Detectors for medical imaging

Gabriela Llosá

Instituto de Física Corpuscular (IFIC, CSIC-UV)

INSTITUT DE FÍSICA CORPUSCULAR

EXCELENCIA SEVERO OCHOA

CSIC

CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

IRIS

Outline

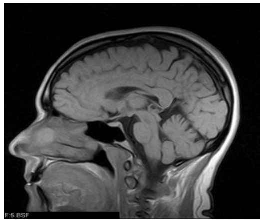
- Emission Imaging techniques.
- Imaging in therapy.

Medical imaging

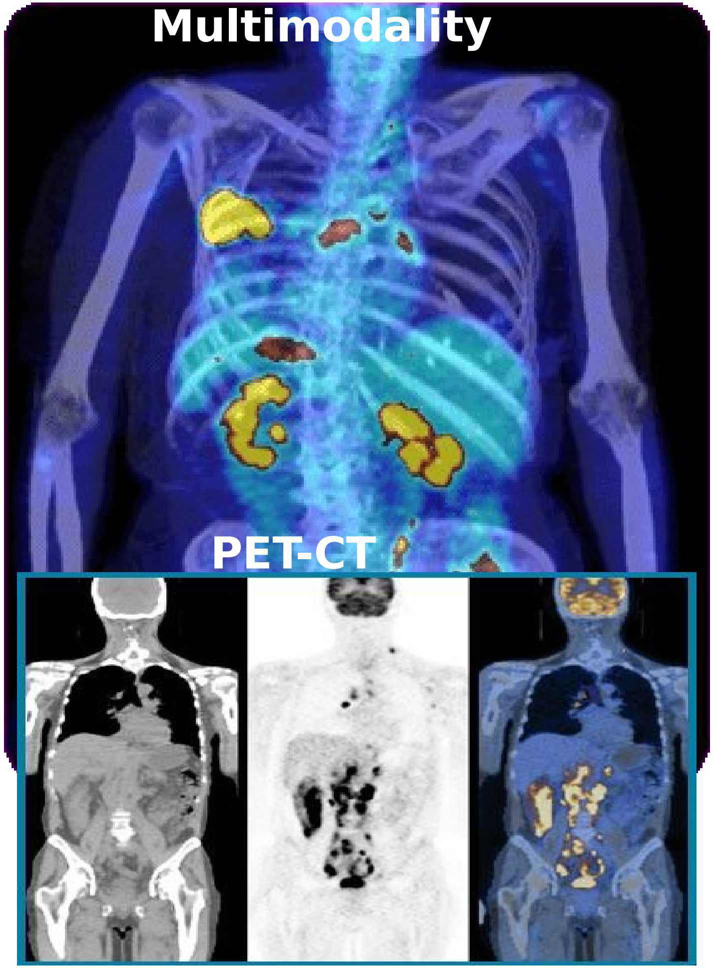
Structural

CT

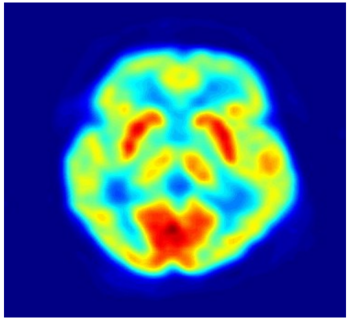
MRI



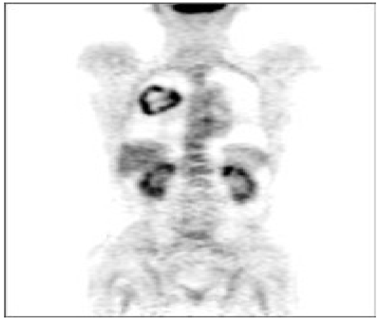
Ultrasounds



Functional



PET



SPECT

Goals

- Improve diagnostic accuracy.
- Reduce dose / time.

+ Lower cost

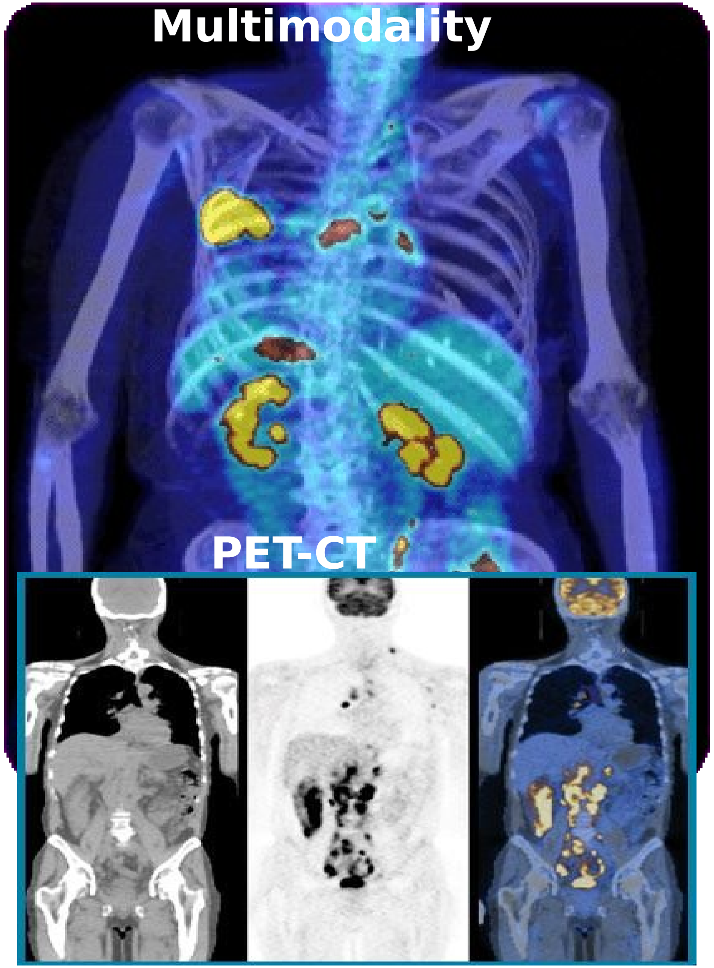
Medical imaging

Structural

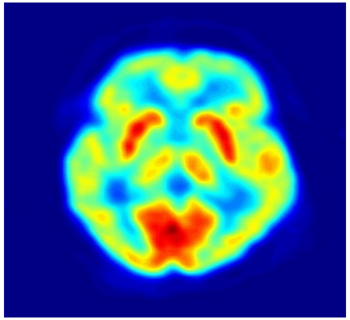
CT

MRI

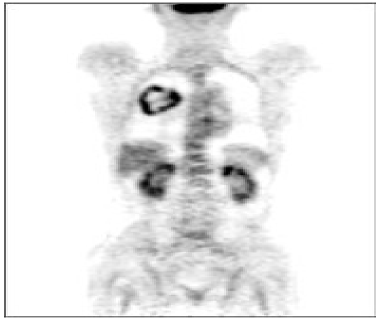
Ultrasounds



Functional

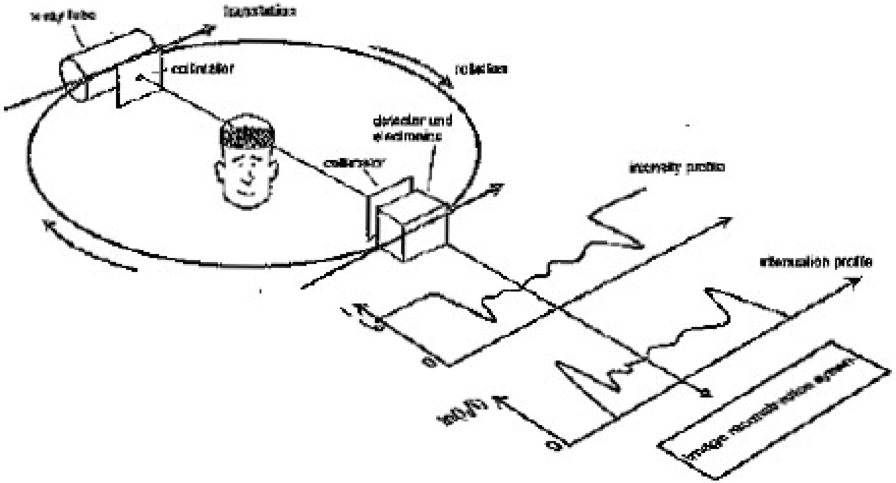


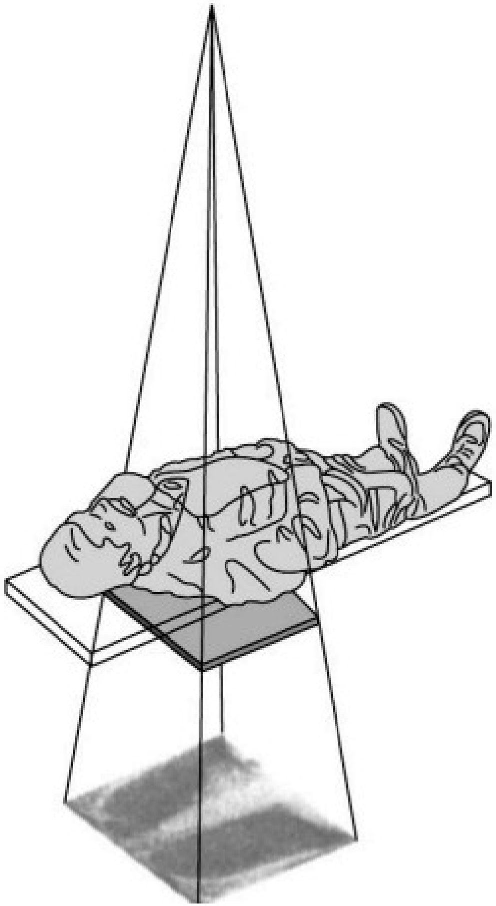
PET



SPECT

X-rays





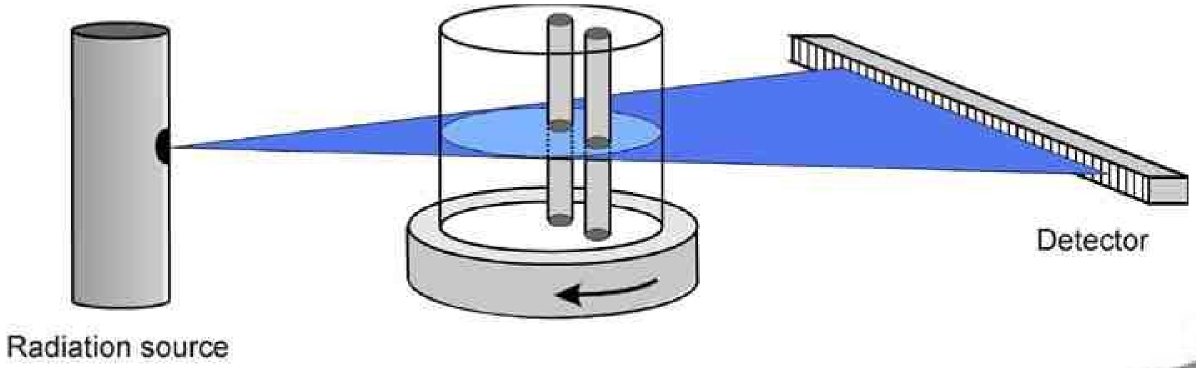
Based on absorption

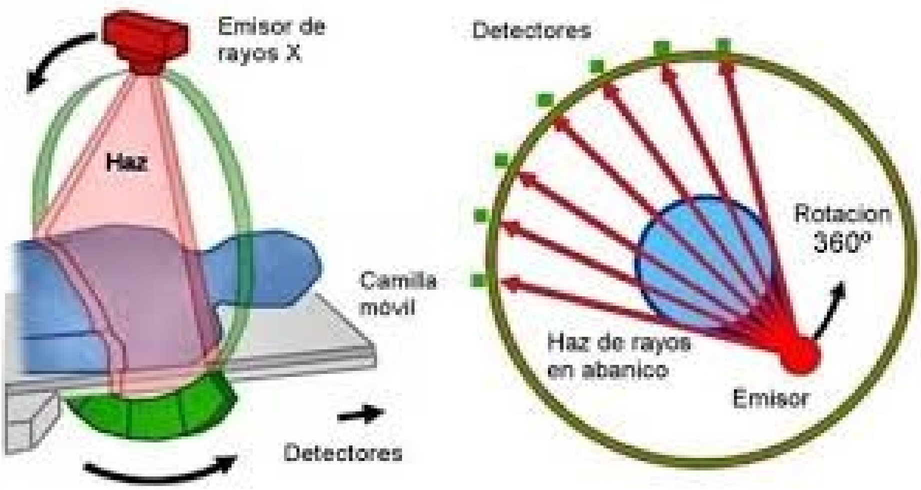
$$I = I_o e^{-\Sigma \mu_i x_i}$$

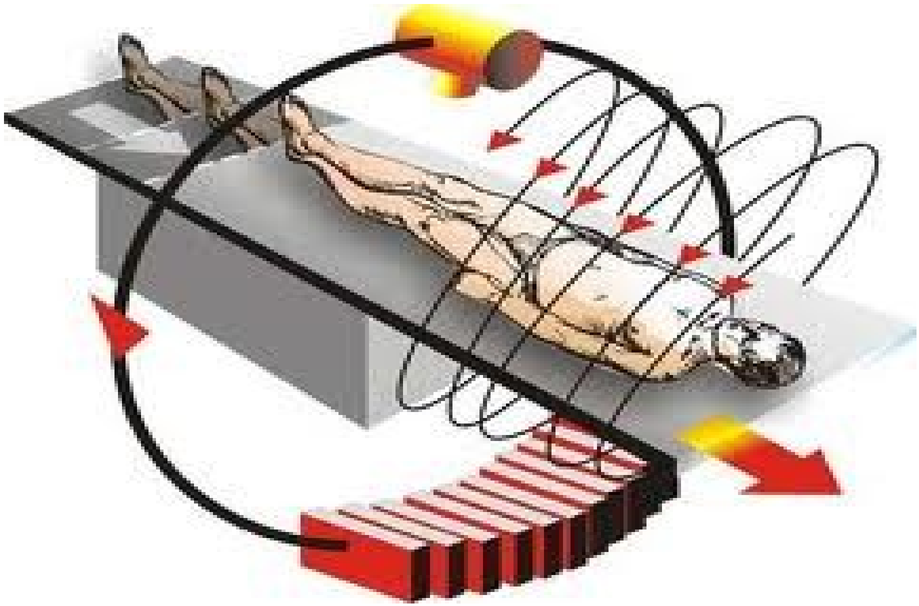
X-rays

Computed tomography (CT)

Combination of data taken at different slices.

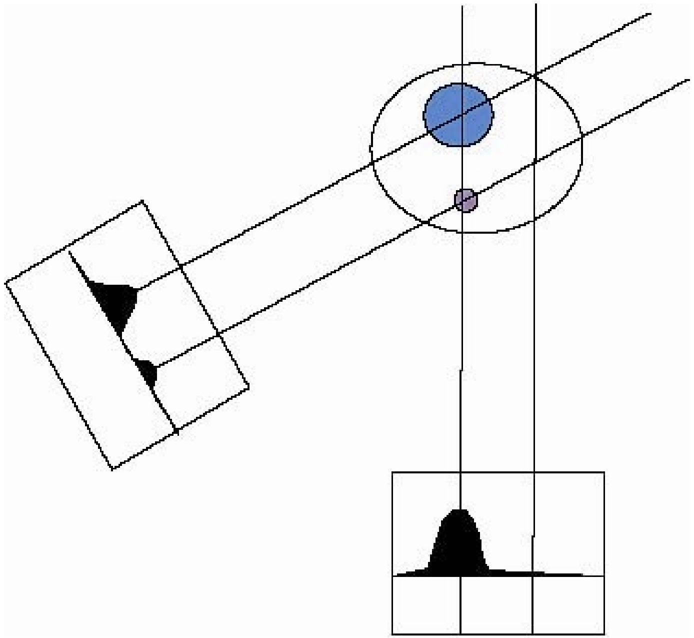


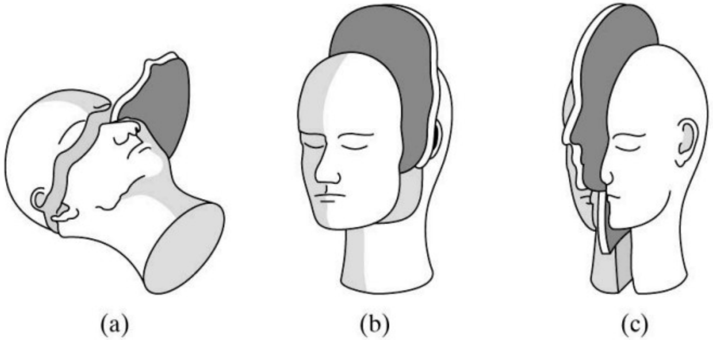


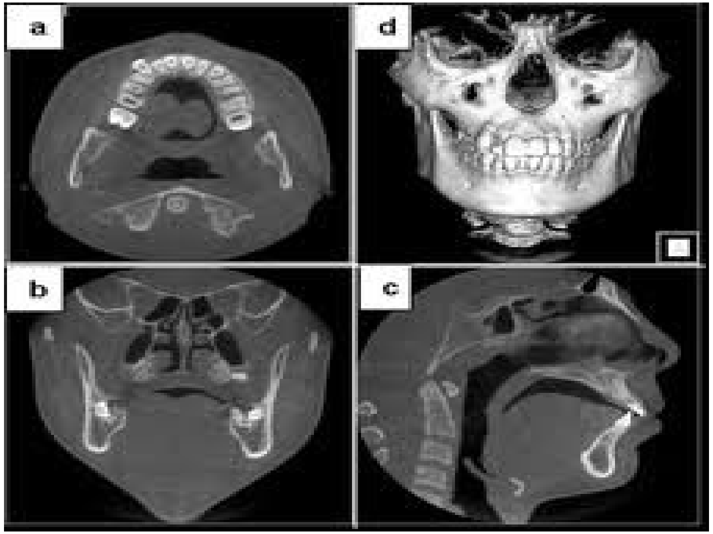


Computed tomography (CT)

Combination of data taken at different slices.



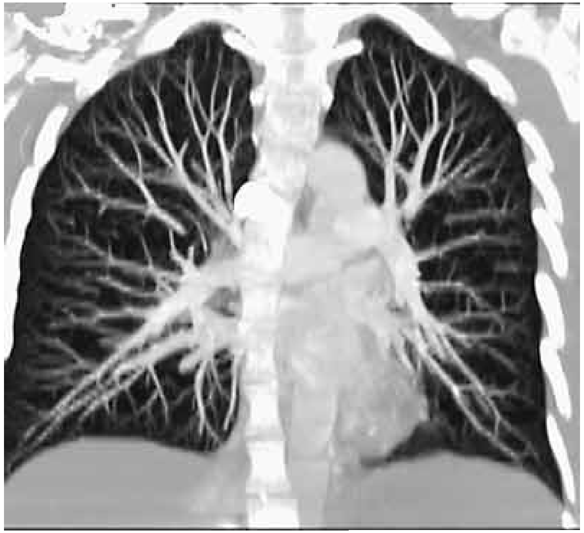




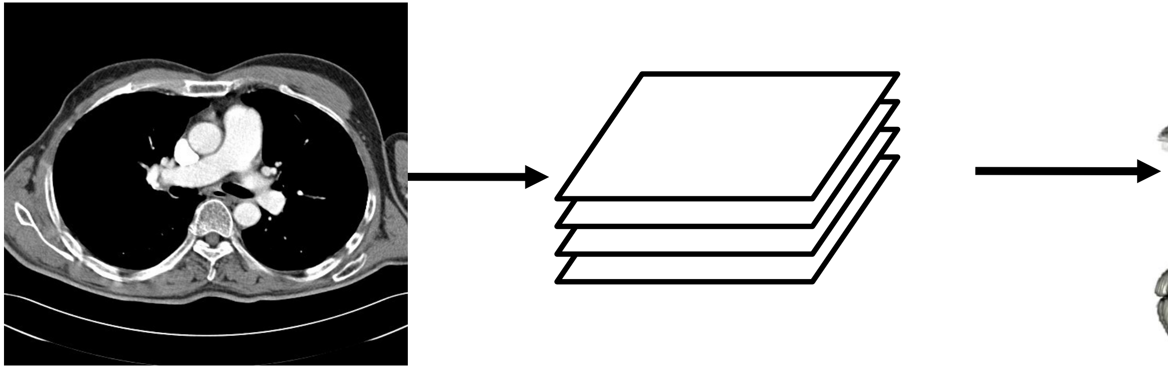
Computed tomography (CT)

Planar

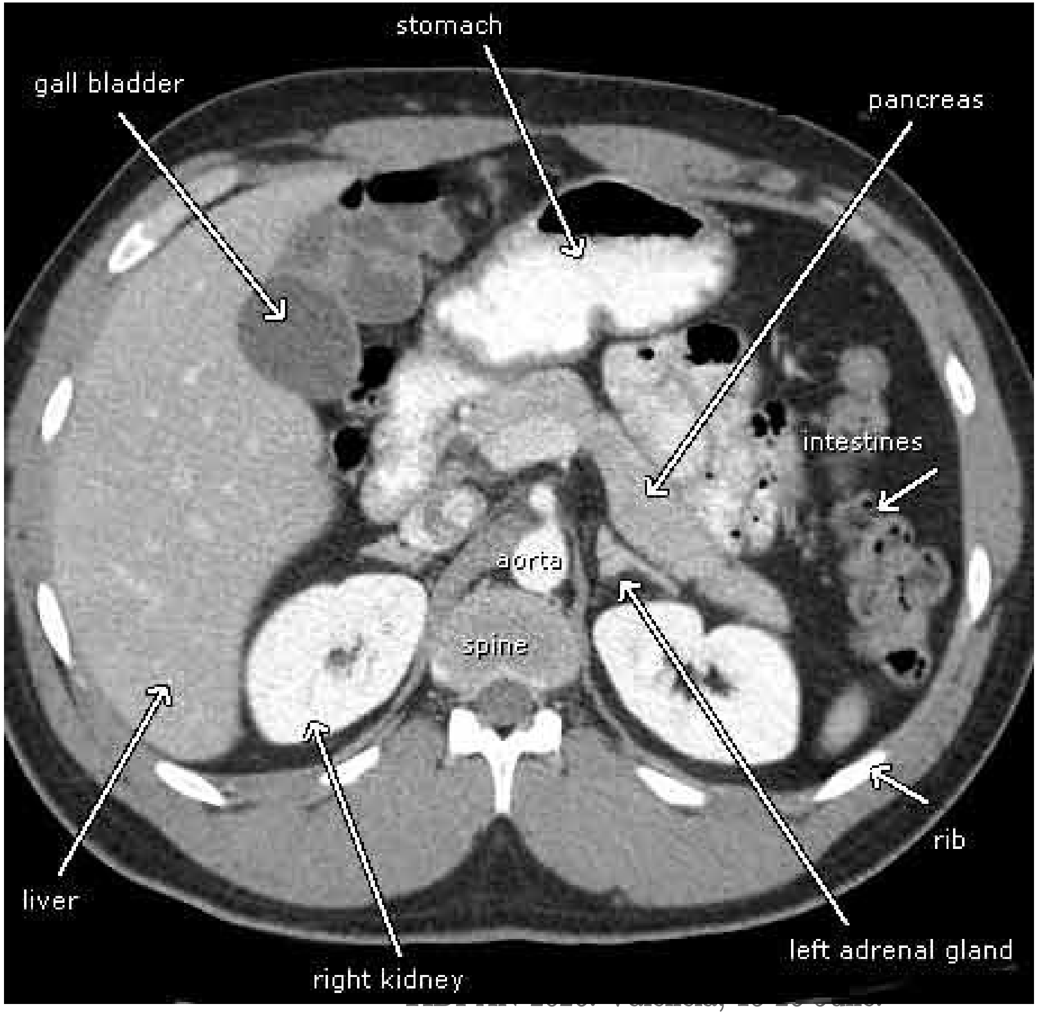
X-rays



CT



Computed tomography (CT)



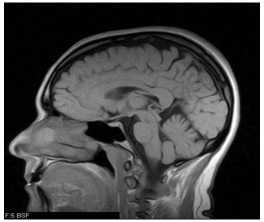
ONLY ANATOMY

Medical imaging

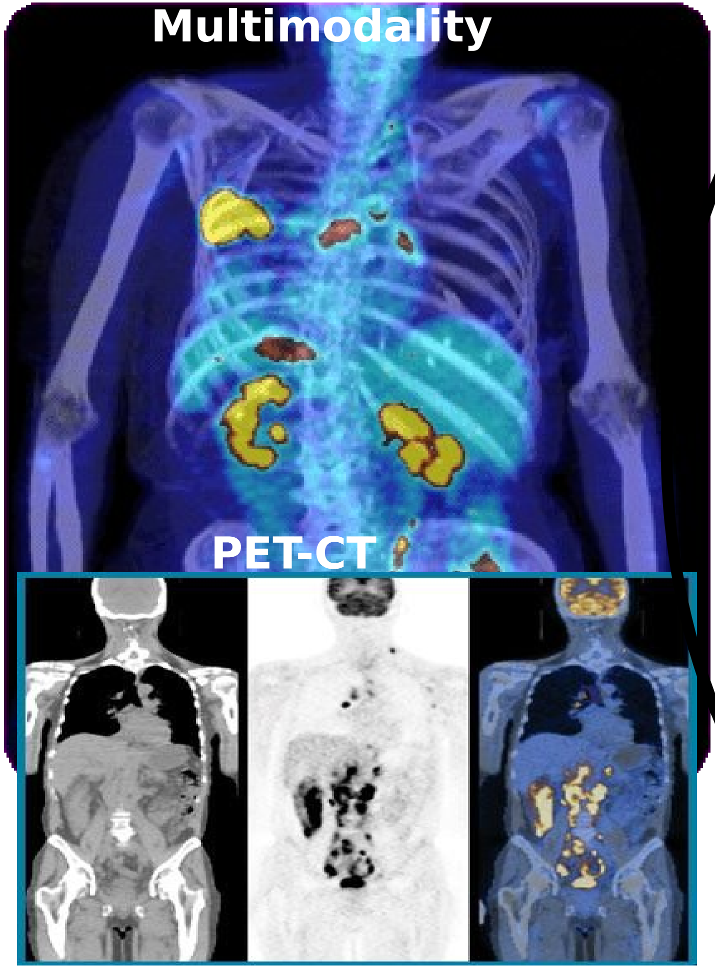
Structural

CT

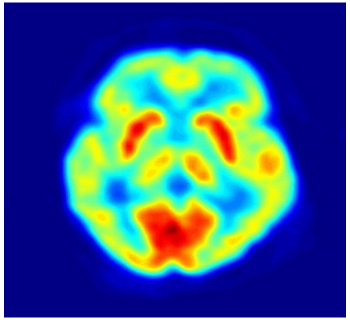
MRI



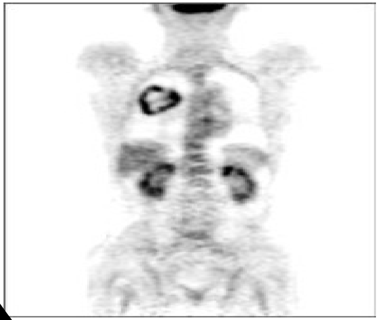
Ultrasounds



Functional

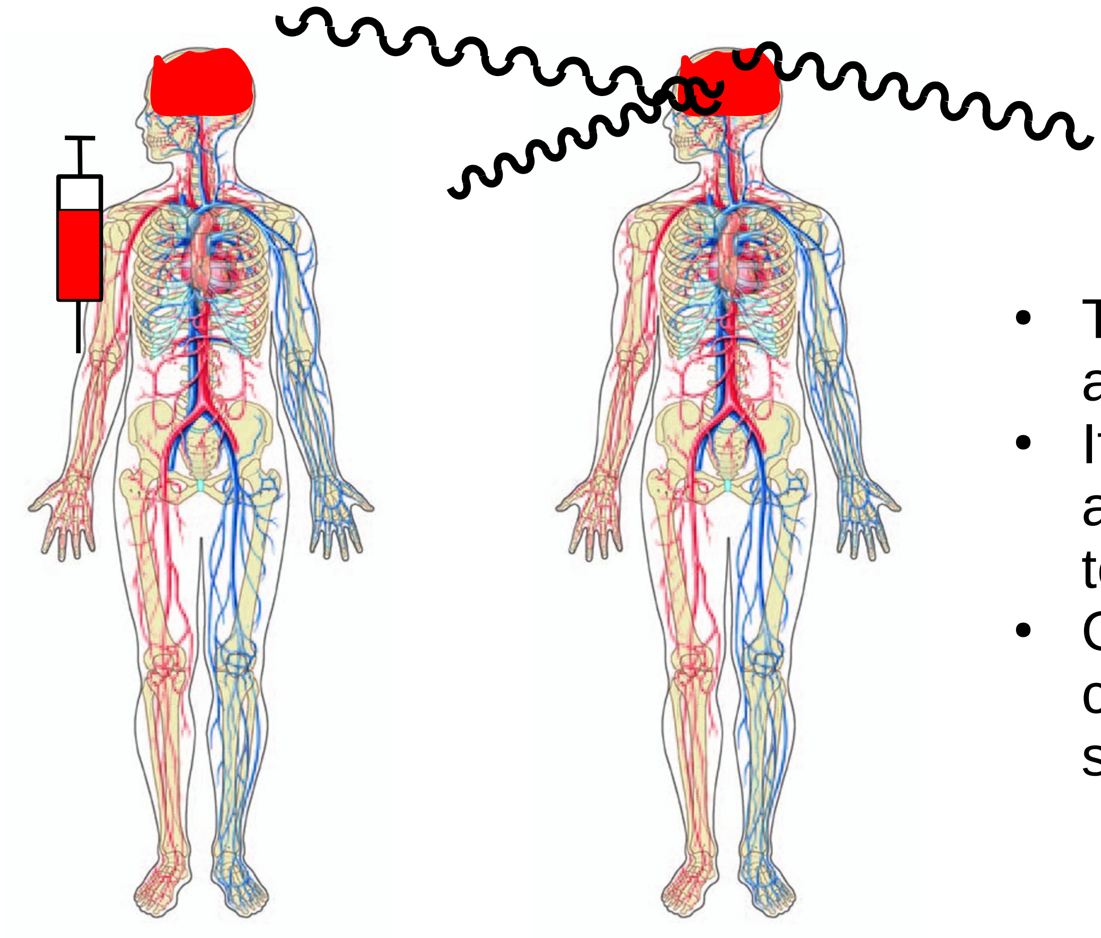


PET



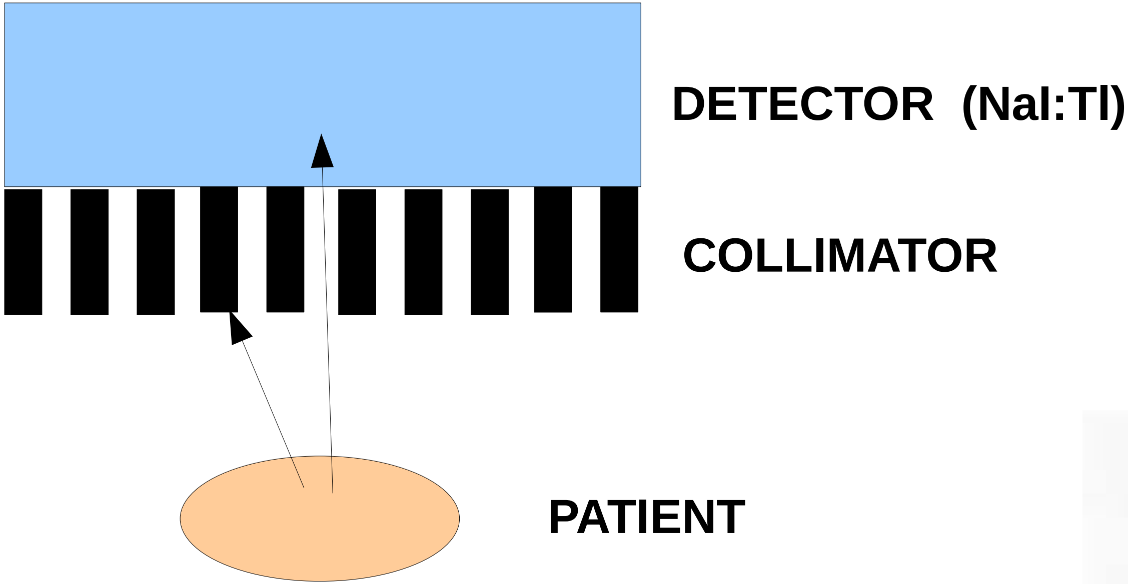
SPECT

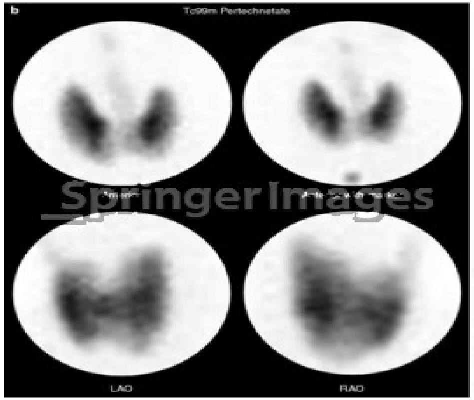
Emission techniques (SPECT, PET...)

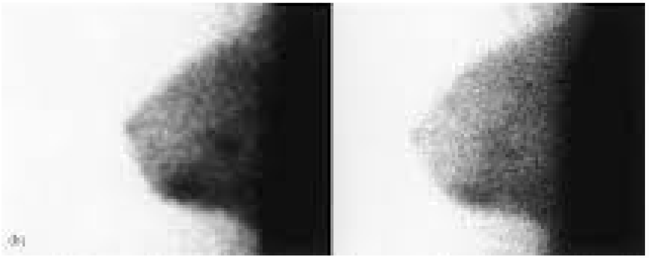


- The radiotracer is labeled with a radioisotope.
- It distributes in the whole body and accumulates in the organ to be imaged.
- One isotope can lable different compounds for different studies.

Gamma cameras

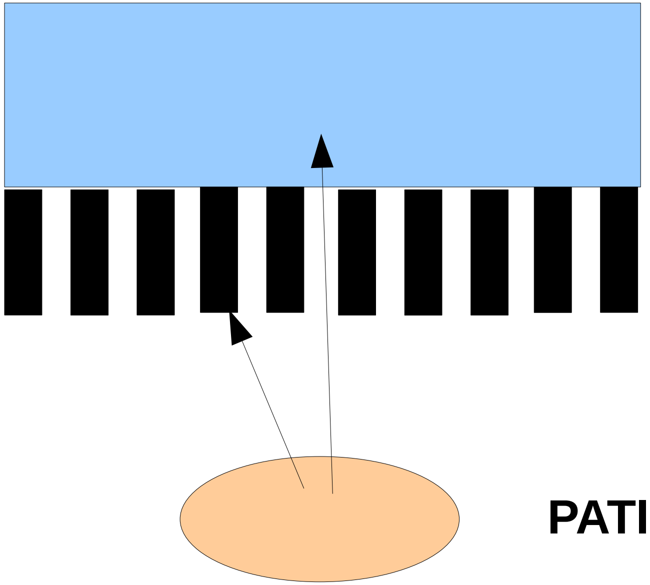




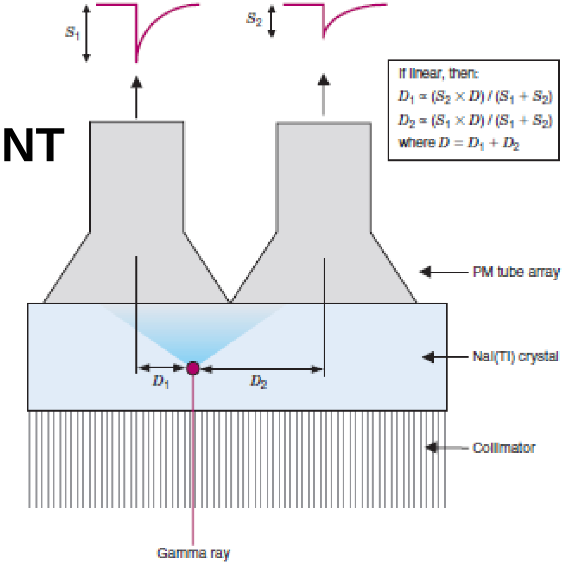


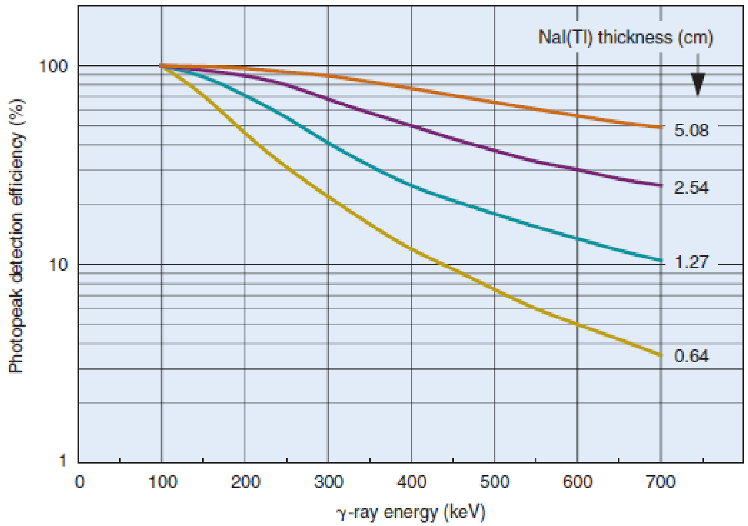
- Single photon emitters. 2-30 mCi (74-1110 Mbq).
- Most common radiotracer: **Tc-99m** (140 keV).
- Others: In-111 (171.3 keV, 245.4 keV), I-131 (364.5 keV).

Typical detector parameters



- Typical scintillator thickness: 6.4-12.5 mm.
- Typical size: 30x40- 50x60 mm.
- Typical energy resolution: 9-10% @ 140 keV.

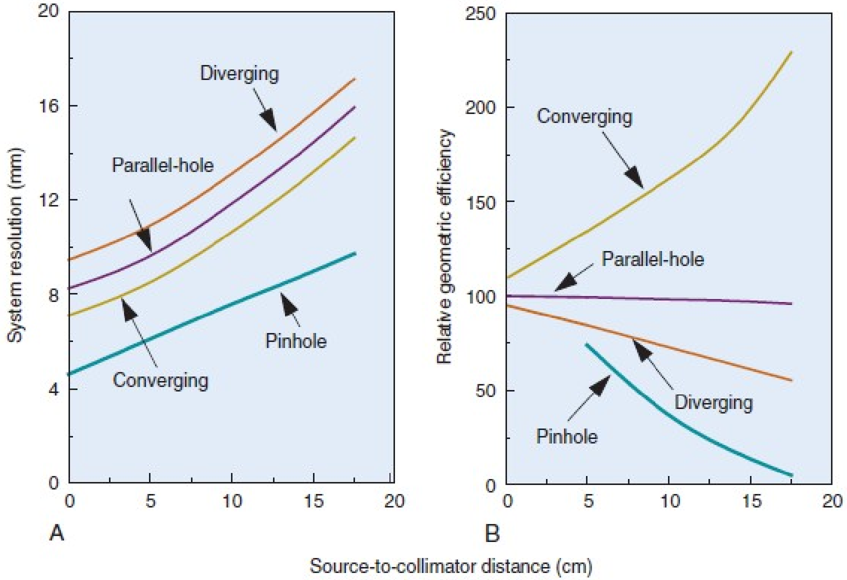


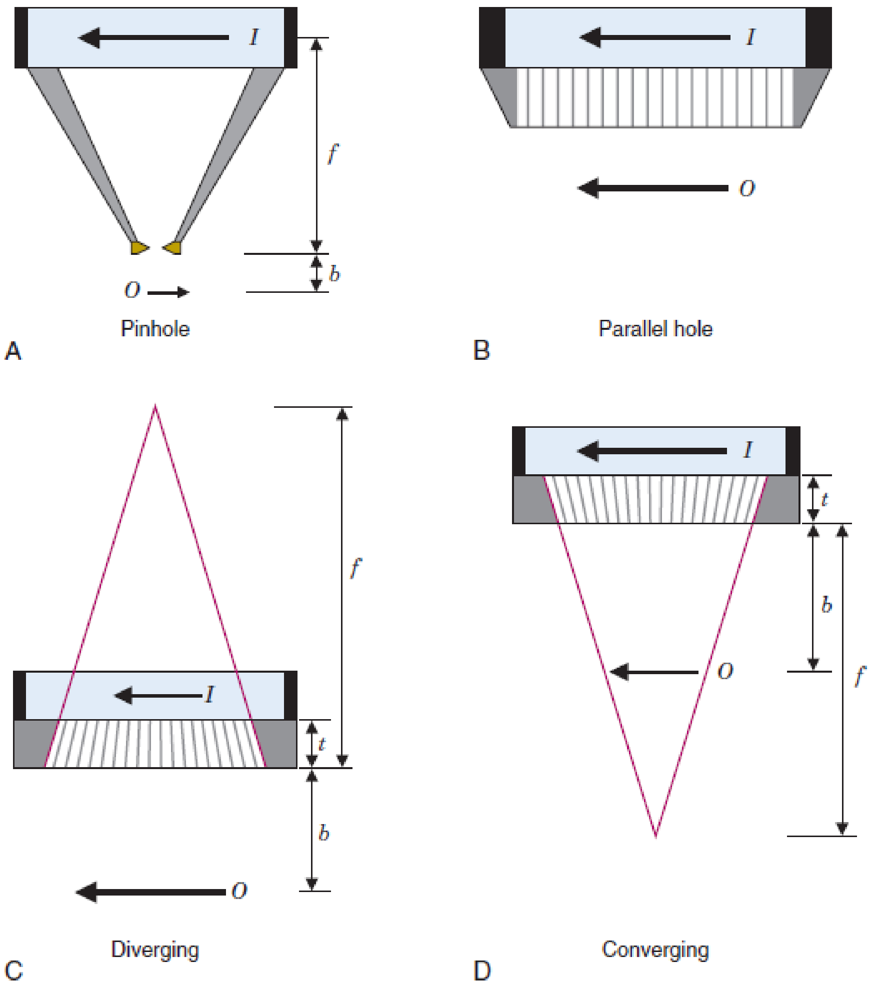


SiPMs replace PMTs as photodetectors, but not critical.

Collimator

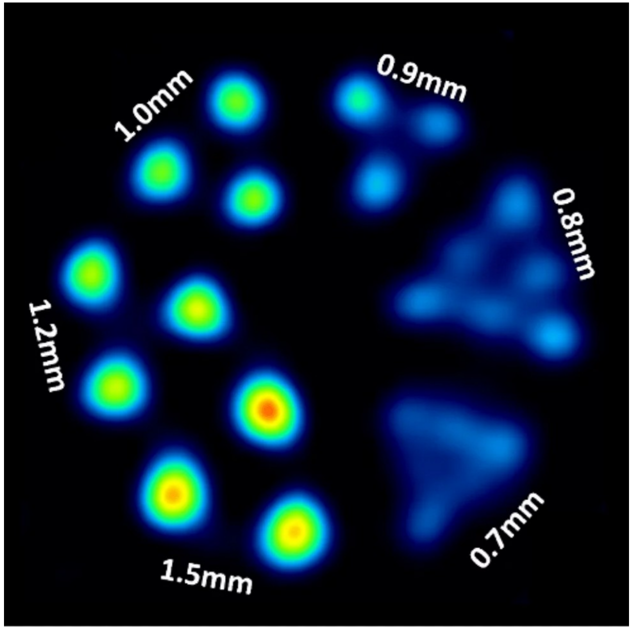
- Strongly determines system performance
- Reduced sensitivity.
- Resolution and sensitivity are inversely coupled.
- Optimized for different energies / activities.

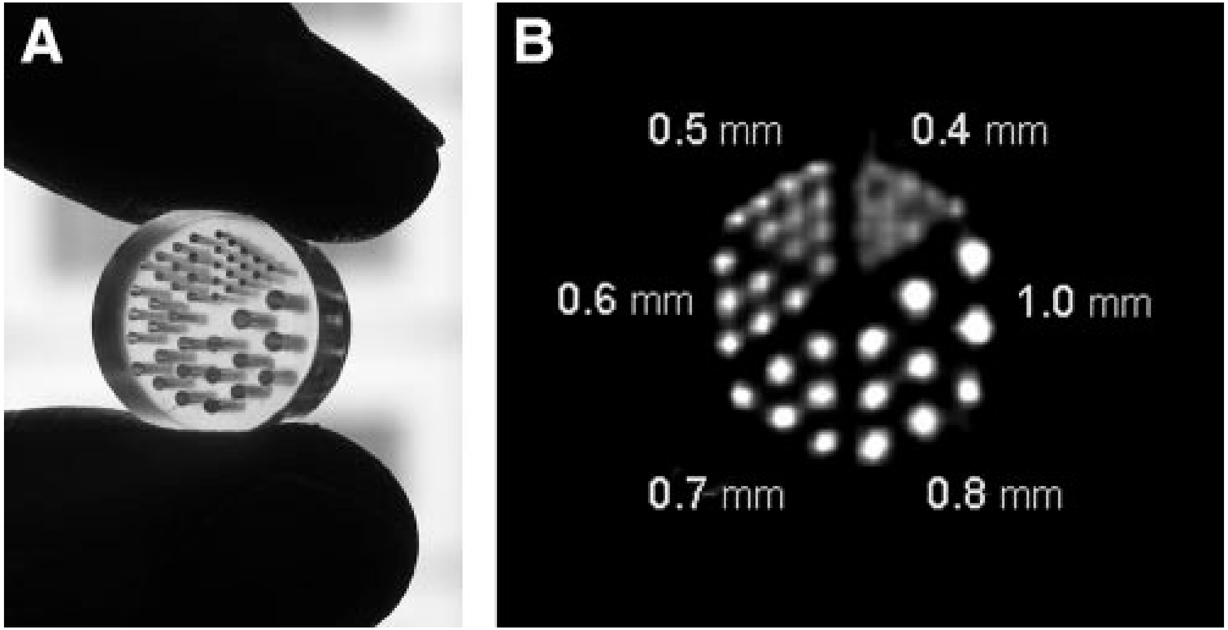




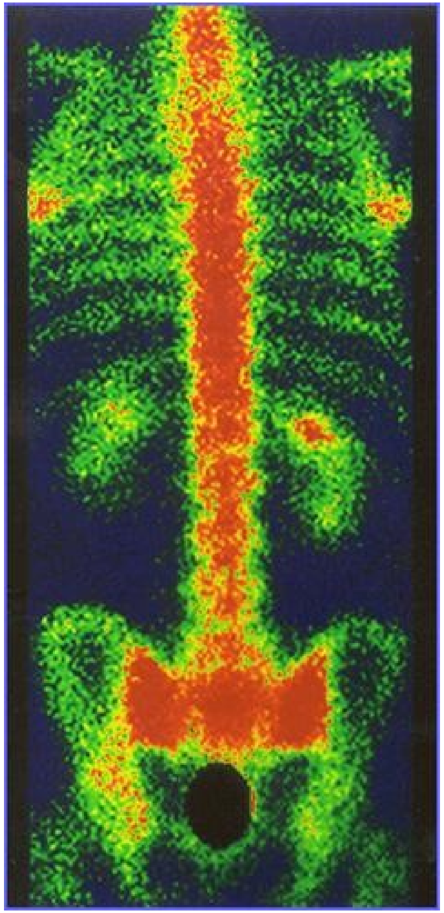
Collimator types

- Typical spatial resolution: 6 -15 mm FWHM.
- Small animal systems achieve < 1 mm FWHM (0.5 mm FWHM).



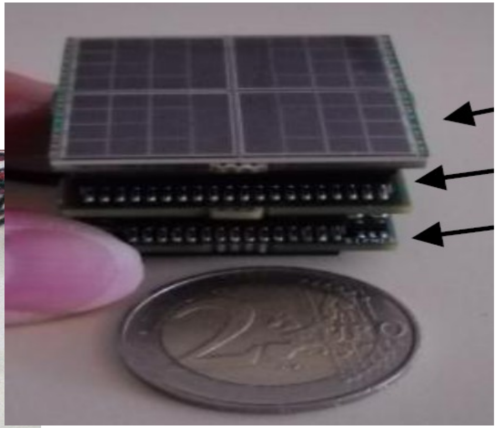


Gamma cameras

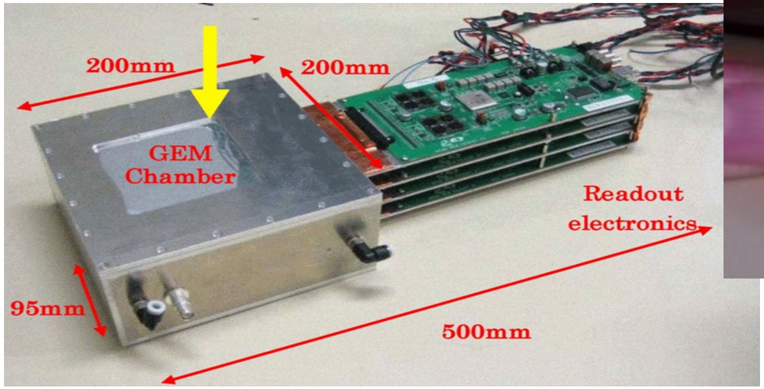


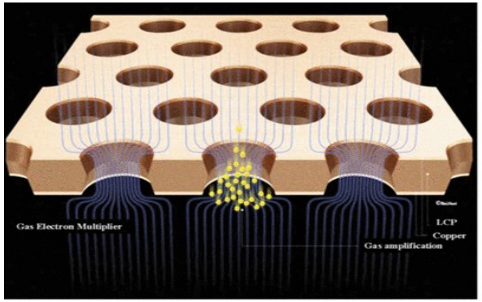
Decicated gamma cameras

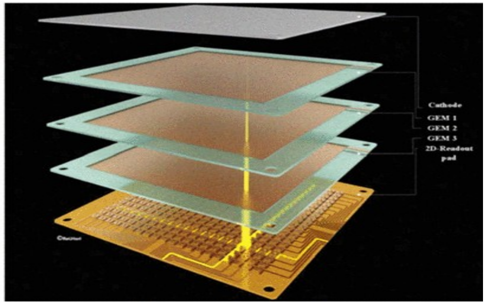
Small, dedicated systems (heart, breast...), small animal systems: also mostly scintillators, but other types considered.



SiPM board
ASIC board
FPGA board

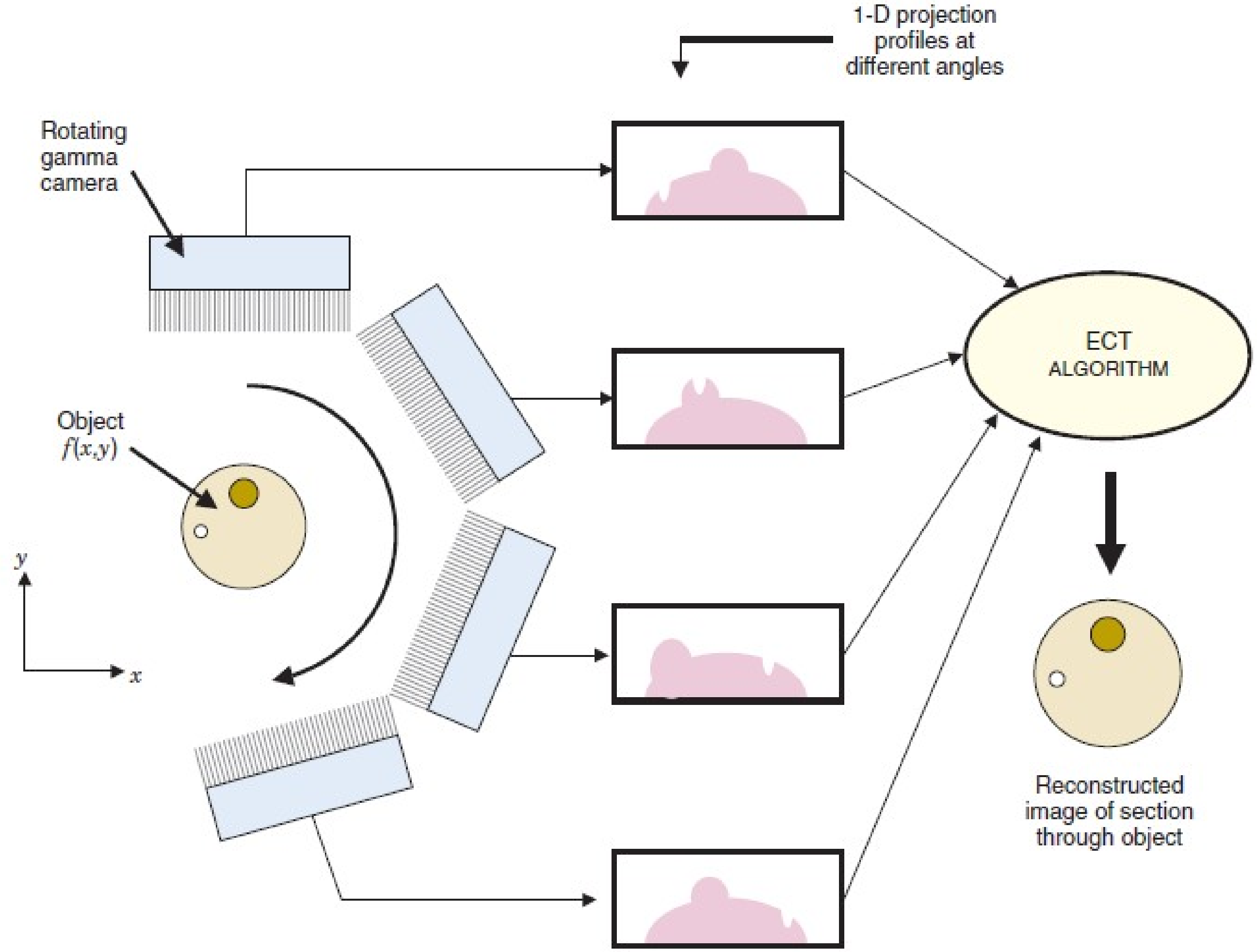




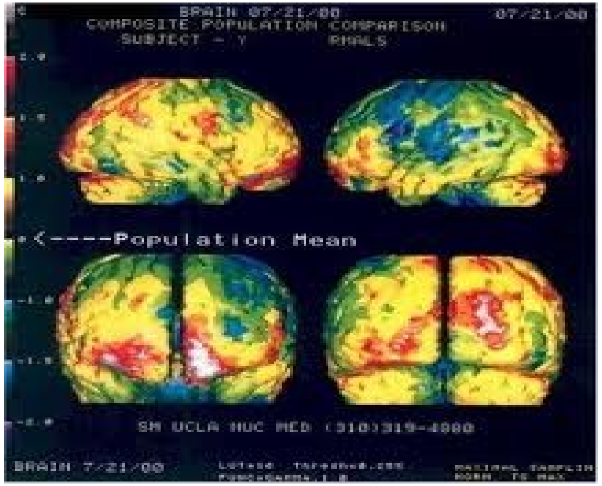


CZT, I. Blevis et al. 2011 IEEE NSS MIC conf record.
LaBr3, R. Pani et al 2015 JINST 10 C06002.
GEM- T. Koike et al. 2011 IEEE NSS MIC conf record.

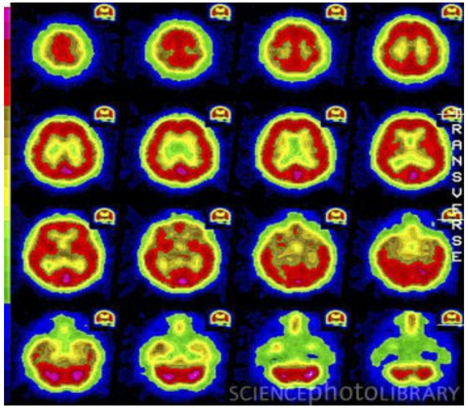
Single Photon Emission Computed Tomography (SPECT)

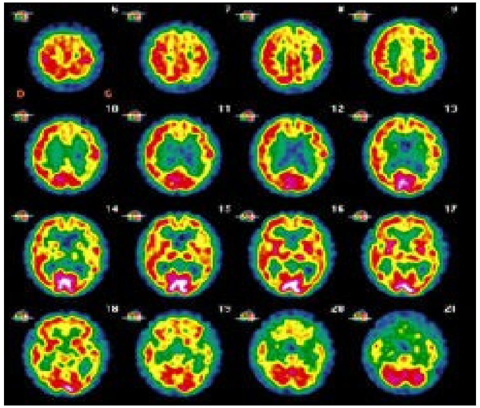


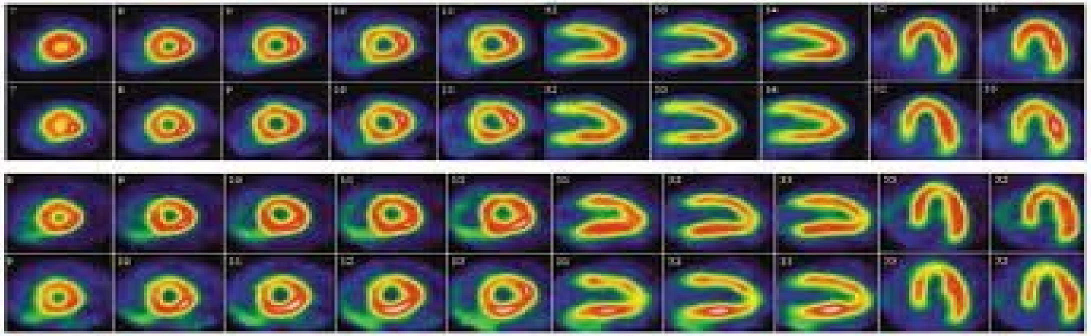
Single Photon Emission Computed Tomography (SPECT)



NM/CT 860 | GE HealthCare



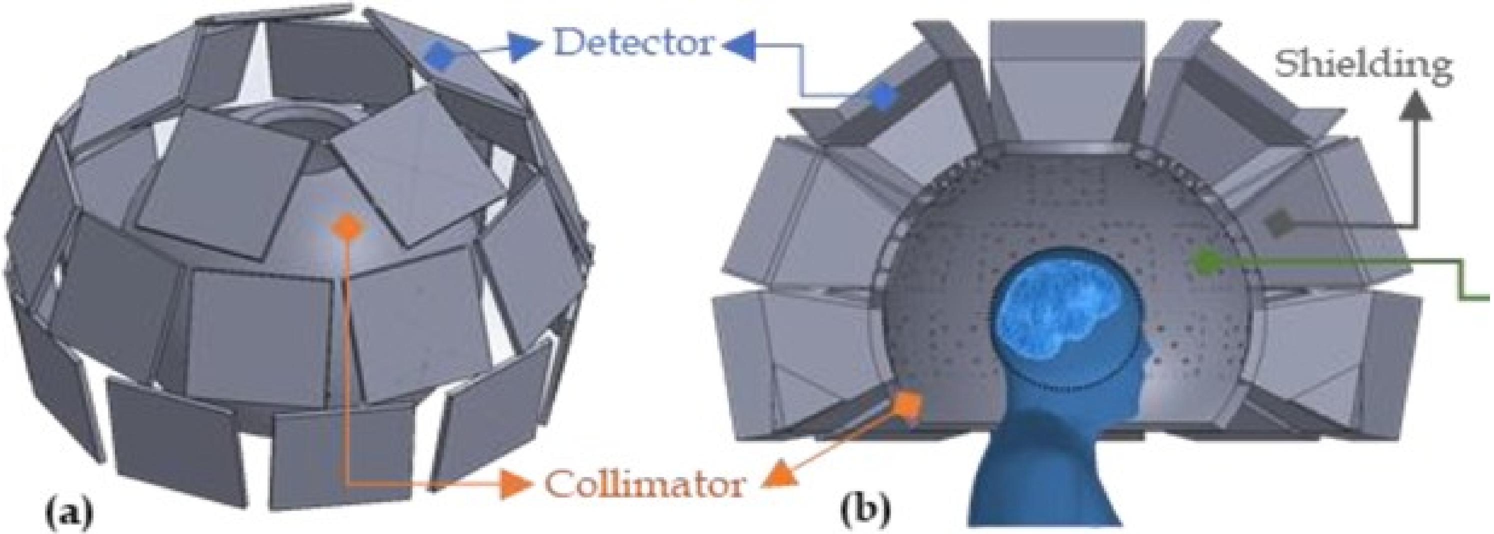




SPECT systems

Dedicated systems

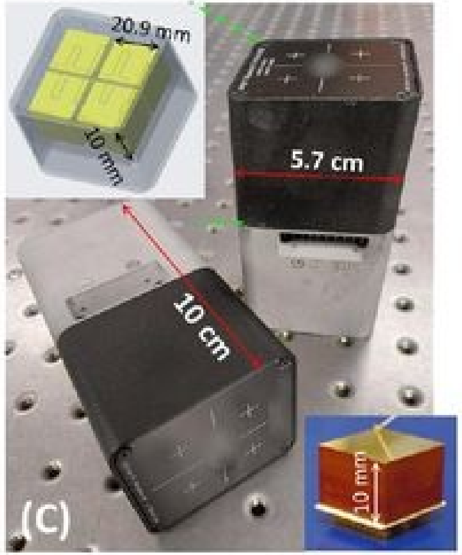
Mutipinhole brain SPECT

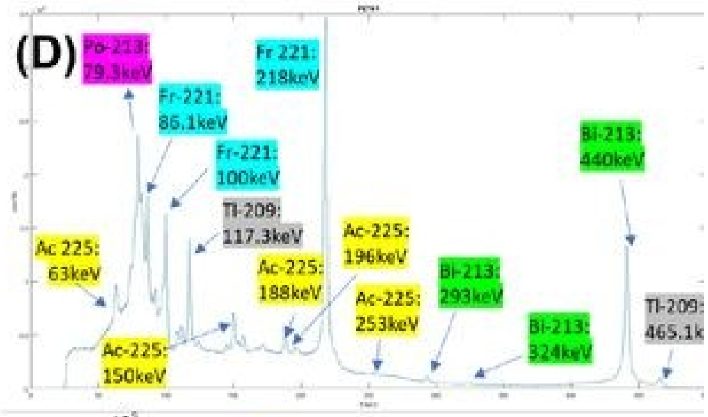


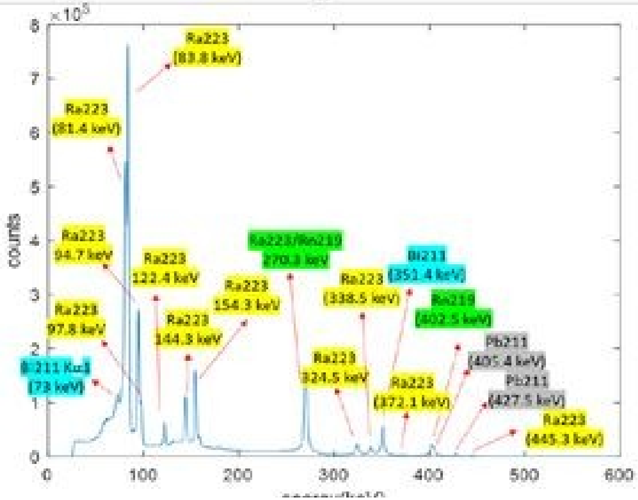
N. Zeraatkar et al. Biomed Phys Eng Express. 2021

Multitracer SPECT

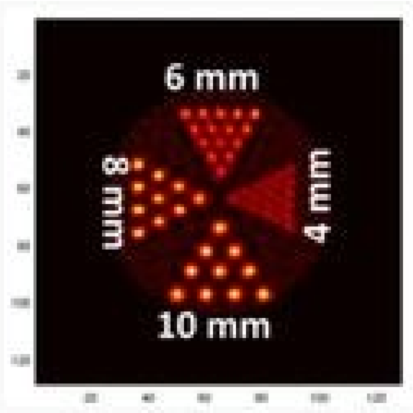
Simultaneous visualization of different radiotracers injected to the patient → higher diagnostic accuracy / different studies.







Solid state (CZT) detectors provide excellent energy resolution.

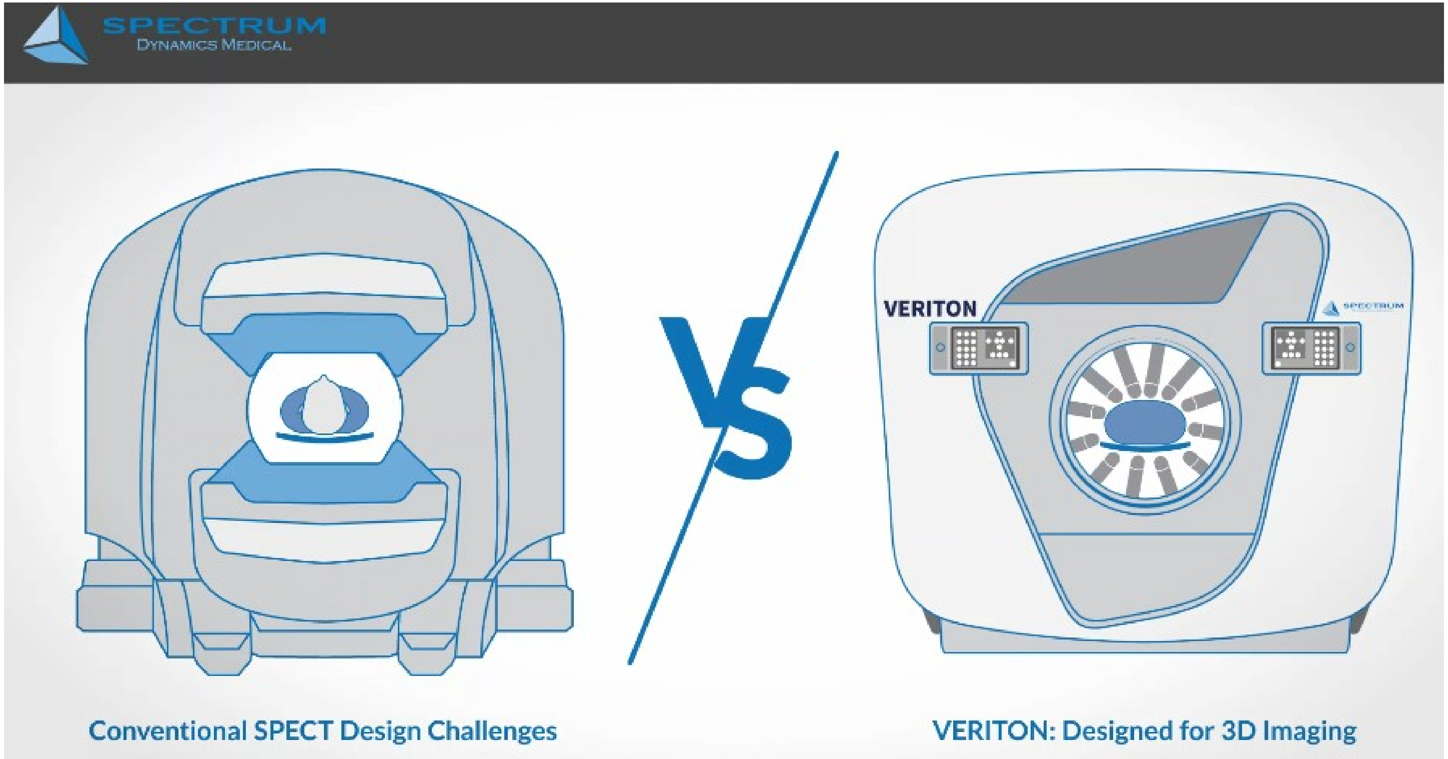


E. Zannoni et al. JNM 2022, 63.

SPECT systems

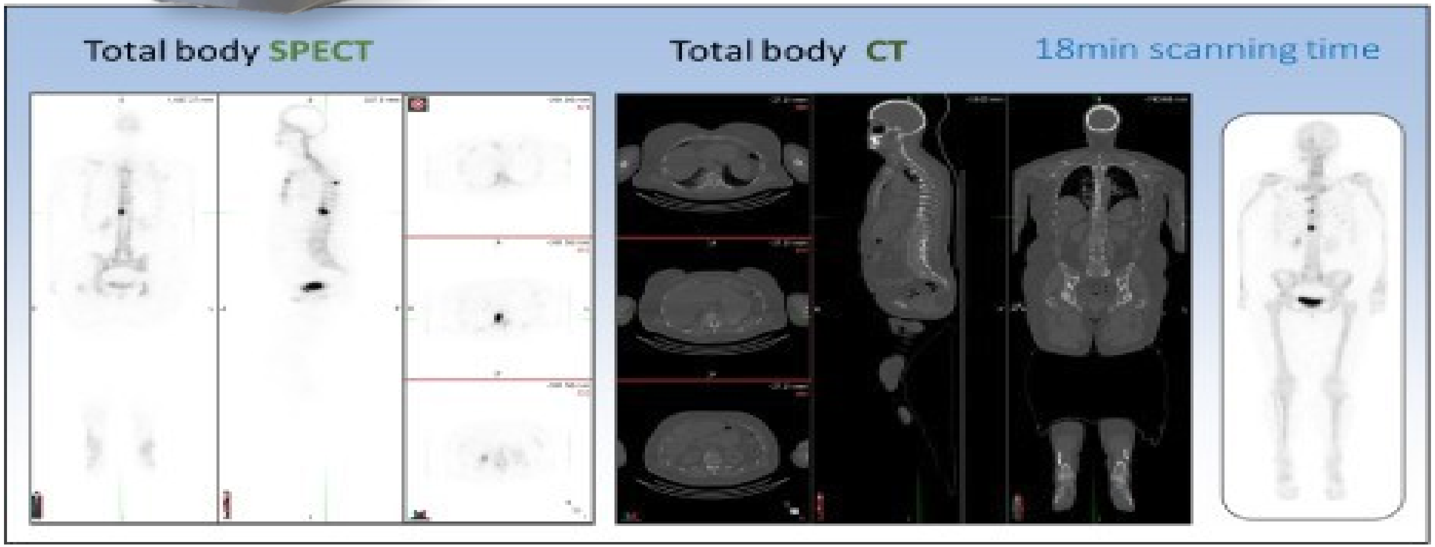
Veriton-CT (Spectrum Dynamics Medical)

CZT detectors. Only SPECT, no gamma camera.

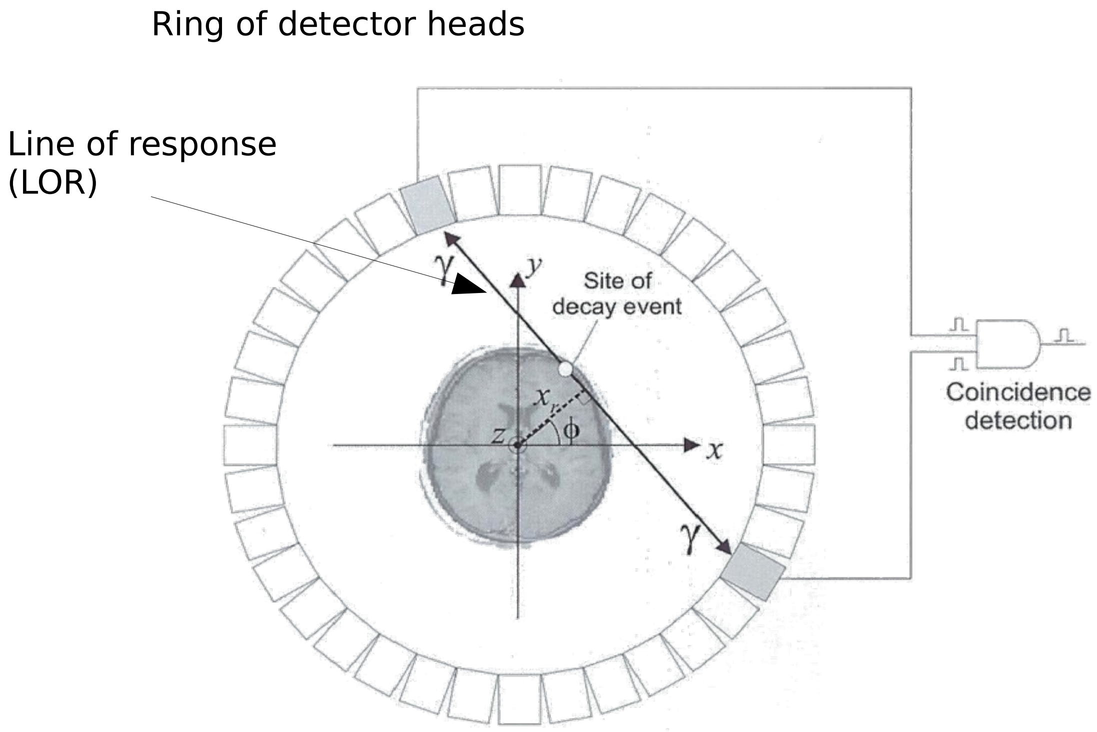


SPECT systems

Veriton-CT (Spectrum Dynamics Medical)

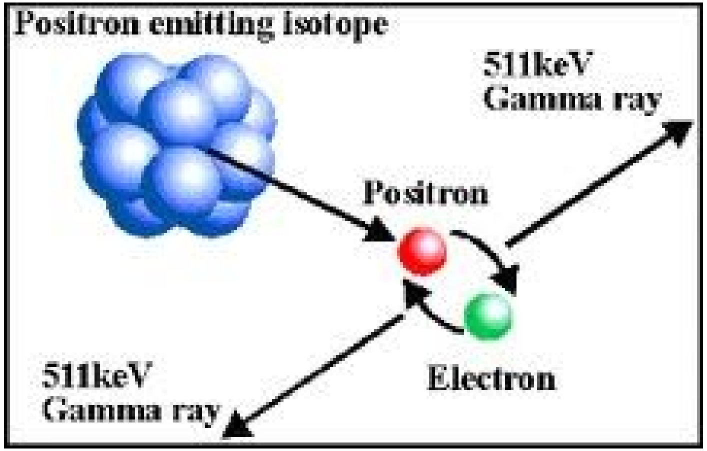


Positron Emission Tomography (PET)

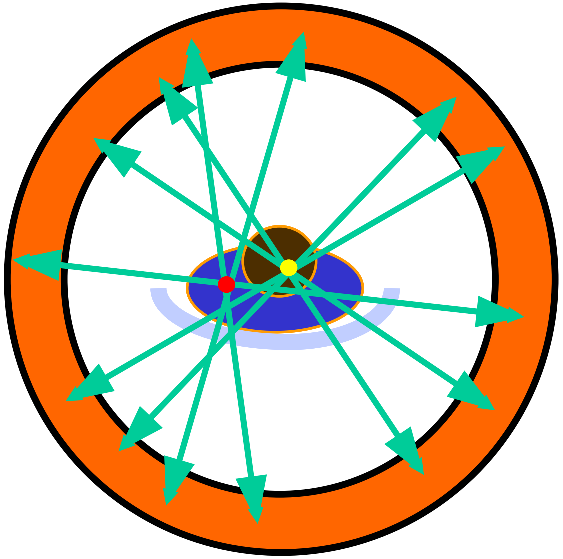


- Positron emitters → 511 keV photons.
- 5-10 mCi (185-370 MBq).
- Electronic collimation - detection in time coincidence → timing becomes relevant.
- Most common radiotracer: **^{18}F-FDG**
- Other: C-11, N-13, O-15, Ga-68.

Higher sensitivity than SPECT



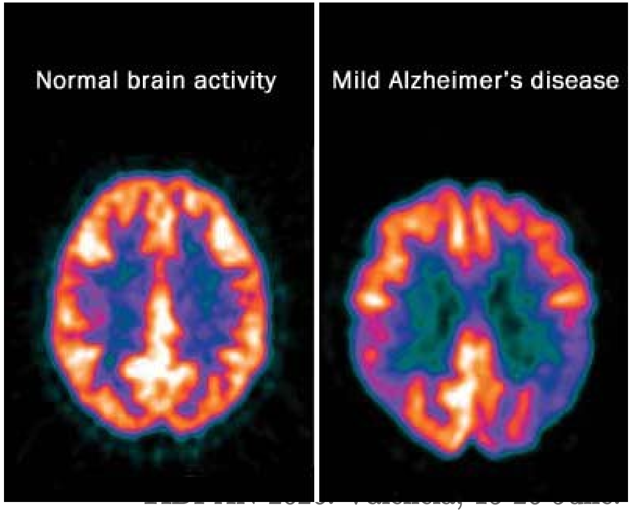
Positron Emission Tomography (PET)

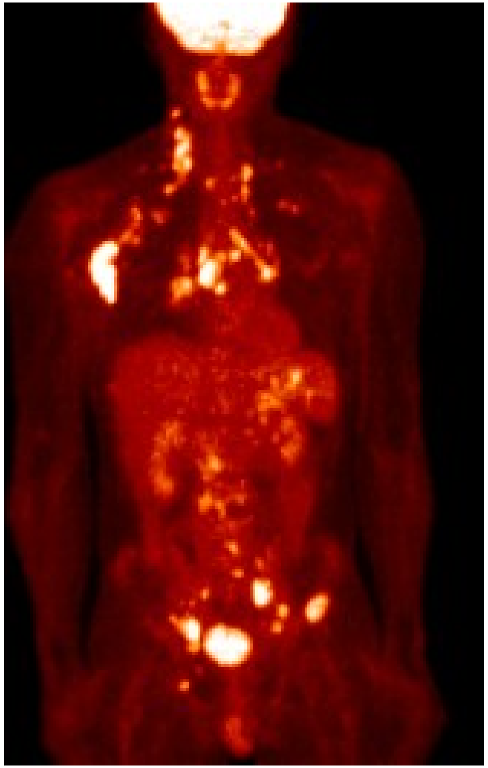


Data acquisition

$$n_j^{k+1} = \frac{n_j^k}{\sum_{i=1}^{I} a_{ij}} \sum_{i=1}^{I} a_{ij} \frac{m_i}{q_i^k}$$

Image reconstruction

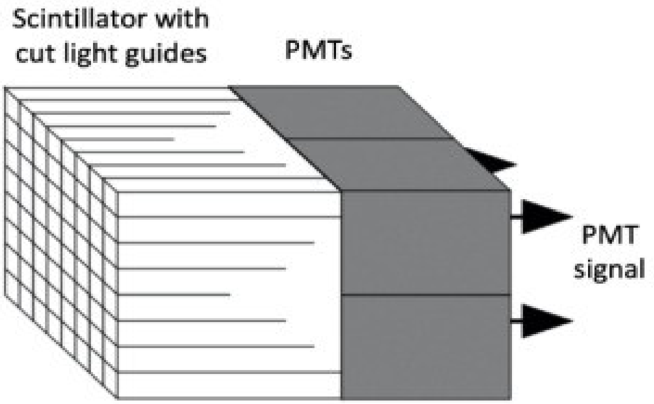


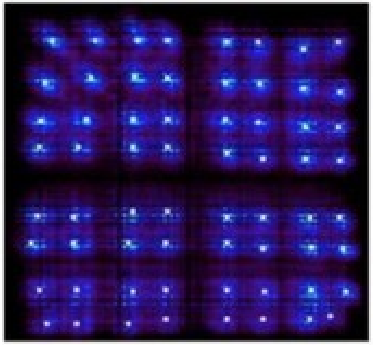


Image

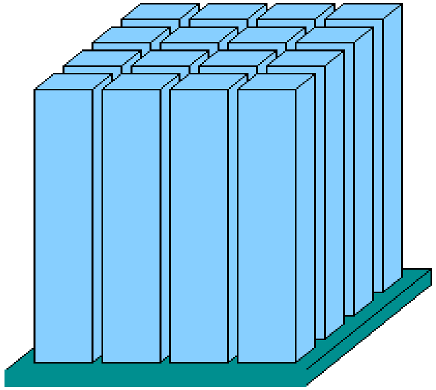
PET - detectors

Block detector: BGO + PMTs.
4-6 mm crystal size





LSO / LYSO + SiPMs. 3-4 mm crystal size

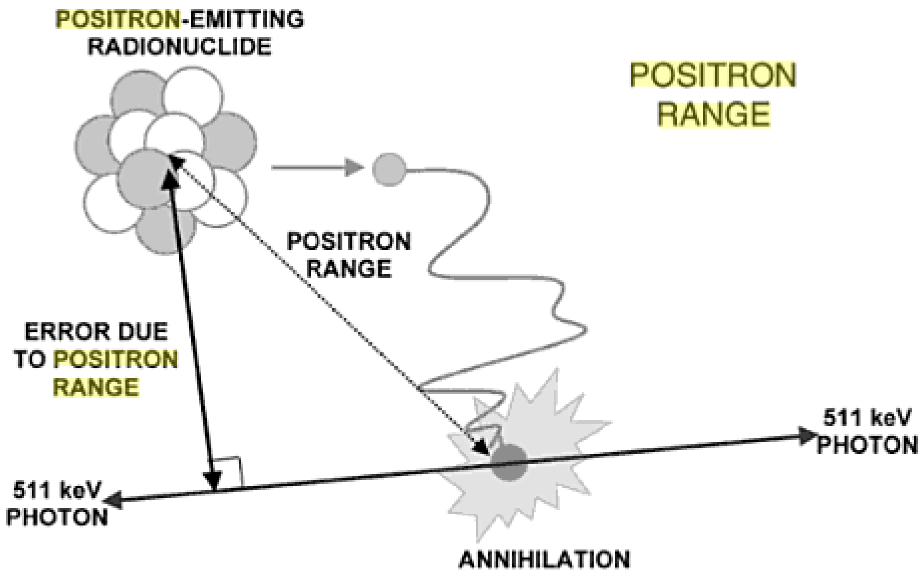


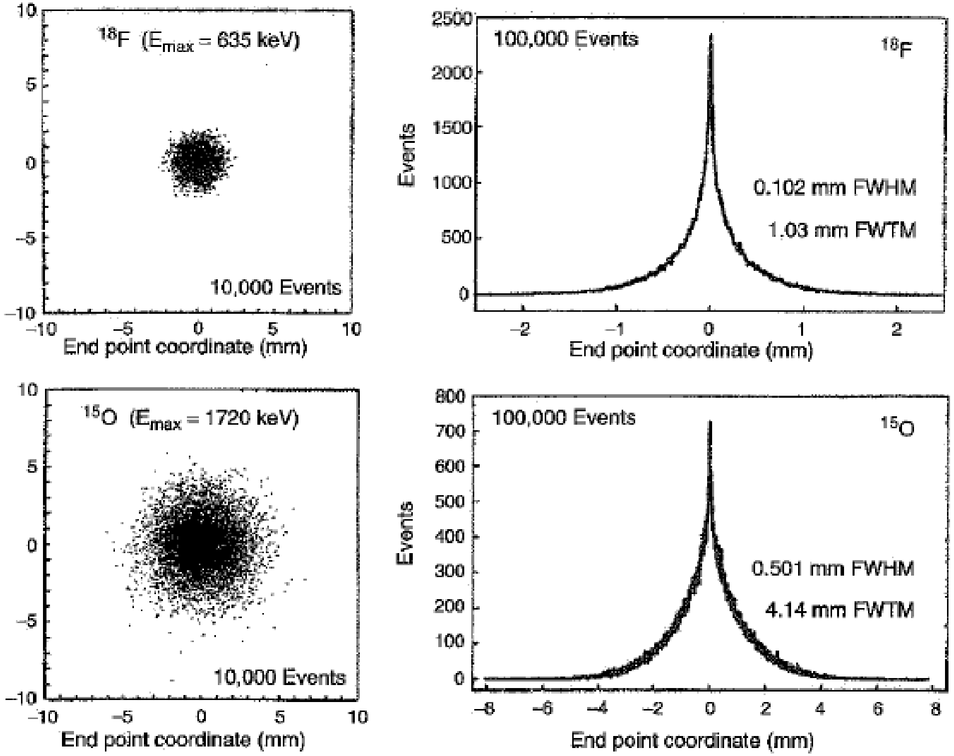
One-to-one coupling or Multiplexing solutions to reduce the number of channels

(→ PET/MR)

Positron range

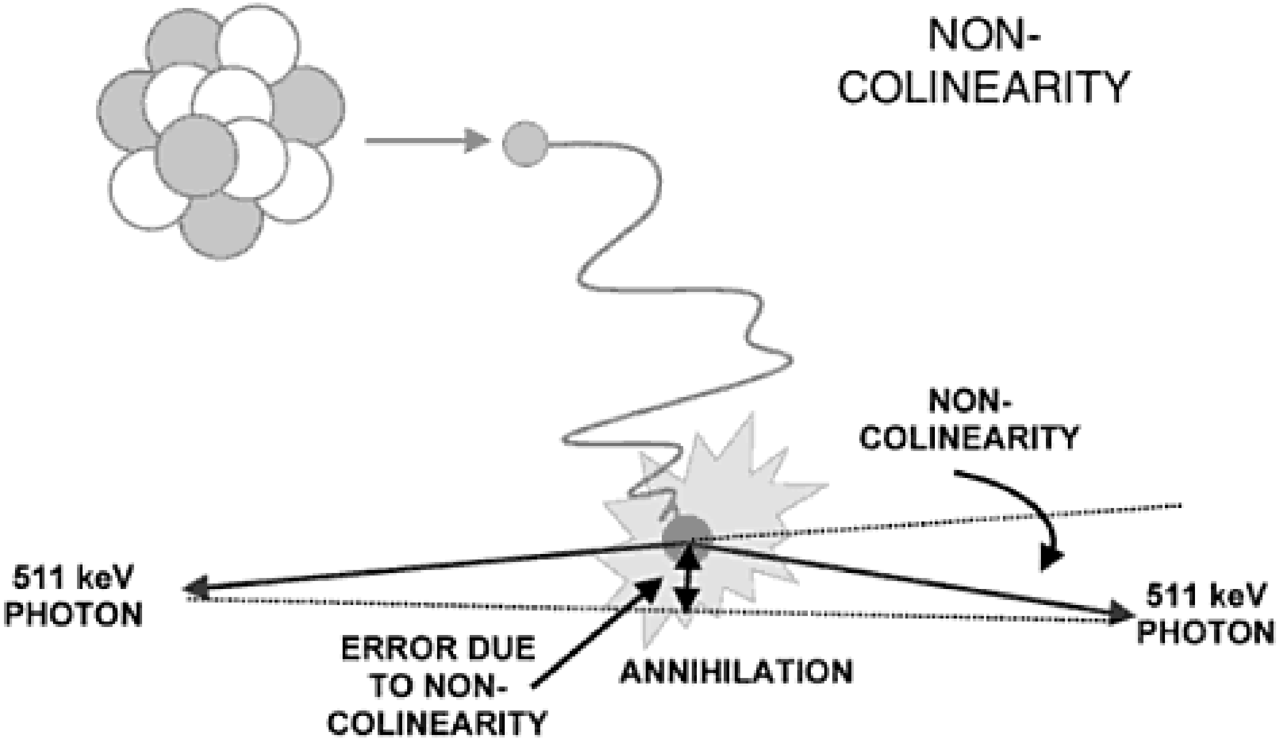
The positron travels before it annihilates



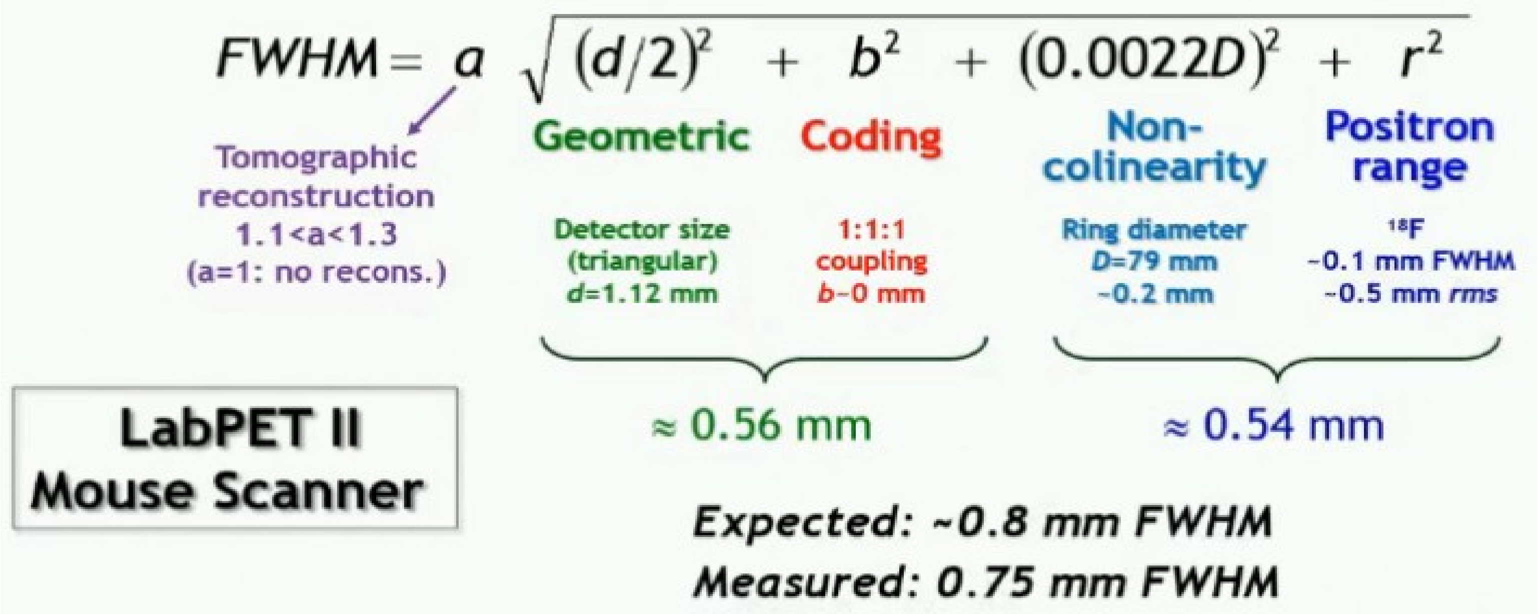


Non-colinearity

The positron is not at rest when it annihilates

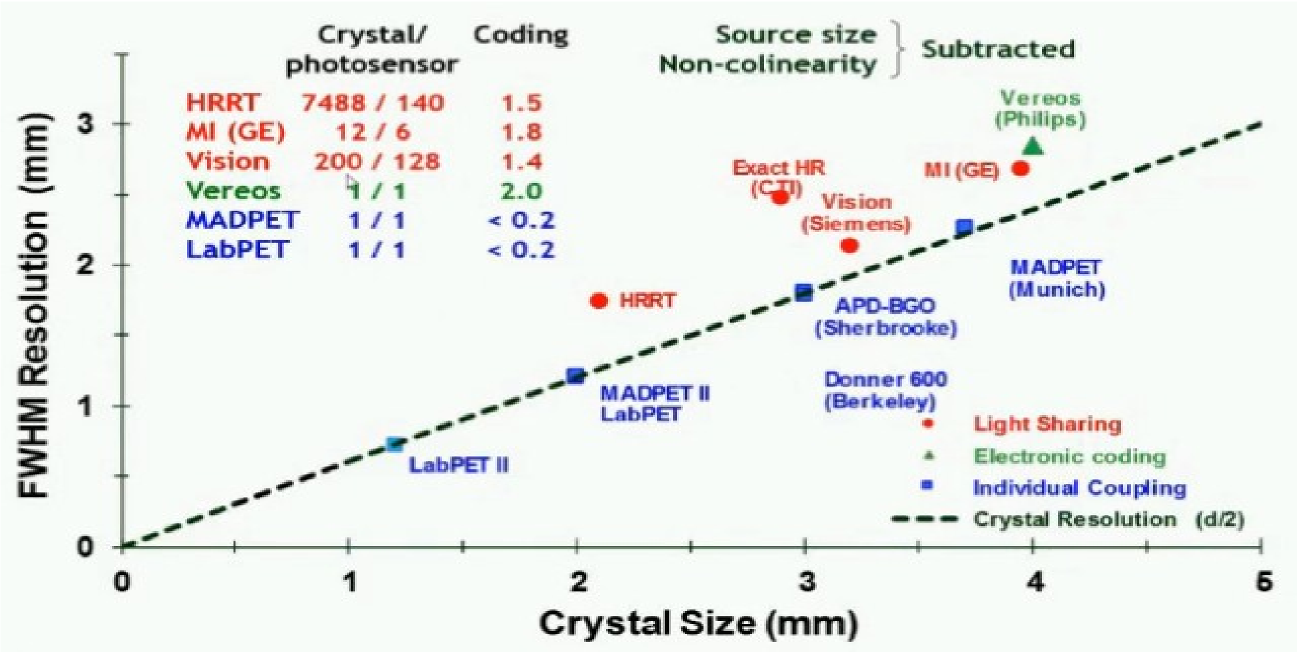


Spatial resolution

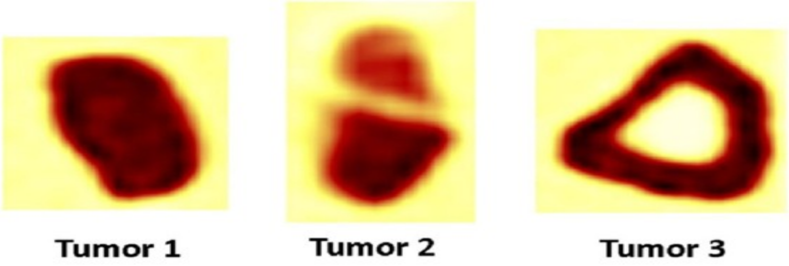


Spatial resolution in PET scanners

Small animal and dedicated scanners

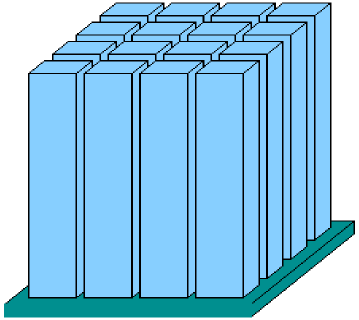


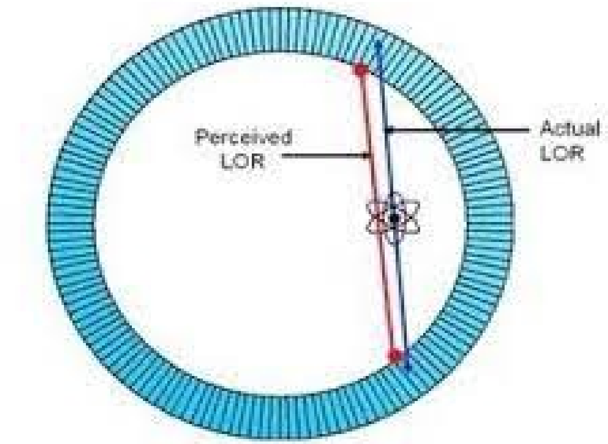
- In clinical systems: 3-4 mm FWHM
- High resolution would allow to visualize tumour heterogeneity

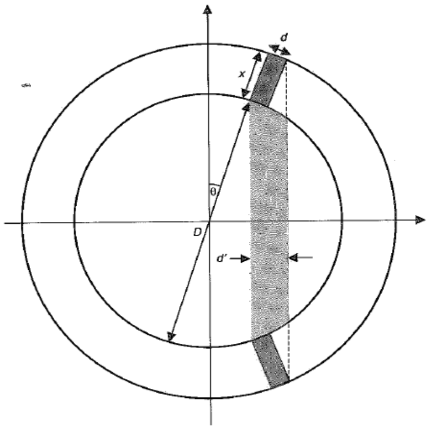


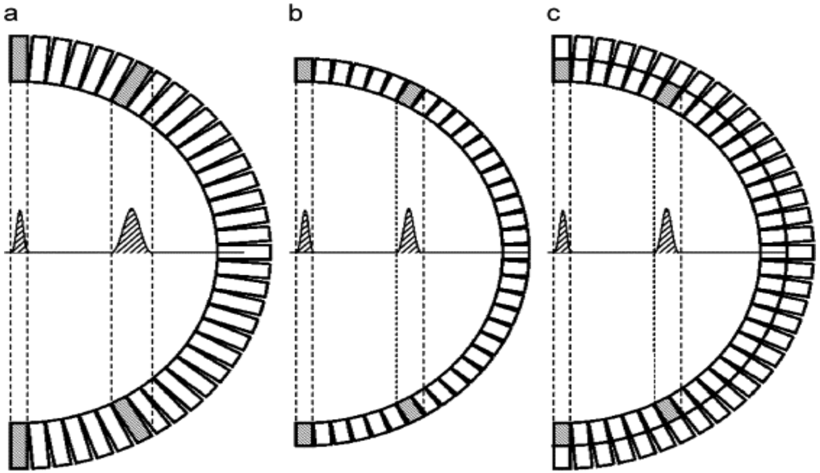
Depth-of-Interaction (DOI) determination

Parallax error degrades the resolution at the edges of the scanner

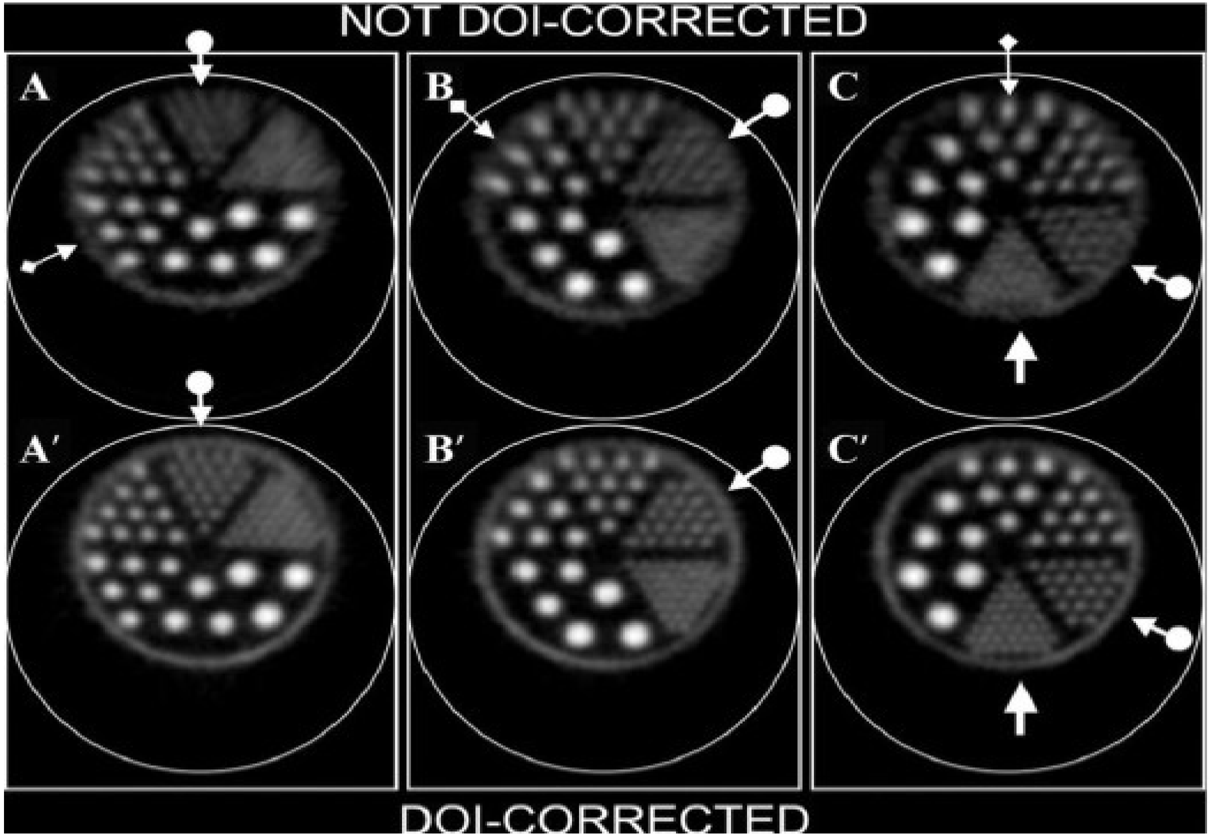






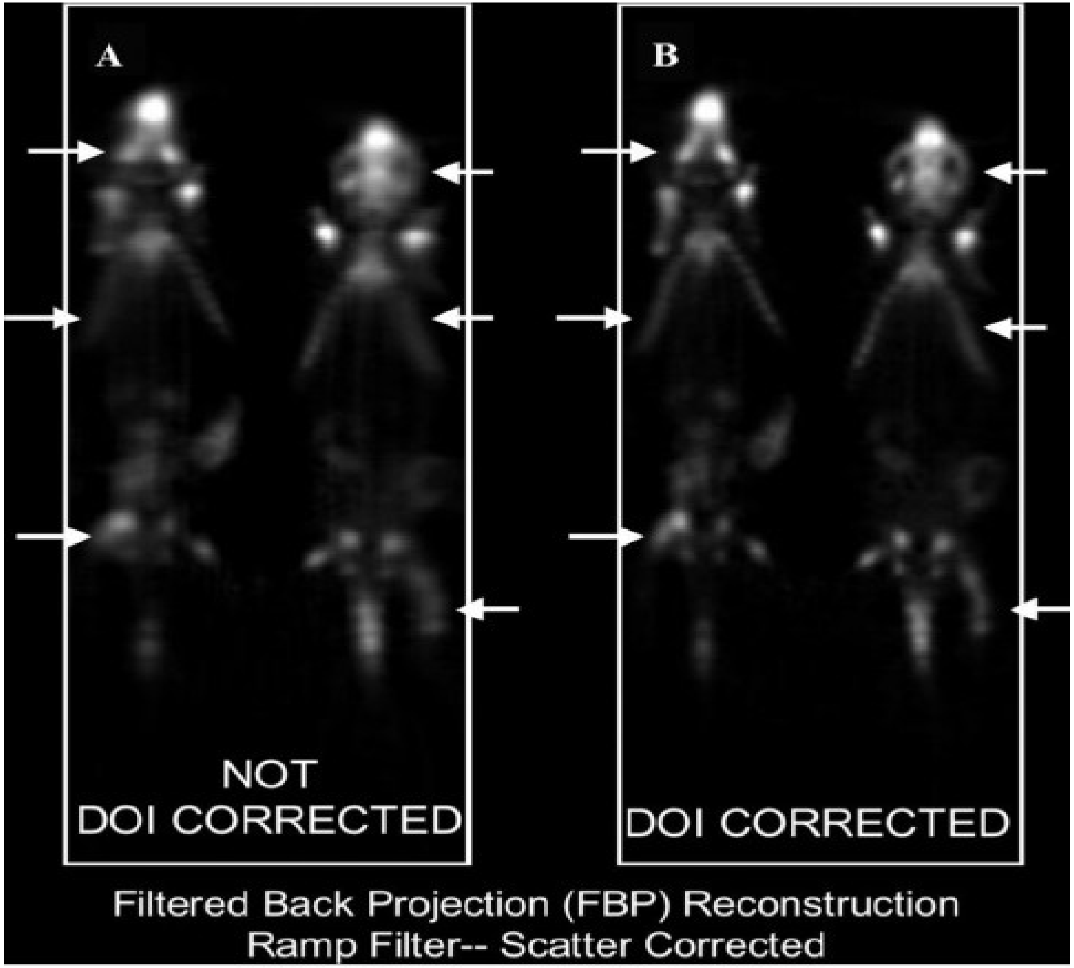


DOI determination



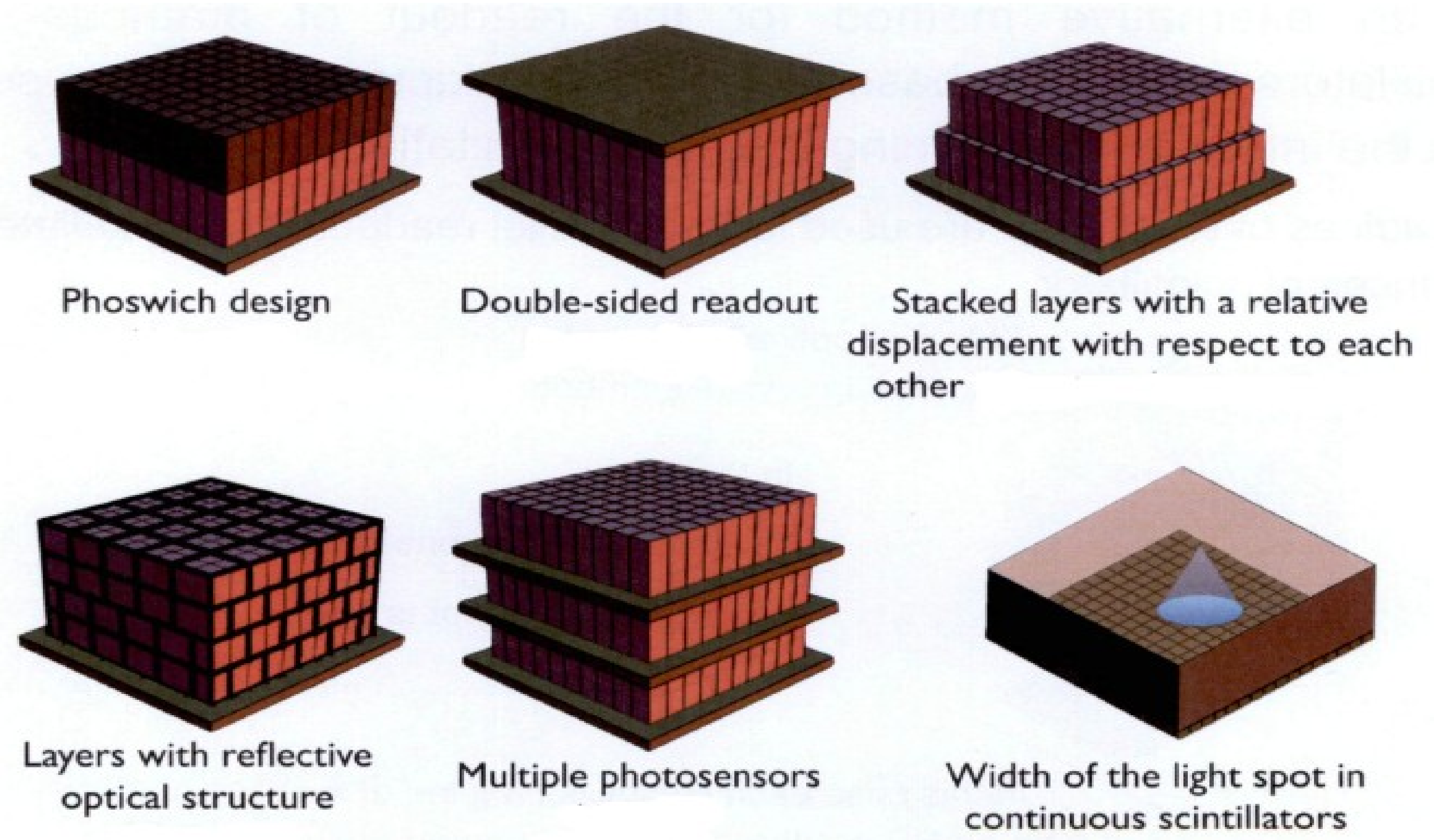
Green et al. Molec. Im. 9(6) 2010

DOI determination

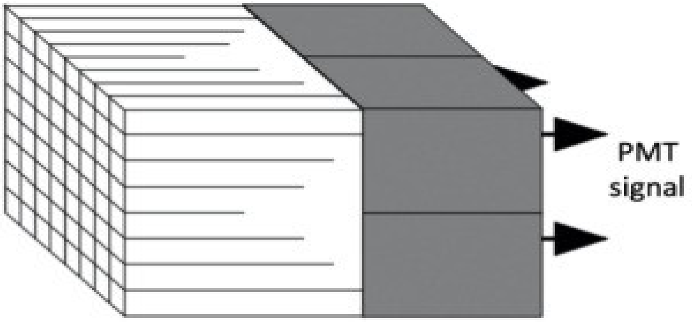


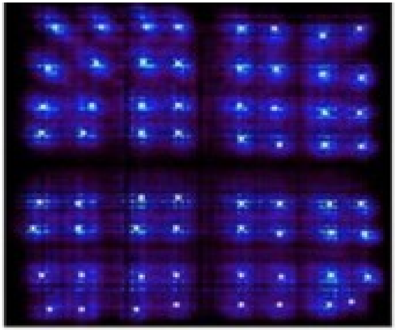
Green et al. Molec. Im. 9(6) 2010

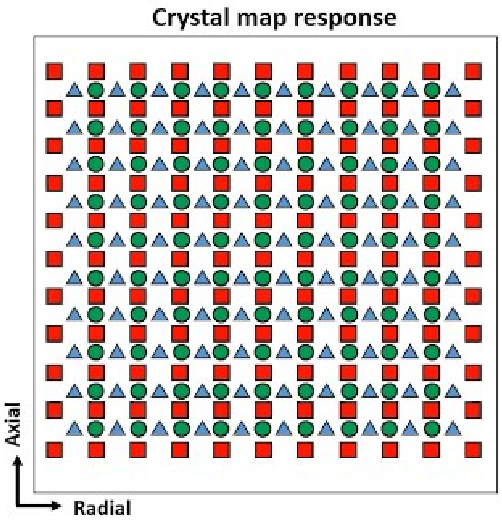
DOI determination

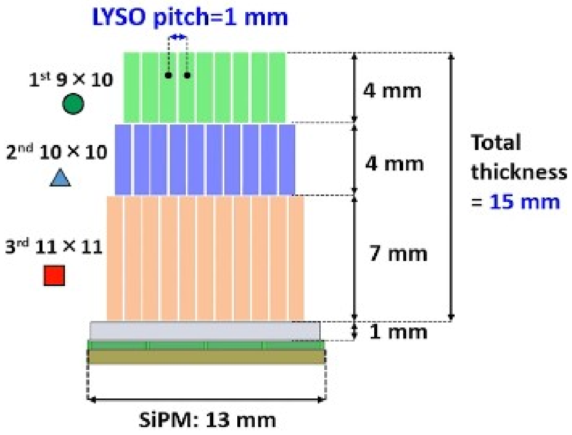


DOI determination



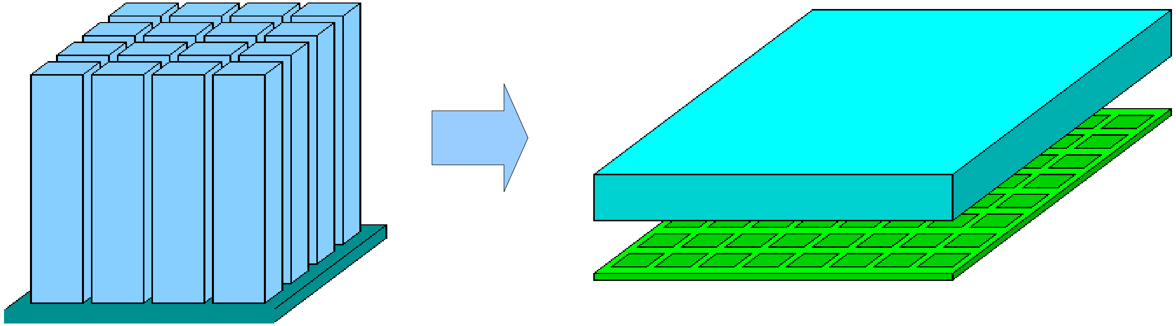


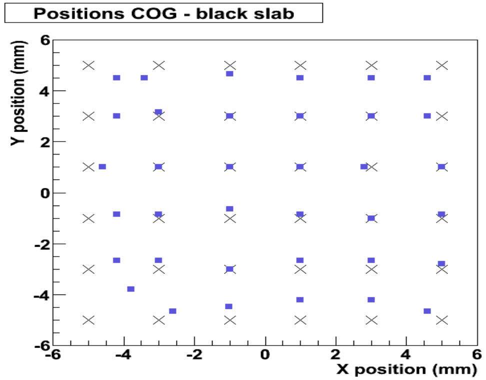


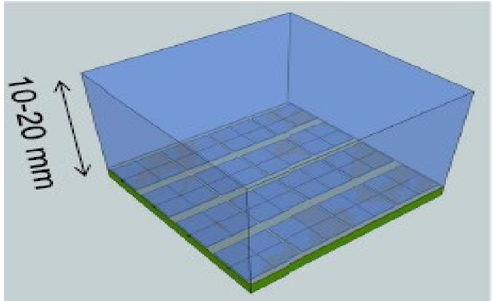


Higher cost
Generally not included in scanners

Monolithic detectors







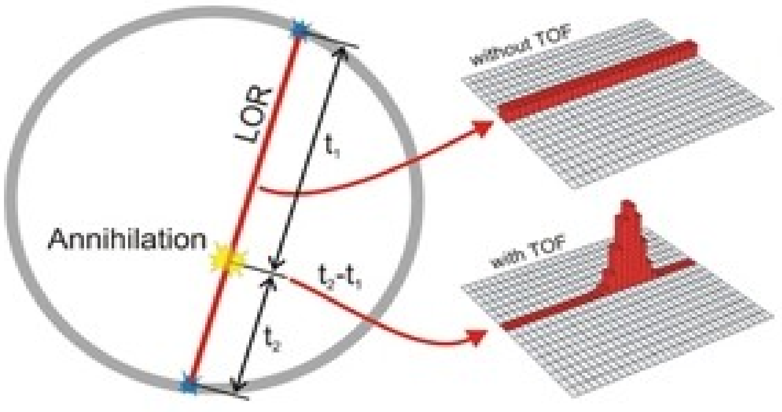
D. Schaart.
ICTR-PHE 2014

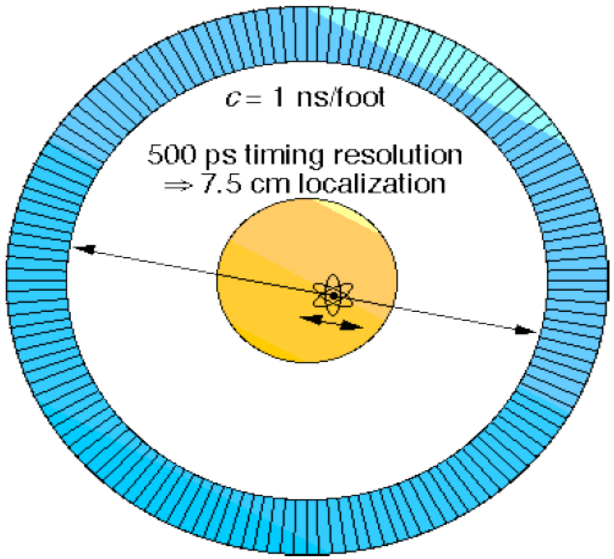
Neural Networks trained with Monte -Carlo simulations are promising

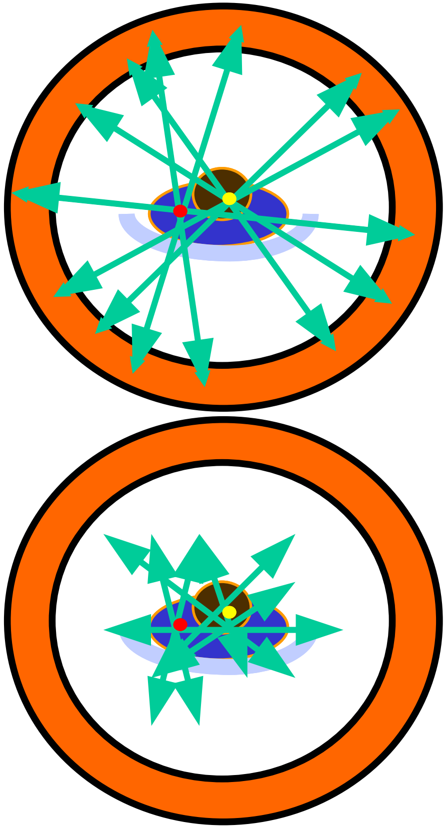
Performance parameter		Monolithic	State of the art
Energy resolution	(% FWHM)	11 - 12	~12
Spatial resolution	(mm FWHM)	1.0 - 1.6	4 - 6
DOI resolution	(mm FWHM)	3 - 5 mm	None
CRT	(ps FWHM)	160 - 185	500 - 650

Time-Of-Flight (TOF) PET

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





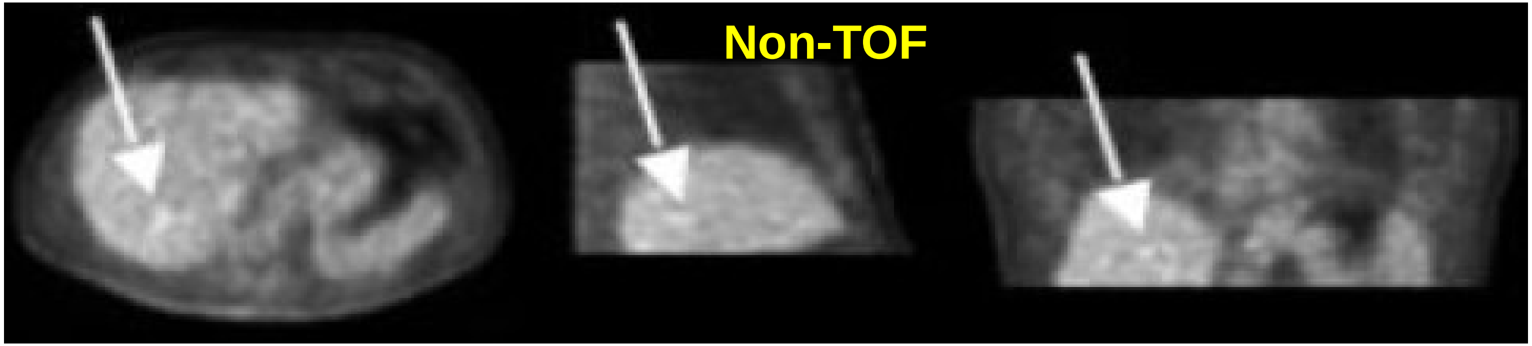


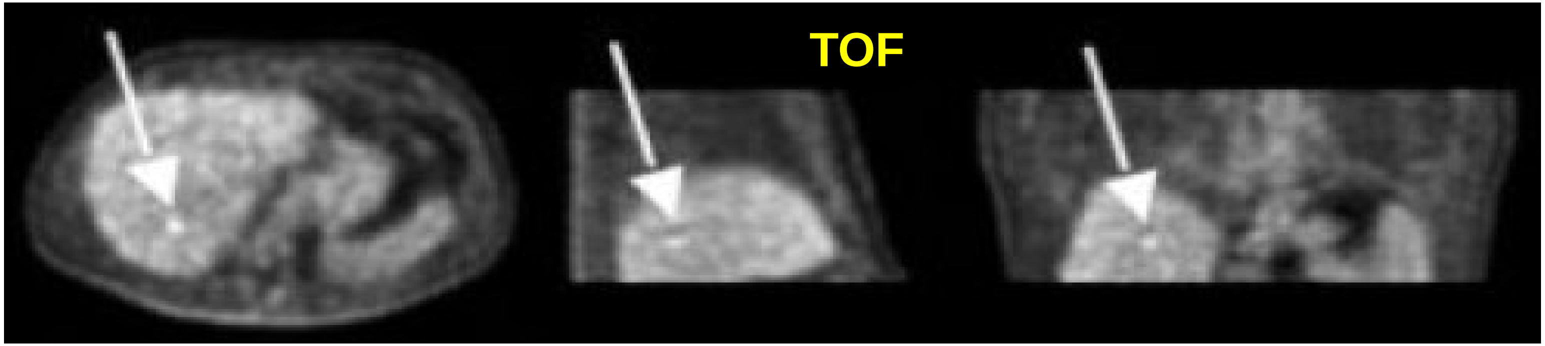
More accurate determination of the emission area of the photons → **better signal-to-noise ratio**.

TOF-PET first generation

- PHILIPS Gemini TF: LYSO ~550 ps FWHM
- Siemens Biograph mCT: LSO ~529 ps FWHM

TOF-PET

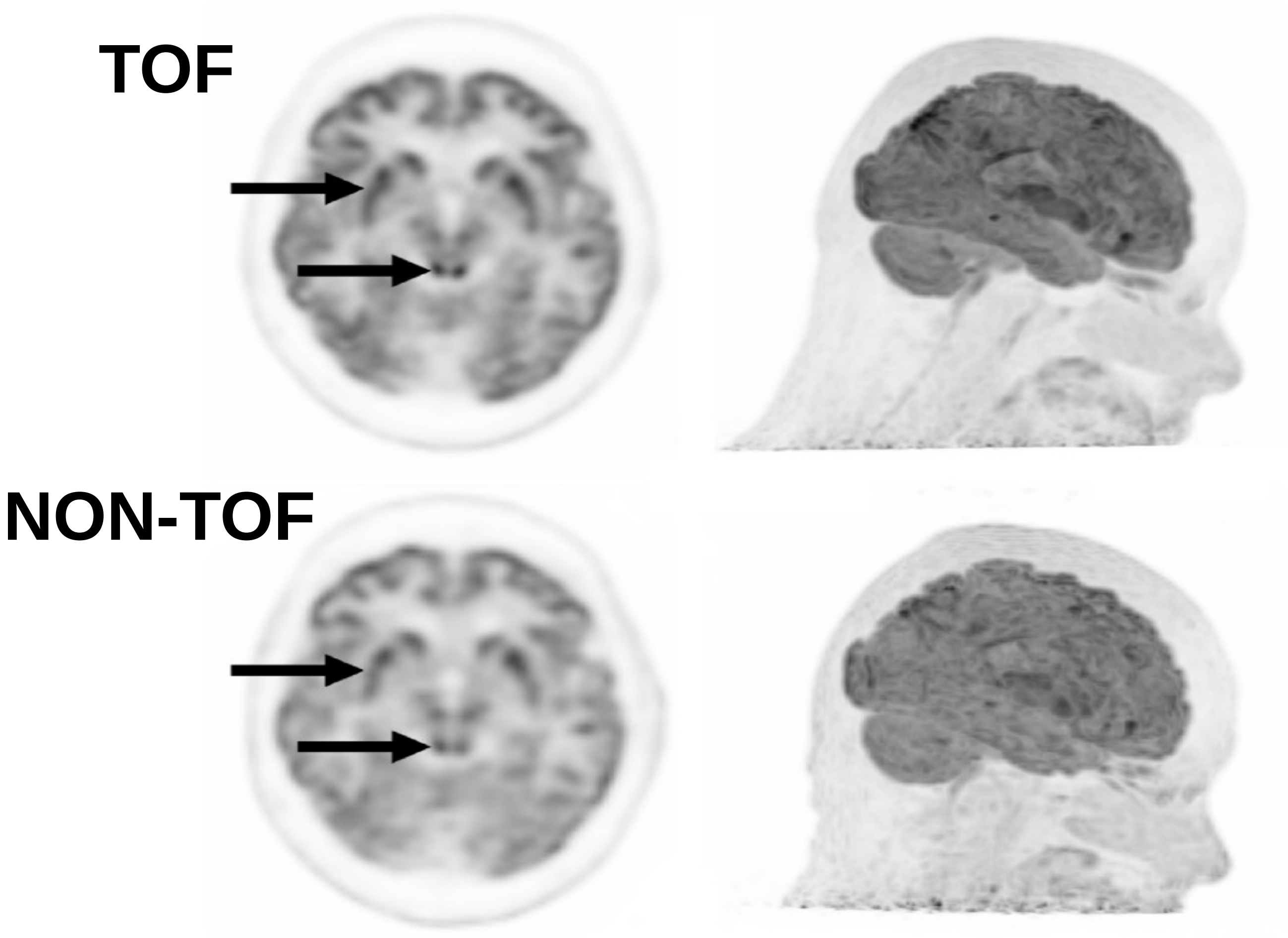




Liver lesion

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

TOF-PET

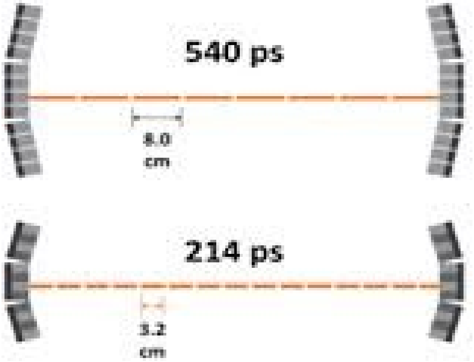


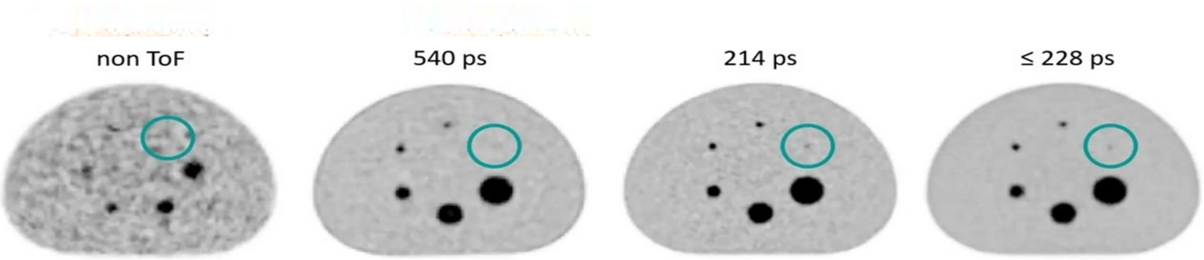
Van Sluis et al.

J Nuc Med 2019

TOF-PET

Last generation with SiPMs: 214-380 ps FWHM



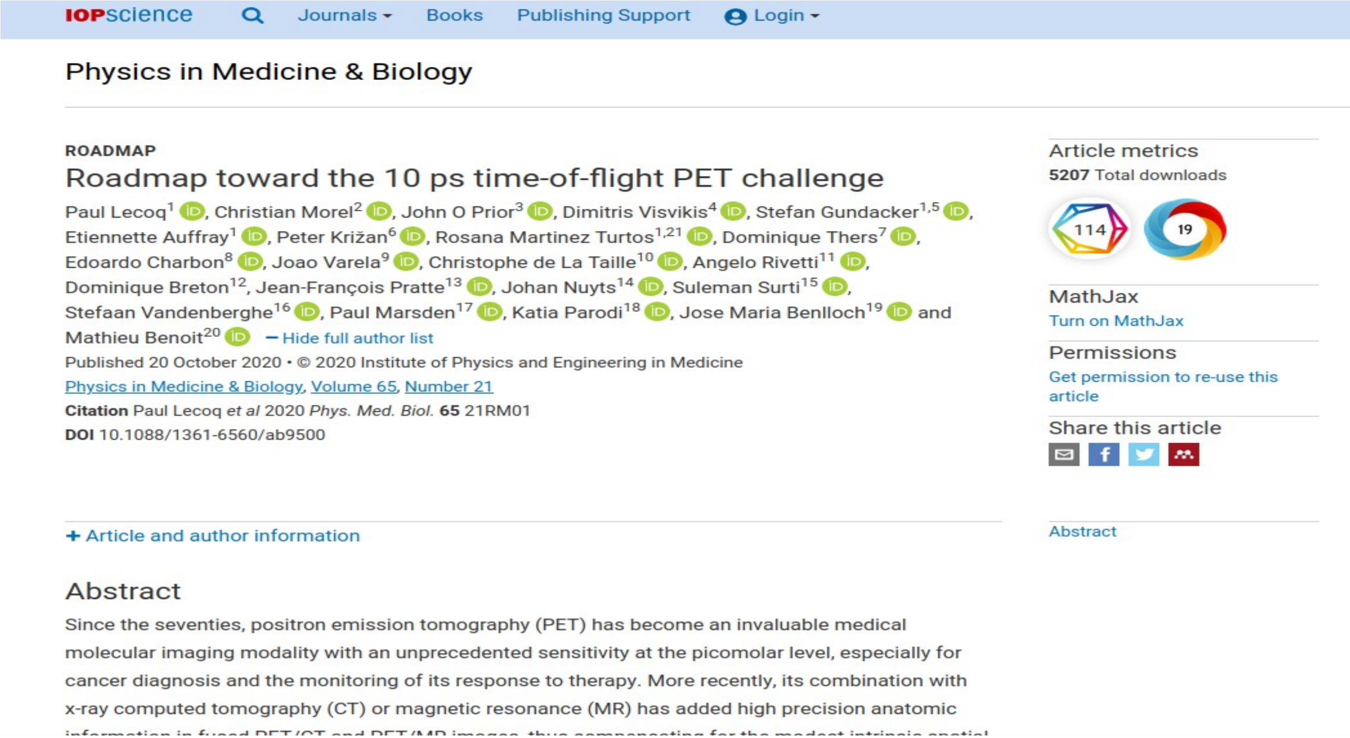


Sphere size (mm): 5, 8, 10, 13, 28, 37; 4:1 CBR

Siemens Biograph Vision: 214 ps.

TOF-PET

The 10 ps challenge → 1.5 mm LOR



IOPscience | Journals | Books | Publishing Support | Login

Physics in Medicine & Biology

ROADMAP

Roadmap toward the 10 ps time-of-flight PET challenge

Paul Lecoq[1], Christian Morel[2], John O Prior[3], Dimitris Visvikis[4], Stefan Gundacker[1,5], Etiennette Auffray[1], Peter Križan[6], Rosana Martinez Turtos[1,21], Dominique Thers[7], Edoardo Charbon[8], Joao Varela[9], Christophe de La Taille[10], Angelo Rivetti[11], Dominique Breton[12], Jean-François Pratte[13], Johan Nuyts[14], Suleman Surti[15], Stefaan Vandenberghe[16], Paul Marsden[17], Katia Parodi[18], Jose Maria Benlloch[19] and Mathieu Benoit[20] — Hide full author list

Published 20 October 2020 • © 2020 Institute of Physics and Engineering in Medicine
Physics in Medicine & Biology, Volume 65, Number 21
Citation Paul Lecoq *et al* 2020 *Phys. Med. Biol.* **65** 21RM01
DOI 10.1088/1361-6560/ab9500

Article metrics
5207 Total downloads
114
19
MathJax
Turn on MathJax
Permissions
Get permission to re-use this article
Share this article

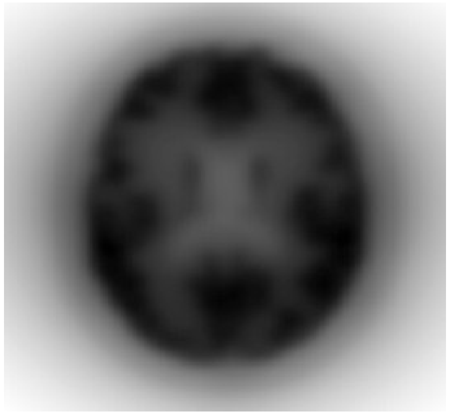
+ Article and author information

Abstract

Abstract

Since the seventies, positron emission tomography (PET) has become an invaluable medical molecular imaging modality with an unprecedented sensitivity at the picomolar level, especially for cancer diagnosis and the monitoring of its response to therapy. More recently, its combination with x-ray computed tomography (CT) or magnetic resonance (MR) has added high precision anatomic information in fused PET/CT and PET/MR images, thus compensating for the modest intrinsic spatial

Non-TOF

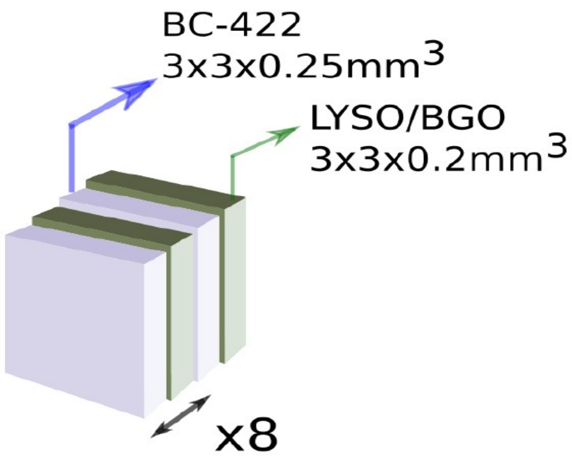


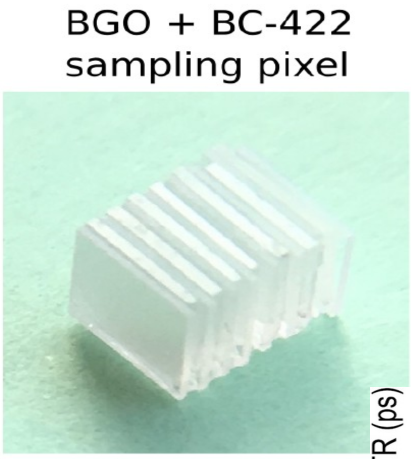
TOF 10 ps

unlikely that a CTR of 100 ps or better can be reached with standard scintillator technology

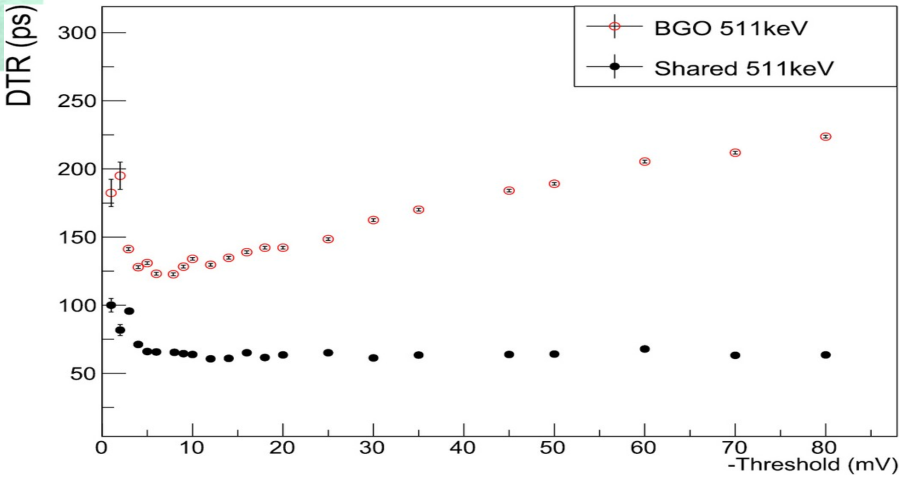
TOF-PET

New materials / metamaterials.



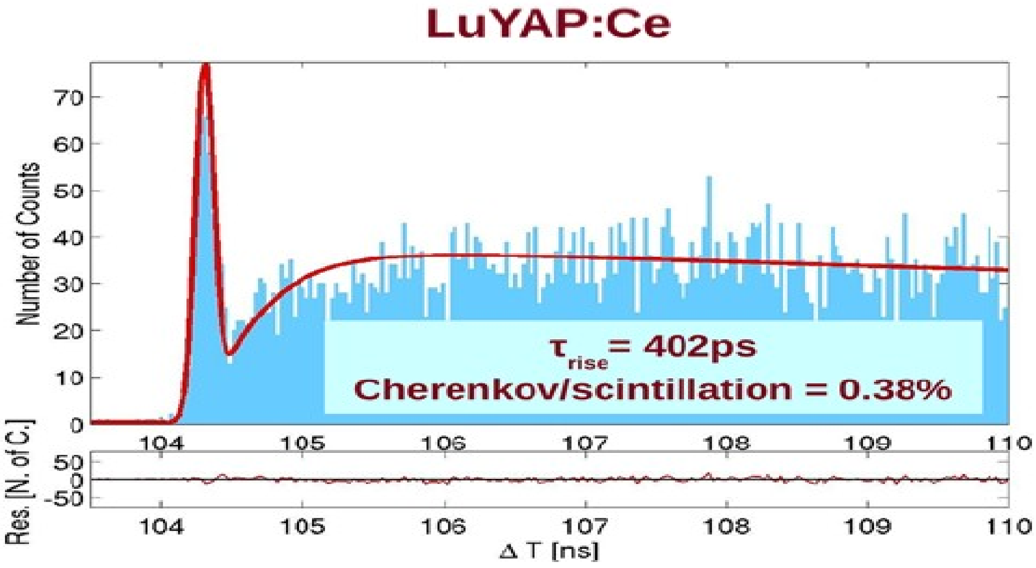


R M Turtos et al. Phys. Med. Biol. 2019



TOF-PET

Prompt / Cherenkov photons in scintillator crystals.



S. Gundacker et al. Phys. Med. Biol. 61 (2016)

BGO could be a promising scintillator for this application

Cherenkov PET

- PbF_2 + MCP PMTs
- 511 keV photons produce
  ~ 10 Cherenkov photons.
- Measured timing resolution: 84.6 ps FWHM.
- Tests with cooled SiPMs.

S. Korpar et al. Physics Procedia 37 (2012)

S. Korpar et al. / Physics Procedia 37 (2012) 1531 – 1536

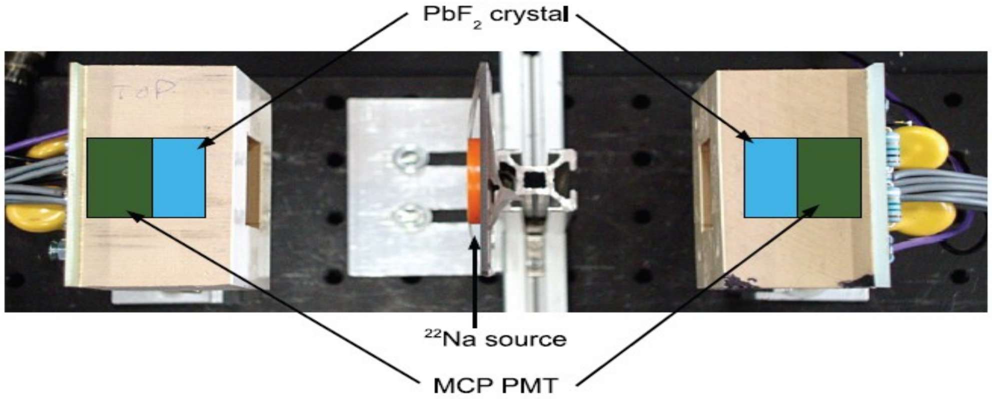


Fig. 1. The experimental setup with ^{22}Na source in between the two PbF_2 crystals coupled to MCP PMTs.

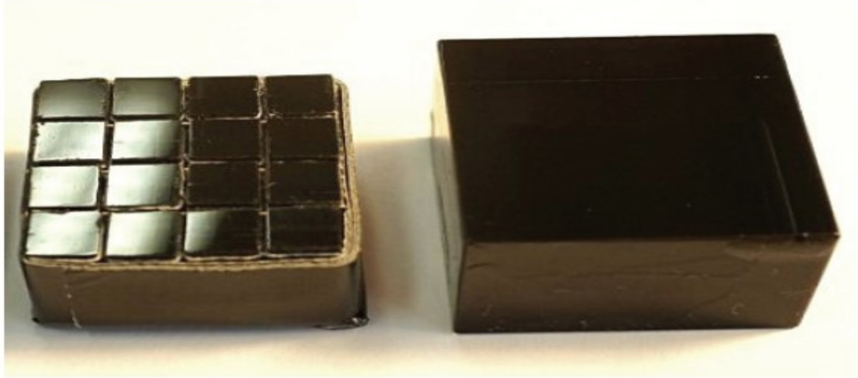
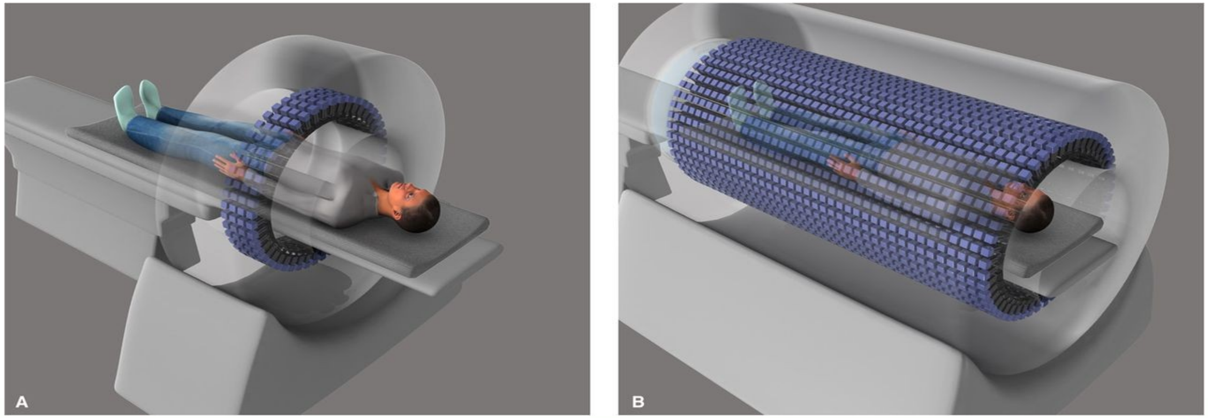
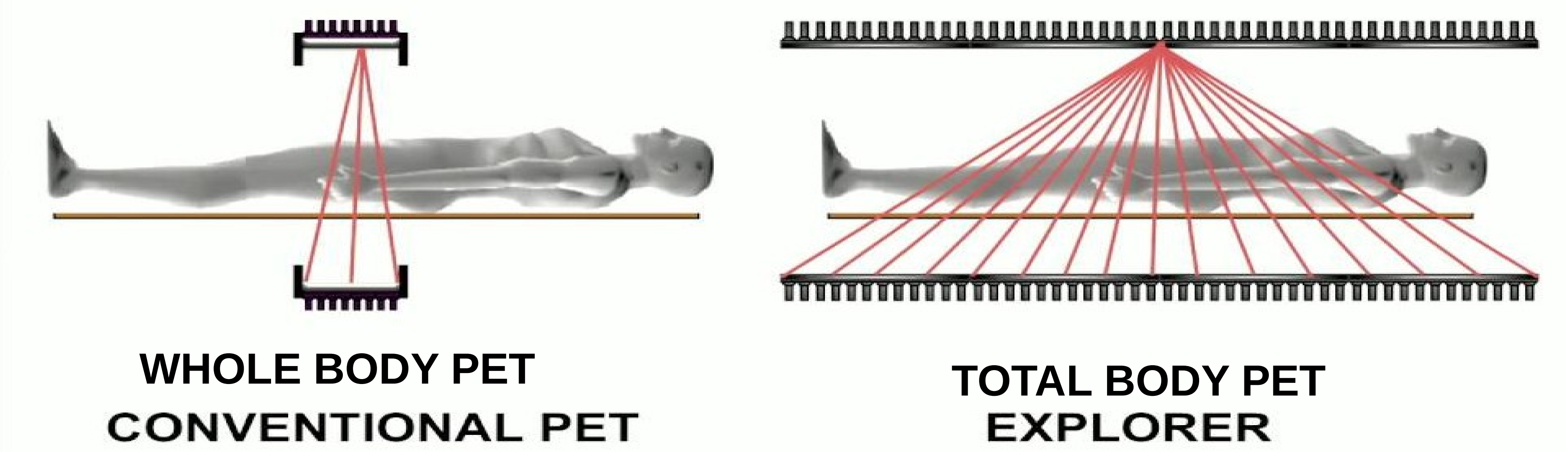


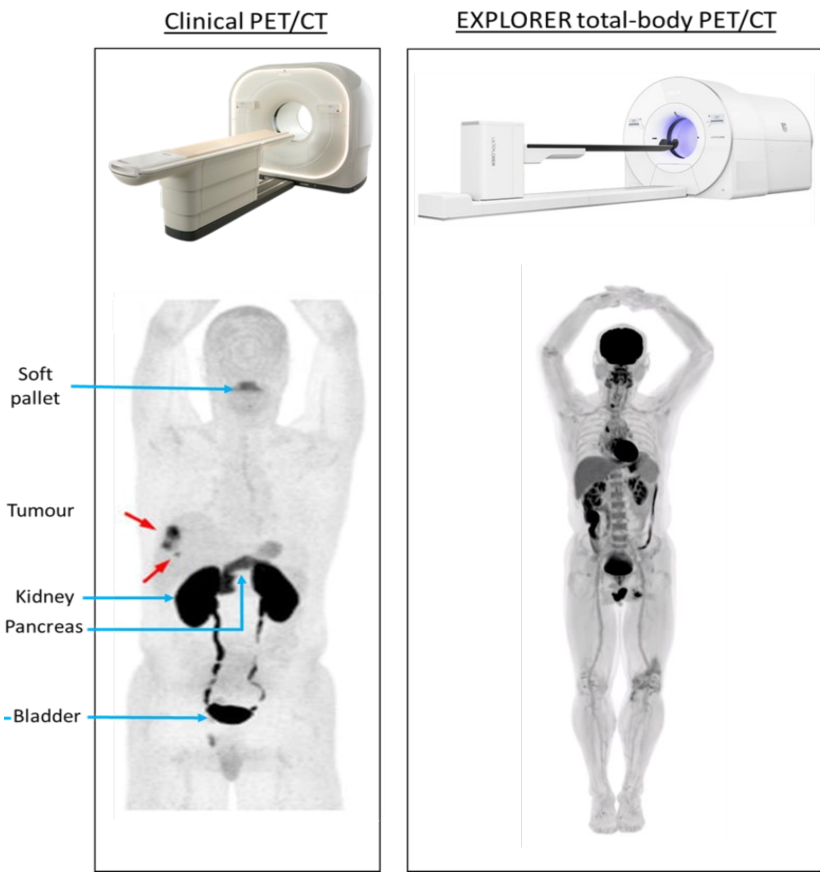
Fig. 2. Cherenkov radiator crystals used for detection of 511 keV photons in the present experiment.

Total Body PET





Total Body PET



- Sensitivity 40x: faster images or lower dose

  → repetition of scans, pediatric scans…

- Image of the whole body in 20-30 s.

- Large FOV: activity in all organs and tissues simultaneusly.

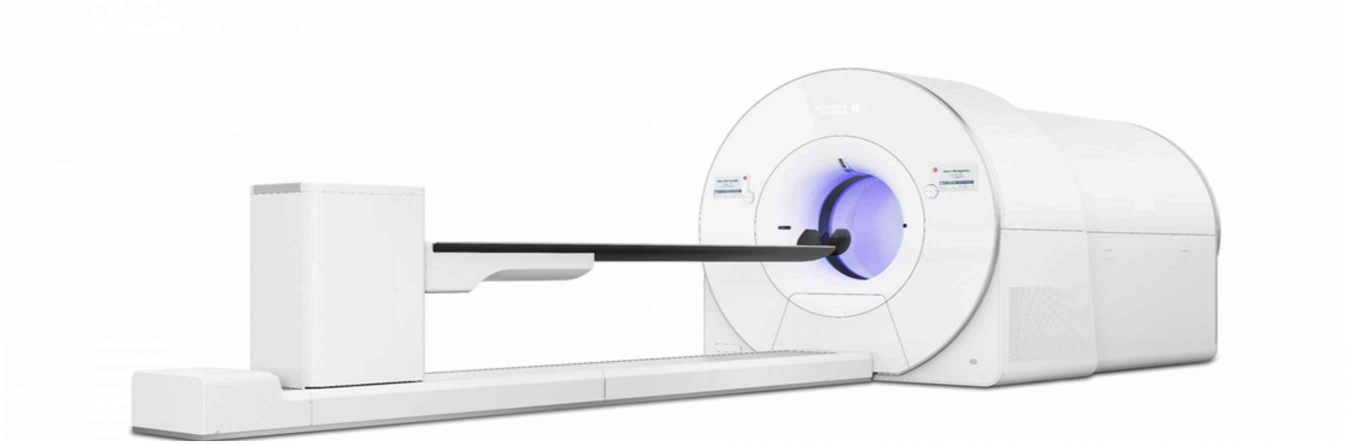
- Possibility of acquiring images furing longer time (reveral radiotracer half lives)

  → Kinetic studies and dynamic images.

- Umprecedented quality.

 Very high cost

Total Body PET

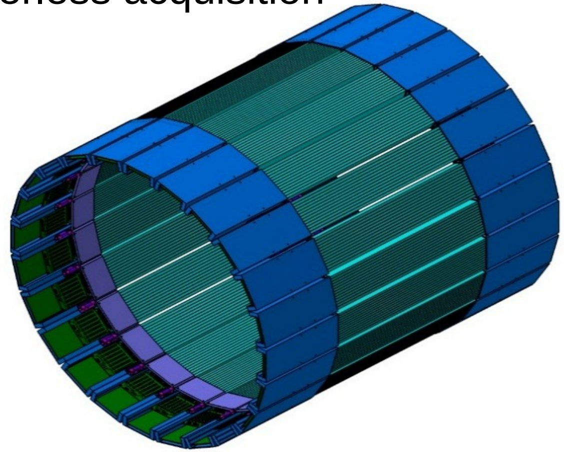


EXPLORER
Whole body length

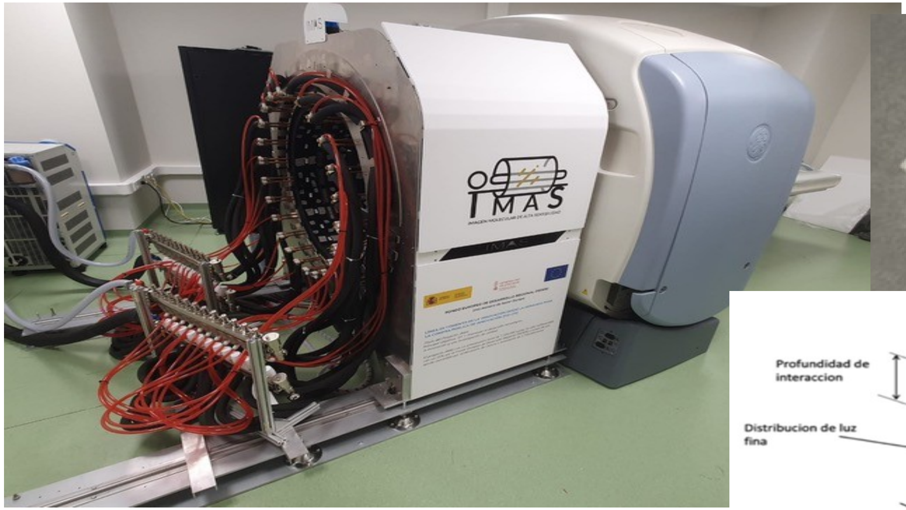
Biograph Vision Quadra
1 m length

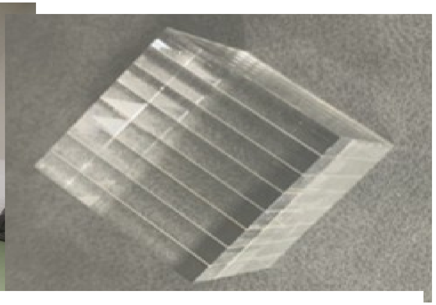
Total Body PET – more affordable approaches

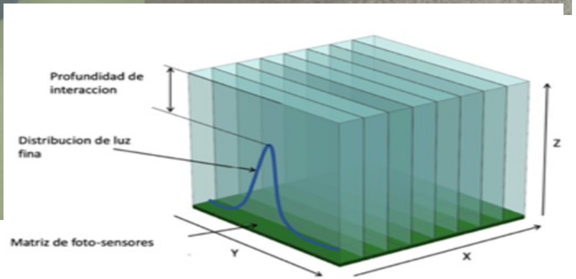
JPET: plastic scintillators
+ triggerless acquisition



IMAS: semi-monolithic LYSO detectors

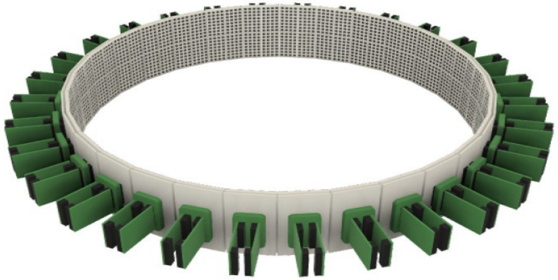


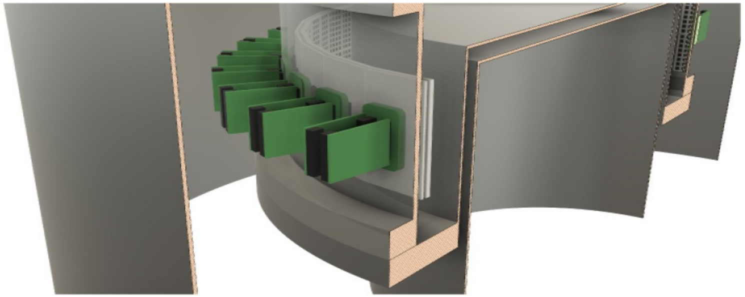




Courtesy of A. González

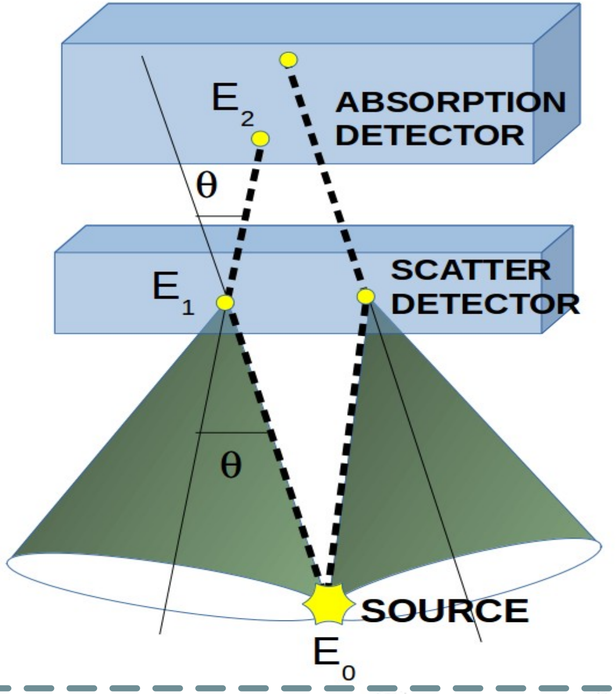
PETALO: liquid Xenon + SiPMs – continuous volume





Again BGO?
Other?

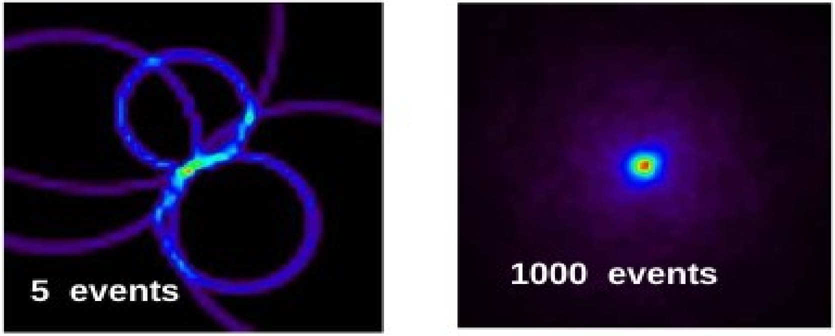
Compton cameras



$$\cos\varphi = 1 - m_0c^2\left(\frac{1}{E_{\gamma'}} - \frac{1}{E_\gamma}\right)$$

$$E_\gamma = E_{e^-} + E_{\gamma'}$$

Backprojection

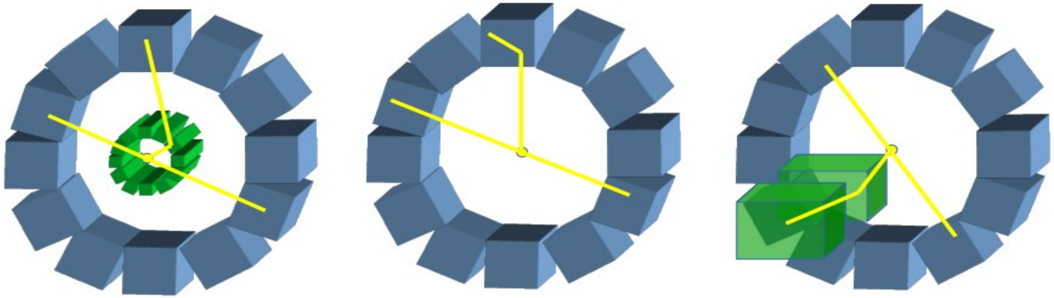


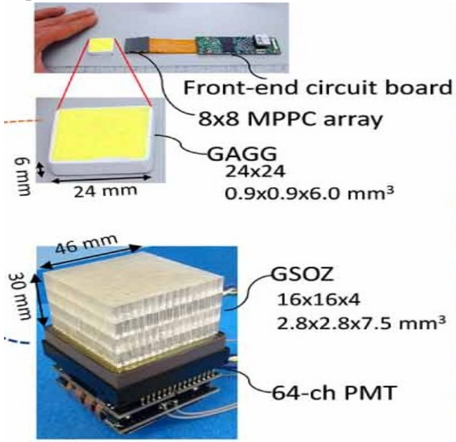
+ Image reconstruction

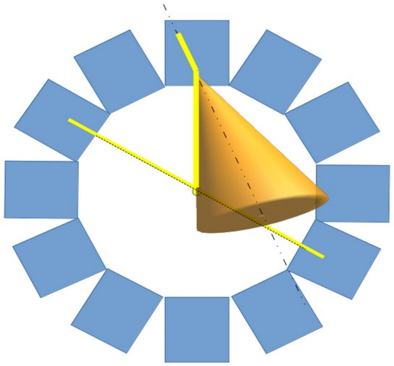
- Higher efficiency than gamma cameras.
- Better at higher energies.
- Better for multiple energies.
- Solid state detectors provide better performance, but are more expensive and complex to operate.

Compton-PET / WGI

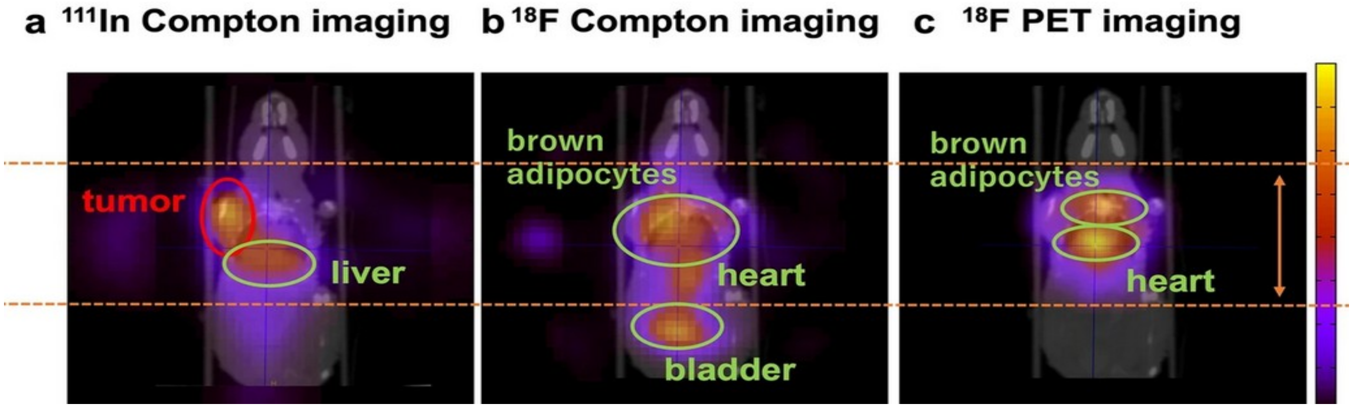
PET and gamma tracers simultaneously





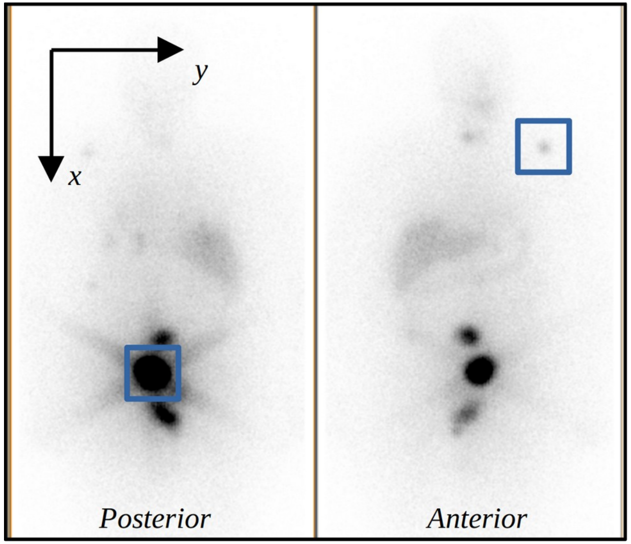


Three gamma imaging ^{89}Zn



Targeted radionuclide therapy

- Injecting a radiopharmaceutical for therapy.
- Expanding due to its good results.
- Imaging can be used to visualize their distribution in the body and carry out dosimetry employing secondary gamma radiation.
- PET and gamma cameras are employed.
- More challenging than diagnostic imaging since photon energies and activities are not optimized for gamma cameras.
- Particularly complicated for alpha emitting radionuclides due to low activities and high secondary photon energies.



Gamma camera images of a patient treated with ^{131}I-NaI.

Beta therapy: 50-300 mCi (1.85 - 11.1 GBq (300 mCi) per treatment cycle.

Alpha therapy: 1-10 mCi (37 - 370 MBq) per treatment

Targeted radionuclide therapy

- Theragnostic pairs:
  - A patient is injected with a diagnostic radiotracer.
  - The diagnostic radioisotope is swapped for a therapeutic isotope.
- Optimized gamma camera collimators – eg for Ac-225.
- Particularly complicated for alpha emitting radionuclides due to low activities and high photon energies.

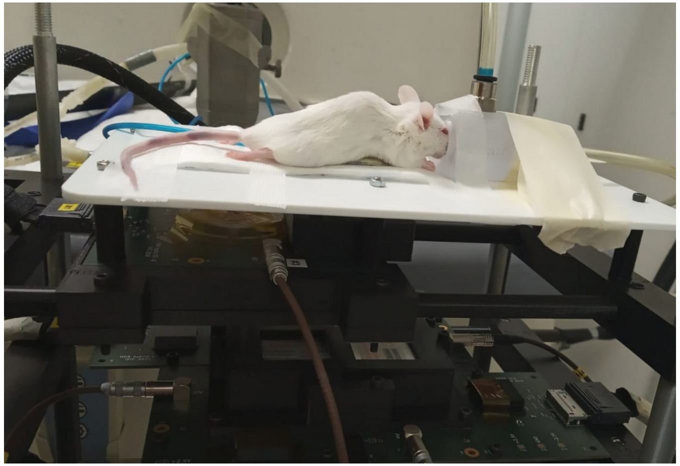
Diagnostic Isotope	Therapeutic Isotope	Primary Target / Use Case
Gallium-68 (^{68}Ga)	Lutetium-177 (^{177}Lu)	Prostate-Specific Membrane Antigen (PSMA) for prostate cancer
Gallium-68 (^{68}Ga)	Lutetium-177 (^{177}Lu)	Somatostatin receptors (SSTR) for neuroendocrine tumors
Yttrium-86 (^{86}Y)	Yttrium-90 (^{90}Y)	Liver tumors, lymphomas, and neuroendocrine tumors
Copper-64 (^{64}Cu)	Copper-67 (^{67}Cu)	Various solid tumors (with highly matched chemical/biological matching)
Iodine-123 (^{123}I)	Iodine-131 (^{131}I)	Thyroid cancer and neuroblastoma

- Compton cameras, initially developed for astroparticle physics experiments, can overcome the difficulties encountered by gamma cameras:
  - higher efficiency,
  - better suited for high energy photons,
  - better suited for multi-gamma emission.

MACACO III+ Compton camera living mice with ^{131}I

Two living mice injected with [^{131}I]NaI:
#1: 30.45g, 1.29 MBq.
#2: 29.06g, 2.22 MBq.

Uptake in thyroid and stomach.

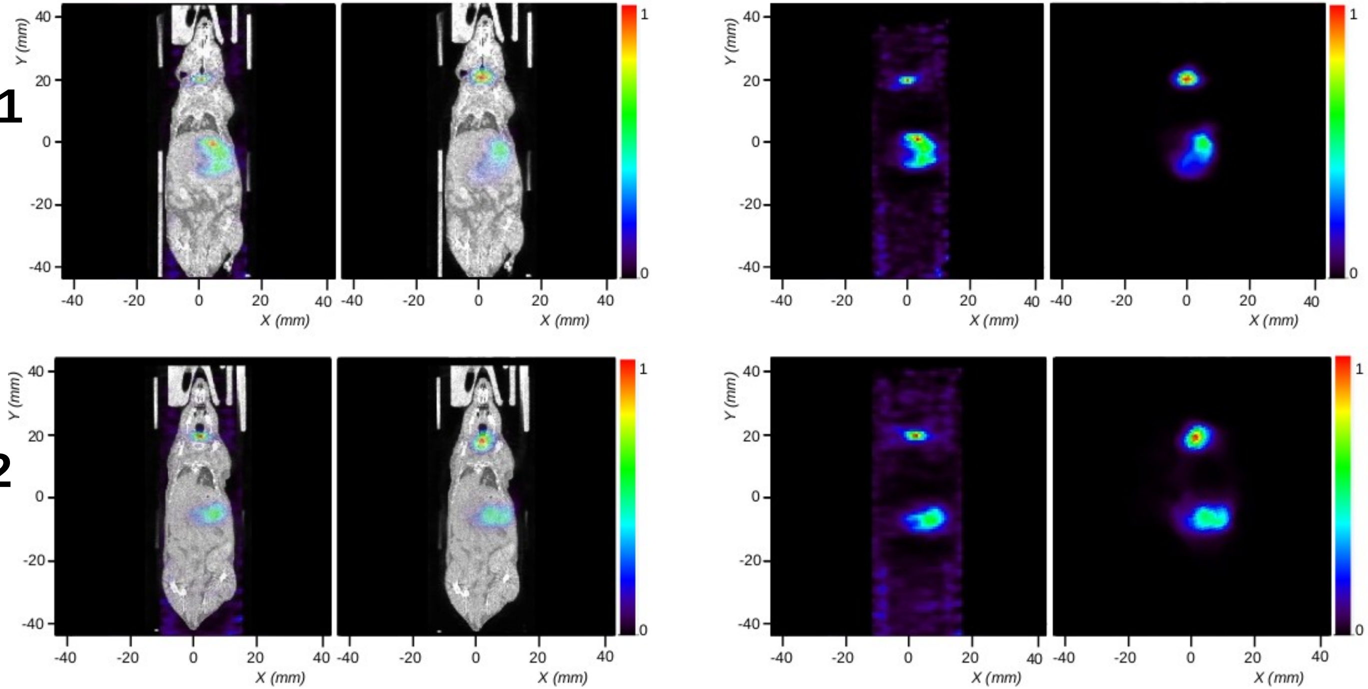


^{131}I (364 keV)

MACACO III+ 30 minutes	γ-CUBE SPECT MOLECUBES 2 hours	MACACO III+ 30 minutes	γ-CUBE SPECT MOLECUBES 2 hours

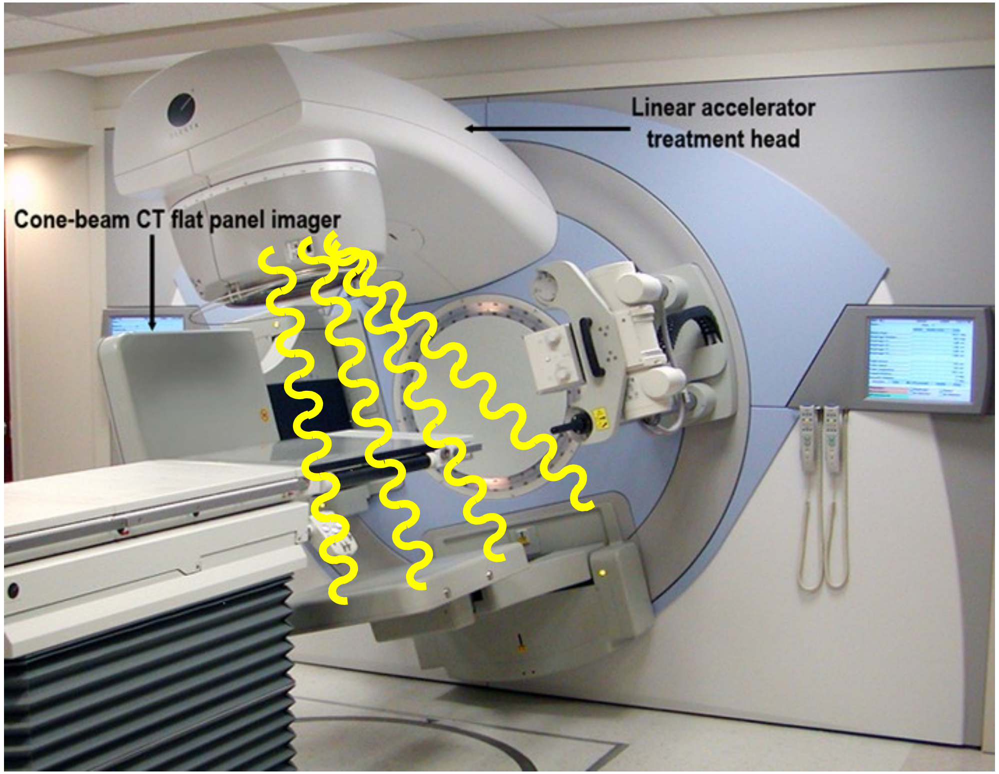
#1

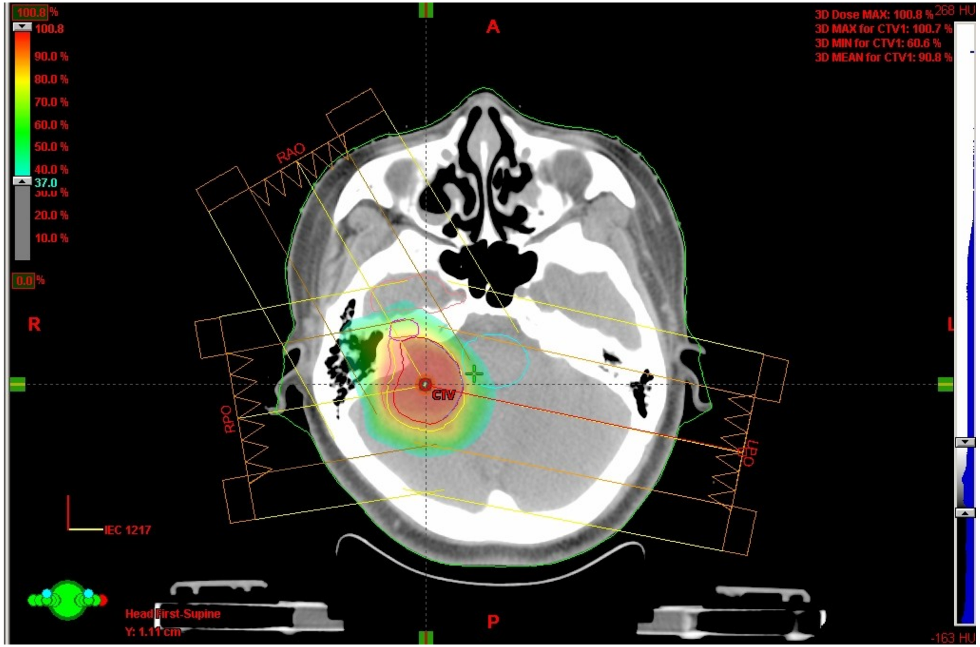
#2



Radiotherapy

Photons employed to destroy cancerous cells

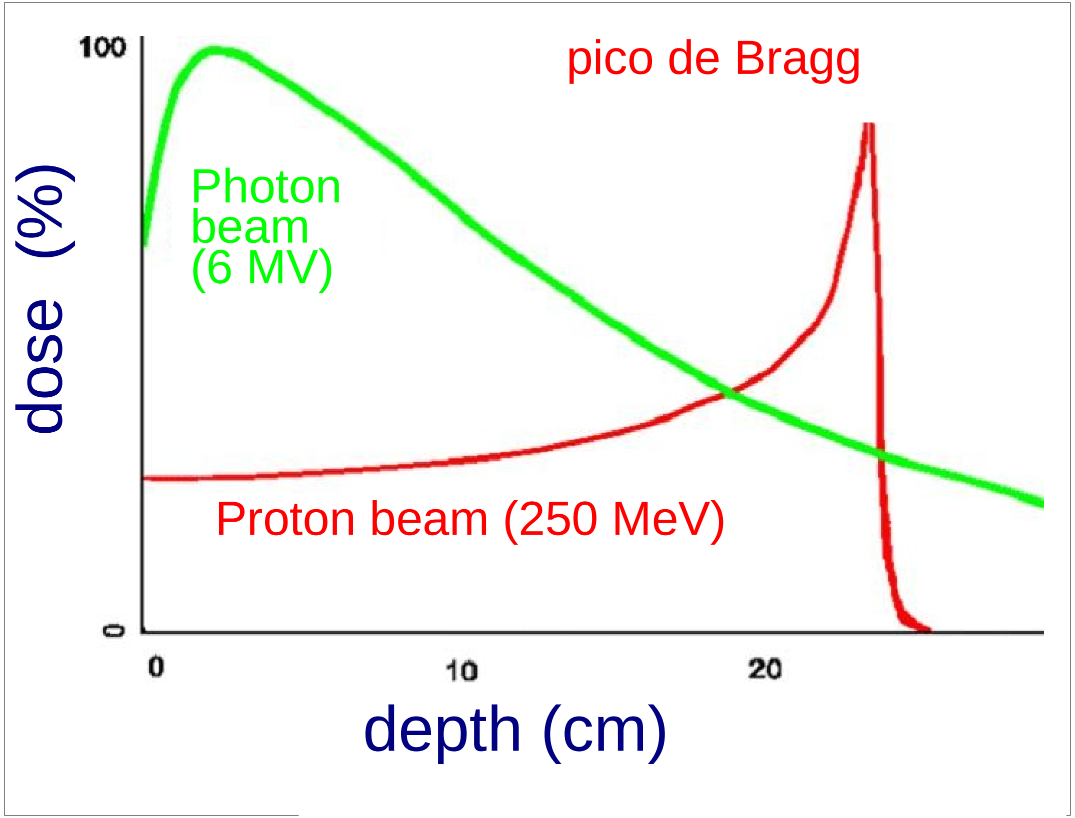


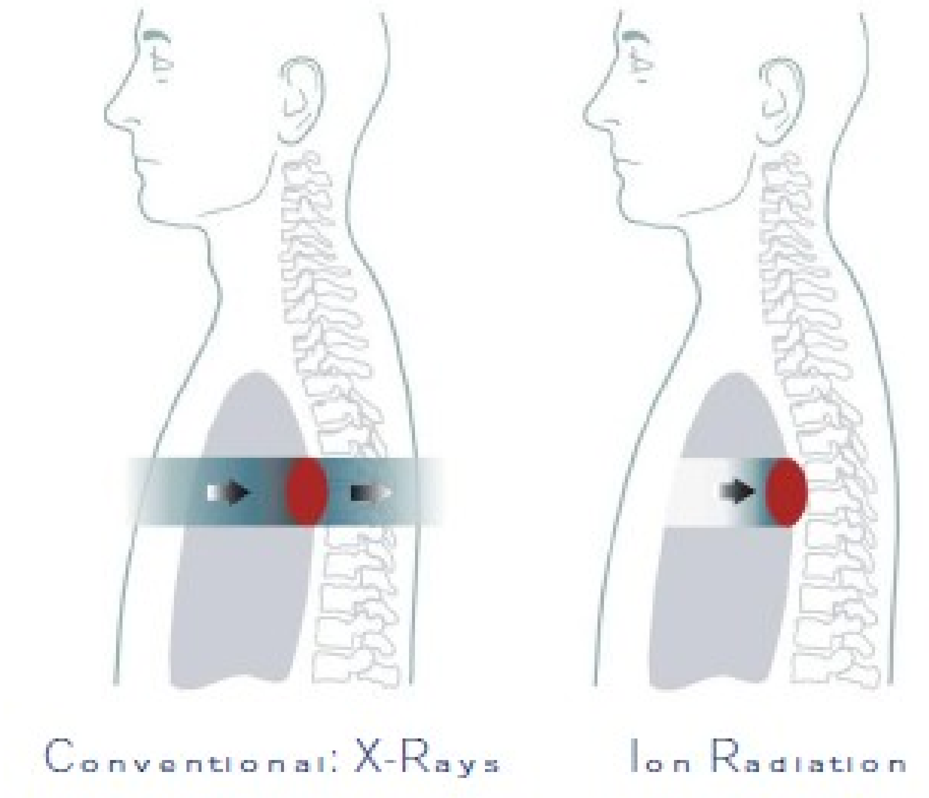


Treatment plan

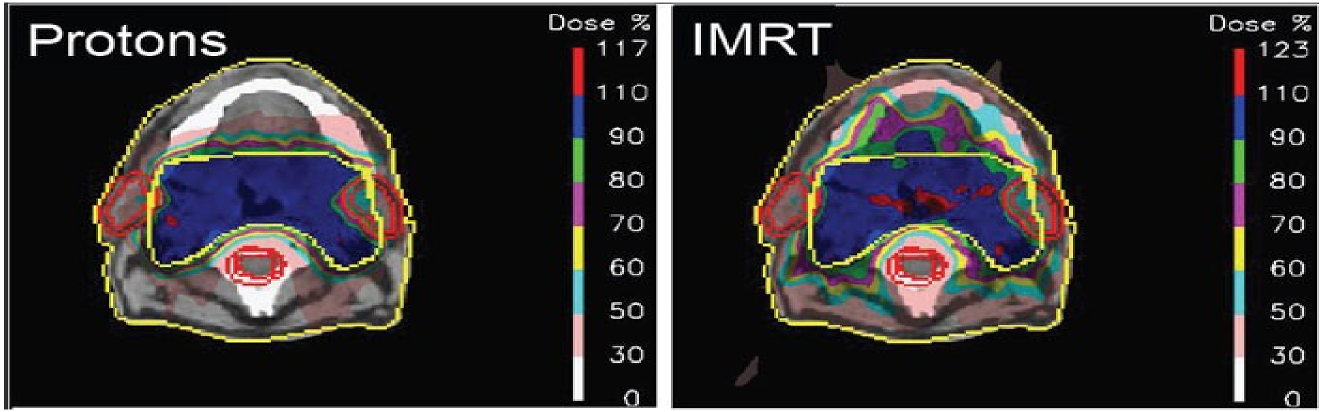
Radiotherapy vs. Hadron therapy

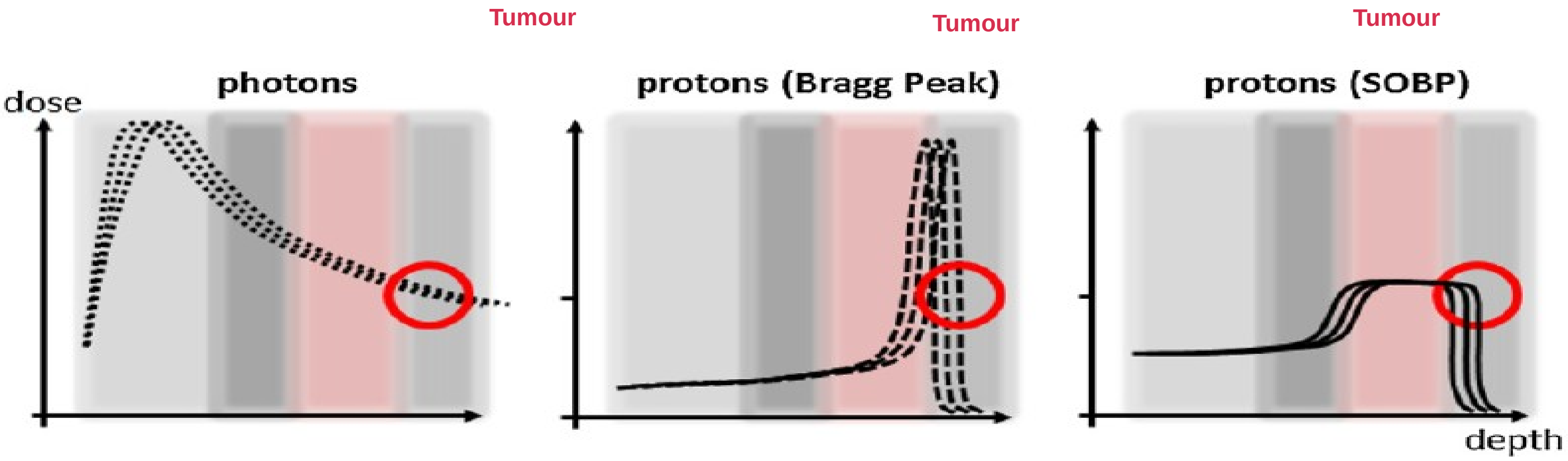
Photons vs. Charged particles





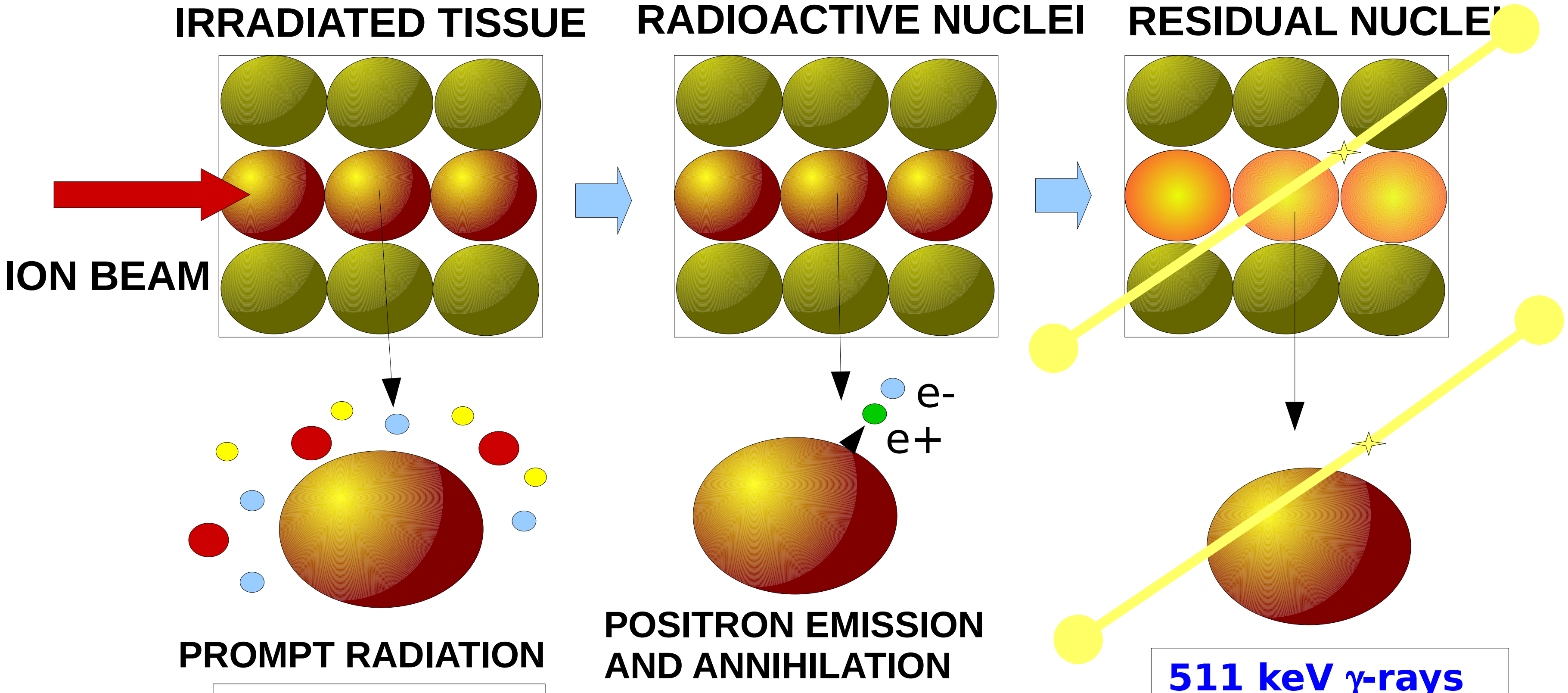
Hadron therapy treatment monitoring





Large safety margins applied to treatment plans.

Hadron therapy treatment monitoring



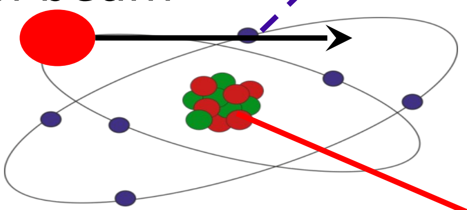
Prompt γ-rays
E **~ 1-15 MeV**

511 keV γ-rays

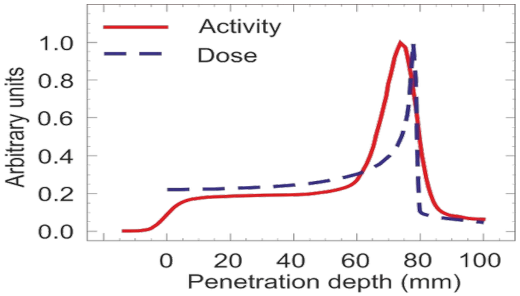
Treatment monitoring

- Dose deposition through electromagnetic interaction.
- Monitoring through secondary particles emission (nuclear interactions).
- Different, but correlated quantities. Indirect measurement.

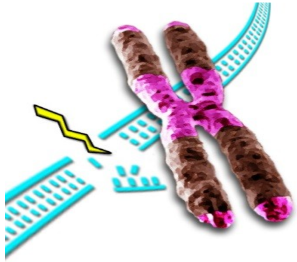
Ion beam

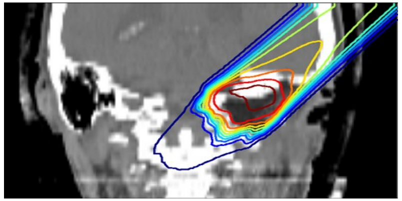


Tissue atom

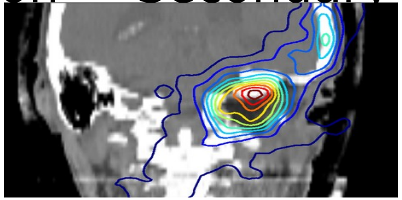


Electromagnetic interaction → Dose deposition



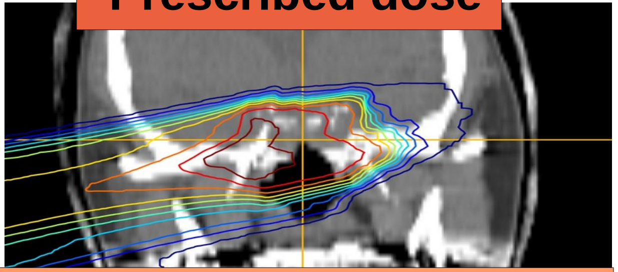


Nuclear Interaction → Secondary particles



Monitoring with PET

Prescribed dose

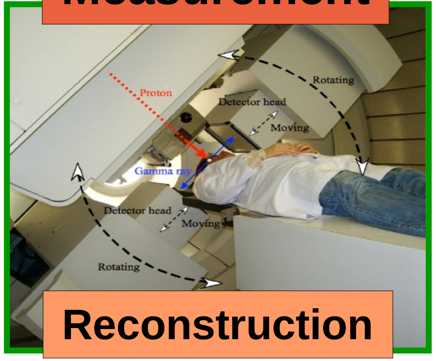


Prediction

Simulation + Reconstruction

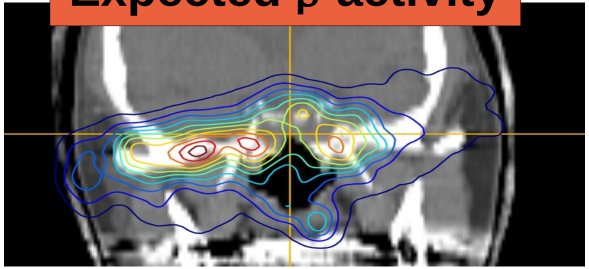
Application

Measurement



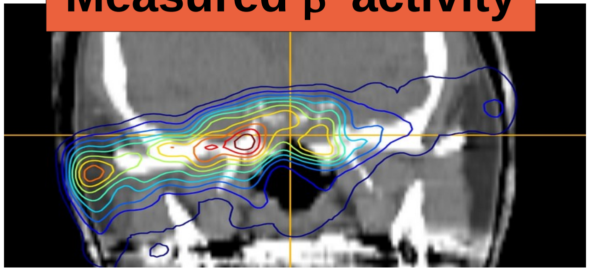
Reconstruction

Expected β⁺activity

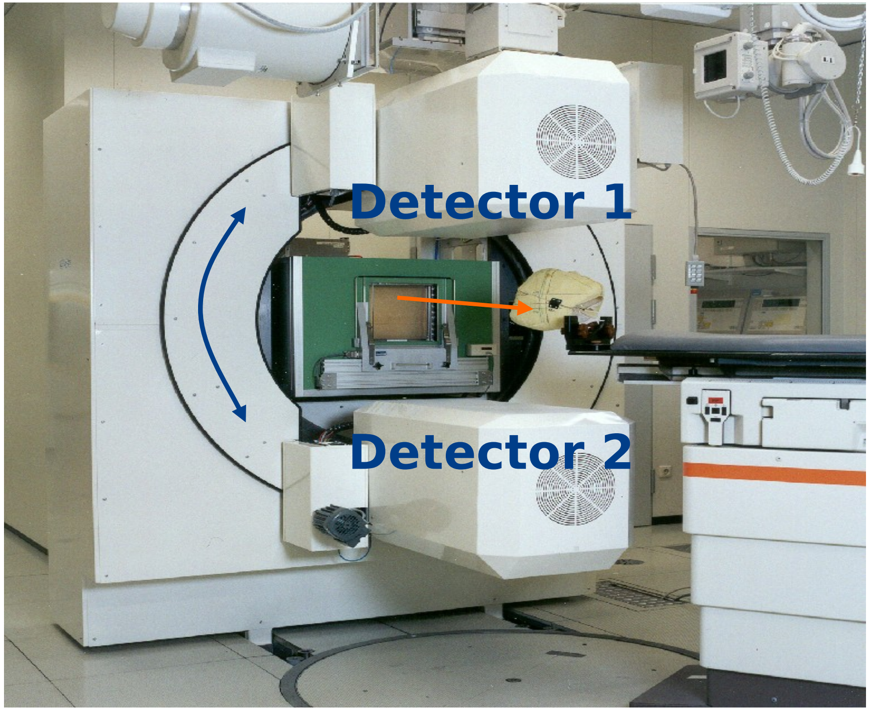


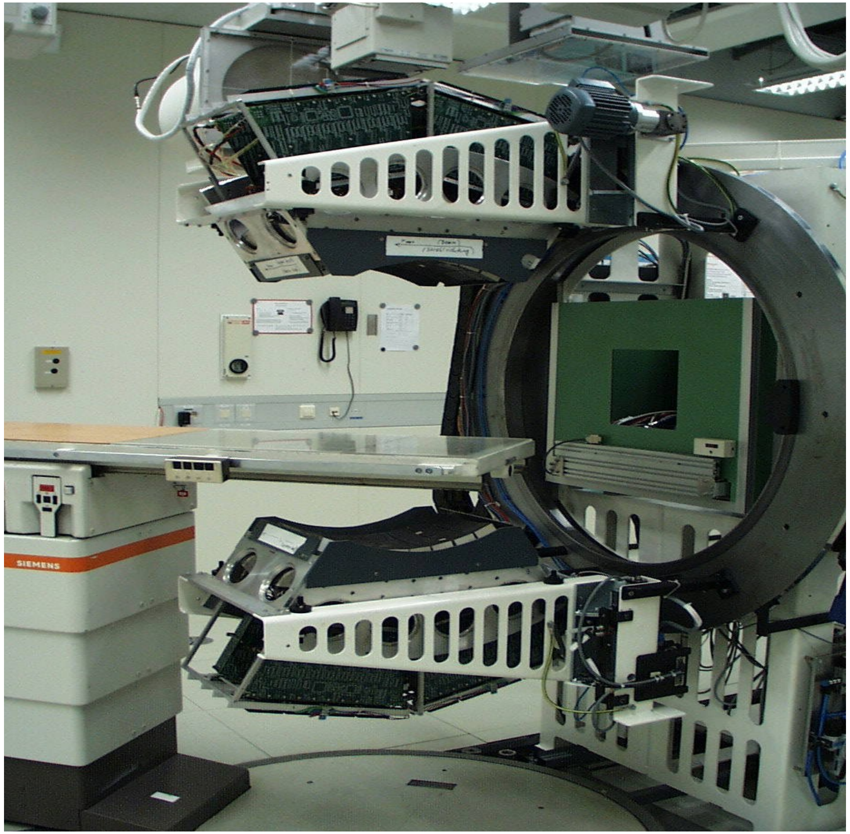
Comparison

Measured β⁺ activity



Monitoring with PET

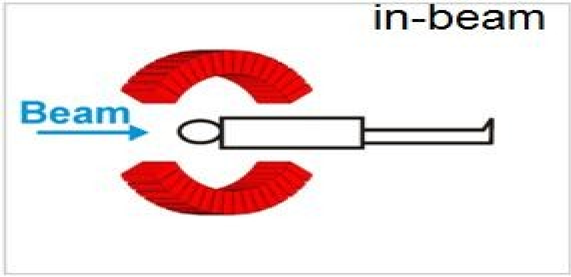




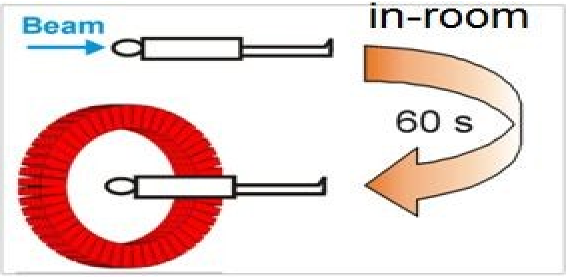
PT PET Scanner @ GSI

Modalities

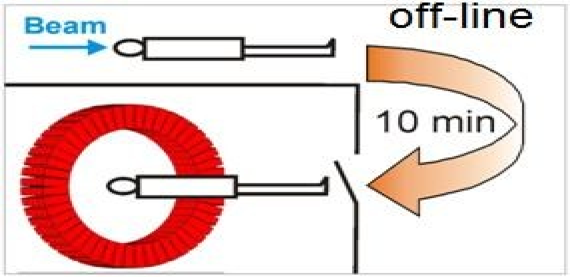
→ Higher influence of the metabolism, lower beta activity →



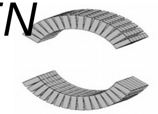
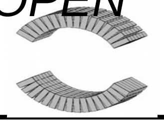
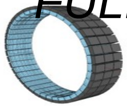
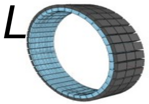
Measurement during irradiation

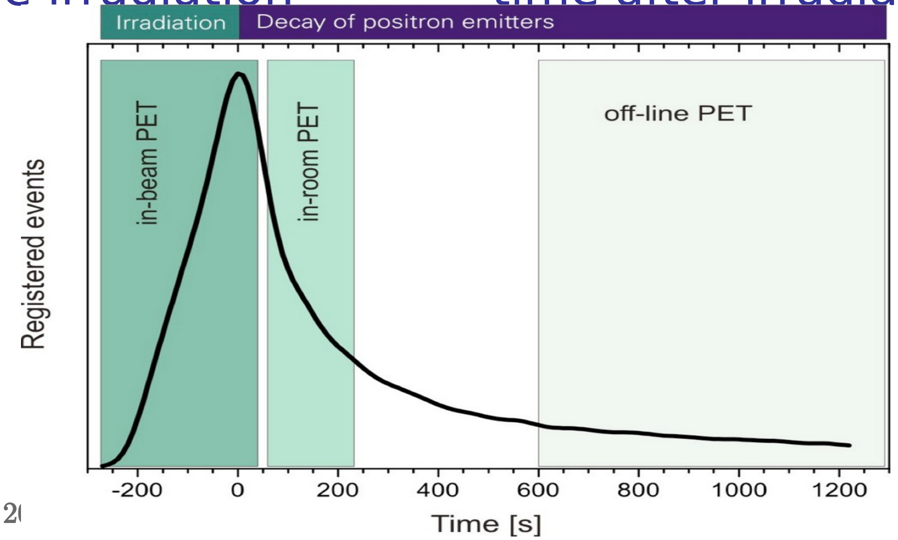


Measurement shortly after the irradiation



Measurement some time after irradiation

IN-BEAM	*OPEN* 	
IN-ROOM	*OPEN* 	*FULL* 
OFF-LINE	*FULL* 	

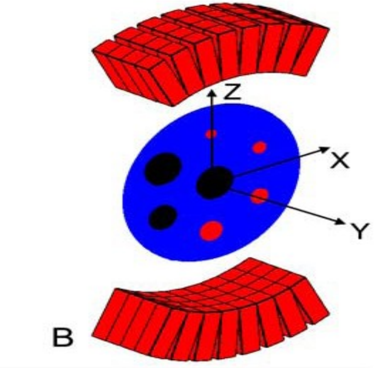


PET Limitations

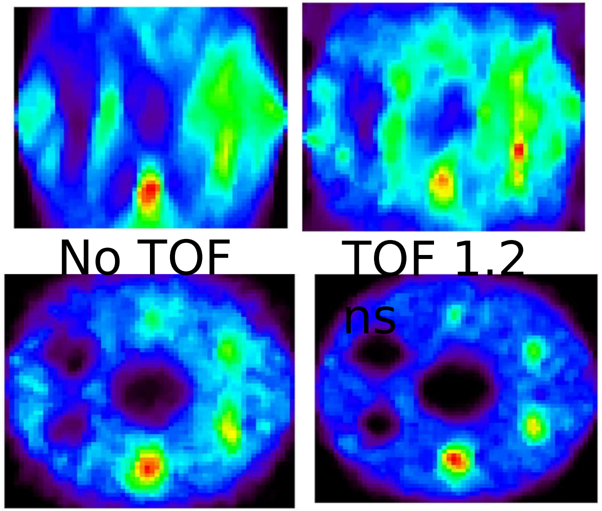
- Positron production does not follow irradiation immediately.
- Biological washout- activity carried away by metabolic processes.
- Low amount of β+ activity induced- low efficiency.
- Difficult online studies – partial ring.
- Photons produce significant background.

Research

- Models for washout.
- Use of short-lived isotopes.
- TOF PET to minimize gap effects.
- PET integration with the gantry.

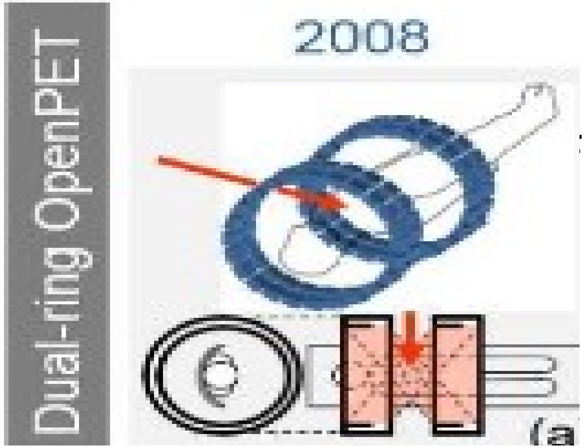


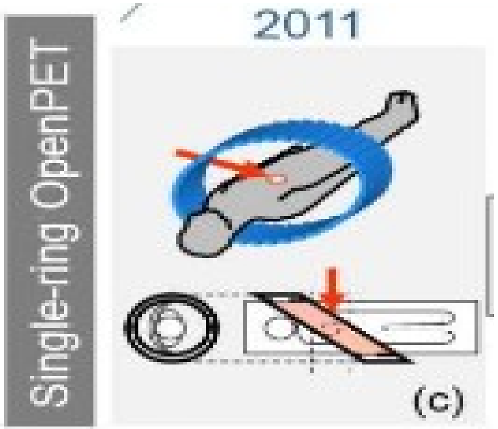
P. Crespo et al.,
Phys. Med. Biol. 51



No TOF | TOF 1.2 ns

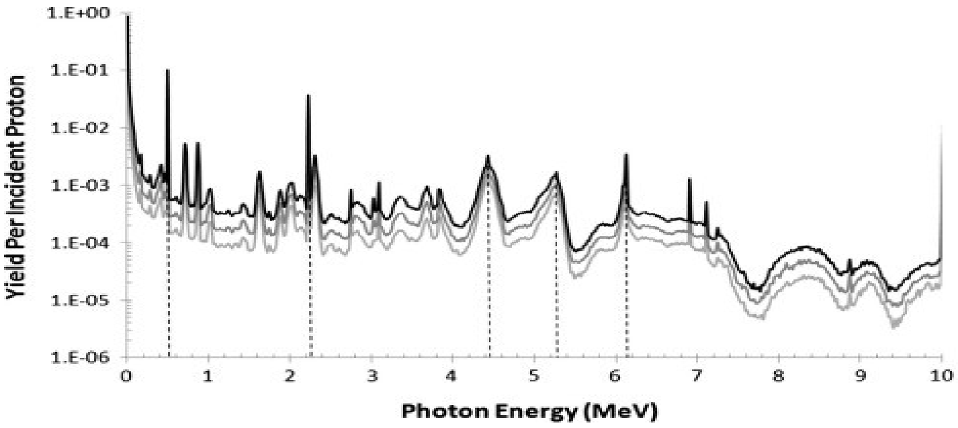
TOF 1.2 | TOF 0.1ns

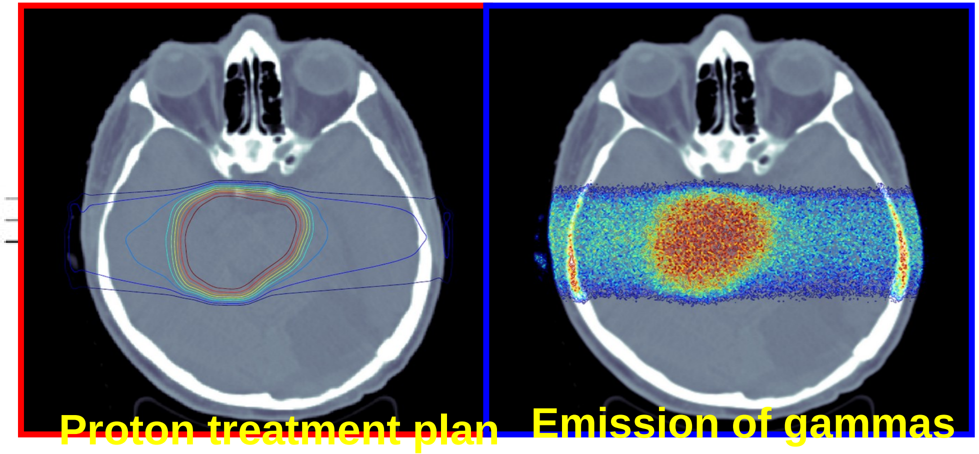




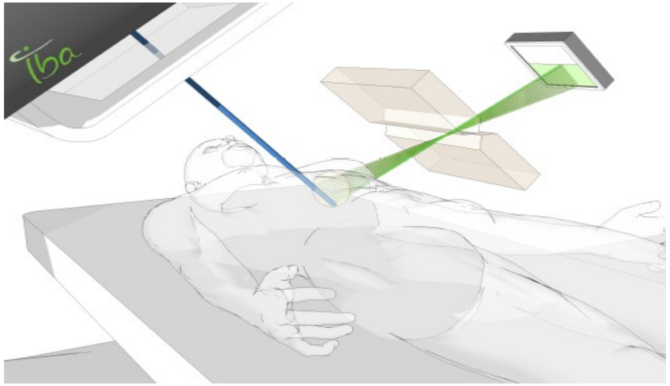
Monitoring with prompt gammas

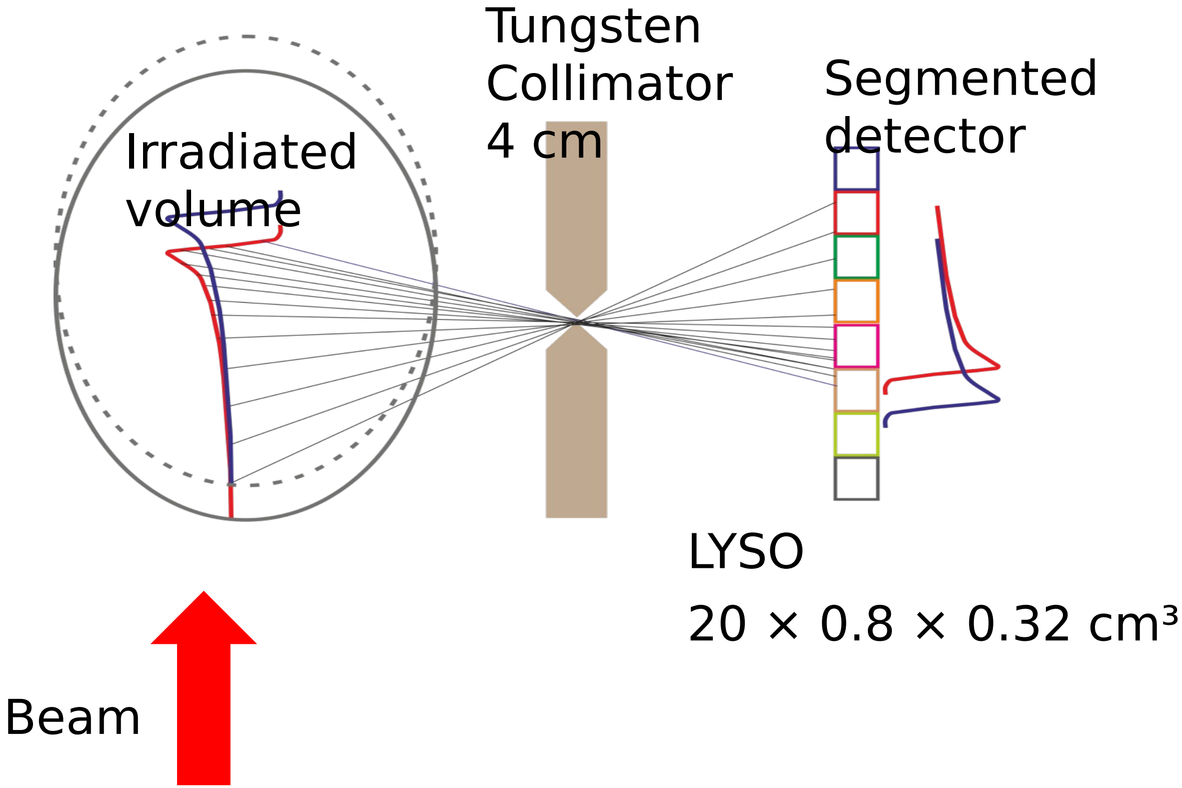
- Most promising approach nowadays
- Emission ~ns after irradiation.
- ~ 7 x more photons /cGy than positrons.
- Emitted in a continuous energy spectrum in the MeV range with characteristic peaks.





Prompt gamma imaging with collimated cameras

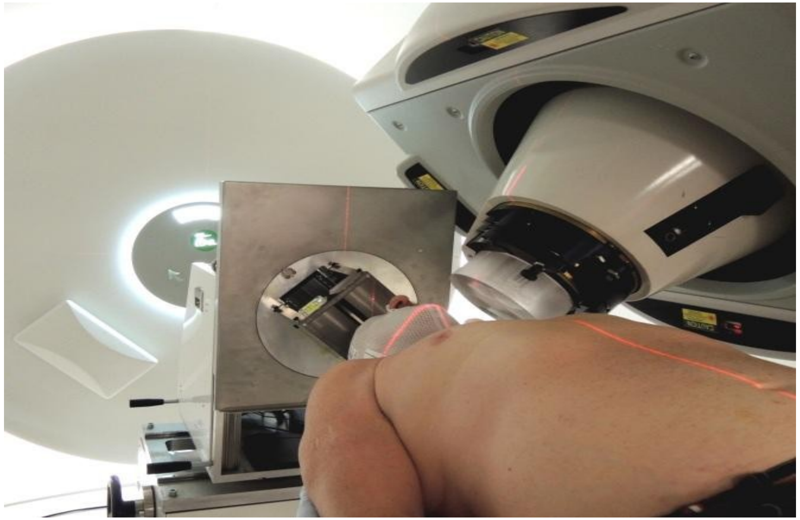


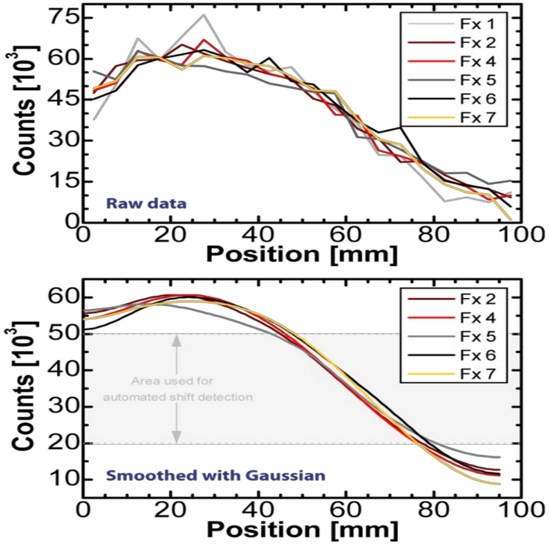


J. Smeets et al.: Phys. Med Biol. 57 (2012) 3371

Prompt gamma imaging with collimated cameras

- Range variations in the ~mm range have been observed.
- Successful results at therapeutic doses.
- Large, heavy system.

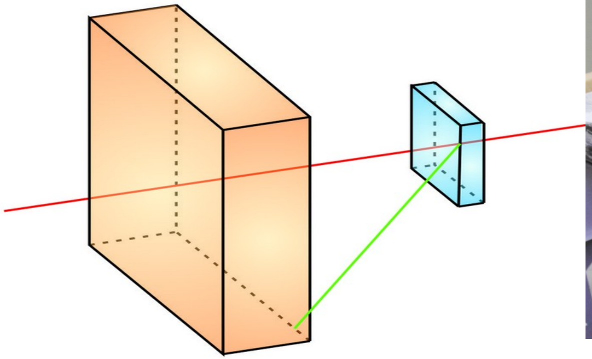


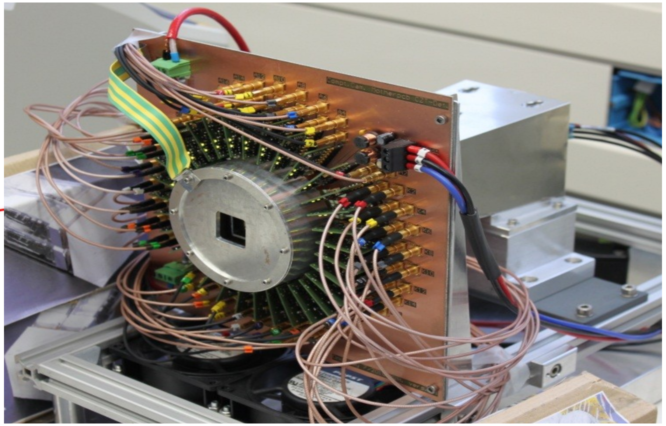


ΔR= [-2.0 mm,1.3 mm]

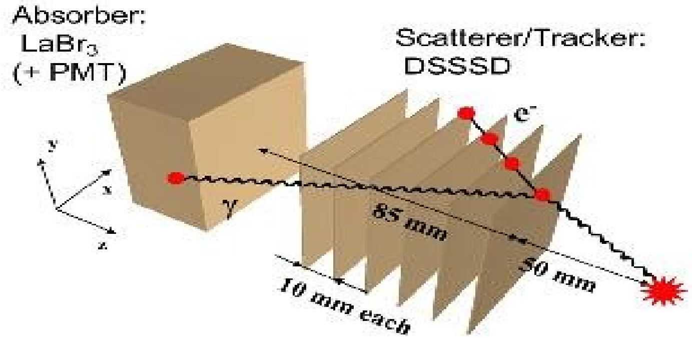
Prompt gamma imaging with Compton cameras

CZT + BGO

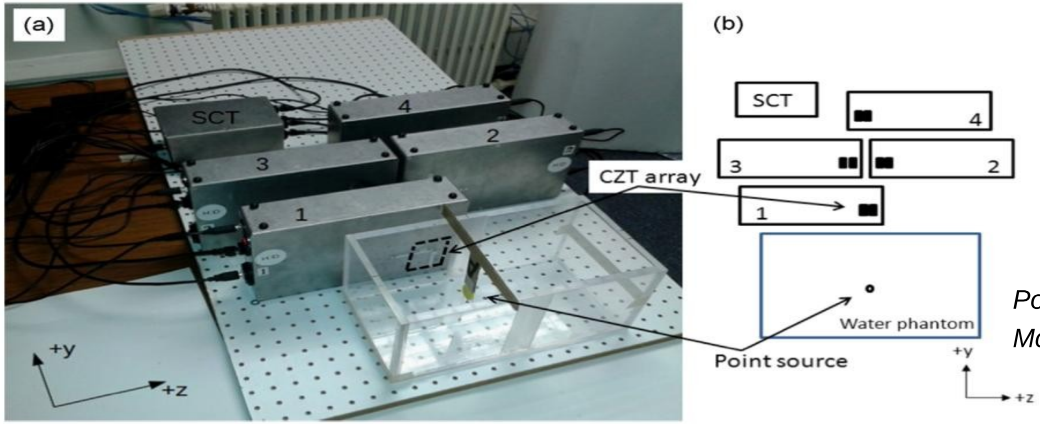




Thirolf et al., NN 2015



DSSD + LaBr$_3$

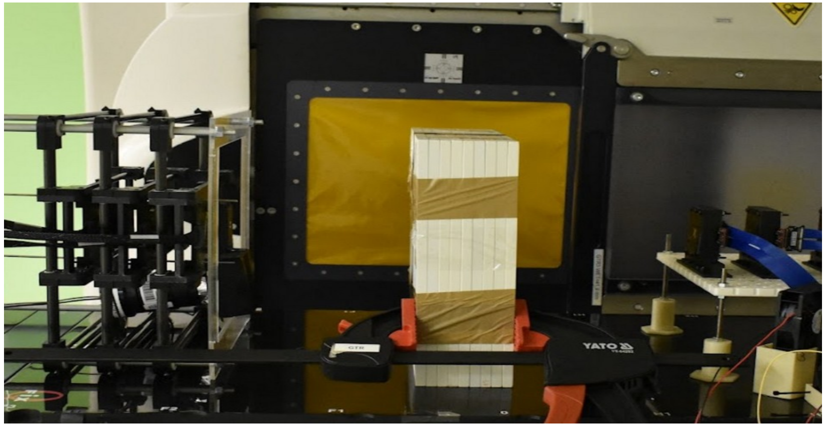


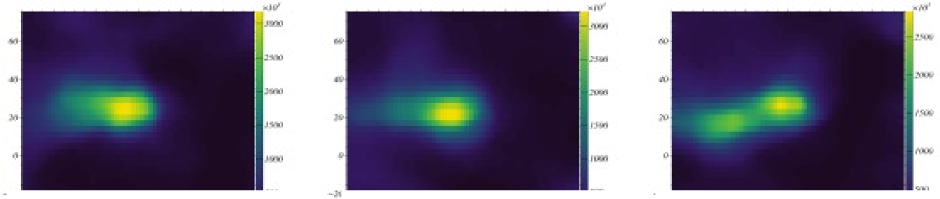
CZT

Polf et al., PMB 60 (2015) 7085
McCleskey et al., NIM A785 (2015) 163

Scintillator CCs

MACACO with $LaBr_3$ detectors

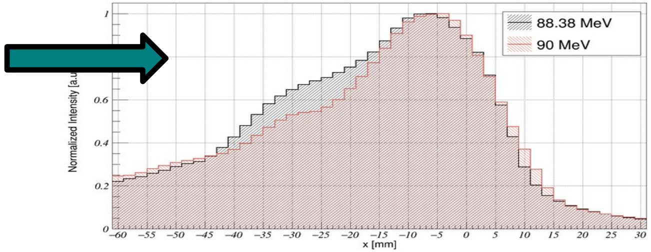




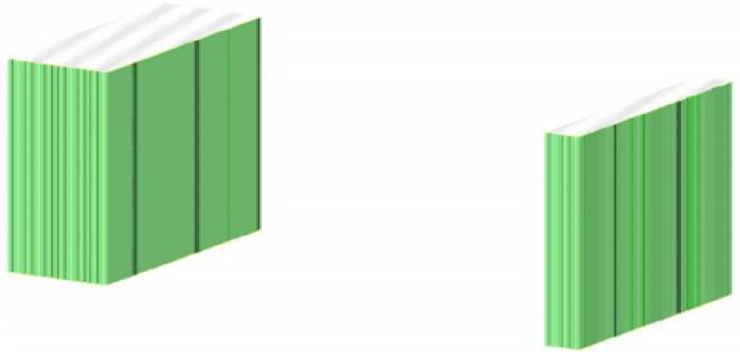
88.38 MeV   90 MeV   91.62 MeV

SiFi- CC: Compton camera with scintillating fibers under development

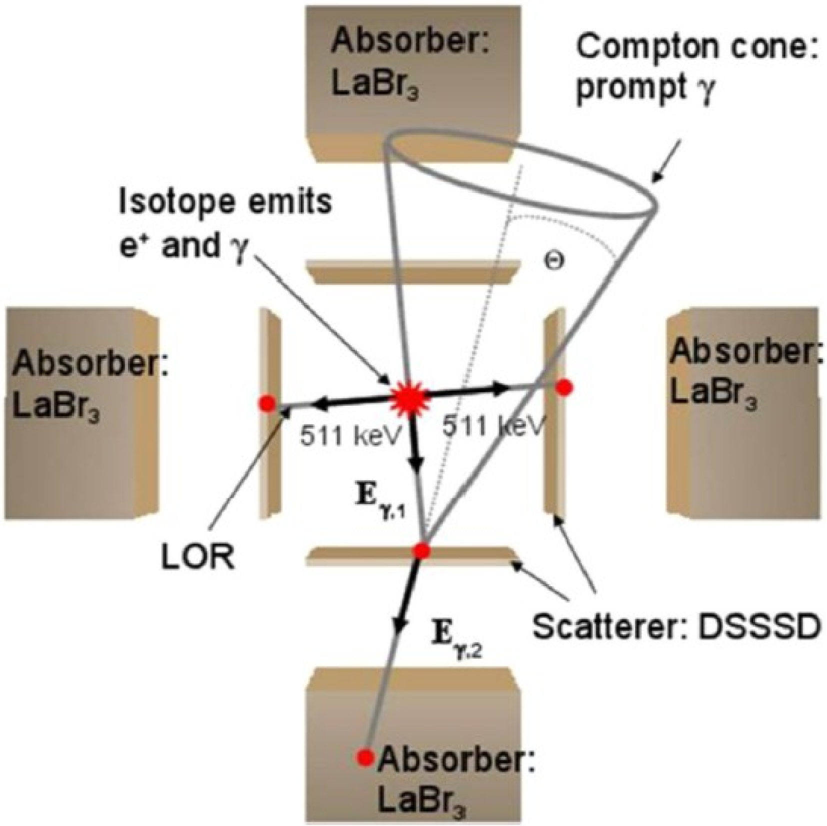
Proton beam at different energies



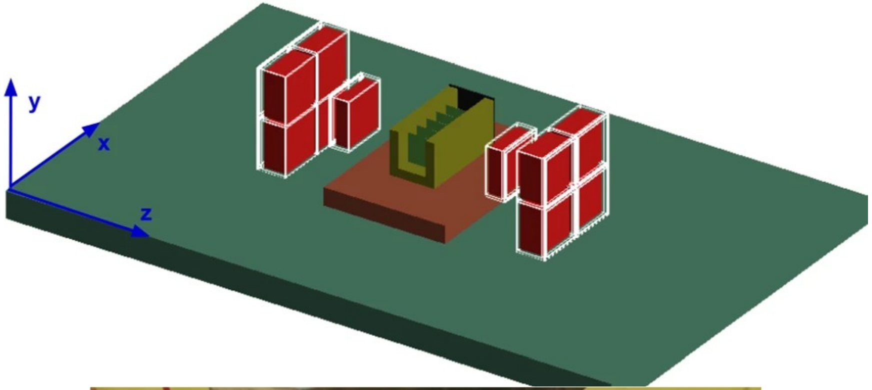
2 mm steps detected

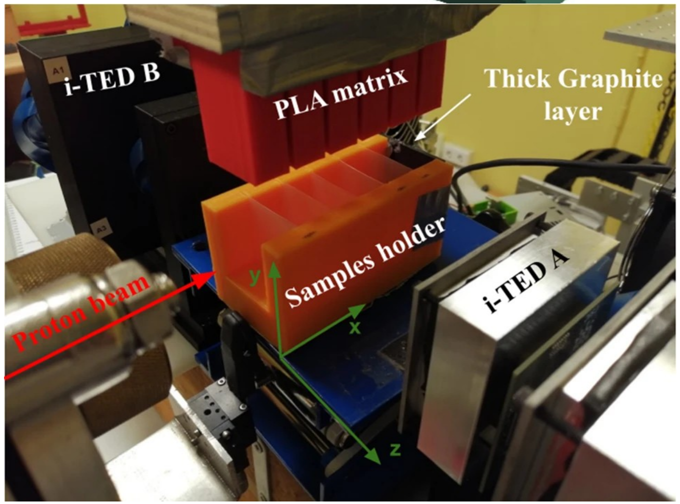


Combination Compton-PET



K. Parodi. NIM A 809 (2016) 113-119





J. Balibrea-Correa et al. Eur. Phys. J. Plus (2022) 137:1258

Hadron therapy treatment monitoring

Unsolved problem

Challenging application

Even more challenging with modern synchrocyclotrons and flash (UHDR) therapy

Needs to be compatible with treatment

Conclusions

- Many aspects in which the performance of medical imaging devices can be improved.
- Instrumentation from particle, astroparticle and nuclear physics can lead to improvements in this field.
- Necessary contact with hospitals / specialized groups to know what the requirements are and to address properly the needs.

Thank you

Gabriela.llosa@ific.uv.es

http://ific.uv.es/iris

MCIU /AEI (PID2022-143246OB-I00)