Nuovi sensori di luce allo stato solido applicati alla medicina nucleare

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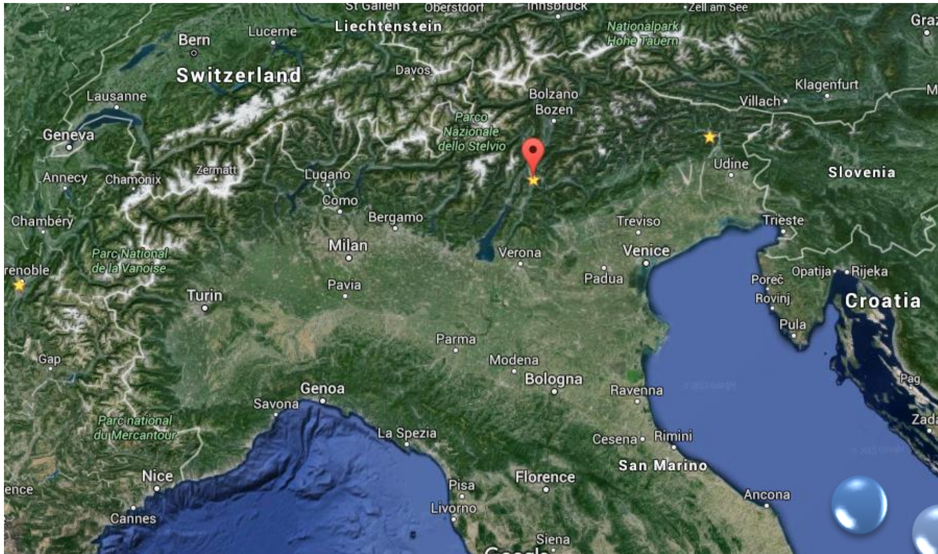
Indice

- 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

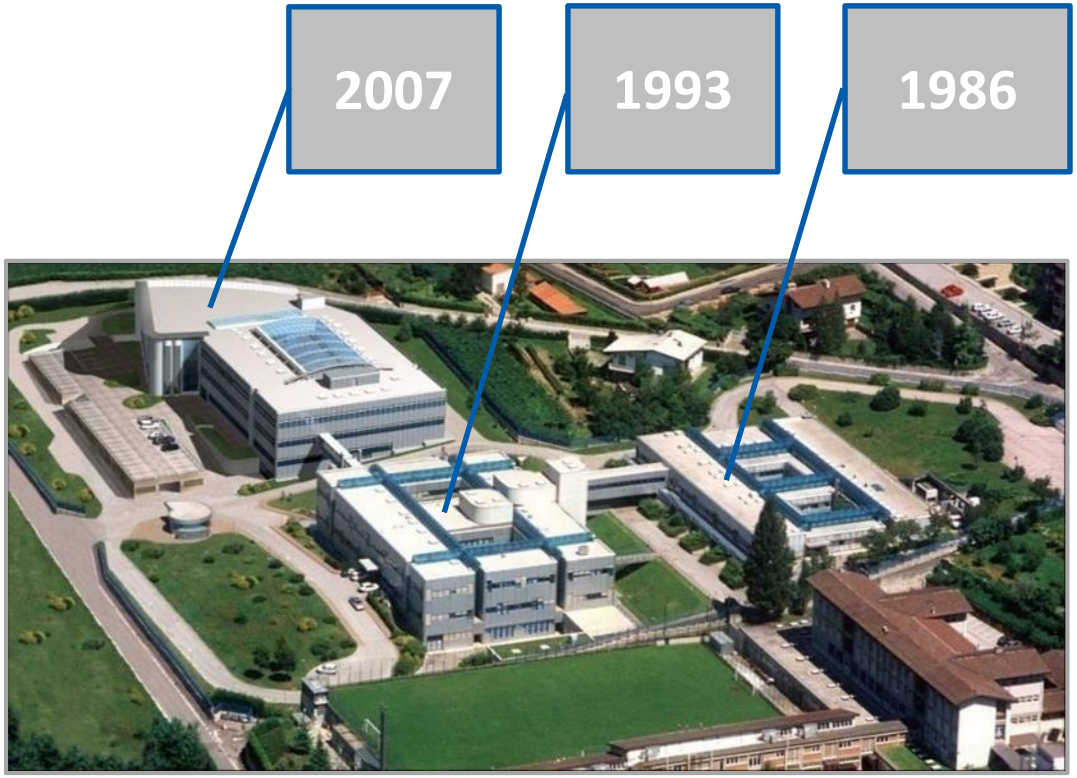
FBK at a glance

About 400 researchers.

Humanities Hub

ECT*

Scientific and Technological Hub



FBK Organization

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

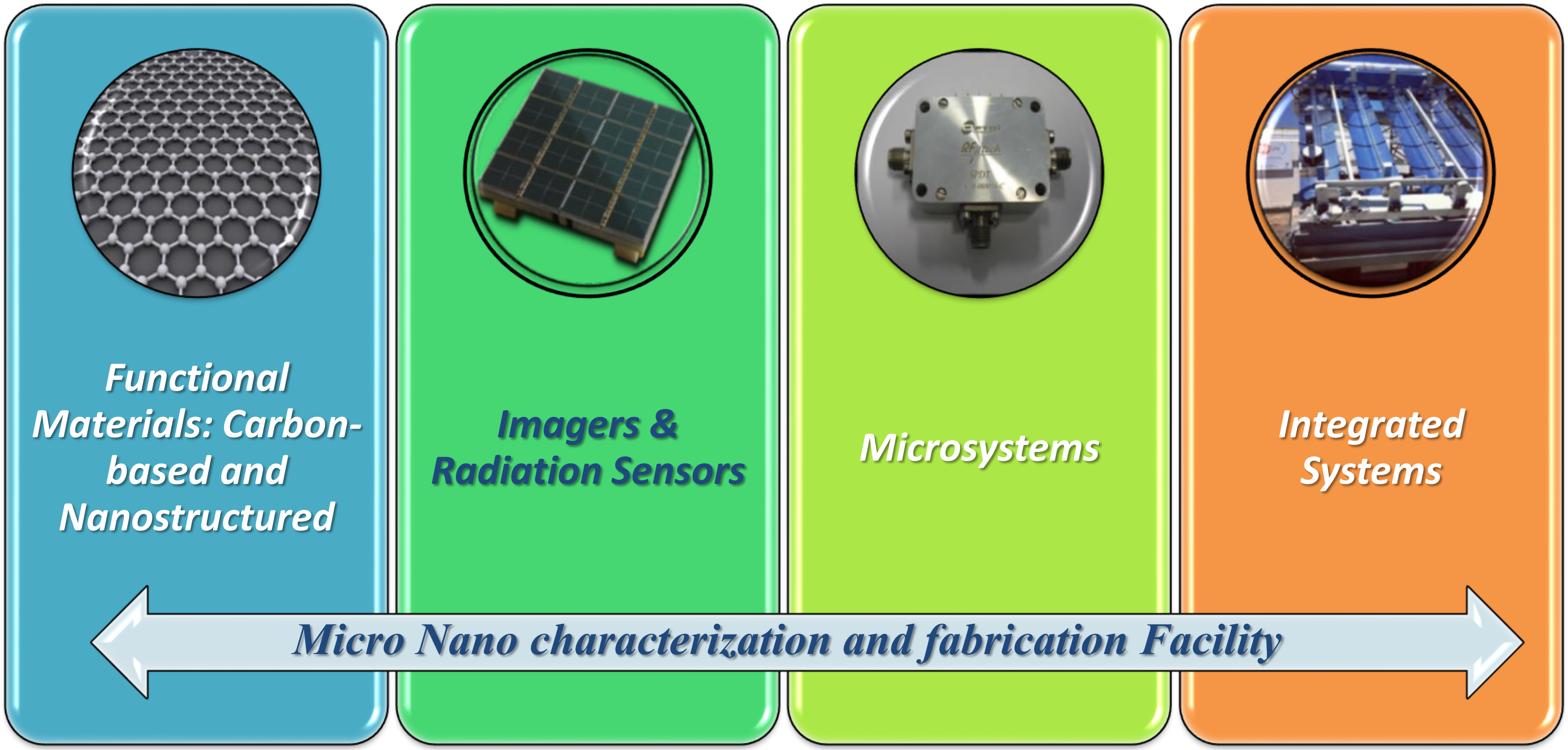
ISIG
Centre for Italian-German Historical Studies

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



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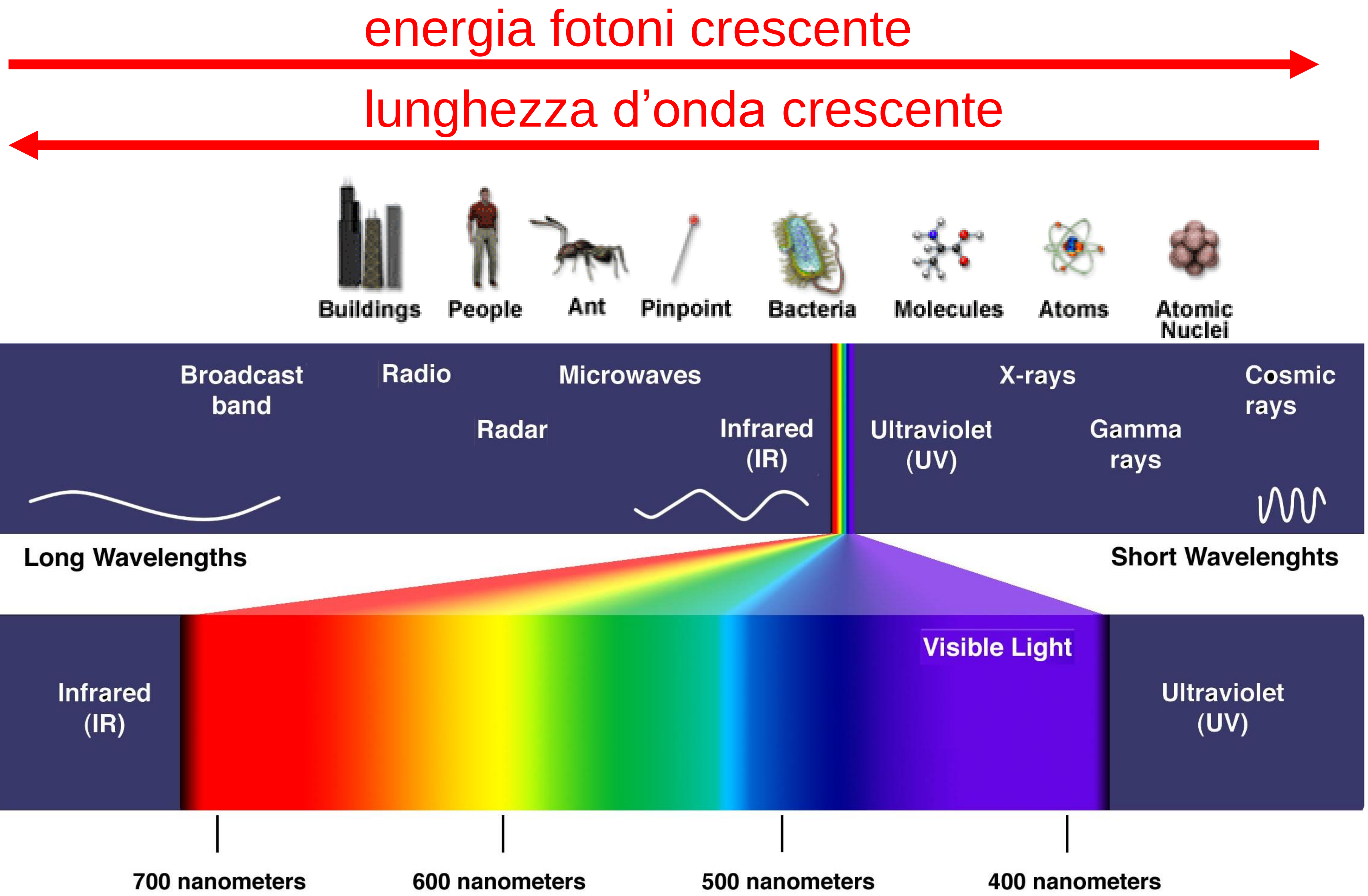
Radiation Detection and Imaging

(RDI)

Research line

2015

Lo spettro elettromagnetico

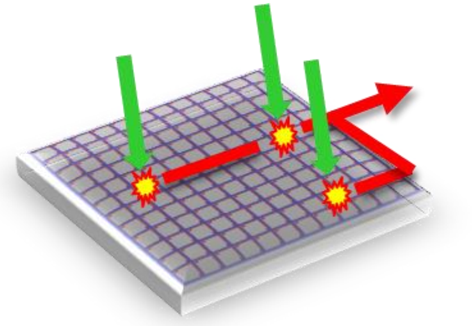


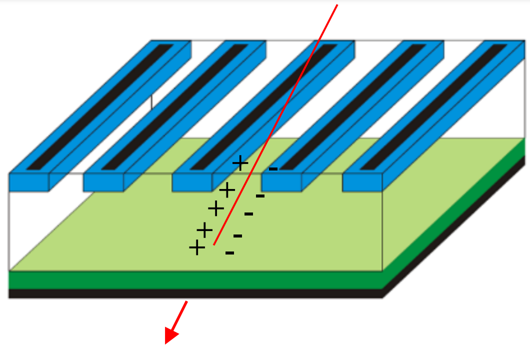
Research topics

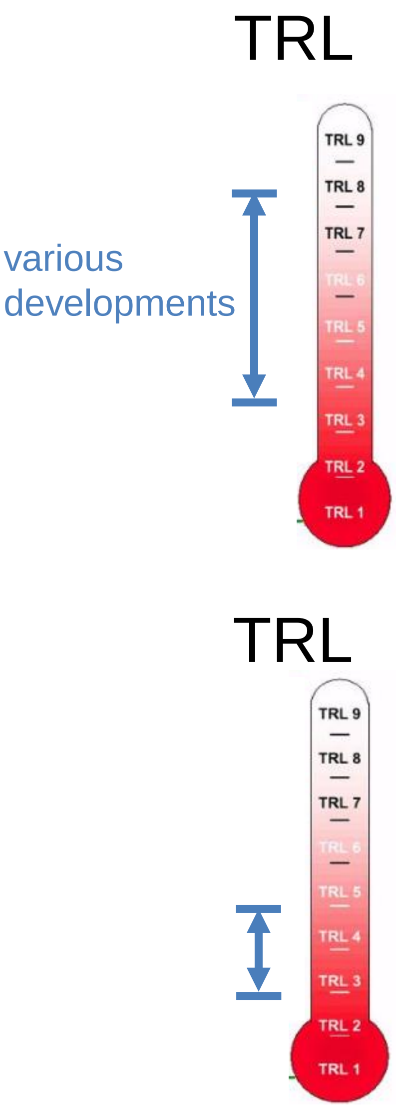
Two main platforms (silicon):

Single-photon light sensors

High-energy radiation detectors







R&D initiatives on:

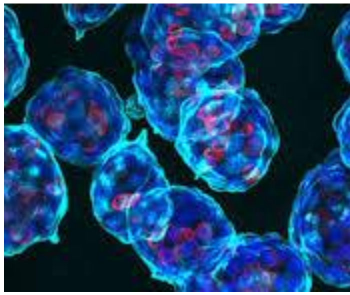
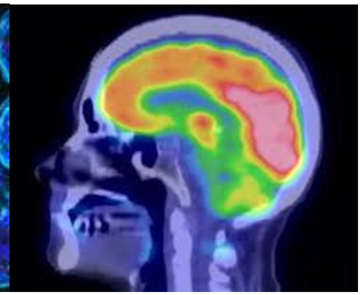
TeraHertz detectors

Low-power imaging

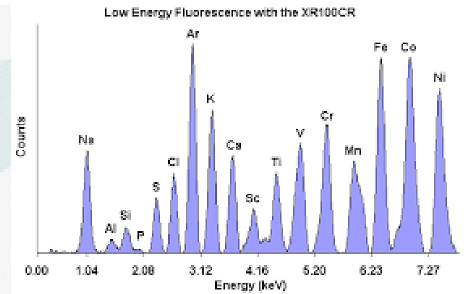
Graphene-based detector

Main Applications

BioMedical instrumentation

Industrial instrumentation

Space and astrophysics


High energy physics

Partnering

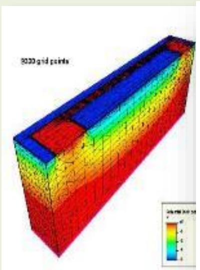
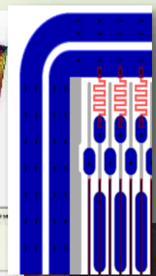
- **R&D and technology transfer with private companies**
  At present we have 3 long-term contracts with multinational companies following this scheme.

- **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

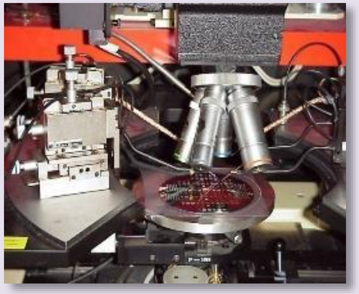
In-house production

State-of-the art CMOS Technologies

Analog and Digital IC Design

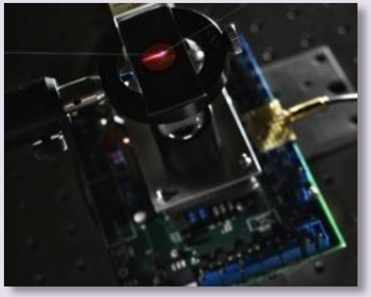
130nm-350nm external Fab

Parametric Testing



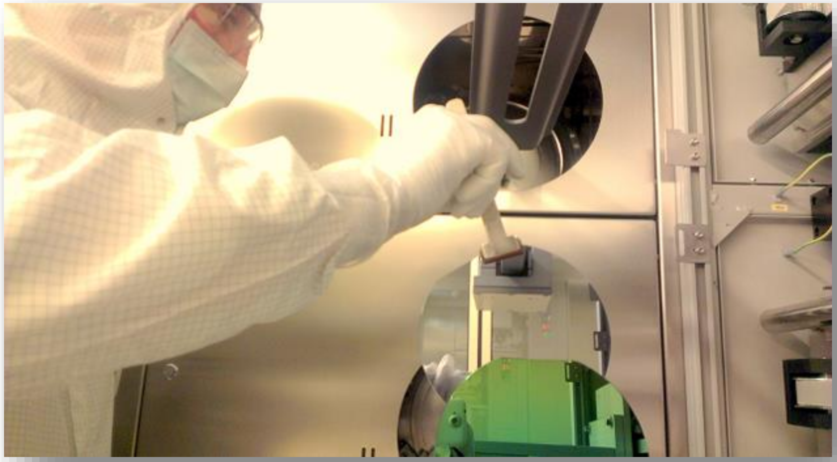
Functional Testing

Prototyping



Infrastructures

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



Infrastructures

Testing Area: on-wafer parametric testing

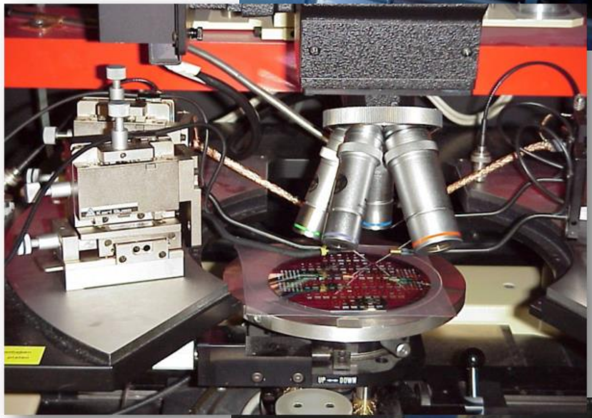
Integration Area:
device packaging and microsystems assembly

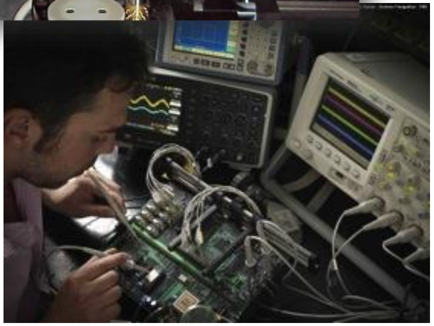
Functional testing area:

- microchip electrical characterization
- PCB and prototype assembly

- electro-optical characterization
- tests with high-energy radiation
- THz Test Bench

- image sensors testing
- TOF tests

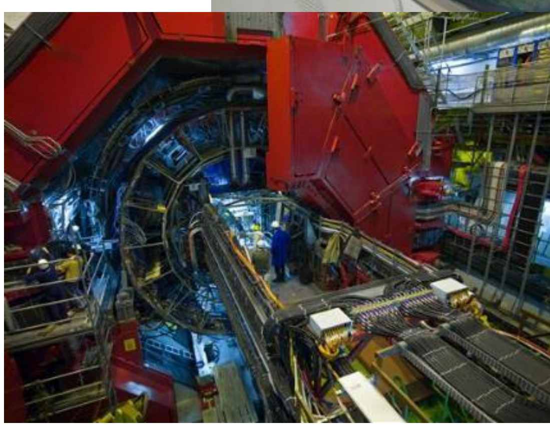




Some examples of radiation detectors @ FBK

AMS experiment (@ISS)

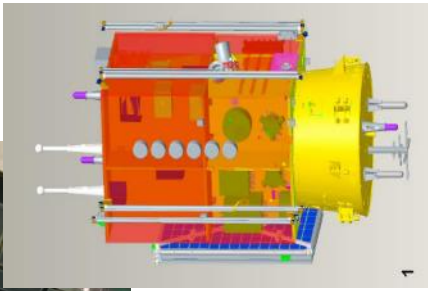
700 detectors



600 detectors

ALICE experiment (@LHC)

Limadou experiment (@CSES)



Custom productions for industry

Single-photon light sensors.

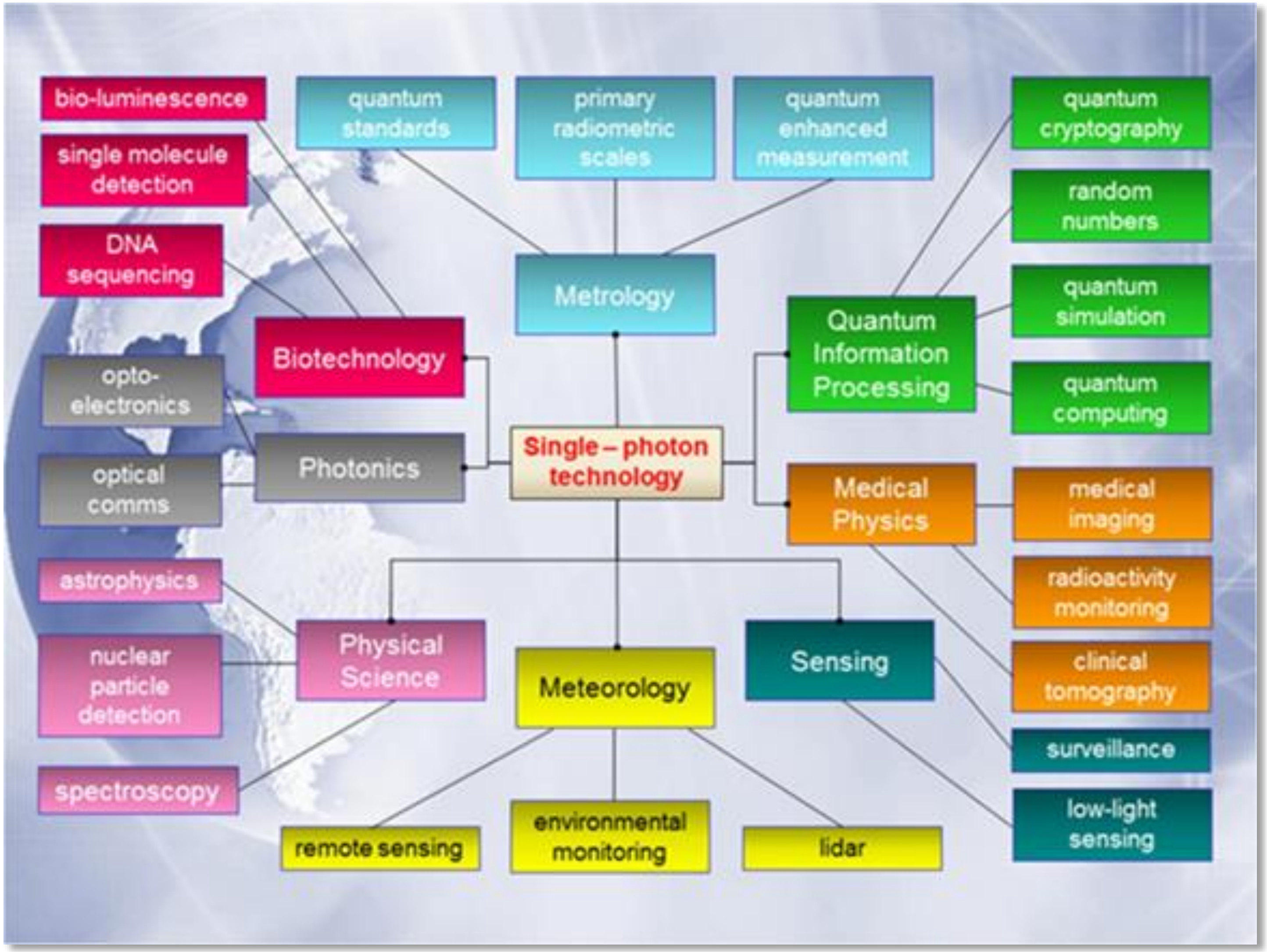
Application to nuclear medicine.

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



Christopher Chunnilal, et al. Opt. Eng. 53(8), 081910 (July 10, 2014). doi:10.1117/1.OE.53.8.081910

Medical Imaging techniques for cancer

Type of information

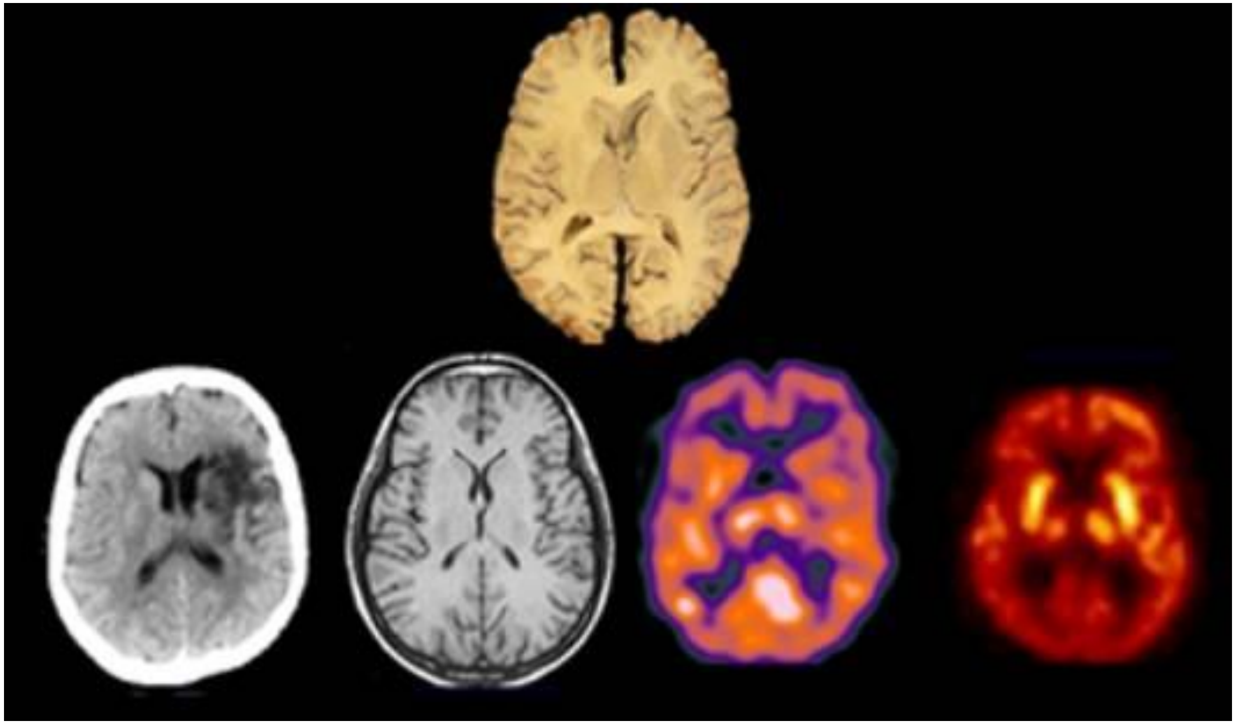
Anatomic

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

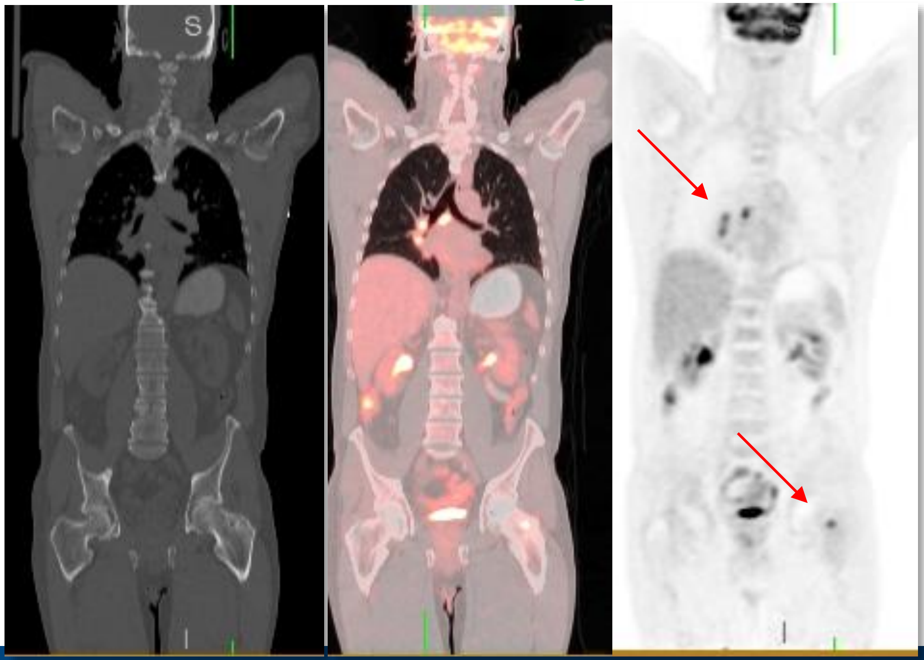
Radionuclide imaging

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

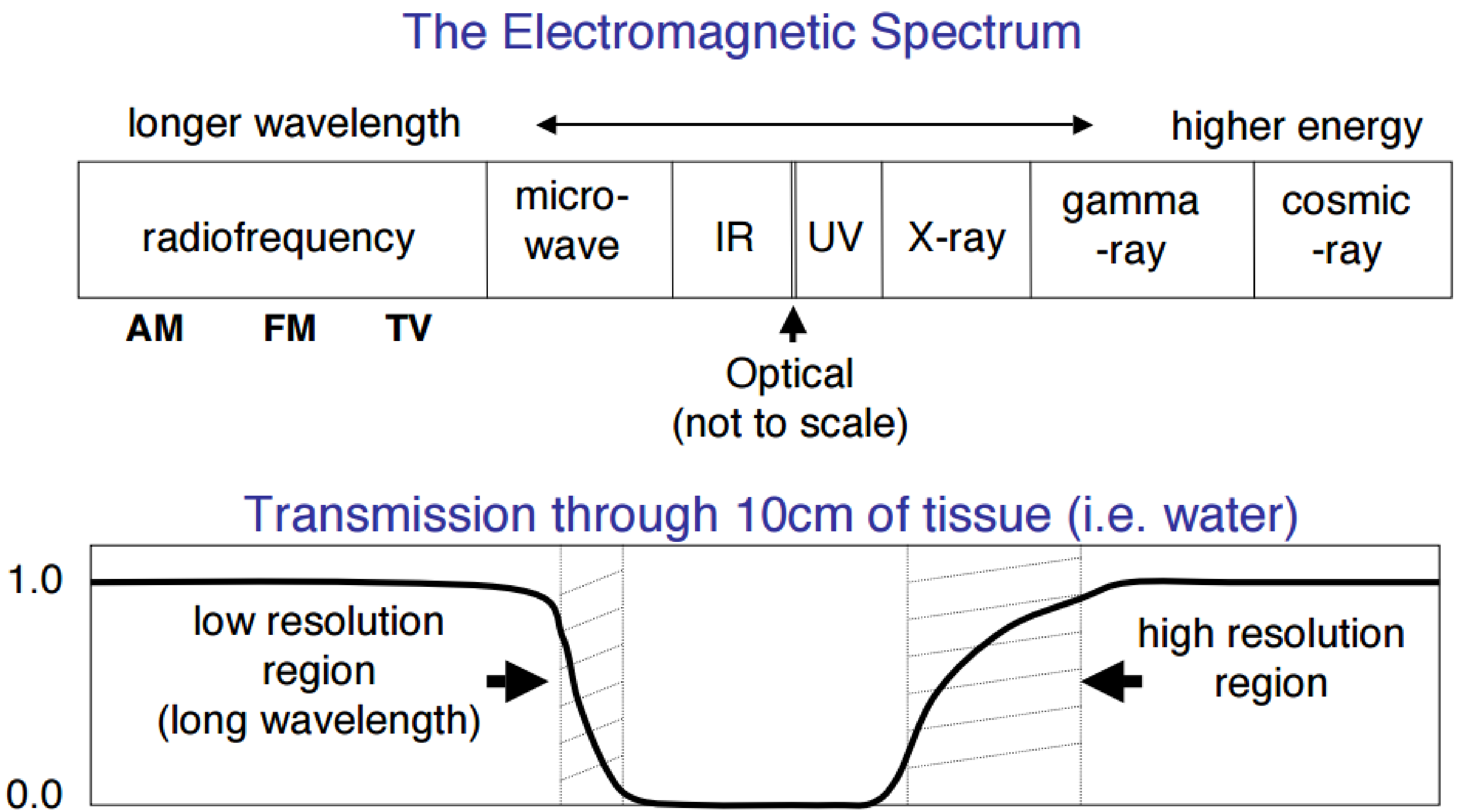
- administered to the patient, they localize to specific organs or cellular receptors;

- 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



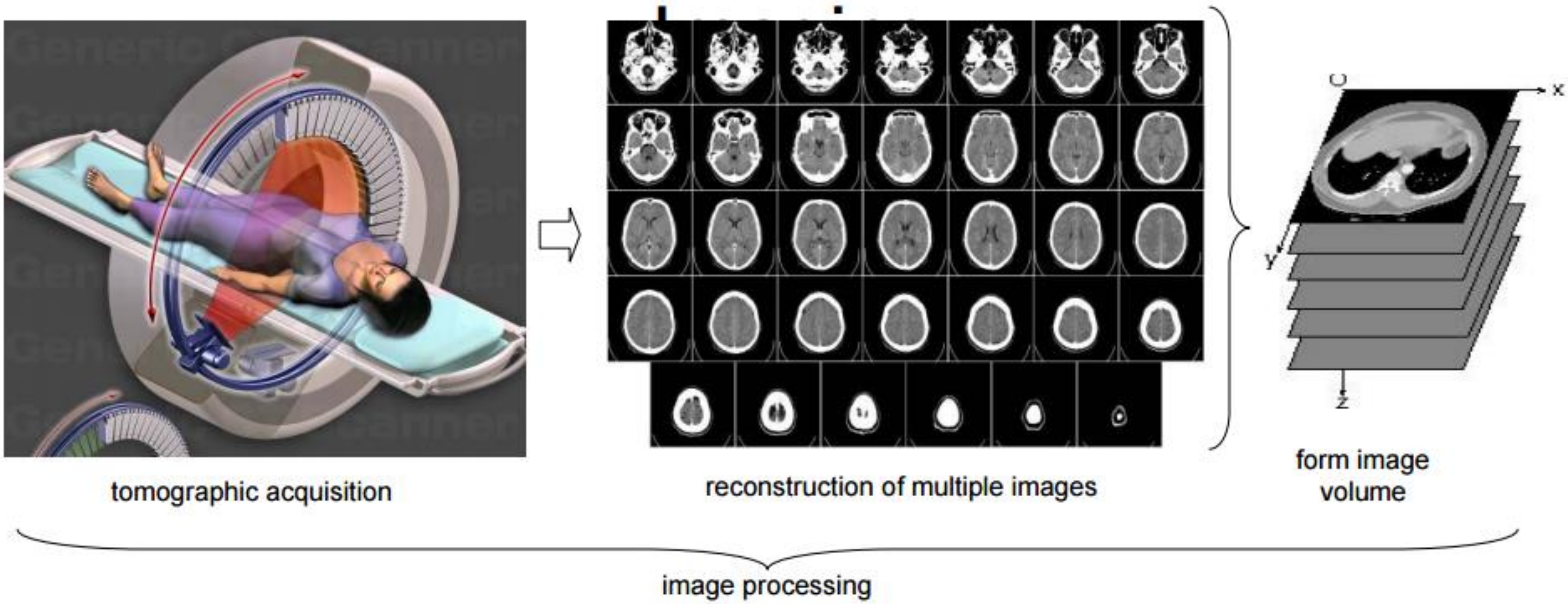
Why high-energy radiation?



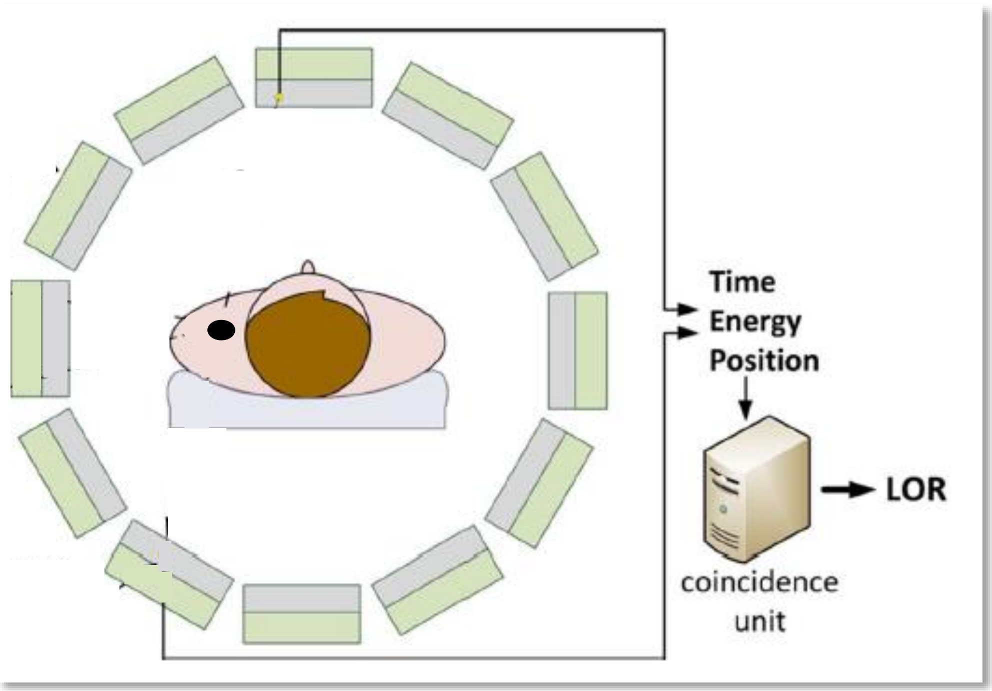
Tomography

"Imaging by sectioning using a penetrating wave"

Example of Computed tomography



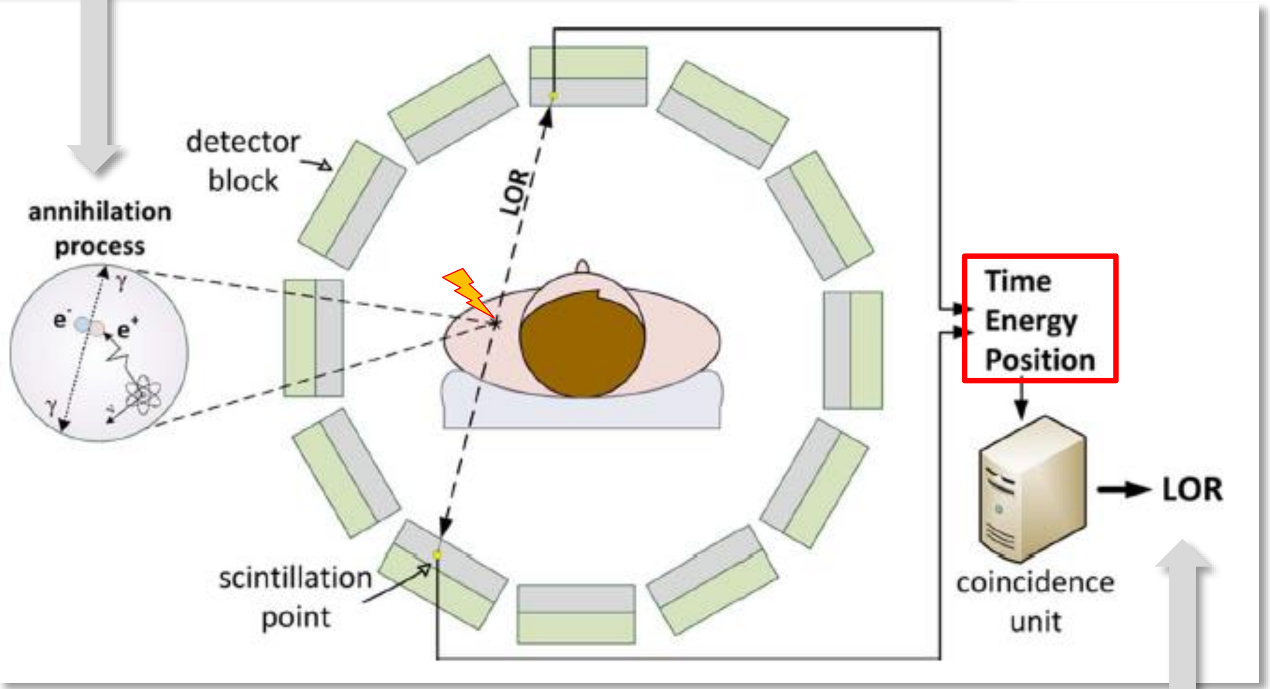
Positron Emission Tomography



Positron Emission Tomography

1

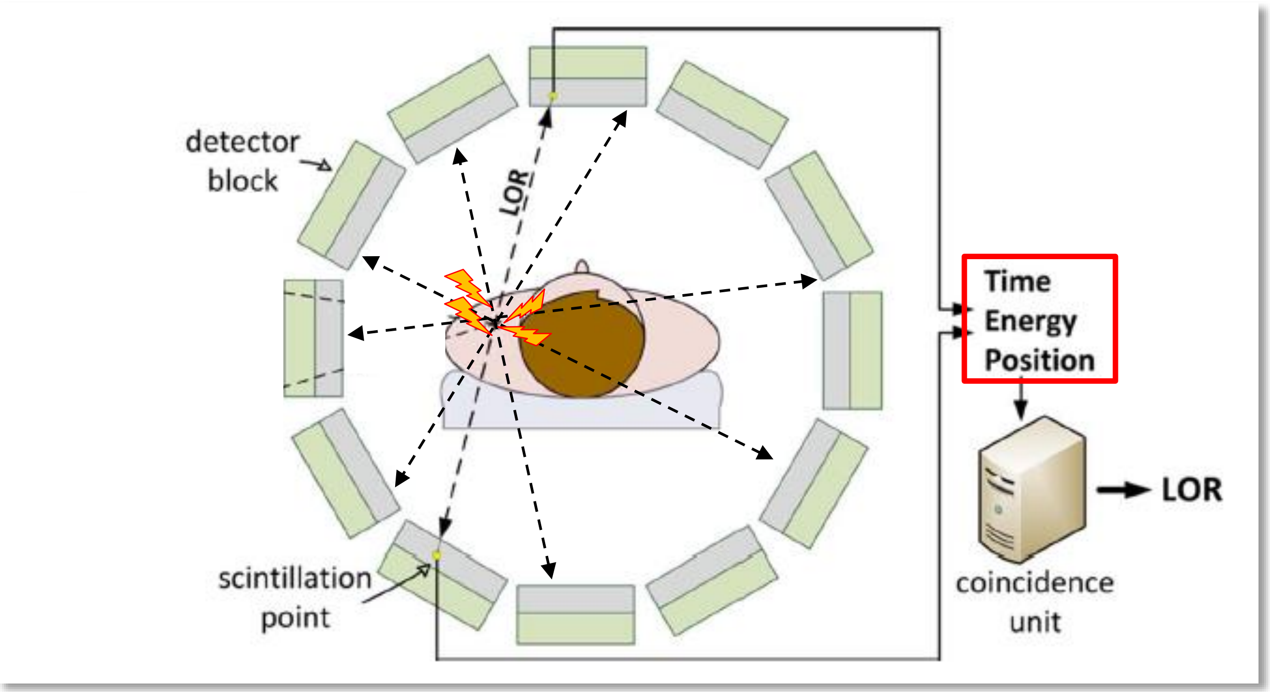
Positrons emitted by radionuclide annihilate with electrons of the tissue generating two gamma rays in coincidence.



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.

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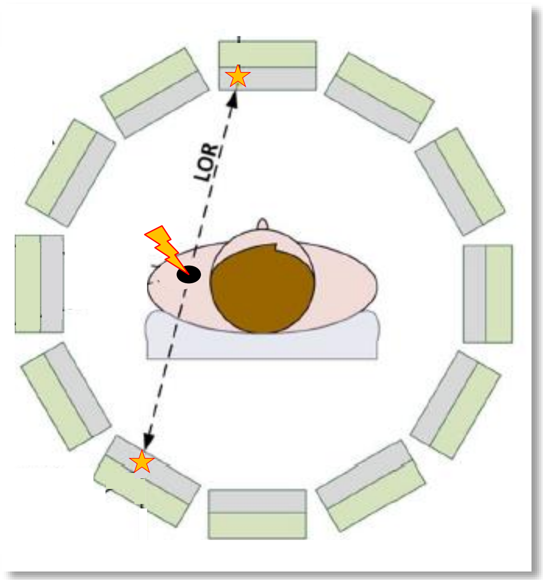
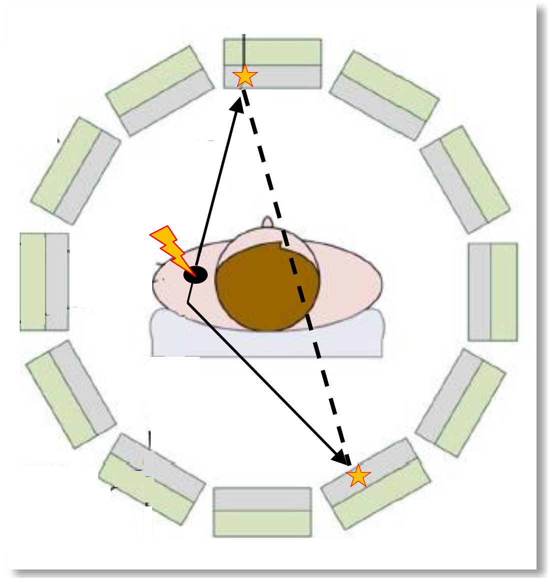
PET: …good events are only a few…

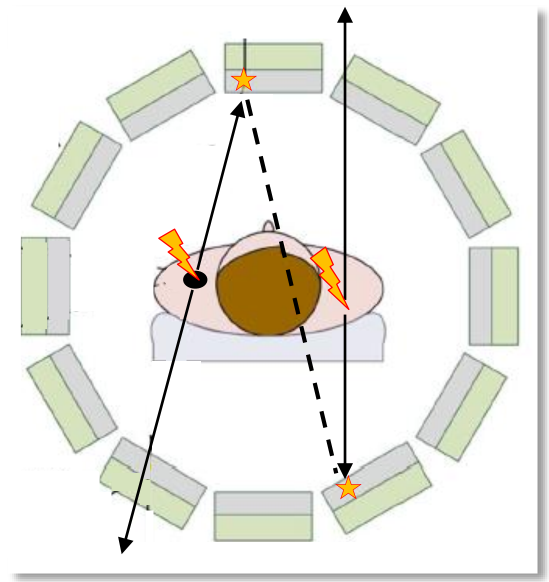
True coincidence

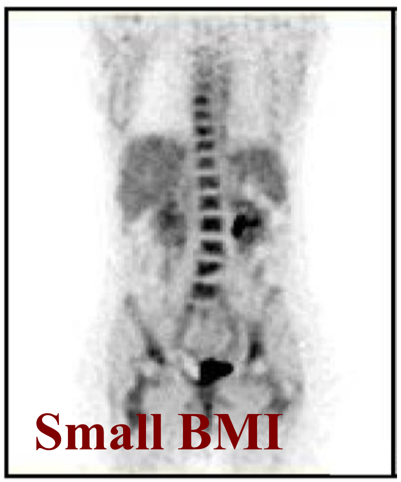


Scattered coincidence



Random coincidence





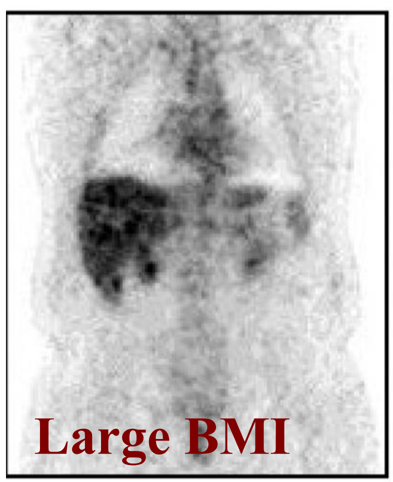
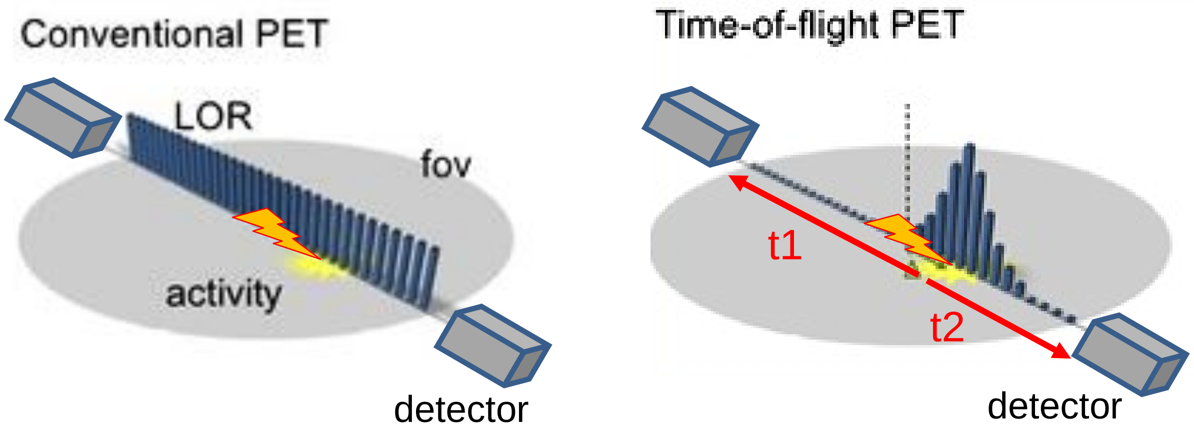


image deterioration

Time-of-Flight PET

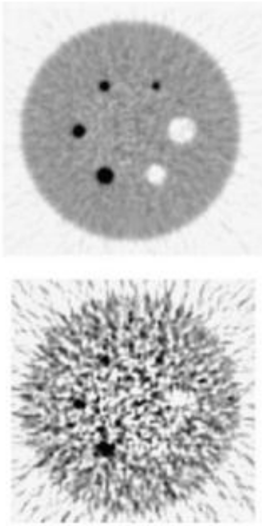


Detectors must provide a precise estimation of the photon arrival time to allow position estimation along LOI.

non TOF

High statistics

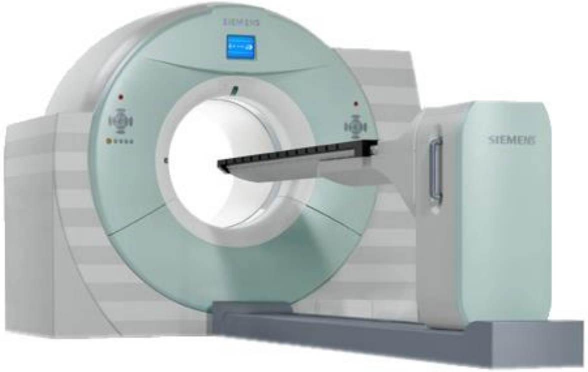
Low statistics



TOF-PET state-of-the-art

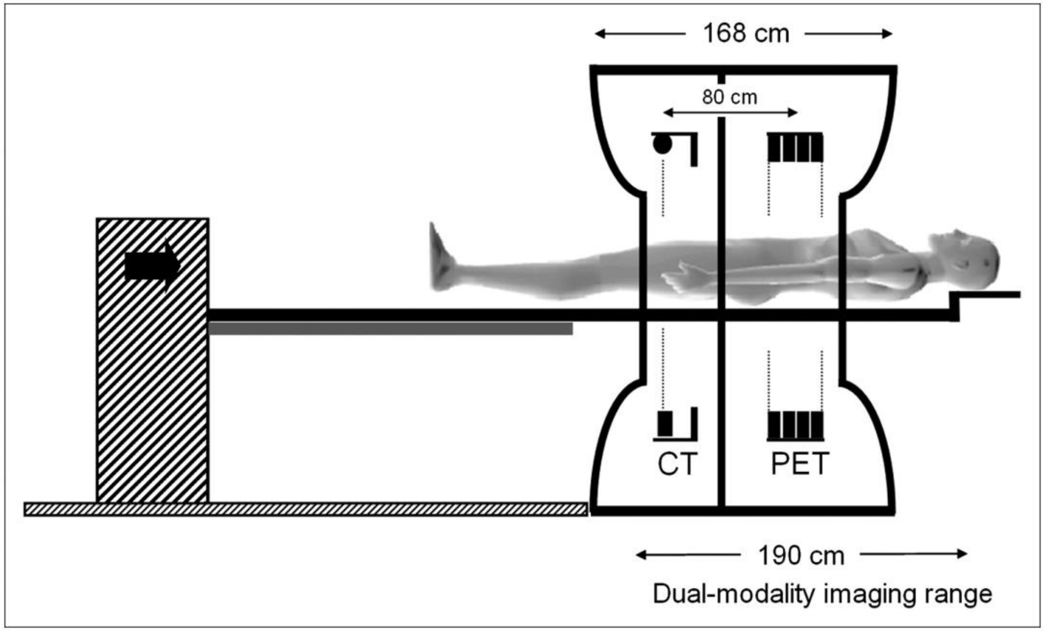
2006
Gemini TF, time resolution 495ps FWHM
(Philips)

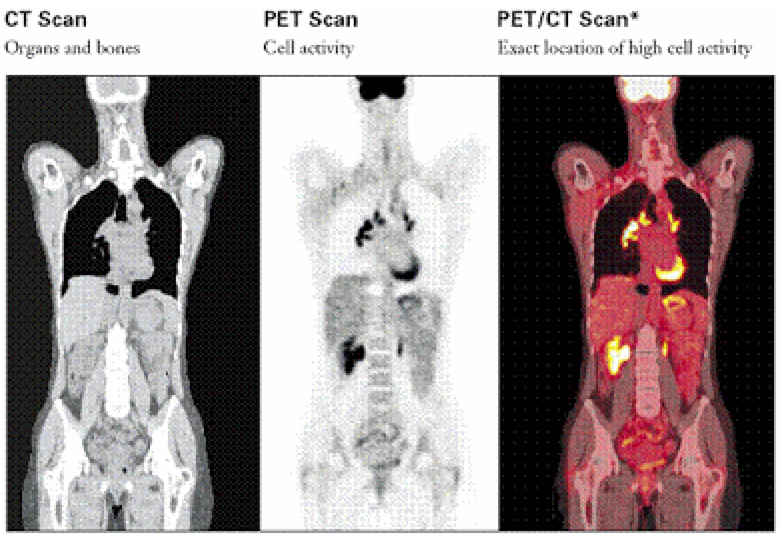
2009
Discovery 690, time resolution 600ps FWHM
(GE)



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.

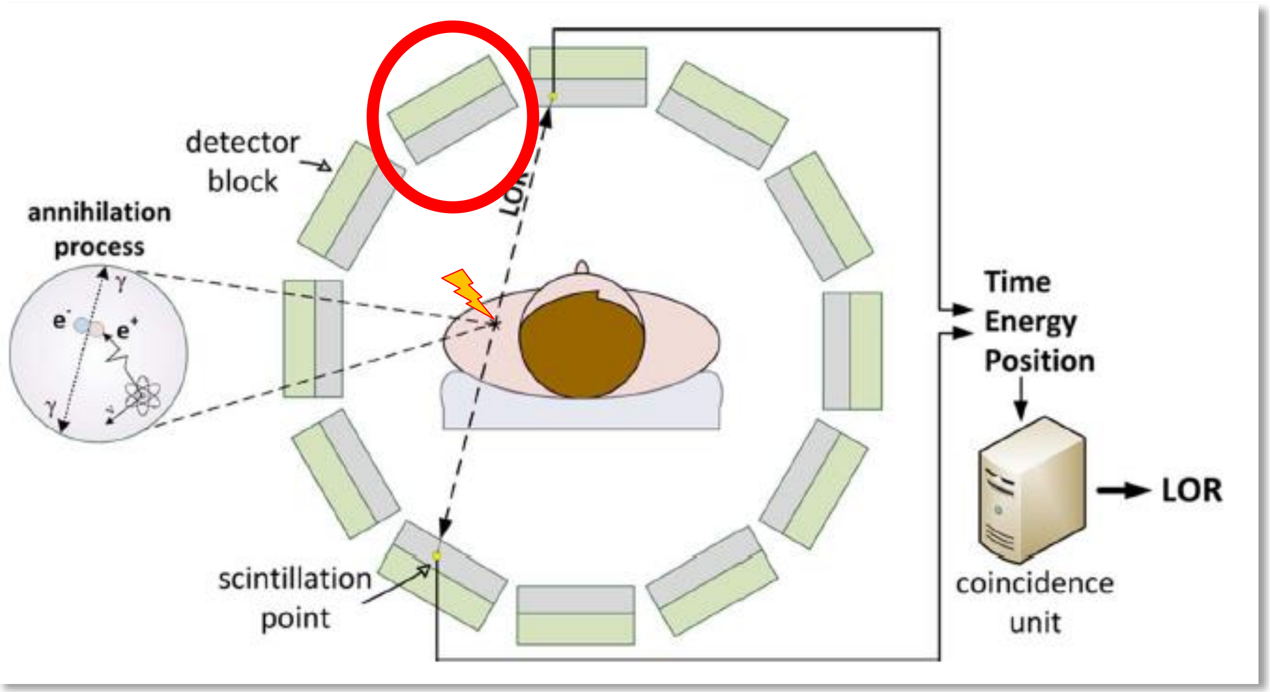
Drawback from CT is the limited soft tissue contrast and radiation dose. Furthermore the acquistions of the image are not simultaneous.

Future directions in PET

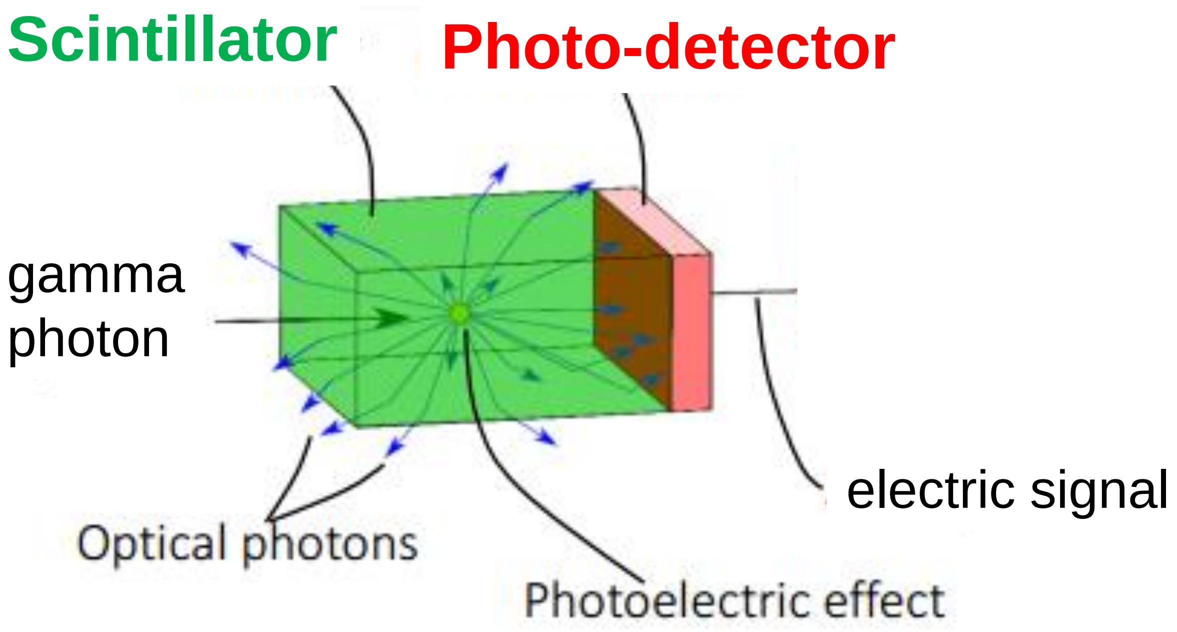
- better image quality
- better image quantitation
- shorter scan times

- 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.

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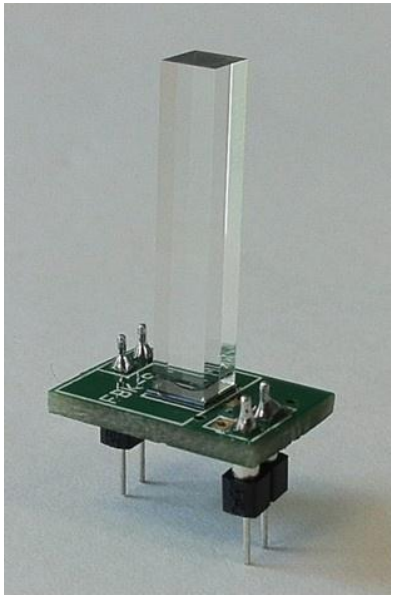
Scintillator



- 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**	cheap, no TOF
LSO/ LYSO	**420**	**14000**	**40**	**7.1**	**NO**	most used today
LaBr3	380	30k	16	5	YES	the future?

Photodetector

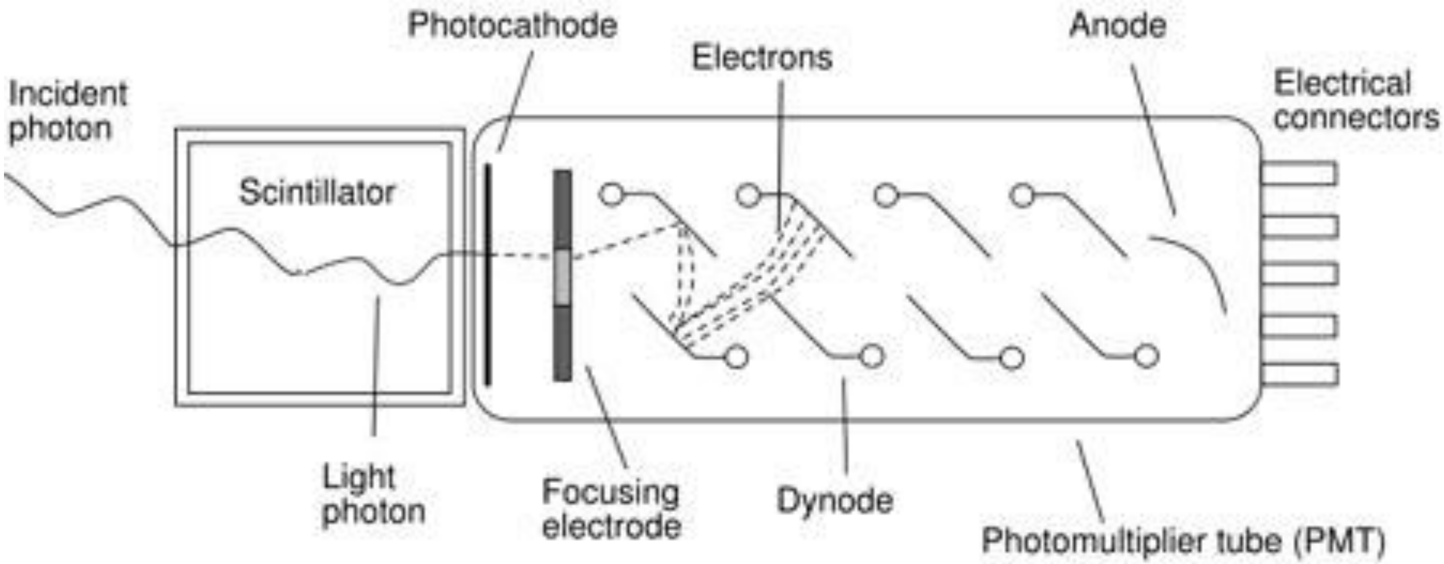
Primary characteristics:

- 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

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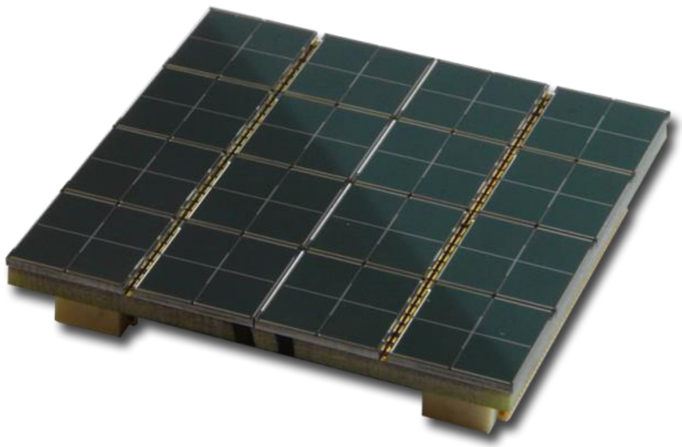
It is clear that the PMT does/will not allow the technology leap in the PET field…

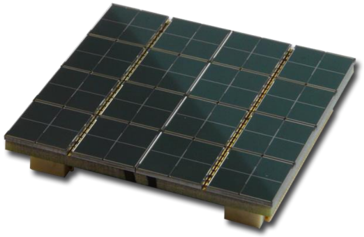
…the **solid-state revolution**

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



Fabricated in standard silicon technology!!

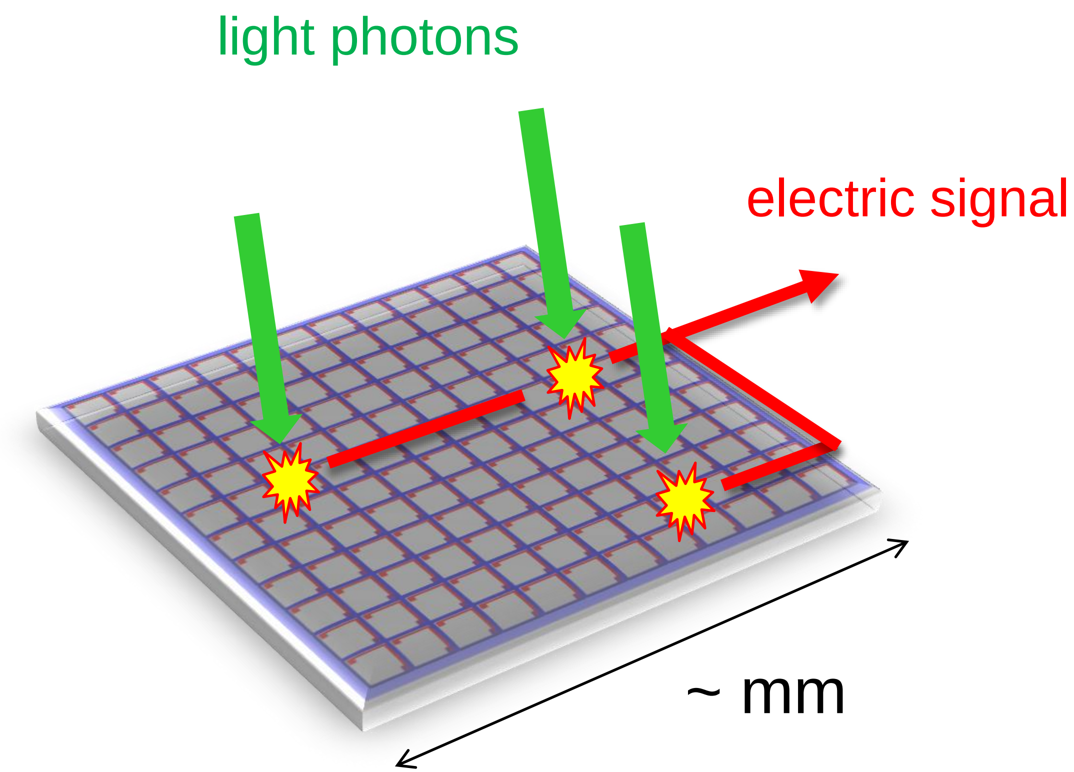
PMT *vs* SiPM

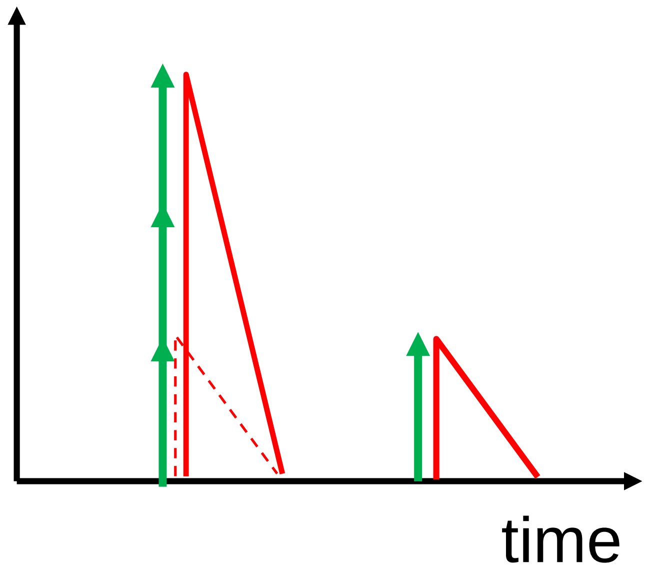


compactness	↓	↑
performance	↑	↑↑
ruggedness	↓	↑
insensitivity to magnetic fields	↓	↑
cost	↑	~↑
market competition	↓	↑

SiPM concept

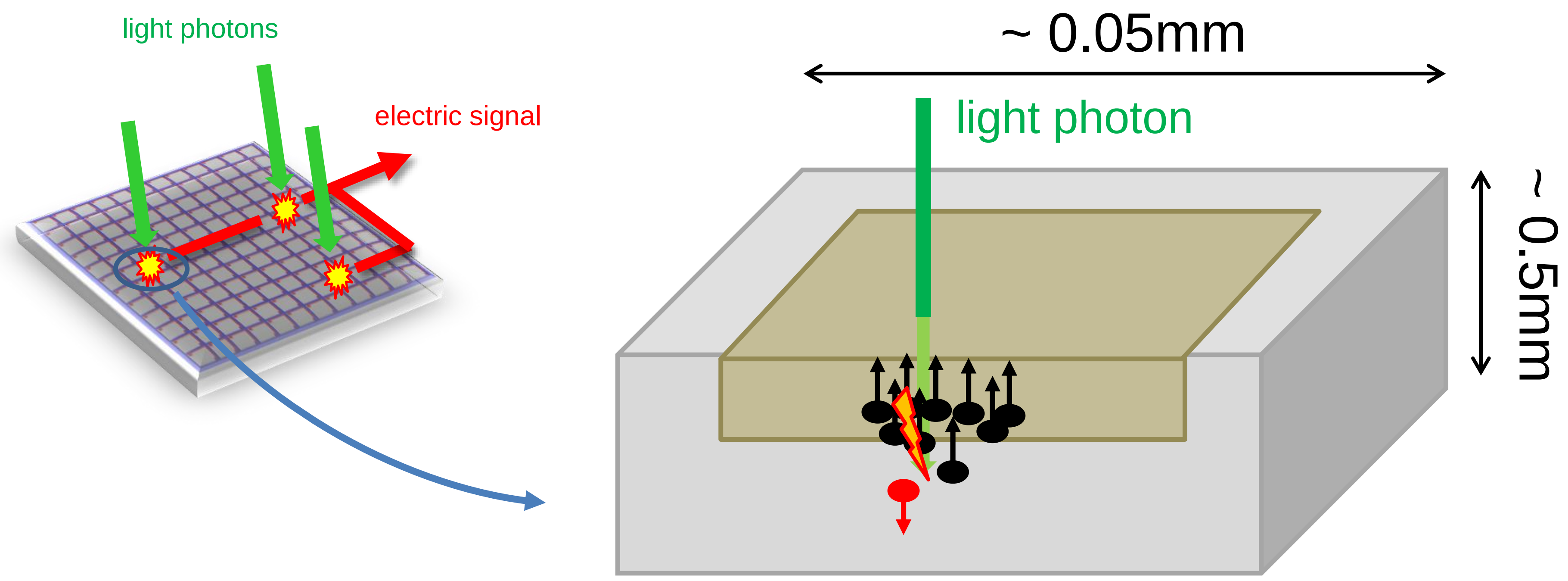
Array of tiny independent cells with common output.
Each cell provides a big electrical signal for each detected photon.
Signals are combine together to a common output.





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 the locally quenched. **About 1 million electrons are generated!!** Similar to PMT!

SiPMs: when, where?

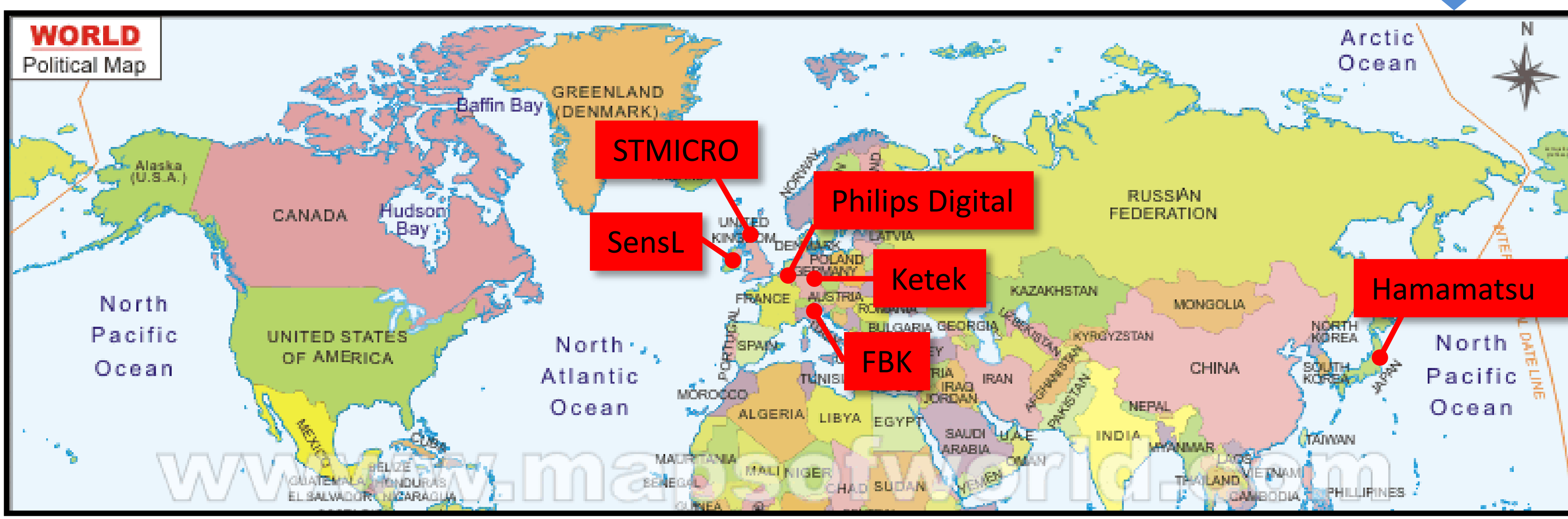
1964
Theory of Geiger mode discharge in pn junctions
R. Haitz, JAP vol.35, n.5 **1964**

1970
Idea of SPAD exploiting G-M theory
Various sources

1980
First SPADs
PoliMI
EG&G, Canada

1995
SiPM concept
Russian researchers

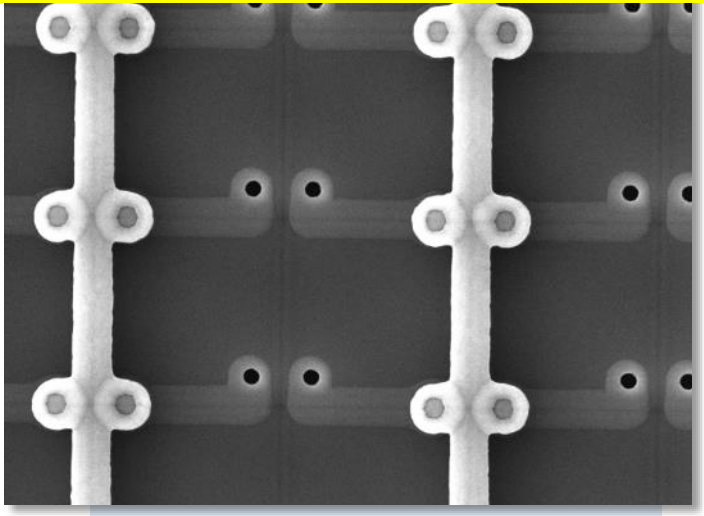
2005
First devices with good performance



Silicon photomultipliers @ FBK

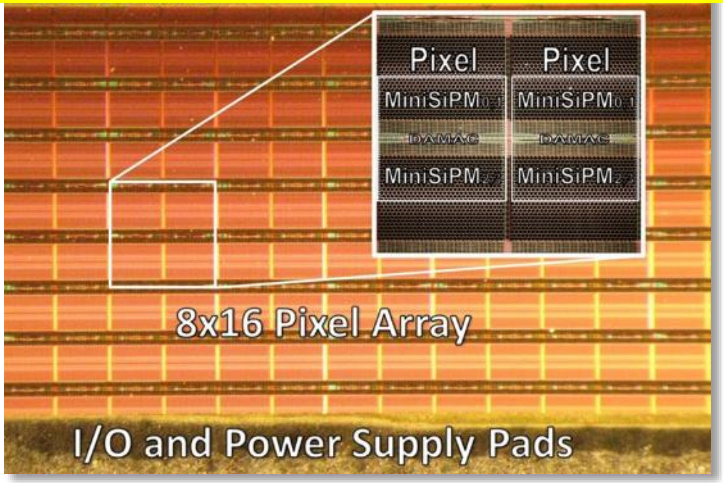
Technology platforms

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

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Main funding

INFN Istituto Nazionale di Fisica Nucleare

HYPER IMAGE — SEVENTH FRAMEWORK PROGRAMME

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

SUBLIMA — SEVENTH FRAMEWORK PROGRAMME

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

INSERT — SEVENTH FRAMEWORK PROGRAMME

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

SPADnet — SEVENTH FRAMEWORK PROGRAMME

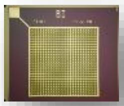
http://www.spadnet.eu/

…and now we work a lot with large industries

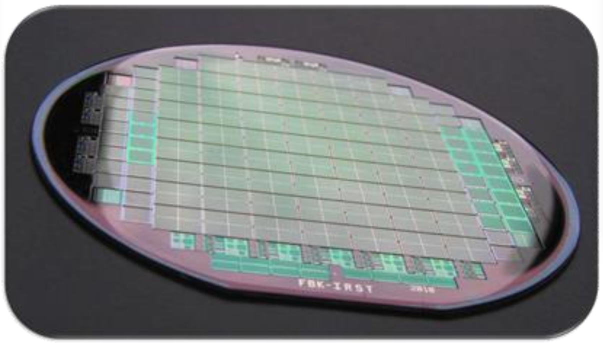
2006 — 2009 — 2012 — 2015

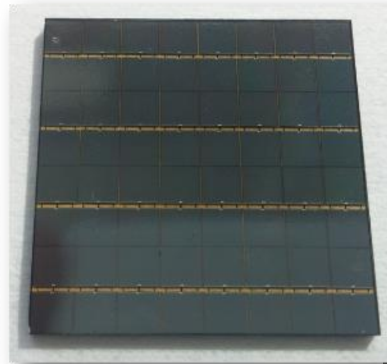
Custom Technology evolution

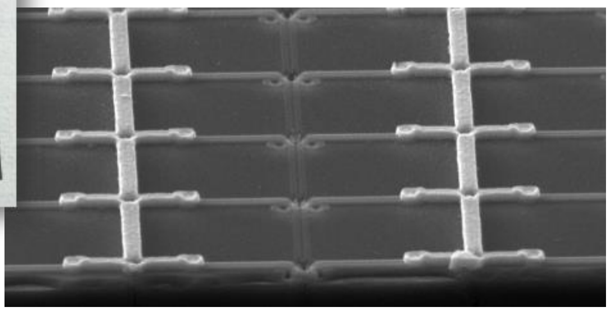
2006



1x1mm^2







Large-area tile

Original SiPM

RGB SiPM

RGB-HD SiPM

NUV-HD SiPM

NUV SiPM

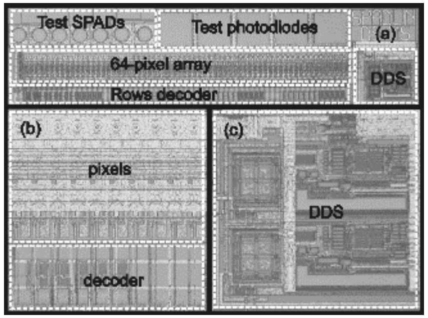
2006

2009

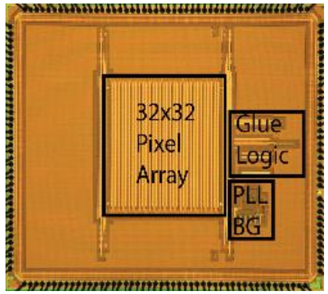
2012

2015

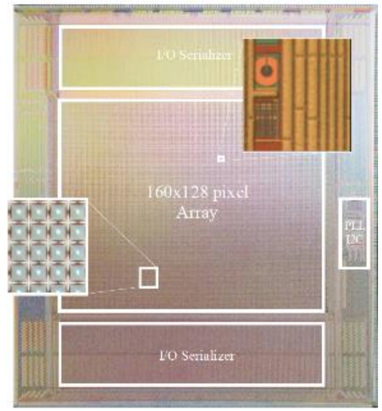
CMOS Technology evolution



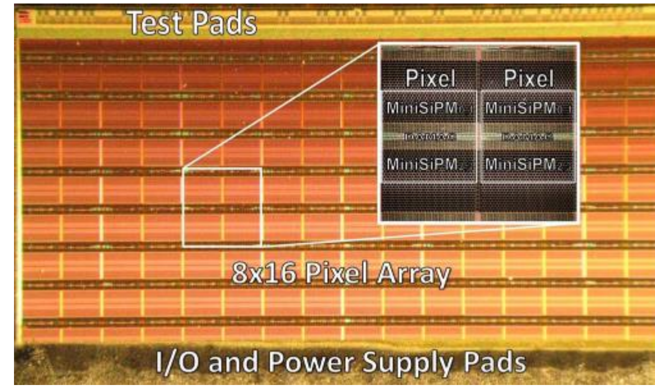
64-pixel linear
0.8um HV



32x32-pixel
130nm CIS



128x160-pixel
130nm CIS



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

SPAD 0.8μm
1 Foundry

64-SPAD
linear array

SPAD 0.35μm
2 Foundries

SPAD 150nm-130nm
4 Foundries

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

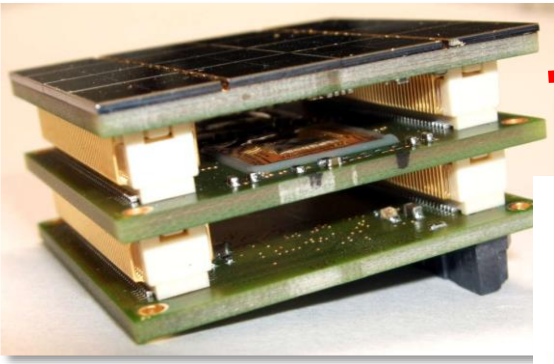
solid-state technology!

HyperImage/Sublima FP7

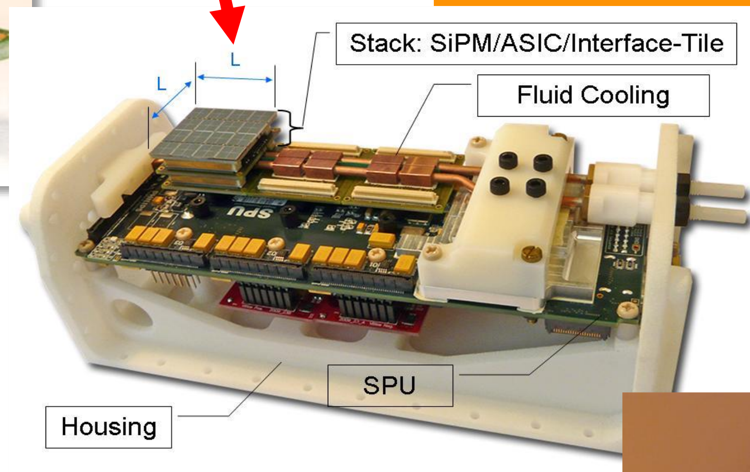
http://www.hybrid-pet-mr.eu/ http://www.sublima-pet-mr.eu/

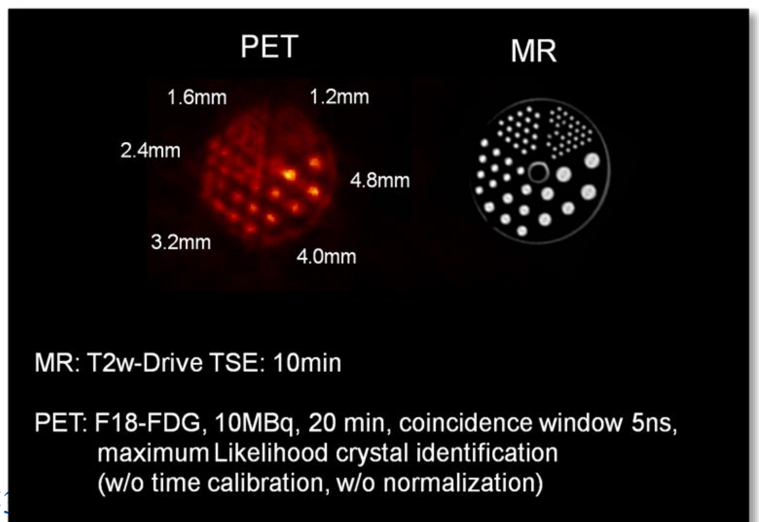
	Partner Name	Representative
1	Philips Technologie GmbH	Torsten Solf
2	Delft University of Technology	Dennis Schaart
3	Fondazione Bruno Kessler	Claudio Piemonte
4	University of Heidelberg	Peter Fischer
5	University of Pennsylvania	Joel Karp
6	University of Ghent	Stefaan Vandenberghe
7	Technolution	Paul 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



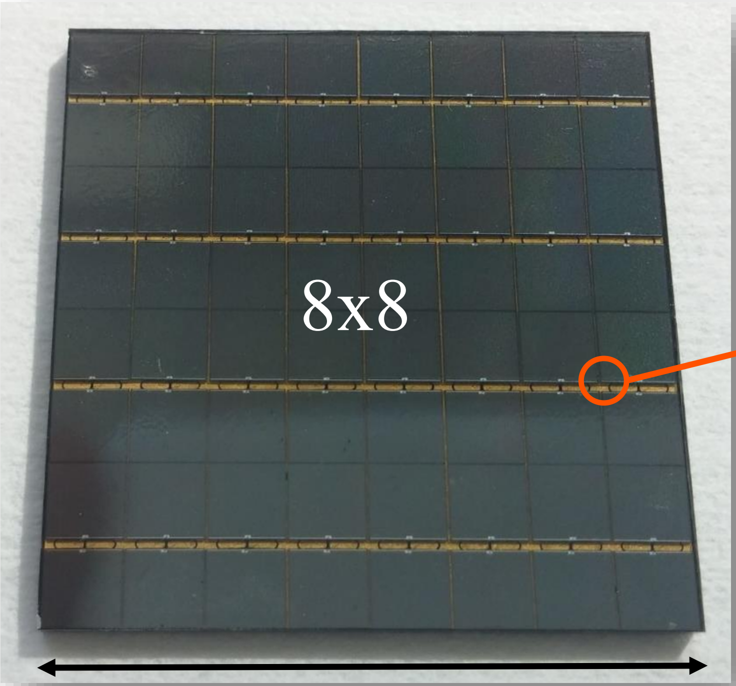
First pre-clinical system working in a MRI.



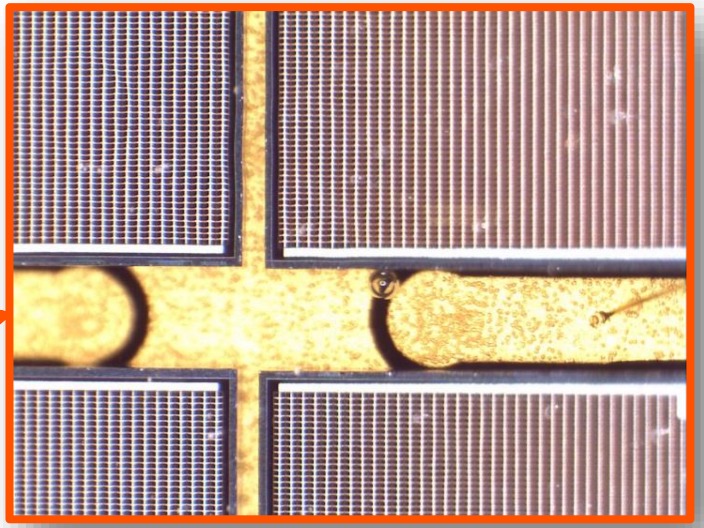


FONDAZIONE BRUNO KESSLER

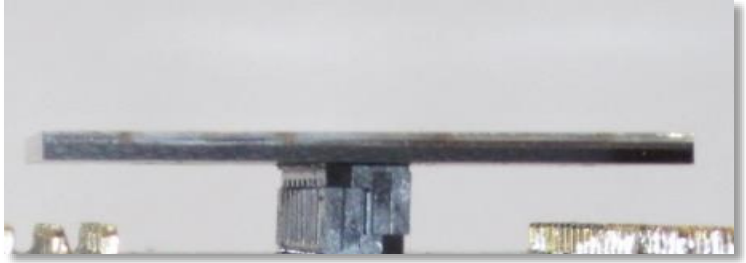
Some pictures of the SiPM tile

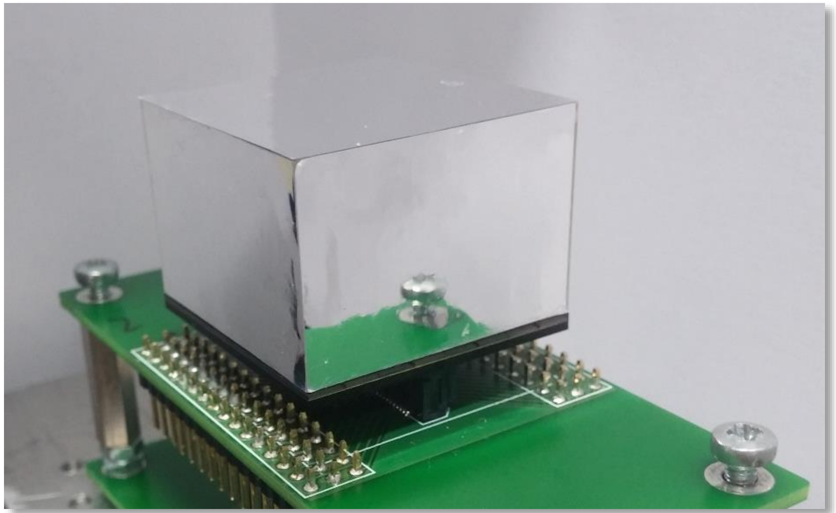


3.23 cm



~ 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.

FAST
Fast Advanced Scintillator Timing

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

SiPM optimization @ FBK

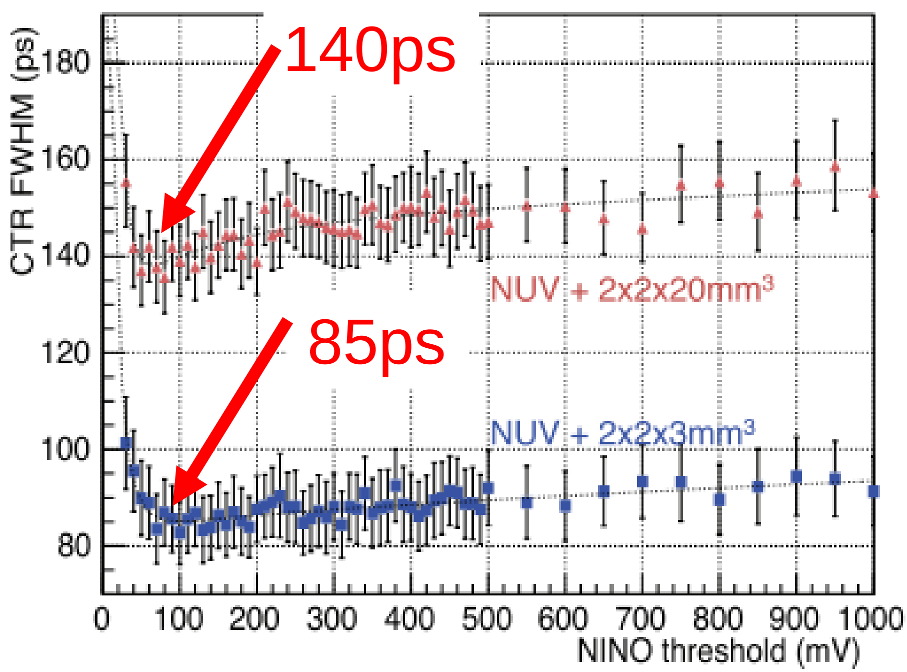
IOP Publishing | Institute of Physics and Engineering in Medicine — Physics in Medicine & Biology

Phys. Med. Biol. **60** (2015) 4635–4649 — doi:10.1088/0031-9155/60/12/4635

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

Mythra Varun Nemallapudi[1], Stefan Gundacker[1], Paul Lecoq[1], Etiennette Auffray[1], Alessandro Ferri[2], Alberto Gola[2] and Claudio Piemonte[2]

[1] CERN, Geneva 23, CH-1211, Switzerland
[2] Fondazione Bruno Kessler, via Sommarive 18, Trento, Italy



thick scintillator (for PET)

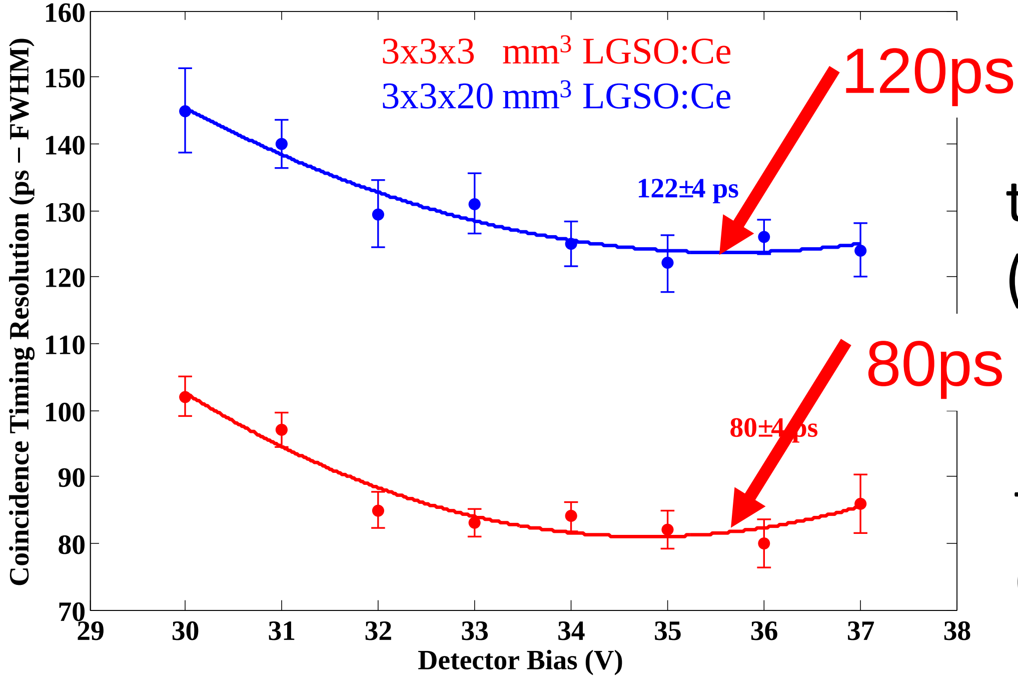
thin scintillator (for benchmarking)

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.

↓

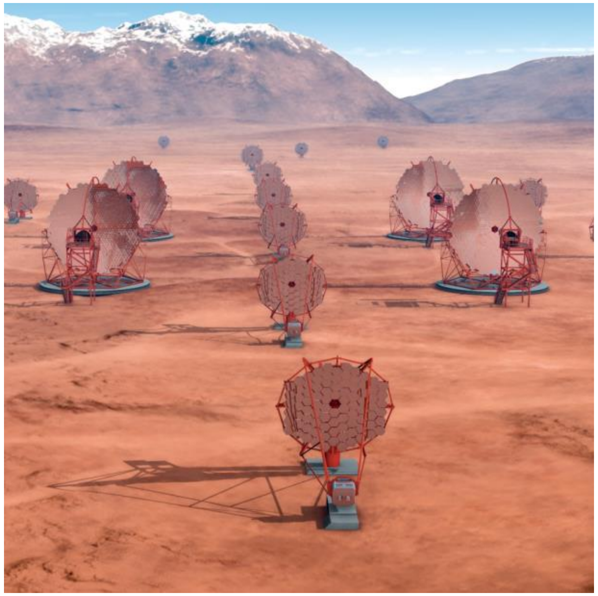
New imaging modalities and better performance.

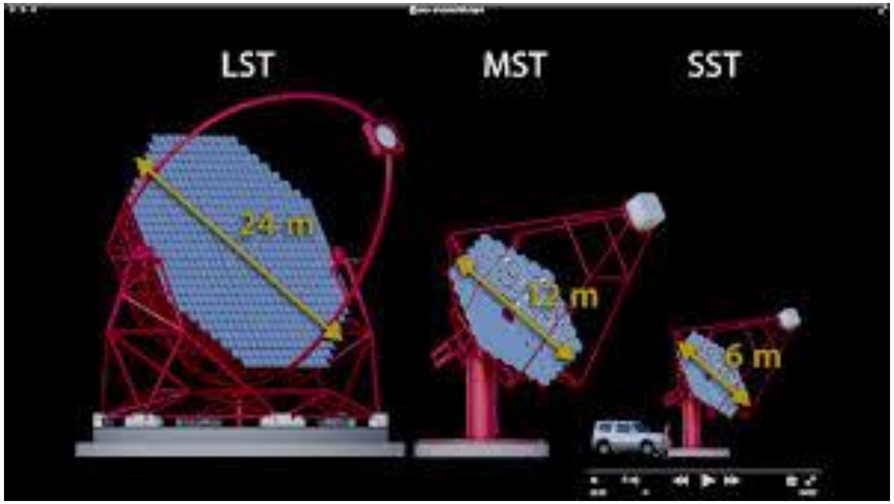
↓

Better diagnosis!

Another interesting application at a glance

Cherenkov Telescope Array

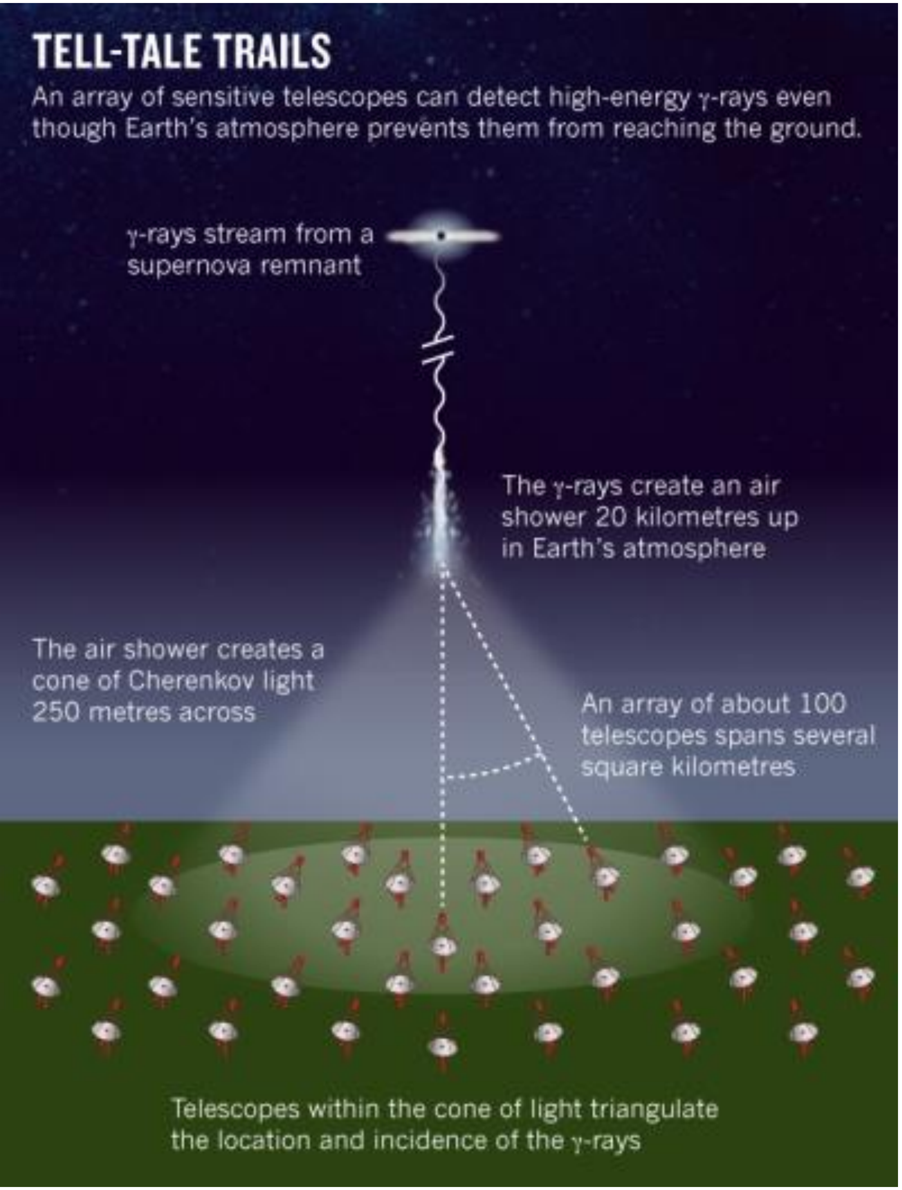




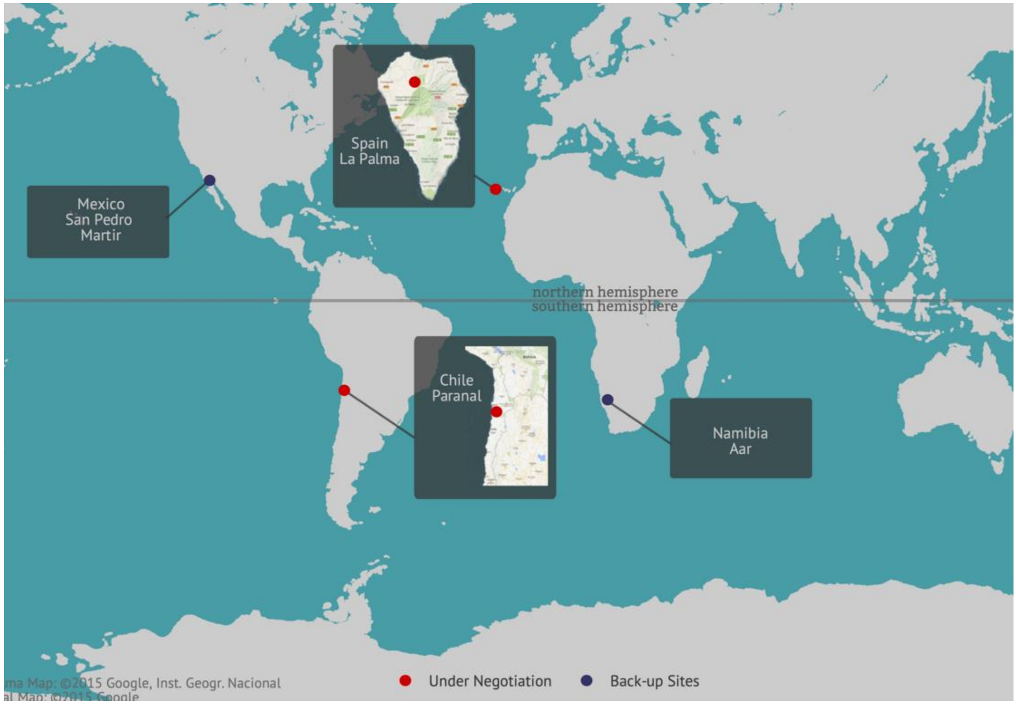
- Understanding the origin of cosmic rays and their role in the Universe
- Understanding the nature and variety of particle acceleration around black holes
- Searching for the ultimate nature of matter and physics beyond the Standard Model

International consortium of over 1000 people.

Cherenkov Telescope Array

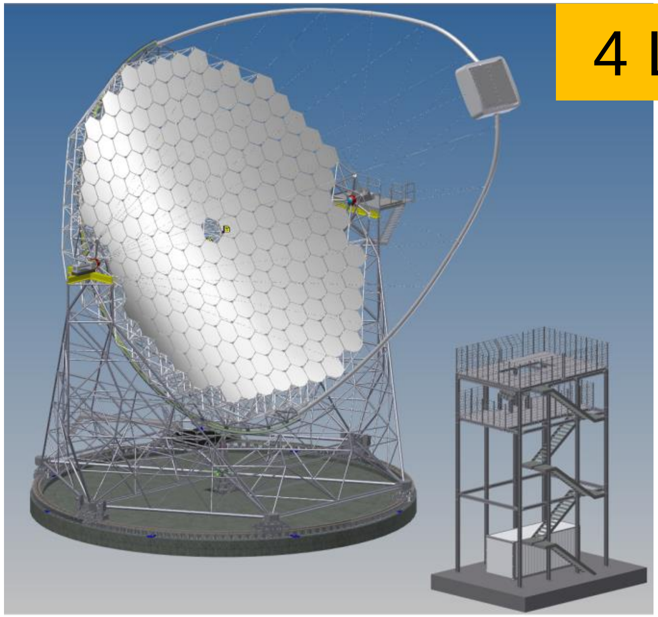


https://portal.cta-observatory.org/Pages/Home.aspx

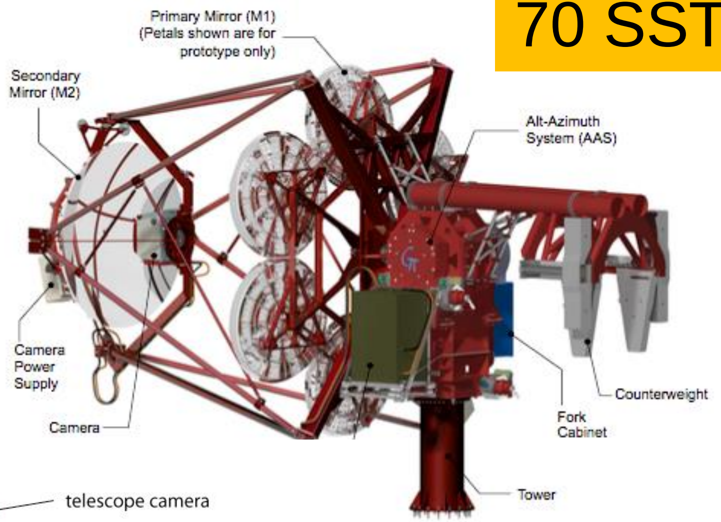


Cherenkov Telescope Array

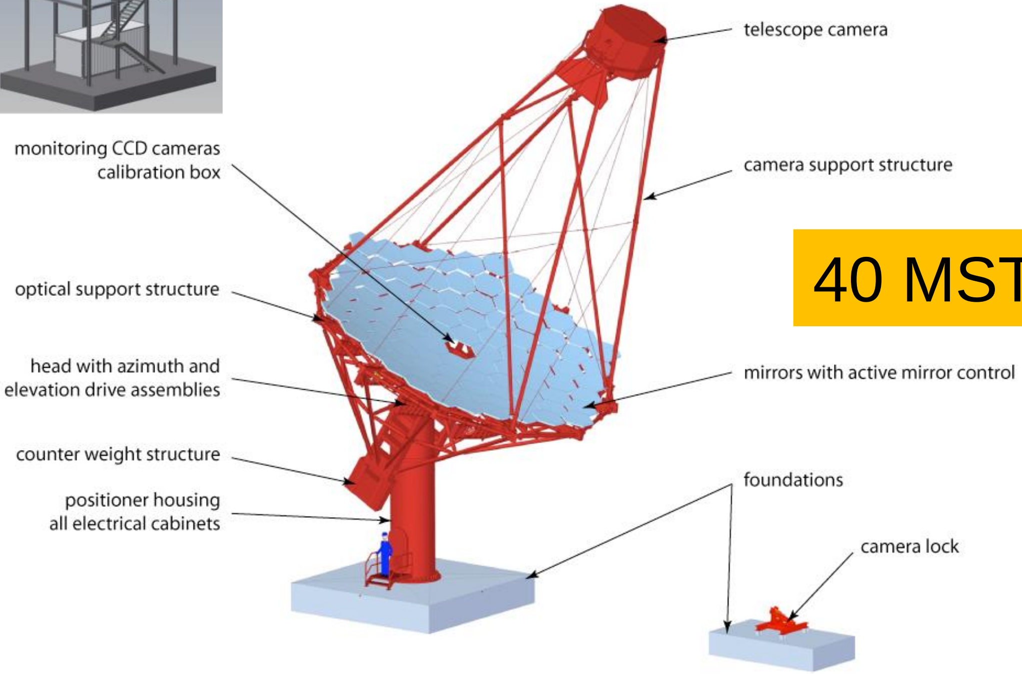
4 LST



70 SST



40 MST



Cherenkov Telescope Array

Main photosensor requirements:
- single photon sensistivity
- 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