DE LA RECHERCHE À L'INDUSTRIE

Mesurer l'infiniment petit et observer l'infiniment grand

Vendredi 5/07 11h (IJCLAB)
Lundi 8/07 12h (CEA IRFU)
Visite Labo 14h (CEA IRFU)
Mercredi 10/07 11h (IAS)

Maxence Vandenbroucke

07/2024

université PARIS-SACLAY

PLAN DES COURS

Cours 1 : Généralités

-Introduction de la théorie à la pratique
-Qu'est-ce qu'une expérience de physique?
-Que veut-on observer à propos d'une particule?
-Architecture générale d'une expérience en physique subatomique

Cours 2 : Les détecteurs dans le détails

- Interaction particule-matière
- Les Détecteurs à ionisations
- L'exemple des détecteurs gazeux
- Experiences de Physique des Particules

Cours 3 : Exemples d'expériences

Basé sur les cours de Stefano Panebianco (CEA/IRFU),
et le cours de Werner Riegler (CERN),
Particle Detectors , Second Edition, C. Grupen & B. Shwartz

PLAN DES COURS

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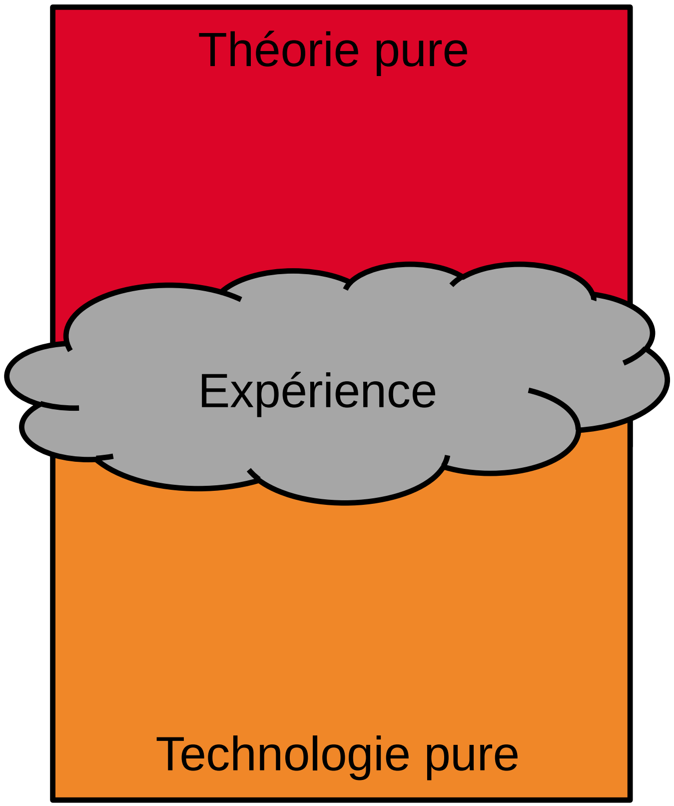
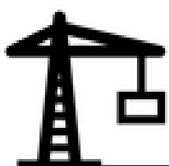
"I'm searching for my keys."

LA THEORIE ET LA PRATIQUE



- Théorie
- Construction des Modèles
- Prédiction avec des Modèles
- Simulation de l’expérience

- Design d’expérience
- Choix du dispositif expérimental
- Electronique/acquisition
- Reconstruction des évènements
- Comparaison avec la simulation/calcul
- Papier, Communication

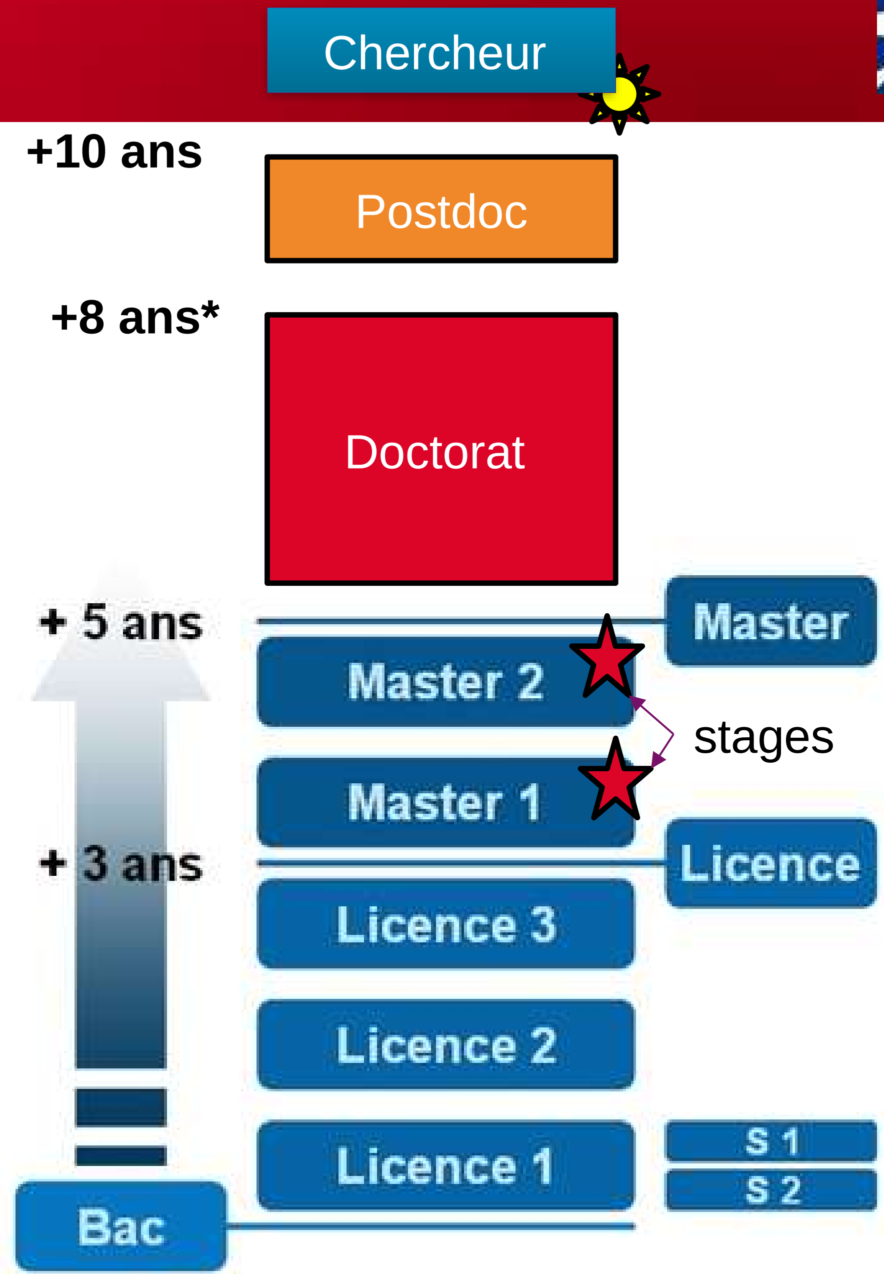


Le physicien complet est à la fois proche des interrogations fondamentales, mais aussi des avancés technologiques pour trouver un espace de découverte potentielle

(vision un peu naïve)

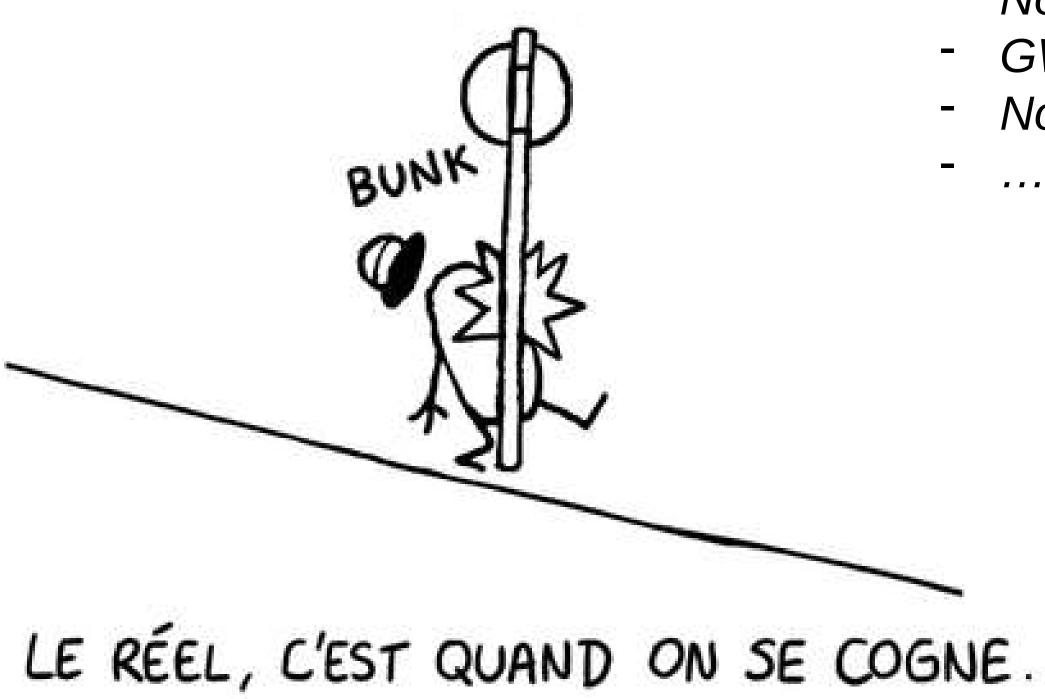
	Astro	Nucleaire	Particules	Cosmo	Medical	…
Inge						
Prof						
Analyse						
Detection			X			
Chef						
Theoricien						
Communication						
… … … …						

Un choix matriciel !



*en France, 3-7ans sinon

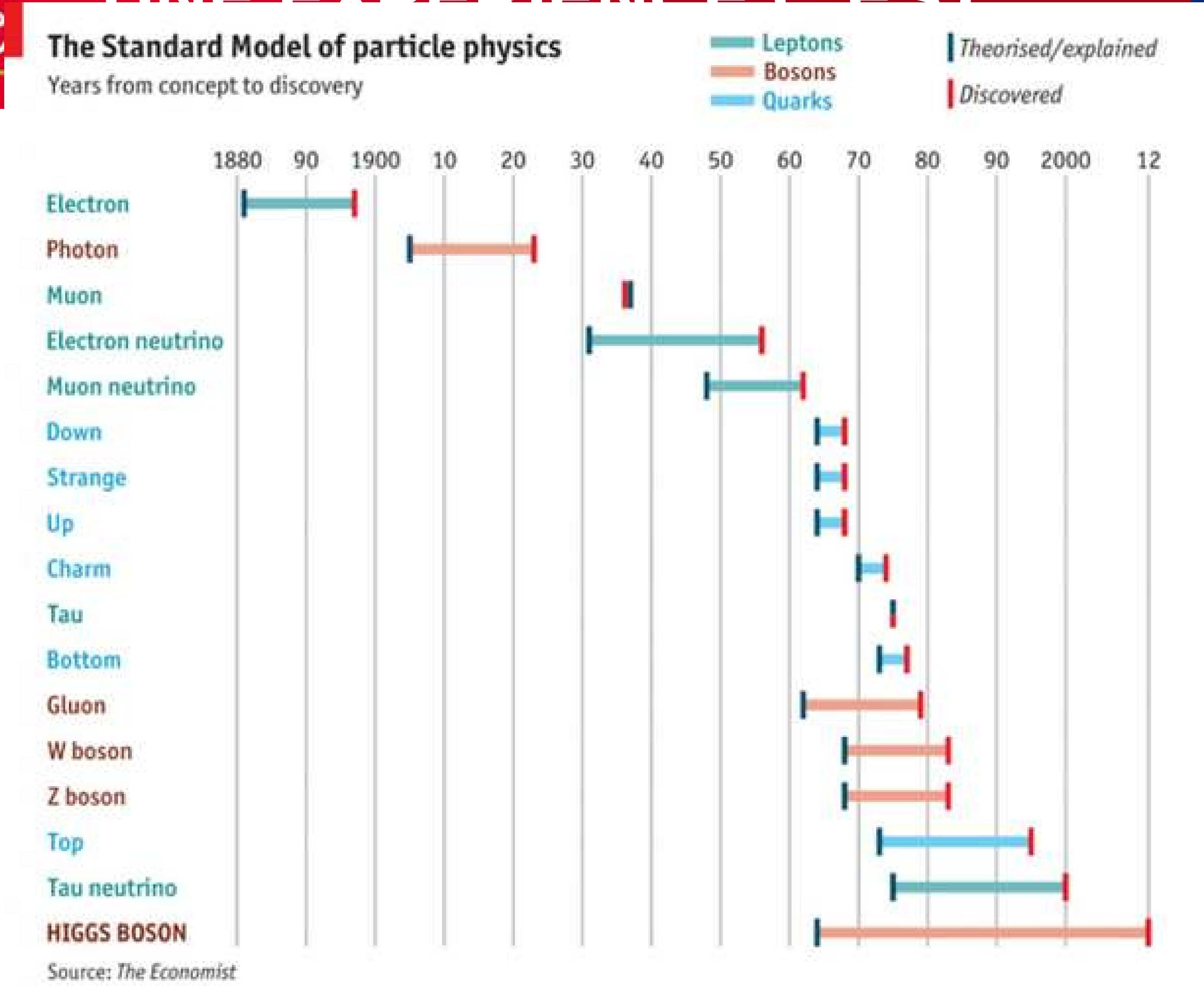
UNE EXPÉRIENCE C'EST QUOI ?



Dernier "***BUNK***"

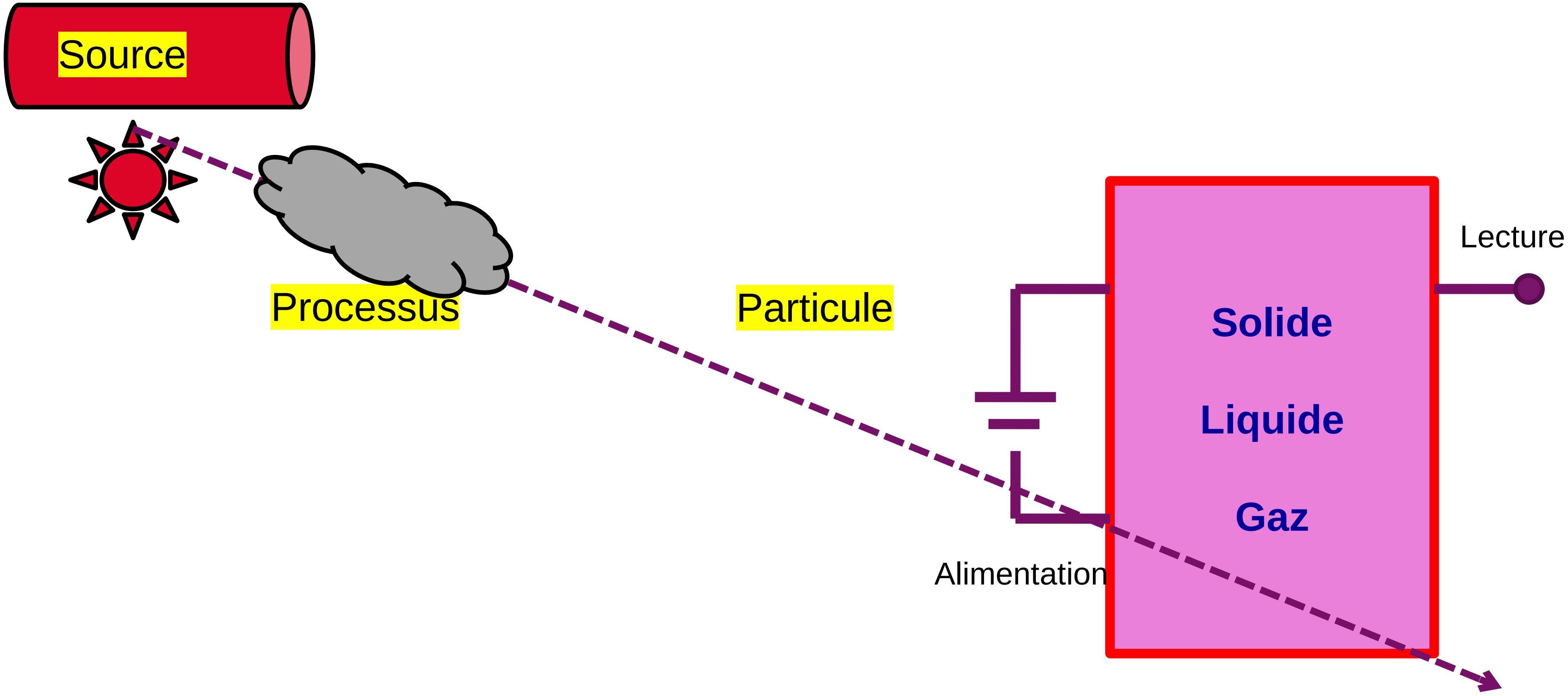
- *Oscillation* ***ν*** *(2002)*
- *Higgs (2012)*
- *No SUSY*
- *GW (2015)*
- *No Wimps ? (2023)*
- *…*

UNE EXPÉRIENCE C'EST



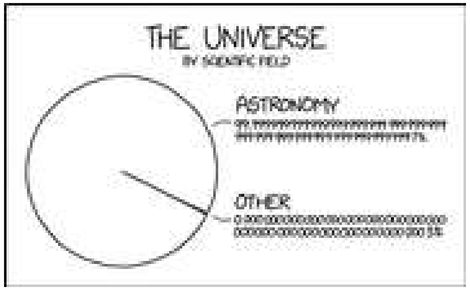
UNE EXPÉRIENCE C'EST QUOI ?

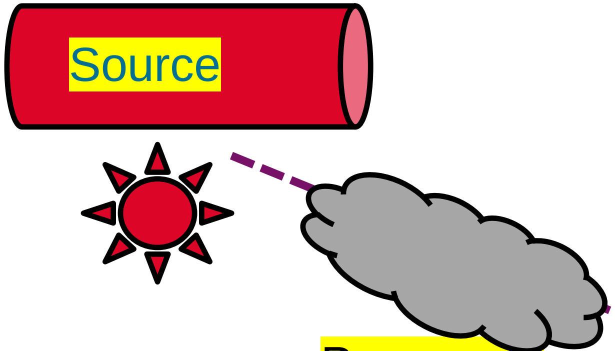
Schématiquement (*****)



UNE EXPÉRIENCE C'EST QUOI ?

Schématiquement (*****)





Source

Processus

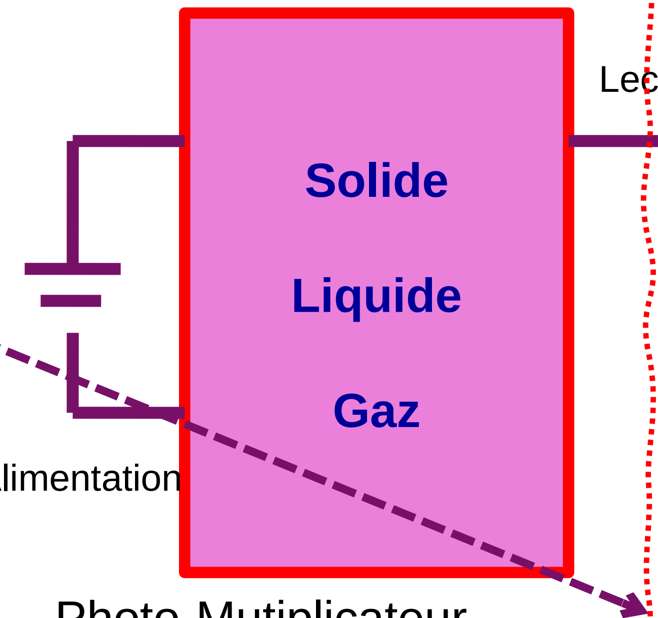
Accelerator
Source Radioactive
Source Astro

Photon
Electron
Hadrons
Noyaux
=> Particule stable

Particule/Onde

Diffusion
Interaction
Reaction
=> Processus physique

Ce cours



Solide

Liquide

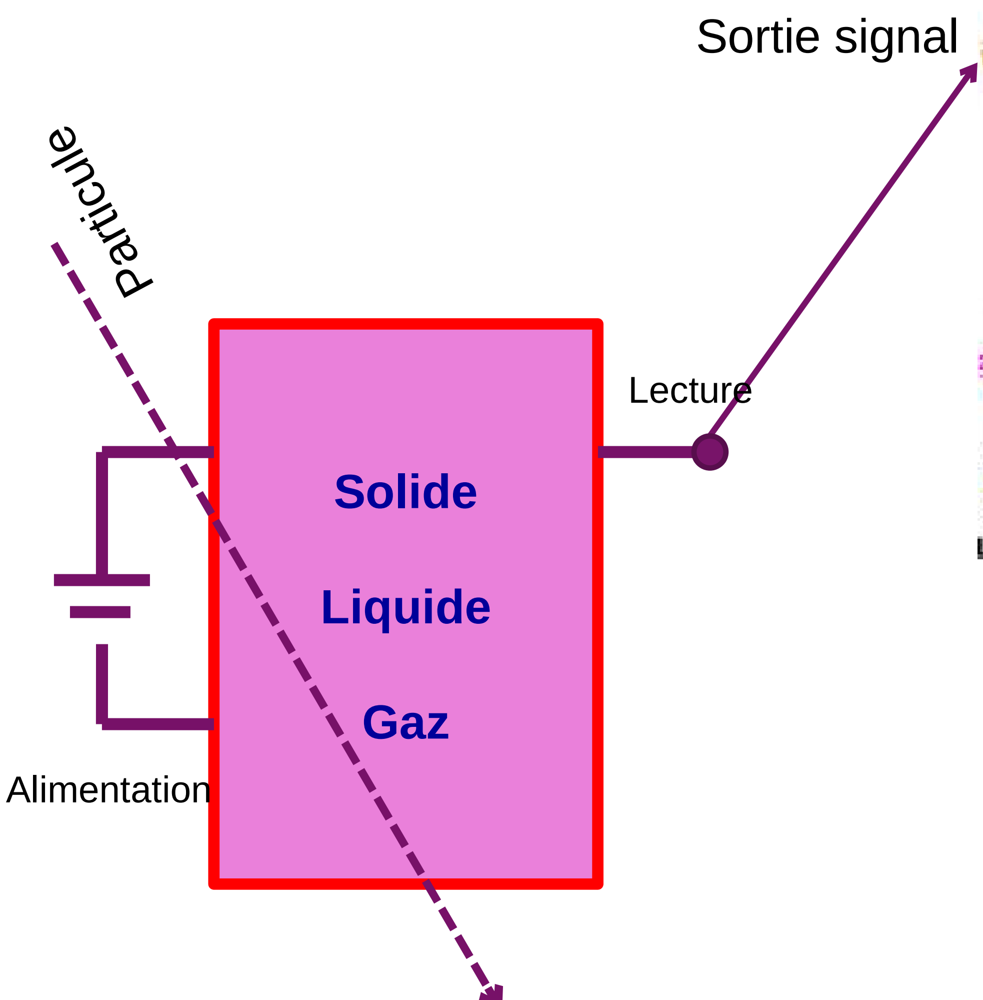
Gaz

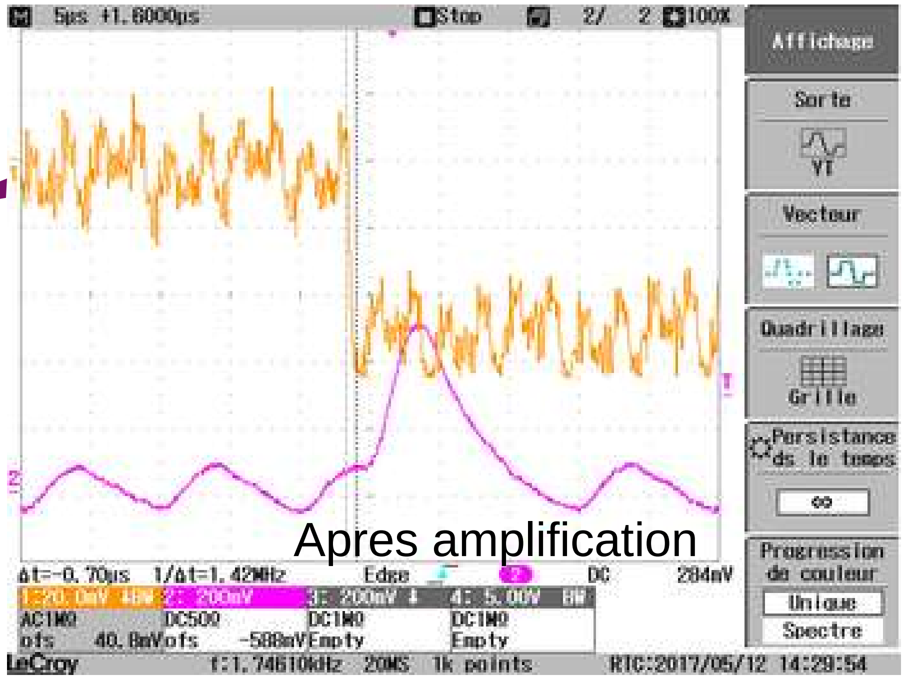
Lec

Alimentation

Photo-Mutiplicateur
Chambre a fils
Telescope

MESURER C'EST QUOI ?



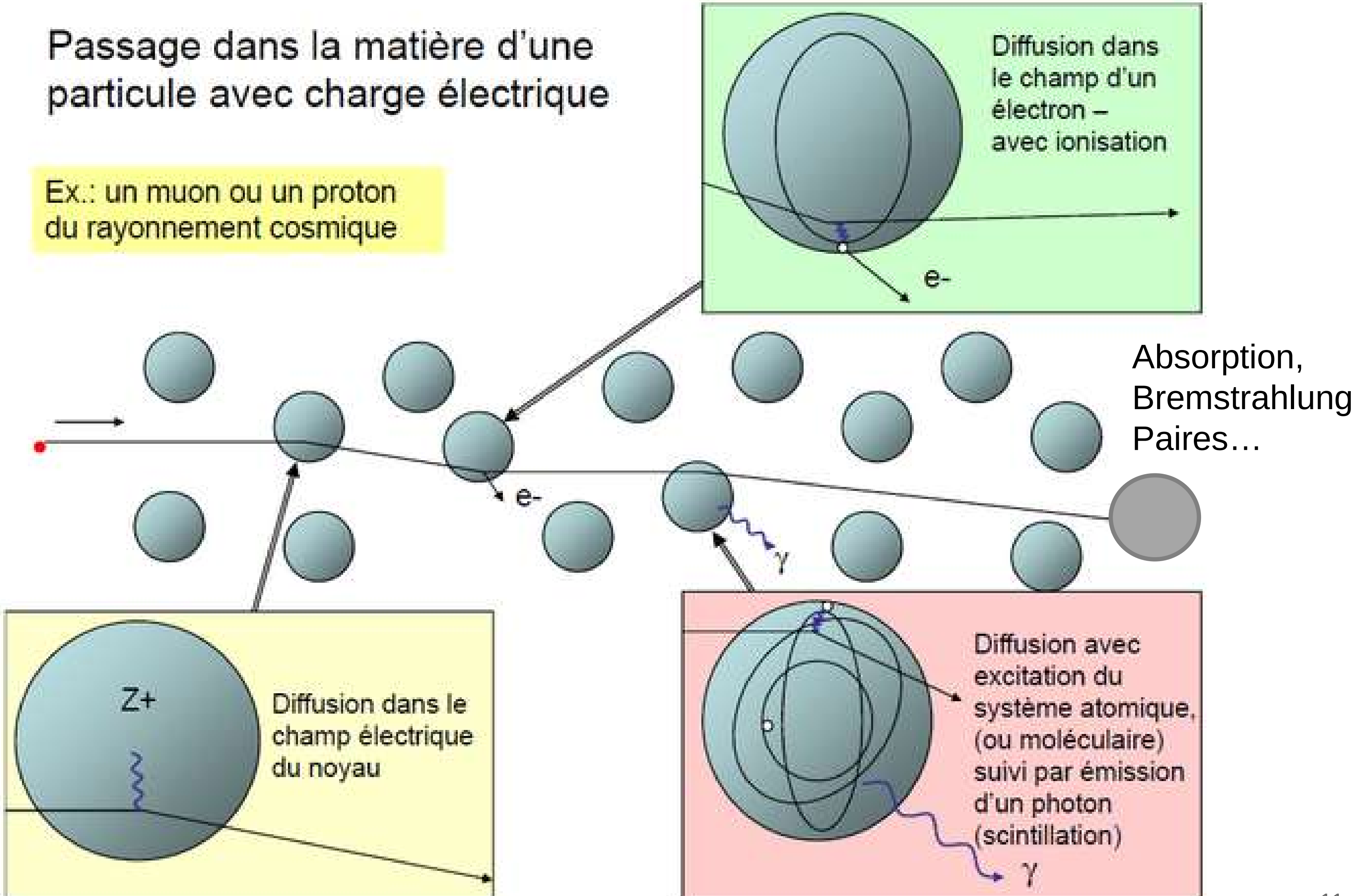


=> A la fin on veut un courant/tension pour mettre ca sur python*

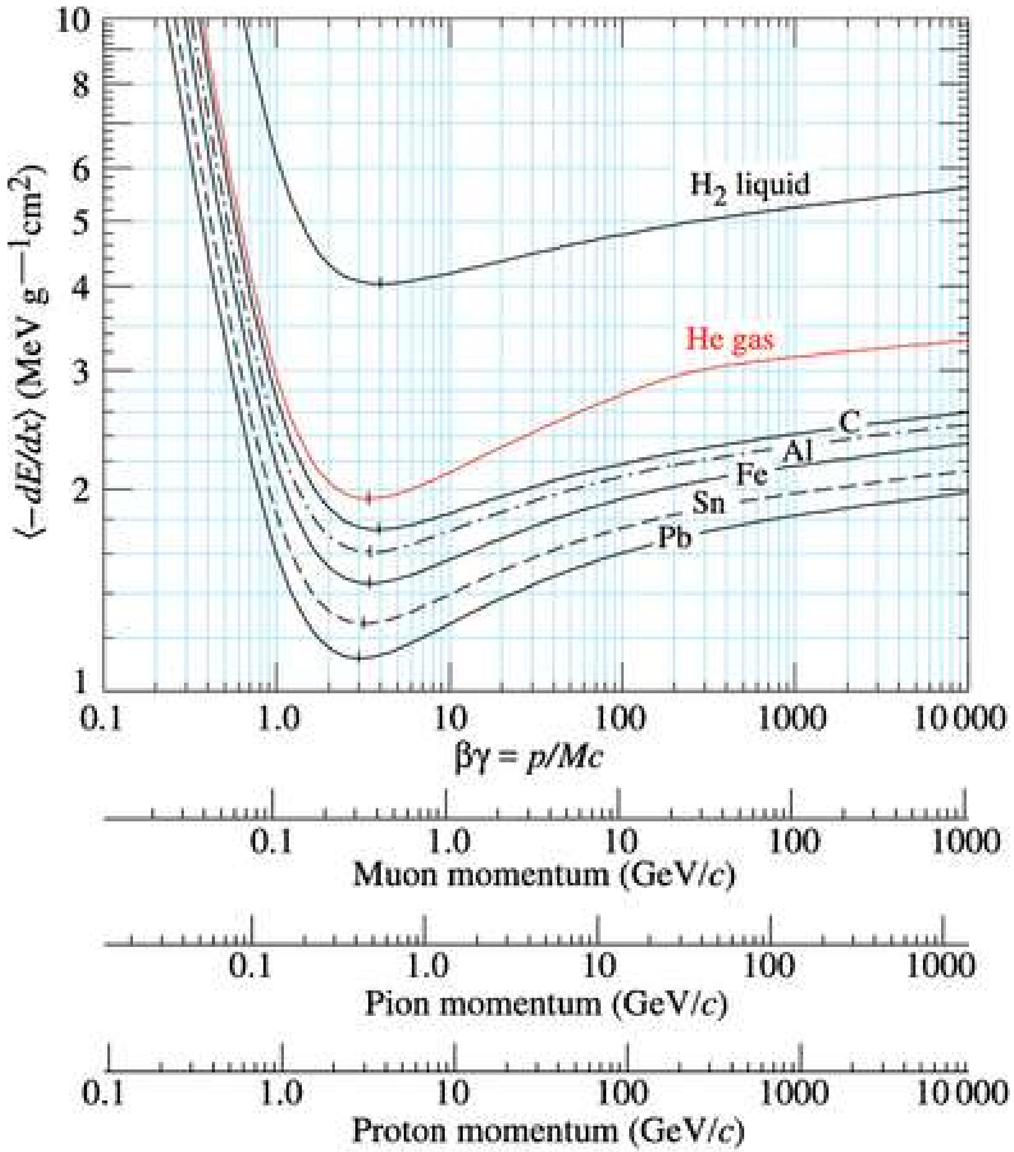
INTERACTIONS PARTICULE-MATIERE

Passage dans la matière d'une particule avec charge électrique

Ex.: un muon ou un proton du rayonnement cosmique

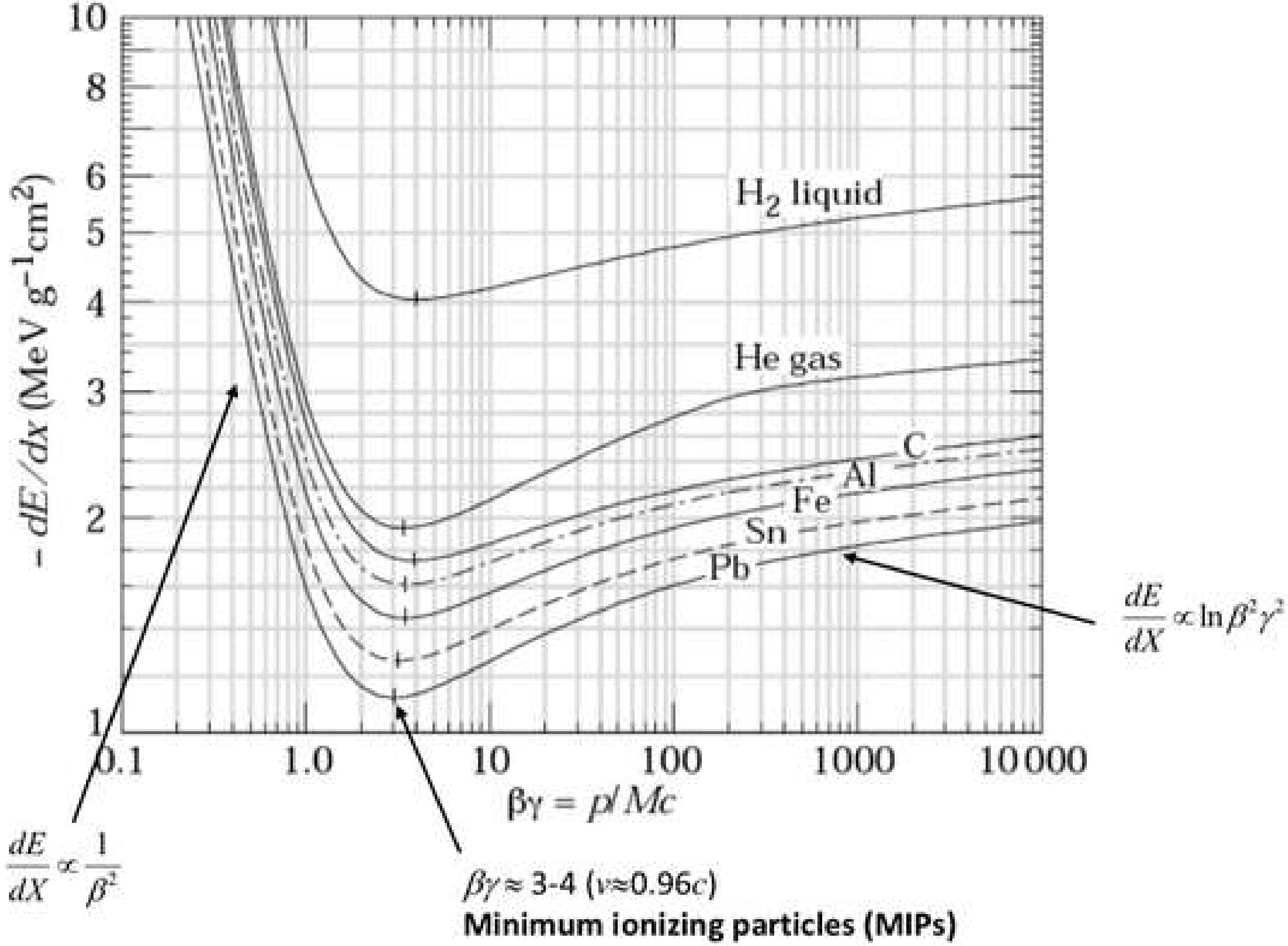


INTERACTIONS PARTICULE-MATIERE

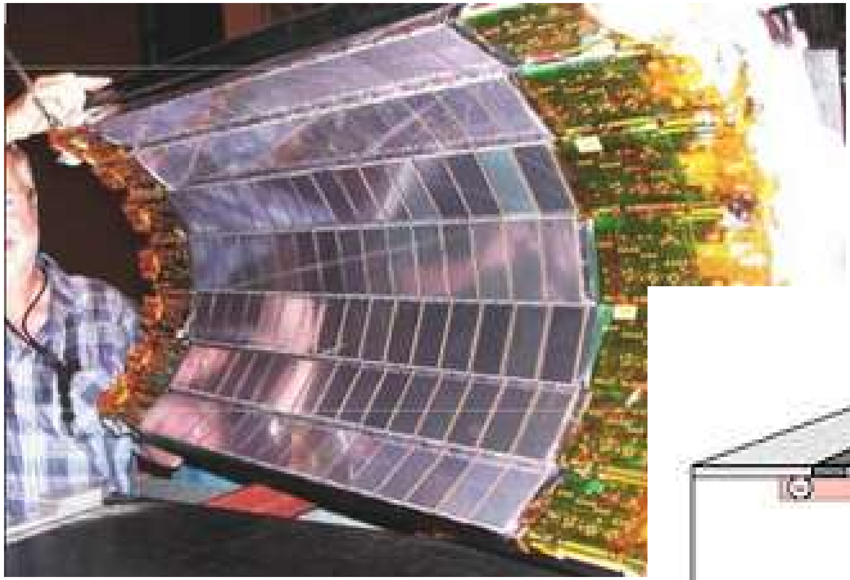


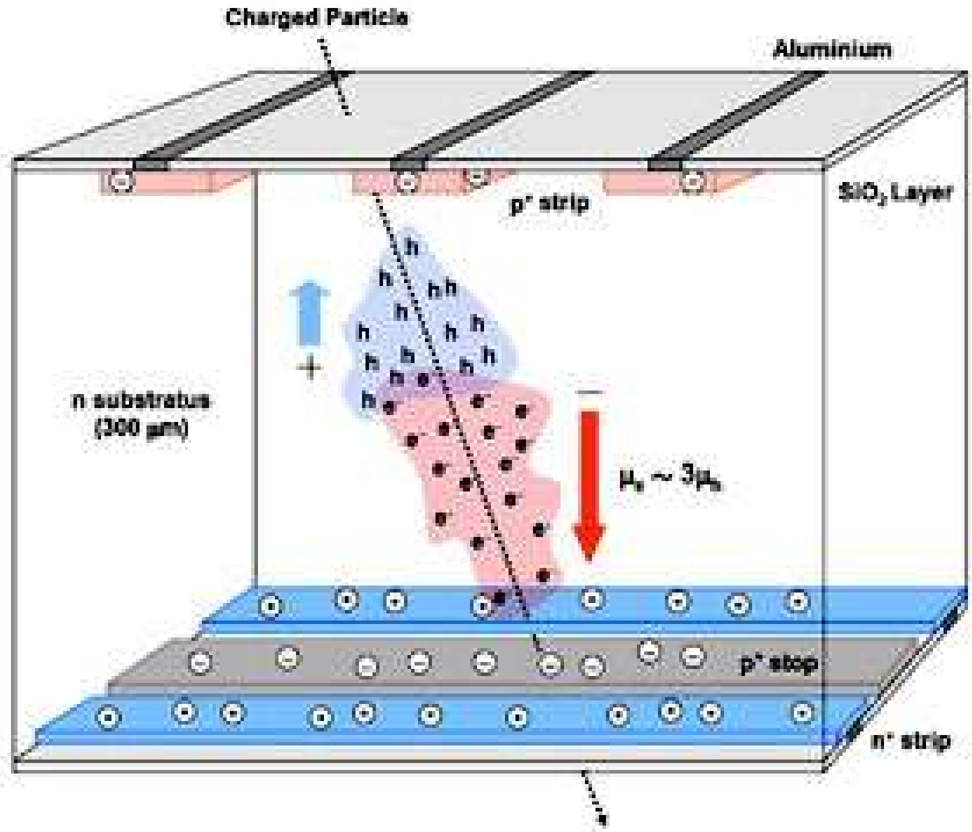
INTERACTIONS PARTICULE-MATIERE

$$-\frac{dE}{dX} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \rho \frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}\right]$$



DÉTECTION : TRACKER SILICIUM



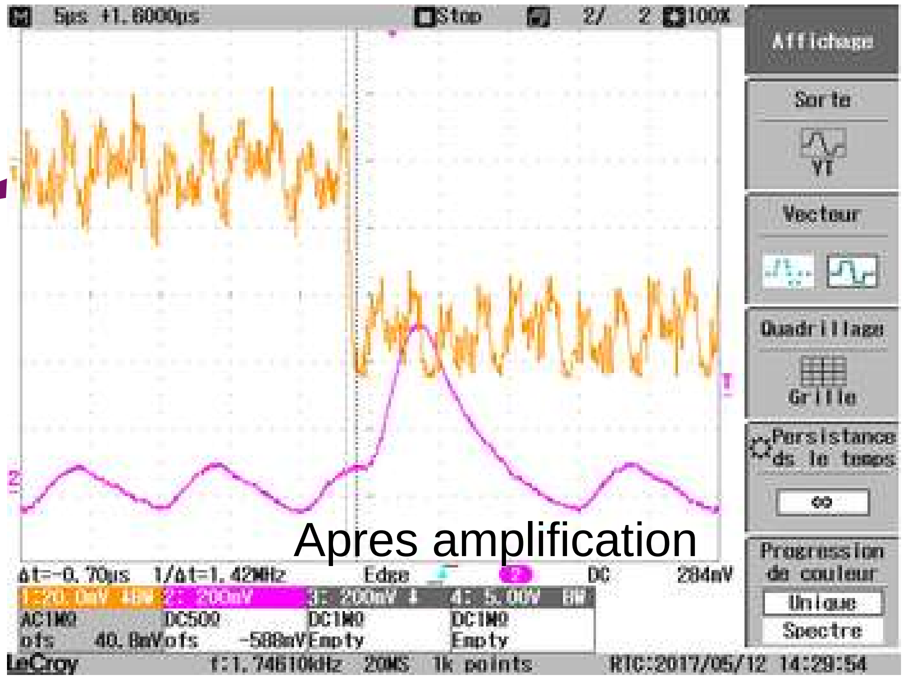


Les autres type de detecteurs => Cours 2

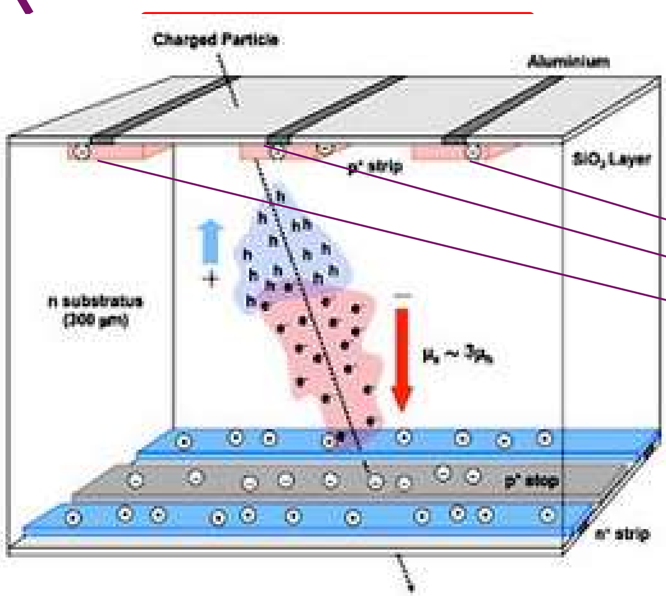
MESURER C’EST QUOI ?

Particule

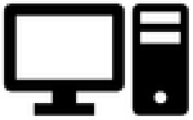
Sortie signal



Apres amplification



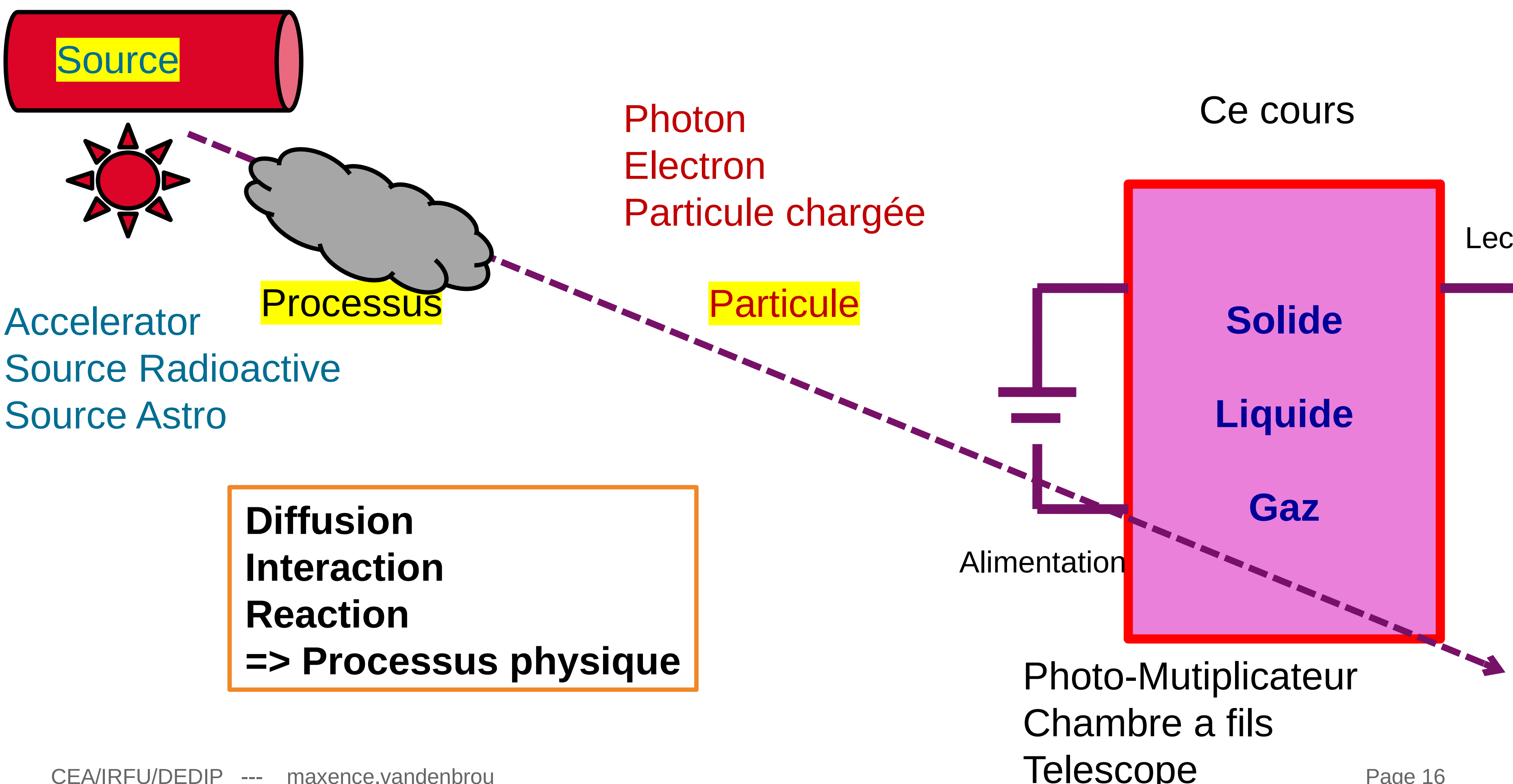
Ali



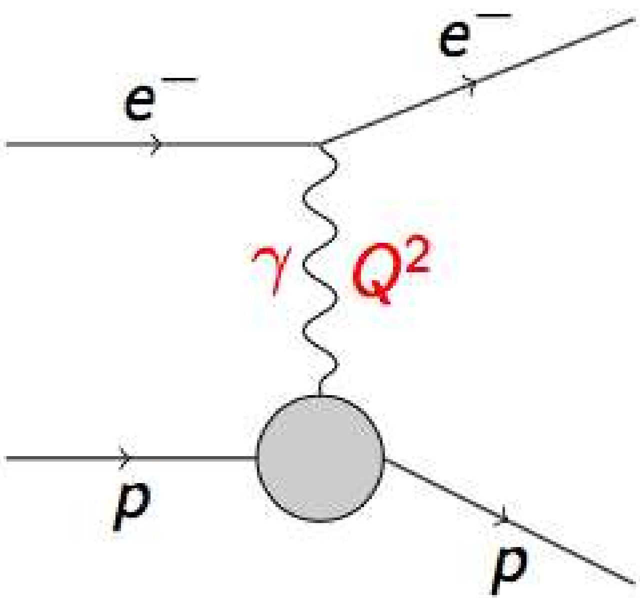
Un Canaux = Un signal
Plein de canals => Analyse

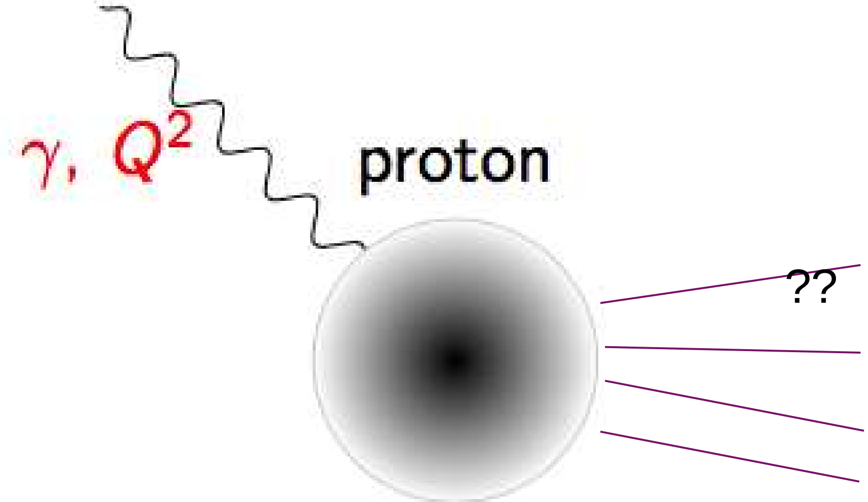
UNE EXPERIENCE C'EST QUOI ?

Schématiquement (*****)

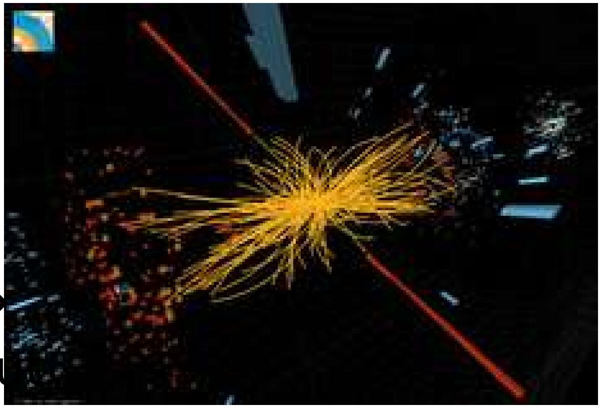


MESURER QUOI ?



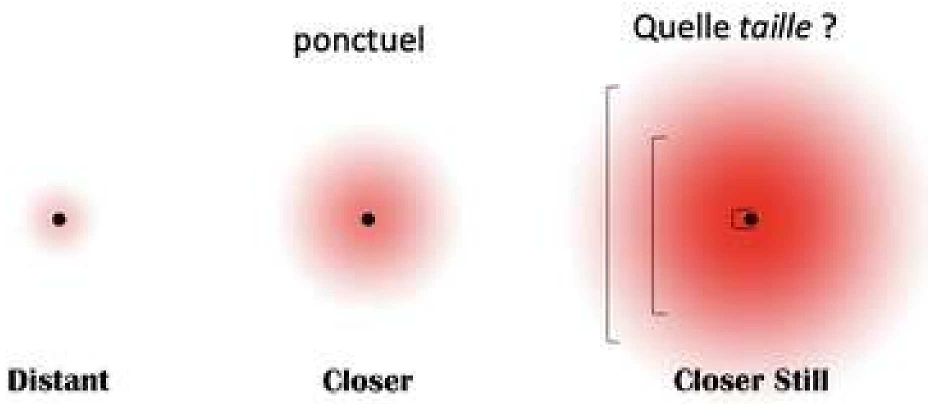


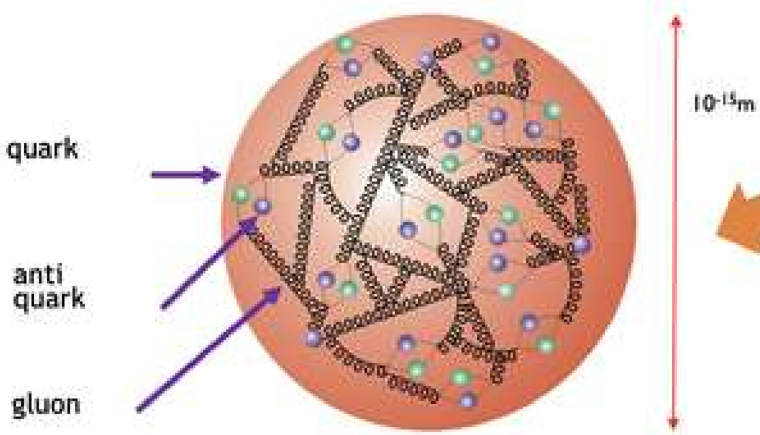
Diffusion élastique.

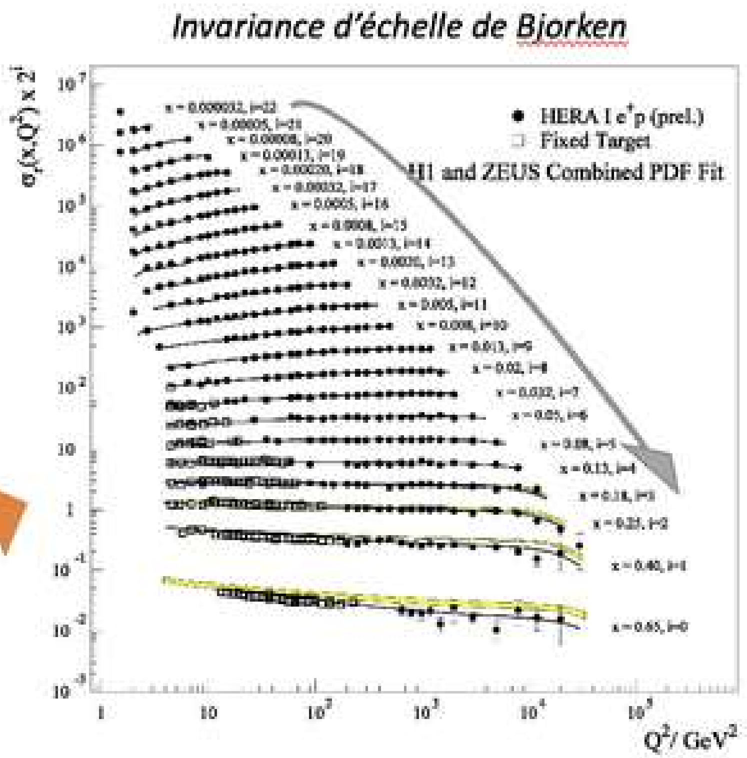


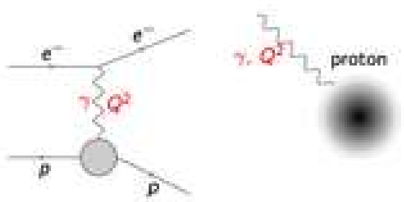
Pas élastique du tou

TOUT N'EST PAS SI CLASSIQUE









MESURER QUOI ?

Déterminer la carte d'identité d'une particule :

Pion

The quark structure of the pion.

Composition	π^+ : $u\bar{d}$ π^0 : $u\bar{u}$ or $d\bar{d}$ π^- : $d\bar{u}$
Statistics	Bosonic
Interactions	Strong, Weak, Electromagnetic and Gravity
Symbol	π^+, π^0, and π^-
Theorized	Hideki Yukawa (1935)
Discovered	César Lattes, Giuseppe Occhialini (1947) and Cecil Powell
Types	3
Mass	$\pi^\pm$: 139.570 18(35) MeV/c^2 π^0 : 134.9766(6) MeV/c^2
Electric charge	π^+ : +1 e π^0 : 0 e π^- : −1 e
Spin	0
Parity	−1

Mesure de l’impulsion (masse et/ou vitesse)

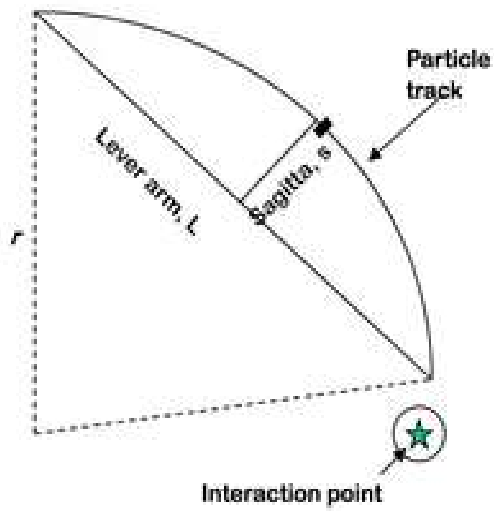
$$p=mv$$

Mesure de l'impulsion

- Technique de spectrométrie magnétique (ou du B-rho)

$$qvB=mv_{2}/\rho \quad \rightarrow \quad p_{\perp}=p\cos\vartheta=qB\rho$$

- **Tracking measures particle 3-momenta**



$$p = qBr \approx \frac{qBL^2}{8s}$$

$$\frac{\sigma_p}{p} = \frac{\sigma_s}{s} = \frac{8p}{qBL^2}\sigma_s$$

Precision of sagitta measurement: $\sigma_s \approx \sqrt{\frac{3}{N}}\sigma_{hit}$ **(*N* position measurements)**

Mesure de l'impulsion

- Technique de spectrométrie magnétique (ou du B-rho)

$$qvB=mv^2/\rho \quad \rightarrow \quad p_\perp=p\cos\vartheta=qB\rho$$

- Technique de temps de vol (TOF pour Time Of Flight)

$$L=v\tau=\beta c\tau=\beta c\gamma\tau_0=p\tau_0/m$$

Mesure de l'impulsion

- Technique de spectrométrie magnétique (ou du B-rho)

$$qvB = mv^2/\rho \quad \rightarrow \quad p_\perp = p\cos\vartheta = qB\rho$$

- Technique de temps de vol (TOF pour Time Of Flight)

$$L = v\tau = \beta c\tau = \beta c\gamma\tau_0 = p\tau_0/m$$

- Effet Vavilov-Tcherenkov

$$\cos\theta_c = \frac{c}{n\beta c} = \frac{1}{n\beta} \, .$$

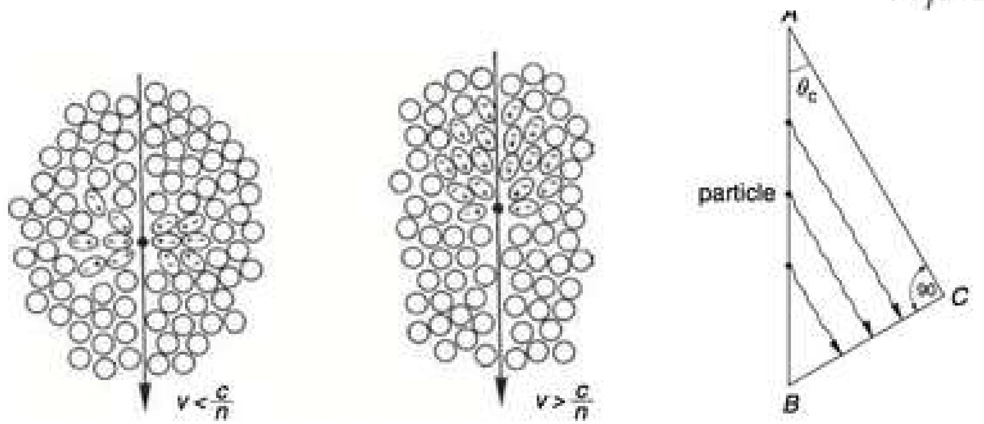


Fig. 5.39. Illustration of the Cherenkov effect [140, 141] and geometric determination of the Cherenkov angle.

DES OBSERVABLES A LA TECHNIQUE DE MESURE

Mesure de l’impulsion

- Technique de spectrométrie magnétique (ou du B-rho)
- Technique de temps de vol (TOF pour Time Of Flight)
- Effet Vavilov-Tcherenkov

Mesure de l’énergie

- Calorimétrie
- Perte d’energie dE/dx

DES OBSERVABLES A LA TECHNIQUE DE MESURE

Mesure de l'impulsion

- Technique de spectrométrie magnétique (ou du B-rho)
- Technique de temps de vol (TOF pour Time Of Flight)
- Effet Vavilov-Tcherenkov

Mesure de l'énergie

- Calorimétrie
- Perte d'energie dE/dx
- Frequence

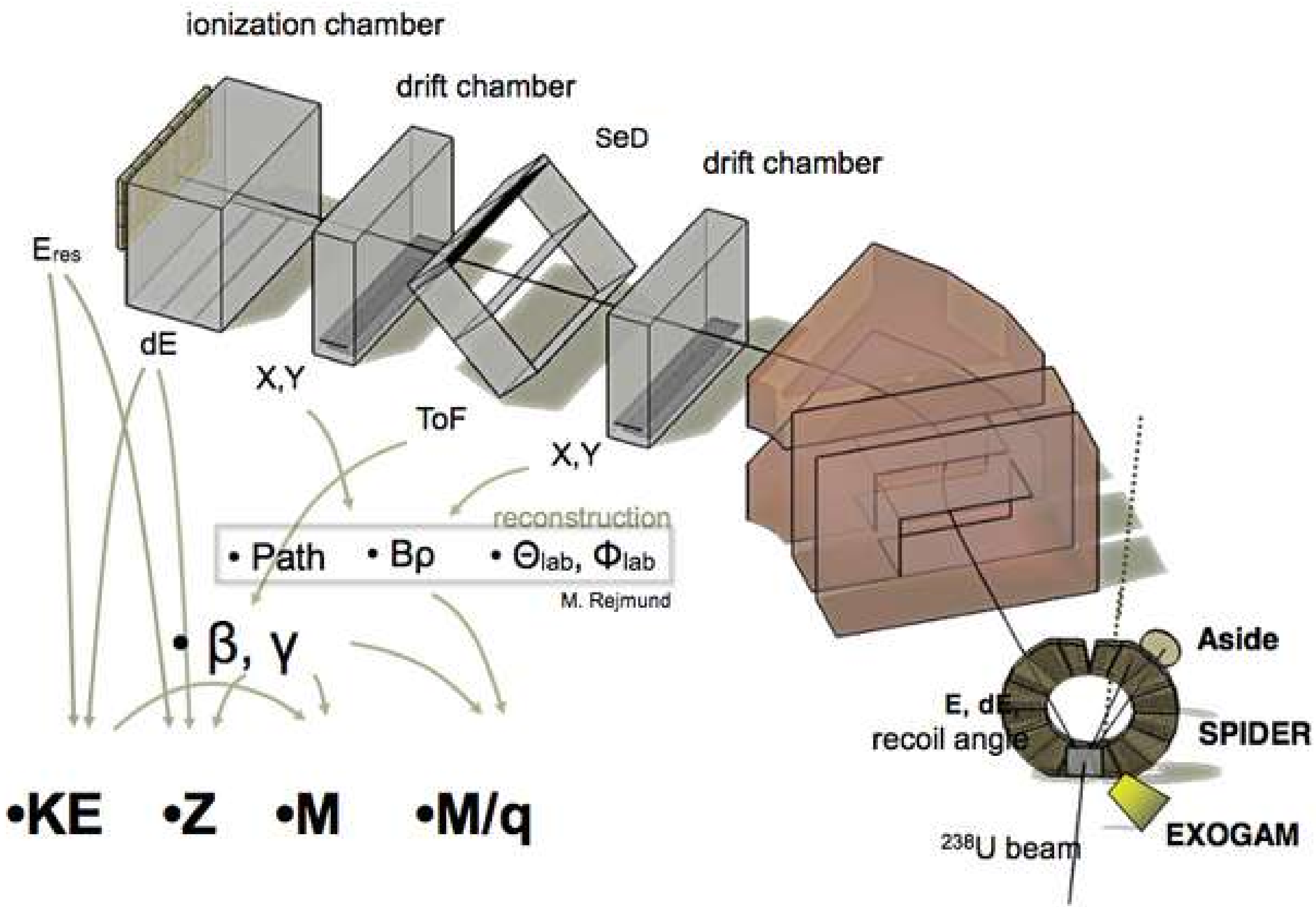
Mesure de spin et de la parité

- (Pas traitée ici)
- Avec un polarimetre indirectement
- Par selection

Mesure de la masse et de la charge (PID)

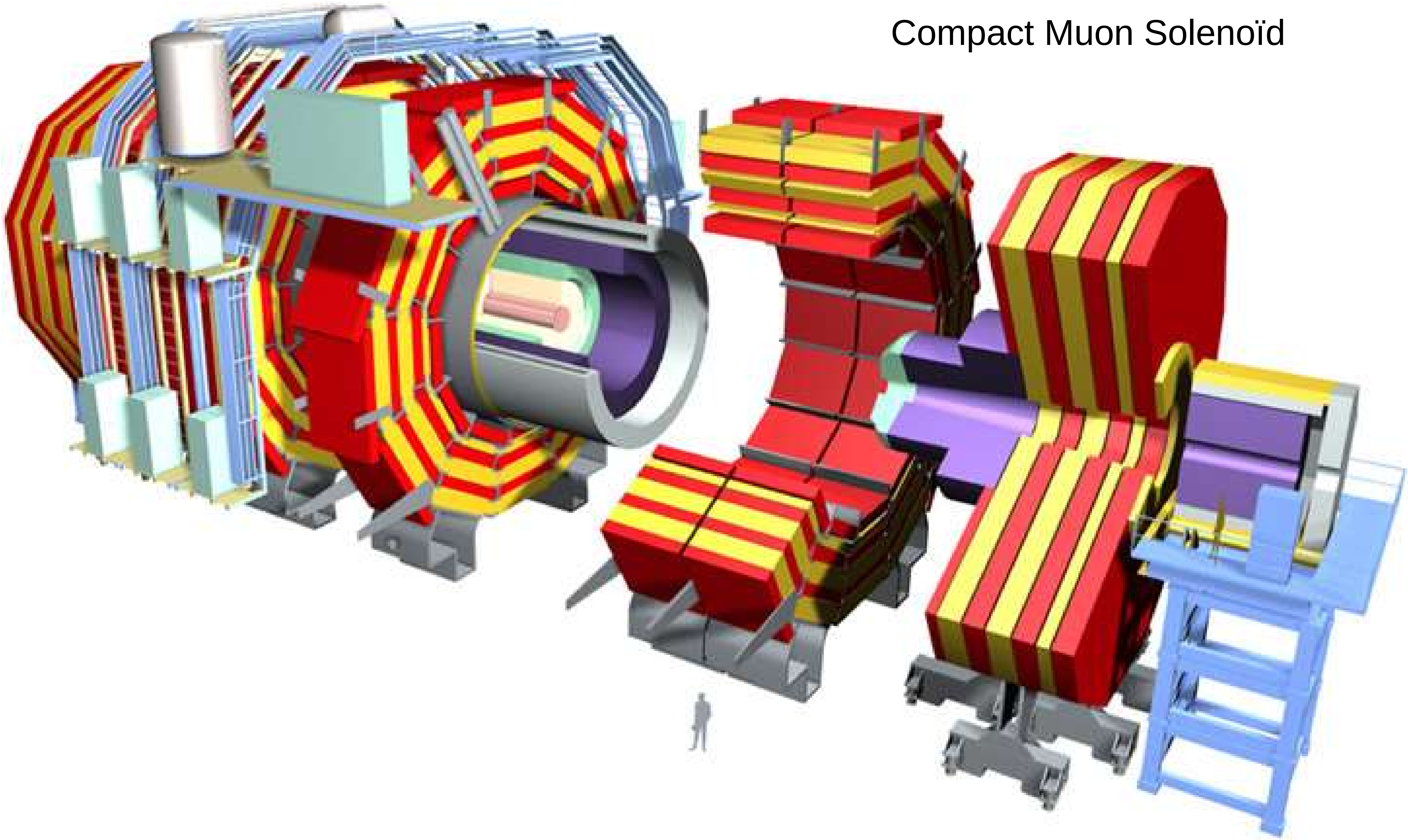
- Combinaison B-rho et TOF
- Combinaison B-rho et dE/dx
- Masse manquante …
- Direction de la courbure dans un spectromètre magnétique
- Mesure de la perte d'énergie dE/dx qui dépend de la charge
- L'electrometre

UN EXEMPLE

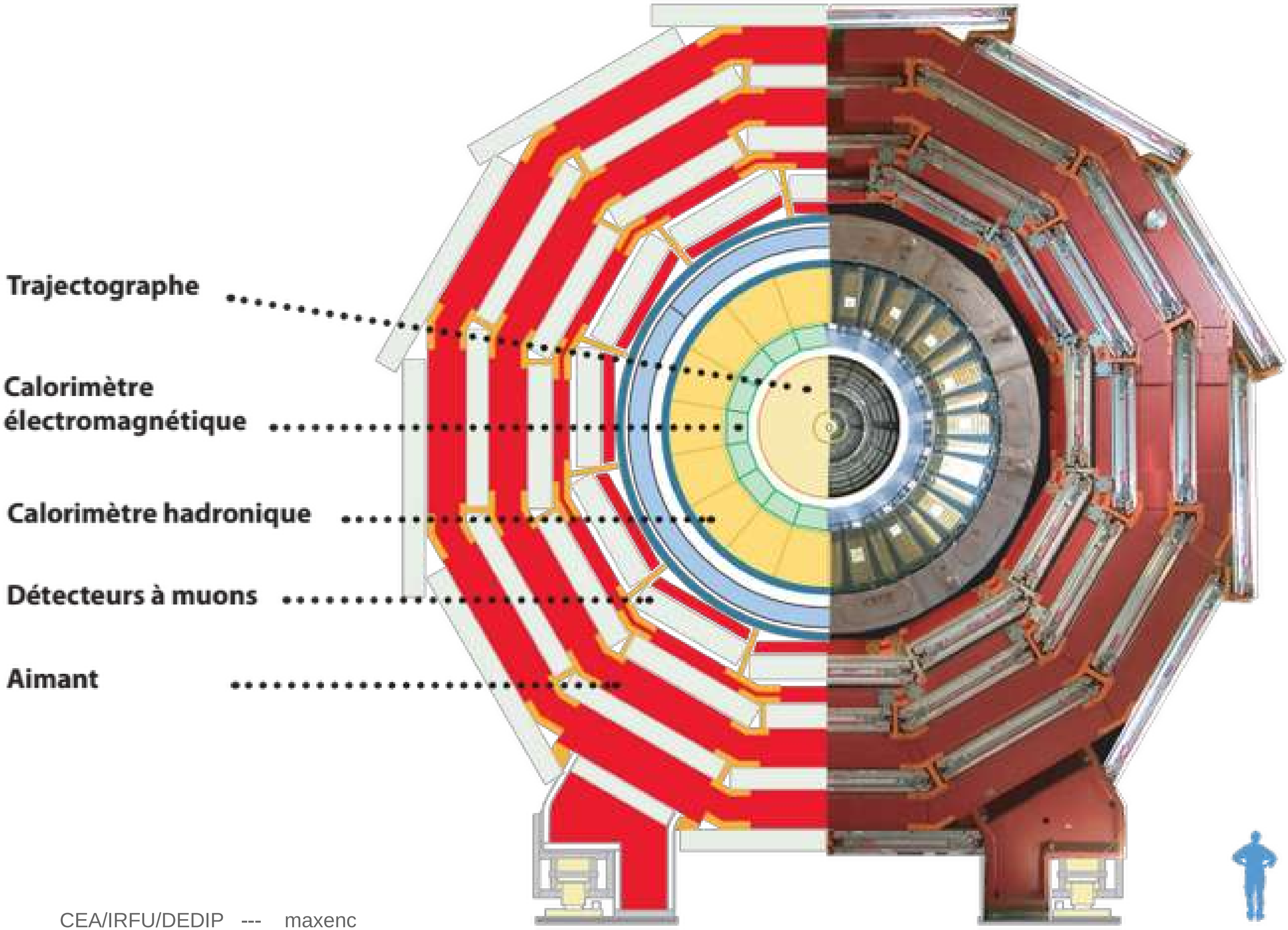

ionization chamber
drift chamber
SeD
drift chamber
Eres
dE
X,Y
ToF
X,Y
reconstruction
• Path • Bρ • Θlab, Φlab
M. Rejmund
• β, γ
•KE •Z •M •M/q
Aside
E, dE,
recoil angle
SPIDER
EXOGAM
238U beam

UN PLUS GROS

Compact Muon Solenoïd

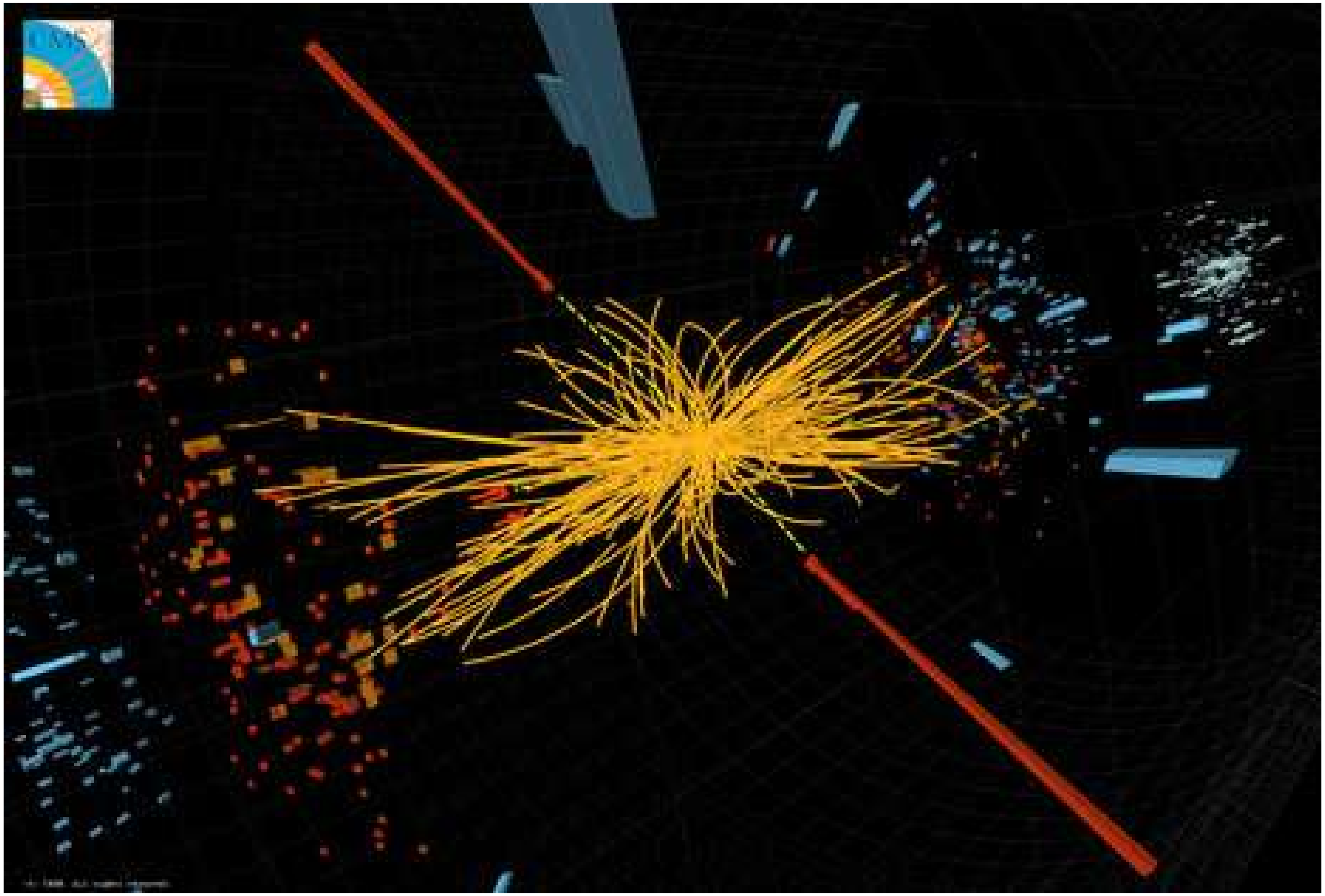


CMS


Trajectographe
Calorimètre électromagnétique
Calorimètre hadronique
Détecteurs à muons
Aimant

The LHC accelerator

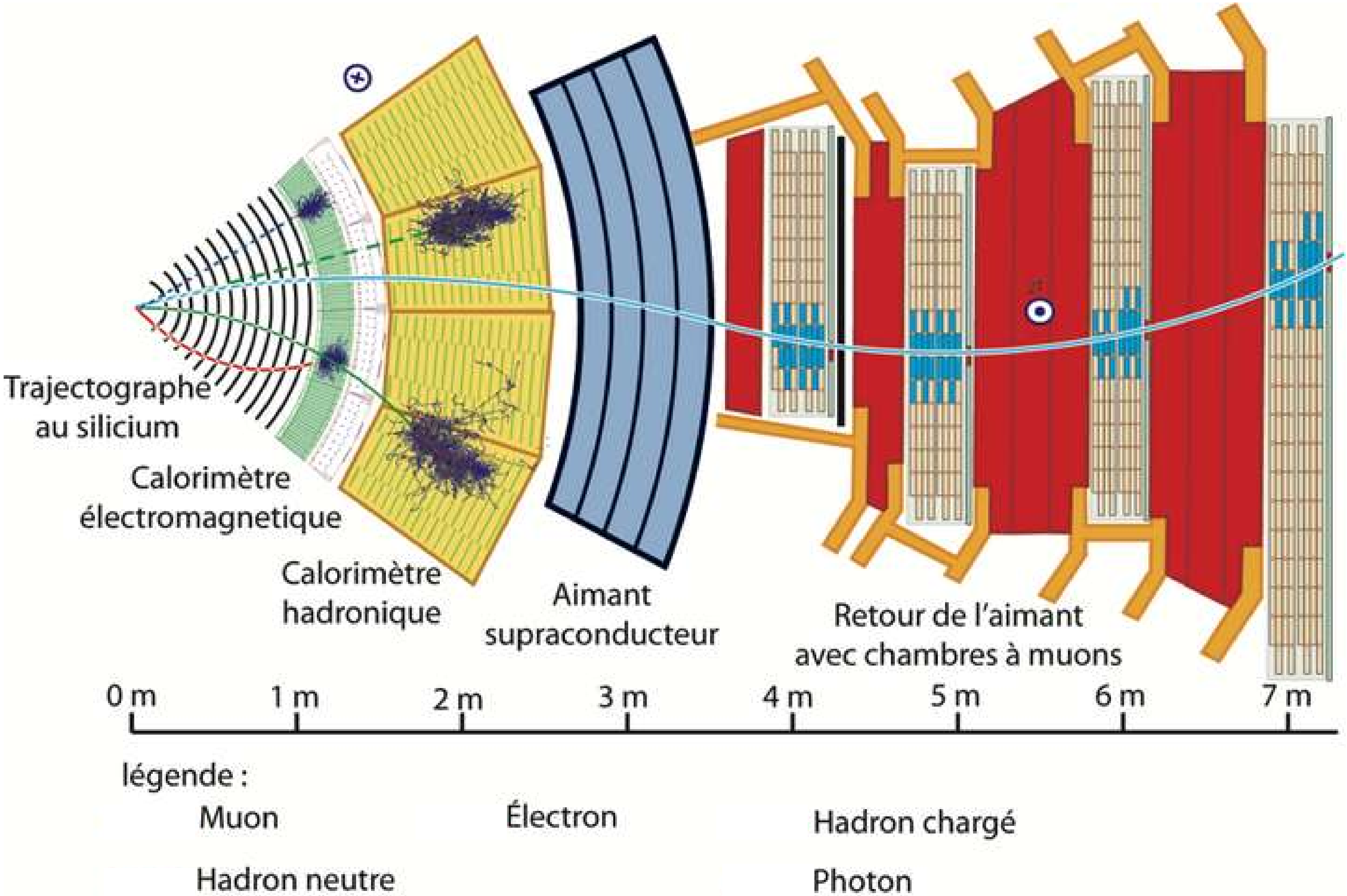
CMS EVENT



Courbes = trajectoire mesurée par les trajectographes

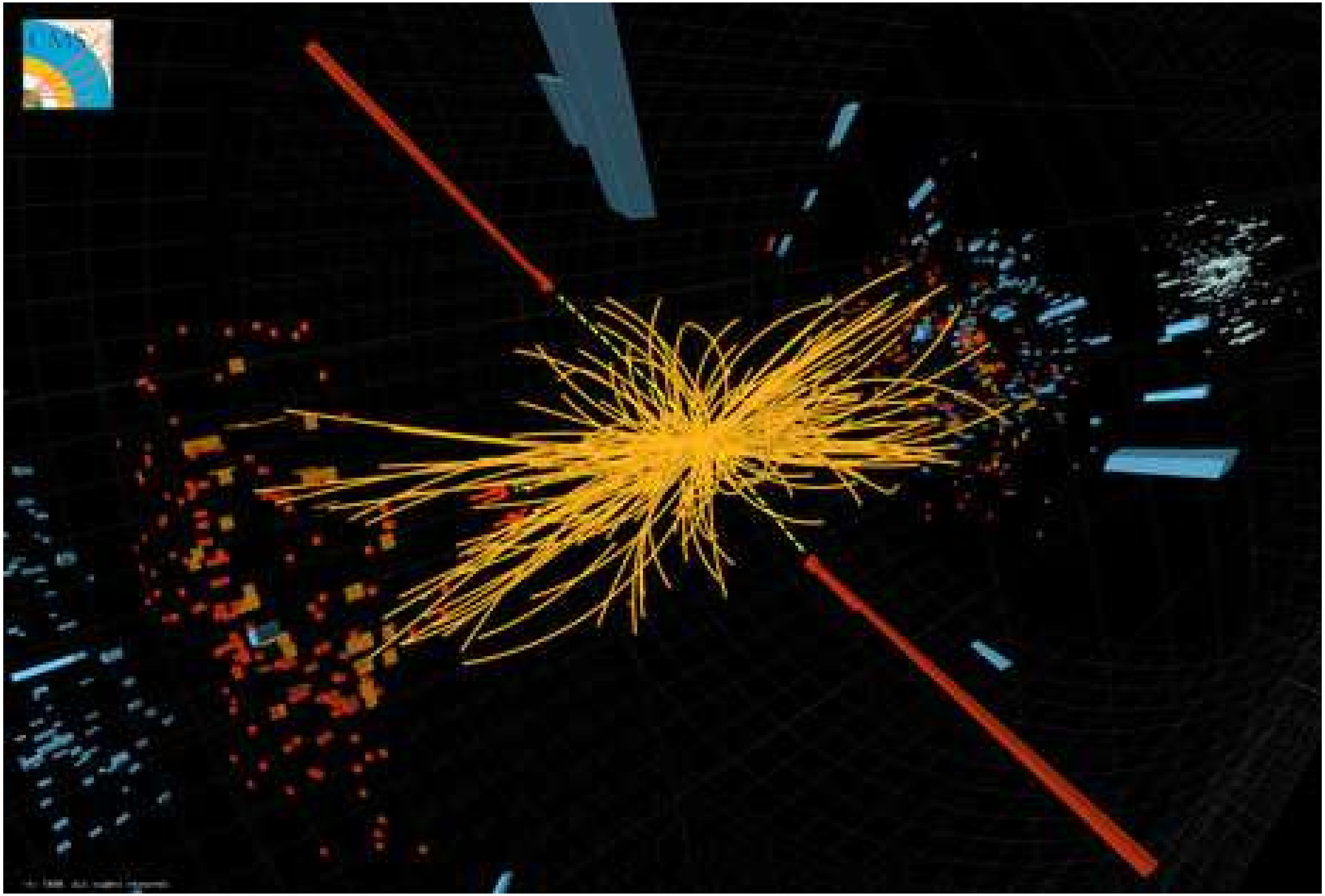
Barres = Mesure d'énergies dans les calorimètre

CMS 3

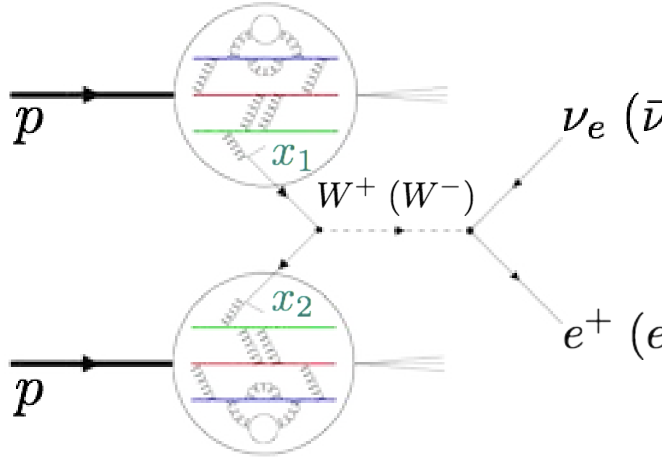


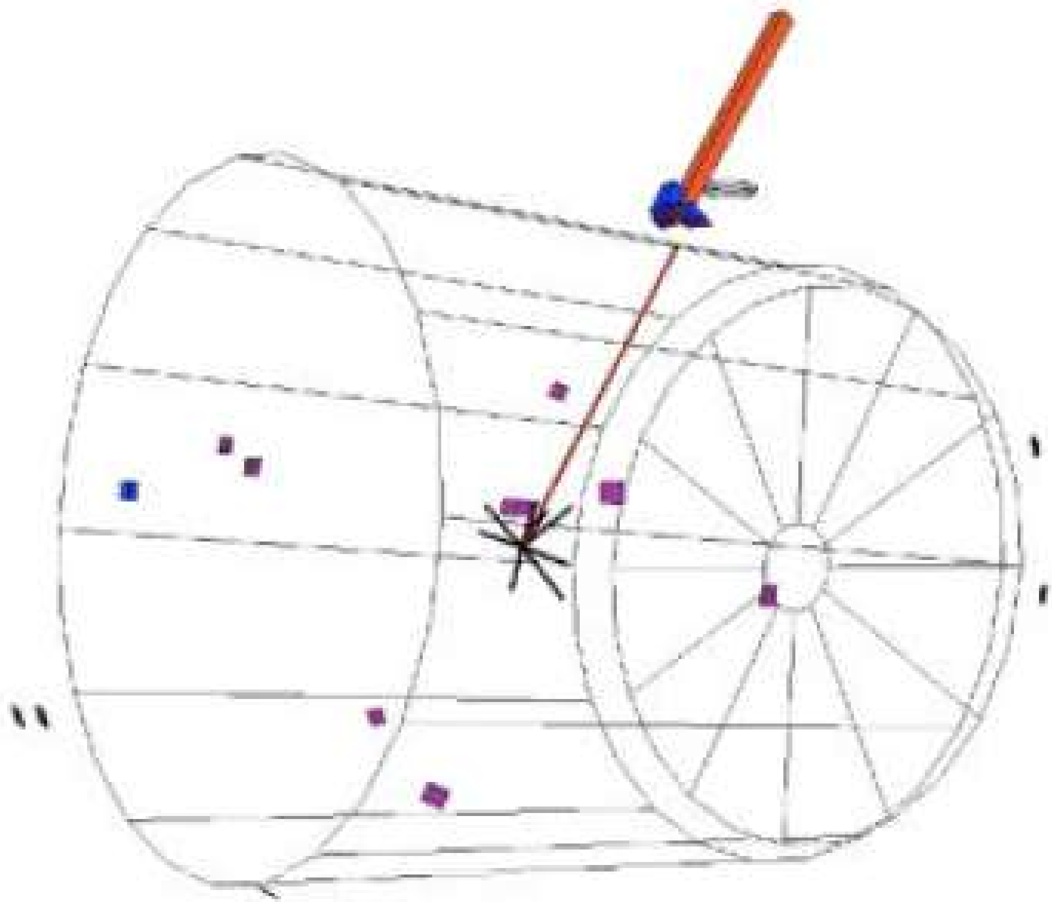
Trajectographe
au silicium
Calorimètre
électromagnetique
Calorimètre
hadronique
Aimant
supraconducteur
Retour de l'aimant
avec chambres à muons
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
légende :
Muon
Électron
Hadron chargé
Hadron neutre
Photon

CMS EVENT

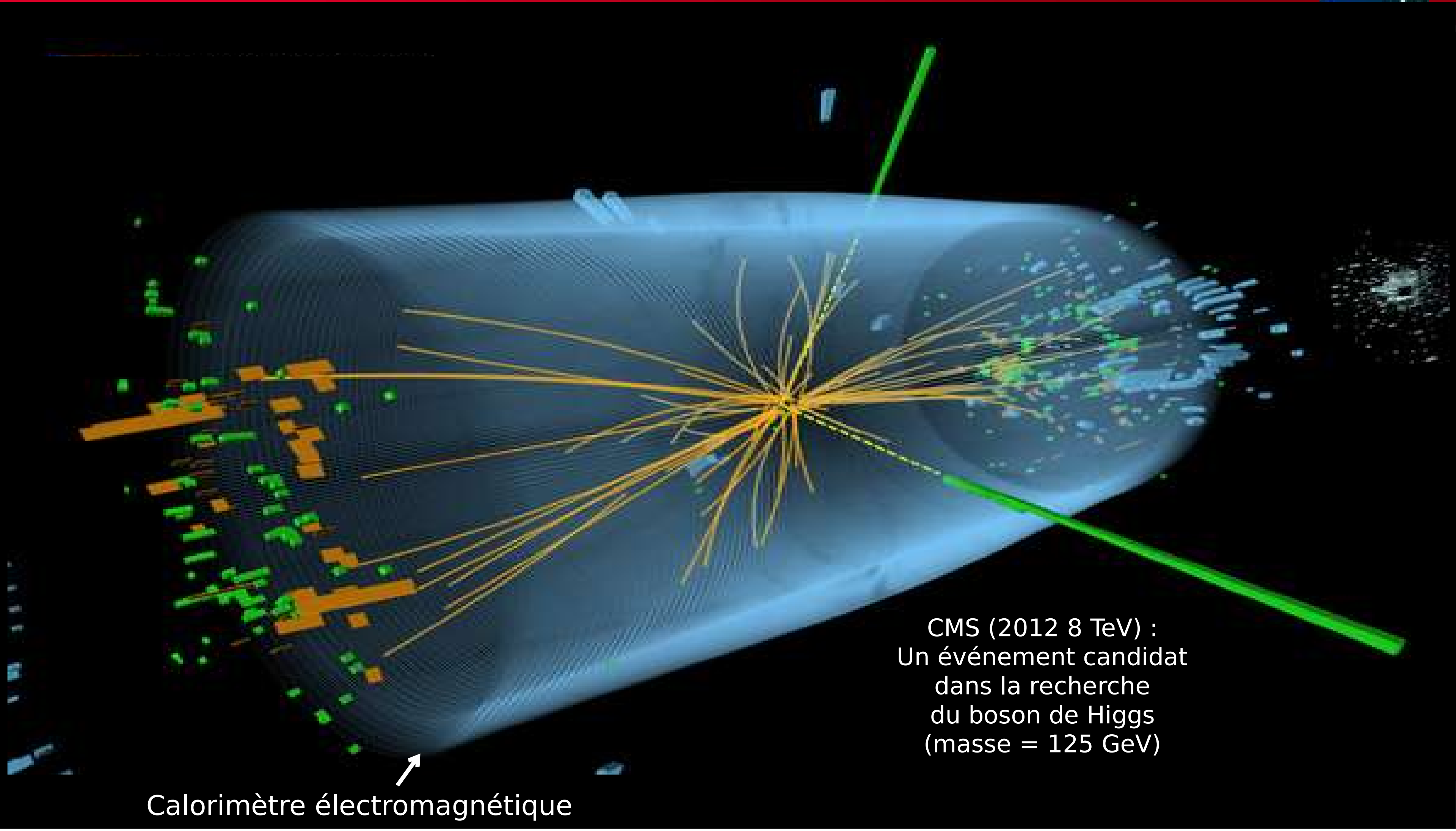


W EVENT -> ISOLATED LEPTON

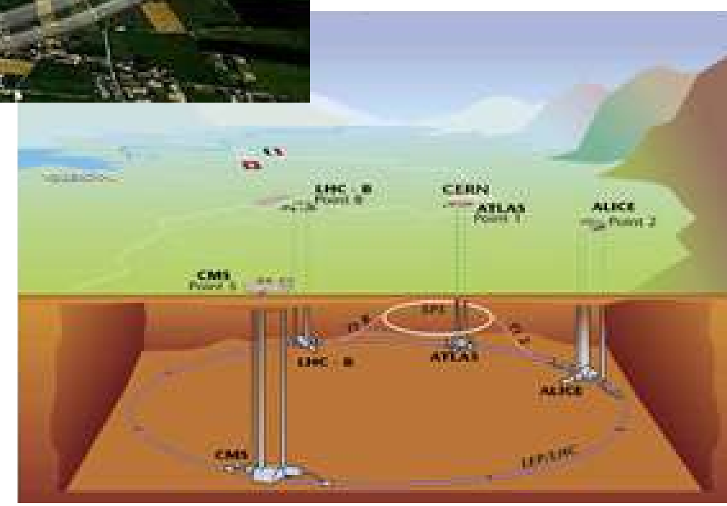




STAR experiment at BNL


CMS (2012 8 TeV) :
Un événement candidat
dans la recherche
du boson de Higgs
(masse = 125 GeV)
Calorimètre électromagnétique

Le Large Hadron Collider



27 km

8.3 T

1.9 K (**-271.3 °C**)

10^{-13} atm

362 **MJ**

Mesurer l’infiniment petit et observer l’infiniment grand

DE LA RECHERCHE À L’INDUSTRIE

Vendredi 5/07 11h (IJCLAB)
Lundi 8/07 12h (CEA IRFU)
Visite Labo 14h (CEA IRFU)
Mercredi 10/07 11h (IAS)

Maxence Vandenbroucke

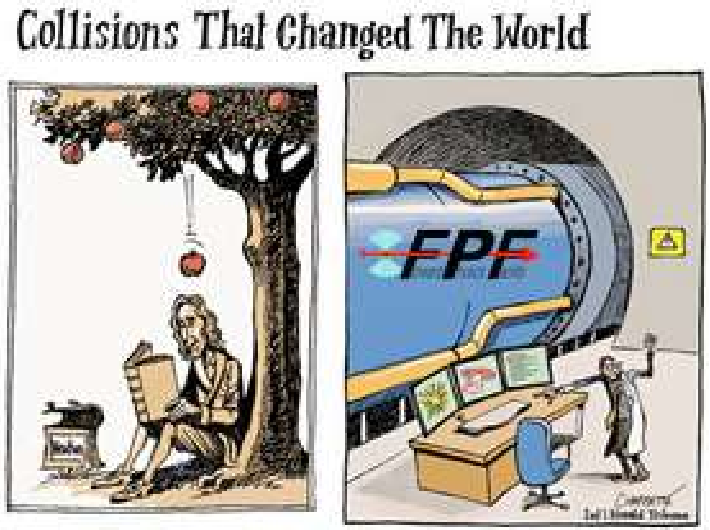
07/2024

université PARIS-SACLAY

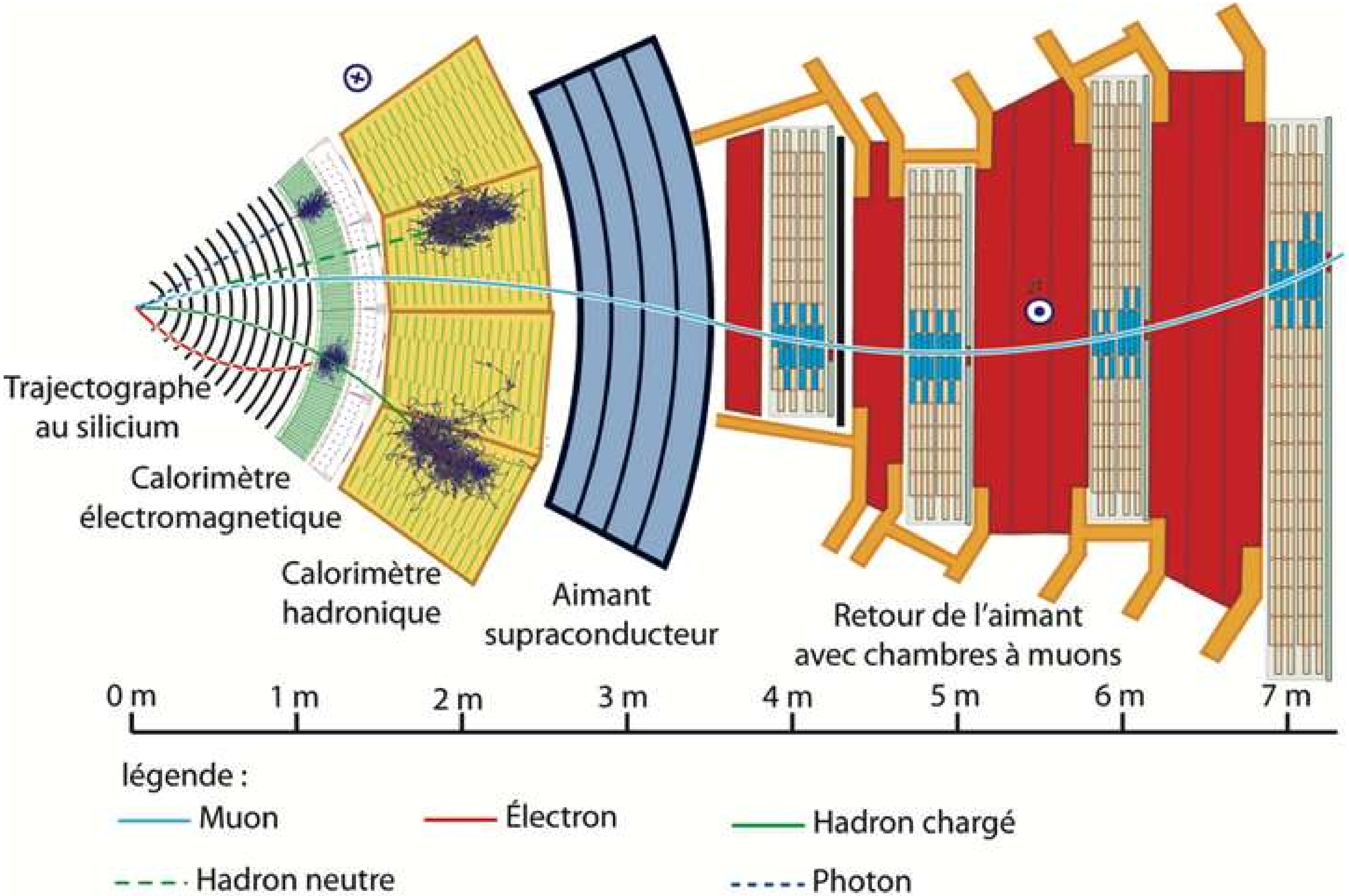
Cours 2 : Les détecteurs de particules

- Détecteurs au Silicium
- Calorimétrie
  - Scintillation
  - Détecteurs Gazeux

Basé sur les cours de Stefano Panebianco (CEA/IRFU),
et le cours de Werner Riegler (CERN),
Particle Detectors , Second Edition, C. Grupen & B. Shwartz

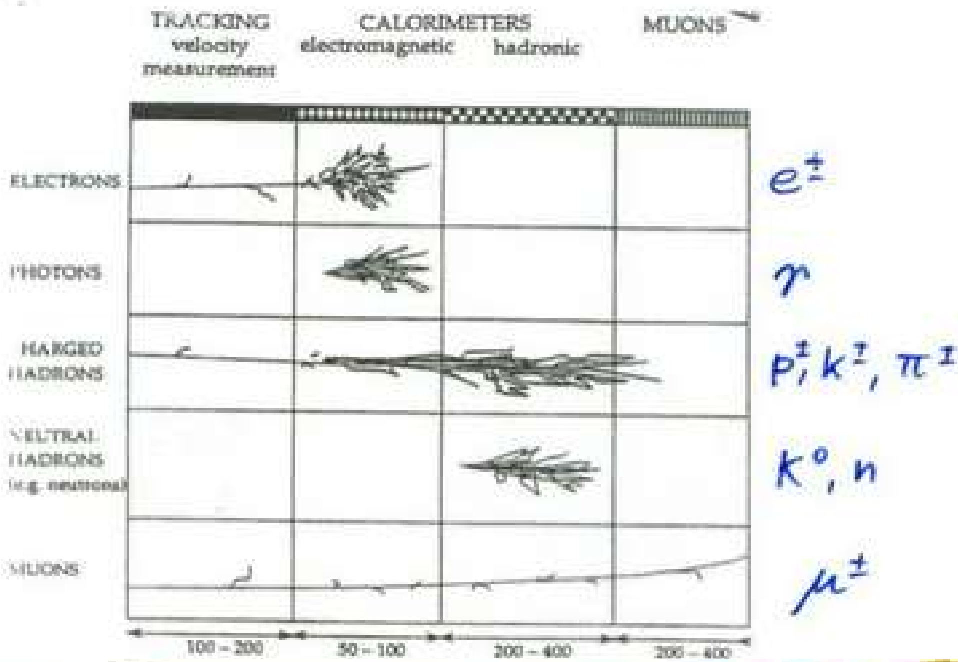


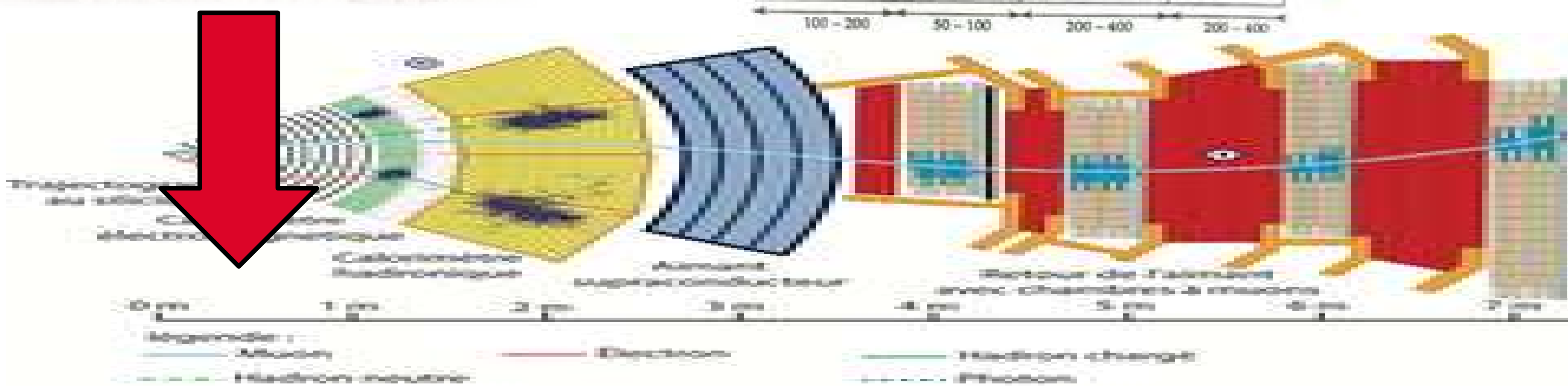
CMS 3



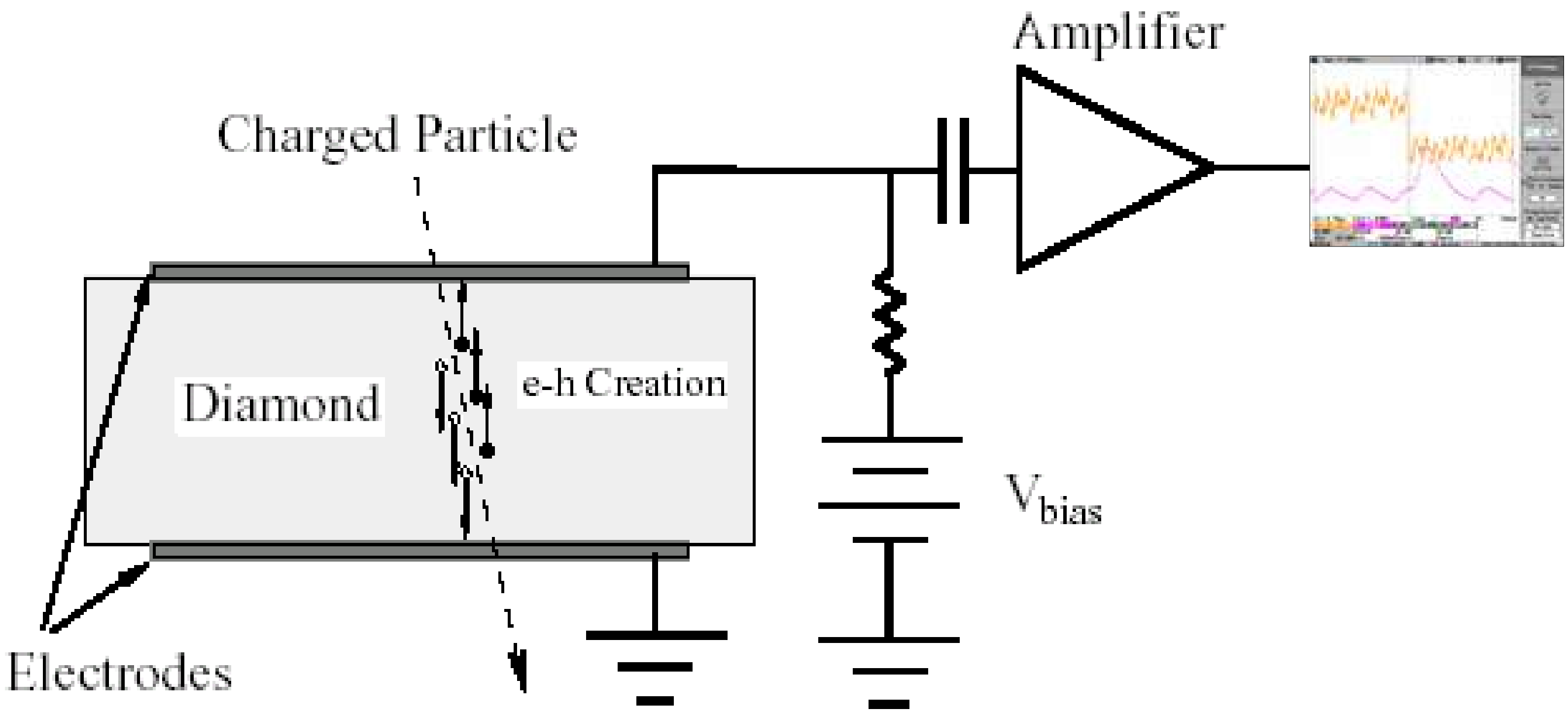
Trajectographe au silicium
Calorimètre électromagnetique
Calorimètre hadronique
Aimant supraconducteur
Retour de l'aimant avec chambres à muons
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
légende :
Muon
Électron
Hadron chargé
Hadron neutre
Photon

Trajectographes Semi-Conducteur

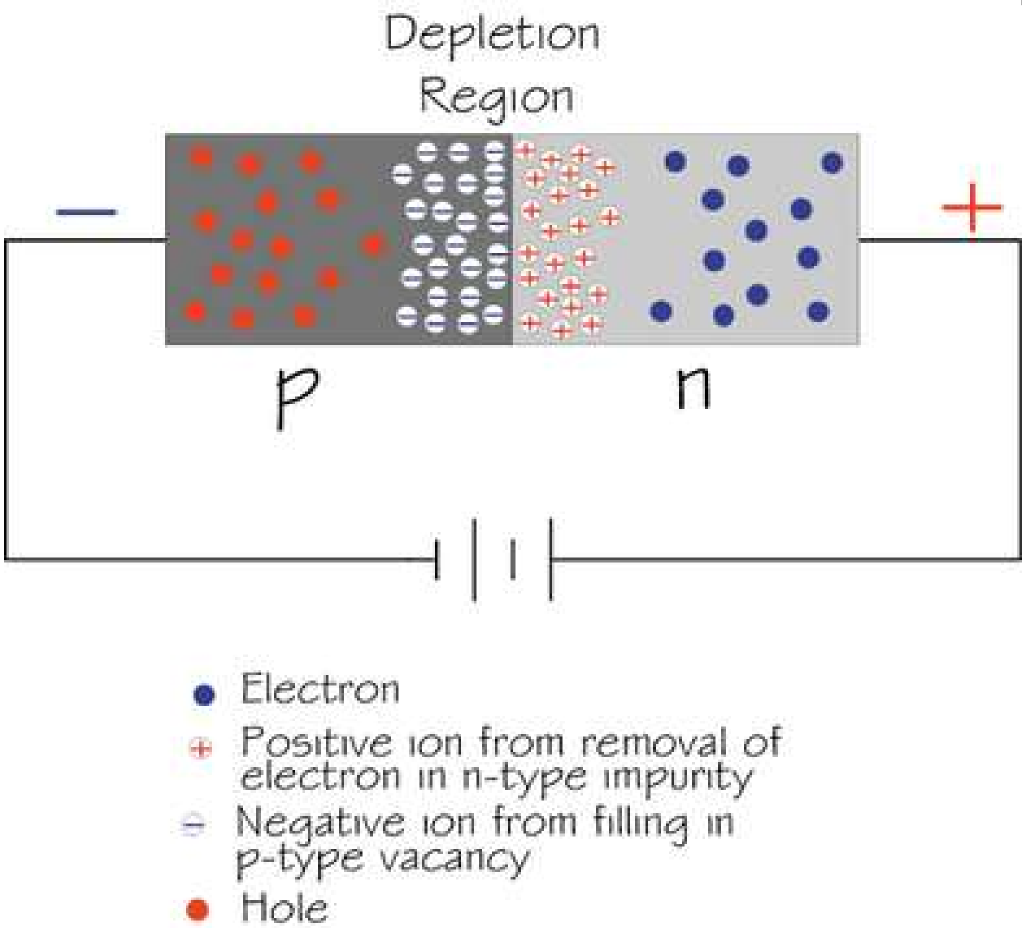


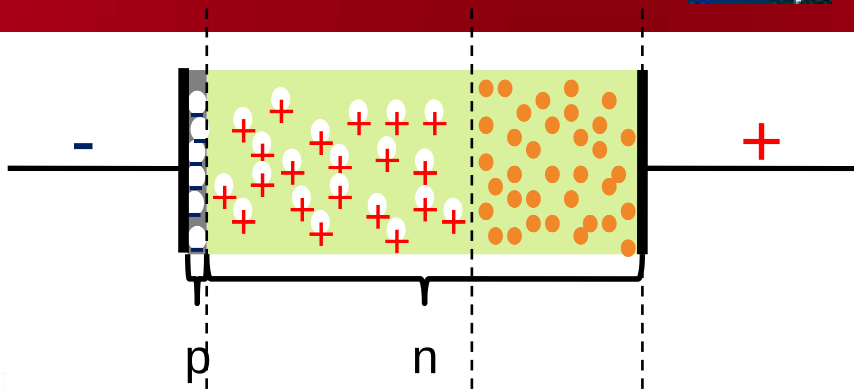


Les Détecteurs à base de Semi-Conducteur



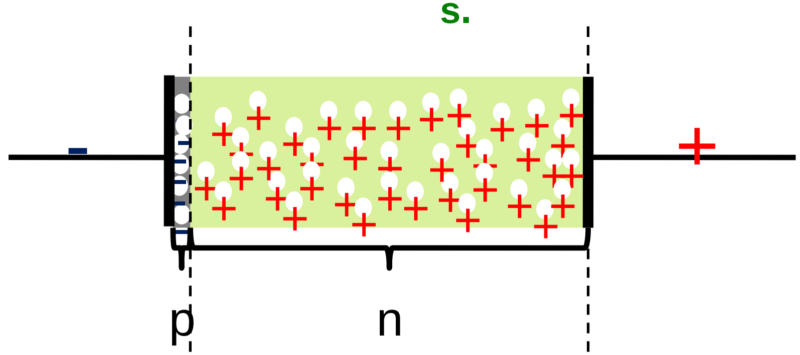
Les Détecteurs à base de Semi-Conducteur





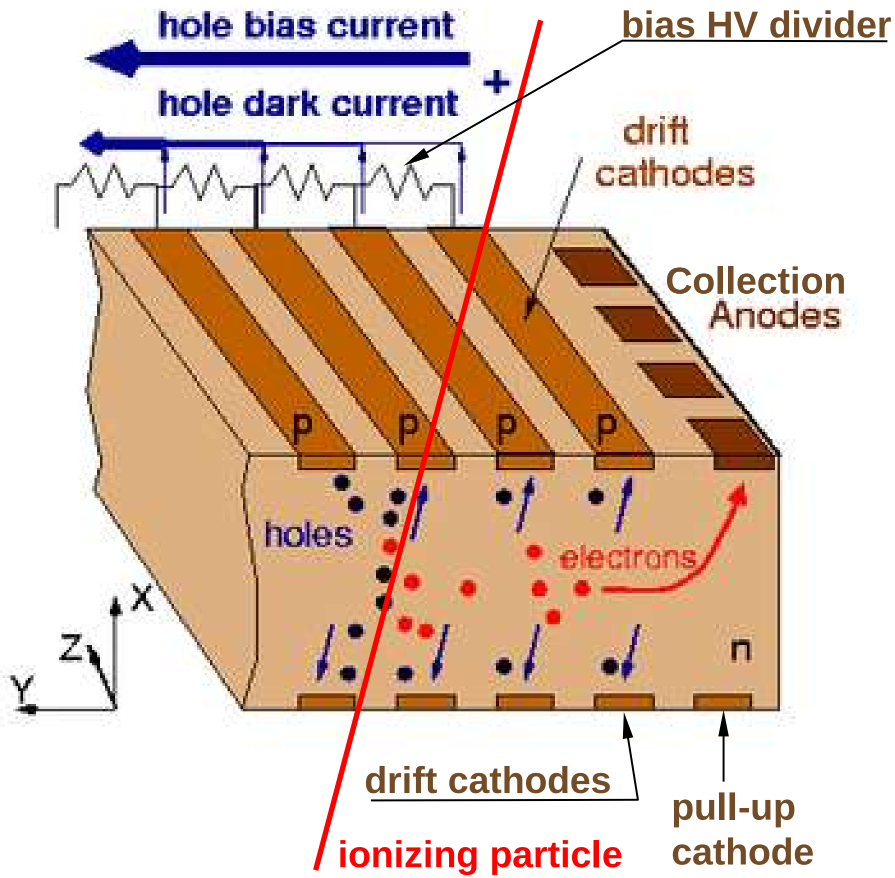
Zone without free charge carriers positively charged. Sensitive Detector Volume.

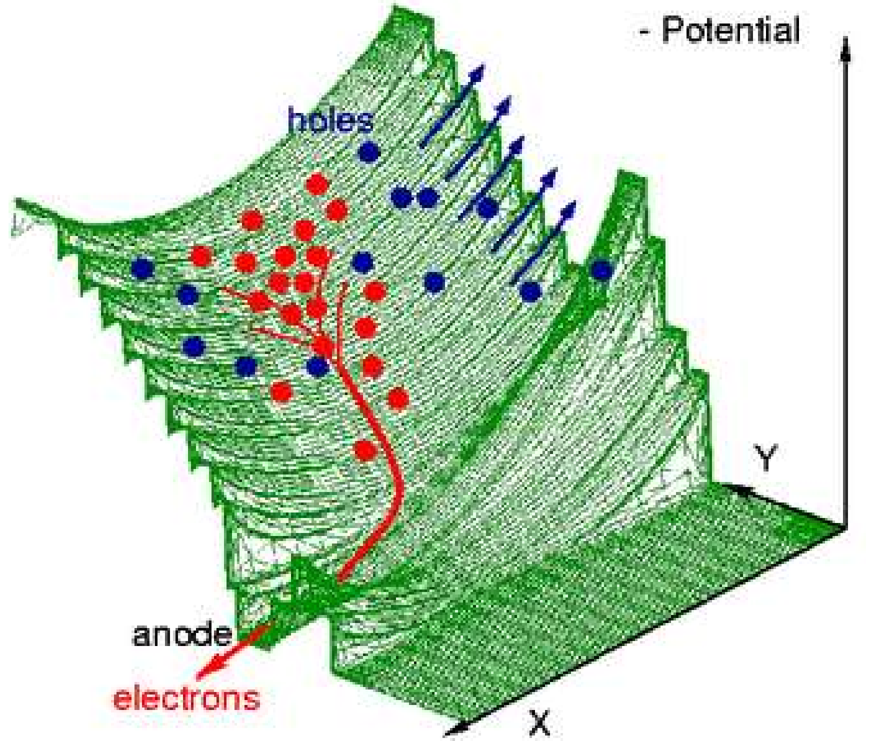
Zone with free electrons. Conductive. Insensitive to particles.

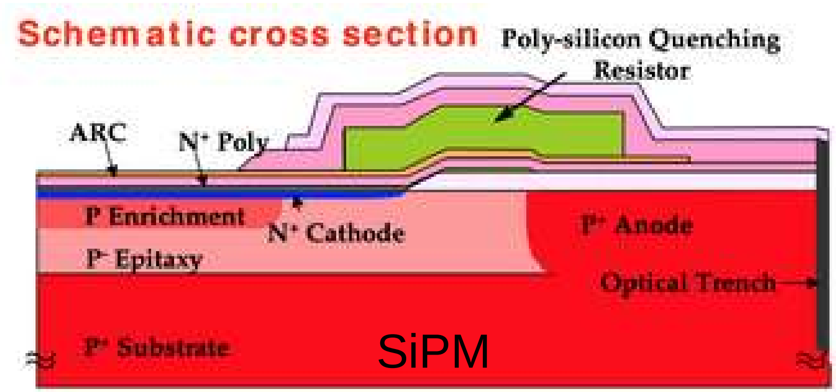


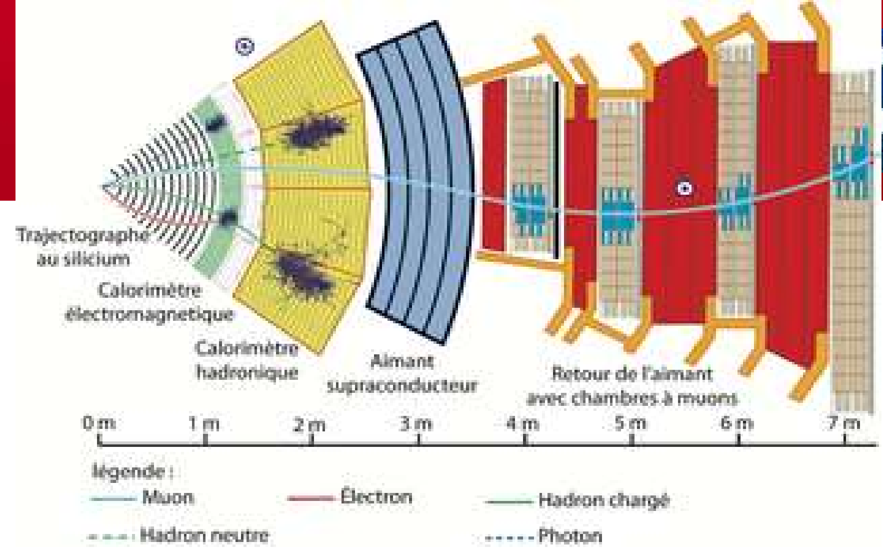
Fully depleted

Silicon Drift Detector

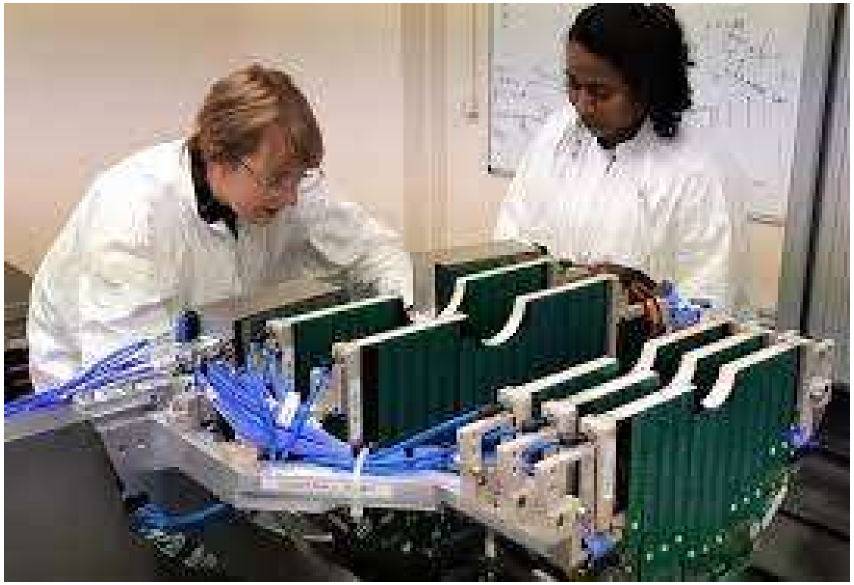


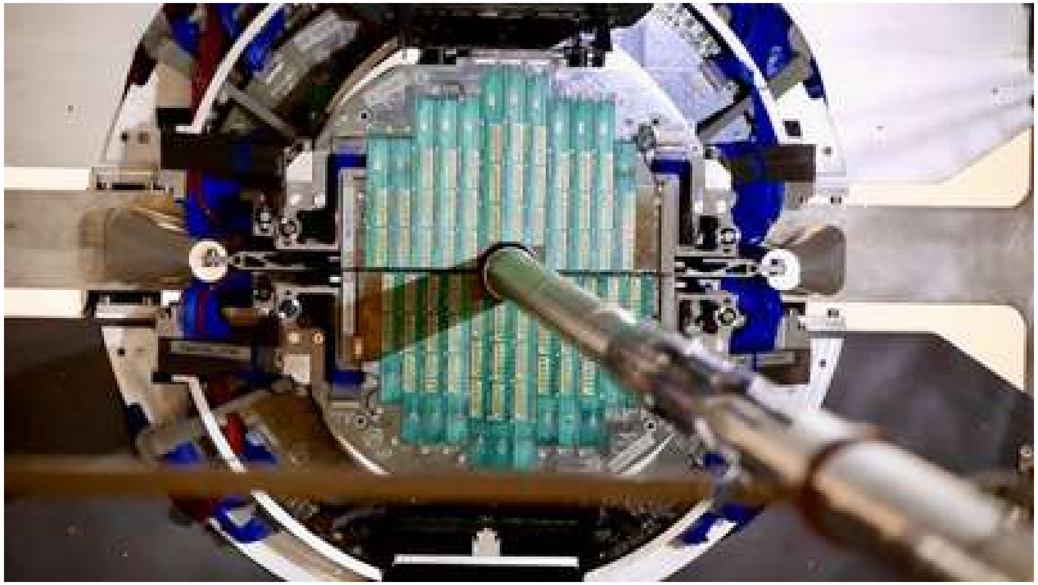




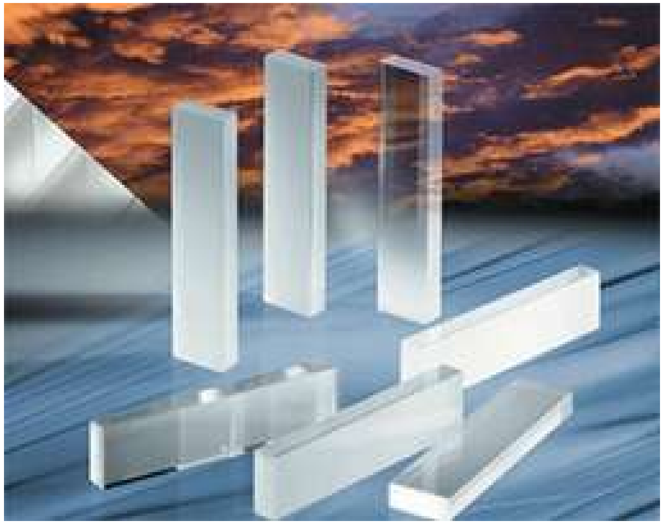


ALICE – MFT (Muon Forward Tracker)

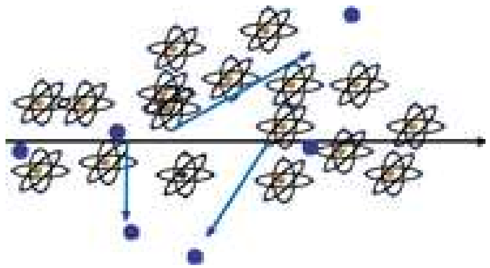




Les Détecteur à base de scintillation



Les Détecteur à base de scintillation

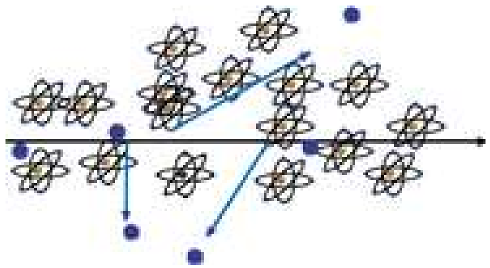


Detectors based on Registration of excited Atoms Scintillators

Emission of photons of by excited Atoms, typically UV to visible light.

What scintillates ?

Les Détecteur à base de scintillation



Detectors based on Registration of excited Atoms Scintillators

Emission of photons of by excited Atoms, typically UV to visible light.

a) Observed in Noble Gases (even liquid !)

b) Inorganic Crystals

→ **Substances with largest light yield. Used for precision measurement of energetic Photons. Used in Nuclear Medicine.**

c) Polyzyclic Hydrocarbons (Naphtalen, Anthrazen, organic Scintillators)

→ ***Most important category. Large scale industrial production, mechanically and chemically quite robust. Characteristic are one or two decay times of the light emission.***

Les Détecteur à base de scintillation

Organic ('Plastic') Scintillators

Low Light Yield **Fast: 1-3ns**

Type	Light[a] output	λ_{max}[b] (nm)	Attenuation[c] length (cm)	Risetime (ns)	Decay[d] time (ns)	Pulse FWHM (ns)
NE 102A	58–70	423	250	0.9	2.2–2.5	2.7–3.2
NE 104	68	406	120	0.6–0.7	1.7–2.0	2.2–2.5
NE 104B	59	406	120	1	3.0	3
NE 110	60	434	400	1.0	2.9–3.3	4.2
NE 111	40–55	375	8	0.13–0.4	1.3–1.7	1.2–1.6
NE 114	42–50	434	350–400	~1.0	4.0	5.3
Pilot B	60–68	408	125	0.7	1.6–1.9	2.4–2.7
Pilot F	64	425	300	0.9	2.1	3.0–3.3
Pilot U	58–67	391	100–140	0.5	1.4–1.5	1.2–1.9
BC 404	68	408	—	0.7	1.8	2.2
BC 408	64	425	—	0.9	2.1	~2.5
BC 420	64	391	—	0.5	1.5	1.3
ND 100	60	434	400	—	3.3	3.3
ND 120	65	423	250	—	2.4	2.7
ND 160	68	408	125	—	1.8	2.7

[a] Percentage of anthracene.
[b] Wavelength of maximum emission.
[c] 1/e length.
[d] Main component.
Source: Catalog, Nuclear Enterprises; Catalog, Bicron Corporation; Catalog, National Diagnostics; M. Moszynski and B. Bengtson, Nuc. Instr. Meth. 158: 1, 1979; G. D'Agostini et al., Nucl. Instr. Meth. 185: 49, 1981.

LHC bunchcrossing 25ns

Inorganic (Crystal) Scintillators

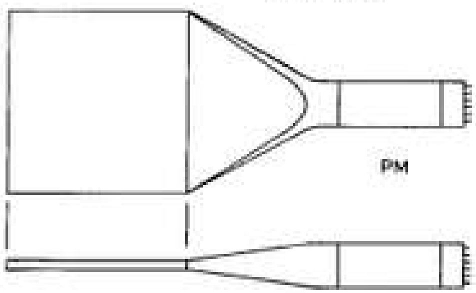
Large Light Yield **Slow: few 100ns**

	Relative light output	λ_{max} emission (nm)	Decay time (ns)	Density (g/cm³)
Inorganic crystals				
NaI(Tl)	230	415	230	3.67
CsI(Tl)	250	560	900	4.51
$Bi_4Ge_3O_{12}$ (BGO)	23–86	480	300	7.13
Organic crystals				
Anthracene	100	448	22	1.25
Trans-stilbene	75	384	4.5	1.16
Naphthalene	32	330–348	76–96	1.03
p,p'-Quarterphenyl	94	437	7.5	1.20
Primary activators				
2,5-Diphenyl-oxazole (PPO)	75	360–416	5[a]	
2-Phenyl-5-(4-biphenylyl)-1,3,4-oxadiazole (PBD)	96	360–5		
4,4''-Bis(2-butyloctyloxy)-*p*-quaterphenyl (BIBUQ)	60	365,393	1.30[a]	

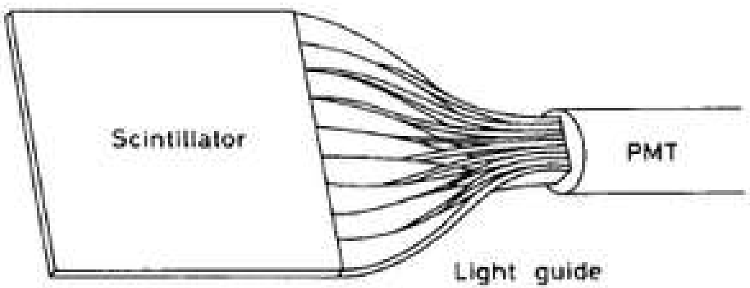
LEP bunchcrossing 25µs

Typical Geometries:

- Light guides: transfer by total internal reflection (+outer reflector)

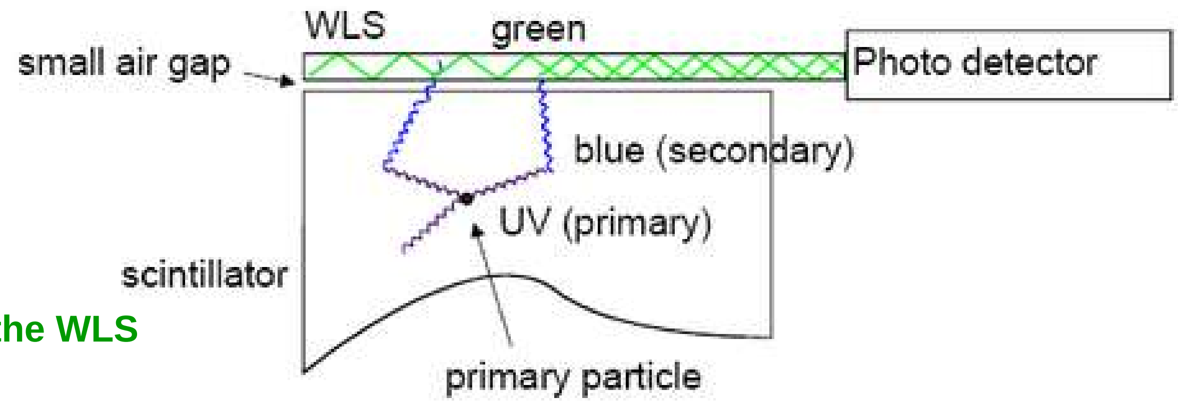


"fish tail"



adiabatic

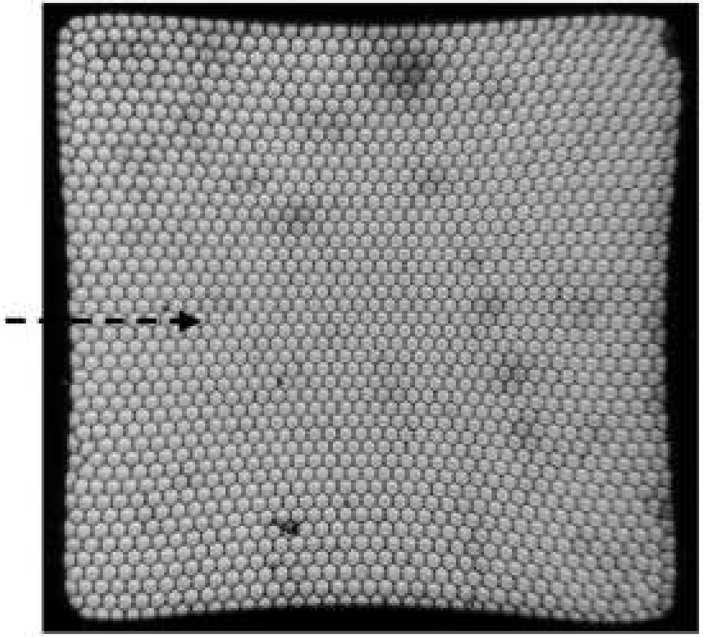
- wavelength shifter (WLS) bars

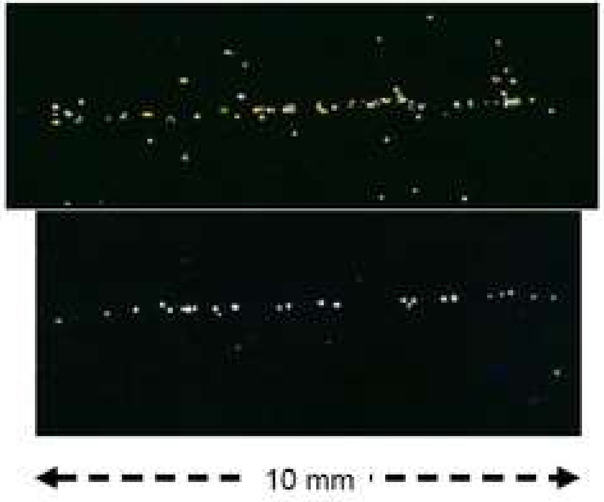


UV light enters the WLS material
Light is transformed into longer wavelength
→Total internal reflection inside the WLS material
→ 'transport' of the light to the photo detector

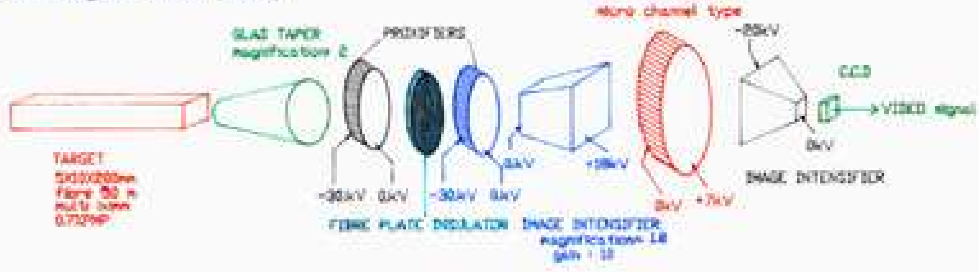
From C. Joram

Fiber Tracking





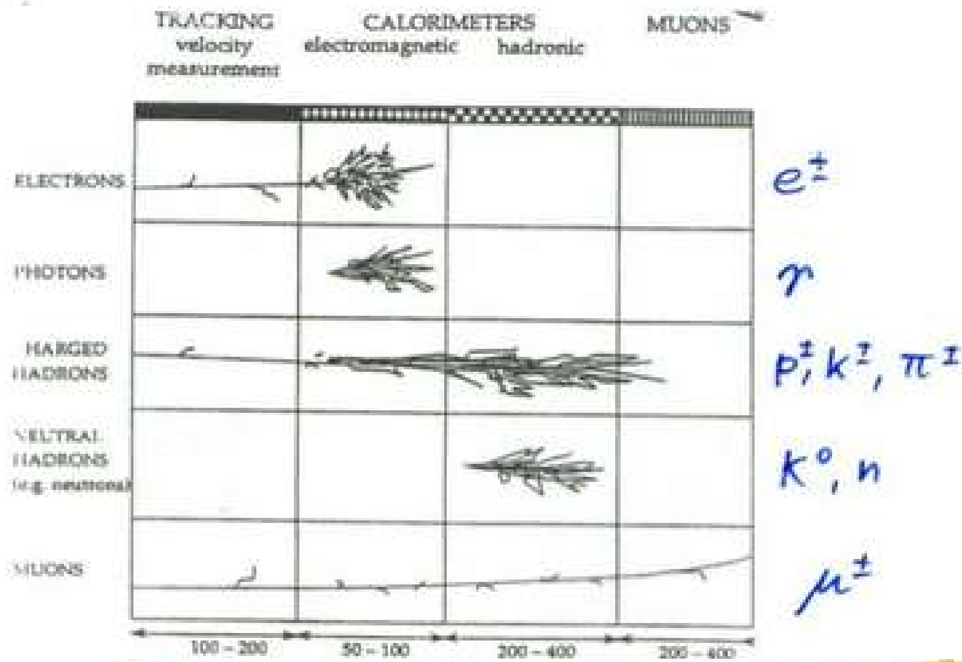
Images of tracks from 5 GeV/c pions (1989)

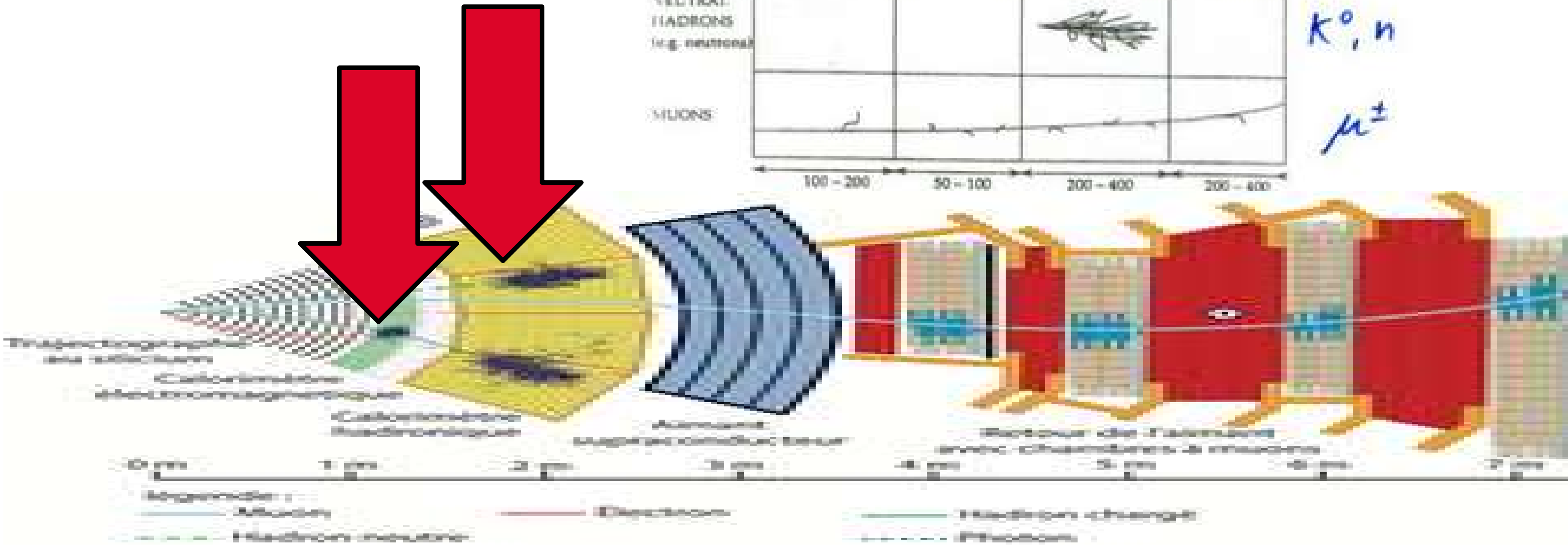


Active target in WA84 (1989)

Readout of photons in a cost effective way is rather challenging.

Calorimétrie





Calorimetry

Calorimeters can be classified into:

Electromagnetic Calorimeters,
to measure electrons and photons through their EM interactions.

Hadron Calorimeters,
Used to measure hadrons through their strong and EM interactions.

The construction can be classified into:

Homogeneous Calorimeters,
that are built of only one type of material that performs both tasks, energy degradation and signal generation.

Sampling Calorimeters,
that consist of alternating layers of an absorber, a dense material used to degrade the energy of the incident particle, and an active medium that provides the detectable signal.

C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, N0. 4, October 2003

EM Calorimetry

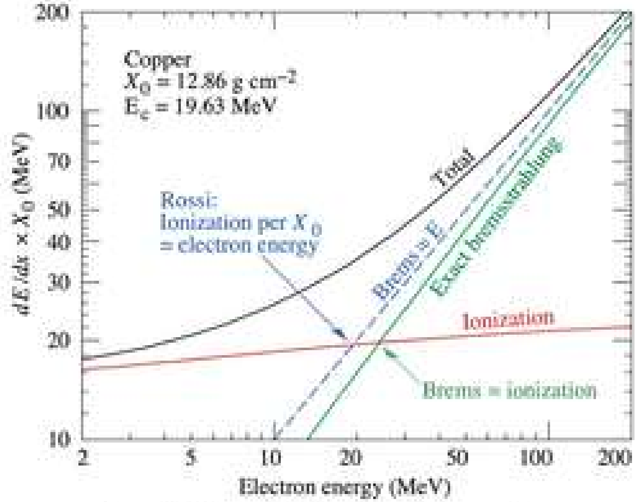
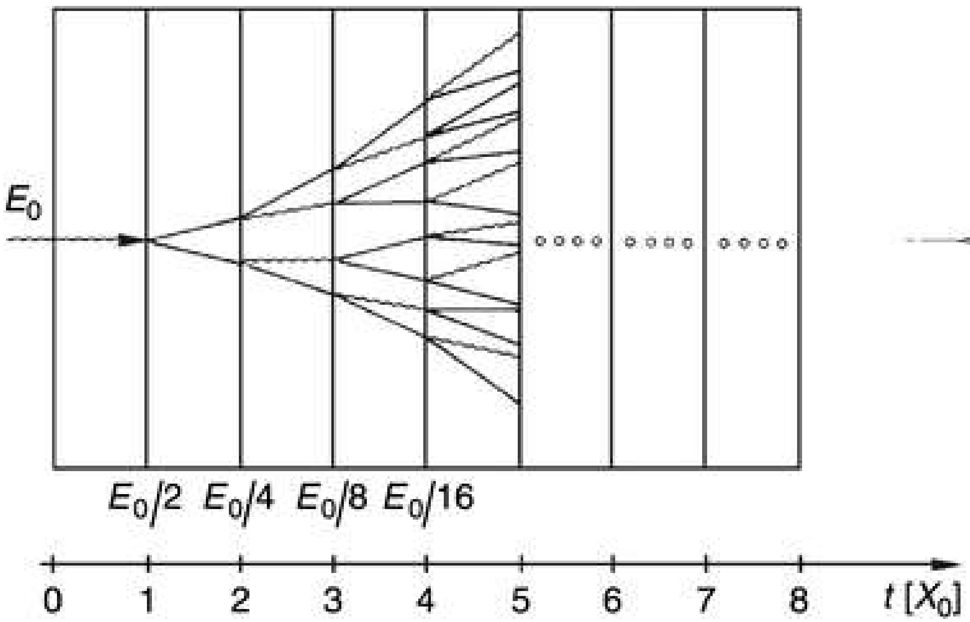
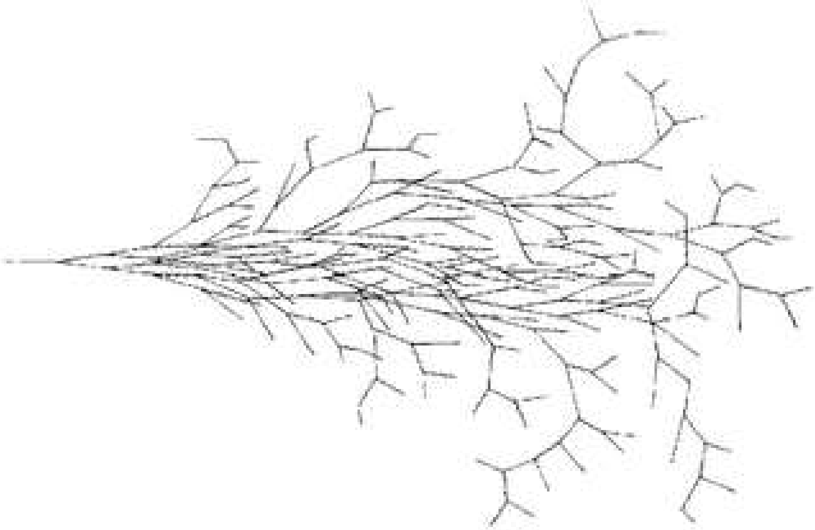


Figure 34.13: Two definitions of the critical energy E_c.

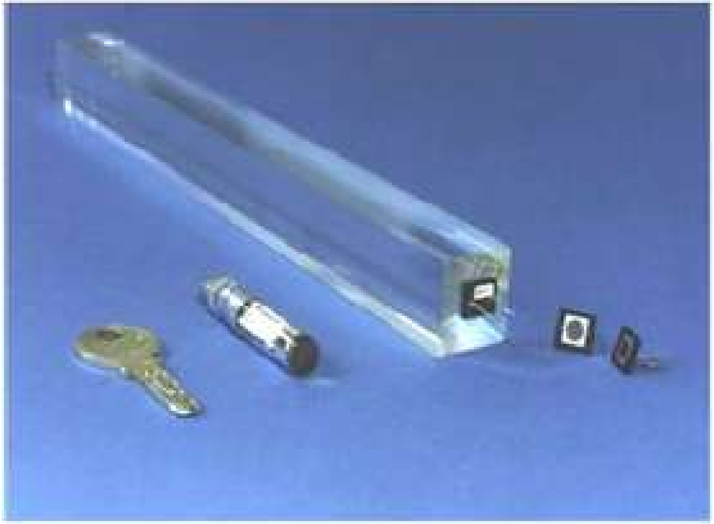
At high energies (higher than 100 MeV) electrons lose their energy almost exclusively by bremsstrahlung while photons lose their energy by electron–positron pair production

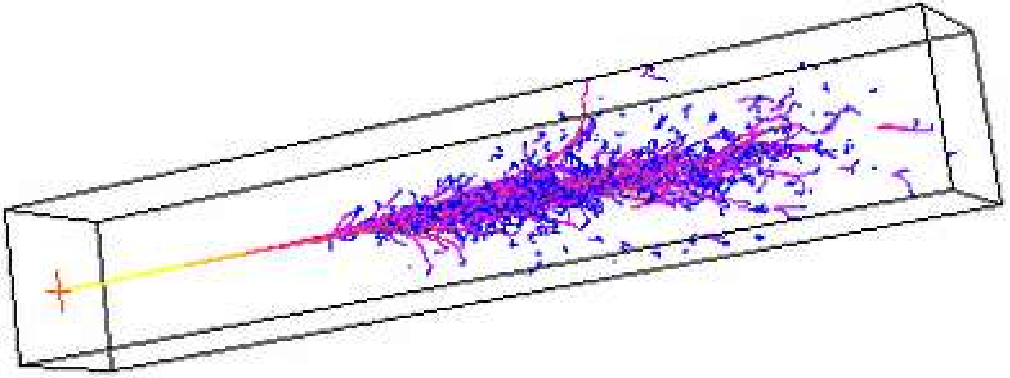


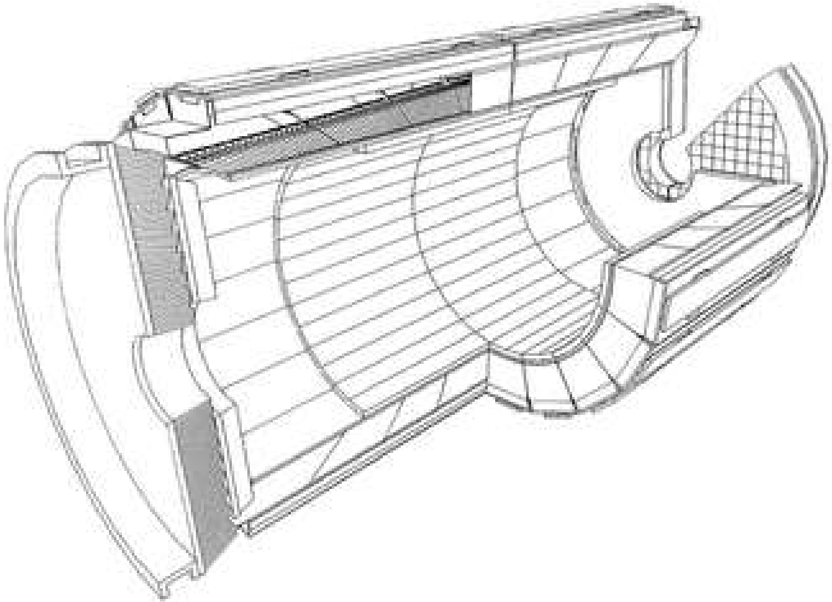


$$\frac{1}{X_0} = 4\left(\frac{\hbar}{m_e c}\right)^2 Z(Z+1)\alpha^3 n_a \log\left(\frac{183}{Z^{1/3}}\right),$$

Crystals for Homogeneous EM Calorimetry







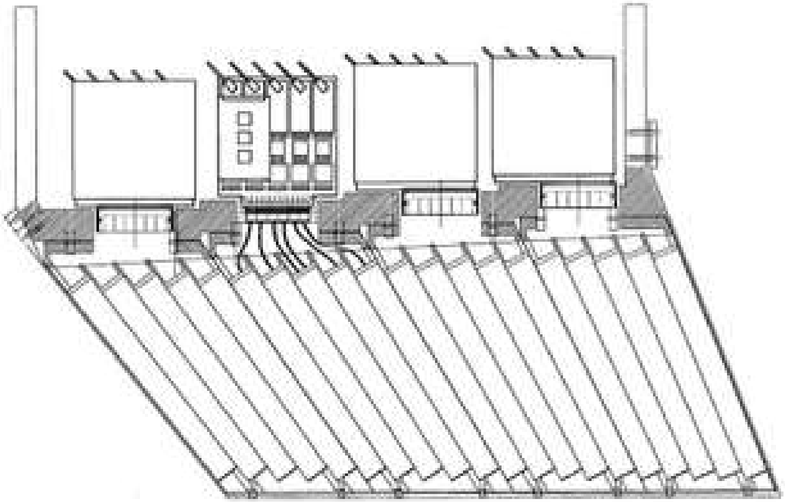


Fig. 2. Longitudinal drawing of module 2, showing the structure and the front-end electronics layout.

Hadron Calorimeters are Large because hadrons are hard to stop

Hadron Calorimeters are large and heavy because the hadronic interaction length alpha, the ‘strong interaction equivalent’ to the EM radiation length X_0, is large (5-10 times larger than X_0)

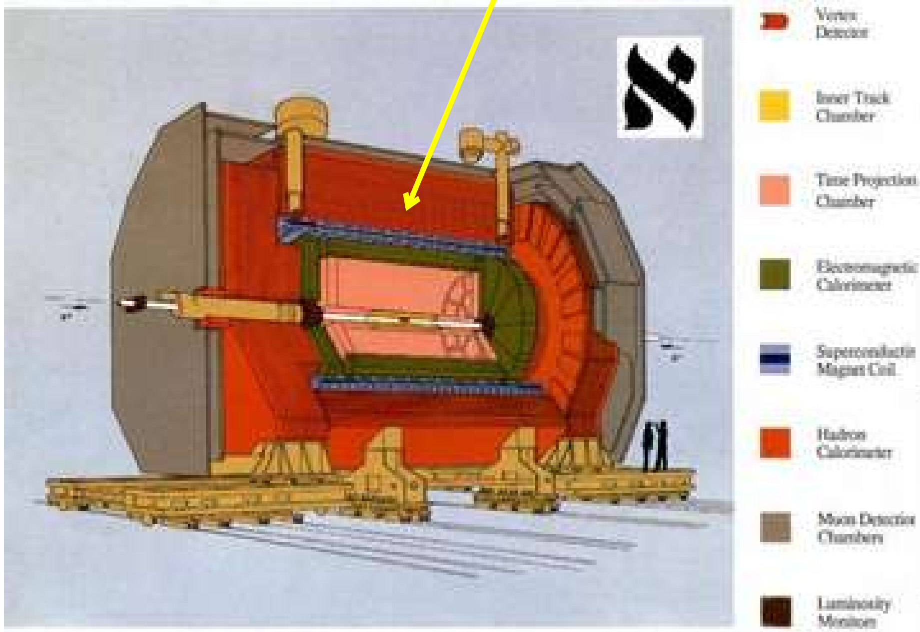
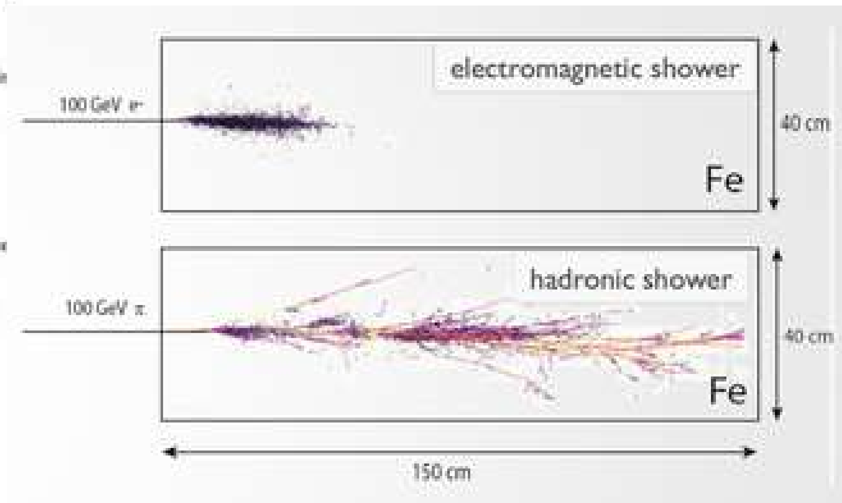


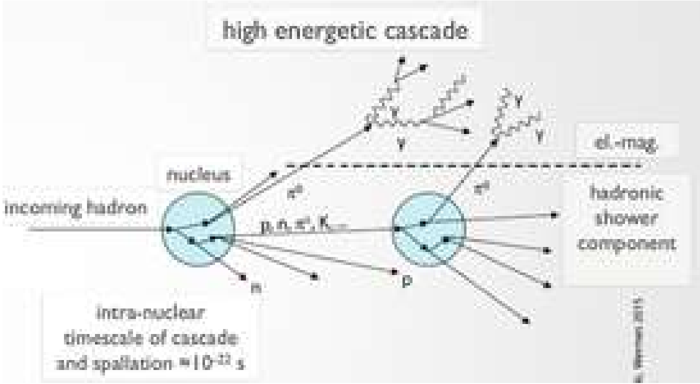
Fig. 1 - The ALEPH Detector



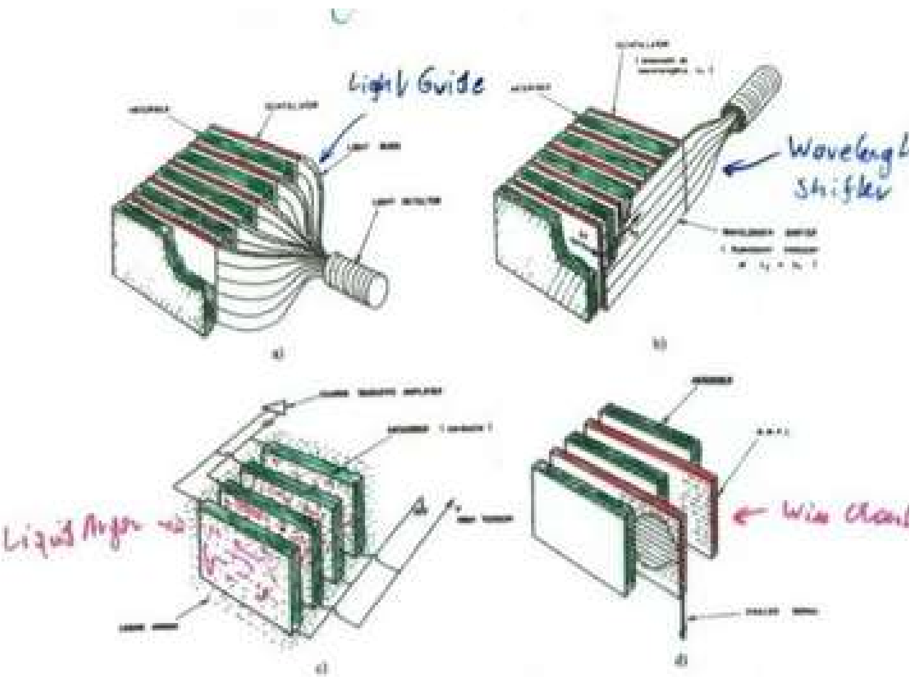
Material	Z	Density [g/cm^3]	E_c [MeV]	X_0 [cm]
C	6	2.2	81.7	19.3
Al	13	2.7	42.7	8.90
Fe	26	7.8	21.7	1.76
Cu	29	8.96	19.4	1.44
W	74	19.3	8.0	0.35
Pb	82	11.4	7.4	0.56

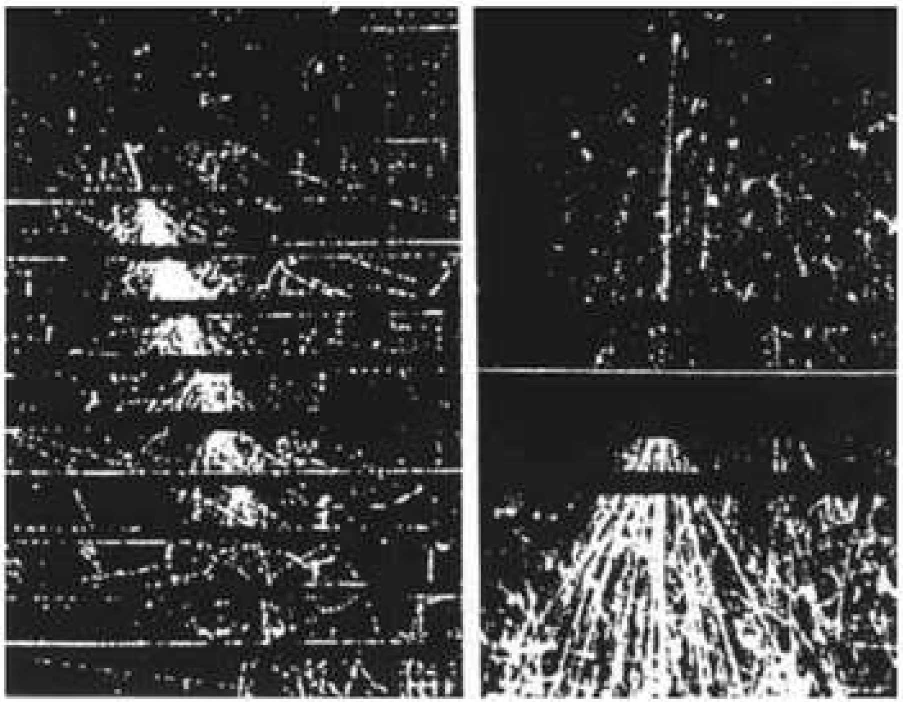
Material	Z	Density [g/cm^3]	λ [cm]
C	6	2.2	37.3
Al	13	2.7	35.4
Fe	26	7.8	15.1
Cu	29	8.96	13.9
W	74	19.3	8.9
Pb	82	11.4	15.7

For 7TeV protons

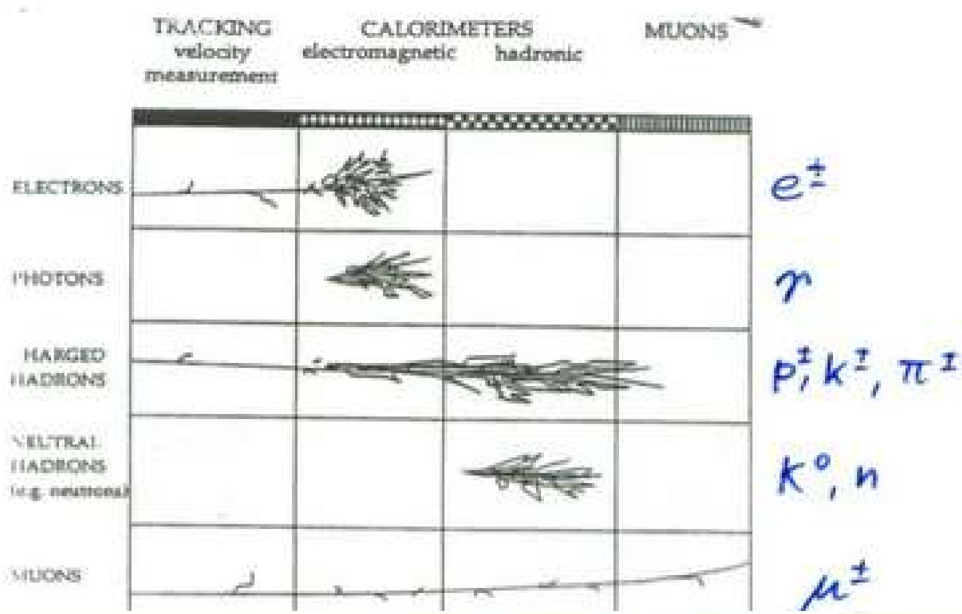


Sampling Calorimeters

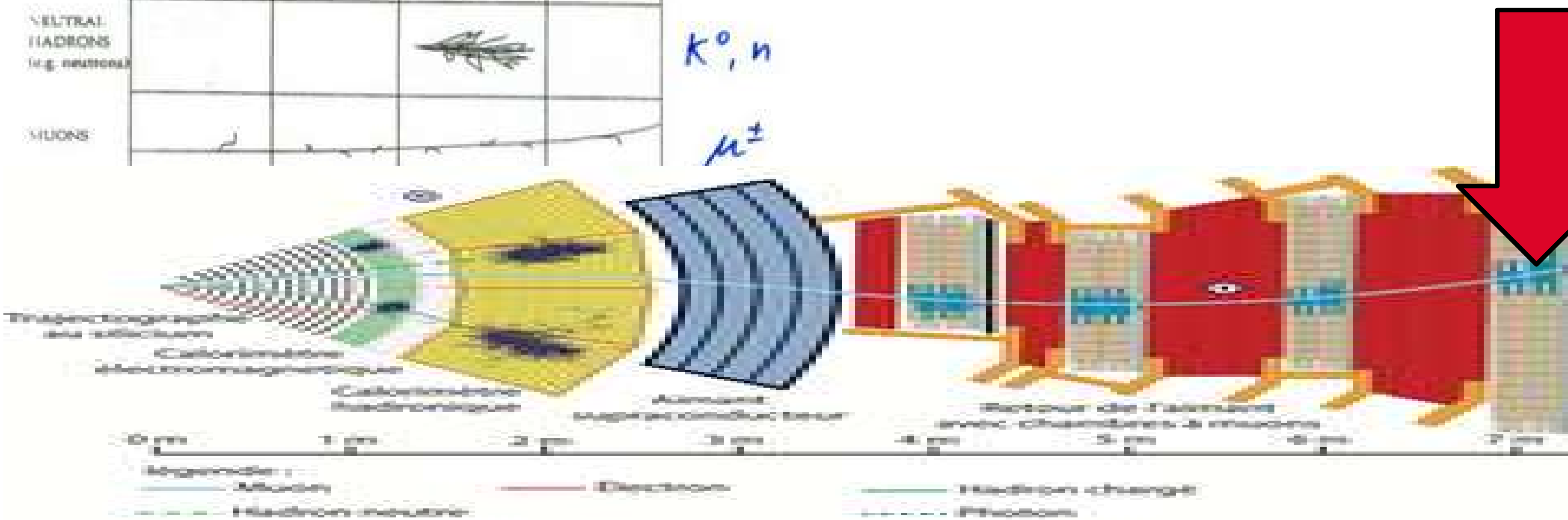




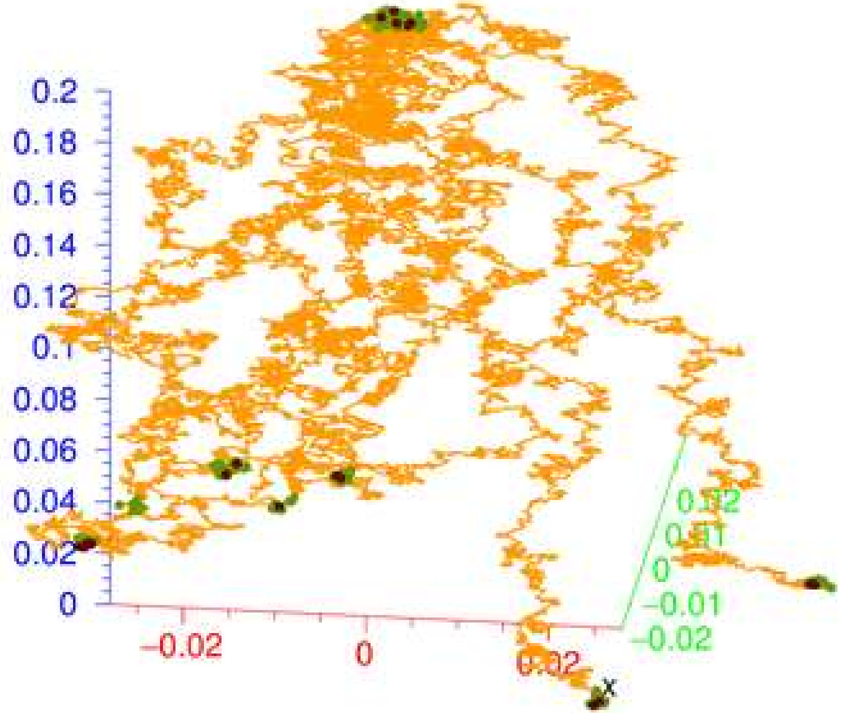
Détecteurs Gazeux



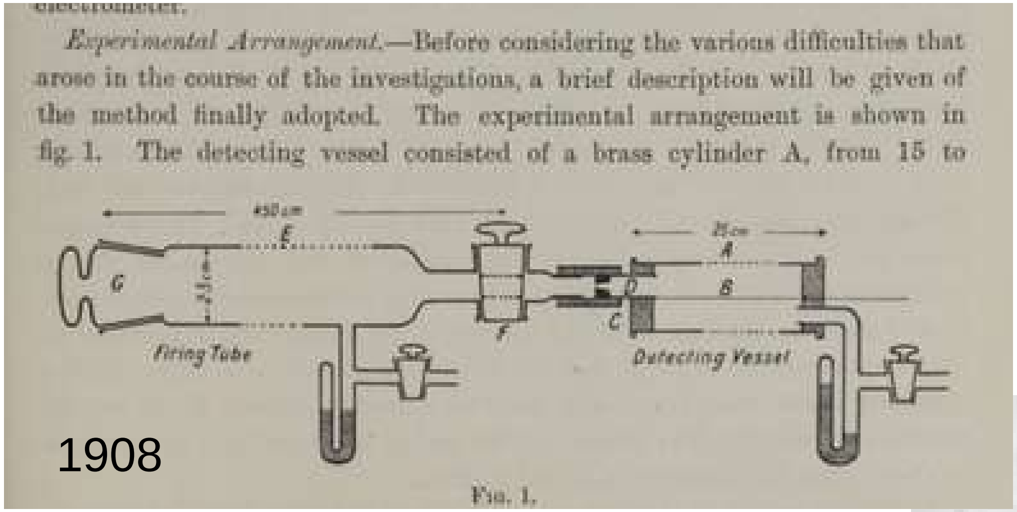
Muon Chambers ->



La détection des particules: exemple des détecteurs gazeux



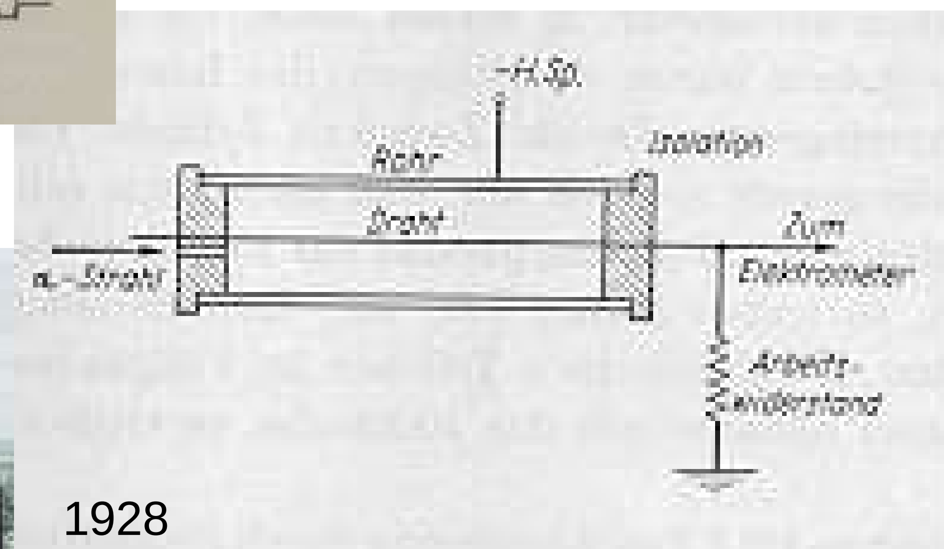
EXEMPLE SIMPLE DE DÉTECTEUR



Experimental Arrangement.—Before considering the various difficulties that arose in the course of the investigations, a brief description will be given of the method finally adopted. The experimental arrangement is shown in fig. 1. The detecting vessel consisted of a brass cylinder A, from 15 to

Fig. 1.

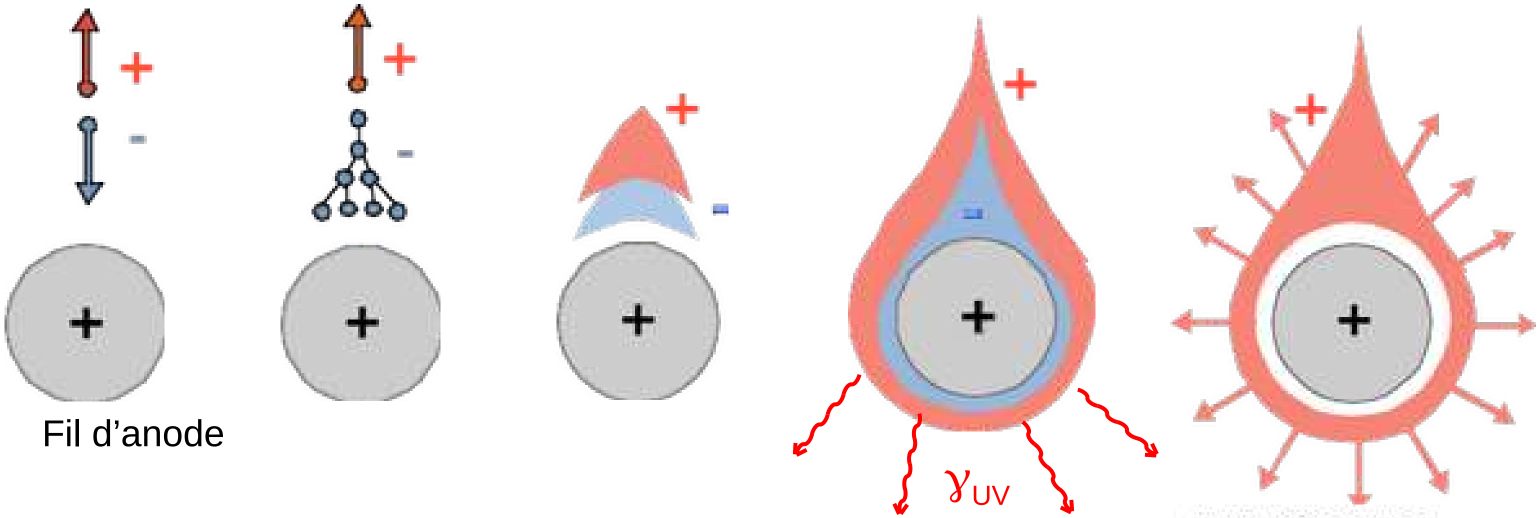
1908



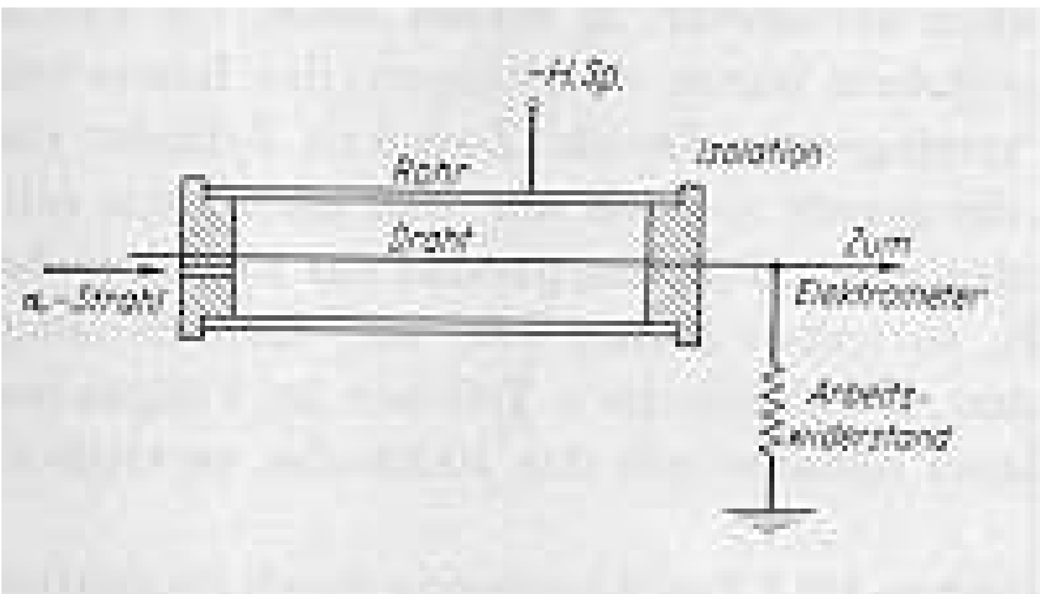
1928

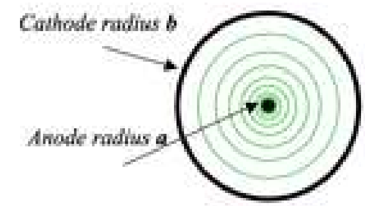
Dans les films ….

PHÉNOMÈNE D'AVALANCHE AUTOUR D'UN FILS



THIN ANODE WIRE





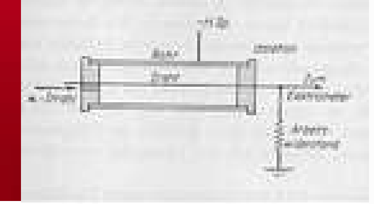
ELECTRIC FIELD AND POTENTIAL:

$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r}$$

$$V(r) = \frac{CV_0}{2\pi\varepsilon_0}\ln\frac{r}{a}$$

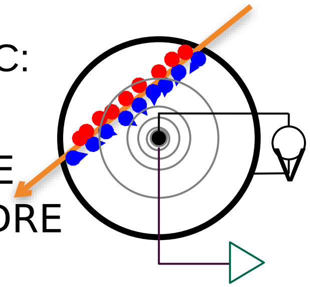
$$C = \frac{2\pi\varepsilon_0}{\ln(b/a)}$$ capacitance per unit length

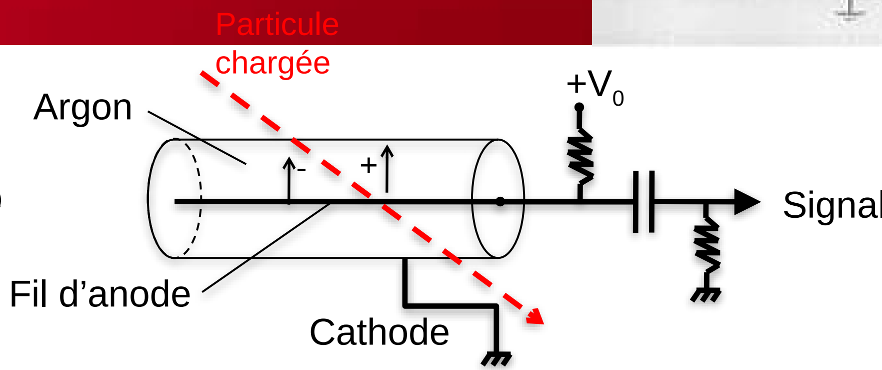
EXEMPLE SIMPLE DE DÉTECTEUR

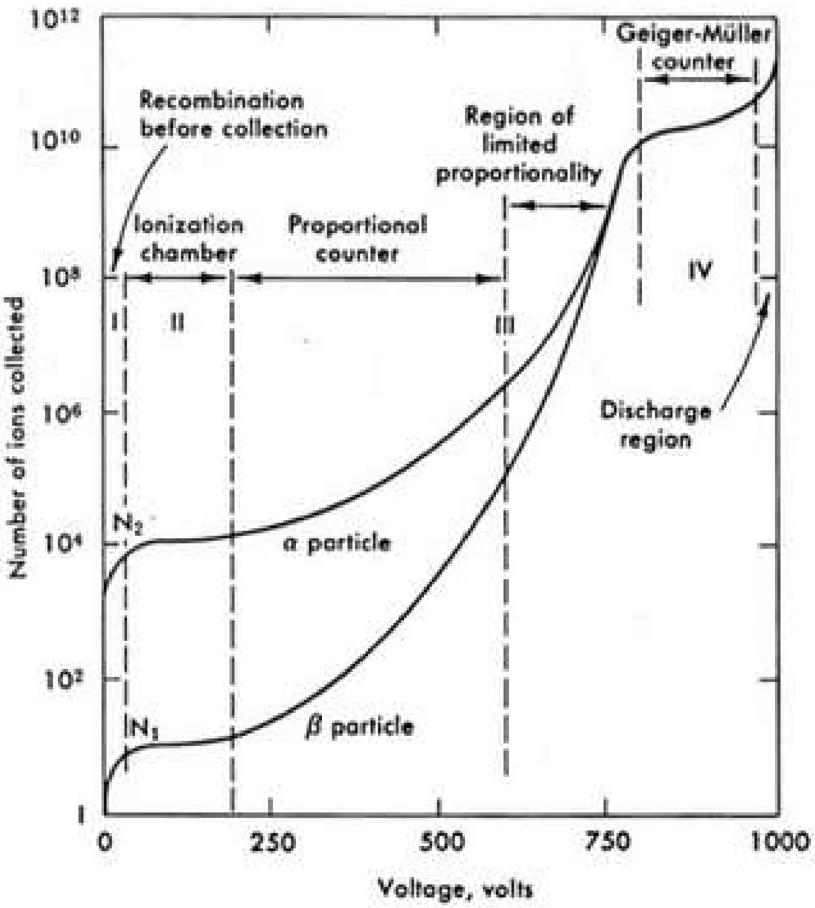


$$E = \frac{1}{r}\frac{V_0}{\ln(b/a)}$$ (RADIAL) AVEC:

- R : DISTANCE RADIALE À L'AXE
- B : RAYON INTERNE DU CYLINDRE
- A : RAYON DU FIL D'ANODE







I: tension trop faible recombinaison

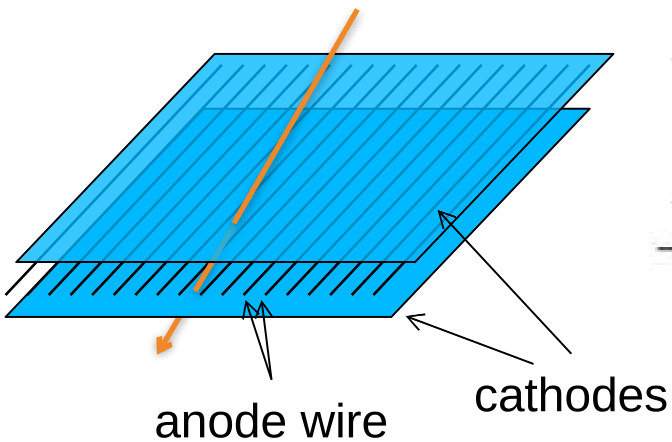
II: <u>Chambre d'ionisation</u>. Collection des charges sans amplification.

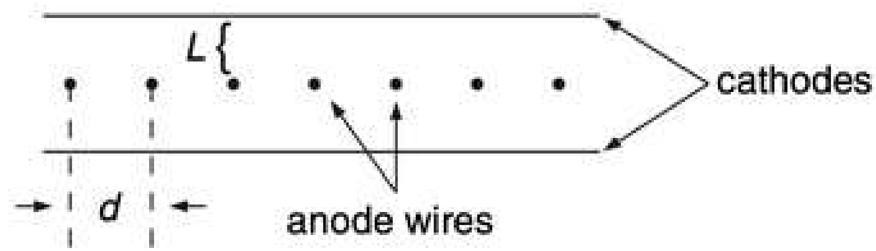
IIIa: Mode **proportionnel**. Le signal est amplifié et proportionnel à l'énergie déposée.

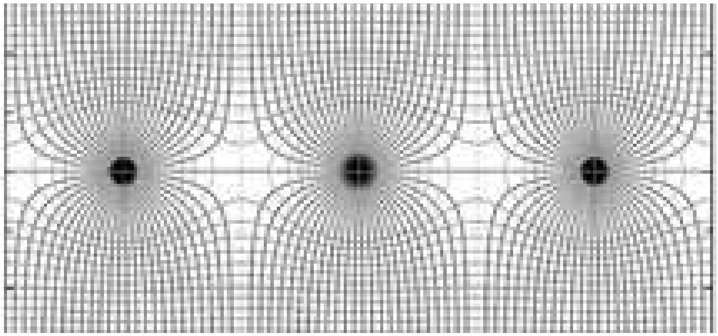
IIIb: Mode **Streamer**. Phénomènes secondaires induits par les photons de la première avalanche Gaz quencher

IV: Mode **Geiger-Müller**. Avalanche dans tout le détecteur. Le courant de sortie est saturé.

MWPCS







GRANDE CHAMBRE À FILS (1972)

EN COMPARAISON DES CHAMBRES À ÉTINCELLES ET DES CHAMBRES À BULLES, LES CHAMBRES À FILS SONT PLUS RAPIDES, PRÉSENTENT DE MEILLEURES RÉSOLUTIONS SPATIALE ET TEMPORELLE, SANS TEMPS MORT SIGNIFICATIF ET RÉSISTANTES AUX RADIATIONS.

PRIX NOBEL DE PHYSIQUE 1992

The Royal Swedish
Academy of Sciences
awards the 1992 Nobel
Prize in Physics to
Georges Charpak
for his invention and
development of particle
detectors, in particular
the multiwire
proportional chamber.

Georges Charpak
CERN, Geneva, Switzerland

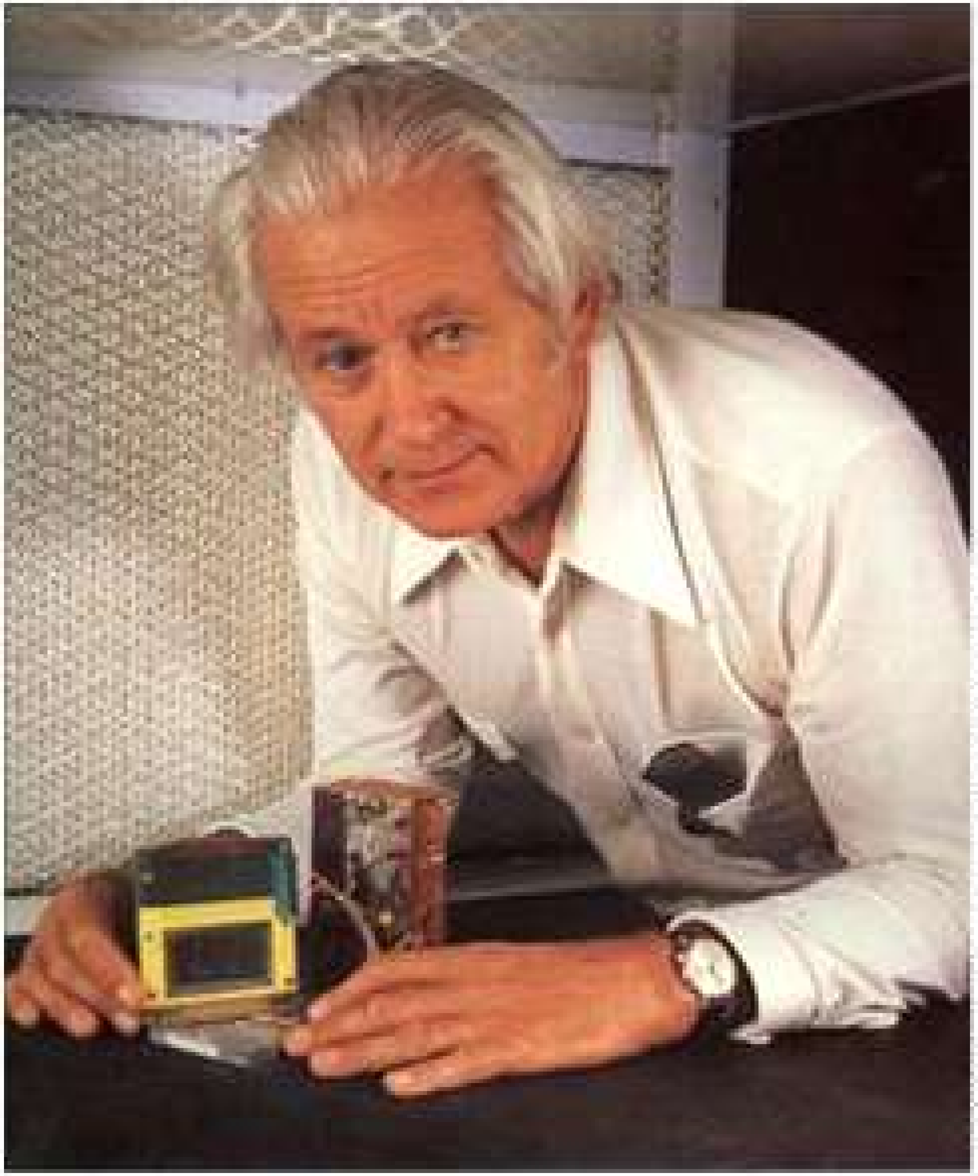
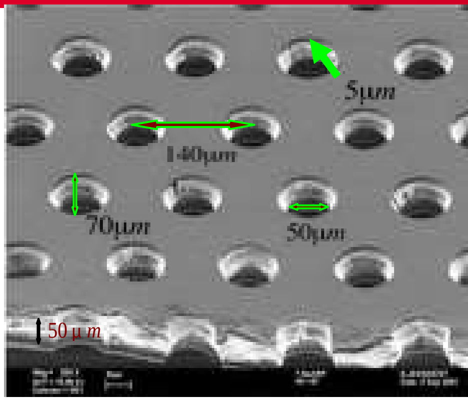


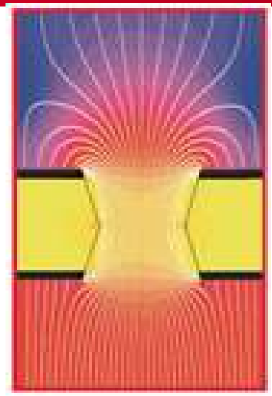
Photo: D. Parker, Science Photo Lab, UK

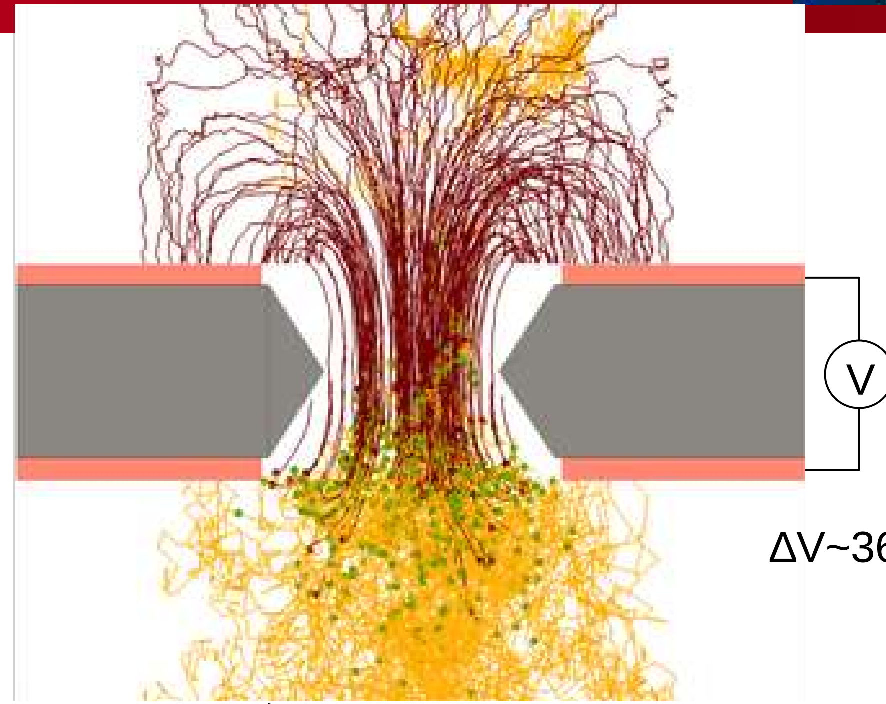
e.vandenbroucke@cea.fr

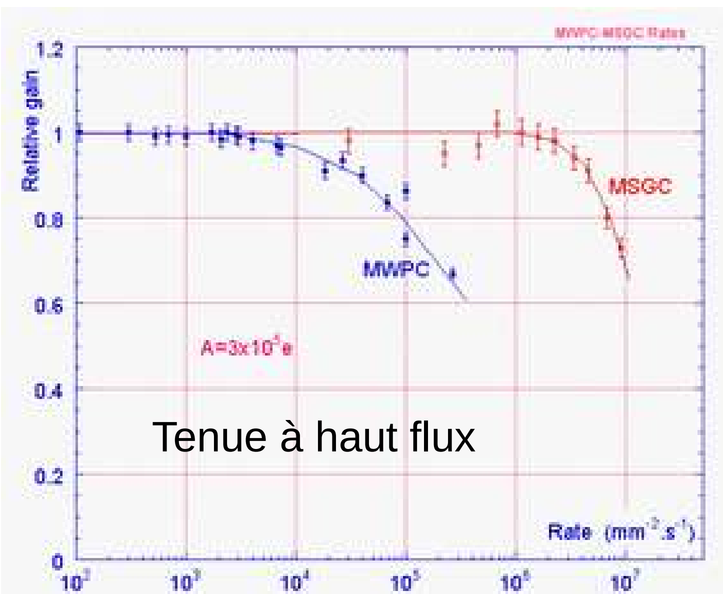
1927: **C.T.R. Wilson, Cloud Chamber**
1939: **E. O. Lawrence, Cyclotron & Discoveries**
1948: **P.M.S. Blacket, Cloud Chamber & Discoveries**
1950: **C. Powell, Photographic Method & Discoveries**
1954: **Walter Bothe, Coincidence method & Discoveries**
1960: **Donald Glaser, Bubble Chamber**
1968: **L. Alvarez, Hydrogen Bubble Chamber & Discoveries**
1992: **Georges Charpak, Multi Wire Proportional Chamber**
2009: **Boyle and Smith for the CCD sensor**
2017: **Weiss, Thorne, Barish LIGO observatory**

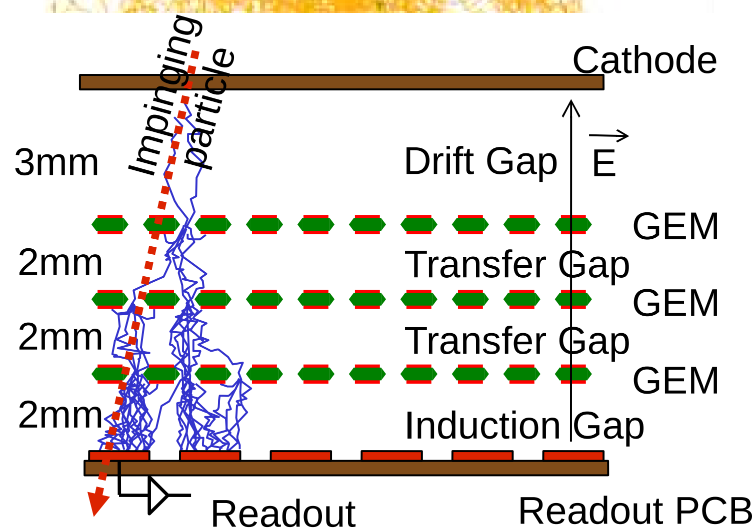
GEM : GASEOUS ELECTRON MULTIPLIER



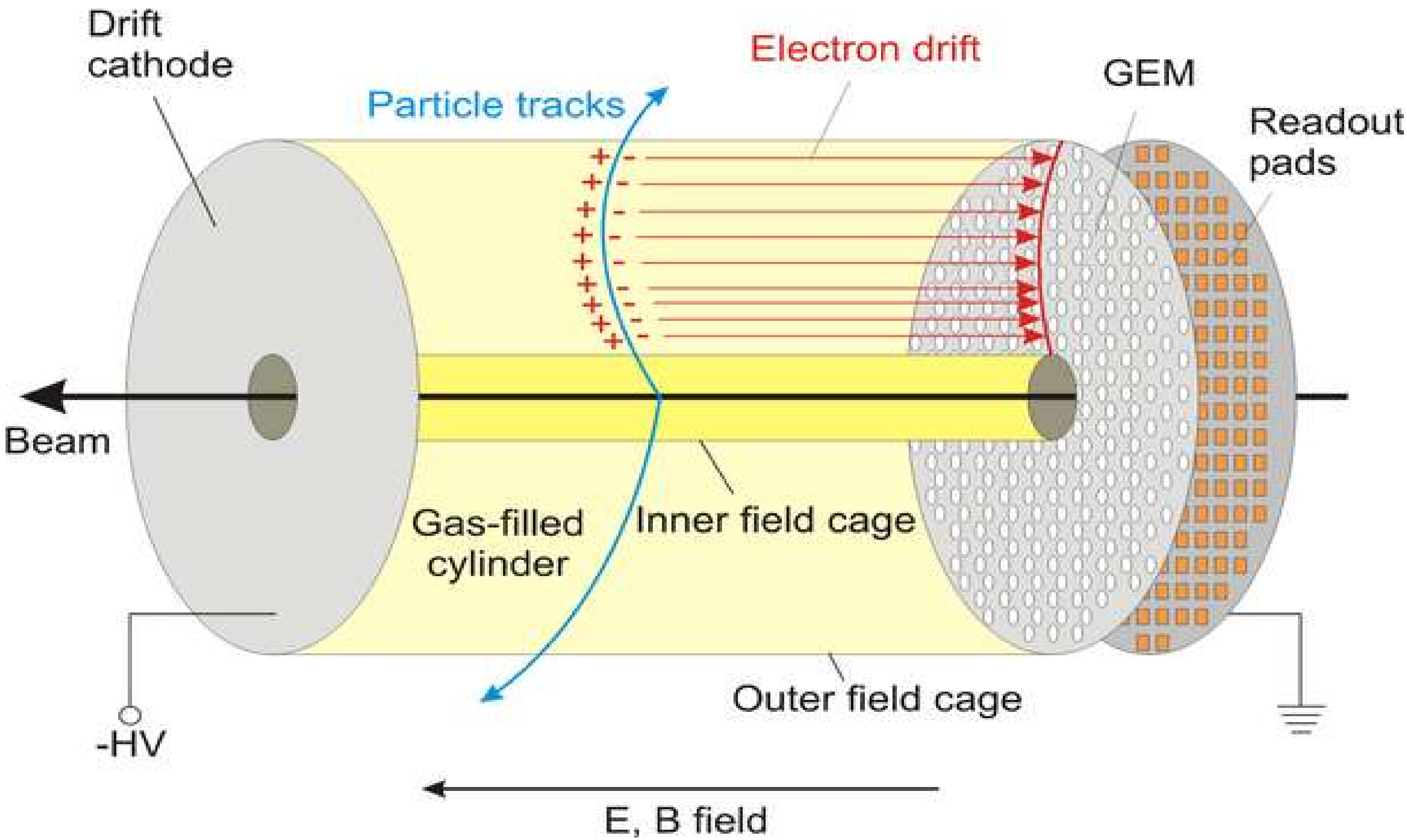






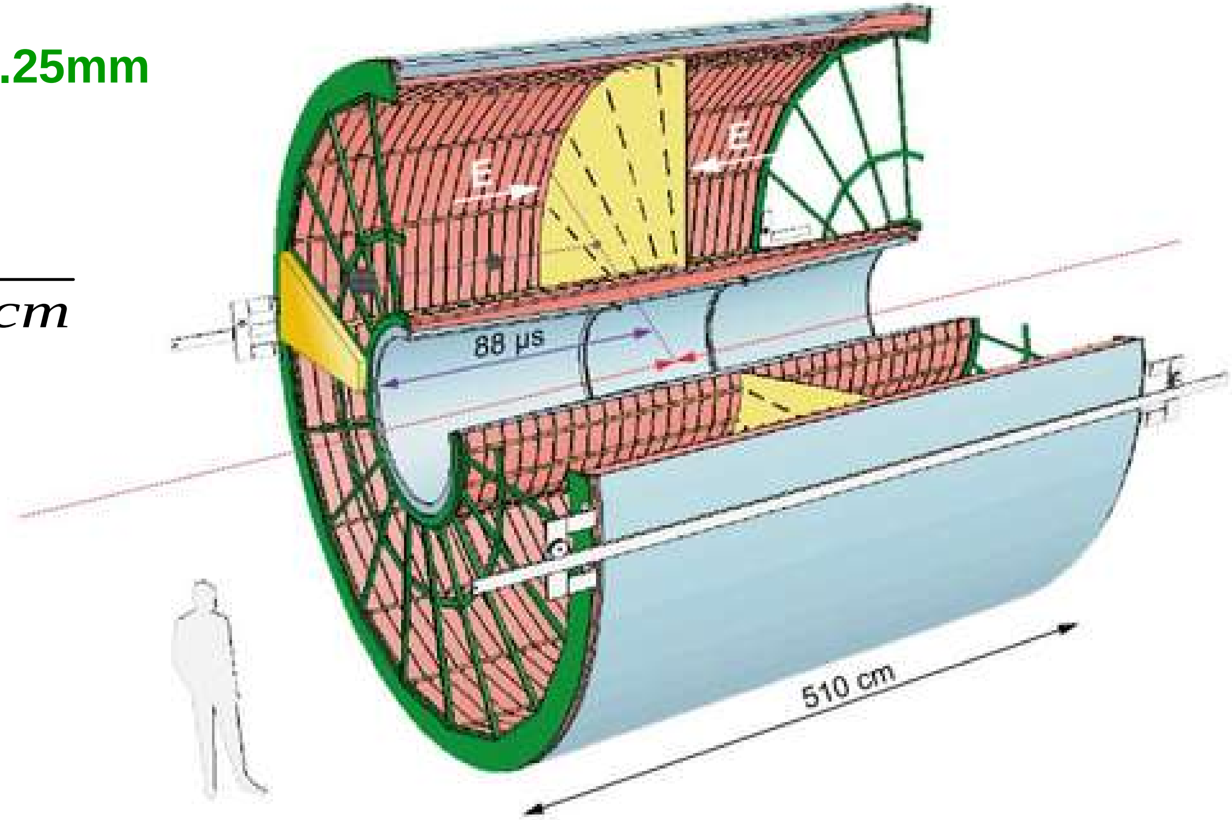


Time Projection Chamber (TPC):



ALICE TPC: Detector Parameters

- Gas Ne/ CO_2 90/10%
- Field 400V/cm
- Gas gain $>10^4$
- Position resolution σ= 0.25mm
- Diffusion: σ_t= 250µm
- Pads inside: 4x7.5mm
- Pads outside: 6x15mm $\sqrt{cm}$
- B-field: 0.5T
- Largest TPC:
  - Length 5m
  - Diameter 5m
  - Volume $88m^3$
  - Detector area $32m^2$
  - Channels ~570 000



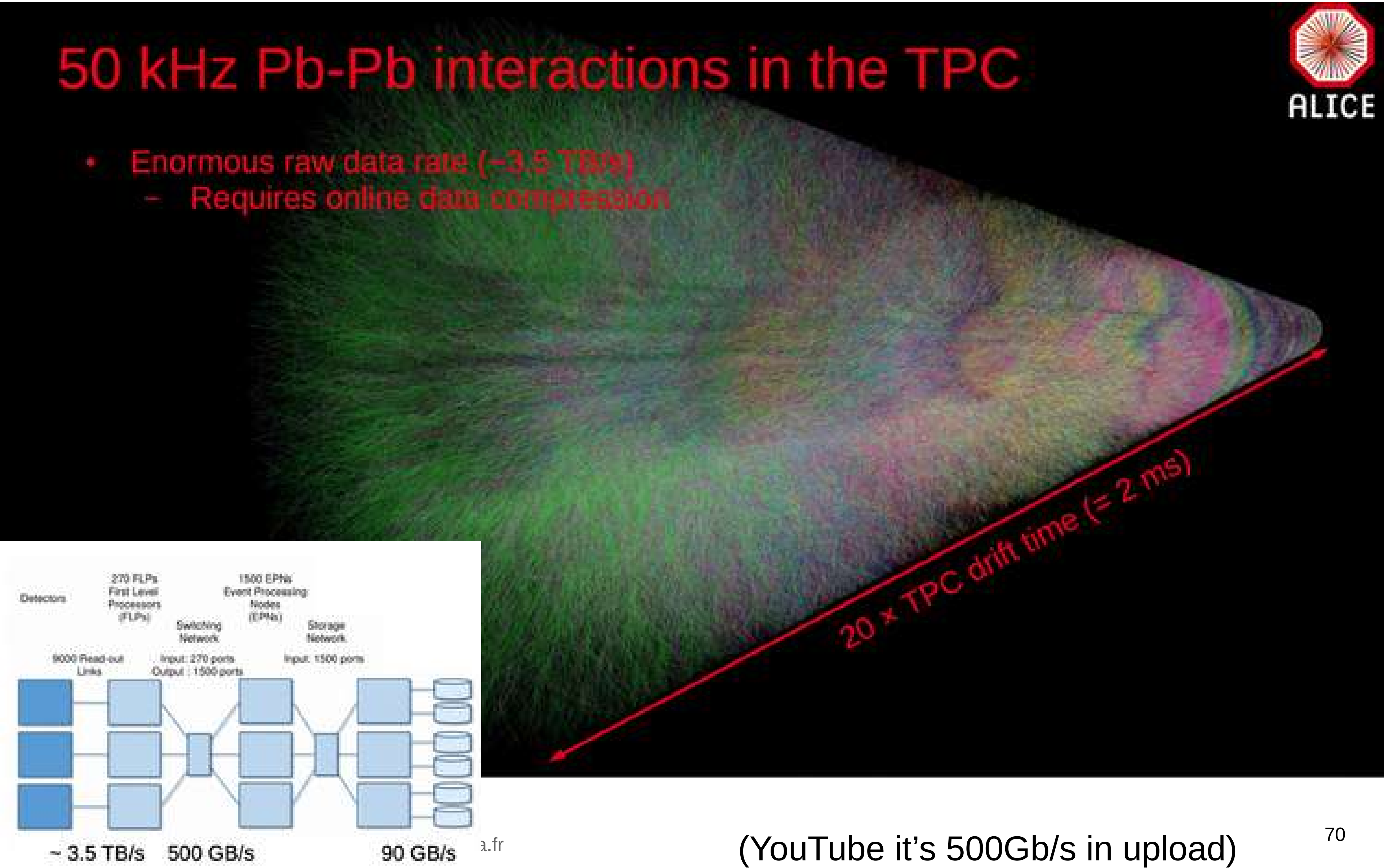
- High Voltage:
  - Cathode -100kV

=> Gated grid ~15kHz max

TPC installed in the ALICE Experiment

ALICE UPGRADE

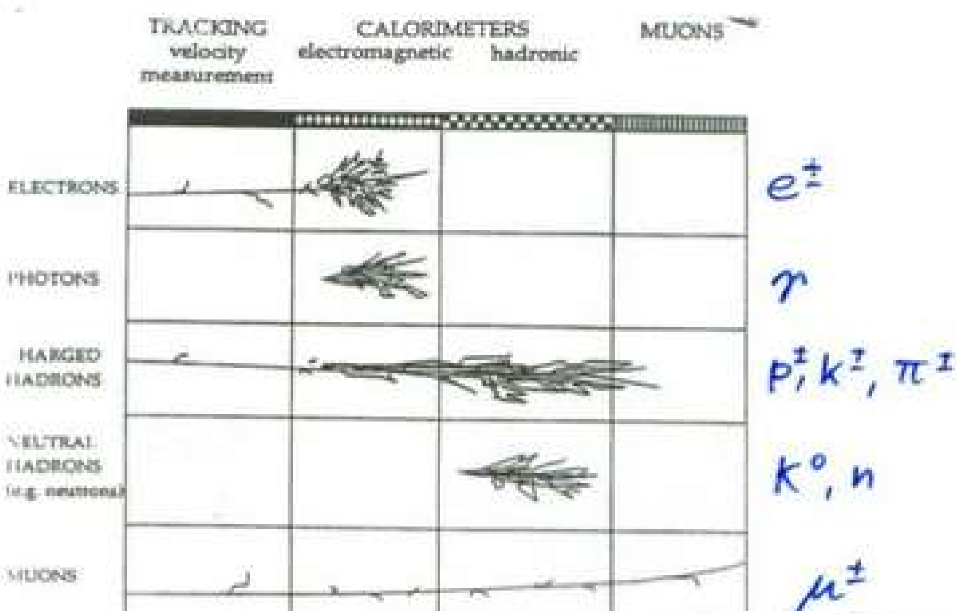
ALICE UPGRADE



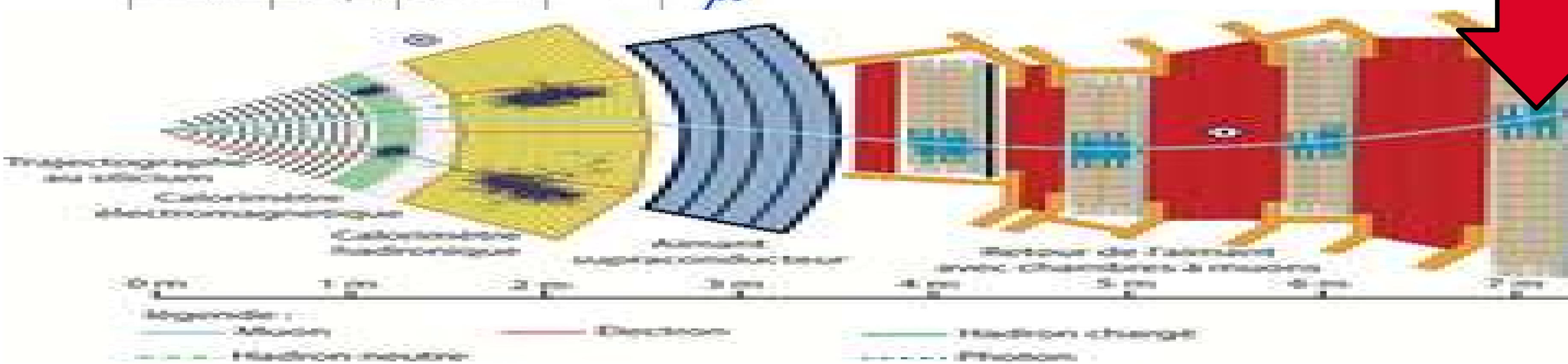
a.fr

(YouTube it's 500Gb/s in upload)

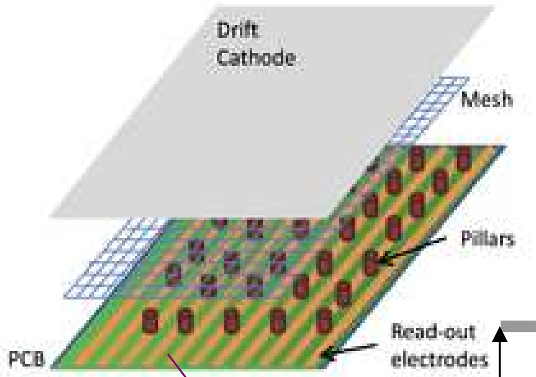
Détecteurs Gazeux

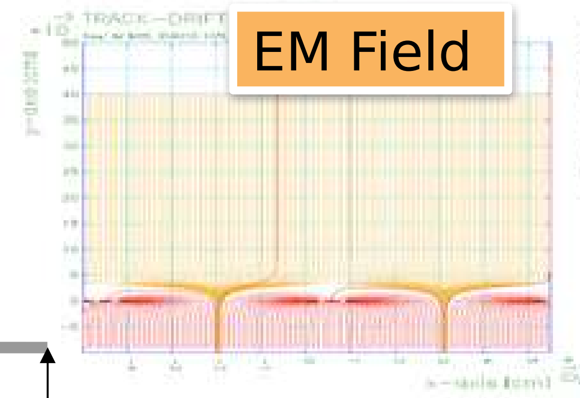


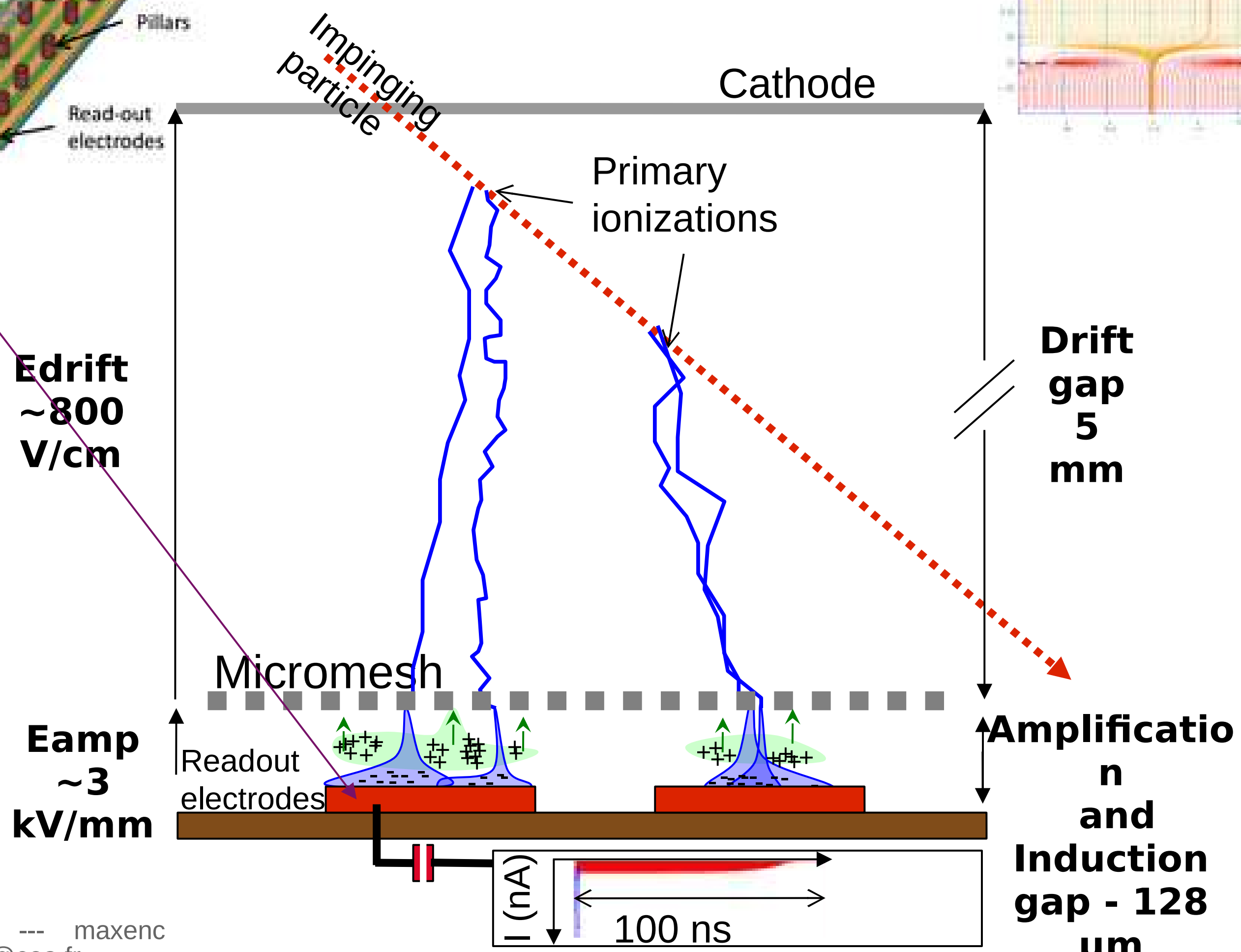
Muon Chambers ->



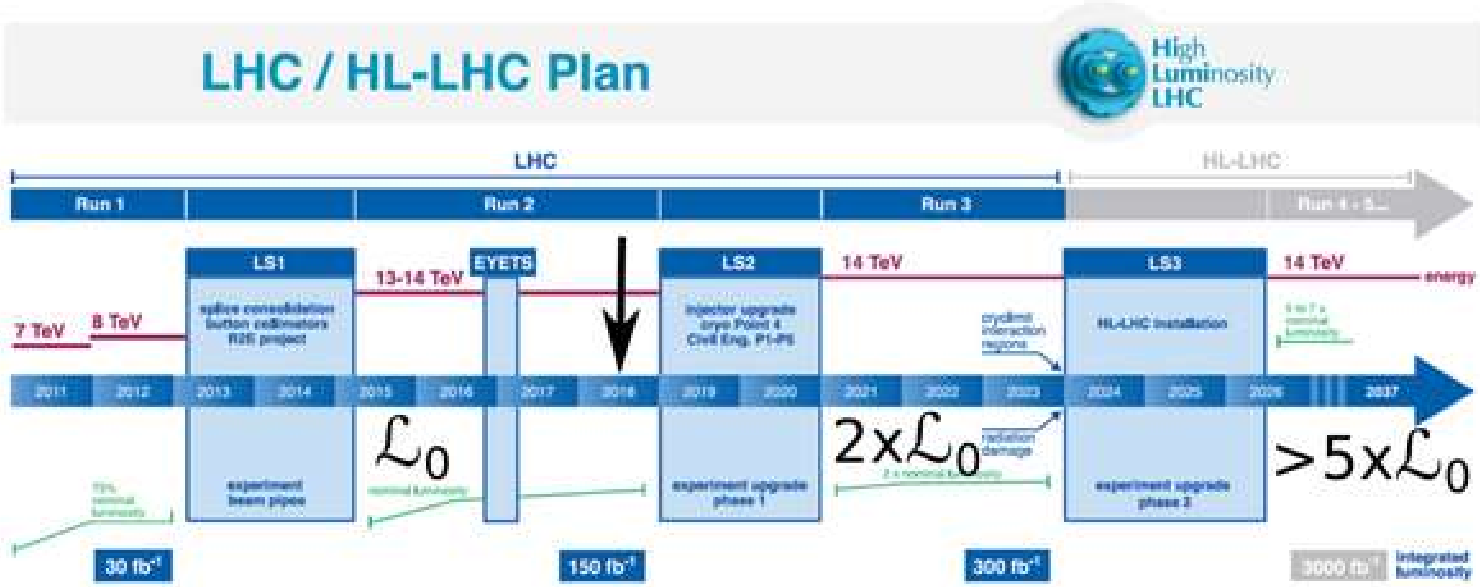
MICROMEGAS

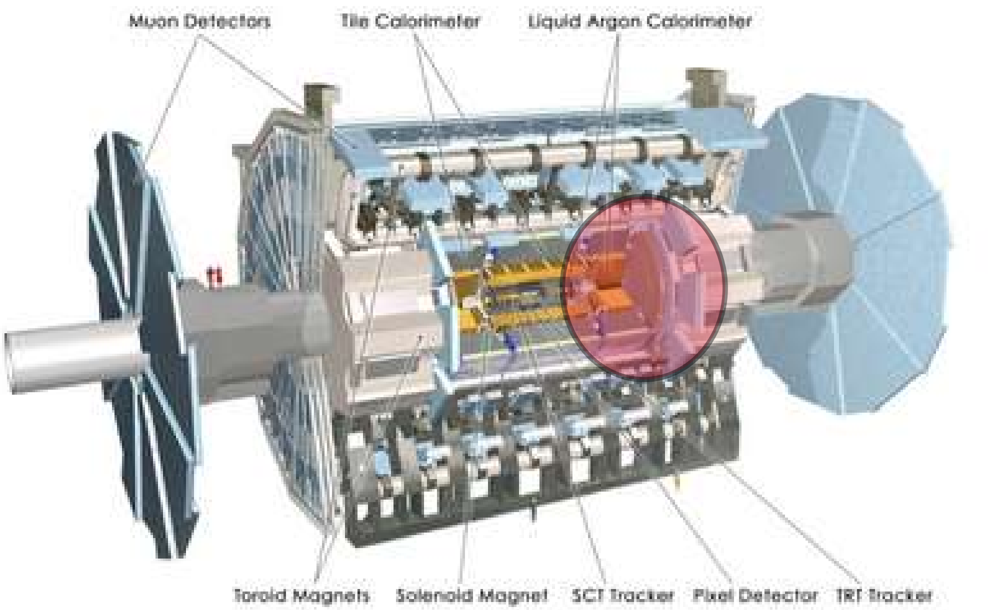

Drift
Cathode
Mesh
Pillars
Read-out
electrodes
PCB

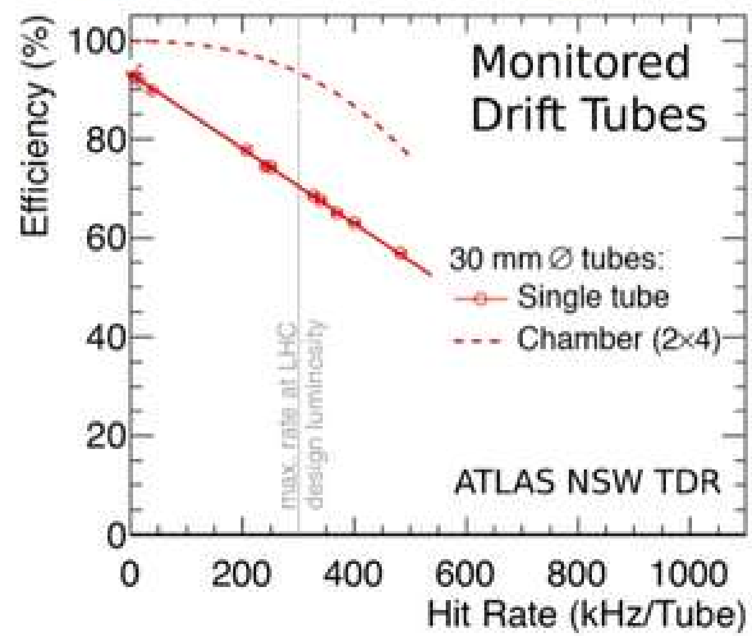

EM Field

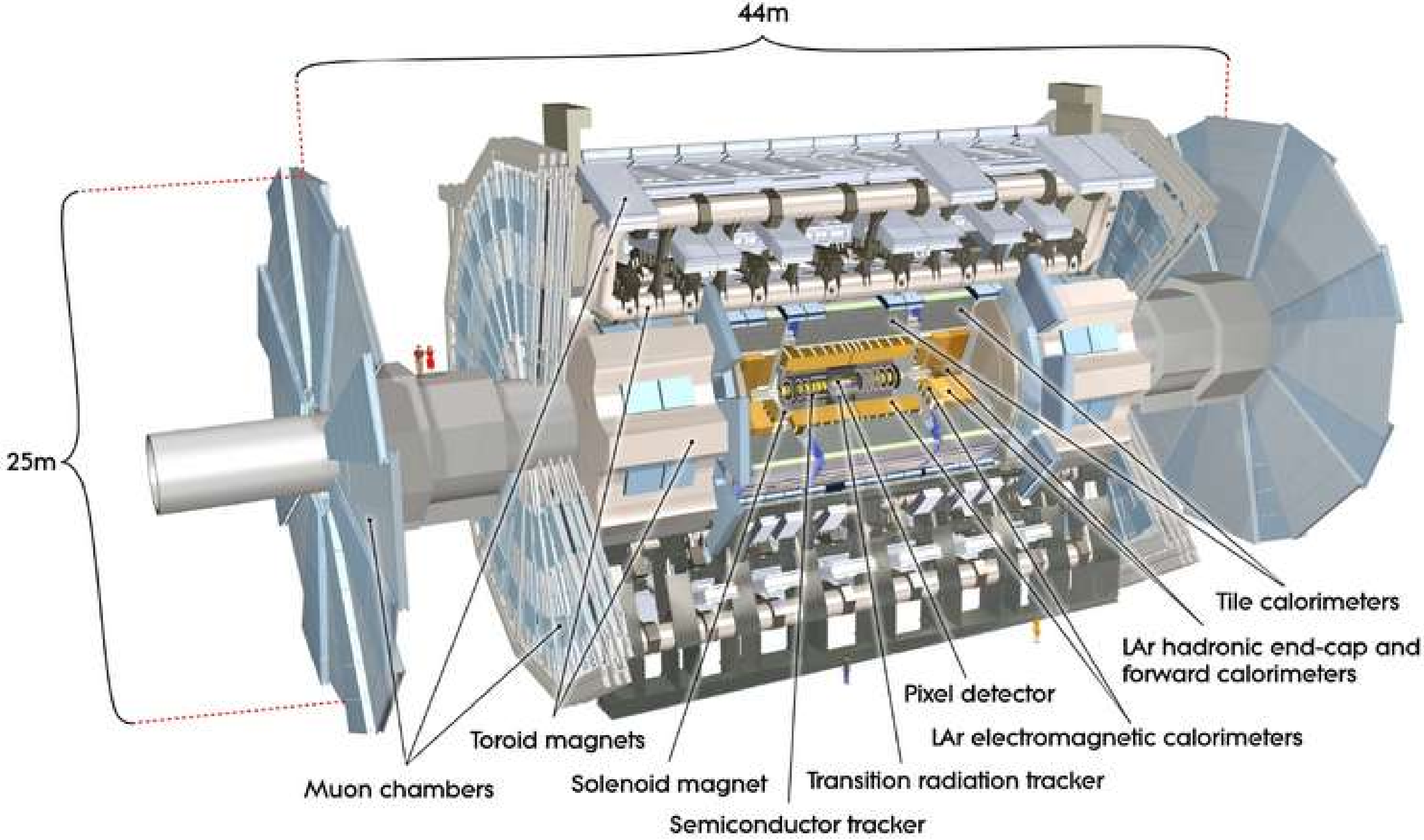

Impinging
particle
Cathode
Primary
ionizations
Edrift
~800
V/cm
Drift
gap
5
mm
Micromesh
Eamp
~3
kV/mm
Readout
electrodes
Amplificatio
n
and
Induction
gap - 128
µm
I (nA)
100 ns

ATLAS - UPGRADE








44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

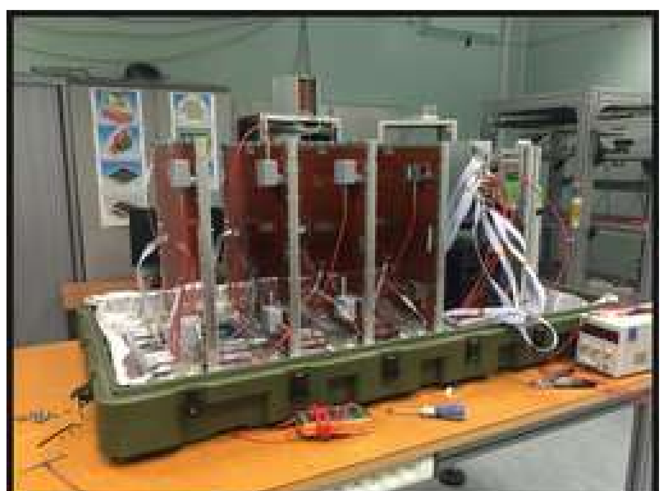
NSW

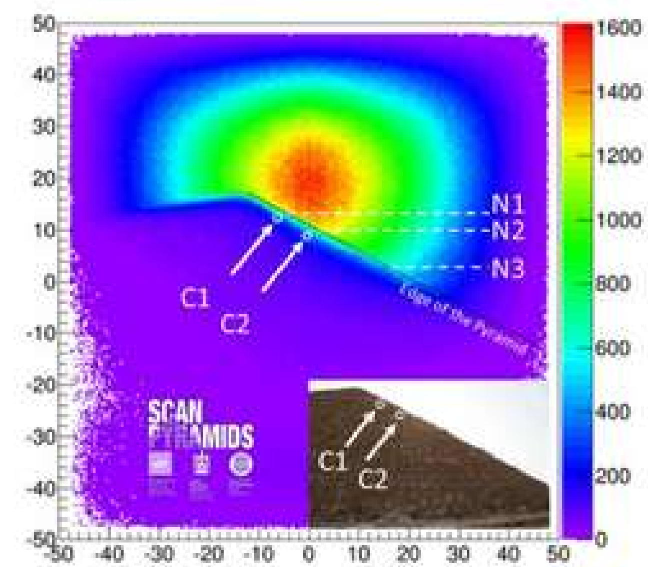
CEA/IRFU/DEDIP --- maxence.vandenbroucke@cea.fr

NSW INSTALLATION

CLAS12/EIC/P2 :

Tomographie :

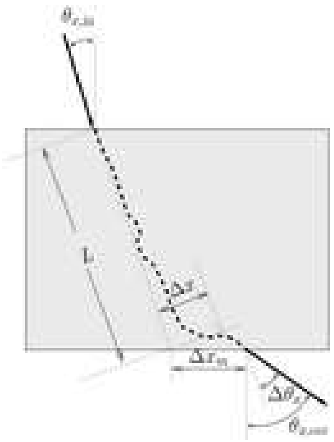


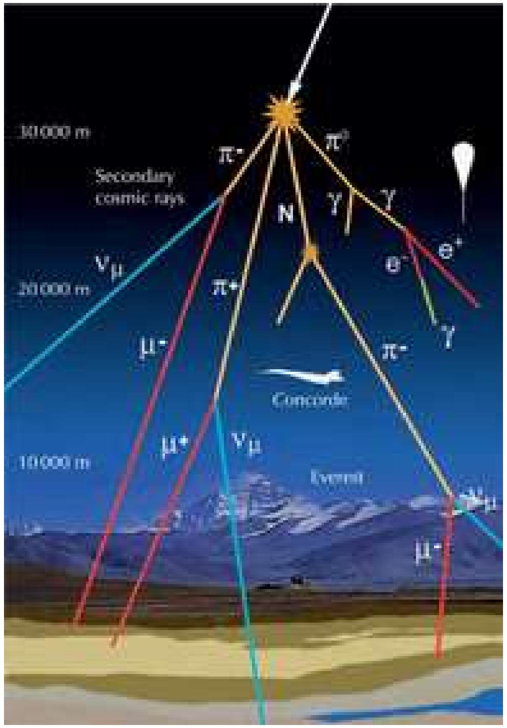


MUON TOMOGRAPHY

MUON TOMOGRAPHY

- Cosmic muons produced by cascade of reactions induced by cosmic rays in the upper atmosphere
  - Flux: ~150/m²/s ~ cos² (maximum in zenith direction)
  - Mean energy: 4 GeV
  - Life-time: 2 μs
  - Natural, free and harmless radiation
  - Straight propagation (in mean)



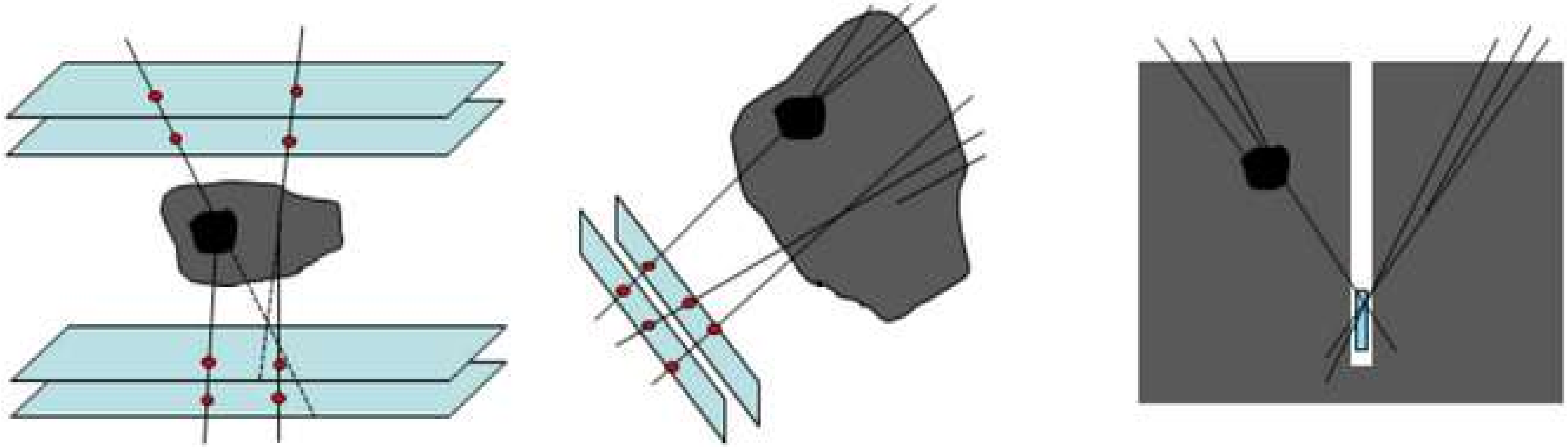


- Muon interaction with matter
  - Bethe-Bloch ionization stopping power
  - Standard deviation of the scattering angle
  - Radiation length

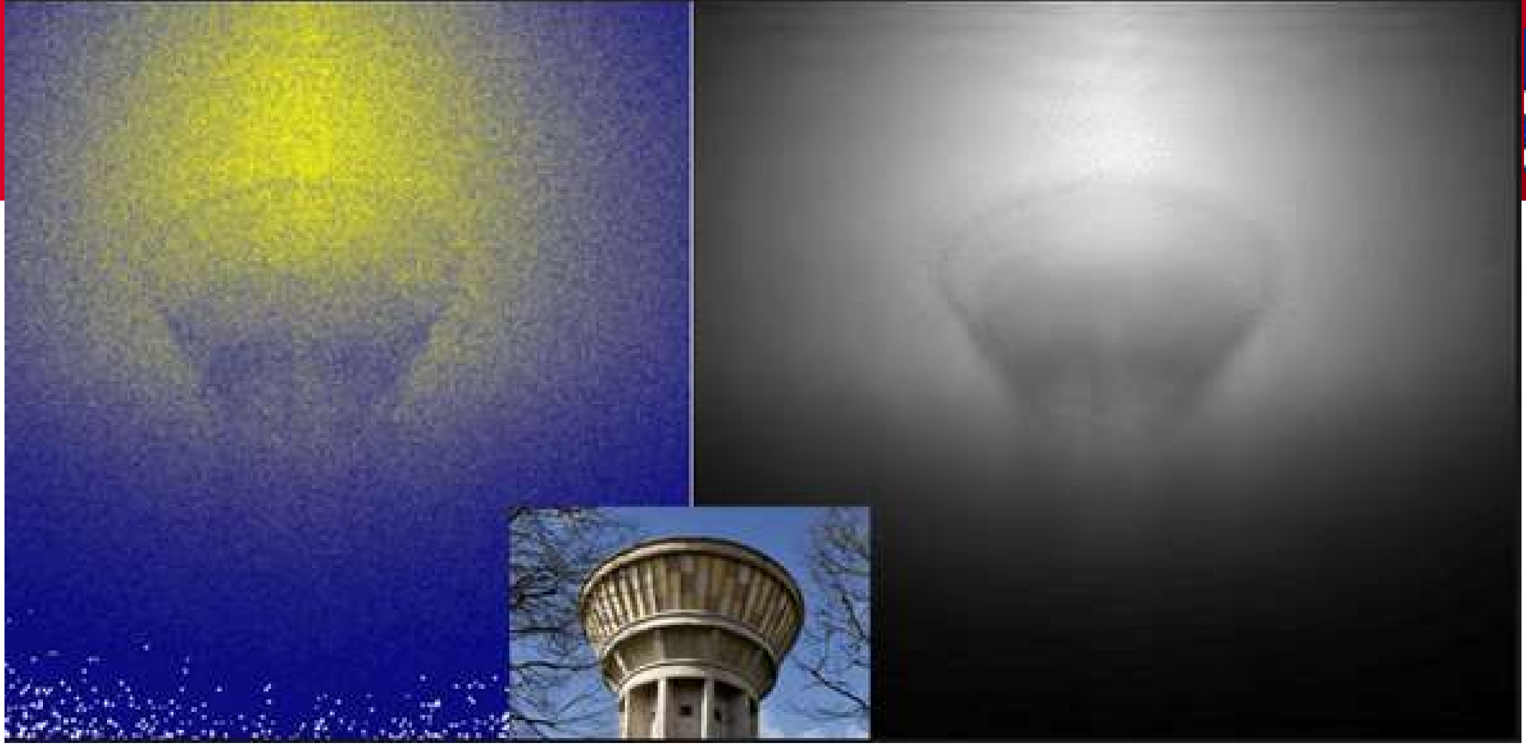
Material	Thickness	(°)	$P_{absorption}$
Air	100 m	0.094	0.78%
Lead	10 cm	1.01	2.9%
Water	1 m	0.35	4.2%
Ground	100 m		99%

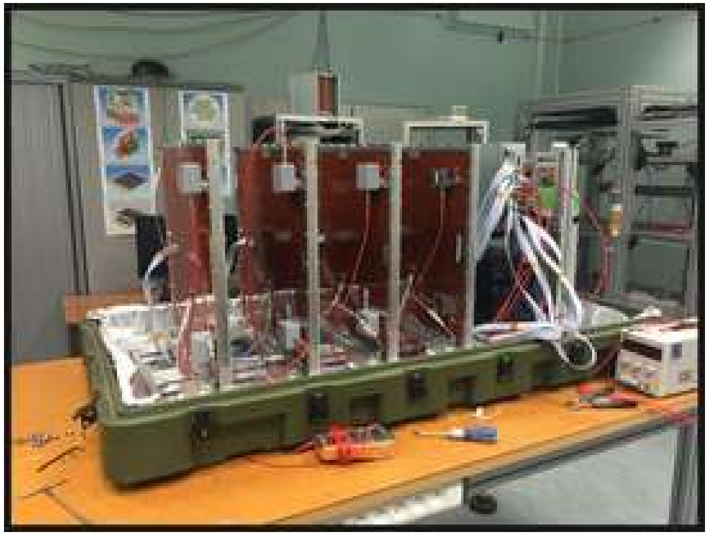
MUON TOMOGRAPHY USING GASEOUS DETECTORS

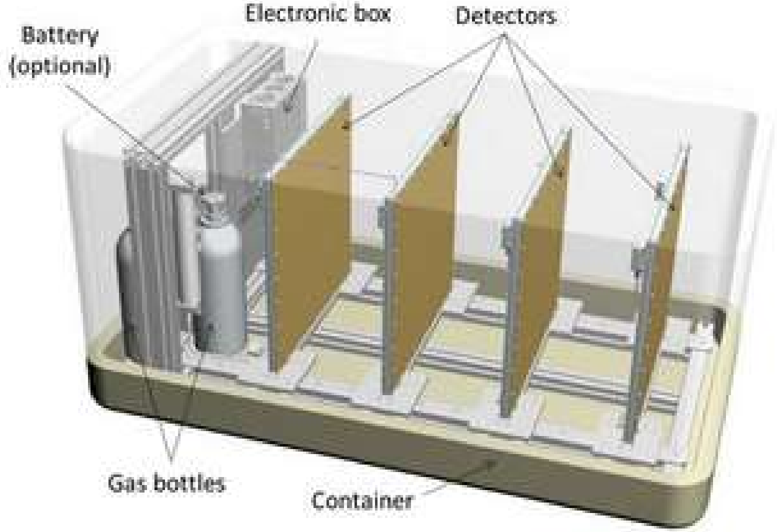
- Muons can be stopped (decay) or their trajectory can be changed
- Two modes of muon tomography can be extracted from muon flux
  - Absorption muography
  - Deviation muography



- High potential of societal applications in many fields:
  - volcanology, archaeology
  - mineral exploration, civil engineering, …





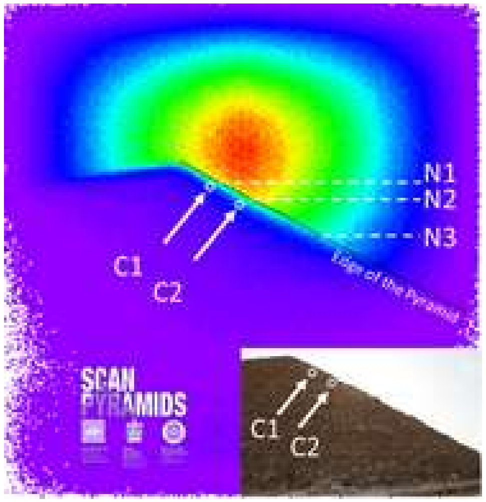

Battery
(optional)
Electronic box
Detectors
Gas bottles
Container

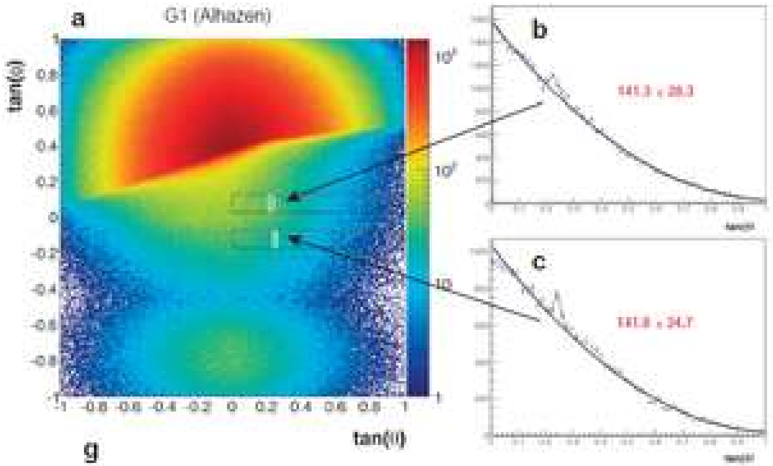
RESULTS

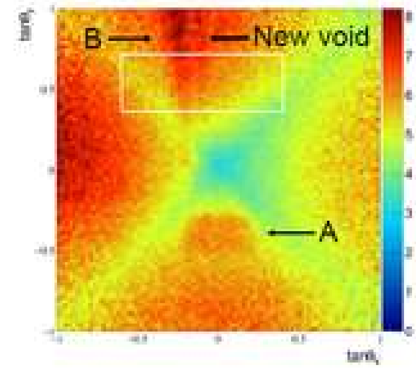
- Discoveries of new cavities large void above the Grand Gallery

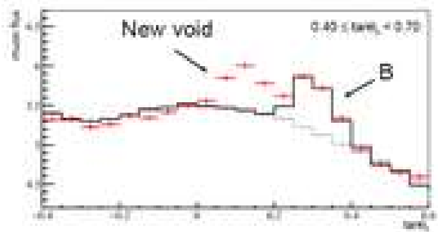
2016 CEA

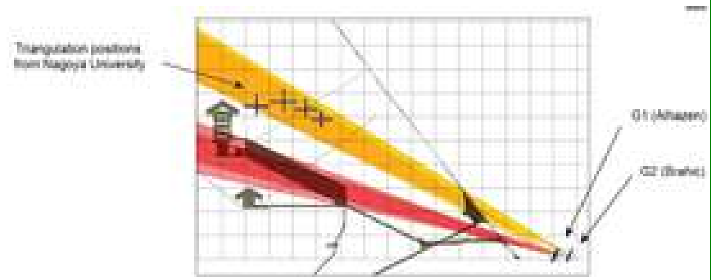
2017 Nagoya











- *Only 2 such voids detected*
- *1st detection ever from outside of a deep structure*

Mesurer l’infiniment petit et observer l’infiniment grand

DE LA RECHERCHE À L’INDUSTRIE

Vendredi 5/07 11h (IJCLAB)
Lundi 8/07 12h (CEA IRFU)
Visite Labo 14h (CEA IRFU)
Mercredi 10/07 11h (IAS)

Maxence Vandenbroucke
07/2024

université
PARIS-SACLAY

PLAN DES COURS

Cours 1 : Généralités

-Introduction générale sur l'importance de la mesure
-Qu'est-ce qu'une expérience de physique subatomique ?
-Que veut-on observer à propos d'une particule?
-Architecture générale d'une expérience en physique subatomique

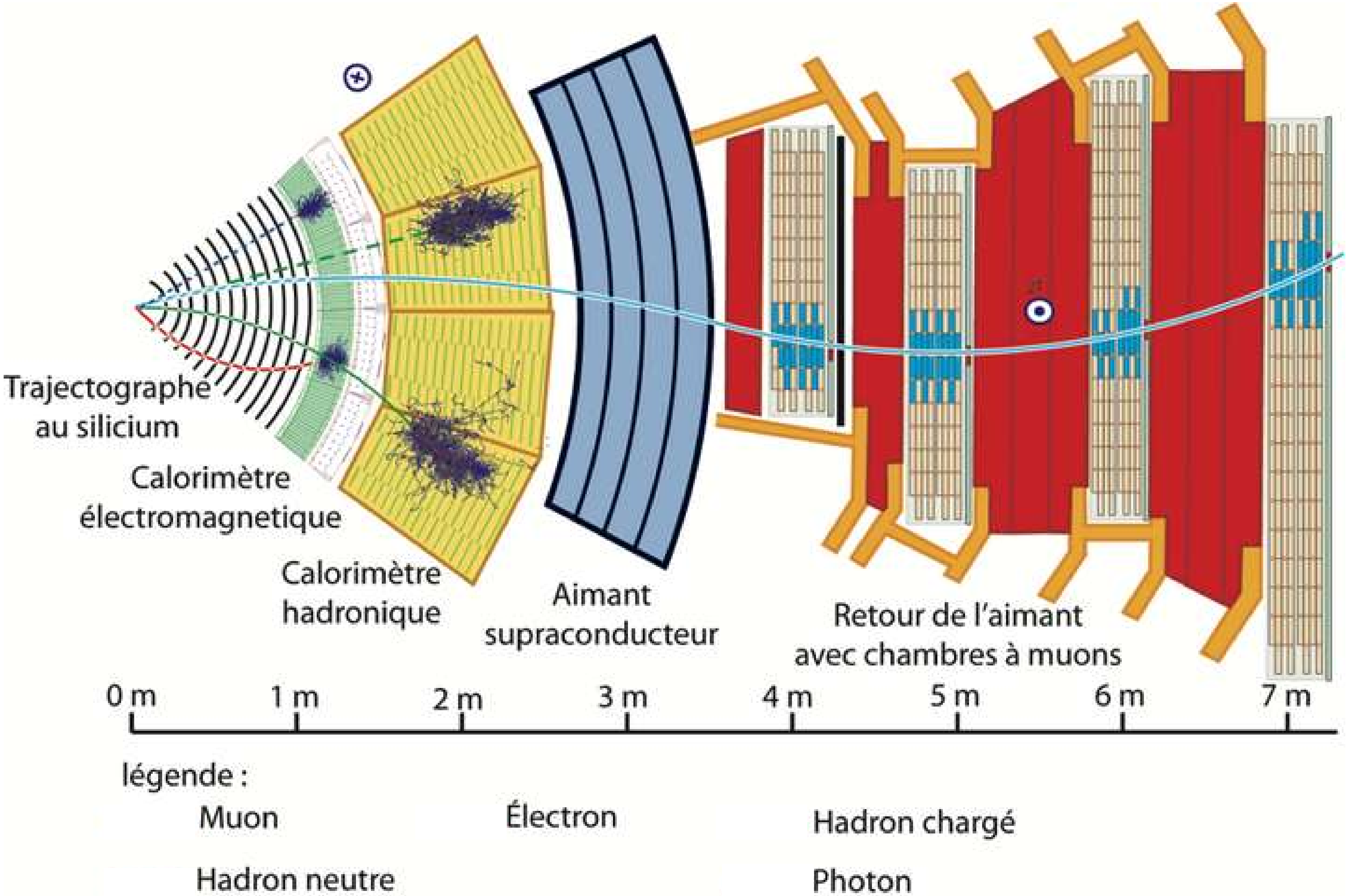
Cours 2 : Les détecteurs de particules

- Trajectographie :
  - -Détecteurs Gazeux
  - -Détecteurs au Silicium
- Calorimétrie
- Scintillation

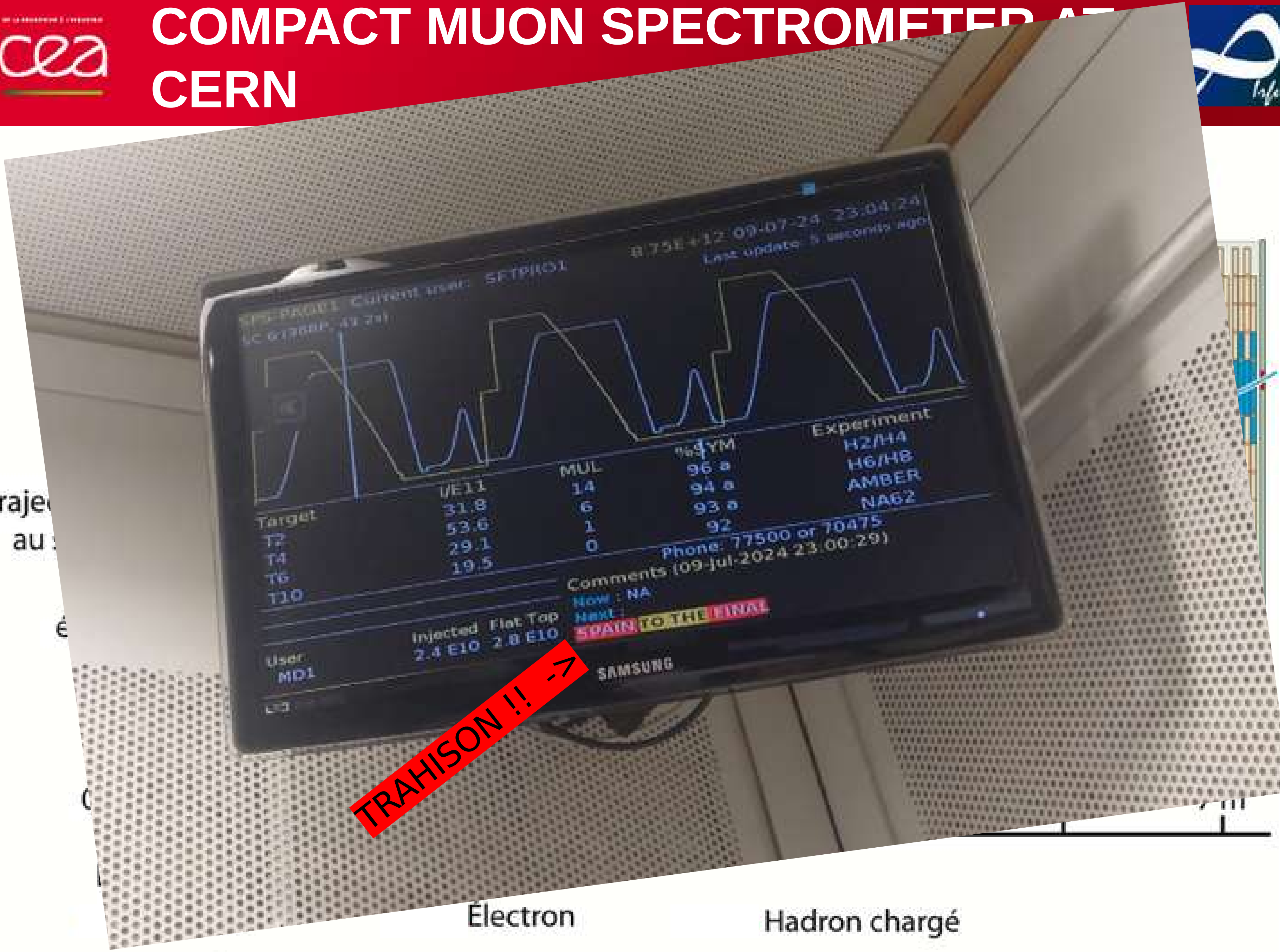
Cours 3 : Exemple d'expériences

- Autour du Neutrino
- Nucléaire et Hadronique
- Rayons Cosmiques
- Antimatière

COMPACT MUON SPECTROMETER AT CERN



COMPACT MUON SPECTROMETER AT CERN



Trajec
au :
é
C

Électron

Hadron chargé

Hadron neutre

Photon

Mesurer l'infiniment petit et observer l'infiniment grand

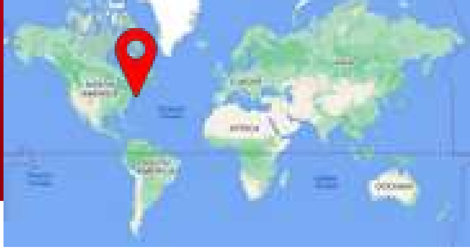
Cours 3 : Exemple d'expériences

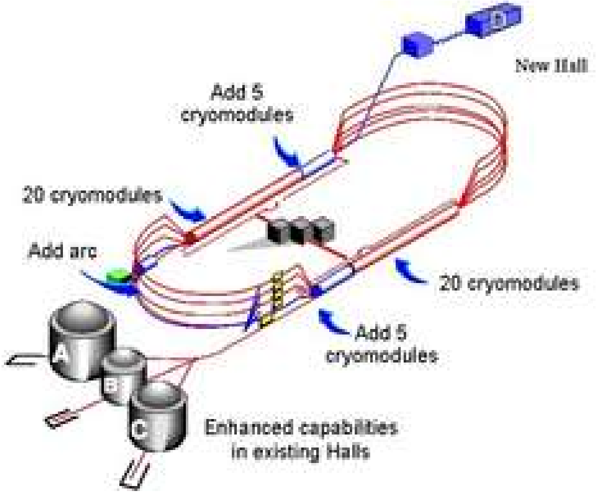
- **Autour du Neutrino**
- **Nucléaire et Hadronique**
- **Rayons Cosmiques**
- **Antimatière**
- **Matière sombre**

Physique Hadronique

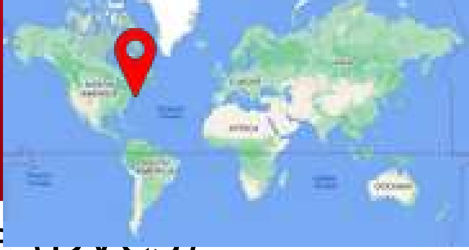
CLAS12

CLAS12 at Jefferson Lab

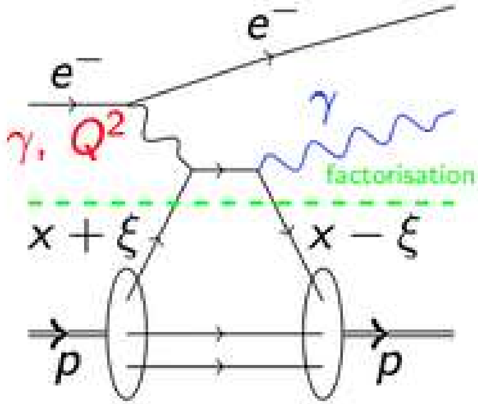


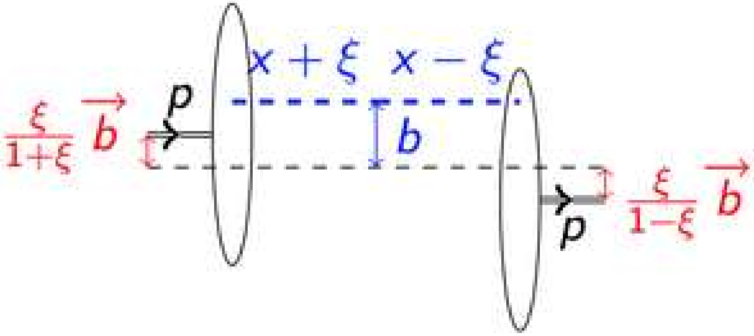


CLAS12 at Jefferson Lab

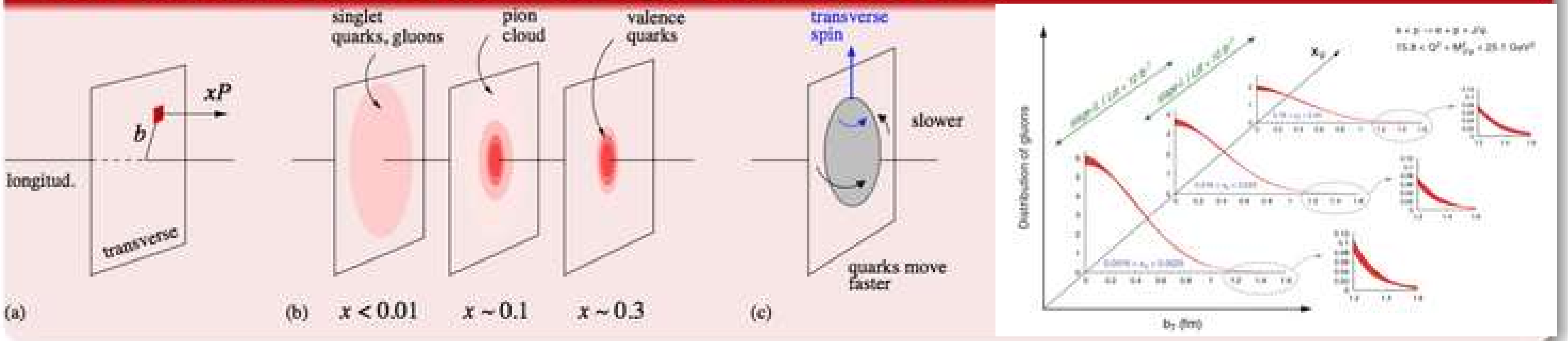


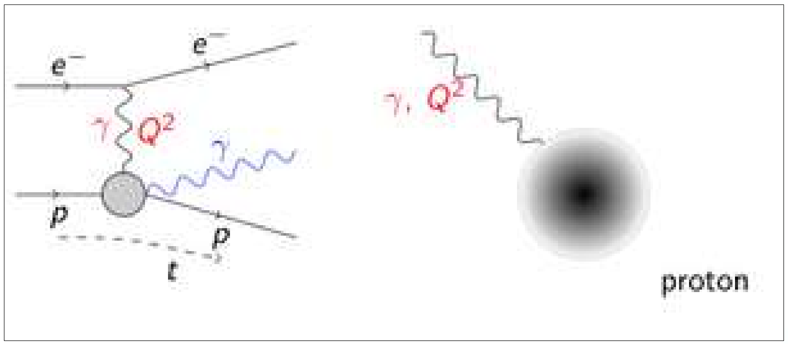
Diffusion Compton profondément virtuelle

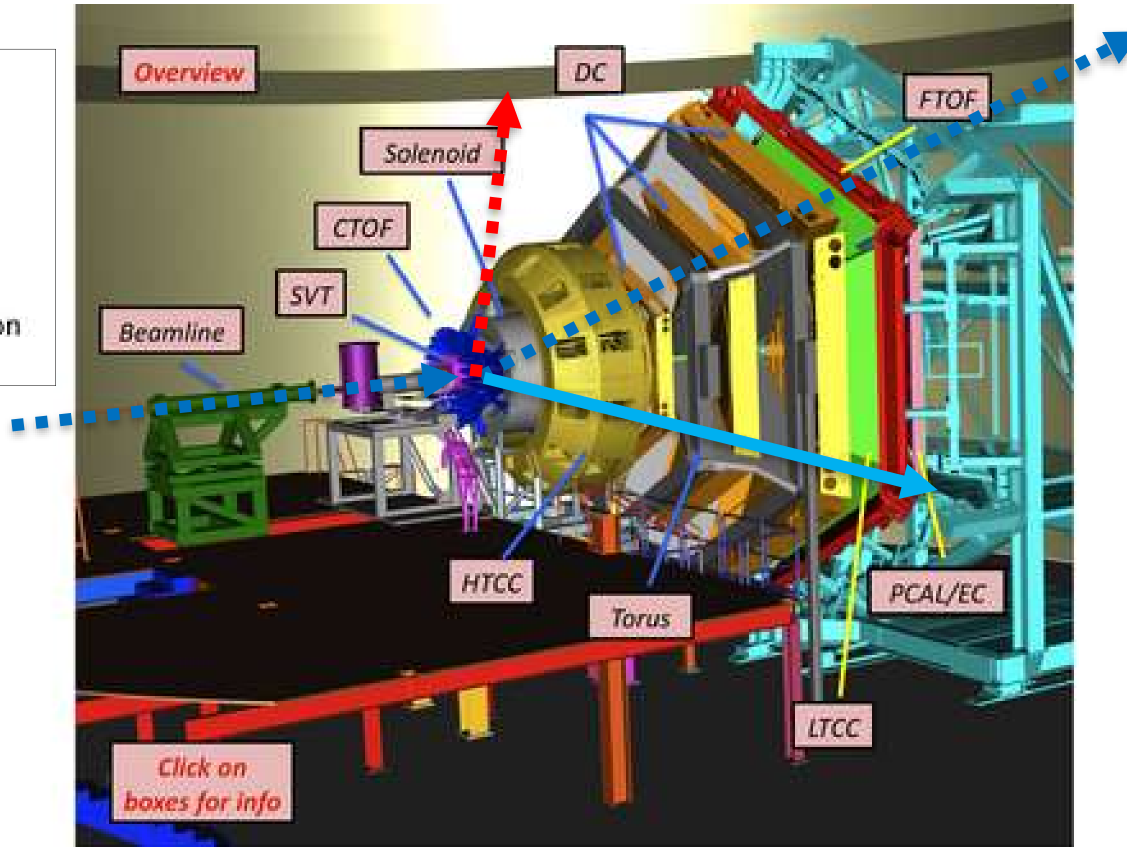




Vers une visualisation en 3d du nucléon !

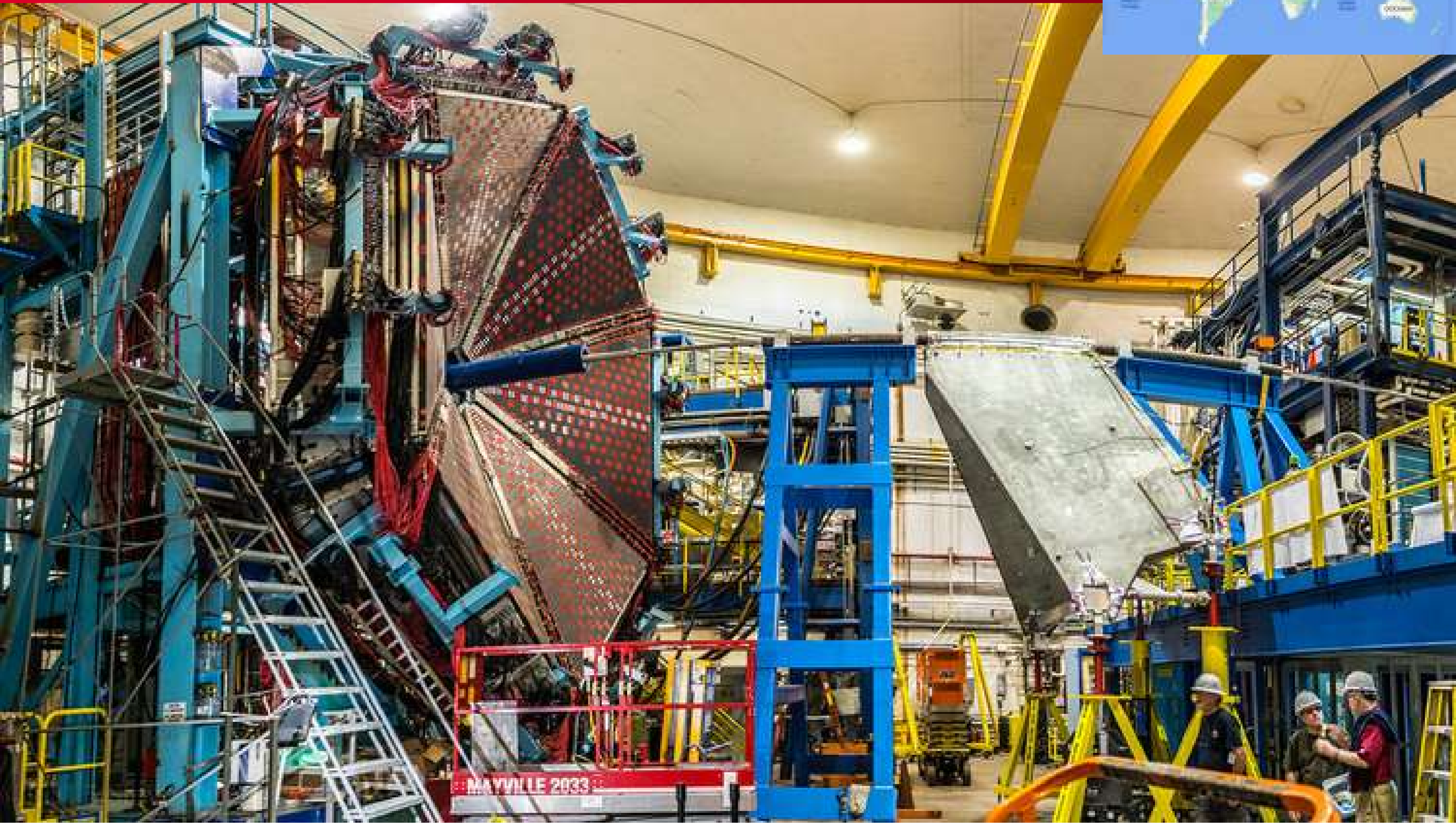



e⁻
e⁻
γ Q²
γ
p
p
t
γ, Q²
proton

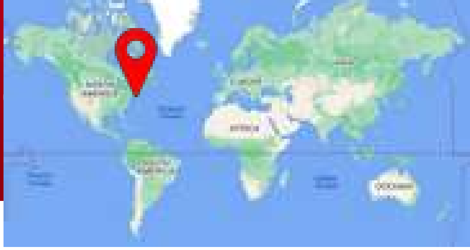

Overview
DC
FTOF
Solenoid
CTOF
SVT
Beamline
HTCC
Torus
PCAL/EC
LTCC
Click on
boxes for info

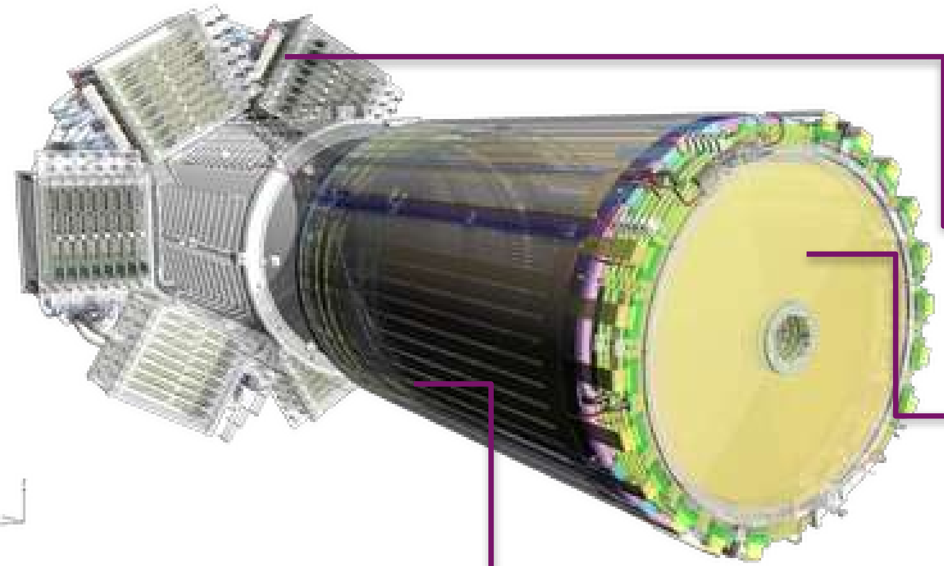
proton

CLAS12 at Jefferson Lab



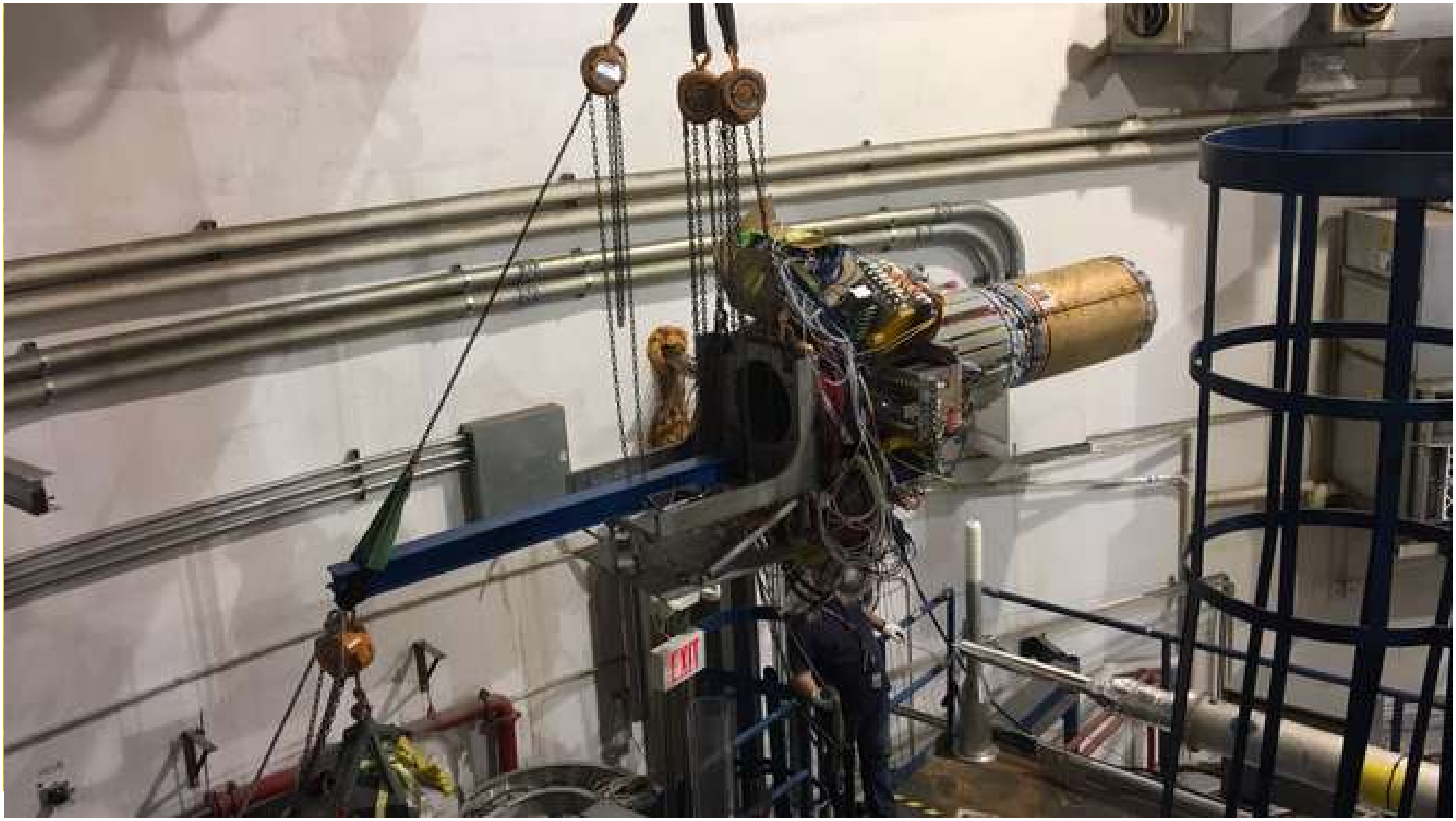
CLAS12 - THE MICROMEGAS VERTEX TRA



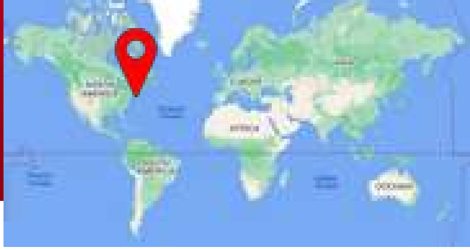


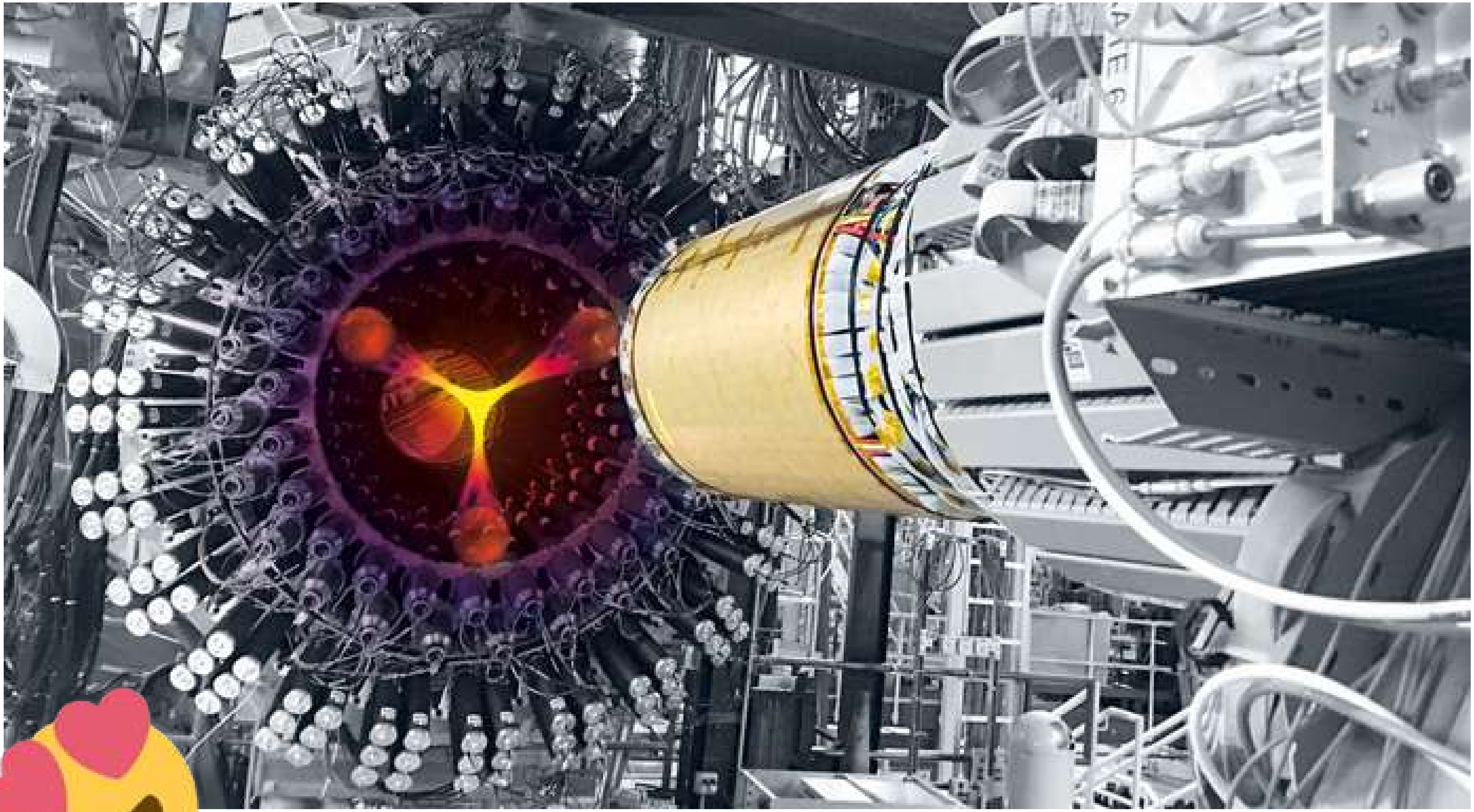
- 4 m² of Micromegas detectors to be installed in 2017
- DREAM based Front-End Electronics
- Remote off-detector frontend electronics connected with 2m micro-coaxial cables
- Forward Detectors
  - High particle rate (30MHz) => Fast detectors
  - Resistive strips divided in 2 zones inner/outer
  - Dimensions: 6x 430 mm diameter disk with a 50 mm diameter hole at the center
- Cylindrical Barrel
  - Low momentum particles => Light Detectors
  - Limited space of ~10 cm for 6 layers
  - High magnetic field (5T)
  - Phase 1 (2016) : 2 Layers (6 Det. of 120°)
  - Phase 2 (2017) : 6 Layers (18 Det.)

CLAS12 at Jefferson Lab



CLAS12 – Central Tracker

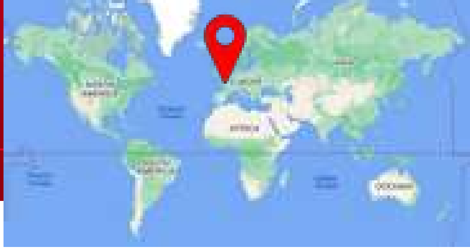




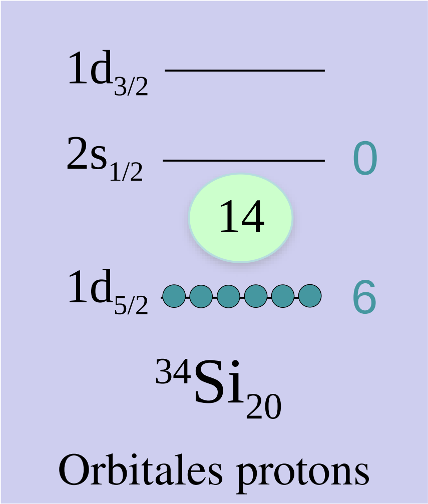
Physique Nucléaire

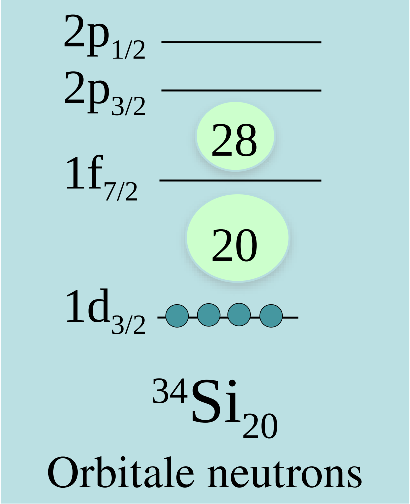
Noyaux Bulles et Spectroscopie Gamma

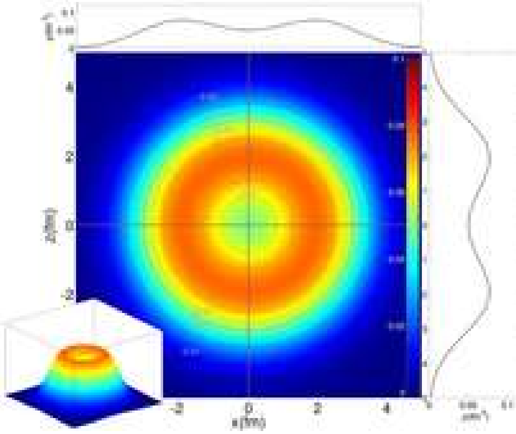
Cas physique : Etude des noyaux bulles

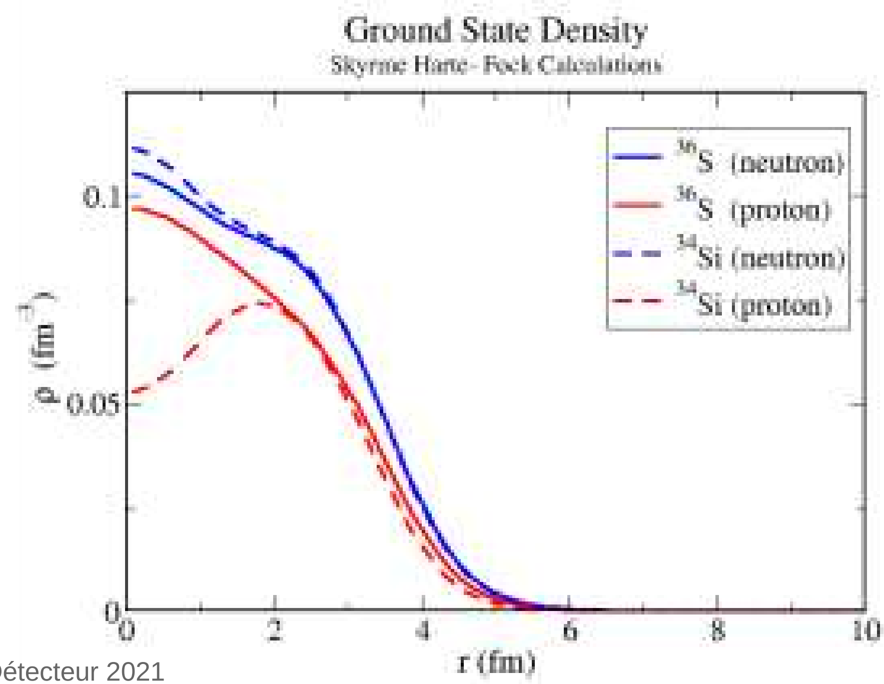


- Origine d'une déplétion centrale dans le noyau ^{34}Si



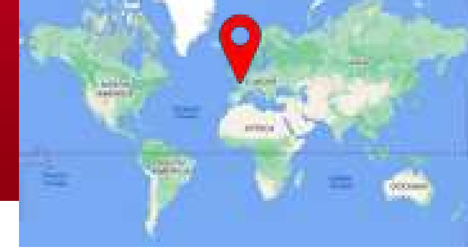






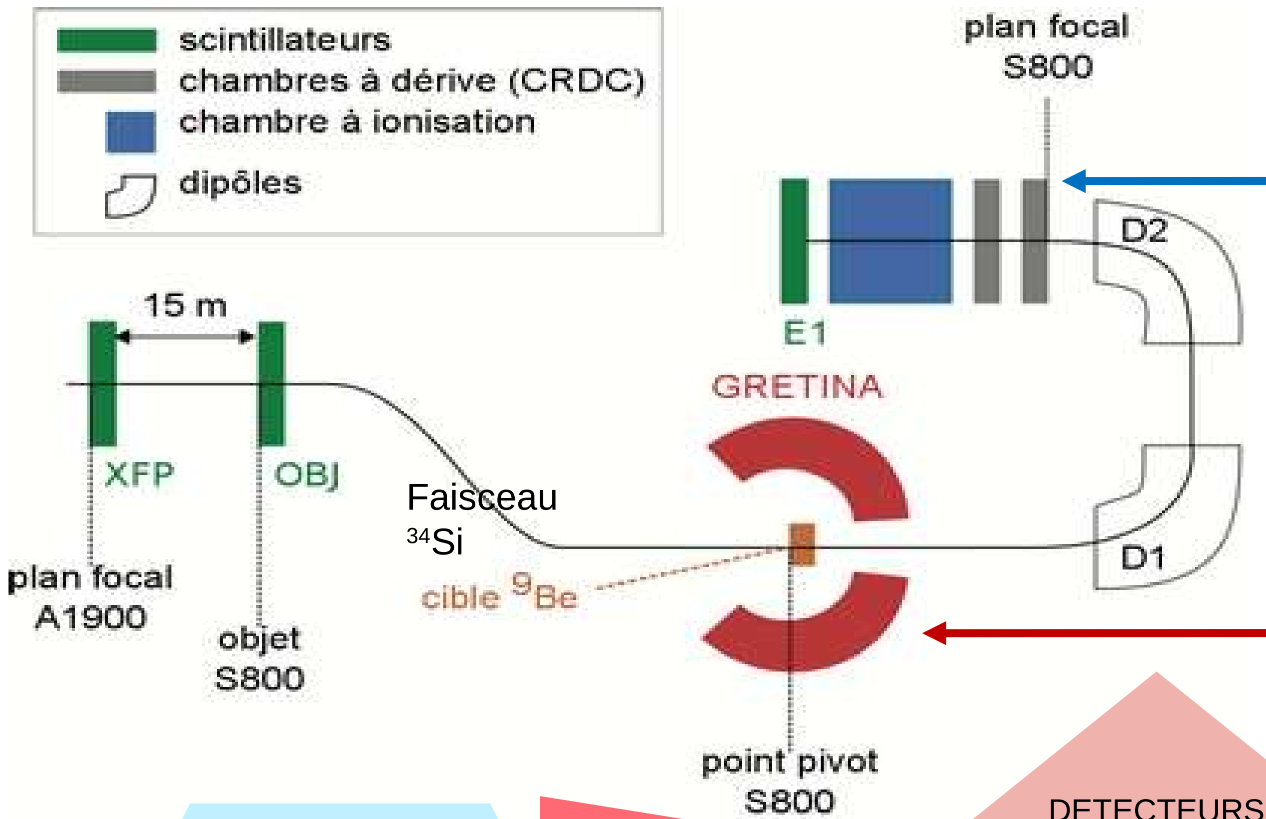
➡ A cause de son orbitale 2s1/2 vide, le ^{34}Si (Z=14, N=20) présenterait une déplétion centrale comparativement au ^{36}S (Z =16, N=20)

Cas physique : Etude des noyaux bulles



- Expérience @NSCL, MSU USA. Objectif : étudier l’occupation de l’orbitale 2s1/2 dans le ^{34}Si et ^{36}S

Réaction d’arrachage d’un proton (1 proton knockout) ^{34}Si(-1p)^{33}Al and ^{36}S(-1p)^{35}P et on essaye d’identifier d’où a été arraché le proton

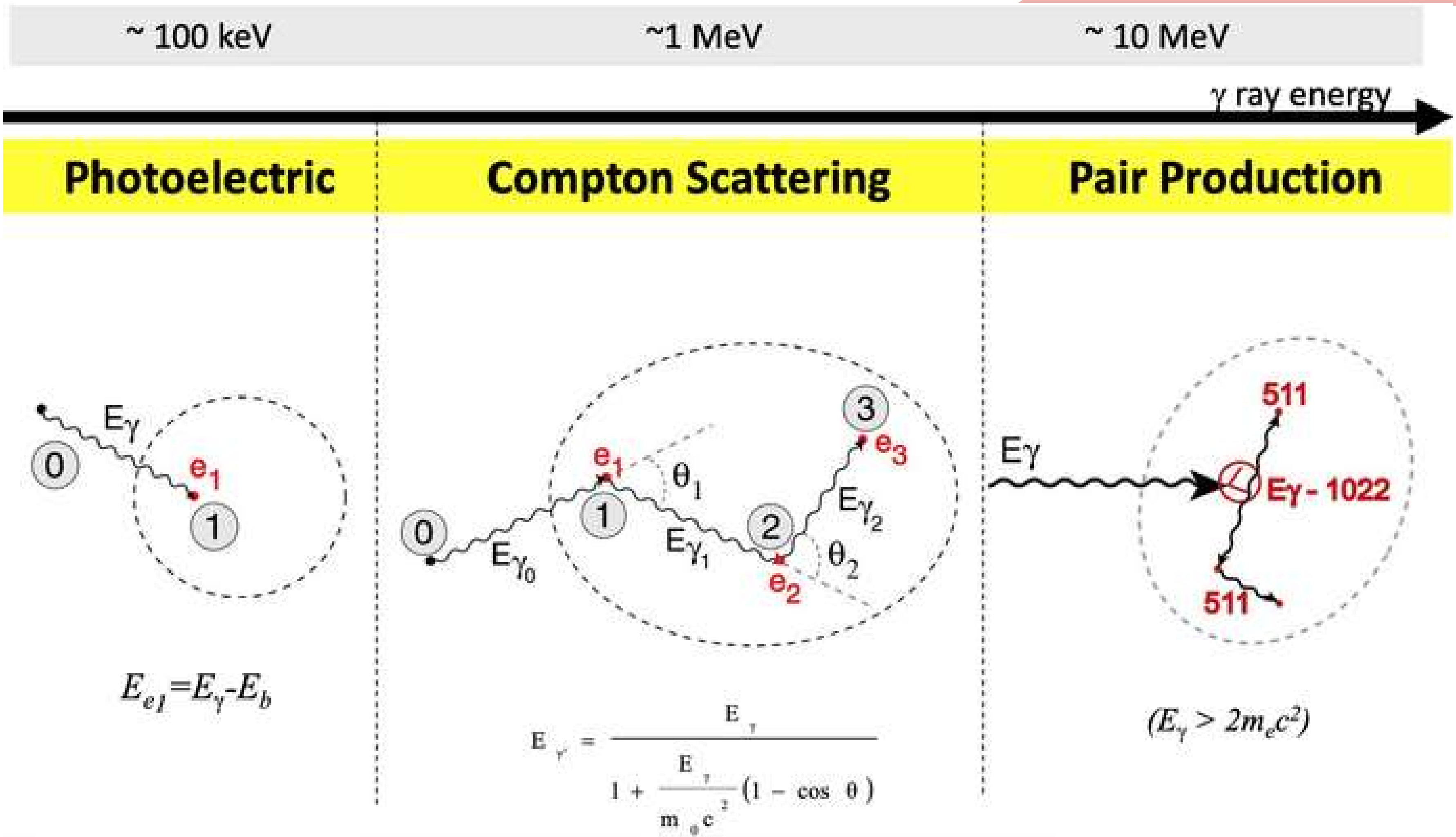


ACCELERATEUR | SYSTEME DE PRODUCTION IONS RADIOACTIFS | SEPARATEUR A1900 | DETECTEURS γ + SPECTRO

Spectroscopie Gamme

DETECTEUR
γ Germanium

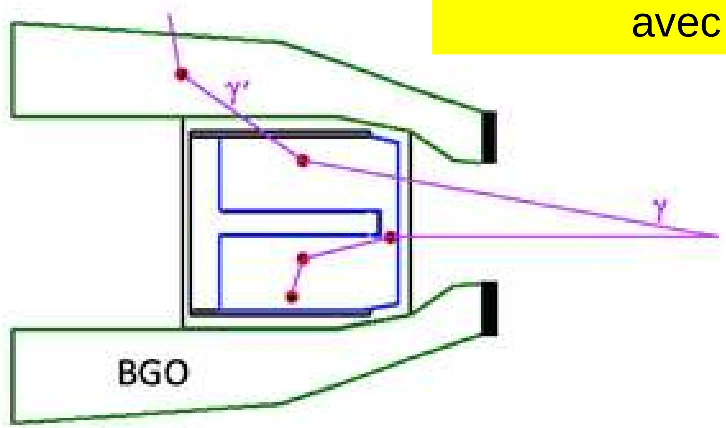
- Comment interagit un γ avec la matière ?

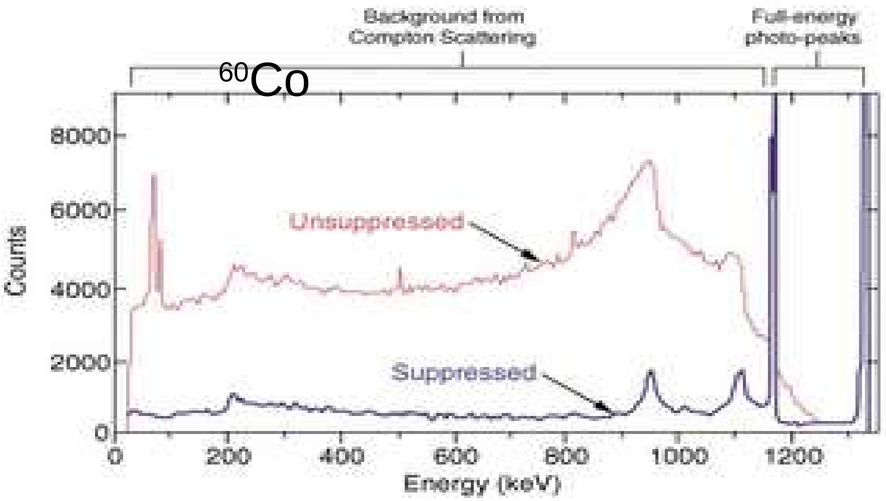


DETECTEUR
γ Germanium

- Les détecteurs γ, la lutte contre la diffusion Compton

Astuce 1 : se débarrasser du Compton avec un bouclier BGO

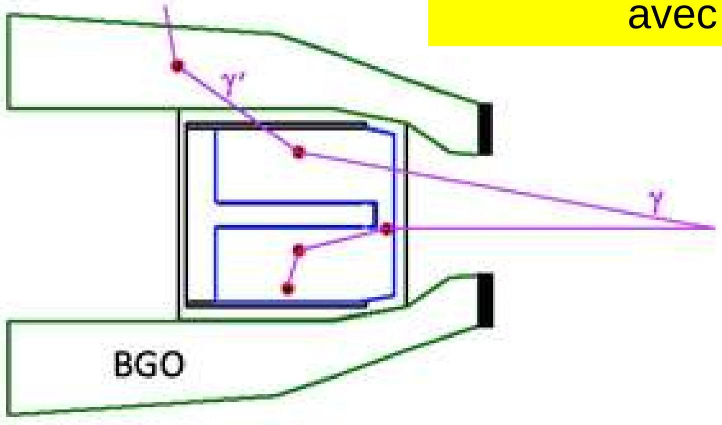


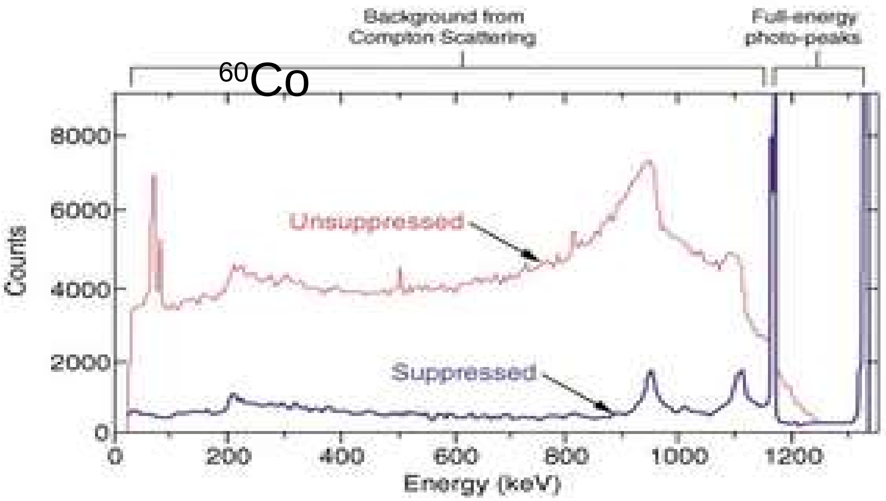


DETECTEUR
γ Germanium

- Les détecteurs γ, la lutte contre la diffusion Compton

Astuce 1 : se débarrasser du Compton avec un bouclier BGO

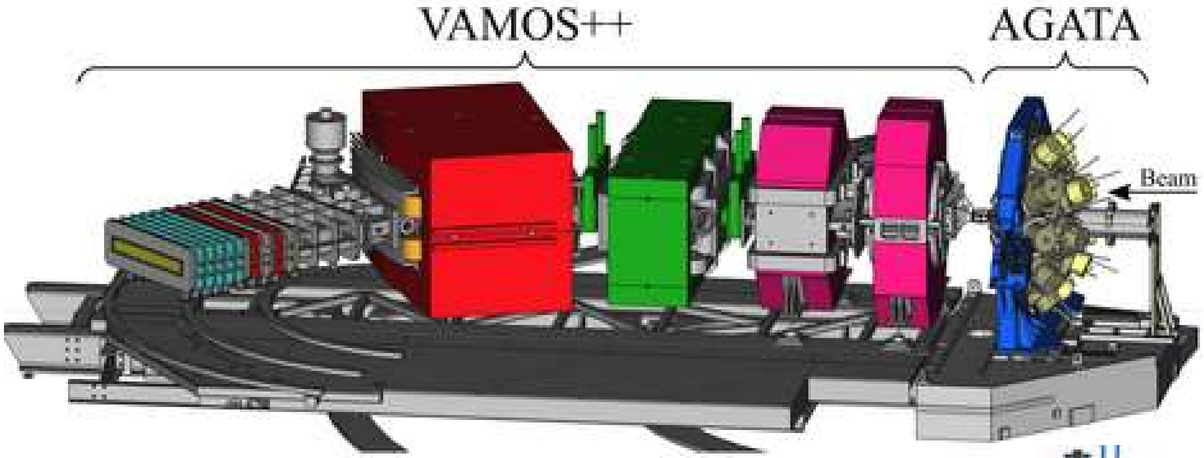


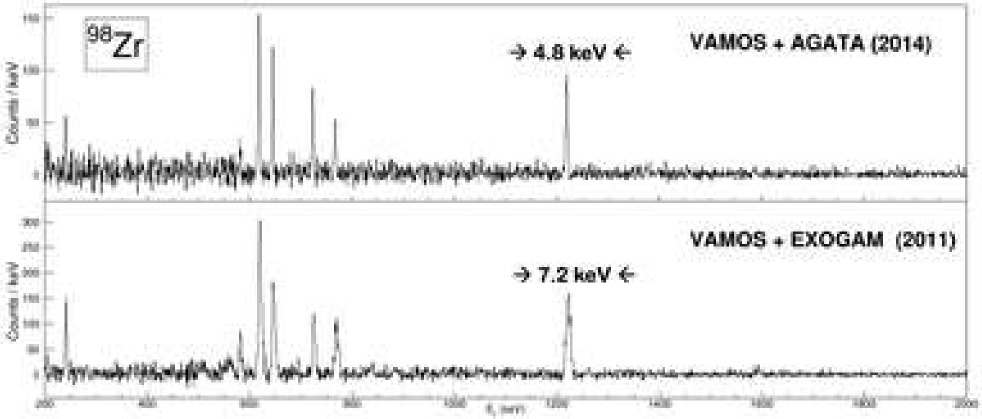


Spectroscopie Gamma

DETECTEUR
γ Germanium

- La campagne VAMOS-AGATA @GANIL 2014-2021





29 expériences

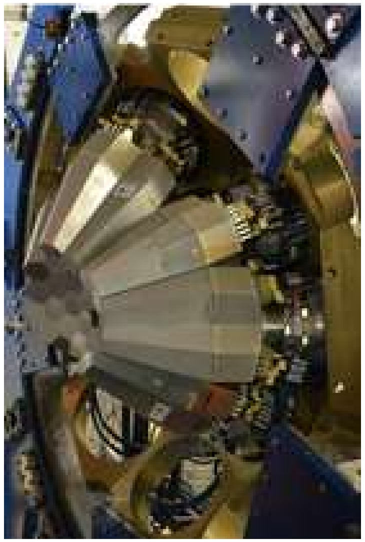
558 To de données

6568 heures de faisceau sur cible

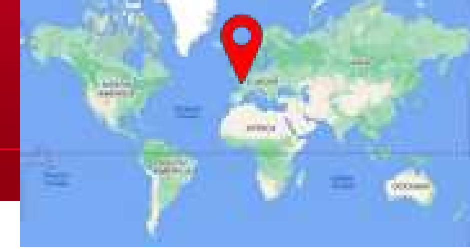
14 034 entrés dans le elog

2386 jours de surveillance cryogénique

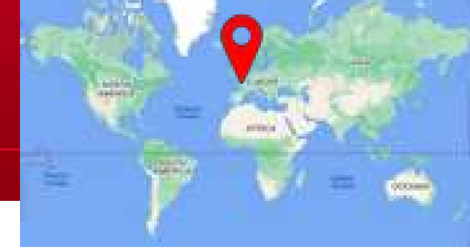
11,5 tonnes de materiel scientifique



Cas physique : Etude des noyaux bulles



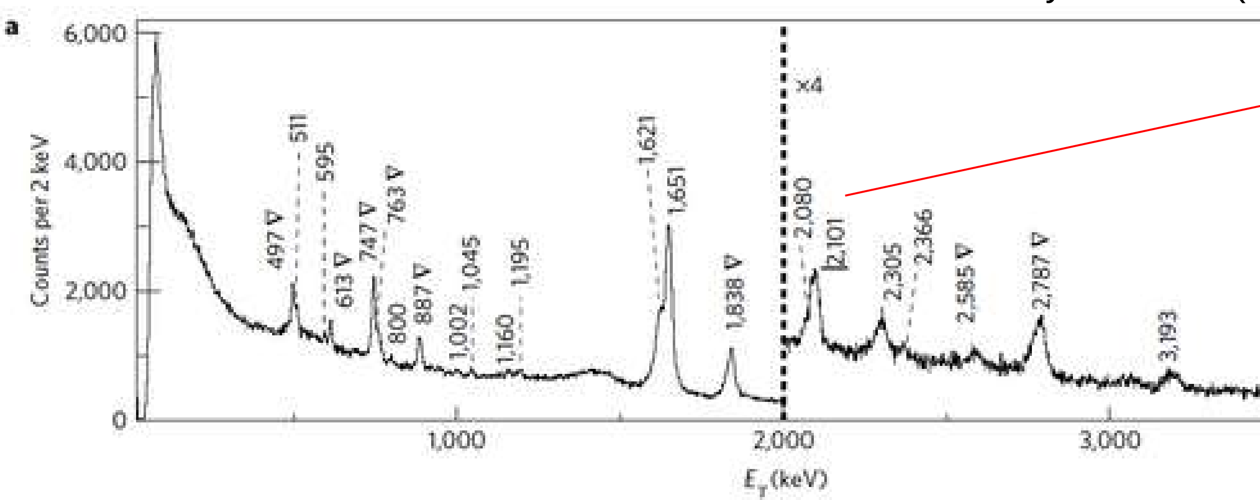
- Alors bulle ou pas bulle ?

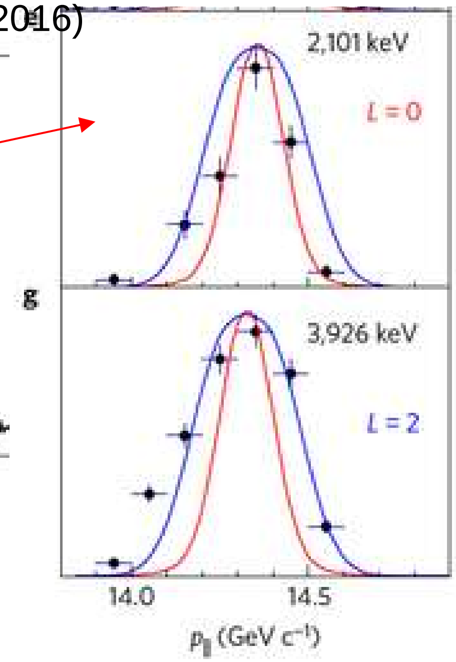


- Alors bulle ou pas bulle ?

1) $^{34}Si(-1p)^{33}Al$, détection des γ issus de la désexcitation du ^{33}Al dans GRETINA en coïncidence avec le noyau 33Al au plan focal du spectromètre S800

A. Mutschler *et al*. Nature Physics 3916 (2016)





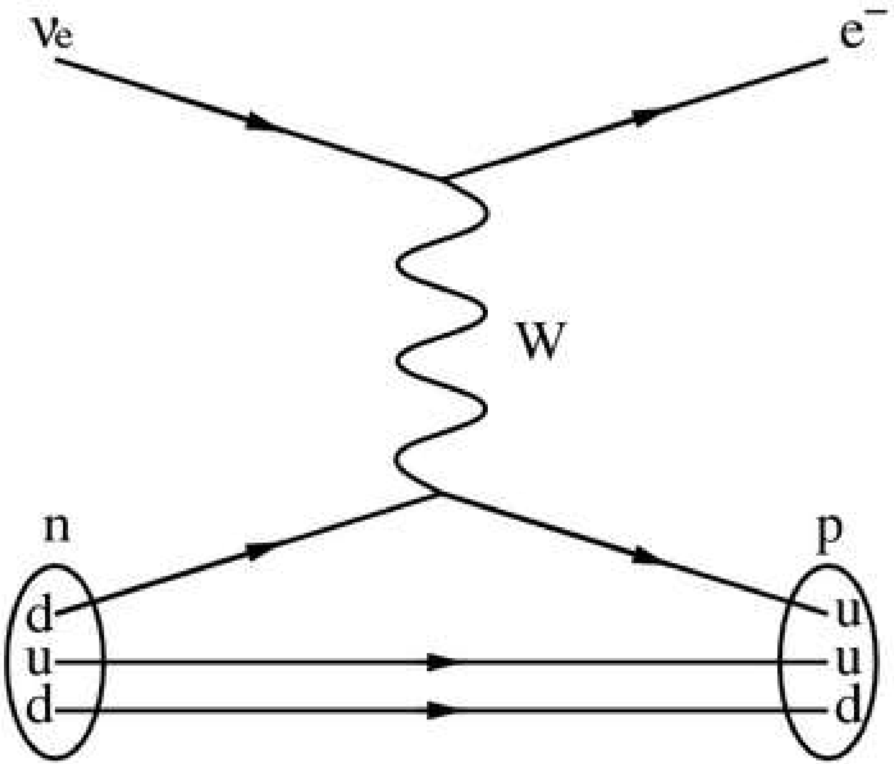
2) Le moment orbital angulaire *l* de l'orbitale d'où est arraché le p est déterminé en mesurant la distribution en moment longitudinal du ^{33}Al pour l'état peuplé

3) L'occupation de l'état 2s1/2 est déduite en de la section efficace expérimentale pour arracher un p depuis cette orbitale (rappel : orbitale 2s1/2 peut accueillir 2 nucléons)

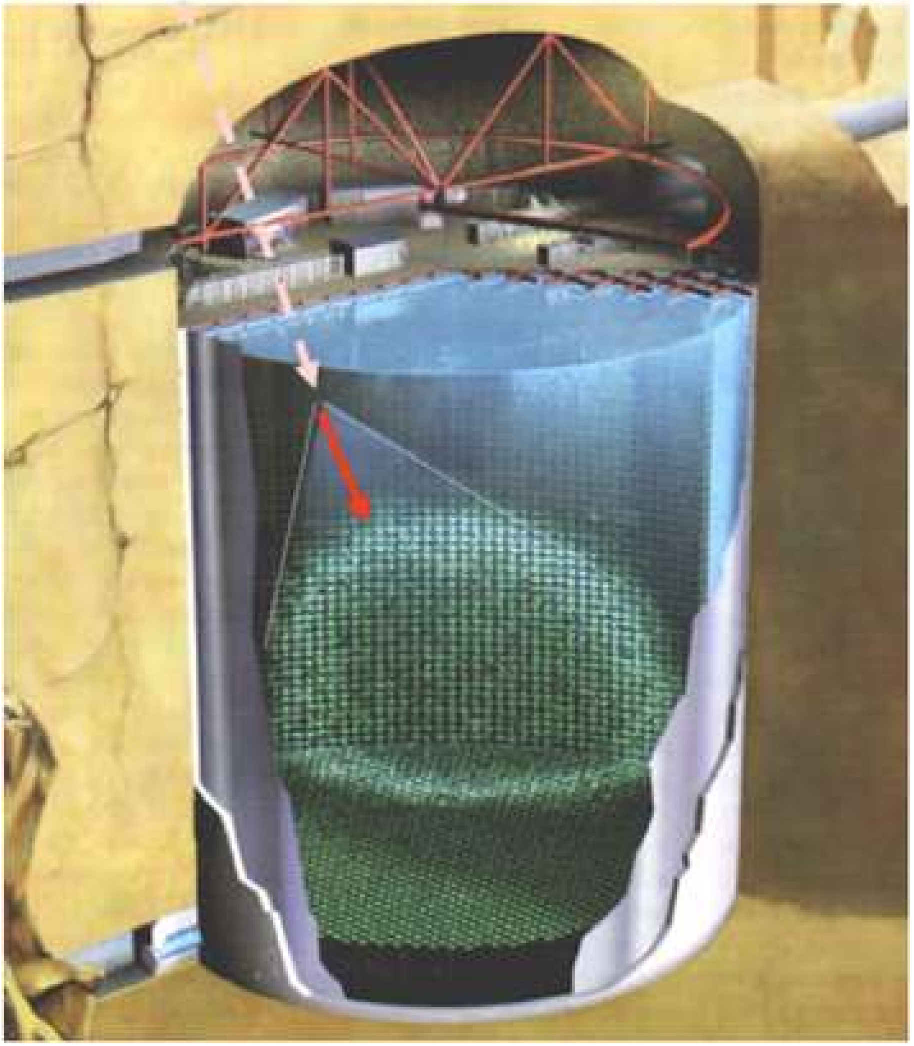
Dans le ^{34}Si 0.17(3)
Dans le ^{36}S 1.7(4)

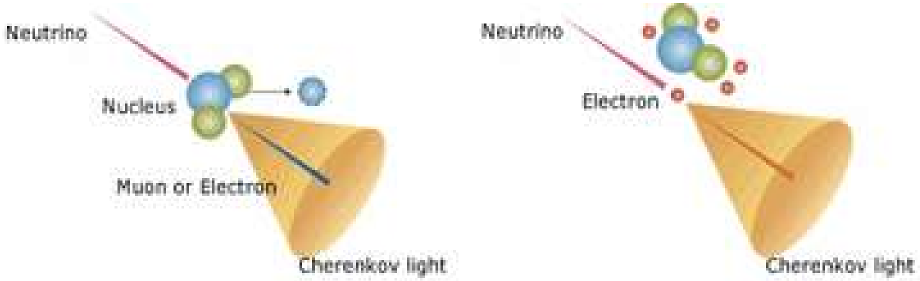
YES !

Observer les neutrinos

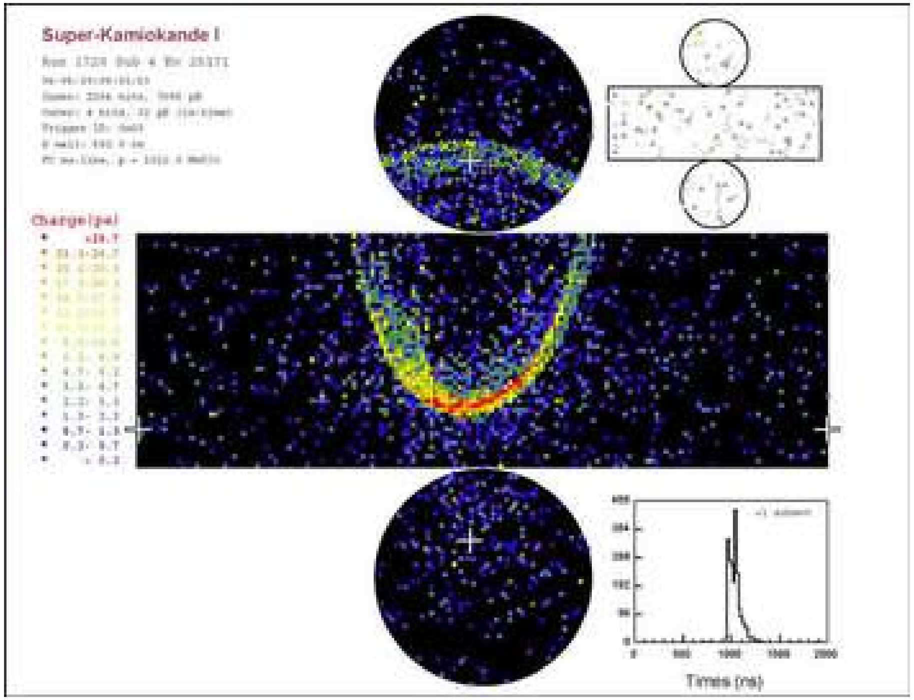


Super Kamiokande



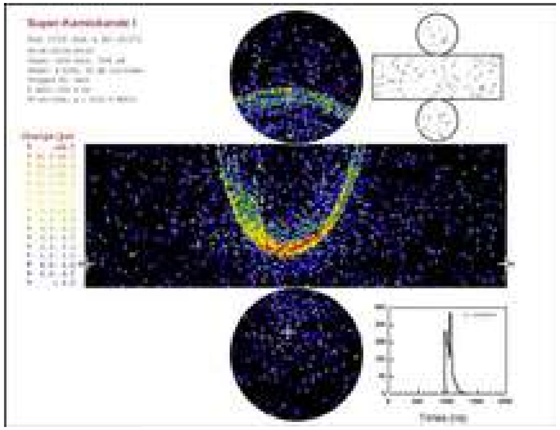


The generated charged particle emits the Cherenkov light.



Super Kamiokande

Super Kamiokande



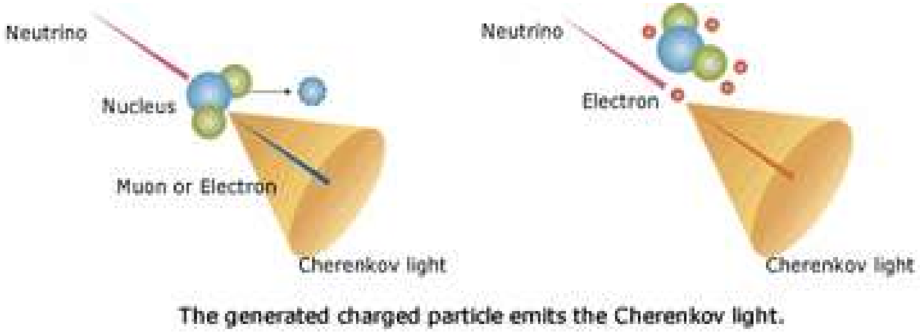
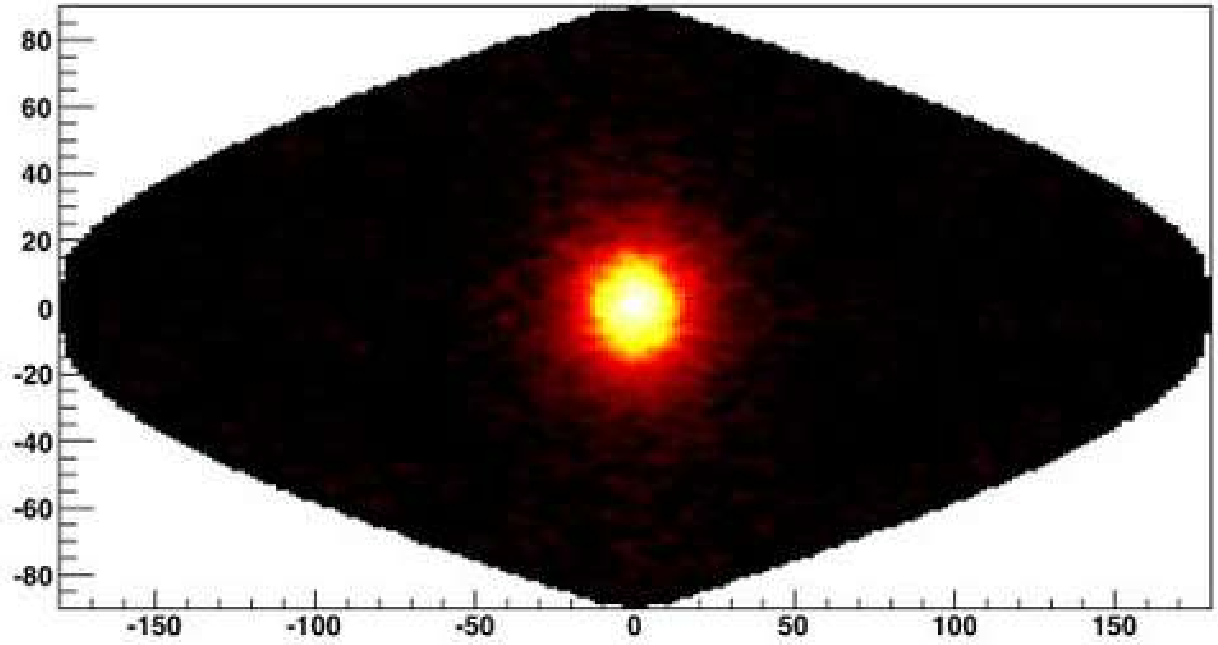
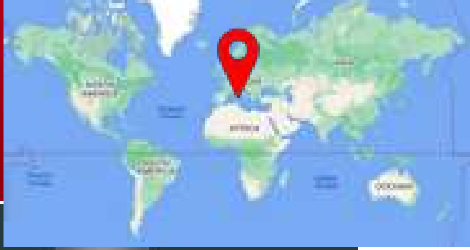


Image du soleil en Neutrino Electronique



Antares



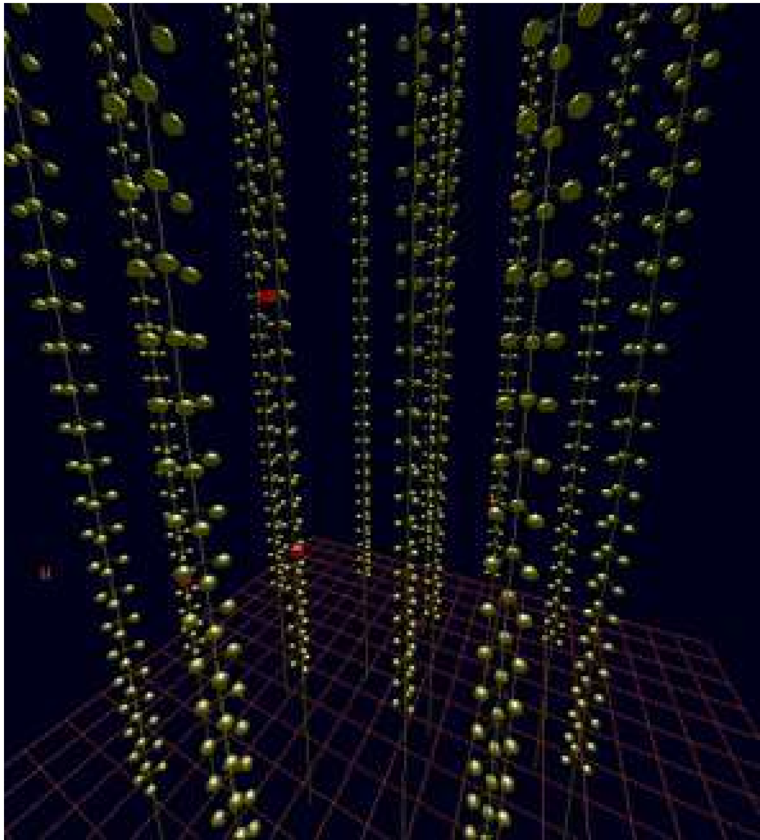
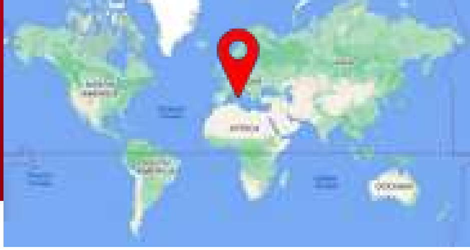
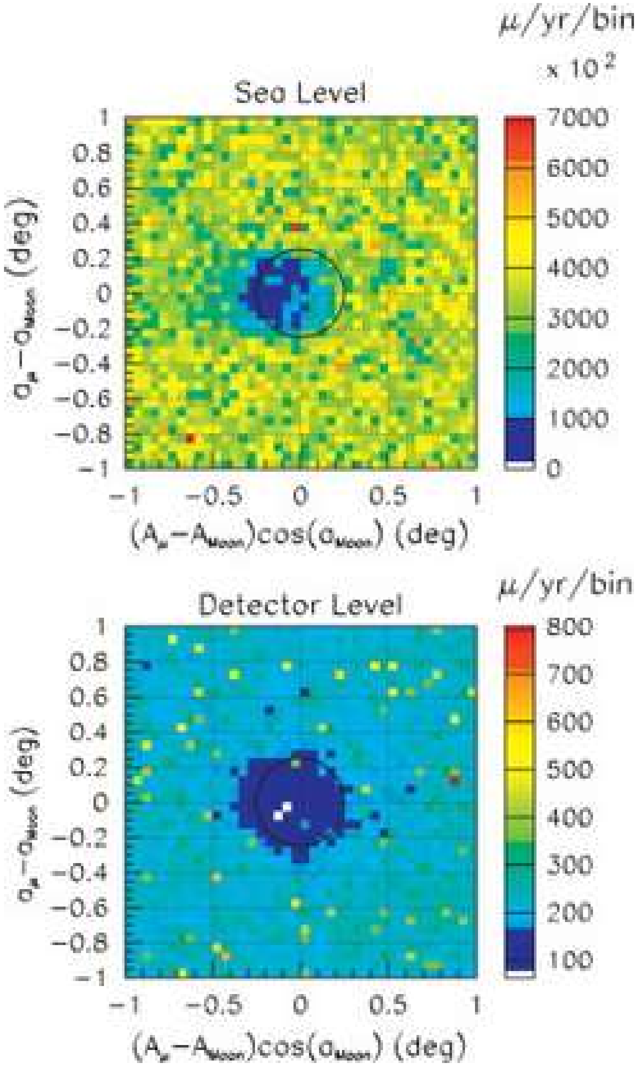


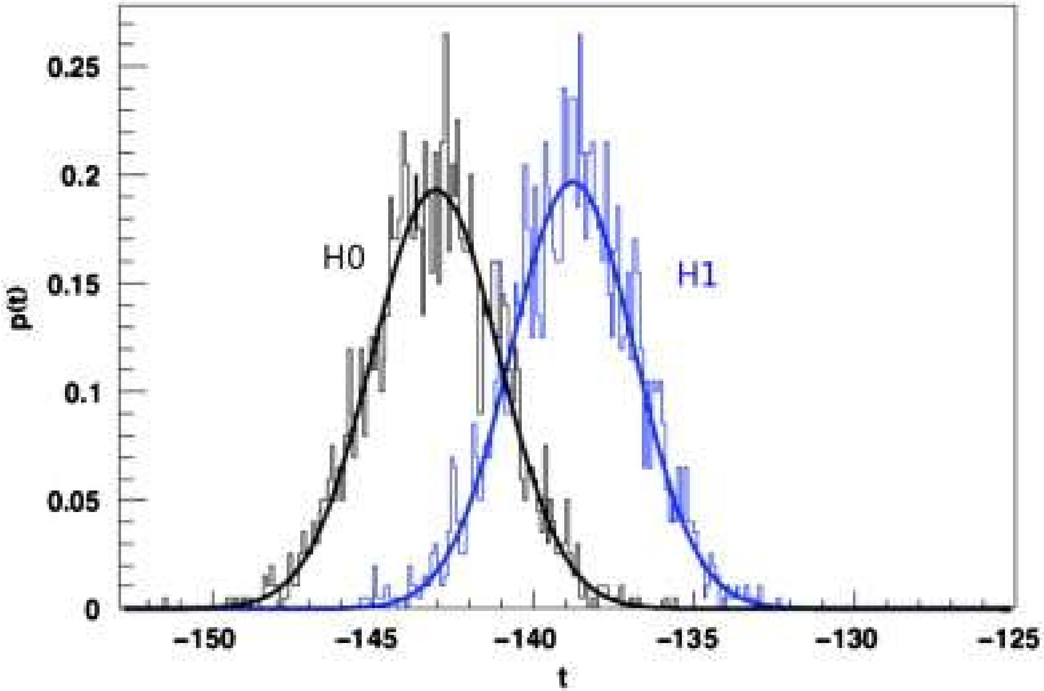
FIG. (II) 1.7: *Photographie d'un individu bioluminescent prise par l'une des caméras installées sur la ligne d'instrumentation IL07 (lire le paragraphe II.3.4). L'échelle n'est pas précisément connue (elle dépend de la distance à la caméra).*

Antares





Moon Shadow in cosmic rays



Moon hypothesis confirms at 2.9 σ

Sun is at 3.7σ

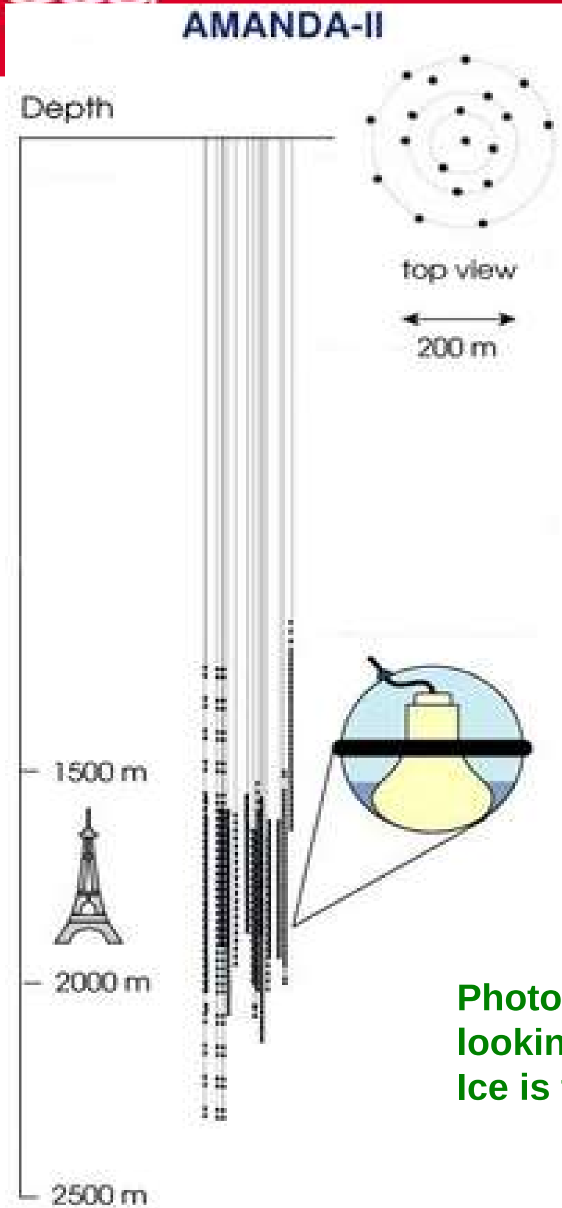
AMANDA

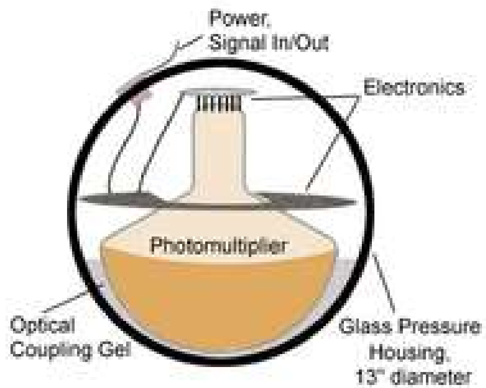
Antarctic **M**uon **A**nd **N**eutrino **D**etector **A**rray

AMANDA

South Pole

AMANDA



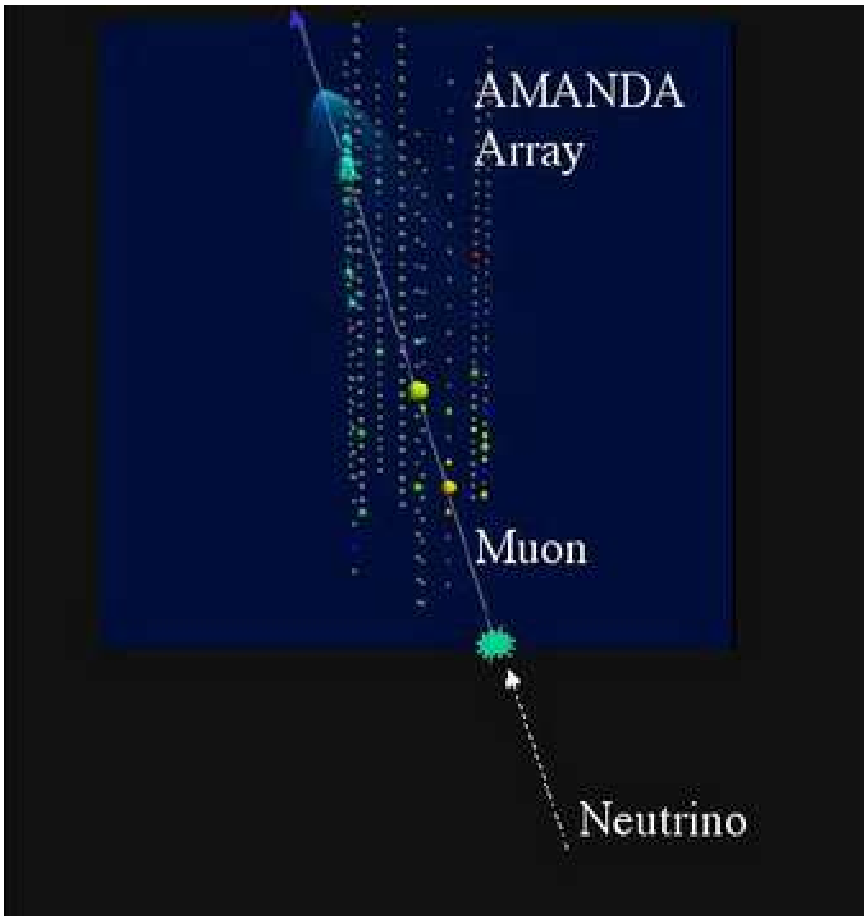


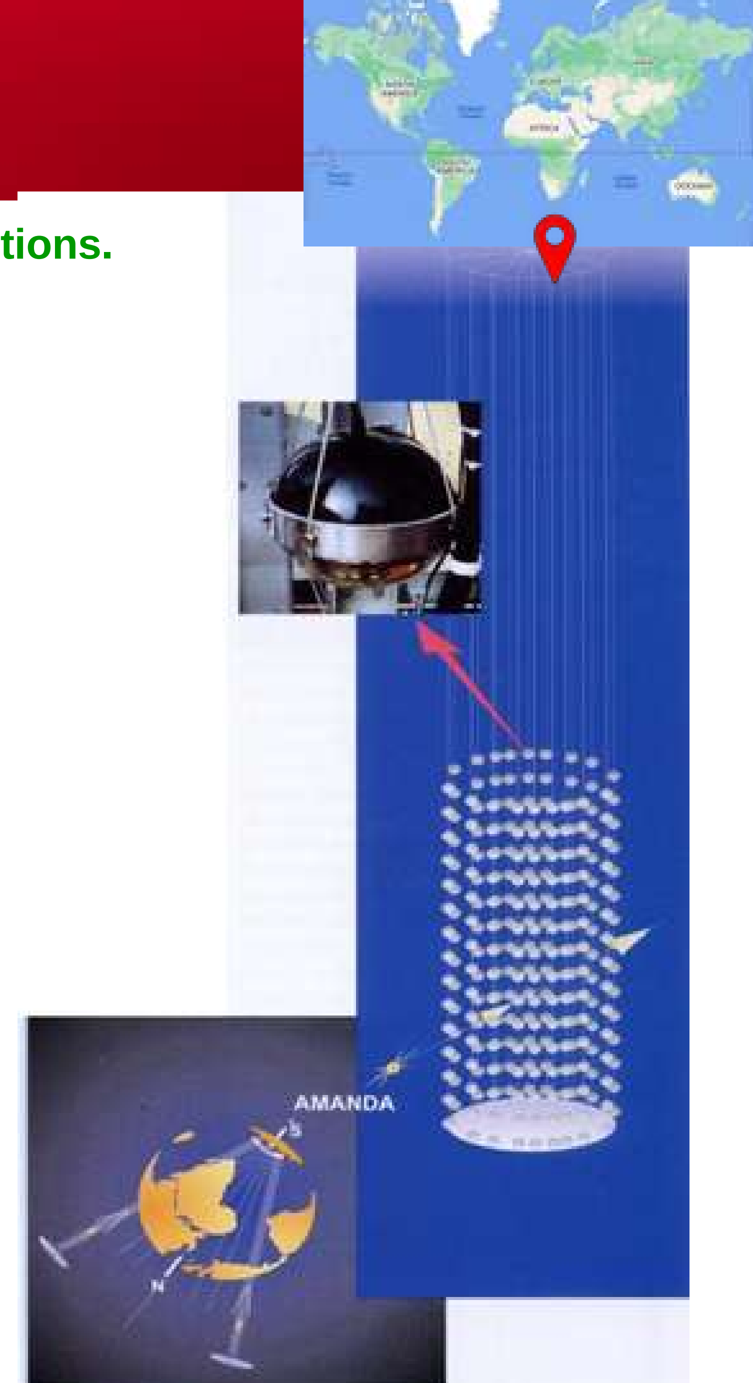
Photomultipliers in the Ice,
looking downwards.
Ice is the detecting medium.

AMANDA

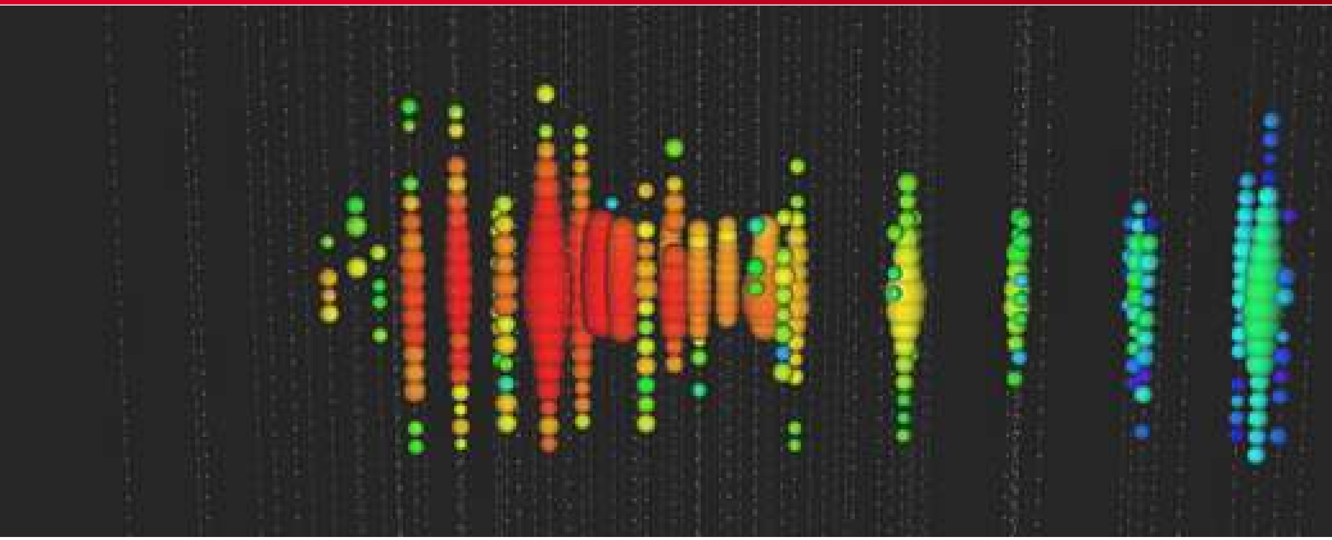
Look for upwards going Muons from Neutrino Interactions.
Cherekov light propagating through the ice.

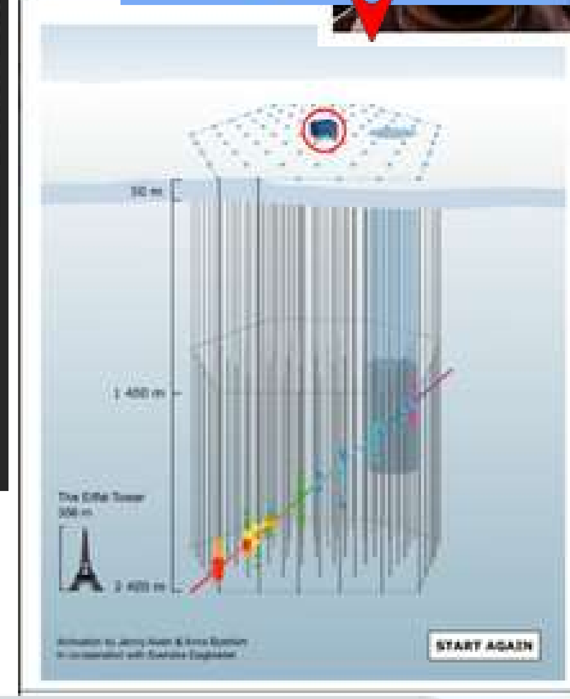
→ **Find neutrino point sources in the universe !**



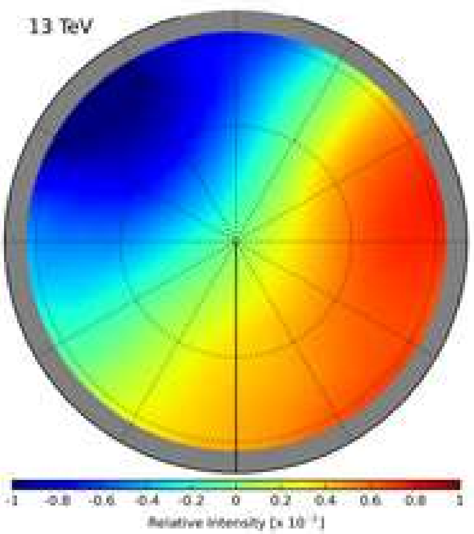


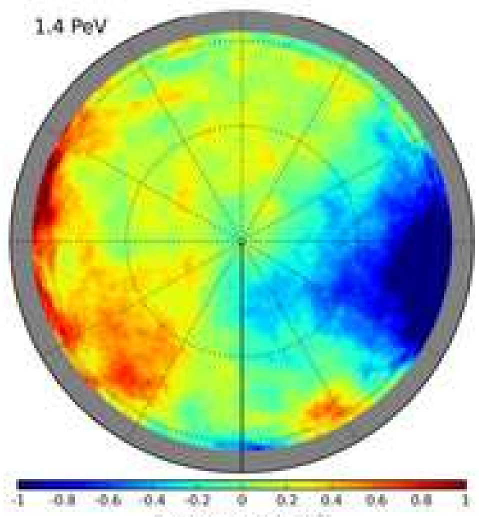
AMANDA – ICE CUBE

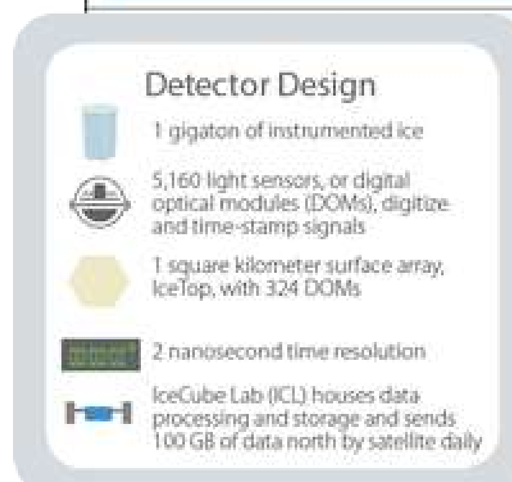




A very high energy neutrino detected in IceCube on November 12, 2010, with an energy of 71 TeV.
Image: IceCube Collaboration



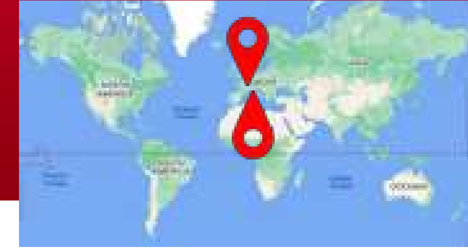




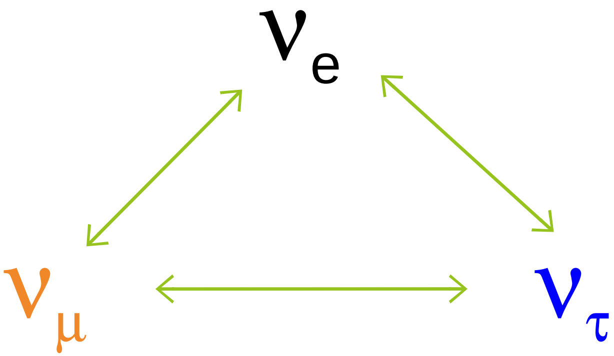
CERN Neutrino Gran Sasso

(CNGS)

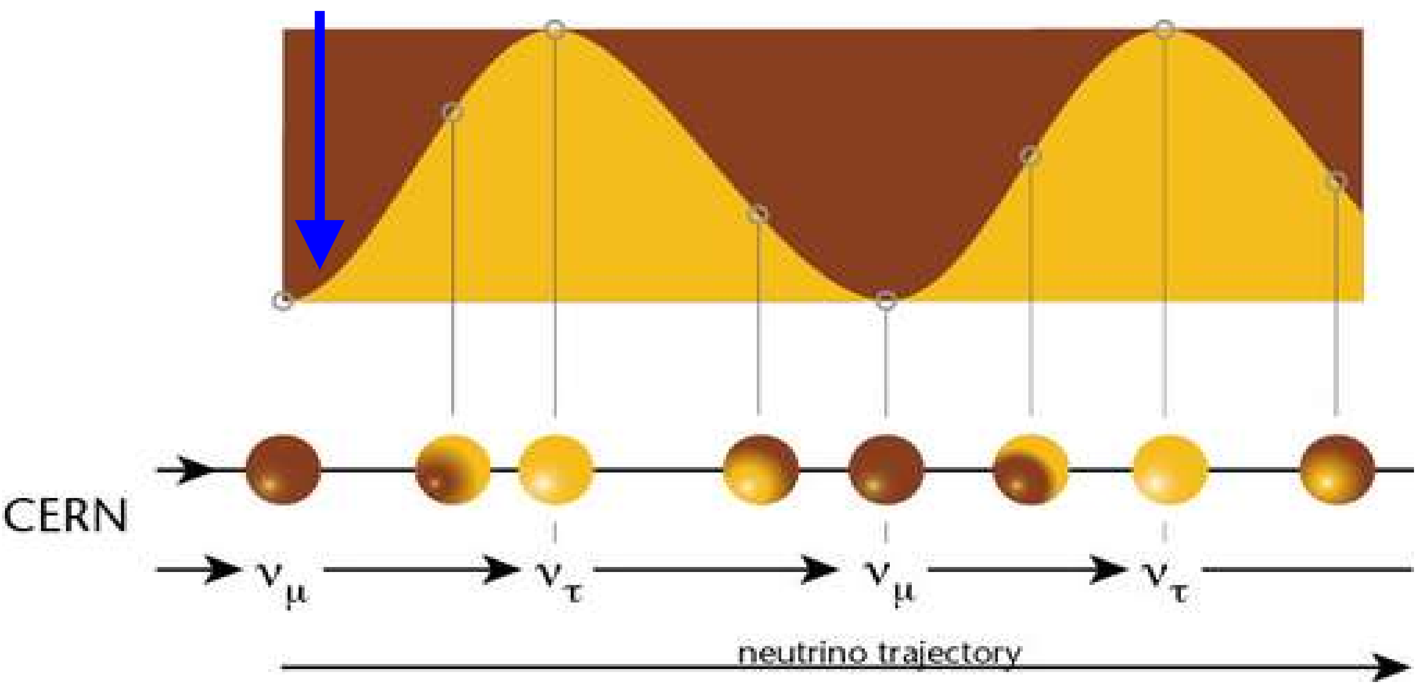
CNGS



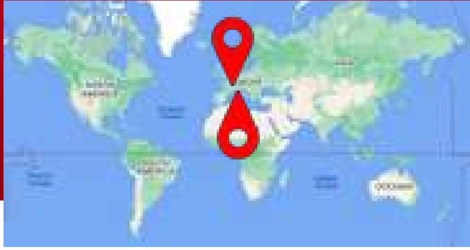
If neutrinos have mass:



Muon neutrinos produced at CERN.
See if tau neutrinos arrive in Italy.



CNGS PROJECT

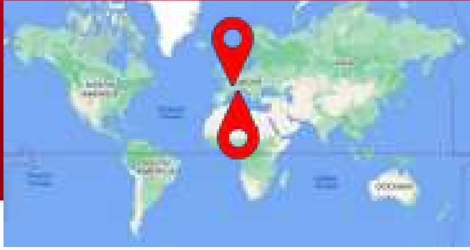


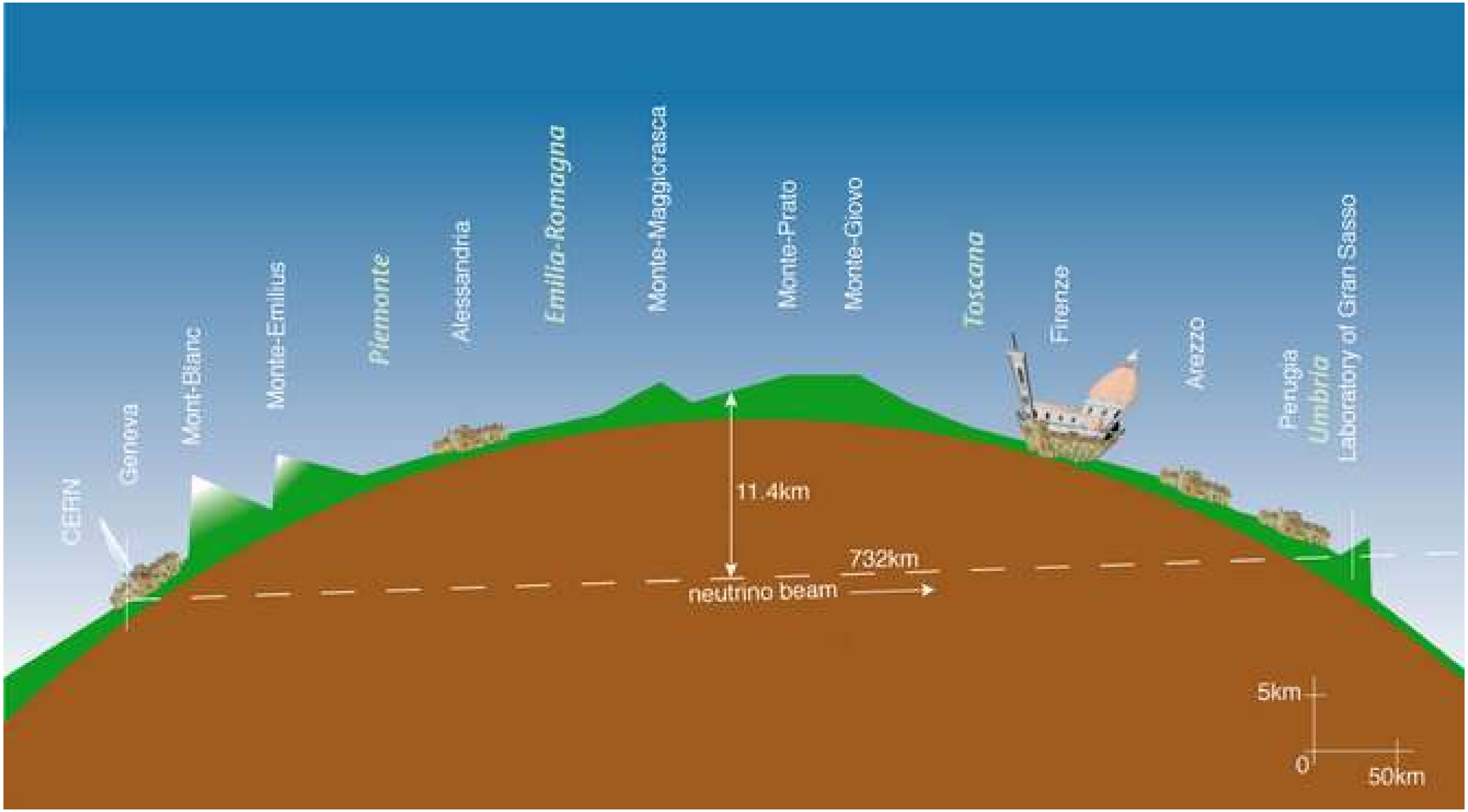
CNGS (CERN NEUTRINO GRAN SASSO)

- A LONG BASE-LINE NEUTRINO BEAM FACILITY (732KM)
- SEND N_M BEAM PRODUCED AT CERN
- DETECT N_T APPEARANCE IN OPERA EXPERIMENT AT GRAN SASSO

□ direct proof of ν_μ - ν_τ oscillation (appearance experiment)

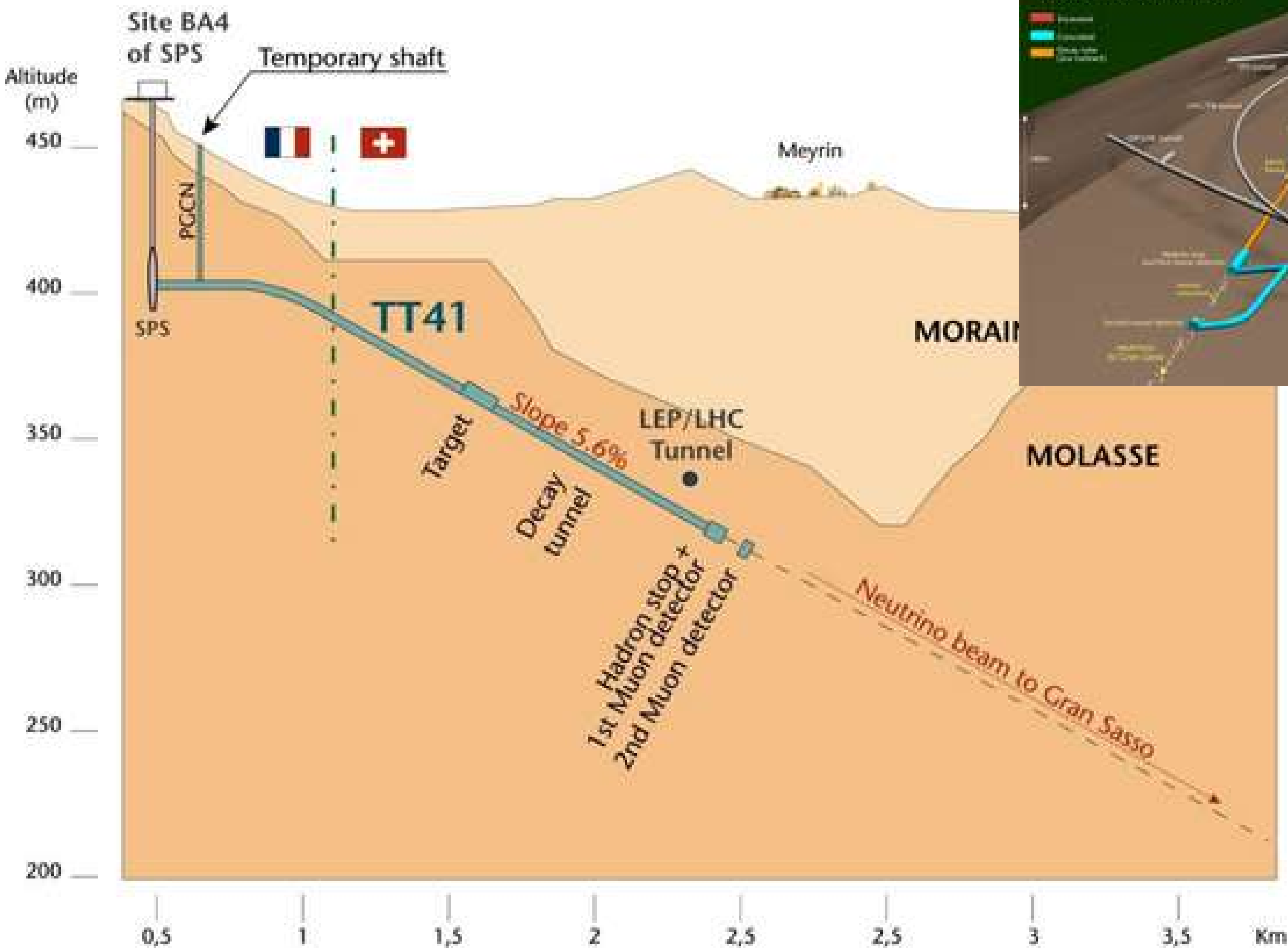
CNGS

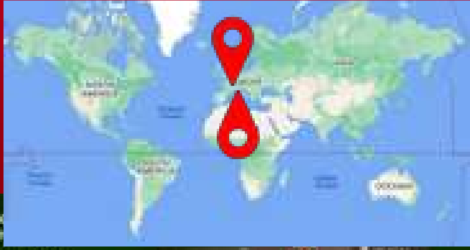




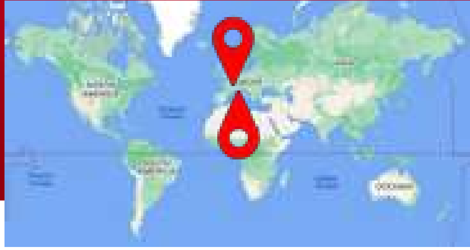
CERN
Genova
Mont-Blanc
Monte-Emilius
Piemonte
Alessandria
Emilia-Romagna
Monte-Maggiorasca
Monte-Prato
Monte-Giovo
Toscana
Firenze
Arezzo
Perugia
Umbria
Laboratory of Gran Sasso
11.4km
732km
neutrino beam
5km
0
50km

CNGS


Site BA4
of SPS
Temporary shaft
Altitude
(m)
450
400
350
300
250
200
PGCN
SPS
Meyrin
TT41
MORAIN
MOLASSE
Target
Slope 5.6%
LEP/LHC
Tunnel
Decay
tunnel
Hadron stop +
1st Muon detector
2nd Muon detector
Neutrino beam to Gran Sasso
0,5
1
1,5
2
2,5
2,5
3
3,5
Km



NEUTRINOS AT CNGS: SOME NUMBERS

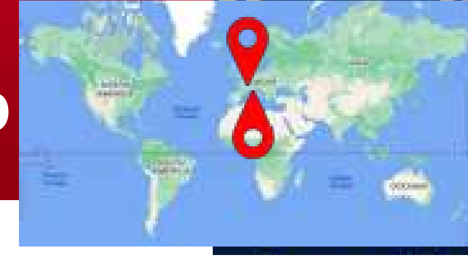


For 1 day of CNGS operation, we expect:

protons on target	**2×10^{17}**
pions / kaons at entrance to decay tunnel	**3×10^{17}**
ν_μ in direction of Gran Sasso	**10^{17}**
ν_μ in 100 m^2 at Gran Sasso	**3×10^{12}**

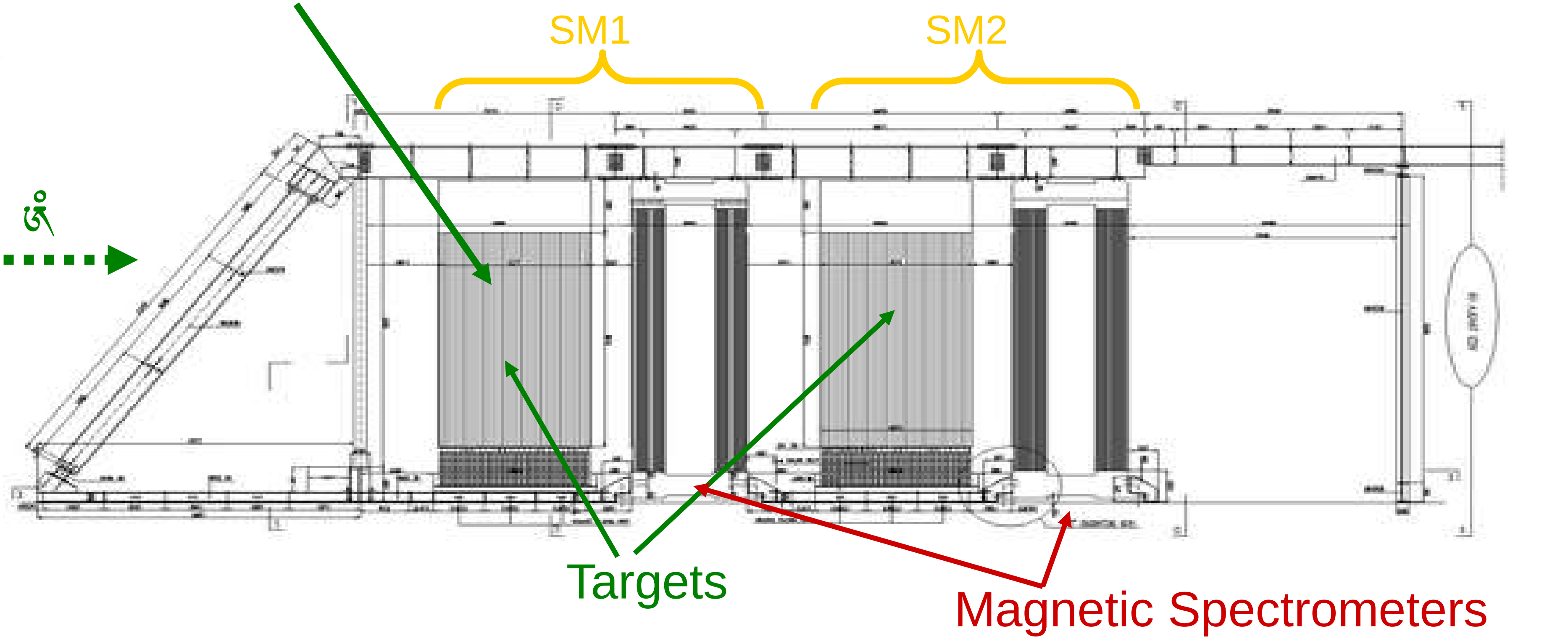
ν_μ events per day in OPERA	25 per day
ν_τ events (from oscillation)	2 per year

Opera Experiment at Gran Sasso



31 target planes / supermodule

In total: 206336 bricks, 1766 tons

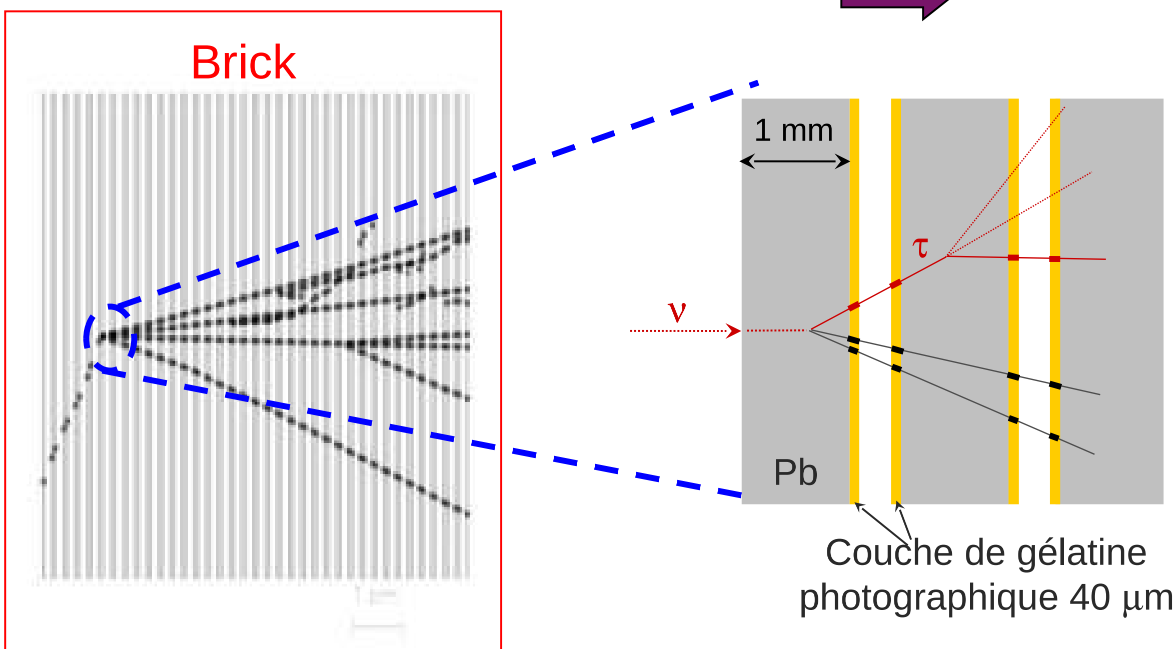


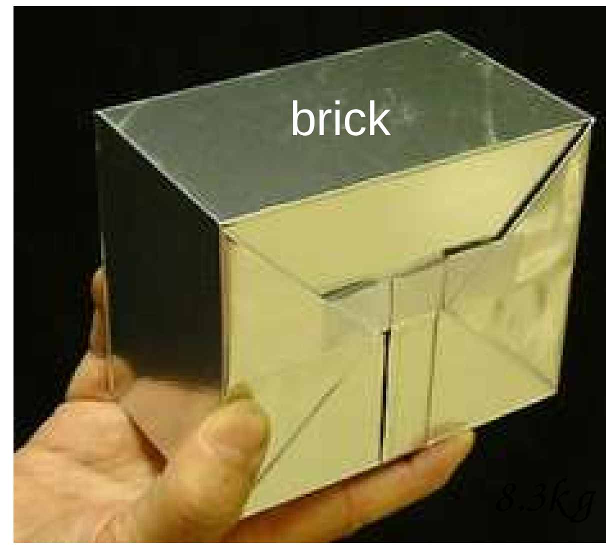
First observation of CNGS beam neutrinos : August 18th, 2006

Basic unit: brick

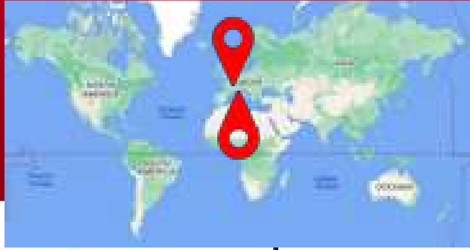
56 Pb sheets + 56 photographic films (emulsion sheets)

Lead plates: massive target
Emulsions: micrometric precision



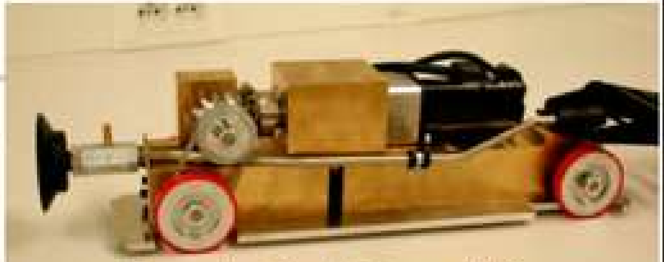


10.2 x 12.7 x 7.5 cm^3



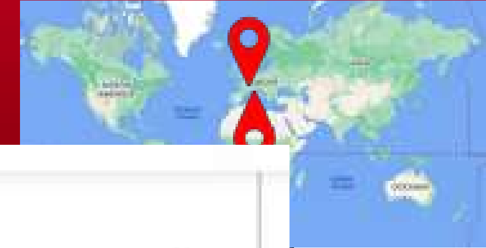
The Brick Manipulator System (BMS) prototype: a lot of fun for children and adults !

Tests with the prototype wall



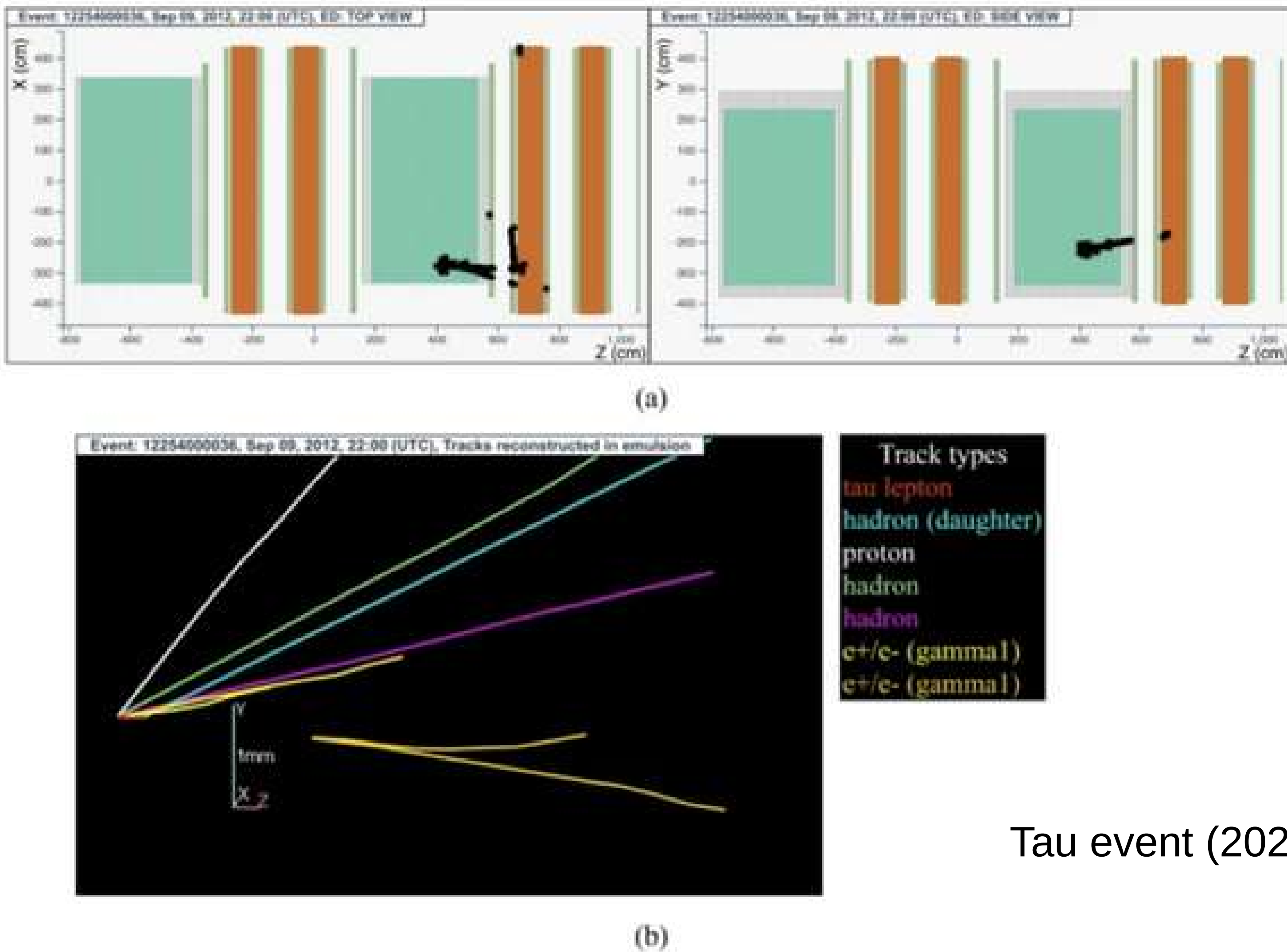
The robotised "Ferrari" for insertion/extraction of bricks with vacuum grip by Venturi valve

"Carousel" brick dispensing and storage system



Opera Experiment at Gran Sasso

Fig. 15



Tau event (2021)

Concept Study for Observing Galactic Neutrinos in Neptune’s Atmosphere

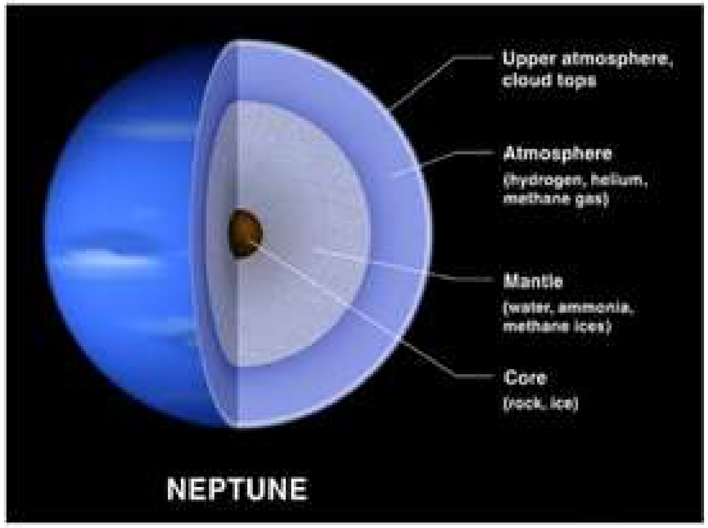


Fig. 15 Sketch of the Internal Structure of Neptune produced by NASA

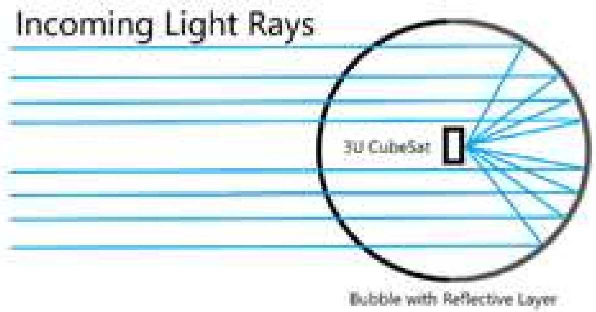


Fig. 14 Diagram of reflective bubble environment redirecting the incoming light rays back to the CubeSat.

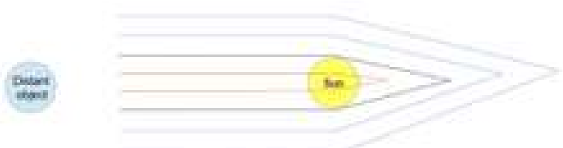


Fig. 4. Depiction of Neutrino Gravitational Lensing of the Sun.

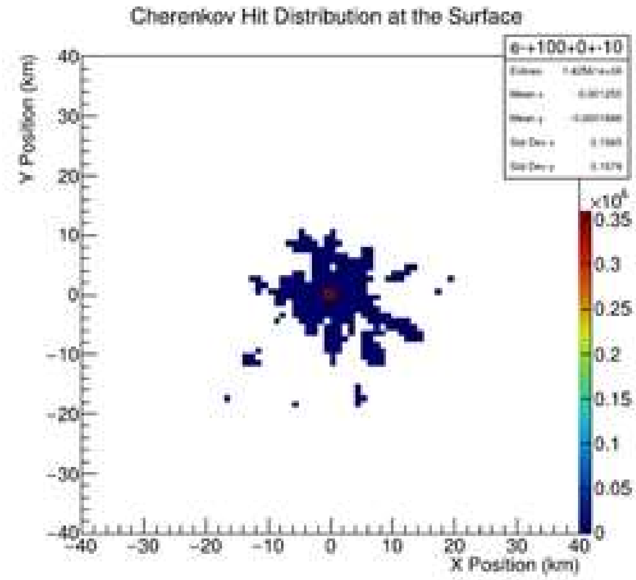
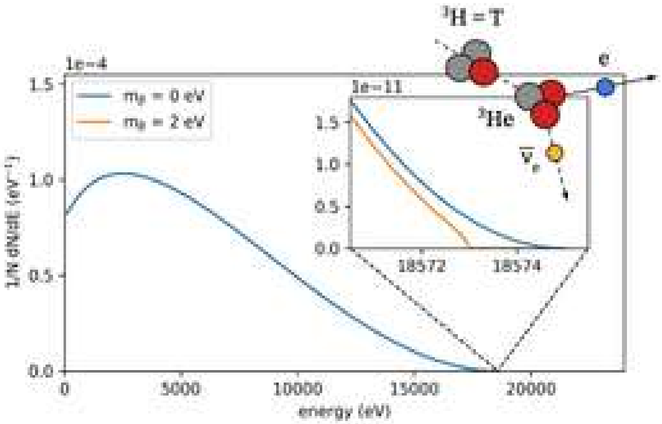
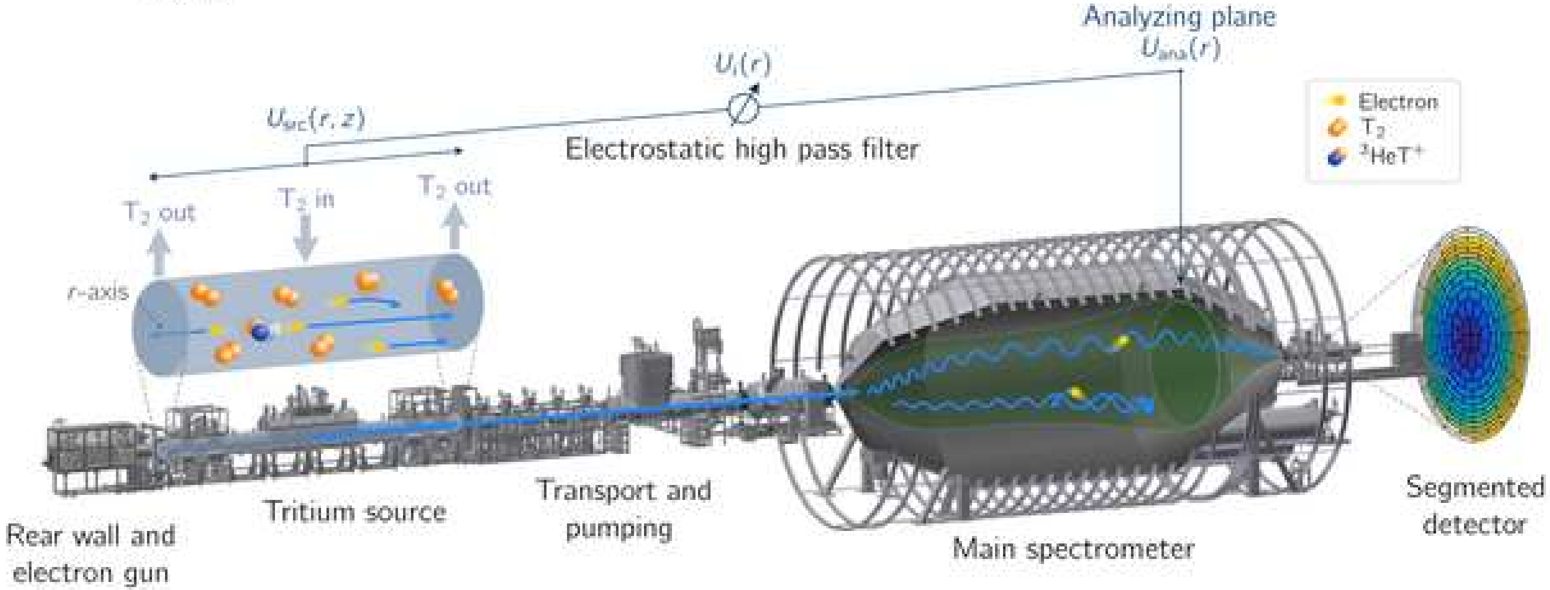


Fig. 7 Cherenkov hit distribution generated by a 100 GeV Electron at the surface of the atmosphere.

To see Galactic core and BH

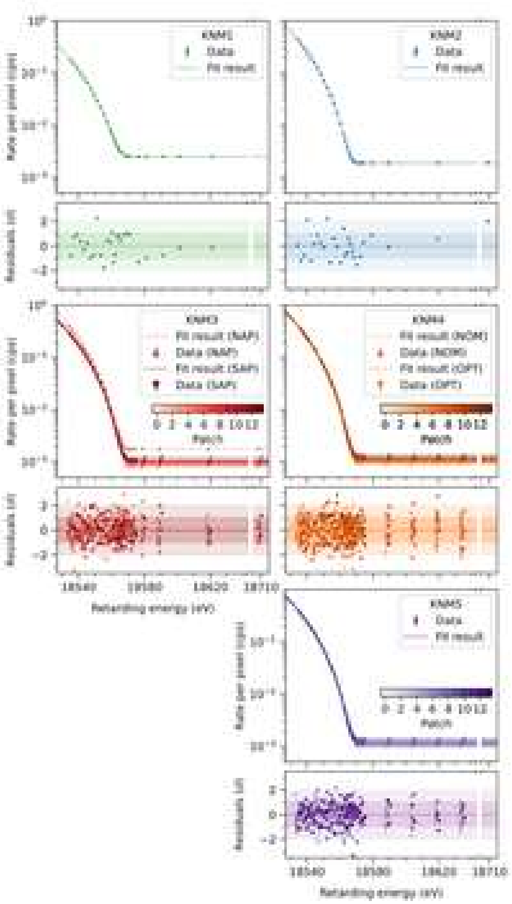
Neutrino Mass Measurement (KATRIN)

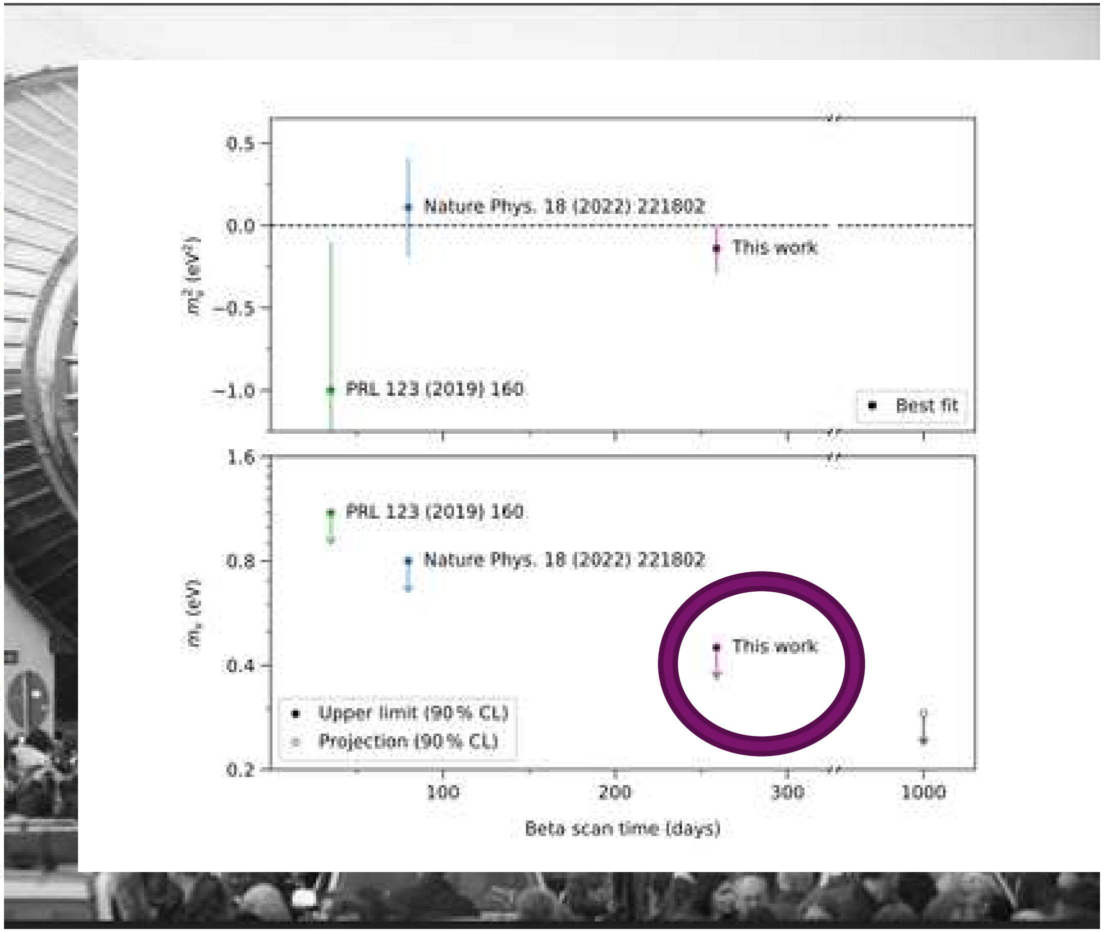




Neutrino Mass Measurement (KATRIN)

Neutrino Mass Measurement (KATRIN)

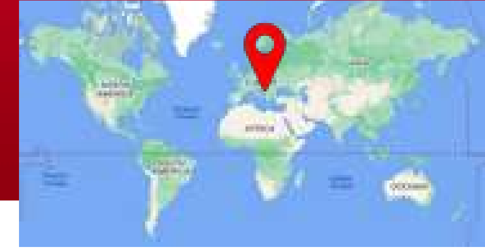


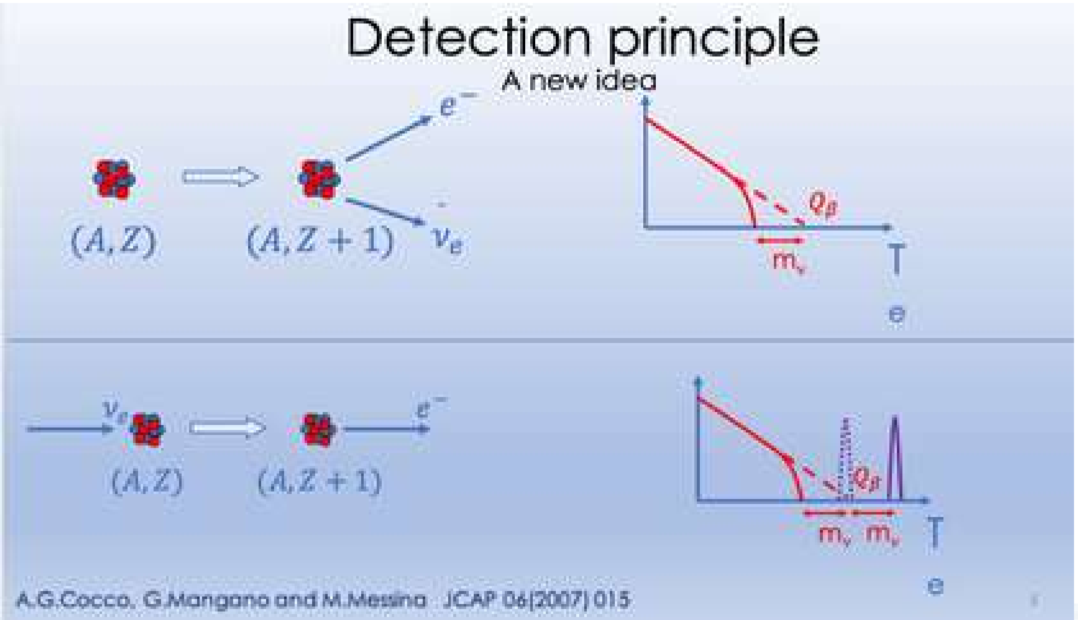


Submitted on 19 Jun 2024

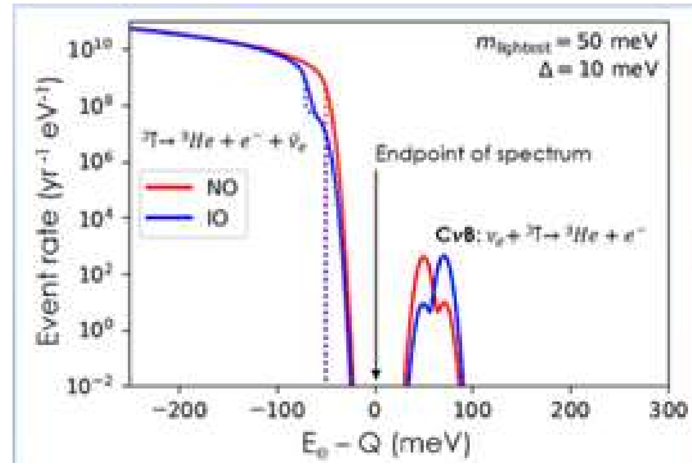
Direct neutrino-mass measurement based on 259 days of KATRIN data

PTOLEMY

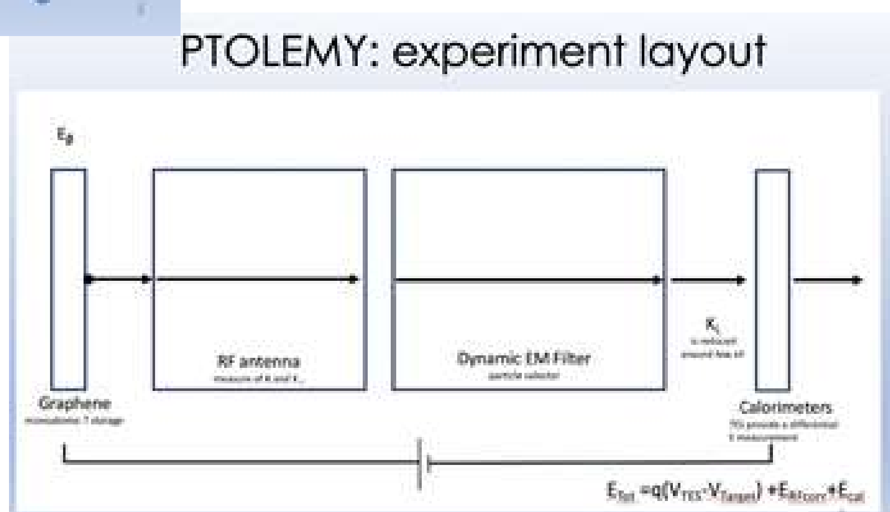




Detection principle
A new idea
e^-
(A,Z)
$(A,Z+1)$
ν_e
Q_β
m_ν
T_e
ν_e
e^-
(A,Z)
$(A,Z+1)$
Q_β
m_ν m_ν
T_e
A.G.Cocco, G.Mangano and M.Messina JCAP 06(2007) 015

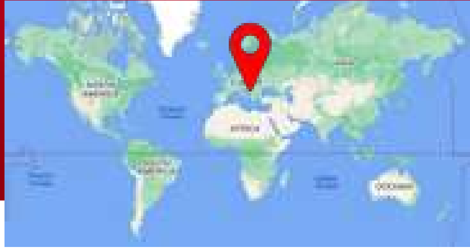


$m_{lightest}$ = 50 meV
Δ = 10 meV
Event rate (yr^{-1} eV^{-1})
$^3T \rightarrow {}^3He + e^- + \bar{\nu}_e$
NO
IO
Endpoint of spectrum
CνB: $\nu_e + {}^3T \rightarrow {}^3He + e^-$
10^{10}
10^8
10^6
10^4
10^2
10^0
10^{-2}
−200
−100
0
100
200
300
$E_e - Q$ (meV)



PTOLEMY: experiment layout
E_β
Graphene
RF antenna
Dynamic EM Filter
K_i
Calorimeters
$E_{tot} = q(V_{TES} - V_{Target}) + E_{RFcorr} + E_{cal}$

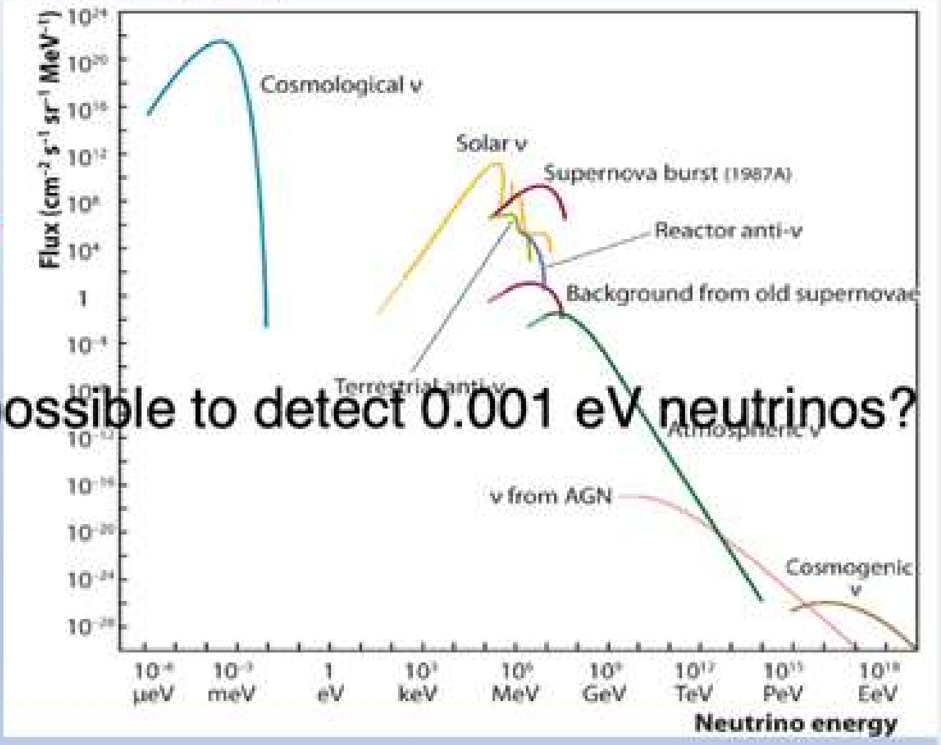
PTOLEMY



Neutrino flow

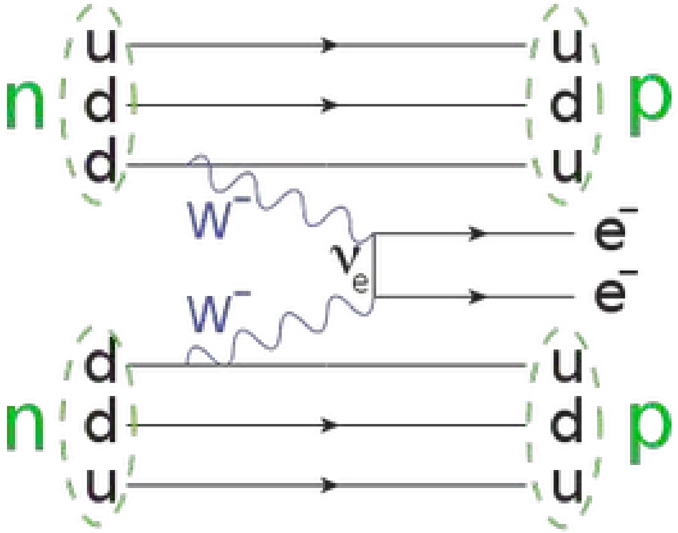
$T \approx 1.9\ K \Rightarrow p_\nu \approx 0.001\ eV$

$n \approx 56\ cm^{-3}\ x\ 6$



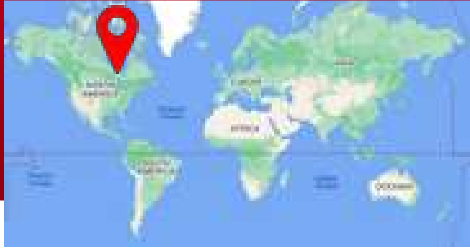
Is it possible to detect 0.001 eV neutrinos?

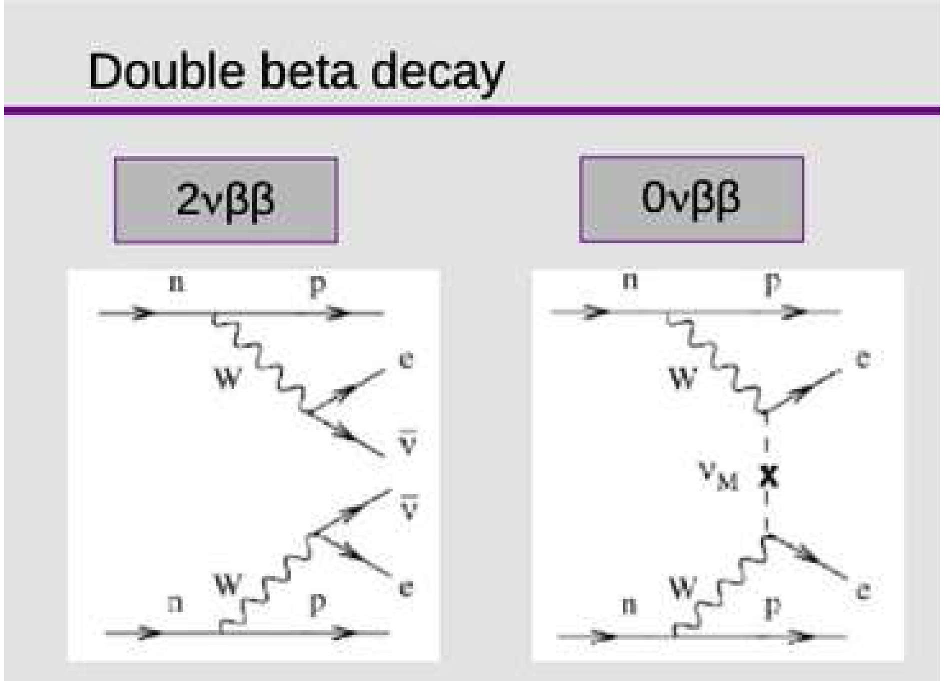
DOUBLE BETA DECAY

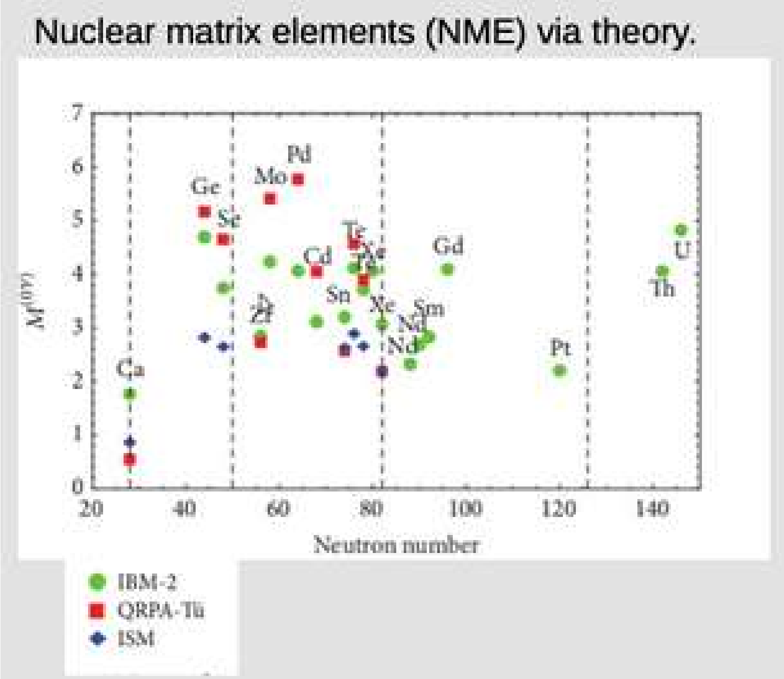


$0\nu\beta\beta$ of ^{136}Xe : $^{136}Xe \rightarrow {}^{136}Ba + 2e^-$

SNO



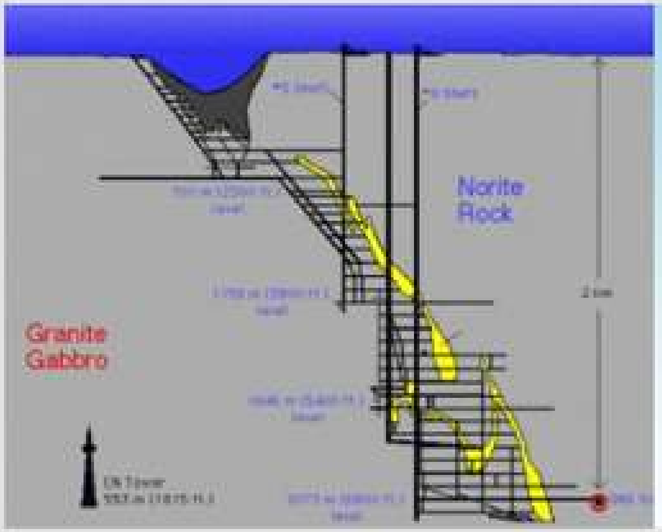




Experiment	Isotope	Technique	Main Strength	
CUORE (LNGS)	130Te	Bolometers	Resolution, Efficiency	On- going or commissioning
GERDA-II (LNGS)	76Ge	Ge Diodes	Resolution, Efficiency	
KamLANDZen (Kamioka)	136Xe	Xe Liquid scintillation	Background, efficiency	
MAJORANA (SURF)	76Ge	Ge Diodes	Resolution, Efficiency	
NEXT (LSC)	136Xe	Tracking + Calorimetry	Background Rejection, Efficiency	
SNO+ (SNOLAB)	130Te	Te Liquid Scintillation	Background, Mass	
SUPERNEMO (LSM)	82Se, 150Nd	Tracking + Calorimetry	Background Rejection, Isotope Selection	R&D
1TGe (GERDA+MJ)	76Ge	Best technology from GERDA, MAJORANA	Resolution, Efficiency	
CUPID	130Te	Hybrid bolometers	Background, Resolution	
nEXO (WIPP)	136Xe	TPC Ionization + Scintillation	Mass, Efficiency, Final State Signal	
AMORE (Y2L)	100Mo	CaMoO4 bolometers	Resolution	R&D further
CANDLES (Kamioka)	48Ca	CaF2 Scintillation	Background, Efficiency	
COBRA (LNGS)	130Te, 116Cd	ZnCdTe Semiconductors	Resolution, Efficiency	
LUCIFER (LNGS)	82Se	ZnSe bolometers	Resolution, Background	
MOON (UW)	100Mo	Tracking + Scintillation	Compactness, Background	

SNO

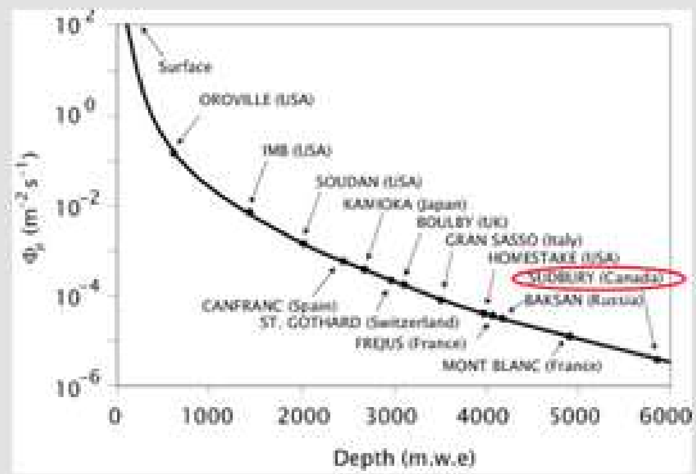
The SNO+ Experiment



SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

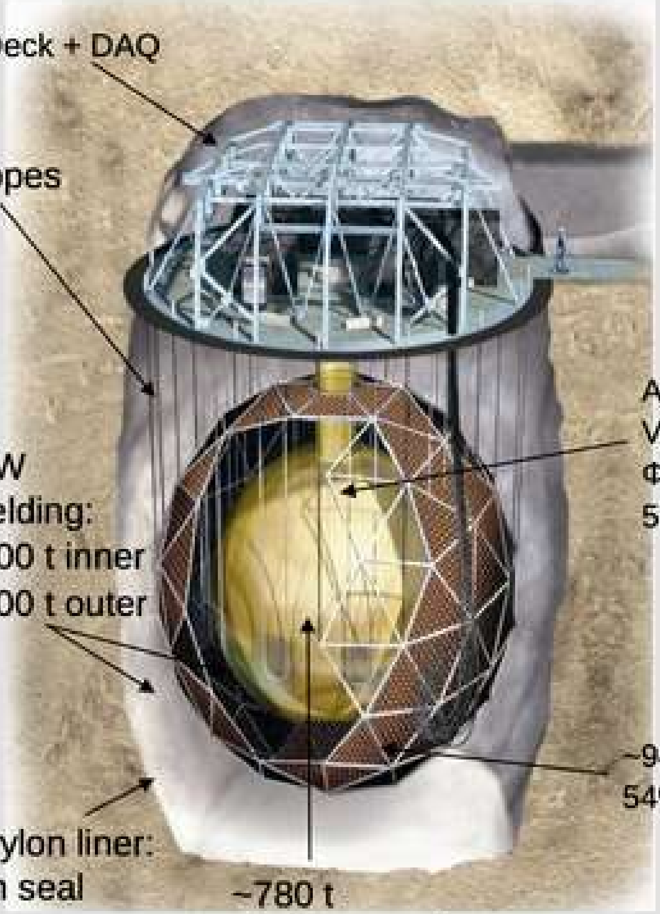
- Located at SNOLAB inside the Creighton mine near Sudbury, Canada.
- SNO+ is the successor to Sudbury Neutrino Observatory (SNO).

- Depth = 2070 m (6000 m.w.e.)
- ~60 muons /day in SNO+
- 10,000 sq ft Class-2000 clean room



SNO

The SNO+ Detector

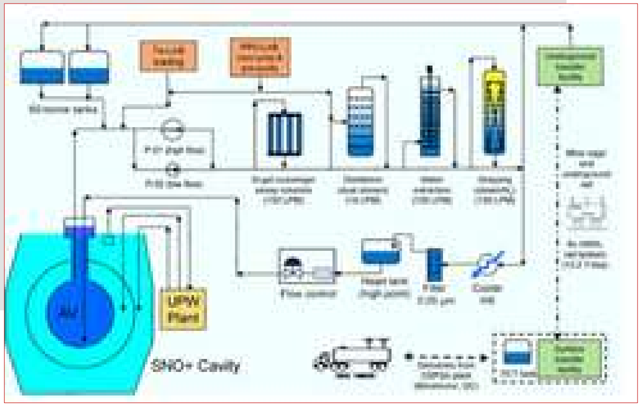


Broad neutrino physics program

- **Neutrinoless double beta decay of ^{130}Te**
- Reactor anti-neutrinos
- Geo anti-neutrinos
- Supernovae neutrinos
- Nucleon decay and exotic physics
- Solar neutrinos (pep, CNO, low E ^{8}B)

Three Experimental Phases

- Water-Phase
- Liquid scintillator phase
- **Te-loaded liquid scintillator**



PandaX

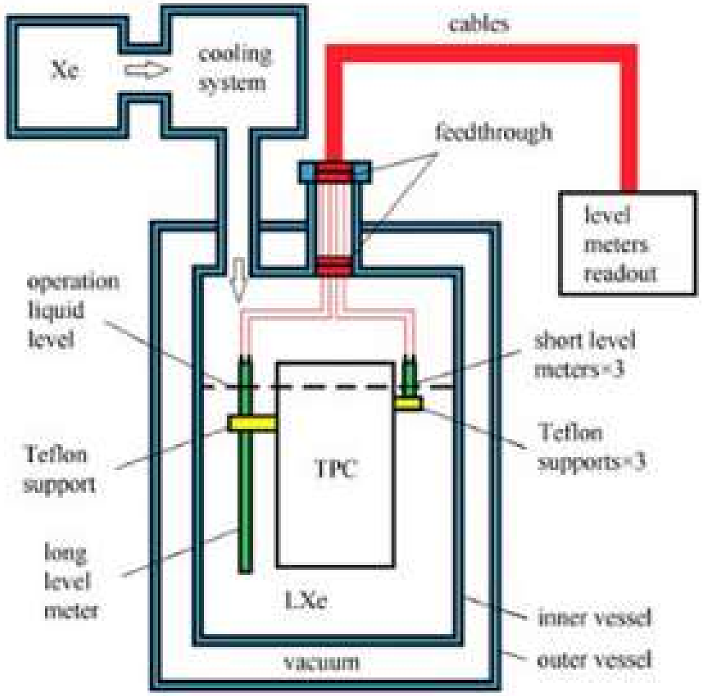
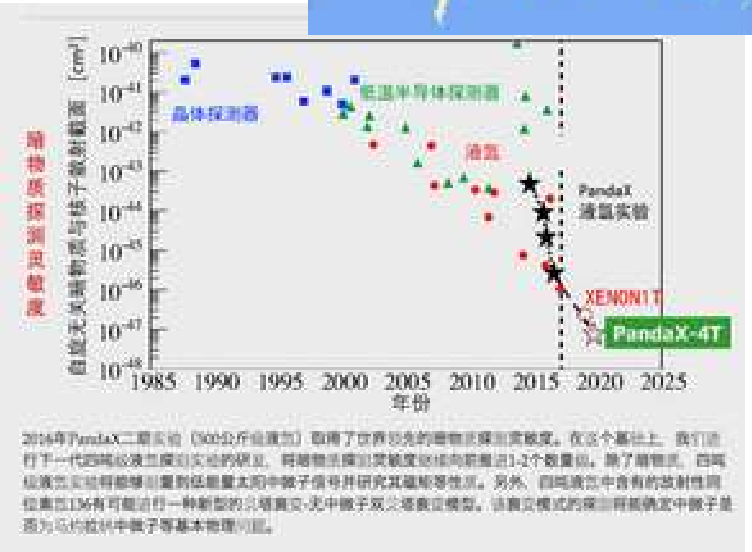
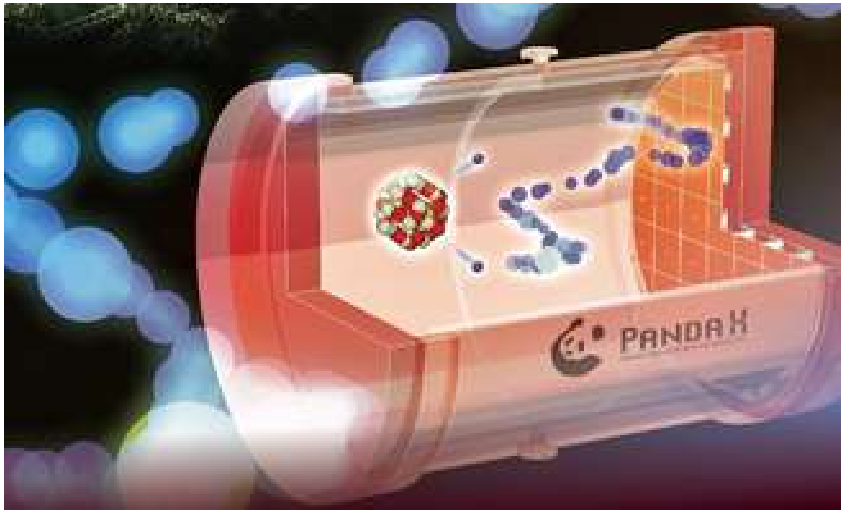


Fig. 1. Schematics of the two-phase xenon detector as used in PandaX. LXe is contained in an inner vessel insulated by vacuum from the outside. One long liquid level meter monitors the overall liquid xenon height and three short level meters monitor the height of the liquid-gas interface around the TPC.





ANTI-MATIERE

The Positive Electron

MARCH 15, 1933 PHYSICAL REVIEW VOLUME 43

The Positive Electron

CARL D. ANDERSON, *California Institute of Technology, Pasadena, California*

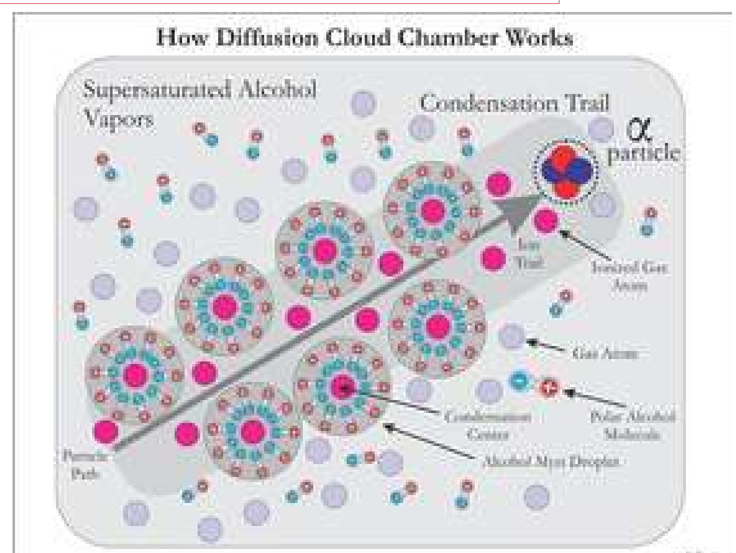
(Received February 28, 1933)

Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

Editor

1930 : Data taking
1932 : Analysis
1933 : Paper

1.5T Wilson Chamber
Rec. Cosmic Rays
1300 events
15 tracks with e$^+$



The Positive Electron

492 CARL D. ANDERSON

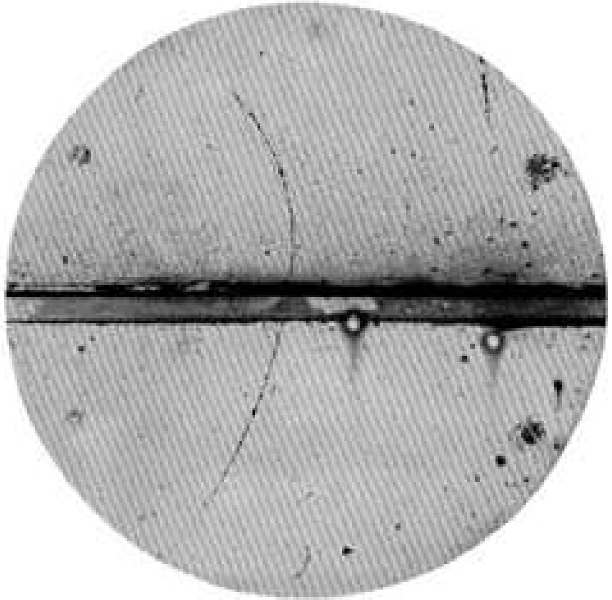
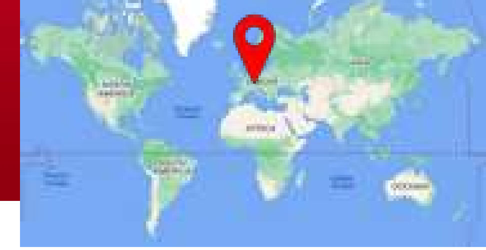


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

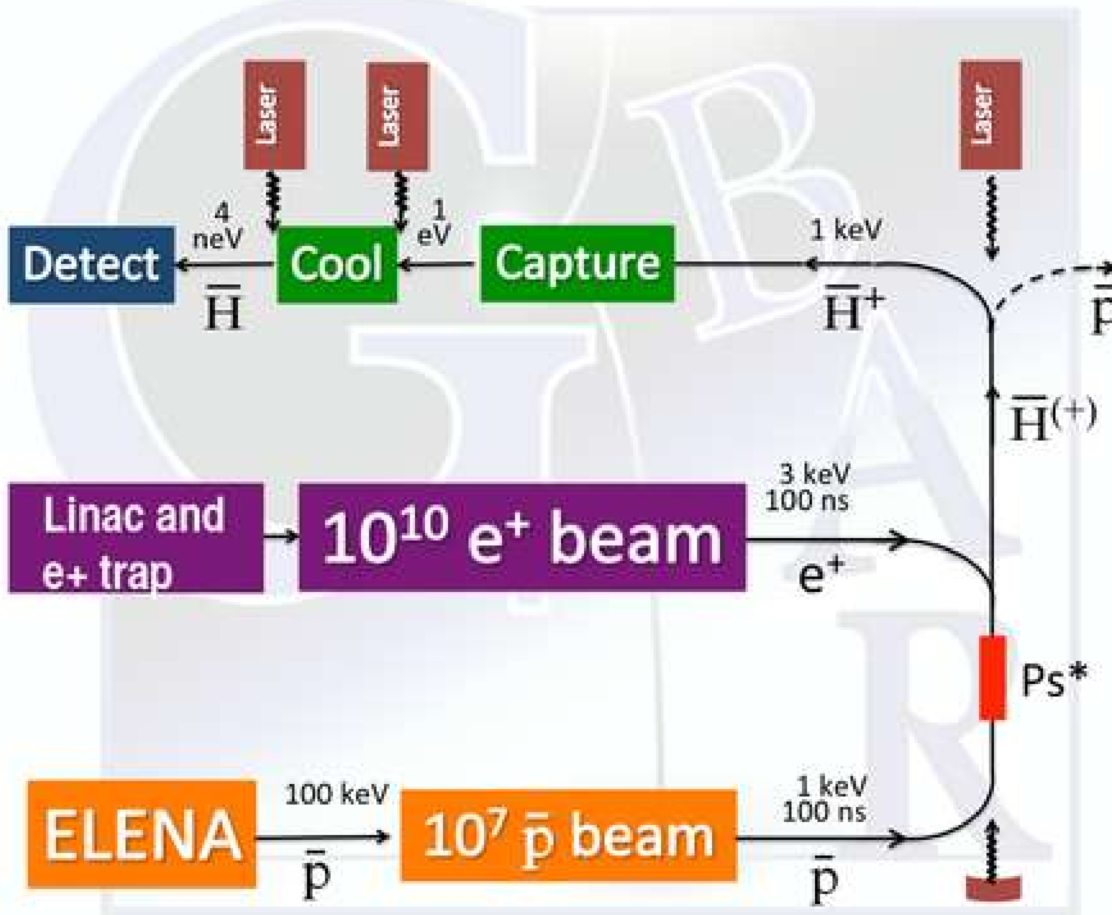
1930 : Data taking
1932 : Analysis
1933 : Paper

1.5T Wilson Chamber
Rec. Cosmic Rays
1300 events
15 tracks with e^+

GBAR at CERN

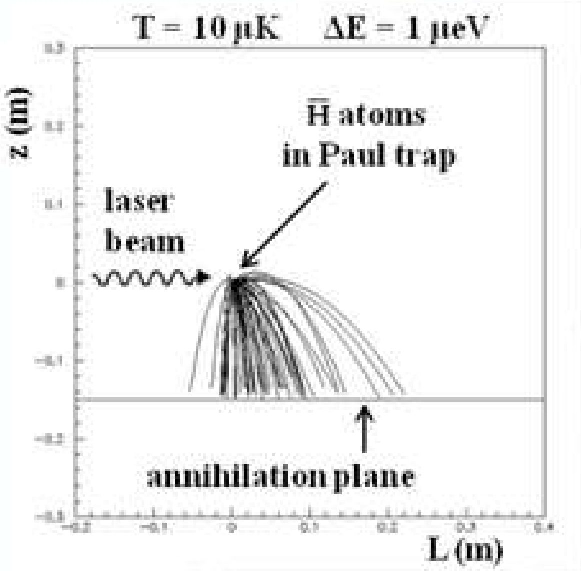


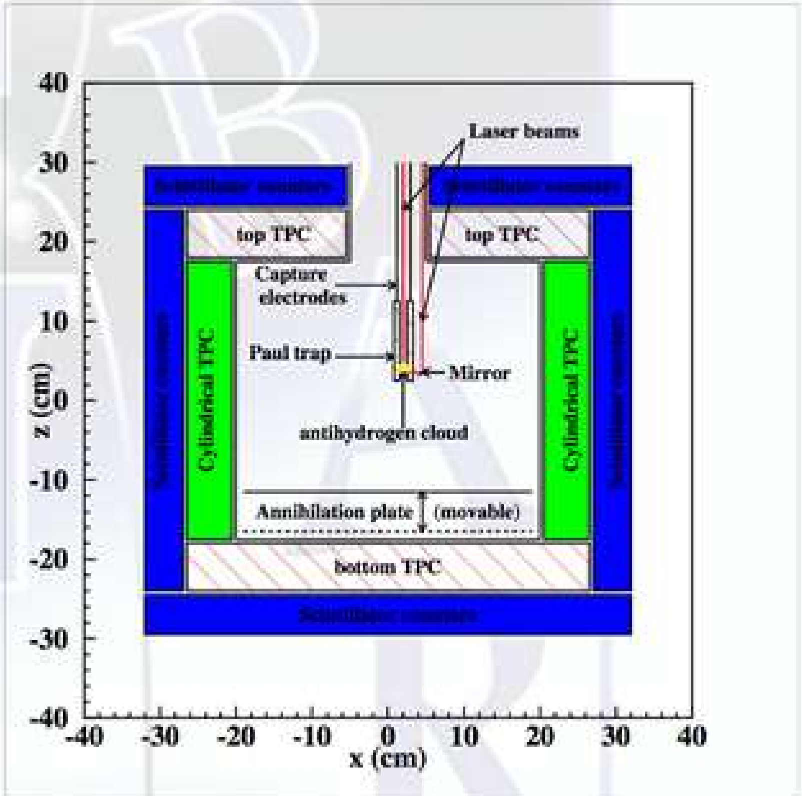
Schematic



GBAR at CERN

Detection



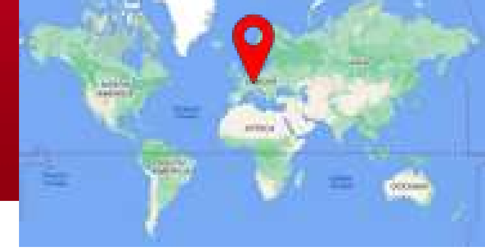


Detection requirement:
- TOF precision : 150 μs
- Annihilation vertex precision : 1 mm
- Background rejection through event topology

Scheme under design: TPC with micromegas chamber (as in T2K near detector)

$$\frac{\Delta\bar{g}}{\bar{g}} \approx 10^{-2}$$

PUMA at CERN

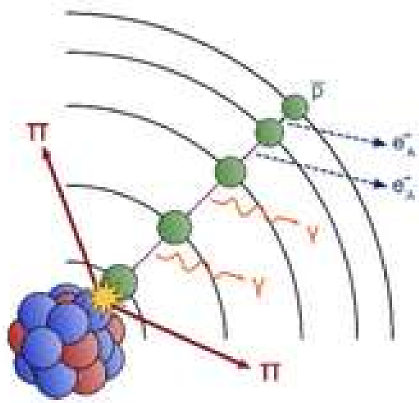


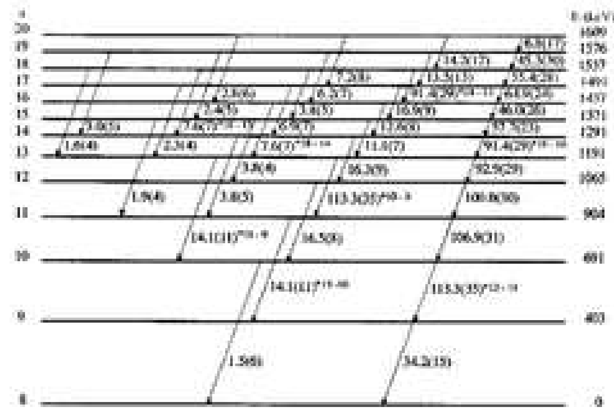
antiProton Unstable Matter Annihilation (PUMA)

TECHNISCHE UNIVERSITAT DARMSTADT

Proposed technique: Low-energy antiprotons as a probe

Capture in excited antiproton orbital → Cascade: Auger transitions → Cascade: radiative transitions → Annihilation with surface nucleon → Final-state interactions of emitted mesons

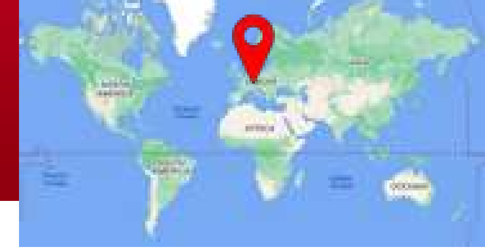




R. Schmidt, PRC (1998)

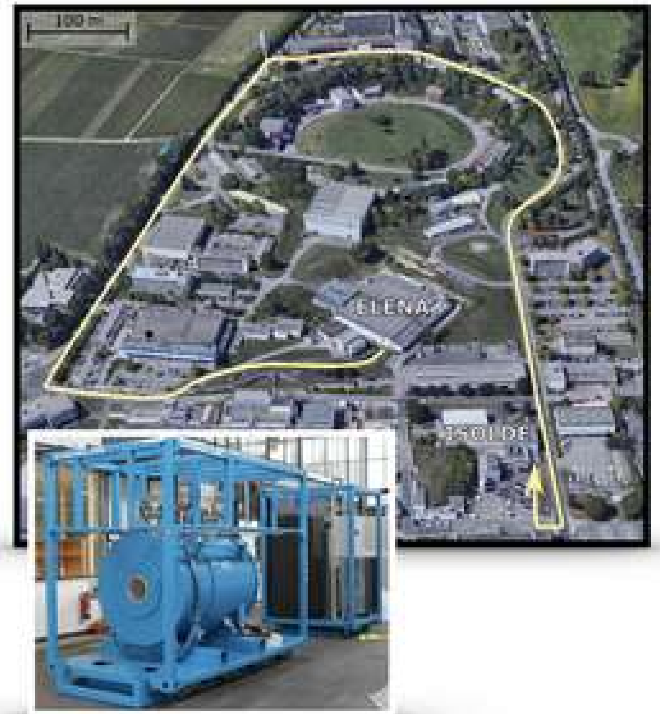
Clara Klink | CERN | TU Darmstadt – Institute for Nuclear Physics
FuPhy 2024 | 08. - 10. Apr 2024, SMI, Wien

PUMA at CERN



Transporting Antiprotons from AD to ISOLDE

TECHNISCHE UNIVERSITÄT DARMSTADT



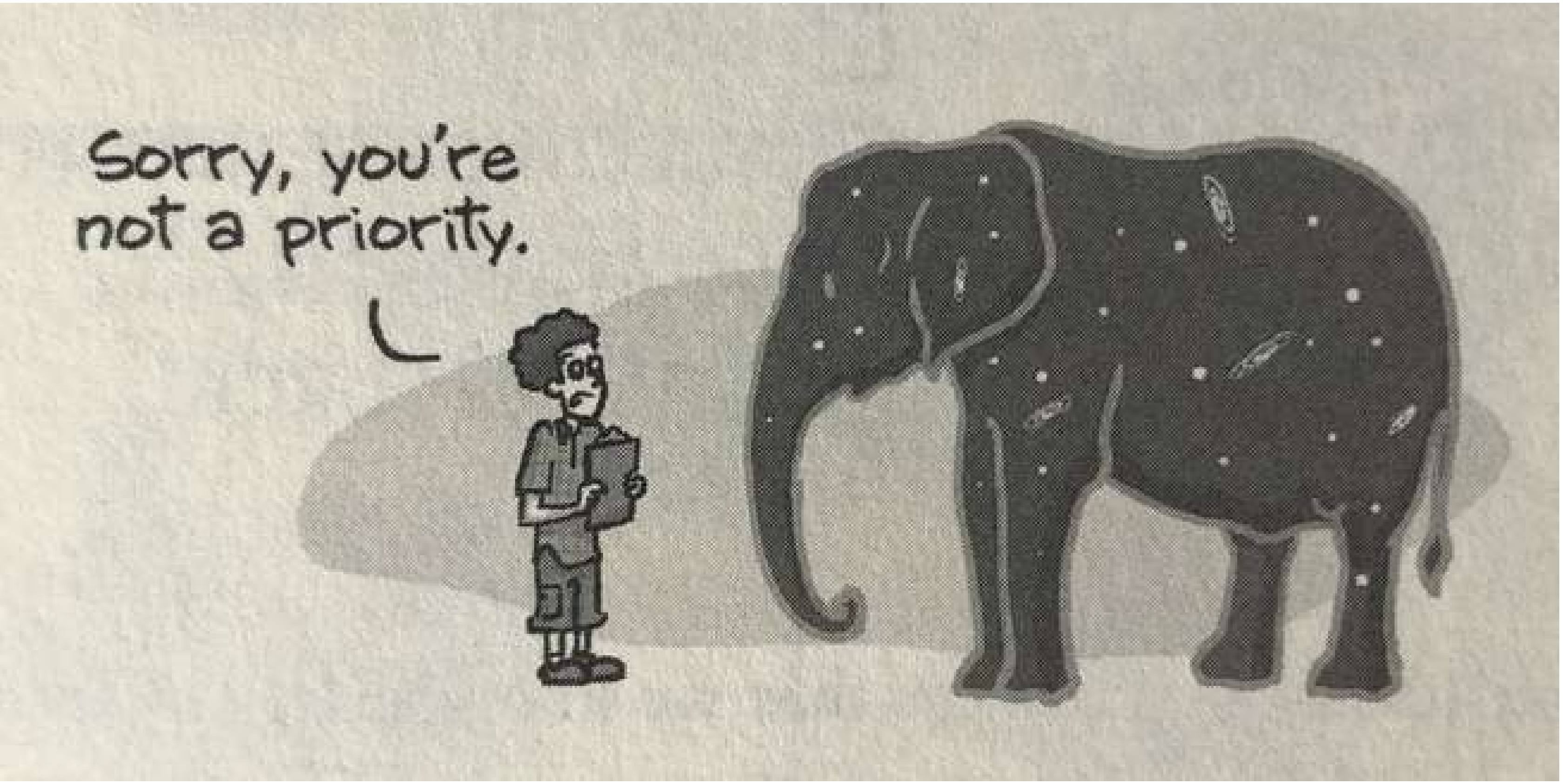
- There is no connecting beam line between the 2 facilities
- Requirements:
  → a transportable ion trap with sufficient storage capabilities
  → XHV vacuum conditions for the storage of antiprotons ($20\, cm^{-3}$)
  → a detection system for monitoring annihilation rates during the transport

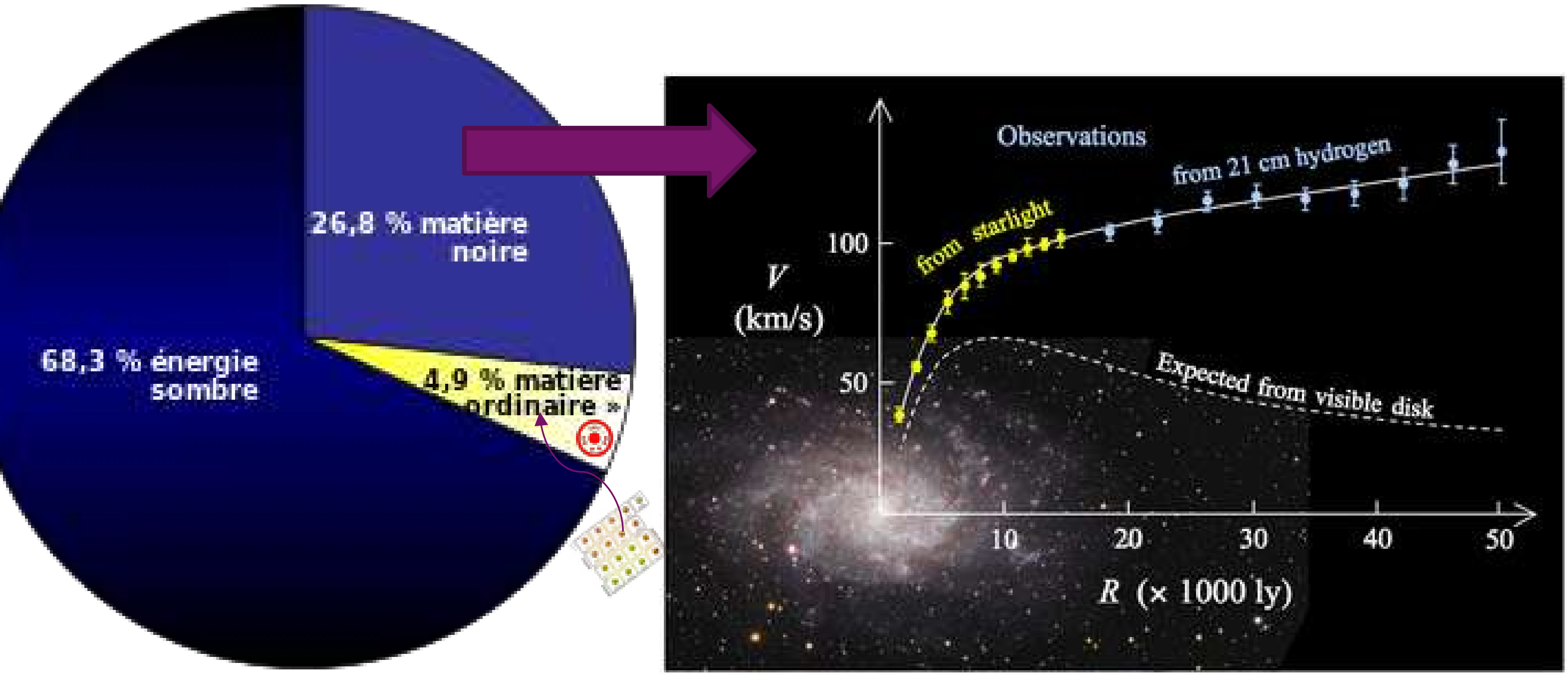
Good news:

- Long antiproton trapping time already achieved.
  Ex. BASE: > 50 years
- Transportation of antiprotons is also a core component of BASE-STEP (PI: C. Smorra, Mainz)

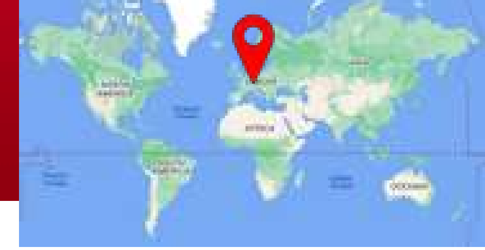
Clara Klink | CERN | TU Darmstadt – Institute for Nuclear Physics
FuPhy 2024 | 08. - 10. Apr 2024, SMI, Wien

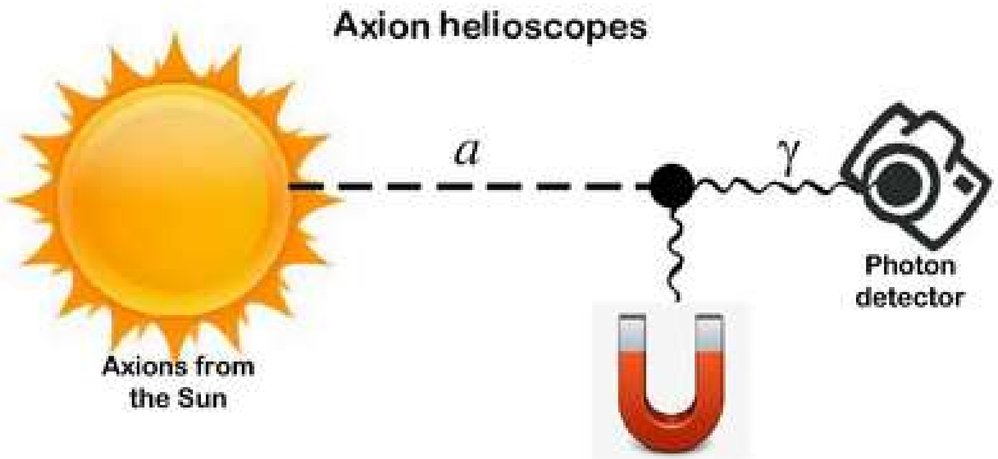
MATIERE SOMBRE




26,8 % matière noire
68,3 % énergie sombre
4,9 % matière « ordinaire »
Observations
from 21 cm hydrogen
from starlight
100
50
V
(km/s)
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)

AXIONS





© *Igor G . Irastorza*

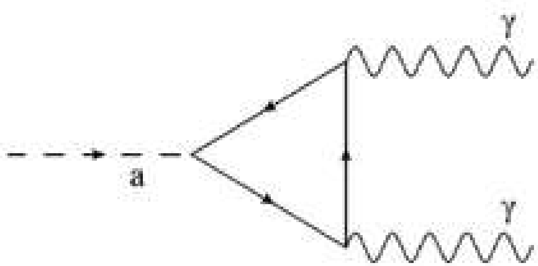
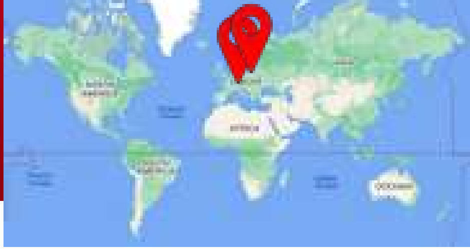
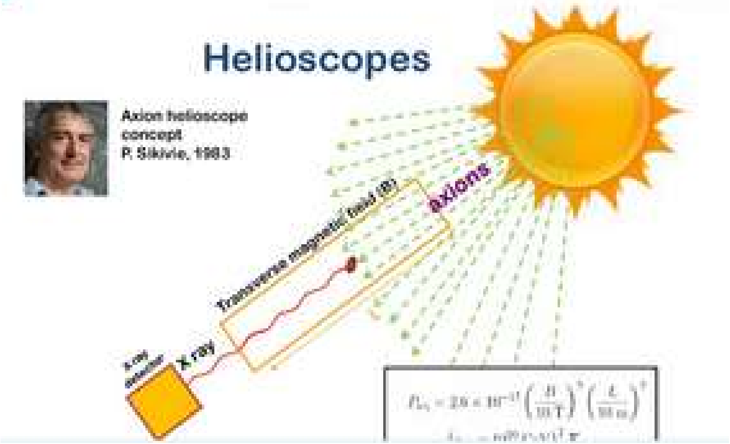
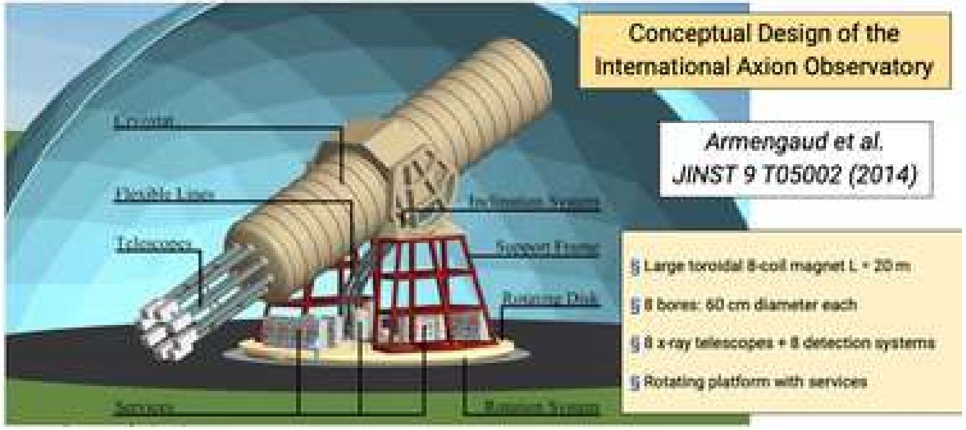


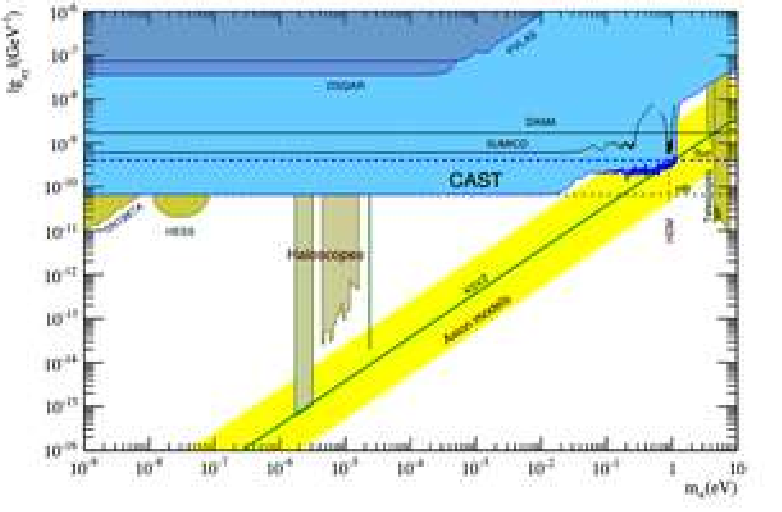
Figure 2: Feynman diagram, associated with the coupling between an axion and two photons.

CAST - IAXO

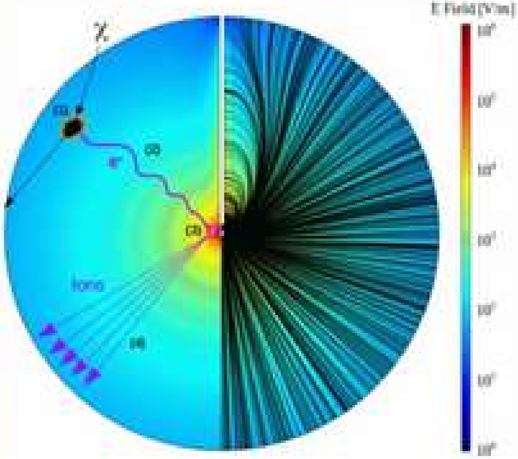


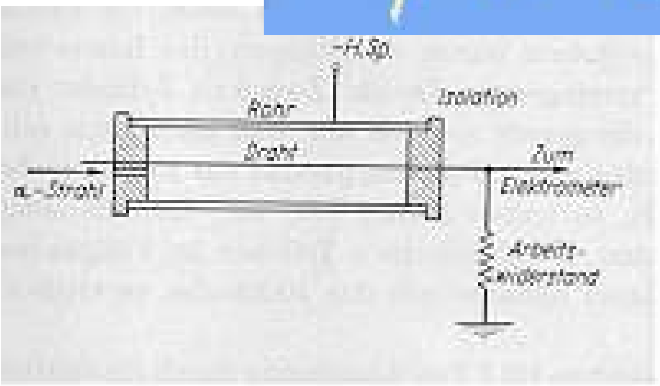

Helioscopes
Axion helioscope concept
P. Sikivie, 1983
axions
Transverse magnetic field (B)
X ray
X-ray detector


Conceptual Design of the International Axion Observatory
Armengaud et al.
JINST 9 T05002 (2014)
Large toroidal 8-coil magnet L = 20 m
8 bores: 60 cm diameter each
8 x-ray telescopes + 8 detection systems
Rotating platform with services

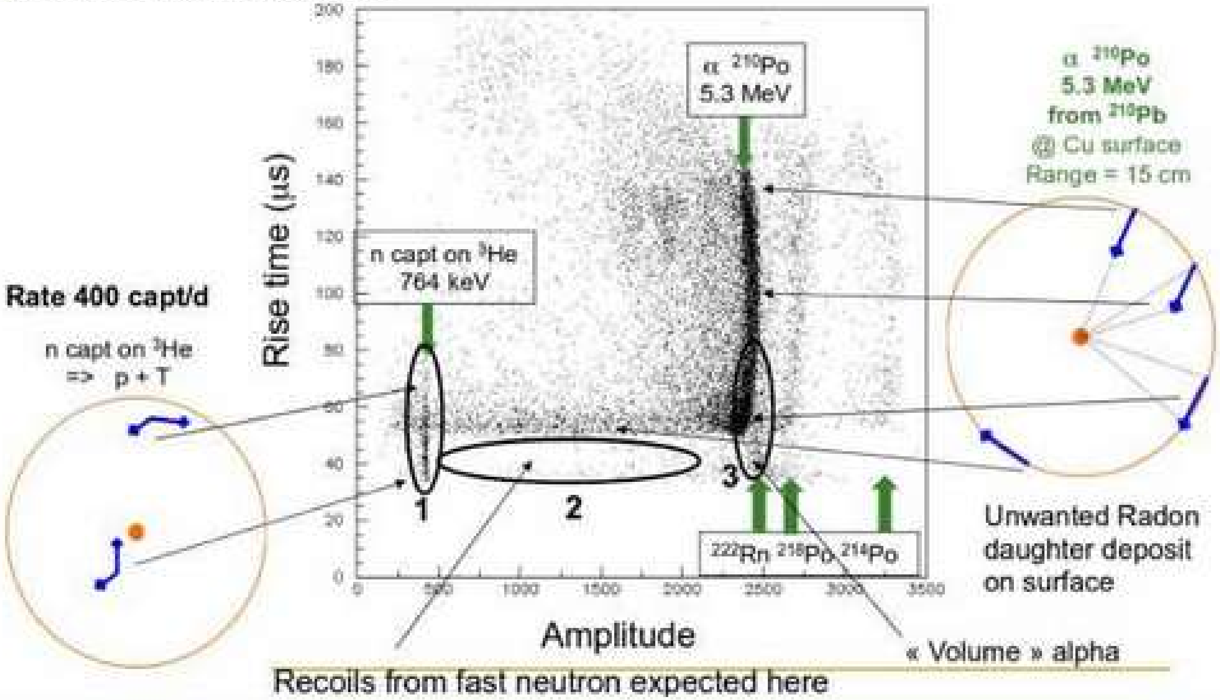

CAST
Helioscopes
Axion models
HESS
m_a (eV)

NEWS

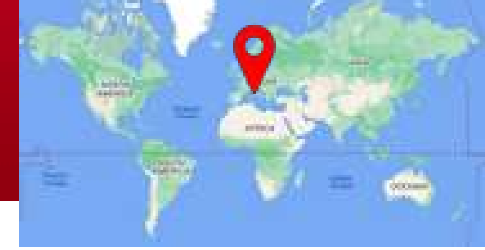




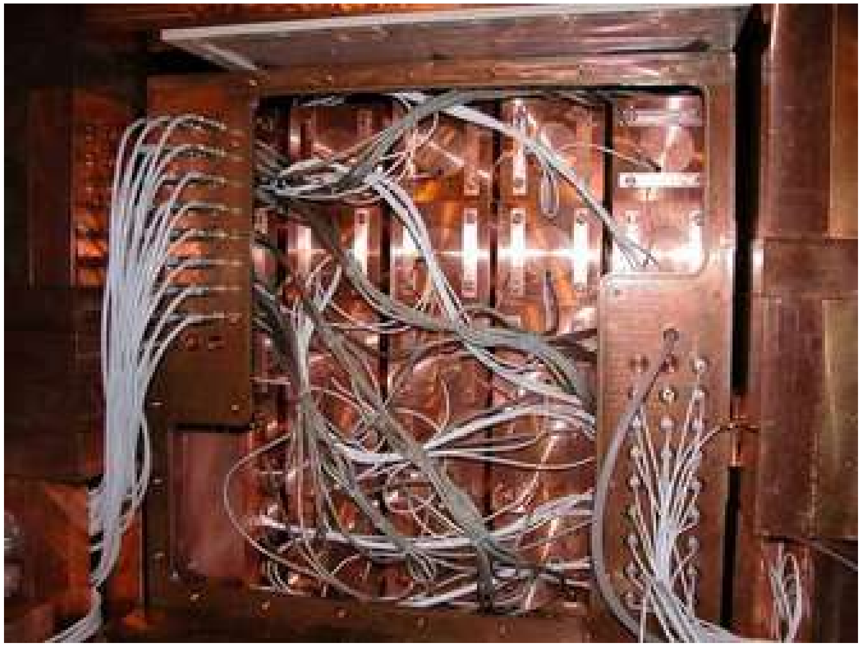
Recul noyau dû aux WIMPs avec threshold la plus basse possible



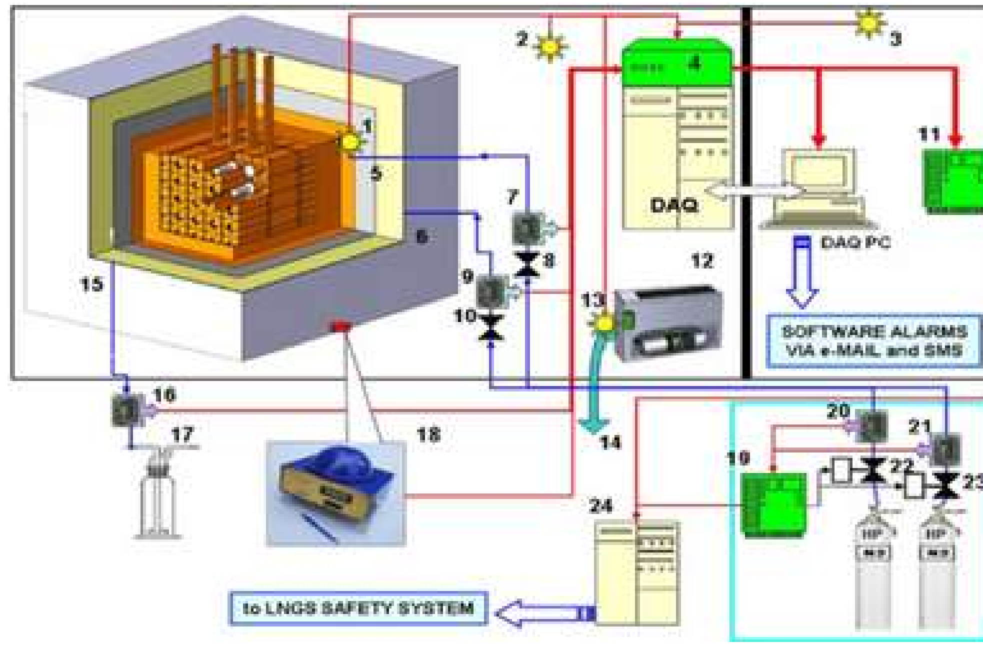
DAMA / LIBRA



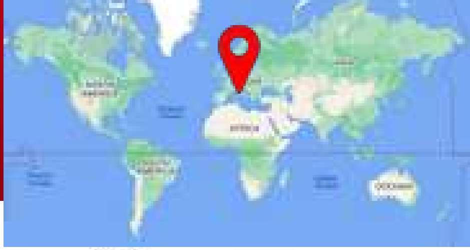
LABORATORI NAZIONALI DEL GRAN SASSO



Thallium-doped sodium detector



DAMA / LIBRA



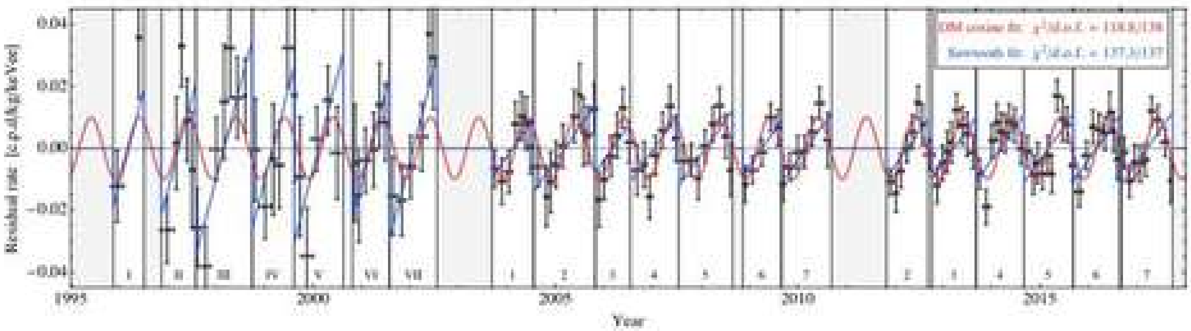
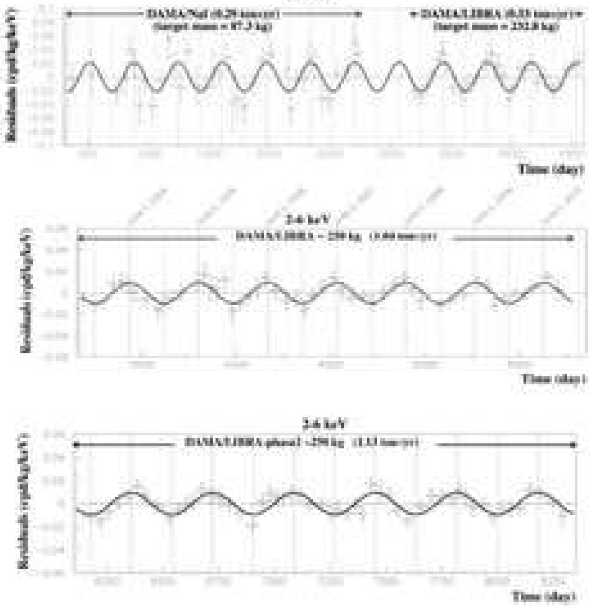
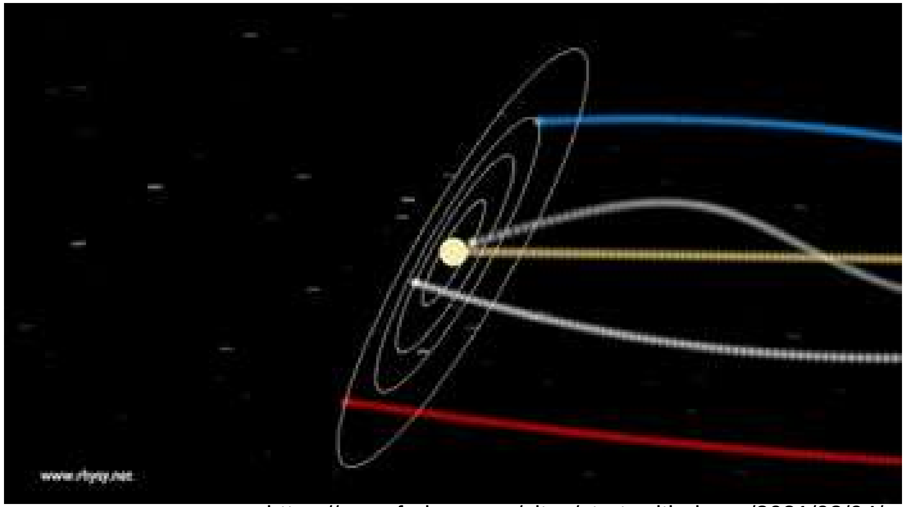


Figure 5. *The black data points are the DAMA residuals in the* (2–6) keVee *energy window, taken from [1, 5]. The curves are fits to a cosine annual modulation peaked on June, 2nd (red curve), as expected for a DM signal, and to the irregular sawtooth obtained from a continuously growing background (blue curve). The roughly annual data-taking cycles of* DAMA/NaI, DAMA/LIBRA *Phase 1, and* DAMA/LIBRA *Phase 2 are shown as vertical lines.*



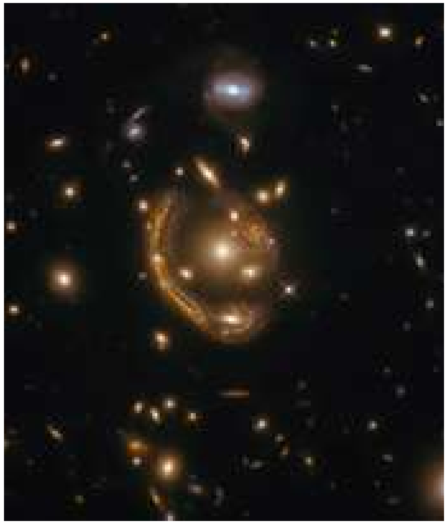


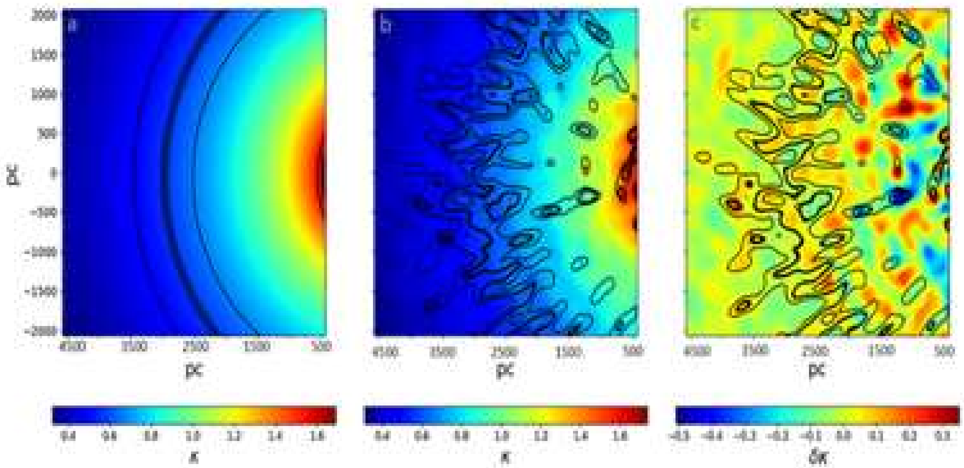
https://www.forbes.com/sites/startswithabang/2021/03/04/goodbye-damalibra-worlds-most-controversial-dark-matter-experiment-fails-replication-test/

But Replication failed
ANAIS (Spain)
COSINE (Germany)

WIMPS

Anomalies in Gravitational-Lensed Images Revealing Einstein Rings Modulated by Wavelike Dark Matter



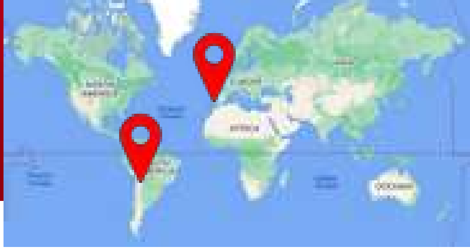


HS 0810+2554 was discovered in 2002 by the Hubble Space Telescope

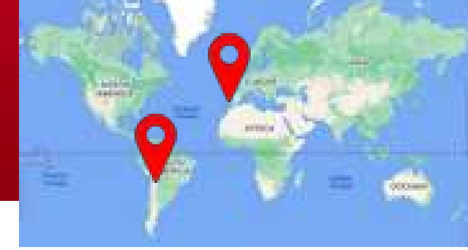
=> The growing success of ψDM in reproducing astrophysical observations tilt the balance toward new physics invoking axions.

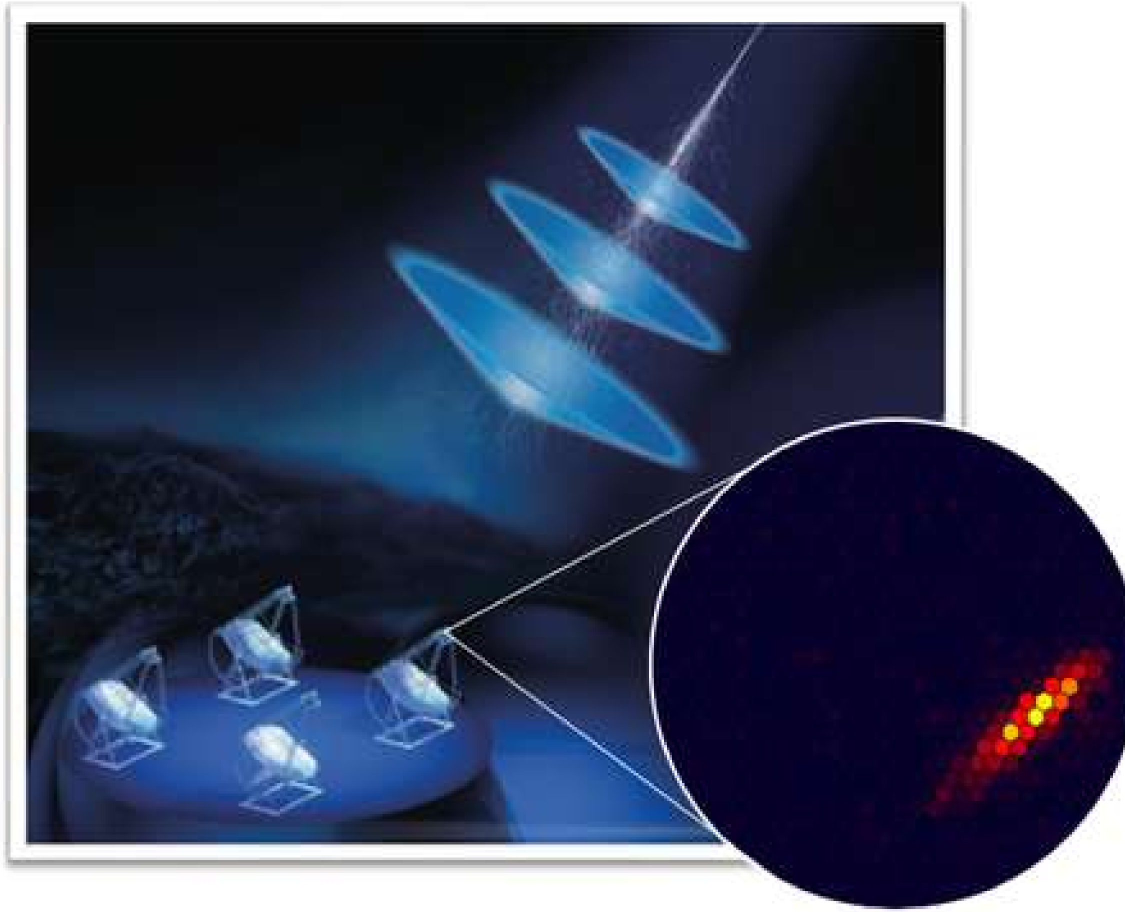
ASTRO-PHYSIQUE

CTA

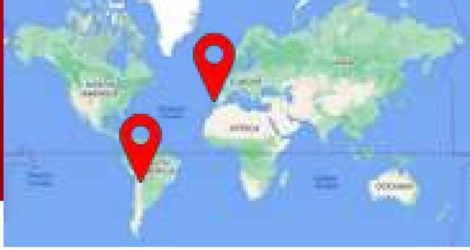


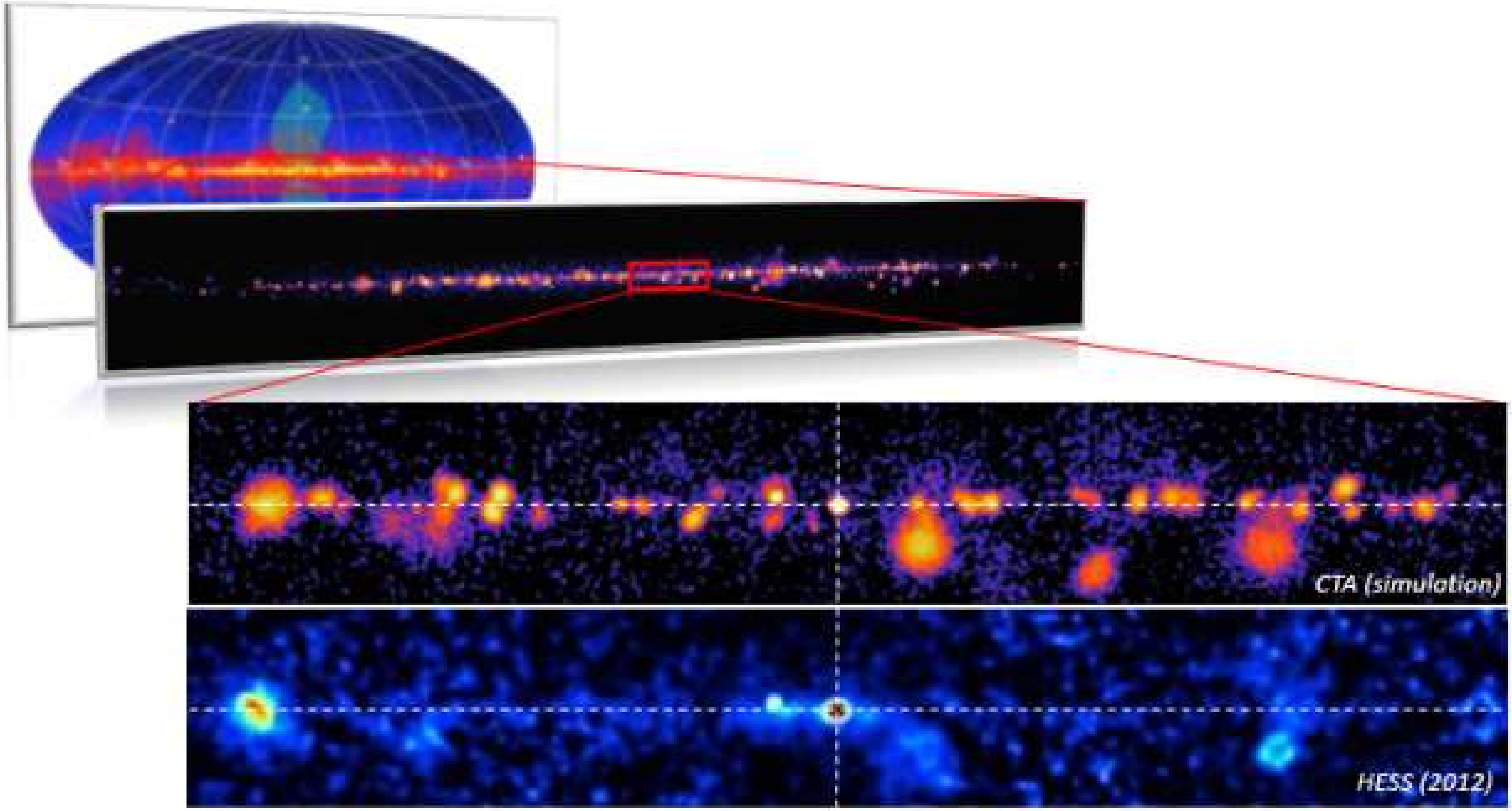
CTA



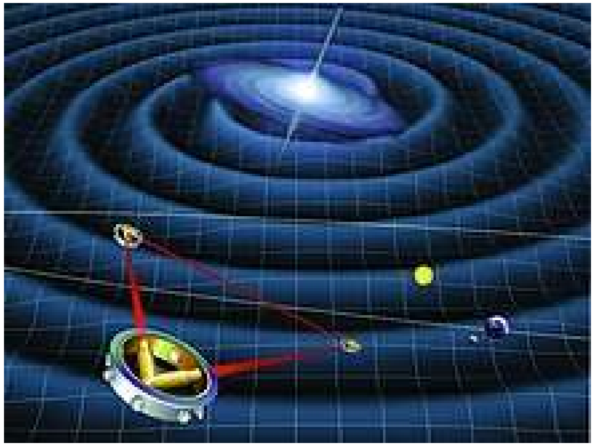


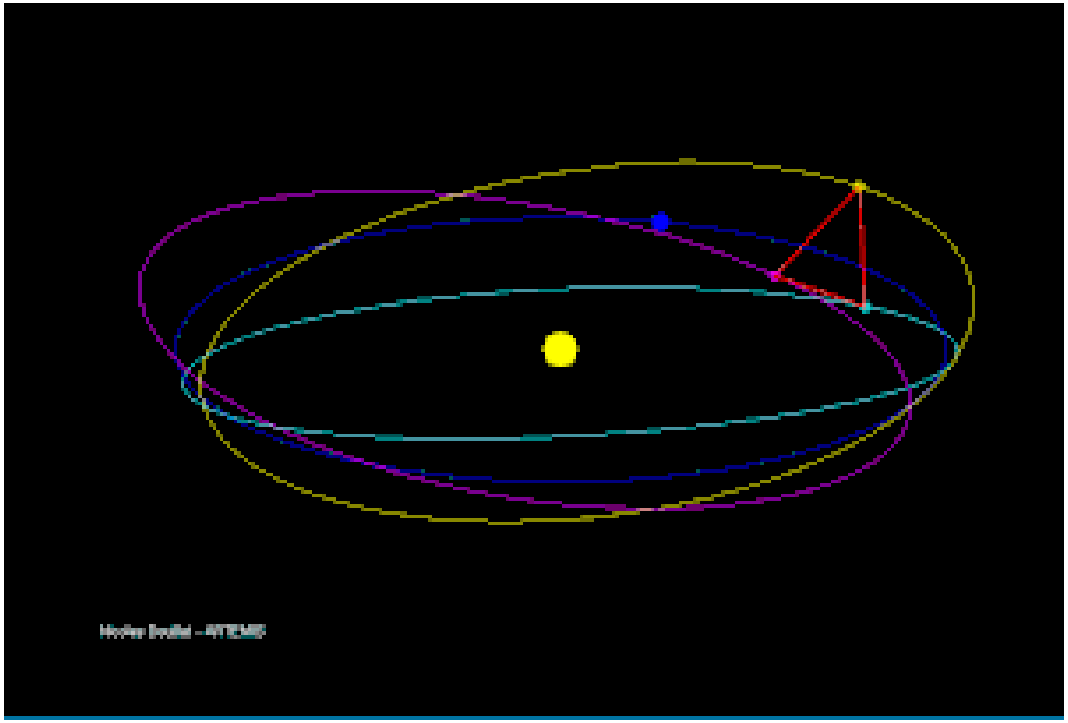
CTA





LISA





LISAMAX

LISAmax: Improving the Gravitational-Wave Sensitivity by Two Orders of Magnitude

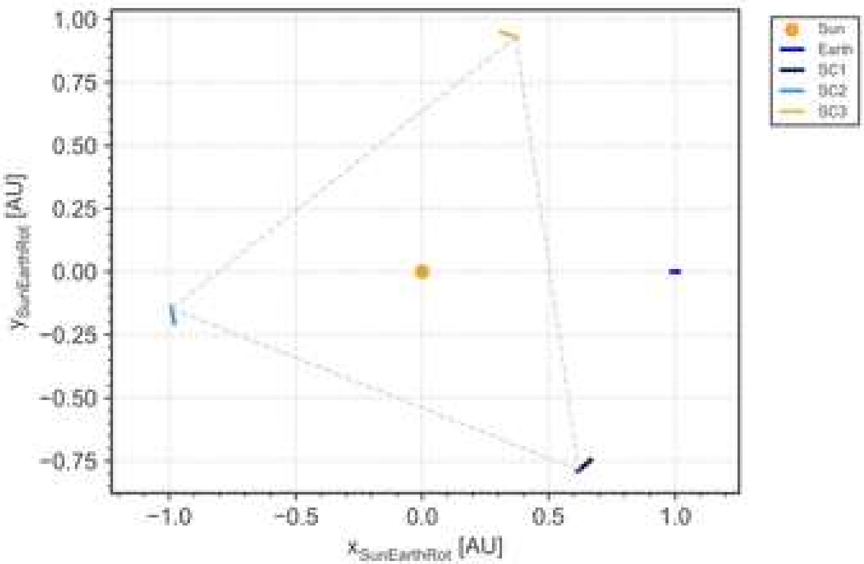
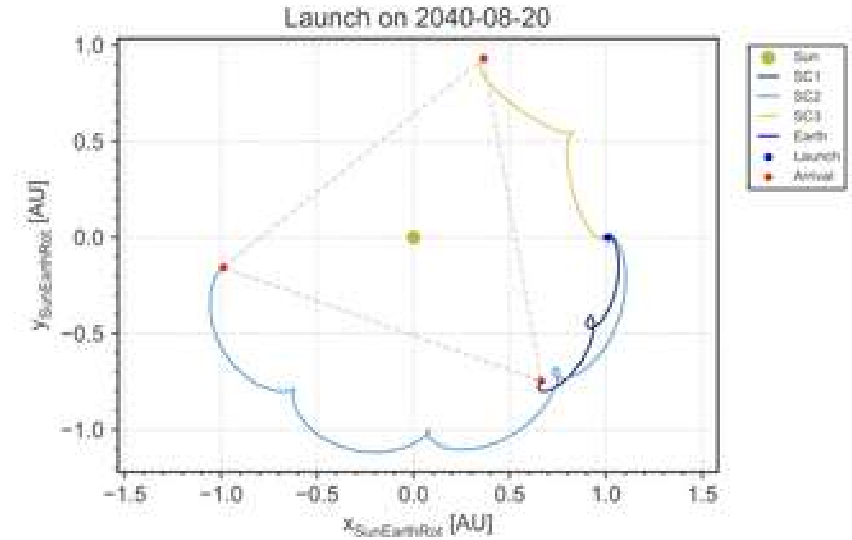
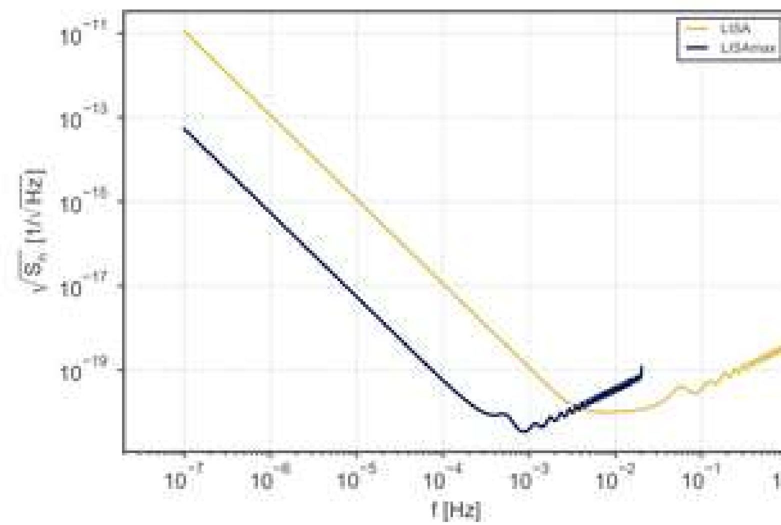
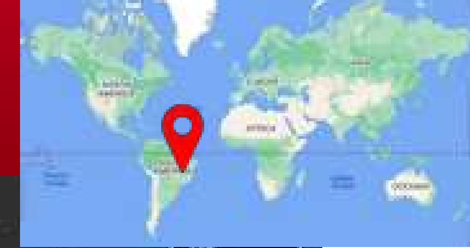


Figure 1: The optimized science orbit of LISAmax over a 10-year duration in the Sun-Earth rotating frame.

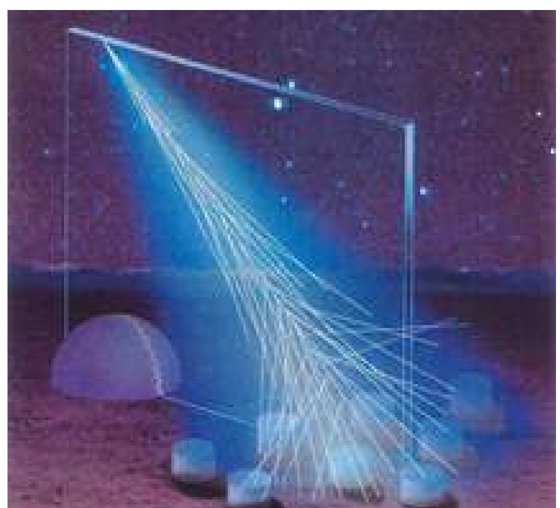




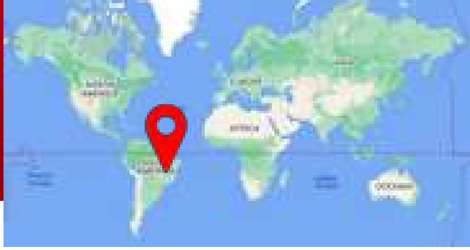
LISAmax: Improving the Gravitational-Wave Sensitivity by Two Orders of Magnitude

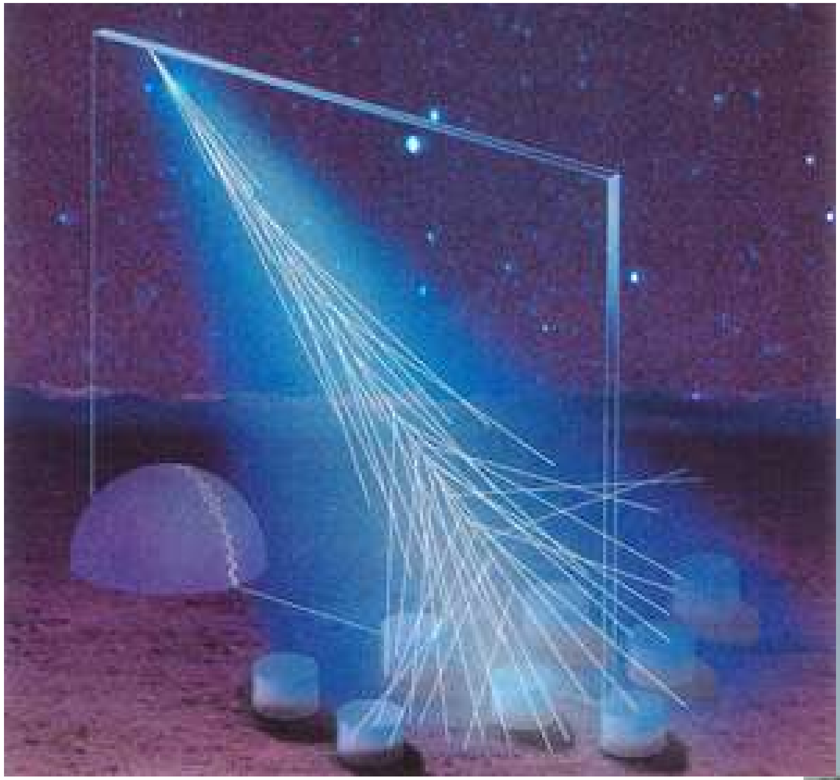


Pierre Auger Cosmic Ray Observatory



Pierre Auger Cosmic Ray Observatory

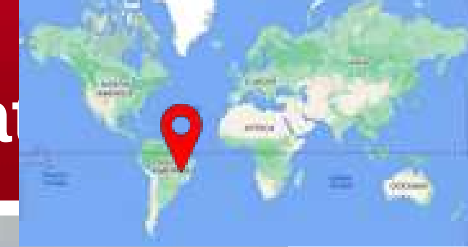


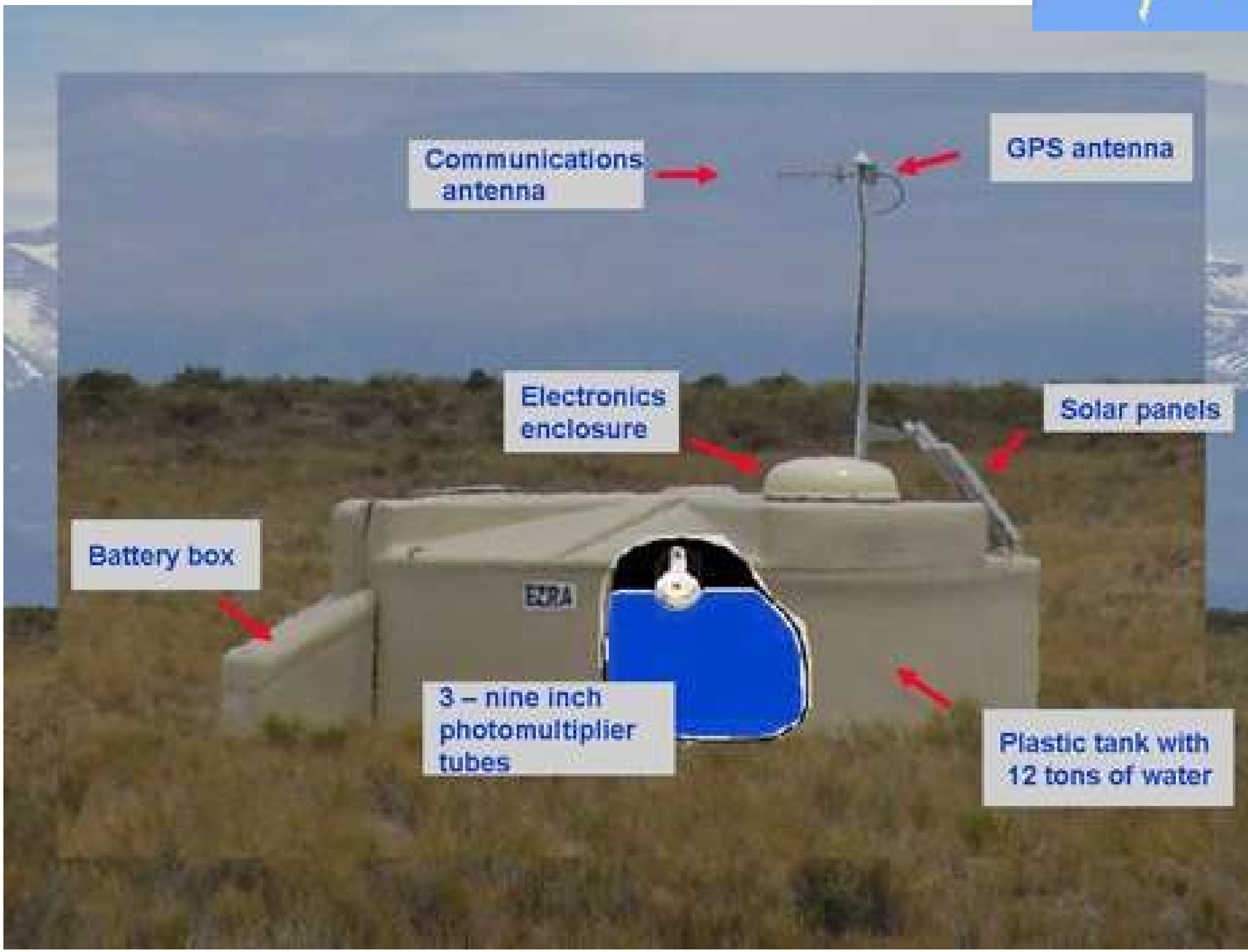


Use earth's atmosphere as a calorimeter. 1600 water Cherenkov detectors with 1.5km distance.

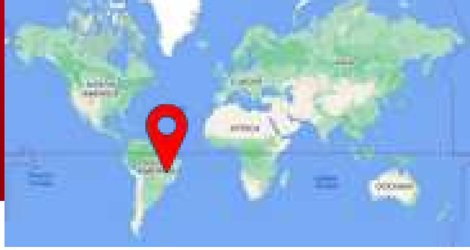
Placed in the Pampa Amarilla in western Argentina.

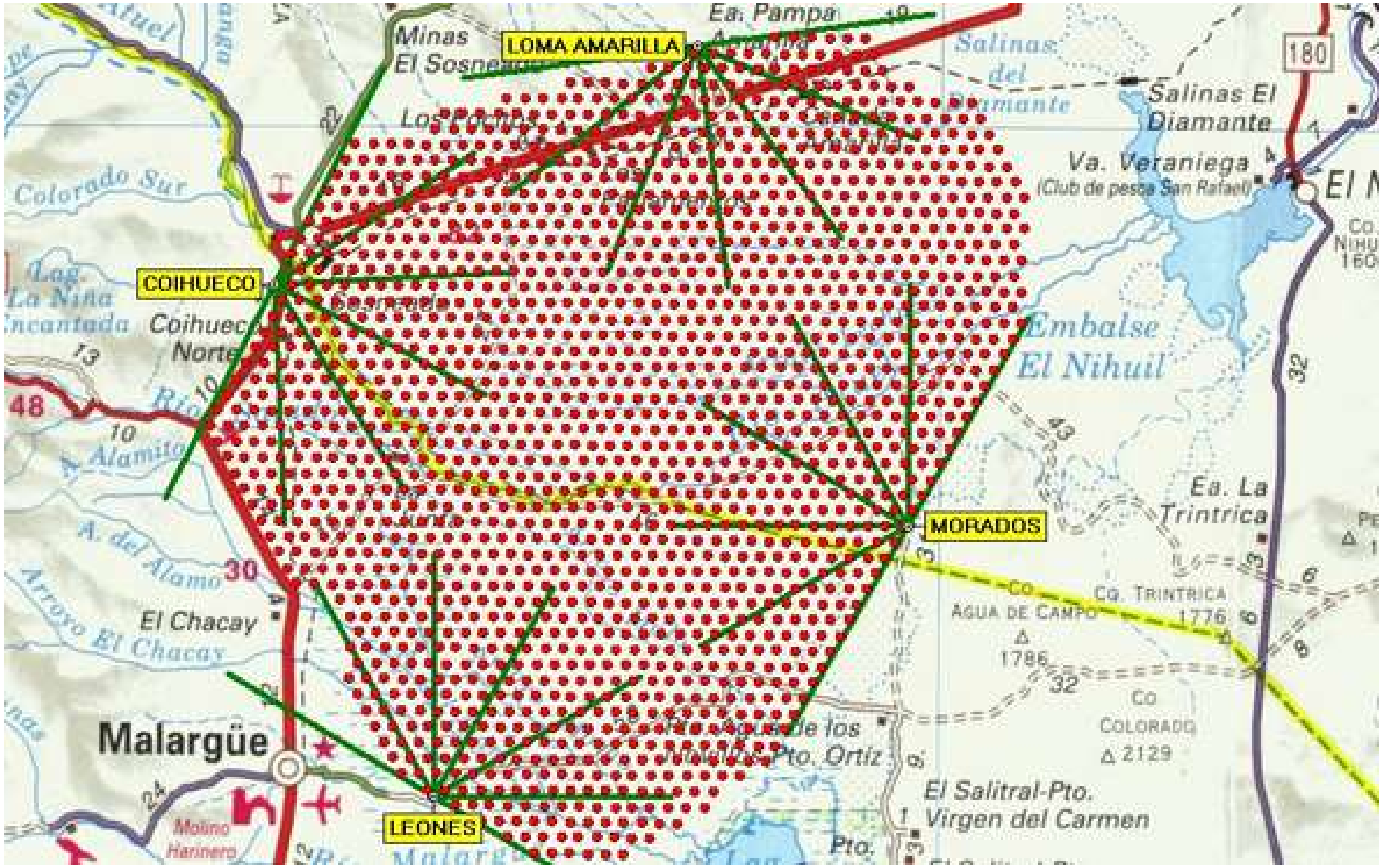
Pierre Auger Cosmic Ray Observat





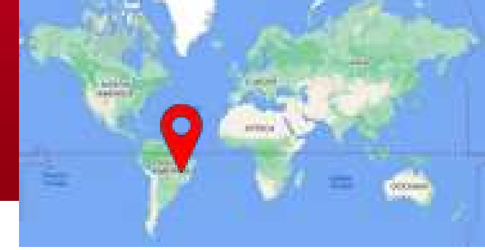
Pierre Auger Cosmic Ray Observatory

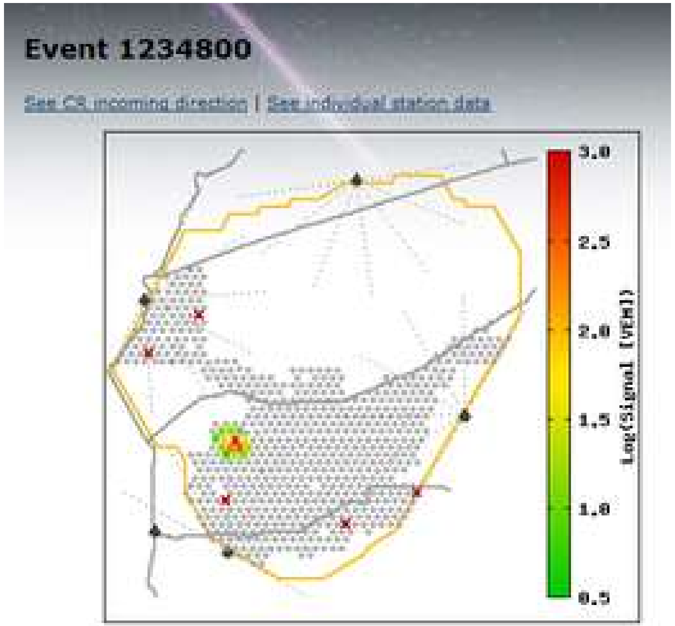


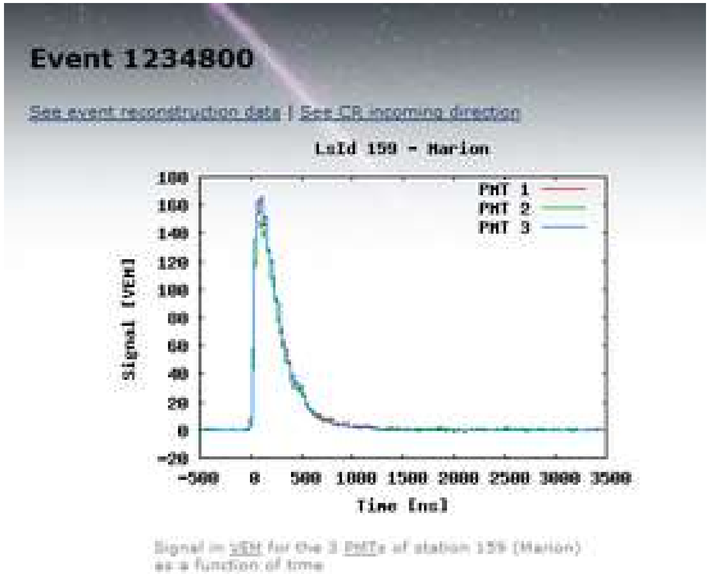


CEA/IRFU/DEDIP --- maxence.vandenbroucke@cea.fr

Pierre Auger Cosmic Ray Observatory

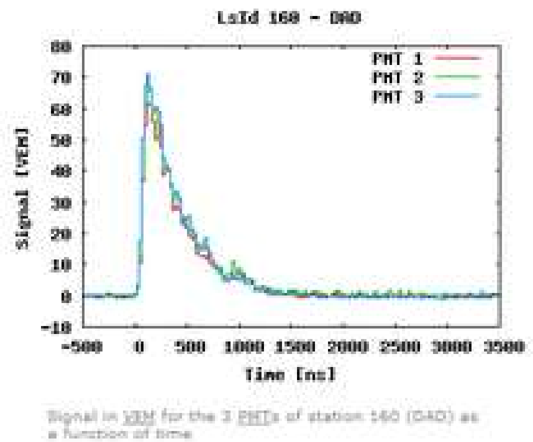




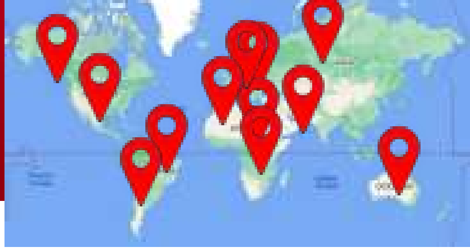


37 EeV = Exa Electron Volt = 37 x 10^{18} eV

Generic Information	
Id	1234800
Date	Sat Mar 5 15:54:48 2005
Nb Station	14
Energy	37.4 ± 1.2 EeV
Theta	43.4 ± 0.1 deg
Phi	-27.3 ± 0.2 deg
Curvature	15.8 ± 0.8 km
Core Easting	460206 ± 20 m
Core Northing	6089924 ± 11 m
Reduced Chi^2	2.30



CRAYFIS



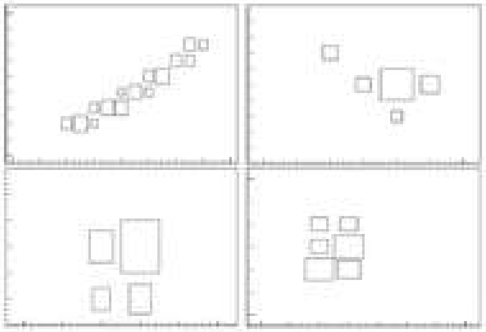
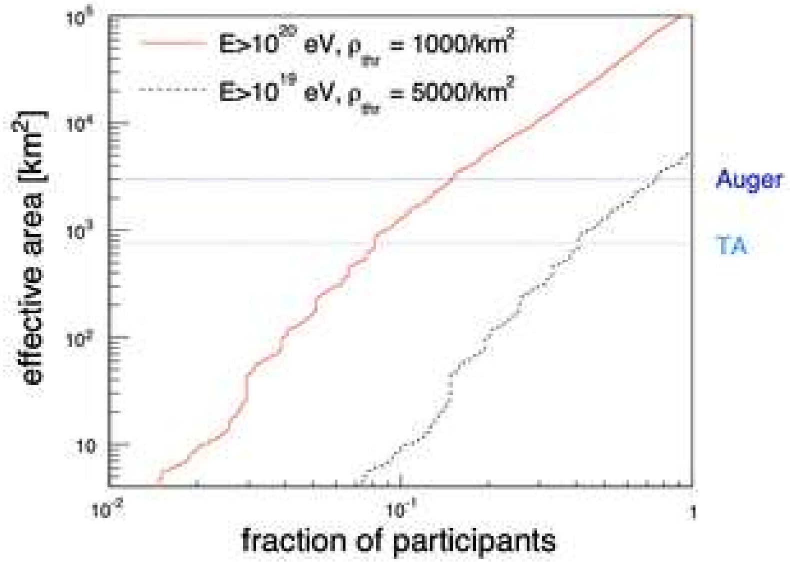


FIG. 4: Activated pixels above threshold in a Samsung Galaxy SIII phone, during exposure to ^{60}Co. Box size is proportional to pixel response values



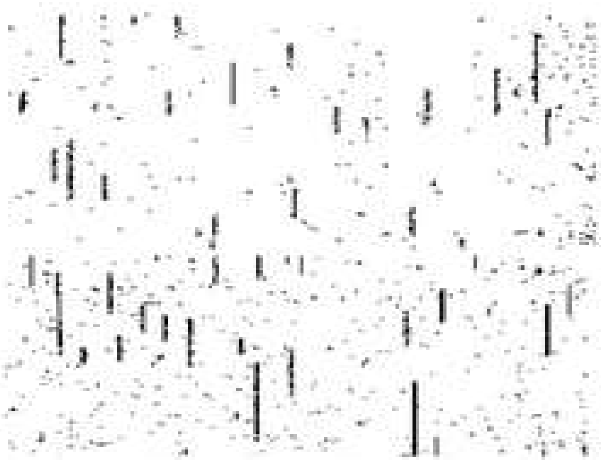


FIG. 5: Composite image of activated pixels in data collected from phones exposed to a muon beam. The phones were arranged such that the muon beam was incident on the side of the sensor, giving visible tracks where muons pass through several pixels.

AMS

Alpha **M**agnetic **S**pectrometer

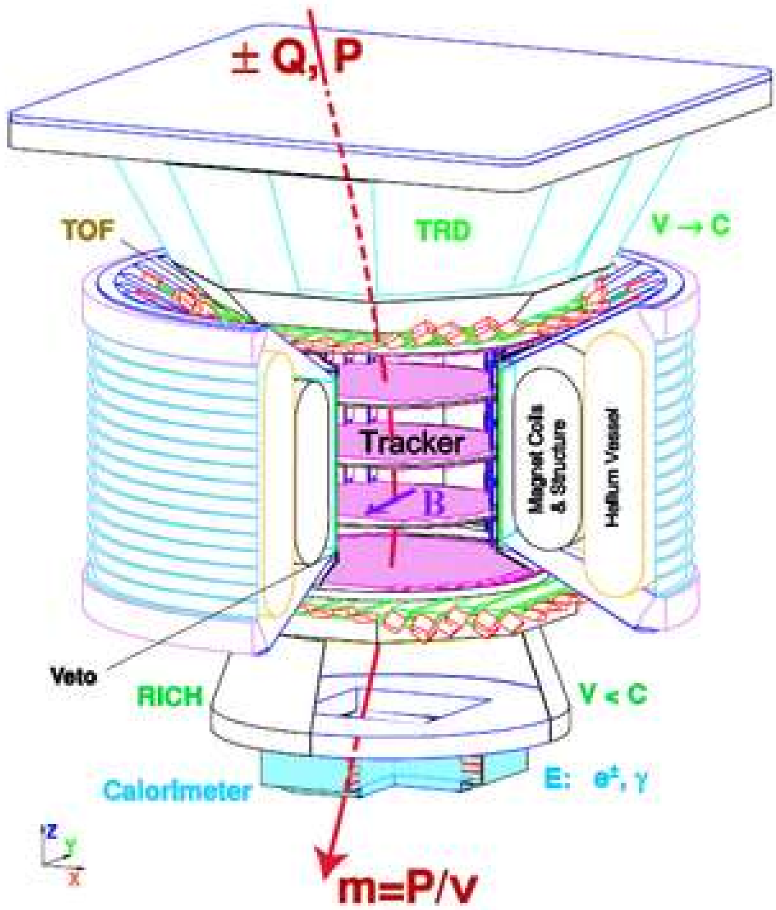
Try to find Antimatter in the primary cosmic rays.
Study cosmic ray composition etc. etc.

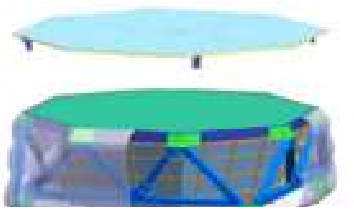
AMS

Will be installed on the space station.

Plot plus moderne

AMS


± Q, P
TOF
TRD
V → C
Tracker
B
Magnet Coils & Structure
Helium Vessel
Veto
RICH
V < C
Calorimeter
E: e±, γ
z
y
x
m=P/v



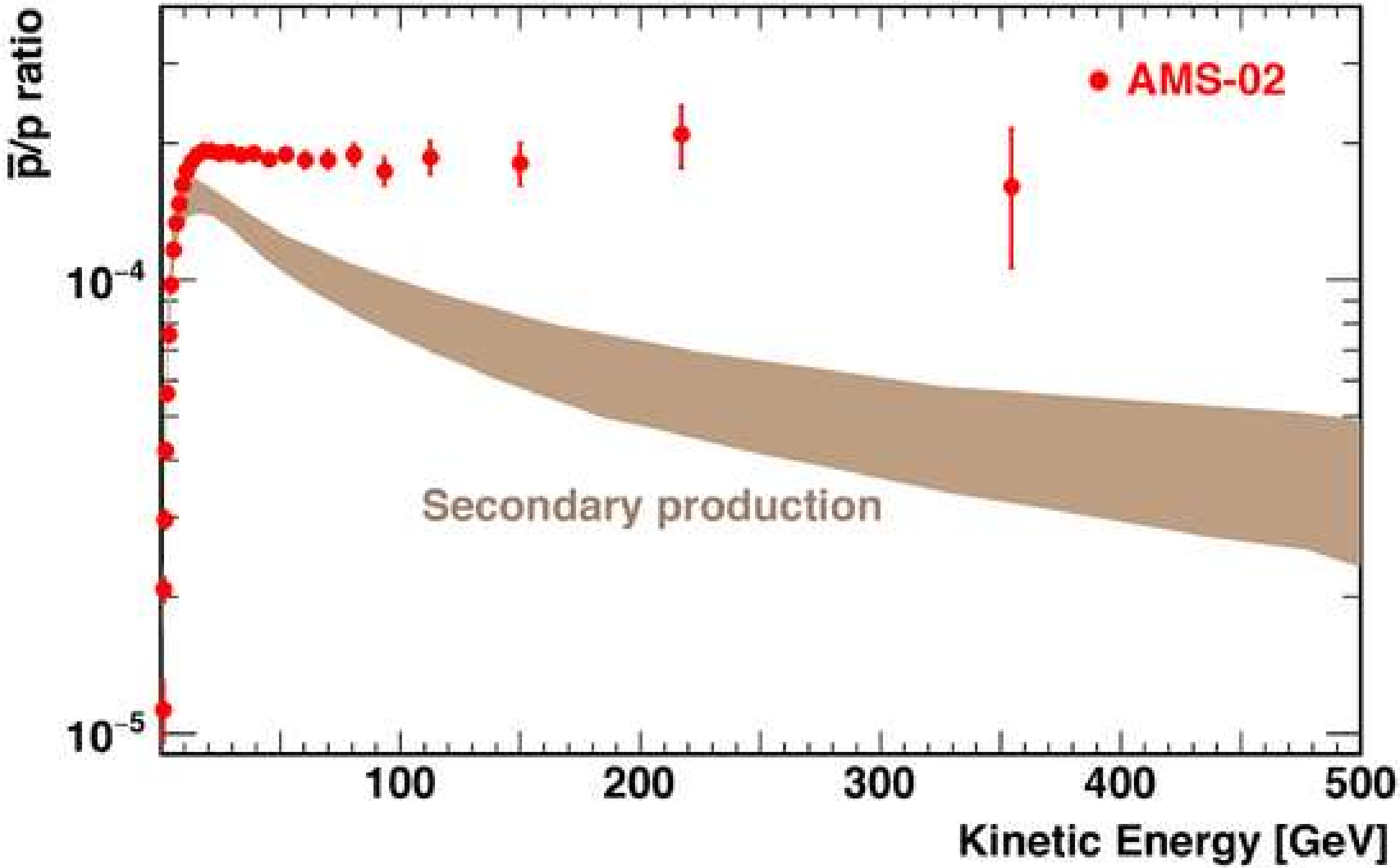


Figure 1. Antiproton to proton ratio measured by AMS. As seen, the measured ratio cannot be explained by existing models of secondary production.

Vendredi 5/07 11h (IJCLAB)
Lundi 8/07 12h (CEA IRFU)
Visite Labo 14h (CEA IRFU)
Mercredi 10/07 11h (IAS)

DE LA RECHERCHE À L'INDUSTRIE

cea

STAGE / QUESTIONS
maxence.vandenbroucke@cea.fr
maxence@cern.ch

Mesurer l'infiniment petit et observer l'infiniment grand

Cours 1 : Généralités

-Introduction générale sur l'importance de la mesure
-Qu'est-ce qu'une expérience de physique subatomique ?
-Que veut-on observer à propos d'une particule?
-Architecture générale d'une expérience en physique subatomique

Cours 2 : Les détecteurs de particules

- Trajectographie :
- **-Détecteurs Gazeux**
- **-Détecteurs au Silicium**

- Calorimétrie
- Scintillation

Cours 3 : Exemple d'expériences

- **Autour du Neutrino**
- **Nucléaire et Hadronique**
- **Rayons Cosmiques**
- **Antimatière**

Maxence Vandenbroucke
07/2024

université PARIS-SACLAY

PLAN DES COURS

Cours 1 : Généralités

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- Nucléaire et Hadronique
- Rayons Cosmiques
- Antimatière

SOURCES

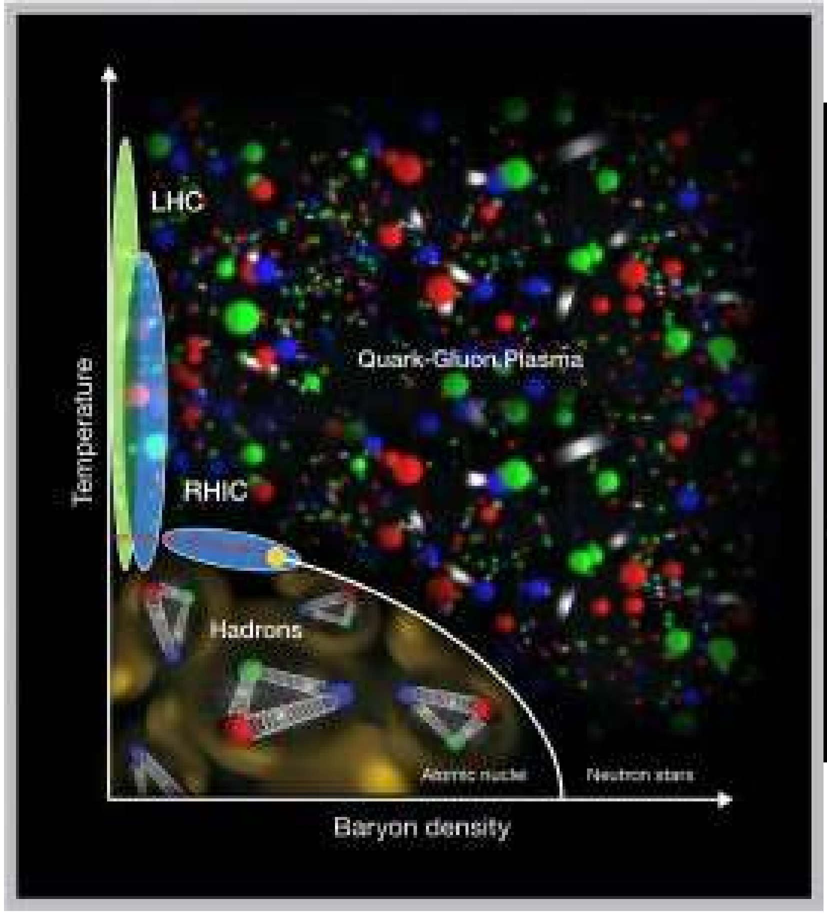
Basé sur les cours de Stefano Panebianco (CEA/IRFU) rencontre d'ete 2016

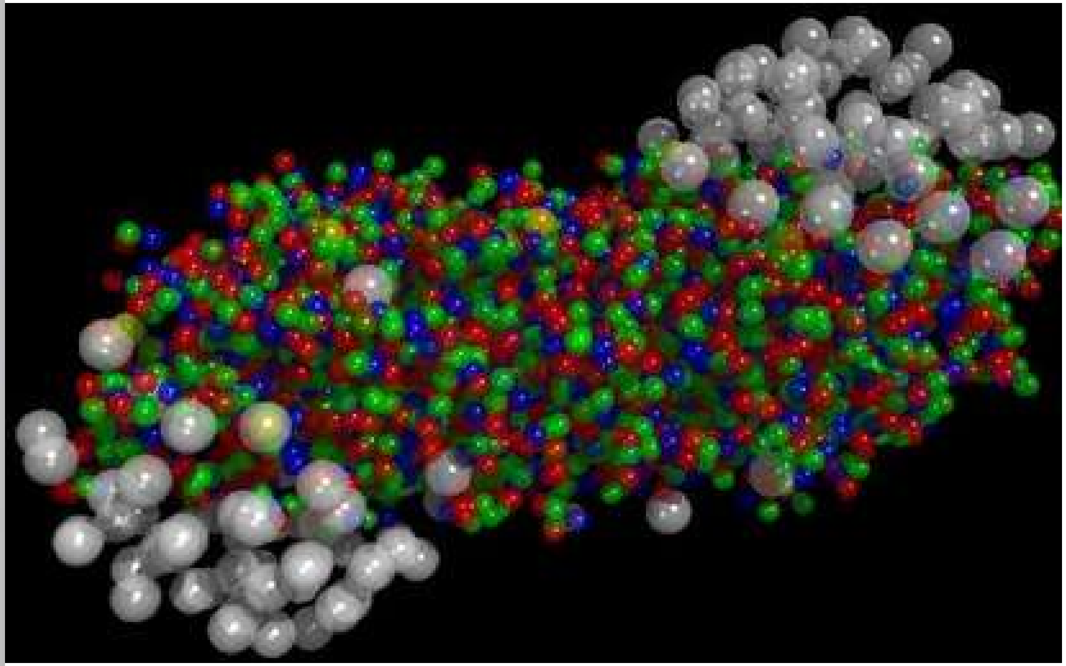
Le cours de Werner Riegler (CERN Summer Student Lecture Program 2009)

Particle Detectors , Second Edition, C. Grupen & B. Shwartz

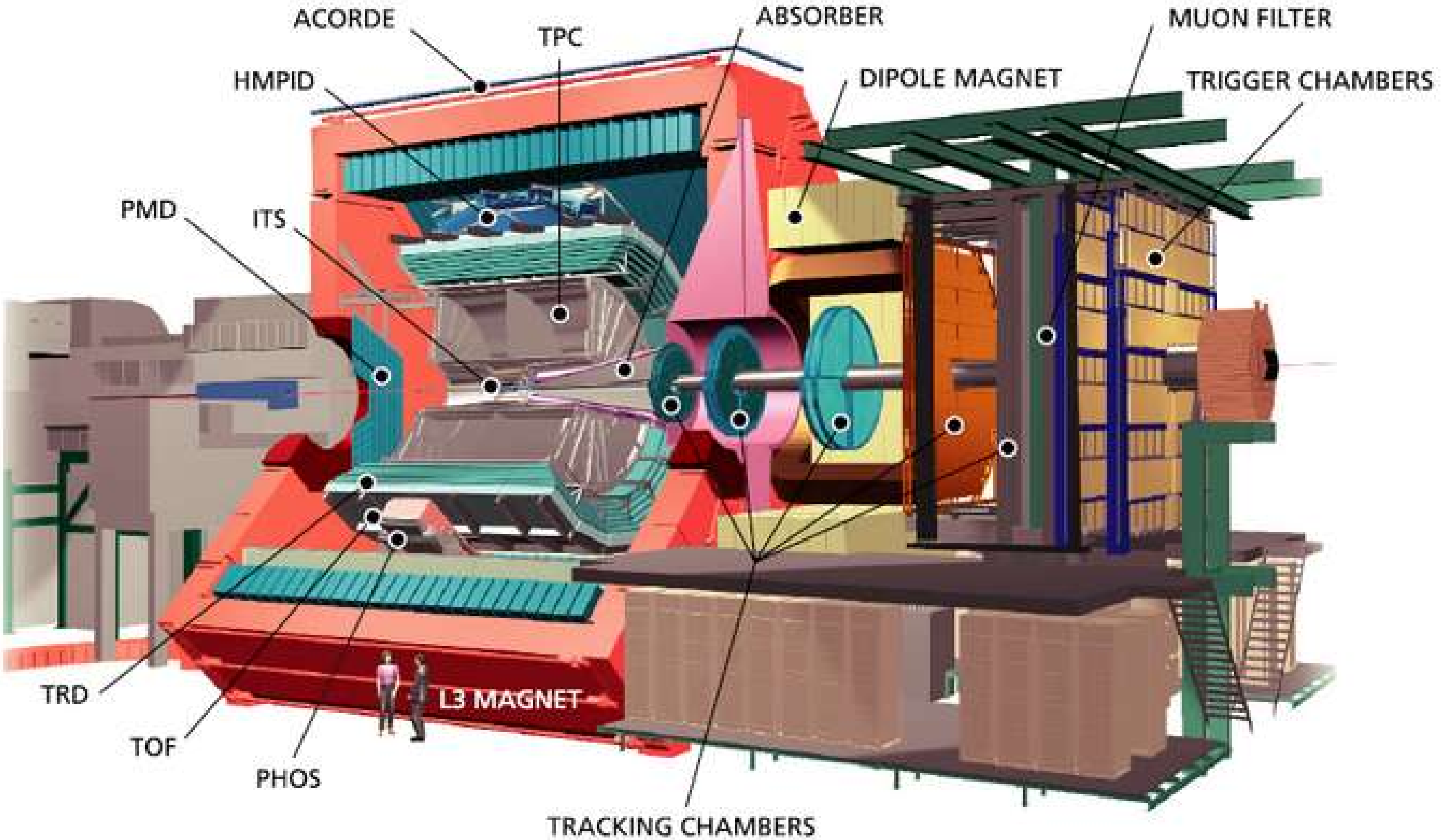
SPARES

ALICE
A heavy Ion Experiment at the LHC



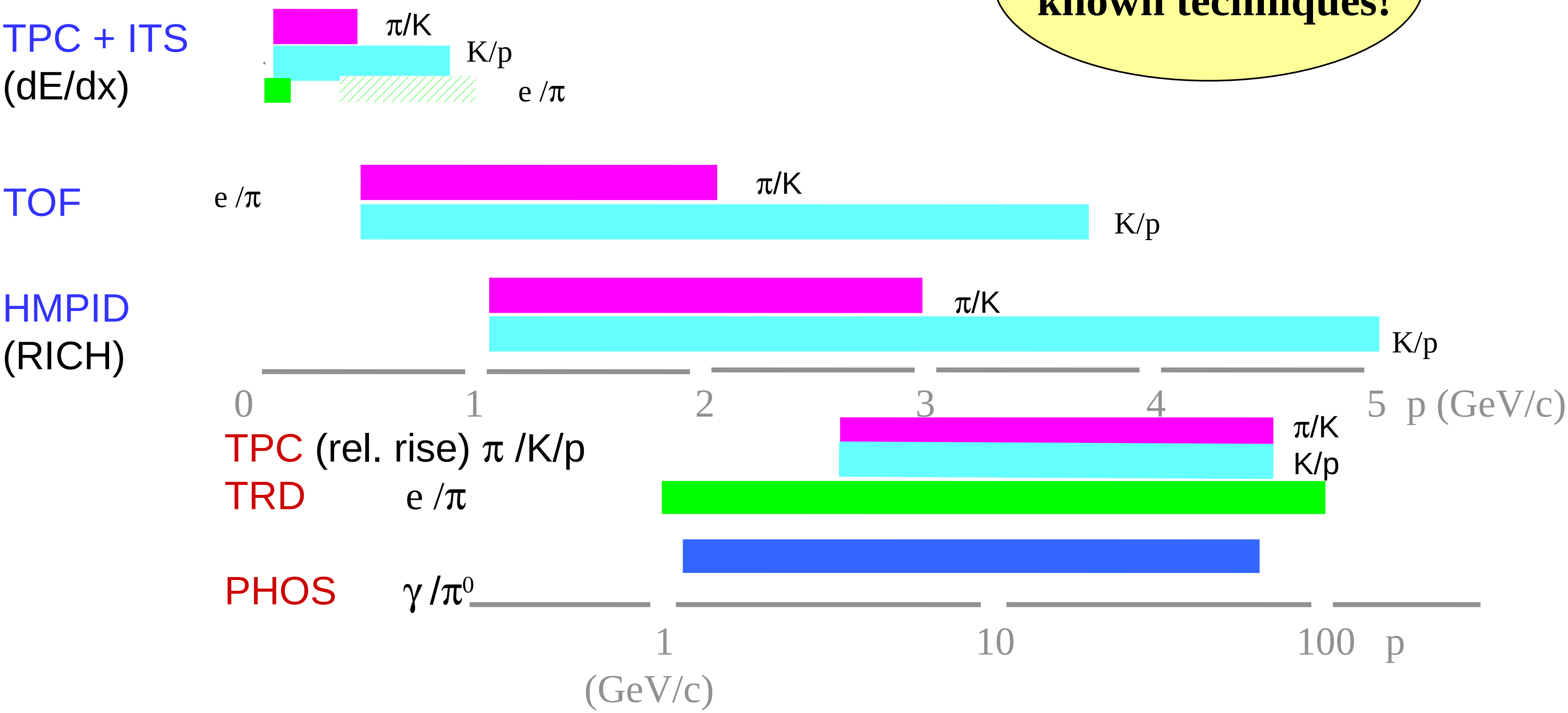


ALICE

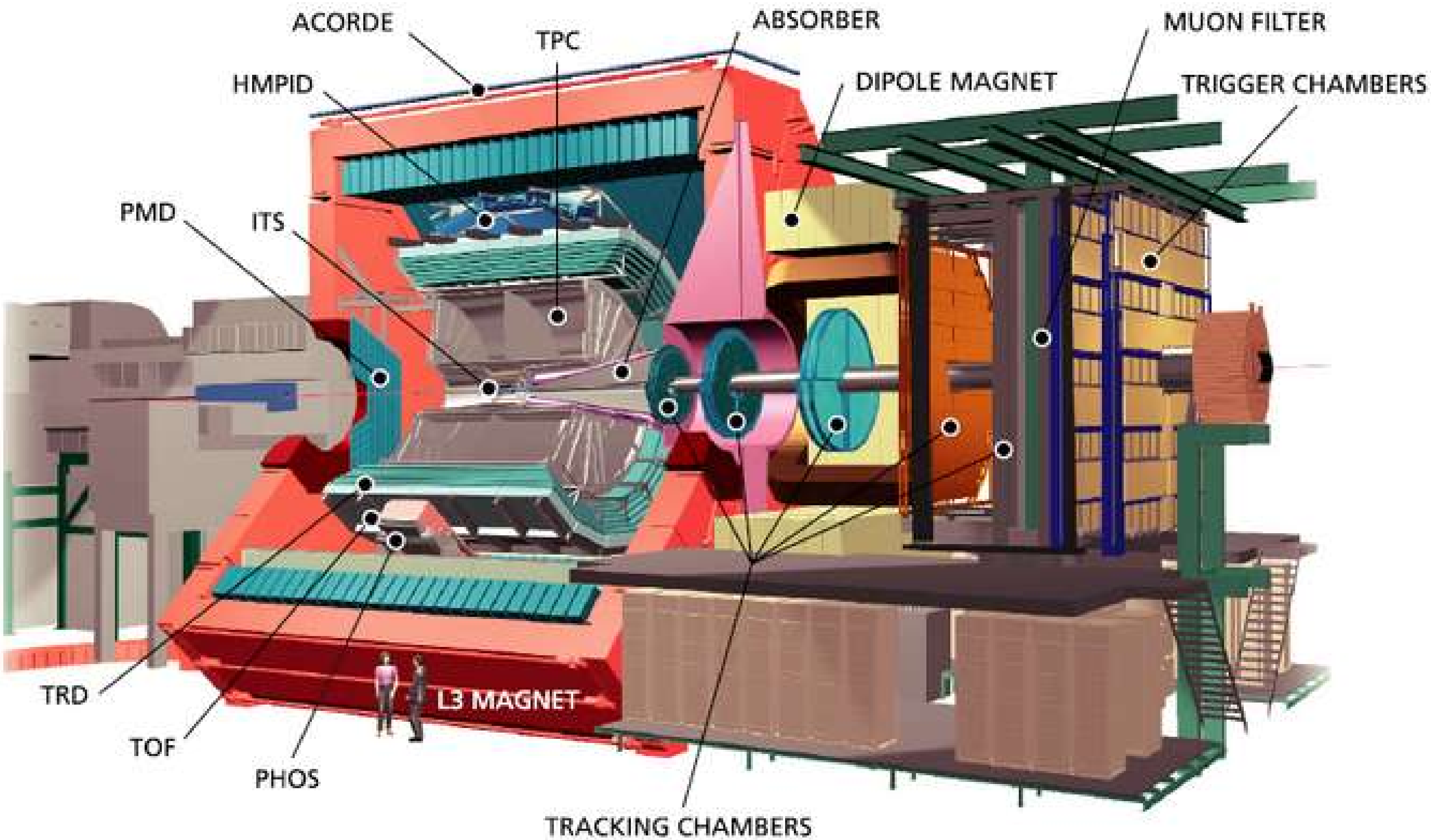

ACORDE
TPC
ABSORBER
MUON FILTER
HMPID
DIPOLE MAGNET
TRIGGER CHAMBERS
PMD
ITS
TRD
TOF
PHOS
L3 MAGNET
TRACKING CHAMBERS

ALICE Particle ID

Alice uses ~ all known techniques!



ALICE


ACORDE
TPC
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MUON FILTER
HMPID
DIPOLE MAGNET
TRIGGER CHAMBERS
PMD
ITS
TRD
L3 MAGNET
TOF
PHOS
TRACKING CHAMBERS

COMPASS at CERN

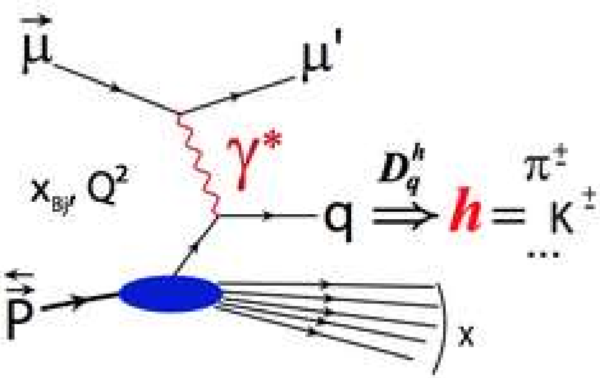
Différentes contributions

$$\frac{1}{2} = \underbrace{\frac{1}{2}(\Delta u + \Delta d + \Delta s)} + \underbrace{\Delta G} + \underbrace{L_g + L_q}$$

Spin des quarks
$\Delta\Sigma \sim 0.3$

Spin des gluons
$|\Delta G| < 0.5$

Moments orbitaux
$L_{q+g} = ??$



Section efficace DIS

$$\frac{d^2\sigma}{dx dQ^2} = \underbrace{c_1 F_1(x,Q^2) + c_2 F_2(x,Q^2)}_{\text{fonctions de structure non-polarisées}} + \underbrace{c_3^{s,S}\, g_1(x,Q^2) + c_4^{s,S}\, g_2(x,Q^2)}_{\text{fonctions de structure polarisées}}$$

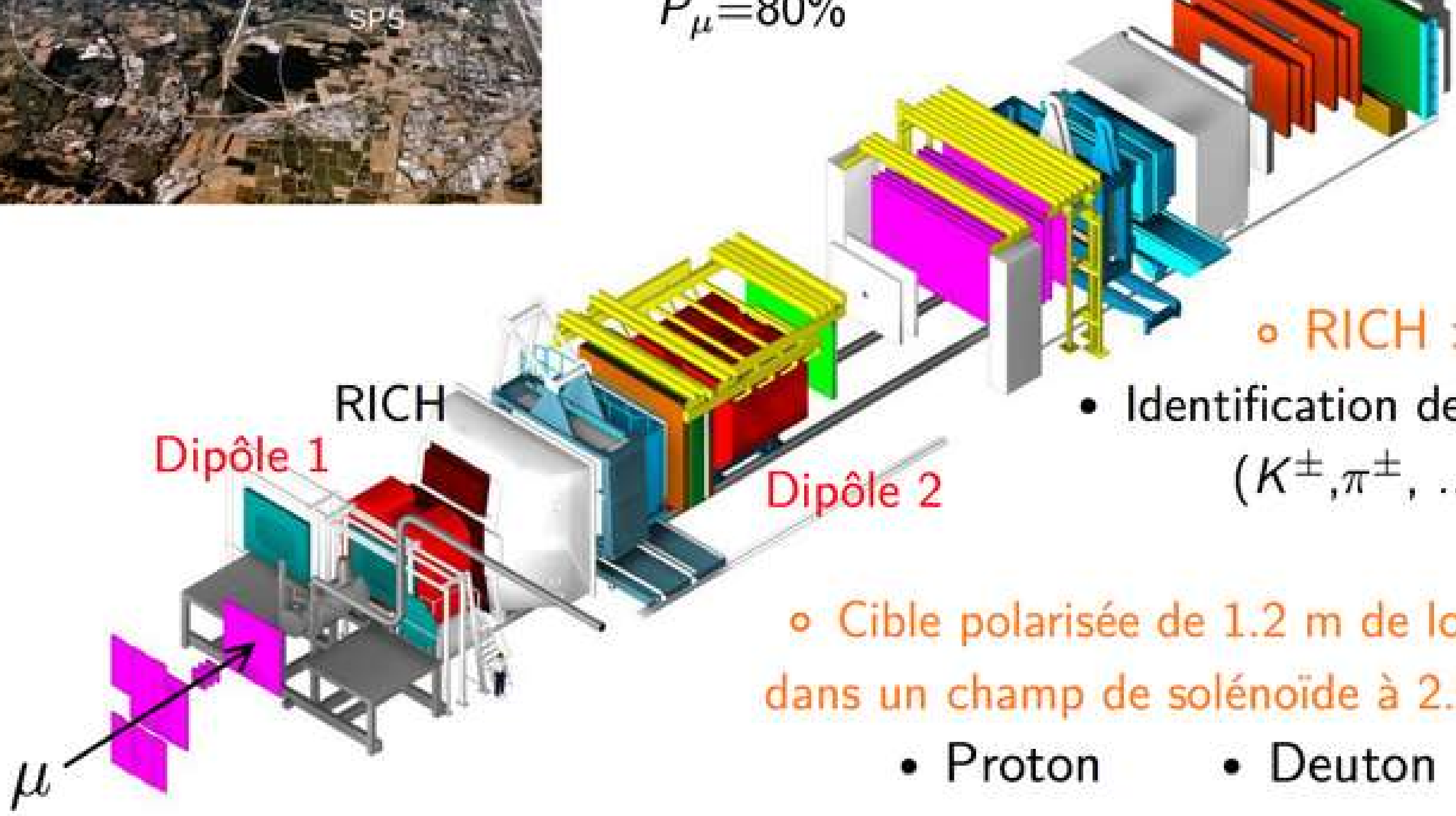
COMPASS at CERN

- Faisceau polarisé de μ^+ du SPS

  $1 \cdot 10^8 / 2 \cdot 10^8$ μ par déversement de ~ 10 s

  200 GeV/160 GeV

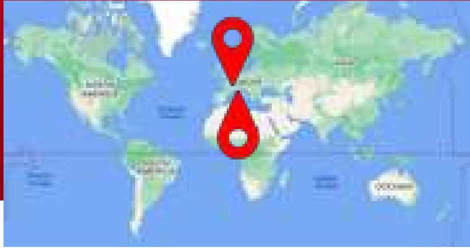
  P_μ=80%



- RICH :
  - Identification des hadrons ($K^\pm$,$\pi^\pm$, ...)

- Cible polarisée de 1.2 m de long dans un champ de solénoïde à 2.5 T
  - Proton
  - Deuton

Opera Experiment at Gran Sasso

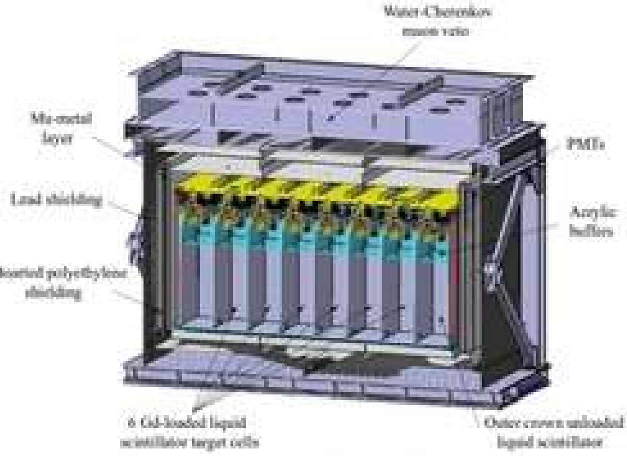


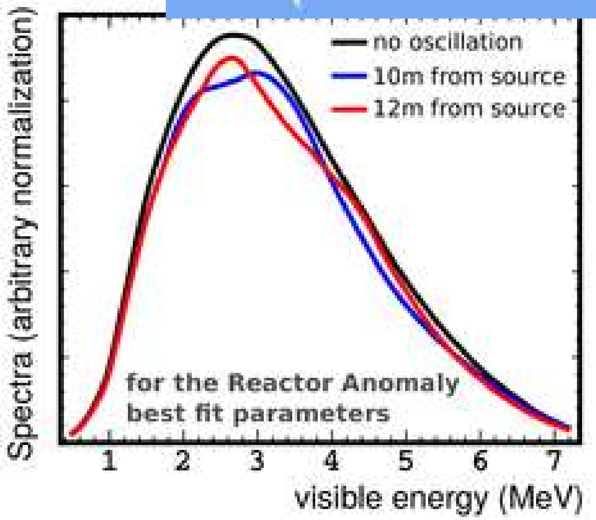
$$\nu_\tau N \rightarrow \tau^- X$$

$$
\begin{aligned}
\tau^- &\rightarrow \mu^- \nu_\mu \bar{\nu}_\tau \quad && with \quad BR = 17.36 \pm 0.05\% && (1)\\
\tau^- &\rightarrow e^- \nu_e \bar{\nu}_\tau \quad && with \quad BR = 17.85 \pm 0.05\% && (2)\\
\tau^- &\rightarrow h^-(n\pi^0)\bar{\nu}_\tau \quad && with \quad BR = 49.52 \pm 0.07\% && (3)\\
\tau^- &\rightarrow 2h^- h^+(n\pi^0)\bar{\nu}_\tau \quad && with \quad BR = 15.19 \pm 0.08\%. && (4)
\end{aligned}
$$

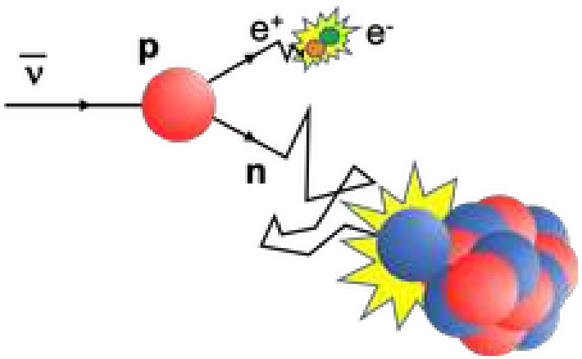
https://arxiv.org/pdf/1305.2513.pdf

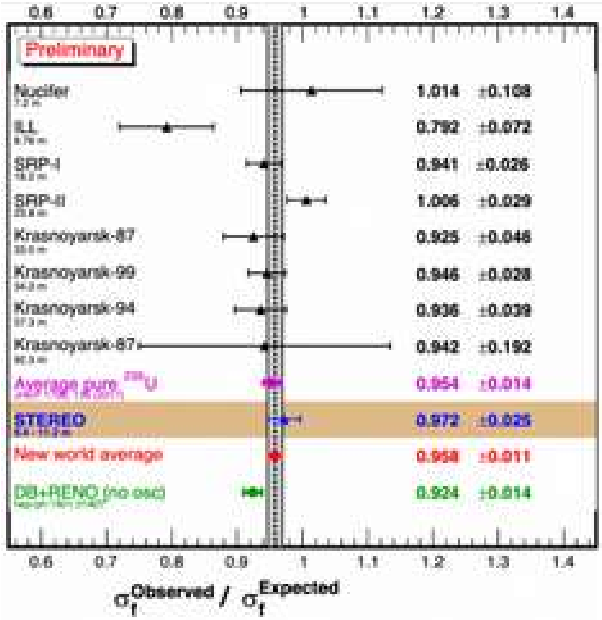
STEREO a ILL



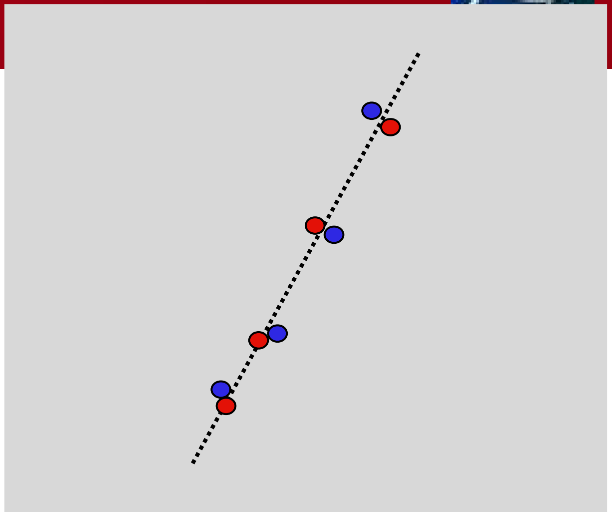


The reactor antineutrino anomaly (RAA) s the observation that the neutrino flux measured in many experiments close to nuclear reactors is significantly (more than 6%) lower than one would expect by theory.





Production de paires électron-ion :



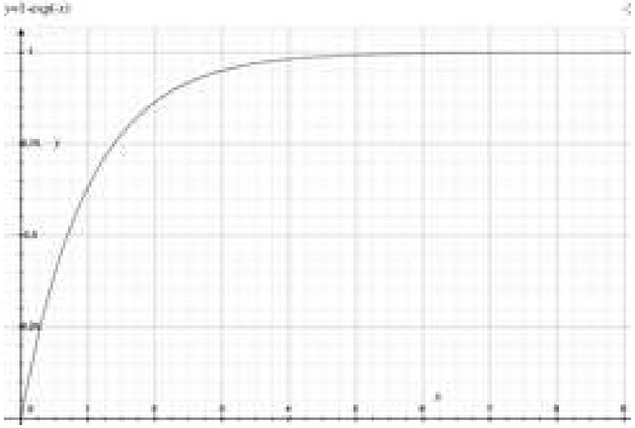
– Les interactions Coulombiennes entre le champ électrique de la particule et les atomes du milieu produisent des paires électron-ion.

– Les ionisations multiples suivent une statistique de Poisson:

$$P_k^n = \frac{n^k}{k!} e^{-n}$$

n : moyen

k : mesuré



– Efficacité de détection:

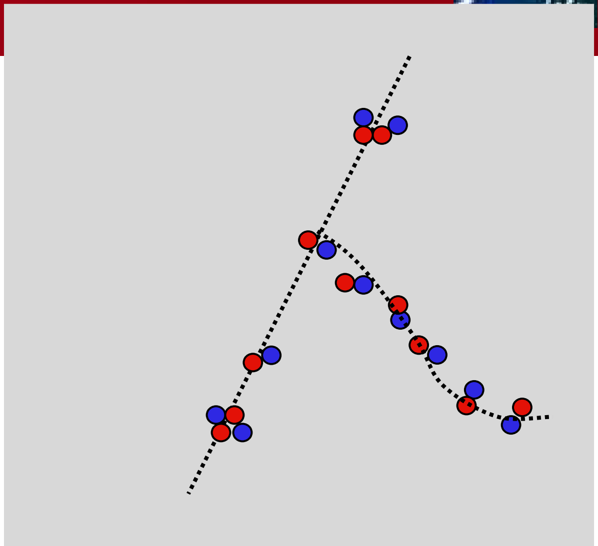
$$\varepsilon = 1 - P_0^n = 1 - e^{-n}$$

– Mécanismes d'ionisation :

- Excitation: X + p → X^* + p puis X^* → $X^+ + e^-$
- Ionisation: X + p → X^+ + p + e^-
- *Effet Penning*: $Ne^* + Ar$ → $Ne + Ar^+ + e^-$

IONISATION TOTALE

- Les électrons primaires ionisent à nouveau le milieu et produisent localement de nouveaux groupes de paires électron-ion. Si l'électron secondaire a suffisament d'énergie il peut produire une longue trace (électronδ).

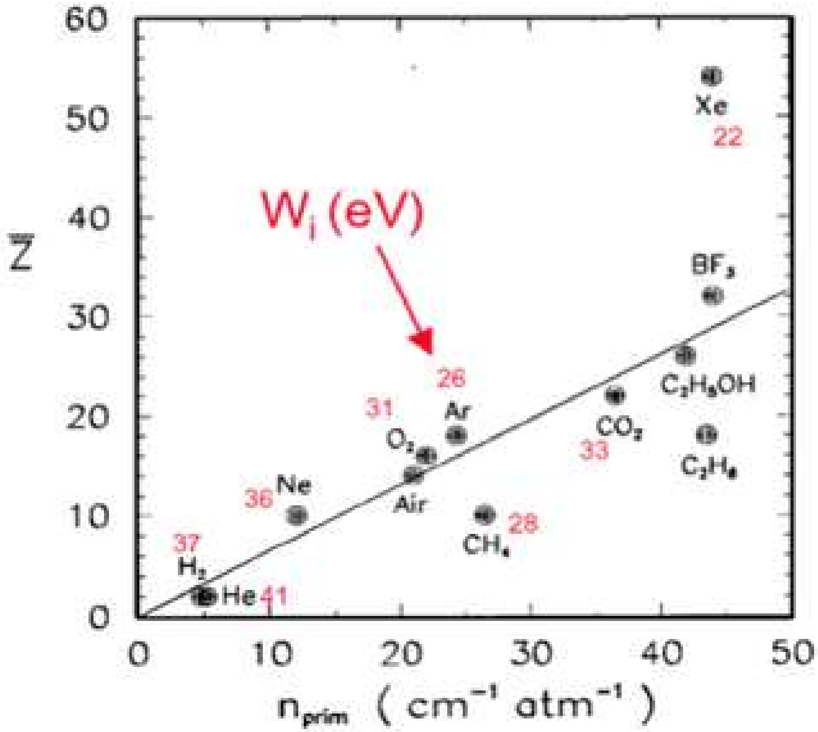


- Nombre total de paires:

ΔE : perte d'énergie de la particule

w_i : énergie moyenne par paire

$$n_T = \frac{\Delta E}{w_i}$$



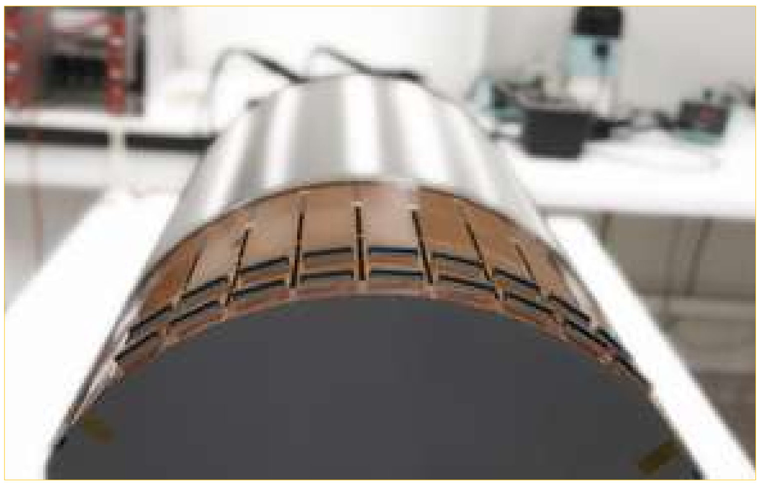
M.I.P. dans l'argon:

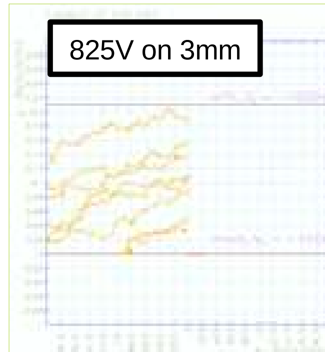
– ΔE= 2,65 keV/cm w_i = 25 eV

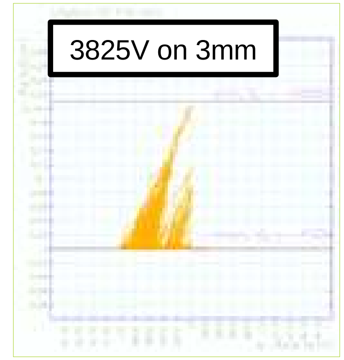
– n_T ≈ 106 paires électron-ion/cm

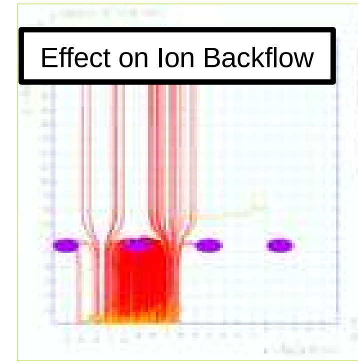
FIG. (II) 1.7: *Photographie d'un individu bioluminescent prise par l'une des caméras installées sur la ligne d'instrumentation IL07 (lire le paragraphe (II) 3.1). L'échelle n'est pas précisément connue (elle dépend de la distance à la caméra).*

CLAS12 - THE MICROMEGAS VERTEX TRA

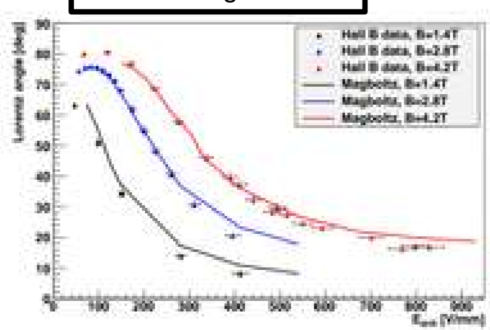




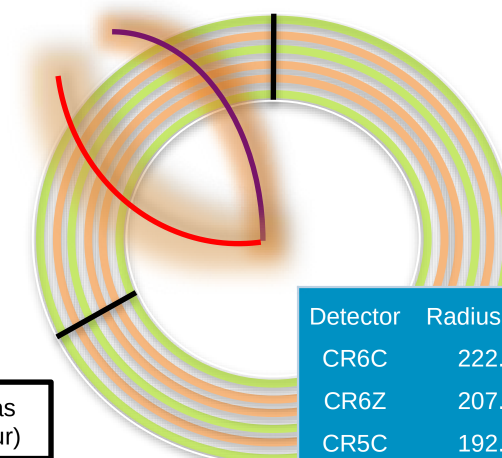




Lorentz Angle Vs HV



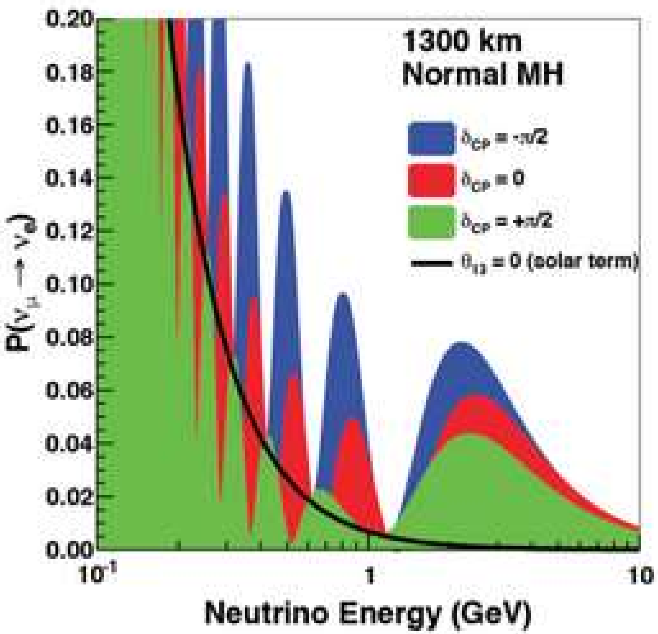
=> Clas-note 2007-004: Simulations of Micromegas detectors for the CLAS12 experiment (S. Procureur)

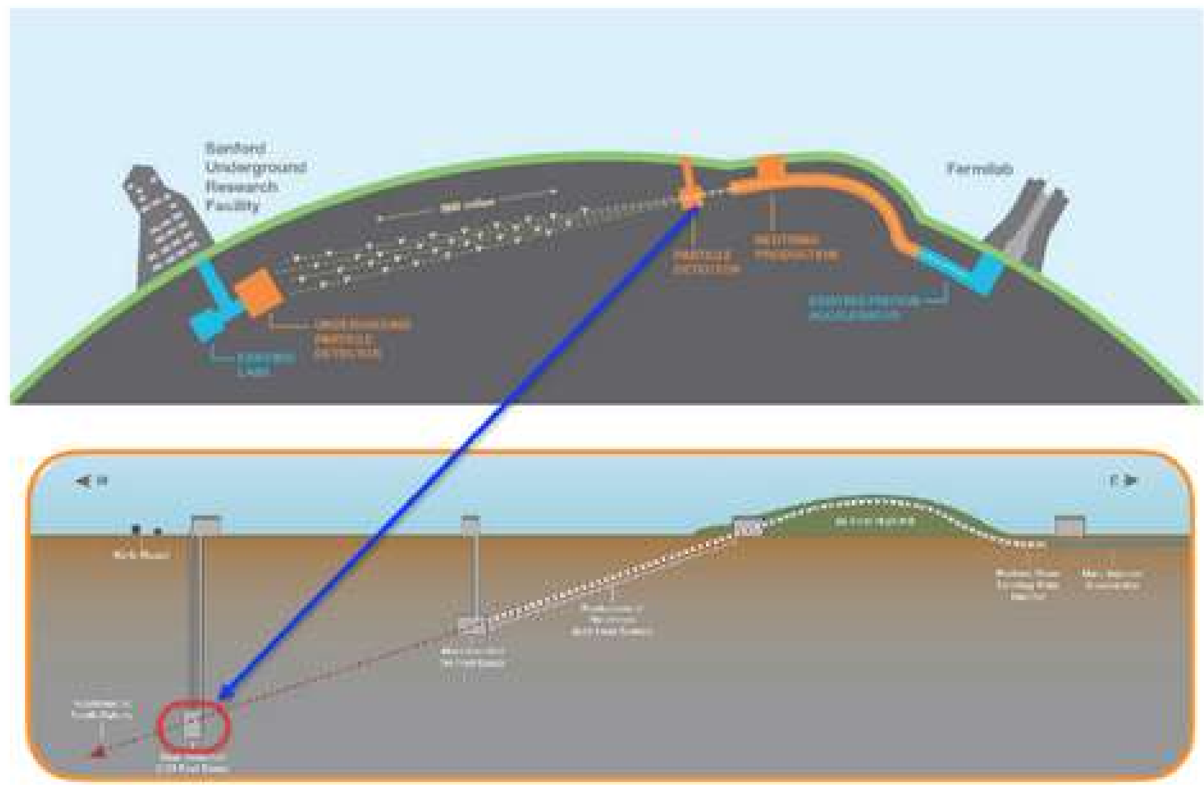


Detector	Radius (mm)
CR6C	222.53
CR6Z	207.54
CR5C	192.65
CR5Z	177.57
CR4Z	162.56
CR4C	147.57

DUNE

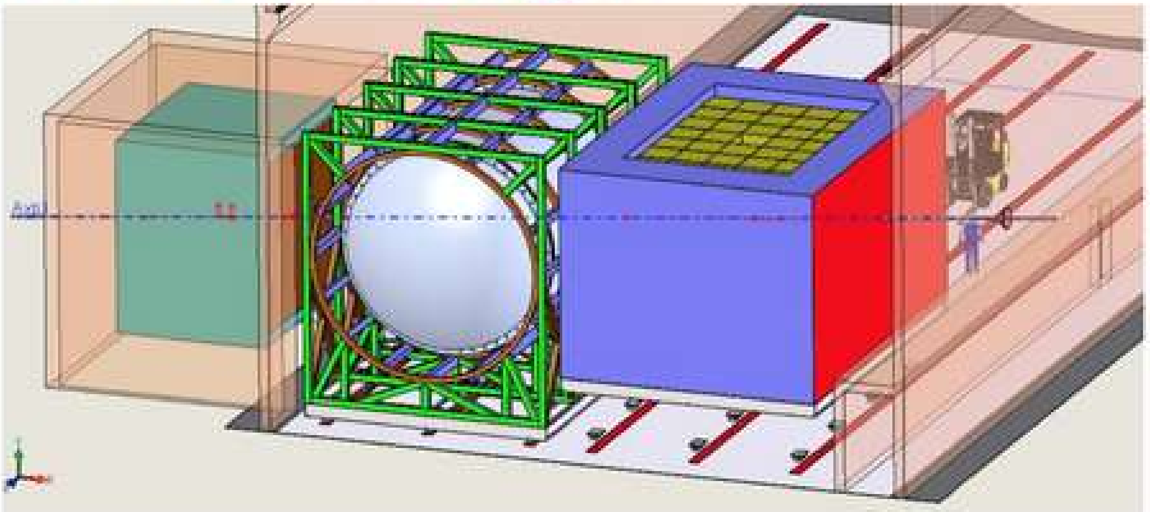
- Observe ν_e appearance and ν_μ disappearance at long baseline in a wideband beam to precisely measure the neutrino oscillation parameters δ_{CP}, θ_{23}, θ_{13}, and Δm^2_{32} in a single experiment.

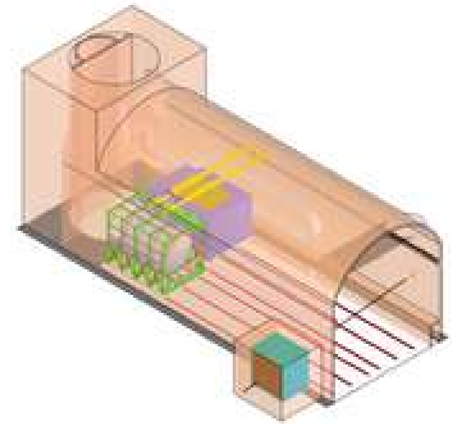




Dune

Reference Design





- 3 components (Right-to-left)
  - LAr TPC with pixelated readout (50t)
  - Multi-Purpose Detector - MPD
    - HPgTPC(1t) + ECAL + magnet
  - 3DST-S: Three-Dimensional Scintillator Track

Z-Y projection full spill & event

- Corresponds to full spill exposure
- Overlay of test event plus 60 events in the ECAL