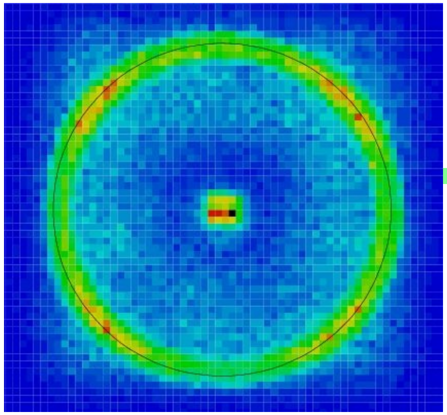

KMI Wine and cheese seminar, Nagoya, May 11, 2016

Cherenkov detectors in particle physics and medical imaging

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Beyond the simple Cherenkov based TOF-PET

Conclusions and summary

Interplay of detector R&D for particle physics and medical imaging

Traditionally excellent collaboration of the two research areas.

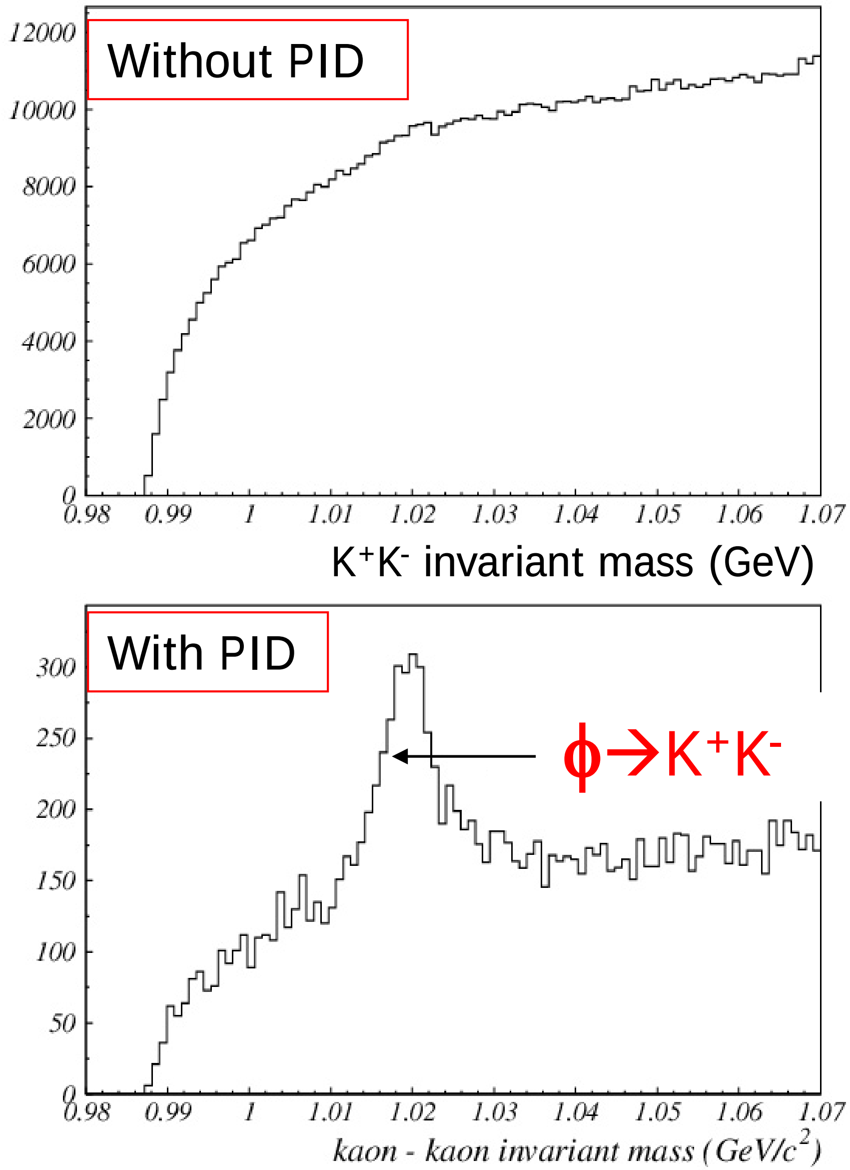
Novel detection techniques required in particle physics
→with modifications a potential application in medical physics

... and vice versa...

One of the recent examples: SiPMs as scintillation light sensors for

- Electromagnetic calorimeters
- PET scanners

Particle identification - which particle species was produced in a reaction - one of the essential features of experiments

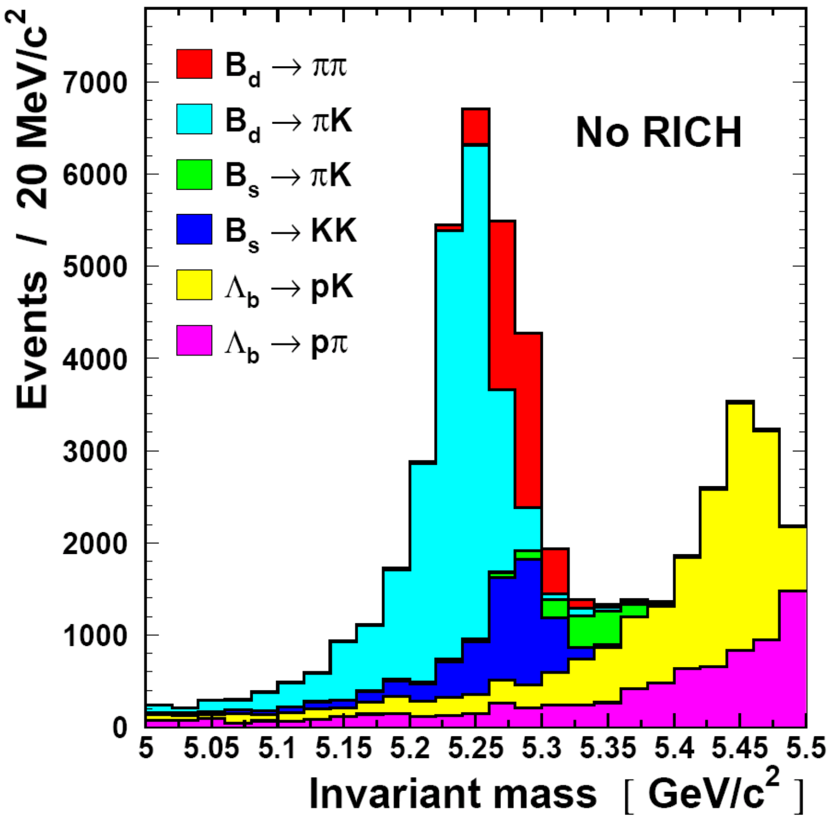


Very often the interesting reaction is burried in a large number other reactions (background).

One important tool: select only reactions (events) with the right type of particles = identify each of them
→particle identification (PID)

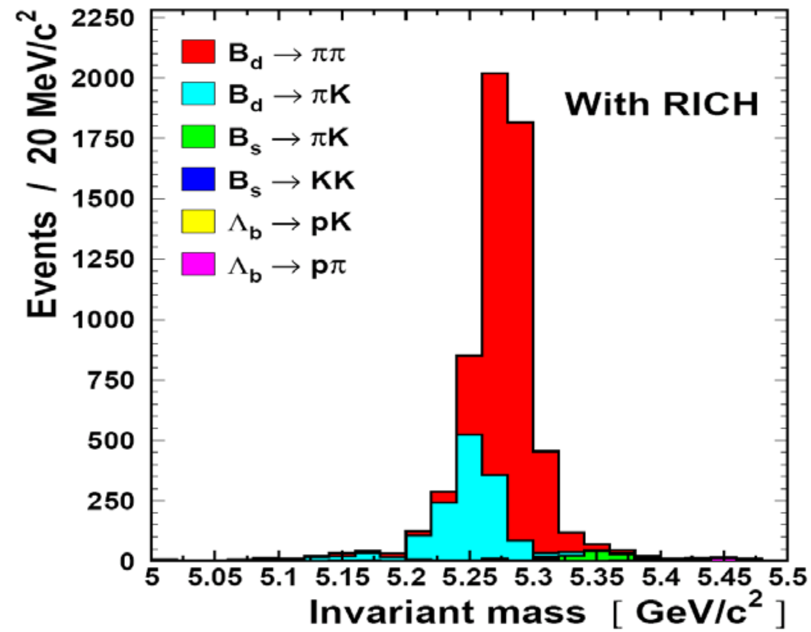
Example: the decay $\phi \rightarrow K^+K^-$ only becomes visible after particle identification is taken into account.

Why particle ID?



Example 2: LHCb

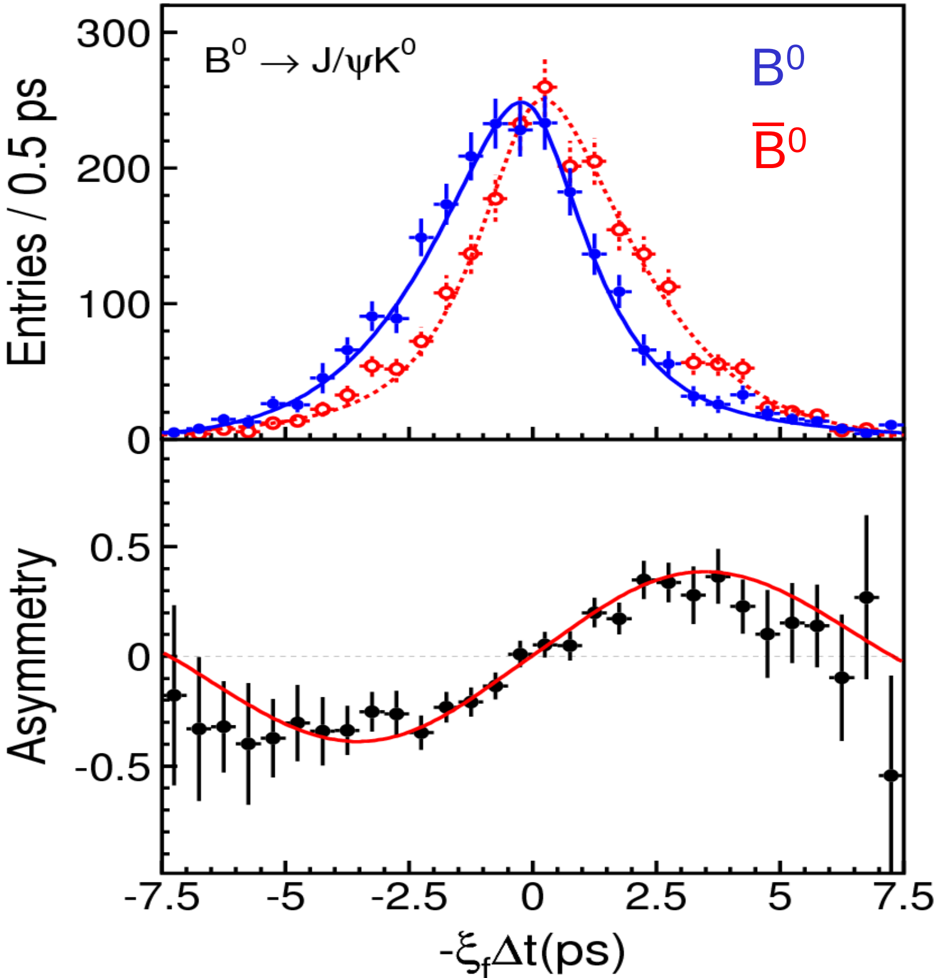
(MC prediction)



Need to distinguish $B_d \rightarrow \pi\pi$ from other similar topology 2-body decays

Why particle ID?

Particle identification at B factories (Belle and BaBar): was essential for the observation of CP violation in the B meson system.



B^0 and its anti-particle decay differently to the same final state $J/\psi\ K^0$

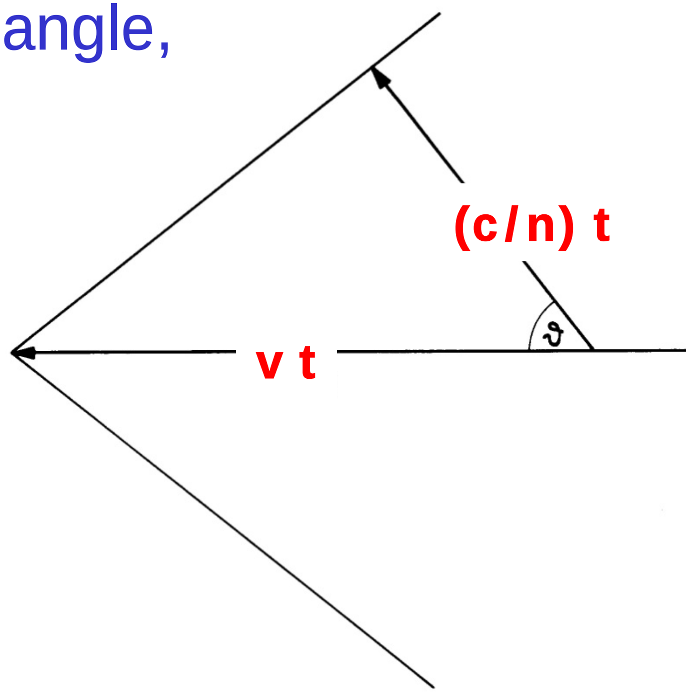
Flavour of the B: from decay products of the other B: charge of the kaon, electron, muon

→particle ID is compulsory

One of the important PID methods: use Cherenkov radiation

A charged track with velocity v=βc exceeding the speed of light c/n in a medium with refractive index n emits polarized light at a characteristic (Cherenkov) angle,

$$\cos\theta = c/nv = 1/\beta n$$

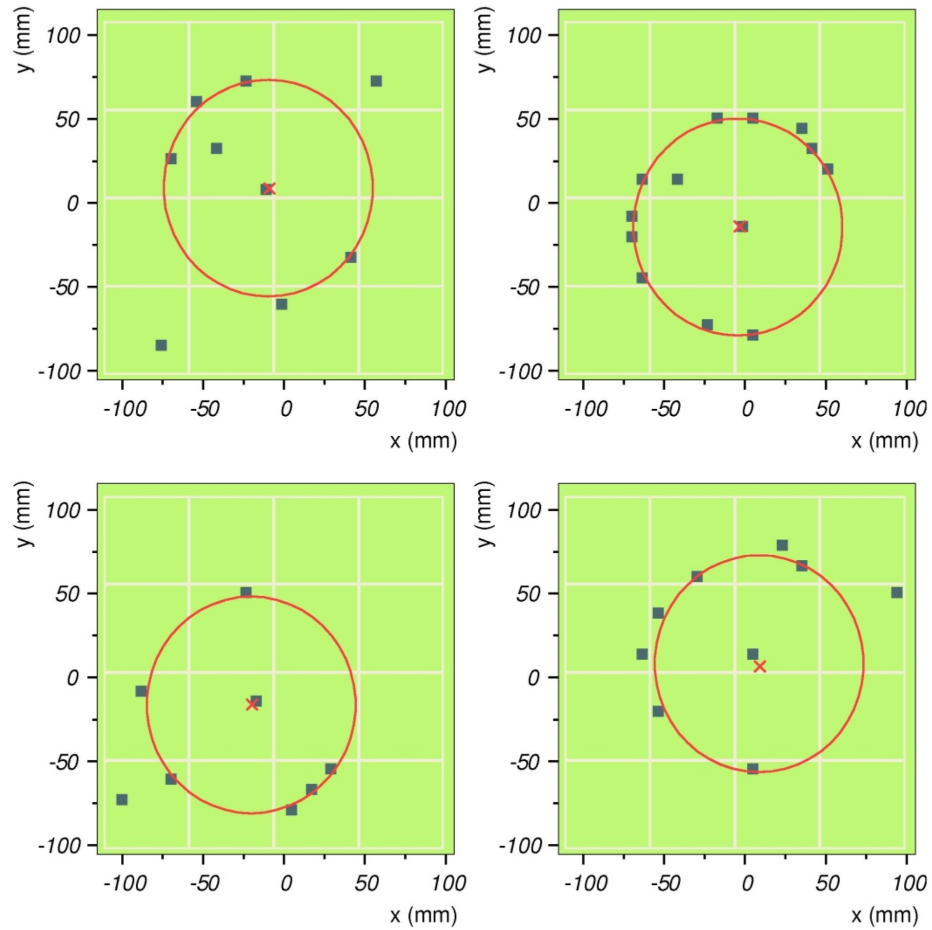


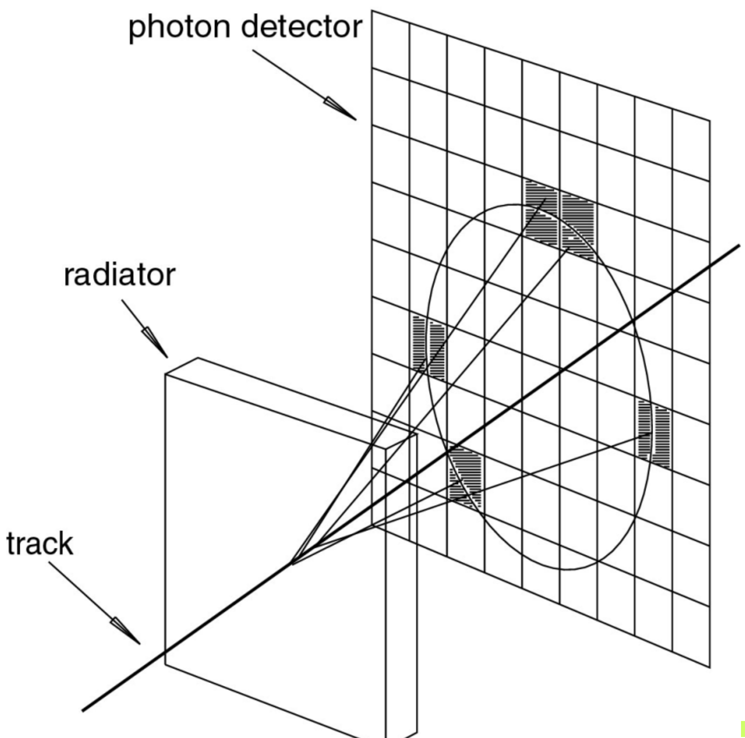
Excellent identification method, but very low light level = few detected photons

Measuring Cherenkov angle

Cherenkov photons detected on a plane: ring (Ring Imaging Cherenkov counter, RICH)

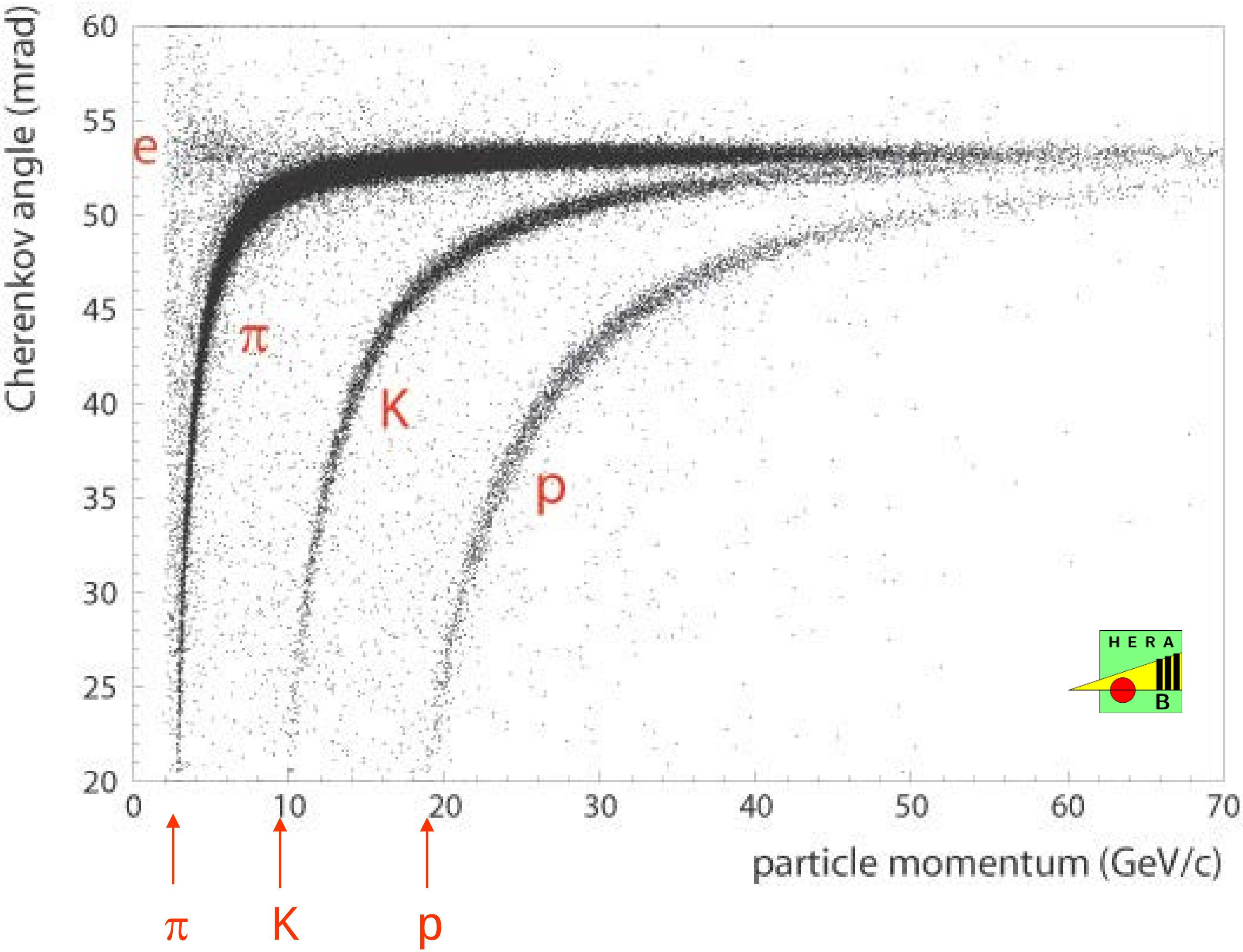
ring radius → Cherenkov angle





Need a fine granularity sensor for single photons with low noise

Measuring Cherenkov angle



Radiator: C_4F_{10} gas

thresholds

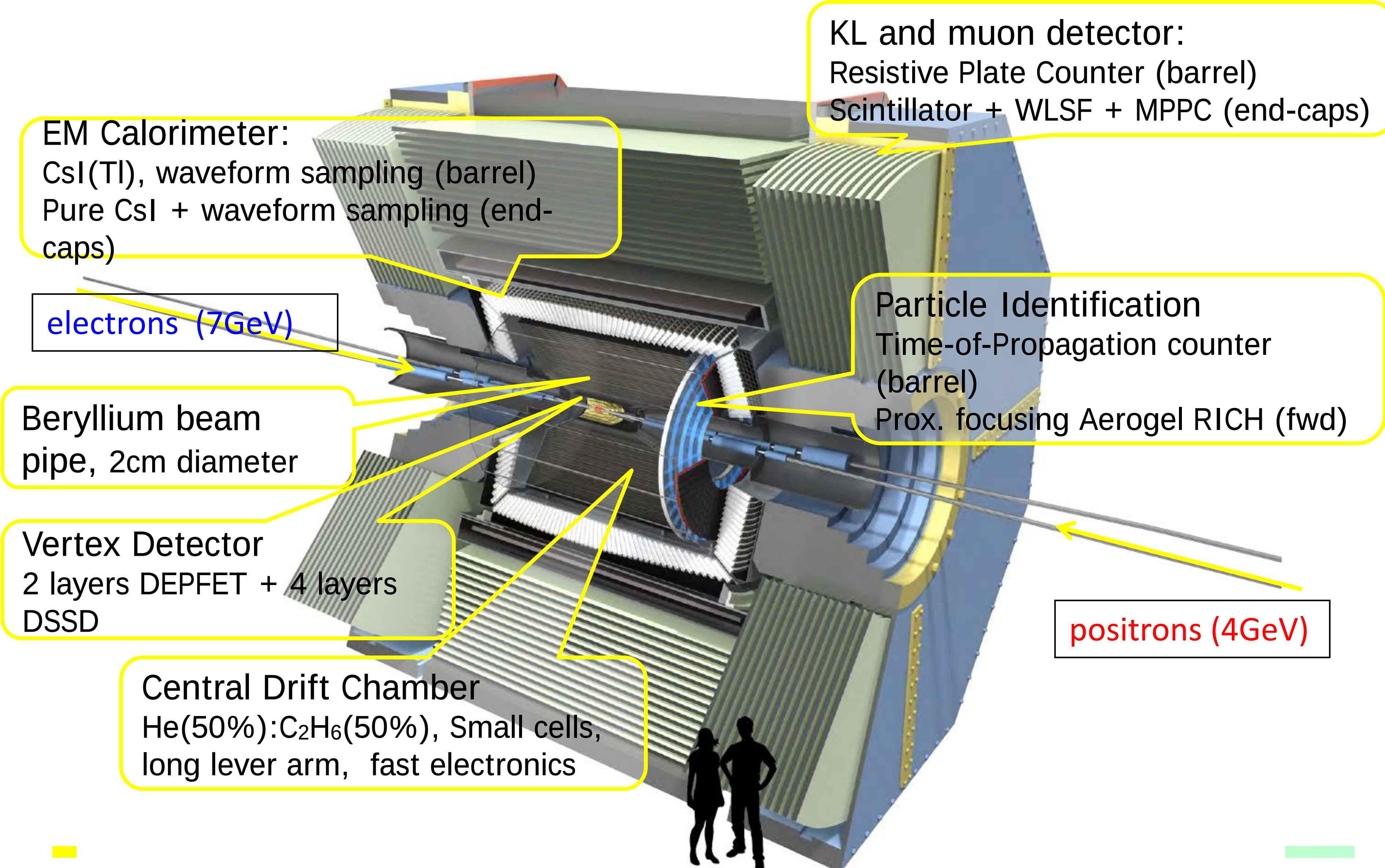
Recent trend: fast photon detection in Cherenkov detectors

New generation of RICH counters: precise time information needed to further improve performance:

- Reduce chromatic abberation (group velocity): Focusing DIRC
- Combine TOF and RICH techniques: TOP (Time-of-propagation counter) at Belle II, TORCH at LHCb

→ Need photo sensors with excellent timing of <50ps (r.m.s.)

Belle II Detector



Recent trend: fast photon detection in Cherenkov detectors

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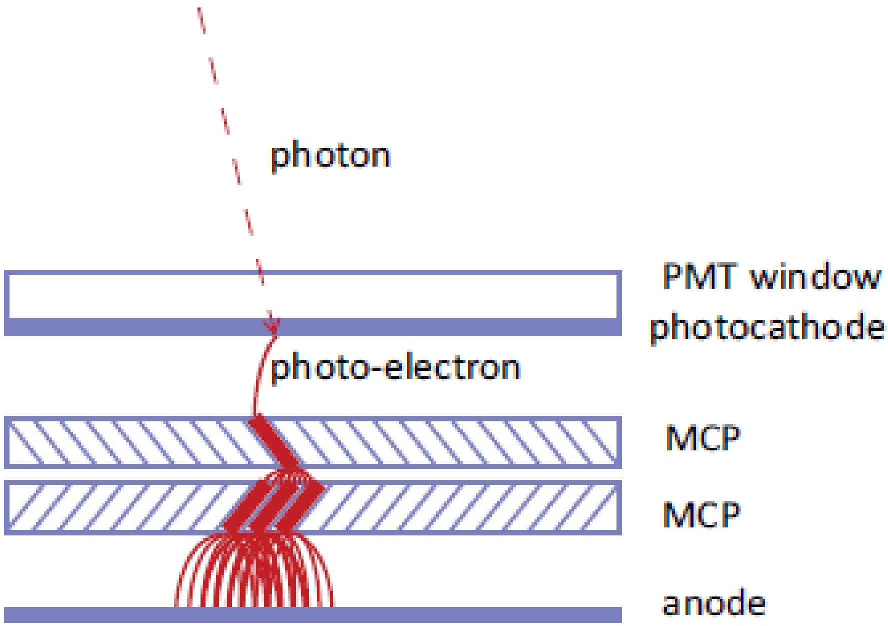
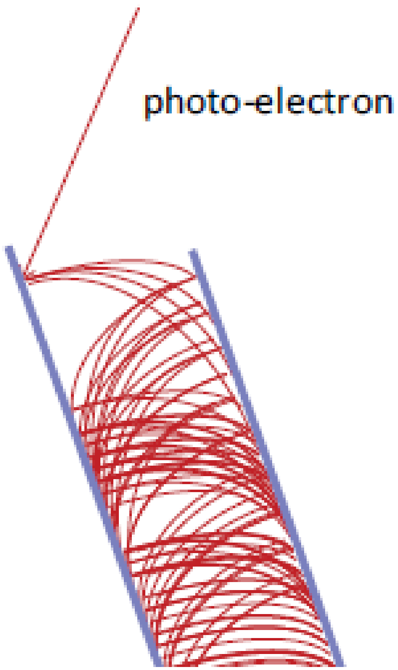
- Reduce chromatic abberation (group velocity): Focusing DIRC
- Combine TOF and RICH techniques: TOP (Time-of-propagation counter) at Belle II, TORCH at LHCb

→ Need photo sensors with excellent timing of <50ps (r.m.s.)

Very fast light sensor: micro-channel plate PMTs



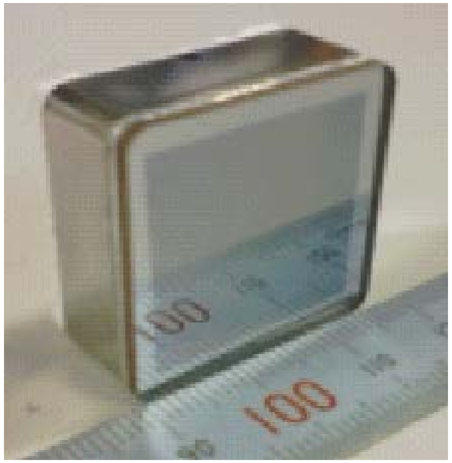


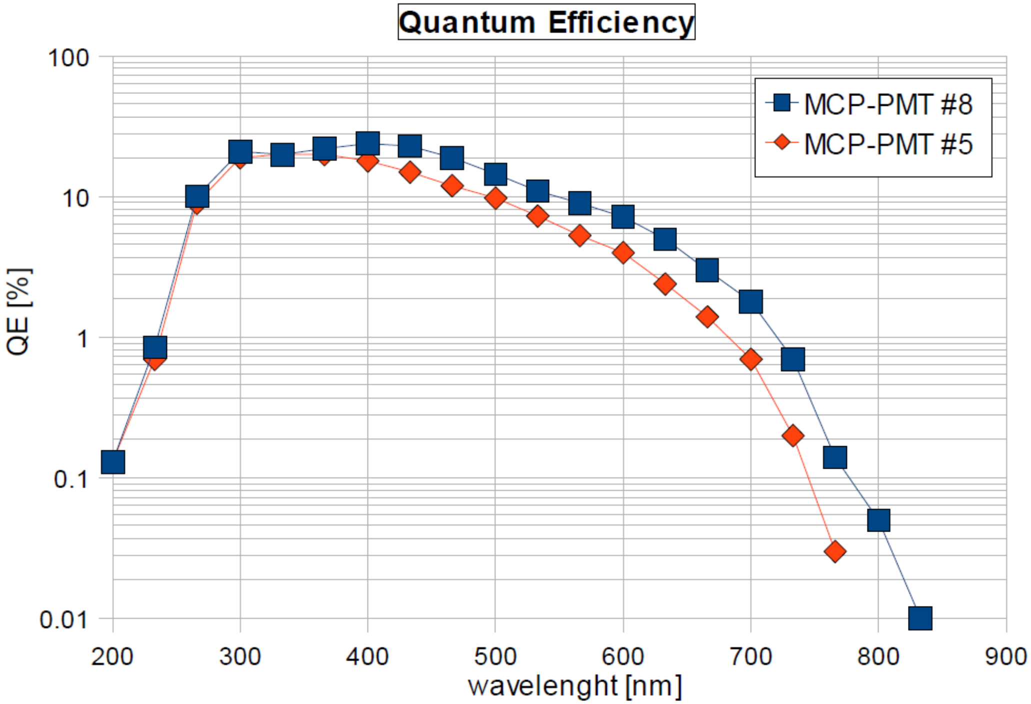
- Faster than PMTs
- Immune to an axial magnetic field

Photon detector: MCP-PMT

Example: Hamamatsu SL10 MCP-PM

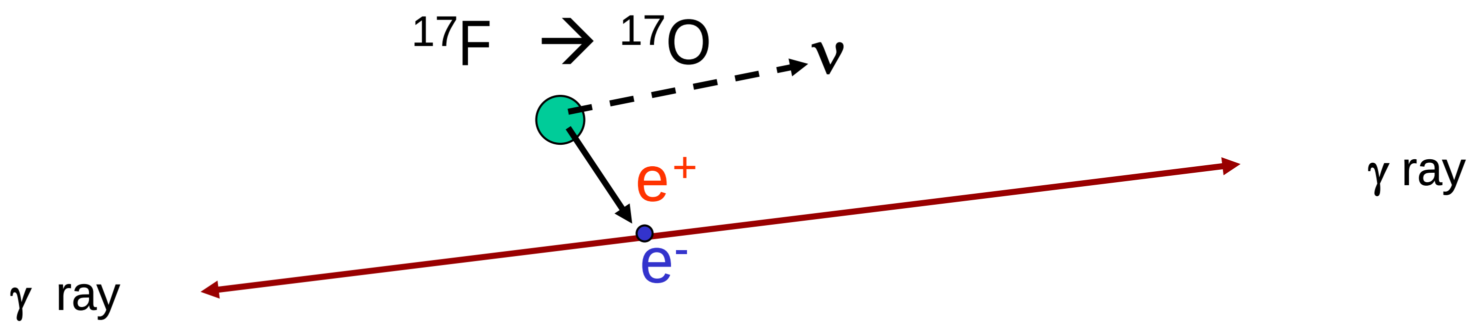
- multi-anode PMT with two MCP steps, 10 mm pores
- 16 (4x4) anode pads, pitch ~ 5.6 mm, gap ~ 0.3 mm
- box dimensions ~ 27.5 mm square
- excellent timing **~ 20ps r.m.s.** for single photons
- multi-alkali photocathode
- 1.5 mm borosilicate window
- gain > 10^6





PET: positron emission tomography

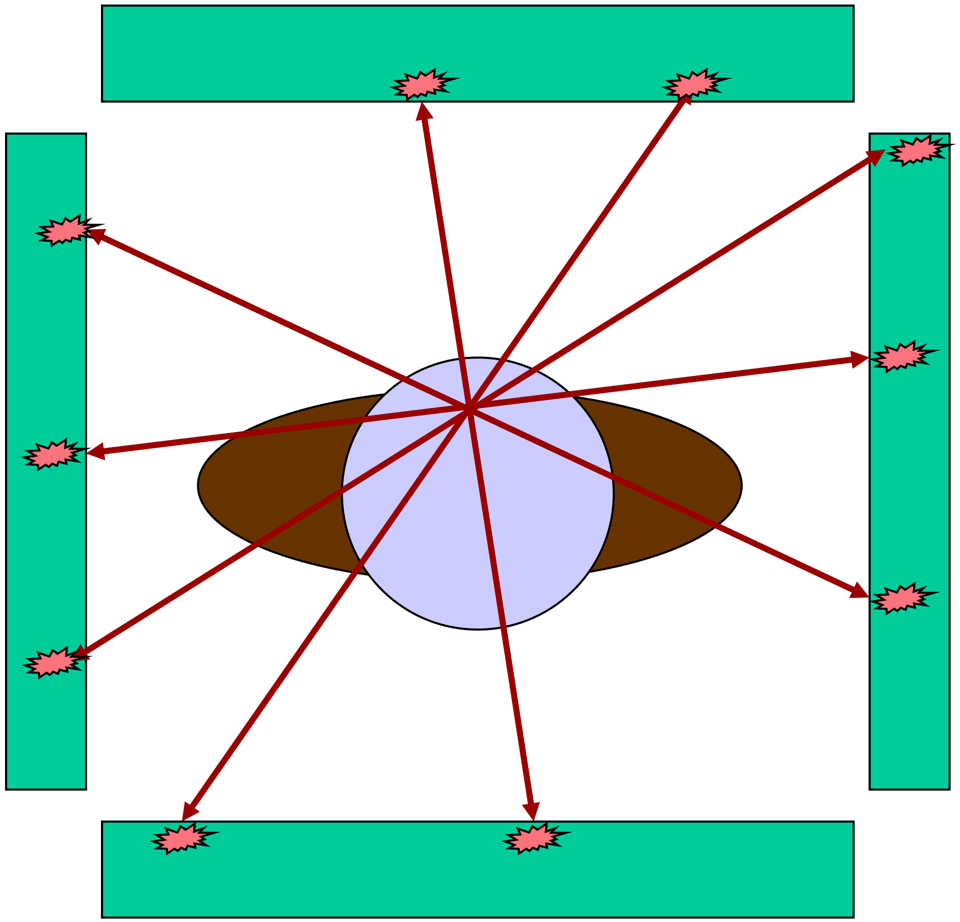
Radioactive fluorine decays via the beta+ decay to oxygen, a positron and a neutrino



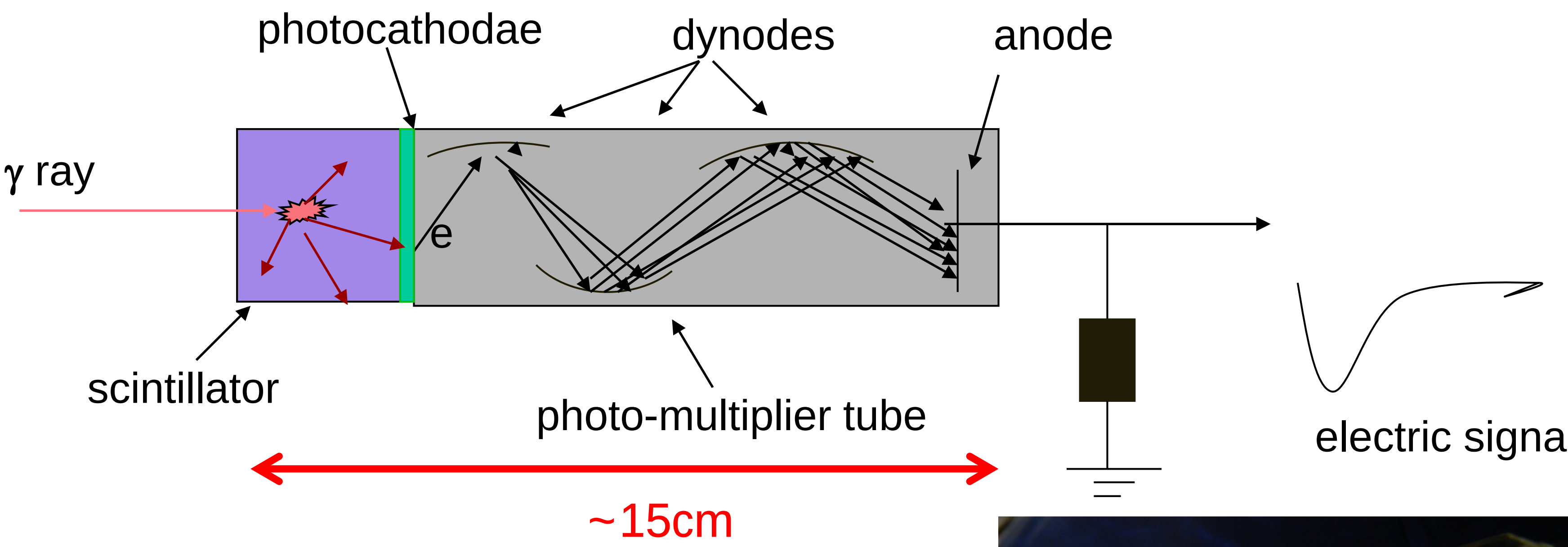
Positron annihilates with an electron in the surrounding matter, producing two back-to-back γ rays

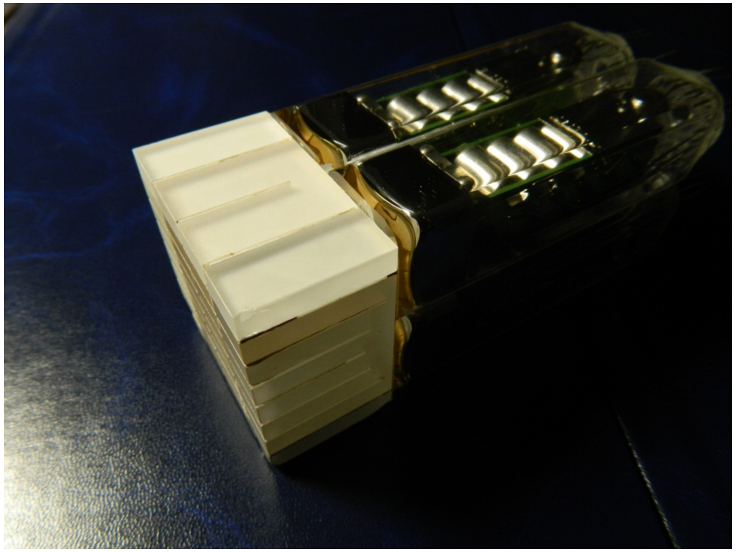
PET: positron emission tomography 2

In the blood of the patient a substance is administered that contains radioactive fluorine (e.g. fluorodeoxyglucosis). The places in the body with a higher substance concentration will show a higher activity.

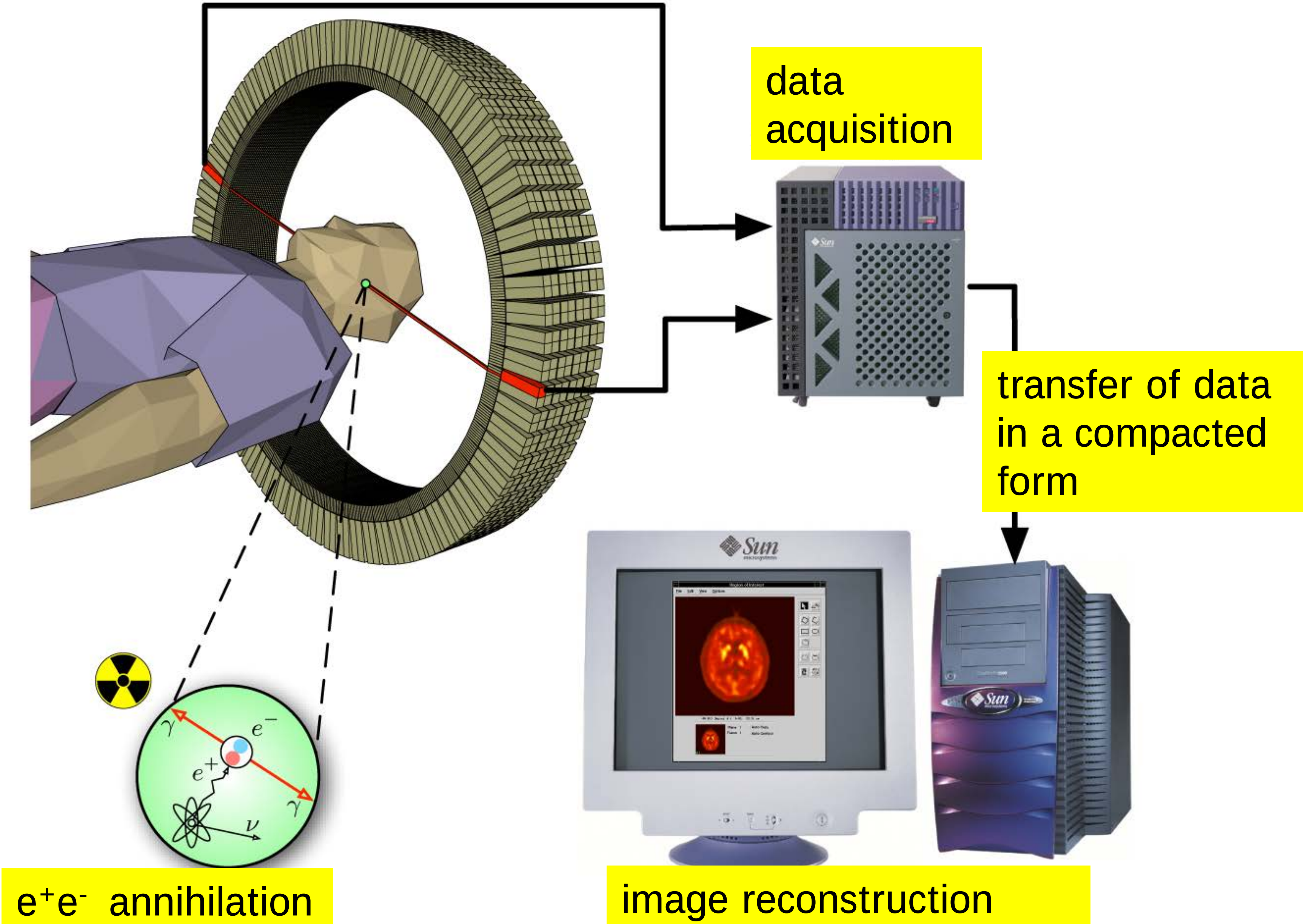


Detector of γ rays: a scintillator with a photomultiplier tube



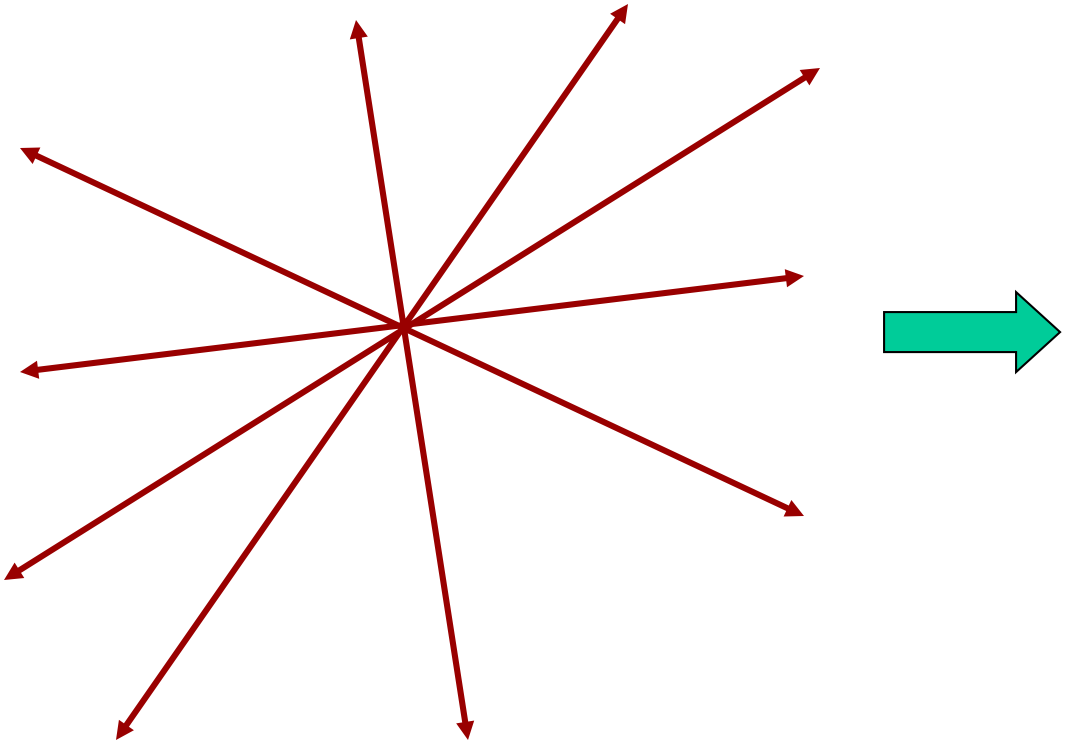


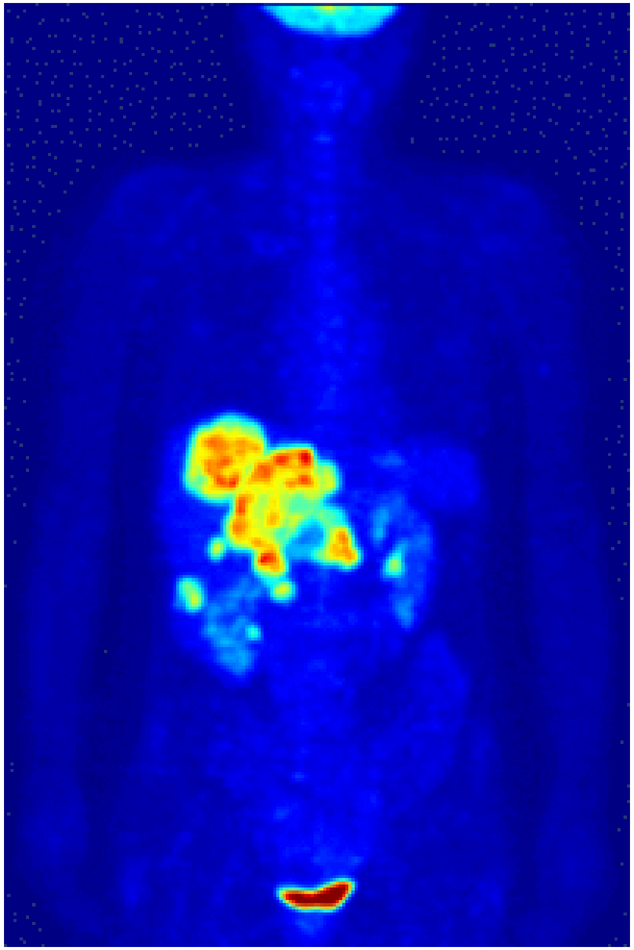
PET: collection of data



PET: image reconstruction

Image reconstruction: from the position and direction of the lines determine the distribution of the radioactive fluorine in the body – similar to the reconstruction of reactions in particle physics





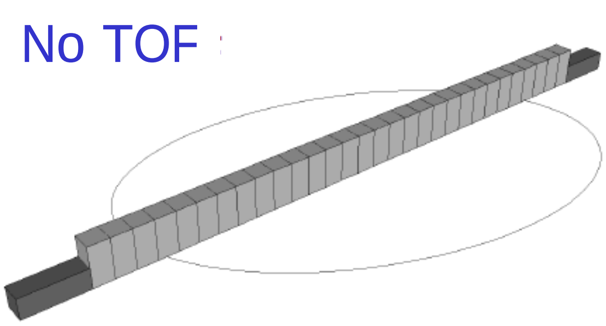
PET with a time-of-flight information

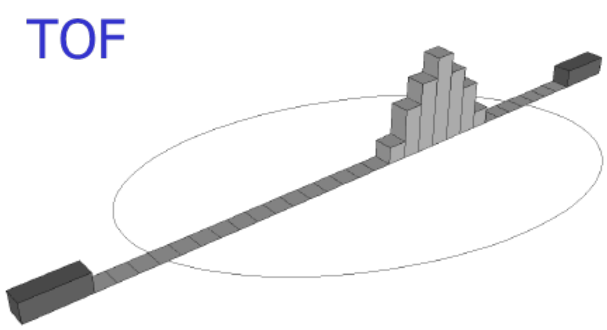
Detectors for γ rays measure also the time of arrival

– coincidence of two hits is only acceted if the two times are <10 ns appart

In case time is measured with a much better precision (<1ns) → an additional constraint on the point of origin of the two γ rays along the line →time-of-flight (TOF) PET

- in the reconstruction, each line contributes to fewer pixels → less noise
- good resolution in time-of-flight → limits the number of hit pixels along the line



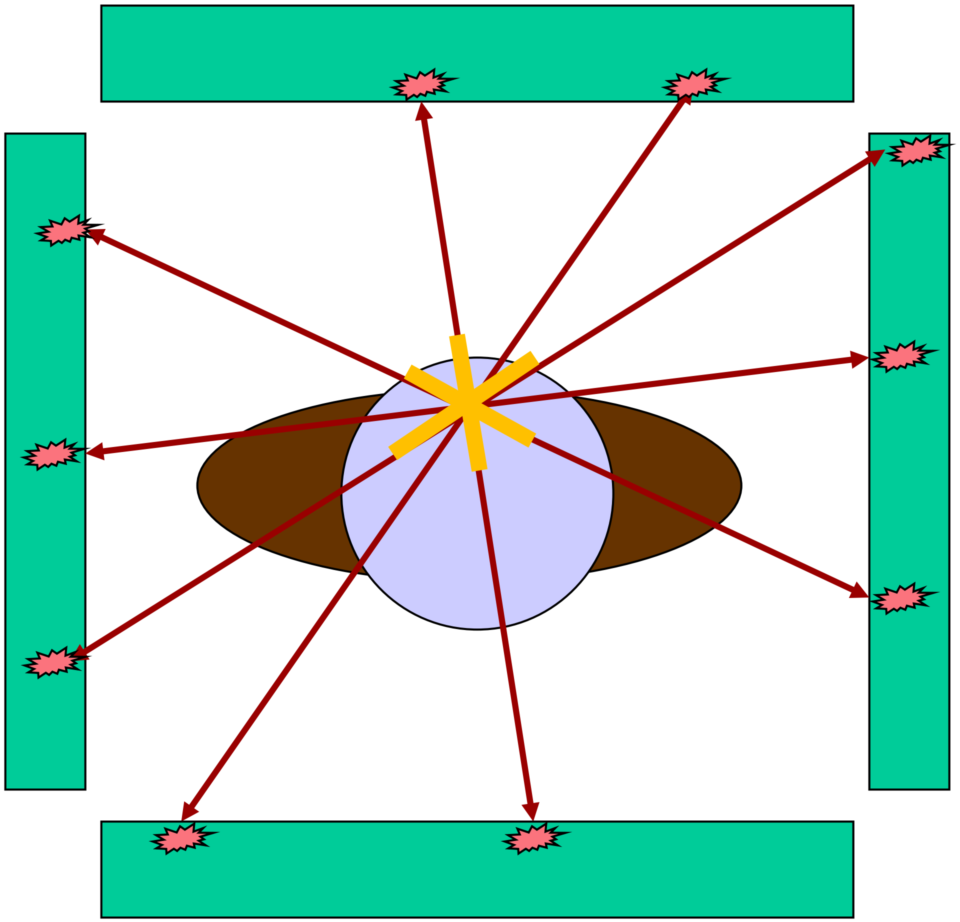


TOF-PET: positron tomography with a time of arrival measurement

Comercially available devices: poor resolution, ~600 ps (FWHM)

Resolution limited by: - photosensor response time

- decay time of the scintillator



TOF PET with a fast scintillator: 300 ps (FWHM) -

Can we do it better?

- Faster sensor: PMT → MCP PMT
- Scintillator → Cherenkov radiator

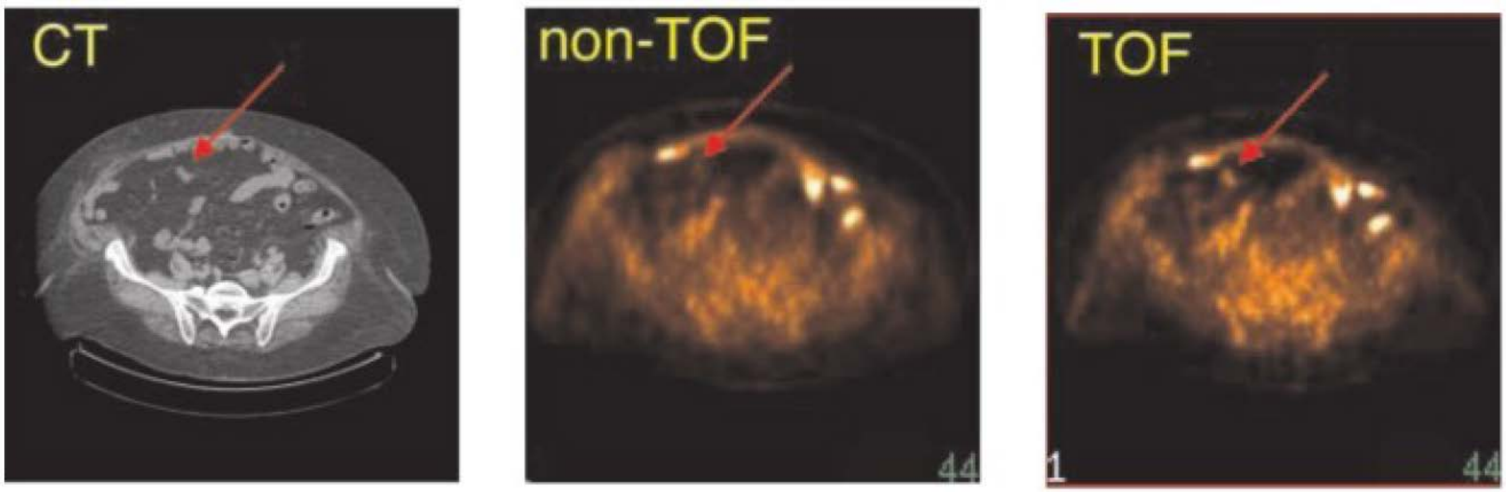
PET vs. TOF-PET

The benefit of TOF PET in PET image reconstruction

Example: bowel cancer

– Philips Gemini TF PET/CT

– resolution in TOF ~ 600 ps



[PET Center of Excellece Newsletter, Vol.3 Issue 3 (2006)]

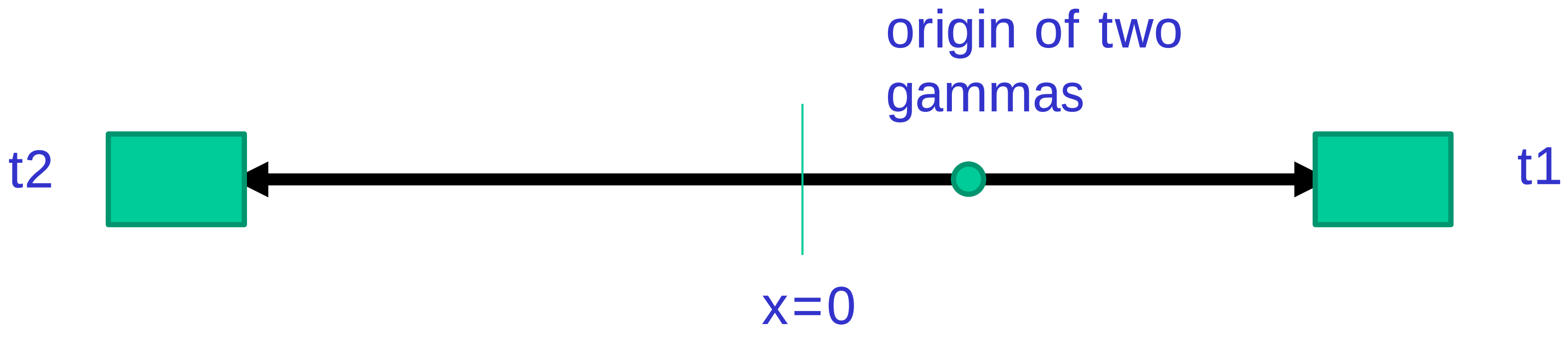
TOF PET allows for a:

– better image quality at a fixed time (or dose)

– same quality with a shorter time (or lower dose)

TOF-PET: time resolution

What kind of time resolution is needed?



t1 = (L/2 – x)/c   source at x, distance between detectors = L

t2 = (L/2 + x)/c

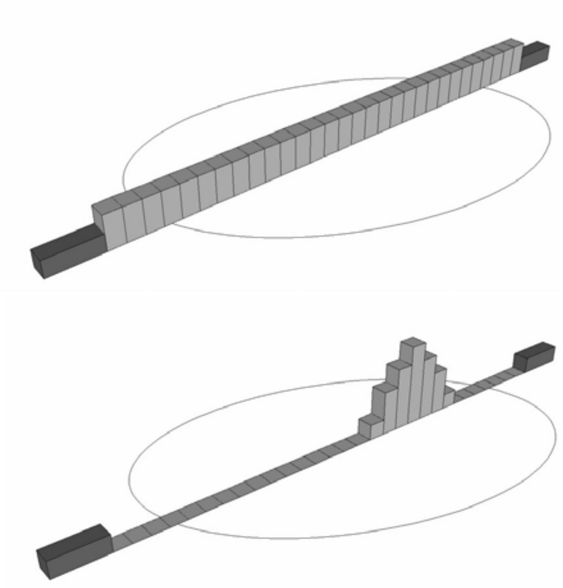
t1 – t2 = 2x/c

x = (t1 – t2) c/2 → Δx = Δ(t1-t2) c /2

resolution in TOF   Δ(t1-t2) = 300 ps → Δx = 4.5 cm

Δ(t1-t2) = 66 ps → Δx = 1 cm

TOF-PET with Cherenkov light



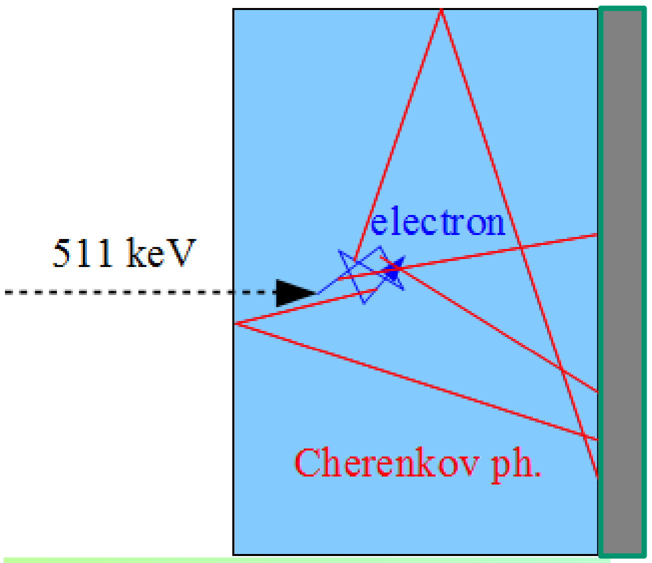
Time-of-Flight difference of annihilation gammas is used to improve the contrast of images obtained with PET:

- localization of source position on the line of response
- reduction of coincidence background
- improvement of S/N

Novel photon detectors – MCP-PMT and SiPM – have excellent timing resolution → TOF resolution limited by the scintillation process

Cherenkov light is promptly produced by a charged particle traveling through the medium with velocity higher than the speed of light c_0/n.

Disadvantage of Cherenkov light is a small number of Cherenkov photons produced per interaction → detection of single photons!



Cherenkov radiator for PET

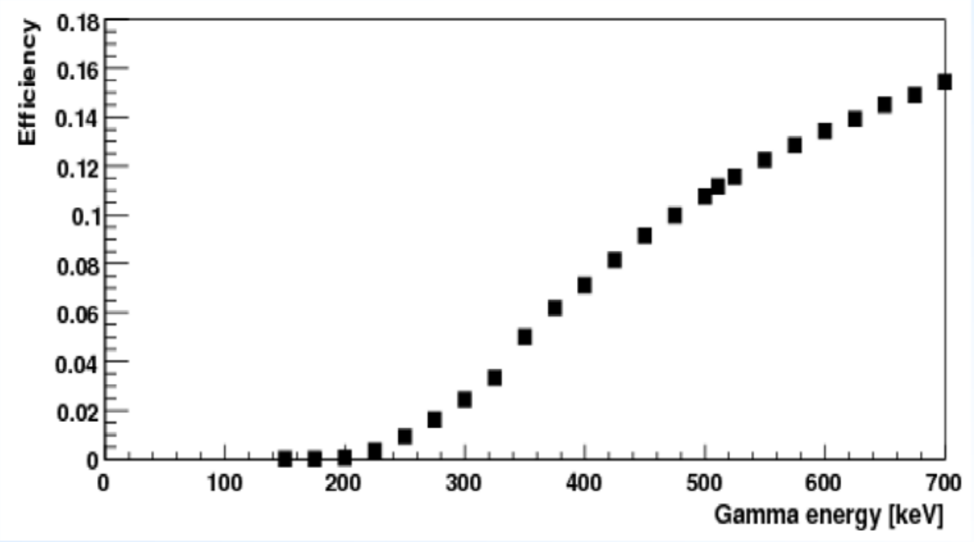
Cherenkov radiator PbF_2:

- high gamma stopping power
- high fraction of gamma interactions via photoeffect → electrons with maximal kinetic energy → more Cherenkov photons
- high transmission for visible and near UV Cherenkov photons

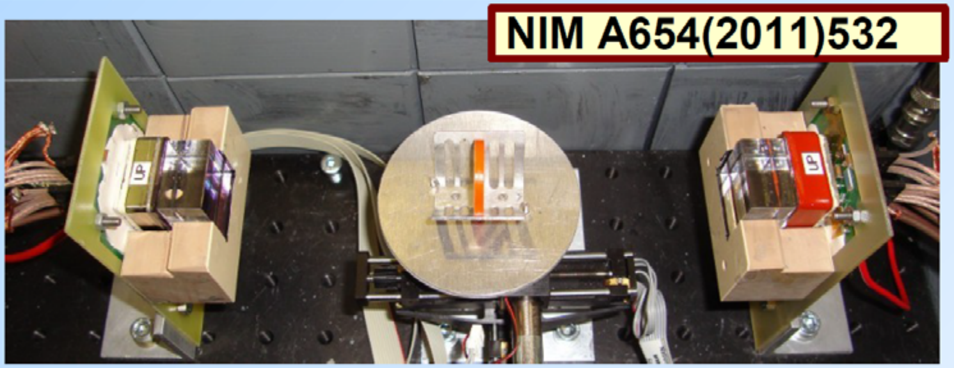
	ρ (g/cm³)	n	e^- Cherenkov threshold (keV)	Cutoff wavelength (nm)	Attenuation length (cm)	Photofraction
PbF_2	**7.77**	**1.82**	**101**	**250**	**0.91**	**46%**
LYSO	7.4				1.14	32%

Traditional PET: large number of photons → gamma energy → rejection of scattered events

Cherenkov PET: a few photons detected → no energy information; efficiency drops with gamma energy → intrinsic suppression



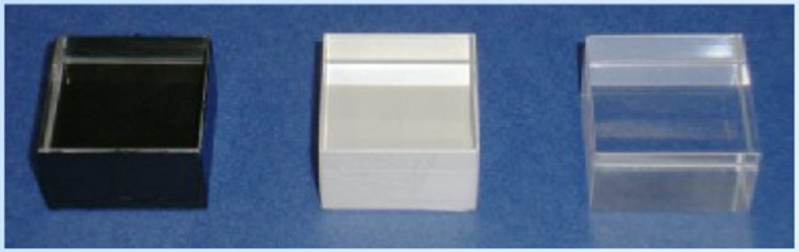
Excellent timing with MCP PMTs



- Cherenkov radiators:

25x25x(5, 15) mm^3 PbF_2

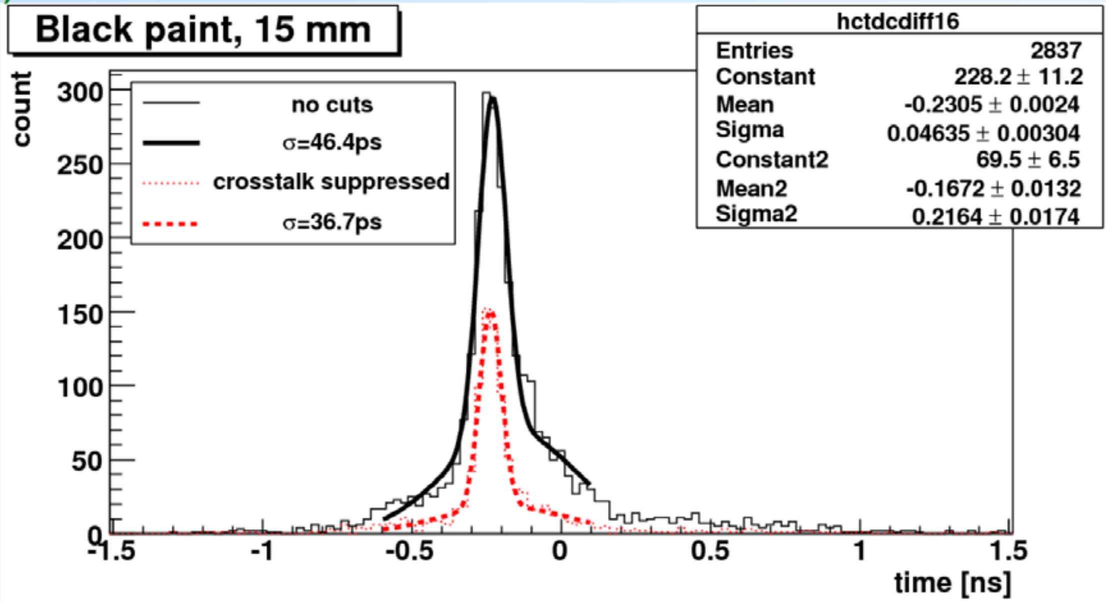
- MCP-PMT photodetectors:
  - single photon timing ~ 50 ps FWHM
  - active surface 22.5x22.5 mm^2



black painted, Teflon wraped, bare

- Timing resolution (black painted):
  - ~ 70 ps FWHM, 5mm
  - ~100 ps FWHM 15mm
- Efficiency (Teflon wraped):
  - ~ 6%, single side

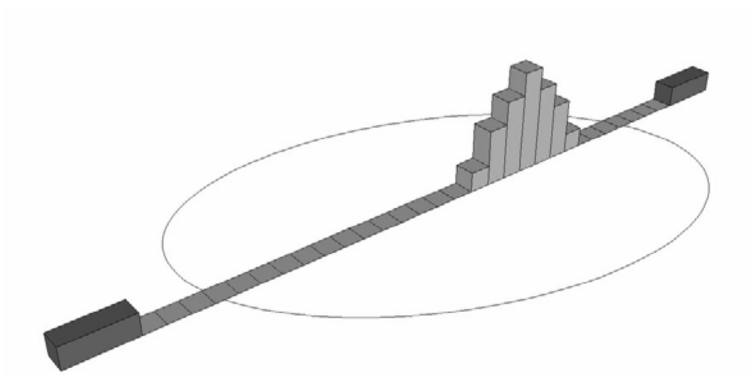
(~ 30% for LSO in ideal case)



Point source position

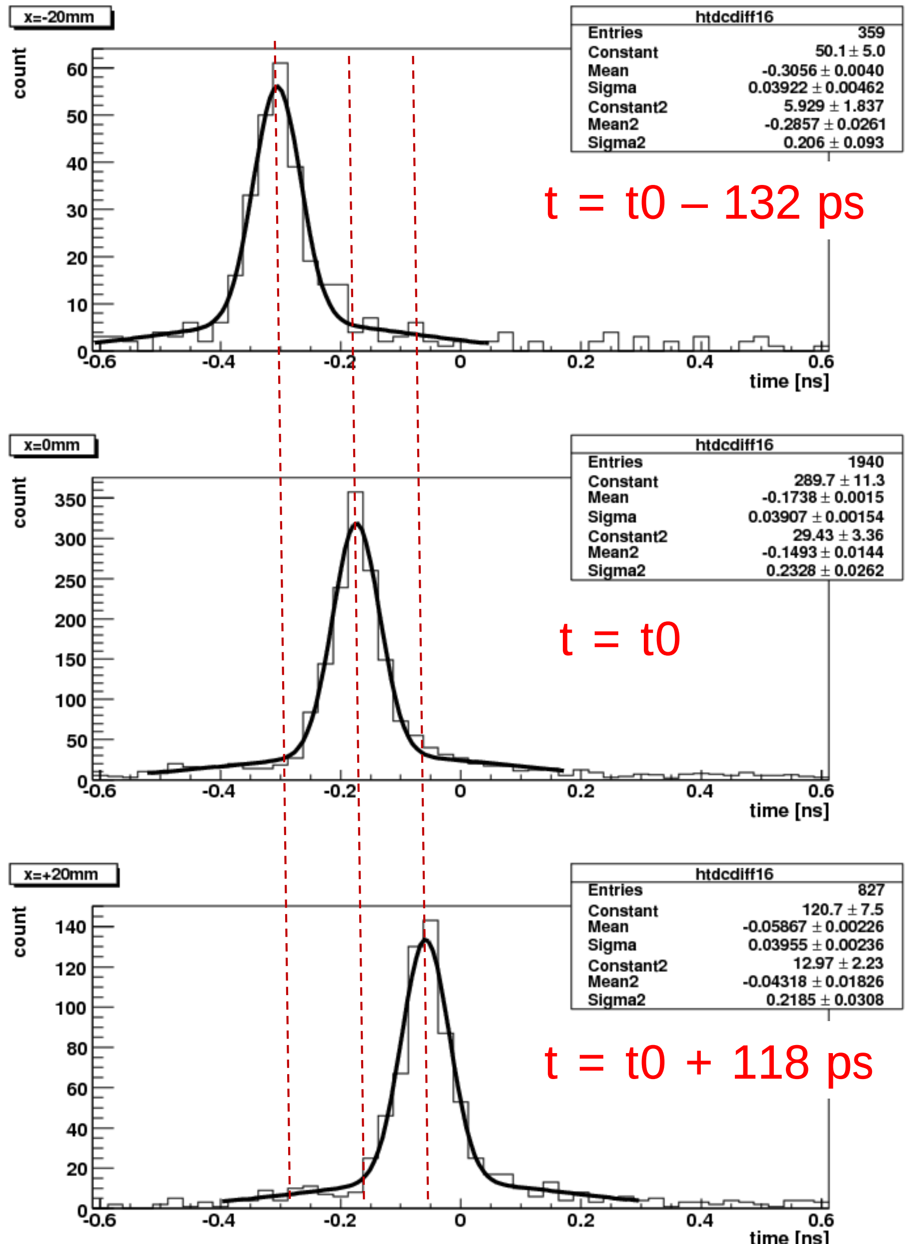
Data taken at three different point source positions spaced by 20 mm:

- average time shift 125 ps
- timing resolution ~ 40 ps rms,
  ~ 95 ps FWHM
- position resolution along line of response ~ 6 mm rms,
  ~ 14 mm FWHM



Black painted 15 mm PbF_2 crystals.

→ NIM A654(2011)532–538



Cherenkov based PET scanner

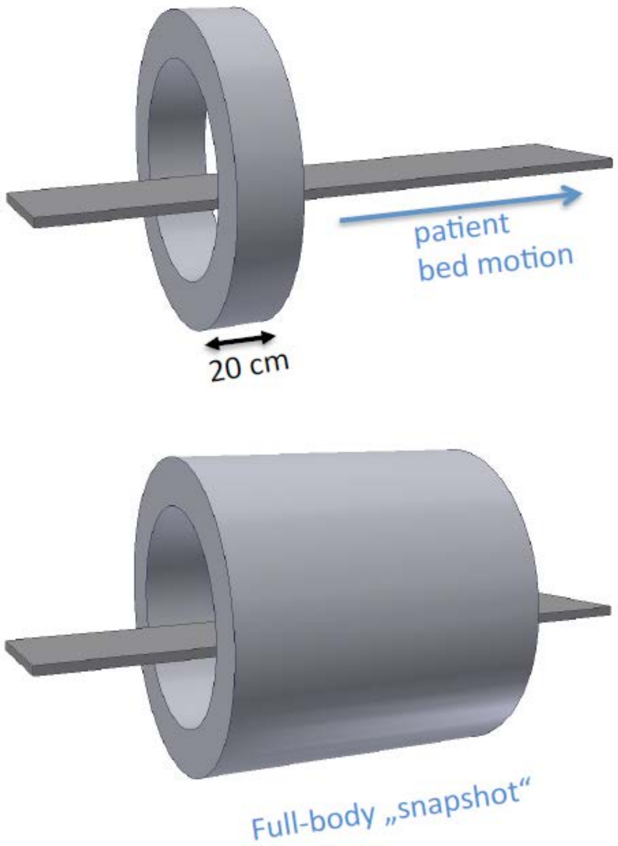
PbF_2 not a scintillator → considerably cheaper!

Small attenuation length than LSO – smaller parallax error

→ **Full body scanner?**

→ Carry out a feasibility study, groups led by

- Sibylle Ziegler, TU Munich
- Alberto Del Guerra, University of Pisa
- Peter Križan, J. Stefan Institute, Ljubljana
- Irene Buvat, IMIV, Orsay, CEA
- Edoardo Charbon, TU Delft
- Paul Lecoq, CERN
- Gabor Nemeth, Mediso Ltd
- Florian Wiest, KETEK GmbH
- Stefan Ritt, Paul Scherrer Institute



One of the outcomes → a preliminary MC simulation study →

Cherenkov based PET scanner, MC study

Simulations were performed in order to estimate the performance of TOF PET scanner based on the Cherenkov method of gamma detection.

The main building block of the simulated scanner was a gamma detector composed of a PbF_2 crystal and a SiPM as light sensor.

The performance of a single gamma detector was first investigated in depth using GEANT4. The simulation was then transferred to GATE and a scanner was simulated.

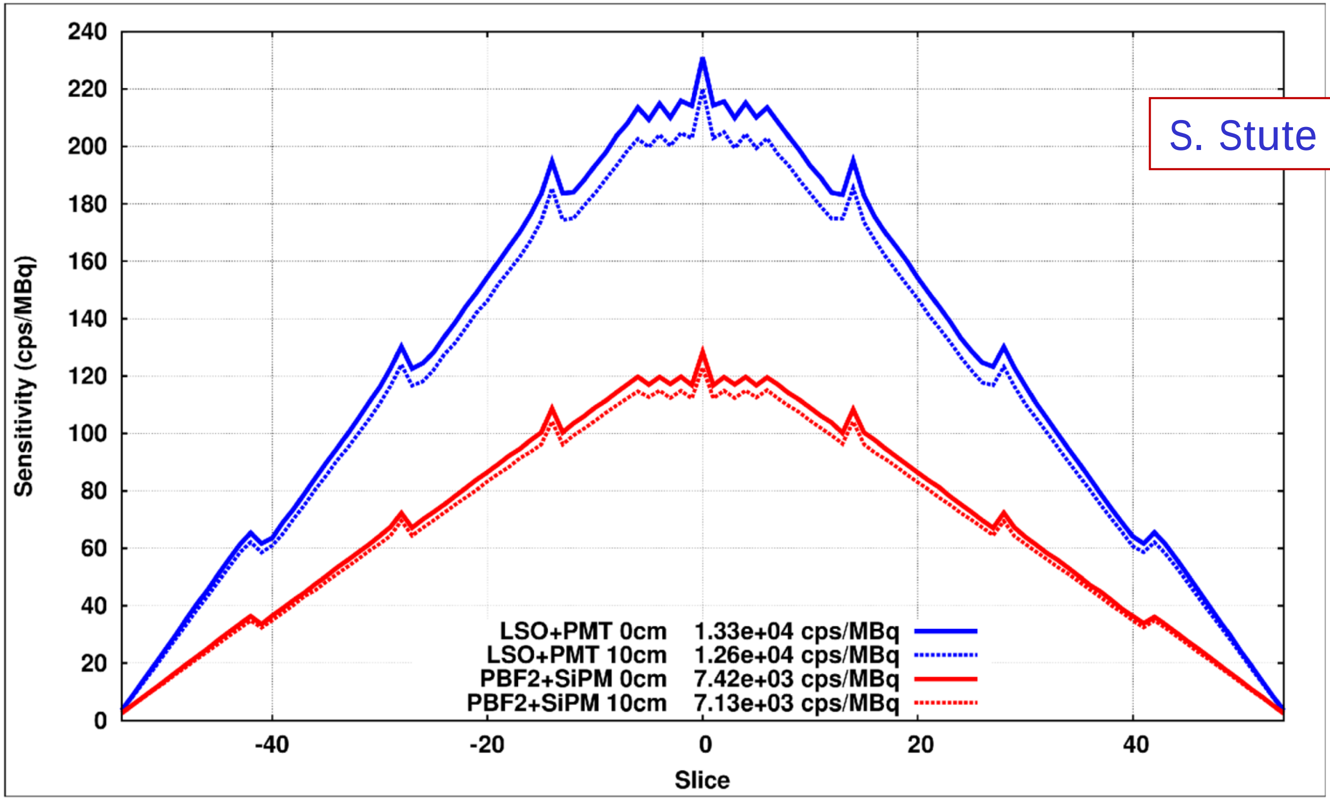
The performance of the scanner based on the Cherenkov method was compared to that of a state-of-the-art LSO scanner.

We studied:

- The standard axial length size scanner (axial extent 218 mm (4 blocks, sampled into 109 slices of 2 mm), diameter 854.8 mm (crystal-to-crystal, front face). diameter of.
- An axially extended 1m long scanner

Cherenkov based PET scanner, MC study

The sensitivity for a standard scanner geometry with the two technologies: the state-of-the art LSO+PMT combination has a higher sensitivity than Cherenkov-PbF2 because of a higher gamma detection efficiency. However, →

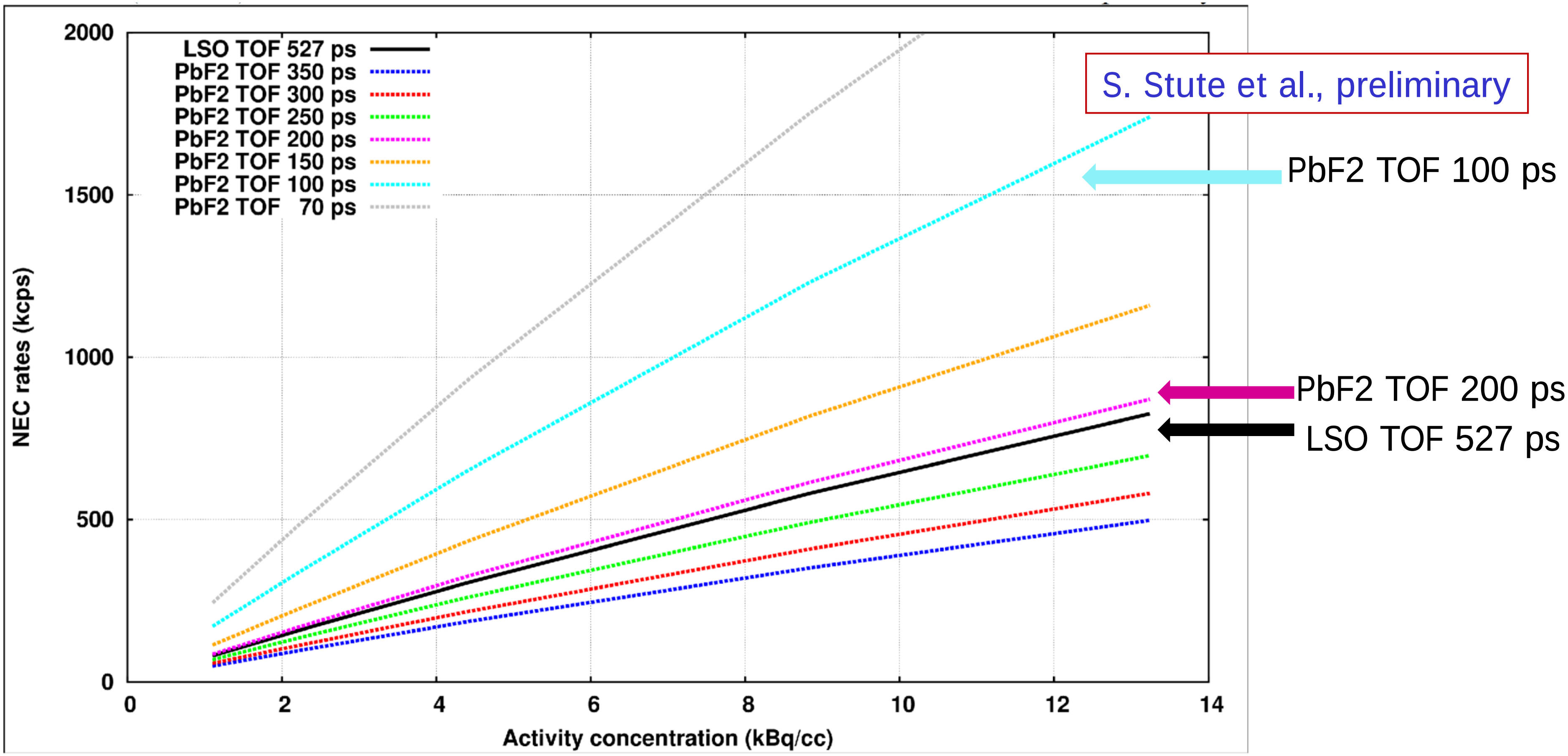


S. Stute et al., preliminary

Axial sensitivity profiles following the NEMA standards, for the two scanners and at radial offsets of 0 and 10 cm; global sensitivity (all slices combined).

Cherenkov based PET scanner, MC study

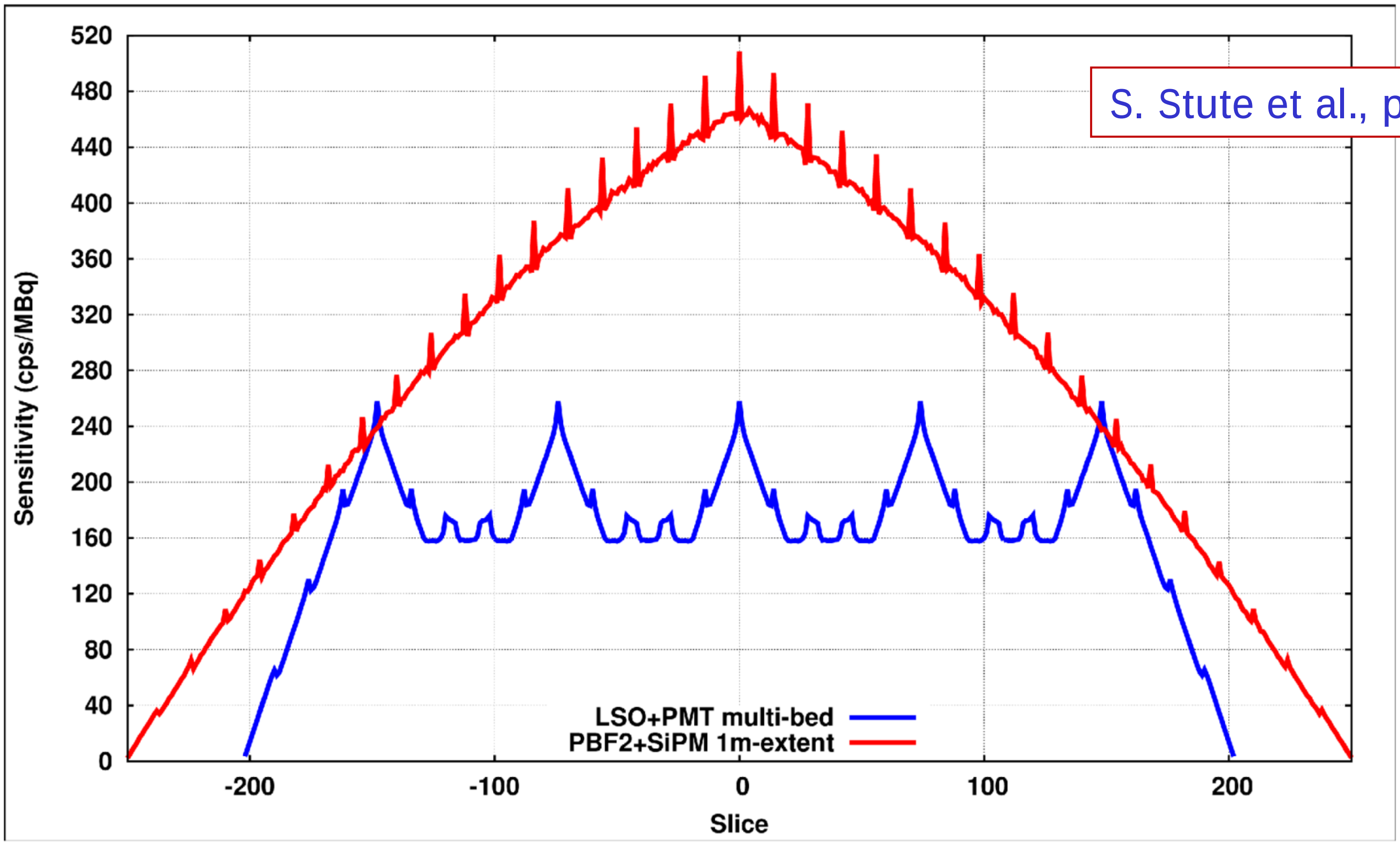
NEC (noise equivalent counts) rates – figure of merit of a PET scanner: Impact of improved TOF using the Cherenkov in PbF2 for a standard scanner.



NEC rates for different activities and for the two scanners, following the Conti formula (with-TOF). Multiple TOF resolution are presented for the PbF_2-based scanner.

Cherenkov based PET scanner, MC study

Comparison of the 1-meter axial sensitivities for the two technologies – note that this is only the theoretical sensitivity without taking TOF into account.



Axial sensitivity profiles following the NEMA standards at the center of the FOV, for the 1meter axial extent PbF_2-based scanner and for a multi-bed LSO-based scanner.

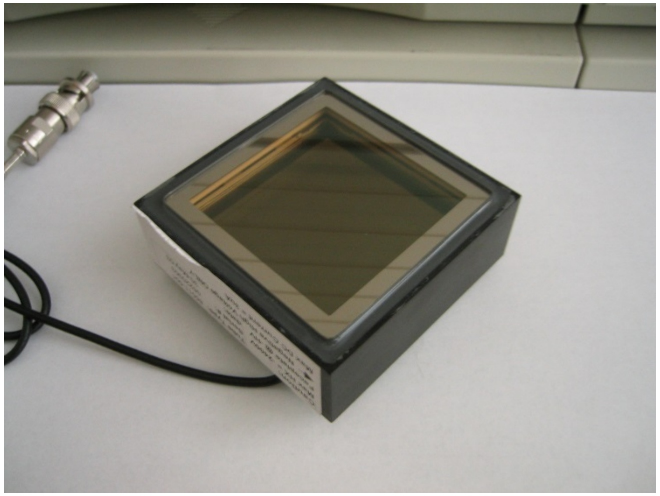
Cherenkov based PET scanner, MC study

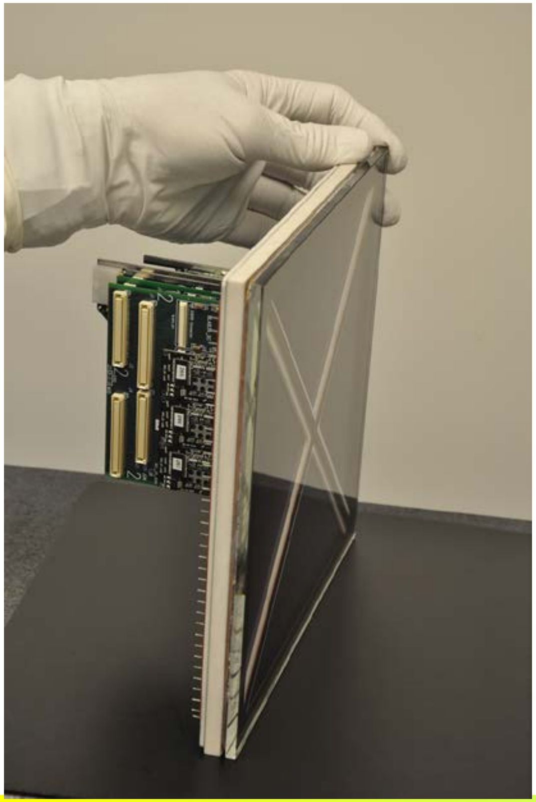
First preliminary Monte Carlo simulation studies have shown that a Cherenkov-PET scanner using Lead fluoride with the same size of detector elements and the same ring geometry as a state-of-the-art LSO based PET scanner will have

- 20% improved spatial resolution, as is now achieved using one-to-one coupling.
- Sensitivity will be about one half, but noise equivalent count rate can be expected to be as good as or better than the standard PET scanner, if TOF resolution is 200 ps or better.

Large system: use larger area MCP PMTs?

Hamamatsu SL10 1“
→Photonis Planacon 5cm x 5cm
→LAPPD 20cm x 20cm





The main problem of a MCP PMT in a Cherenkov based annihilation gamma detector: low quantum efficiency of a typical photocathode in a PMT

→ Detection efficiency: a few %

SiPM for Cherenkov TOF PET?

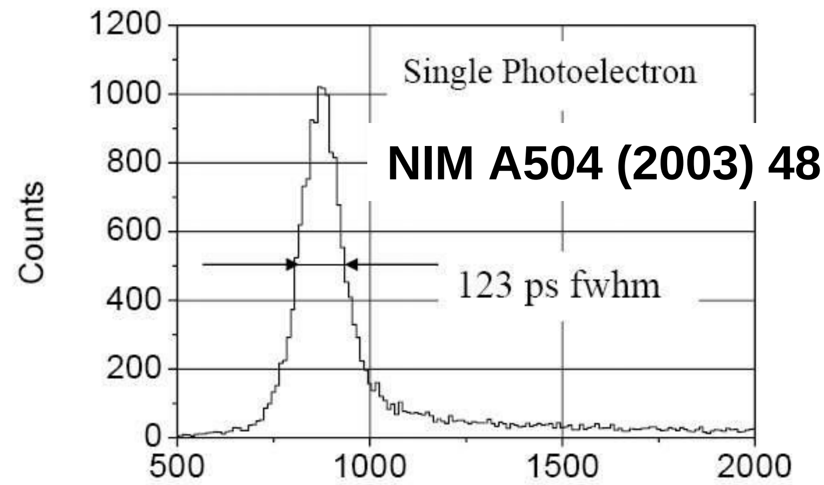
Advantages:

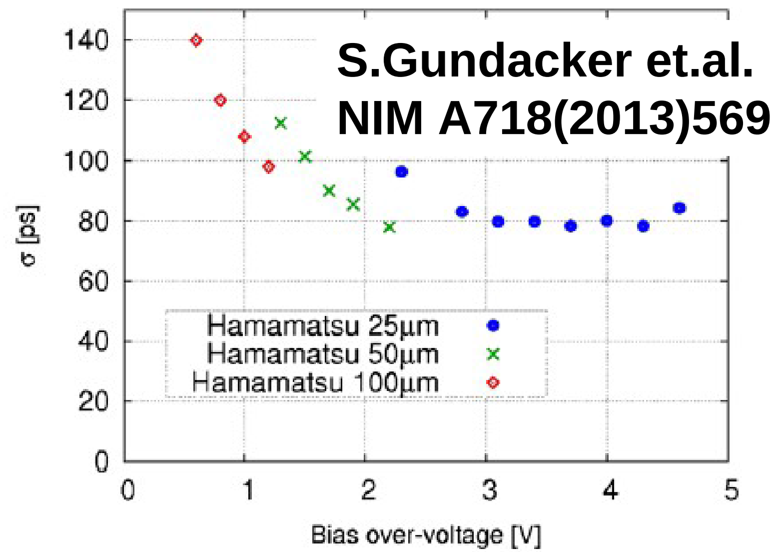
- high PDE – more than 50%
- flexible granularity
- low operation voltage
- operation in magnetic field
- affordable price (potentially)

Disadvantages:

- high dark count rate (DCR) ~ 100kHz/mm^2 (cooling?)
- single photon timing

resolution not yet below 100 psFWHM (specially for large area devices)?





→ Explore new devices and test them

→ A joint project of Nagoya (Iijima, Kobayashi) and Ljubljana (Korpar, Pestotnik, Dolenec, Križan)

SiPM – Geiger mode APD

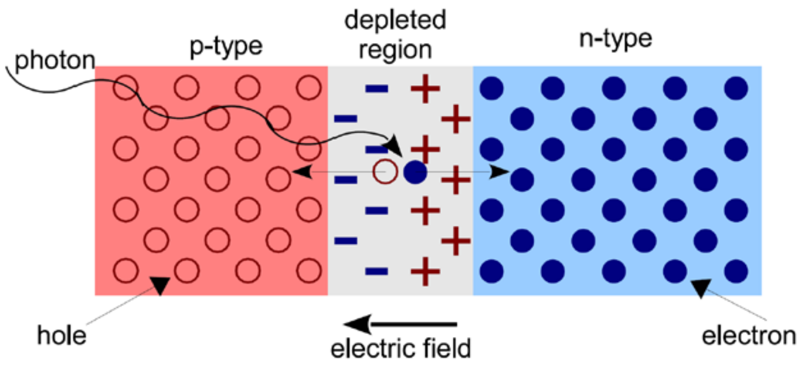
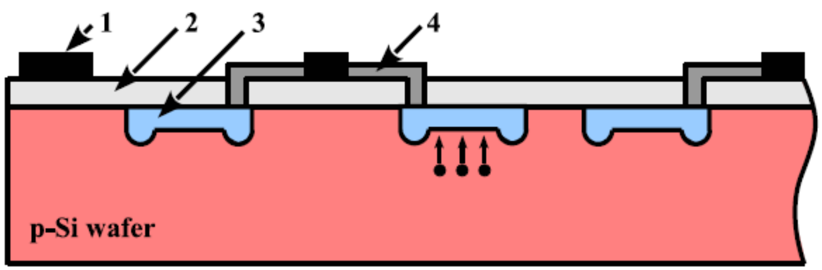


Photo-diode: (visual) photon is absorbed in the depleted region, produces an electron-hole pair.

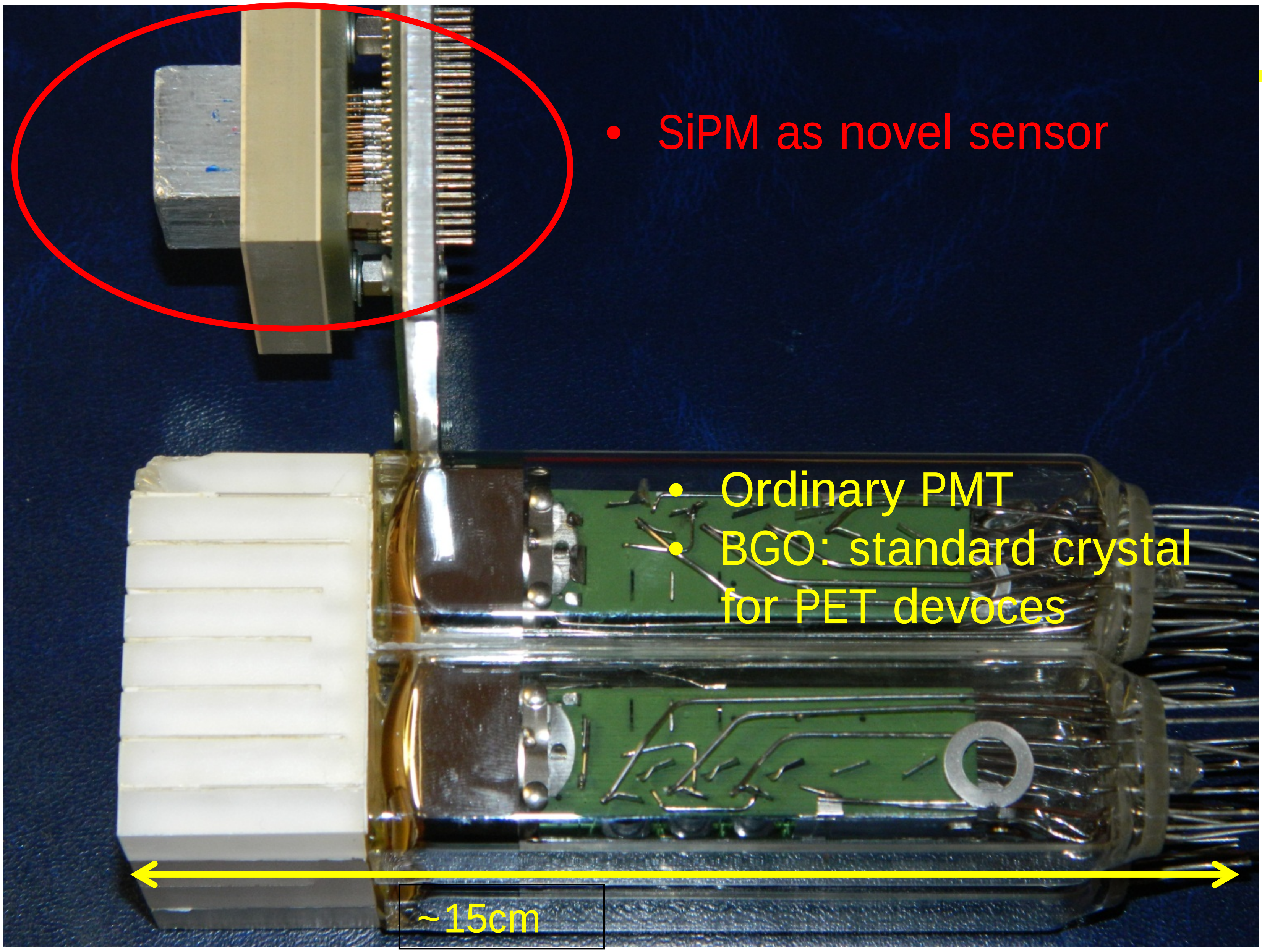
→ Many pairs needed to result in a detectable signal → cannot detect single photons



Geiger mode avalanche photo-diode (APD): with an appropriate doping profile, high electic field is created → e or h multiplication (avalanche)

→ Large signal (10^6 e)

Known also as SiPM.


• SiPM as novel sensor
• Ordinary PMT
• BGO: standard crystal for PET devoces
~15cm

SiPMs in a back-to-back configuration

Cherenkov radiator (PbF_2):

- 5 x 5 x 15 mm^3 (SiPM),

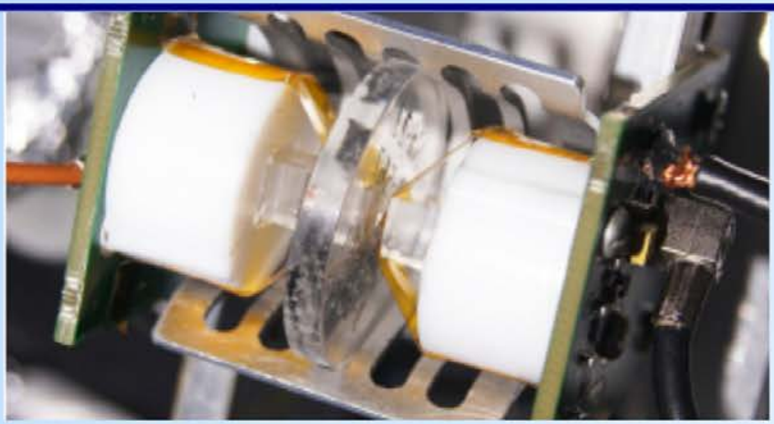
black painted, Teflon wrapped, bare

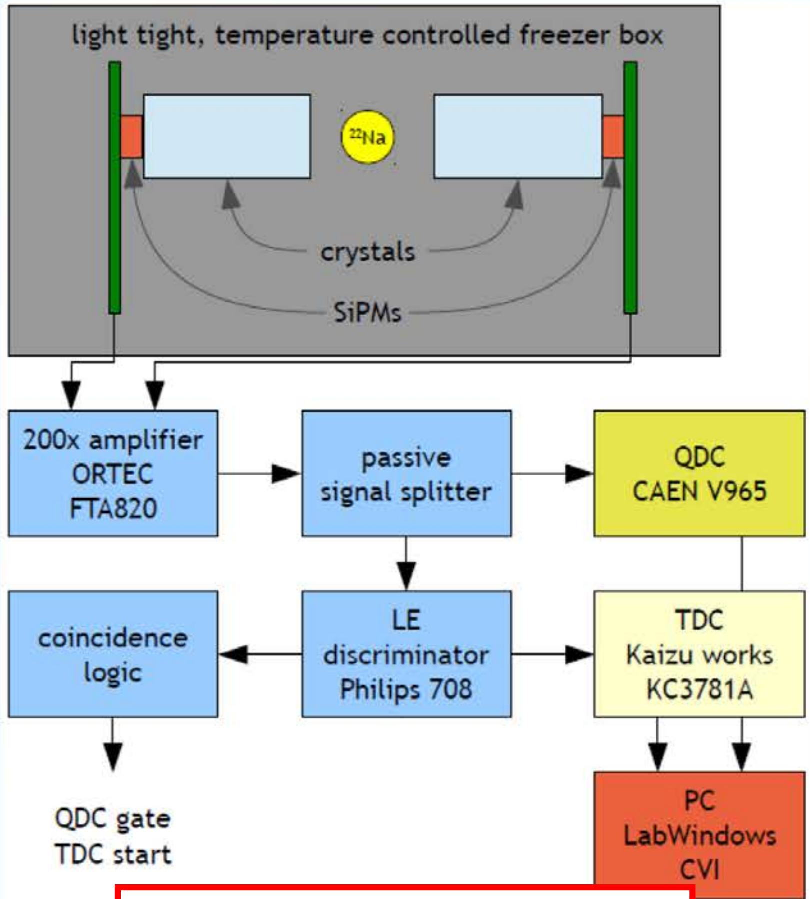
Readout: (timing ~25 ps FWHM)

- custom board with NEC μPC2710TB amp.
- amplifier: ORTEC FTA820
- discriminator: Philips sc. 708 LE
- TDC: Kaizu works KC3781A (25ps)
- QDC: CAEN V965

3x3 mm^2 SiPMs:

Producer	Model	Pixel pitch [μm]	Vbr [V]
Hamamatsu	S10931-050P, 'old'	50	69
Hamamatsu	S12641-PA050, 'new'	50	65
AdvanSiD	ASD-NUV3S-P-40	40	26
KETEK	PM3375TS-SBO, 'old'	75	25
SensL	MicroFC-30050-SMT-GP	50	25



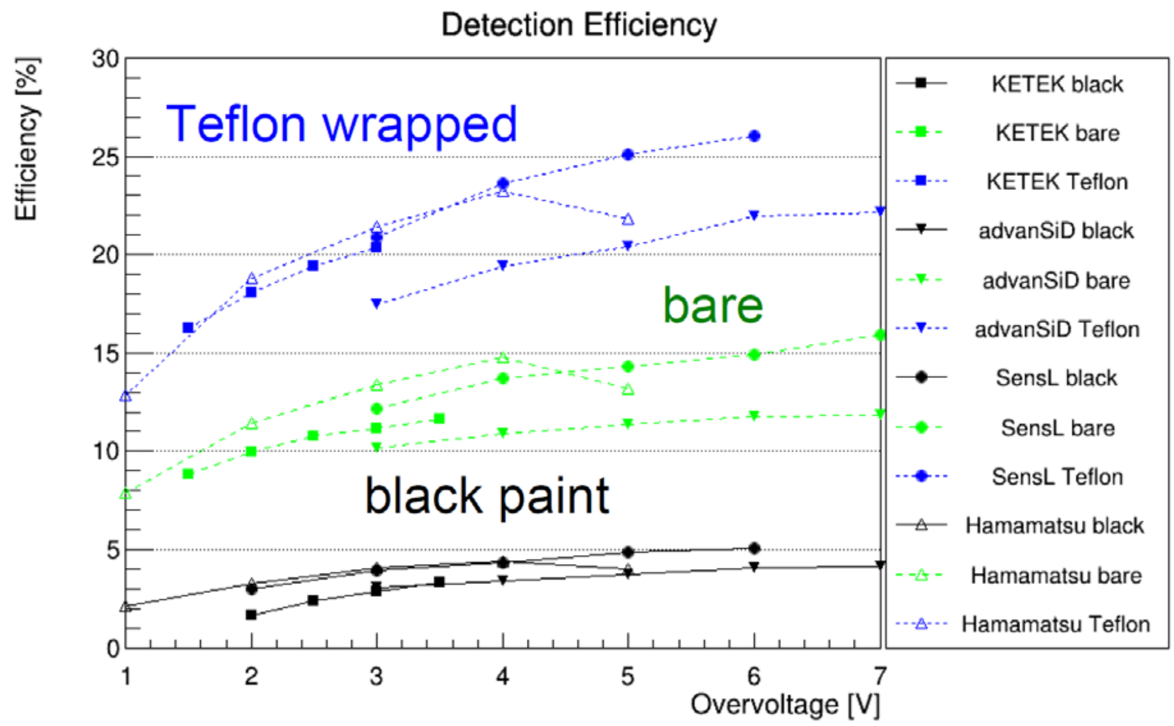


NIMA 804 (2015) 127

Single side detection efficiency

- best efficiency: 26% with SensL SiPM and Teflon wrapped crystals
- T = -25°C

(5x5mm² crystal on 3x3mm² SiPM)



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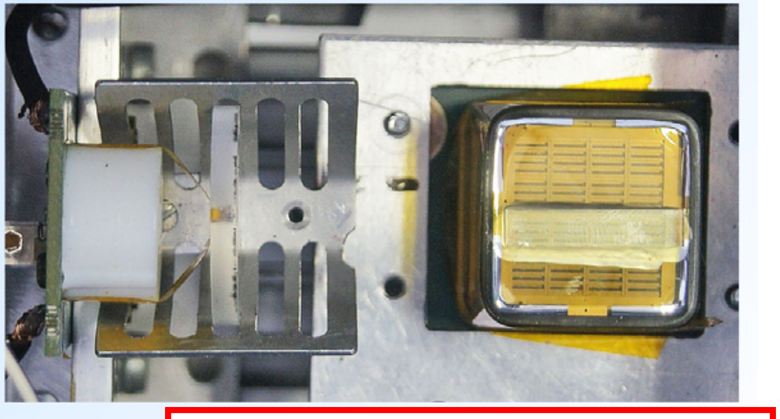
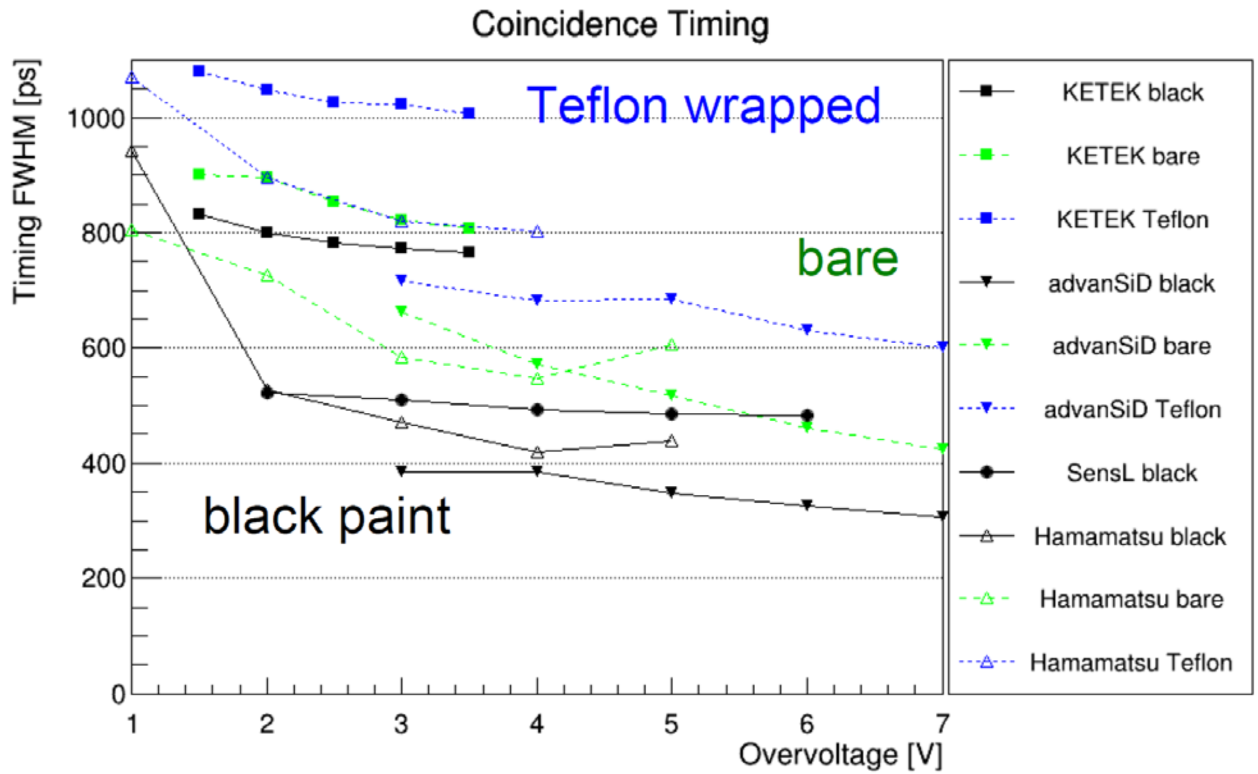


S. Korpar, IEEE/NSS 2015

Coincidence time resolution

- best timing: 309 ps with AdvanSiD
- T = -25°C

(5x5mm² crystal on 3x3mm² SiPM)



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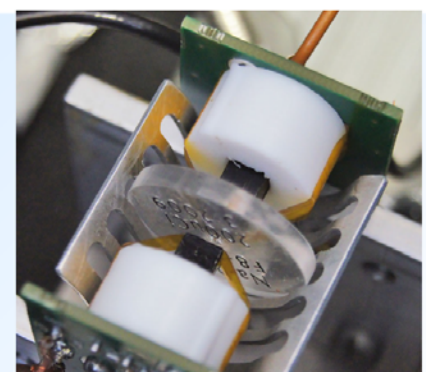


S. Korpar, IEEE/NSS 2015

Coincidence timing, continued

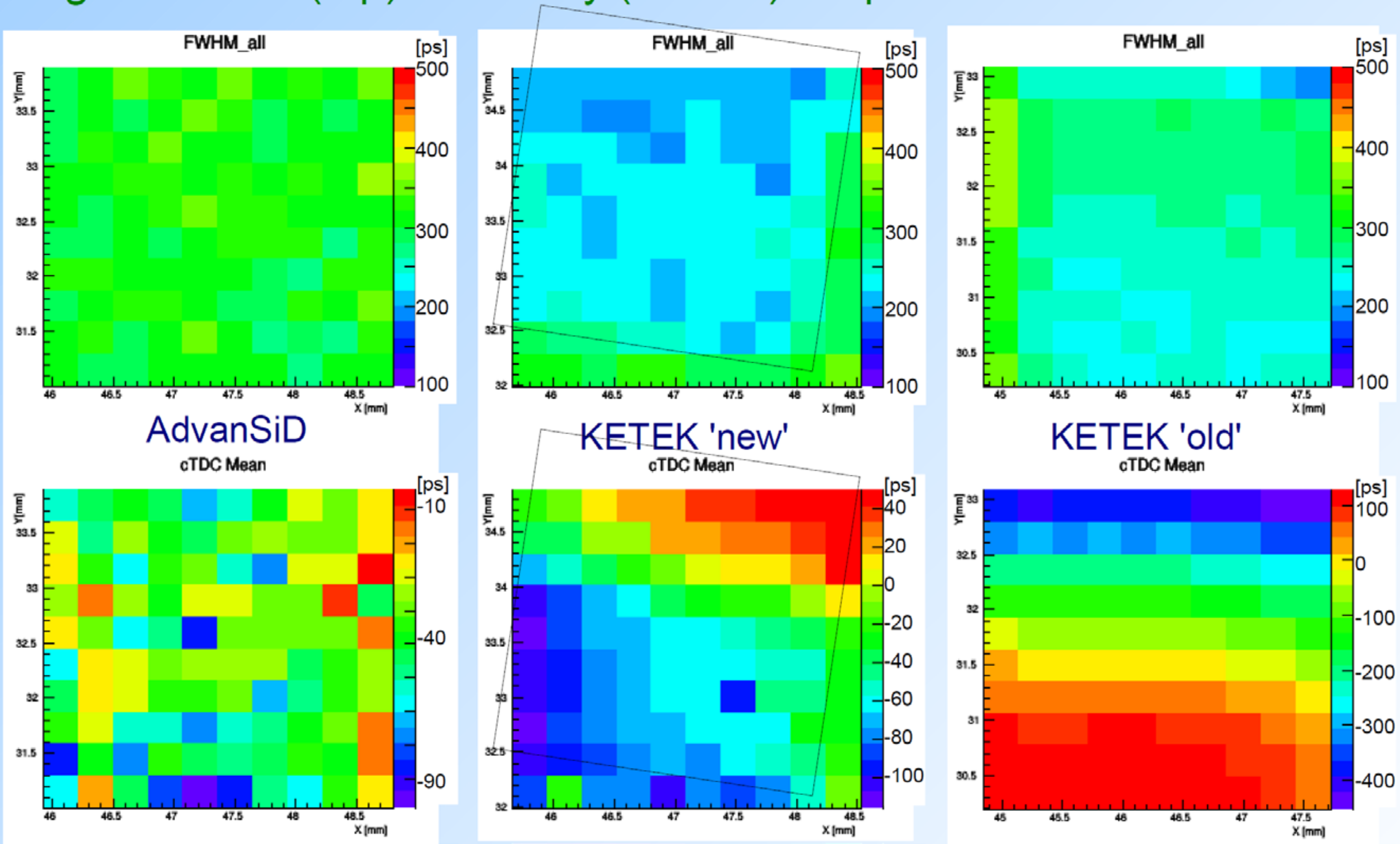
What is behind the best value of FWHM=300ps?

= Can we improve?

→ Perform picosecond laser scans

Timing resolution and delay vs position

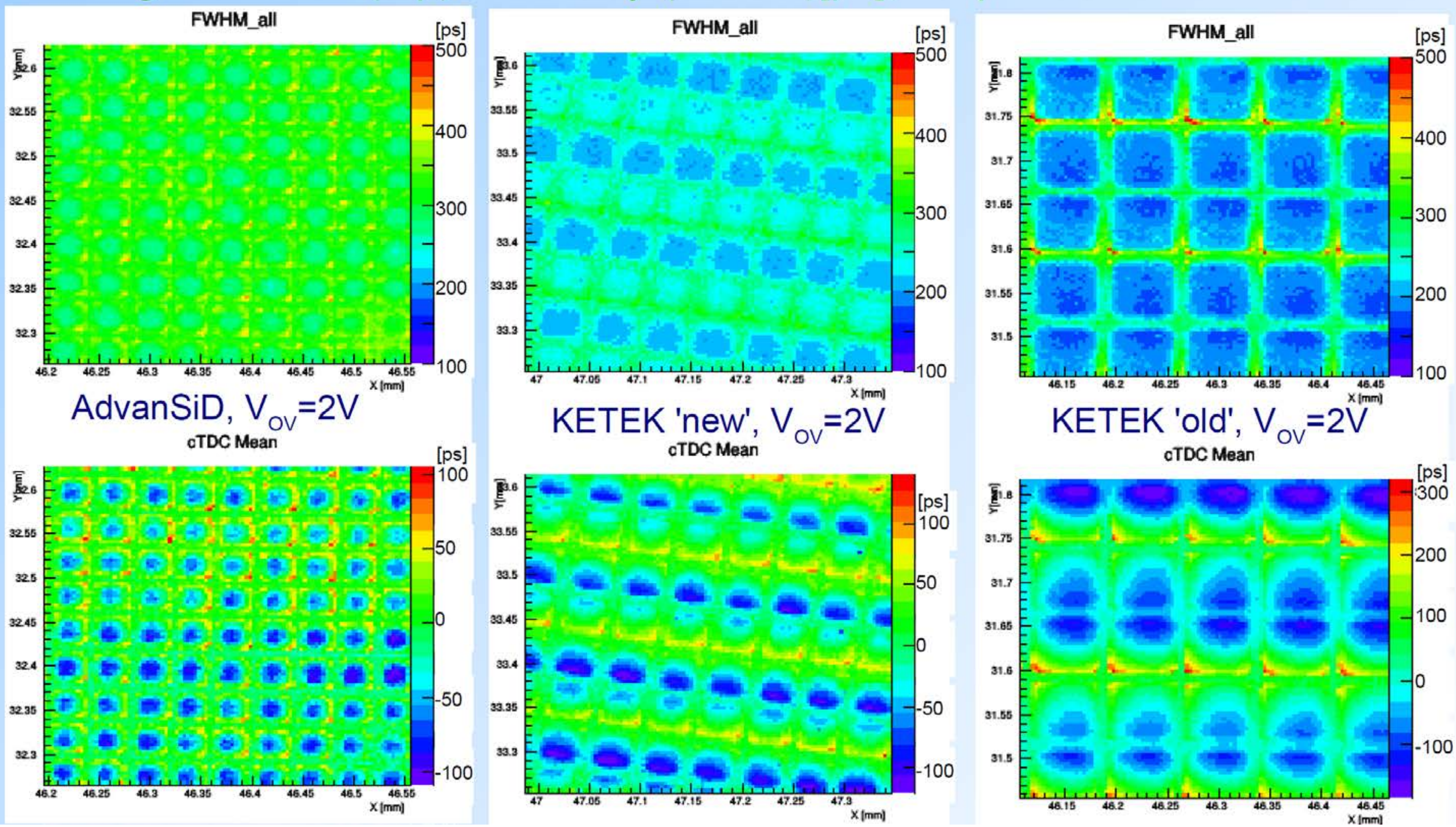
- Defocused red laser (σ ~ 300μm), T=25°C, ~ 3 x 3 mm^2
- Higher dark count rates and lover V_{OV}
- Timing resolution (top) and delay (bottom) vs. position



S. Korpar, IEEE/NSS 2015

SiPM timing with a fine laser scan

- Focused red laser (σ ~ 3μm), T=25^{o}C, area ~250 x 250 μm^2
- Higher dark count rates and lover V_{OV}
- Timing resolution (top) and delay (bottom)[ps], vs. position



Cherenkov based TOF PET - summary

- main advantage prompt emission
- main disadvantage low number of photons
- requires very fast single photon sensor with high PDE.

- We have studied several SiPMs from different producers to find the best candidate for the application → the best value for the efficiency reached 26% and the best CRT was ~300 ps (will improve with SiPM and crystal size matching).
- Performance of SiPMs is constantly improving and hopefully it will reach optimal performance → coincidence efficiency > 10% and timing < 200 ps FWHM

Summary

Interplay of detector R&D for particle physics and medical imaging has a long history, and this will remain one of the sources of innovation in medical imaging

Cherenkov radiation based annihilation gamma detectors offer a promising method for very fast detection and potentially cheaper devices

Full body PET: very promising new medical imaging method, lower dose than multiple scans

Example of the excellent collaboration between Nagoya and Ljubljana

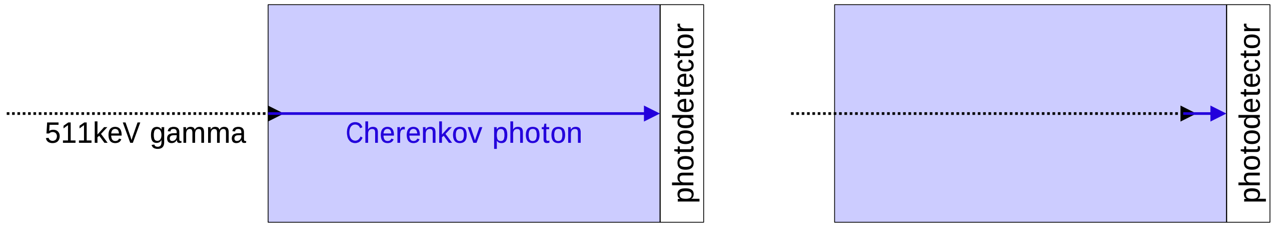
Back-up slides

Limitations of Cherenkov photon timing

Cherenkov photons are produced promptly, but still need to reach the photodetector

Gamma rays travel faster than Cherenkov light!

Radiator dimensions, refractive index → intrinsic travel time spread due to different gamma interaction depths



d = 15 mm, n = 1.8: $t = d \cdot n / c_0 = 90$ ps $t = d / c_0 = 50$ ps → $\Delta t = 40$ ps

→ For a 15 mm long crystal the resulting FWHM contribution is ~40 ps

Can in principle be corrected for by

- a multi layer configuration with shorter crystals, or by
- measuring the depth of interaction (DOI)

N.B. This applies to all very fast light emission mechanisms.

DOI in Cherenkov based γ detectors

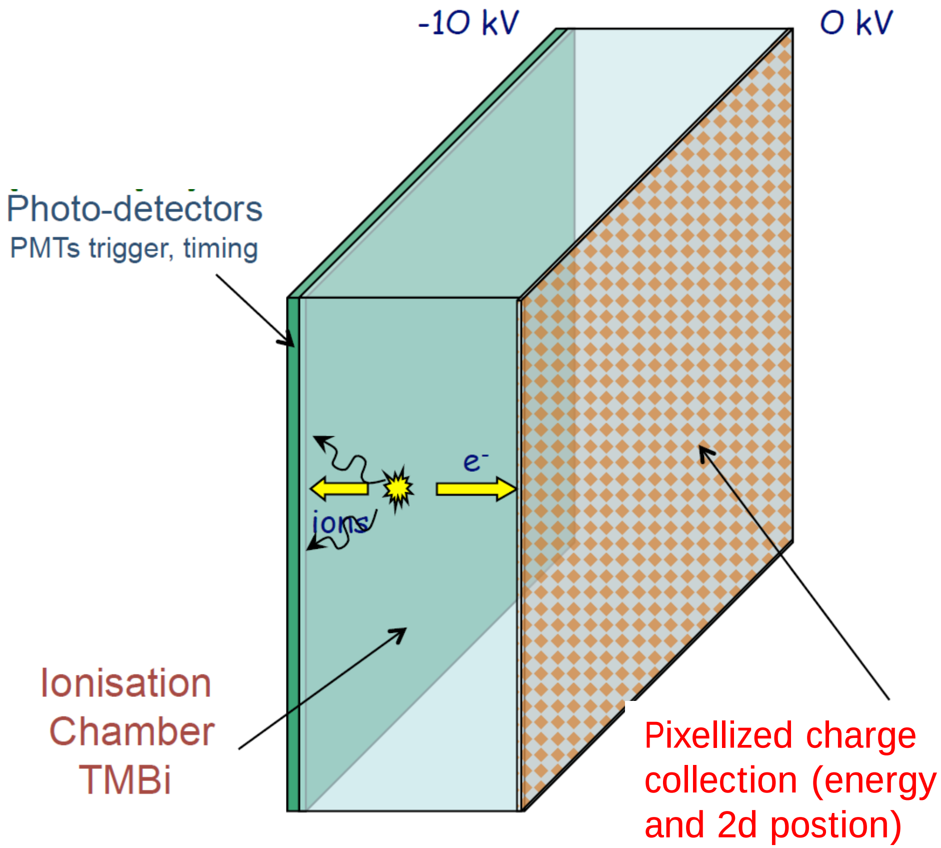
By measuring DOI we would

- Improve the timing
- Further mitigate the paralax error

A very interesting novel concept: CaLIPSO (D. Yvon et al., CEA Saclay)

Use a heavy high Z liquid, TriMethyl Bismuth (TMBi), for gamma conversion and dual mode detection

- Cherenkov light for timing
- Ionisation for energy measurement and 3d gamma interaction point determination (2d pixels for charge collection and drift time)



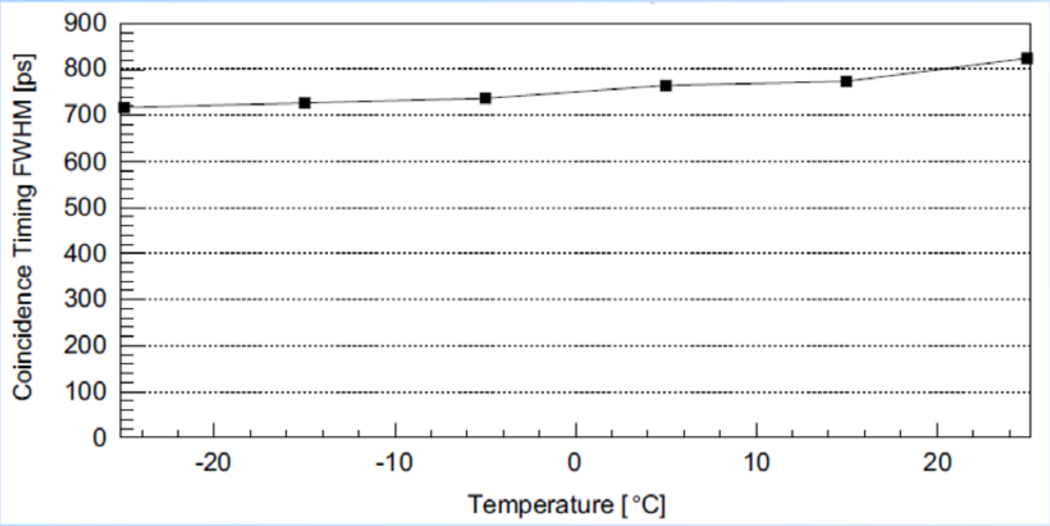
D. Yvon et al., IEEE TNS, 61 (2014) 60.

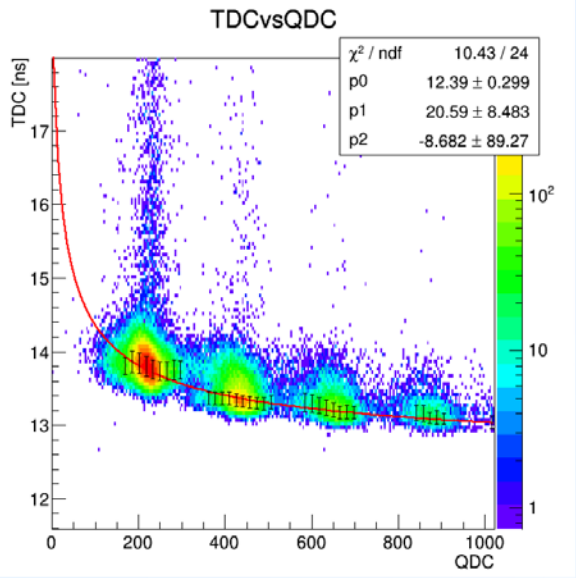
N.B. Again a nice example of HEP → medical imaging

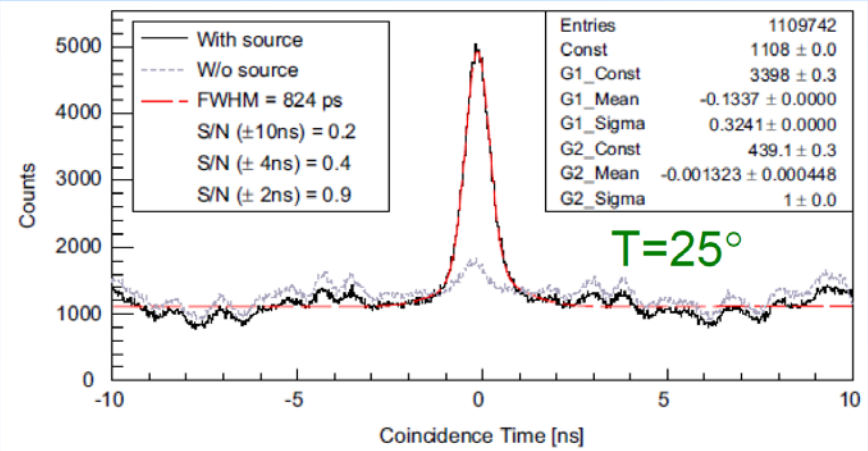
Coincidence time resolution vs temprature

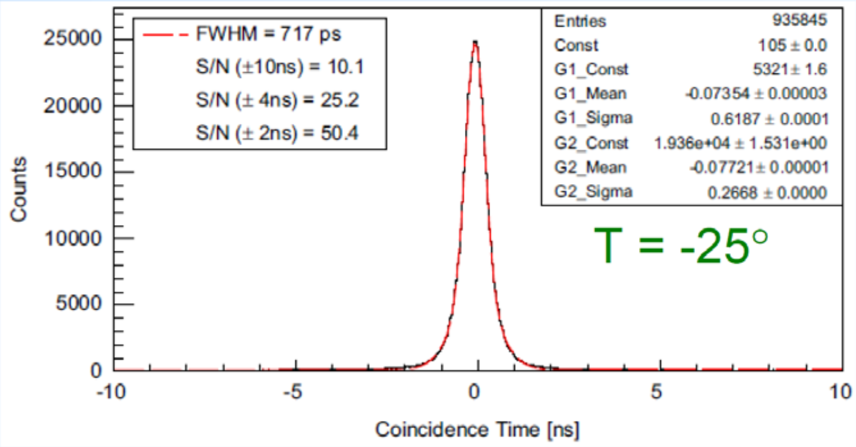
- coincidence time resolution ~ 800 ps FWHM

(Hamamatsu S10931-050P at V_{ov} = 1.5V)





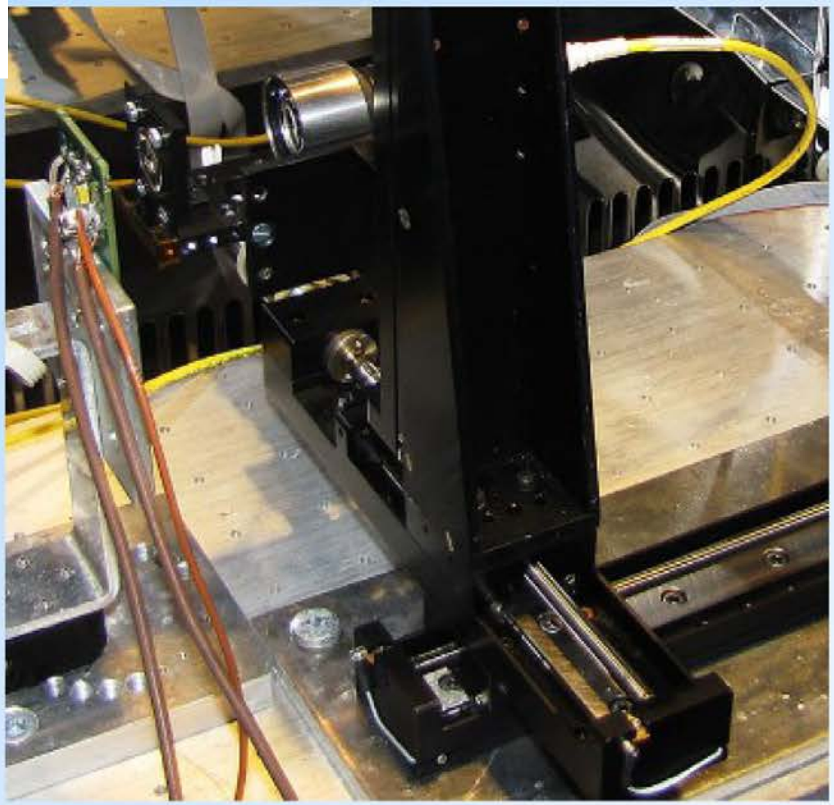




Laser set-up

- PiLas diode laser system EIG1000D, 404nm and 635nm laser heads (ALS)
- ND filters (0.3%, 12.5%, 25%)
- optical fiber (single mode,~4μm core)
- focusing lens (min. spot size $\sigma \sim 3\mu m$)
- laser timing ~35 ps FWHM
- readout system the same as for CRT

- Additional SiPM from KETEK with improved timing (@PhotoDet 2015)



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KETEK	PM3350TP-SBO, 'new'	50	25
SensL	MicroFC-30050-SMT-GP	50	25

CaLIPSO Detector Basics (1)

TriM**ethyl** **Bi**smuth (**TMBi**), $Bi(CH_3)_3$

Bi, Z = 83, highest Z non radioactive element.

Phot. Electric Efficiency 47%

Limpid, dielectric, Chem. Stable.

***Double** Detection*

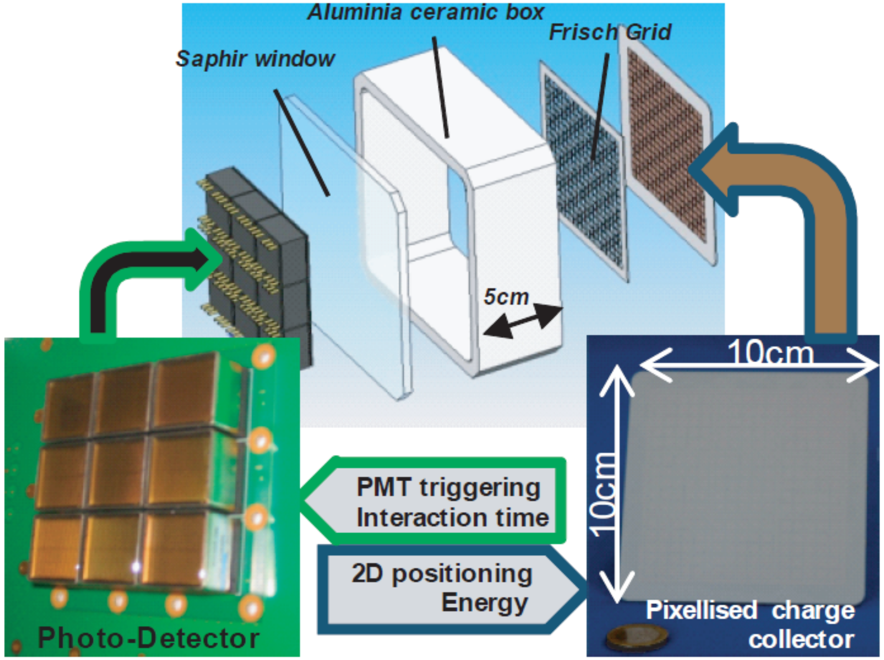
Photo-detectors

Fast! => Trigger, timing.

Ionization chamber

Pixelated detector, Frisch Grid

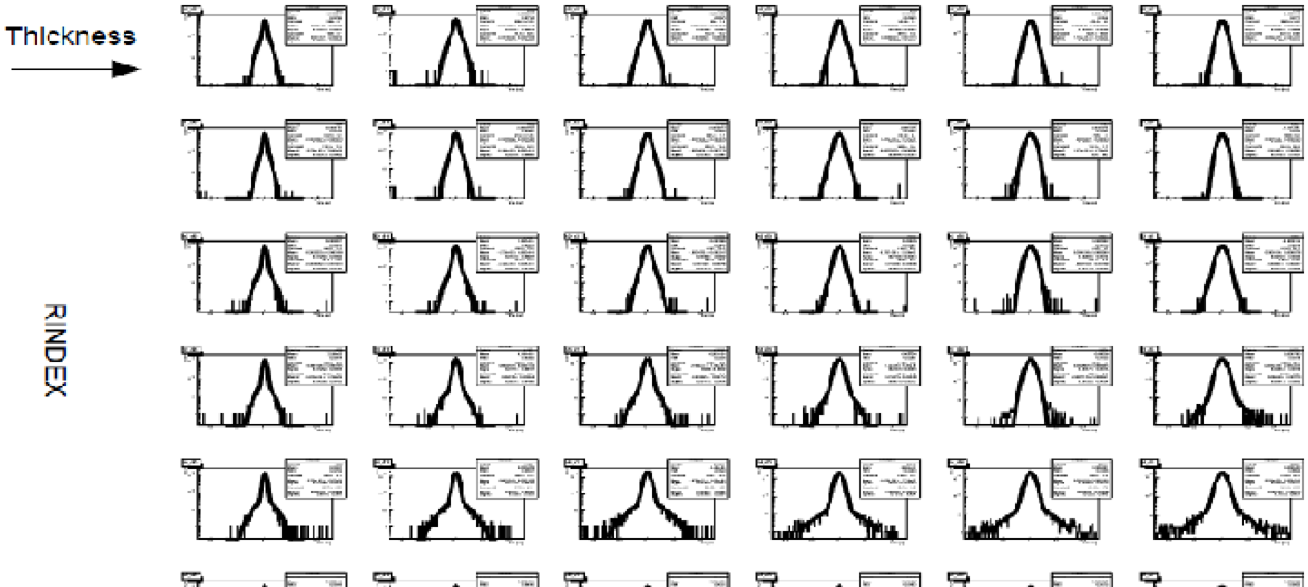
Energy, positioning 2D

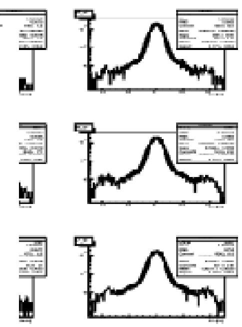


PCT/EP2011/054153

D. Yvon et al., "CaLIPSO: An novel detector concept for PET imaging", IEEE TNS, 61 (2014) 60.

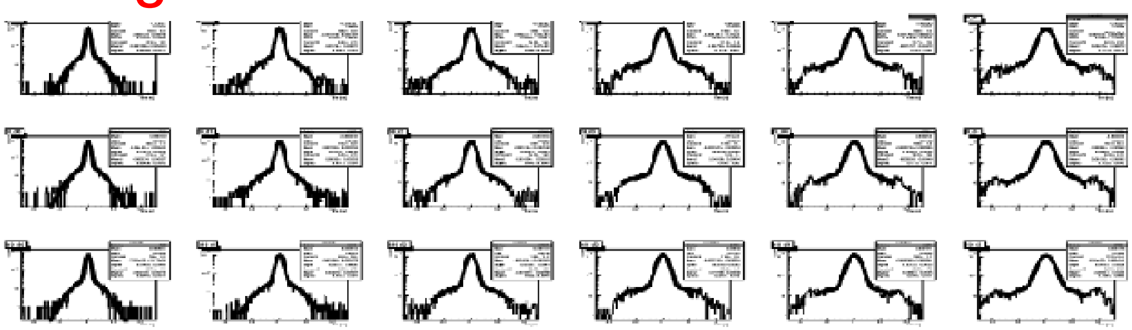
Simulation: search for optimum radiator parameters



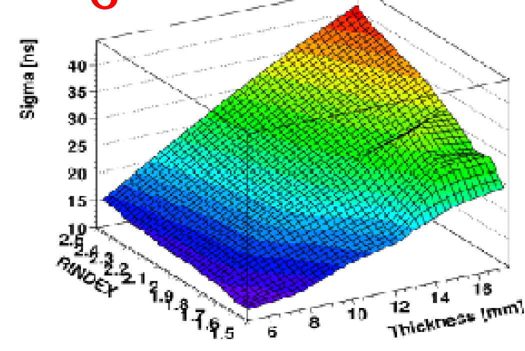


→ Best:

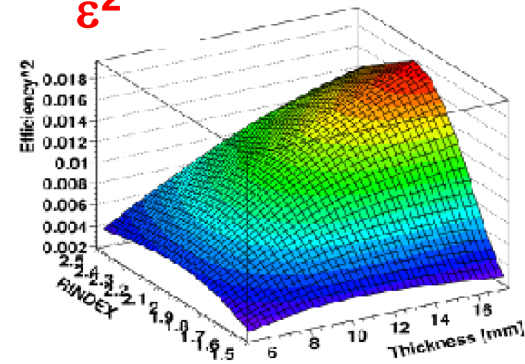
- High Z
- Refractive index n~2
- Length ~ 15 mm



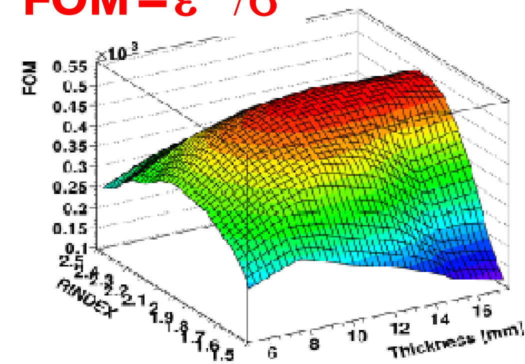
σ



ε^2



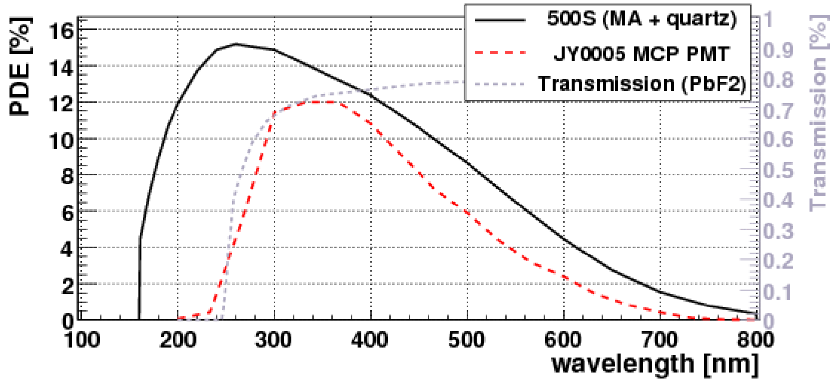
FOM = ε^2 / σ



Efficiency improvements, MC estimates

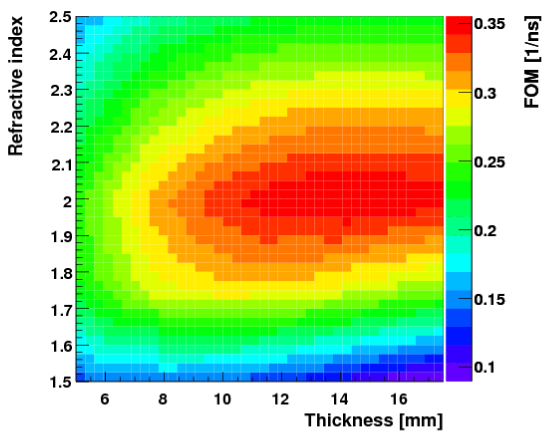
- **Photodetector**:
  - improved photon detection efficiency
    - photocathode with better QE
    - window, transparent to lower λ (quartz → 160 nm)
  - example: Hamamatsu 500S photocathode

  → **1.4x** detection efficiency (2x in FOM=ε^2/σ)



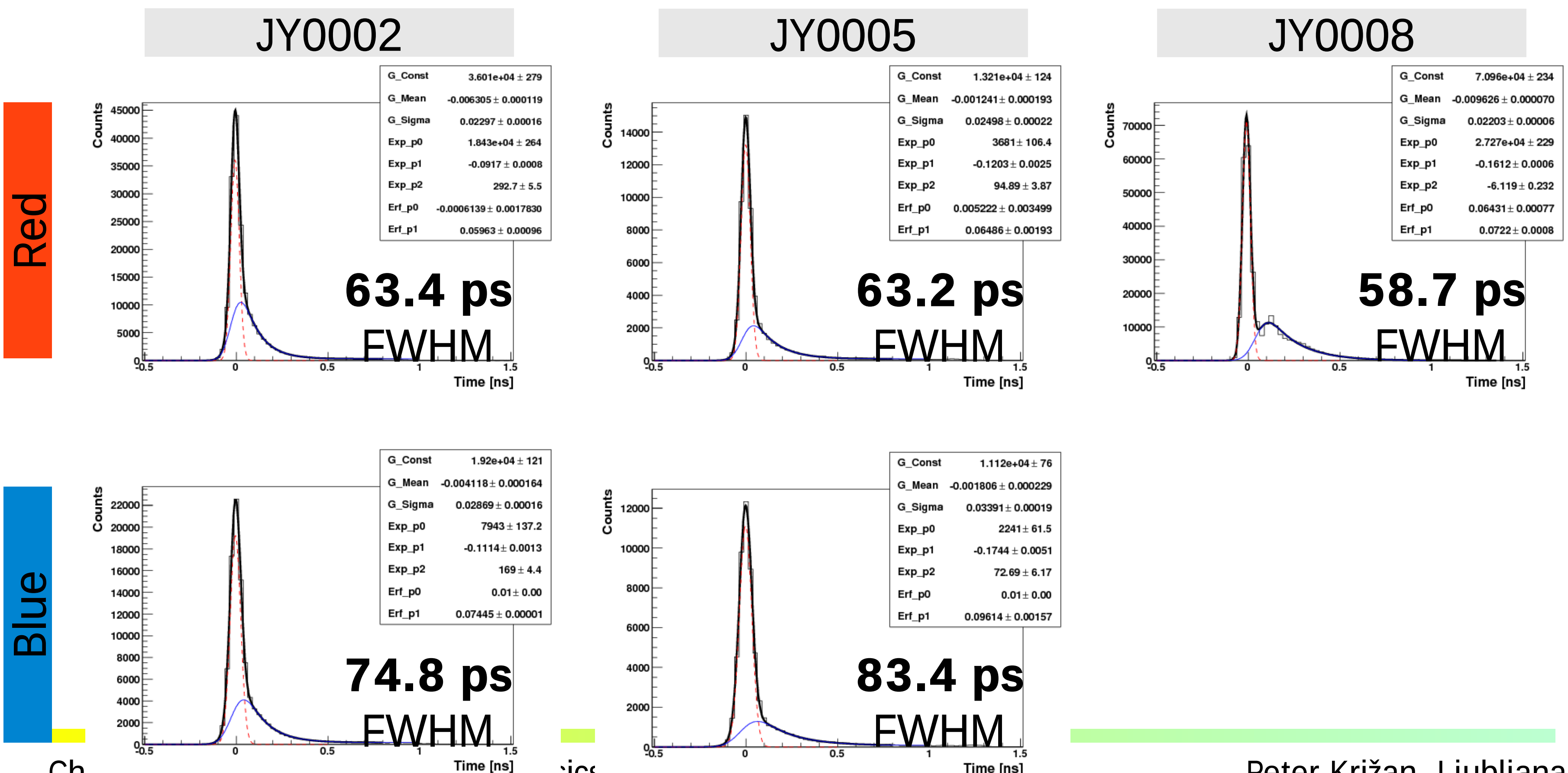
- **Transport of photons** from radiator to photo-detector:
  - optimal optical coupling of the radiator to the photon detector (at present radiator refractive index n=1.8, optical grease n=1.5, PMT window n=1.5) → ~**1.4x** efficiency (2x FOM)

- **Radiator optimization** with a hypothetical, PbF_2-like crystal (using 500S photocathode):
  - With an optimized refractive index, thickness (n=2.0, d~14mm) → **1.5x** efficiency (3x FOM)
  - Improved optical transmission (λ_{cutoff} = 160 nm) → **2.4x** efficiency (6x FOM)



MCP PMT timing

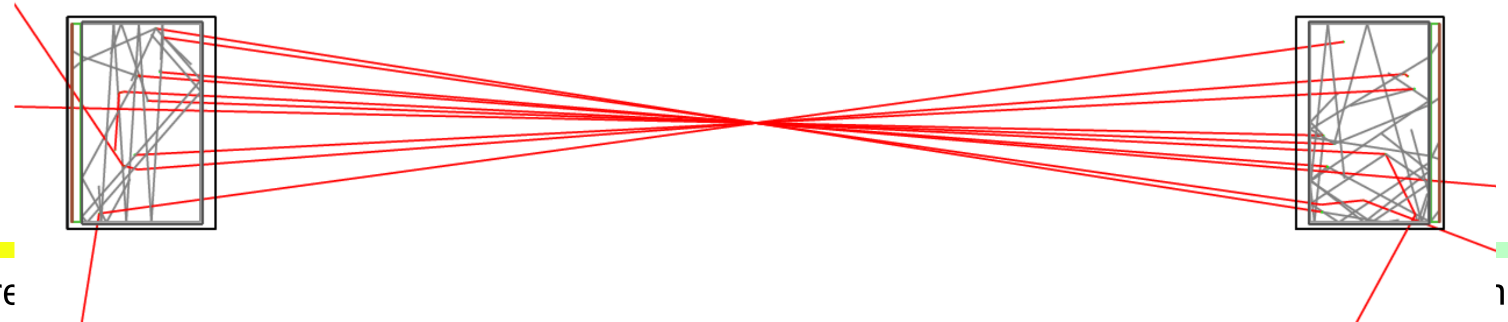
- Surfaces of MCP PMTs illuminated with very weak (single photon level) red (636 nm) and blue (404 nm) laser light pulses
- Time responses of 3 MCP PMT samples (incl. laser and electronics):



Simulation: GEANT4

Interactions in a single crystal and in a full back-to-back setup were simulated in GEANT4, taking into account:

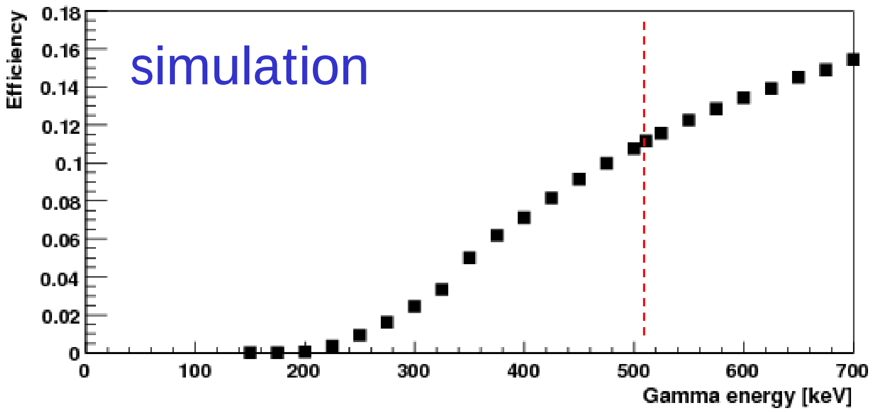
- gamma interactions with detector
- optical photons (Cherenkov and scintillation) produced between 250 nm – 800 nm (no scintillation assumed for PbF2)
- optical photon boundary processes (exit surface polished, other surfaces polished and wrapped in white reflector or black painted)
- photo-detector window coupled with optical grease (n=1.5)
- photo-detector QE (peak 24% @ 400nm)
- photo-detector intrinsic timing modeled according to the measured response function



Intrinsic suppression of scattered events

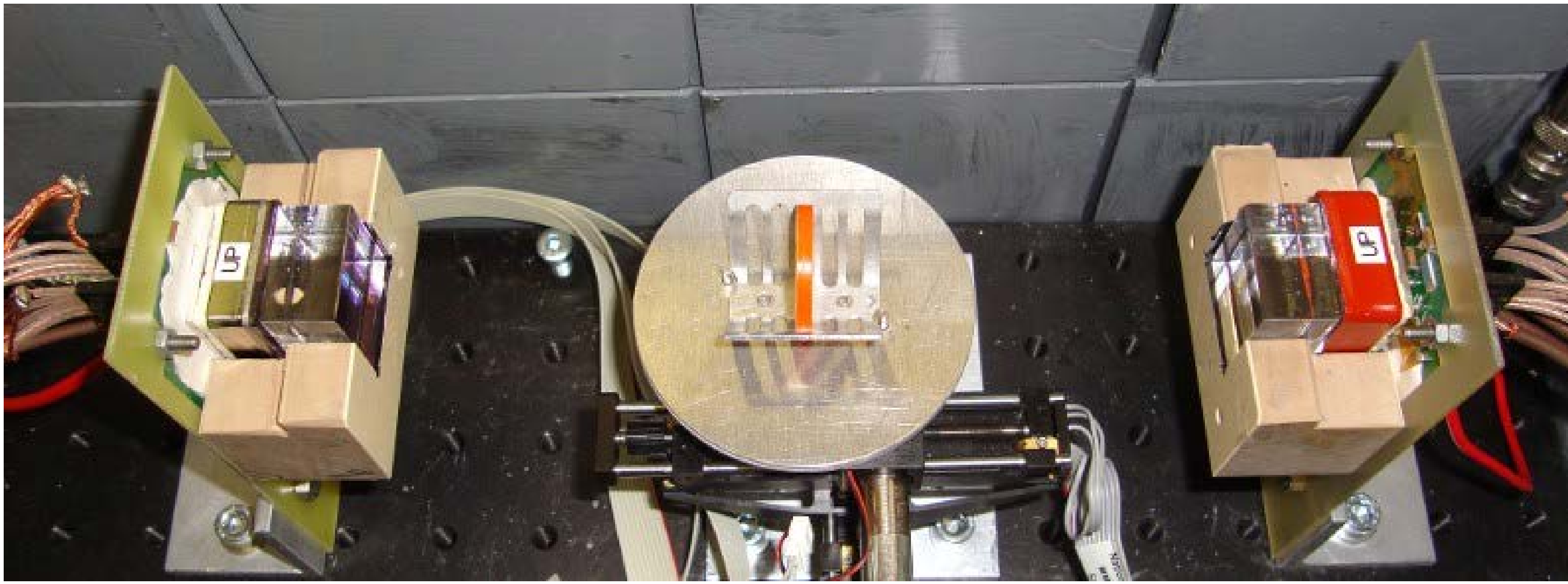
Annihilation gammas scatter in patient or detector → unwanted background when scattered gamma is detected in coincidence

- Traditional PET
  - number of scintillation photons proportional to energy deposited
  - measurement of gamma energy → rejection of scattered (lower energy) events
- Cherenkov PET
  - at most a few photons detected → no energy information available
  - but: detection efficiency drops with gamma energy → intrinsic suppression

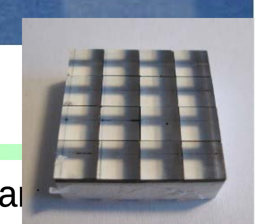


Experimental setup

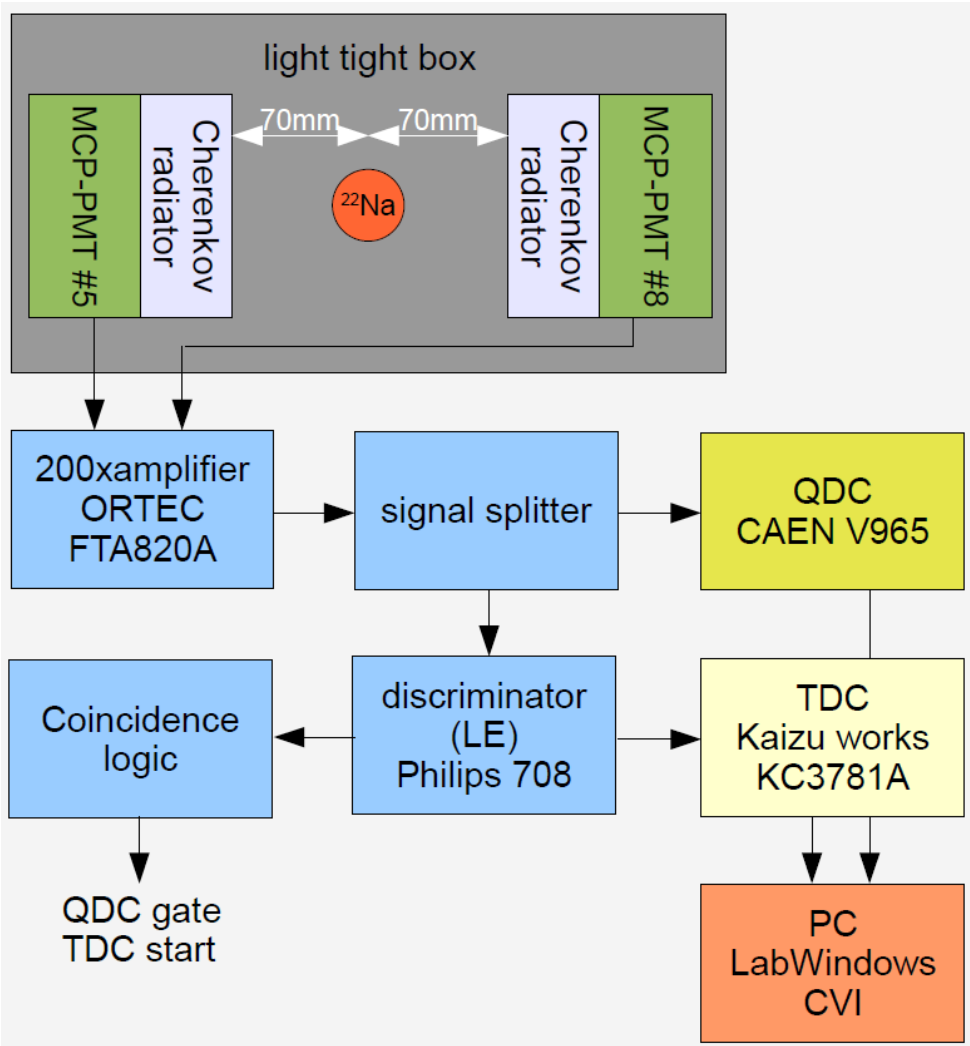
Two detectors in a back-to-back configuration with 25x25x15 mm^3 crystals coupled to MCP-PMT with optical grease.



Cherenkov radiators:
-monolithic: 25 x 25 x 5,15 mm^3 (PbF_2, $PbWO_4$)
-4x4 segmented: 22.5x22.5x7.5 mm^3 (PbF_2)
-black painted, Teflon wrapped, bare



Experimental setup: read-out

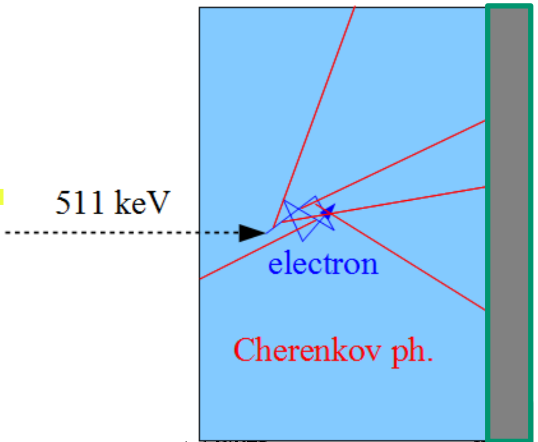


Readout:
- amplifier: ORTEC FTA820
- discriminator: Philips sc. 708LE
- TDC: Kaizu works KC3781A
- QDC: CAEN V965

- Time-walk correction applied in the analysis step

Experimental results: Back-to-back time resolution

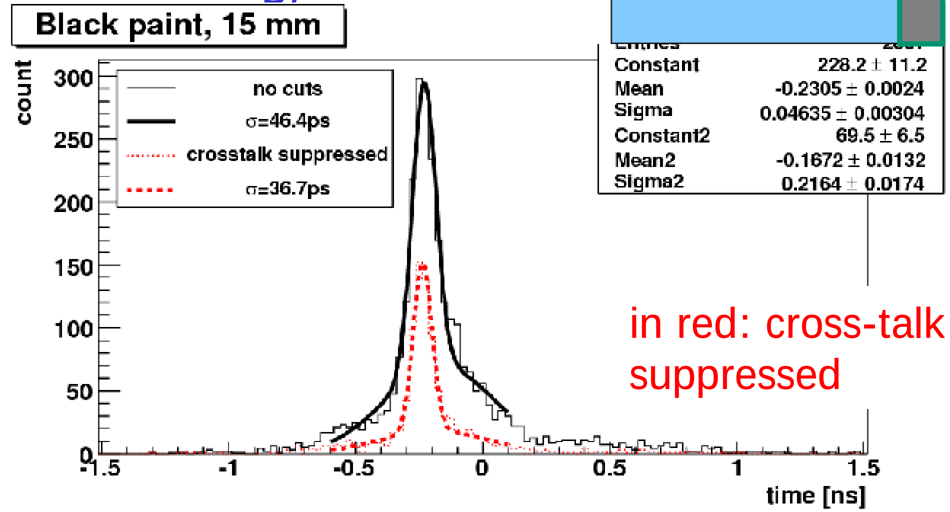
Best timing resolution: black painted PbF_2 crystals (Cherenkov light hitting the walls is absorbed - delayed Cherenkov photons suppressed → improved timing, reduced efficiency)



Data taken with :

- 15 mm long crystal:

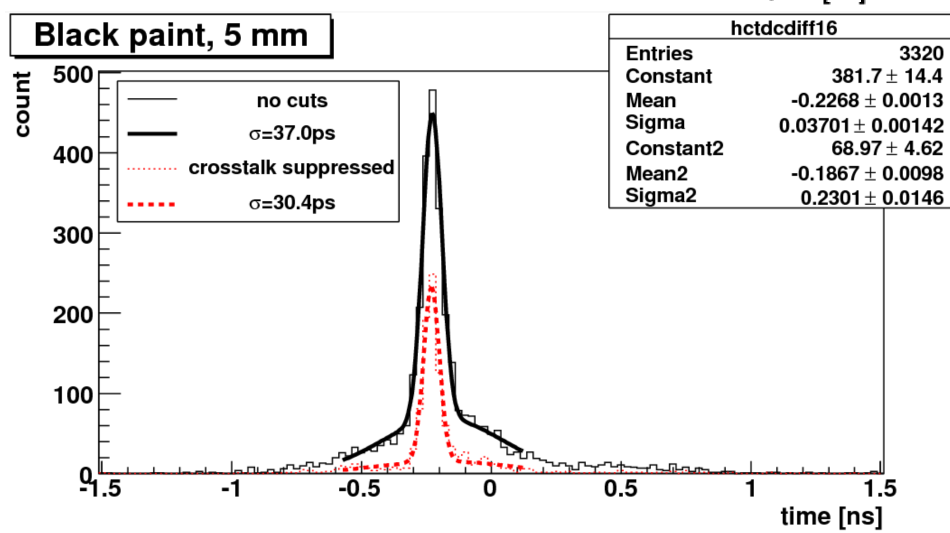
→ FWHM ~ 95 ps



in red: cross-talk suppressed

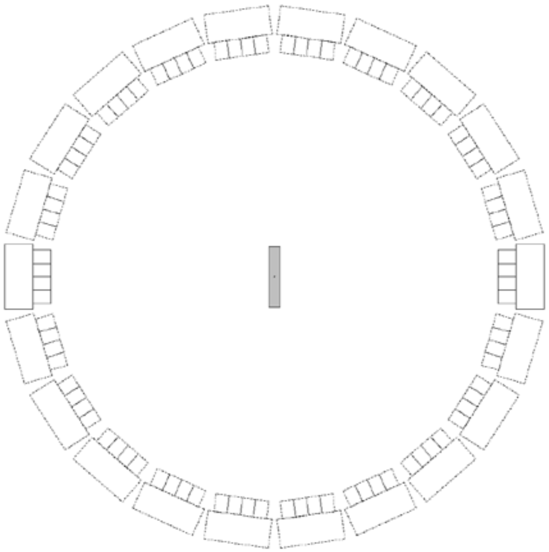
- 5 mm long crystal:

→ FWHM ~ 70 ps



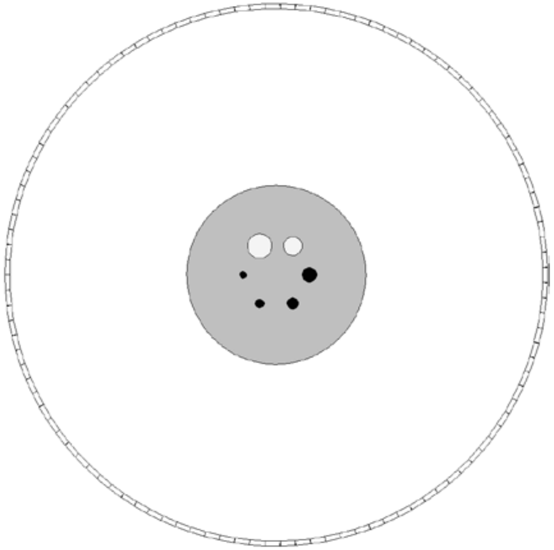
→ NIM A654(2011)532–538

Reconstruction



Cherenkov PET tested experimentally

- data equivalent to one PET ring obtained with only two detectors
- source rotated in discrete steps
- data collected at each step for the same amount of time
- D = 185 mm, H = 22.5 mm



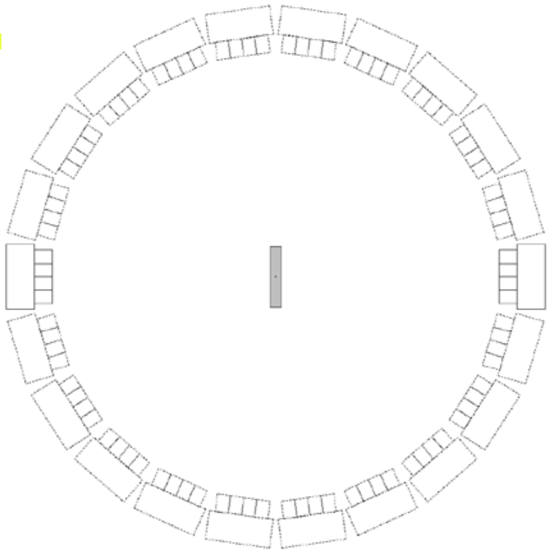
Full body PET scanner simulated

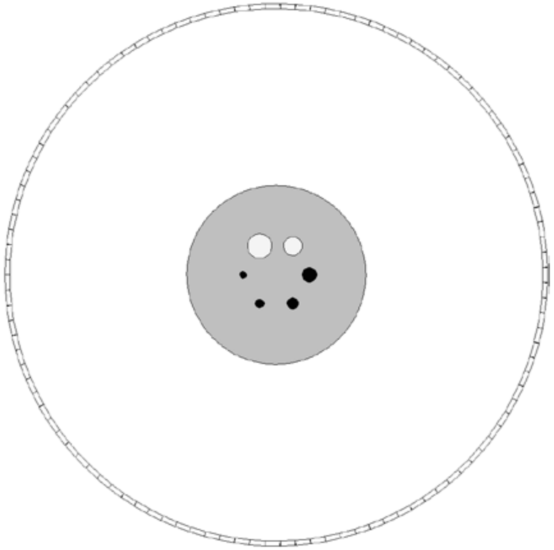
- D = 800 mm, 15 rings (H = 340 mm)
- phantom with d = 270 mm, 4 hot spheres (d: 10 - 22 mm) and 2 cold spheres (d = 28, 37mm)

Reconstruction

Reconstruction algorithms:

- **Filtered backprojection (FBP):** basic non-TOF algorithm
- **TOF weighted FBP:** pixels along LOR incremented with TOF response defined weight
- **Most likely position (MLP):** point of decay on LOR calculated from TOF information
- **Filtered MLP:** MLP image deconvoluted for TOF response

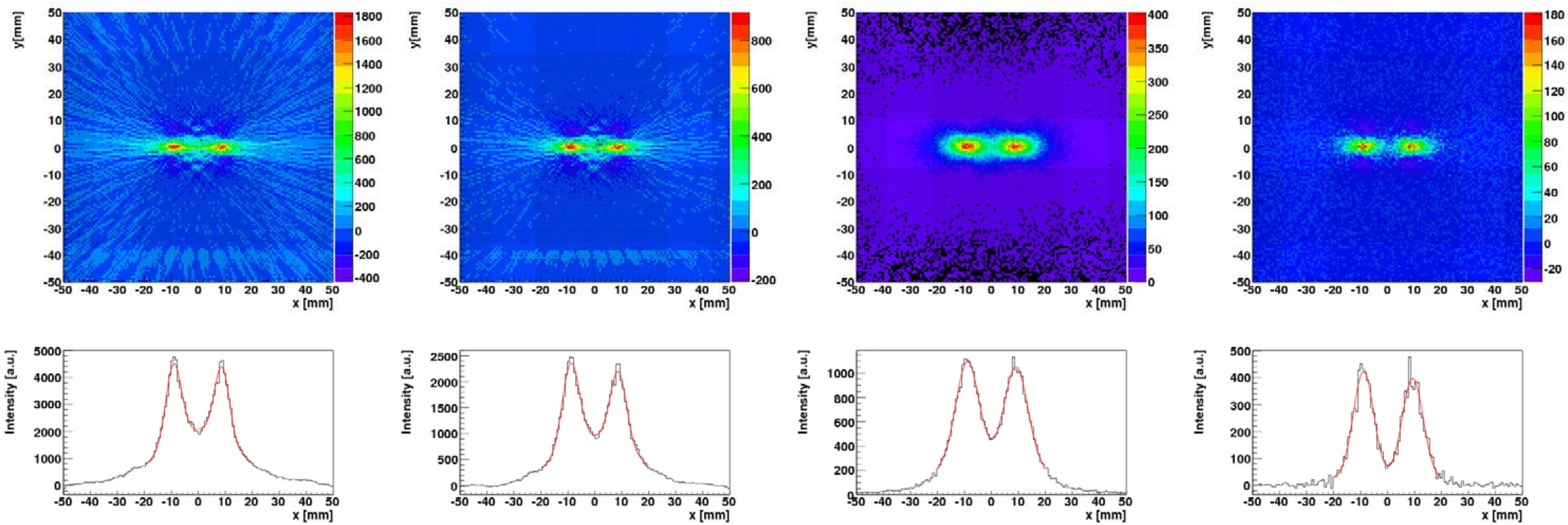




Reconstruction - experiment

- ^{22}Na point sources at +10 mm and -10 mm
- 4x4 segmented, black painted PbF_2 radiators

(non-TOF) FBP | TOF w. FBP | MLP | Filtered MLP

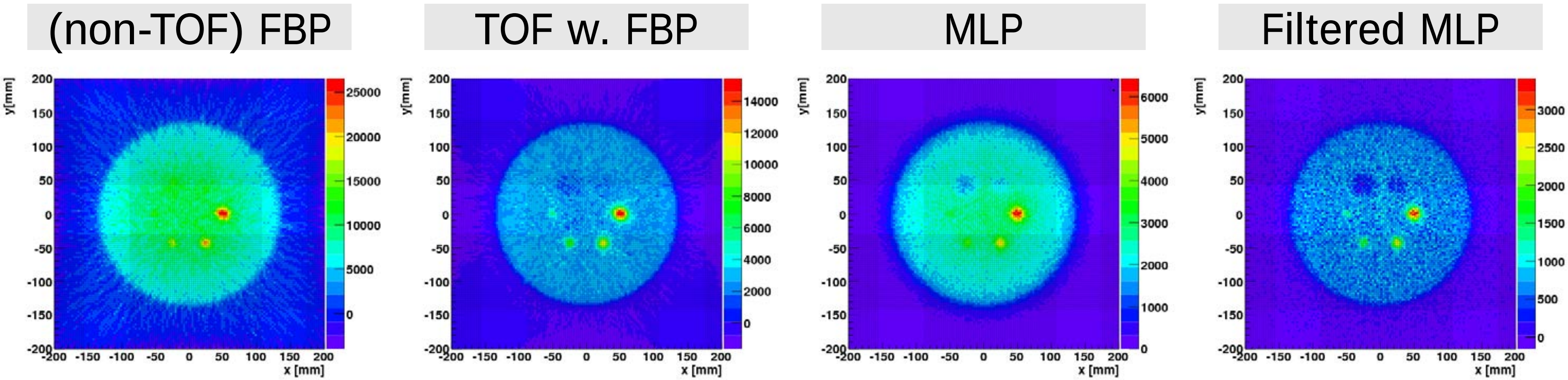


→ Simple, very fast Most-likely-point (MLP) method (~histograming of points) already gives a reasonable picture

→ NIM A732 (2013) 595

Reconstruction - simulation

- Hot spheres activity concentration: 3x phantom background
- Statistics equivalent to 163 s of PET examination
- 4x4 segmented, Teflon wrapped PbF_2 radiators
- 20 mm thick axial slices



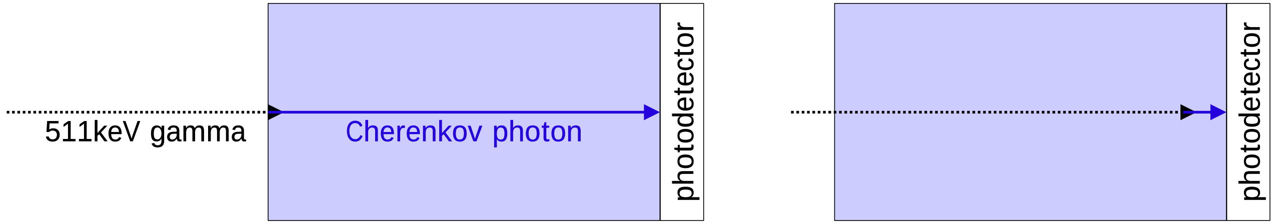
First tries, have to understand how the possible improvements in the detection efficiency will influence the performance.

Again: the simple, very fast Most-likely-point (MLP) method (~histograming of points) already gives a reasonable picture

→ NIM A732 (2013) 595

Limitations of Cherenkov photon timing

- Cherenkov photons are produced promptly, but still need to reach the photodetector (gamma rays travel faster than Cherenkov light!)
  - Radiator dimensions, refractive index → intrinsic travel time spread due to different gamma interaction depths
  -

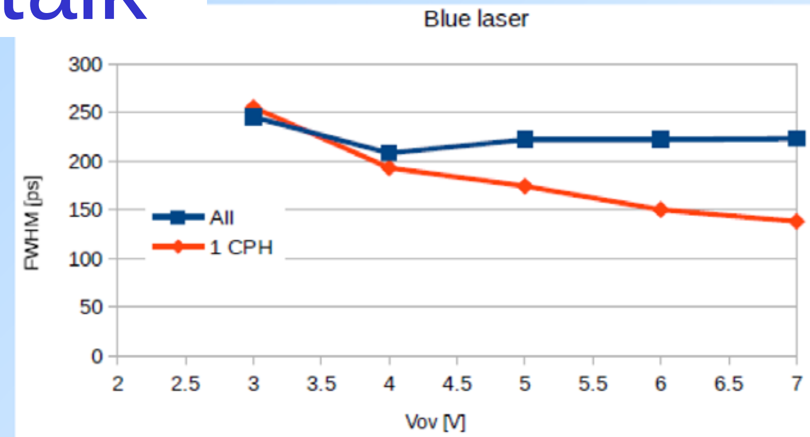


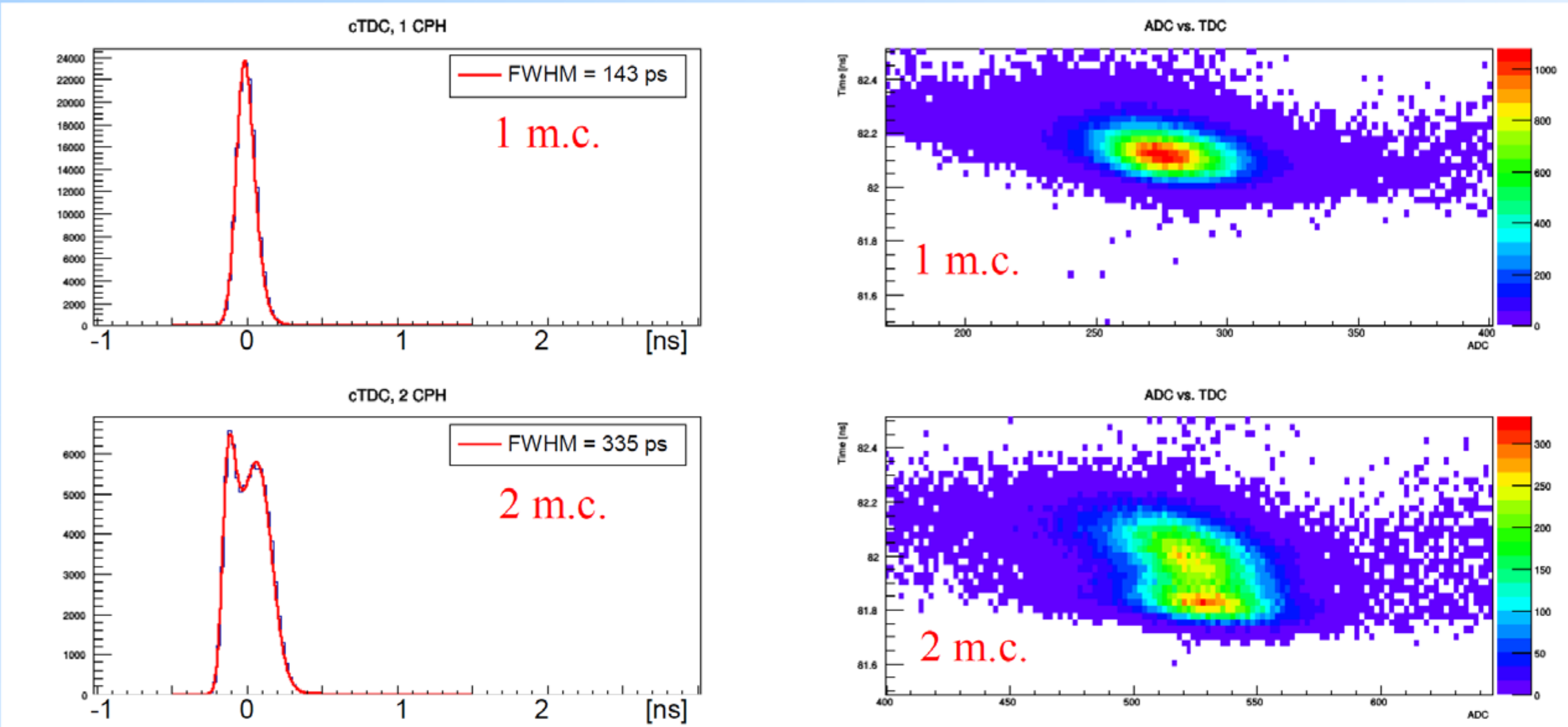
d = 15 mm, n = 1.8: $t = d \cdot n/c_0 = 90$ ps $t = d/c_0 = 50$ ps → $\Delta t = 40$ ps

  - Different photon emission angles
  - Reflections from radiator entry and side surfaces
    - total internal reflection (high refractive index)
    - reflective wrapping
- Black paint reduces total internal reflections and stops many photons
  - improved timing
  - reduced detection efficiency (but from photons with worse timing)

Impact of optical cross talk

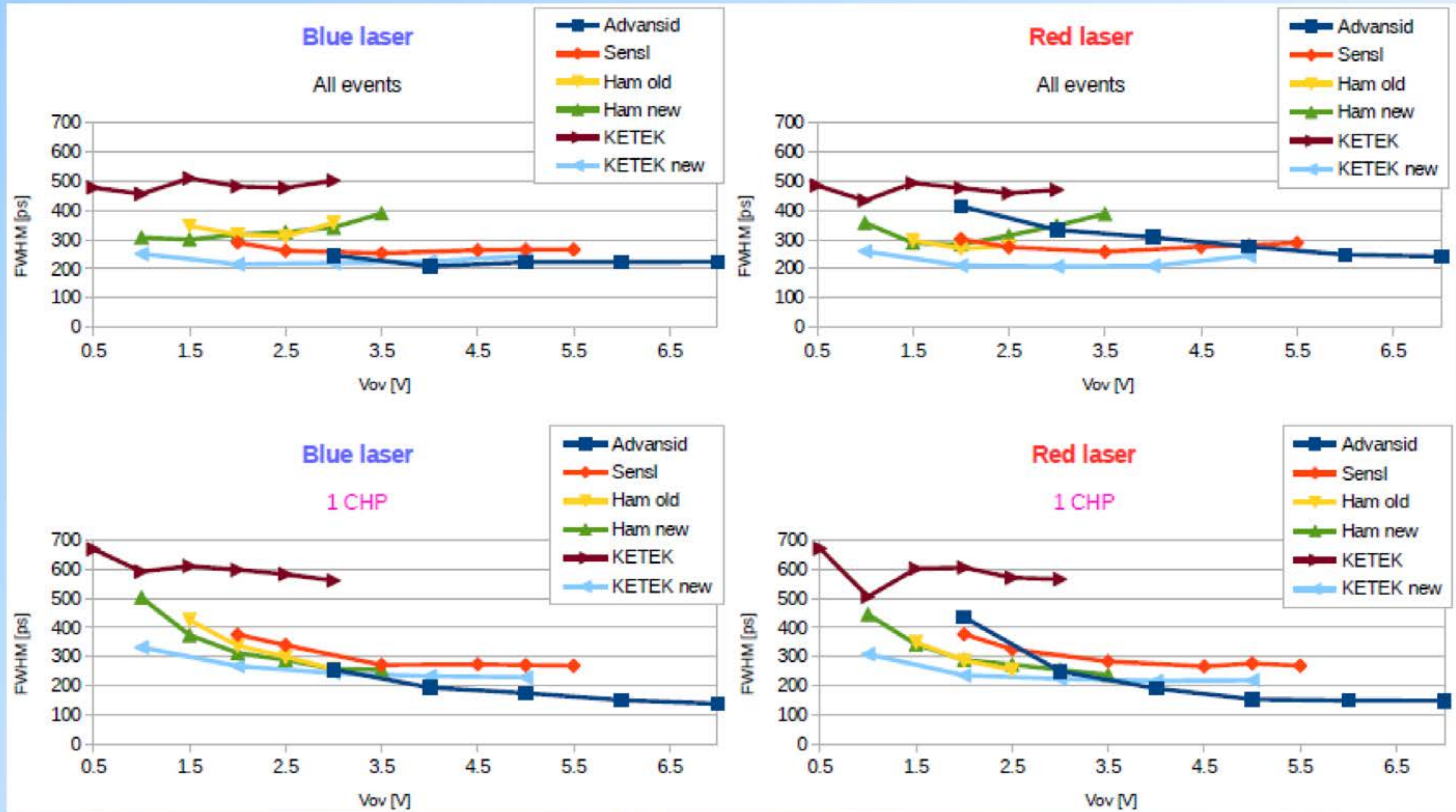
- AdvanSiD SiPM, V_{OV}=6V, T=-25°C
- blue laser λ=404nm
- events vith 2m.c. signal have two contributions: real double hit events with better resolution and optical crosstalk events





SiPM timing with uniform illumination

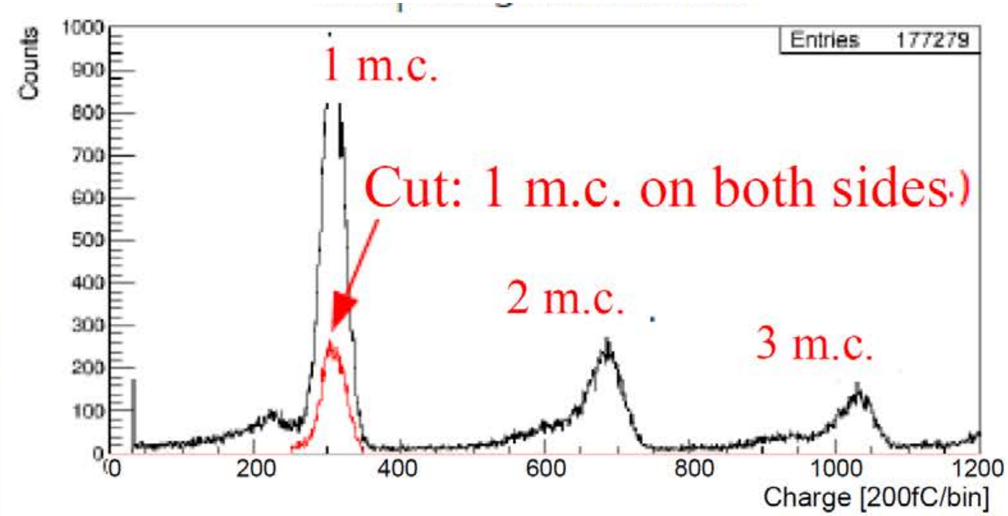
- Uniform illumination of SiPMs, T=-25°C
- Timing for all events (top) and events with single micro cell signal (bottom)

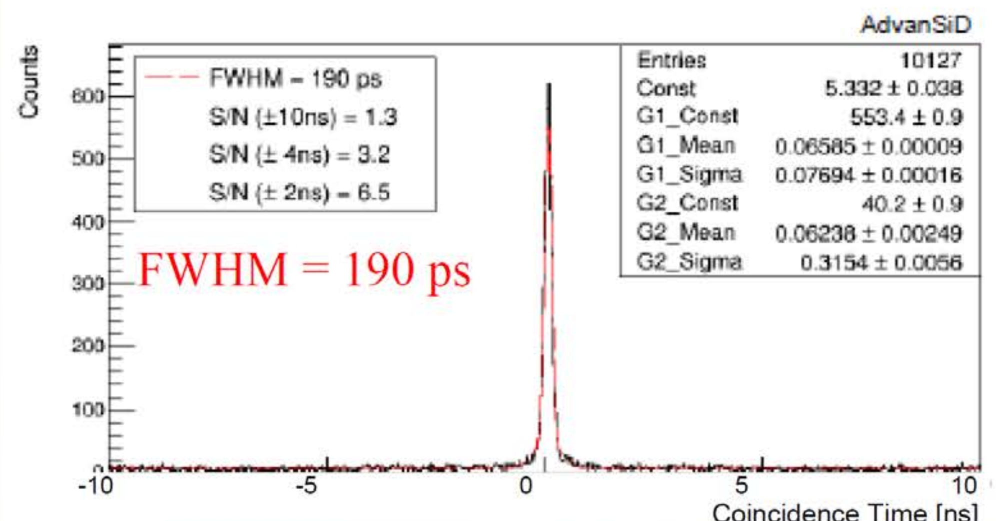


Coincidence time resolution with single cell events on both sides

- Using only events with single micro cell signal on both sides: CRT= 190 ps FWHM (AdvanSiD, V_{OV}=7V, black-painted PbF_2, T=-25°C)

- To get the resolution below 200 ps we need to improve the resolution for the events with more than 1m.c. signal; stronger suppression of optical crosstalk and/or find the way to correct the timing (waveform sampling?)

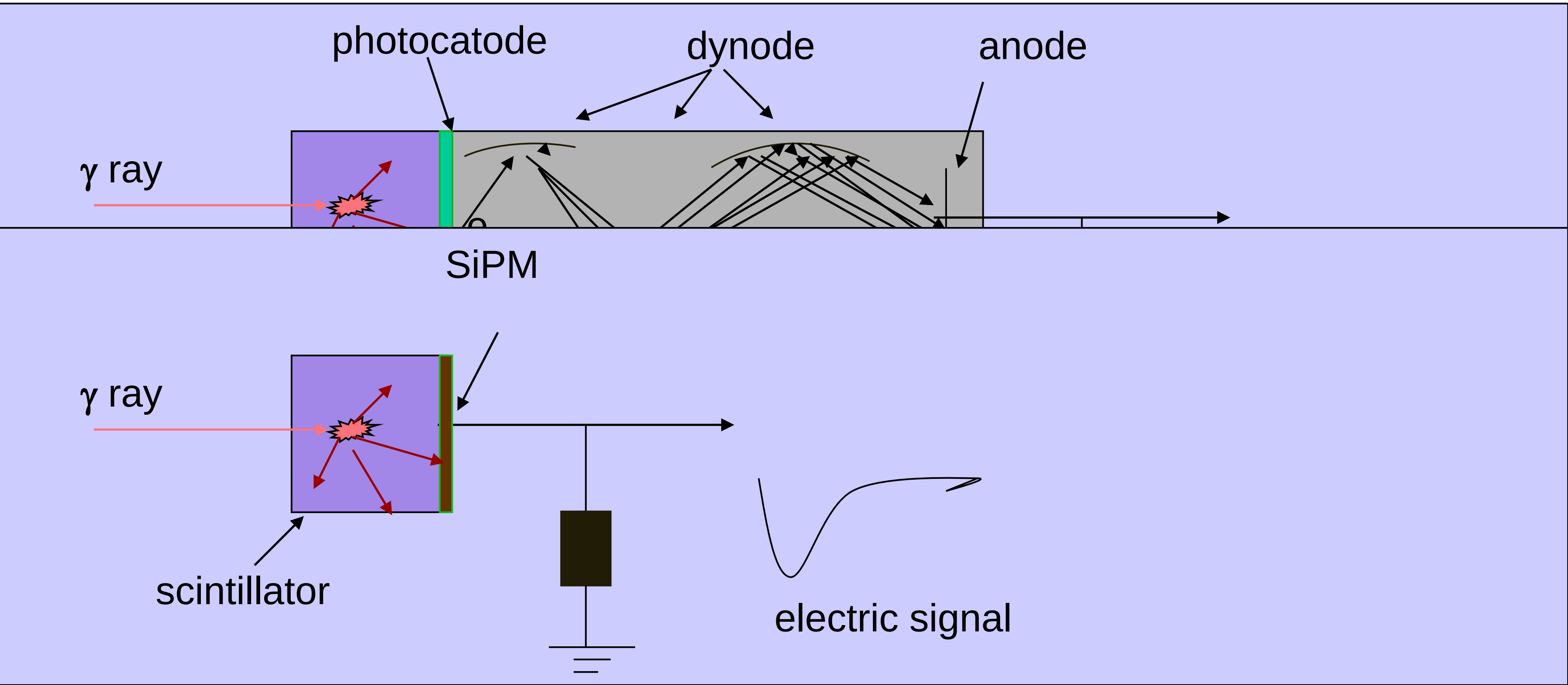




S. Korpar, IEEE/NSS 2015

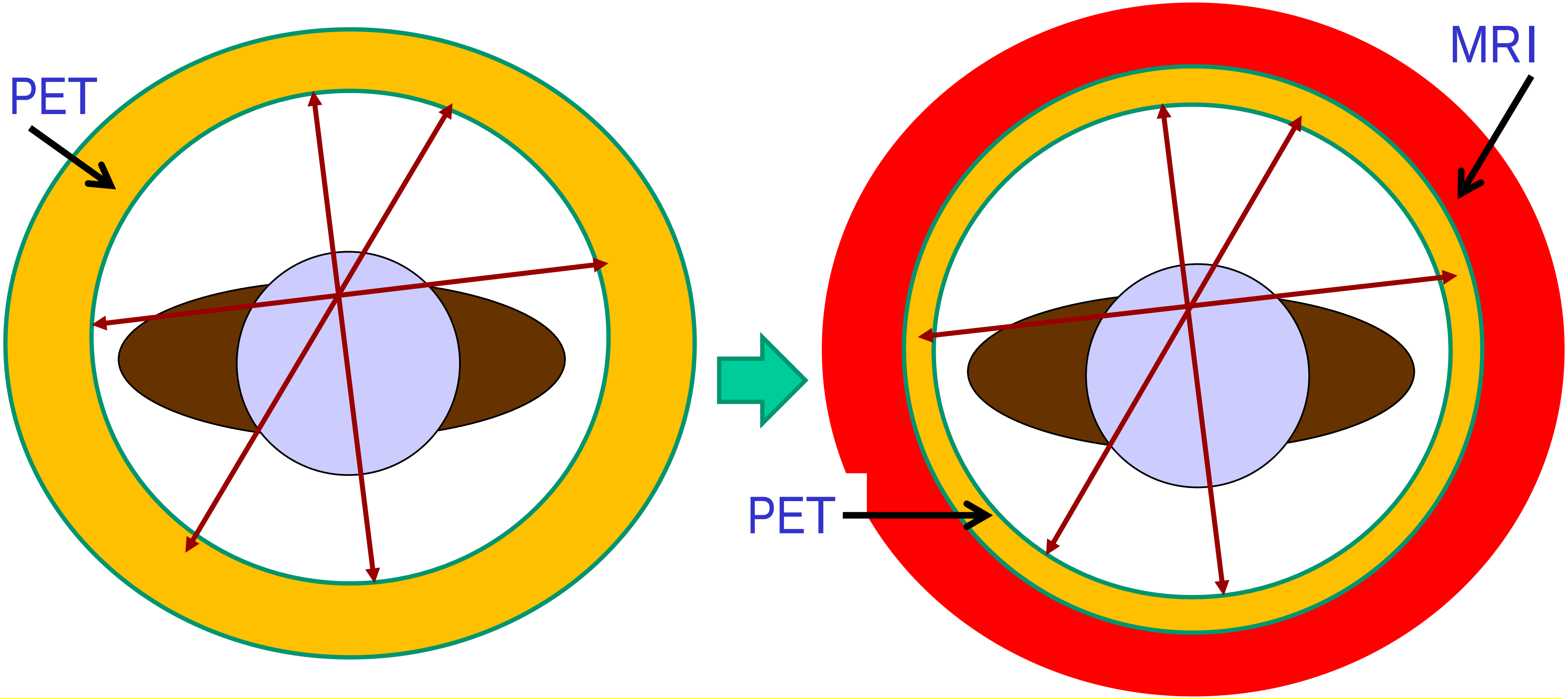
A new sensor for PET

Silicon PM (Geiger mode avalanche photodiode, G-APD): a novel photo-sensor, developed for exeriments in particle physics → considerably smaller than PMTs, no high voltage needed, can operate in high magnetic fields (several T).



How does the new sensor impact medical imaging?

- Significantly smaller than the usual sensor (PMT)
- Can be operated in high magnetic fields.



Allows imaging with magnetic resonance (MRI) **and** PET at the same time – an important improvement for an efficient diagnostics!

PET + MRI slikanje