

Nuovi sensori di luce allo stato solido applicati alla medicina nucleare

Claudio Piemonte

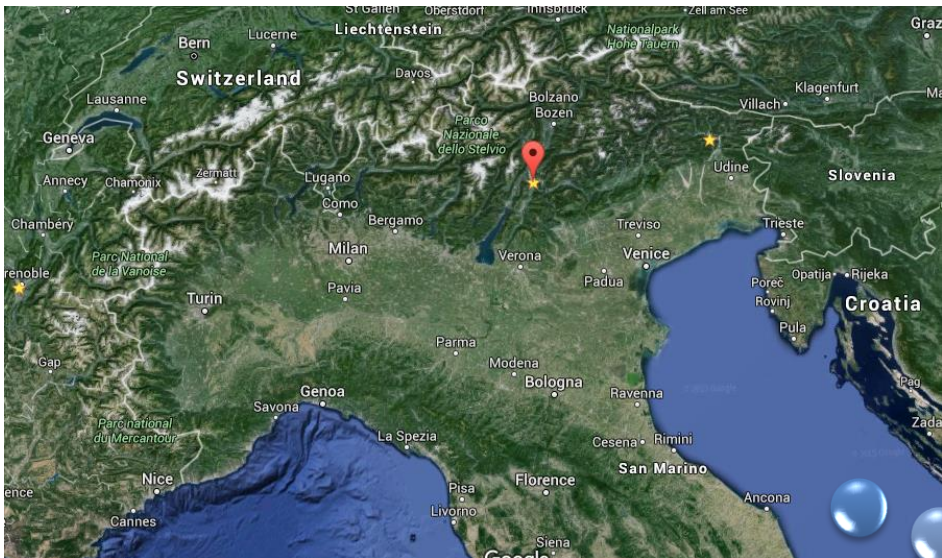
Chief Scientist, Fondazione Bruno Kessler

piemonte@fbk.eu

Indice

- La Fondazione Bruno Kessler
 - *Chi siamo, cosa facciamo*
 - *I sensori di radiazione in FBK*
- Sensori a *singolo fotone* allo stato solido: tecnologia abilitante (KET) per l'avanzamenti nella diagnostica nucleare

Trentino and its Research System



**Autonomous
Province of
Trento**

**University of
Trento**

**Fondazione
Bruno
Kessler**

**Fondazione
Edmund
Mach**

FBK at a glance

About 400 researchers.

Humanities Hub



ECT*



Scientific and Technological Hub

2007

1993

1986





Scientific and Technological Area

CMM
Centre for
Materials
and
Microsystem

~120
people

ICT
Centre for
Information
Technology

~200
people

ECT*
European
Centre for
Theoretical
Physics

CIRM
International
Center for
Mathematical
Research

Humanities Area

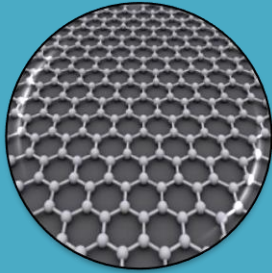
ISIG
Centre for
Italian-
German
Historical
Studies

ISR
Centre for
Religious
Sciences

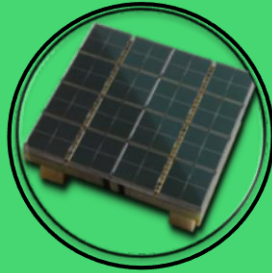
IRVAPP
Research
Institute for
the
Evaluation of
Public
Policies

CERPEG
Research
Center on
War, Peace
and
International
Change

CMM: The Four Research Lines



*Functional
Materials: Carbon-
based and
Nanostructured*



***Imagers &
Radiation Sensors***



Microsystems



*Integrated
Systems*

Micro Nano characterization and fabrication Facility

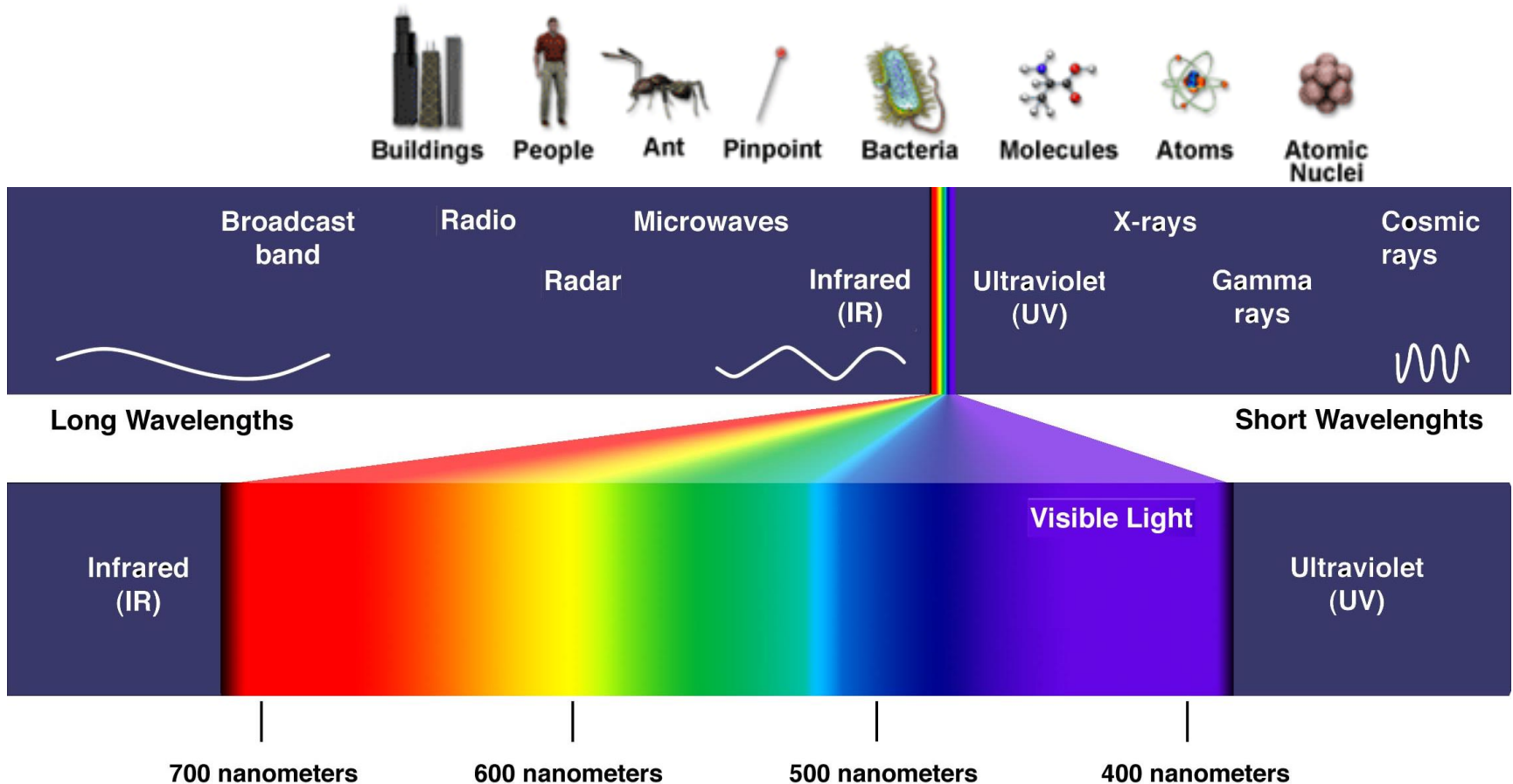
Radiation Detection and Imaging (RDI) Research line

2015

Lo spettro elettromagnetico

energia fotoni crescente

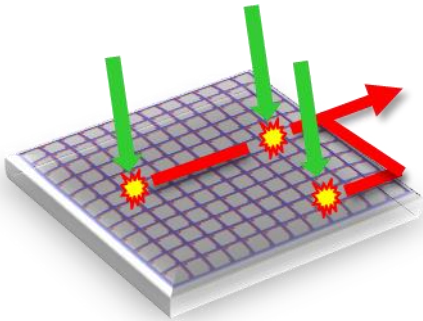
lunghezza d'onda crescente



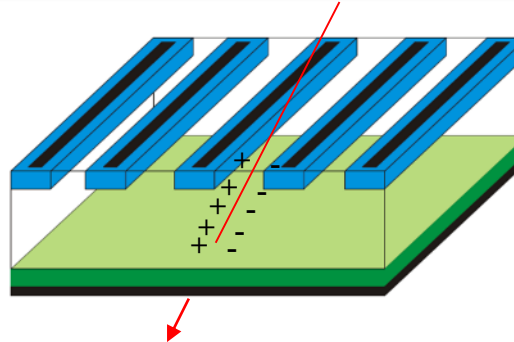
Research topics

Two main platforms (silicon):

Single-photon light sensors

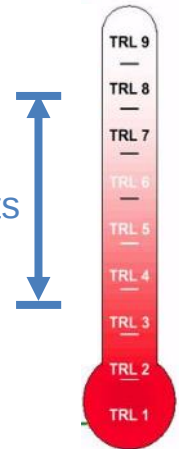


High-energy radiation detectors



TRL

various
developments



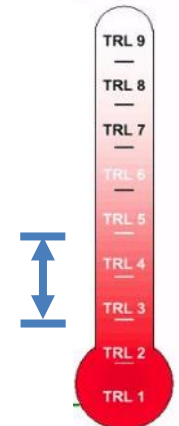
R&D initiatives on:

TeraHertz
detectors

Low-power
imaging

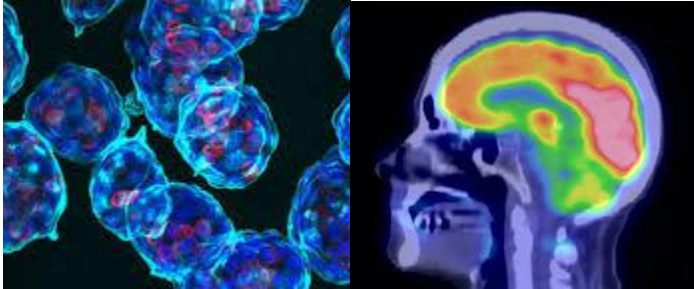
Graphene-based
detector

TRL

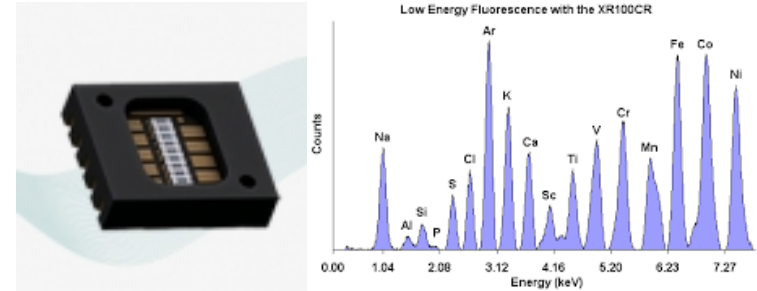


Main Applications

BioMedical instrumentation



Industrial instrumentation



Space and astrophysics



High energy physics



Partnering



- **R&D and technology transfer with private companies**

At present we have 3 long-term contracts with multinational companies following this scheme.

- **Collaborative projects**

with public funding (H2020, ESA...)

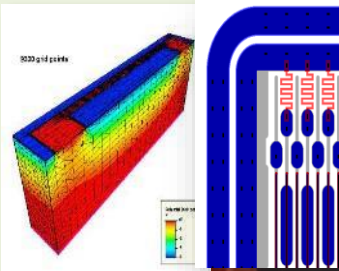
In the past 5 years we participated to ~10 FP7/H2020 projects.

- **Small productions for public and private entities**

Mainly dealing with custom technologies both for industrial and research applications.

Technologies & Competencies

Full Custom Silicon Technology



Modeling-design



In-house
production

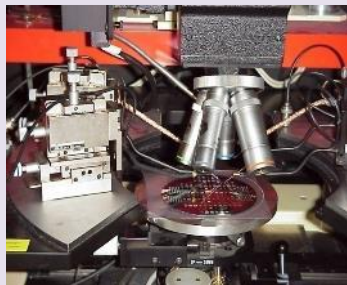
State-of-the art CMOS Technologies



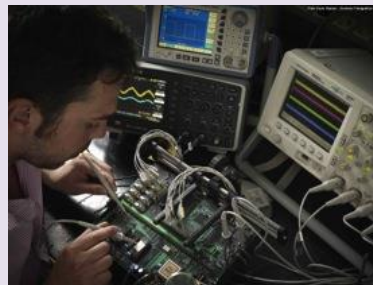
Analog and Digital
IC Design

130nm-350nm
external Fab

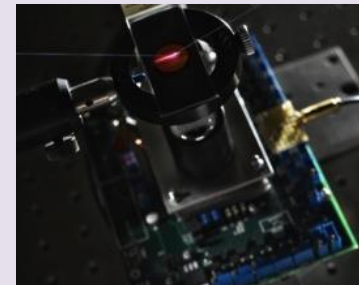
Parametric Testing



Functional Testing



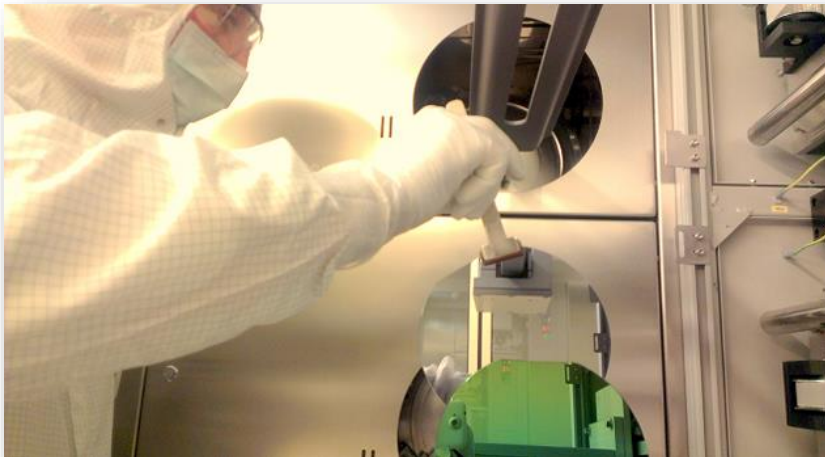
Prototyping



Infrastructures



Microfabrication Area:
CMOS-like pilot line (6" wafers)
with 2 Clean Rooms for
device fabrication

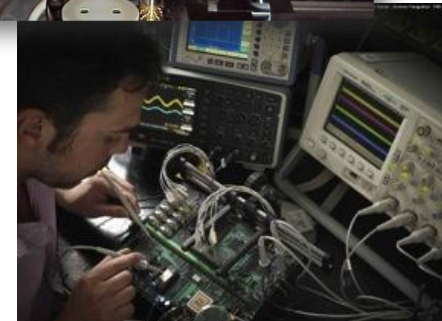
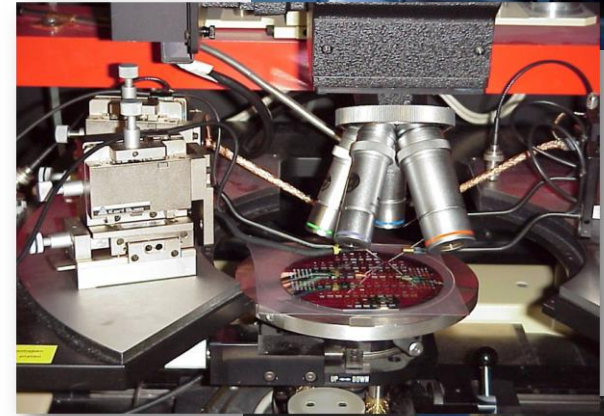


Testing Area: on-wafer parametric testing

Integration Area:
device packaging and microsystems
assembly

Functional testing area:

- microchip electrical characterization
- PCB and prototype assembly
- electro-optical characterization
- tests with high-energy radiation
- THz Test Bench
- image sensors testing
- TOF tests

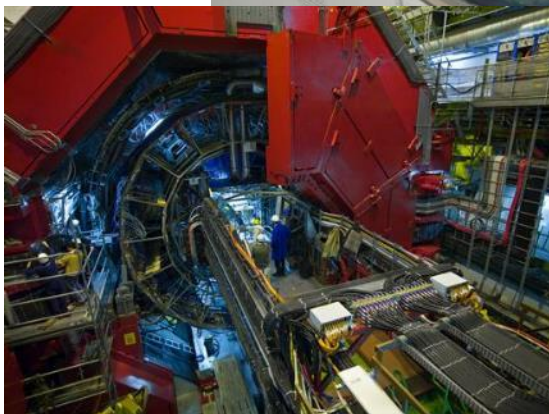
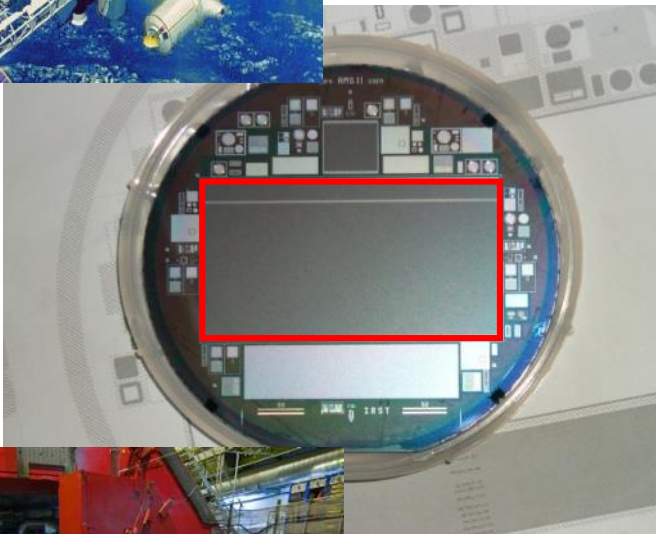


Some examples of radiation detectors @ FBK

AMS experiment (@ISS)



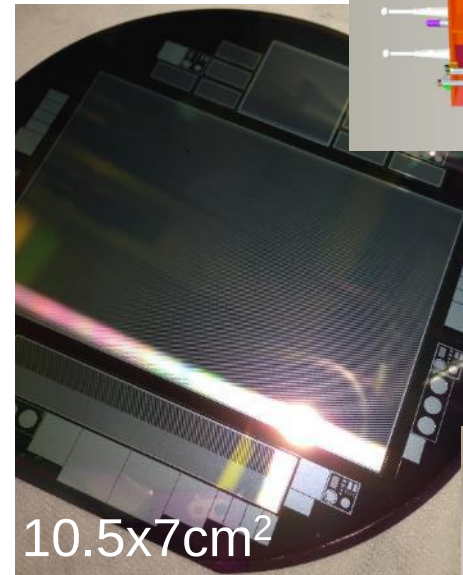
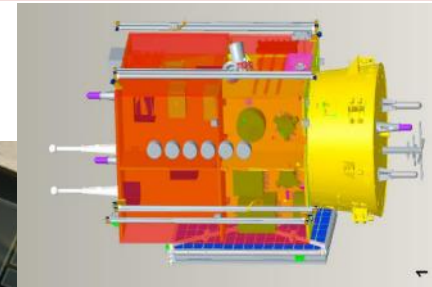
700 detectors



600 detectors

ALICE experiment (@LHC)

Limadou experiment (@CSES)



10.5x7cm²



Custom productions for industry

Single-photon light sensors.

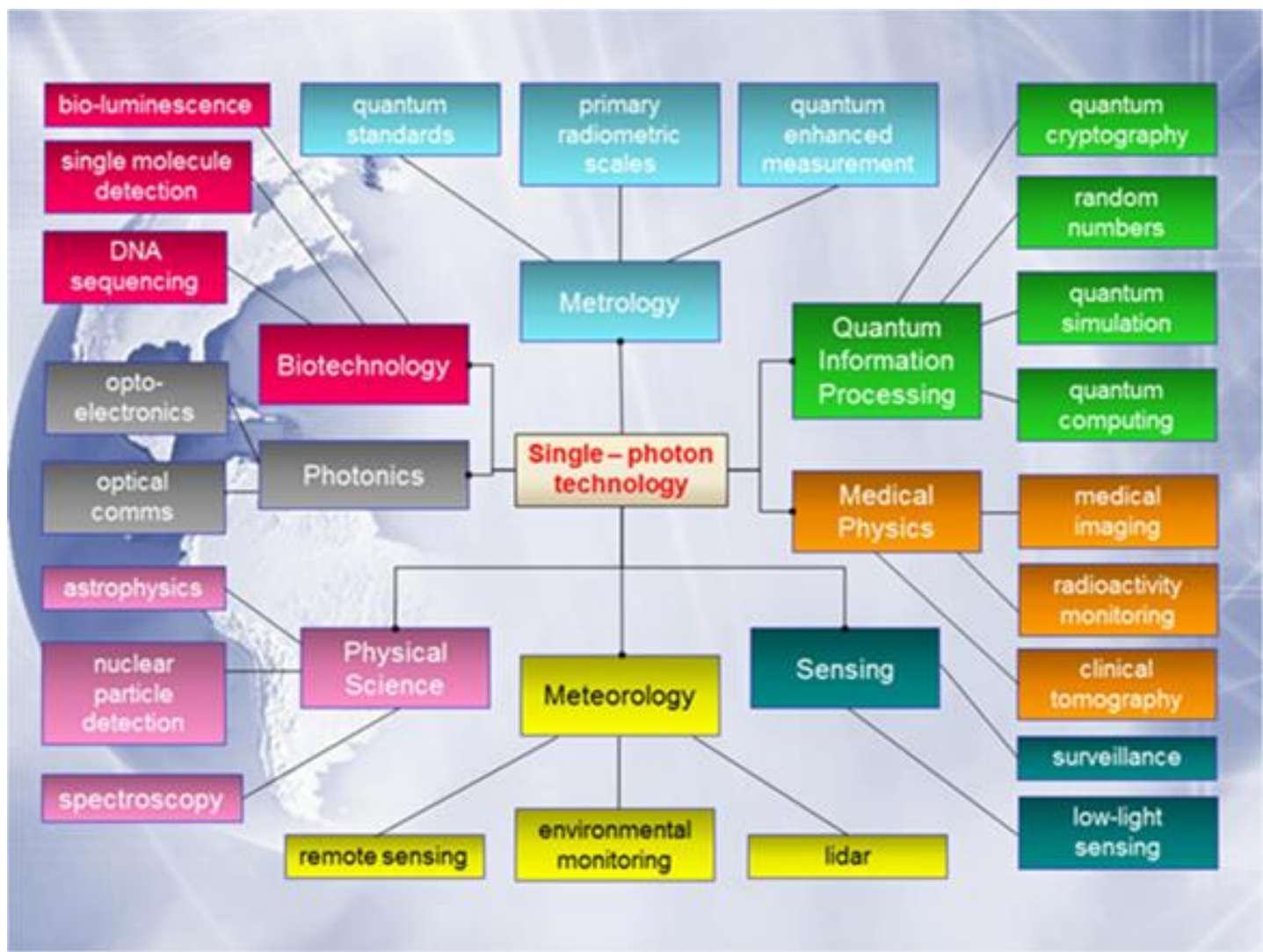
Application to nuclear medicine.

Single-photon detectors?

Sensors able to count single light photons both in faint light conditions.

Not an easy task since the energy of a light photon is low.

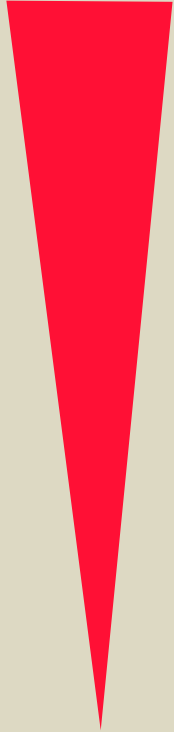
Single-photon applications



Medical Imaging techniques for cancer

Type of information

Anatomic

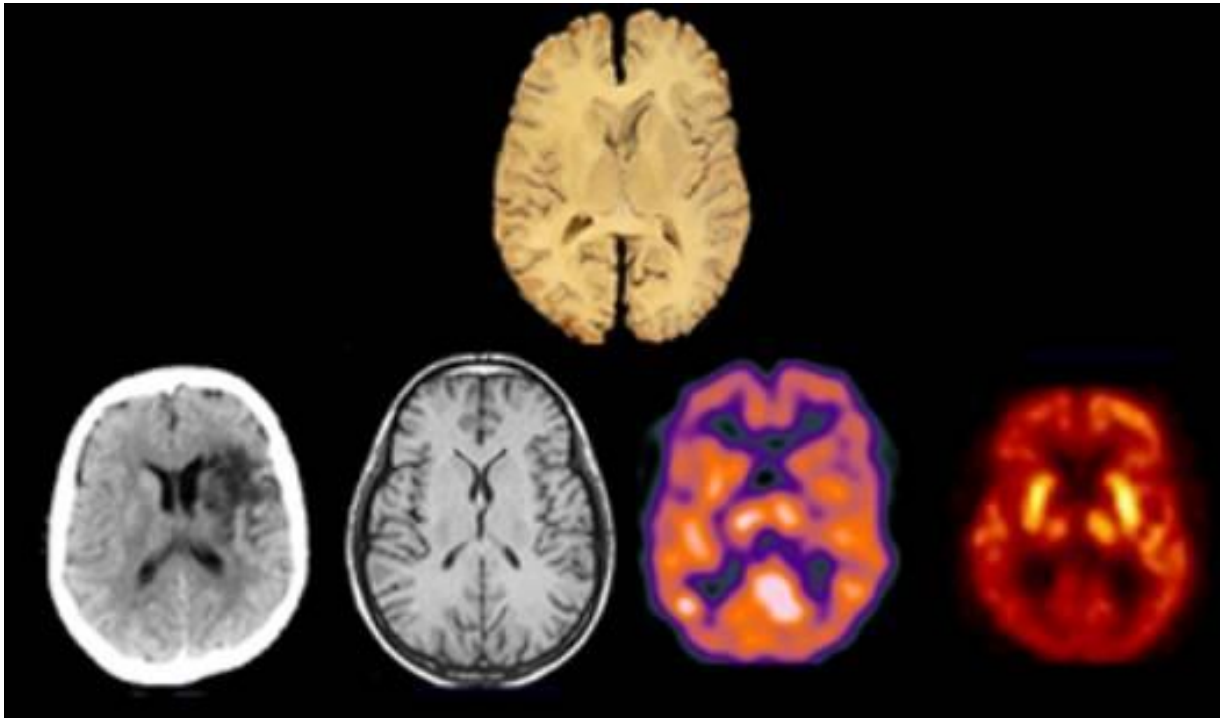


Functional
and
Molecular

- X-ray Computed Tomography (CT)
- Ultrasound
- Magnetic Resonance Imaging (MRI)
- Optical Imaging
- Magnetic Resonance Spectroscopy (MRS)
- Radionuclide imaging (**Nuclear Medicine**):
 - Positron Emission Tomography (PET)
 - Single-Photon Emission Computed Tomography (SPECT)

Medical Imaging techniques

Transaxial slice of the human brain



...acquired with different imaging modalities from left to right:
X-ray CT, MRI, SPECT and PET

Radionuclide imaging

- radionuclides are combined with other elements to form chemical compounds: **radiopharmaceuticals**;

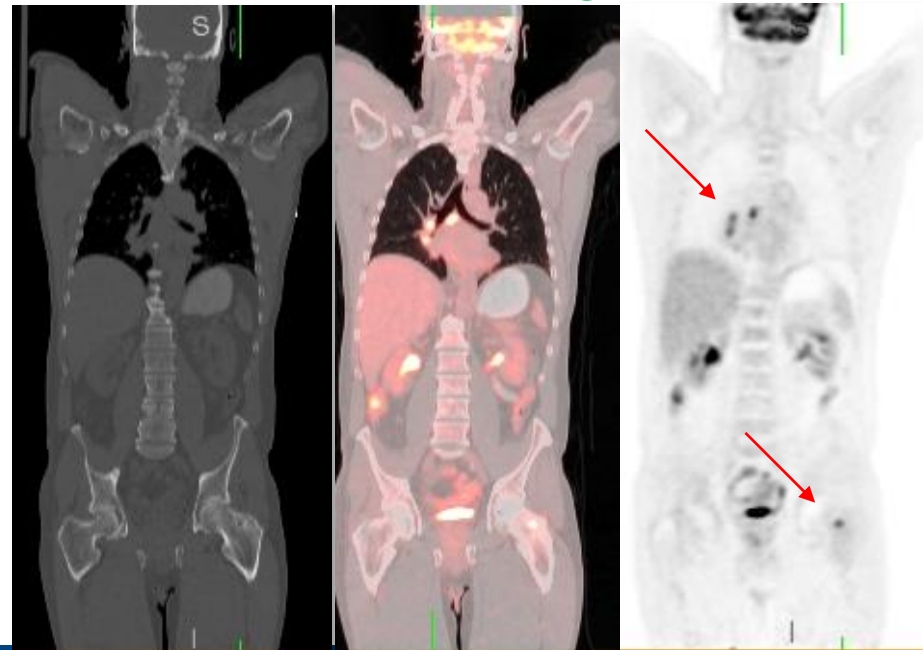


- administered to the patient, they localize to specific organs or cellular receptors;



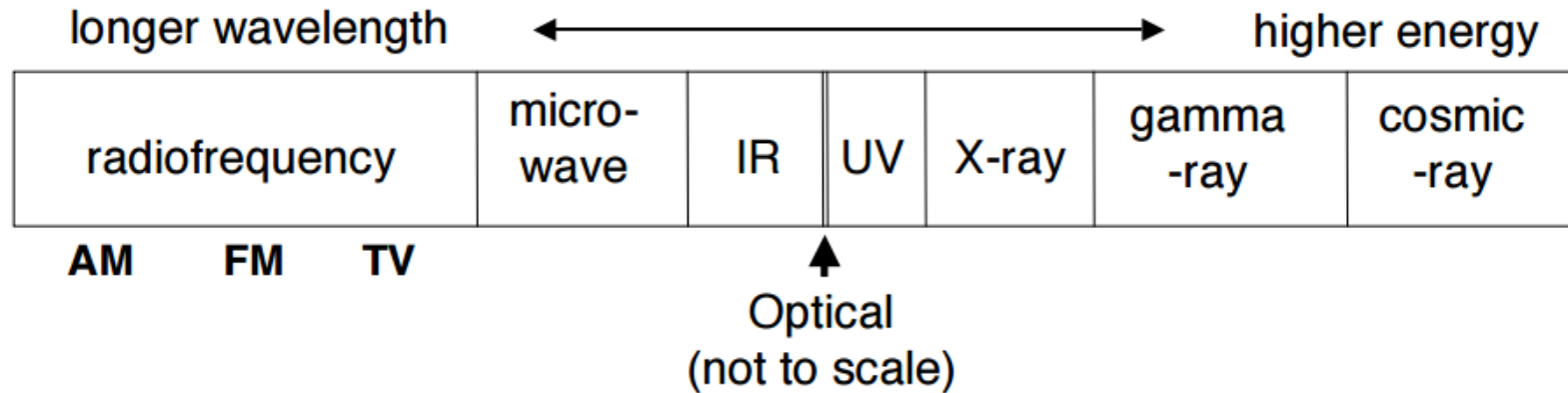
- imaging of emitted radiation allows to localize and understand the disease process in the body, based on the cellular function and physiology

FDG PET/CT: lung cancer

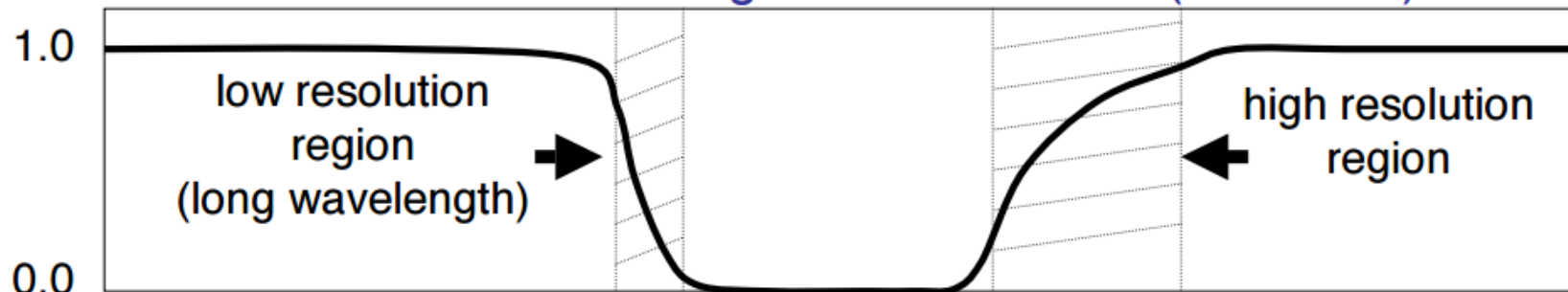


Why high-energy radiation?

The Electromagnetic Spectrum



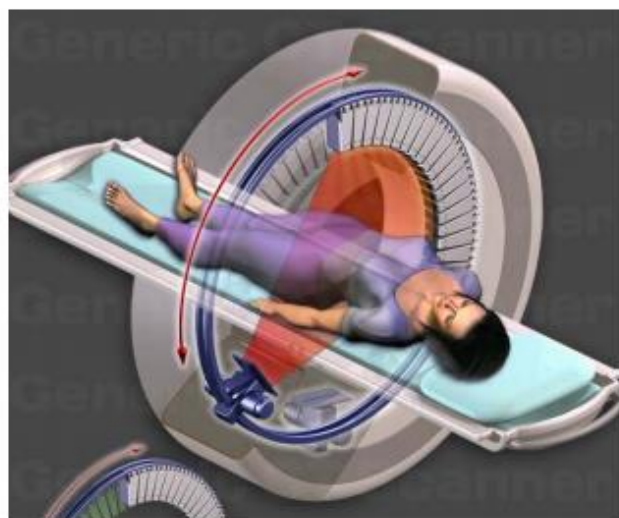
Transmission through 10cm of tissue (i.e. water)



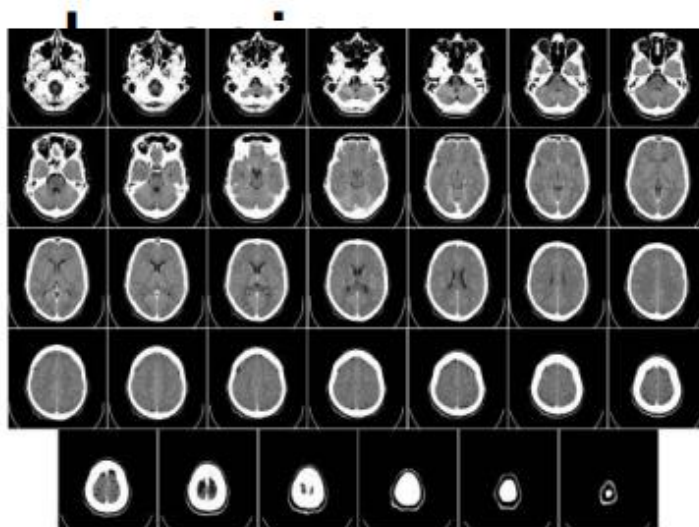
Tomography

“Imaging by sectioning using a penetrating wave”

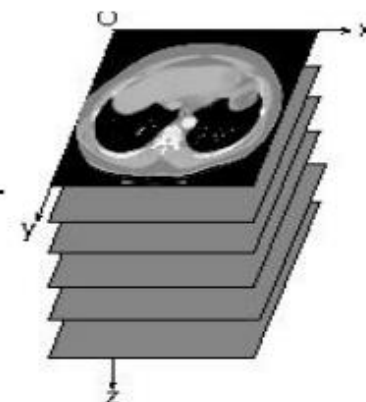
Example of Computed tomography



tomographic acquisition



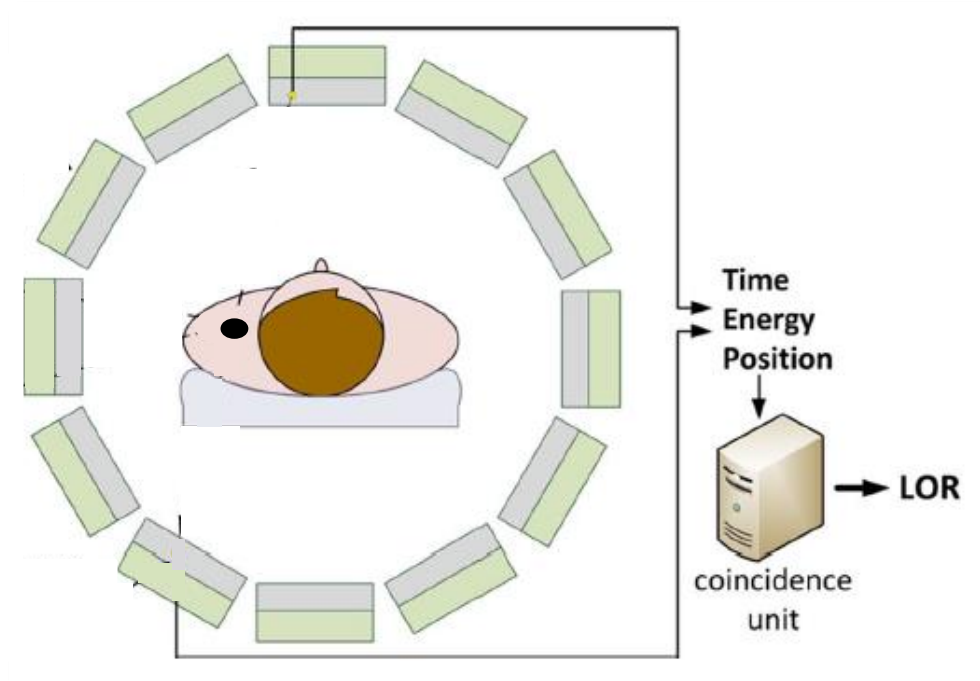
reconstruction of multiple images



form image
volume

image processing

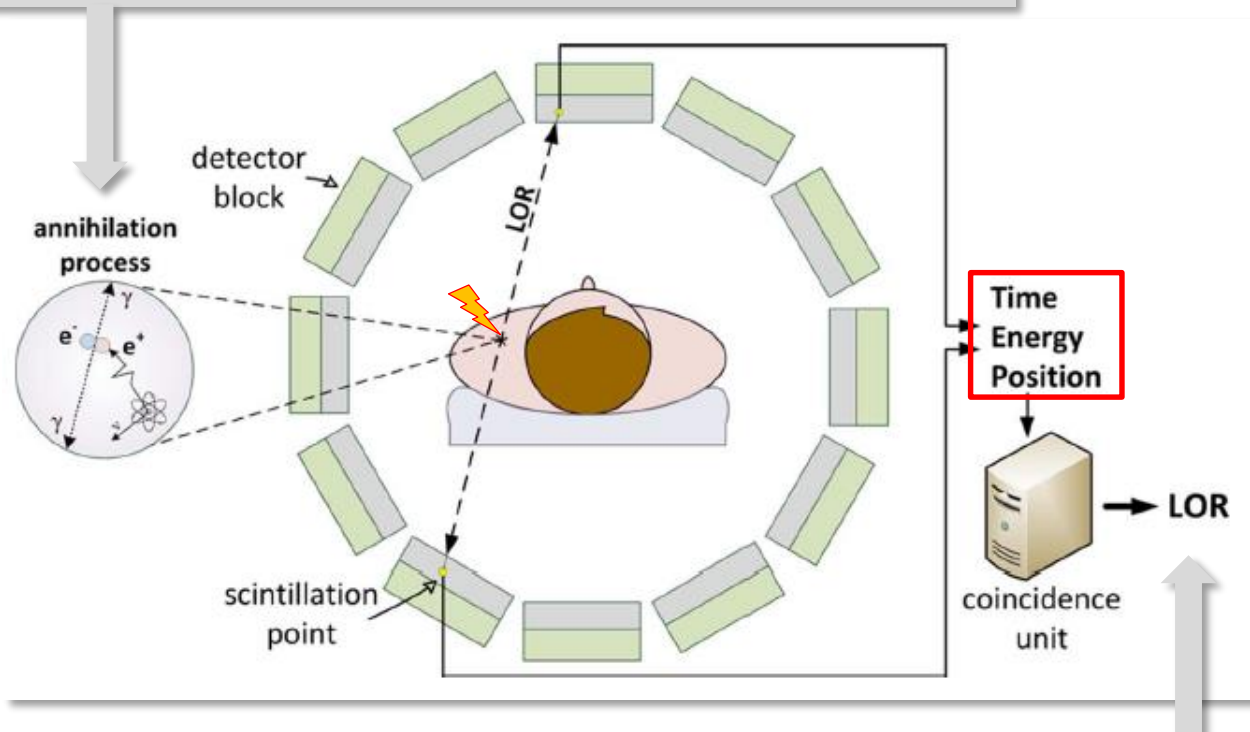
Positron Emission Tomography



Positron Emission Tomography

1

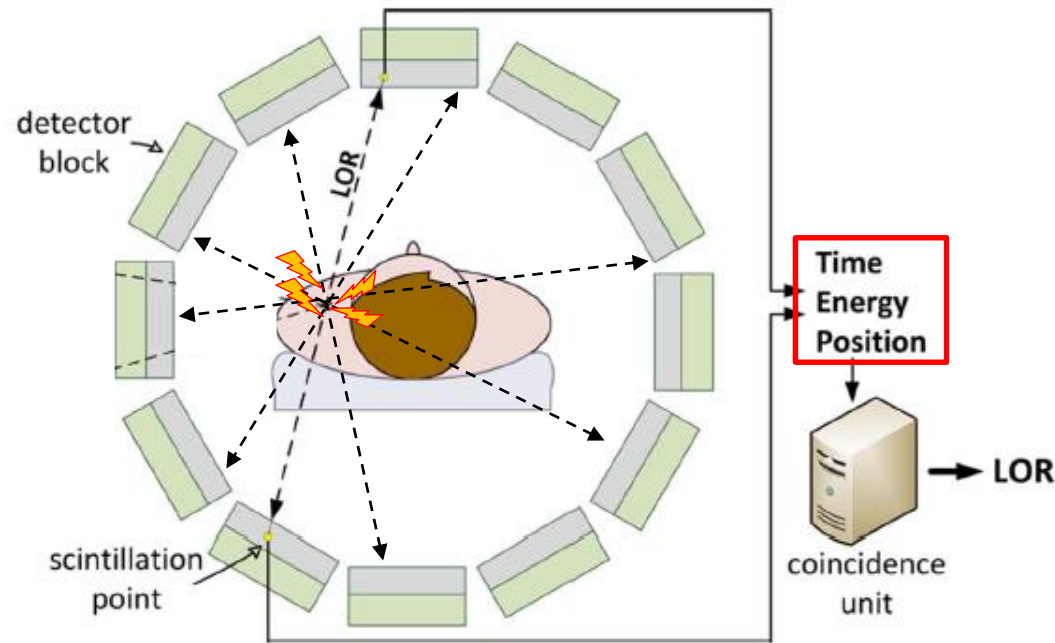
Positrons emitted by radionuclide annihilate with electrons of the tissue generating two gamma rays in coincidence.



2

Two detector blocks identify the events and a coincidence unit reconstructs a Line-Of-Response (LOR)

Positron Emission Tomography

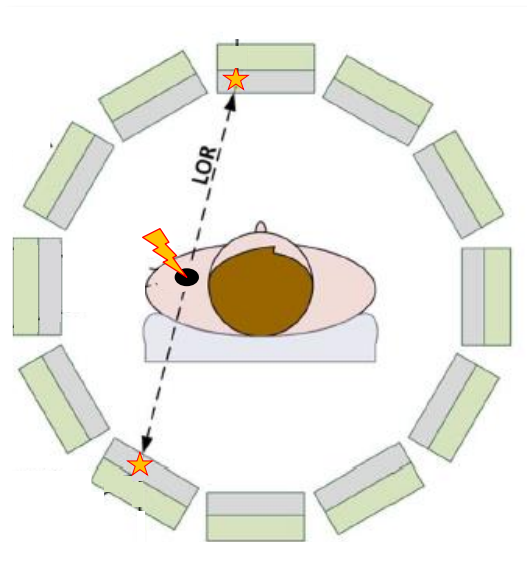


3

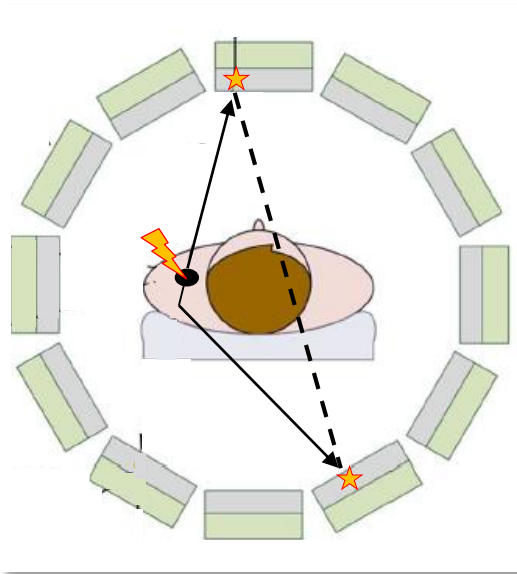
From a large set of lines of response it is possible to reconstruct the 3-dimensional density distribution of the tracer. This is usually done with an iterative reconstruction algorithm, very computer intensive.

PET: ...good events are only a few...

True coincidence



Scattered coincidence



Random coincidence

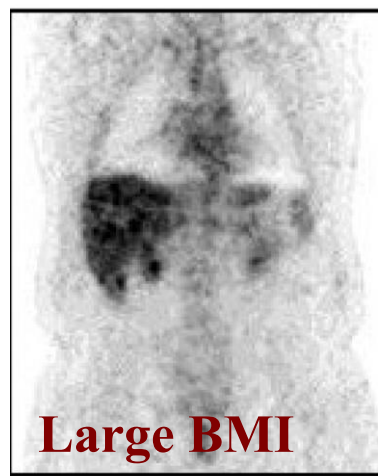
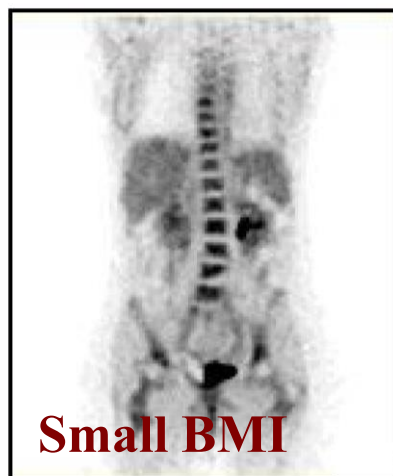
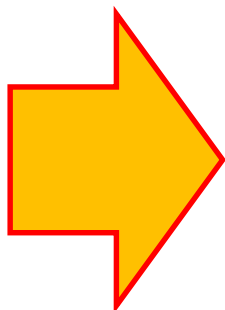
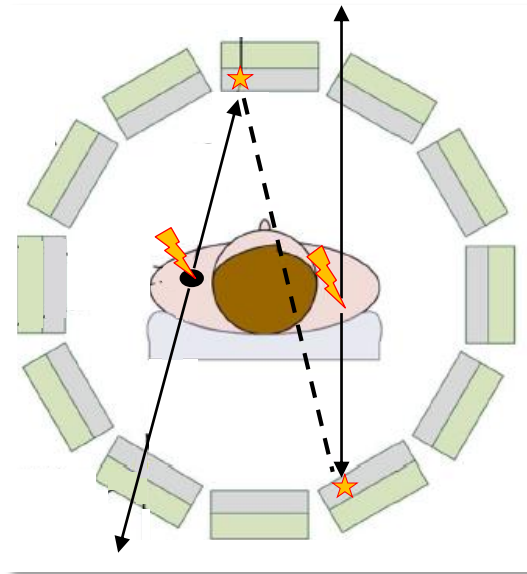
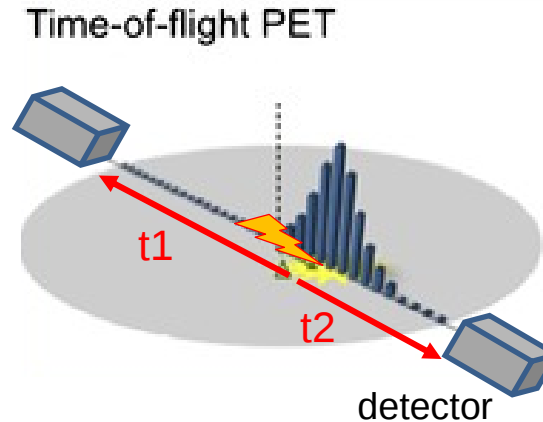
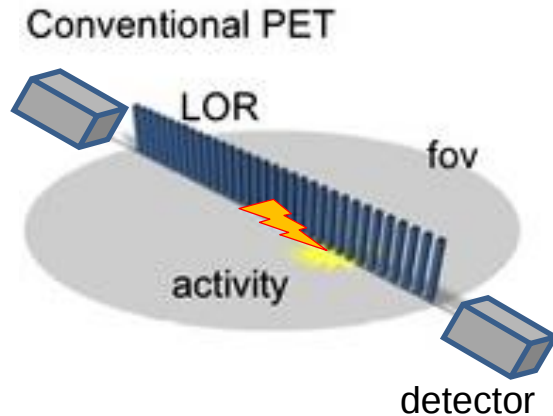


image
deterioration

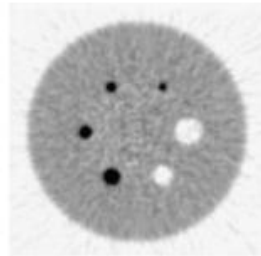
Time-of-Flight PET



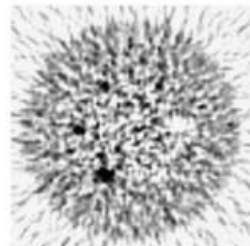
Detectors must provide a precise estimation of the photon arrival time to allow position estimation along LOI.

non TOF

High statistics



Low statistics



TOF-PET state-of-the-art



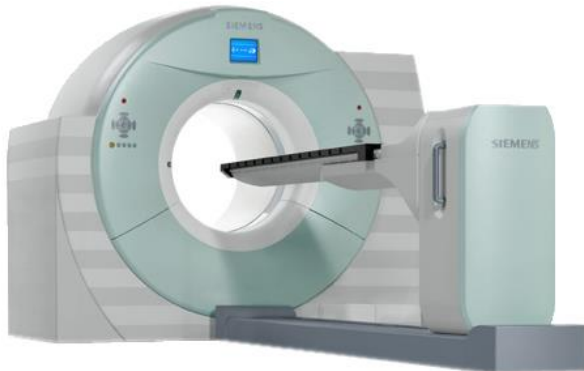
2006

Gemini TF, time resolution 495ps FWHM
(Philips)



2009

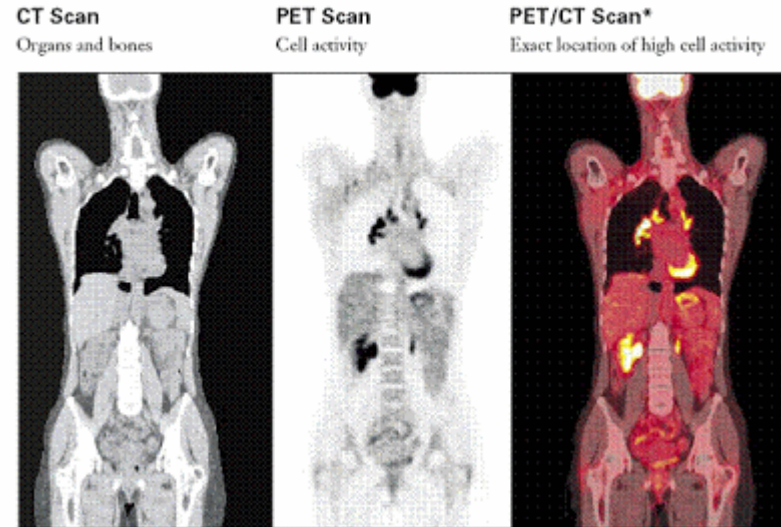
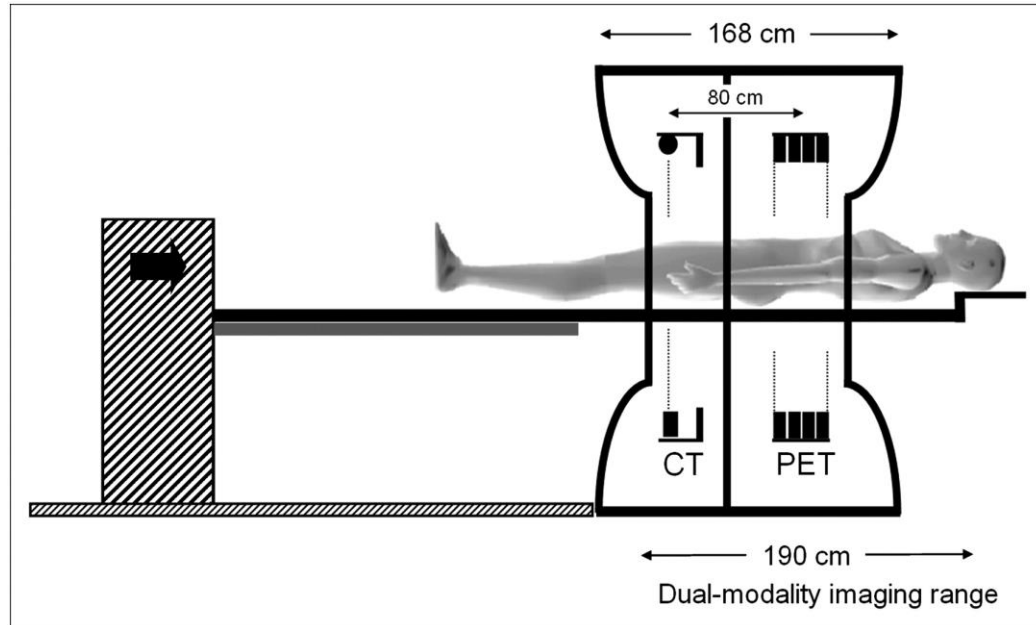
Discovery 690, time resolution 600ps FWHM
(GE)



2009

Biograph mCT, time resolution 550ps FWHM
(Siemens)

Multimodality: PET/CT

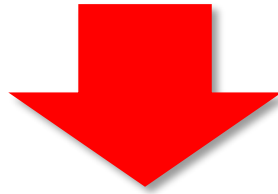


Combination of anatomical structures (from CT) and functional information (from PET) into one image, with high fusion accuracy, provides an advanced diagnostic tool.

Drawback from CT is the limited soft tissue contrast and radiation dose. Furthermore the acquisitions of the image are not simultaneous.

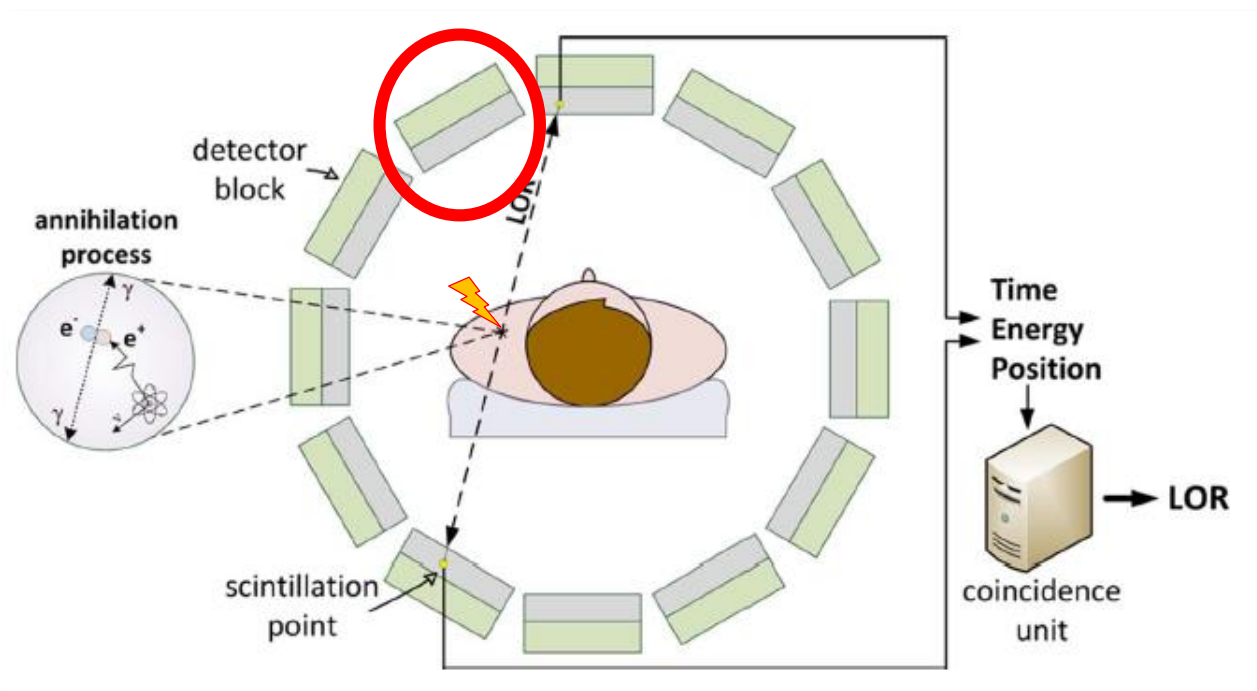
Future directions in PET

- **better image quality**
- **better image quantitation**
- **shorter scan times**

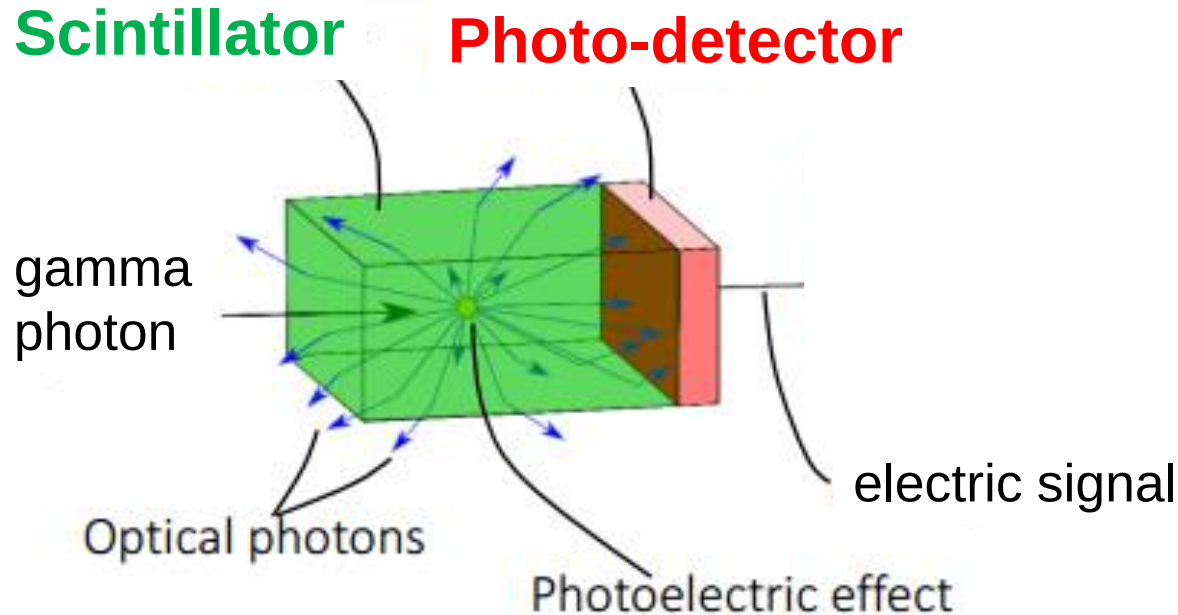


- **New multi-modality systems: PET-MR**
- **Better time-of-flight (→ tens of ps)**
- **Longer scanners, more stopping power**
- **dedicated PET scanners**

Today most of the limitations come from the detector block!

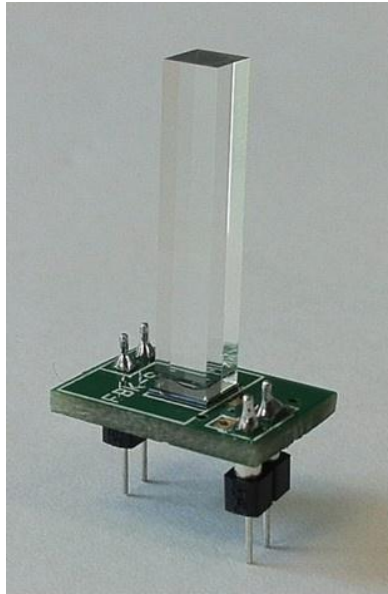


Detector Block



Gamma photons are difficult to be absorbed and detected directly → they have to be converted in something else
→ scintillator convert gammas to optical photons.

Scintillator



- Very high density
- Transparent to light
- fast light emission
- high number of optical photons (bright)

→ lot of R&D ongoing

	peak emission (nm)	light yield (ph/511keV)	decay time (ns)	density (g/cc)	hygroscopic
BGO	480	6000	300	7.1	NO
LSO/ LYSO	420	14000	40	7.1	NO
LaBr3	380	30k	16	5	YES

cheap, no TOF

most used today

the future?

Photodetector

Primary characteristics:

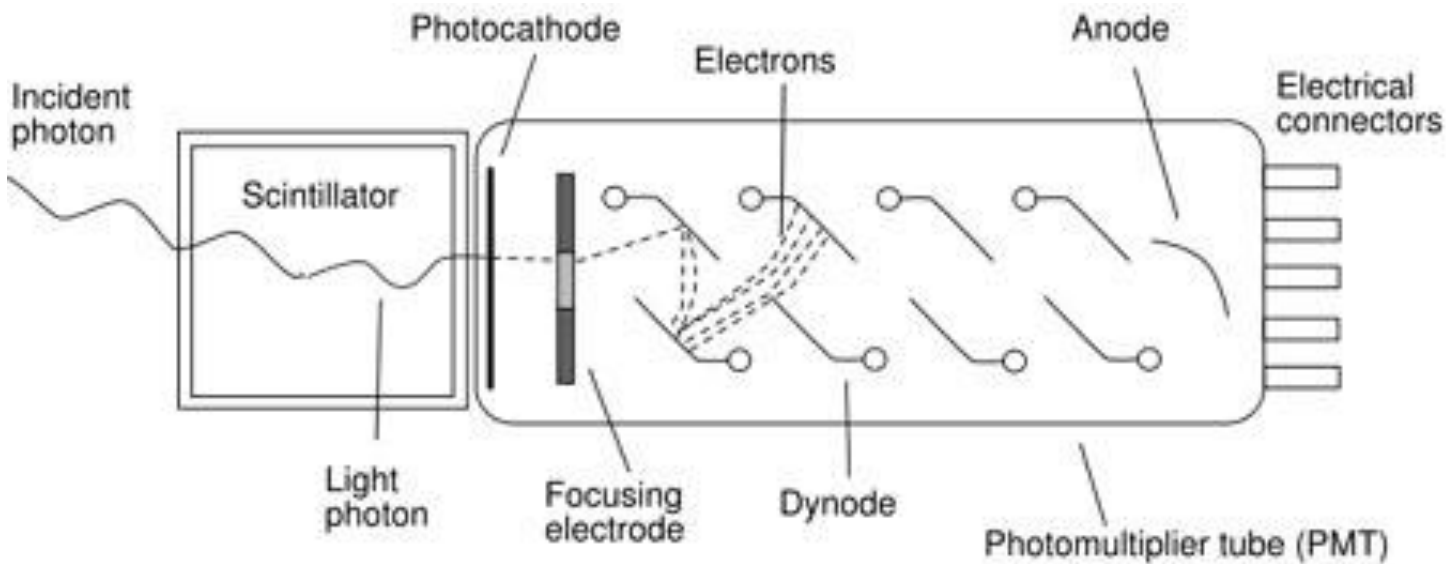
- high sensitivity to detect few hundred of photons
- very fast to allow TOF



The TOF-PET systems seen above
use the **photomultiplier tube**

Photomultiplier Tube

100 year-long history



Photomultiplier Tube

Goods:

- single photon capability
- fast
- high gain
- low noise
- **cost**

Bads:

- bulky
- fragile
- damaged by ambient light
- no magnetic fields
- high voltage

Facts:

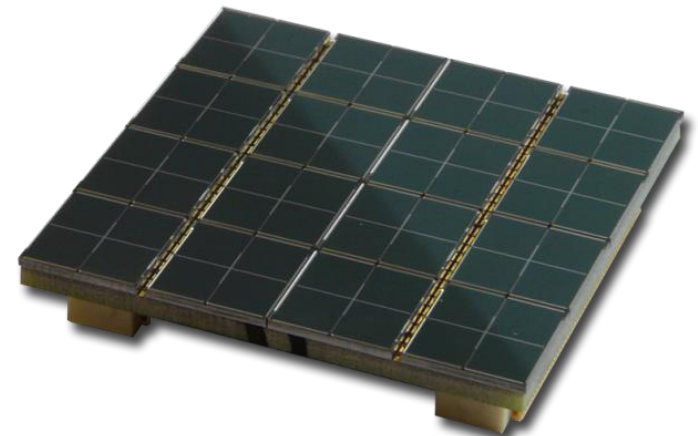
- Despite the long history this sensor is still (slowly) improving
- Only one big supplier



It is clear that the PMT
does/will not allow the
technology leap in the
PET field...

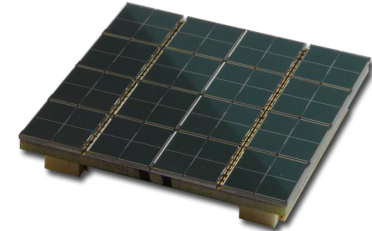
...the **solid-state revolution**

The Silicon photomultiplier: Key Enabling Tech. for new PET.



**Fabricated in standard
silicon technology!!**

PMT vs SiPM

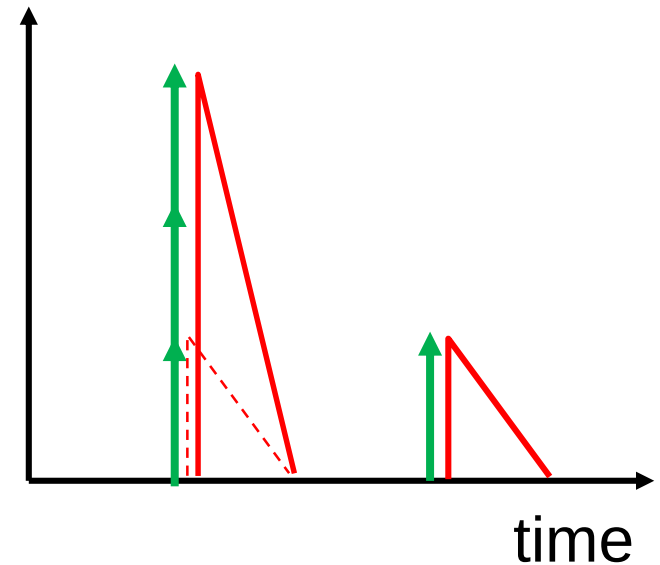
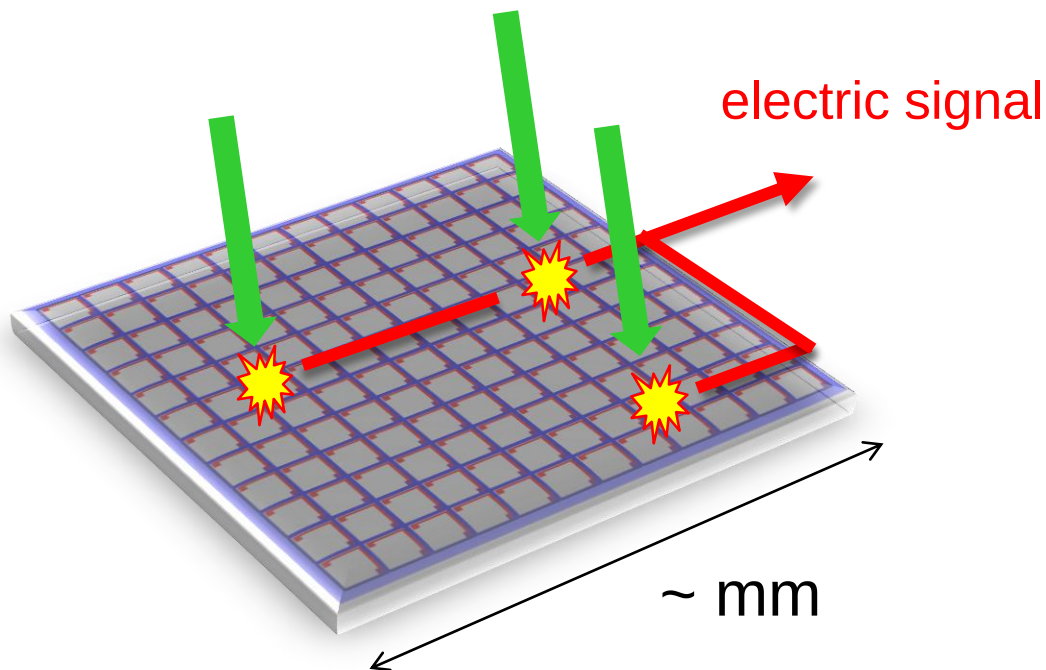


compactness	↓	↑
performance	↑	↑↑
ruggedness	↓	↑
insensitivity to magnetic fields	↓	↑
cost	↑	~↑
market competition	↓	↑

SiPM concept

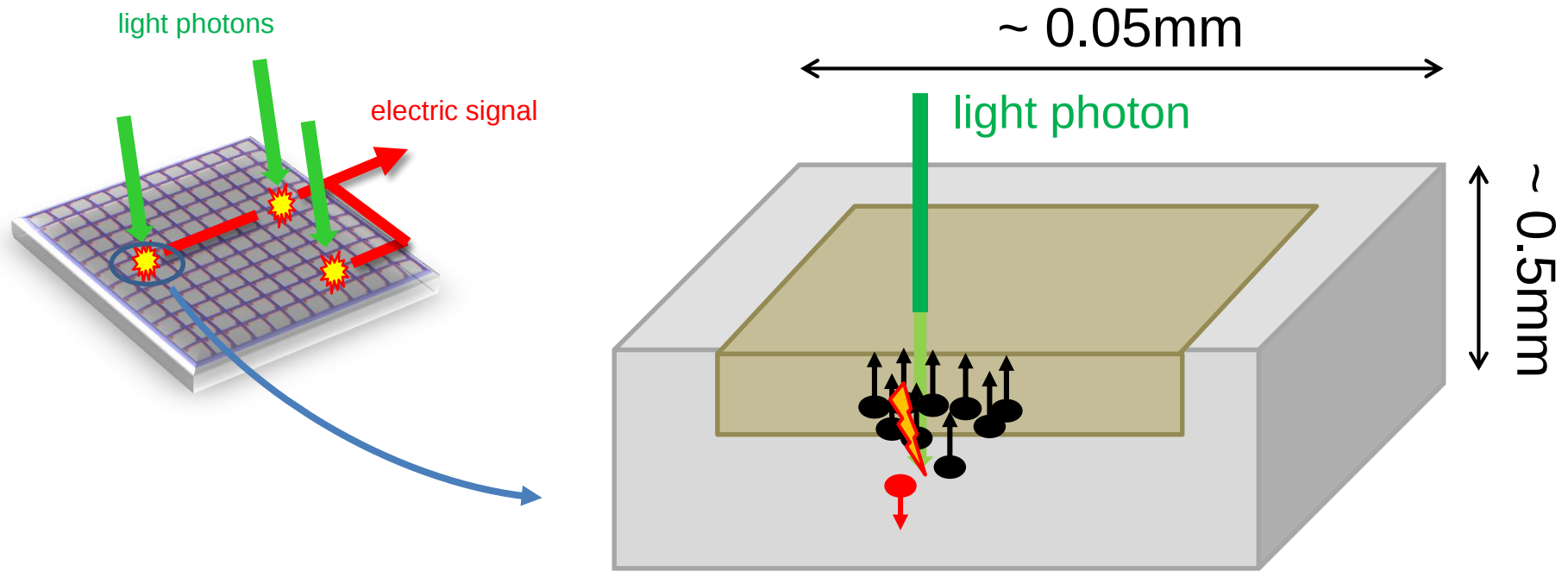
Array of tiny independent cells with common output.
Each cell provides a big electrical signal for each detected photon.
Signals are combine together to a common output.

light photons



The SPAD: SiPM Building block

SPAD = Single-Photon Avalanche Diode



Within the SPAD a high electric field generates an avalanche when the electron passes. The avalanche is locally quenched. **About 1 million electrons are generated!!** Similar to PMT!

SiPMs: when, where?

1964

1970

1980

1995

2005

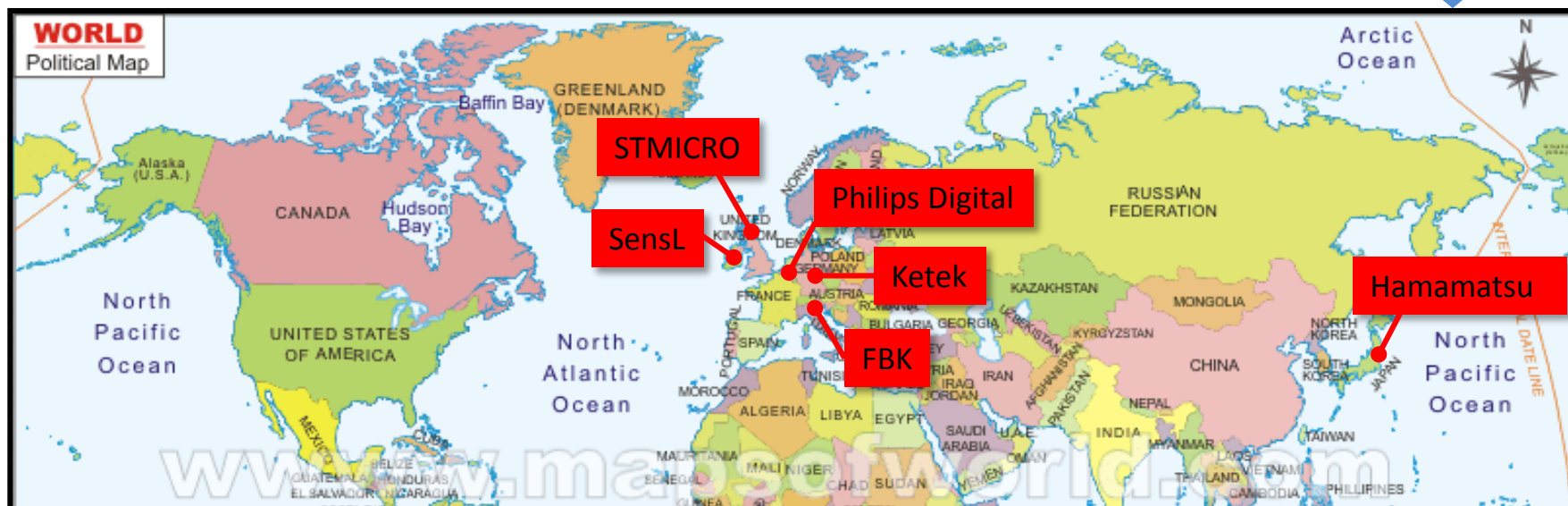
Theory of Geiger mode discharge in pn junctions
R. Haitz, JAP vol.35, n.5 **1964**

Idea of SPAD exploiting G-M theory
Various sources

First SPADs
PoliMI
EG&G, Canada

SiPM concept
Russian researchers

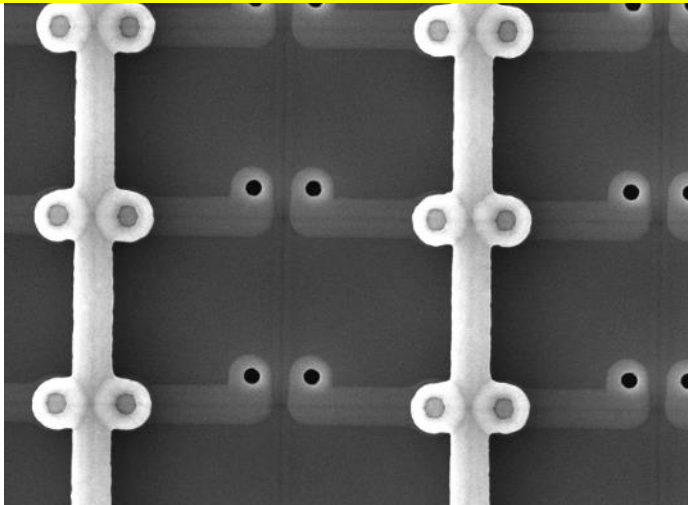
First devices with good performance



Silicon photomultipliers @ FBK

Technology platforms

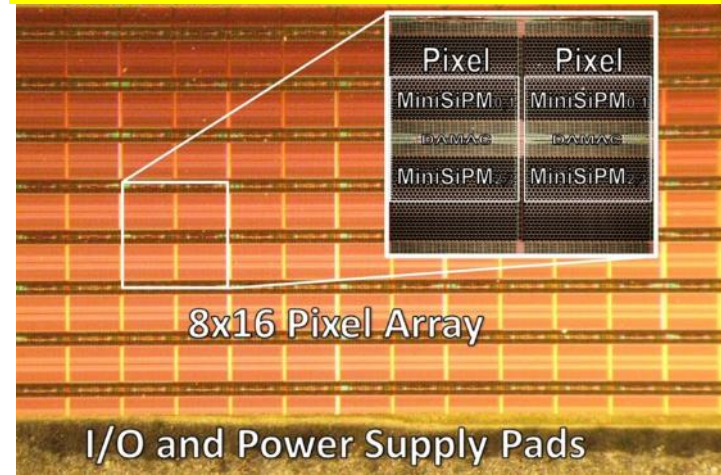
Produced in the FBK silicon foundry



Custom technology:

- high efficiency
- low noise
- high flexibility

Produced in external CMOS foundry



Standard CMOS technology:

- smart architecture
- high-level integration

FBK ha a unique expertise on silicon single-photon detectors

Main funding



<http://www.hybrid-pet-mr.eu/>



<http://www.sublima-pet-mr.eu/>



<http://www.insert-project.eu/>



<http://www.spadnet.eu/>

...and now we work a lot
with large industries

2006

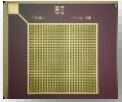
2009

2012

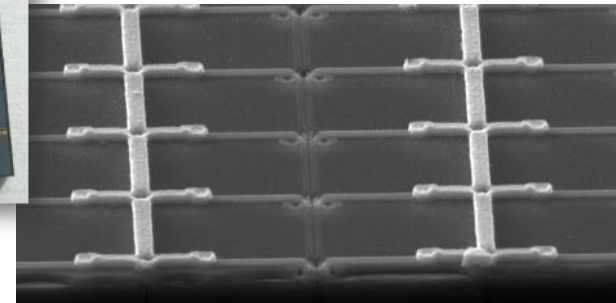
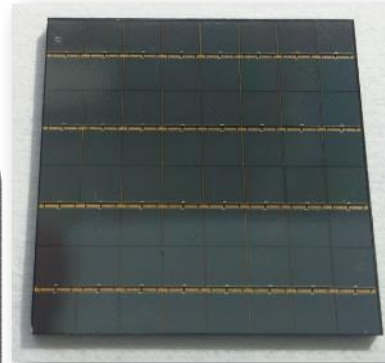
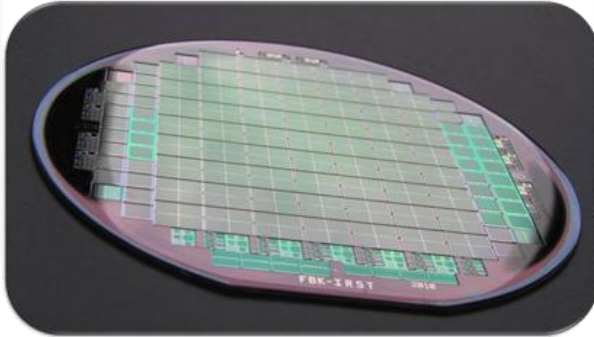
2015

Custom Technology evolution

2006



1x1mm²



Large-area
tile

Original
SiPM

RGB SiPM

RGB-HD SiPM

NUV-HD
SiPM

NUV SiPM

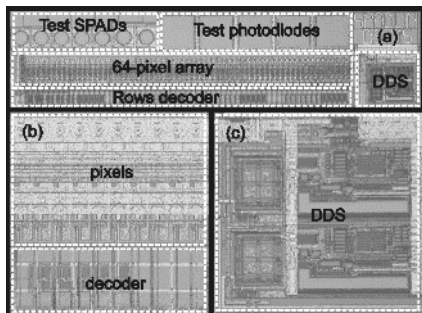
2006

2009

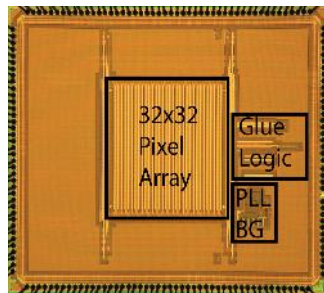
2012

2015

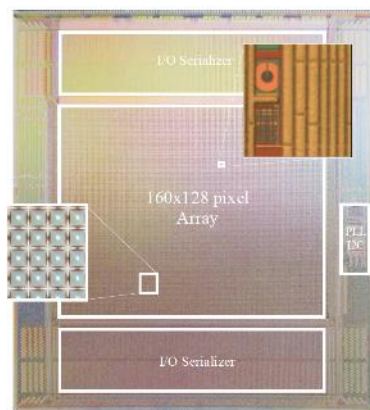
CMOS Technology evolution



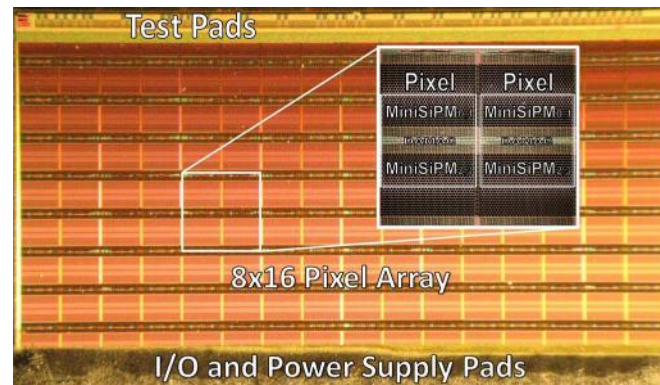
64-pixel linear
0.8um HV



32x32-pixel
130nm CIS



128x160-pixel
130nm CIS



8x16-pixel (92k SPADs)
130nm CIS

SPAD 0.8μm
1 Foundry

SPAD 0.35μm
2 Foundries

SPAD 150nm-130nm
4 Foundries

64-SPAD
linear array

Largest array
CMOS SPAD
(ST 130nm)

Digital SiPM
(ST 130nm)

2006

2009

2012

2015

Future directions in PET

- **New multi-modality systems: PET-MR**
- **Better time-of-flight (→ tens of ps)**
- **Longer scanners, more stopping power**
- **dedicated PET scanners**

PET/MR

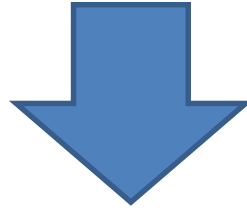


Philips, first, proposed a sequential PET-MR system

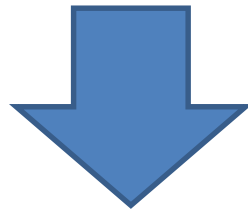
Goal is to have a simultaneous acquisition in a completely integrated system.

Problem: compatibility between the two systems.

- MR involves static and dynamic magnetic fields
- PET occupies space inside the MR



Need of slim and
magnetic field-tolerant
photodetectors



solid-state technology!

HyperImage/Sublima FP7



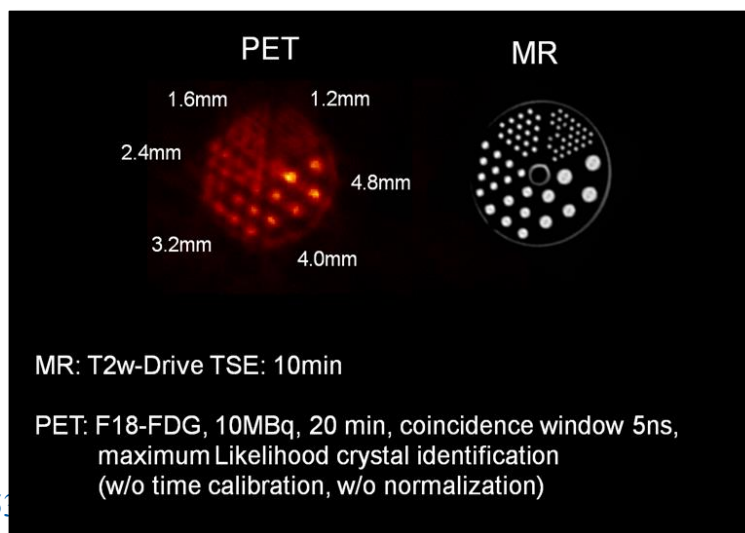
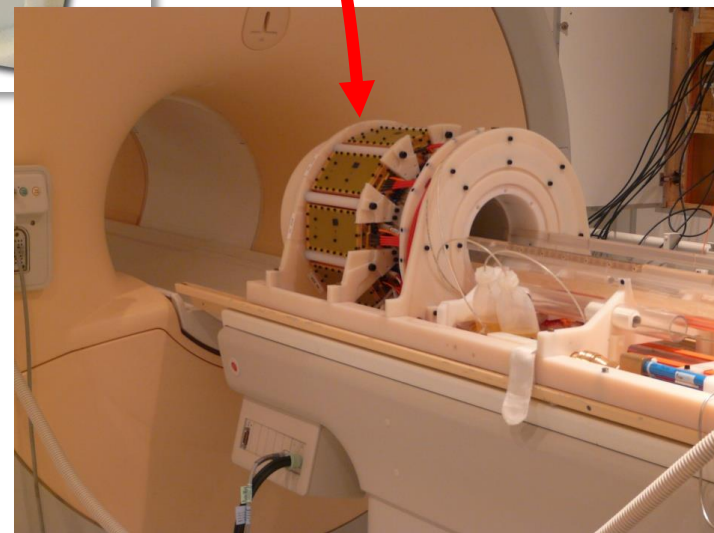
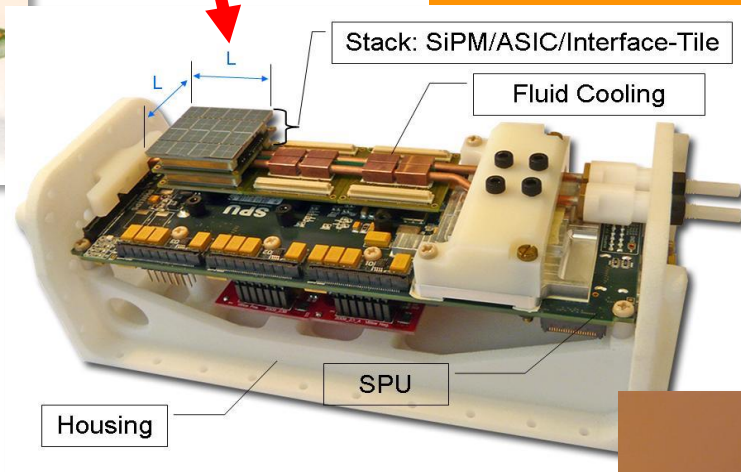
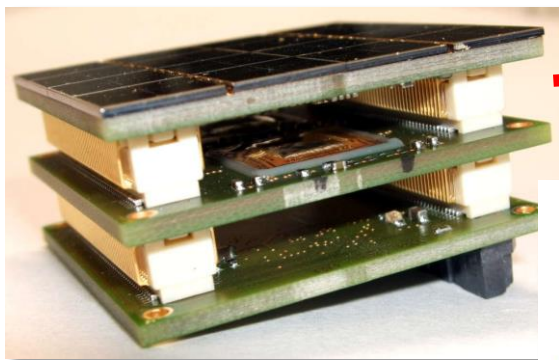
<http://www.hybrid-pet-mr.eu/>

<http://www.sublima-pet-mr.eu/>

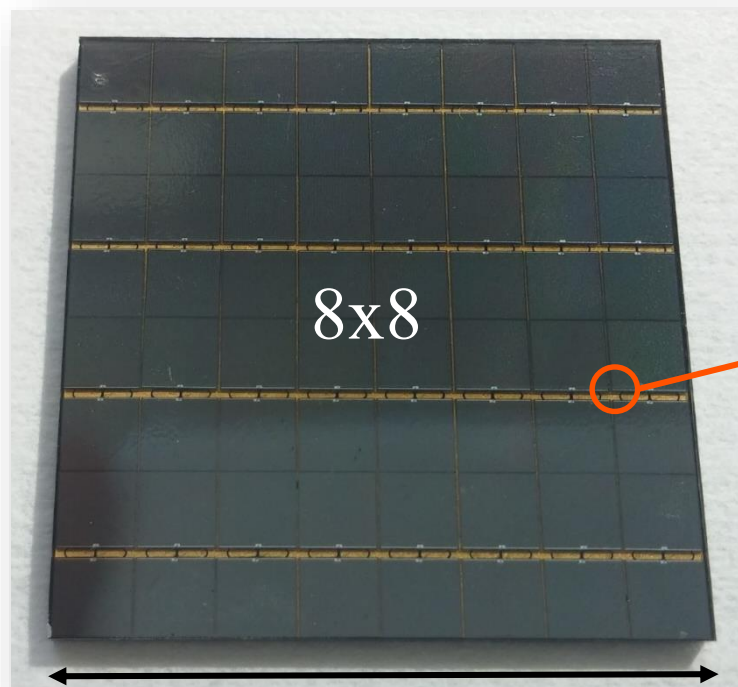
	Partner Name	Representative
1	Philips Technologie GmbH	Torsten Solf
2	Delft University of Technology	Dennis Schaart
3	Fondazione Bruno Kessler	Claudio Piemonte
4	University of Heidelberg	Peter Fischer
5	University of Pennsylvania	Joel Karp
6	University of Ghent	Stefaan Vandenberghe
7	Technolution	Paul van Haaren
8	Ecole Polytechnique Fédérale de Lausanne	Hans Peter Herzig
9	King's College London	Paul Marsden
10	Leiden University Medical Center	Andrew Webb
11	Micro Systems Engineering GmbH	Joerg Gossler
12	Philips Electronics Nederland B.V	Rob Smeets
13	Universitäts Klinikum Aachen	Fabian Kießling

One important achievement

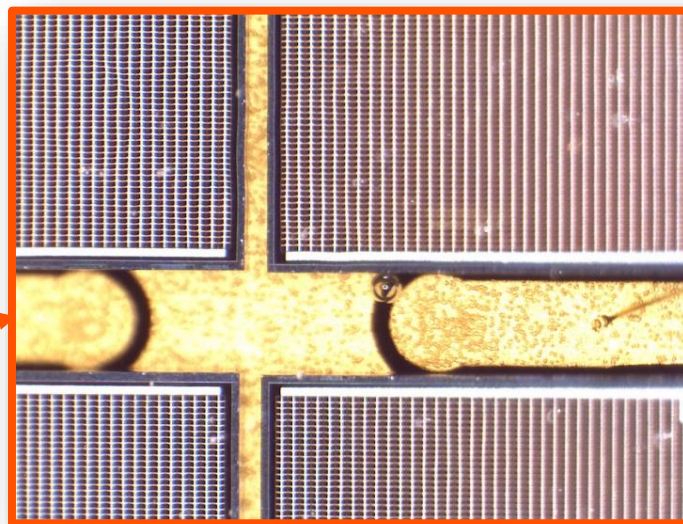
First pre-clinical system working in a MRI.



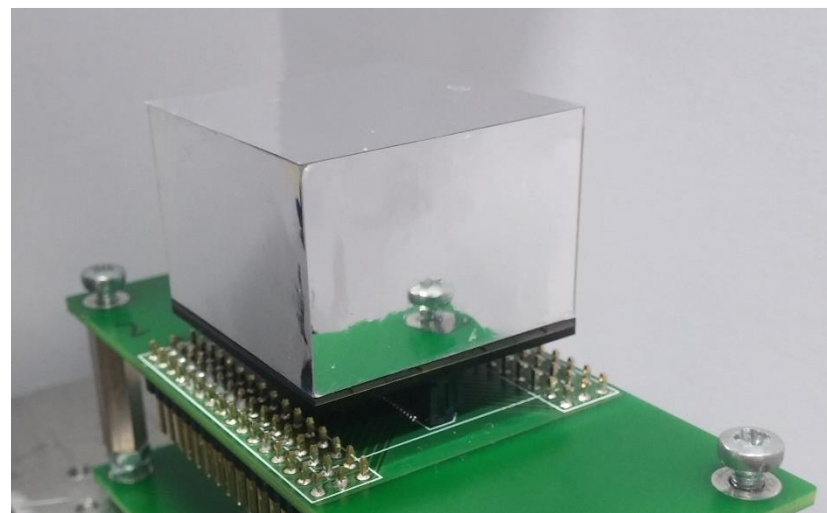
Some pictures of the SiPM tile



3.23 cm



~ 200mm active-to-active distance



First commercial SiPM-based PET-MR by GE



PET Detector - a highly sensitive silicon photomultiplier tube (SiPM) is complimented with a 25mm deep LBS scintillator/crystal for photon detection efficiency. This includes the specifications listed below:

- **< 400ps** timing resolution for fast TOF performance
- 25cm axial FOV for sensitivity and coverage

The dream: 10ps Time-of-Flight

Why? The origin of each coincidence is exactly located. No need of complicated reconstruction.

The best system available today features 350-380ps.

How can we reach 10ps? **Hot topic!!**



Need to work on:

- photodetector
- scintillator
- electronics.



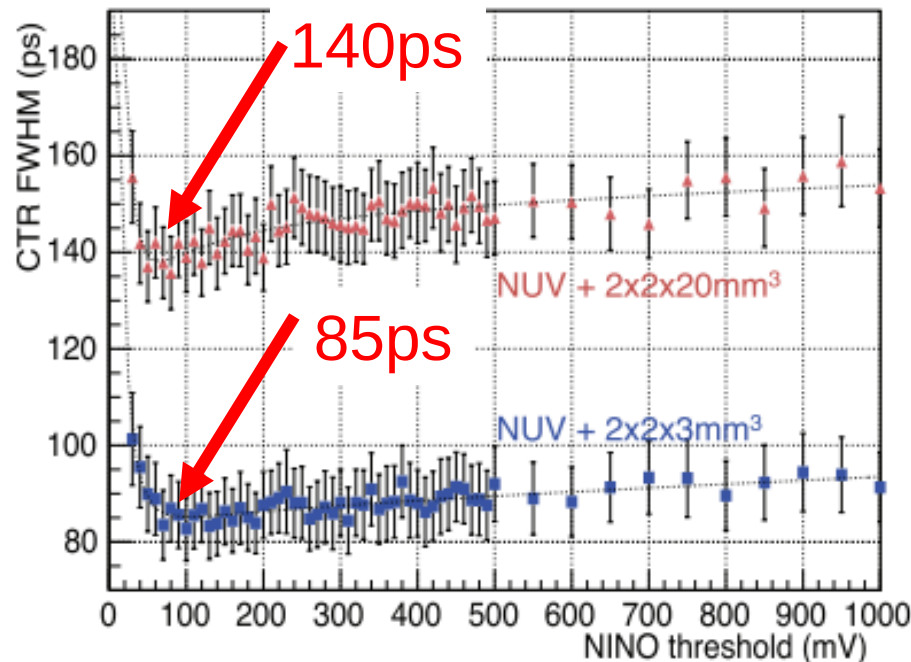
<https://fast-cost.web.cern.ch/fast-cost/>

Sub-100 ps coincidence time resolution for positron emission tomography with LSO:Ce codoped with Ca

Mythra Varun Nemallapudi¹, Stefan Gundacker¹,
Paul Lecoq¹, Etienne Auffray¹, Alessandro Ferri²,
Alberto Gola² and Claudio Piemonte²

¹ CERN, Geneva 23, CH-1211, Switzerland

² Fondazione Bruno Kessler, via Sommarive 18, Trento, Italy



thick scintillator
(for PET)

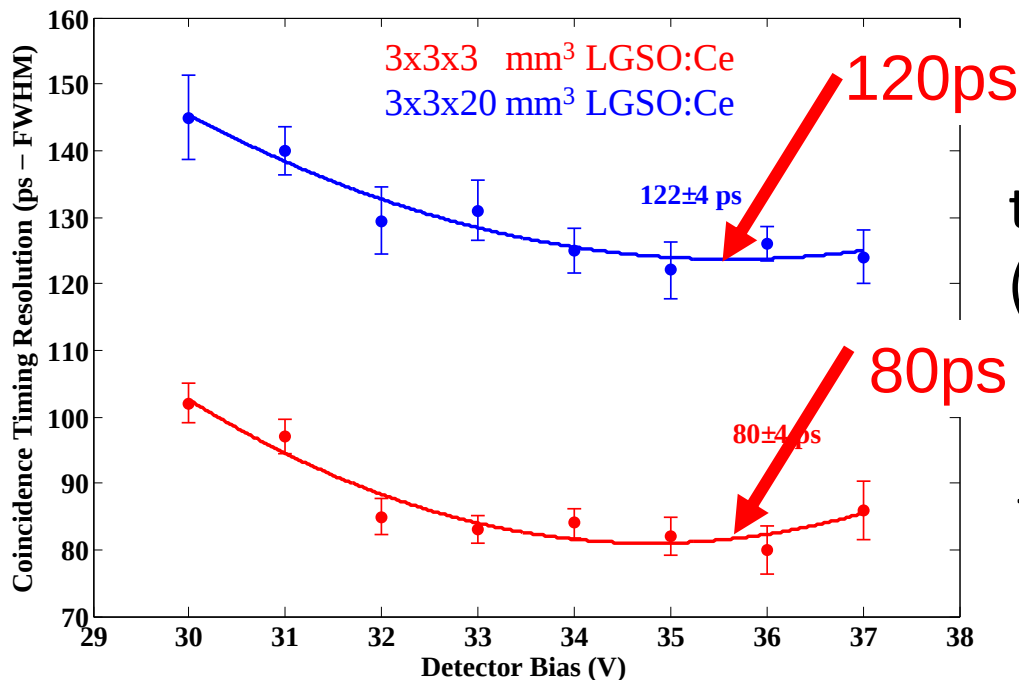
thin scintillator
(for benchmarking)

SiPM optimization @ FBK

Timing Performance of Fast LGSO:Ce Scintillators with FBK NUV-HD Silicon Photomultipliers

J. W. Cates, *Member, IEEE* and C. S. Levin, *Member, IEEE*

Stanford



thick scintillator
(for PET)

thin scintillator
(for benchmarking)

Conclusions for nuclear medicine

Transition from vacuum tubes to solid-state single-photon sensors is revolutionizing the nuclear medicine field.



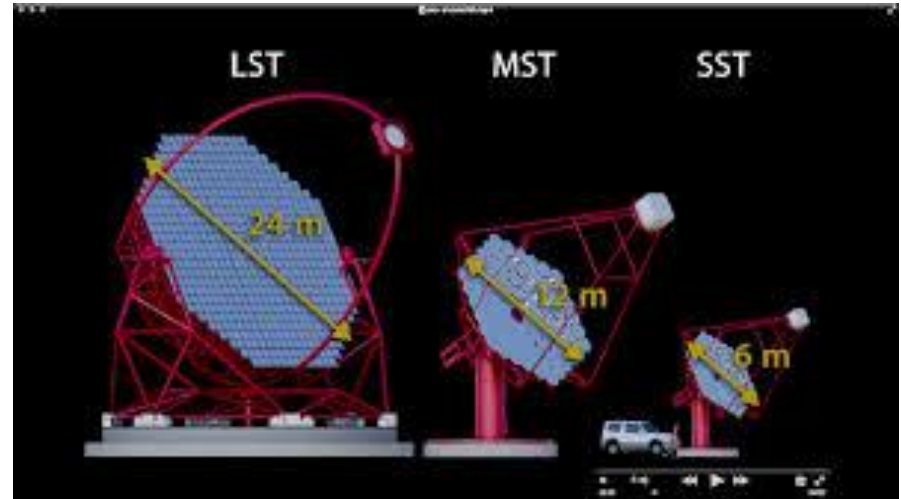
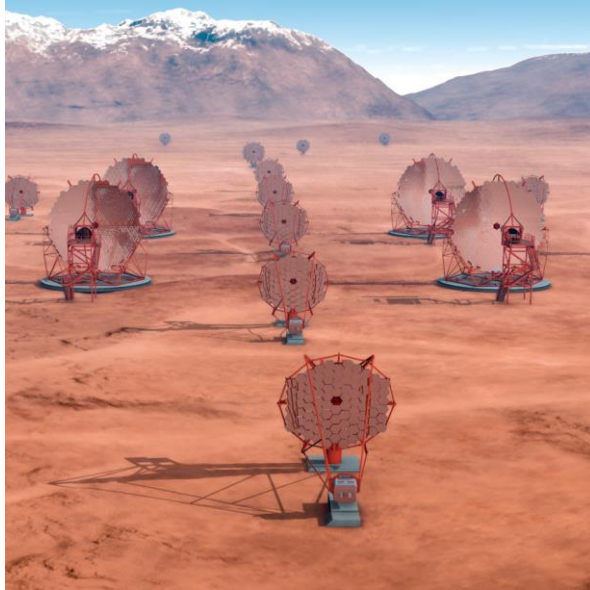
New imaging modalities and better performance.



Better diagnosis!

Another interesting application at a glance

Cherenkov Telescope Array



- Understanding the origin of cosmic rays and their role in the Universe
- Understanding the nature and variety of particle acceleration around black holes
- Searching for the ultimate nature of matter and physics beyond the Standard Model

International consortium of over 1000 people.

Cherenkov Telescope Array

TELL-TALE TRAILS

An array of sensitive telescopes can detect high-energy γ -rays even though Earth's atmosphere prevents them from reaching the ground.

γ -rays stream from a
supernova remnant

The γ -rays create an air
shower 20 kilometres up
in Earth's atmosphere

The air shower creates a
cone of Cherenkov light
250 metres across

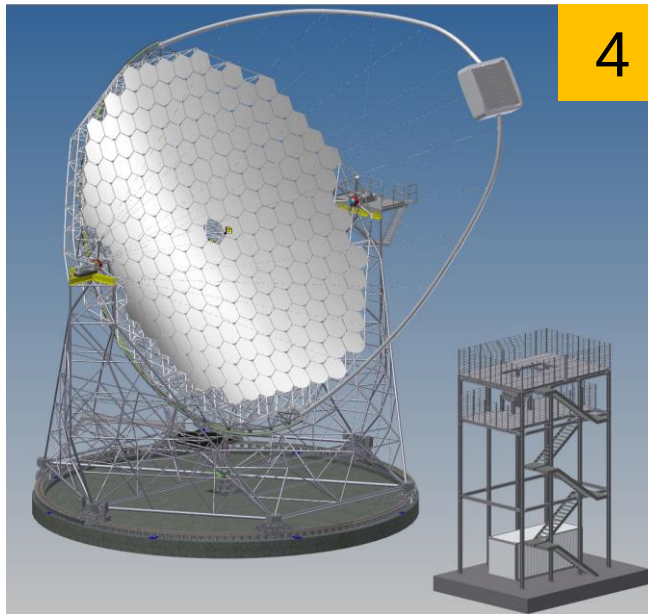
An array of about 100
telescopes spans several
square kilometres

Telescopes within the cone of light triangulate
the location and incidence of the γ -rays

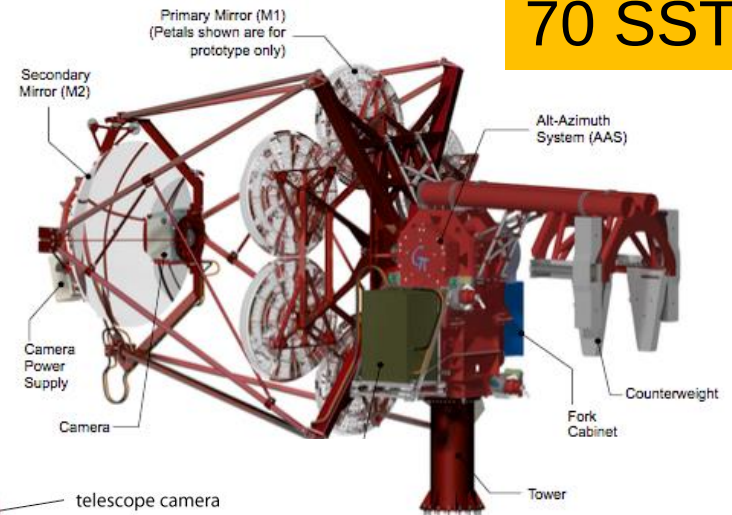
<https://portal.cta-observatory.org/Pages/Home.aspx>



Cherenkov Telescope Array



4 LST



70 SST

monitoring CCD cameras
calibration box

optical support structure

head with azimuth and
elevation drive assemblies

counter weight structure

positioner housing
all electrical cabinets

telescope camera

camera support structure

40 MST

mirrors with active mirror control

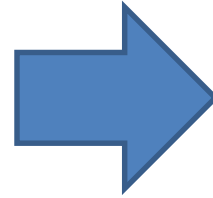
foundations

camera lock

Cherenkov Telescope Array

Main photosensor requirements:

- single photon sensitivity
- fast (background rejection)
- high efficiency in ultra-violet



PMT vs SiPM

Possible advantages of SiPMs:

- mechanical robust
- not damaged by light (moon, sun)
- performance reproducibility
- low operation voltage
- lower cost



SiPMs for CTA @ FBK

In collaboration with INFN and INAF we are optimizing the SiPM performance to provide a viable solution.

Esempio di moduli sviluppati a INFN Padova

