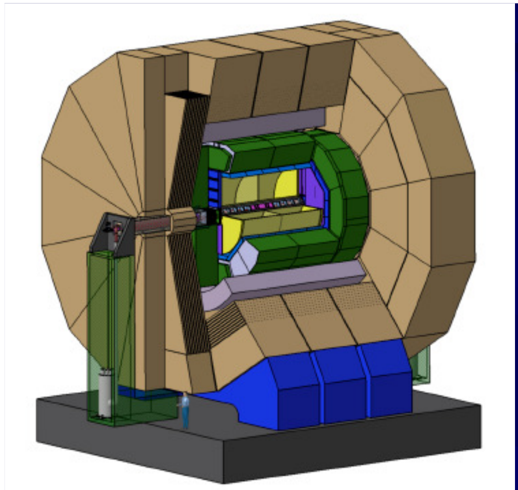
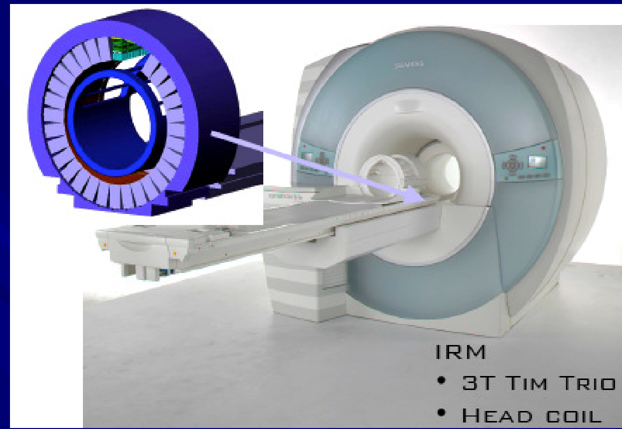
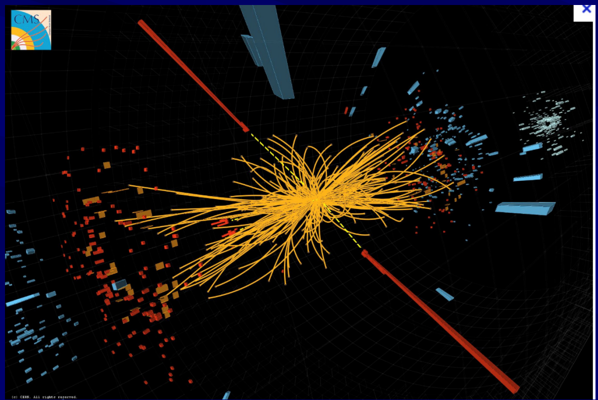


Application of fundamental physics in medicine





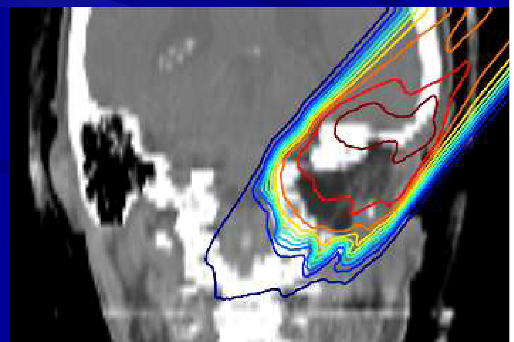
P. Le Dû

patrickledu@me.com

CNRS IN2P3 Les deux infinis

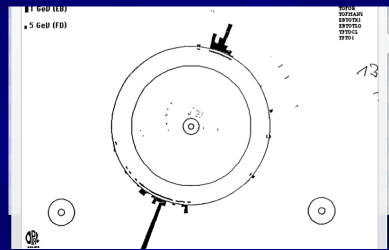
IPNL

IEEE NPSS NUCLEAR & PLASMA SCIENCES SOCIETY



Who I am ? -

- NA3 @ CERN (Di-Muon Drell Yan) : 1974-1980
  - Large MWPC (4x4 m2)
  - **Trigger & DAQ**
- LEP - OPAL @ CERN (1980-1990)
  - TOF system
  - **Trigger & DAQ → First Z^0**



- SSC- SDC @ Dallas/LBL Berkeley (1990-1994)
  - **Trigger L2**
  - Shower Max Detector electronics (APD & SCA)
- LHC- ATLAS @ CERN (1994-2000)
  - **L2 trigger** & LARG calorimeter Read Out electronics (SCA)
- D0 @ FNAL (1996-2005)
  - **L1 Calormeter trigger and L2 trigger.**
- ILC study group (1996-2008)
  - **Trigger & DAQ convener → Software trigger**
- **2000→Technology transfer advisor for medical application (PET & Particle therapy)**
- **Ultra fast (picosecond) timing**

Experimental Physicist
-CEA Saclay (1969-2008)
-IN2P3-IPN Lyon (2009 ..)

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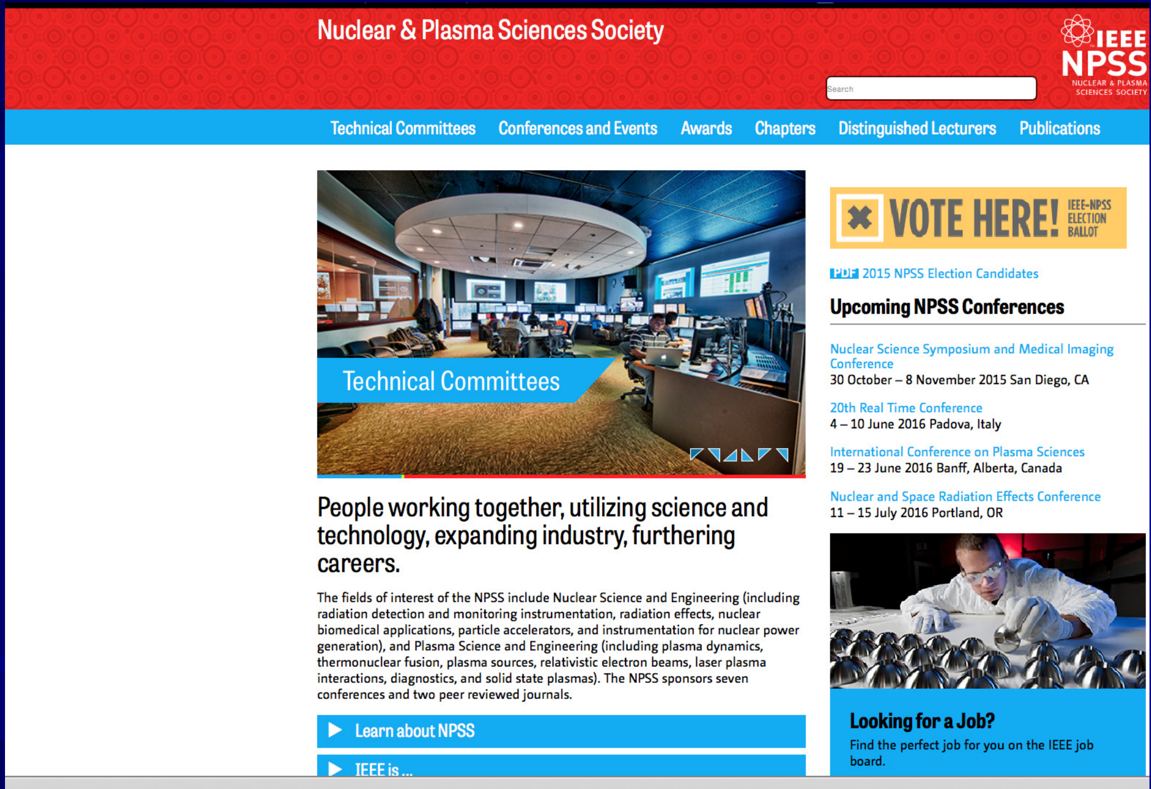
NPSS ADCOM
-RITC Chair

IEEE Nuclear and Plasma Science Society

http://ieee-npss.org

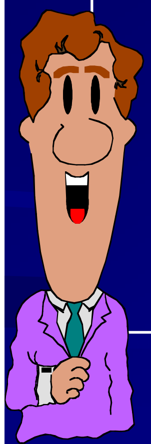


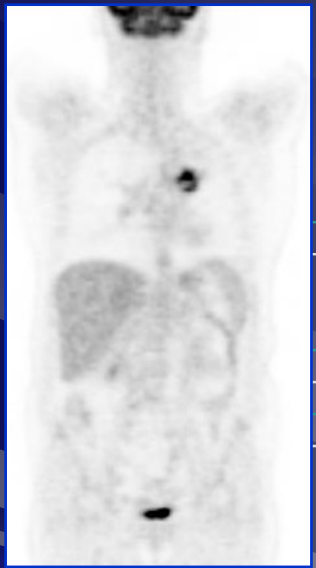
IEEE NPSS NUCLEAR & PLASMA SCIENCES SOCIETY

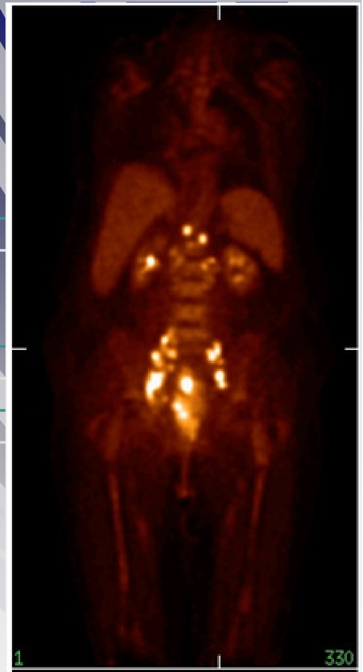
- Technical Committees
  - Radiation Instrumentation
- Conferences
  - NSS-MIC
- Publications
  - Digital library
  - Transaction in NS
- Network

Goals of this presentation

- A flavor of valorisation of Particle Physics
  - Can we use the tools and techniques and state of the art technologies developped for HEP experiments in another field ?
- Illustrate using sucessfull examples in the most challenging and innovative biomedical field for diagnostic and treatment of cancer (PET and particle therapy)
- X Ray Radiography and dose reduction (CT)





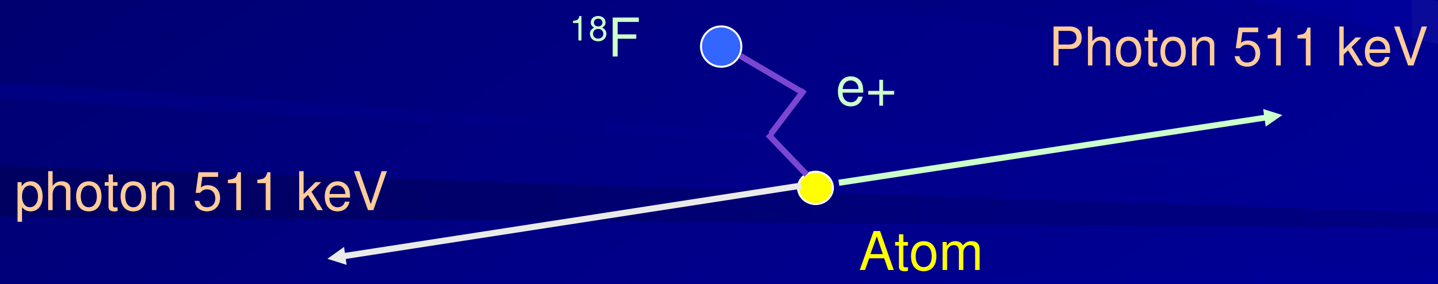


The best 'typical example → The PET

PET imaging
From past, present to future

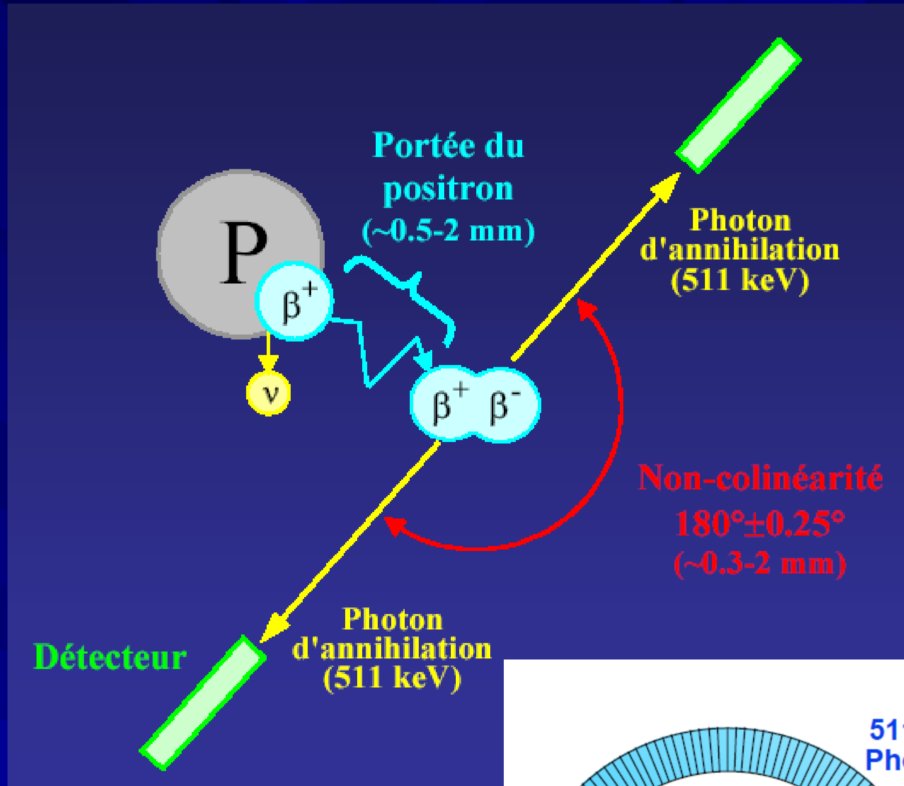
Positron Emission Tomography principle

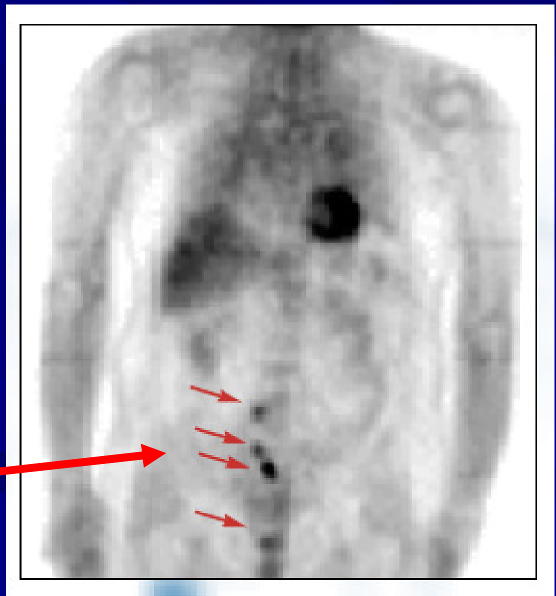
- Functional imaging device
- Molecular tracers with doped beta + emitters
  - ^{11}C(20 min), ^{15}O (2min) , ^{13}N (10 min),^{18}F (2h)
  - Produced by a 18 Mev Proton cyclotron
  - The most common → ^{18}F => ^{18}FDG fluoro-deoxy-glucose
    - Sign the degree of activity of an organ hungry of glucose
- annihilation positron with an electron
  - emission of two 511 keV photons back to back



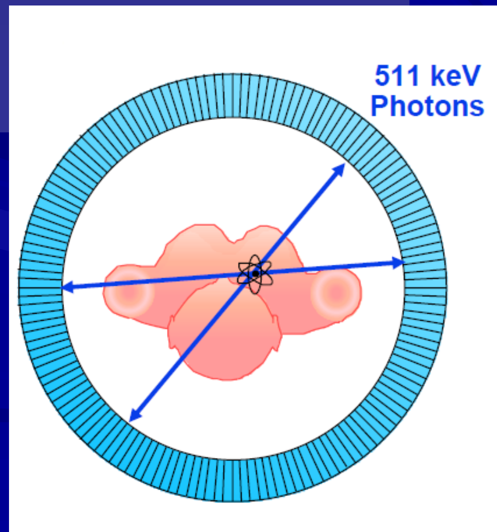
Positron Emission Tomography principle

- Sign the degree of activity of an organ hungry of glucose ---> show abnormal glucose metabolism like cancer tumour cells





Colon cancer spots



The PET sequence

Produce radio-active sugar (FDG)

Intravenous injection

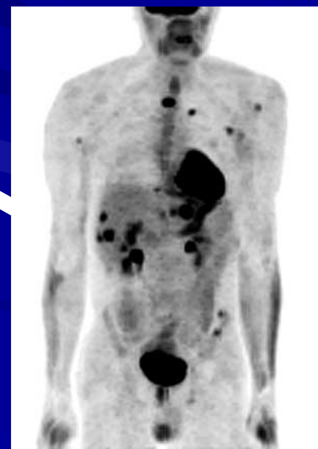
10mC

Wait for accumulation in target site

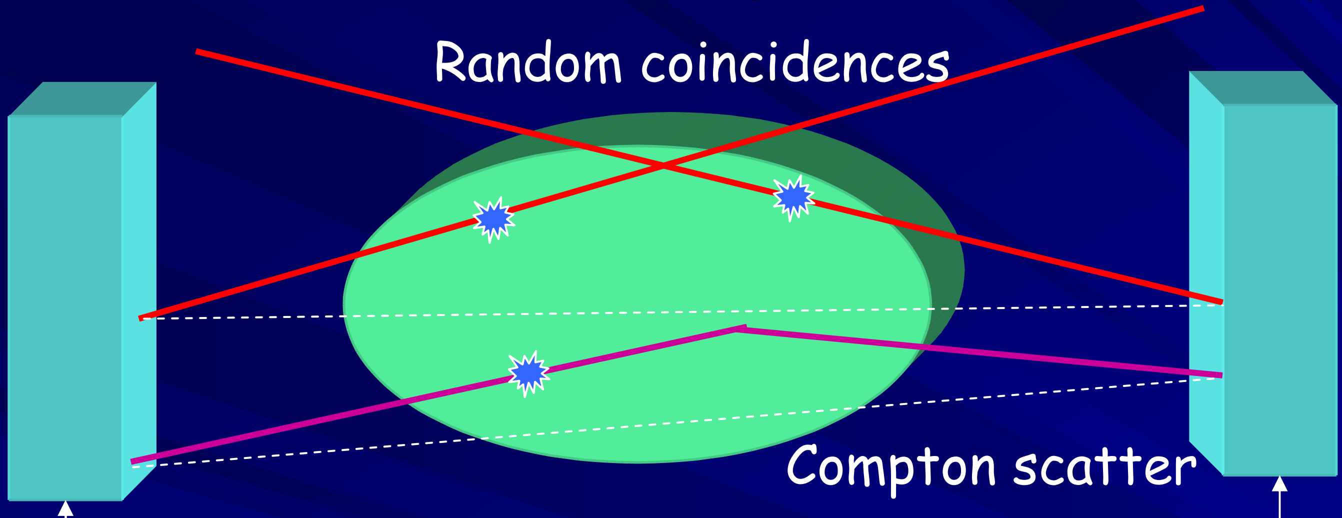
Detect coincidence events

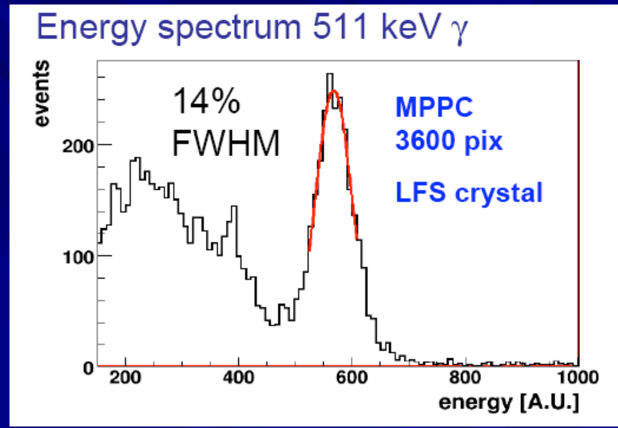
Get 2 gamma events

Reconstruct image coincidence events



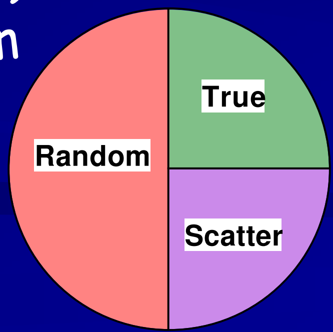
The experimental aspect

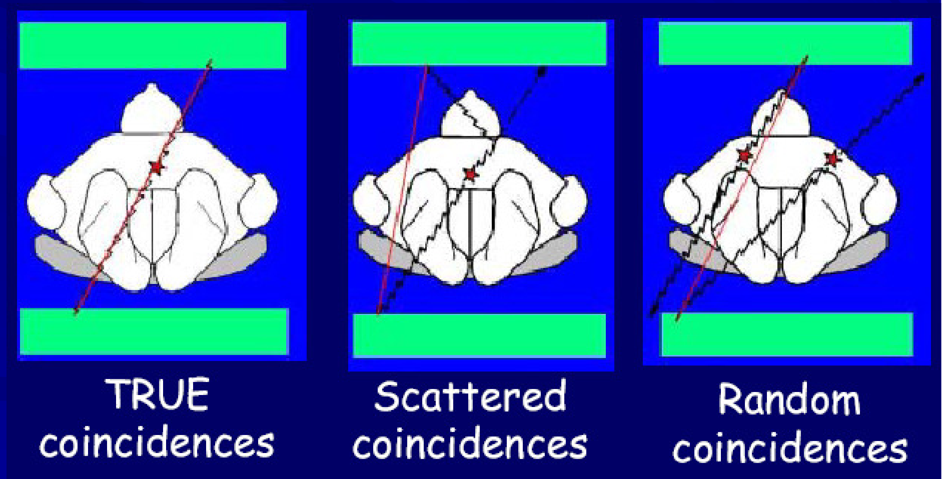




Detector in coincidences
Energy window around 511keV
Time window < ns
Limited Acceptance (Field Of View)

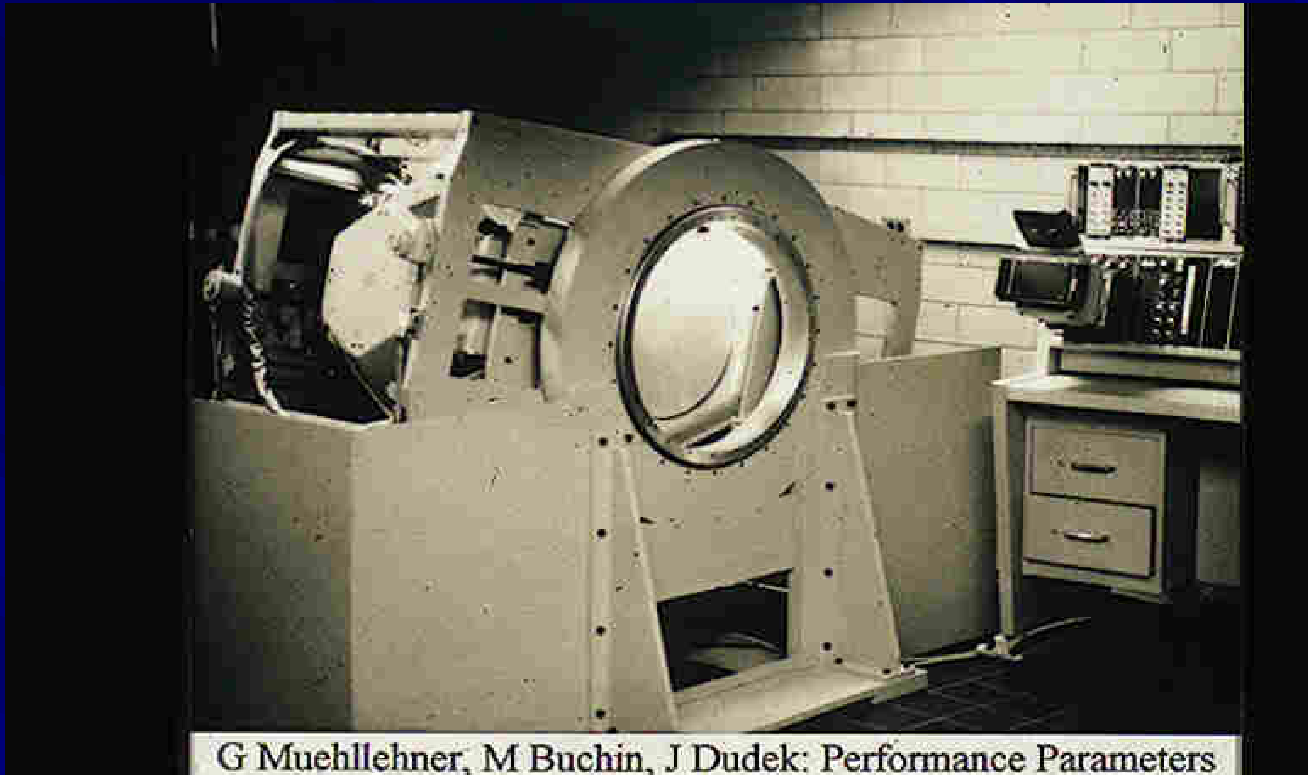
Signal : true concidences (25%)
Background: Compton + Random





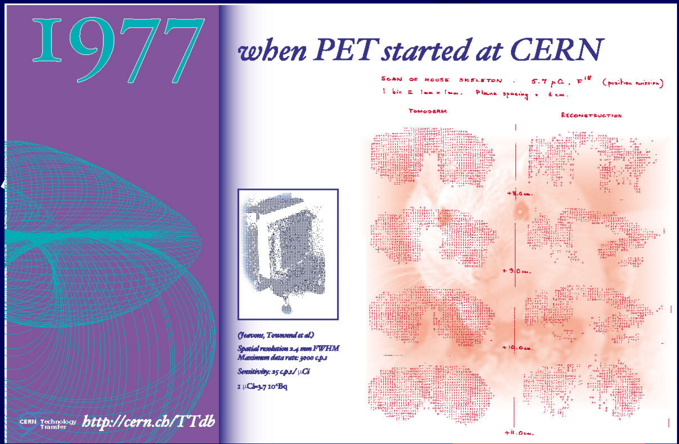
Efficiency ≈ 0,01 (1 photon / 100)

First PET with Anger Cameras



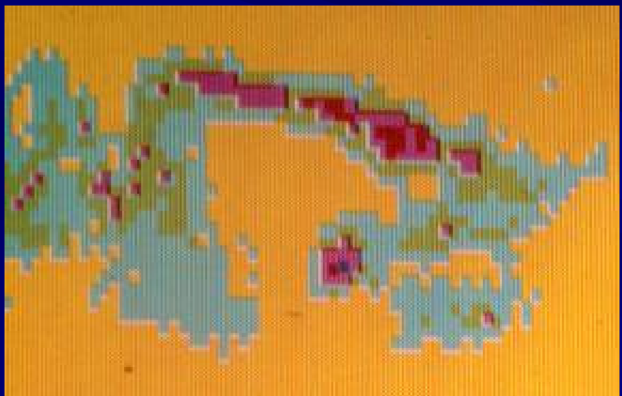
University of Chicago 1975

Historical Evolution of PET



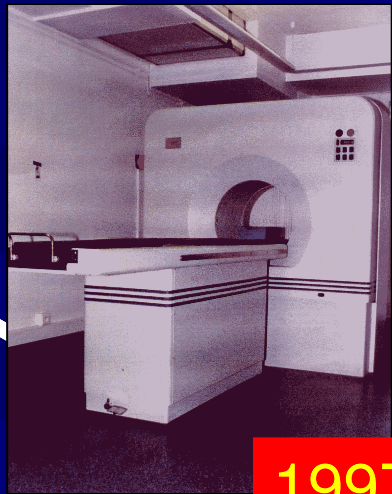
1977

First Steps
Townsend & Jeavons

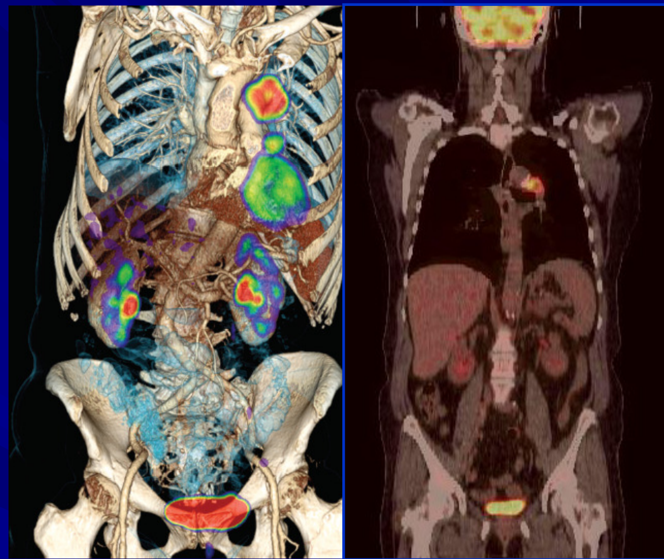


First mouse imaging with ^{18}F

C-PET Philips



1997



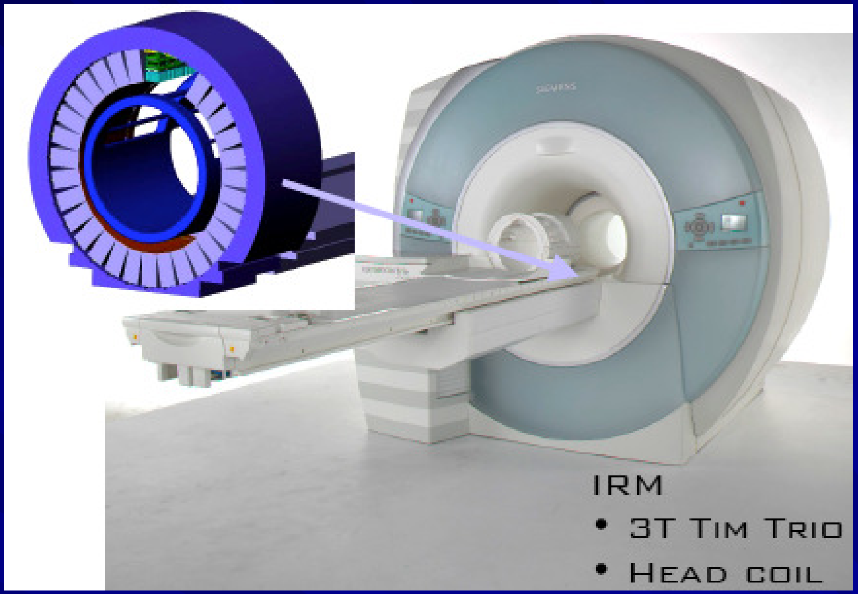
2007

Biograph PET + X ray-CT

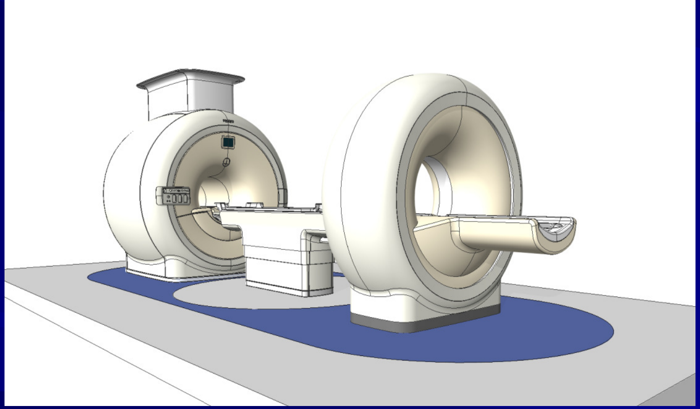
From Today ---> Tomorrow Challenge

TDM/PET-TOF (500 psec)

Today



Siemens



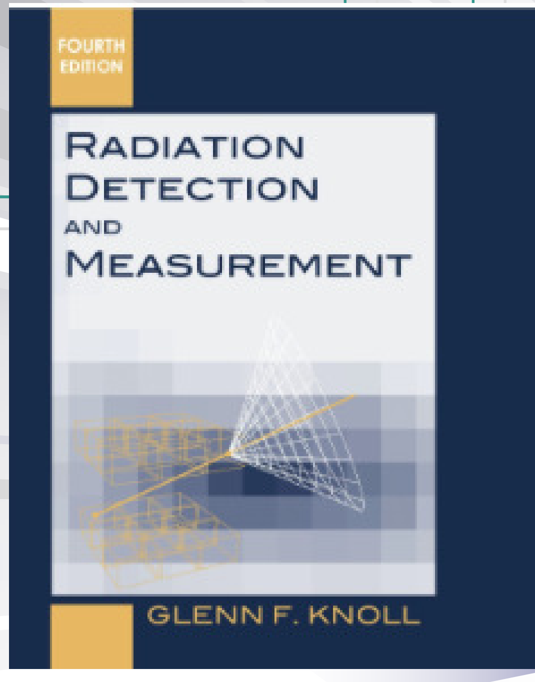
PET-MRI

Philips

Next ?

Few words about Particle Physics Detector

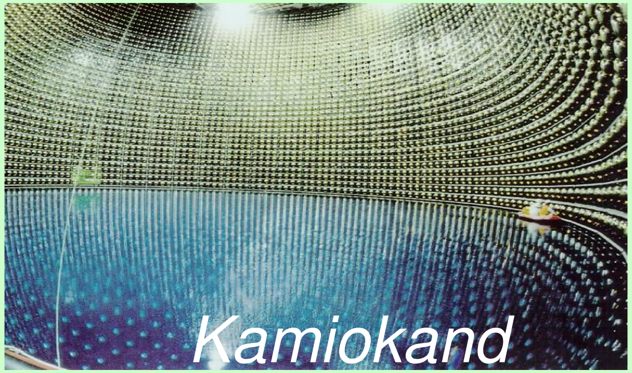
Radiation Instrumentation The Bible Glenn Knoll



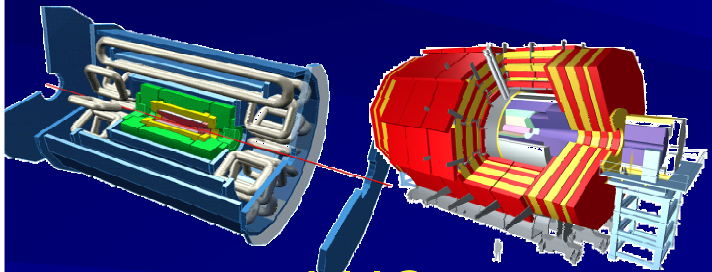
Particle detectors

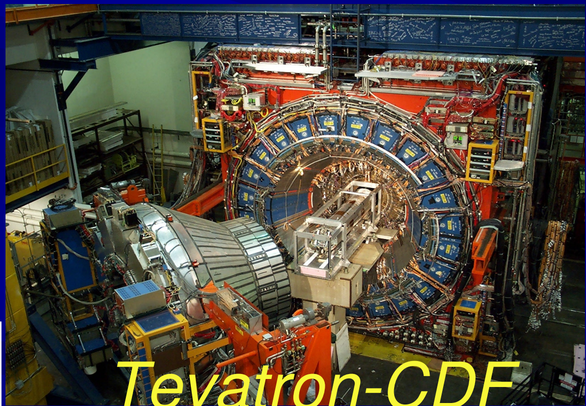
- Colliders

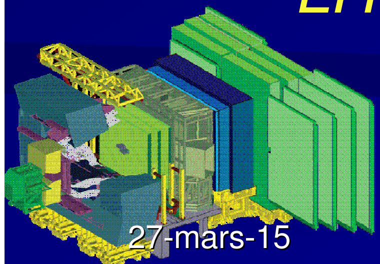
- Fixed target

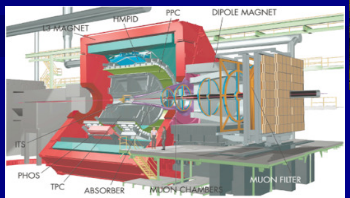


- Non accelerator

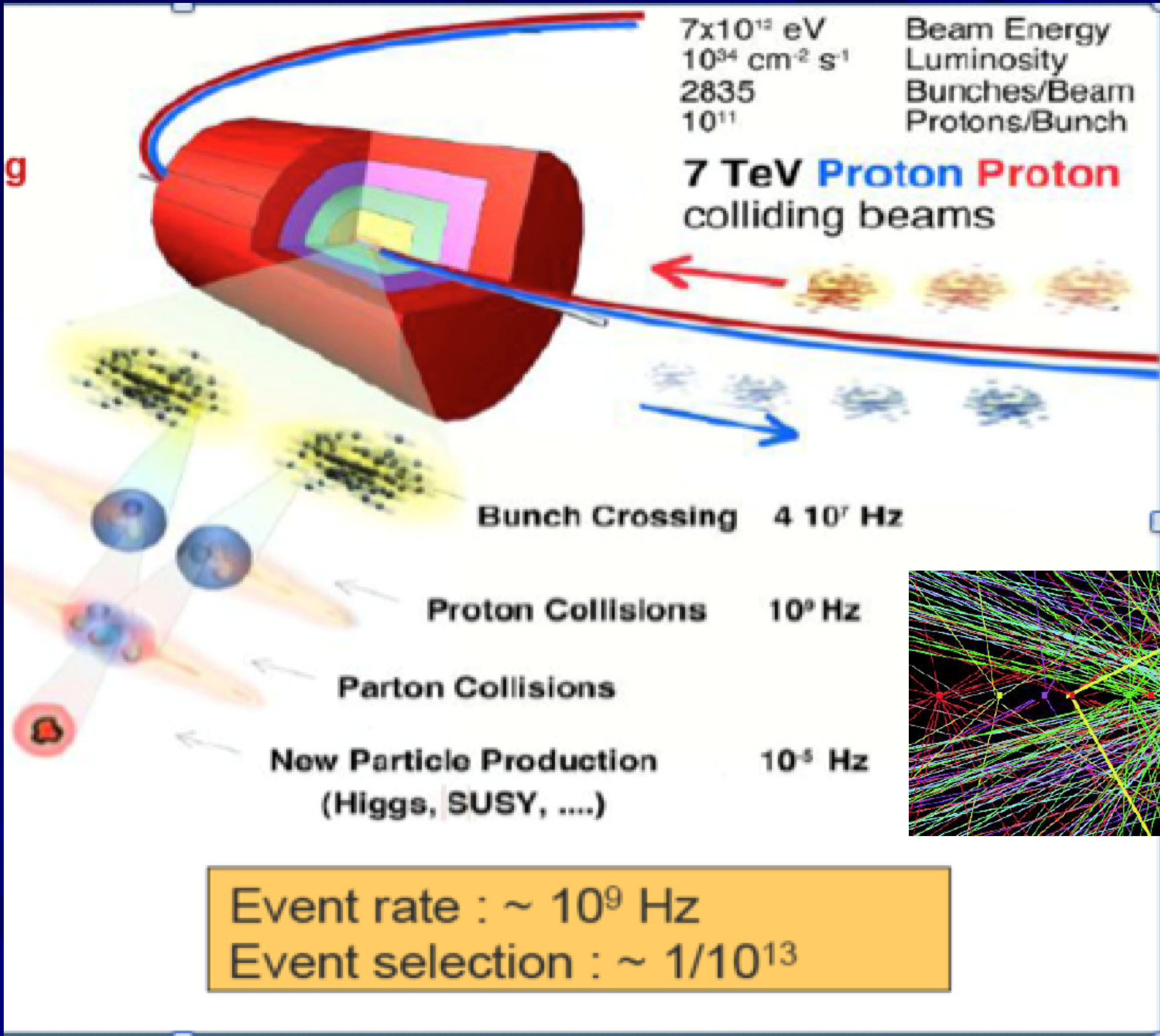






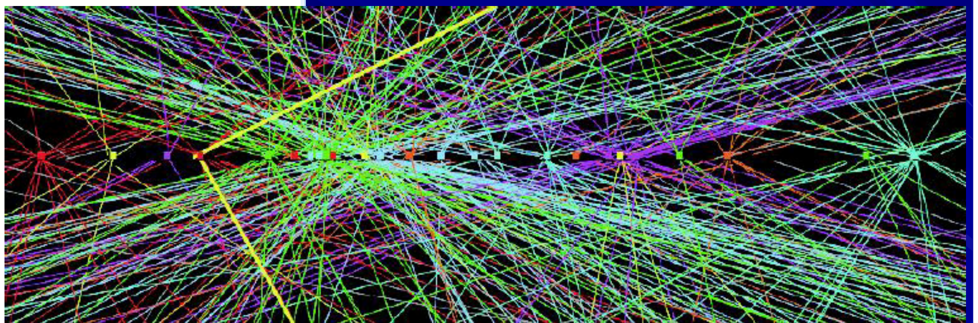


Challenging : The LHC



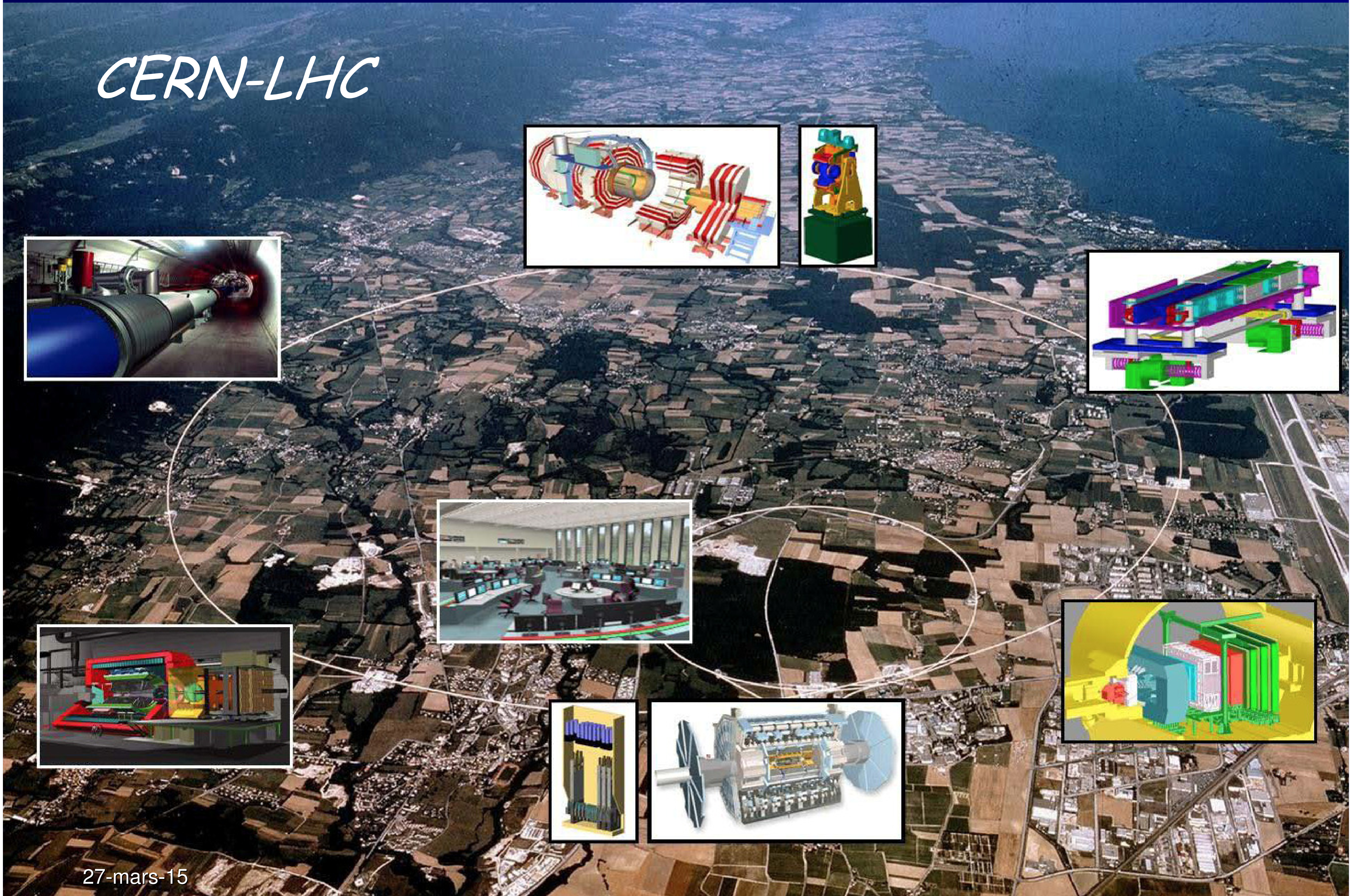
Quark-Quark collisions

Collision Every 25 ns



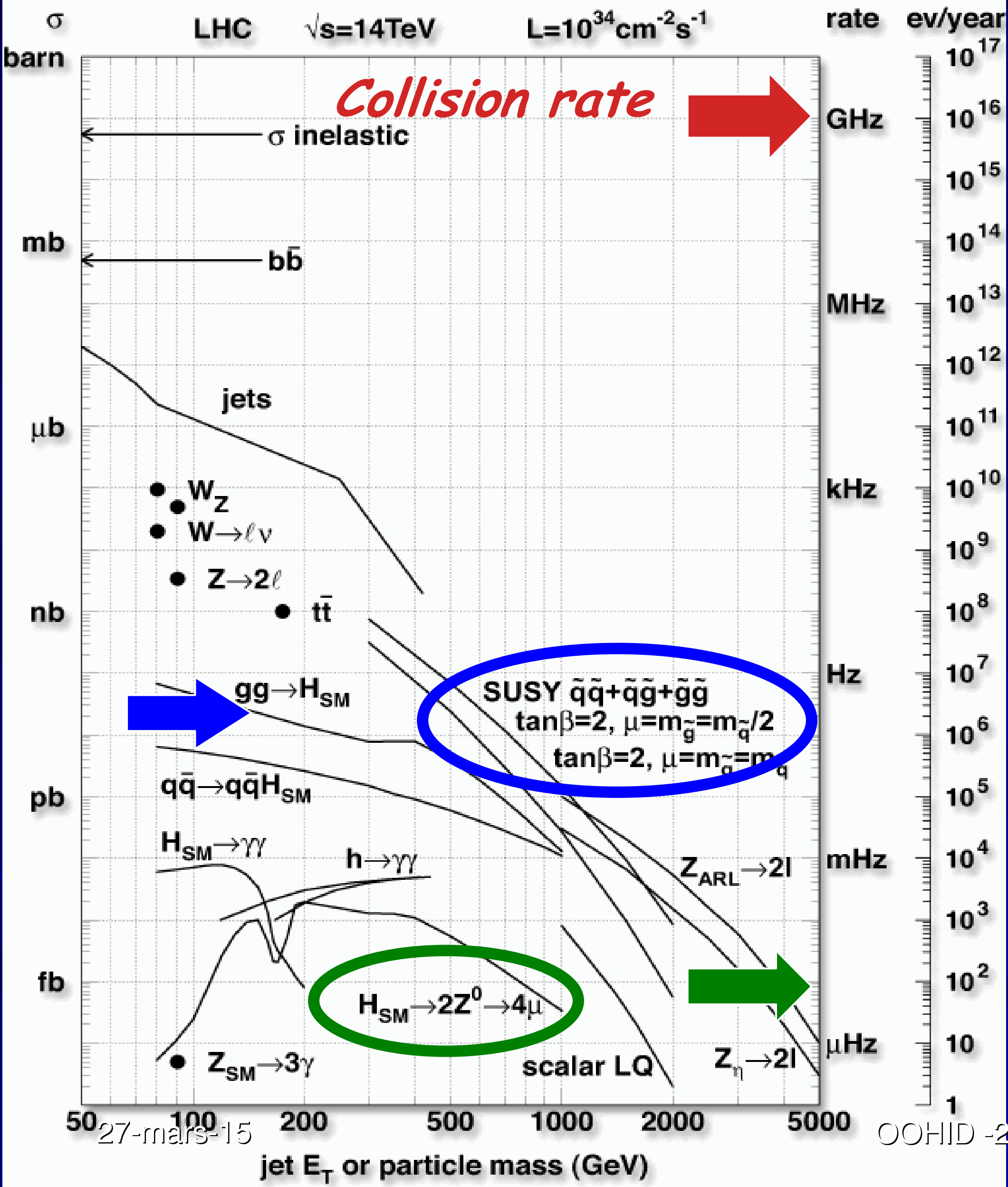
Z -> μ μ event at LHC ATLAS 15 April 2012

CERN-LHC



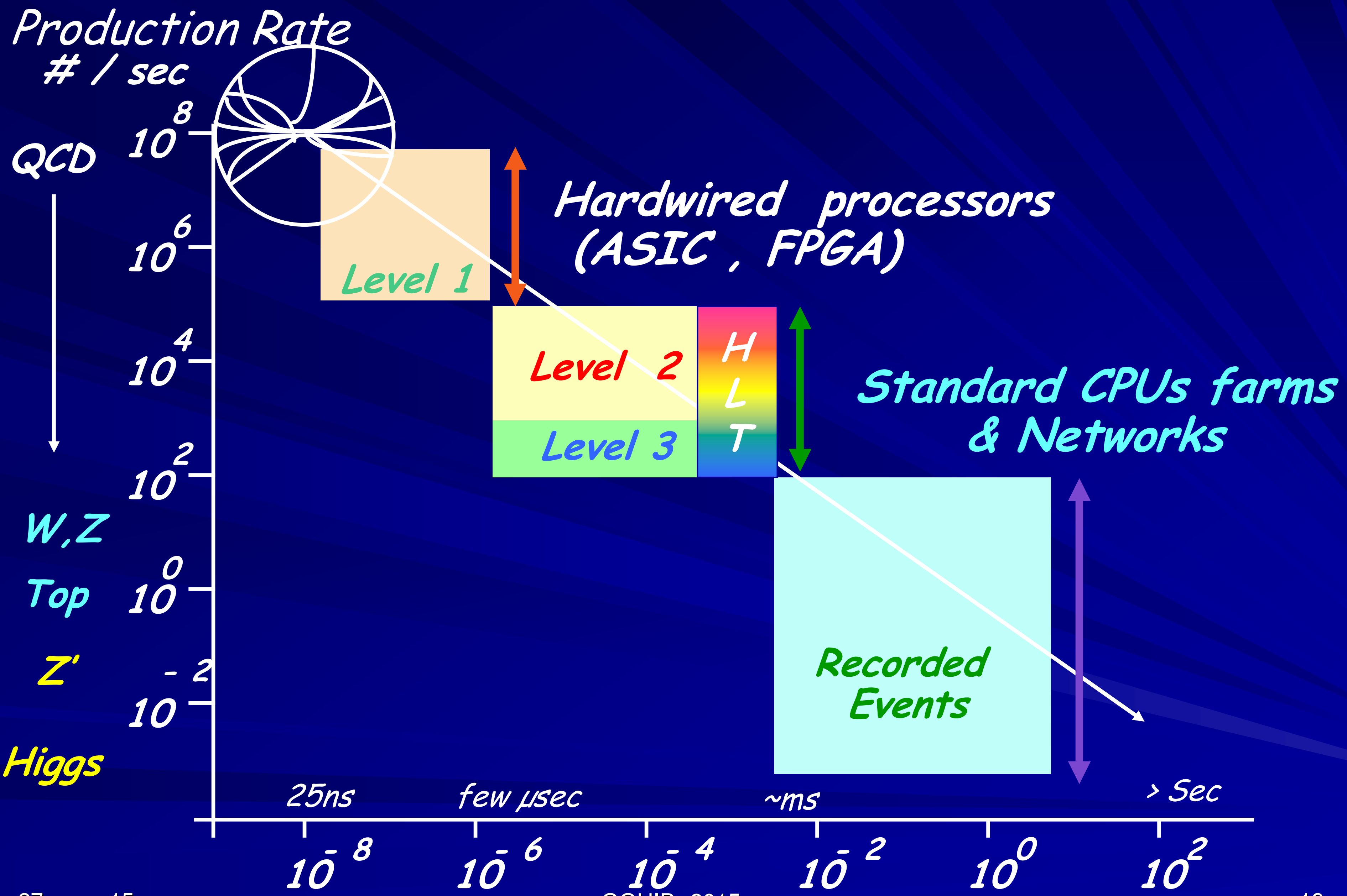
27-mars-15

The LHC challenge

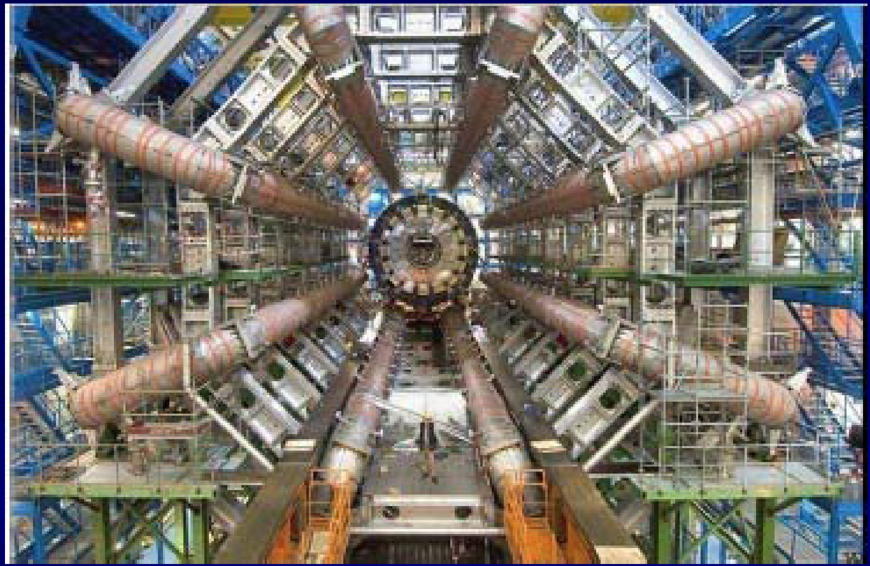


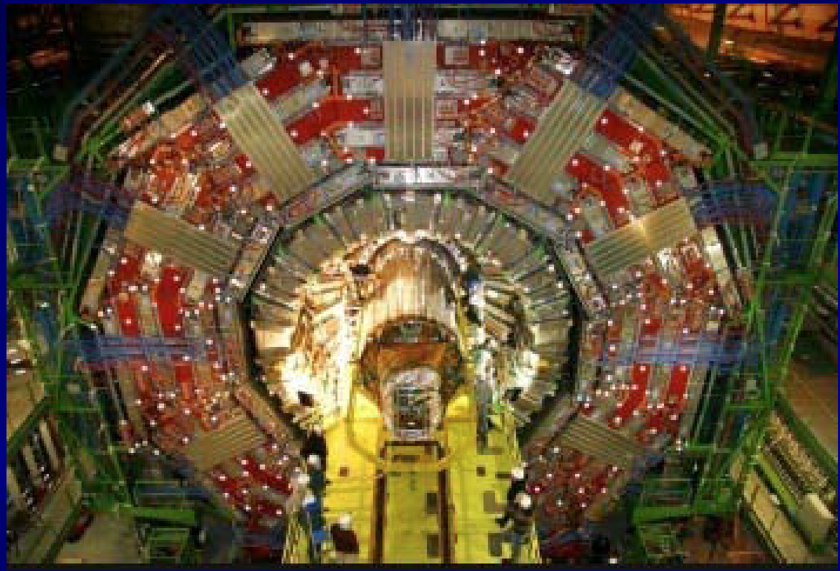
- "Interesting" physics is about 6-8 orders of magnitude below (EWK & Top)
- "Exciting" physics involving new particles/discoveries is ≥ 9 orders of magnitude below σ_{tot}
- We *just* ☺ need to efficiently identify these rare processes from the background before reading out & storing the whole event
- **Conclusion: Need to watch out for high transverse momentum electrons, jets or muons**

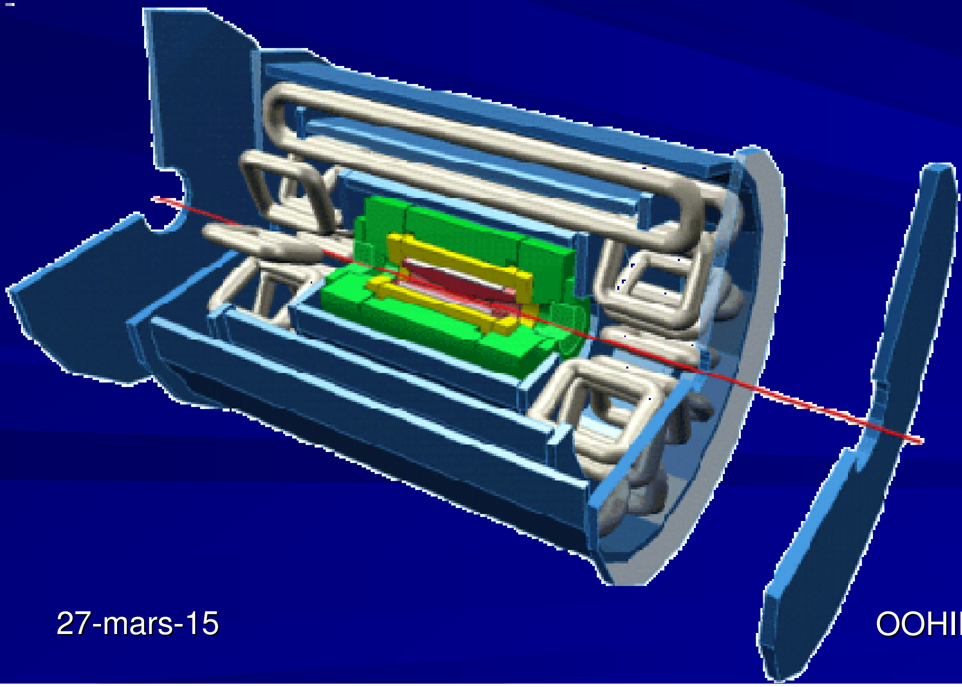
LHC Multilevels Selection scheme

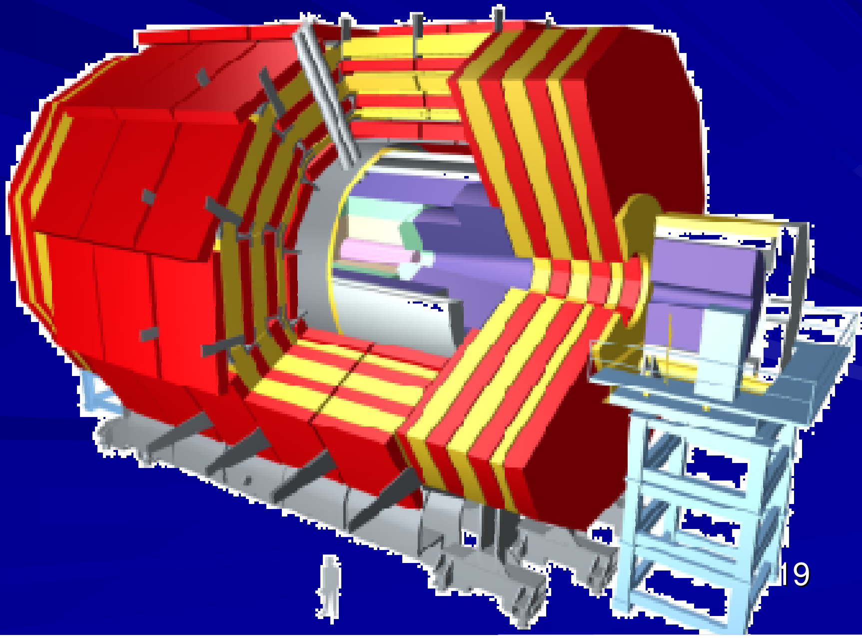


LHC Detectors

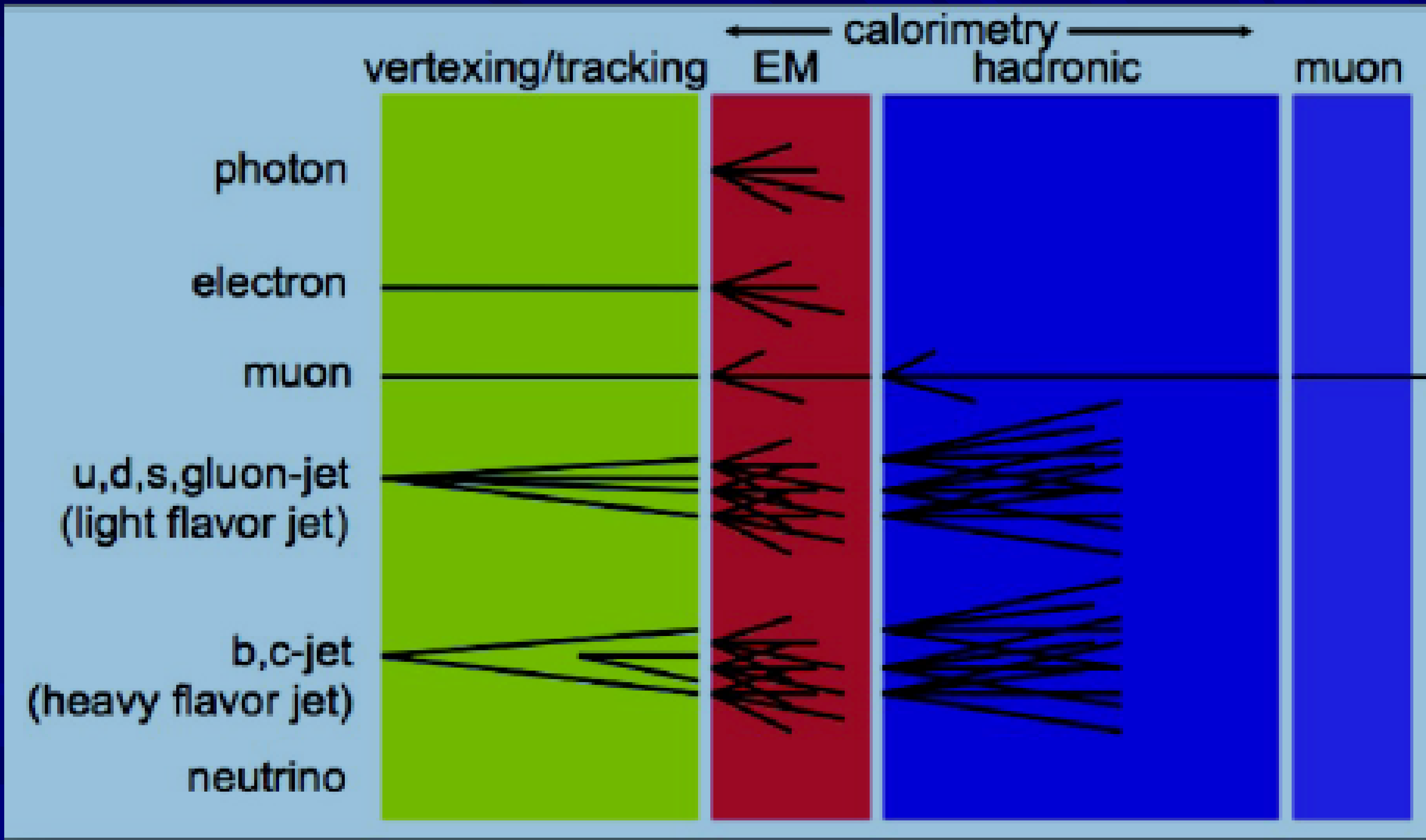


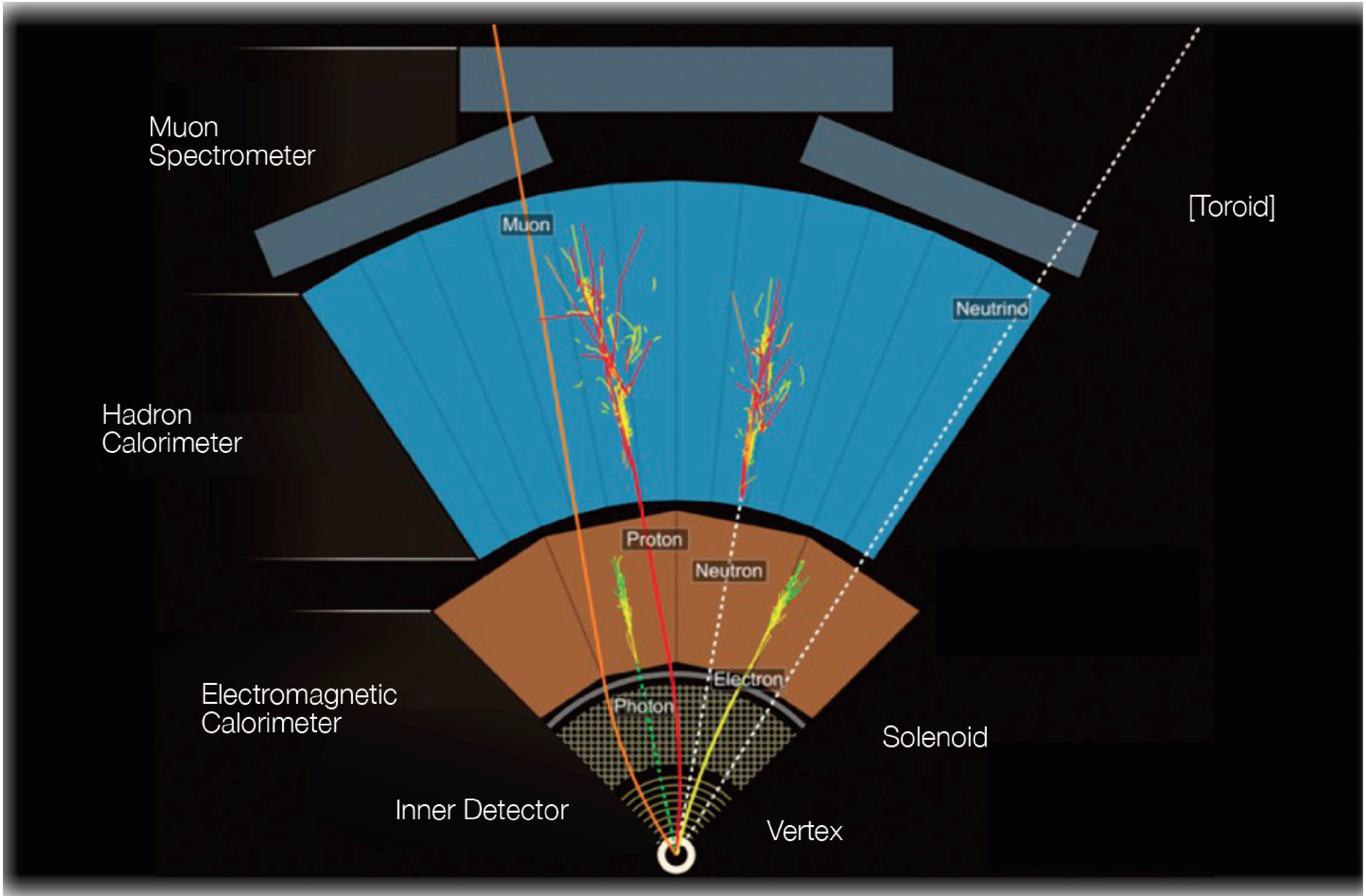


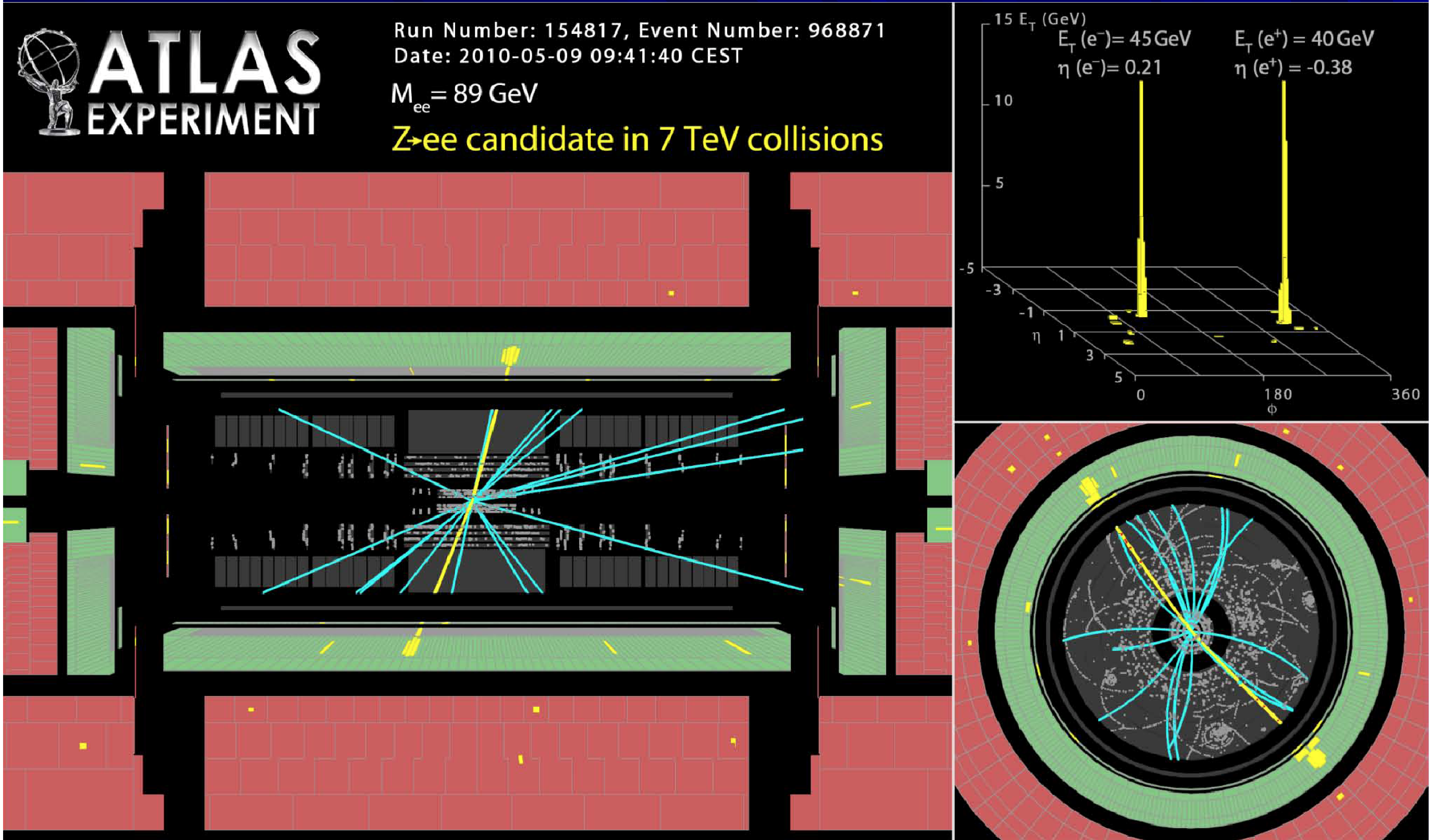




Physics signals & Trigger signatures

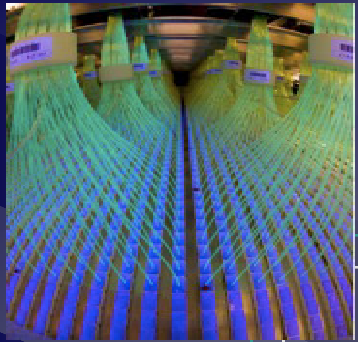


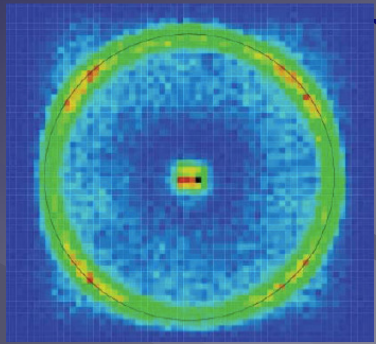

Muon
Spectrometer
[Toroid]
Muon
Neutrino
Hadron
Calorimeter
Proton
Neutron
Electron
Photon
Electromagnetic
Calorimeter
Solenoid
Inner Detector
Vertex

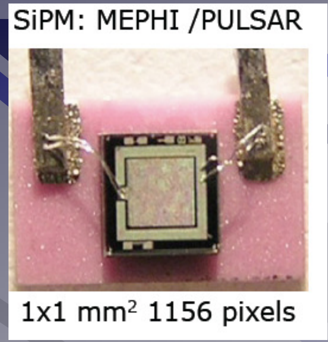

ATLAS EXPERIMENT
Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST
M ee = 89 GeV
Z→ee candidate in 7 TeV collisions
15 E T (GeV)
E T (e⁻)= 45GeV
η (e⁻)= 0.21
E T (e⁺) = 40GeV
η (e⁺) = -0.38
10
5
-5
-3
-1
η
1
3
5
0
180
360
ϕ

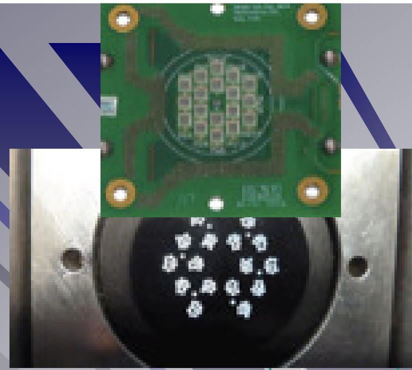
HEP ' state of the art ' parameters

- Beam
  - 230 superimpose event every 25 ns @ SLHC
  - 700 picosecond collision time @ CLIC
- Tracking and vertexing
  - The Micron or less
- Energy
  - From Kev to Tev with very good resolution
- Timing
  - We are speaking today to achieve the PICOSECOND
- # Channels
  - Billions due to 'pixellated & high granularity detectors
- integration, large scale apparatus









T2K
scintillators
WLS fiber
60000 SiPM

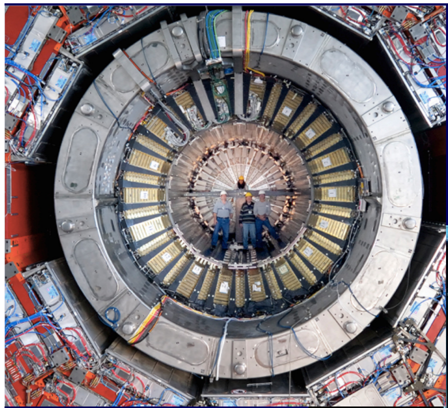
Belle2 RICHs
single γ

ILC - CALICE
$8x10^6$ SiPM

CMS HCAL
$2 x10^3$ SiPM

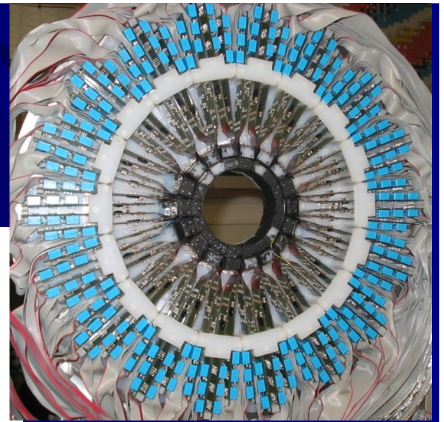
Some technologies that can make a breakthrough

Why a lot of experimental physicists are interested to TEP ?



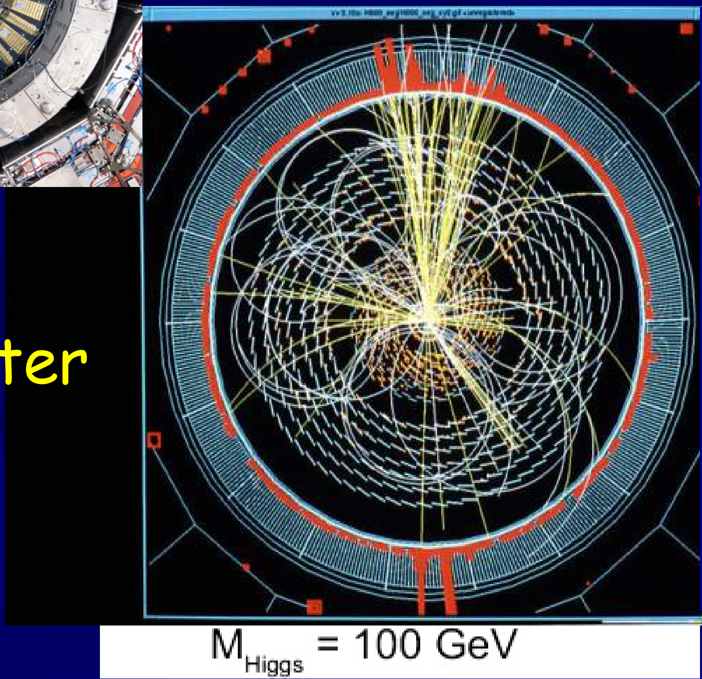
HEP & PET

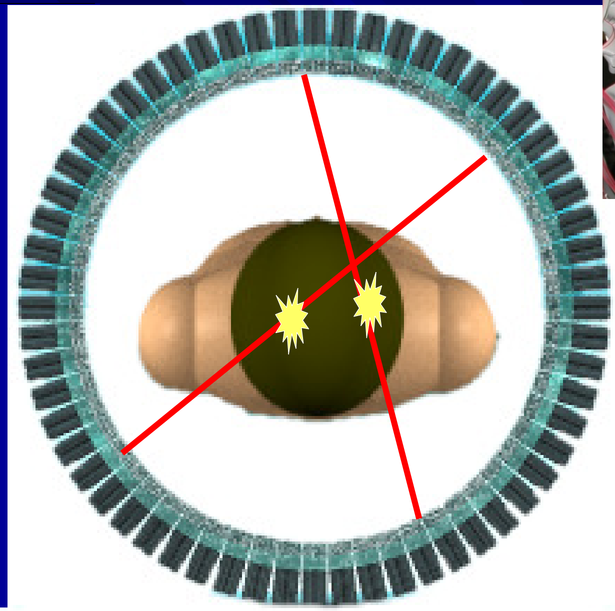
Similarities and differences



Calorimeter

HEP

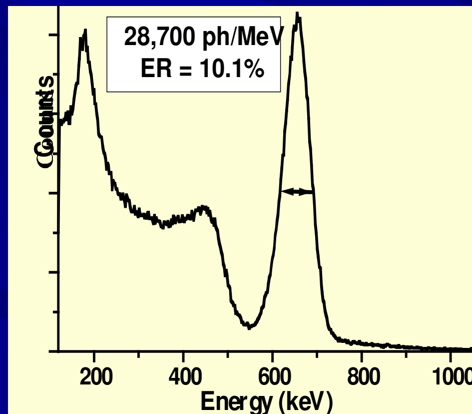




PET
Camera

Biomedical
Imaging

Similarities
Geometry and granularity
Detector (Crystals & scintillator)
Sensor Photodetectors (PMT,APD)
Digitizers: ADC,TDC,
Data volume (Gbytes)



Differences
Energy range
(10GeV → -511keV)
Event Rate 40 → 10 MHz

No synchronization
Self triggered elrctronics
Multiple vertices

A survey of common areas

LSO

- Material for photon detection
  - Standard : Crystal
    - From LEP/ L3 BGO ,LHC/ CMS PbO4
    - → Crystal Clear Collaboration.
  - Possible alternatives: LXenon, MG-RPC's ... ????

- Photon detectors :

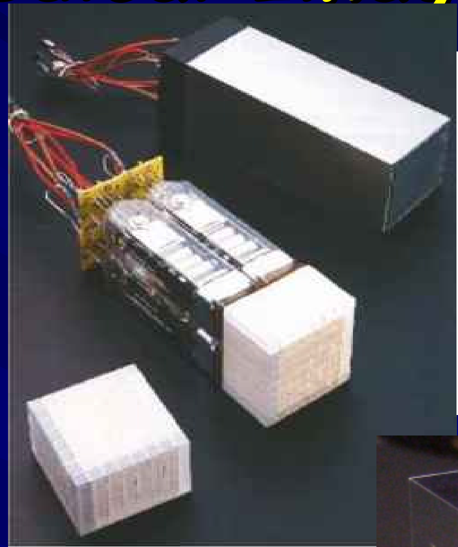
compact, high QE, high gain and stability
  - Standard : PMT ---> MAPMT --> MCP
  - Semiconductor : APD --> SiPM/MPPC,DSiPM

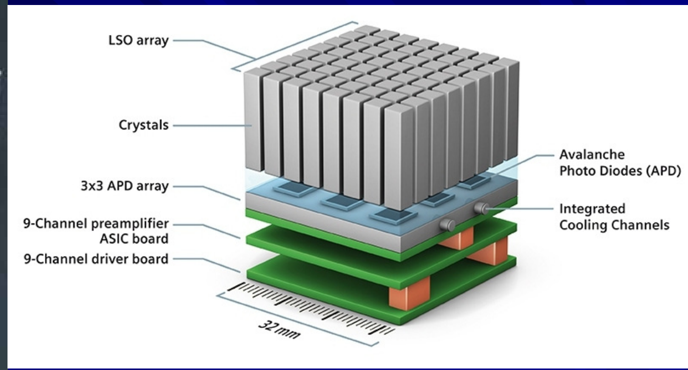
Scintillators for PET

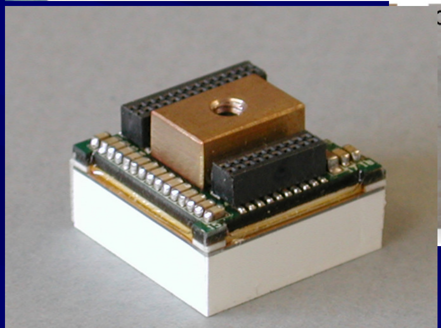
	1962	1977	1995	1999	2001	2003	2007
	NaI	BGO	GSO:Ce	LSO:Ce	LuAP:Ce	$LaBr_3$:Ce	LuAG:Ce
Density (g/cm^3)	3.67	7.13	6.71	7.40	8.34	5.29	6.73
Atomic number	51	75	59	66	65	47	63
Photofraction	0.17	0.35	0.25	0.32	0.30	0.13	0.30
Decay time (ns)	230	300	30-60	35-45	17	18	60
Light output (hv/MeV)	43000	8200	12500	27000	11400	70000	>25000
Peak emission (nm)	415	480	430	420	365	356	535
Refraction index	1.85	2.15	1.85	1.82	1.97	1.88	1.84

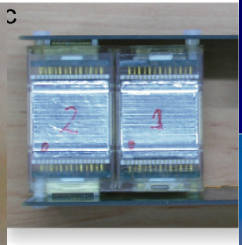
- No Scintillator with Superior Properties in All Aspects

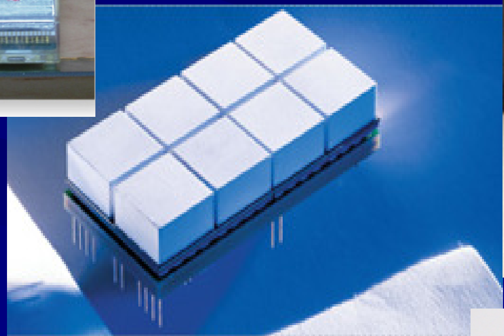
Scintillation Detectors in Nuclear Medical Imaging

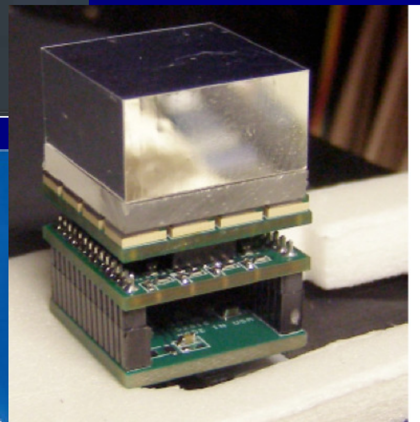


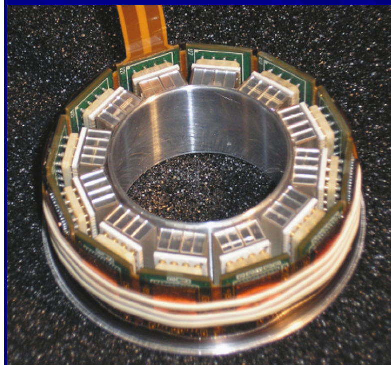


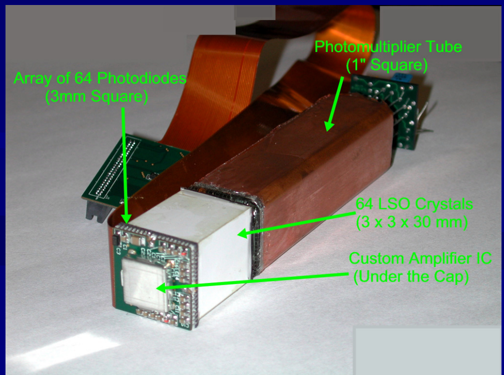


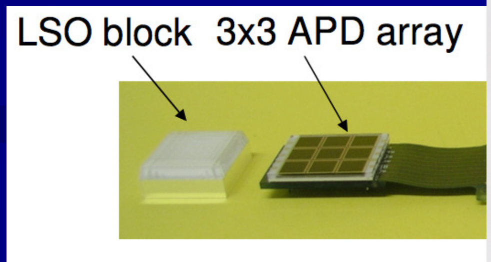


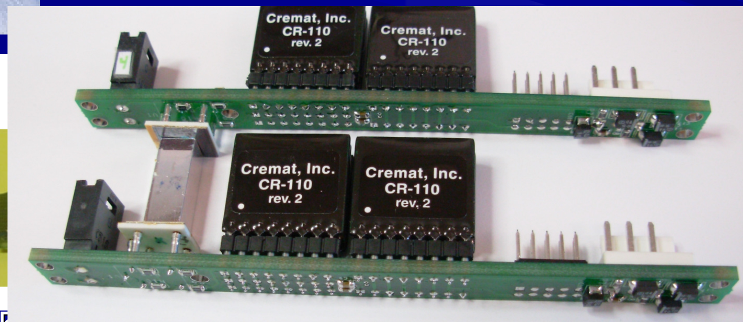




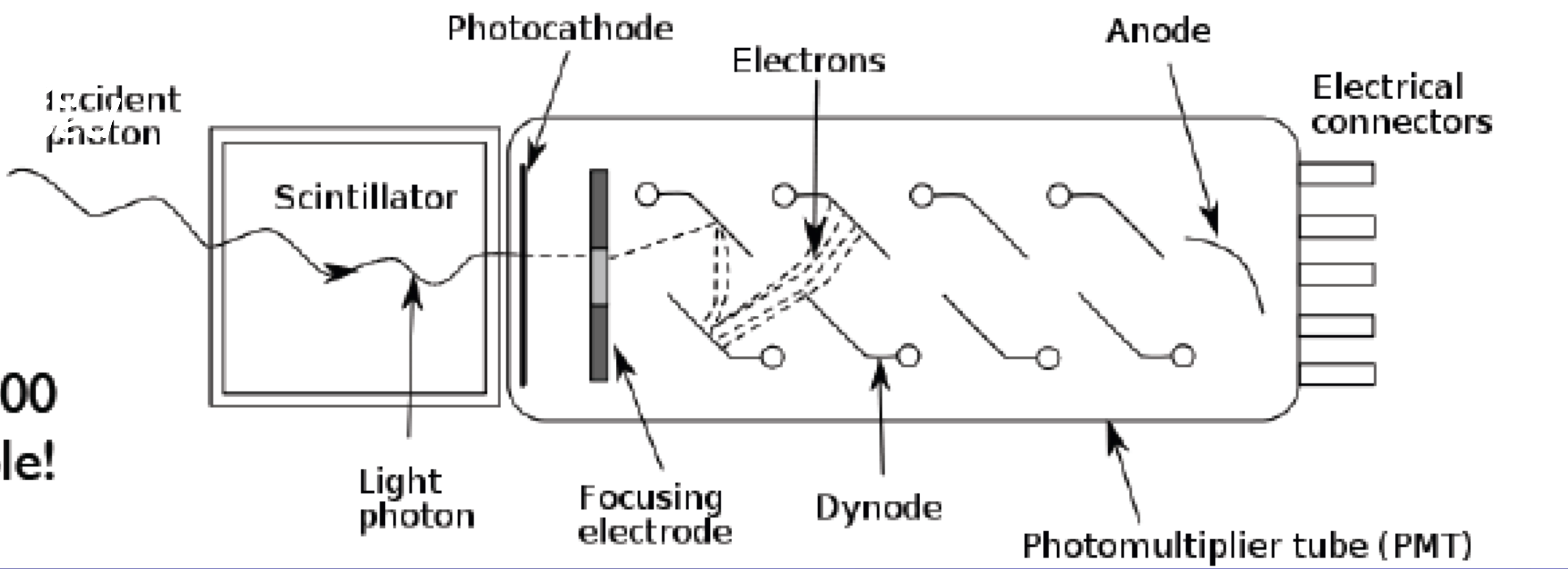








Photomultiplier Tube (PMT)



Gains of
x100,000,0000
are achievable!

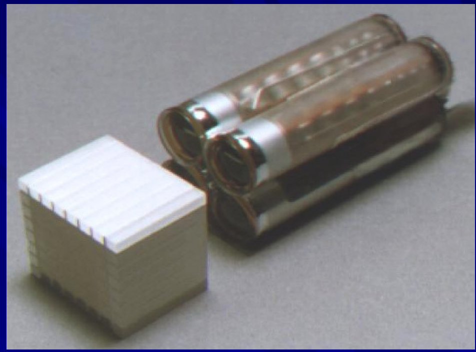
Use since 75 years

Large gain

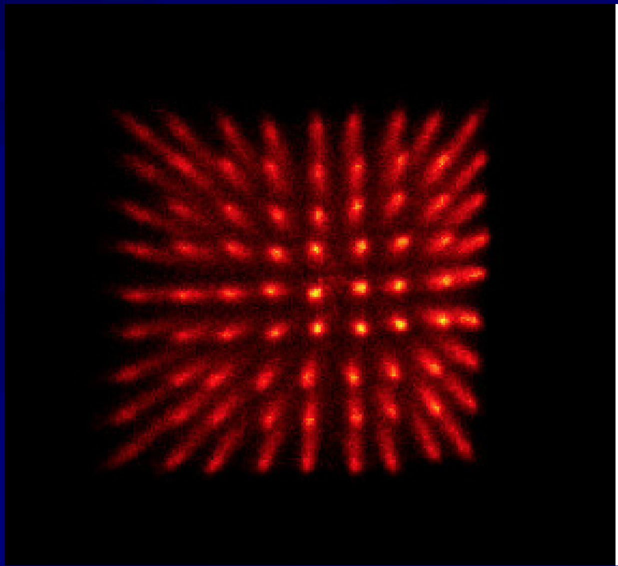
Bulky

Sensitive to magnetic field

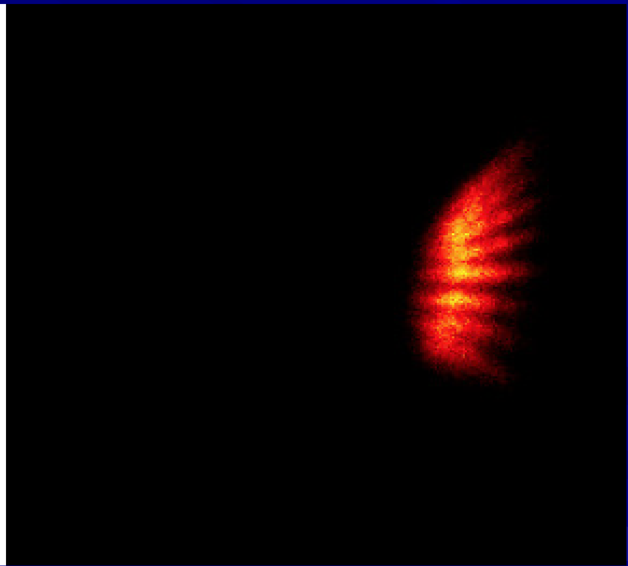
Effect of PMT Inside Magnetic Field



Conventional PET Detector Block



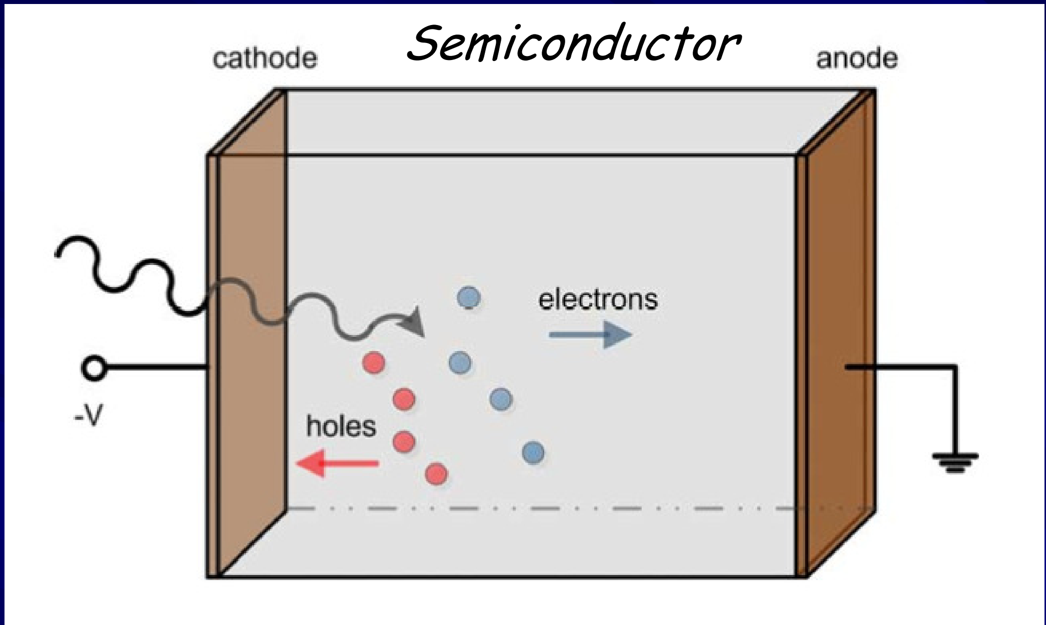
B=0

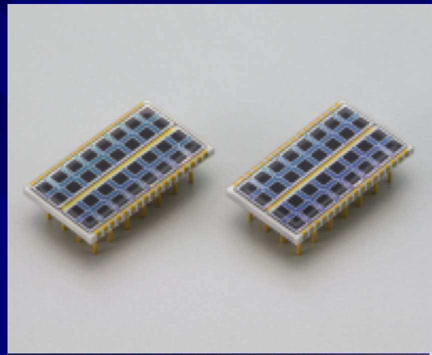


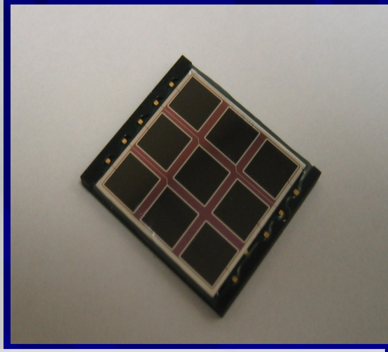
B≠0

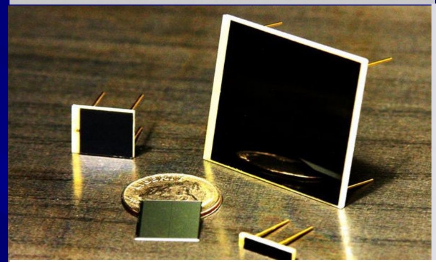
PMT does not work inside magnetic field!!

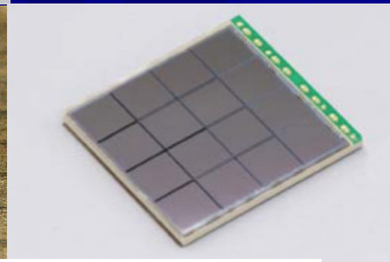
The'solid state' photodetector

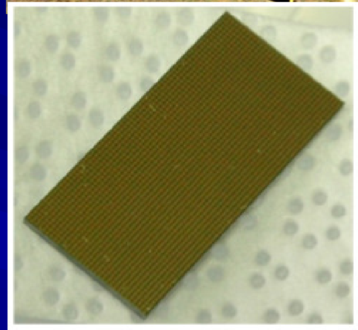


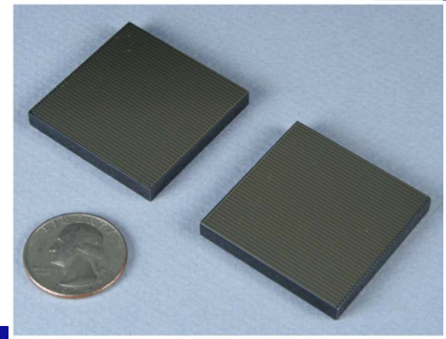












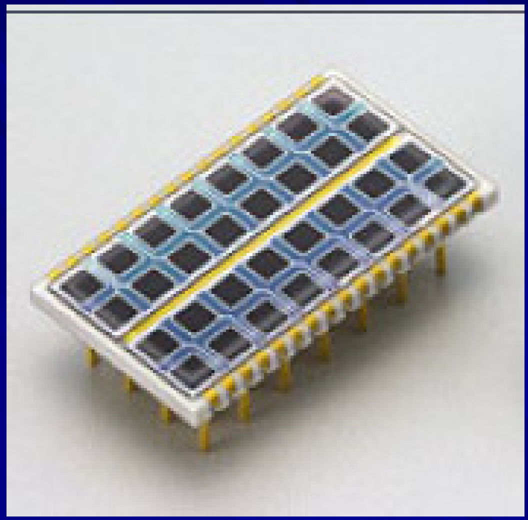
- *Electric field is created by an applied bias voltage*
- *e-h pairs are created by incoming radiation*
- *Electrons move to the anode and holes move to the cathode*
- *Electrical signal is induced on the electrodes by the moving charges*

Photodiode (PIN)
Avalanche Photodiode (APD)
Silicon Photomultiplier (SiPM)
CdZnTe
CdTe/

Evolution: PMT → Silicon photodetectors : SiPM

Advantages:

- *High QE (>70% for 400–600 nm)*
- *APD operating in Geiger mode*
- *High internal gain ($10^5 - 10^6$)*
- *Very fast response (~100 ps rise time)*
- *Capable of detecting single photoelectron*
- *Insensitive to magnetic field*

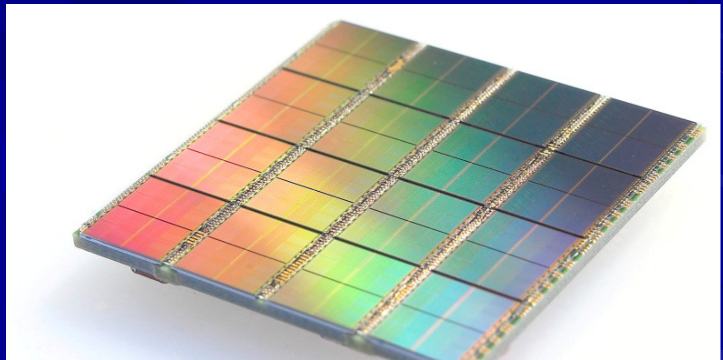


Drawbacks:

- *Geometric fill factor*
- *Limited micro-cell => limited dynamic range*

Sensitive to temperature and voltage fluctuations in analog mode, but not in purely digital mode

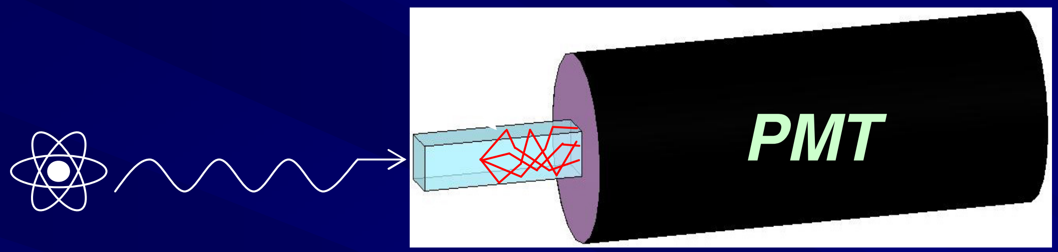
- *Cross-talk and after-pulses issues*



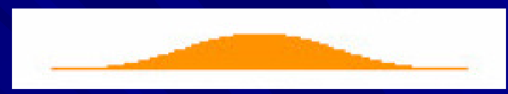
Philips Digital SiPM
32x32 mm2

Scintillation Detectors vs Solid-State Detectors

Scintillator



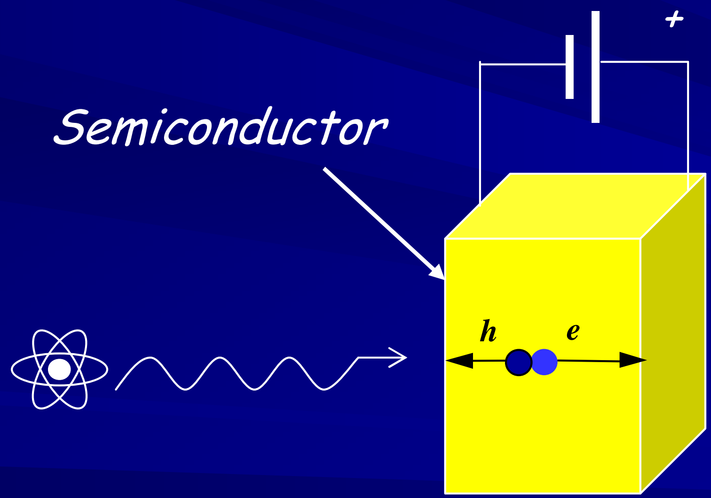
~1,500 e^-
@ 140 keV



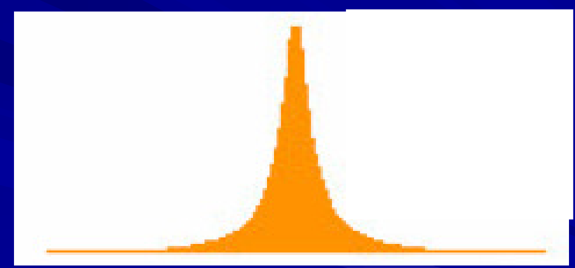
Energy per e^- ~ 10 – 200 eV

Gamma Ray --> Visible Light --> Electrical Signal (Indirect Detection)

Semiconductor



~30,000 e^-
@ 140 keV



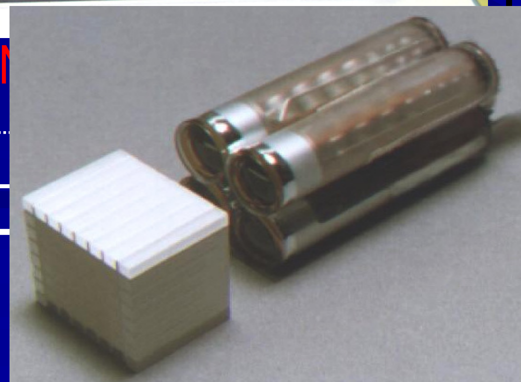
Energy per e^- ~ 3 – 5 eV

Gamma Ray --> Electrical Signal (Direct Detection)

Photodetector Technologies: A Comparison

Photo detector	PMT		
Technology	Vacuum-Based		
Gain	High		
Detection Efficiency	Low to Moderate	Hi	
Noise	Low	Mod	
Timing Response	Moderate to Fast	Sl	
Packaging	Bulky	Con	
Sensitivity to Magnetic Field	Yes	No	N
Bias Voltage	>1kV	~50V	100–

Conventional SPECT & PET detectors has been dominated by the use of PMT.



Photodetector Technologies: A Comparison

Photo detector	PMT	PIN	APD	SiPM
Technology	Vacuum-Based	Solid-State	Solid-State	Solid-State
Gain	High			
Detection Efficiency	Low to Moderate			
Noise	Low			
Timing Response	Moderate to Fast			
Packaging	Bulky			
Sensitivity to Magnetic Field	Yes			
Bias Voltage	>1kV	~50V	100–1000V	~50V

Cannot be used in PET/MRI & SPECT/MRI. The timing response is fast, but may be the limiting factor in next generation TOF PET.

Photodetector Technologies: A Comparison

Photo detector	PMT	PIN	APD	SiPM
Technology	Vacuum-Based	Solid-State	Solid-State	Solid-State
Gain	High	Poor	Moderate	High
Detection Efficiency	[illegible]	[illegible]	High	Moderate to High
Noise	[illegible]	[illegible]	Moderate	Moderate
Timing Response	[illegible]	[illegible]	Slow	Fast
Packaging	Bulky	Compact	Compact	Compact
Sensitivity to Magnetic Field	Yes	No	No	No
Bias Voltage	>1kV	~50V	100–1000V	~50V

Has low SNR and not suitable for TOF PET.

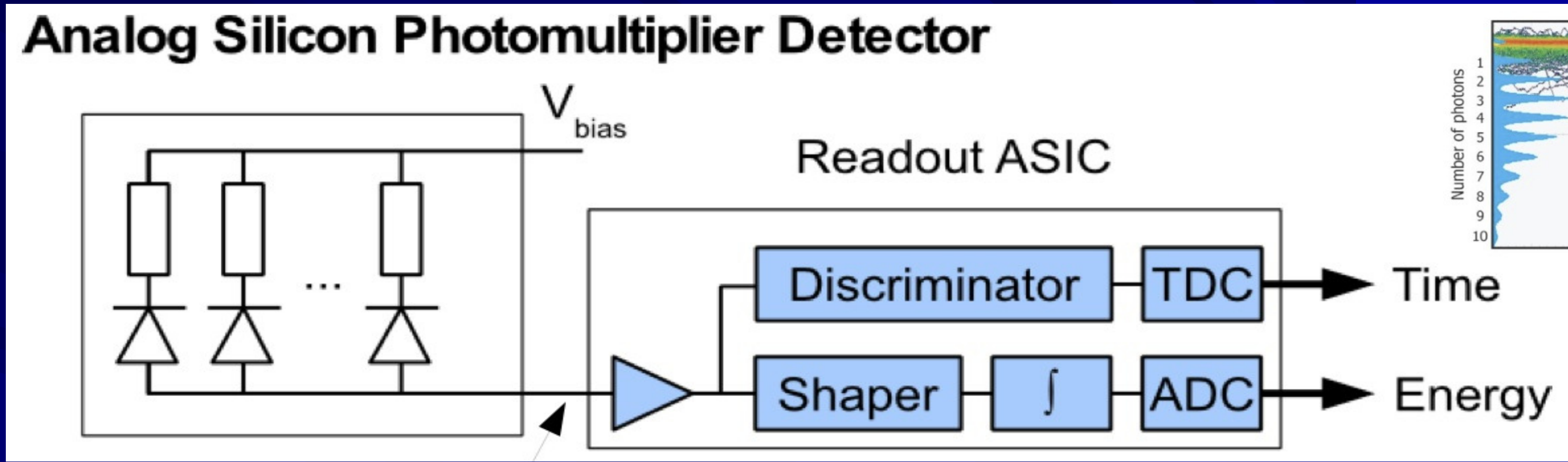
Photodetector Technologies: A Comparison

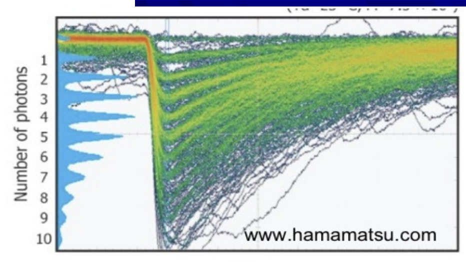
Photo detector	PMT	PIN	APD	SiPM
Technology	Vacuum-Based	Solid-State	Solid-State	Solid-State
Gain	High	Poor	Moderate	High
Detection Efficiency	Low to Mo	High	High	Low to Moderate
Noise	Low	[illegible]	ate	Moderate
Timing Response	Moderate t	[illegible]	y	Fast
Packaging	Bulky	[illegible]	act	Compact
Sensitivity to Magnetic Field	Yes	No	No	No
Bias Voltage	>1kV	~50V	100–1000V	~50V

Good choice for both TOF PET, PET/MRI & SPECT/MRI

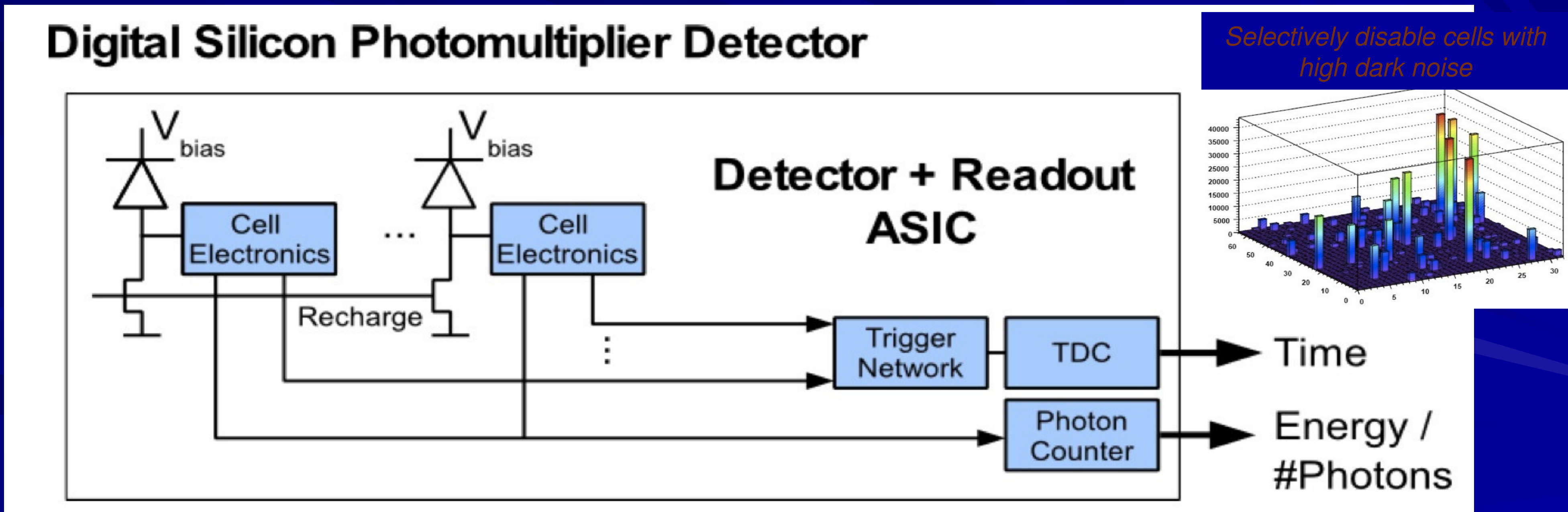
Digital SiPM detectors (PDPC)

Analog signal sums many photons



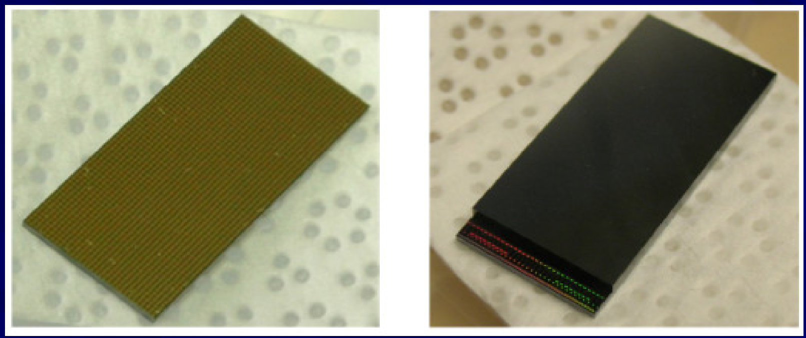


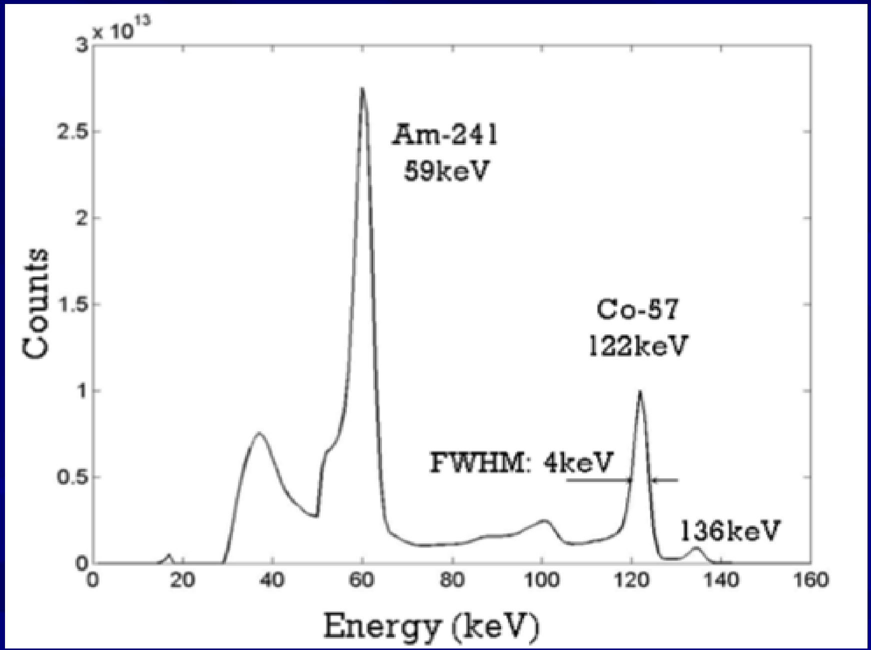
Selectively disable cells with high dark noise



Examples of CdTe/CdZnTe Detectors for SPECT and PET

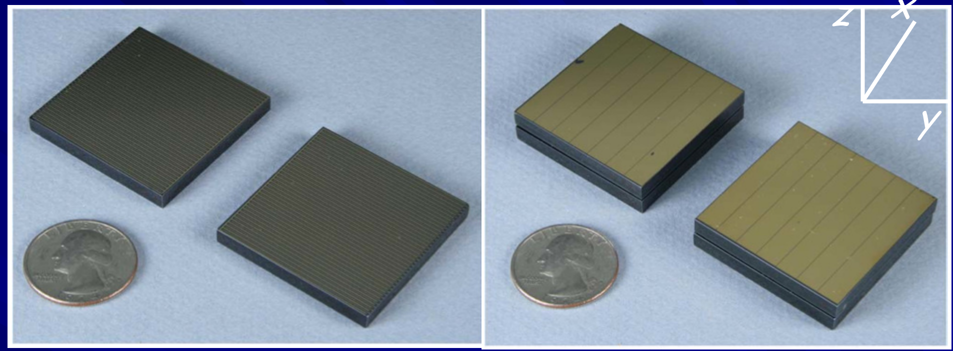
CdTe: 11x22x1 mm³, 350 µm pixels



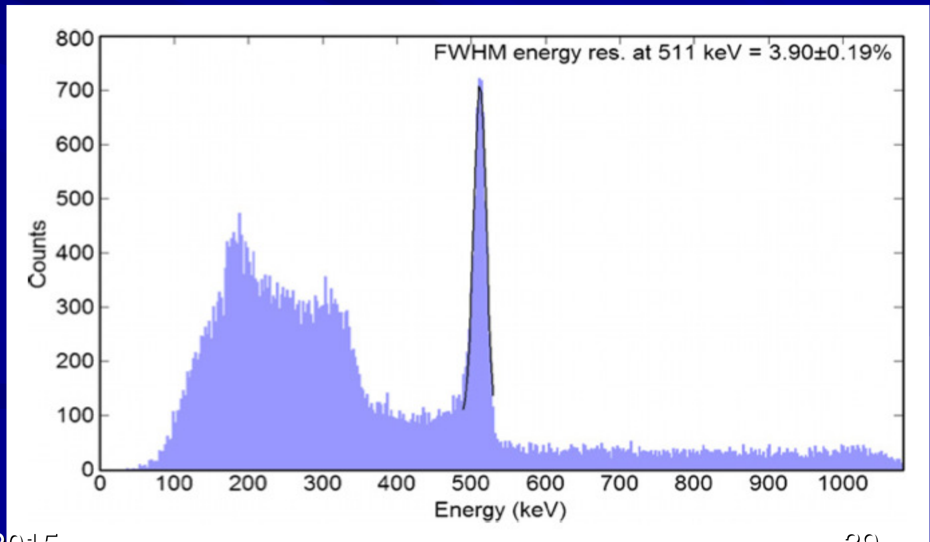


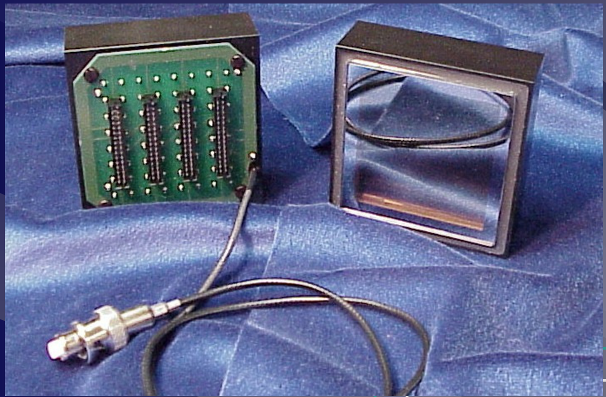
Source: L.J. Meng, et al., Nucl. Instr. Meth., vol. A604, 548 (2009)
Y. Gu, et al., Phys. Med. Biol., vol. 56, 1563 (2011)

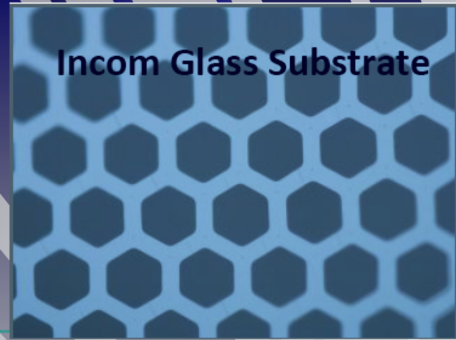
CdZnTe: 39x39x5 mm³, double-sided strip



Edge-on geometry, 3-D positioning
X position: anode strip, 1 mm pitch
Z position: cathode-anode ratio, ~1 mm
Y position: cathode strip, 5 mm pitch





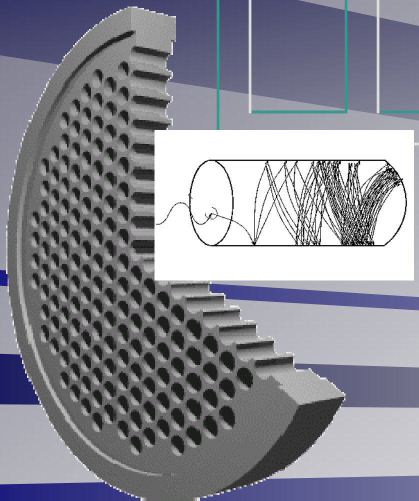


ALD Nanolayer

Photek, HPK, Burle-Photonis 2" x 2"

The large area Micro Channel Plate

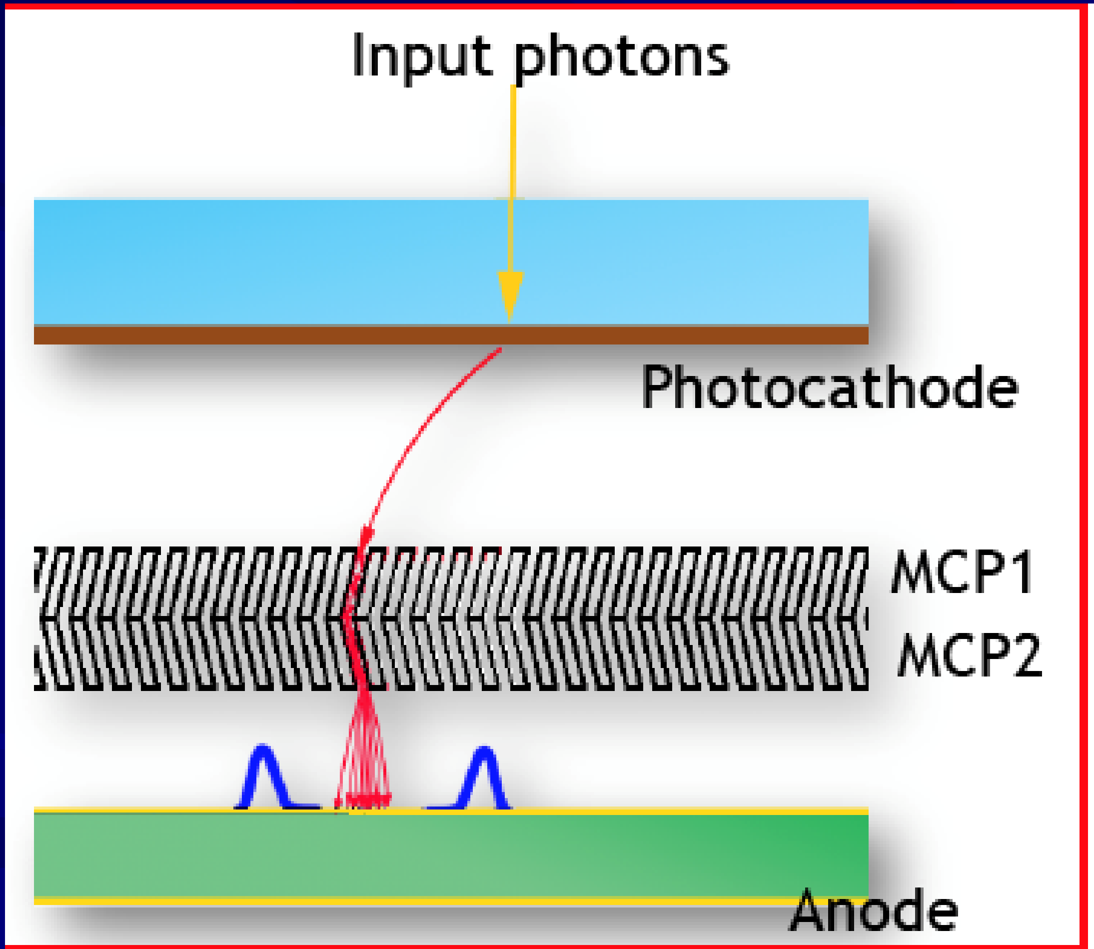
Coming soon !

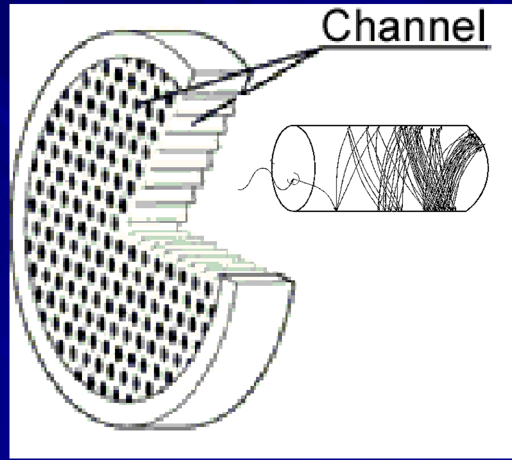


http://psec.uchicago.edu

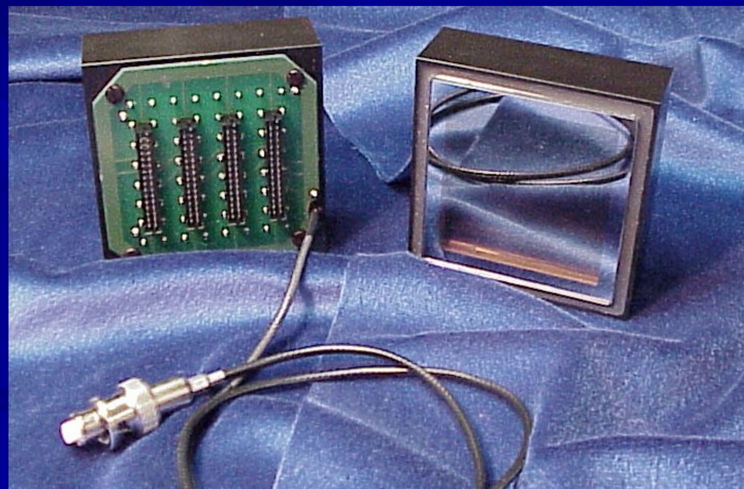
Micro Channel Plate → How does it work ?

- High,gain>10^7,low noise,low power, $\sigma(t)<10$ psec, $\sigma(x)<\$1$mm
- Goal → large area, low cost:



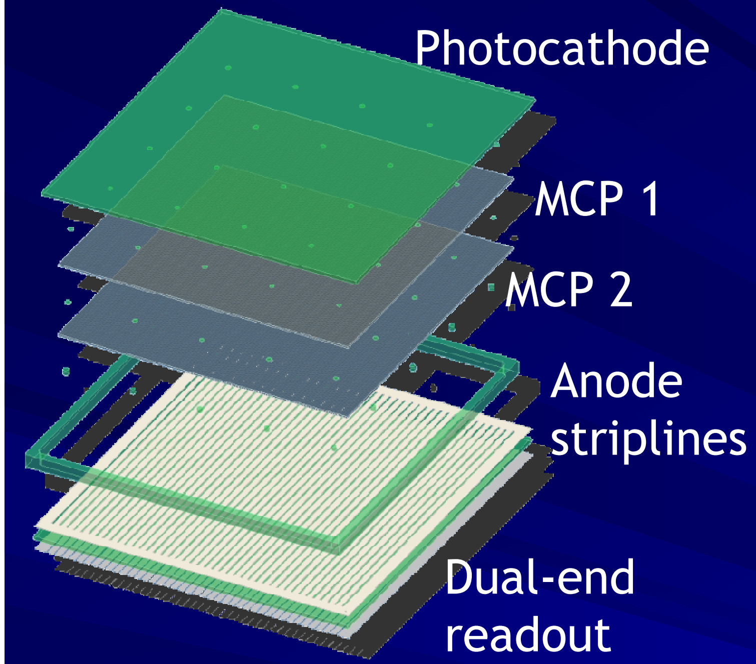


pore sizes 2-20μm



Photonis

Large Area Micro-Channel Plates Devices



LAPPD project : Chicago-ANL-Hawaii

*Large Area MCP pad **8" x 8"***

Transmission lines 2D readout:

limits the number of electronic channels compared to pixels

Goal: Both position σ(mm²) and timing

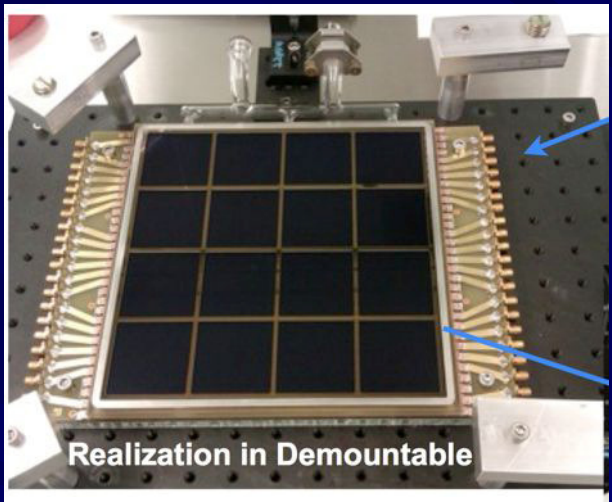
σ (10-100ps)

Electronics

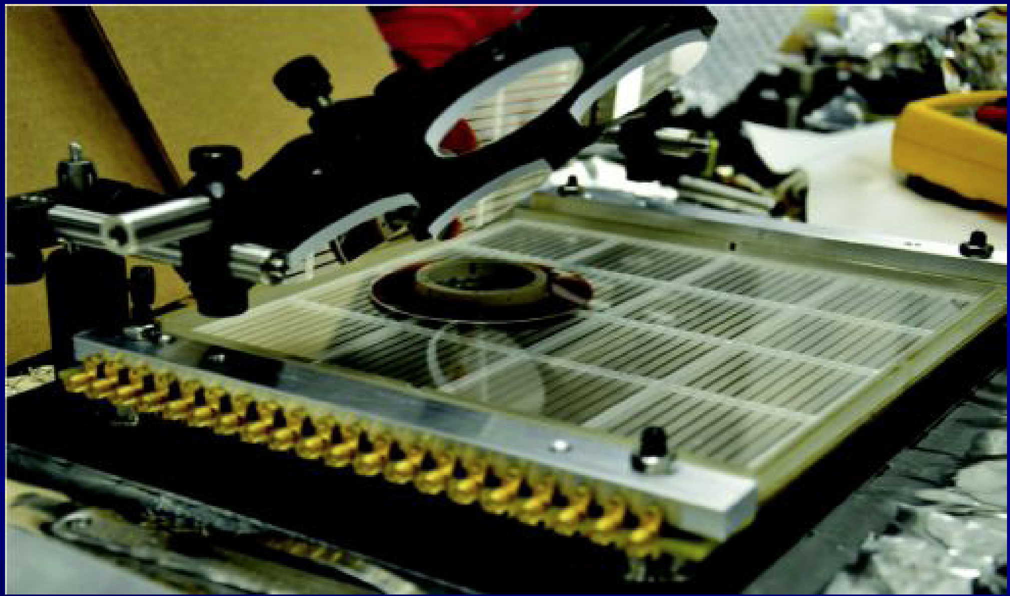
PSI, Orsay/Saclay, Chicago-Hawaii

- GigaSample/s Waveform Sampling and Digital Processing

Workshop on Pico-second sensors,
LPC Clermont-Ferrand March 12-14th 2014



Coming soon

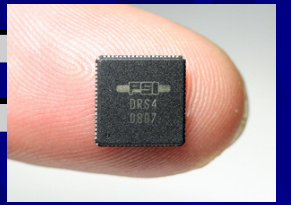


A Super Module holds 12 tiles in 32 rows.15 waveform sampling ASICS on each end of the tray Digitze 90 strips. 2$layers of local Processing (Altera) measuer extract Charge,time,positon,goodnessof fit

- ***Application in tracker sampling calorimeters & PET***

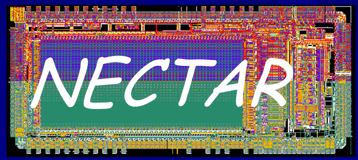
Some words about electronics

A survey of common area (cont't)

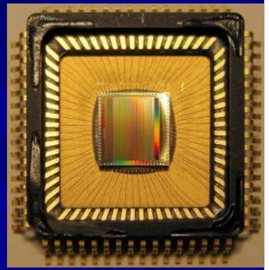


- Front end electronics & signal treatment
  - Fast shaping, integrated, low noise, low power, self trigger
  - Digital filtering and signal analysis

    --> Waveform Digitizer :SCA



Giga sampling chip
LAL-Saclay)

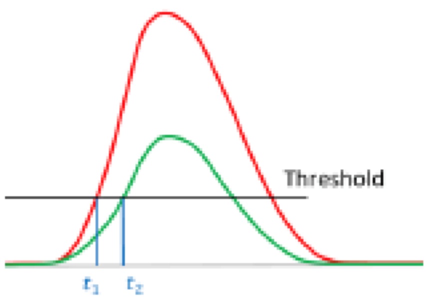


DRS4 (PSI)

- Trigger & DAQ
  - Pipeline and parallel read-out → FPGA
  - Feature extraction techniques →like Time Of Flight (TOF)
  - Real Time selection → GPU's image processing
  - High bandwidth networks → new telecom standard (xTCA)
- Computing & software : handling high quantity of data
  - Reconstruction, simulation & modelling --> GATE
- Global design
  - Compact integration of large number of channels

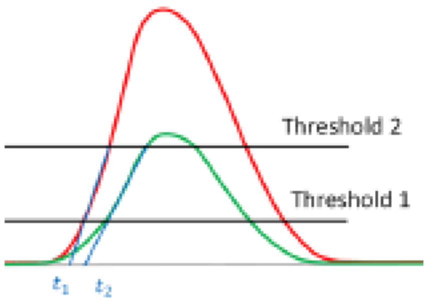
Timing extraction method

Single threshold



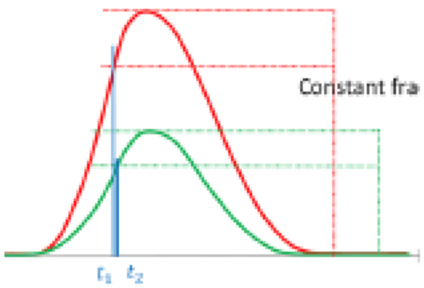
The single threshold is the least precise time extraction measurement. It has the advantage of simplicity.

Multiple threshold



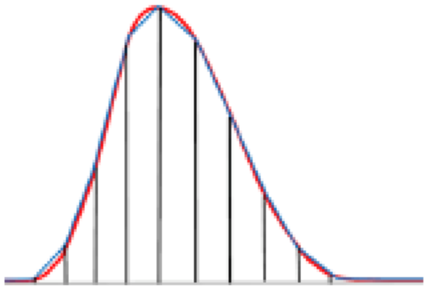
The multiple threshold method takes into account the finite slope of the signals. It is still easy to implement.

Constant fraction



The constant fraction algorithm is very often used due to its relatively good performance and its simplicity.

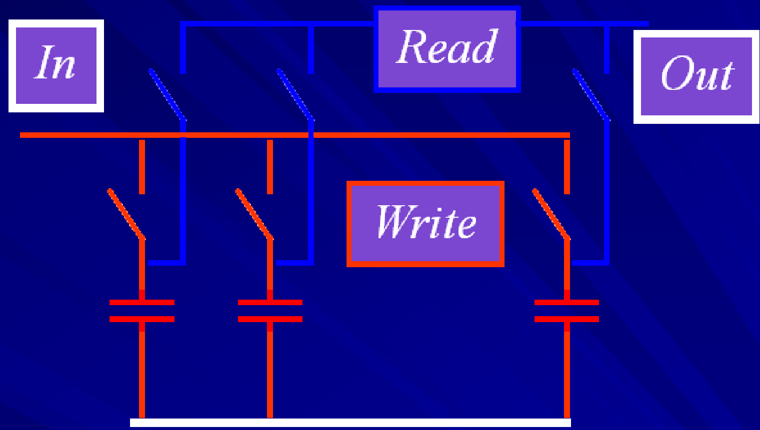
Waveform sampling



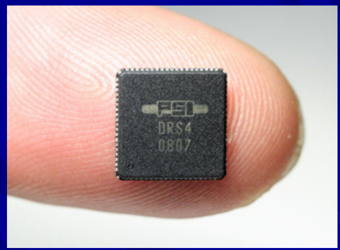
The waveform sampling above the Nyquist frequency is the best algorithm since it is preserves the signal integrity.

Analog memories → Waveform digitizers

Switched Capacitor Arrays (SCA)
Store signal on capacitors (~pF)
High speed (up to 5 GHz)
Slower readout (~10MHz)
High channel density
9 channels on 5x5 mm^2
Dynamic range : 10-13 bits
Depth : 100-2000 cells
Low power (10-40 mW / channel)
Low cost (~ 10€ / channel)

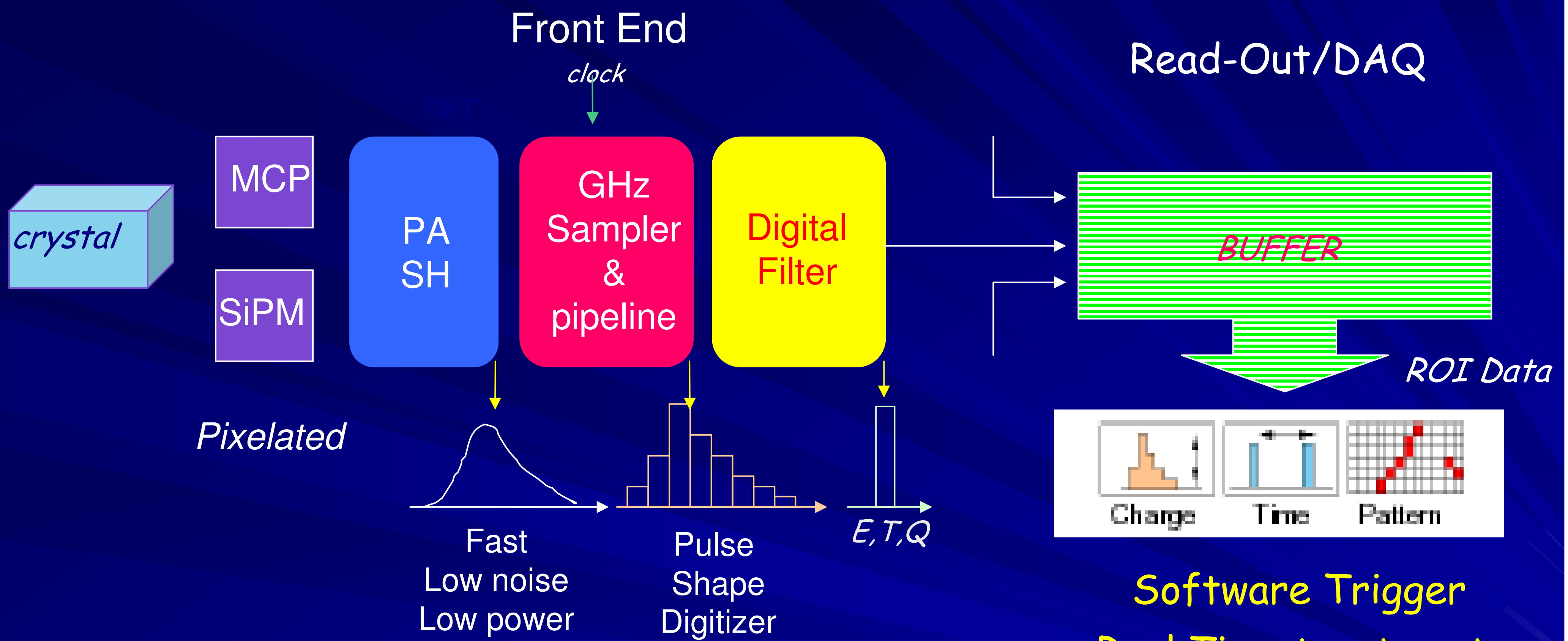


DRS4



But possible loss of data integrity
limited deeph
leakage current,
non linear timing

Exemple of Conceptual TOF-PET architecture model

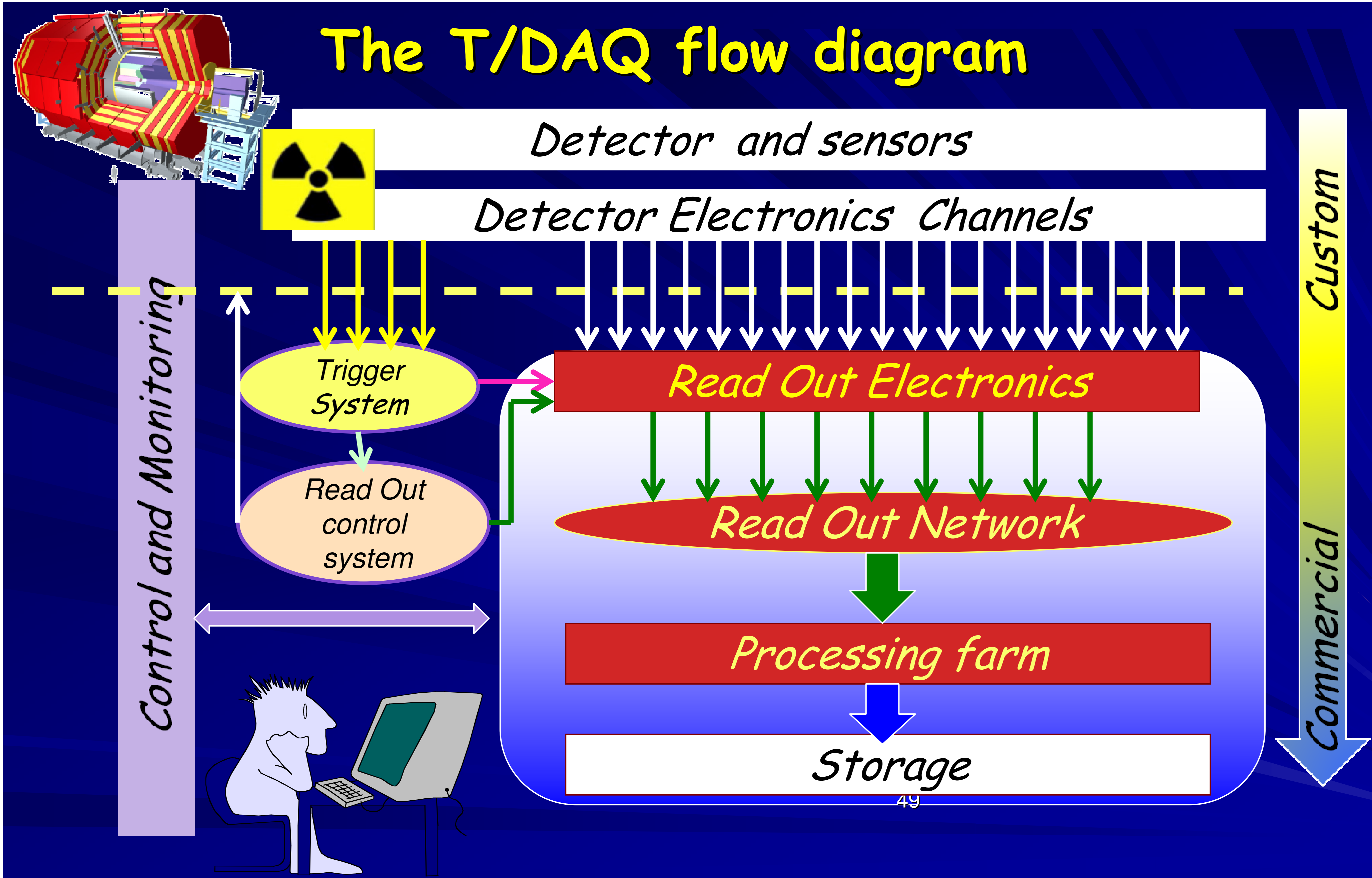


Software Trigger

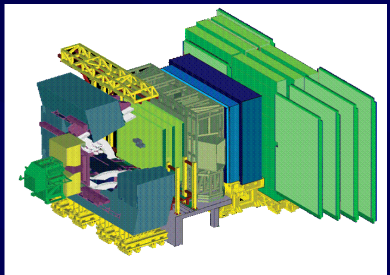
Real Time treatment

- ♦Free-running analog waveform sampling and digitizer (SCA)
- ♦ Digital filter used to extract pulse amplitude and high resolution timing (FPGA)
- ♦ Pipelined processing architecture to avoid deadtimes (GPU's)
- ♦Parallel digital read out
- ♦Terabit network for communication and processing (xTCA)

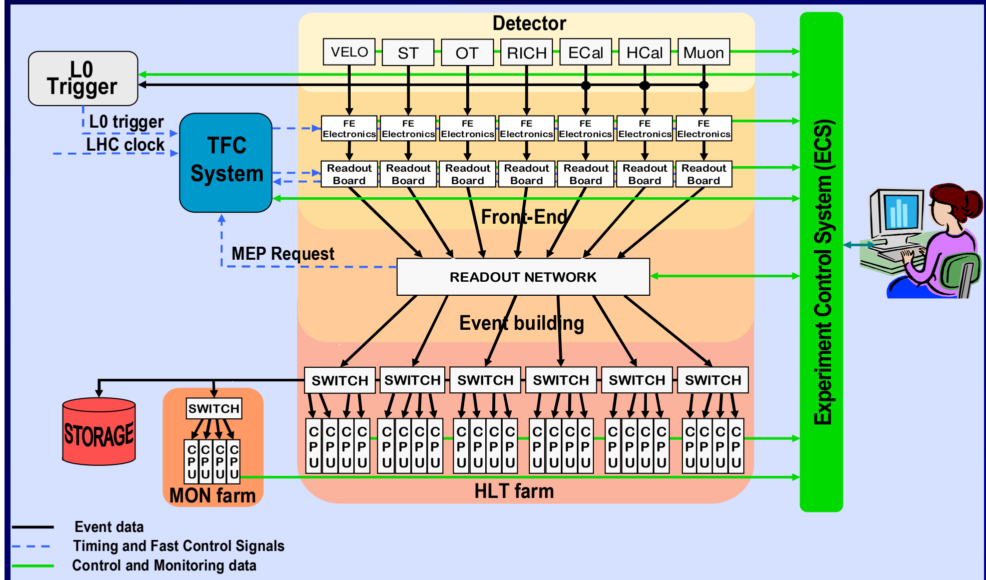
The T/DAQ flow diagram



DAQ = The evolution of architecture

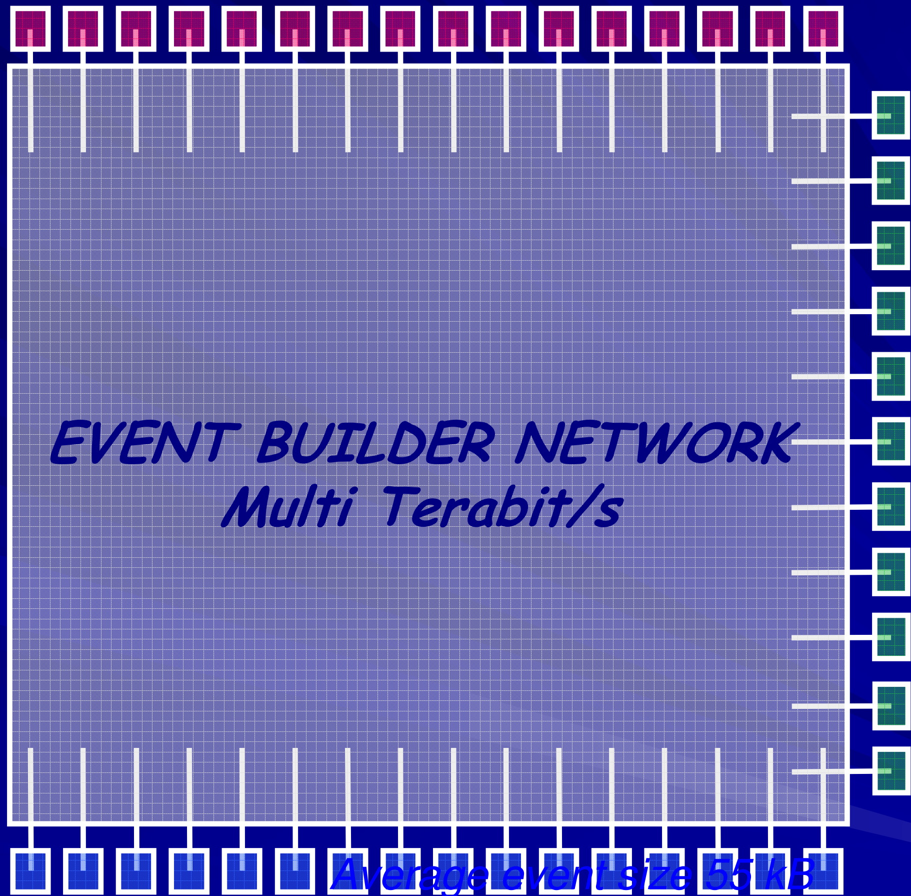


LHCb



Average event size 55 kB
Average rate into farm 1 MHz
Average rate to tape 4 – 5 kHz

Direct network access From Detectors and Machine



Controls & Storage servers

Trigger Farms & Analysis

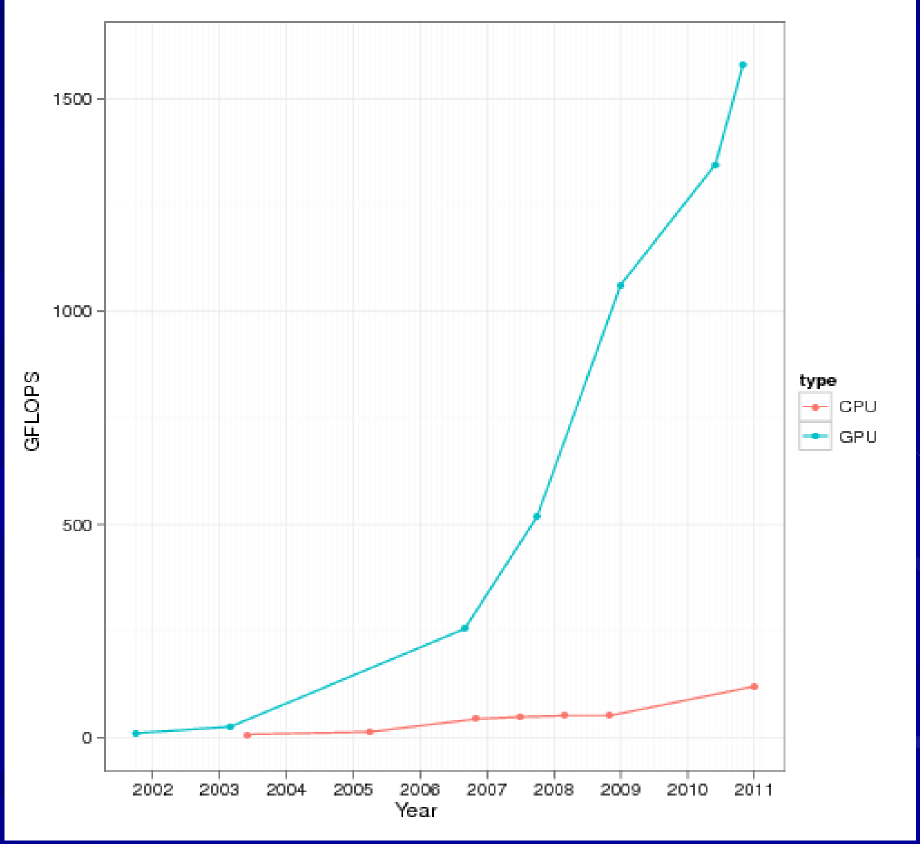
Average event size 55 kB
Average rate into farm 1 MHz
Average rate to tape 4 – 5 kHz

Computer farm evolution → GPU's

- GPUs: Graphical Processor Units :

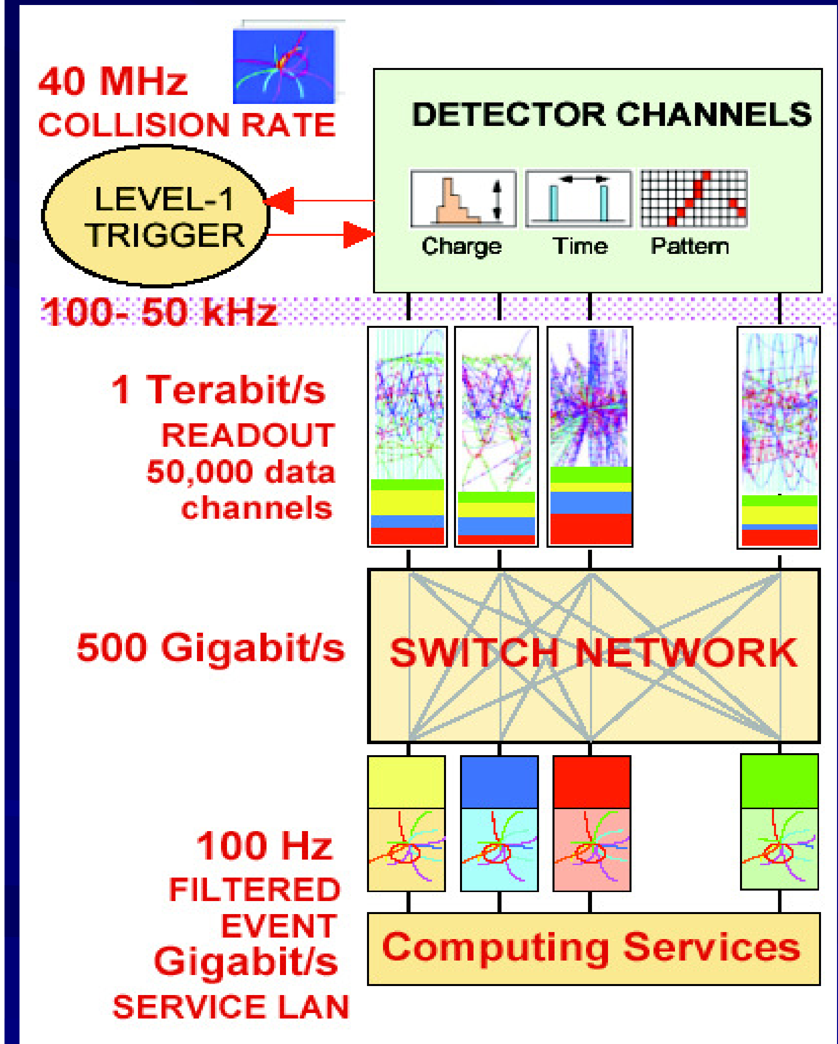
highly parallel, multi-threaded, multicore processors with remarkable computational power and high memory bandwidth: promising candidate for fast track fitting at high luminosity

From the video game world



DAQ = Pipeline Architectures

LHC

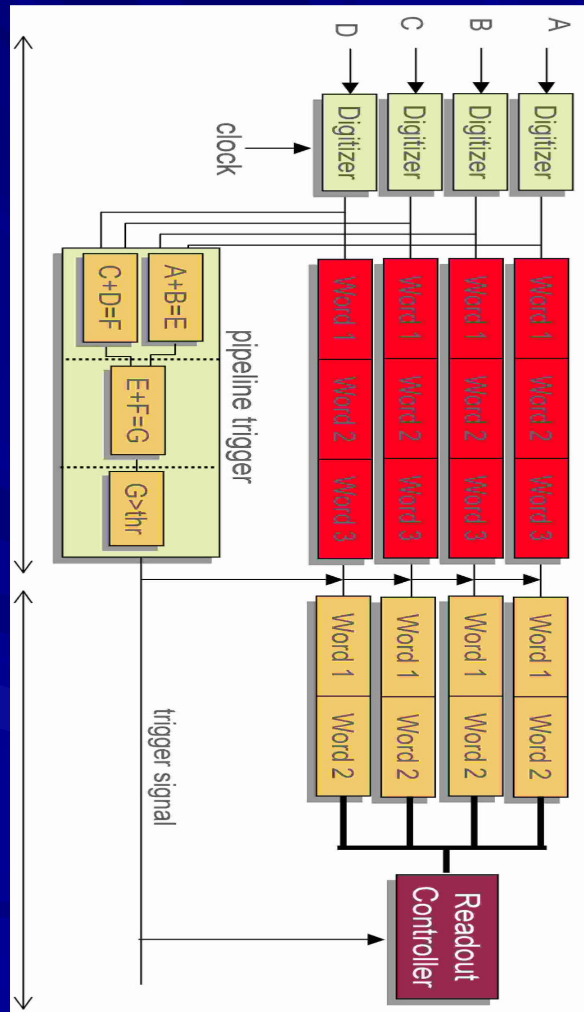


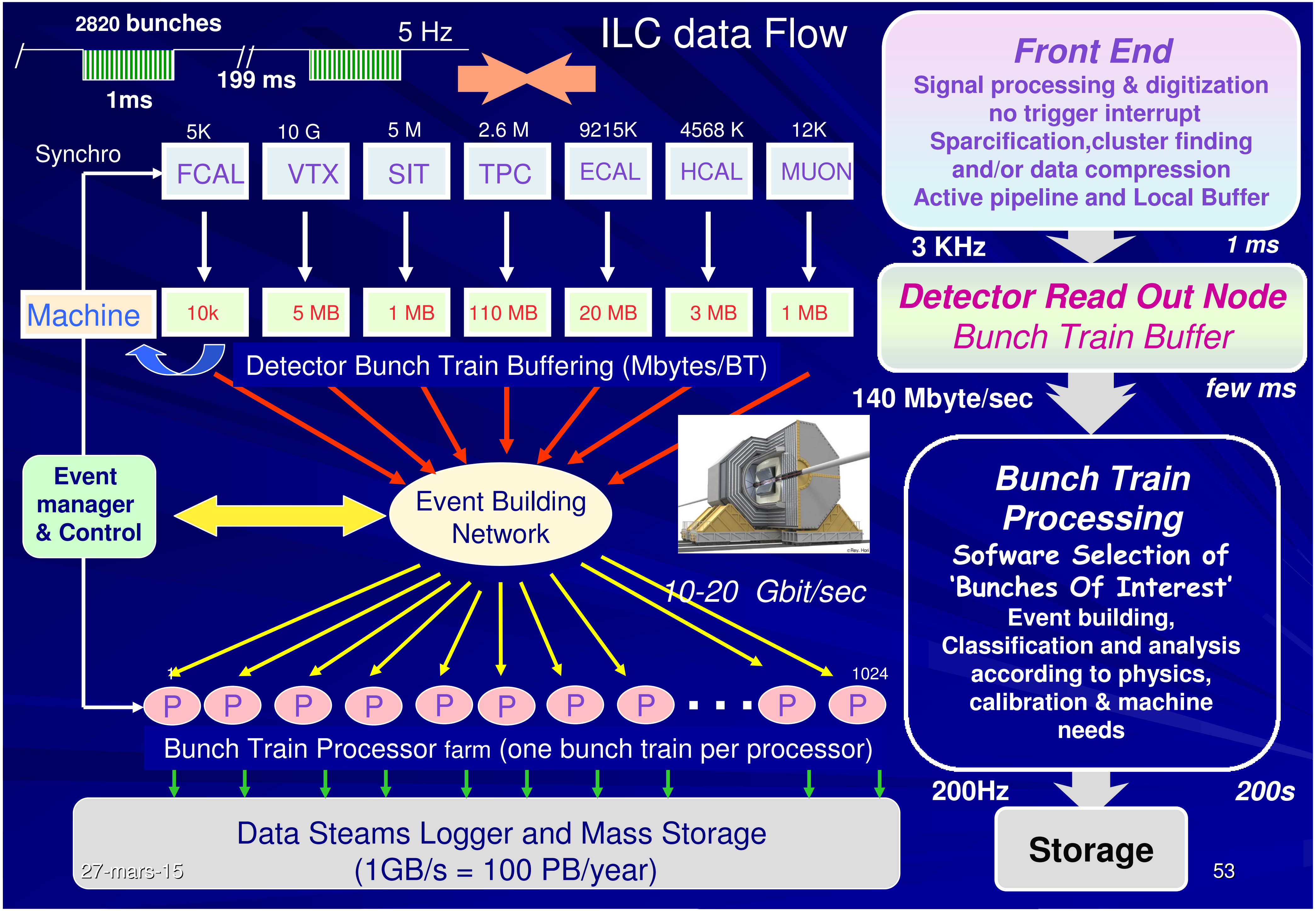
Digitisation

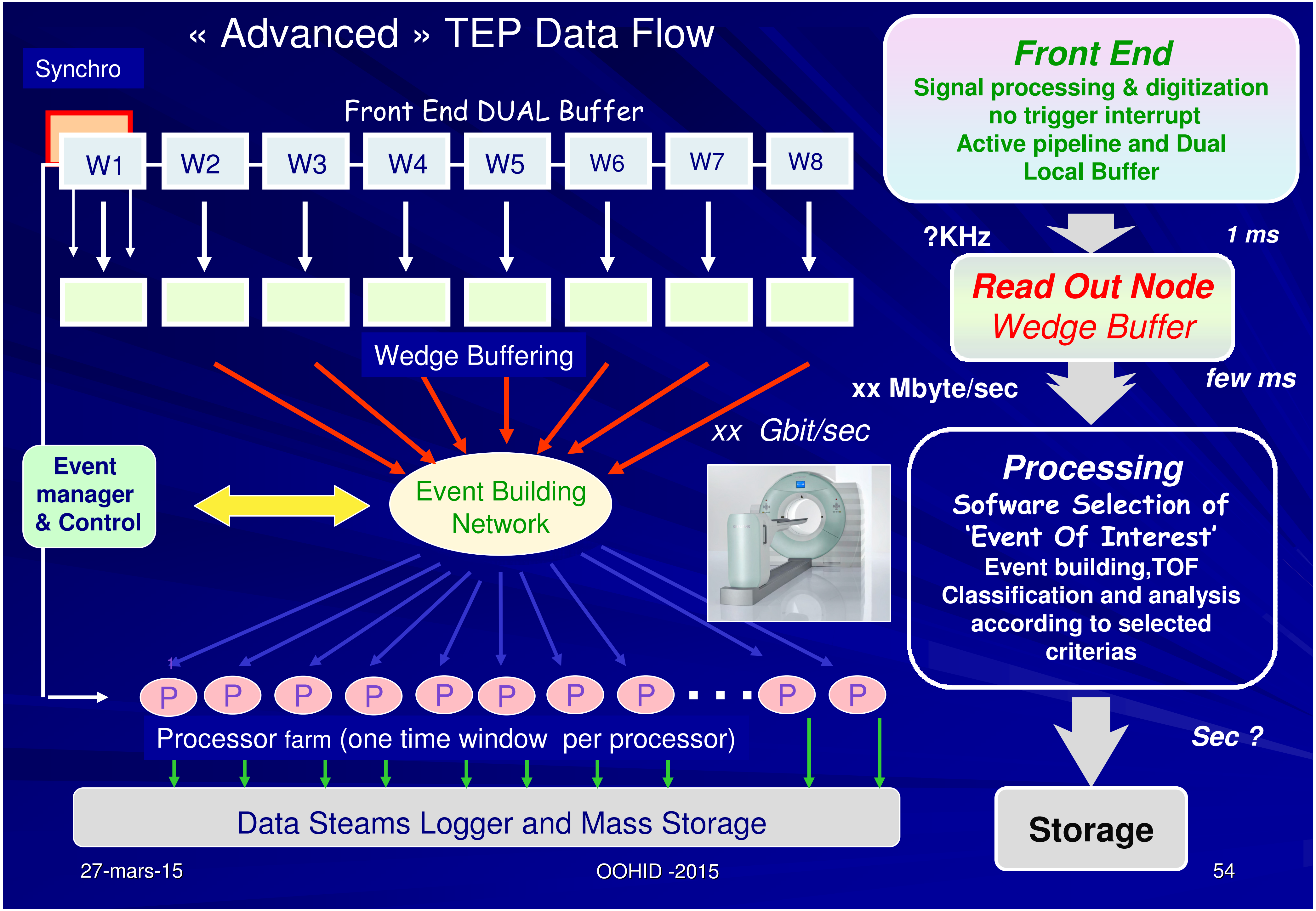
Pipeline

Event builder

Future PET



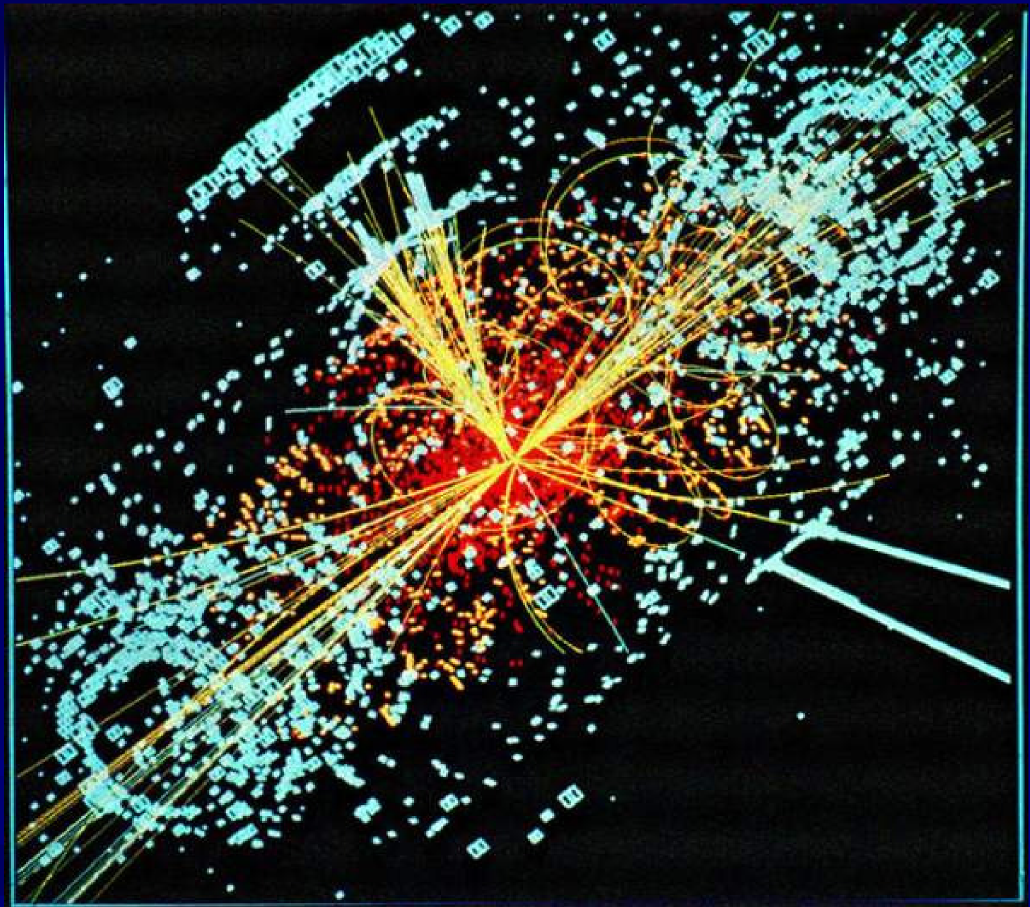

ILC data Flow
2820 bunches
5 Hz
199 ms
1ms
Synchro
5K
10 G
5 M
2.6 M
9215K
4568 K
12K
FCAL
VTX
SIT
TPC
ECAL
HCAL
MUON
Machine
10k
5 MB
1 MB
110 MB
20 MB
3 MB
1 MB
Detector Bunch Train Buffering (Mbytes/BT)
Event manager & Control
Event Building Network
10-20 Gbit/sec
1
1024
P P P P P P P P . . . P P
Bunch Train Processor farm (one bunch train per processor)
Data Steams Logger and Mass Storage
(1GB/s = 100 PB/year)
Front End
Signal processing & digitization
no trigger interrupt
Sparcification,cluster finding
and/or data compression
Active pipeline and Local Buffer
3 KHz
1 ms
Detector Read Out Node
Bunch Train Buffer
140 Mbyte/sec
few ms
Bunch Train Processing
Sofware Selection of 'Bunches Of Interest'
Event building,
Classification and analysis
according to physics,
calibration & machine
needs
200Hz
200s
Storage
27-mars-15
53


« Advanced » TEP Data Flow
Synchro
Front End DUAL Buffer
W1
W2
W3
W4
W5
W6
W7
W8
Wedge Buffering
Event manager & Control
Event Building Network
xx Gbit/sec
Processor farm (one time window per processor)
Data Steams Logger and Mass Storage
Front End
Signal processing & digitization
no trigger interrupt
Active pipeline and Dual Local Buffer
?KHz
1 ms
Read Out Node
Wedge Buffer
xx Mbyte/sec
few ms
Processing
Sofware Selection of 'Event Of Interest'
Event building,TOF
Classification and analysis according to selected criterias
Sec ?
Storage
27-mars-15
OOHID -2015
54

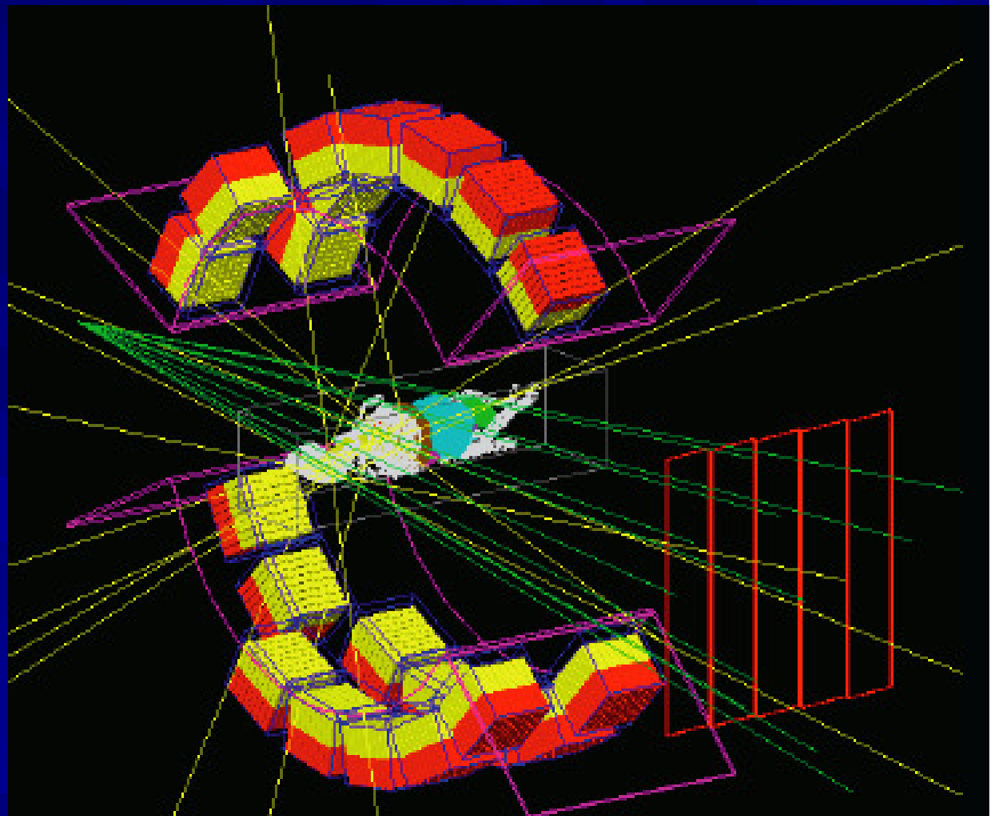
Simulation

Simulation

Higgs event at LHC (CMS) with Geant4



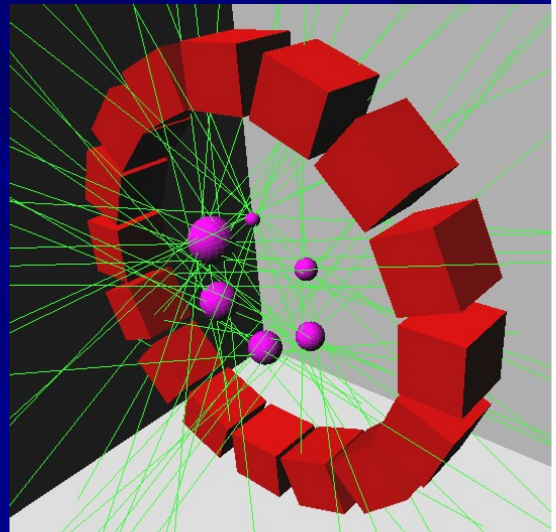
PET with GATE: Geant4 Application for Tomographic Emission

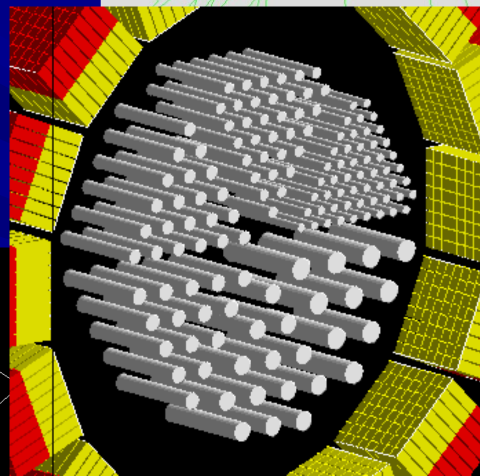


GATE : Geant4 Application for Tomographic Emission

Monte-Carlo simulation allowing to :

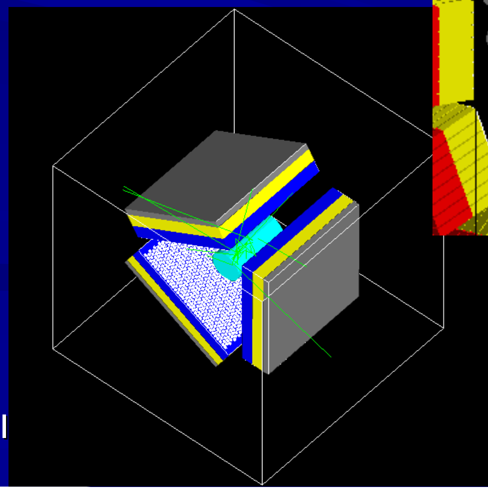
✓define geometries
(size, materials,…)
✓ define sources
(geometry, nature, activity)
✓ choice of physical process
(low energy package of G4)
✓ follow track point by point



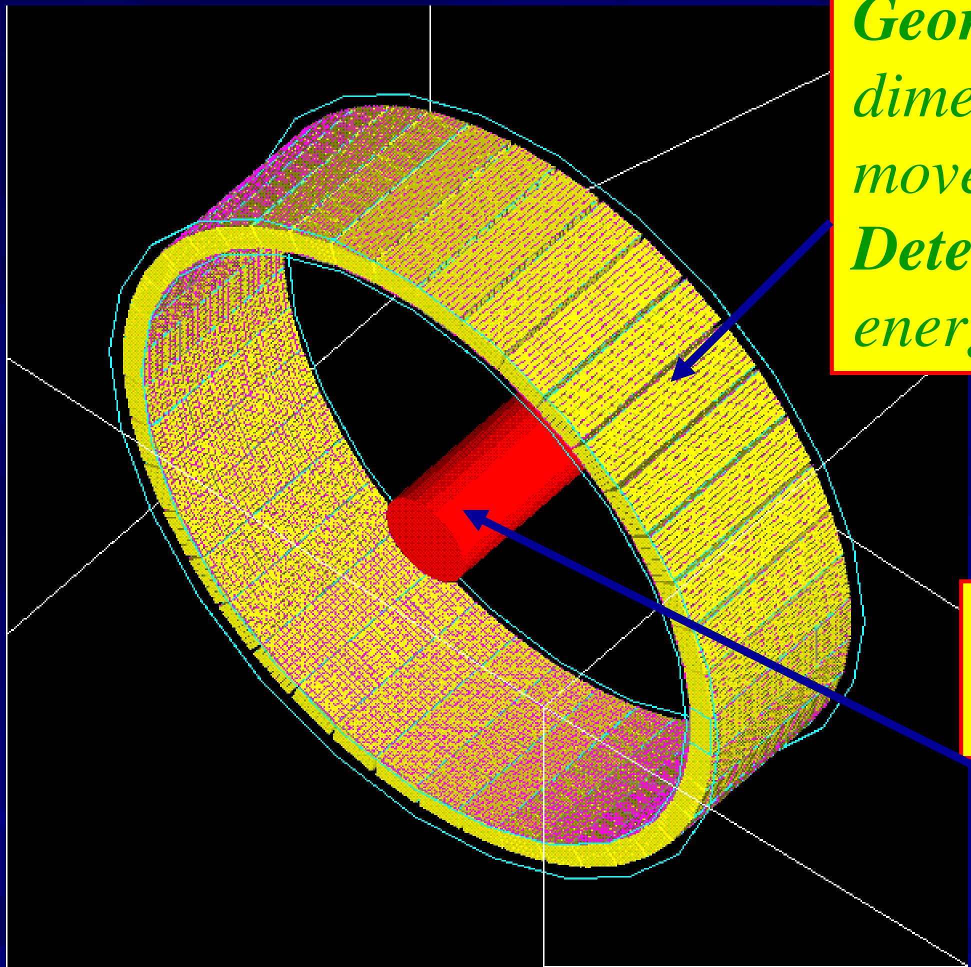


GATE specificities:

✓CERN GEANT4 libraries
✓Time modellign
(sources , movement,random…)
✓Script language(avoid C++)
✓Code interactivity
✓Sharing development



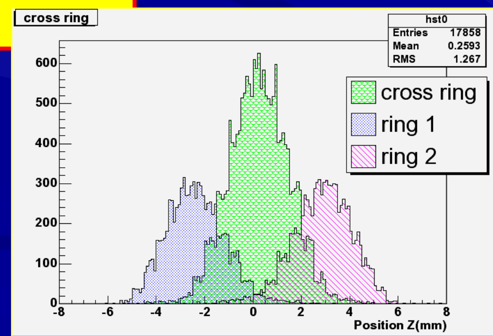
Typical PET simulation



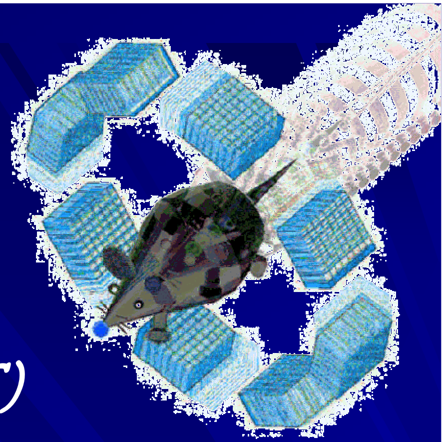
Geometry: *number of detectors, dimension, Materials, movements...*

Detection chain: *light yield, energy threshold, energy resolution...*

Source: *nature, activity, movements, ...*



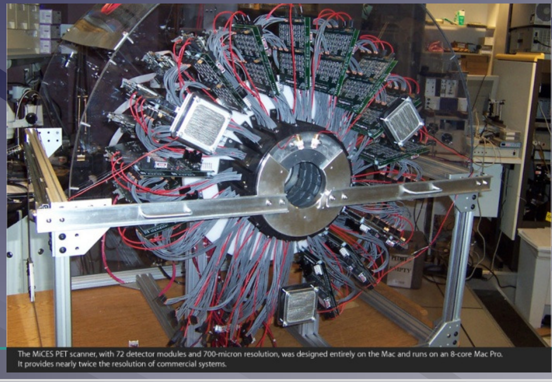
GATE 'early 'Collaboration 2004)

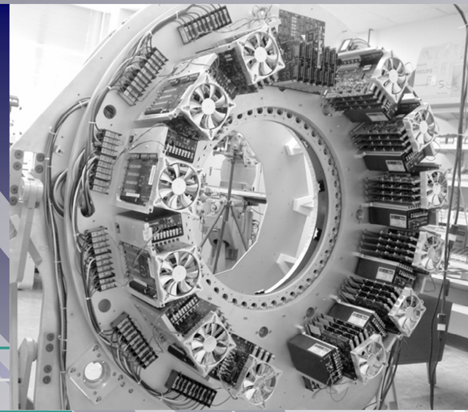


Uni Louis Pasteur (IRES) Strasbourg
Uni Joseph Fourier (LPSC) Grenoble
Forschungszentrum-Jülich (IME)
Uni. Massachusetts, Worcester
CHU Morvan (LATIM) Brest
Uni California (CRUMP) Los Angeles
Uni Toronto (CAMH)
CEA (DAPNIA) Saclay
MSKCC New York
Uni Athens (IASA)

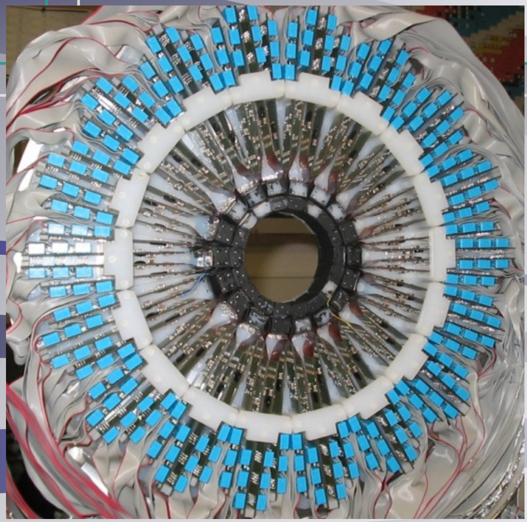
- Irène Buvat CEA SHFJF – Orsay-F)
- Technical Coordinator: **S. Jan** (CEA - Orsay, F)

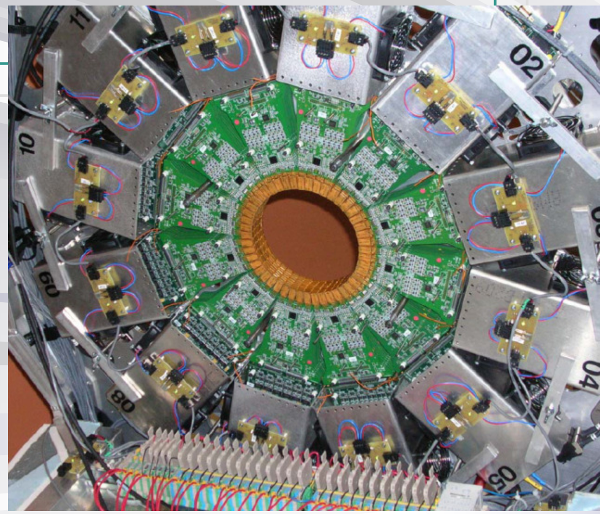
Uni Lausanne (IPHE)
Uni Clermont-Ferrand (LPC)
Uni Ghent (ELIS)
CHU Pitié-Salpêtrière (U494 INSERM) Paris
Vrije Uni Brussel (IIHE)
CERMEP, Lyon
CEA (SHFJ) Orsay
CHU Nantes (U463 INSERM)
Sungkyunkwan Uni. Seoul
Uni Claude Bernard (IPNL) Lyon



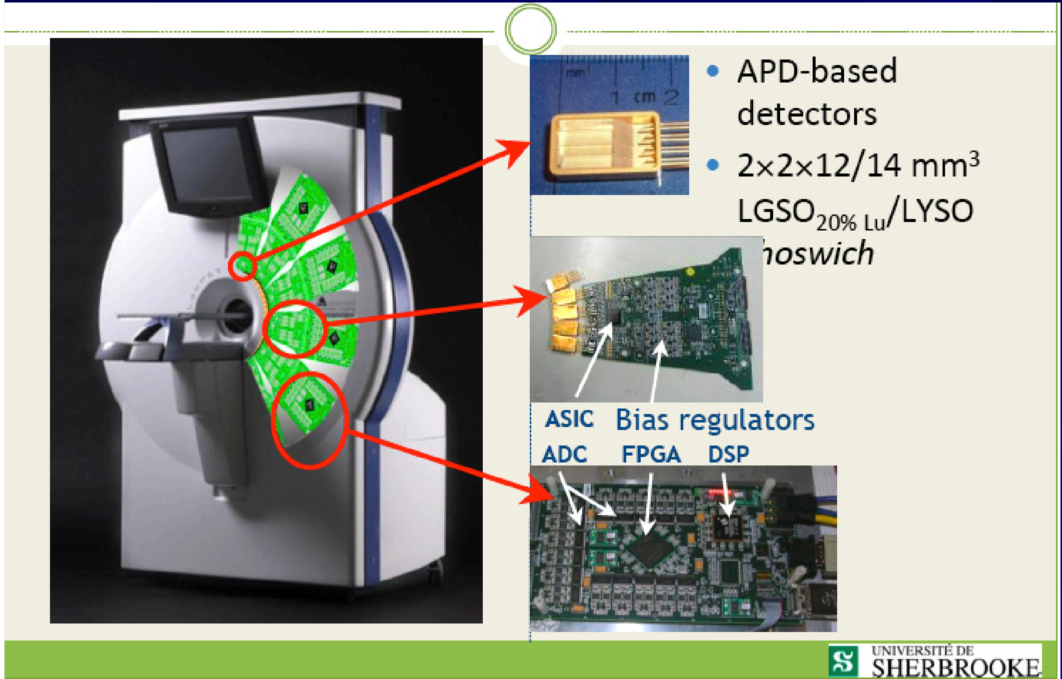


Some 'dedicated PET examples



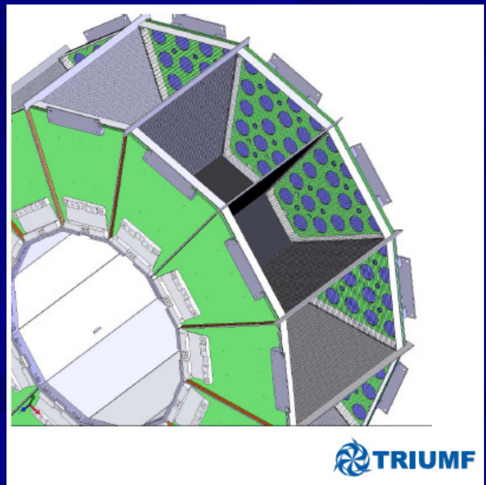


MicroPET for small animals

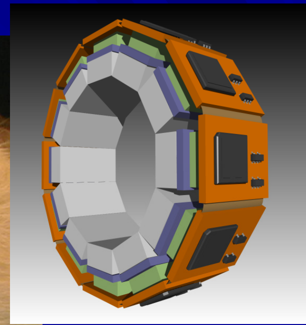


- Φ=20cm
- FOV few cm
- Development
  - Radio pharmacology
  - Tracer development

Crystal Clear Col.



Liquid Xenon



RatCap
BNL

The Rat Conscious Animal PET scanner

Small animal PET images

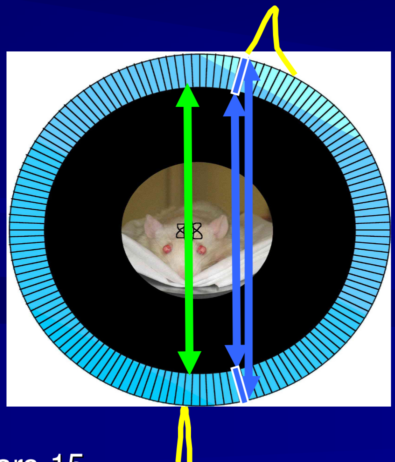
31 g mouse
1 mCi $^{18}F^{-}$

Whole-body
FDG-PET scan
250 g rat
(Sherbrooke APD)

μPET vs whole body PET → different requirements

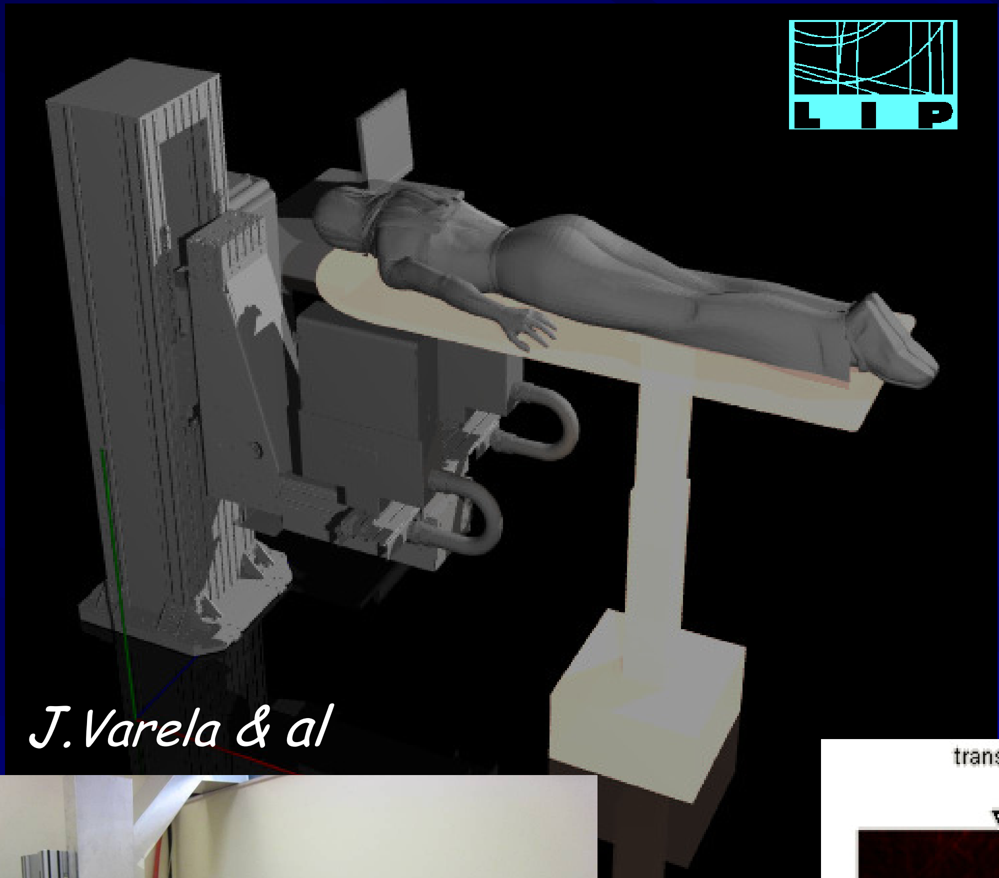
- **High Spatial resolution →fundamental**
  - Objective ~ 1mm or less
  - Today → 1,2 mm
- **High sensitivity**
  - Less Compton event
  - Small dose
- **Paralax correction**

  → Deph Of Interaction Technique



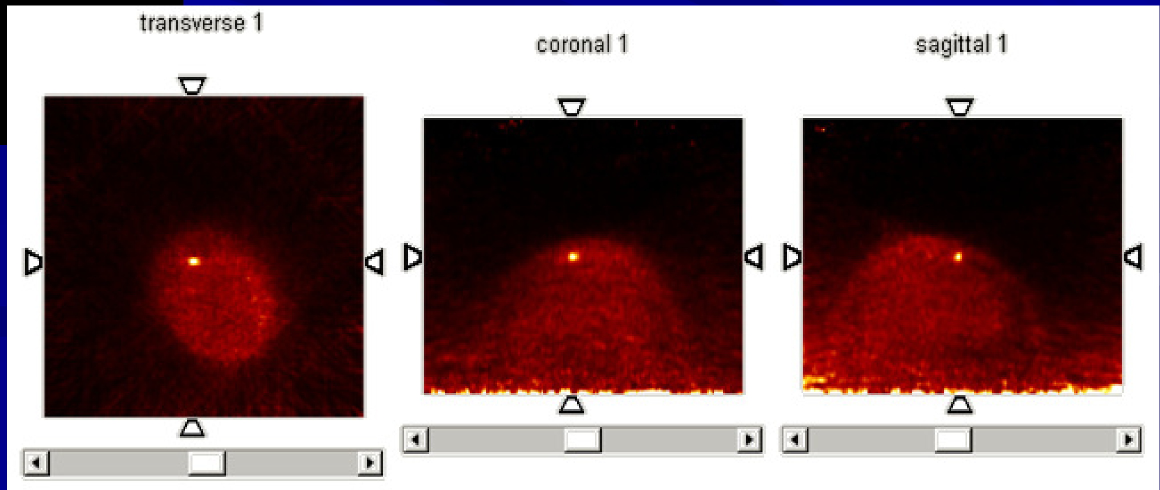
- High Efficiency (>85%)
- Good Spatial Resolution (<5 mm)
- Low Cost (<$100/cm2)
- Short Dead Time (<1 μs)
- High Timing Resolution (< ns fwhm)
- Good Energy Resolution (<100 keV fwhm)

The ClearPEM Breast Imaging Scanner

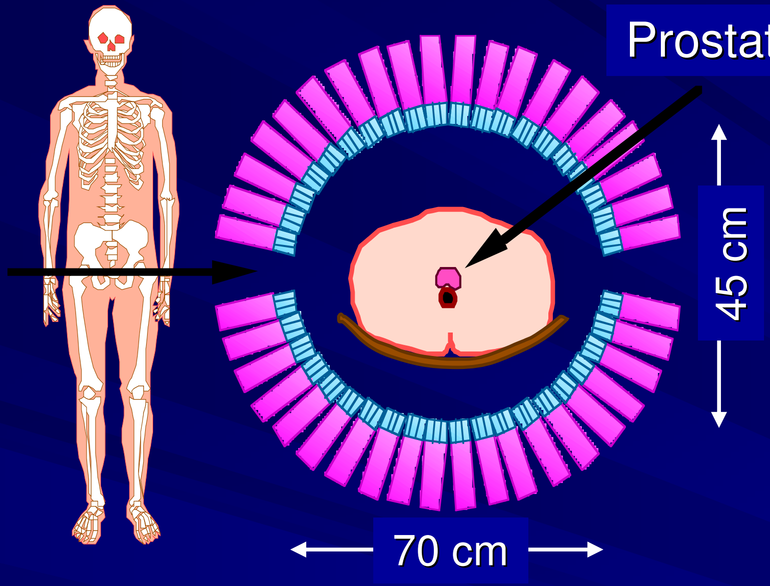


- 160 x 180 mm2 active area
- 6144 scintillation crystals LYSO:Ce
- 12288 APD pixel channels
- Double readout of crystal pixels for Depth-of-Interaction measurent (to minimize parallax effect)

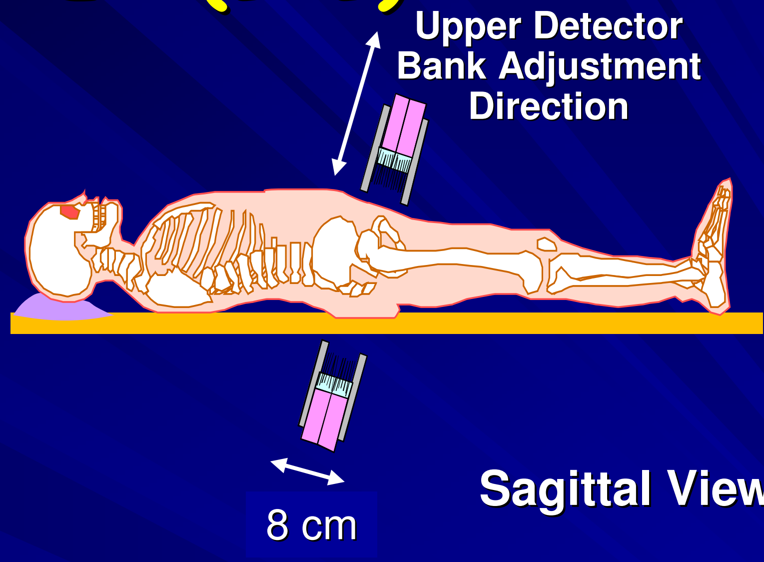
--> Reach 1,2 mm patial resolution



Prostate PET (LBL)

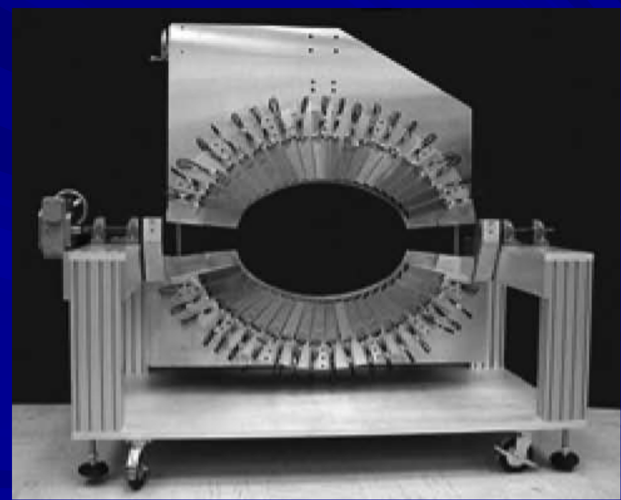


Transaxial View



Sagittal View

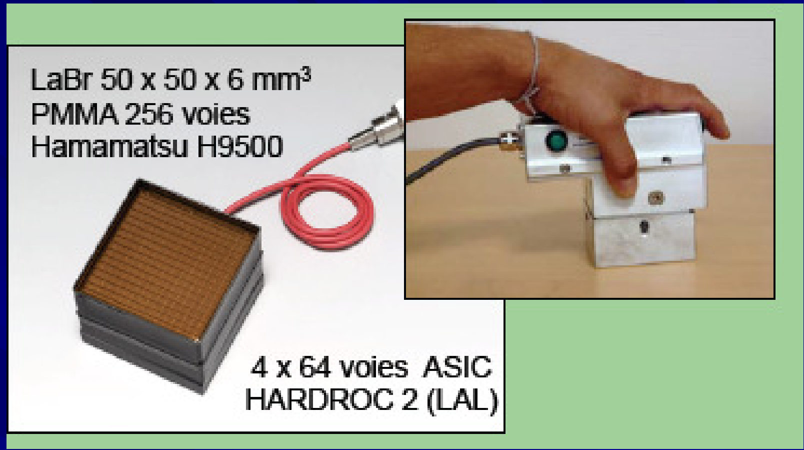
Lower cost and higher performance
than conventional commercial PET camera

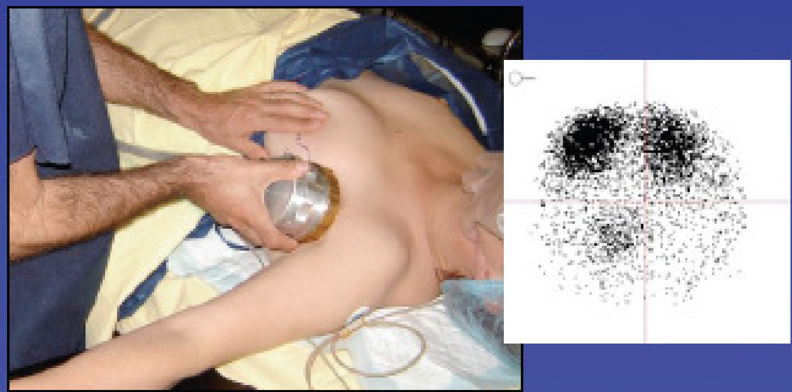


W.Moses & al.

Surgical portable probes

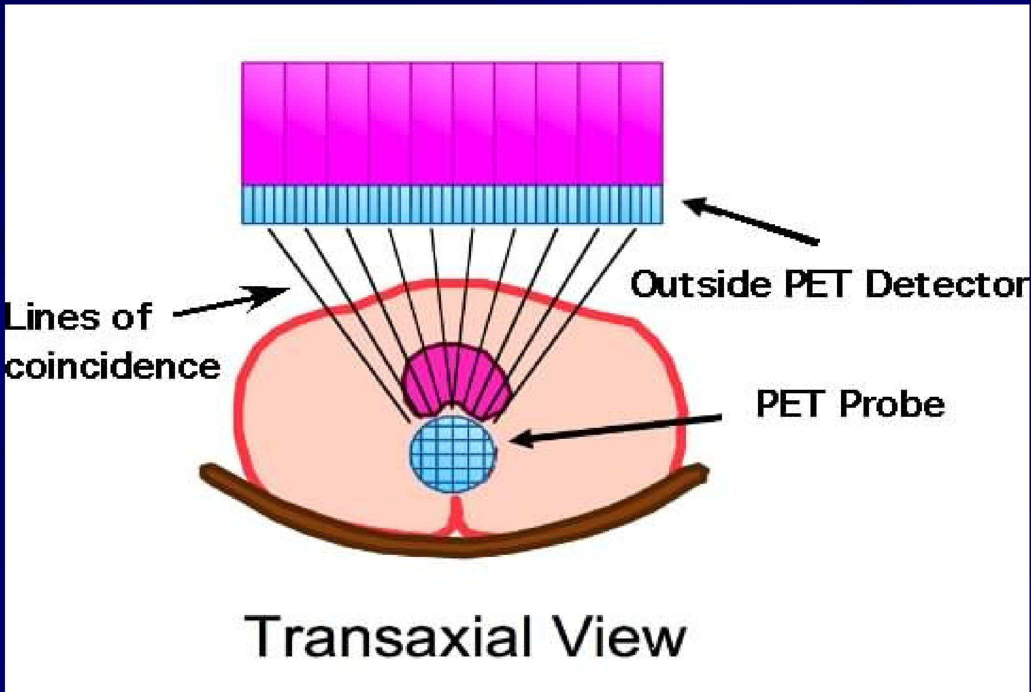
- Developent of very sensitive detectors, miniaturized and ergonimics with a great capability of rejecting noise and background
  - Based on SiPM,CMOS pixels,Scintillating cristals LaBr3:Ce, LuI3:Ce, …, and integrated electronics
- Objectives : portable small imaging systems for beta/gamma probes adapted to new tumor tracers





POCI : PHRC 162 patientes (Hôpital Tenon)
Barranger et al, 2007 Bull Cancer 94(5)
Barranger et al, 2007 The Breast 16

High resolution PET Imaging probes



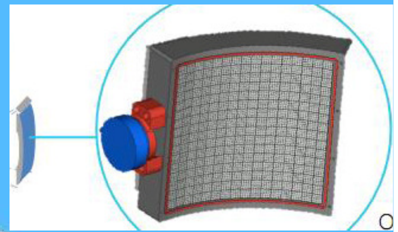
Prostate PET probe principle

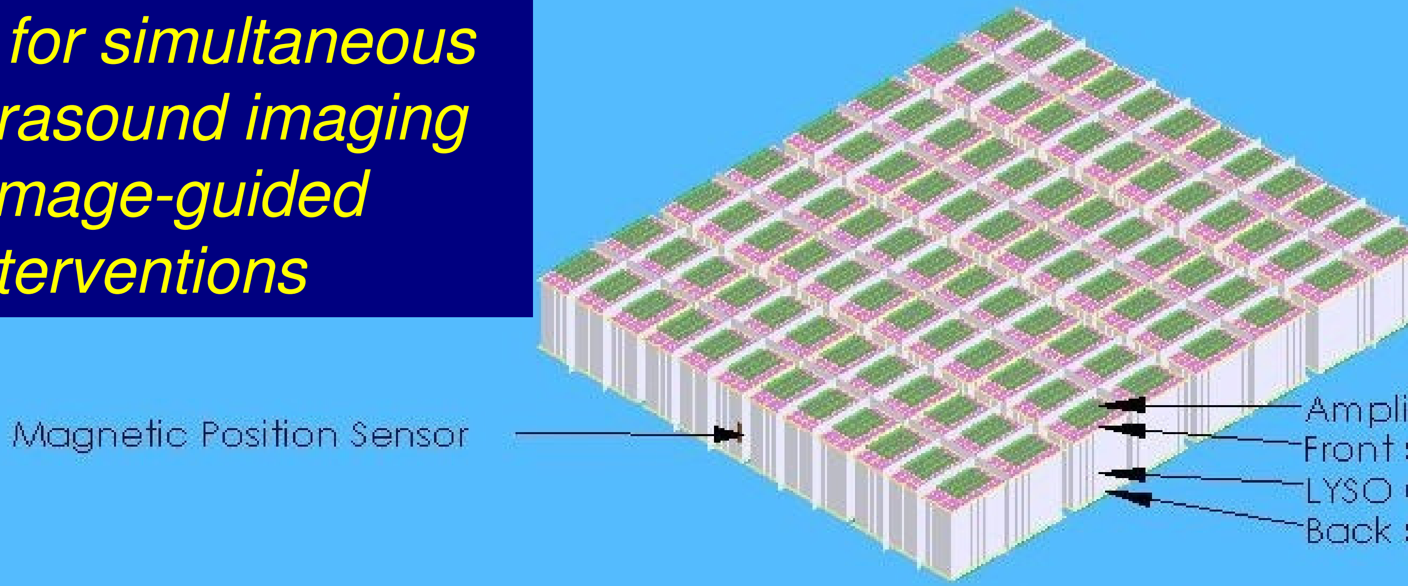
- *Non-conventional PET configuration*
- *Assymetric: one PET head in near contact to ROI*
- *Endoscopic: one PET head inside the body*
- *Miniaturization*
- *High background from other organs (heart, bladder,…)*
- *Variable geometry*
- *Reconstruction problems*

Novel multimodal endoscopic probes for simultaneous PET/ultrasound imaging for image-guided interventions

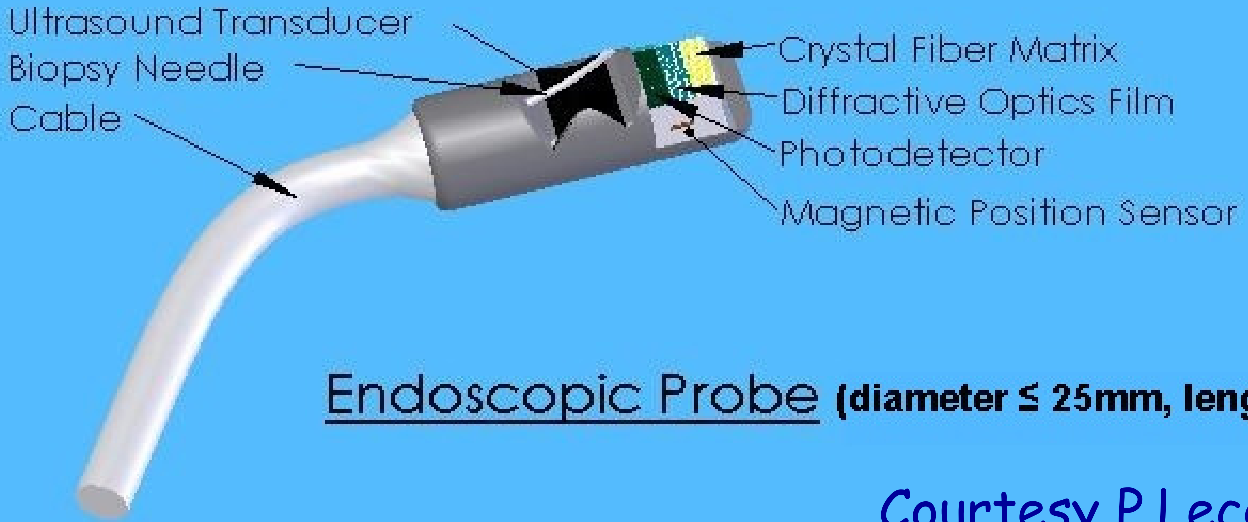
TOFPET-US

EU FP7 project, call Health 2010





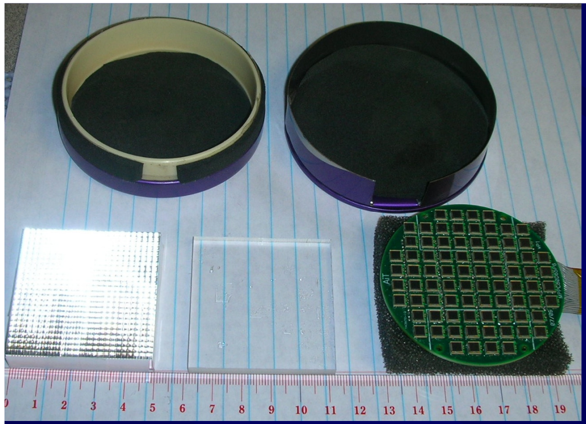
External PET Plate **(16cm X 16cm)**

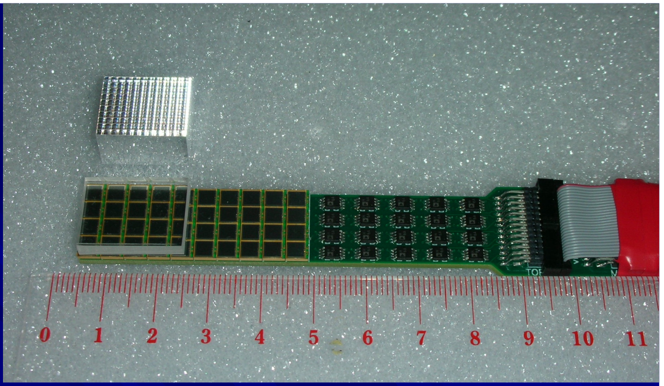


Endoscopic Probe **(diameter ≤ 25mm, length ≤ 5**

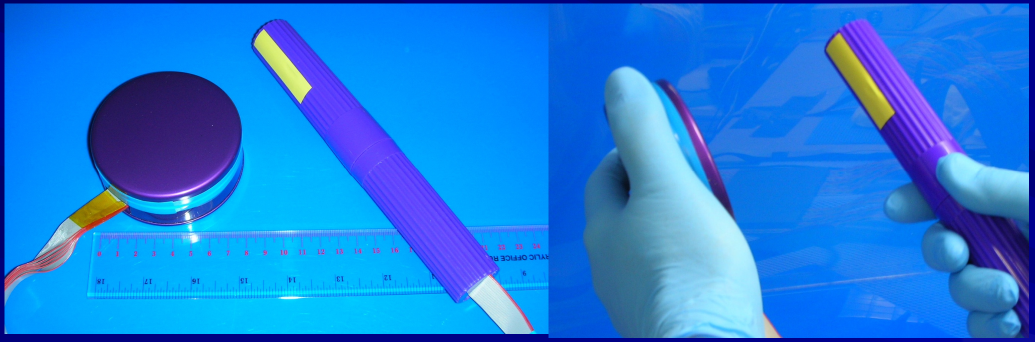
Courtesy P.Lecoq et

SiPM hand-held PET probe





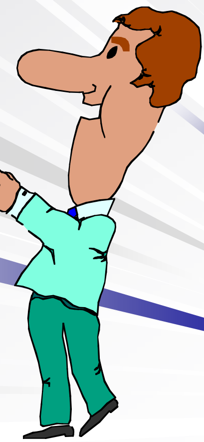
- The 'Central' part
  - 64 MPPC
  - LYSO crystals
- The photosensor 'stick' part
  - 4x10 array of Hamamatsu MPPC
  - Amplifier and connector banks are in the handle region of the probe



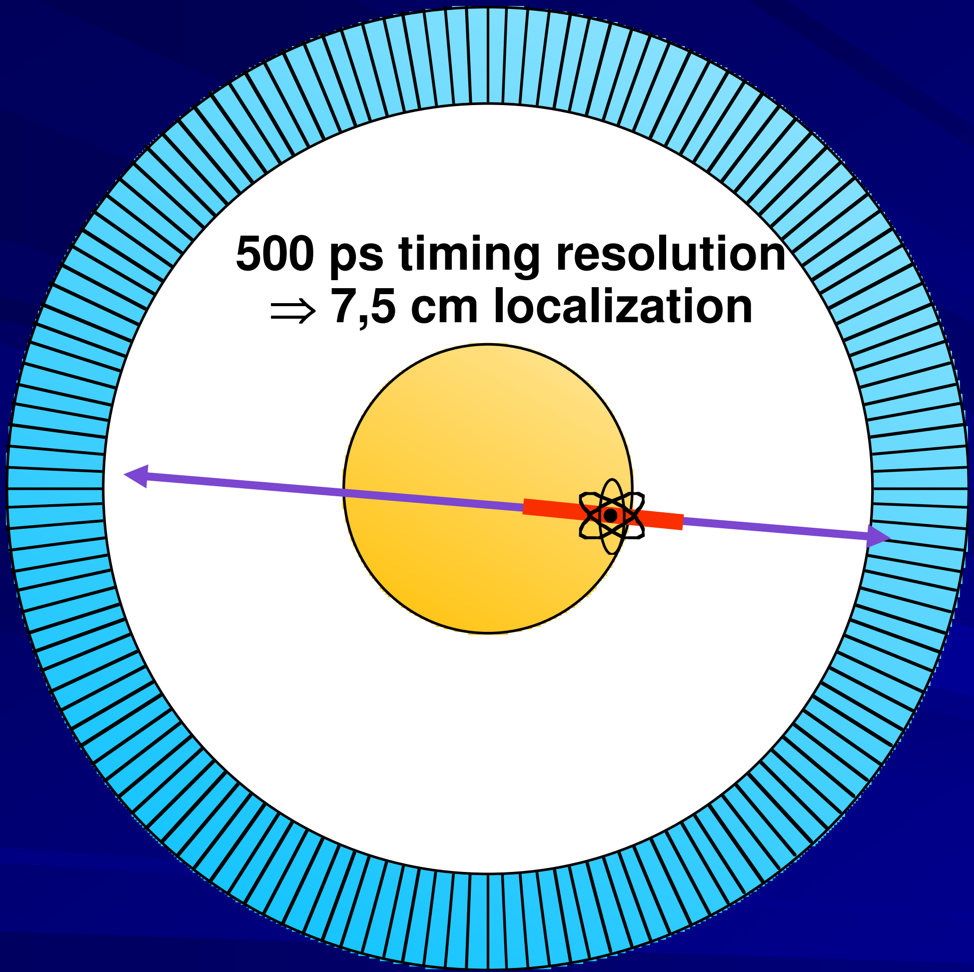
S. Majewski et al. (WVU)

- Biopsy guidance
- Surgical imaging with radio-guided surgery procedures in breast, melanoma, head and neck, pulmonary, pancreas and prostate cancer cases

A succesfull transfer the TOF technique



Time-of-Flight in medical PET



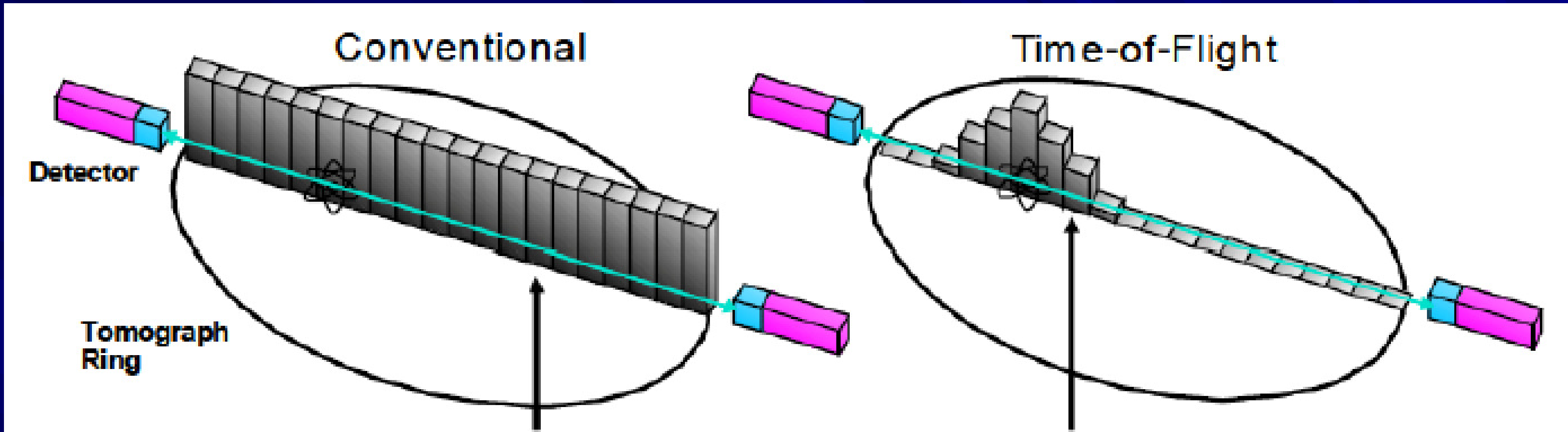
- Can localize source along line of flight.
- Time of flight information reduces noise in images.
- Line Of Response ---> list mode

	δt (ps)	Δd (cm)	SNR*
	100	1.5	5.2
	300	4.5	3.0
Today	500	7.5	2.3
	600	9.0	2.1

** SNR gain for 40 cm phantom*
= SNR_{TOF} / $SNR_{non\text{-}TOF}$

W.Moses courtesy

TOF technique (Con't)



- But need to use list mode data
- More complex data analysis and computing power

TOF PET Cameras Built in the 1980's

- *~One dozen TOF cameras constructed*
- *Some were commercial cameras*
- *500 ps timing resolution*
- *BaF_2 scintillator*
- *~1 cm spatial resolution*
- *1–4 layers*
- *Advantages of TOF were experimentally verified*

TOF PET Demonstrated

Problems With TOF in the 1980's

- *CsF & BaF_2 have drawbacks (compared to BGO)*
  - *Lower density & atomic number (worse spatial resolution & efficiency)*
  - *"Fast" emission of BaF_2 is in UV (quartz PMTs, no transparent glues)*
- *Few "fast" PMTs (most 2" diameter, all expensive)*
- *GHz electronics was "beyond state-of-the-art"*
  - *Time alignment and stability problems*

Non-TOF PET with BGO Dominates

The 2000's — The LSO Explosion in PET

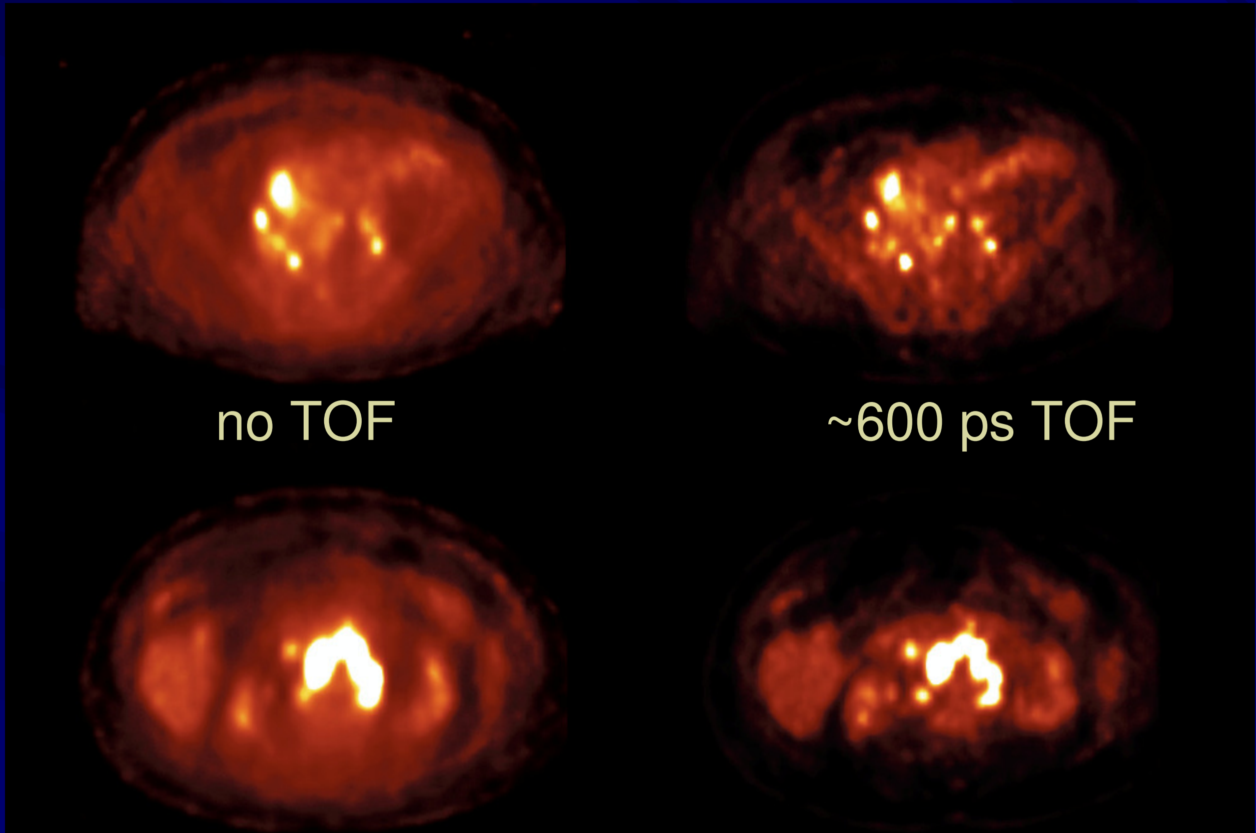
- *220 ps coincidence timing resolution demonstrated with small crystals*
- *350 ps coincidence timing resolution demonstrated with PET-shaped crystal*
- *550 ps coincidence timing resolution demonstrated for PET detector module*
- *First Commercial LSO PET camera in 2001*

- *Camera not designed for TOF run in TOF mode*
  - *1.2 ns timing resolution (electronics limited)*

Commercial TOF PET Available in 2006

- *Uses LYSO: ~550 ps Timing Resolution*
- *Similar Prototype Camera Developed by Siemens*

TOF PET example



www.medical.philips.com Philips Gemini TruFlight PET/CT promo brochure

TOF-PET allows

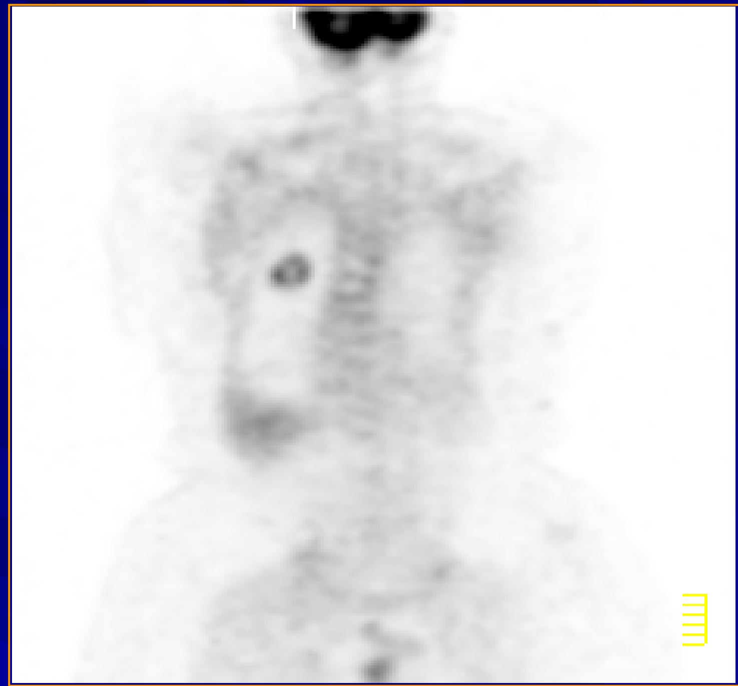
- better images
- shorter scans
- smaller radiation dose to patients

- **Time of Flight provides a Huge performance increase**
- **Largest improvment for large patients**

However: Impaired Image Quality in Larger Patients

Slim Patient

Large Patient



For an equivalent data signal to noise ratio, a 120 kg person would have to be scanned 2.3 times longer than a 60 kg person

Courtesy

PHILIPS

What is the limit ?

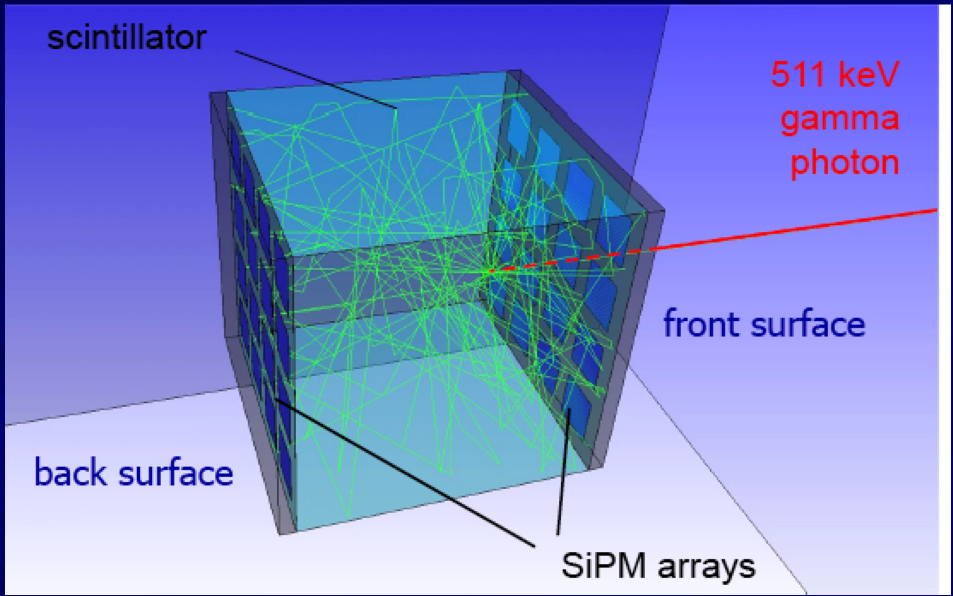
Hardware	Δt (ps)	TOF Gain
BGO Block Detector	3000	0.8
LSO Block (non-TOF)	1400	1.7
LSO Block (TOF)	550	4.2
$LaBr_3$ Block	350	6.7
LSO Single Crystal	210	11.1
LuI_3 Single Crystal	125	18.7
$LaBr_3$ Single Crystal	70	33.3

Research $LaBr_3$ Camera Built by U. Penn

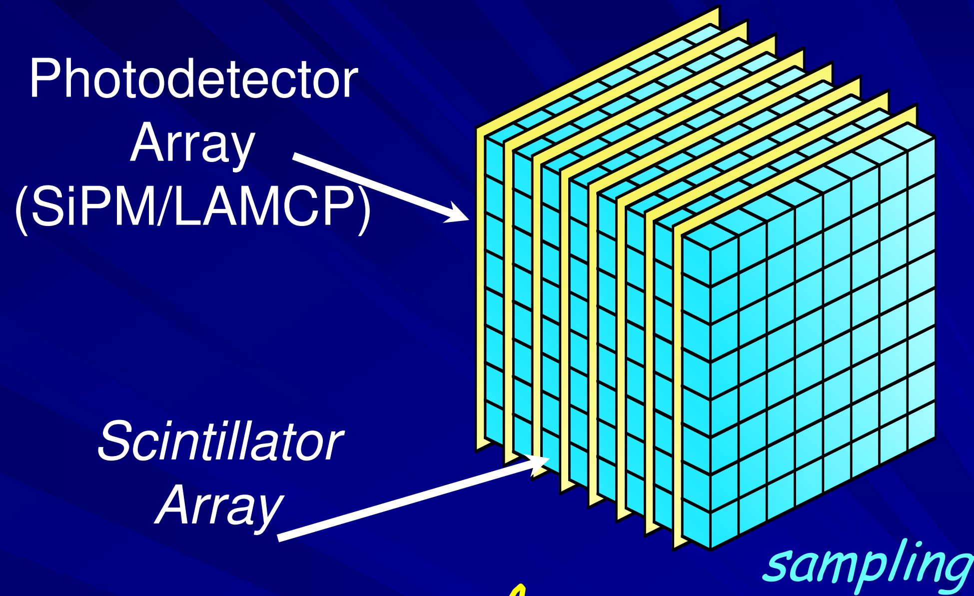
- ~350 ps Intrinsic Detector Resolution
- 420–500 ps Camera Resolution (Electronics Limited)

New 'picosecond development → 100 psec goal

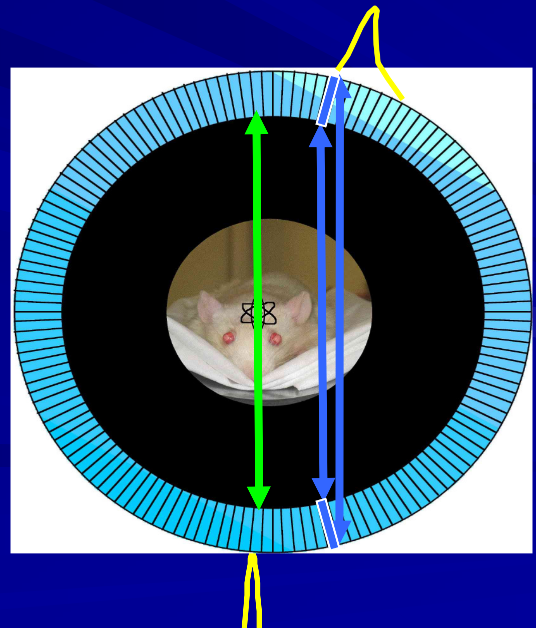
On going TOF-PET module development



Monolithic scintillator TUDelf)

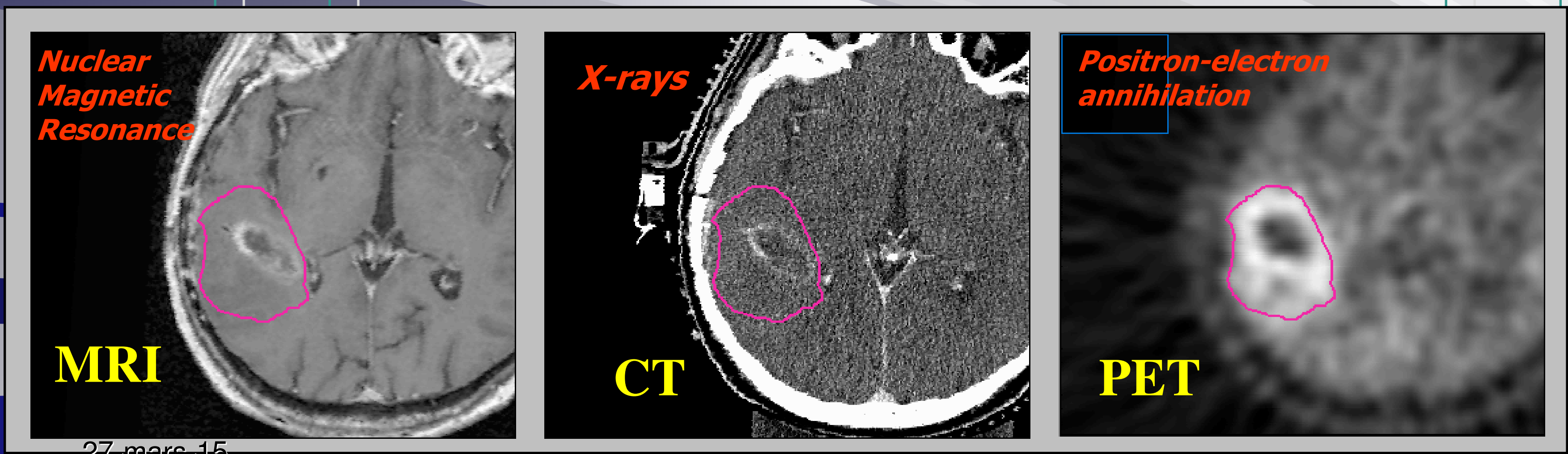


- Goal
  - TOF: 100 psec resolution
  - Position : 1 mm
  - DOI* capability

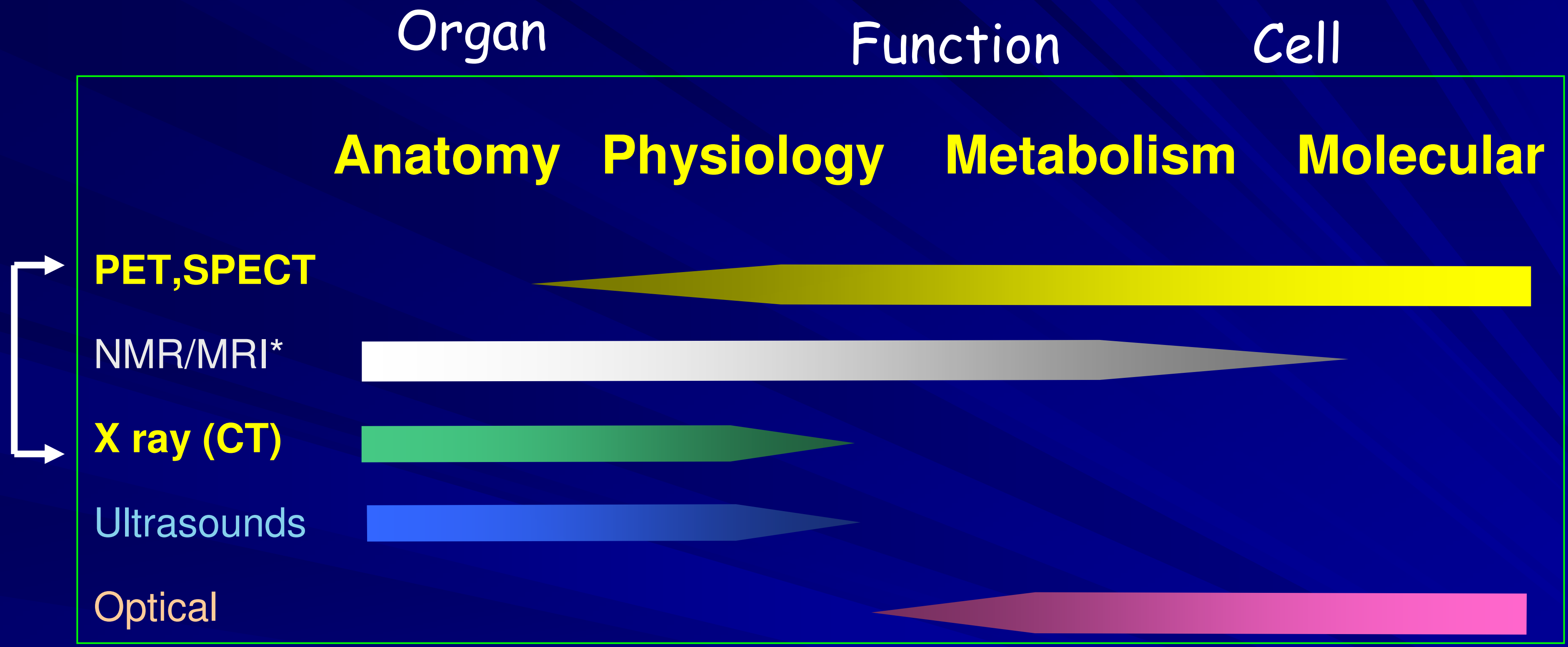


*Depth Of Interaction

Multimodality



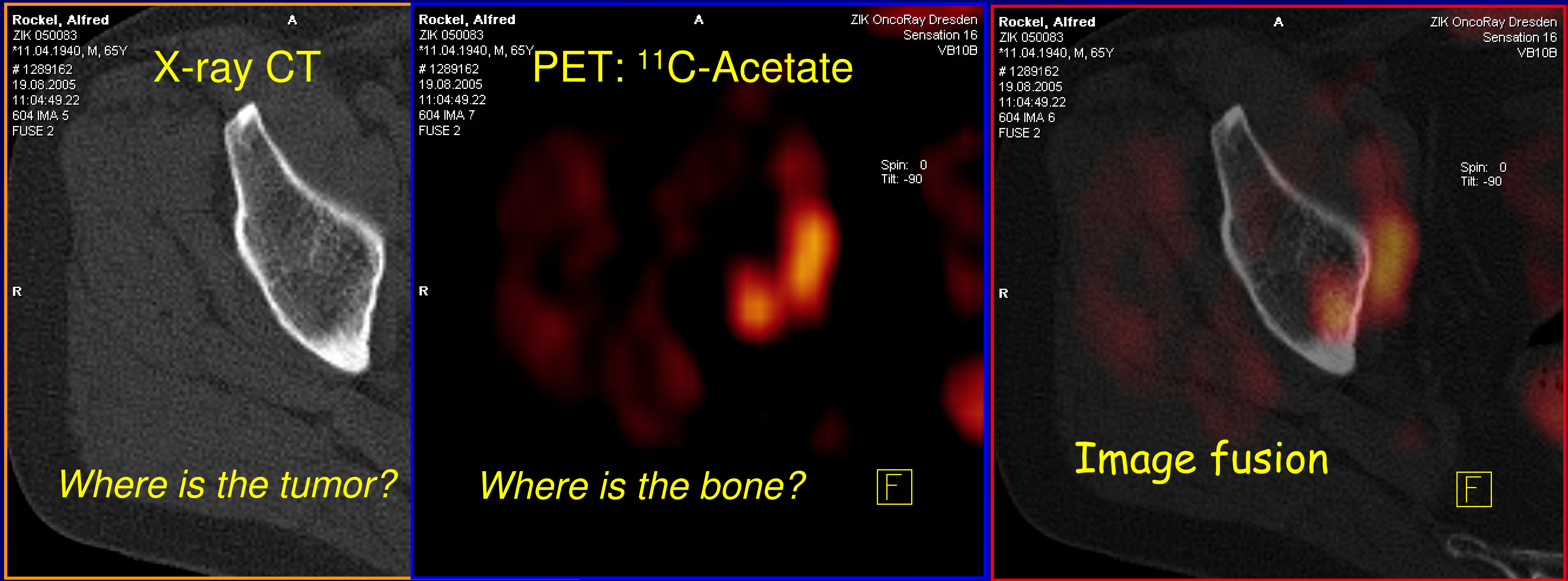
The various types (modalities) of imaging



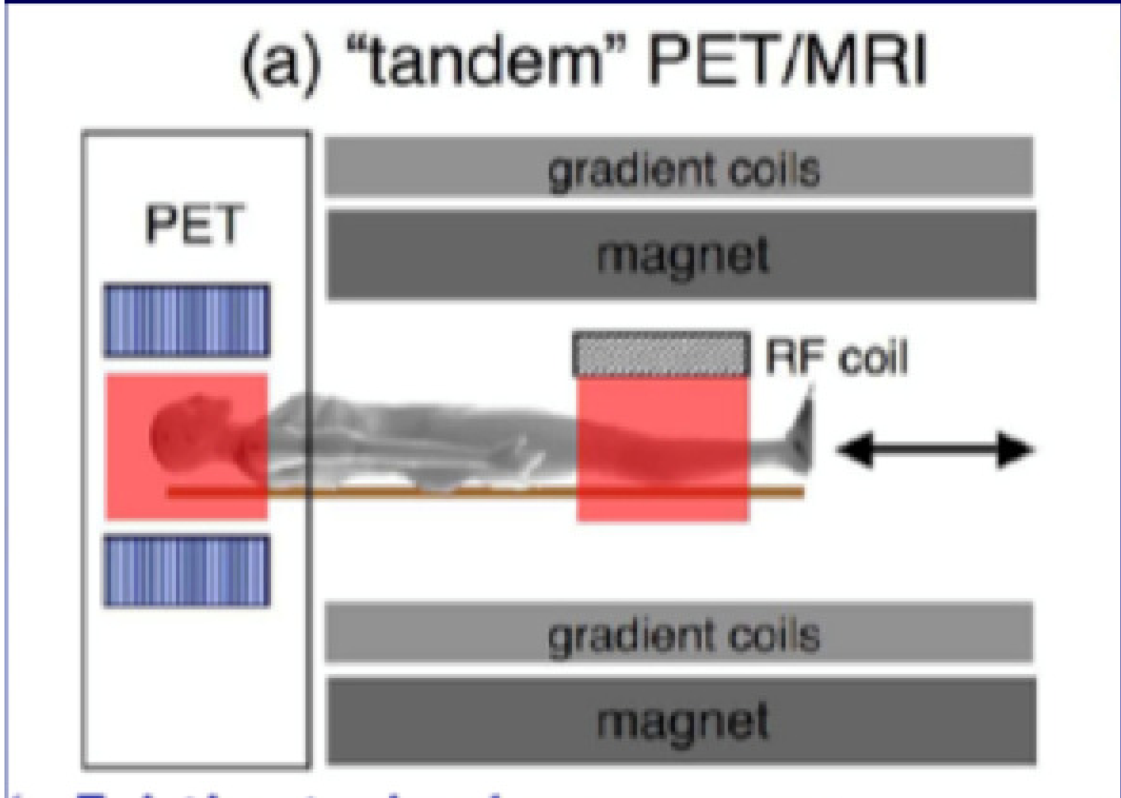
- Complementary !
- Depends on what you want to see

MRI/MMR = Magnetic resonnance*

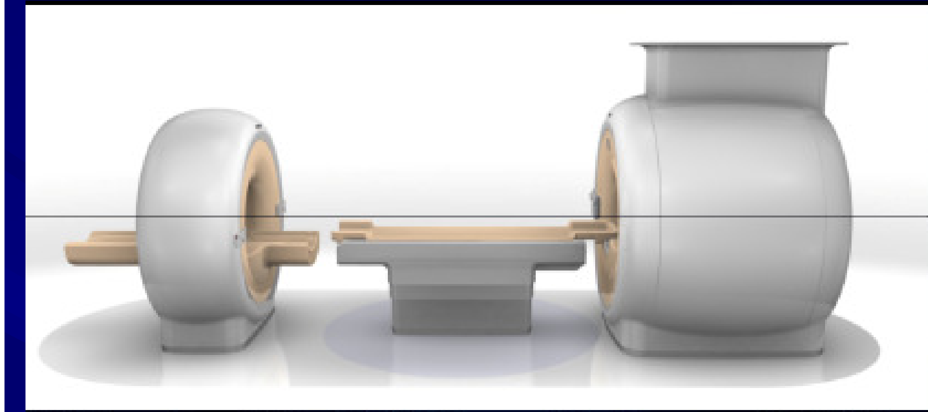
Multimodalities issues --> Image fusion



Metastases of a prostate carcinoma
Courtesy: N. Abolmaali, OncoRay Dresden

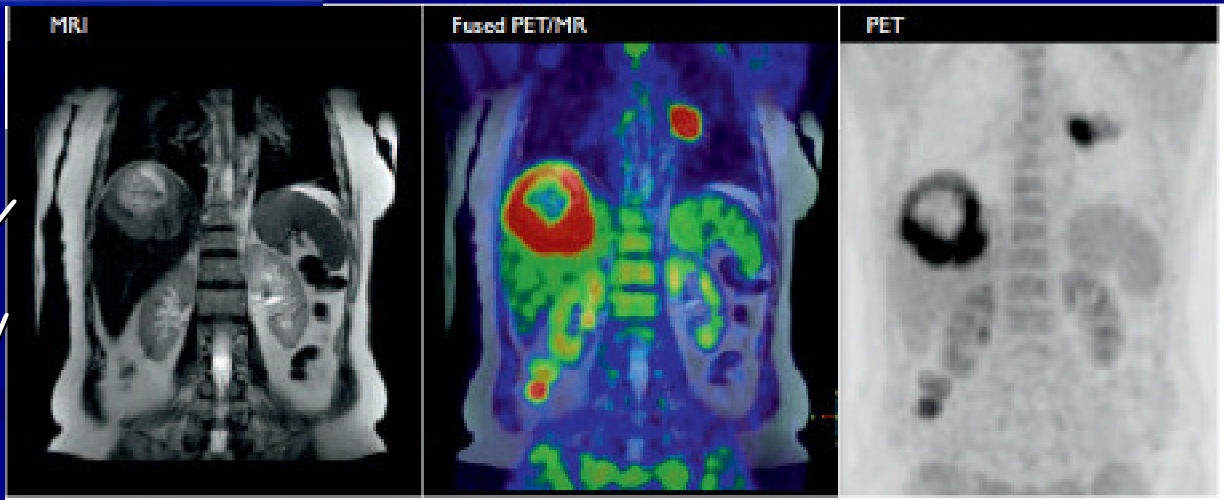


PET-MRI

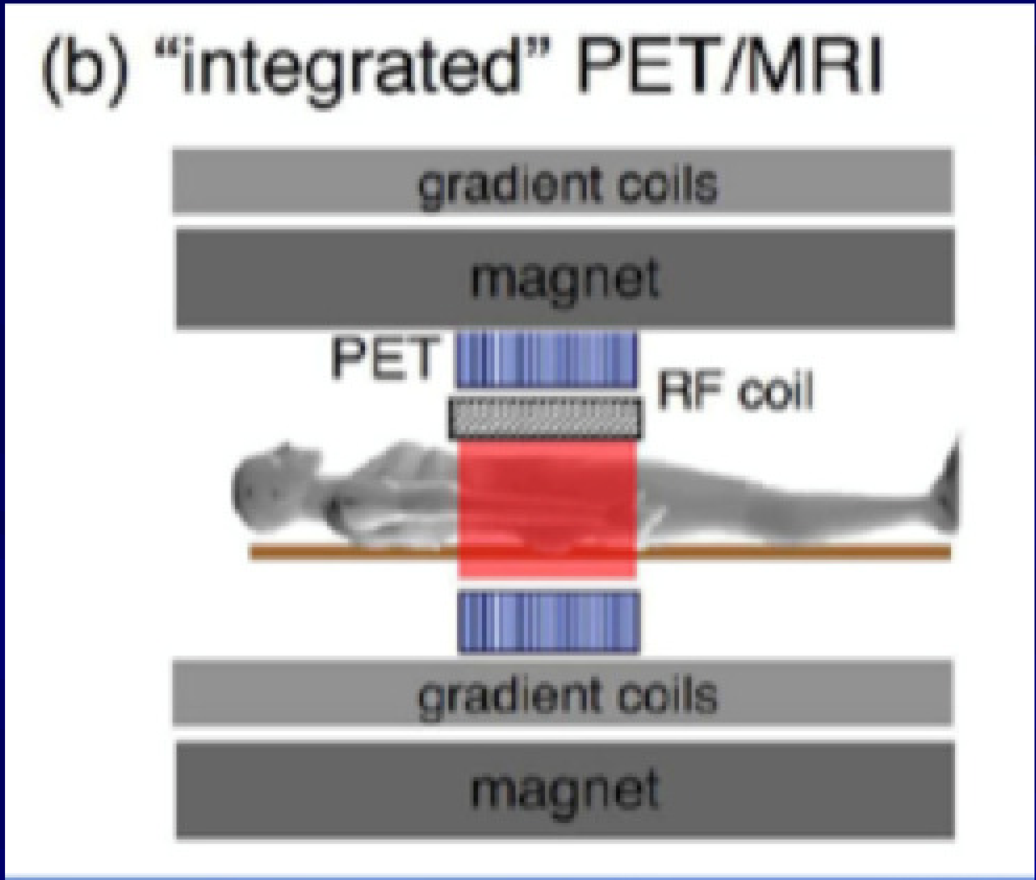


Philips Gemini TF (PET) and Achieva 3T (MRI)

- *Standard 'old' approach*
  - *Existing technologies*
  - *PET design not limited by geometrical constraints*
  - *Interferences minimized*
  - *Require image fusion*
  - *Not simultaneous*

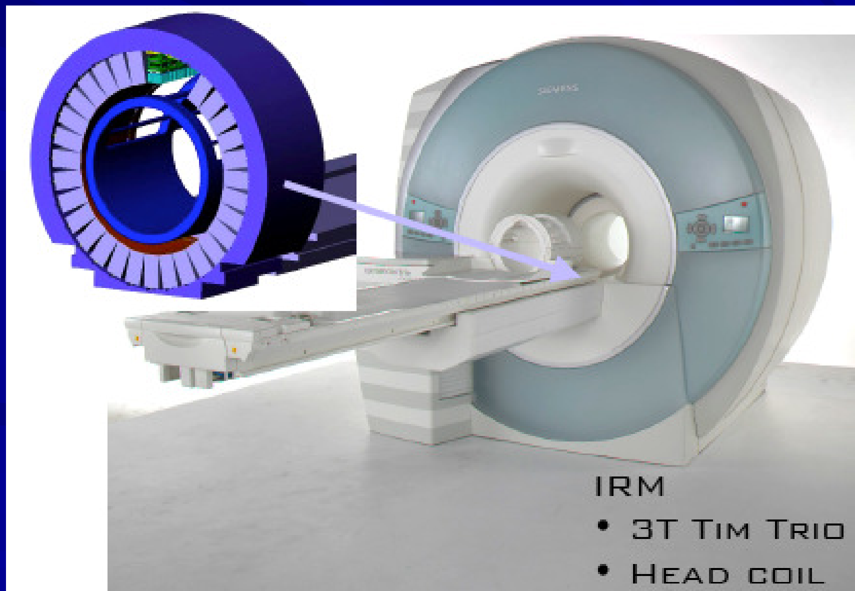


Courtesy Philips and University Hospital of Geneva



PET/MRI

- New approach
  - Simultaneous image acquisition
  - Shorter acquisition time geometrical constraints
  - Some geometrical constraints
  - System interference

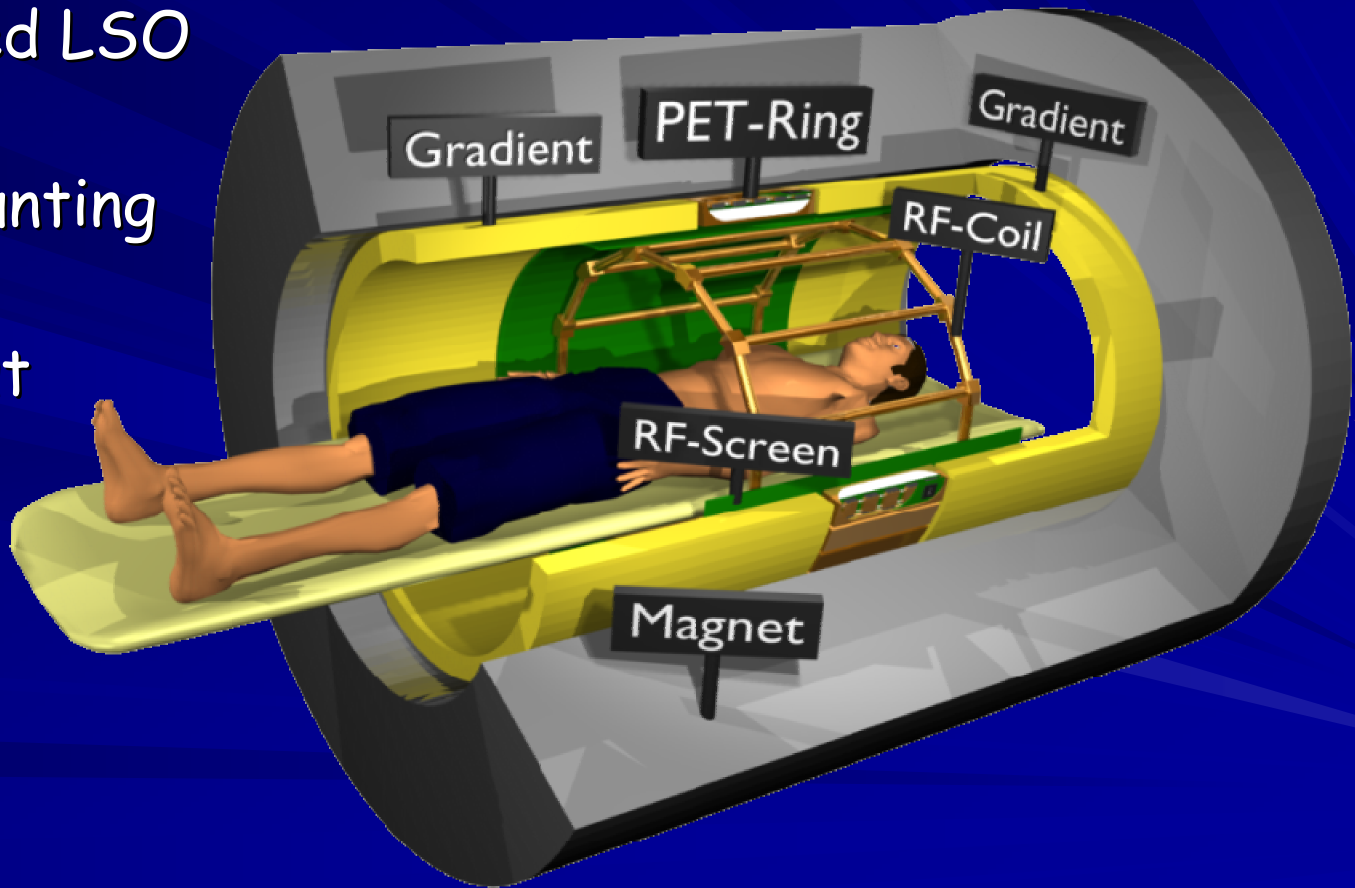


A lot of developments Since SiPM availablility

The SUBLIMA project: High resolution TOF-PET / MRI

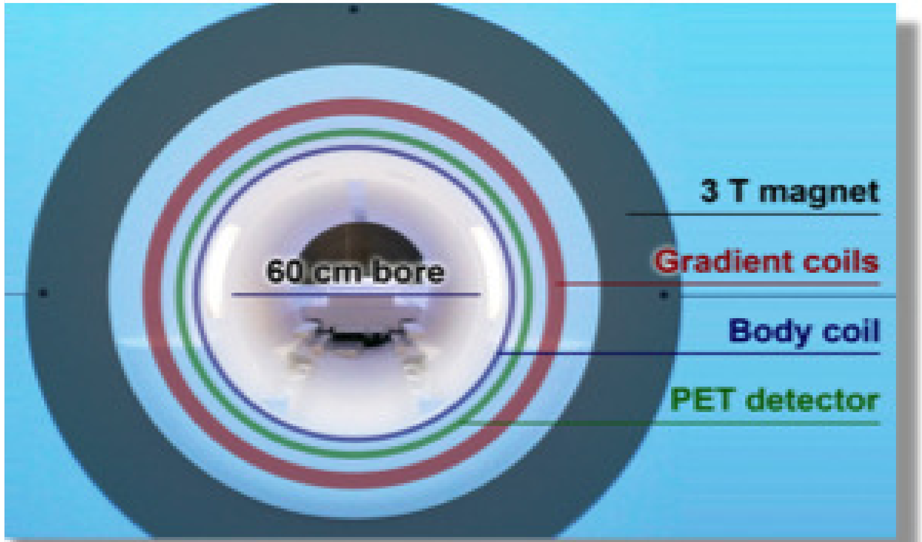
www.sublima-pet-mr.eu

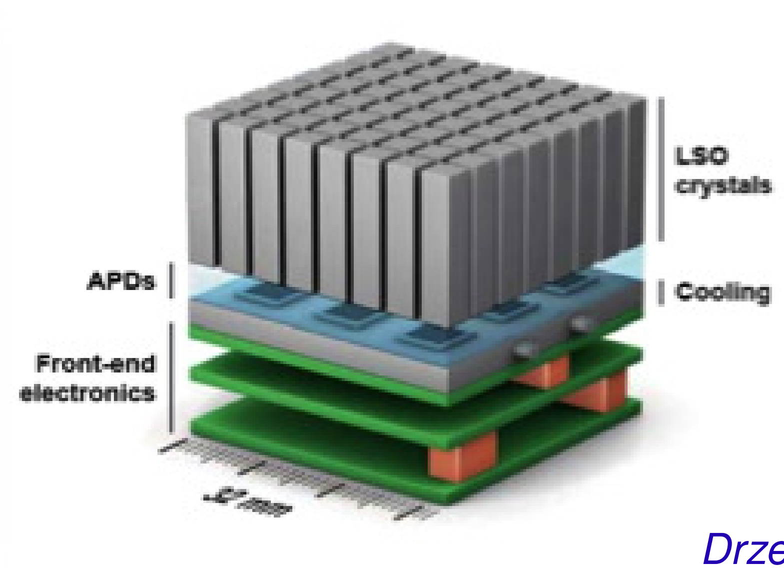
- Monolithic TOF/DOI detector
- Improved performance due to Ca co-doped LSO scintillator,
- Digital photon counting (dSiPM)
- Optimized readout algorithms



APD detectors in human PET/MRI

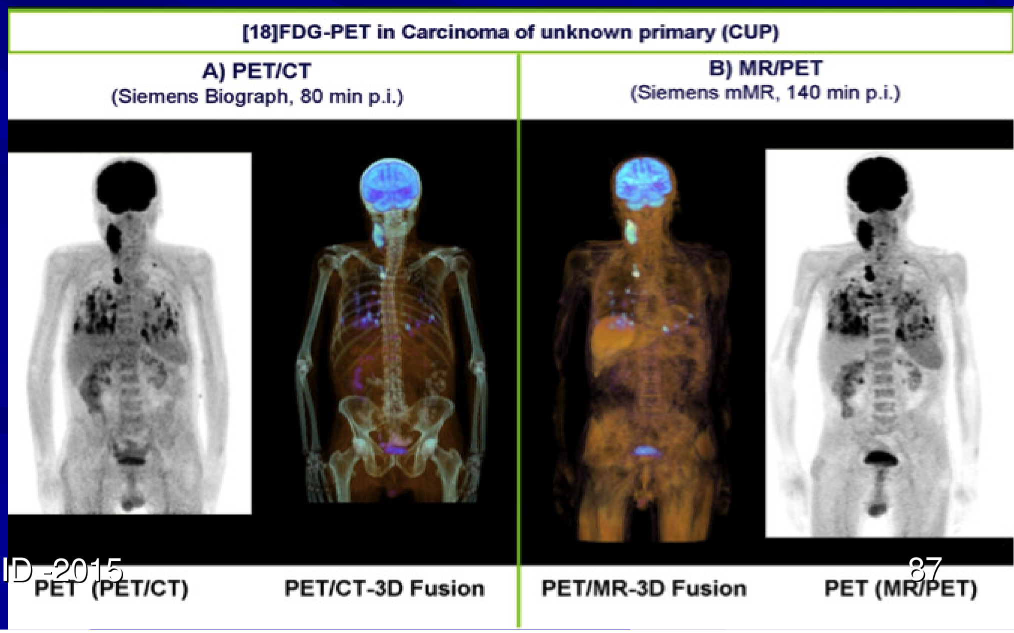
Siemens Biograph mMR



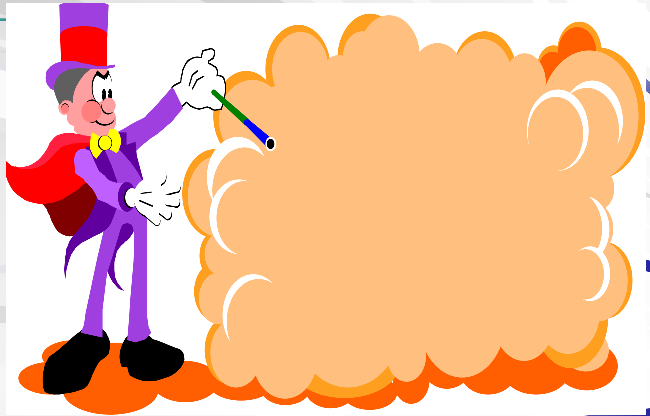


Drzezga SNM 2011

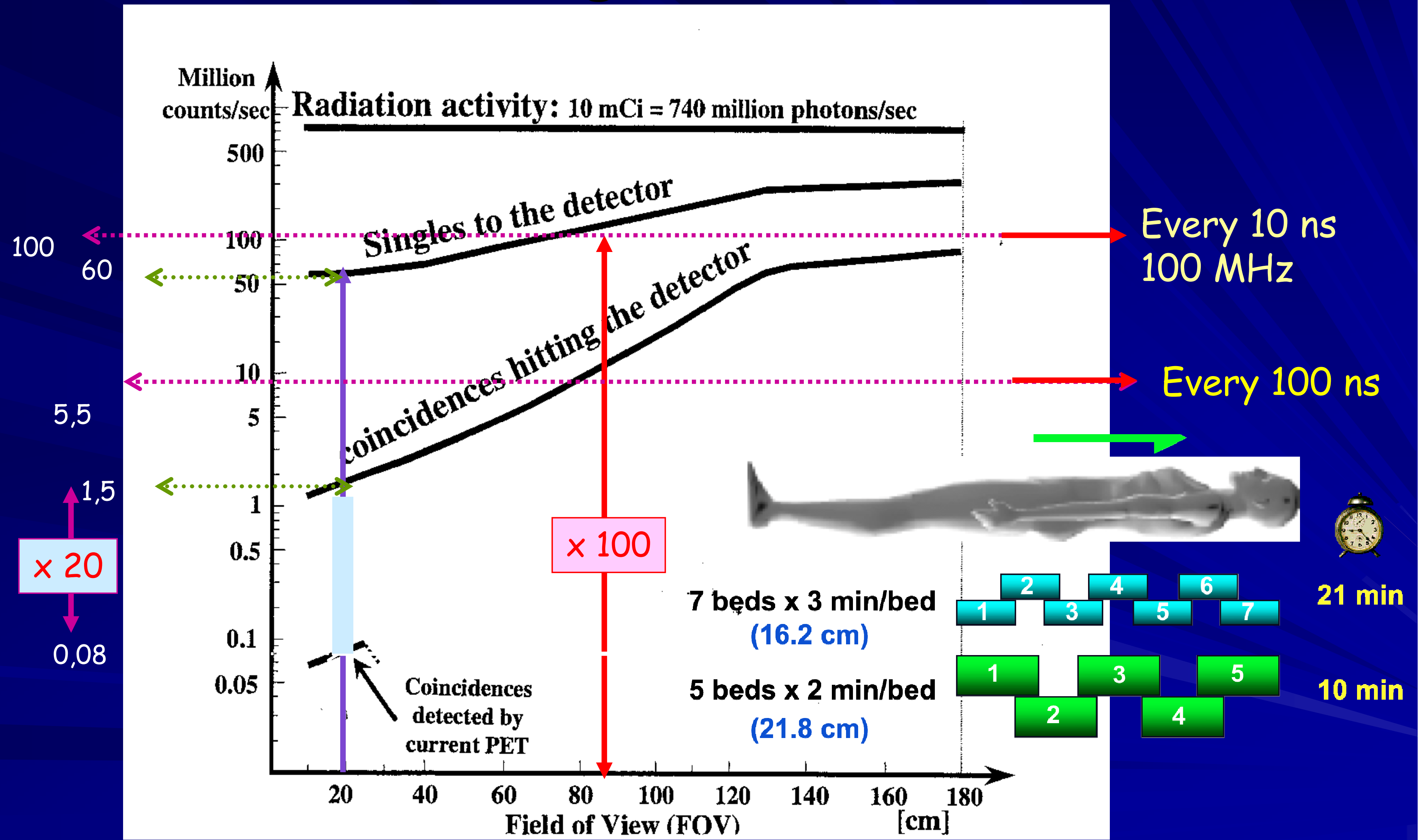
	Biograph mMR
Ring diameter	65.6 cm
Axial FOV	25.8 cm
Energy window	430 – 610 keV
Sensitivity (0 cm)	1.47 % (1.47 %)
(10 cm)	1.38 % (1.38 %)
Scatter fraction[1]	36.7 %
Spatial resolution[2]	4.3 mm (4.3 mm)



The Physician dream
' the minute PET'



Counting rate estimate

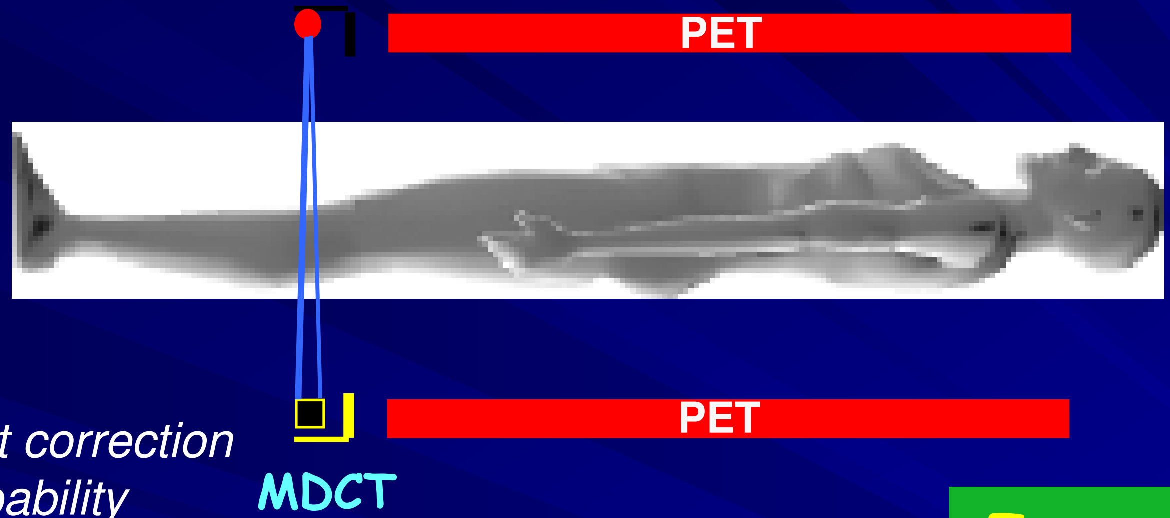


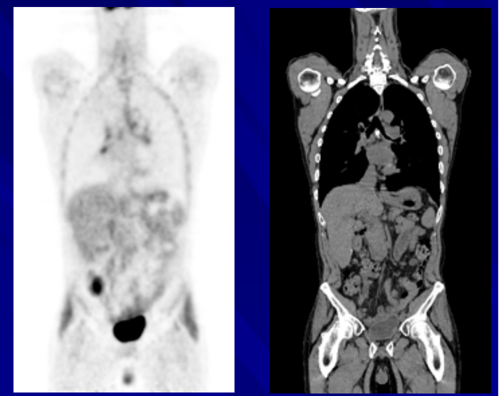
The Physician Dream

Courtesy of D.Townsend

Combined whole-body PET/CT or PET/MR…..

Minute PET/CT

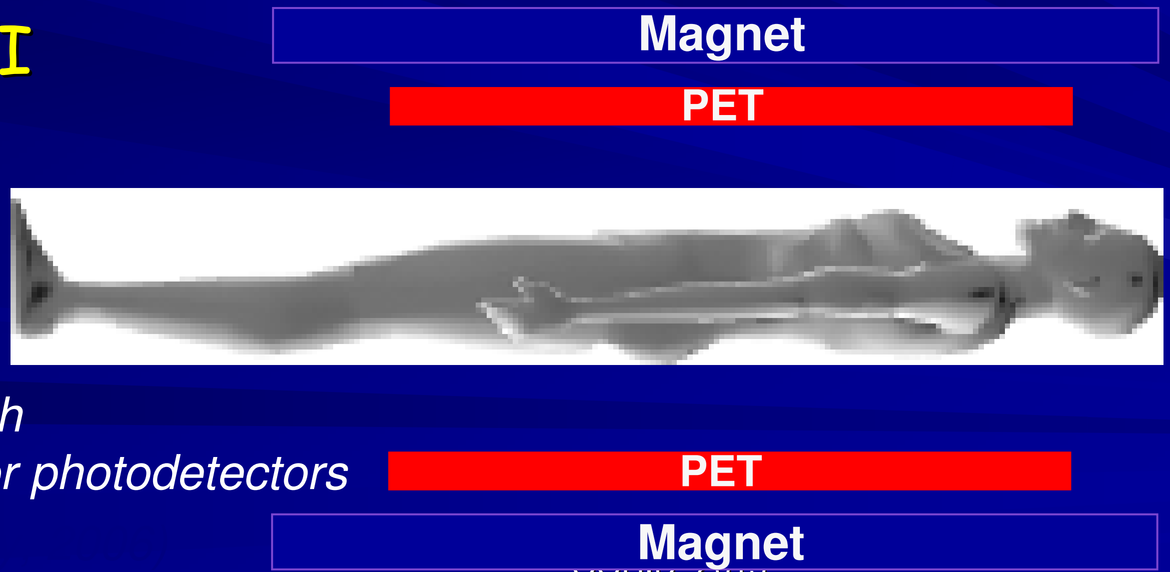


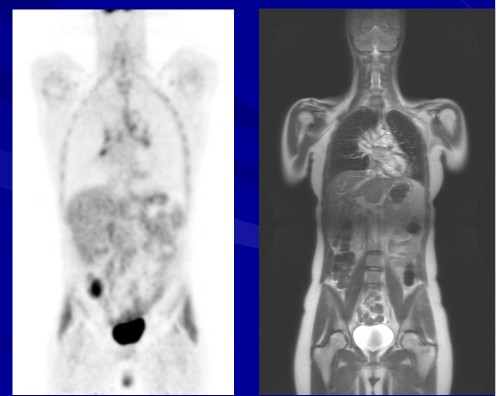


Less dose
Less movment correction
Screaning capability

Image In Real Time !

PET/MRI





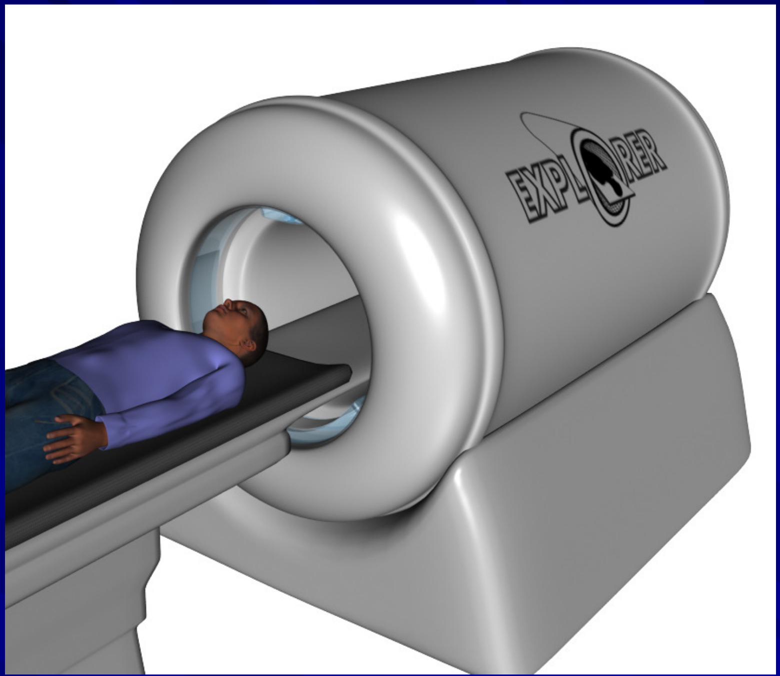
PET Insert with
Semiconductor photodetectors

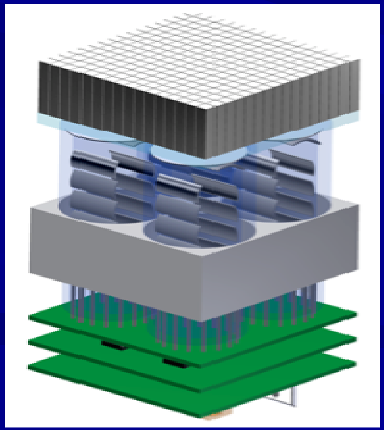
The total body 'explorer' project

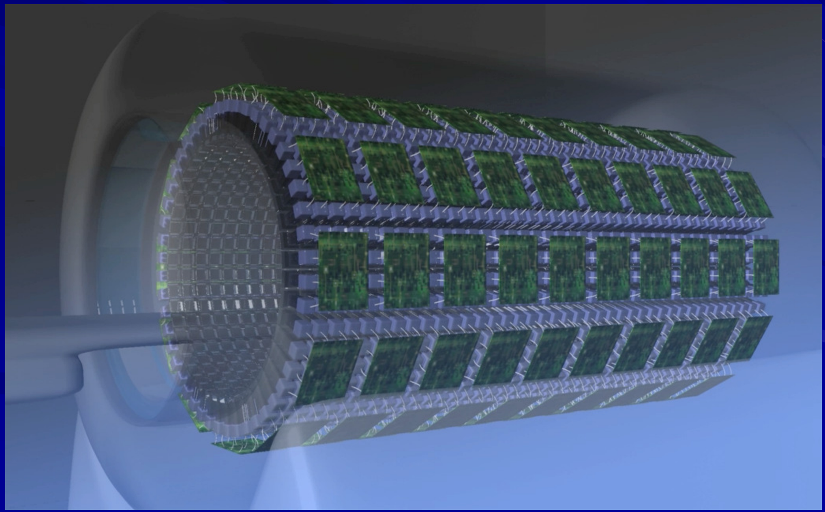
Davis,LBL,Upenn

- Modular "Block" Detectors
- ~3.1 x 3.1 x 20 mm L(Y)SO (16 x16)
  - 880 kg of L(Y)SO!
- PMT (possibly SiPM) readout
- Time of flight and 1-bit DOI
- 40 rings, 48 detectors/ring
- ~78.6 cm ring diameter
- 215 cm axial FOV
- OpenPET electronics

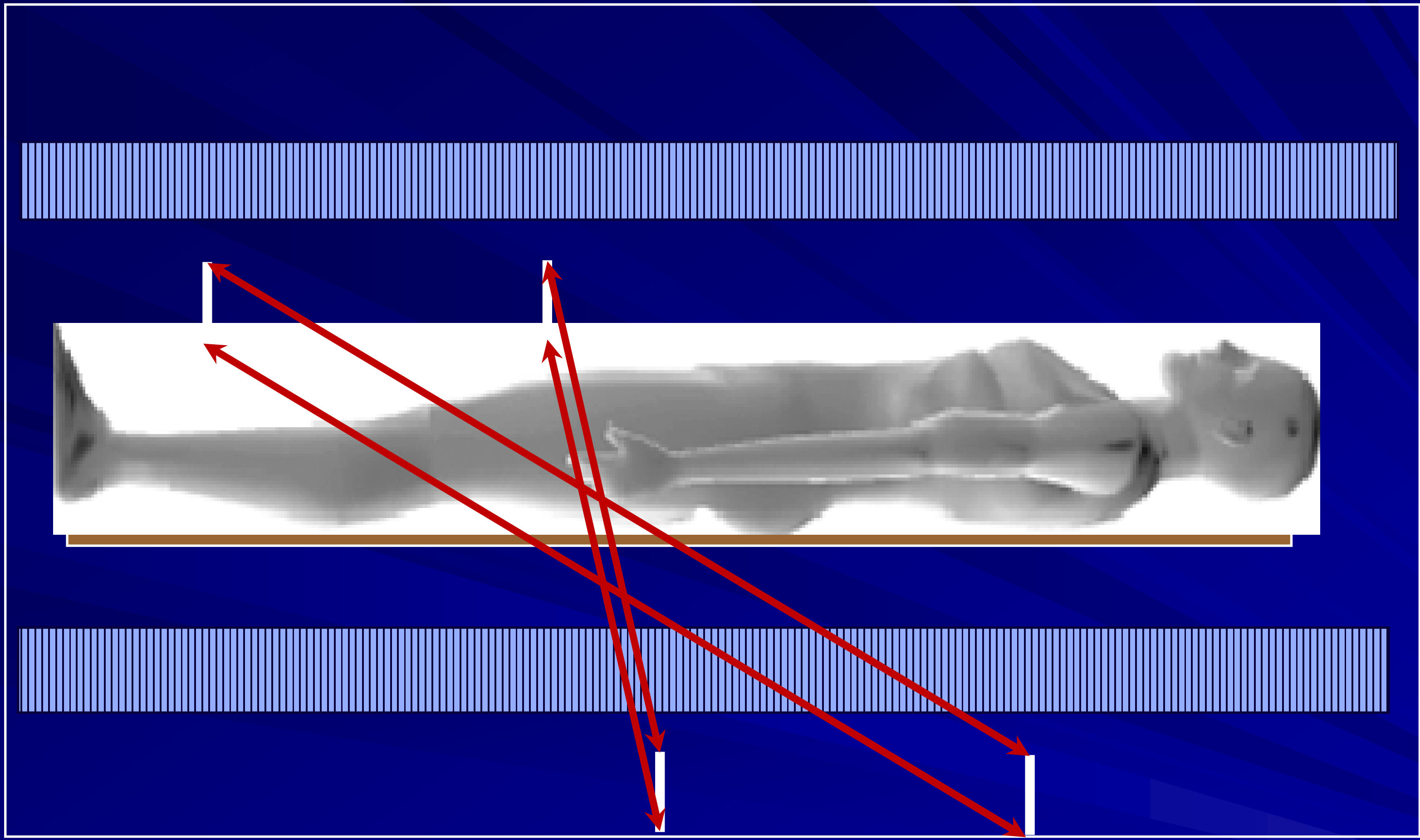
S. Cherry, J3-7
NSS-MIC 2013 Seoul







Estimated data production

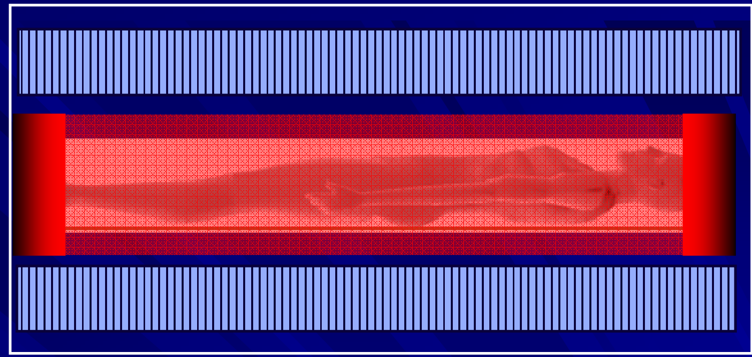


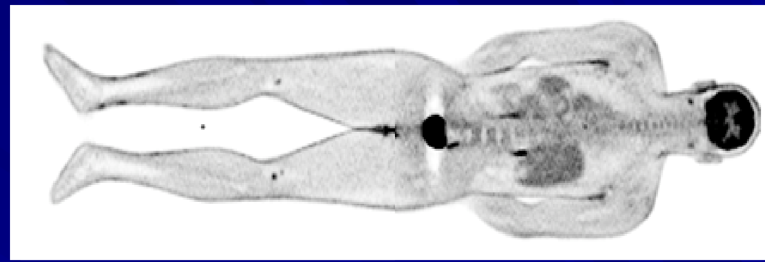
Singles: *164 MHz*
Prompts: *47 MHz*
Randoms: *34 MHz*

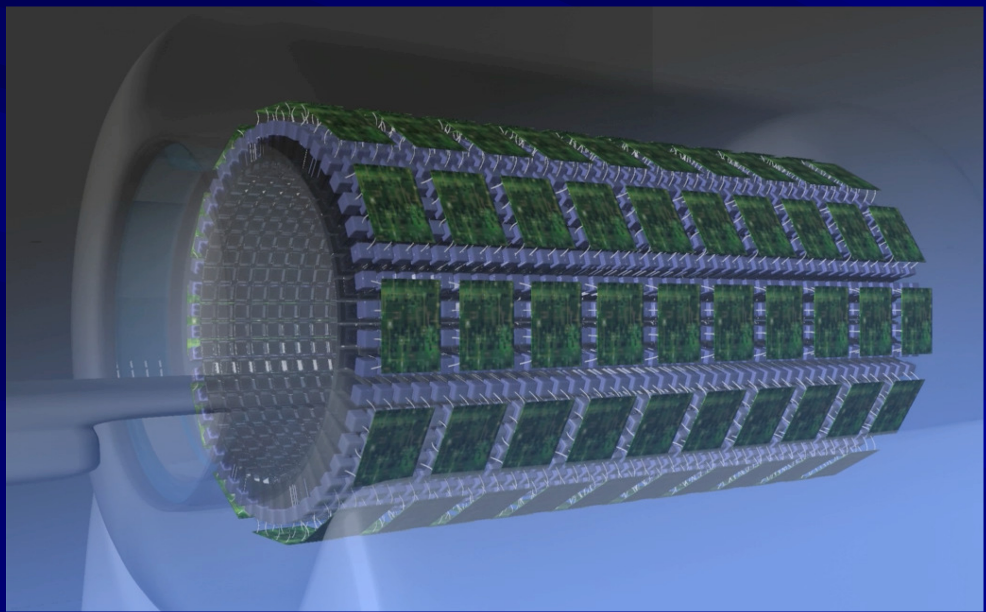
A very interesting subject for T/DAQ experts

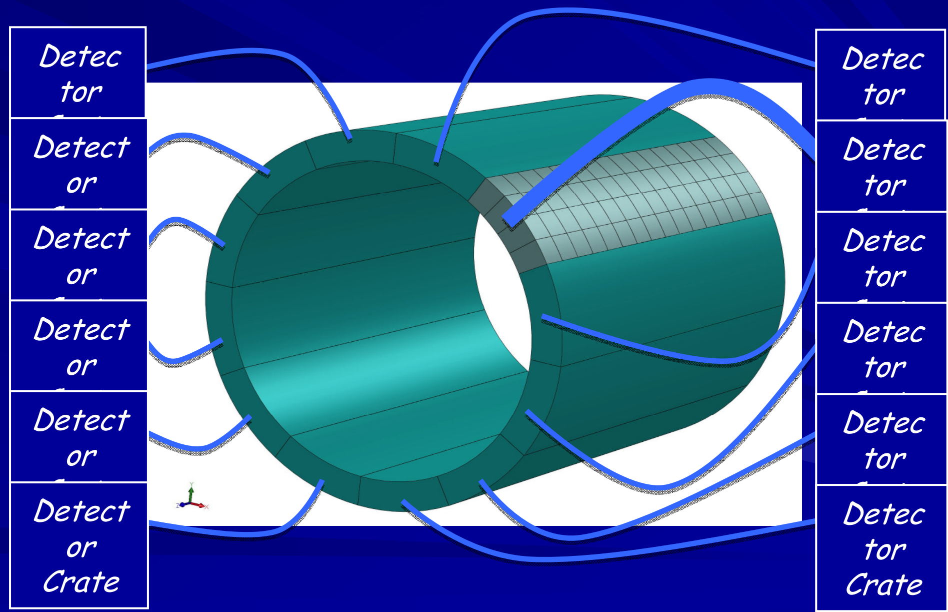
This idea is coming …..

- The Total body PET







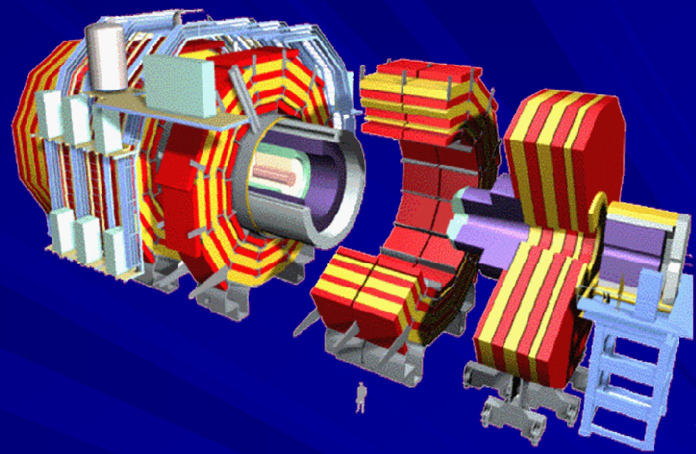


The Challenge

Total-Body "Explorer" Project

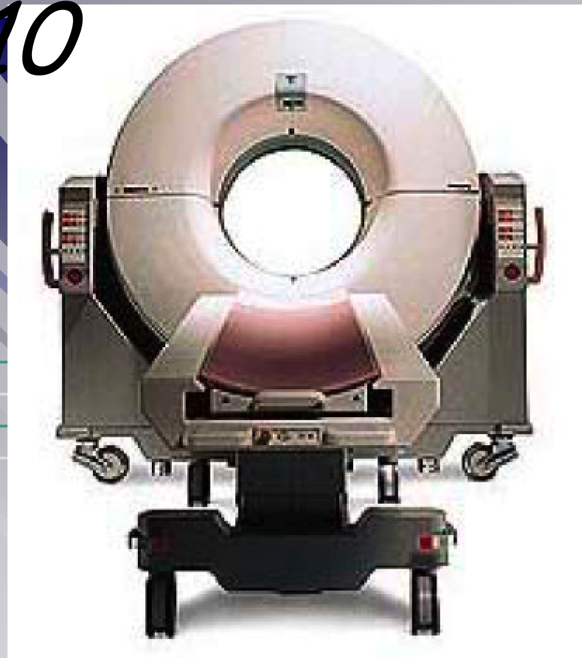
- Very large number of channels (20 → 2m FOV)
  ~ 500 k channels (2x2 mm2 pixels)
- High trigger rate ~ 10 MHz
  (10 mCi, 20% sensitivity)
- High data rate
  ~ 10 Gbyte/s (1 kbyte event size)
- Large number of events
  - *160 x 160 x 1000 image matrix*
  - Large data volume per image
  - 1 billion events

  Real Time analysis
- Simultaneous merging of multimodality data
  - CT- MRI



Looks like

2010

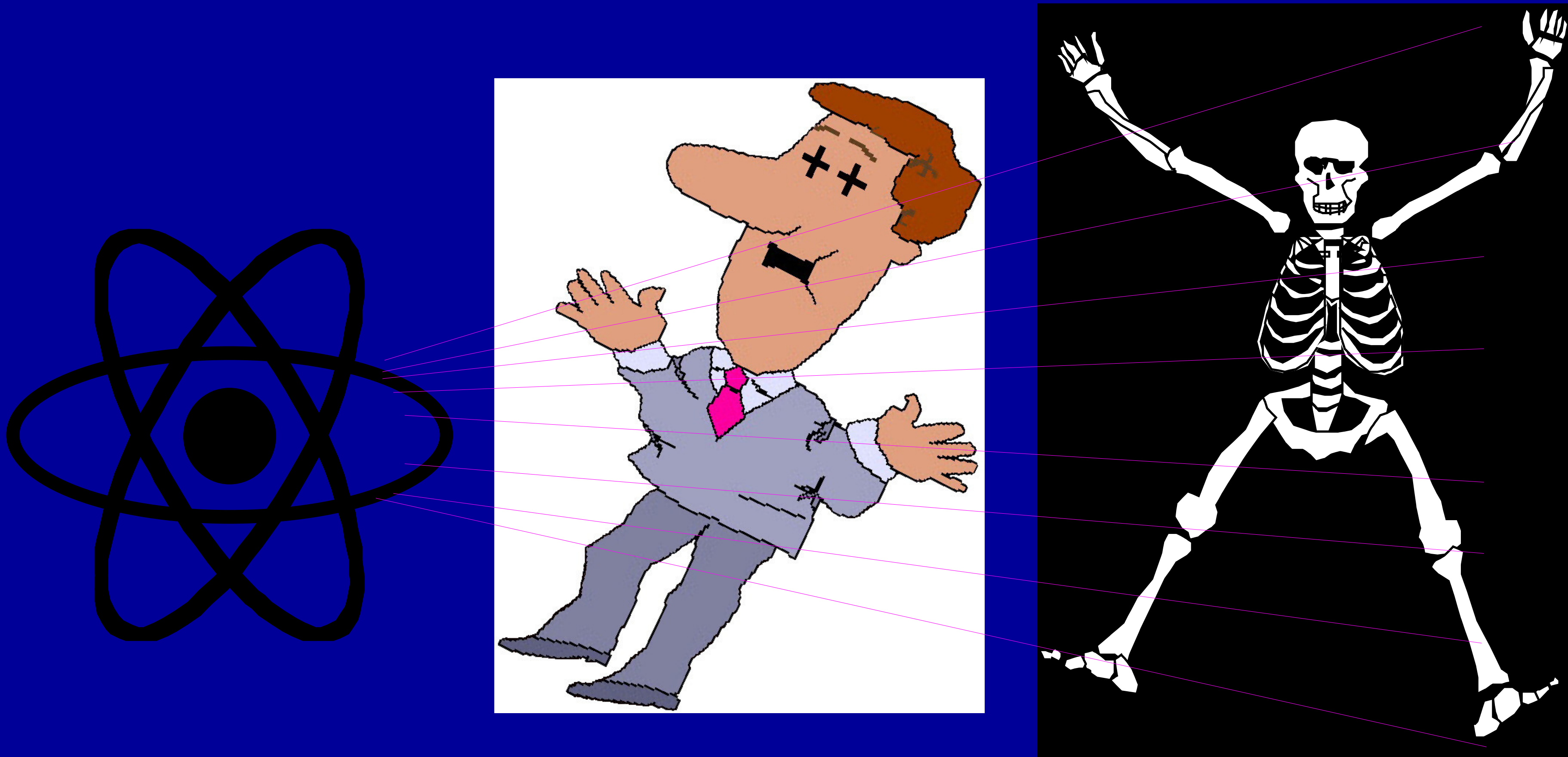


X Ray imaging

Deacreasing the dose with HEP Gazeous detector

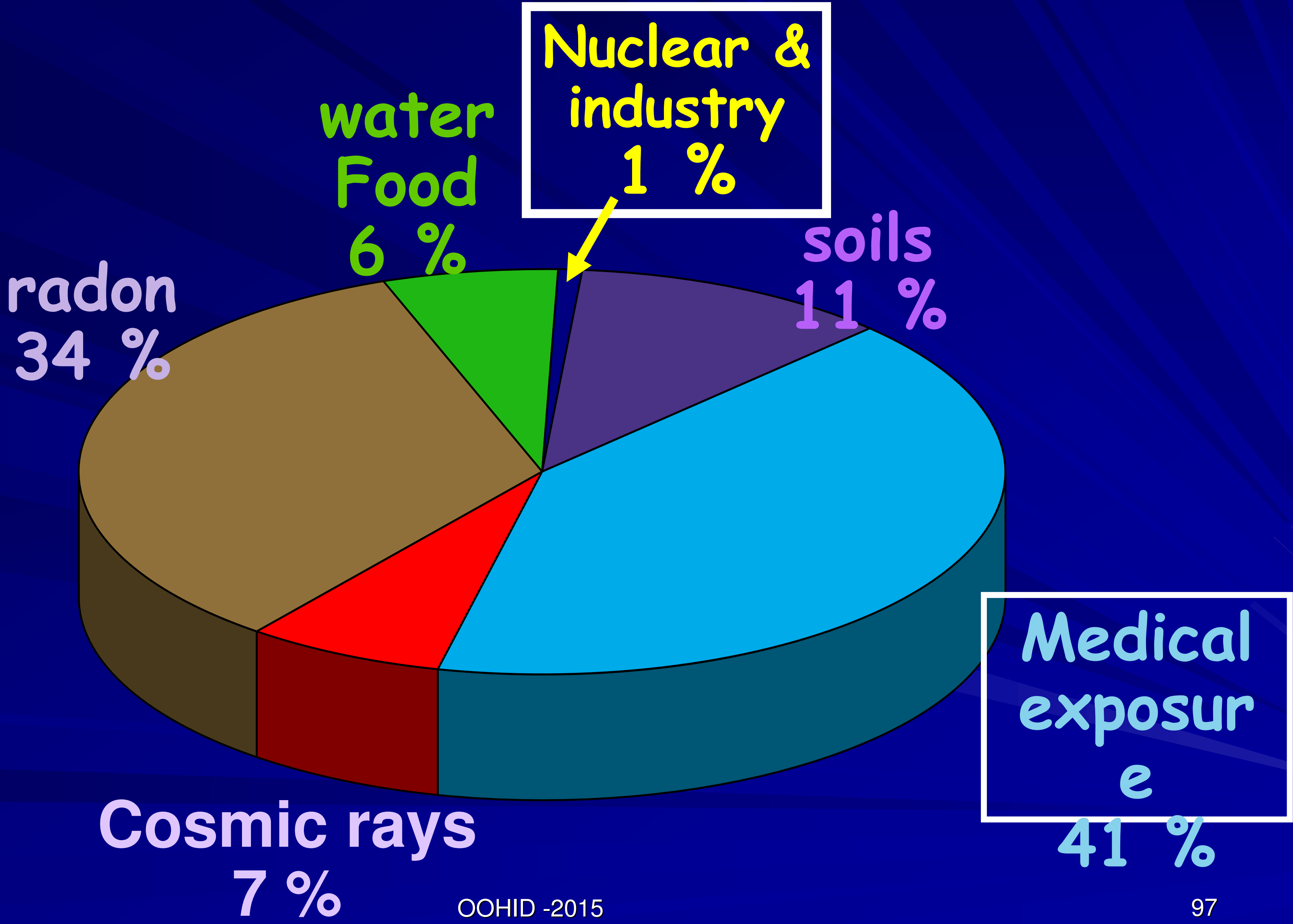
CT

Patient Radiation Dose is Limited!



- Image Noise Is Limited by Counting Statistics
- Cannot Increase too much Source Strength

Natural versus medical irradiation

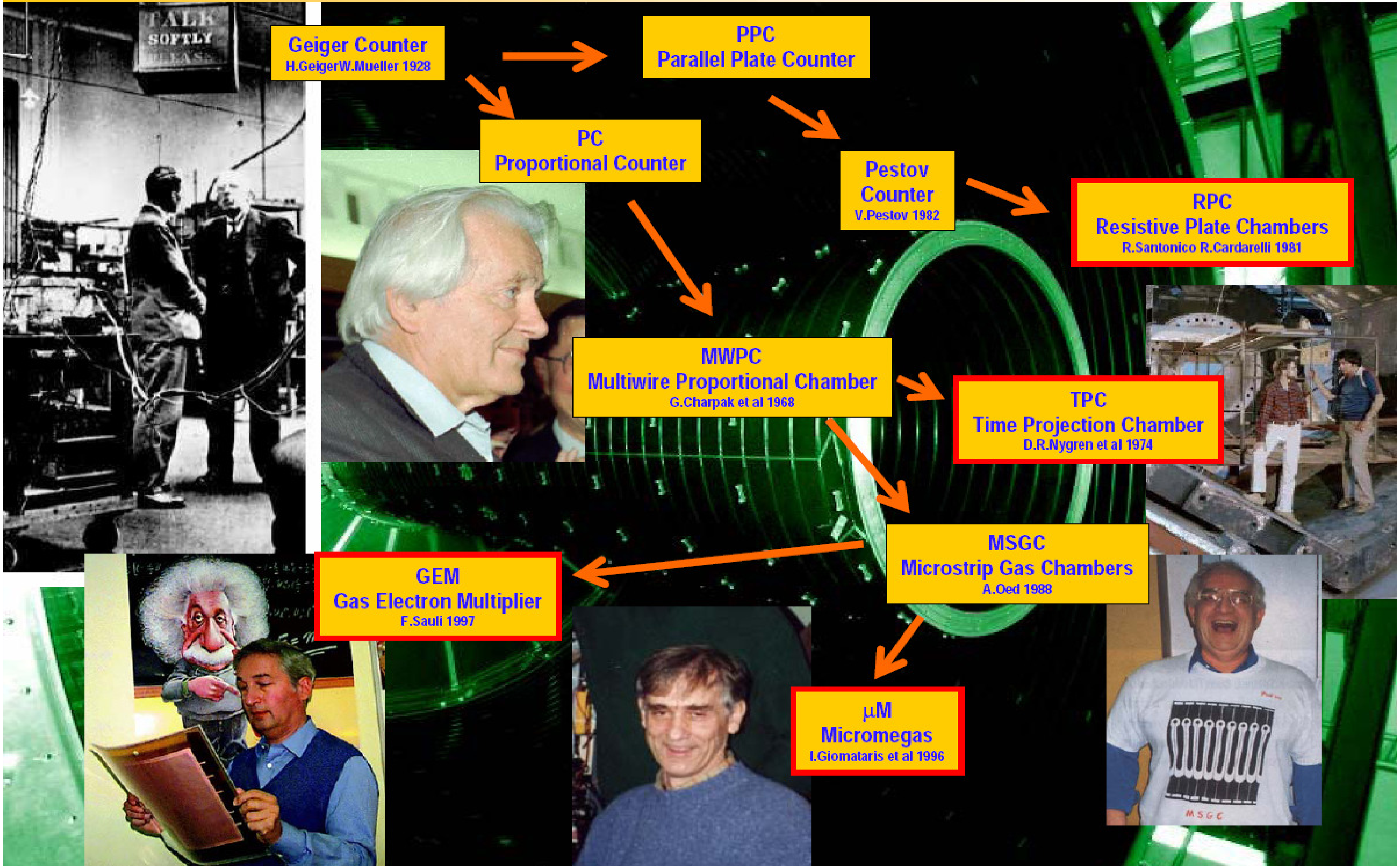


Exposure for radiological exams

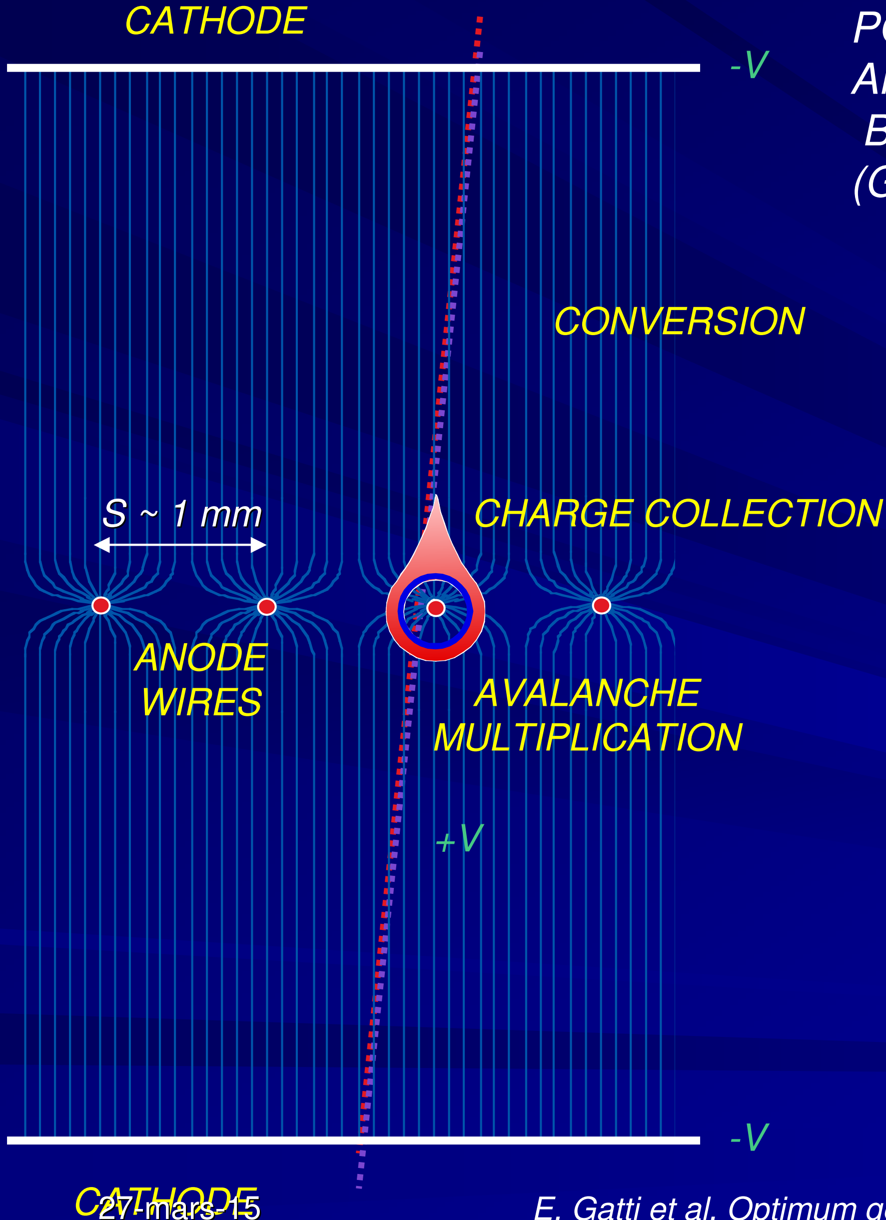
- Some examples

organ	dose skin mGy	effective dose mSv
Thorax, face	0,2 - 0,5	0,015 - 0,15
Lumbar region	4 - 28	1,5
Urography	40 - 60	3
Brain scan	7 - 78	1
Whole Body scan	30 - 60	4 - 10
Mammography	7 - 25	0,5 - 1

Gas Detector History

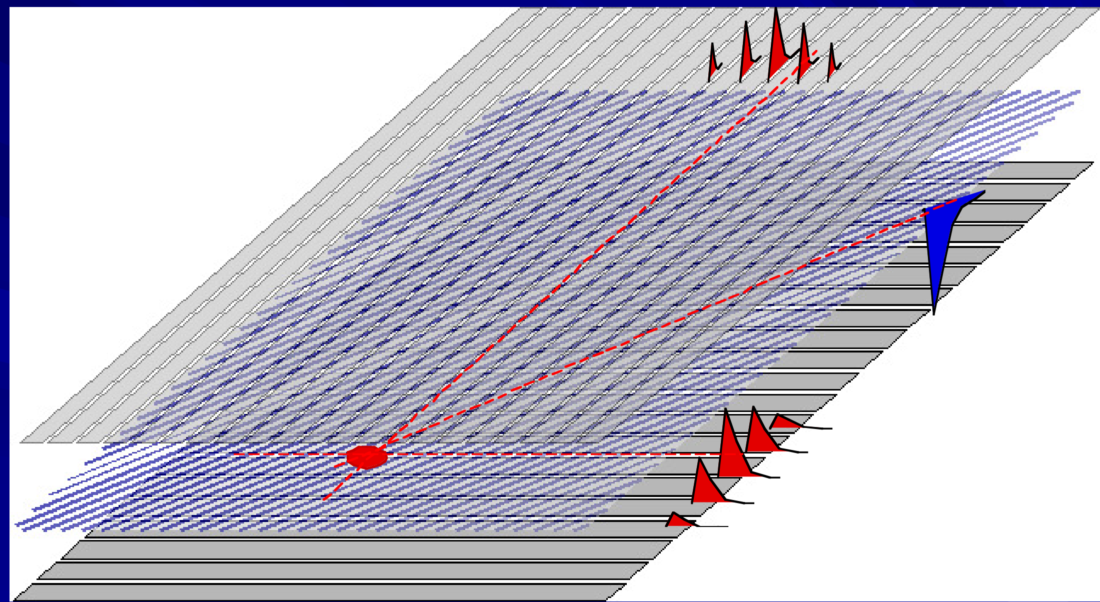


Multi Wires Proportional chambers MWPC



MODERN GASEOUS DETECTORS:
POWERFUL TOOLS FOR RADIATION DETECTION
AND LOCALIZATION IN PARTICLE PHYSICS,
BASED ON THE MULTIWIRE PROPORTIONAL CHAMBER
(Georges Charpak, 1967)

TWO-DIMENSIONAL MWPC READOUT CATHODE
INDUCED CHARGE (Charpak and Sauli, 1973)

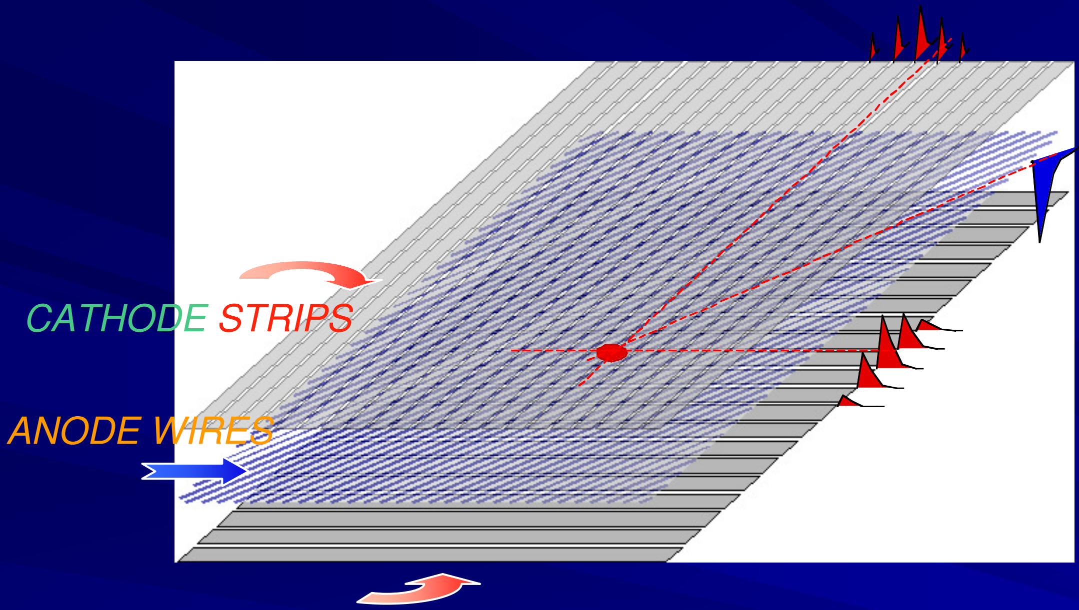


Spatial resolution determined by: Signal / Noise Ratio
Typical (i.e. 'very good') values: S ~ 20000 e: noise ~ 1000e
Space resolution < 100 μm

E. Gatti et al, Optimum geometry for strip cathodes … , Nucl. Instr. and Meth. 163(1979)83

TWO-DIMENSIONAL LOCALIZATION

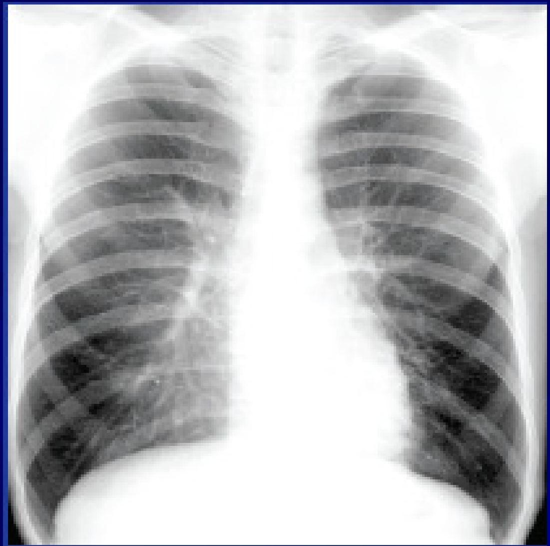
TWO-DIMENSIONAL LOCALIZATION FROM SIGNALS INDUCED ON CATHODE PLANES (Charpak & Fabio Sauli, ~1973)

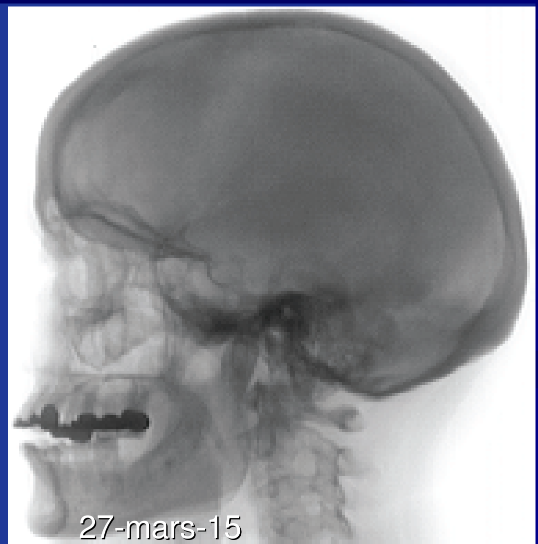


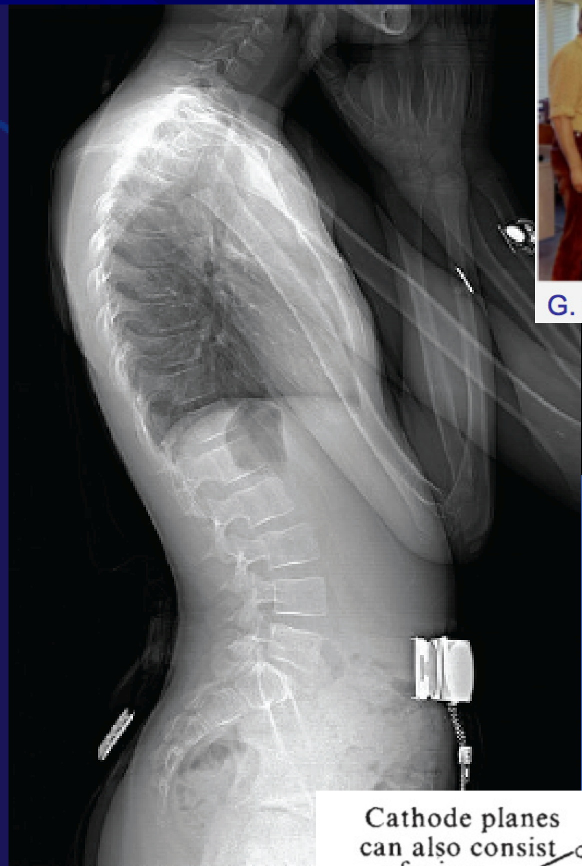
LOW-DOSE DIGITAL RADIOGRAPHY
WITH MWPC:
CHARPAK'S HAND (2002):

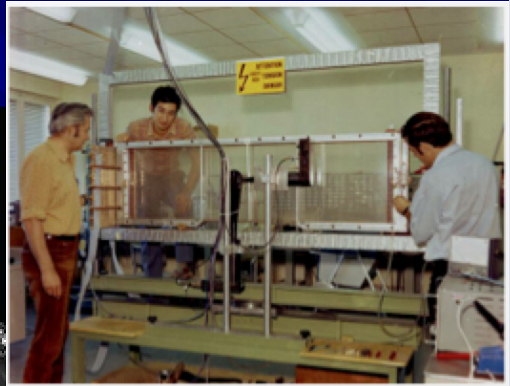
The 1970's dream : Digital radiography with MWPC
A tribute to George Charpak

- With 10 time less dose

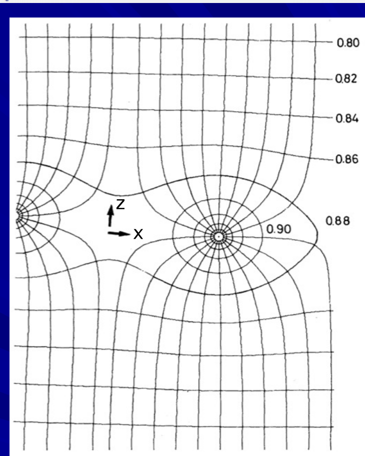


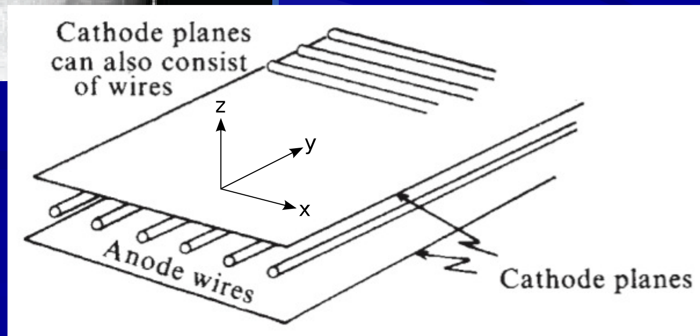






G. Charpak, F. Sauli and J.C. Santiard





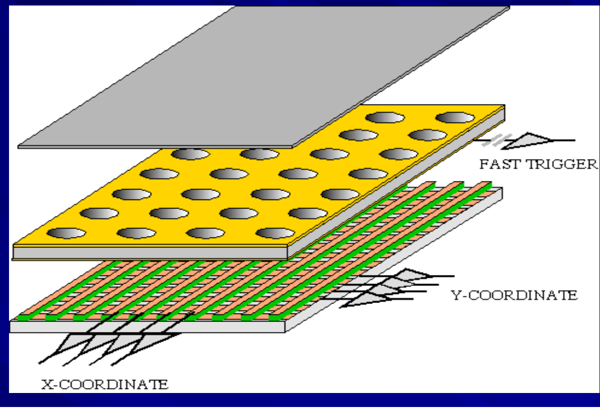
X Ray imaging

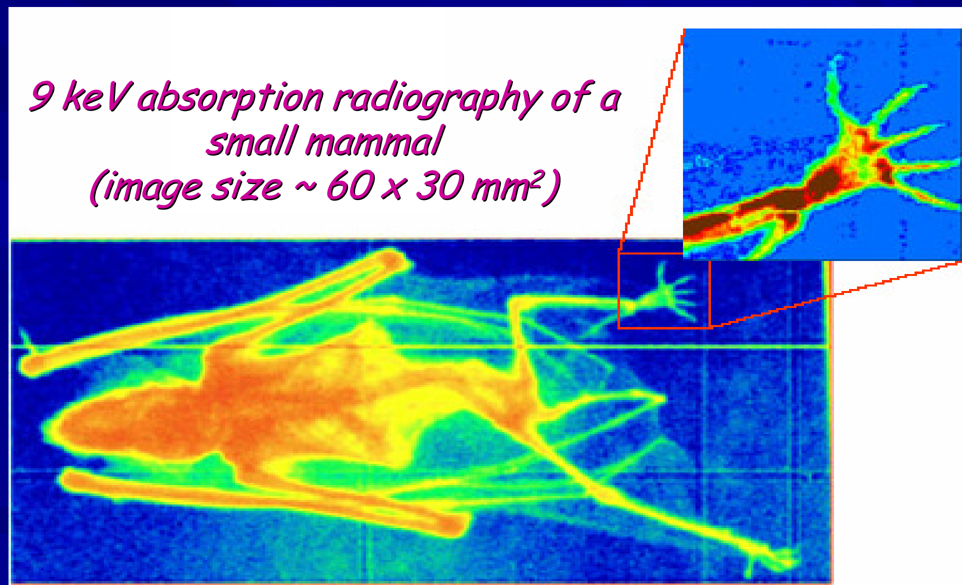
Wire Chamber Radiography:

Position resolution ~ 250 µm

GEM for 2D Imaging:

Using the lower GEM signal, the readout can be self-triggered with energy discrimination:





9 keV absorption radiography of a small mammal (image size ~ 60 x 30 mm²)

Position resolution ~ 100 µm
(limited by photoelectron range in the gas)

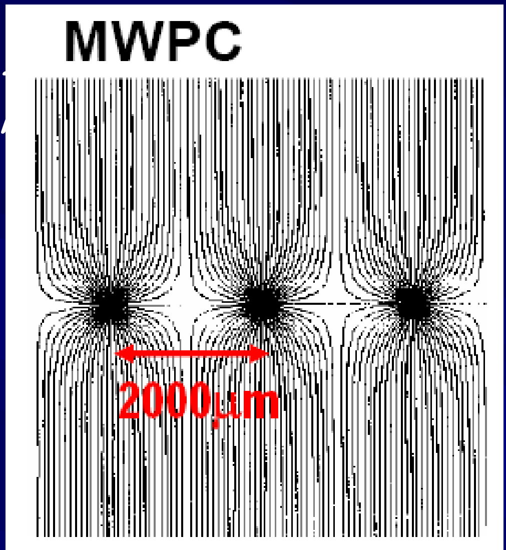
A. Bressan et al, Nucl. Instr. and Meth. A 425(1999)254
F. Sauli, Nucl. Instr. and Meth.A 461(2001)47
G. Charpak, Eur. Phys. J. C 34, 77-83 (2004)
F. Sauli, http://www.cern.ch/GDD

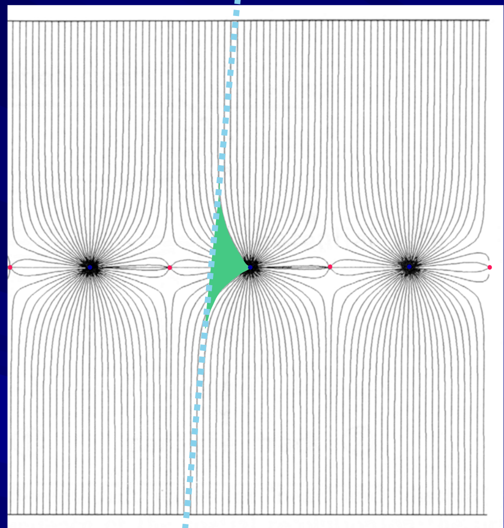
From MWPC's to MGPD's

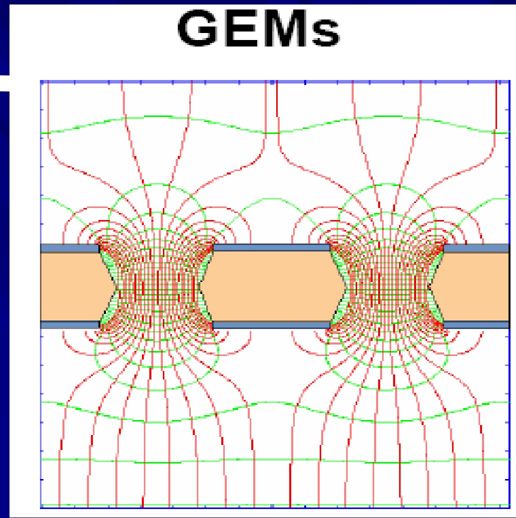
MGPD

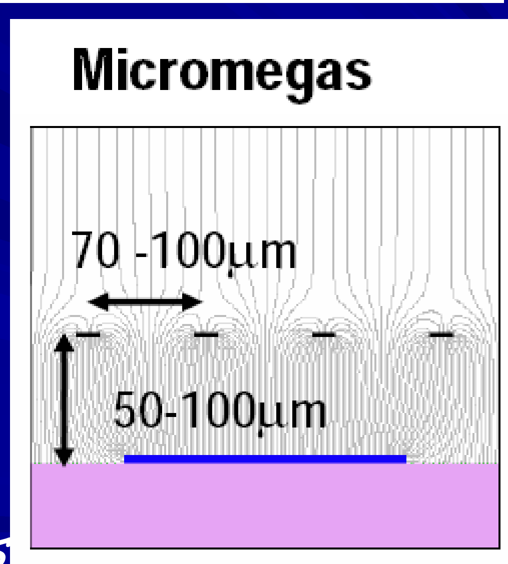
MWPC

Drift Chambe









1975 - 1995 UA2-LEP

1990 -

Multiwire Proportional Chamber

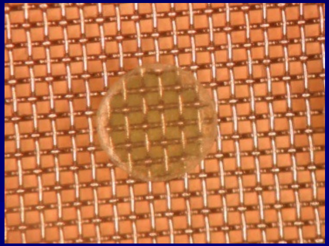
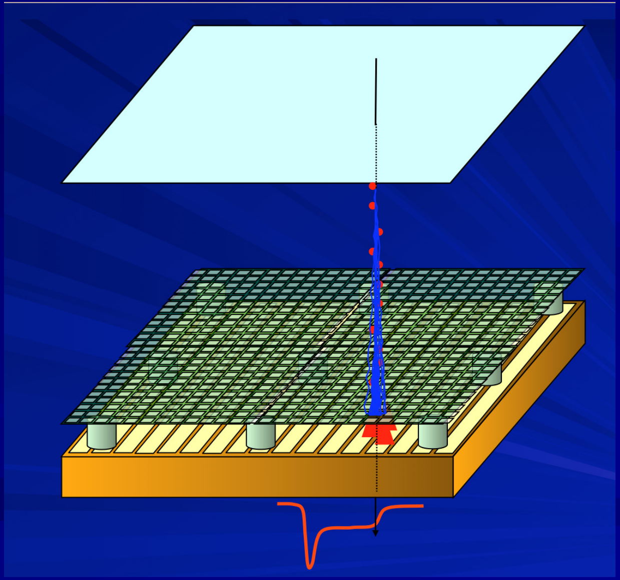
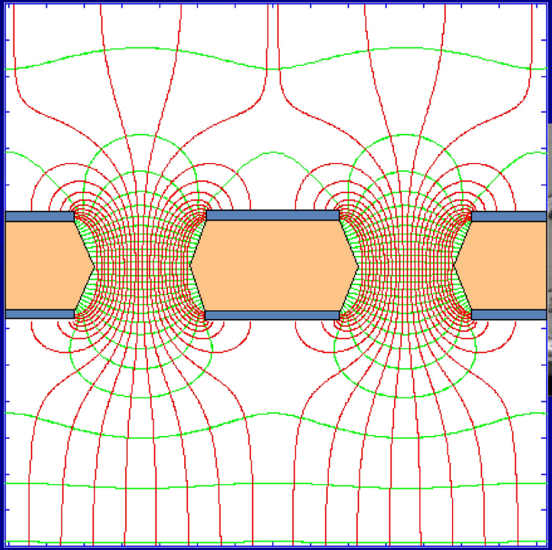
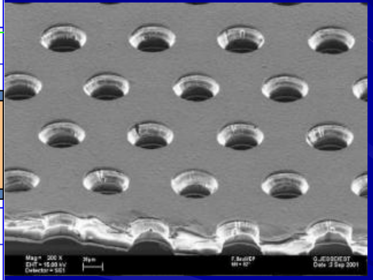
Georges Charpak 1968

GEM F.Sauli)

Micromegas Y. Giomataris

MPGD

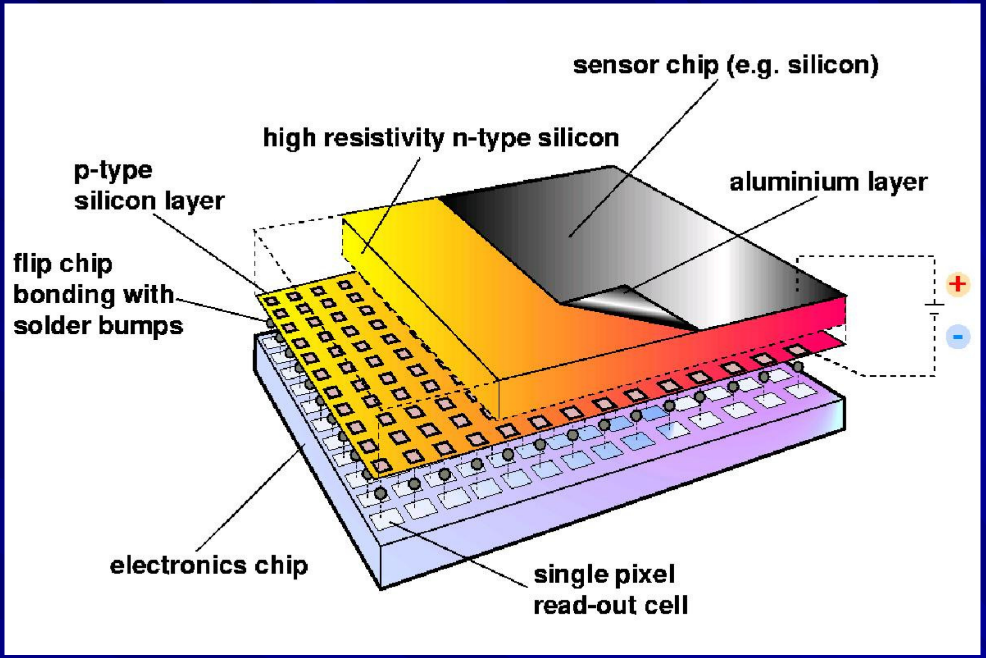
- From 1988-1998 Micro-technologies and etching techniques allowed development of Micro Patter Gaseous Detectors
  - MICROMEsh GAseous Structure
    - Thin gap Parallel Plate Chamber: micromesh stretched over readout electrode.
  - Gas Electron Multiplier
    - Thin, metal-coated polymer foil with high density of holes, each hole acting as an individual proportional counter.

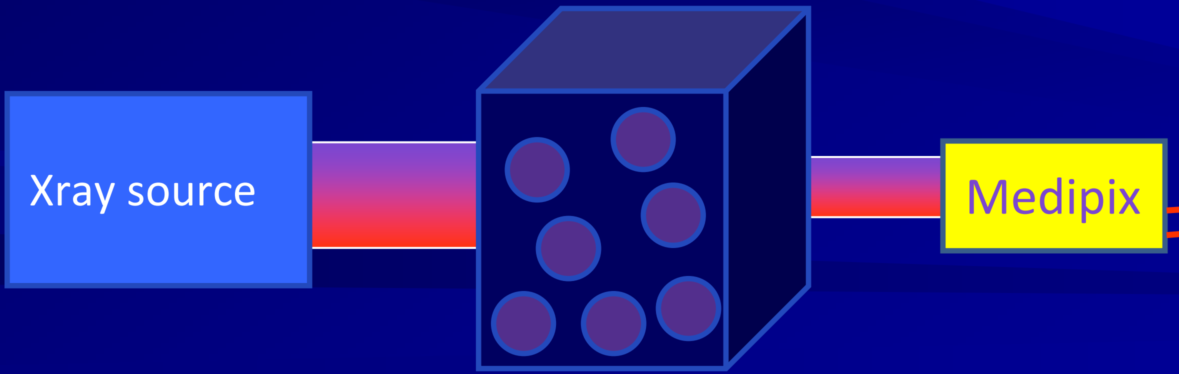





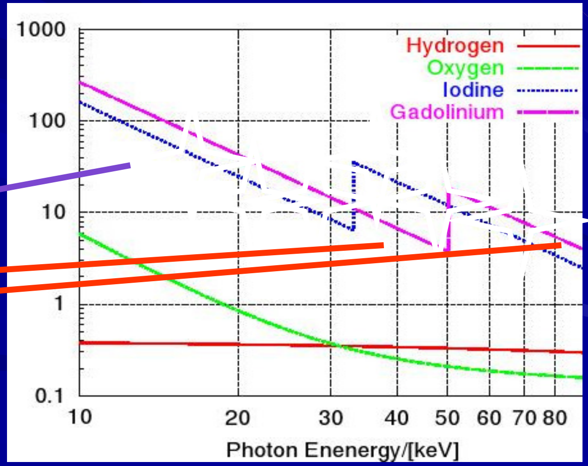
The Future : New Si detector and signal processing On the way to photon counting?

Medipix3

- 8 simultaneous energies
- 55 µm isometric resolution
- Excellent energy resolution
- 10^8 photons per second per mm^2

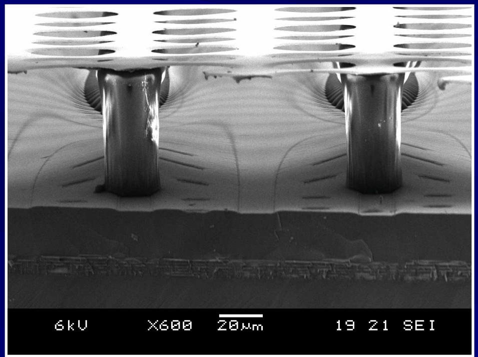




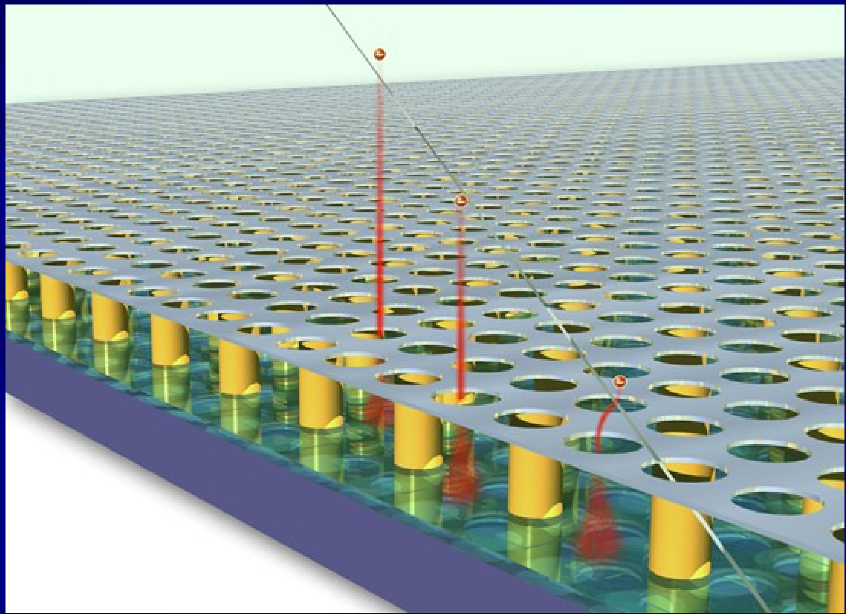


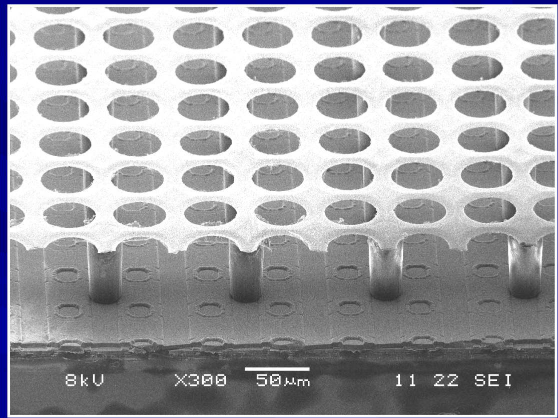
Next → INGRID

- InGrid :integrate the Micromegas/GEM concept on top of a MediPix pixel CMOS chip (Timepix)
    - pixel size: 55 x 55 μm^2
    - per pixel: preamp – shaper – 2 discr. –
    - Thresh. DAQ - 14 bit counter



metalized foil
~100 µm ~1mm





Cmos Medipix chip

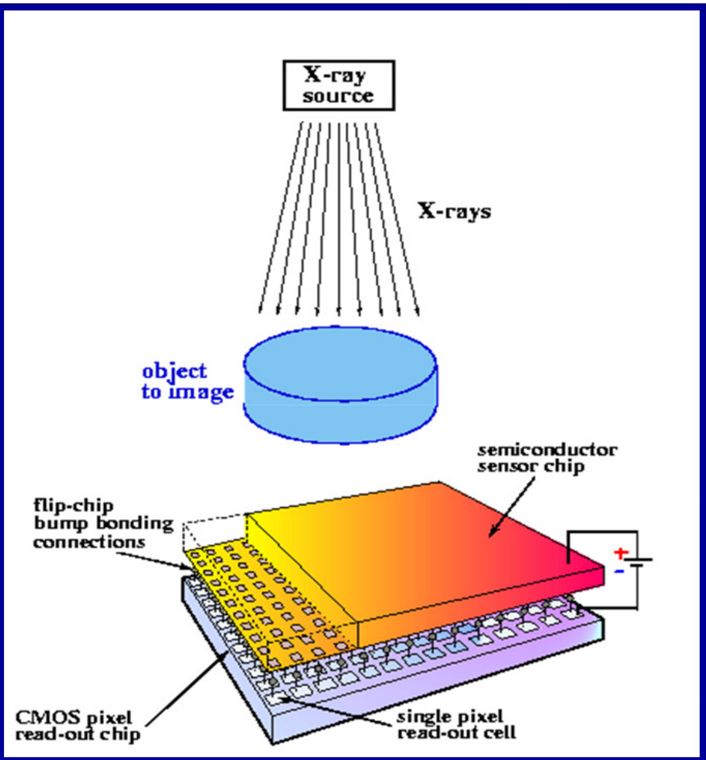
- Use → Large Trackers & Calorimeters

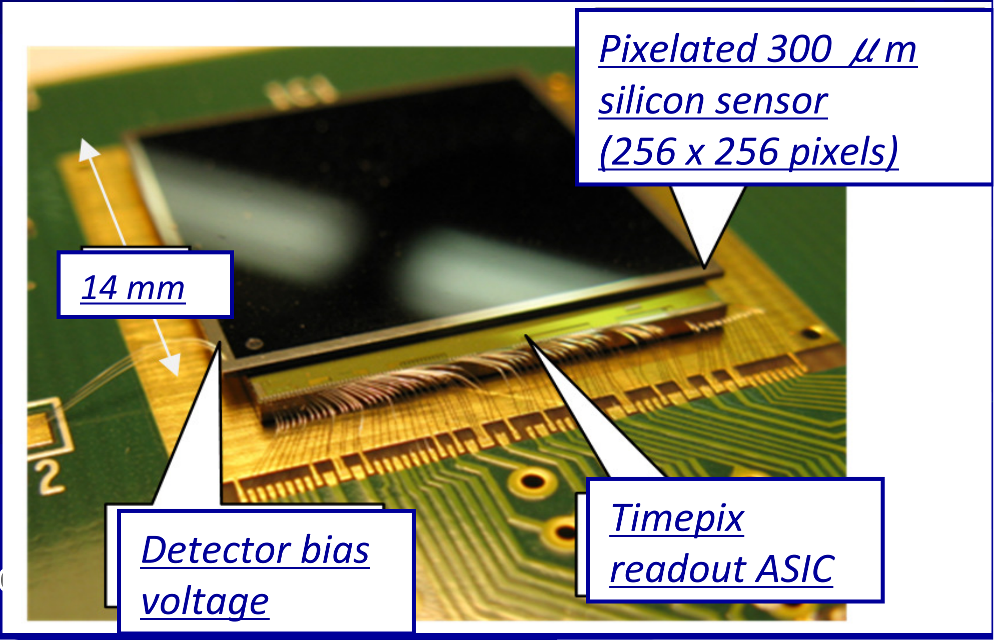
Timepix Hybrid detector

On the way of photon counting

- Medipix is a Silicon pixel-based detector technology AND signal processing that can be employed to measure charged particles,photons, and neutrons.
- It is based on a read-out chip that embeds the electronics for each pixel within the pixel's footprint!
- Detector and electronics readout are optimized separately
- developed for use in the CERN LHC Central Trackers
- Medipix 3/TimePix This technology is an extension of designs originally
  - Integrate a TDC ….

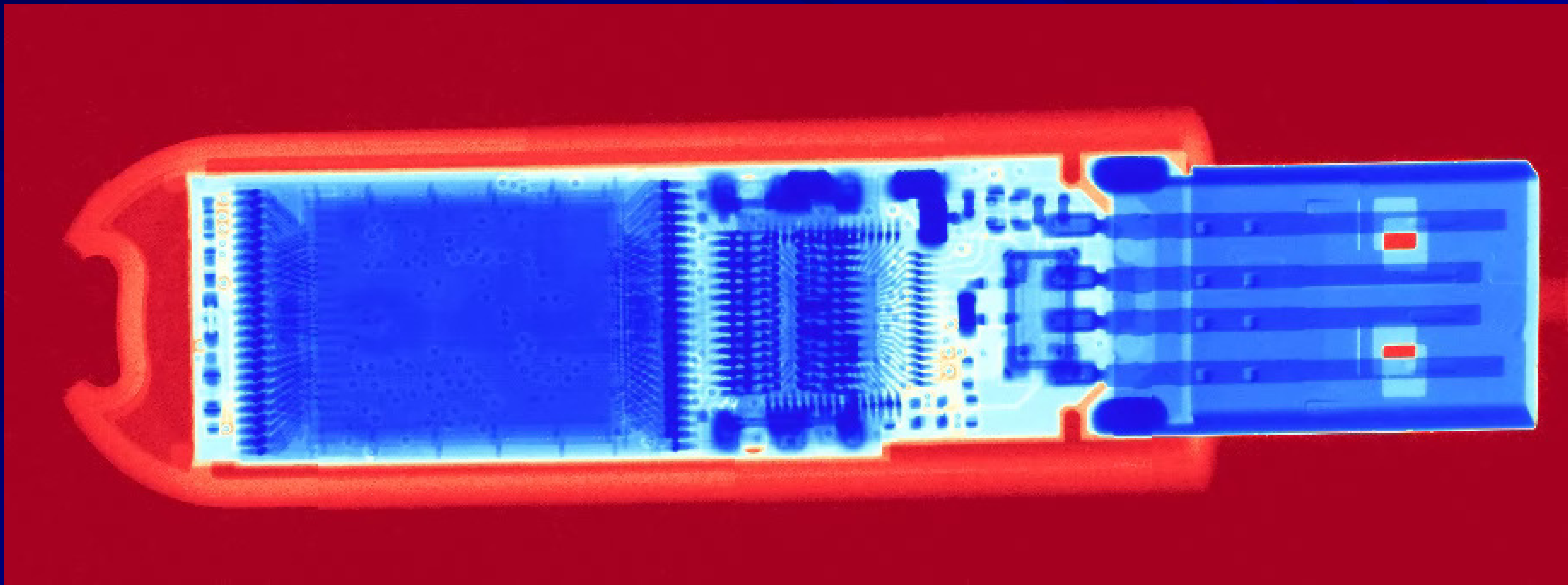
TU Prague - J. Jakubec
NSS-MIC 2013 Seoul J4-3





Medipix-CT setup for detector investigations & material analysis

Example → USB flash drive



TPX 110µm + CdTe 2mm
8x2 tiles / mag. 1.5x
65kV / 200µA

Example

PORTAL IMAGING

PORTAL IMAGING: VERY HIGH RATE GAMMA RAYS DETECTION

ROYAL INSTITUTE OF TECHNOLOGY AND KAROLINSKA HOAPITAL (STOKHOLM)

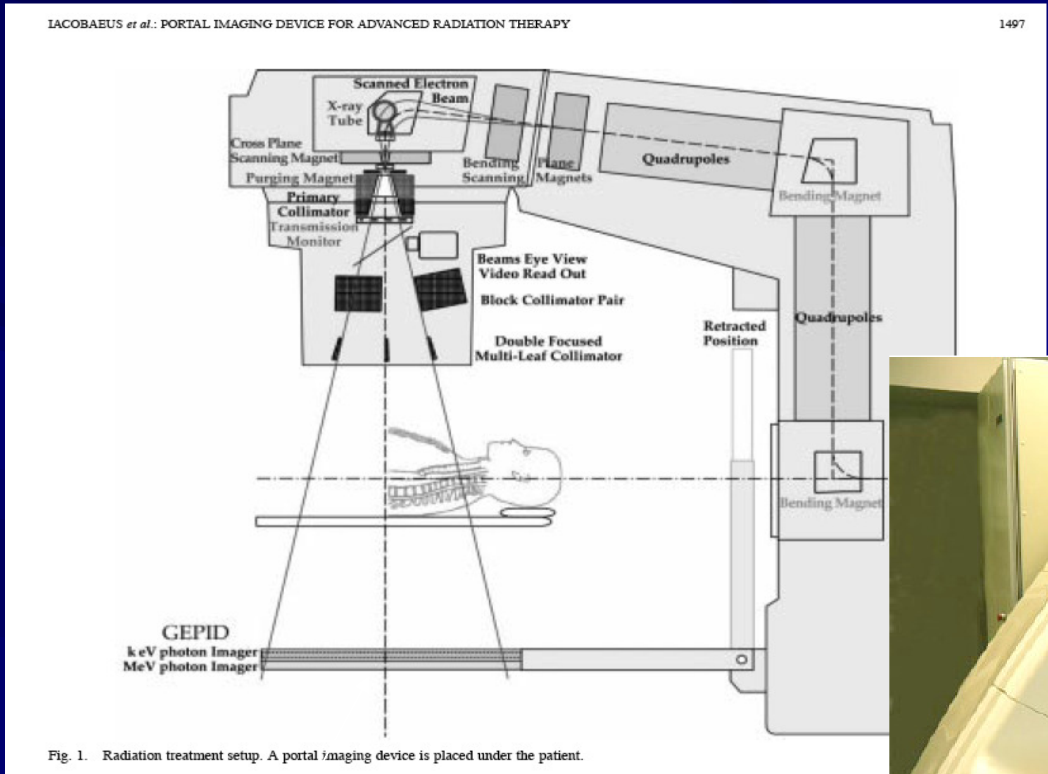


Fig. 1. Radiation treatment setup. A portal imaging device is placed under the patient.

Real Time Imaging and Dosimetry

GEM-BASED PIXEL DETECTOR

C. Iacobaeus et al, IEEE Trans. Nucl. Sci. NS-48 (2001)1496

Summary & Conclusions (1)

- HEP has considerable acquired knowledge, expertise and resources that can, when transferred properly, significantly impact the practice of medical imaging and therapy
- A lot of exciting ideas and developments!
  - Should attrack young 'experimentalists'
- Activity that need to be 'promoted' actively outside our community for the benefit of us…in these hard time !
  - HEP is not only hunting the Higgs !

Summary & Conclusions (2)

- It take sometime between the discovery and initial ideas.
- But when the technology is mature, it can make a gigantic breakthrough in the development of a technical device or system
- Collaboration between various scientists and expert is fundamental and the key factor for success.
- Building a community (network) about a specific subjects is the way to integrate students and experts

Final Conclusions

There is a lot to do

Particularly for students

References Proceedings of NSS-MIC conferences

Transaction on Nuclear Sciences (TNS)

http://www.nss-mic.org/2013/NSSMain.asp

Thanks to

- D.Townsend (U. Singuapor)
- W. Enghardt (Dresden)
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- P. Lecoq (CERN)
- R. Lecomte (Sherbrooke)
- W. Moses (LBL)
- J. Karp (U. Penn)
- J. Varela (LIP)
- S. Ritt (PSI)
- S.Majewski (WVU)
- K.Parodi (HIT)
- Pr. J.N. Talbot (Hopital Tenon - Paris)
- Pr. J.P. Gerard (Nice)
- ... and many others

Thank you
for your attention