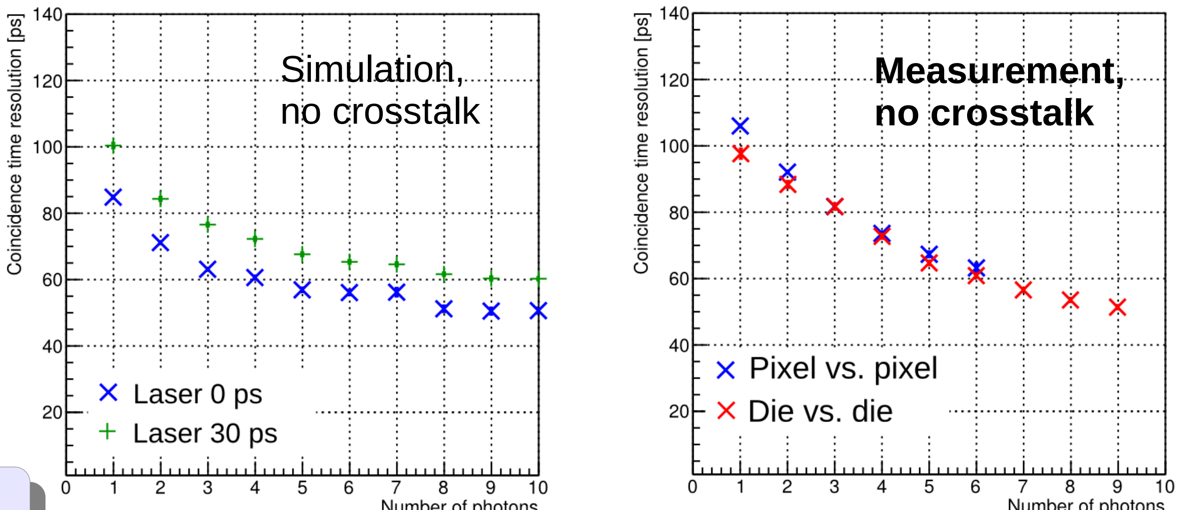


Figure 3.20 Figure 3.20

Time resolution of the digital SiPM: simulation

- Correlated triggers cause artefact → opt. cross talk
- Experimental validation:

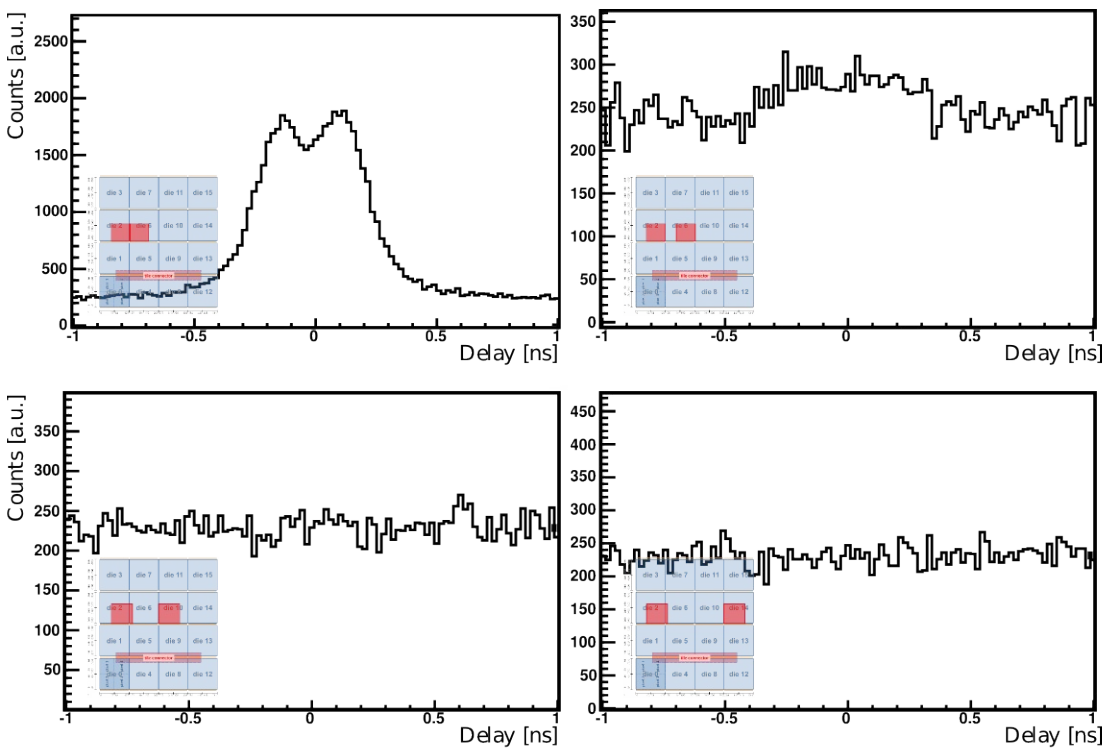


Figure 3.19

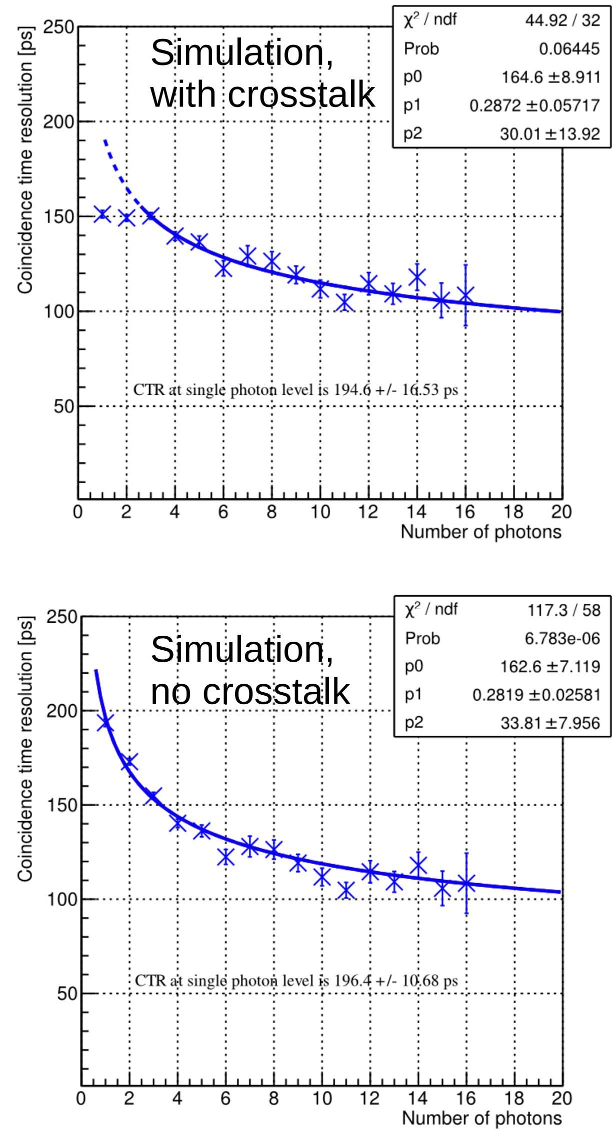
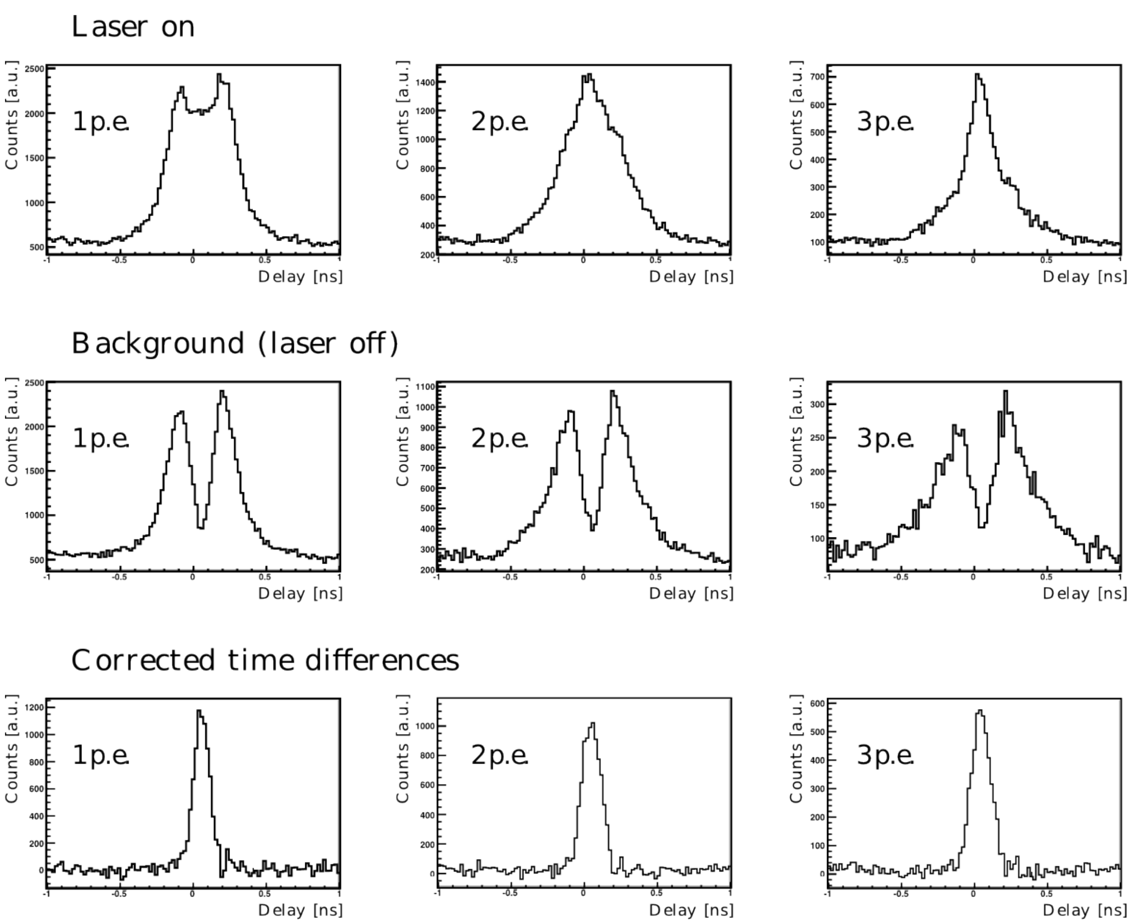
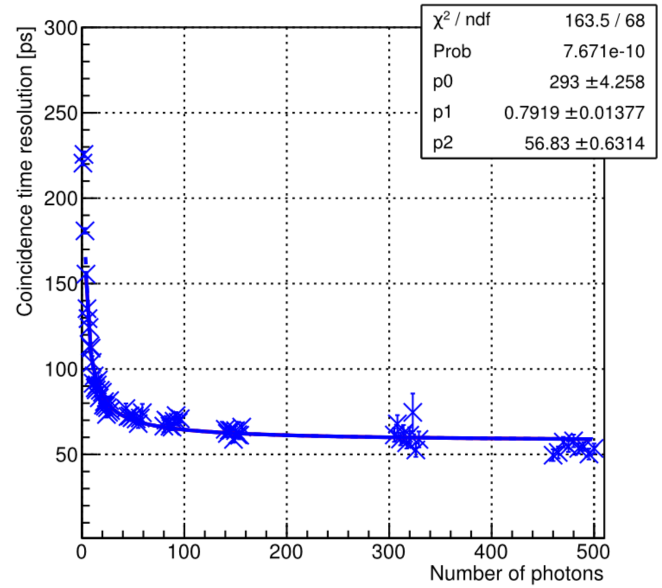
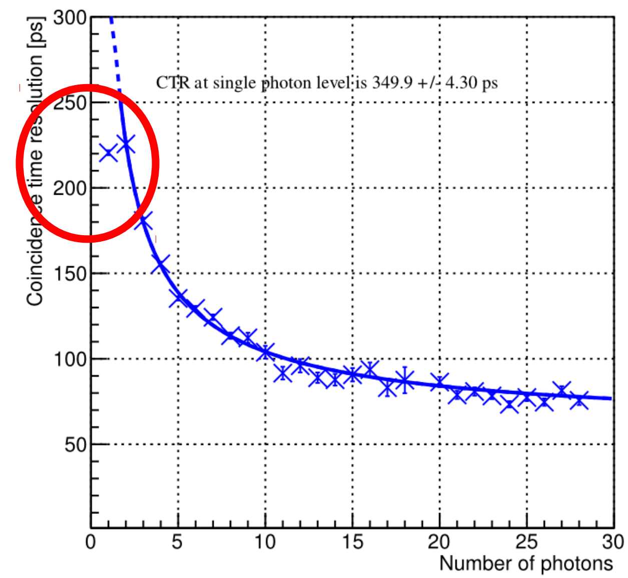


Figure 3.21

Time resolution of the digital SiPM: **Results**







Ref.: figure 3.14 & 3.15

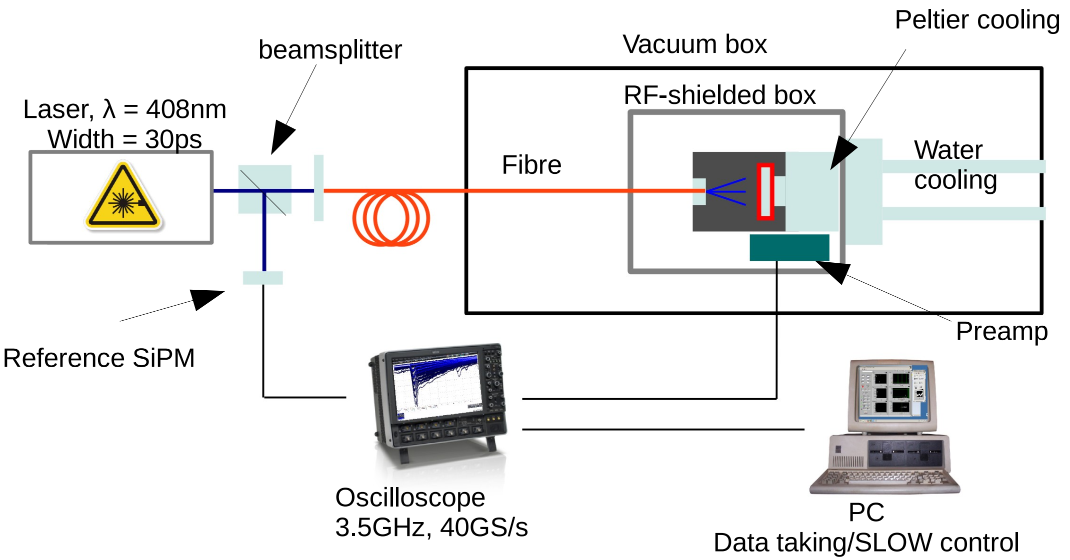
Single photon time resolution of SiPM

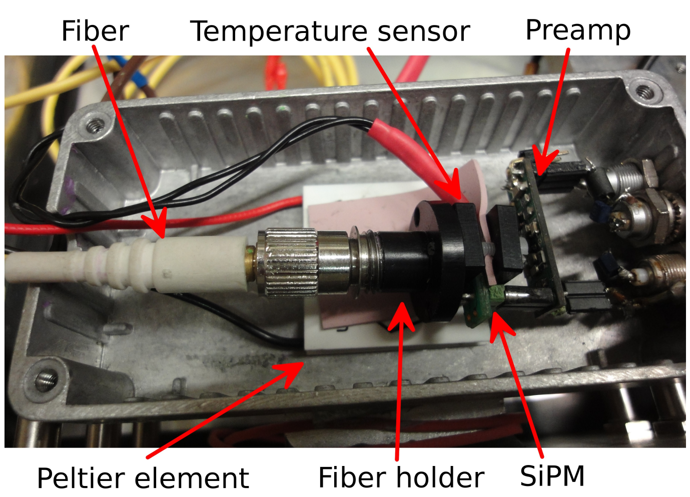
- Figure of merit: single photon time resolution
- Semi-automatic test stand
- PC (LabView) controls:

  bias, cooling, oscilloscope
- PC records:

  bias, current, temperature, signal (amplitude, area, risetime), time difference to trigger
- Offline data analysis, including automatic determination of the breakdown voltage

→ time resolution as function of number of photons, bias, temperature





Single photon time resolution of SiPM

Manufact.	AdvanSiD	Hamamatsu	Ketek	Ketek	Ketek
Type	SiPM3S P-50	S10931-100P	PM3375-B72	PM3360-A2*	PM3350-B63
Size [mm²]	3x3	3x3	3x3	3x3	3x3
SPAD size [µm]	50	100	75	60	50
Breakdown v. [V]	~35	~70	~23	~23	~23
DC-rate [MHz]	<45	<12	<4.5	<4.5	<4.5
Gain [x10^6]	2.5	2.4	14	9	6
PDE [%]	22	70	62	39	50
Cell cap. [fF]	-	2800	650	380	270
SPTR** [ps]	200	200	160	200	140

*prototype
** best value

Best time resolution by sensors with the smallest cell capacitance (Ketek).
Large contribution of the system to the time resolution!