Recent developments in photodetection for medical applications

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IRIS group http://ific.uv.es/iris

7th international conference on New developments in photodetection.
Tours, France, June 30th -July 4th 2014.

Outline

- Detectors for medical applications
- Positron Emission Tomography (PET)
  - Innovative designs
  - Depth Of Interaction(DOI)
  - PET-MR
  - Time of Flight (TOF)
  - Other
- Intra-operative probes and gamma cameras
- Hadron Therapy
  - Beam monitoring
  - Treatment monitoring

Detectors for medical applications

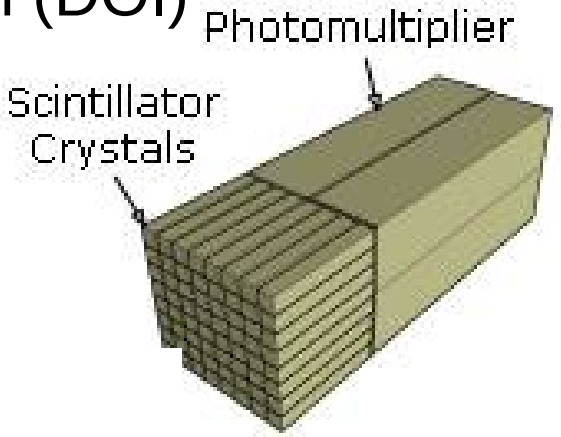
- What and what not:
  - Medical applications in general with advance in medical diagnostics -> *Nuclear medical imaging*
  - Trends:
    - Scintillators + Photodetectors – SiPMs ***YES***
    - ~~Solid State: SPECT, PET, Compton Cameras~~ ***NO***
- Requirements:
  - Higher PDE -> Better energy, timing and spatial resolution.
  - Compact, stable, low cost.
  - Insensitive to magnetic fields -> Compatible with Magnetic Resonance Imaging

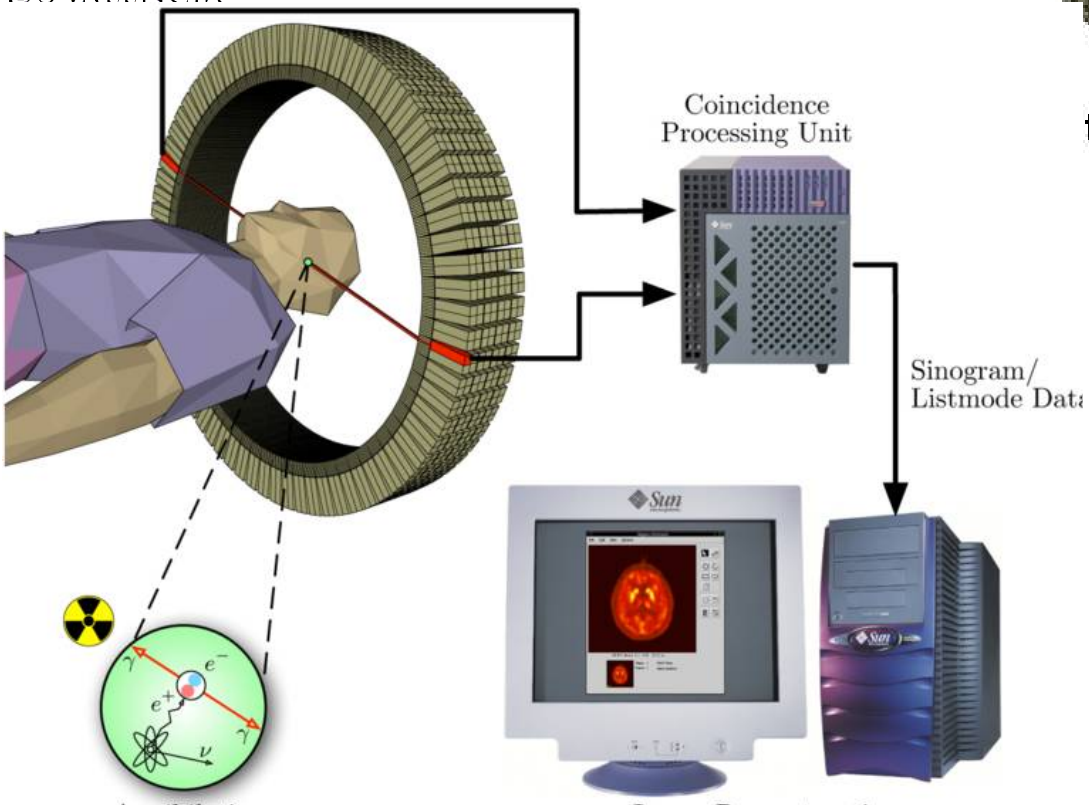
Some examples- my personal choice. dSiPMs

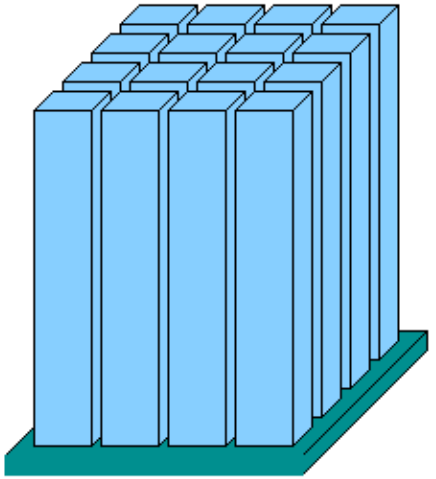
Positron Emission Tomography

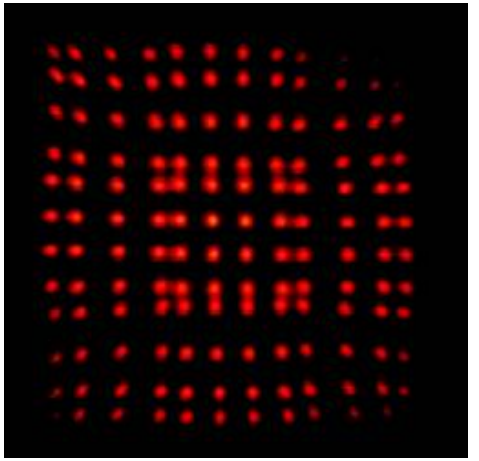
- New detector designs
- Depth Of Interaction (DOI)
- PET-MR
- Time Of Flight
- Other

Conventional PET detector



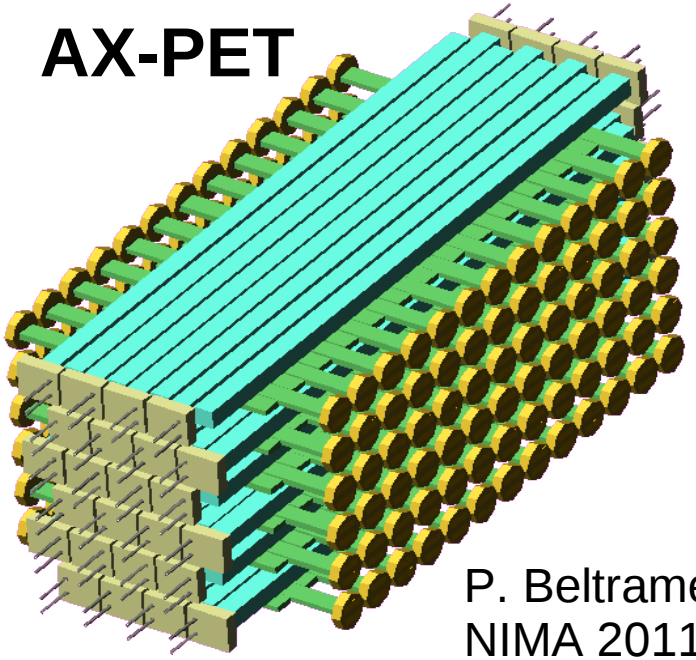




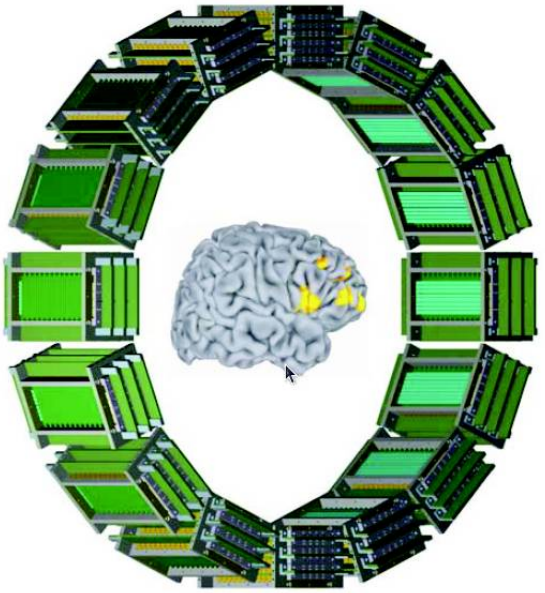


Innovative detector designs with SiPMs

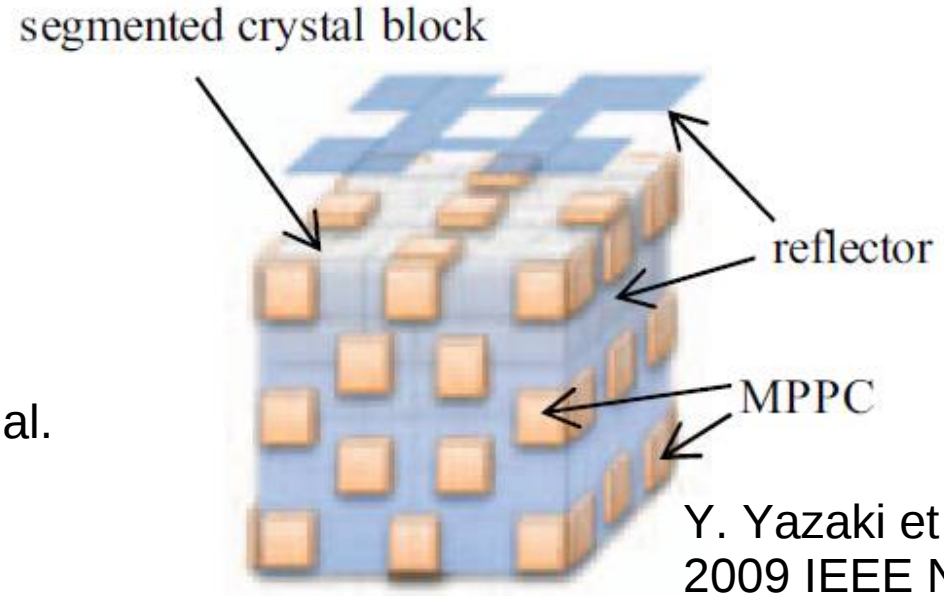
AX-PET



P. Beltrame et al.
NIMA 2011



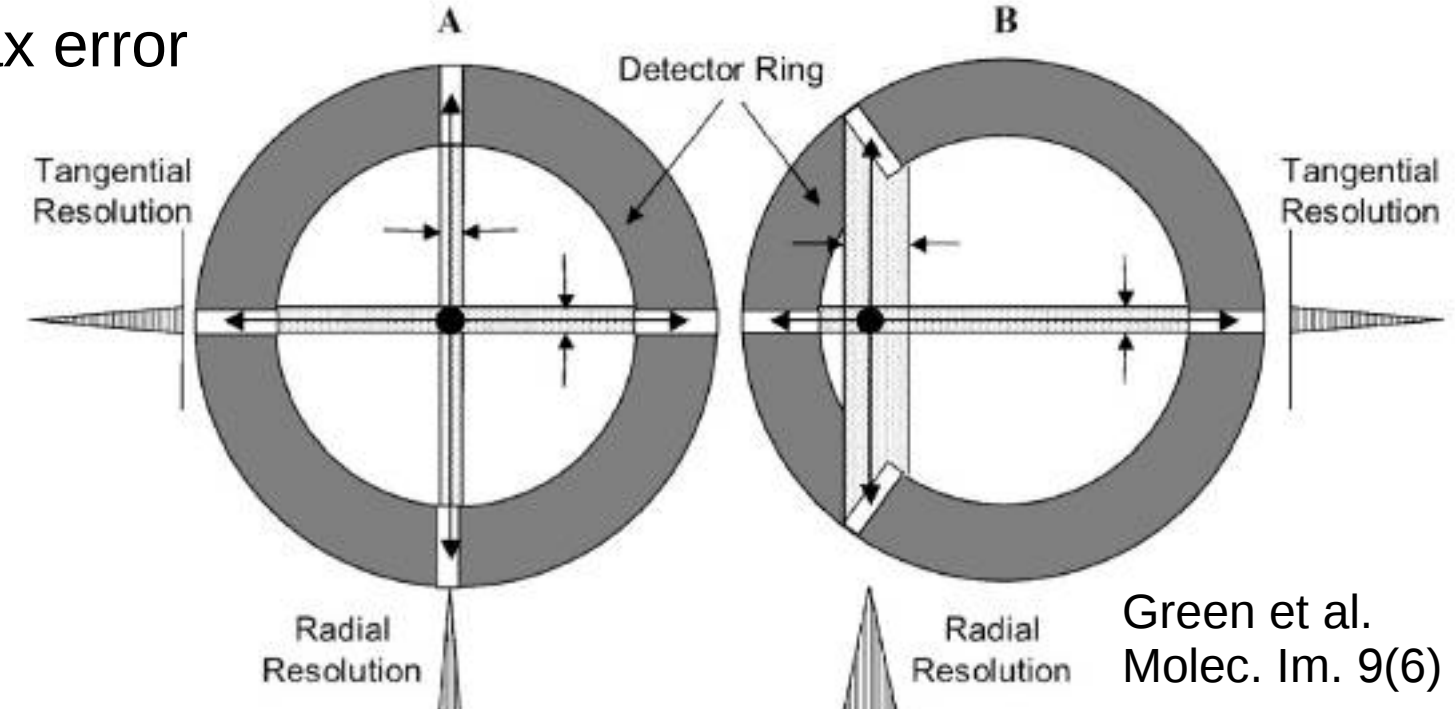
X'tal cube



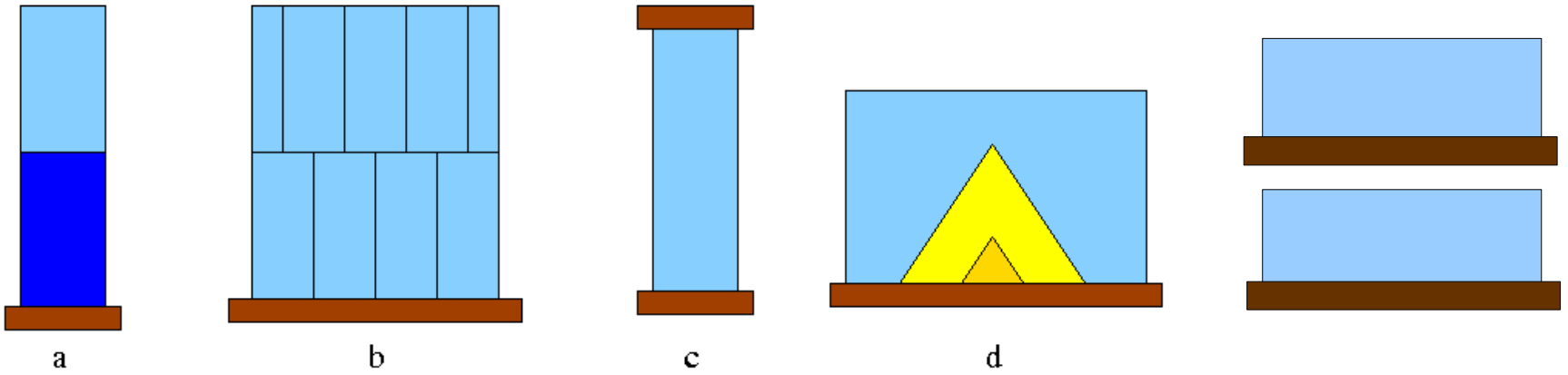
Y. Yazaki et al.
2009 IEEE NSS
MIC Conf Rec

Depth Of Interaction (DOI)

Parallax error

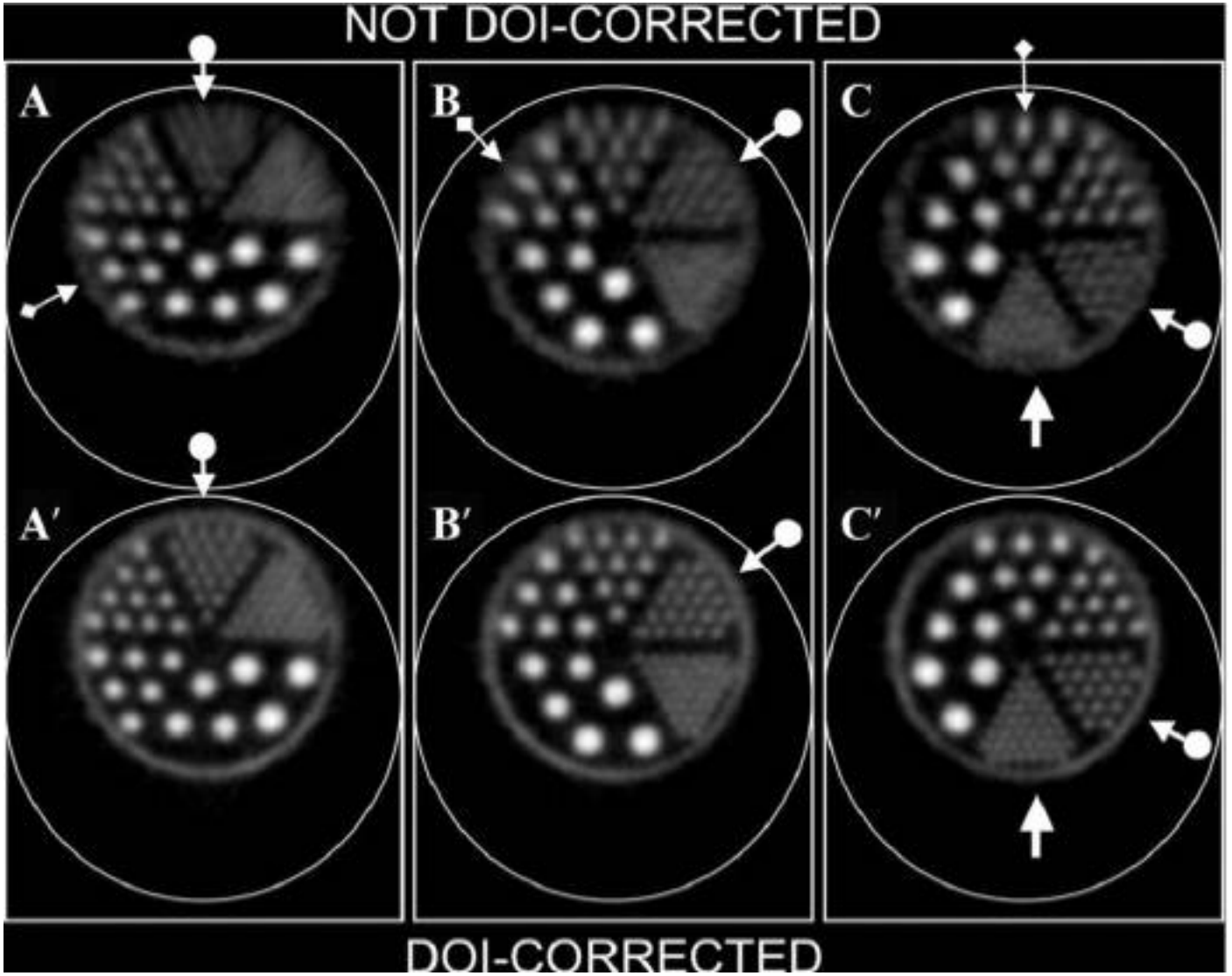


Green et al.
Molec. Im. 9(6) 2010

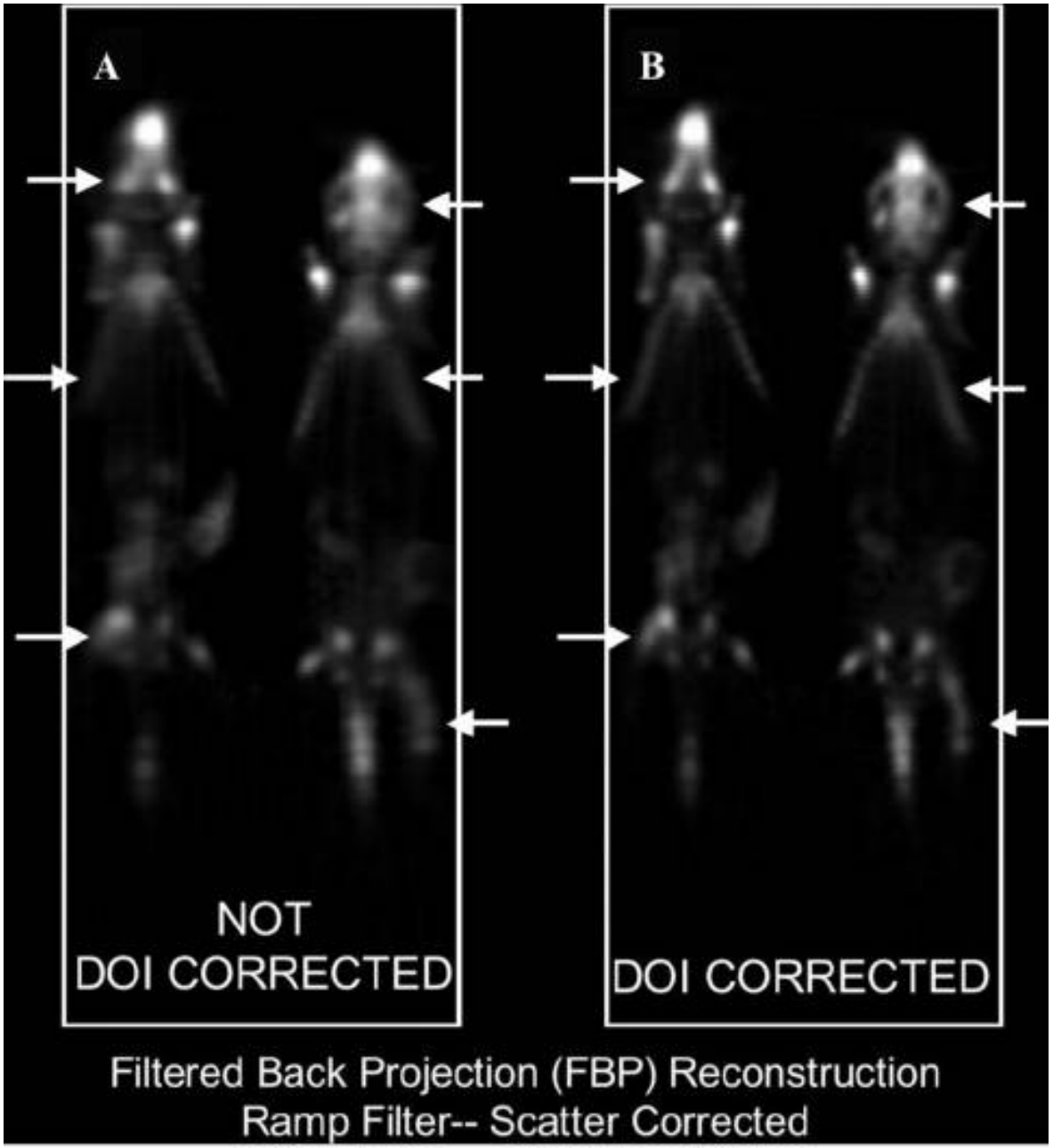


DOI

Green et al.
Molec. Im. 9(6) 2010



DOI

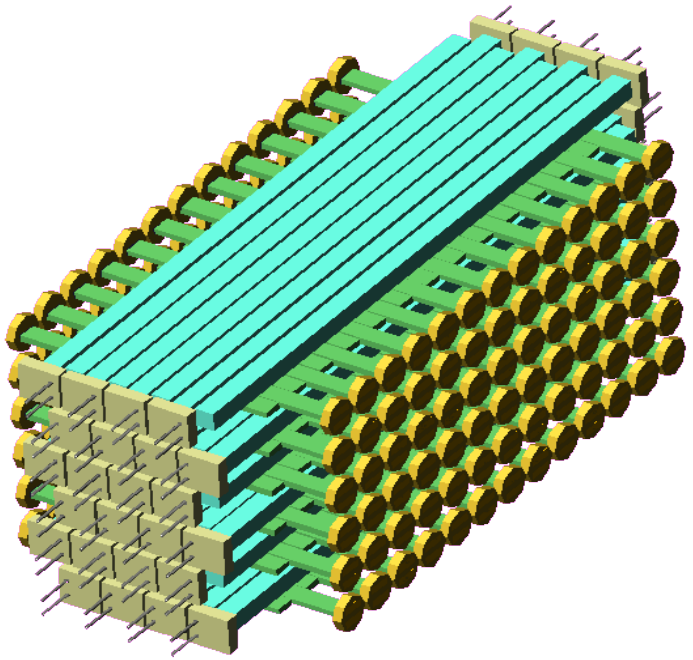


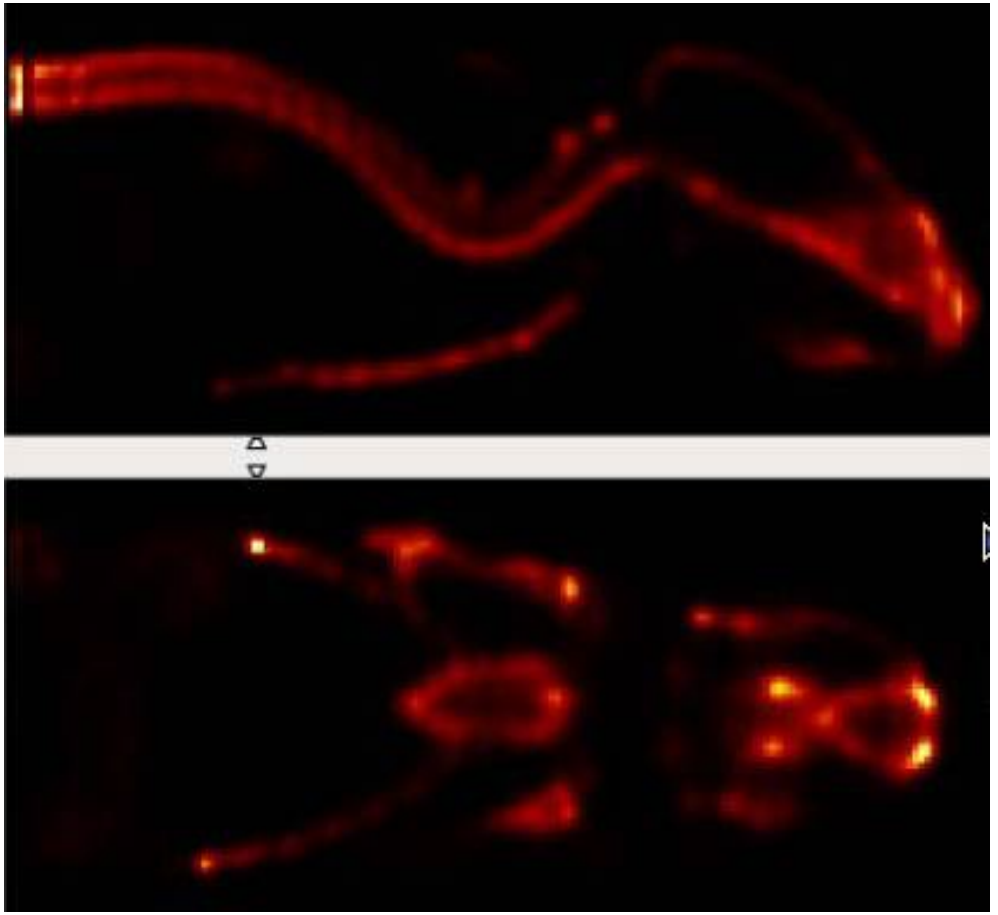
Green et al.
Molec. Im. 9(6) 2010

DOI

- AX-PET working prototype

E. Bolle et al. 2013 IEEE NSS MIC Conf Rec. M03-2.

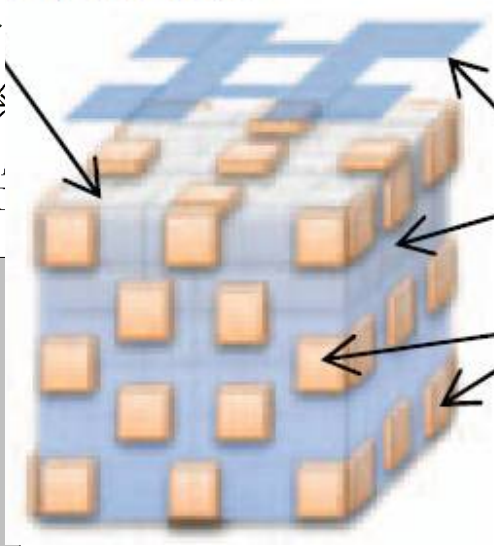




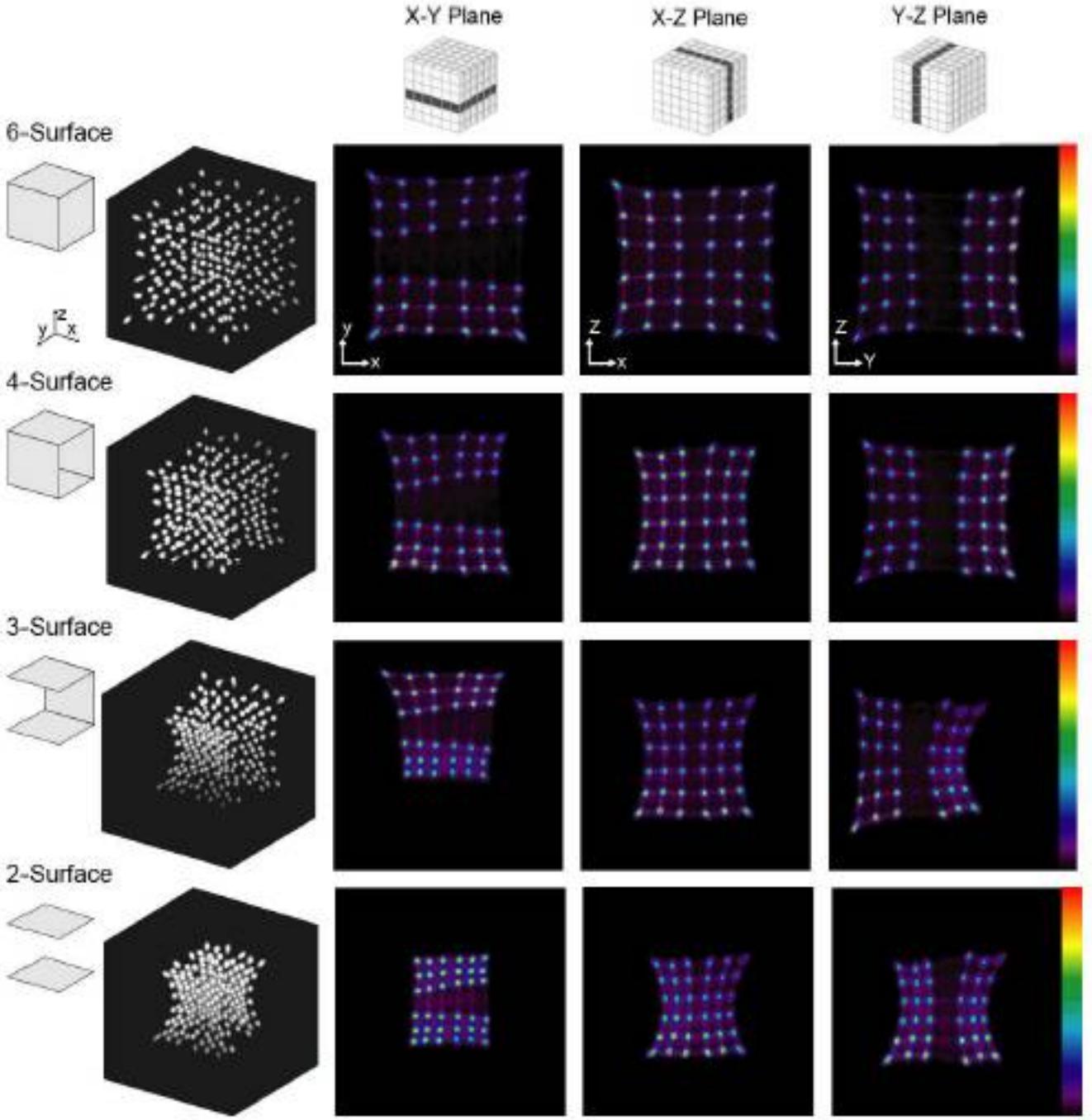
DOI

X'tal cube

3D position determination

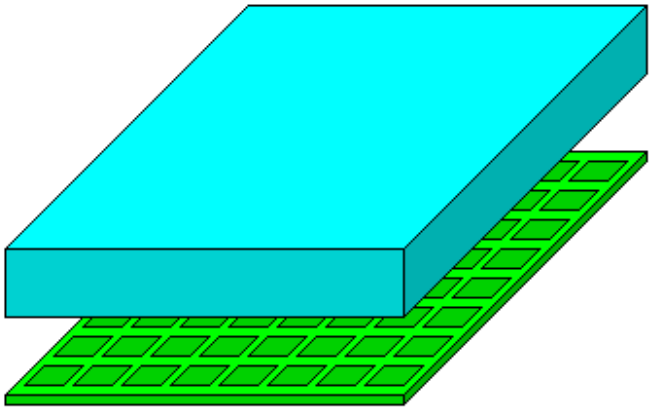


Y. Yazaki et al.
2009 IEEE NSS MIC Conf Rec



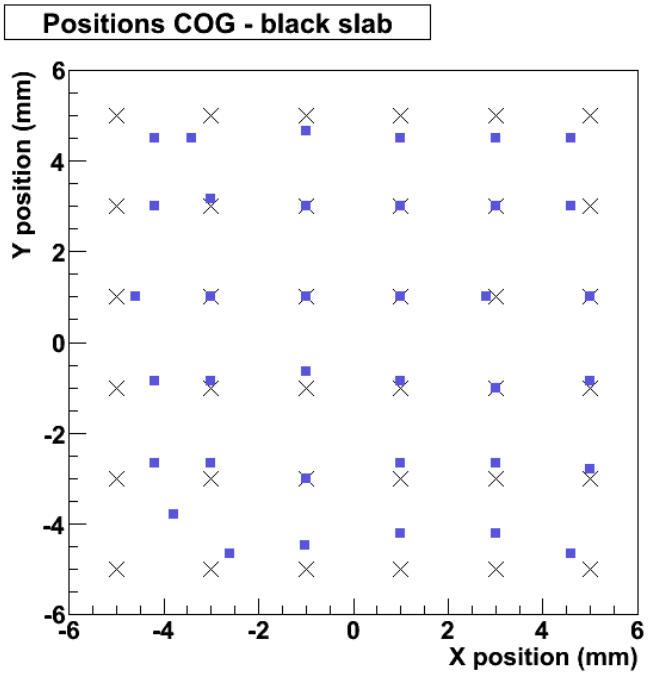
Continuous crystals

- Renewed interest in continuous crystals - white

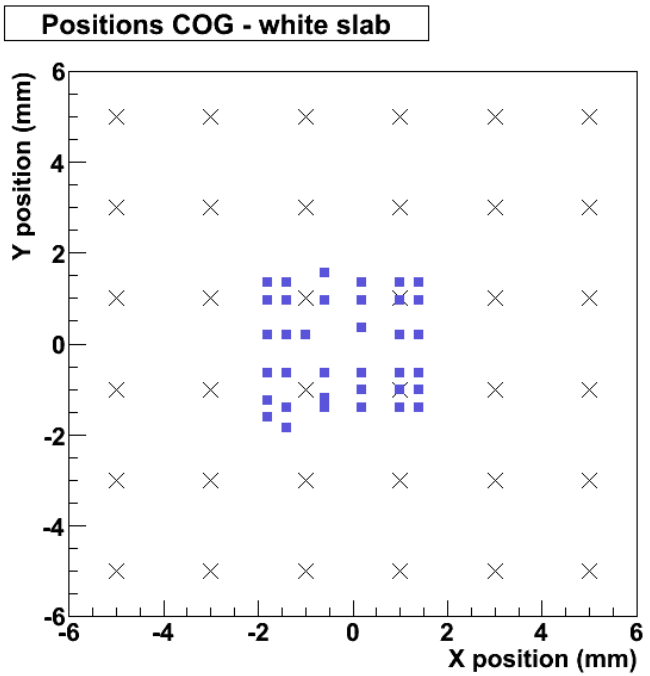


Position determination with COG algorithm:

Black crystal



white crystal



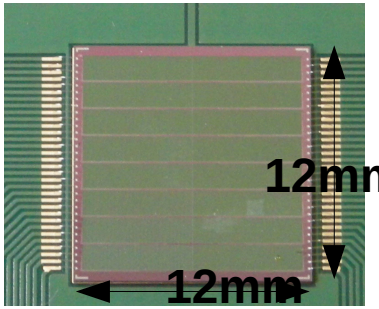
Accurate positioning algorithms required

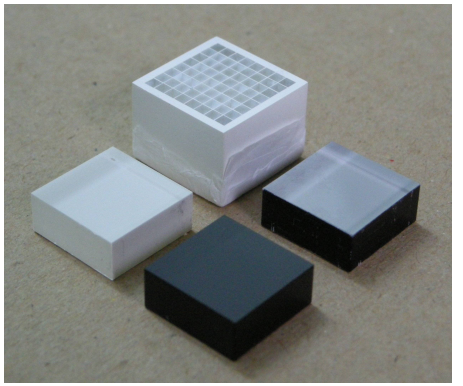
Continuous crystals

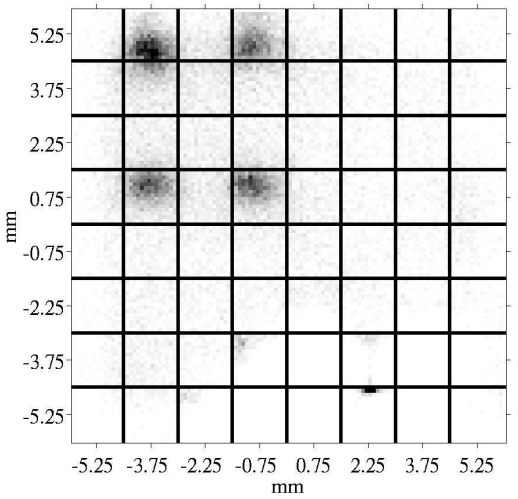
- Continuous LYSO crystals

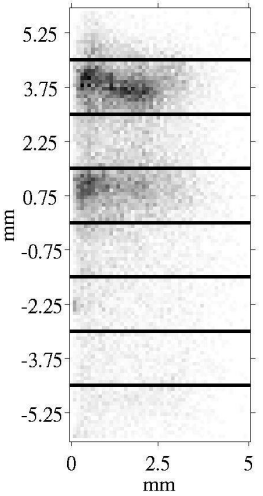
  12 x 12 x 5/10 mm^3
- SiPM arrays

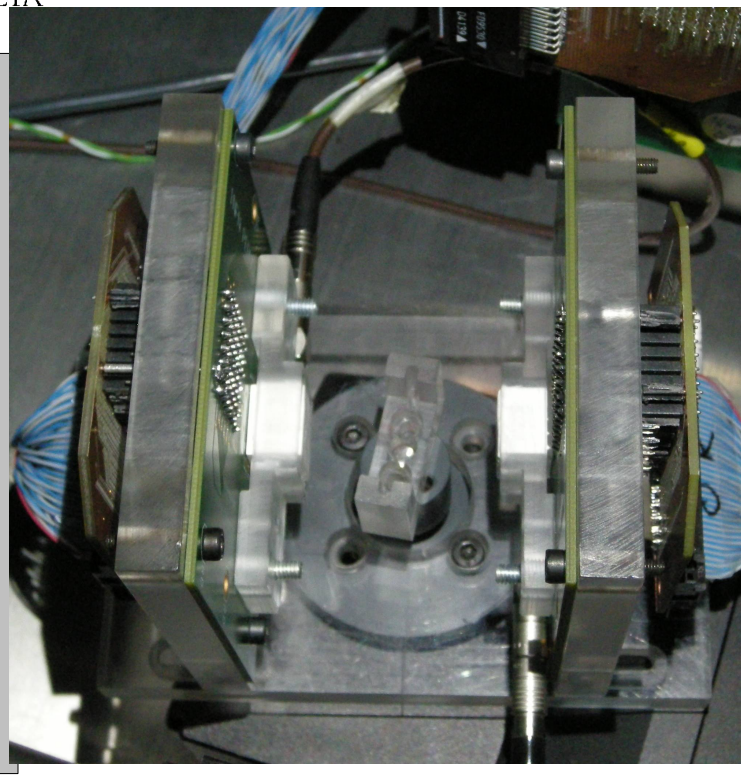
  1.4 x 1.5 mm pitch

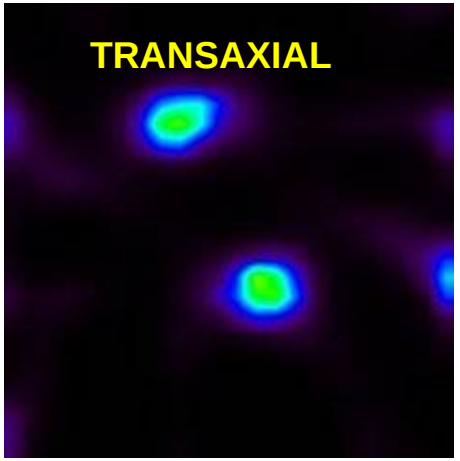












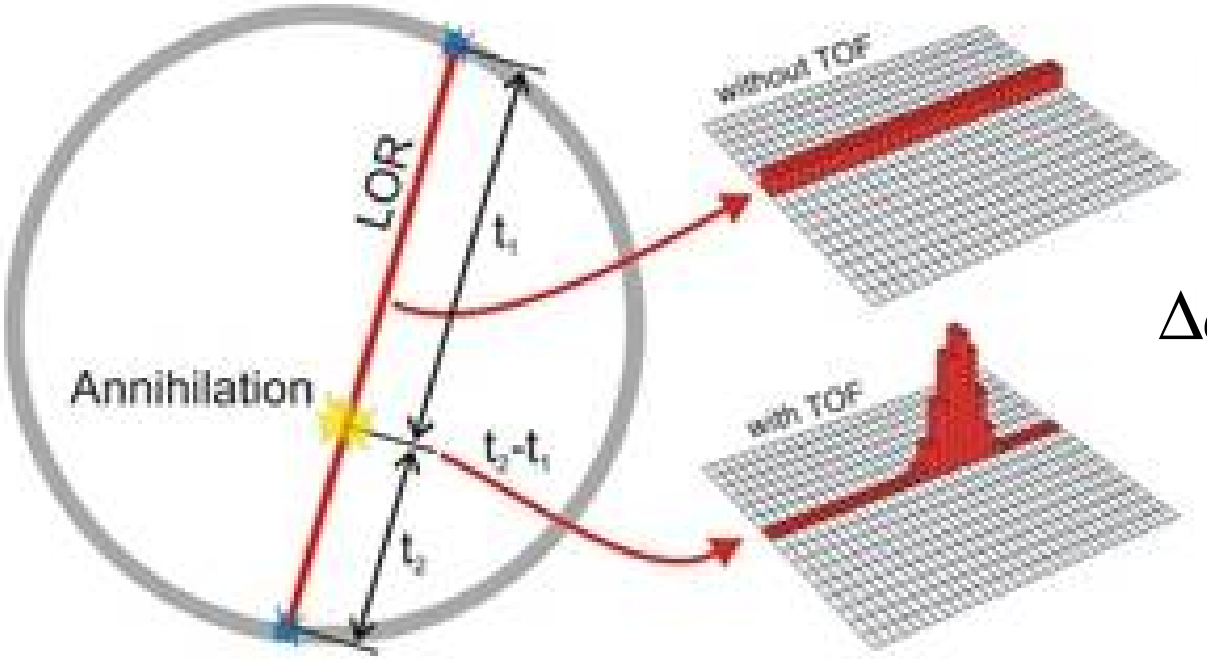
Intrinsic resolution
0.7 mm FWHM

FWHM better than 1 mm

Llosá et al. NIM A 2012

Time of Flight PET

- Good timing resol. allows to reject accidental coincidences
- Very good: TOF-PET.



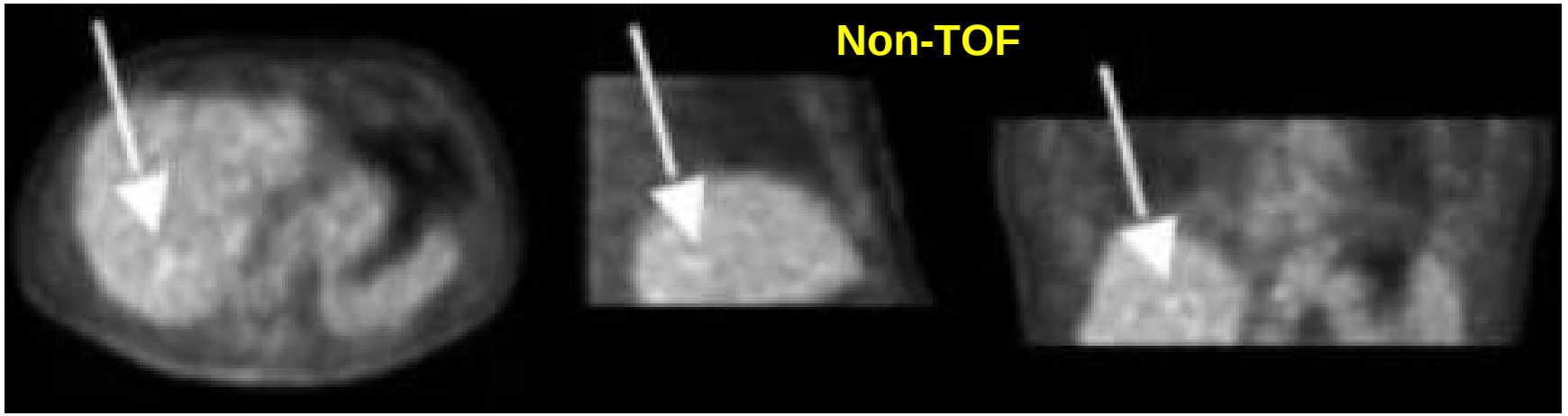
$$\Delta d = \Delta t \times \frac{c}{2}$$

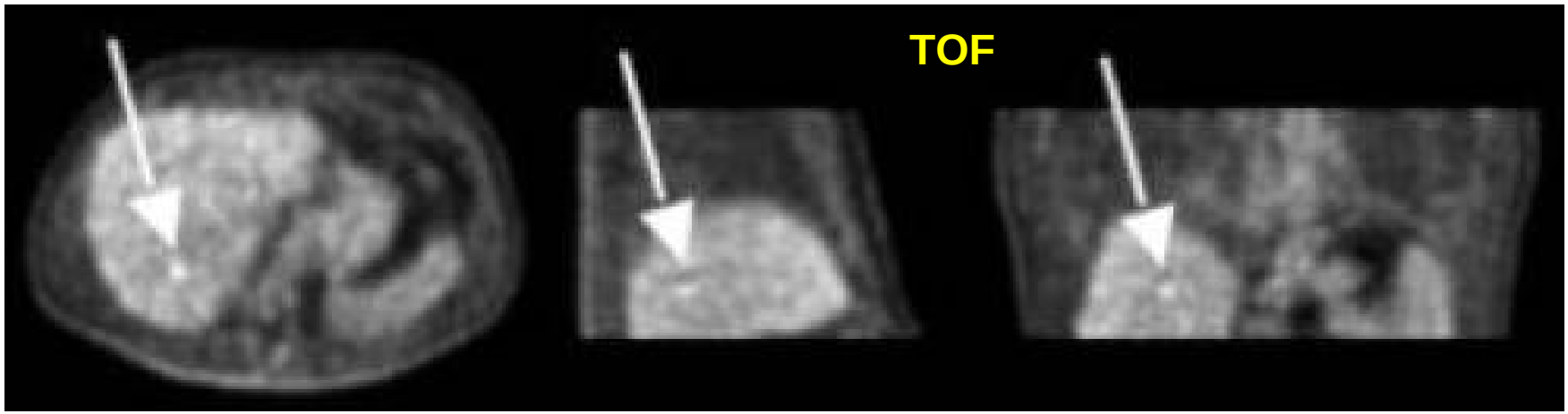
Commercial systems: coincidence timing resolution
~ 500 ps FWHM

TOF-PET

Surti et al.
J Nucl Med 52(5). 2011

- Liver lesion





- Photodetectors: PMTs, MCPs, SiPMs, DSiPMs

TOF-PET

- Research results beter than 200 ps with small crystals

101 ps FWHM with

- $LaBr_3$:Ce crystals
  3 x 3 x 5 mm^3
- Hamamatsu MPPCs 3x3mm^3, 50 x 50μm^3 microcells
- Own electronics

D. Schaart et al, PMB 2010

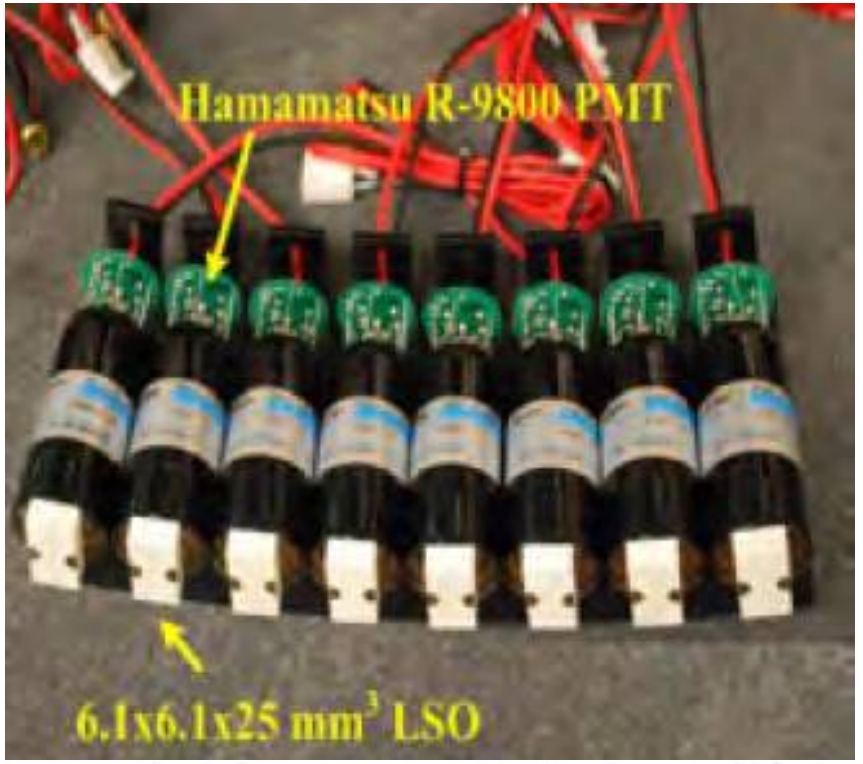
170 ps FWHM with

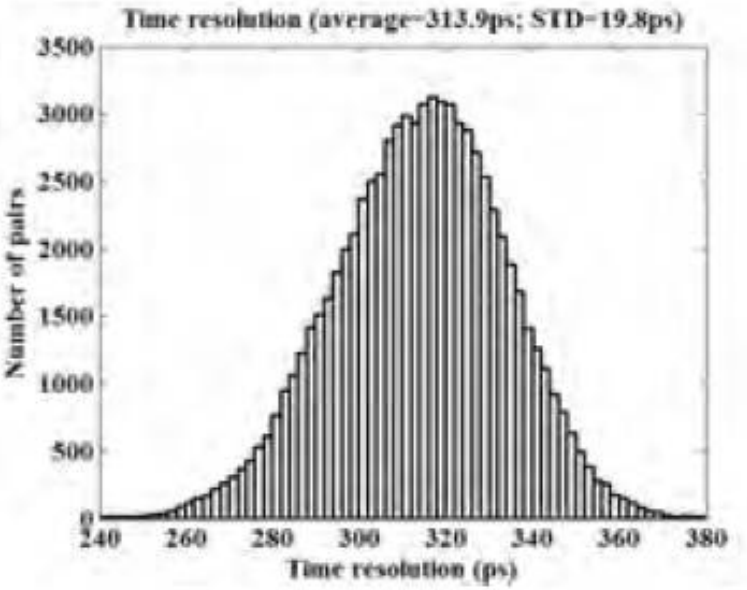
- LSO_3:CeCa crystals
  2 x 2 x 20 mm^3
- Hamamatsu MPPCs 3x3mm^3, 50 x 50μm^3 microcells
- NINO ASIC

E. Auffray et al, 2011 IEEE NSS MIC CR

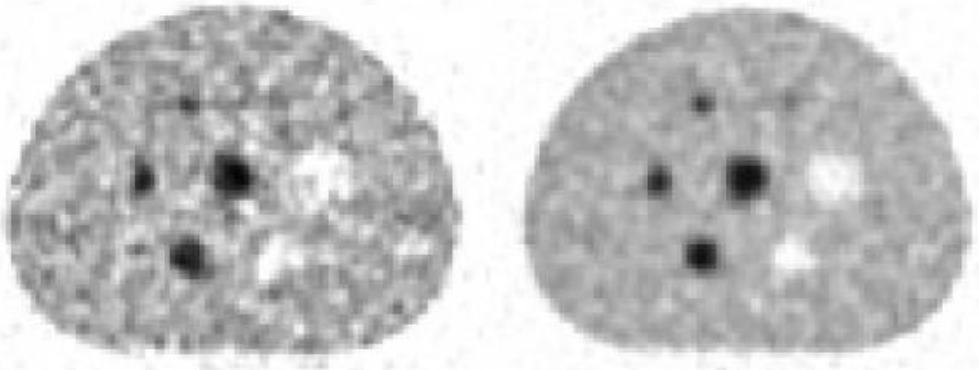
TOF-PET

- Full ring with PMTs. 76.6 cm diameter. 192 detector modules, 384 scintillator crystals.





System timing resolution
314 ± 20 ps FWHM

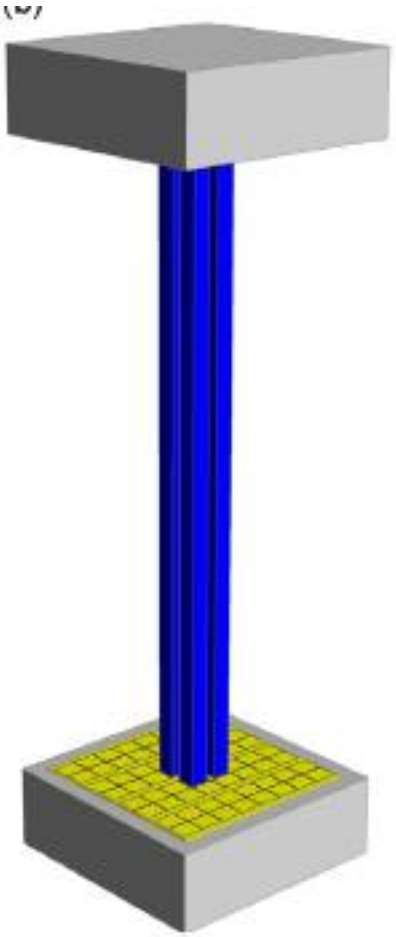


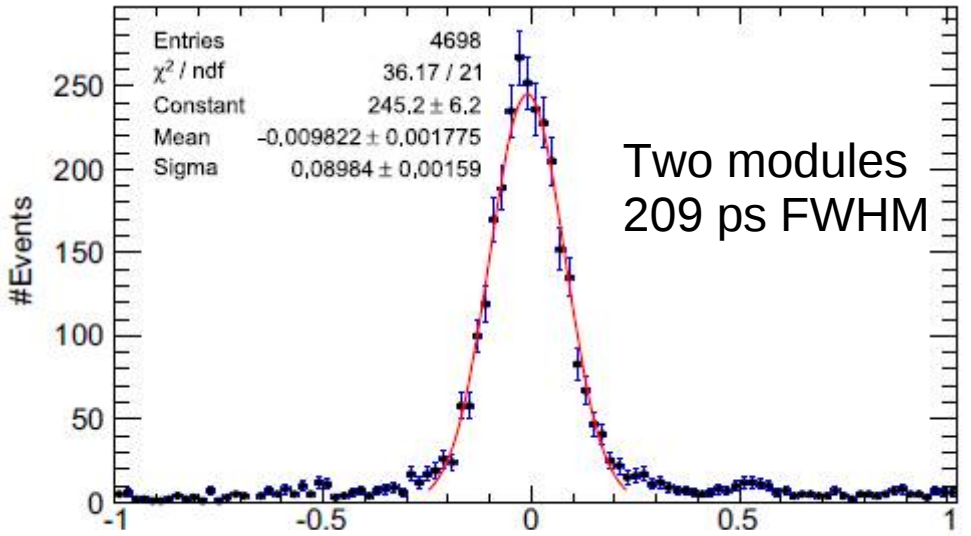
Q. Peng et al.
2103 IEEE NSS MIC M11-1

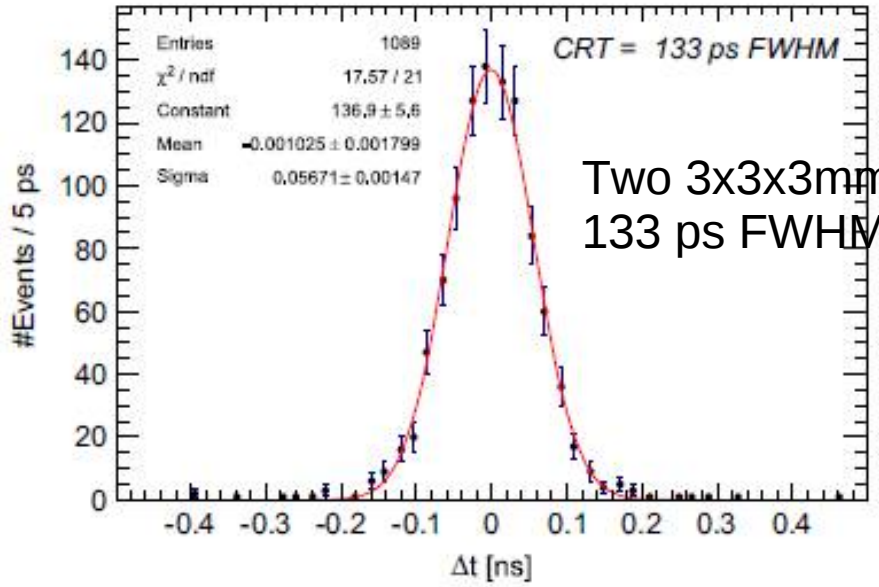
TOF-PET

Casella et al. NIMA 736, 2014

- Module: four 100 mm LYSO crystals coupled to dSiPMs on both sides

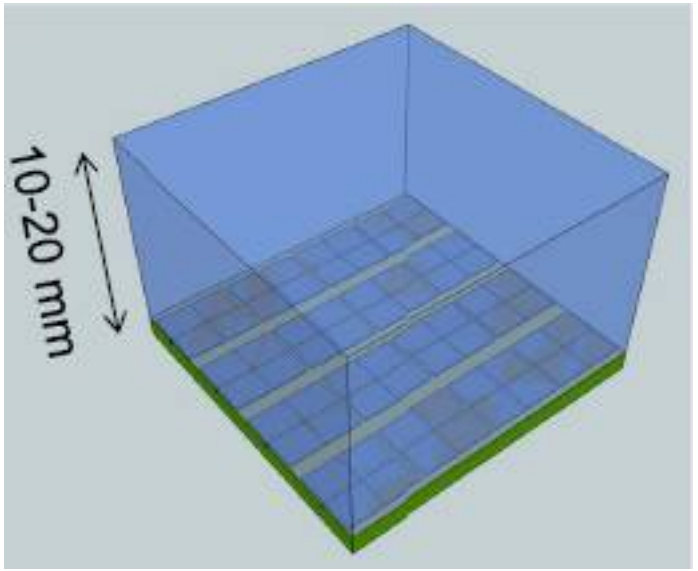






TOF-PET

- Monolithic LYSO crystals + dSiPMs

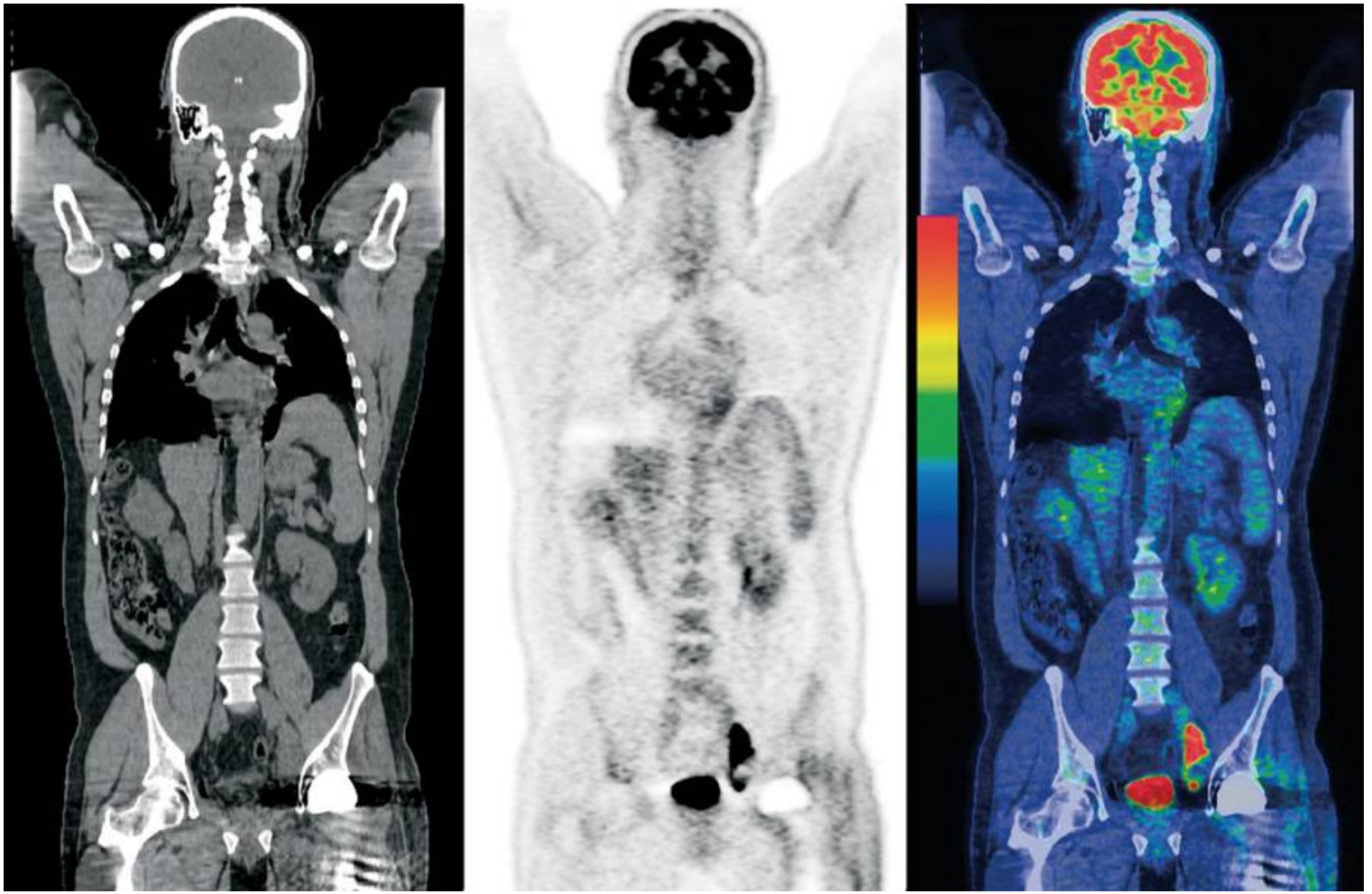


D. Schaart.
ICTR-PHE 2014

Performance parameter		Monolithic	State of the art
Energy resolution	(% FWHM)	11 - 12	~12
Spatial resolution	(mm FWHM)	1.0 - 1.6	4 - 6
DOI resolution	(mm FWHM)	3 - 5 mm	None
CRT	(ps FWHM)	160 - 185	500 - 650

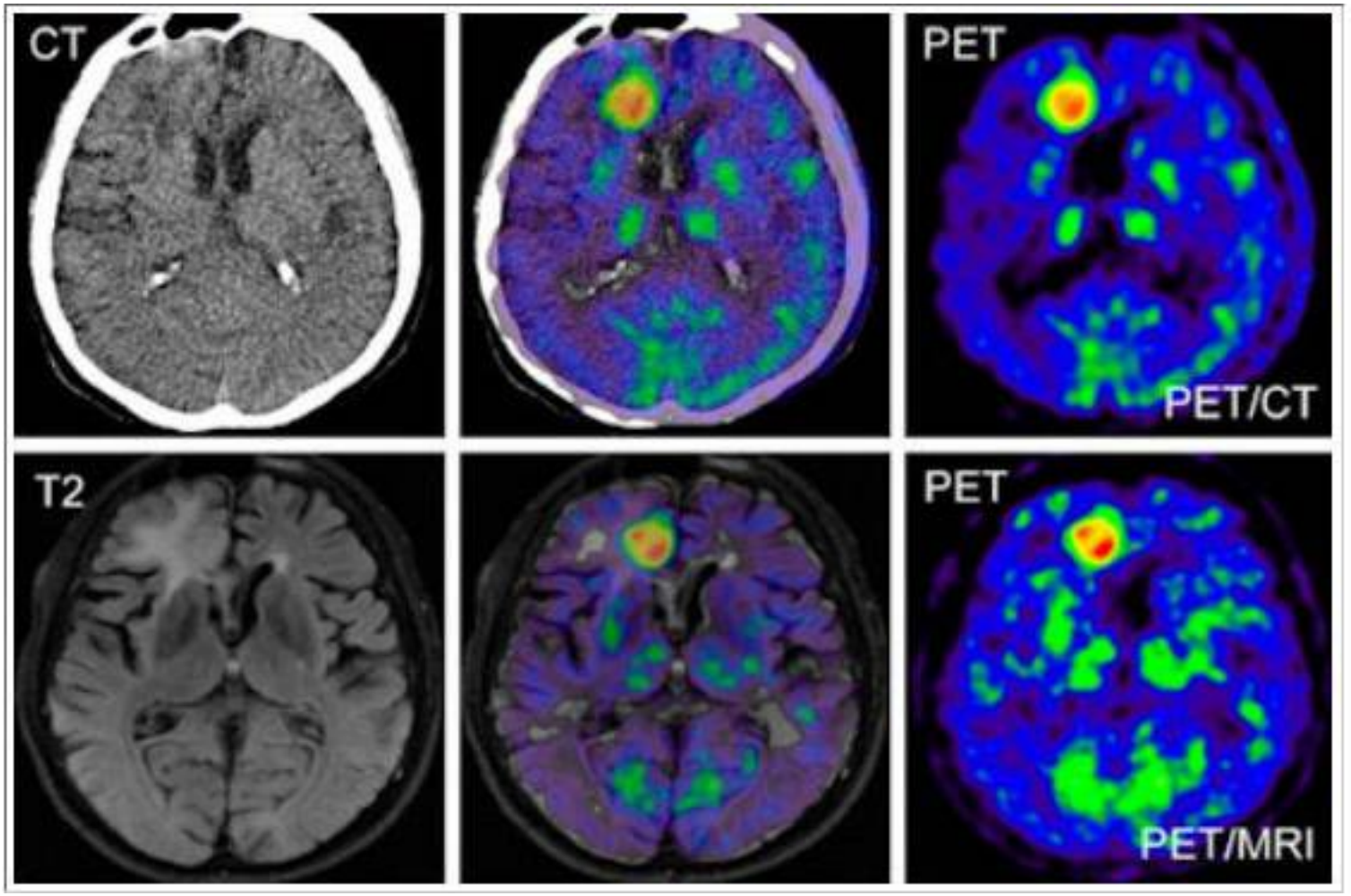
PET-MR

- Combining anatomical and functional images increases diagnostic accuracy
- PET-CT is now the standard.



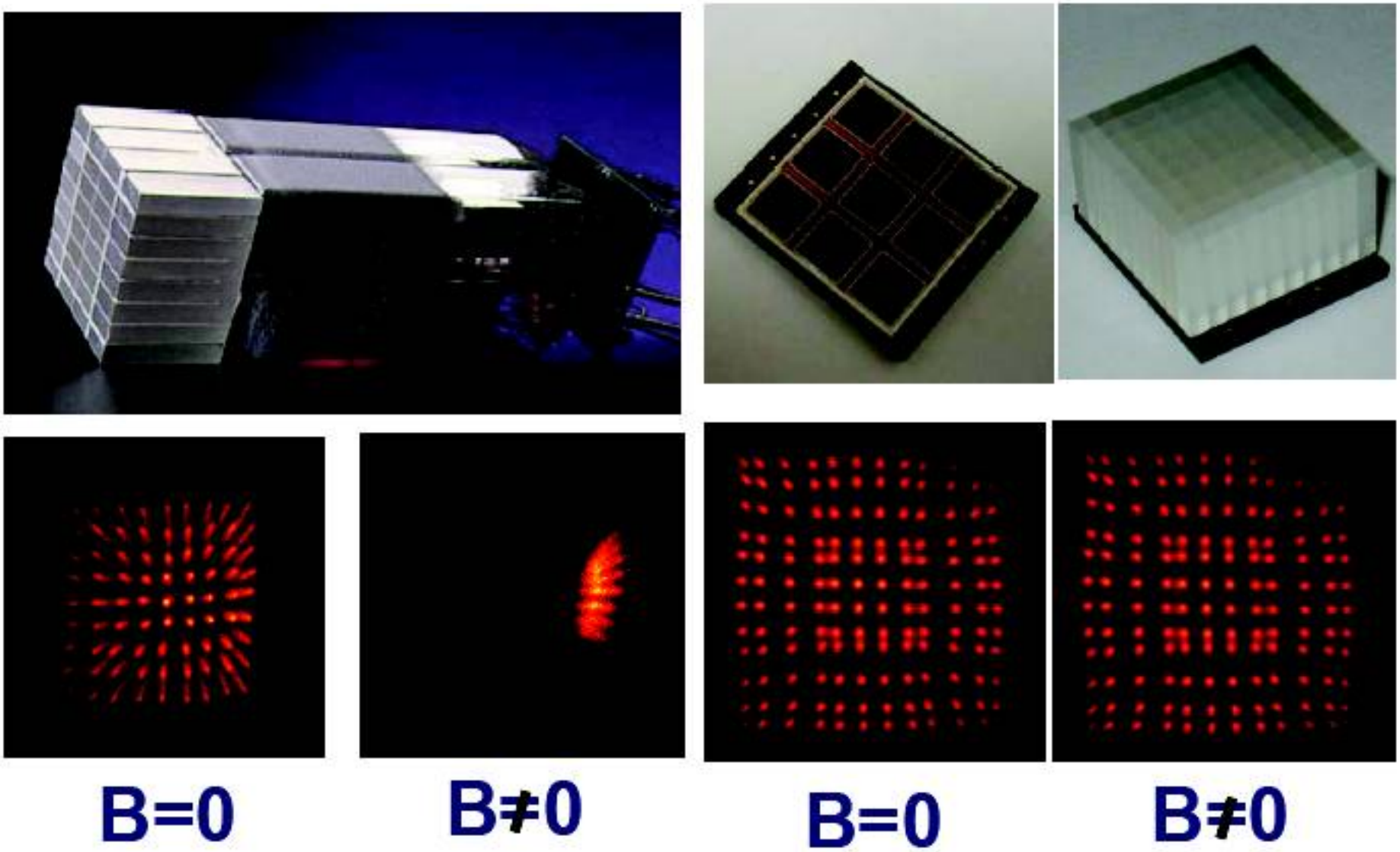
PET-MR

- PET-CT vs PET-MR.



PET-MR

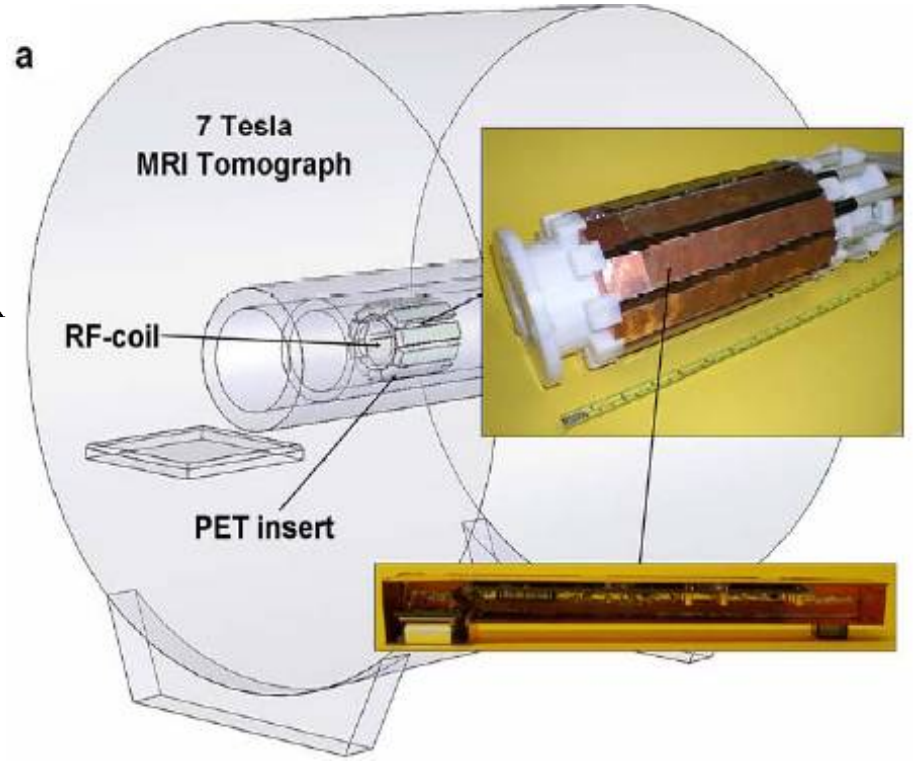
- PET-MR: problems due to PMT sensibility to magnetic fields



PET-MR

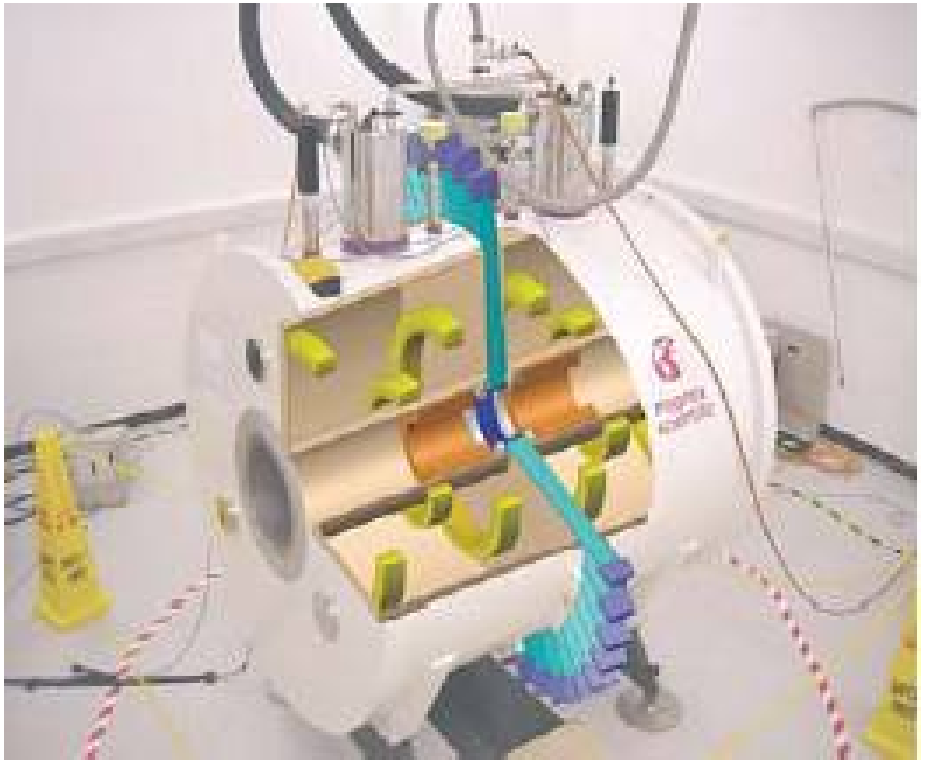
- First, small animal systems.

APDs



B.J. Pichler et al.J. Nucl Med 2006 Apr;47(4):639-47.

PMTs+ light guides

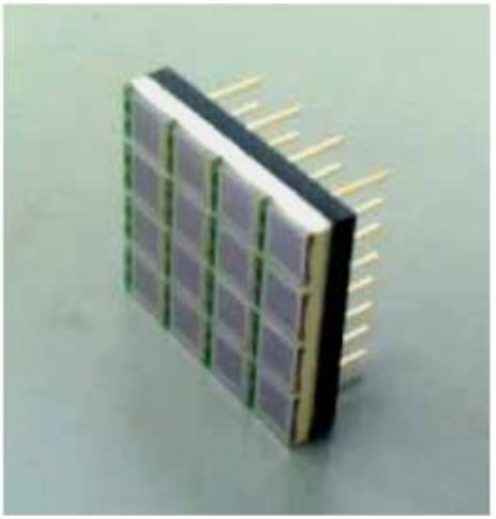


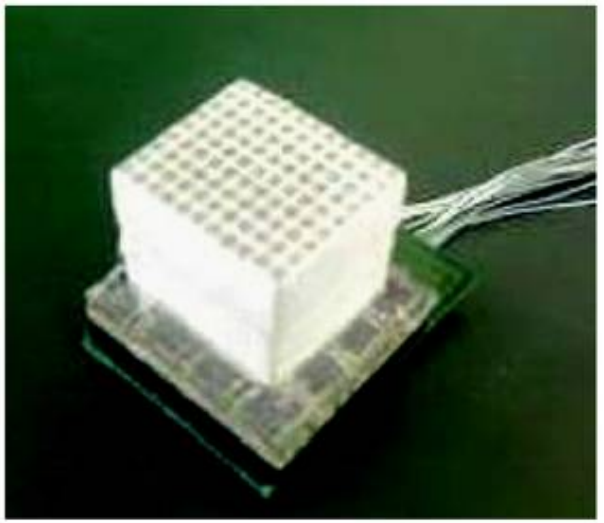
R.C. Hawkes et al.
Tech. Cand. Res. Treat. 9 (1) 2010.

- Clinical systems already exist. Sequential or APD based.
- Recents developments with SiPMs

PET-MR

Small animal PET ring





Two types of LGSO crystals (phoswich)

1.1mm x 1.2mm x 5mm

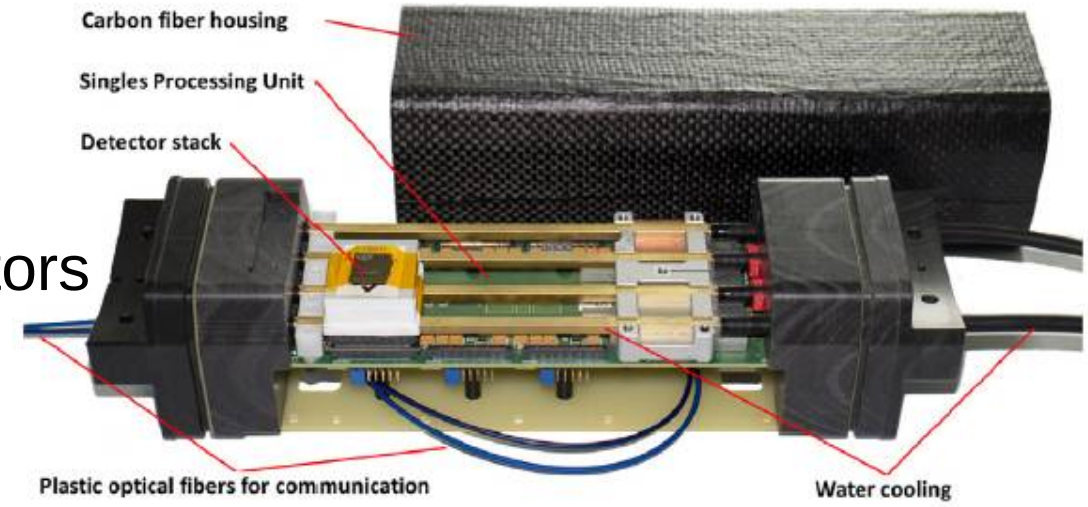
1.1mm x 1.2mm x 6mm

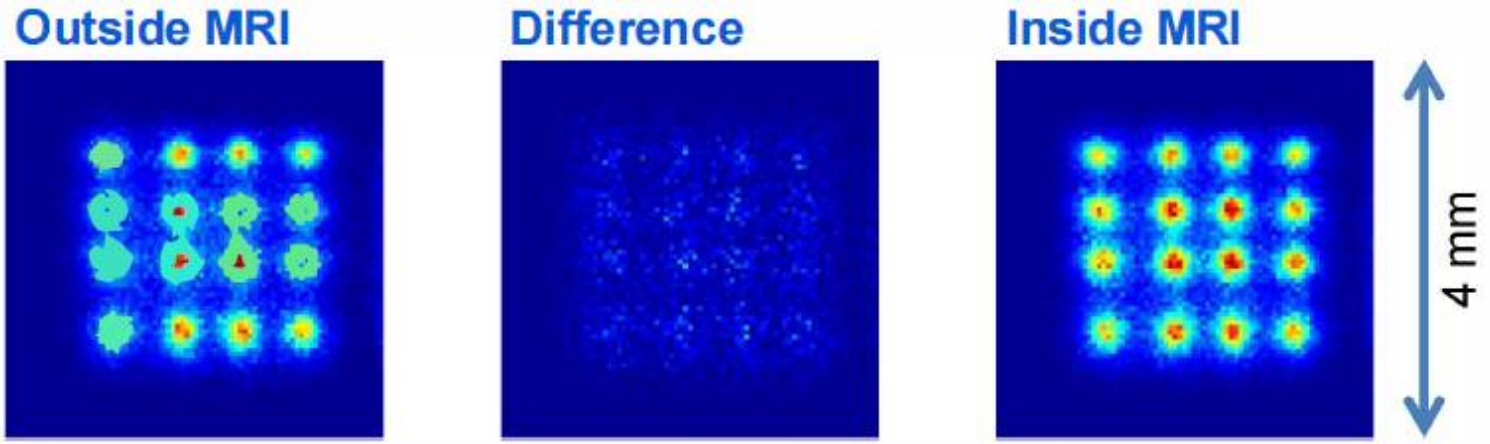
Yamamoto et al.
PMB 2010

MR-compatible

PET-MR

- Detector stack:
  - LYSO scintillator array : 30 x 30 pixels of with 1mm pitch and 12 mm length
  - DSiPM
  - cooling system
- Module: up to 6 detectors
- Ring: 10 modules. 210 mm diameter



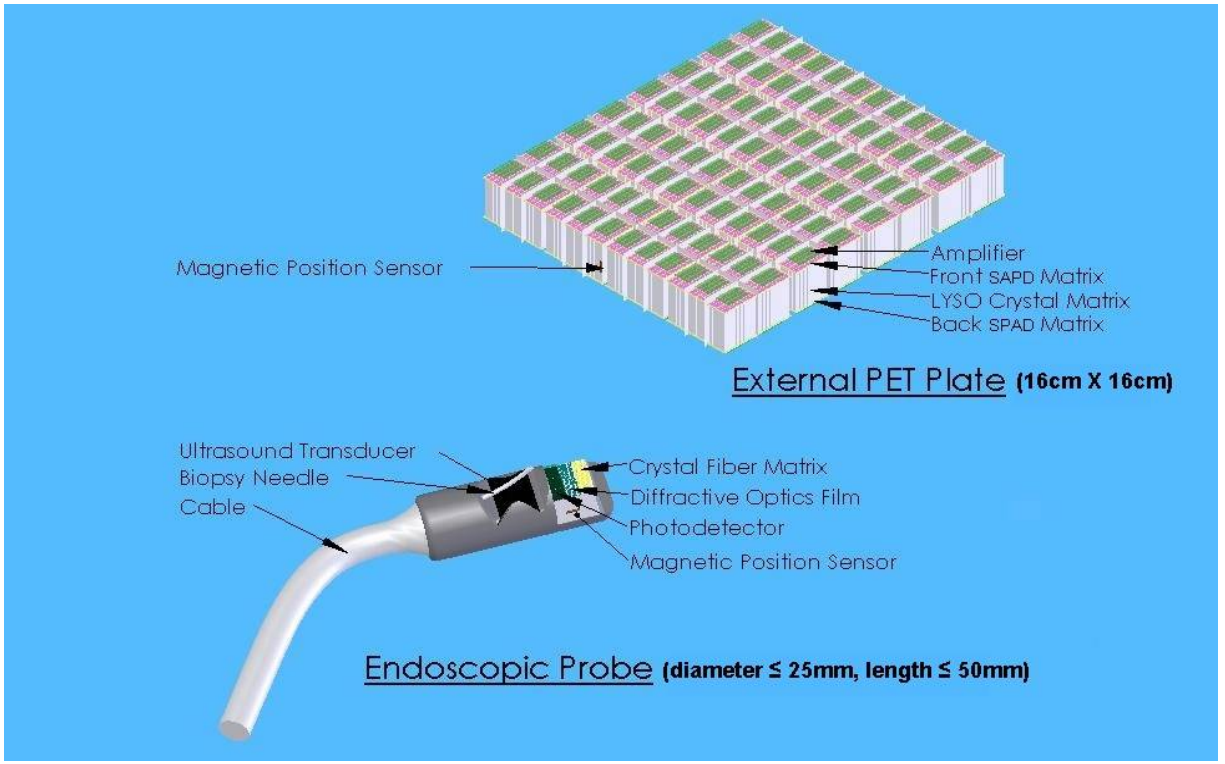


Dueppenbecker et al. 2012 IEEENSS MIC Conf Rec. M18-3

Wehner et al. NIMA 734, 2014

Compact, fast, multimodal

- ENDO TOFPET-US: endoscopic probe for pancreatic and prostatic cancer
- PET probe in coincidence with an external system. Aims:
  - 1mm spatial resolution
  - High sensitivity
  - Coincidence timing resolution 200 ps.

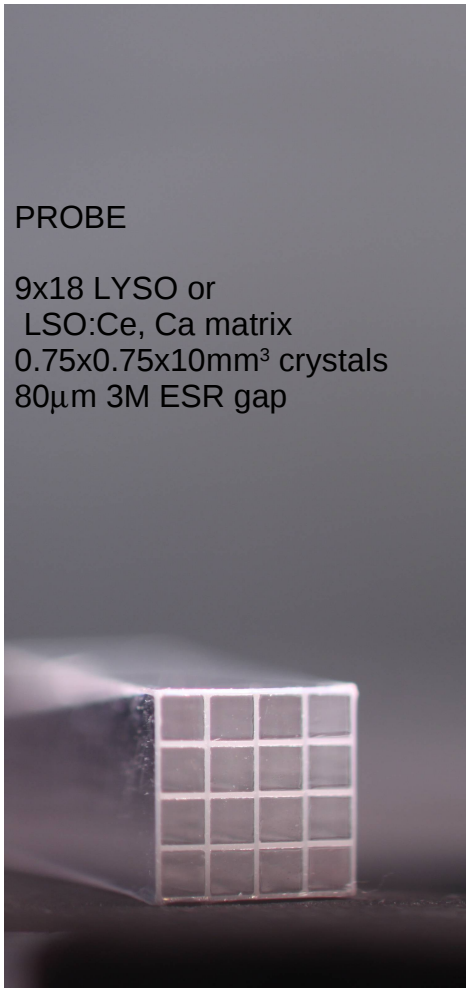


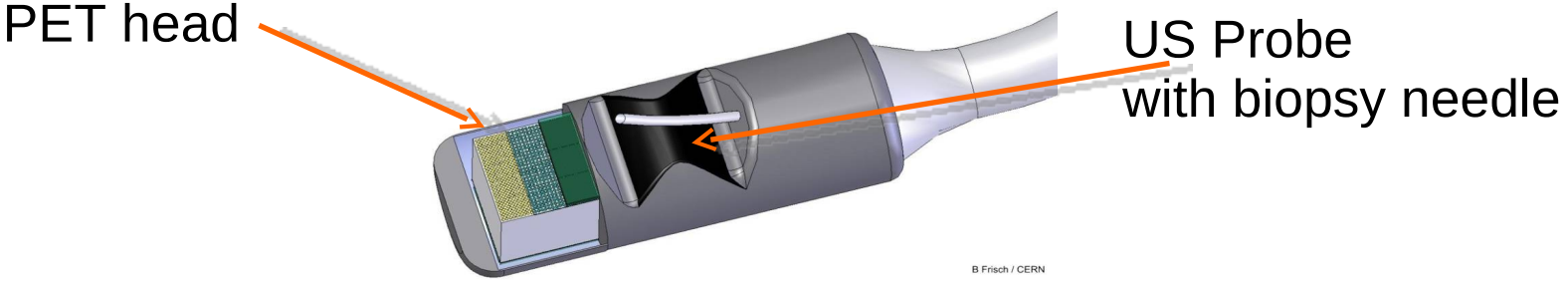
Pictures courtesy of Paul Lecoq

https://endotofpet-us.web.cern.ch/endotofpet-us/

Compact, fast, multimodal

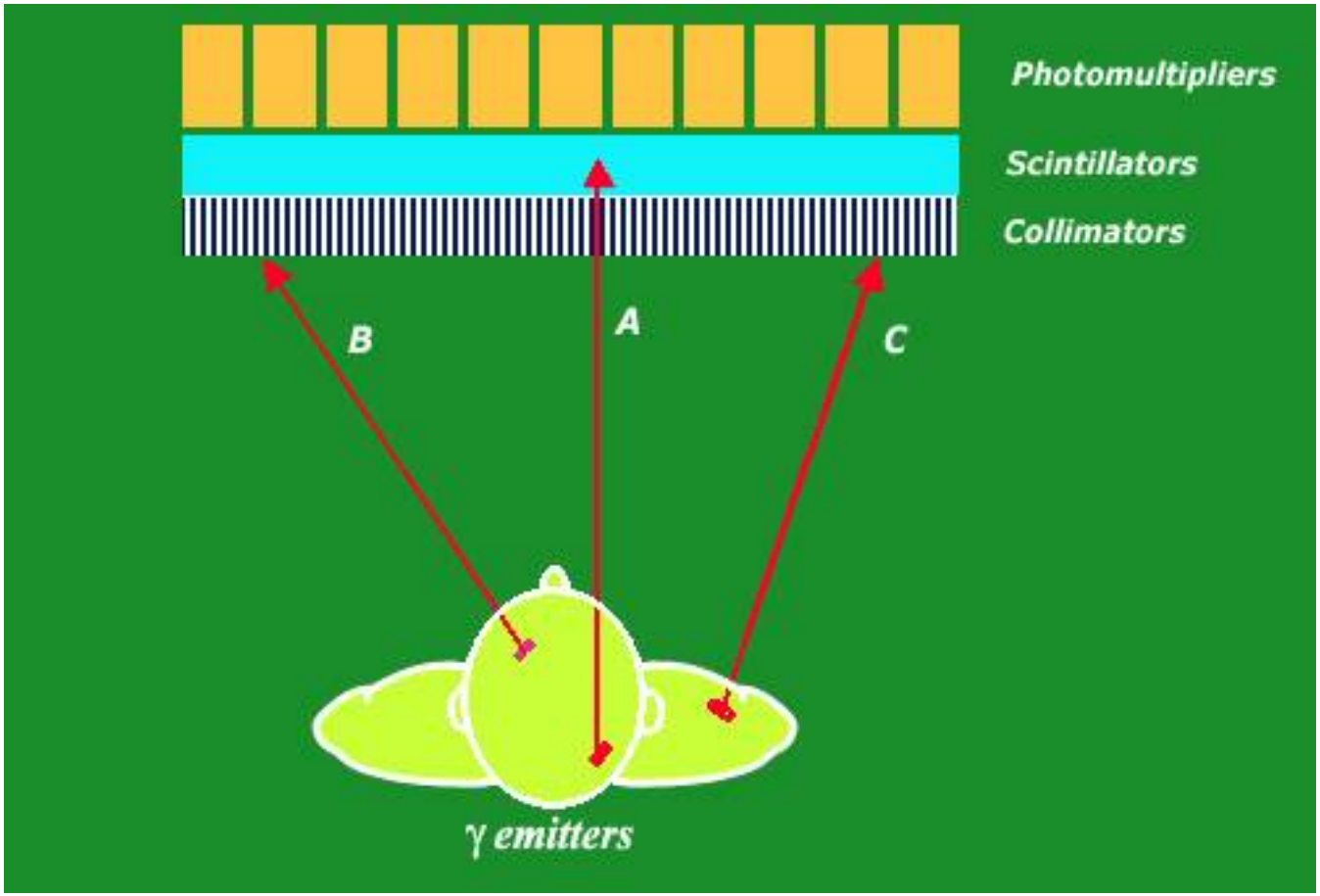
- Probe:
  - Pixellated crystals 0.75x0.75x10mm^3
  - DSiPMs Dev at TU Delft
  - US system
  - Tracking sensor.
- Coincidence timing resolution better than 240 ps FWHM achieved





Gamma cameras

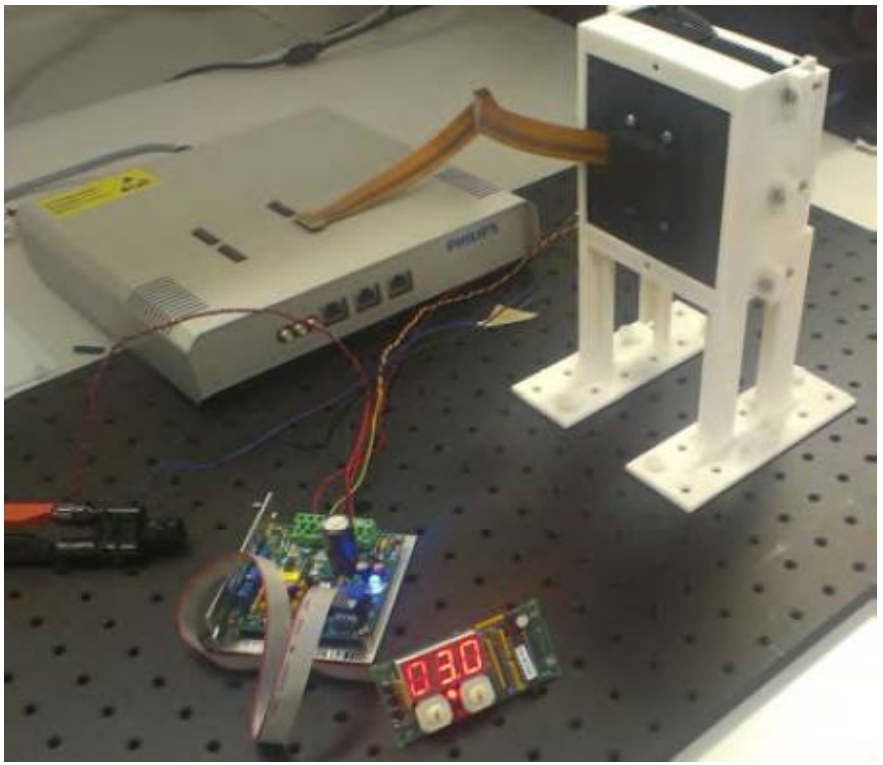
- Principle

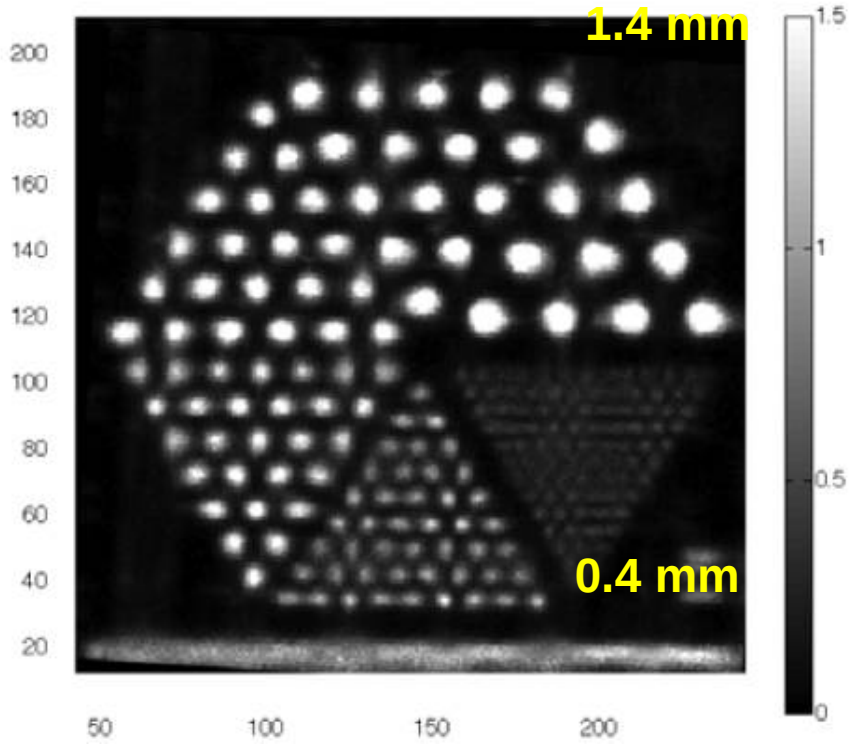


- Performance dominated by collimator

Gamma cameras

- Gamma cameras with dSiPMs, MR-compatible.
  - Monolithic 32 x 32 x 2mm3 LYSO crystal + dSiPM
  - Resolution collimator – 0.49 ± 0.11 corrected for beam size

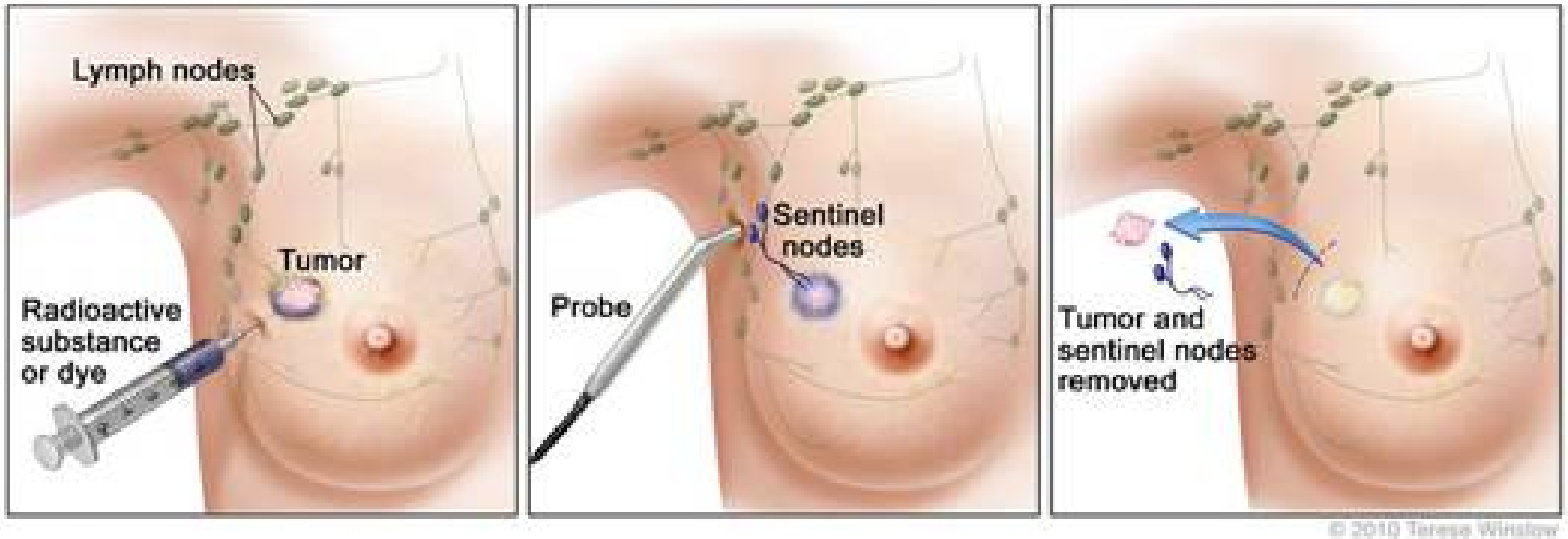




C. Bouckaert. 2013 IEEE NSS MIC. M14-7.

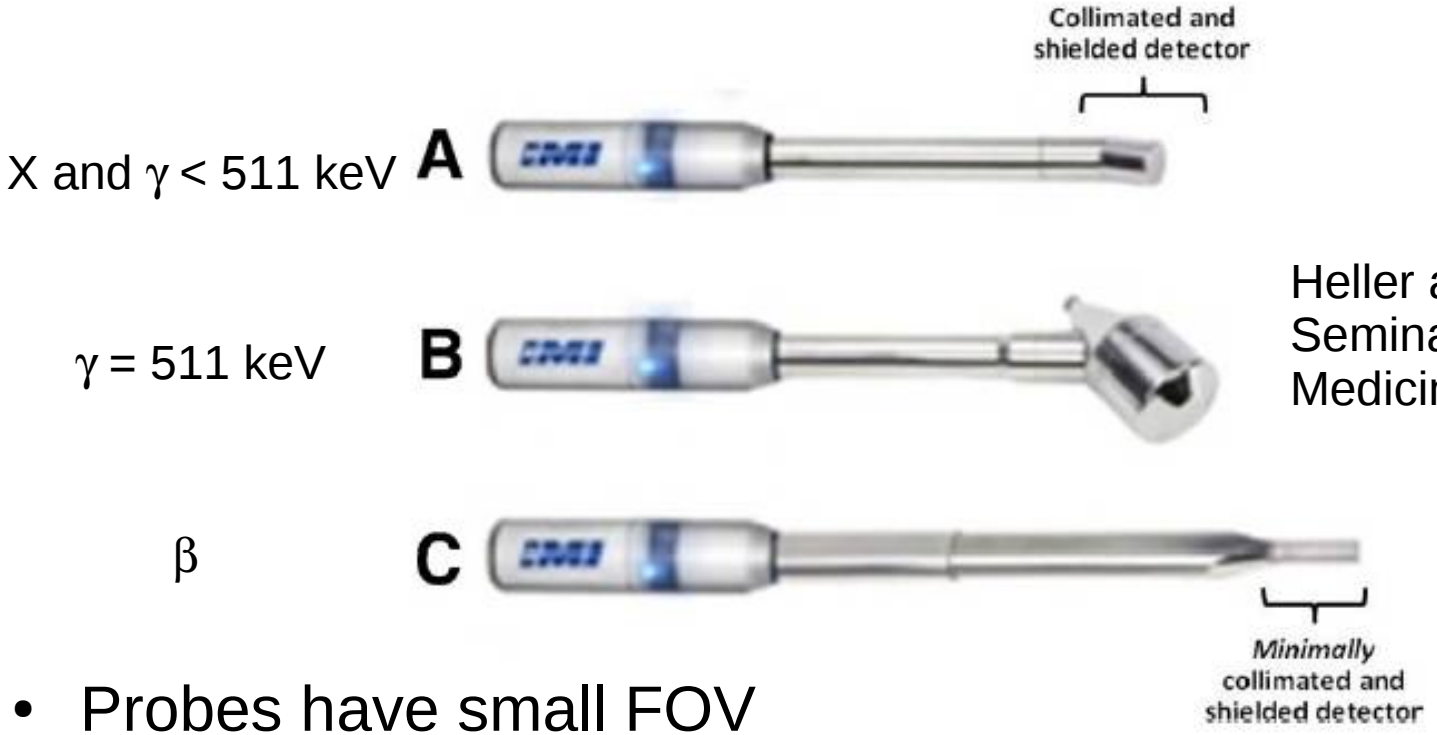
Intraoperative probes

- Intra-operative imaging of tumours helps the surgeon to determine precisely the tumour extension and separate from healthy tissue.
- Typical application: sentinel lymph node.



Intraoperative probes

- Beta and gamma intraoperative probes (photon counting) and mini gamma cameras (imaging).

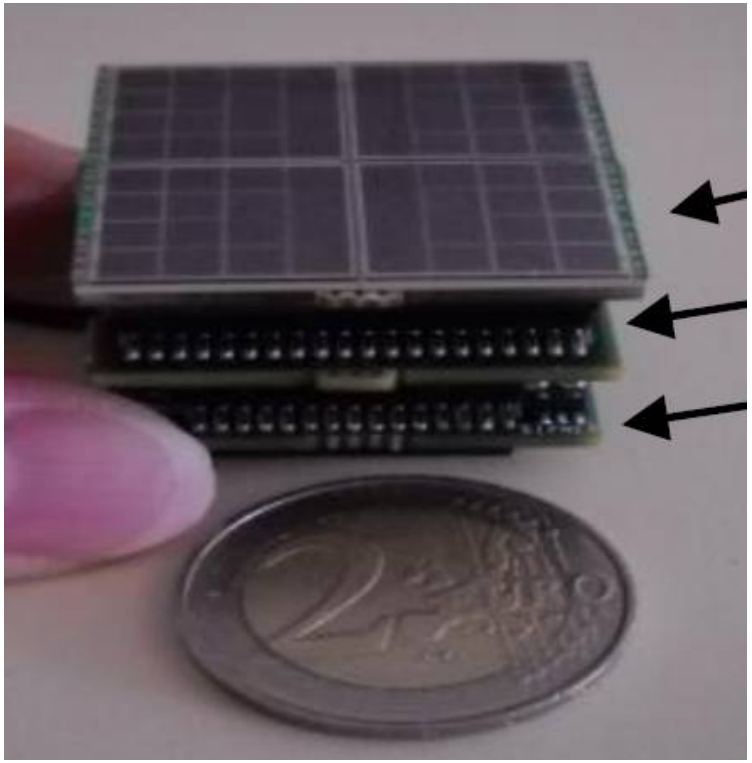


Heller and Zanzonico Seminars in Nuclear Medicine

- Probes have small FOV
- Need large FOV (5x5 cm^2) with excellent spatial resolution while portable and small.
- Recently solid state or scintillator + SiPMs (lower cost)

Mini gamma cameras

- SIPMED:
  - $LaBr_3$ scintillator 5.5 cm x 5.5cm
  - ~ 6 cm thick, 700 g; 256 readout channels
  - E resolution: 10.5% FWHM @ 122 keV
  - Spatial resolution: 1.23 mm FWHM @ 122 keV

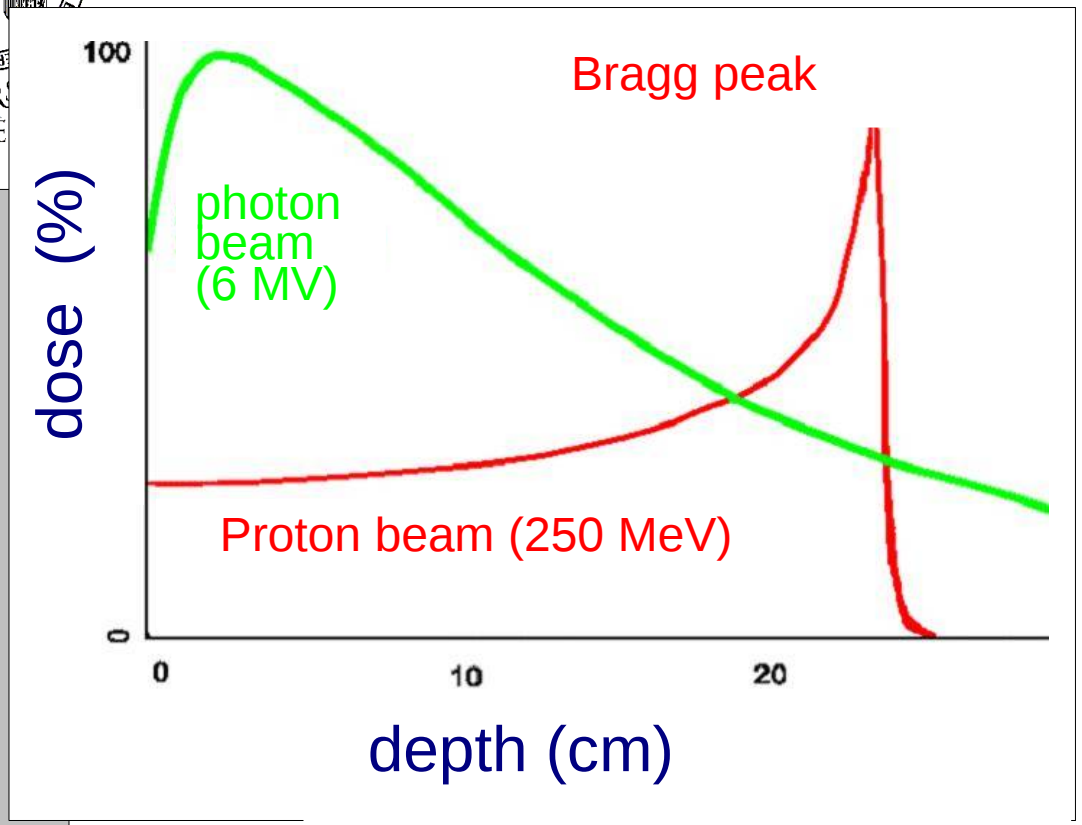


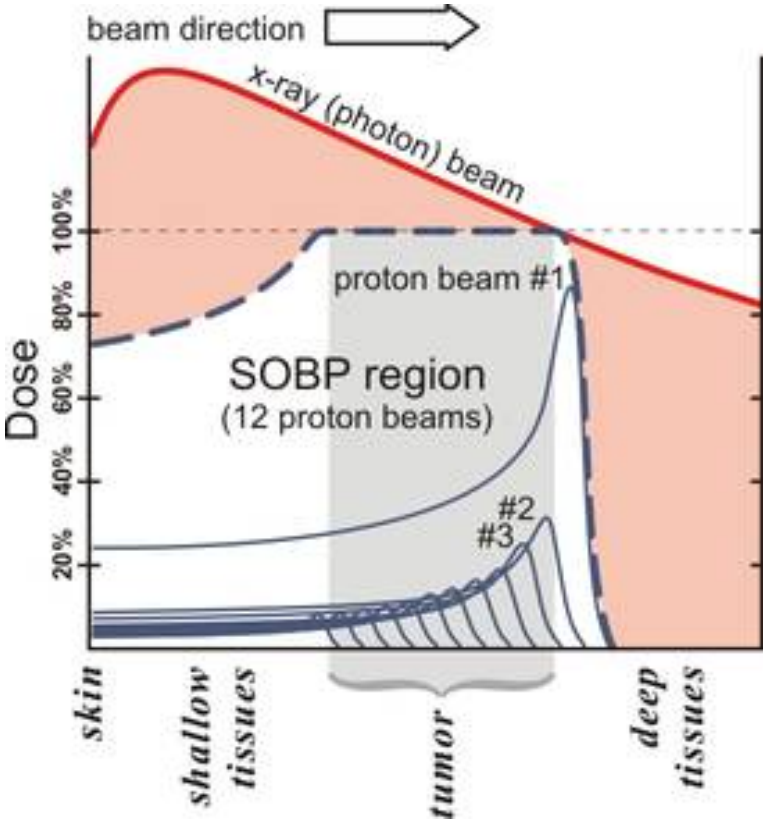
Imando et al.
PoS 2012.

See N. Dinu et al. Session 8

Hadron therapy

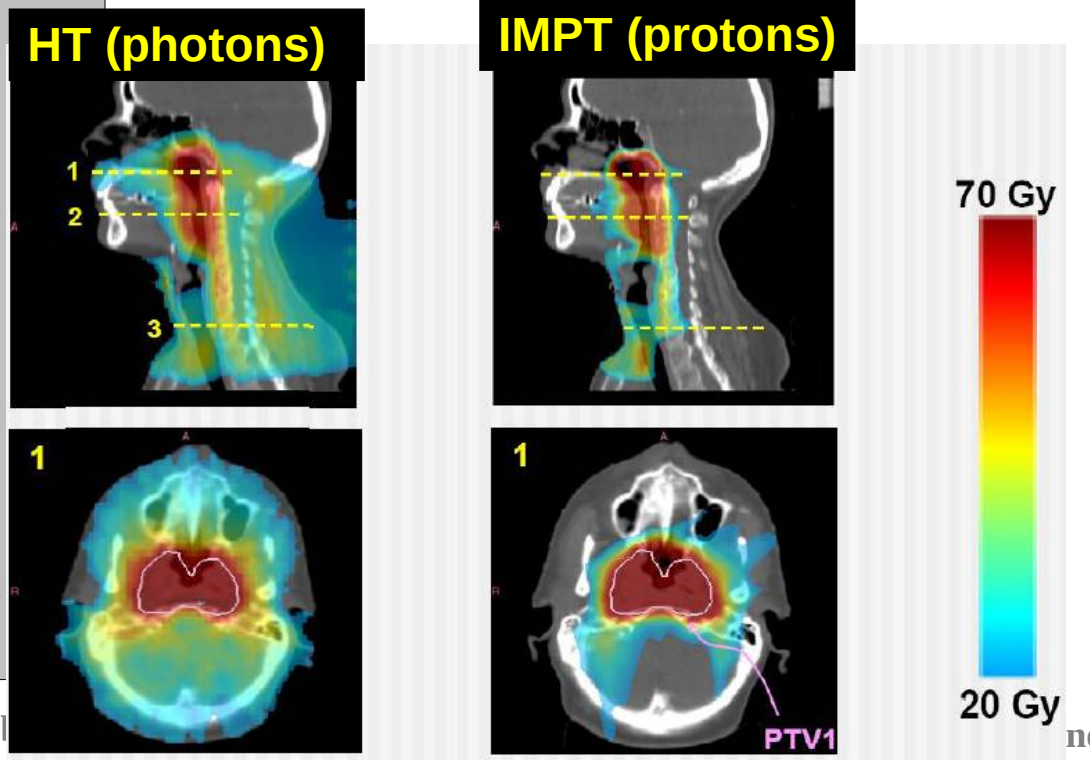
- Hadron therapy: charged particles (protons or Carbon ions), precise delivery of radiation dose (Bragg peak).
- Reduce the dose to healthy tissue.

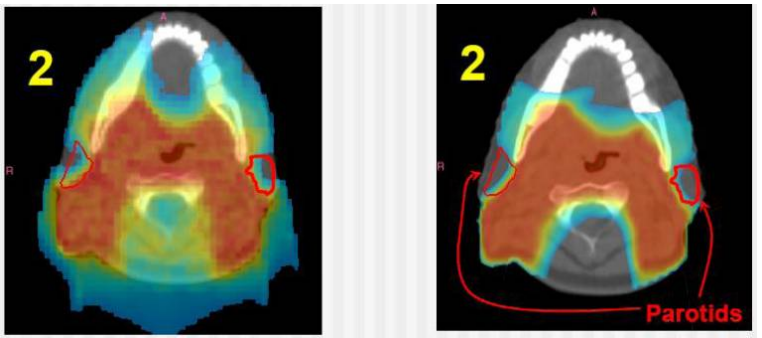




Hadron therapy

- Large benefit over conventional radiation therapies in some cases (ocular tumours, children, organs at risk, radioresistant tumours).
- Higher relative biological effectiveness (RBE) than photons
- Precise delivery to tumour area => increase of cure rates and reduction of side and long term effects and secondary cancer.





L. Widesott et al.
IJROBP 72(2):589, 2008

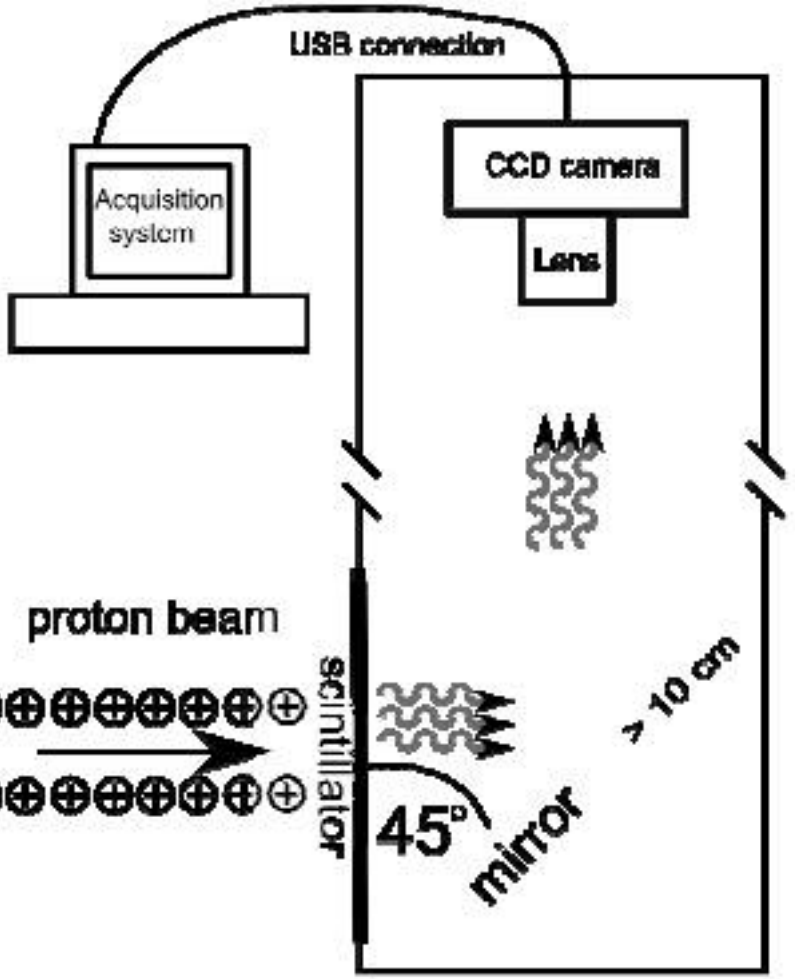
Hadron therapy

- Gaining increasing importance -> growing number of centers in Europe and in the world.

Hadron therapy centers in the world (from http://ptcog.web.psi.ch/ptcentres.html)

Beam monitoring

- Quality assurance in a proton ocular treatment facility.
- PROBIMS (PROton Beam IMaging System):
  - 2 mm thick Gd_2O_2S:Tb (Gadolinium Sulphate Oxide doped with Terbium - inorganic phosphor) convert proton beam to visible light
  - CCD camera (3362 x 2504 pixels)
  - 45º angle to avoid radiation damage

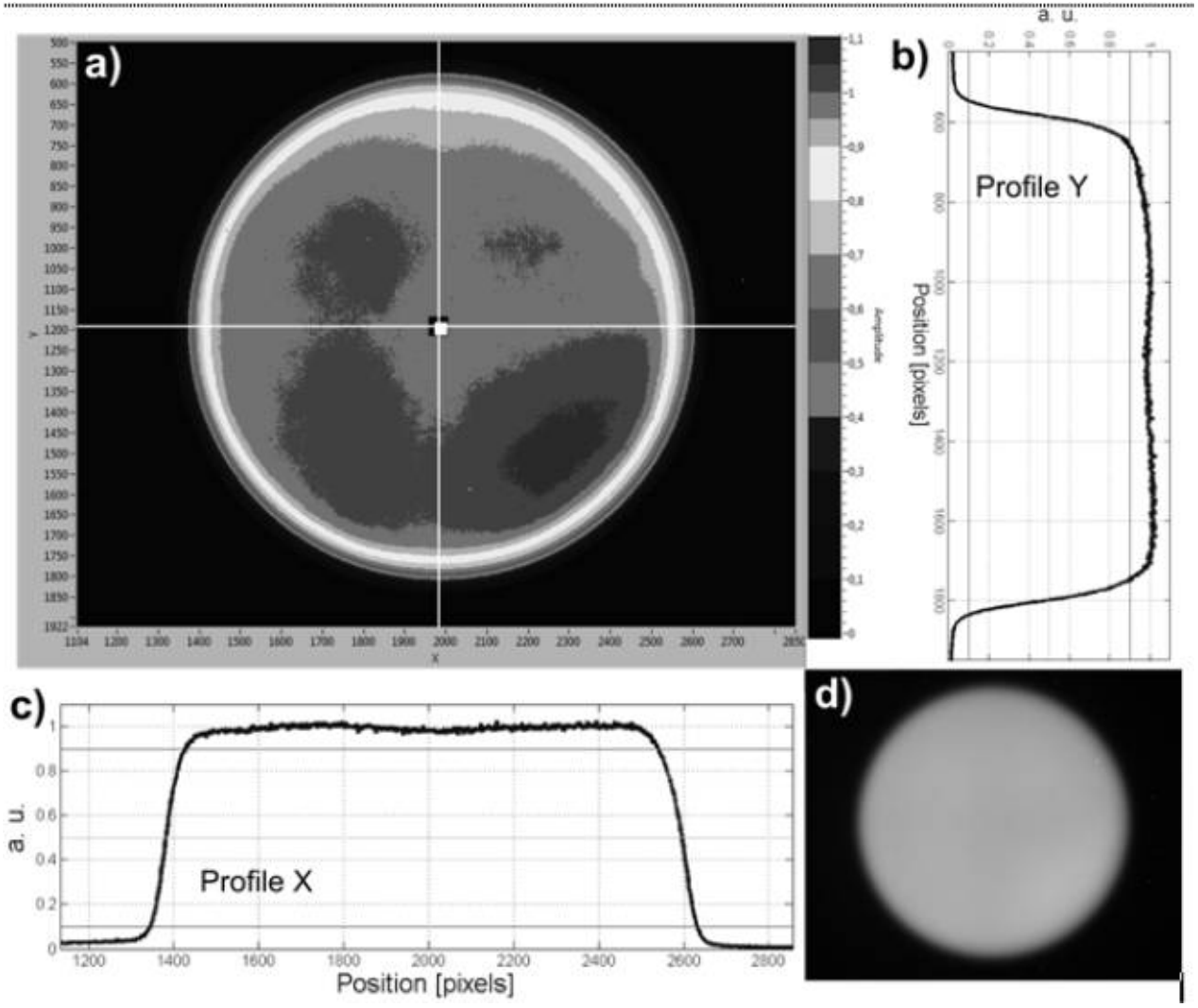


Boberek et al.
Rom. Rep. Phys.66, 2014.

Beam monitoring

Boberek et al.
Rom. Rep. Phys.66, 2014.

- Measurements in a 60 MeV proton beam.
- 2D beam profile characterization



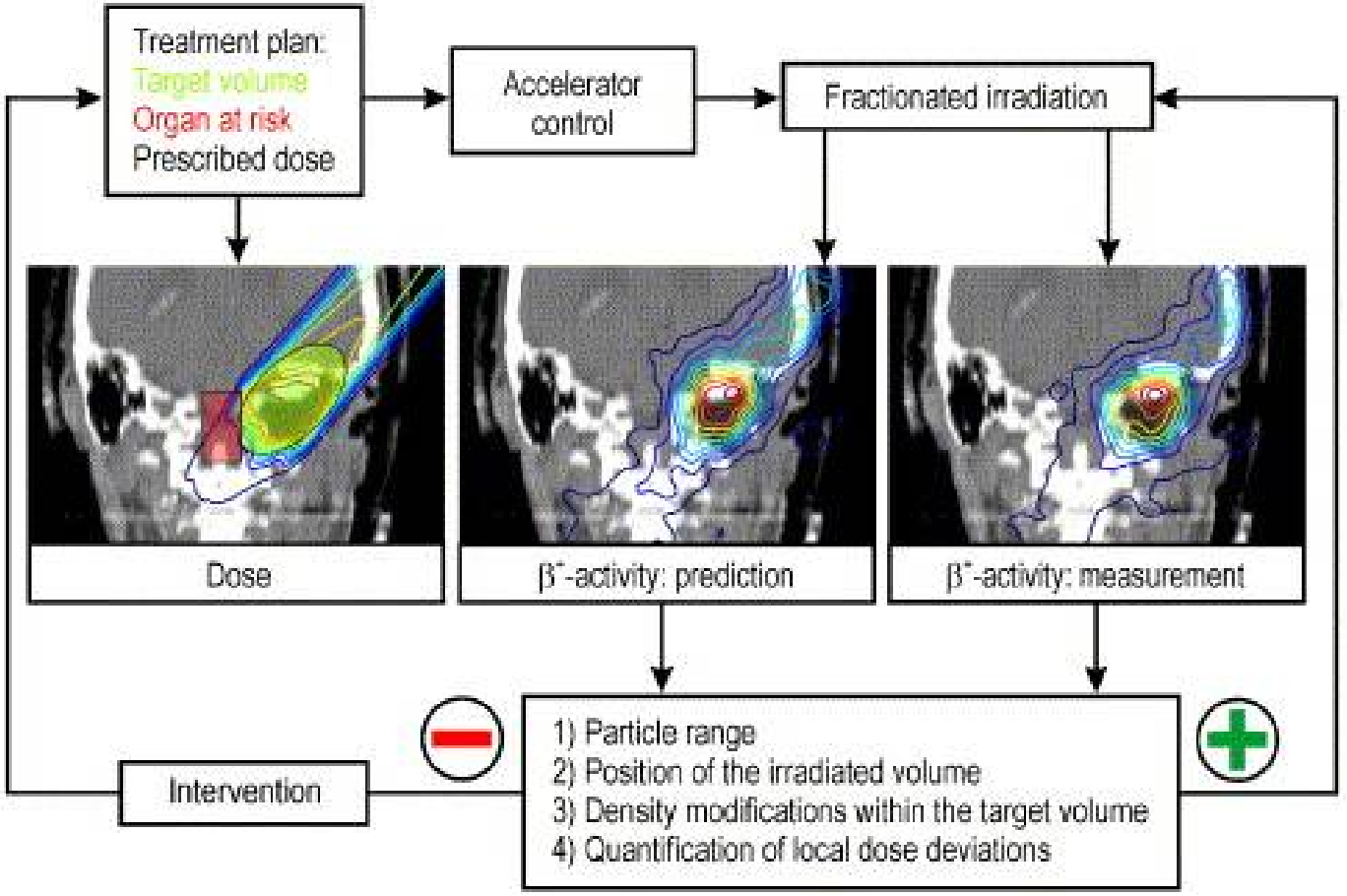
Dose monitoring in Hadron therapy

- PROBLEM: the dose administered can not be directly measured (as done in conventional radiotherapy).
- Secondary particles emitted during treatment can be used for monitoring the dose delivery.

- An accurate monitoring system is essential:
  - To verify dose delivery and correct for treatment deviations.
  - To reduce safety margins.

Dose monitoring in Hadron therapy

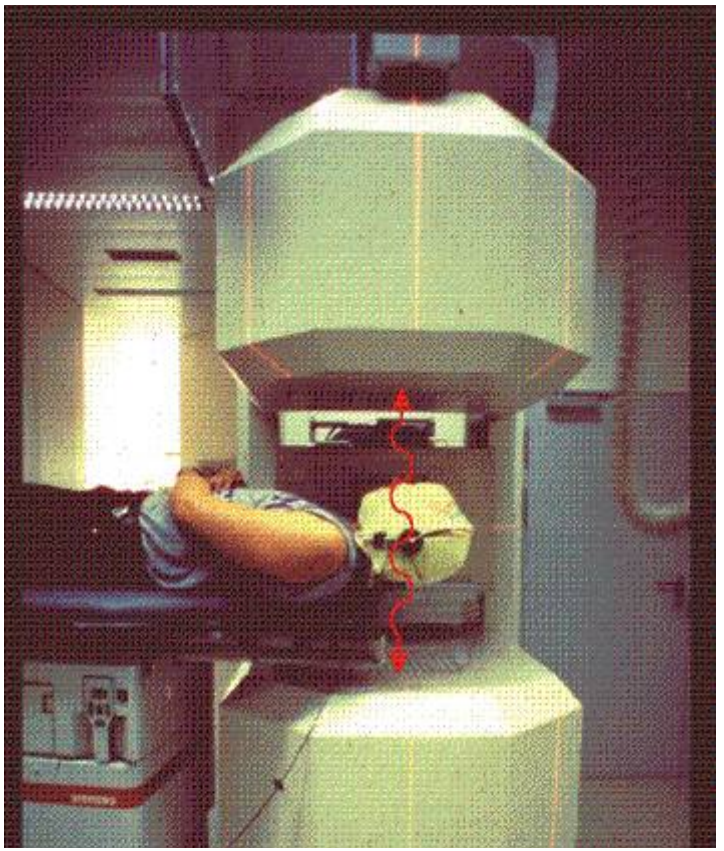
- Positron Emission Tomography (PET) + MC currently employed.



•Dose verification: comparison of dose planned and estimated from detected β+ activity.

PET for dose monitoring

- Irradiated tissue nuclei become positron emitters (O, C).
- In-beam, in-room, offline



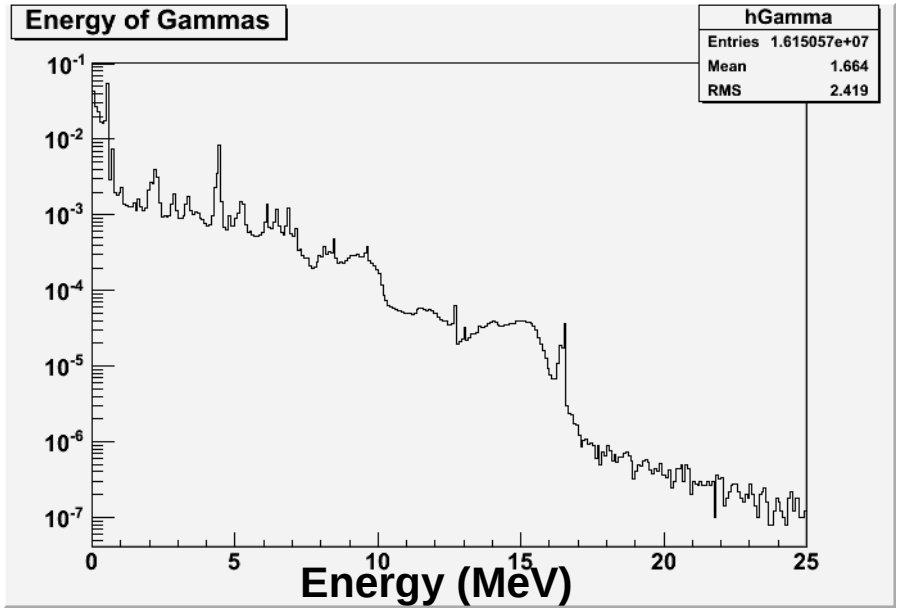
- In-beam -> gaps. Improved results with TOF-PET
- Many groups working on such systems. dSiPMs.

Dose monitoring in hadron therapy

- Limitations:
  - Positron production does not follow irradiation immediately
  - Biological washout- activity carried away by metabolic processes
  - Low amount of β+ activity induced- low efficiency
  - Difficult online studies – in-beam -> partial ring
  - Photons produce significant background

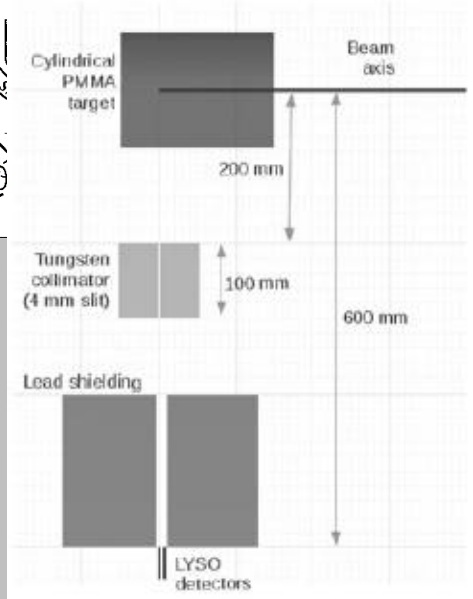
Dose monitoring in hadron therapy

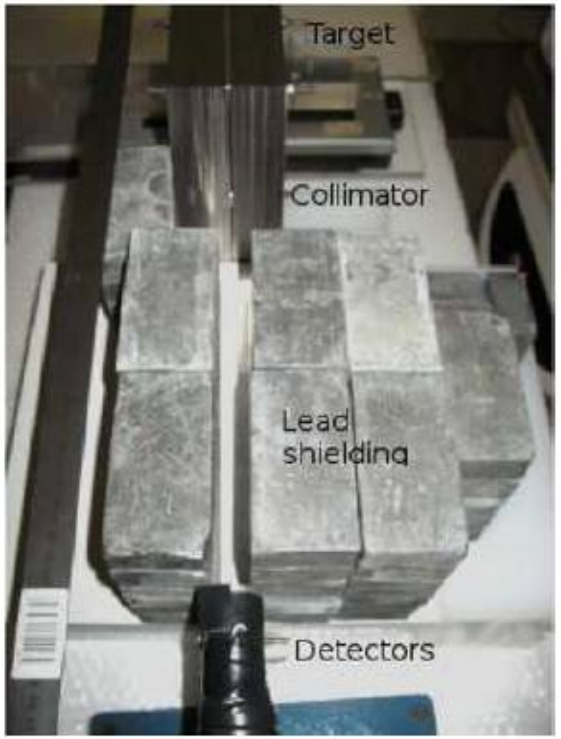
- Alternative: Prompt gammas also emitted from nuclei excited during therapy and can be used for this purpose.
  - Emission ~ns after irradiation.
  - ~ 7 times more particles/cGy
- Emitted in a continuous energy spectrum with energies of MeVs.



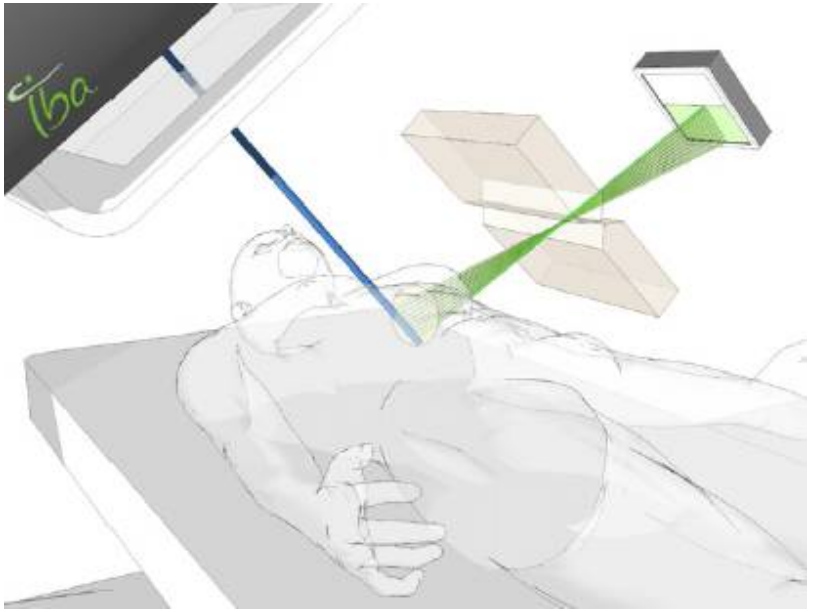
Collimated systems

- Conventional gamma cameras not suited for such high energies.
- Collimated cameras -projection.





F. Roellinghoff et al.
Phys. Med. Biol. 59 (2014)

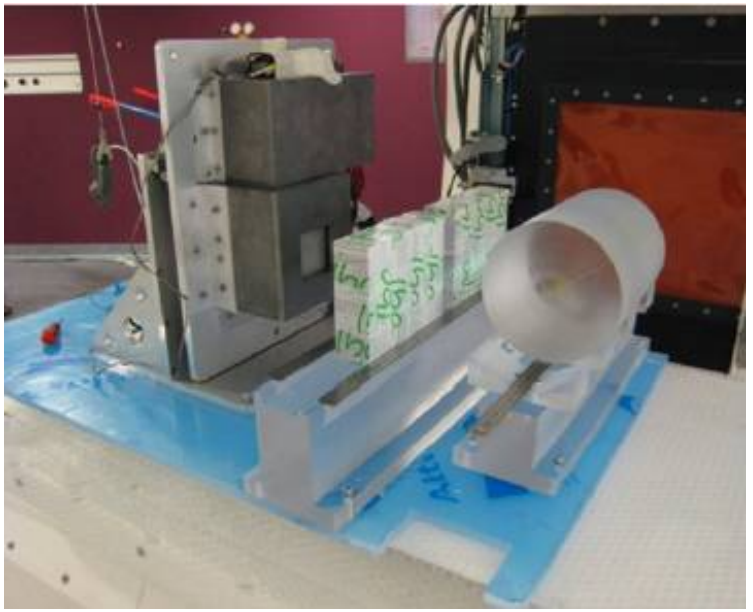


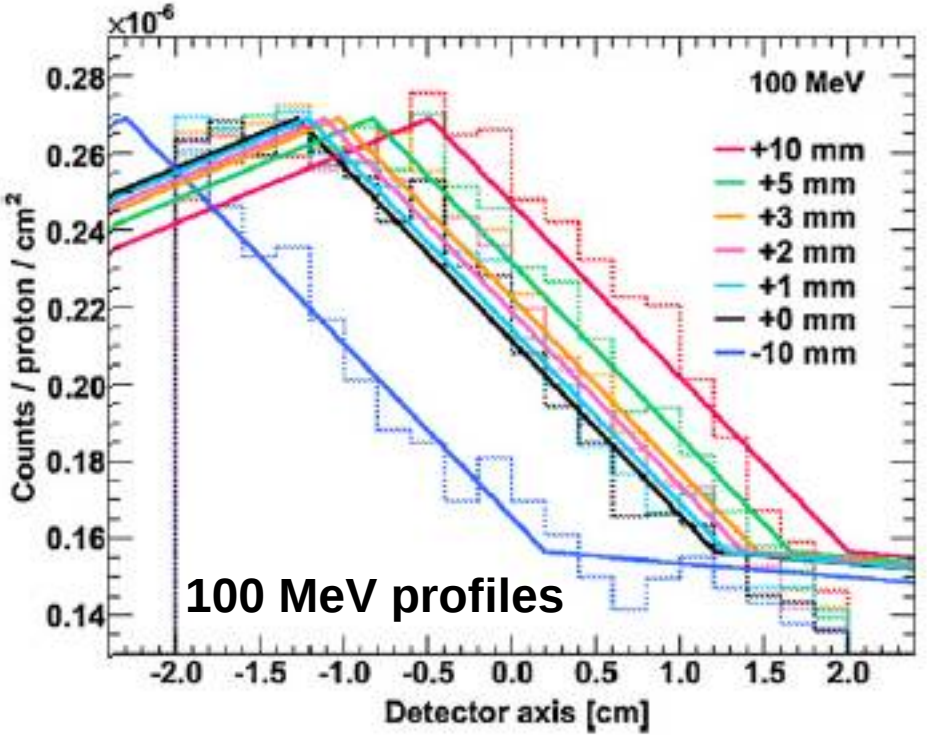
J. Smeets.
Phys. Med. Biol. 57 (2012)

Collimated systems

J. Smeets.
Phys. Med. Biol. 57 (2012)

- Slit system:
  - Tungsten collimator, PMMA target
  - Modified HiCam system; 1 cm thick continuous LYSO scintillator crystal + SDD.
- Data at 100 and 160 MeV. Profiles moving the target.





Also Scintillators + PMTs, SiPMs, DSiPMs

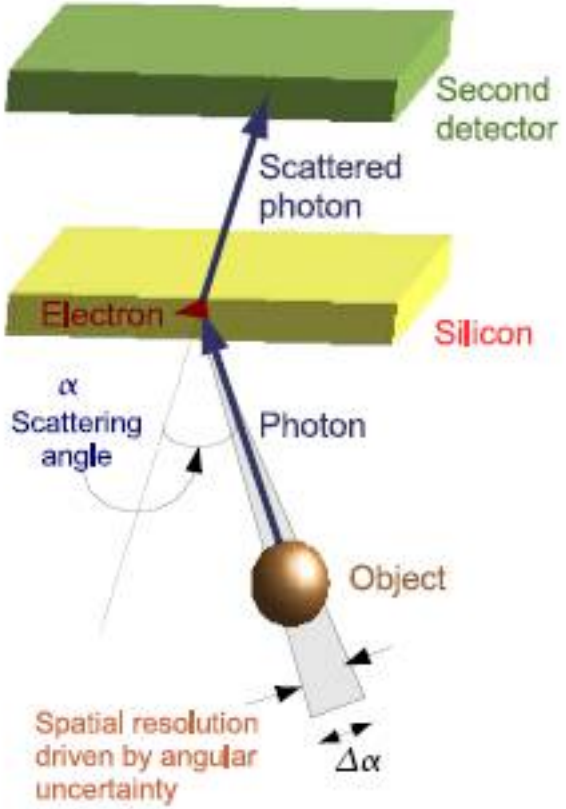
Compton cameras/telescopes in HT

- Used in homeland security, astroparticle physics and medical imaging- only prototypes
- Attempts to use them for particle therapy monitoring.
- ENVISION European project:
  - CZT – 2/3 planes.
  - Si + scintillator- See J. Krimmer el al. Session 3.
  - $LaBr_3$+ SiPMs

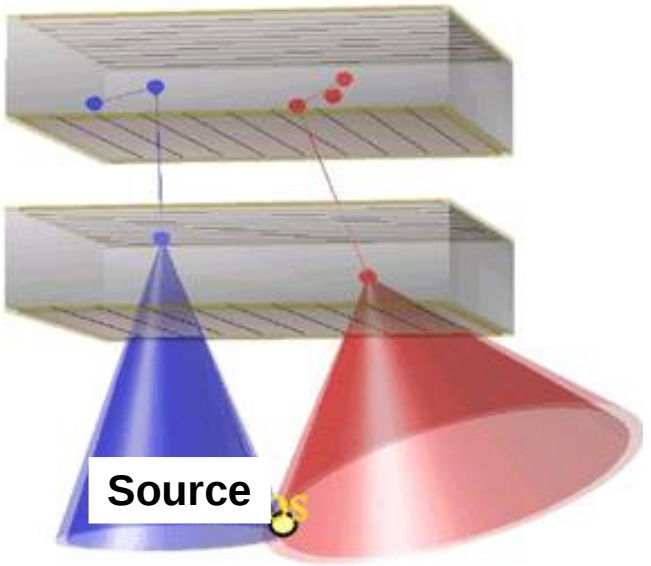
Compton cameras

'Conventional' Compton camera (scatterer + absorber):
2 interactions

problems if the photon energy is unknown or if it can escape (high E)



$$cos\theta = 1 - m_0c^2\left(\frac{1}{E_0 - E_e} - \frac{1}{E_0}\right)$$

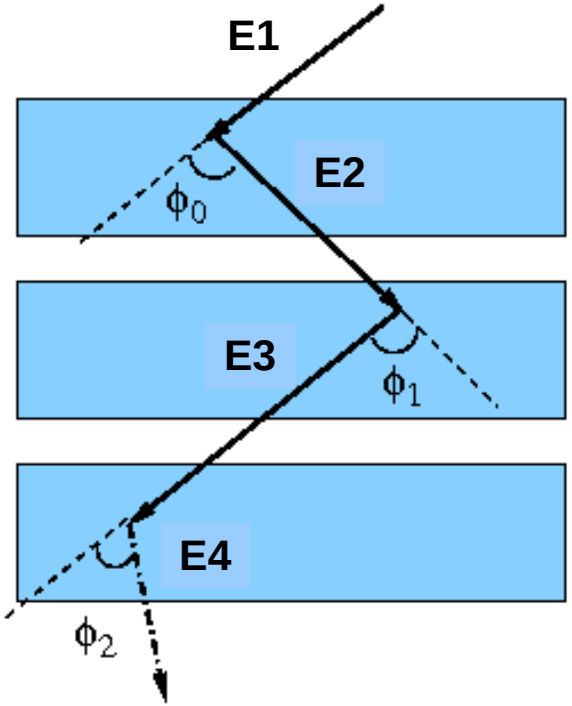


Compton Cameras

Three Compton technique:
3 interactions in 3 detectors
(+ correct ordering)

⇨ Position determined

lower efficiency



$$\cos\varphi_1 = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1} \right)$$

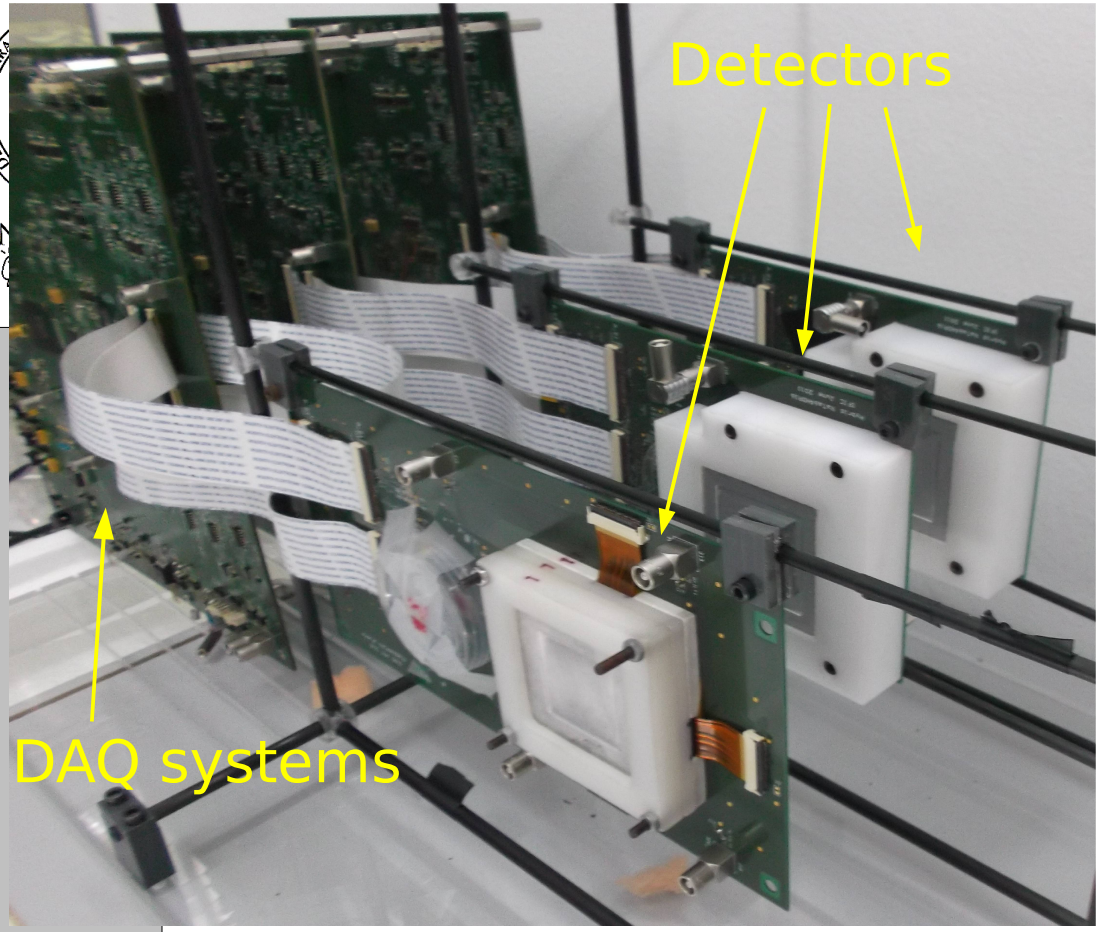
$$\cos\varphi_2 = 1 - m_e c^2 \left(\frac{1}{E_3} - \frac{1}{E_2} \right)$$

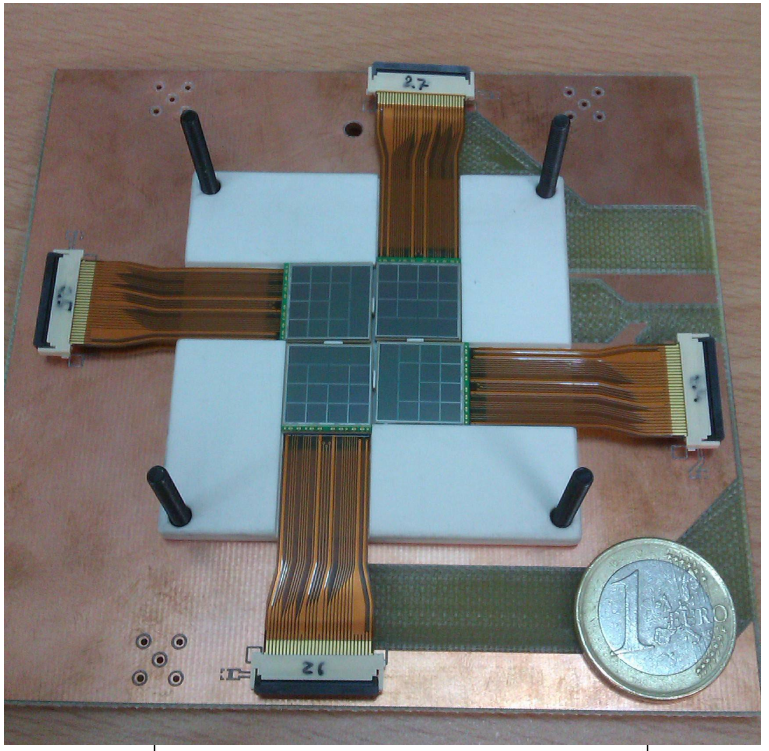
$$L_1 = E_1 - E_2$$

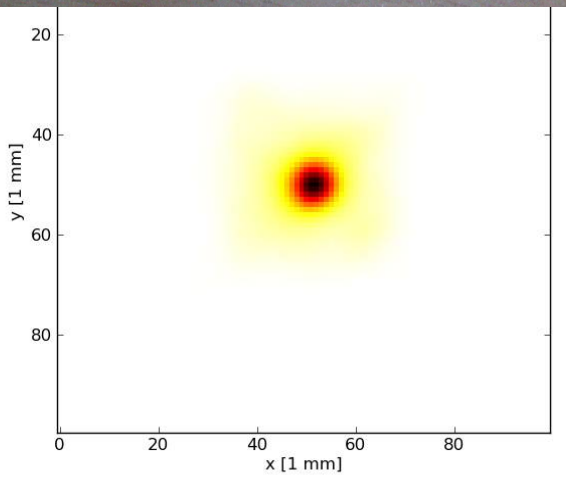
$$L_2 = E_2 - E_3$$

Compton cameras

- Compton telescope with 3 (2) planes.
- $LaBr_3$ crystals + SiPMs







Images reconstructed with 3 planes

Conclusions

- Significant advances are being made in different areas of medical imaging that contribute to a better and more accurate diagnosis.
- The development of new detectors / photodetectors / associated electronics and transfer of knowledge from other areas can help a lot in this aspect.

Thank you! Questions?