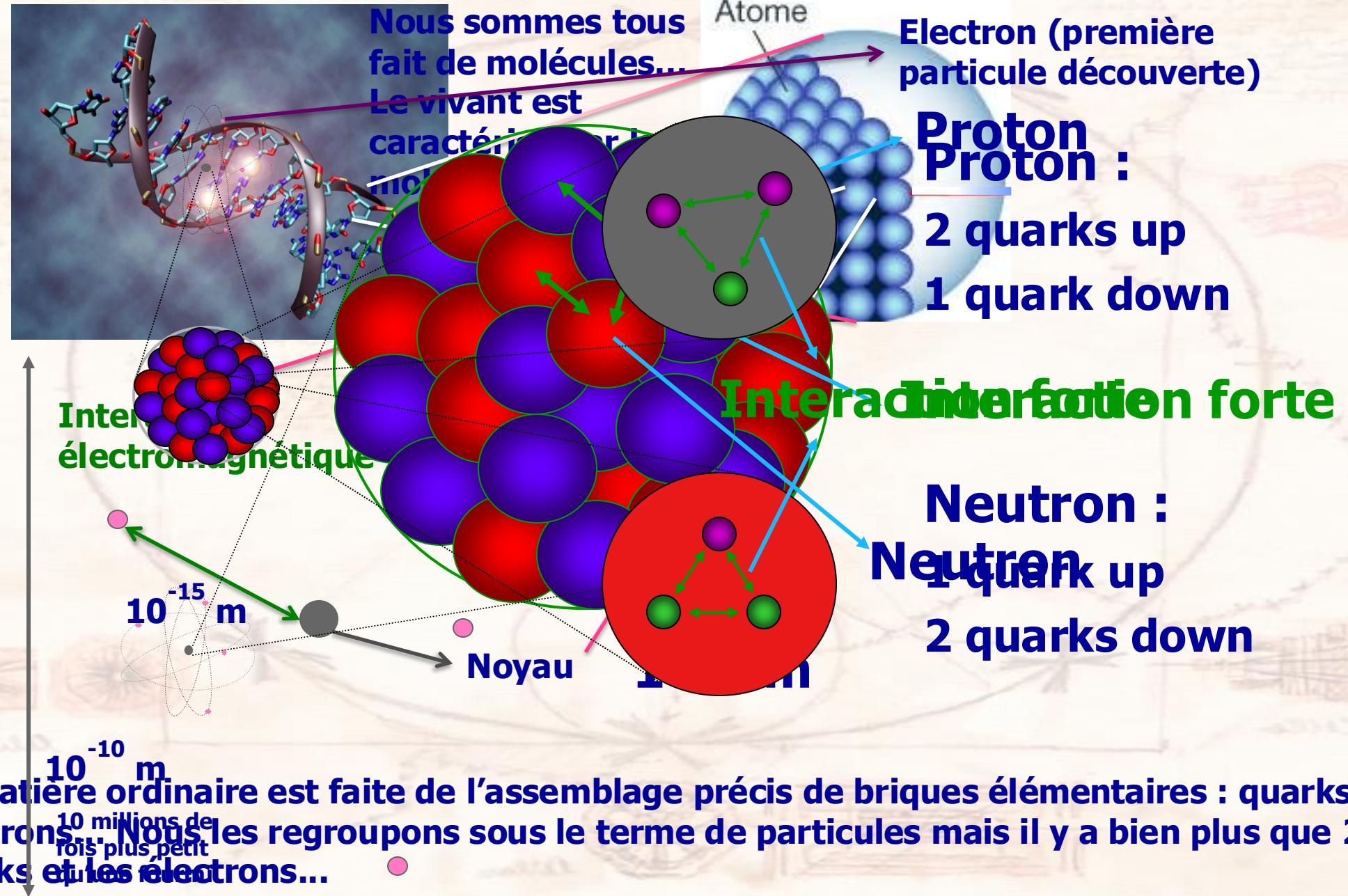


# La physique des particules et Atlas

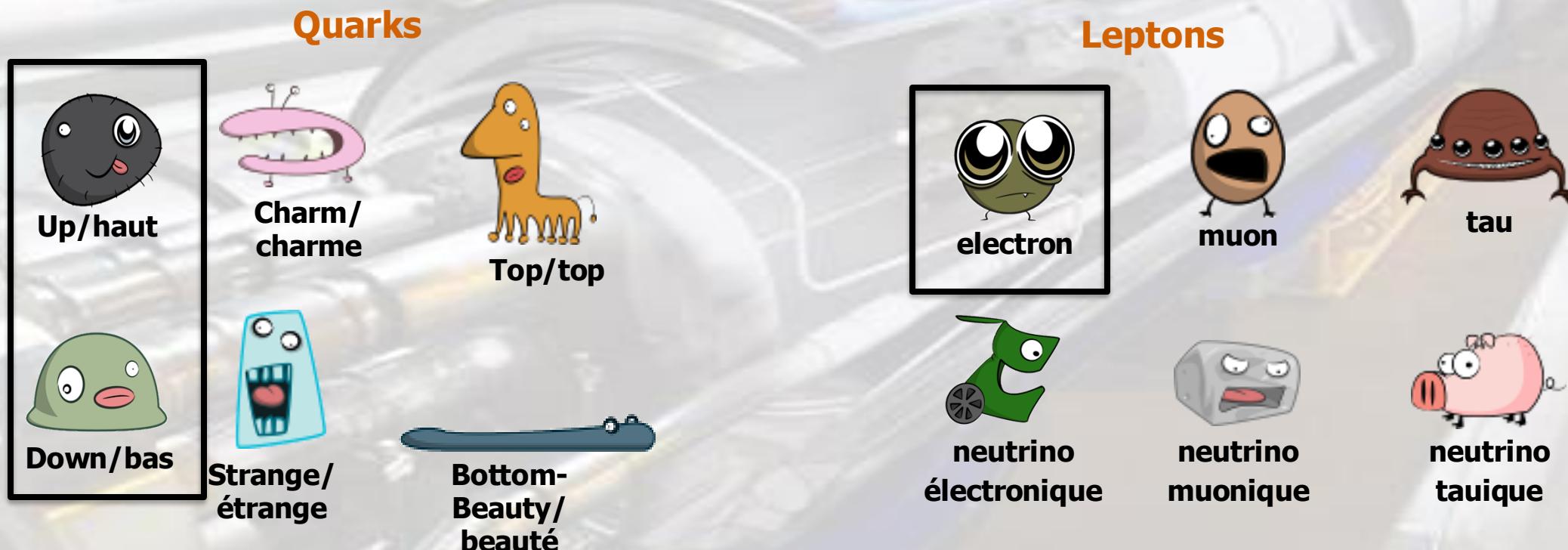
Stéphanie Beauceron (LPNHE)

# Qu'est ce que la matière?



# Le Zoo des particules

**Ces 2 Quarks et 1 Lepton (+neutrinos) constituent tout L'Univers connu**



**Les autres particules vont se désintégrer dans des particules « stables ».**

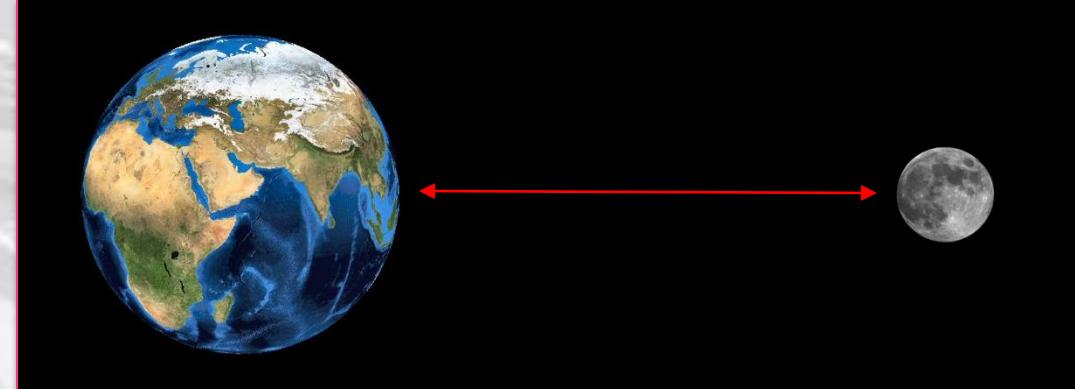
# Les forces/interactions

Isaac Newton



(1643-1727)

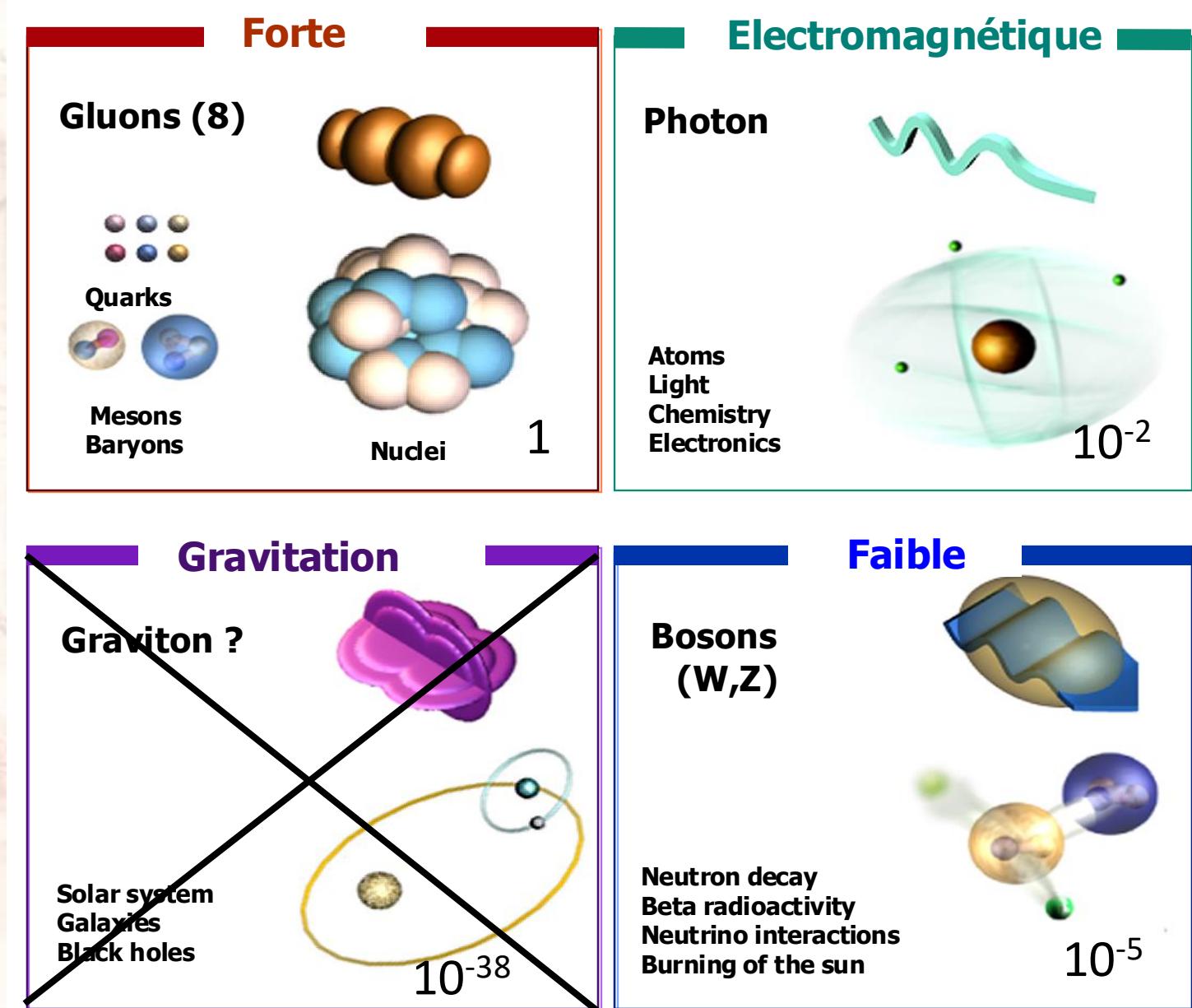
Vision « classique »:  
Action instantanée à distance



Vision « moderne » : échange de particules



# Les Forces



Intensité  
relative

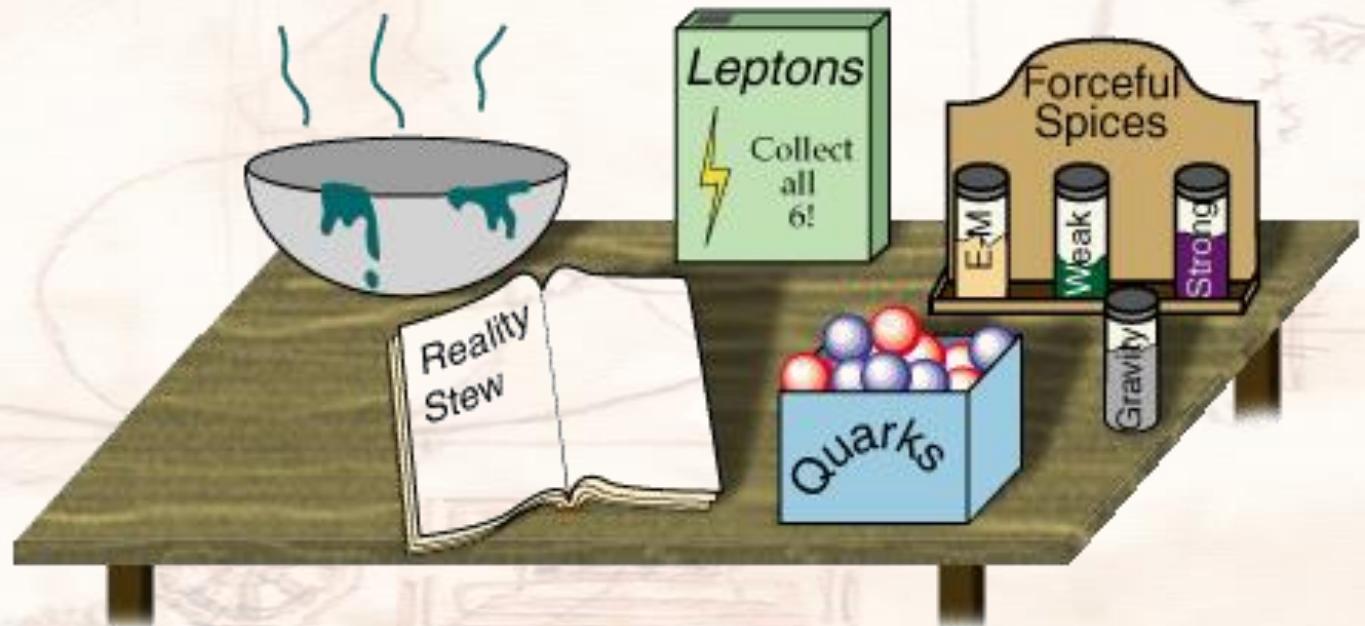
# Le modèle standard

Depuis le début des années 70, les physiciens des particules ont synthétisé toutes leurs connaissances au sein d'un modèle unique :

le « Modèle Standard »

On connaît et comprend beaucoup mais on ne sait pas tout...

Des mystères restent inexplicables, des choses à découvrir...





Une théorie : Modèle standard de la physique des particules décrit les interactions de toutes ces particules.

De nombreuses mesures montrent que ce modèle marche bien, mais encore des questions :

- Comment inclure la gravité?
- composition de l'Univers : Matière noire, nouvelles particules pas encore observées
- Où a disparue d'antimatière...



$$\partial_\mu \phi = \partial_\mu \phi - i e A_\mu \phi$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

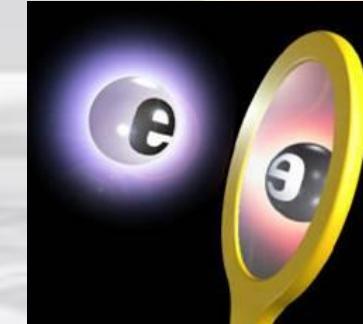
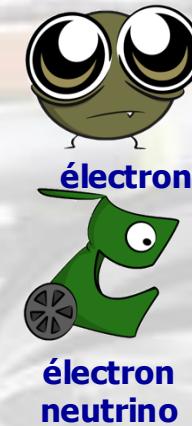
$$V(\phi) = \frac{1}{2} \phi^\dagger \phi + \beta (\phi^\dagger \phi)^2$$

$$\alpha < 0, \beta > 0$$

Peter Higgs

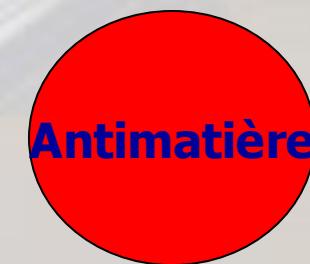
# Qu'est-ce que l'antimatière?

Pour chaque type de particule



Il y a une antiparticule

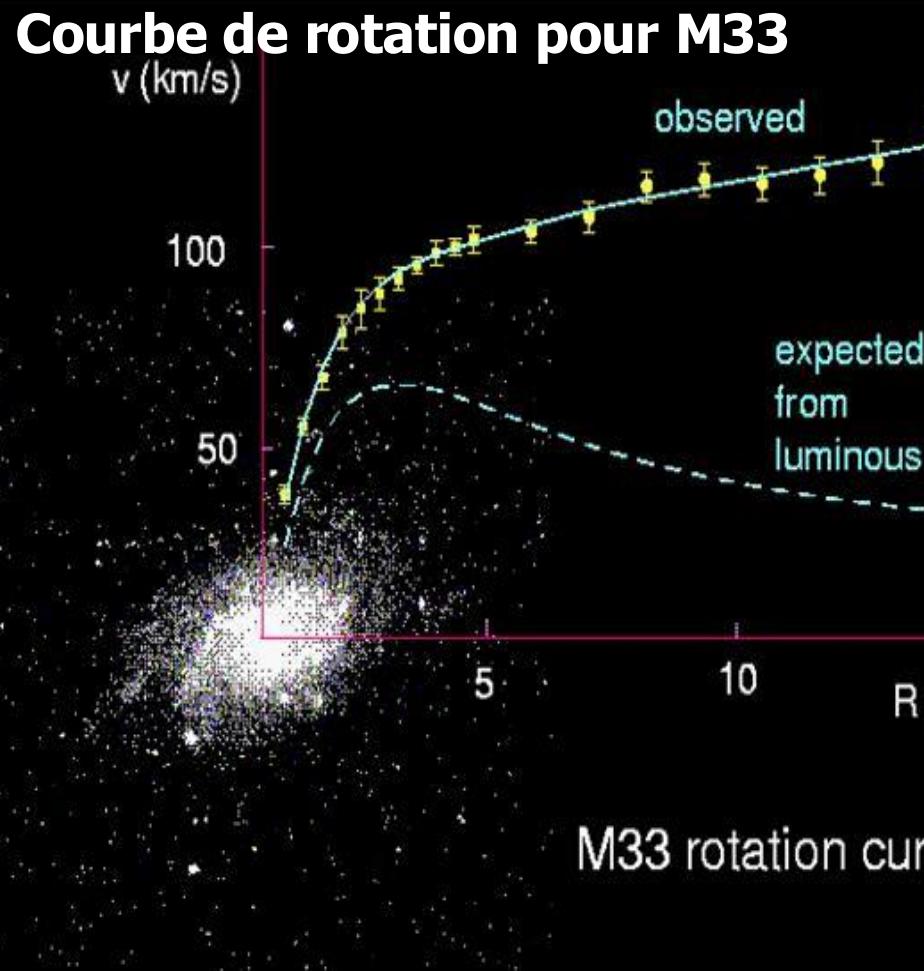
**Les particules et les antiparticules ont des charges électriques de polarités opposées**



**Il y a 14 milliards d'années, le Big Bang a créé la matière et l'antimatière en quantités égales. Nous existons parce qu'il n'y a plus d'antimatière. Où est-elle donc passée? Pourquoi la nature préfère-t-elle la matière?**

# Rotation des galaxies

indice de l'existence de la matière noire au niveau galactique (Vera Rubin ~1980 -1990)



L'étude de la rotation des galaxies spirales montre que la masse de la galaxie est :

$$M_{\text{total}} \sim 10 \times M_{\text{luminous matter}}$$

Explications possibles :

- Matière dite noire car non visible dans le halo galactique
- Présence d'objets compacts massifs (Machos = massive compact objects)...

# De quoi est fait notre Univers...

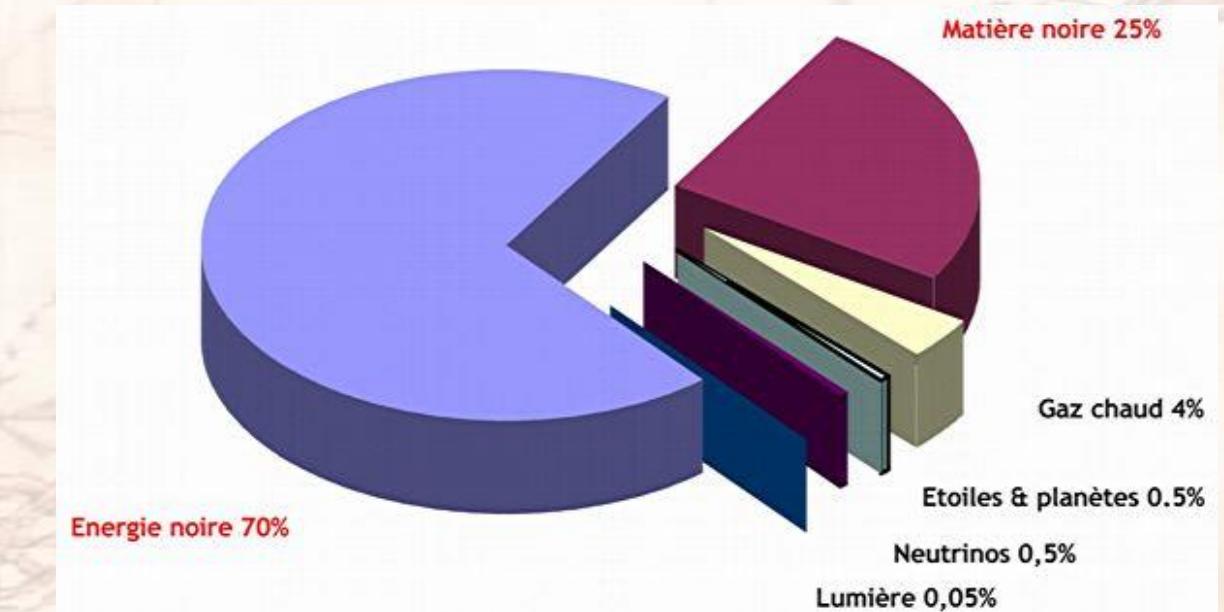
**Des effets sur des galaxies nous disent qu'il y a bien plus de matière/énergie que ce que l'on voit**

→ “matière/énergie” noire

On ne voit que ~4% de la matière de l'Univers!

Cette « matière/énergie noire » pourrait être constituer de particules pas encore découvertes ?

Le LHC pourrait créer ces particules et les détecteurs sur l'anneau pourraient les détecter indirectement.



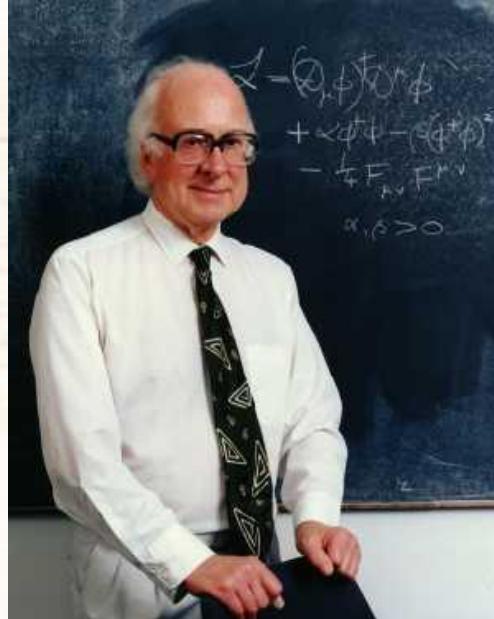
# Des particules massives!



quarks

leptons

Avant 2012, notre théorie nous dit que les particules sont « sans » masse, sauf que l'expérience nous dit l'inverse...  
La raison est l'existence d'une nouvelle particule appelée “le Boson de Higgs”



# Le boson de Higgs

Dans le modèle standard, l'origine des masses trouve sa place via un mécanisme appelé d'après le nom du physicien britannique : Peter Higgs (et Brout, Englert)

Ce mécanisme prédit l'existence d'une nouvelle particule : le boson de Higgs.



Le 4 juillet 2012, nous avons découvert une particule qui est le boson de Higgs : cette particule a une masse de  $\sim 125 \text{ GeV}/c^2$

# Les outils

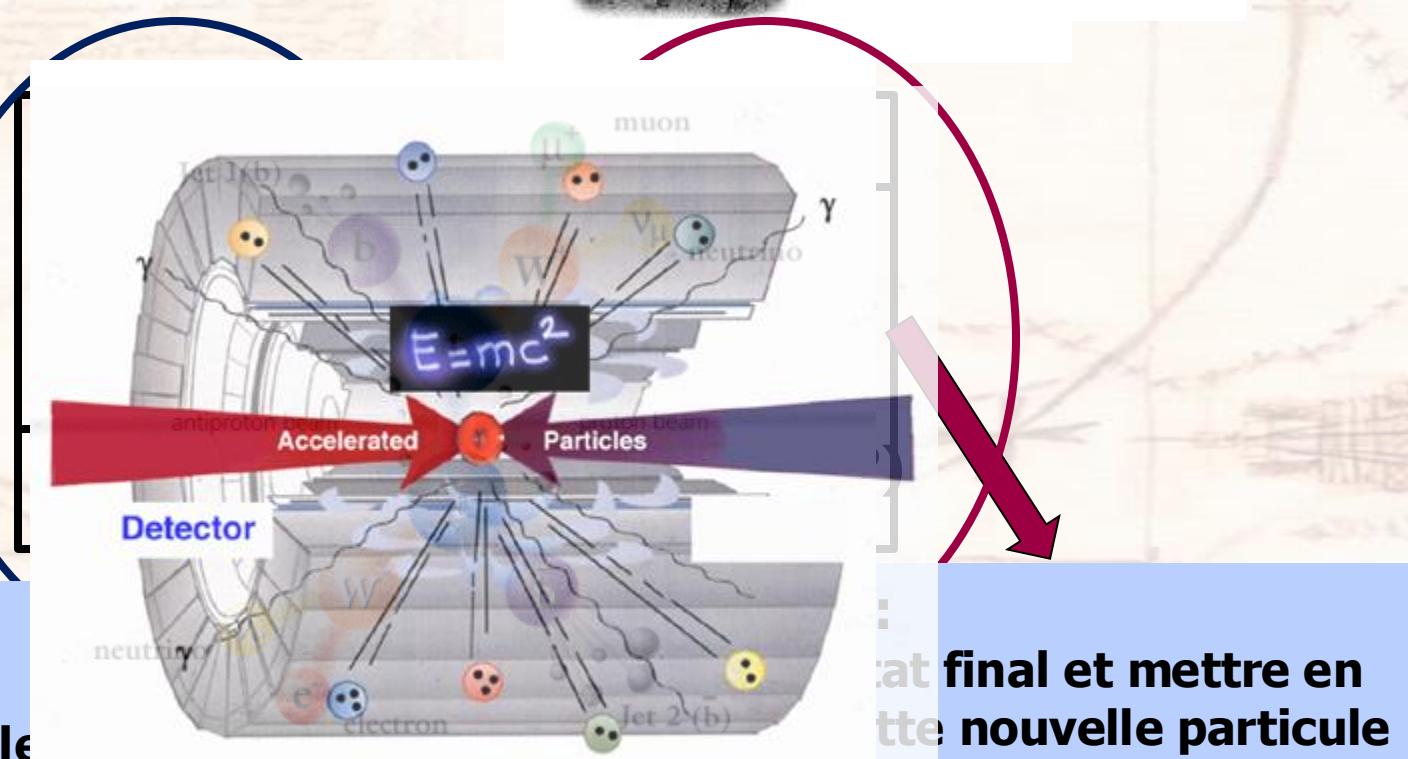
Comment « voir » les particules élémentaires ?  
en “cassant” des particules lors de collisions  
en créant des particules à partir d'énergie pure

**Les outils**  
**un accélérateur**  
**des détecteurs de particules**



La masse est juste  
une forme d'énergie

$$E=mc^2$$



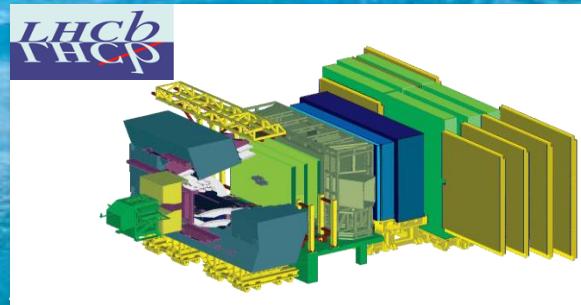
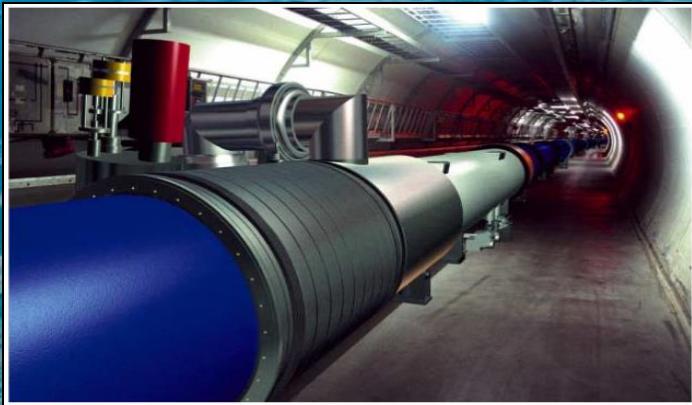
**Accélérateur :**  
Donner de l'énergie  
(vitesse aux particule

mat final et mettre en  
tte nouvelle particule

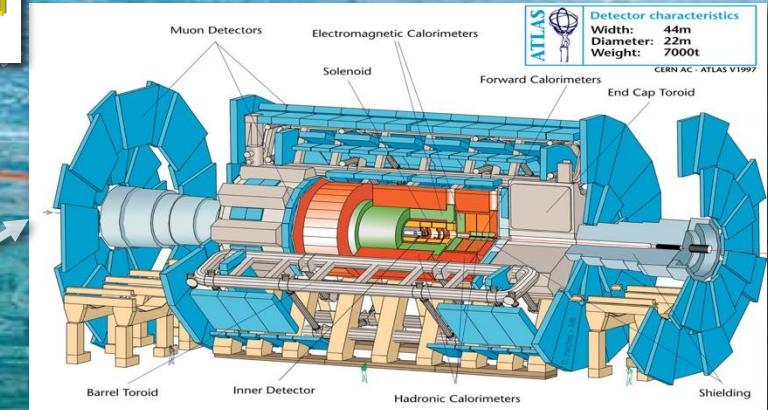
# Le LHC (Large Hadron Collider)

Le projet a démarré en 1989... Mais la conférence ECFA à Aix-la-Chapelle en Octobre 1990 est le vrai point de départ.

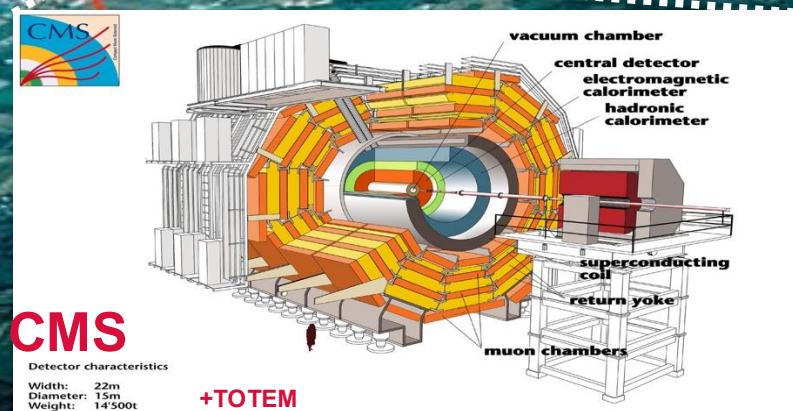
LHC : 28 km (7km en Suisse)  
100m sous terre



pp, physique du B  
Violation de CP



Exp. généralistes,  
pp, ions lourds



Ions lourds



# LHC : quelques chiffres

## Energie des collisions

Actuelle: **13,6 TeV** (1 faisceau autant d'énergie qu'un TGV à 300 km/h)

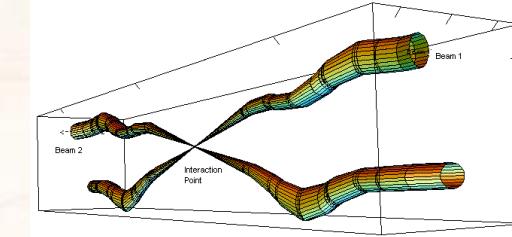
## La précision absolue

paquets : quelques cm de long,

taille transverse: **16 µm x 50 µm**

~ diamètre d'un cheveu

~**2800 paquets de 100 milliards de protons, séparation entre paquet ~7 m**



## La plus grande machine du monde

Circonférence : **26659m**

**9300 aimants** (→maîtrise des matériaux supraconducteurs)

## Le circuit le plus rapide de la planète

Proton: c-**40km/h**

(**99.999991%** de la vitesse de la lumière)

~**40 millions collisions par secondes**

## L'espace le plus vide du système solaire

Pression 10 fois plus faible que sur la lune

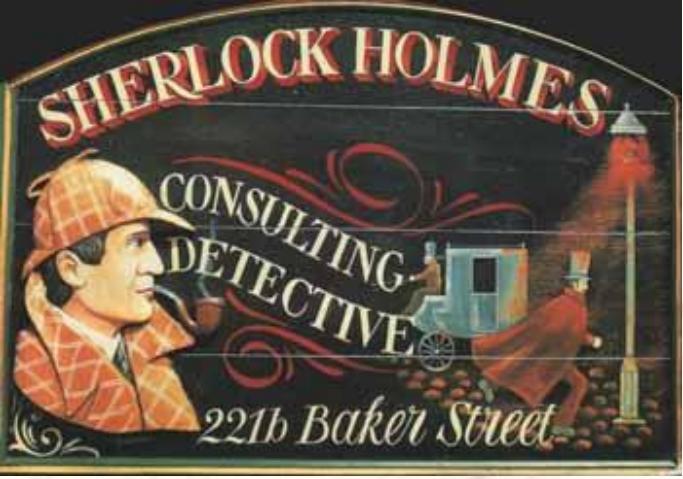
## Le plus grand réfrigérateur

Aimants sont refroidis à **-271°C**, plus froid que l'espace intersidéral

**Coût (construction)** : 3 milliards d'Euros pour l'accélérateur,

~**400 millions d'Euros** pour ATLAS et CMS

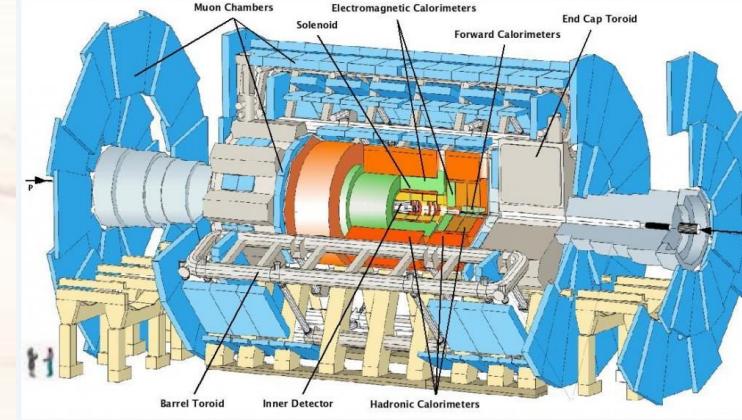
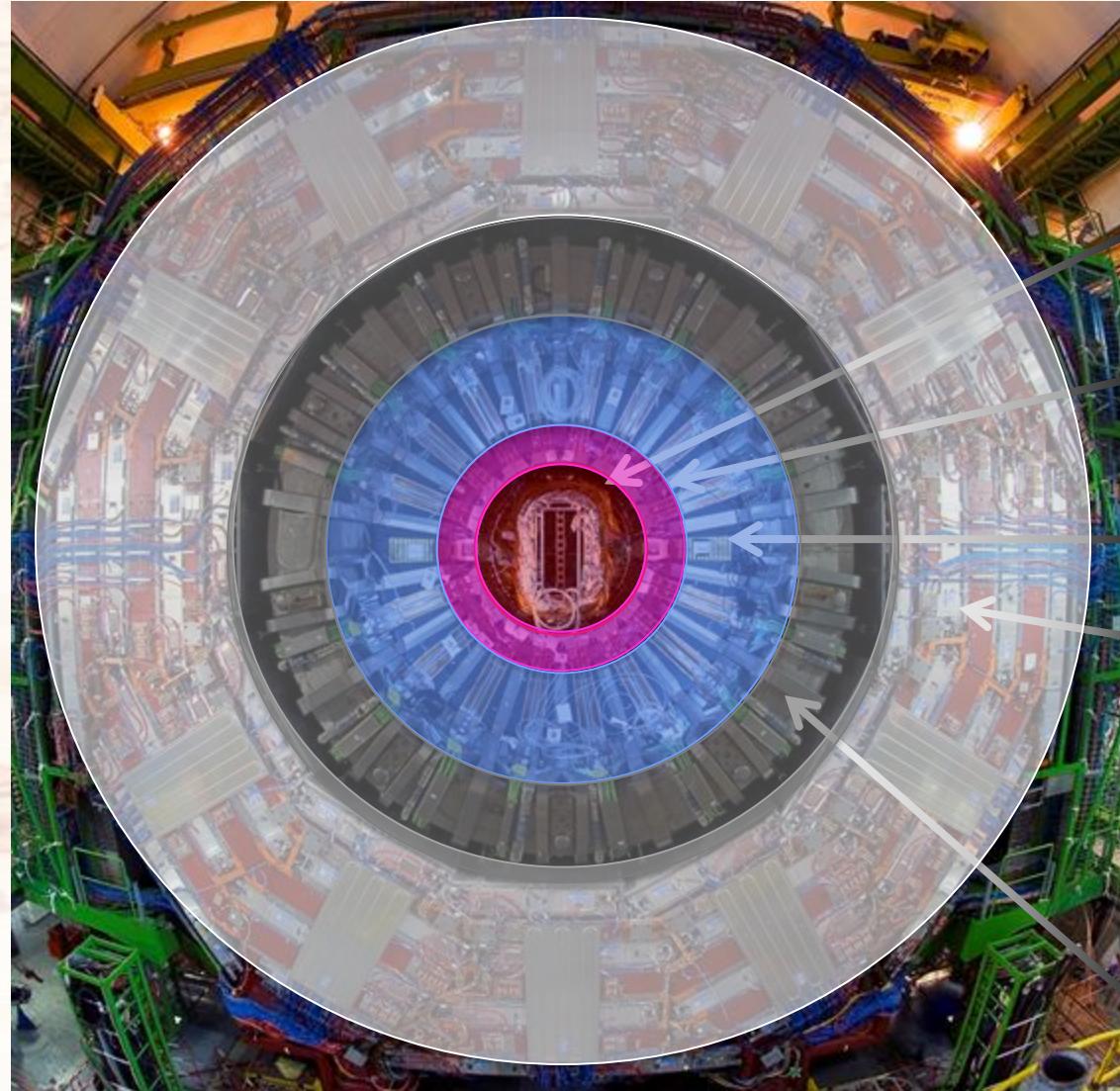




# Le pistage, ou comment savoir qu'une particule est passée par là...

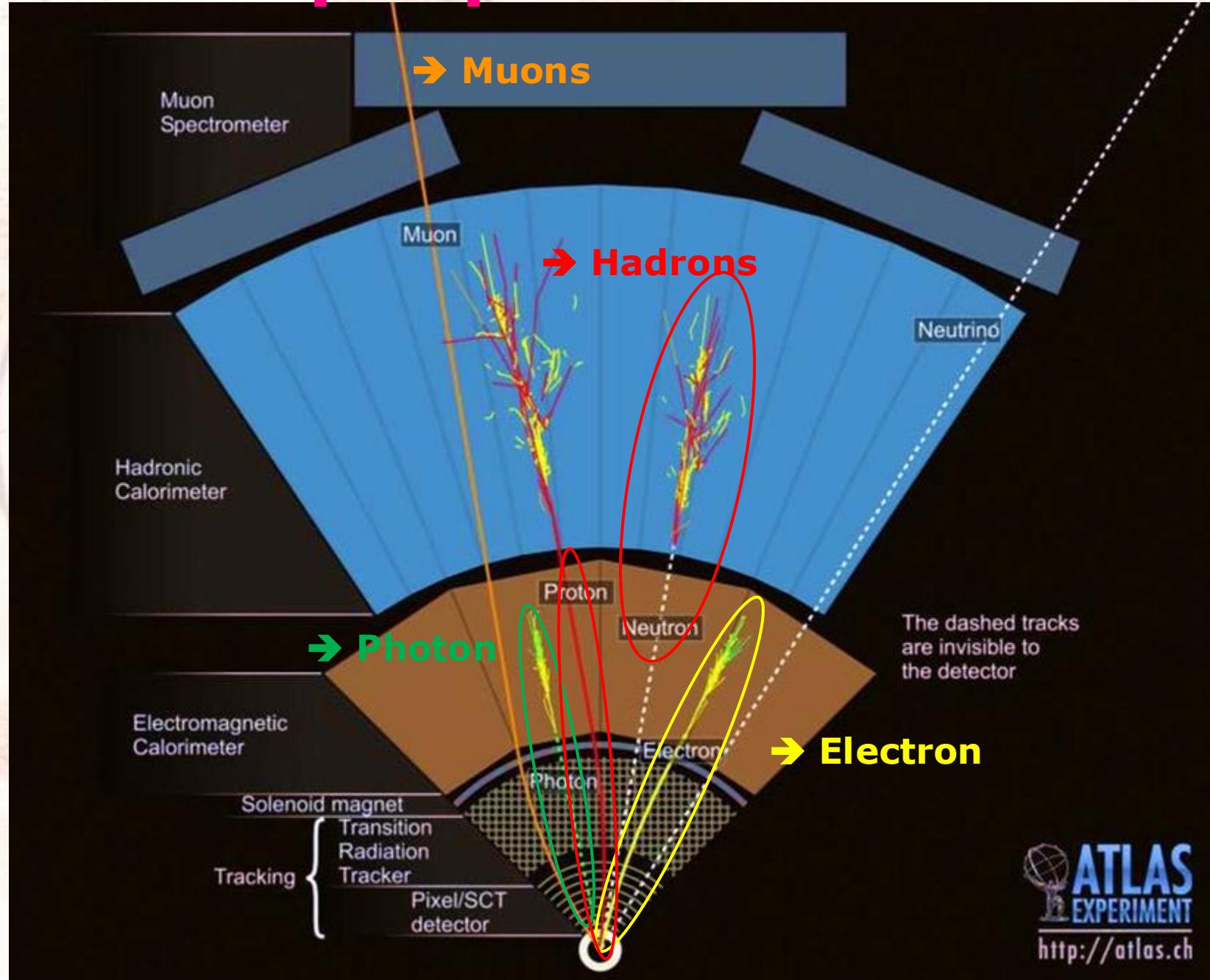


# Un détecteur “classique”



- **Trajectographe**
- **Calorimètre électromagnétique**
- **Calorimètre hadronique**
- **Chambres à muons**
- **Toutes les sous-parties sont plongées dans un champ magnétique**

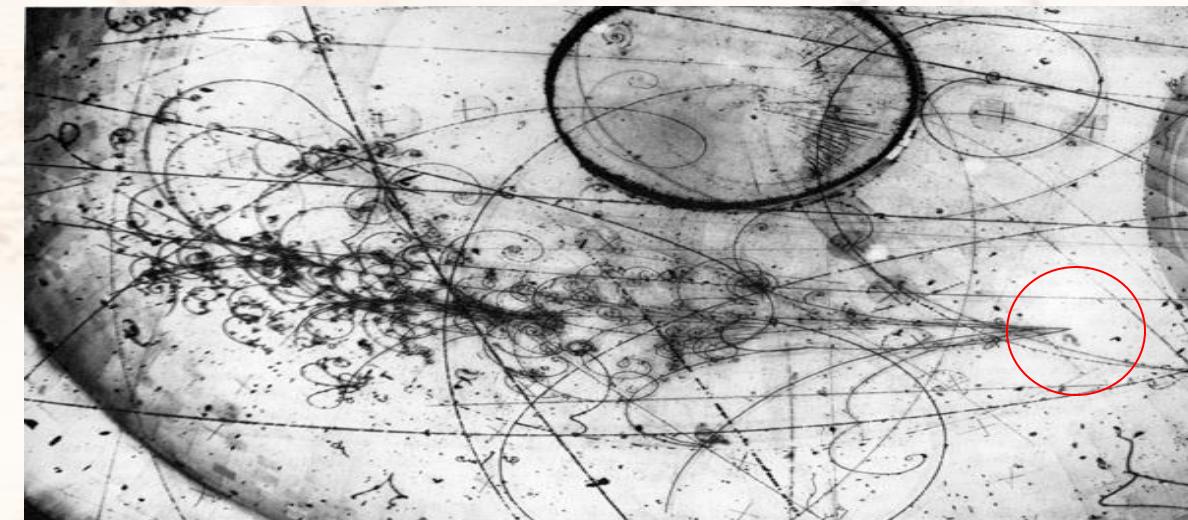
# Un peu plus réellement...



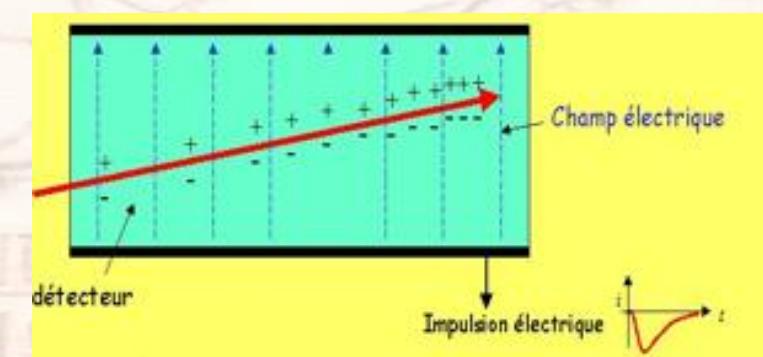
# Trajectographes : déetectent toutes les particules chargées

En plongeant le détecteur dans un champ magnétique, la trajectoire de la particule est courbée information (impulsion, masse, charge)

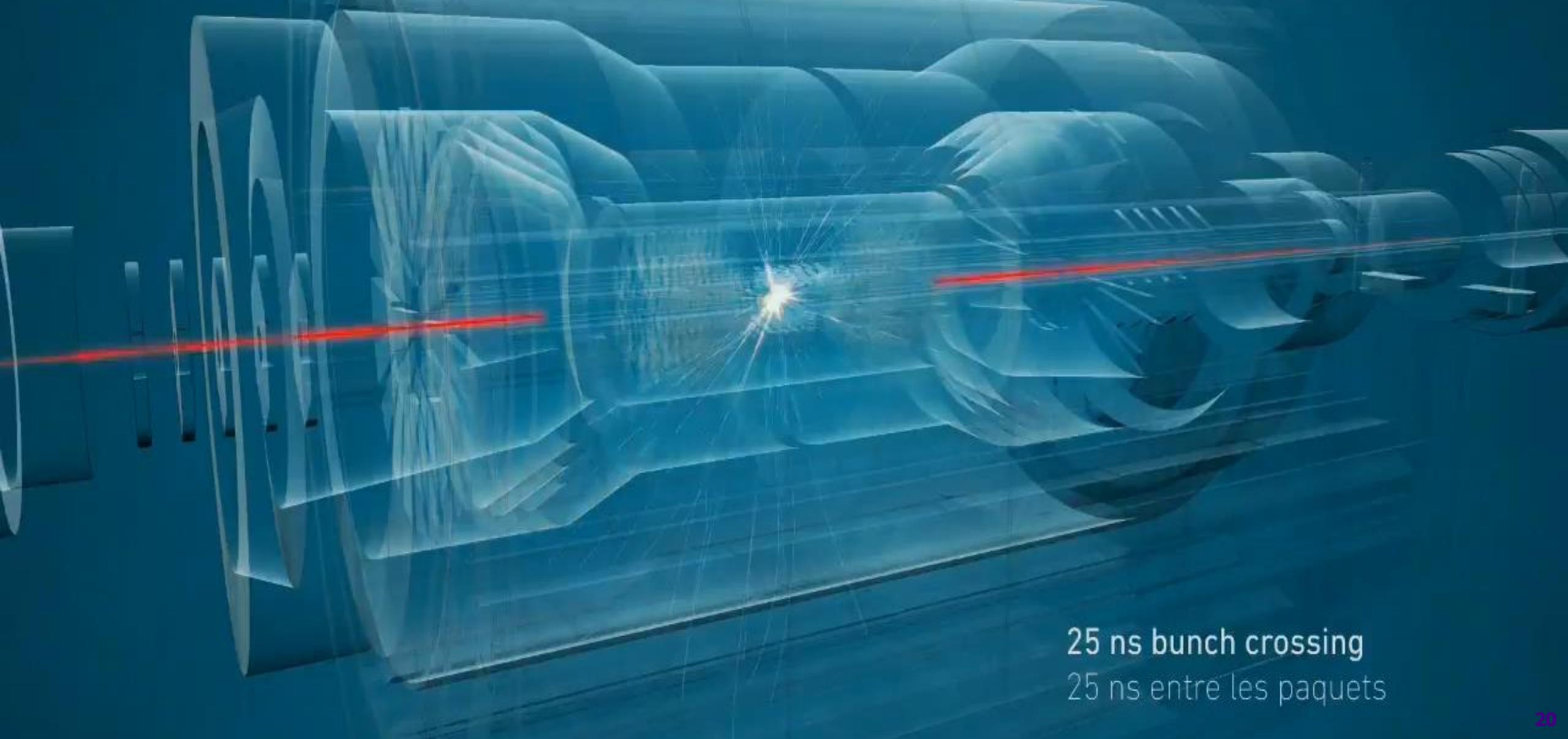
Un outil merveilleux :  
les chambres à bulles



La méthode moderne :  
le détecteur électronique: Ionisation des  
atomes du milieu par des particules chargées  
Récupération des charges créées



# Des millions de collisions



25 ns bunch crossing  
25 ns entre les paquets



irfu

**iJC** Lab  
Irène Joliot-Curie

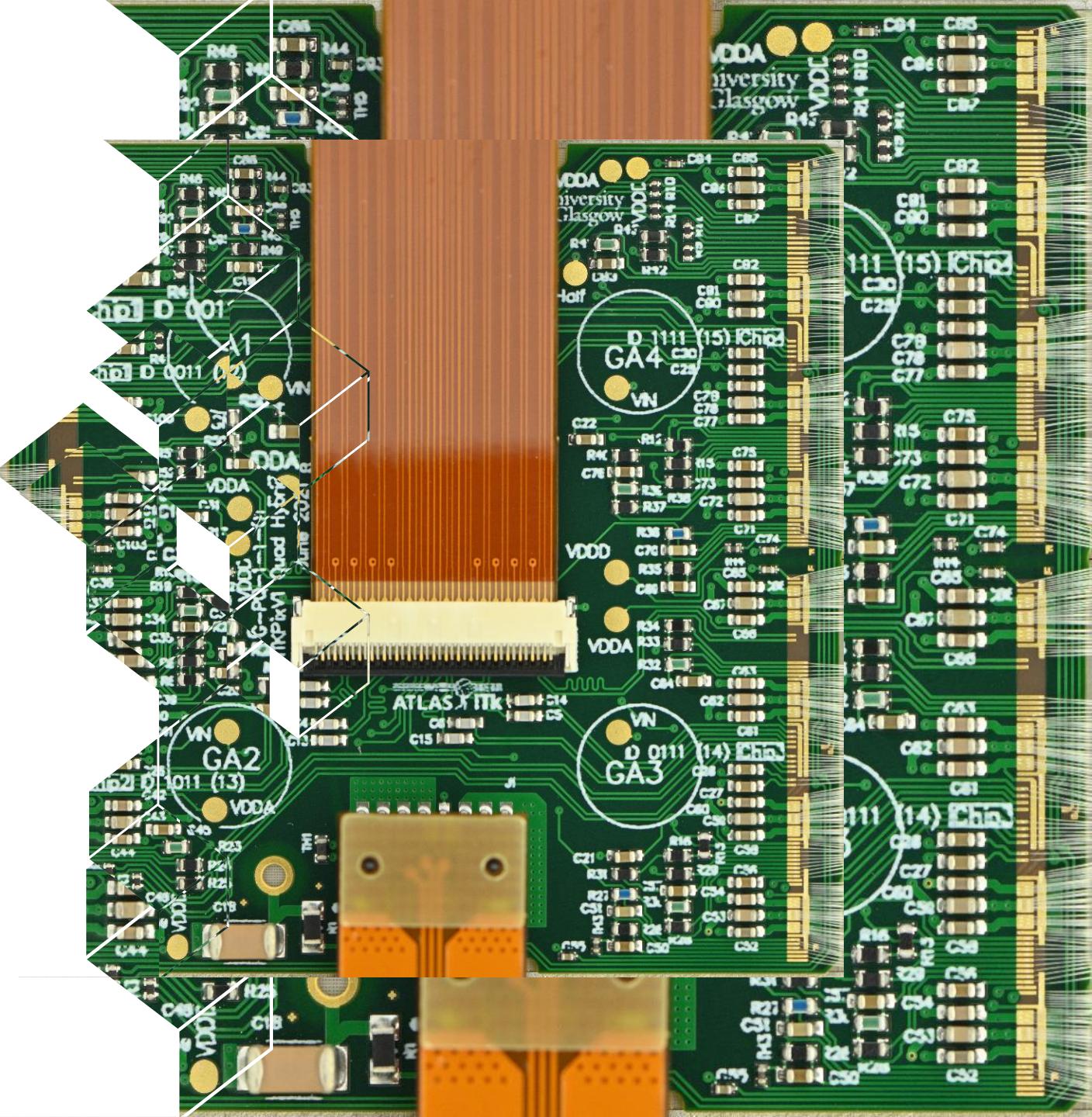
LPNHE  
PARIS

ITK

## Paris Cluster workshop

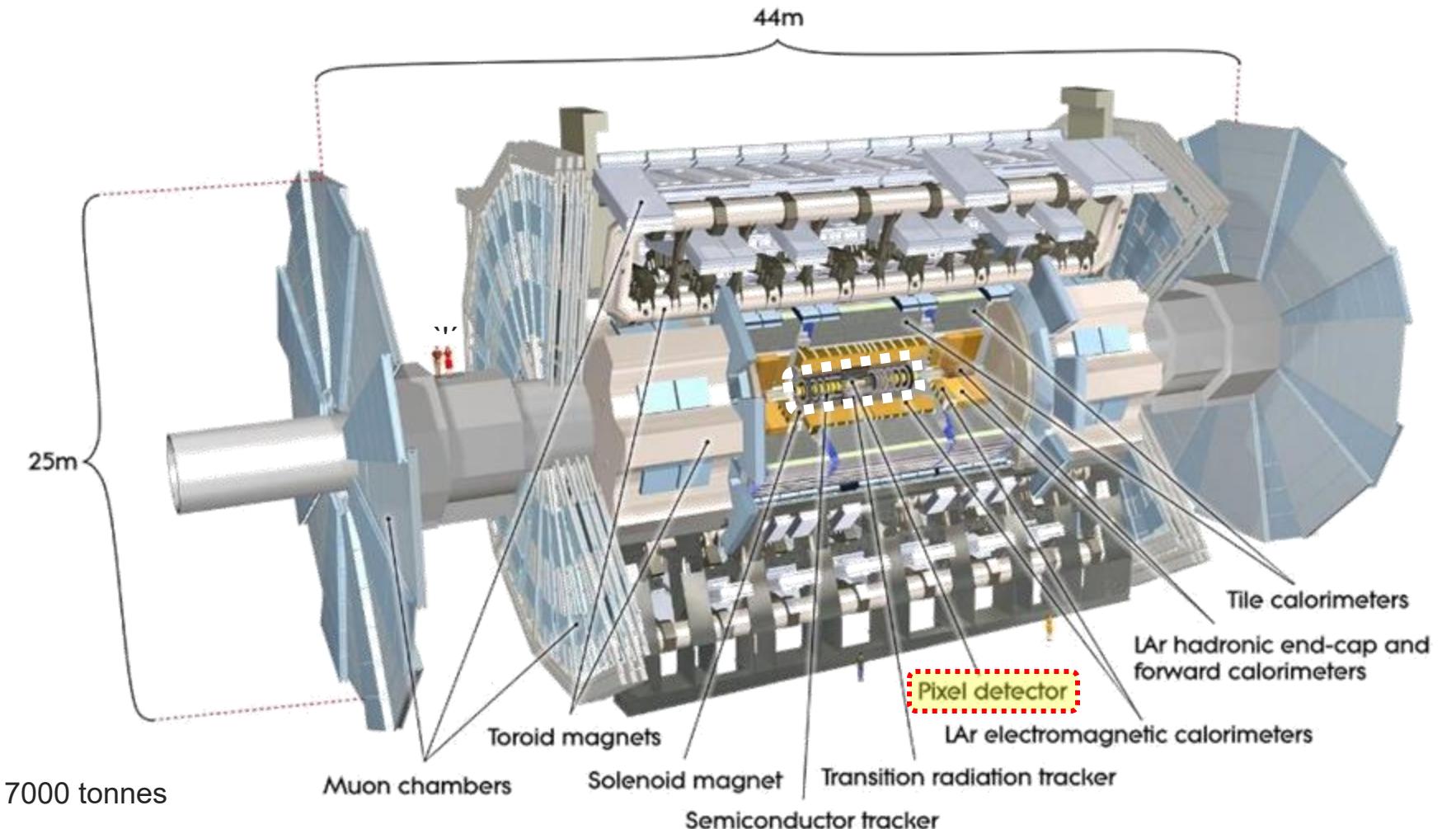
2025-11-27

ATLAS ITk





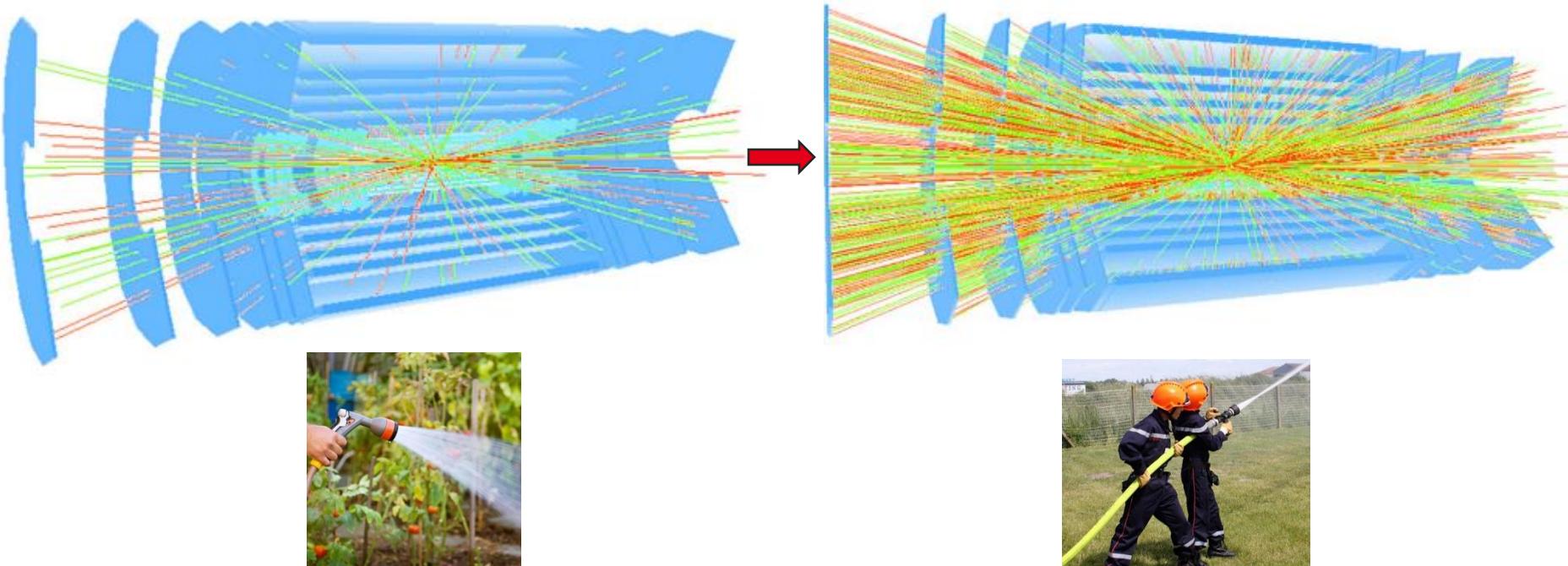
# ATLAS





# Amélioration de l'accélérateur – Conséquences pour ATLAS

25 → 200 INTERACTIONS PAR CROISEMENT DE FAISCEAUX



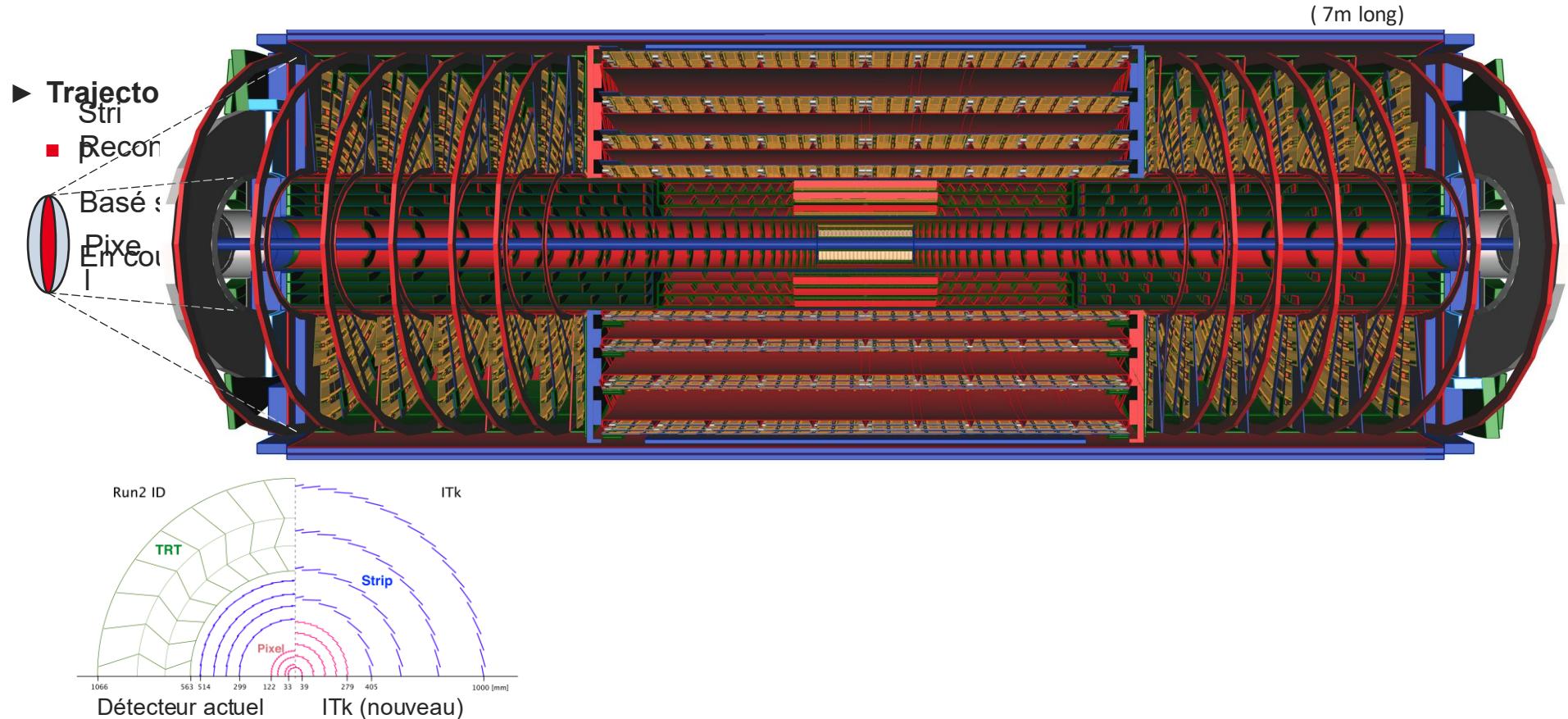
Remplacement nécessaire de certains détecteurs (qui autrement seraient 'aveugles' 90% du temps)



# ■ ATLAS Inner Tracker (ITk)



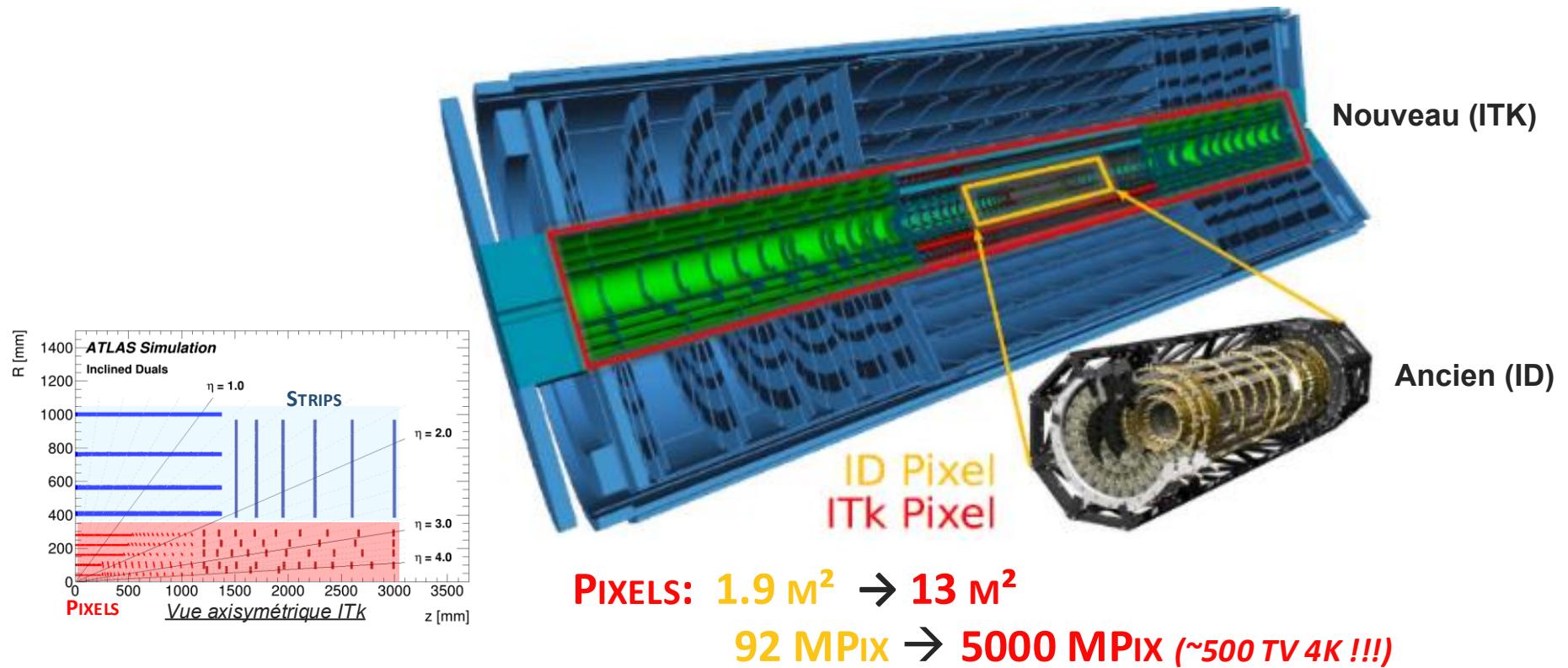
# ATLAS Inner Tracker (ITk)





# ATLAS ITk - Un sacré facteur d'échelle !!!

STRIPS:  $60 \text{ m}^2 \rightarrow 160 \text{ m}^2$  (50 MILLIONS DE VOIES)

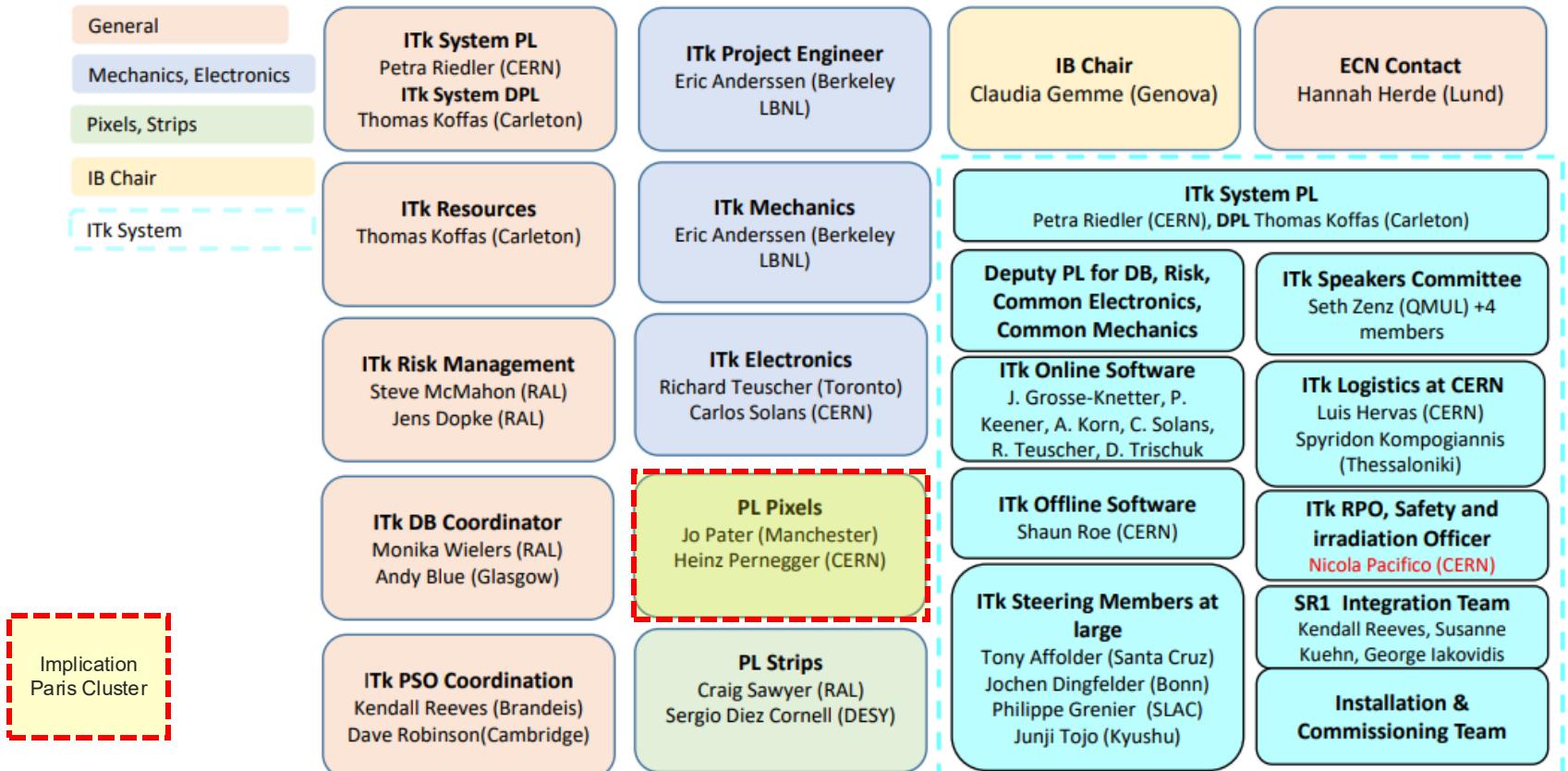




# **Une collaboration à la mesure de l'enjeu**

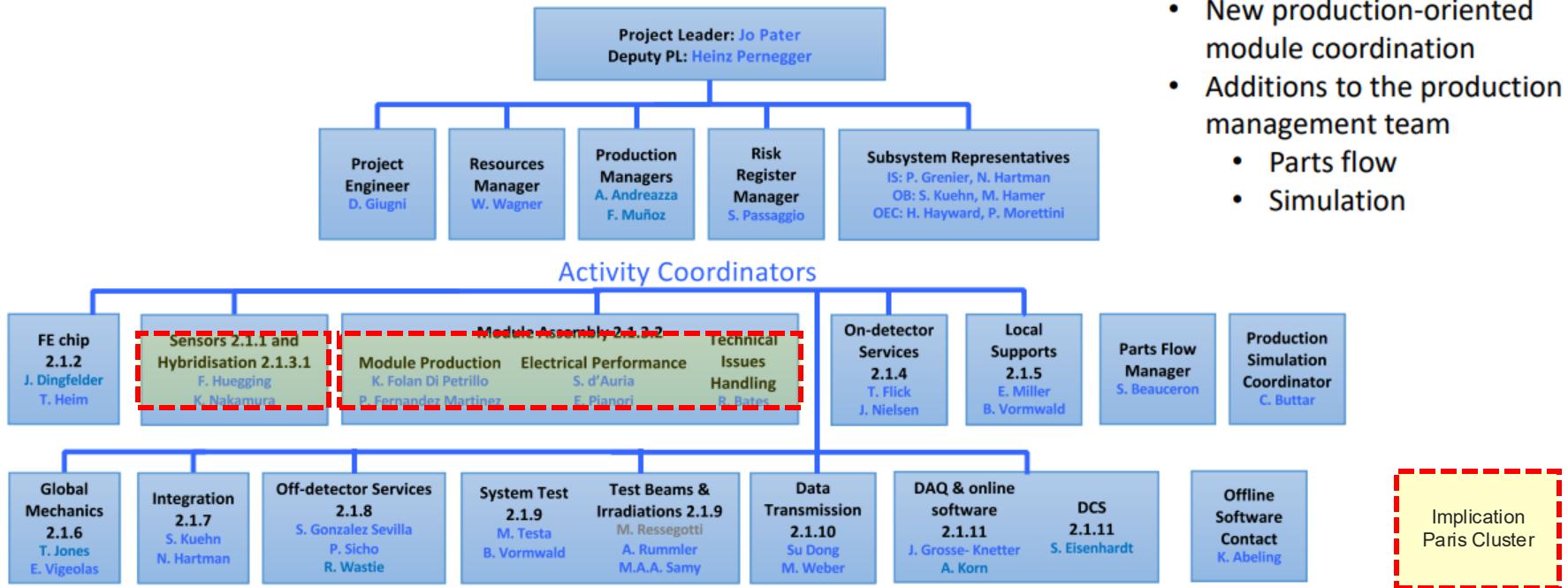


# ATLAS-ITk – Organisation (April 1, 2025)





# ATLAS-ITK – Pixel - Organisation





# ATLAS-ITK – Pixel - Collaboration

► 15 countries (without Russia) >> 62 labs

ATLAS COLLABORATION			CERN-MoU-2019-227	
ANNEX 1: List of Upgrade Institutes and Contact Persons				
Institutes by Funding Agency	Institute Short Name	Institute Representative		
<b>CERN</b>				
European Organization for Nuclear Research (CERN), Geneva	CERN	C. Rembser		
Czech Republic				
Institute of Physics of the Czech Academy of Sciences, Prague	Prague AS	A. Kupco		
Czech Technical University in Prague, Prague	Prague CTU	Z. Hubacek		
France CEA				
IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette	Saclay CEA	C. Guyot		
France IN2P3				
LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy	Annecy LAPP	E. Sauvan		
LPSI, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble	Grenoble LPSC	B. Trocmé		
CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille	Marseille CPPM	M. Barbero		
LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay	Orsay LAL	L. Iacoboudi-Fayard		
LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris	Paris LPNHE	D. Lacour		
Germany BMBF				
Physikalisch-Technische Institut, Universität Bonn, Bonn Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund	Bonn	N. Wermes		
	Dortmund	K. Kroeninger		
II. Physikalisches Institut				
Georg-August-Universität Göttingen, Göttingen	Göttingen	A. Quadt		
Department of Physics, Universität Siegen, Siegen	Siegen	P. Buchholz		
Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal	Wuppertal	W. Wagner		
Germany MPI				
Max-Planck-Institut für Physik ( Werner-Heisenberg-Institut), München	Munich MPI	S. Bethke		
Hong Kong				
Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong	Hong Kong CUHK	L. Castillo		
Department of Physics, University of Hong Kong, Hong Kong	Hong Kong HKU	Y. Tu		
Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong	HKUST	K. Prokofiev		
Italy				
INFN Sezione di Bologna; INFN Bologna and Università di Bologna, Dipartimento di Fisica	Bologna	B. Giacobbe		
INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Dipartimento di Fisica, Università della Calabria, Rende	Cosenza	M. Schioppa		
INFN e Laboratori Nazionali di Frascati, Frascati	Frascati	M. Antonelli		
INFN Sezione di Genova; Dipartimento di Fisica, Università di Genova, Genova	Genova	S. Passaggio		
INFN Sezione di Lecce; Dipartimento di Matematica e Fisica, Università del Salento, Lecce	Lecce	E. Gorini		
INFN Sezione di Milano; Dipartimento di Fisica, Università di Milano, Milano	Milano	G. Tartarelli		
INFN-TIFPA; Università degli Studi di Trento, Trento	Trento	G. F. Dalla Betta		

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ATLAS COLLABORATION			CERN-Mou-2019-227	
ATLAS COLLABORATION			CERN-Mou-2019-227	
INFN Gruppo Collegato di Udine, Sezione di Trieste;	Udine	M. Cobal		
Dipartimento Politecnico di Ingegneria e Architettura,				
Università di Udine, Udine				
Japan				
Research Center for Advanced Particle Physics and Kyoto University of Education, Kyoto	Kyushu	K. Kawagoe		
Department of Physics, Kyushu University, Fukuoka	Kyoto UE	R. Takashima		
Graduate School of Science, Osaka University, Osaka	Osaka	H. Nanjo		
Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo	Ochanomizu	T. Kono		
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo	Tokyo MU	T. Kumita		
Department of Physics, Tokyo Institute of Technology, Tokyo	Tokyo Tech	O. Jinnochi		
KEK, High Energy Accelerator Research Organization, Tsukuba	Waseda	K. Yonita		
Division of Physics and Tomonaga Center for the History of the University, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba	KEK Tsukuba	K. Hanagaki		
Eugene OR		F. Ukegawa		
Department of Physics, University of Bergen, Bergen	Bergen	B. Stugu		
Department of Physics, University of Oslo, Oslo	Oslo	F. Ould-Saada		
Russia				
National Research Nuclear University MEPhI, Moscow	Moscow MEPhI	A. Romaniouk		
P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow	Moscow RIAN	K. Zhukov		
Constantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", NPPI, St. Petersburg	Petersburg NPI	O. Fedin		
Slovenia				
Department of Experimental Particle Physics, Jozef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana	Ljubljana	M. Mikuz		
Spain				
Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona	Barcelona	M. Bosman		
Switzerland				
Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern	Bern	M. Weber		
Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève	Geneva	G. Iacobucci		
UK				
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, as part of United Kingdom, Research and Innovation	RAL	S. Haywood		
SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh	Edinburgh	P. Clark		
SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow	Glasgow	C. Buttar		
Physics Department, Lancaster University, Lancaster	Lancaster	R. Jones		
School of Physics and Astronomy, University of Liverpool, Liverpool	Liverpool	M. D'Onofrio		
School of Physics and Astronomy, Queen Mary University of London, London	London QMUL	E. Rizvi		
Department of Physics and Astronomy, University College London, London	London UC	N. Konstantinidis		
School of Physics and Astronomy, University of Manchester, Manchester	Manchester	A. Oh		
Department of Physics, Oxford University, Oxford	Oxford	I. Shipsey		
US DOE				

2019-10-29

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ATLAS COLLABORATION			CERN-Mou-2019-227	
Department of Physics, University of Massachusetts, Amherst MA	Massachusetts	S. Willocq		
High Energy Physics Division, Argonne National Laboratory, Argonne	Argonne	J. Zhang		
Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA	Berkeley LBNL	K. Einsweiler		
Ohio State University, Columbus OH	Ohio SU	K. Gan		
Physics Department, Southern Methodist University, Dallas TX	Dallas SMU	R. Stroynowski		
Center for High Energy Physics, University of Oregon, Eugene OR	Oregon	J. Brau		
Department of Physics, University of Wisconsin, Madison WI	Wisconsin	S. Wu		
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK	Oklahoma	P. Skubic		
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA	Santa Cruz UC	A. Seiden		
Department of Physics, University of Washington, Seattle WA	Seattle Washington	H. Lubatti		
SLAC National Accelerator Laboratory, Stanford CA	SLAC	D. Su		
Department of Physics, Oklahoma State University, Stillwater OK	Oklahoma SU	F. Rizatdinova		

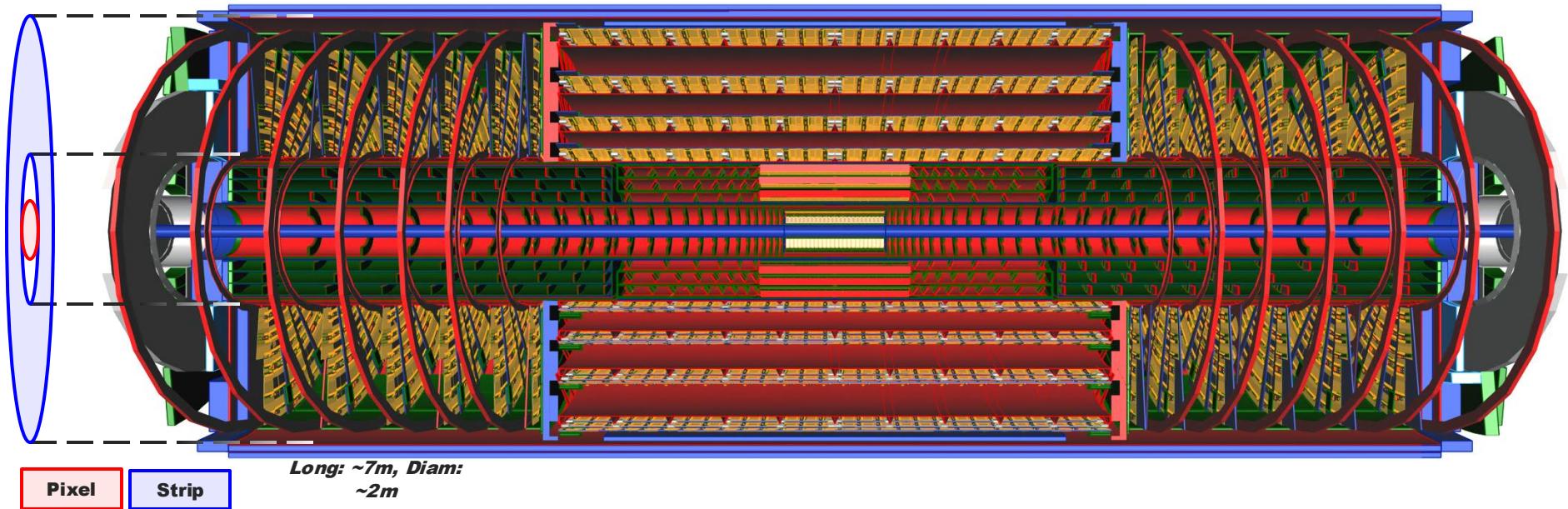


## ■ Outer Barrel

Où est-ce?

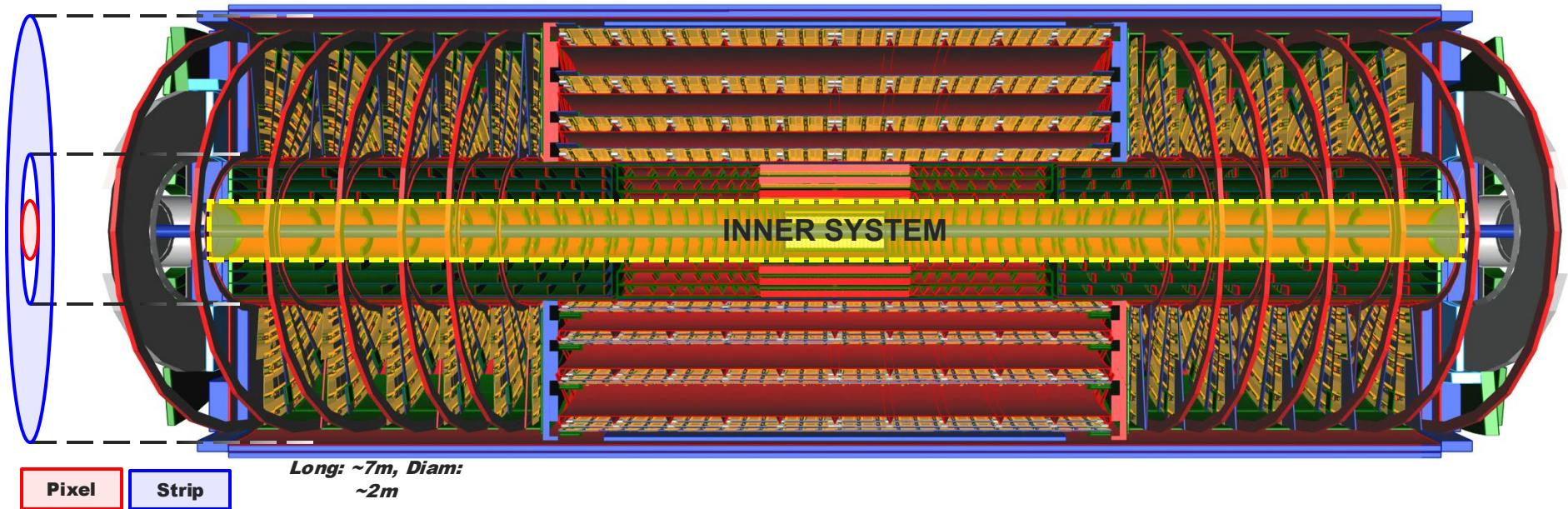


# Trajectographe ITk



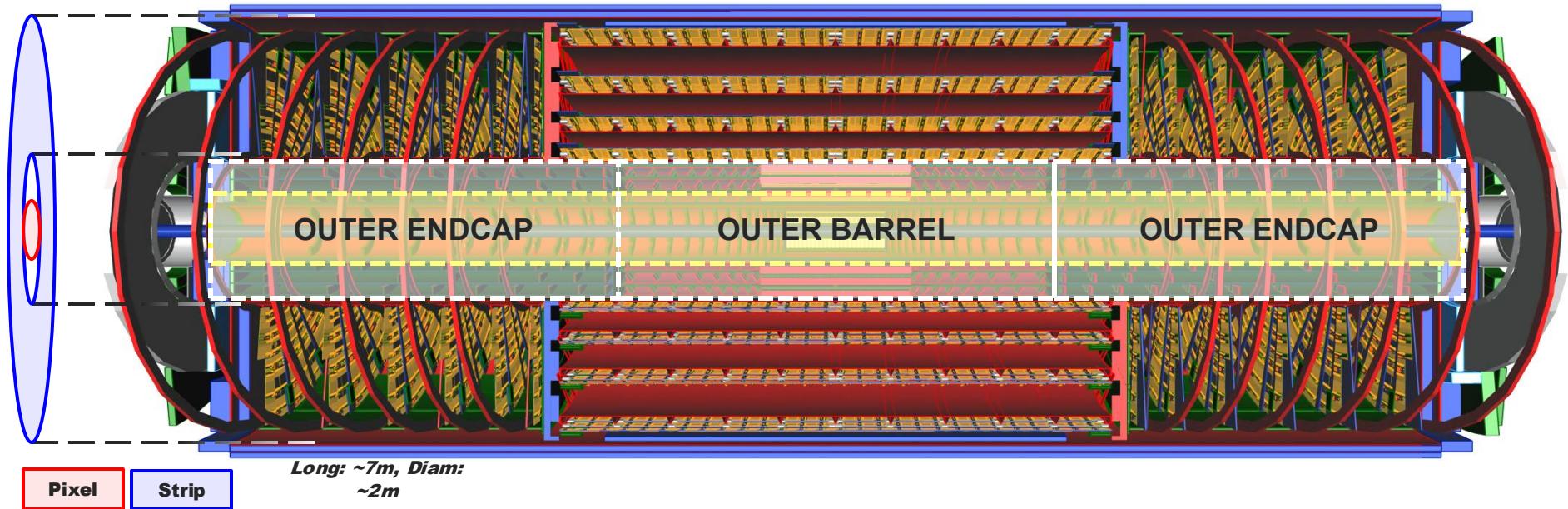


# Inner system





# Barrel & Endcaps



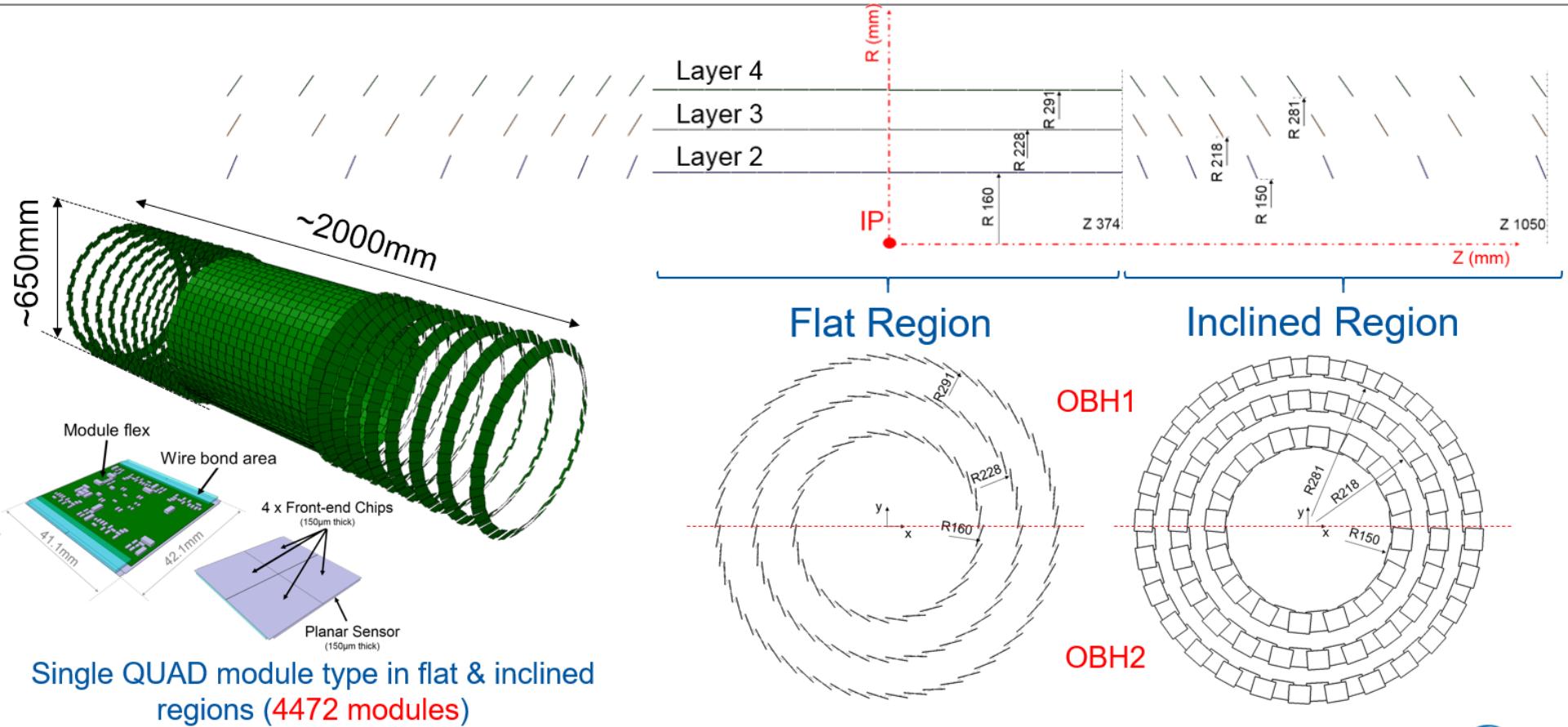


# ■ Outer Barrel

Composition générale



# Outer Barrel: Layout

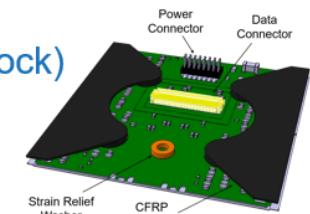
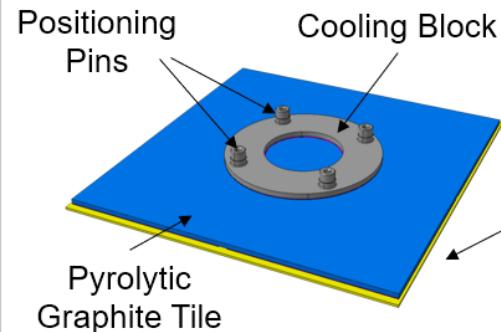




# Outer Barrel: Local Supports

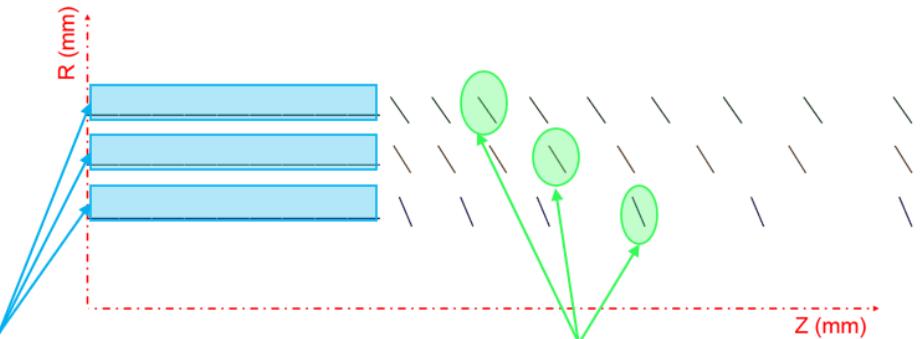
## Module Cells

(Module + PG Tile + Cooling Block)

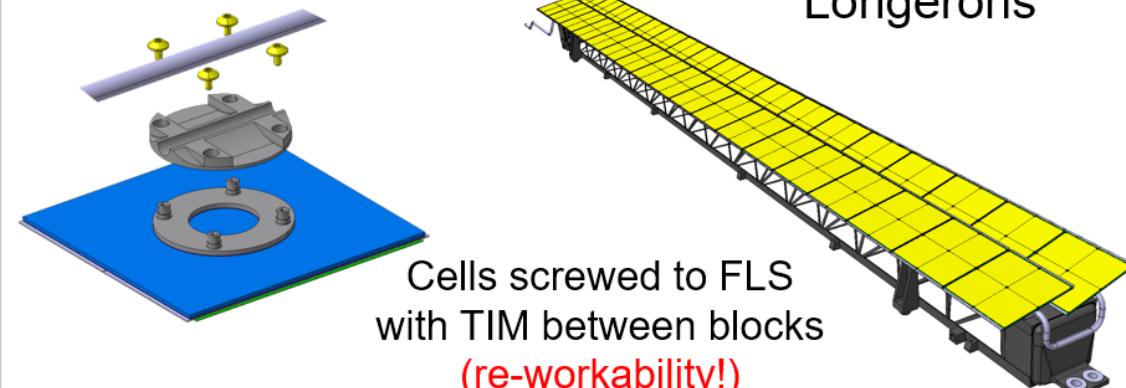


## Functional Local Supports

(Base Blocks + Cooling Pipe + CFRP Support Structure)



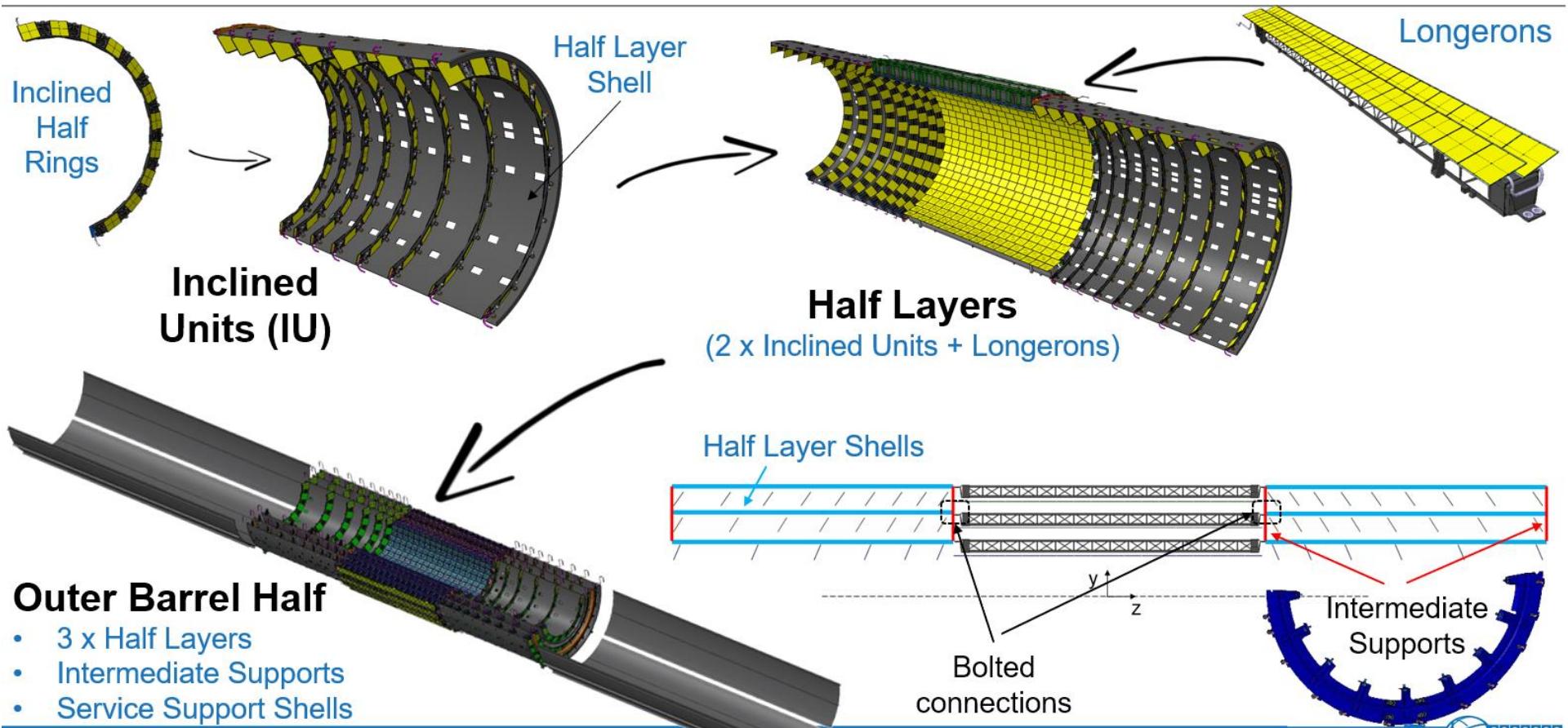
Longerons



Inclined Half-Rings



# Outer Barrel: Global Support Structures

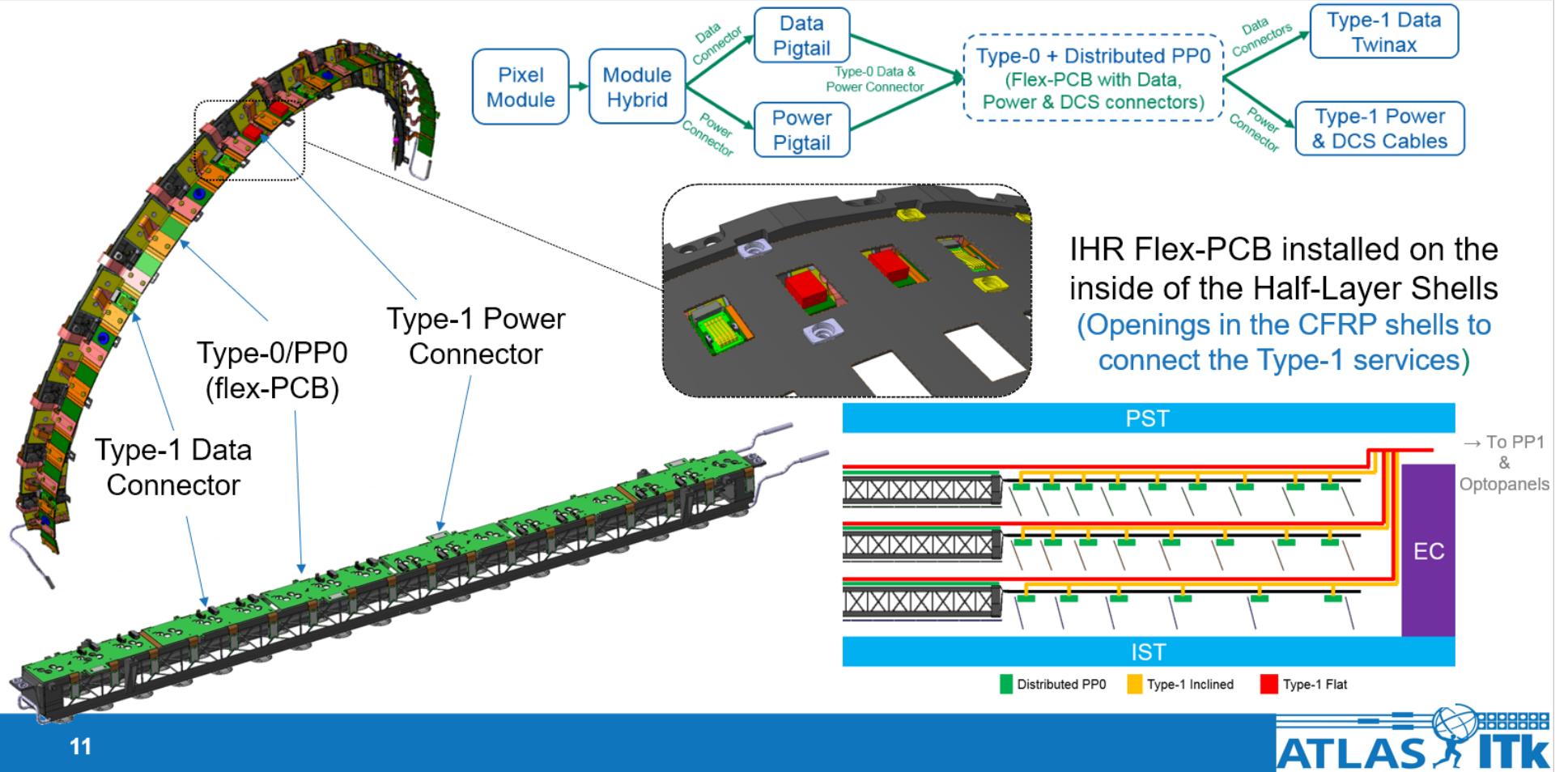


9

ATLAS ITk

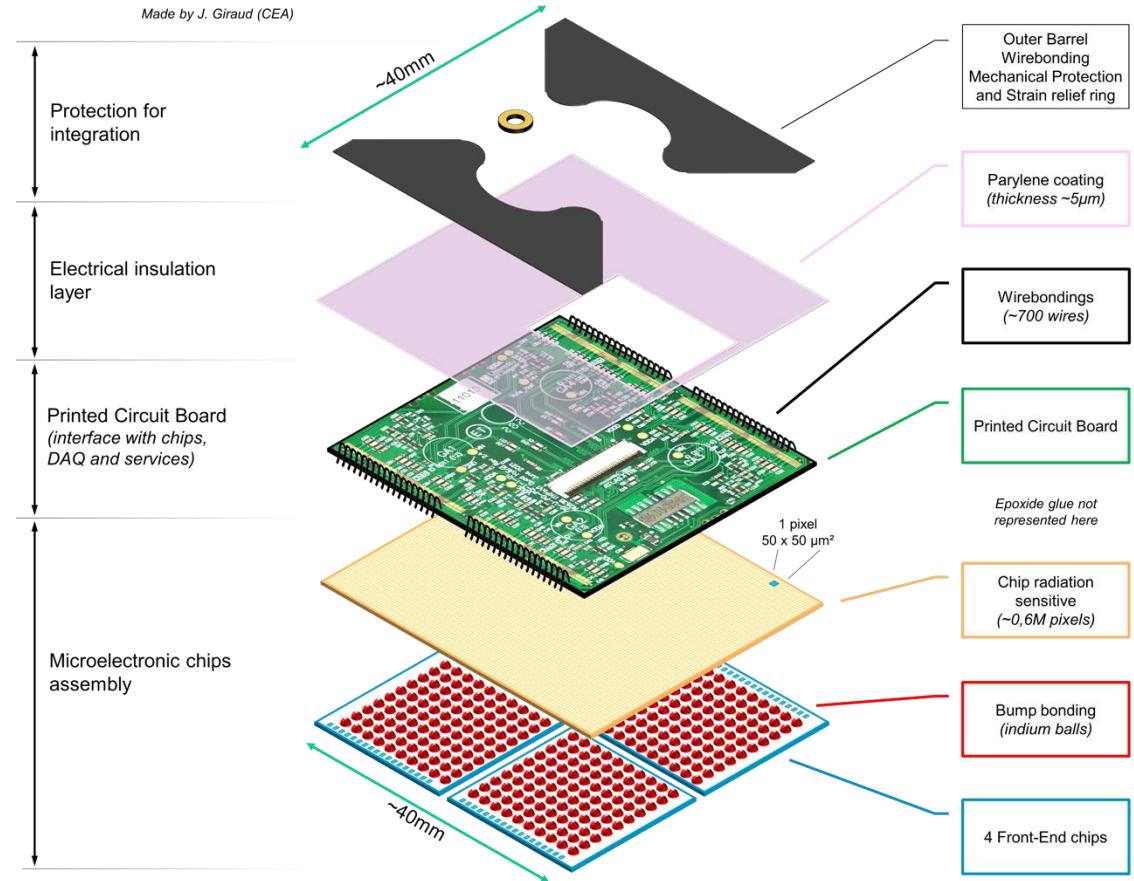


# Outer Barrel: Service Scheme





# Qu'est-ce qu'un module Pixel Quadruplet?

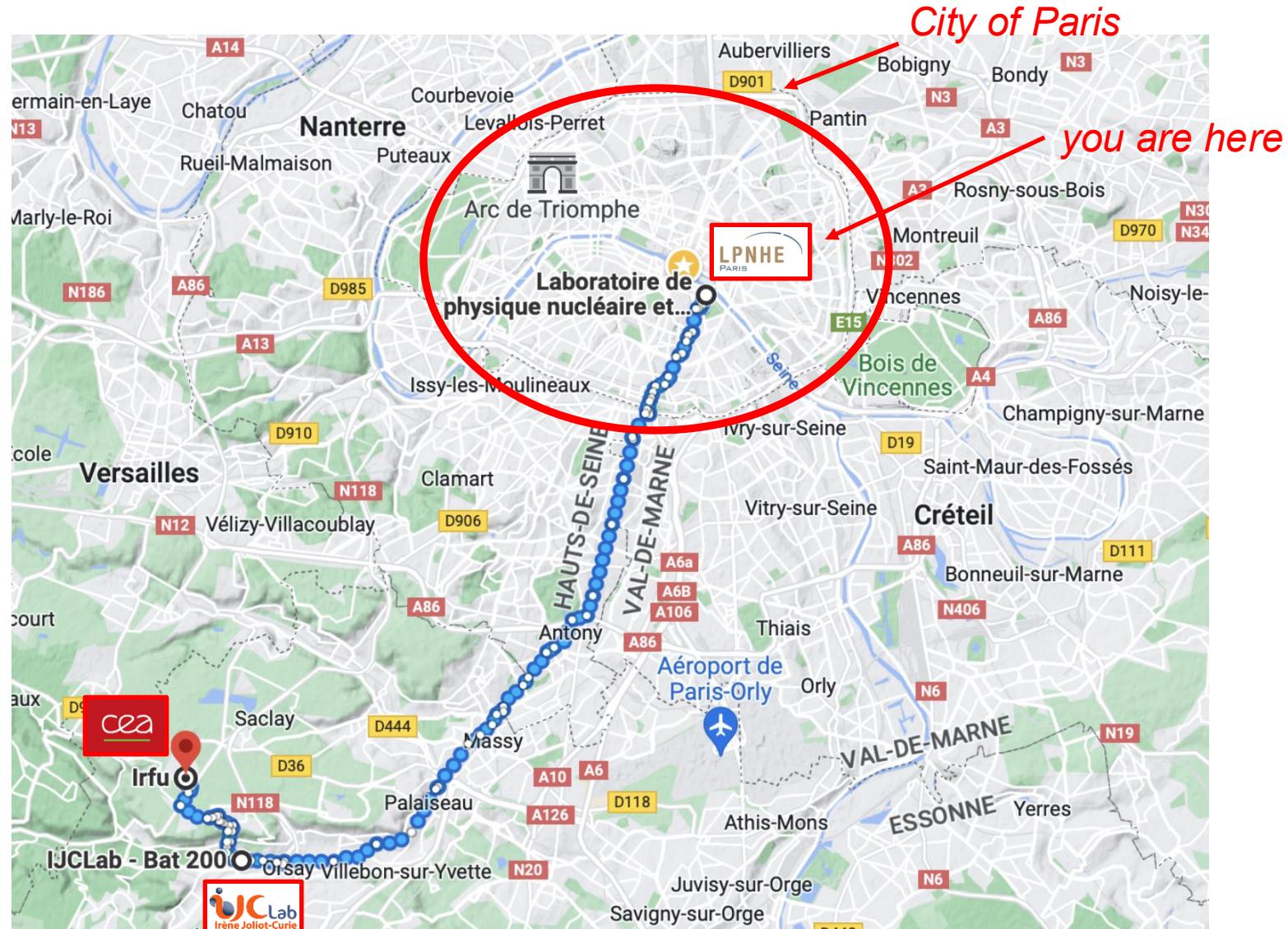


# Paris cluster



*Dimitris Varouchas (IJCLab)*

- **Paris cluster:** CEA-Irfu, IJCLab, LPNHE
- 3 ATLAS laboratories that work on ITk and are in Paris region
  - LPNHE – IJCLab: 25 km
  - LPNHE – CEA-Irfu: 29 km
  - IJCLab – CEA-Irfu: 5 km
- We work all together to deliver a big fraction of **good** Pixel-ITk modules to future ITk detector
- **Pixel module assembly and module testing cluster**
- Assembly + testing → production

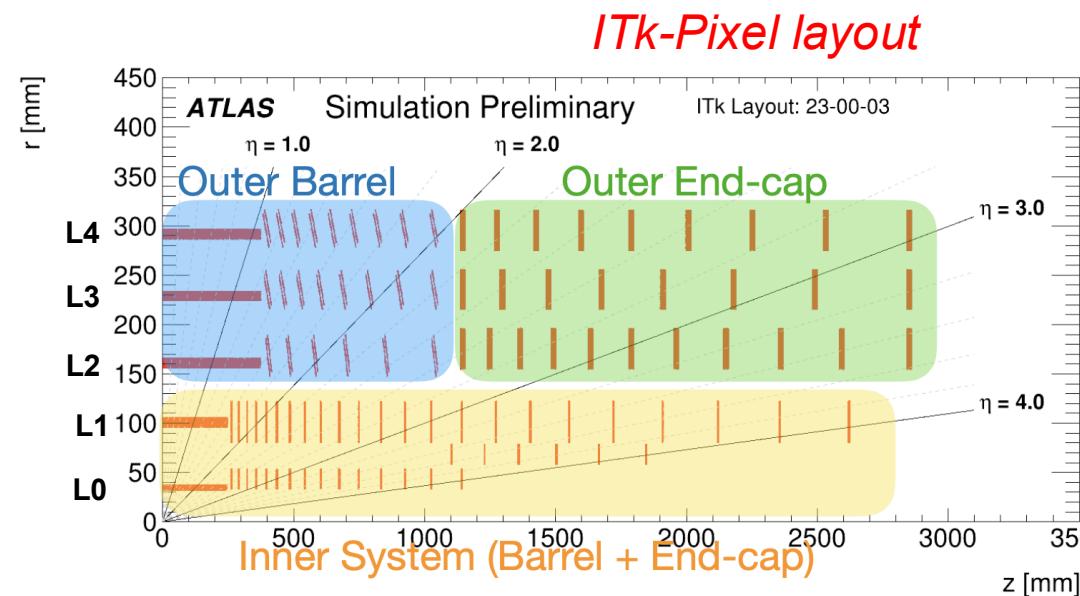


# Paris cluster deliverables

- Paris cluster is an ITk-Pixel modules production site
- We are committed (MoU) in building 33% of the ITk-Pixel outer barrel (OB) modules
  - IN2P3 (IJCLab, LPNHE) 25%, CEA-Irfu 8%
  - In practise we share the tasks as evenly as possible among the 3 sites

[MoU](#)

- Outer barrel has **~4.5k installed good modules**
- Paris cluster share is 1/3 of outer barrel  $\Rightarrow$  **1.5k good modules**
- Taking into account the module production and loading/integration yield ( $\sim 1.5$ )
- **Paris cluster deliverable** including yield: **~2200 modules**

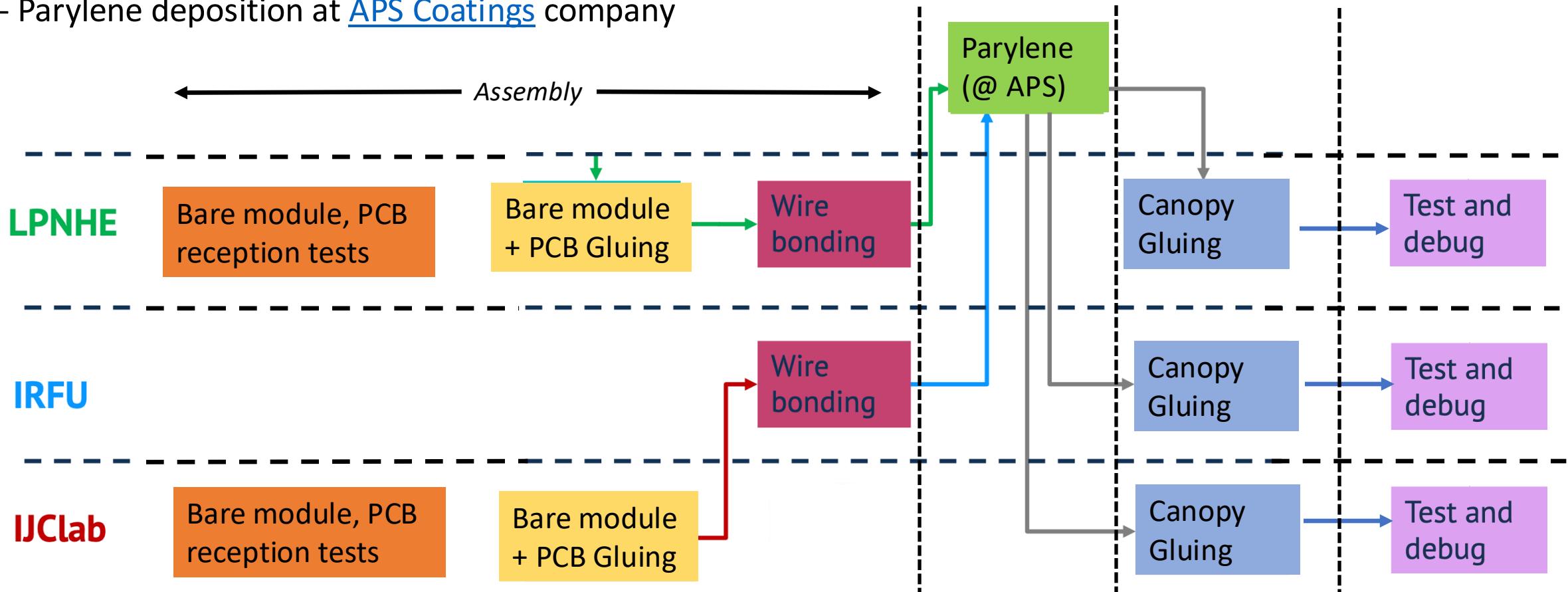


ATLAS COLLABORATION		Outer Barrel module assembly	End-Cap module assembly	Inner System module assembly
		2.1.3.2.2	2.1.3.2.2	2.1.3.2.2
CERN		18.0%		
Czech Republic				
France IN2P3	25.0%			
France CEA	8.0%			
Germany BMBF	29.0%			
Germany MPI				6.0%
Hong Kong				
Italy				
Japan	20.0%			
Netherlands				
Norway				
Russia				
Spain				
Switzerland				
United Kingdom				
USA DOE	48.5%			43.0%
<b>Total</b>	<b>100%</b>			<b>100%</b>

- In absolute numbers
  - We are building the **largest share of modules in OB**
  - Together with Japan (though they externalise), the **largest share of modules in ITk-Pixel**

# Paris cluster production diagram

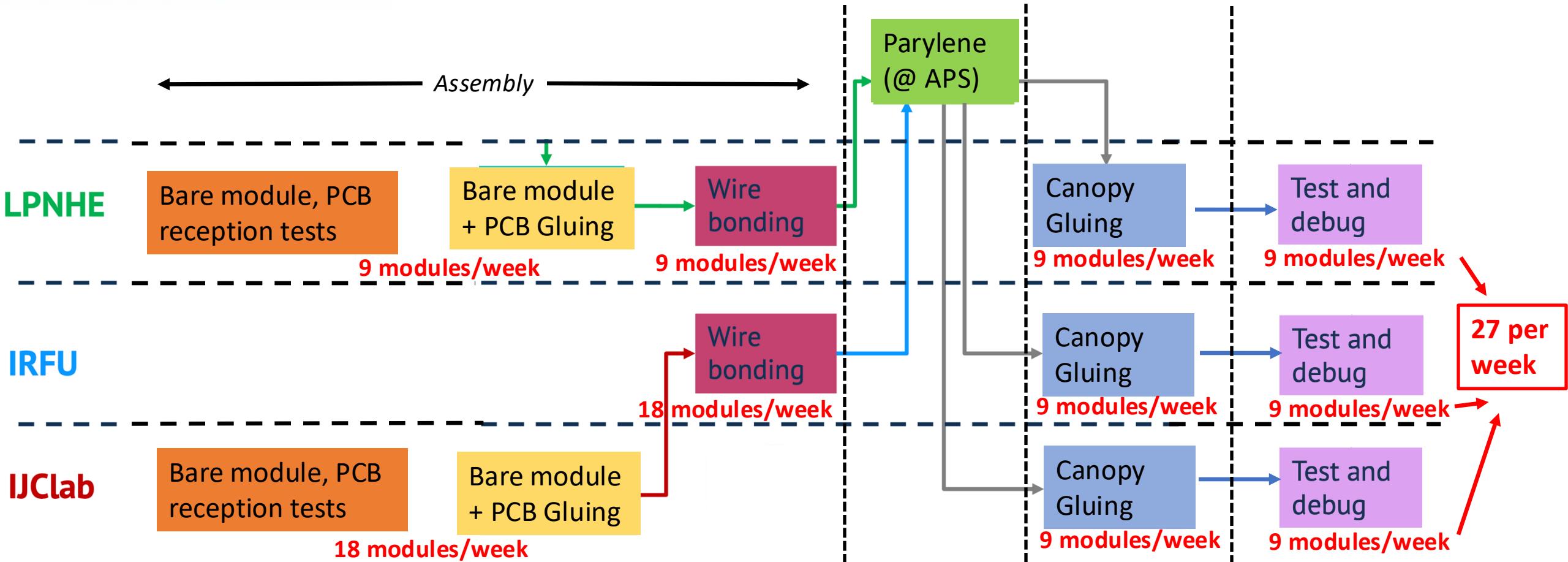
- We maintain **two assembly lines**
  - A. IJCLab – IRFU
  - B. LPNHE
- And **three canopy gluing and testing lines**
- Parylene deposition at [APS Coatings](#) company



# \*Nominal\* production plan

- Production period: **2 years**, assuming nominally 3 months off per year → **80 working weeks** in total
- Production started at T2 of 2025, but we are far from nominal production rate at the moment because of lack of good quality module components
- With the goal of having to produce **2200 modules** in Paris cluster
  - Nominal production rate target: **27 modules /week**

# Paris cluster \*nominal\* production rates



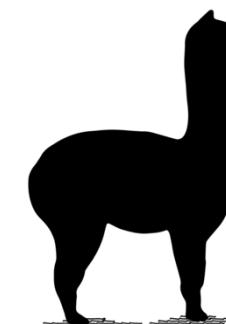
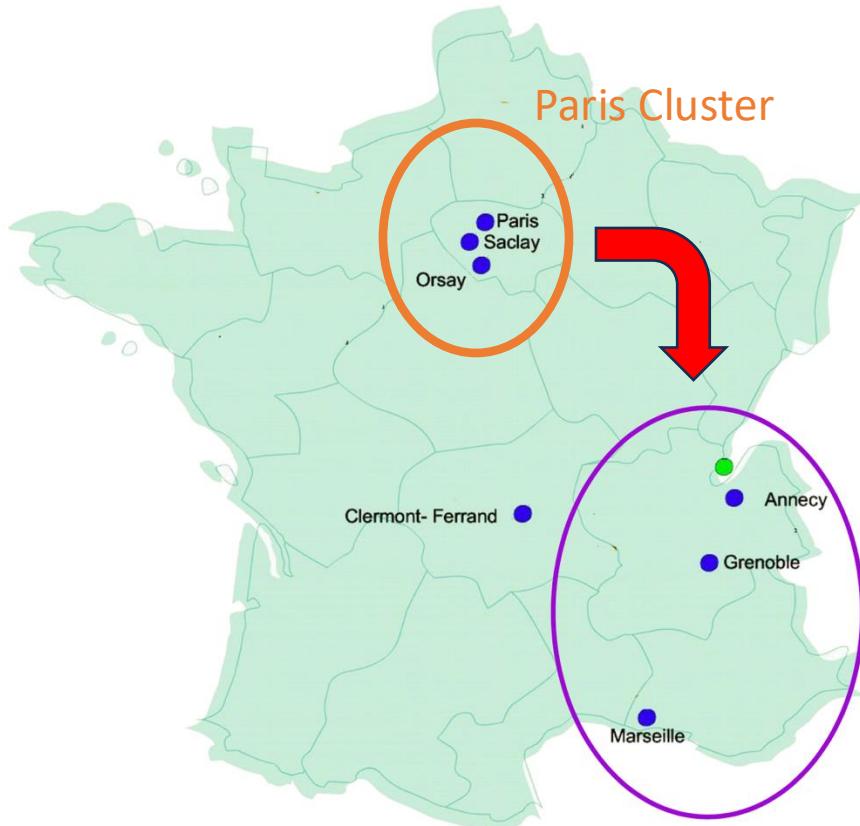
## Nominal share

- LPNHE: 1/3 at all steps
- IJCLAb: 2/3 up to BM+PCB gluing, then 1/3 of canopies gluing and 1/3 of testing
- CEA-Irfu: 2/3 for wire bonding, then 1/3 of canopies gluing and 1/3 of testing

- Redundancy at every step
- 2 or 3 sites working **@ every step**

# Modules following Paris production

- Modules will be shipped to ALPACA cluster: CPPM (Marseille), LPSC (Grenoble), LAPP (Annecy)
- These 3 other French groups will perform the **cell loading** and integration to **local supports** of our modules

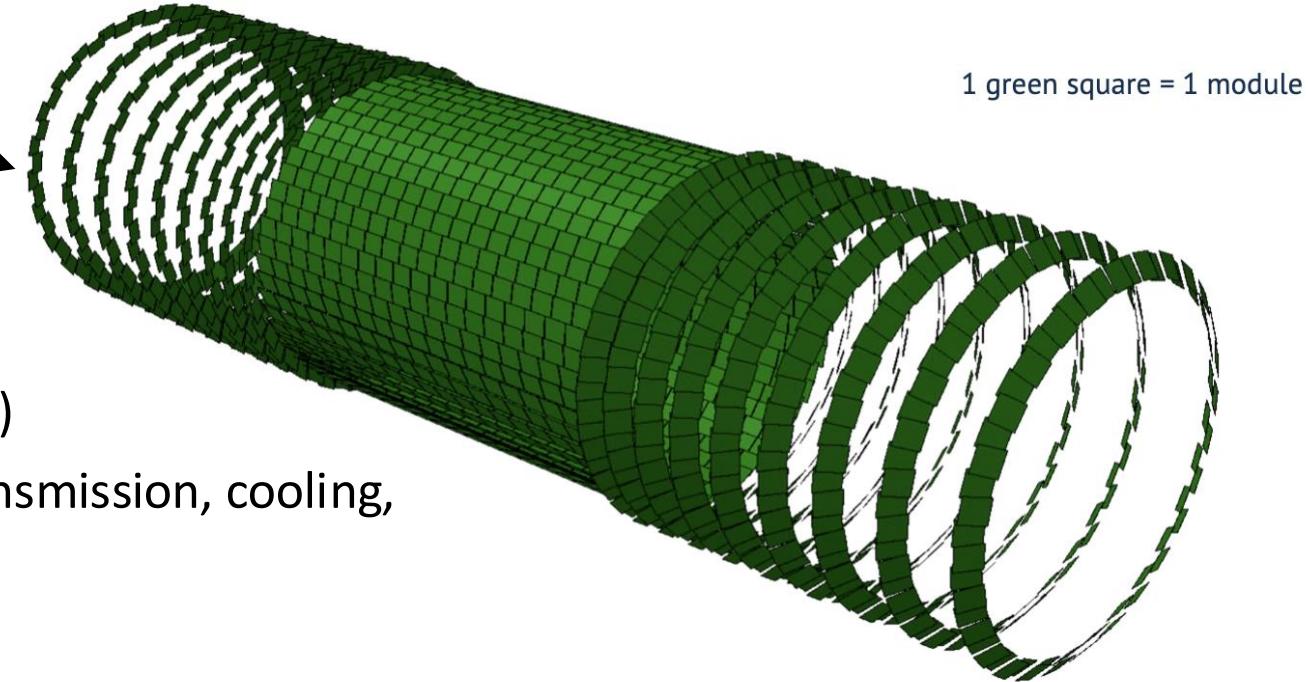


Alpaca  
Cluster

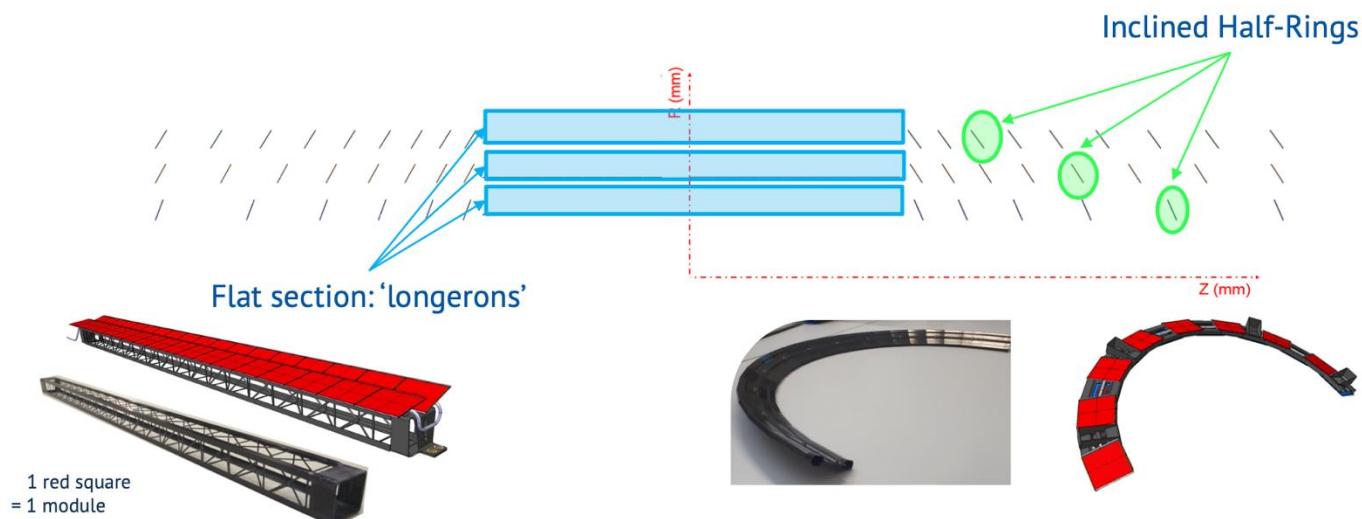


# OB mechanics: local supports

- This is how one layer of an ideal detector would like
- Only composed by our modules, floating in the air... ☺
- In practise, the modules should be mounted on supports (local supports)
- And all the services (power, data transmission, cooling, sensors) have to be installed

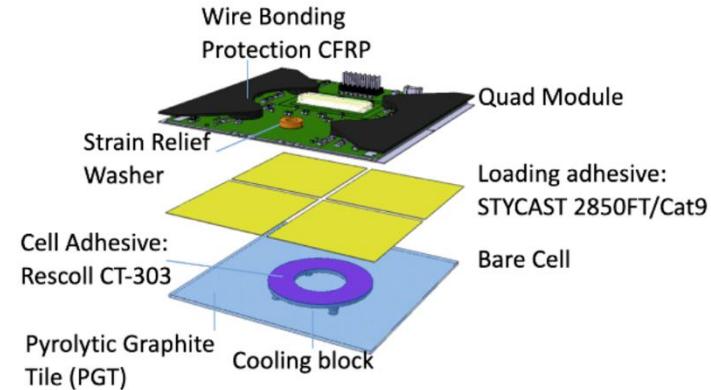
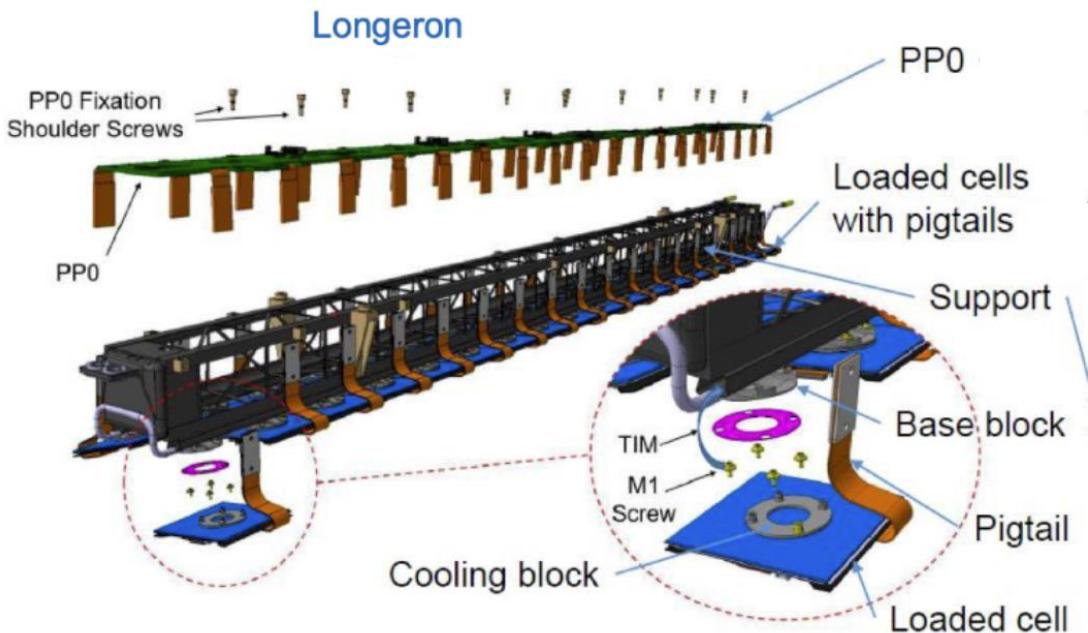


- Depending on the location of the module in the outer barrel, the local supports can be
  - Longerons (central part of the detector)
  - Half-rings for modules installed with an inclination



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- **Cell loading:** a structure with a cooling block (**cell**) is glued on the backside of the module (FE chip side); this explains why this side of the module has to be masked during parylene

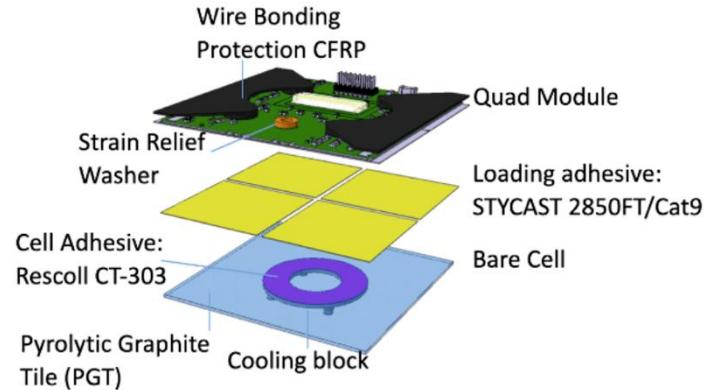
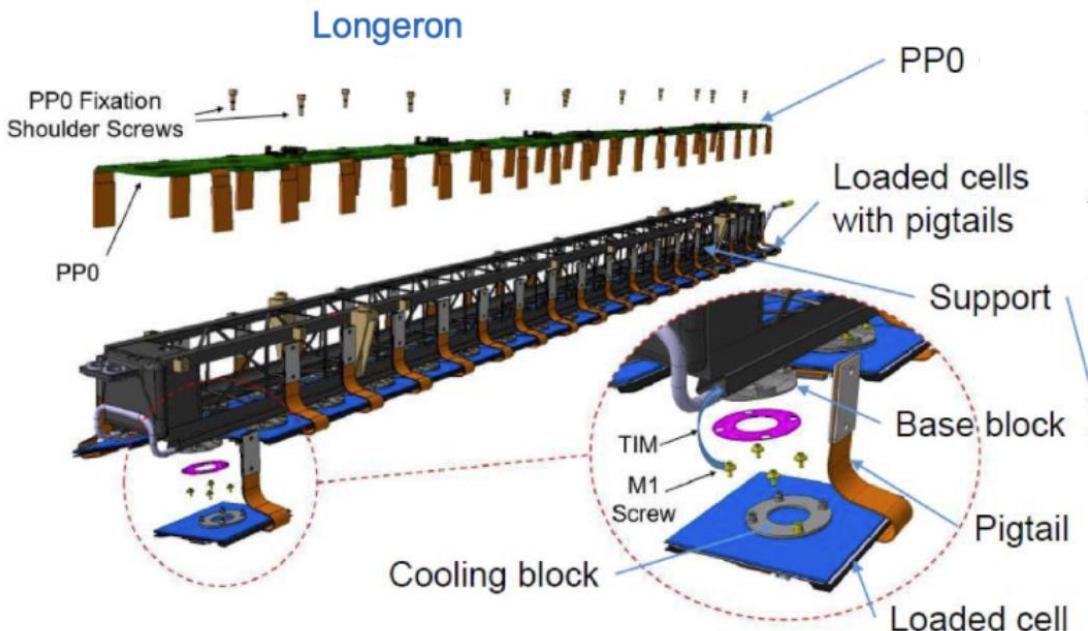


## Integration

- Loaded cells are attached to **local supports**
- Type-0 (PP0) services are installed
  - on-detector service directly attached to the pixel modules
  - Power services, Data transmission, Cooling interfaces, etc

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- After integration
  - Loaded local supports are tested
  - And finally they are shipped to CERN for the installation in the detector
- Still, long journey and tests for our modules after they leave Paris cluster

# Paris cluster, a few facts

- Undergone two joint IN2P3/IRFU reviews (2021 and 2024)
- ~ 30 FTEs in all 3 sites; **big fraction is IT**
- Weekly meetings: <https://indico.cern.ch/category/9094/>
- A pretty active mattermost group: <https://mattermost.web.cern.ch/itkpariscluster/>
- Exchange of expertise, we try to share the work as much as possible
- Common cluster Local (hosted at IJCLab) Data Base, where all members of cluster have access
- Common reporting in ITk Pixel meetings as much as possible, speakers rotation is being in place
- Numerous transfers of components, tools, modules, common material, etc. among the 3 sites over the years

# Paris cluster organization chart

## Paris Cluster extended committee

Max 12 pers

Giovanni, Stéphanie, Francesco  
Dimitris, Lydia,  
Matthias, Julien, Fred

## Paris Cluster Risk Manager

(8 months rotating)

Julien + Dimitris

(among the extended committee)

## Logistics

resp+ 1 ou 2 deputies  
Stéphanie + Fred Déliot  
(APS budget: Dimitris,  
APS technique: Giovanni)

## Production Report

(verify yield + reporting)

Matthias + Zirui

## Database infrastructure

Fred Derue + Rei

## Database software

Francesco

## Assembly Line Managers

- Metrology
- Gluing
- Wirebond
- Parylene masking
- Wirebond Protection
- Yield

Francesco, Julien, Dimitris/Nicolas

## Testing Managers

- Tests analysis
  - X-rays
  - Yield
- David, Matthias, Lydia/Dmytro

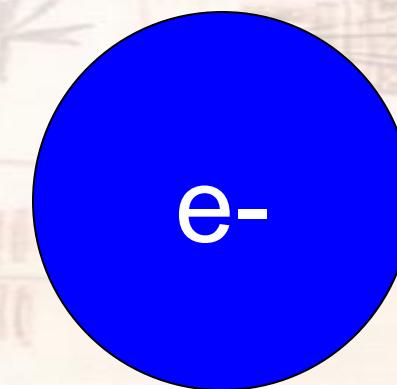
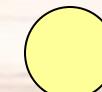
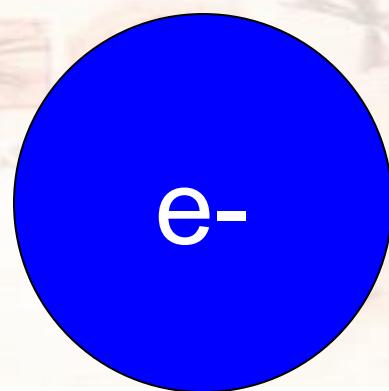
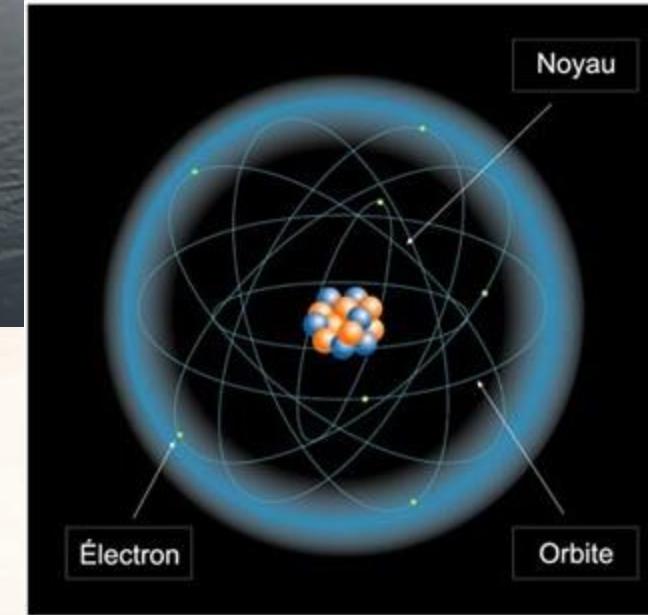


# L'interaction électromagnétique

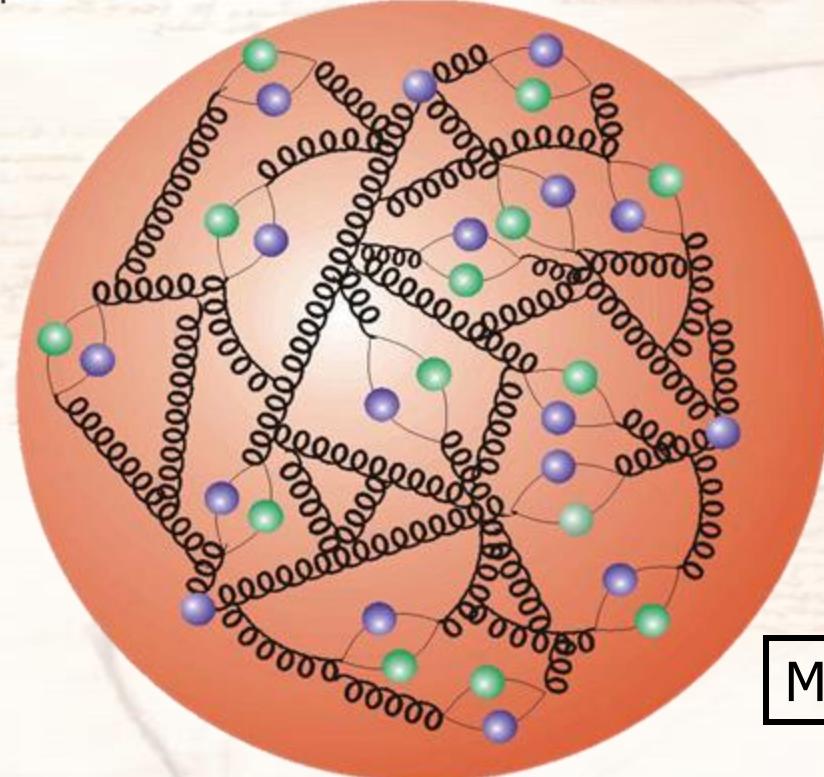
Responsable des phénomènes **électriques et magnétiques** :  
aimantation, lumière,  
cohésion des atomes,...

Répulsion entre objets de charges électriques identiques (attraction si charges opposées)

Médiateur (=boson) :  
**photon**



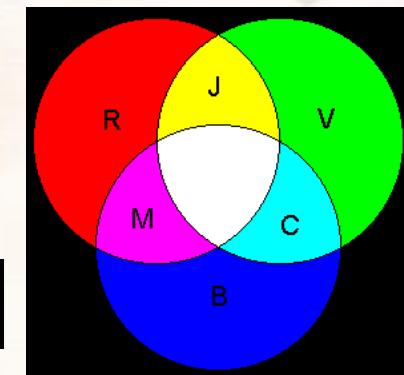
# L'interaction forte



Médiateurs: **gluons**

En plus de la charge électrique,  
les quarks portent une charge de couleur:  
**Bleu vert rouge**

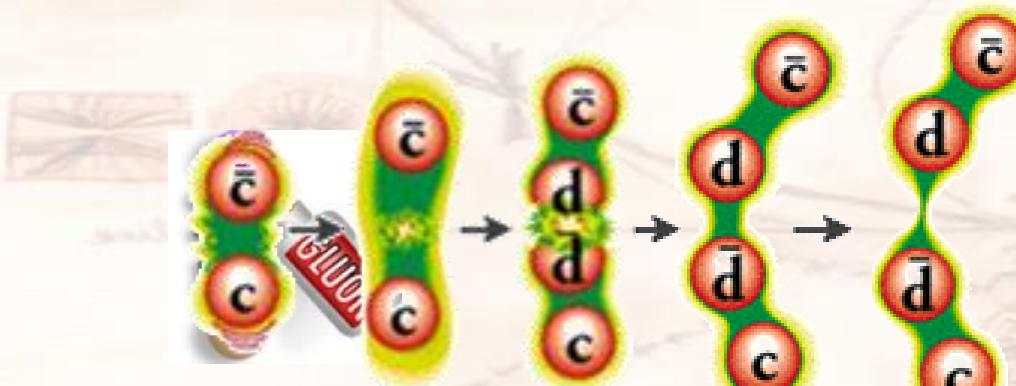
Ainsi le proton est "incolore"



Les gluons « collent » les quarks entre eux : ils sont confinés à l'intérieur des hadrons (proton, neutron,...). On ne peut pas observer un quark seul.

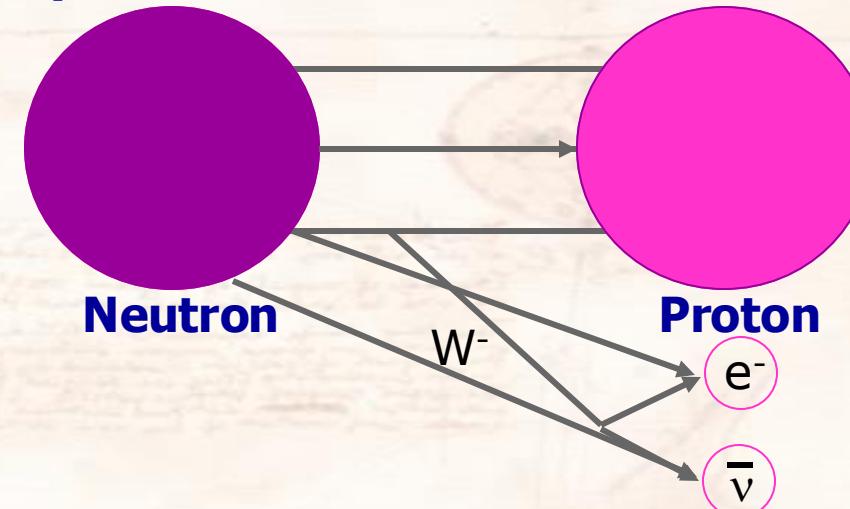
⇒ Stabilité des noyaux

⇒ Tout ce qui est constitué de quark s'appelle un hadron



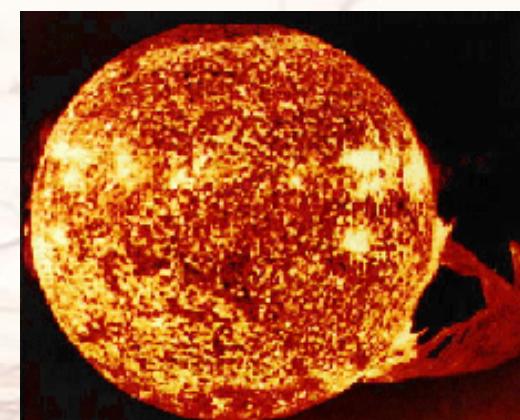
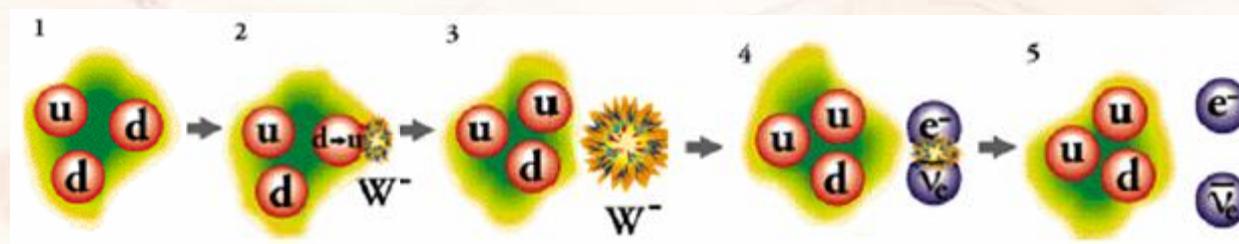
# L'interaction faible

**Radioactivité:** Phénomène physique naturel au cours duquel des noyaux atomiques instables, se transforment spontanément en dégageant de l'énergie sous forme de rayonnements divers.



Médiateurs: **W/Z**

Un neutron (libre) se désintègre après 15 min



C'est un temps très long!!! (15min est une éternité en physique des particules!)  $\Rightarrow$  "faible"

sans ces interactions faibles le soleil s'éteindrait!

# La gravité : une interaction à part...

Explique le phénomène de **pesanteur**  
(chute des corps terrestres)

Explique les orbites des planètes du **Système Solaire**... mais aussi les galaxies et l'évolution de l'Univers !



Portée : infinie...  
Médiateur : **graviton** ? (non encore découvert)