Scintillating Crystals From High Energy Physics to Medical Imaging

ASCIMAT School

E. Auffray,
CERN, EP-CMX

Many Applications of scintillators

- High Energy Physics
- Astronomy and dark matter searches
- X ray and gamma spectroscopy
  - Safety inspection
- Imaging:
  - Medical imaging: PET/SPECT
  - Gamma imaging
- Monitoring in nuclear plants
- Oil wellsoil drilling

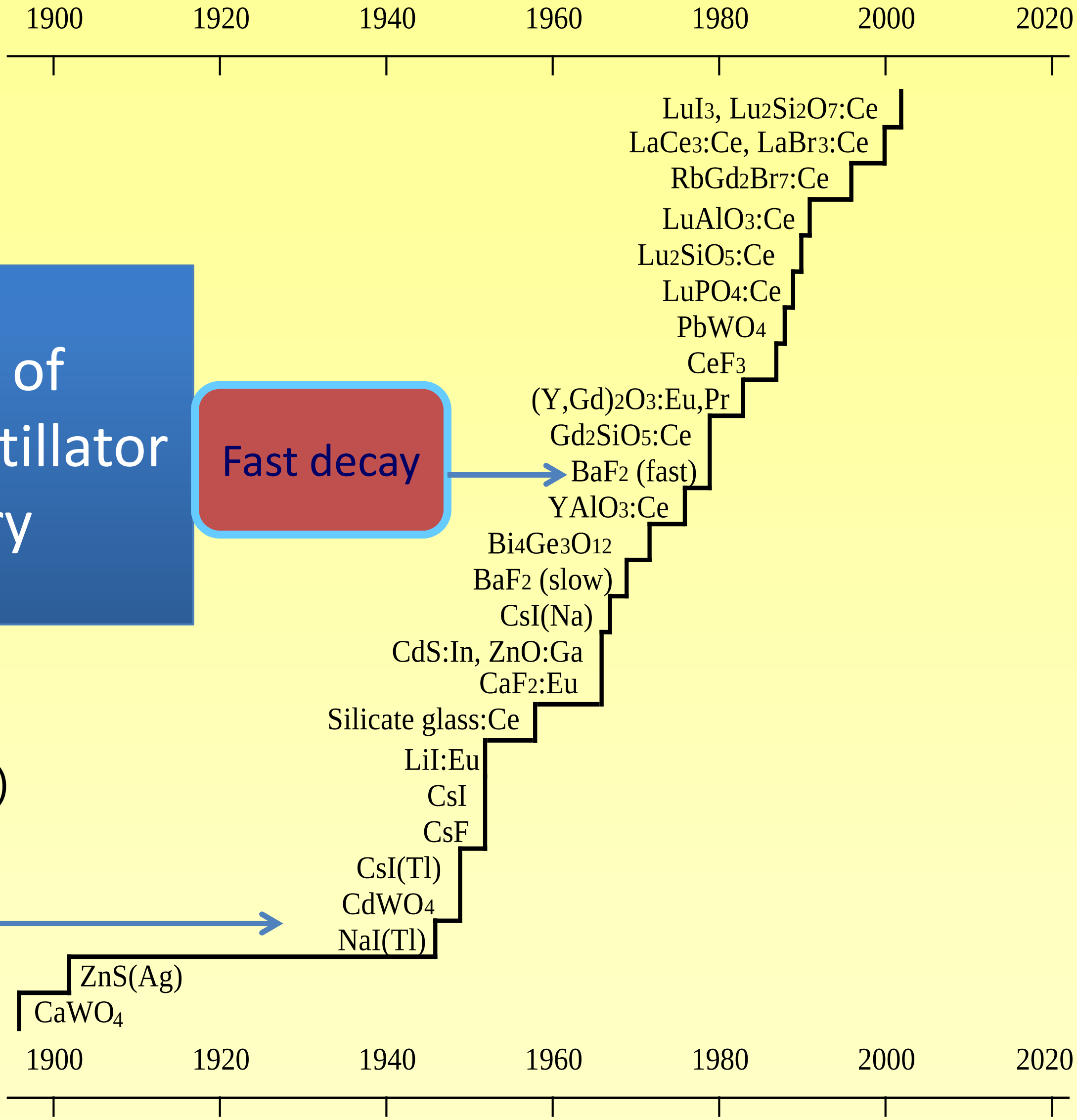
Many scintillators available

120 Years of inorganic scintillator Discovery

Fast decay

(Marv Weber)

Invention of the photomultiplier tube



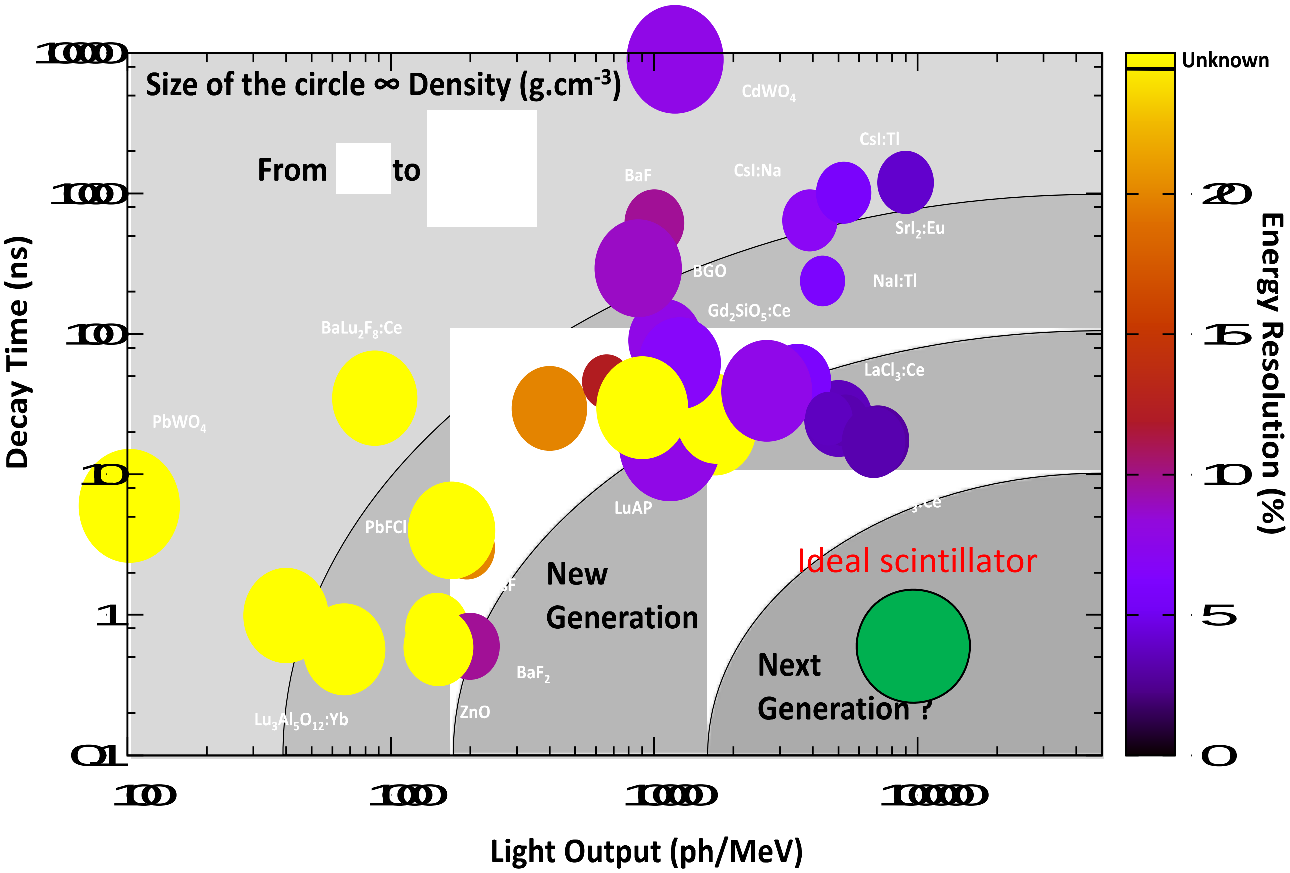
M. J. Weber J. Lumin. 100 (2002) 35

Choice depends on the requirements

- High density
- High light yield
- Short decay time
- Inexpensive, “easy” to manufacture, reproducible
- Large size, easy handling and “machinable
- Radiation hardness (for some applications HEP, Astronomy)

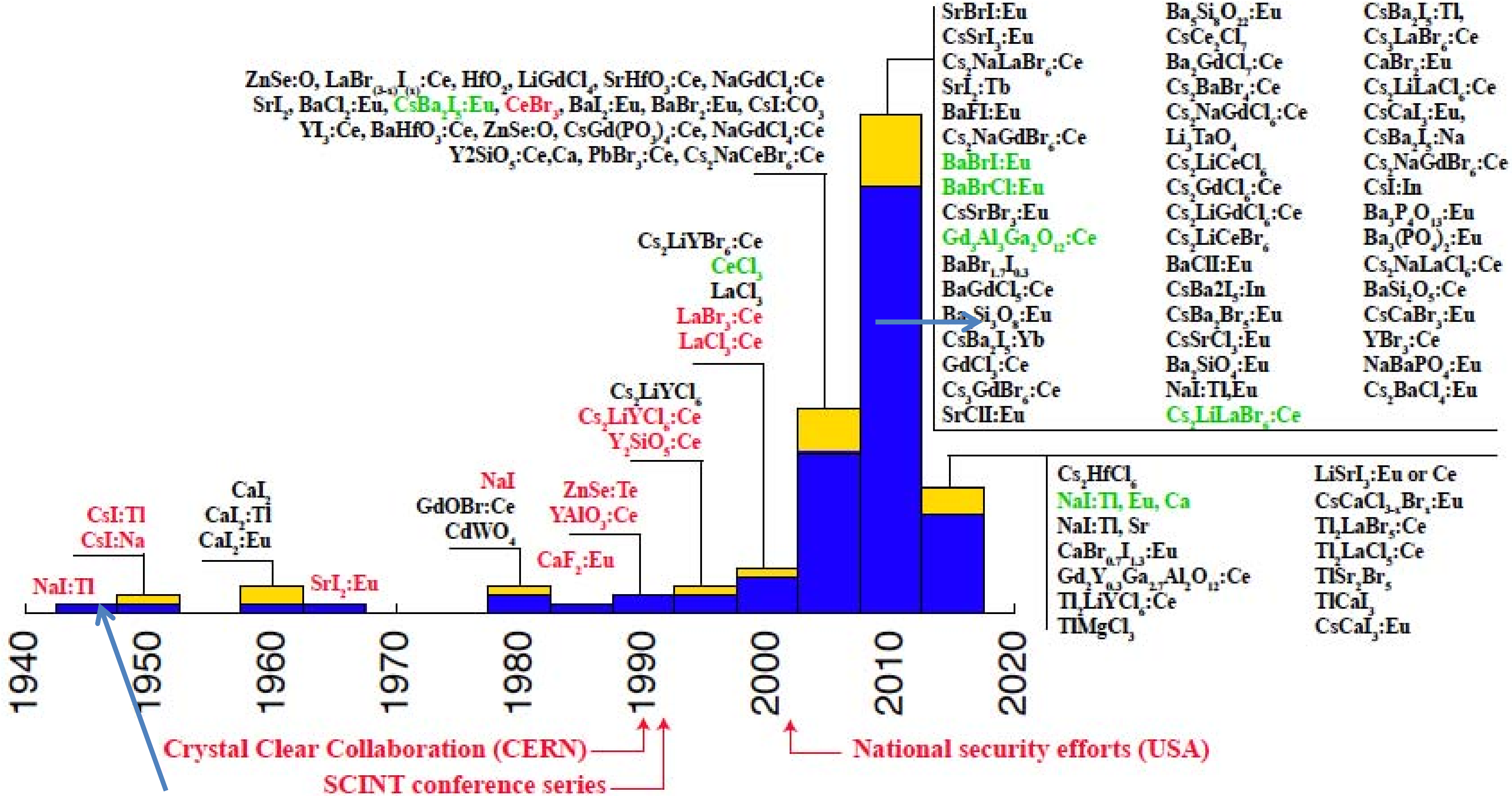
Classification of scintillators

- Density
- Light Yield
- Energy Resolution
- Decay Time



Courtesy P. Lecoq

History of first publication of scintillators with light output of >20 000 ph/MeV,



Invention of the photomultiplier tube

C. Dujardin et al., Needs, Trends, and Advances in Inorganic Scintillators, to be published on TNS

Many Applications

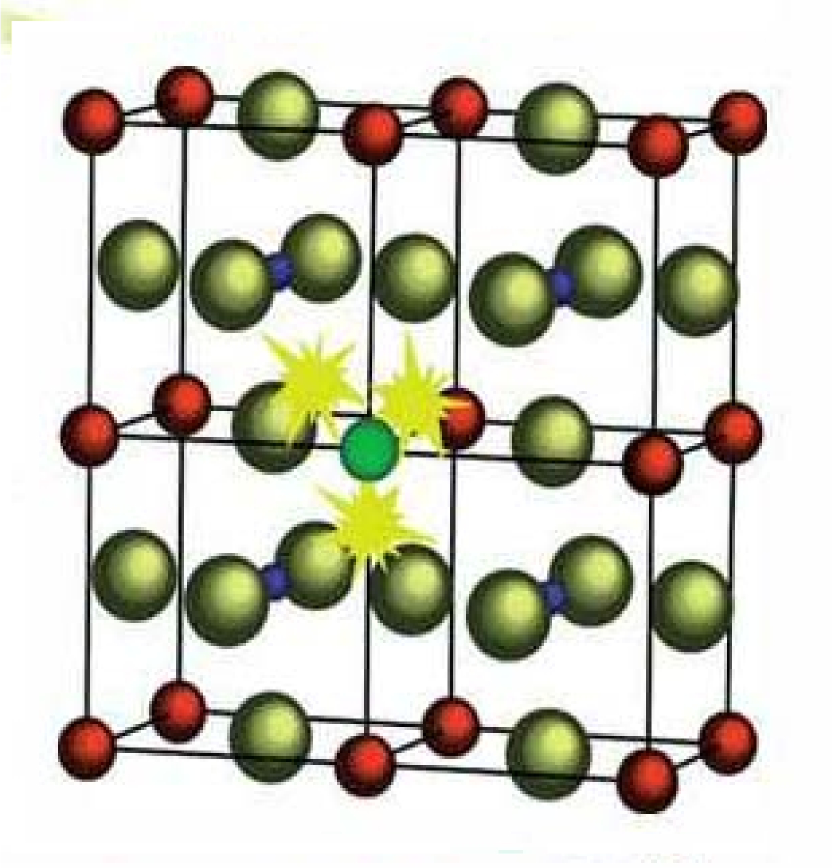
- **High Energy Physics**
- Astronomy and dark matter searches
- X ray and gamma spectroscopy
  - Safety inspection
- Imaging:
  - **Medical imaging: PET/SPECT**
  - Gamma imaging
- Monitoring in nuclear plants
- Oil wellsoil drilling

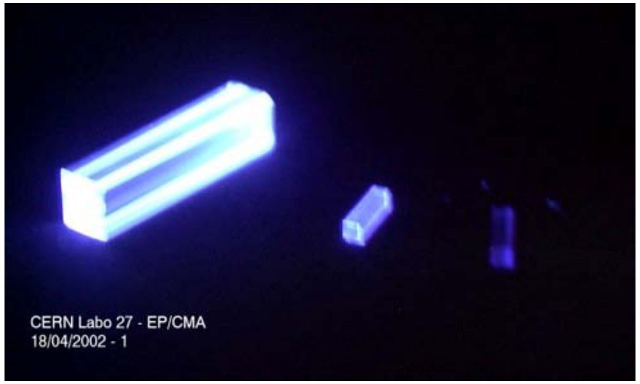
Application in High Energy Physic
Electromagnetic calorimeter

Principle of calorimeter

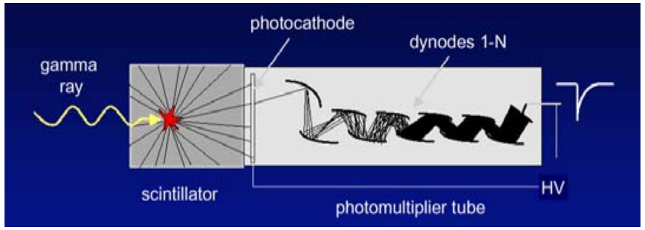
Calorimeter measures the energy of incident particle:

Incident particle is stopped by collison with atoms of the materials and Its energy is converted in light





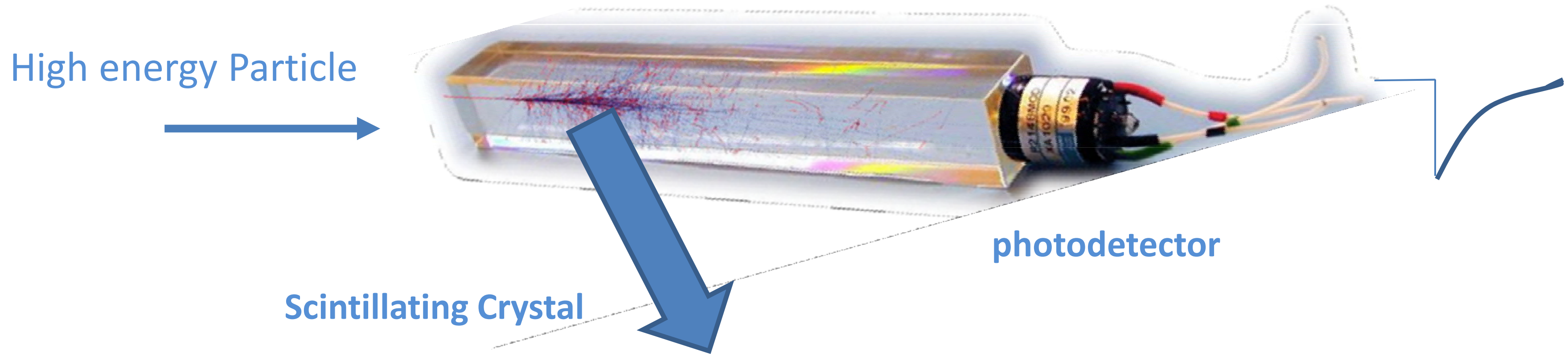
Light output is proportional to energy deposited



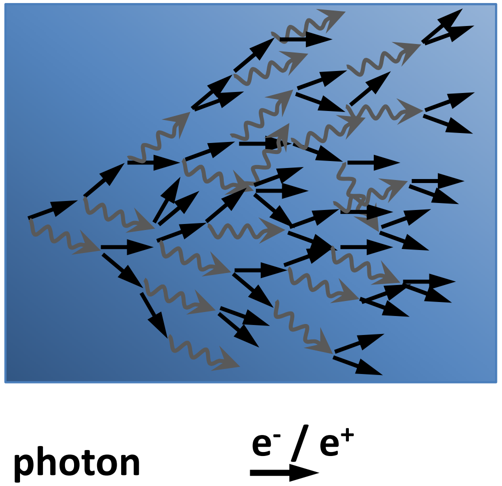
The light is readout with photodetector

- To convert ALL the energy of the incident particle in to light => dense materials

Interaction of a high energy gamma ray in a scintillator

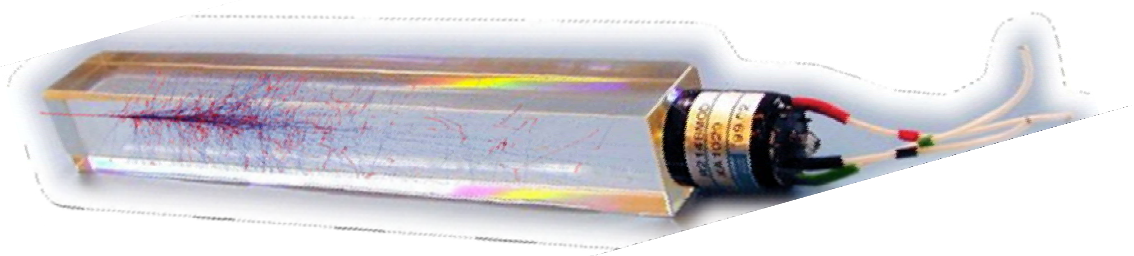


Development of an electromagnetic shower



Interaction of a high energy gamma ray in a scintillator

Development of an electromagnetic shower



Characterized by:

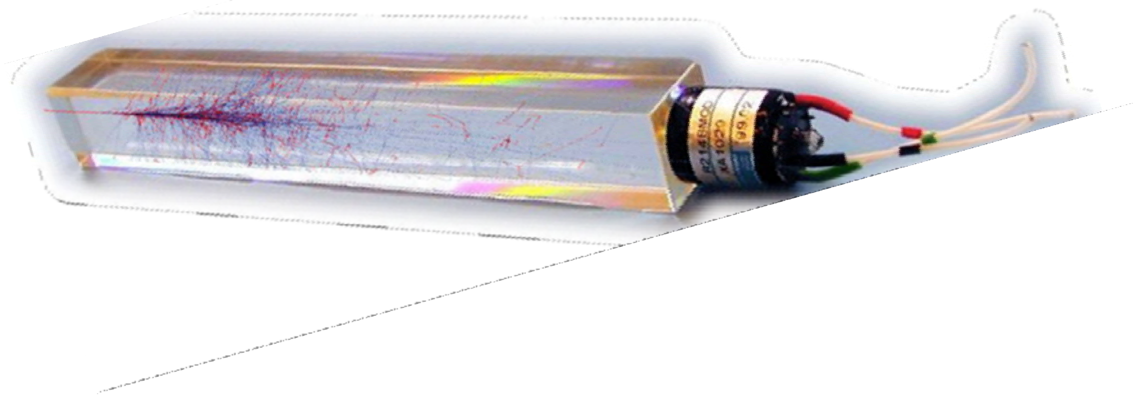
- Radiation length X_o (g/cm^2)

$$X_0 = \frac{716.4A}{Z(1+Z)\ln\left(\frac{287}{\sqrt{Z}}\right)}$$

- Molière radius R_m(g/cm^2)

$$R_m = 0.035 * X_o * (Z + 1.4)$$

Energy resolution of a electromagnetic calorimeter



$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

a: statistical term: depends mainly on light yield

b: noise term negligeable

c: Constant term: depends of light uniformity, calibration

Scintillators requirements for high energy physics

- High density
  - Stopping power, short radiation length X_0 & Molière radius
- Decay time
- Radiation hardness
- light yield less important for high energy gamma rays detection

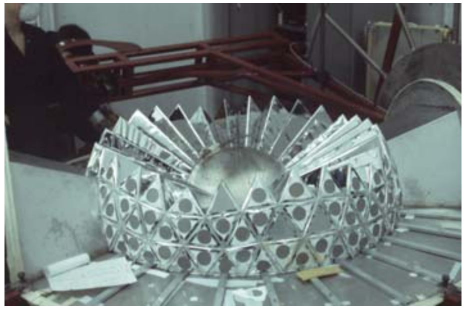
Some popular crystals in HEP

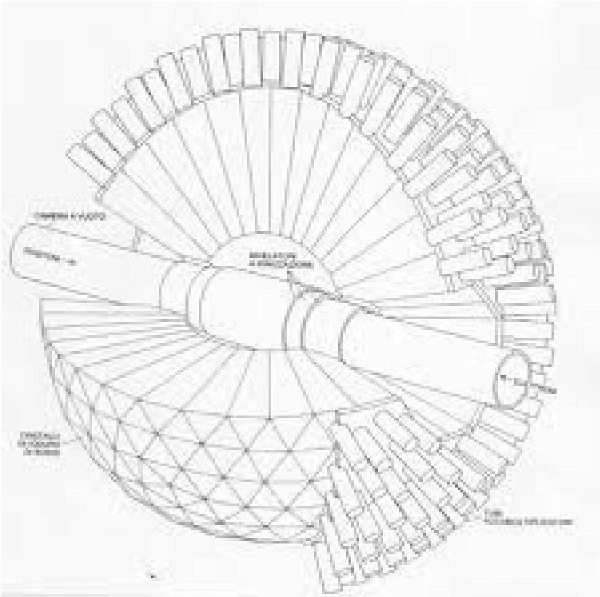
	NaI(Tl)	BaF_2	CsI(Tl)	CeF_3	BGO $Bi_4Ge_3O_{12}$	PWO $PbWO_4$
Xo [cm]	2.59	2.03	1.86	1.66	1.12	0.92
ρ [g/cm^3]	3.67	4.89	4.53	6.16	7.13	8.2
τ [ns]	230	0.6 620	1050	30	340	15
λ [nm]	415	230 310	550	310 340	480	420
$n@\lambda_{max}$	1.85	1.56	1.80	1.68	2.15	2.3
LY [%NaI]	100	5 16	85	5	10	0.5

Crystal ball calorimeter

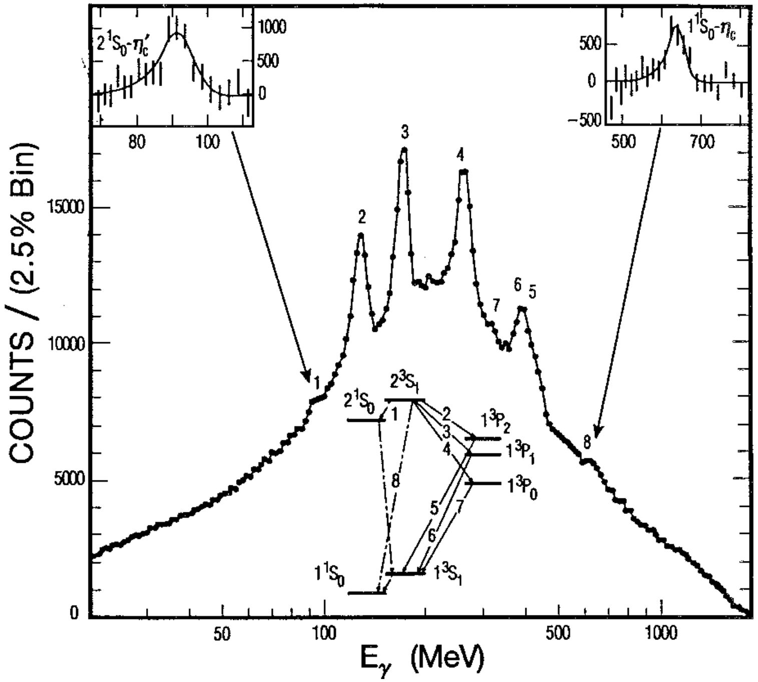
Crystal Ball @SLAC, 1979 for Charmonium spectroscopy

- 50cm diameter spherical ball of NaI(Tl) crystals
- 672 crystals 42cm long, PMT readout
- Very good resolution allowed precise spectroscopic study of charmonium states





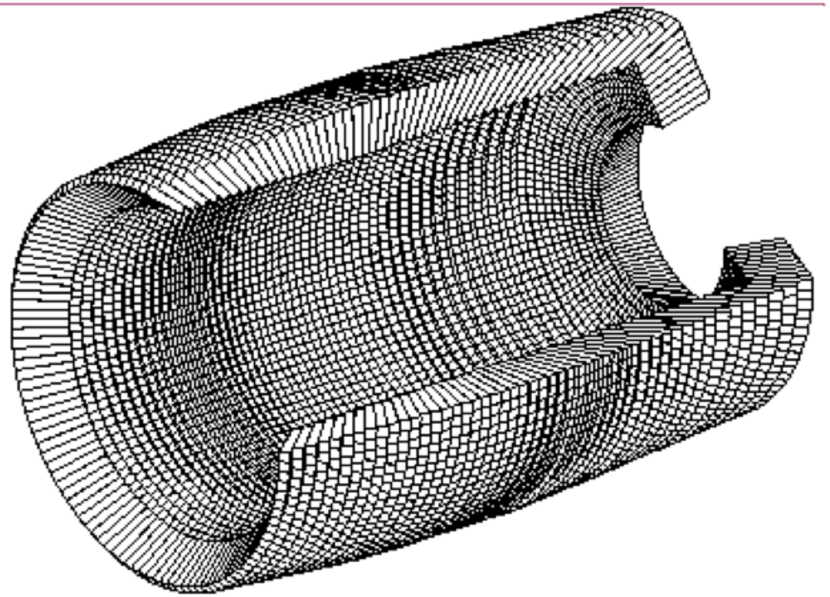
Charmonium decay

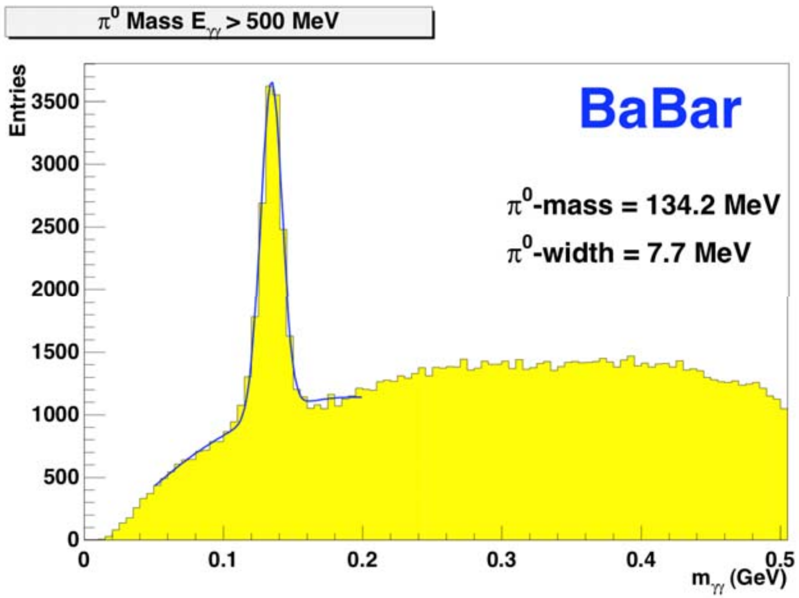


Babar detector at SLAC (PEP-2)

Detailed study of b-quarks, b-quark containing hadrons, and CP violation

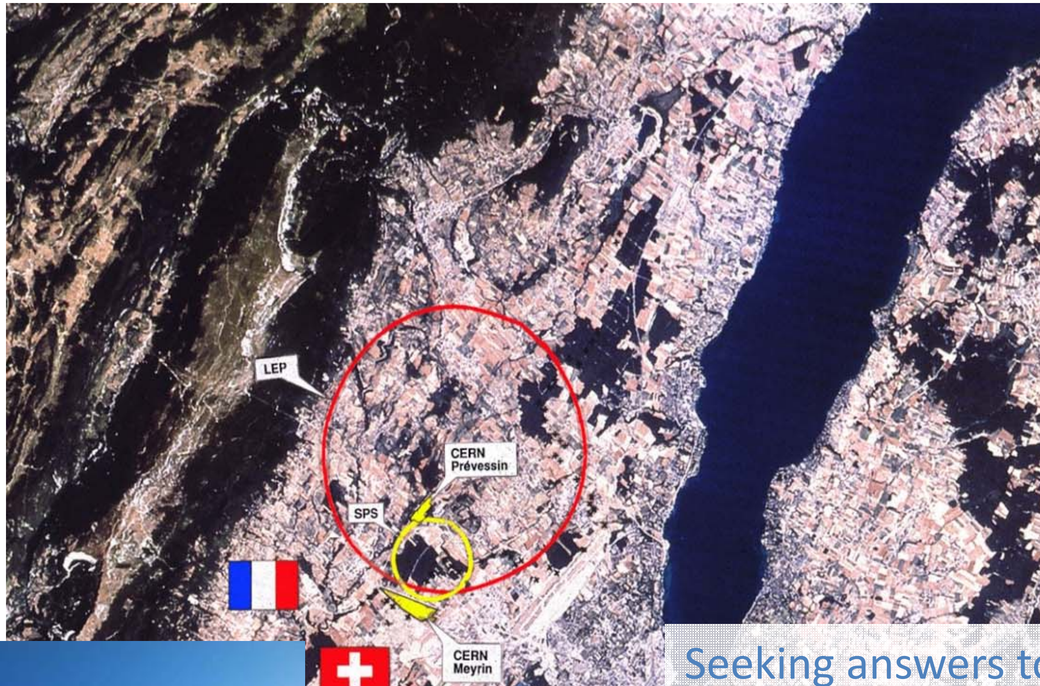
- Cylindrical geometry
- 6580 CsI:Tl crystals, ≈34 cm long,
- Excellent energy, position resolution to reconstruct π0s.





CERN

CERN (the European Organization for Nuclear Research) is the world's largest particle physics laboratory, where physicists and engineers probe the fundamental structure of the universe.



Seeking answers to questions about the Universe

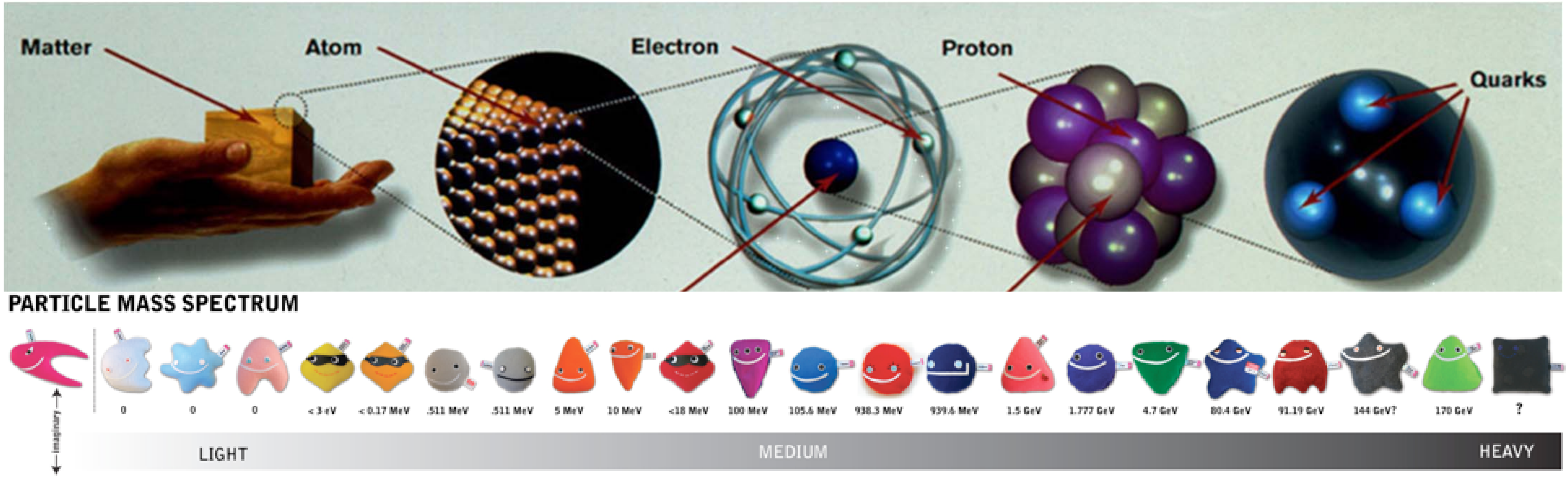
Advancing the frontiers of technology

Training the scientists of tomorrow

Bringing nations together through science

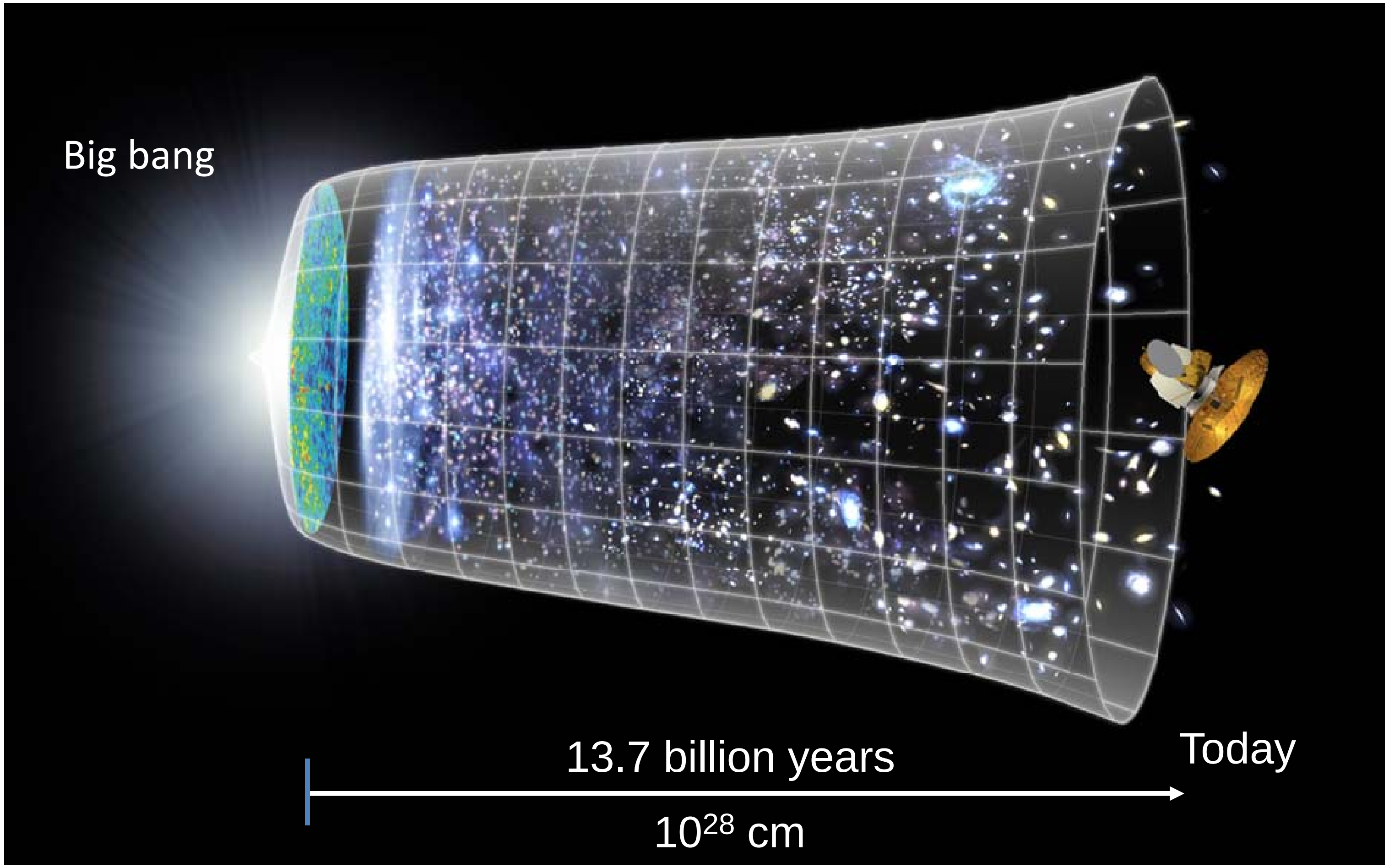
@ CERN

Basic research on particle physics



To understand the fundamental properties of matter

@ CERN



To understand the origin of the universe

What is our universe made of ?

From the observation of galaxies we know that there must be more matter & energy than what we can see

We see only **4%** of the matter in universe

What is the origin of the rest:
26% Dark matter & 70% dark energy

Can this be undiscovered particles ?

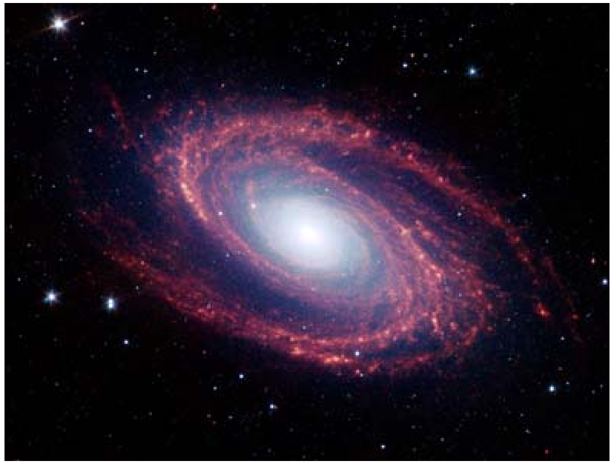
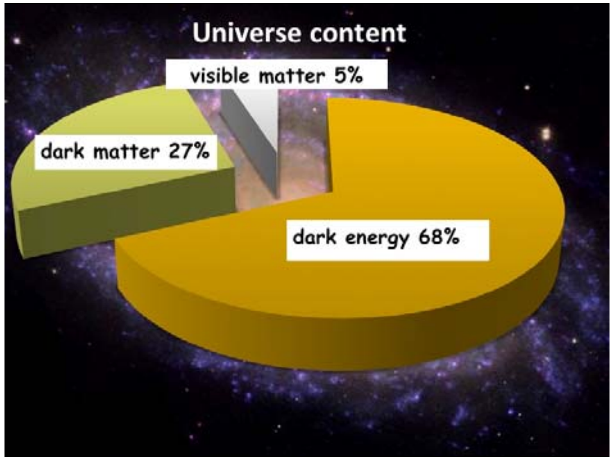


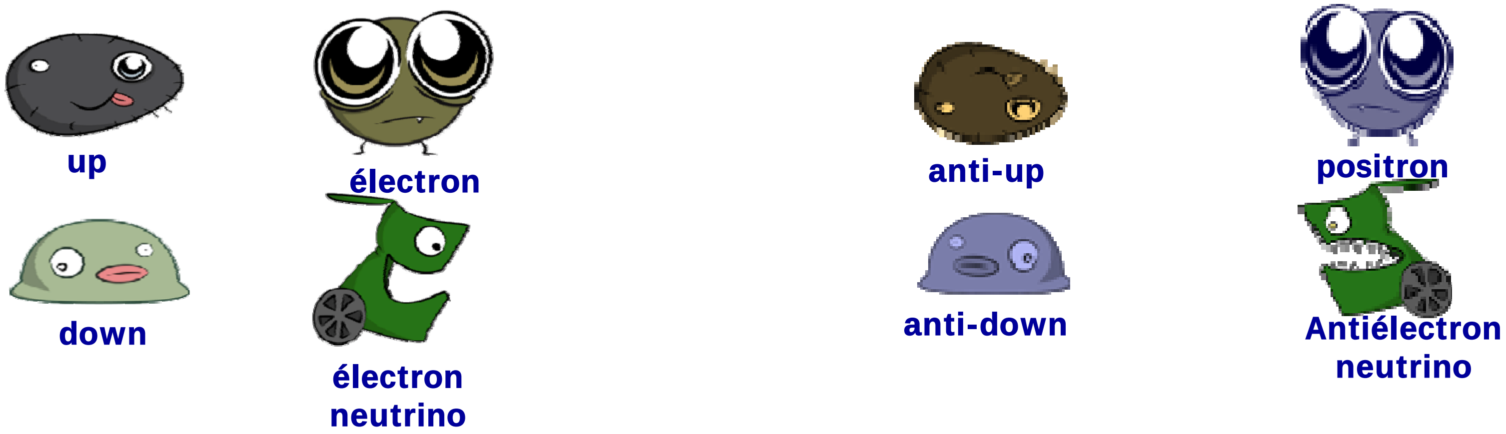
Image courtesy NASA Jet Propulsion Laboratory.



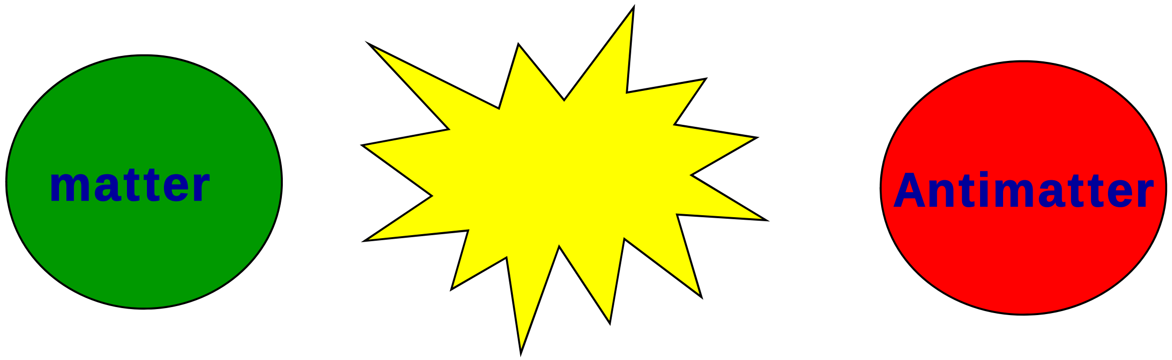
Matter/Antimatter asymmetry ?

For each particle

One antiparticle



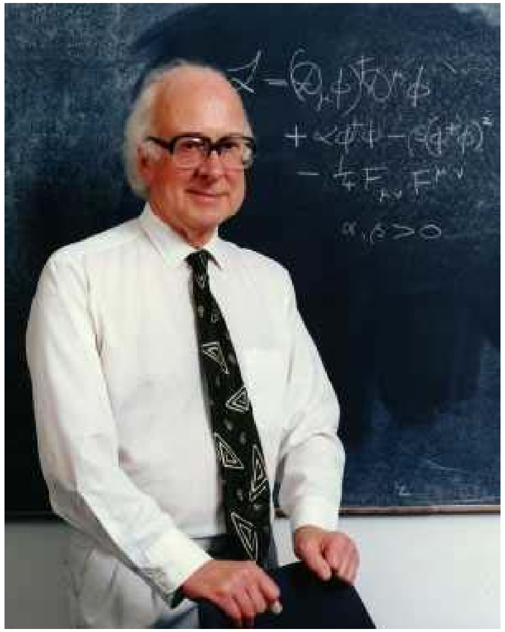
With opposite electrical charge



13.7 billions years ago, the big bang should have created the same amount of matter & antimatter

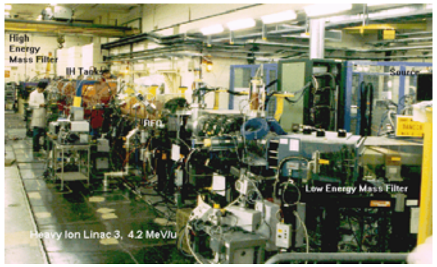
Why today there is more matter than antimatter ?

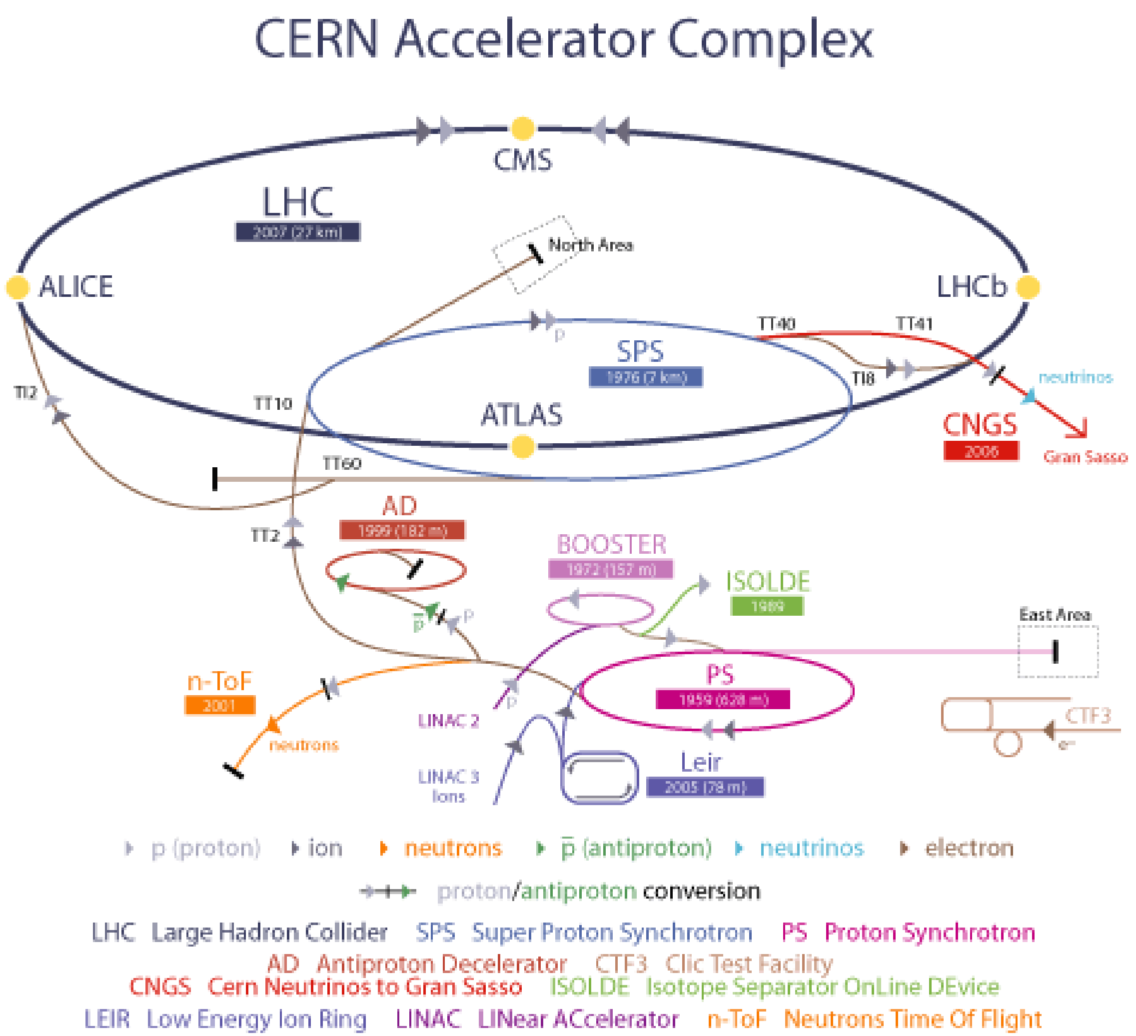
the origin of particle mass



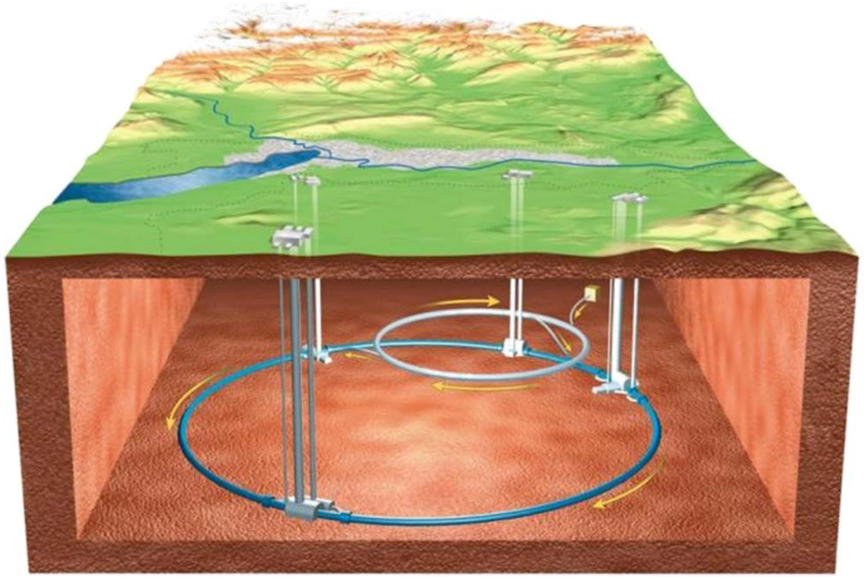
In the standard model, the most precise theory in physics today, the origin of mass is explained by the **Brout–Englert–Higgs** mechanism and leads to the existence of at least one Higgs particle

CERN Accelerator complex



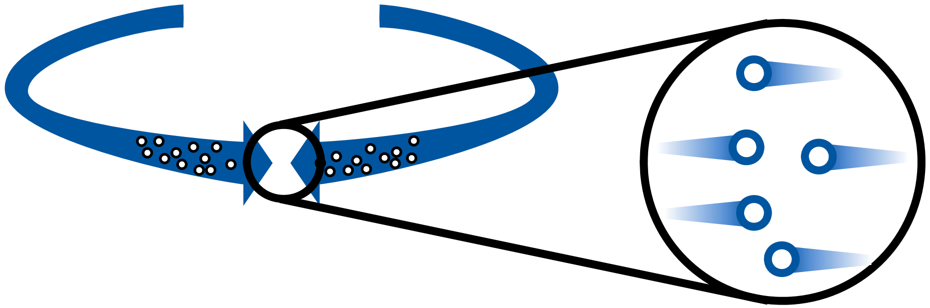


The Large Hadron Collider (LHC)

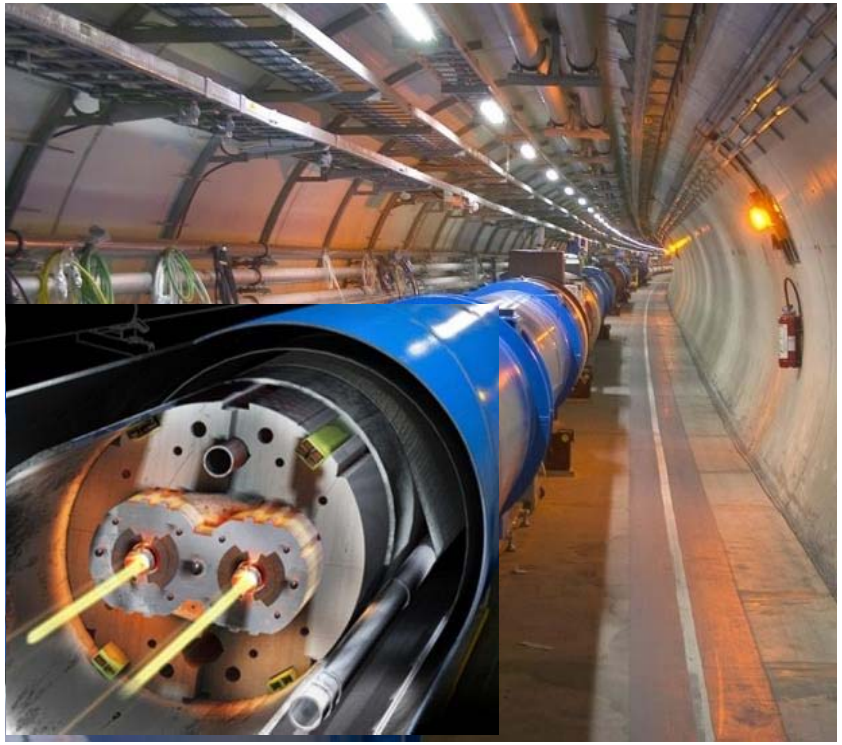


Length of ring: **27 km**

Collision energy: **8 TeV** (at present)



Protons or Lead ions



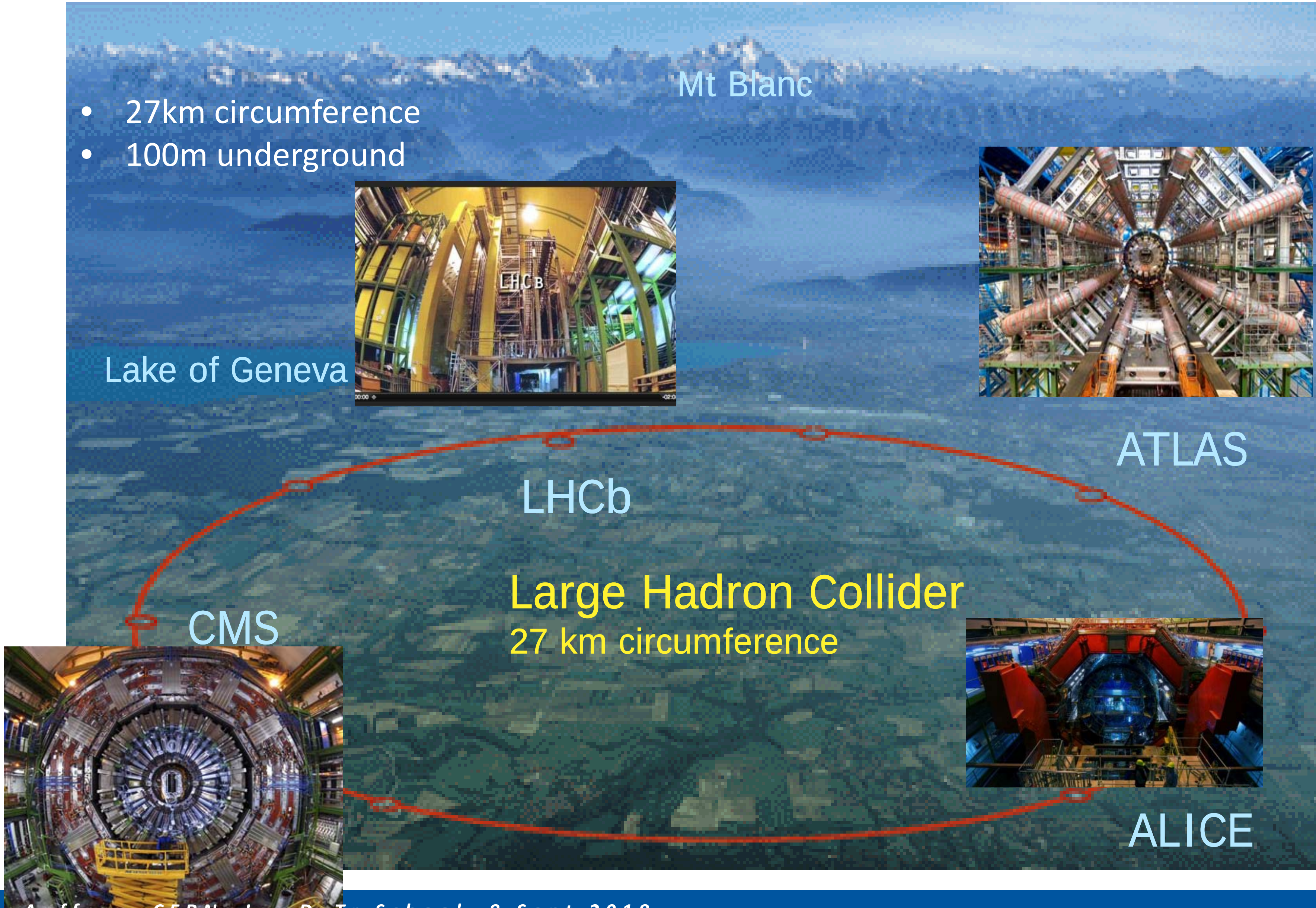
Based on superconducting magnets of Niobium-Titanium

Operating temperature:

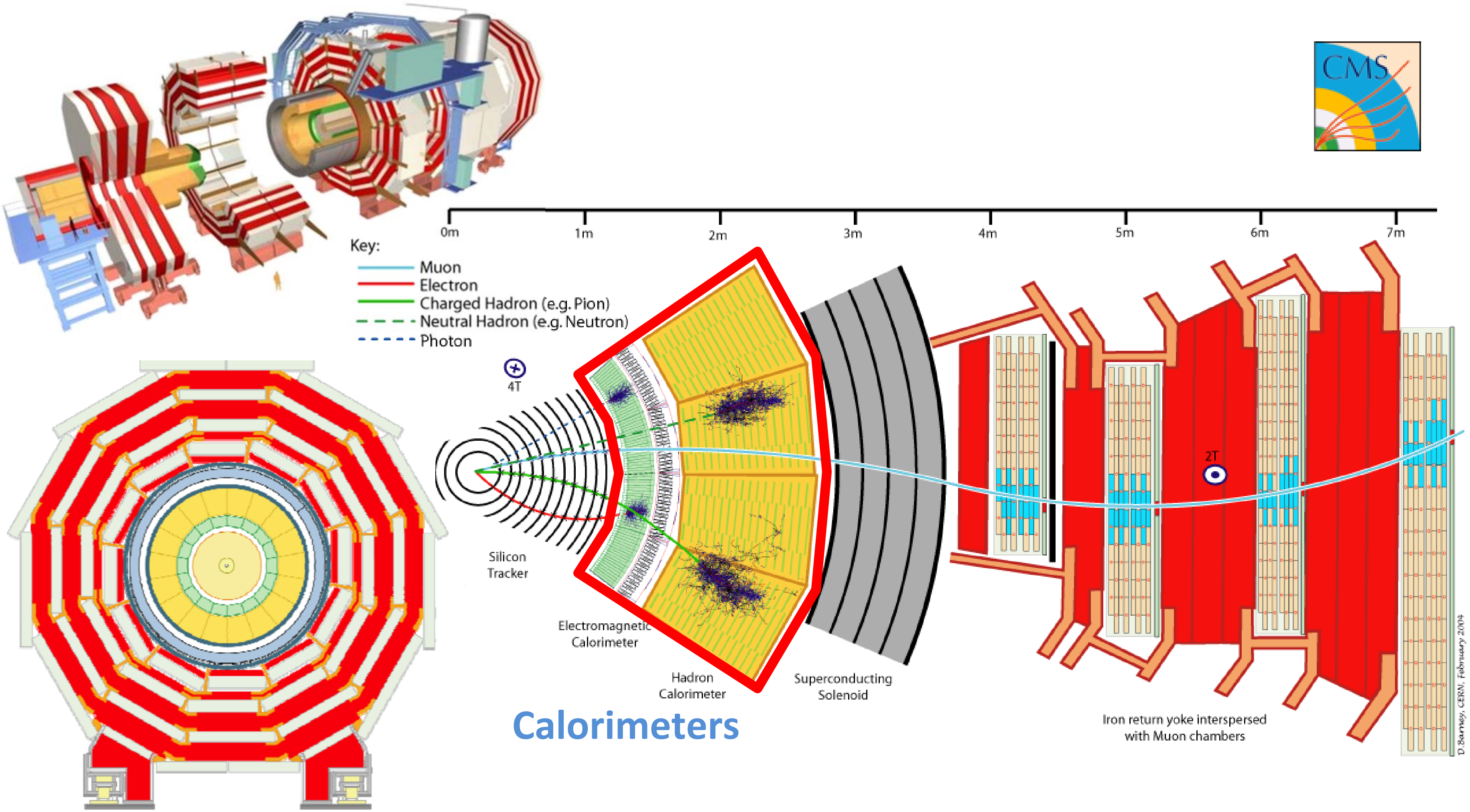
1.9 K (−271.25 °C)

The Large Hadron Collider LHC

- 27km circumference
- 100m underground

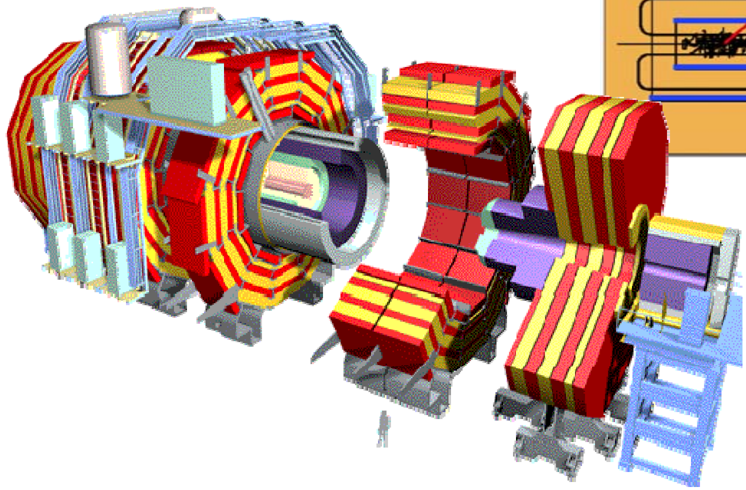


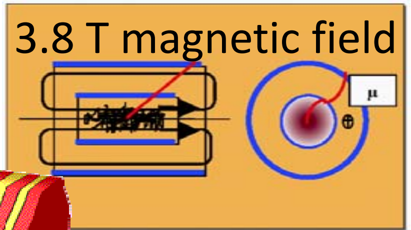
CMS: a multi-layer detector to reconstruct collision events



Calorimeters

CMS : Compact Muon Solenoid @LHC





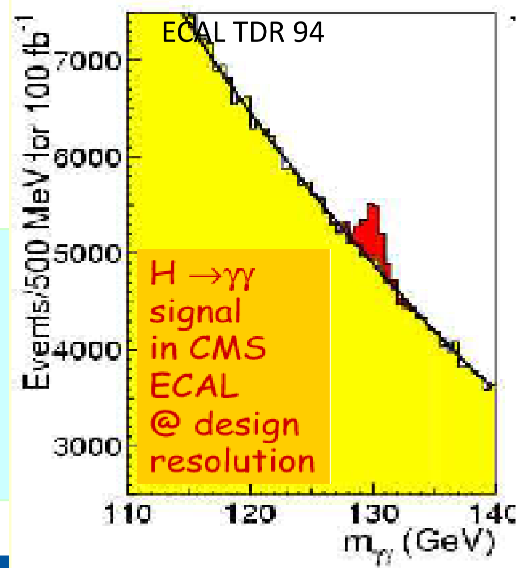
Length ~ 22 m
Diameter ~ 15 m
Weight ~ 14000 t

For a light Higgs

H→γγ best channel. Narrow width, but irreducible background:

Electromagnetic calorimeter (ECAL) resolution crucial !

=>Choice of homogeneous crystal calorimeter



Challenges for ECAL

Fast response (25ns between bunch crossings at LHC)

- High radiation doses and neutron fluences

  500fb^{-1} : 0.3 Gy/h & 4.10^{11} p/cm^2 at $|\eta| < 1.48$;

  6.5 Gy/h & 3.10^{13} p/cm^2 at $|\eta| = 2.6$

Strong magnetic field (3.8 teslas)

Long term stability monitoring capability

@ CERN

The Crystal Clear Collaboration was created in 1991
initially as part of an R&D (RD18) program for the LHC to study new scintillators for electromagnetic calorimeters.

The Crystal Clear Collaboration CERN LIBRARIES, GENEVA 1

CERN / DRDC / 91-15
DRDC / P27
06 march 1991

R&D PROPOSAL FOR THE STUDY OF
NEW FAST AND RADIATION HARD SCINTILLATORS
FOR CALORIMETRY AT LHC

CERN , Geneva , Switzerland
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Abstract

In the recent past, several scintillating crystals have been developed and mass produced for large high resolution electromagnetic calorimeters, such as NaI, CsI, and BGO. In the new generation of ee and pp colliders, the very high design luminosities bring new constraints on the crystals : they must have a fast response, higher resistance to radiation, and be as dense as possible for calorimeter compactness. From our systematic studies of scintillation properties and radiation damage mechanisms in scintillators, several fluoride crystals or glasses should have the wanted properties. The purpose of this R&D program is to study these materials and the conditions of their mass production in order to find the best suited scintillator for calorimetry at future colliders.

Heavy fluoride glasses

CRYSTAL CLEAR

http://crystalclear.web.cern.ch/crystalclear/

Crystal choice in 1994

From 1991 to 1994:

- Birth of the "scintillator community"
- Many progress in the understanding of the properties of 3 materials:
- CeF_3 had very good scintillation and radiation hardness properties **but no capability for large production**
- Heavy Glasses had good scintillation properties, **low cost but were not enough radiation hard for LHC**

⇒ **In 1994: Choice of PWO by CMS for the electromagnetic calorimeter**

⇒ **Choice of PWO for PHOs detector in ALICE**

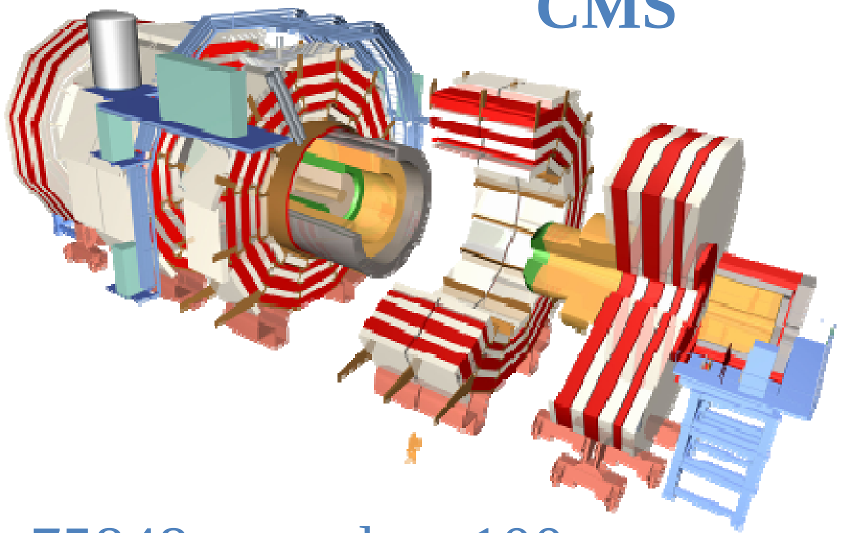
	Developed for LHC Crystal Clear/CMS		
	CeF_3	PWO $PbWO_4$	HFG Glass
Xo [cm]	1.66	☺ 0.89	1.6
ρ [g/cm^3]	6.16	☺ 8.2	6
τ [ns]	30	☺ 15	25
λ [nm]	310 340	☺ 420	320
Ref index $n@\lambda_{max}$	1.68	☹ 2.3	1.5
LY [%NaI]	5	☹ 0.5	0.5

@CERN in LHC

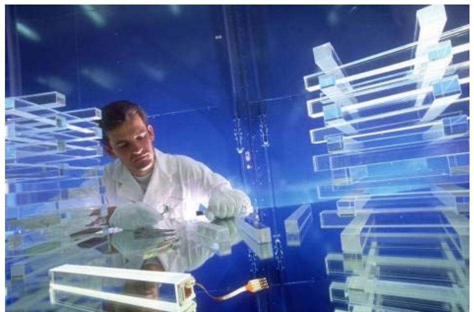
2 experiments use scintillating crystals : Lead tungstate crystals : $PbWO_4$

ALICE :17920 crystals

CMS

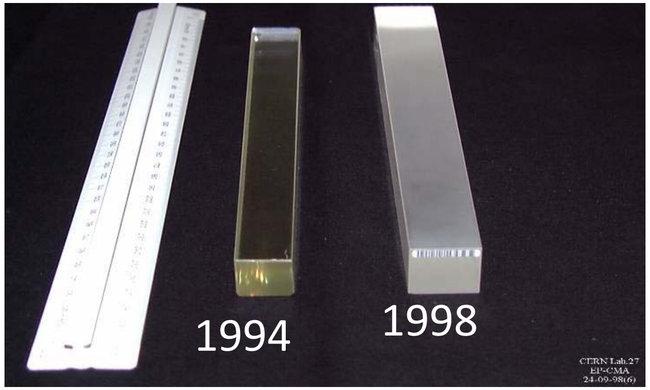


75848 crystals = 100 tons

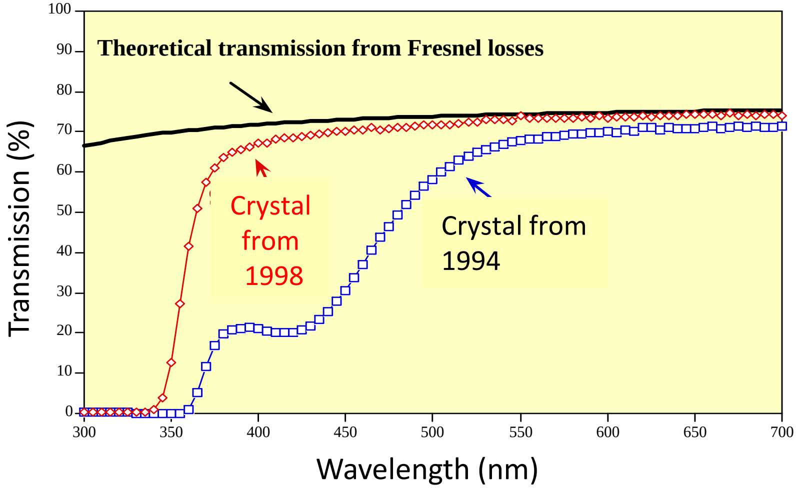


From R&D to Production

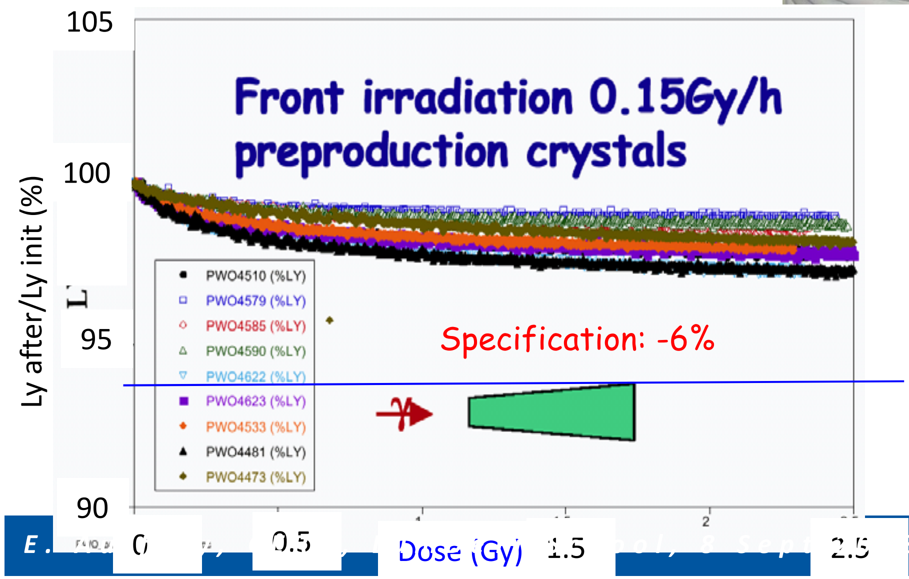
Optical properties improvement



Transmission improvement



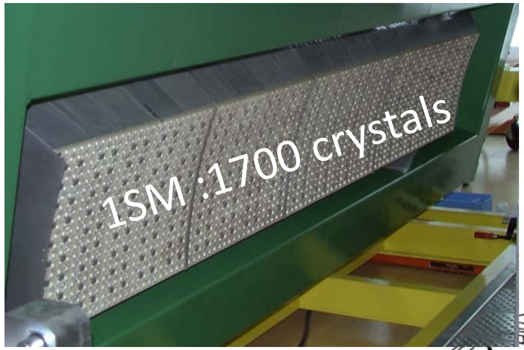
Radiation hardness improvement

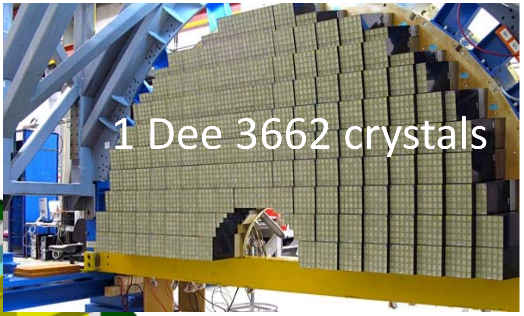


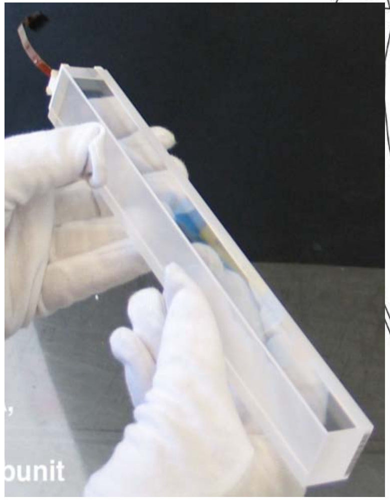
Delivery of the first 100 PWO Crystals Sept 98

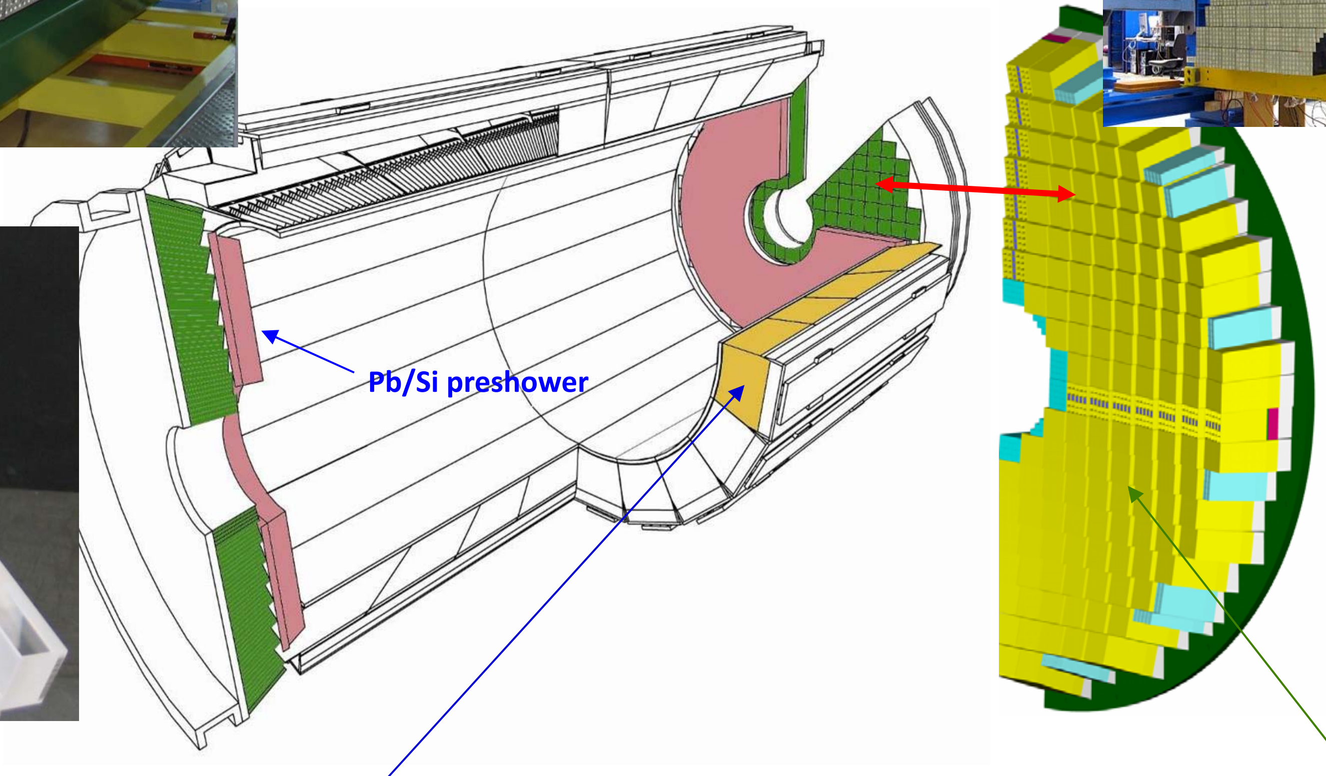
CMS ECAL Design

75848 PWO crystals
about 10 m³, 90 t







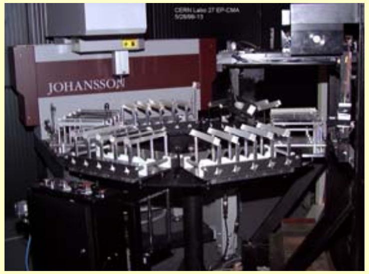


Barrel: |η| < 1.48
36 Super Modules (SM)
61200 crystals (2.2x2.2x23 cm³)

EndCaps: 1.48 < |η| < 3.0
4 Dees
14648 crystals (3x3x22 cm³)

CMS ECAL assembly: 1998-2007

61200 crystals



Caracterisation des cristaux/

61200 sub-units

Collage des photodétecteurs sur les cristaux

6120 sub-modules

Montage des sous-modules

144 modules

Montage des modules

36 Super- modules

Montage des Supermodules

36 Super- modules

Installation d'écran thermique

36 Super- modules

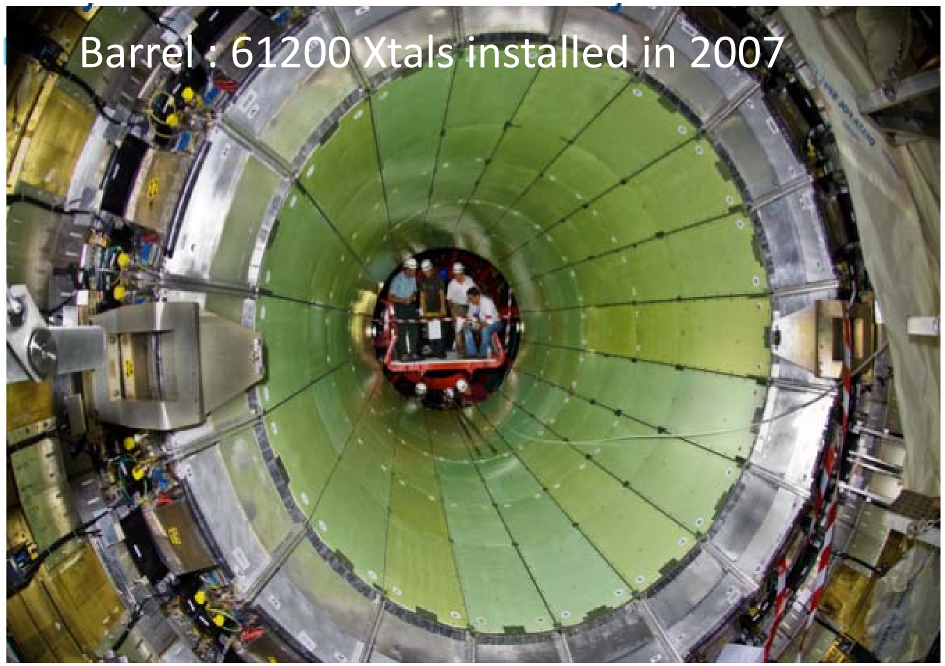
Installation du système de monitoring

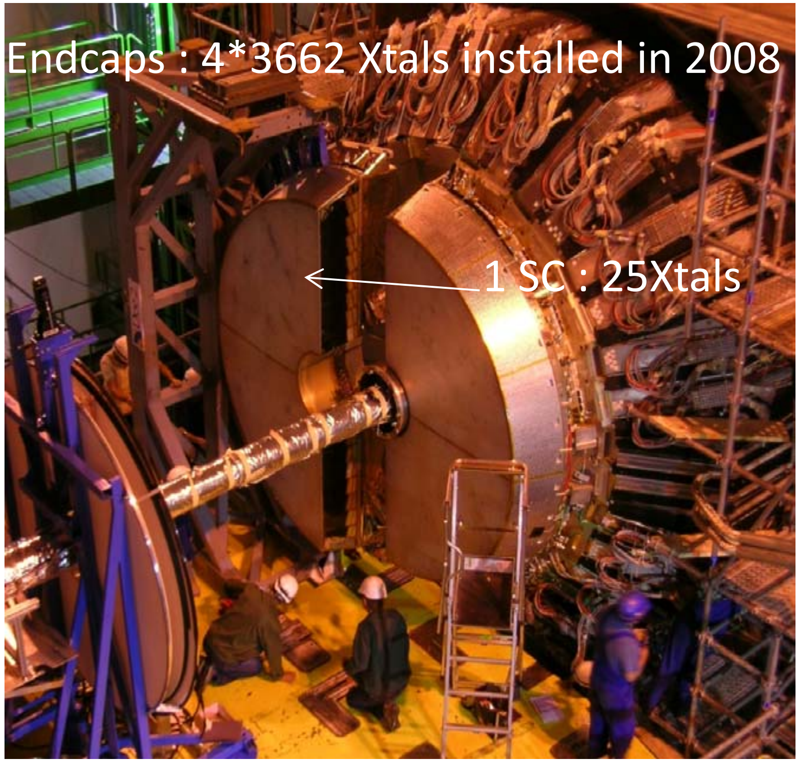
36 Super- modules

Installation du système de refroidissement

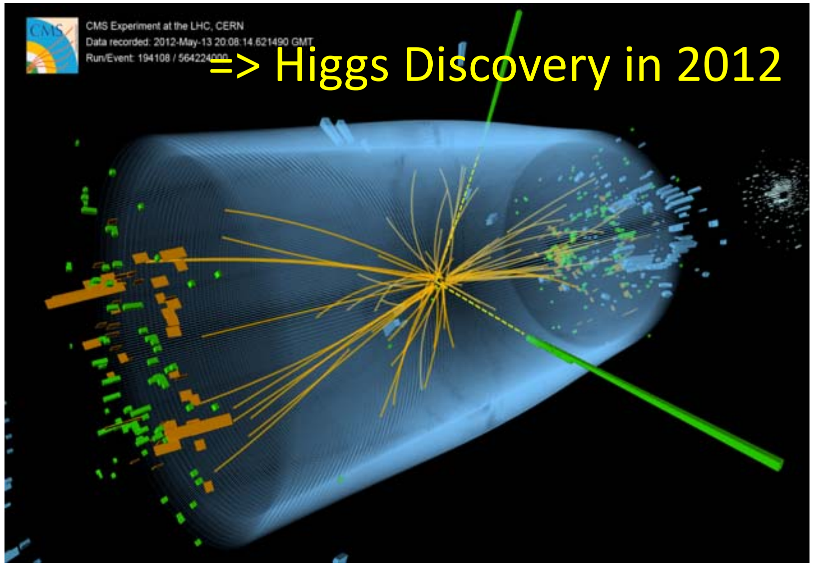
36 Super- modules

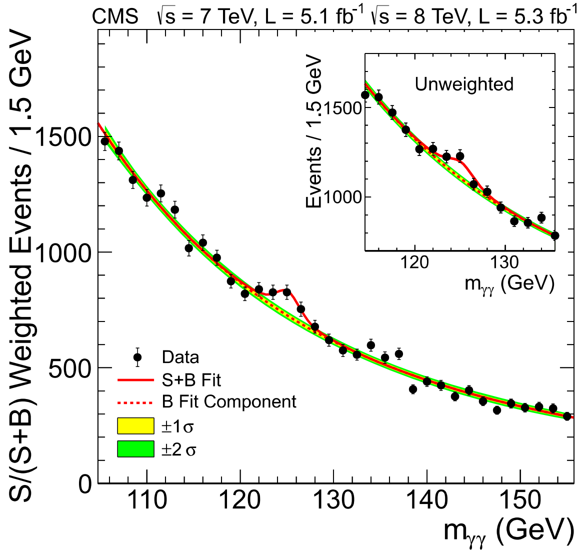
ECAL in CMS at P5 Cessy, France





CMS ECAL: Higgs bosons





François Englert et Peter Higgs, Physic Nobel Price in 2013

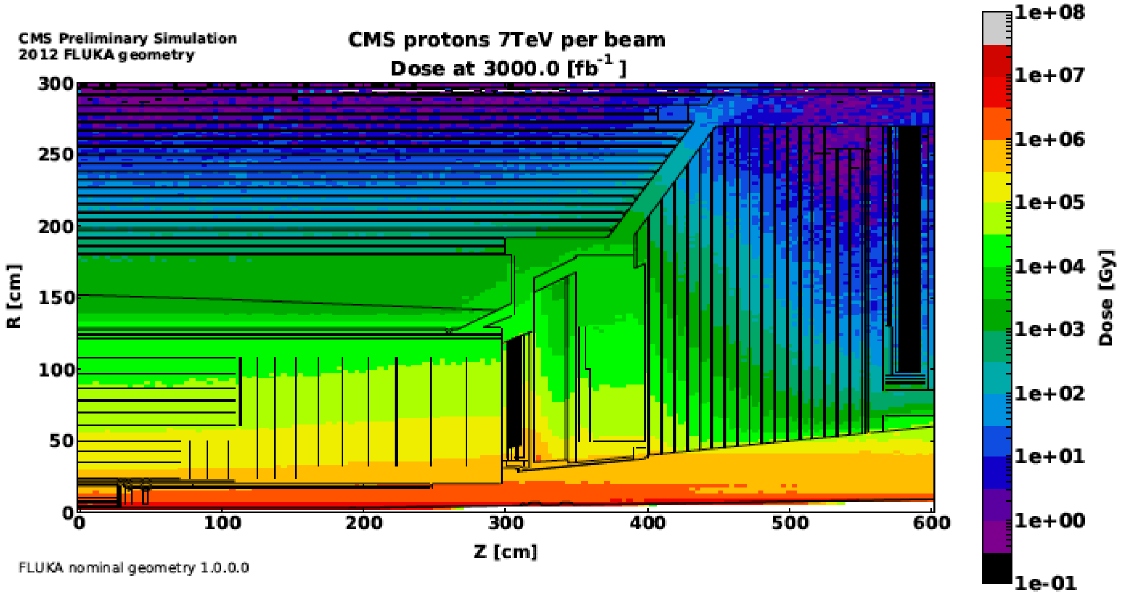
The calorimetry challenge in future High Energy colliders

- Precision Physics at future colliders required
  - High luminosity (high radiation level)
  - High granularity
  - Fast timing response

New challenge at High Luminosity LHC : radiation level

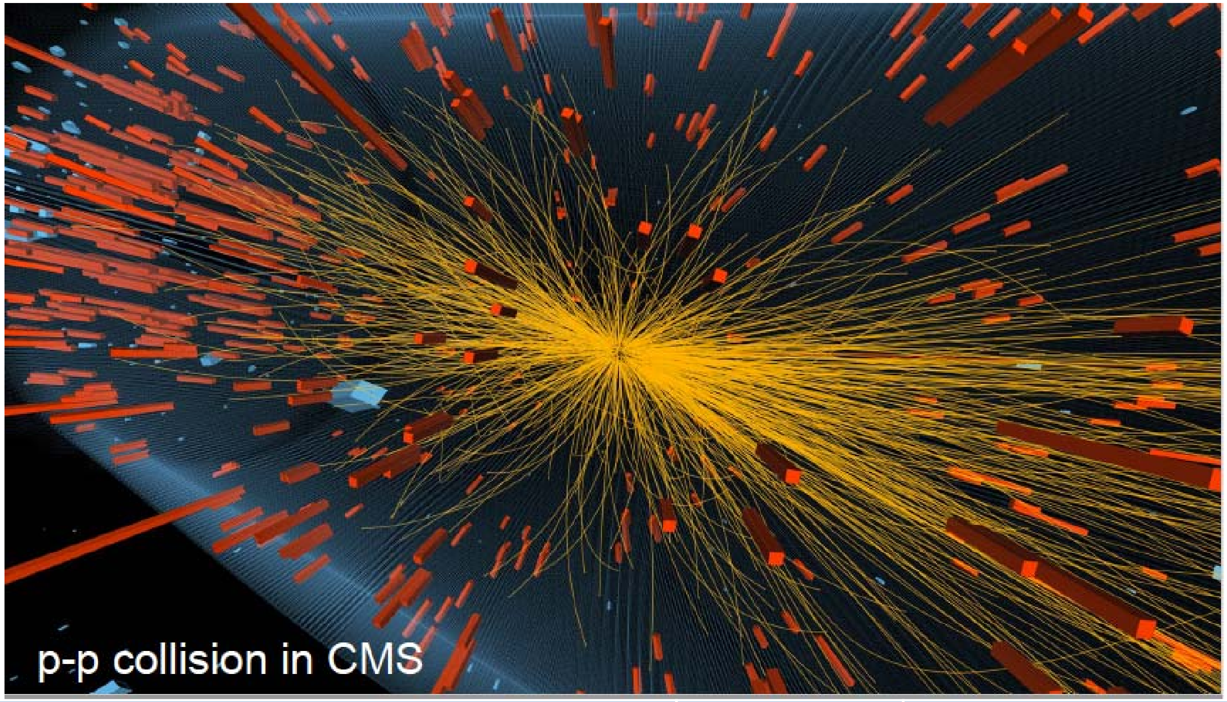
In CMS:

- ionizing radiation dose up to 1 MGy
- charged hadron up to 2 10^{14} cm^2



=> Need for very radiation hard material

New challenge : high rate

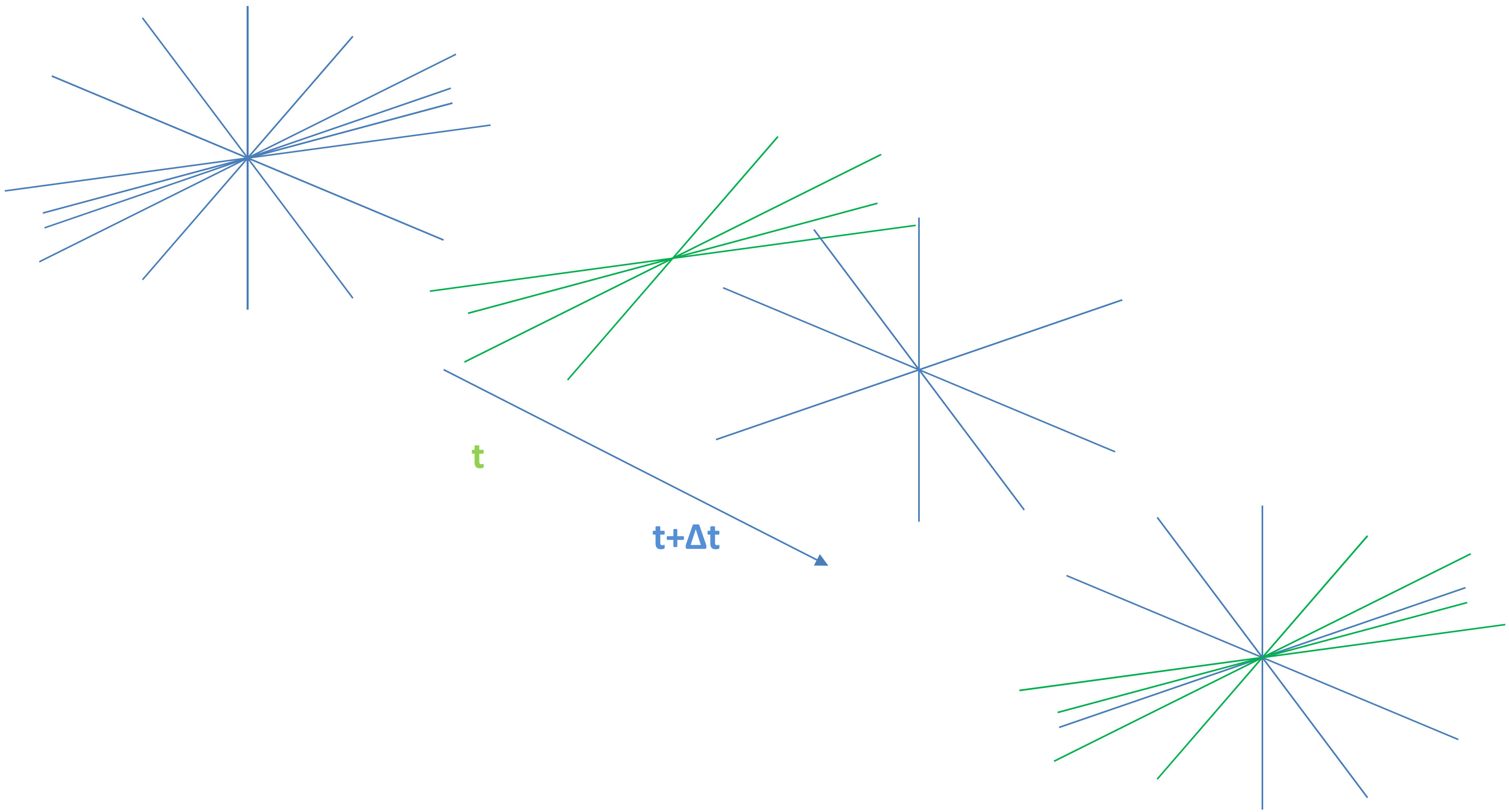


	LHC	High Luminosity
Distance between bunch crossing (BX)	50ns	25ns
Number of proton collisions/BX	<40>	<200>
Spatial density of interaction vertices	$0.3mm^{-1}$	$1.9mm^{-1}$

=> Need for fast timing detector

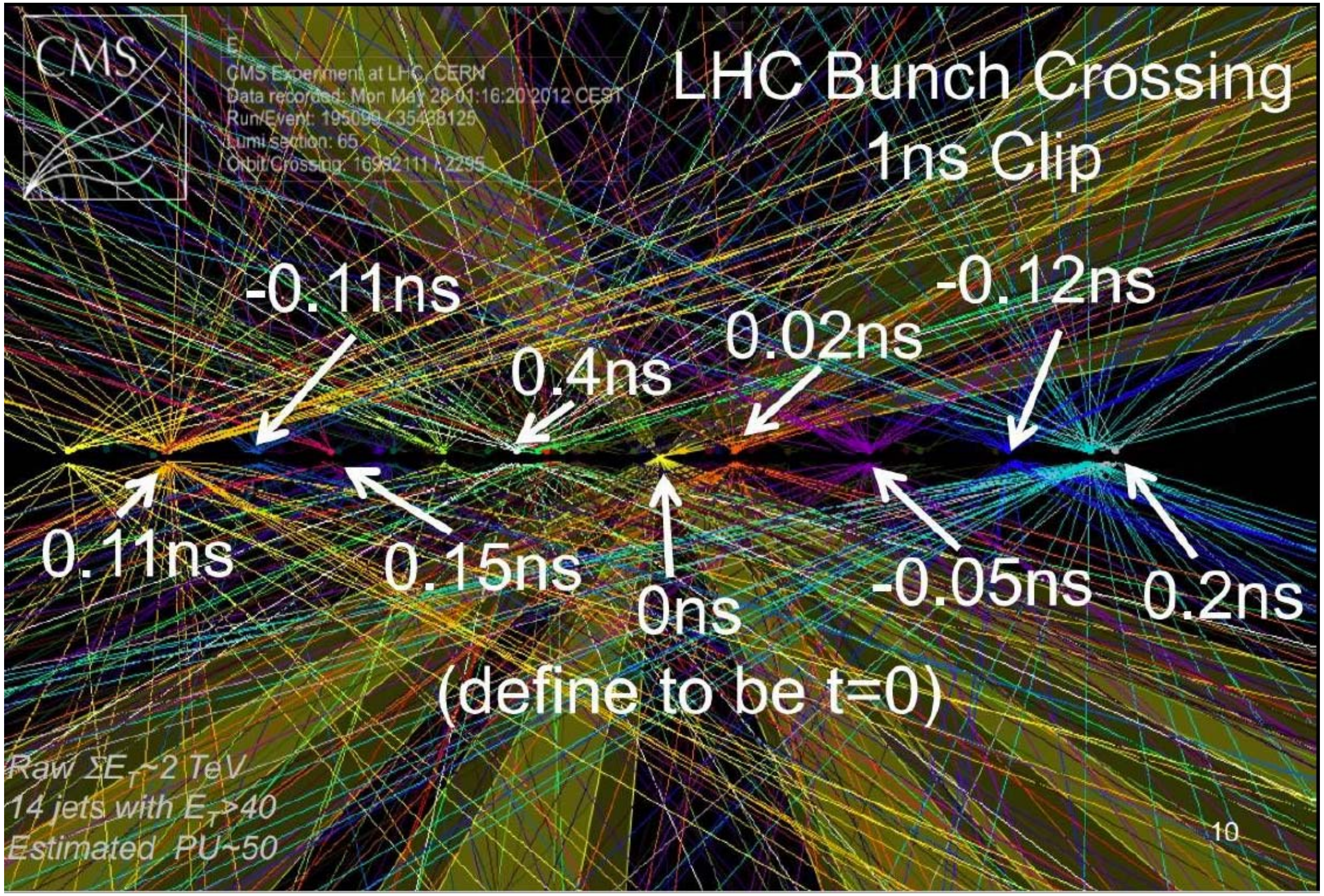
The advantage of timing information

Without timing information

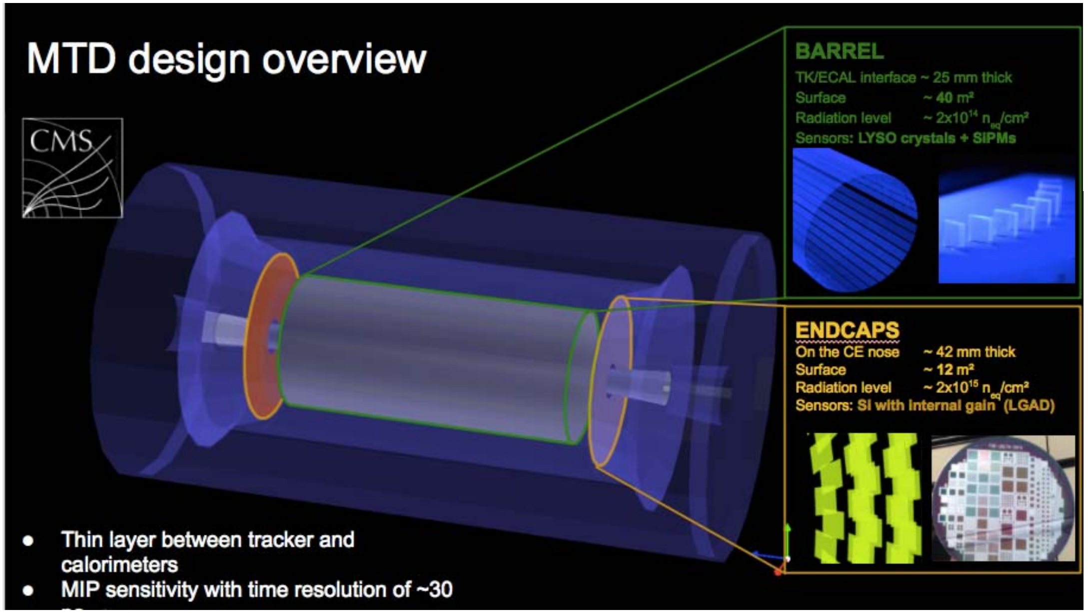


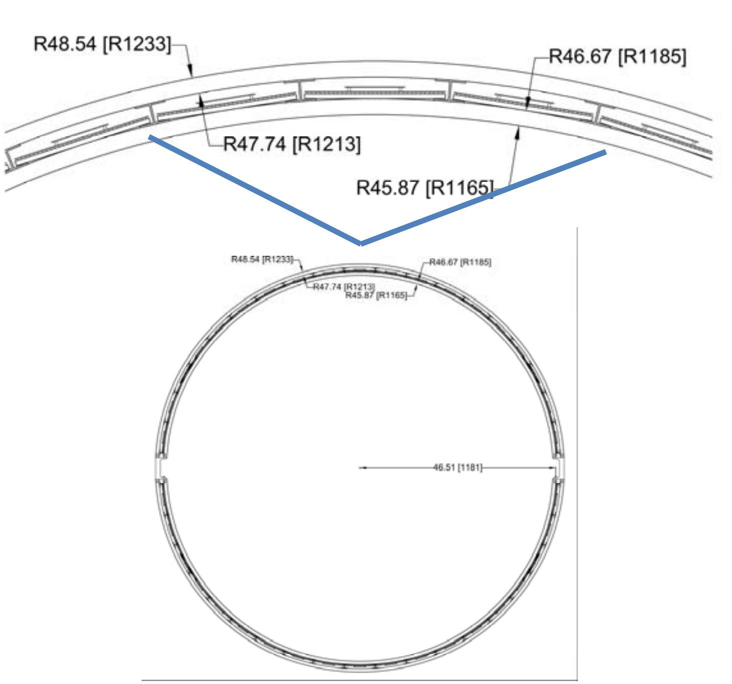
With timing information identification of vertex

Separation of the tracks with timing



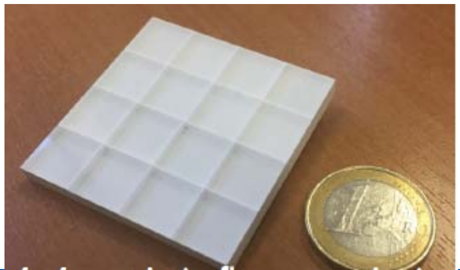
CMS Barel timing layer (BTL)



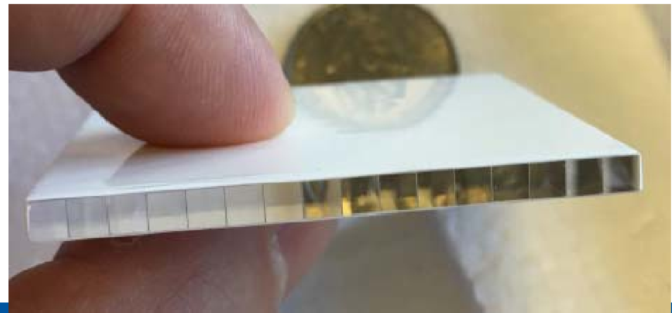


2 possible geometries

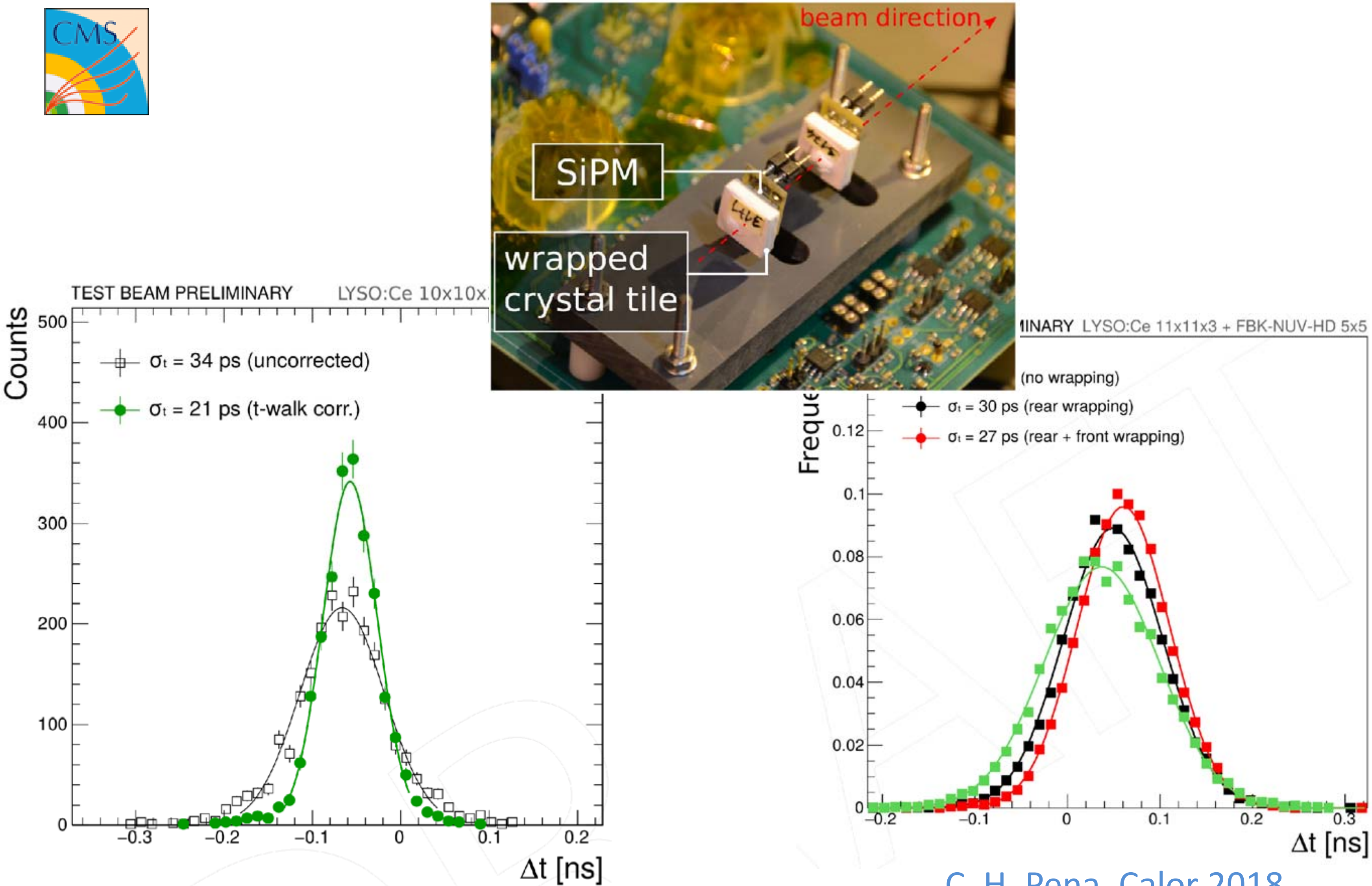
Plate $11.5*11.5*3mm^3$



short fibers ($3*3*50mmm^3$)

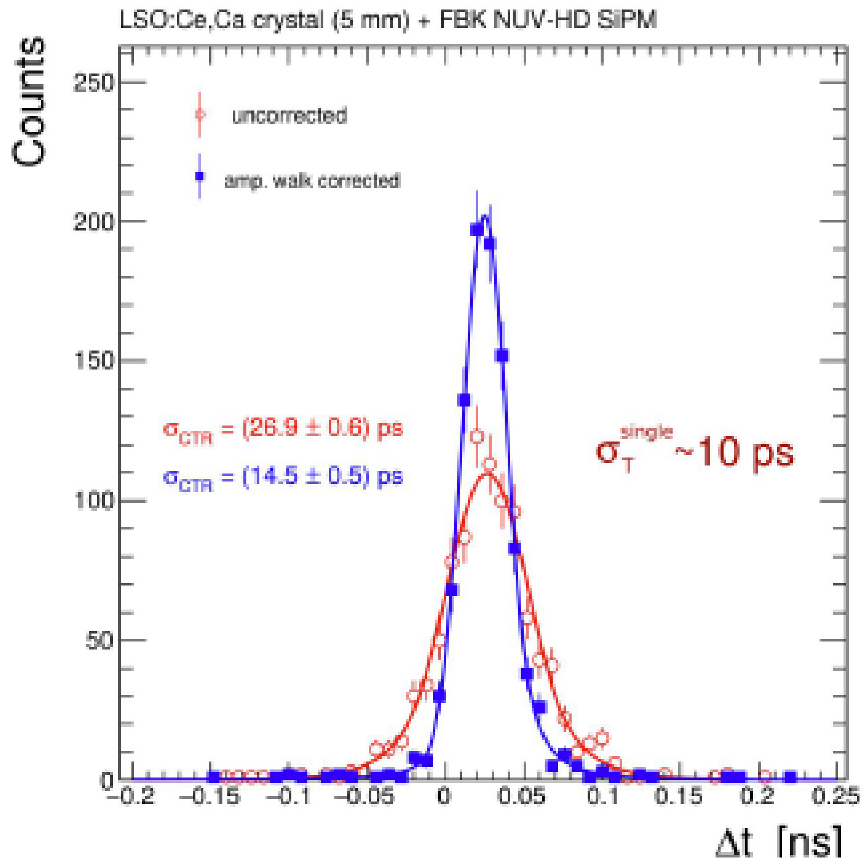


Timing resolution Prototype BTL



C. H. Pena, Calor 2018

Best time resolution with mip

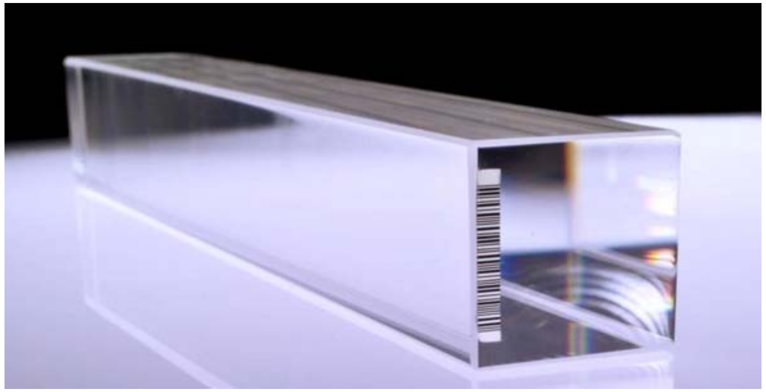


M.T. Lucchini et al., NIM A 852 (2017) 1-9

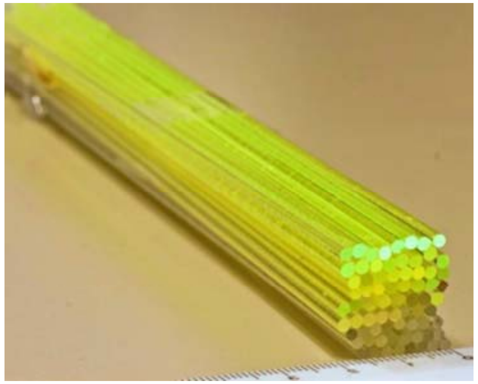
Scintillating crystal fibers: Flexibility for the calorimeter design

Homogeneous calorimeter

From bulk crystal



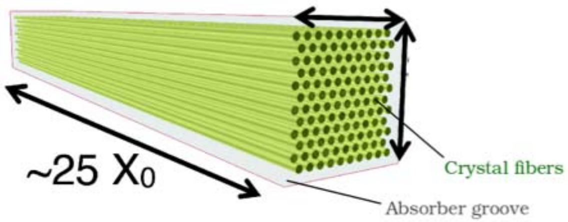
To bloc of fibers



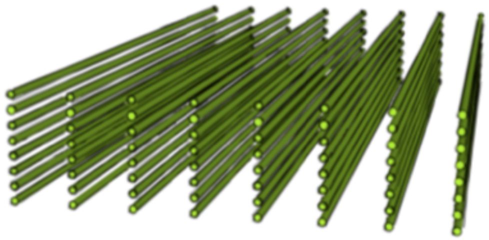
=> Need large volume of fibers with high density

Sampling calorimeter

Pointing Fibers
in a Spaghetti Calorimeter

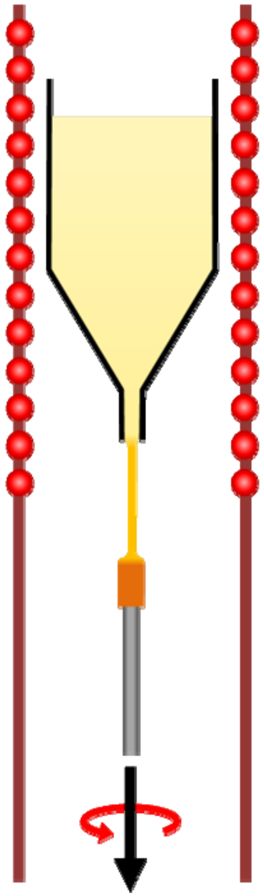


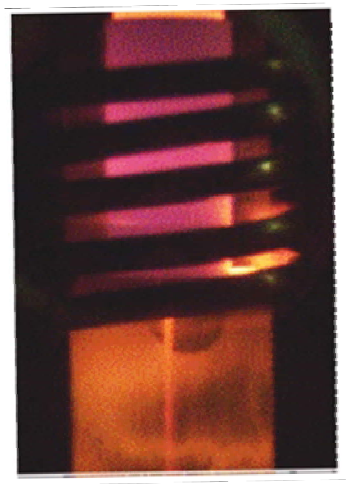
Layers of Crystal Fibers
in a sampling calorimeter



=> Need less fibers, possibility to use materials with lower density

Micro-Pulling down technology for crystal fiber growth



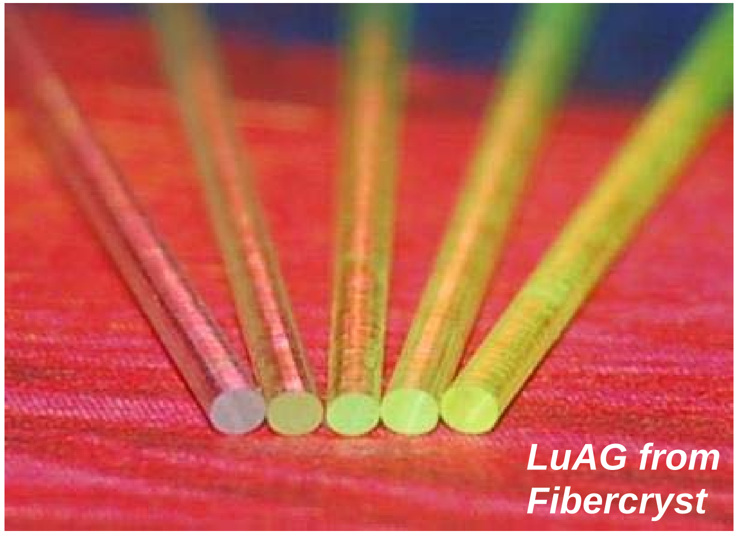


Courtesy Fibercryst

See lecture J. Pejchal Yesterday

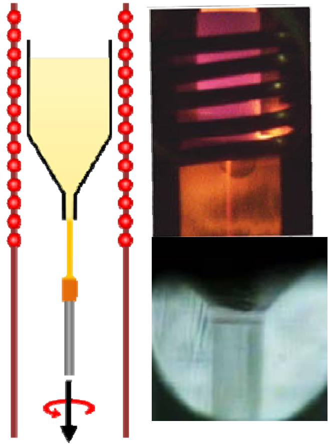
Micro-pulling down (µPD) : multiple advantages

- Wide range of diameters 300 µm – 3 mm
- Lengths up to 2 m
- Multiple geometries for capillary die ○ □ ⬡
- Fast pulling rates
- Multi-fibers pulling possibilities (in parallel)

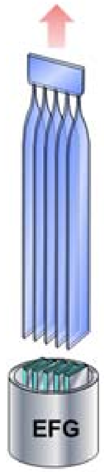


Crystal fiber productions

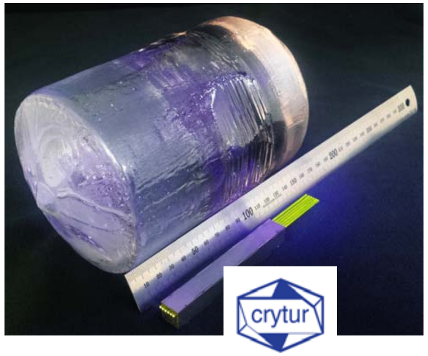
Micropulling down technique

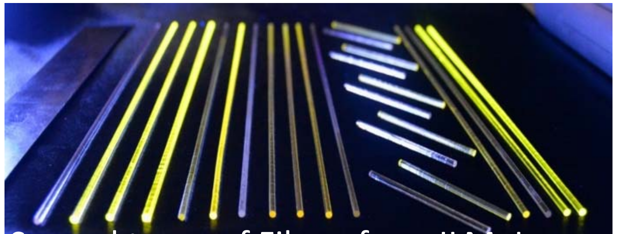


EFG

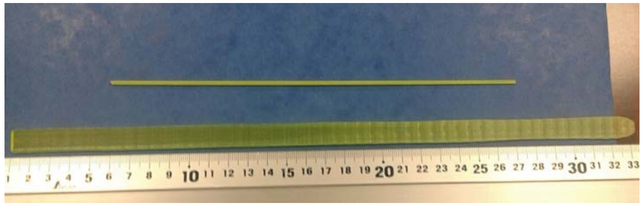


Czochralski method
Cut from large ingot

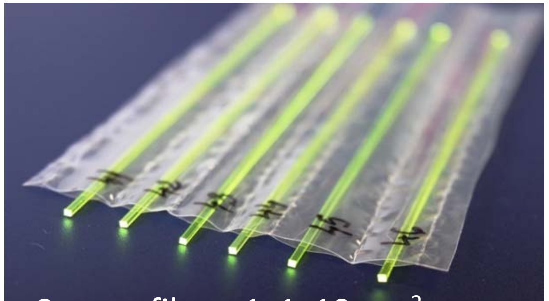




Several types of Fibers from ILM; Lyon



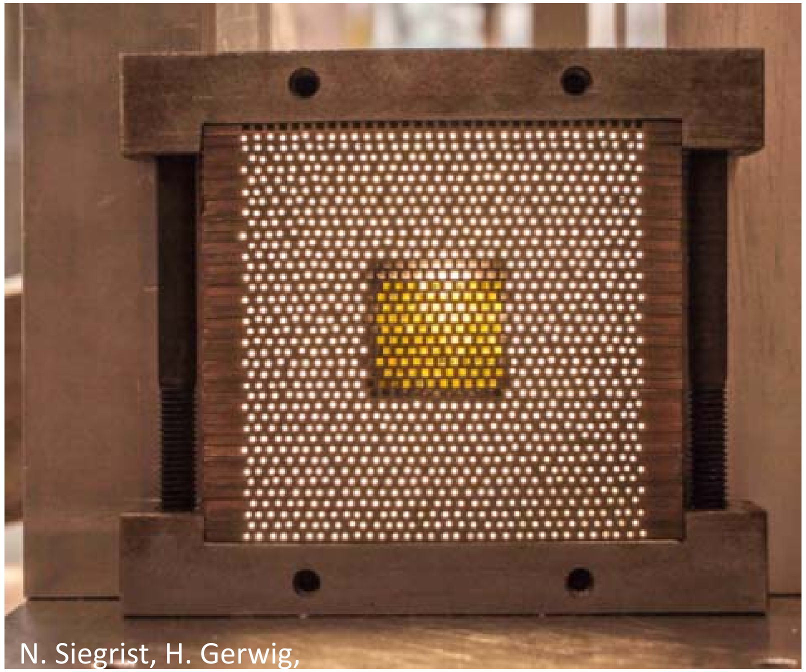
EFG-grown plate & fiber of LuAG:Ce
from Adamant Namiki Co , Japan

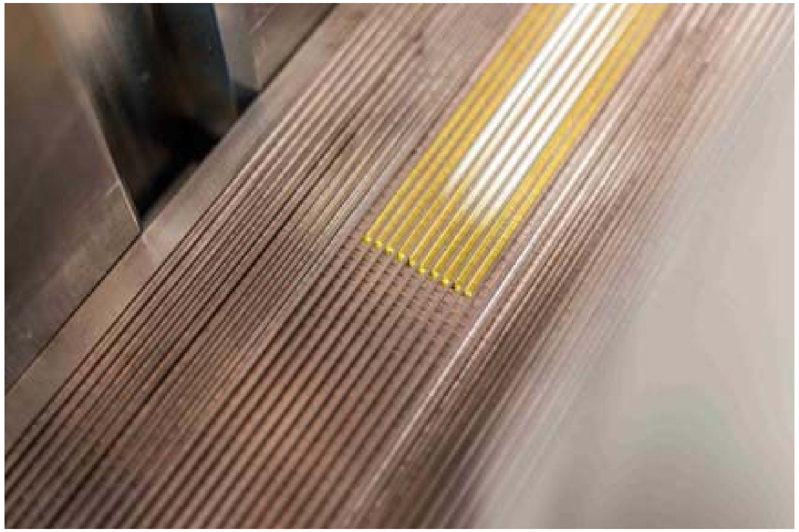


Square fibers 1x1x10mm^3

=> Feasibility study on going: main goal of Intelum project (European Rise project grant 644260) with 16 Partners (many from CCC) from 12 different countries: 11 academia and 5 companies

A SPACAL calorimeter unit developped at CERN



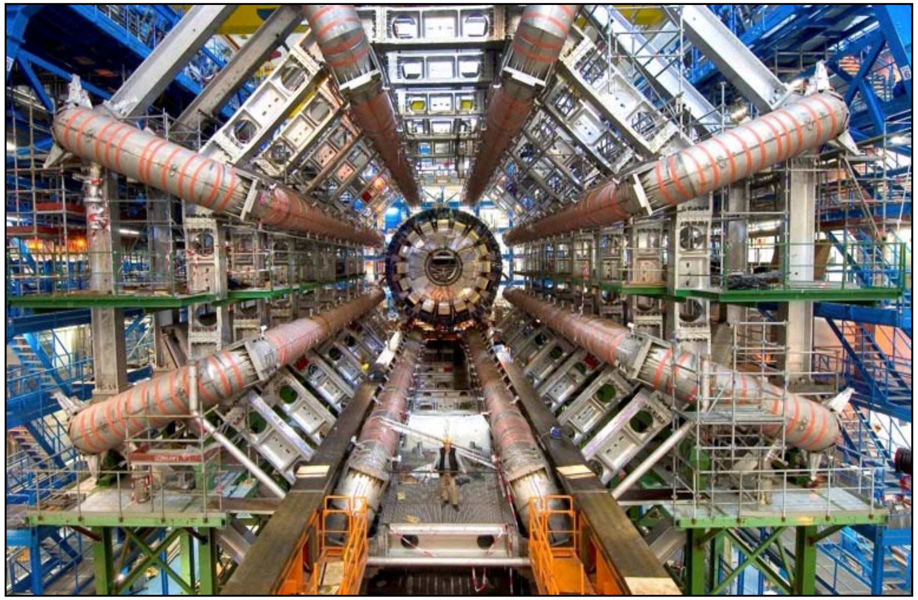


YAG square fibers
in a W-Cu Absorber
(stacked grooved plates)

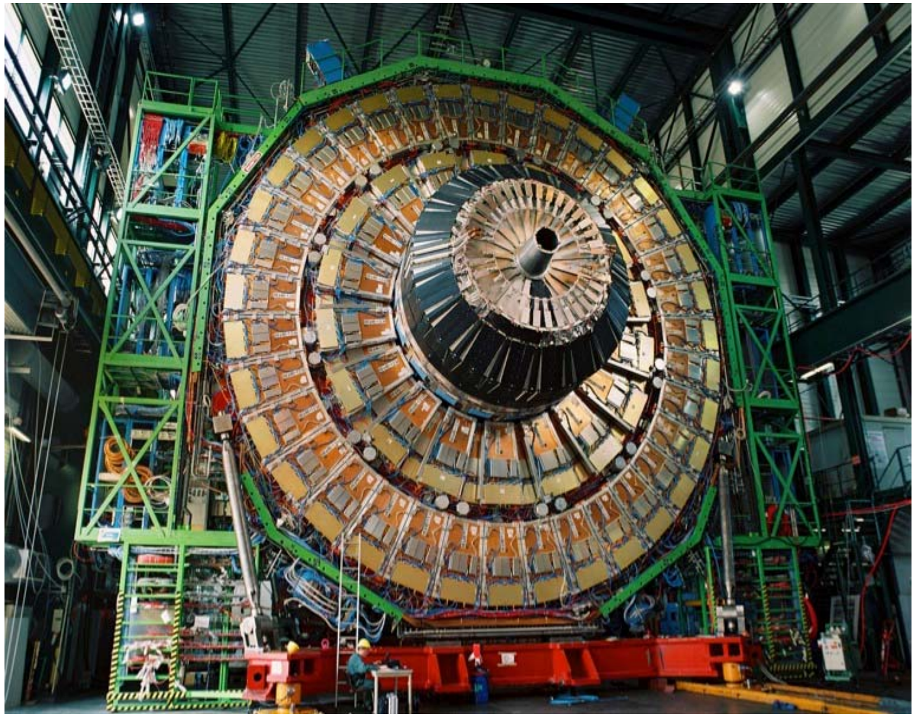
@ CERN development of leading edge technology

To build particles detectors like

ATLAS



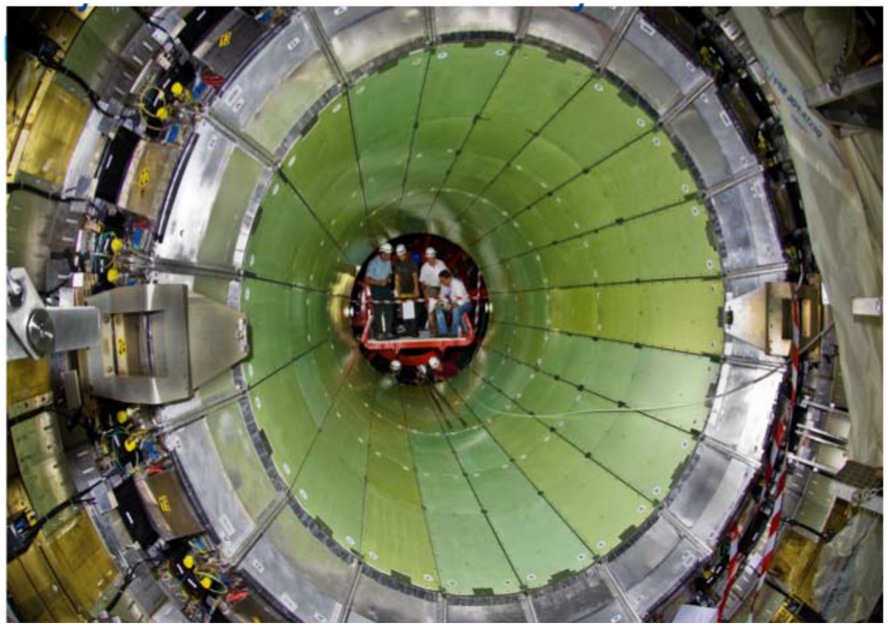
CMS



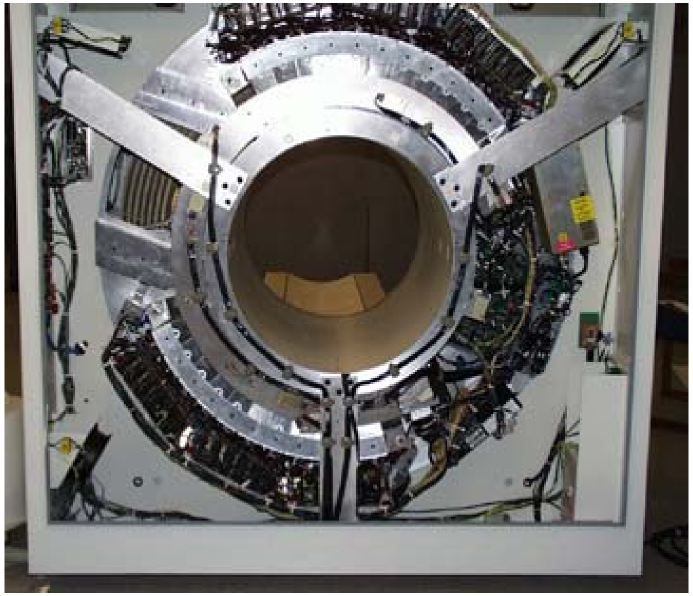
⇒ Application for medical imaging

Similar Challenges in HEP and medical imaging

CMS Electromagnetic calorimeter



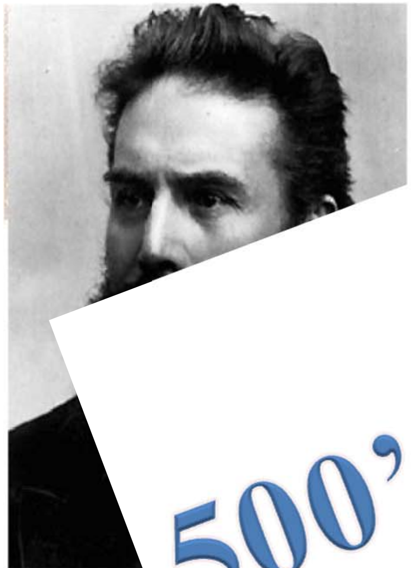
Positron Emission Tomograph (PET)



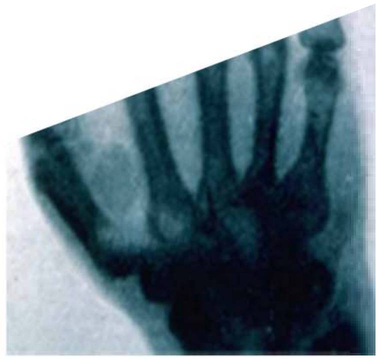
At LHC : Energy of particles < TeV

For PET: 0.000000511 TeV (511keV)Photons

X rays discovery: 1895



Today
500’000’000 Xray exams/y
In the world



895 Röntgen discovered Xrays

- vember 1895: First image of spouse’s hand

1st Nobel prize in Physics in 1901

Several imaging modalities

Anatomical / structural imaging	Fonctional Imaging
Information on the organs **STRUCTURE**, their shape, their limits, in some cases their contain (bone structures, calculs vesicaux)	Informations on the organs **FUNCTION** des organes, tissus or cells => **METABOLISM.**
Typical exams - **Radiology, CT scan,** - Échography, MRI, optical imaging	**Typical exams** - Scintigraphy - **Positrons emission Tomograph (PET)** - In some applications MRI, imagerie optique

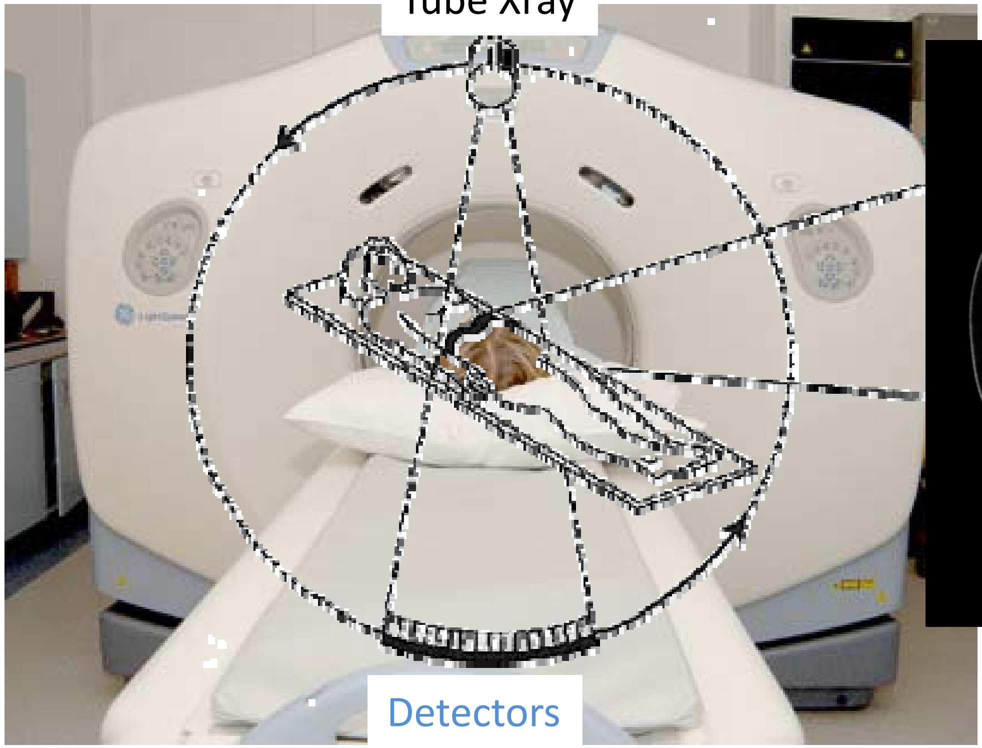
Scintillators in medical imaging

- X-ray detection, radiology, CT-scanner
- Single gamma detection: scintigraphy, SPECT
- Positron emission tomography (PET)

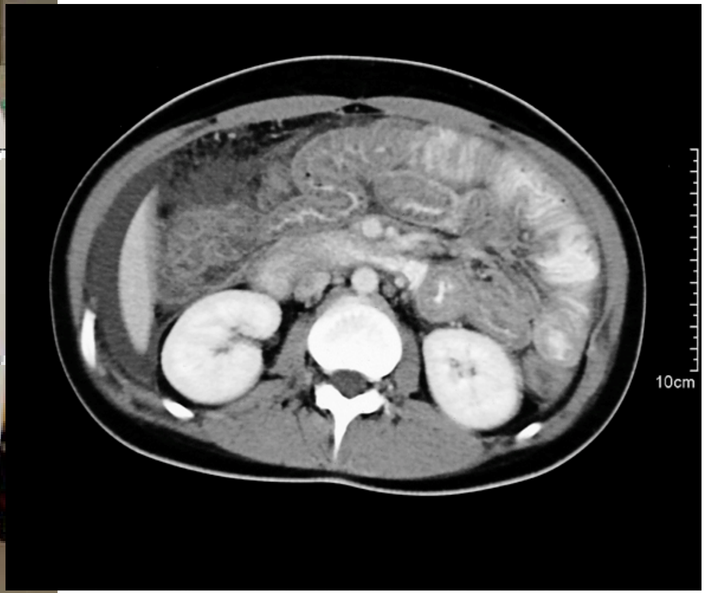
X ray CT
(Computed Tomograph)

Anatomical image

Tube Xray



Detectors

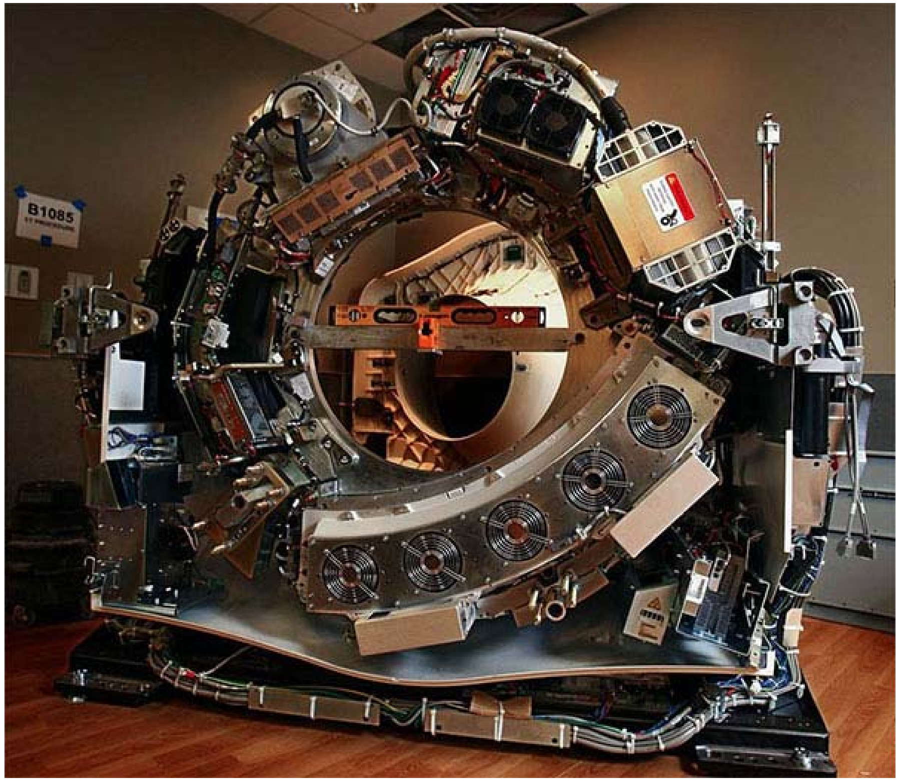


GE Medical Systems Discovery

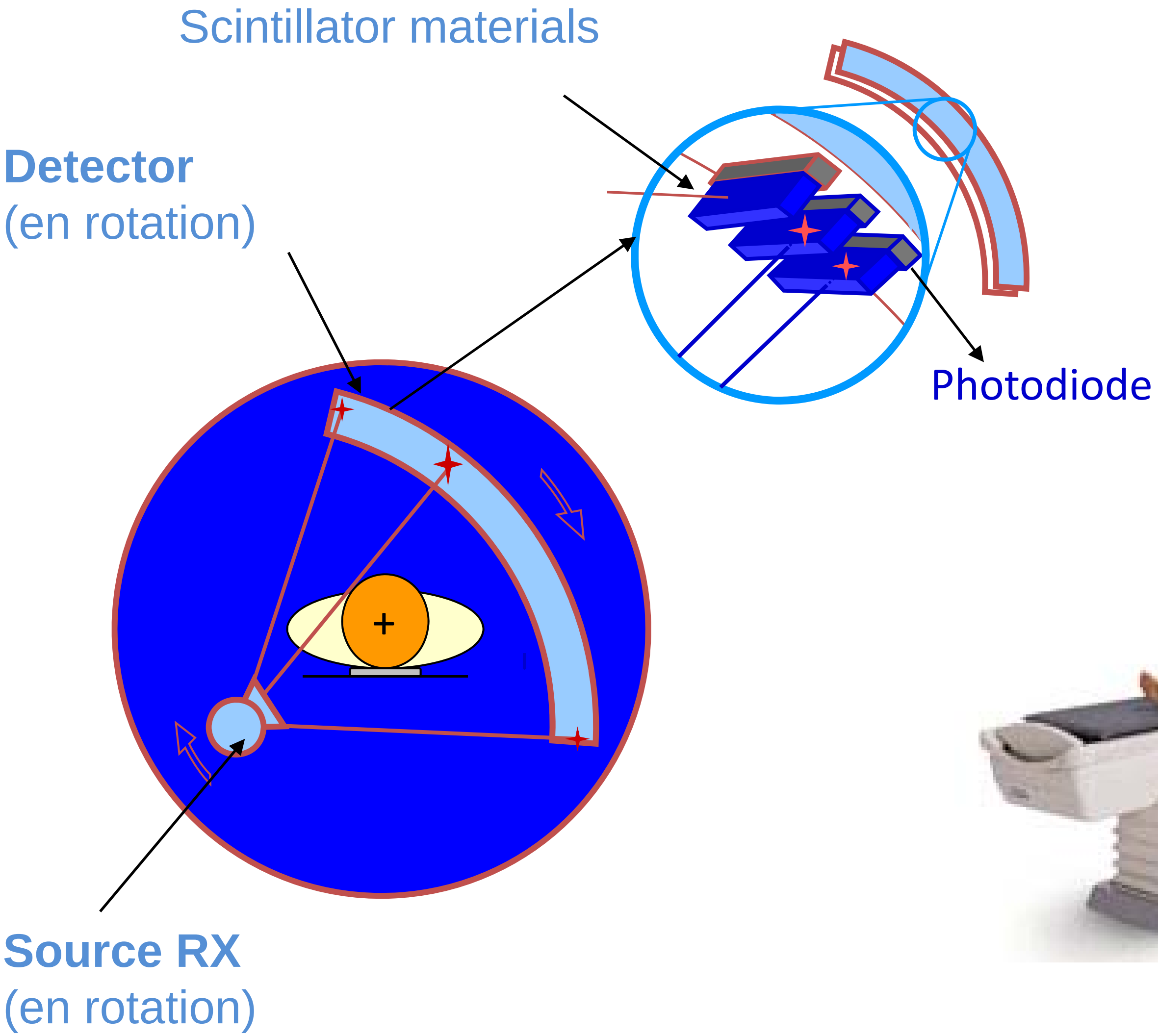
X ray CT
(Computed Tomograph)

Inside CT

GE Medical Systems Discovery



Xrays CT



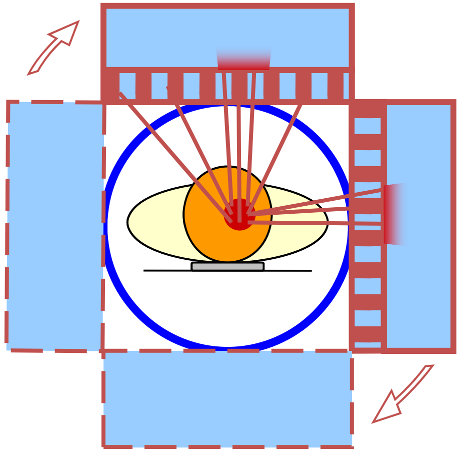
X-ray
Computed
Tomography

Scintillator for CT

	CsI (Tl)	$CdWO_4$	Gd_2O_3: Eu^{3+}	$(YGd)_2O_3$: Eu, Pr, Tb (YGO)	Gd_2O_2S: Pr, Ce, F (GOS) Tb(Ce)	La_2HfO_2:Ti
Density (g/cm^3)	4.52	7.9	7.55	5.9	7.34	7.9
Thickness to stop 99% 140keV X rays (mm)	6.1	2.6	2.6	6.1	2.9	2.8
LY (ph/MeV)	54000	28000		42000	50000	13000
Emission (nm)	550	495	610	610	520	475
Decay time (µs)	1	2,15		1000	2.4/600	10
Afterglow (% at 3ms)	0.5	0.05		5	<0.1/ 0.6	

P. Lecoq, NIM A809 (2016) 130-139

Single Photon Emission: SPECT



- SPECT requires large size crystals
- Most commonly used scintillator: NaI:Tl
  - inexpensive, large size
  - gamma m. f. p. ≈ 4 mm. @ 140 keV
  - large light yield
  - moderately good timing; τ= 230 nm

Marconi/Picker IRIX system for SPECT and PET

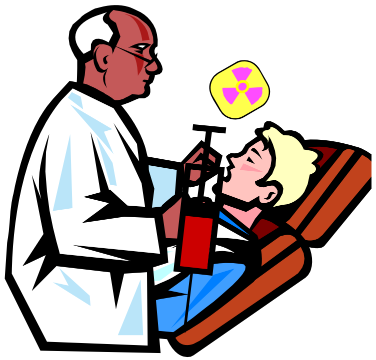
NaI:Tl single crystal

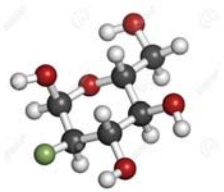
∅520 mm, mass > 550 kg

Institute of Single Crystals Kharkhov, Ukraine

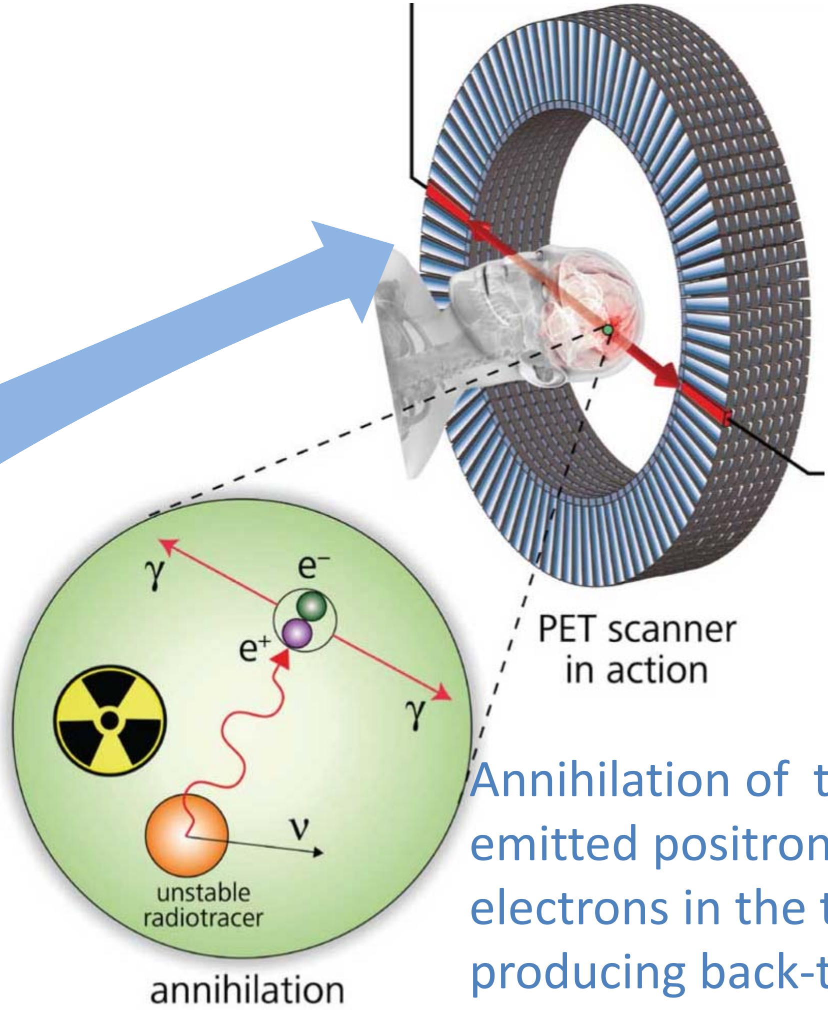
PET Principle

A positron emitting radiopharmaceutical is injected into the patient: the distribution





Fludeoxyglucose (18F-FDG)

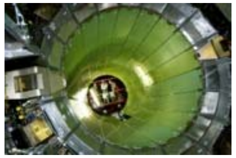


The patient is placed in the imaging scanner

Annihilation of the emitted positrons with electrons in the tissue producing back-to- bac photons detected by scintillating crystals

See more in
M. Pizzichemi lecture

From High Energy Physics to medical Imaging



Requirements for HEP EM calorimetry		Requirements for Medical Imaging
Crystals High density (> 6 g/cm³) Fast emission (< 100 ns), visible spectrum Moderate to high light yield High radiation resistance	Technology transfer →	**Crystals** High density (> 7 g/cm³) Fast emission (< 100 ns), visible spectrum High light yield Moderate radiation resistance
Photodetectors Compact High quantum efficiency and high gain High stability	Technology transfer →	**Photodetectors** Compact High quantum efficiency and high gain High stability
Readout electronics Fast shaping, low noise Highly integrated	Technology transfer →	**Readout electronics** Fast shaping, low noise Highly integrated
Intelligent and parallel DAQ Reduce dead time	Technology transfer →	**Intelligent and parallel DAQ** Reduce dead time
Software Accurate Monte Carlo simulation	Technology transfer →	**Software** Accurate Monte Carlo simulation
General design Compact integration of a large number of channels (> 10' 000)	Technology transfer →	**General design** Compact integration of a large number of channels (> 10' 000)

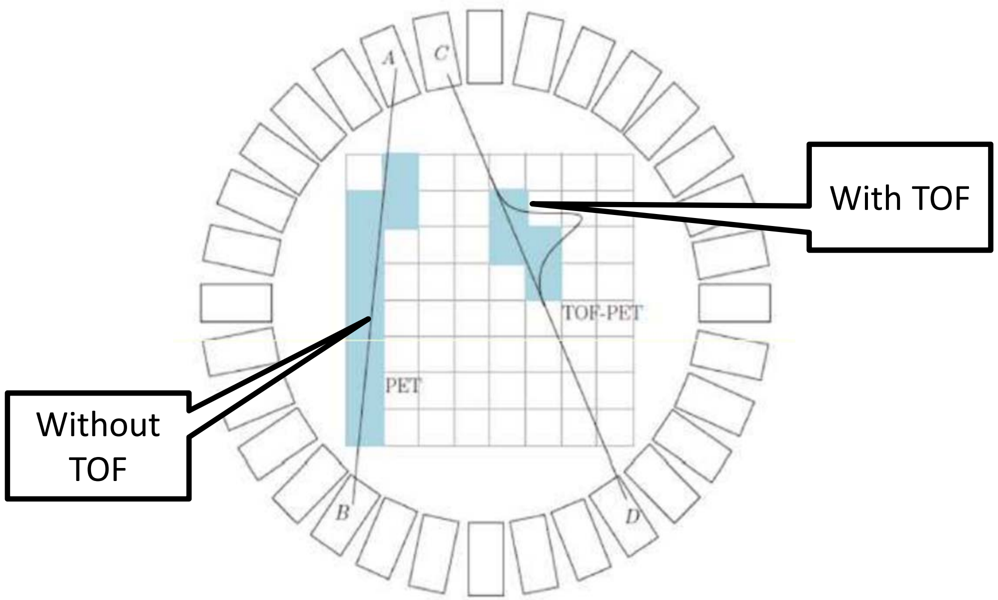
PET application

- Brain study
- Brain Disorder
- Heart problem
- Cancer
- Development of medecine

Scintillators for PET

	1962	1977	1995	1999	2001	2003	2007	2015
	NaI	BGO	GSO:Ce	LSO:Ce	LuAP:Ce	$LaBr_3$:Ce	LuAG:Ce	GAGG:Ce
Density g/cm^3	3.67	7.13	6,71	7.4	8.34	5.29	6.73	6.63
Atomic number	51	75	59	66	65	47	63	54
Decay Time (ns)	230	300	30-60	35-45	17	18	60	88-230
Light output (ph/MeV9	43000	8200	12500	27000	11400	70000	25000	46000
Peak emission (nm)	415	480	430	420	365	356	535	520
Refraction index	1.85	2.15	1.85	1.82	1.97	1.88	1.84	1.9

Time Of Flight (TOF)

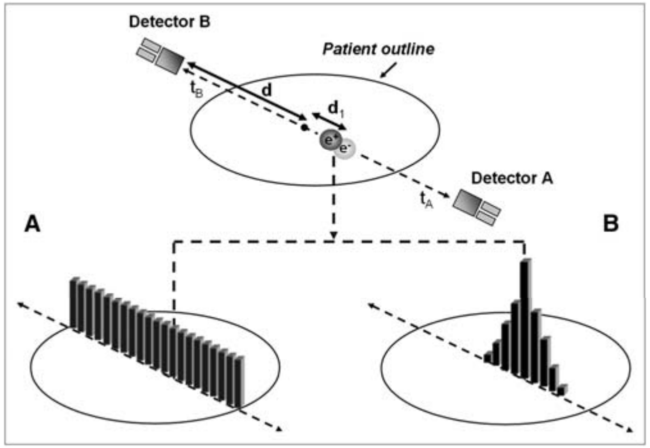


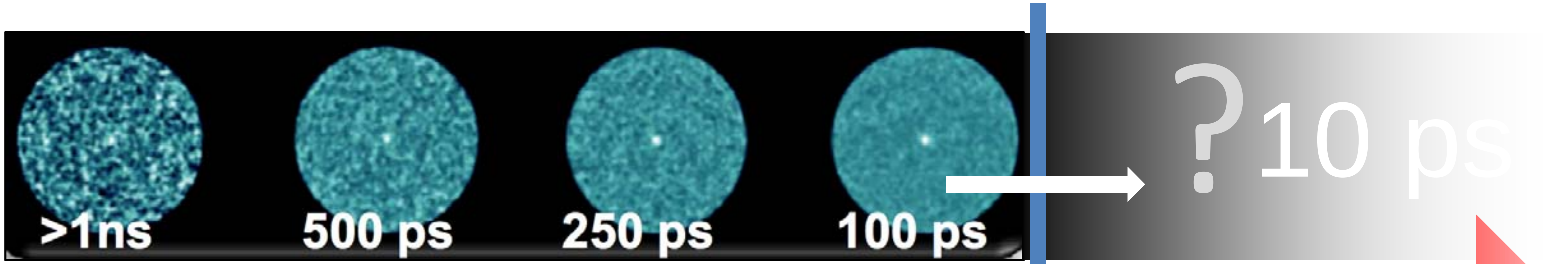
Compute the difference in **time of arrival** of gamma rays on detectors:

- Improved event localization along the LORs $\Delta x = c\frac{\Delta t}{2}$
- Decreased noise correlation in overlapping LORs $SNR_{TOF} \sim \sqrt{\frac{D}{\Delta x}} \cdot SNR_{CONV}$

The Merits of Time of Flight in PET (TOF-PET):

- In vivo: More precise, less invasive, more compact systems
- In vitro: Faster analysis of disease biomarkers
- Ultimatelly: Pave the way into precision medicine





Commercial systems

Effective event collimation
→ Background rejection
→ cm resolution along LOR (EndoTOFPET-US)

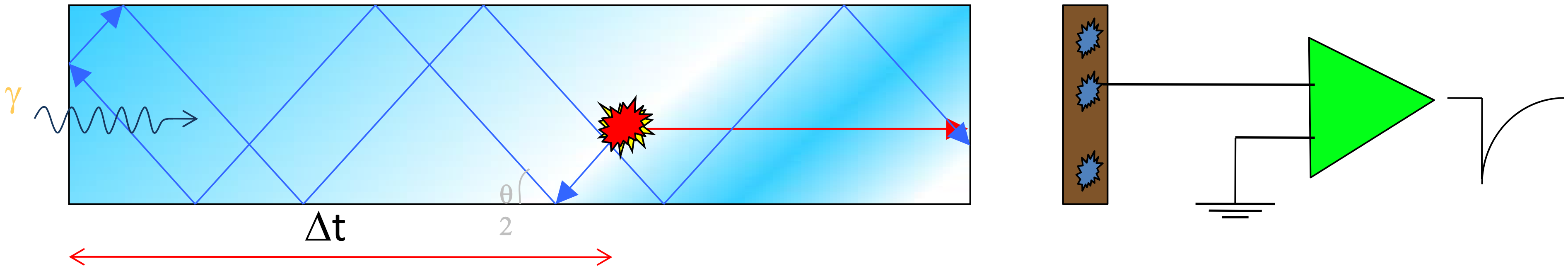
Five-fold S/N improvem.
→ Sensitivity gain of 25
→ Dose reduction

Direct 3D image reconstruction with:
→ mm resolution along LOR, and
→ Allow limited field of view

Commercial TOFPET today
550ps (250ps)

Lab today
100-200ps

Need to understand the photodetection Chain



$t_{kth\ pe} = \Delta t + t_{k'\ ph} + t_{transit} + t_{SPTR} + t_{TDC}$

- Δt: Conversion depth
- $t_{k'\ ph}$: Scintillation process
- $t_{transit}$: Transit time jitter
- t_{SPTR}: Single photon time spread
- t_{TDC}: TDC conversion time

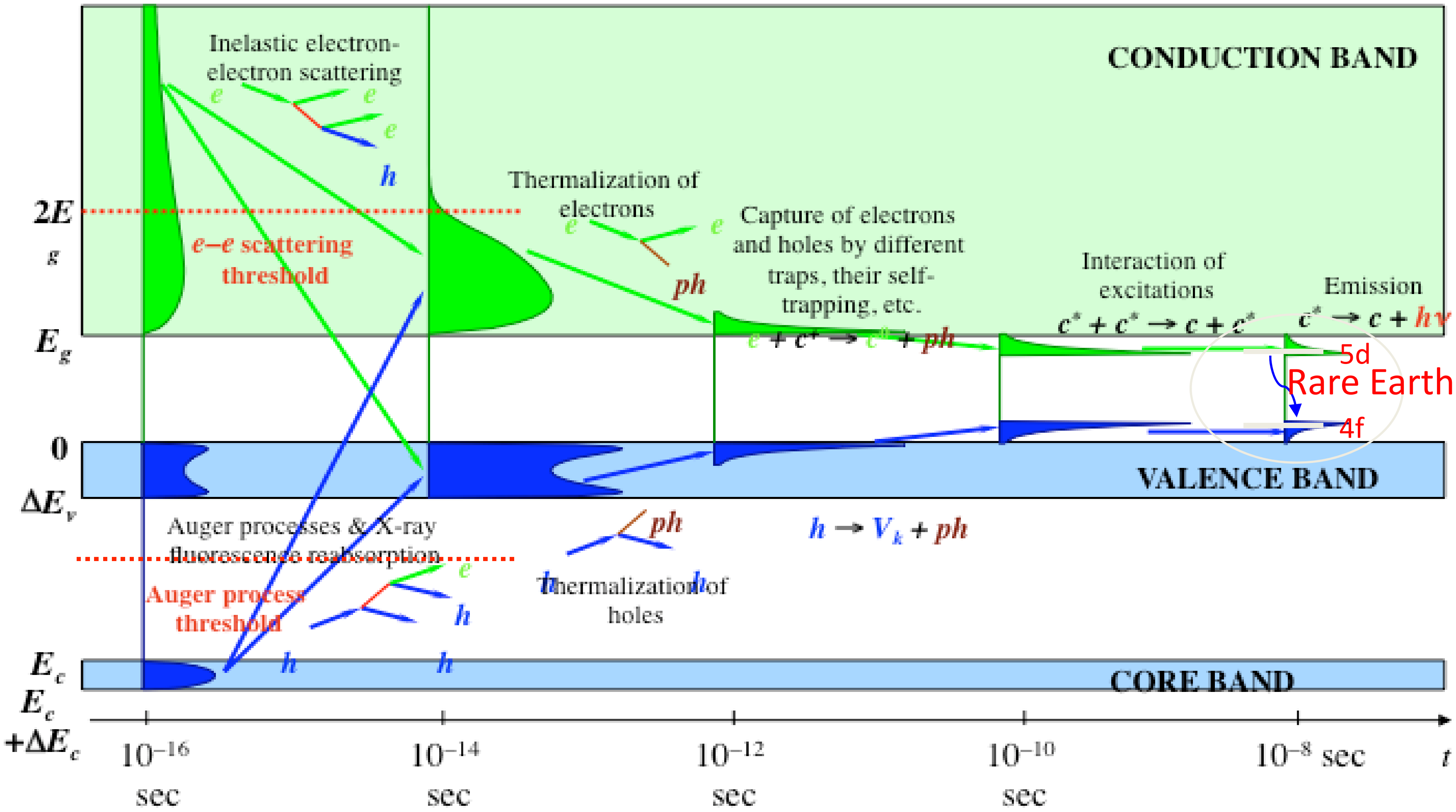
Scintillator R & D
- Particule Interaction
- Light generation
- Light transport
- Light transfer
- Light collection

Photodetector R & D
- Reduce SPTR and DCR
- Increase fill factor (PDE)
- Digital SiPM
- MCP for PET & HEP

Electronics R & D
- TDC < 10ps bins
- Monolithic architecture
- High bandwidth
- Low noise
- Massive parallel data
- High number of channels

⇒ **Challenge: Understanding key factors of timing resolution**
Proposing routes toward 10ps
FAST Action TD1401

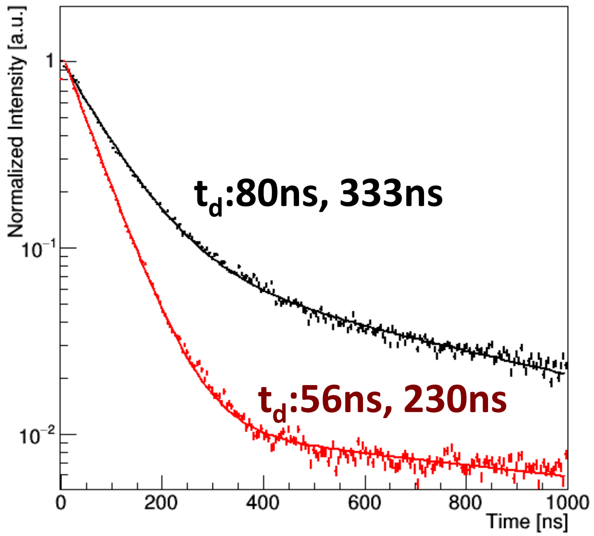
Light generation



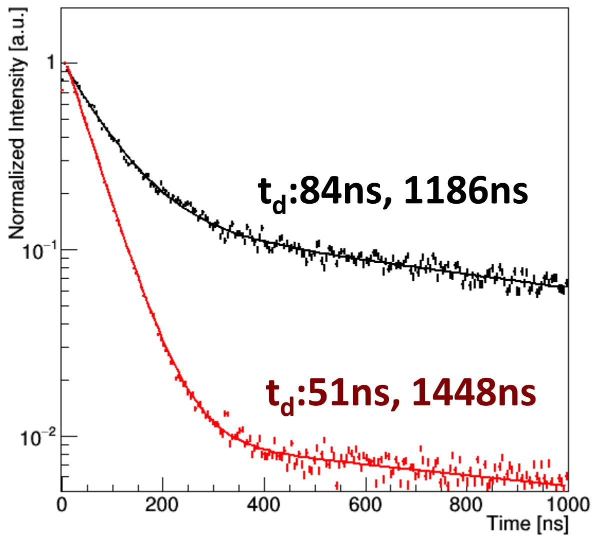
A. Vasil'ev, SCINT2001 proceedings, NIMA 486 (2002) 367

Influence of codoping on decay time

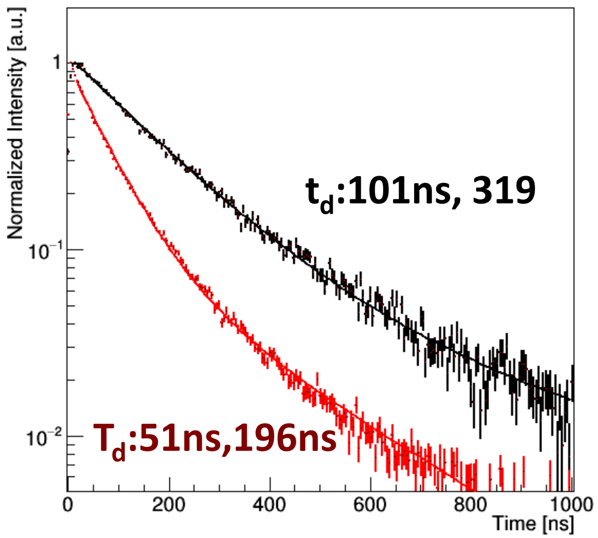
YAG



LuAG



GAGG

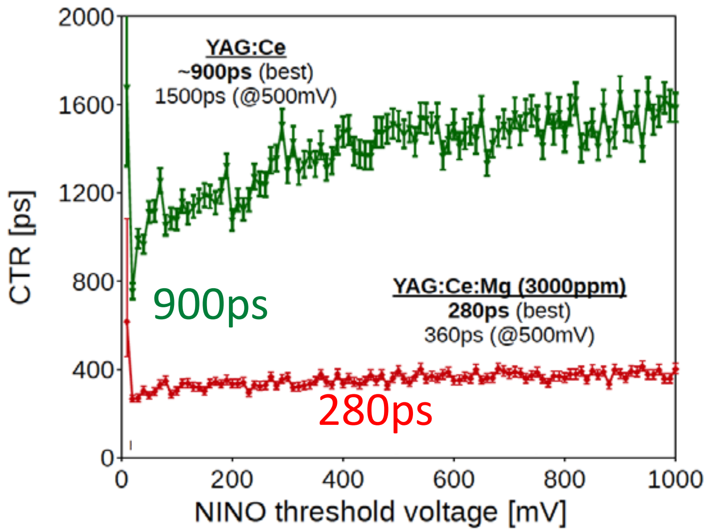


with Mg codoping: shorter decay time and strong decrease of slow component

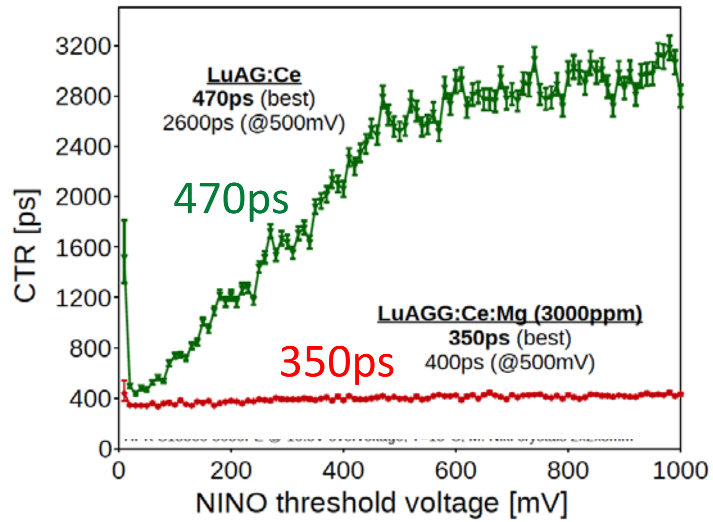
Kamada et al, O-14-3 at SCINT2015
M. Lucchini et al, NIM A Volume 816 (2016), pp 176–183,

CTR results with 511 keV

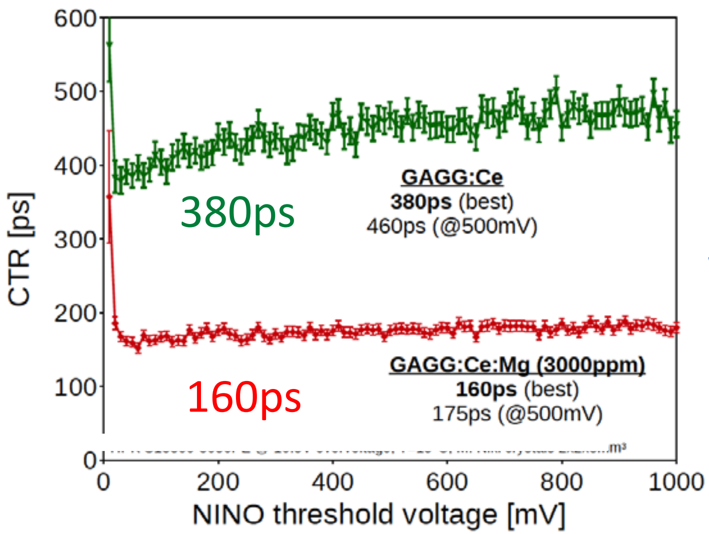
YAG



LuAG



GAGG



Very good CTR with GAGG

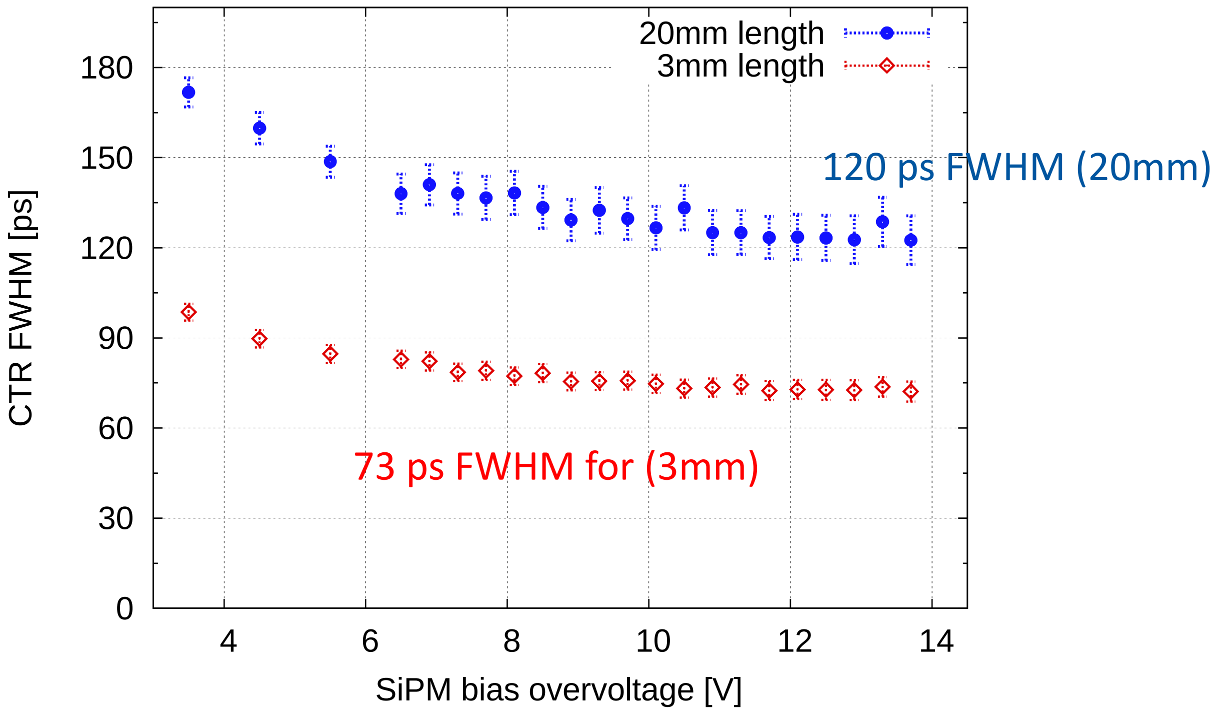
Measured with SiPM HPK
S13360-3050PE, T15°C

S. Gundacker et al., to be published in NIMA

Current state of the art time resolution with bulk crystals

LSO:Ce:Ca crystal - FBK NUV-HD SiPMs

CTR results @511keV:

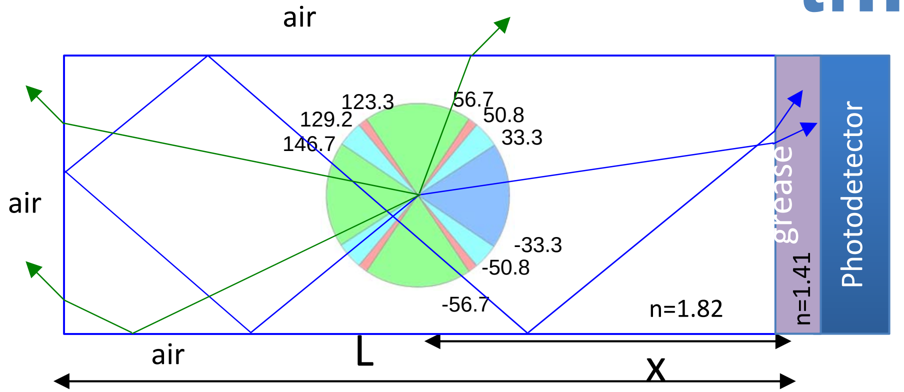


S. Gundacker et al, JINST 11P08008

Light transport, light collection improvement

- R&D on innovative ways to transport the light
- R&D on increase light collection
  - surface treatment,
  - photonic crystals,
  - light guide

Influence of crystal length on timing



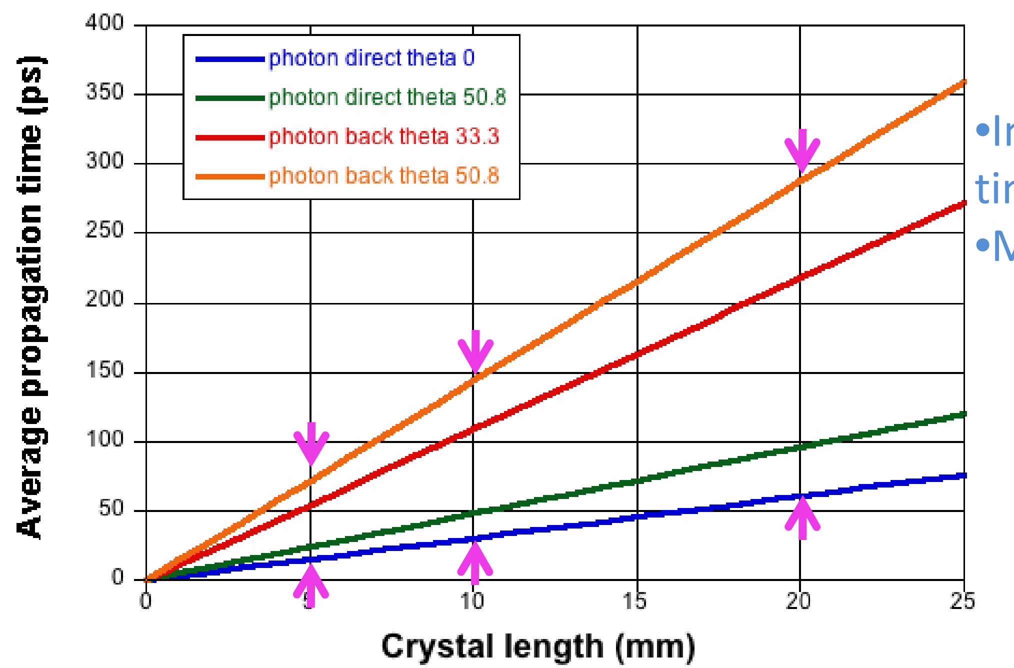
$$-50.8° \square \theta \square 50.8° \ : \ t_{prop} = \frac{n}{c} L_p = \frac{n}{c} * \frac{x}{\cos(\theta)}$$

$$129.2° \square \theta \square 146.7° \ \mathit{or} \ -129.2° \square \theta \square -146.7° :$$

$$t_{prop} = \frac{n}{c} L_p = \frac{n}{c} * \frac{(2L - x)}{\cos(\theta)}$$

50.8° critical angle for crystal-grease interface

Propagation time @ different emission angles for emission position averaged over crystal length

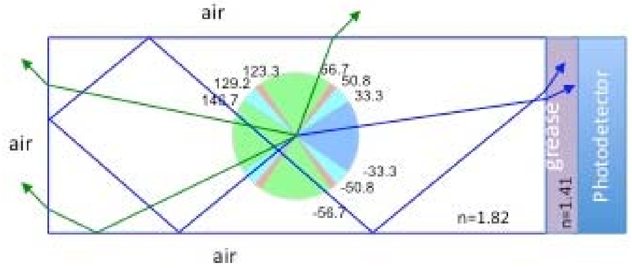


- Impact of light propagation on the coincidence time resolution increases with length;
- Maximum contribution averaged over length
  - For L= 5mm : Δt=56.8ps
  - For L=10mm : Δt=113.6ps
  - For L=20mm : Δt=227.2ps

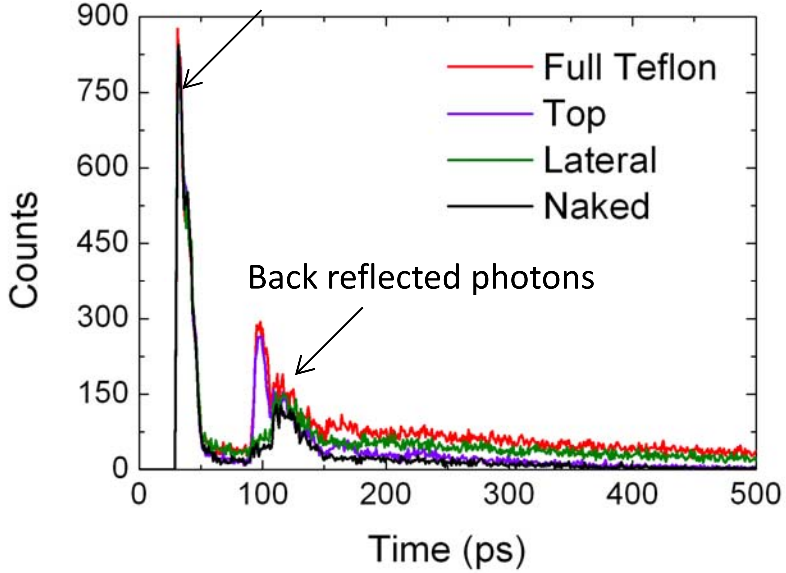
E. Auffray, TNS Vol. 60, no. 5, 2013, 3161-3171

Influence of crystal wrapping on timing

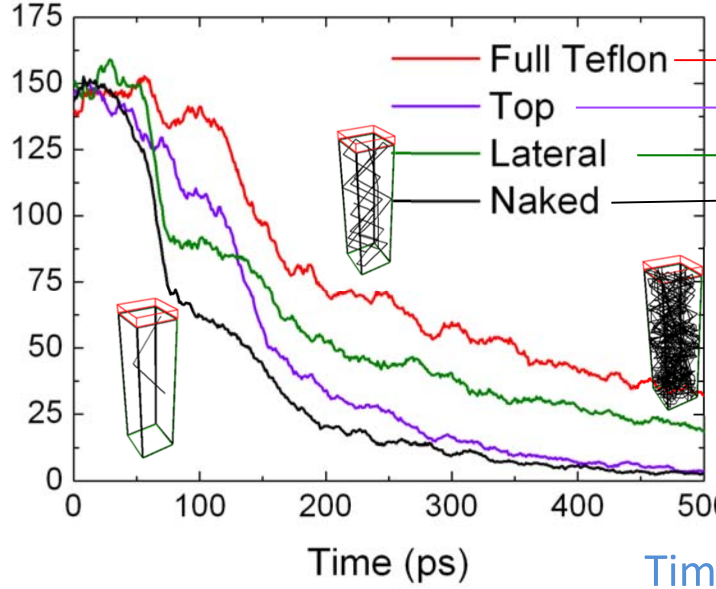
Simulation : LYSO 2x2x10mm³, 0.36m absorption length, 100µm diffusing edges



Extracted photons for 100'000 photons generated in the middle of crystal volume



Extracted photons for 100'000 photons generated in the entire crystal volume



Extraction efficiency:

- Full Teflon → 52%
- Top → 24.2%
- Lateral → 36.8%
- Naked → 18.5%

Time binning 1ps

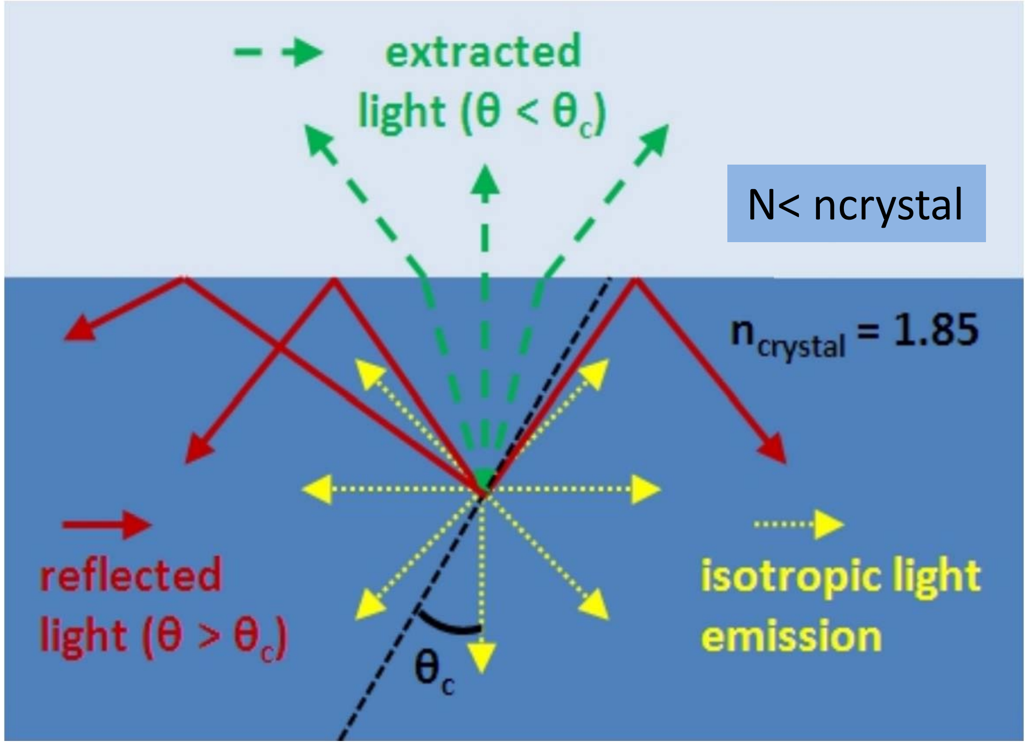
E. Auffray, TNS Vol. 60, no. 5, 2013, 3161-3171

Improvement of light collection

Inorganic scintillating crystals usually have high index of refraction

Coupling medium
Air, Glue
Photodetector

Crystal



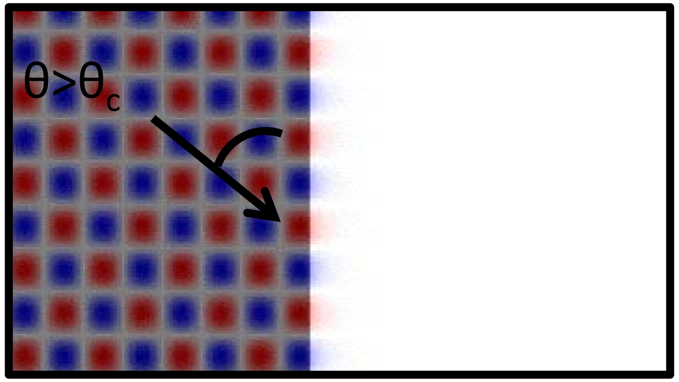
Up to 50% of the light may not exit the crystal

See R. Pots talk wednesday

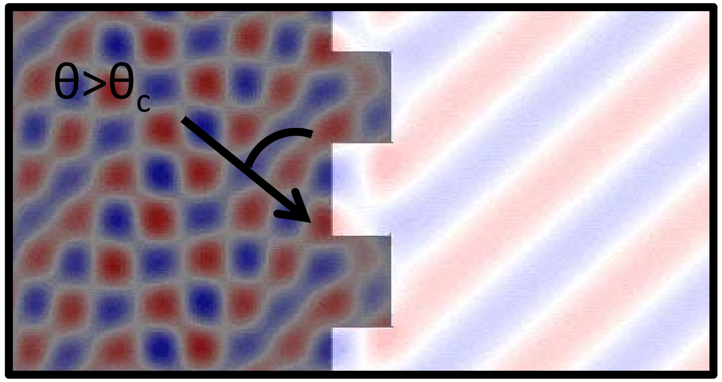
S. Gundacker et al 2016 JINST 11 P08008

Eg Photonic crystals

Structuration of exit surface with nanopaterning



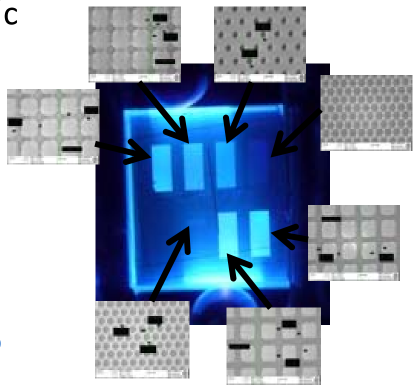
Crystal- air interface with PhC grating:



Total Reflection at the interface

$\theta > \theta_c$

Extracted Mode



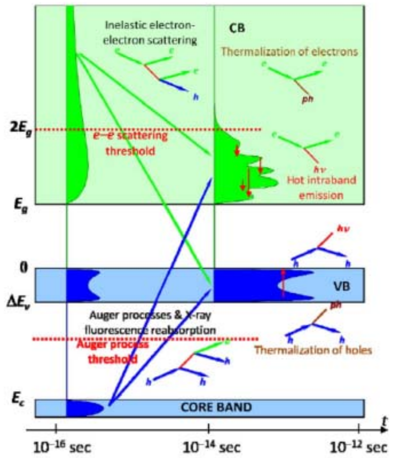
See R. Pots talk wednesday

A gain of up to factor 2

Knapitsch et al. IEEE TNS, VOL. 63, NO. 2, April 2016

To go towards 10ps time resolution

HIB mechanisms



A. Vasiliev

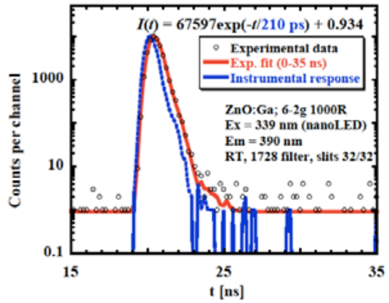
- **Need to exploit ultrafast emission process**
  - **Crossluminescence**
  - **Quantum confinement driven luminescence**
  - **Hot intraband luminescence (HIL)**
  - **Cherenkov radiation**

- **Develop new concepts of multifunctional materials**

Eg Combined bulk material with nanomaterial

ZnO:Ga nanopowders embedded in a thin layer of SiO_2

Procházková et al., Radiat Meas 90, 2016, 59-63



=> Next challenge for future years

See lectures yesterday
C. dujardin, V. Cuba, A. Hospodkova

Conclusion

- Scintillators are used in a large number of scientific and industrial domains
- But no ideal scintillator

  => Need for new idea & development

eg. by combining “standard material and nanomaterial

- Fascinating field of research !!

Acknowledgement

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