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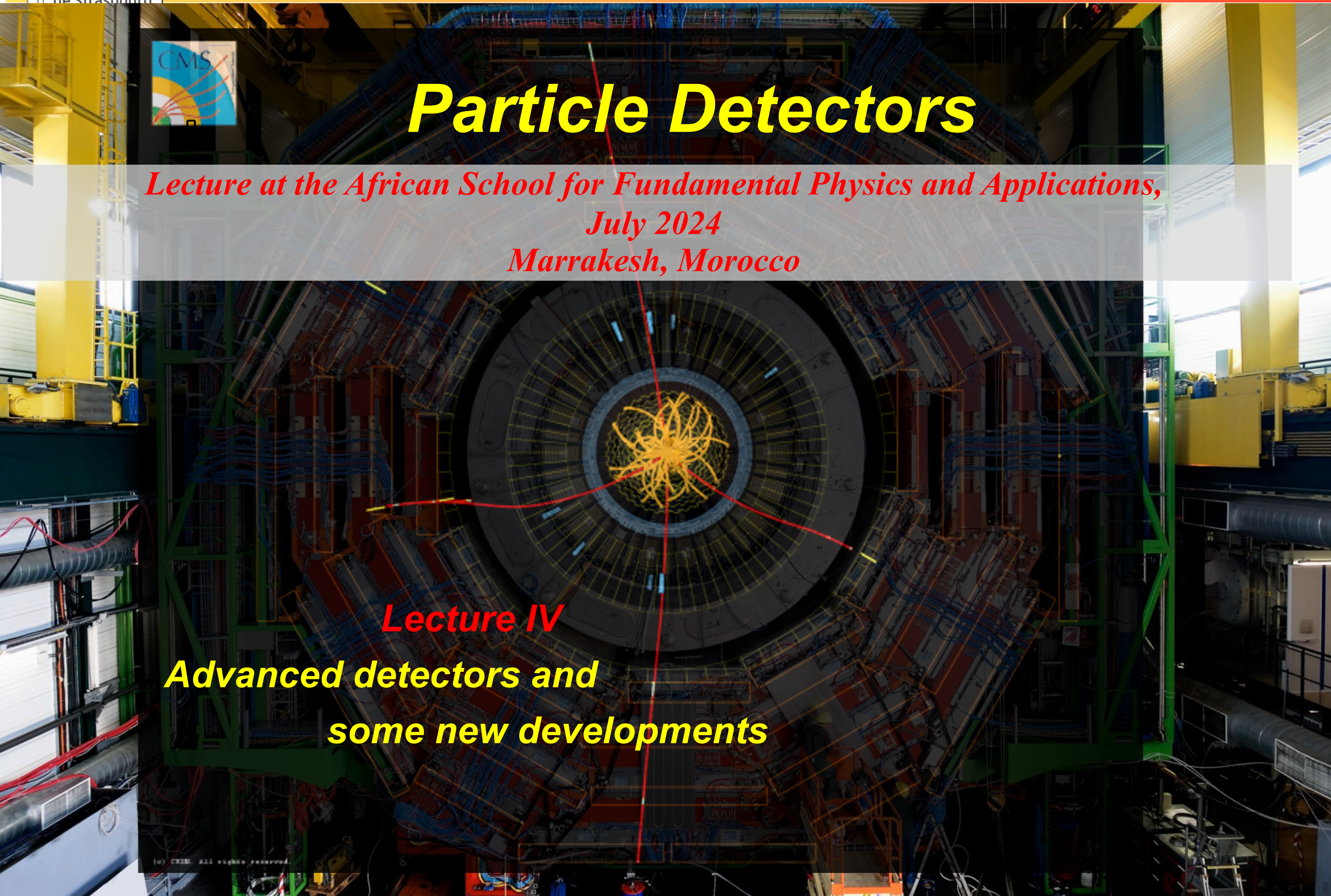


# Particle Detectors

*Lecture at the African School for Fundamental Physics and Applications,*
*July 2024*
*Marrakesh, Morocco*

## Lecture IV

## Advanced detectors and some new developments

# Particle Detectors

*Lecture at the African School for Fundamental Physics*
*Marrakesh, Morocco, July 2024*

**Goal this lecture:**

**to discuss some examples**

**Looking at recent technological developments**

**infinite number of ideas for new detectors**

**Lecture IV**

- **LHC detectors**
- **Recent developments of CMOS pixel detectors**
- **Fast detectors for time of flight measurements**
- **High granularity calorimeters**
- **High purity segmented Ge-detectors for Nuclear physics**
- **A glimpse at cryogenic detectors for particle and astrophysics**

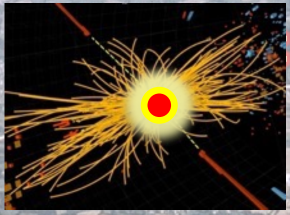
***Don't forget the Exercises!!!!!***

# *The LHC*

## Large Hadron Collider

### *7 TeV protons + 7 TeV protons*

CMS



Large Hadron Collider

- **Proton beams circulate 11,245 times/sec**
- **100's of millions of proton-proton collisions/second**
- **65 pp collisions every 25 ns**
- **new particles are created ($E = mc^2$)**

# The LHC

## Large Hadron Collider

*7 TeV protons + 7 TeV protons*

CMS

Large Hadron Collider

- Pr rculate 11,245 times/sec
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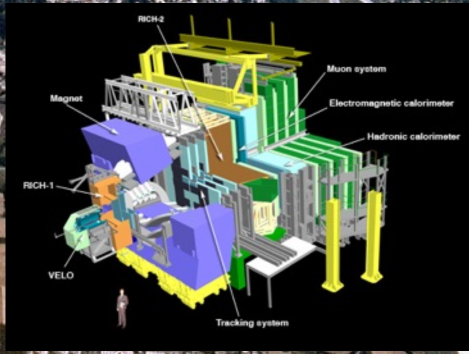
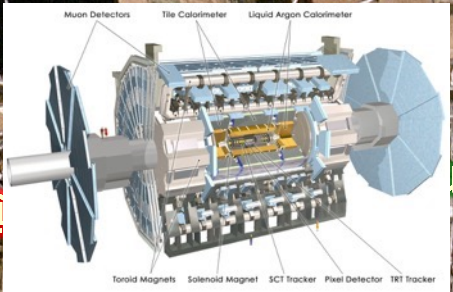



ALICE




CMS Centre @

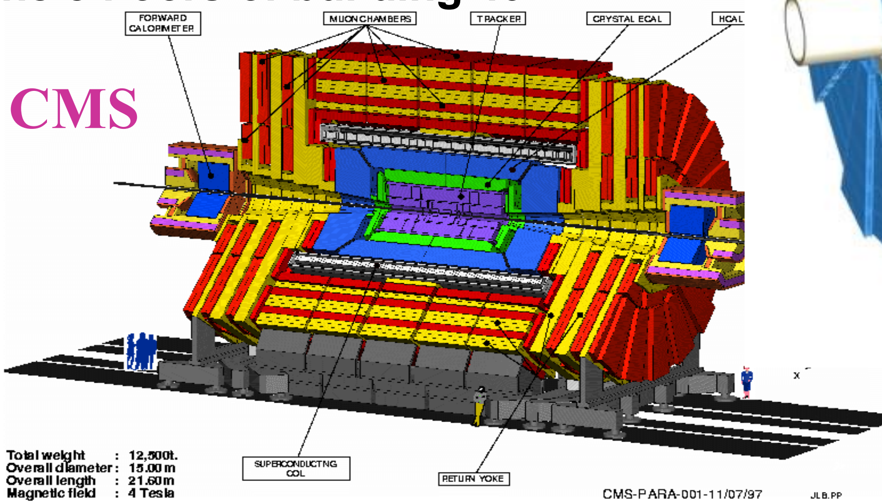
uter Centre

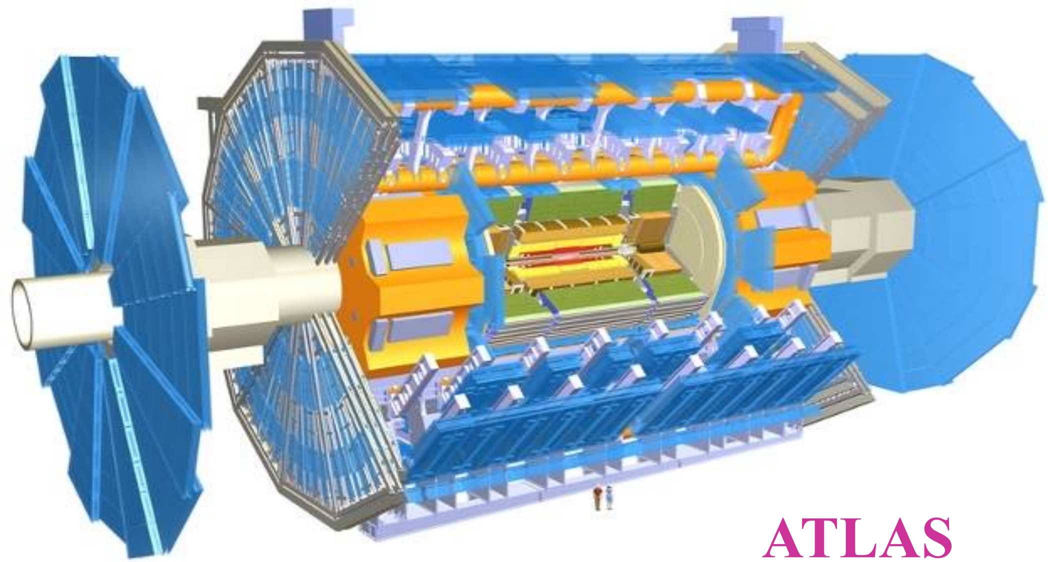
# How huge are ATLAS and CMS?

ATLAS superimposed to

the 5 floors of building 40

CMS



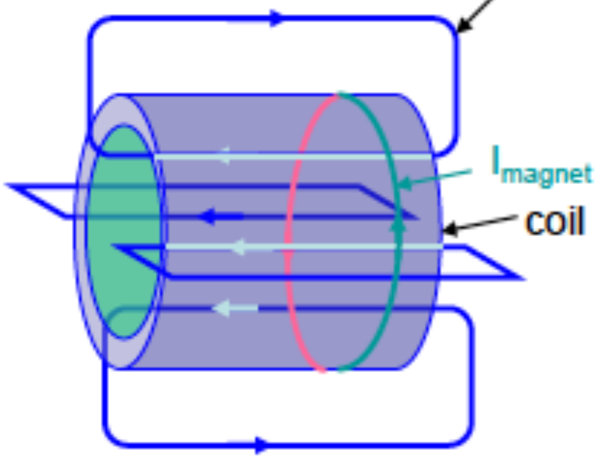



ATLAS

| | ATLAS | CMS |
|---|---|---|
| Overall weight (tons) | 7000 | 12500 |
| Diameter | 22 m | 15 m |
| Length | 46 m | 22 m |
| Solenoid field | 2 T | 4 T |

Magnetic field configurations:

solenoid

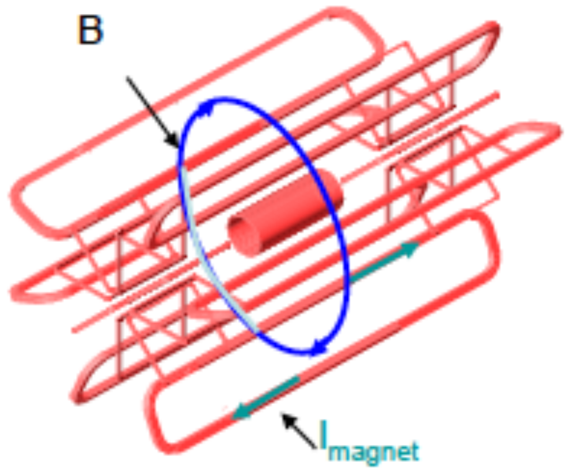



+ Large homogenous field inside coil
- weak opposite field in return yoke
- Size limited (cost)
- rel. high material budget

Examples:

- DELPHI (SC, 1.2T)
- L3 (NC, 0.5T)
- CMS (SC, 4T)

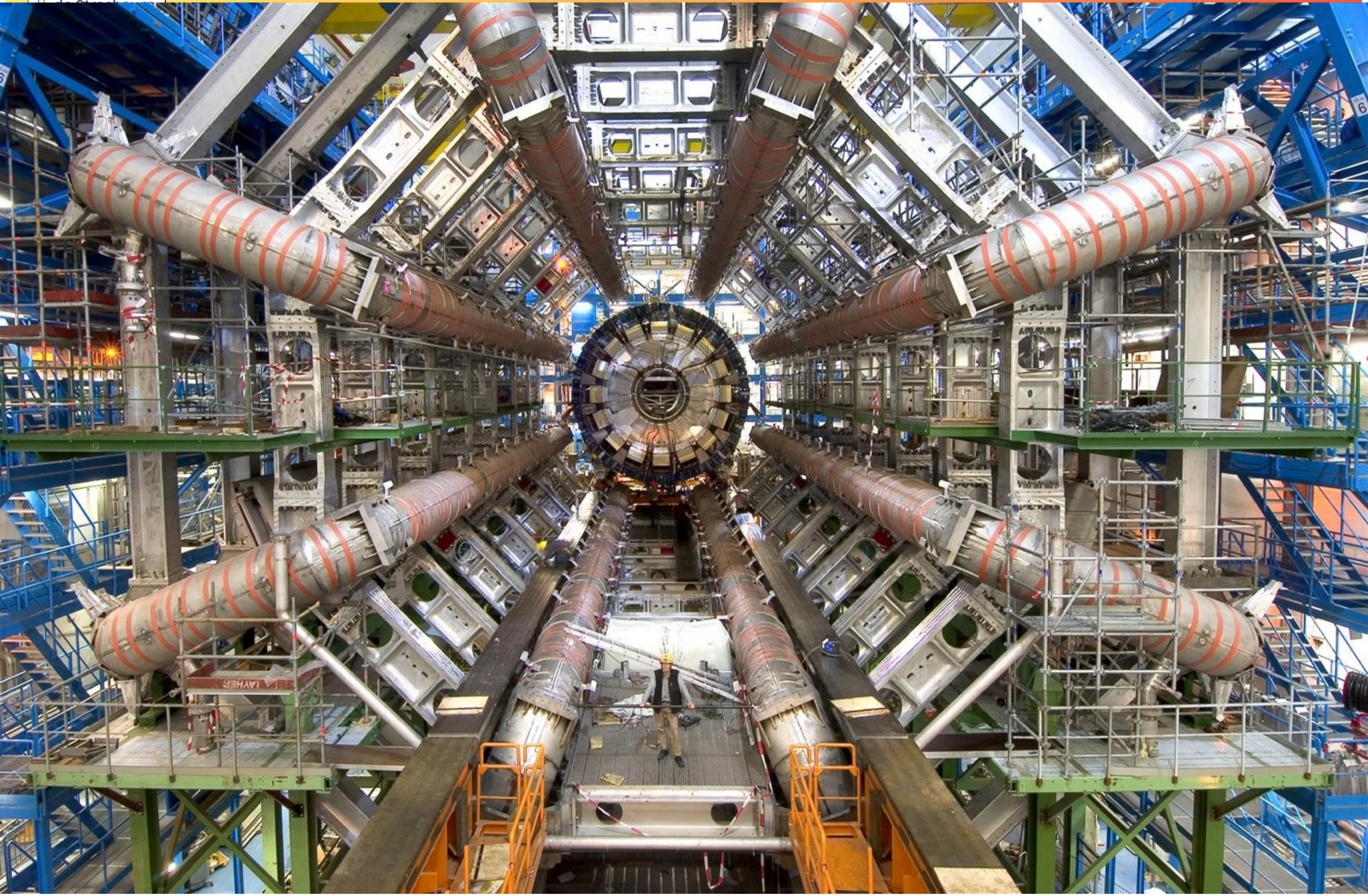
toroid

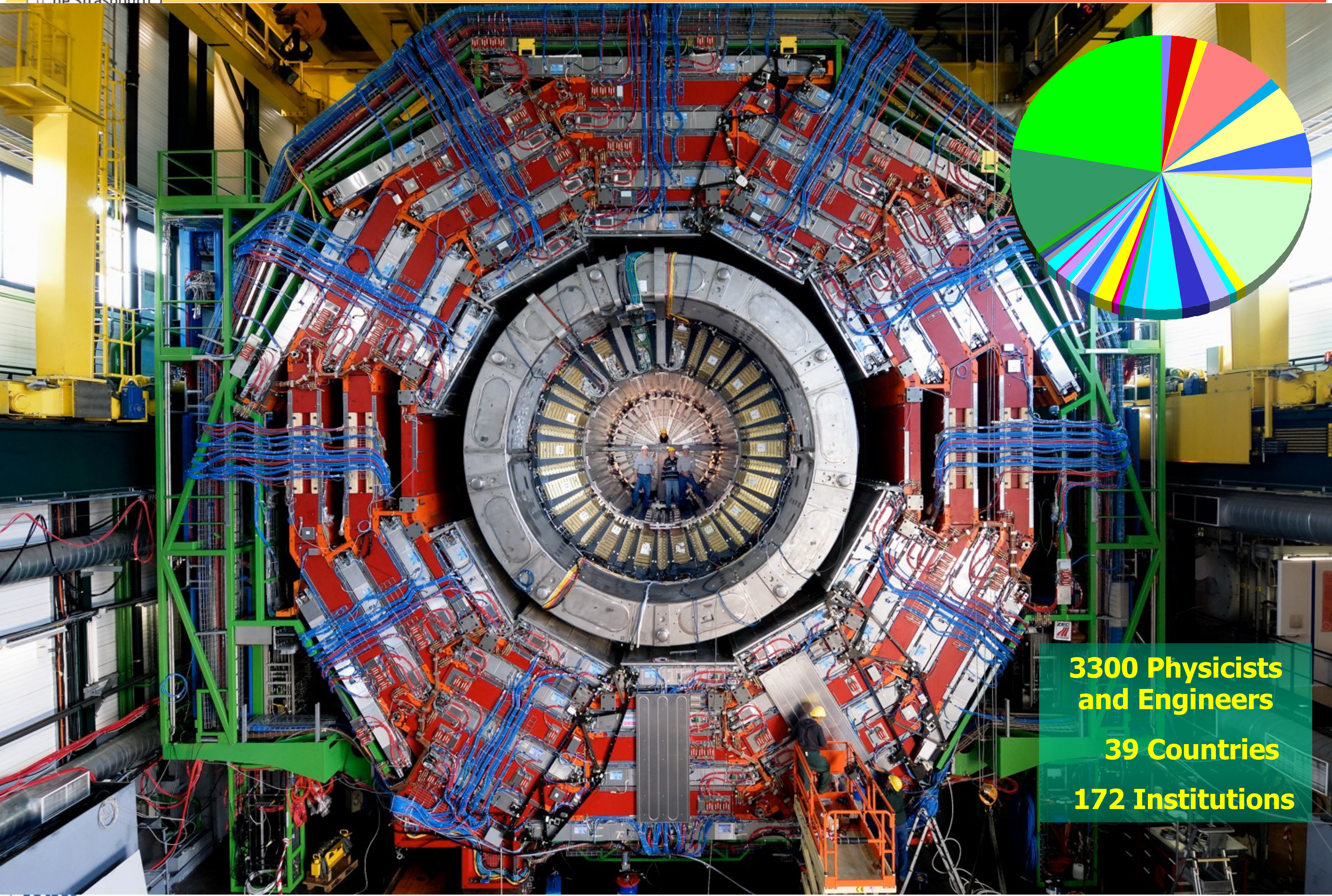



+ Rel. large fields over large volume
+ Rel. low material budget
- non-uniform field
- complex structure

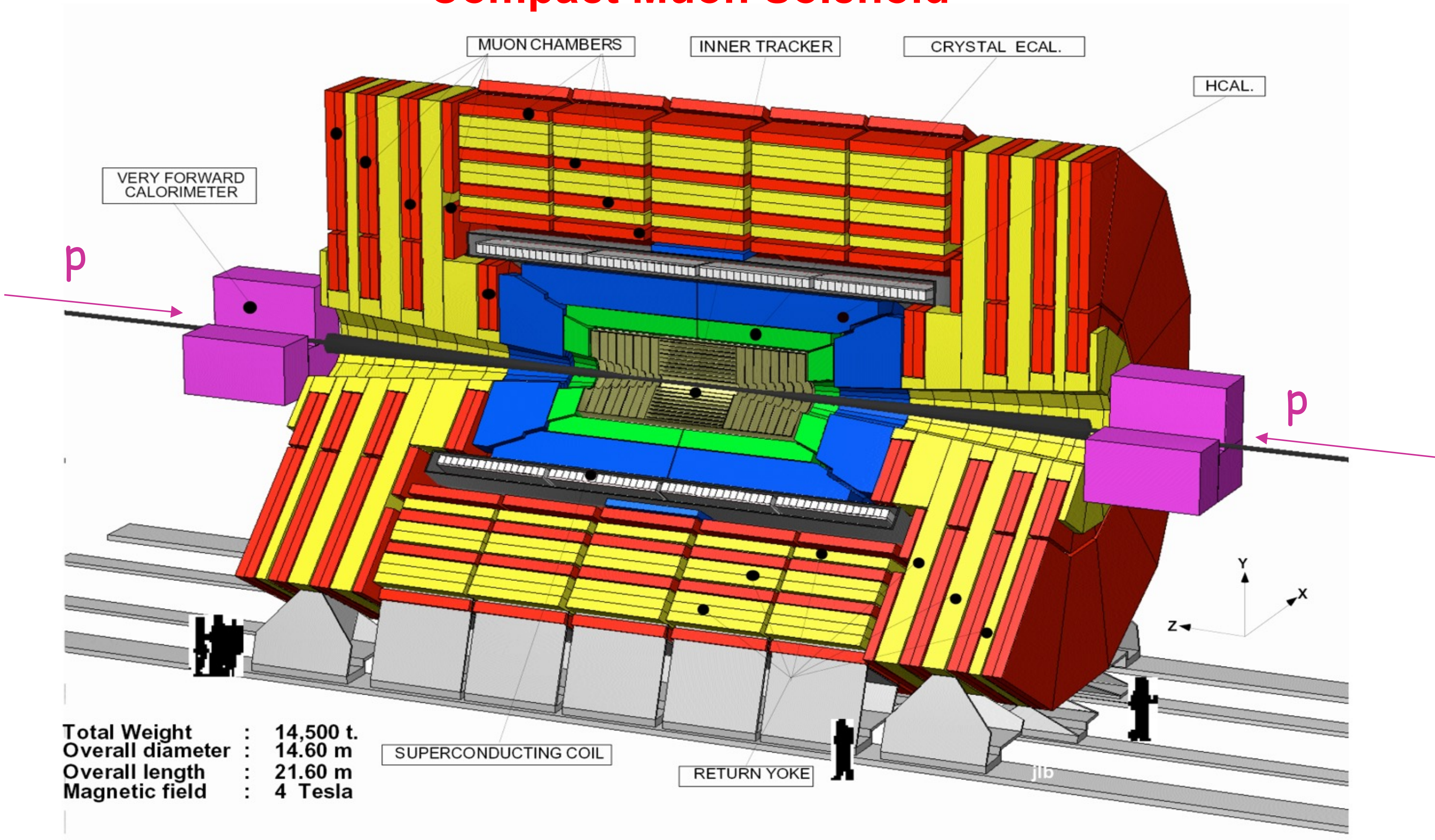
Example:

- ATLAS (Barrel air toroid, SC, 0.6T)

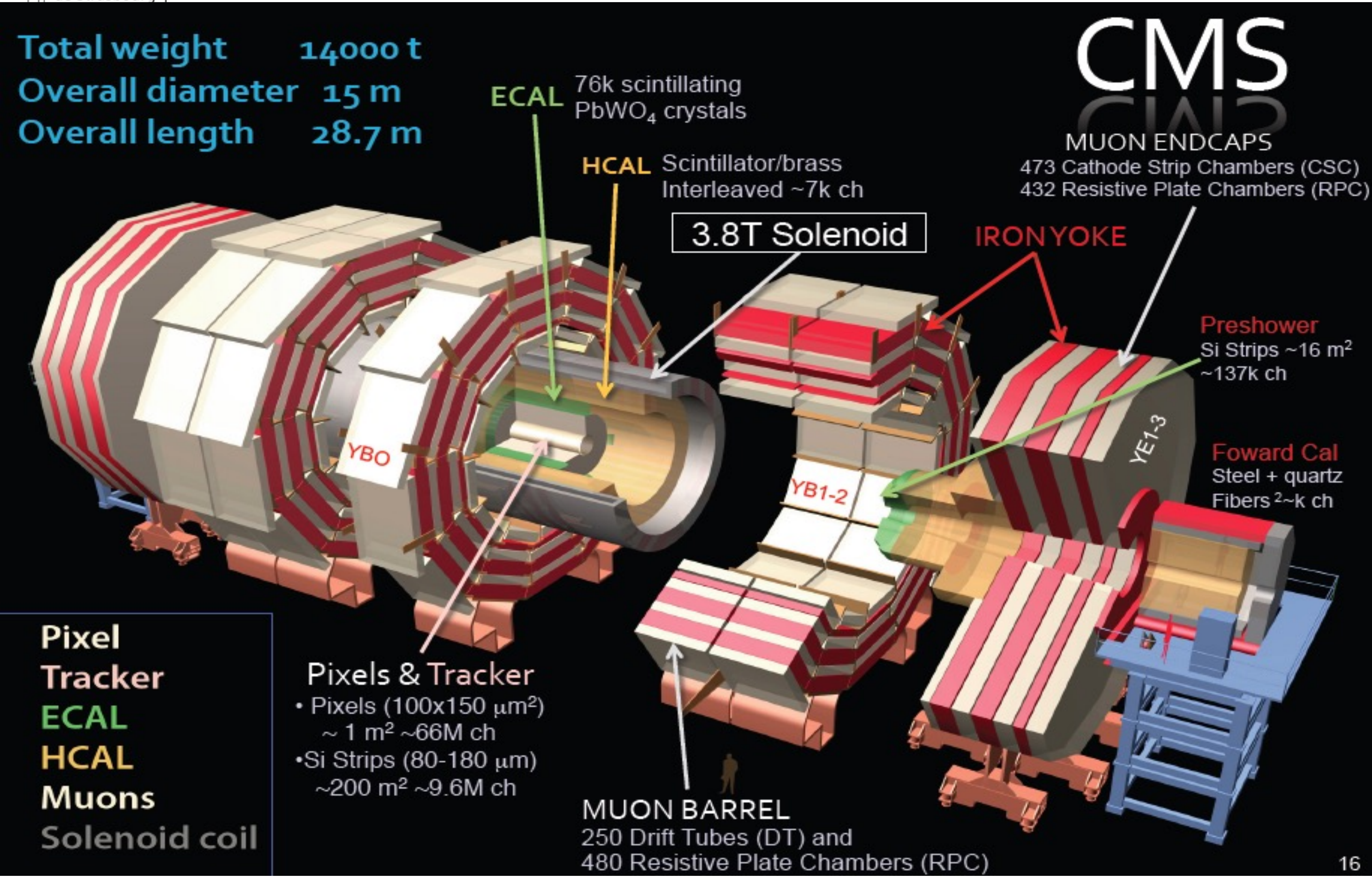


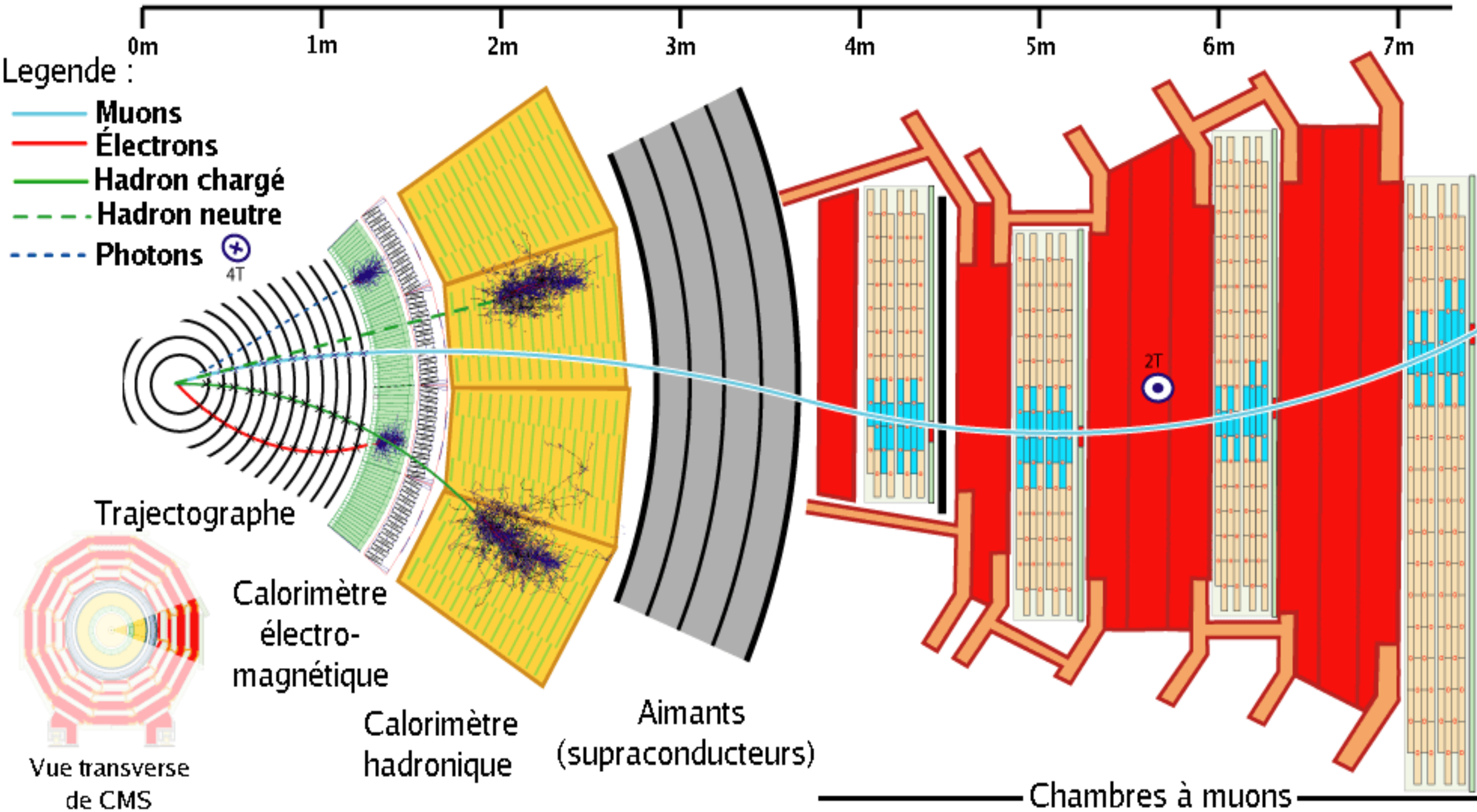

3300 Physicists
and Engineers
39 Countries
172 Institutions

# Compact Muon Solenoid

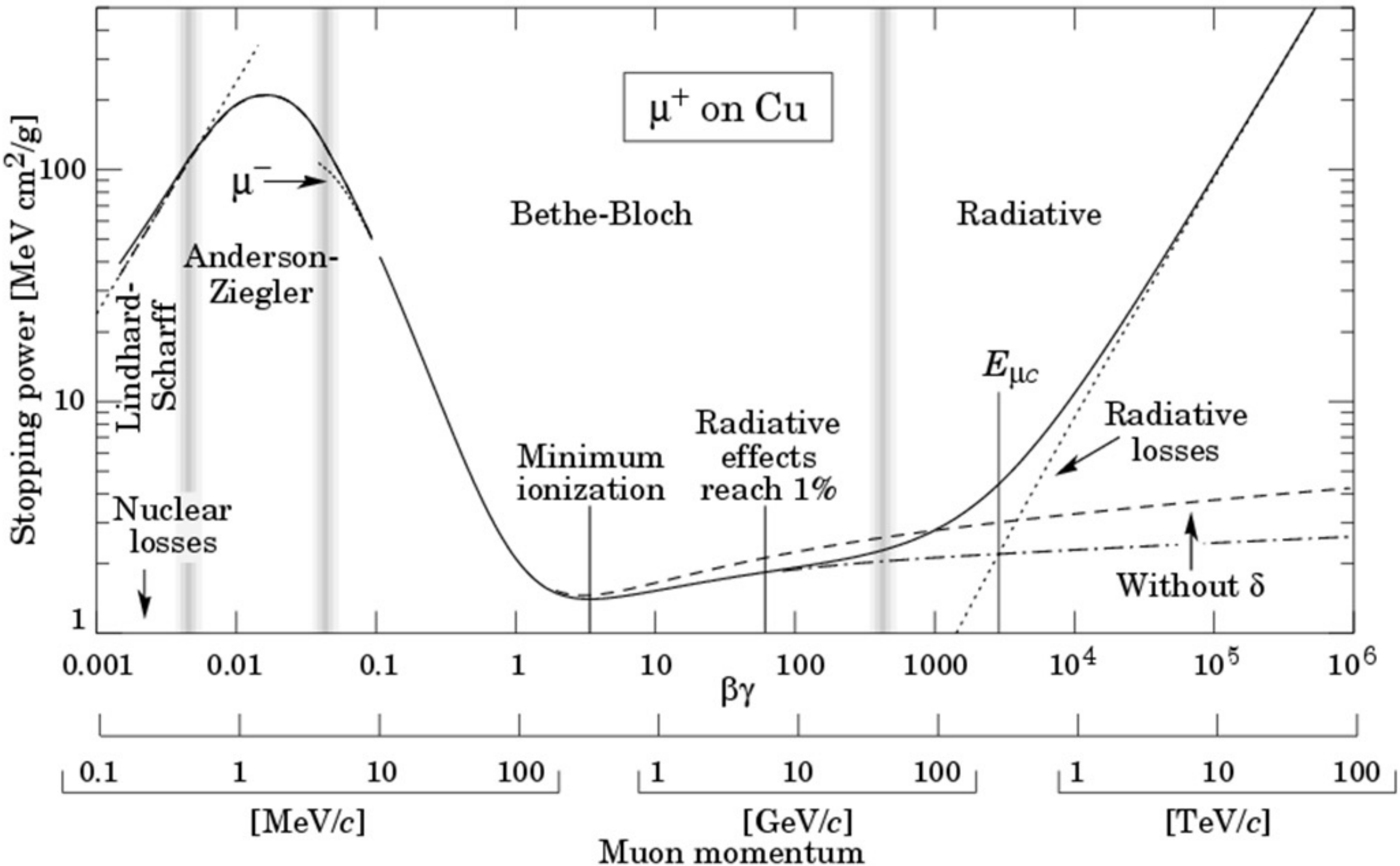



Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

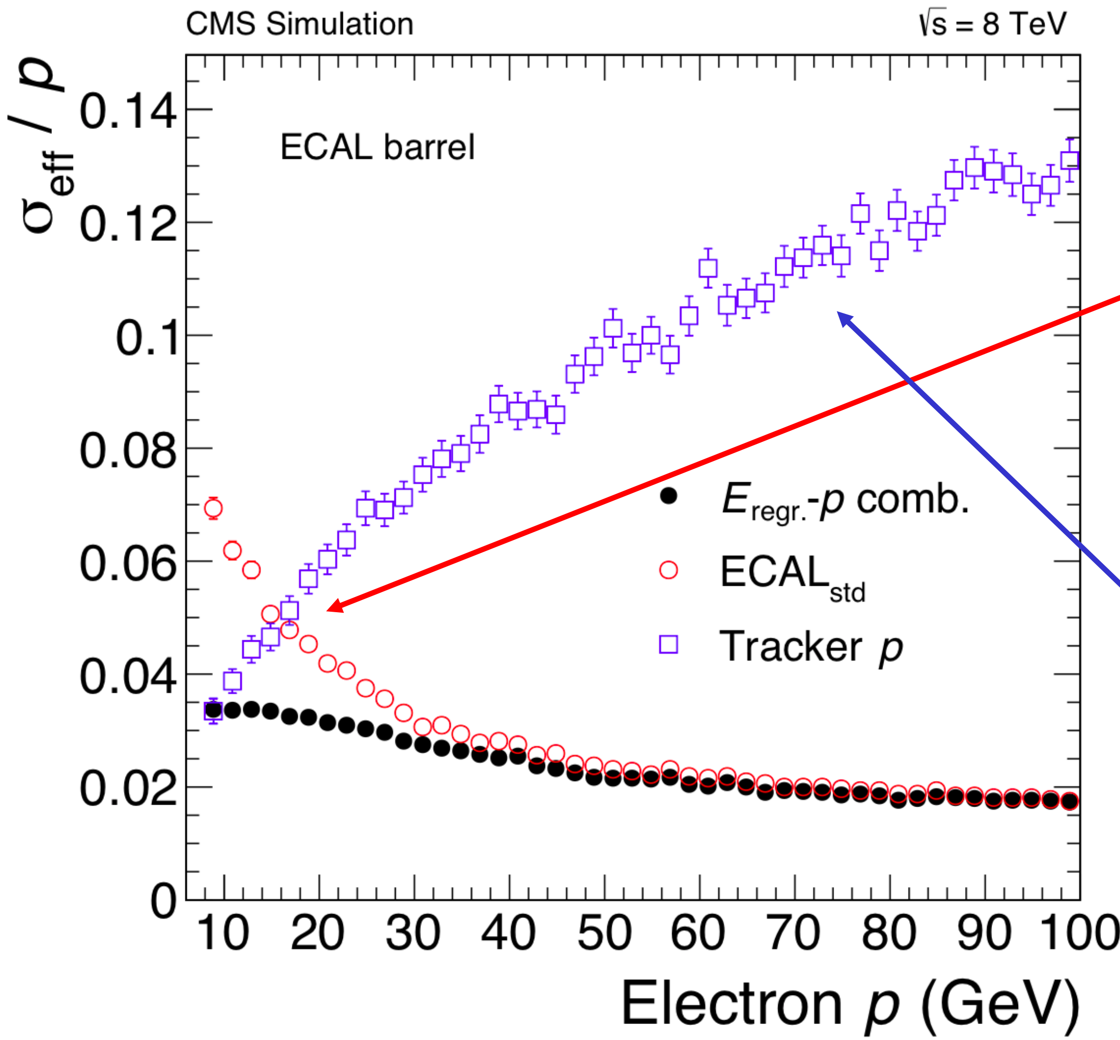

Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
CMS
ECAL 76k scintillating PbWO4 crystals
HCAL Scintillator/brass Interleaved ~7k ch
3.8T Solenoid
IRON YOKE
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
Preshower
Si Strips ~16 m2
~137k ch
Foward Cal
Steel + quartz
Fibers 2~k ch
YBO
YB1-2
YE1-3
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm2)
~ 1 m2 ~66M ch
•Si Strips (80-180 μm)
~200 m2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)
16




# Transverse slice through CMS detector


μ+ on Cu
Stopping power [MeV cm2/g]
100
10
1
Lindhard-Scharff
Anderson-Ziegler
μ−
Bethe-Bloch
Radiative
Eμc
Minimum ionization
Radiative effects reach 1%
Radiative losses
Nuclear losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

# Energy / momentum resolution




**Calorimetry**

$$\frac{dE}{E} \sim \frac{1}{\sqrt{E}};$$

**Tracking**

$$\frac{dp_T}{p_T} \sim \frac{\Delta s}{BL^2} p_T$$

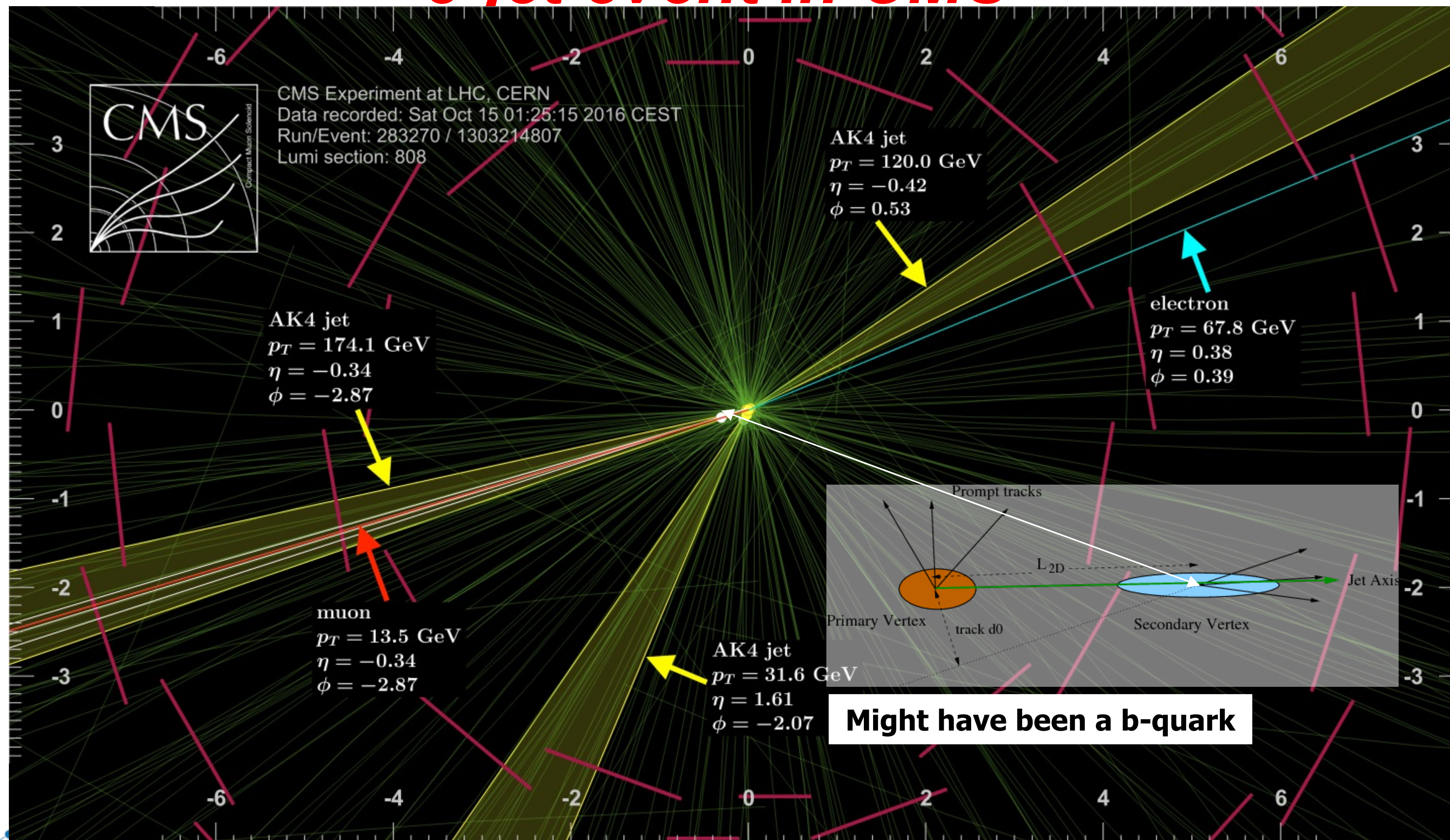
The number of created secondary particles is proportional to the energy

E ~ N, $\sigma_{RMS}$ ~ √N ~ √E

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)}$$

(for N ≥ ~10)

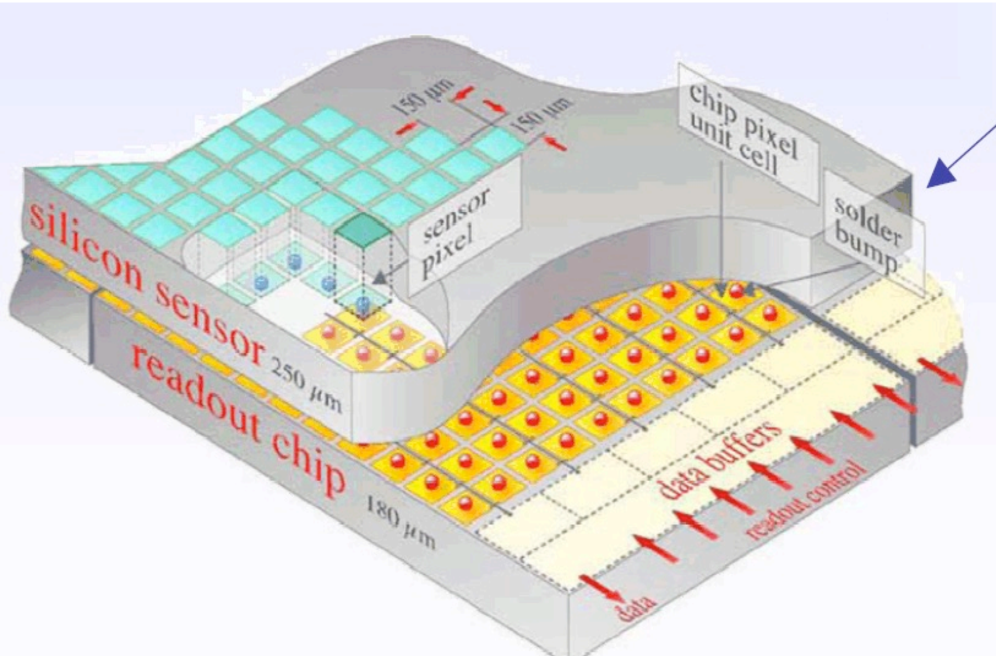
# 3-jet event in CMS

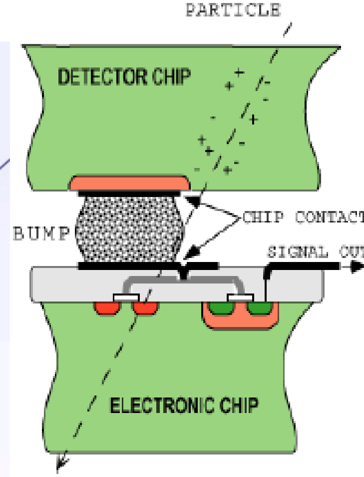


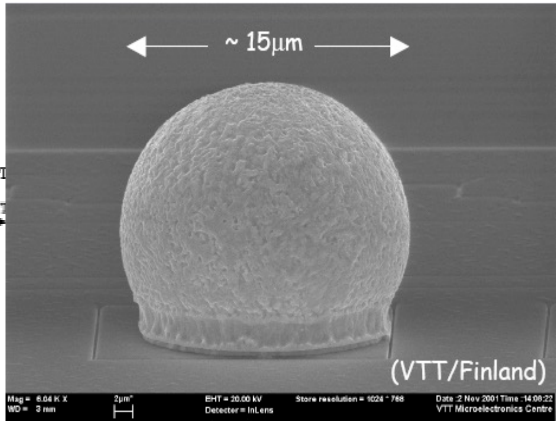
# CMOS Pixel detectors

- Powerful vertex detectors
- For high resolution tracking
- Industrial processes
- Very small material budget (thin detectors)
  - Remember multiple scattering !
  - Photon conversion to $e^+ e^-$
  - Bremsstrahlung of electrons
- MAPS = Monolithic Active Pixel Sensors

# Classical Hybrid Pixel detector

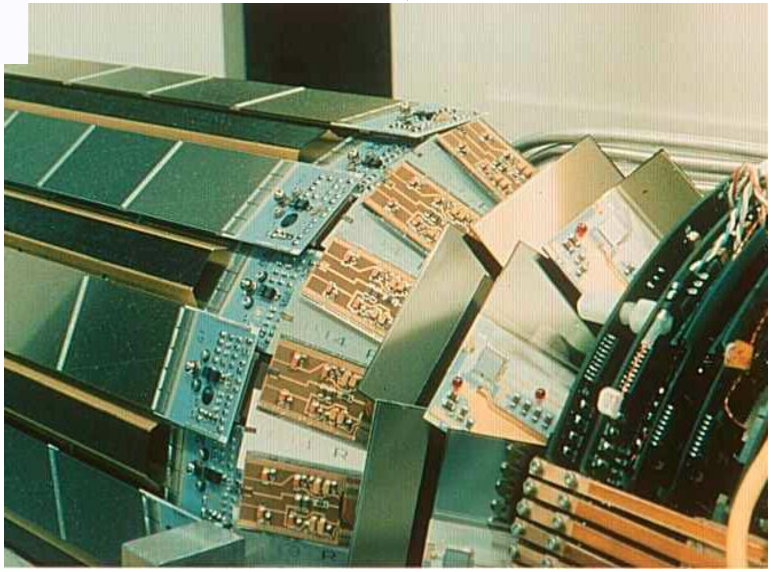


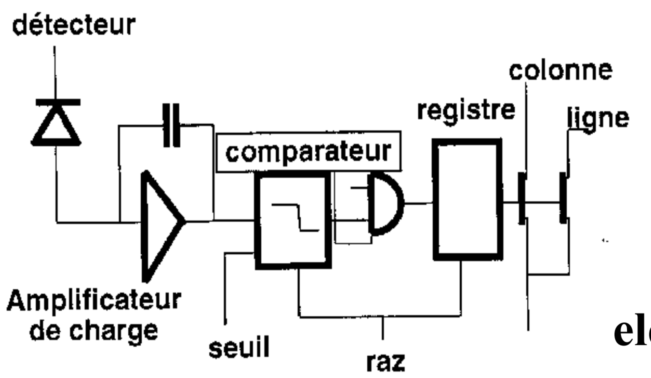




**DELPHI-LEP-CERN**

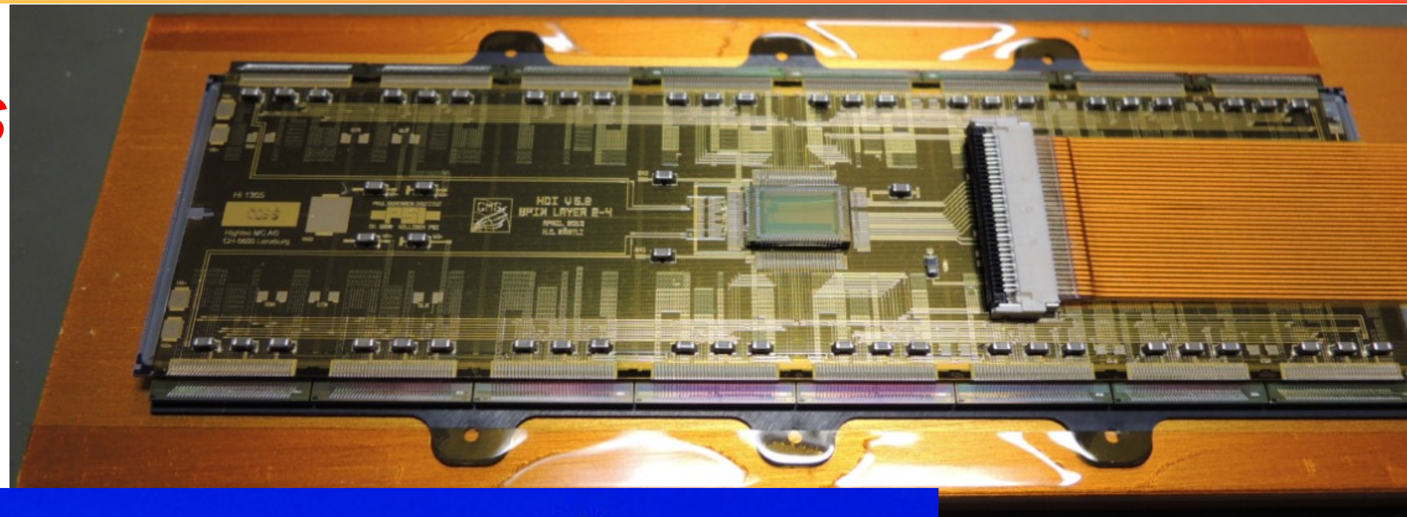
**Pixels : 330x330 µm**
**152 modules, 1.22 M channels**



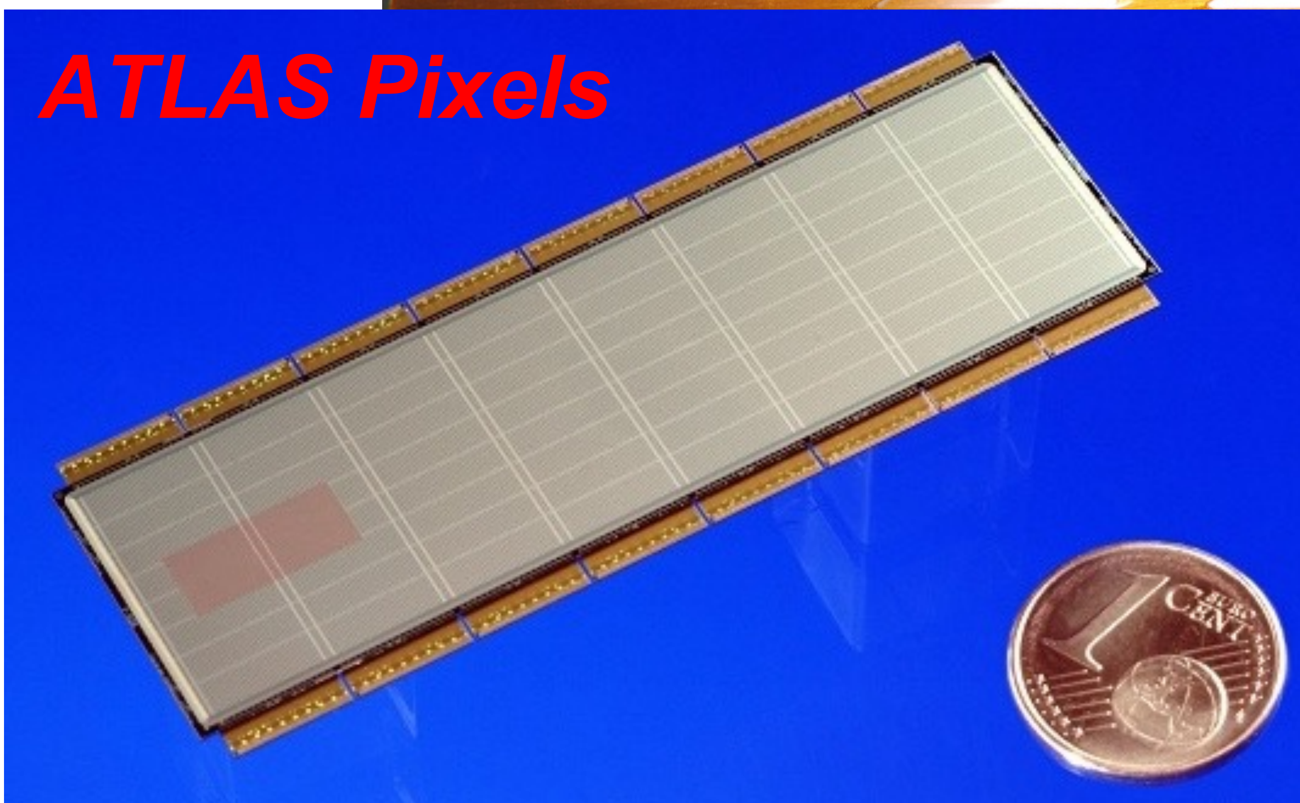



**Pixel electronics: complex!**

# CMS Pixels

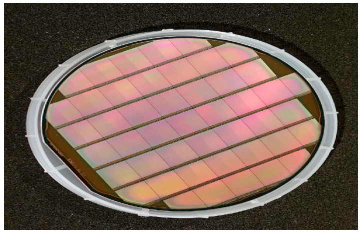


# ATLAS Pixels

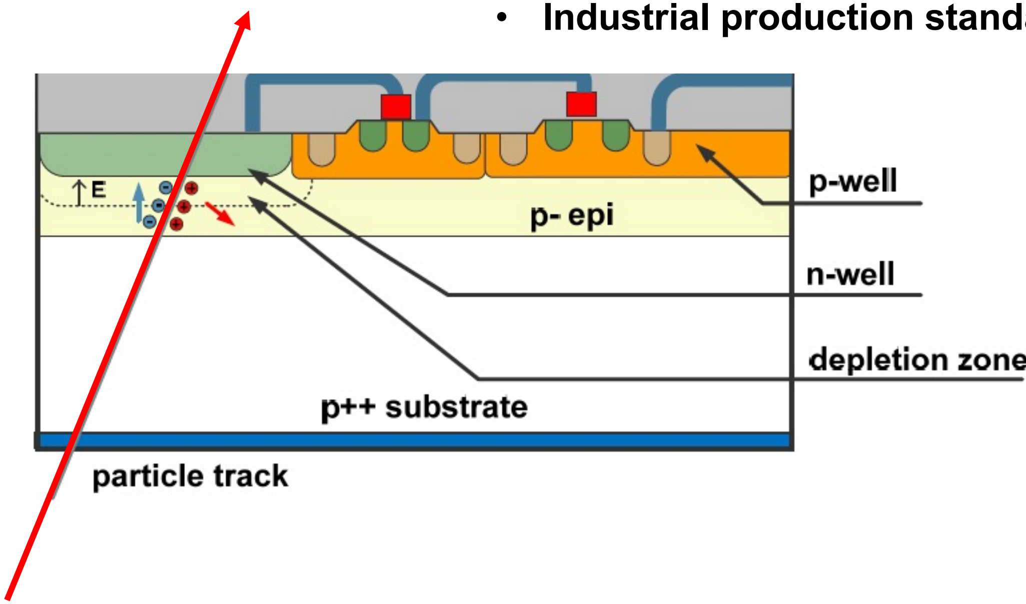


Ulrich.Goerlach@iphc.cnrs.fr, ASP Particle detectors

# CMOS (Complementary metal-oxide-semiconductor) Detectors



Avantages of CMOS VLSI technology:
- μ-circuits integrated but still
- 100% fill factor
- Small sensitive volume (≈ épitaxial layer) ≈10 μm thick detectors can be very thin
- Industrial production standards ⇒ « modestes » costs,




- Signal is created in p-epitaxial layer (lower doping):

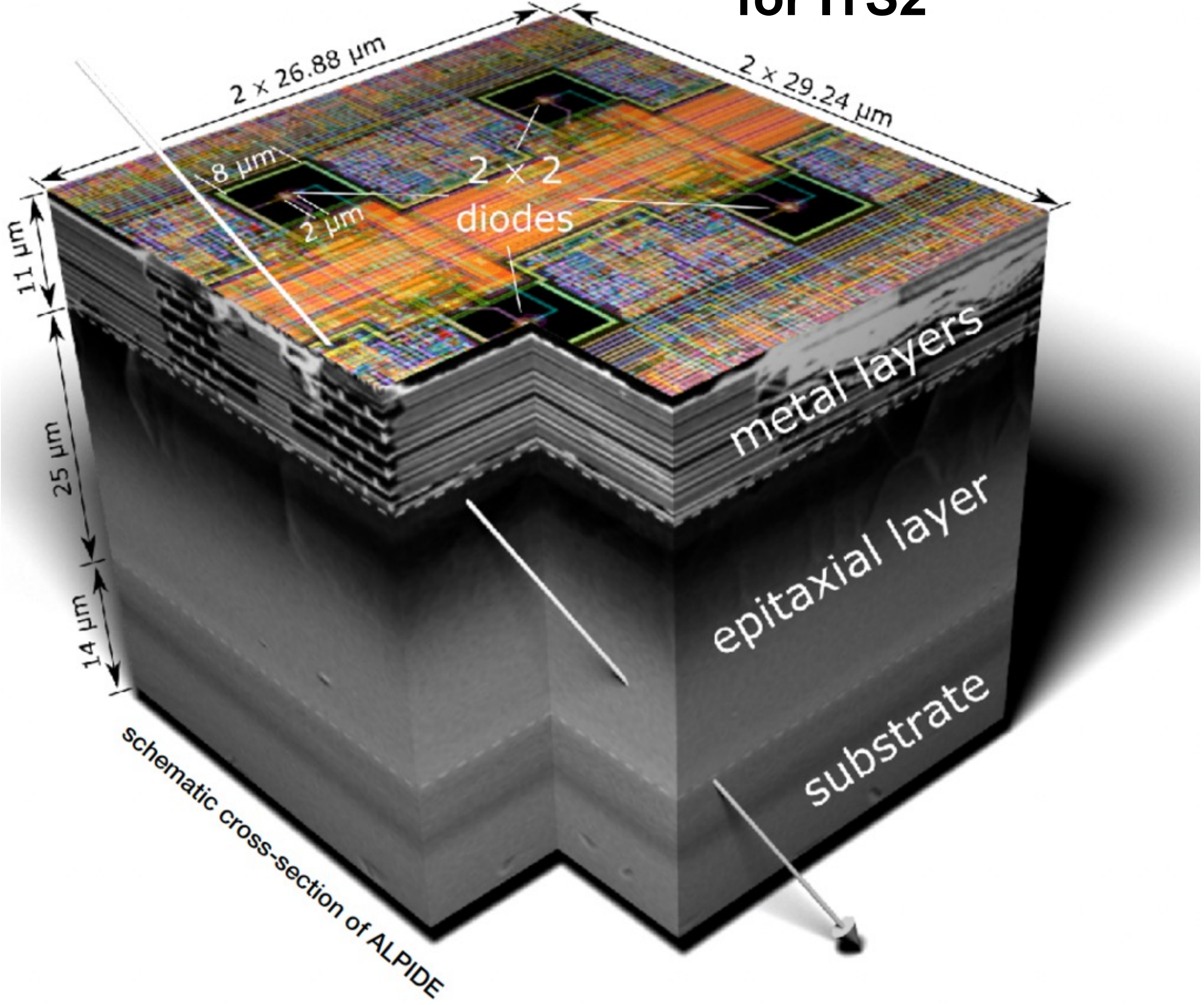
  $Q \approx 80$ e-h / μm ⇒ signal < 1000 $e^-$

- $e^-$ diffusent (thermiquement) to the jonction helped by reflexions at the boundaries formed by the p-well and the substrat (higher doping)
- Diffusion time < 100ns
- Charge is collected by the diode formed by the jonction n-well/p-epitaxial layer

**<u>Short coming</u>:**

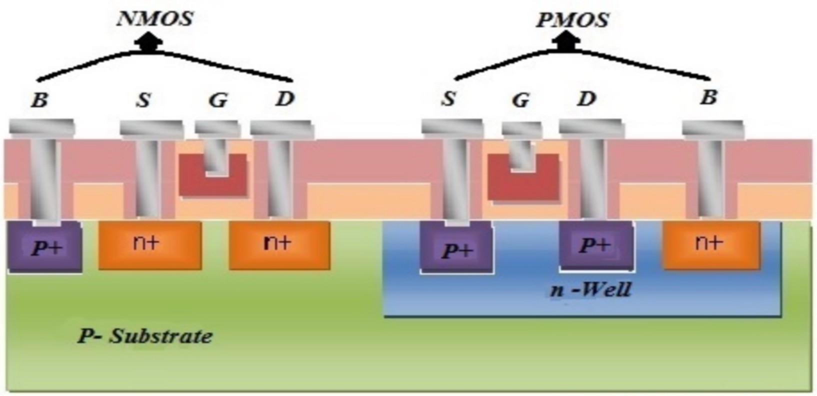
**Circuitry of the electronic circuit is limited to only NMOS transistors.**

# ALPIDE — the Monolithic Active Pixel Sensor (MAPS) for ITS2



# Characteristics:

- Pixel detector could be made very thin, low material budget!
- Thin epitaxial layer → Small signals
- Small pixel size possible (10x10µm$^2$) to obtain very good spatial resolution, but then limited space for electronic circuit available
- (Only n-well Transistors)
- Simple on pixel-cell electronics → slow Read Out (next slide)

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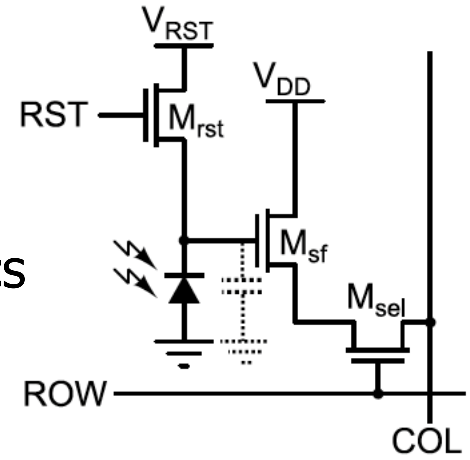
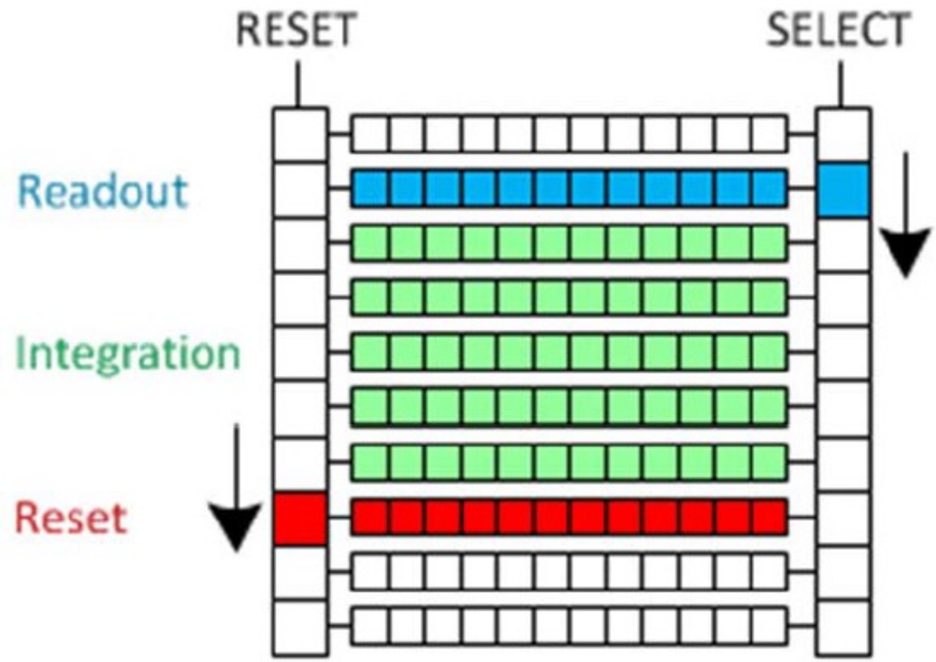
Ulrich.Goerlach@iphc.cnrs.fr, ASP Particle detectors

# Overview of Rolling Shutter Architecture

On chip electronics




**Rolling shutter readout concept where the integrated signal is read out and reset row by row:**

- **In this case all pixel outputs in the column are connected.**
- **Only one row of pixels is selected at a time for readout and/or reset.**
- **The column outputs can be multiplexed at the periphery in case of limited analog outputs.**
- **The recorded values can be digitized by external or internal components**

Tomasz Hemperek, PhD thesis

# Typical layout of a MAPS chip

**CMOS 0.35 µm OPTO technology**

**Chip size : 13.7 x 21.5 mm²**

- Pixel array: 576 x 1152, pitch: 18.4 µm
- Active area: ~10.6 x 21.2 mm²
- In each pixel:
  - Amplification
  - CDS (Correlated Double Sampling)

- Testability: several test points implemented all along readout path
  - Pixels out (analogue)
  - Discriminators
  - Zero suppression
  - Data transmission

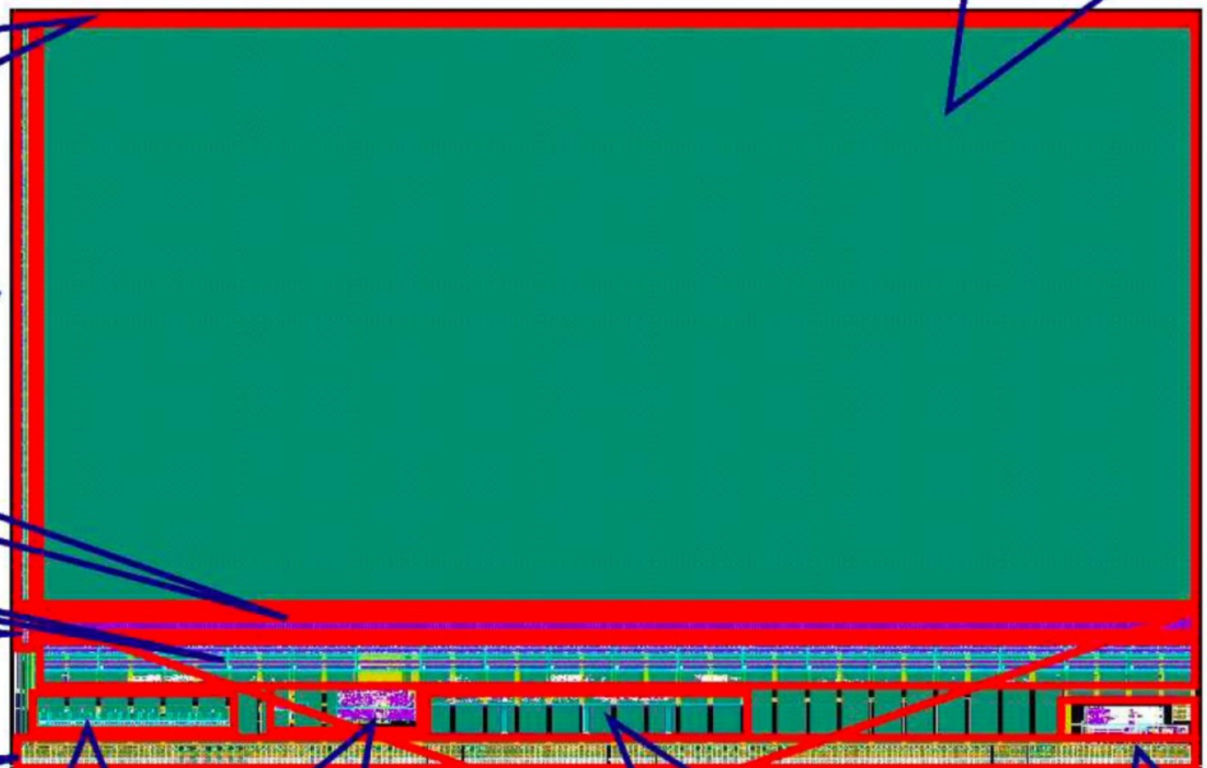
- Row sequencer
- Width: ~350 µm

- 1152 column-level discriminators
  - offset compensated high gain preamplifier followed by latch

- Zero suppression logic

- Reference Voltages Buffering for 1152 discriminators

- I/O Pads
  Power supply Pads
  Circuit control Pads
  LVDS Tx & Rx



- Current Ref.
- Bias DACs

- Readout controller
- JTAG controller

- Memory management
- Memory IP blocks

- PLL, 8b/10b optional

courtesy of Ch. Hu-Guo / TWEPP-2010

# Developments to improve performance for different experiments

- Several labs develop CMOS pixel sensors : Italy (INFN, Univ.), UK (RAL), CERN, France (IPHC, Saclay), USA, ...
- Increase and speed up collected charge by drift in depleted silicon
- Use of high resistivity silicon wafers
- Use of different (more complicated) CMOS processes
- Change layout to use the complete design potential (use of p-MOS transistors)
- Speed up Read Out architecture
- Large area (wafer size) devices (stitching)
- Curved thin detector layers without additional support material
- ….

# Depleted Monolithic Active Pixels (HV-MAPS or D-MAPS)

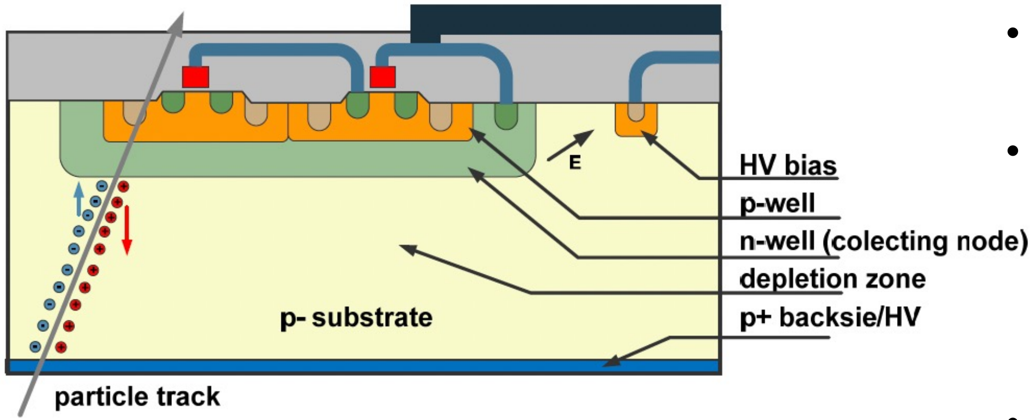
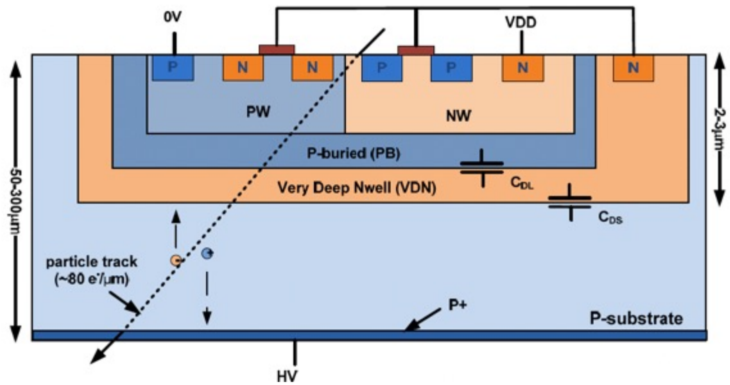



Figure 1-4 Cross section of a depleted MAPS detector with fully depleted bulk with backside contact where charge is collected by drift.

Tomasz Hemperek, PhD thesis

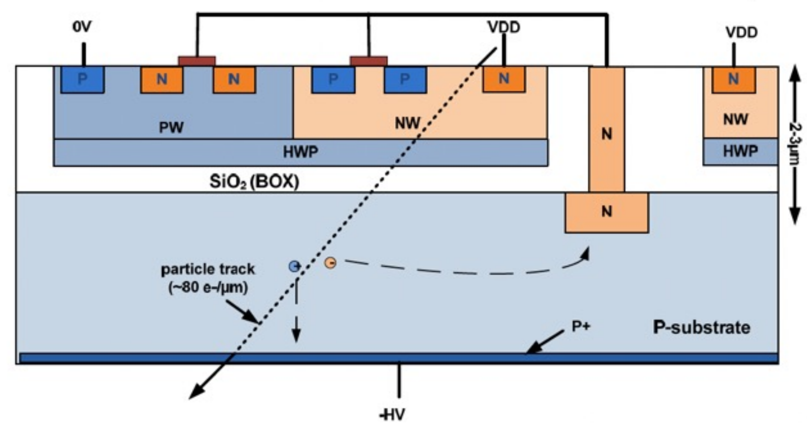
**Goals:**

- **large signals**
- **fast charge collection by drift in a 50µm – 200µm thick depleted layer**
- **the use of PMOS and NMOS transistors in the pixel cell (full CMOS),**
- **The entire CMOS pixel electronics is placed inside the deep n-well.**
- **This way, the pixel contains only one deep n-well without any inactive secondary wells that could attract the signal charge and cause detection inefficiency.**
- **it is reversely biased with respect to the substrate from the front side.**
- **By applying high voltage reverse bias (>60V) it is possible to create a depletion depth of a few to tens of microns**
- **implementation in a commercial technology**



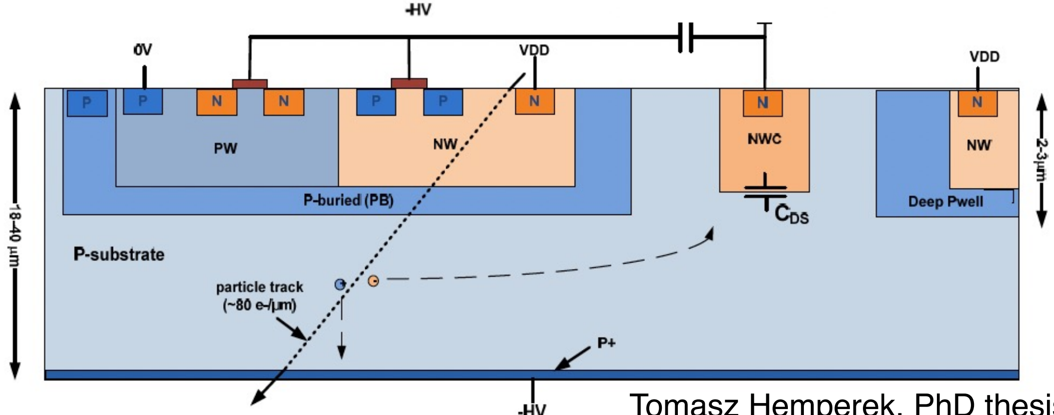

**Depleted MAPS**, logic inside collecting node

***Many different designs are being explored and tested***




**Depleted MAPS, HV-SOI**

(BOX = buried layer of silicon oxide)




**Depleted MAPS,**

Logic located outside collecting node

Tomasz Hemperek, PhD thesis

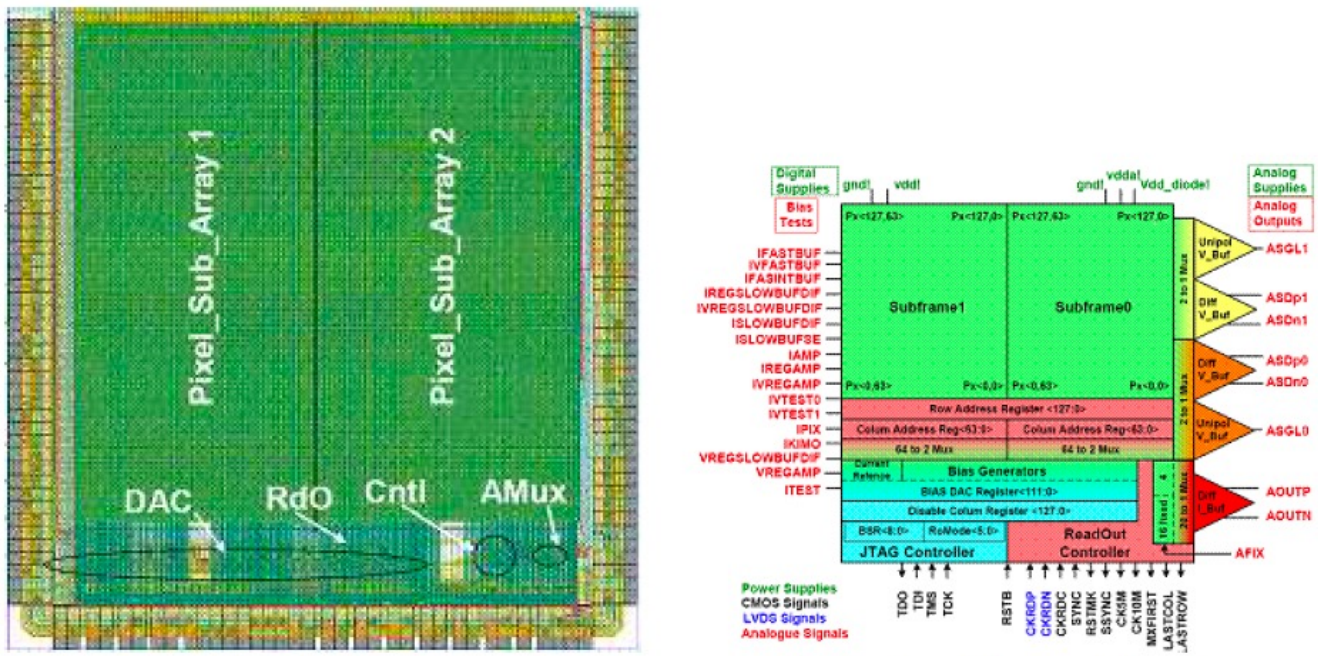
Université de Strasbourg

# Building Vertex detectors with MAPS

# STAR experiment at RHIC, BNL

**First large scale application of MAPS in an experiement**

- ## 2 layers of MAPS for pixel vertex detector




(a) chip layout

(b) functional diagram of the chip

**M. A. Szelezniak PhD thesis 2008**

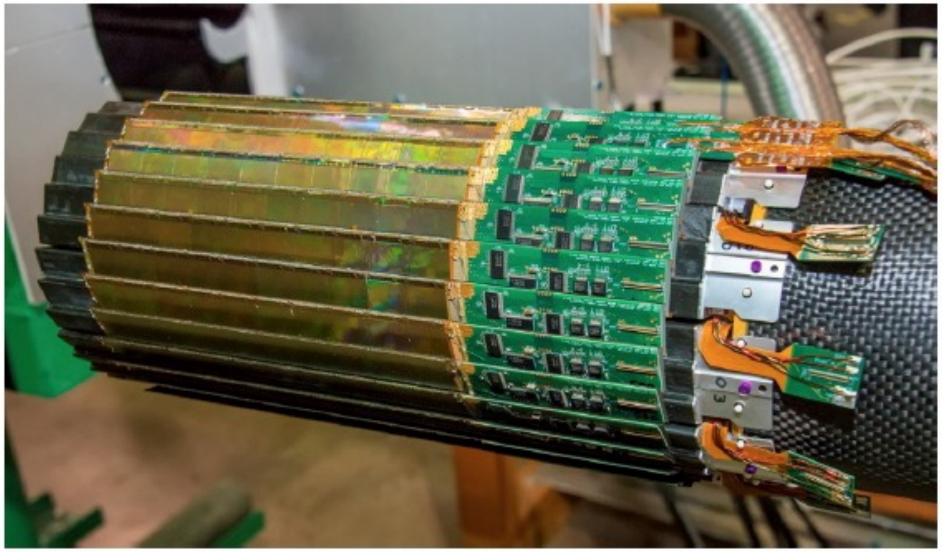
Figure 6.3: MIMOSTAR chip - layout, (a), and a functional schematic diagram, (b).

iPHC

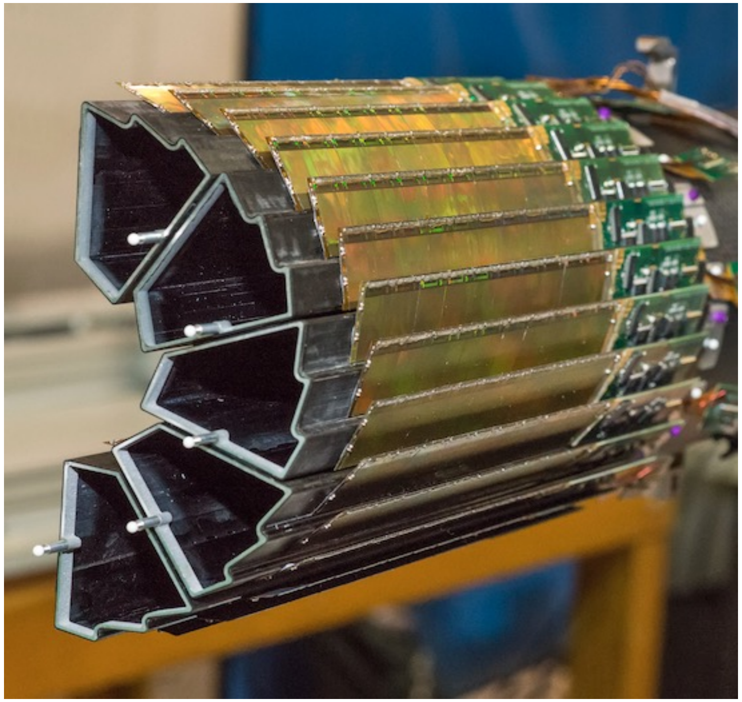
# STAR experiment at RHIC, BNL

***First large scale application of MAPS in an experiement***

- **2 layers of MAPS for pixel vertex detector**

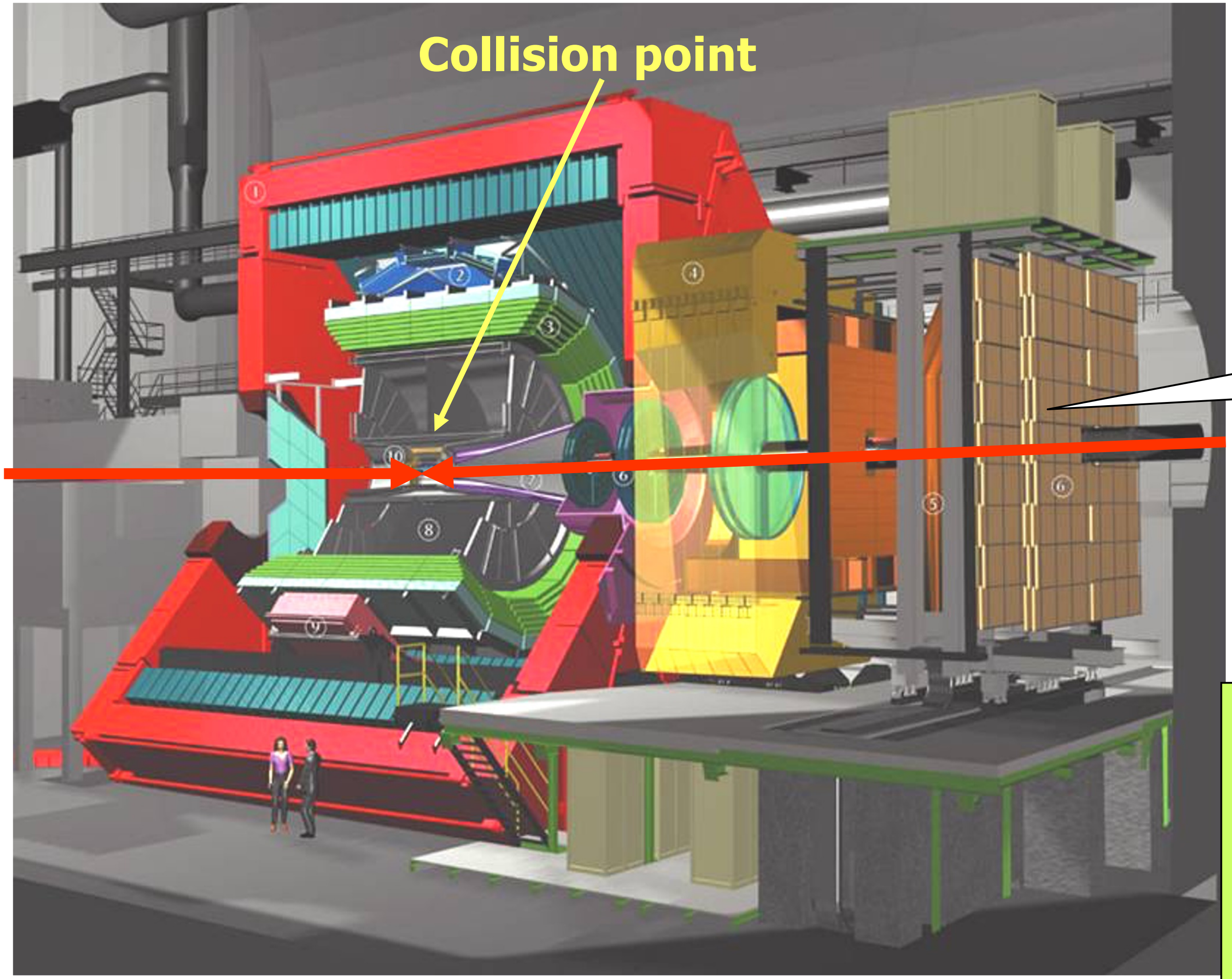


**356 M pixels in 2 layers ~0.16 m$^2$**
**R=28mm, 80mm**
**Pixels size 20.7x20.7 $\mu$m$^2$**
**$X/X_0$ = 0.39% for layer 1**
**Integration time 185.6 $\mu$s**



**carbon fiber sector tubes (~ 200 µm thick)**

# ALICE




**Over 1000 physicists**

**Muon spectrometer**

**Dimensions :**

**Length : 26m.**

- **Hight : 16m.**
- **Weight : 10000 tonnes.**

Université de Strasbourg

# Building Vertex detectors with MAPS

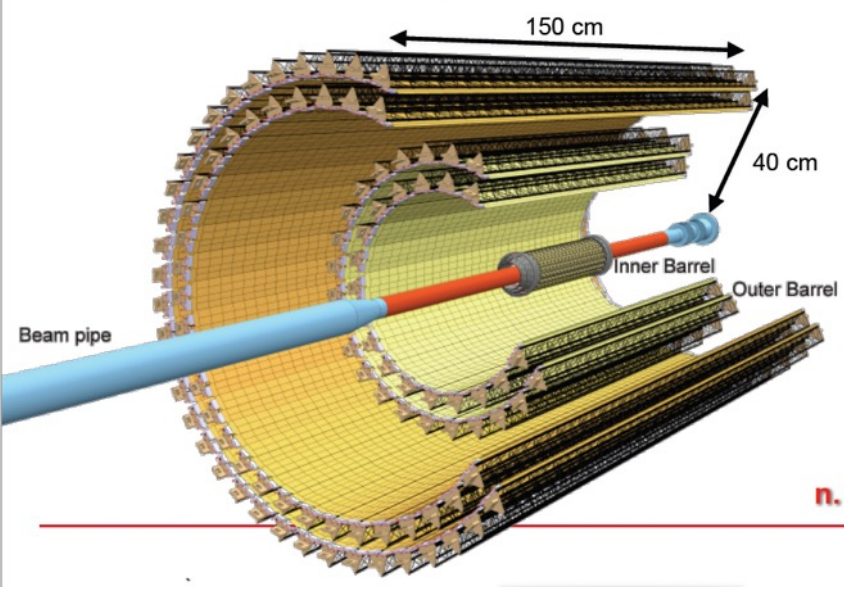
## ALICE (LHC-CERN)

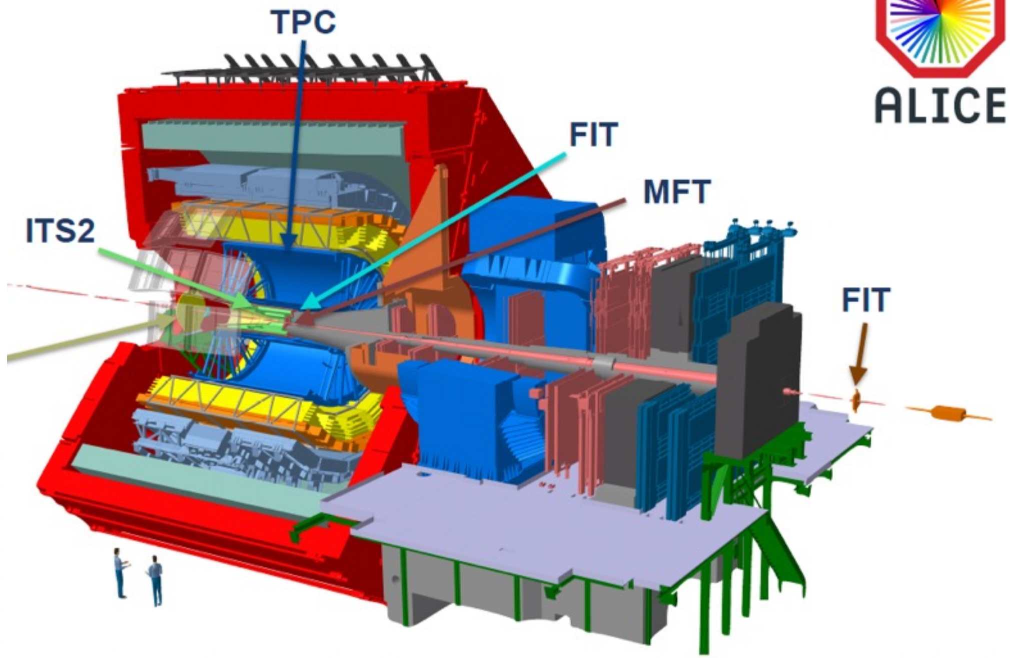
A Large Ion Collider Experiment

### ITS2 layout

- 7 layers (inner/middle/outer): 3/2/2
  from R = 23 mm to R = 400 mm
- 192 staves (IL/ML/OL): 48/54/90
- Ultra-lightweight support structure and cooling

**10 m² active silicon area, 12.5×10⁹ pixels**




**CMOS MAPS:**

**Spatial resolution ≈ 5 µm**

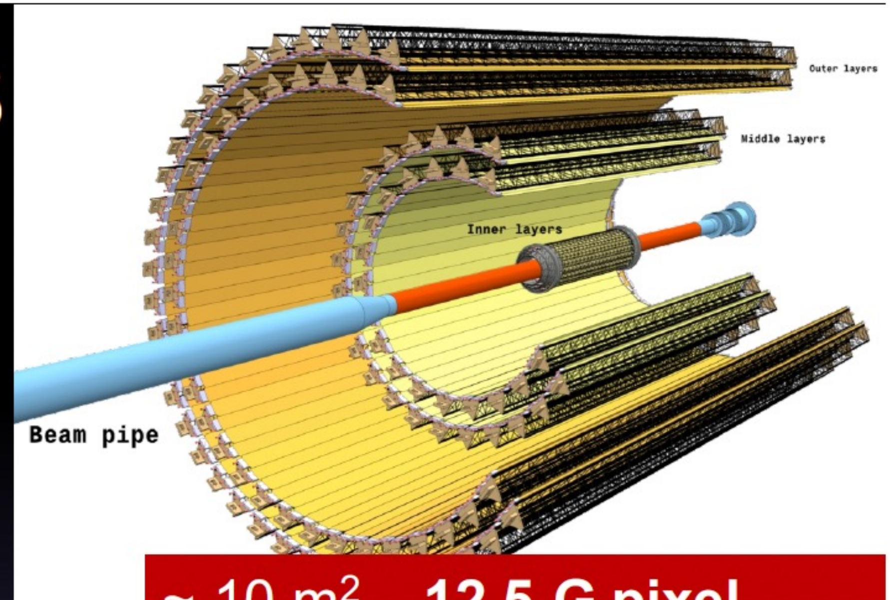
**Integration time < 10 µs**

**high-resistivity silicon epitaxial layer**

UNIVERSITY OF OXFORD

# ALICE: MAPS

- Improve impact parameter resolution by a factor of ~3 in (r-$\phi$) and ~5 in (z)
  - –Closer to IP: 39 mm → 21 mm (layer 0)
  - –Reduce beampipe radius: 29 mm → 18.2 mm
  - –Reduce pixel size: (50 µm x 425 µm) → O(30 µm x 30 µm)
  - –Reduce material budget: 1.14 % $X_0$ → 0.3 % $X_0$ (inner layers)




**~ 10 m$^2$ 12.5 G pixel**

- High tracking efficiency and $p_T$ resolution
  - – Increase granularity and radial extension → 7 pixel layers
- Fast readout of Pb-Pb interactions at 50 kHz (now 1kHz) and 400 kHz in p-p interactions
- Rad hard to TID: 2.7 Mrad, NIEL: 1.7 x $10^{13}$ 1 MeV $n_{eq}$ $cm^{-2}$ (safety factor 10)
- Fast insertion/removal for maintenance

P. Riedler

Ulrich.Goerlach@iphc.cnrs.fr, ASP Particle detectors

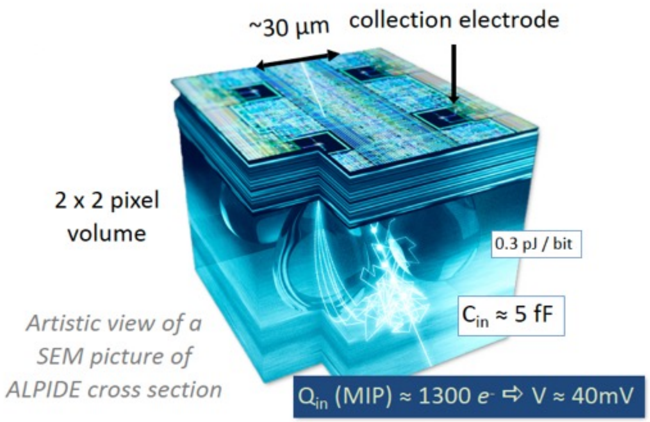
# Building Vertex detectors with MAPS

## ALICE (LHC-CERN)

A Large Ion Collider Experiment

ALICE

### ALPIDE — the Monolithic Active Pixel Sensor (MAPS) for ITS2

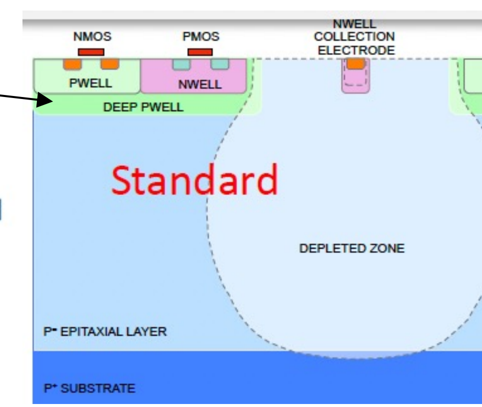


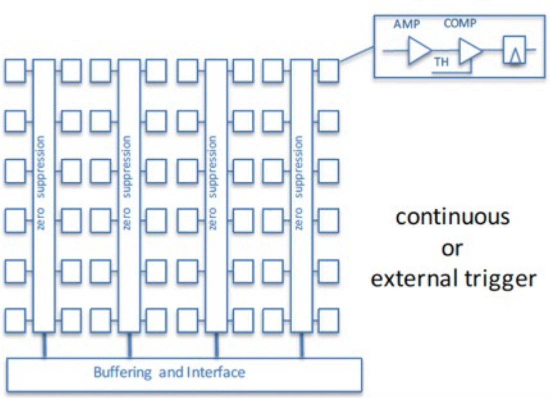

- Developed within the ITS2 project

### Technology

Technology now used in other applications

- TowerJazz 180 nm CMOS Imaging Process
- High-resistivity (> 1kΩ cm) p-type epitaxial layer (25 µm) on p-type substrate
- Small n-well diode (2 µm diameter), ~100 times smaller than pixel (~30 µm)
  ➔ low capacitance (~fF)
- Reverse bias voltage (-6 V < $V_{BB}$ < 0 V) to substrate to increase depletion zone around NWELL collection diode
- Deep PWELL shields NWELL of PMOS transistors
  ➔ full CMOS circuitry within active area



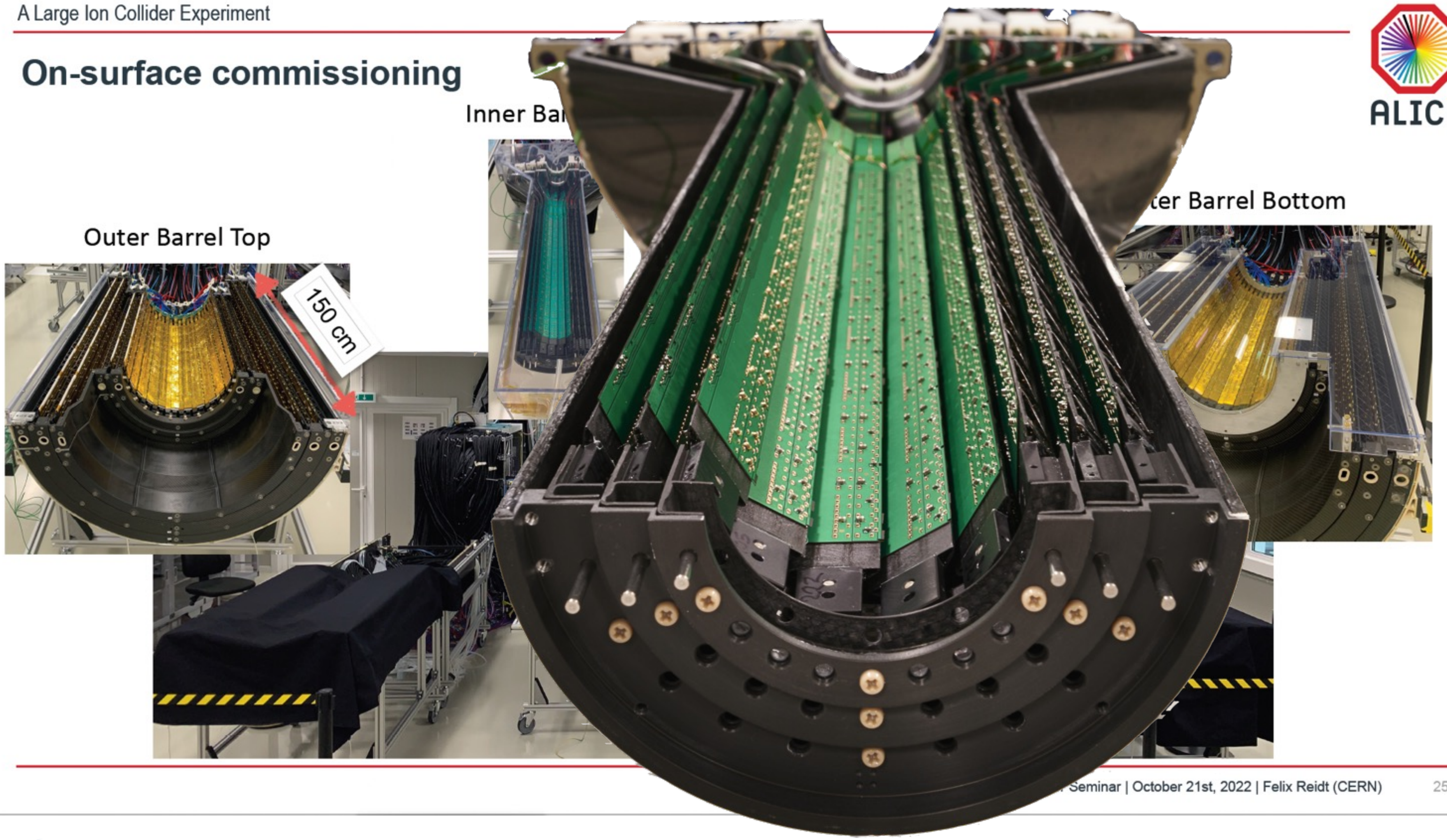

### Key features

- In-pixel amplification and shaping, discrimination and Multiple-Event Buffers (MEB)
- In-matrix data sparsification
- On-chip high-speed link (1.2 Gbps)
- Low total power consumption < 40 mW/cm²

ESE Electronics seminar by T. Kugathasan

Capture d'écran

# ALICE (LHC-CERN) ITS 2



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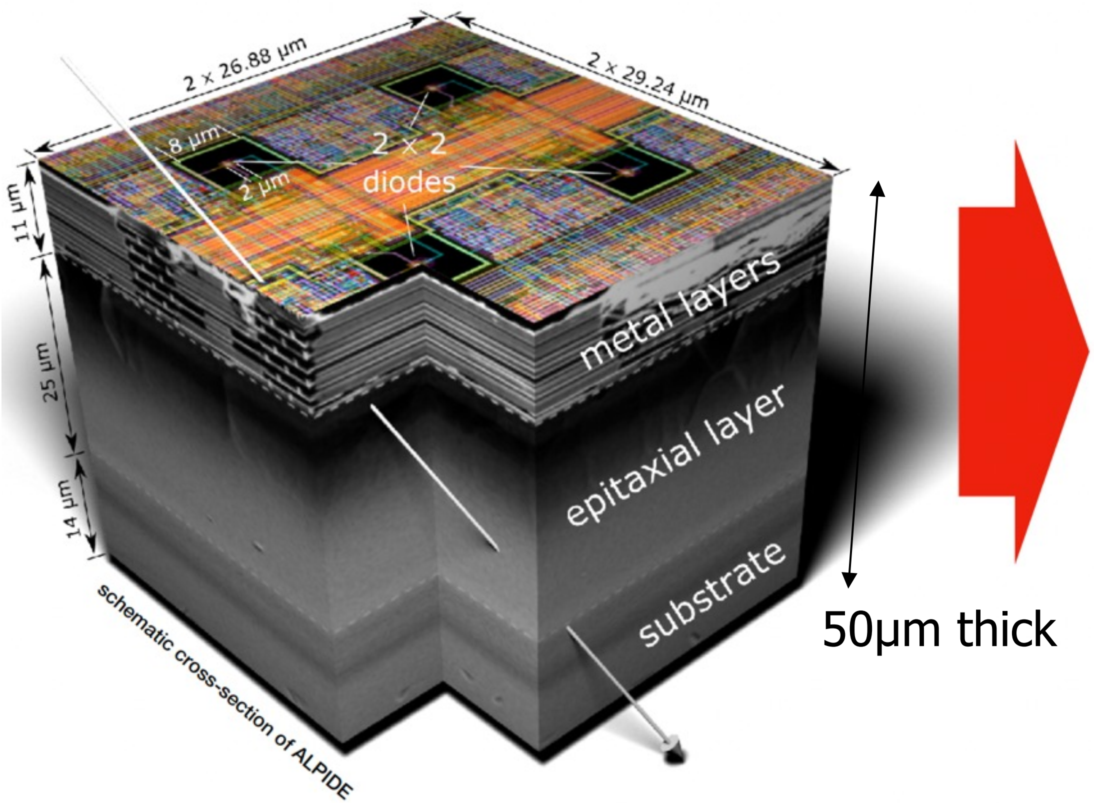
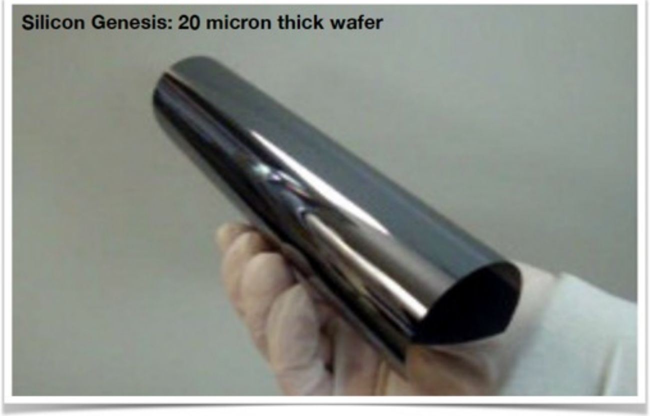
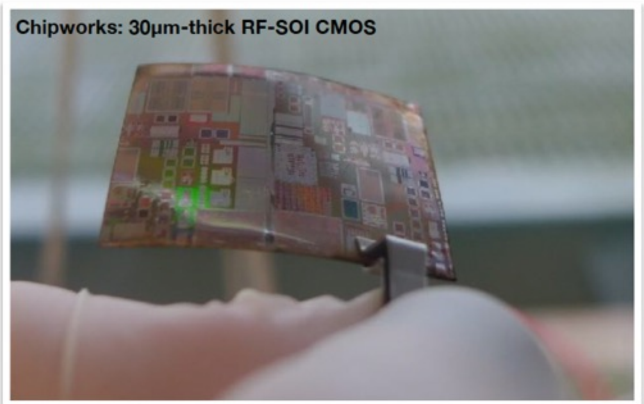
# ITS3

## the idea (1): make use of the flexible nature of thin silicon




50µm thick



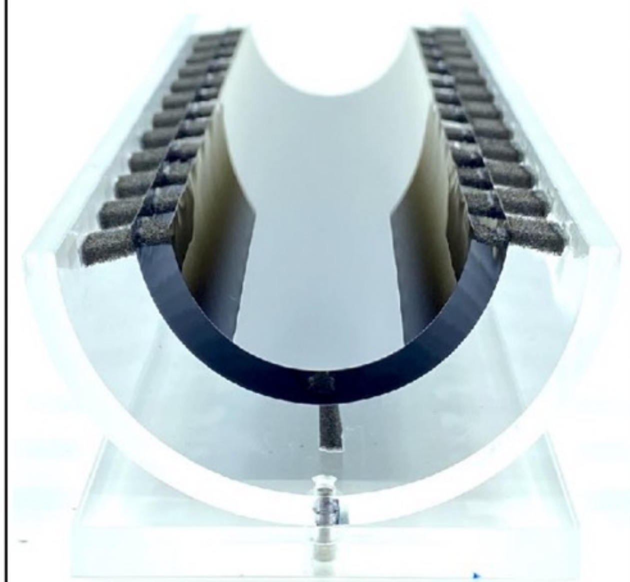




Magnus Mager (CERN) | ALICE ITS3 | CERN detector seminar | 24.09.2021 | 9

# Layer assembly

**Layer 2**

**Layers 2+1**



**Layers 2+1+0**

3-layer integration successful!

Magnus Mager (CERN) | ALICE ITS3 | CERN detector seminar | 24.09.2021 | 26

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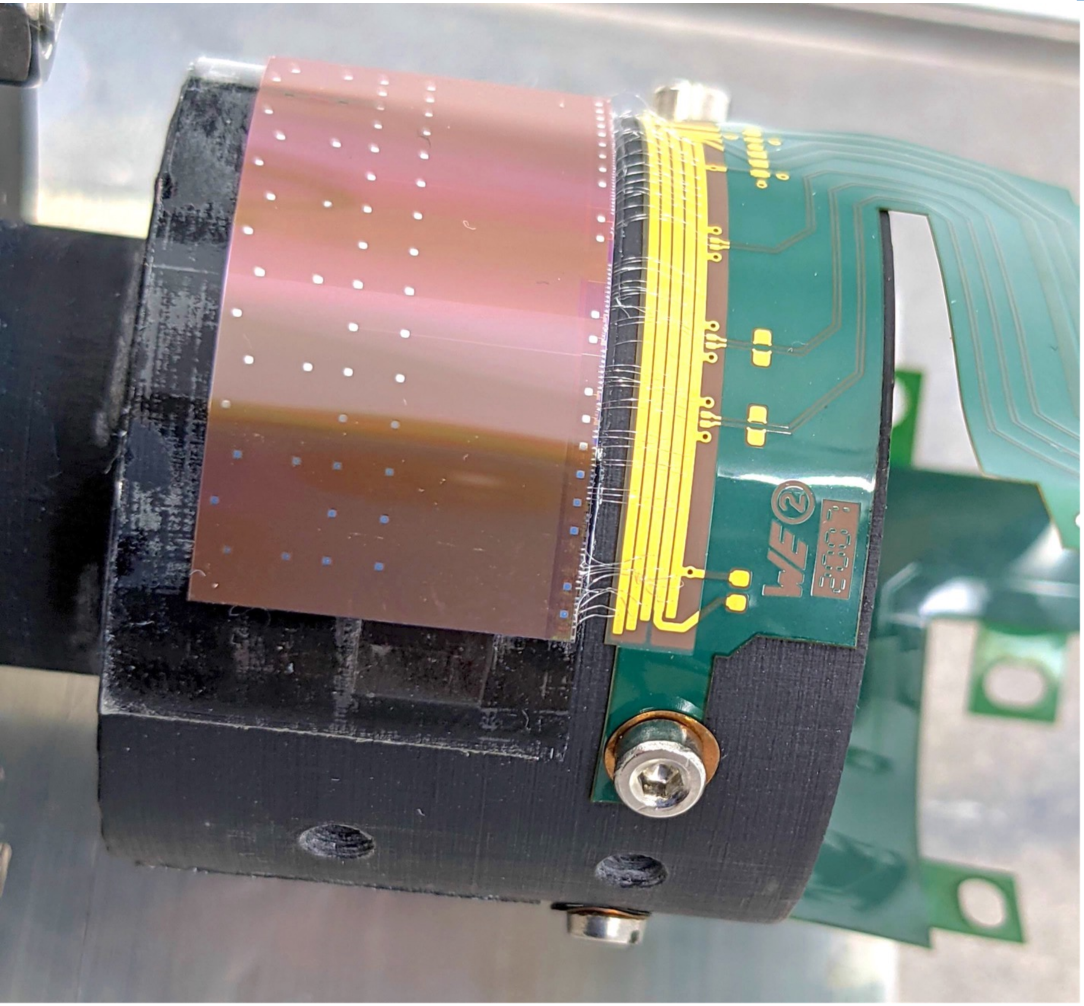
## Development of Interconnects

## Bonding on curved chips and circuits

*Procedures, jigs, mandrels, integration*

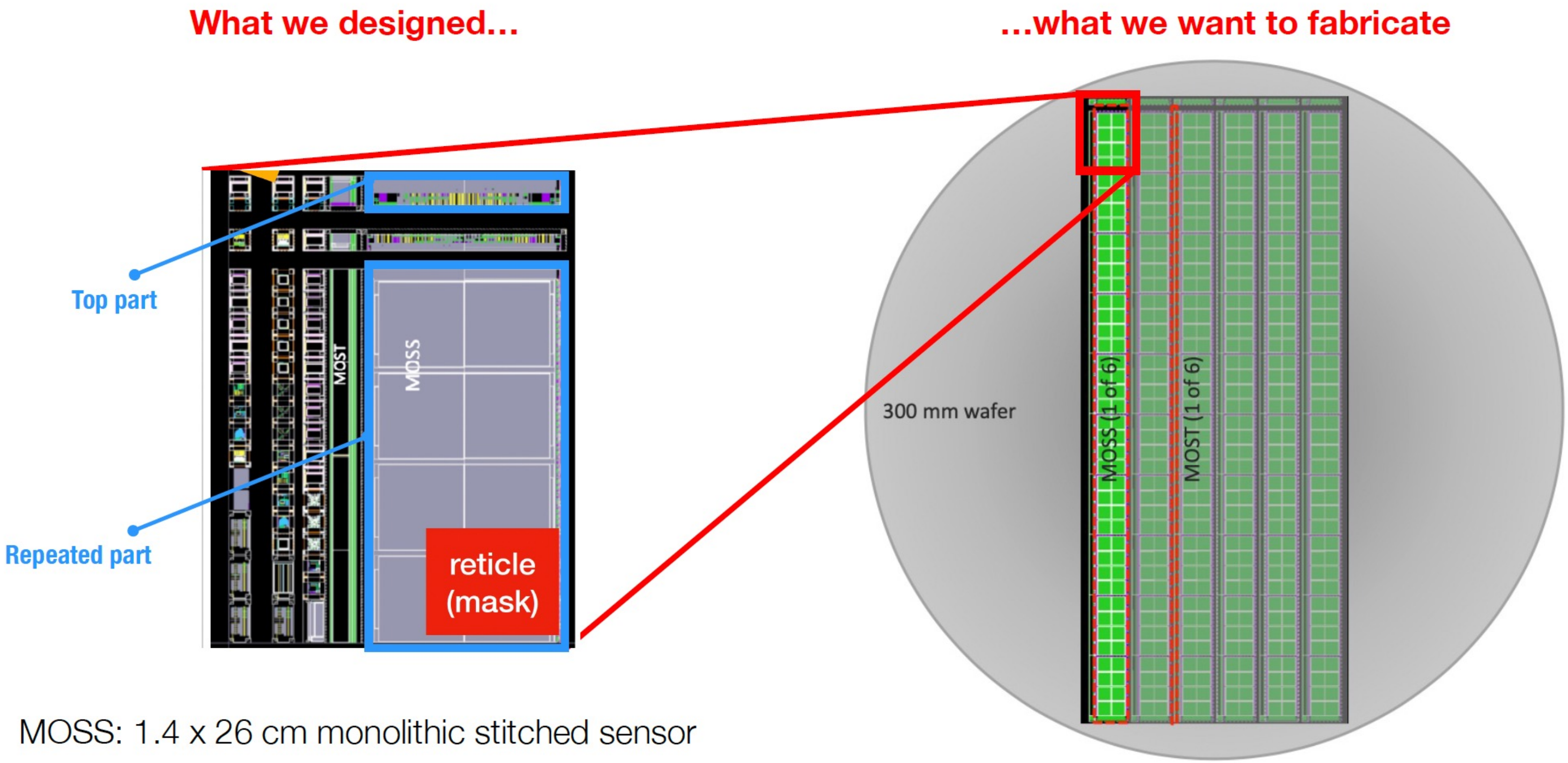
*with bonding machine*




ALICE

# Stitching – MOnolithic Stitched Sensor prototype

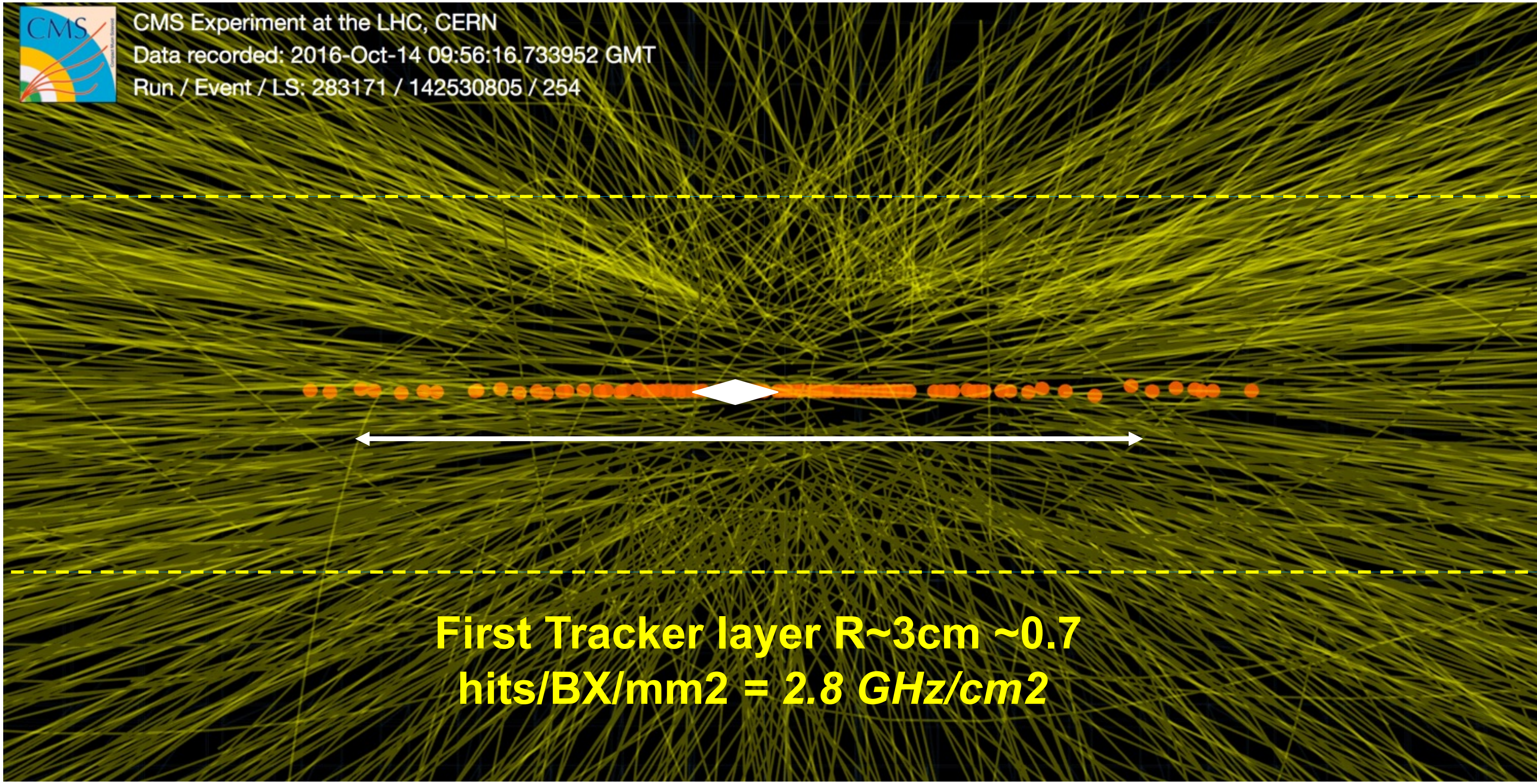
**our target**: ~**280 x 94 mm** → wafer scale sensor
→ stitching needed: a true single piece of silicon




MOSS: 1.4 x 26 cm monolithic stitched sensor

F.Carnesecchi, 25th October 2022, VERTEX, ALICE ITS3

25


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-14 09:56:16.733952 GMT
Run / Event / LS: 283171 / 142530805 / 254
First Tracker layer R~3cm ~0.7
hits/BX/mm2 = 2.8 GHz/cm2

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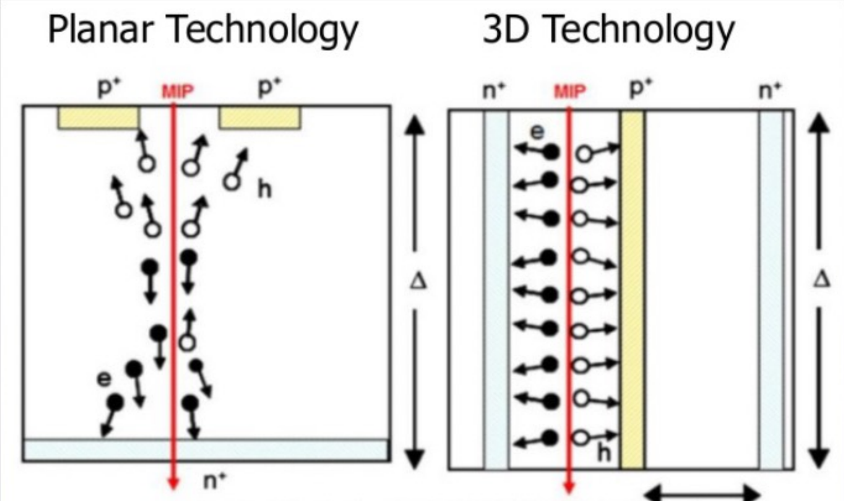
# 3D sensors

- Advantages
  - Decouple thickness from electrode distance
  - Lower depletion voltage, less power dissipation
  - Smaller drift distance, less trapping
- Disadvantage
  - More complex production process
  - Lower yield, higher costs
  - Higher capacitance (more noise)



C. Da Via et al., NIM A 694 (2012) 321

- 3D is the most radiation hard technology to-day
- Similar performance than planar sensors, but less demanding in terms of bias voltage and cooling.
- For the HL-LHC we need :
  - More radiation hard (innermost layer(s), 1-2E16 $n_{eq}/cm^2$)
  - Smaller pixels (compatible with new readout chip, 50 µm – 25 µm)
  - Thinner (reduce cluster size/merging, 200 µm – 100 µm)

S. Parker and C. Kenney



IPHC Institut Pluridisciplinaire Hubert Curien Strasbourg

# 3D Silicon

## Silicon pixels: 3D **FBK** — single-side

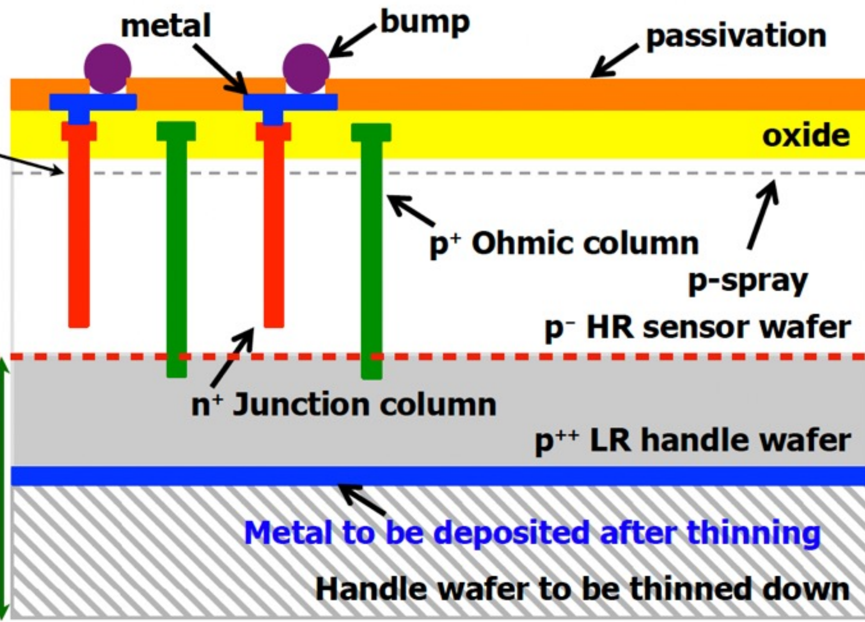
Column diameter **~5 µm**

**High Resistivity layer**

- Active layer thickness **~150 µm**
- Resistivity > 3 kOhm•cm

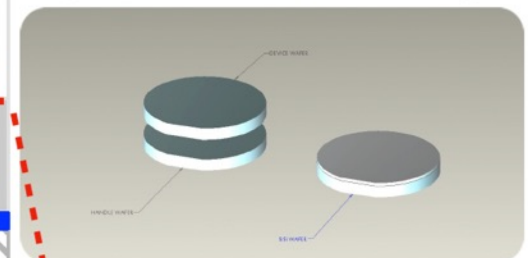
**Low Resistivity layer**

- Resistivity 0.1-1 Ohm•cm
- Initial wafer thickness **~500 µm**
- Residual wafer thickness after thinning **50-100 µm**

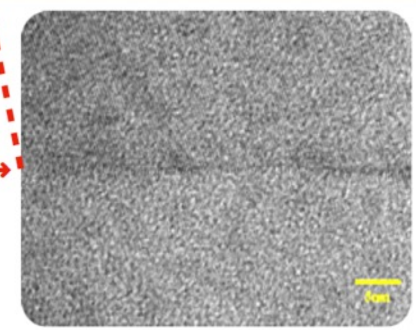



*G.F. Dalla Betta et al., NIMA 824 (2016) 386*

**Two wafers:**
**H**igh-**R**esistivity and **L**ow-**R**esistivity, bonded with **D**irect **W**afer **B**ond - **DWB** technique by IceMos Technology, Belfast



Divide between layers →



High resolution TEM image of two bonded wafers cross section

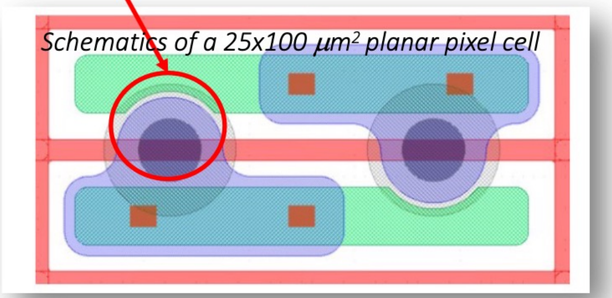
**Columns produced by:**
single-side **D**eep **R**eactive **I**on **E**tching - **DRIE** process optimised by ***FBK*** (less expensive than double-side process)

# CMS Pixel upgrade for HL-LHC

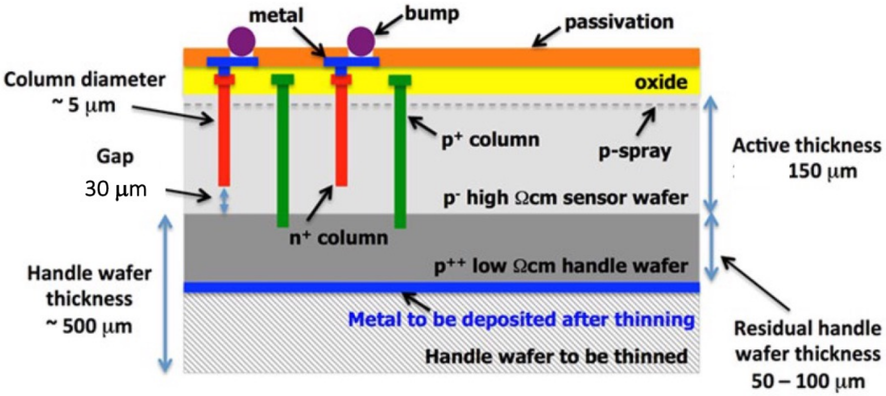
## Pixel sensors

- 150 μm bulk thickness, 25x100 $\mu m^2$ pixels cells everywhere
- Planar n-in-p sensors:
  - Bias up to 600V and spark protection between ROC and sensors
  - Three vendors qualified in the Market Survey, Tender being closed in these days
- Bump bonding pattern is 50x50 $\mu m^2$
  - Cross-talk issues studied and minimized (i.e. bitten implant on planar)
- 3D sensors for barrel L1
  - Short drift distance ~50 μm (3D) vs 150 μm (Planar)
  - Slim edges (150 μm ) vs planar (~450 μm ) → smaller dead zone
  - Sensors produced at FBK on 6" wafers and CNM on 4" wafers

*No $n^+$ implant under metal to reduce x-talk*

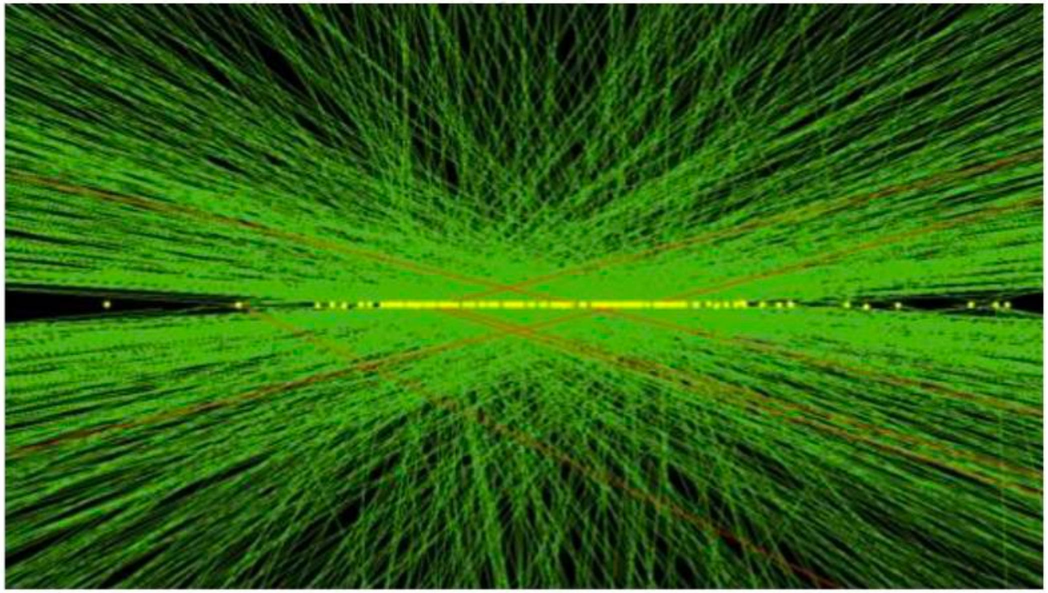



*Structure of a 3D sensor – FBK process*

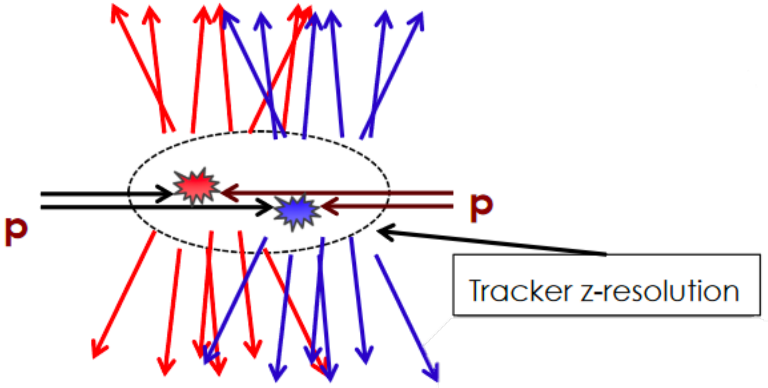



*A. Macchiolo, The CMS Pixel Upgrade, Pixel 2022, 13 Dec 2022*

# 4D Detectors (x,y,z and time)



**Tracking z-resolution can be larger than vertex-separation: Ambiguous Track-to-vertex association**



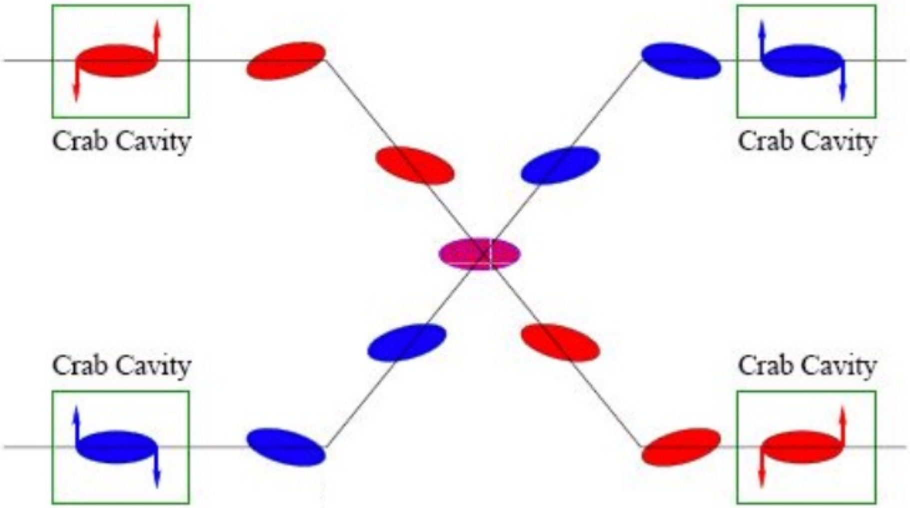

N. Cartiglia, INFN, Hiroshima Conference 2017

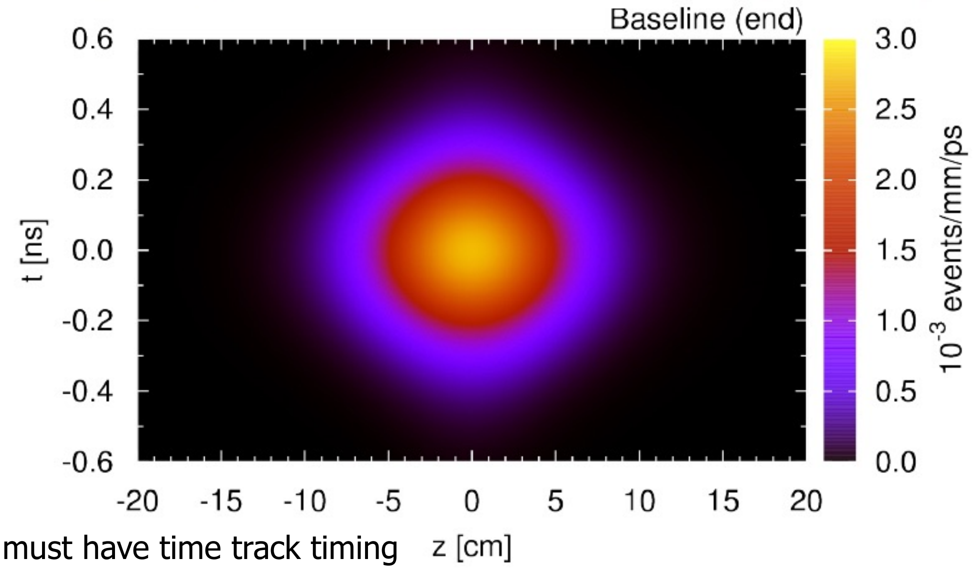
**Timing at each point along the track:**

- **Massive simplification of patter recognition**
- **Faster tracking algorithm**
- **Even in very dense environments by using only "time compatible points »**

# The Time Structure of Crossing Bunches

- In addition to extent in z, there is an extent of the bunch crossing in time
- For nominal HL-LHC optics the core of the bunches pass through each other in ~300 ps
- When bunches overlap entirely, achieve maximum spread in z and maximum pileup density
- Normally an experiment only sees the integral of this distribution over time




Need to discriminate vertices with time spread of ~180 ps, must have time track timing resolution significantly smaller than beamspot spread so that tracks cluster in time.

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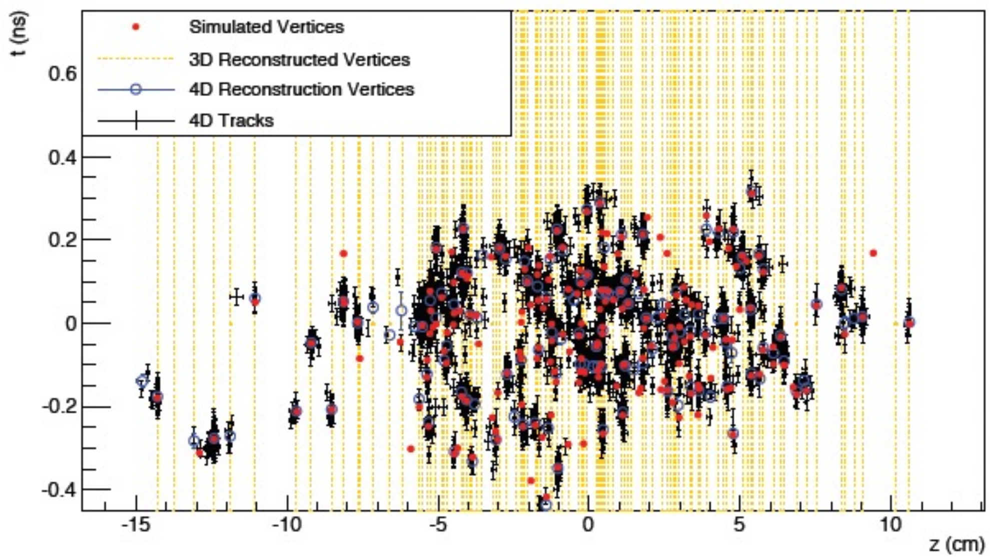


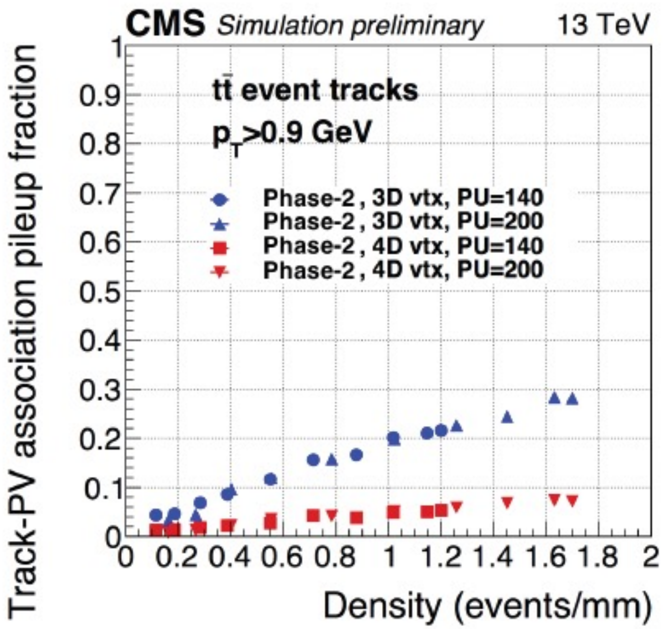
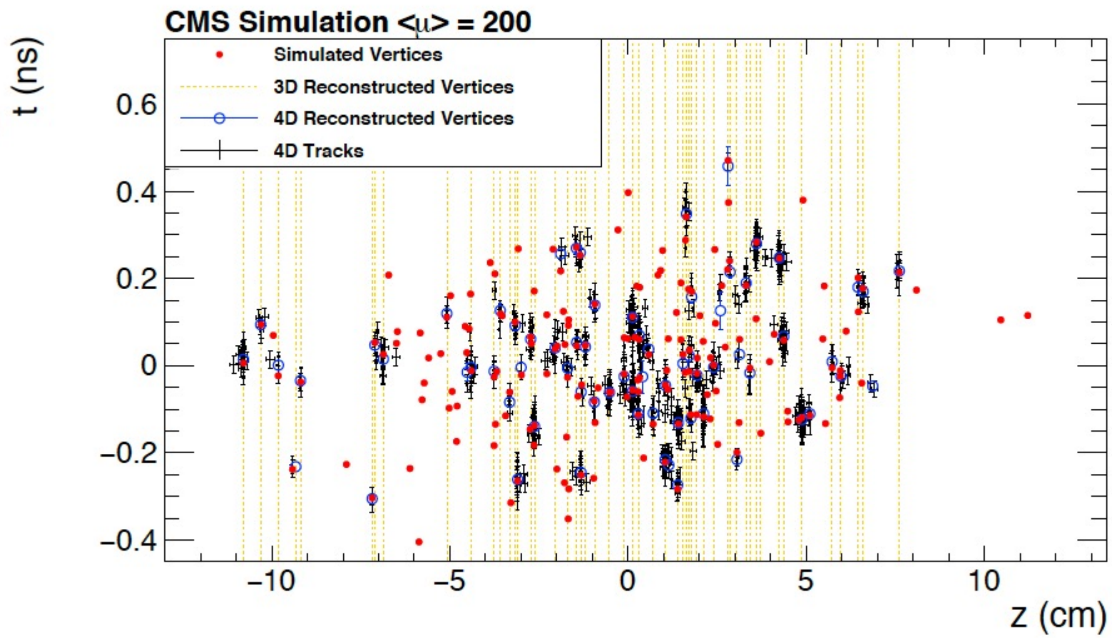




Figure 1.2: Left: Simulated and reconstructed vertices in a 200 pileup event assuming a MIP timing detector covering the barrel and endcaps. The vertical lines indicate 3D-reconstructed vertices, with instances of vertex merging visible throughout the event display. Right: Rate of tracks from pileup vertices incorrectly associated with the primary vertex of the hard interaction normalized to the total number of tracks in the vertex.

# Using the Time-at-vertex in Reconstruction

- With the track-time at distance of closest approach it becomes possible to cluster tracks in 2D into vertices
- This significantly increases the distance between vertices and hence makes them harder to confuse
- Expect 5-10x improvement in vertex merging rate (achieved 9x)
- Expect 3-5x reduction in track-vertex association false positives (achieve ~3x)




CMS Simulation

| <μ> | 4D Merged Vertex Fraction | 3D Merged Vertex Fraction | Ratio of 3D/4D |
|---|---|---|---|
| 50 | 0.5% | 3.3% | 6.6 |
| 200 | 1.5% | 13.4% | 8.9 |

# Crystals

**lutetium-yttrium orthosilicate crystals activated with cerium (LYSO:Ce) read out with SiPMs. The**

**The barrel timing layer will cover the pseudorapidity region up to lhl = 1.48 with a total active surface of about 40 m2.**

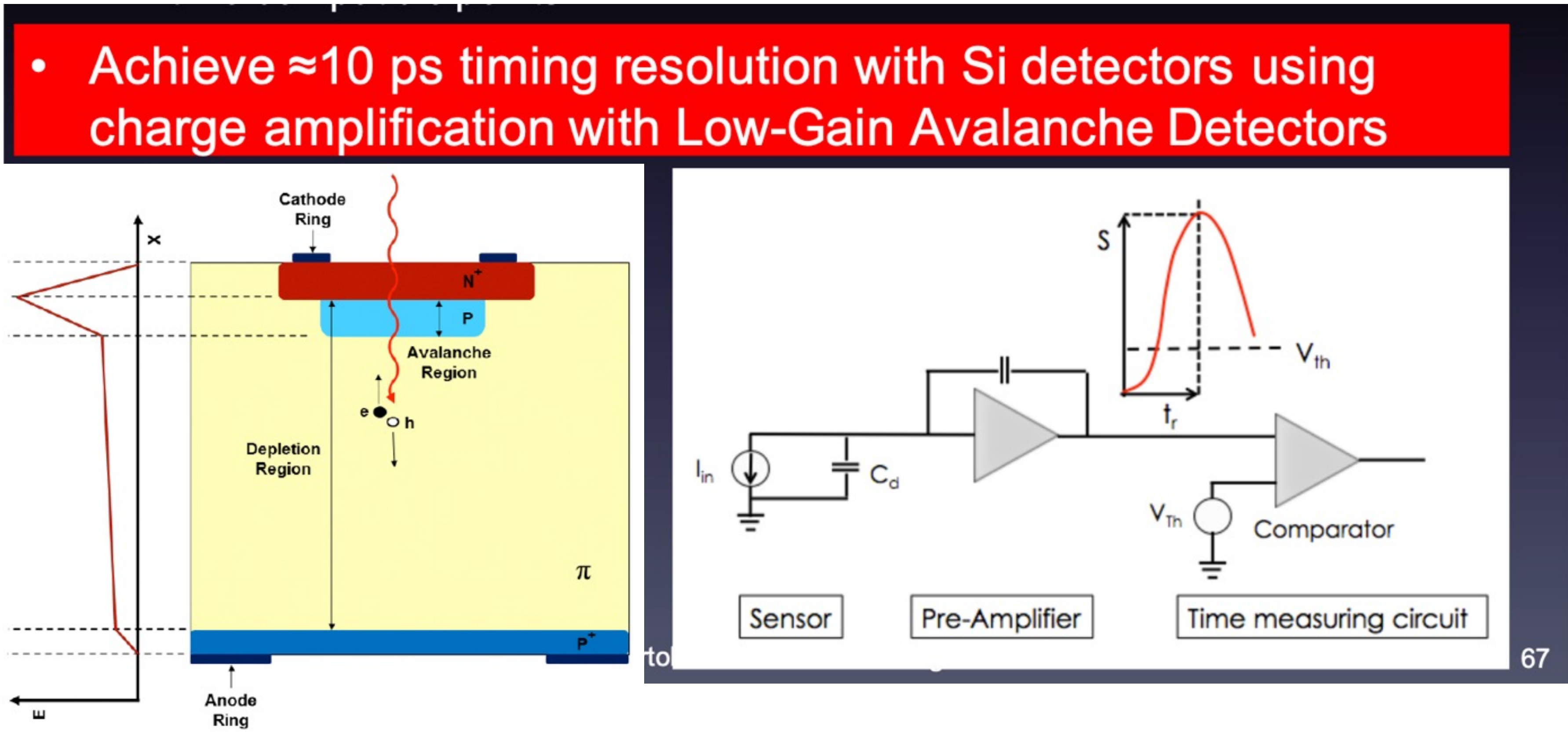
**The fundamental detecting cell will consist of a thin LYSO:Ce crystal with about 12⇥12 mm2 cross-section coupled to a 4x4 mm2 SiPM.**

**The crystal thickness will vary between about 3.7 mm (lhl < 0.7) and 2.4 mm (lhl > 1.1),**


Figure 2.4: Top left: Set of $11 \times 11 \times 3$ mm$^3$ LYSO:Ce crystals with depolished lateral faces, before and after Teflon wrapping. Bottom left: $6 \times 6$ mm$^2$ HPK SiPMs glued on LYSO crystals. Right: Crystal+SiPM sensors plugged on the NINO board used for test beam studies.

# LGADs

Nicolo Cartiglia




**Lots of R&D, DC and AC coupled, chip design, test beams**

**Both ATLAS and CMS but also for Higgs factories etc**

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# HL-LHC necessitates upgrades to the CMS detector

3

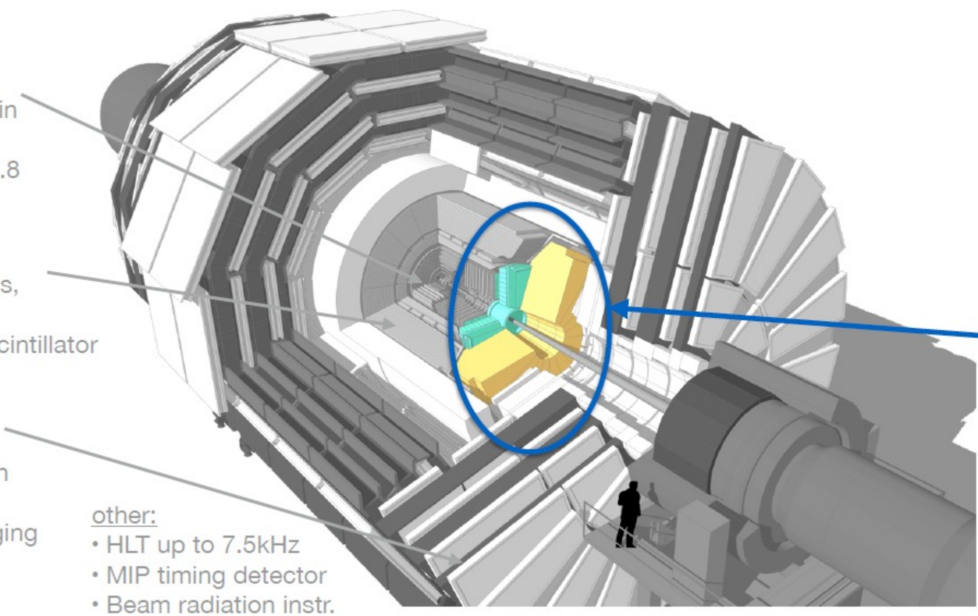
| Experimental challenges | LHC | | HL-LHC | General mitigation strategy |
|---|---|---|---|---|
| • inst. luminosity | $2 \times 10^{34}\ s^{-1}\ cm^{-2}$ | → | up to $7.5 \times 10^{34}\ s^{-1}\ cm^{-2}$ | • improved trigger & computing |
| • detector irradiation | $O(10^{14}\ neq/cm^2)$ | | $>O(10^{15}\ neq/cm^2)$ | • radiation-tolerant sensors & electronics |
| • pile-up interactions | O(40) | | 140-200 | • timing and increased granularity |

**Compact Muon Solenoid (CMS)**
HL-LHC Upgrades

Tracker:
Radiation tolerant,
high granularity,
less materials, tracks in
hardware trigger (L1),
coverage up to |η| = 3.8

Barrel Calorimeter:
New BE/FE electronics,
ECAL: lower temp.,
HCAL: partially new scintillator

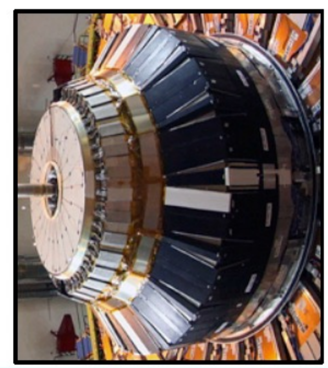
Muon system:
New electronics
GEM/RPC coverage in
1.5 < |η| < 2.8,
investigate muon tagging
at
higher η



other:
• HLT up to 7.5kHz
• MIP timing detector
• Beam radiation instr.
and luminosity

**To be replaced for HL-LHC**

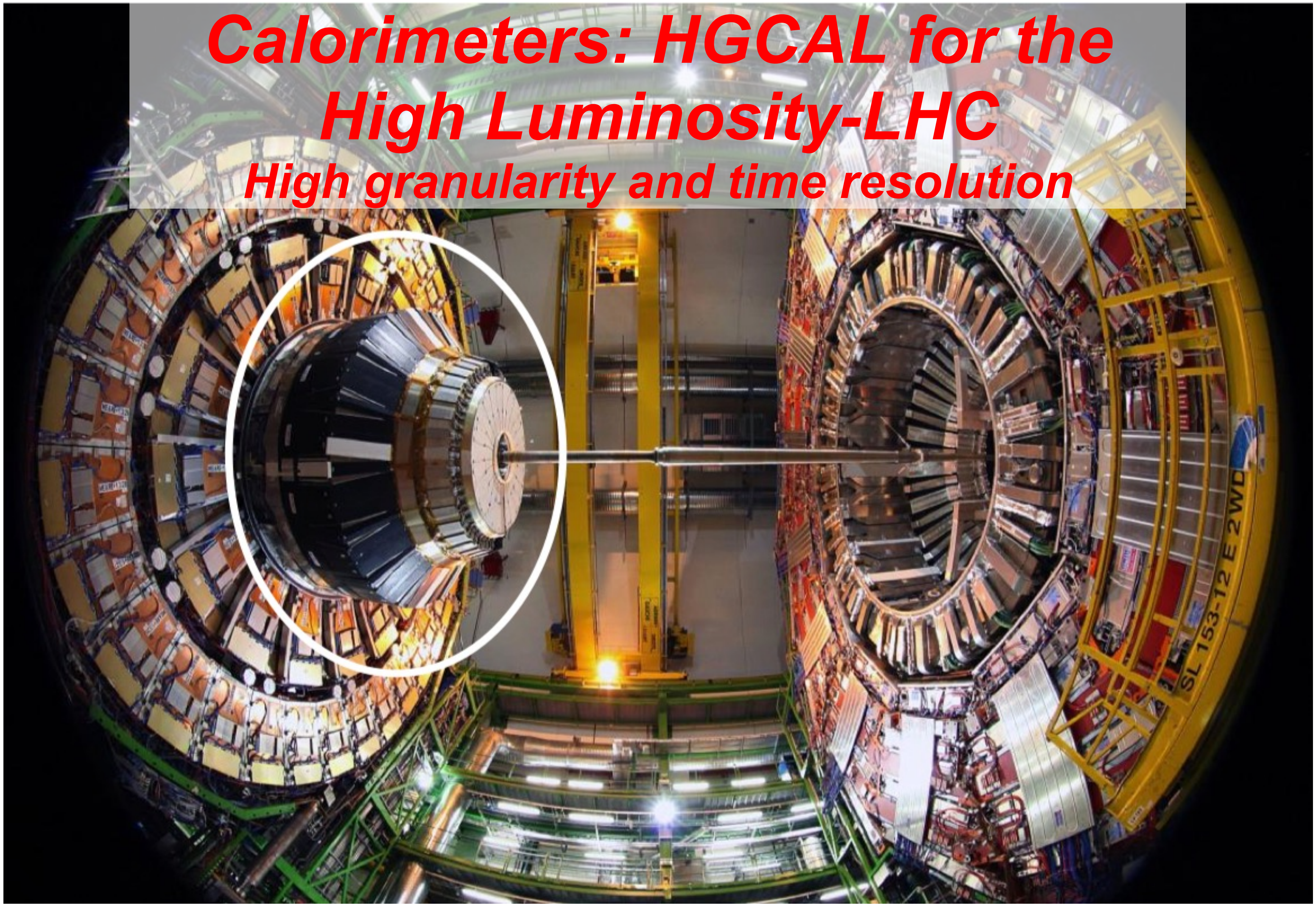
**Endcap Calorimeters:**
**1.5 < |η| < 3.0**



Thorben Quast | Pisa Meeting 2022, 25 May 2022

# Calorimeters: HGCAL for the High Luminosity-LHC

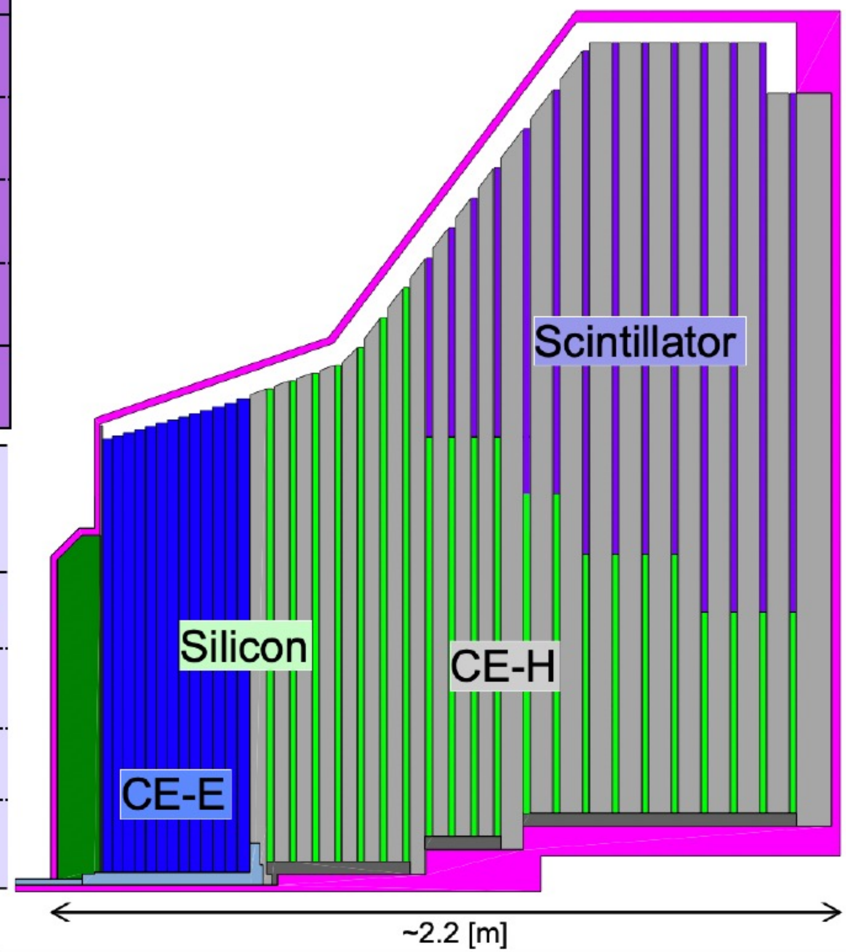
## High granularity and time resolution



# Technology Choices

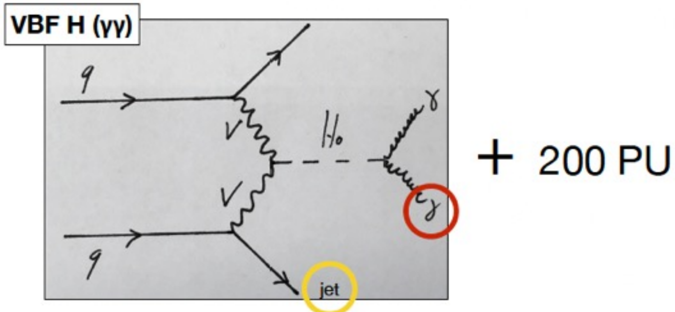
| Both Endcaps | Silicon | Scintillator |
|---|---|---|
| Area | ~620 $m^2$ | ~370 $m^2$ |
| Channel Size | 0.5 - 1.2 $cm^2$ | 4 - 30 $cm^2$ |
| # Channels | ~6 M | ~240 k |
| # Modules | ~27000 | ~4000 |
| Op. Temp. | -30 C | -30 C |

| Per Endcap | CE-E | CE-H | |
|---|---|---|---|
| | | Si | Si+Scint |
| Absorber | Pb, CuW, Cu | Stainless steel, Cu | |
| Depth | 27.7 $X_0$ | 10 λ | |
| Layers | 26 | 7 | 14 |
| Weight | 23 t | 205 t | |

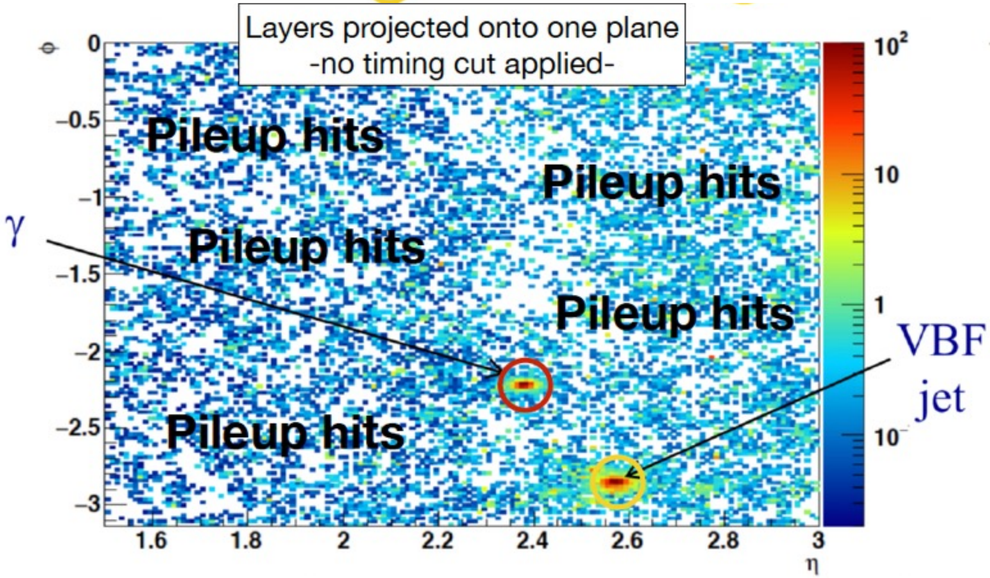


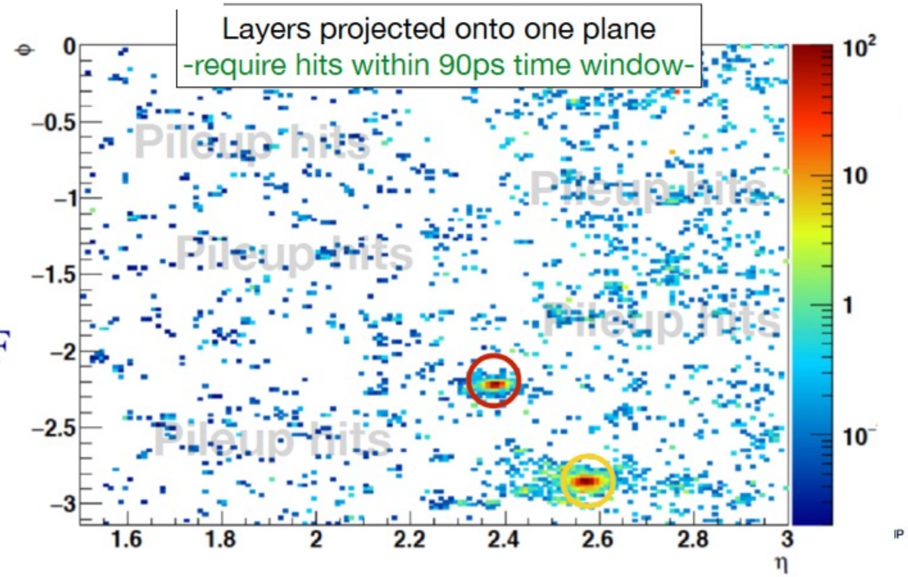

- Dissipated power ~250 kW
- Removed with two-phase $CO_2$ cooling operated at -35 C
- Geometry slightly adjusted since the TDR release

# Idea: HGCAL will be 3D imaging calorimeter **with timing capabilities** 8



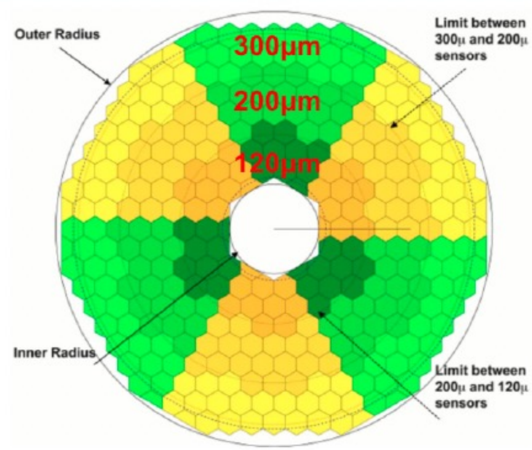

- Plots show cells with E >~3.5 MIPs, projected to the front face of the endcap calorimeter
- Concept: identify high-energy clusters, then make timing cut to retain hits of interest
- Design HGCAL to obtain a ~30ps timing measurement for multi-MIP energy deposits

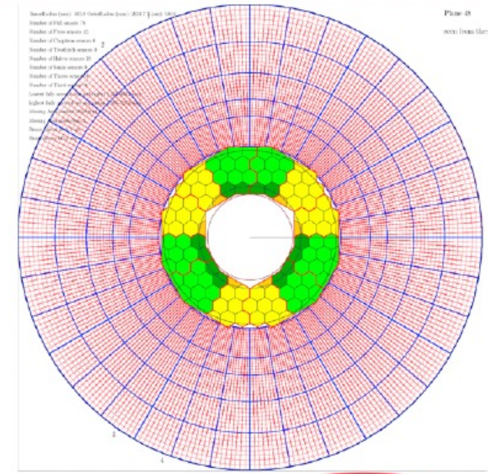


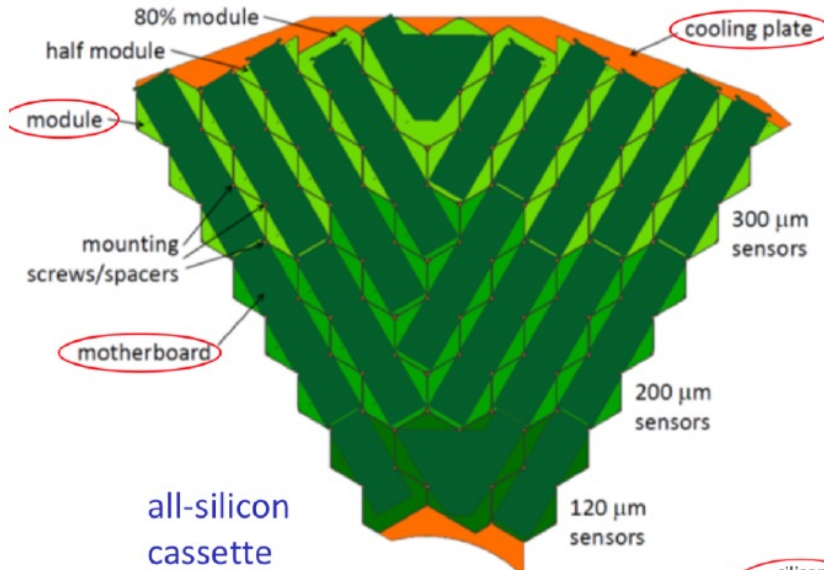



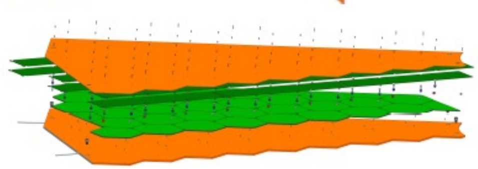
# Lateral Structure, Cassettes

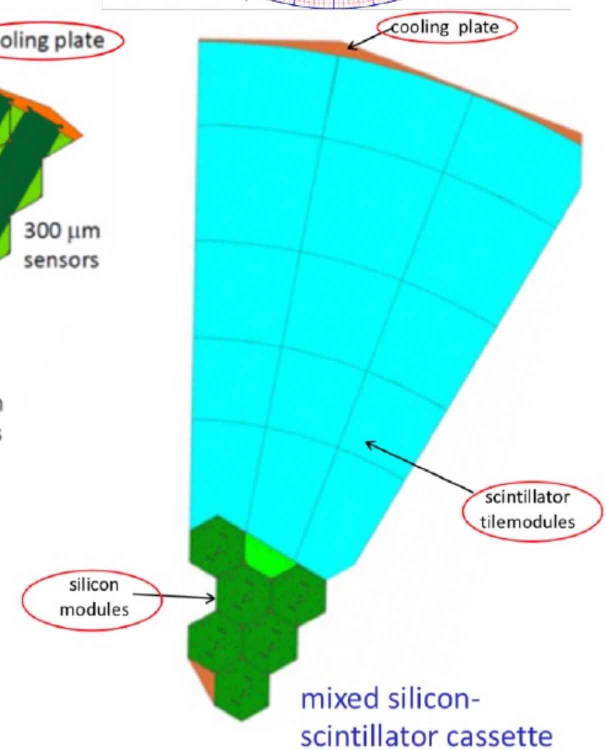
- **Silicon and scintillator modules assembled into cassettes**
- **Supported and cooled by copper cooling plate**
- **Data from modules collected by motherboards**
- **Cassettes house all services and DC2DC converters**



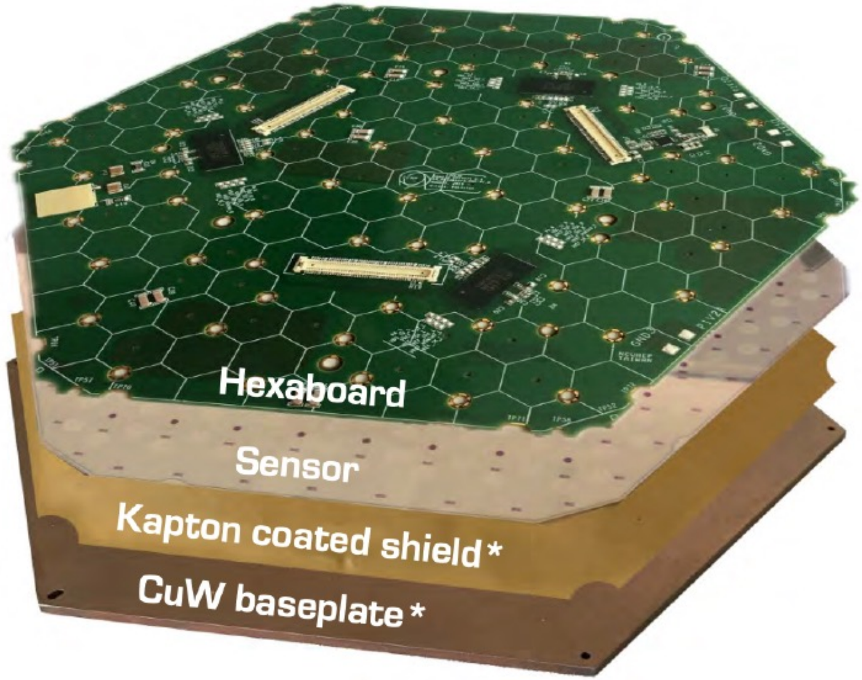


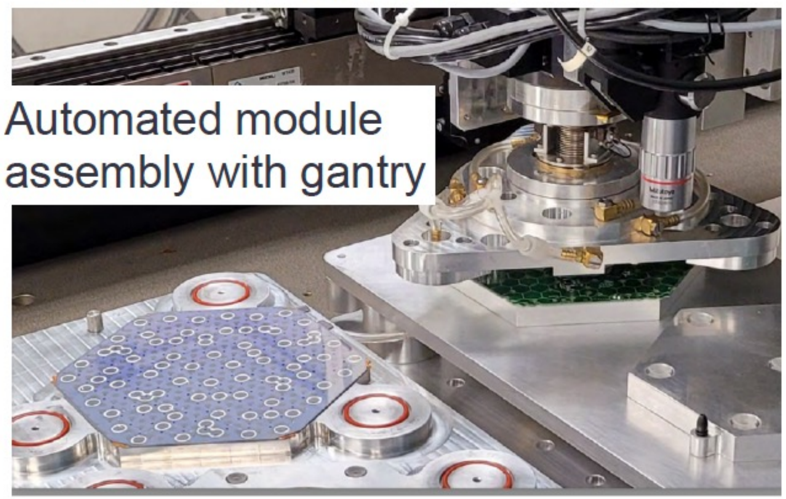


# Silicon Modules

- Glued stack of baseplate, sensor and readout hexaboard
- baseplates are made of CuW in CE-E, PCB in CE-H
- Relative alignment within ~50um achieved with gantry based automated assembly
- Electrical connections are done with wire-bonds

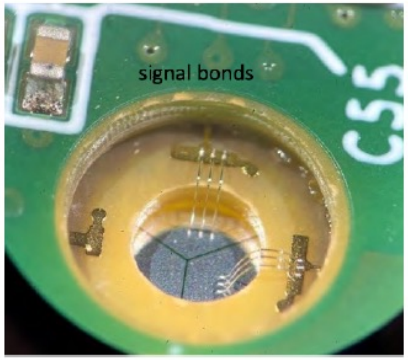



* In CE-H, PCB baseplate with laminated Kapton™

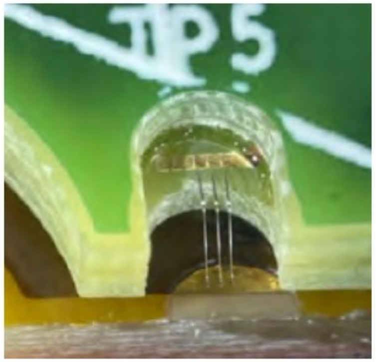


Automated module assembly with gantry

signal bonds




shield bonds



backside HV bonds

# HGCAL for the High Luminosity-LHC is a very complex instrument

# *High purity segmented Ge-detectors for Nuclear physics*

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μ = 0.6 cm$^{-1}$

μ = 0.18 cm$^{-1}$

μ = 0.007 cm$^{-1}$

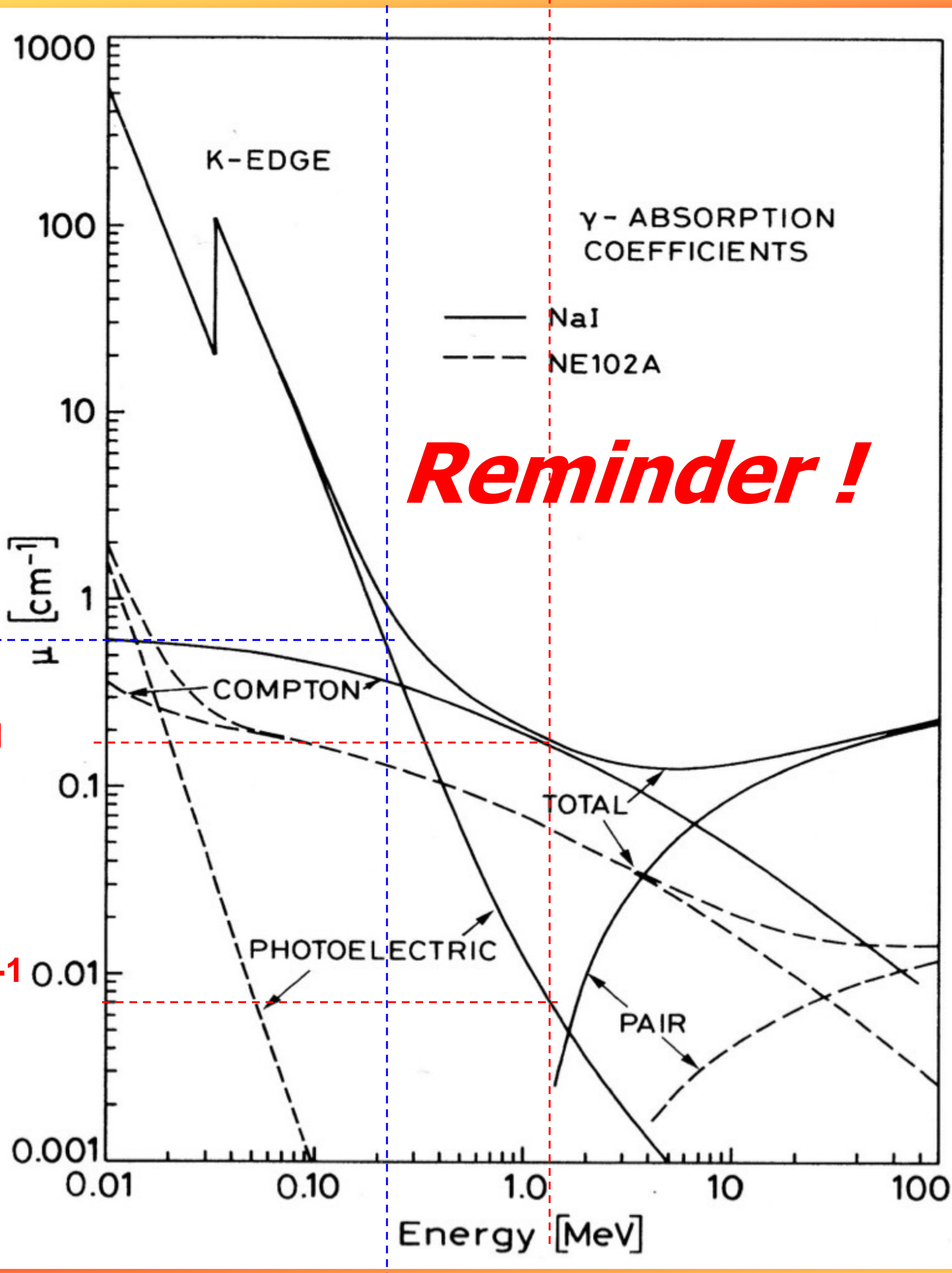


**Photo-electric effect**

**Absorption of γ**

**Compton scattering**

**scattering γ –> γ'**

**Creation of ($e^+e^-$) pairs**

**Absorption of γ**

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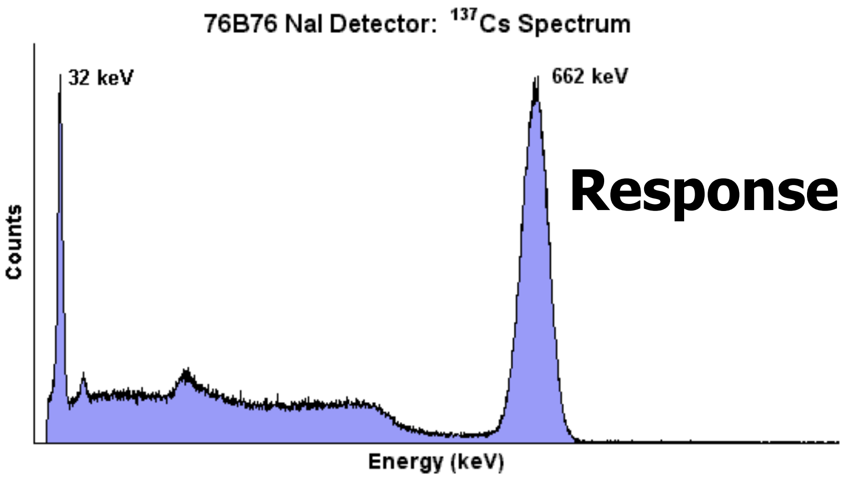
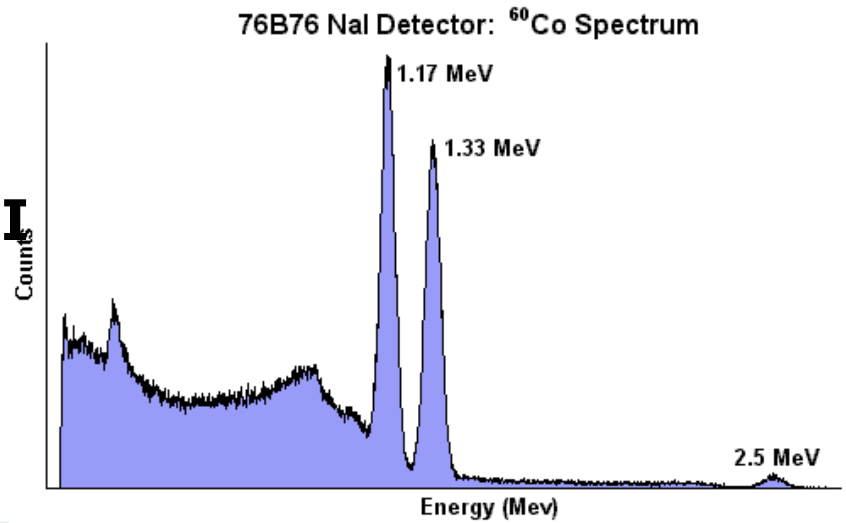
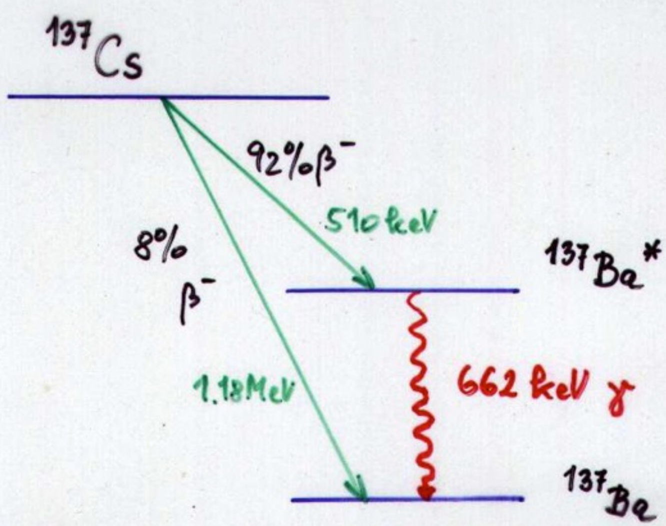
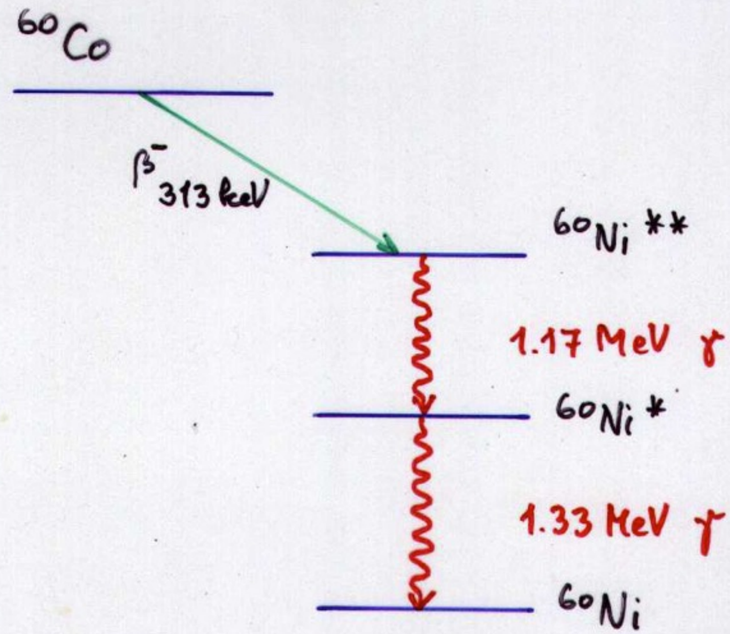
# Response of NaI




Univ. of Tennessee, Dept. of Physics & Astronomy



Ulrich.Goerlach@iphc.cnrs.fr, ASP Particle detectors

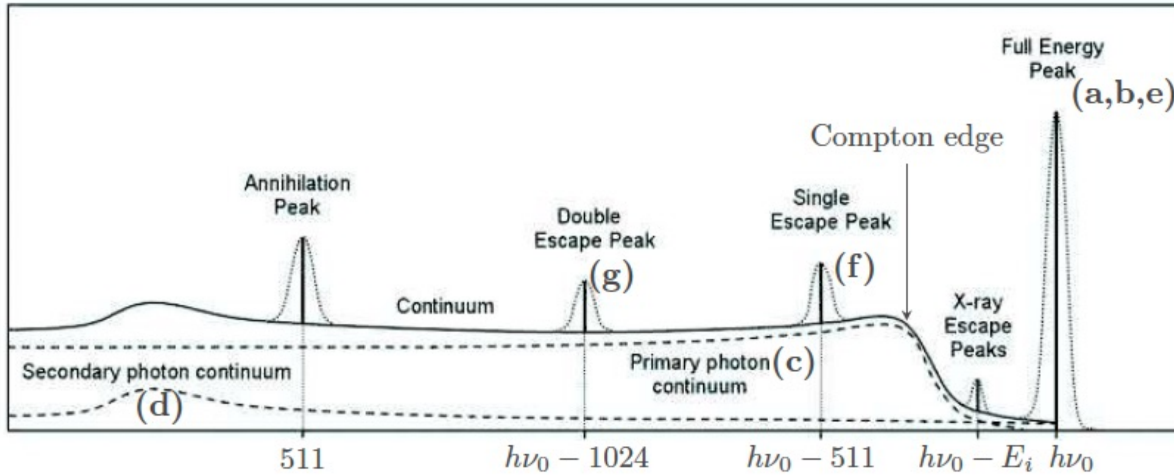
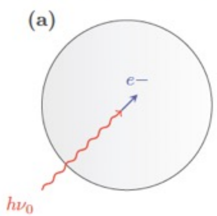
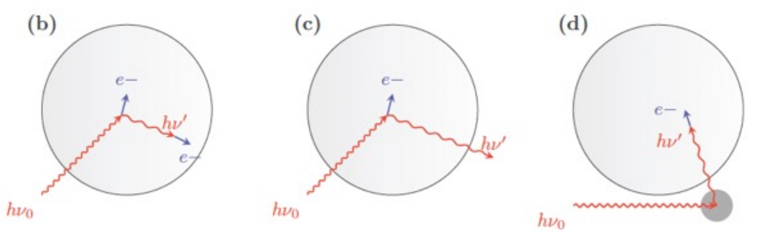



Figure 1.3: Effect of interaction processes on the predicted detector response function for mono-energetic $\gamma$-rays with $h\nu_0 >> 1.022MeV$.

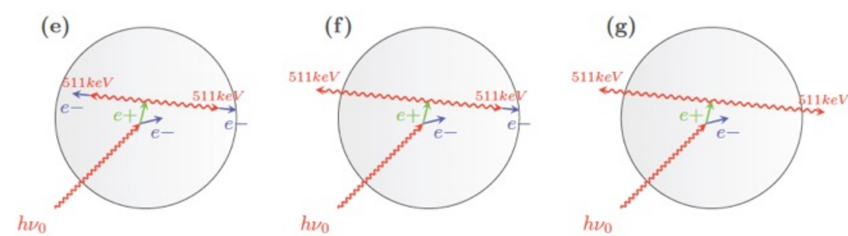
PHOTO-ELECTRIC EFFECT

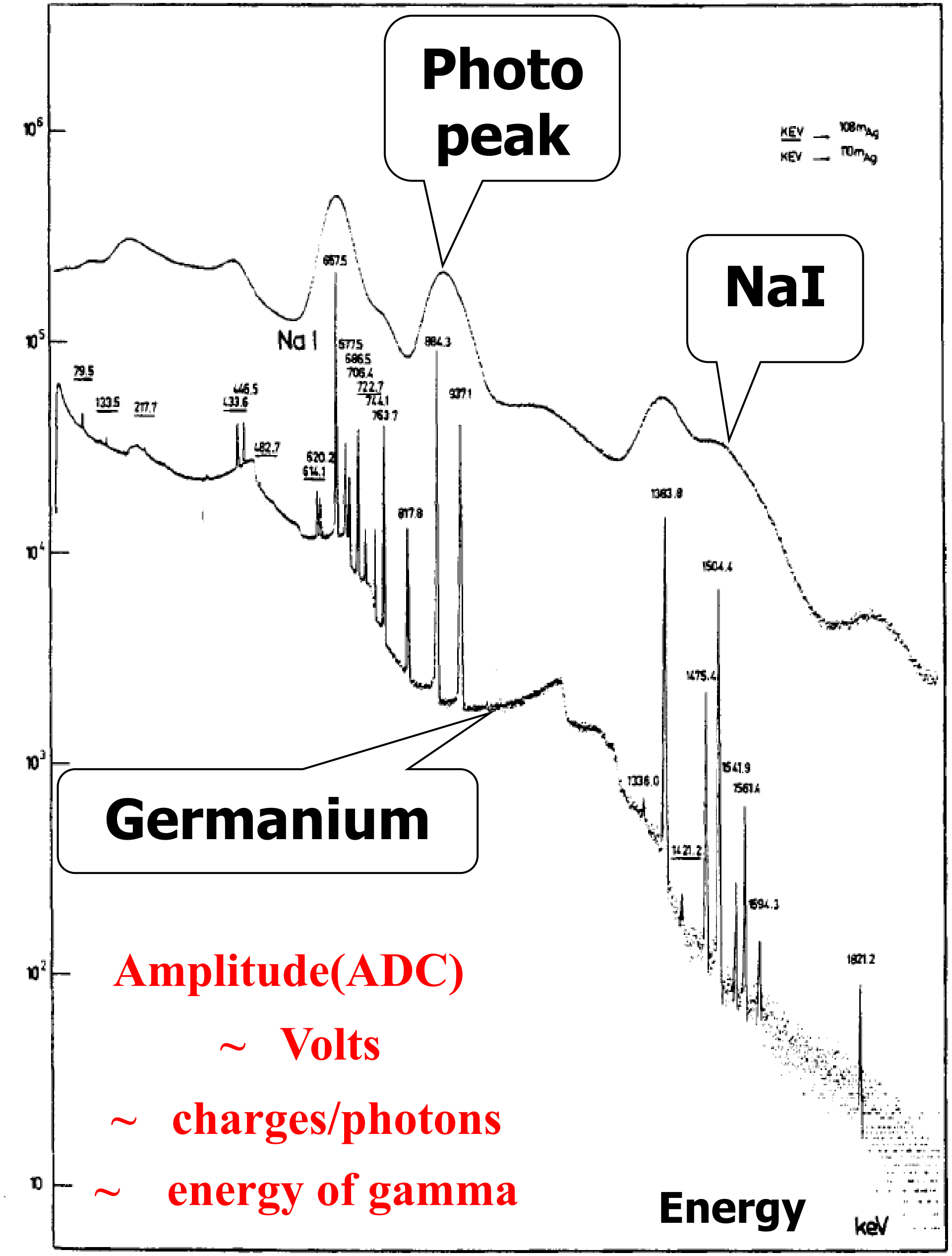



COMPTON SCATTERING




PAIR CREATION






**Large volume semi-conductor detector**

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# Semi-conductor detectors

| Material | $E_g$ [eV] | w [eV] | Mobility (velocity/*E*) | | $\tau_e$ [s] | $\tau_h$ [s] | density | Z [a.m.u] |
|---|---|---|---|---|---|---|---|---|
| | | | $\mu_e$ [cm$^2$/Vs] | $\mu_h$ [cm$^2$/Vs] | | | g/cm$^3$ | |
| C (diamond) | 5.5 | 13 | 1800 | 1200 | $2\ 10^{-9}$ | $2\ 10^{-9}$ | 3.515 | 6 |
| Si | 1.12 | 3.61 | 1350 | 480 | $5\ 10^{-3}$ | $5\ 10^{-3}$ | 2.33 | 14 |
| Ge | 0.67 | 2.98 | 3900 | 1900 | $2\ 10^{-5}$ | $2\ 10^{-5}$ | 5.32 | 32 |
| GaAs | 1.42 | 4.70 | 8500 | 450 | $5\ 10^{-8}$ | $5\ 10^{-8}$ | 5.32 | 31,33 |
| CdTe | 1.56 | 4.43 | 1050 | 100 | $1\ 10^{-6}$ | $1\ 10^{-6}$ | | 48,52 |
| $HgI_2$ | 2.13 | 4.20 | 100 | _ | $1\ 10^{-6}$ | $2\ 10^{-6}$ | | 53,80 |

$$\frac{dN}{N} = \frac{1}{\sqrt{N}} \; ; \quad E \sim N ; \quad N = \text{numb. of (e,h))}$$

**Parameters Values for Materials Used in Fabricating Semiconductor Radiation Sensors [3]**

# Inverse Polarisation

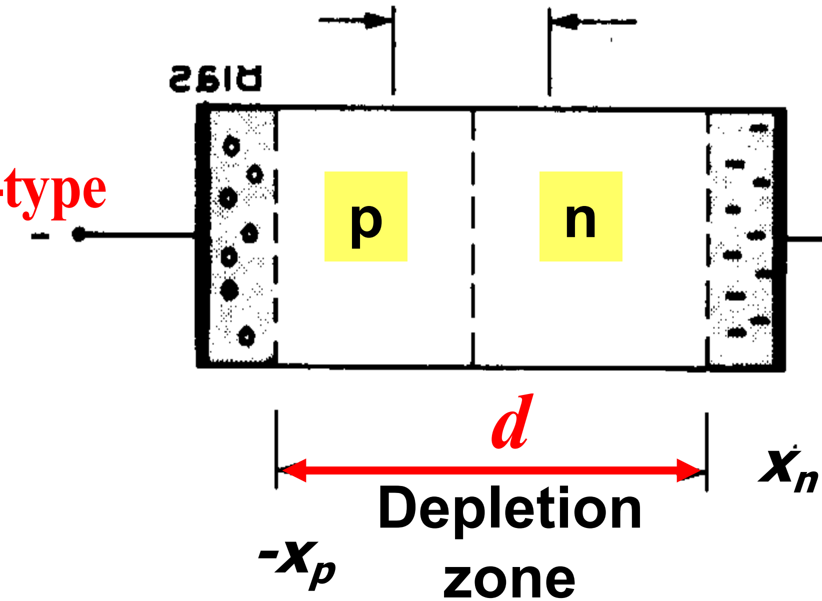
$$d\Big|_{V_{bias}} = x_n + x_p = \sqrt{\frac{2\varepsilon\left(\phi_0 + V_{bias}\right)}{e}\frac{\left(N_A + N_D\right)}{N_A N_D}}$$

Holes move to « - »

electrons move to contact "+"

$N_A \gg N_D$

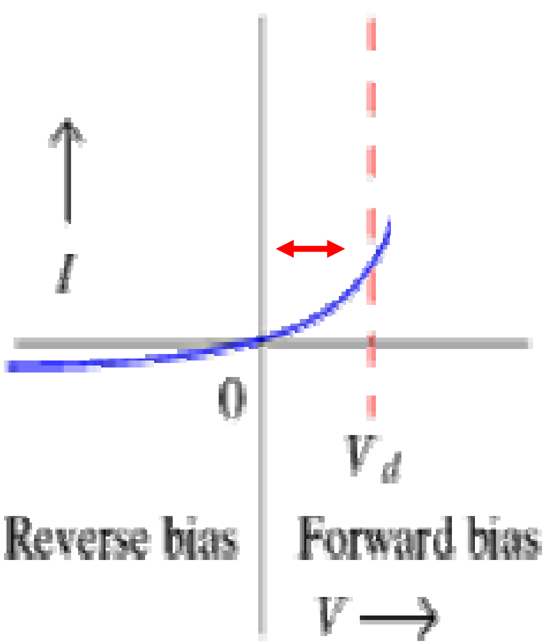
depletion in n-type



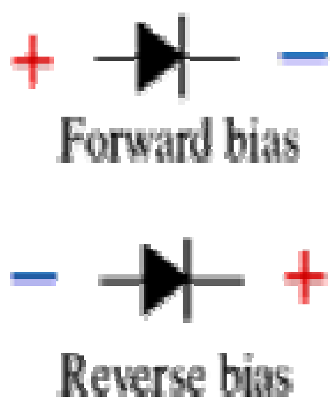

$d \simeq x_n \approx 0.53\sqrt{\rho_n \phi_0}\ \mu m$

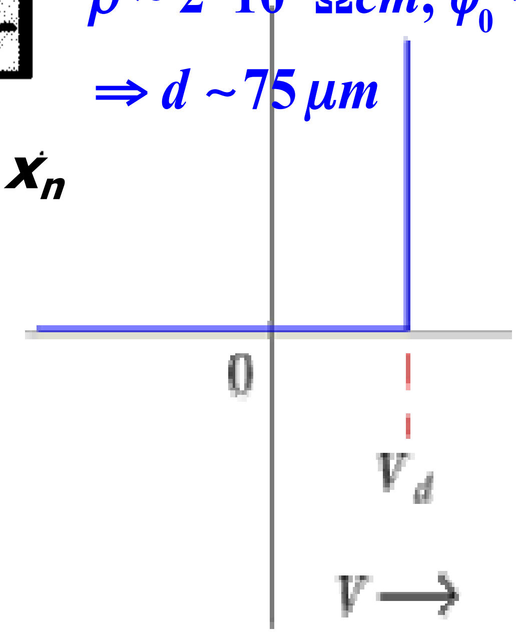
$\rho \sim 2\cdot 10^4\ \Omega cm,\ \phi_0 \sim 1V$

$\Rightarrow d \sim 75\ \mu m$




Real Diode




'Ideal' Diode

# Large volume detectors

- **Depletion zone :**

$$d\Big|_{V_{bias}} = x_n + x_p = \sqrt{\frac{2\varepsilon\left(\phi_0 + V_{bias}\right)}{e}\frac{\left(N_A + N_D\right)}{N_A N_D}}$$

$$N = N_A \ll N_D;\ \ \phi_0 \ll V_{bias}$$

$$d\Big|_{V_{bias}} = \sqrt{\frac{2\varepsilon V_{bias}}{eN}}\ ;\ N = N_A \text{ ou } N_D = \text{net impurity of material}$$

$$N = 10^{+13}\, atoms/cm^3;\ V_{bias} = 3000\,Volt;$$

$$d\Big|_{V_{bias}=3000\,Volt} = 2.2\,mm$$

- **High purity :**

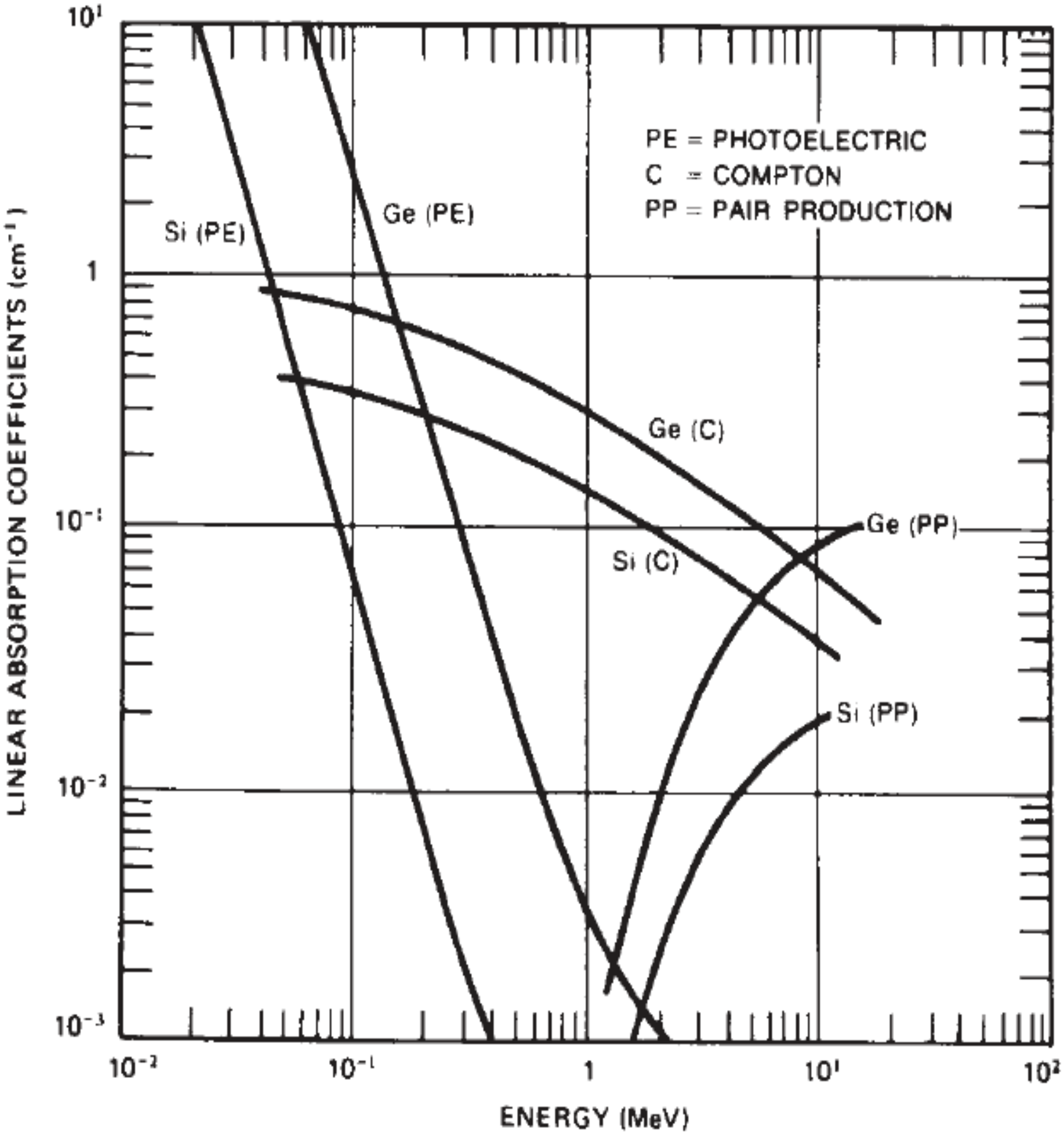
$$N_A\ ou\ \ N_D = 10^{+10}\, atoms/cm^3;\ V_{bias} = 1000\,Volt;\ \varepsilon = 16\cdot\varepsilon_0;$$

$$\varepsilon_0 = 8.85\cdot 10^{-12}\ F/m;\ F = Coulomb/Volt\ ;\ e = 1.6\cdot 10^{-19}\,Coulomb$$

$$d\Big|_{V_{bias}=1000\,Volt} = 1.8\,cm$$

$$d\Big|_{V_{bias}=2000\,Volt} = 2.5\,cm$$

$$d\Big|_{V_{bias}=3000\,Volt} = 3.1\,cm$$




# High Purity Germanium

## Energy measurement of gammas

($|N_A-N_D| \cong 10^{10}$ $cm^{-3}$):

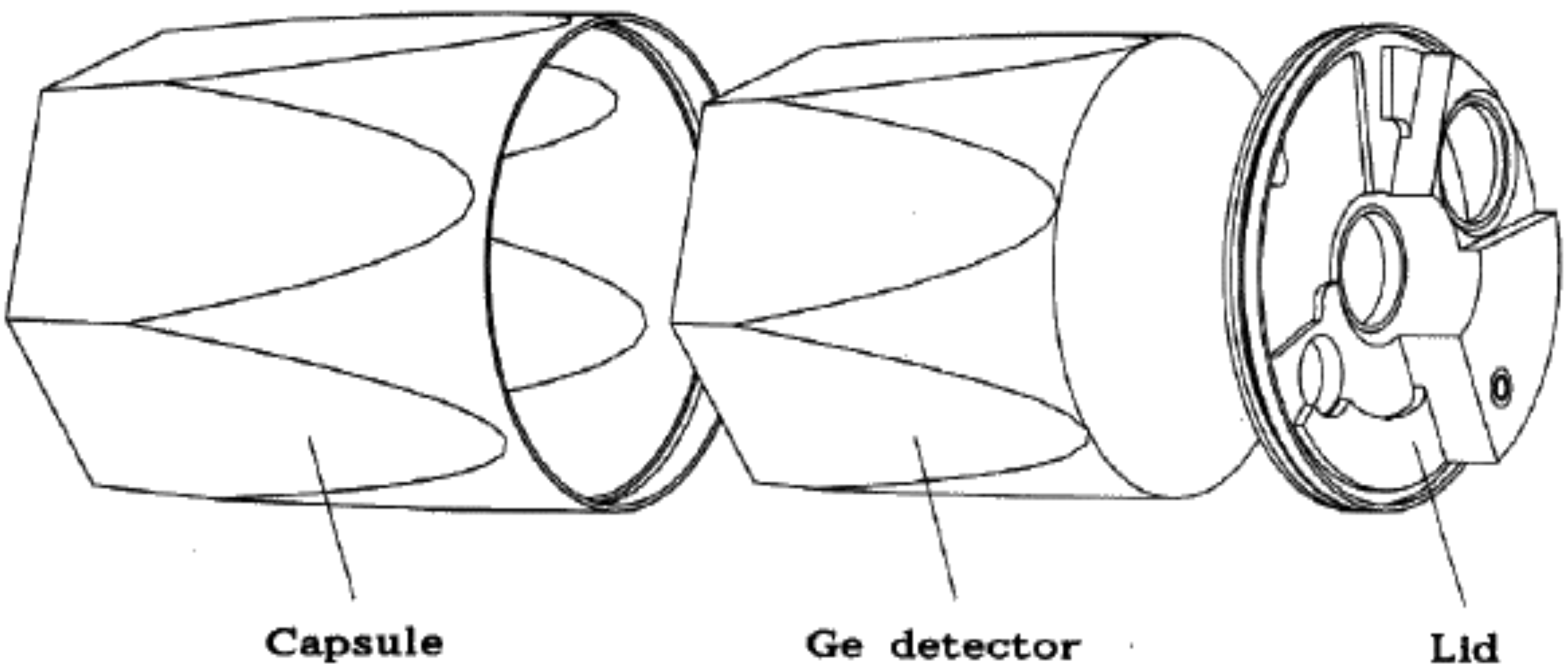
- $E_{gap}$ = 0.74 eV ⇒ operation temperature : T= 77K
- $w_{eh}$=2.98 eV ⇒excellent resolution
  - $E_\gamma$ = 1 MeV, dE ≅ 1 keV
  - "High" photo peak efficiency

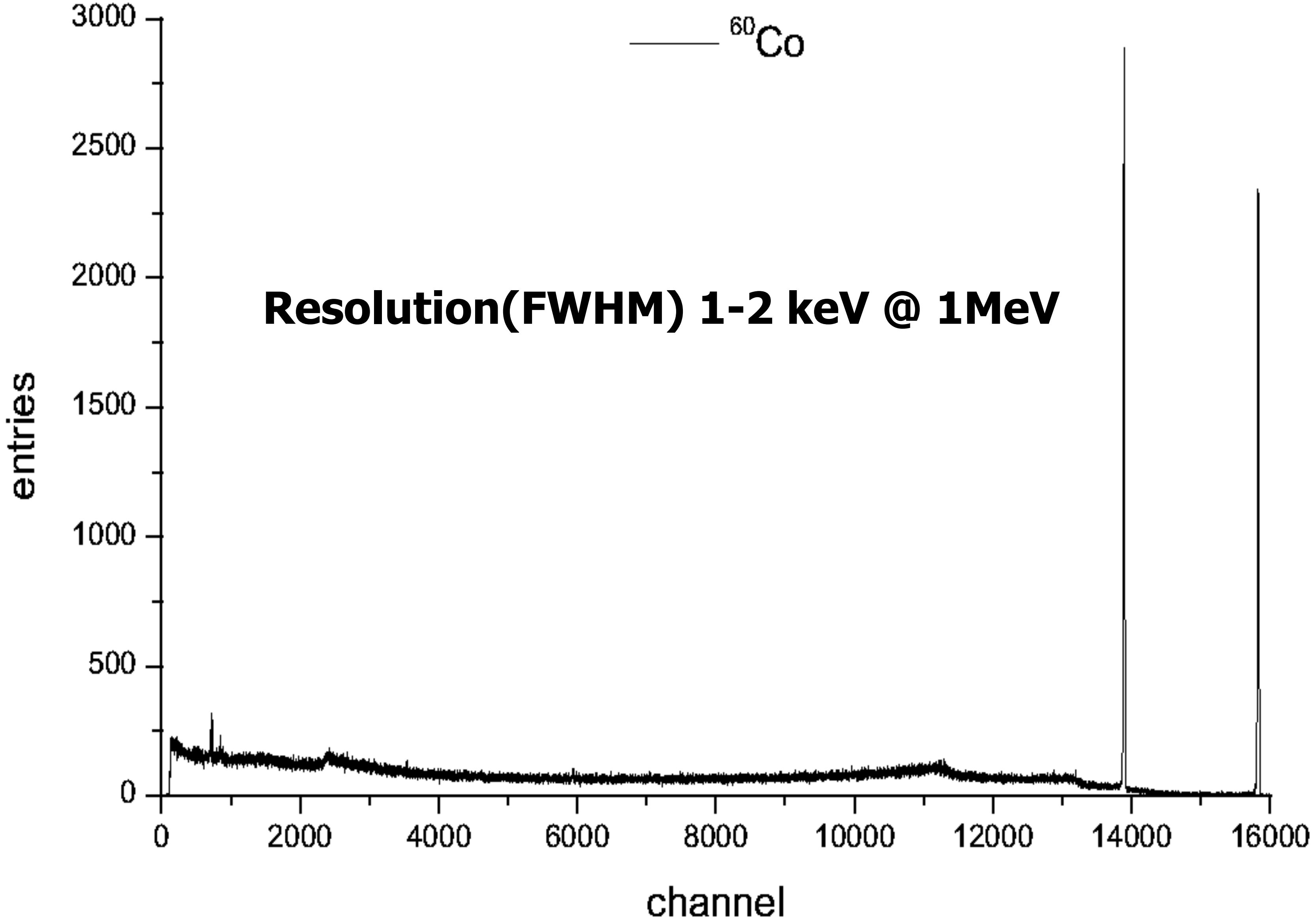
# Germanium detectors

**Operation temperature: T= 77K (Liquid Nitrogen)**

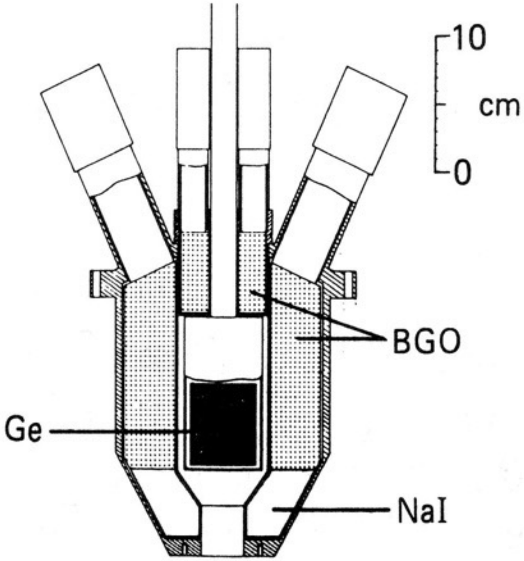
**Configuration : co-axial**

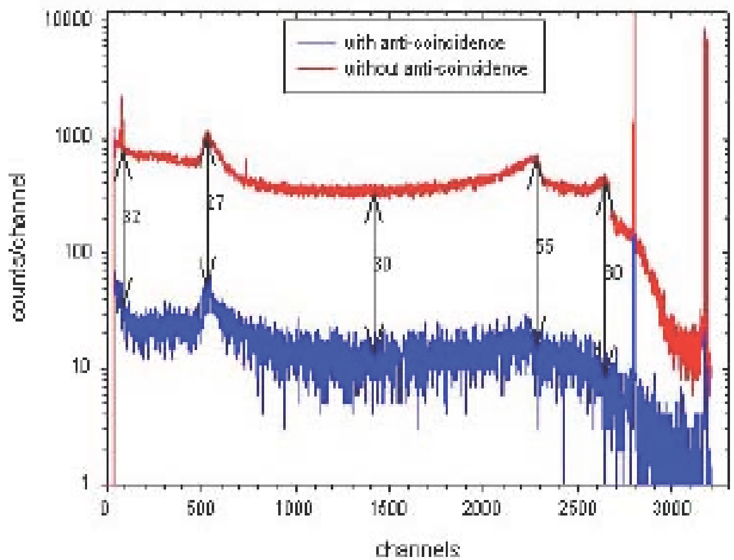
**Electronics is mounted very close to the Crystal**

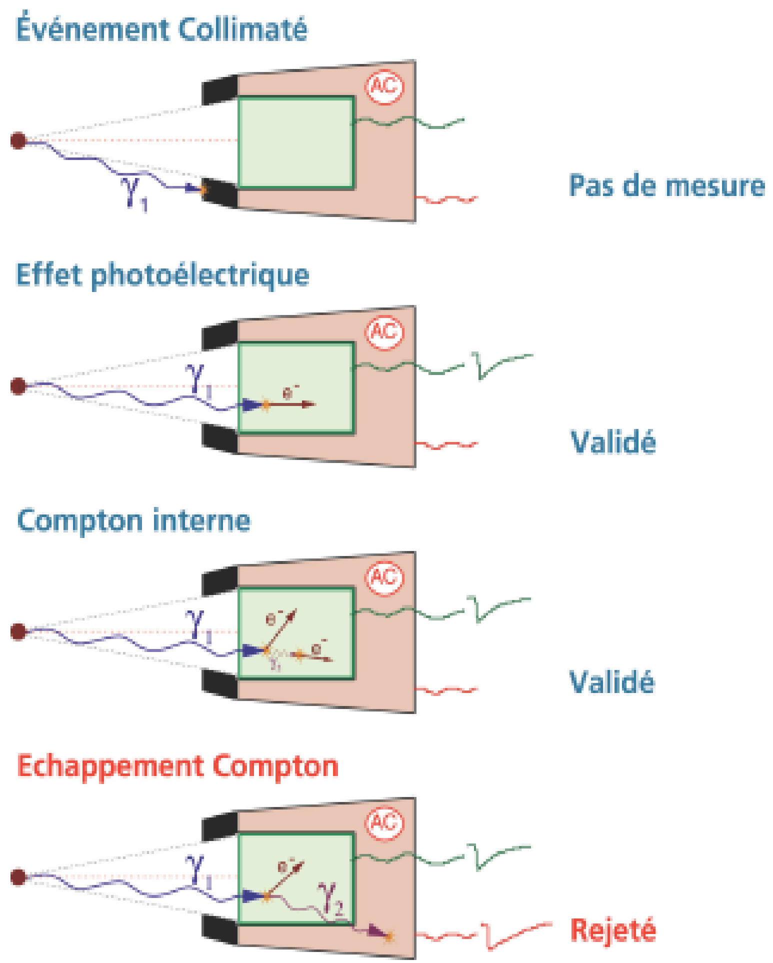



60Co
Resolution(FWHM) 1-2 keV @ 1MeV
entries
channel
0
500
1000
1500
2000
2500
3000
2000
4000
6000
8000
10000
12000
14000
16000

## ïncidence : système anti-Compton



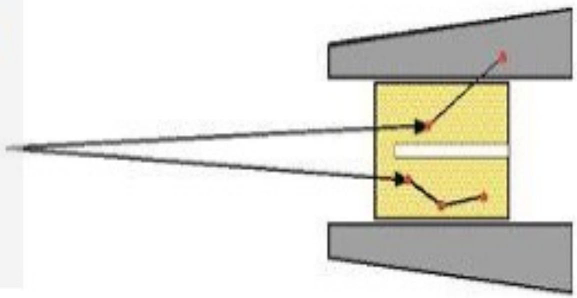



# The idea of γ-ray tracking

## Compton Shielded Ge

$\varepsilon_{ph}$ ~ 10%
$N_{det}$ ~ 100

$\Omega$ ~ 40%
$\theta$ ~ 8°



large opening angle means poor energy resolution at high recoil velocity.

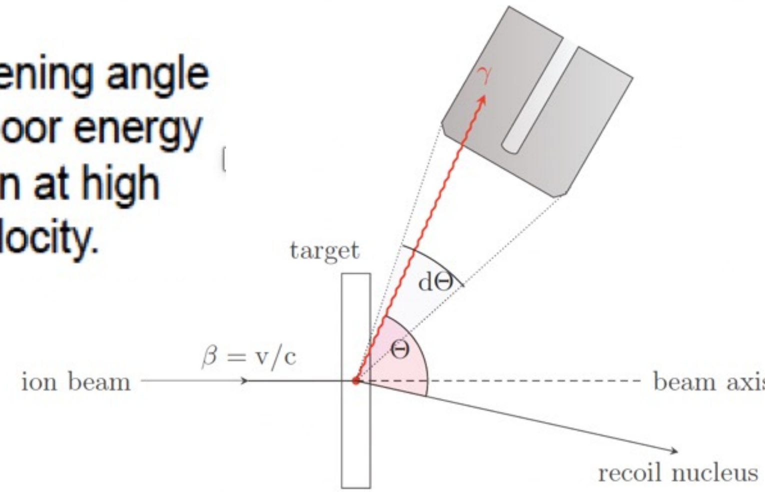


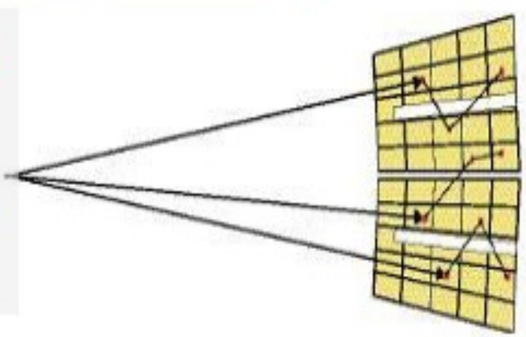

Figure 1.12: Doppler broadening

Previously scattered gammas were wasted.
Technology is available now to track them.

## Ge Tracking Array

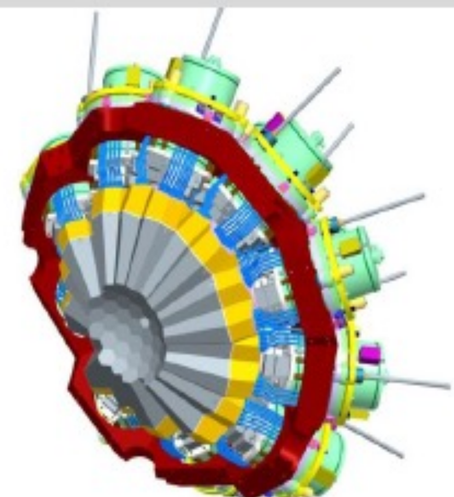
$\varepsilon_{ph}$ **~ 50%**
$N_{det}$ ~ 100

$\Omega$ ~ 80%
$\theta$ **~ 1°**



Combination of:

- segmented detectors
- digital electronics
- pulse processing
- tracking the γ-rays



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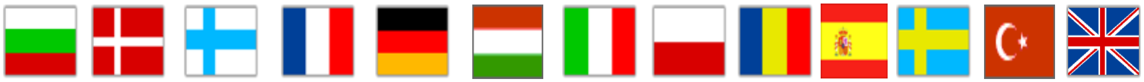
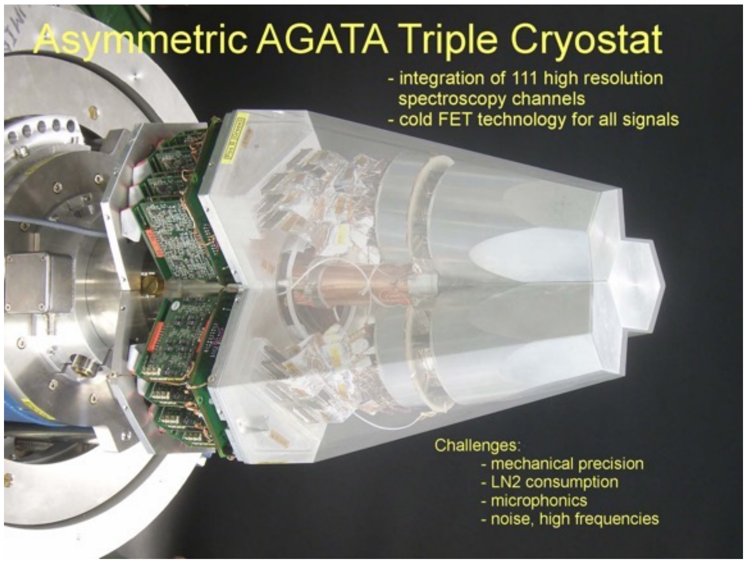
# What is AGATA?

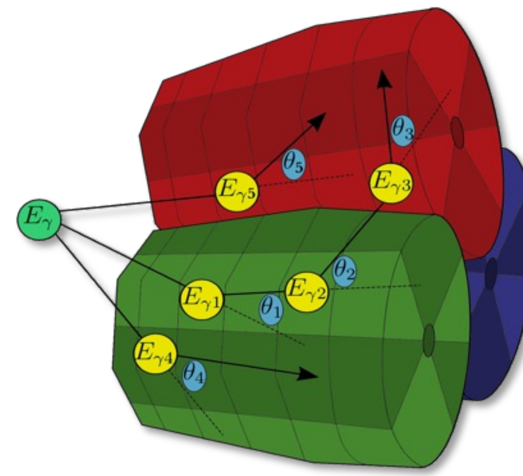


**13 Countries, > 40 Institutions**

AGATA Definition: NIM A 668 (2012) 26




- **Solid Sphere of Ge material: Solid angle coverage ~ 82 %**
- **36-fold segmentation of crystal**
- **Track each gamma interaction through the crystal**
- **Reconstruct and disentangle gammas**




| | | |
|---|---|---|
| Rates | 3 MHz (Mγ= 1) | 300 kHz (Mγ= 30) |
| Efficiency | 43% (Mγ= 1) | 28% (Mγ = 30) |
| Peak/Total | 58% (Mγ= 1) | 49% (Mγ = 30) |
| Angular Resolution | ~1° | |
| FWHM (1MeV), v/c = 50% | ~6keV | |

| | |
|---|---|
| **180 hexagonal crystals:** | **3 shapes** |
| **3 fold clusters (cold FET):** | **60 all equal** |
| **Inner radius (Ge):** | **23.5 cm** |
| **Amount of germanium:** | **362 kg** |
| **36-fold segmentation** | **6480 segments** |

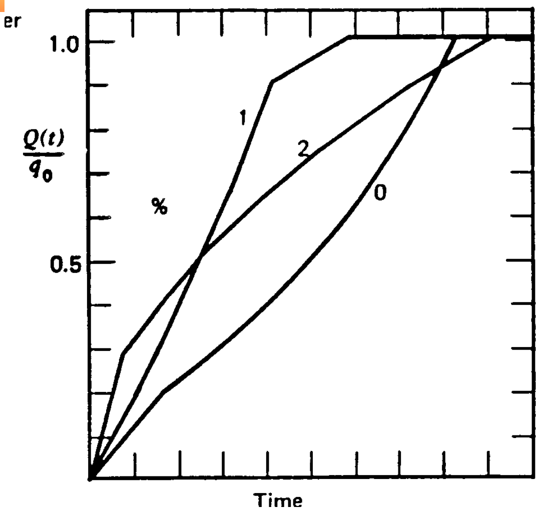
AGATA ADVANCED GAMMA TRACKING ARRAY

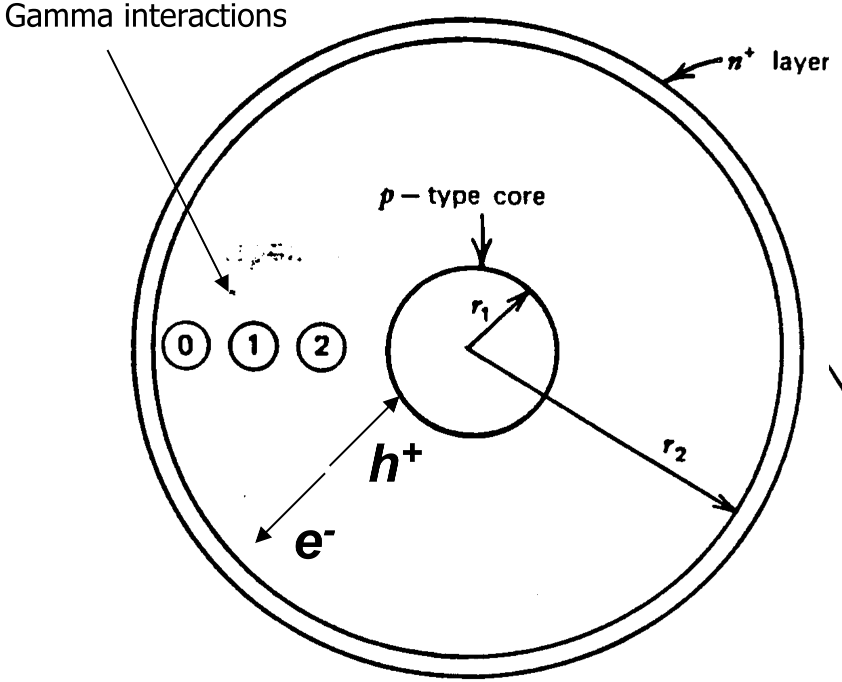
IPHC Institut Pluridisciplinaire Hubert Curien Strasbourg

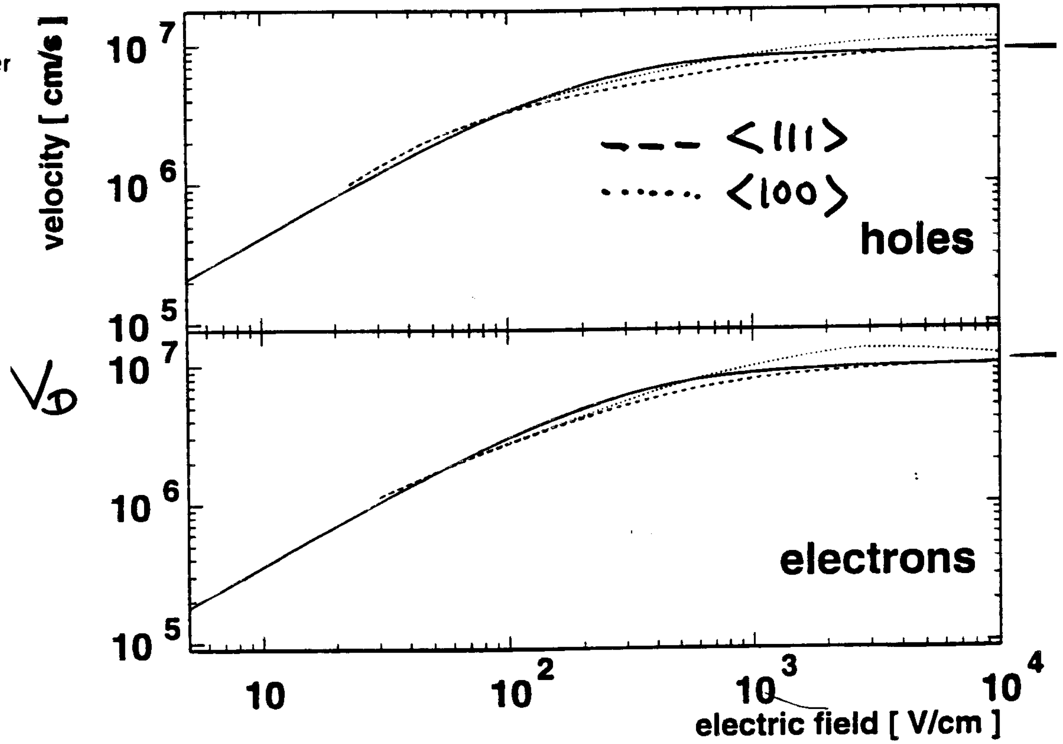
Dr Helen Boston

# signal formation in Ge-HP

## Cylindrical geometry

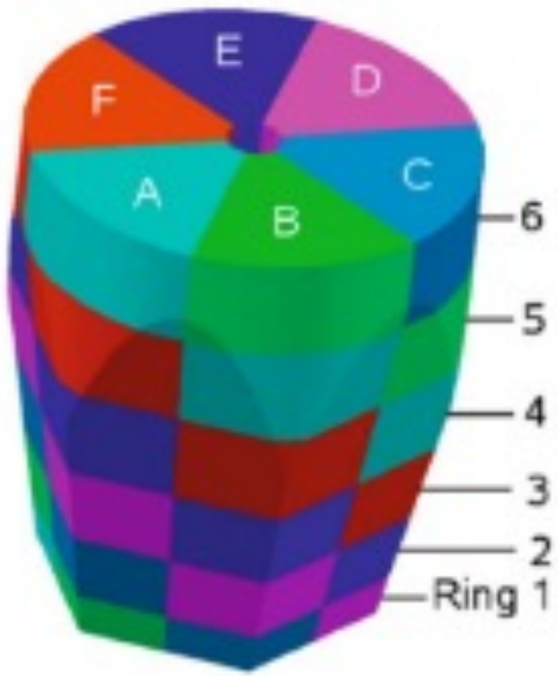


# Segmentation of High Purity Ge crystal

**Divide the electrodes on the surface of the detector**




**Weighting field shows how the segmentation works**

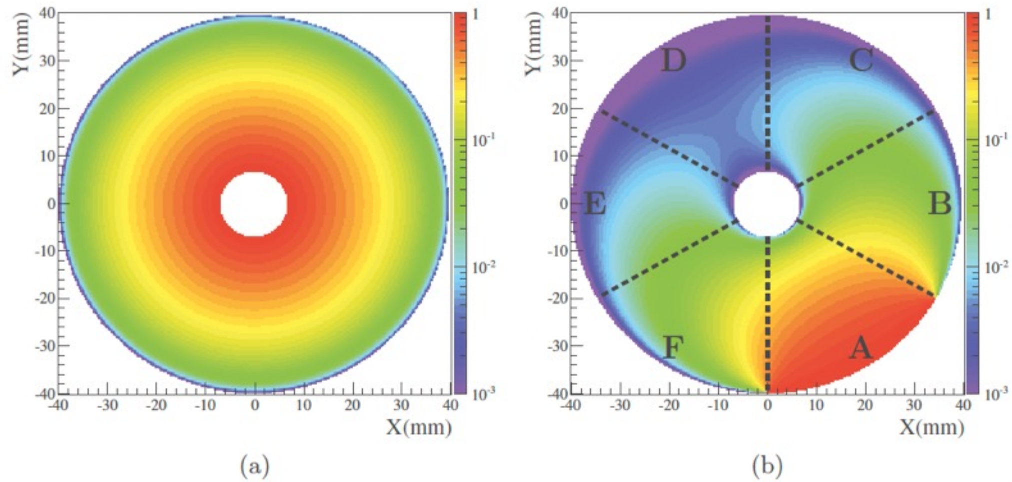



Figure 2.2: Weighting-potential distributions of the Core (a) and of segment A (b). Calculation conditions are the following: readout electrode at unit potential, all other electrode at zero potential, no space charge inside the material.

$$Q(t) = -q \cdot [\phi_w(x_h(t)) - \phi_w(x_e(t))]$$

$$i(t) = q \cdot [E_w(x_h(t)) \cdot v_h(t) - E_w(x_e(t)) \cdot v_e(t)]$$

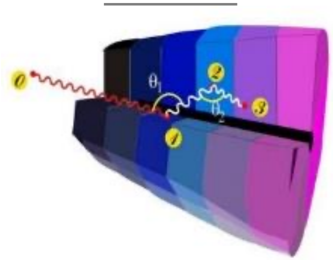
$\phi_w$ and $E_w$ are the weighting potential and the weighting field.

Michaël Ginsz, PhD thesis 2017

# AGATA Tracking Concept

1
Highly segmented
HPGe detectors

γ



2
Digital
electronics
to record and
process signals

3

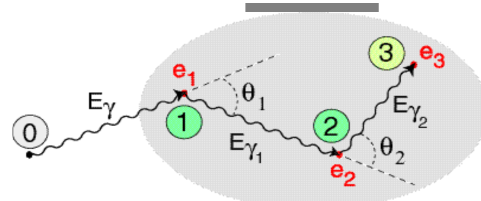
Pulse Shape Analysis
to decompose
recorded waves

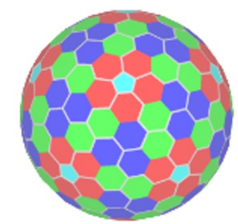
$(x,y,z,E,t)_i$

Identified
interaction points

4

Evaluation of
permutations of
interaction points

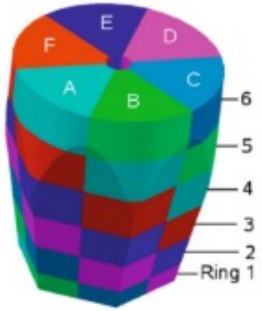


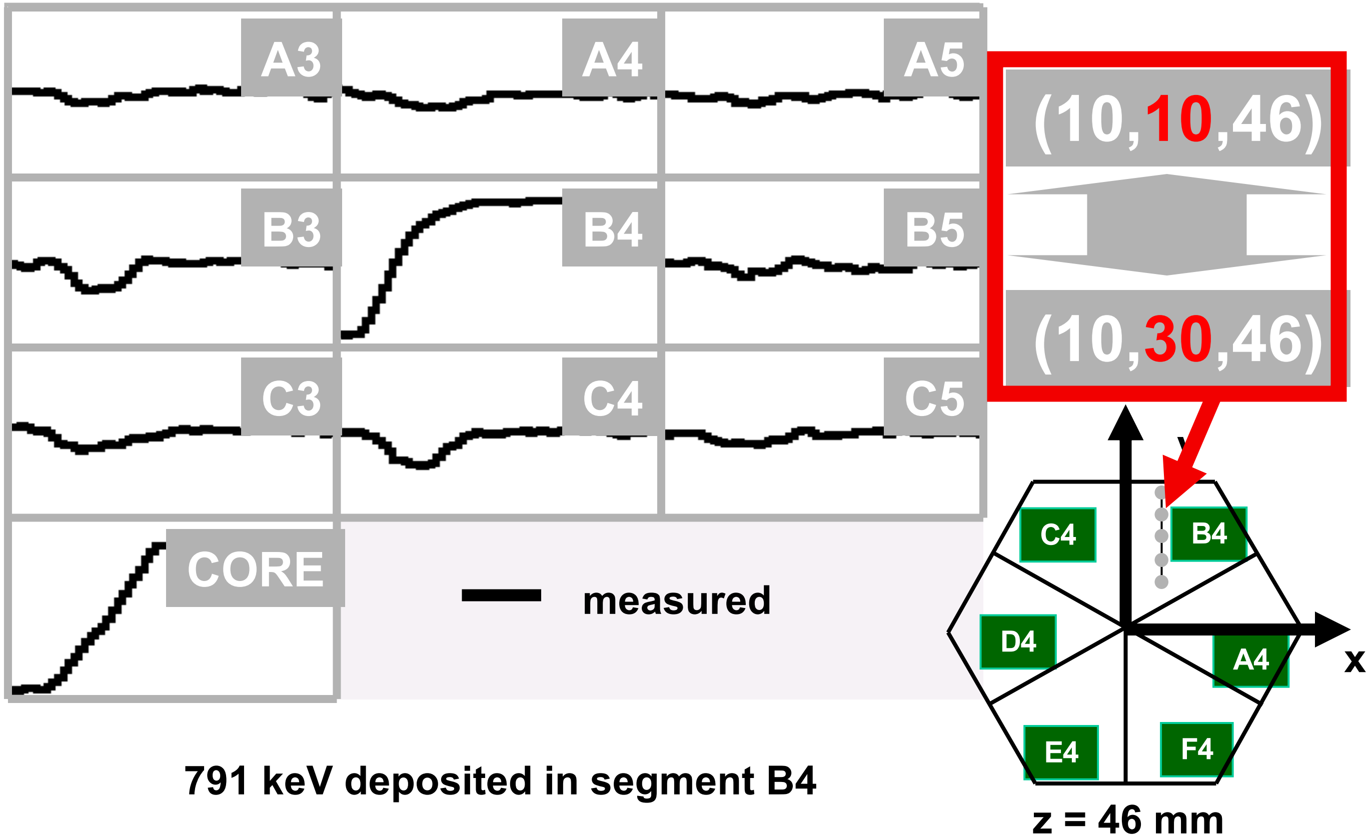



Reconstructed γ rays

Ulrich.Goerlach@iphc.cnrs.fr, ASP Particle detectors

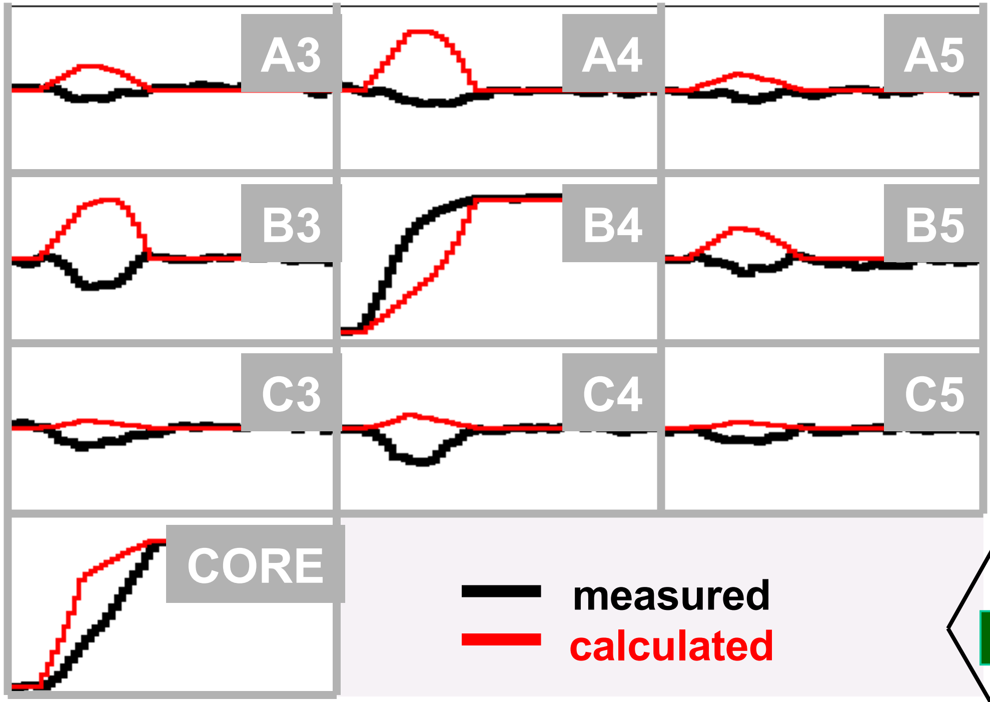
# Pulse Shape Analysis Concept



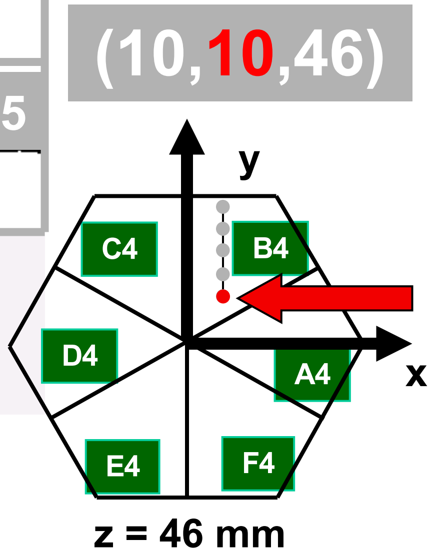

791 keV deposited in segment B4

# Pulse Shape Analysis Concept

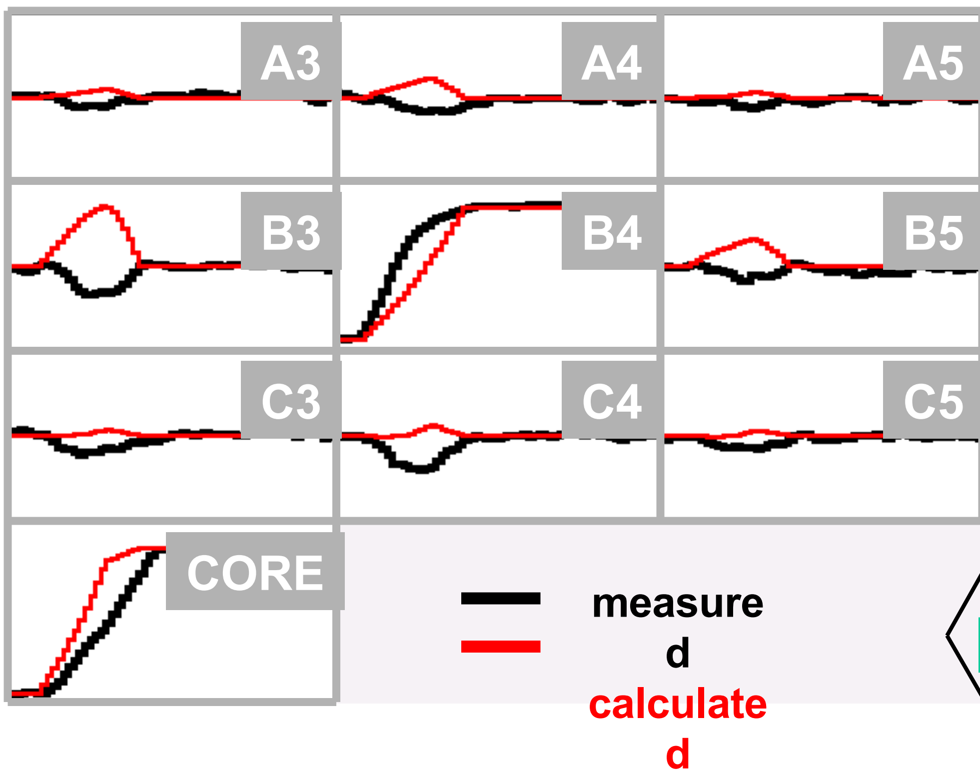



791 keV deposited in segment B4

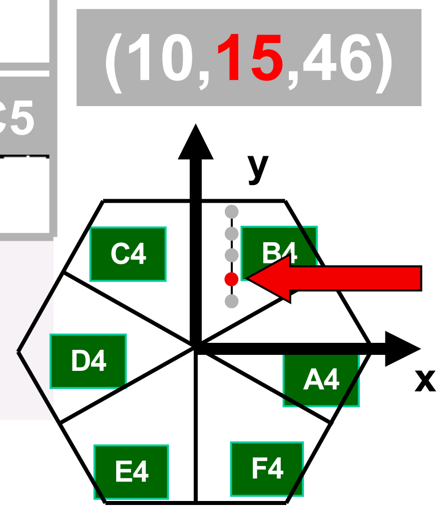
**Calculated from Electric field simulation**



# Pulse Shape Analysis Concept




791 keV deposited in segment B4




z = 46 mm

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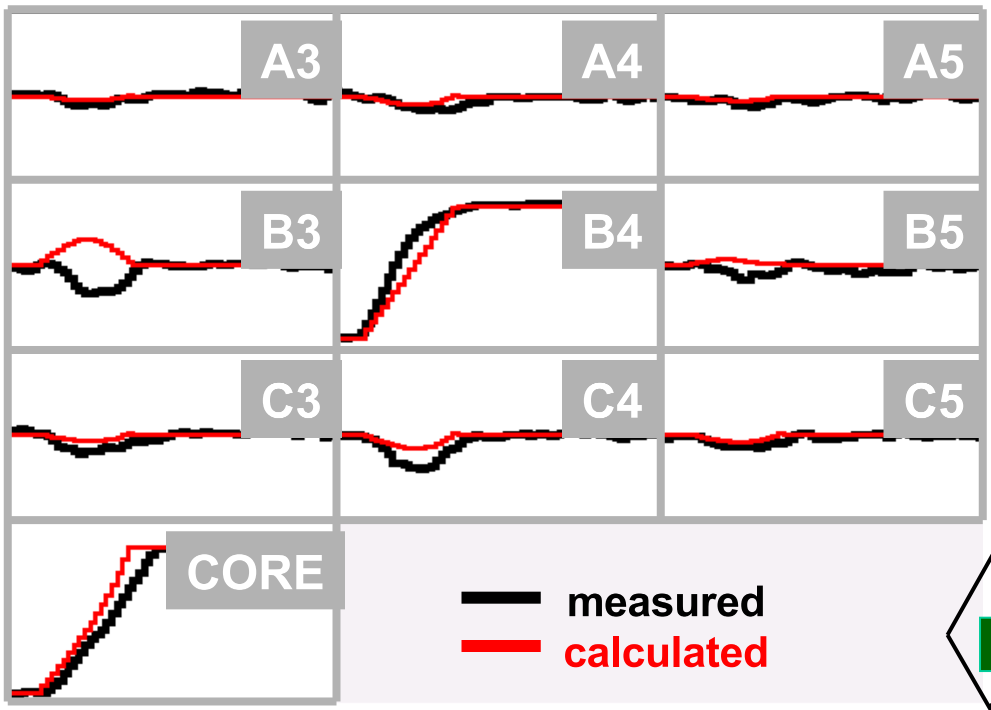
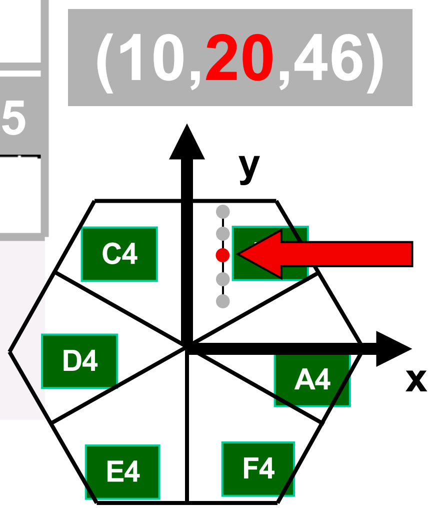
# Pulse Shape Analysis Concept

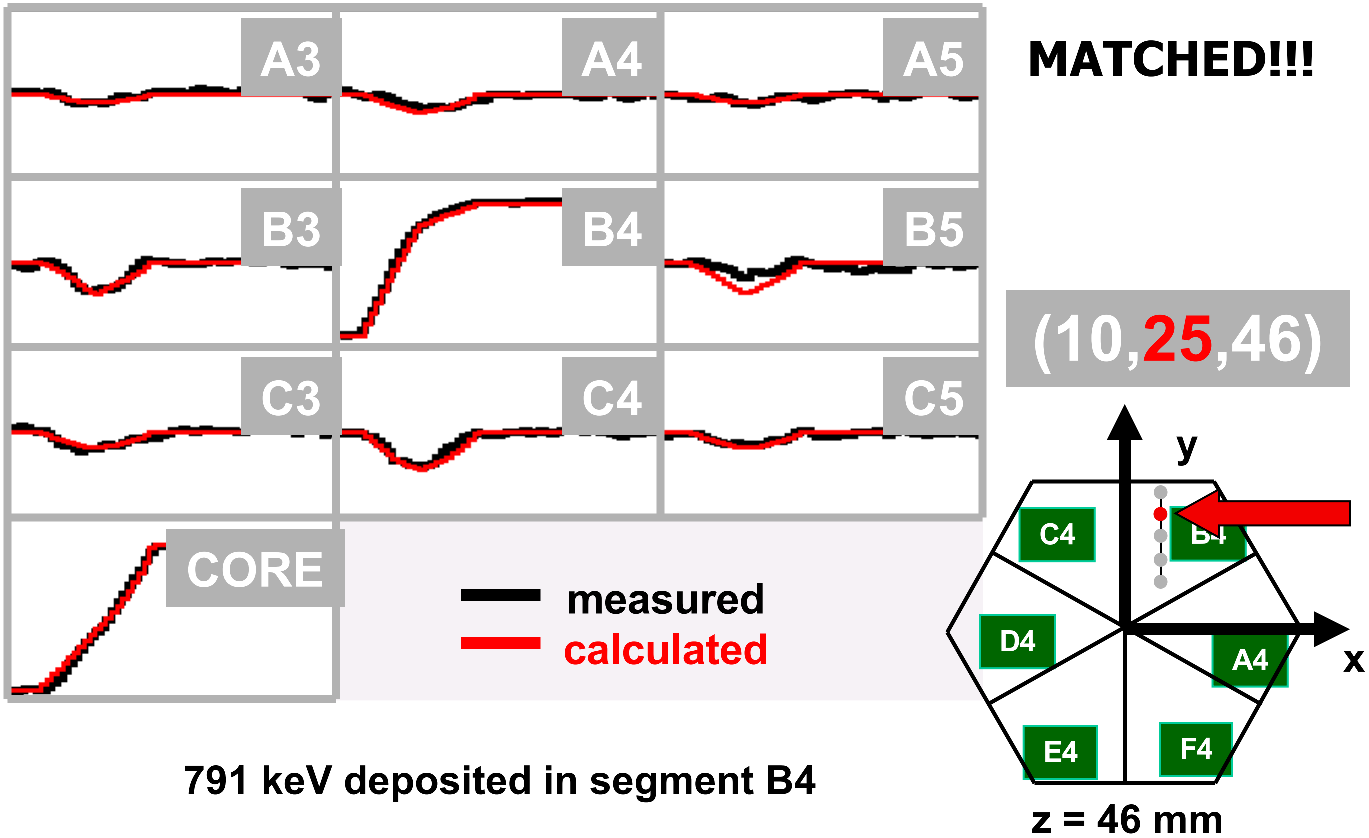



791 keV deposited in segment B4



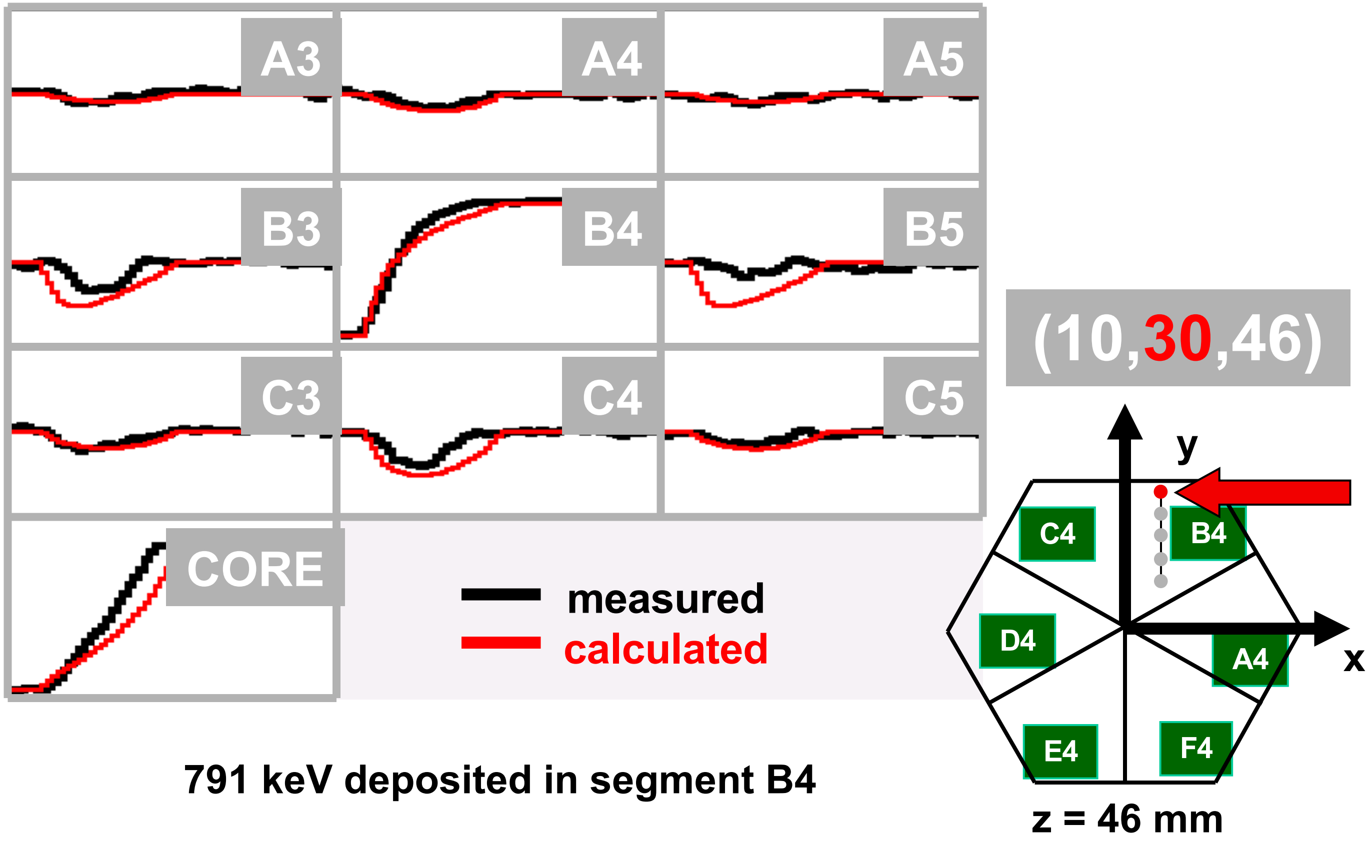

z = 46 mm

# Pulse Shape Analysis Concept




791 keV deposited in segment B4

# Pulse Shape Analysis Concept




791 keV deposited in segment B4

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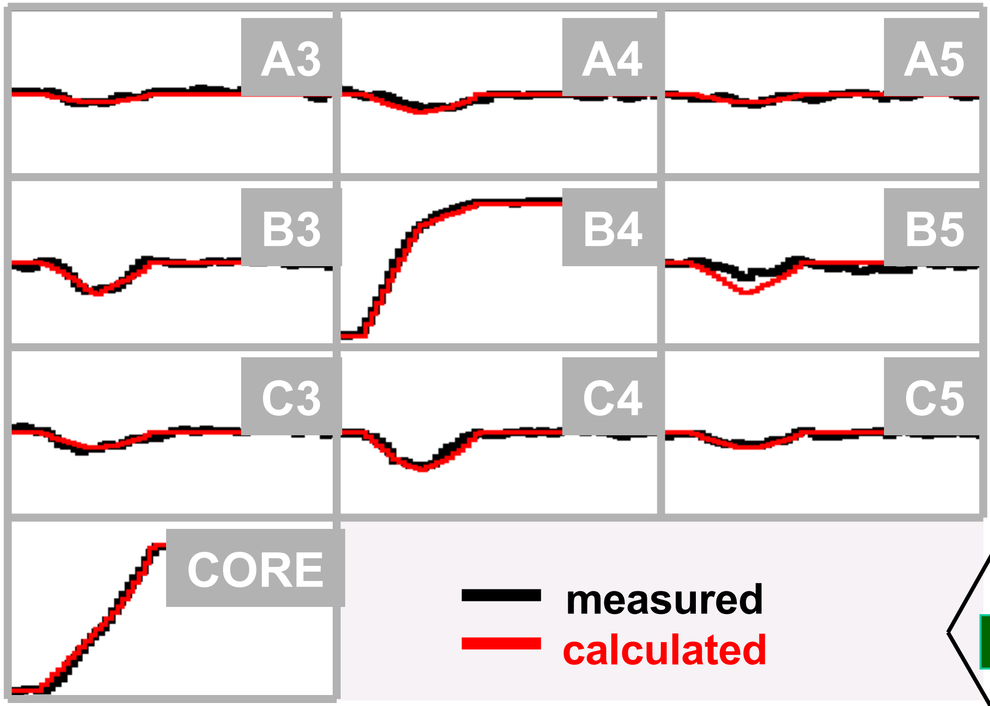
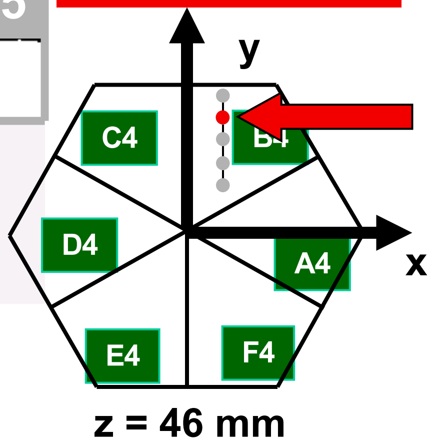
# Pulse Shape Analysis Concept




**Result of *Grid Search* algorithm**

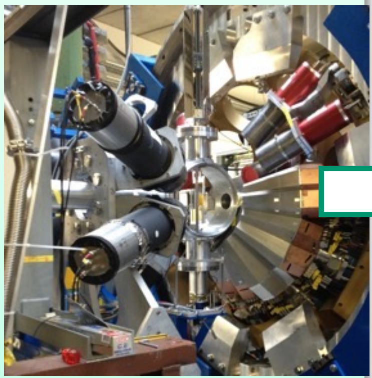
**(10,25,46)**




**791 keV deposited in segment B4**

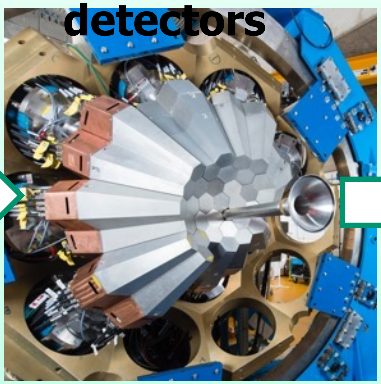
# Evolution of AGATA

**2012-2014**
**GSI, Germany**
**~25 detectors**



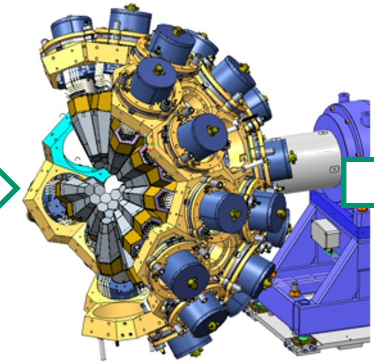
**AGATA at GSI**

**2014-2021**
**GANIL, France**
**45 -> detectors**



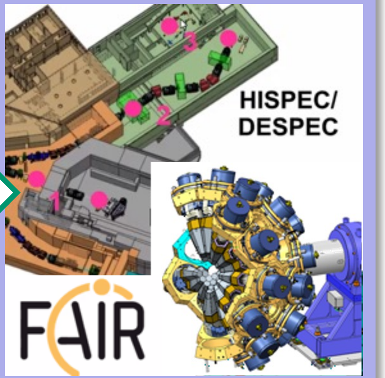
**AGATA at GANIL**

**2021-2024**
**Legnaro, Italy**
**60 -> detectors**



**AGATA at LNL**

**2025 ->**
**FAIR, Germany**
**80-90 detectors**




**AGATA at NUSTAR**

**Reaccelerated RIBs:**
- **Coulomb Excitation, Direct Reactions, Deep Inelastic, Fusion**
- **Direct and inverse kinematics $\beta$ ~ 10%**

**In-flight RIBs:**
- **Relativistic Coulomb Excitation, Knockout, Fragmentation.**
- **$\beta$ ~ 50%**

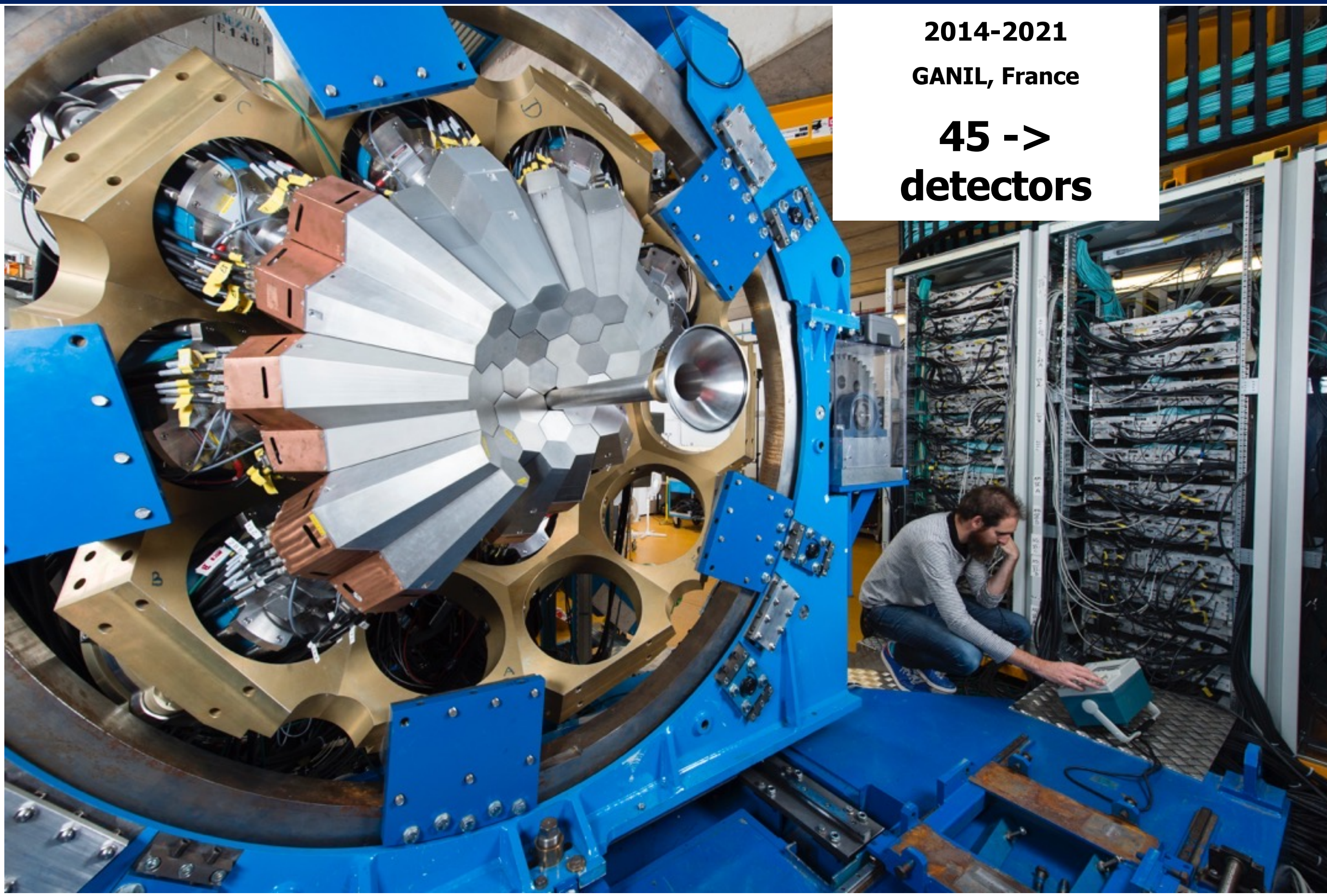
They had about 60 detectors for AGATA by end 2023

# Evolution of AGATA

**2014-2021**

**GANIL, France**

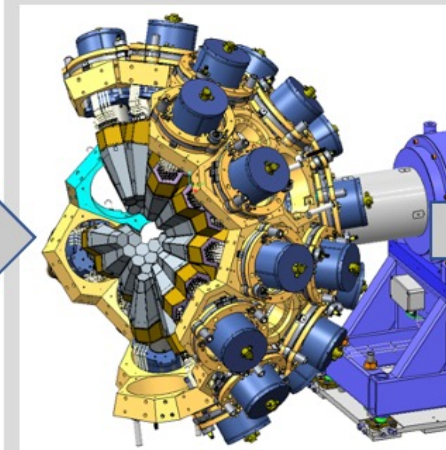
**45 -> detectors**



**2021-2024**

**Legnaro, Italy**

**60 -> detectors**



AGATA at LNL

# Conclusions
## (nuclear detectors)

- **High Z Scintillators are used for gamma spectroscopy, particular for anti Compton spectrometers**
- **Low Z (organic)-Scintillators used for particle detection/stopping**
- **Semiconductors: Si used for charged particle spectroscopy (alpha, protons, ... Fission fragments)**
- **Semiconductors: HP-Ge for high resolution and high efficient Gamma spectroscopy**

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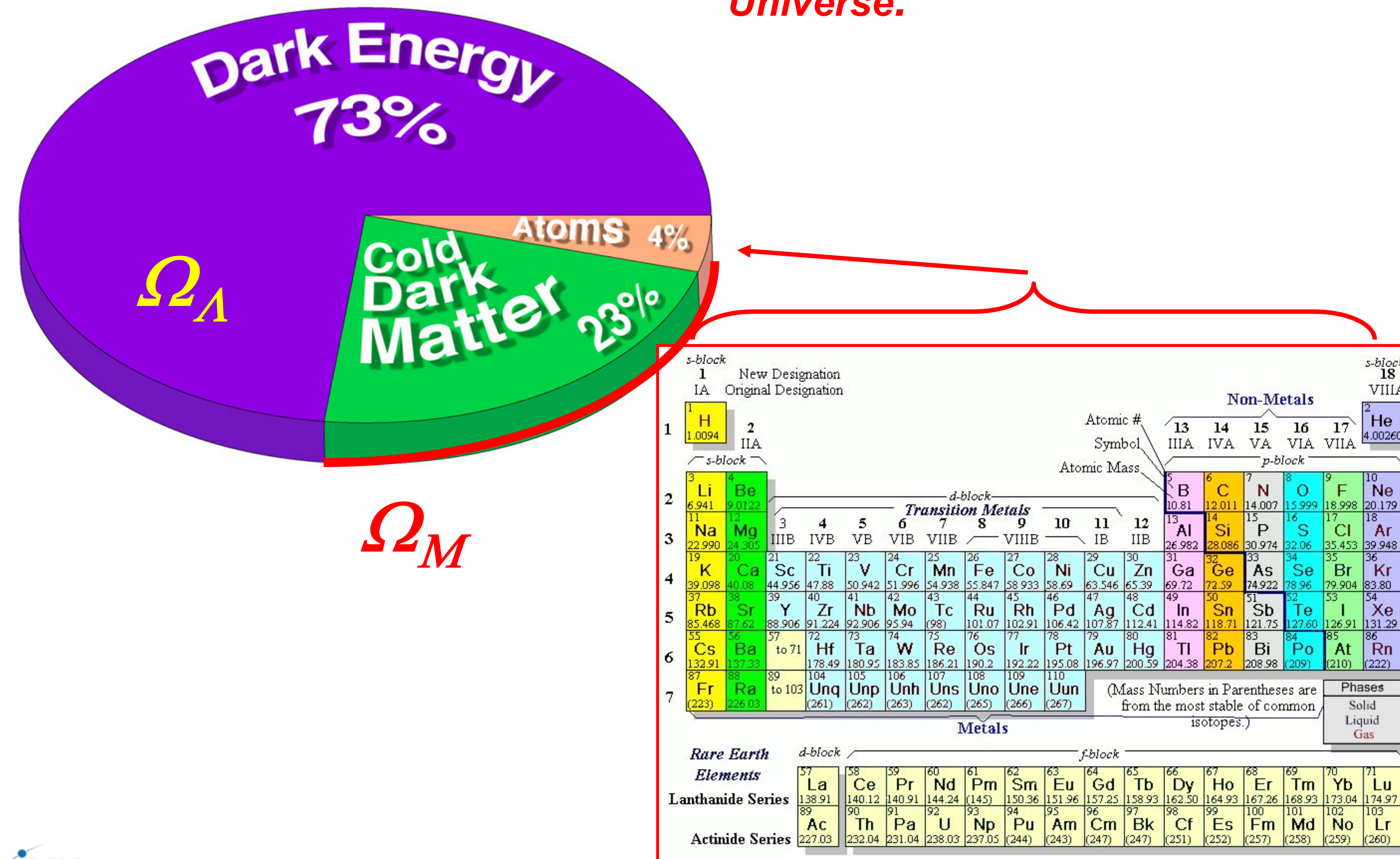
# We (and all of chemistry) are a small minority in the Universe.

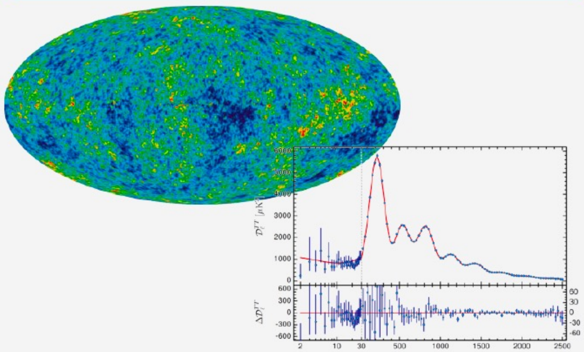


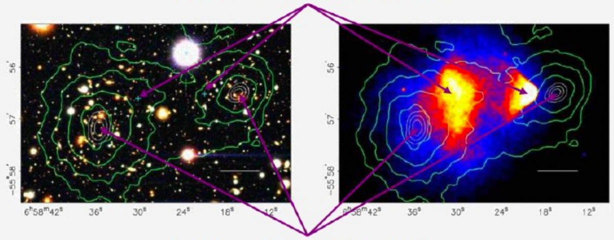
Ulrich.Goerlach@iphc.cnrs.fr, ASP Particle detectors

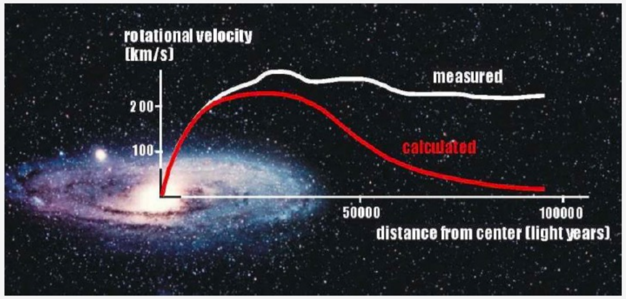
# Dark Matter ?

## Dark Matter Evidence

**Cosmic Microwave Background** | **Bullet Cluster** | **Rotation curves**





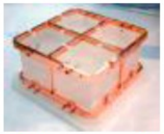

… non-atomic (if not PBH) – non-luminous – stable – neutral – massive – non-relativistic …

… **Axions / ALPs** ~meV | **Sterile $\nu$** ~keV | **WIMPs** ~GeV | **Primordial Black Holes** …

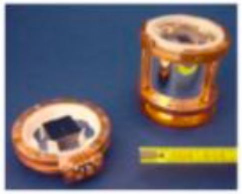
mass →

# Direct Dark Matter Search Modalities

CRESST-I, CUORICINO



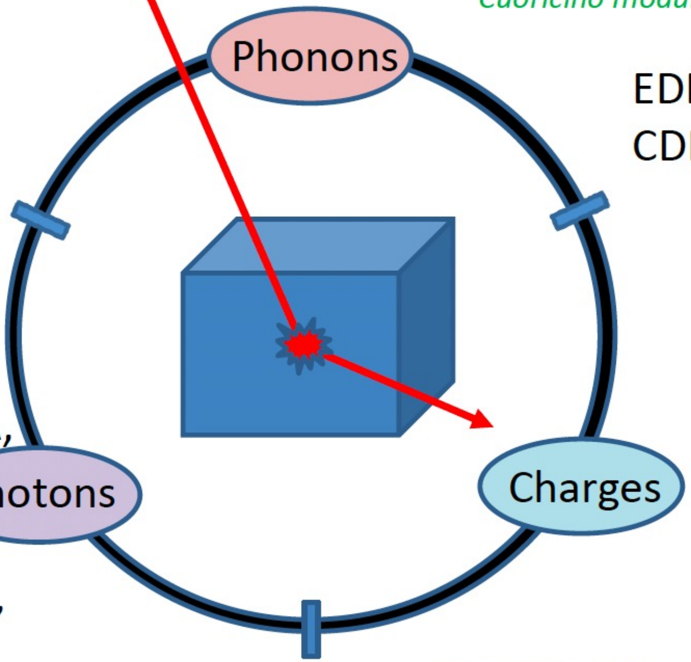
*Cuoricino module*



CRESST-II

EDELWEISS
CDMS

*CDMS module*



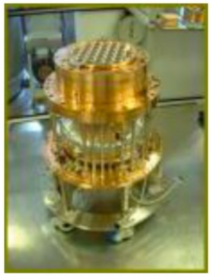


*XMASS*

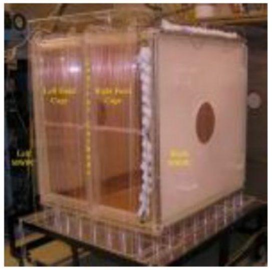
DAMA/LIBRA,
KIMS,
XMASS,
DEAP/CLEAN,
ZEPLIN-I

CoGeNT, DM-TPC,
DRIFT, MIMAC,
NEWAGE

ZEPLIN-II/III, **XENON**,
LUX, WARP, ArDM,
PANDA-X



*ZEPLIN-III*



*DRIFT*

# A double phase liquid xenon TPC

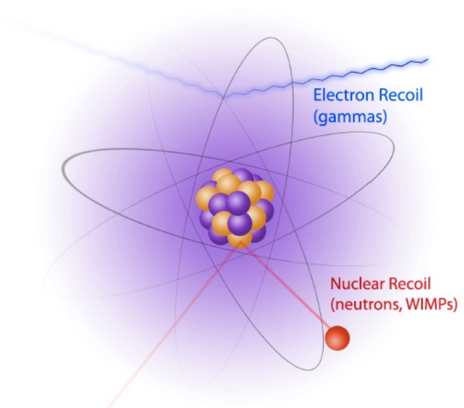
Dark Matter and Axion Searches - Belina von Krosigk

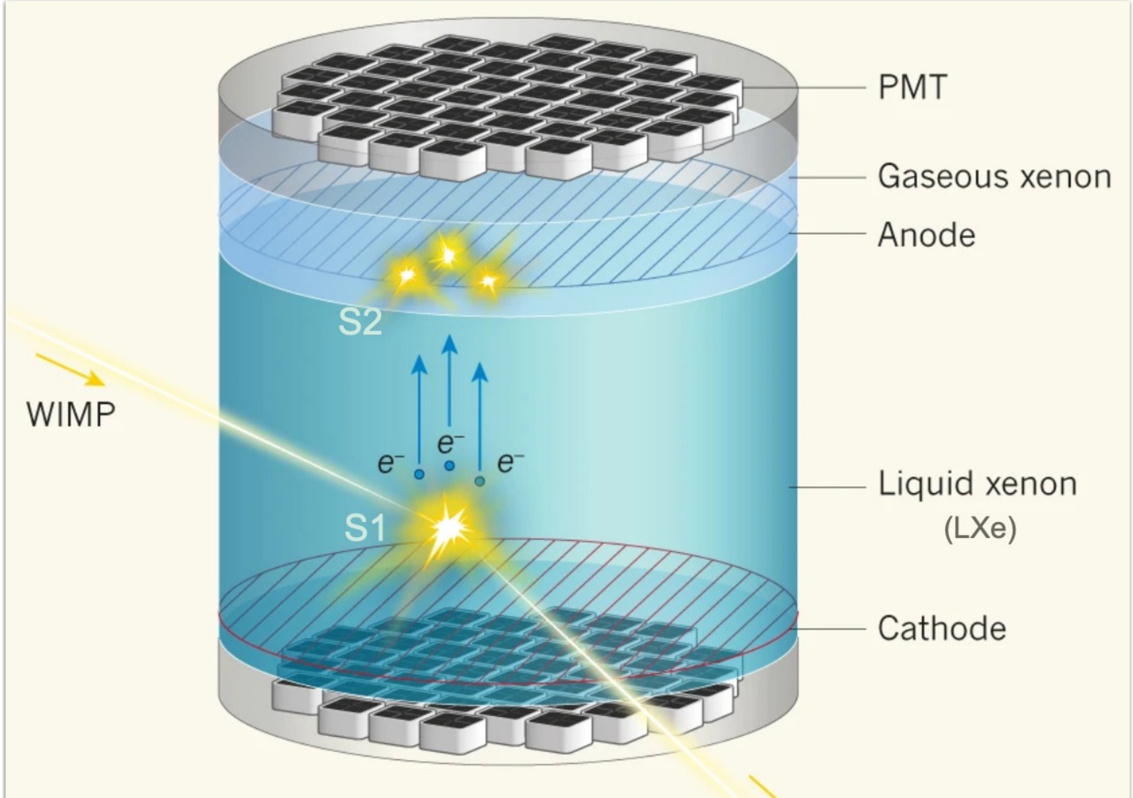
12

## Most recent results >1 GeV: LZ, XENONnT

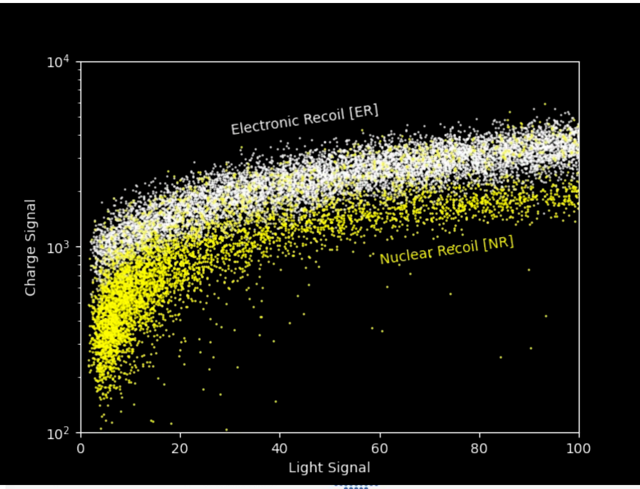
**LZ:**
5.5 t fiducial mass, LXe

**XENONnT:**
4.2 t fiducial mass, LXe



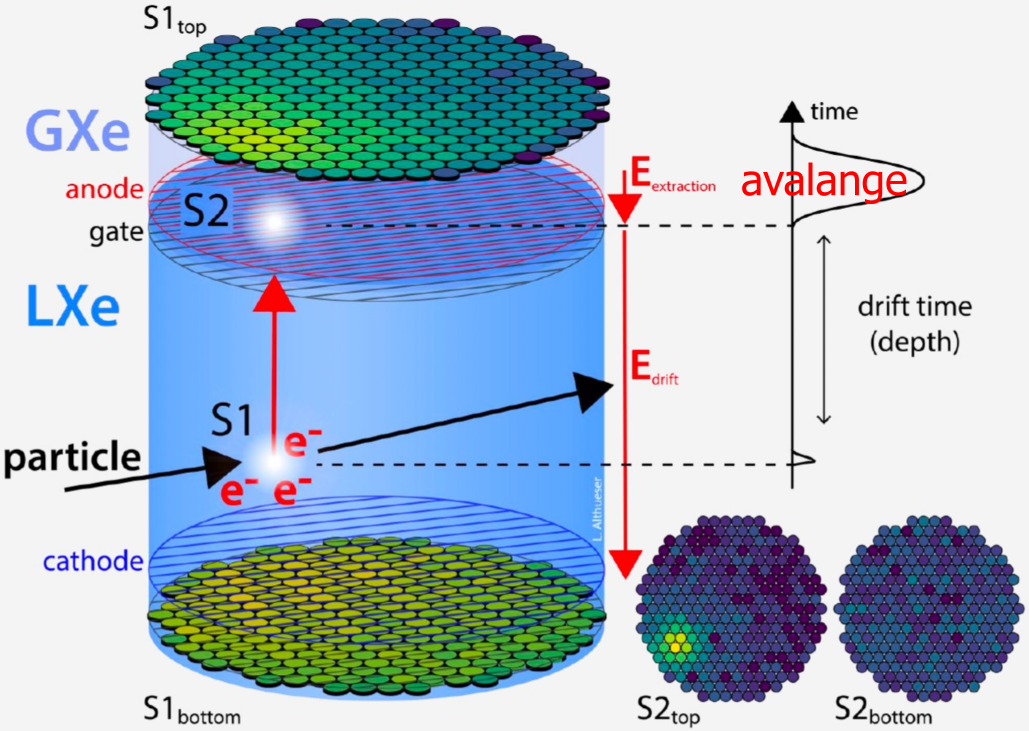

X. Ji, Nature 542, 172–173 (2017)




# A double phase liquid xenon TPC

Latest results from XENONnT

## Working Principle



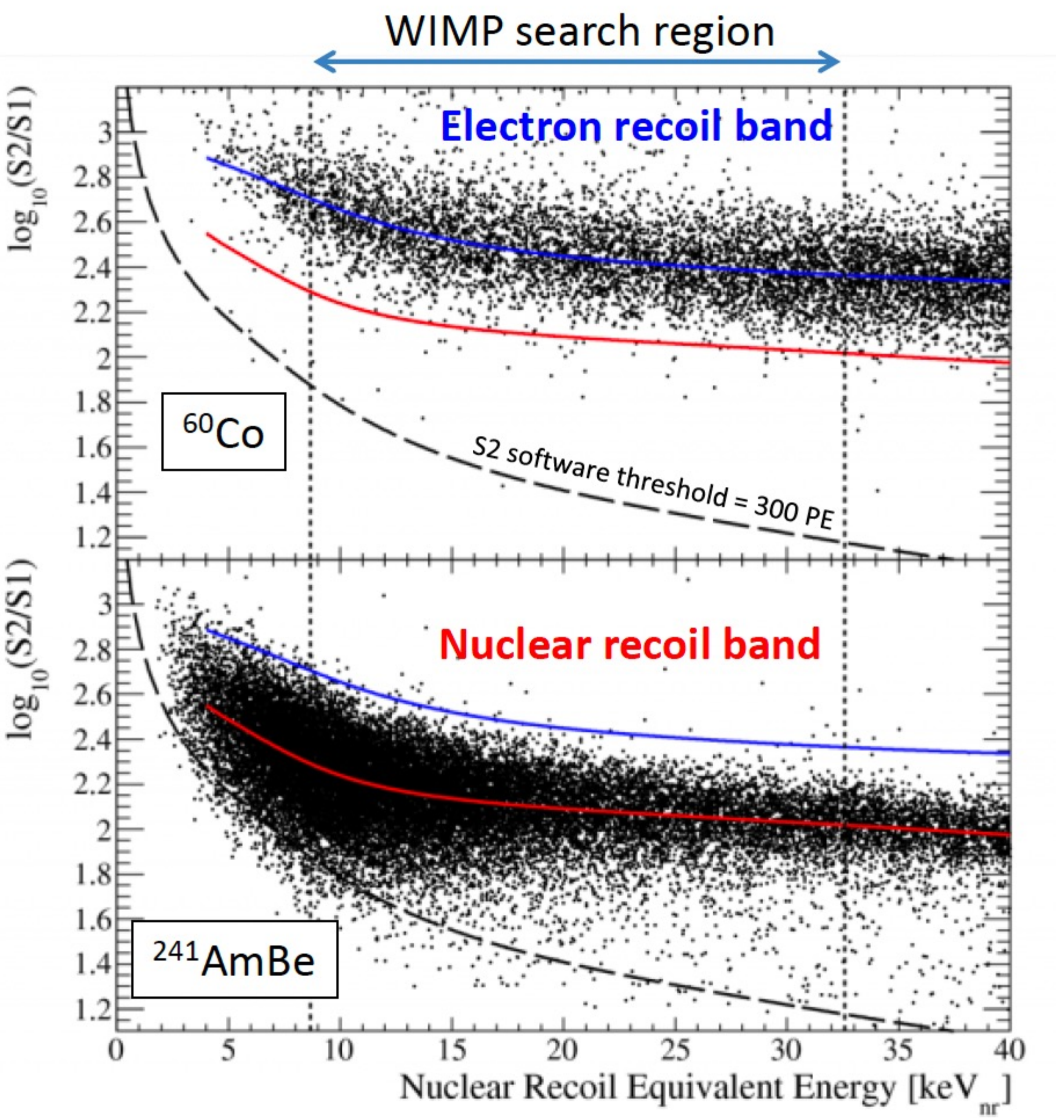

**Working principle of dual-phase liquid noble gas time projection chambers (TPCs)**

- Prompt light signal (**S1**)
- Secondary light in GXe from drifted charges (**S2**)
- Energy reconstruction using the combined S1 and S2 signal
- Position reconstruction
  - **z** from S1-S2-delay time
  - **x-y** from S2 hit pattern



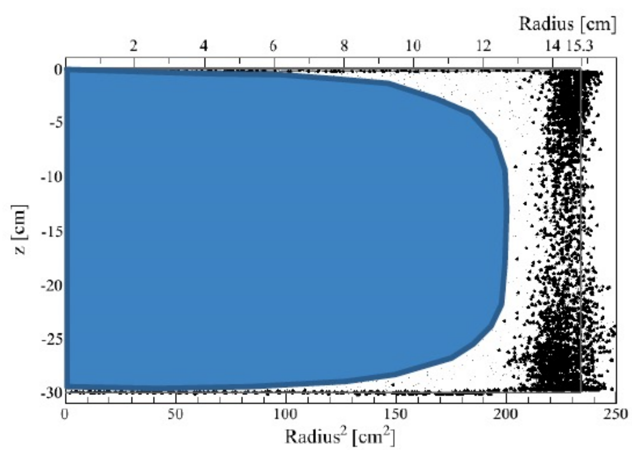
Phys. Rev. D 100, 052014 (2019)
Phys. Rev. D 99, 112009 (2019)

# Background discrimination

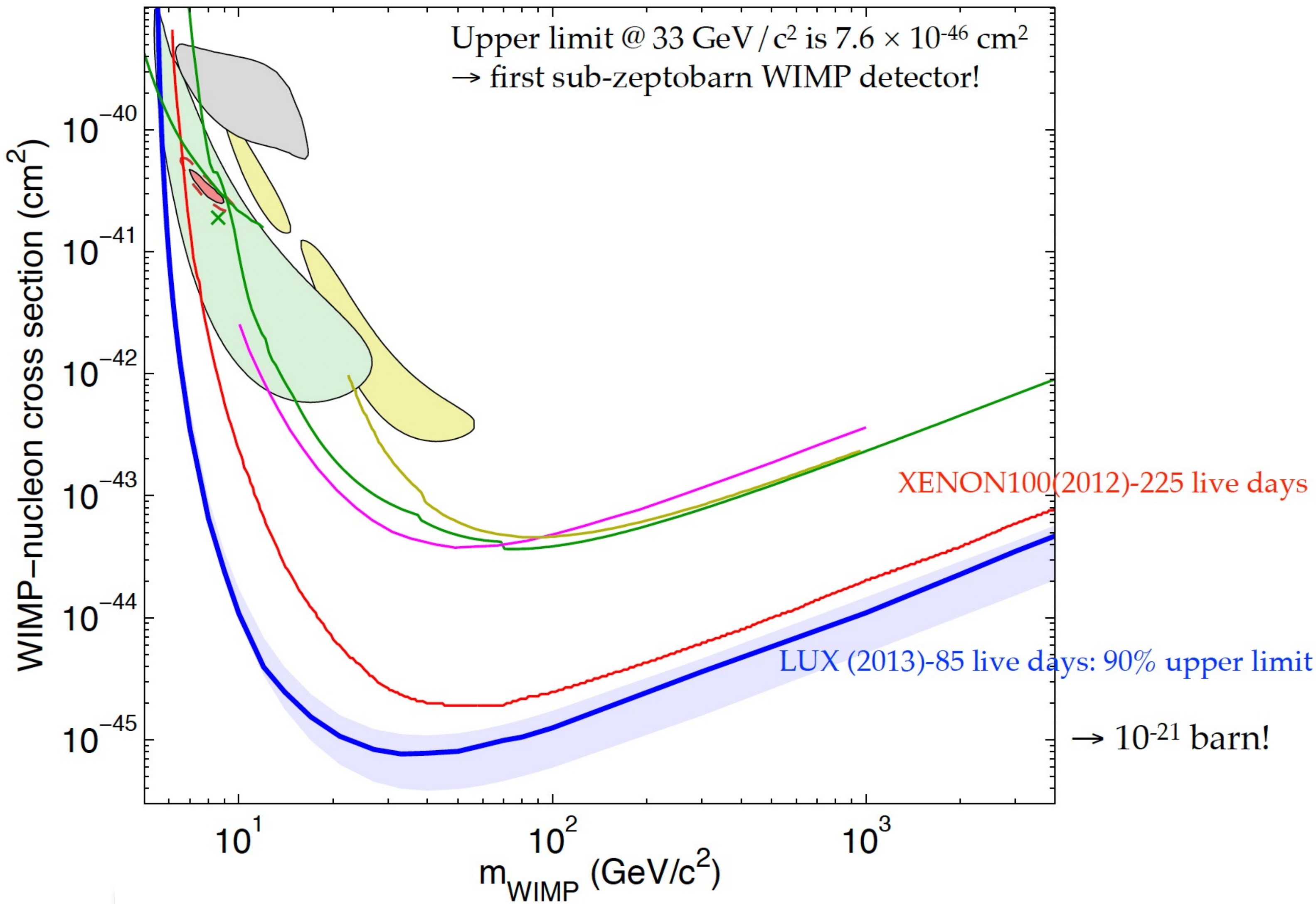


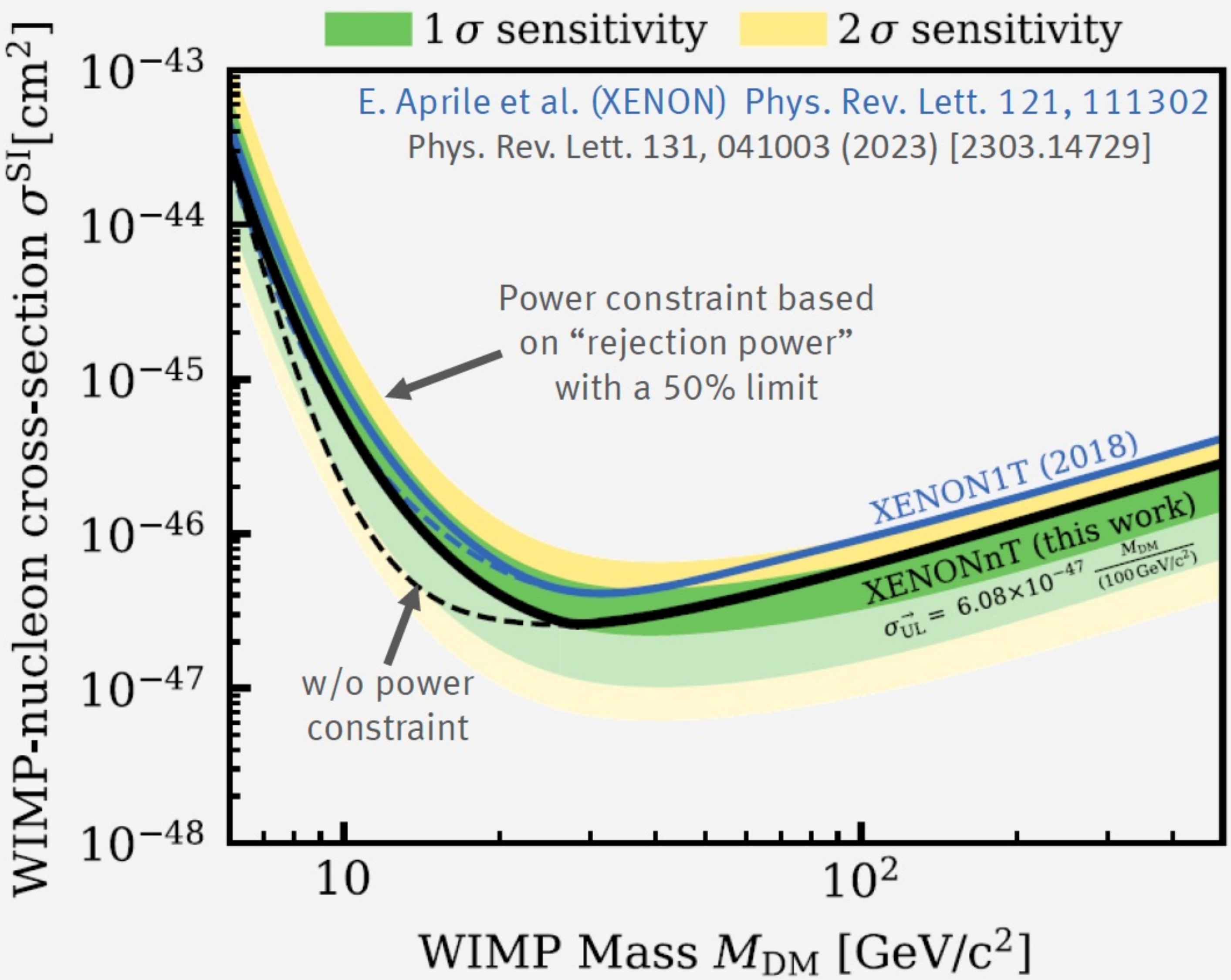

**Identification of recoil species by S2/S1 ratio**

- from $^{60}$Co $\gamma$-ray source and $^{241}$AmBe neutron source
- selecting single scattered events




*E. Aprile et al. (XENON100), Phys. Rev. Lett. 105, 131302 (2010)*


Upper limit @ 33 GeV / c² is 7.6 × 10-46 cm²
→ first sub-zeptobarn WIMP detector!
WIMP–nucleon cross section (cm²)
m_WIMP (GeV/c²)
XENON100(2012)-225 live days
LUX (2013)-85 live days: 90% upper limit
→ 10-21 barn!




Phys. Rev. Lett. 131, 041003 (2023) [2303.14729] 23

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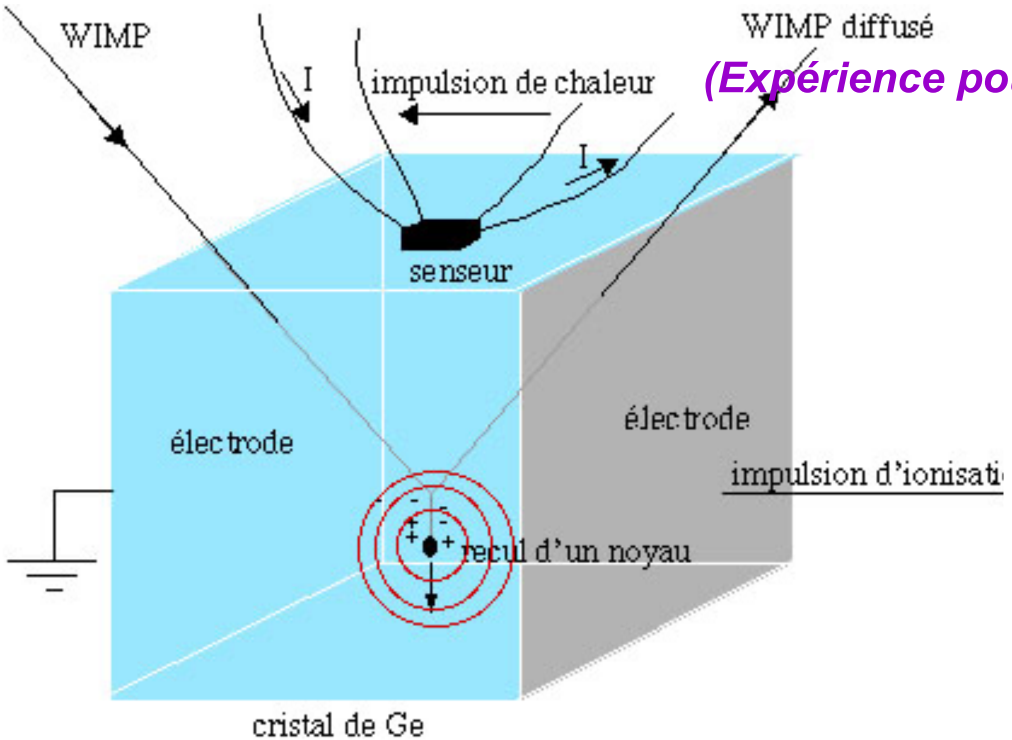
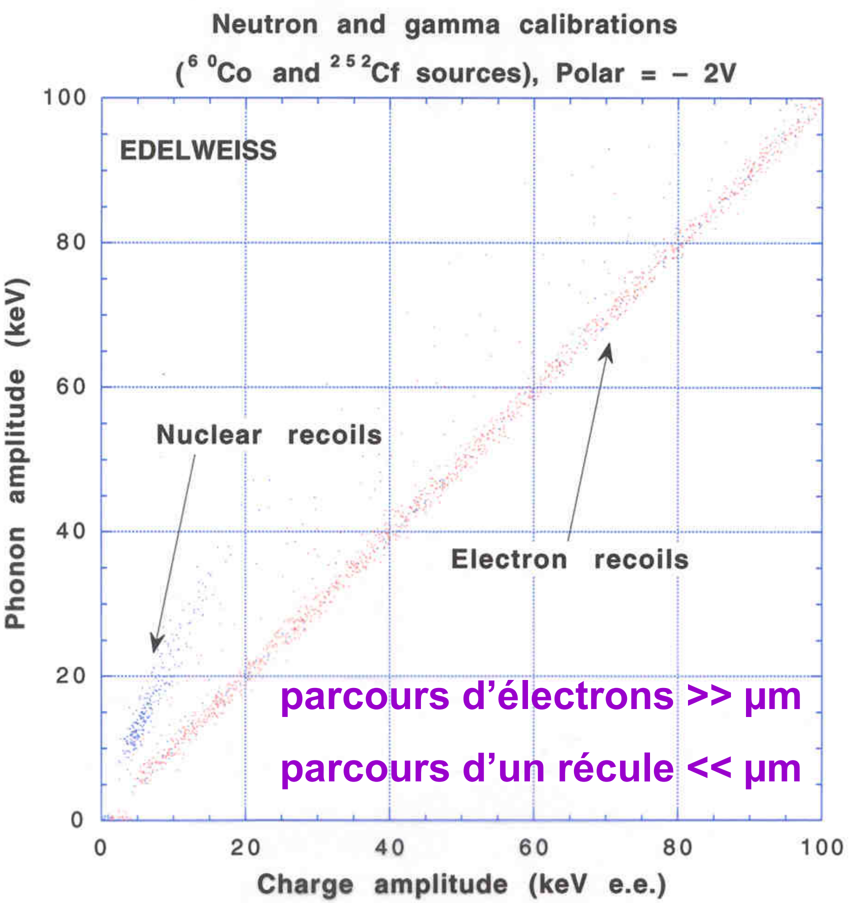
# EDELWEISS

## (Expérience pour Détecter Les Wimps en Site Souterrain)




parcours d'électrons >> µm

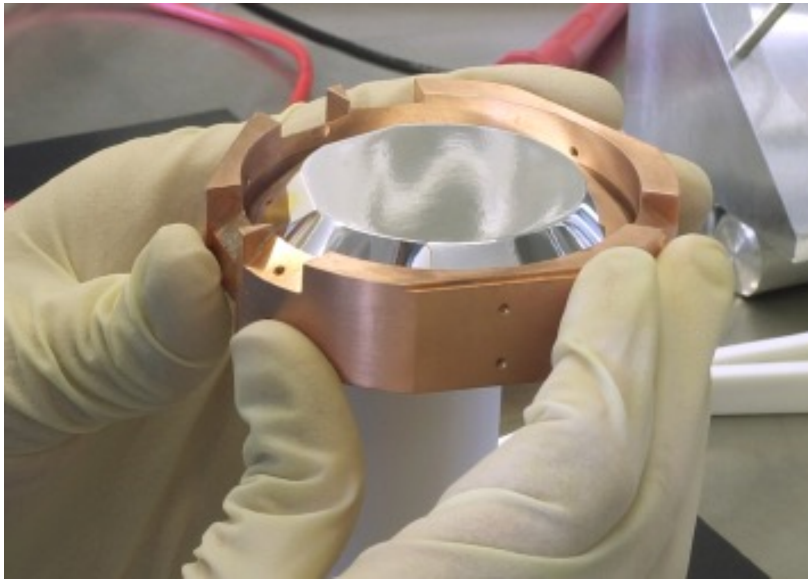
parcours d'un récule << µm

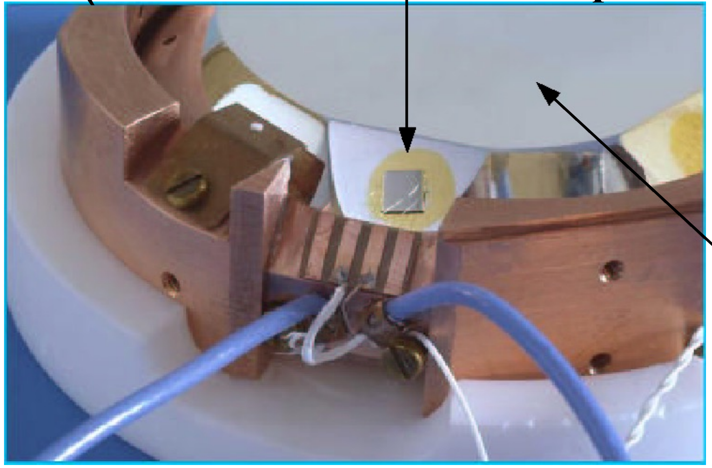
- **Ge cristals of up to 1Kg**
- **Very rare events about**

  **1 event/Kg/year**
- **Recoil of some keV**
- **Heat changes of**
  - **$\Delta T \approx$ few mK => cryostat($^3He$-$^4He$)**
  - **Operation temperatur of 10 milli-Kelvin**

IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

# Ge ionization – phonon detectors I






- bolometer mass: 320 g
- 100nm sputtered Al layer as electrode (center + guard ring)
- 60nm Ge(Si) amorphous layer below electrode
- NTD temperature sensor glued on sputtered gold pad on guard ring electrode
- electrical contacts/heat links via gold wire bonding (Ø=25μm)
- **operating temperature T=17.00±0.01mK**

# Ionisation&heat: pulses & signals

## Ge-NTD detector in EDELWEISS:

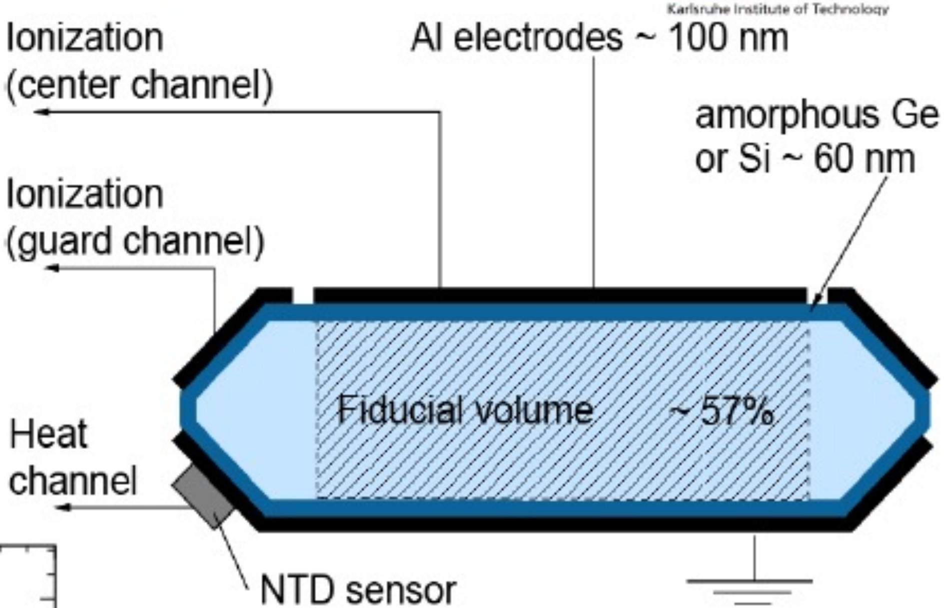
E ~ 10 $keV_{ee}$

heat: $\Delta T=1.3\mu K$; $\Delta U=1\mu V$

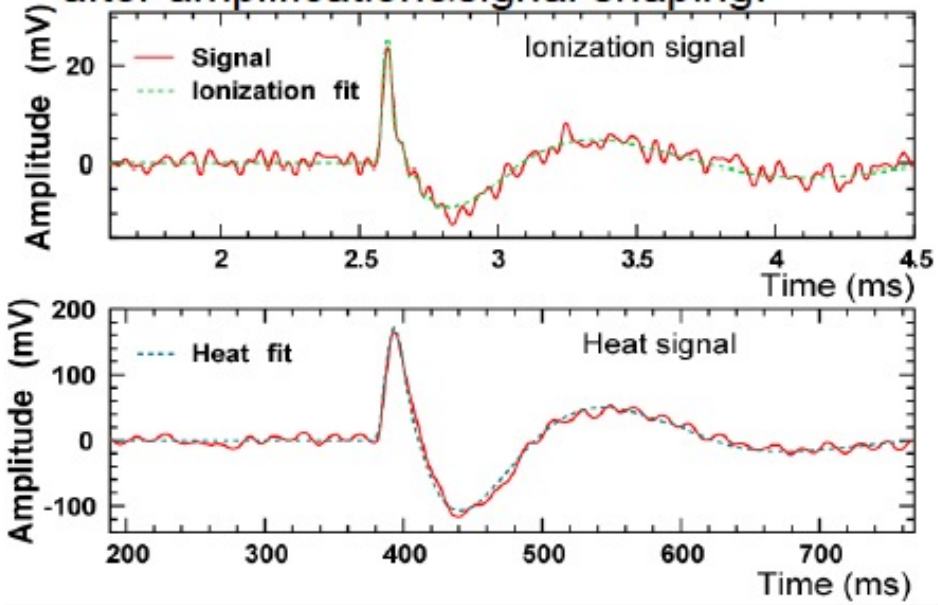
$t_{rise}$~10μs-10ms; $t_{fall}$~100ms

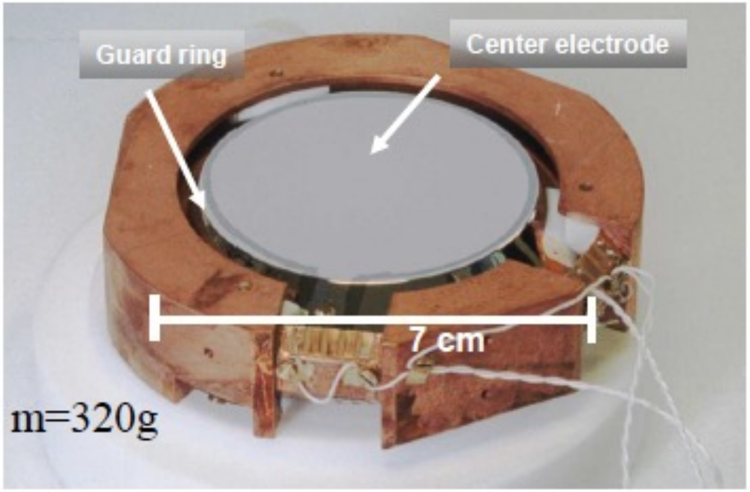
ionisation: $\Delta U=0.5mV$

$t_{rise}$~100ns-1μs; $t_{fall}$~100μs




after amplification&signal shaping:



# ionization – phonon signal plane

$^{73}$Ge(n,n' γ) 68.8 keV

13.3 keV

n/γ discrimination

> 99.9%

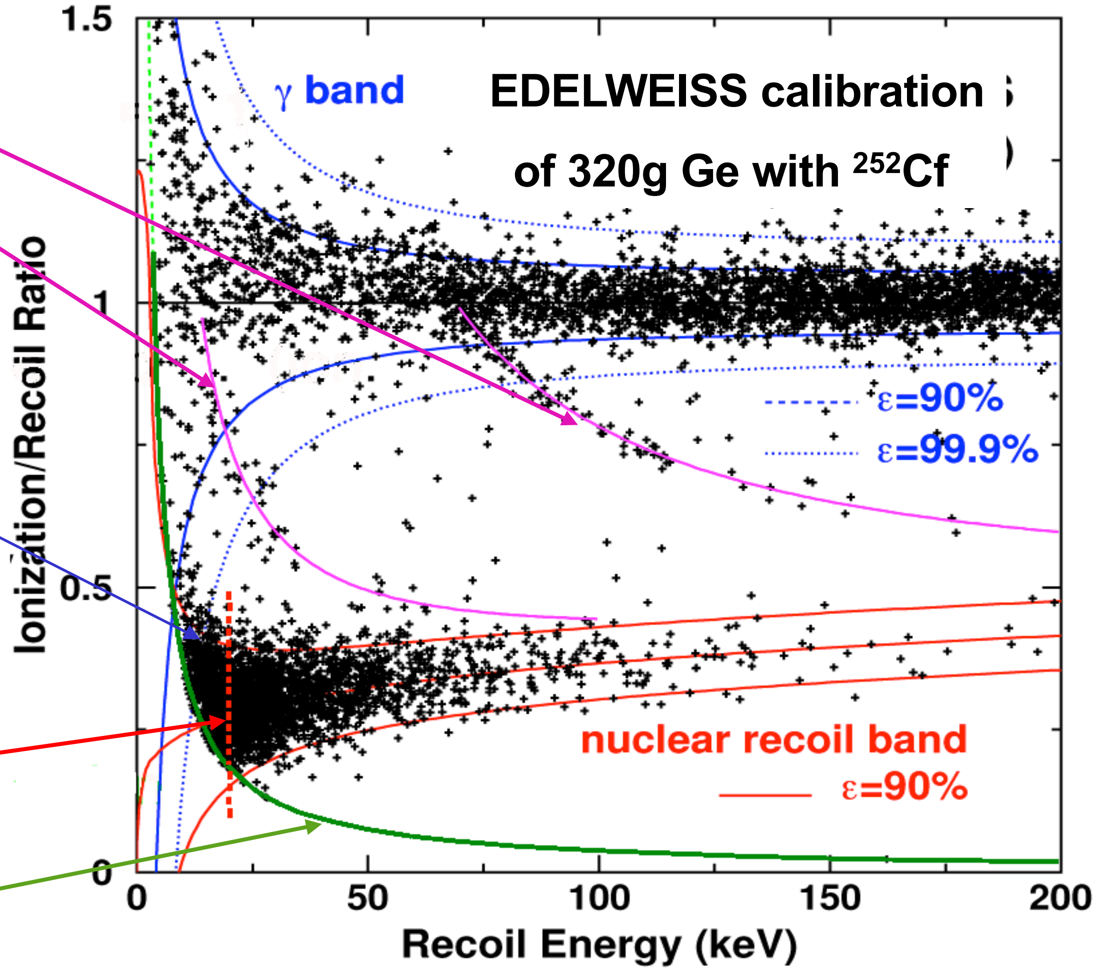
for $E_r$ >15 keV

Recoil threshold

20 keV

Ionization threshold

3.7 keV



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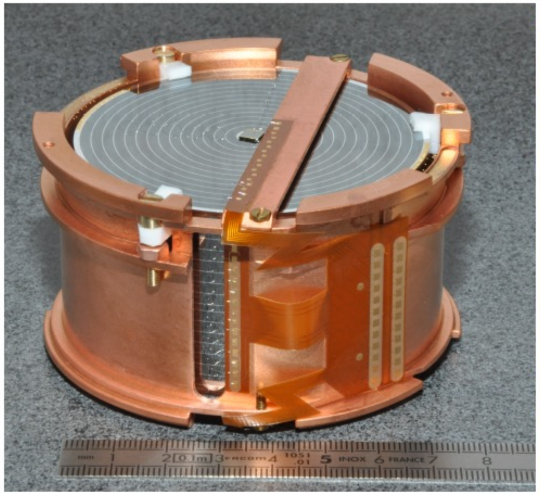
# Ex. of instrument : EDELWEISS-III




**36 * FID-800**

- **Ge 820 g**
- High impedance Ge-NTD thermometer (neutron doped Ge crystals)
- 4 sets of Al electrodes for charge collection
  - Simultaneous measurement of **ionization & heat**
  - Background active rejection

**Running 2013-2023**

- **10mK Cryostat** + 40 tons of shielding (PE + Pb) @ LSM
- **3000 coax. cables (6 km)**
- **350 Si-JFET transistors@ 120K**
- 36*2 « Bolometers Boxes » @ 300K

5

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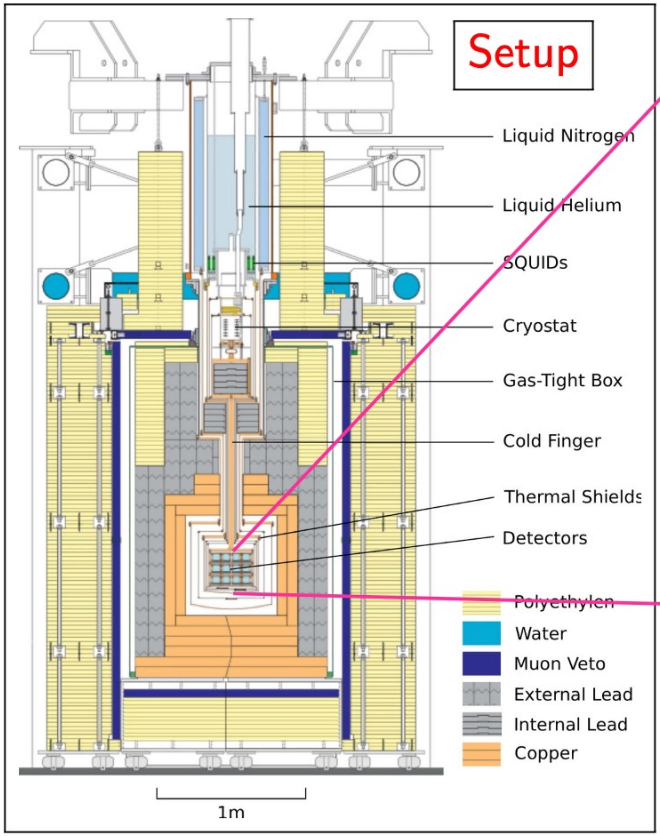
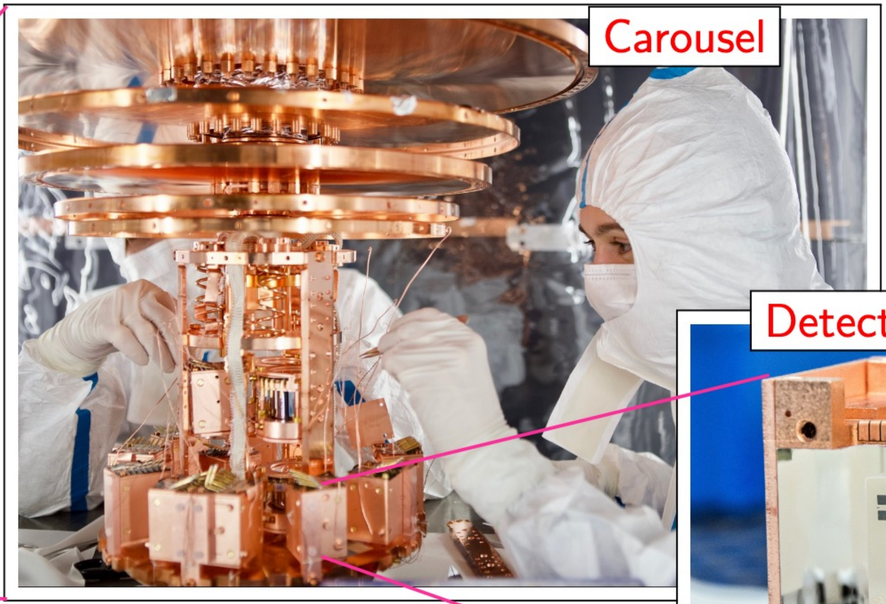
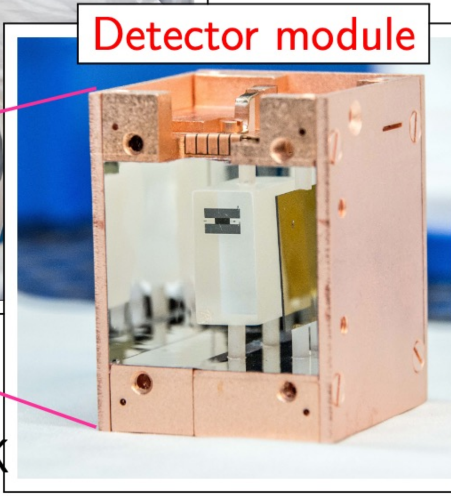
# The CRESST experiment

- Protected from backgrounds by layers of shielding (PE, Pb, Cu) and an active muon veto



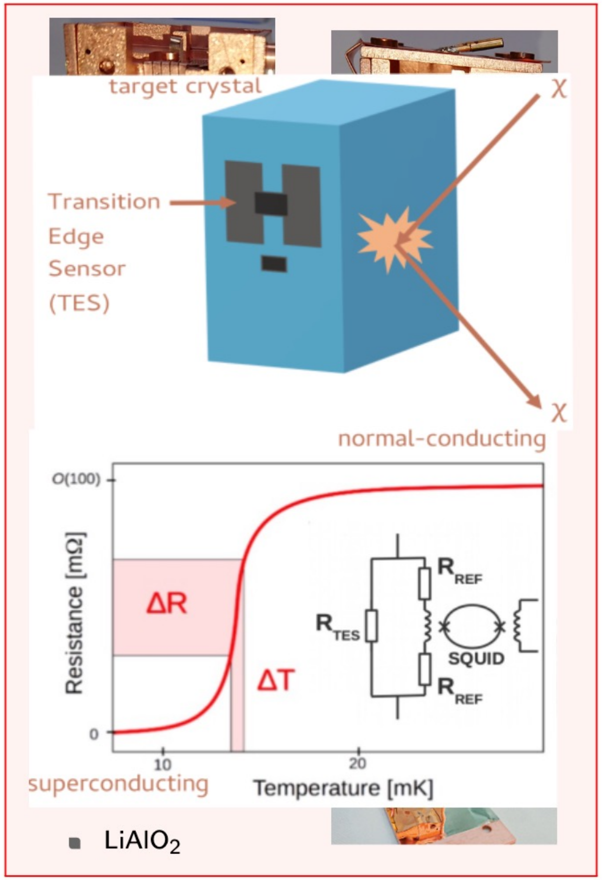




- Detector modules mounted in "carousel" and cooled to ~10 mK

# CRESST-III detectors

- Cryogenic scintillating detectors
- Measure phonon and light
- $CaWO_4$ traditionally used as target material
- **Capable of using range of target materials** ($\sim 2 \times 2 \times 1\,cm^3$): $CaWO_4$ (24 g), $Al_2O_3$ (16 g), $LiAlO_2$ (10 g), Si (9 g)
- Thin light detector ($2\times 2\times 0.04\,cm^3$): Si or silicon-on-sapphire (SOS)
- Sensors: W-TES directly evaporated on the crystals
- Particle interaction→energy deposition→temperature rise→resistance change read out by SQUID



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# CRESST-III detectors

- Cryogenic scintillating detectors
- Measure phonon and light
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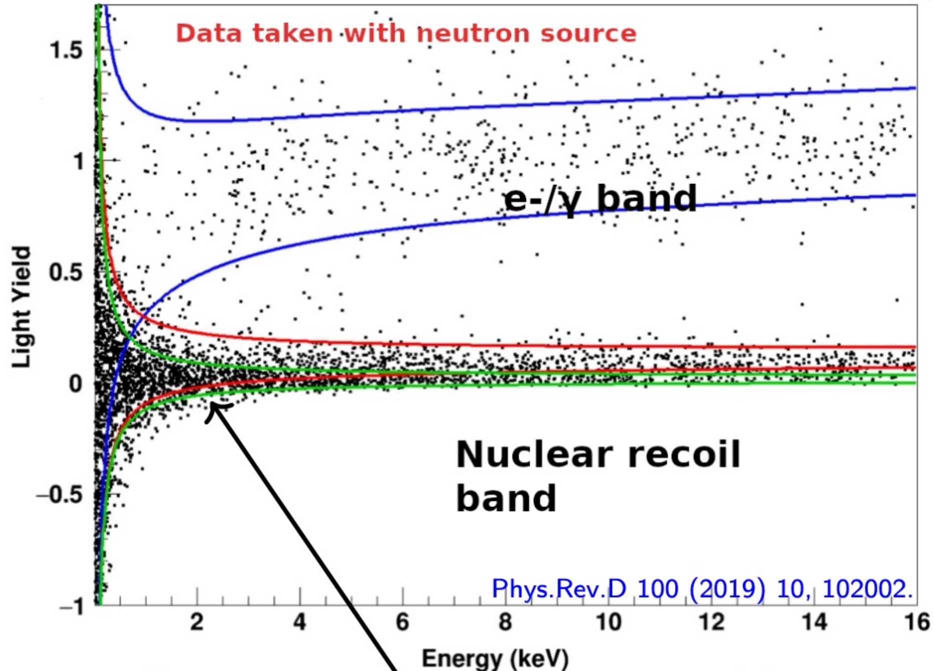
- Thin light detector ($2\times 2\times 0.04\,\mathrm{cm}^3$): Si or silicon-on-sapphire (SOS)
- Particle interaction→energy deposition→temperature rise→resistance change read out by SQUID
- Seperation between $e/\gamma$ background and nuclear recoil from two channel measurements

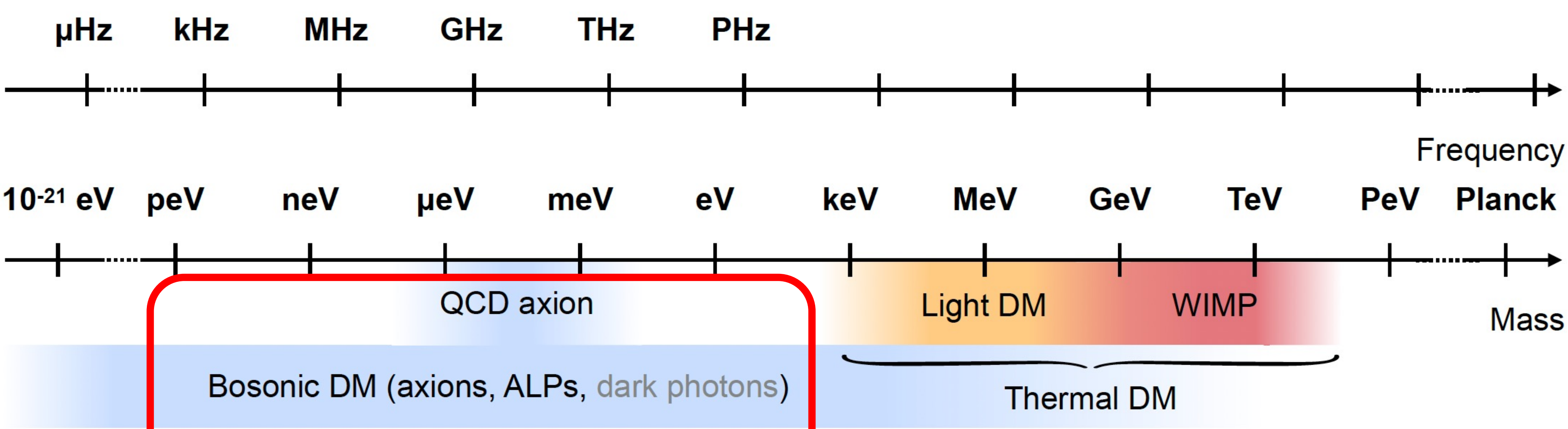



**Dark matter expected in the nuclear recoil band**

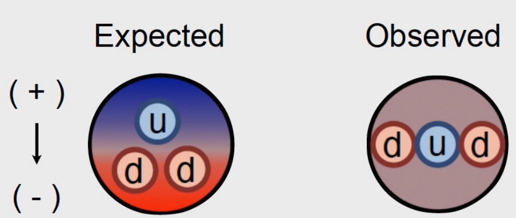
# Dark matter searches



## Mass ranges of some beyond SM particles




Axions



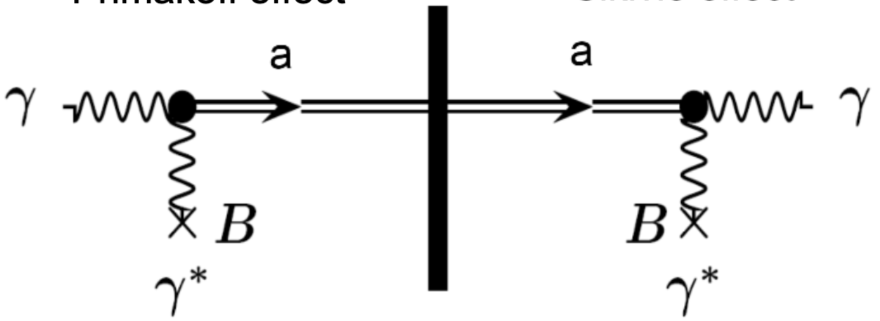

Strong-CP problem:

Strange absence of measurable neutron Electric Dipole Moment (EDM)

**Direct DM search experiments**

# Axions and Axion-like particles (ALPs)

- Proposed as solution to strong CP problem
- Motivated by astrophysical observations:
  - Stellar evolution
  - TeV transparency
- Very weak interaction, good candidate for dark matter
- The main mechanism for detection of light weight axions is through its coupling to photons




## Light Shining through a Wall (LSW)

Model independent approach, independent of dark matter paradigm

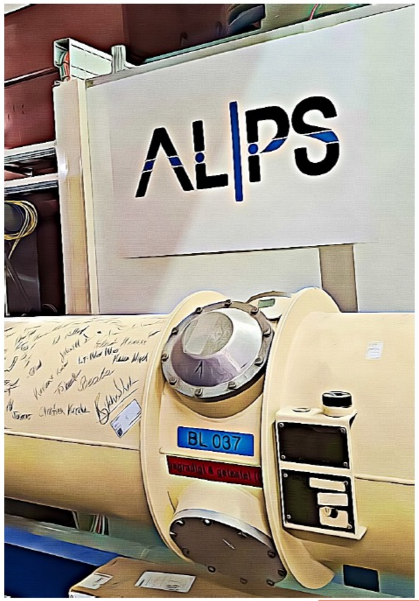
Ulrich.Goerlach@iphc.cnrs.fr, ASP Particle detectors

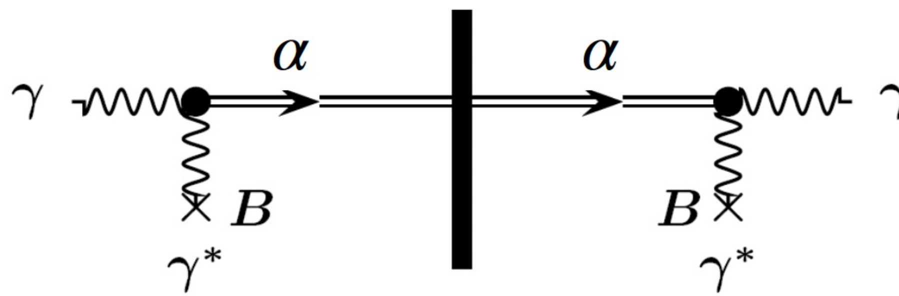
# Axions and Axion-like particles (ALPs)

## Any Light Particle Search II

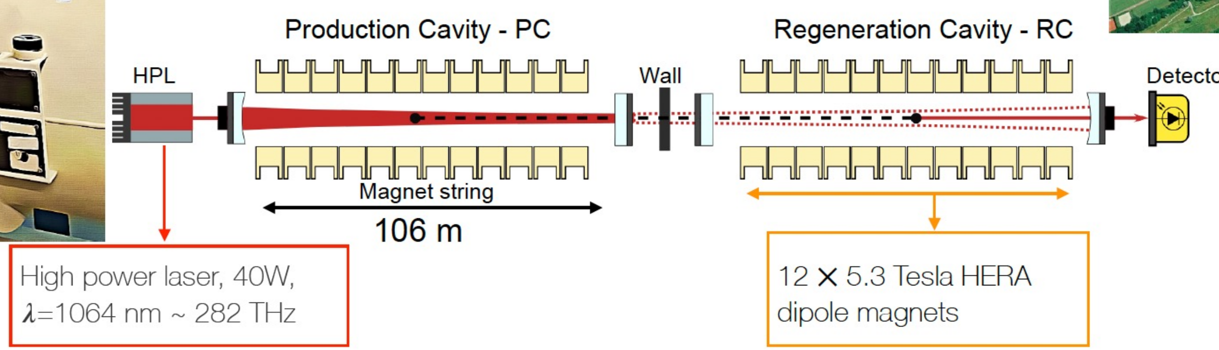
### The axion factory

DESY







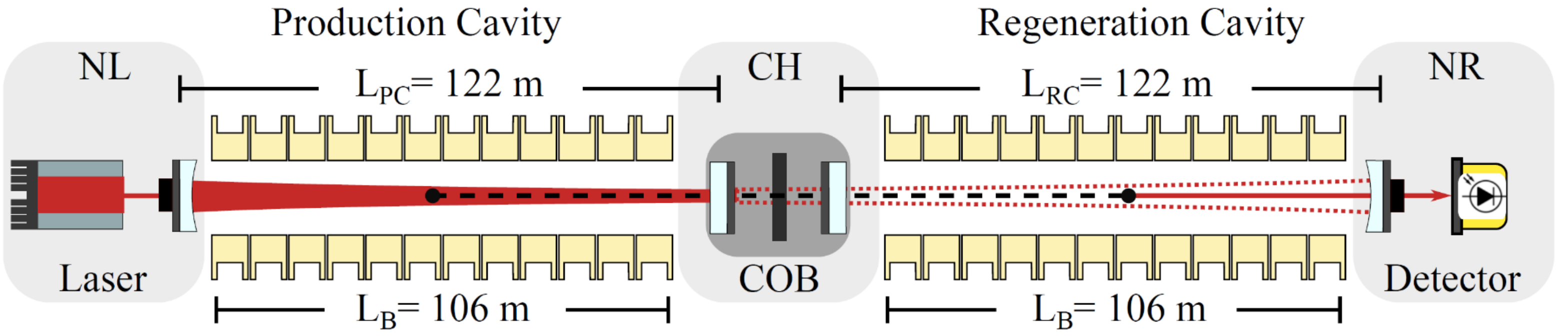

$\beta$: power buildup R

$\eta$: quantum efficien

$$n_{\text{signal}} \approx \frac{1 \text{ photon}}{37 \text{ hours}} \cdot \left(\frac{P_{\text{PC}}}{150 \text{ kW}}\right)\left(\frac{\beta_{\text{RC}}}{10{,}000}\right)\left(\frac{\eta}{0.9}\right)\left(\frac{g_{a\gamma\gamma}}{2\times 10^{-11} \text{ GeV}^{-1}}\right)^4\left(\frac{B}{5.3 \text{ T}}\right)^4\left(\frac{L}{106 \text{ m}}\right)$$

# Any Light Particle Search II (ALPS II)

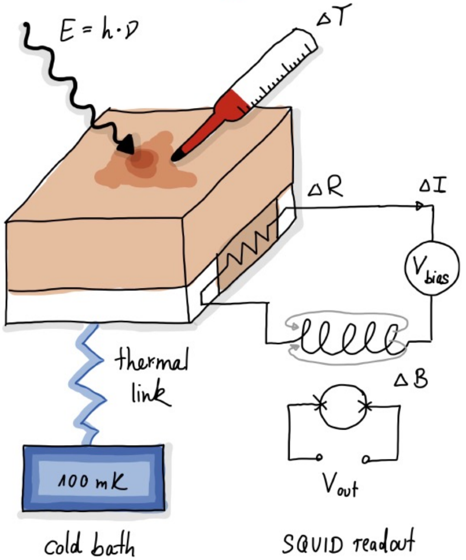
Initial Science Run started on 23.05.2023

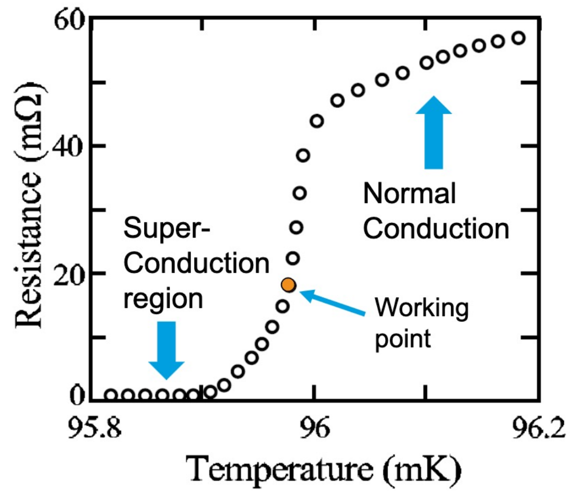




ALPS II might produce a rate in the order of 1 reconverted photon per day

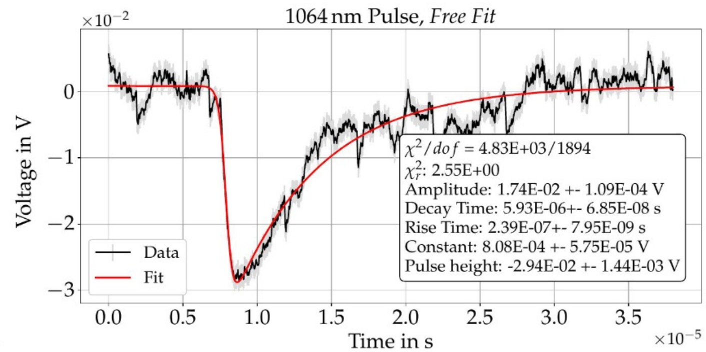
# TES Single Photon Detection

## Transition Edge Sensors




K. Irwin, G. Hilton, Transition-edge sensors, in: Cryogenic Particle Detection, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150, http://dx.doi.org/10.1007/10933596_3.




Courtesy of Rikhav Shah

- Cryogenic microcalorimeters
- Operated at superconducting transition temperature
- Read-out using **S**uperconducting **Q**uantum **I**nterference **D**evices (SQUIDs)

- Incident photon leads to temperature increase
- Small temperature increase leads to large variation in resistance

- Change in resistance is measured in changing current
- Signal is proportional to photon energy
- Energy resolution ≤ 10%
- DM signal expected to look like photon

Drawings courtesy of Katharina-Sofie Isleif



## Requirements for ALPS II:

- **Sensitivity to very low rates (1-2 photons a day)**
- **Low energy photon detection (1064nm equivalent to 1.16eV)**
- **Long term stability (~20 days)**

- **Low background rate: < 7.7 □ 10–6 cps**

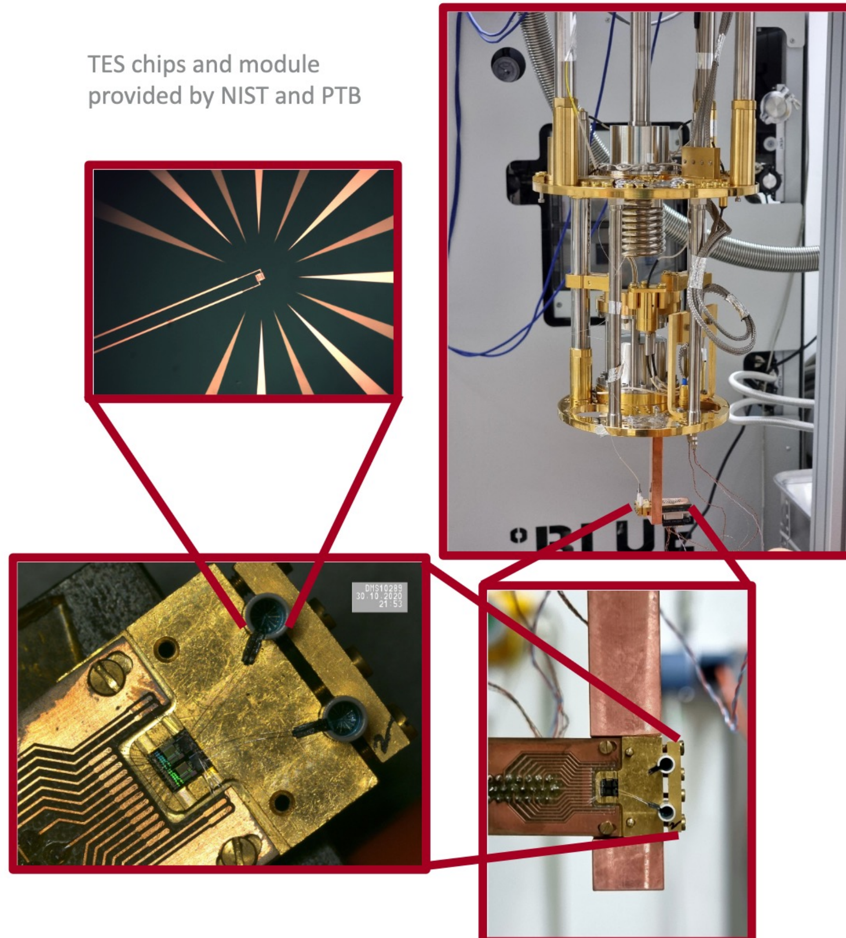
**~ 1 photon (1064nm–like) every 2 days**

- **High detection efficiency**

# TES as Dark Matter Detector

## Current Challenges

TES chips and module provided by NIST and PTB



| TES @ ALPS II Status | Challenge/Goal |
|---|---|
| • Optimized infrastructure (setup, analysis) for signals at 1064 nm→**1.165 eV**<br>• Limited knowledge about response to other wavelengths | • Determine TES response at different (lower, sub – eV) energies<br>• Calibration measurements currently prepared using different wavelengths (880 nm – 2000 nm) |
| Low background (electronic noise, radioactivity, cosmic backgrounds)<br>→ currently: $6.9 \times 10^{-6}$ cps[1] (intrinsic background for 1.165 eV signals) | • Further investigate intrinsic backgrounds<br>• Investigate alternative TES modules with lower noise background |

[1] R. Shah et al., PoS, EPS-HEP2021, 801 (2022)

# Résumé

- **This was a very short and limited snapshot of some of the many ideas and developments on detectors.**
- **There are many more ideas for sensors and experiments**
- **Just to mention a few:**
  - **Kinematic Inductance Detector (KID)**
  - **Superconductor QUantum Interference Device (SQUID)**
  - **Nano-dots, nano wires, graphene…..**
  - **…**