DE LA RECHERCHE À L'INDUSTRIE

Mardi 11/07 11h (Orme)
Lundi 17/07 12h (Centre)
Visite Labo 14h (Centre)
Mardi 18/07 10h30 (Orsay)

Mesurer l'infiniment petit et observer l'infiniment grand

Maxence Vandenbroucke

07/2023

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

PLAN DES COURS

Cours 1 : Généralités

-Introduction de la théorie à la pratique

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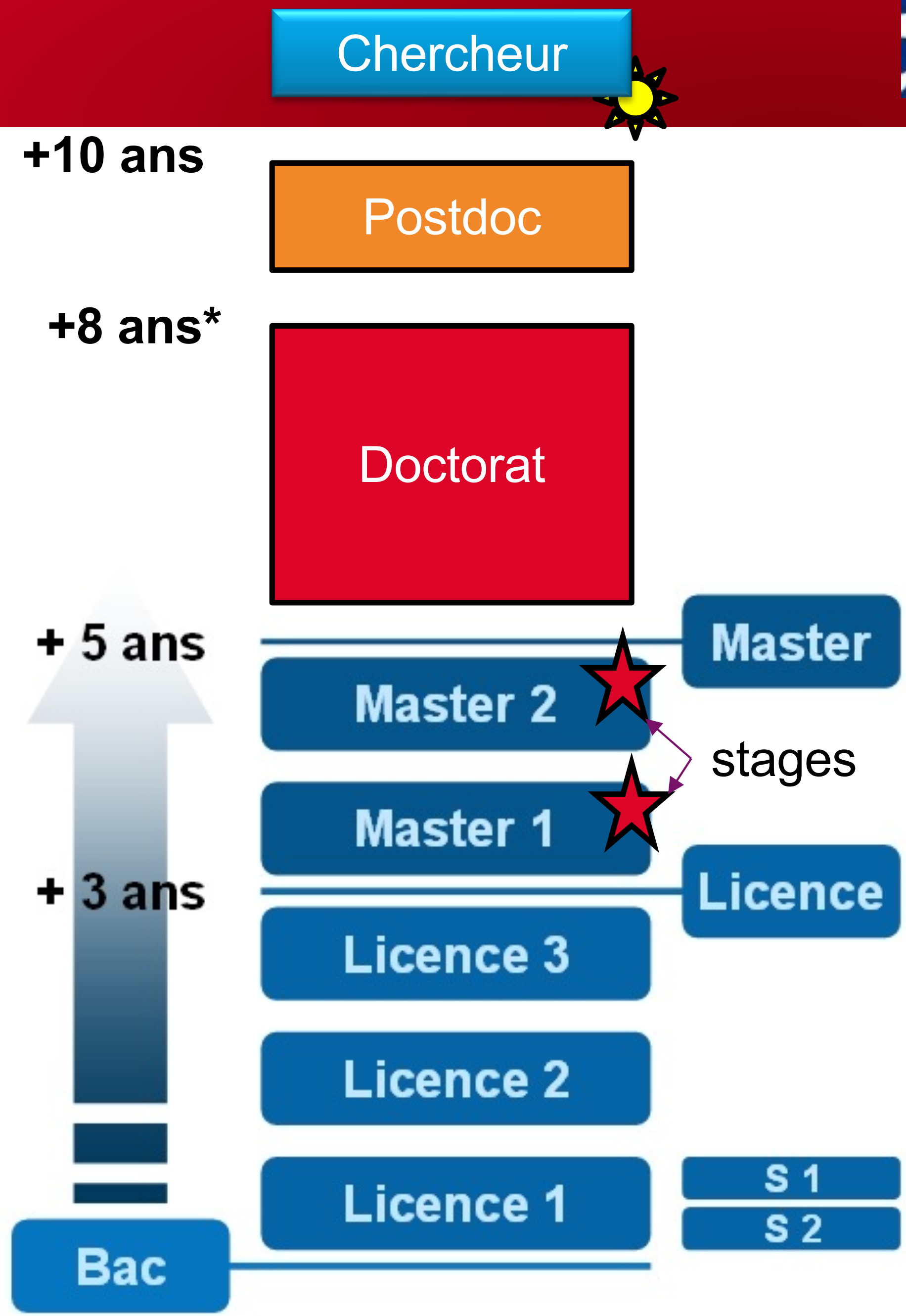
"I'm searching for my keys."

ORIENTATION

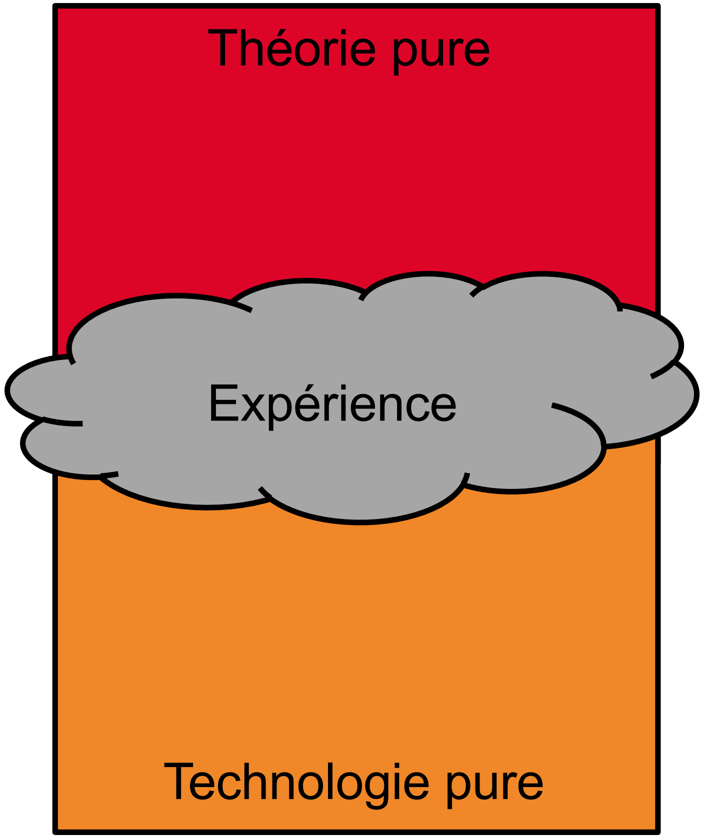
	Astro	Nucleaire	Particules	Cosmo	Medical	…
Inge						
Prof						
Analyse						
Detection			X			
Chef						
Theoricien						
Communication						
… … … …						

Un choix matriciel !



*en France, 3-7ans sinon

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

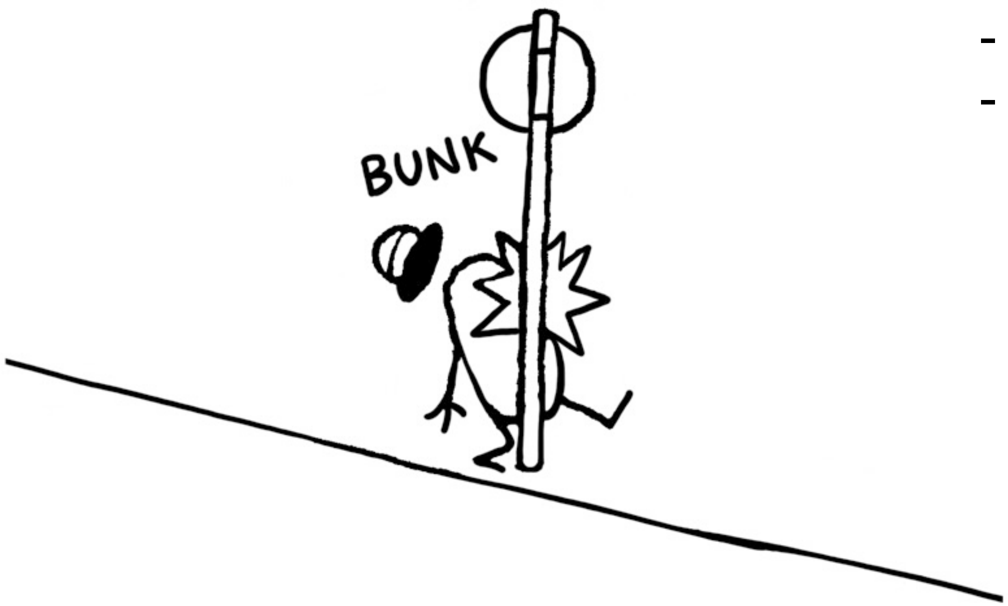
Le physicien complet est à la fois proche des interrogations fondamentales, mais aussi des avancés technologiques pour trouver un espace de découverte potentielle

(vision un peu naïve)

UNE EXPÉRIENCE C'EST QUOI ?

Dernier "***BUNK***"

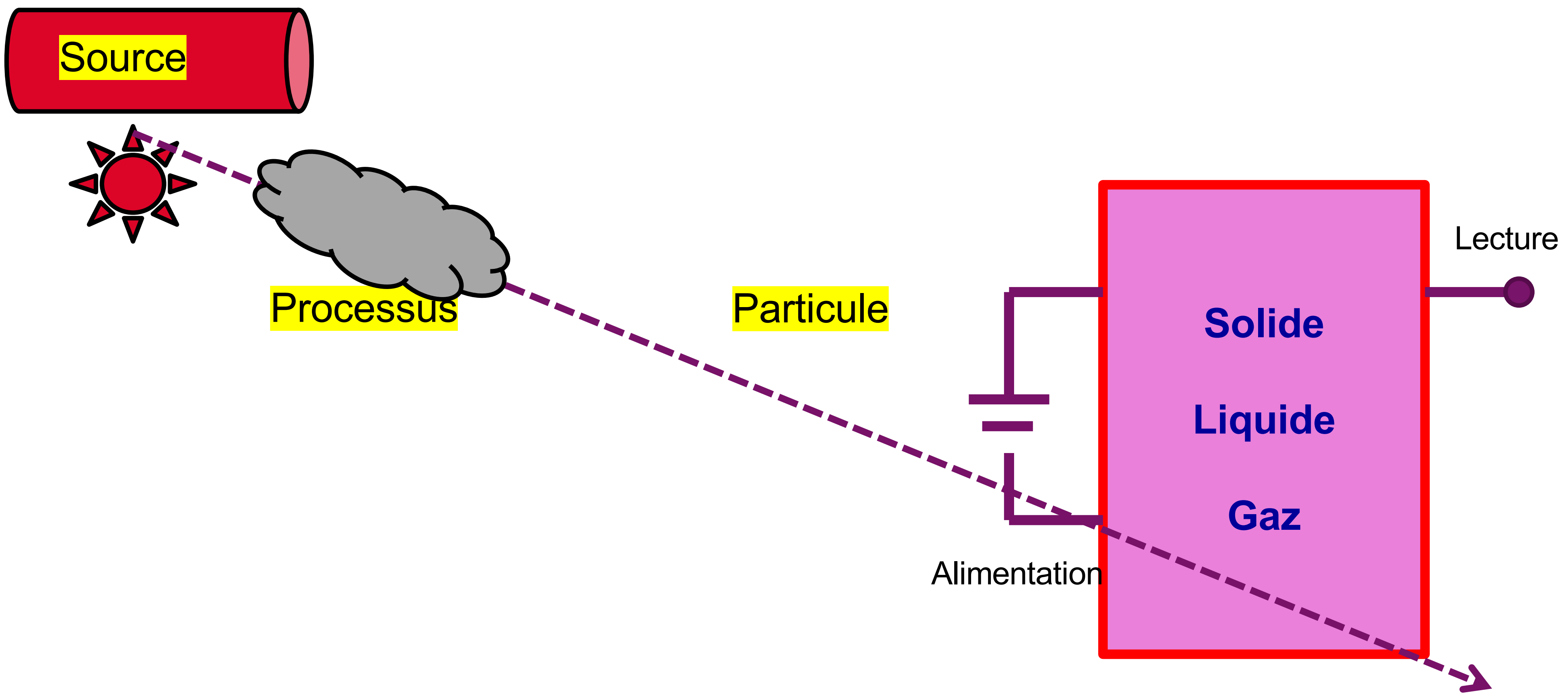
- *Higgs (2012)*
- *No SUSY*
- *GW (2015)*
- *No Wimps ? (2023)*
- *…*



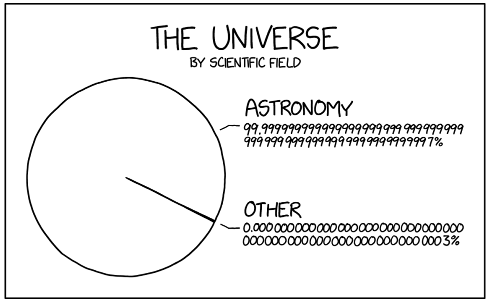
LE RÉEL, C'EST QUAND ON SE COGNE.

UNE EXPÉRIENCE C'EST QUOI ?

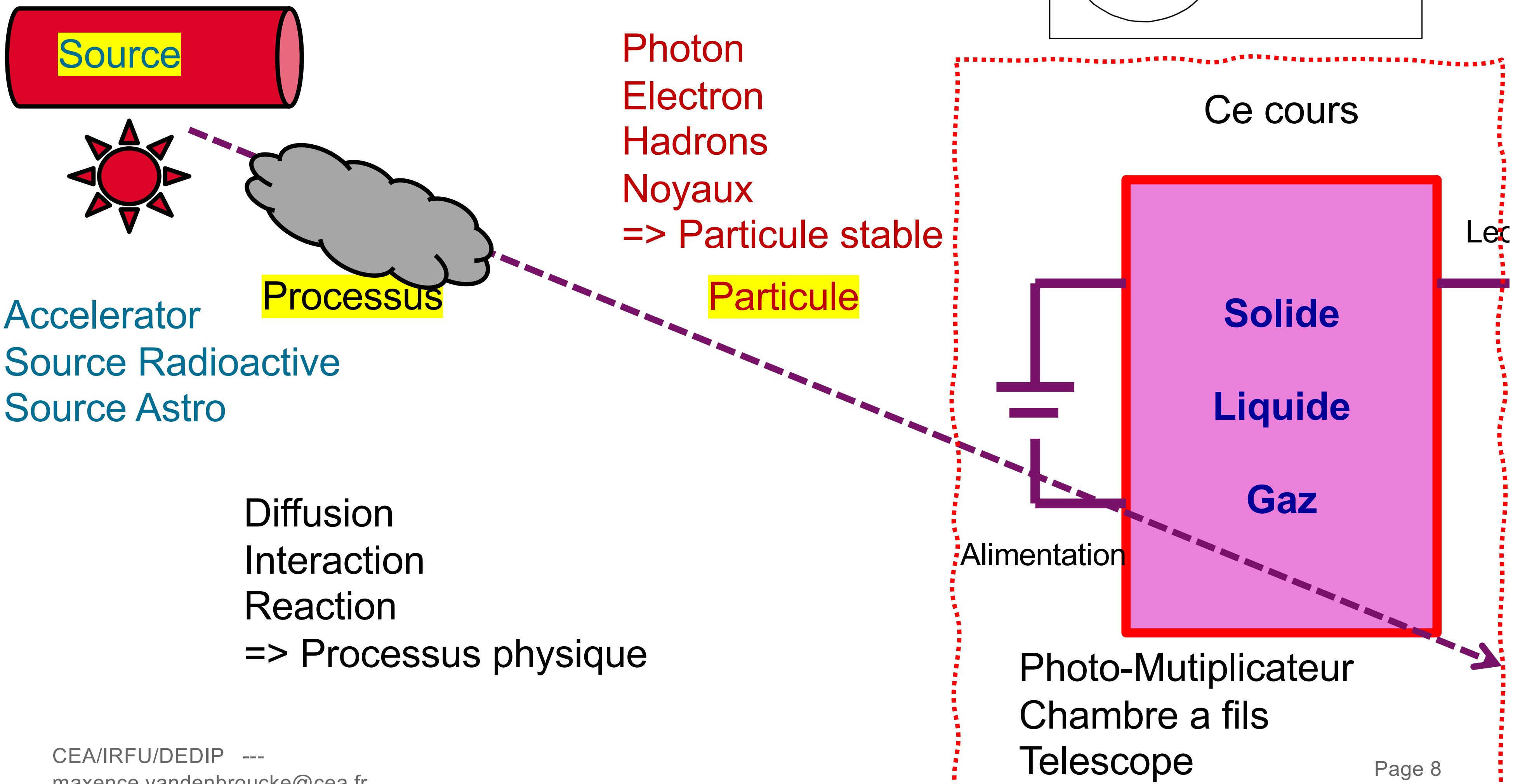
Schématiquement (*****)



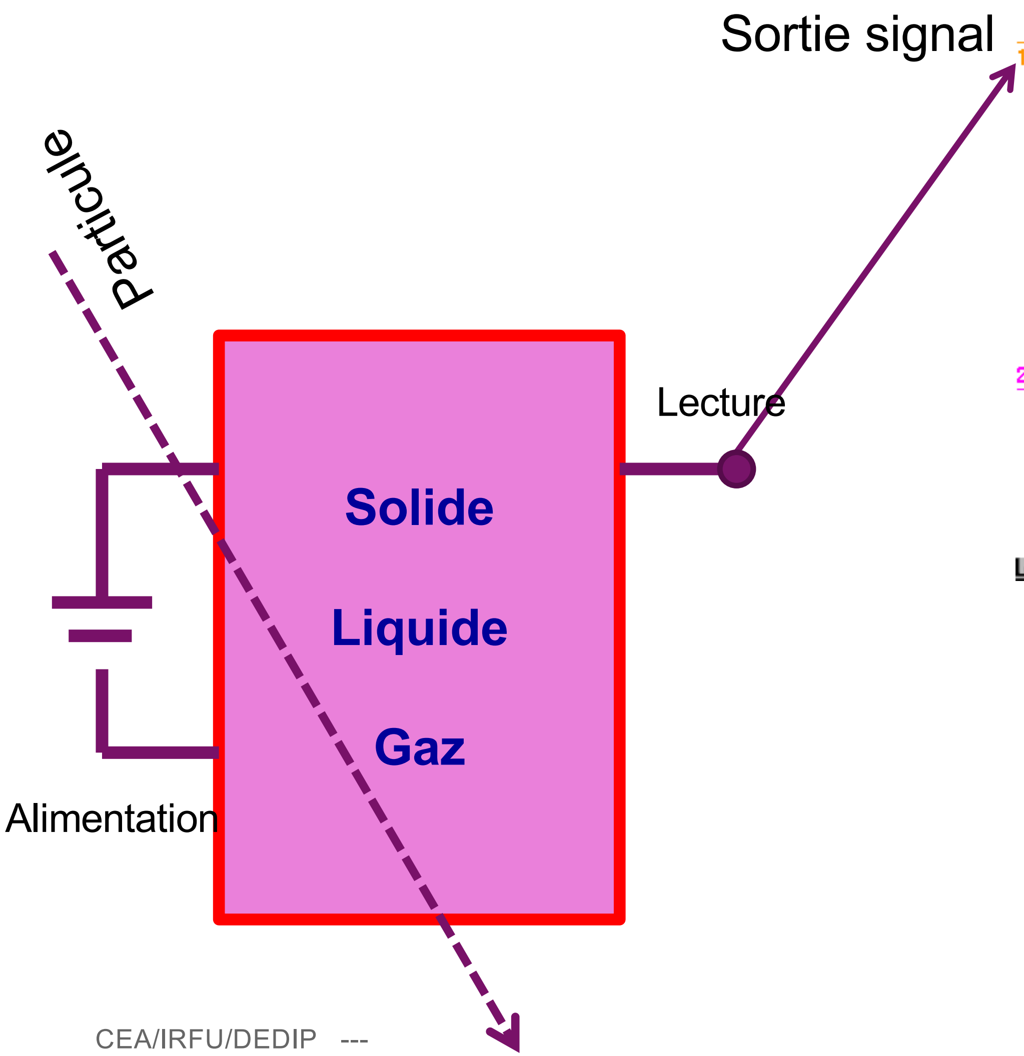
UNE EXPÉRIENCE C'EST QUOI ?

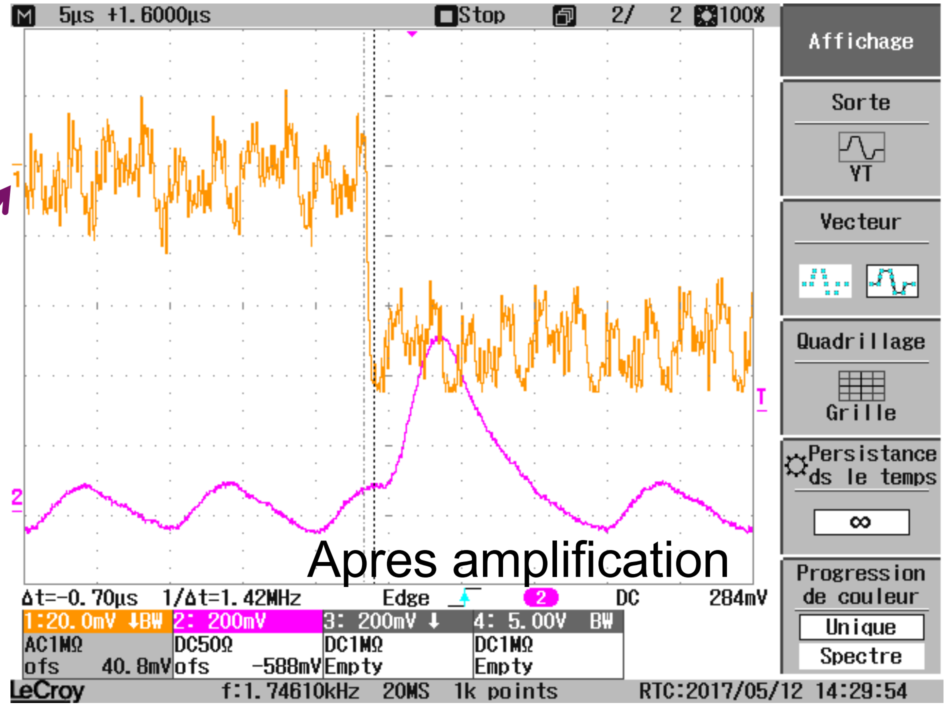


Schématiquement (*****)



MESURER C'EST QUOI ?



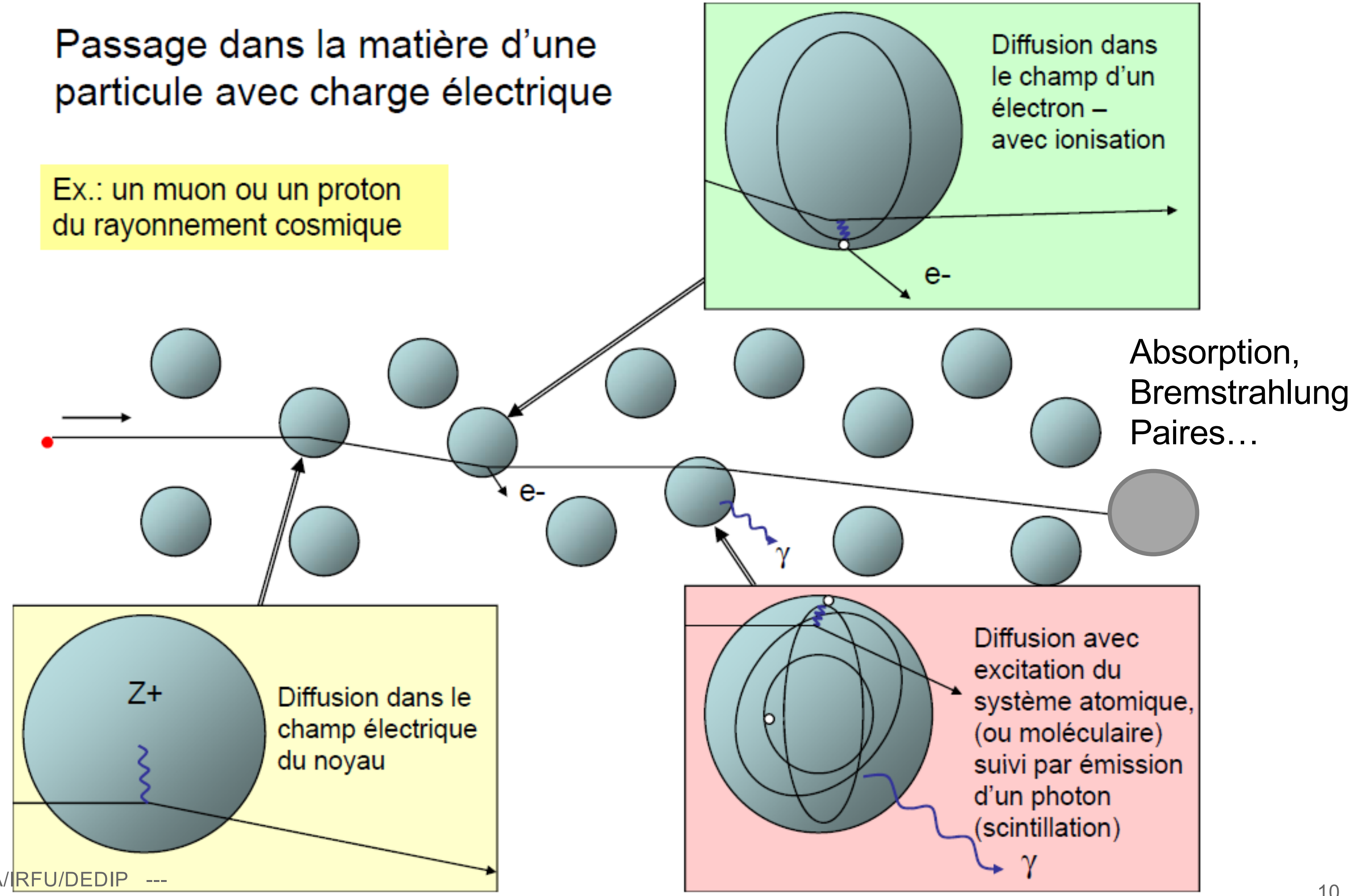


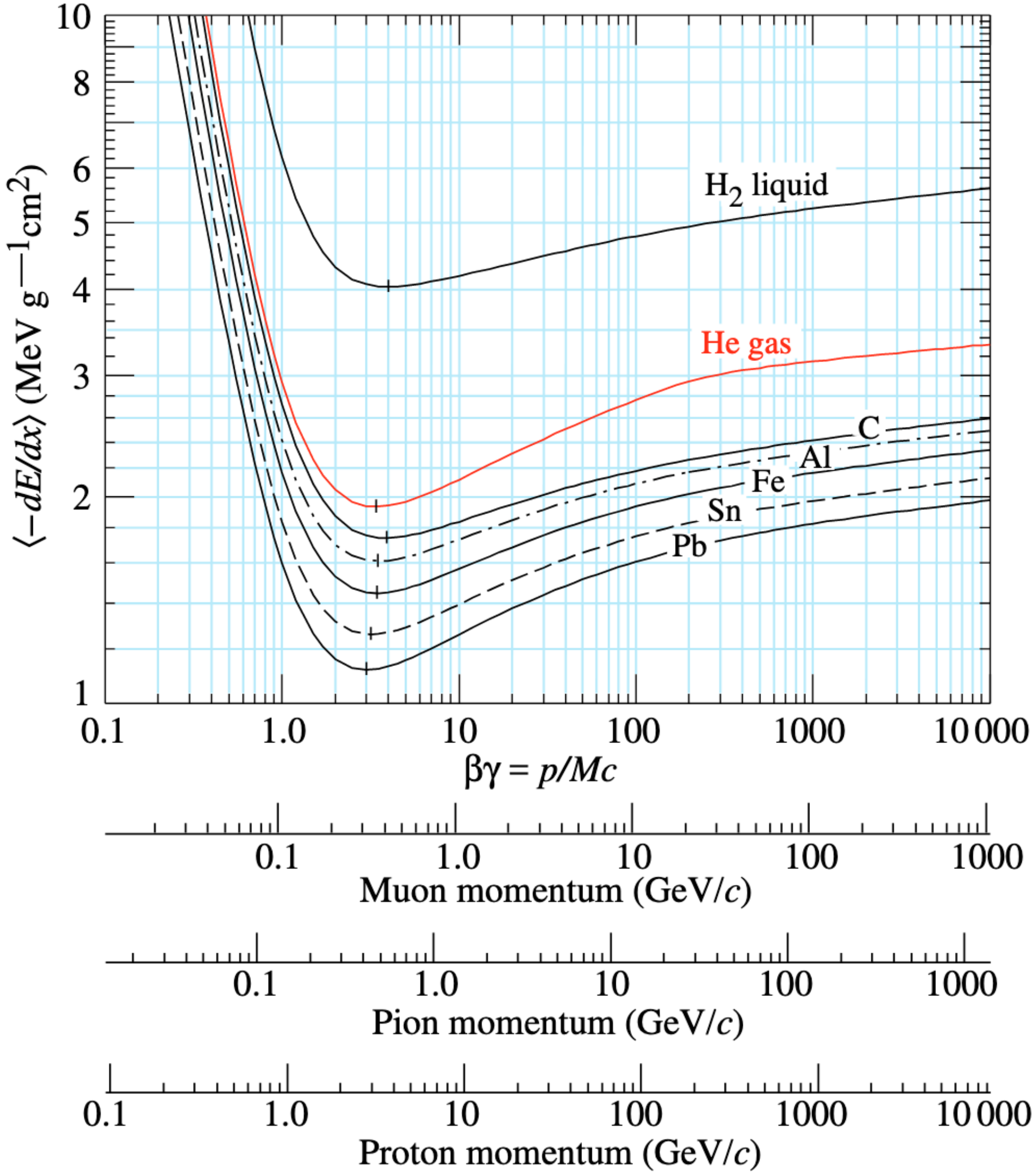
=> A la fin on veut un courant/tension.

INTERACTIONS PARTICULE-MATIERE

Passage dans la matière d'une particule avec charge électrique

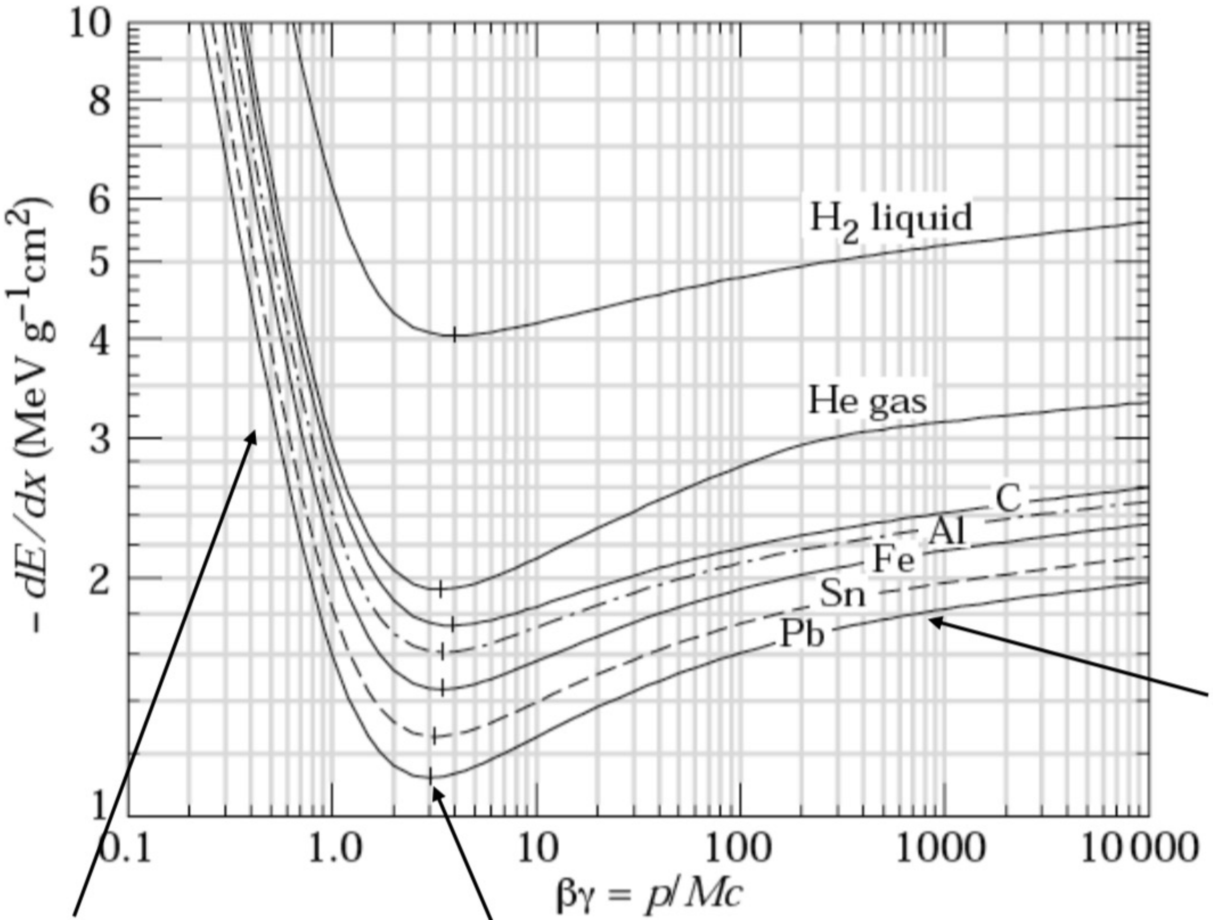
Ex.: un muon ou un proton du rayonnement cosmique




10
8
6
5
4
3
2
1
⟨−dE/dx⟩ (MeV g−1cm2)
H2 liquid
He gas
C
Al
Fe
Sn
Pb
0.1
1.0
10
100
1000
10 000
βγ = p/Mc
0.1
1.0
10
100
1000
Muon momentum (GeV/c)
0.1
1.0
10
100
1000
Pion momentum (GeV/c)
0.1
1.0
10
100
1000
10 000
Proton momentum (GeV/c)

INTERACTIONS PARTICULE-MATIERE

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



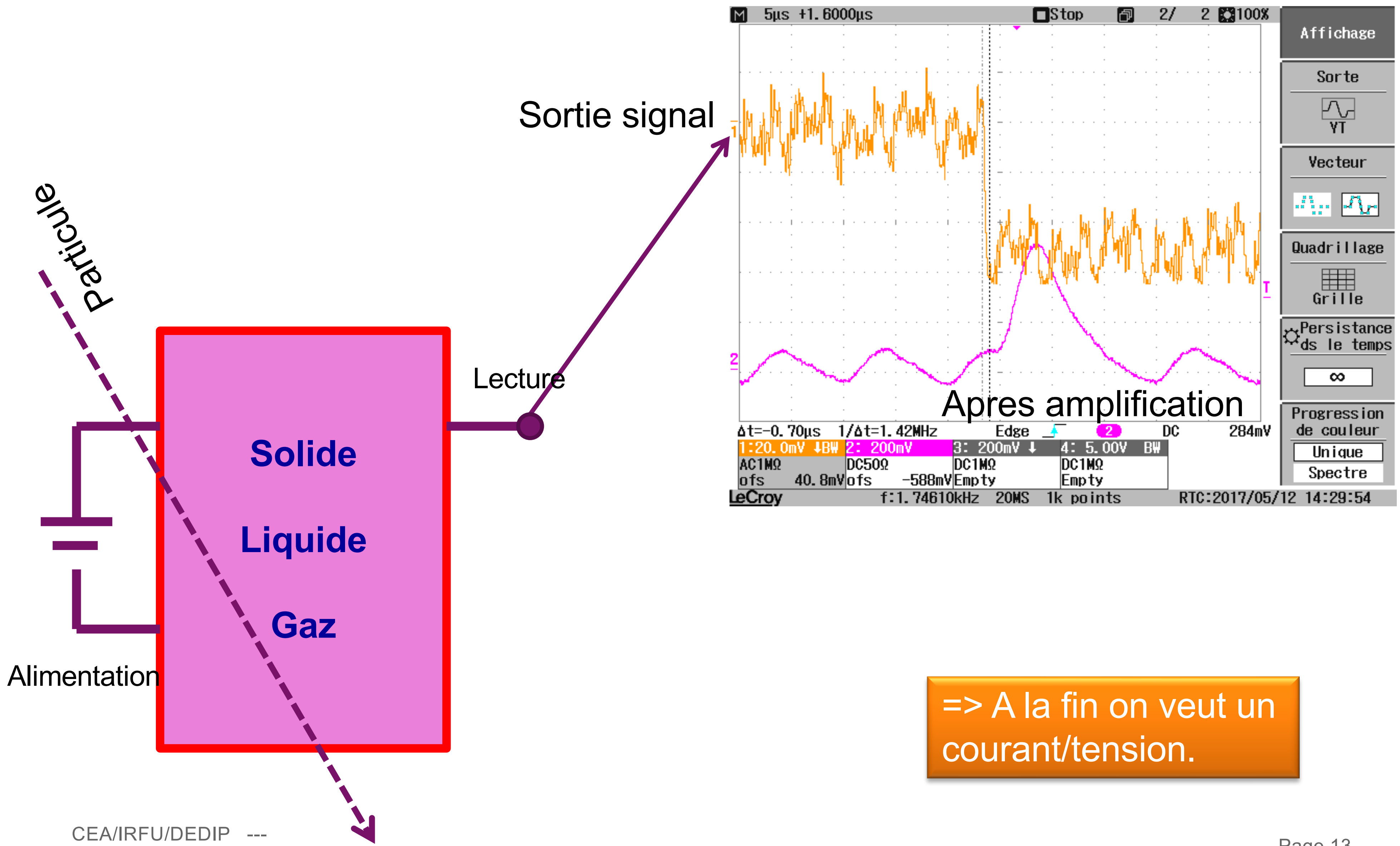
$\frac{dE}{dX} \propto \ln \beta^2\gamma^2$

$\frac{dE}{dX} \propto \frac{1}{\beta^2}$

$\beta\gamma \approx$ 3-4 ($v \approx 0.96c$)

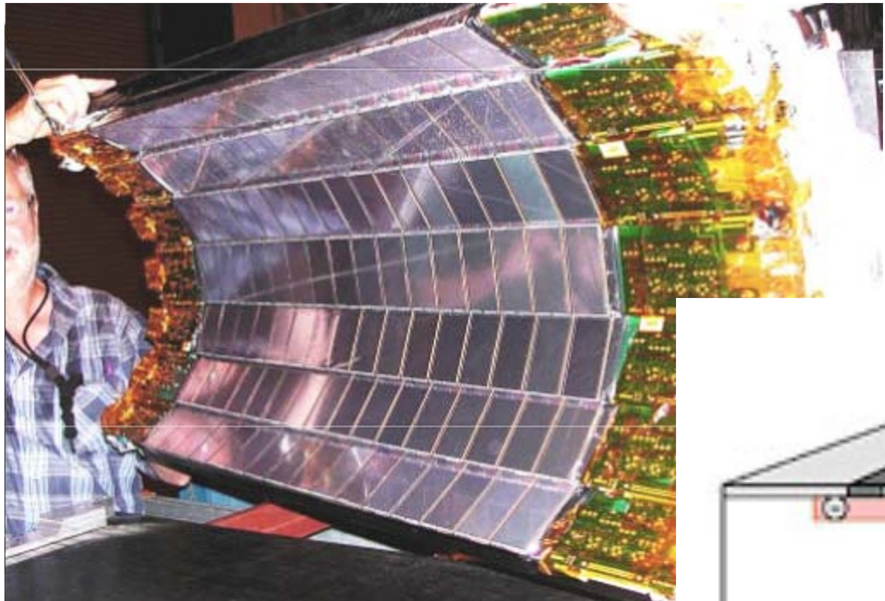
Minimum ionizing particles (MIPs)

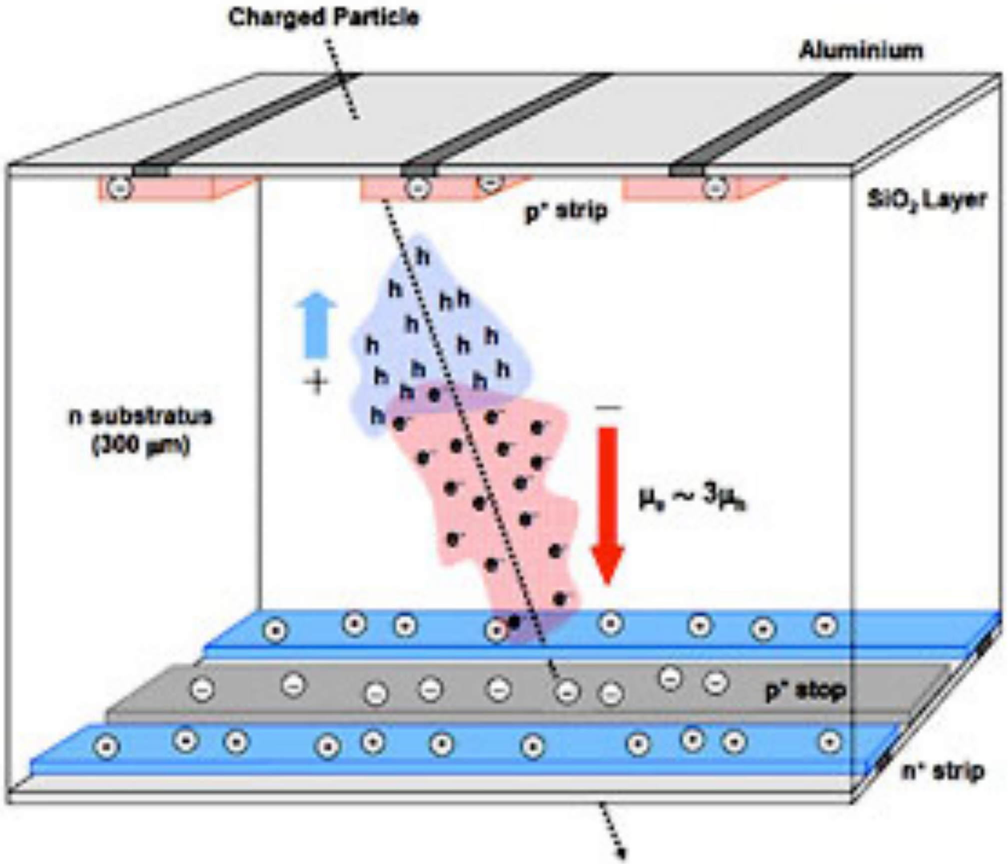
MESURER C'EST QUOI ?



=> A la fin on veut un courant/tension.

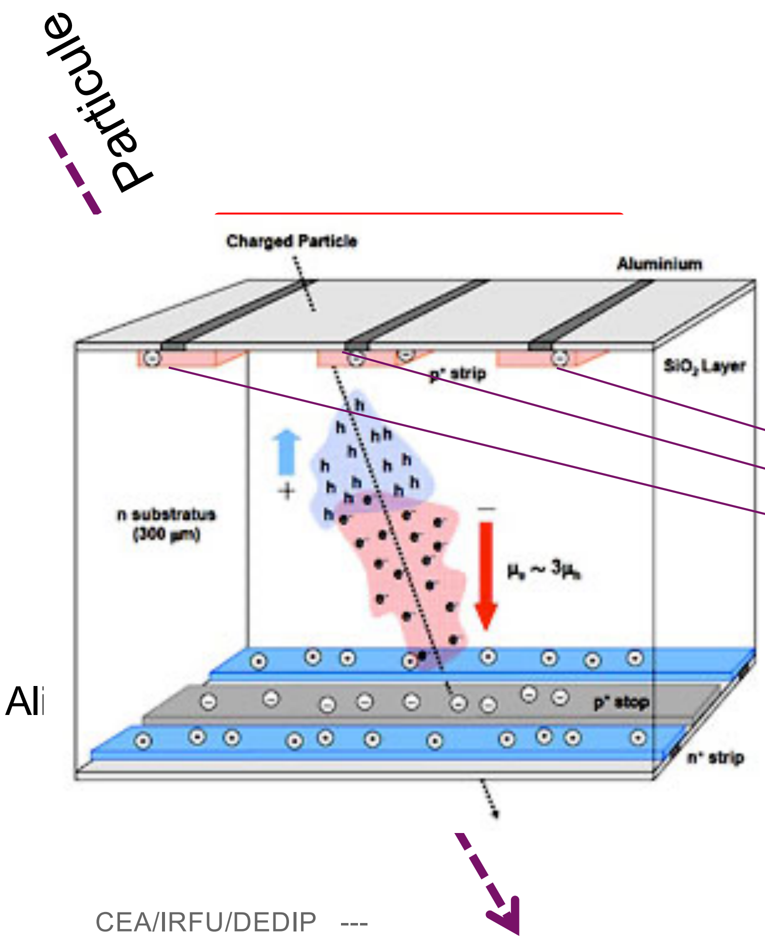
DÉTECTION : TRACKER SILICIUM



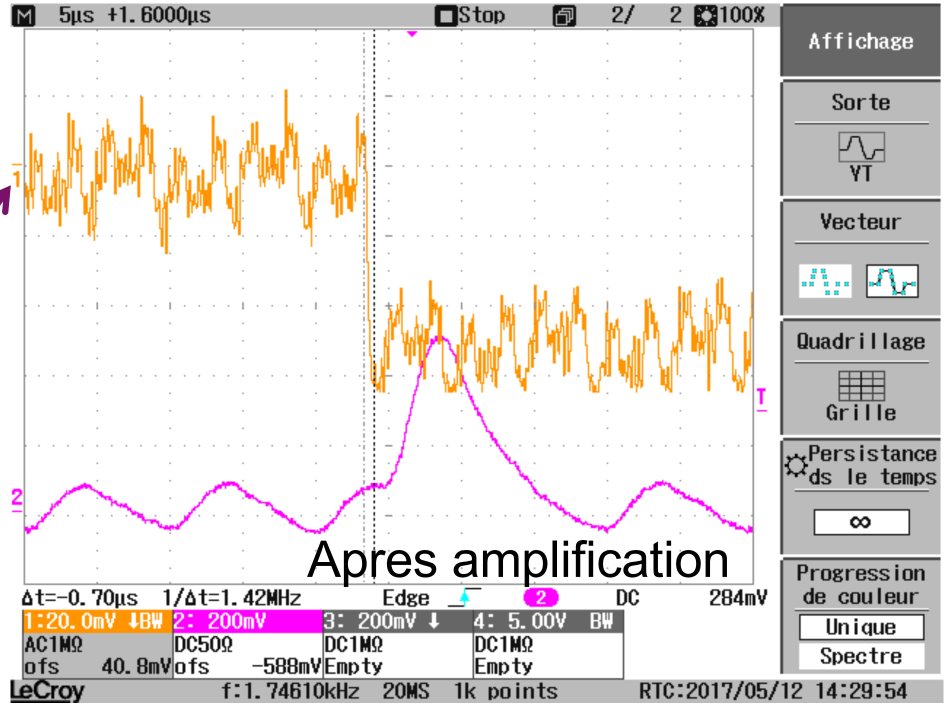


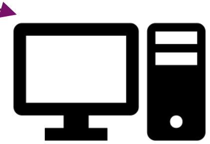
Les autres type de detecteurs =>
Cours 2

MESURER C'EST QUOI ?



Sortie signal



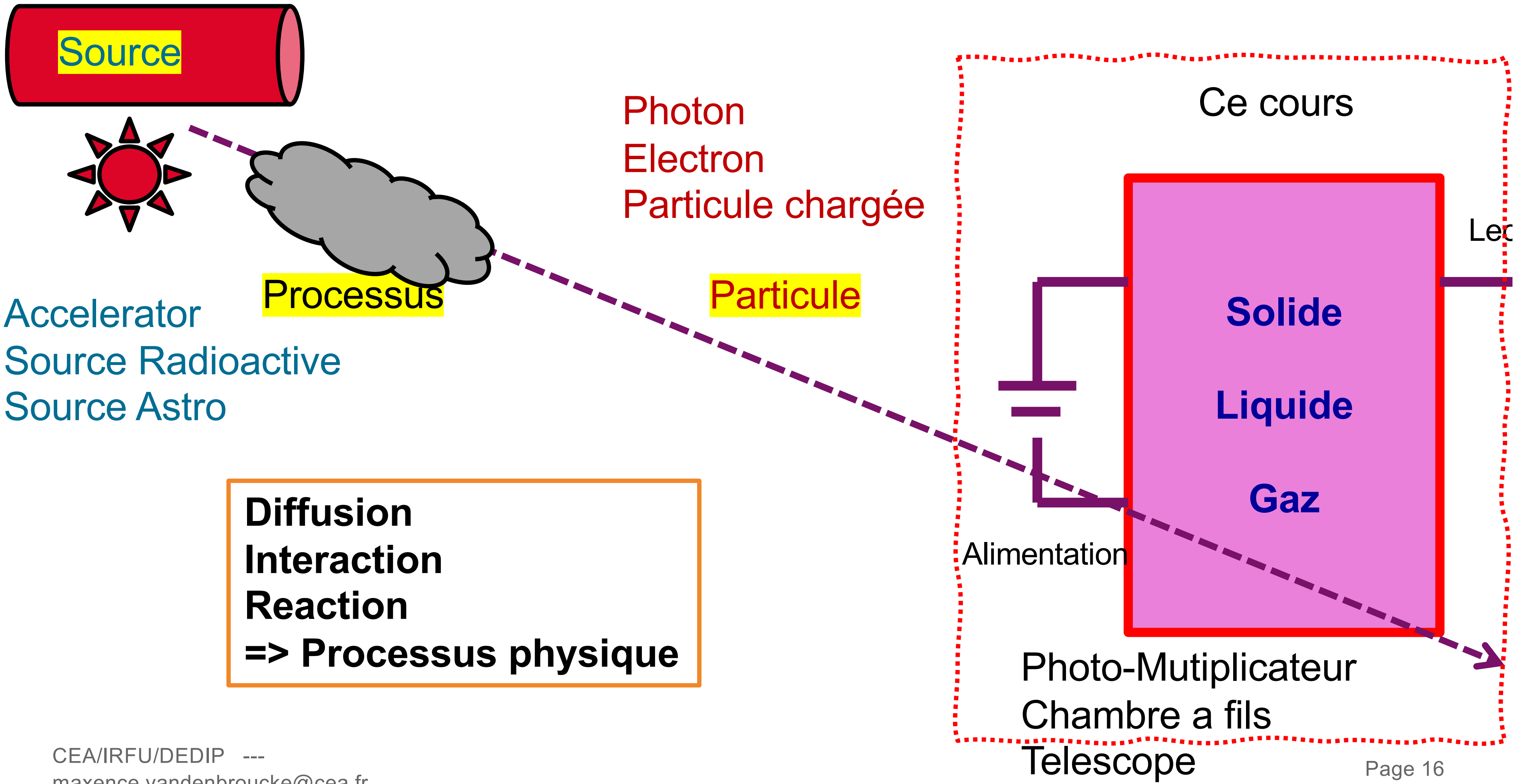


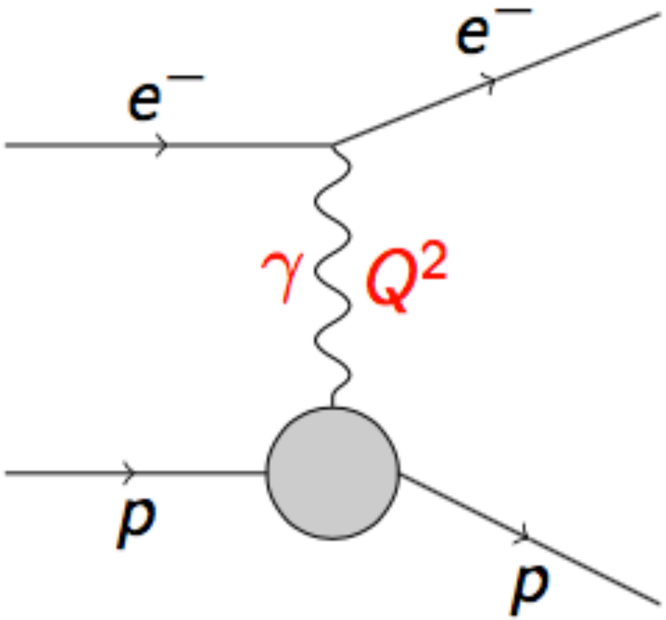
Un Canaux = Un signal

Plein de canals => Analyse

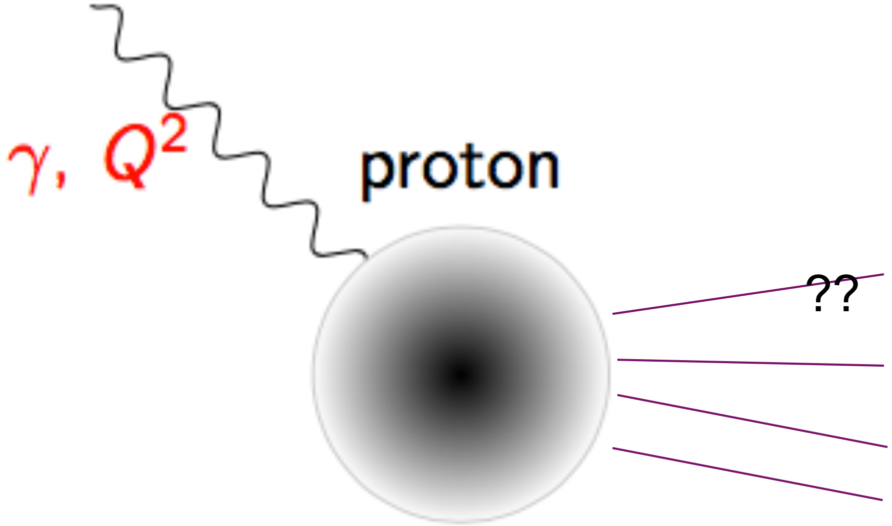
UNE EXPERIENCE C'EST QUOI ?

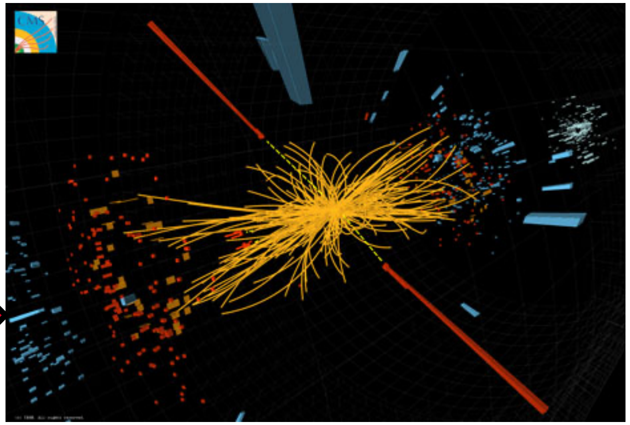
Schématiquement (*****)





Diffusion élastique.



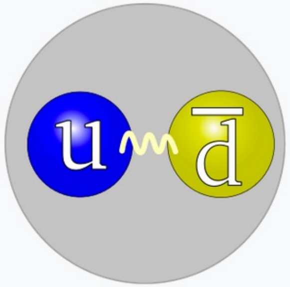


Pas élastique du tout

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

CEA/IRFU/DEDIP ---
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Mesure de l’impulsion (masse et/ou vitesse)

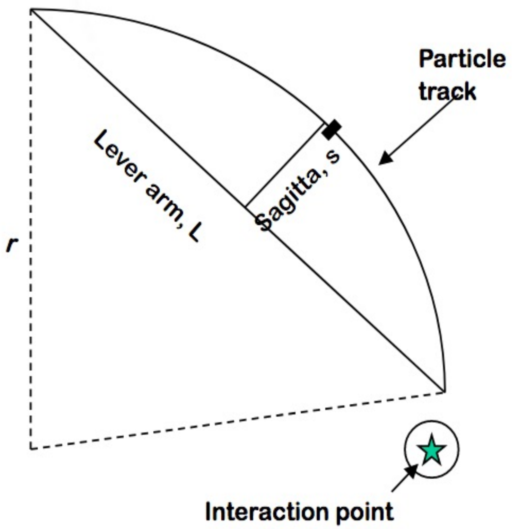
$$p=mv$$

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)

$$L = v\tau = \beta c\tau = \beta c\gamma\tau_{0} = p\tau_{0}/m$$

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Mesure de l'impulsion

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

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- 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

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

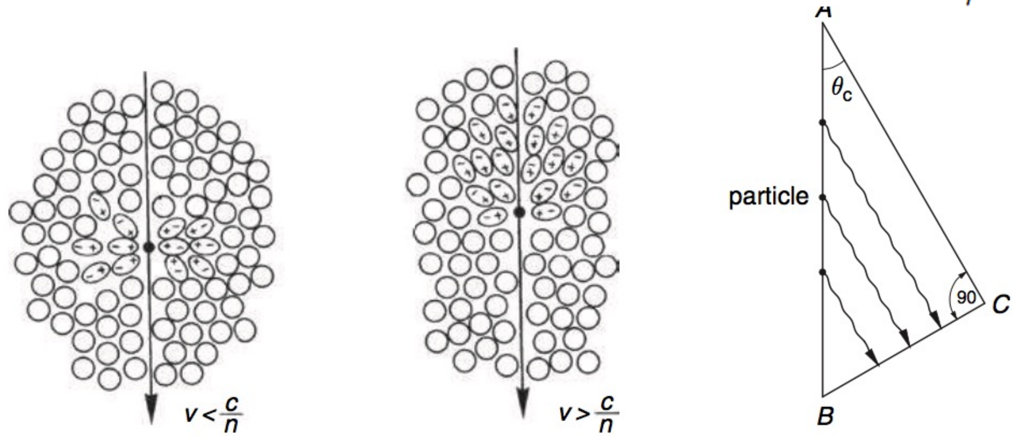


Fig. 5.39. Illustration of the Cherenkov effect [140, 141] and geometric determination of the Cherenkov angle.

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

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

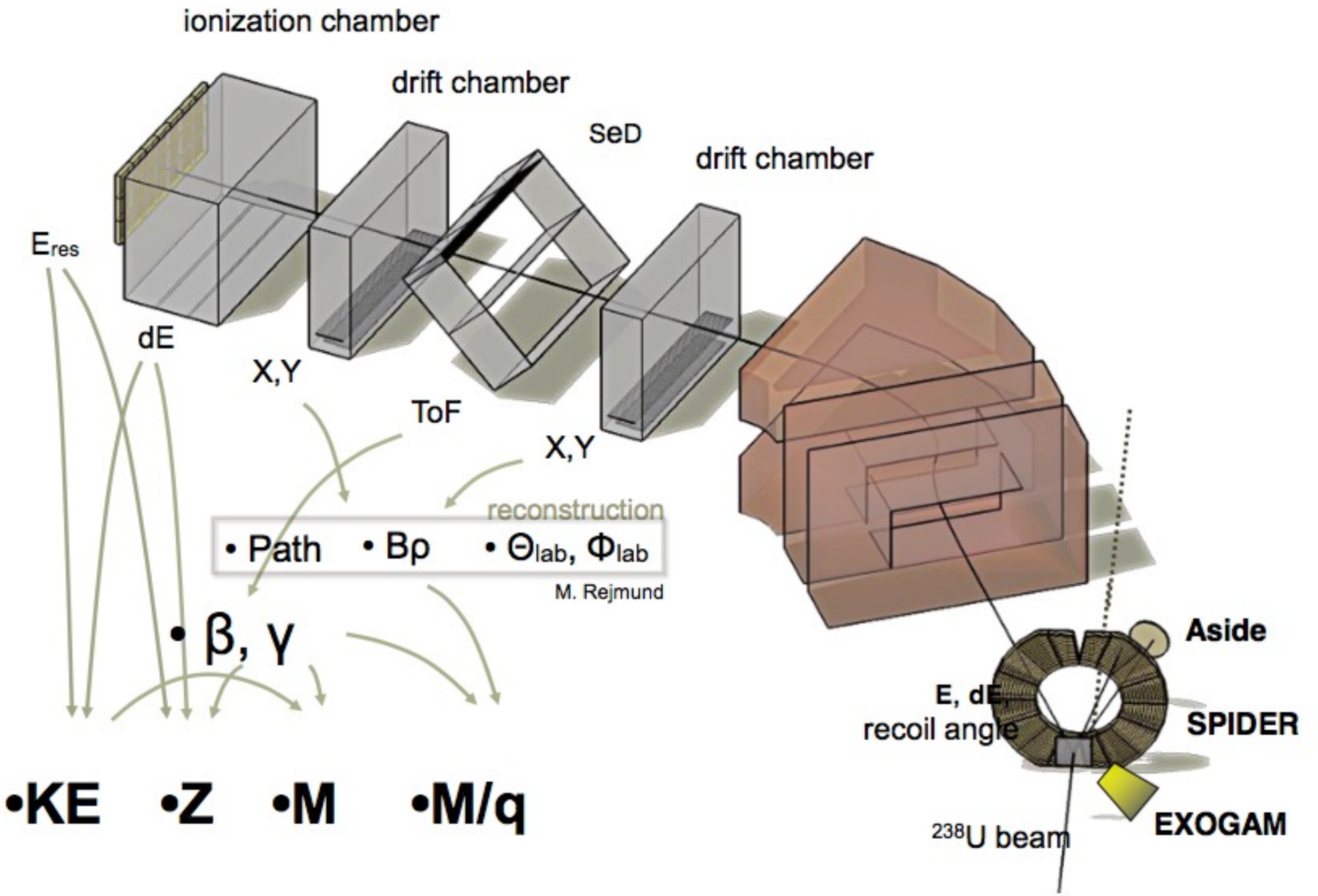
Mesure de spin et de la parité

- (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



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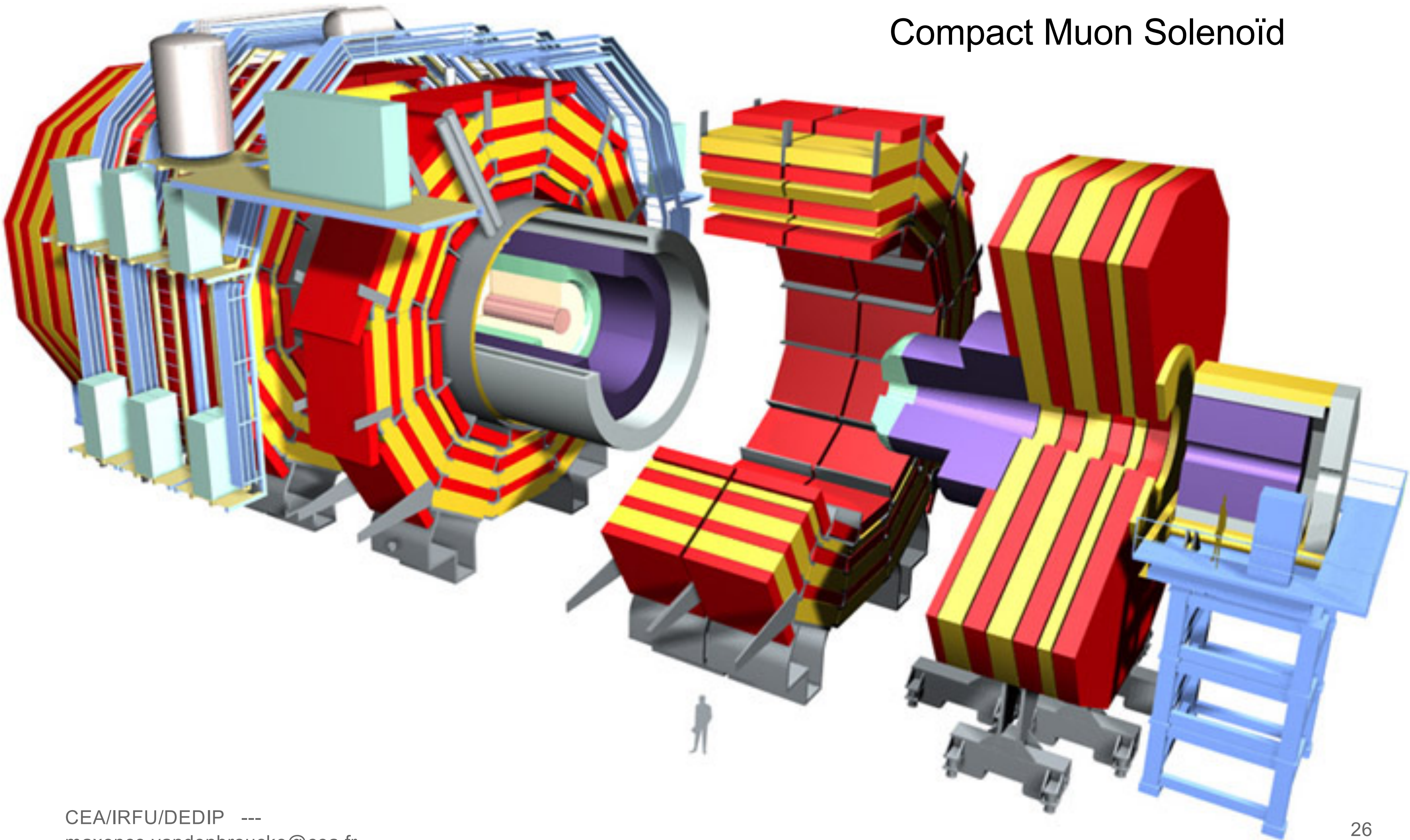
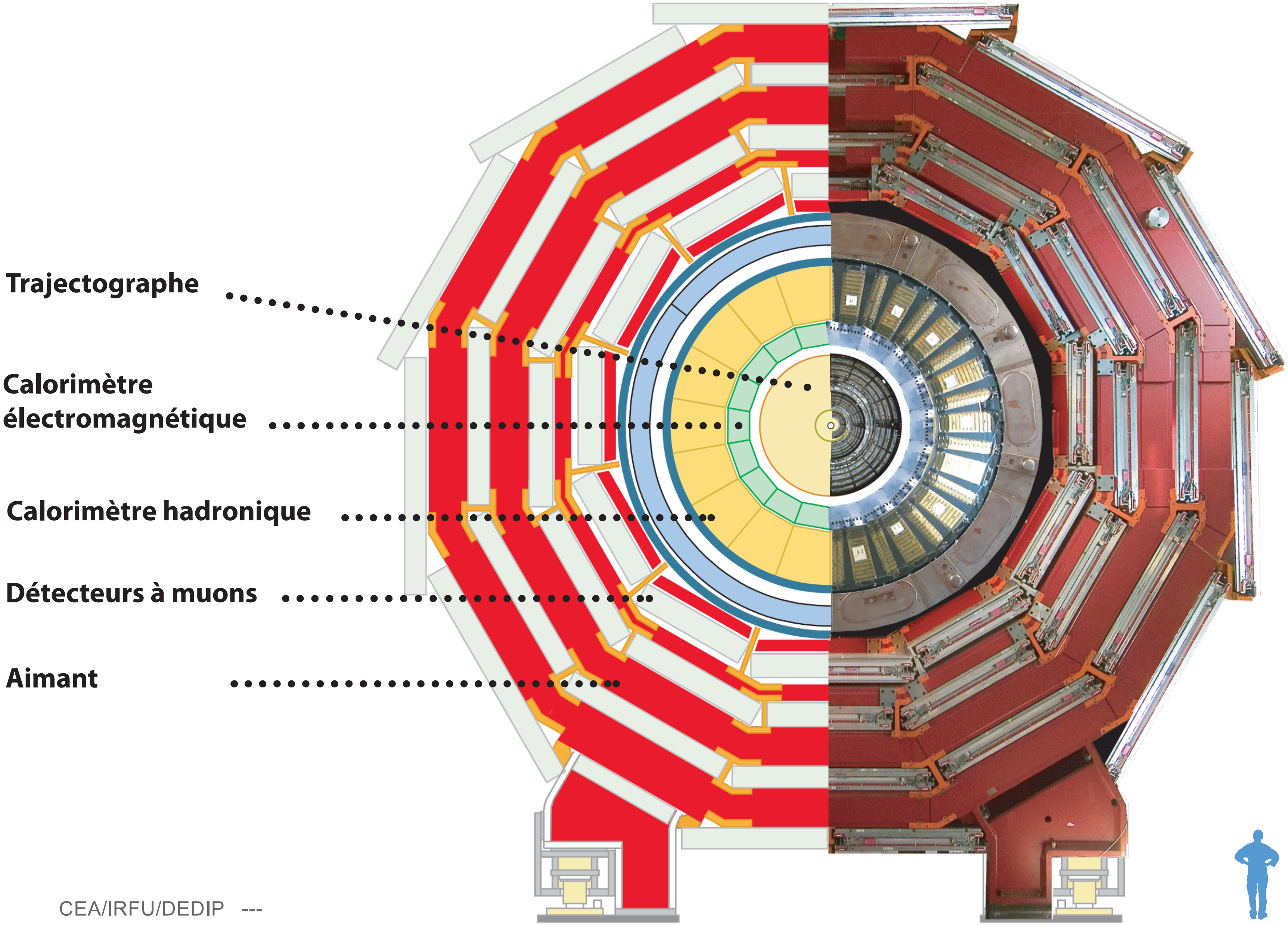
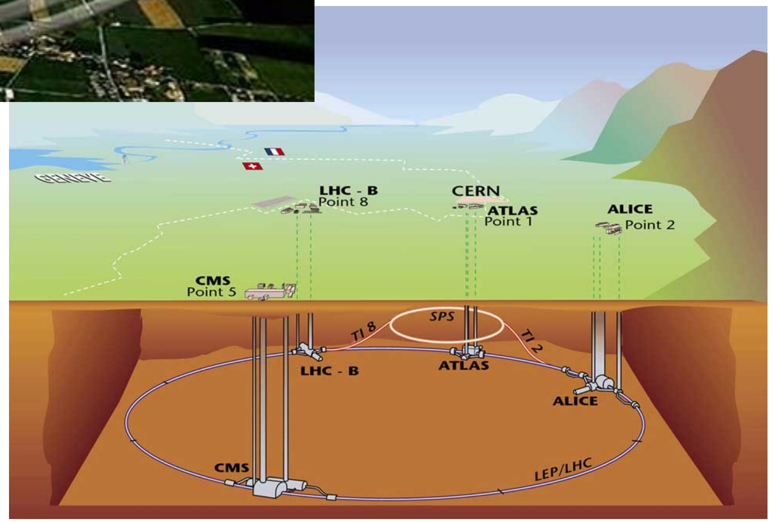
Compact Muon Solenoïd



CMS


Trajectographe
Calorimètre électromagnétique
Calorimètre hadronique
Détecteurs à muons
Aimant

Le Large Hadron Collider



27 km

8.3 T

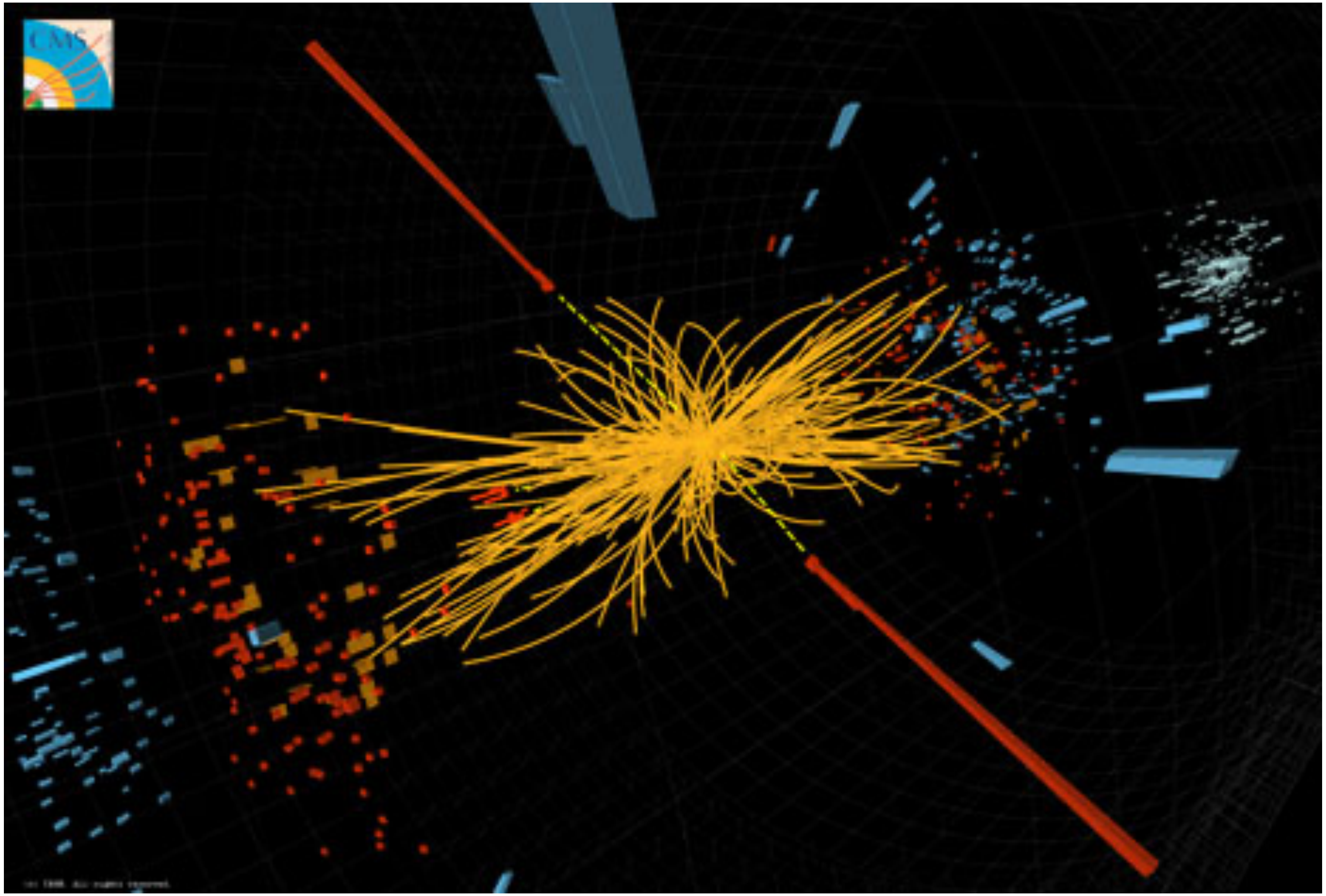
1.9 K (**-271.3 °C**)

10^{-13} atm

362 **MJ**

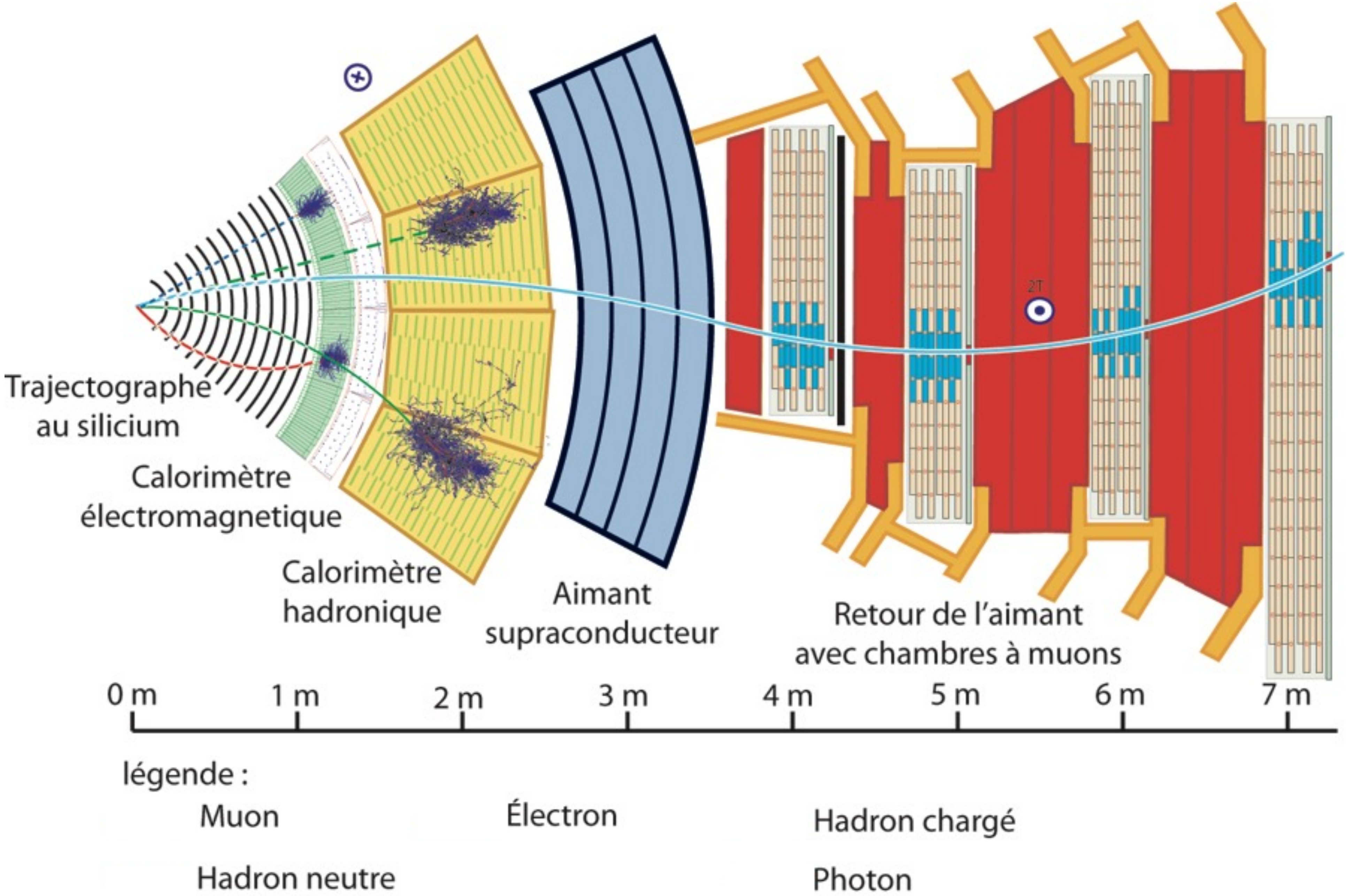
The LHC accelerator

CMS EVENT

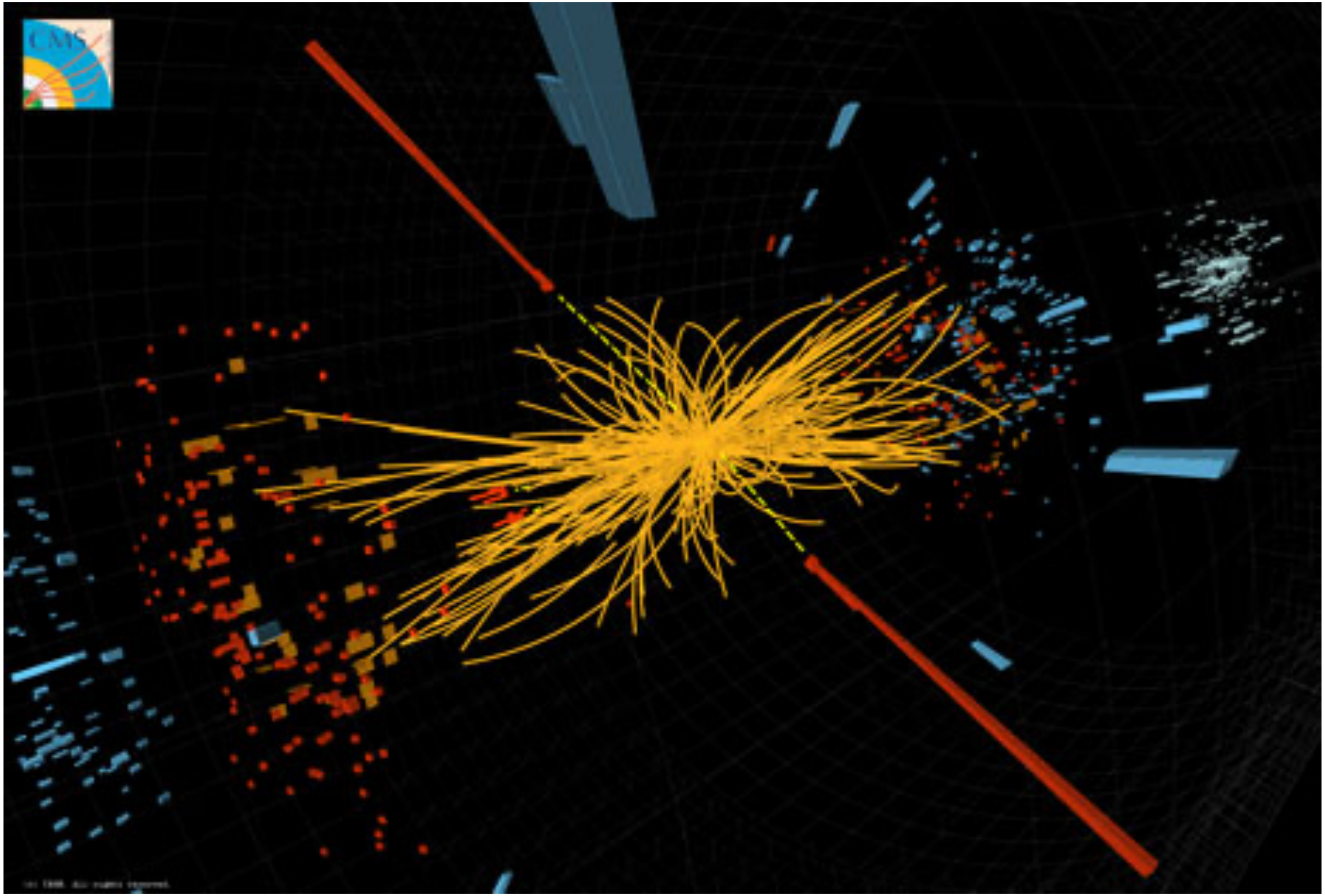


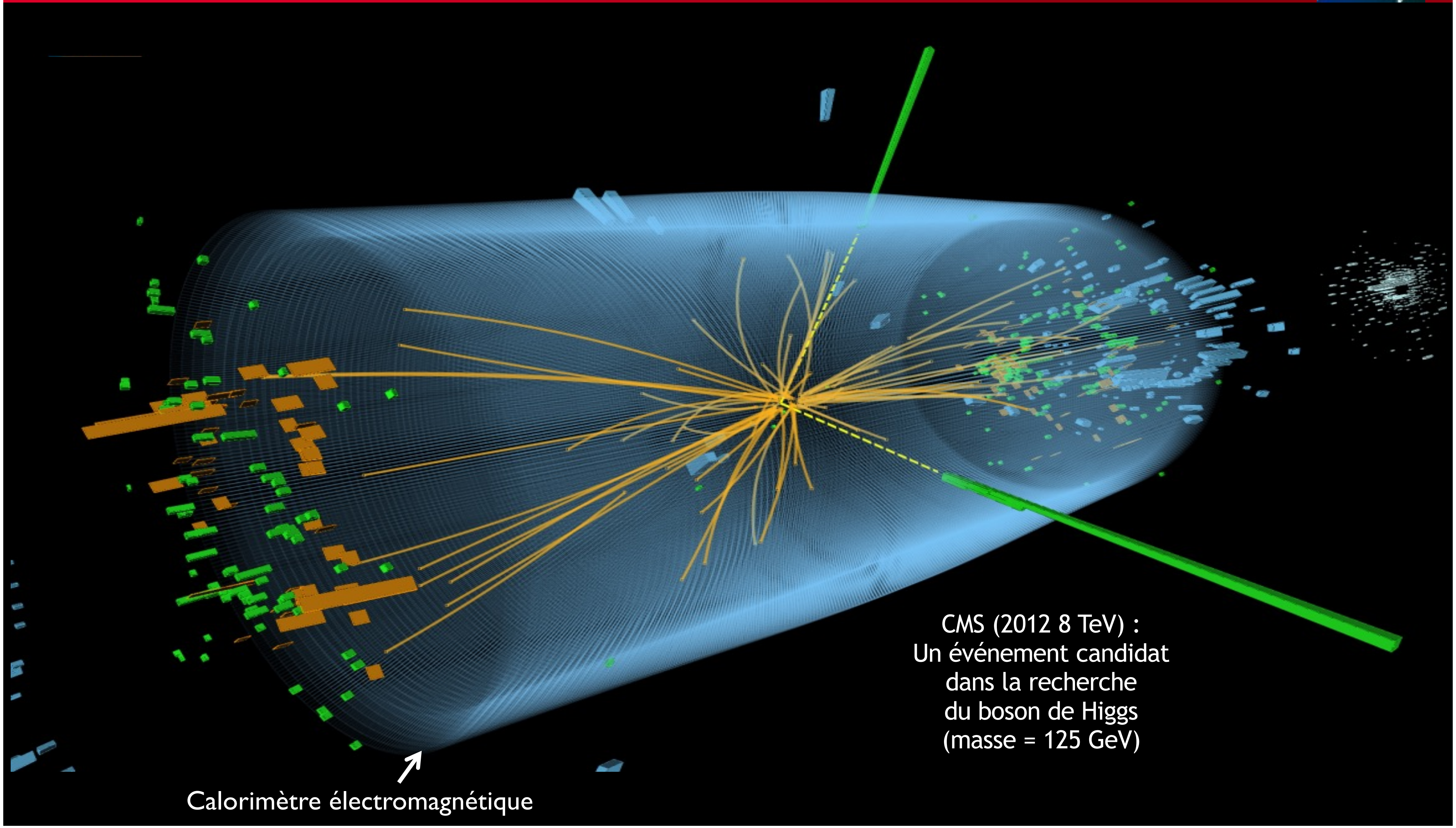
Courbes = trajectoire mesurée par les trajectographes

Barres = Mesure d'énergies dans les calorimètre


2T
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

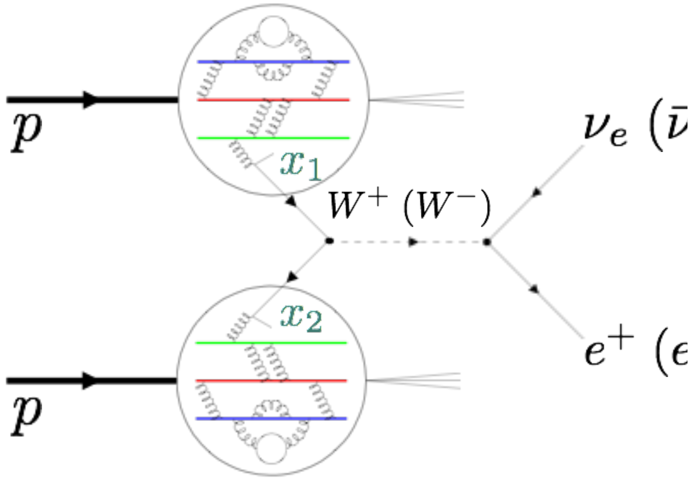
CMS EVENT

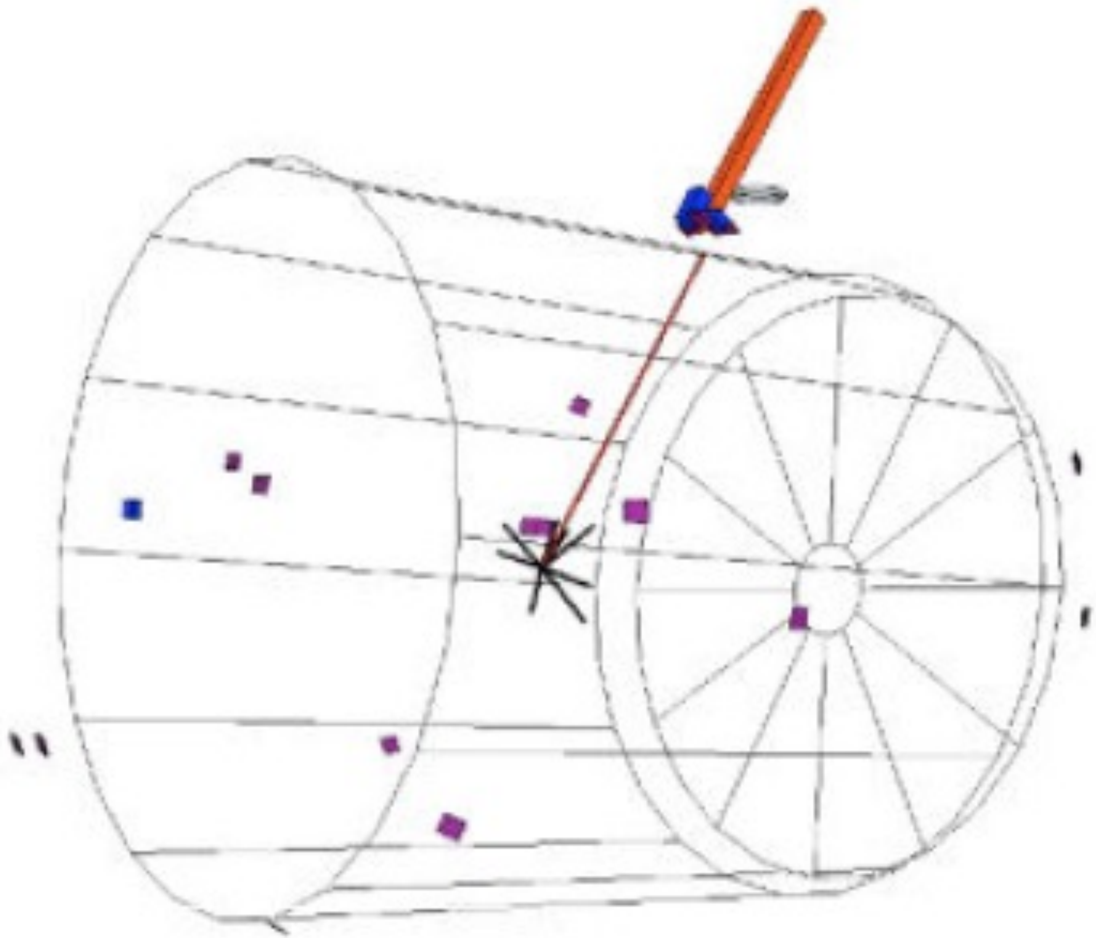



CMS (2012 8 TeV) :
Un événement candidat
dans la recherche
du boson de Higgs
(masse = 125 GeV)
Calorimètre électromagnétique

QCD EXAMPLE – W CROSS-SECTION

W event -> Isolated lepton





STAR experiment at BNL

Mesurer l'infiniment petit et observer l'infiniment grand

DE LA RECHERCHE À L'INDUSTRIE

Mardi 11/07 11h (Orme)
Lundi 17/07 12h (Centre)
Visite Labo 14h (Centre)
Mardi 18/07 10h30 (Orsay)

Maxence Vandenbroucke
07/2023

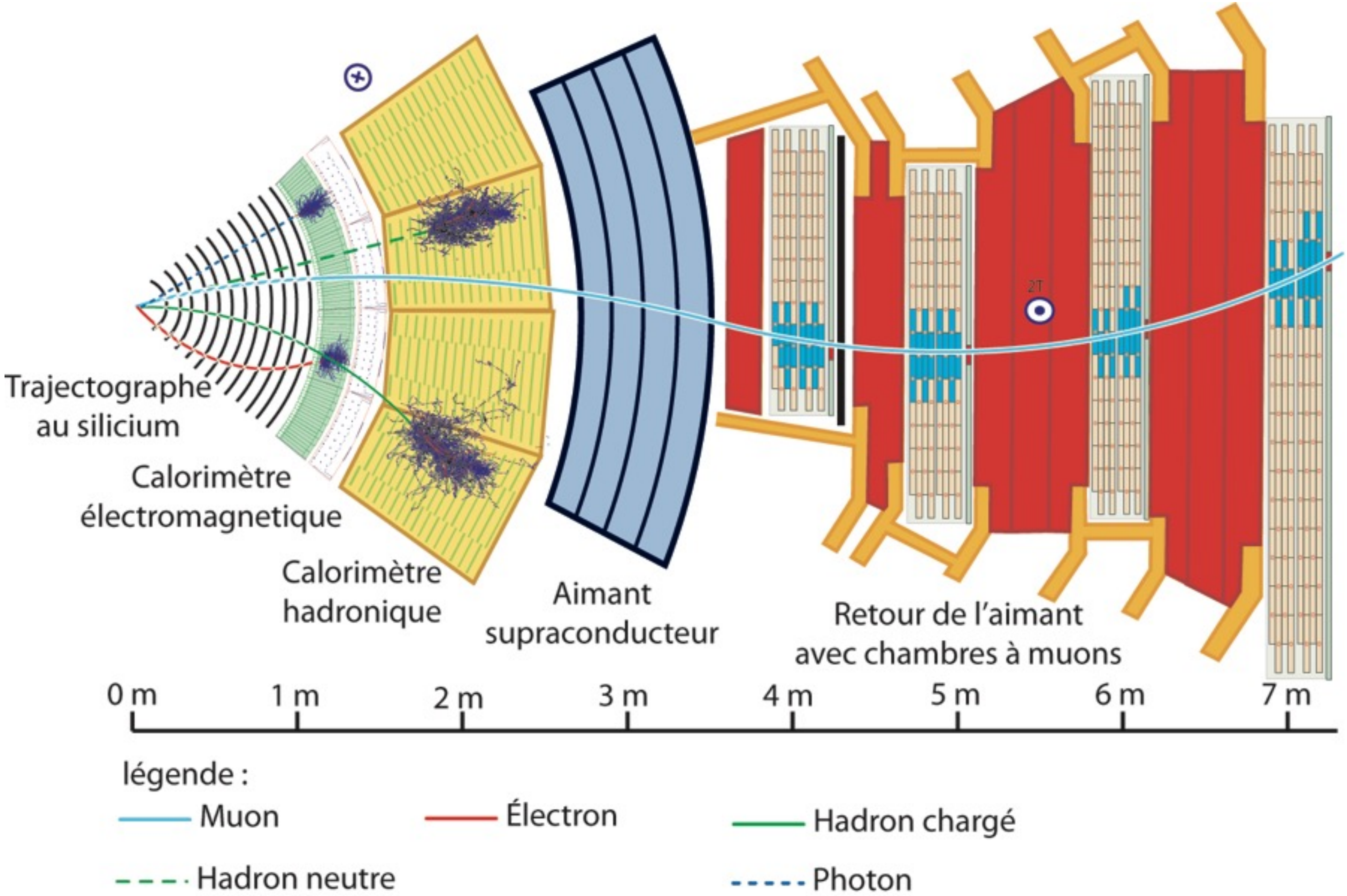
université PARIS-SACLAY

Cours 2 : Les détecteurs de particules

- Détecteurs au Silicium
- Calorimétrie
- Scintillation
- Détecteurs Gazeux

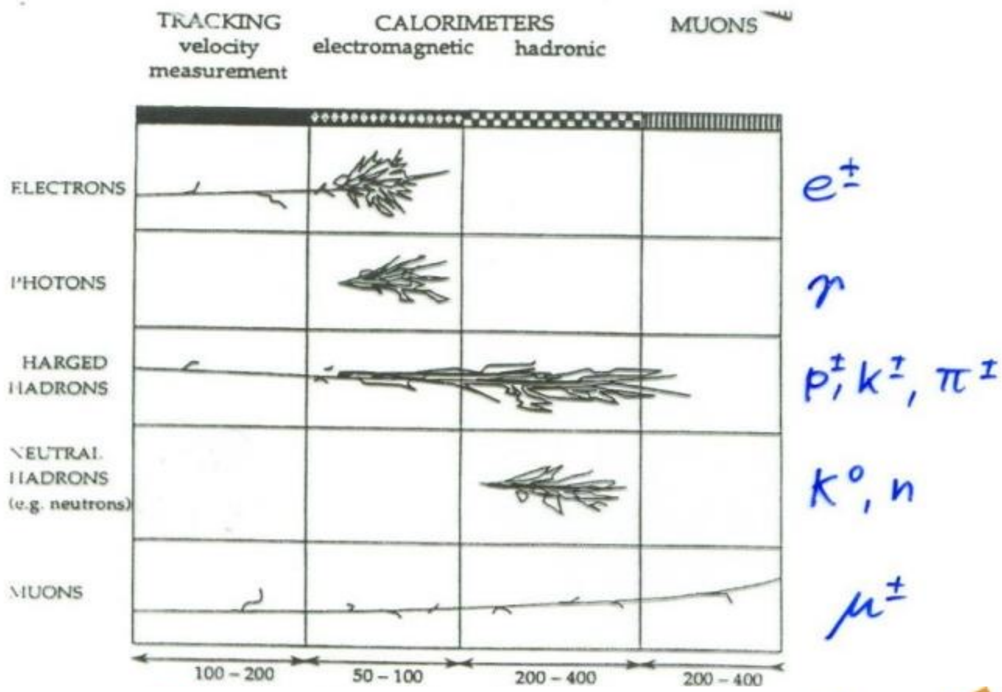
Basé sur les cours de Stefano Panebianco (CEA/IRFU),
et le cours de Werner Riegler (CERN),
Particle Detectors , Second Edition, C. Grupen & B. Shwartz

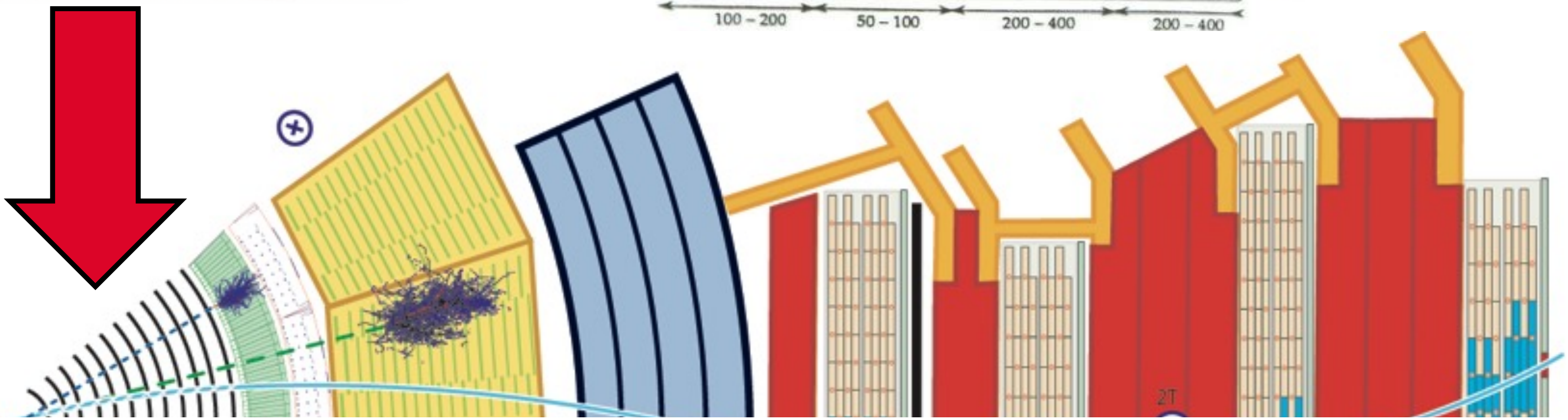
CMS 3



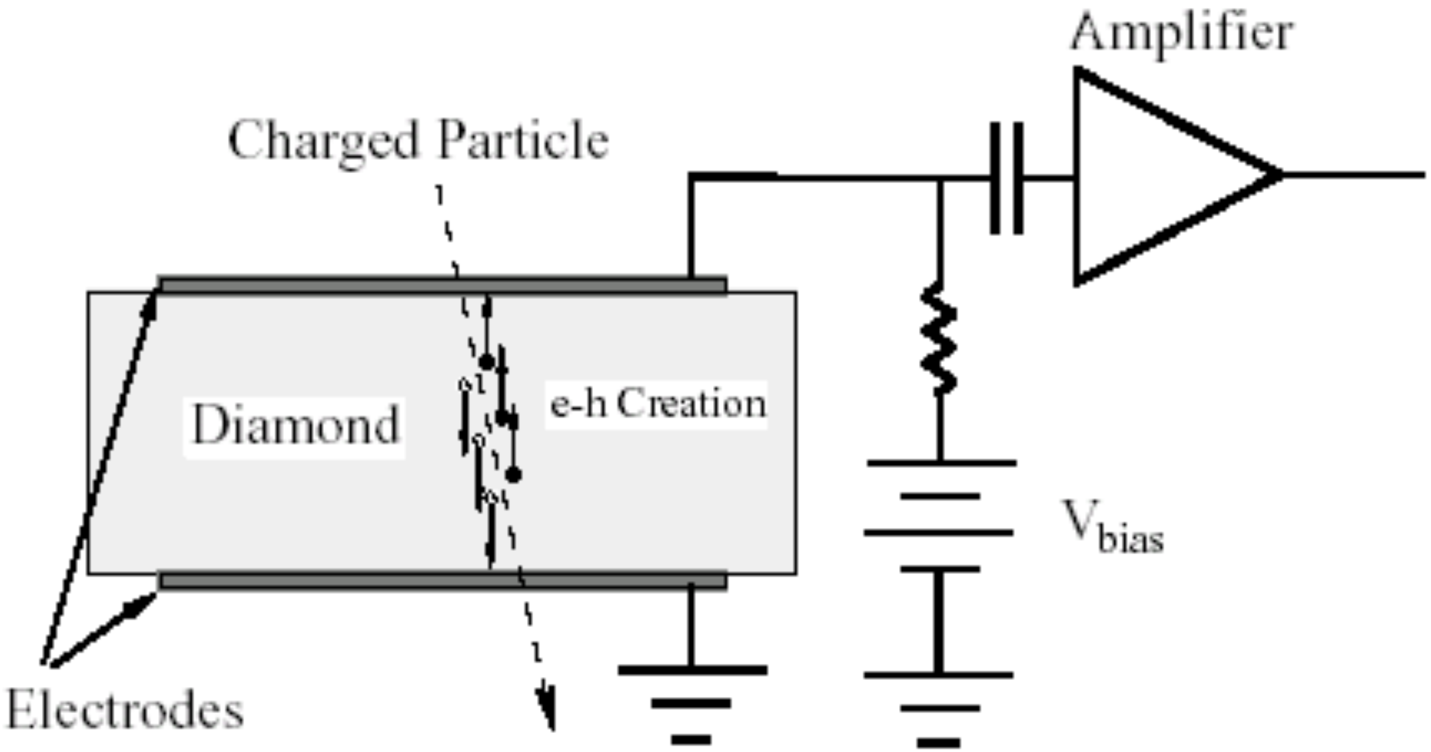
2T
Trajectographe au silicium
Calorimètre électromagnetique
Calorimètre hadronique
Aimant supraconducteur
Retour de l'aimant avec chambres à muons
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
légende :
Muon
Électron
Hadron chargé
Hadron neutre
Photon

Trajectographes Semi-Conducteur

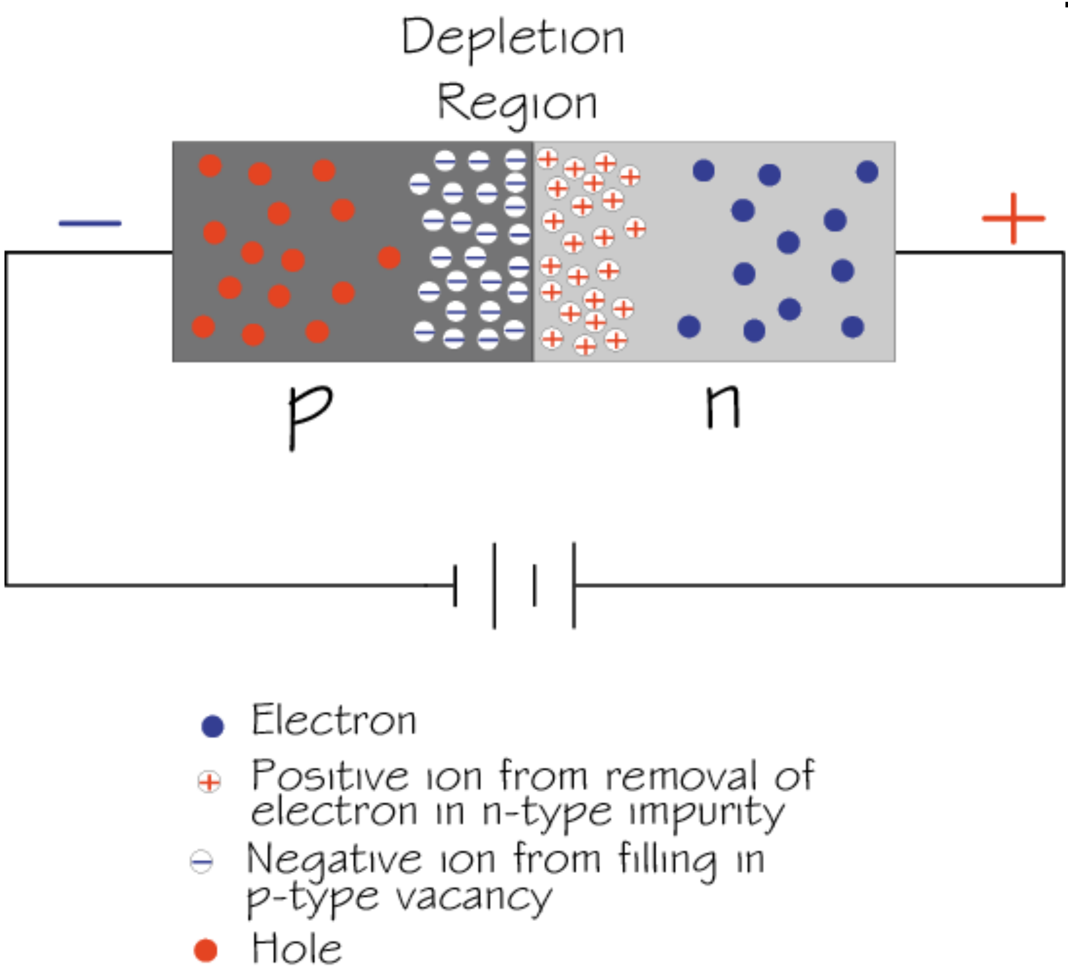


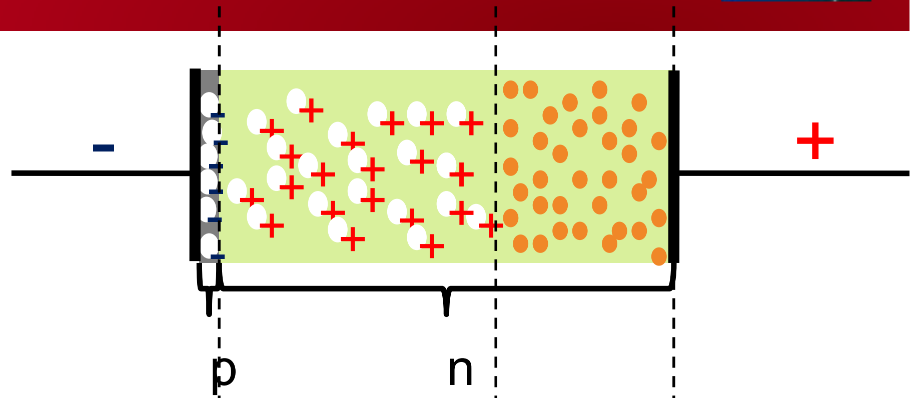


Les Détecteurs à base de Semi-Conducteur



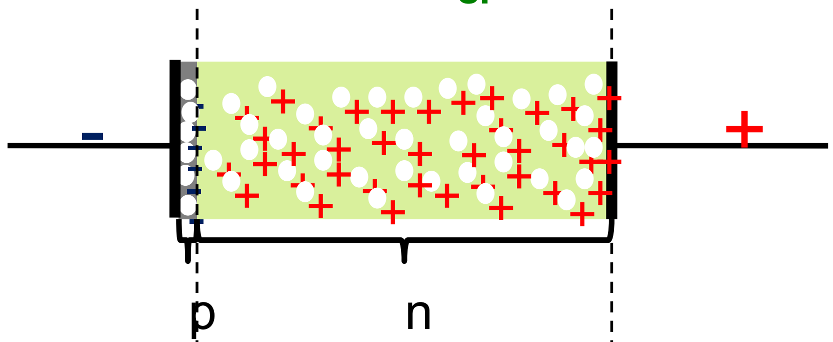
Les Détecteurs à base de Semi-Conducteur





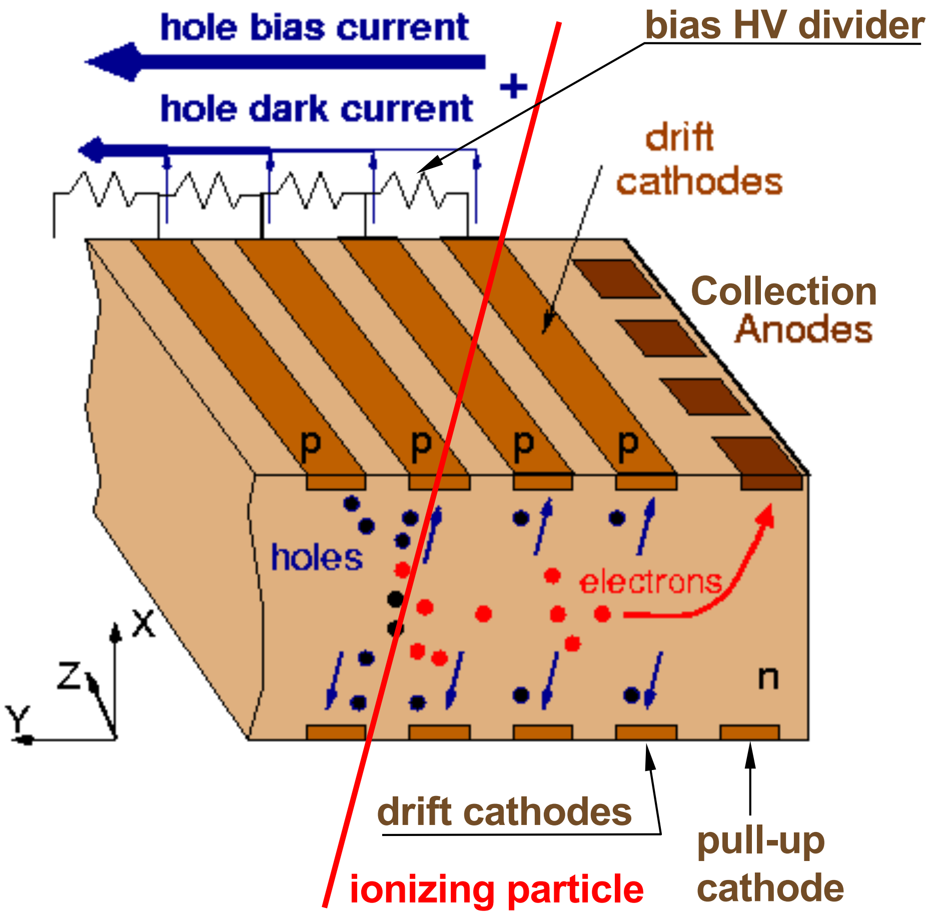
Zone without free charge carriers positively charged. Sensitive Detector Volume.

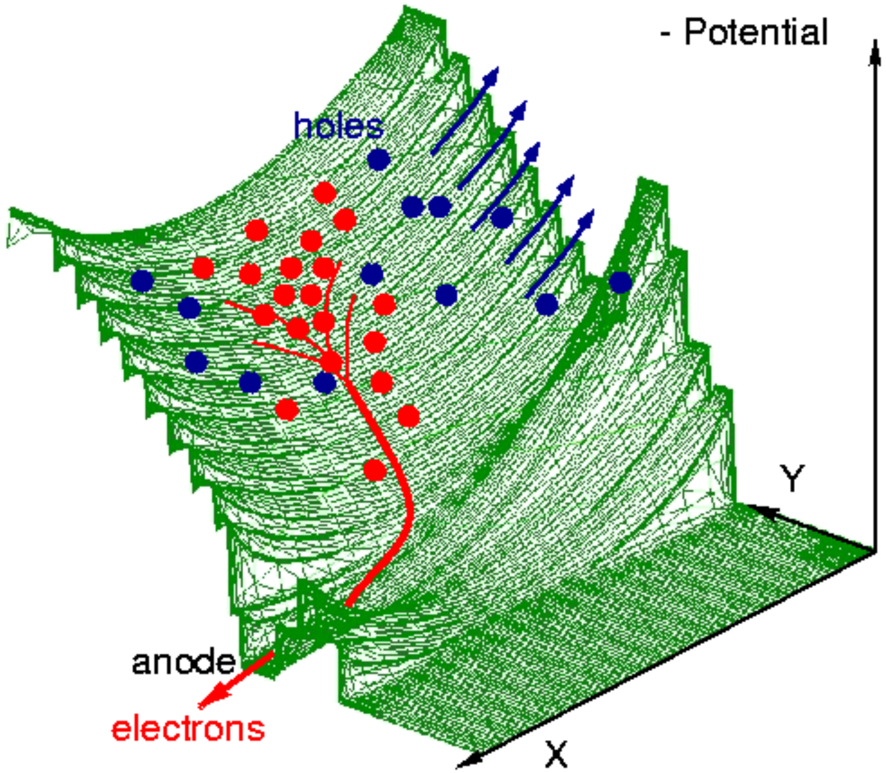
Zone with free electrons. Conductive. Insensitive to particles.

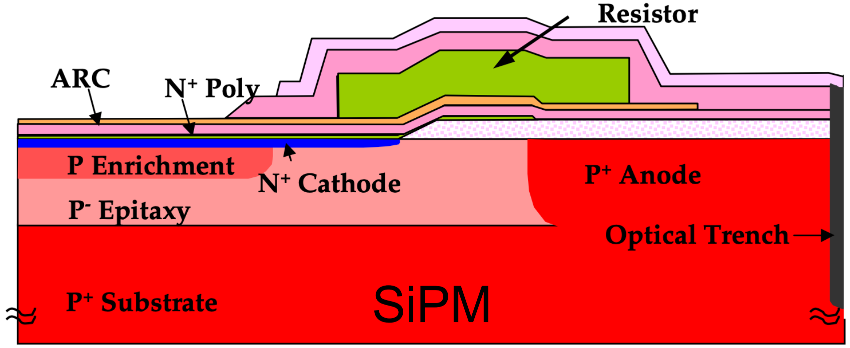


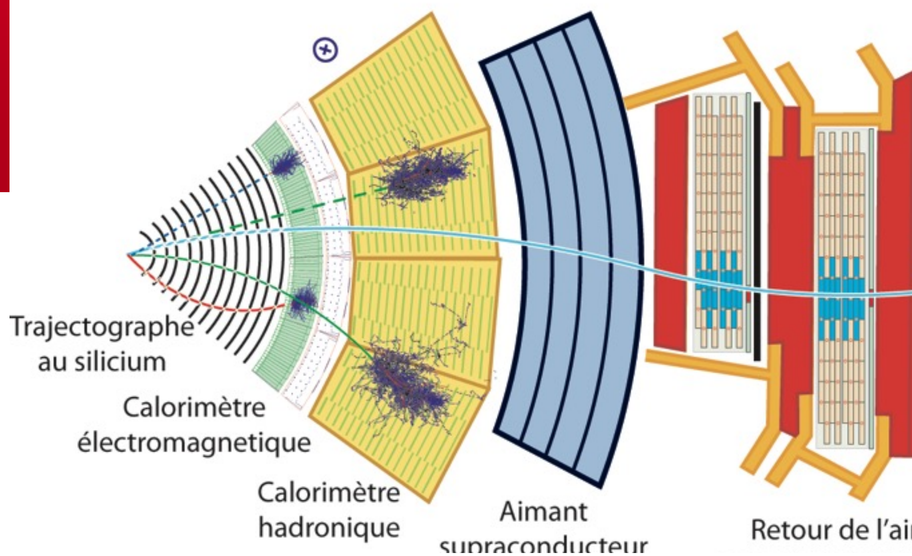
Fully depleted

Silicon Drift Detector

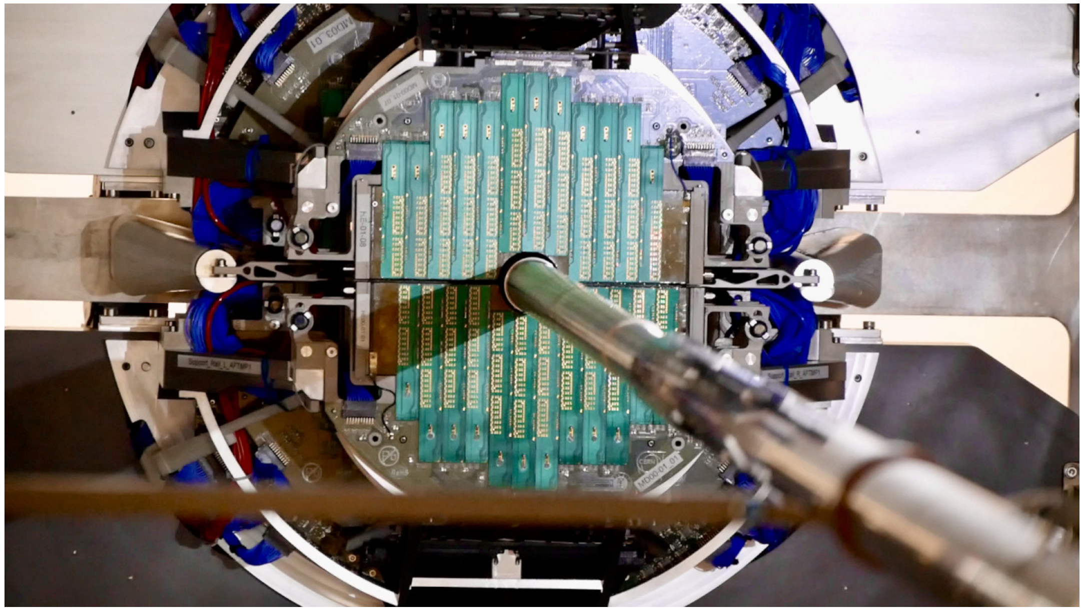


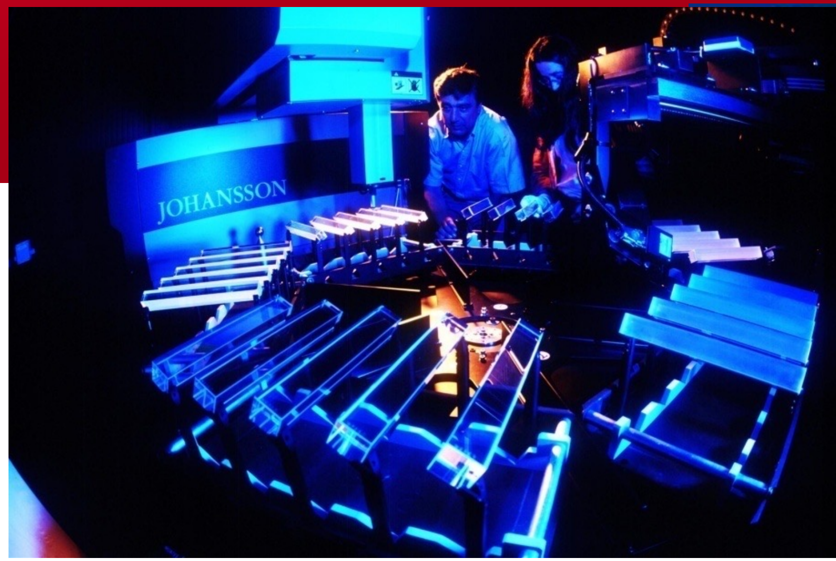




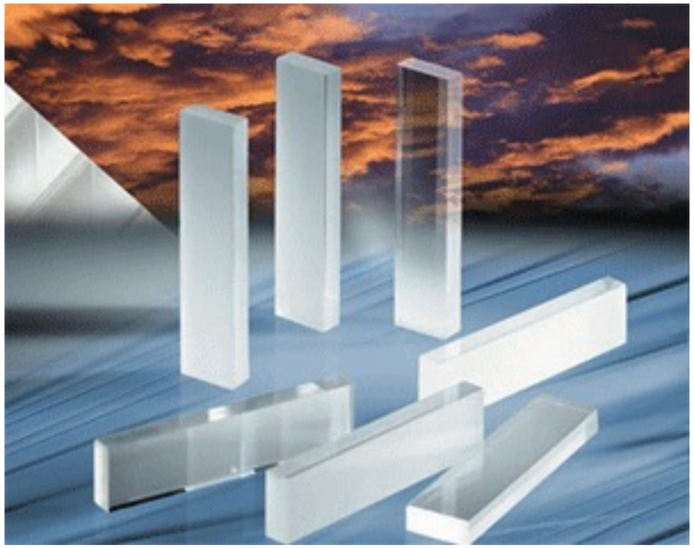


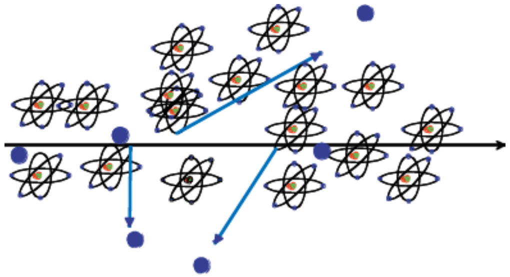
ALICE – MFT (Muon Forward Tracker)





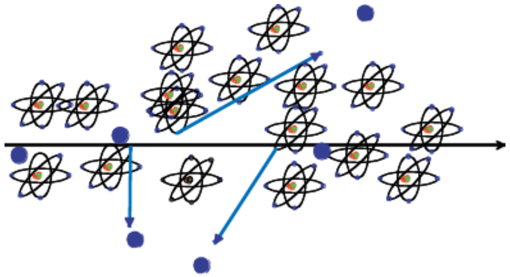
Les Détecteur à base de scintillation





Detectors based on Registration of excited Atoms → Scintillators

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



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.*

Organic ('Plastic') Scintillators

Inorganic (Crystal) Scintillators

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

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

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

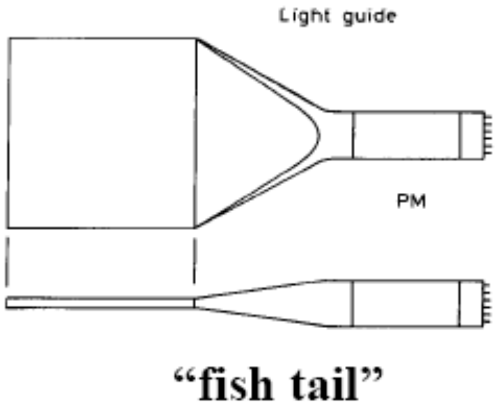
	Relative light output	λ_{max} emission (nm)	Decay time (ns)	Density (g/cm^3)
Inorganic crystals				
NaI(Tl)	230	415	230	3.67
CsI(Tl)	250	560	900	4.51
$Bi_4Ge_3O_{12}$ (BGO)	23–86	480	300	7.13
Organic crystals				
Anthracene	100	448	22	1.25
Trans-stilbene	75	384	4.5	1.16
Naphthalene	32	330–348	76–96	1.03
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[b]	

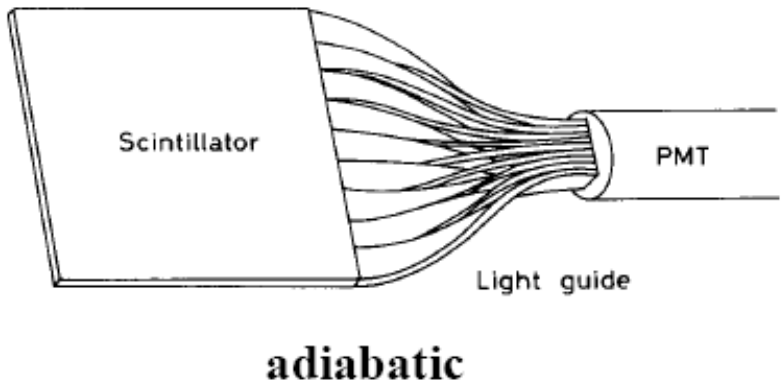
LHC bunchcrossing 25ns

LEP bunchcrossing 25µs

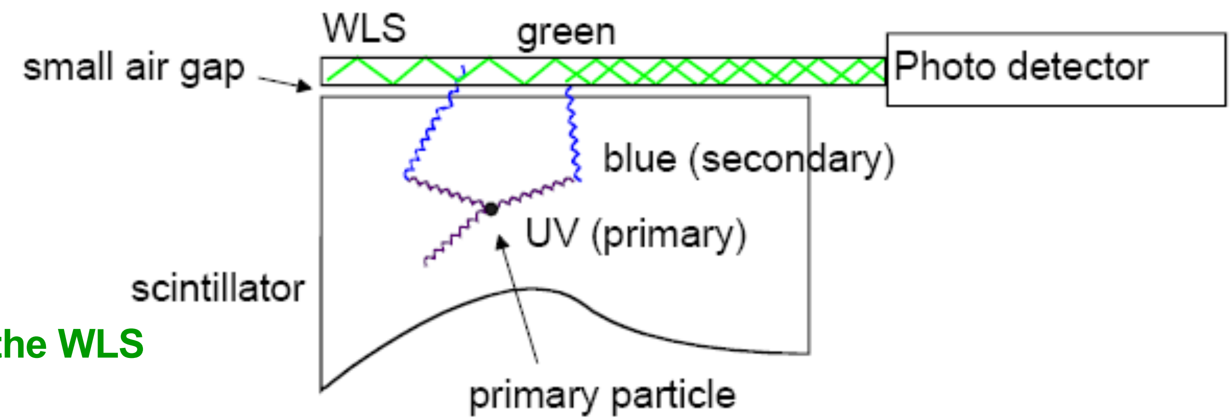
Typical Geometries:

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



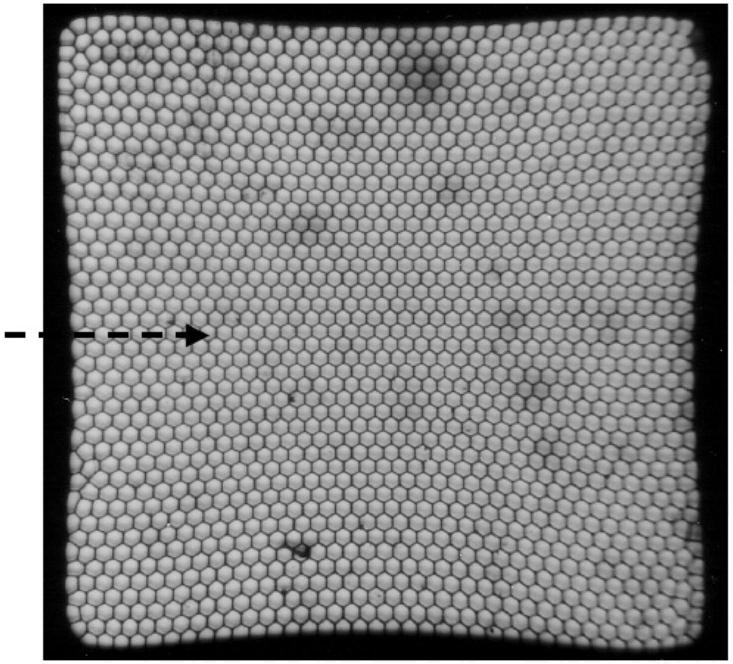


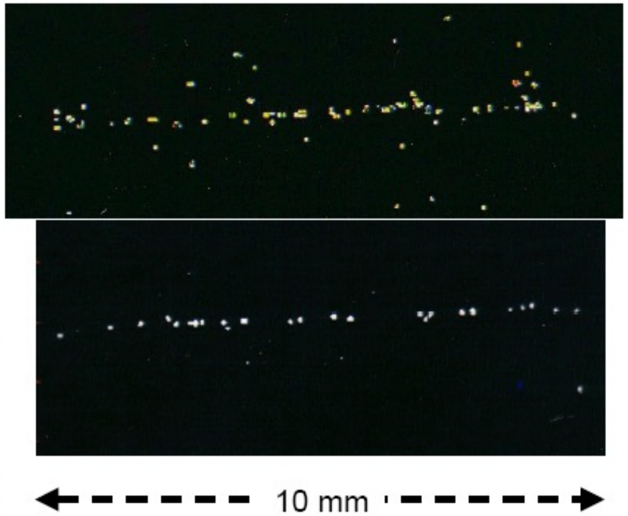
- wavelength shifter (WLS) bars



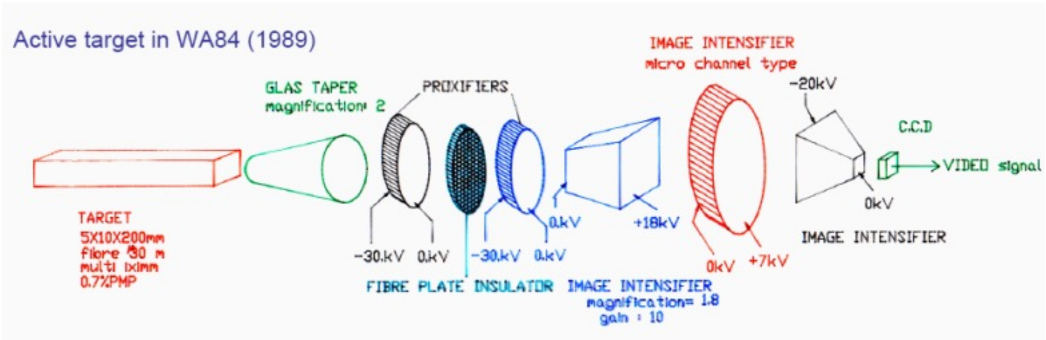
UV light enters the WLS material
Light is transformed into longer wavelength
→Total internal reflection inside the WLS material
→ 'transport' of the light to the photo detector

From C. Joram



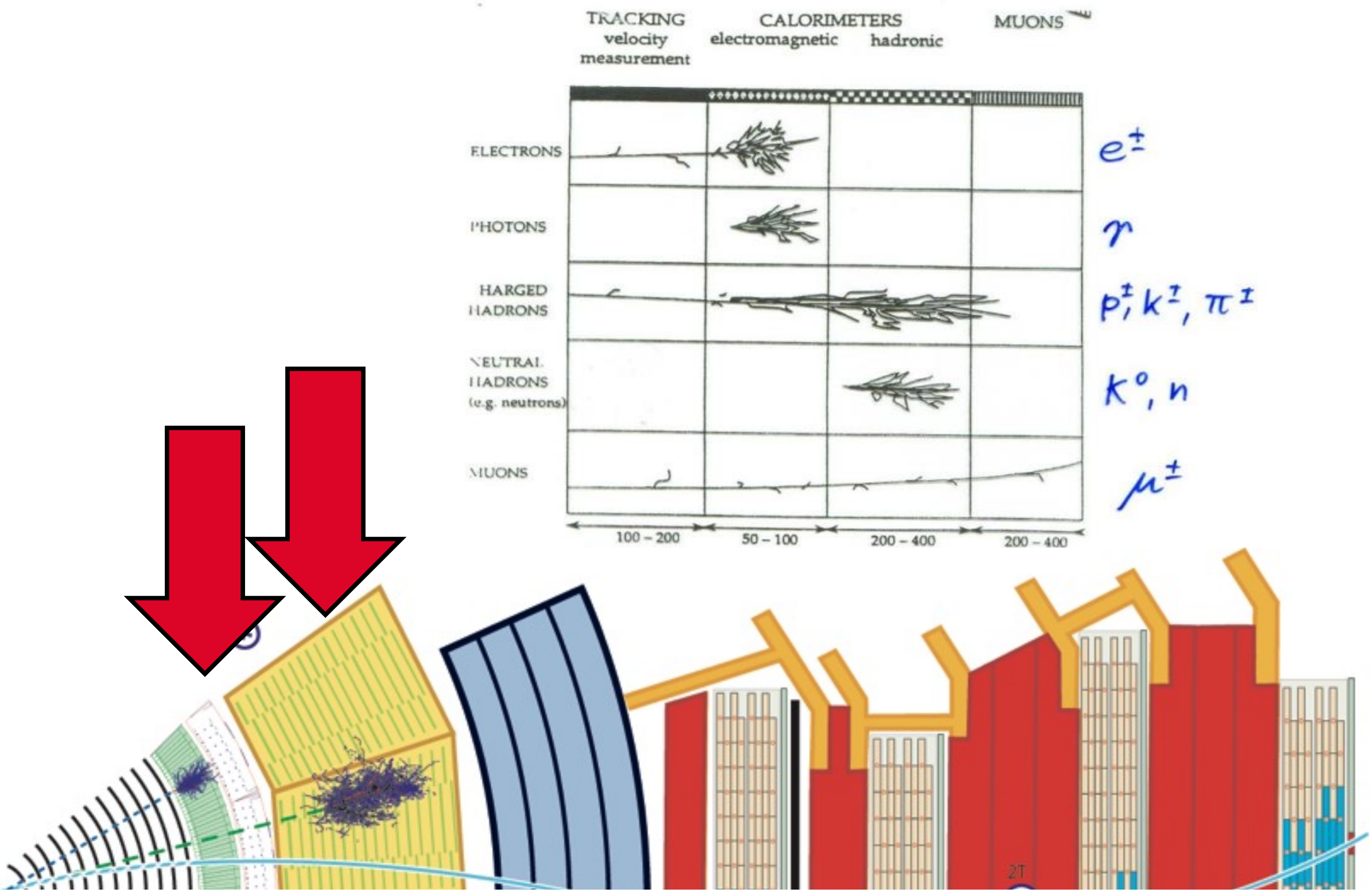


Images of tracks from 5 GeV/c pions (1989)



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:

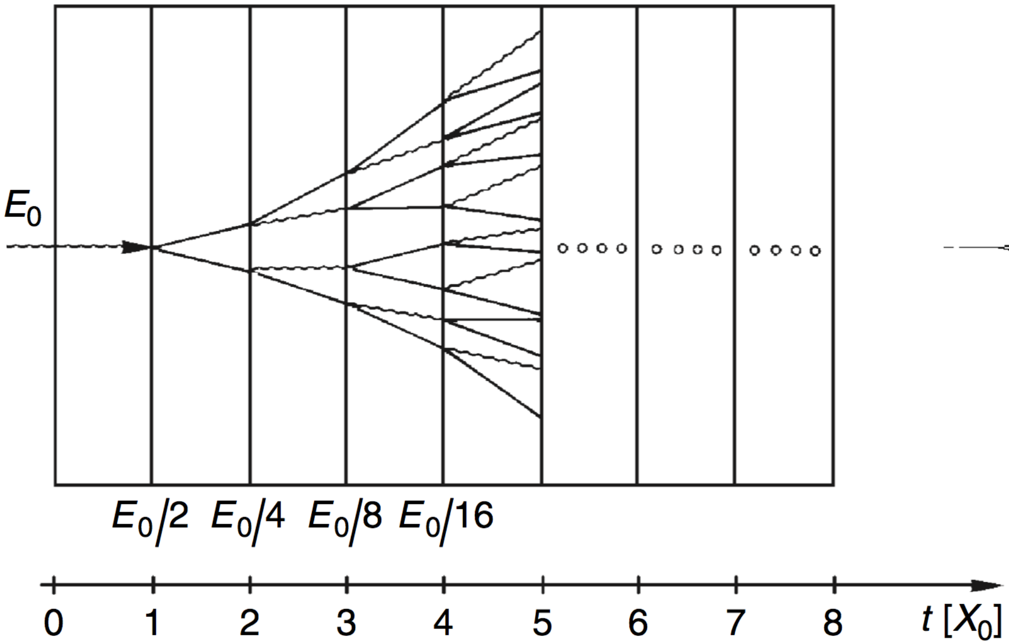
Homogeneous Calorimeters,
that are built of only one type of material that performs both tasks, energy degradation and signal generation.

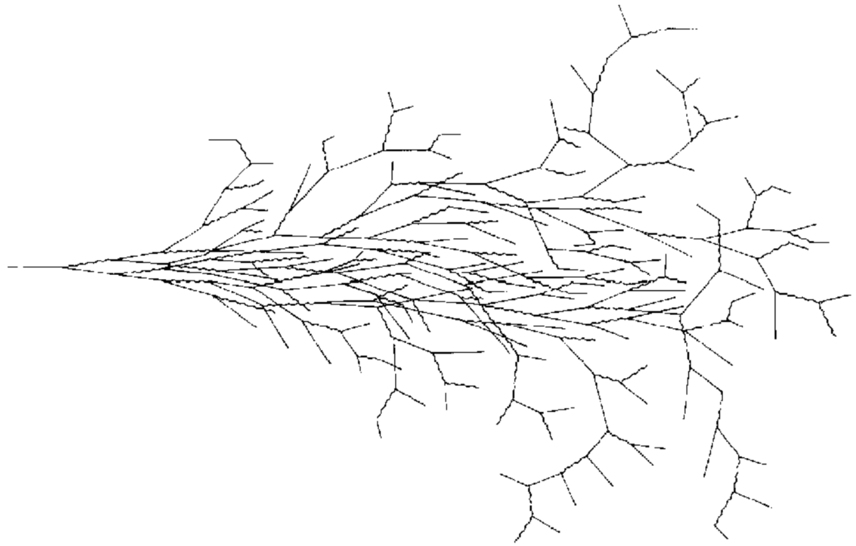
Sampling Calorimeters,
that consist of alternating layers of an absorber, a dense material used to degrade the energy of the incident particle, and an active medium that provides the detectable signal.

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

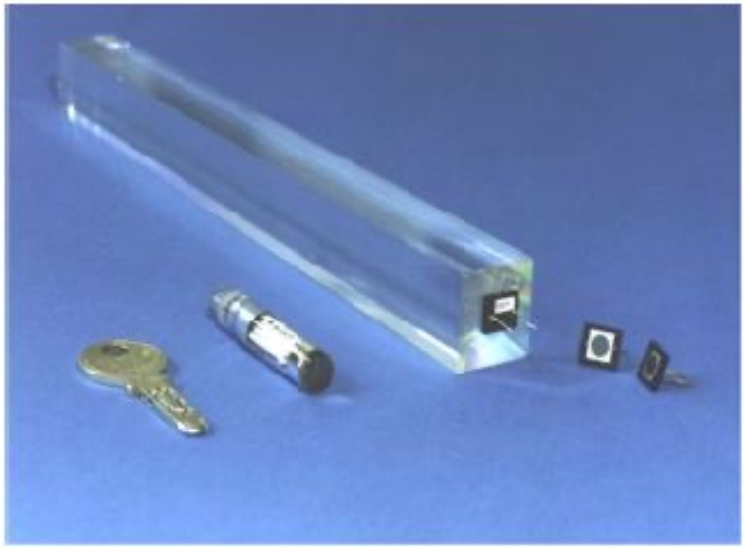
EM Calorimetry

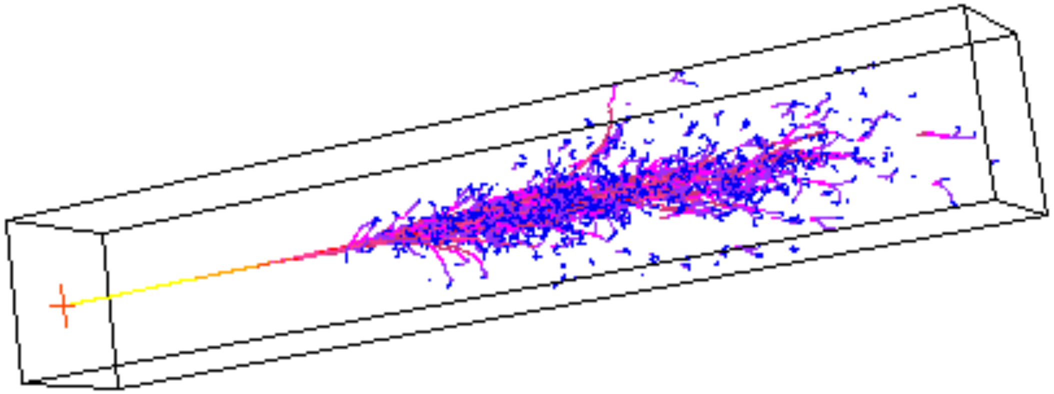
At high energies (higher than 100 MeV) electrons lose their energy almost exclusively by bremsstrahlung while photons lose their energy by electron–positron pair production

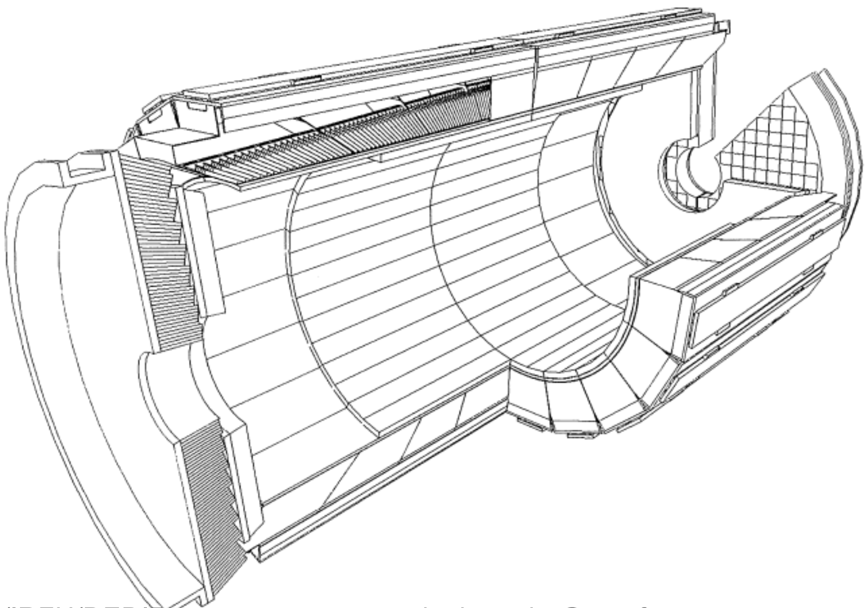




Crystals for Homogeneous EM Calorimetry







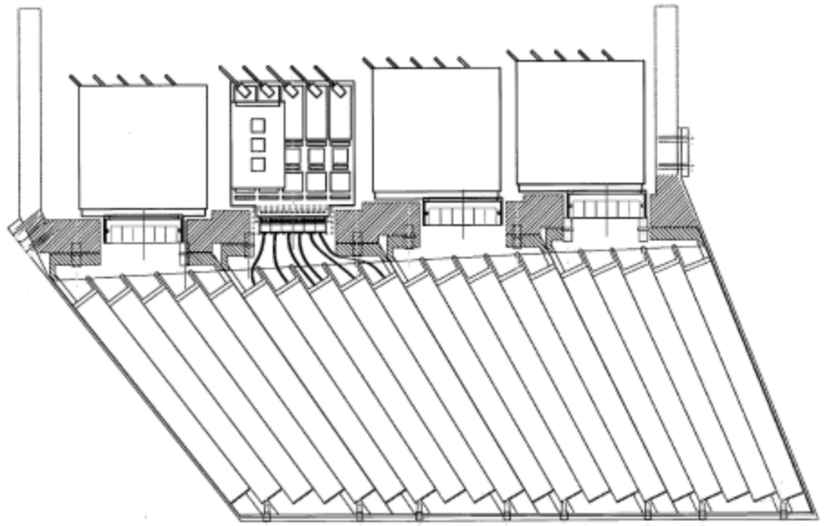


Fig. 2. Longitudinal drawing of module 2, showing the structure and the front-end electronics layout.

Hadron Calorimeters are Large because ⍰ is large

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

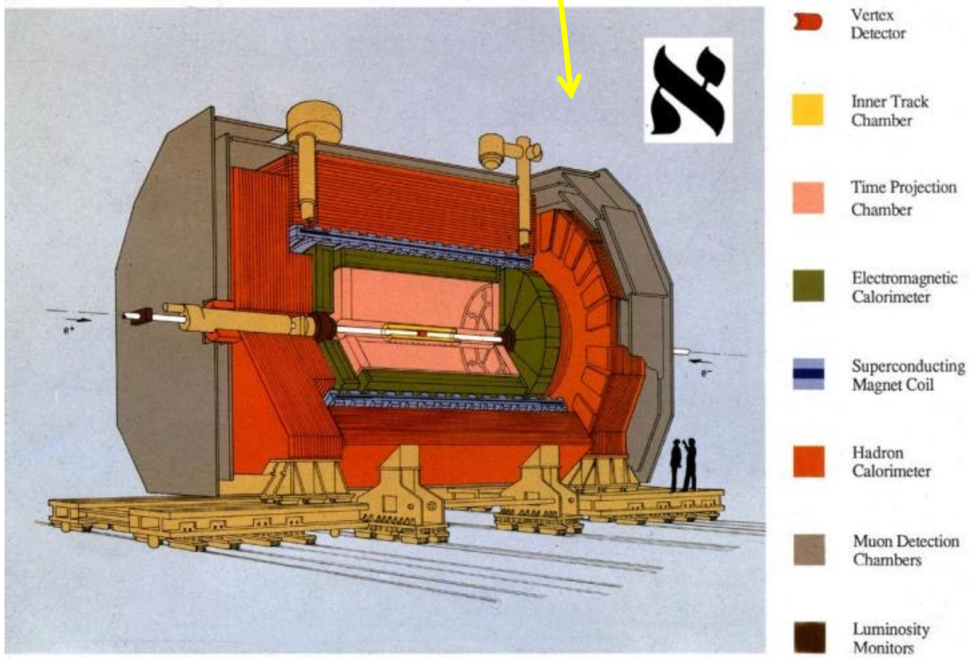
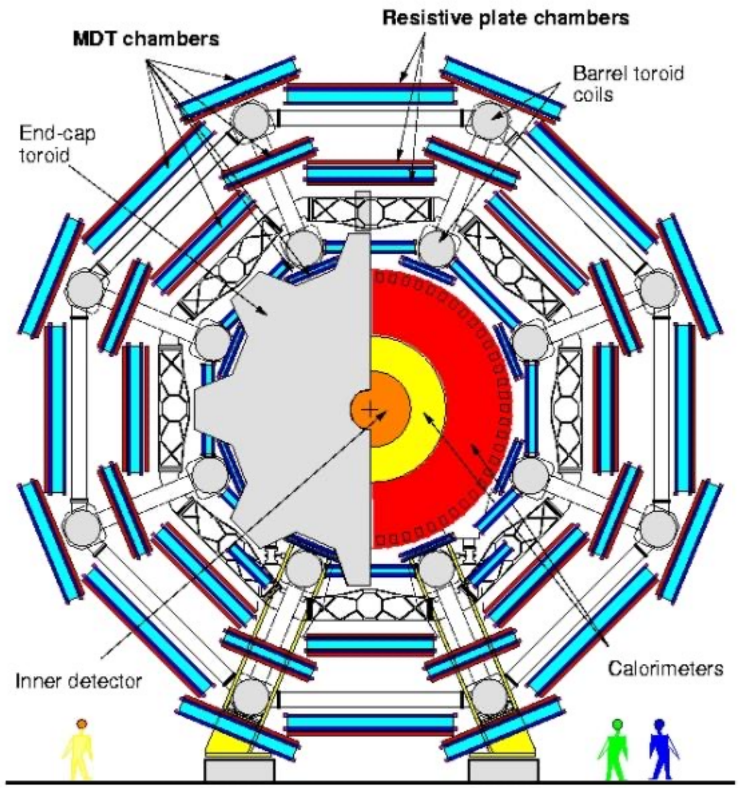
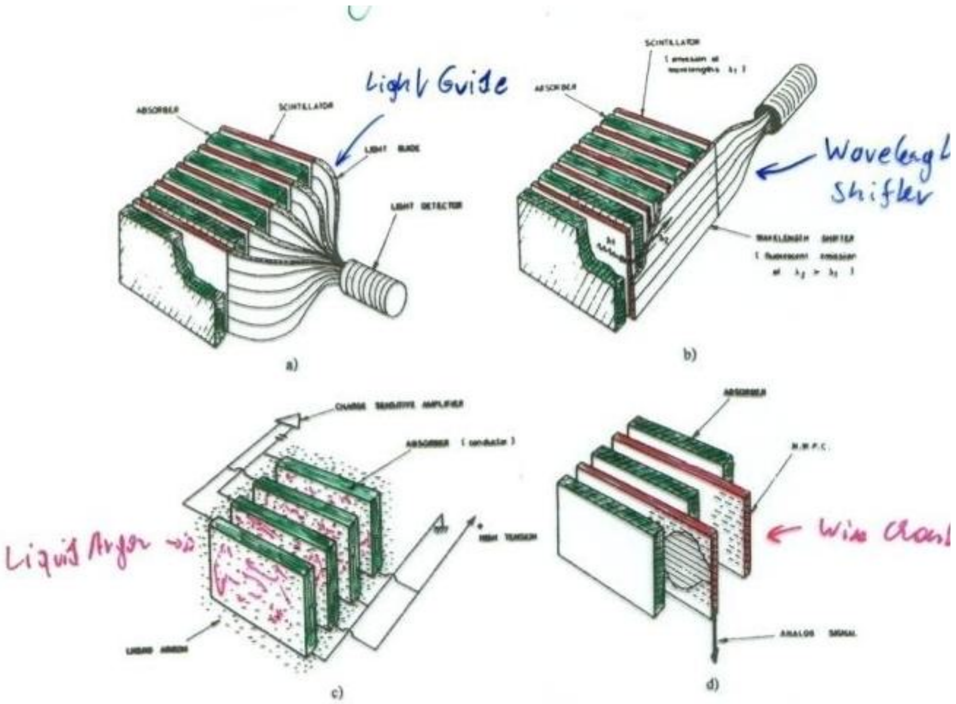
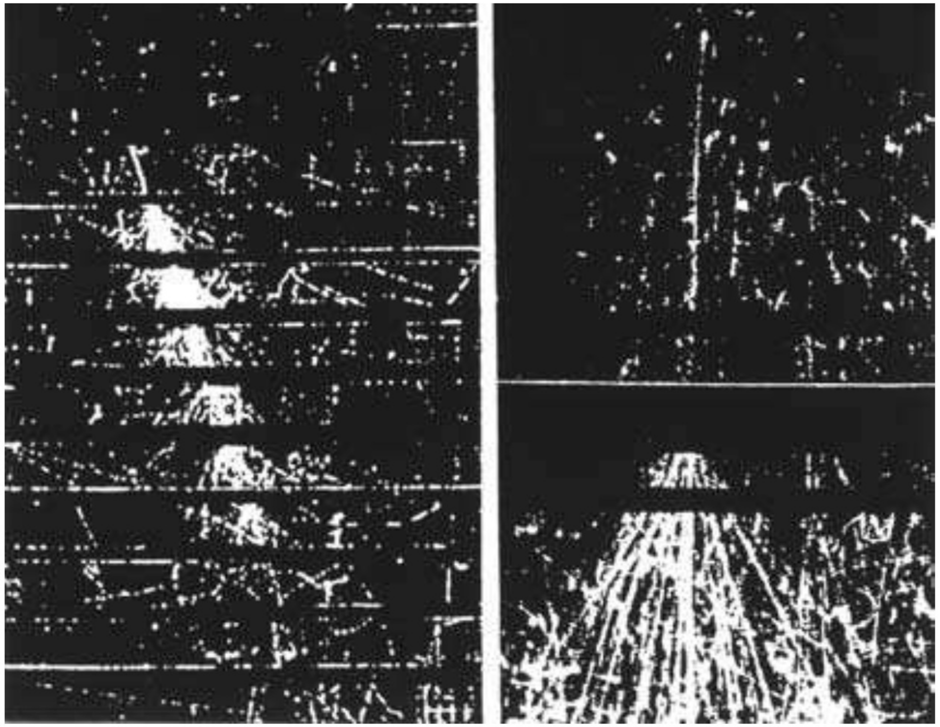


Fig. 1 - The ALEPH Detector

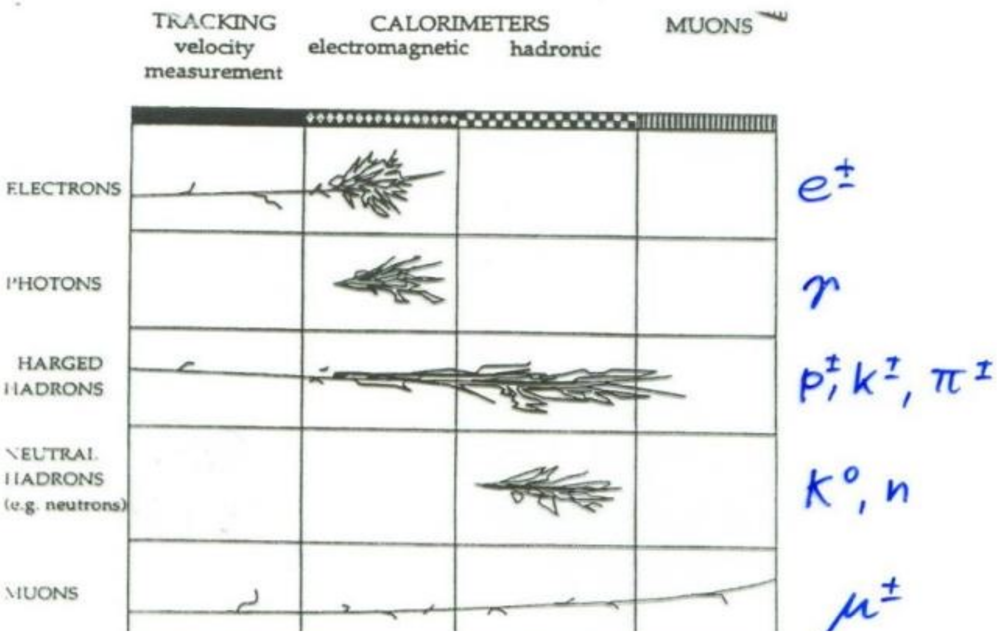


Sampling Calorimeters

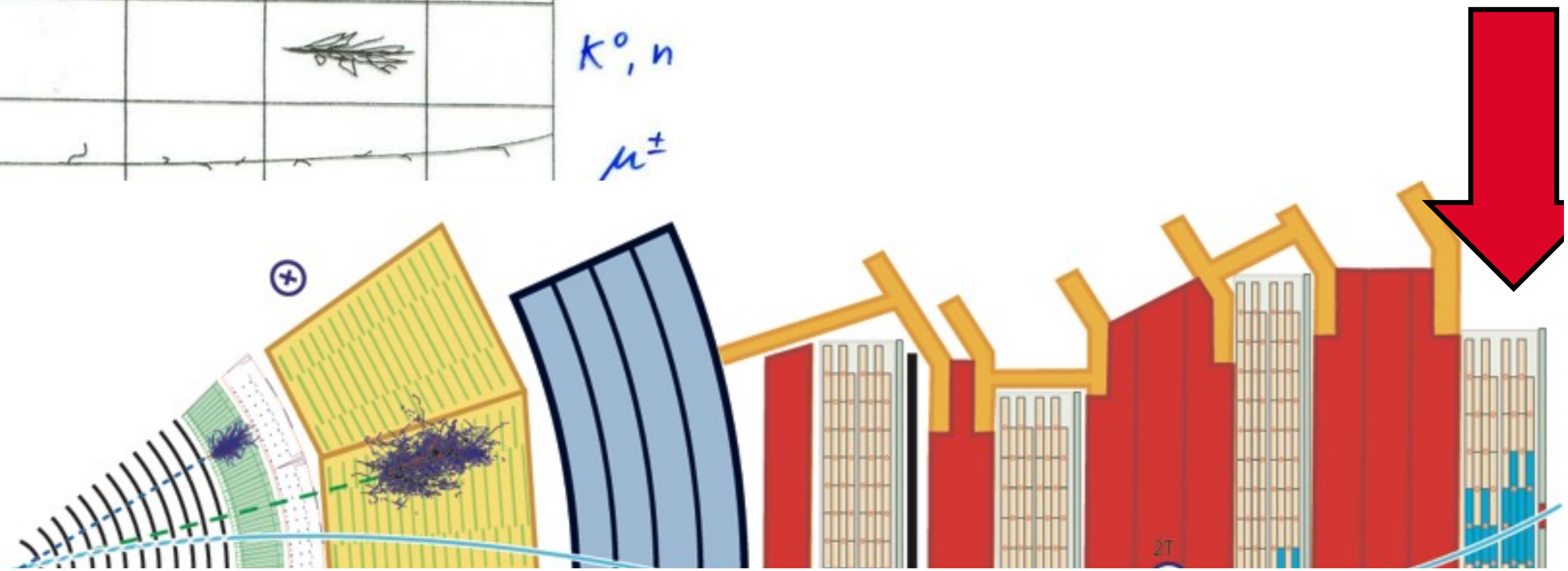




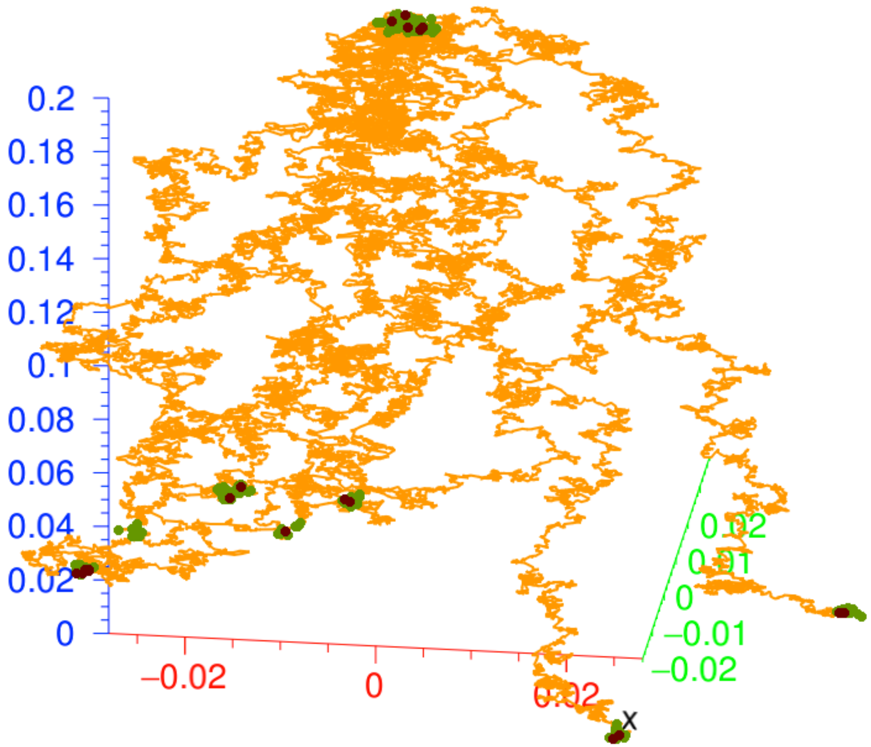
Détecteurs Gazeux



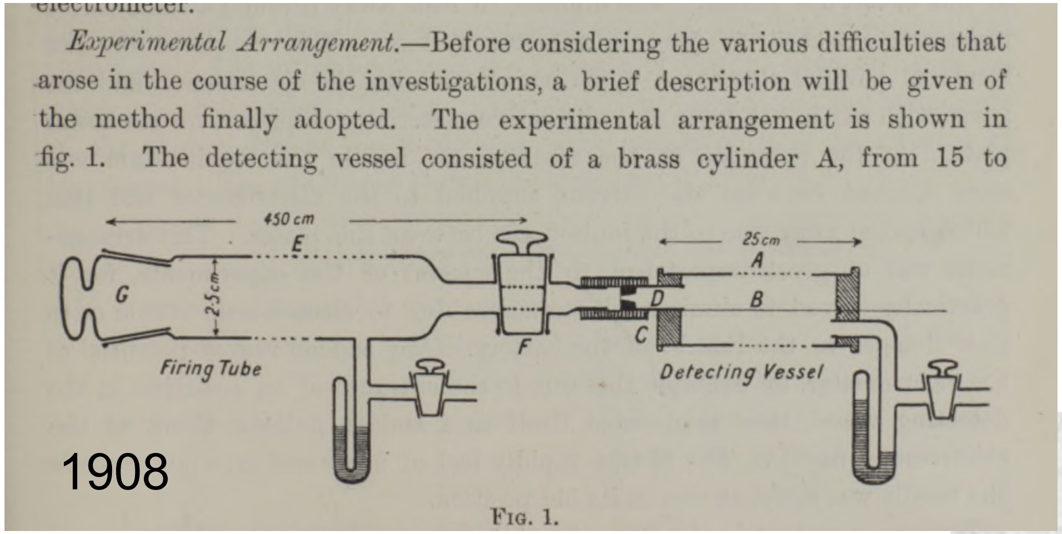
Muon Chambers ->



La détection des particules: exemple des détecteurs gazeux

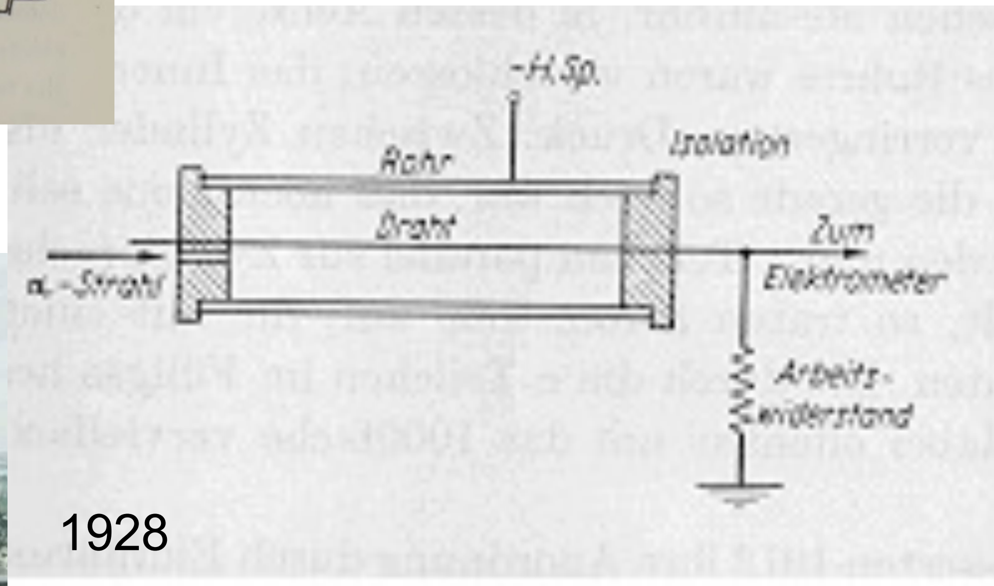


EXEMPLE SIMPLE DE DÉTECTEUR

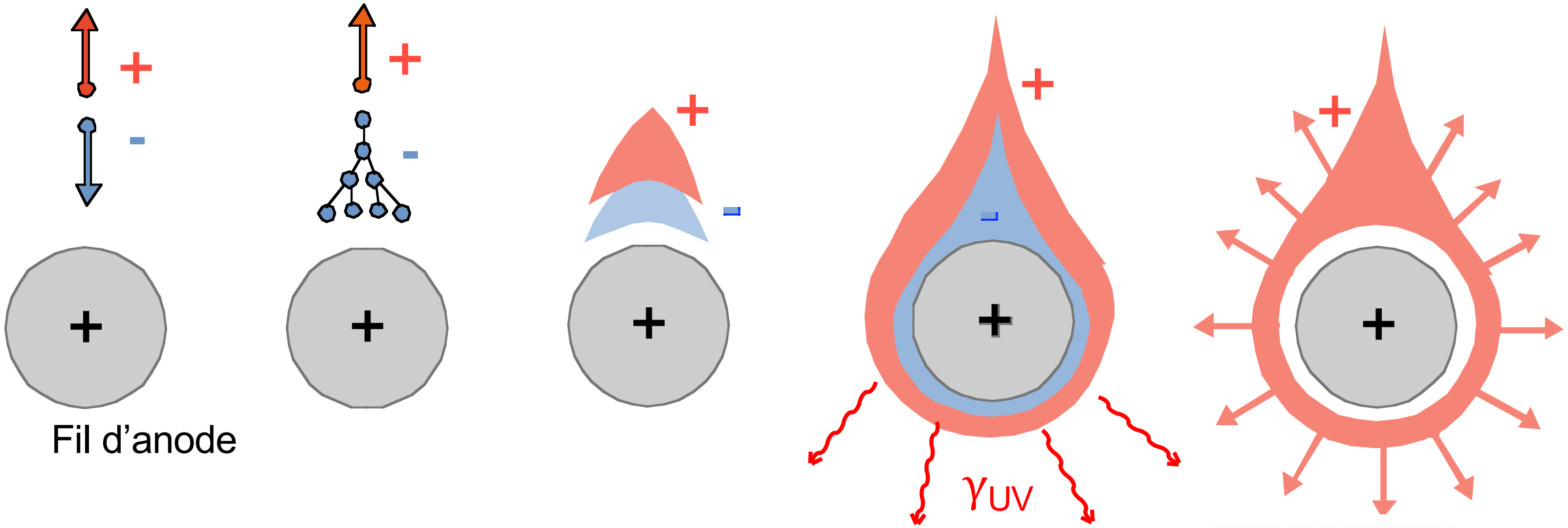

electrometer.

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

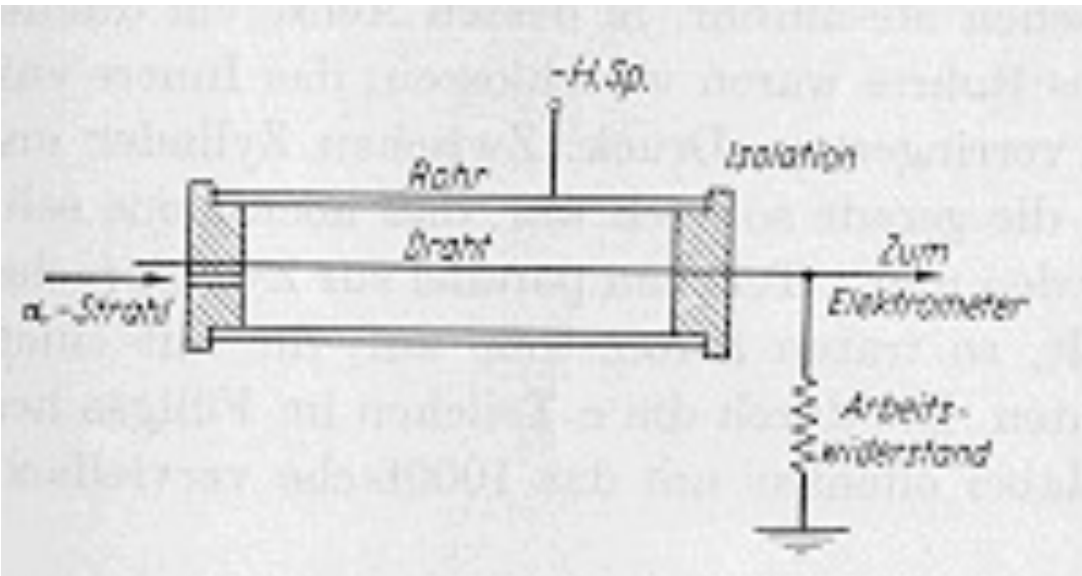
Fig. 1.

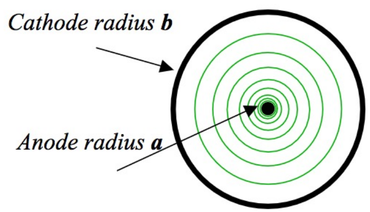


PHÉNOMÈNE D'AVALANCHE AUTOUR D'UN FILS



THIN ANODE WIRE





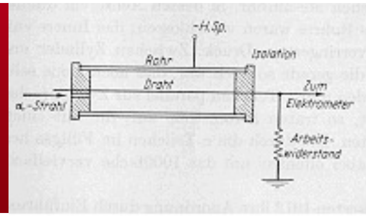
ELECTRIC FIELD AND POTENTIAL:

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

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

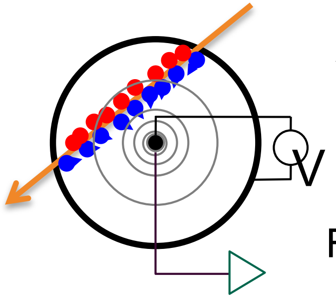
$$C = \frac{2\pi\varepsilon_0}{\ln(b/a)}$$ capacitance per unit length

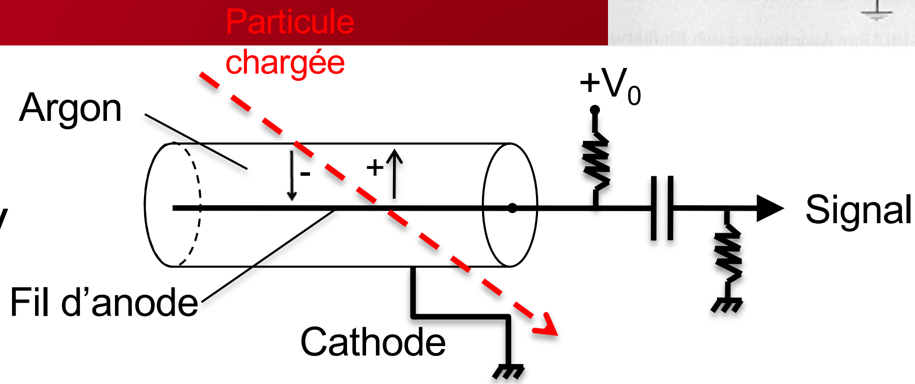
EXEMPLE SIMPLE DE DÉTECTEUR

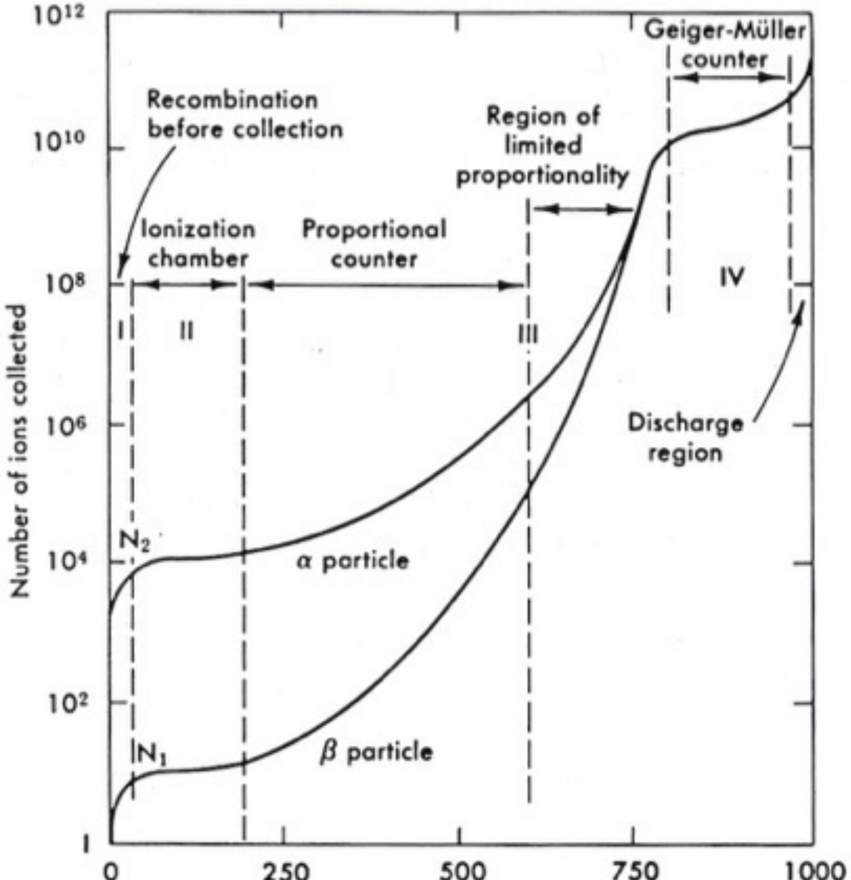


(RADIAL) AVEC: $$E = \frac{1}{r}\frac{V_0}{\ln(b/a)}$$

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







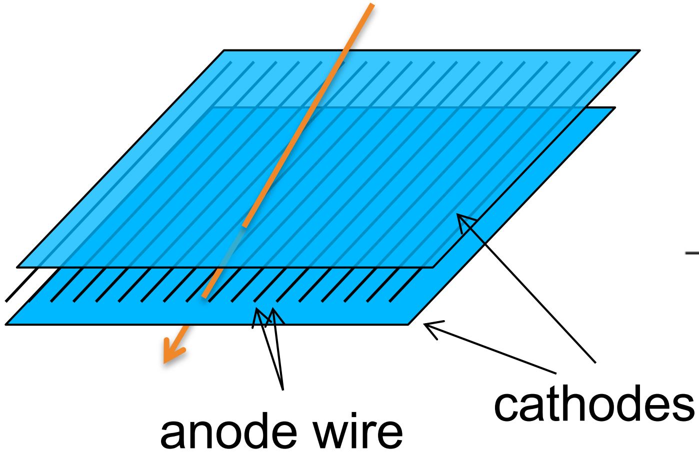
I: tension trop faible→ recombinaison

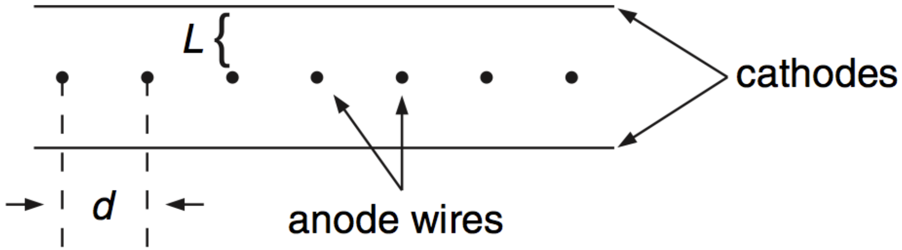
II: Chambre d'ionisation. Collection des charges sans amplification.

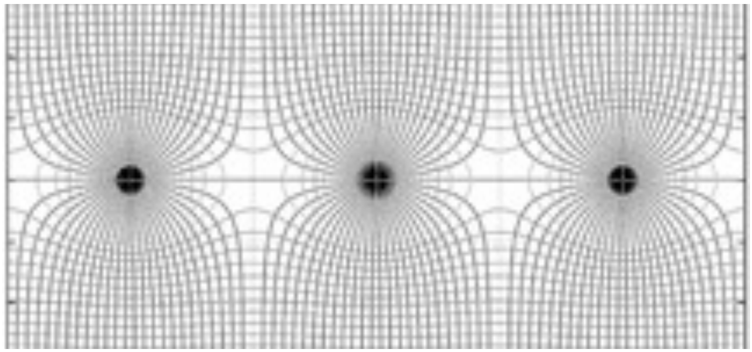
IIIa: Mode **proportionnel**. Le signal est amplifié et proportionnel à l'énergie déposée.

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.


anode wire
cathodes


L
d
cathodes
anode wires



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.

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.

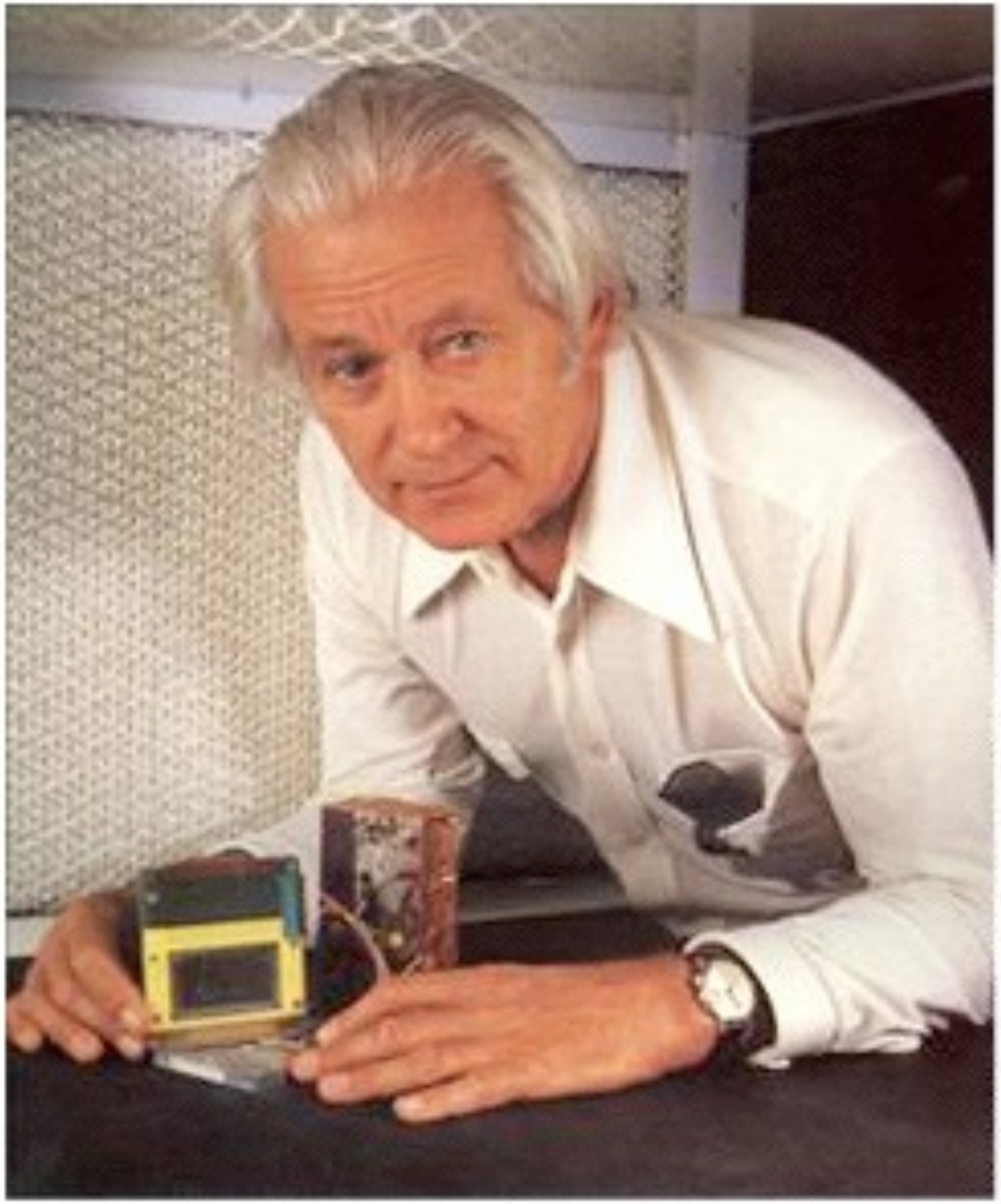
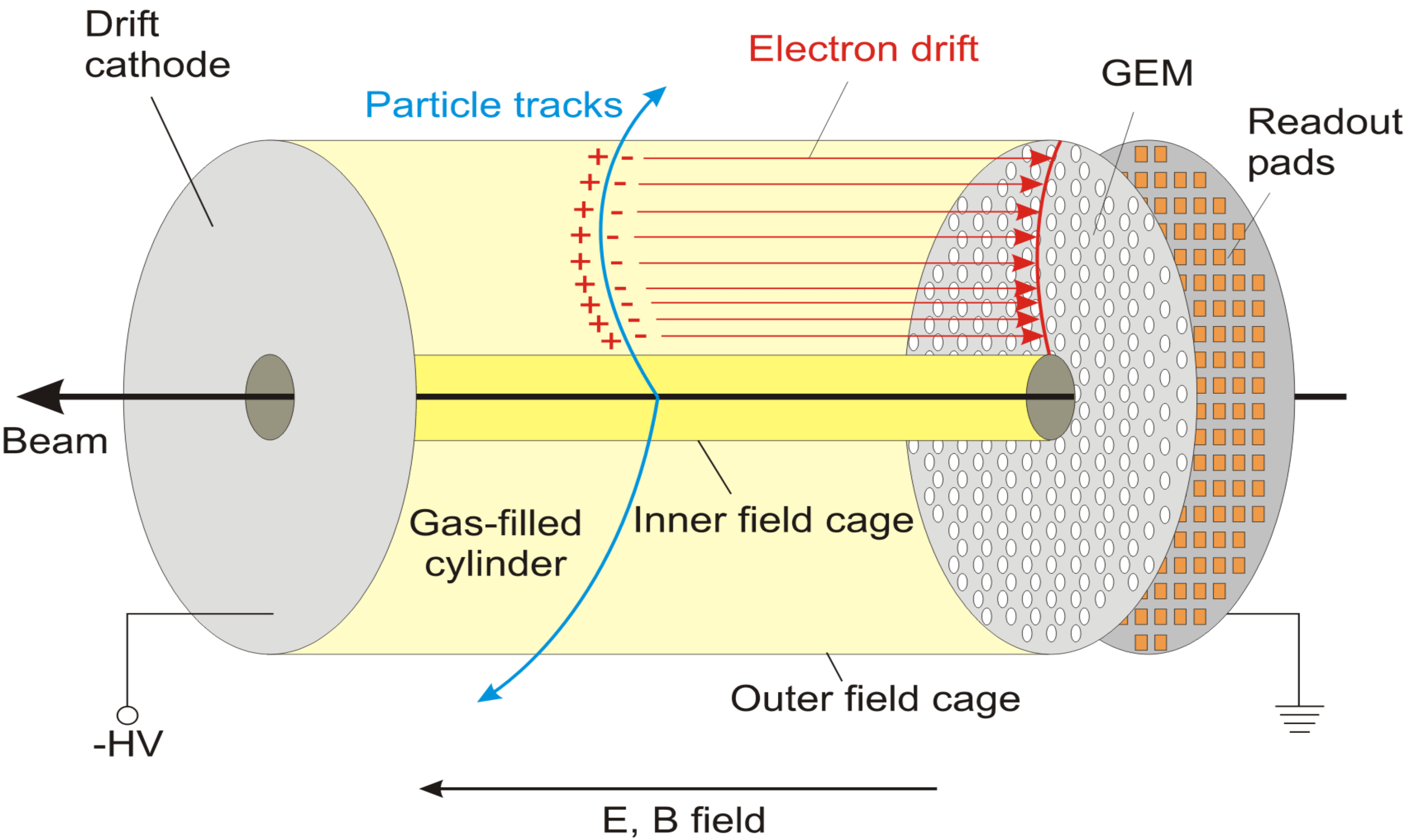


Photo: D. Parker, Science Photo Lab. UK

Georges Charpak
CERN, Geneva, Switzerland

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

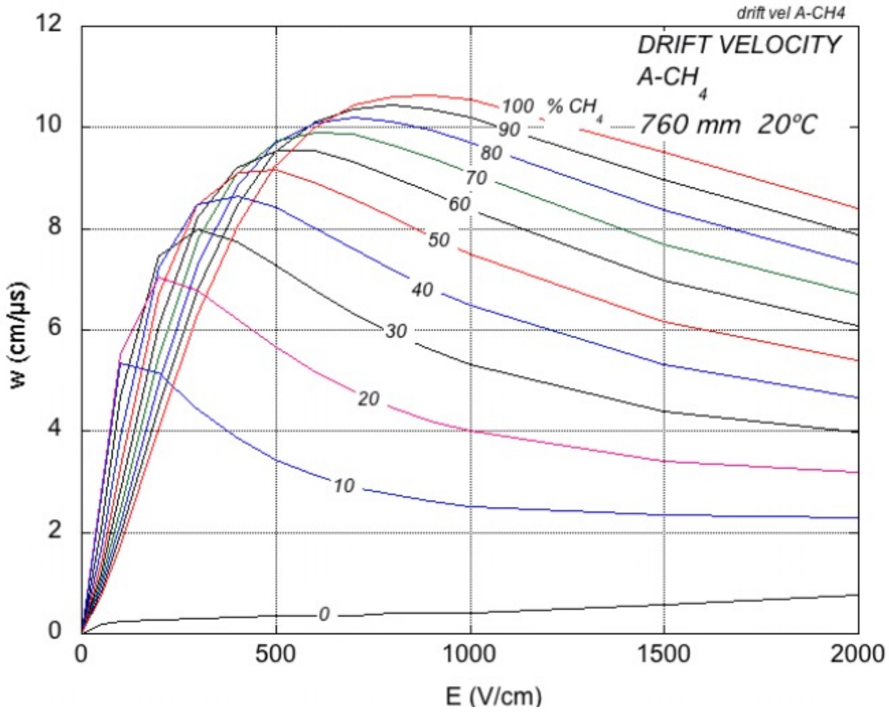
Time Projection Chamber (TPC):

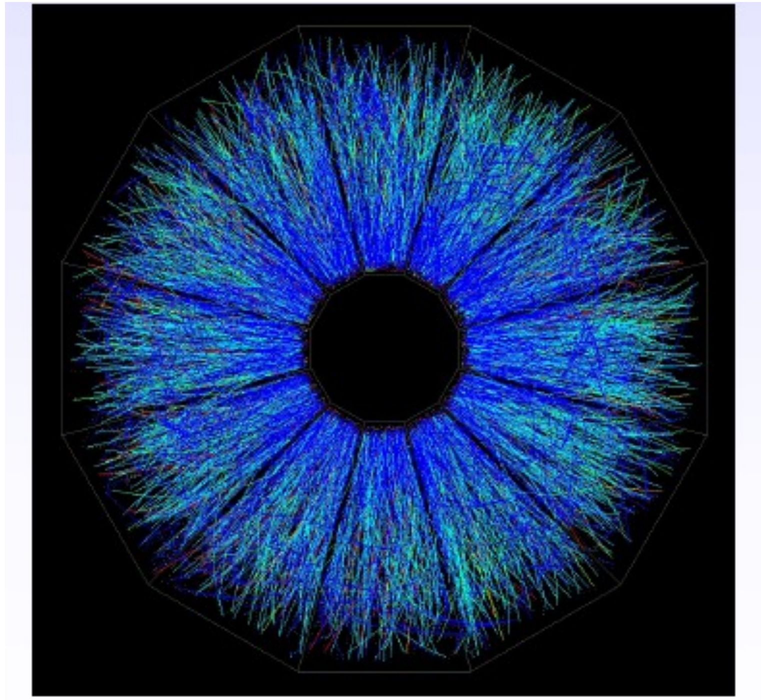


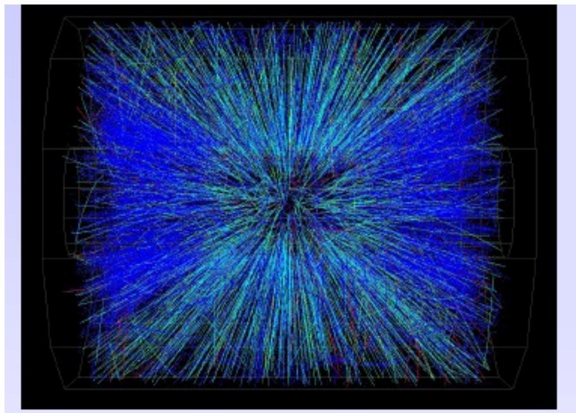
Time Projection Chamber (TPC):

Event display of a Au Au collision at CM energy of 130 GeV/n.

Typically around 200 tracks per event.

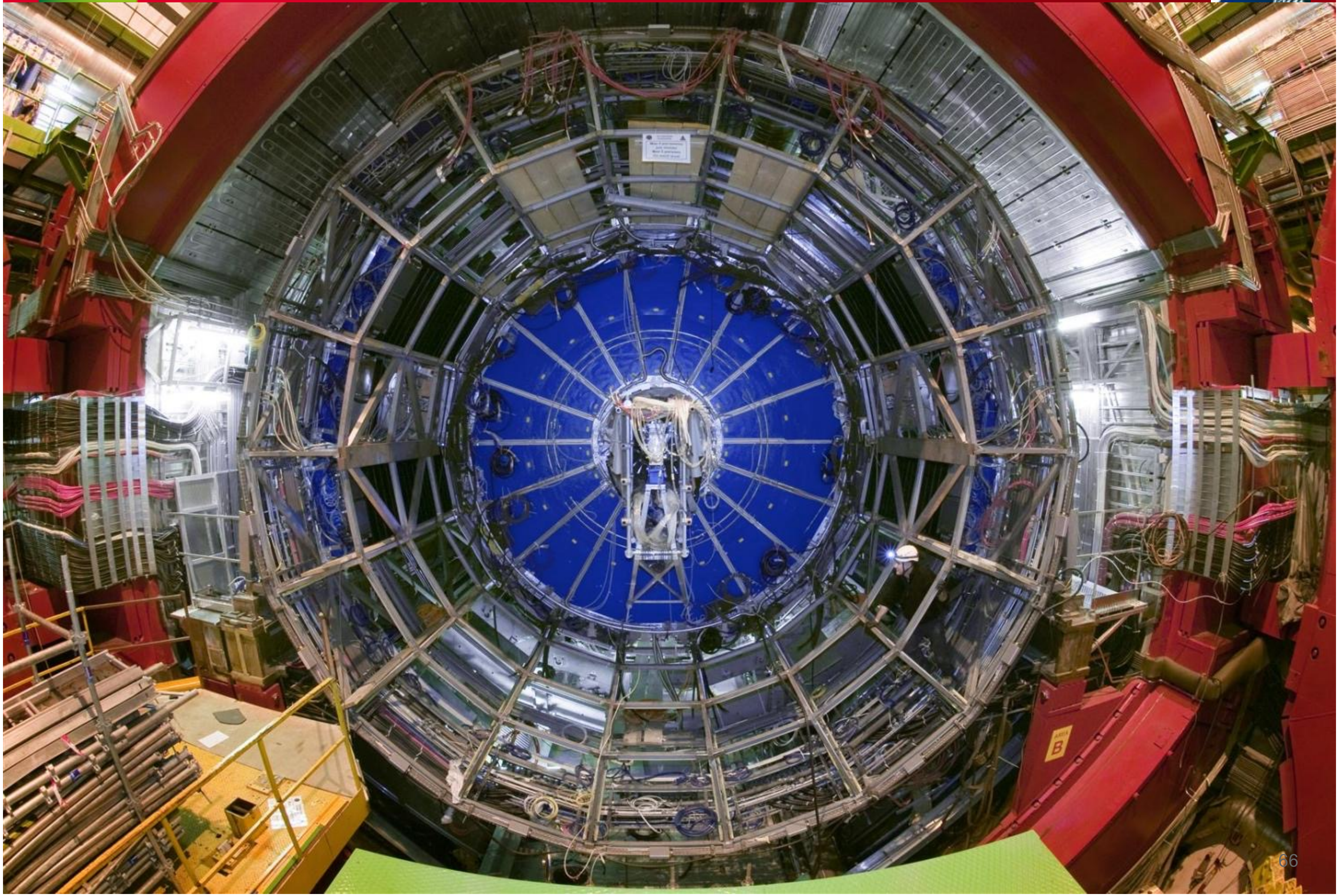






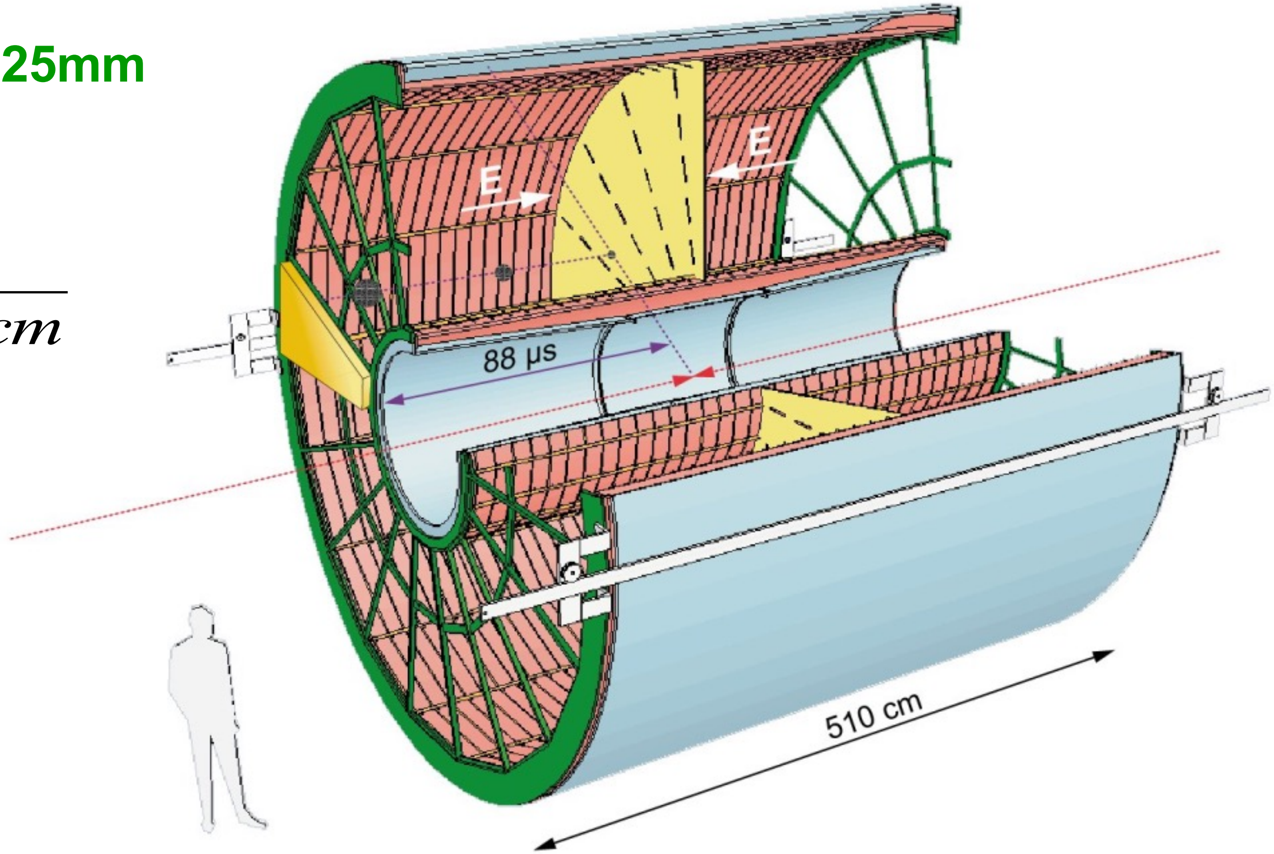
EXAMPLE: Ar-CH_4 90-10 , E=1kVcm^{-1} w_- = 2.5 cm μs^{-1}

TPC installed in the ALICE Experiment



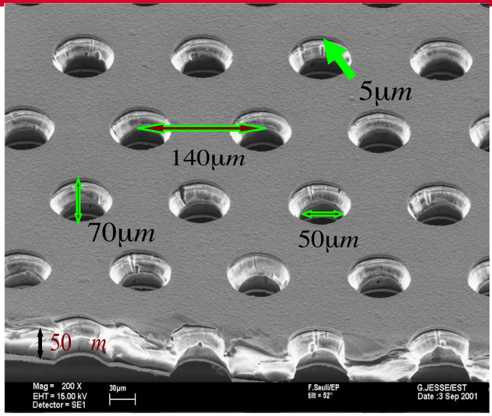
ALICE TPC: Detector Parameters

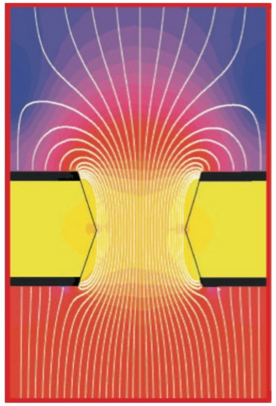
- **Gas Ne/ CO_2 90/10%**
- **Field 400V/cm**
- **Gas gain >10^4**
- **Position resolution σ= 0.25mm**
- **Diffusion: σ_t= 250μm** $\sqrt{cm}$
- **Pads inside: 4x7.5mm**
- **Pads outside: 6x15mm**
- **B-field: 0.5T**
- **Largest TPC:**
  - **Length 5m**
  - **Diameter 5m**
  - **Volume 88m^3**
  - **Detector area 32m^2**
  - **Channels ~570 000**
- **High Voltage:**
  - **Cathode -100kV**

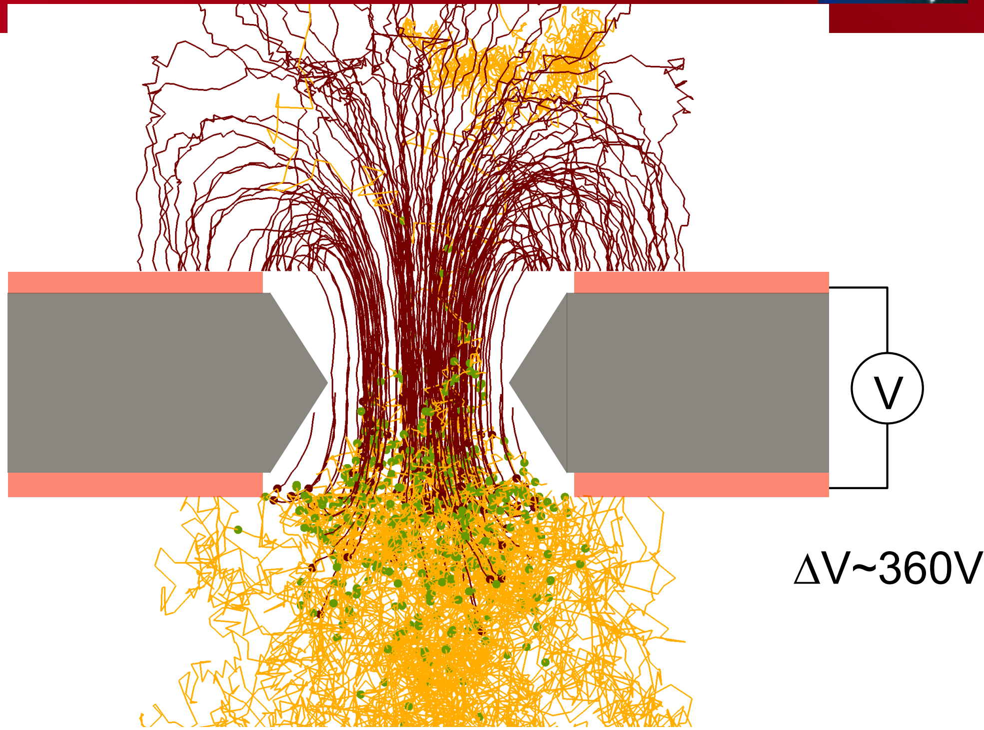


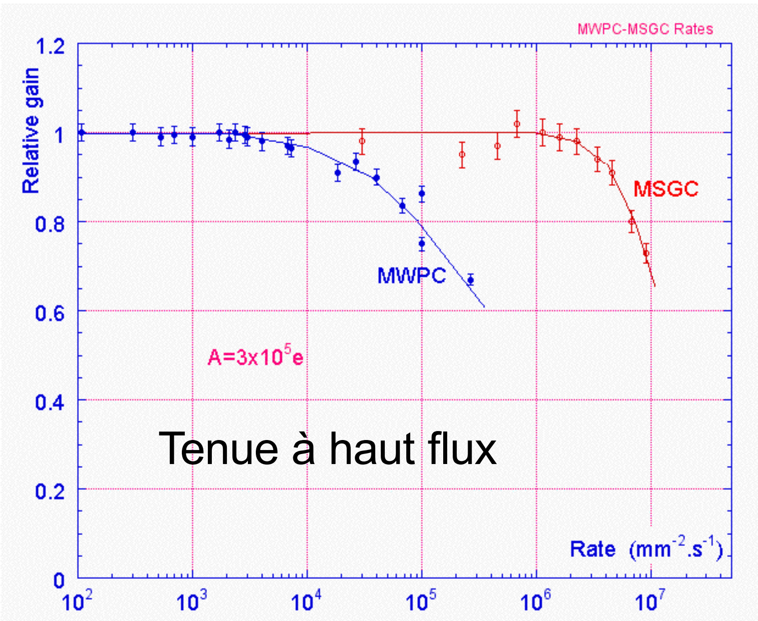
=> Gated grid ~15kHz max

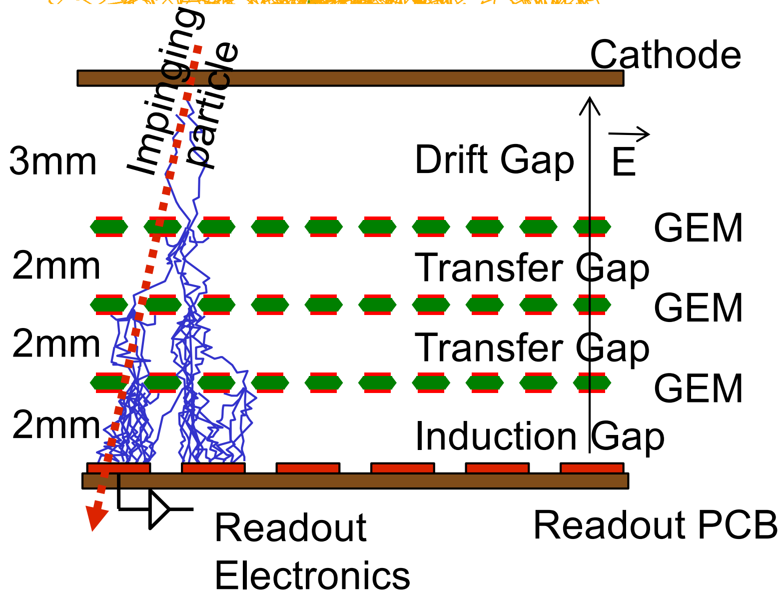
GEM : GASEOUS ELECTRON MULTIPLIER



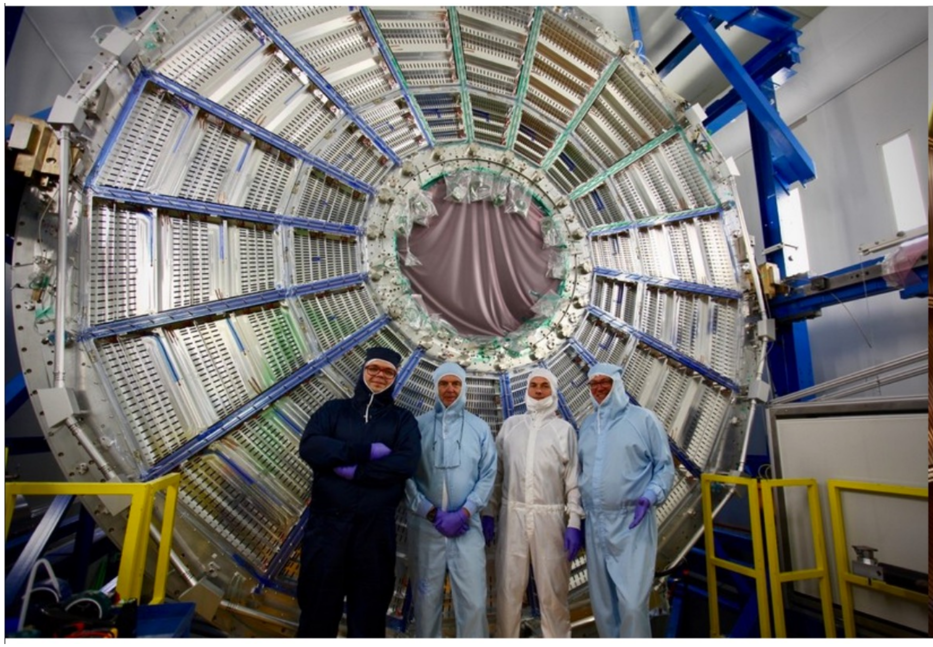


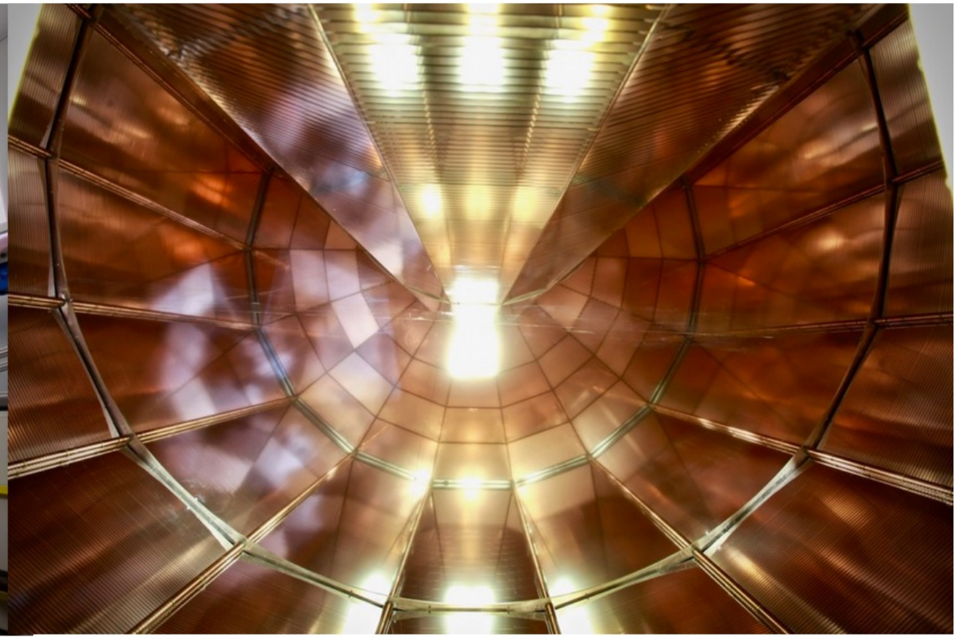






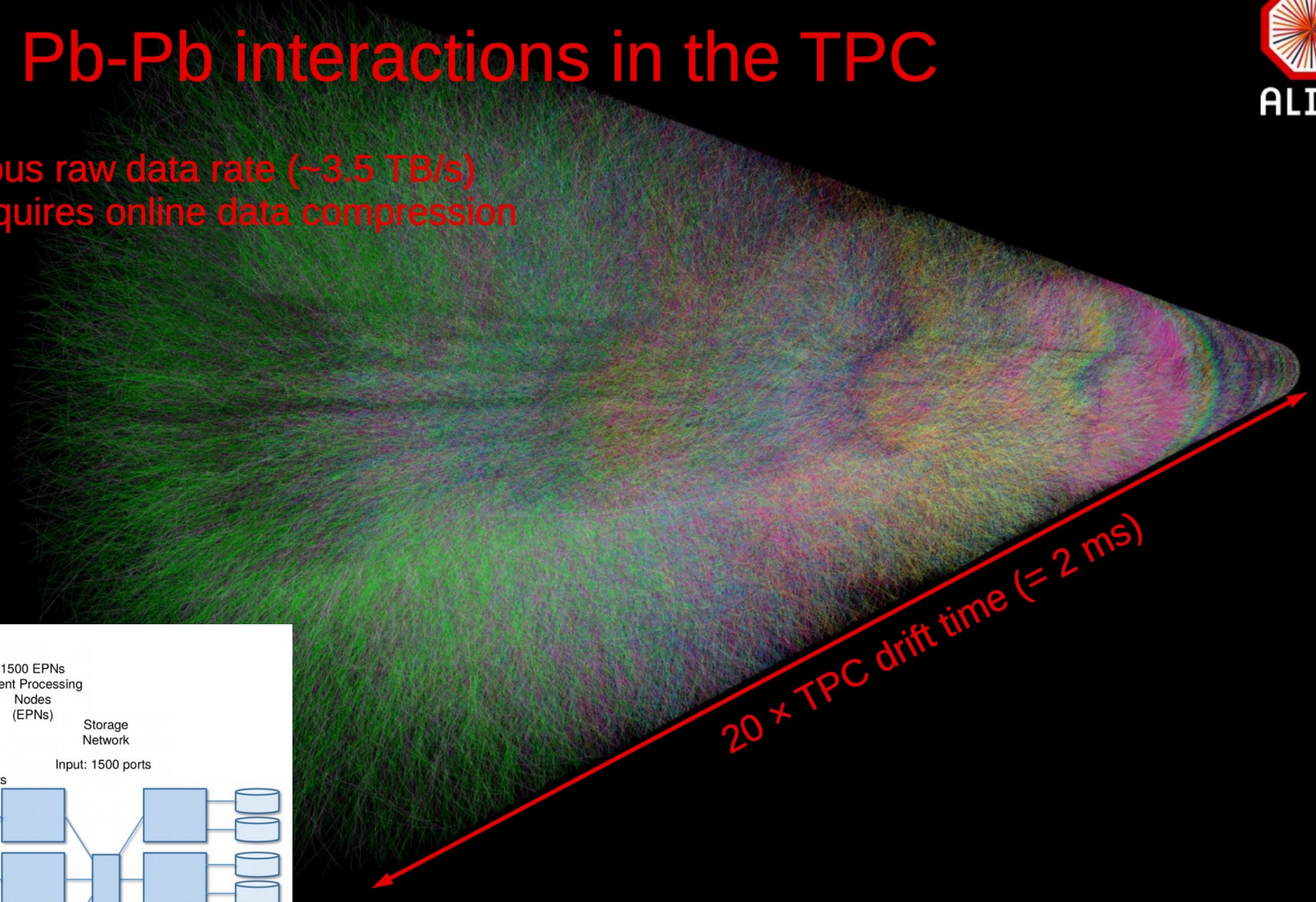
ALICE UPGRADE

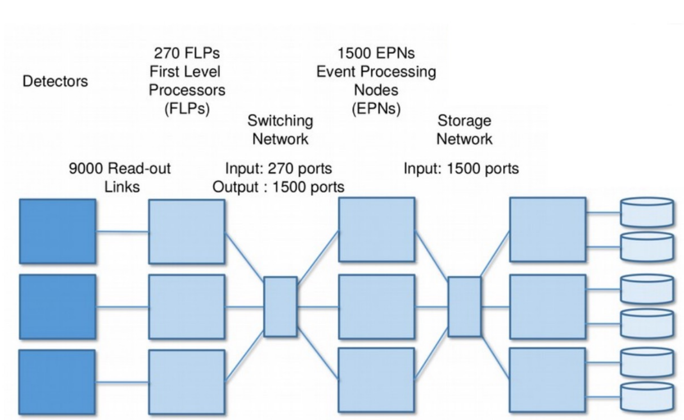




50 kHz Pb-Pb interactions in the TPC

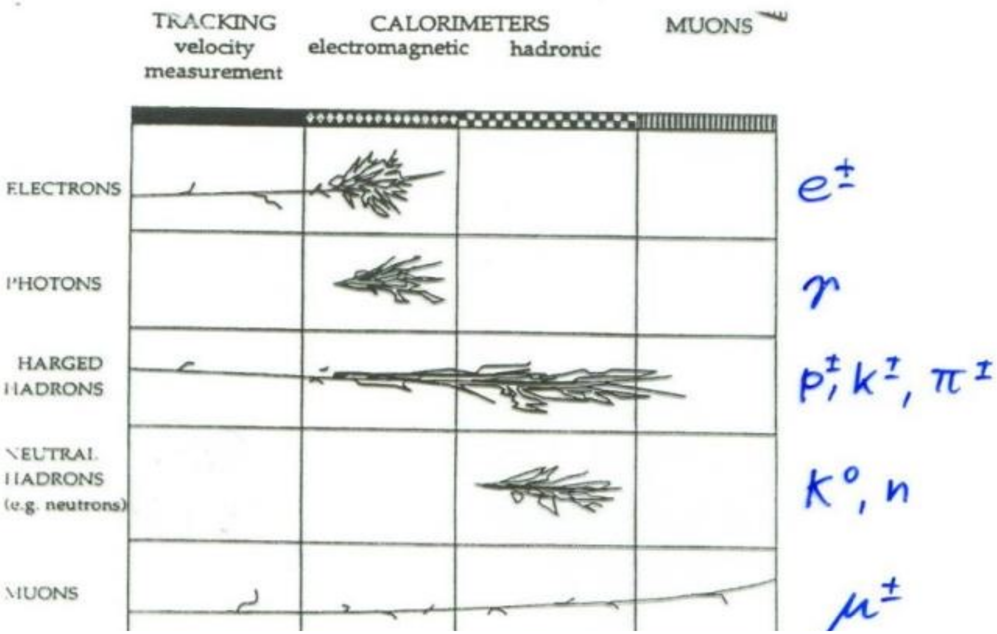
- Enormous raw data rate (~3.5 TB/s)
  - Requires online data compression



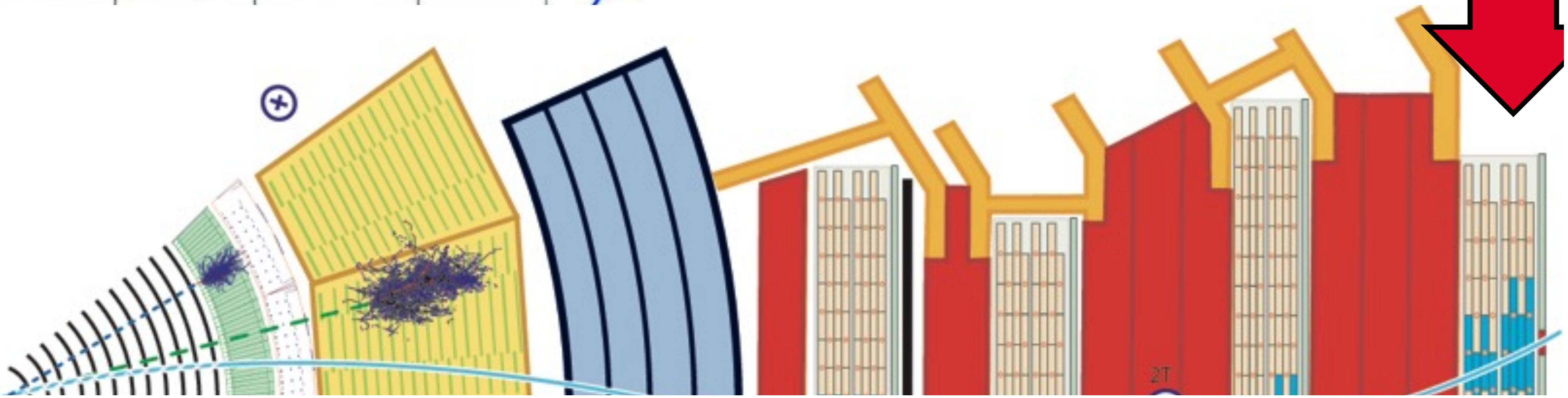


(YouTube it's 500Gb/s in upload)

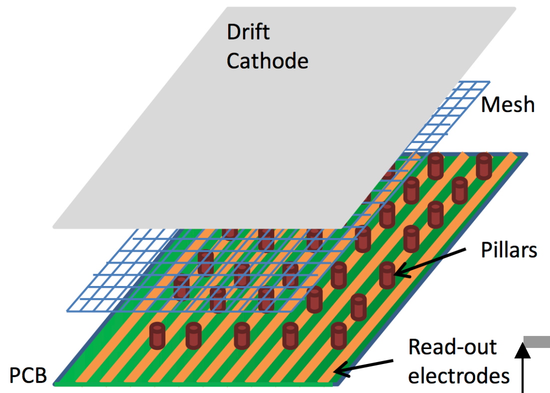
Détecteurs Gazeux

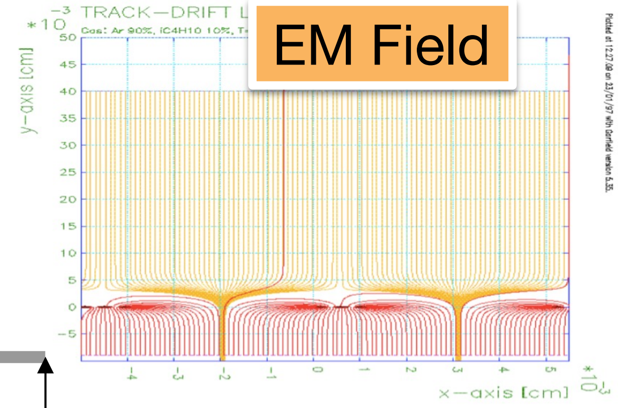


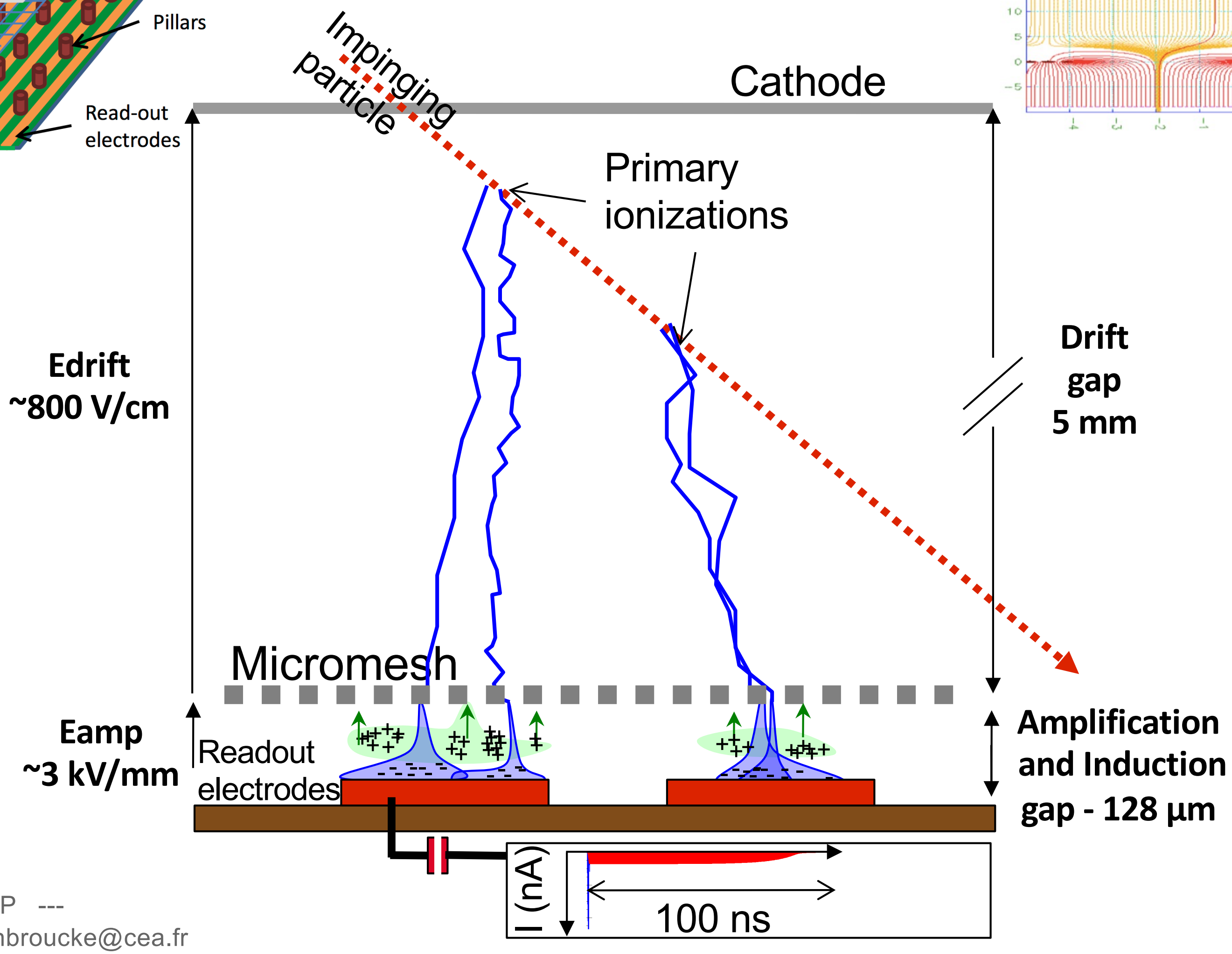
Muon Chambers ->



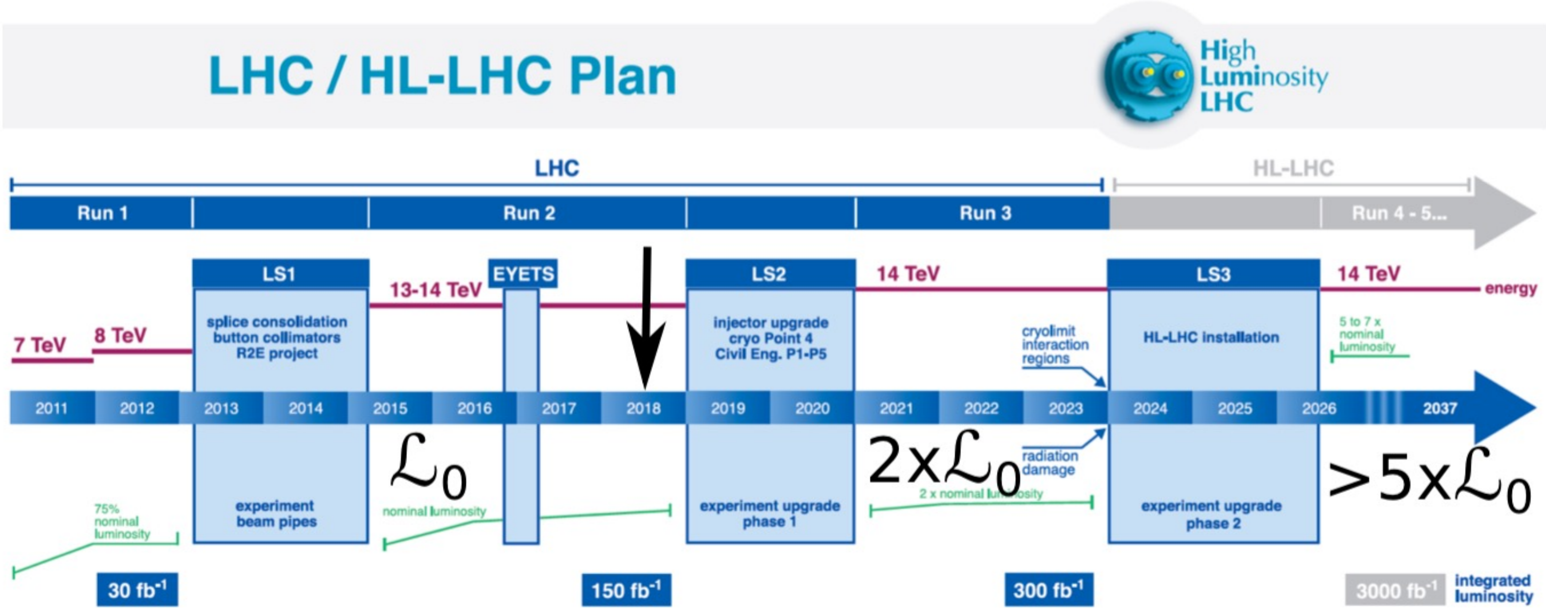
MICROMEGAS

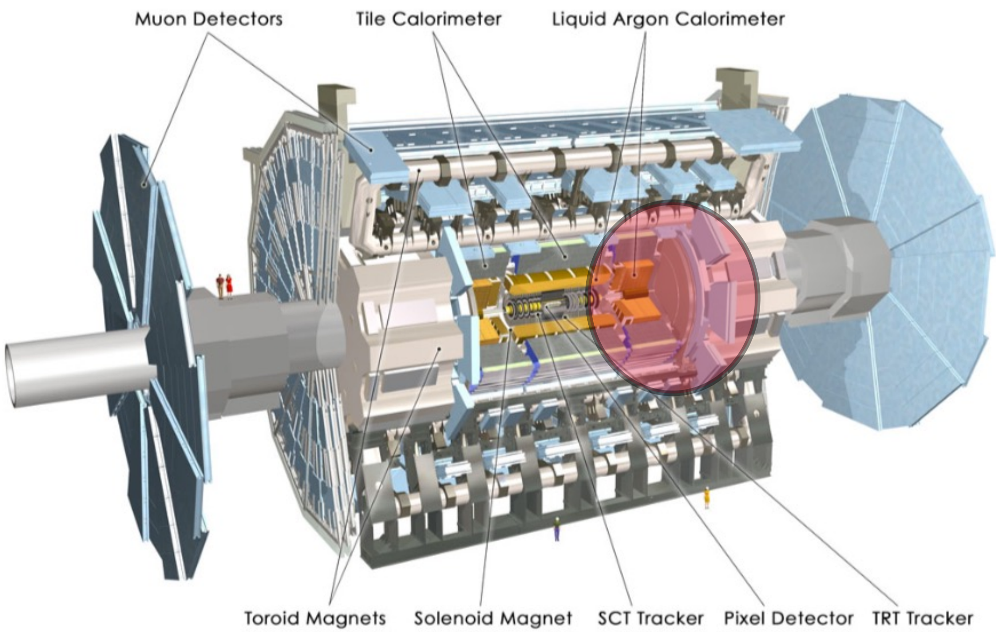

Drift
Cathode
Mesh
Pillars
Read-out
electrodes
PCB

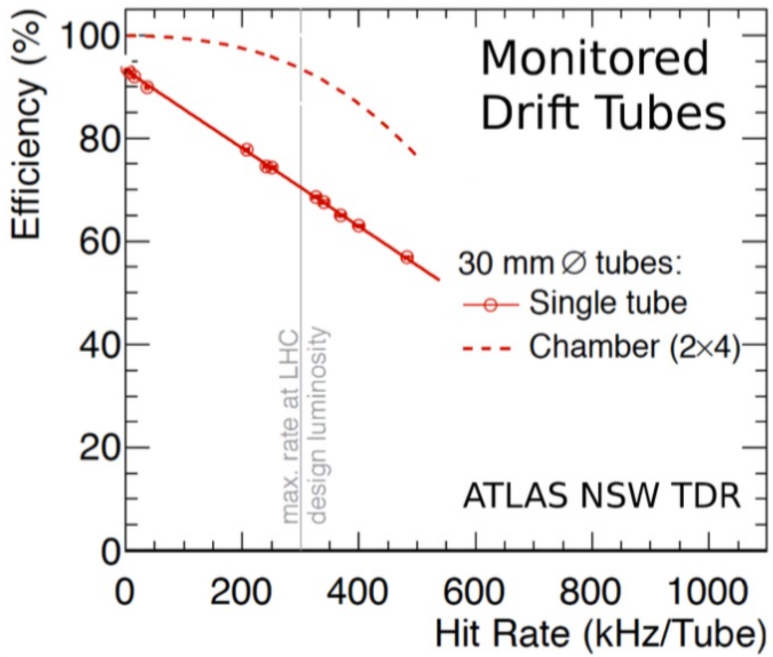

EM Field
TRACK—DRIFT L
y–axis [cm]
x–axis [cm]

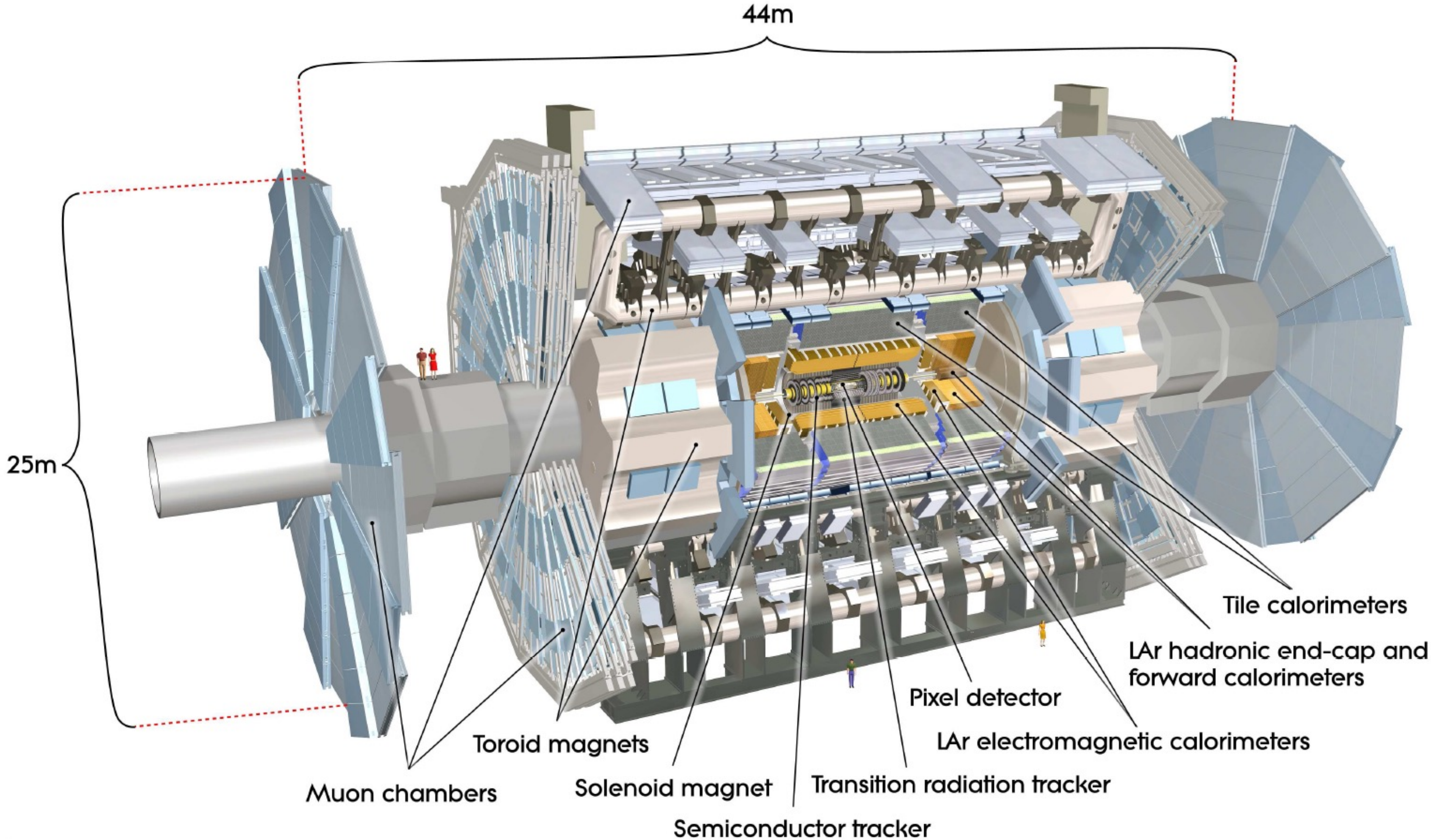

Impinging
particle
Cathode
Primary
ionizations
Edrift
~800 V/cm
Drift
gap
5 mm
Micromesh
Eamp
~3 kV/mm
Readout
electrodes
Amplification
and Induction
gap - 128 µm
I (nA)
100 ns

ATLAS - UPGRADE



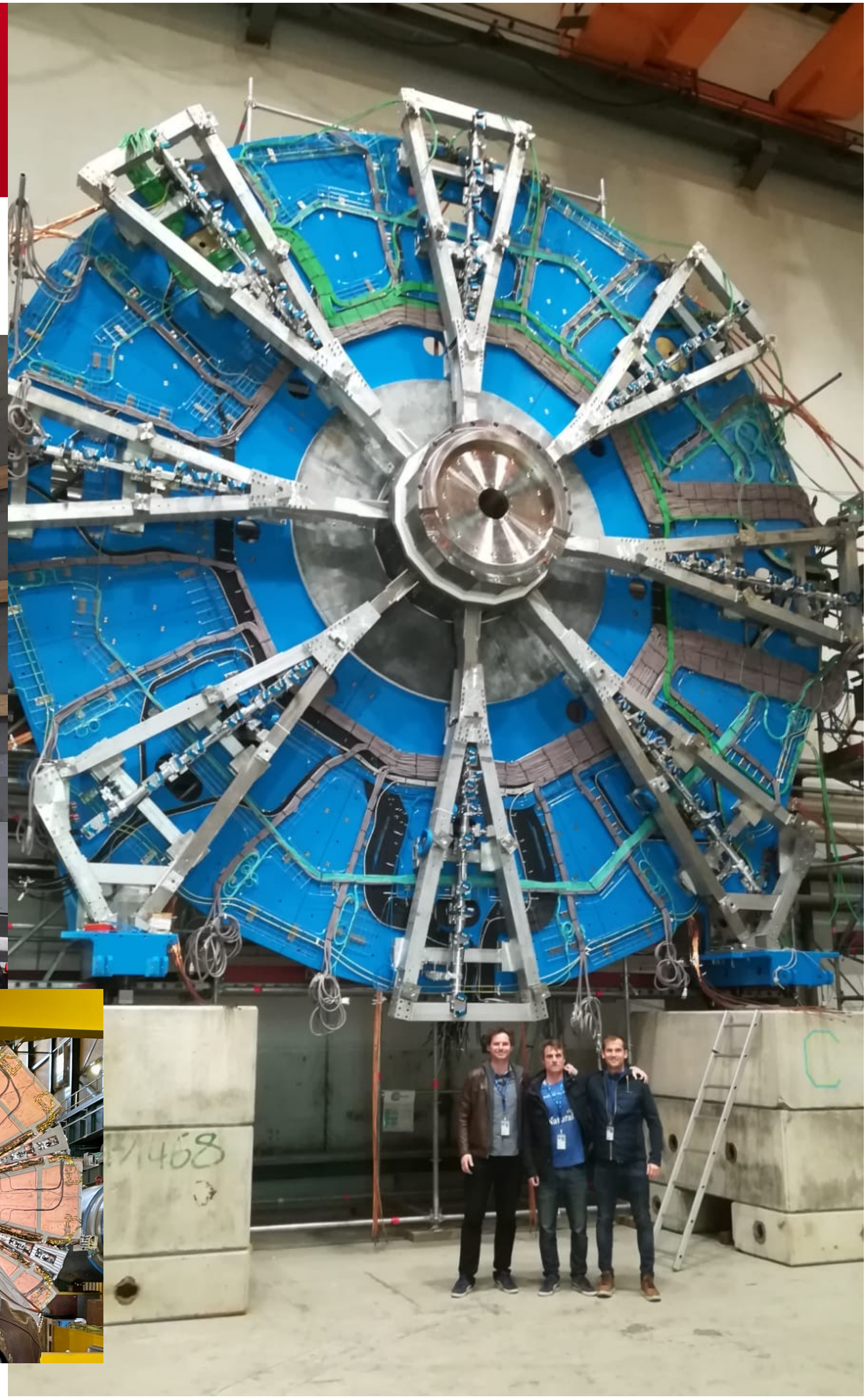






44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

NSW

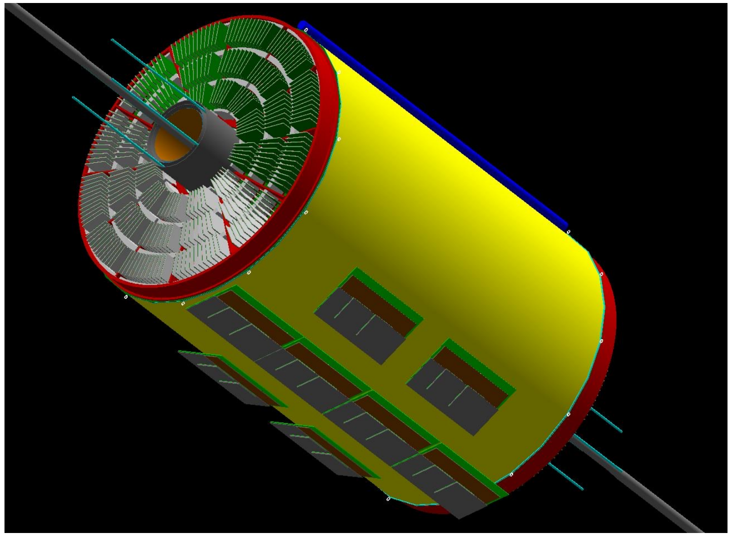


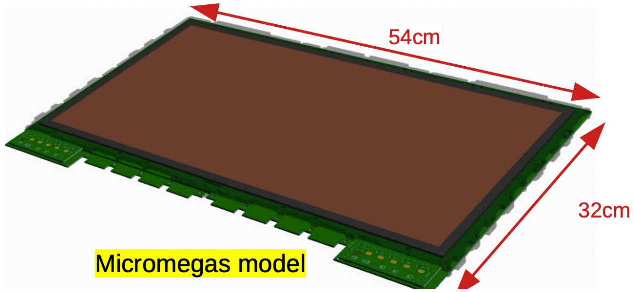
CEA/IRFU/DEDIP ---
maxence.vandenbroucke@cea.fr

NSW INSTALLATION

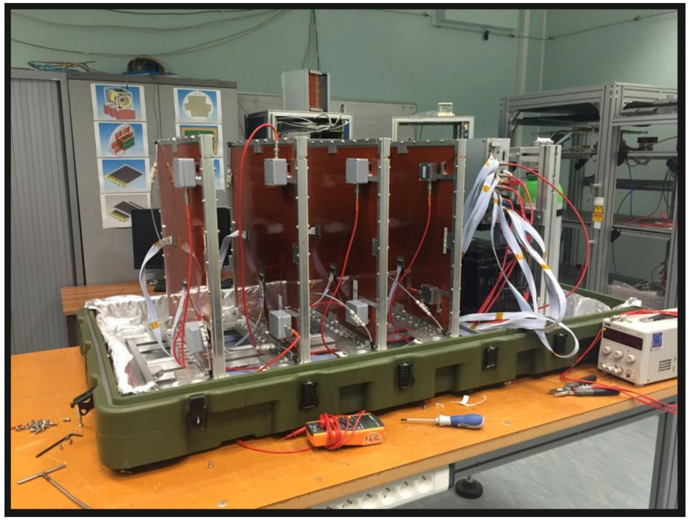
NSW : Dernière chambre vers ITK (Tanguy)

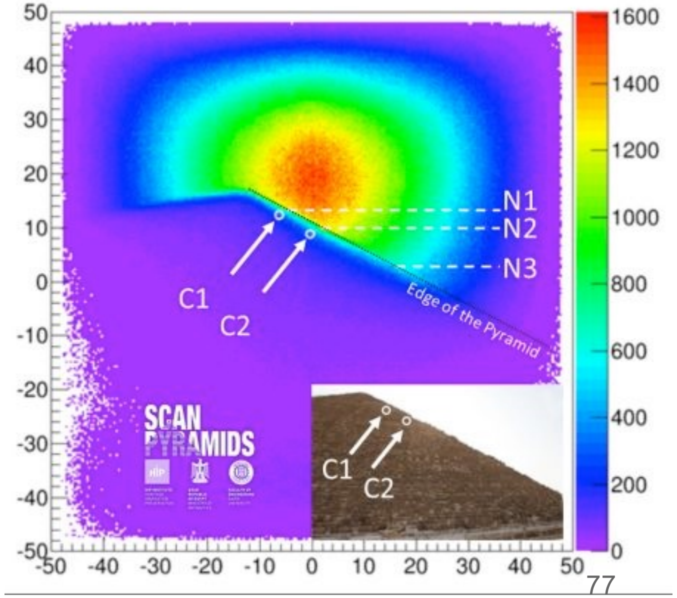
TPOT :





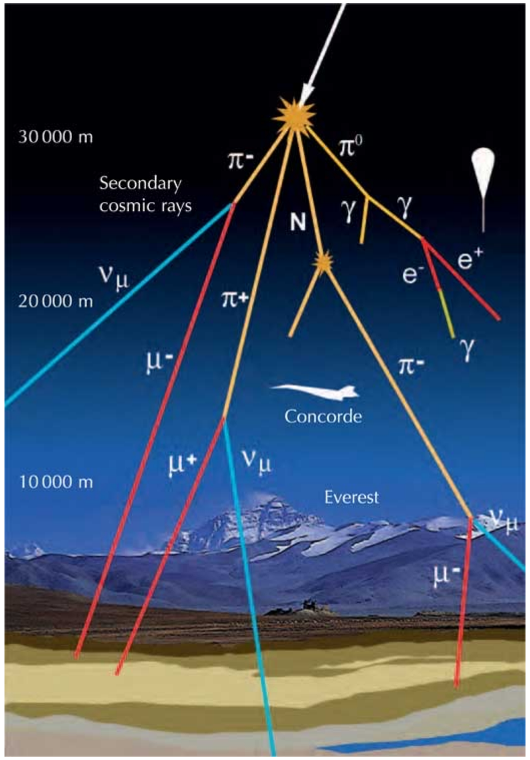
Tomographie :



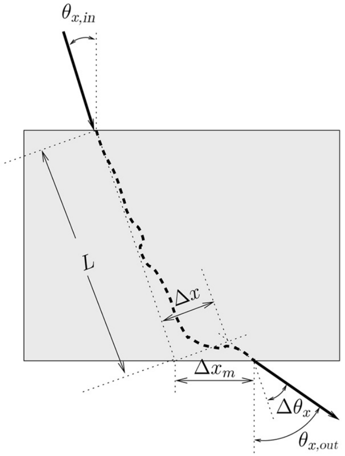


MUON TOMOGRAPHY

- Cosmic muons produced by cascade of reactions induced by cosmic rays in the upper atmosphere
  - Flux: ~150/m²/s ~ $\cos^2\theta$ (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

$$-\frac{dE}{ds} = \rho q^2 \frac{N_A e^4}{4\pi\epsilon_0^2 m_e c^2} \frac{Z}{A} \frac{1}{\beta^2} \left(\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right)$$

  - Standard deviation of the scattering angle

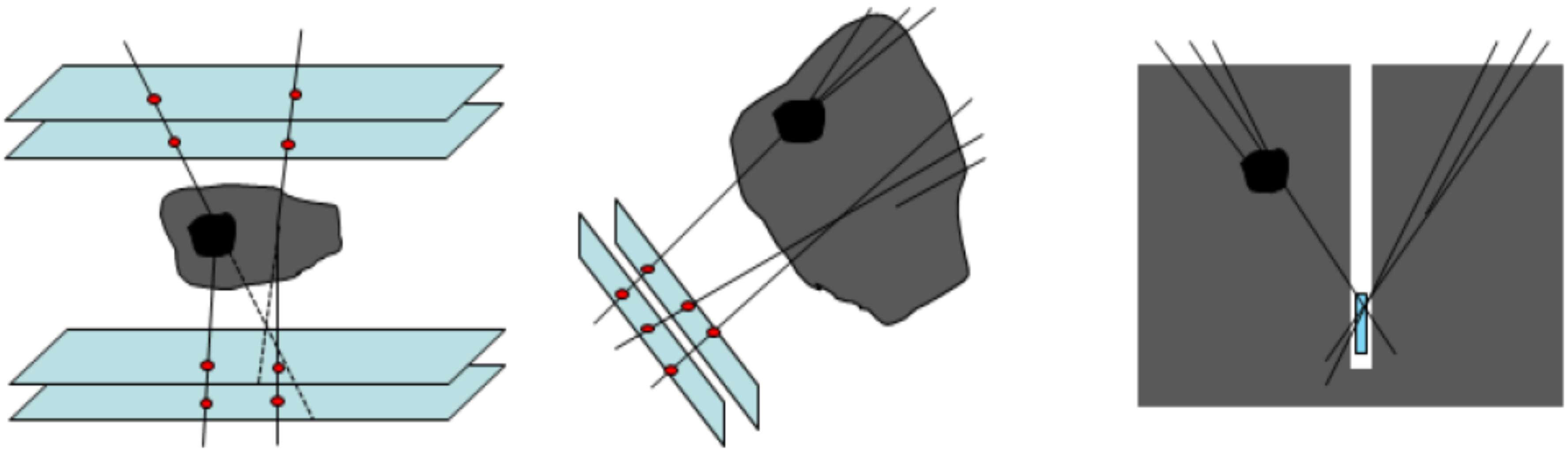
$$\sigma_\theta = \frac{19.2 MeV}{\beta p c} \sqrt{\frac{\rho s}{X_0}} \left(1 + 0.038 \ln \frac{\rho s}{X_0} \right)$$

  - Radiation length

$$X_0 = 716.4 g cm^{-2} \frac{A}{Z(Z+1) \ln \frac{287}{\sqrt{Z}}}$$

Material	Thickness	θ (°)	$P_{absorption}$
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%

- 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

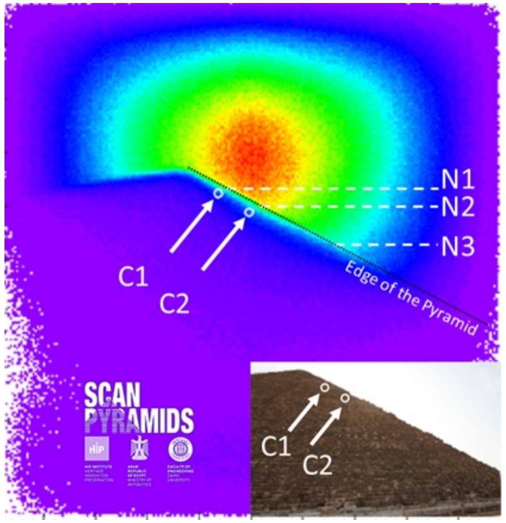


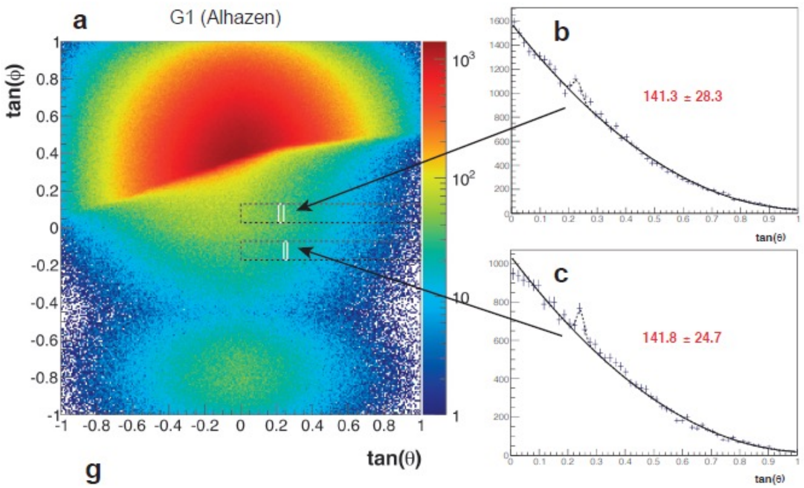
- High potential of societal applications in many fields:
  - volcanology, archaeology
  - mineral exploration, civil engineering, …

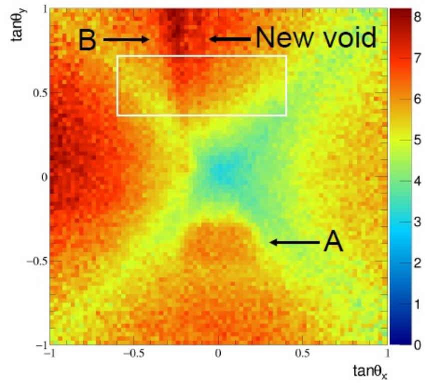
RESULTS

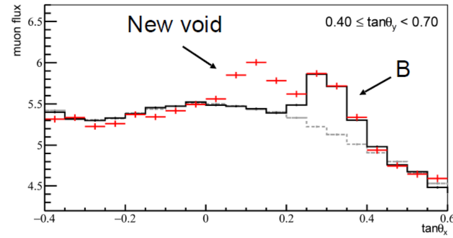
- Discoveries of new cavities large void above the Grand Gallery

2016 *CEA* 2017 *Nagoya*

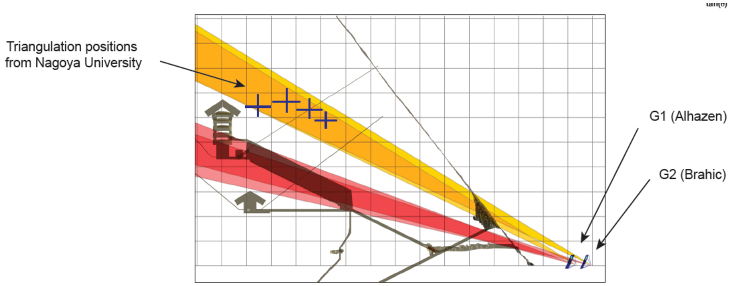








- *Only 2 such voids detected*
- *1st detection ever from outside of a deep structure*



DE LA RECHERCHE À L'INDUSTRIE

Mesurer l'infiniment petit et observer l'infiniment grand

Mardi 12/07 11h (Orme)
Lundi 18/07 12h (Centre)
Visite Labo (Centre)
Lundi 18/07 17h15 (Centre)

[Stages : http://irfu.cea.fr/Phocea/stages/index.php](http://irfu.cea.fr/Phocea/stages/index.php)

Maxence Vandenbroucke
07/2022

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

Mesurer l'infiniment petit et observer l'infiniment grand

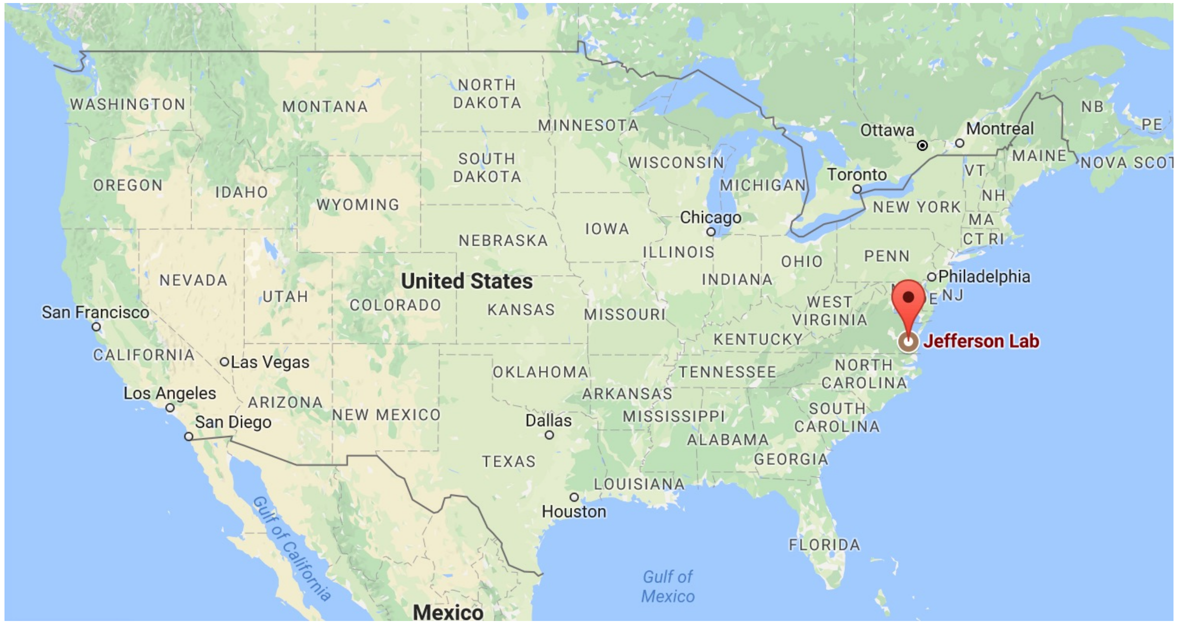
Cours 3 : Exemple d'expériences

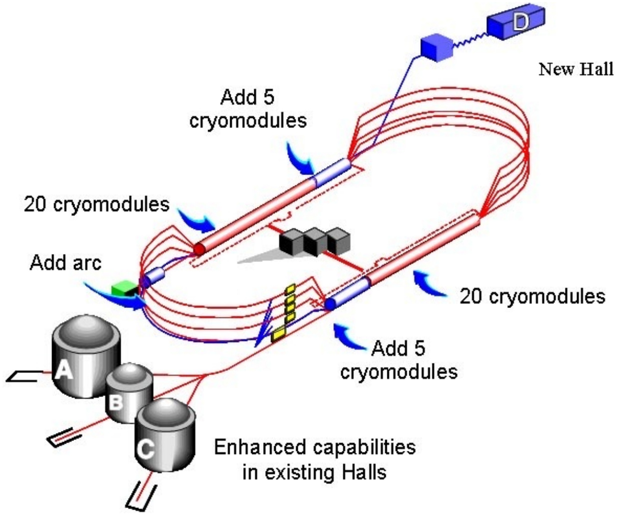
- **Autour du Neutrino**
- **Nucléaire et Hadronique**
- **Rayons Cosmiques**
- **Antimatière**
- **Matière sombre**

Physique Hadronique

COMPASS et CLAS12

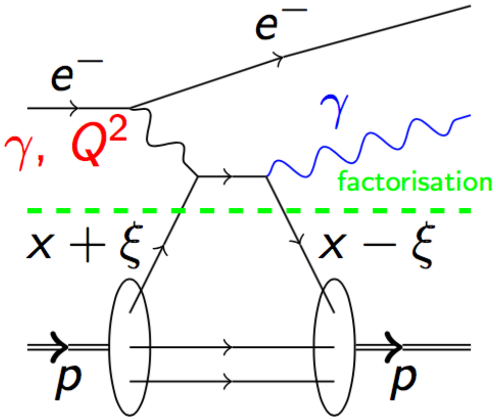
CLAS12 at Jefferson Lab

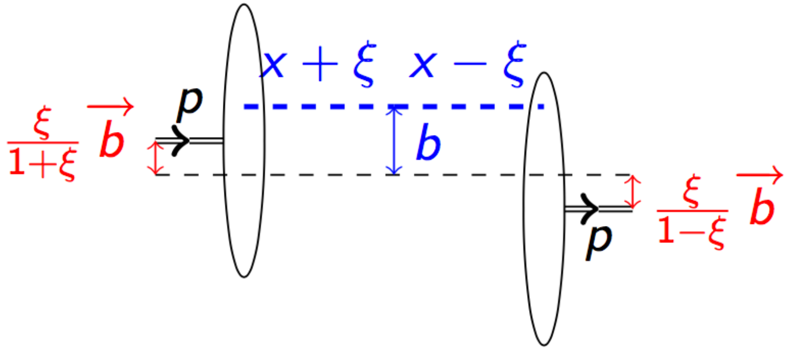




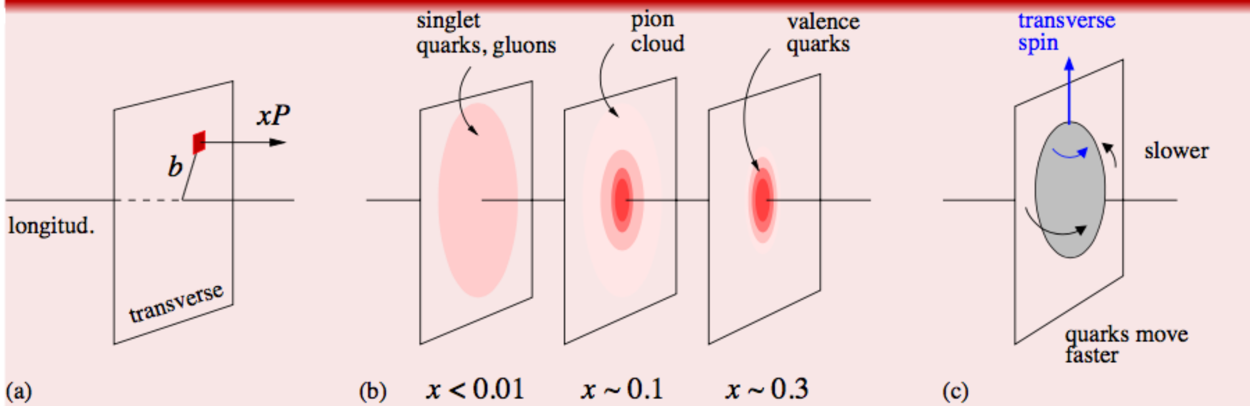
CLAS12 at Jefferson Lab

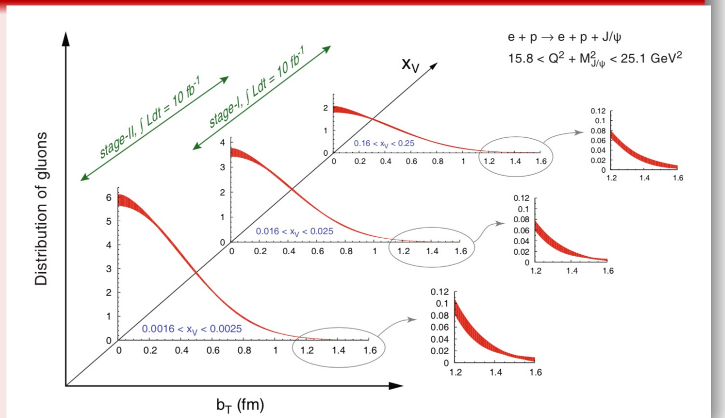
Diffusion Compton profondément virtuelle (DVCS)



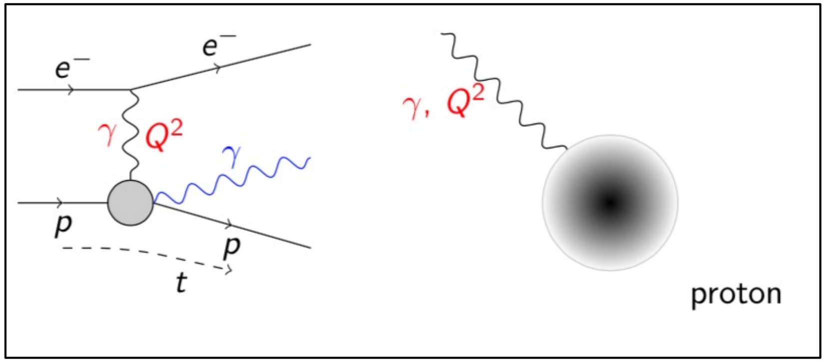


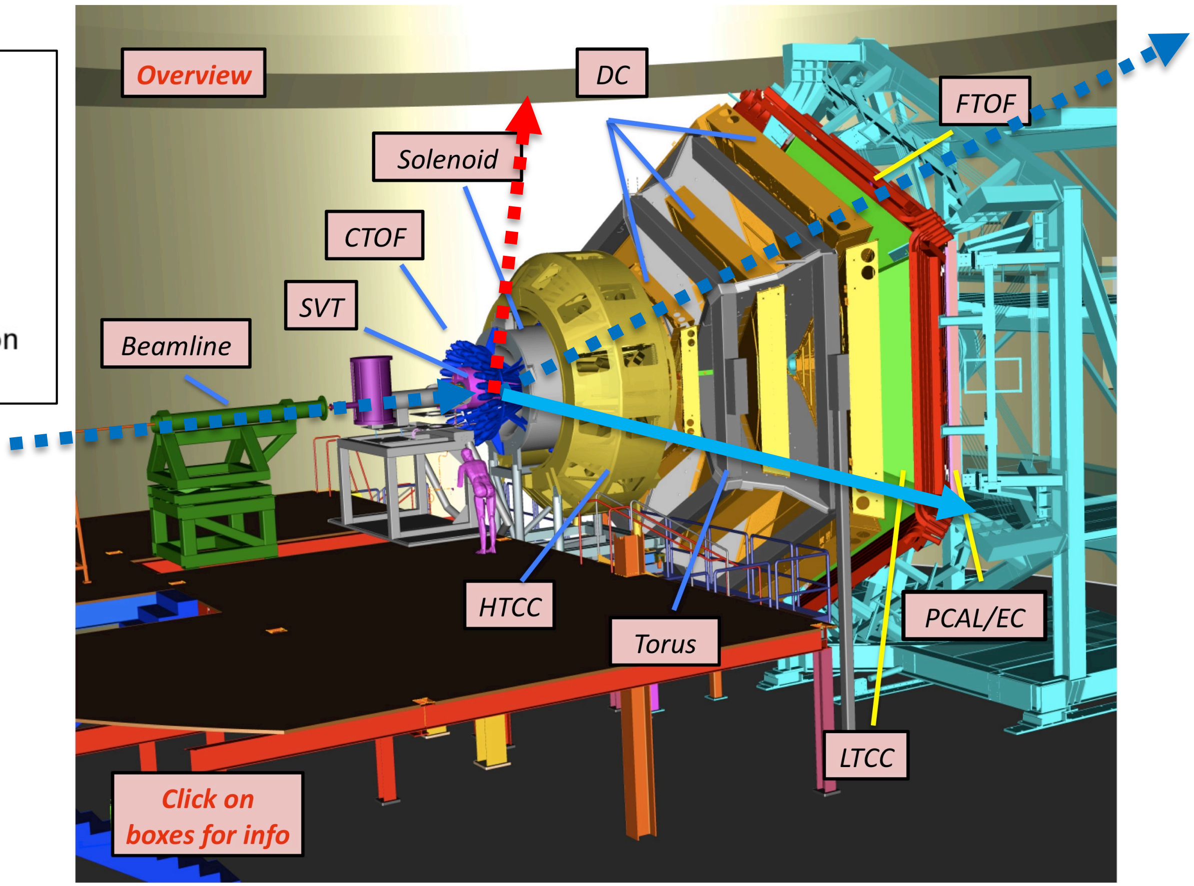
Vers une visualisation en 3d du nucléon !





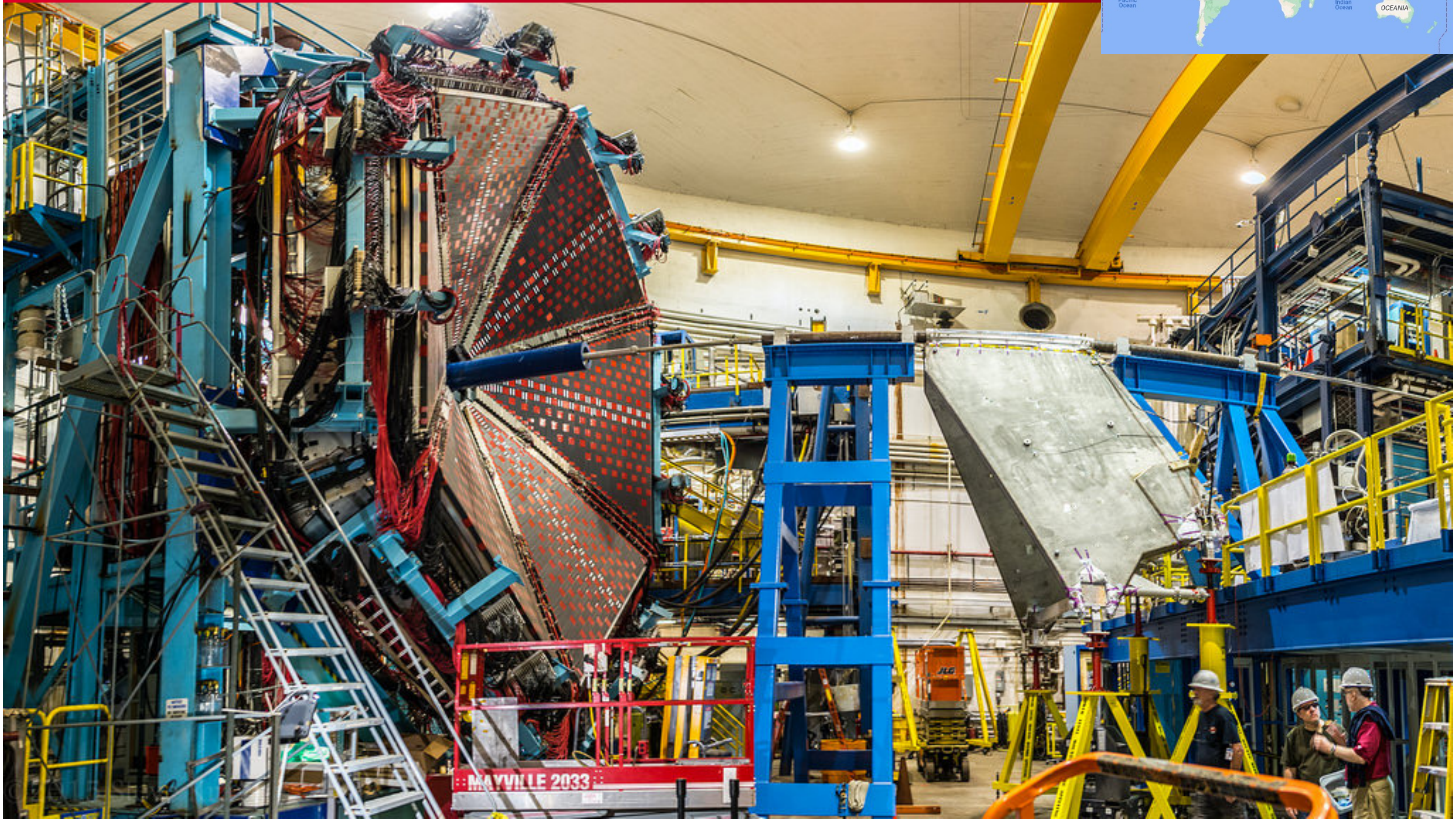

NORTH AMERICA
Atlantic Ocean
EUROPE
ASIA
AFRICA
SOUTH AMERICA
Pacific Ocean
Indian Ocean
OCEANIA


e^-
e^-
γ
Q^2
γ
p
p
t
$\gamma,\ Q^2$
proton

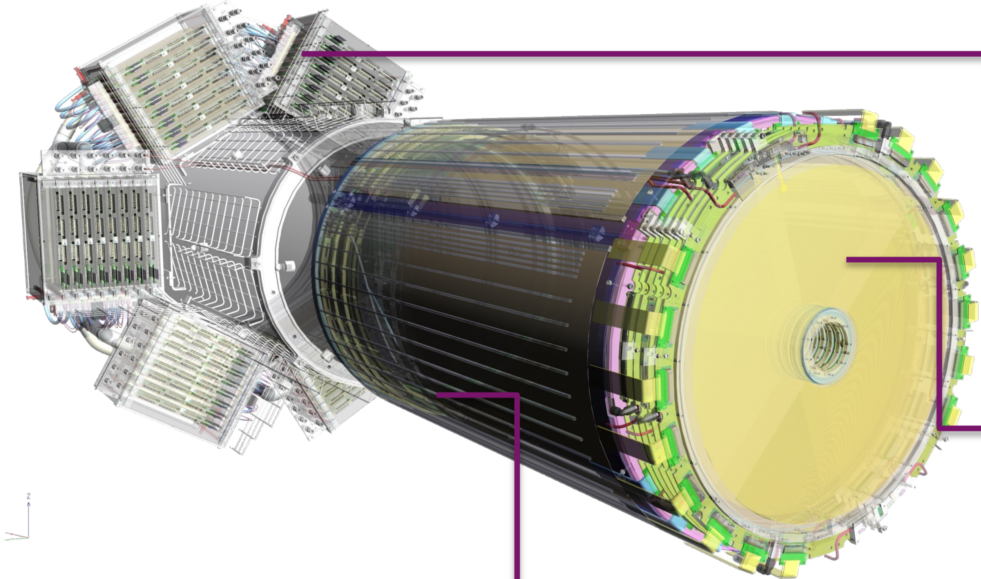

Overview
DC
FTOF
Solenoid
CTOF
SVT
Beamline
HTCC
Torus
PCAL/EC
LTCC
Click on boxes for info

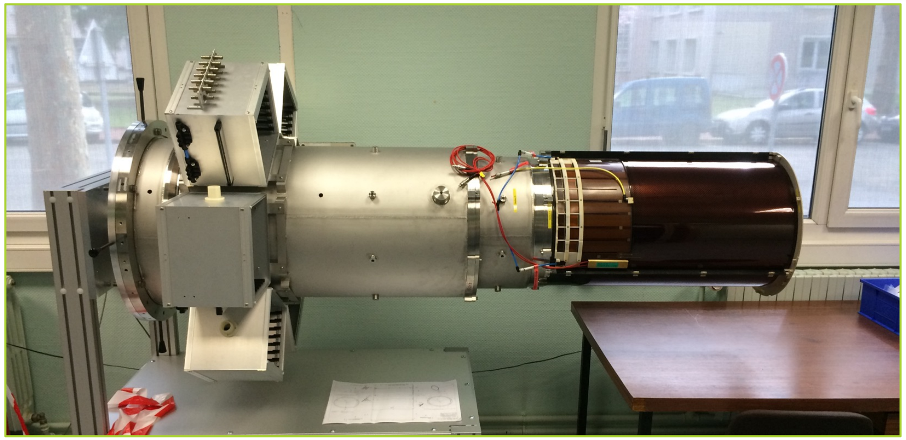
proton

CLAS12 at Jefferson Lab



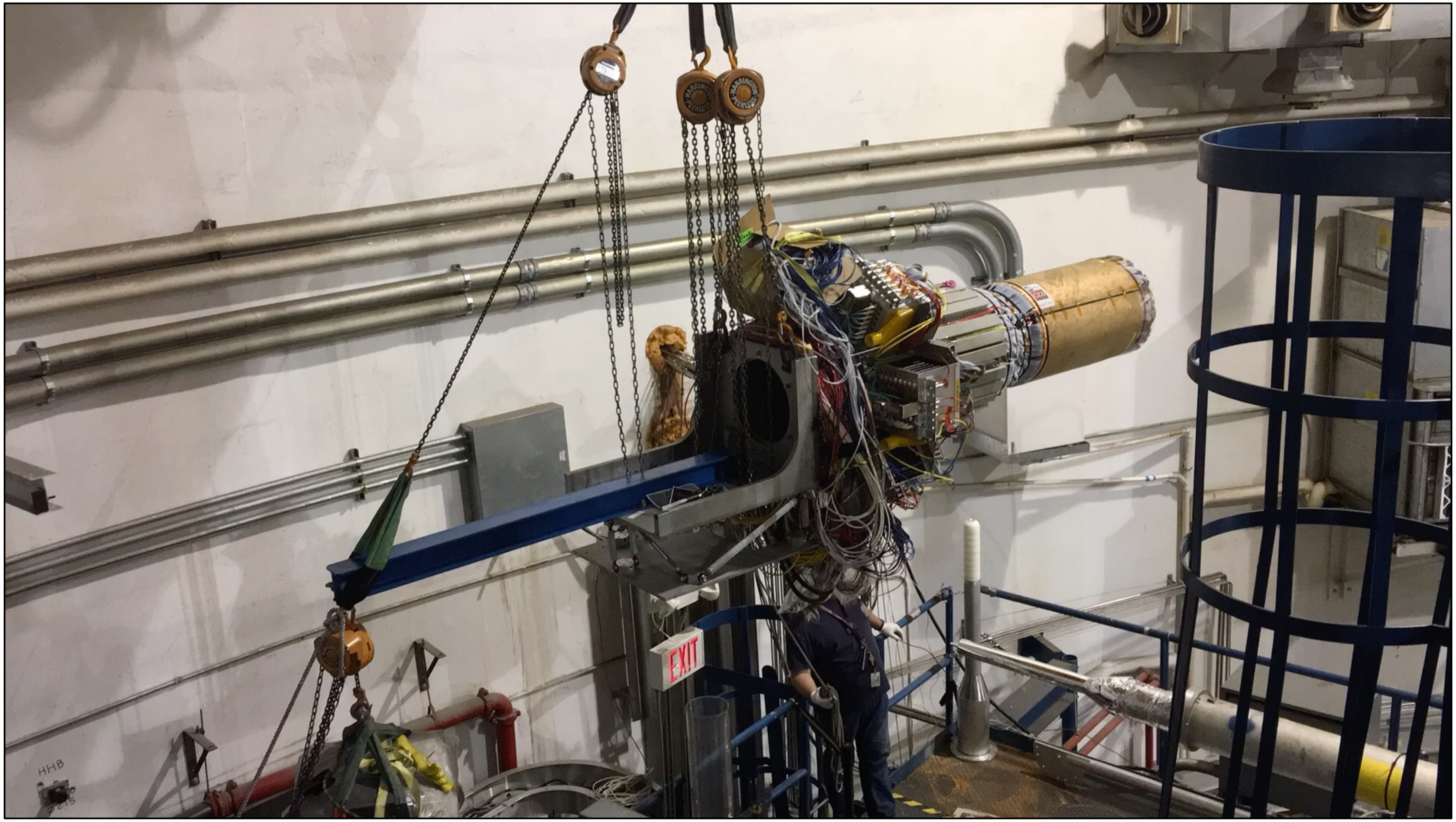
CLAS12 - THE MICROMEGAS VERTEX TRA

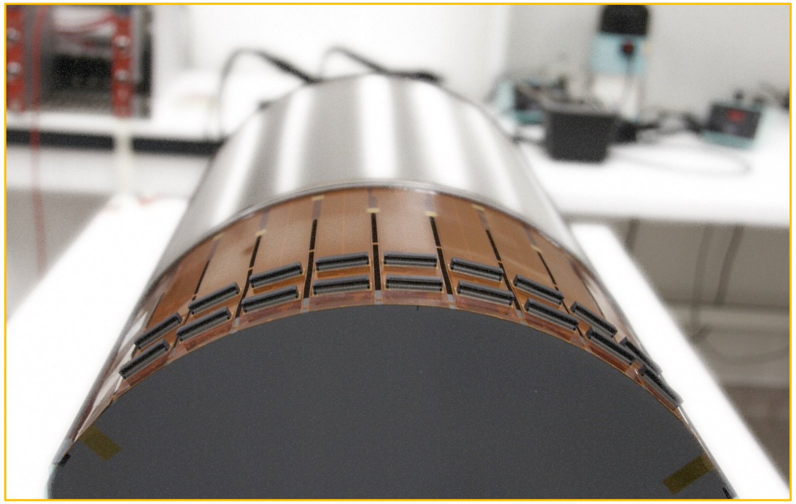


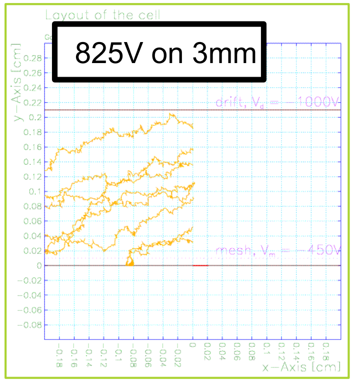


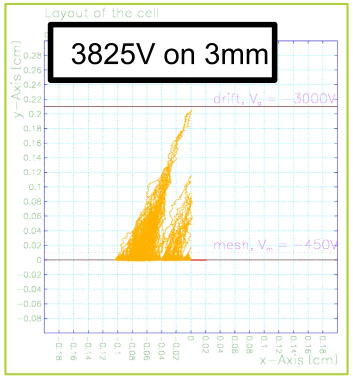
- 4 m² of Micromegas detectors to be installed in 2017
- DREAM based Front-End Electronics
- Remote off-detector frontend electronics connected with 2m micro-coaxial cables
- Forward Detectors
  - High particle rate (30MHz) => Fast detectors
  - Resistive strips divided in 2 zones inner/outer
  - Dimensions: 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.)

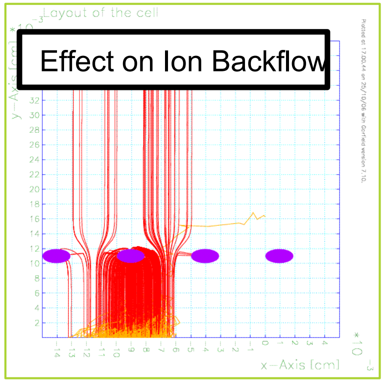
CLAS12 at Jefferson Lab

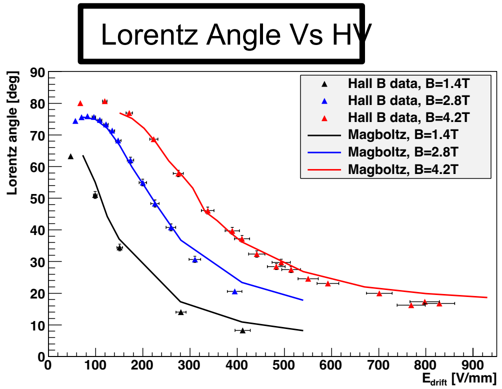




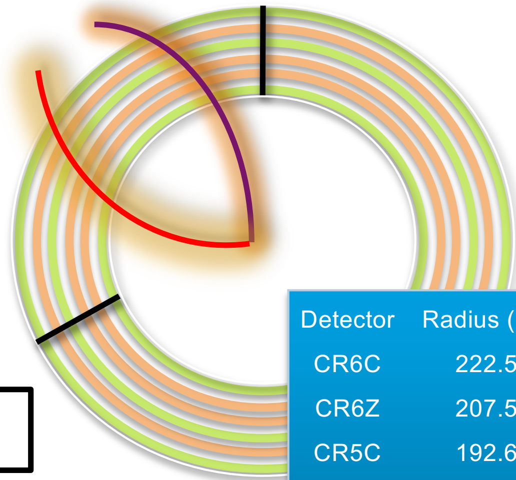






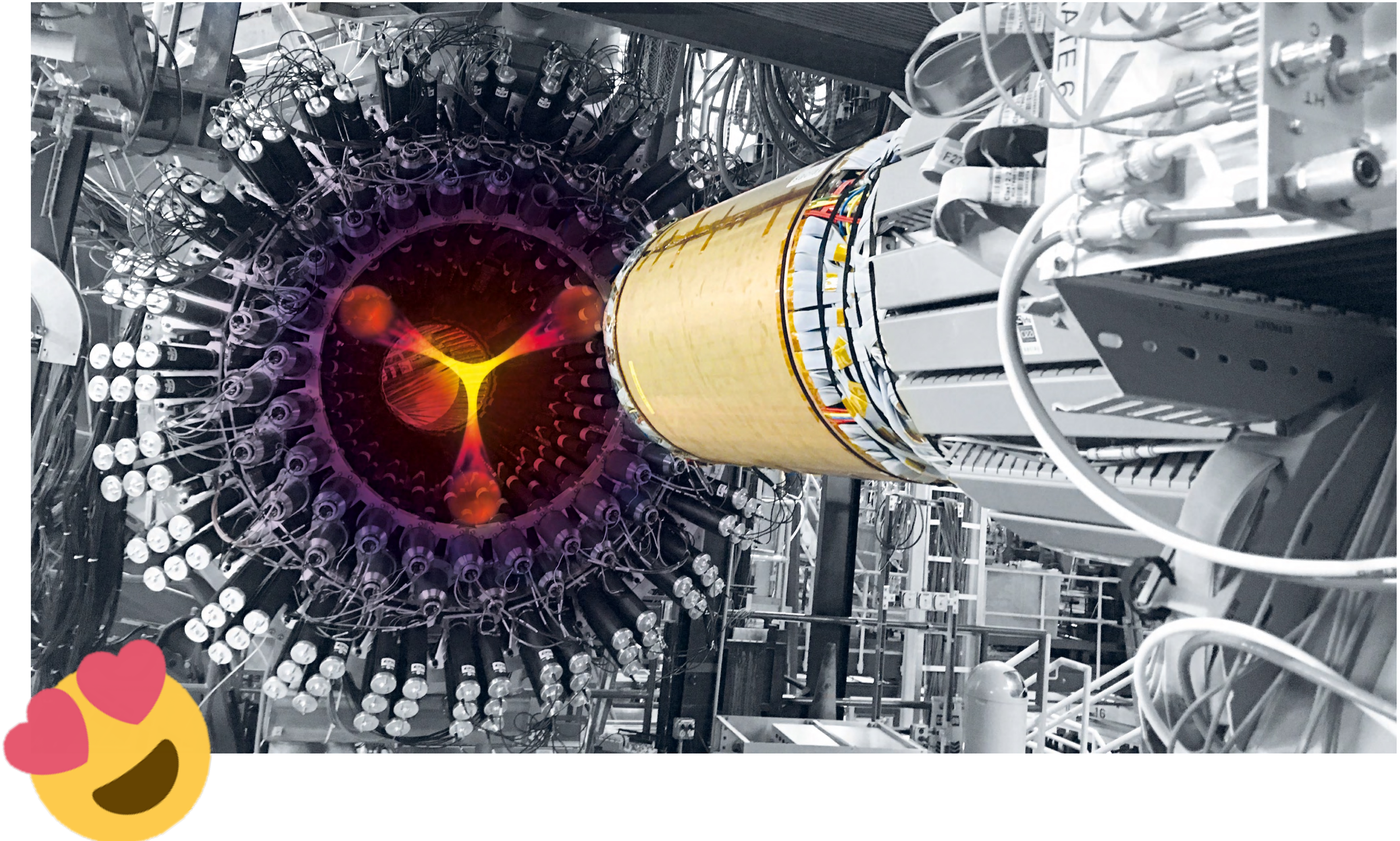


=> Clas-note 2007-004: Simulations of Micromegas detectors for the CLAS12 experiment (S. Procureur)



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

CLAS12 – Central Tracker

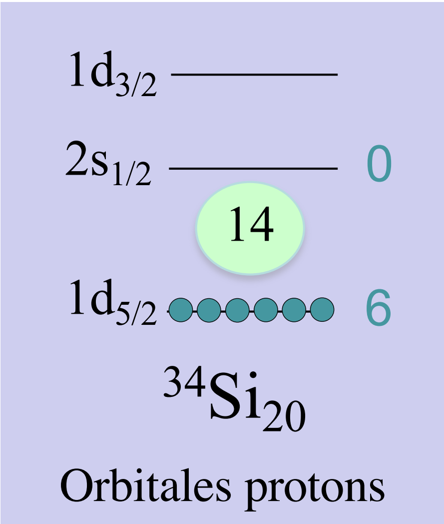


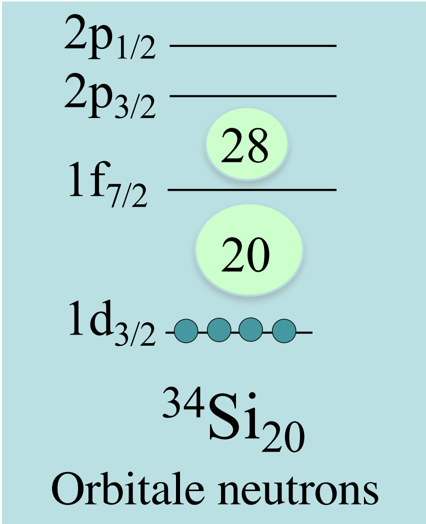
Physique Nucléaire

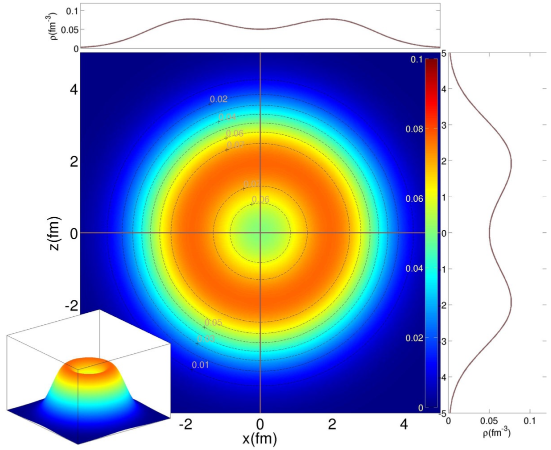
Noyaux Bulles et Spectroscopie Gamma

Cas physique : Etude des noyaux bulles

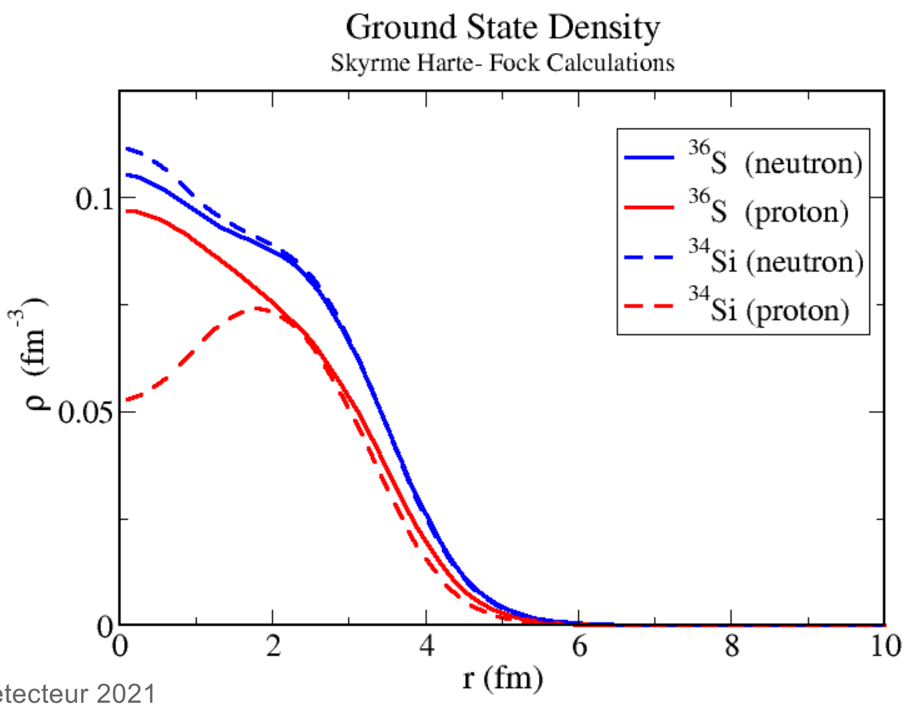
- Origine d'une déplétion centrale dans le noyau ^{34}Si





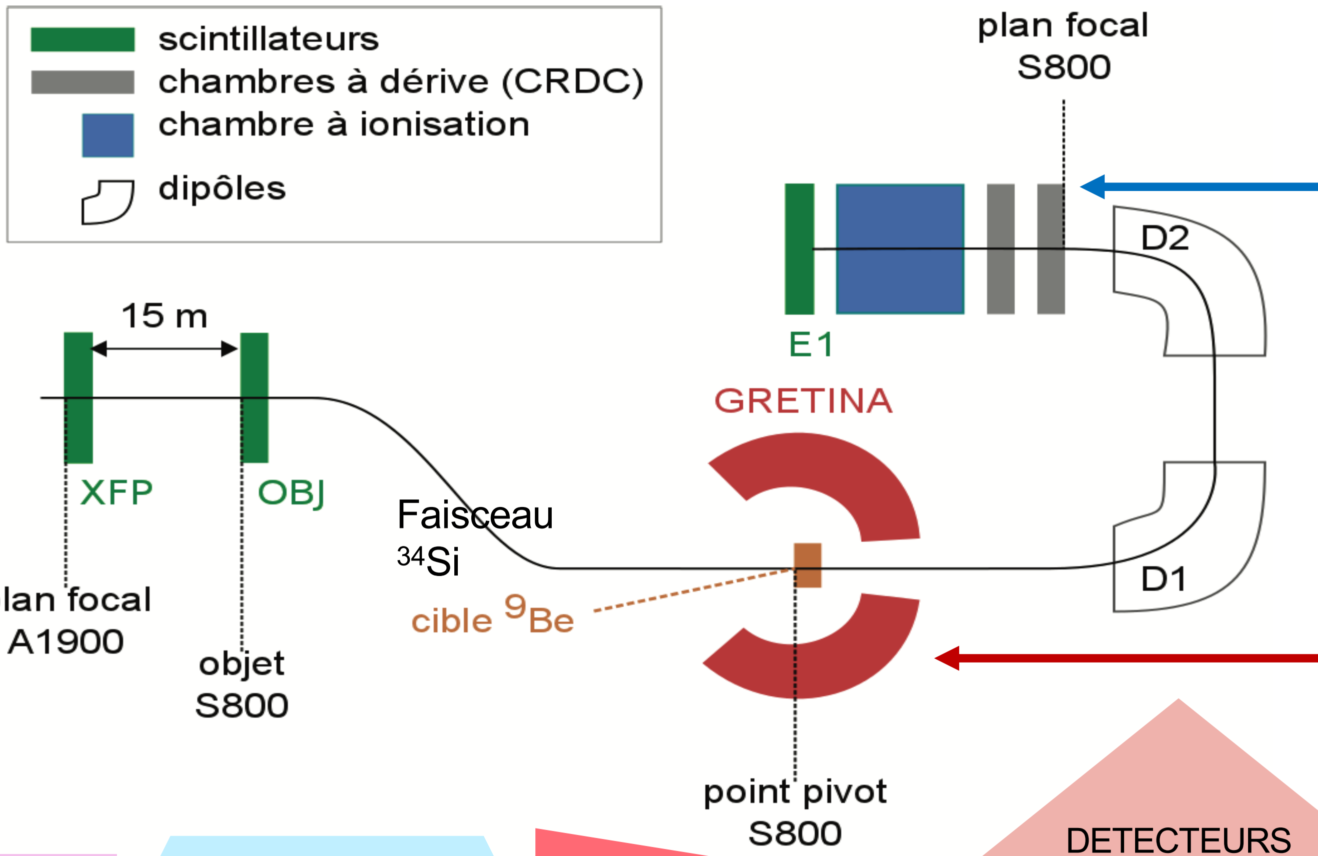


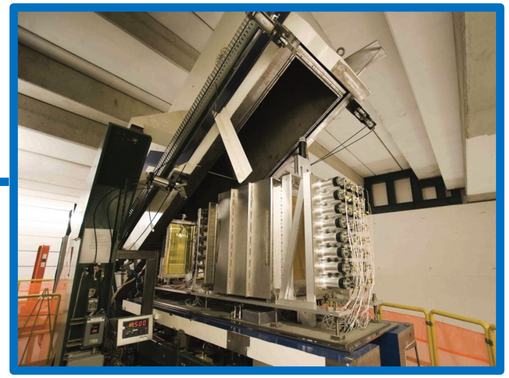
➡ A cause de son orbitale 2s1/2 vide, le ^{34}Si (Z=14, N=20) présenterait une déplétion centrale comparativement au ^{36}S (Z =16, N=20)



- 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 Gamma

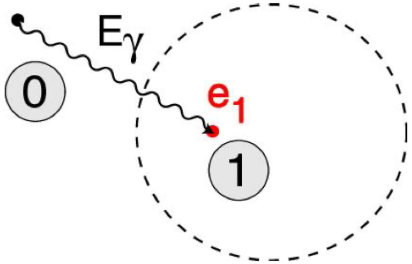
DETECTEUR
γ Germanium

- Comment interagit un γ avec la matière ?

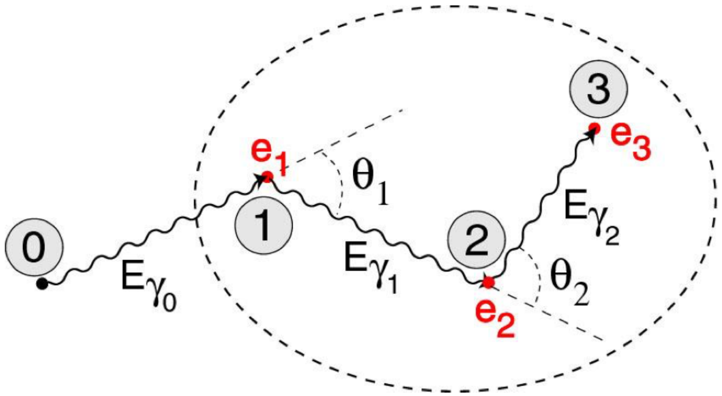
~ 100 keV	~1 MeV	~ 10 MeV

γ ray energy

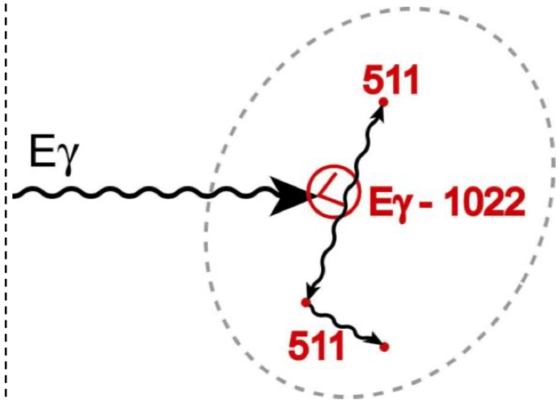
Photoelectric	**Compton Scattering**	**Pair Production**



$$E_{e1}=E_{\gamma}-E_b$$



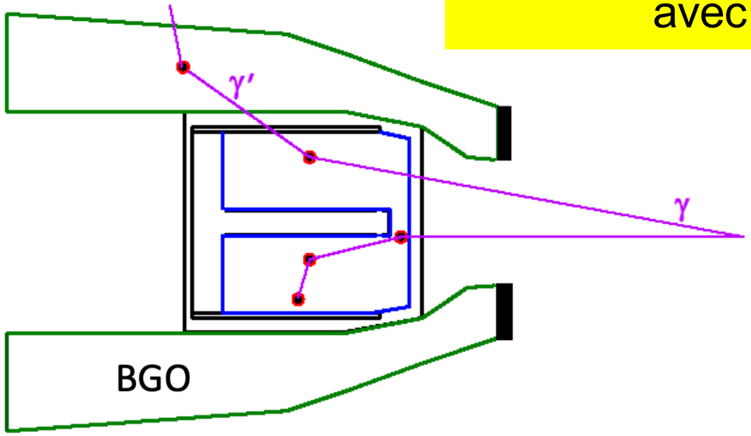
$$E_{\gamma'} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_0 c^2}(1 - \cos\theta)}$$

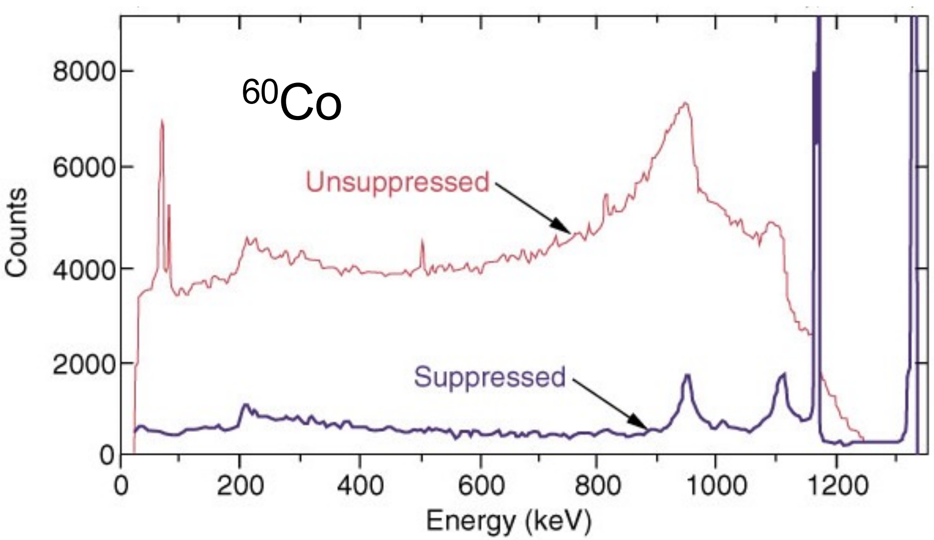


$$(E_{\gamma} > 2m_ec^2)$$

- Les détecteurs γ, la lutte contre la diffusion Compton

Astuce 1 : se débarrasser du Compton avec un bouclier BGO

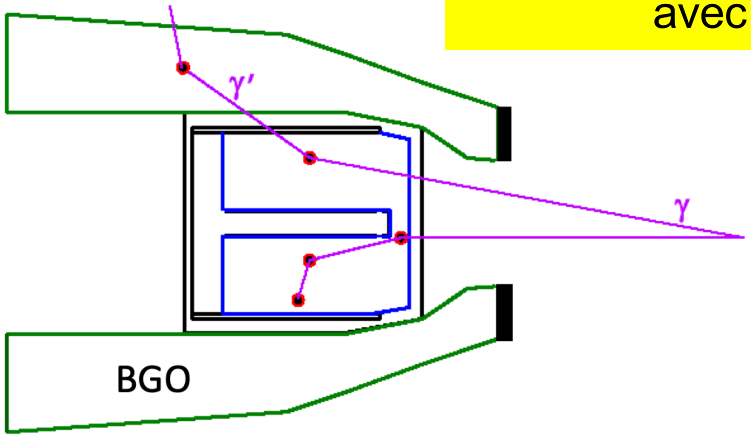


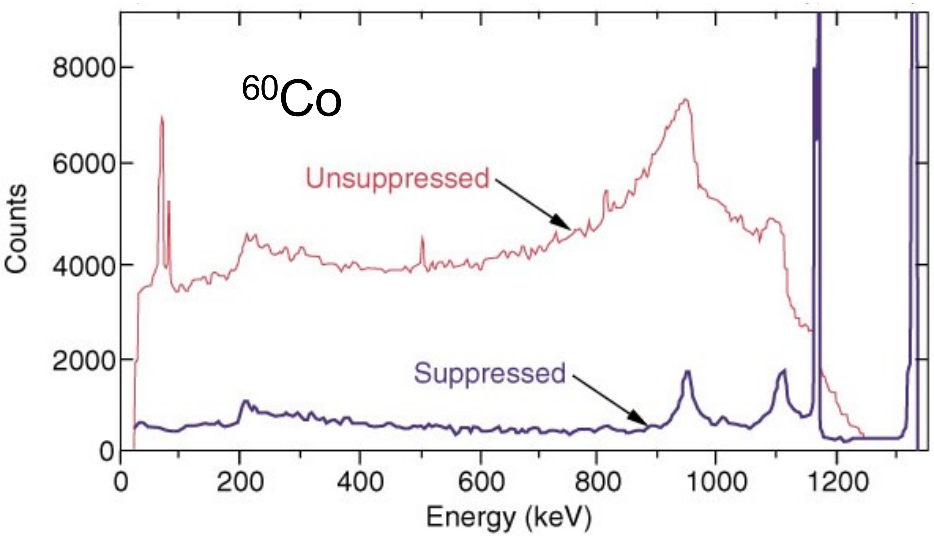


DETECTEUR
γ Germanium

- Les détecteurs γ, la lutte contre la diffusion Compton

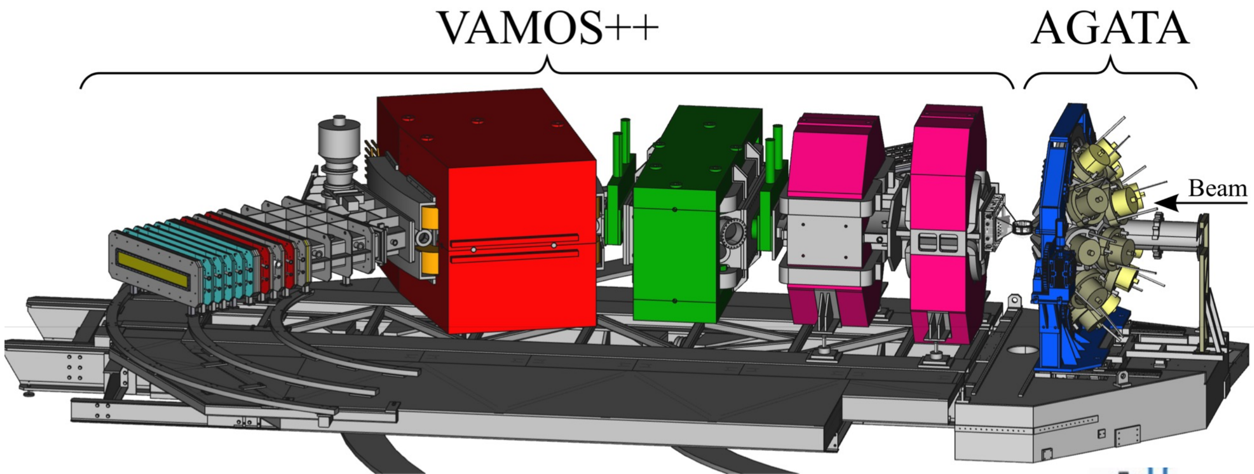
Astuce 1 : se débarrasser du Compton avec un bouclier BGO

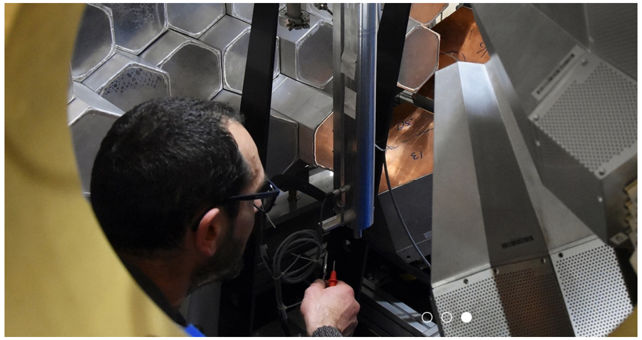


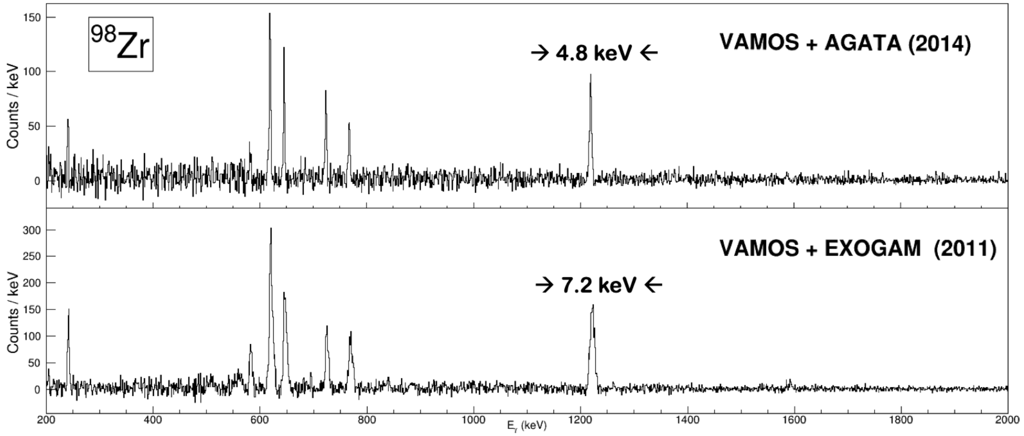


DETECTEUR
γ Germanium

- La campagne VAMOS-AGATA @GANIL 2014-2021







29 expériences

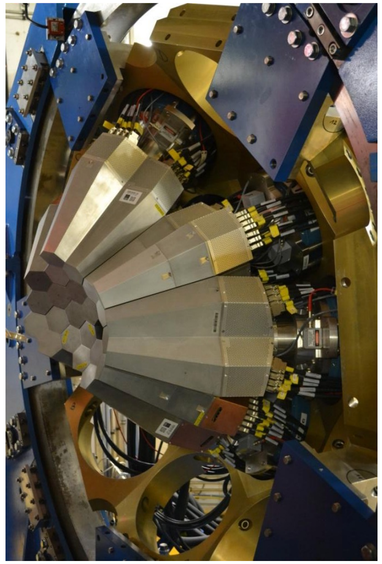
558 To de données

6568 heures de faisceau sur cible

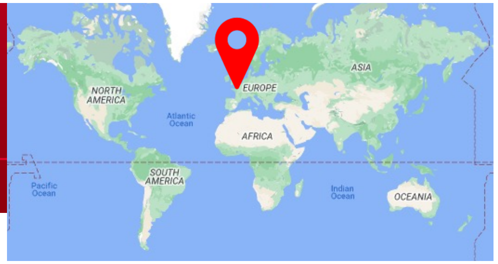
14 034 entrés dans le elog

2386 jours de surveillance cryogénique

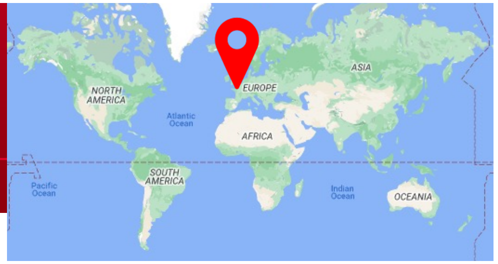
11,5 tonnes de materiel scientifique



Cas physique : Etude des noyaux bulles



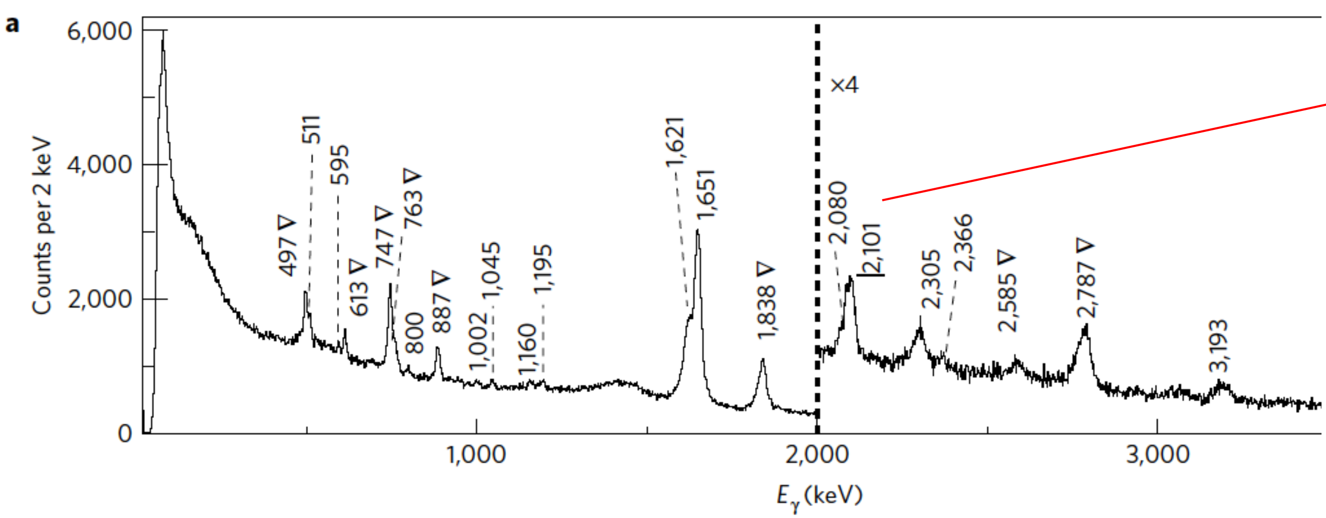
- Alors bulle ou pas bulle ?

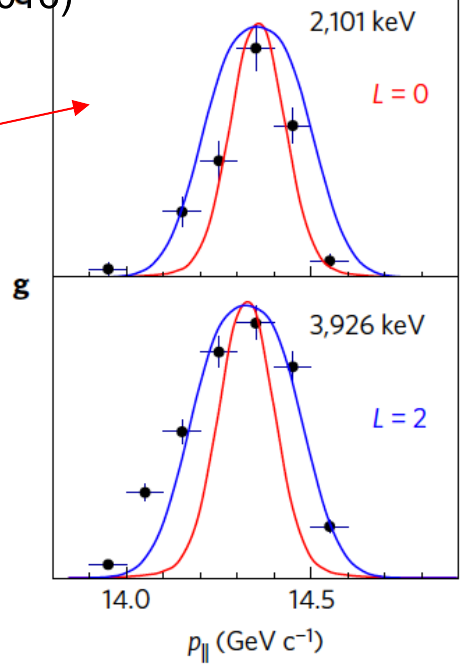


- Alors bulle ou pas bulle ?

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)





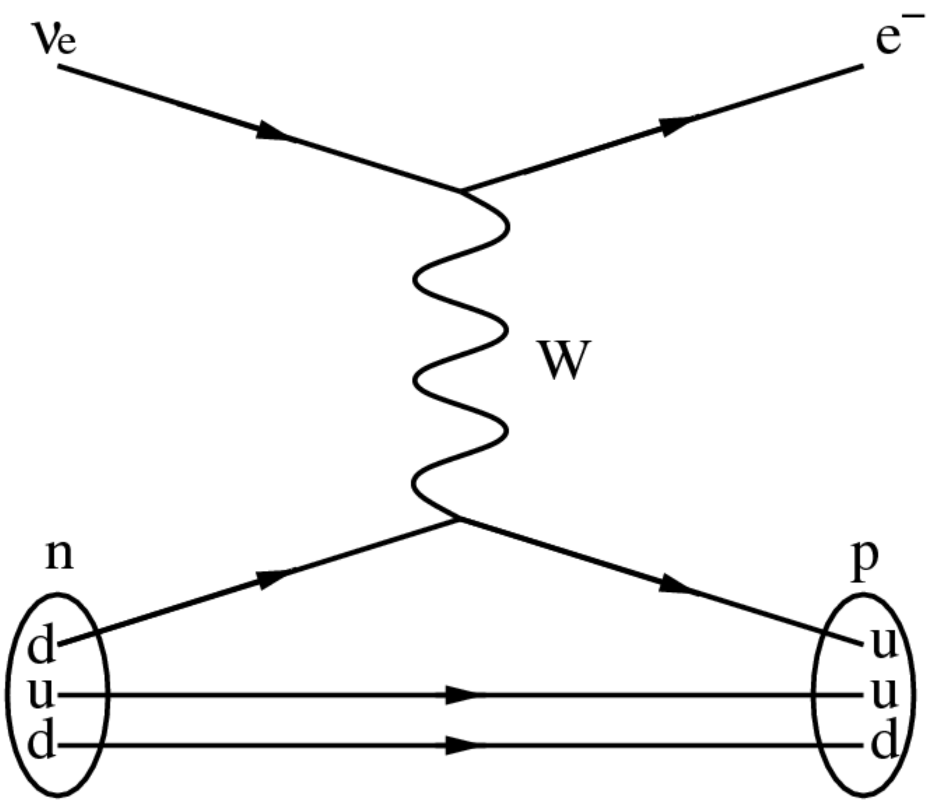
2) Le moment orbital angulaire *l* de l'orbitale d'où est arraché le p est déterminé en mesurant la distribution en moment longitudinal du ^{33}Al pour l'état peuplé

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)

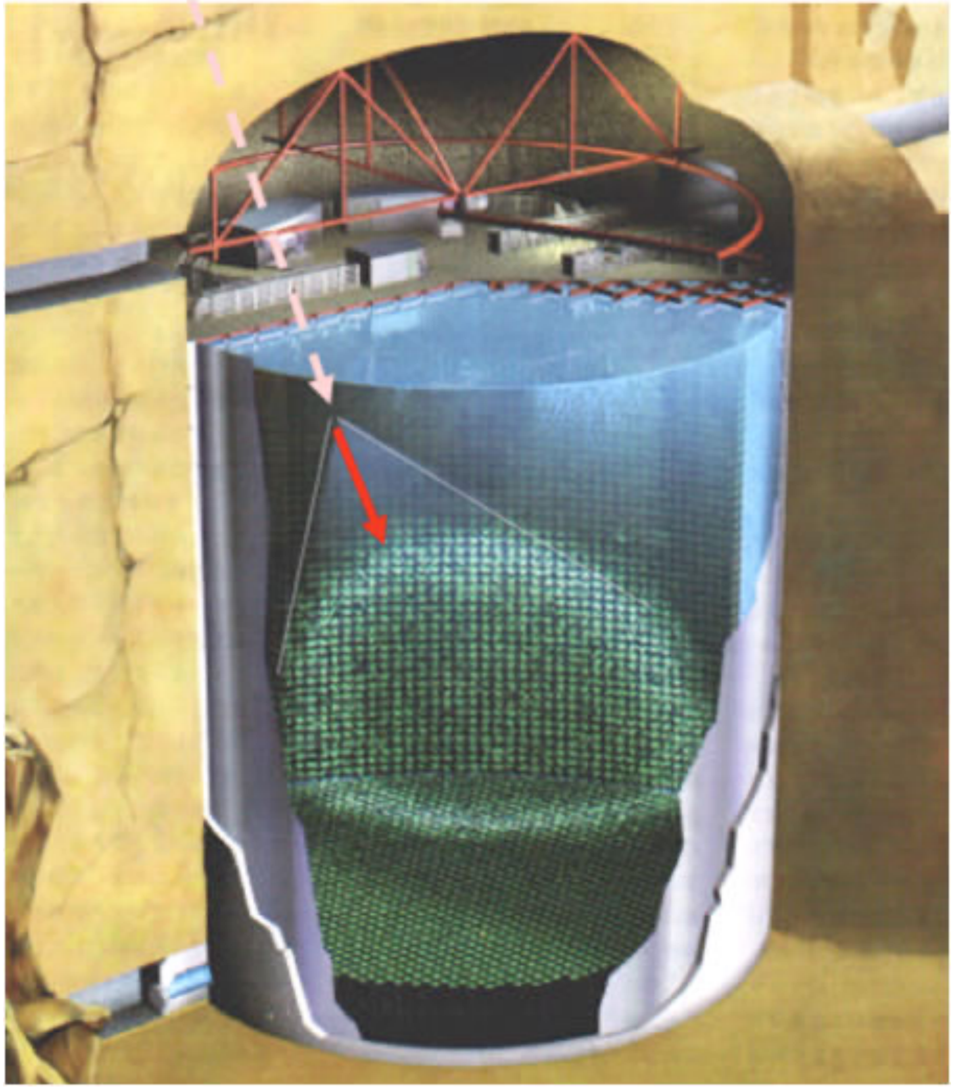
Dans le ^{34}Si 0.17(3)
Dans le ^{36}S 1.7(4)

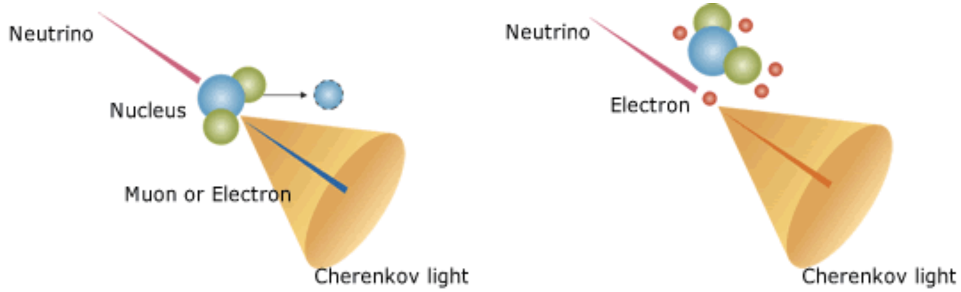
!

Observer les neutrinos

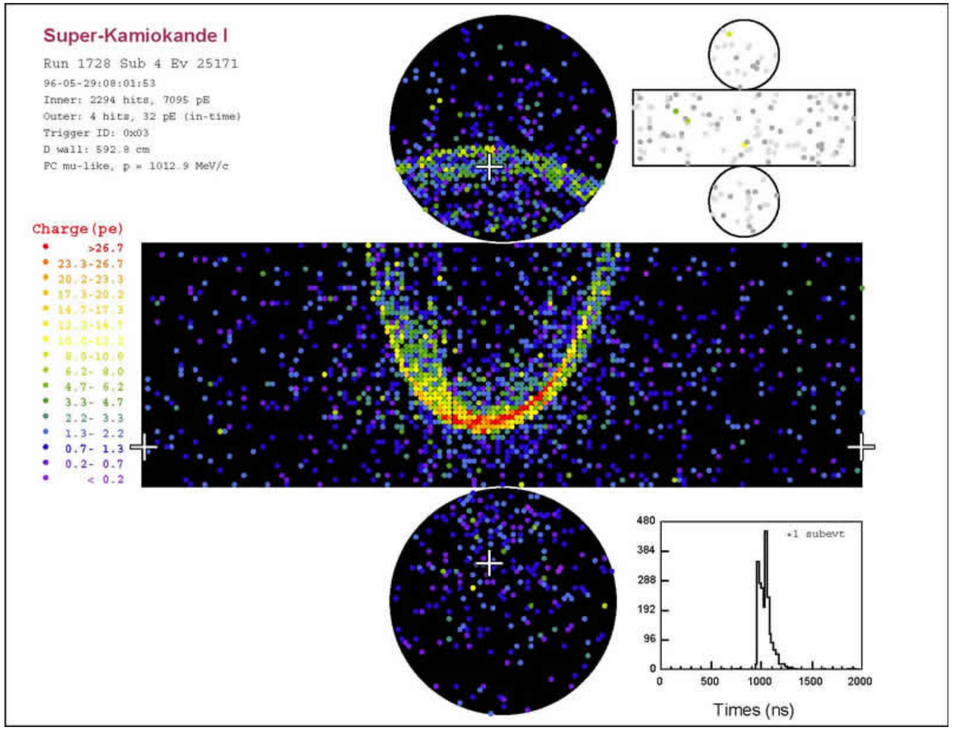


Super Kamiokande

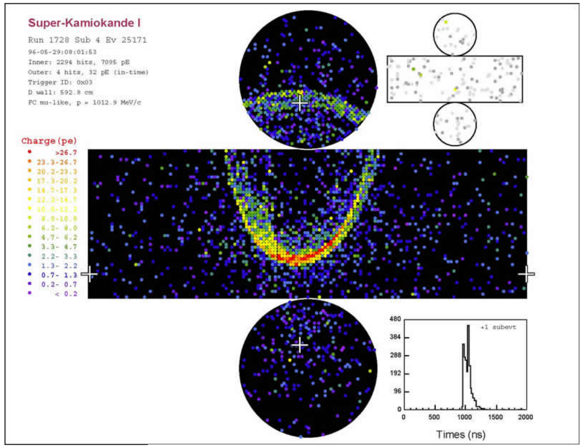


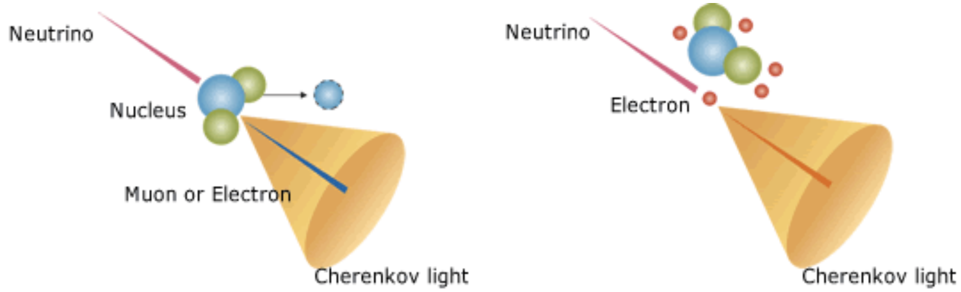


The generated charged particle emits the Cherenkov light.



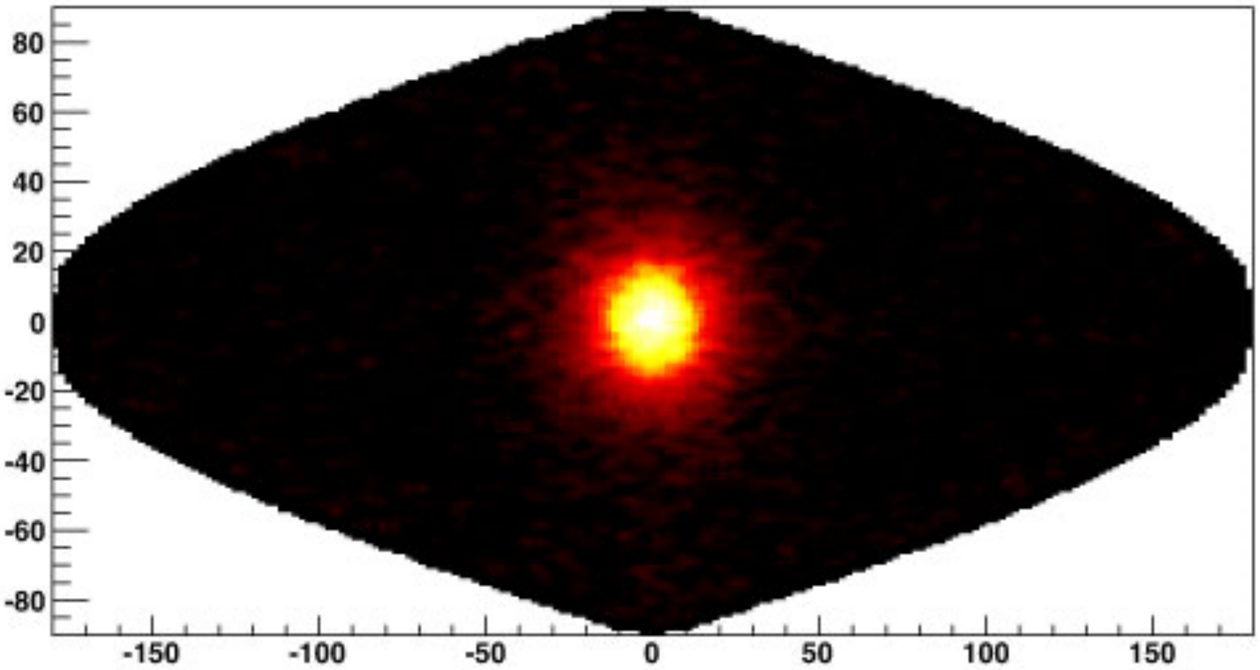
Super Kamiokande





The generated charged particle emits the Cherenkov light.

Image du soleil en Neutrino Electronique



Antares

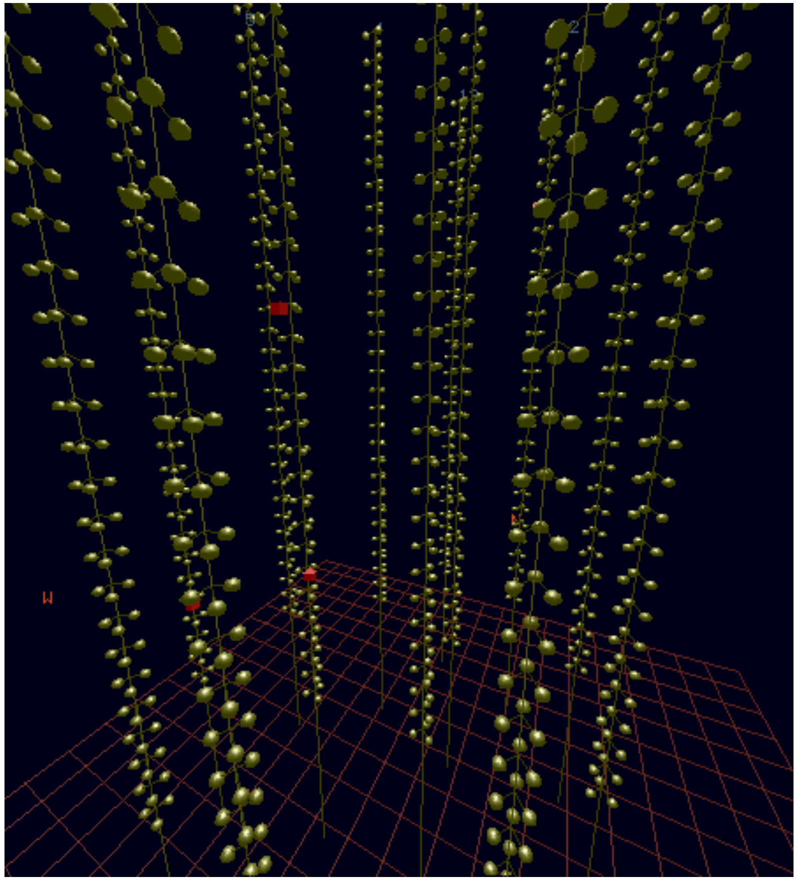
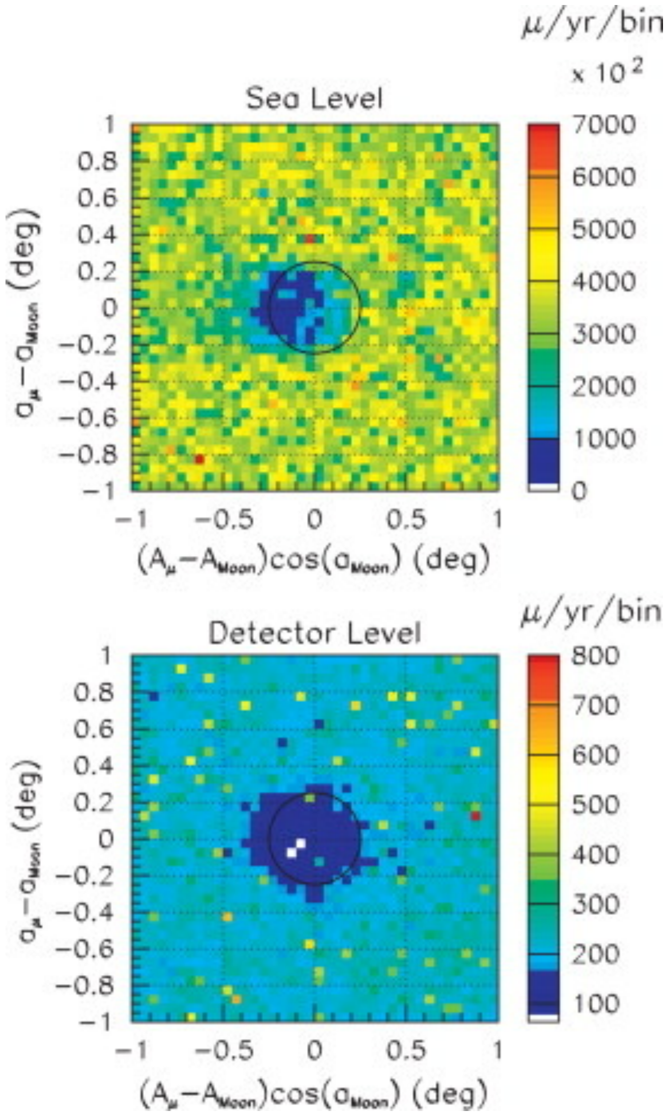
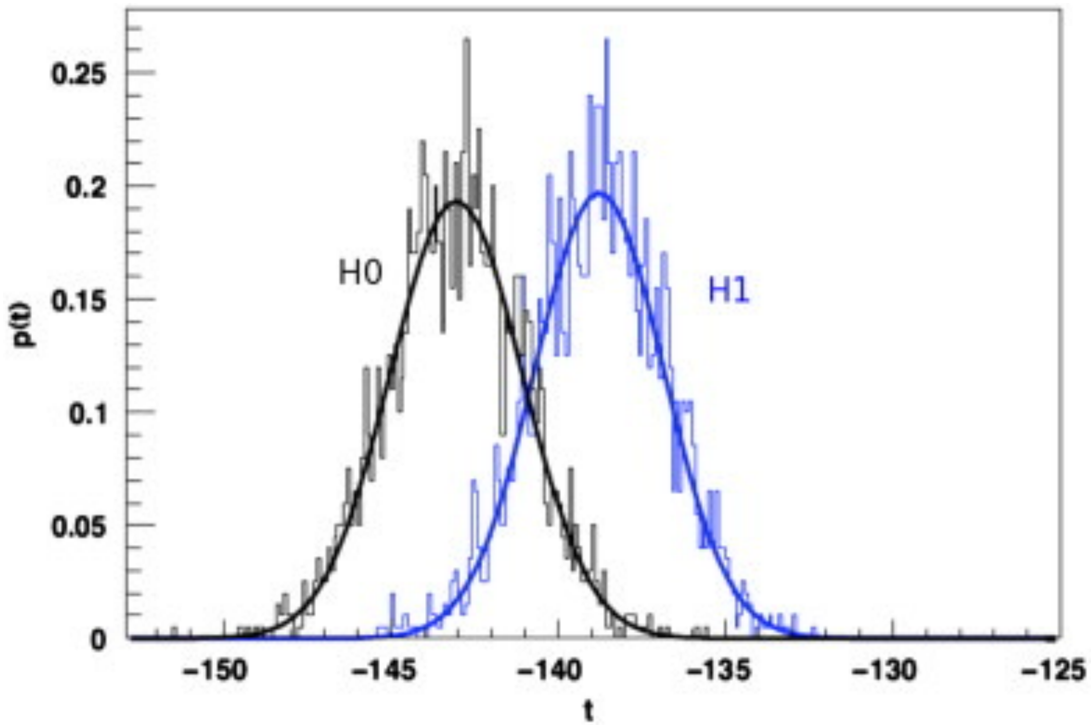


FIG. (II) 1.7: *Photographie d'un individu bioluminescent prise par l'une des caméras installées sur la ligne d'instrumentation IL07 (lire le paragraphe (II) 3.1). L'échelle n'est pas précisément connue (elle dépend de la distance à la caméra).*

Antares

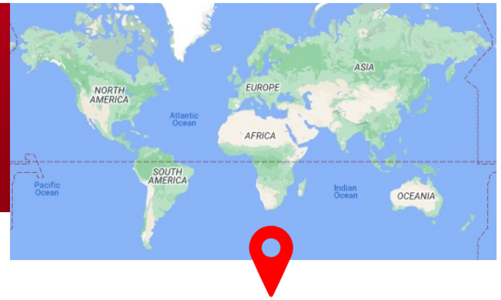


Moon Shadow in cosmic rays



Moon hypothesis confirms at 2.9 σ

Sun is at 3.7σ

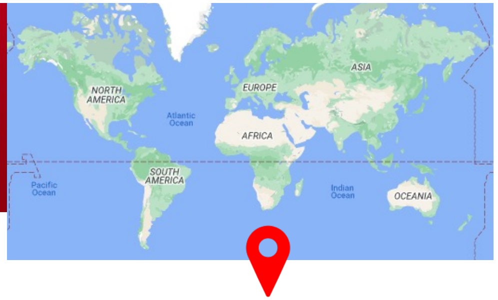


AMANDA

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

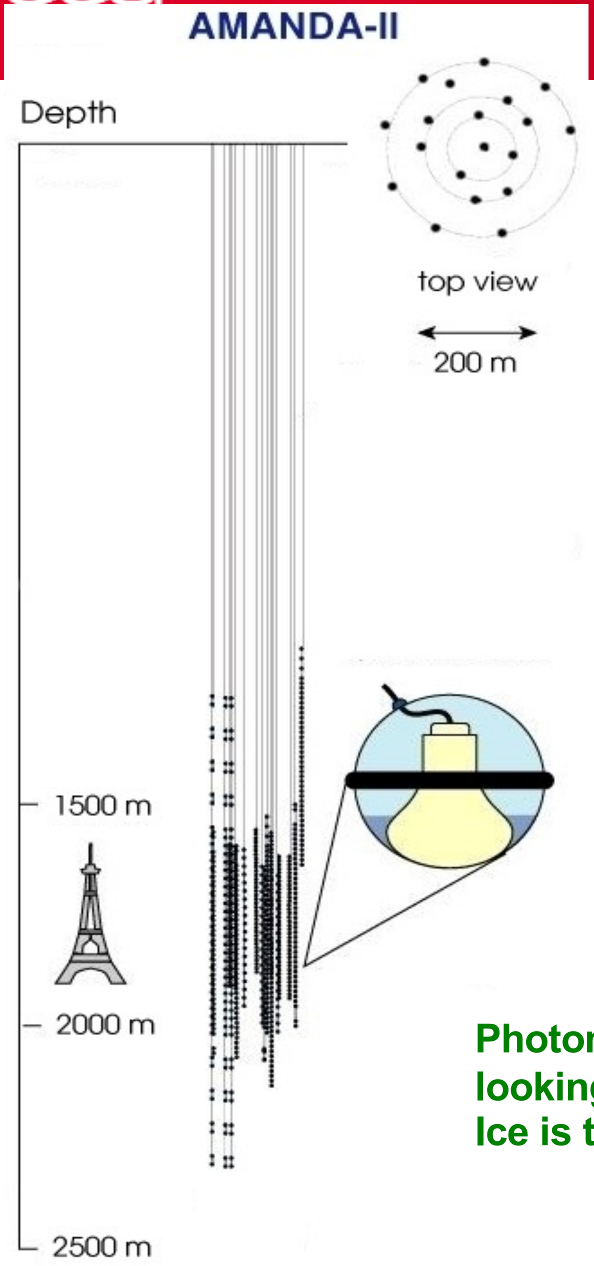
IceCube

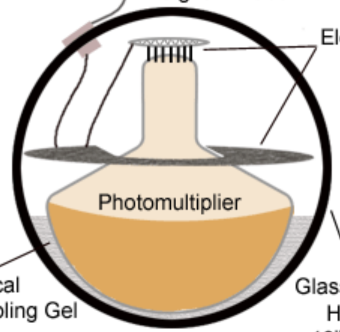
AMANDA



South Pole

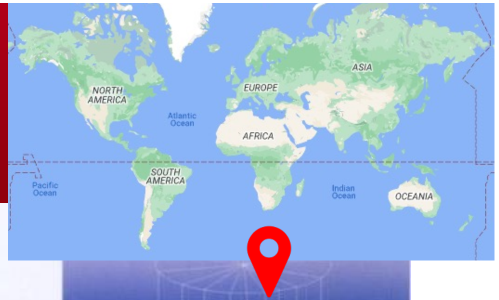
AMANDA





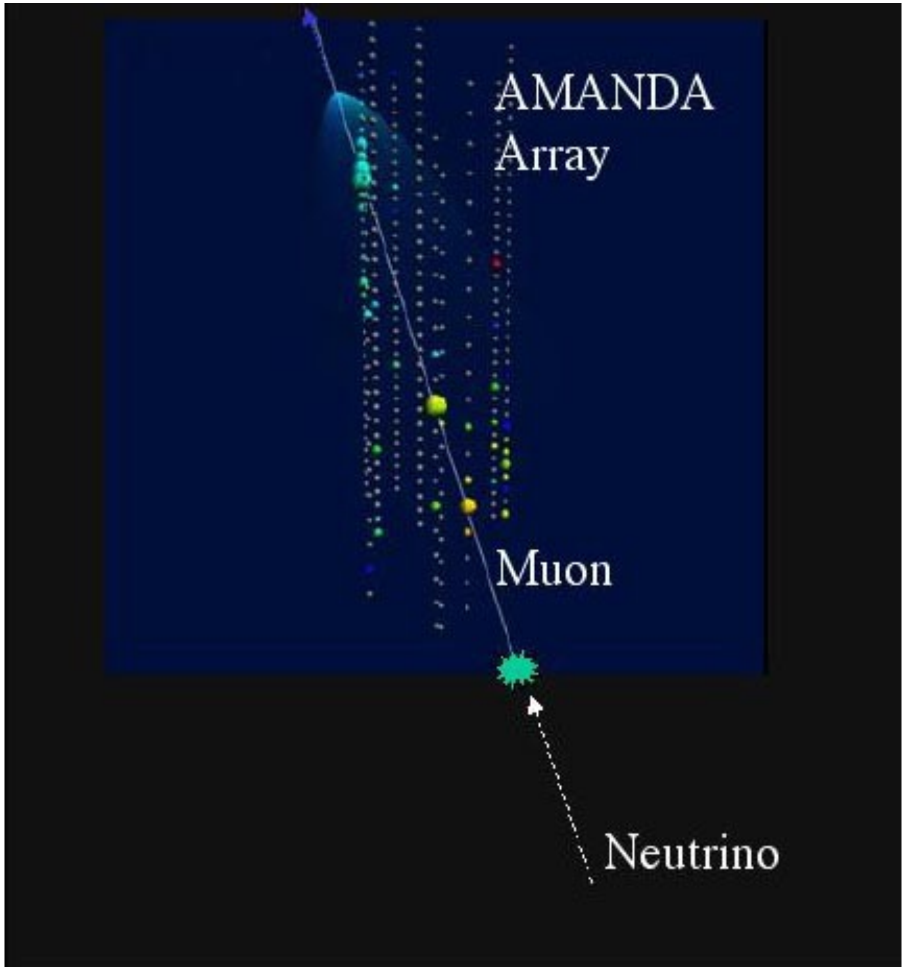
Photomultipliers in the Ice,
looking downwards.
Ice is the detecting medium.

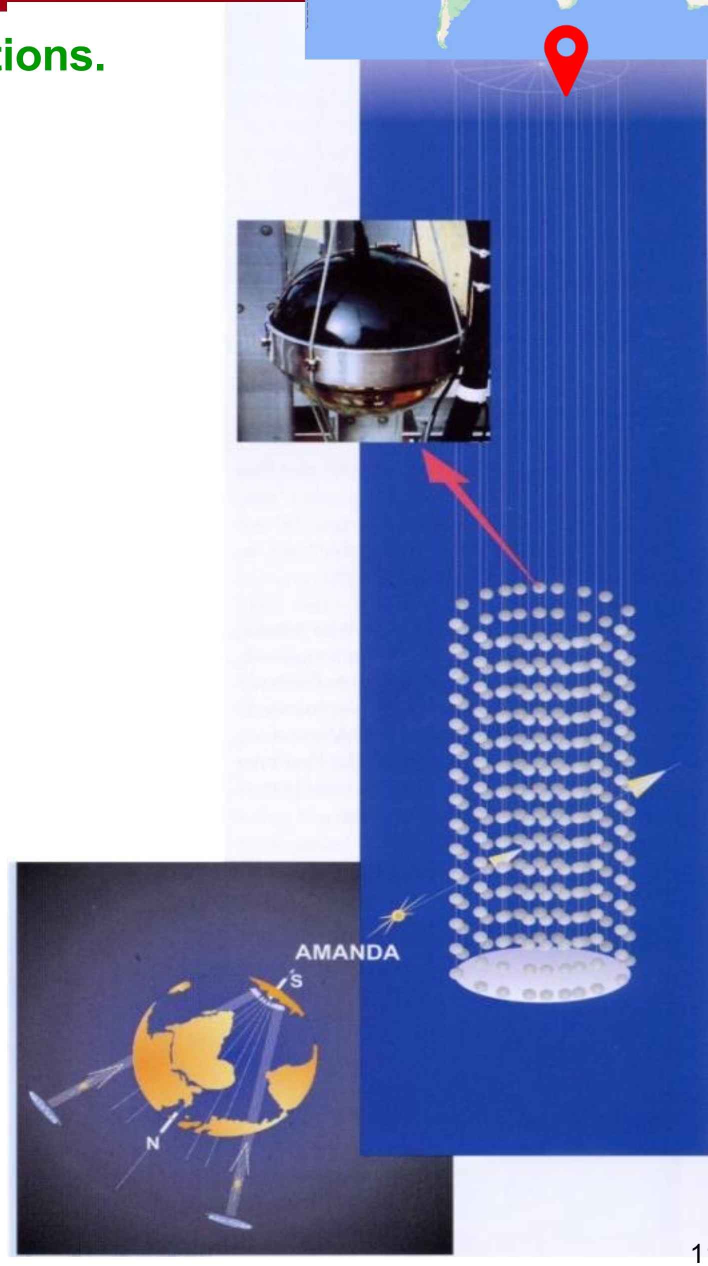
AMANDA



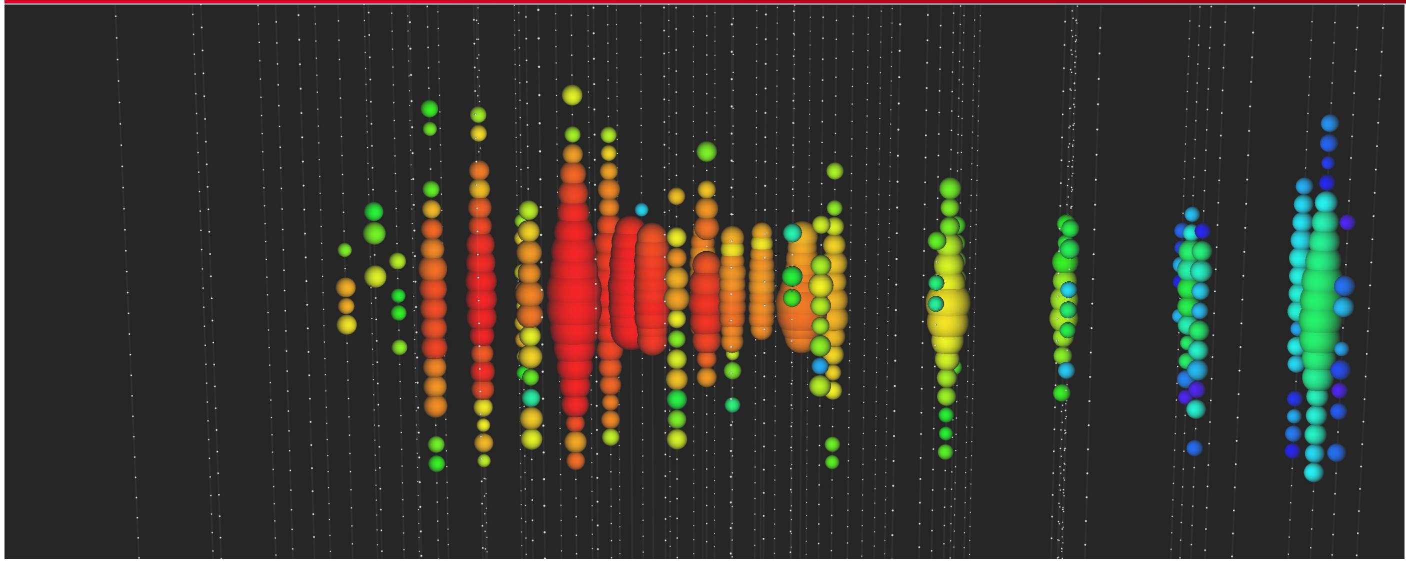
Look for upwards going Muons from Neutrino Interactions.
Cherekov light propagating through the ice.

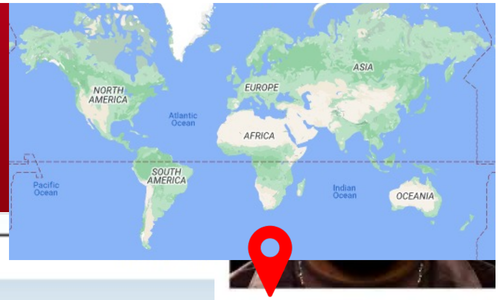
→ Find neutrino point sources in the universe !

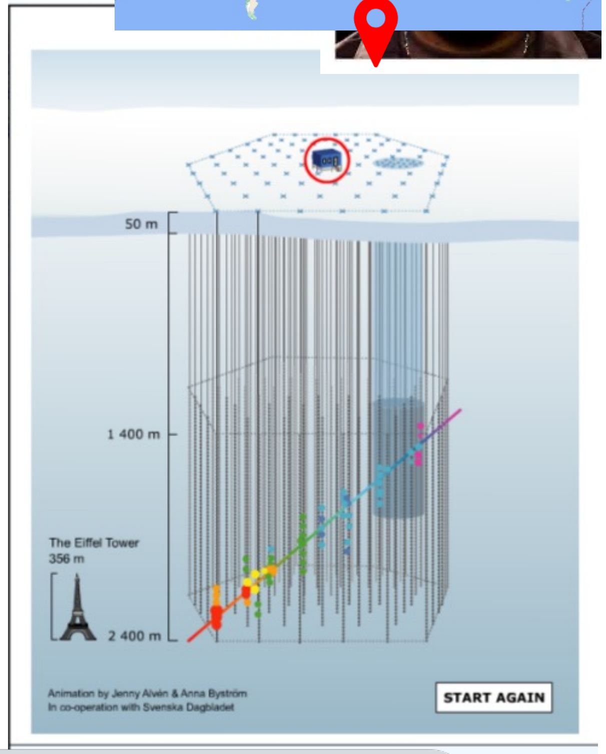




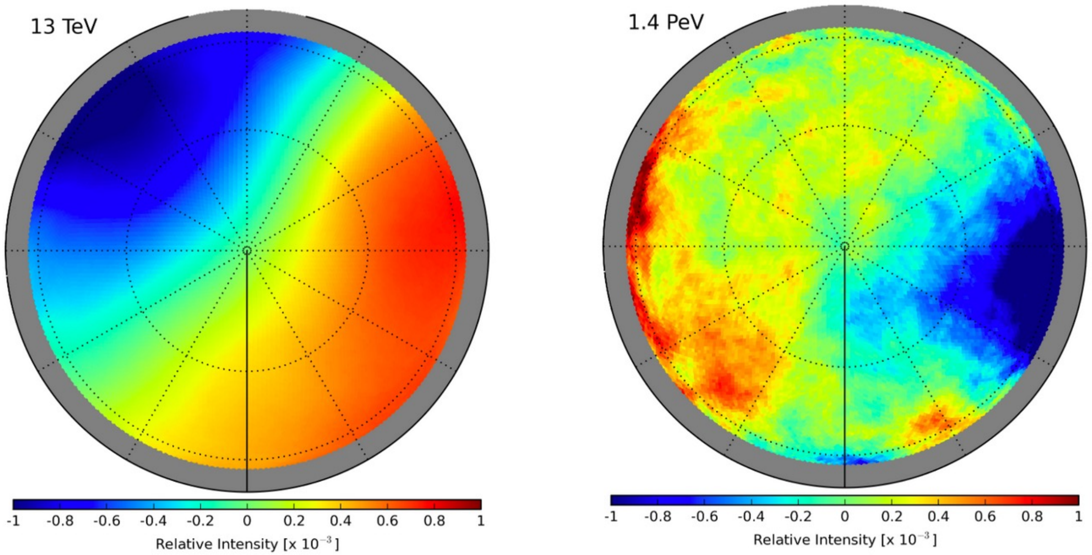
AMANDA – ICE CUBE







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



Detector Design

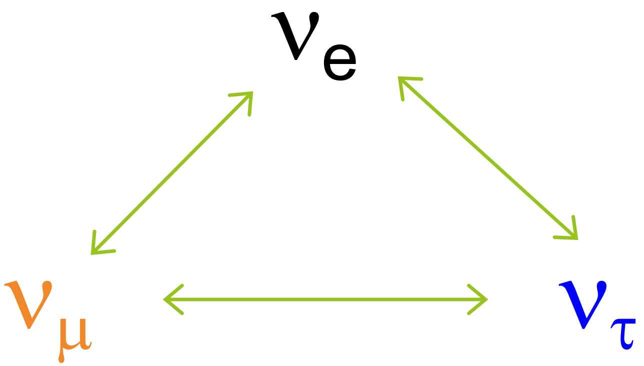
- 1 gigaton of instrumented ice
- 5,160 light sensors, or digital optical modules (DOMs), digitize and time-stamp signals
- 1 square kilometer surface array, IceTop, with 324 DOMs
- 2 nanosecond time resolution
- IceCube Lab (ICL) houses data processing and storage and sends 100 GB of data north by satellite daily

CERN Neutrino Gran Sasso

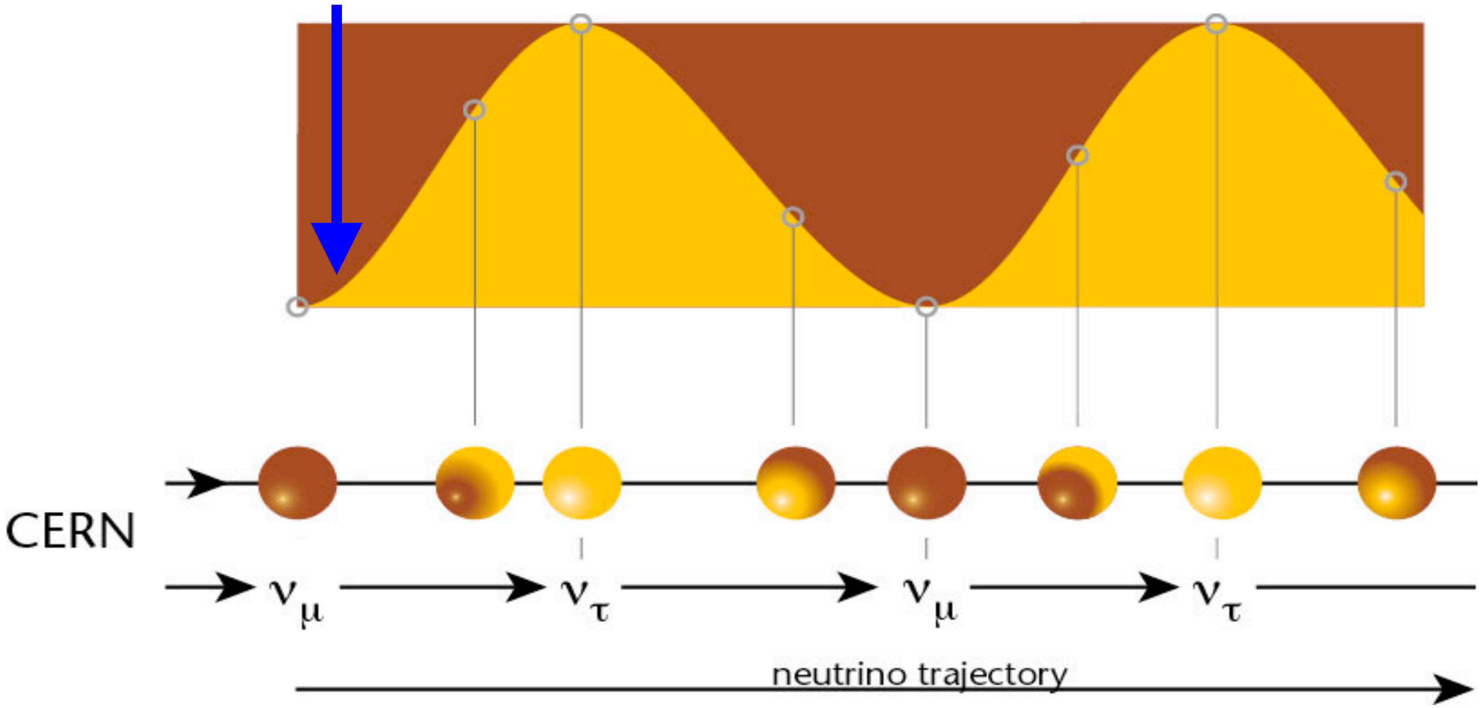
(CNGS)

CNGS

If neutrinos have mass:



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



CNGS PROJECT

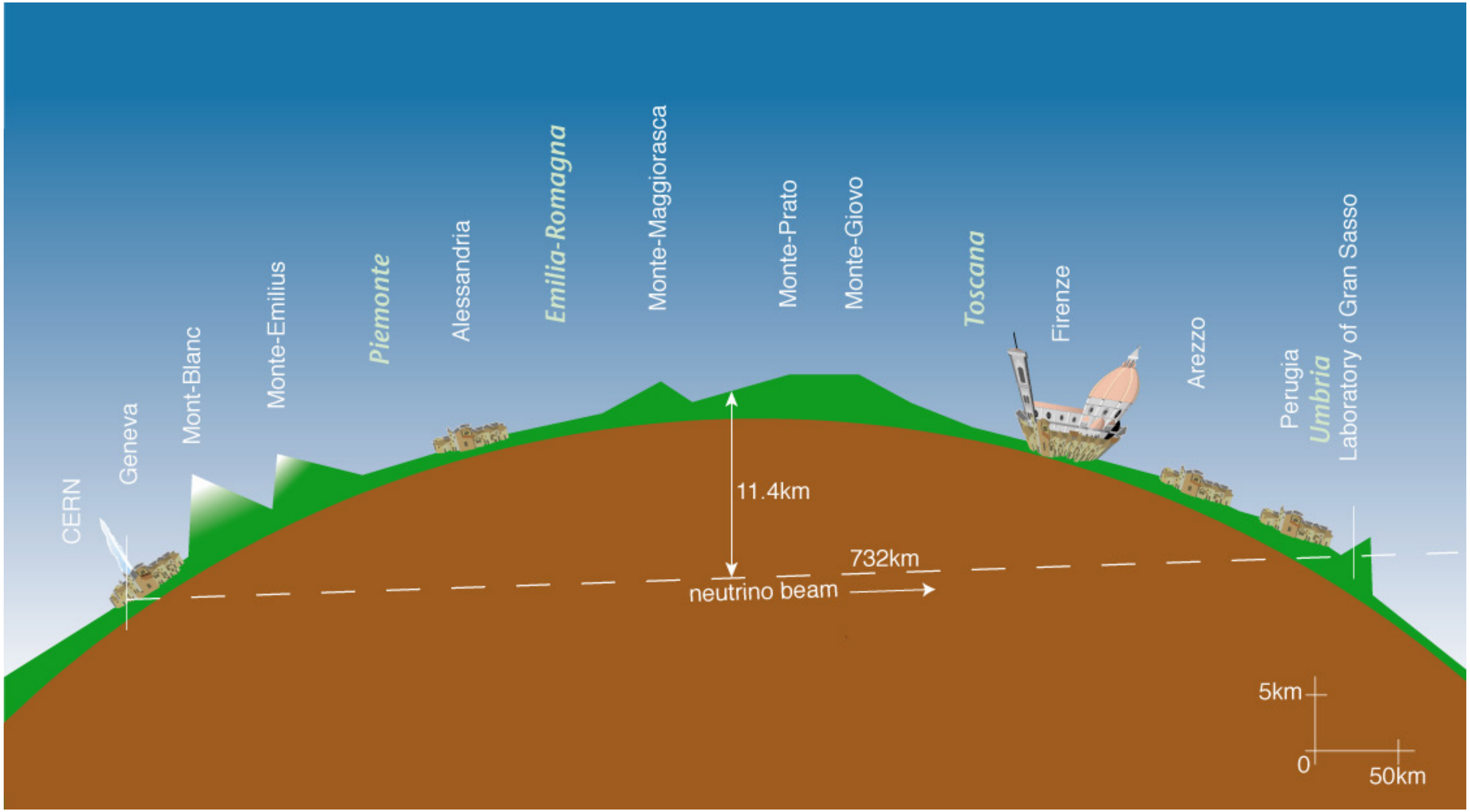
CNGS (CERN Neutrino Gran Sasso)

- 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)

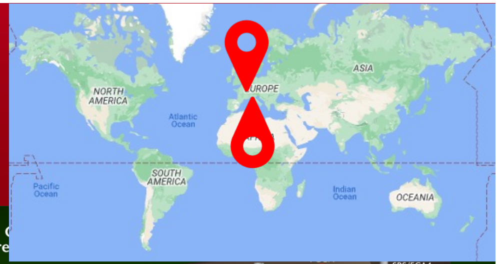
CNGS

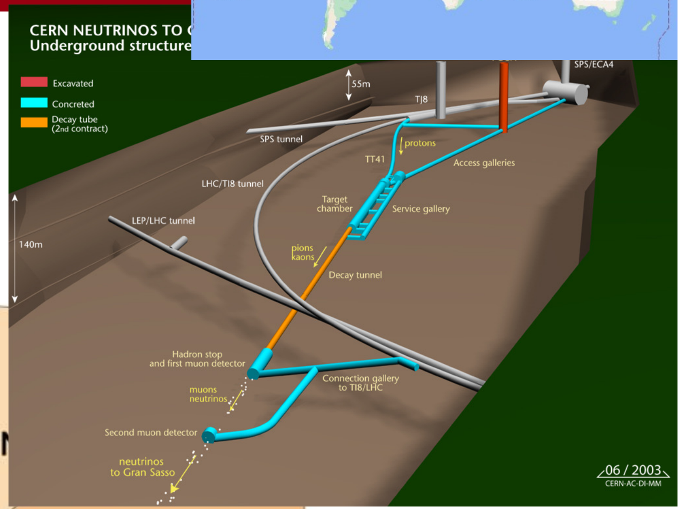
NORTH AMERICA
EUROPE
ASIA
Atlantic Ocean
SOUTH AMERICA
Pacific Ocean
Indian Ocean
OCEANIA

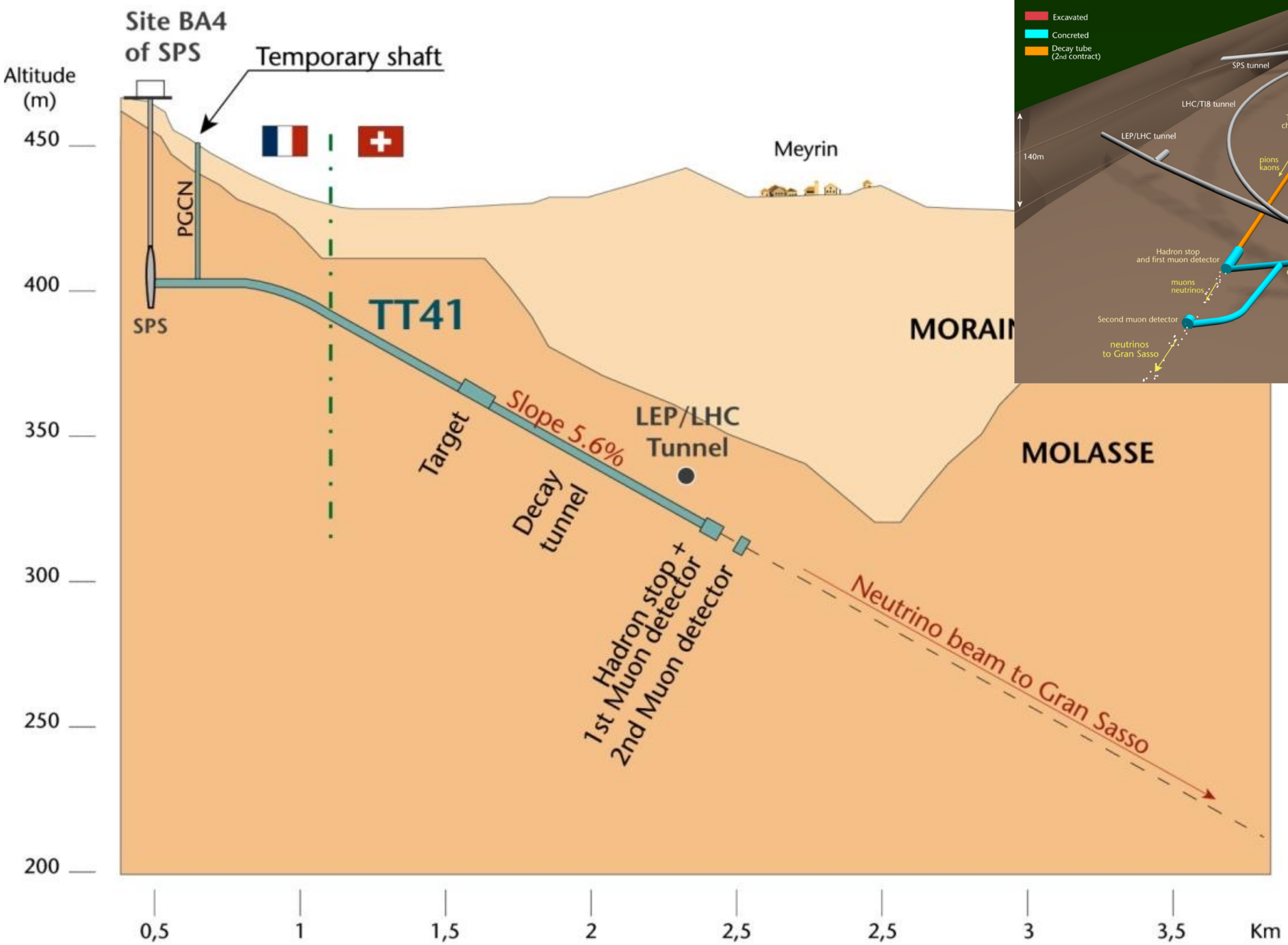


CERN
Geneva
Mont-Blanc
Monte-Emilius
Piemonte
Alessandria
Emilia-Romagna
Monte-Maggiorasca
Monte-Prato
Monte-Giovo
Toscana
Firenze
Arezzo
Perugia
Umbria
Laboratory of Gran Sasso
11.4km
732km
neutrino beam
5km
0
50km

CNGS


NORTH AMERICA
Atlantic Ocean
SOUTH AMERICA
Pacific Ocean
EUROPE
ASIA
Indian Ocean
OCEANIA


CERN NEUTRINOS TO G
Underground structure
Excavated
Concreted
Decay tube (2nd contract)
55m
140m
SPS/ECA4
TJ8
SPS tunnel
protons
TT41
Access galleries
LHC/TI8 tunnel
LEP/LHC tunnel
Target chamber
Service gallery
pions kaons
Decay tunnel
Hadron stop and first muon detector
Connection gallery to TI8/LHC
muons neutrinos
Second muon detector
neutrinos to Gran Sasso
06 / 2003
CERN-AC-DI-MM


Site BA4
of SPS
Temporary shaft
Altitude
(m)
450
400
350
300
250
200
PGCN
SPS
TT41
Meyrin
MORAI
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

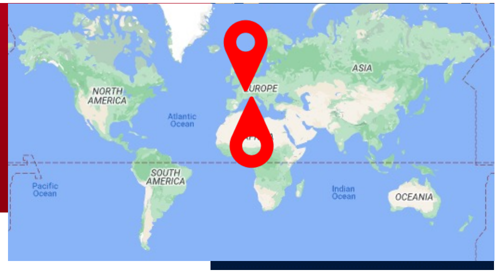
NEUTRINOS AT CNGS: SOME NUMBERS

For 1 day of CNGS operation, we expect:

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

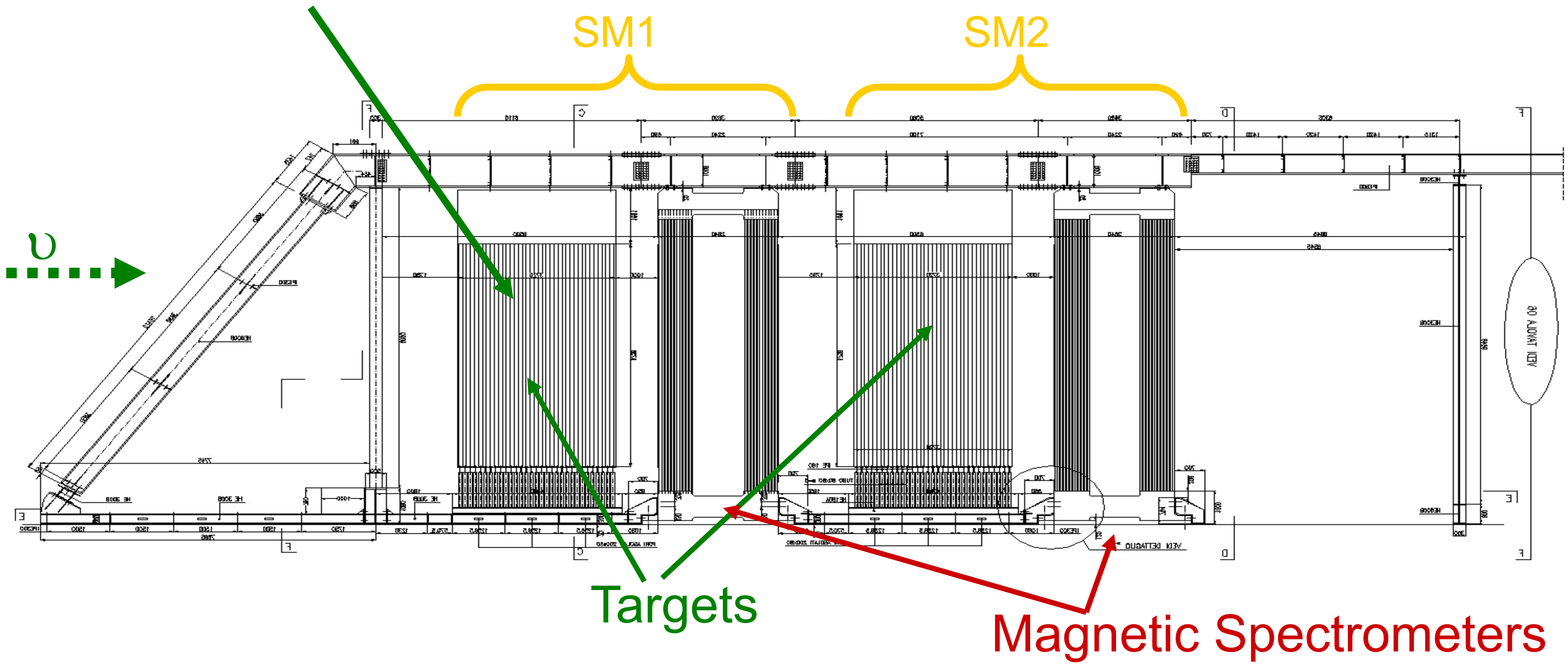
ν_μ events per day in OPERA	$\approx$ 25 per day
ν_τ events (from oscillation)	$\approx$ 2 per year

Opera Experiment at Gran Sasso



31 target planes / supermodule

In total: 206336 bricks, 1766 tons

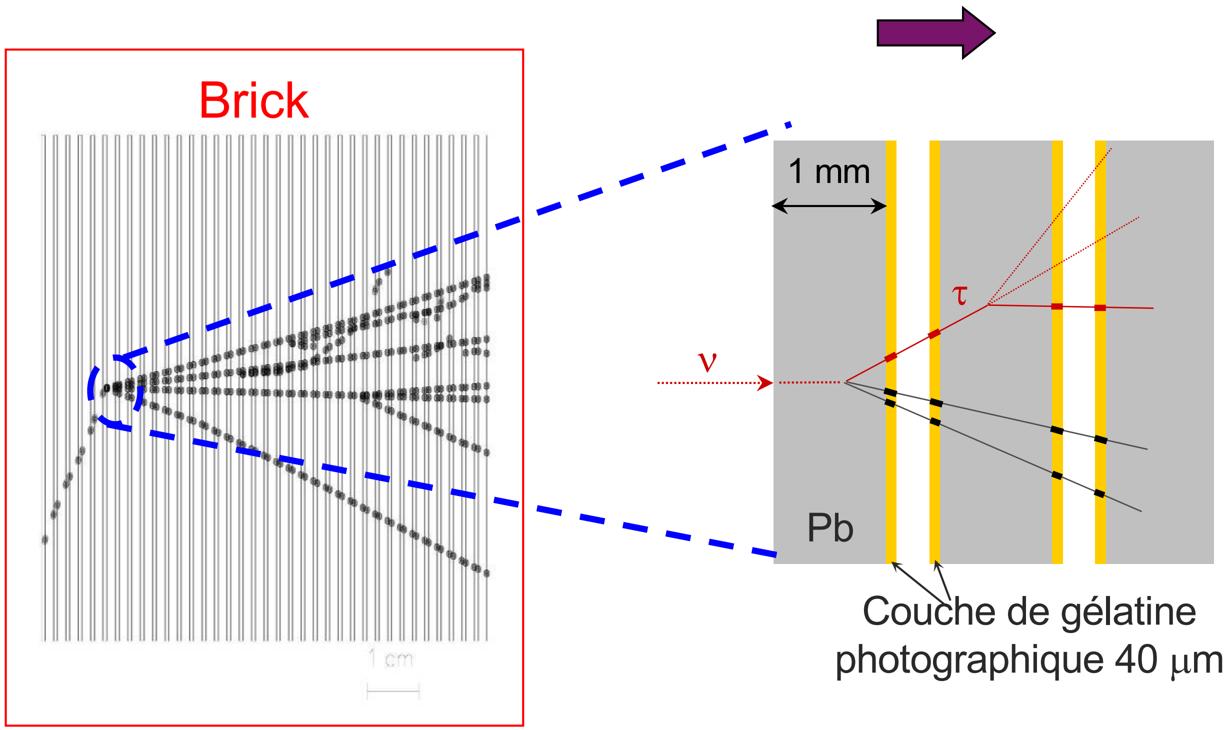


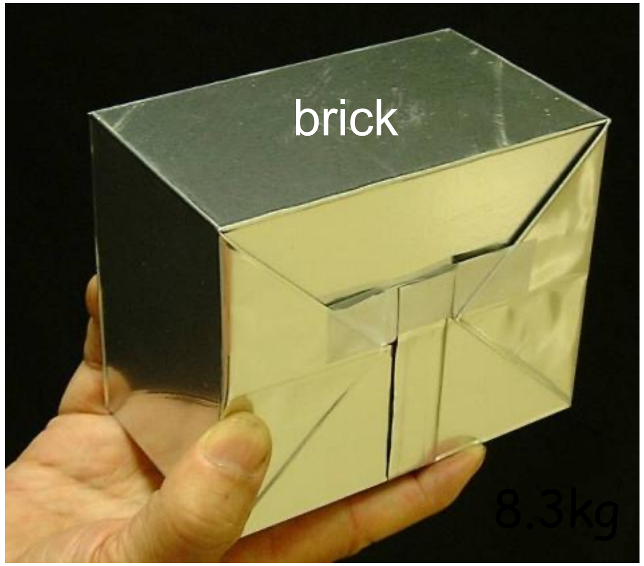
First observation of CNGS beam neutrinos : August 18th, 2006

Basic unit: brick

56 Pb sheets + 56 photographic films (emulsion sheets)

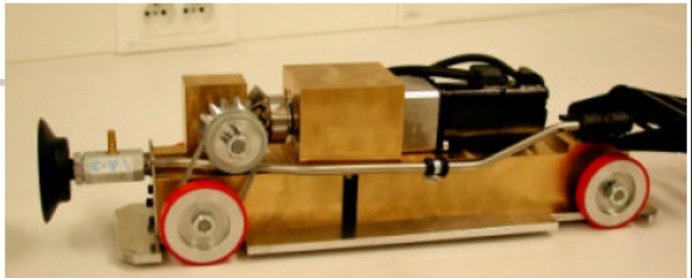
Lead plates: massive target
Emulsions: micrometric precision



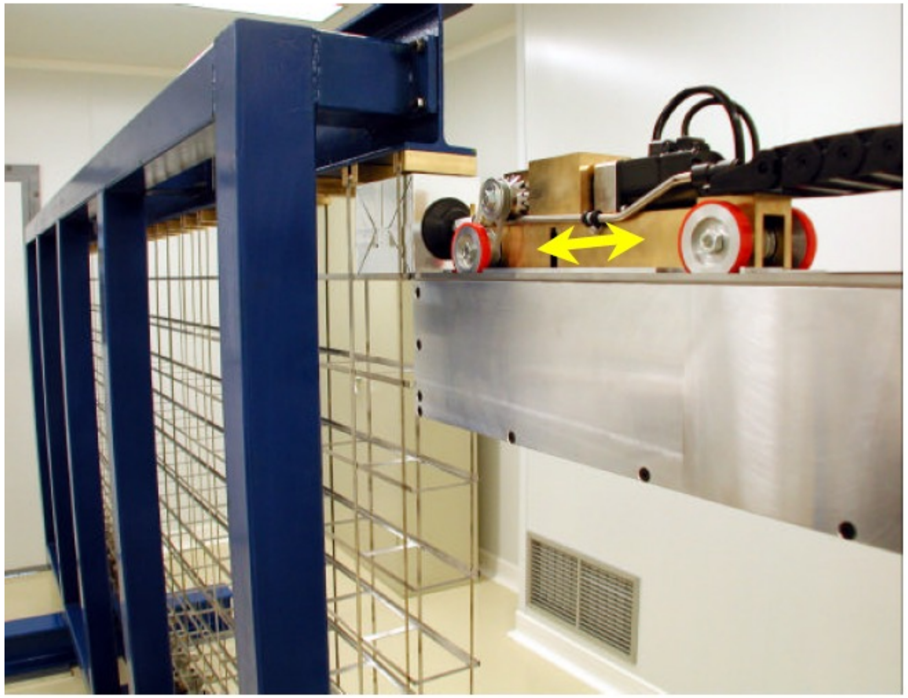


10.2 x 12.7 x 7.5 cm^3

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



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

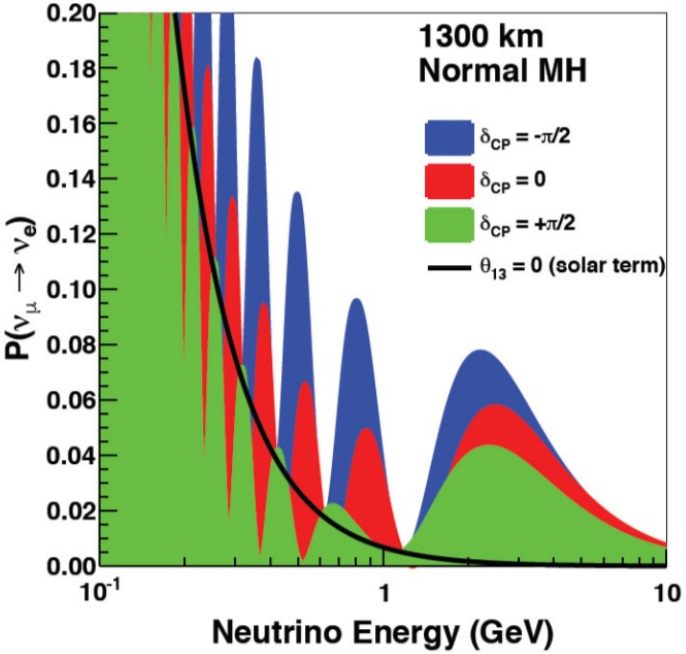


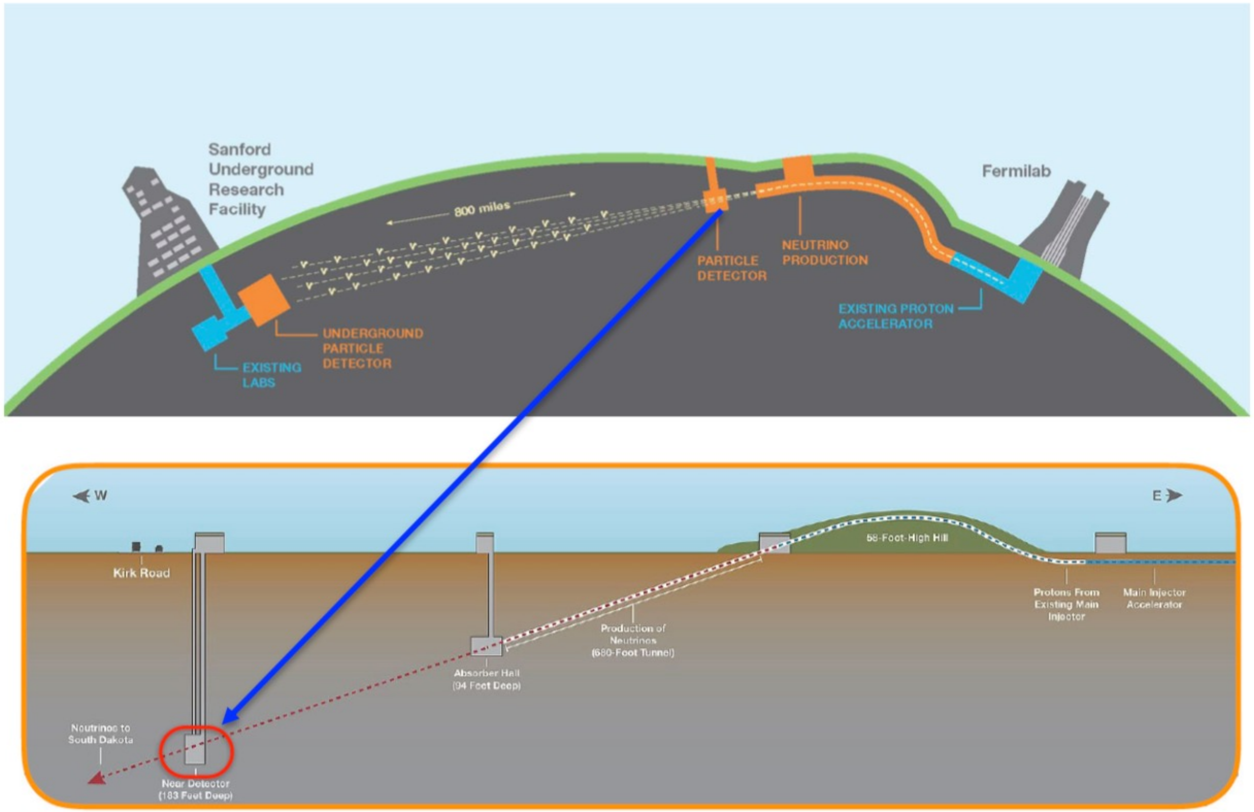
Tests with the prototype wall

"Carousel" brick dispensing and storage system

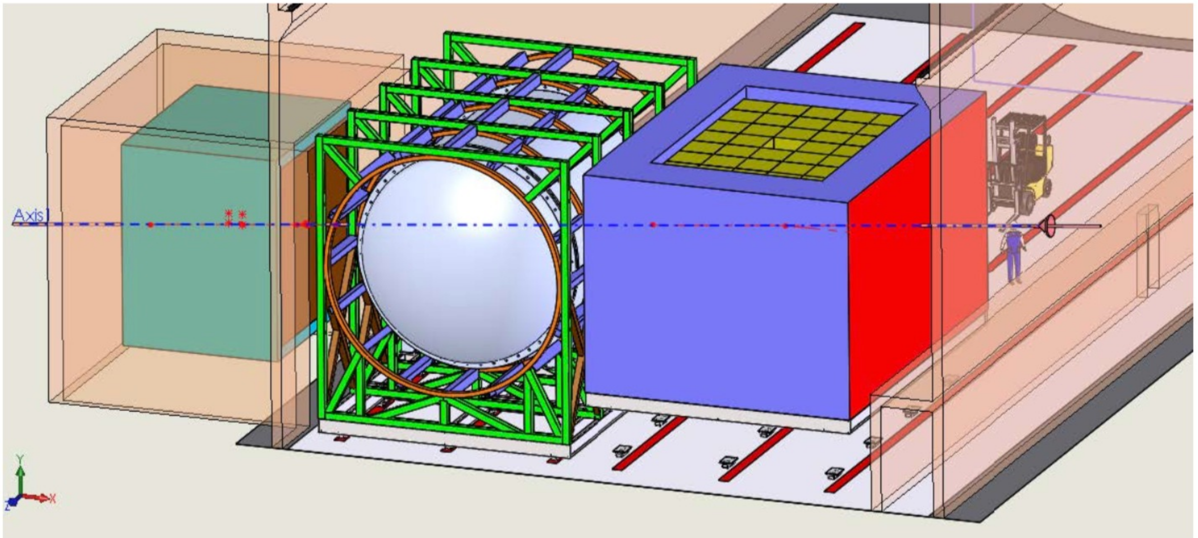
DUNE

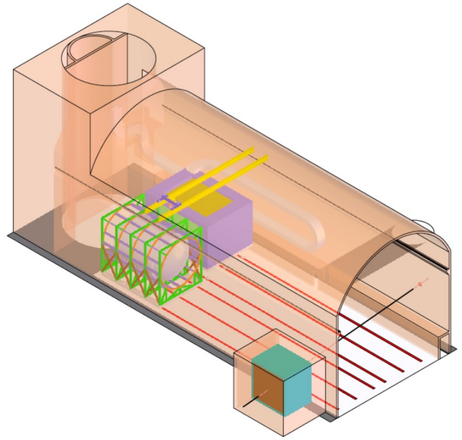
- Observe ν_e appearance and ν_μ disappearance at long baseline in a wideband beam to precisely measure the neutrino oscillation parameters δ_{CP}, θ_{23}, θ_{13}, and Δm^2_{32} in a single experiment.





Reference Design

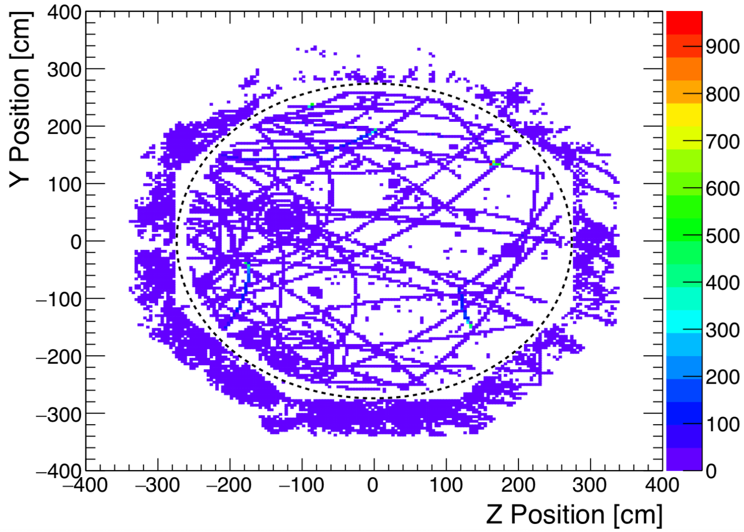




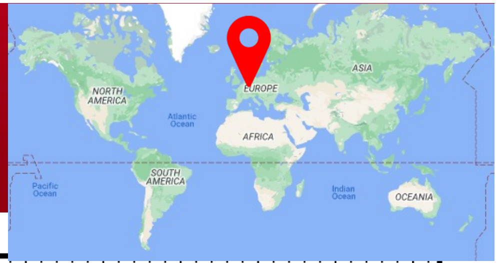
- 3 components (Right-to-left)
  - LAr TPC with pixelated readout (50t)
  - Multi-Purpose Detector - MPD
    - HPgTPC(1t) + ECAL + magnet
  - 3DST-S: Three-Dimensional Scintillator Track

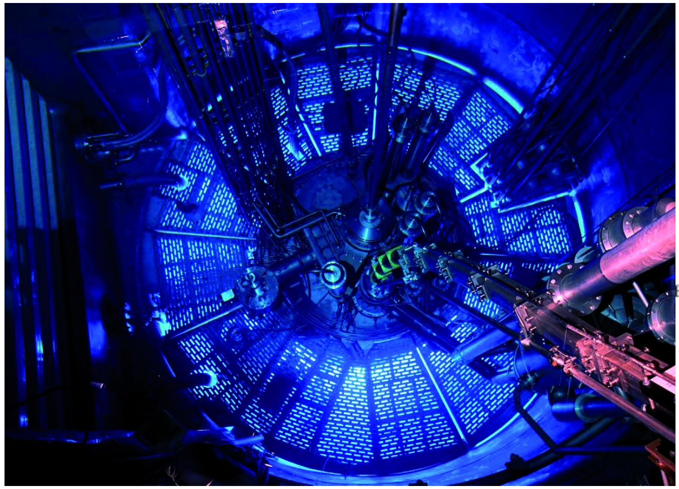
Z-Y projection full spill & event

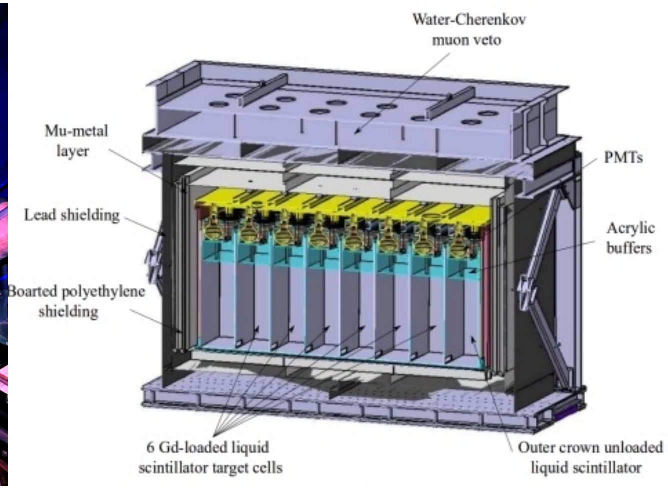
- Corresponds to full spill exposure
- Overlay of test event plus 60 events in the ECAL

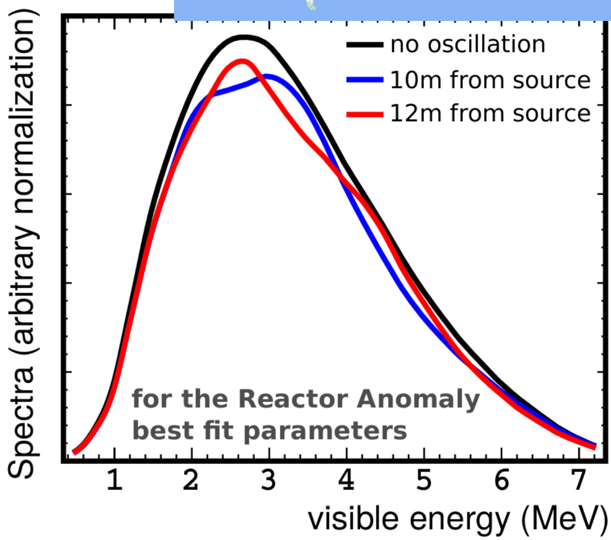


STEREO a ILL

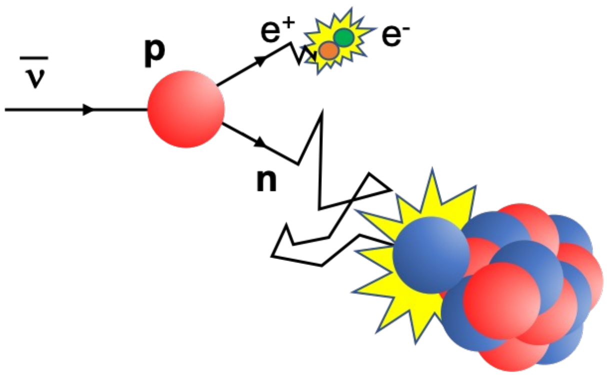


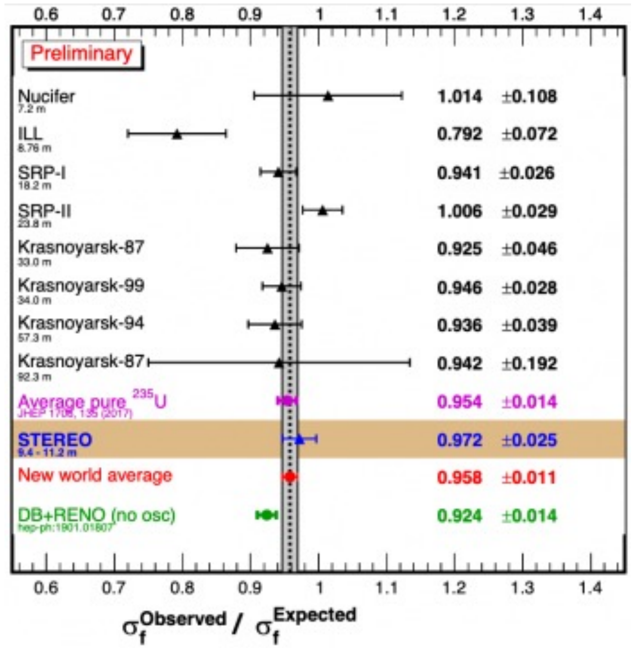




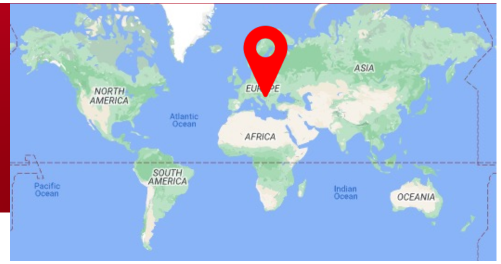


The reactor antineutrino anomaly (RAA) s the observation that the neutrino flux measured in many experiments close to nuclear reactors is significantly (more than 6%) lower than one would expect by theory.





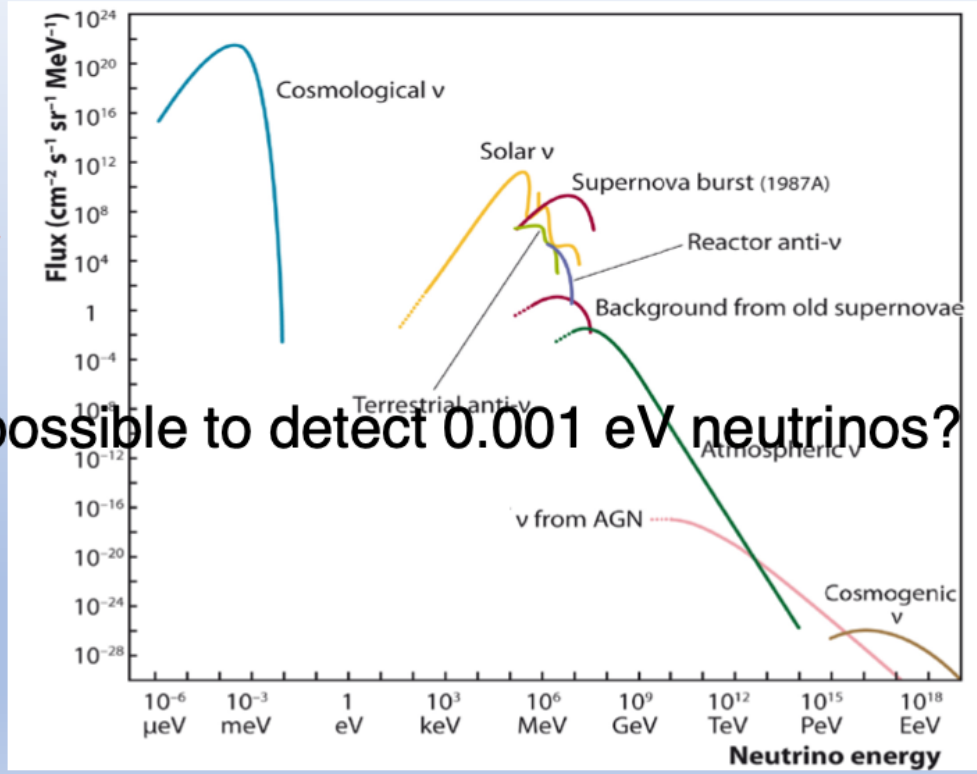
PTOLEMY



Neutrino flow

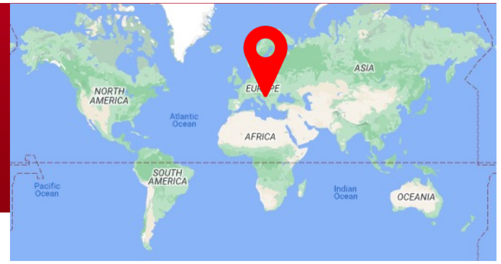
T≈ 1.9 K ⟹ p_ν ≈ 0.001 eV

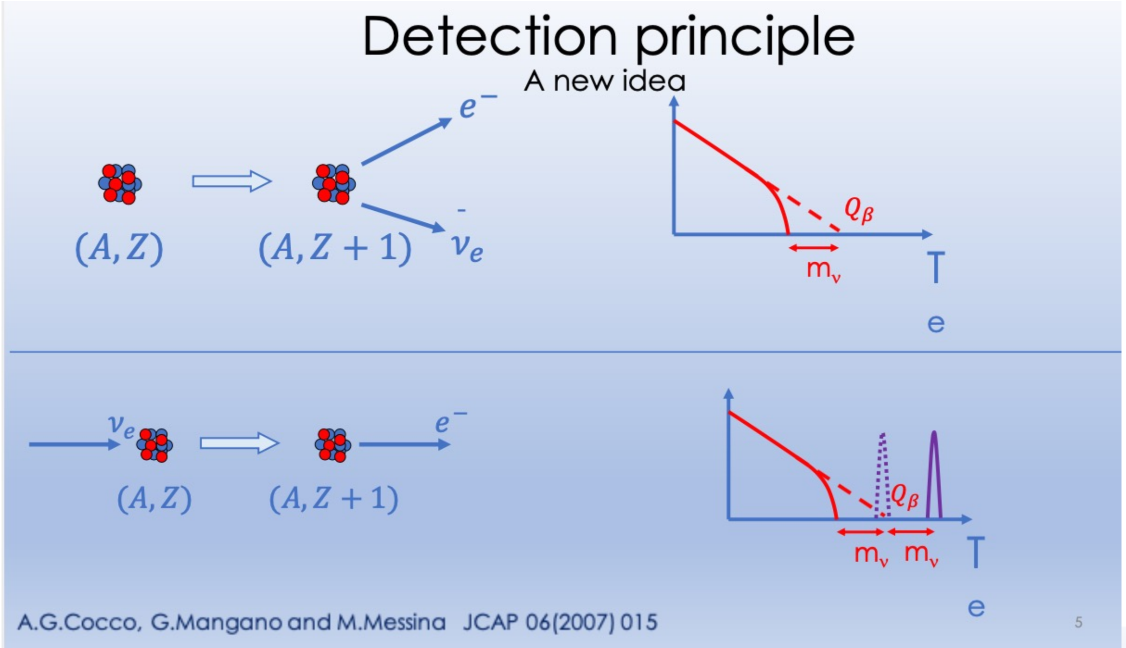
n ≈ 56 cm^{-3} x 6

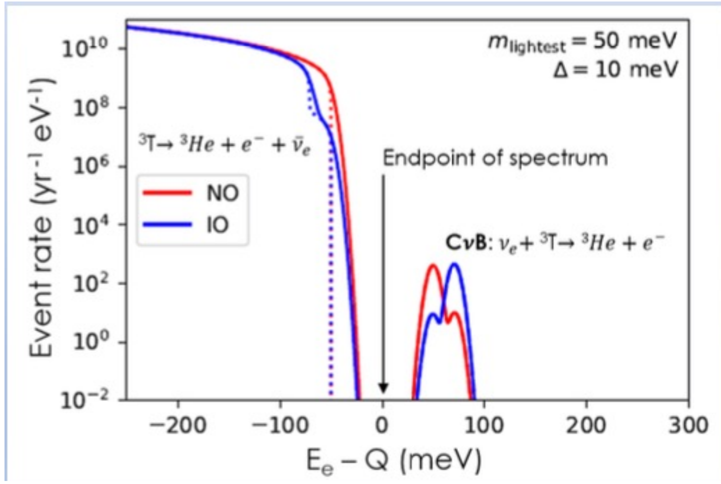


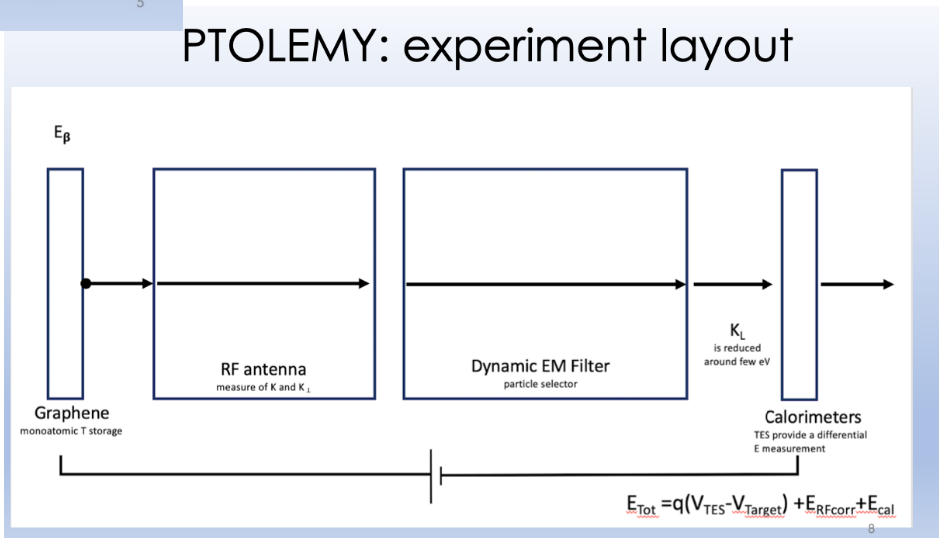
Is it possible to detect 0.001 eV neutrinos?

PTOLEMY

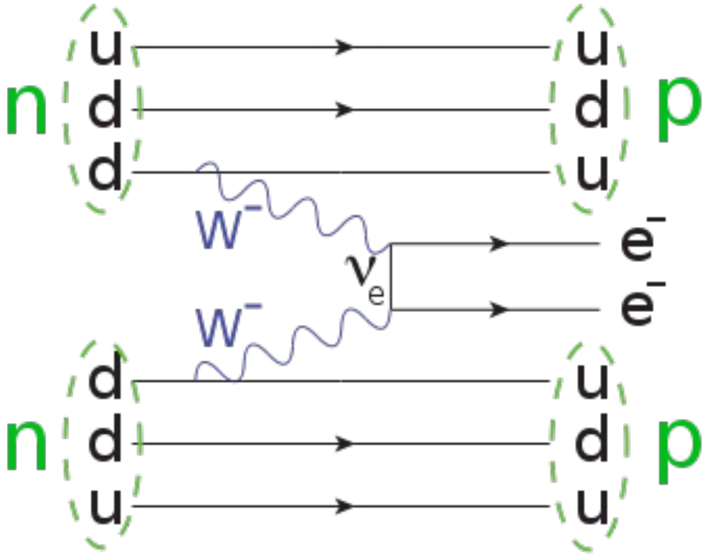

NORTH AMERICA
EUROPE
ASIA
AFRICA
SOUTH AMERICA
OCEANIA


Detection principle
A new idea
(A,Z)
(A,Z + 1)
e^-
$\bar{\nu}_e$
Q_β
m_ν
T_e
ν_e
(A,Z)
(A,Z + 1)
e^-
Q_β
m_ν m_ν
T_e
A.G.Cocco, G.Mangano and M.Messina JCAP 06(2007) 015
5


$m_{lightest} = 50$ meV
$\Delta = 10$ meV
$^3T \rightarrow {}^3He + e^- + \bar{\nu}_e$
Endpoint of spectrum
NO
IO
CνB: $\nu_e + {}^3T \rightarrow {}^3He + e^-$
Event rate (yr^{-1} eV^{-1})
$E_e - Q$ (meV)


PTOLEMY: experiment layout
E_β
Graphene
monoatomic T storage
RF antenna
measure of K and K⊥
Dynamic EM Filter
particle selector
K_L
is reduced
around few eV
Calorimeters
TES provide a differential
E measurement
$E_{Tot} = q(V_{TES} - V_{Target}) + E_{RFcorr} + E_{cal}$
8

DOUBLE BETA DECAY

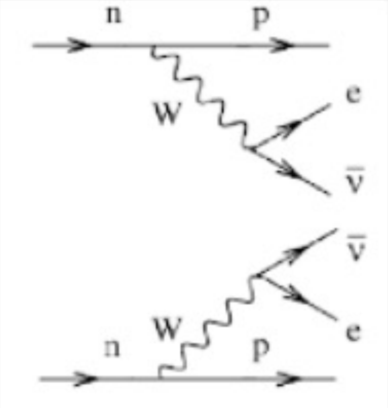


$0\nu\beta\beta$ of ^{136}Xe : $^{136}Xe \rightarrow {}^{136}Ba + 2e^{-}$

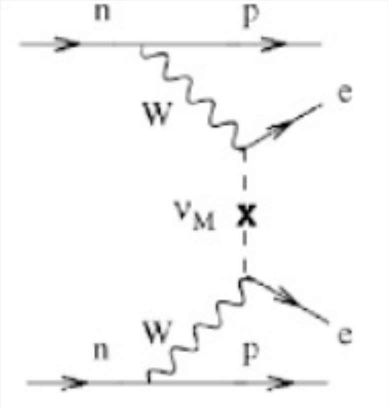
SNO

Double beta decay

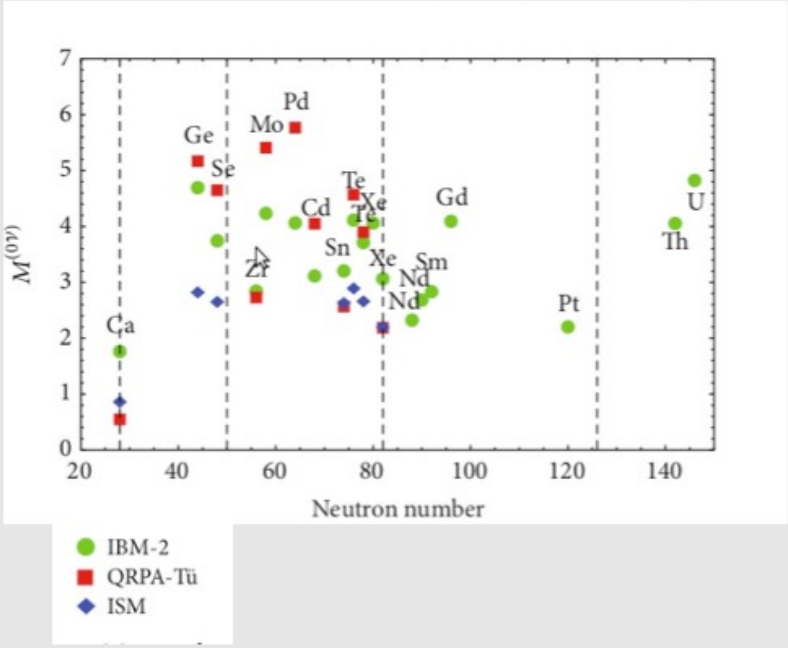
2νββ



0νββ



Nuclear matrix elements (NME) via theory.

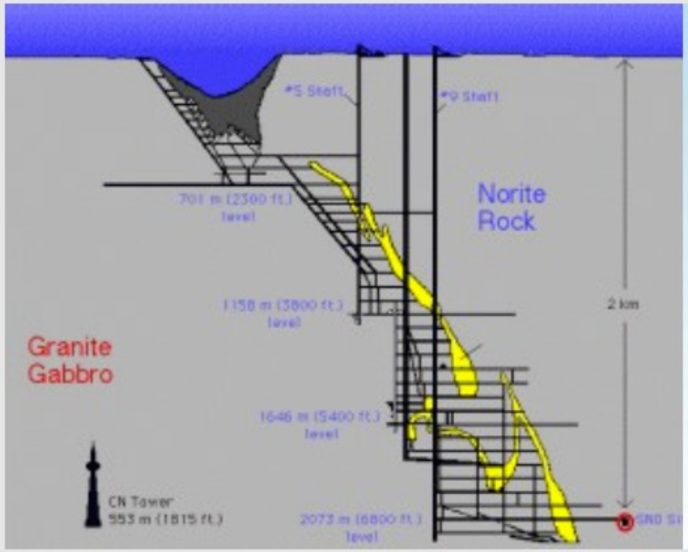


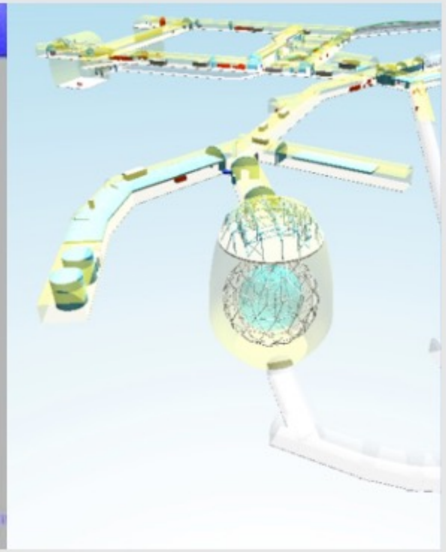
Experiment	***Isotope***	***Technique***	***Main Strength***	
CUORE (LNGS)	130Te	Bolometers	Resolution, Efficiency	On- going or commissioning few kg
GERDA II (LNGS)	76Ge	Ge Diodes	Resolution, Efficiency	
KamLANDZen (Kamioka)	136Xe	Xe Liquid scintillation	Background, efficiency	
MAJORANA (SURF)	76Ge	Ge 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	Bakground Rejection, Isotope Selection	R&D ~tonne
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

3.- T

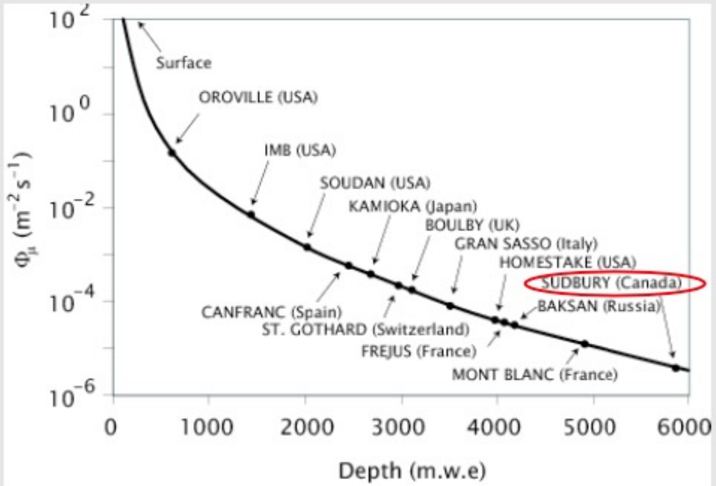




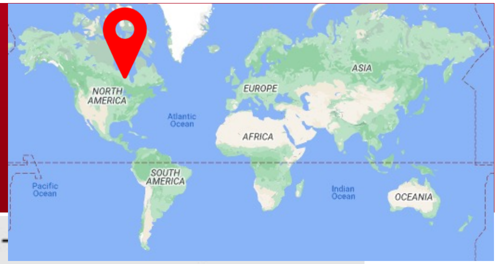
SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

- 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

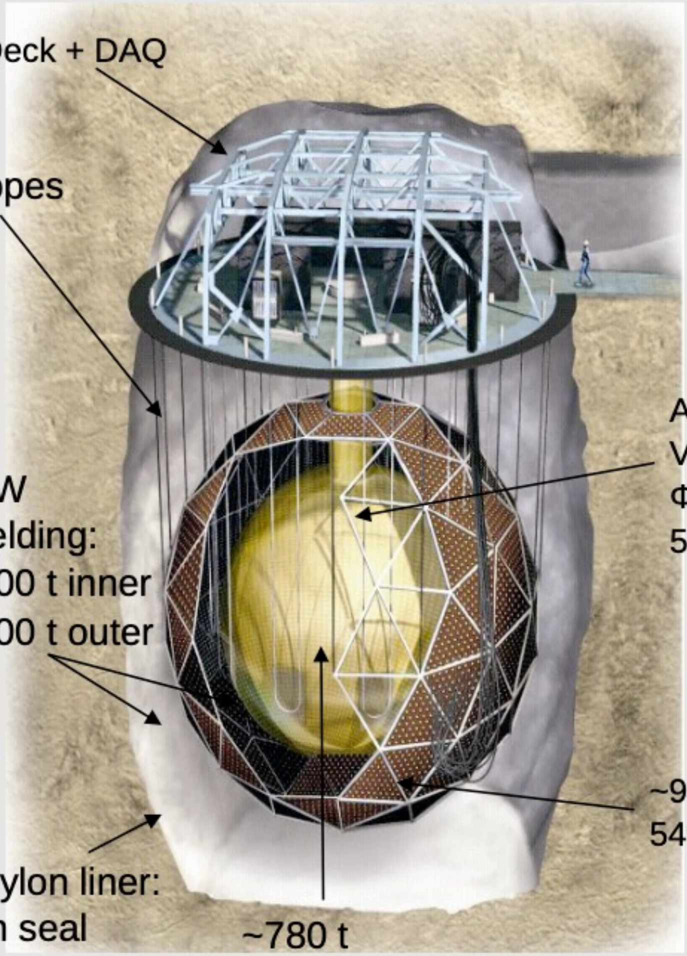


SNO



The SNO+ Detector

3.-

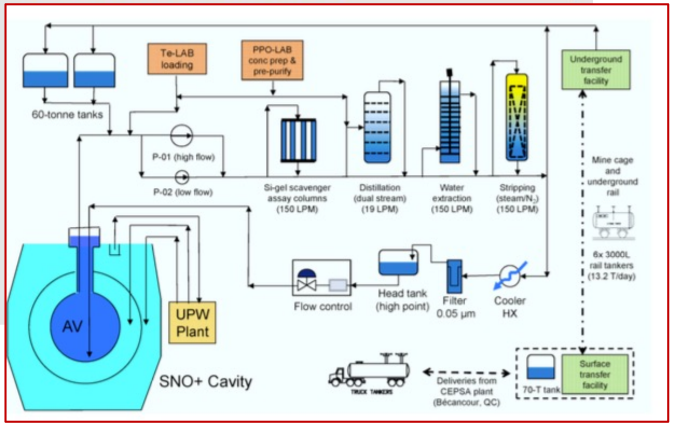


Broad neutrino physics program

- **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)

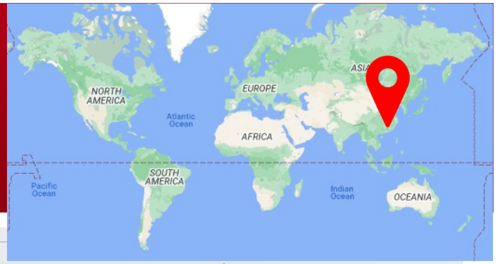
Three Experimental Phases

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



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

PandaX



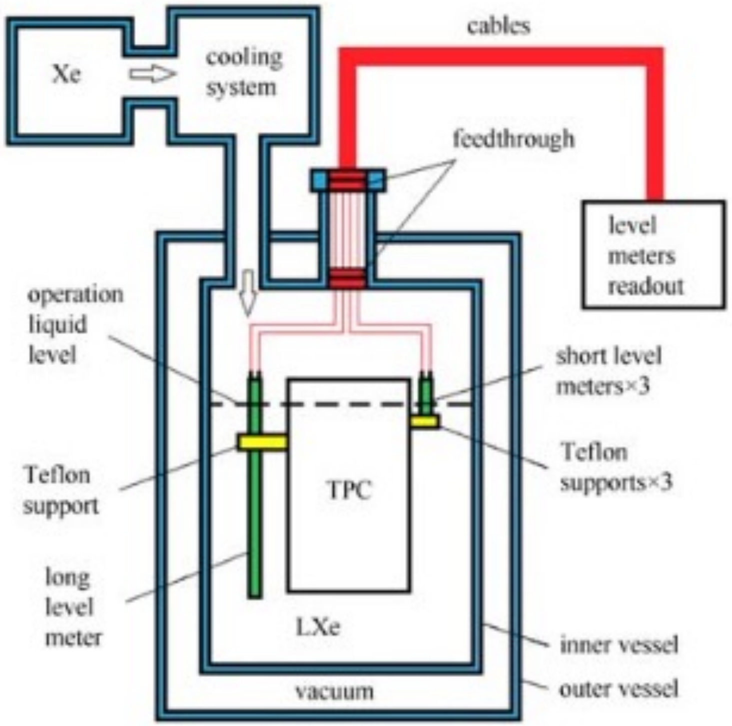
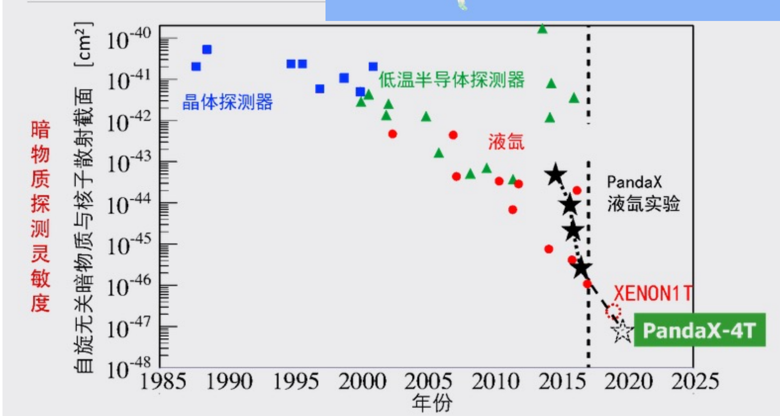
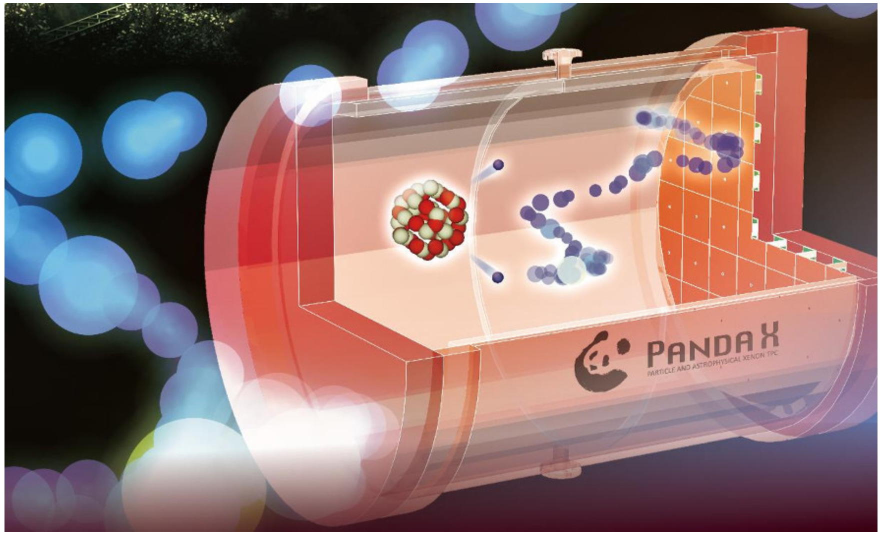


Fig. 1. Schematics of the two-phase xenon detector as used in PandaX. LXe is contained in an inner vessel insulated by vacuum from the outside. One long liquid level meter monitors the overall liquid height and three short level meters monitor the height of the liquid-gas interface around the TPC.



2016年PandaX二期实验（500公斤级液氙）取得了世界领先的暗物质探测灵敏度。在这个基础上，我们进行下一代四吨级液氙探测实验的研发，将暗物质探测灵敏度继续向前推进1-2个数量级。除了暗物质，四吨级液氙实验将能够测量到低能量太阳中微子信号并研究其磁矩等性质。另外，四吨液氙中含有的放射性同位素氙136有可能进行一种新型的贝塔衰变-无中微子双贝塔衰变模型。该衰变模式的探测将能确定中微子是否为马约拉纳中微子等基本物理问题。



ANTI-MATIERE

The Positive Electron

MARCH 15, 1933 PHYSICAL REVIEW VOLUME 43

The Positive Electron

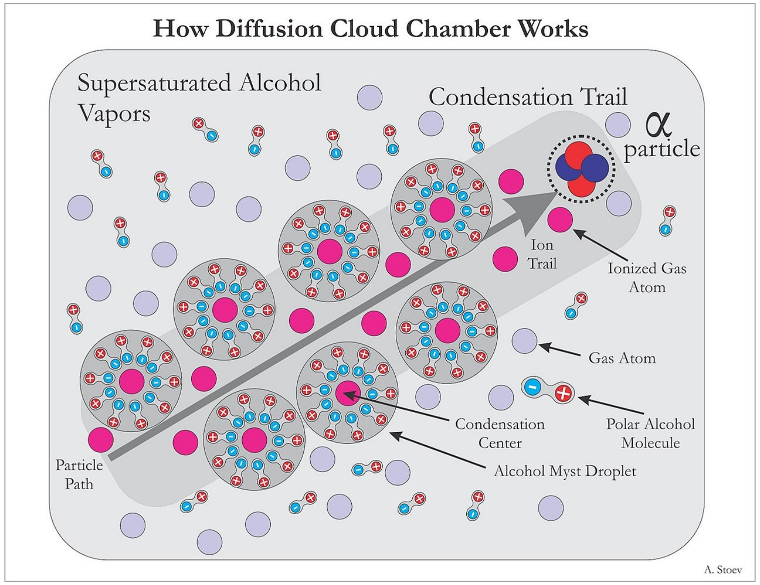
Carl D. Anderson, *California Institute of Technology, Pasadena, California*
(Received February 28, 1933)

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 Electro

1930 : Data taking
1932 : Analysis
1933 : Paper

492 CARL D. ANDERSON

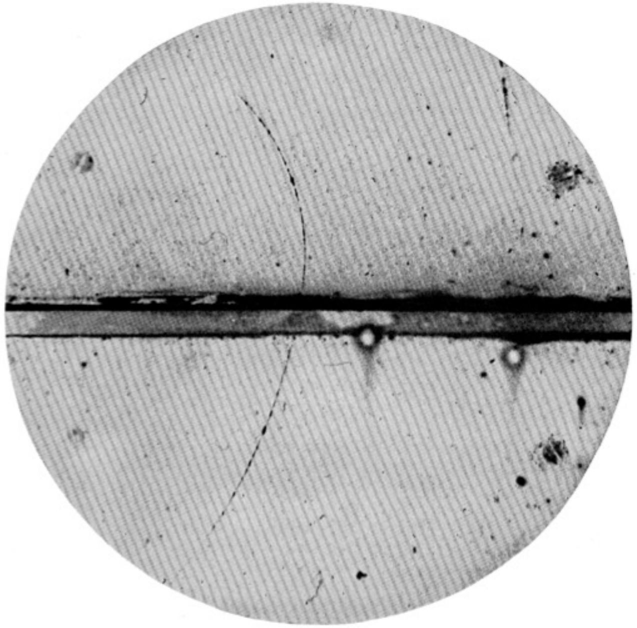
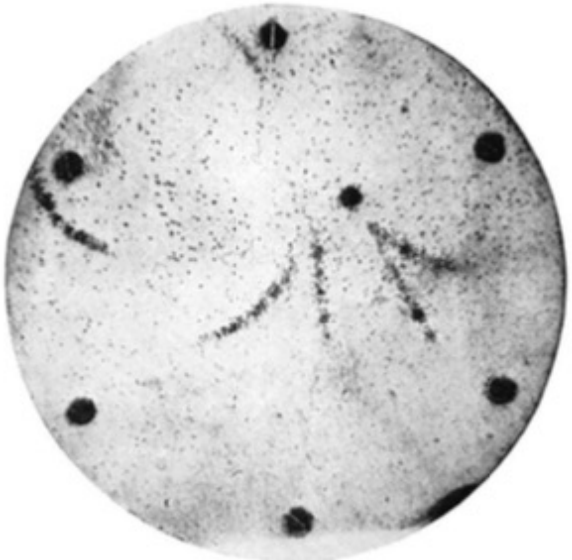


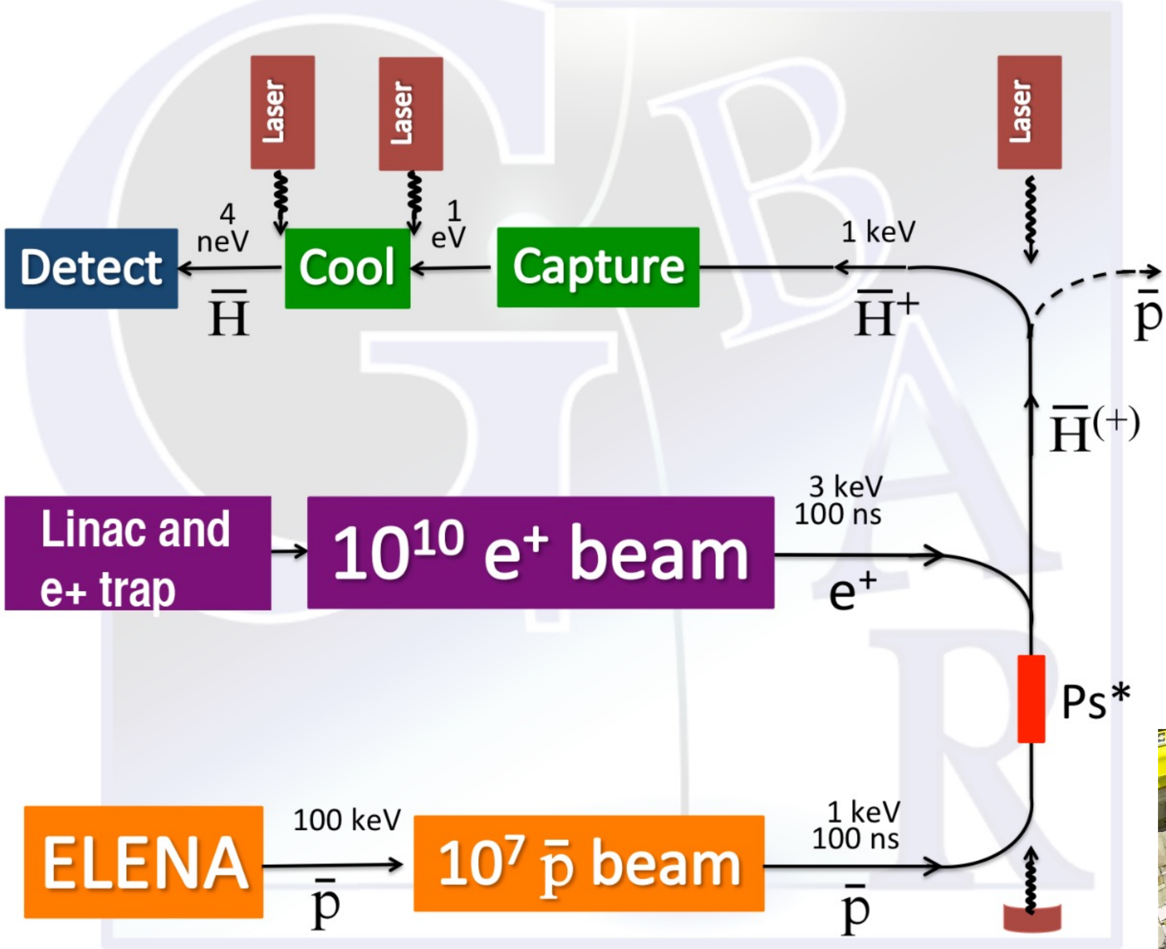
FIG. 1. A 63 million volt positron ($H\rho=2.1\times10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho=7.5\times10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

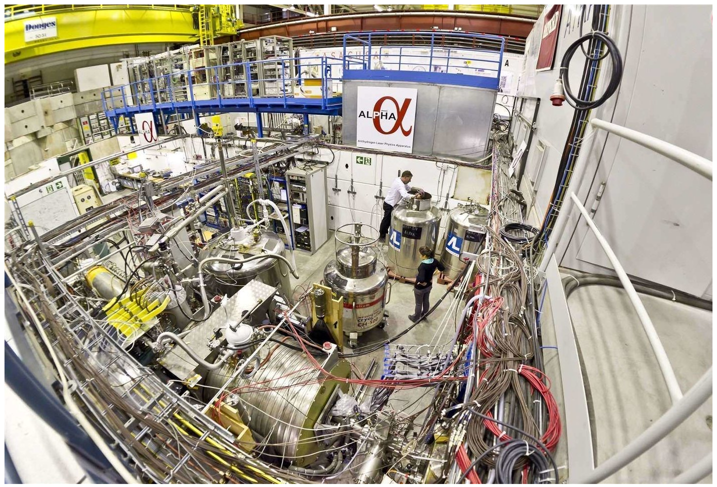


1.5T Wilson Chamber
Rec. Cosmic Rays
1300 events
15 tracks with e^+

GBAR at CERN

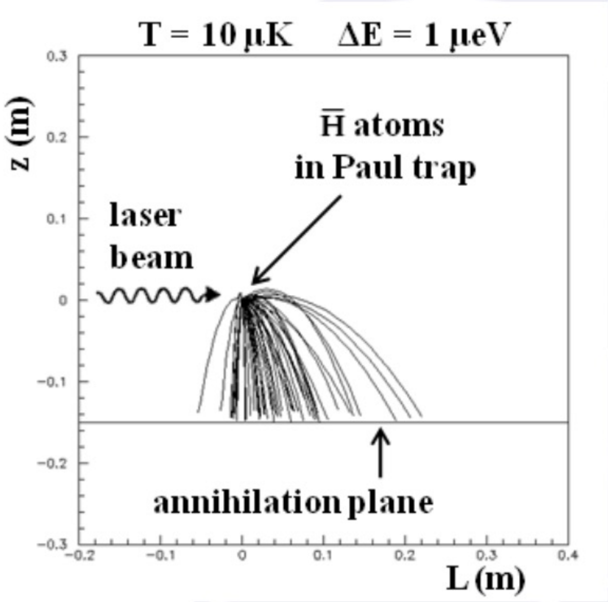
Schematic

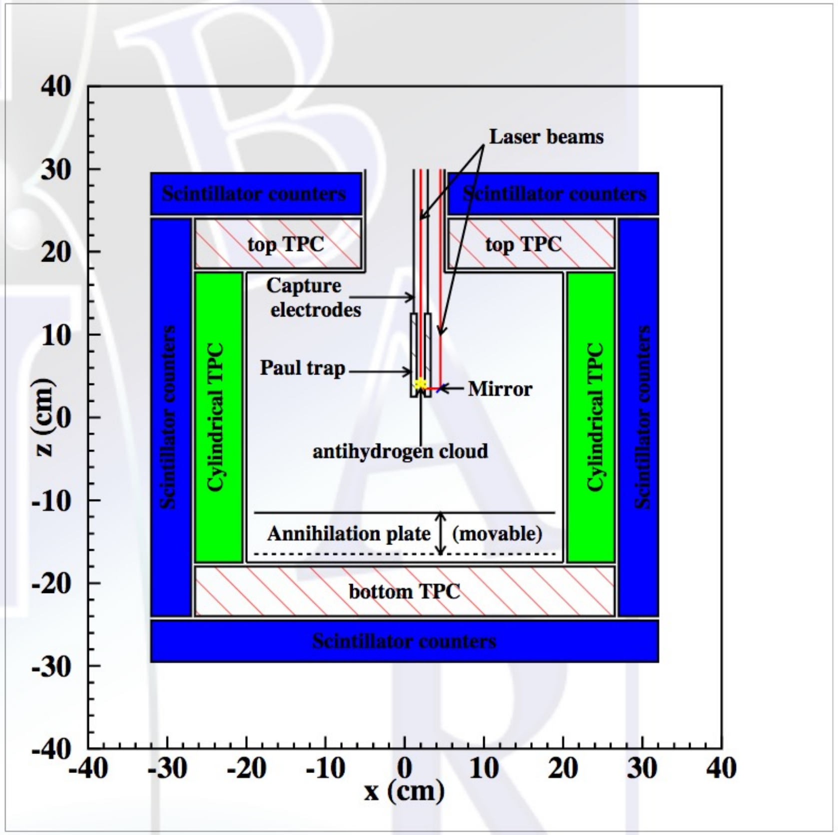




GBAR at CERN

Detection



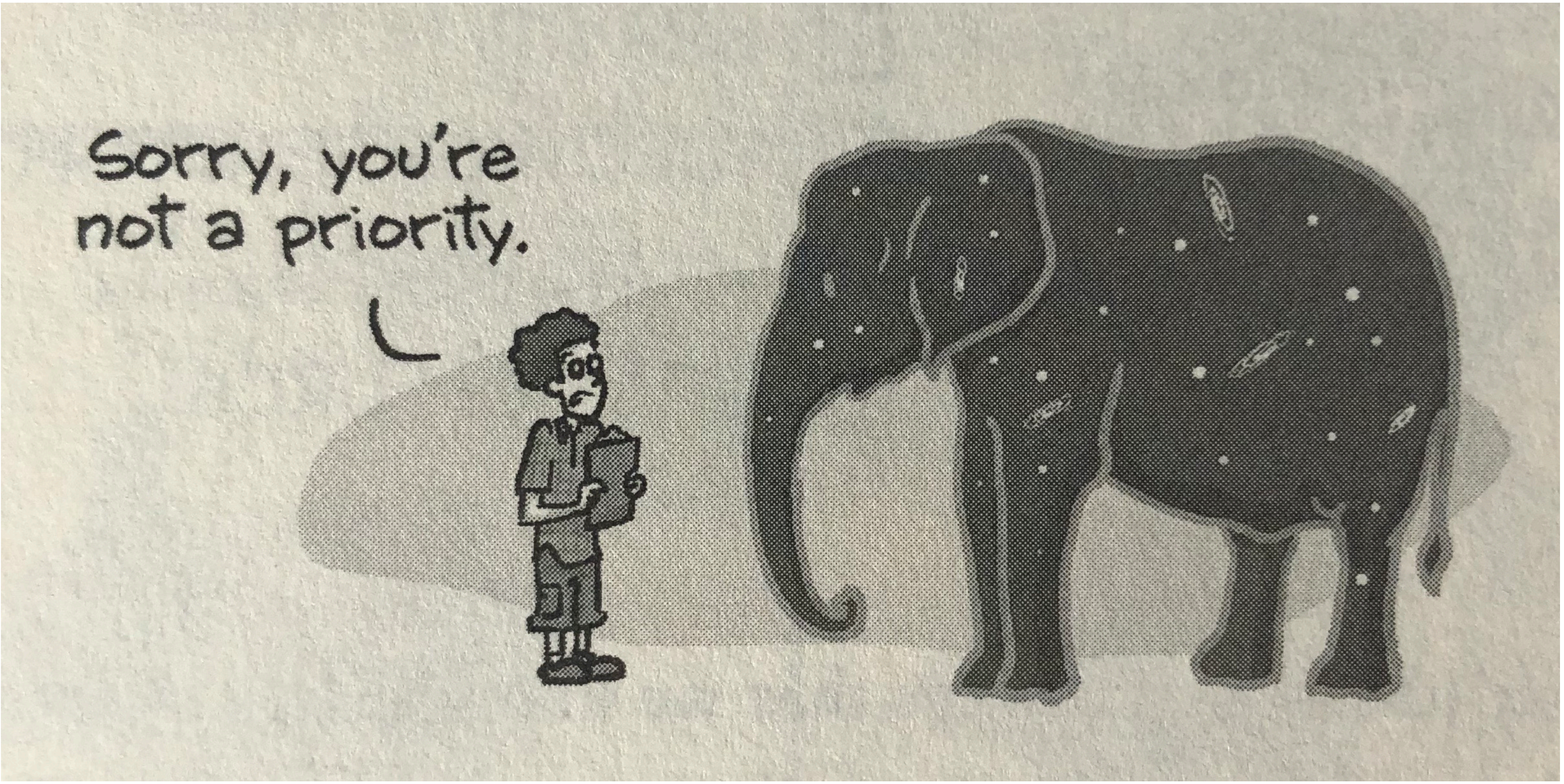


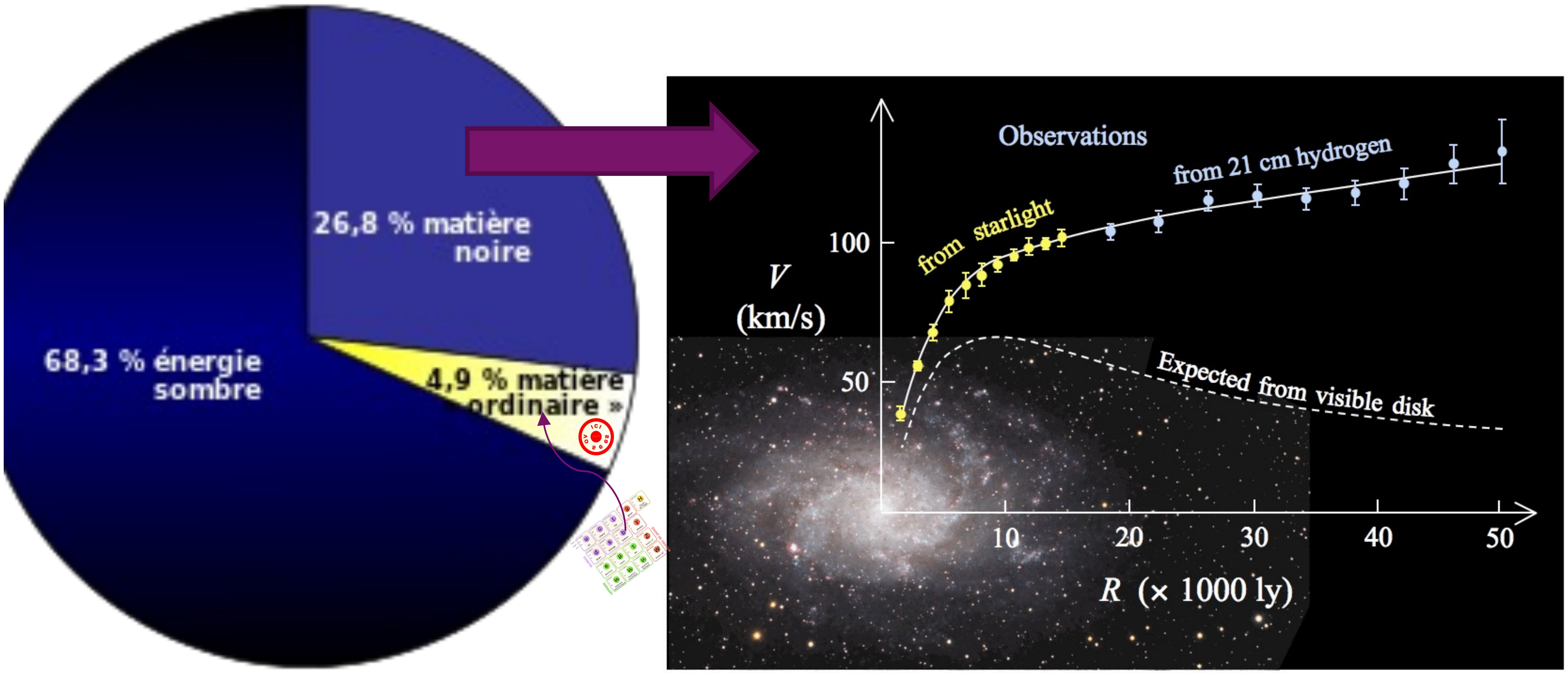
Detection requirement:
- TOF precision : 150 μs
- Annihilation vertex precision : 1 mm
- Background rejection through event topology

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

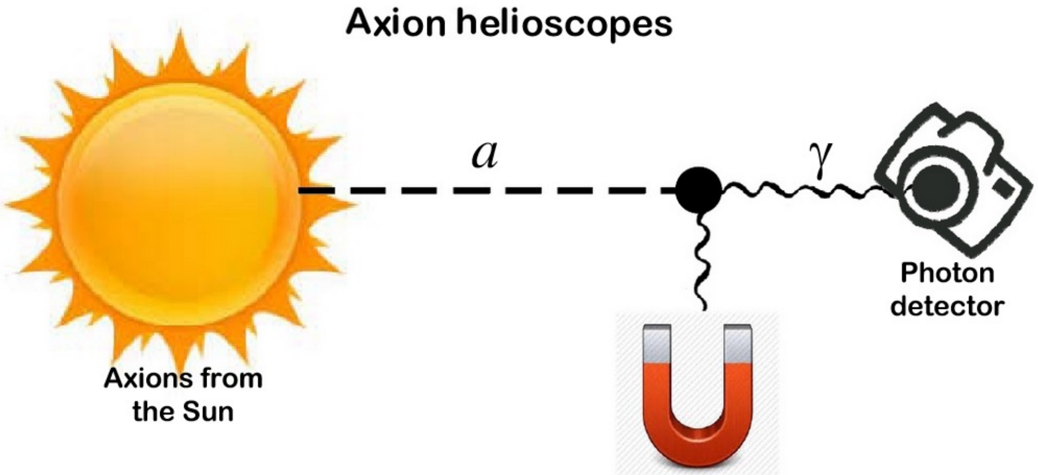
$$\frac{\Delta \bar{g}}{\bar{g}} \approx 10^{-2}$$

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



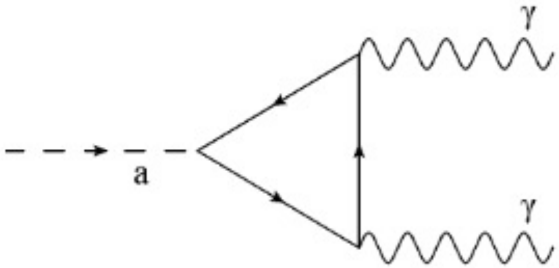
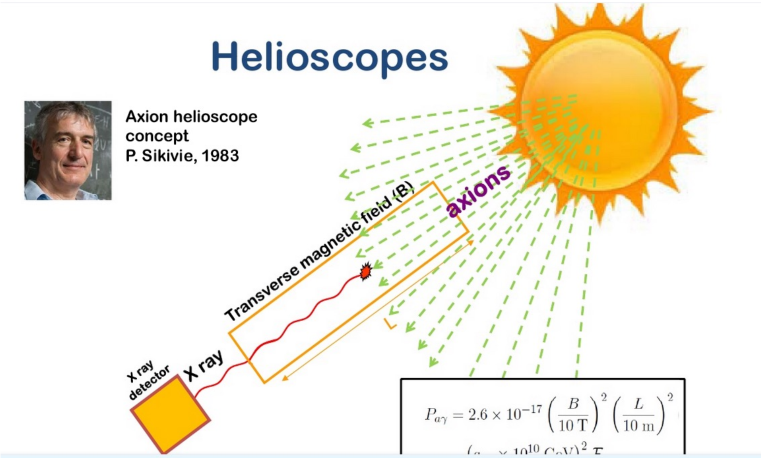


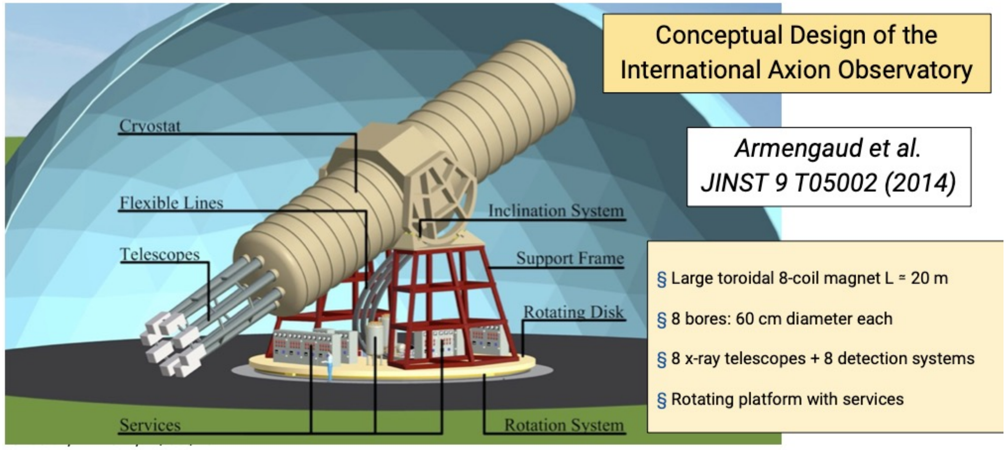
Figure 2: Feynman diagram, associated with the coupling between an axion and two photons.

© Igor G. Irastorza

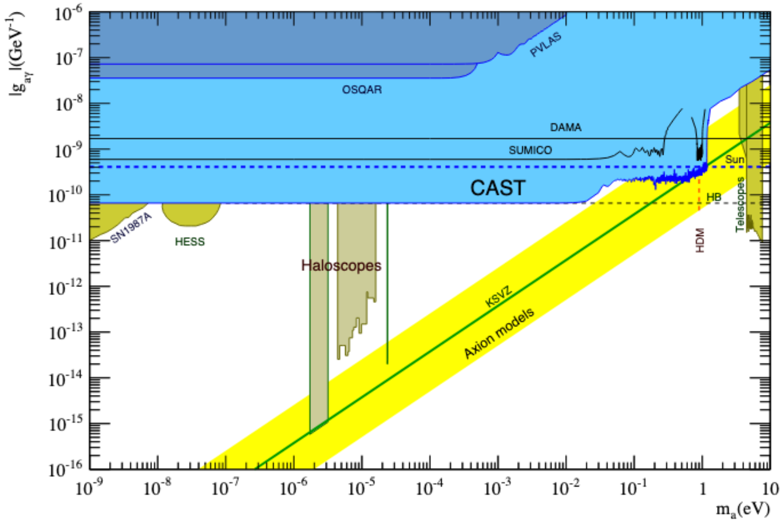
CAST - IAXO


NORTH AMERICA
EUROPE
ASIA
AFRICA
SOUTH AMERICA
OCEANIA
Atlantic Ocean
Pacific Ocean
Indian Ocean

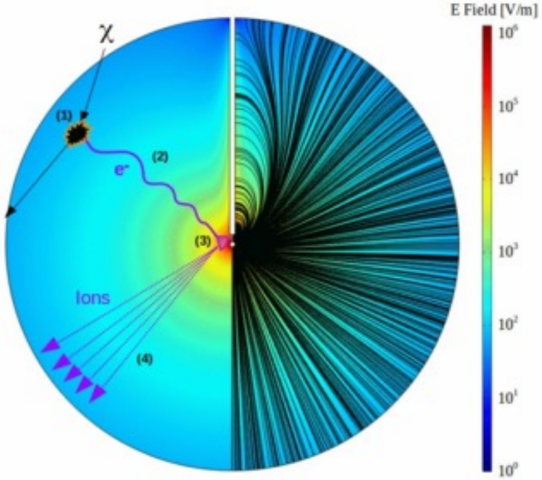

Helioscopes
Axion helioscope concept
P. Sikivie, 1983
axions
Transverse magnetic field (B)
X ray
X ray detector
$P_{a\gamma} = 2.6 \times 10^{-17} \left(\frac{B}{10\,\mathrm{T}}\right)^2 \left(\frac{L}{10\,\mathrm{m}}\right)^2$

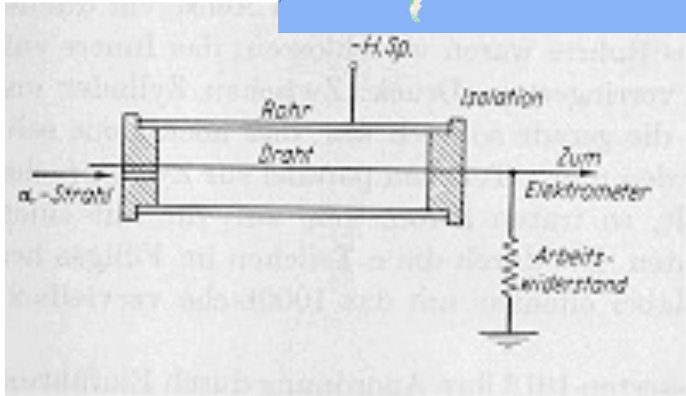

Conceptual Design of the International Axion Observatory
Armengaud et al.
JINST 9 T05002 (2014)
Cryostat
Flexible Lines
Telescopes
Services
Inclination System
Support Frame
Rotating Disk
Rotation System
§ Large toroidal 8-coil magnet L = 20 m
§ 8 bores: 60 cm diameter each
§ 8 x-ray telescopes + 8 detection systems
§ Rotating platform with services


LHC DIPOLE PROTOTYPE
CAST

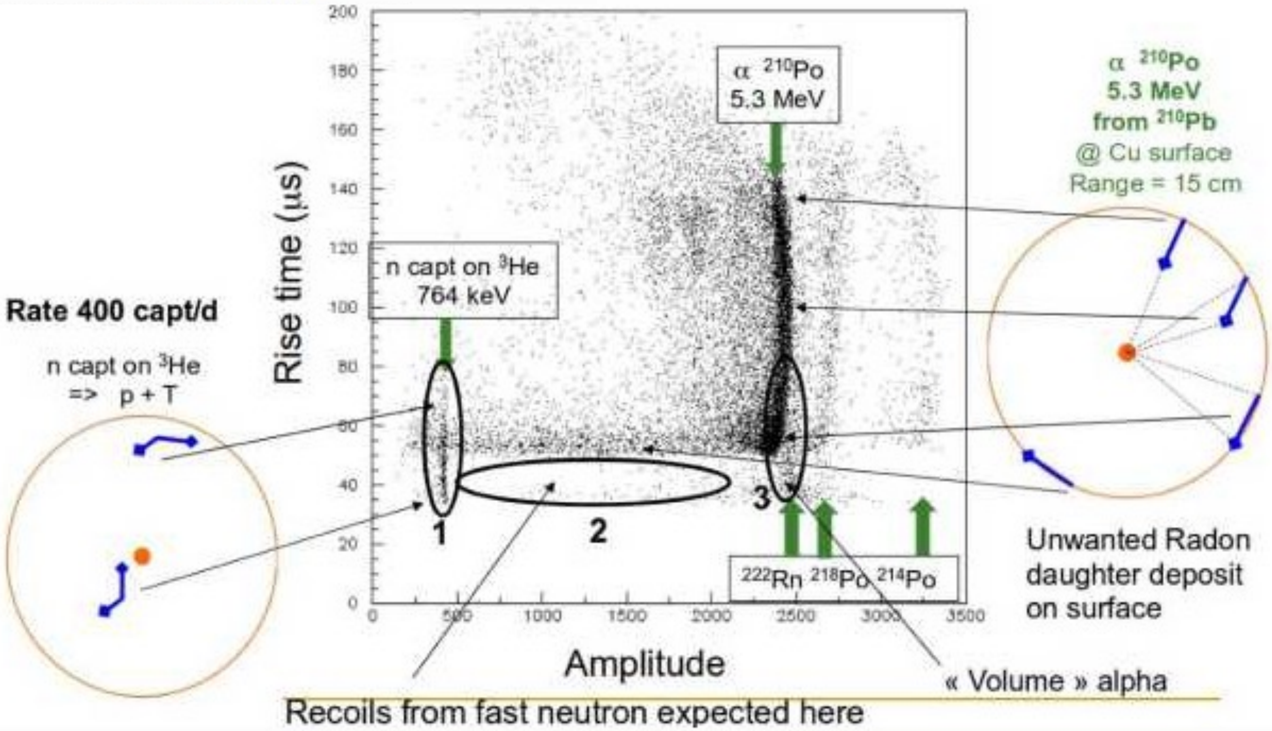

$|g_{a\gamma}|$(GeV^{-1})
m_a(eV)
OSQAR
PVLAS
DAMA
SUMICO
CAST
Sun
HB
Telescopes
HDM
SN1987A
HESS
Haloscopes
KSVZ
Axion models

NEWS



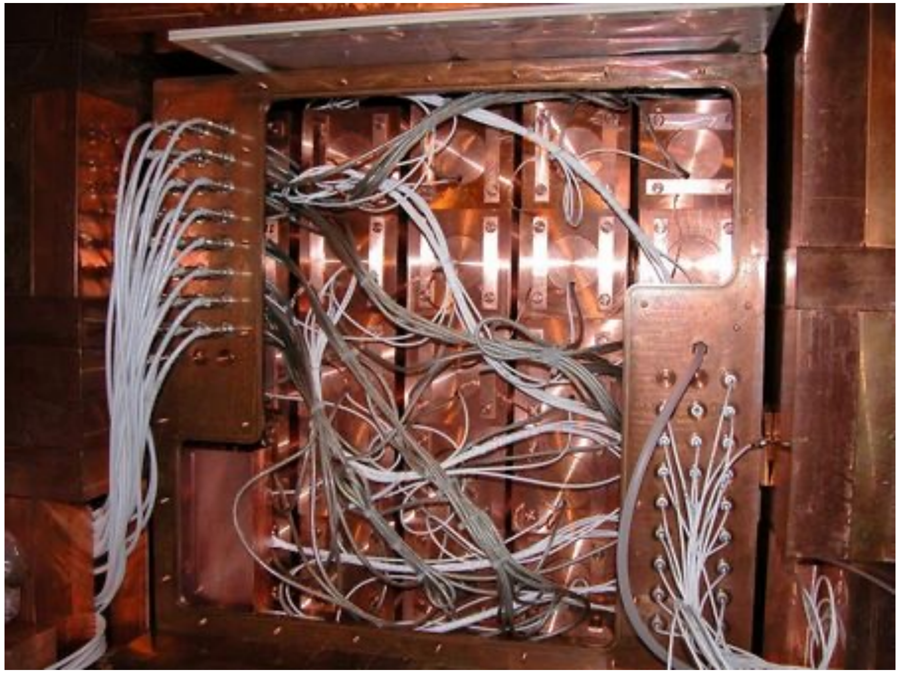


Recul noyau dû aux WIMPs avec threshold la plus basse possible

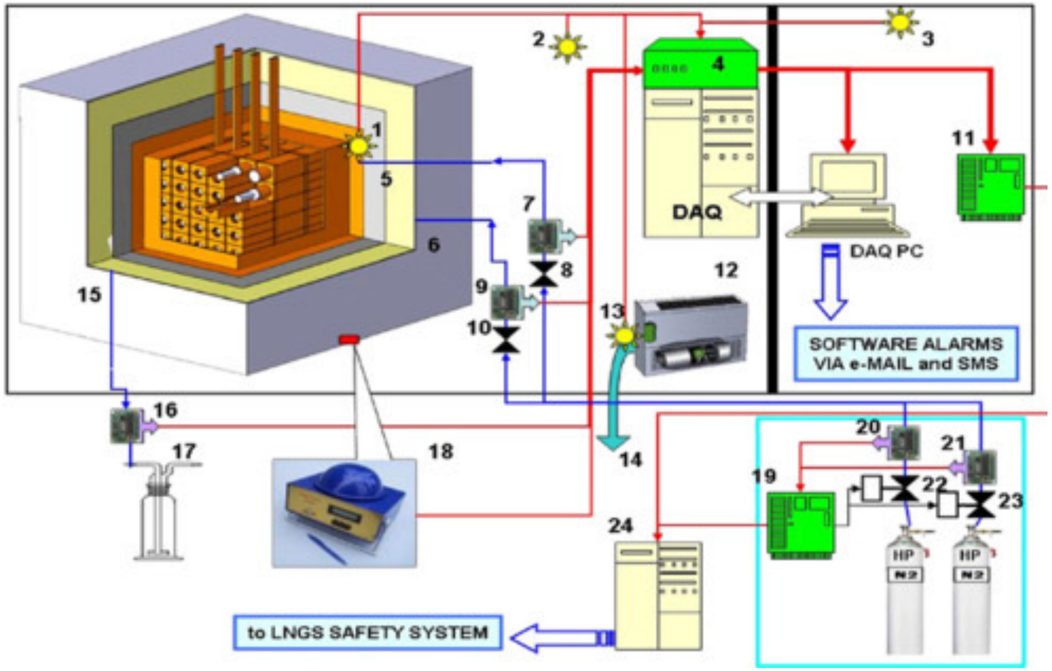


DAMA / LIBRA

LABORATORI NAZIONALI DEL GRAN SASSO



Thallium-doped sodium detector



DAMA / LIBRA

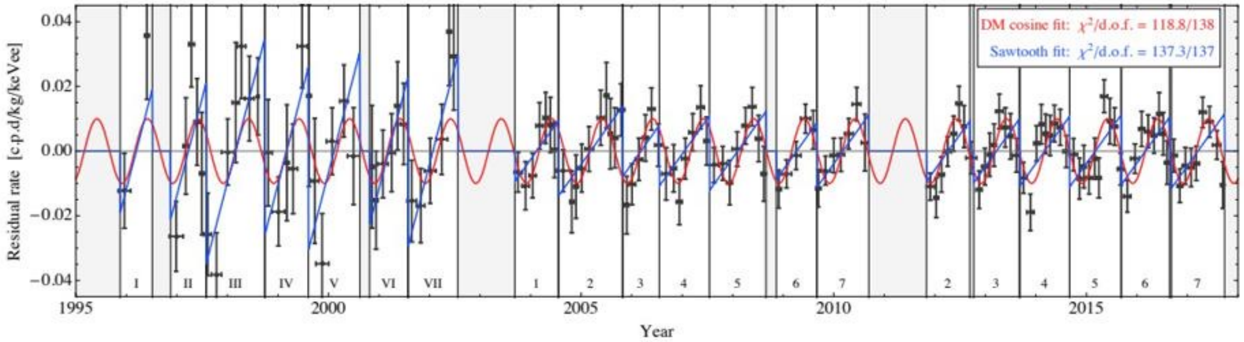
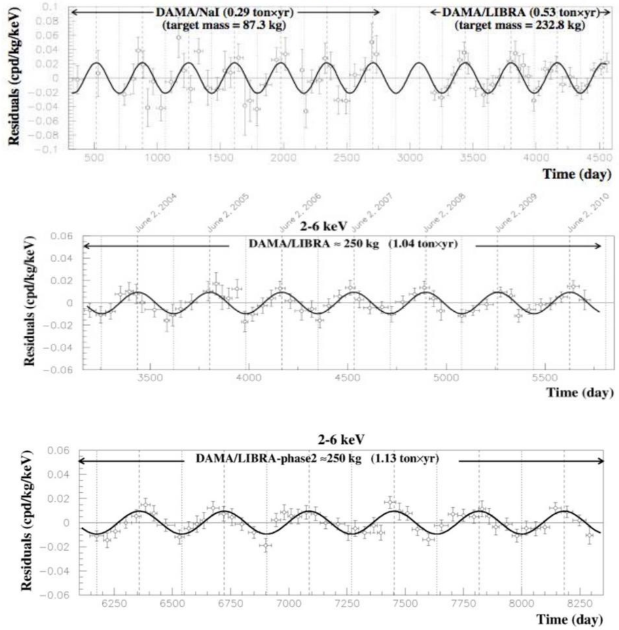
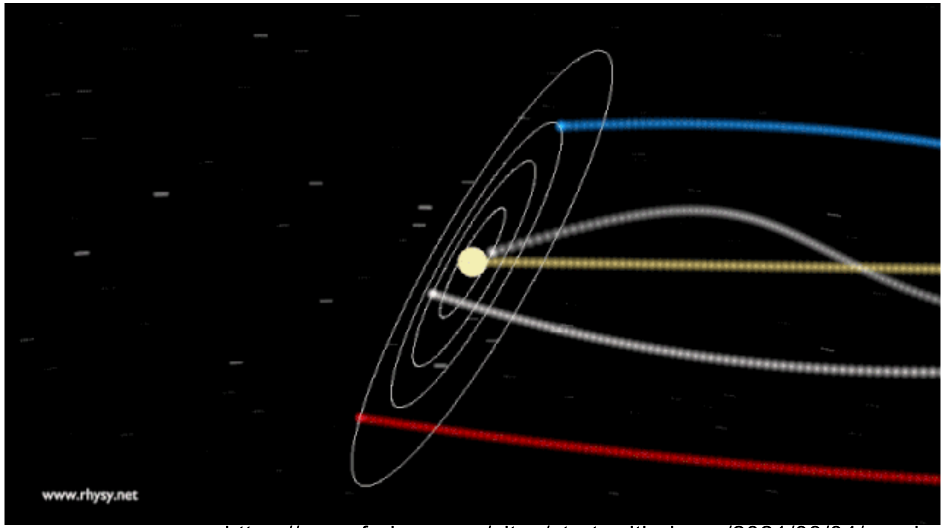


Figure 5. *The black data points are the* DAMA *residuals in the* (2−6) keVee *energy window, taken from [1, 5]. The curves are fits to a cosine annual modulation peaked on June, 2nd (red curve), as expected for a DM signal, and to the irregular sawtooth obtained from a continuously growing background (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.*



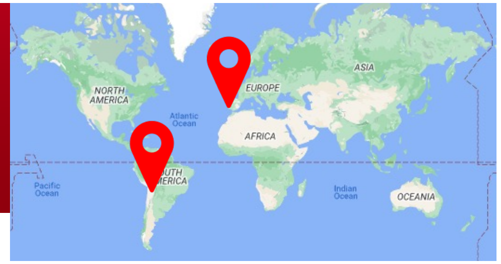


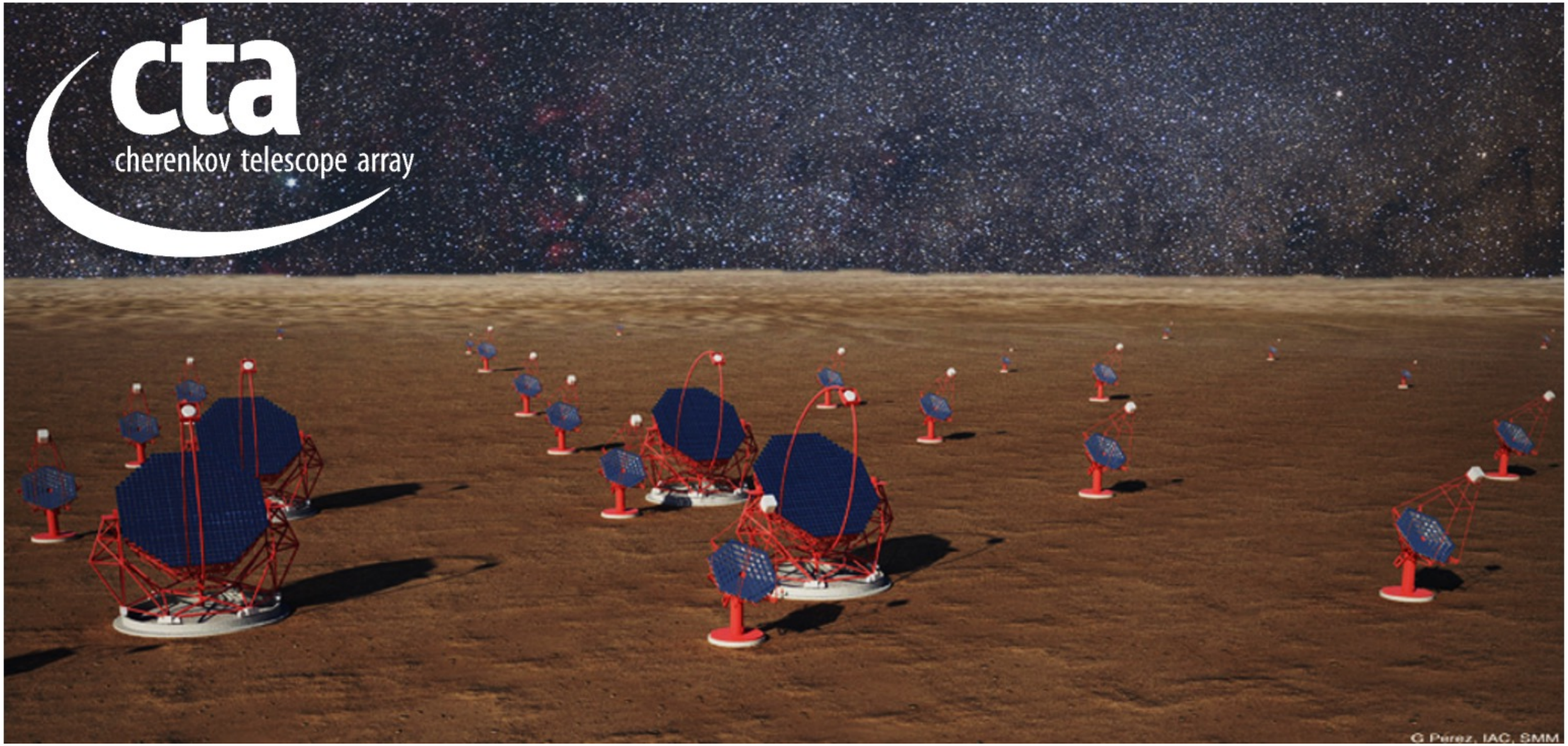
But Replication failed ☹
ANAIS (Spain)
COSINE (Germany)

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

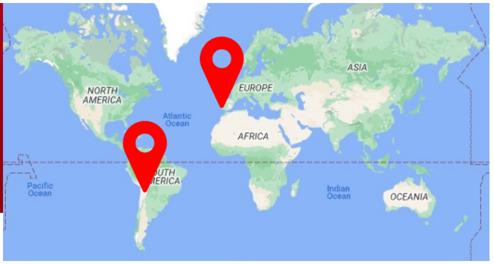
ASTRO-
PHYSIQUE

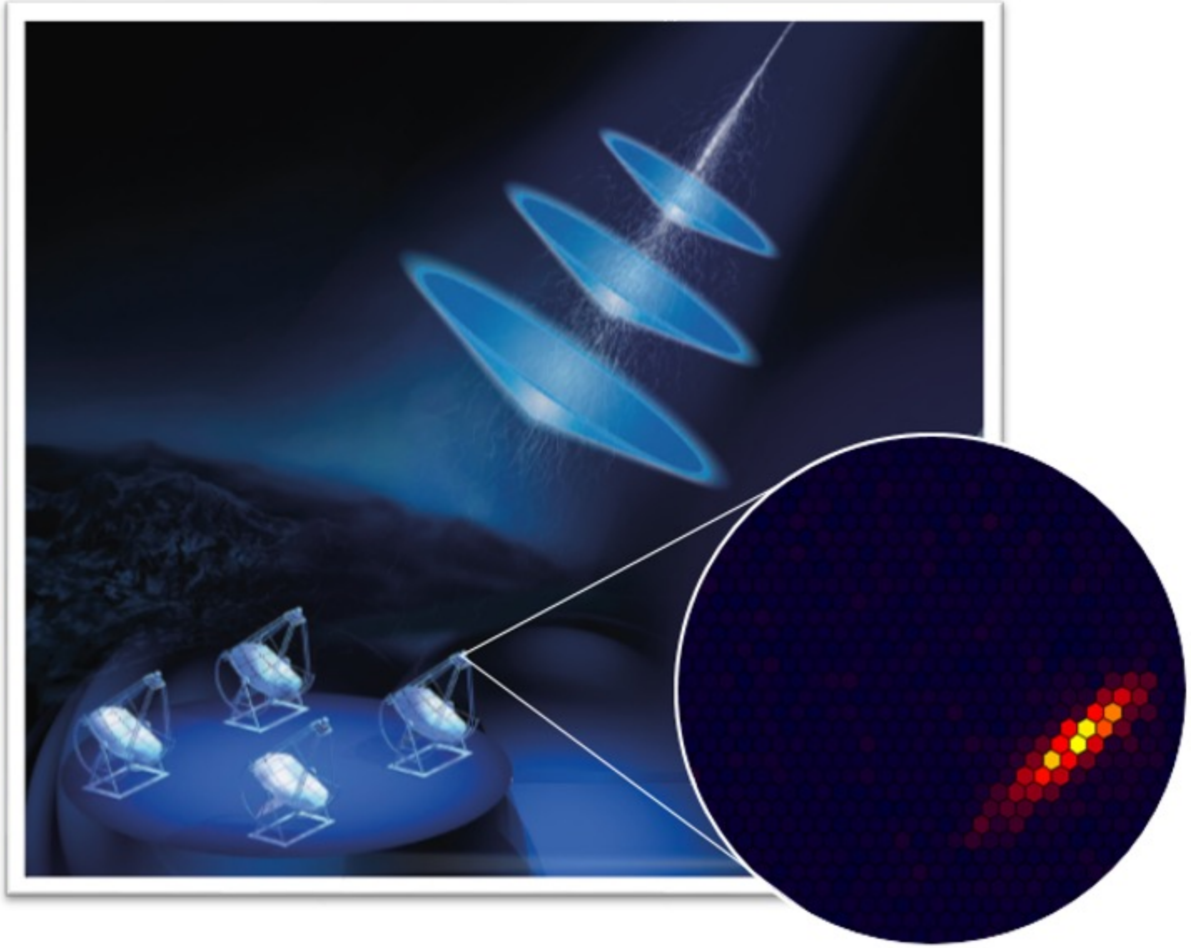
CTA


NORTH AMERICA
Atlantic Ocean
EUROPE
ASIA
AFRICA
Pacific Ocean
Indian Ocean
OCEANIA

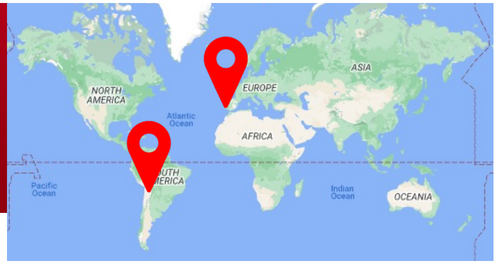

cta
cherenkov telescope array
G Perez, IAC, SMM

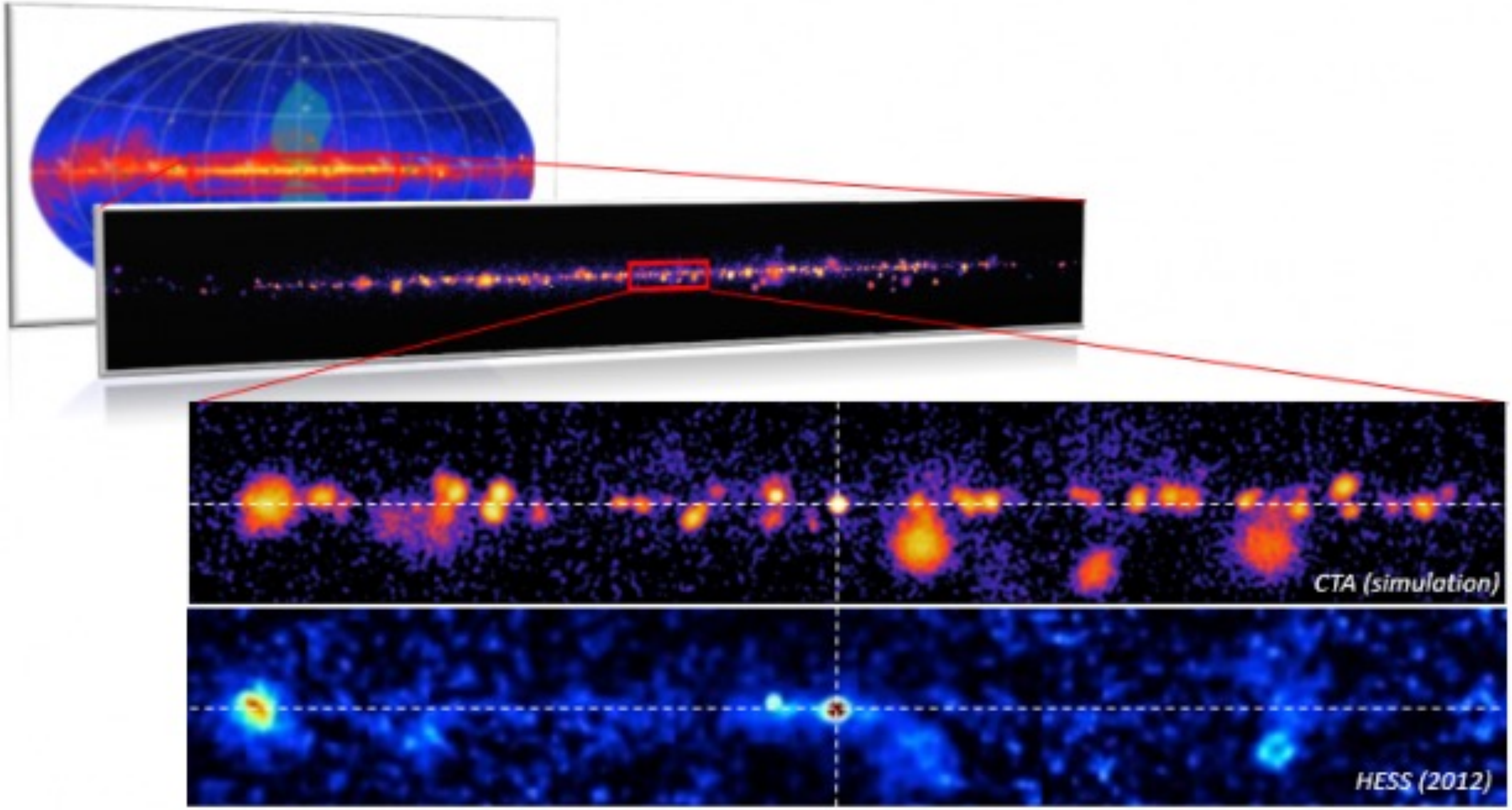
CTA

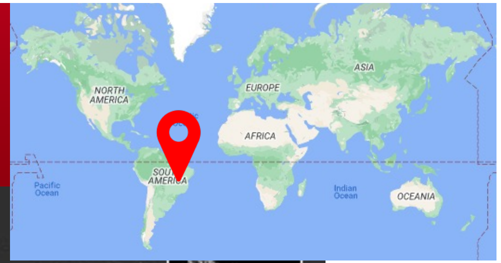

NORTH AMERICA
EUROPE
ASIA
AFRICA
Atlantic Ocean
Pacific Ocean
Indian Ocean
OCEANIA

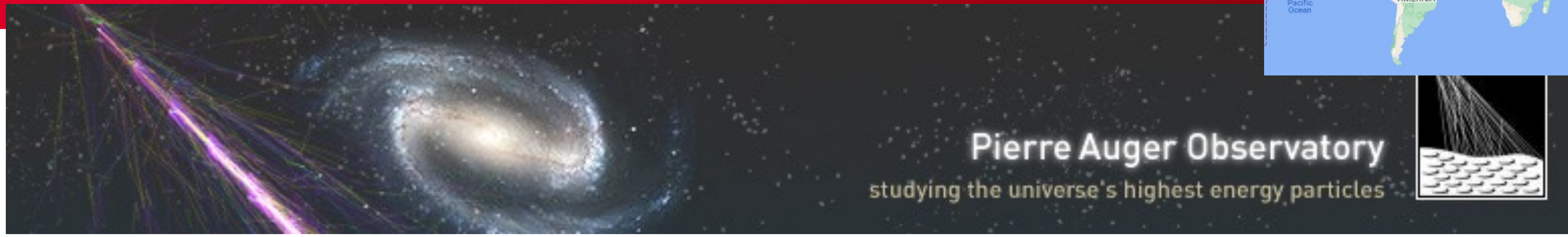


CTA

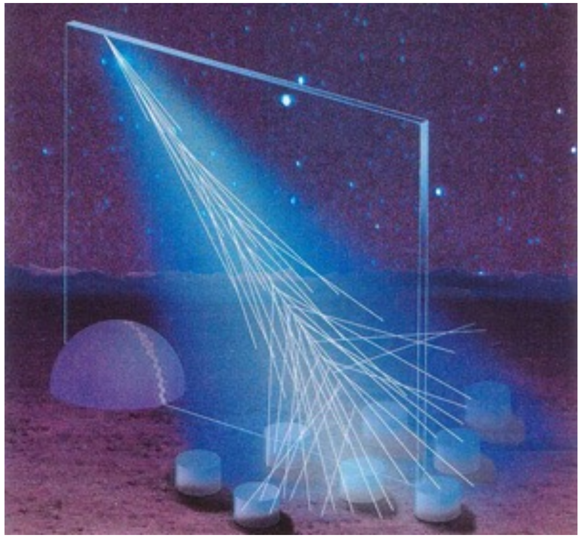

NORTH AMERICA
Atlantic Ocean
EUROPE
ASIA
AFRICA
Pacific Ocean
Indian Ocean
OCEANIA


CTA (simulation)
HESS (2012)

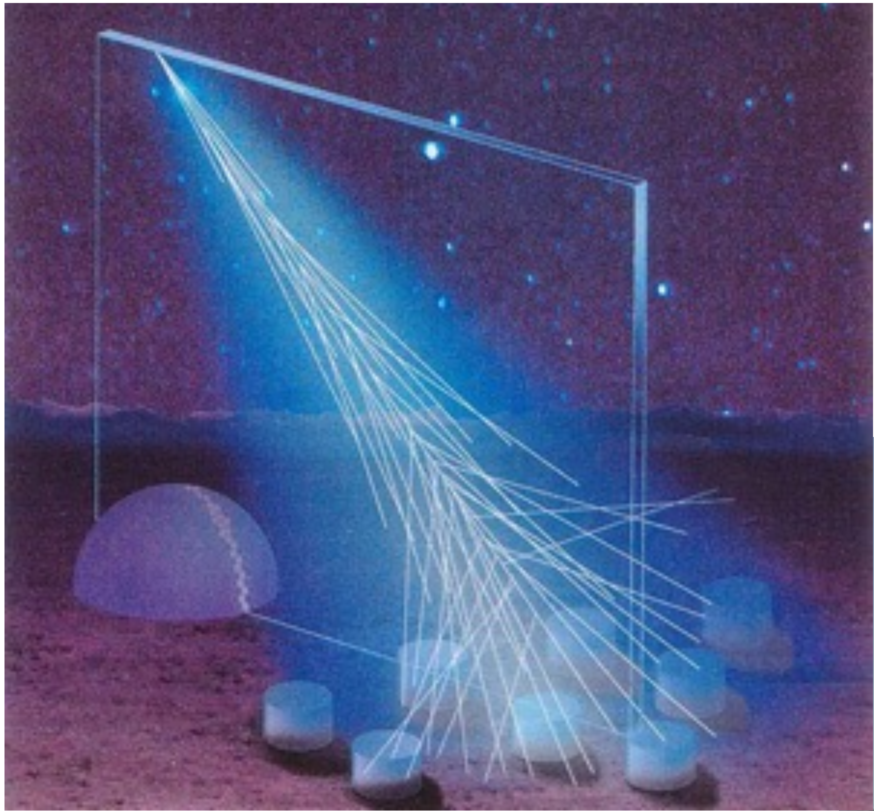




Pierre Auger Cosmic Ray Observatory



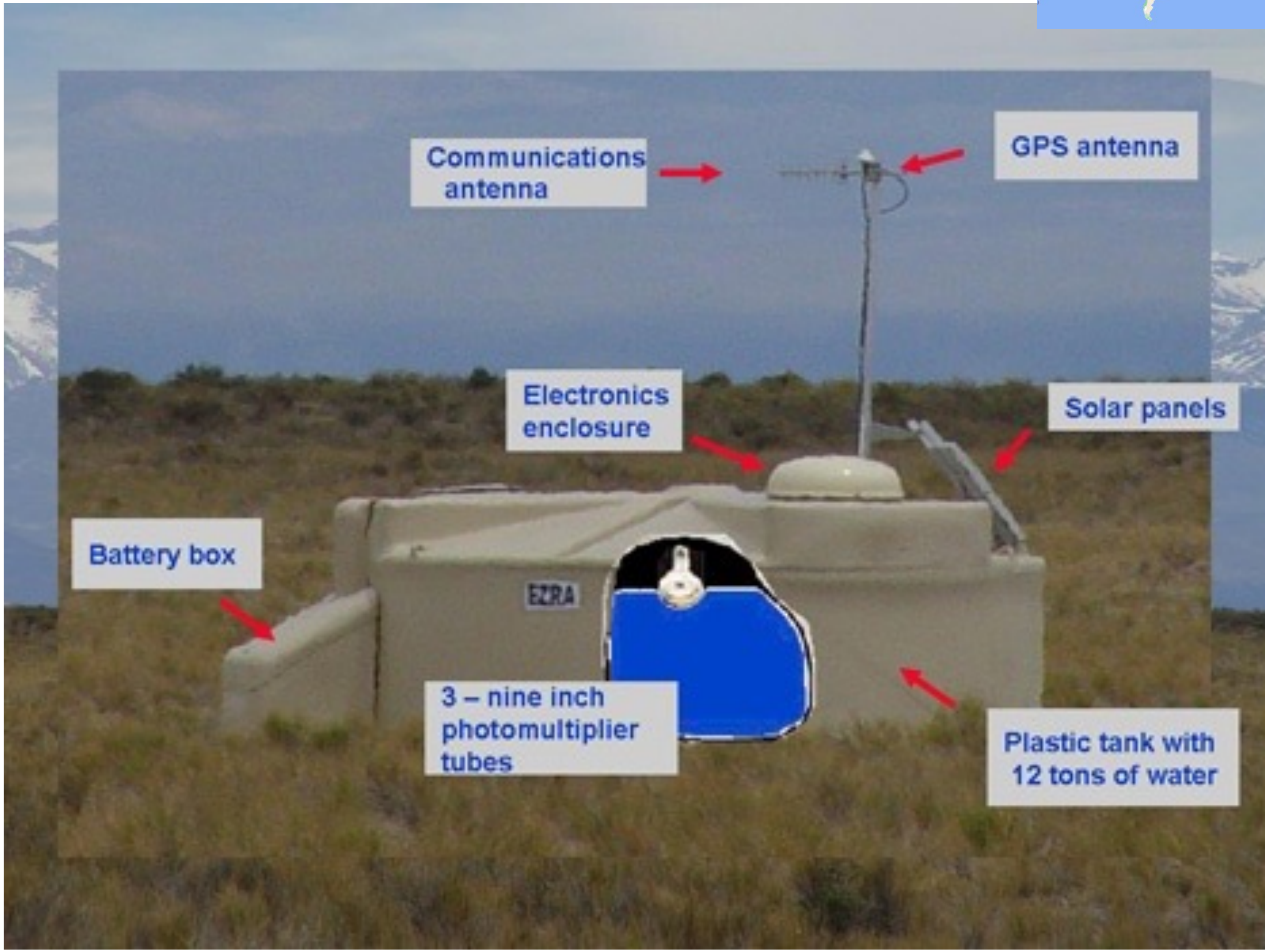
Pierre Auger Cosmic Ray Observ



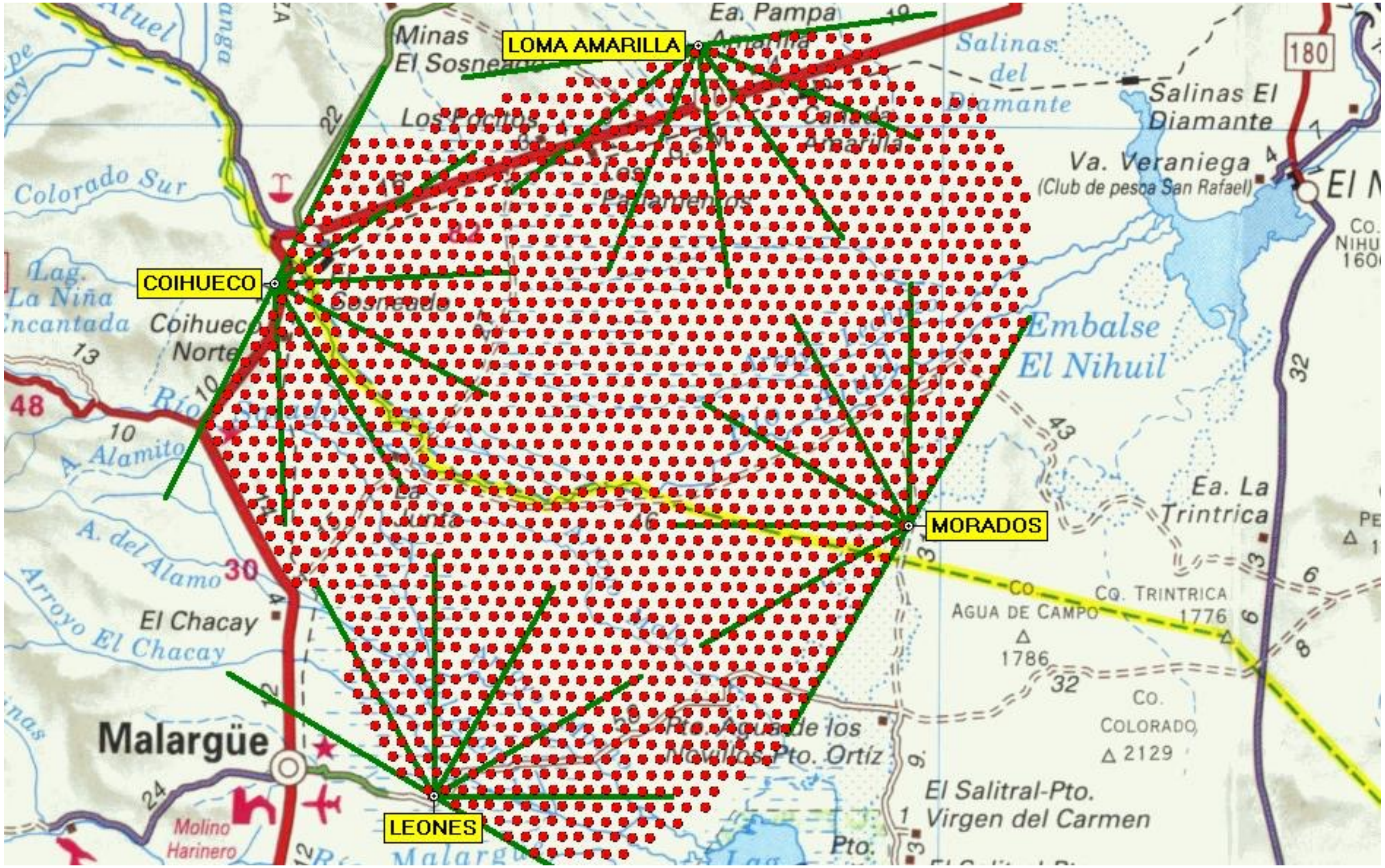
Use earth's atmosphere as a calorimeter. 1600 water Cherenkov detectors with 1.5km distance.

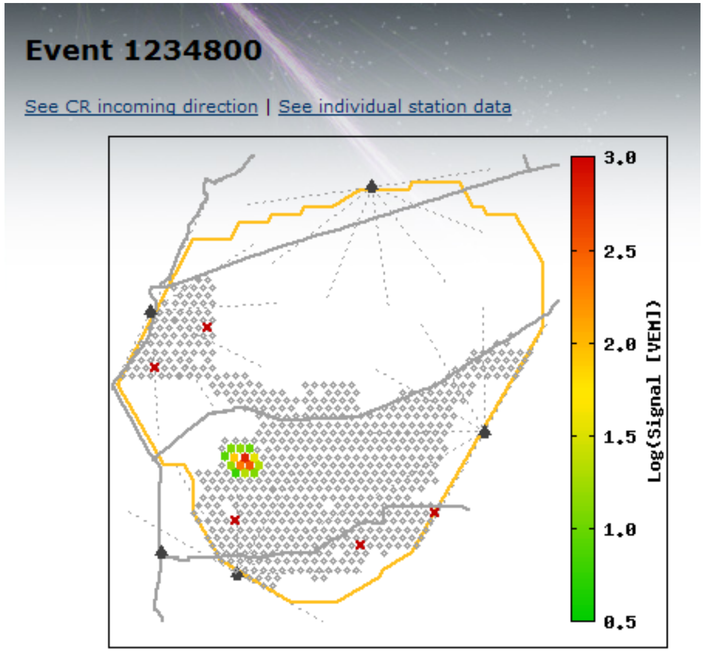
Placed in the Pampa Amarilla in western Argentina.

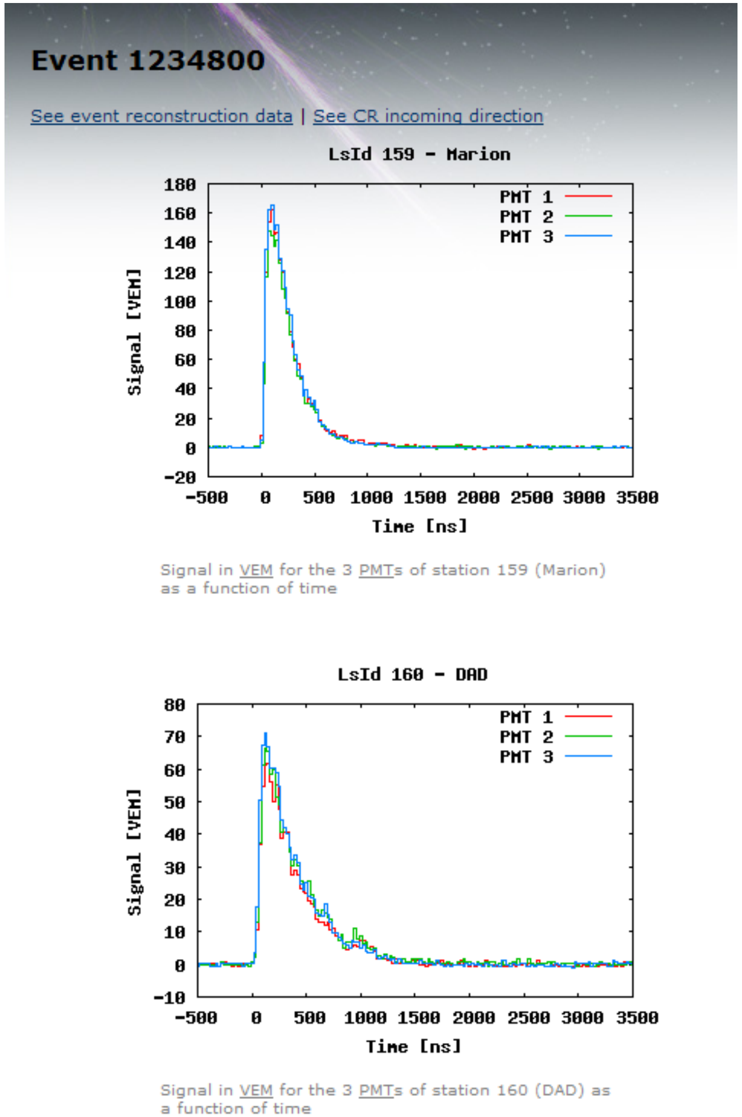
Pierre Auger Cosmic Ray Observa



Pierre Auger Cosmic Ray Observa



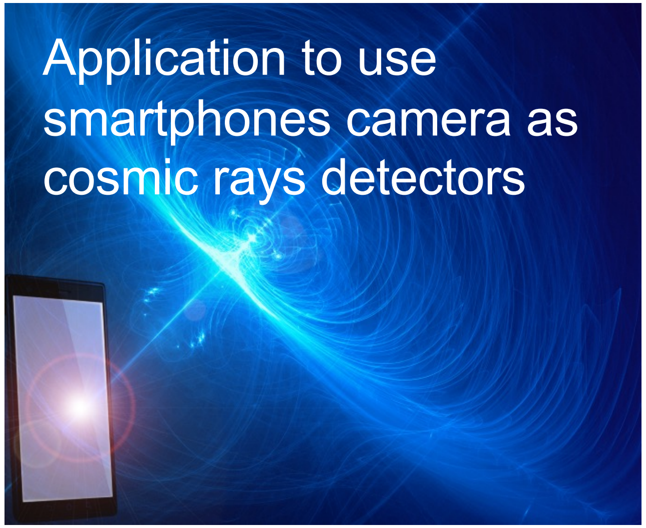




37 EeV = Exa Electron Volt = 37 x 10^{18} eV

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



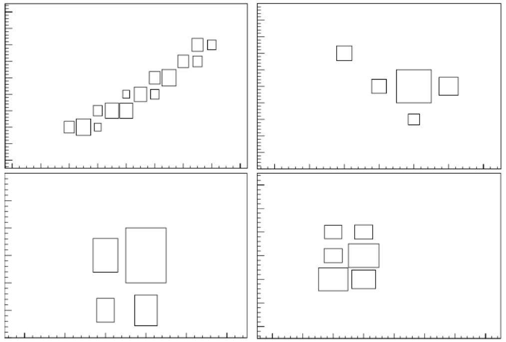
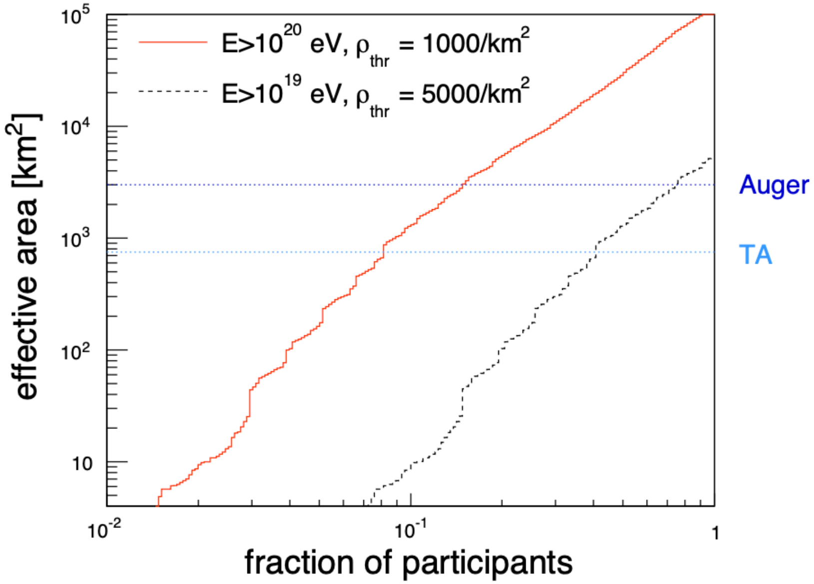


FIG. 4: Activated pixels above threshold in a Samsung Galaxy SIII phone, during exposure to ^{60}Co. Box size is proportional to pixel response values



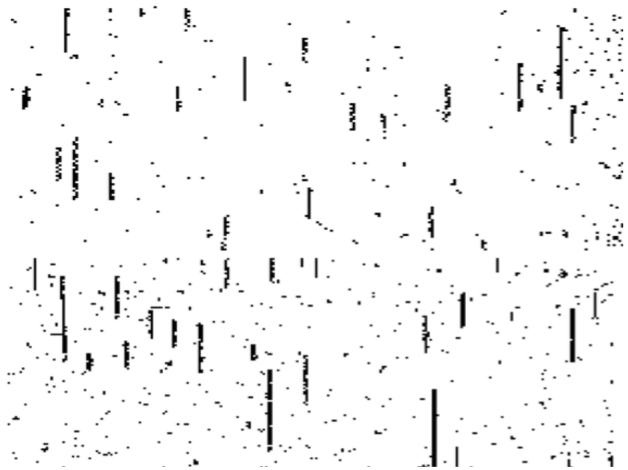


FIG. 5: Composite image of activated pixels in data collected from phones exposed to a muon beam. The phones were arranged such that the muon beam was incident on the side of the sensor, giving visible tracks where muons pass through several pixels.

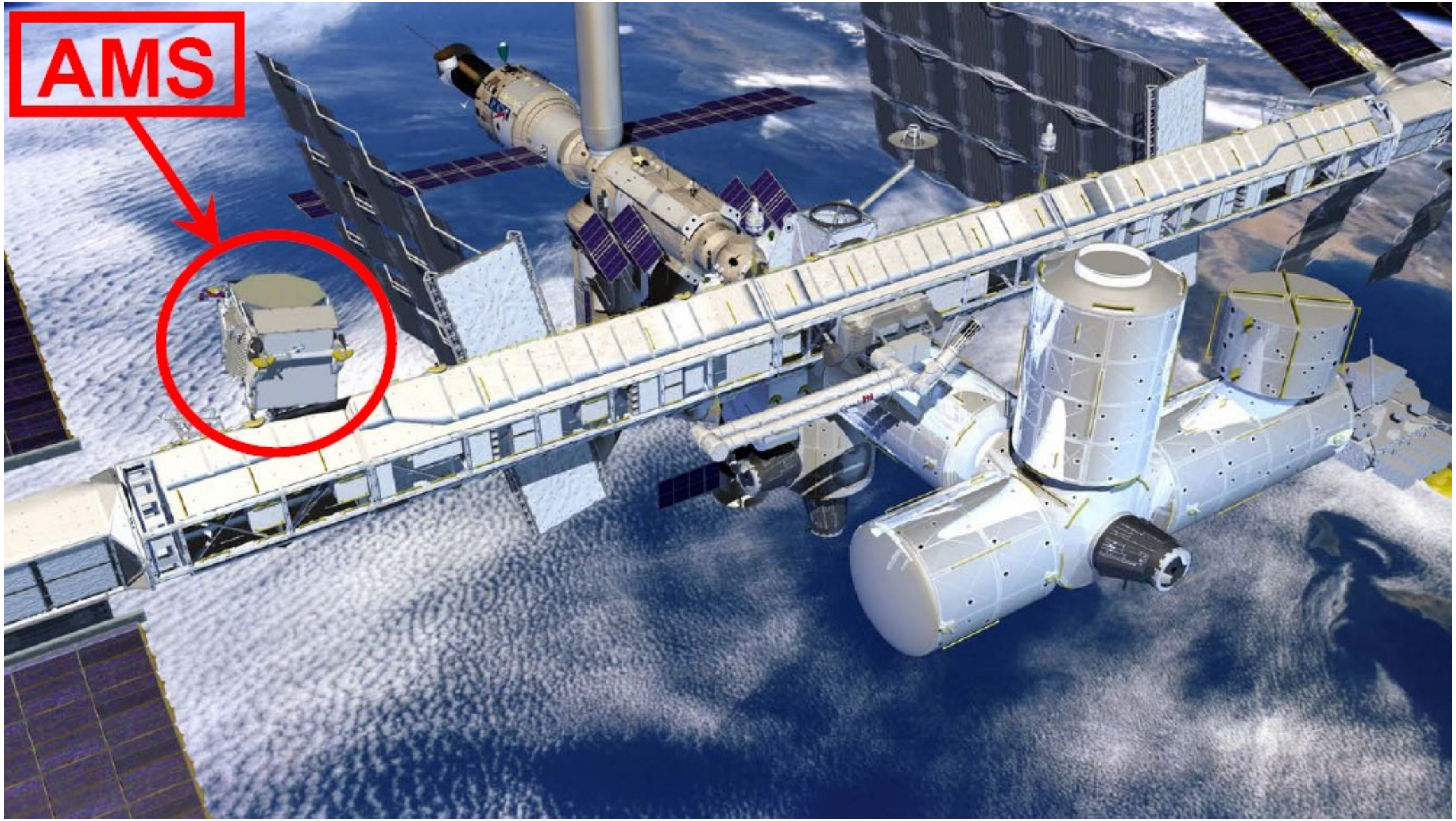
AMS

ALPHA MAGNETIC SPECTROMETER

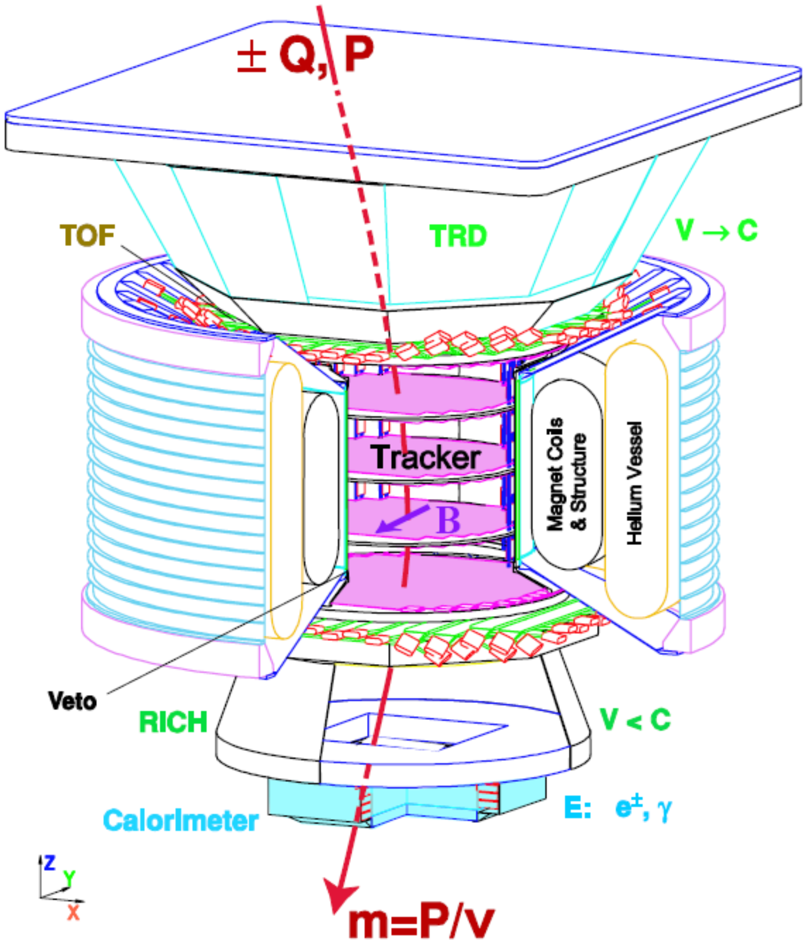
Try to find Antimatter in the primary cosmic rays.
Study cosmic ray composition etc. etc.

AMS

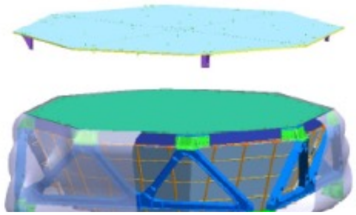
Will be installed on the space station.



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



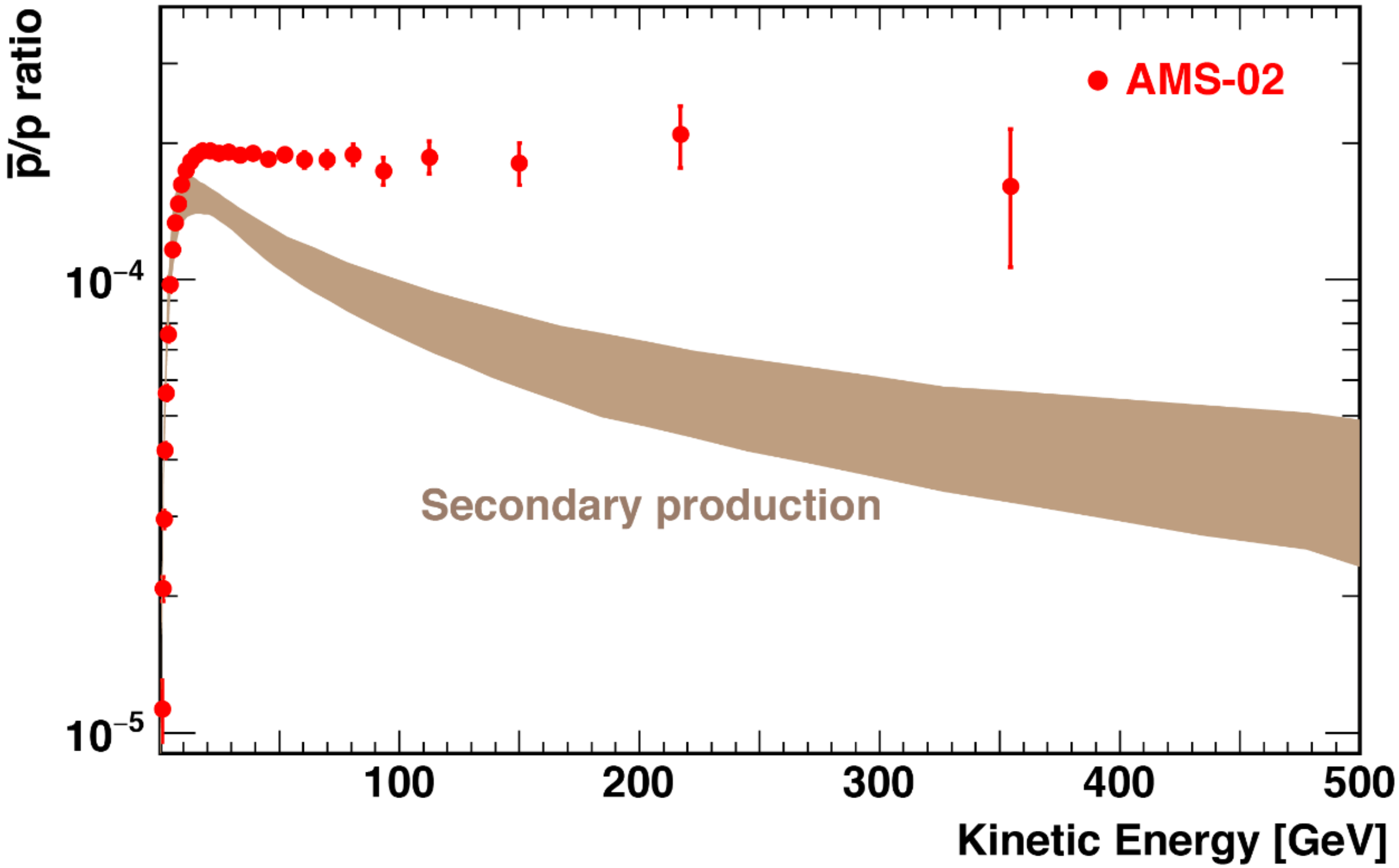


Figure 1. Antiproton to proton ratio measured by AMS. As seen, the measured ratio cannot be explained by existing models of secondary production.

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

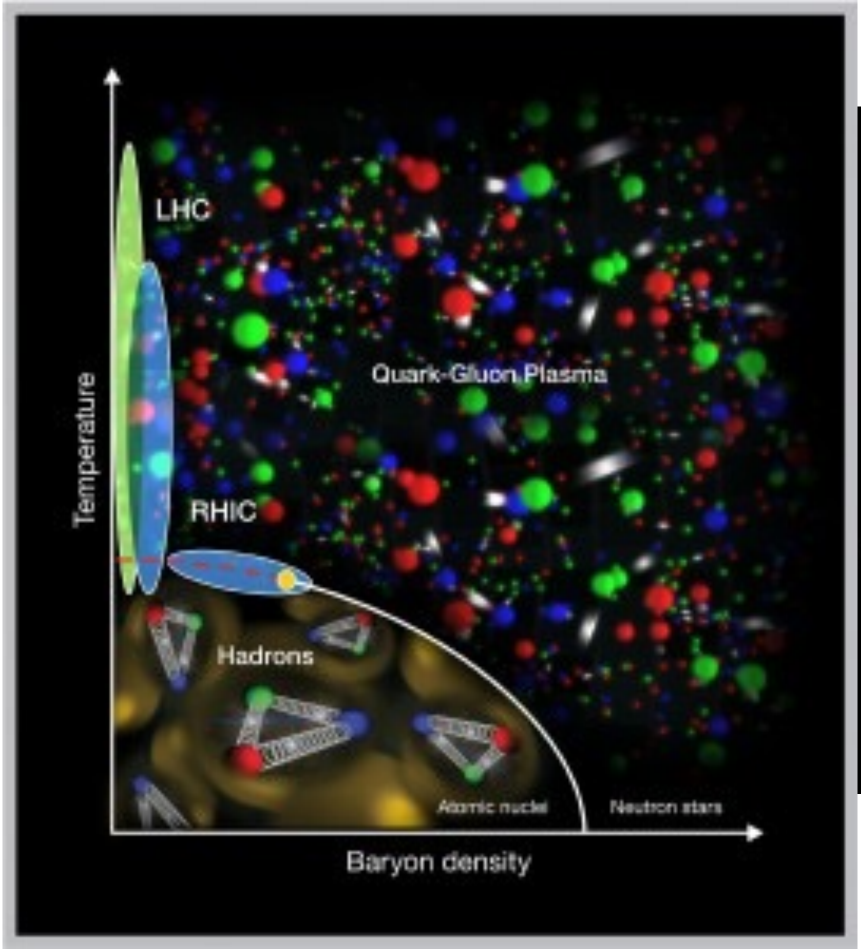
SOURCES

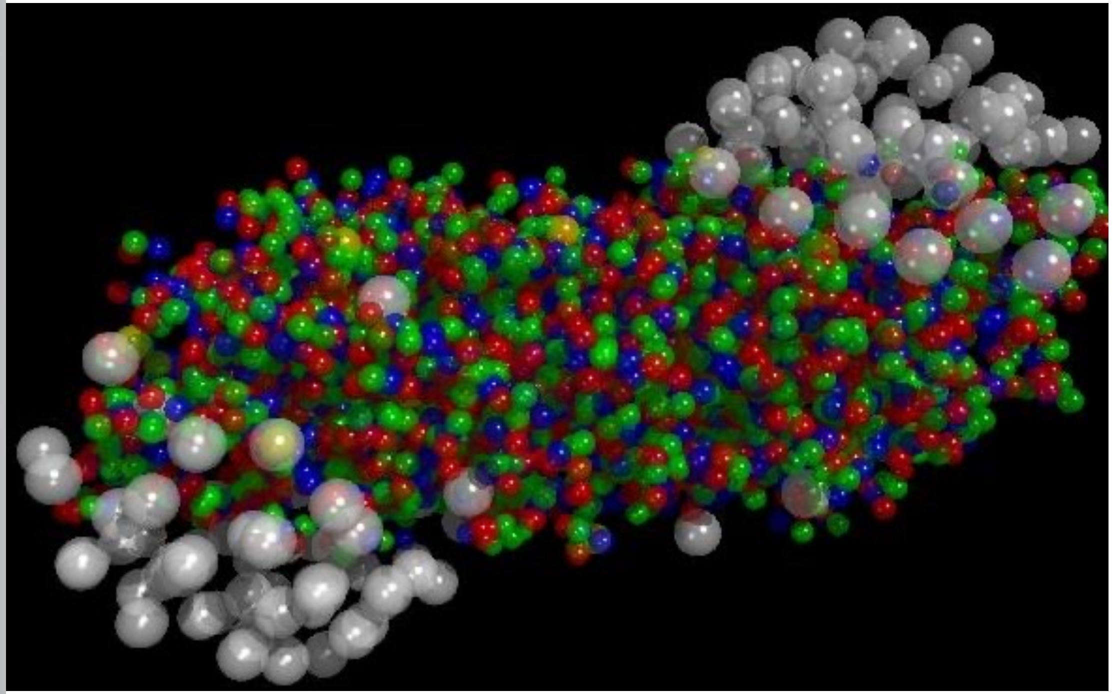
Basé sur les cours de Stefano Panebianco (CEA/IRFU) rencontre d'ete 2016

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

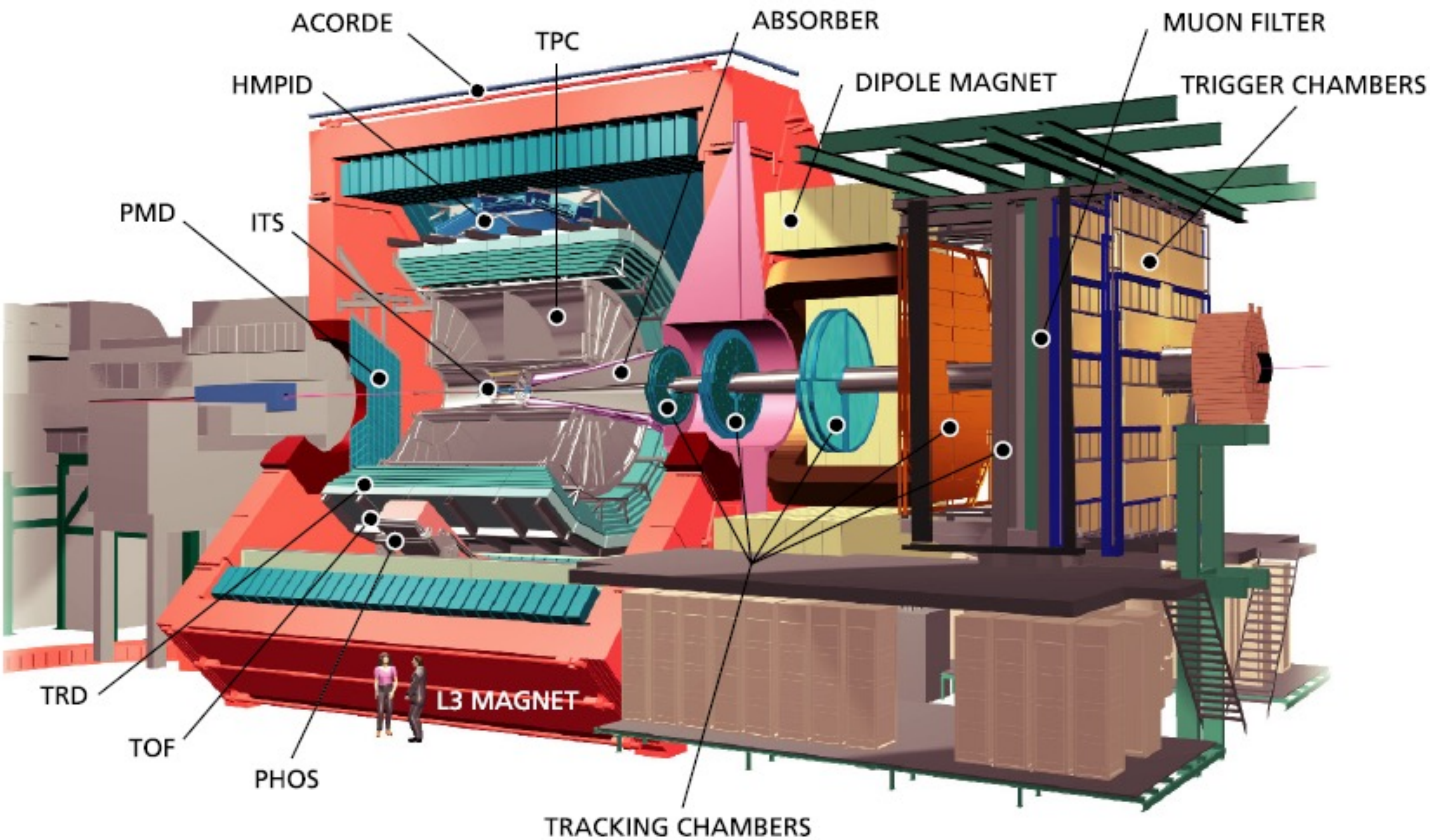
Particle Detectors , Second Edition, C. Grupen & B. Shwartz

ALICE A heavy Ion Experiment at the LHC

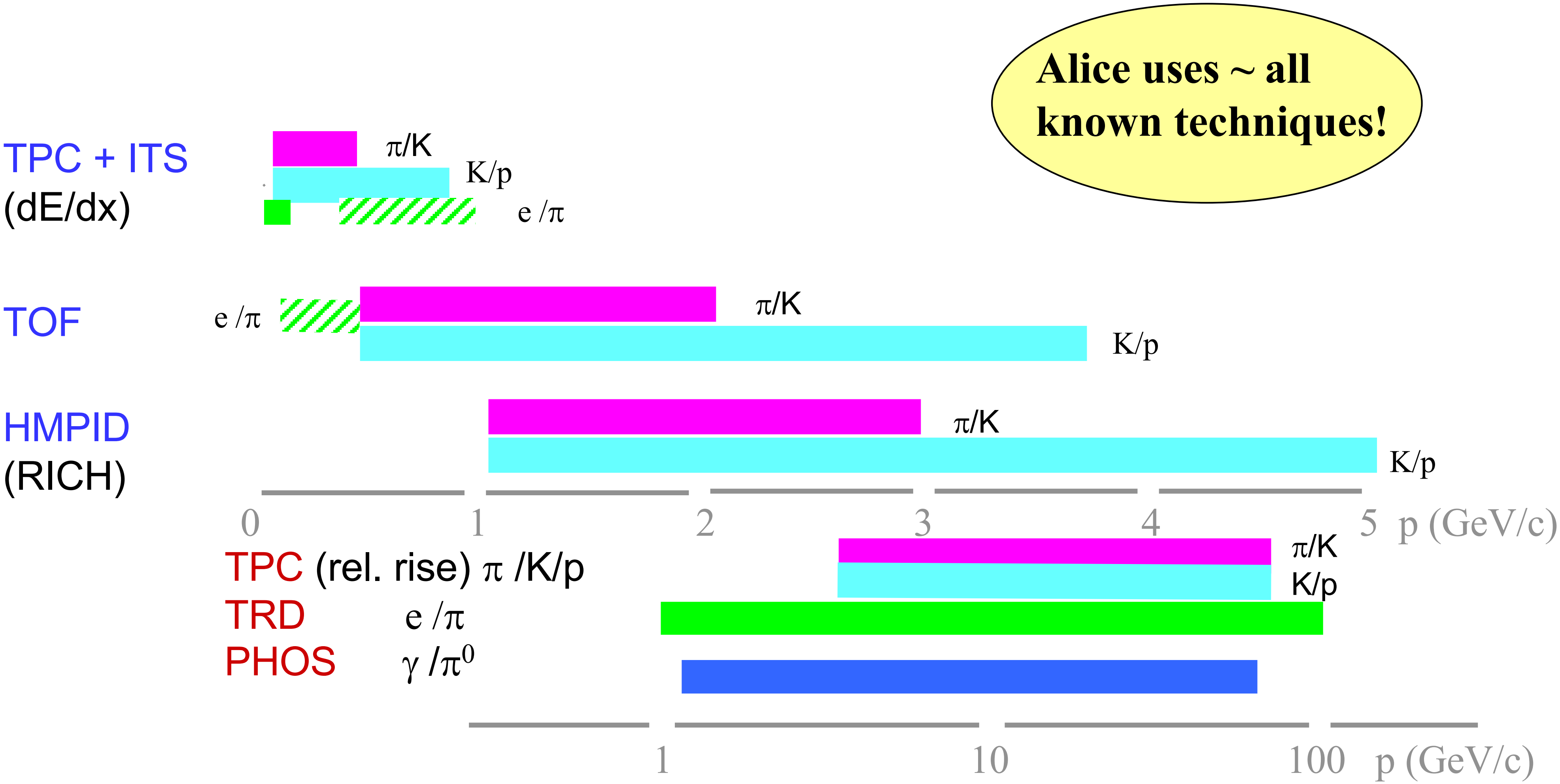




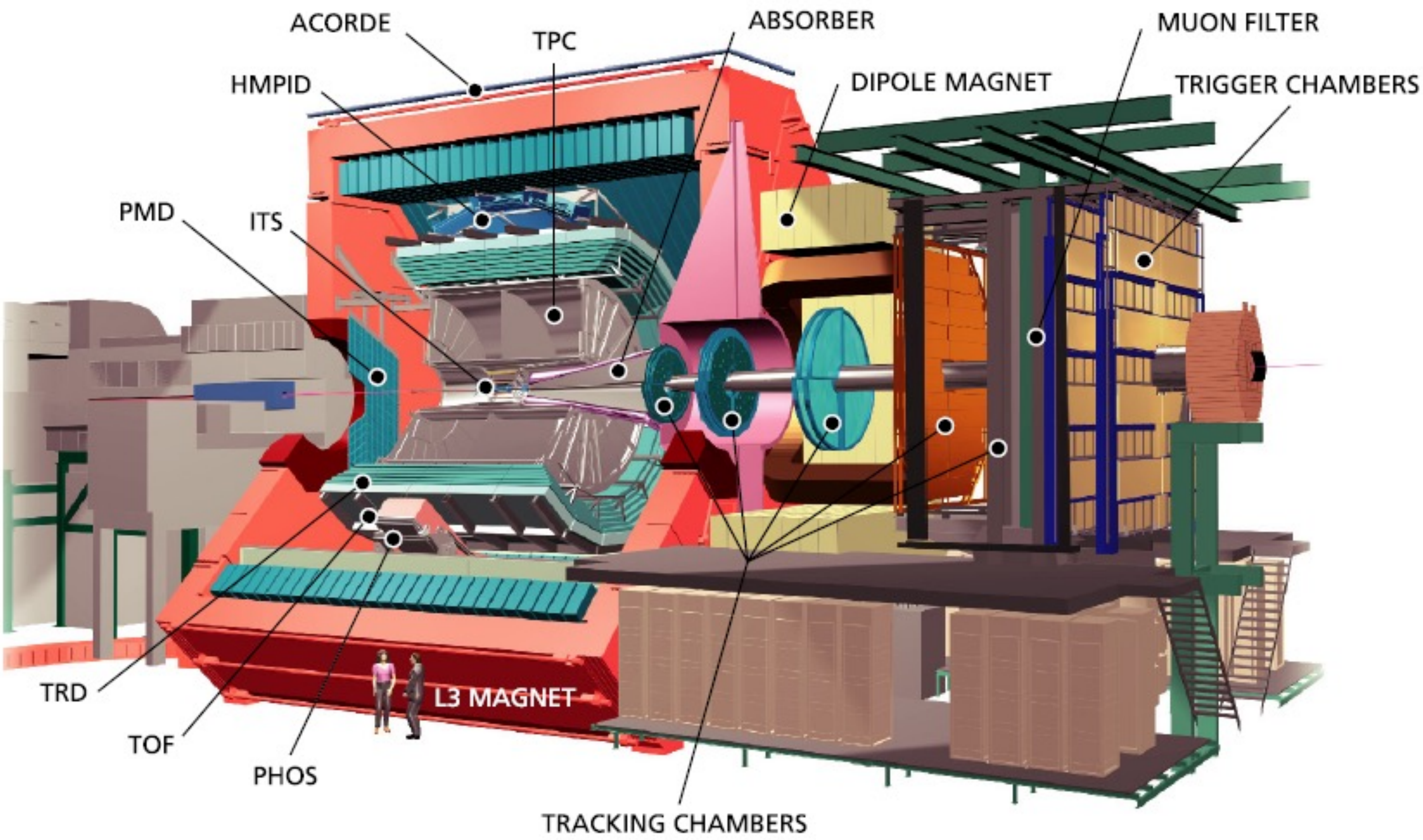
ALICE


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

ALICE Particle ID

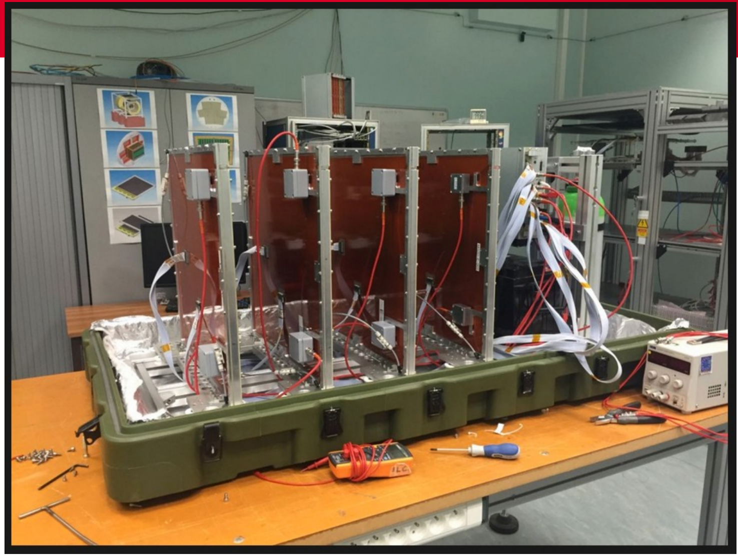


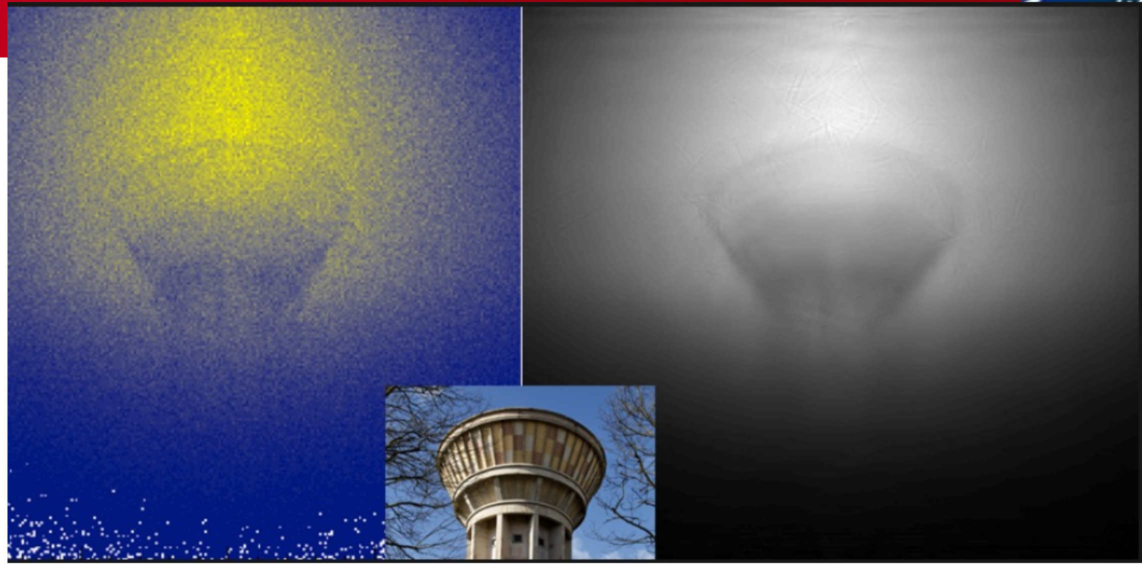
ALICE

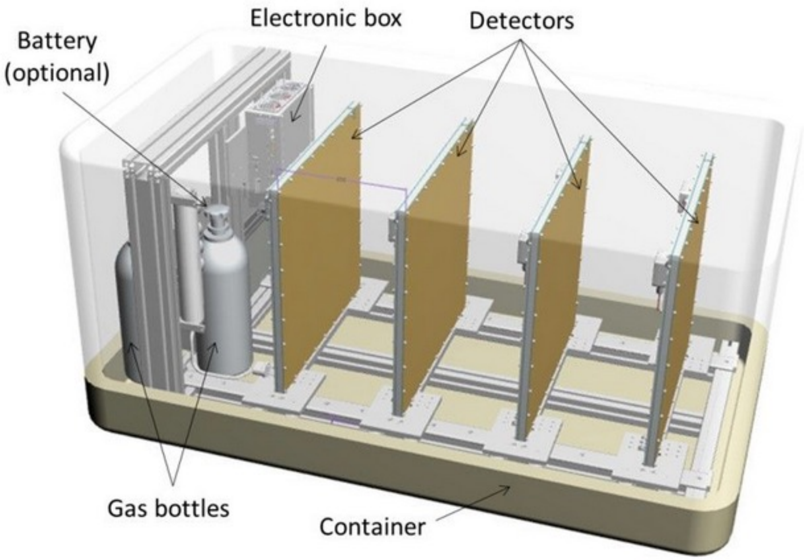


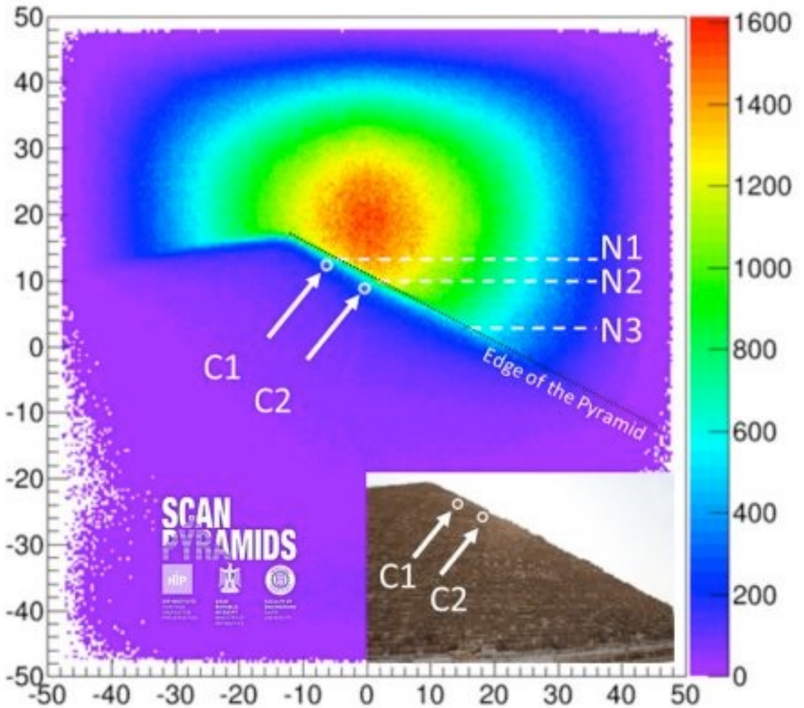
ACORDE
TPC
ABSORBER
MUON FILTER
HMPID
DIPOLE MAGNET
TRIGGER CHAMBERS
PMD
ITS
TRD
TOF
PHOS
L3 MAGNET
TRACKING CHAMBERS

MUONGRAPHY

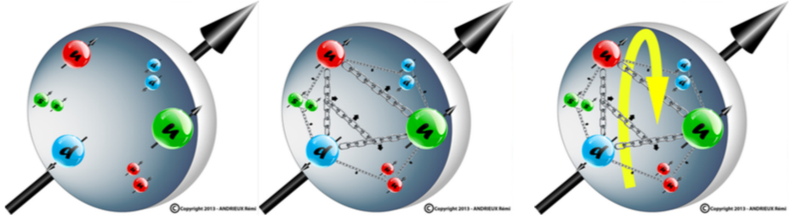





Battery
(optional)
Electronic box
Detectors
Gas bottles
Container


N1
N2
N3
C1
C2
Edge of the Pyramid
SCAN
PYRAMIDS
C1
C2
50
40
30
20
10
0
-10
-20
-30
-40
-50
-50 -40 -30 -20 -10 0 10 20 30 40 50
1600
1400
1200
1000
800
600
400
200
0

COMPASS at CERN



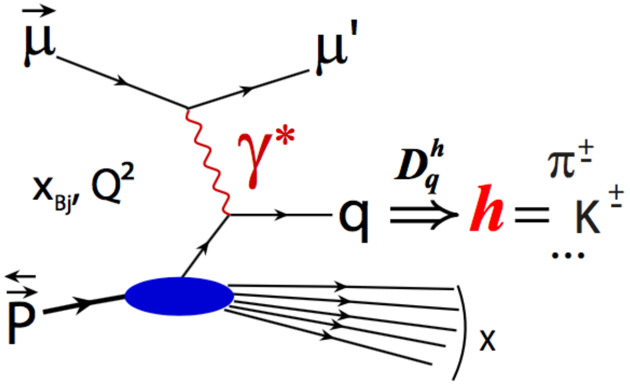
Différentes contributions

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

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

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

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



Section efficace DIS

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

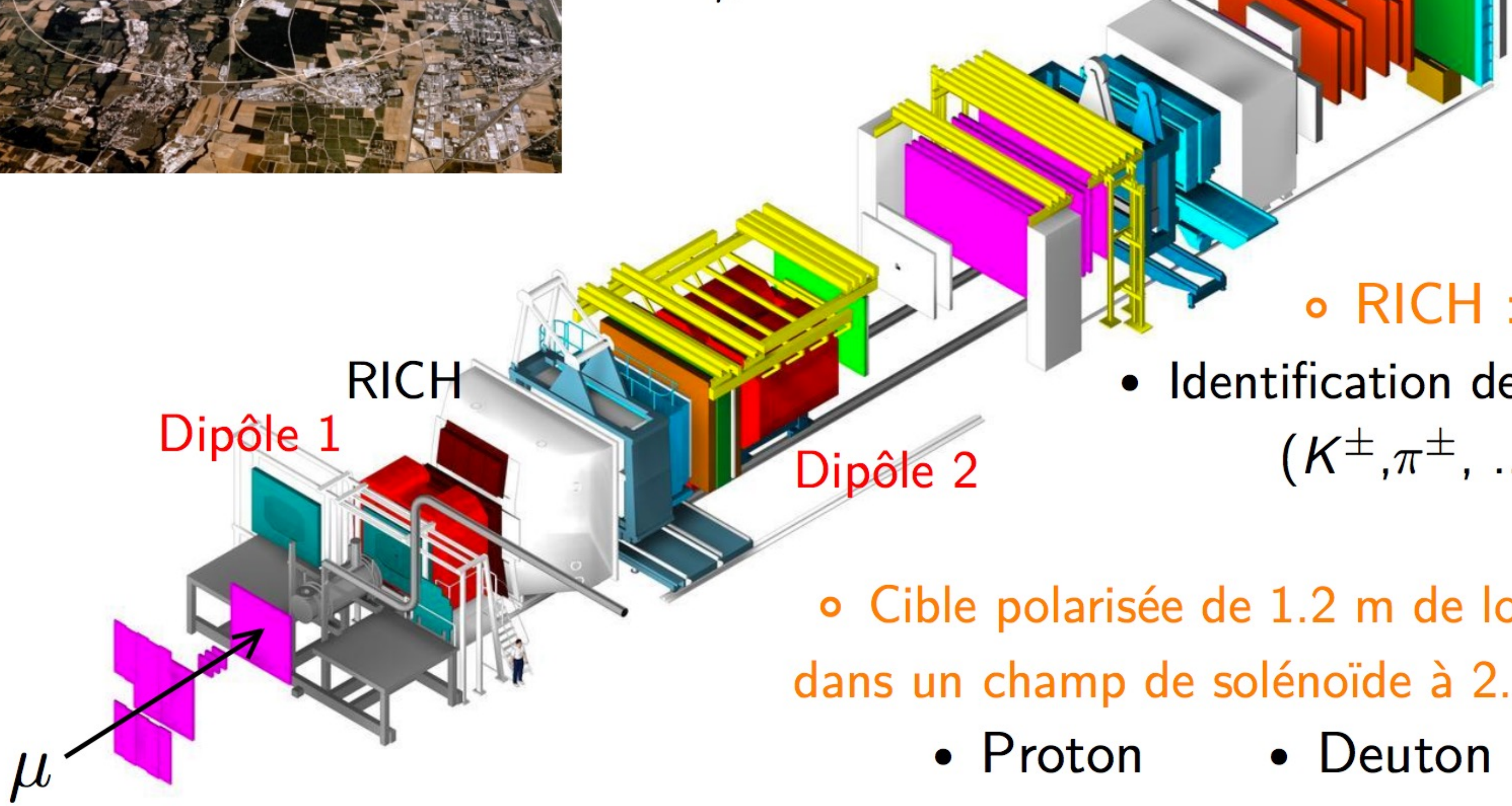
COMPASS at CERN

- Faisceau polarisé de μ^+ du SPS

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

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

$$\tau^- \rightarrow \mu^- \nu_\mu \bar{\nu}_\tau \quad with \quad BR = 17.36 \pm 0.05\% \qquad (1)$$

$$\tau^- \rightarrow e^- \nu_e \bar{\nu}_\tau \quad with \quad BR = 17.85 \pm 0.05\% \qquad (2)$$

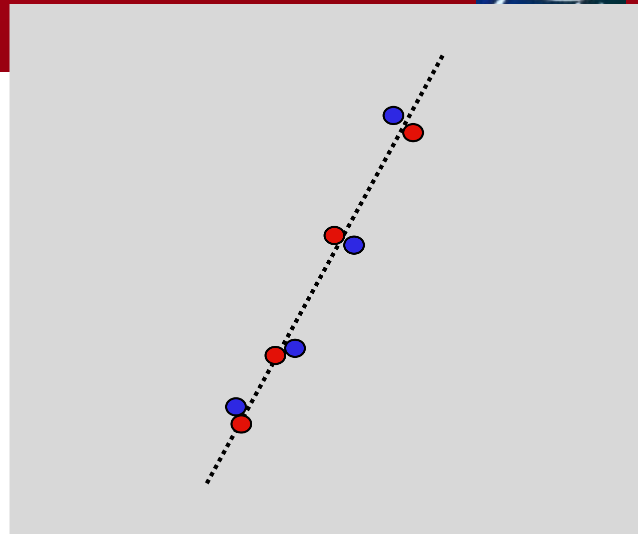
$$\tau^- \rightarrow h^- (n\pi^0) \bar{\nu}_\tau \quad with \quad BR = 49.52 \pm 0.07\% \qquad (3)$$

$$\tau^- \rightarrow 2h^- h^+ (n\pi^0) \bar{\nu}_\tau \quad with \quad BR = 15.19 \pm 0.08\%. \qquad (4)$$

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

IONISATION PRIMAIRE

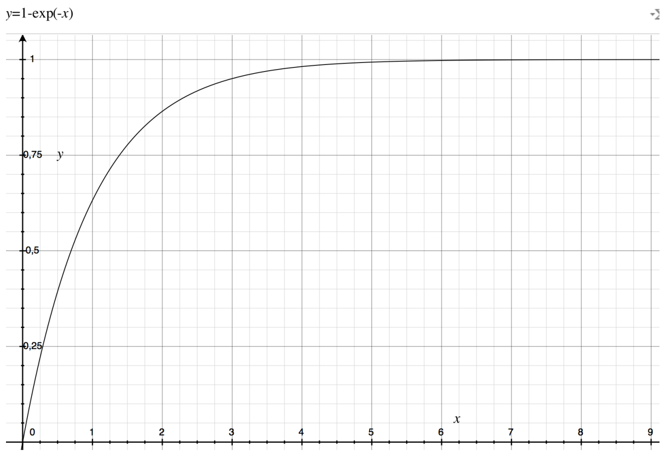
Production de paires électron-ion :



- 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:

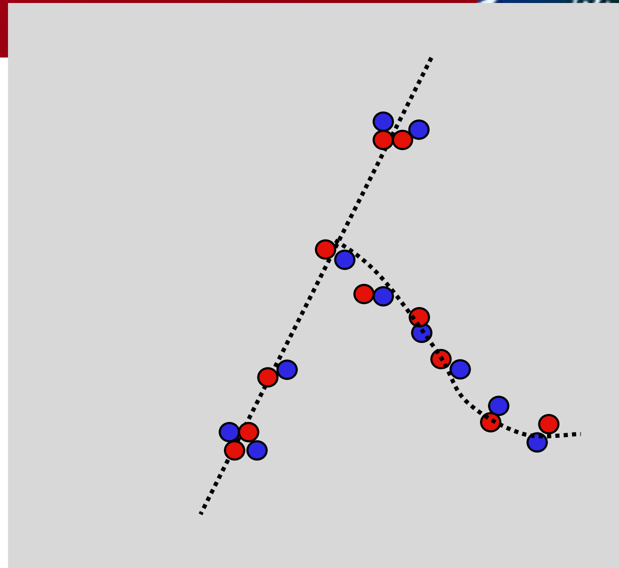
$$P_k^n = \frac{n^k}{k!} e^{-n}$$

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:

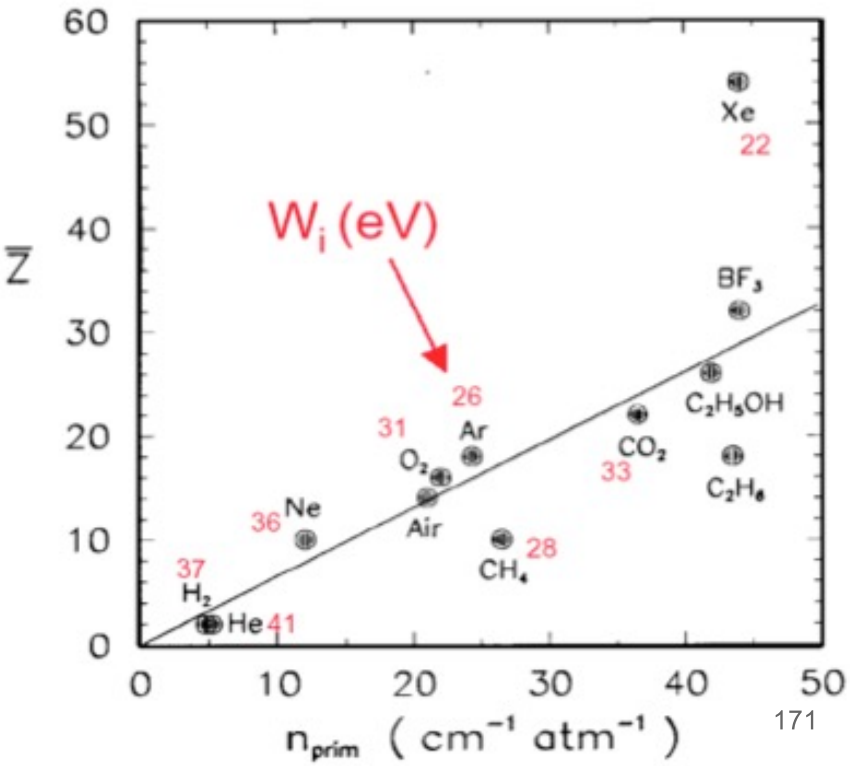
$$n_T = \frac{\Delta E}{w_i}$$

ΔE : perte d'énergie de la particule
w_i : énergie moyenne par paire

M.I.P. dans l'argon:

– ΔE= 2,65 keV/cm w_i = 25 eV

– n_T ≈ 106 paires électron-ion/cm



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

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).*

maxence.vandenbroucke@cea.fr

NOTES EMAILS

JFP : SNO pour les neutrinos et il y a longtemps l'experience sur la violation de la parité de Me Wu.

MVDB : (cours)

FS : Corrélations à courte portée, Anna Corsi
Recherche d'un neutrino stérile à Stereo, Alain Letourneau (David Lhuillier n'a pas le temps en ce moment)
Calibration de bolomètres par recul nucléaire, procédé CRAB, Loïc Thulliez (là encore, David serait possible mais il est trop occupé)

DN :
Maxence tu peux aussi parler de PandaX-III ! Enfin bon du double-beta en général, c'est quand même amusant comme idée que le neutrino soit ça propre antiparticule. Mais PandaX-III on a aussi une TPC sous pression avec des events tout diffusés mais qu'on reconstruit quand même !

Tu peux aussi parler de Ptolemy, pour la détection des neutrinos cosmologiques avec du tritium. La physique derrière est vraiment flashy, et techniquement c'est assez complexe vu qu'il faut mesurer un e^- de 18keV avec une résolution d'une dizaine de meV...
Voilà qq liens:
https://arxiv.org/abs/hep-ph/0703075
https://arxiv.org/abs/1808.01892
https://agenda.infn.it/event/14775/contributions/26316/attachments/18707/21206/Messina_Ptolemy_VULCANO2018.pdf

Sinon tu peux parler de la sphère de Ioannis, c'est assez original aussi...

Rq :

APP COSMIQUE

PB :

Autre truc, mais moins pro : mettre les téléphones portables en réseau pour détecter les cascades atmosphériques associées aux rayons cosmiques de très haute énergie. Il me semble que c'est en lisant la ccd des appareils photos qu'on peut détecter le passage d'une particule ionisante (à vérifier), on laisse tourner un app, et de temps en temps il y a des coincidences, on détecte des RC comme ça. Tu connais ce truc ?
Oui ! bonne idée : https://hackaday.com/2014/10/17/detect-cosmic-rays-with-your-smartphone-using-crayfis/
mais visiblement ca n'est plus en train de tourner :(https://blog.crayfis.io/