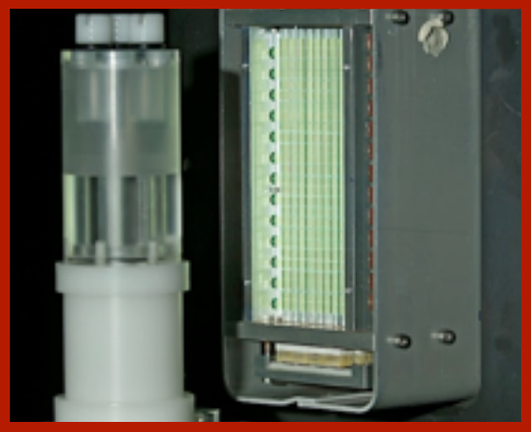
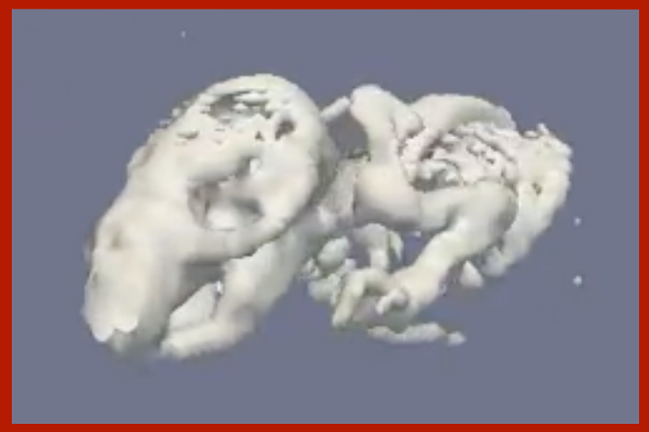
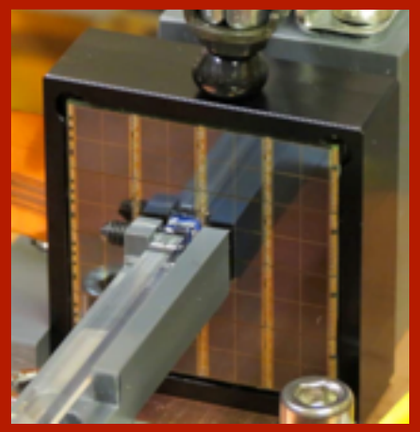
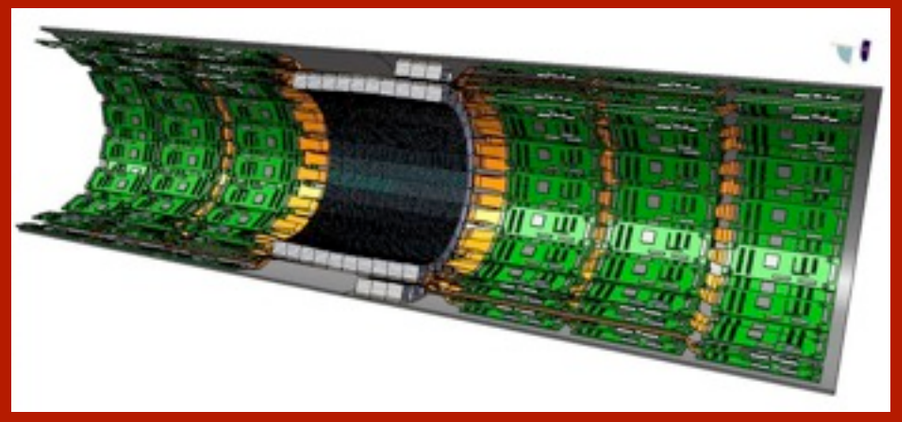





From high energy physics to medical applications: PET (Positron Emission Tomography) detectors

summary of the present and past activities at ETH-IPP

- AX-PET experiment (completed experiment)
- long scintillation crystals with dSiPM readout (ongoing)
- new project for PET-MRI detector at ETH (starting)

ETH Institute for Particle Physics

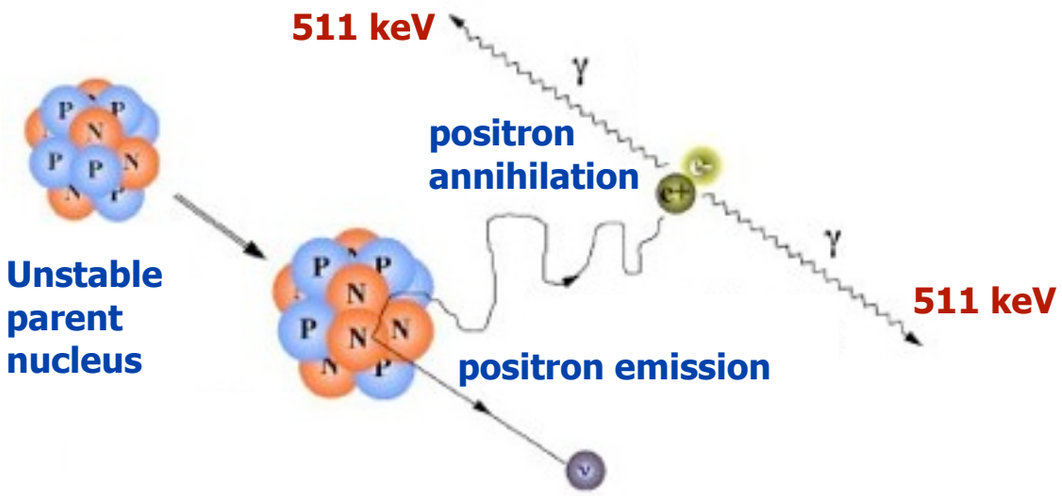
Chiara Casella

2nd CHIPP workshop on detector R&D
PSI - 13.09.2013

Swiss Institute of Particle Physics

Positron Emission Tomography

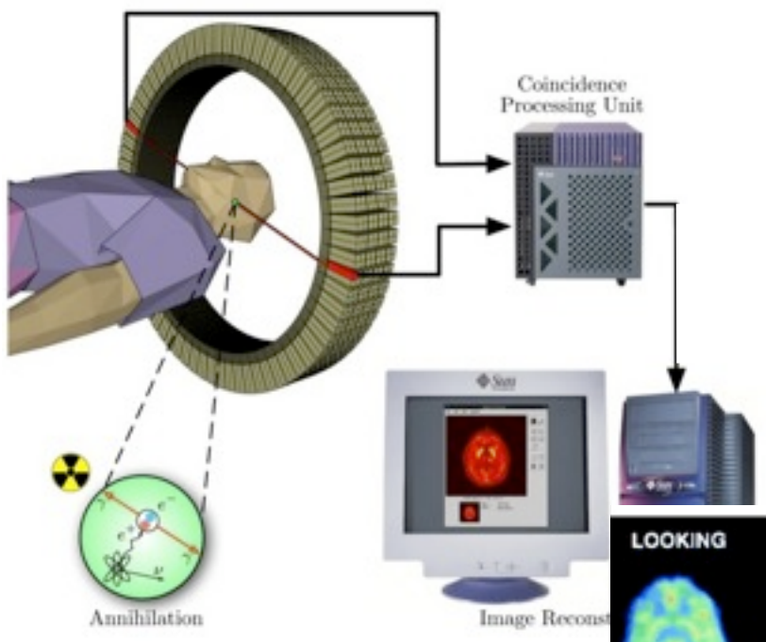
- In-vivo functional nuclear imaging technique with excellent sensitivity (at the molecular level)
- Relies on **positron emission** from radio-tracers followed by **positron annihilation**

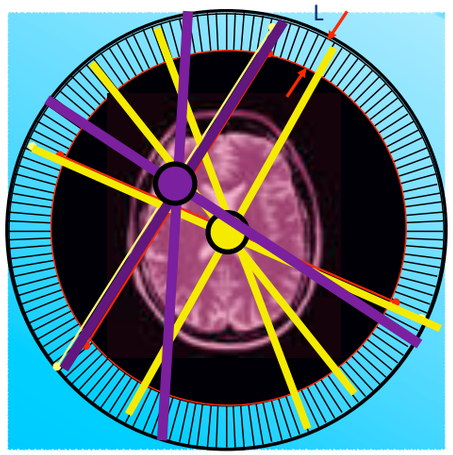


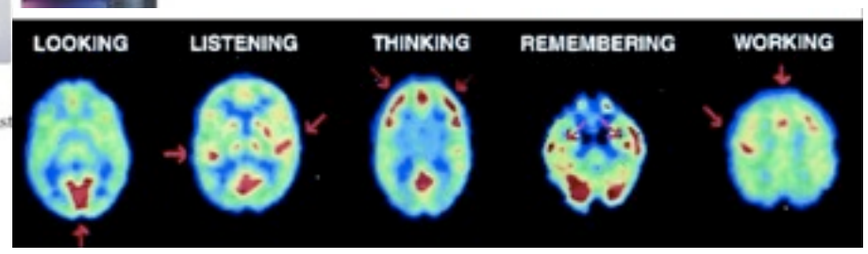
$$p \rightarrow n + e^+ + \nu_e$$

$$e^+ e^- \rightarrow \gamma\gamma$$

- Detector principle: **detection of 511 keV colinear photons** and **identification of the "lines of response" for all detected events**





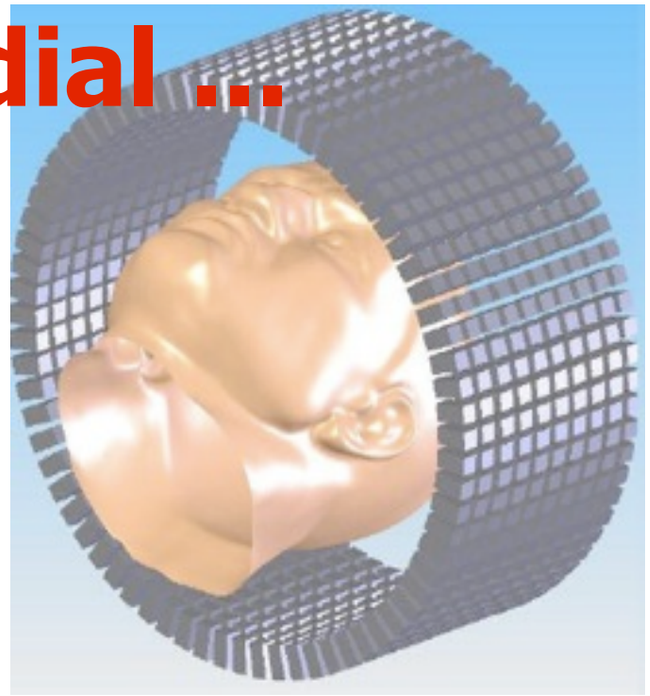


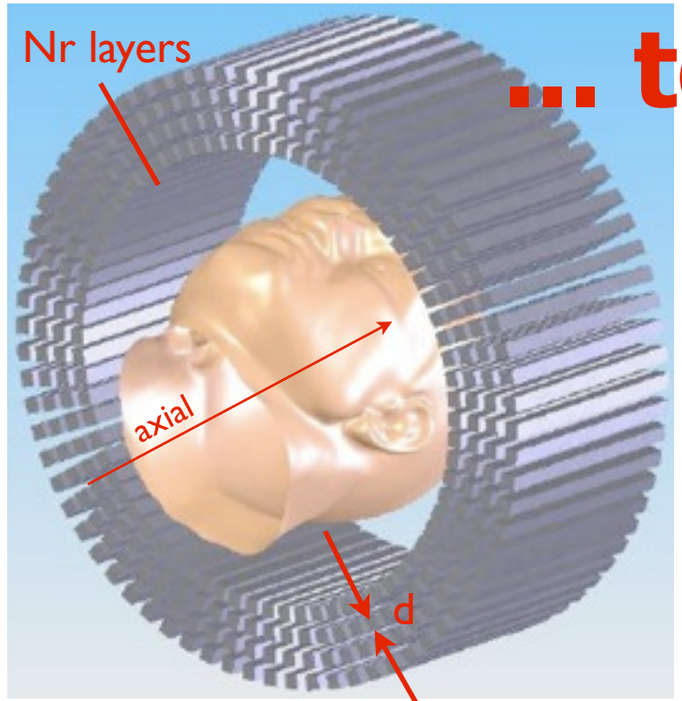
PET applications, examples :

- **clinical**
  - oncology (tumor diagnosis and staging)
  - neuroscience
- **pre-clinical** (small animals)
  - cancer research
  - neurobiology research
  - pharmacology
  - tracers development
  - ...

Novelty of AX-PET : AXial geometry

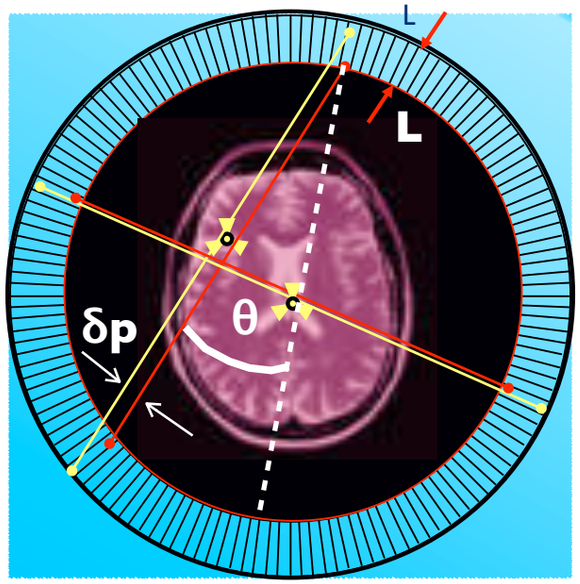
from radial ...





... to axial !

- long crystals
- oriented along the axial direction
- several layers arrangement



max **interaction efficiency => long L**

$$\epsilon = 1 - e^{-\mu \cdot L}$$

min **parallax error => short L**
- deterioration of the spat. resol.
- non uniformity in the field of view

$$\delta p = L \cdot sin\theta$$

parallax error => always a compromise between good spatial resolution (small L, small δp) or good sensititvity (long L)

the axial geometry allows for a parallax free system, in which spatial resolution and sensitivity are completely decoupled :

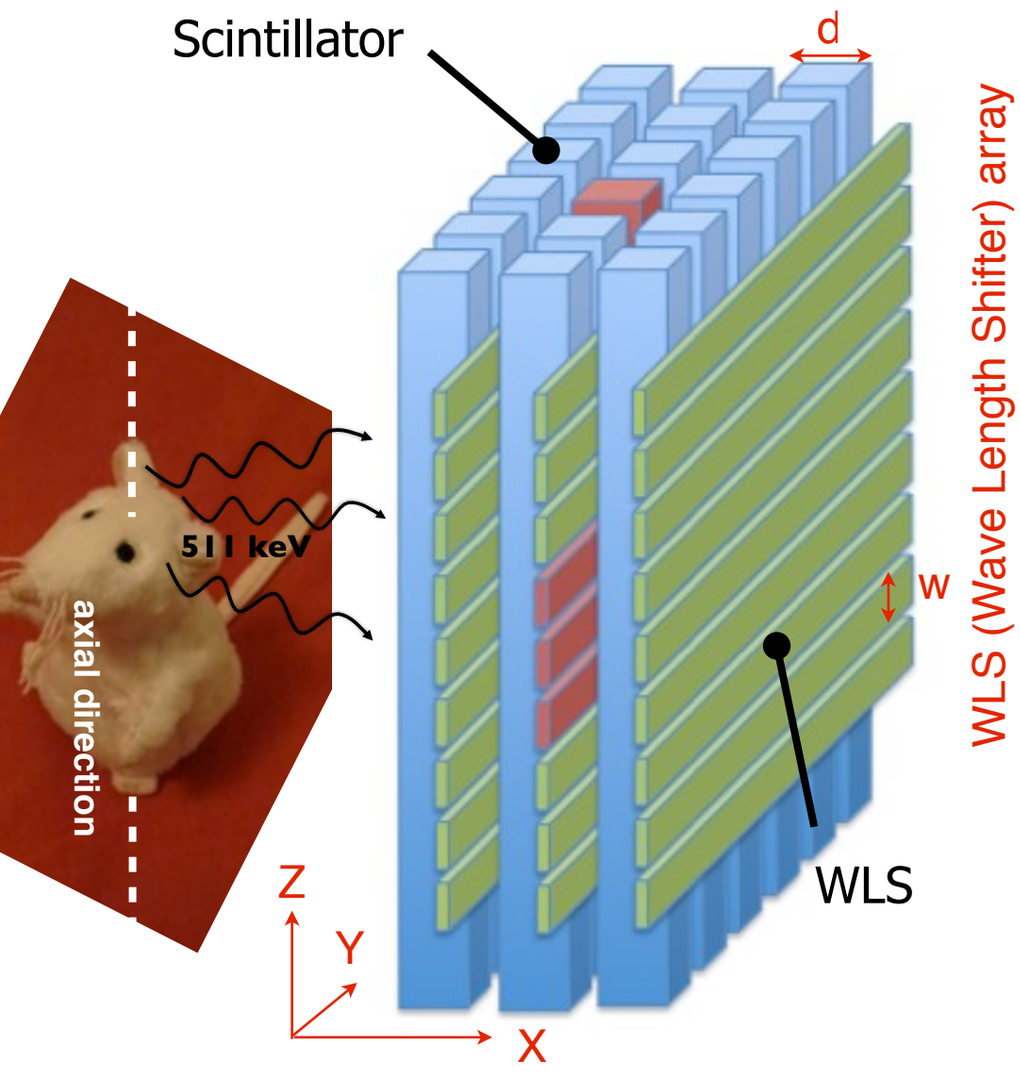
- improve spatial resolution => reduce d

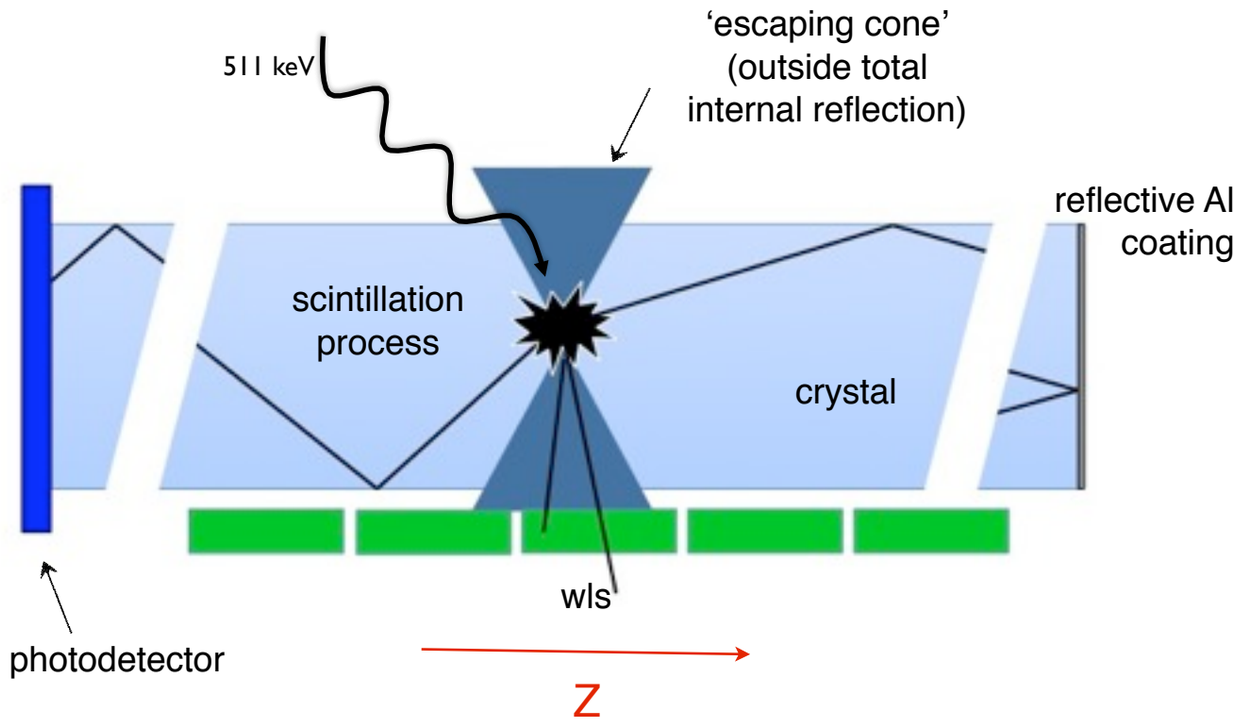
- improve sensitivity => increase Nr layers

AX-PET: novel geometrical approach for a PET detector (long, axially arranged xtals)

AX-PET detector concept

AX-PET detector : matrix of scintillator crystals and WLS strips





Crystals:

- trans-axial coordinate (x,y)
  - digital resolution from crystal size ($d/\sqrt{12} \times 2.35$ FWHM)
- energy

Wave length shifter strips :

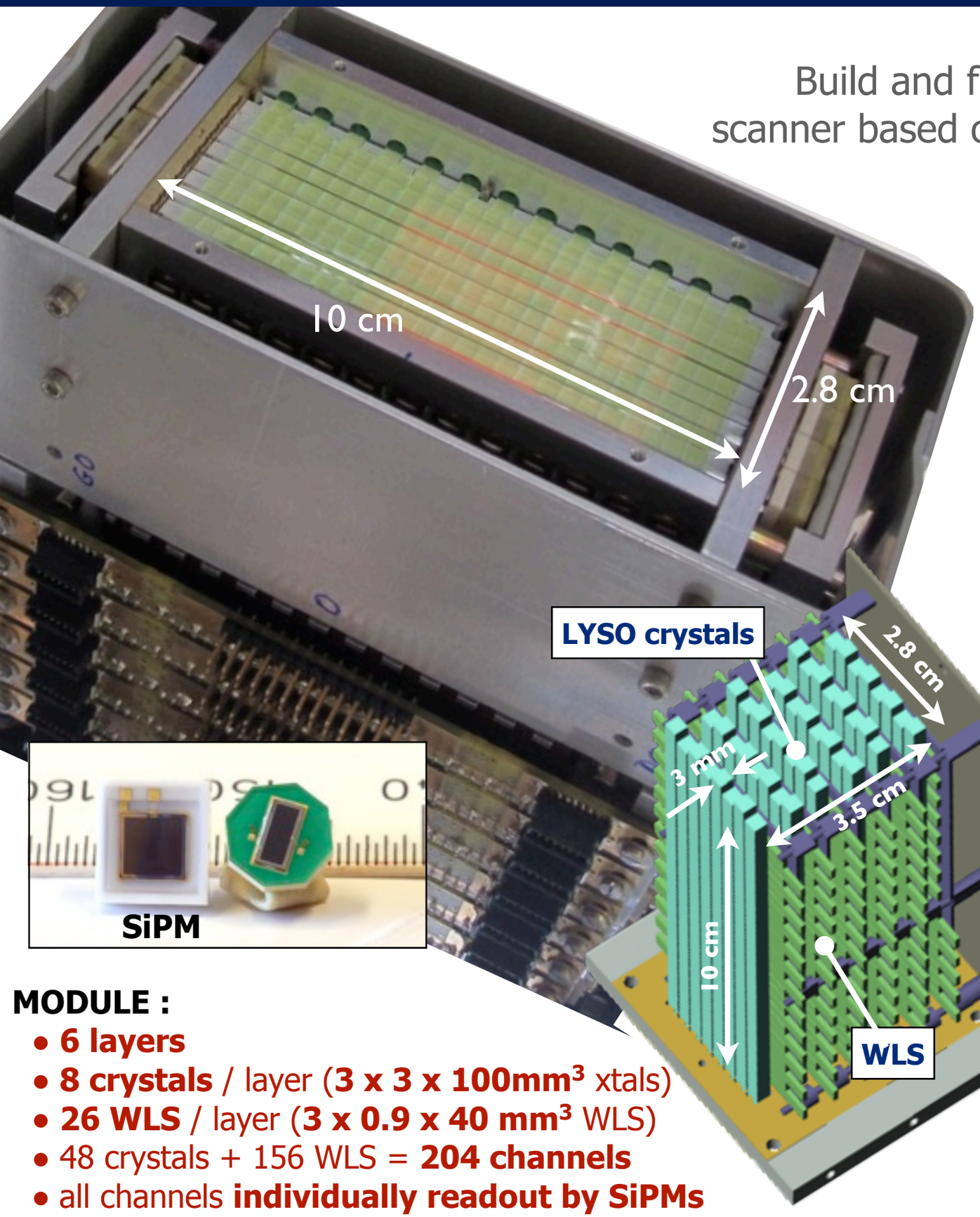
- axial coordinate (z)
  - center of gravity => resolution better than digital (<w)

- materials and techniques "borrowed" from calorimetry in High Energy Physics
- 3D localization of the photon interaction point + energy measurement

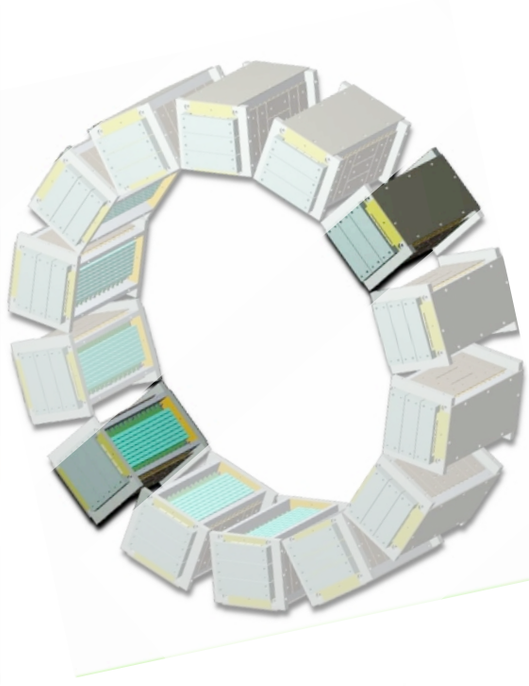
AX-PET modules and "demonstrator"

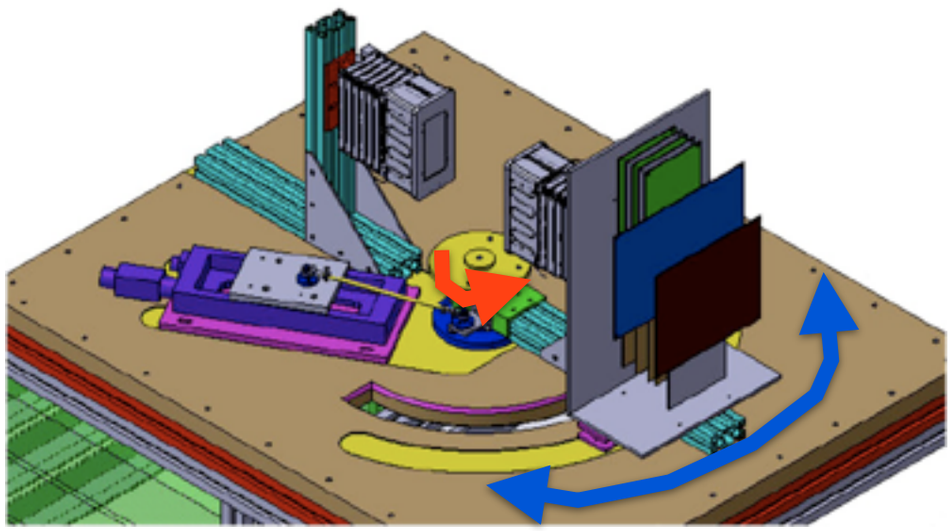
Goal of the collaboration:

Build and fully characterize a **"demonstrator"** for a PET scanner based on the axial concept. Assess its performances.



Demonstrator : Two identical AX-PET modules, used in coincidence with a dedicated gantry setup

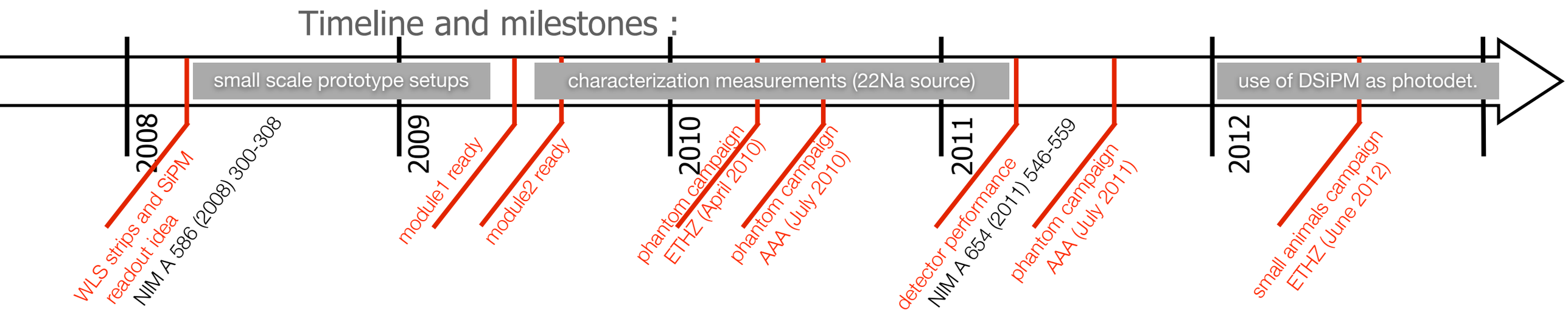




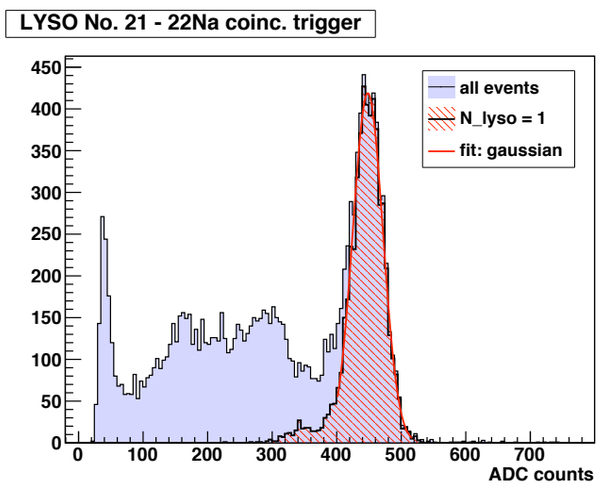
MODULE :

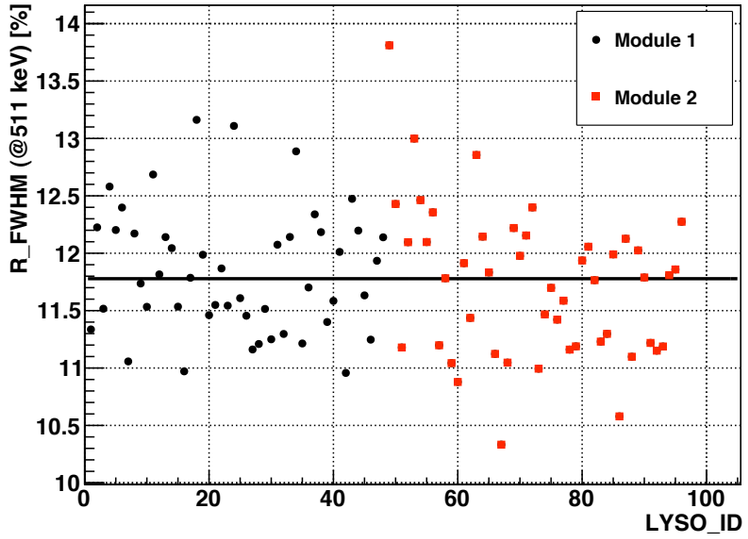
- **6 layers**
- **8 crystals** / layer (**3 x 3 x 100mm³** xtals)
- **26 WLS** / layer (**3 x 0.9 x 40 mm³** WLS)
- 48 crystals + 156 WLS = **204 channels**
- all channels **individually readout by SiPMs**

AX-PET milestones



AX-PET detector performance

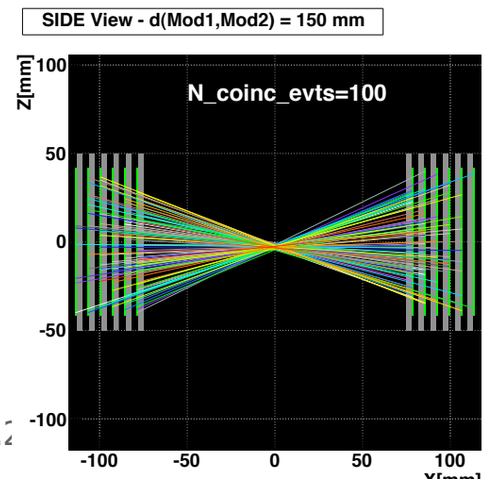


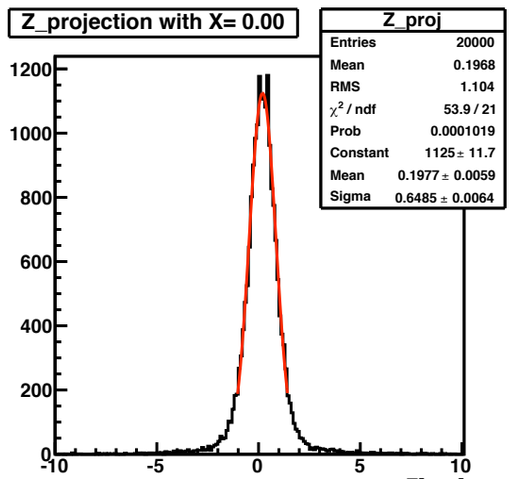


energy resolution

<ΔE/E> ≈ 12 % FWHM

(at 511 keV, 96 crystals average)





axial resolution

contribution from physics of positron annihilation

$$R_{intr} = \sqrt{R^2_{meas} - R^2_{\rho} - R^2_{180}}$$

≈ 1.35 mm, FWHM

Phantoms image reconstruction

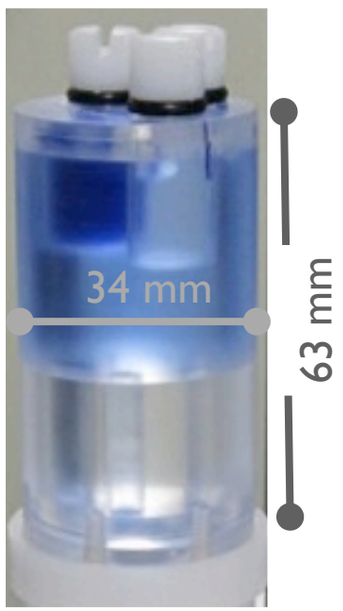
dedicated AX-PET reconstruction software

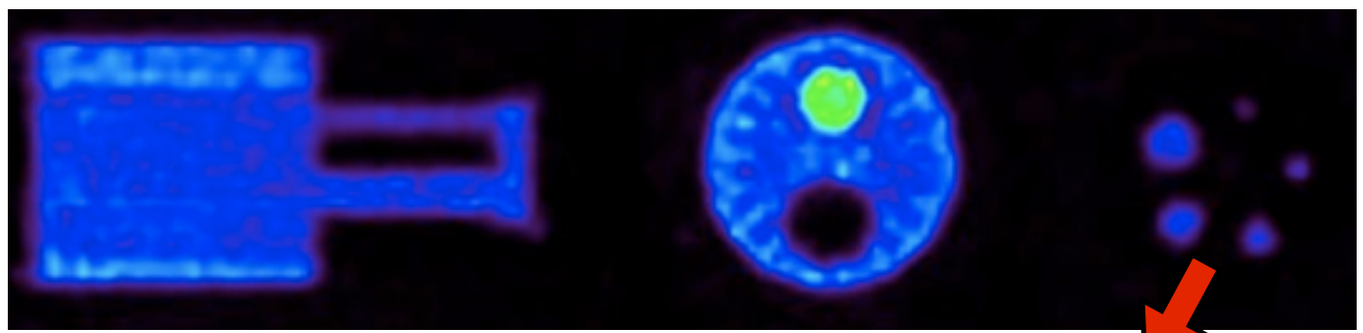
NEMA : Three regions in the same phantom to address three different aspects

Hot & Cold rods for **contrast**

Homogeneous cylinder for assessing the **ability to reconstruct homogeneous distributions**

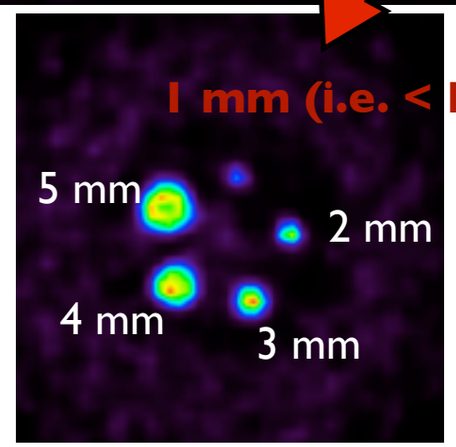
Series of small rods for **resolution**



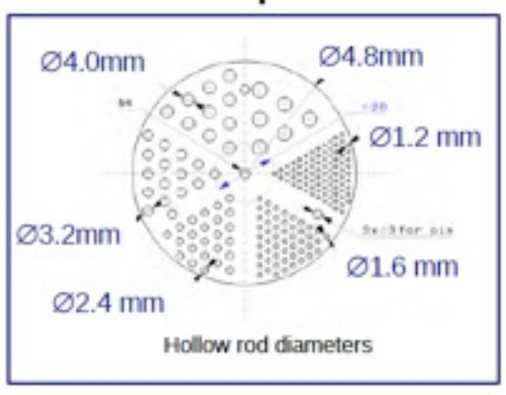


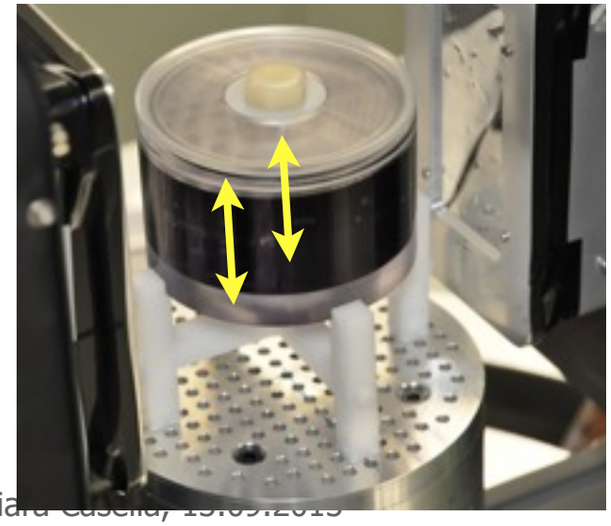
different color scale !

Reconstructed 1 mm rod
=> **FWHM ~ 1.6 mm**



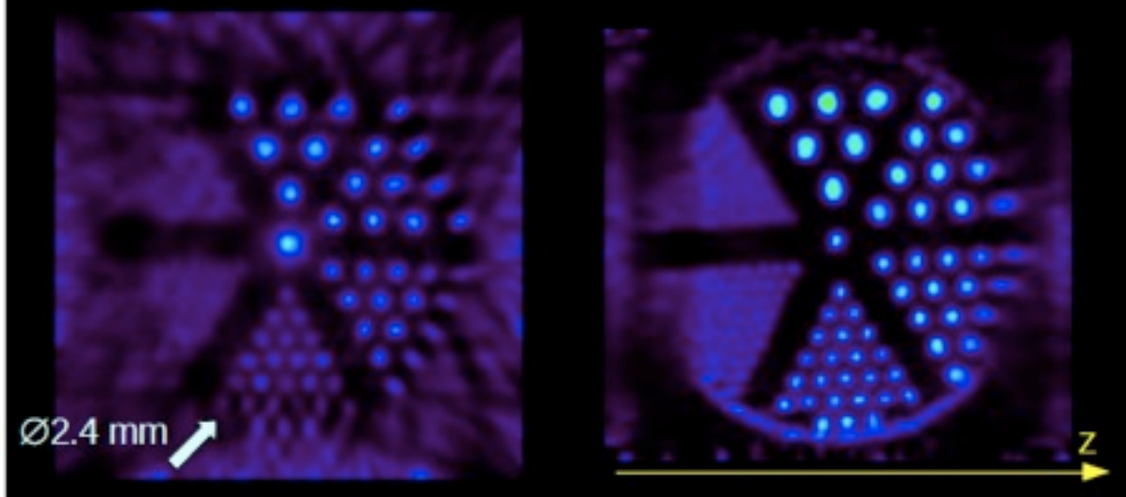
Resolution phantom : different sectors with different rods diameters



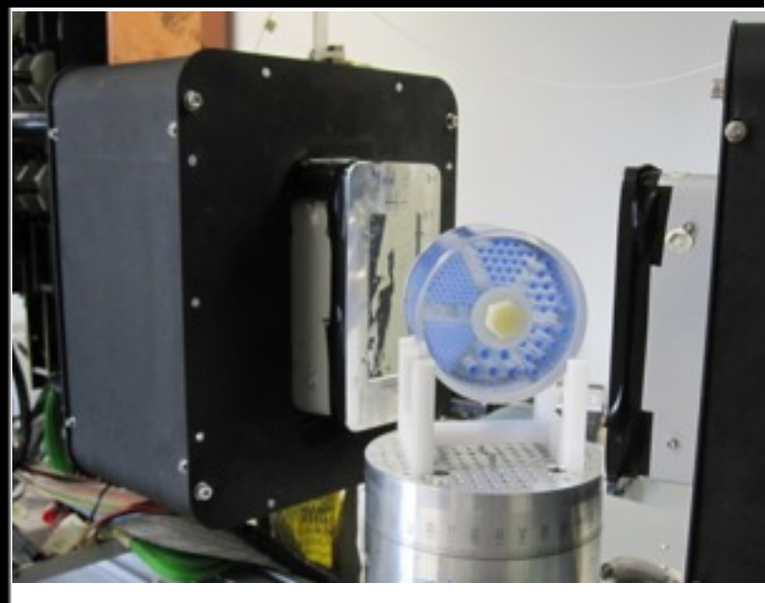


Rods oriented parallel to Z axis

Rods oriented perpendicular to Z axis



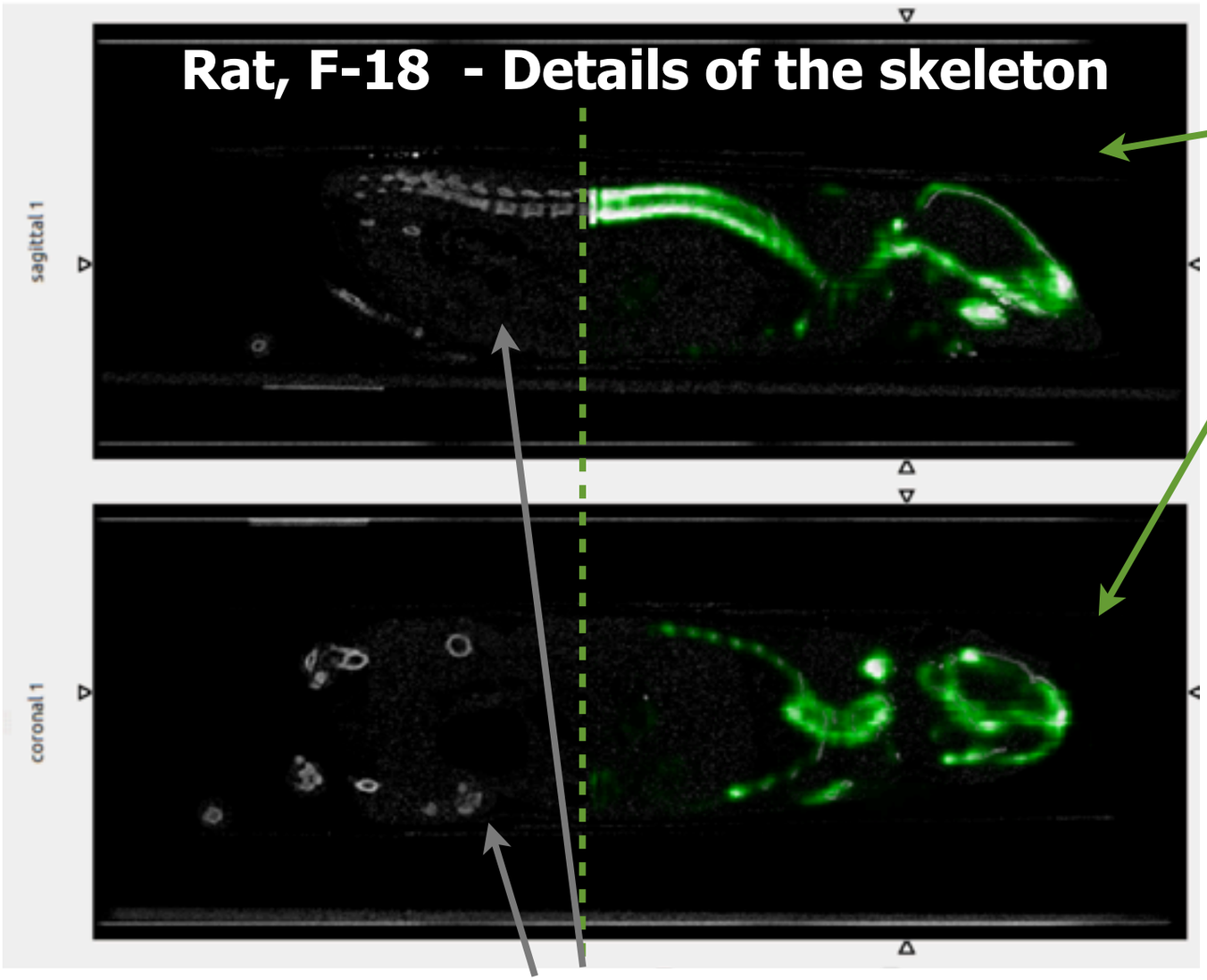
- Fixed time acquisition: 120 s /step
- 60 iterations + post-reconstruction smoothing
- No corrections
- Artefacts due to data truncation (FOV too small...)



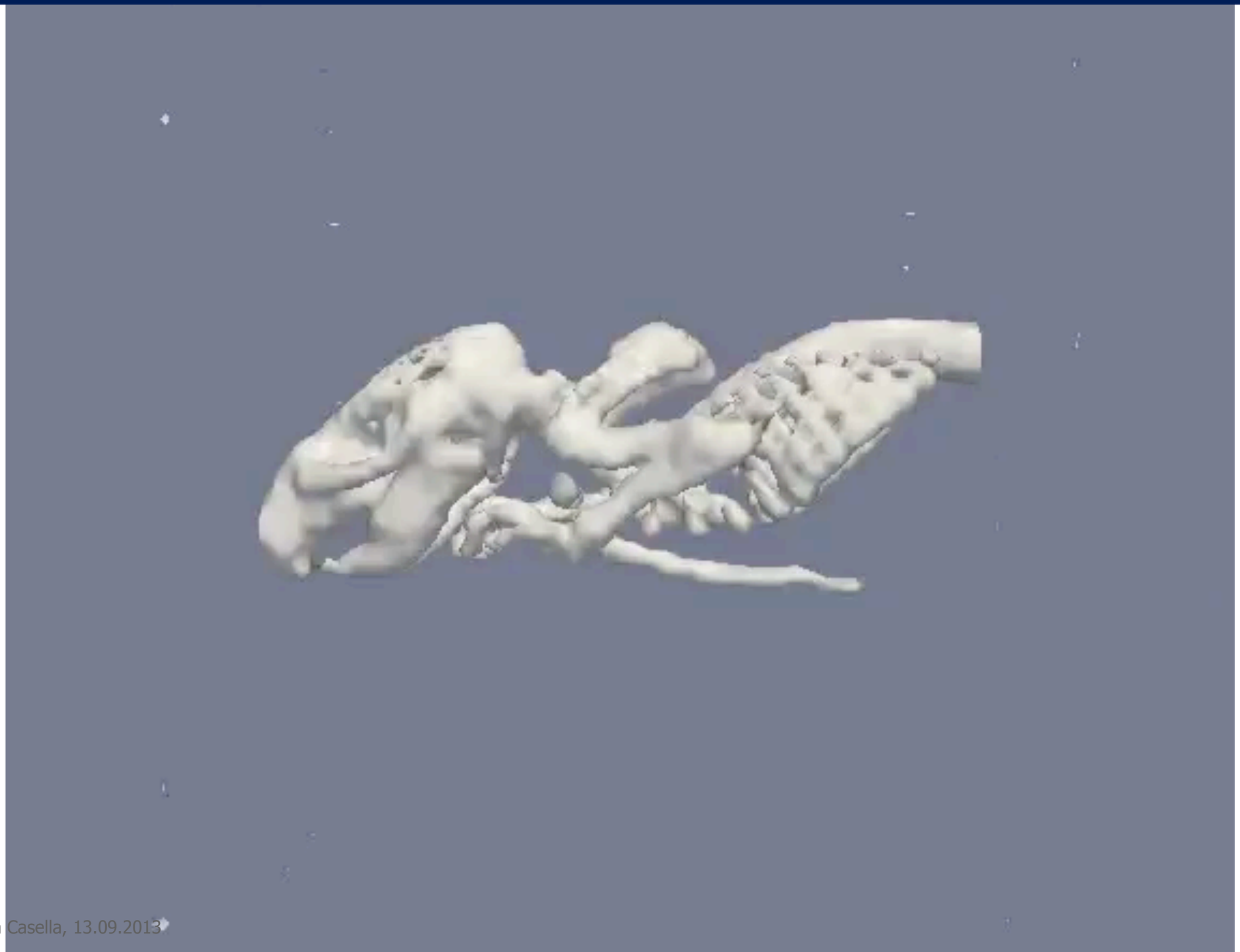
Small animals image reconstruction

- June 2012, small animals tests
- at ETH, Radiopharmaceutical Institute; small animals PET lab (GE Explore Vista PET/CT scanner)
- one mouse, FDG + one (young) rat, FDG + one (young) rat, 18-F

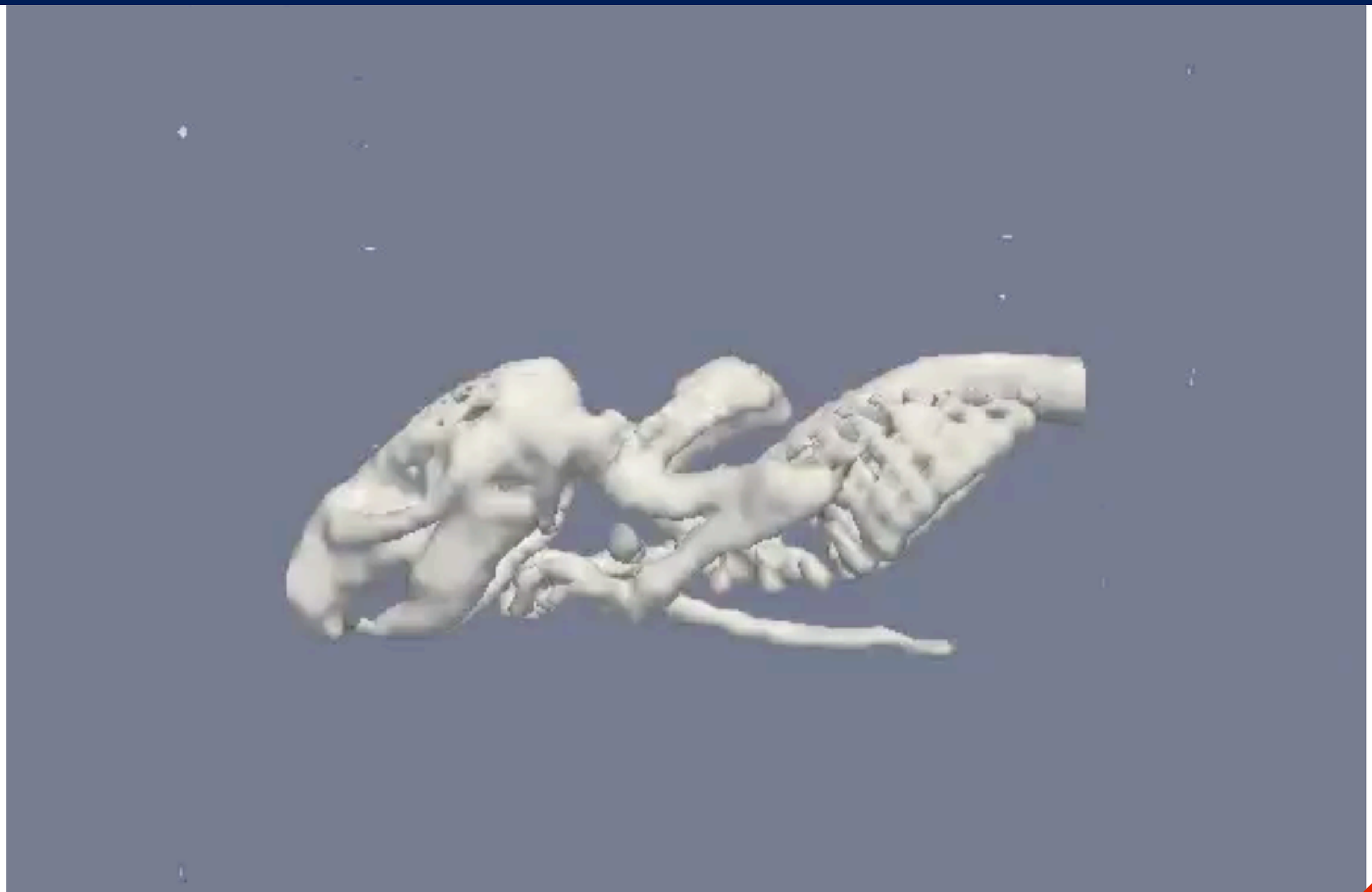
- Acquisition :
  - PET acquisition with AX-PET (multi-step acquisition)
  - PET / CT acquisition with Explore Vista (if enough activity was left in the animal



Small animals image reconstruction



Small animals image reconstruction



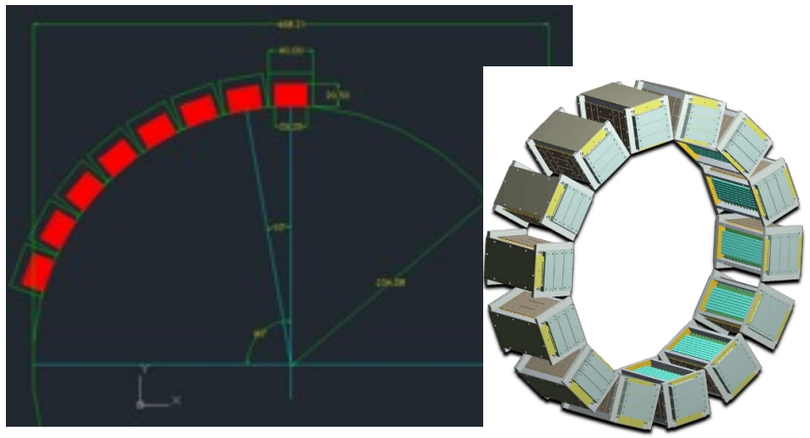
AX-PET Demonstrator performance have been demonstrated !

AX-PET: status & outlook

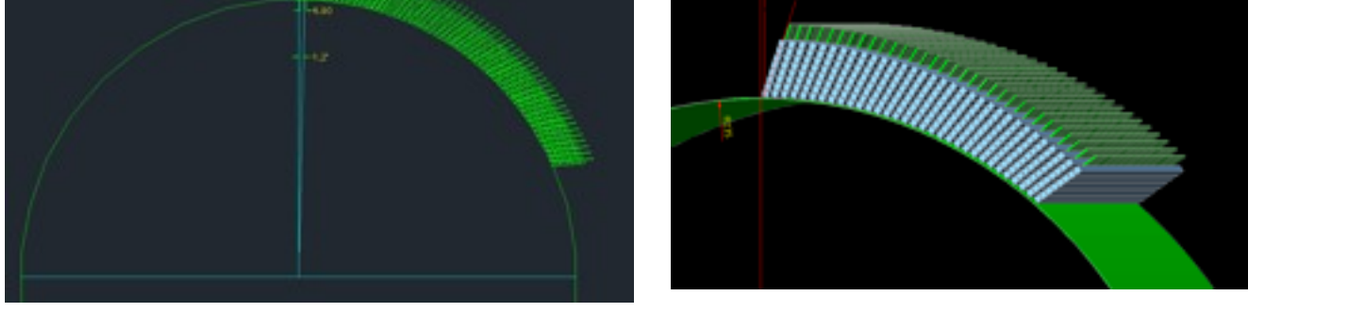
From the detector development point of view, the AX-PET project is completed. The AX-PET detector (now at CERN) will be moved to ETH by the end of the year.

- Simulations of an hypothetical full ring scanner (ongoing)

  - flexibility of AX-PET
  - completely scalable design (crystal size, number of layers, distance between modules...)
  - from simulations : assess the final performance expected in a full ring vs various parameters



AX-PET geometry extended to n modules



different geometries (no gaps), towards higher sensitivity

- Improving the reconstruction algorithms with the inclusion of Compton scattered events

AXPET collaboration

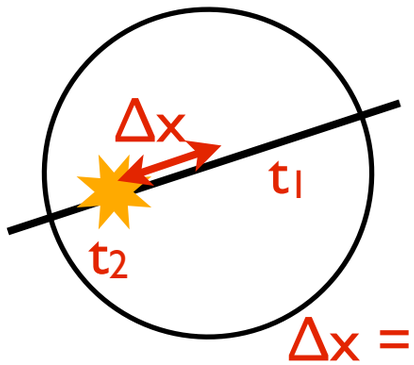
ETH Zurich, CERN, INFN (Bari, Cagliari), IFIC and University of Valencia, Ohio State University, University of Michigan, University Oslo, Tampere University

Beyond AX-PET...

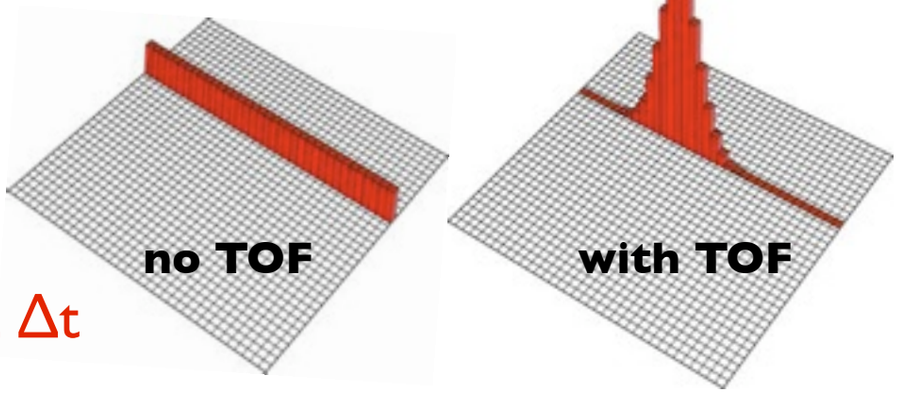
Current trends in PET instrumentation

1. Towards TOF-PET

measure the time difference in the arrival of the two photons to constraint the position of the interaction point along the line of response i.e. improve S/N



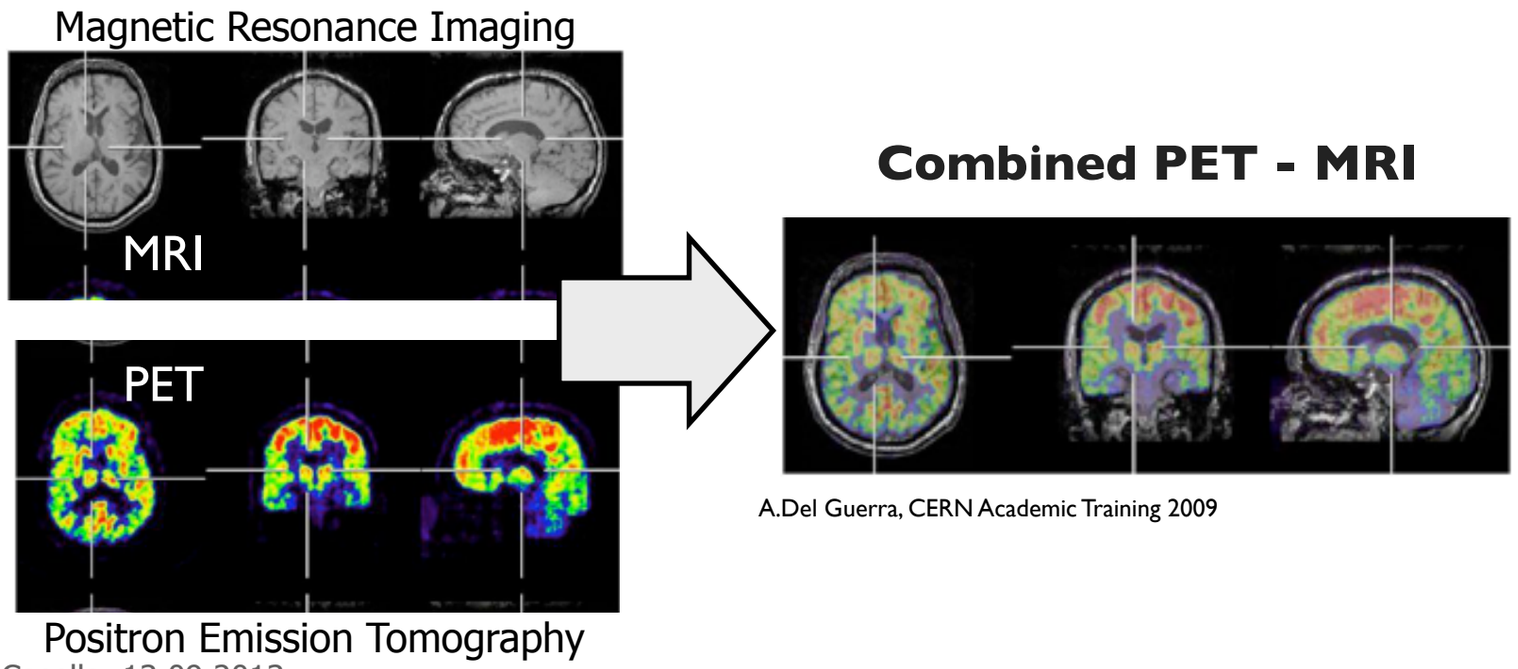
$\Delta x = c/2\ \Delta t$



Δ t	Δ x
500 ps	7.5 cm
100 ps	1.5 cm

2. Towards PET-MRI

combine two different and complementary imaging technique to best exploit the potential of nuclear imaging



A.Del Guerra, CERN Academic Training 2009

morphological information from MRI [**excellent resolution**]

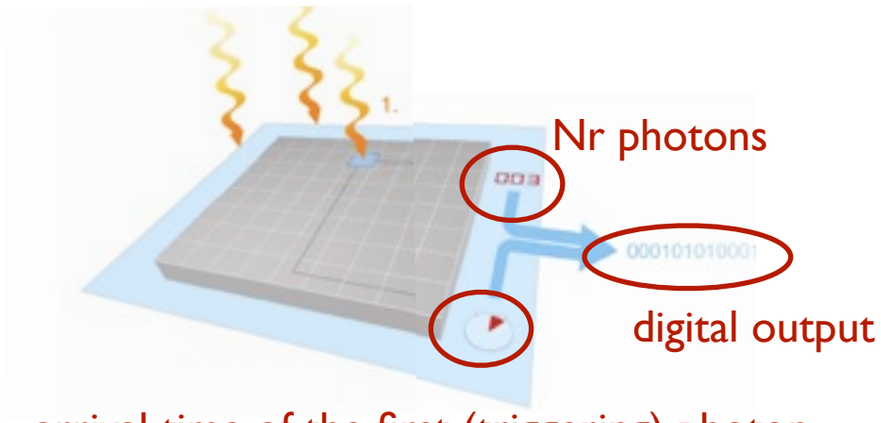
+

functional information from PET [**excellent sensitivity**]

AX-TOF-PET: Would that be possible?

- excellent timing resolutions are needed
- one possibility: use the **Digital SiPM** (**dSiPM**) as photodetector

Δ t	Δ x
500 ps	7.5 cm
100 ps	1.5 cm



- novel photodetector development (by Philips)
- fully digital implementation of SiPM
- CMOS electronics integrated in the same substrate of each photodiode
- Photon counter
- high resolution TDC (19.5 ps res.)
  => time information (**intrinsic time res ~ 50 ps**)

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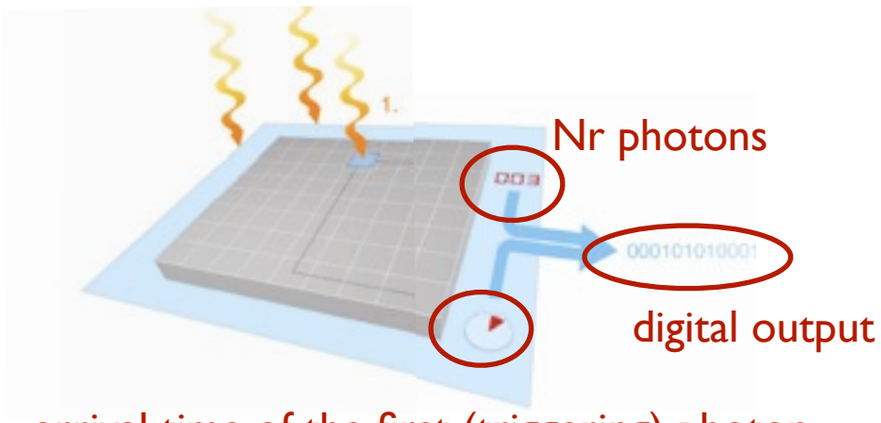

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- high resolution TDC (19.5 ps res.)
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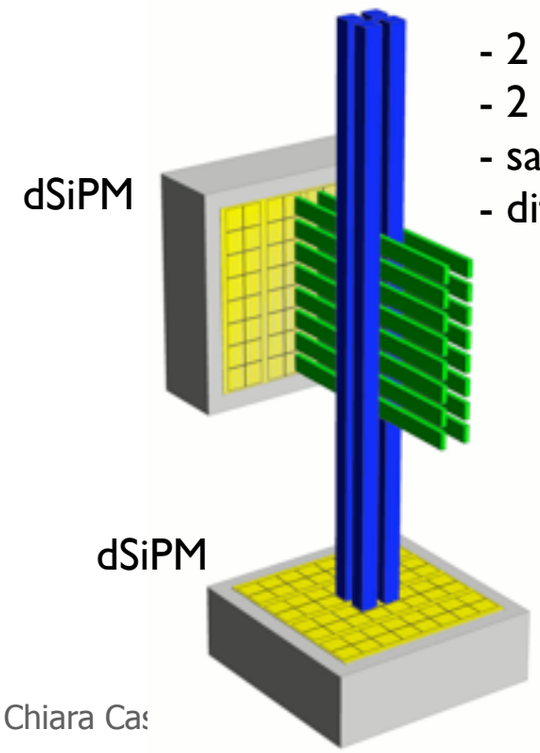
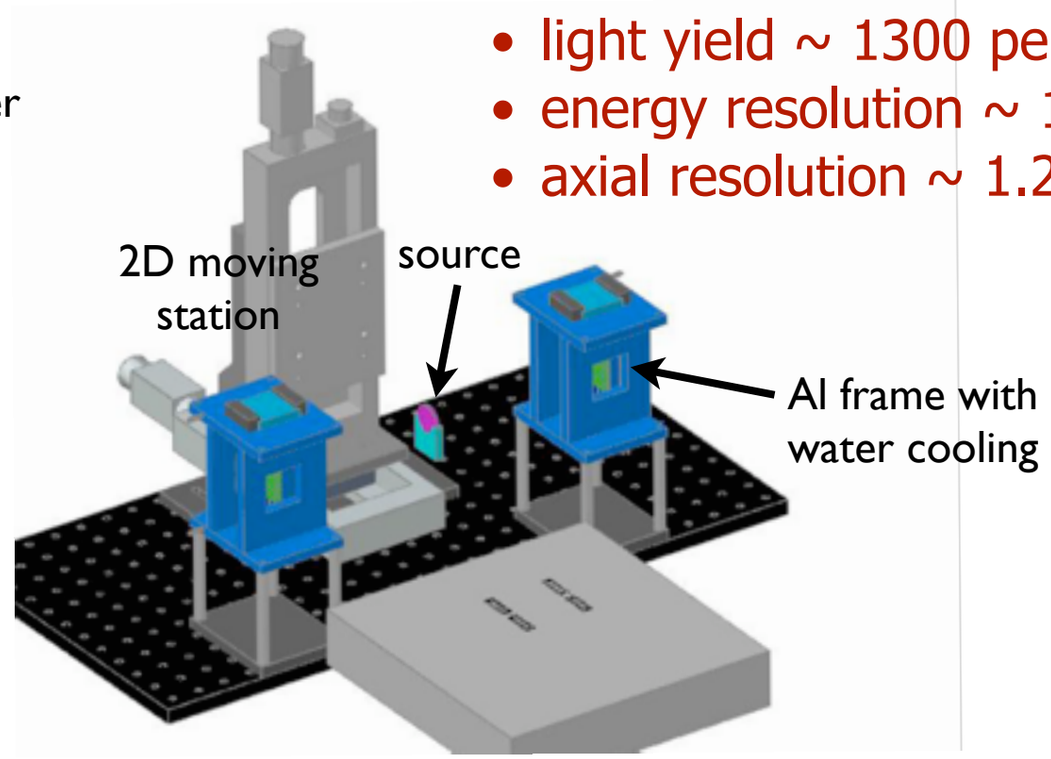
- first step: "**digital (small-scale) AXPET modules**"
- prove that using dSiPM exactly reproduces the same performance of AXPET



- 2 layers
- 2 crystals and 8 WLS / layer
- same elements of AXPET
- different pitches



- light yield ~ 1300 pe (raw)
- energy resolution ~ 13%
- axial resolution ~ 1.22 mm fwhm (coinc)

“Digital AX-PET modules”: Timing performance

- dSiPM => timing capabilities
- **which time resolution** with long crystals ?

=> arrival time at photodetector depends on the axial coordinate

“Digital AX-PET modules”: Timing performance

- dSiPM => timing capabilities
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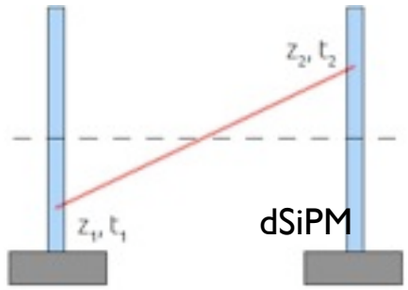
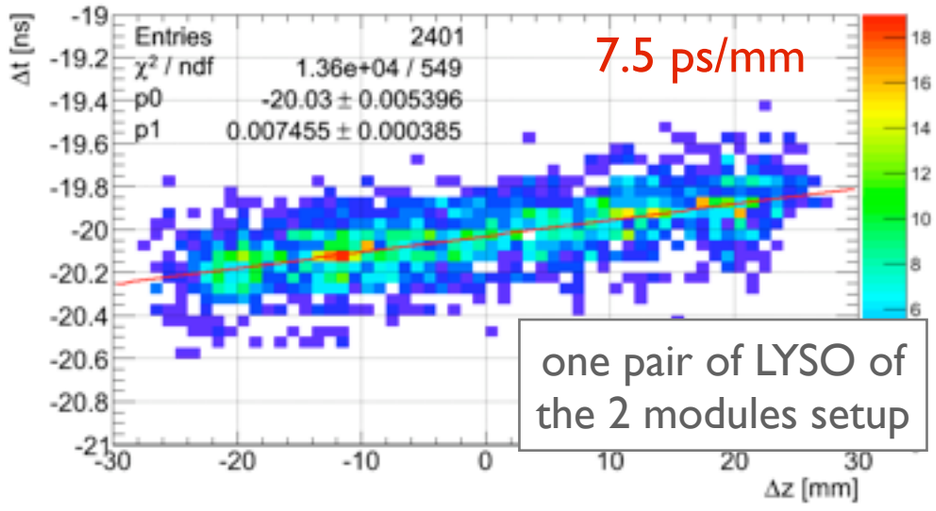
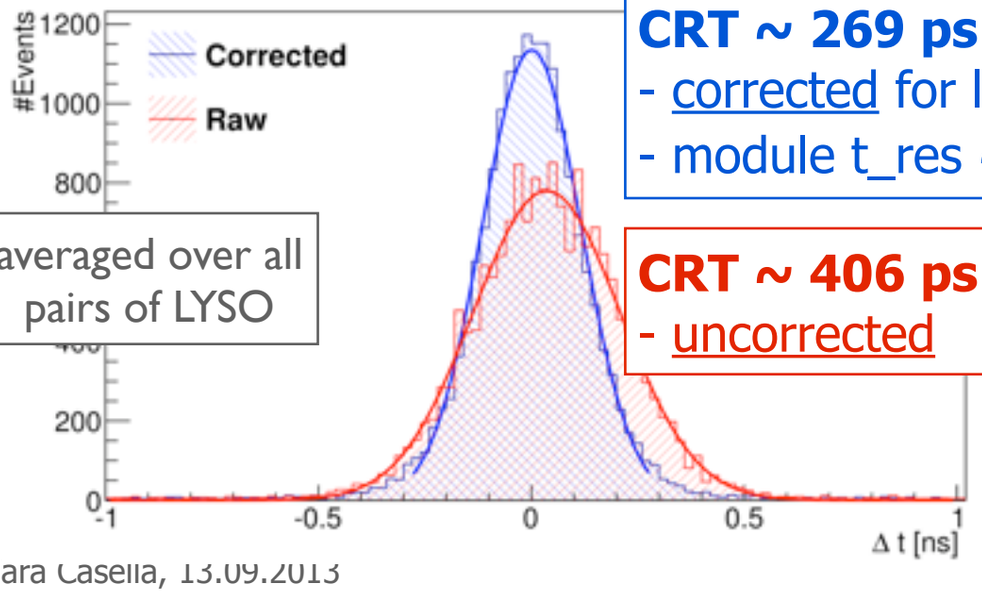
(a) correct for the axial coordinate
(using information from WLS)





one pair of LYSO of the 2 modules setup



averaged over all pairs of LYSO

CRT ~ 269 ps FWHM
- corrected for light path
- module t_res ~ 190 ps FWHM

CRT ~ 406 ps FWHM
- uncorrected

"Digital AX-PET modules": Timing performance

- dSiPM => timing capabilities
- **which time resolution** with long crystals ?

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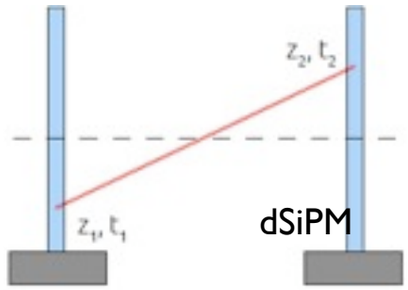
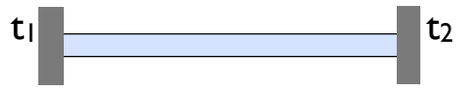
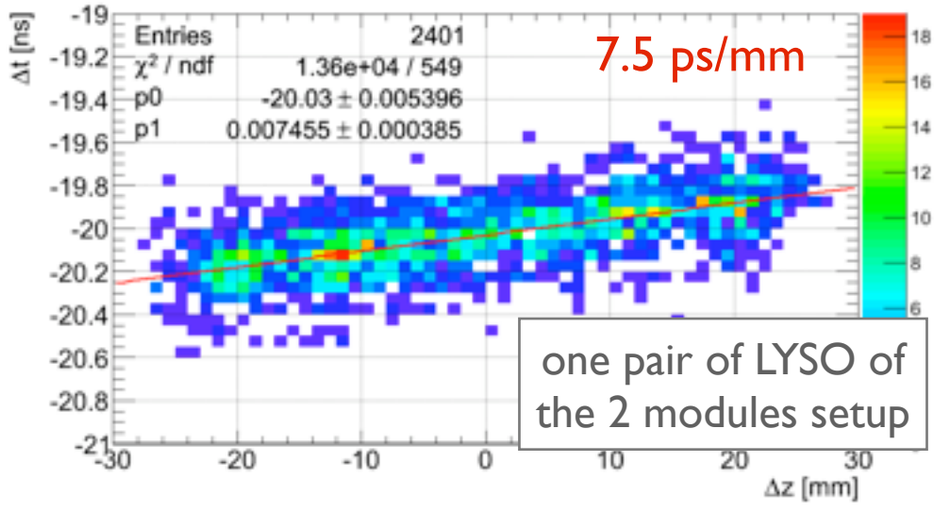


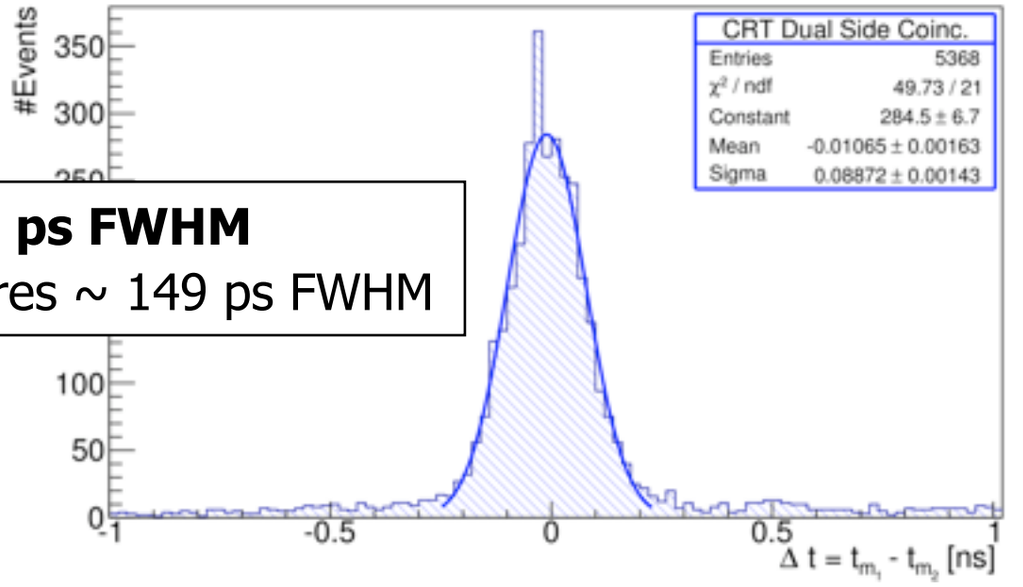
(b) dual sided readout with a mean timing



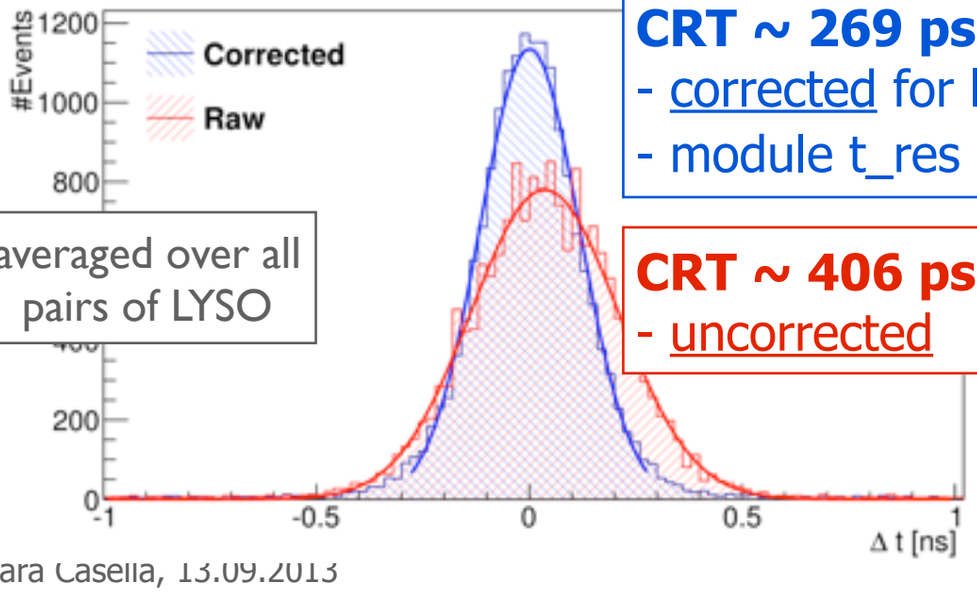
$t_m = (t_1+t_2)/2$



one pair of LYSO of the 2 modules setup



CRT ~ 211 ps FWHM
- module t_res ~ 149 ps FWHM

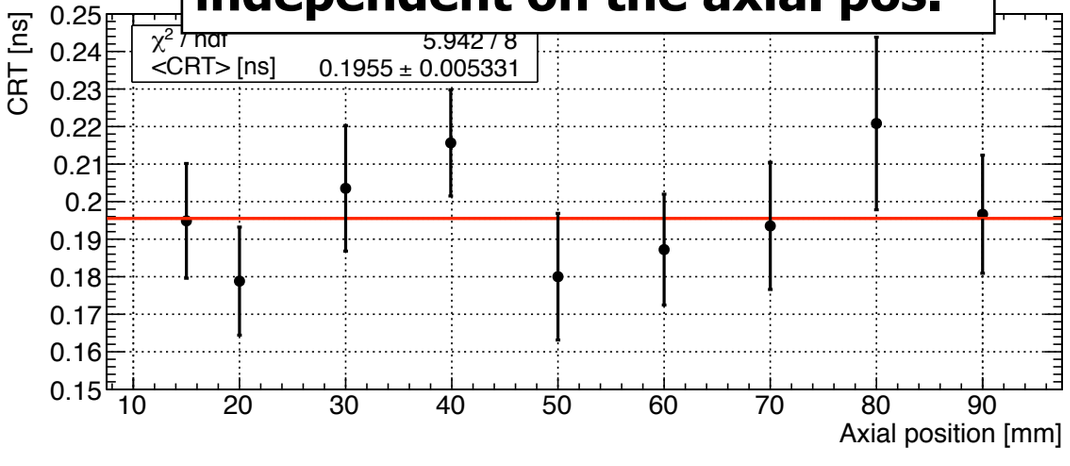


averaged over all pairs of LYSO

CRT ~ 269 ps FWHM
- corrected for light path
- module t_res ~ 190 ps FWHM

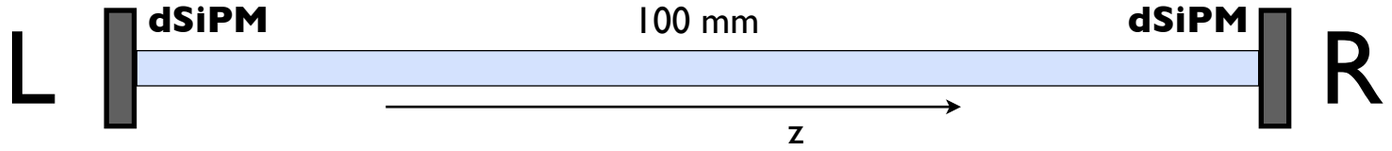
CRT ~ 406 ps FWHM
- uncorrected

independent on the axial pos.



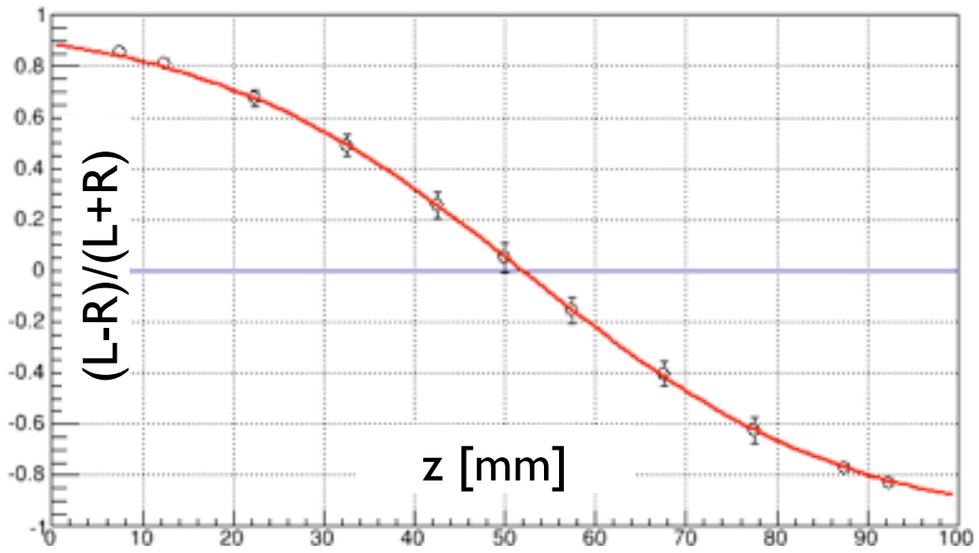
Dual sided readout: Axial coordinate

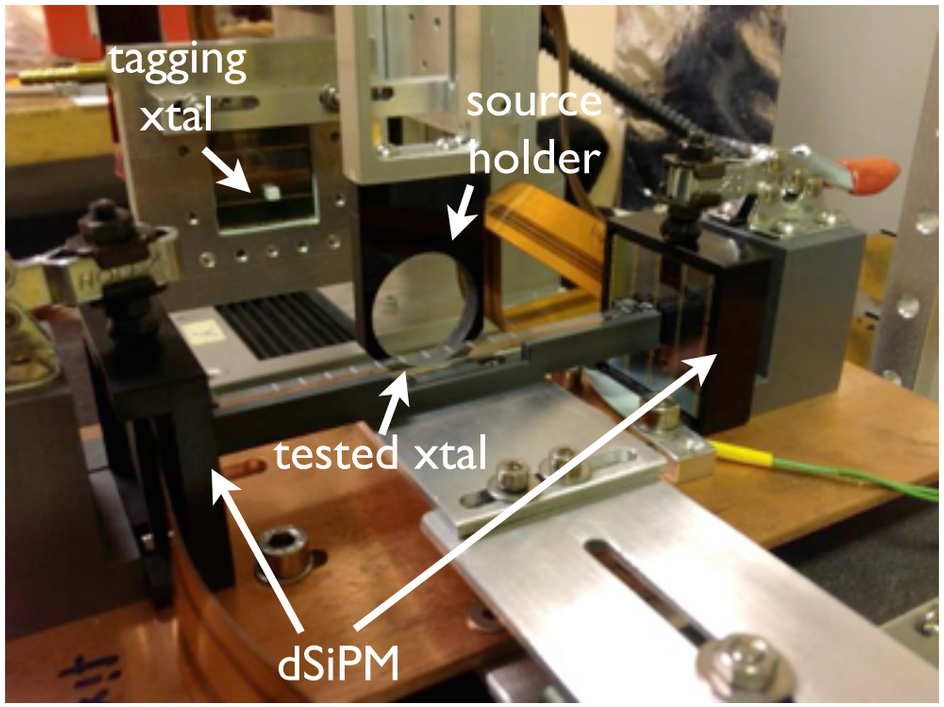
axial coordinate :



a) **by timing** (Δt) **?** No, achievable resolution is not good enough (7.5 ps/mm)

b) **by light sharing** (Δ light yield) **!**

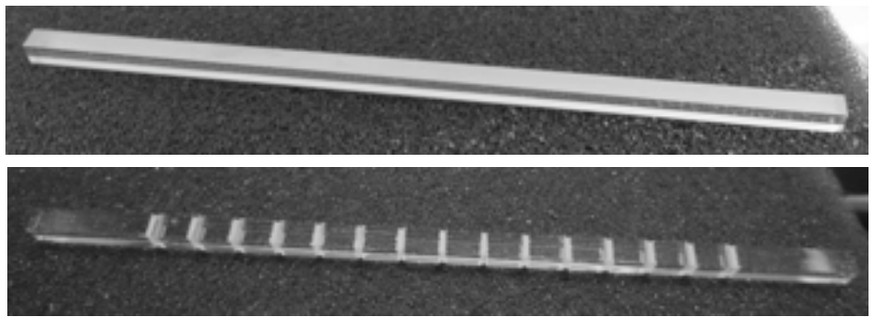


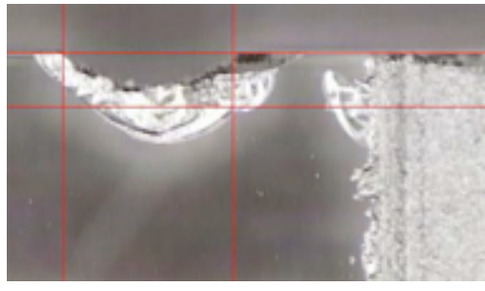


This method requires significant difference between L and R

=> artificially enhance attenuation length inside crystal
(e.g. **mechanical etching** of the crystal surface)

+ keep high enough global light yields (**wrapping**)





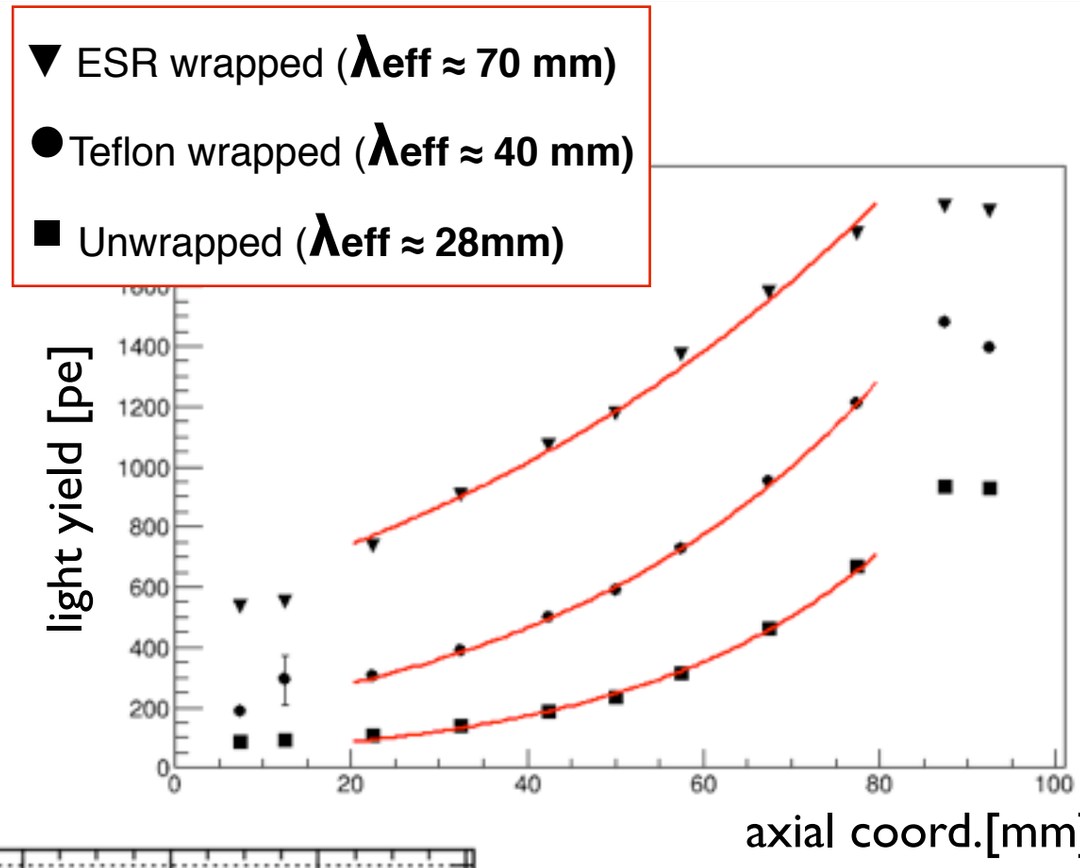
CNC machining diamond tool @ CERN

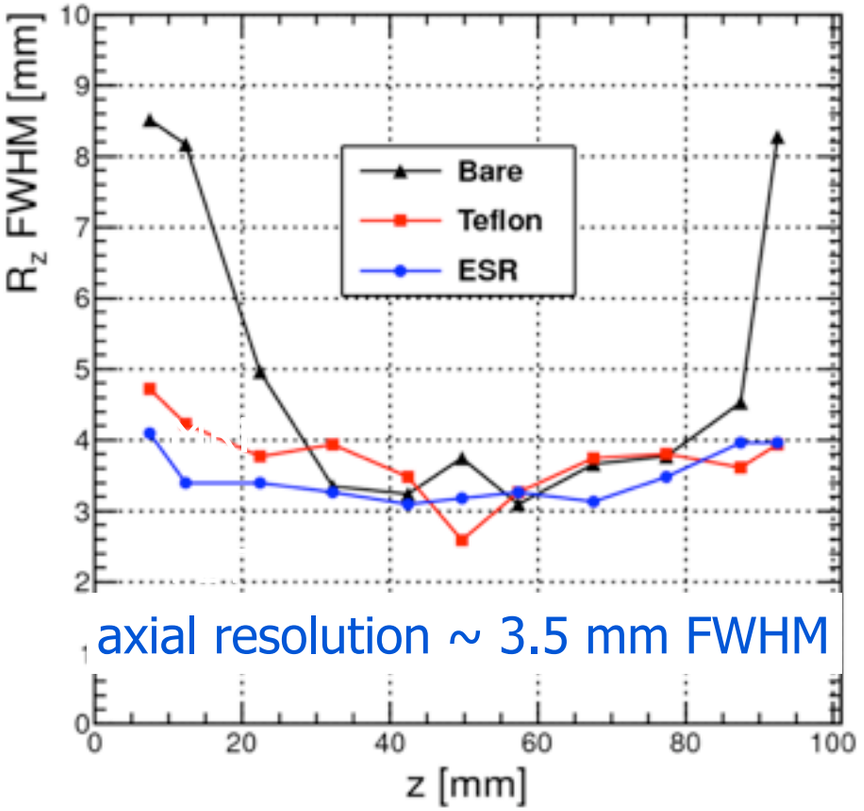
Dual sided readout: Axial coordinate

different etching patterns / wrapping tested

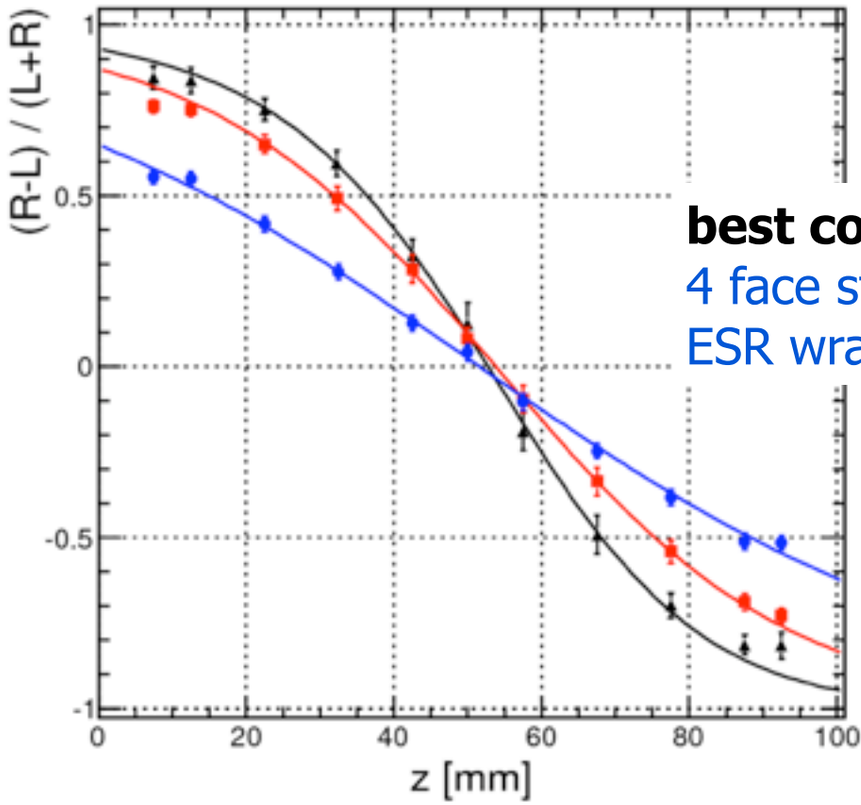
- Every 5mm, aligned on four faces

- Every 5mm, staggered by 1.25mm on four faces





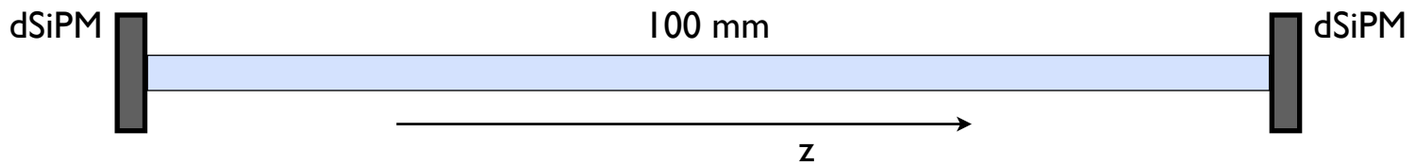
axial resolution ~ 3.5 mm FWHM



best configuration :
4 face staggered etching
ESR wrapping

Long crystals, dual sided dSiPM readout

Main conclusions :



- **timing perfs :**
  - dSiPM dual sided readout + mean timing method
  - bare crystals
  - **CTR ~ 200 ps , uniform along z**

competitive with state of the art
TOF-PET development
(with the complication of long crystals)

- **axial spatial resolution :**
  - dSiPM dual sided readout
  - surface treated crystals (etching) + wrapping ("spiral" etching pattern + ESR wrapping)
  - **R_{fwhm} ~ 3.5 mm, uniform along z**

not competitive with e.g. WLS solution
but advantages of:
simplicity
compactness
sensitivity
....

Interesting development towards new PET detectors ? (Best candidate : Brain TOF-PET)

Still to be done to complete this study :
- 60 mm long etched crystals : which axial resolution ?
- etched crystals (100 mm and/or 60 mm) : which timing resolution?

Talk at IEEE2013 - MIC conference (Oct 2013)

"Usage of long axial crystals for PET applications: the AX-PET demonstrator and beyond"

PET-MRI project

PET-MRI project

- **brand new project, just initiated at ETH**
- hybrid PET/MRI imaging : fused functional (PET) and morphological (MRI) information ++
- **goal**: conception - construction - characterization - commissioning of a fully operational **pre-clinical (i.e. small animals) PET detector insert**

  to be used :

  (a) inside the bore of a 7T commercial MRI scanner

  (b) at ETH/UniZh IBT - Institute for Biomedical Engineering

  (c) for quantitative dynamic hybrid imaging, in truly simultaneous PET and MRI acquisitions

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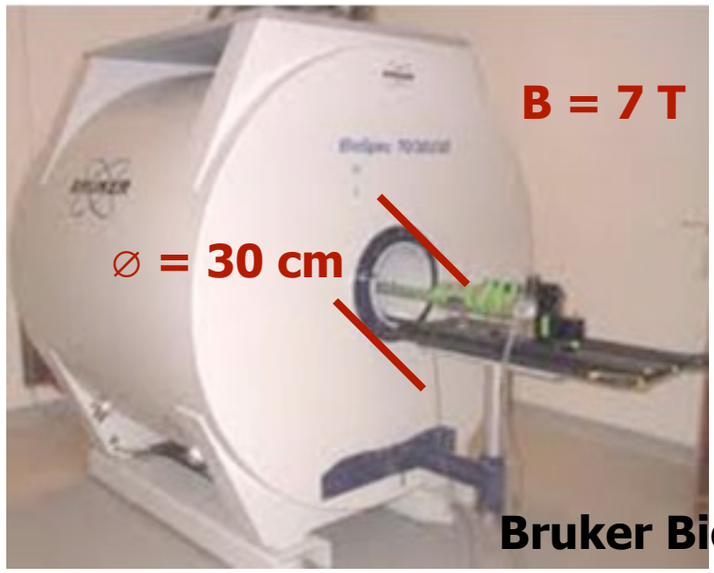

Bruker BioSpec 70/30

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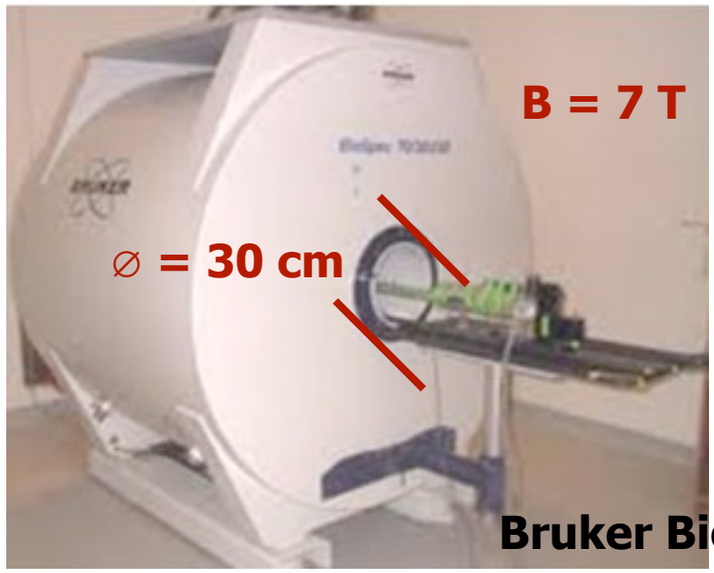


Bruker BioSpec 70/30

(b) at ETH/UniZh IBT - Institute for Biomedical Engineering

- interdisciplinary collaboration between **IPP** and **IBT**
- **IPP** (group Prof. Dissertori)
- **IBT :** (groups Prof. Rudin, Dr. Weber) : neurobiological researches **;** expertise in MRI and hybrid imaging ; no PET/MRI yet

(c) for quantitative dynamic hybrid imaging, in truly simultaneous PET and MRI acquisitions

Biomedical relevance & Detector requirements

- **Target**: form fast dynamic images of mice organs (brain / hearth) to study the kinetics of different (high speed) biological processes
  e.g. Cerebral Blood Flow (CBF)
  - changes up to 20% in the blood flow in secs
  - excellent tracer : O-15 (t1/2 ~ 2 mins)

=> **FAST ACQUISITIONS** (5-10 secs duration)
at VERY HIGH REPETITION RATE (every few secs)

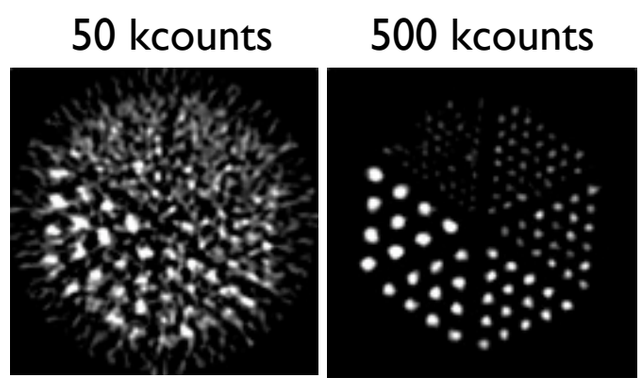
- Goal :
  - Understanding of the biological processes
  - Explore the possibility of using MRI as a quantitative functional tool (eventually replacing PET)

=> **PERFECT TIME CORRELATION PET/MRI** (TRUE SIMULTANEITY)
=> **Full compatibility with / to magnetic field from MRI**

NOVELTY in PET & PET/MRI !

- Short time acquisition => potentially too low stats for high quality images
  => high dose injection (~ 500 MBq, x10 wrt standard) (1Bq = 1Hz)

=> **HIGH RATE CAPABILITIES**
=> SMALLEST POSSIBLE COINCIDENCE WINDOW
(to minimize the effects of the random coincidence)
=> **VERY GOOD TIME RESOLUTION**



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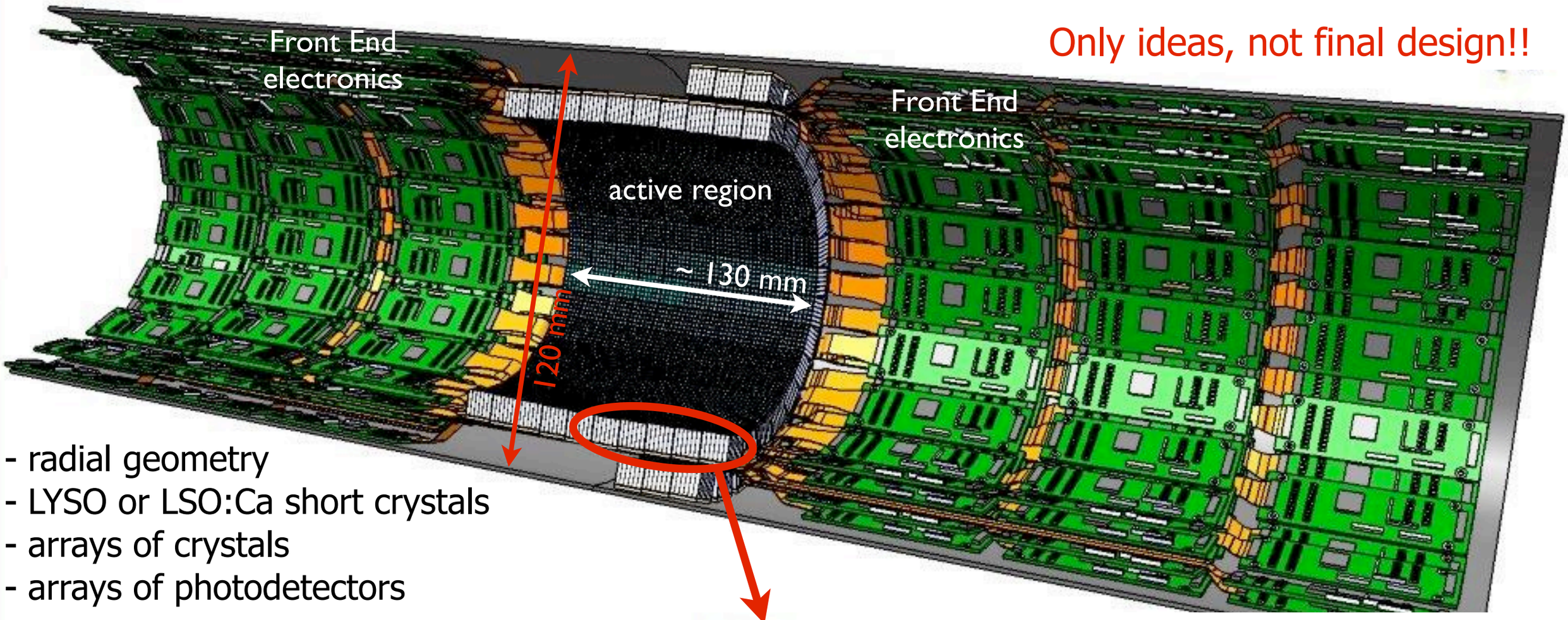
=> **VERY GOOD TIME RESOLUTION**
HIGH SPATIAL RESOLUTION (~mm)
VOLUME CONSTRAINTS
SHORT TIME SCALE (~ few years)

detector requirements specifically targeted to a medical application (PET) but not far from the constraints of standard HEP experiments...

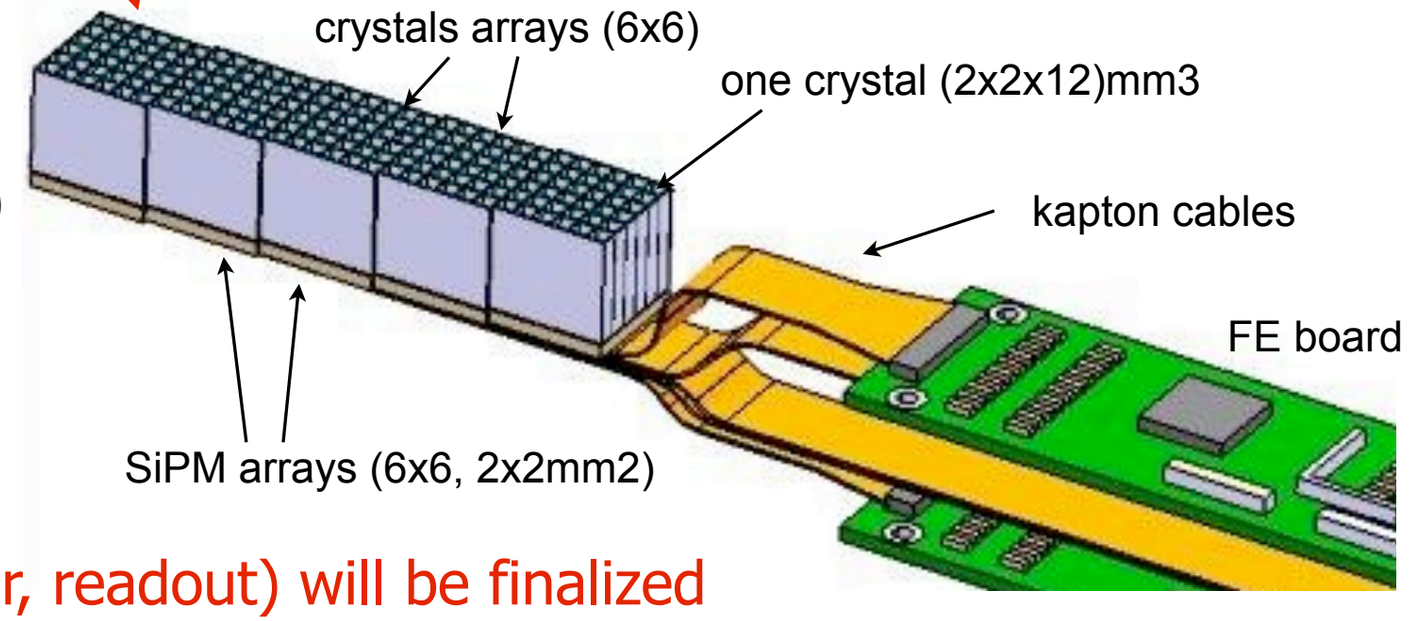
Possible geometrical layout

Only ideas, not final design!!



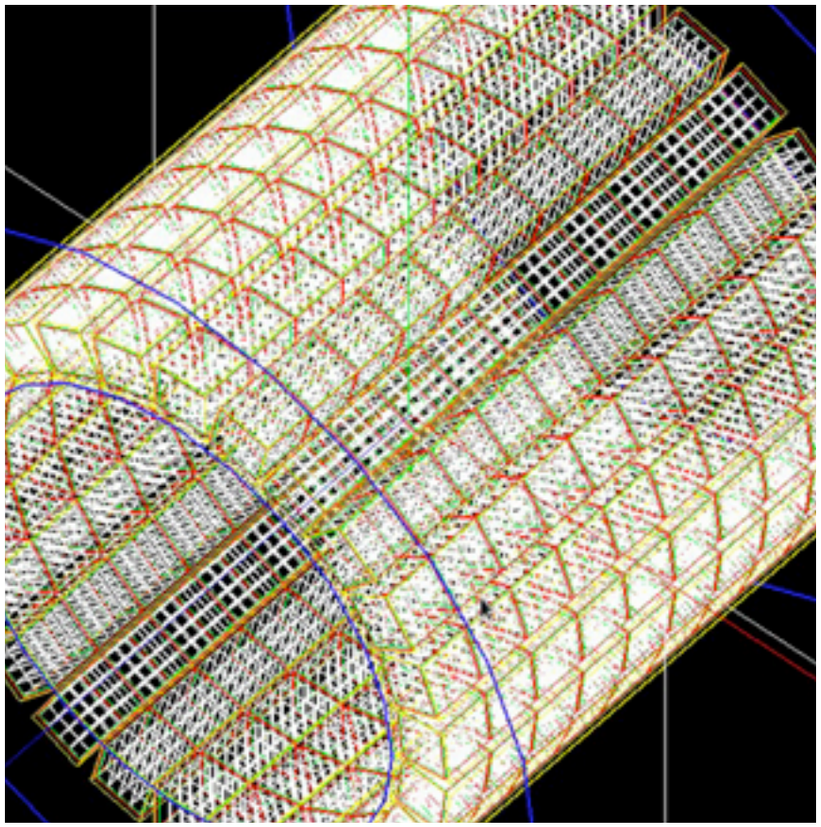
- radial geometry
- LYSO or LSO:Ca short crystals
- arrays of crystals
- arrays of photodetectors

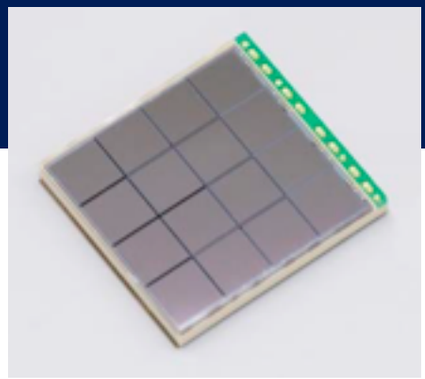
in this example:
2x2X12 mm3 crystals
SiPM arrays Hamamatsu (6x6, 2x2mm^2 ; not existing)



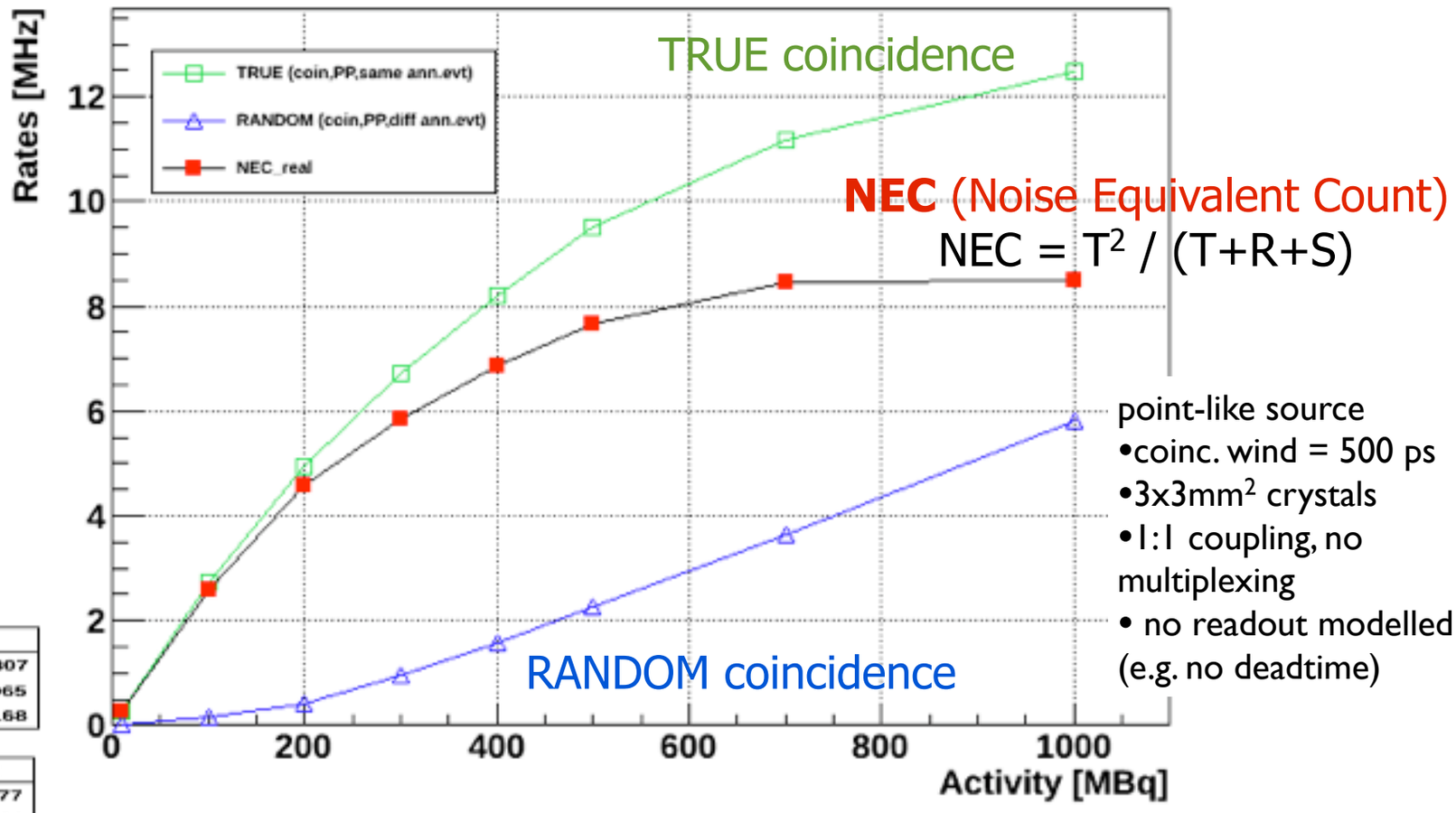
Design (detector solution, photodetector, readout) will be finalized only after dedicated studies involving both simulations and lab tests

Simulations GATE (G4 toolkit for PET)

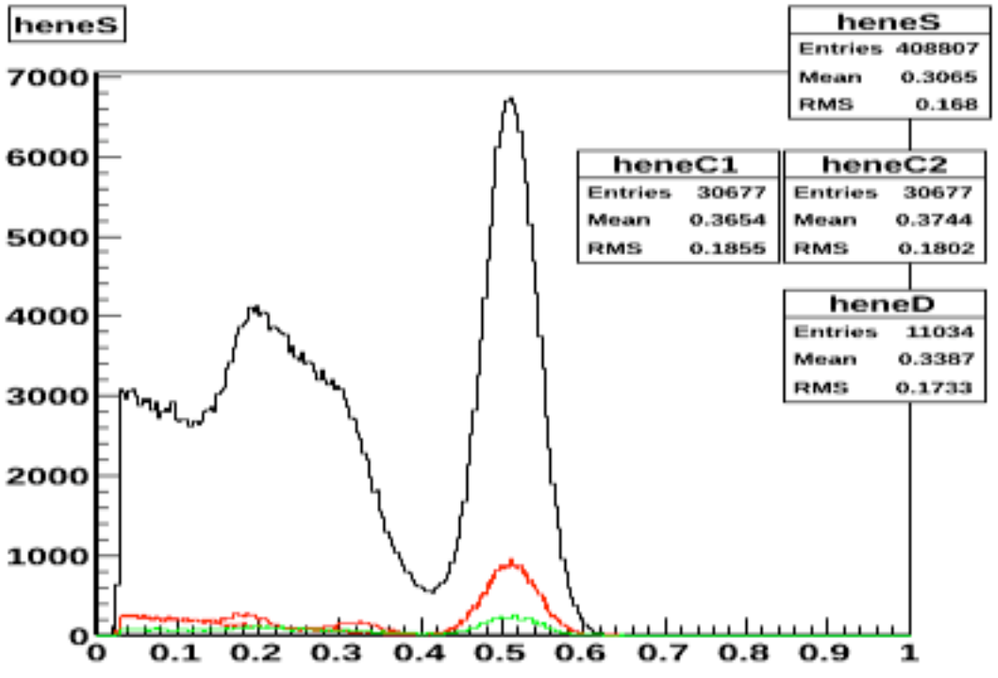




Monolithic MPPC array in SMD package S11828-3344M
existing layout : **3x3 mm2 / channel**
4x4 channels array



- point-like source
- coinc. wind = 500 ps
- 3x3mm² crystals
- 1:1 coupling, no multiplexing
- no readout modelled (e.g. no deadtime)



crystal size [mm³]	Nchannels	rate/crystal (@500MHz)
3x3x12	4160	~ 100 kHz
2x2x12	9360	~ 45 kHz
1x1x12	37440	~ 10 kHz

PET-MRI: Status & Conclusions

Innovative, high performance, fully MRI-compatible PET insert for quantitative dynamic PET/MRI hybrid imaging (small animals)

Evaluative phase started (expected duration ~ 1 year)

- decision on the detector/geometry layout
- photodetectors and readout system
- MonteCarlo Geant4 (GATE) simulations + small scale lab measurements
- MRI compatibility
- at the end of the evaluation phase : assessment of the expected performance

Agreement with ETH/UniZh authorities => Significant refurbishing of lab space at ETH Honggenberg with direct access to in-situ cyclotron facility (works started)
- MRI scanner : expected by 2nd half 2014

Partners in the collaboration :

- ETH Institute for Particle Physics (IPP), G. Dissertori
- ETH/UniZh Institute for Biomedical Engineering (IBT), M. Rudin/B. Weber
- RWTH Aachen, department of Experimental Molecular Imaging, V. Schulz

... NEW PARTNERS ARE WELCOME !

ETH grant for 2 PhD students
Open post-doc position at ETH-IPP

Not much material to show so far, only ideas at the moment!
See you in the next CHIPP R&D workshop!