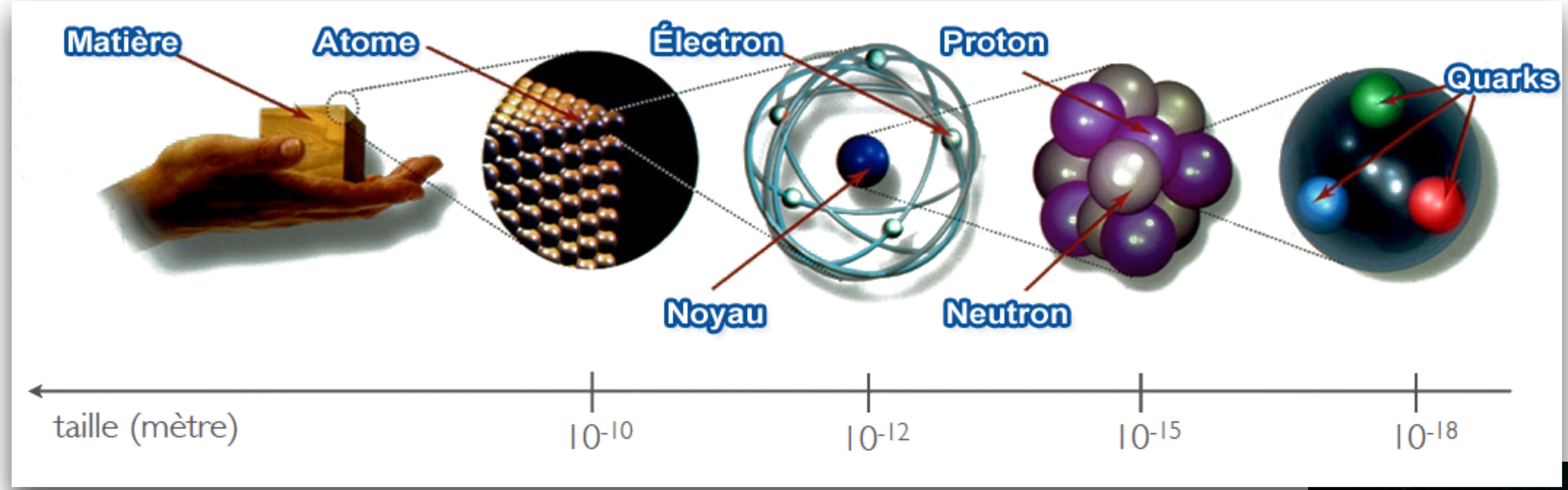
Introduction to detectors

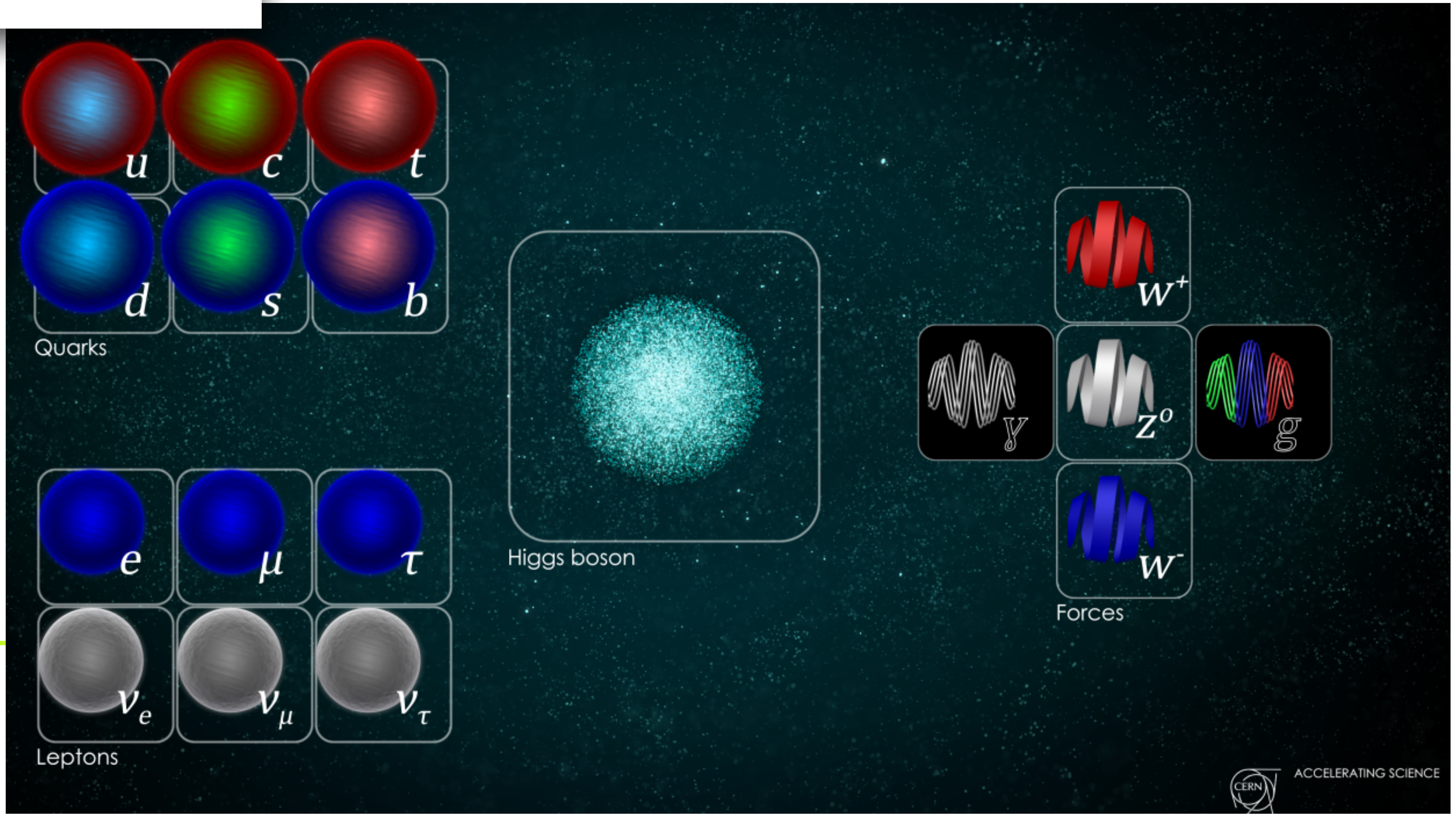
For particle physics and astroparticles

NAREI LORENZO MARTINEZ - LAPP/CNRS - JULY 16TH 2024

What do we want to detect ?

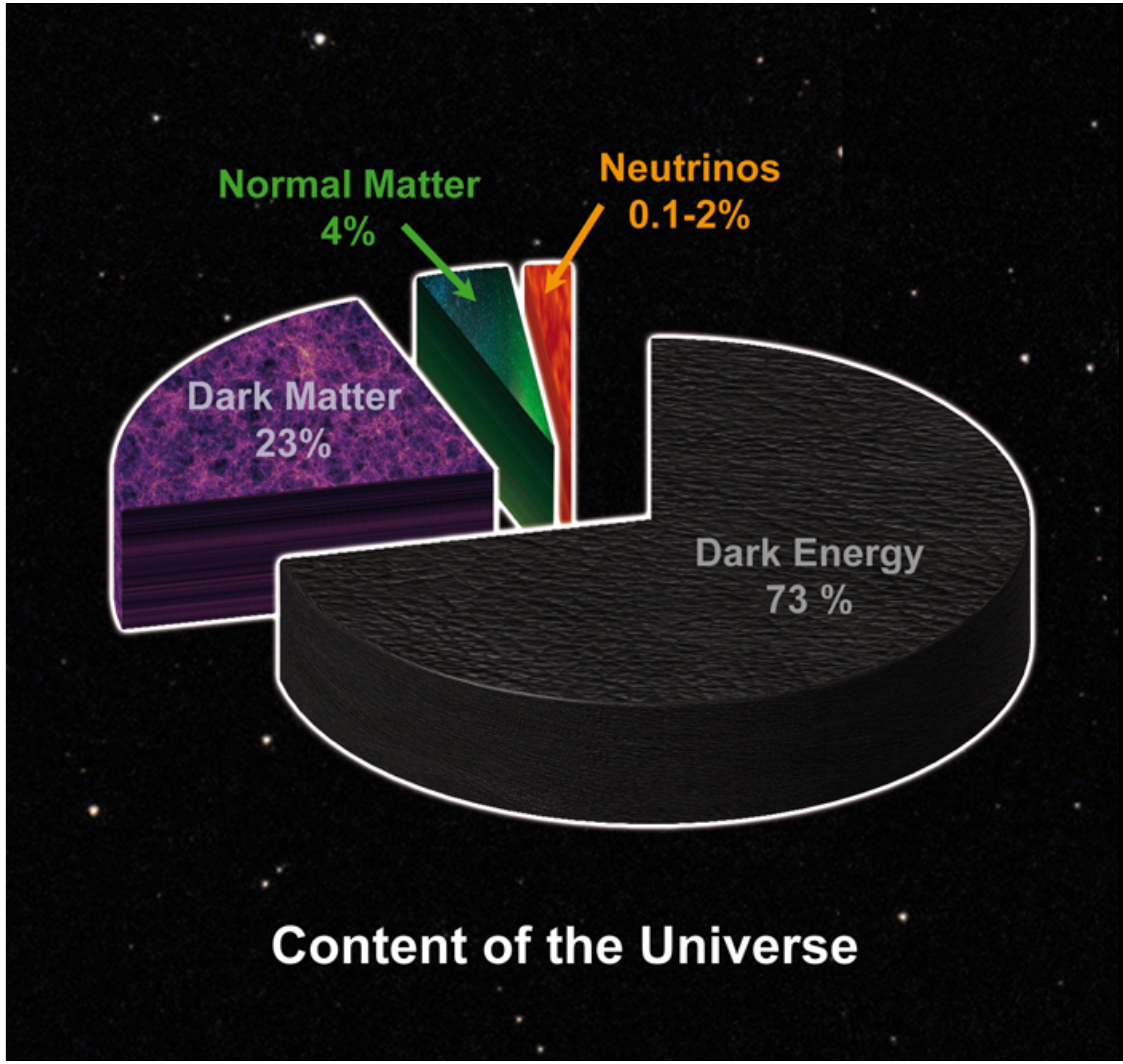


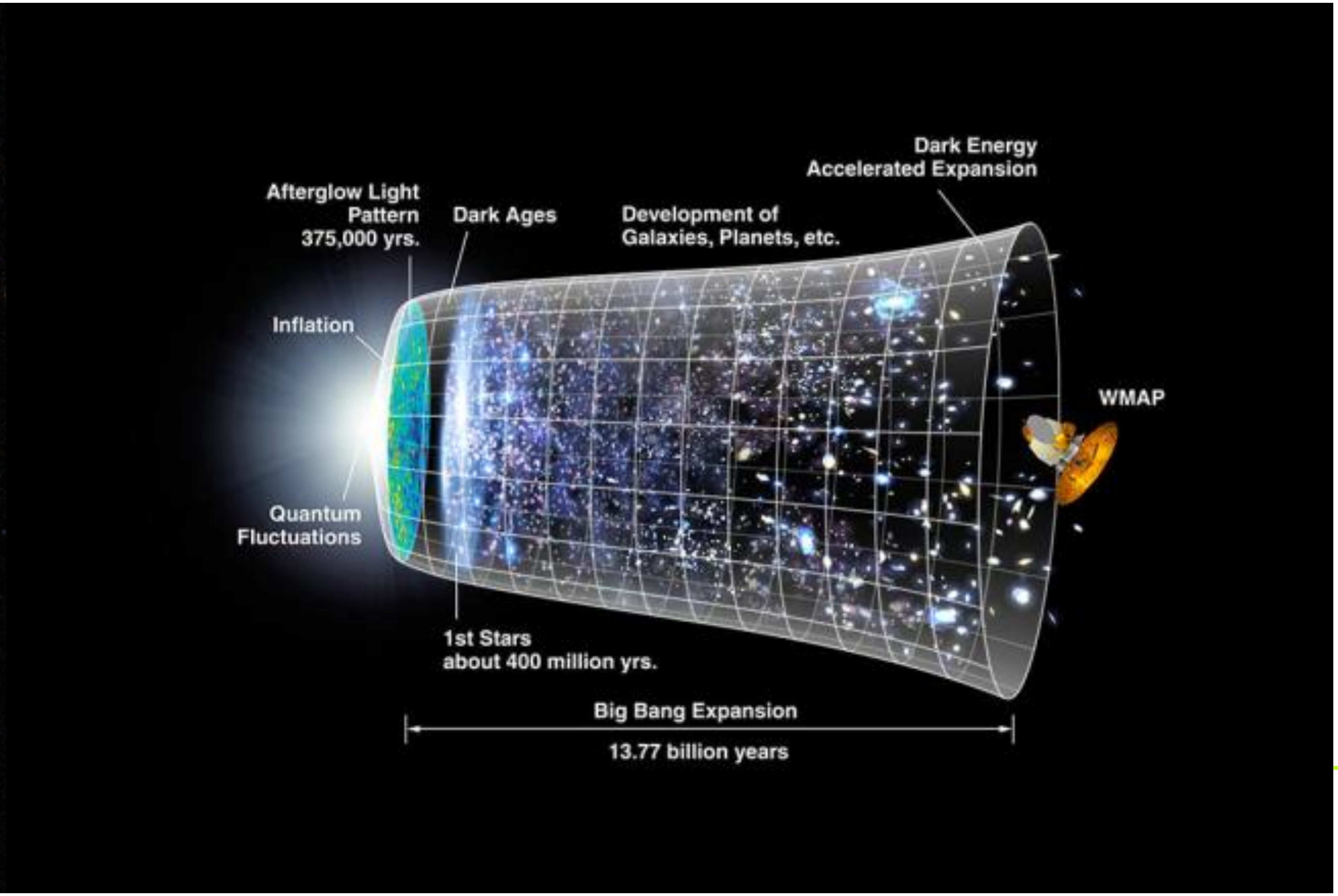
- + unknown particles !



What do we want to detect ?

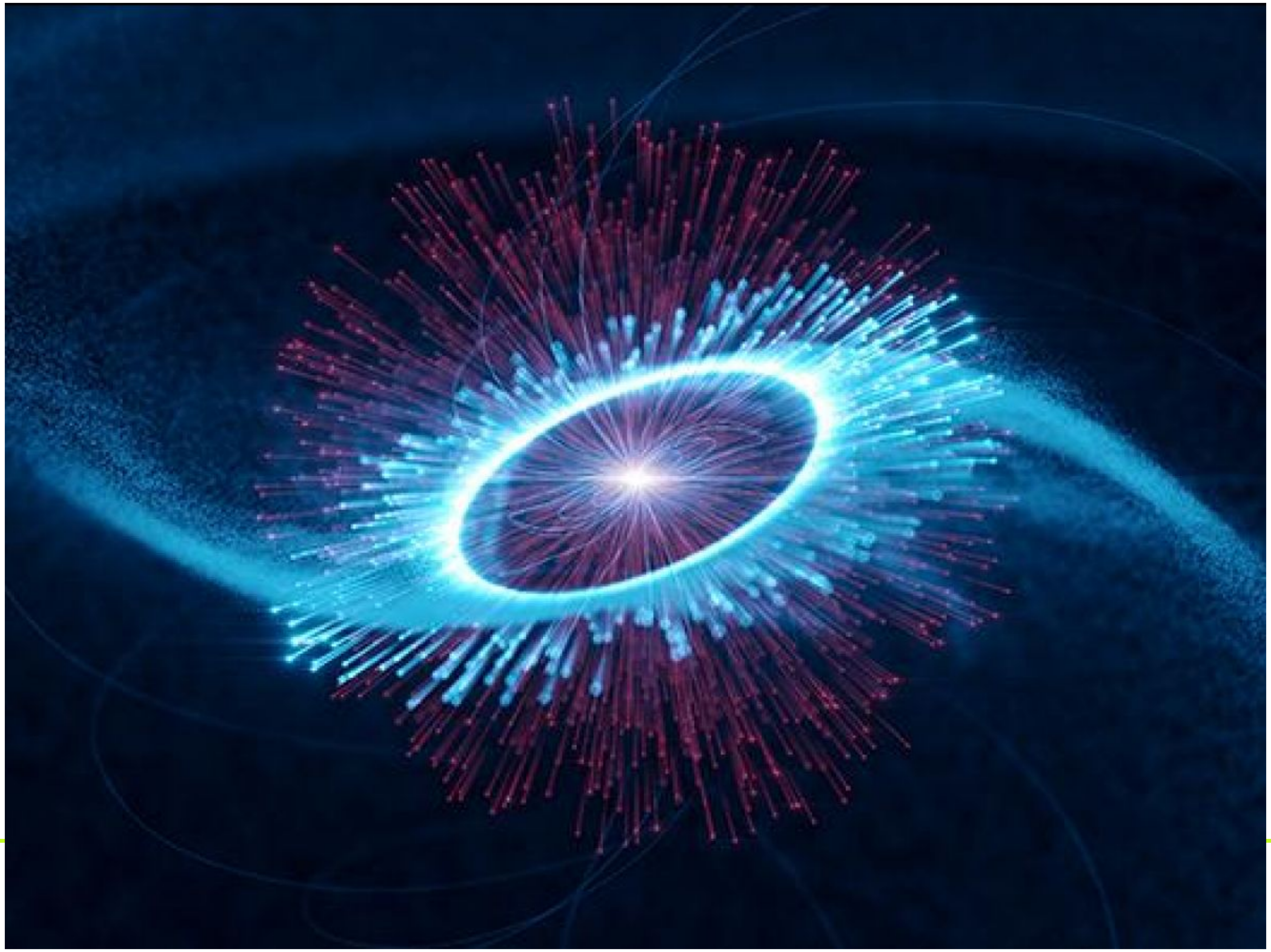
- **Not just random particles, we want high-energy (HE) particles**





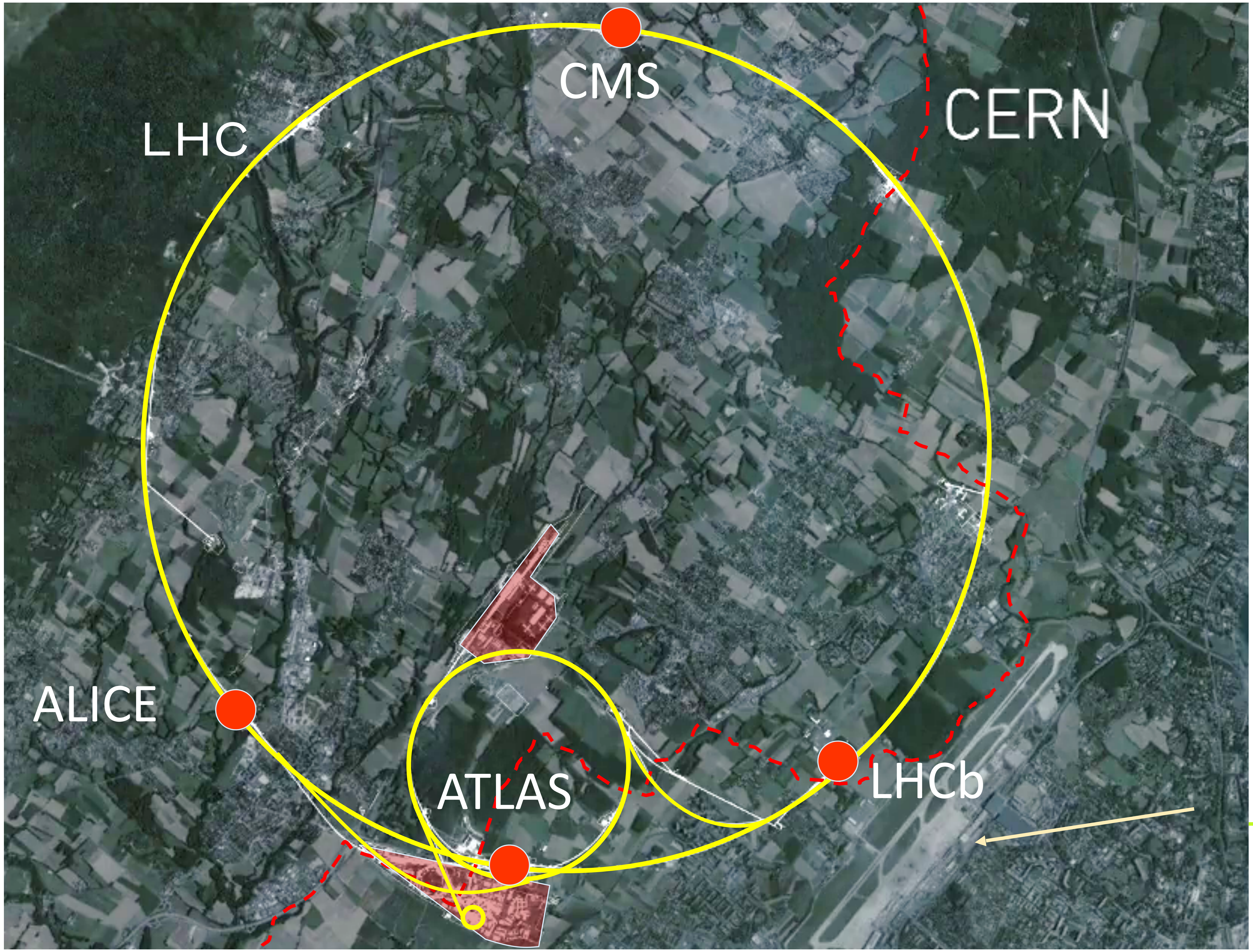
How are HE particles produced ?

- **Cosmic accelerators**

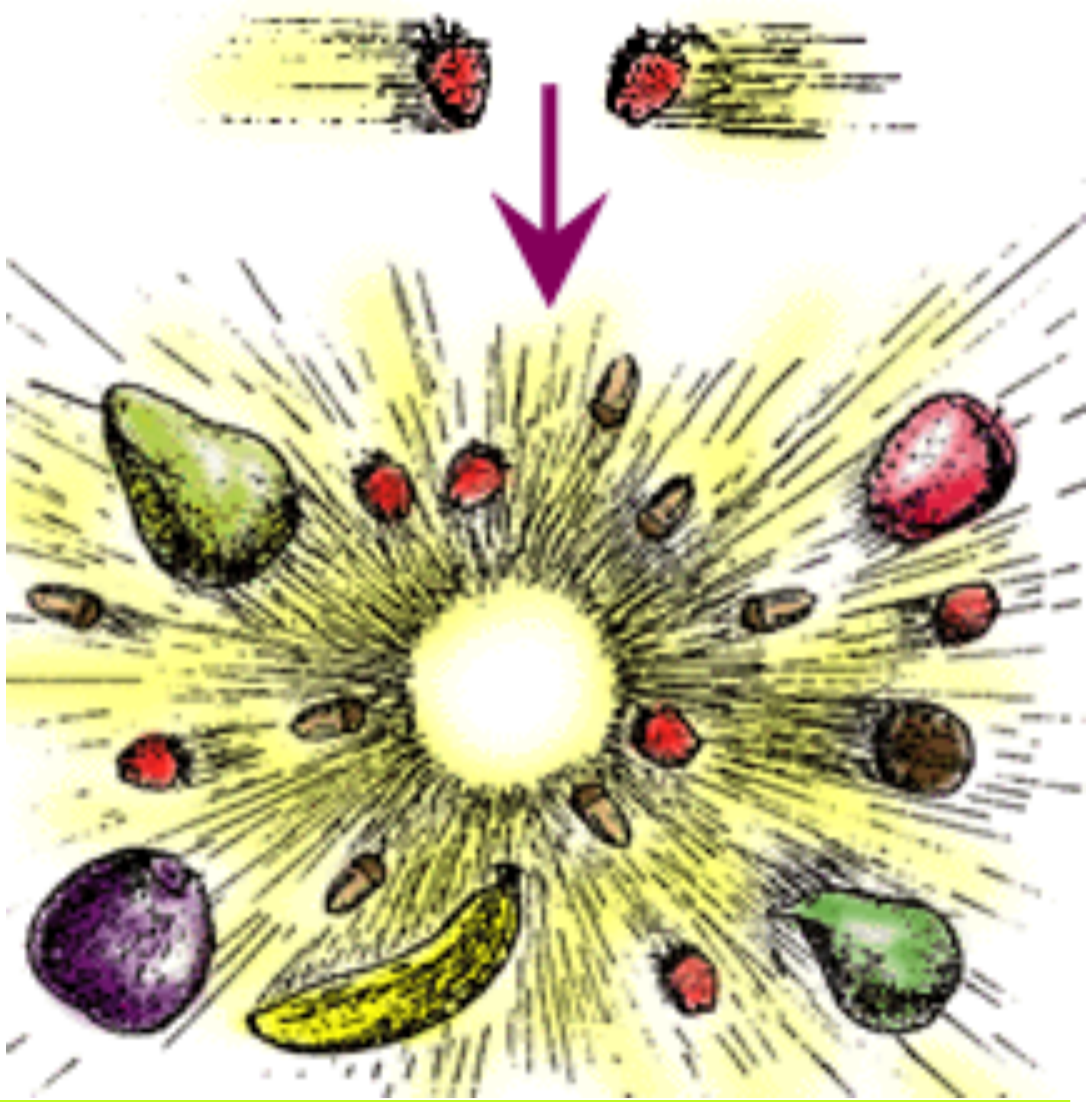


How are HE particles produced ?

- **Human accelerators**



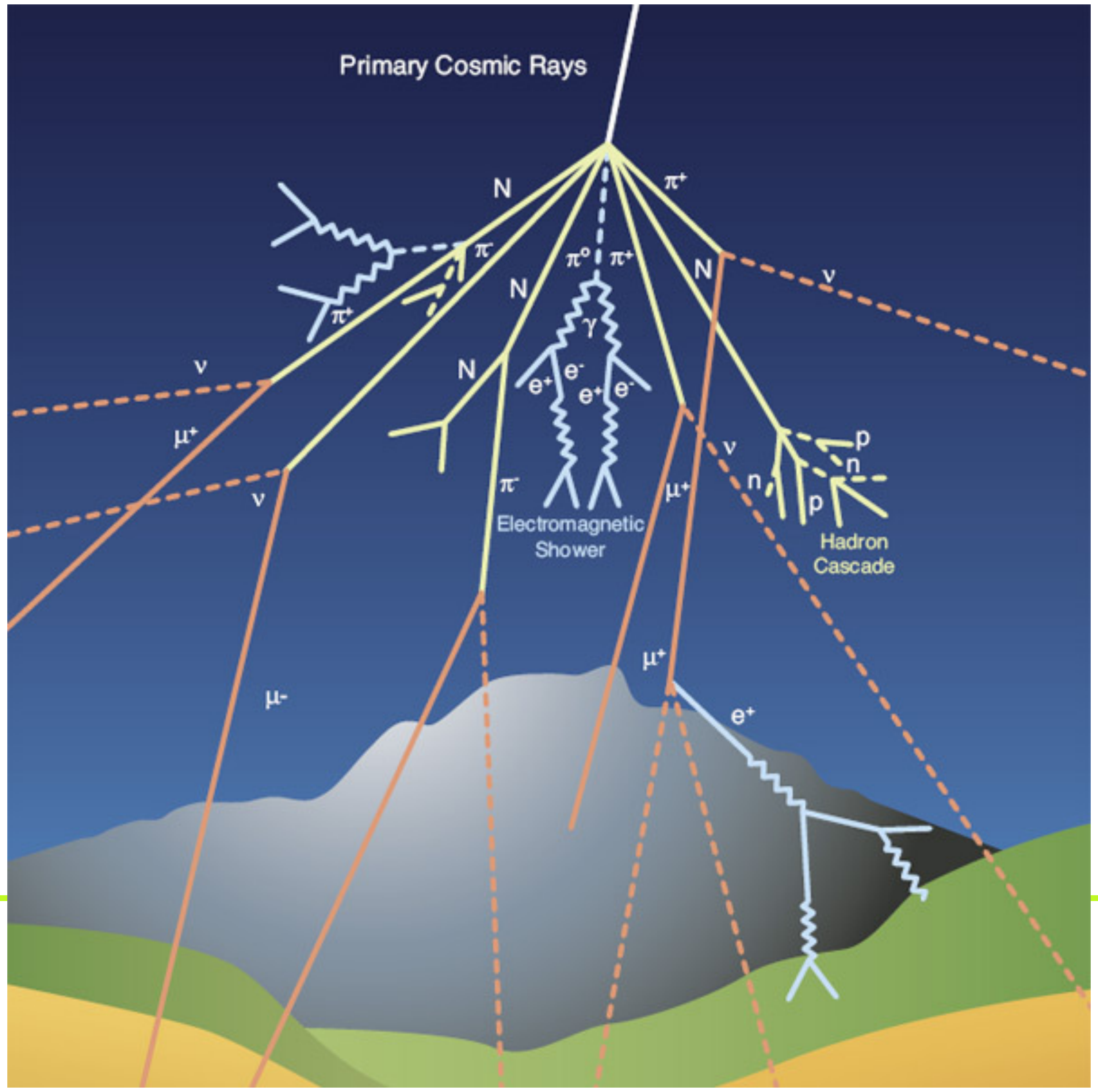
LHC = Large Hadron **Collider**

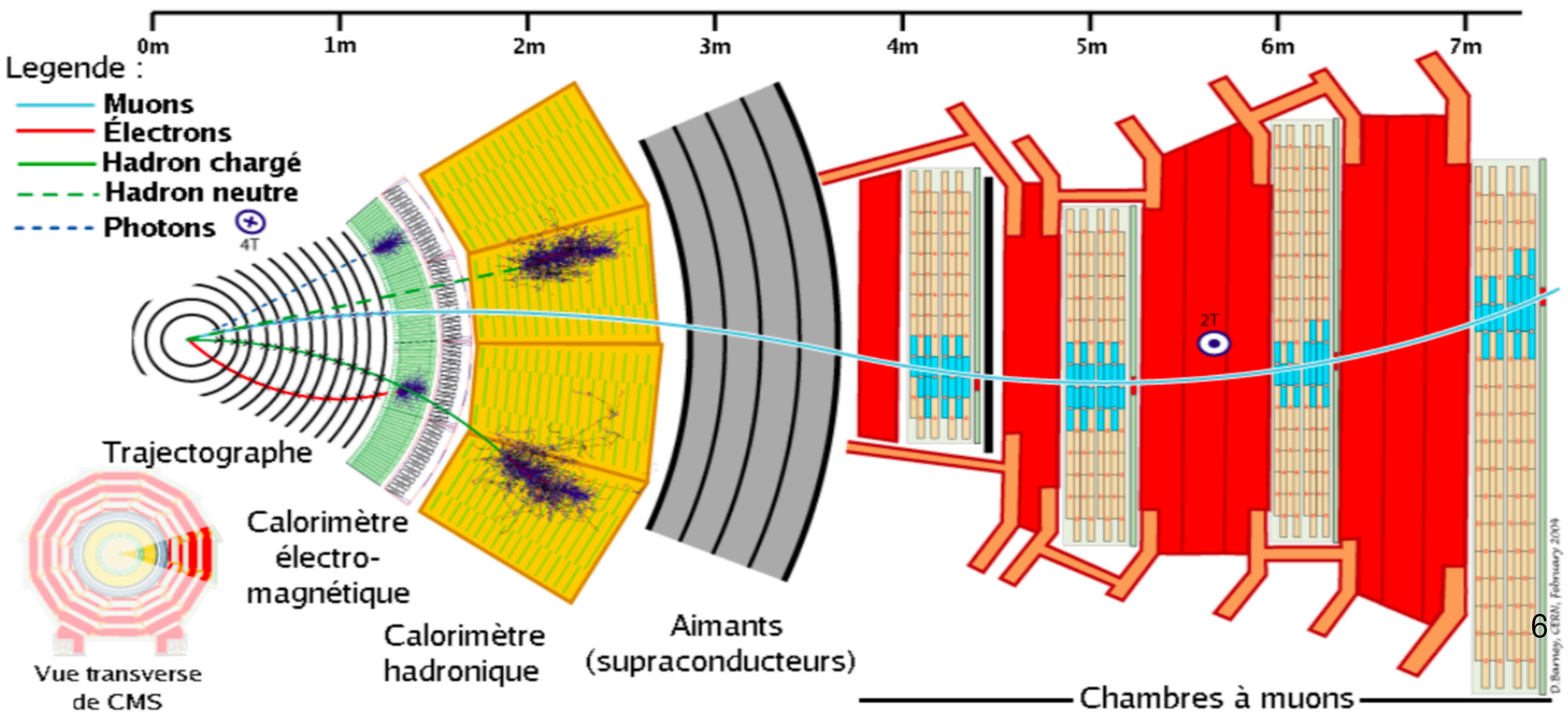


$$E = mc^2$$

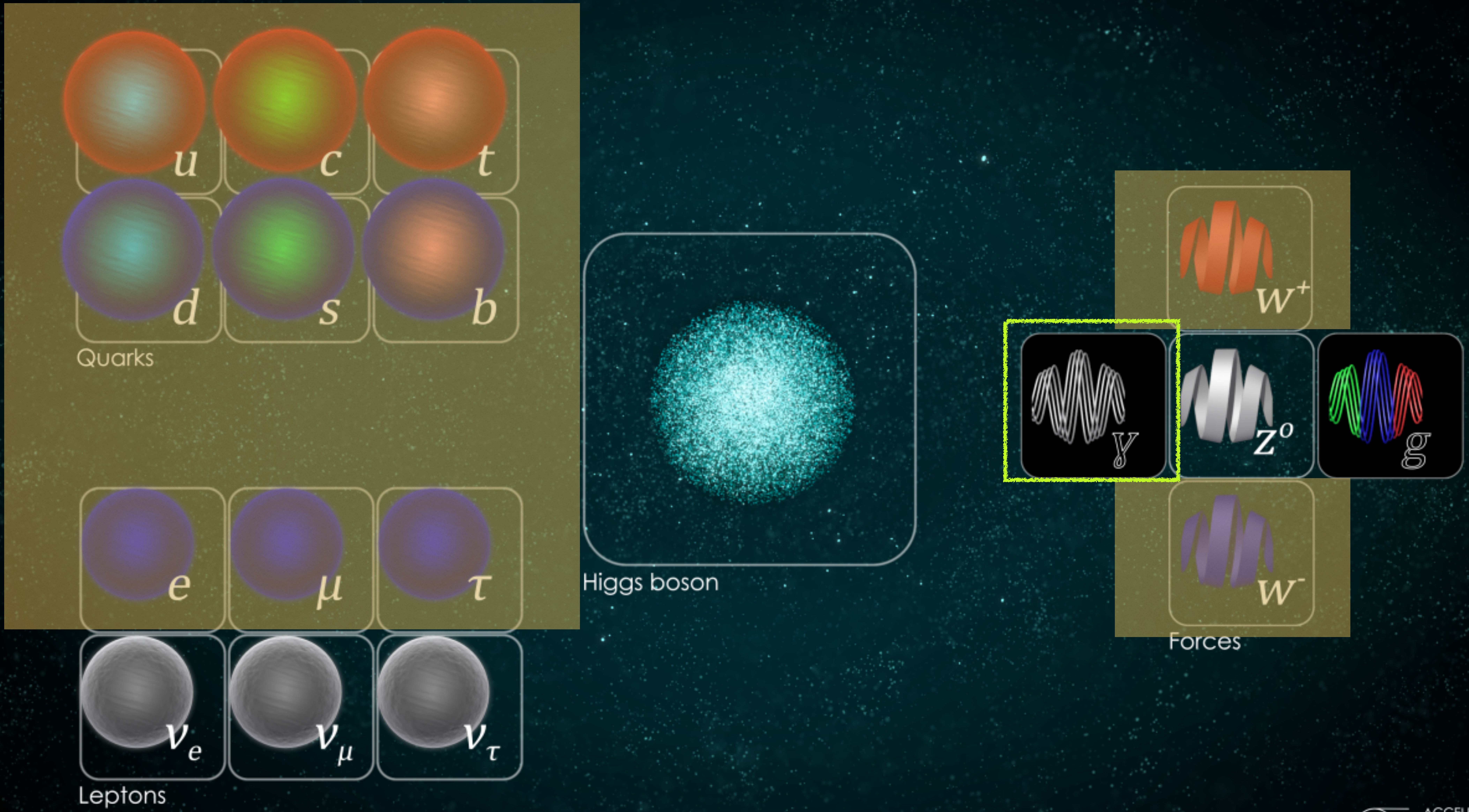
How can we detect particles ?

- **Thanks to their INTERACTION with matter ! Examples:**
  - cosmic particles can interact with **atmosphere** (hydrogen, oxygen, azote, ….)
  - accelerator particles interact with **detectors** (lead, tungsten, copper, silicium, …)





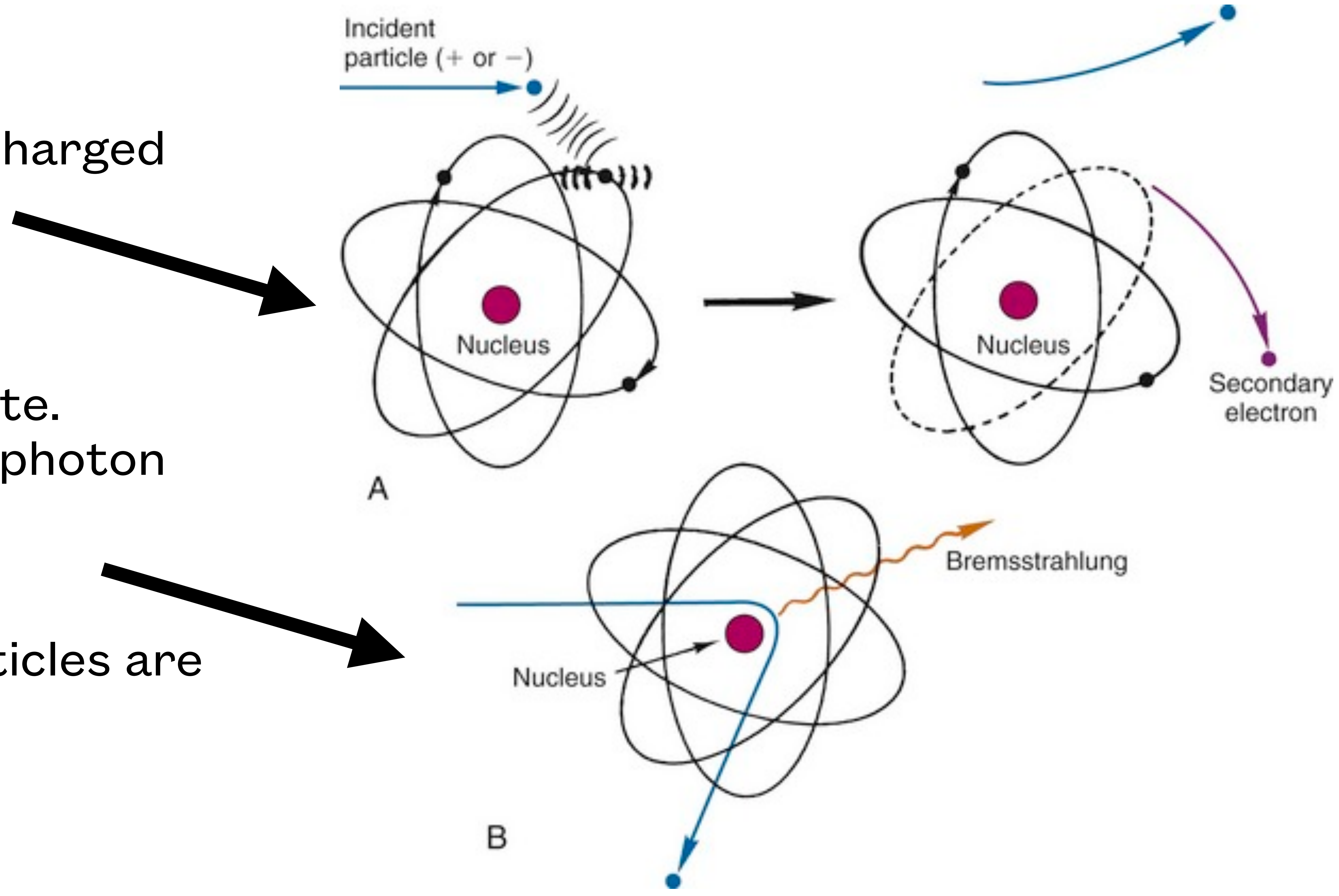
Interaction : Electromagnetic



ACCELERATING SCIENCE

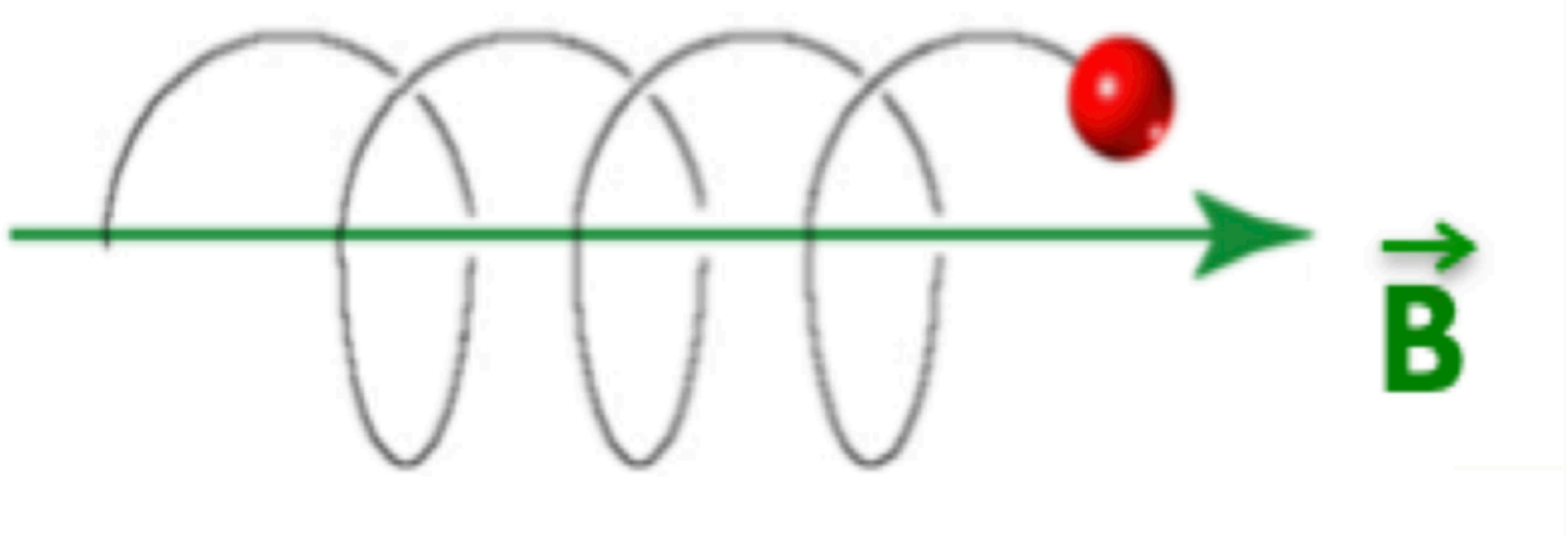
Interaction of charged particles with matter

- **Ionisation -> primary mechanism of energy loss**
  - remove one or more electrons from an atom near the charged particle's trajectory
- **Excitation**
  - promote one of atom's electrons to a higher energy state. Excited atom de-excite and emit low energy ultraviolet photon
- **Bremstrallung**
  - electromagnetic radiation produced when charged particles are deflected
- **Cerenkov radiation**
  - blue light emitted by charged particles that travel through a transparent medium (e.g., water) faster than speed of light in that medium. Essentially limited to electrons.



Charged particle in a magnetic field

- Curvature gives access to mass, charge and momentum of particule

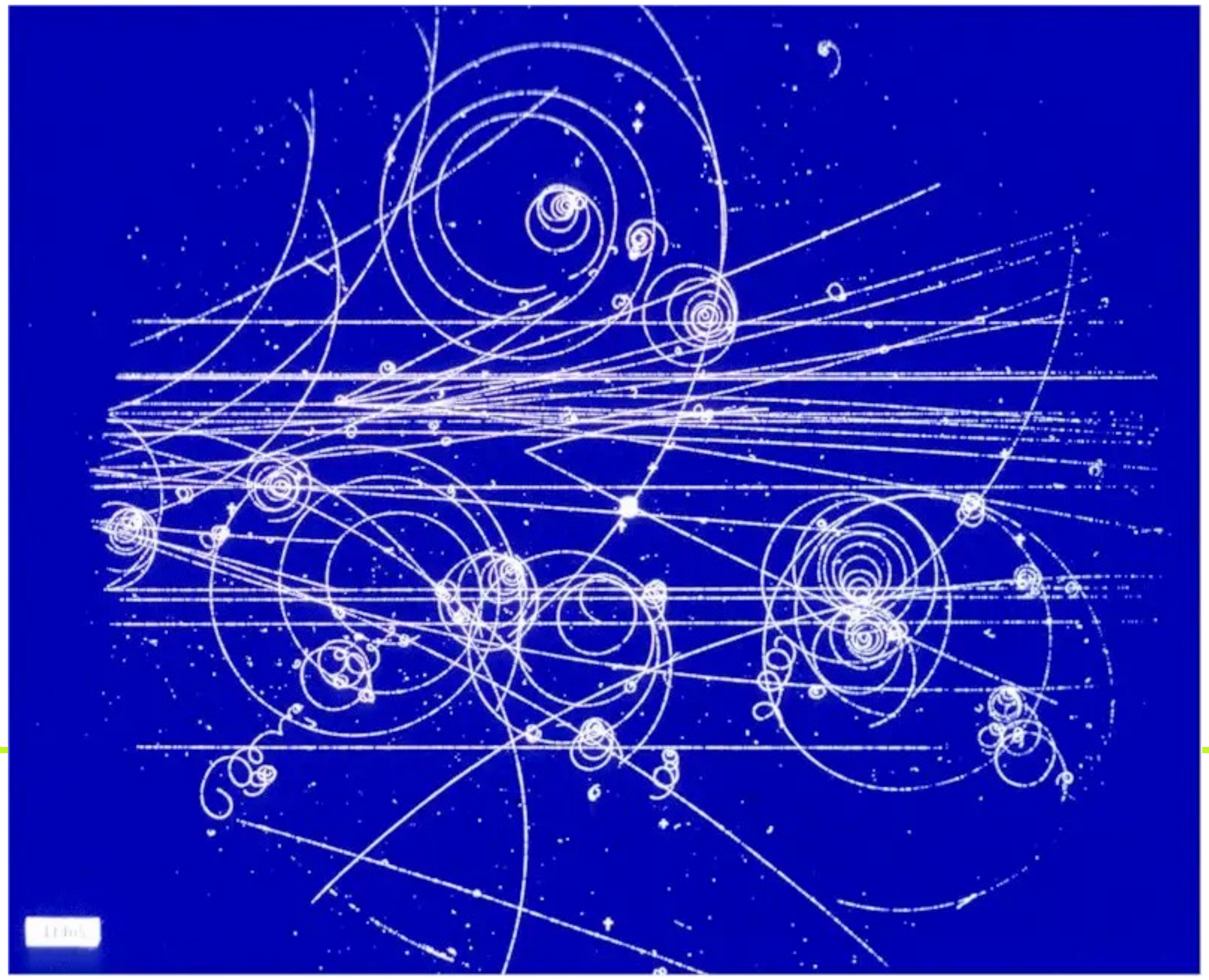


$$\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

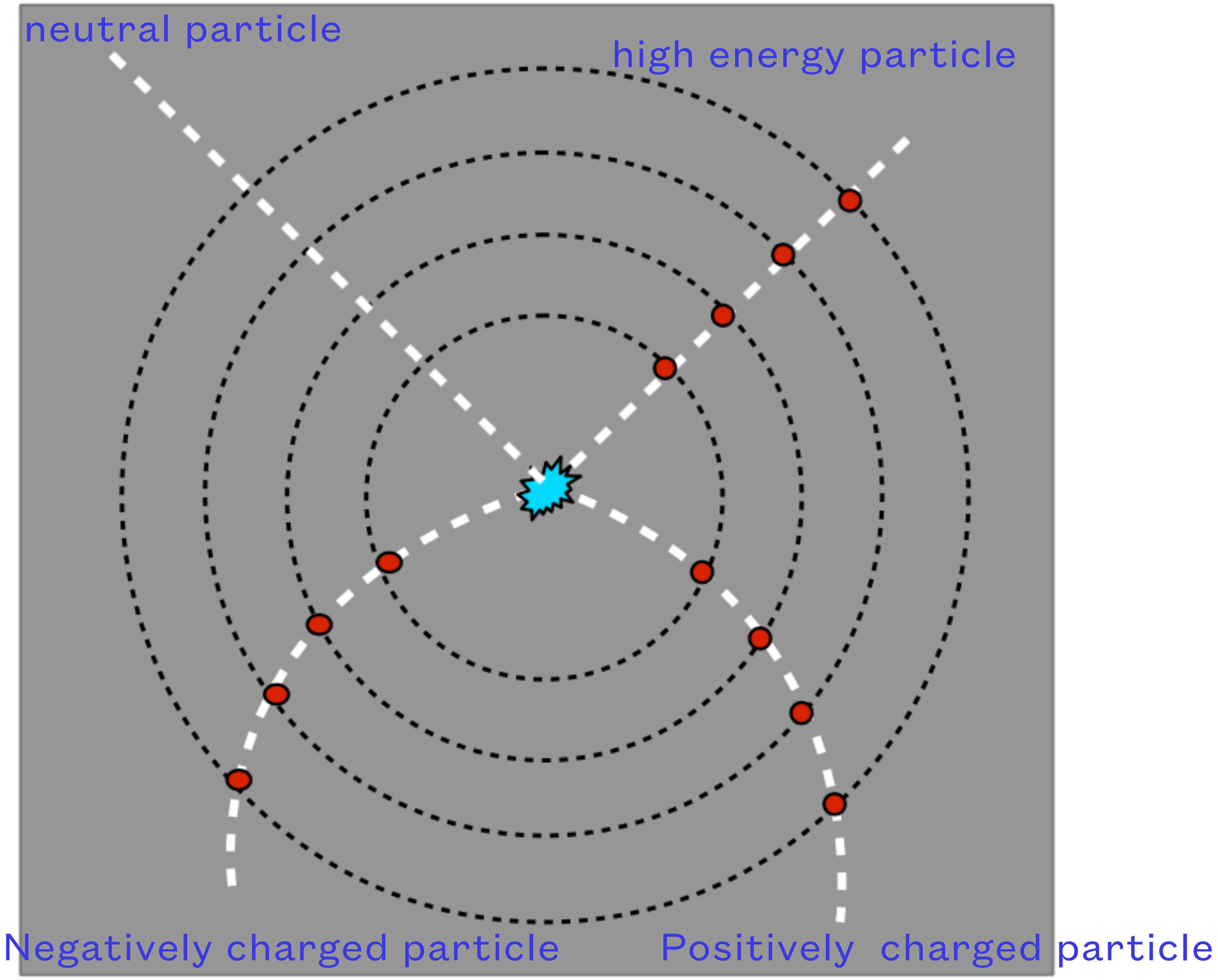
$$\vec{p} = m.\vec{v}$$

$$r = \frac{mv}{qB}$$

radius of curvature



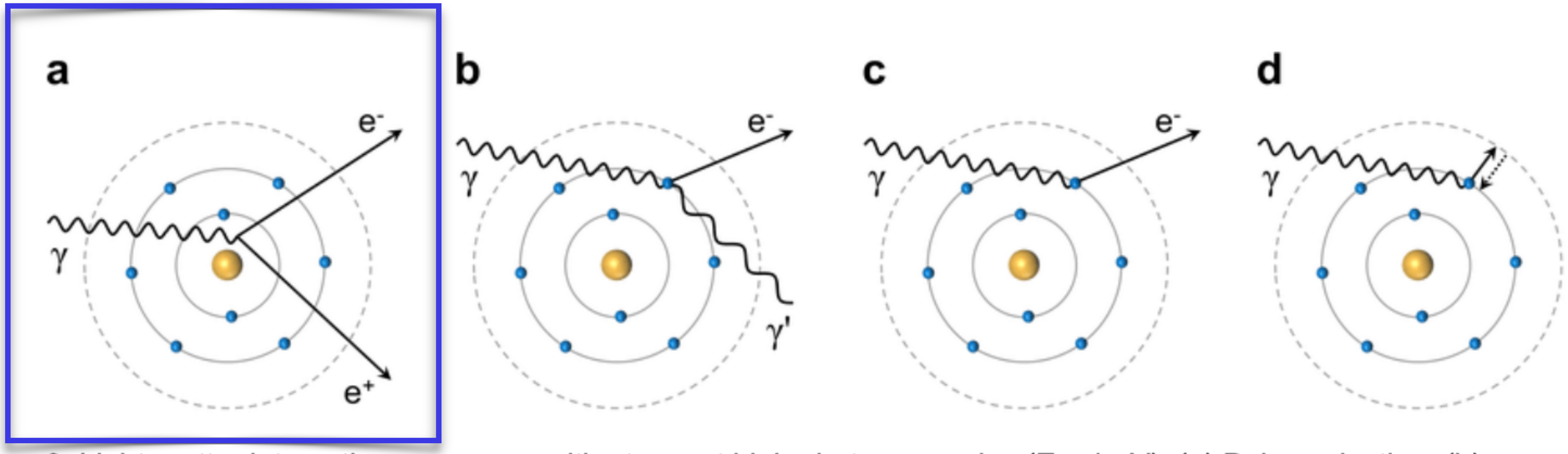
Bubble chamber



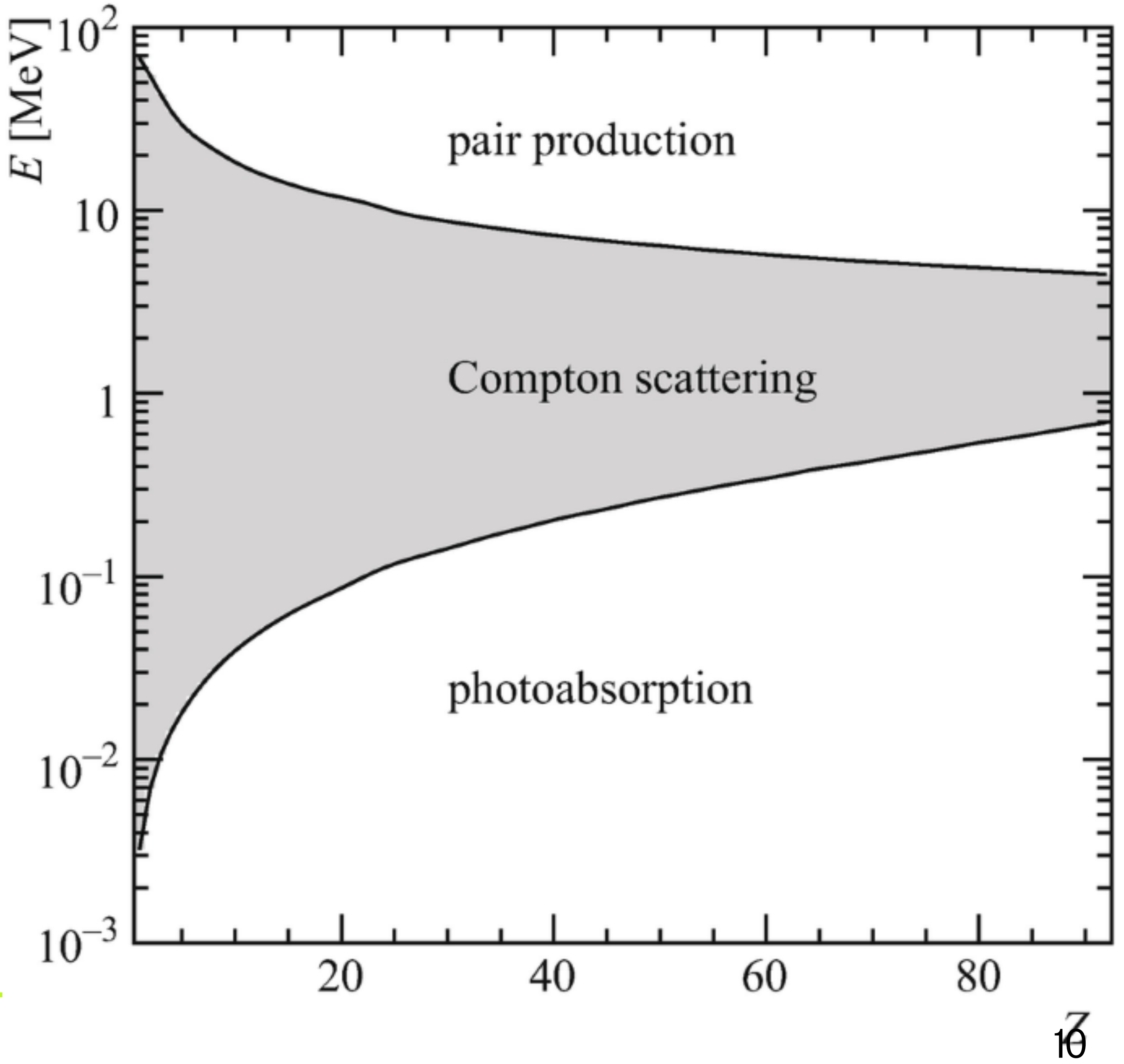
Interaction of photon with matter

- **At high-energy it is essentially pair production**

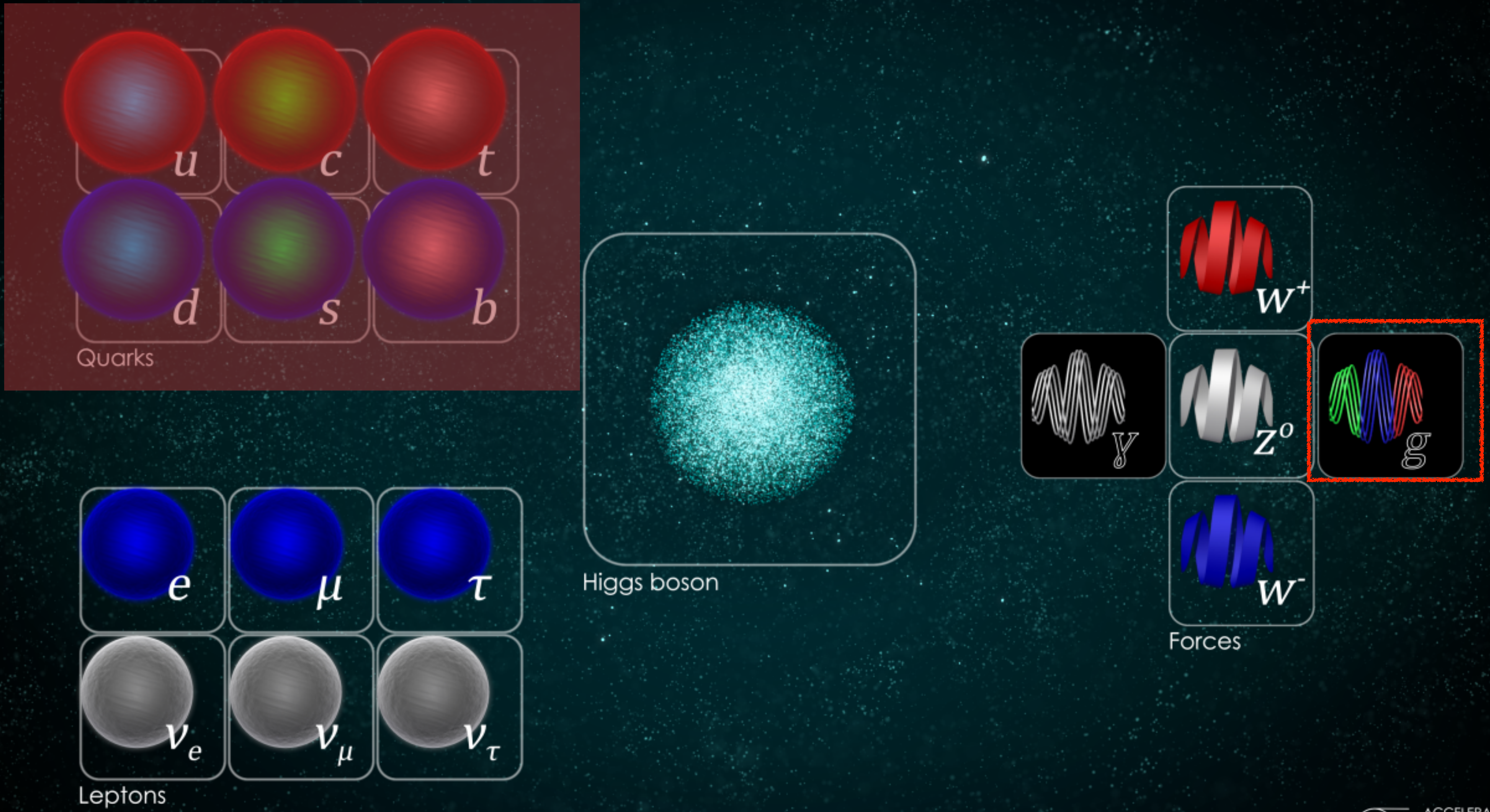
pair production Compton Scattering Photo-electric Excitation



3: Light-matter interaction processes with atoms at high photon energies (E γ 1 eV). (a) Pair production. (b) Compton scattering. (c) Photoelectric effect. (d) Electronic excitation and de-excitation. Yellow spheres: atomic nuclei. Blue spheres: bound electrons.



Strong interaction

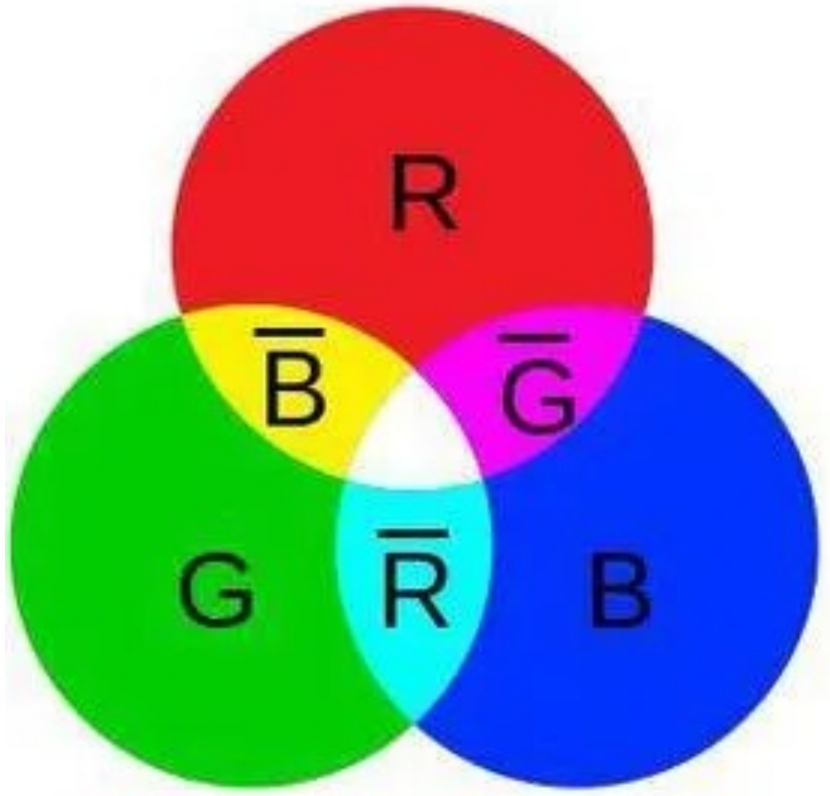


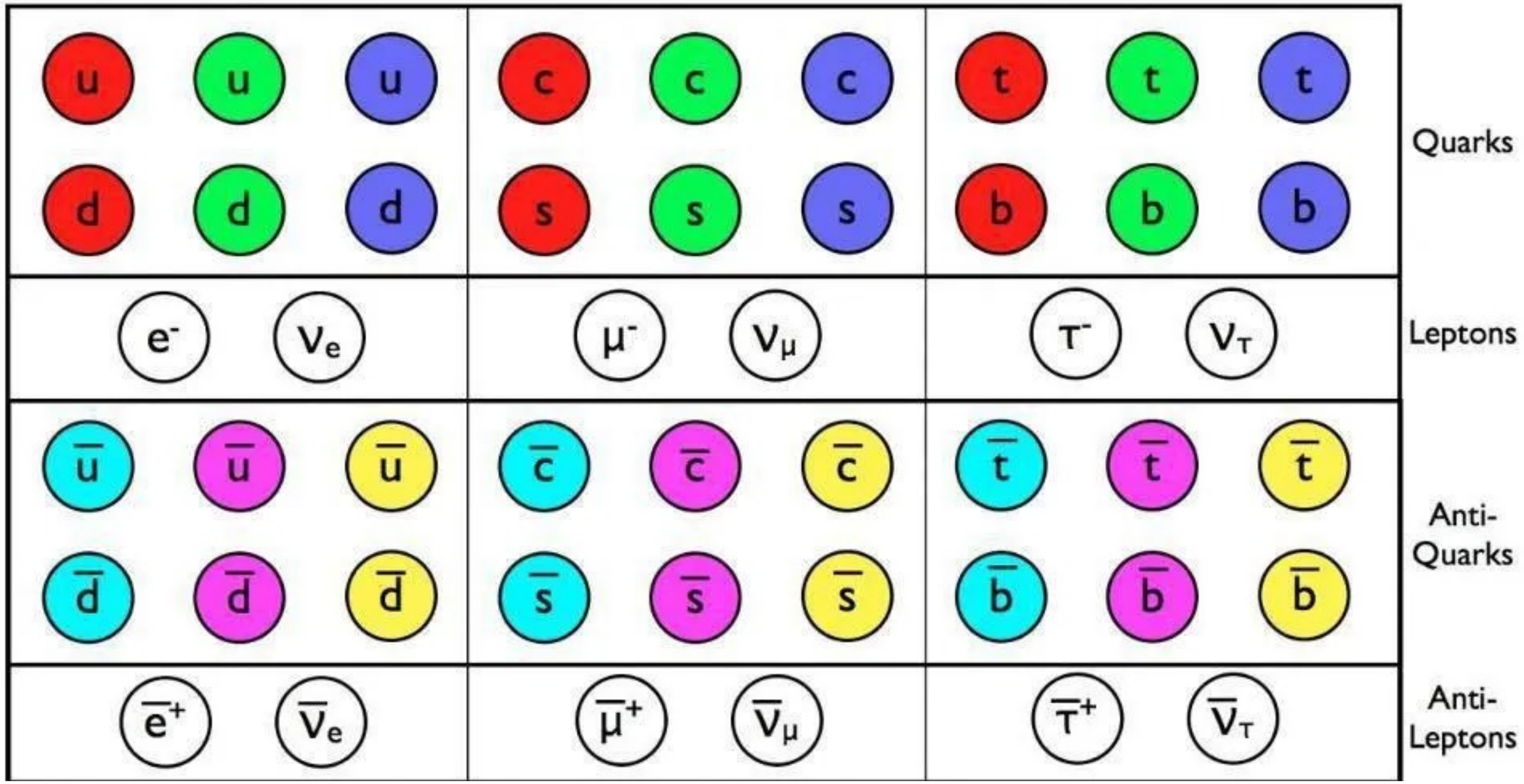
ACCELERATING SCIENCE

Strong force and color charge

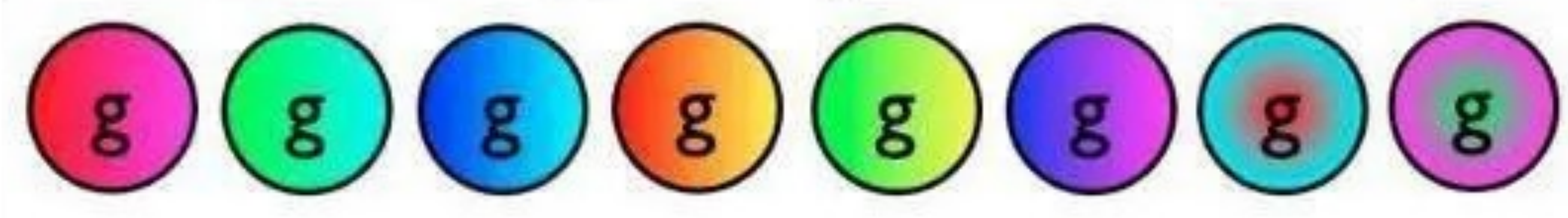
3 colors

3 anti-colors





8 gluons



–> THERE ARE THEN 36 QUARKS IN THE THEORY

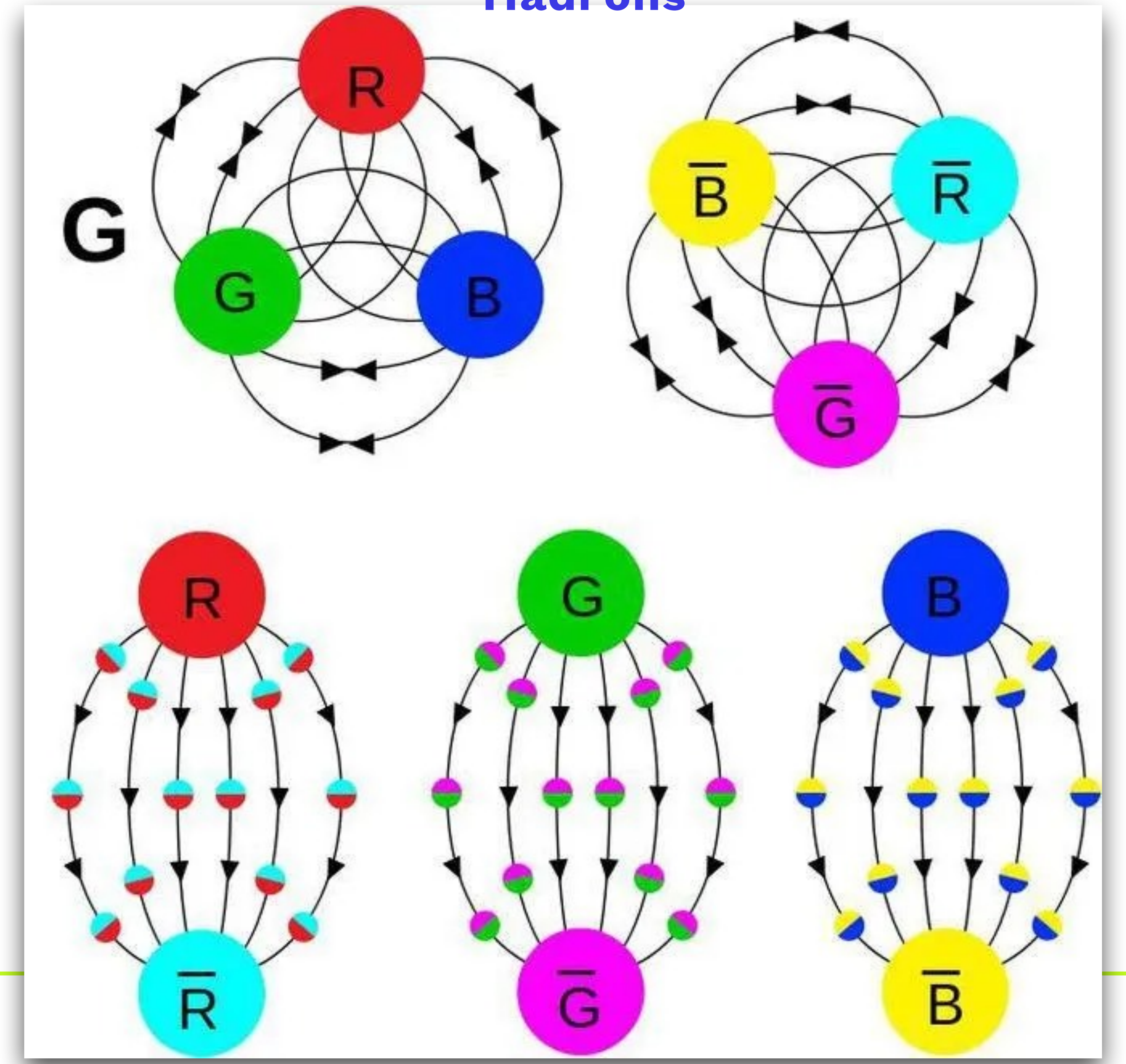
Color confinement

- **Not possible to find a colored particle alone ! Only « white » particles allowed**

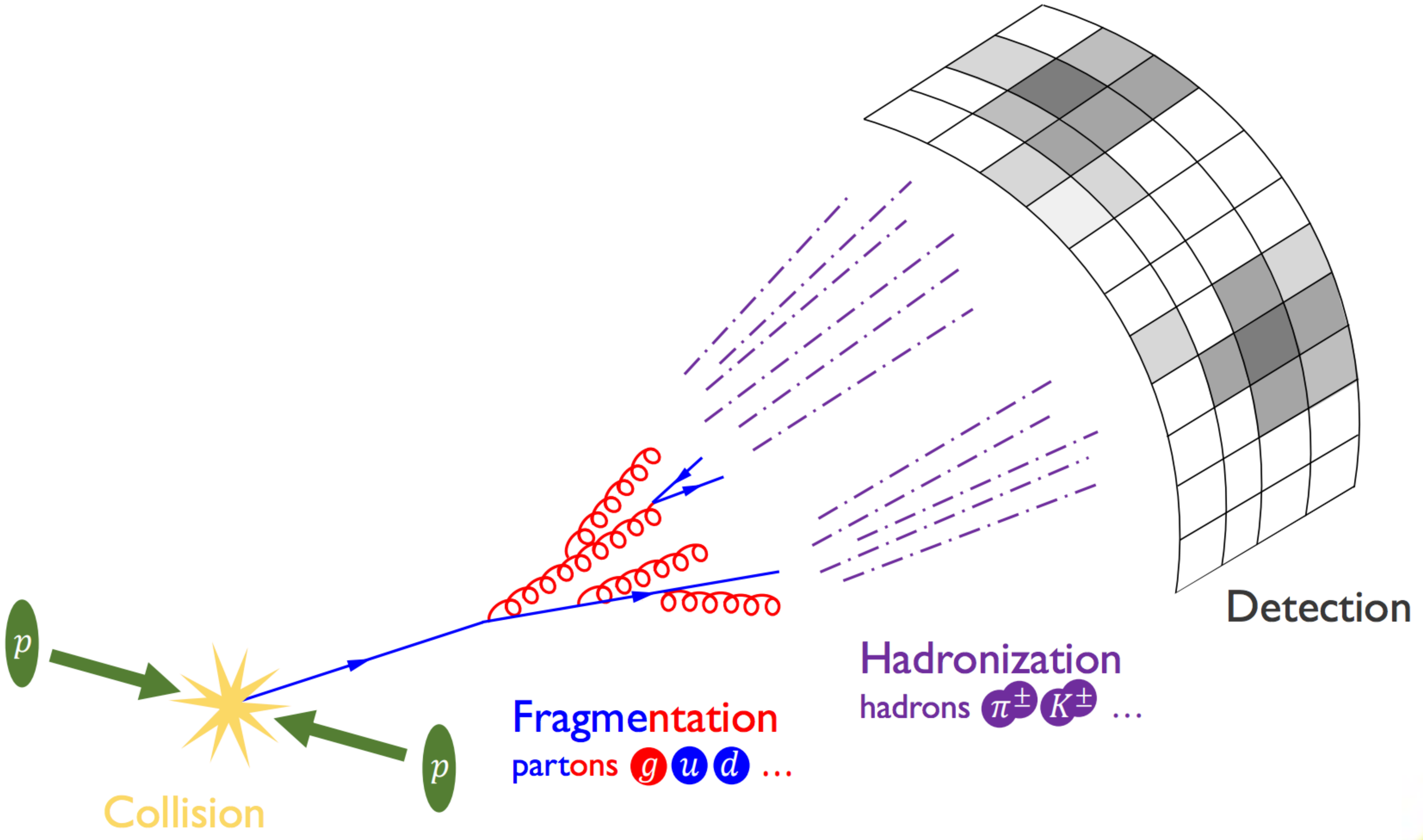
Hadrons

Baryons

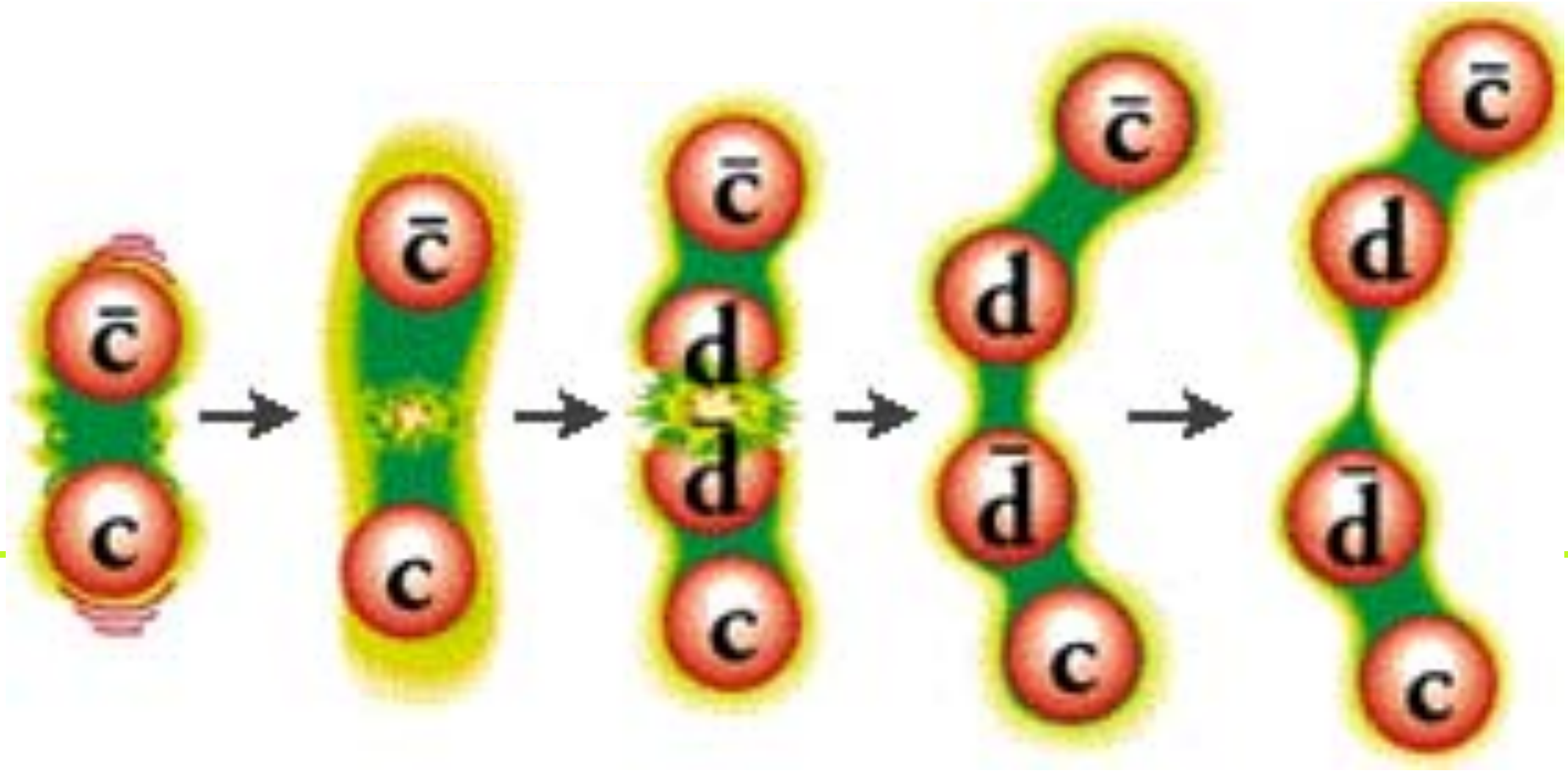
Mésons



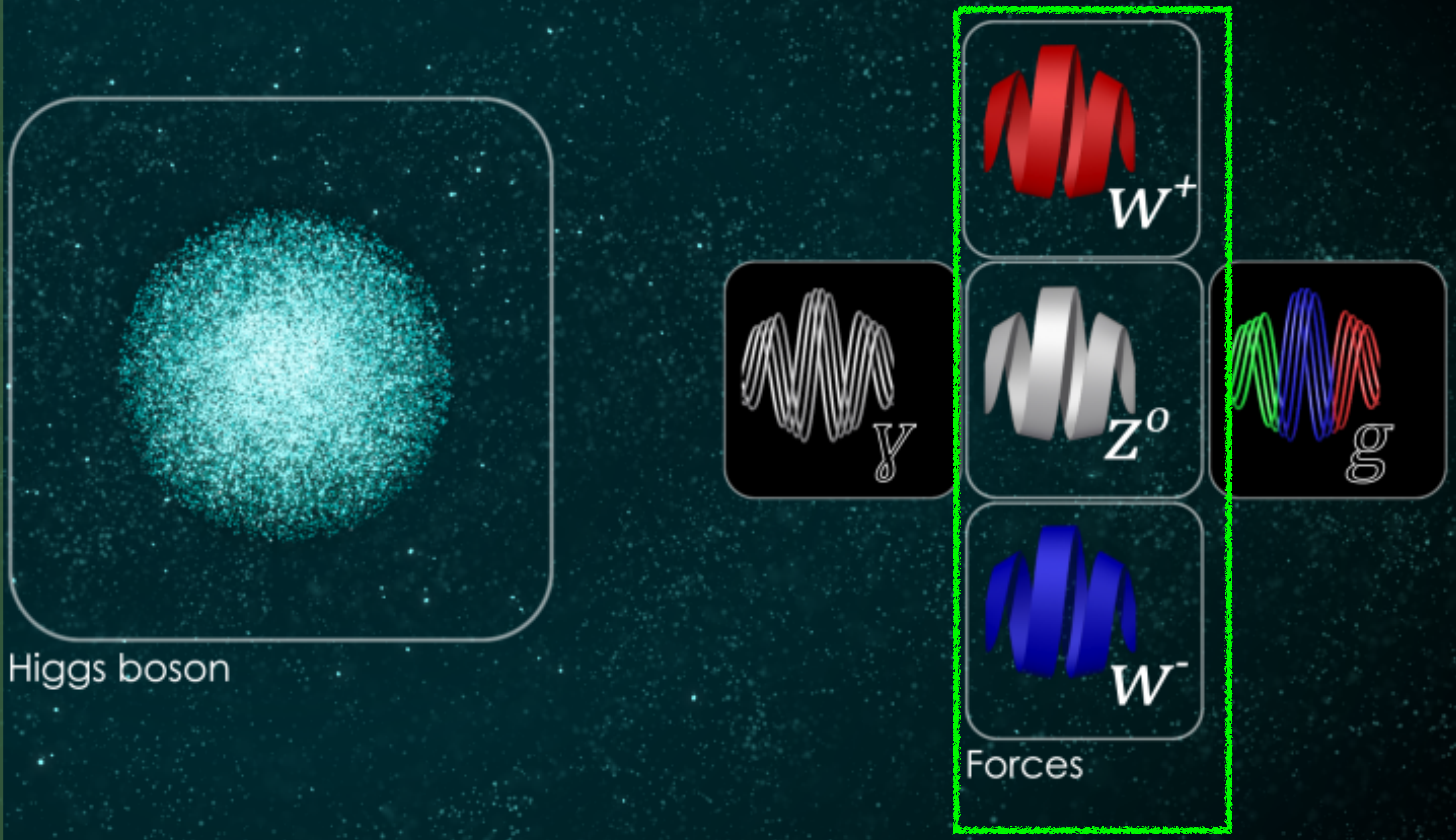
Fragmentation and hadronisation



- **When a single quark or gluon is emitted, process of fragmentation and hadronisation occurs to « whiten » the particle**
- **Results in a hadronic « jet »**

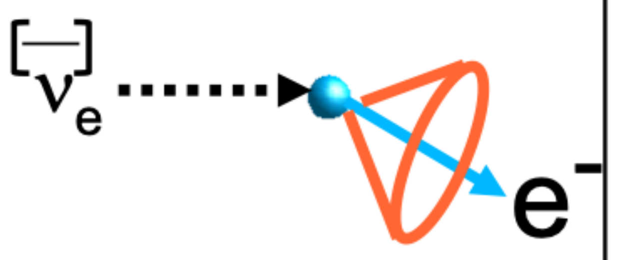
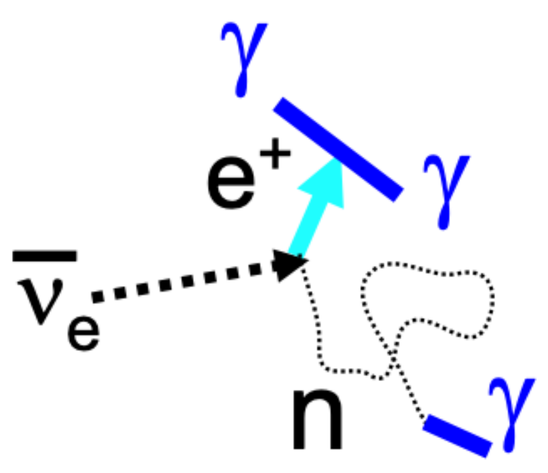
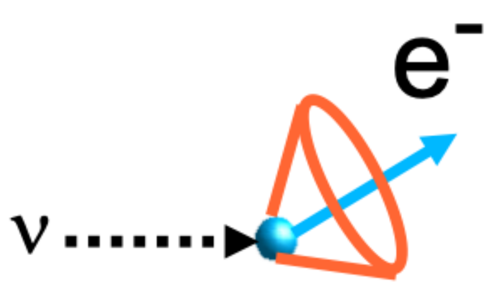
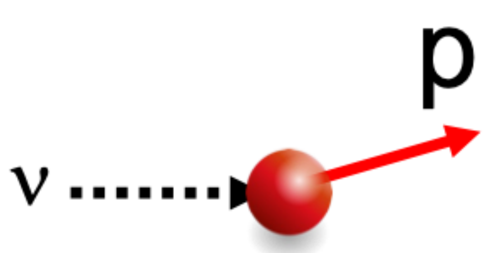


Weak interaction

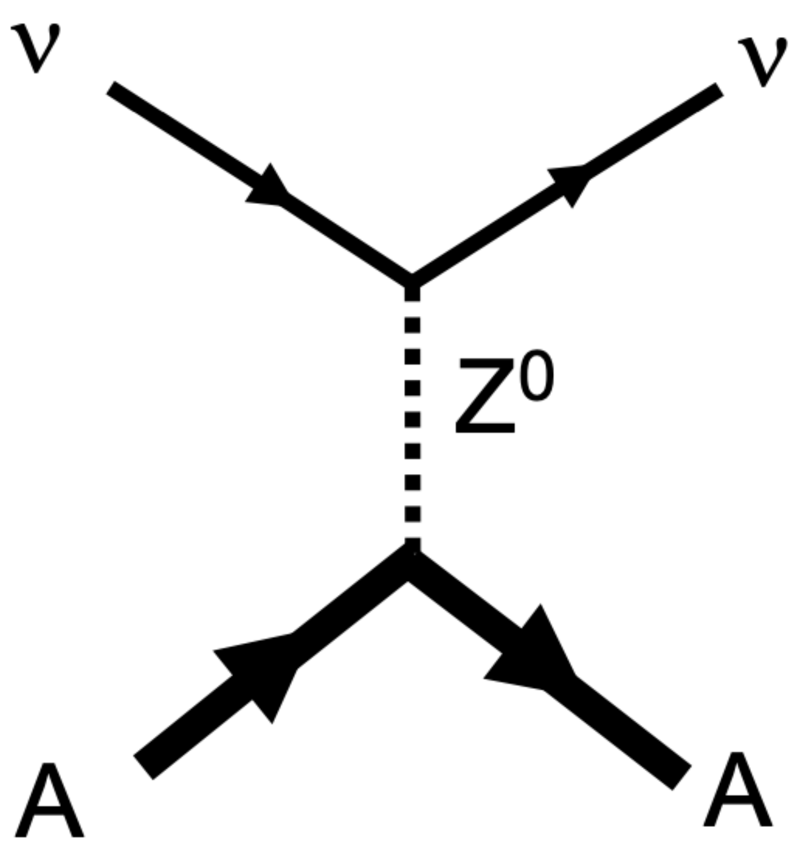


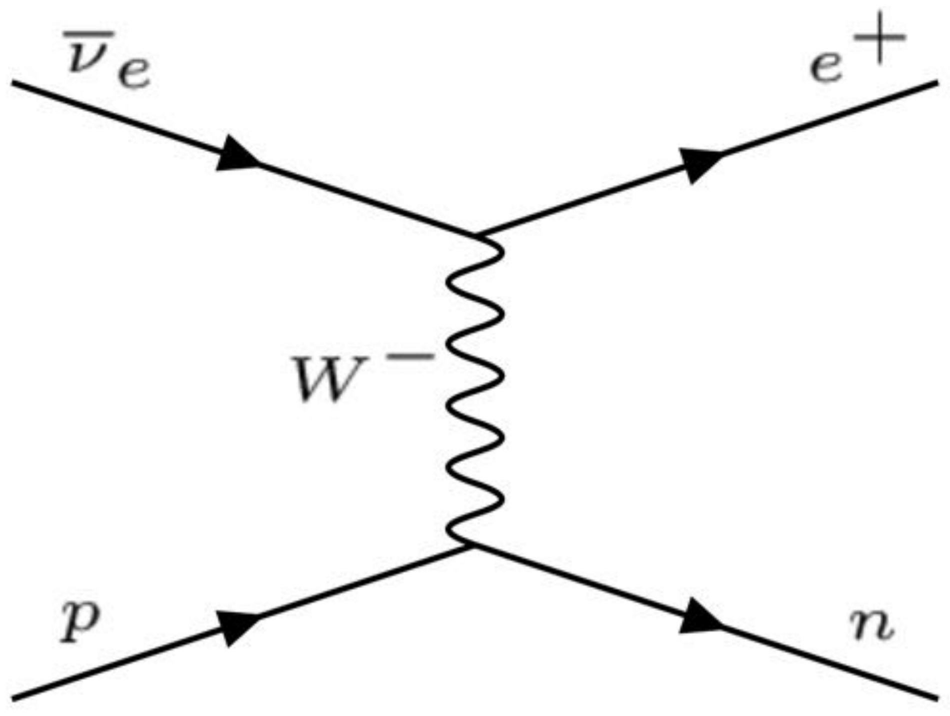
Unique force to which neutrinos are sentitive to !

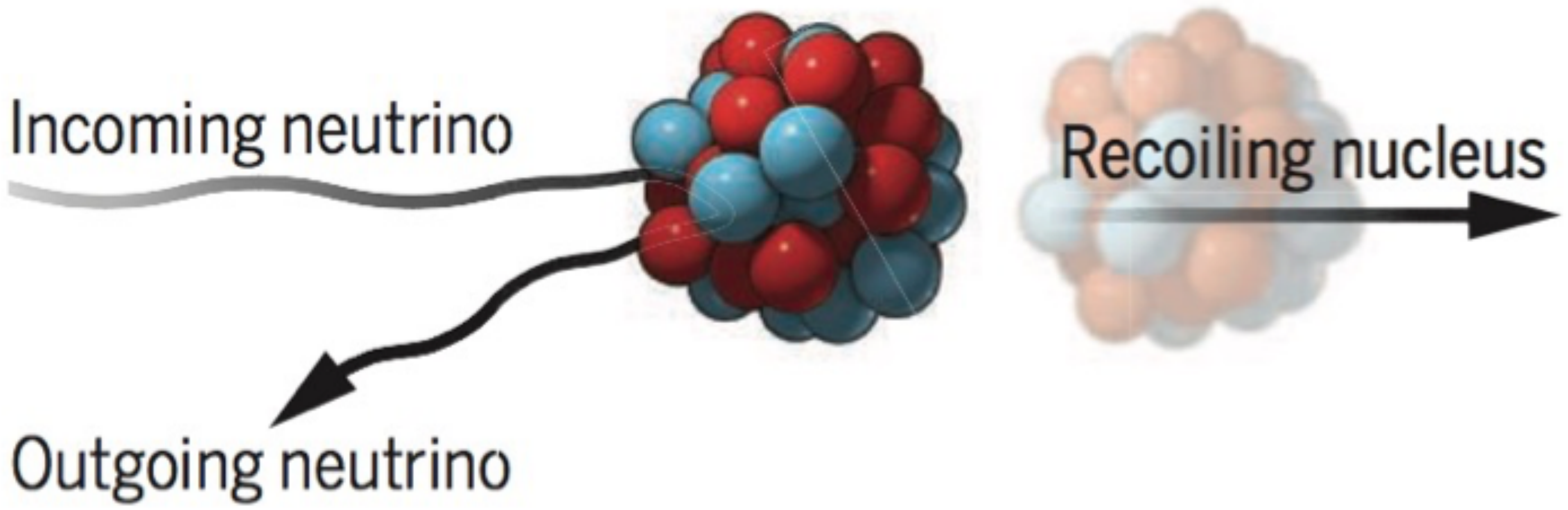
Interaction of neutrinos with matter

	Electrons	Protons
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$ 
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils

- **Very rare interactions and tiny effects**

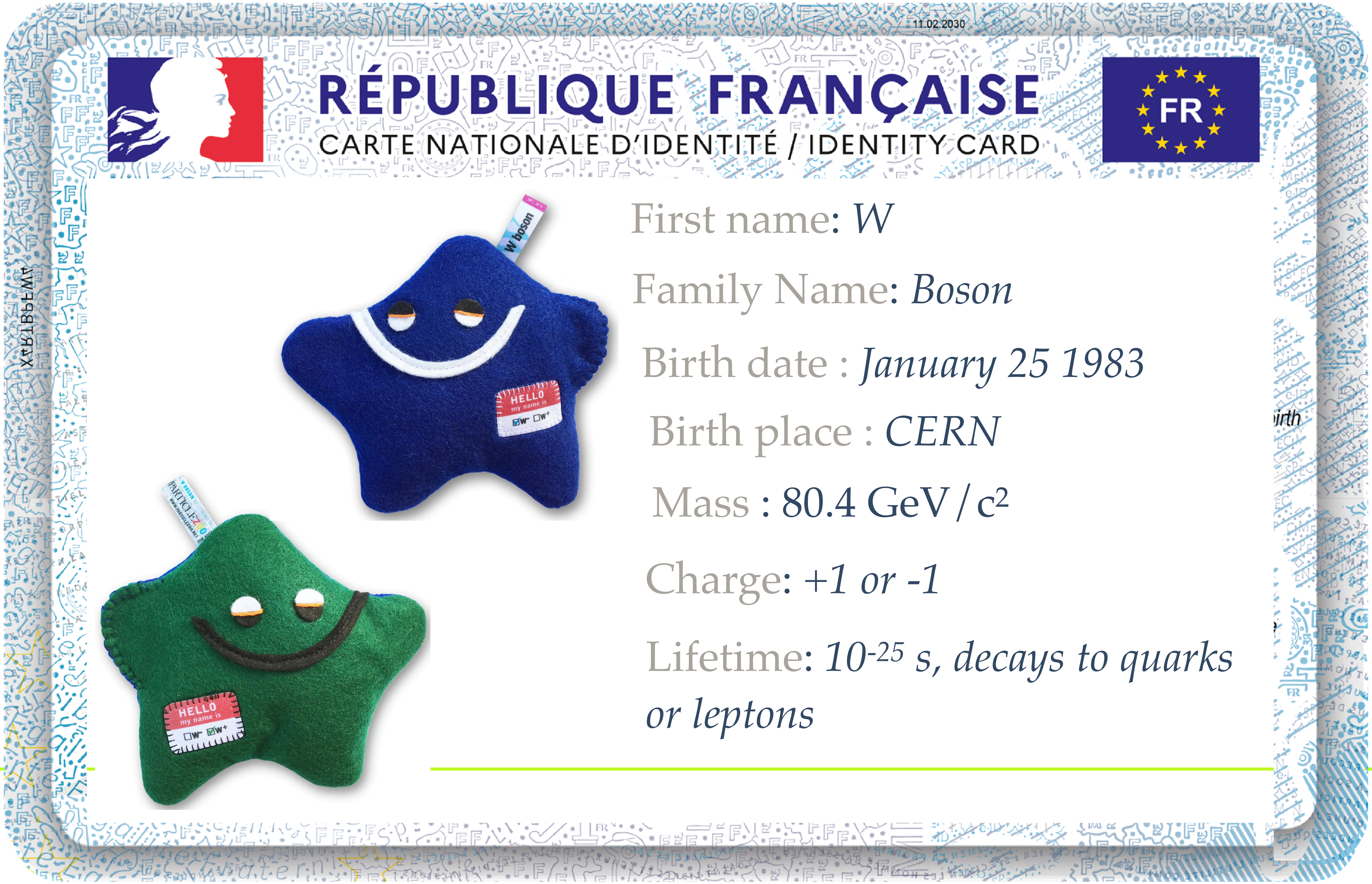




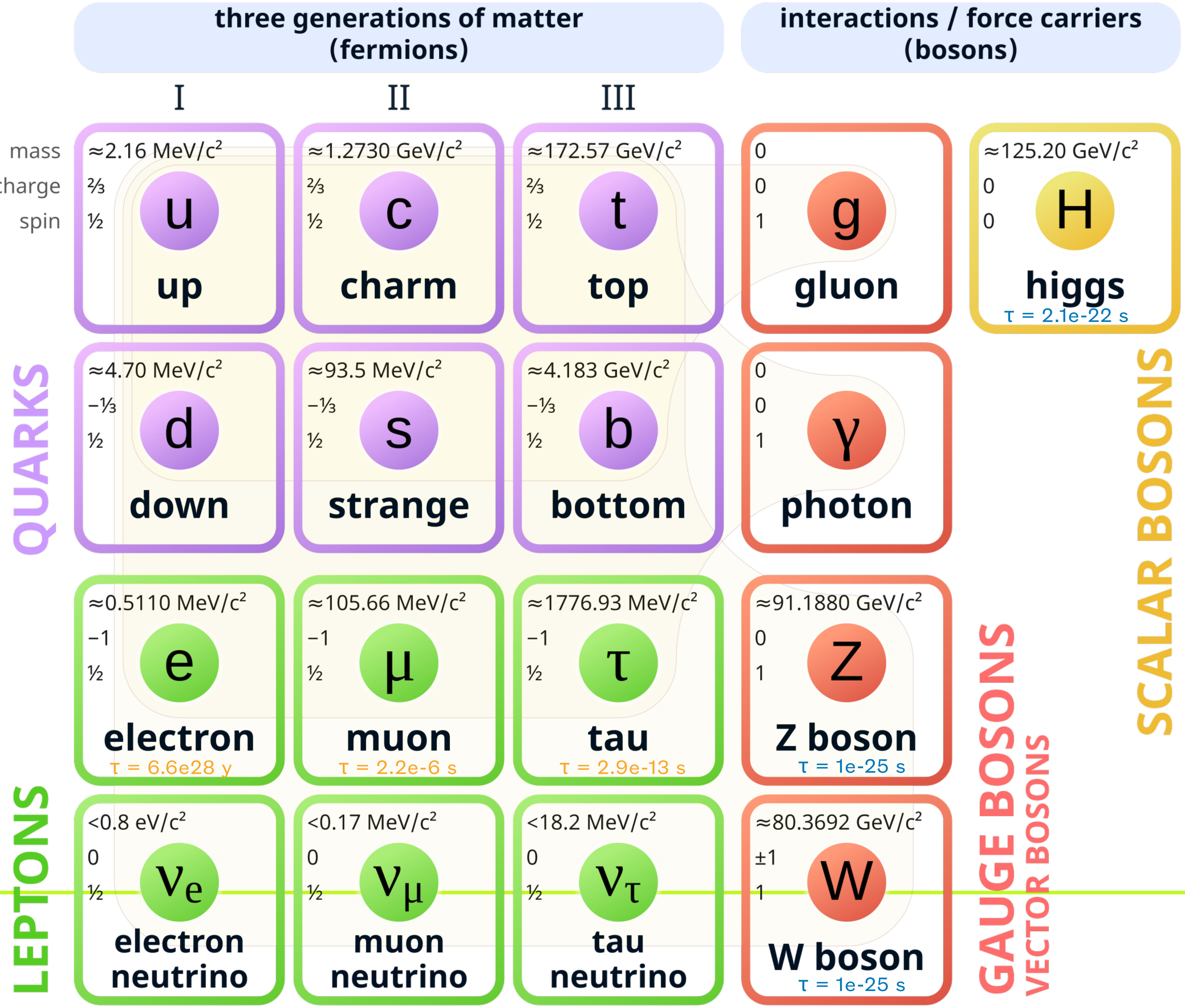


How can we recognize particles ?

- Thanks to their specific properties !
- And the way they interact with matter



Particle mass, charge and lifetime

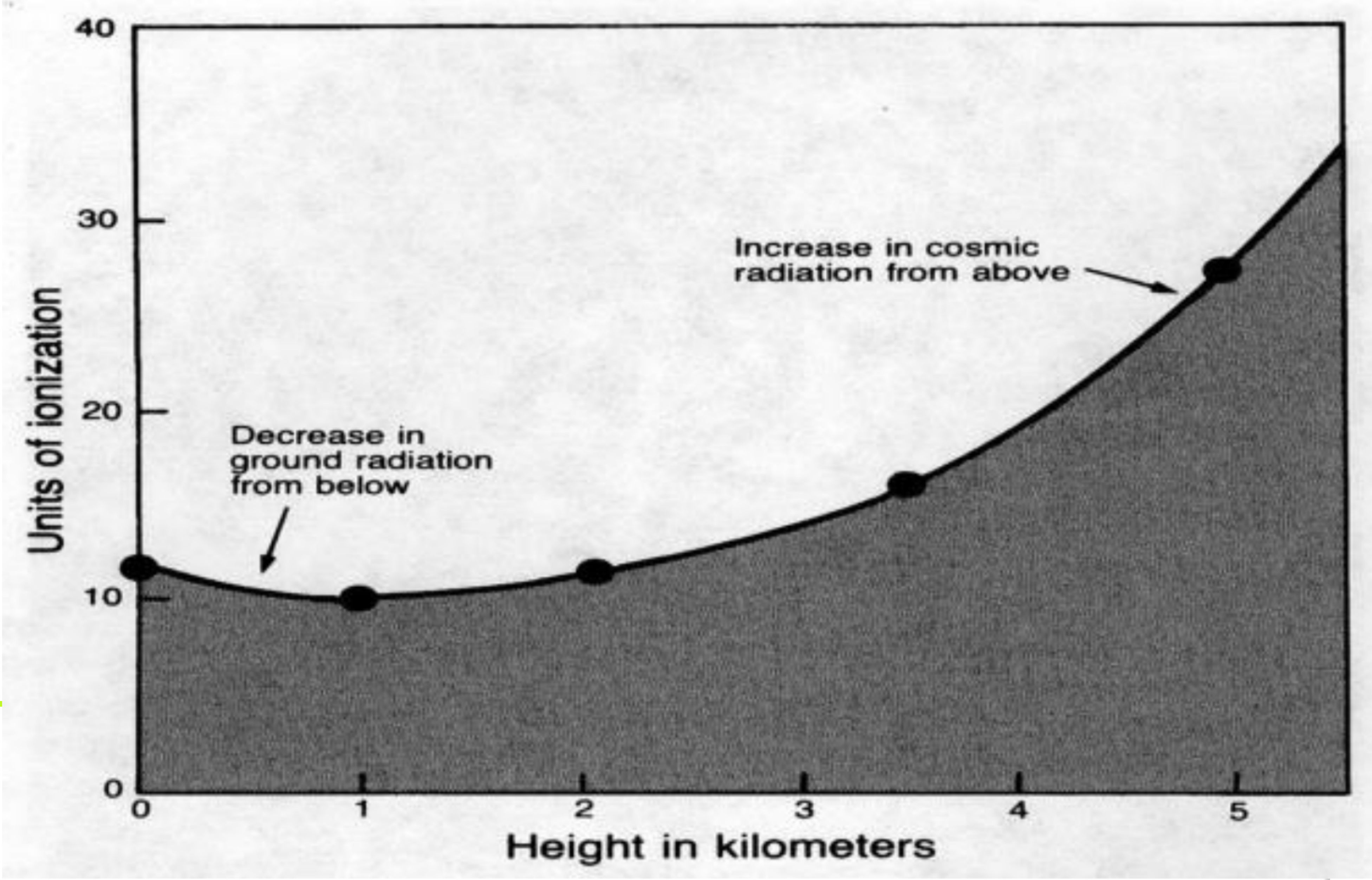


How were particles detected in the past ?

Some examples ....

Ballons flight and cosmic rays - 1912

- In 1909, Theodor Wulf was looking for origin of ionizing radiation registered on an **electroscope** -> tested on Eiffel tower (300 m) -> no much decrease compared to ground
- In 1912, several ascents, one of which at 5300m by Victor Hess -> increase of radiation level ! —> **Discovery of cosmic rays**



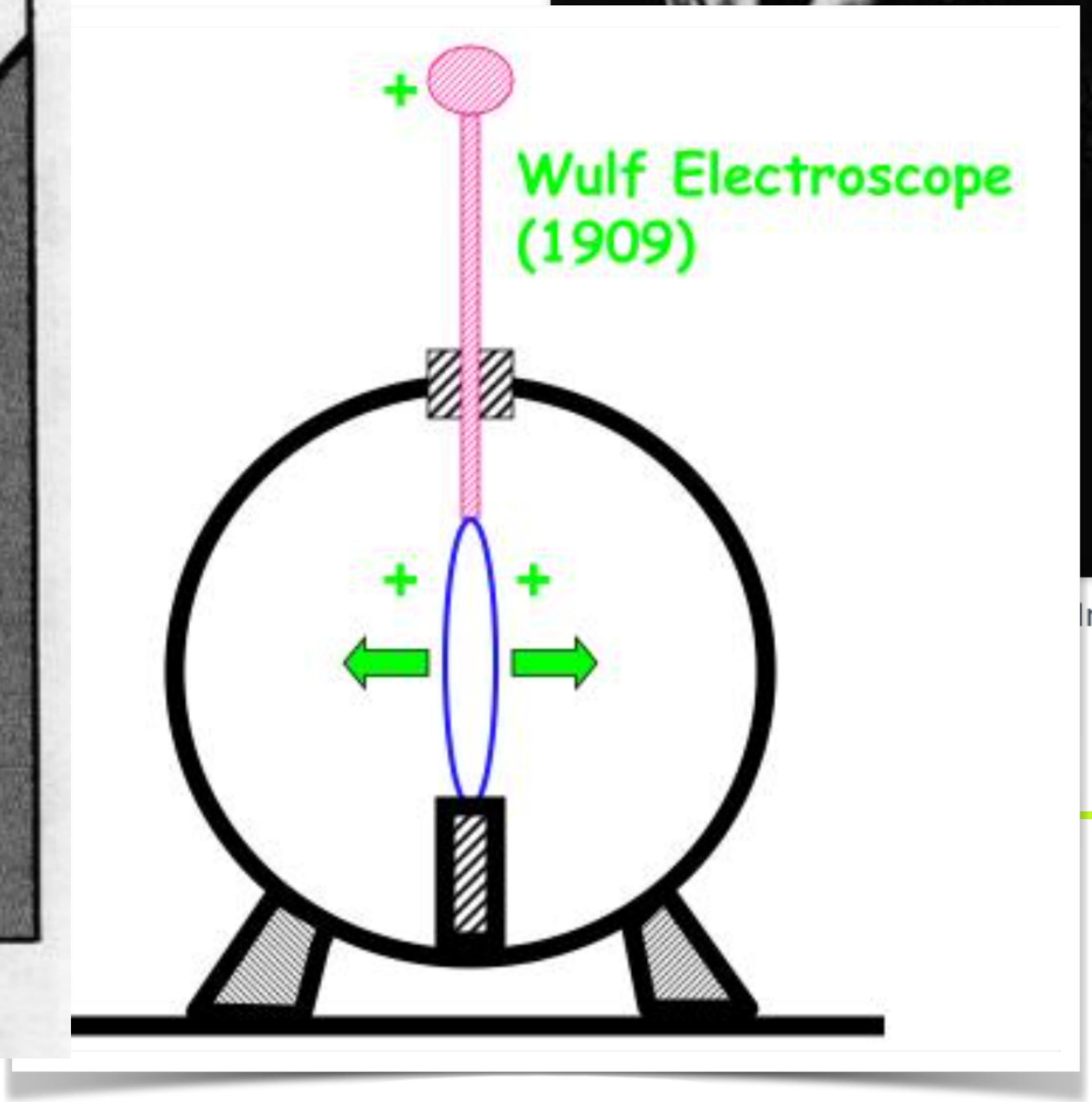
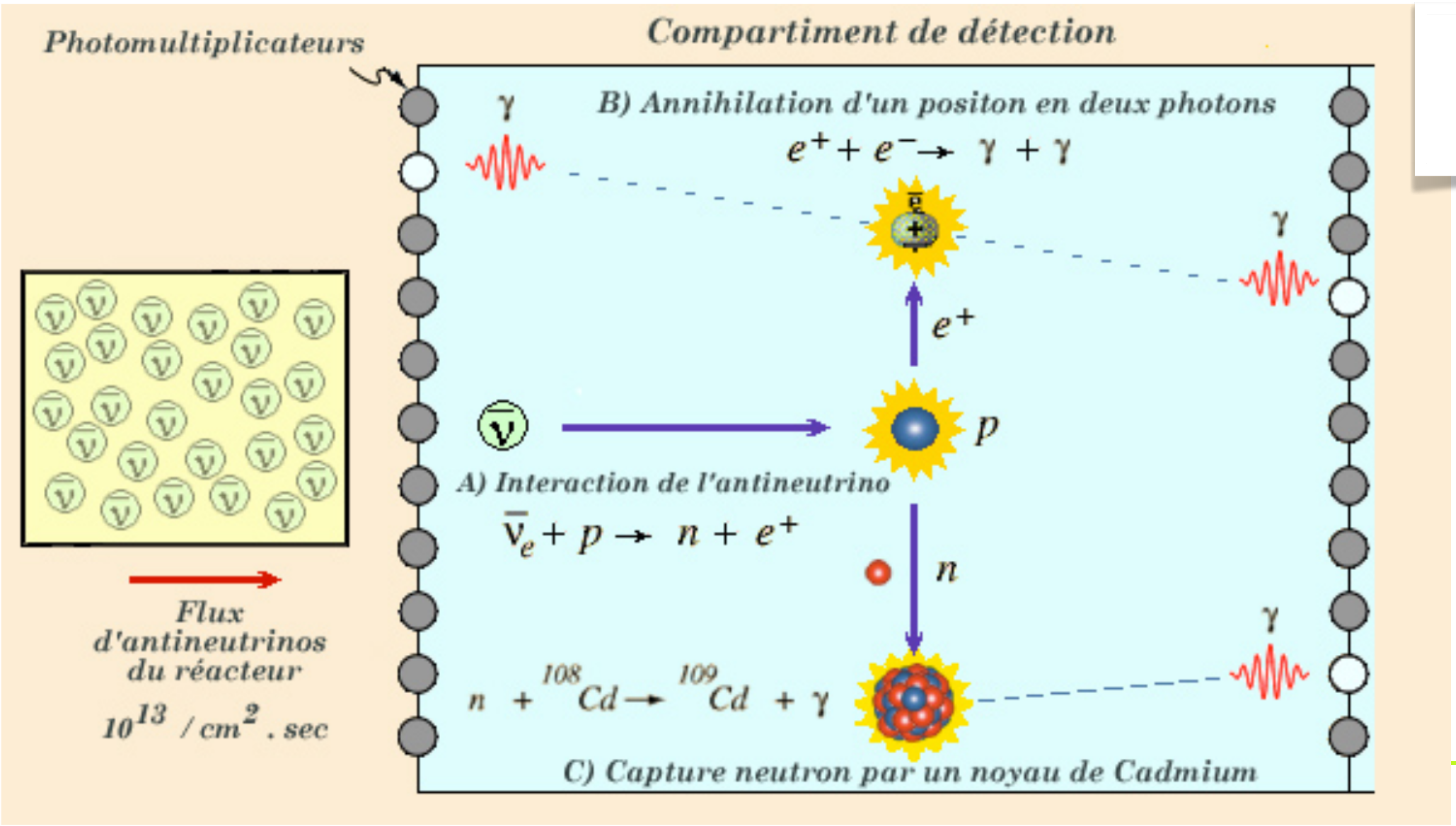


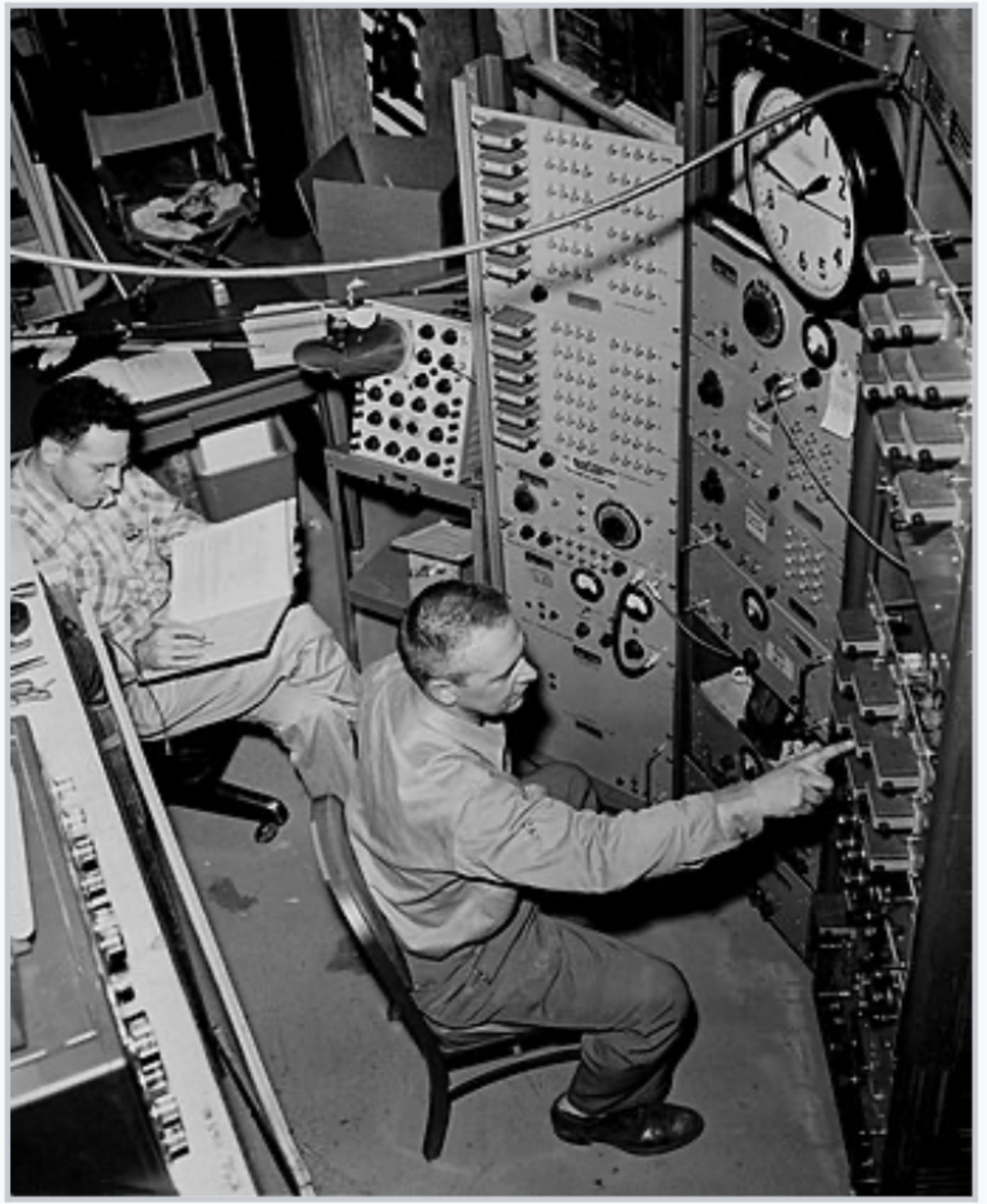
Image:Wikimedia commons)

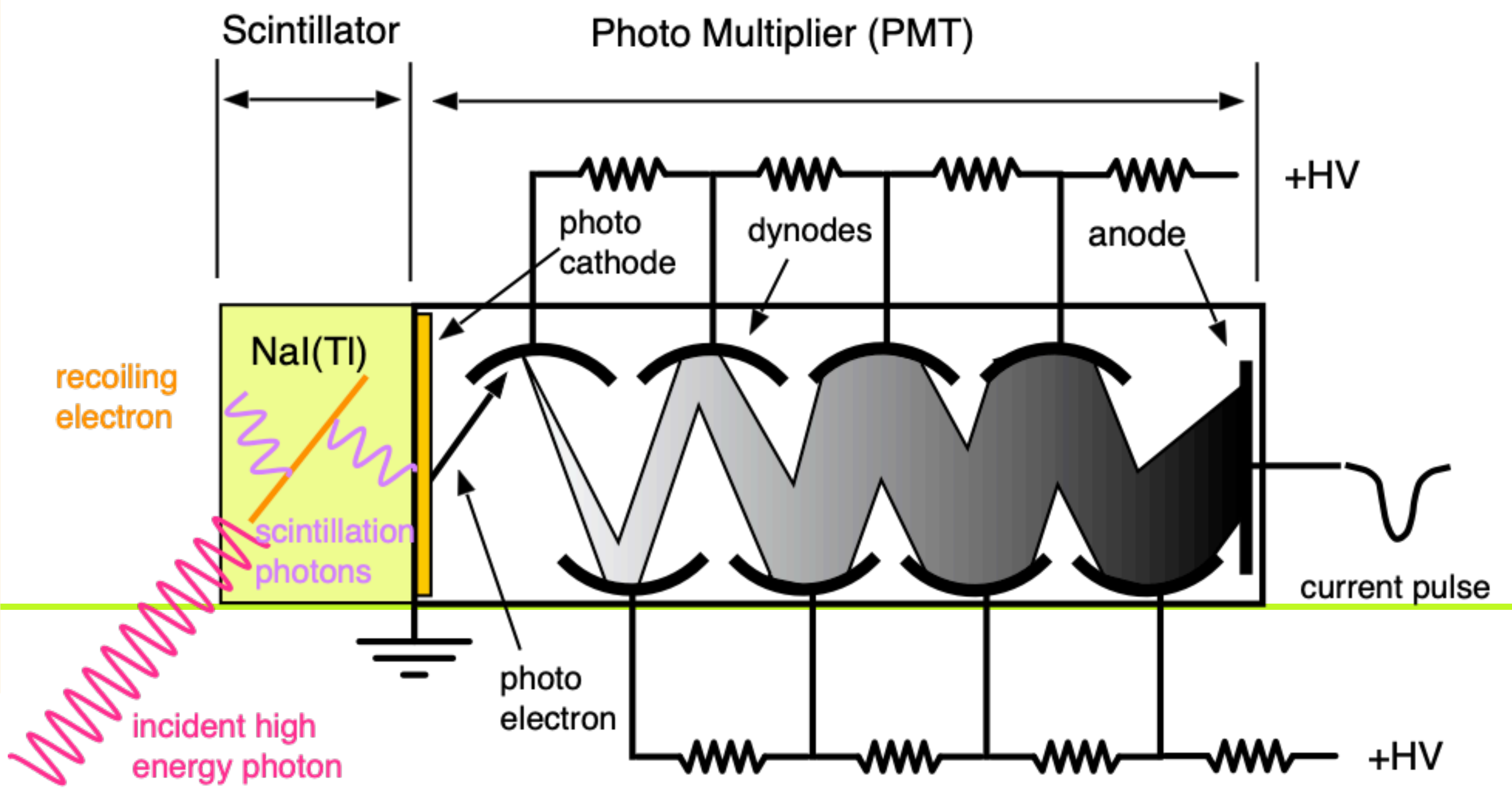
First neutrino detection and scintillators - 1956

- In 1956, Fred Reines and Clyde Cowan conducted an experiment (project Poltergeist) close to a reactor in USA : two tanks with 200 liters of water with ~40 kg of dissolved cadmium (great absorber of neutrons).
- Water tanks sandwiched between **two layers of organic liquid scintillators** (just invented !) containing 110 photomultiplier tubes —> **observation of neutrino**



$$\bar{\nu}_e + p^+ \rightarrow n^0 + e^+$$



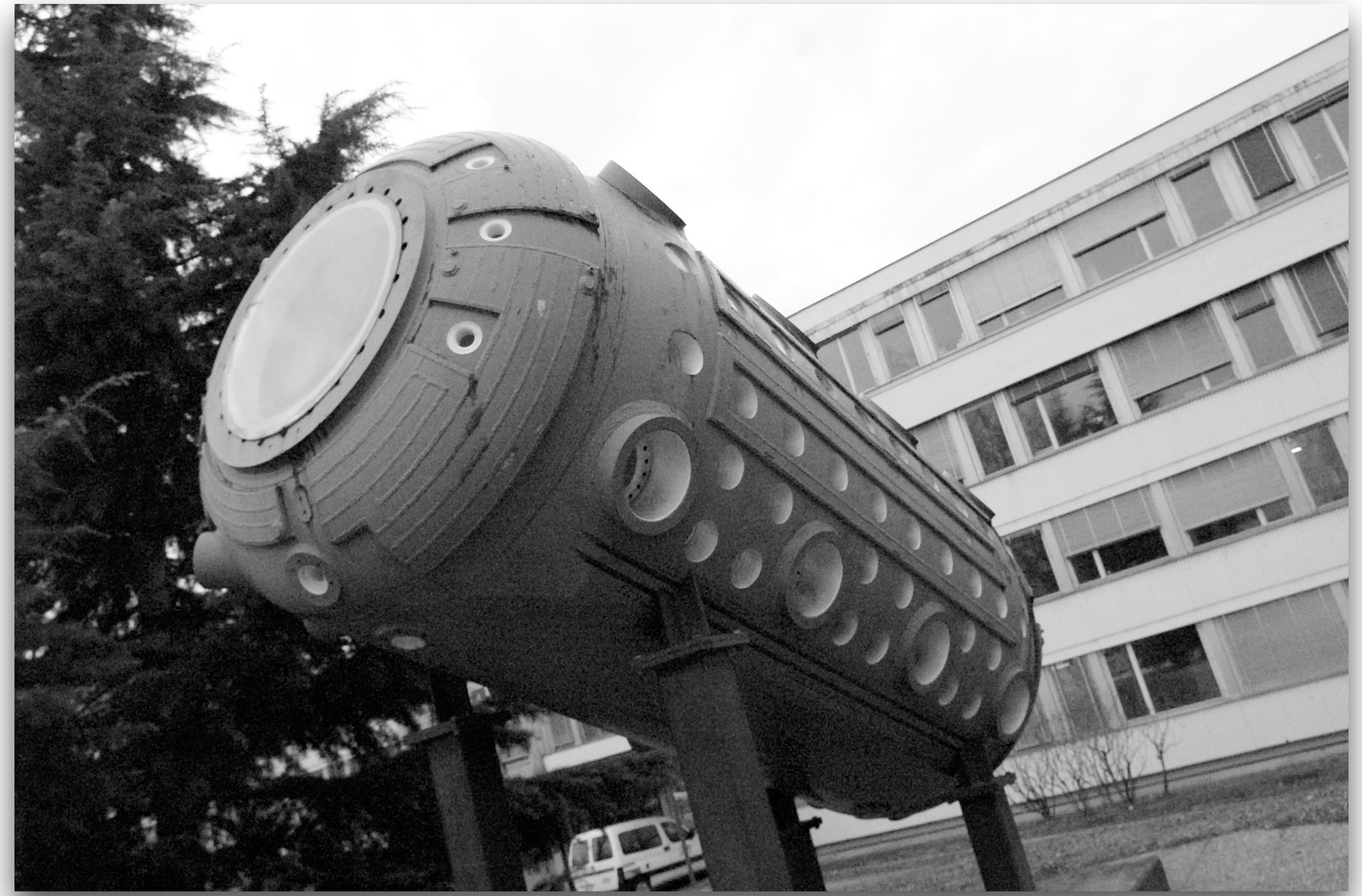


https://laradioactivite.com/articles/le-phenomene/observation-neutrino

Bubble chamber and neutral current - 1973

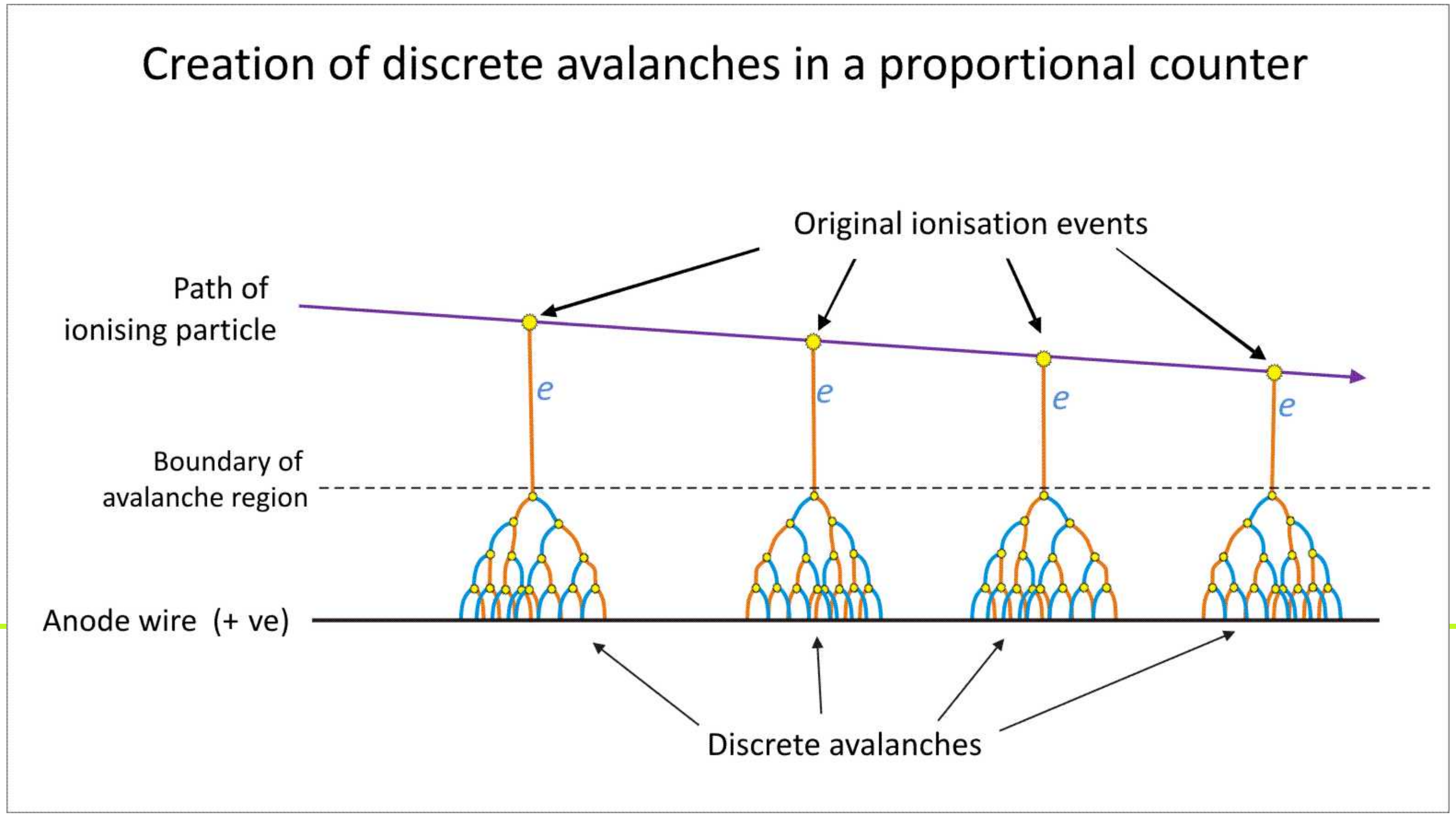
- **Bubble chamber (Donald Glaser)**: closed cavity filled with liquid (hydrogen) in metastable state, at precise limit of boiling. When external particle interacts with atoms of the liquid -> small rise in local temperature -> small bubbles form, trajectory curved thanks to magnetic field -> photos
  - need to examine thousands of photographs !
- **Discovery of neutral currents**, Gargamelle (CERN), 1973

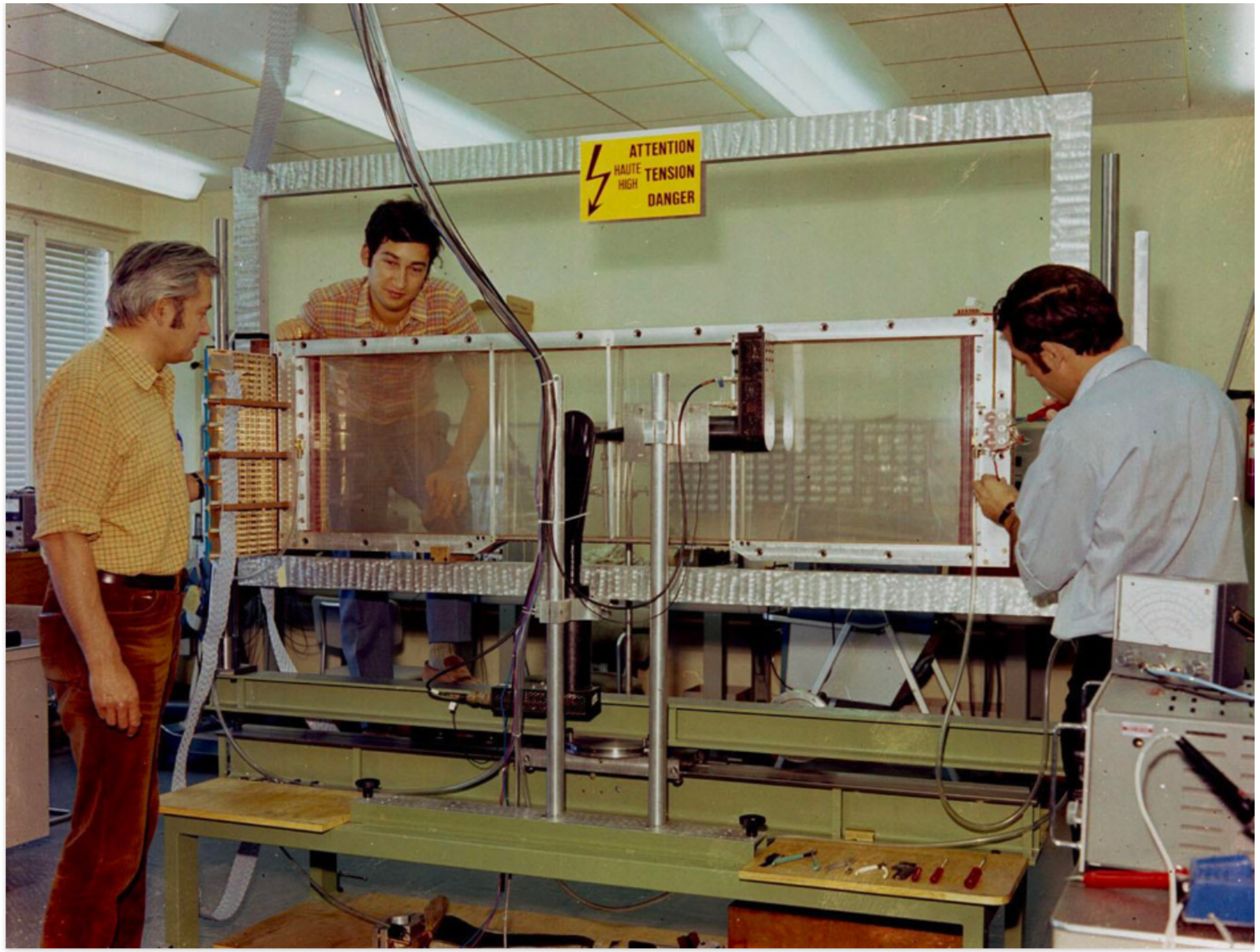
Le 19 juillet 1973, le CERN (European Laboratory for Particle Physics) annonçait sa première découverte majeure : les "courants neutres faibles". - 1973-2024 CERN (License: CC-BY-4.0)



Wire chamber - W, Z bosons, gluon - 1968

- 1968: invention by Georges Charpak of **multiwire proportional chamber** -> new detector technique that could record millions of particle tracks each second, instead of examining photograph one by one
- Electrical voltage applied to a gas-filled tube with a wire running through its centre.
- Thanks to this technique, discovery of **charm quark** (BNL, SLAC - 1975), of **gluon** (TASSO in PETRA- DESY, 1979), and of **W and Z bosons** (UA1/UA2 -CERN, 1983)





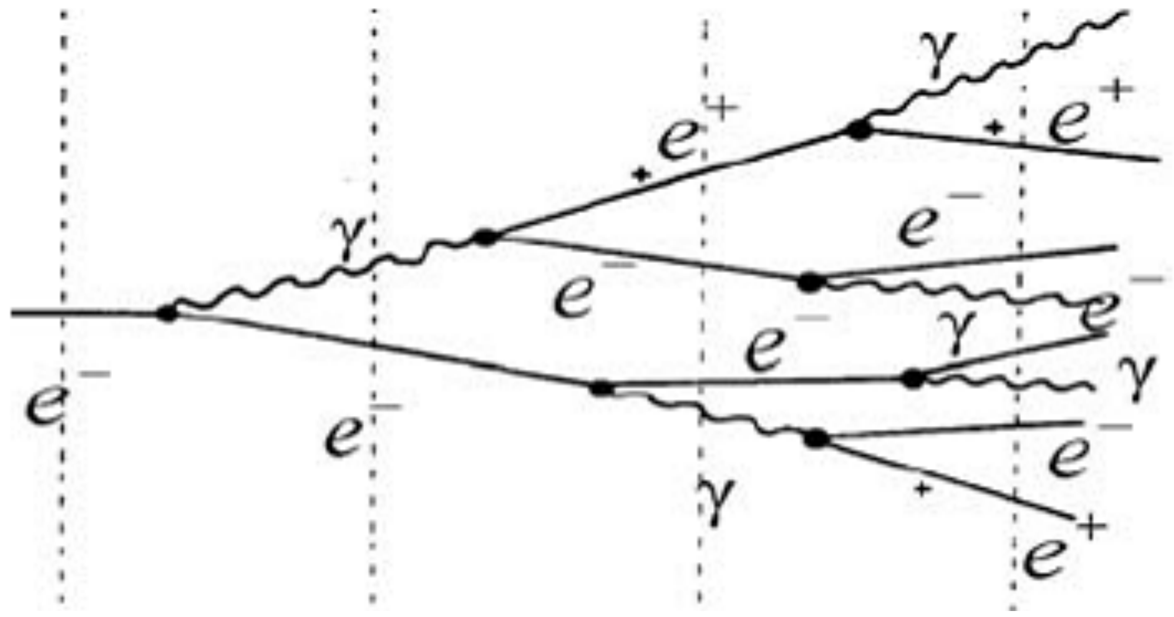
Georges Charpak's 'multiwire proportional chamber' particle detector consisted of many parallel wires, each connected to individual amplifiers. Linked to a computer, it could achieve a counting rate a thousand times better than before (Image: CERN)

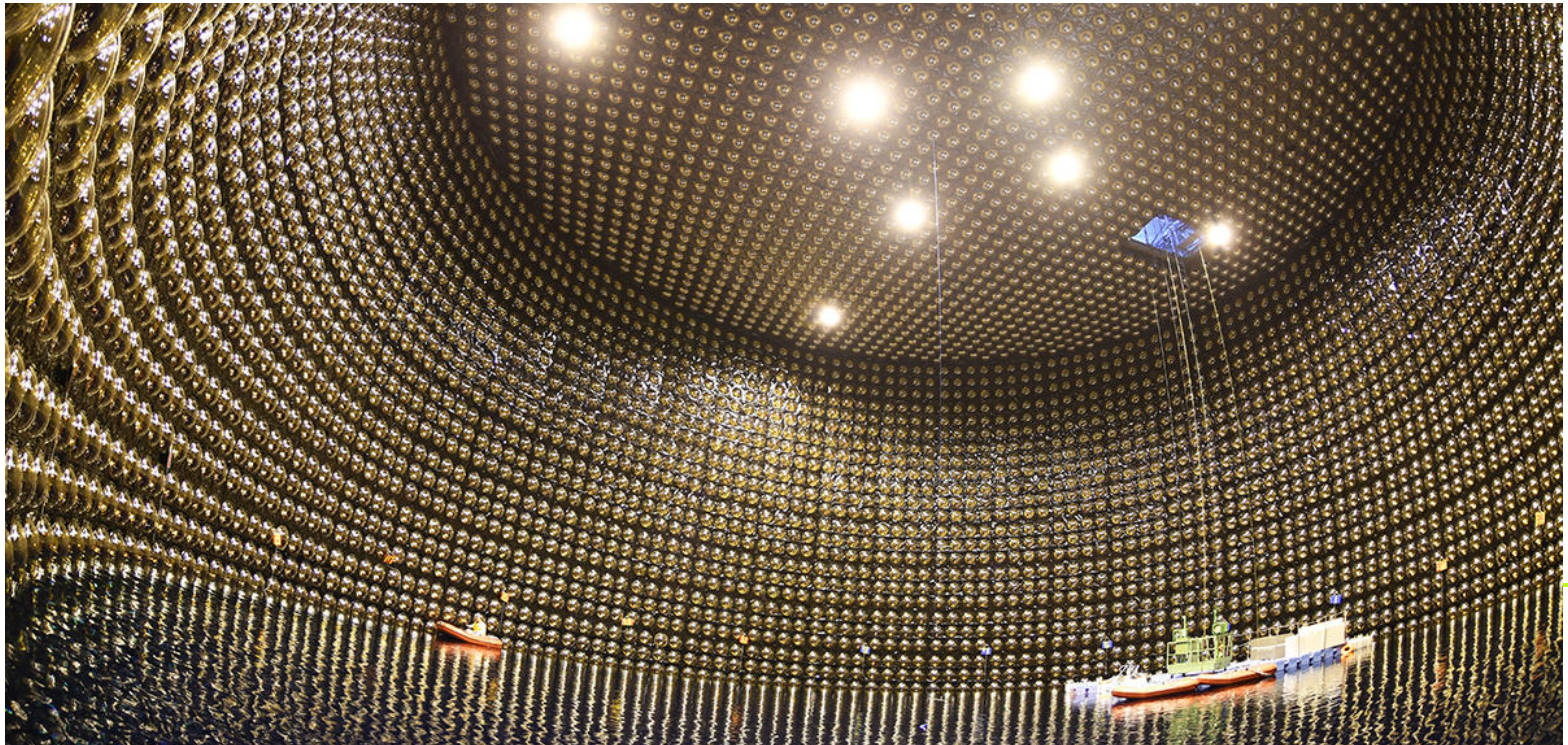
Current detection techniques

Some examples ....

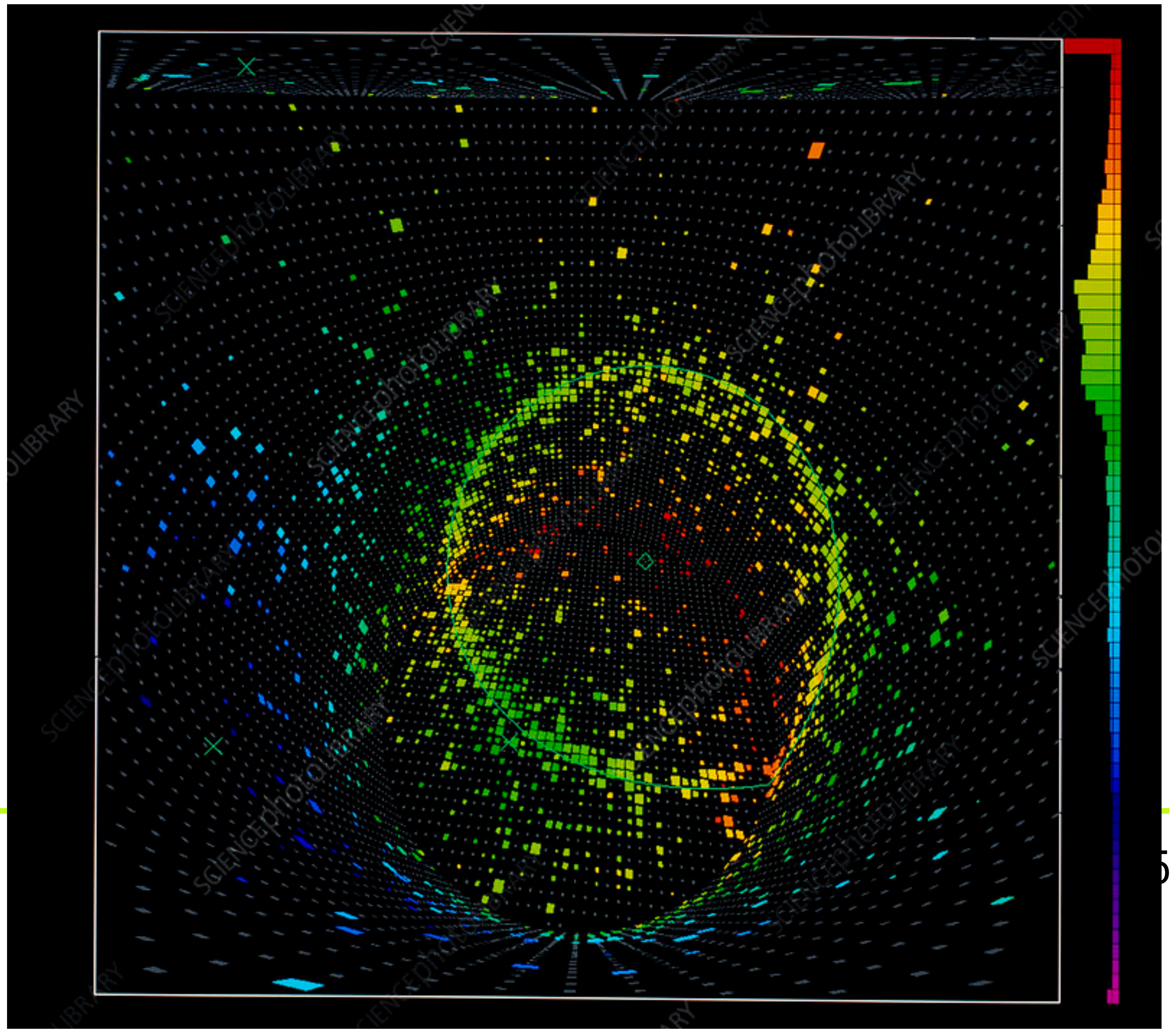
Neutrinos detection

- Very rare interactions -> very large detectors volumes + underground to protect against background
- **Super-Kamiokande (Japan, 1000 m underground)**: 50 000 tons of water with ~10000 PMTs to detect Cerenkov light, 40m x 40 m. Electron-neutrino interacts to create an electron. Electron produces a 'ring' due to radiation of subsidiary photons that turn into electron-positron pairs. -> electromagnetic cascade
  - only 90 candidates in a decade !
- Extension (Hyper-Kamiokande) expected in ~2027 (258 ktons of pure water)



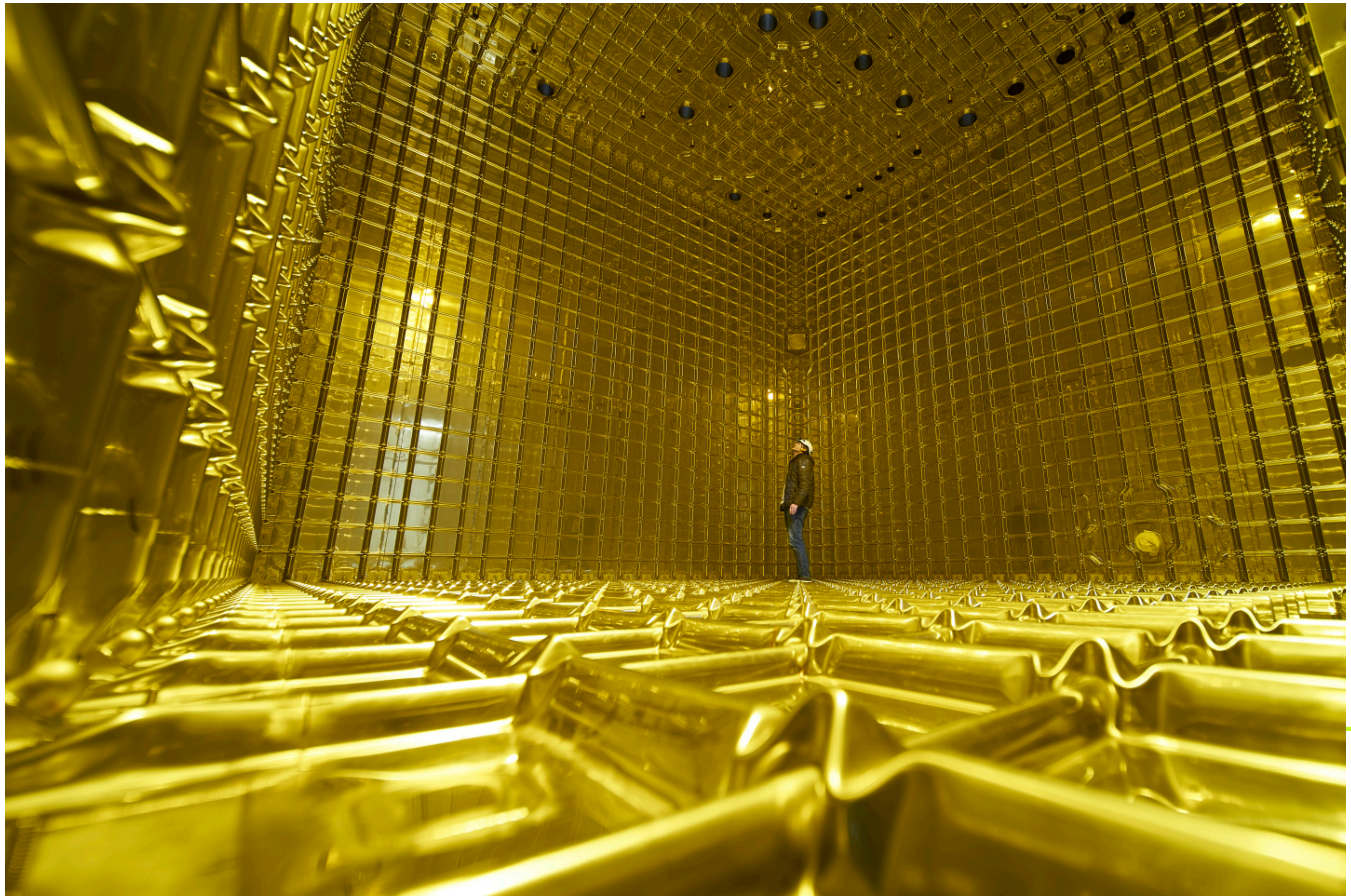


red indicates the earliest light to arrive

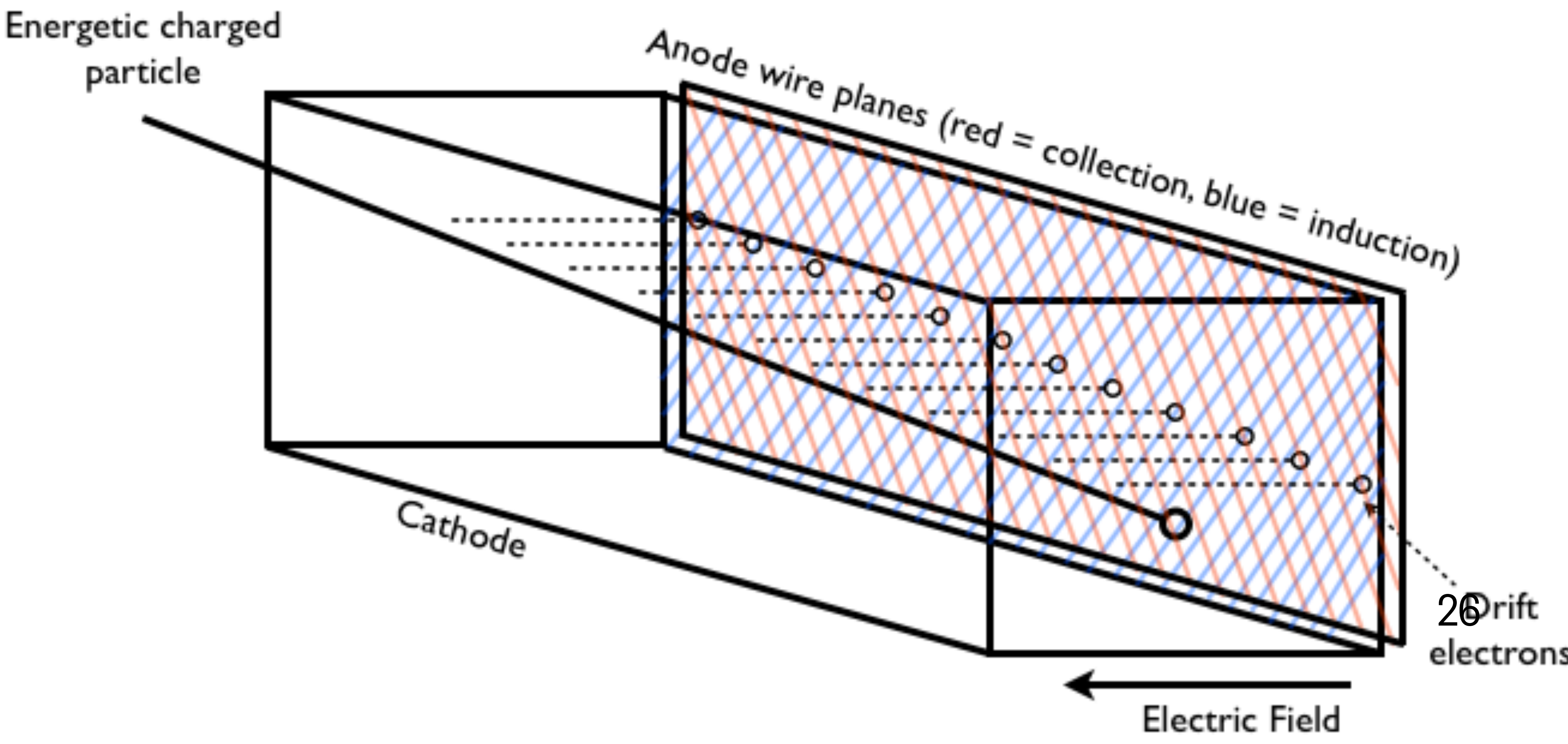


Neutrinos detection

- **Dune (2032)**: 70 ktons of of liquid argon (LAr), 1.5 km underground, when neutrinos enter in detector, they collide with Argon atoms -> charged particules created -> ionisation of the argon detected with time projection chambers (TPC) -> 3D images.
  - argon used because does not reabsorb ionisation electrons (noble element) + scintillations
- ProtoDune currently taking data at CERN, to prove feasibility (20 times smaller than DUNE) -> ***LAPP team !***

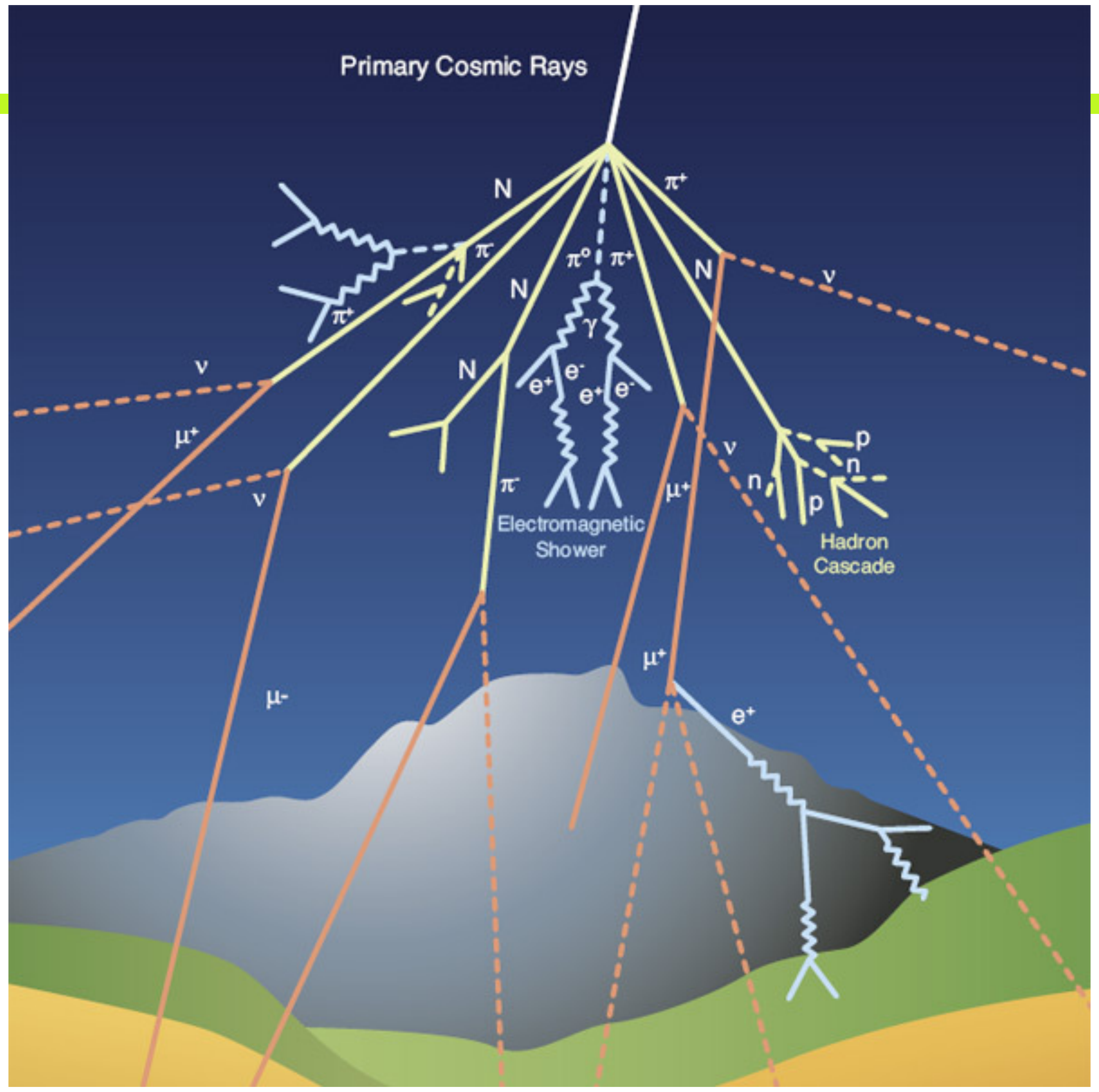


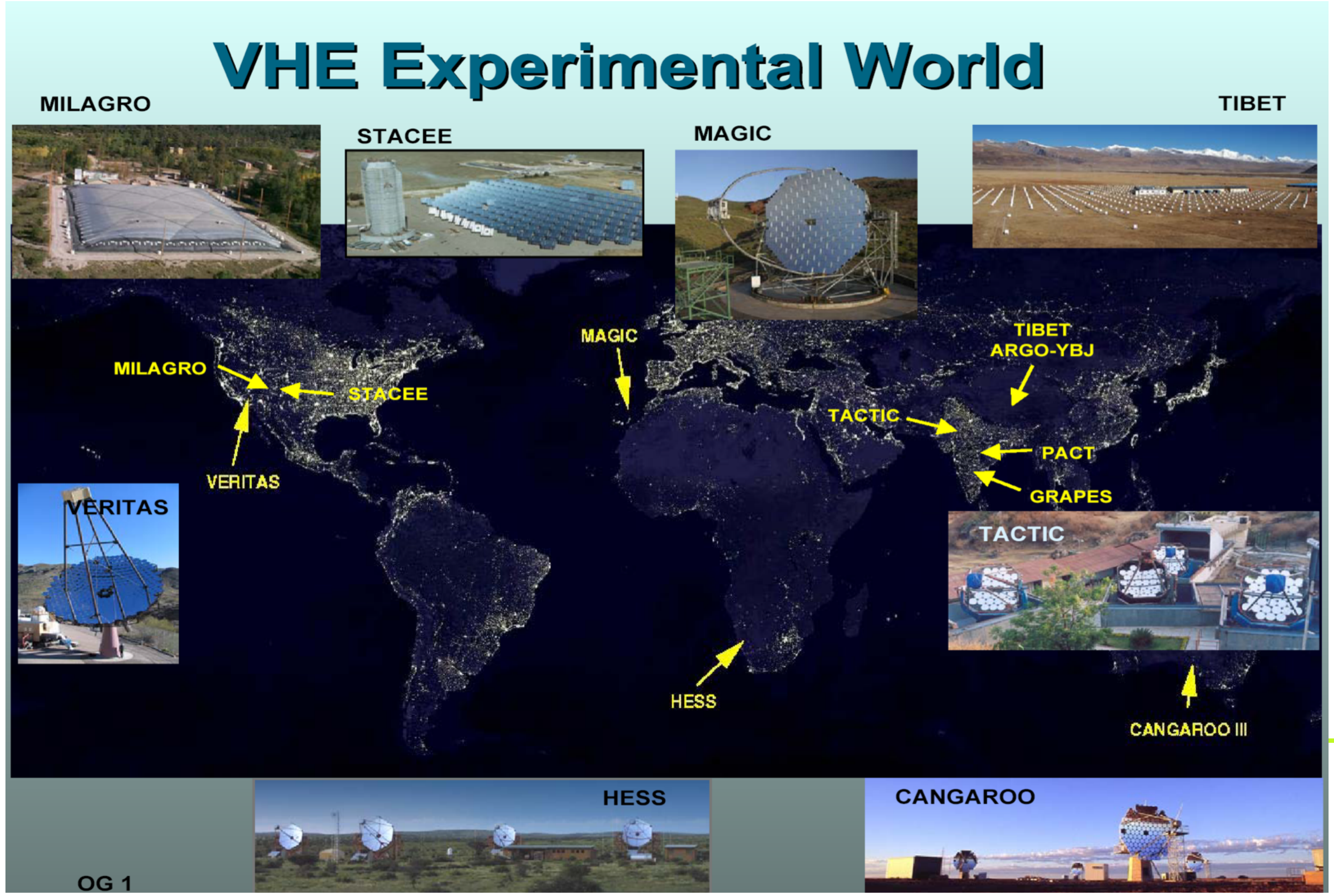
LArTPC

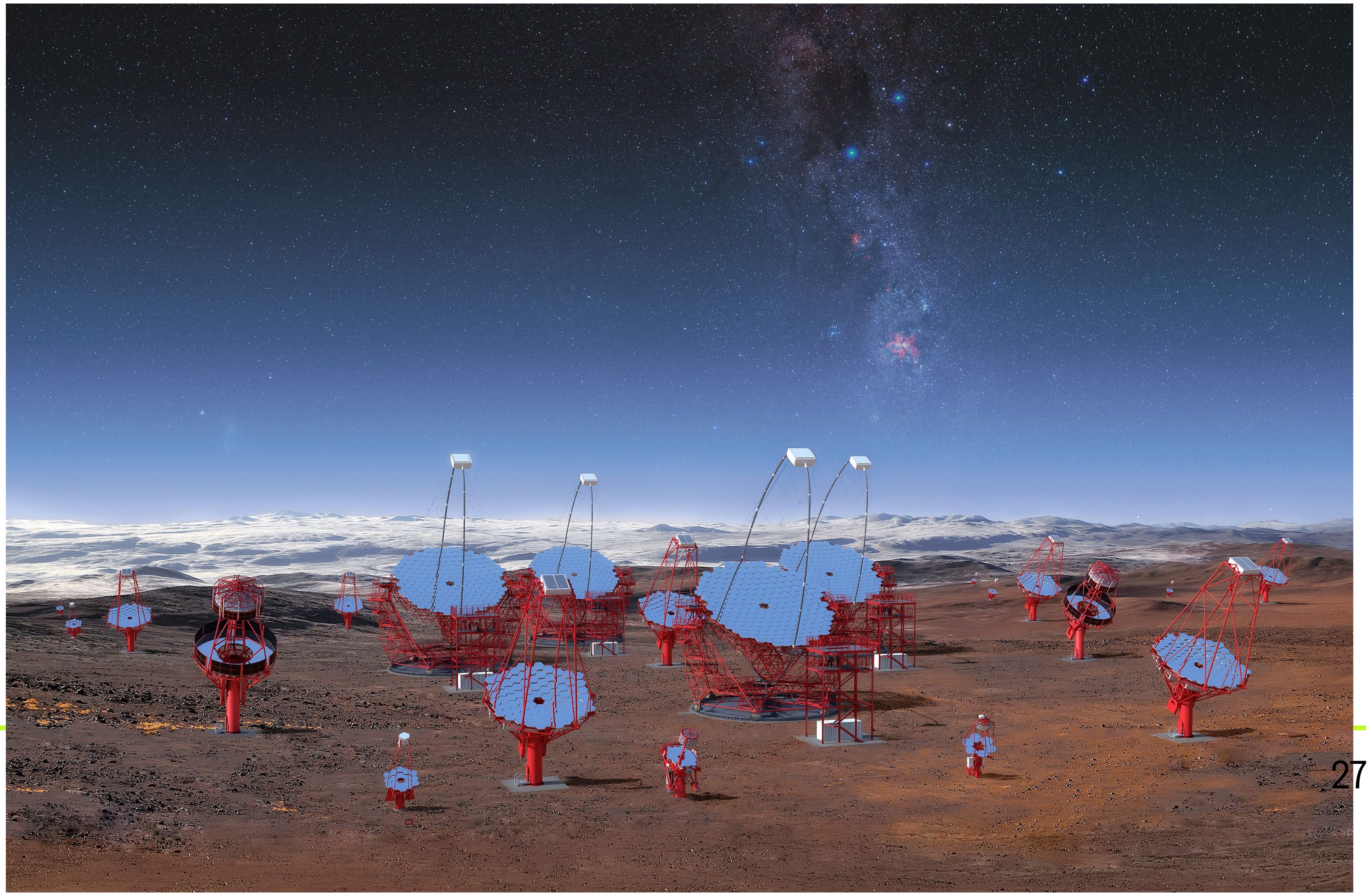


Cosmic rays

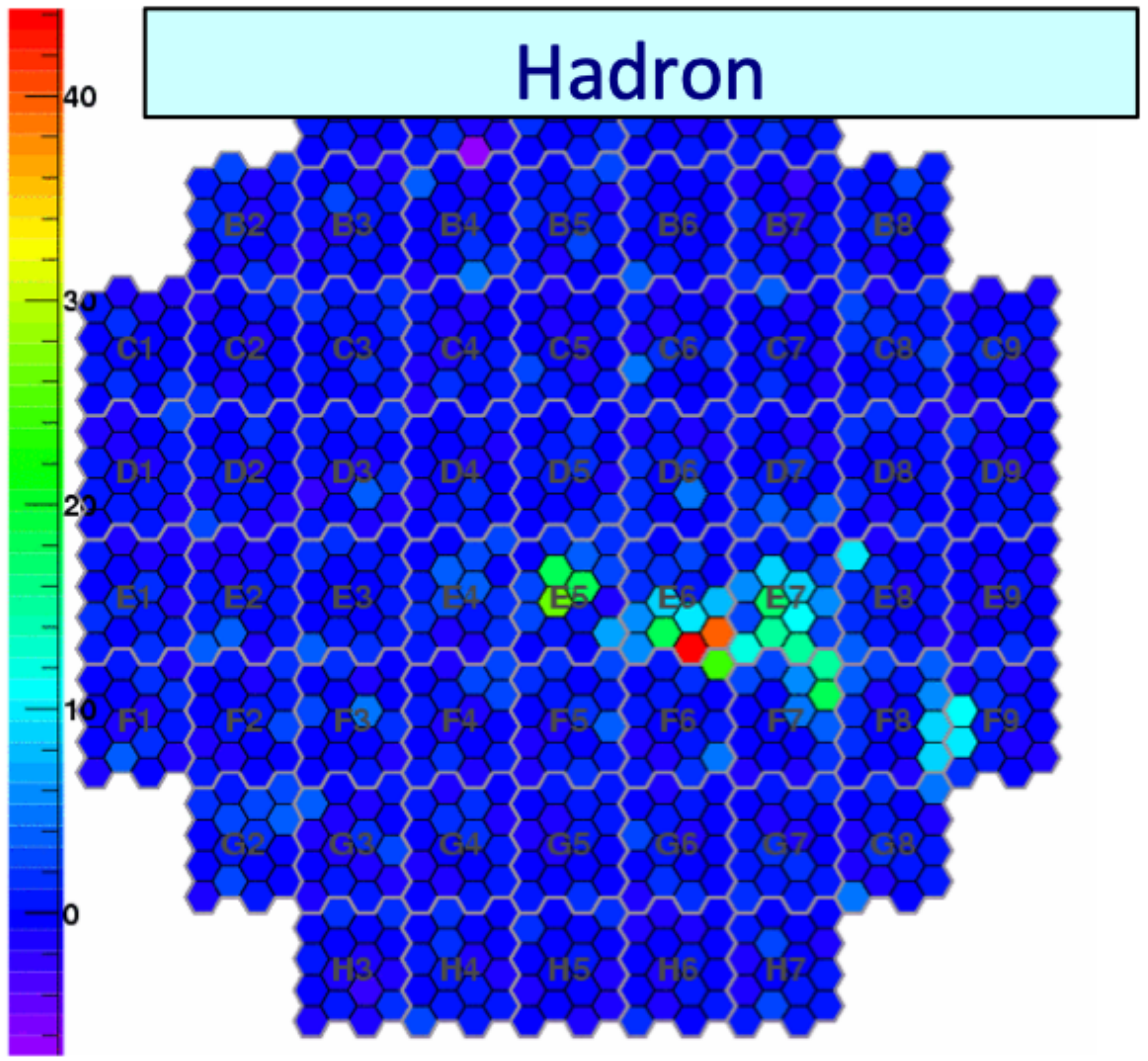
- Cosmic particules entering in atmosphere -> cascade -> Cerenkov light cone of ~250 m for a few nanoseconds close to ground
- **CTA (~2025)** : 118 telescopes with 3 different sizes on two sites (Palma, Chili). Large mirrors to converge light + camera with PMTs with short exposure time to record the signal -> ***LAPP team !***

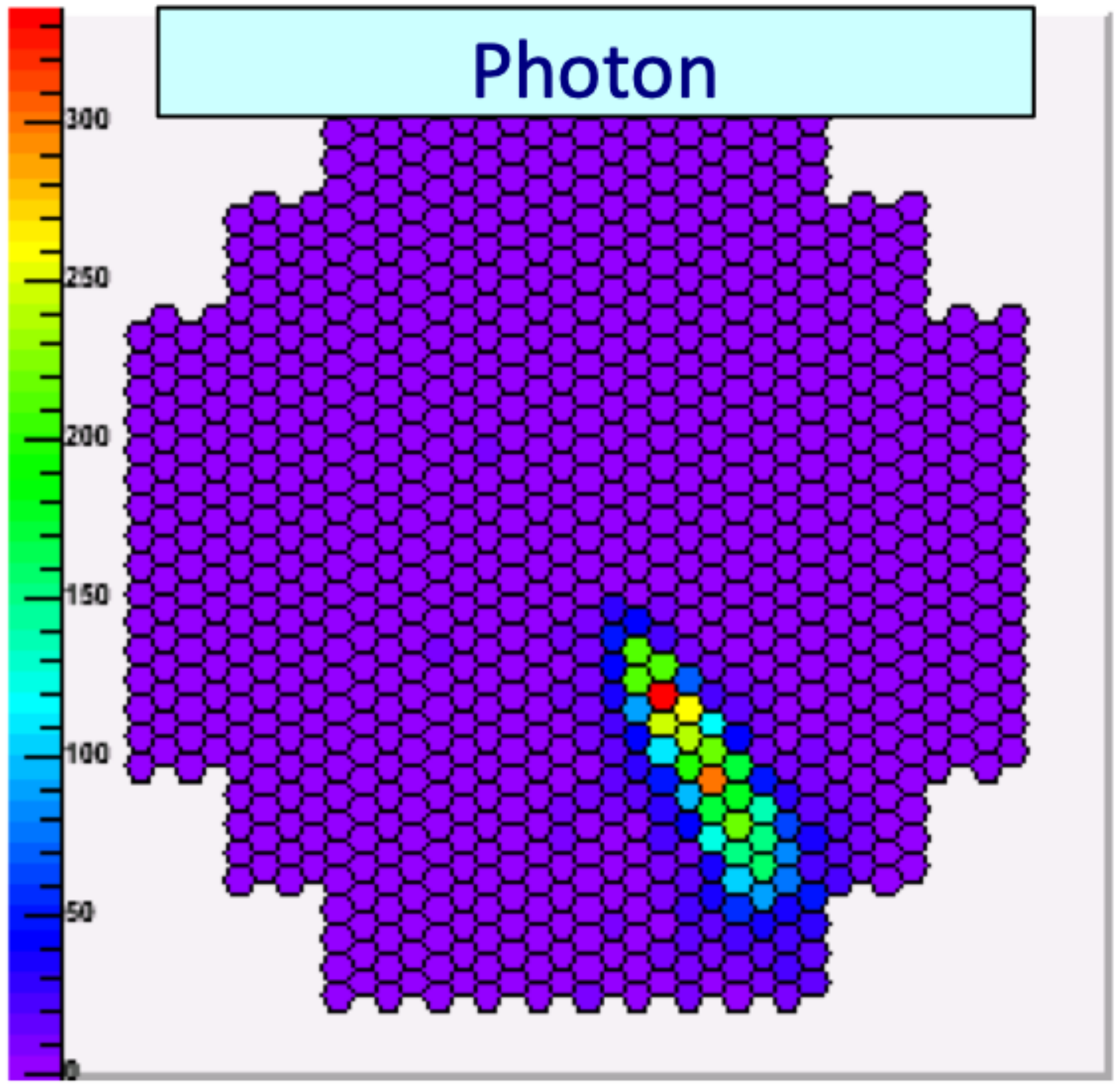


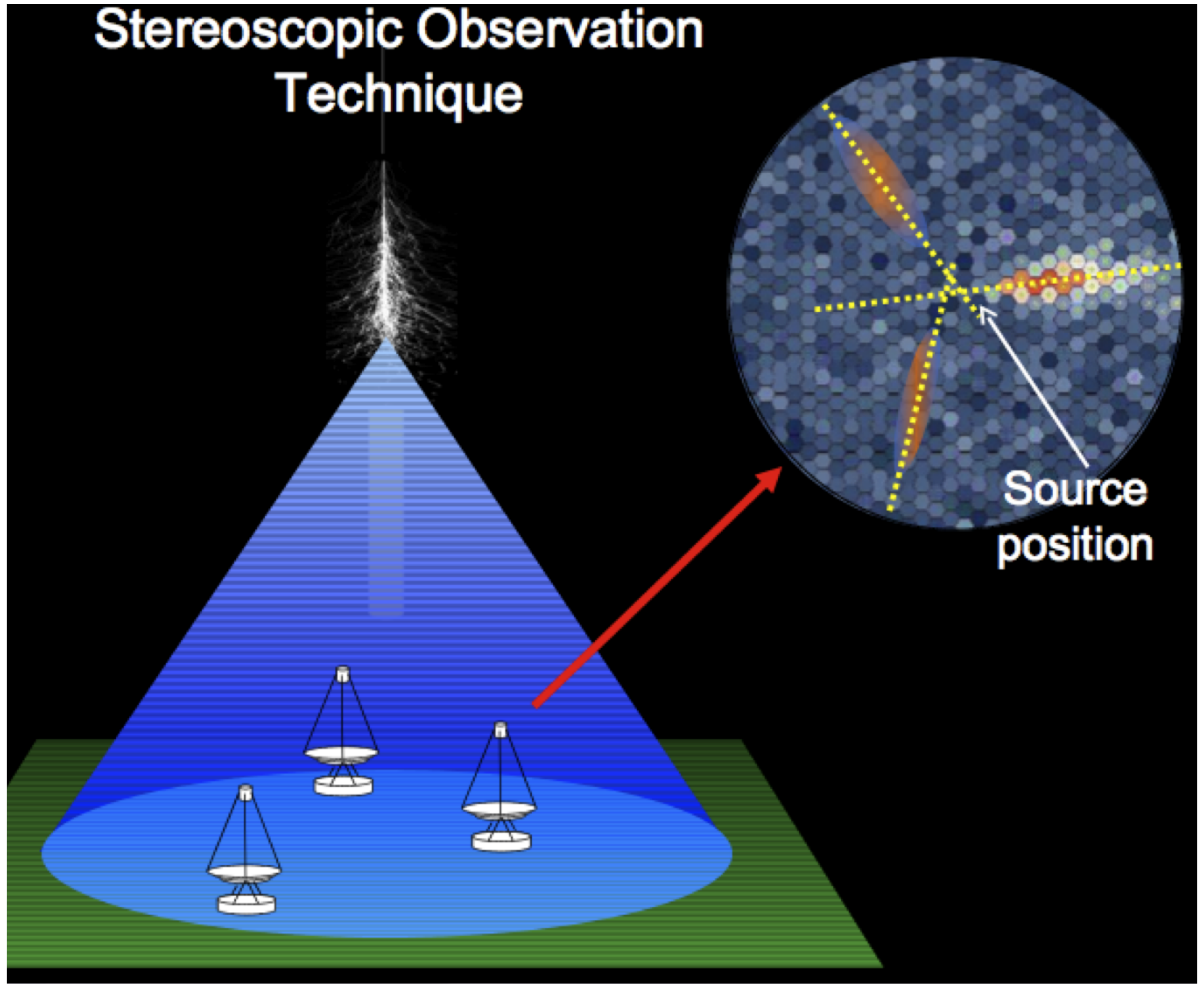




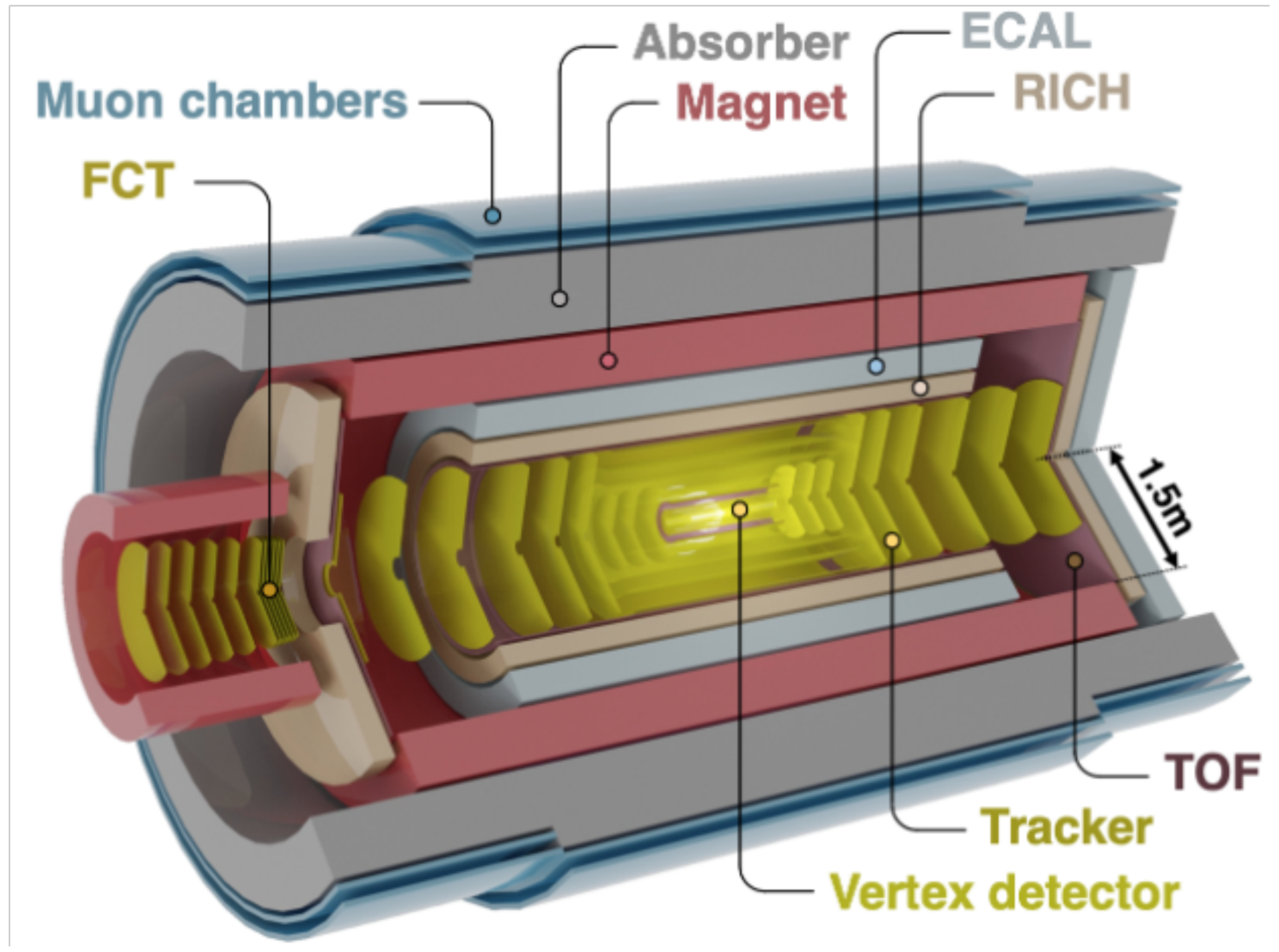
Identifying particule





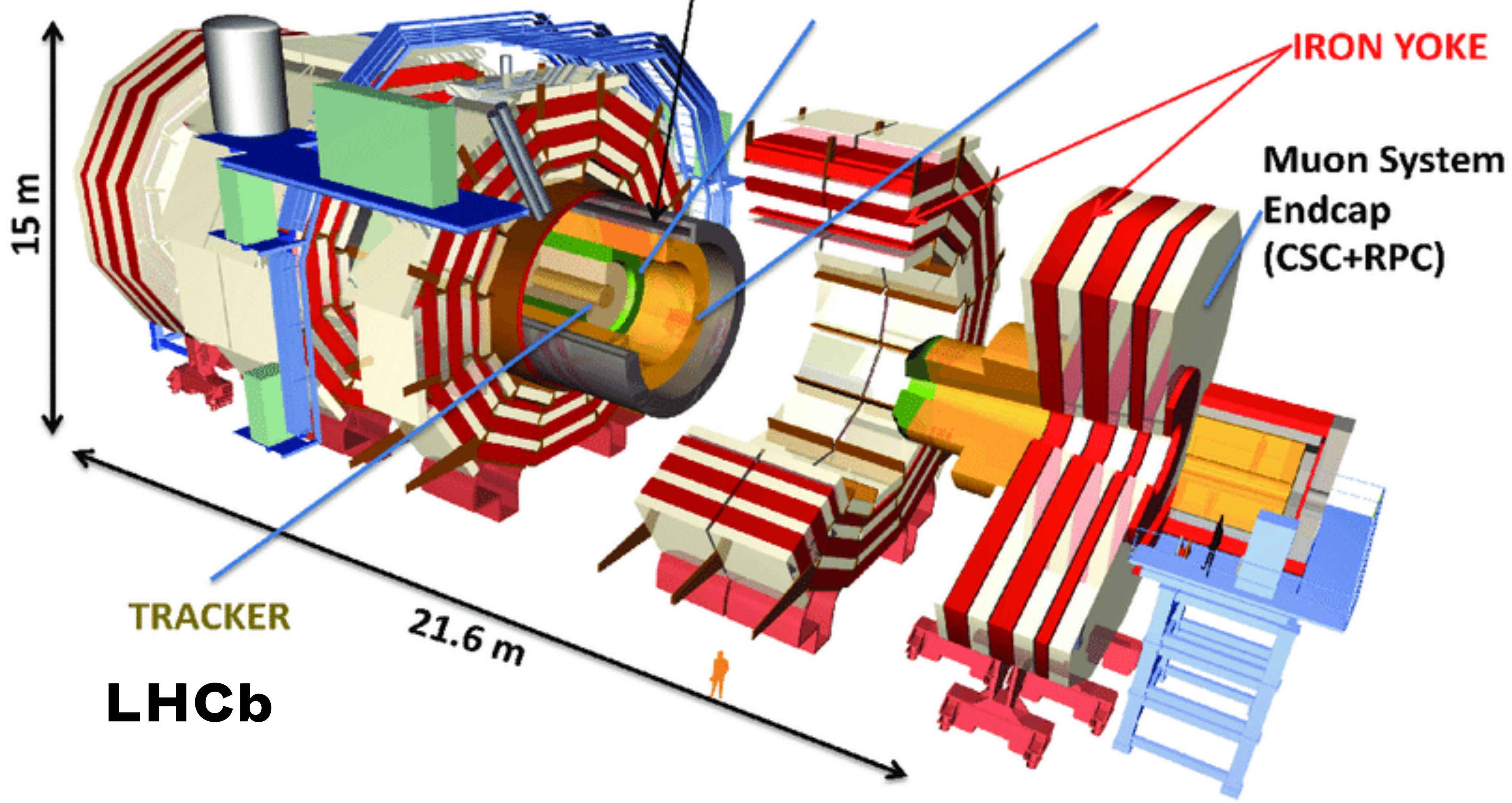


LHC detectors



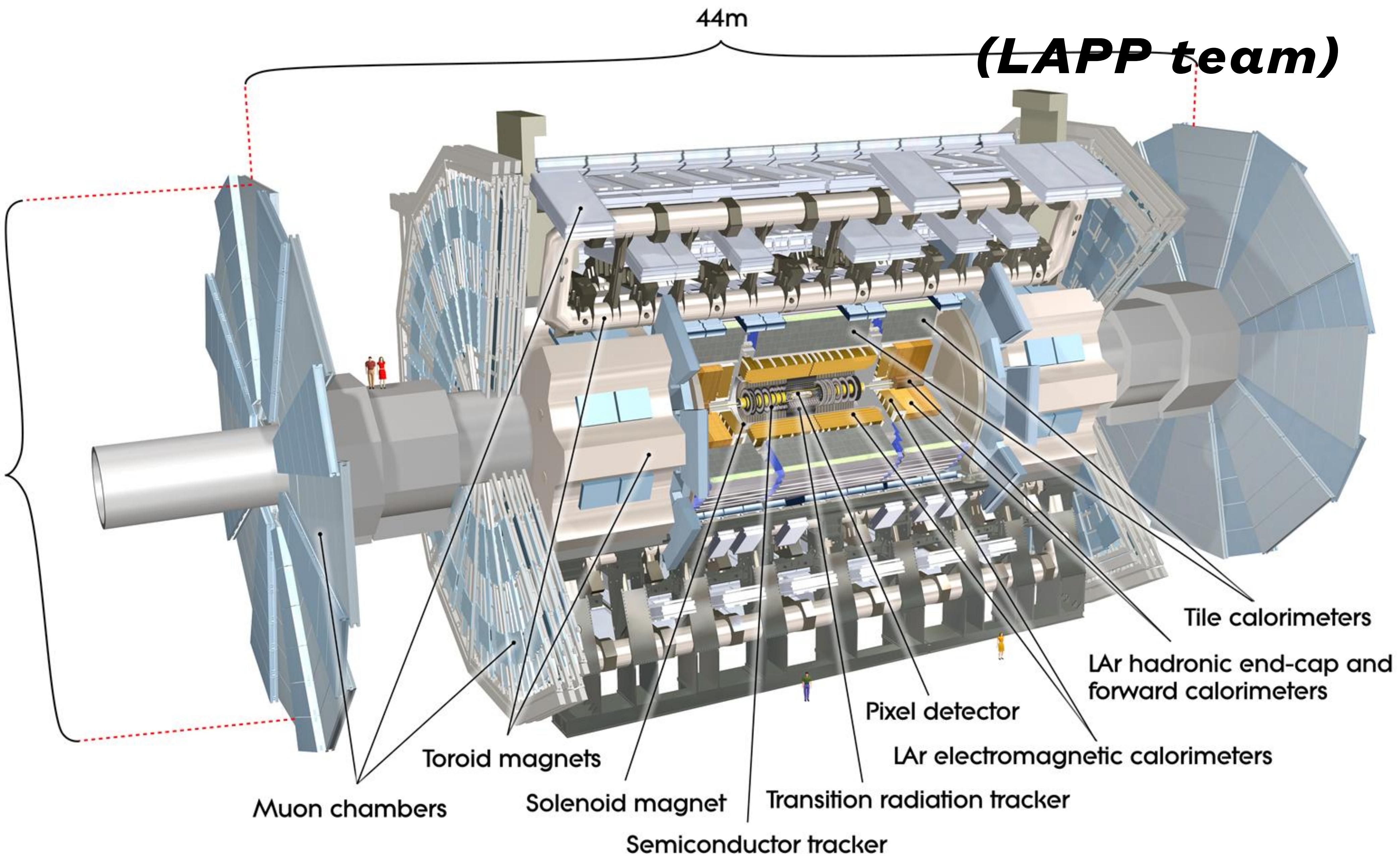
ALICE

CMS



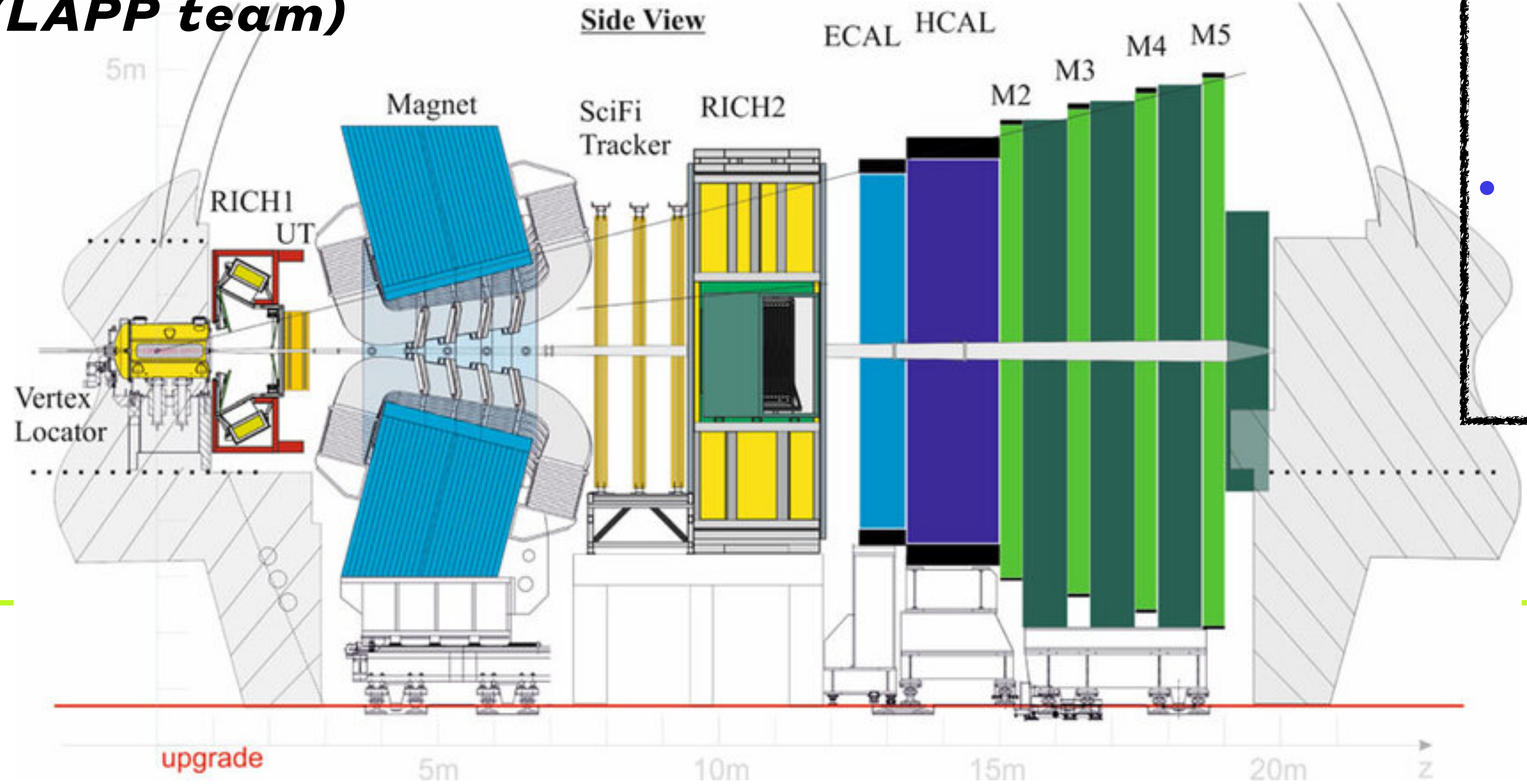
ATLAS

(LAPP team)



LHCb

(LAPP team)

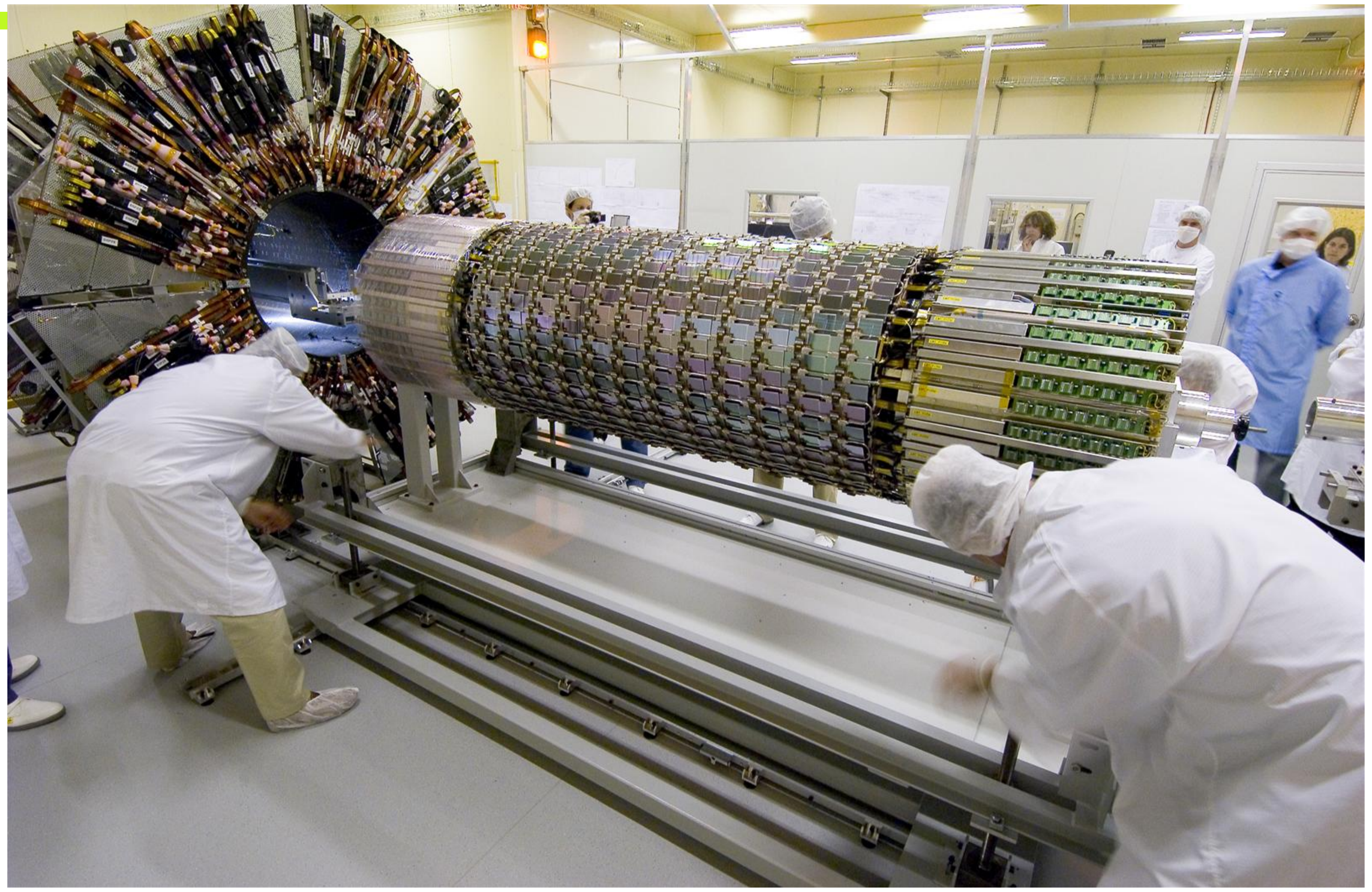


- High magnetic field to curve trajectories
- Tracker to reconstruct trajectory of produced particles
- Calorimeter to measure the energy
- Muon spectrometer for escaping muons

ATLAS

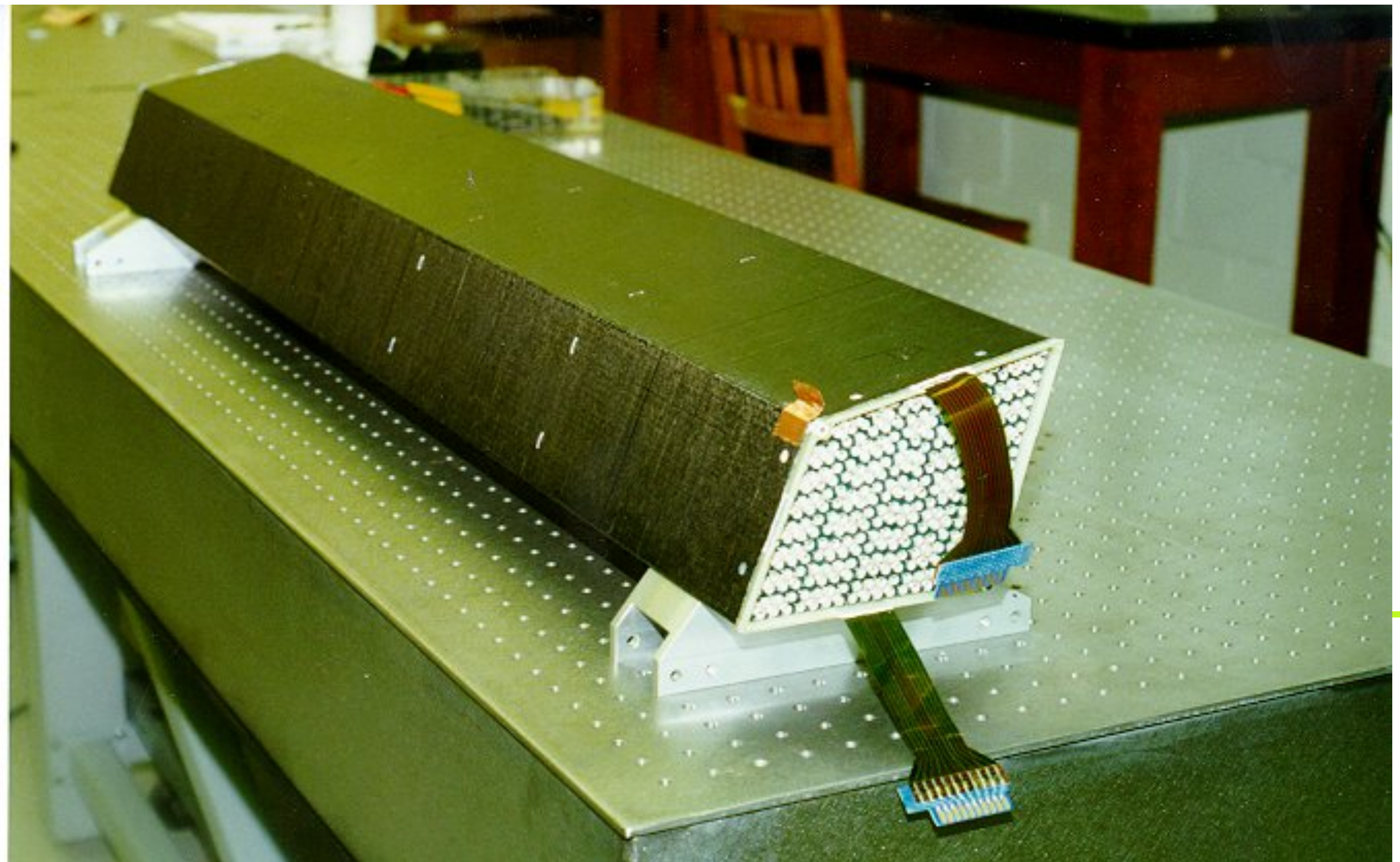
Trackers

- **3 main technologies**
  - **gaseous**: ionization in gaz (electron-ion pair). Amplification needed
  - **silicon** : ionisation in solid material (electron-hole pair). No amplification needed
  - **scintillating fibers** : light detected with photodetectors
- Need very low density to avoid shower development
- Measurement of particle momentum and decay vertices

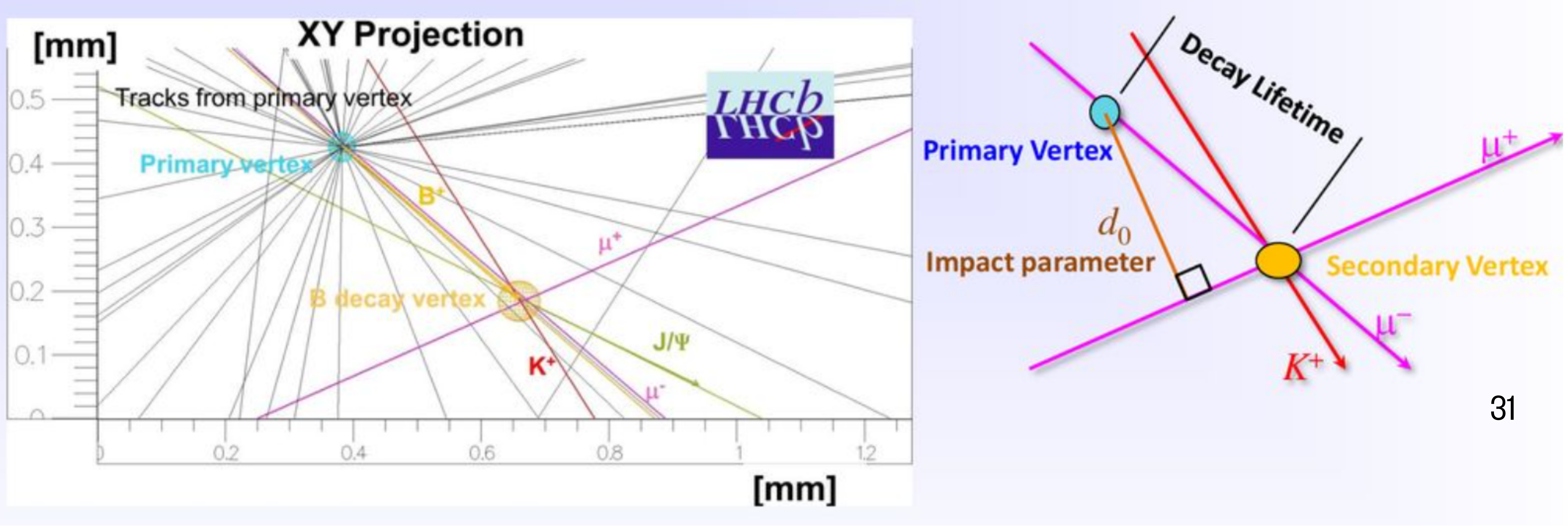


Semiconductor Tracker of ATLAS (silicon)

Transition Radiation Tracker of ATLAS (gas)

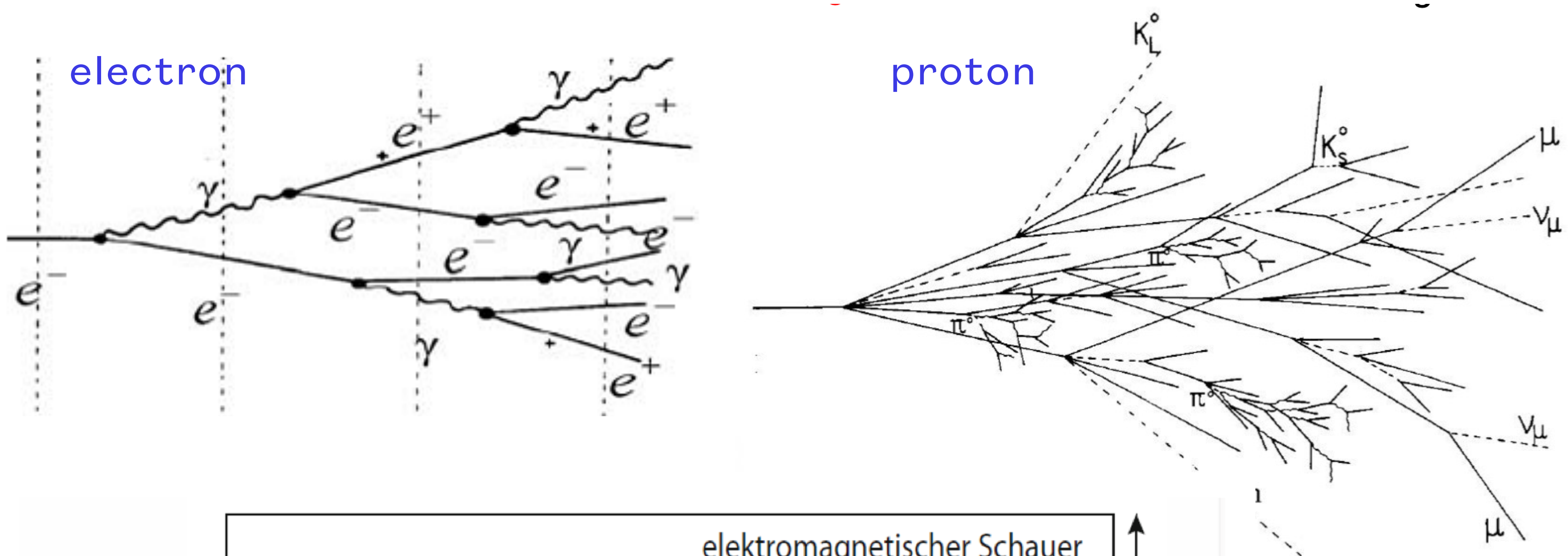


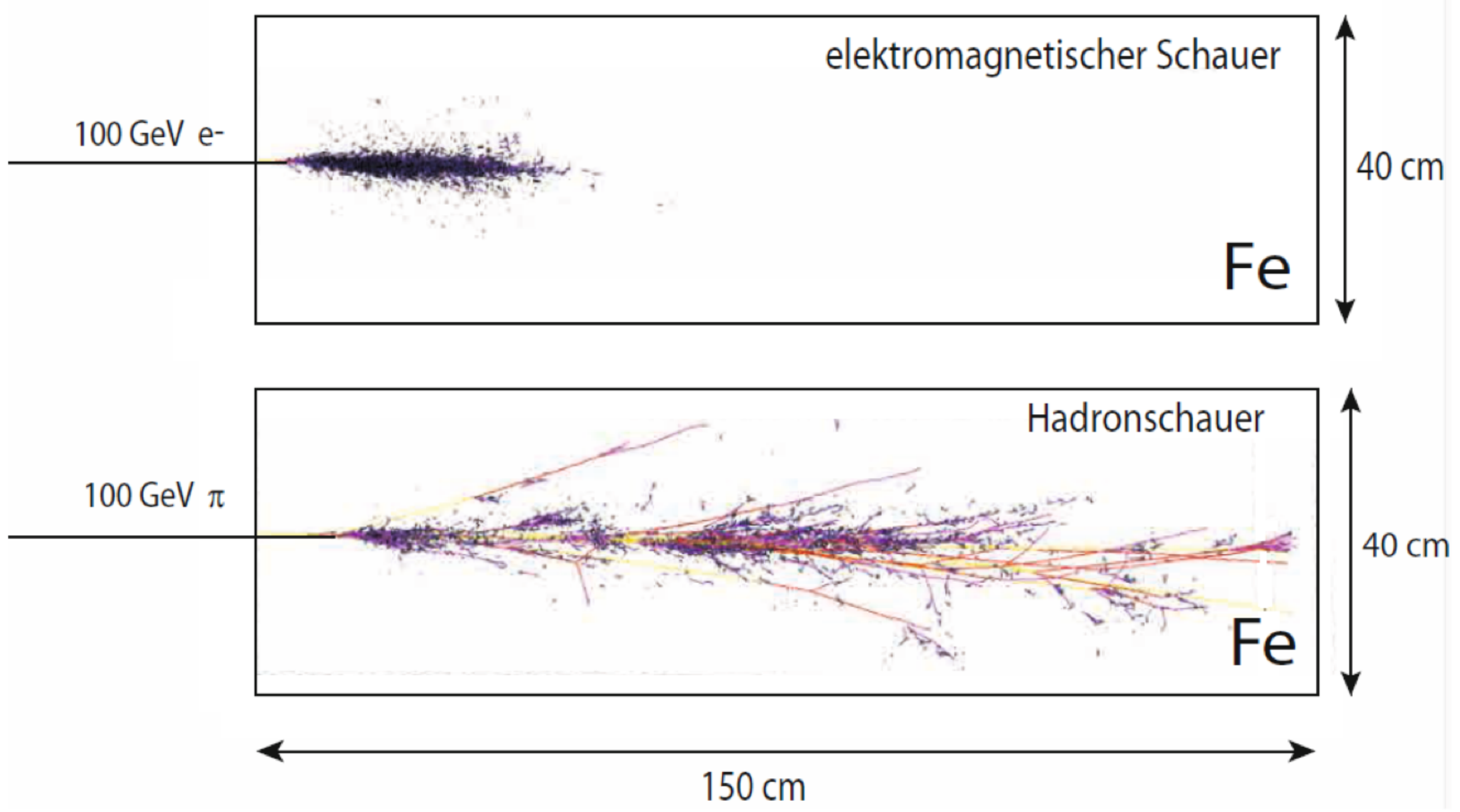
Decay vertices

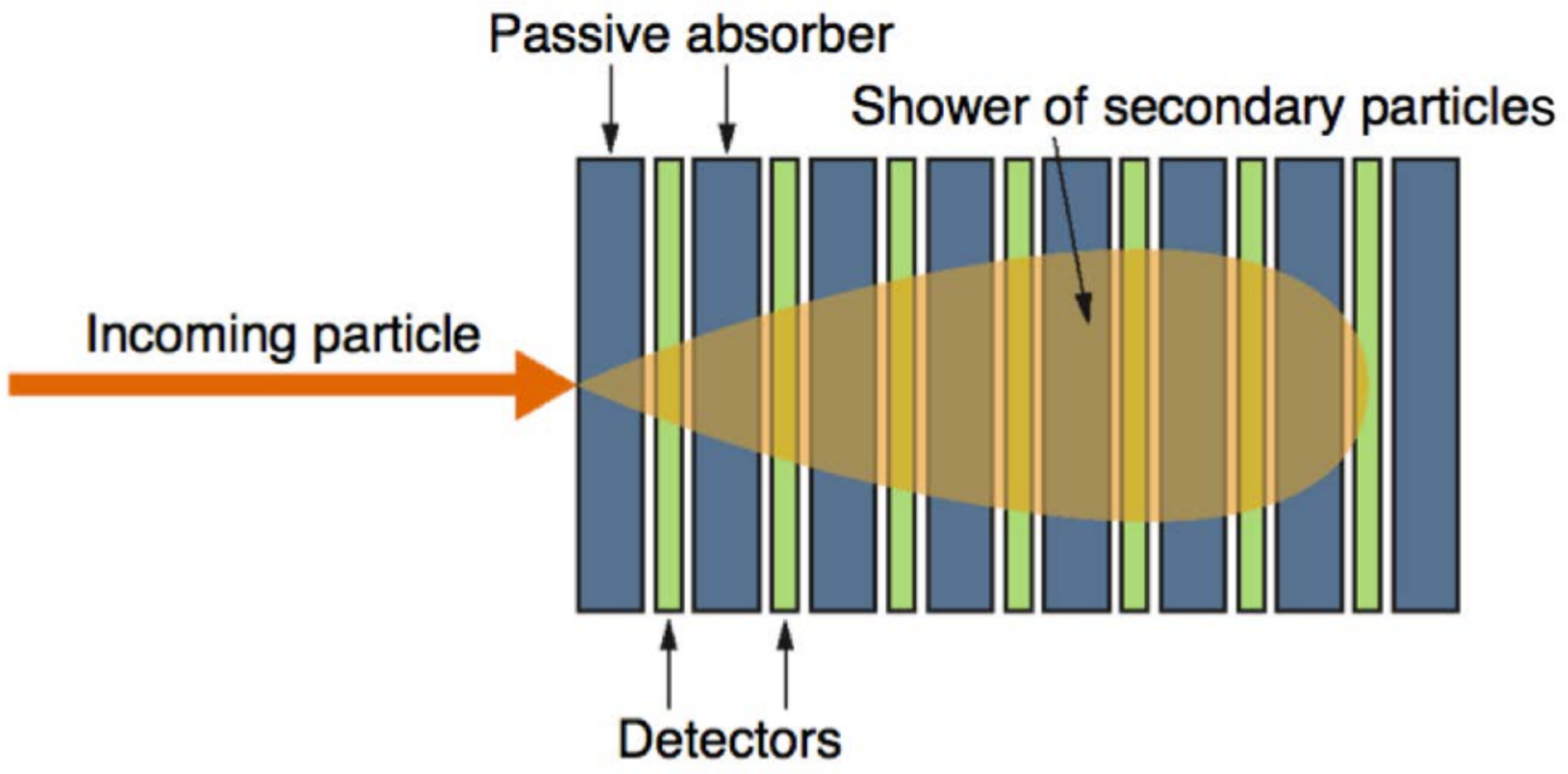


Calorimeters

- Particules initiates a shower due to dense material (**bremstrallung and pair production**)
  - electromagnetic (electron/photon) or hadronic (particule sensitive to strong force -> denser material to develop completely)
- Shower is either contained entirely or sampled (dense material and active material)
  - Shape of shower helps to identify the particule
- Shower development scales with radiation length
  - distance in which the energy of the particle is reduced by 1/e (≈63.2%) due to bremsstrahlung







	Air	Eau	Al	LAr	Fe	Pb	$PbWO_4$
Z	-	-	13	18	26	82	-
X_0 (cm)	30420	36	8,9	14	1,76	0.56	0.89

Approximation : $X_0 \approx \frac{(716\,\mathrm{g\,cm^{-2}})\,A}{Z(Z+1)\ln(287/\sqrt{Z})}$

Calorimeters : energy resolution

- Intrinsic resolution ~1/sqrt(E)
- Electronic noise : 1/E
- Non-uniformities : constant term -> dominant at high energy

$$\frac{\sigma(E)}{E} \approx \sqrt{\left(\frac{c_1}{\sqrt{E}}\right)^2 + \left(\frac{c_2}{E}\right)^2 + c_3^{\,2}}$$

Homogeneous calorimeters:

Experiment	Material	Energy resolution (E in GeV)
NA48	Liquid Kr	4.8%/√E ⊕ 0.22%
BELLE	CsI(Tl)	0.8%/√E ⊕ 1.3%
CMS	$PbWO_4$	2.7%/√E ⊕ 0.55%*

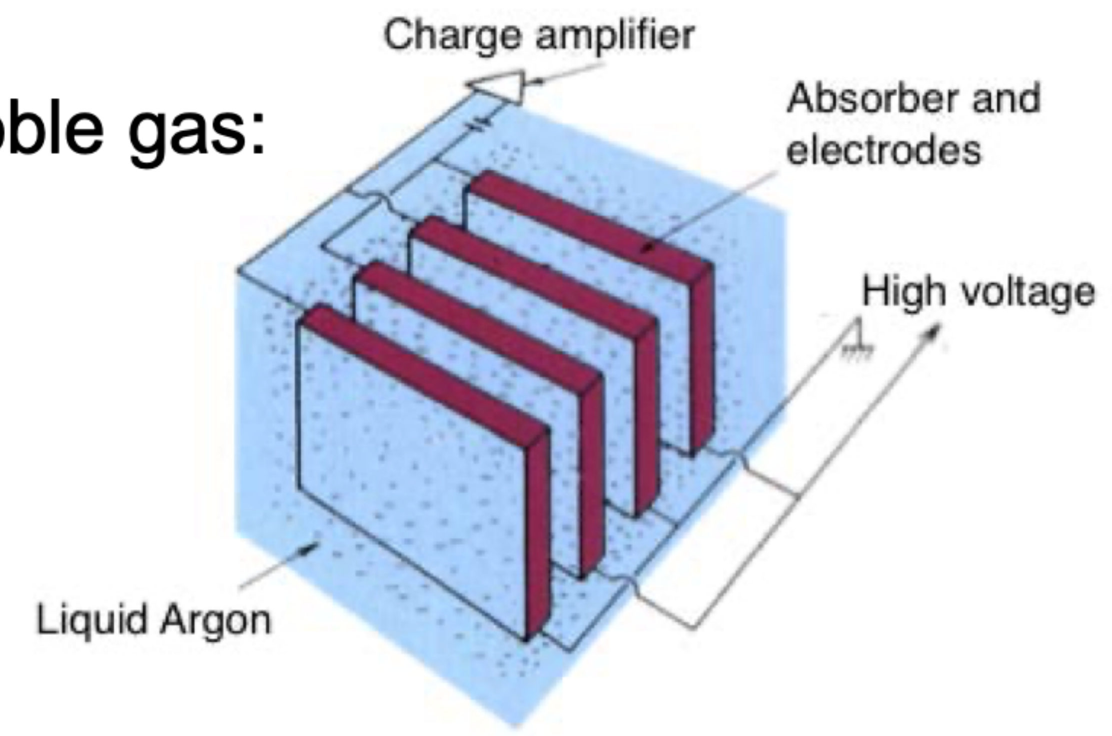
reference

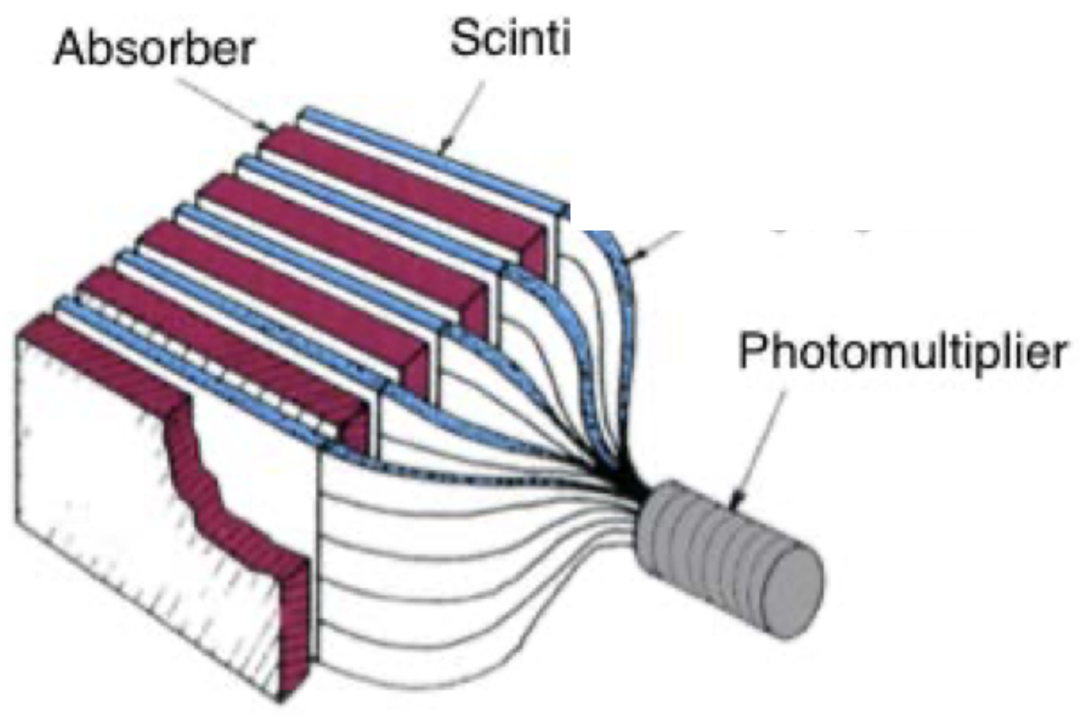
Sampling calorimeters:

Experiment	Detector	Detector thickness [mm]	Absorber material	Absorber thickness [mm]	Energy resolution (E in GeV)
UA1	Scintillator	1.5	Pb	1.2	15%/√E
SLD	liquid Ar	2.75	Pb	2.0	8%/√E
DELPHI	Ar + 20% CH_4	8	Pb	3.2	16%/√E
ALEPH	Si	0.2	W	7.0	25%/√E
ATLAS	liquid Ar		Pb		10%/√E ⊕ 0.7%*
LHCb	Scintillator		Fe		10%/√E ⊕ 1.5%*

* Design values

Liquid noble gas:

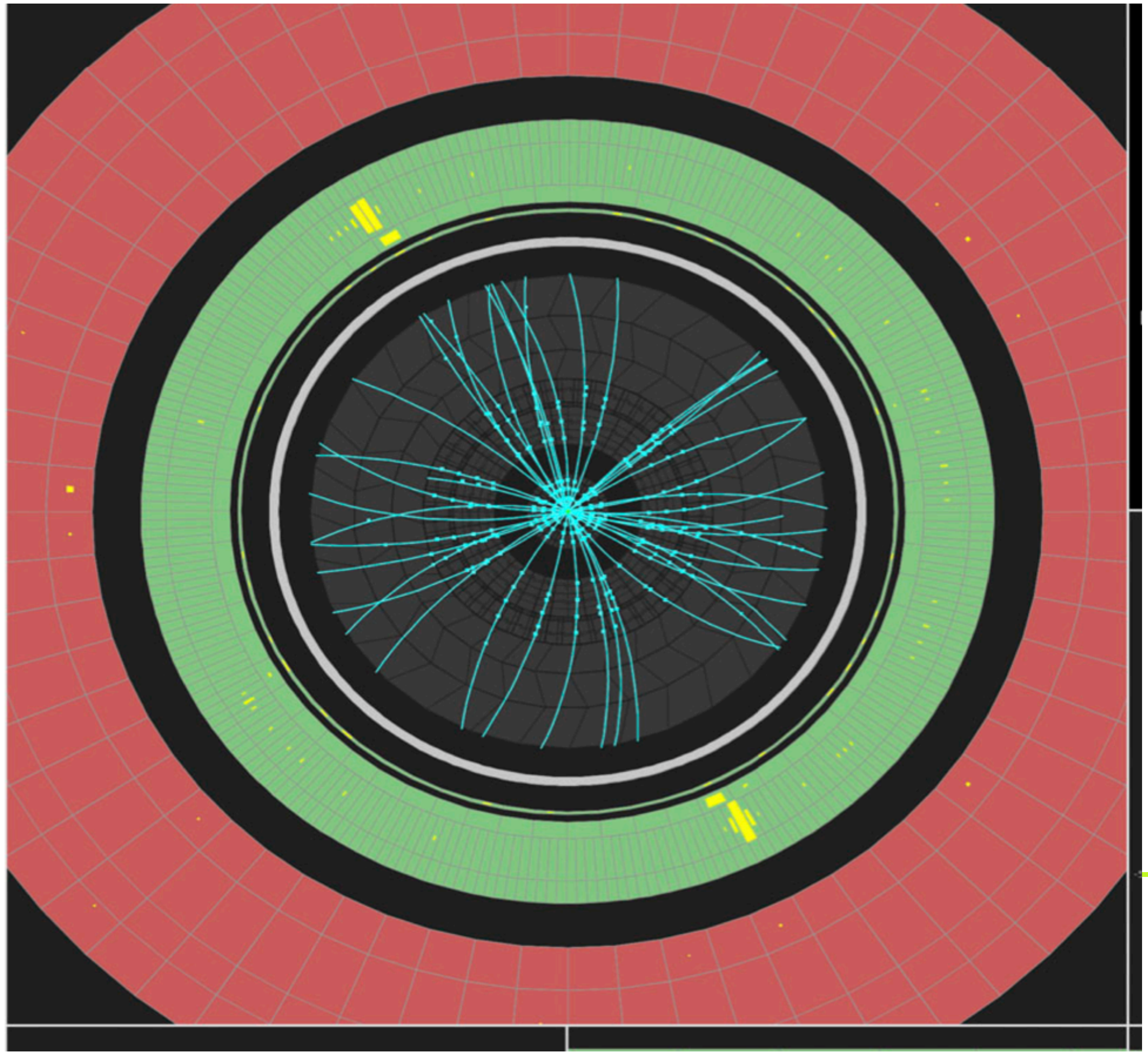


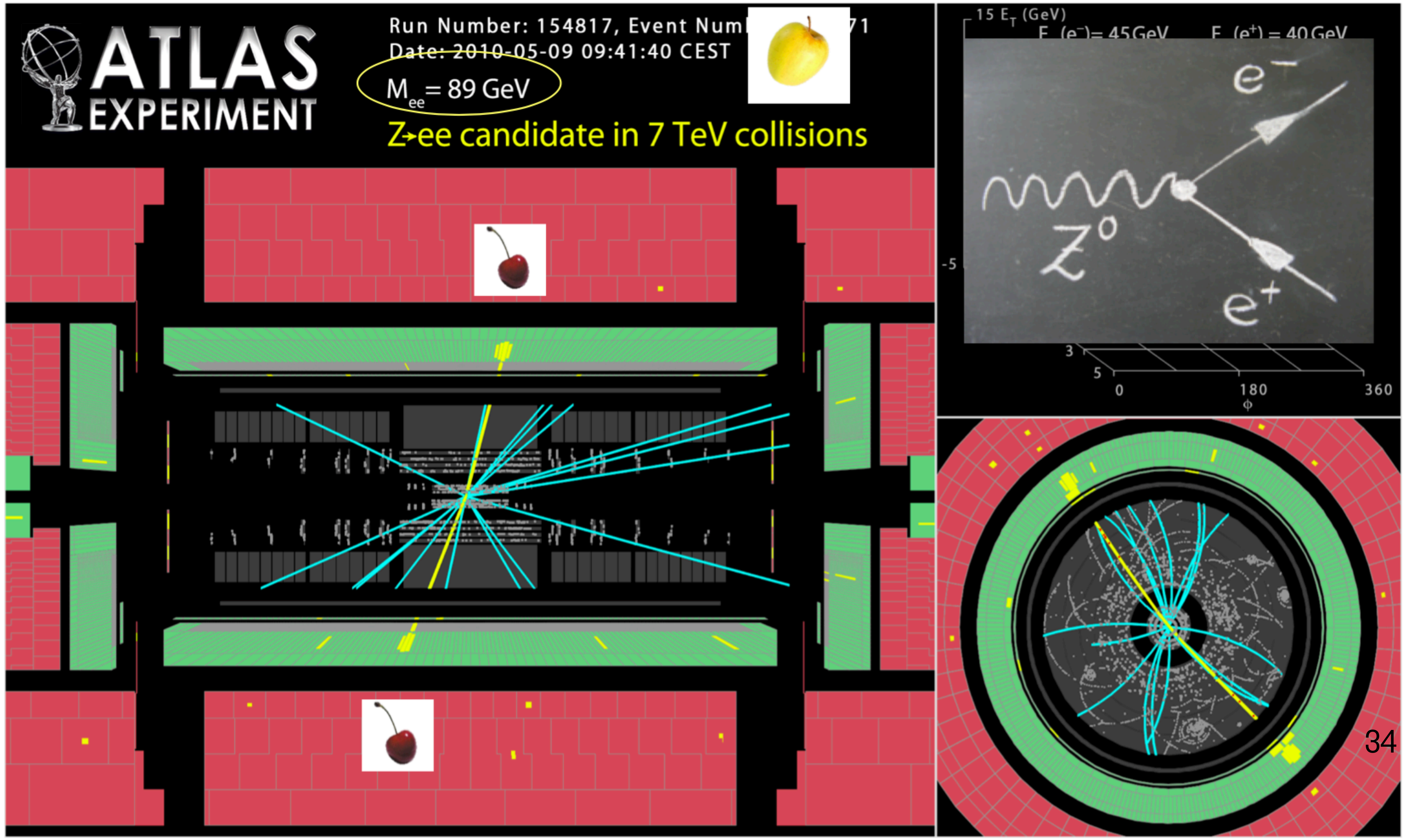


scintillators plates

Photons and electrons in ATLAS

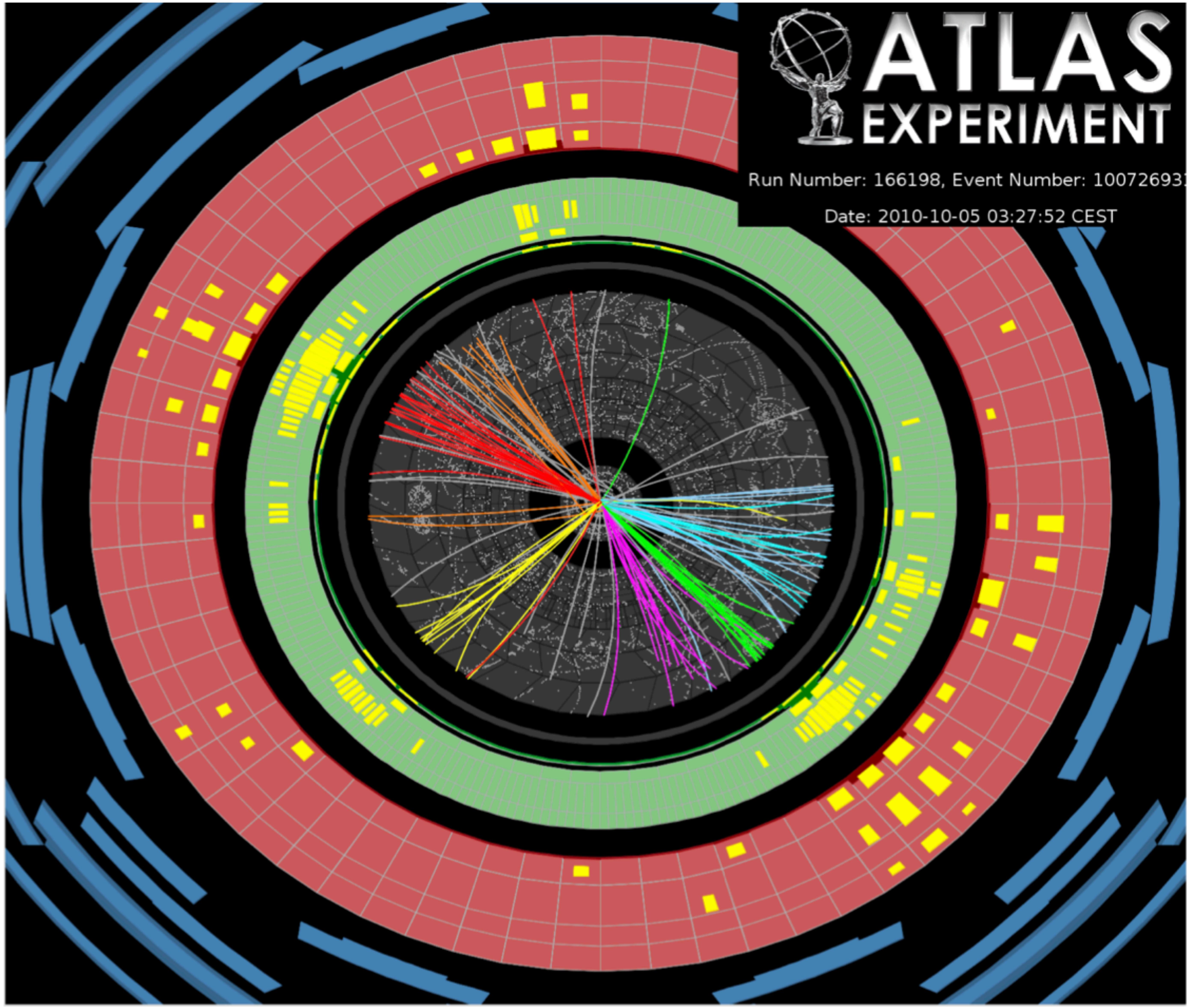
- Reconstructed from **electronic** signals recorded by **readout system**





Jets of hadrons

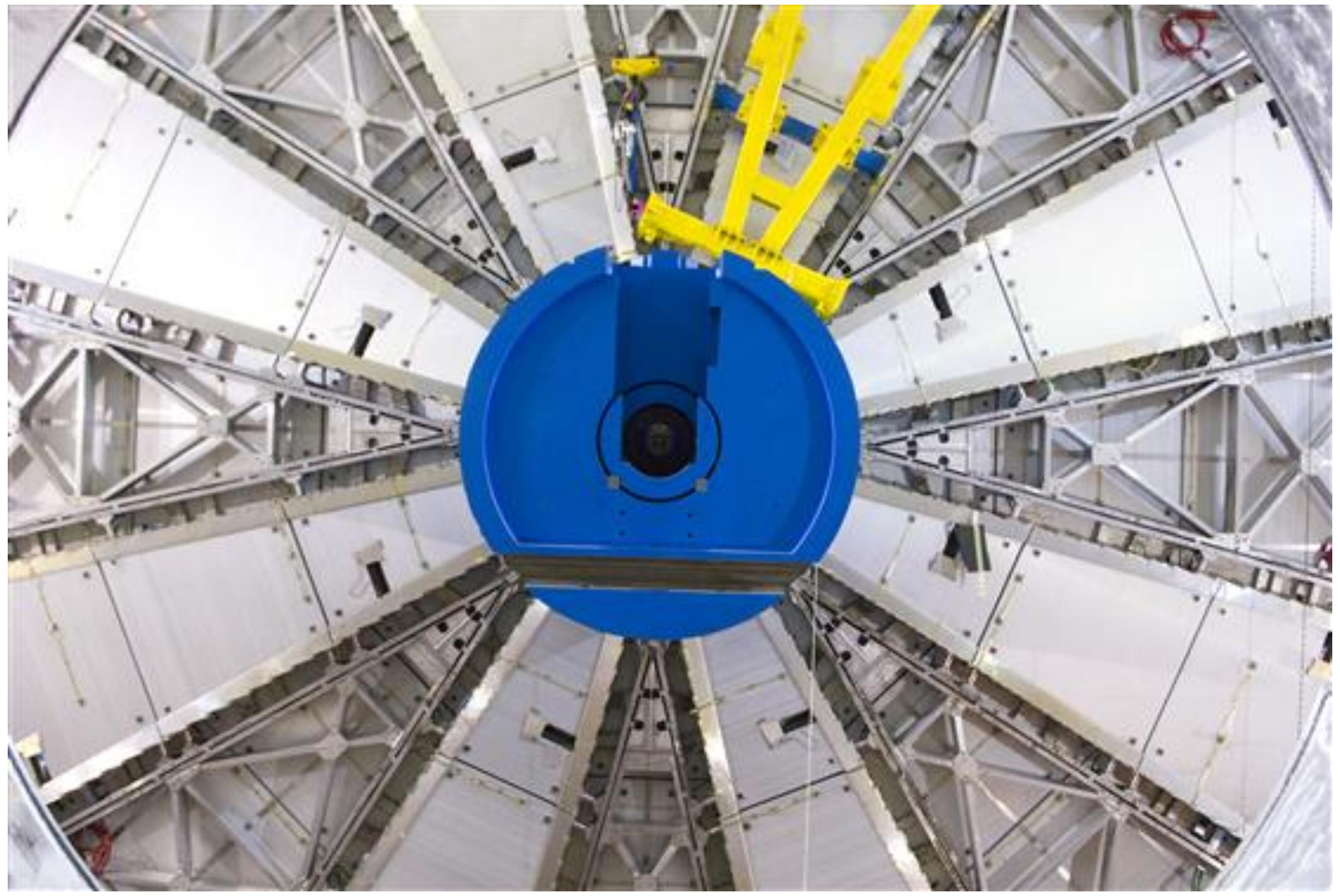
- The hadronisation seen as a « jet » in detector (several hadrons developing hadronic showers at the same time)

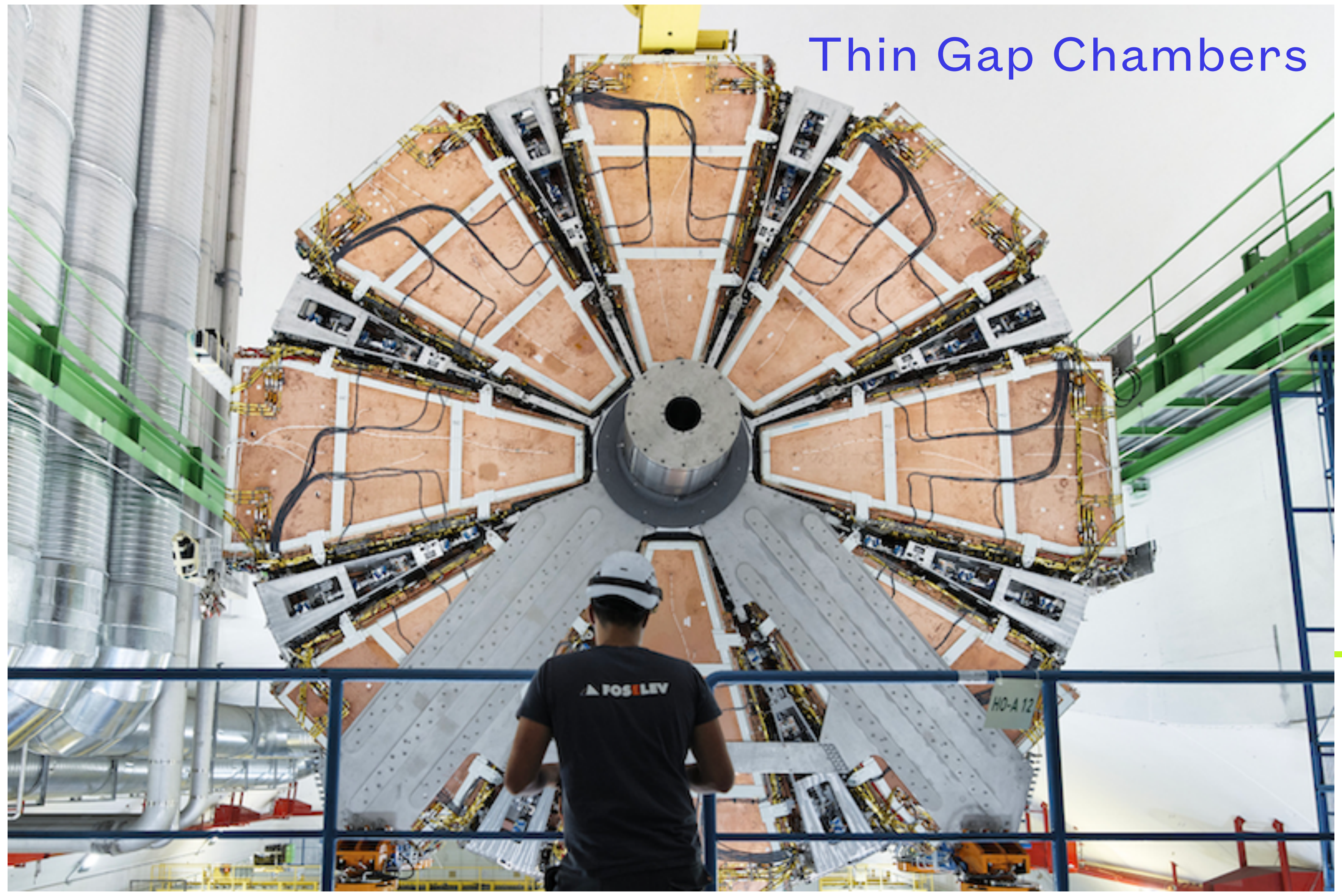


Muon spectrometers

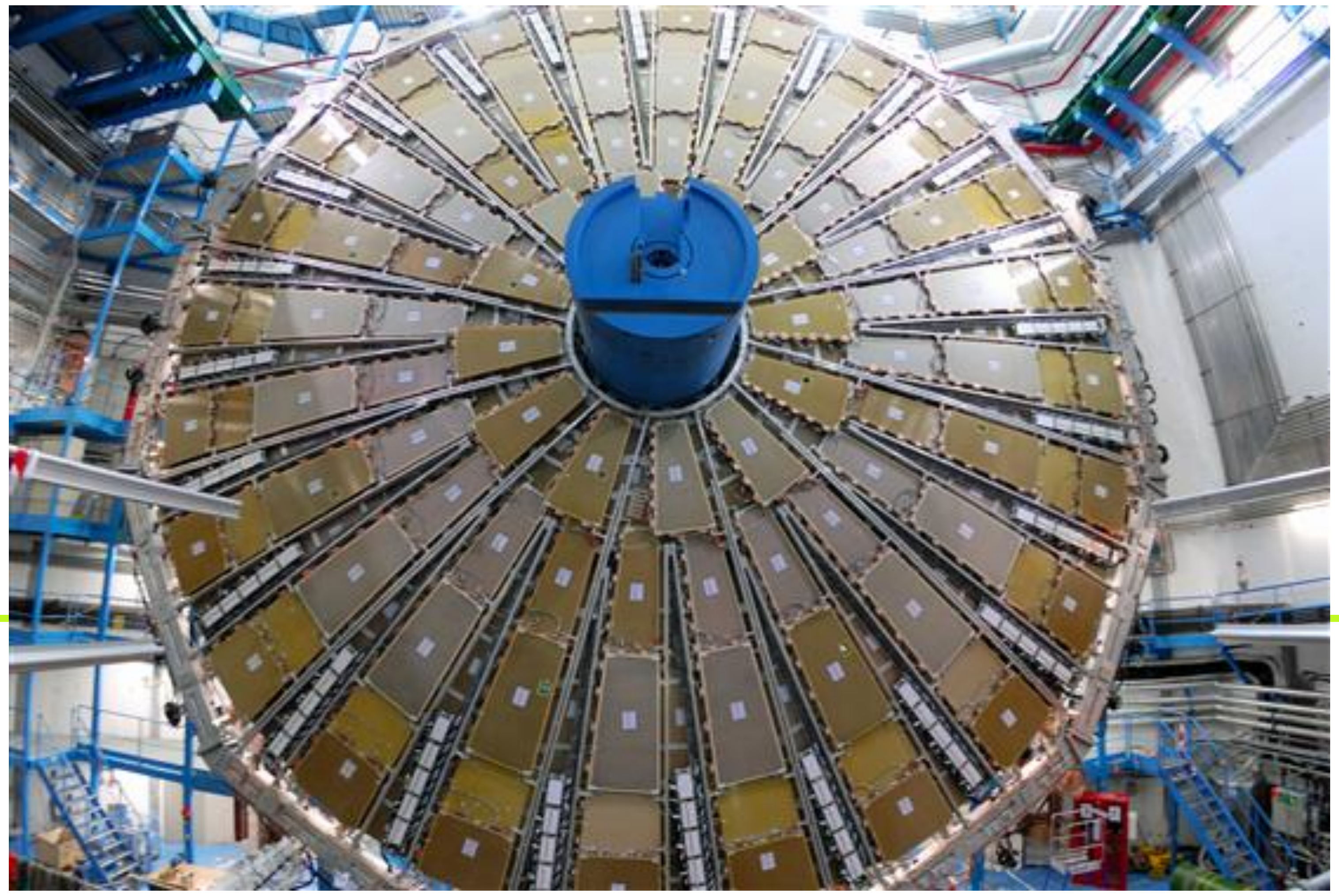
- Identify and measures momentum of muons
- Thousands of chambers, big magnetic field to curve high-energy muons
- Biggest sub-detector
- Main technologies (in ATLAS) : **Monitored Drift Tubes** (0.1 mm precision, aluminium tube filled with gas mixture + wire at the center), **Resistive Plate Chambers** (tracking within 2.5us), **Small-Strip Thin-Gap Chambers** and **Micromegas** (taking in high-intensity collisions

Monitored Drift Tubes

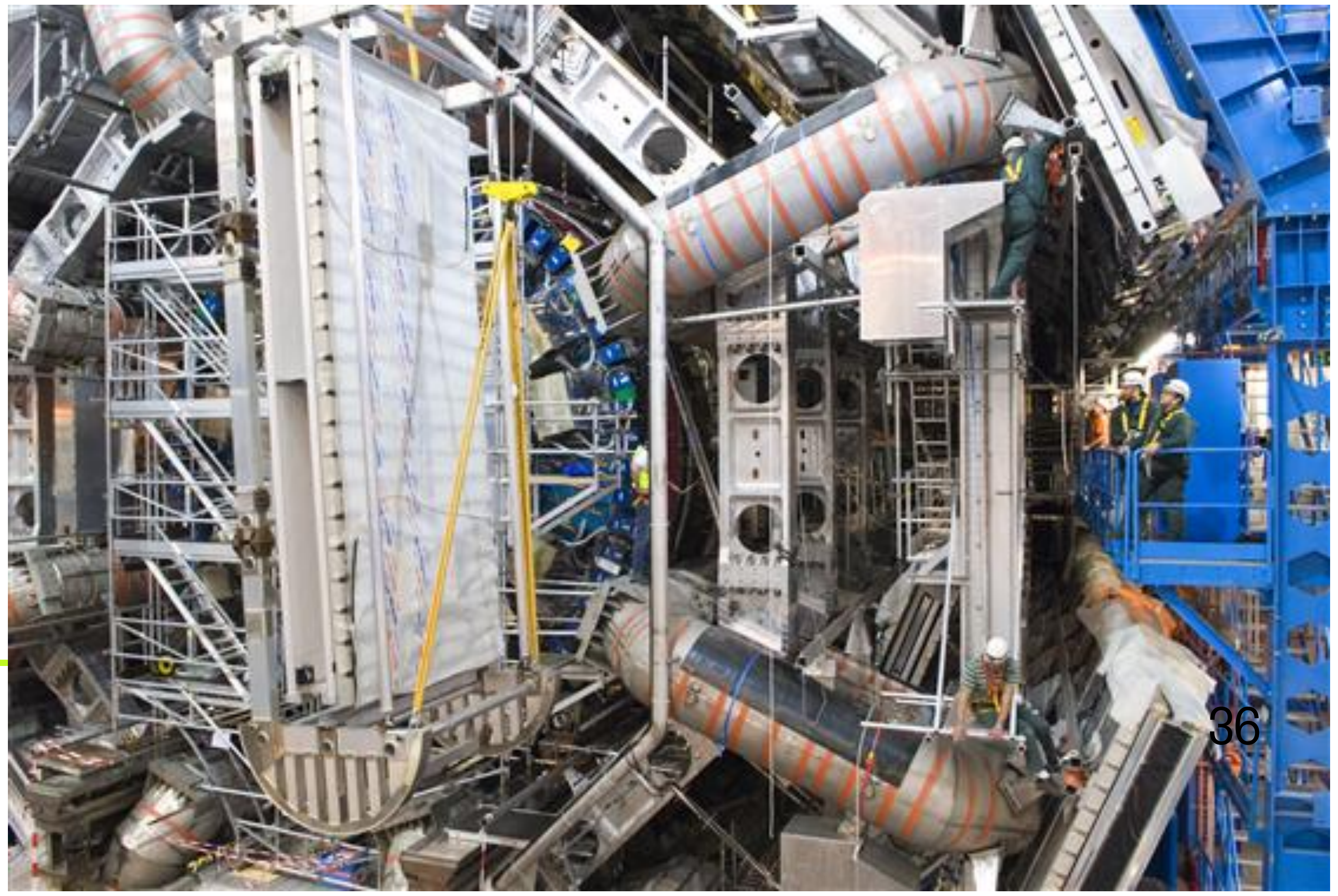




Thin Gap Chambers

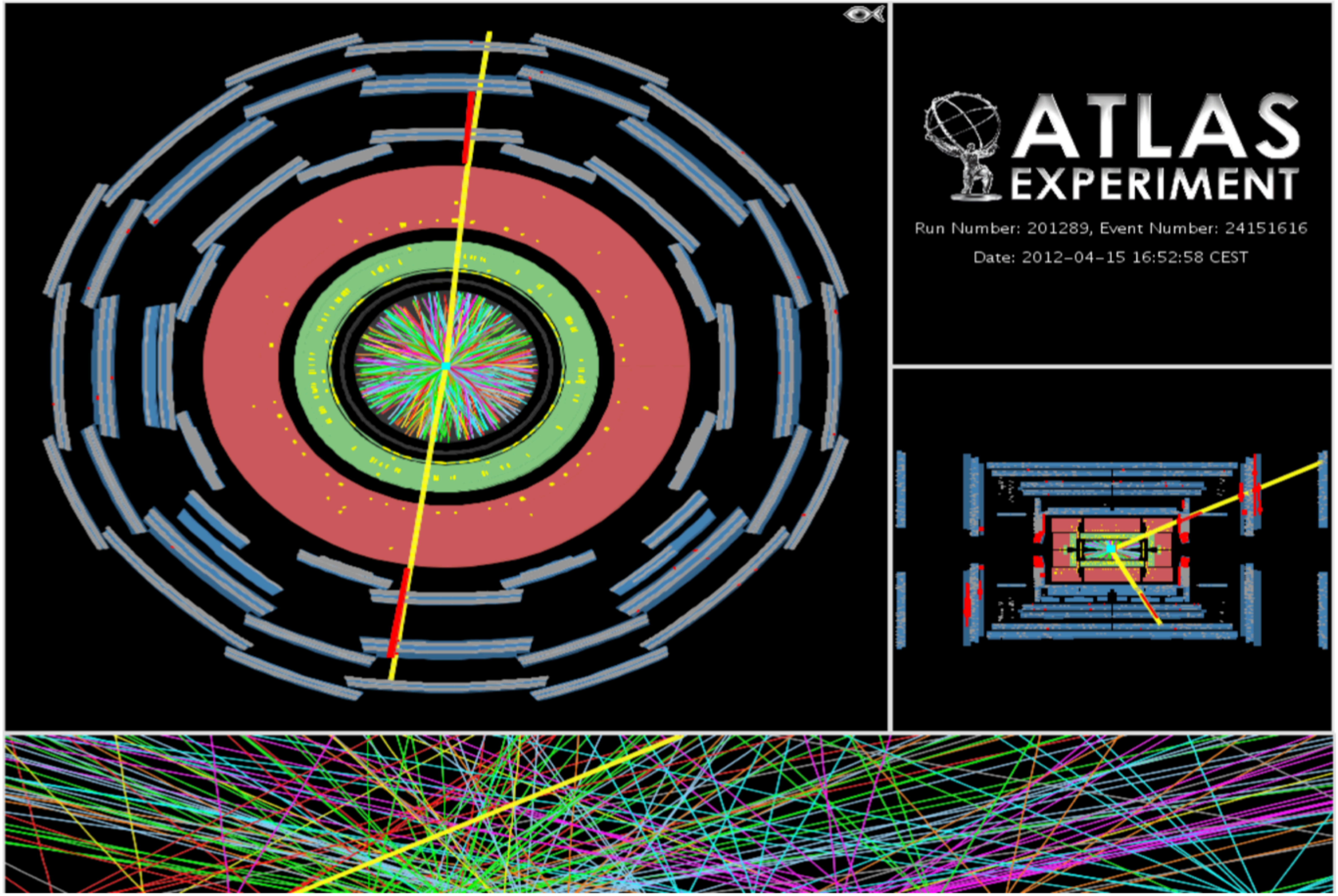


Resistive Plate Chambers

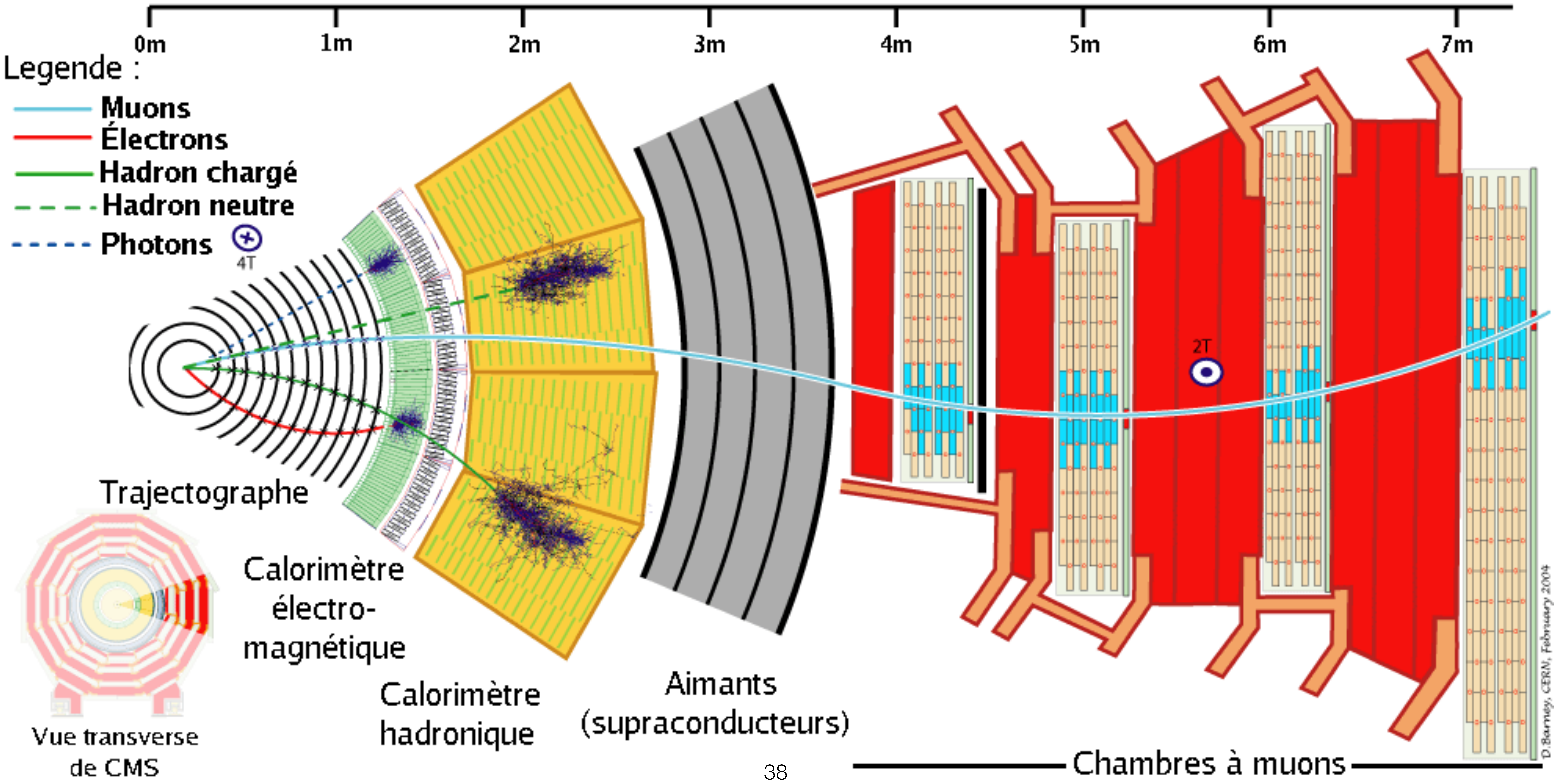


Muons in ATLAS

- Escape calorimeters, track recorded in spectrometer



Particule identification



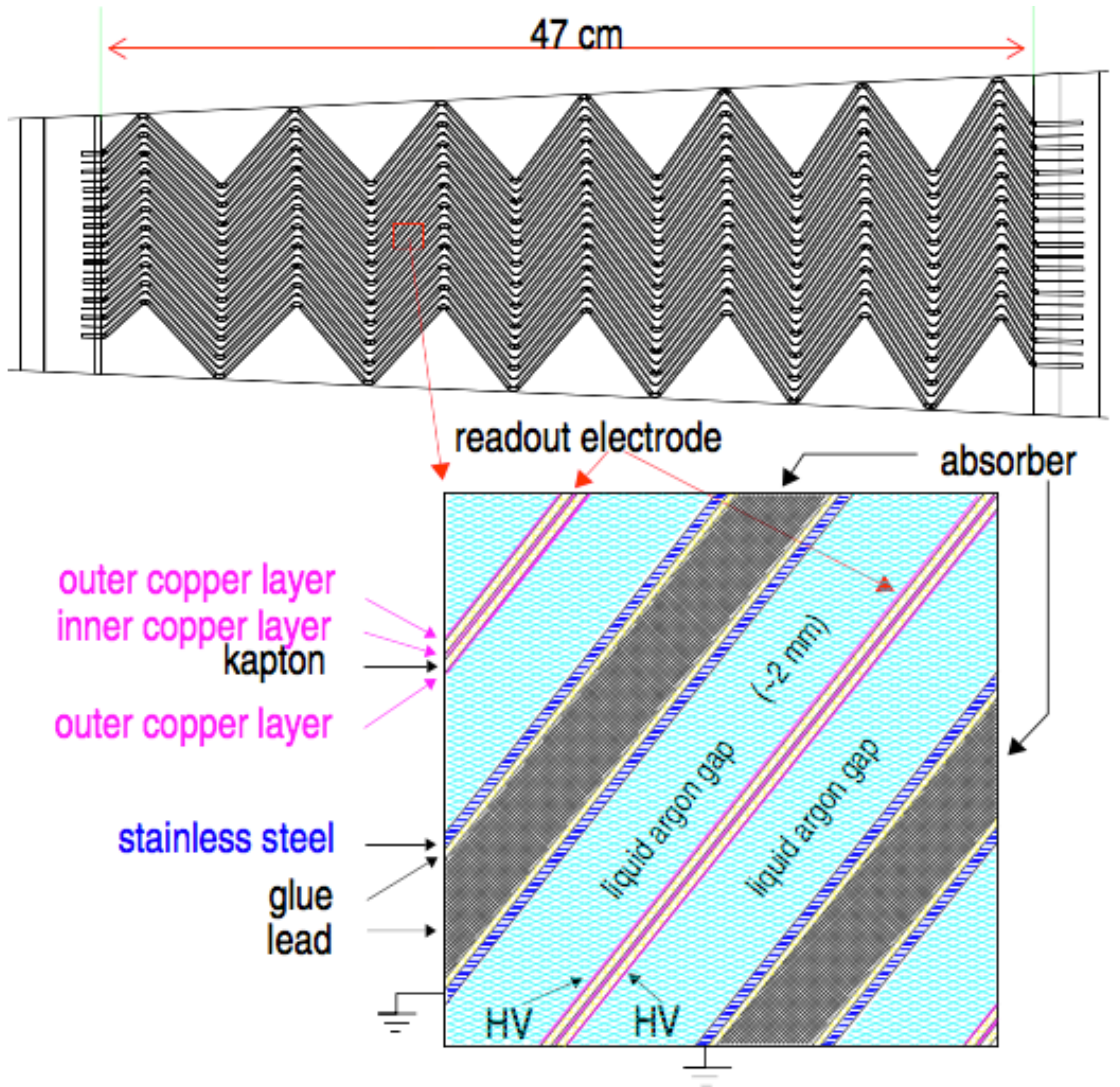
How to read the signal ?

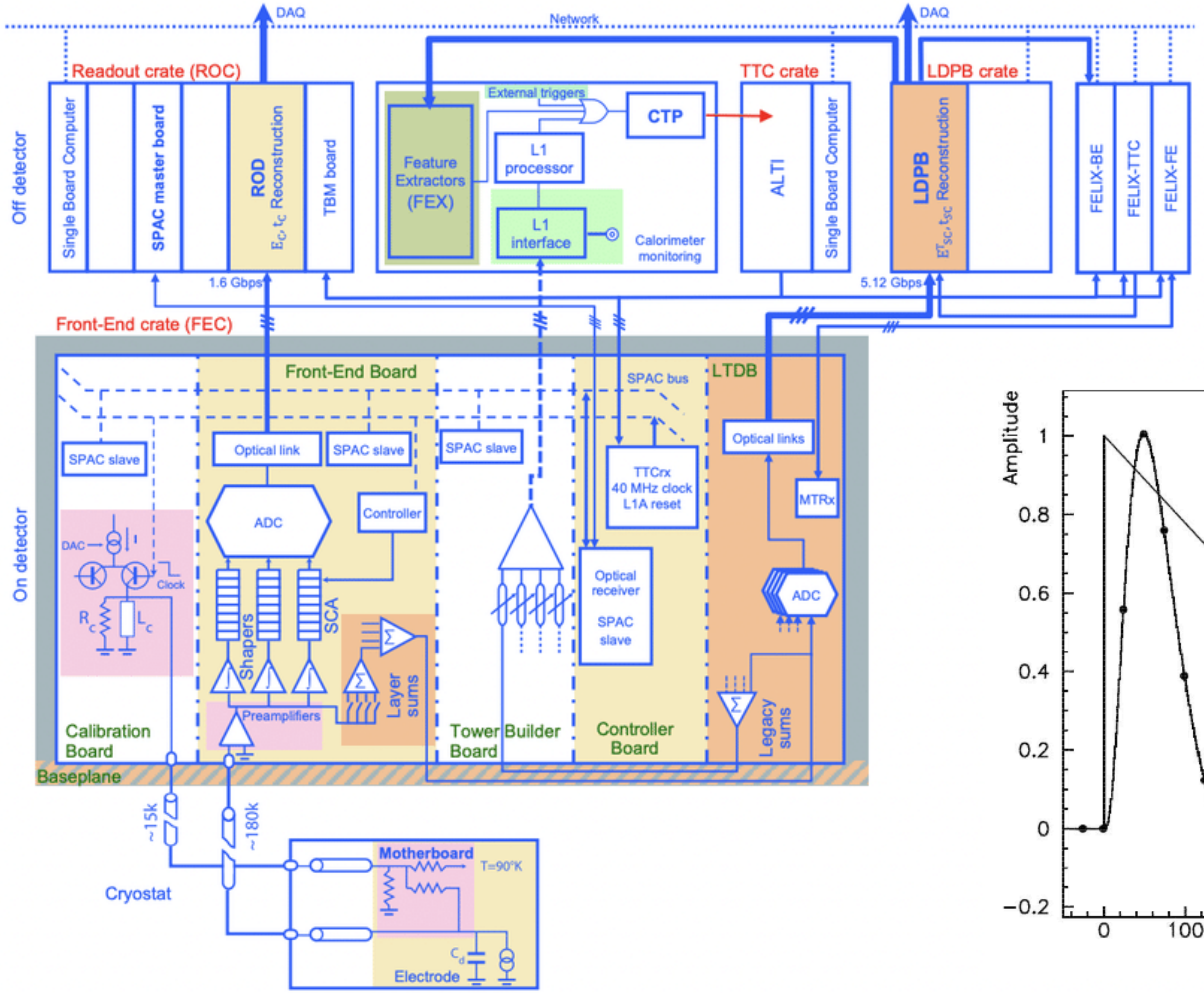
IN DETECTOR :
- AMPLIFICATION AND SHAPING OF SIGNAL
- DIGITIZATION (SAMPLING)

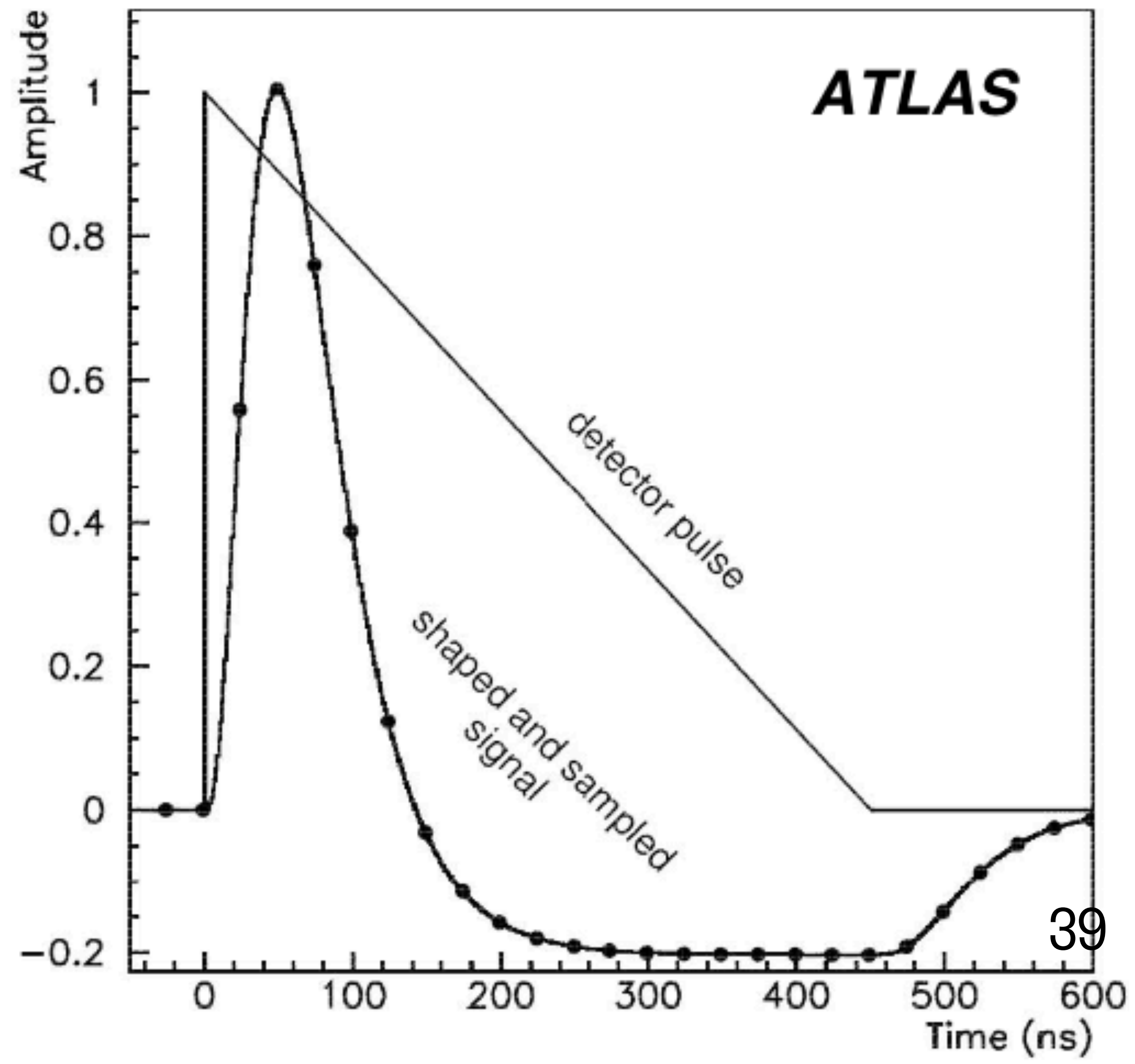
OFF-DETECTOR
- COMPUTATION OF ENERGY, QUALITY, TIMING

–> THOUSANDS OF ELECTRONIC BOARDS !

- Example with ATLAS calorimeter :





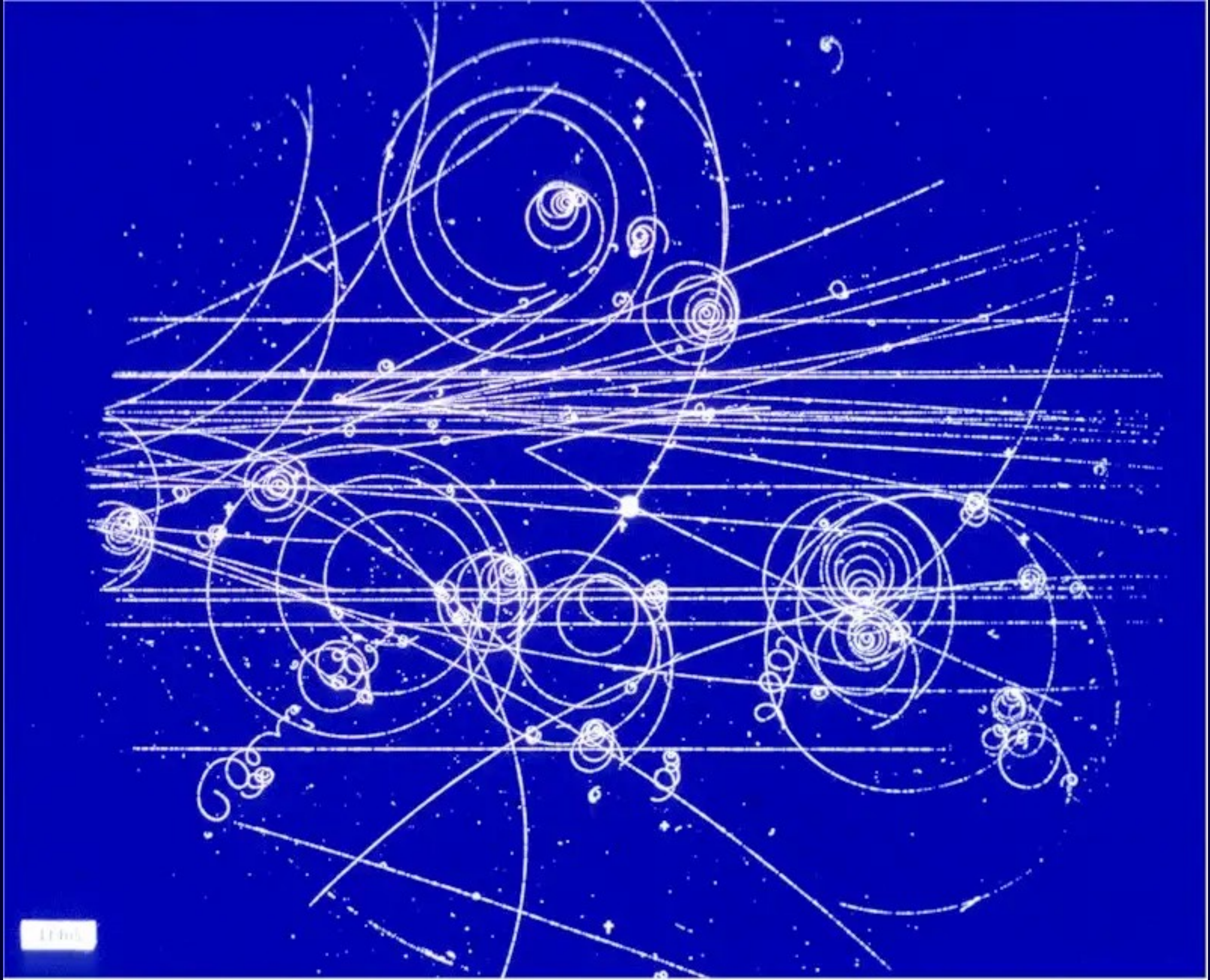


Building the future detectors - HL-LHC

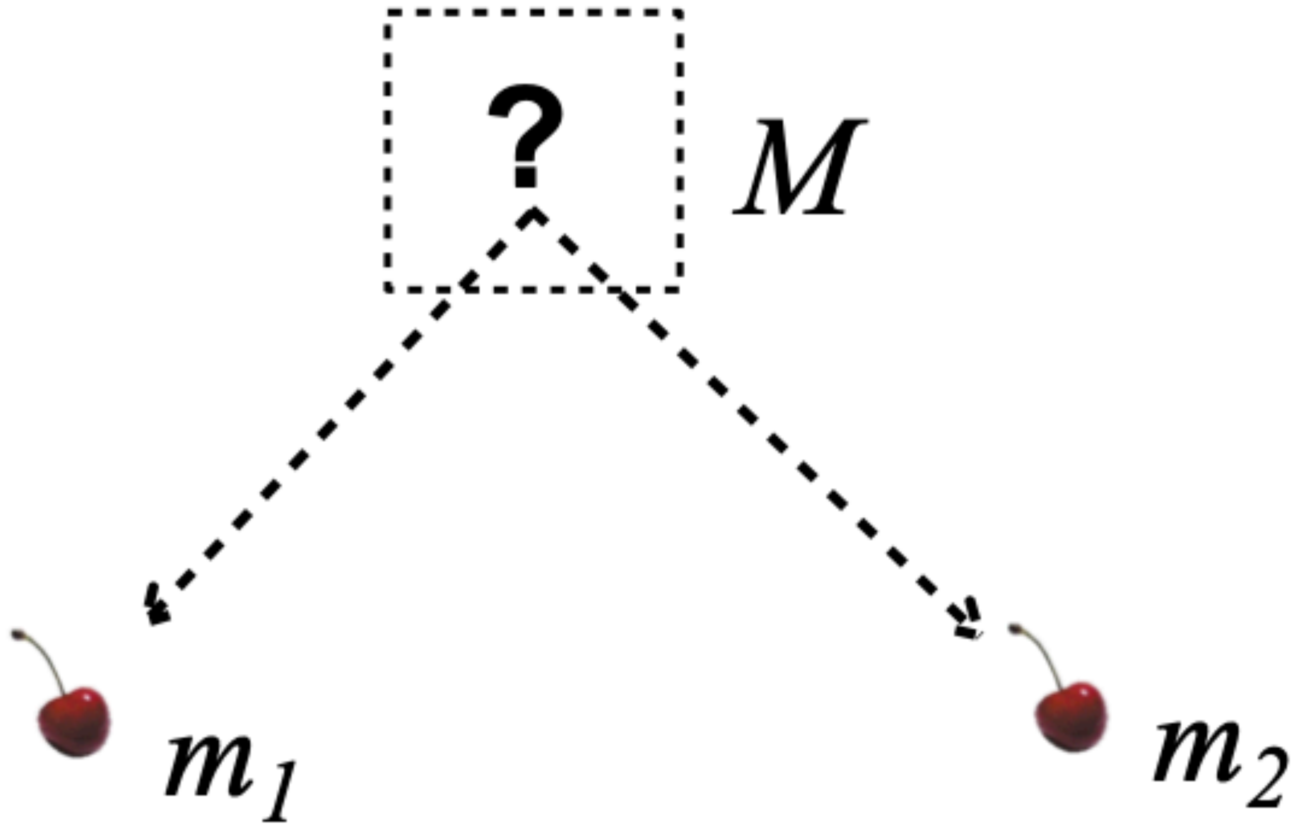
Summary

- Detection of particles essentially based on how they interact with matter
- With time, detectors technics have improved : more precision, faster detection, better recording of signals
- Technologies will continue to improve, allowing us to see even deeper in fundamental laws

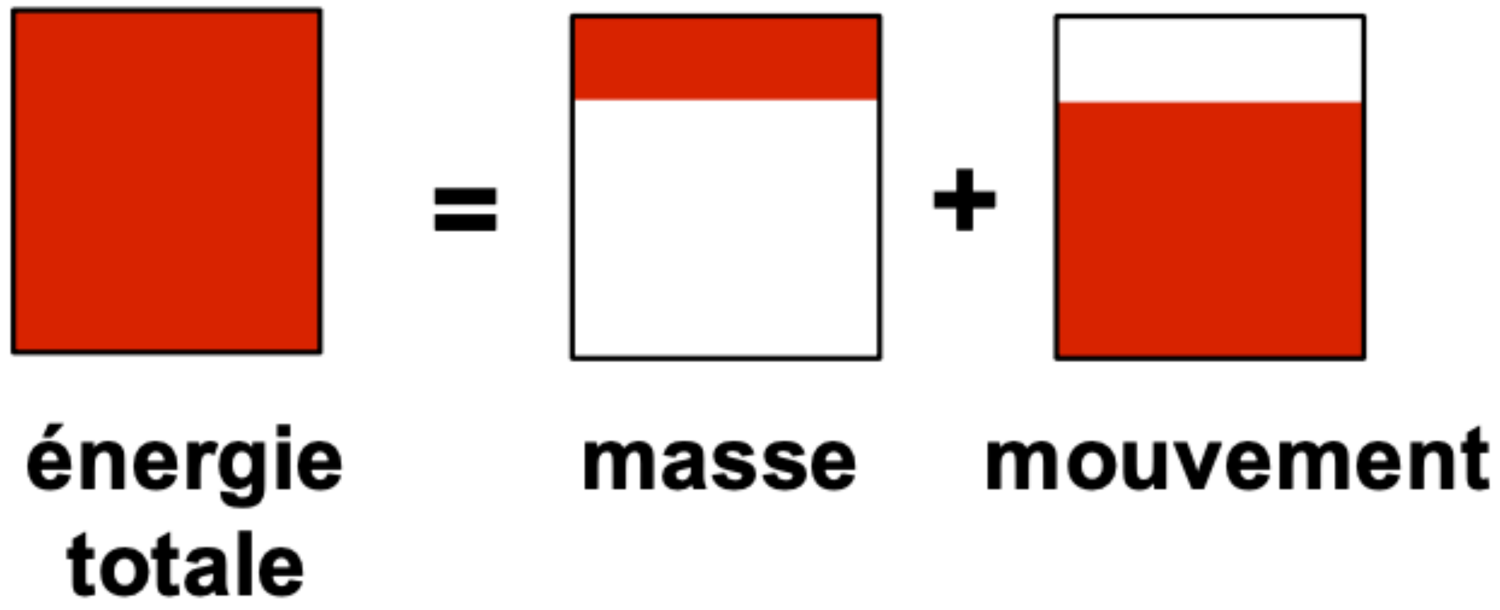
Thank you !



Comment retrouver la particule de départ ?



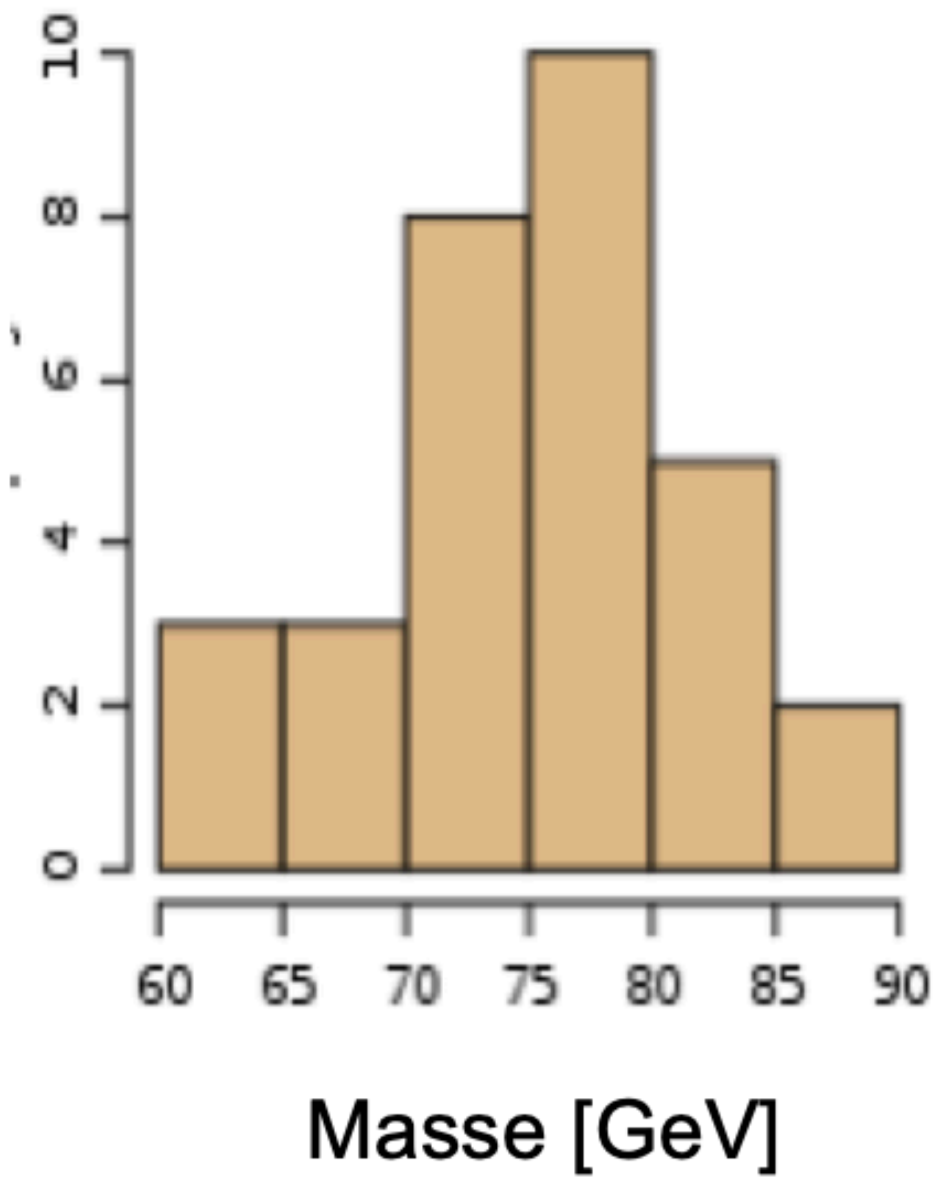
$$M > m_1 + m_2$$



Pour reconstruire la masse des particules désintégrées, il faut mesurer <u>l'énergie</u> et la <u>masse</u> de toutes les particules produites lors de la collision

Histogrammes et mesures

- Une mesure est **toujours** entachée d'incertitude :
  - **Précision** de l'instrument de mesure
  - **Calibration** de l'instrument
  - **Erreur de manipulation**
  - **Fluctuations statistiques**



- Pour **limiter** ces erreurs, il faut :
  - **Faire un grand nombre de mesures**
  - Utiliser des **objets connus** pour calibrer notre instrument
  - Si possible, réaliser la même mesure plusieurs fois avec des **instruments différents**

Médiateur = gluon

Prédit en 1962 (Gell-Mann)

Découvert en 1979 (PETRA,Hambourg)

d'après une idée de J. Ellis