Comparative timing performance study of SiPMs for gamma detectors using hybrid Cherenkov-scintillation readout

S. E. Brunner,
L. Gruber, A. Hirtl, J. Marton, K. Suzuki

Stefan Meyer Institute for Subatomic Physics – Austrian Academy of Sciences

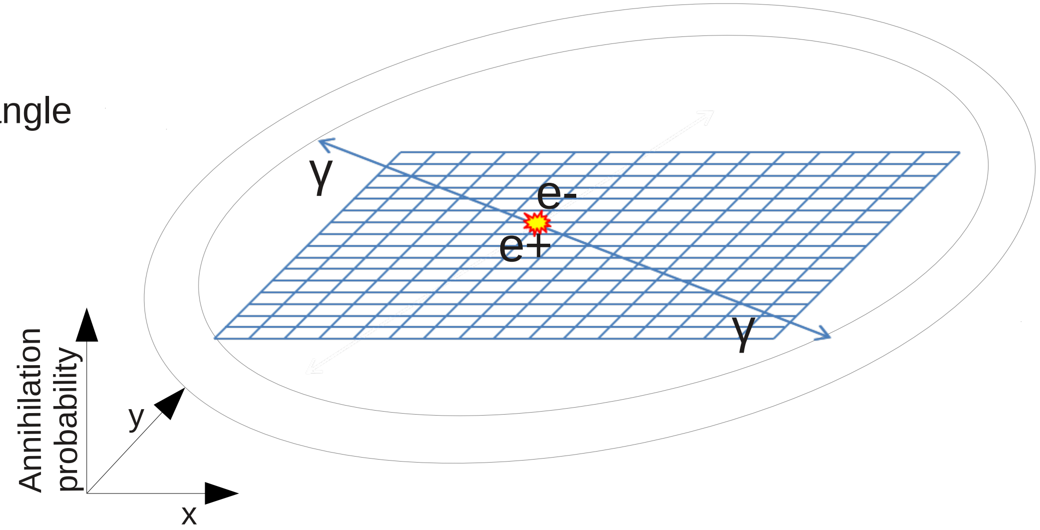
Introduction

- Motivation: TOF-PET
- Hybrid Cherenkov photon – scintillation detection
- Silicon photomultipliers
- SiPM time resolution measurements

Motivation: Time of flight positron emission tomography

PET

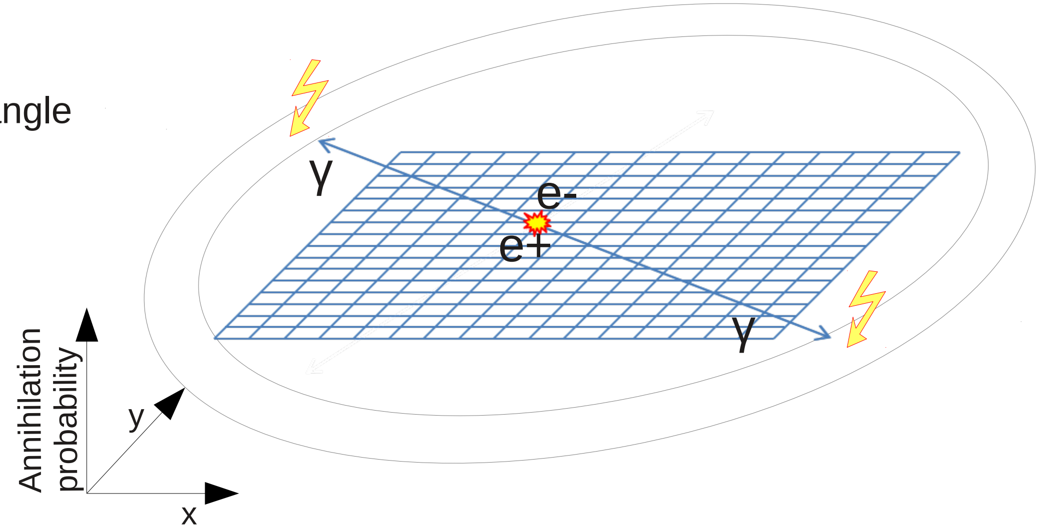
- Electron – positron annihilation
- Emission of two photons with 511keV at rel. angle of 180°



Motivation: Time of flight positron emission tomography

PET

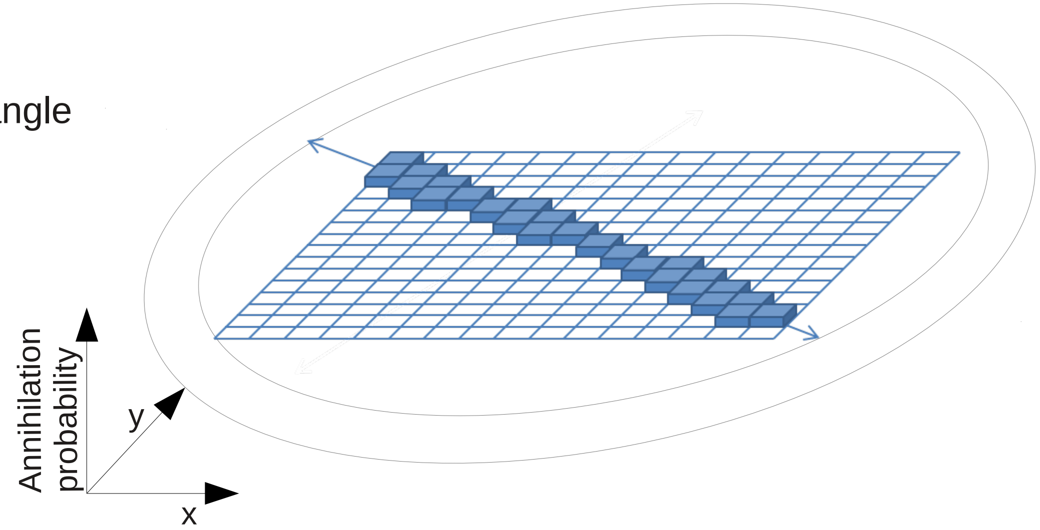
- Electron – positron annihilation
- Emission of two photons with 511keV at rel. angle of 180°
- The two photons are detected by a ring of detectors (within coinc. time window)



Motivation: Time of flight positron emission tomography

PET

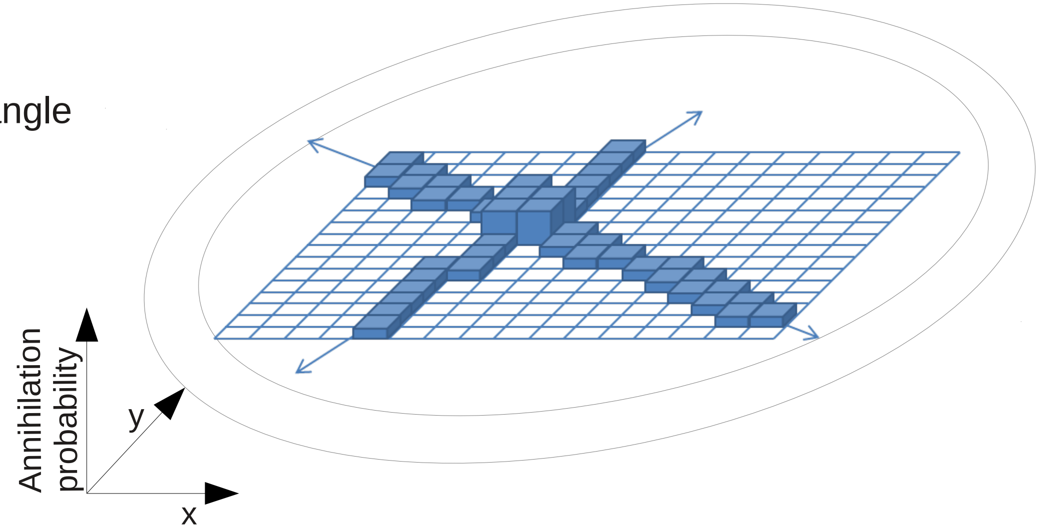
- Electron – positron annihilation
- Emission of two photons with 511keV at rel. angle of 180°
- The two photons are detected by a ring of detectors (within coinc. time window)
- A LOR is drawn between the responding detectors



Motivation: Time of flight positron emission tomography

PET

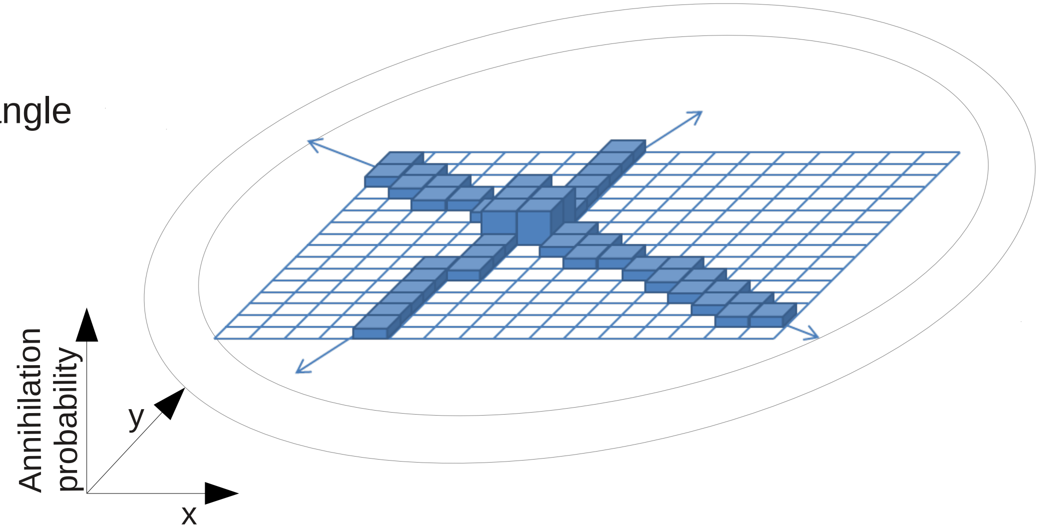
- Electron – positron annihilation
- Emission of two photons with 511keV at rel. angle of 180°
- The two photons are detected by a ring of detectors (within coinc. time window)
- A LOR is drawn between the responding detectors
- Statistics → Image reconstruction



Motivation: Time of flight positron emission tomography

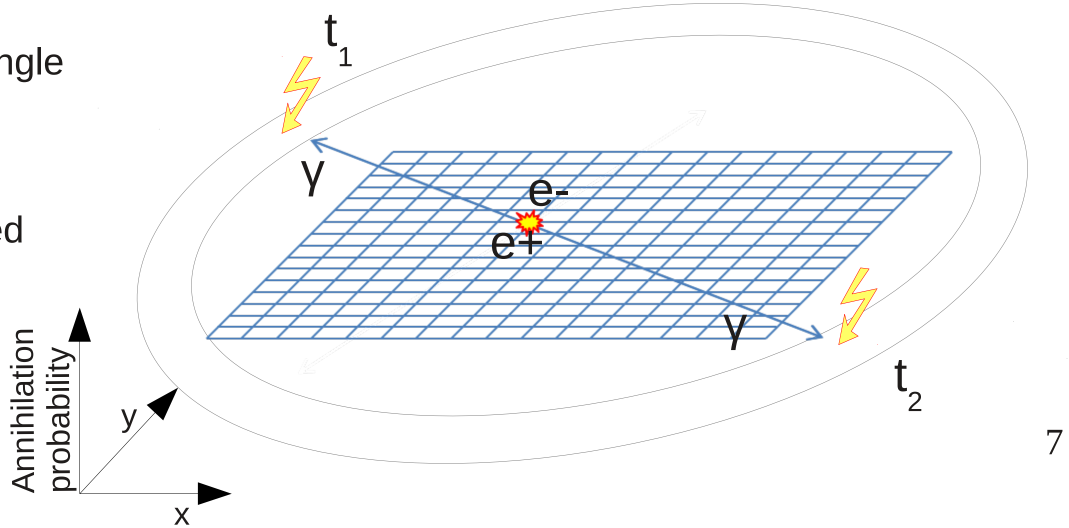
PET

- Electron – positron annihilation
- Emission of two photons 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



TOF - PET

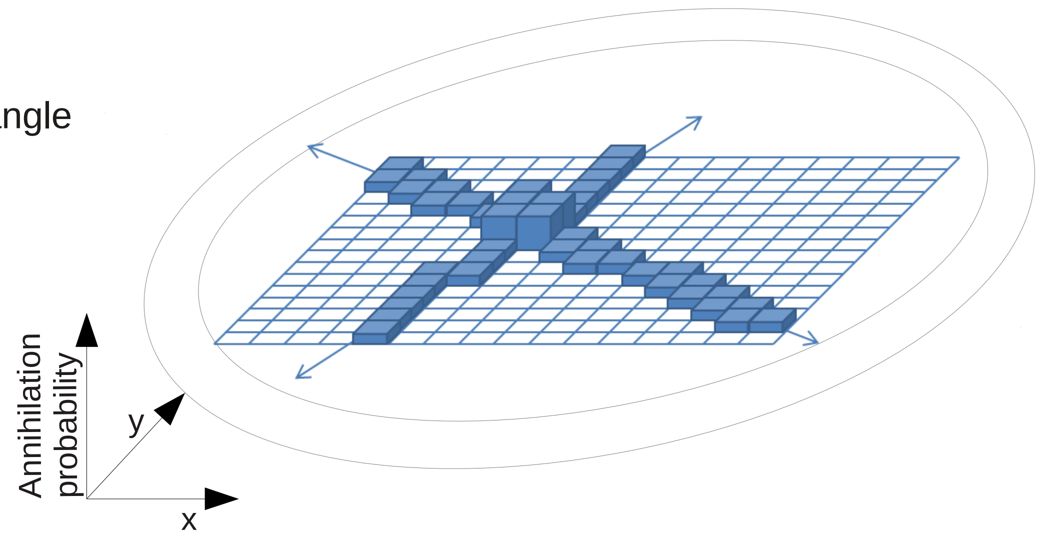
- Electron – positron annihilation
- Emission of two photons with 511keV at rel. angle of 180°
- The two photons are detected by a ring of detectors
- Arrival time of the 511keV photons is measured



Motivation: Time of flight positron emission tomography

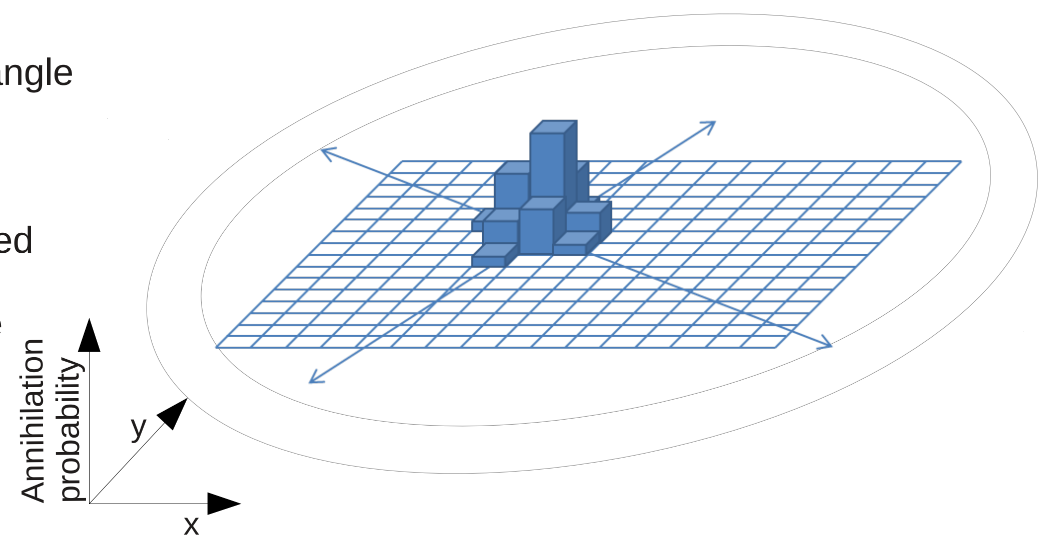
PET

- Electron – positron annihilation
- Emission of two photons 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

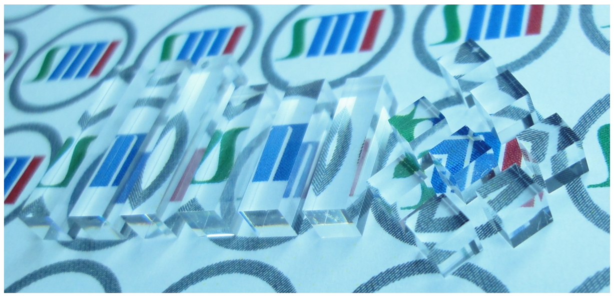


TOF - PET

- Electron – positron annihilation
- Emission of two photons with 511keV at rel. angle of 180°
- The two photons are detected by a ring of detectors
- Arrival time of the 511keV photons is measured
- LOR between responding detectors with a probability distribution determined by the time difference of the photon detection
  → **Need less statistics**
  → **Faster image reconstruction**
  → **Less artifacts**

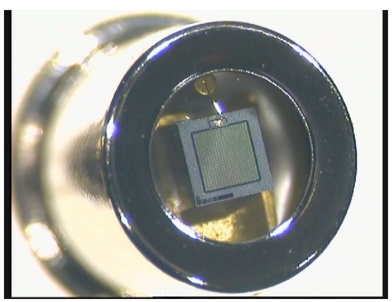


PET detector



Standard PET detector:

- Inorganic scintillator (gamma conversion)
- Photon detector for detection of optical photons attached to scintillator
- Readout electronics



TOF – PET requires fast scintillators and fast photon detectors

Gain for PET using TOF (SNR) for 40cm diameter patient [1]:

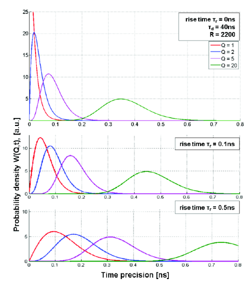
CTR [ns]	Δx [cm]	SNR gain
2.7	40	1
1.2	18	1.5
0.3	4.5	3
0.1	1.5	5.2

[1] M. Conti, "Focus on time-of-flight PET: the benefits of improved time resolution.," EJNM 38-6 (2011) 1147–57.

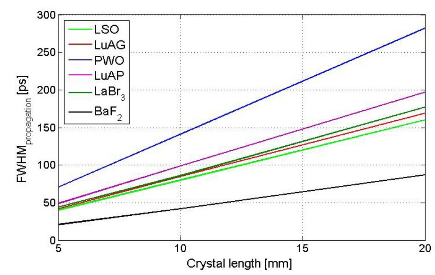
Factors influencing the time resolution

Scintillator

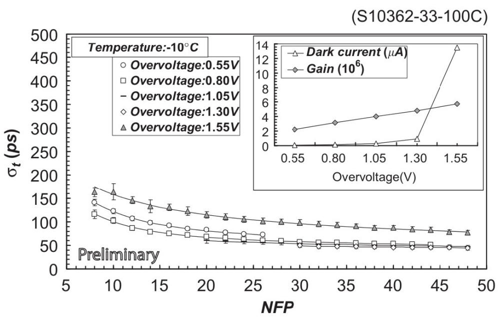
Photon statistics



Photon propagation

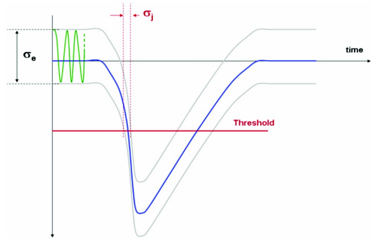


Transit time jitter of photo detector



Electronics

$$\sigma_j = \frac{\sigma_e}{(dV/dt)_{threshold}}$$



Ways to improve the time resolution

- Smaller crystals (improves time spread due to photon propagation)
- Coating / Wrapping of scintillators (affects light output)
- Shorter rise- and decay times
- High light yield
- High light output at the face coupled to the photo detector (grease, photonic crystals)
- High PDE at emission wavelength + good time resolution of the photo detector
- Low electronics noise (shielding)

Improve the rise time by using the Cherenkov effect for 511keV photons!

Cherenkov effect for 511 keV photons?

Relaxation processes in inorganic scinitillators

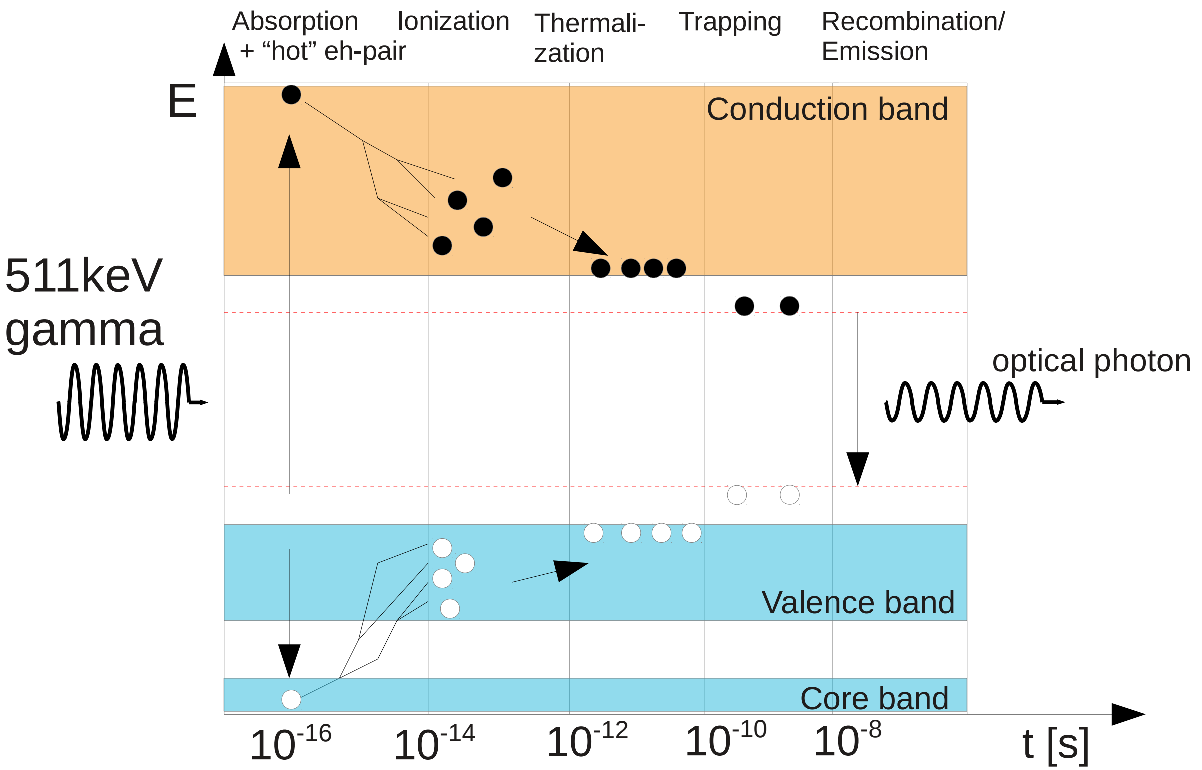


Fig: Vasil'ev, SCINT99

Cherenkov effect for 511 keV photons?

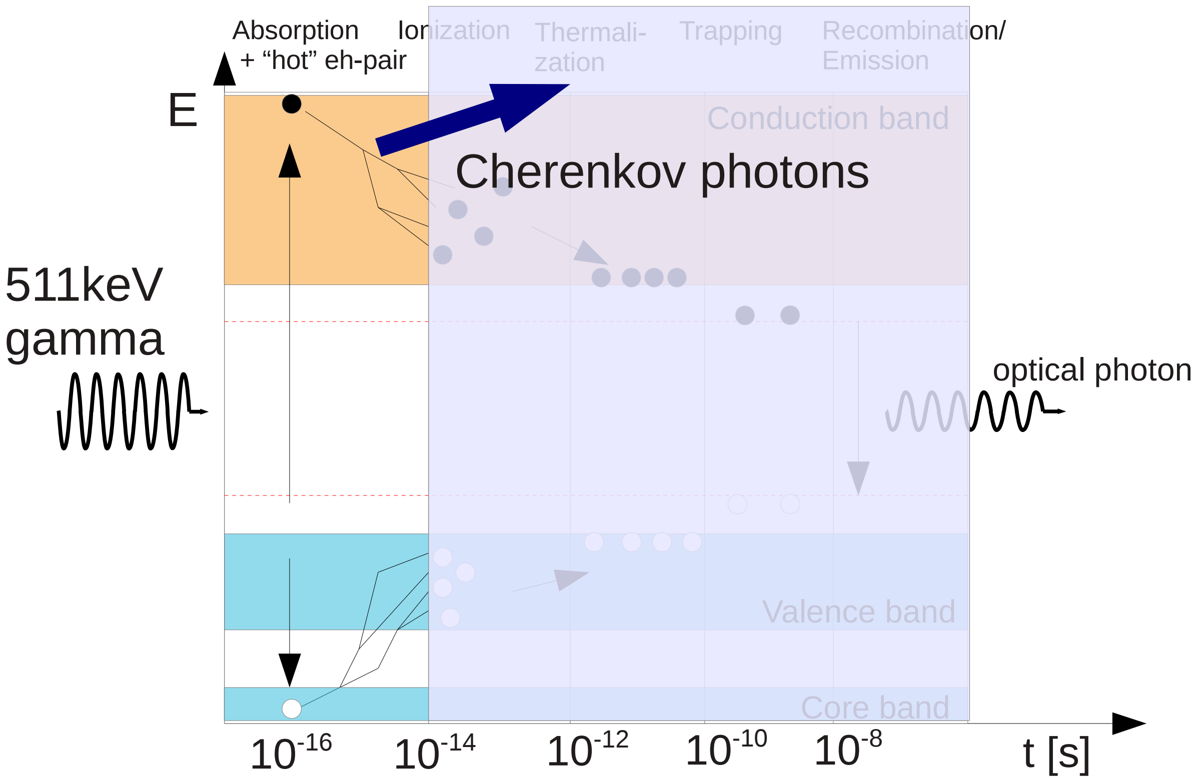
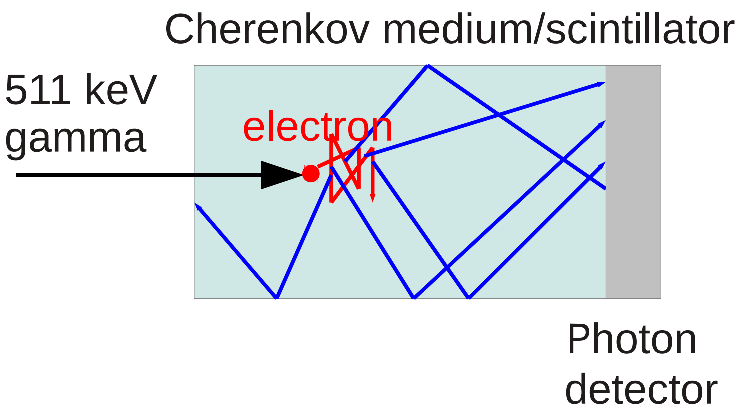


Fig: Vasil'ev, SCINT99

Cherenkov effect for 511 keV photons?



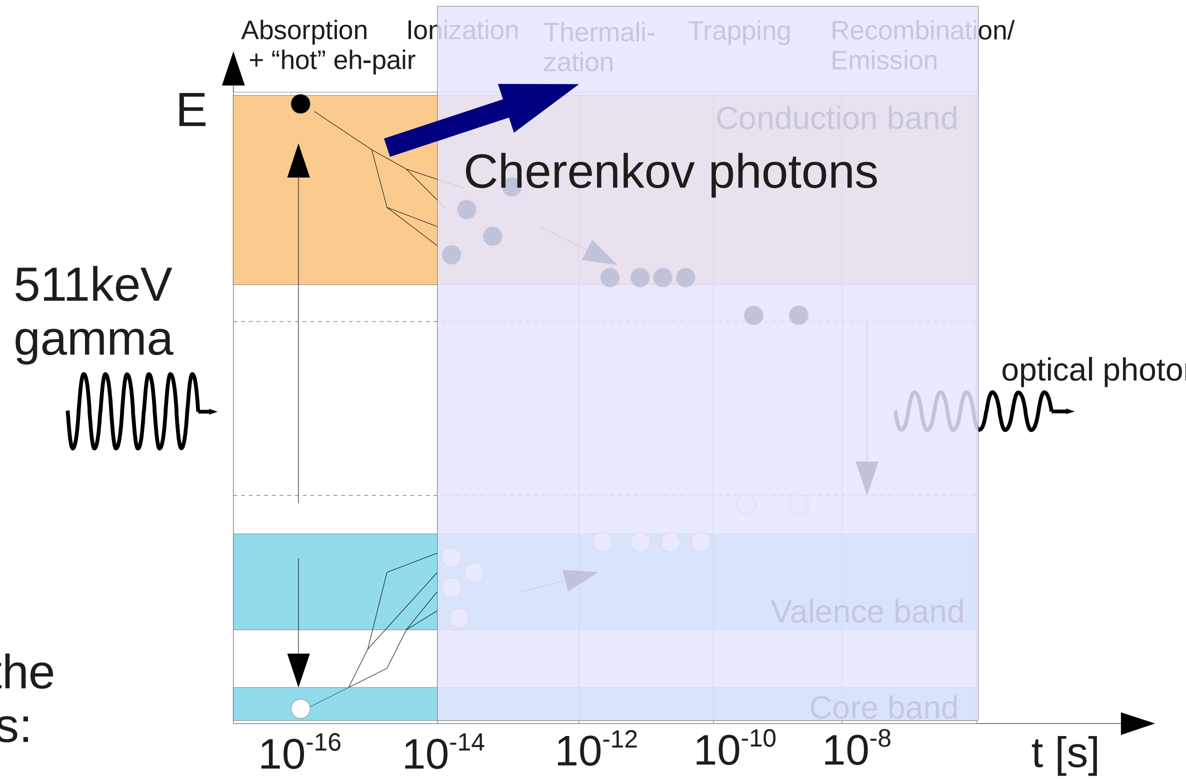
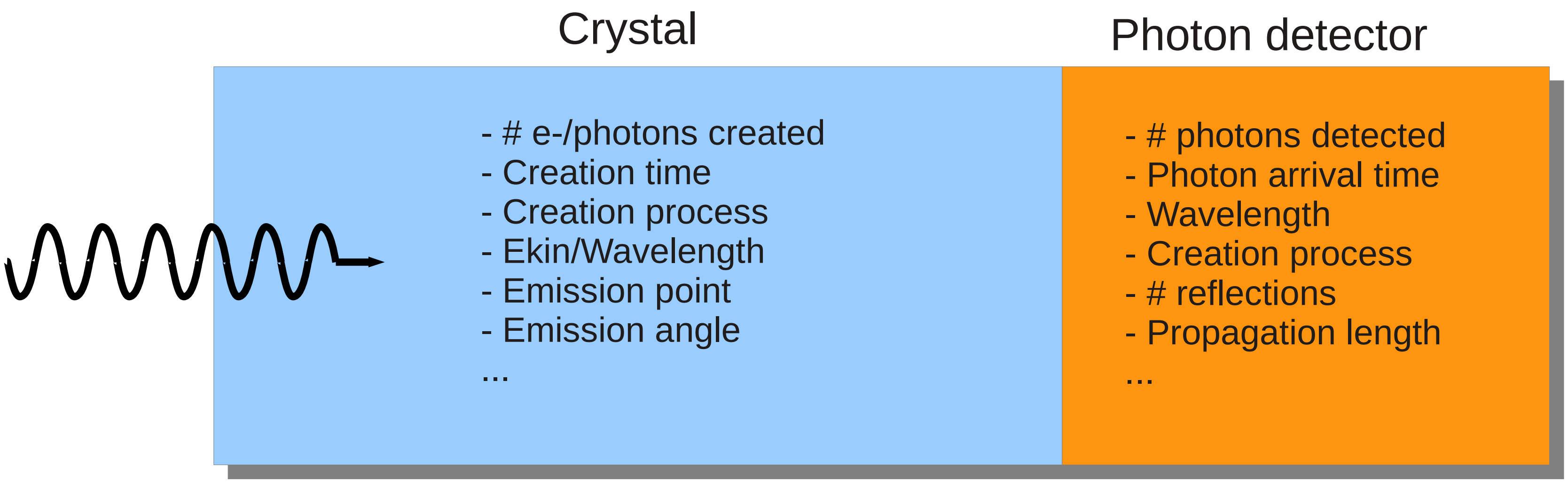


Fig: Vasil'ev, SCINT99

Cherenkov photons are emitted at the beginning of the relaxation process:
→ Provide a precise time stamp (compared to scintillation)

Monte Carlo simulations

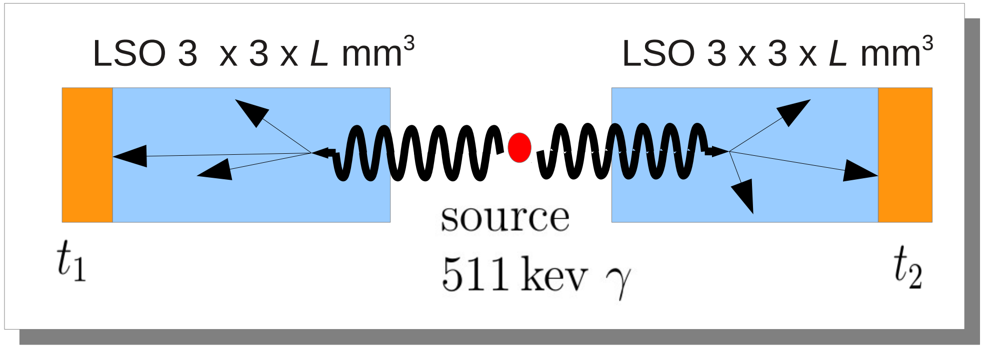
- Using Geant 4 (Litrani not suitable)
- Simple setups: small, bar shaped scintillators + photon detector
- Perfect photon detector (QE = 1, TTS = 0)
- Values used for LSO: 100ps rise time, 40ns decay time, LY: 30k Phot/MeV
- Transmission cutoff at ~ 360 nm



Geant4 Version: 4.9.4p3, G4Livermore libraries used

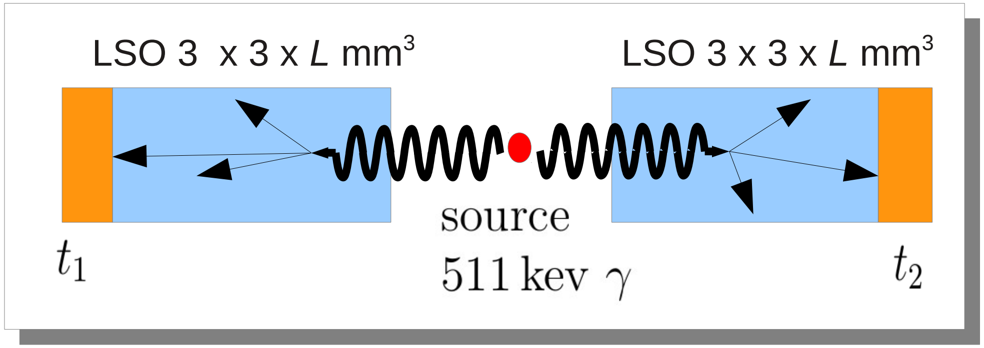
TOF-PET: Coincidence Time Resolution

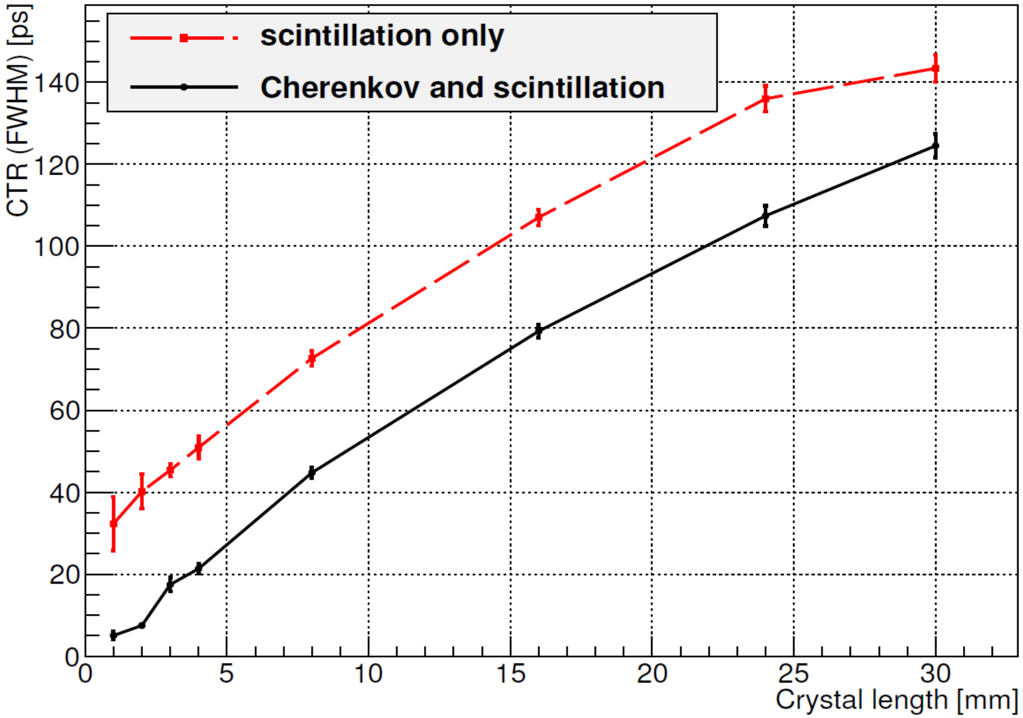
- Simple coincidence setup
- Two crystals + two photon detectors
- Var. crystal lengths *L*
- Calculate $\Delta t, \sigma$
- Trigger on the first arriving photon



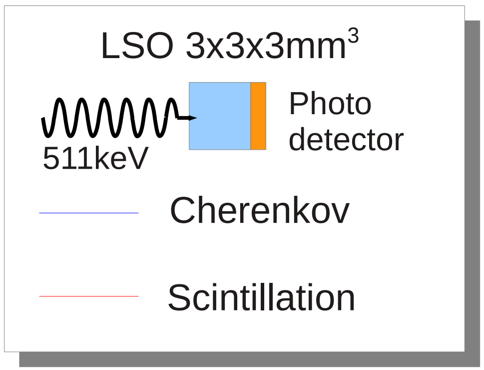
TOF-PET: Coincidence Time Resolution

- Simple coincidence setup
- Two crystals + two photon detectors
- Var. crystal lengths *L*
- Calculate $\Delta\,\mathrm{t},\ \sigma$
- Trigger on the first arriving photon

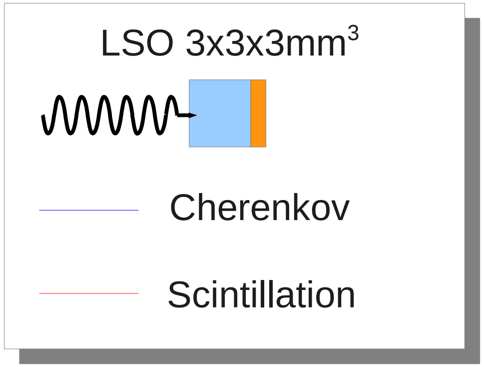


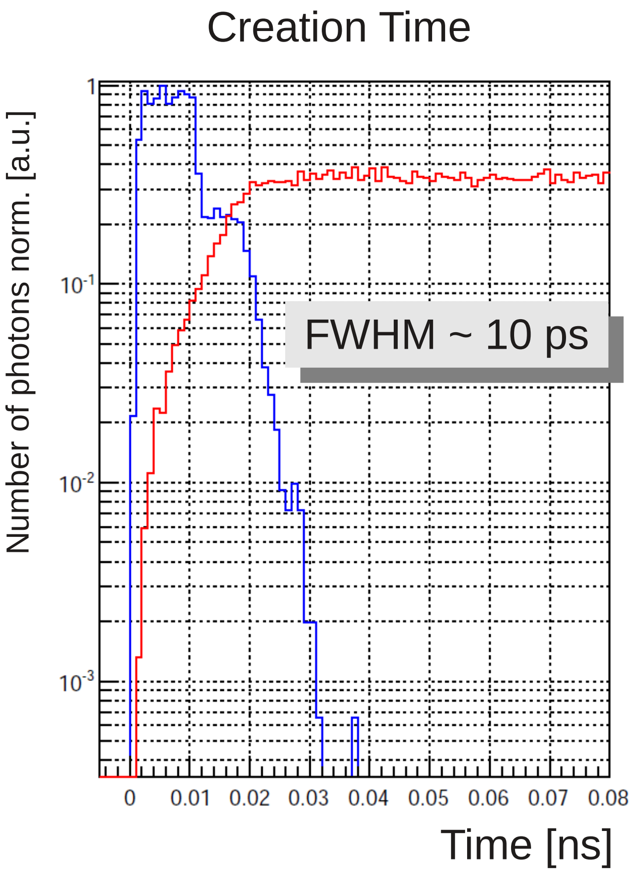


Photon time distributions

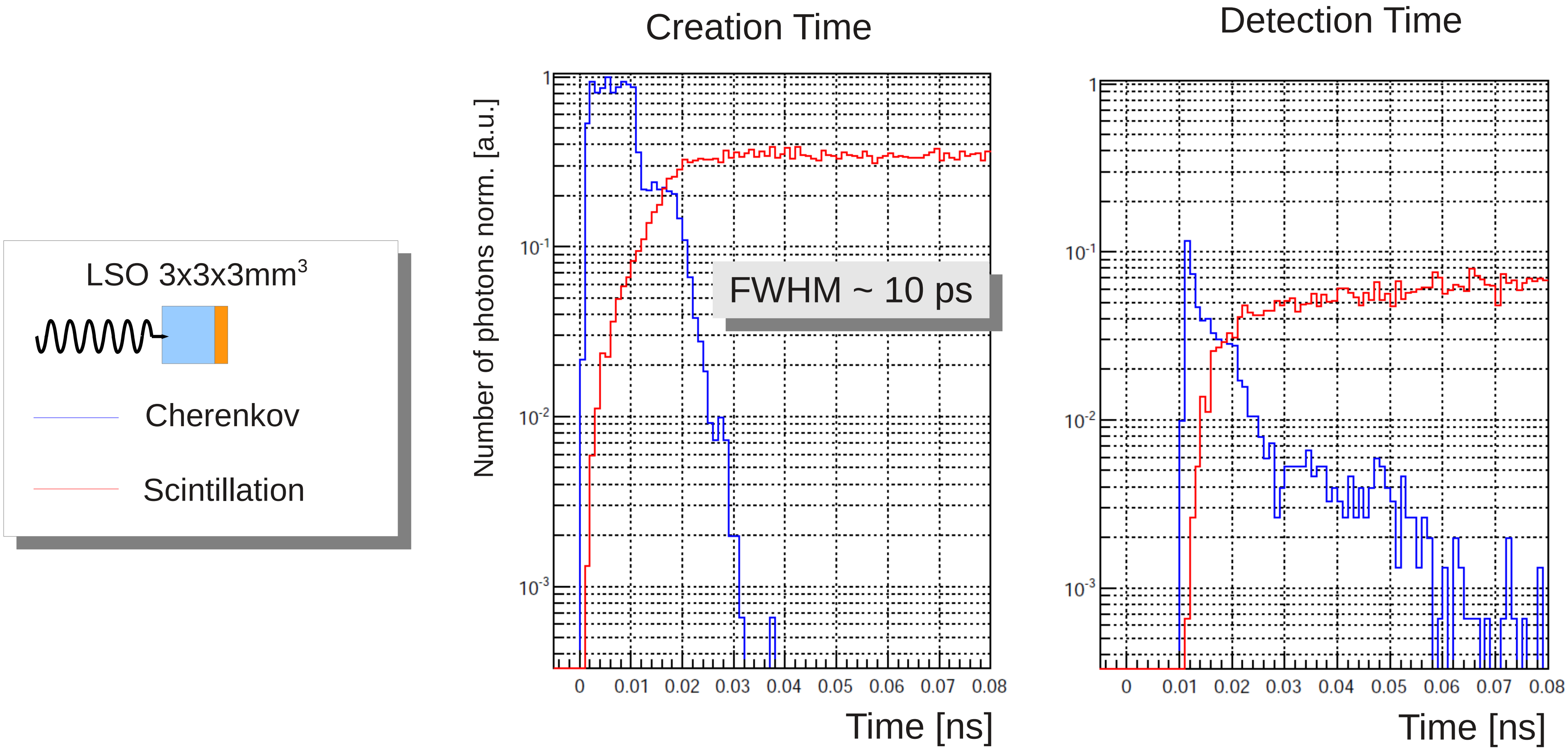


Photon time distributions

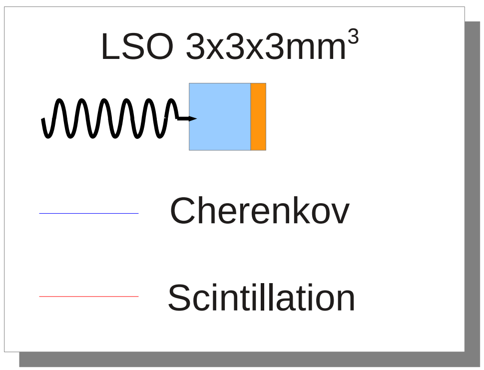




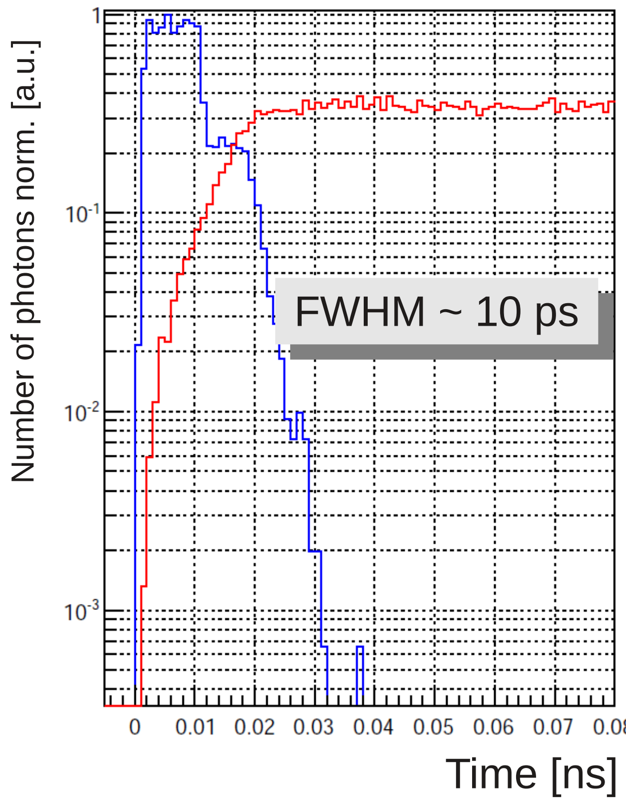
Photon time distributions



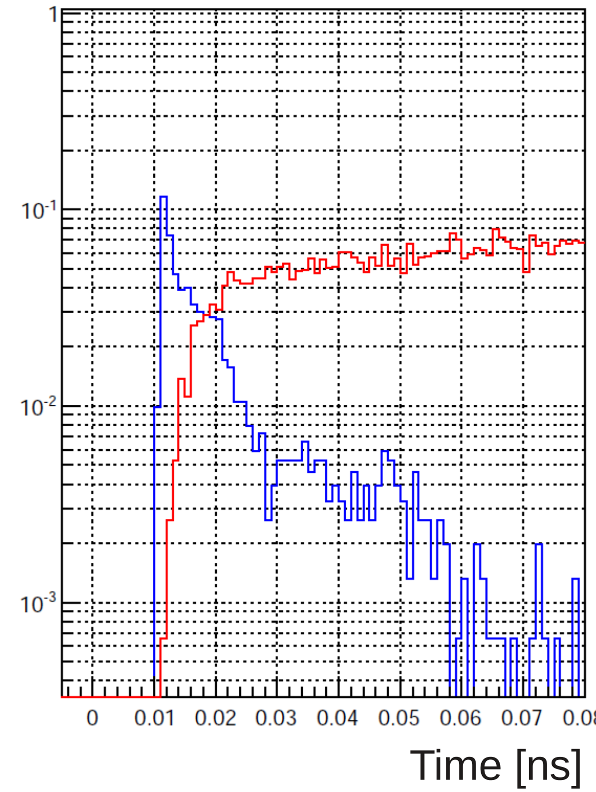
Photon time distributions



Creation Time



Detection Time

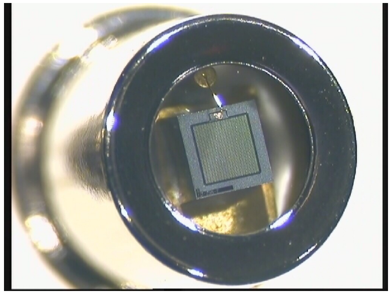


Cherenkov photons are influencing the rise time in inorganic scintillator!

Possibility: Crystal parameter engineering to optimize the rise time!

To make use of the good time resolution of the scintillators we need photo detectors with low transit time spread!

SiPM – Why?



Advantages

- Fast
- Small

  → small pixel detectors (decrease Cherenkov photon absorption in the material)

  → reduce time spread due to photon propagation
- Good PDE
- High gain
- Cheap
- Robust
- Insensitive to magnetic fields (Hybrid PET-MR)

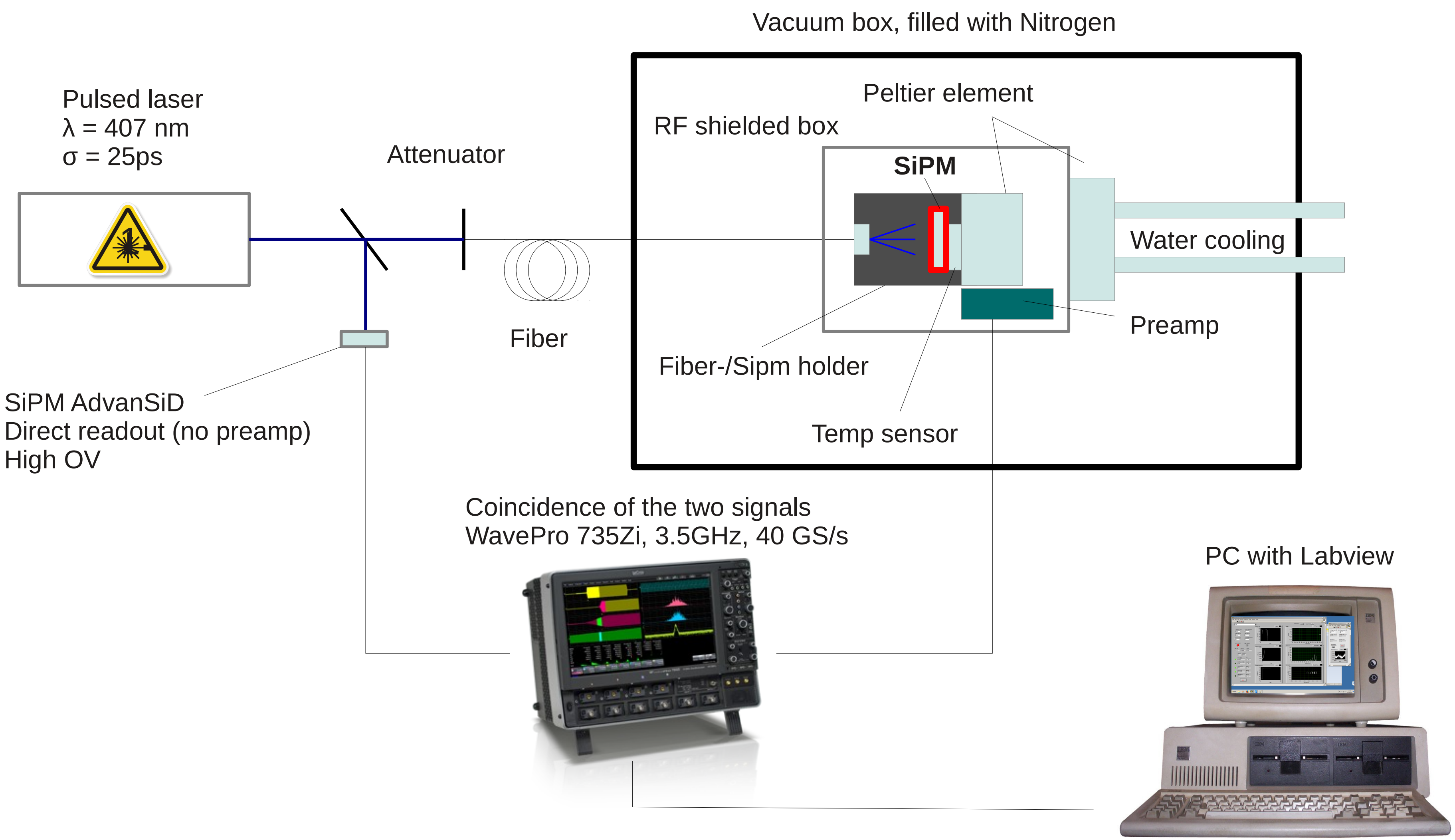
  ...

Disadvantages

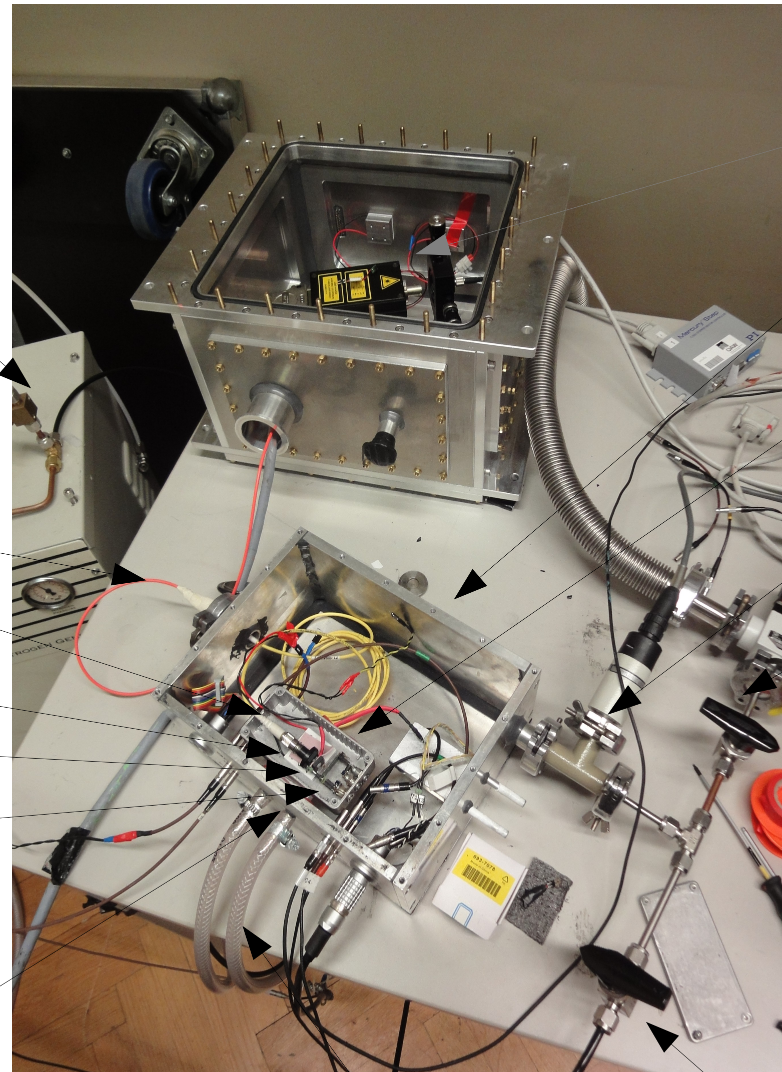
- High dark count rate
- Temperature sensitive
- Low sensitivity in the UV

  ...

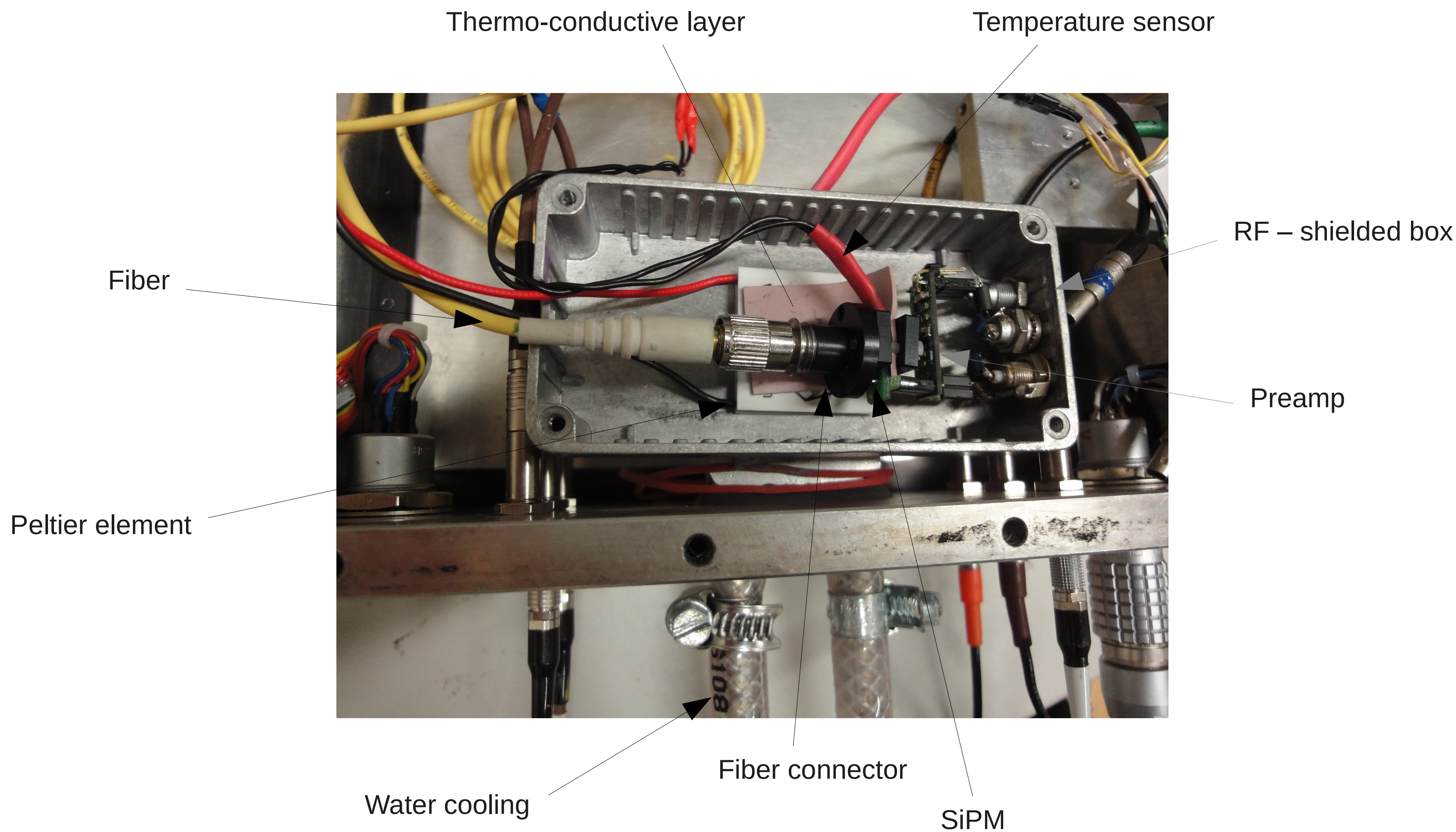
SiPM time resolution: setup



SiPM-time resolution: setup



SiPM time resolution: setup



Automatized measurement

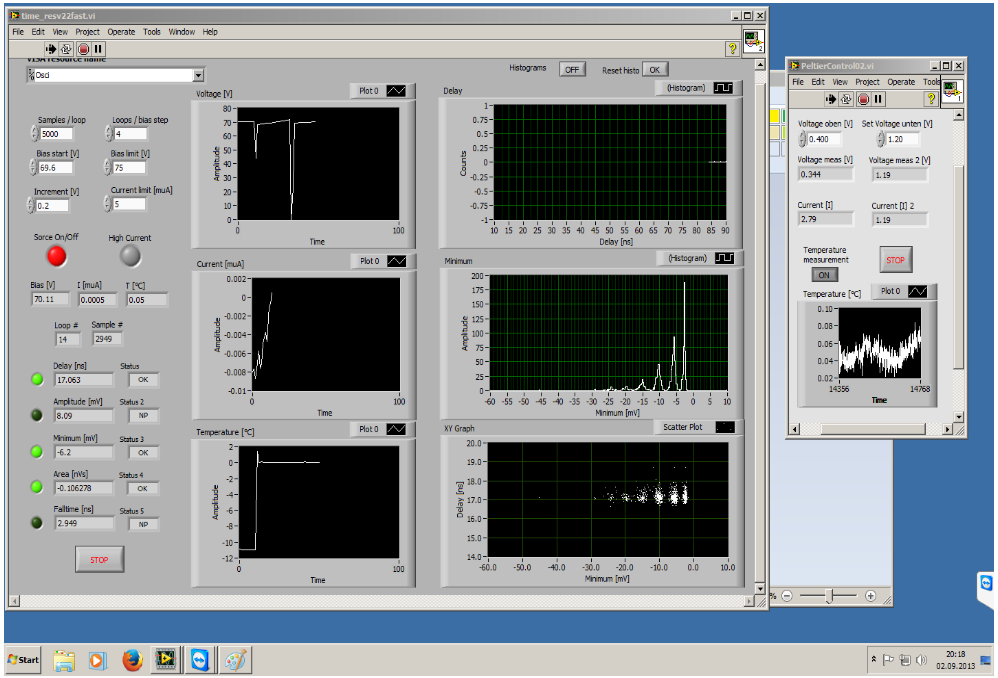
- **Bias is controlled by a Labview program → automatized bias scans**
- **Data is recorded by the same program**

Parameters measured with oscilloscope (LeCroy WavePro 735Zi, 3.5GHz, 40GS/s):

- “delay” (time difference of trigger and time of threshold crossing of the SiPM pulse)
- Minimum
- Amplitude
- Area
- Fall-time (10%-90%)

Other parameters measured:

- Bias voltage (Keithley Electrometer 617)
- Current (Keithley 6517A, is also the bias source)
- Temperature (LakeShore 211, Pt100)



Measurement time:
~ 1 day per SiPM (4 diff. temperatures)

Preamplifier

- Currently preamp from Photonique is used for readout
- Gain and linearity were measured for charge and amplitude (~18)
- Rise time of the preamp is ~ 1ns

Results will be compared with measurements of an own developed preamplifier board:

- 2 channels with full differential readout (signal from cathode and anode are used) → robust against noise
- Only one bias supply: 5 V
- Including an time over threshold discriminator
- Bias and threshold settings of the two SiPM are controlled remotely via an Arduino Leonardo board
- The boards can be daisy chained up two 256 channels
- Gain: 16 - 100 (by changing two resistors) → **rise time can be set**

Tested SiPMs

Tested SiPMs:

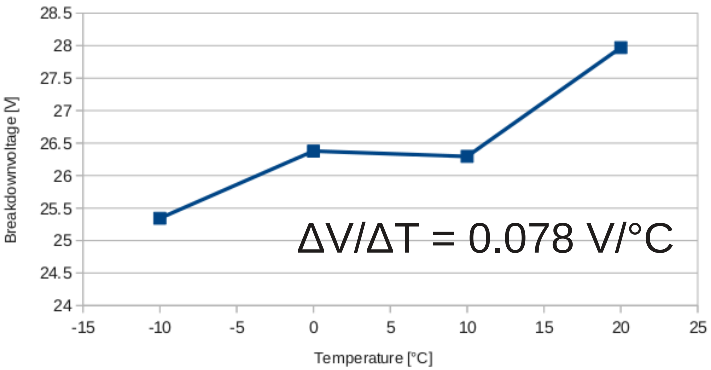
- **AdvanSiD:**
  - ASD-SiPM3S-P50 (3x3mm²)
- **Hamamatsu**
  - MPPC S10931-33-100P (3x3mm²)
- **Ketek**
  - PM3350-B63 (3x3mm²)
  - PM3360-B66T75S (3x3mm²)
  - PM3375-B72 (3x3mm²)

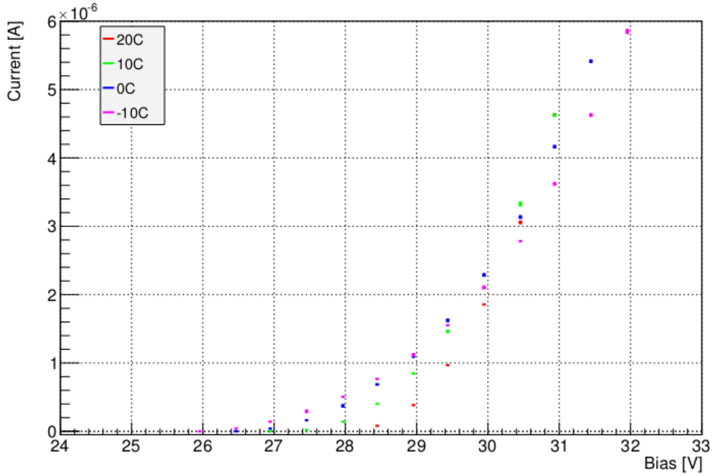
SiPMs to test:

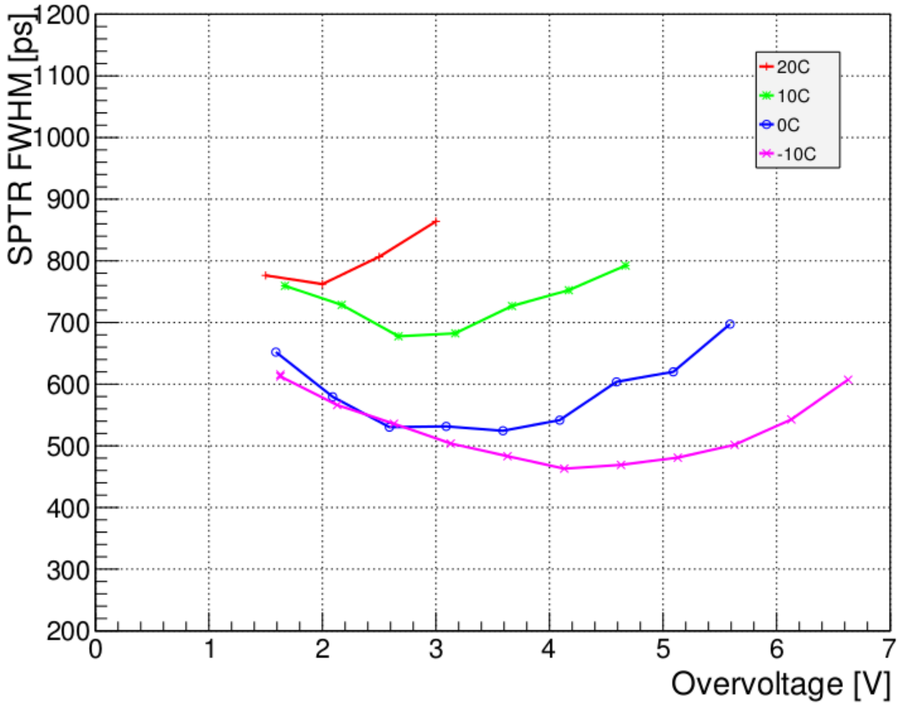
- **AdvanSiD**
  - ASD-SiPM3S-P-50 RGB
  - ASD-SiPM3S-P-50 NUV
- **Hamamatsu**
  - MPPC 3x3 S10362-33-100C
  - MPPC 3x3 S10362-33-050C
  - MPPC 3x3 S10362-33-050P
  - MPPC 3x3 S10362-33-025 P
  - MPPC 1x1 S10362-11-050CK
  - MPPC 1x1 S10362-11-100U
  - MPPC 1x1 S10362-11-050U
  - MPPC 1x1 S10362-11-025U
  - MPPC 1x1 S1x112571-025C
  - MPPC 1x1 S12571-050C
  - MPPC 1x1 S12571-100C
  - MPPC 1x1 S12651-50C
  - MPPC 1x1 S12651-100C
- **Philips**
  - DPC3200
  - DPC6400
- **SensL**
  - MicroFM-30050-SMT

Single photon time resolution AdvanSiD

ASD-SiPM2S-P50 (3x3mm²)
ID: adv02

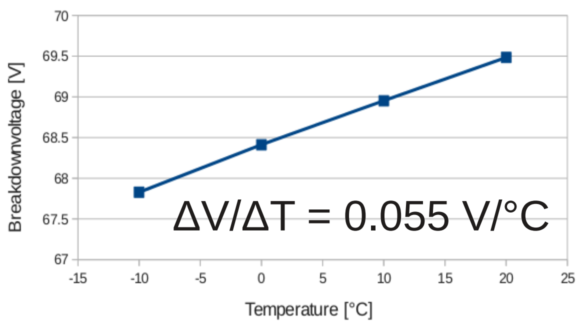


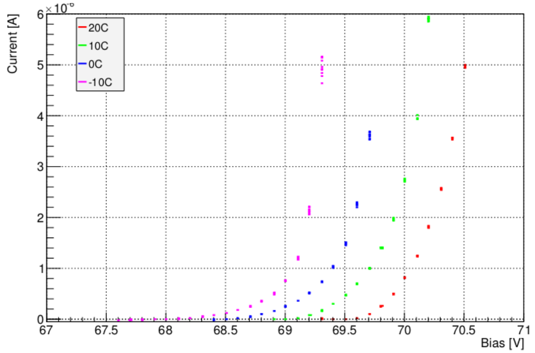


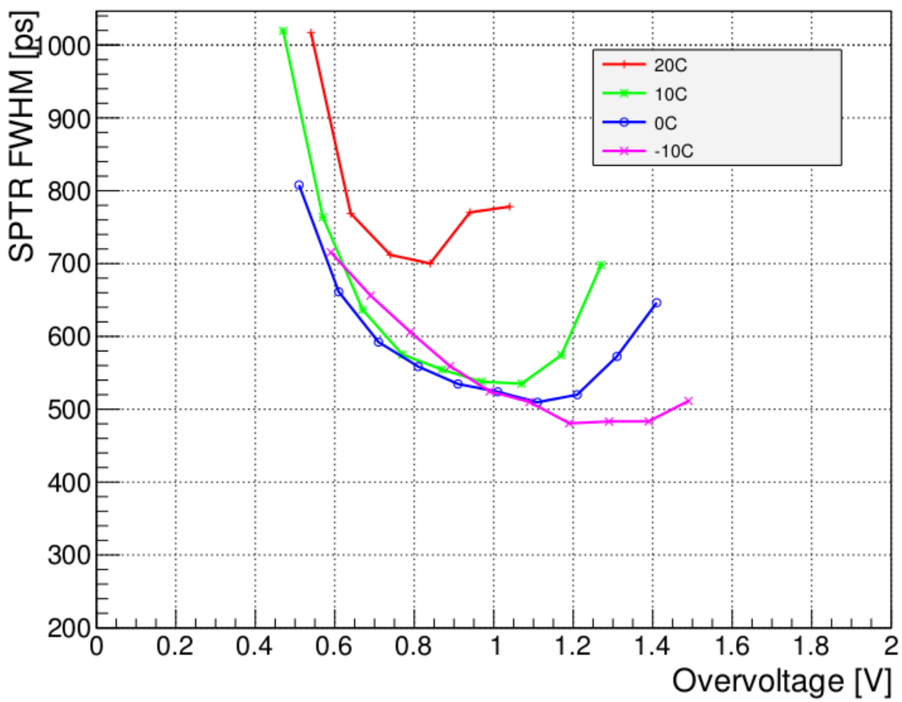


Single photon time resolution Hamamatsu I

MPPC 3x3 S10931-33-100P
ID: ham01

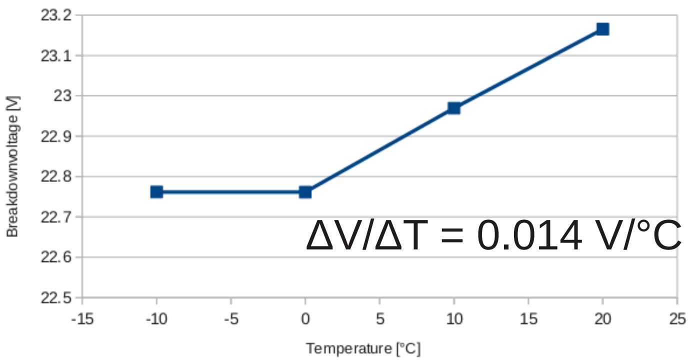


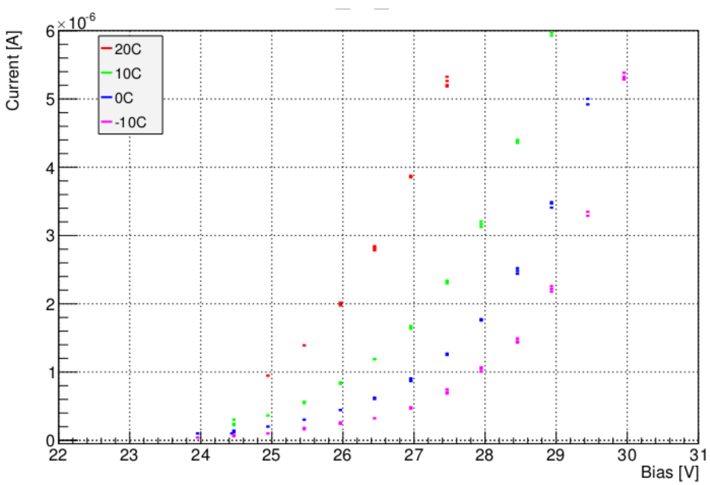


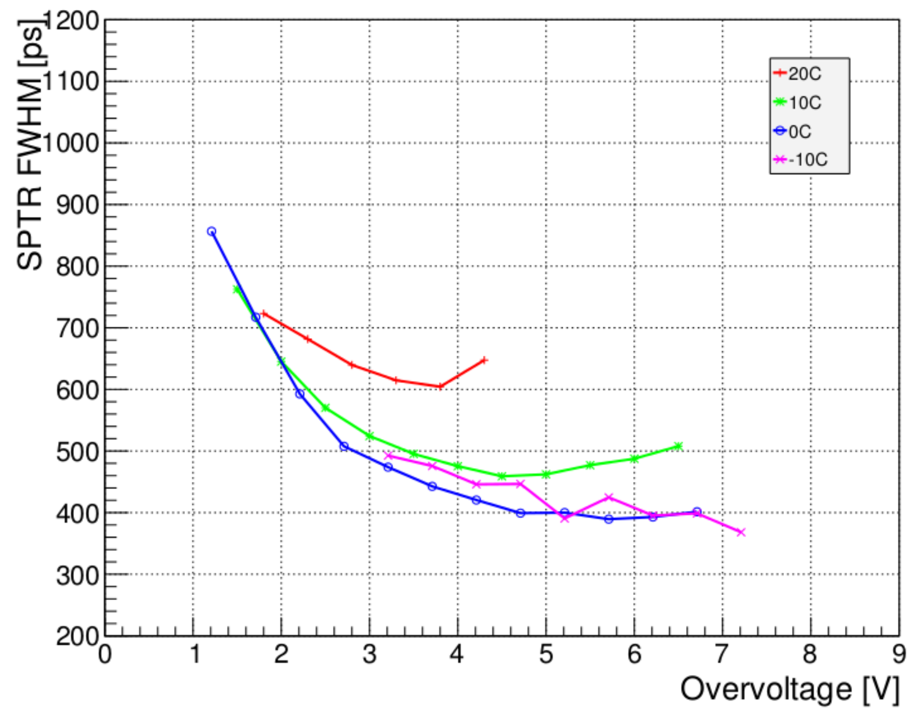


Single photon time resolution KETEK I

Device: PM3375-B72 with trenches
ID: ket02

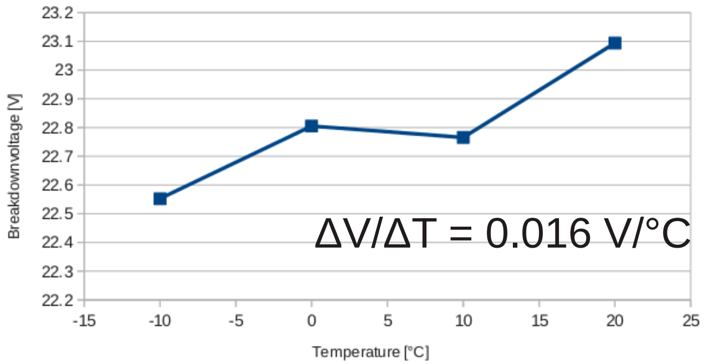


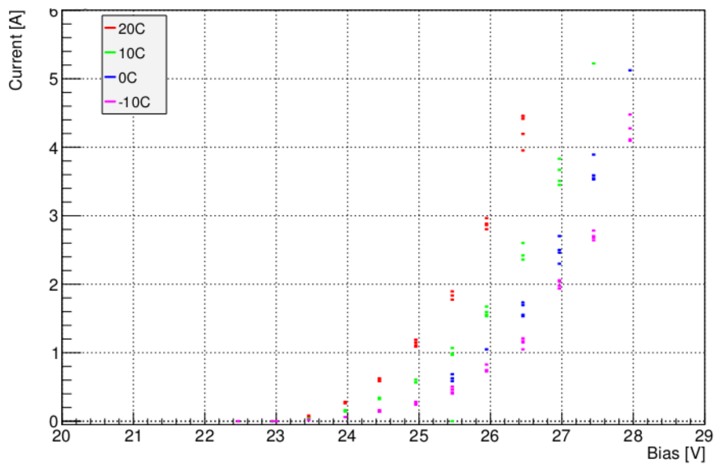


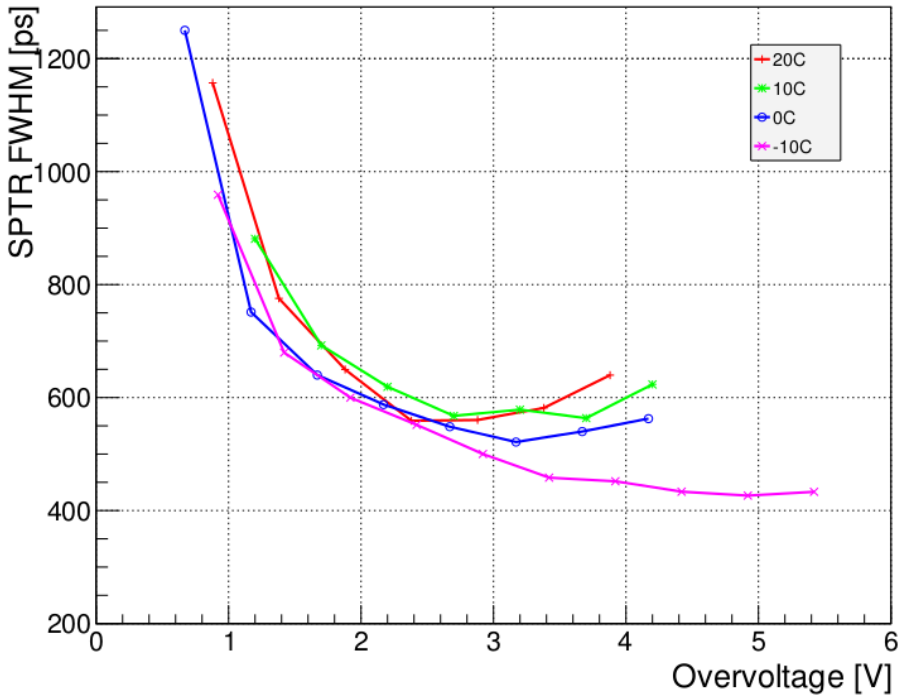


Single photon time resolution KETEK II

Device: PM3360-B66T75S with trenches
ID: ket01

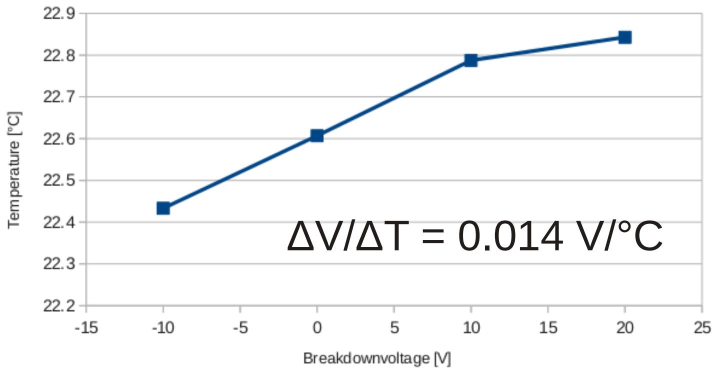


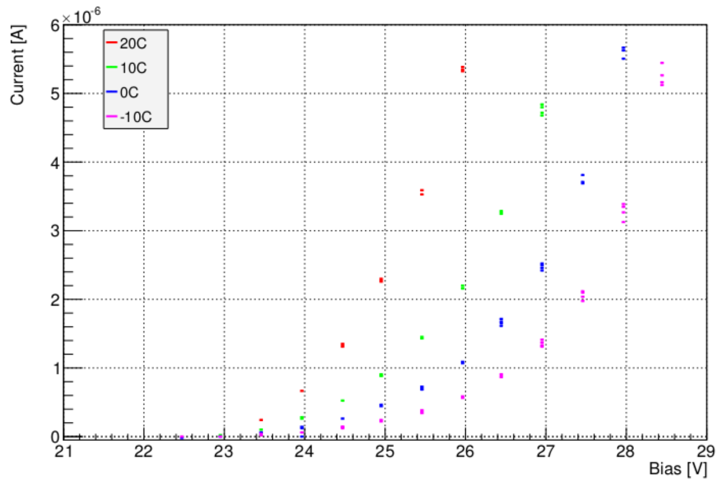


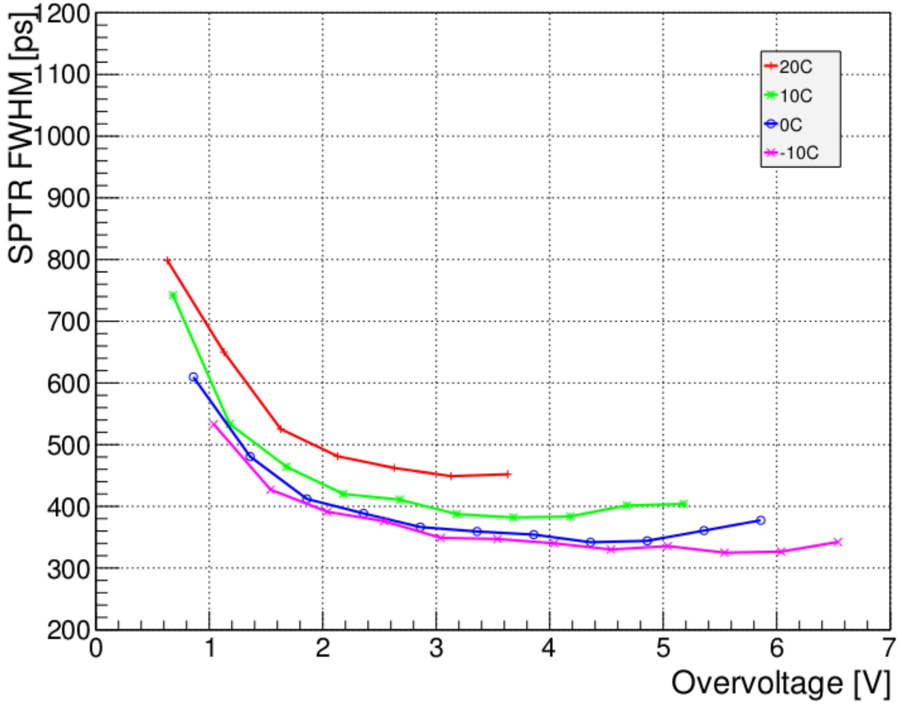


Single photon time resolution KETEK III

Device: PM3350-B63 with trenches
ID: ket03







Summary

- The best values for single photon time resolution ranges from ~450ps FWHM (20°C) to <350 ps FWHM (-10°C) but still many devices to test
- System TR (laser, oscilloscope, fibers, preamp, ...) is included in the measurement (will be measured) → values do not give the absolute TR of the SiPM!
- The TR is improving with increasing number of photons $\propto \frac{1}{\sqrt{n_{phe}}}$
- Time resolution of the SiPM is strongly temperature dependent (dark count rate)
- Measurement is almost automatized → many devices will be compared
- New preamplifier will be tested with the same setup