Timing in PET: state-of-the-art and challenges to harvest prompt photons

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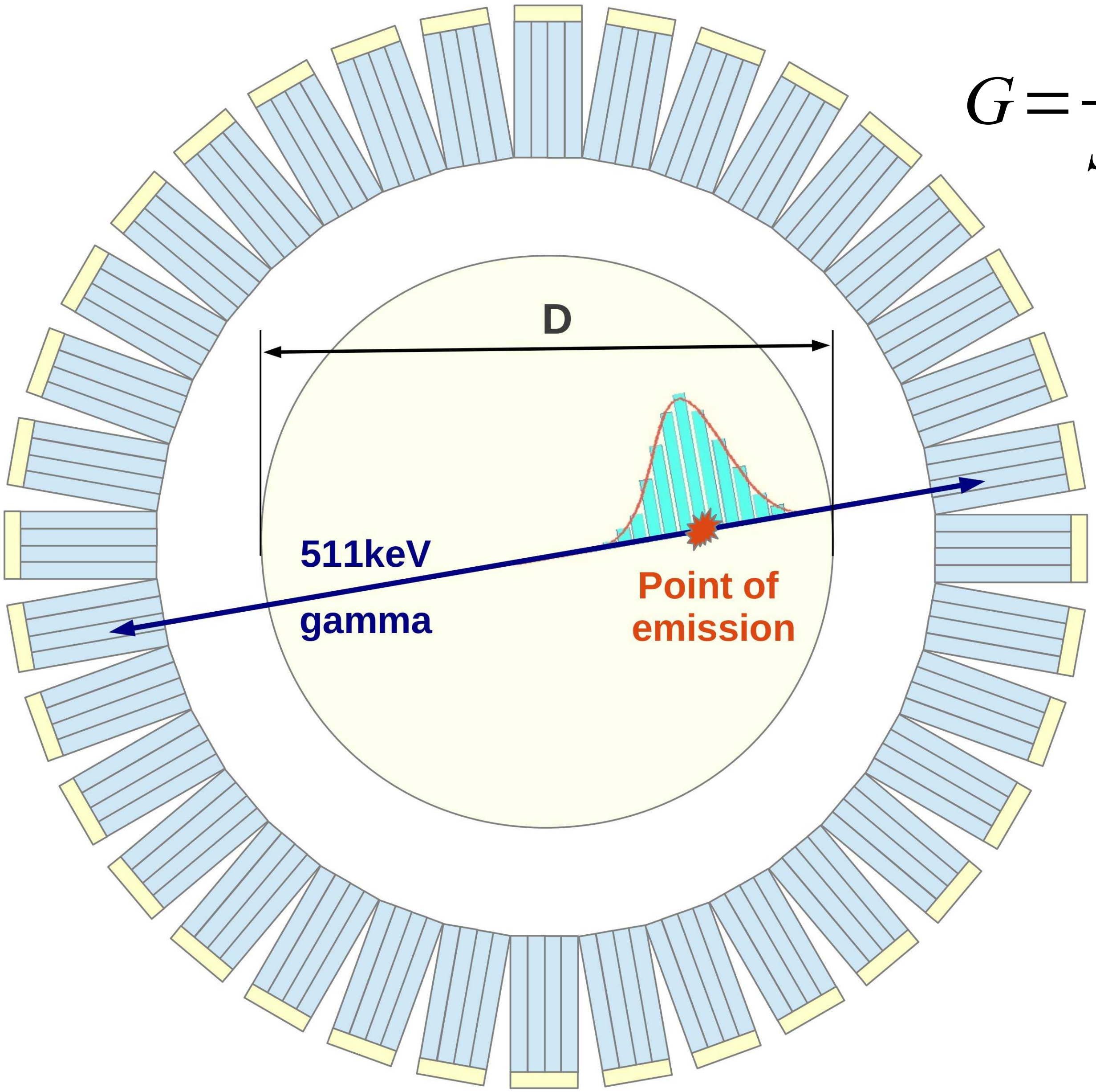
This work was carried out in the frame of the Cost Action TD1401 (FAST), the TICAL ERC Grant 338953 and the Crystal Clear Collaboration

Time of flight in PET



$$G = \frac{SNR_{TOF}}{SNR_{non\,TOF}} = \sqrt{\frac{2 * D}{c * CTR}}$$

For whole body PET (D=40cm):

CTR=1ns → G=1.6

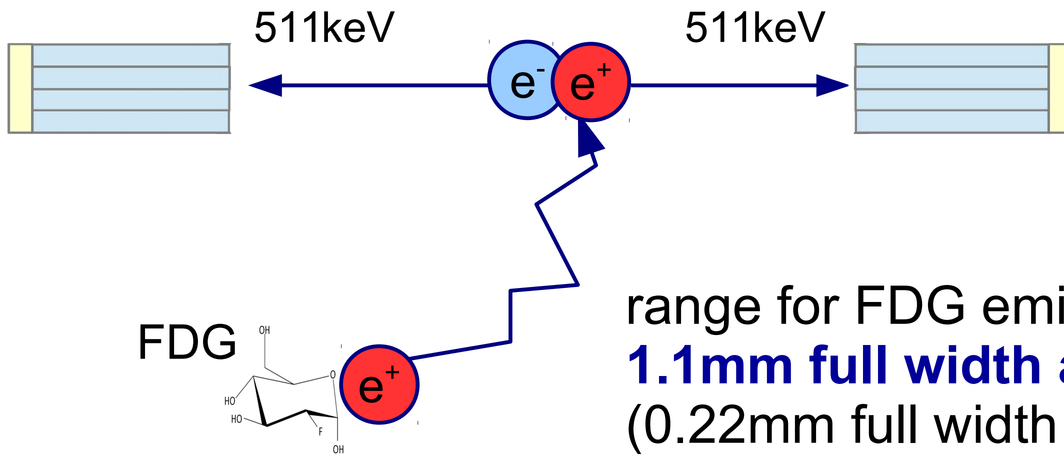
CTR=500ps → G=2.3

CTR=100ps → G=5.2

100ps FWHM CTR corresponds to 1.5cm position resolution.

M. Conti, Physica Medica (2009) 25, 1-11

10ps in TOF-PET: the holy grail?



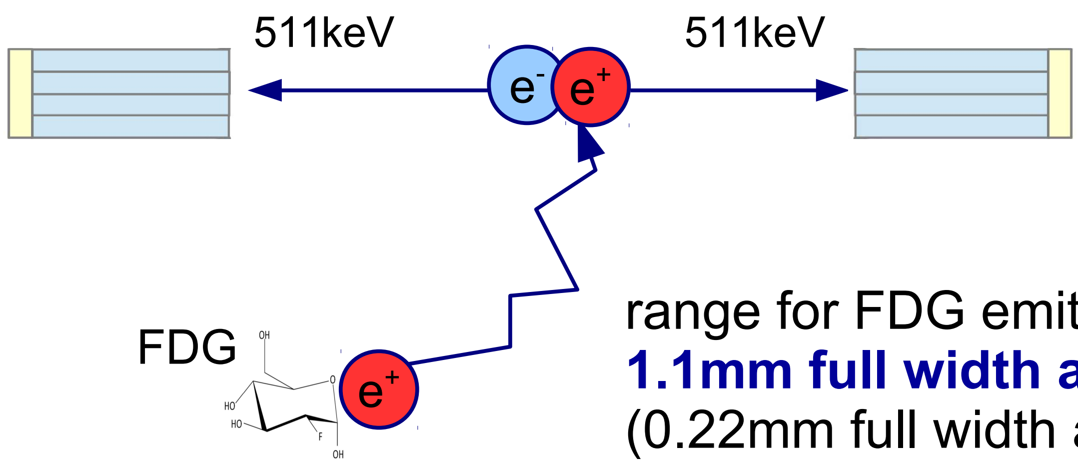
range for FDG emitted positron:
1.1mm full width at ten maximum
(0.22mm full width at half maximum)

→ CTR of **10ps FWHM correspond to 1.5mm resolution** along LOR

→ direct imaging without reconstruction would be possible and very likely could mean a paradigm shift in PET diagnostics

→ other geometries than the standard ring thinkable, like endoscopic probes (EndoTOFPET-US)

10ps in TOF-PET: the holy grail?

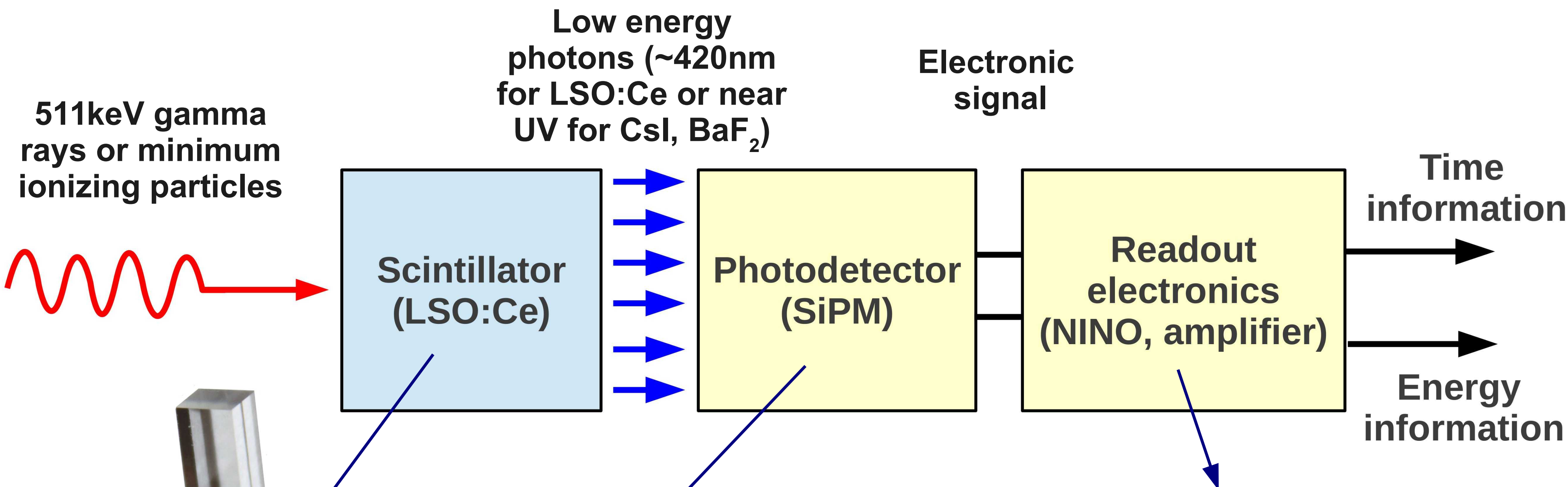


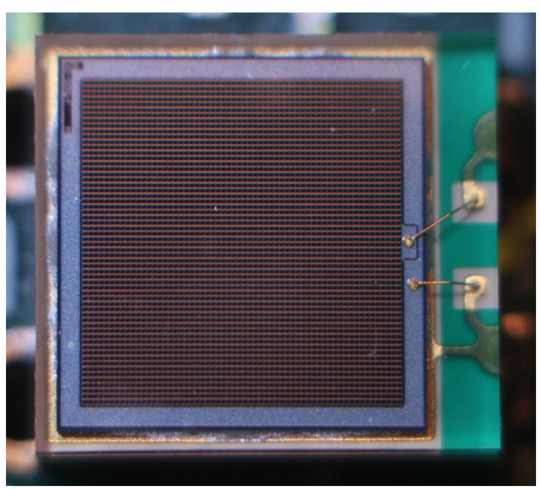
range for FDG emitted positron:
1.1mm full width at ten maximum
(0.22mm full width at half maximum)

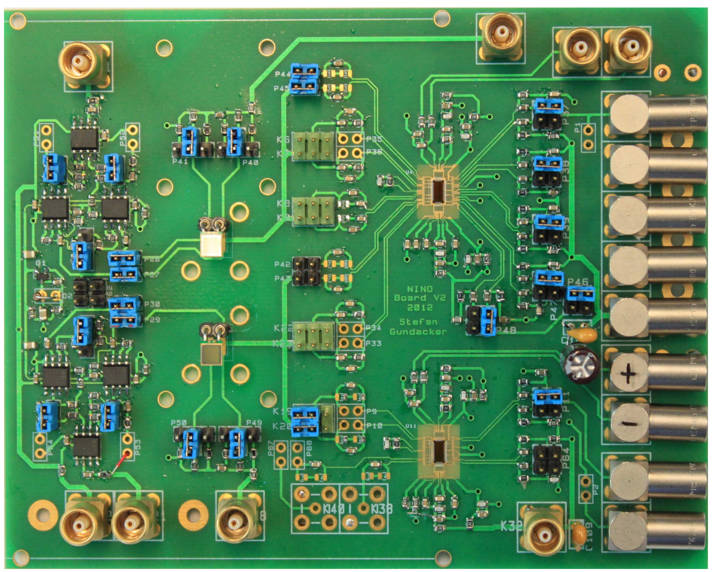
However,
resolution of actual whole body PET around 3-5mm:

→ Time resolution of 20-35ps FWHM enough for direct imaging
(Still ambitious but important relaxation of constraints)

Components of the radiation detector

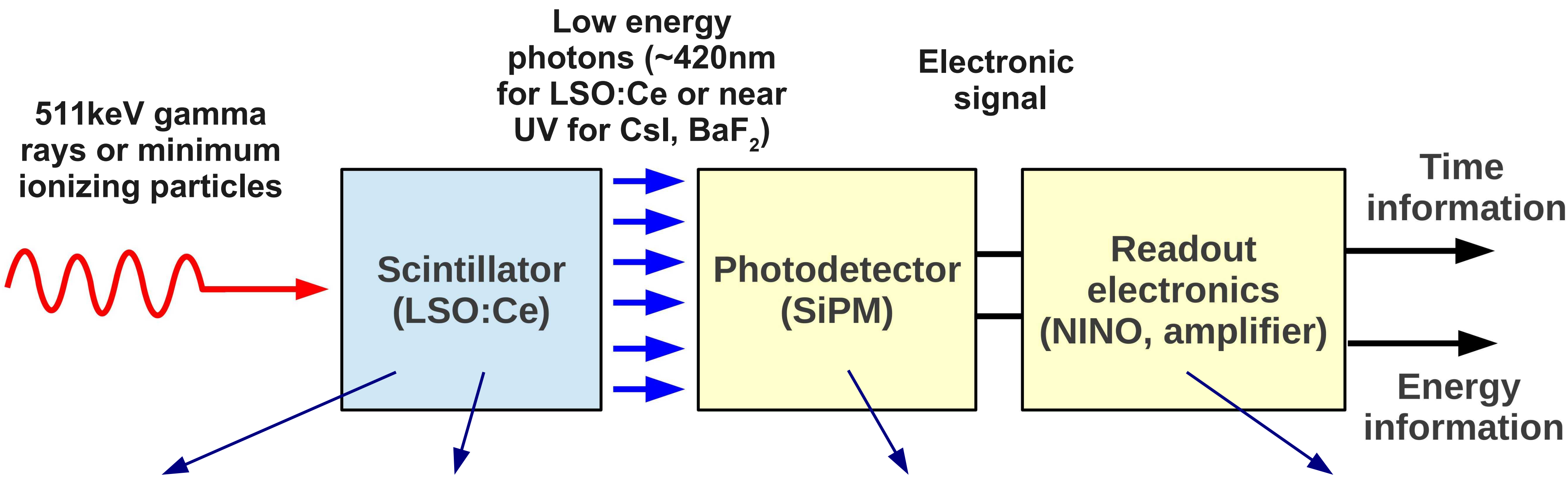






S. Gundacker et.al., ''Time of flight positron emission tomography towards 100ps resolution with L(Y)SO: an experimental and theoretical analysis”, JINST, 8 P07014, 2013

Components of the radiation detector



Scintillation:
- → rise time (τ_r)
- → decay time (τ_d)
- → light yield (**LY**)
- → **prompt photons**

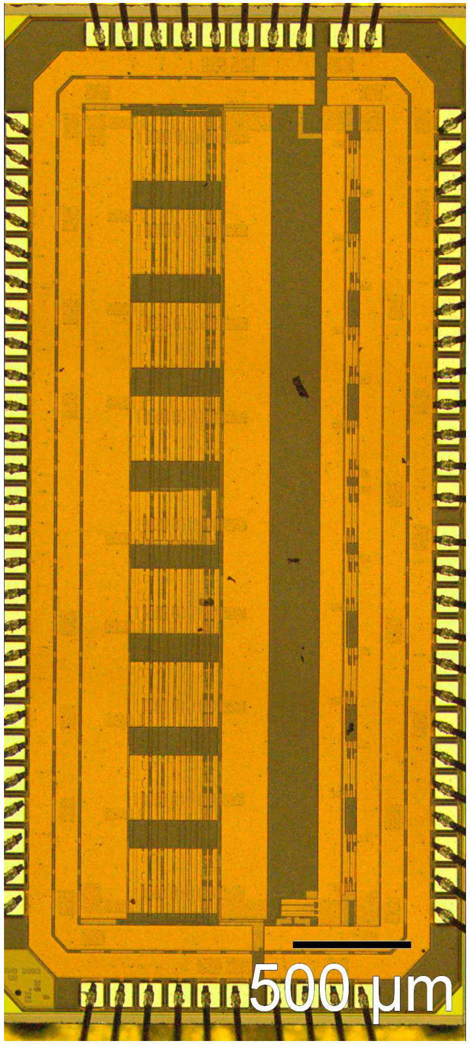
Crystal:
- → light transfer efficiency (**LTE**)
- → photon transfer time spread (**PTS**)

- → photon detection efficiency (**PDE**)
- → single photon time resolution (**SPTR**)
- → additional randomly and correlated photons generated in the SiPM

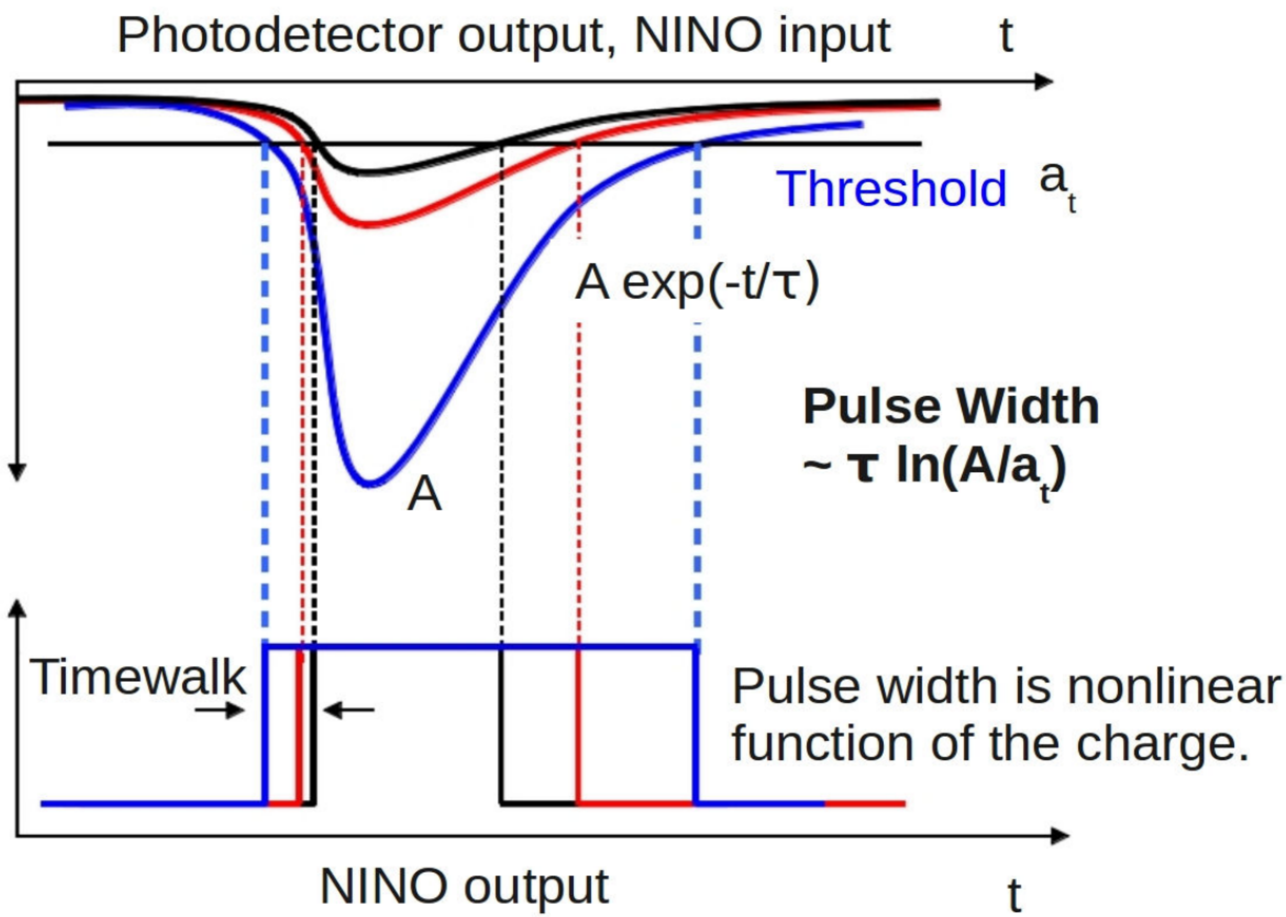
- → electronic and baseline noise
- → signal rising slope (dV/dt)
- → leading edge time discrimination

$$time\ resolution \propto \sqrt{\frac{\tau_d \cdot \sqrt{\tau_r^2 + c_1 \cdot SPTR^2 + c_2 \cdot PTS^2}}{LY \cdot PDE \cdot LTE}}$$

NINO ASIC with leading edge discrimination



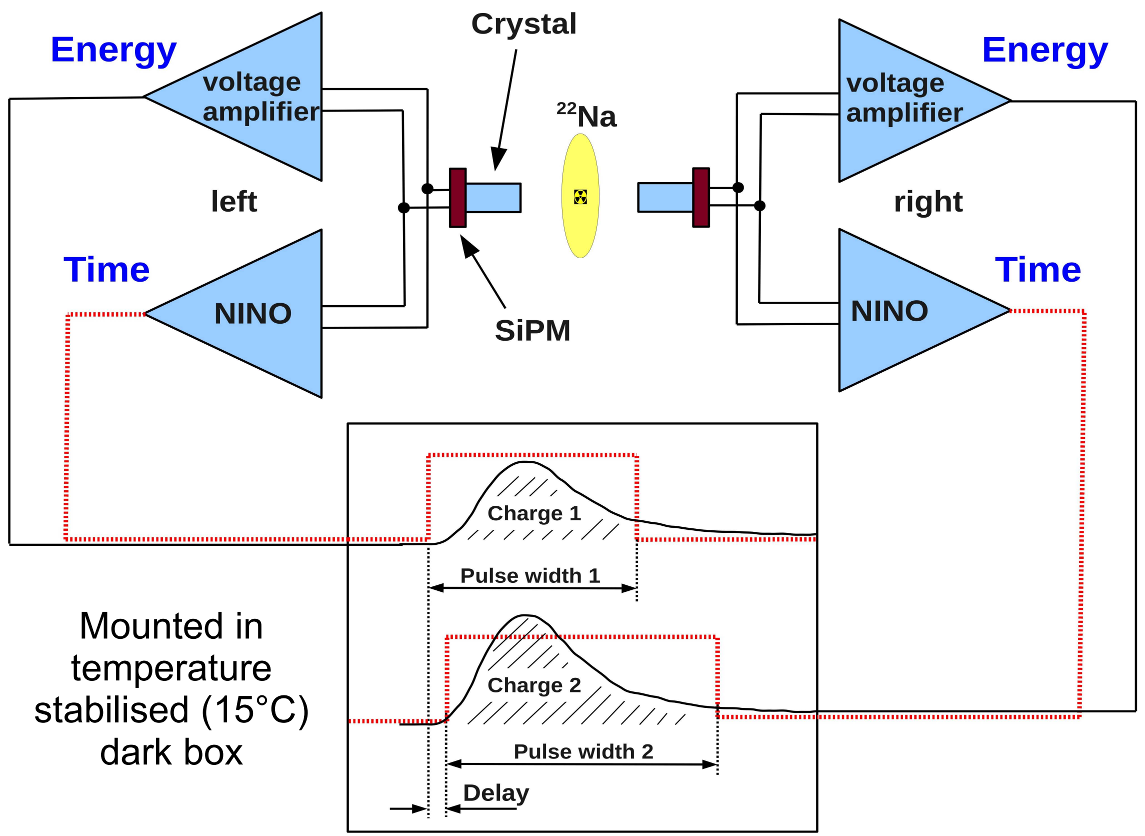
500µm



- Time-over-threshold discrimination: leading edge gives time information and pulse width is a function of the energy.

F. Powolny et. al., IEEE Trans. Nucl. Sci., vol. 58, pp. 597–604, June 2011.

Coincidence time resolution (CTR) measurements



Mounted in temperature stabilised (15°C) dark box

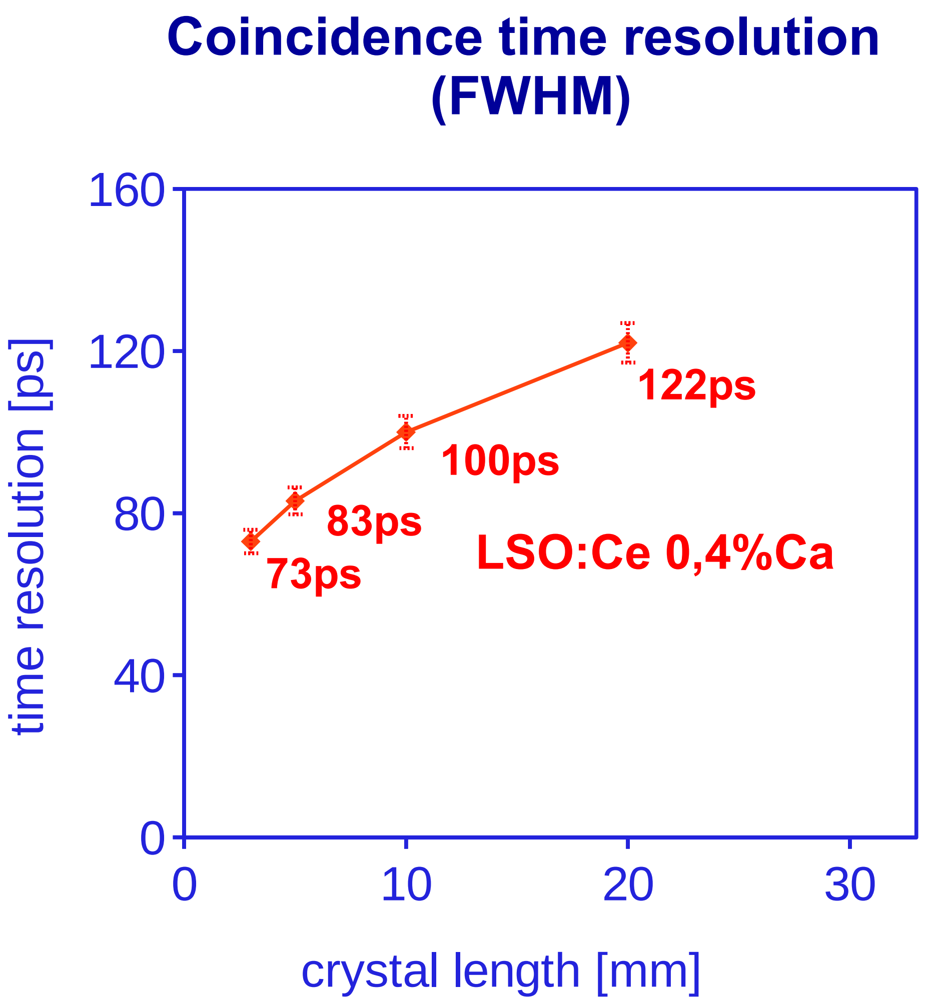
Data acquisition:
LeCroy Oscilloscope DDA 735Zi with 3.5GHz bandwidth and 40Gs/s

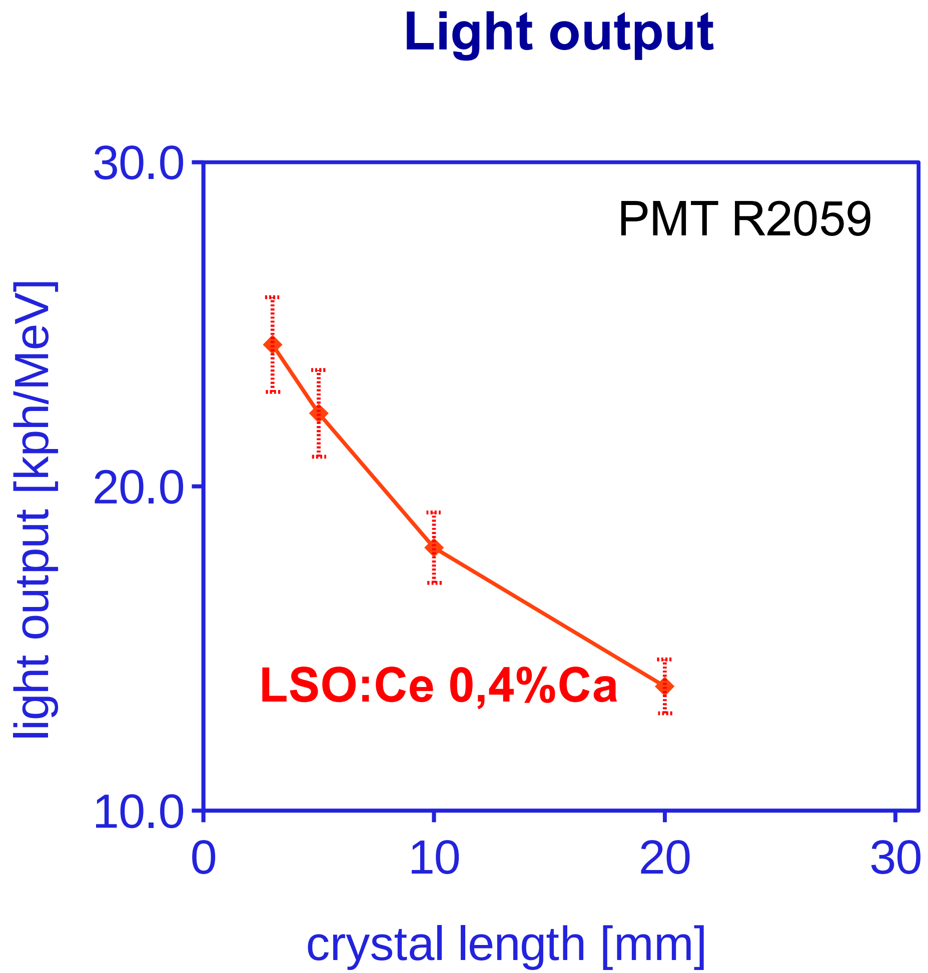
Measure NINO-ASIC leading edge time delays and energy deposit in the crystals.
Select photopeak (511keV) within a window of -2σ to +3σ.

Temperature for measurements stable at 15°C.

S. Gundacker et.al, JINST, August 2013. JINST 8 P07014

Best CTR values so far achieved

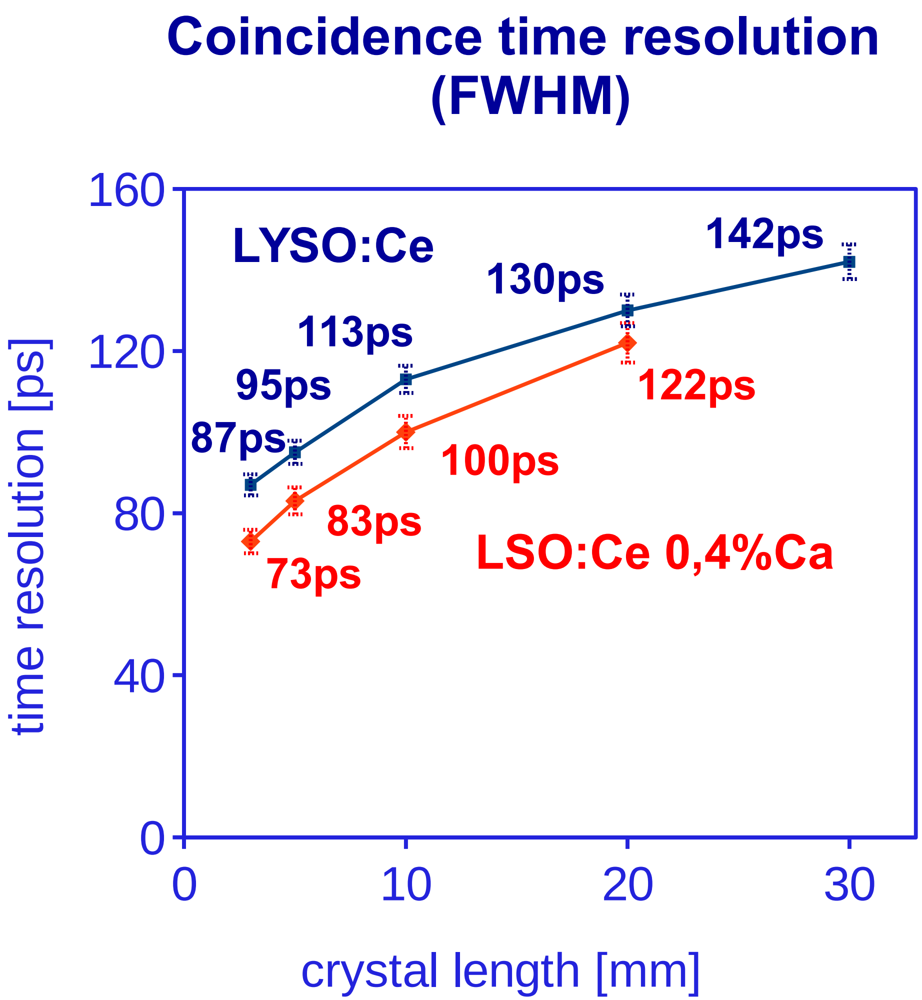


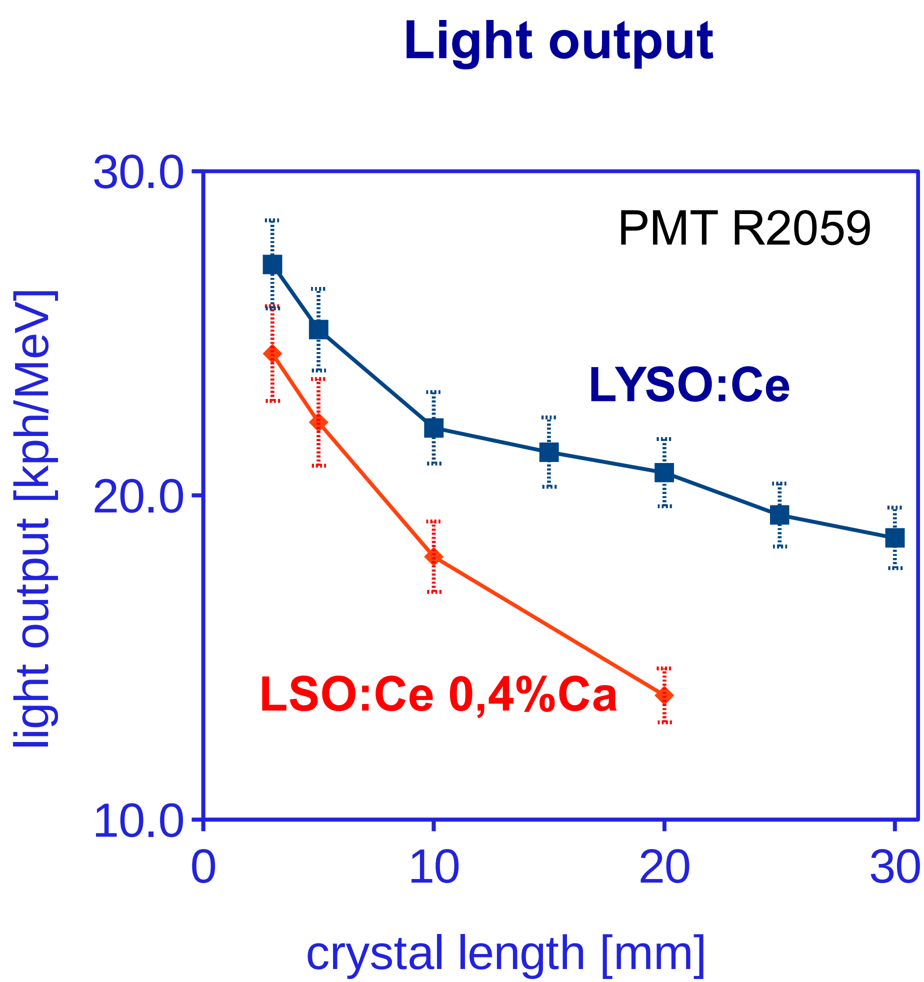


Measured with NUV-HD (25µm SPAD size, 4x4mm^2 device size)
LSO:Ce co-doped 0.4% Ca, 2x2mm^2 crystal cross section, T=15°C

S. Gundacker et.al, JINST, August 2016. JINST 11 P08008

Best CTR values so far achieved



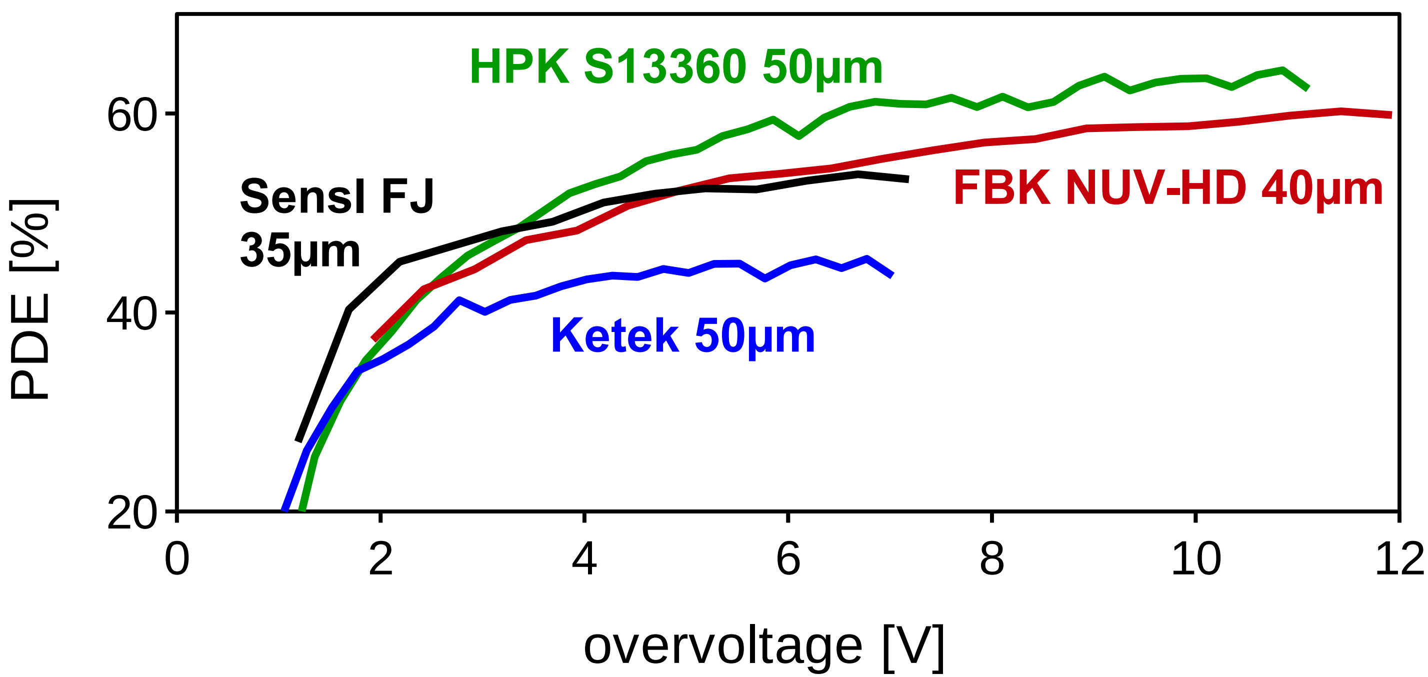


Measured with NUV-HD (25µm SPAD size, 4x4mm^2 device size)
LYSO:Ce, 2x2mm^2 crystal cross section, T=15°C

S. Gundacker et.al, JINST, August 2016. JINST 11 P08008

Very similar CTR with different producers

*SiPM + **LSO:Ce codoped with Ca** coupled with Meltmount (n=1.68)*	*CTR [ps] 2x2x3mm^3*	*CTR [ps] 2x2x20mm^3*	*PDE [%] @ 410nm*	*~~SPTR [ps] FWHM~~*
HPK S13360 3x3mm² (50µm)	**85 ± 3**	**128 ± 5**	62 ± 3	~~157 ± 7~~
HPK S13360 3x3mm² (75µm)	**80 ± 4**	**121 ± 4**	67 ± 3	~~148 ± 7~~
Ketek PM 3350 3x3mm² (50µm)	**94 ± 5**	**150 ± 5**	45 ± 3	~~223 ± 7~~
Sensl FJ 30035 3x3mm² (35µm)	**89 ± 3**	**140 ± 5**	54 ± 3	~~277 ± 12~~
FBK NUV-HD 4x4mm² (25µm) **no resin**	**73 ± 2**	**117 ± 3**	55 ± 3	~~193 ± 12~~
FBK NUV-HD 4x4mm² (40µm) **no resin**	**70 ± 3**	**112 ± 3**	60 ± 3	~~129 ± 9~~



The CTR is strongly related to the PDE.

SPTR measured with NINO, electronic noise component high.

Where are we on the way to reach 10ps in PET?

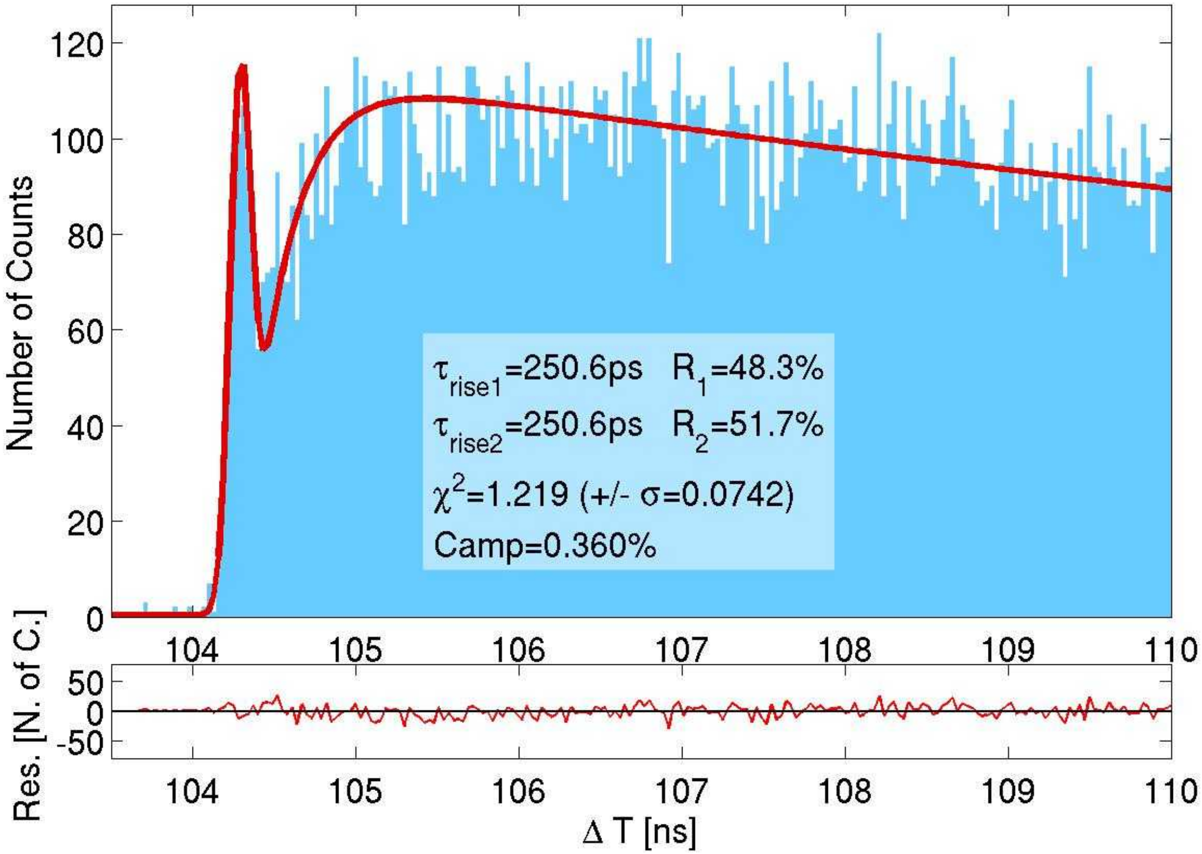
- The light transfer efficiency (LTE) in the crystal:
  - is almost 90% for 2x2x3mm³ size
  - and around 50% for 2x2x20mm³ size,
    (when coupled with Meltmount to SiPM without resin)

→ Hence, CTR improvement by more efficient light collection is limited. Additionally the PDE in modern analog SiPMs reaches already 70%.

- Aiming at a CTR of 10ps FWHM needs to put efforts in finding faster scintillators and/or **improving the single photon time resolution (SPTR) of the SiPM, together with the detection of prompt photons, e.g. Cherenkov or hot intraband luminescence**.

Measured evidence and impact of prompt photons

LuAG:Pr prompt photon-emission



Measured with highly precise time correlated single photon counting setup using 511keV excitation.

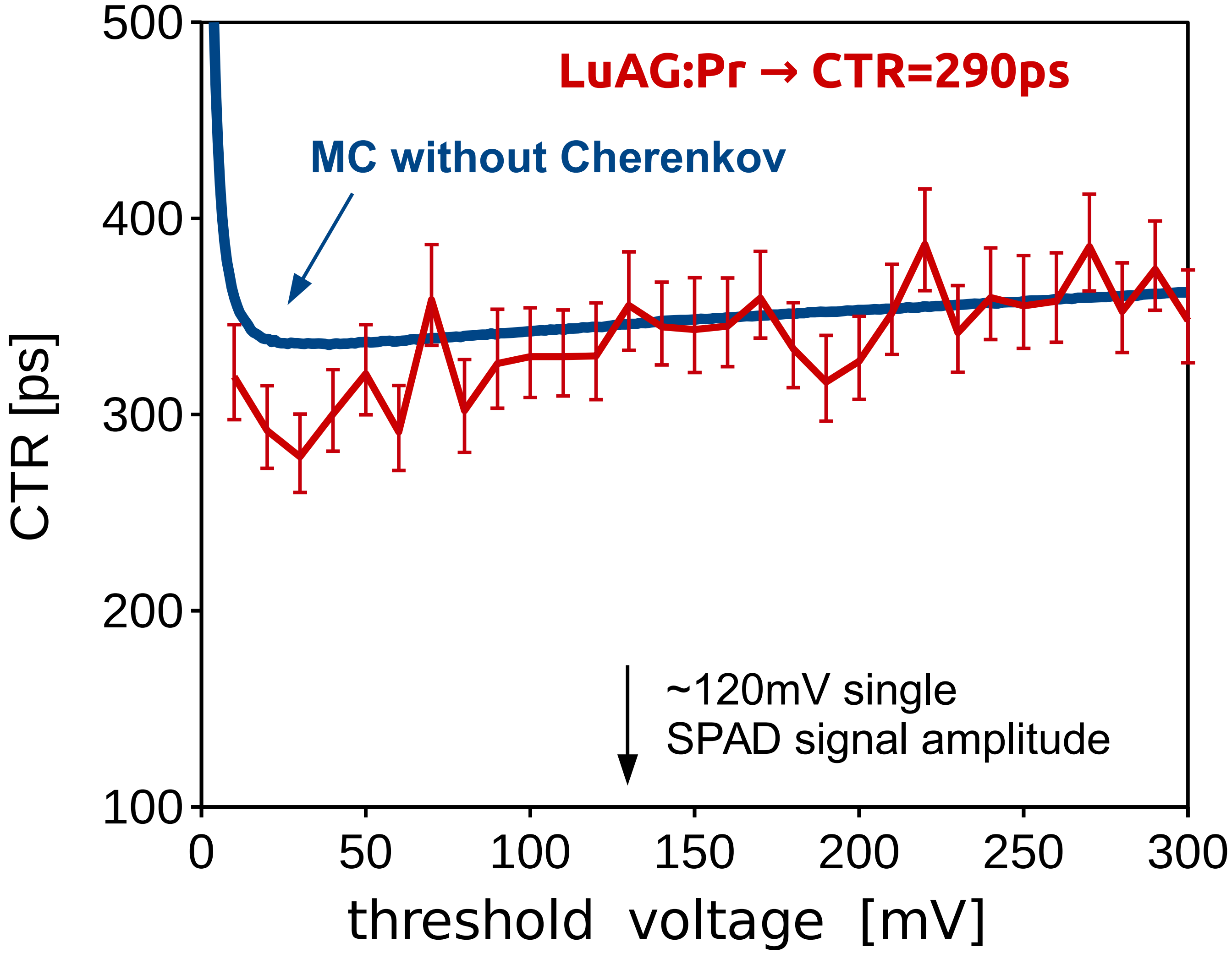
→ 54% relative light output compared to LYSO:Ce (with 40kph/MeV for LYSO:Ce)
→ 0.283% ratio of prompt to scintillation emission (corrected for PDEs)

→ **PDE*LTE=11%** (Meltmount glue with cutt-off at 400nm + NUV-HD 25µm)
→ **3.4 prompt (mainly Cherenkov) photons detected** (on average)

S. Gundacker, et.al "Measurement of intrinsic rise times for various L(Y)SO and LuAG scintillators with a general study of prompt photons to achieve 10ps in TOF-PET", Phys. Med. Biol. 61 (2016) 2802–2837

LuAG:Pr coupled to FBK NUV-HD 25µm

FBK NUV-HD 25µm @ 12.5V overvoltage, T=15°C,
crystal size 2x2x8mm³, wrapped in Teflon and coupled with Meltmount (n=1.68)



S. Gundacker et.al, JINST, August 2016. JINST 11 P08008

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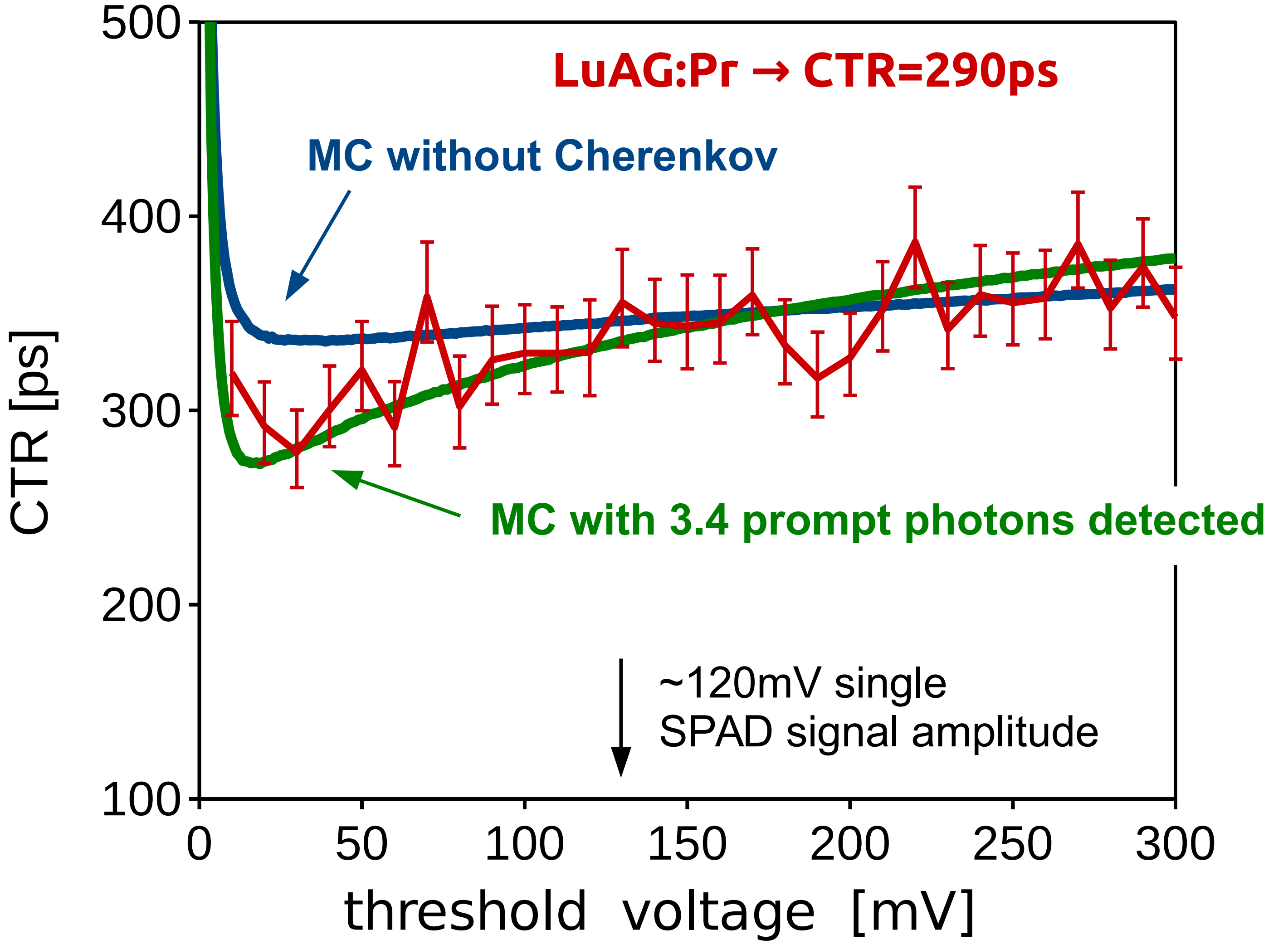
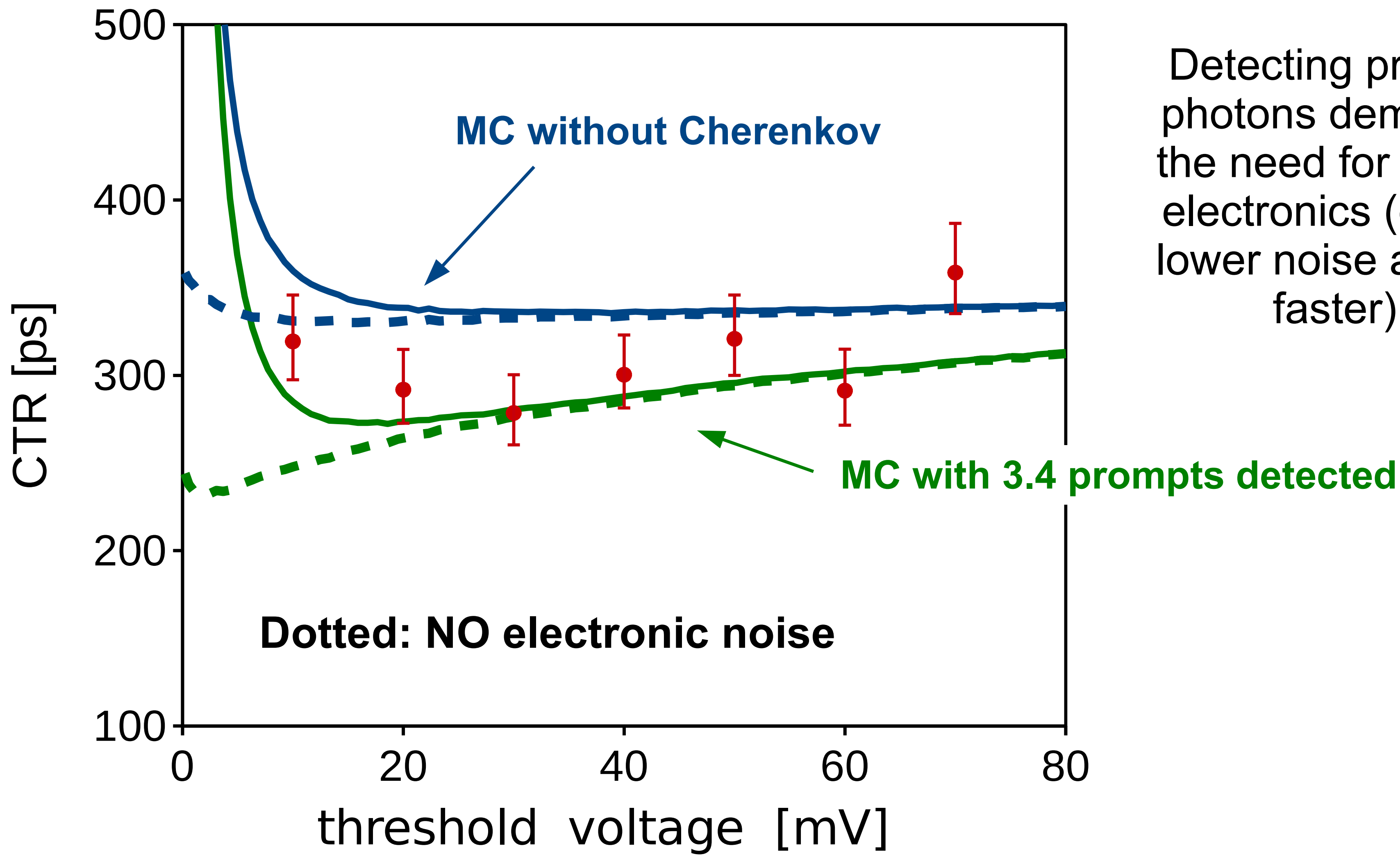


S. Gundacker et.al, JINST, August 2016. JINST 11 P08008

Influence of the electronic noise

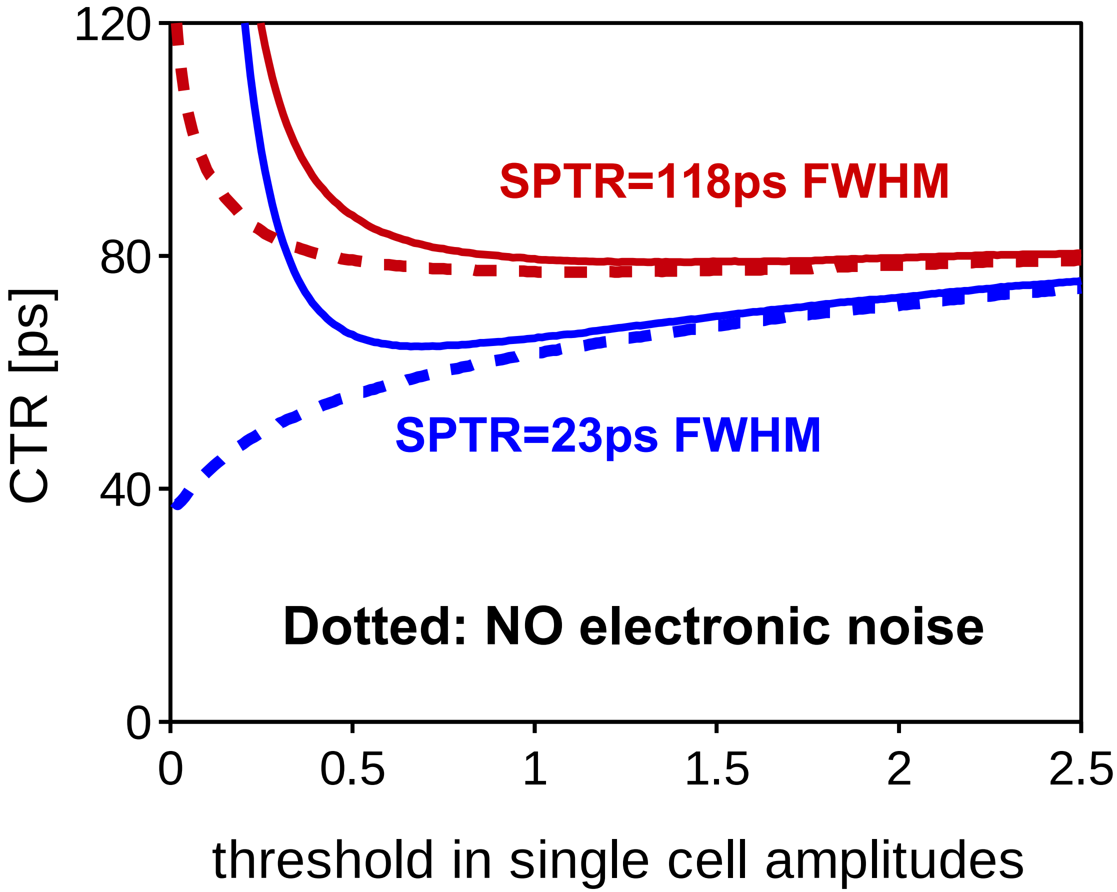
FBK NUV-HD 25μm @ 12.5V overvoltage, T=15°C,
crystal size 2x2x8mm³, wrapped in Teflon and coupled with Meltmount (n=1.68)



Detecting prompt photons demands the need for better electronics (either lower noise and/or faster)

S. Gundacker et.al, JINST, August 2016. JINST 11 P08008

LYSO:Ce and 30 prompt photons



Impact of the electronic noise:

-) **30 prompt photons produced**

-) scintillator size 2x2x3mm³

i^{th} crosstalk modeled as Gaussian with:

$$\mu = \mu_0 + SPTR * \sqrt{i}$$

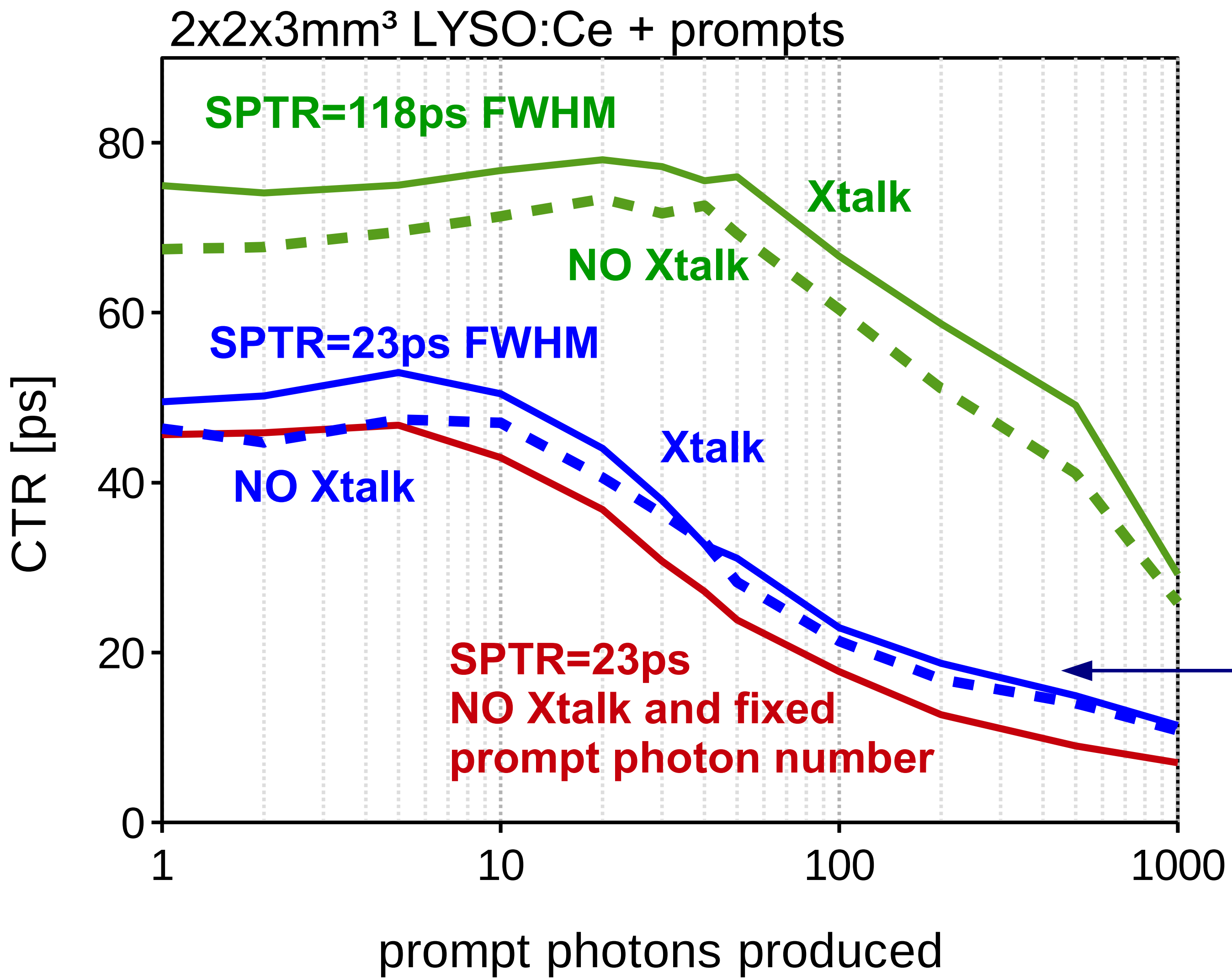
$$\sigma = SPTR * \sqrt{i}$$

Maybe the digital SiPM is the only way to reach these low detection thresholds?
But, having the time stamp of the first photon seems to be enough.

Around 30 prompt photons are produced by Cherenkov in the scintillator.

What if we have more?

Full MC simulation with prompt photon generation



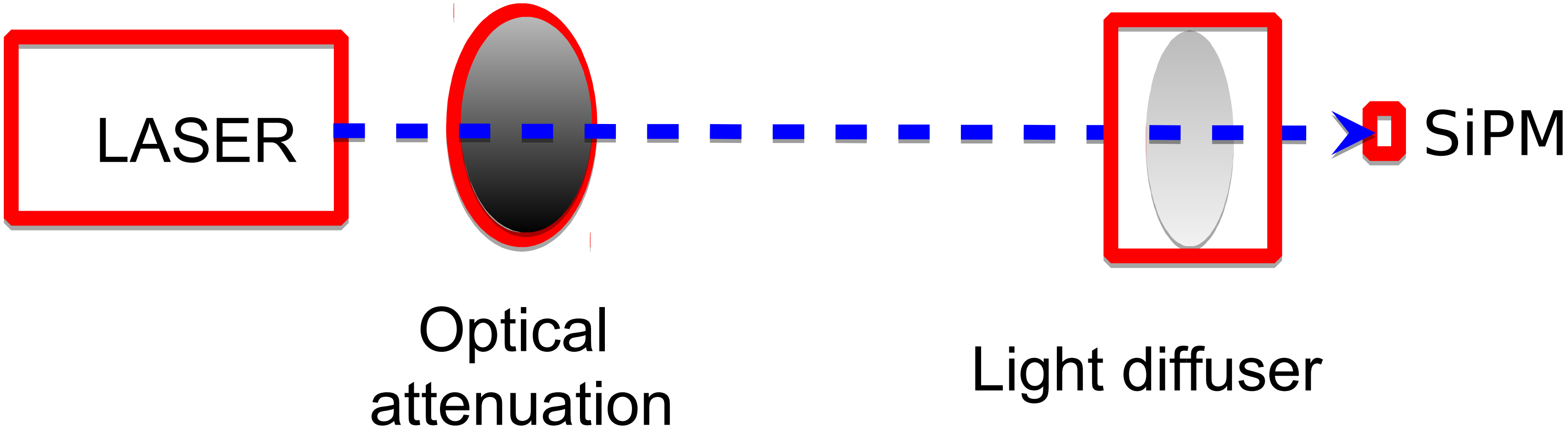
Promising sources for "prompt" photons are nanocrystal, e.g. CdSe, ZnO. However, the challenge is to build a detector out of it.

Prompt photons are produced with 30% energy resolution on top of Poisson

If the SPTR shows low values (~20ps) and the crosstalk follows this trend, crosstalk seems not to be the limiting factor (for very low detection thresholds)

The single photon time resolution (SPTR) of the SiPM is a crucial parameter

Method: measurement setup

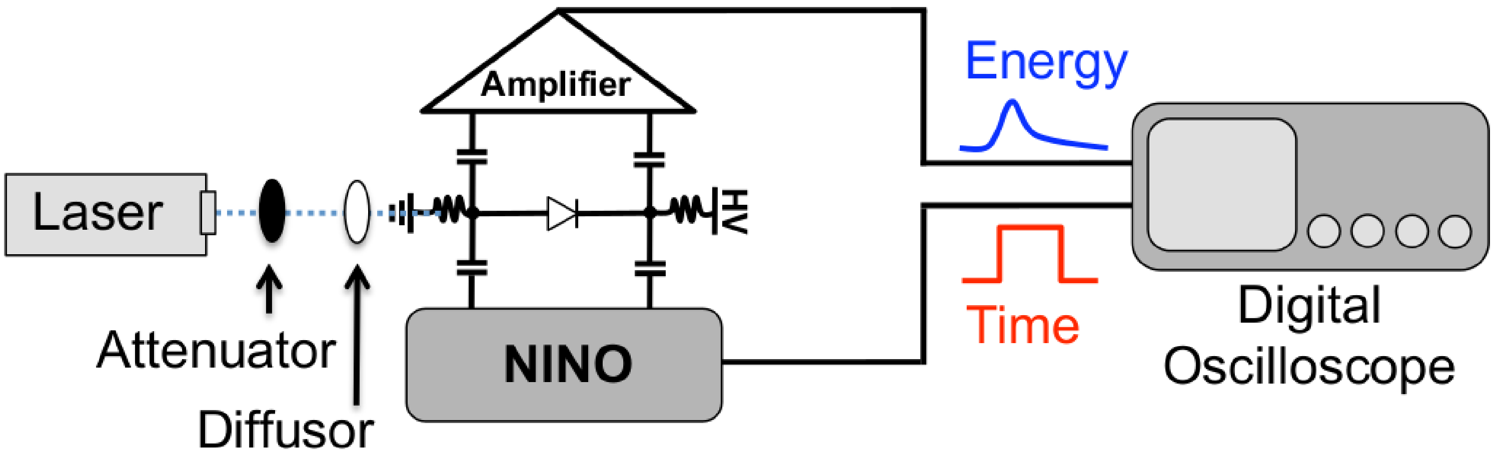


LASER operating parameters

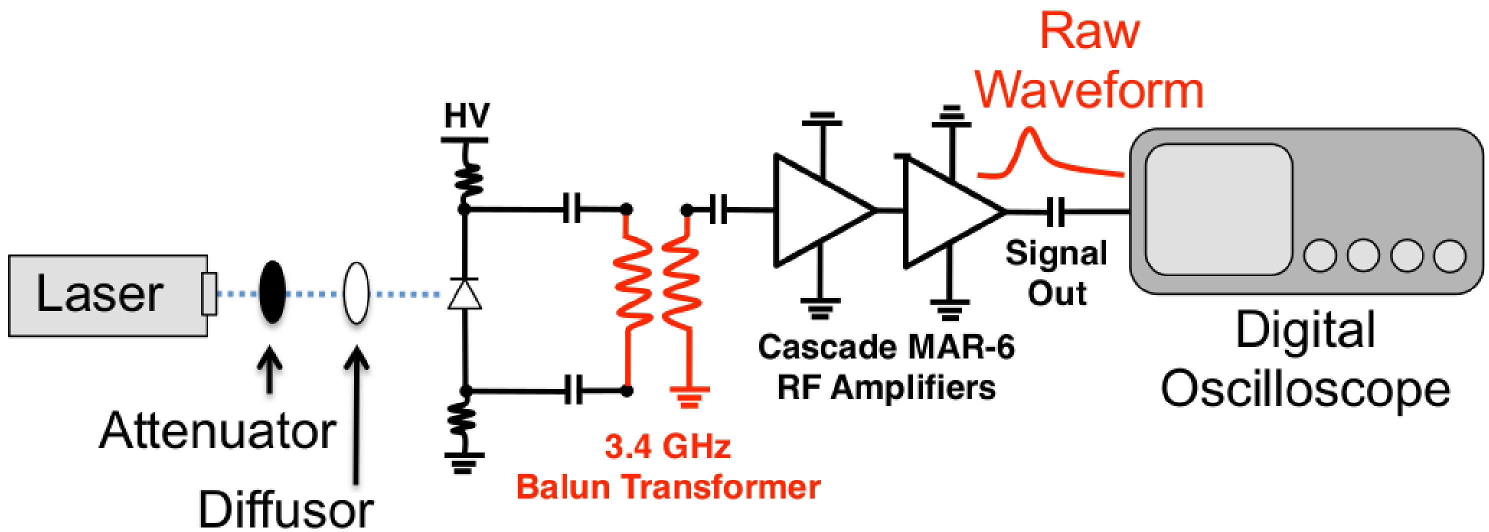
- Wavelength: 420nm
- Repetition : 10kHz
- Attenuation: ND filters for single photon level
- Pulse Width: **42ps (FWHM)**

Method: measurement setups

NINO:

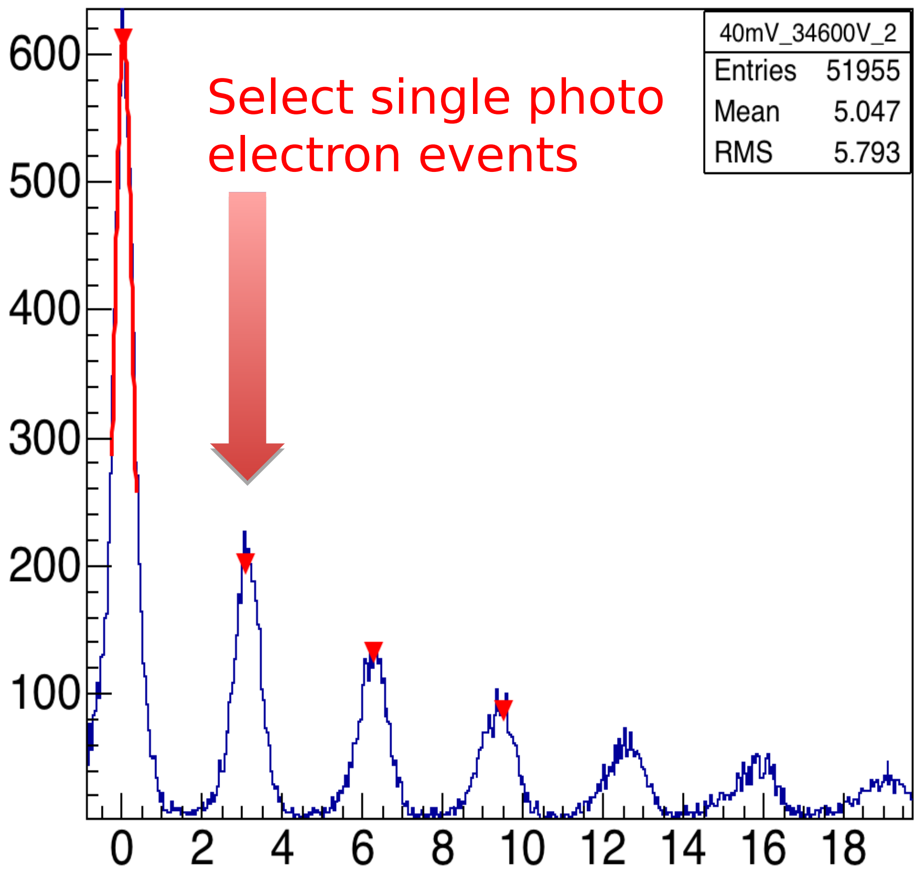


Passive Compensation Circuit:

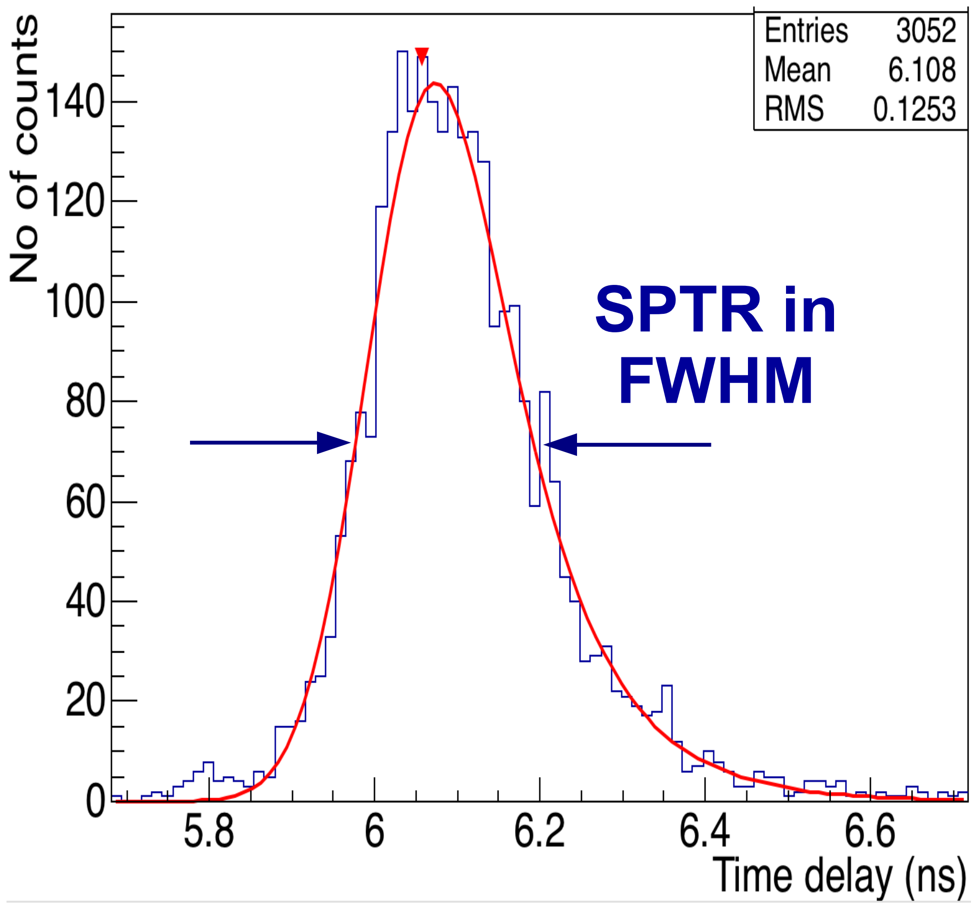


Method: data analysis

Single photon spectrum



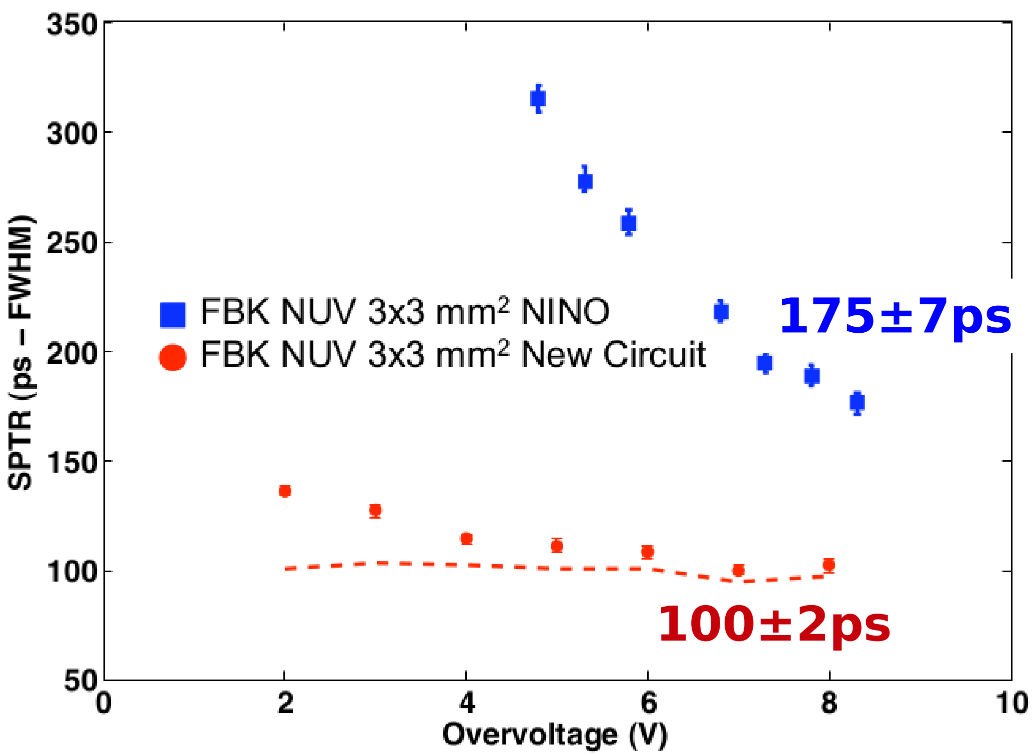
Pulse delay histogram

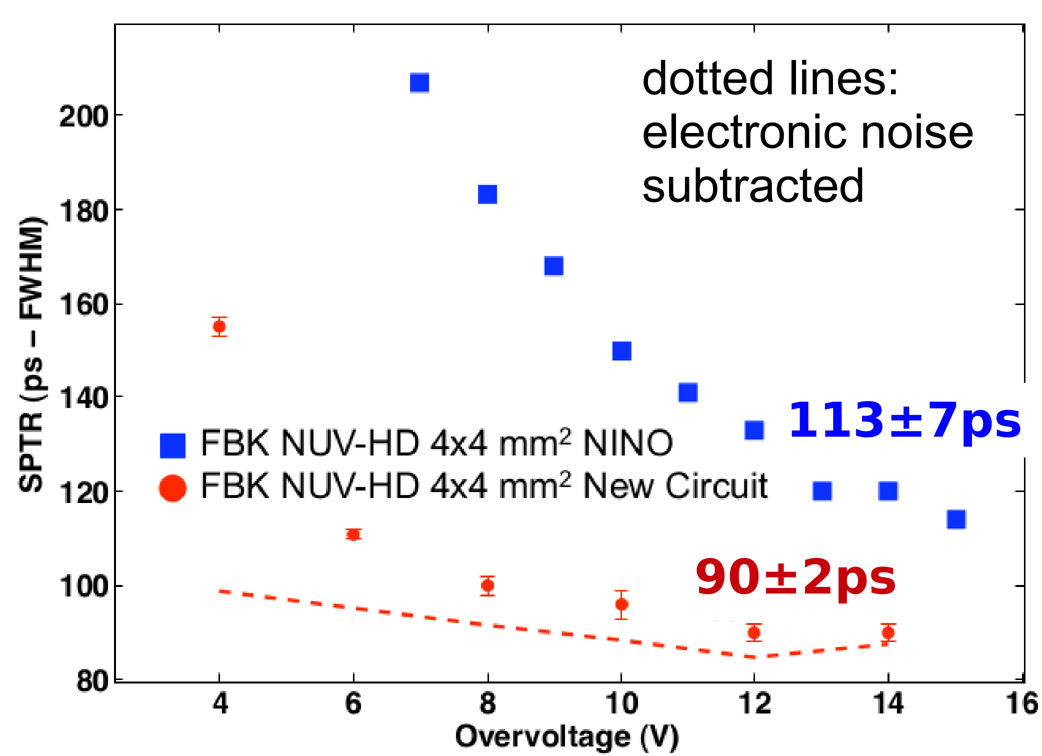


SPTR with analog NUV 3x3mm² & NUV-HD 4x4mm²

Both SiPMs (3x3mm² NUV and 4x4mm² NUV-HD) have a SPAD size of 40µm.

Laser pulse width: 42ps FWHM





FBK NUV 3x3mm² (40µm):

NINO:	SPTR=175ps FWHM
Impr. electr.:	SPTR=100ps FWHM

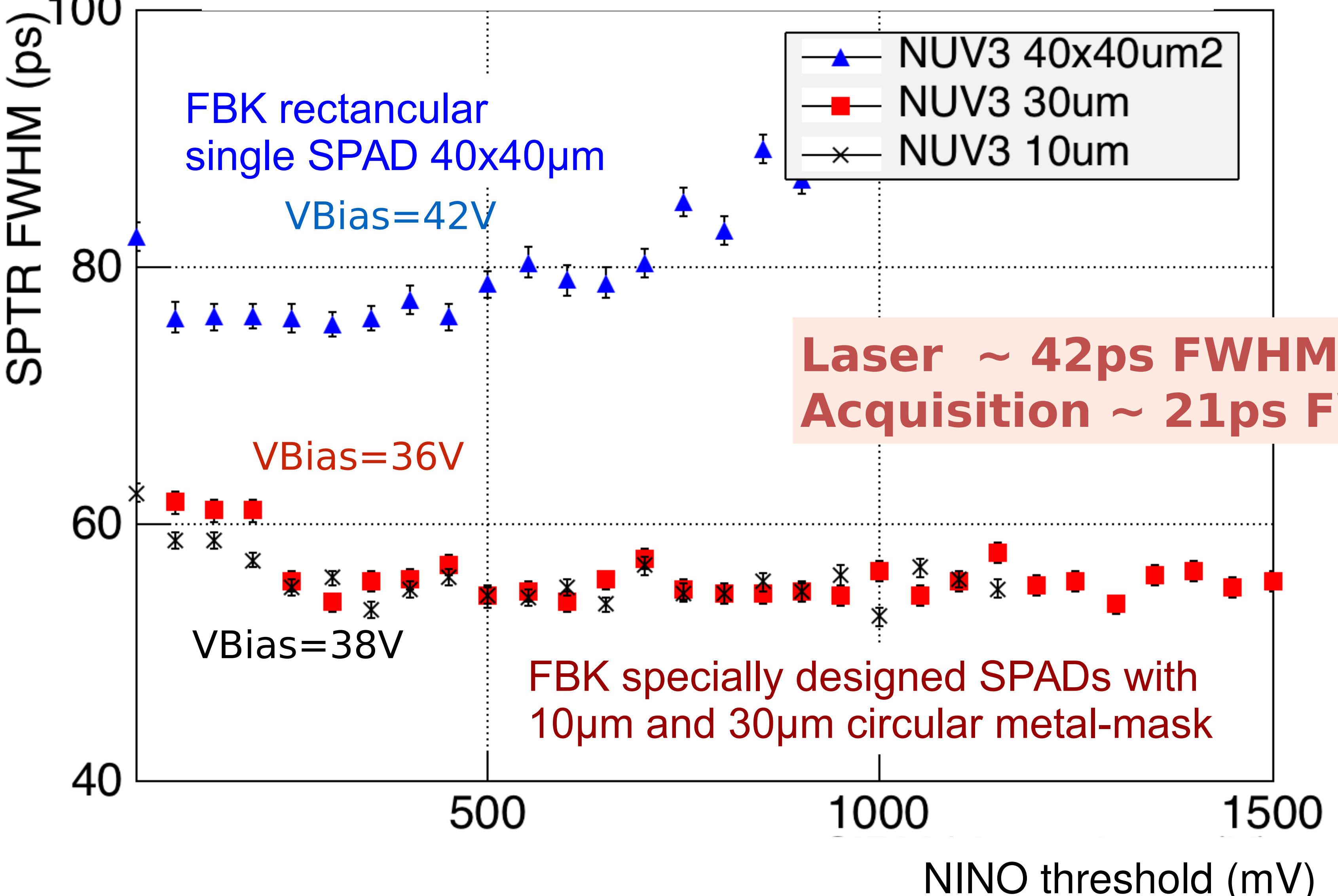
FBK NUV-HD 4x4mm² (40µm):

NINO:	SPTR=113ps FWHM
Impr. electr.:	SPTR=90ps FWHM

The limits of single SPADs are promising

Single photon level at optimum bias voltage

$$\sigma^2_{measured} = \sigma^2_{SPADjitter} + \sigma^2_{LASERwidth} + \sigma^2_{noise}$$



M.V. Nemallapudi et.al, October 2016. JINST 11 P10016

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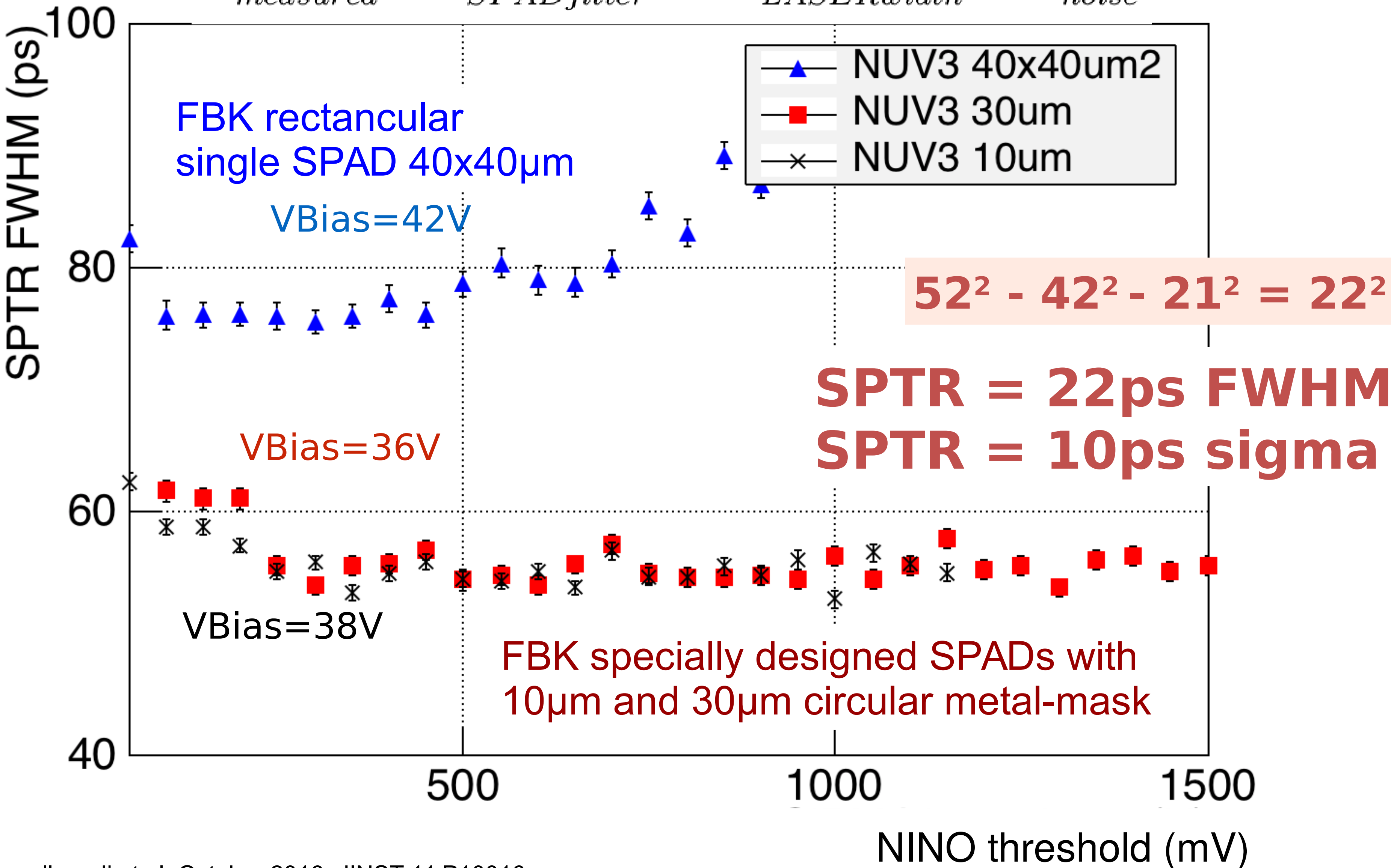

M.V. Nemallapudi et.al, October 2016. JINST 11 P10016

Conclusions

- Huge improvement in SiPMs (PDE) done by all producers (FBK, Ketek, HPK, Sensl) allowing for excellent timing, 70ps FWHM for $2x2x3mm^3$ and 112ps FWHM for $2x2x20mm^3$ with LSO:Ce codoped Ca when coupled to FBK NUV-HD $4x4mm^2$ and 40µm SPAD size.

- The SPTR of SPADs can be very good reaching 10ps sigma which opens the door for prompt photon time tagging.

- Having a very high SPTR to harnest prompt photons shows new challenges:
  - => need of very low leading edge thresholds
  - => lowest electronic noise necessary which means that the front-end and the SiPM have to be developed as a unit
  - => digital SiPM?

- If a CTR of 30ps should be achieved in longer crystals many more prompt photons have to be produced (e.g. in nanocrystals) and the detector design has to be re-invented taking into account depth-of-interaction correction.

Questions?

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