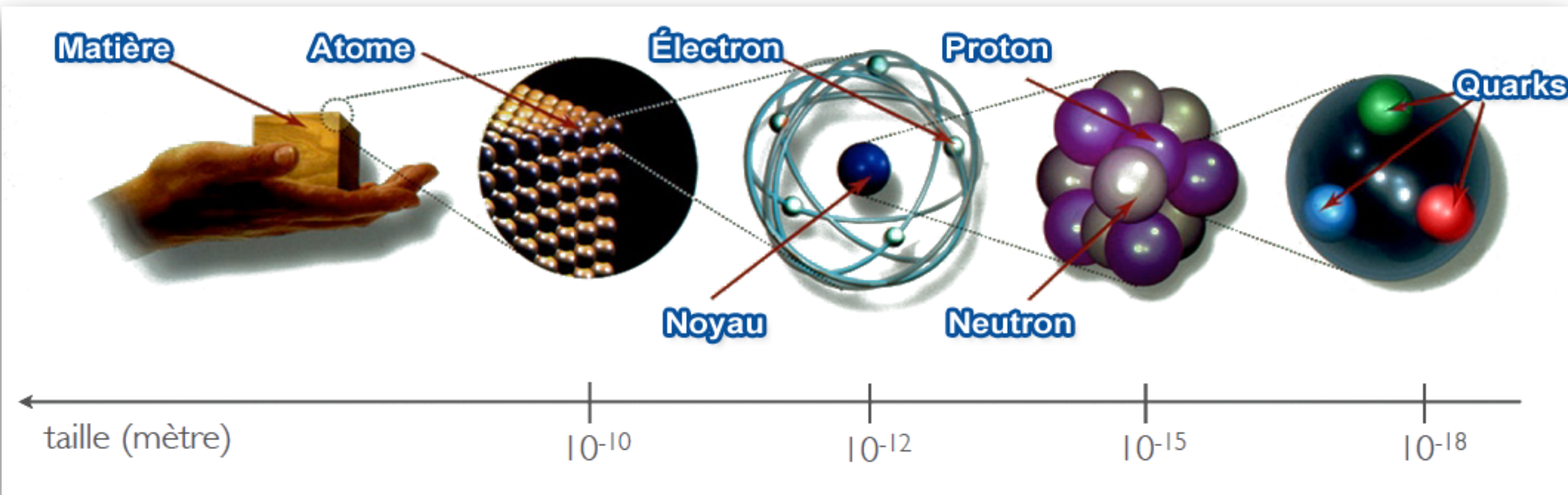


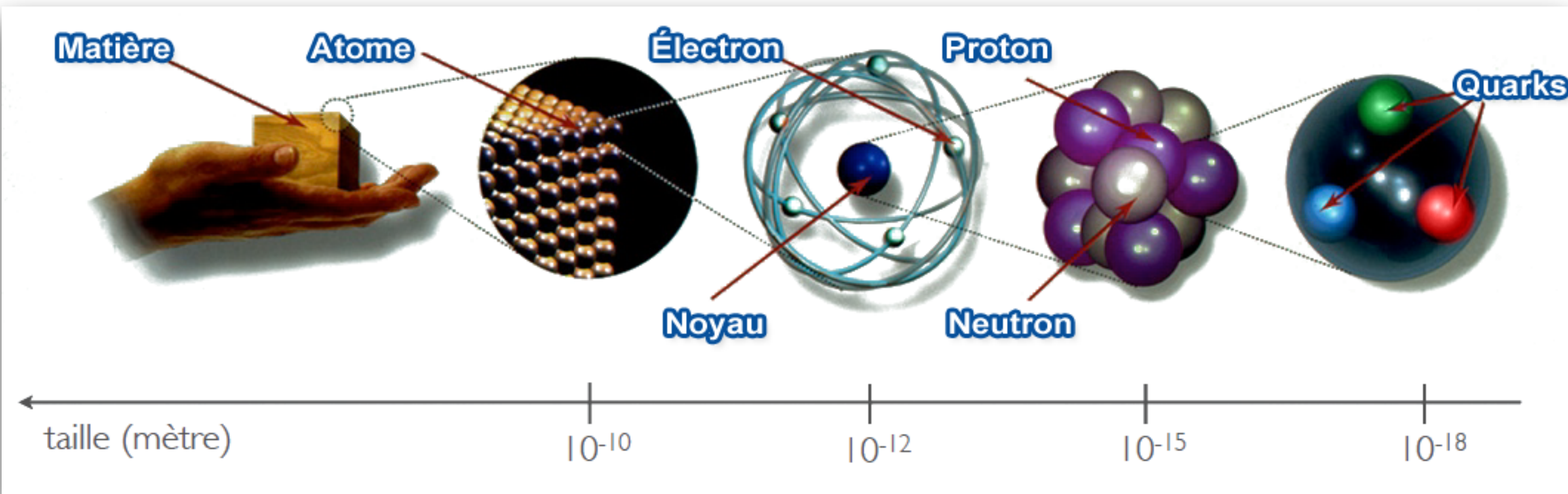
Introduction to detectors

For particle physics and astroparticles

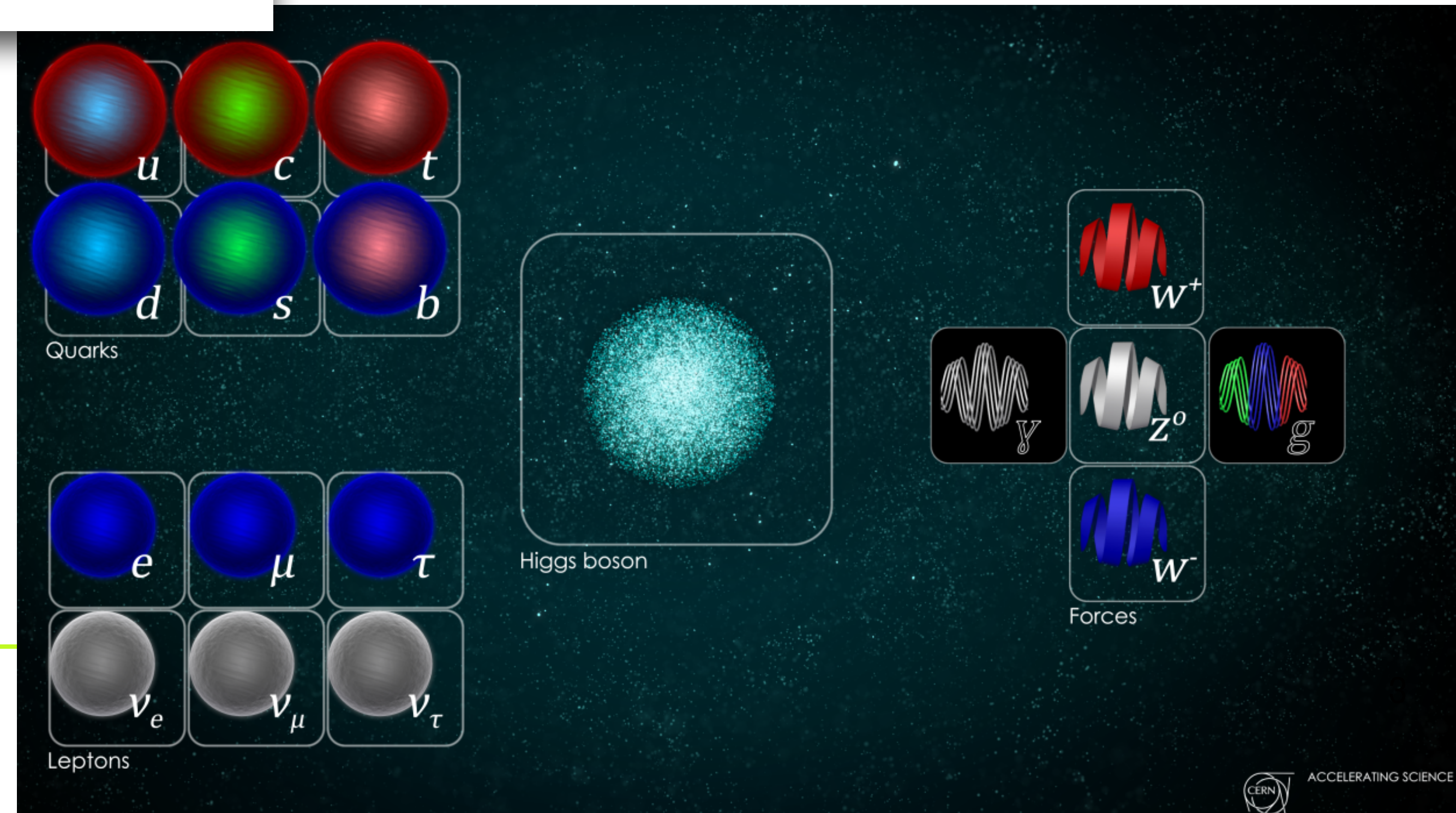
What do we want to detect ?



What do we want to detect ?

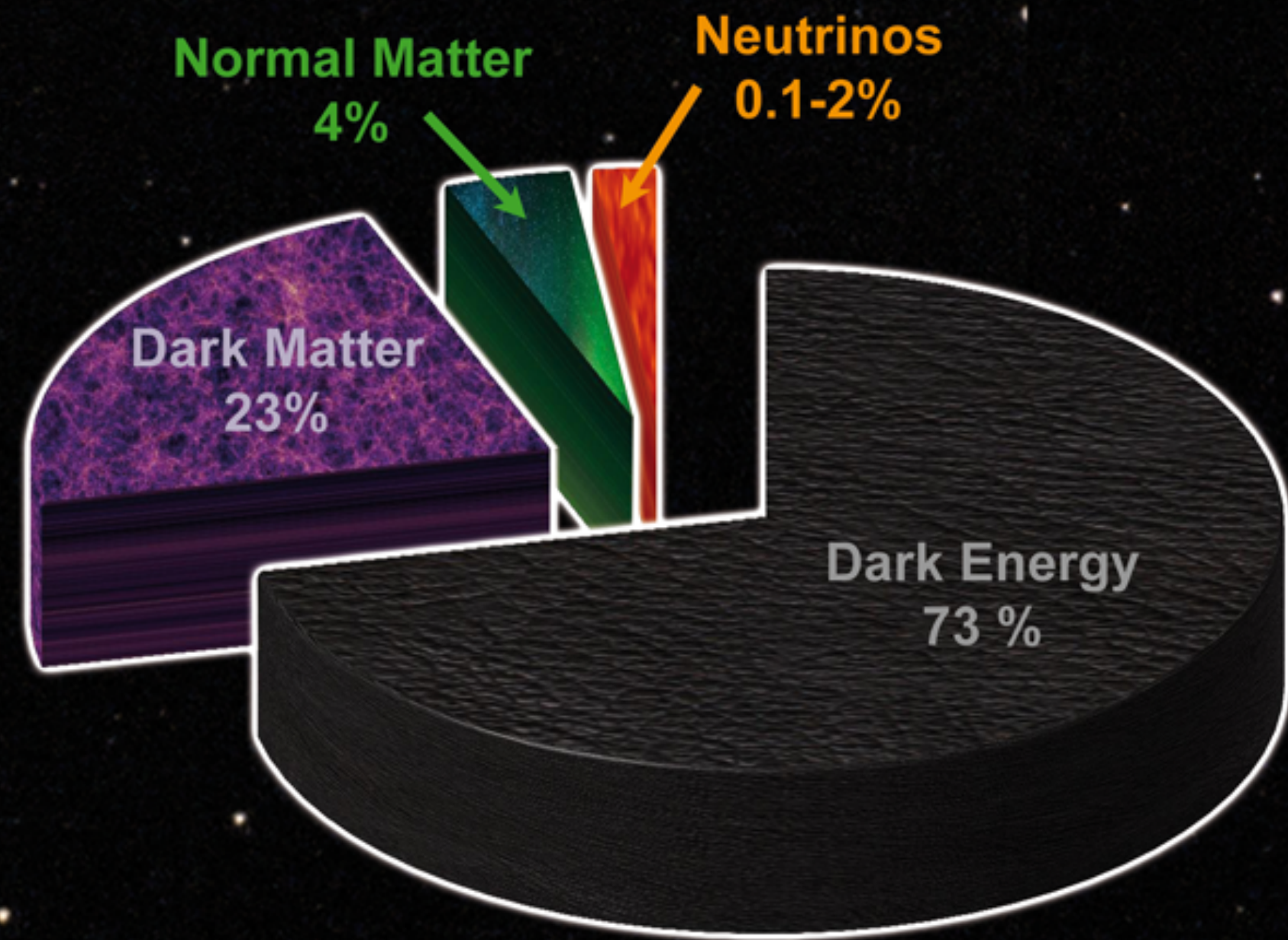


**Better understanding of Standard Model
of Particules Physics**



What do we want to detect ?

- + unknown particles !



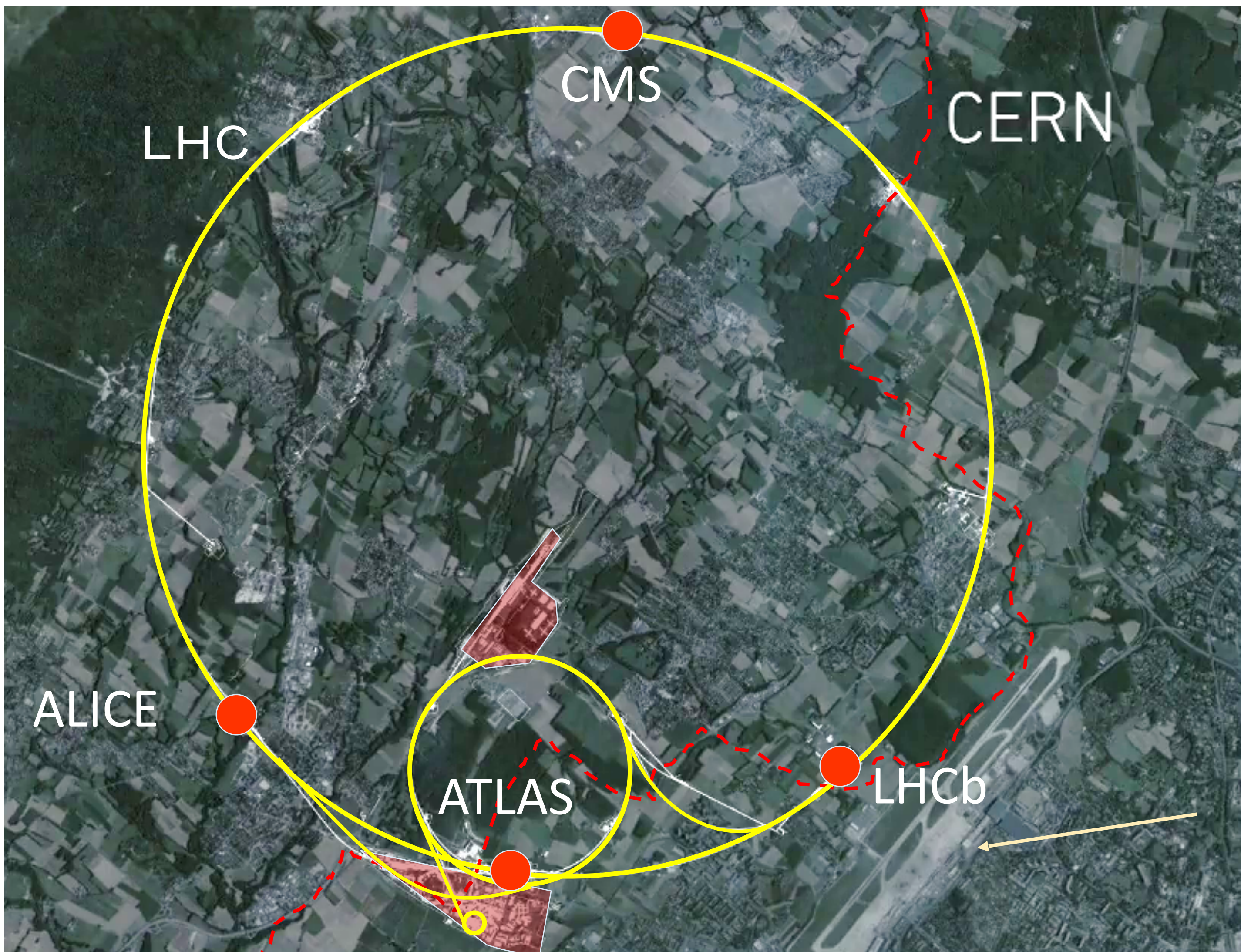
Content of the Universe



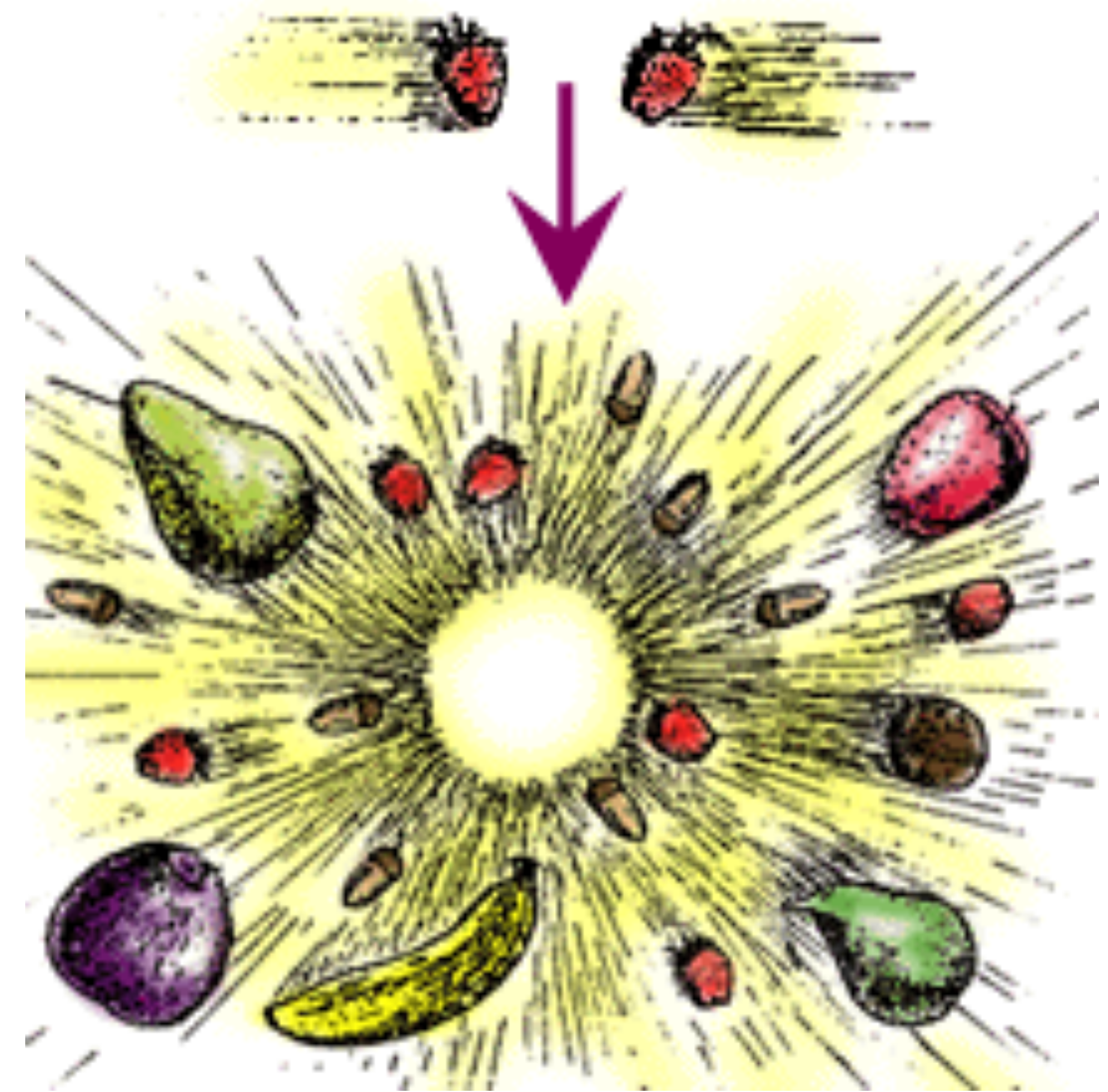
Abell 370, <https://hubblesite.org/contents/media/images/2017/20/4024-Image.html>

How are these particles produced ?

- Human accelerators



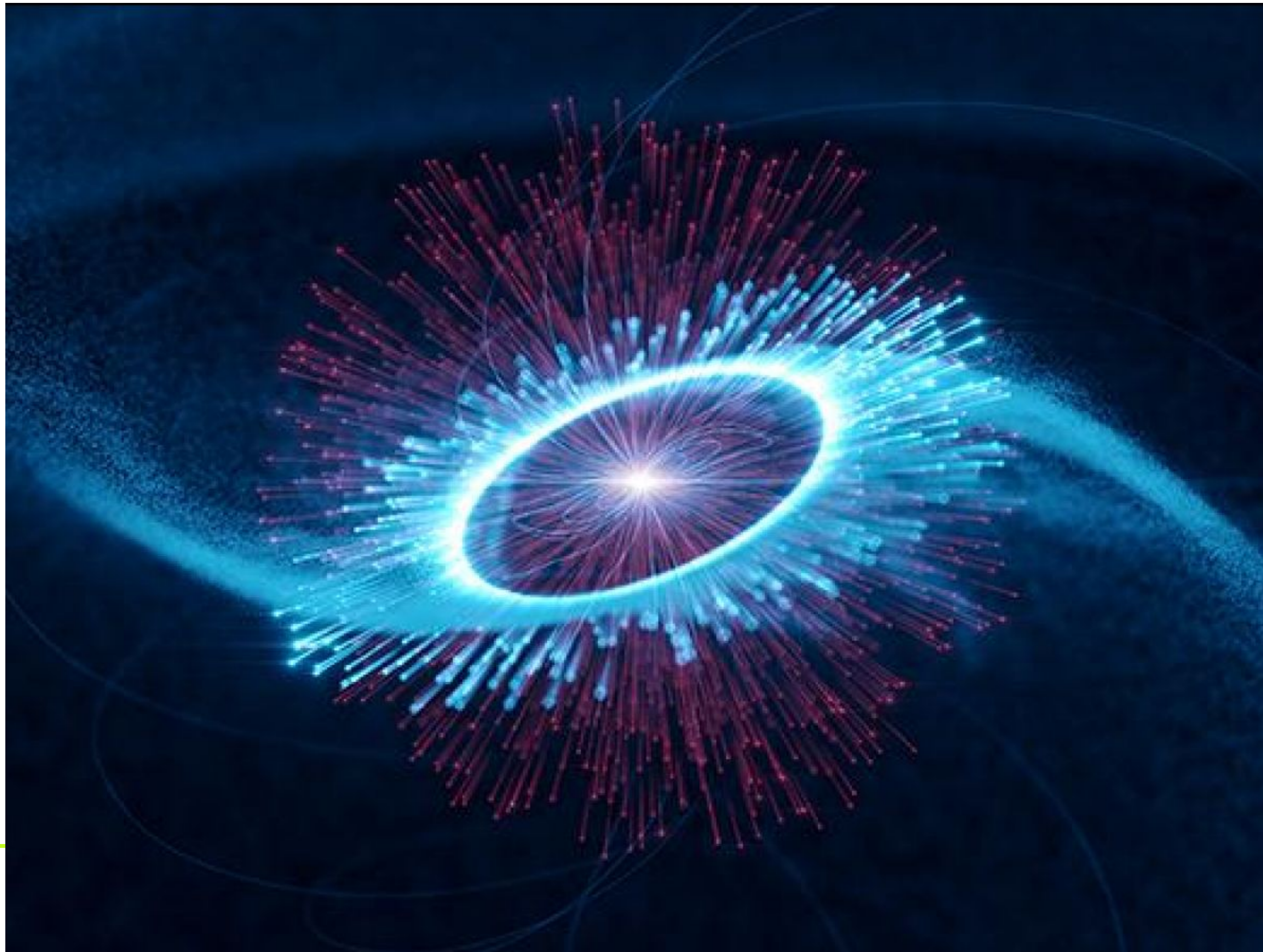
LHC = Large Hadron **Collider**



$$E = mc^2$$

How are these particles produced ?

- High-energy phenomena in universe



How do we detect particles ?

Most of these particles have very small lifetime !

How do we detect particles ?

Most of these particles have very small lifetime !

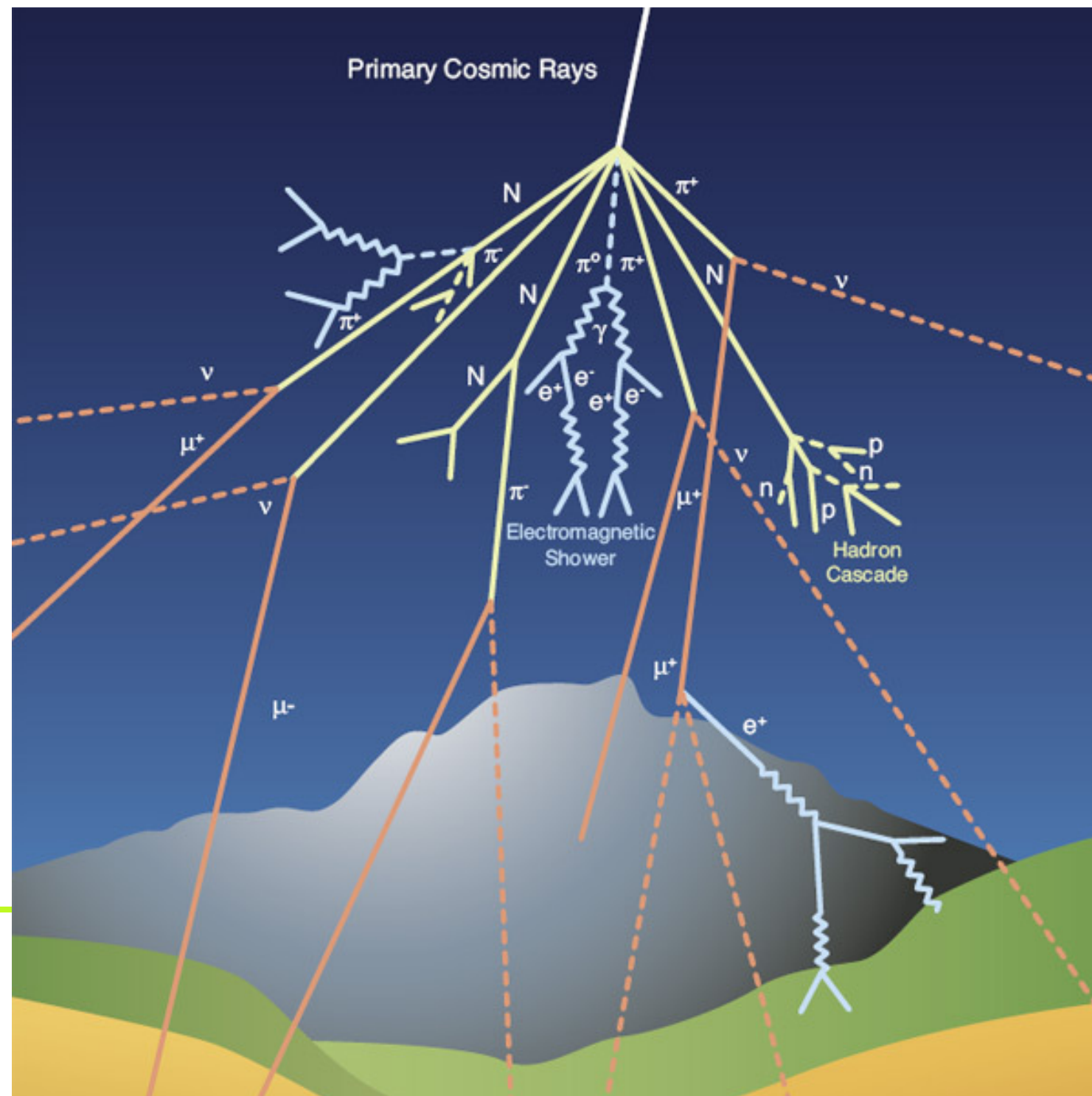
- Thanks to their **INTERACTION** with matter -> convert invisible to visible

How do we detect particles ?

Most of these particles have very small lifetime !

- **Examples:**

- cosmic particles interact with **atmosphere** (hydrogen, oxygen, azote,)

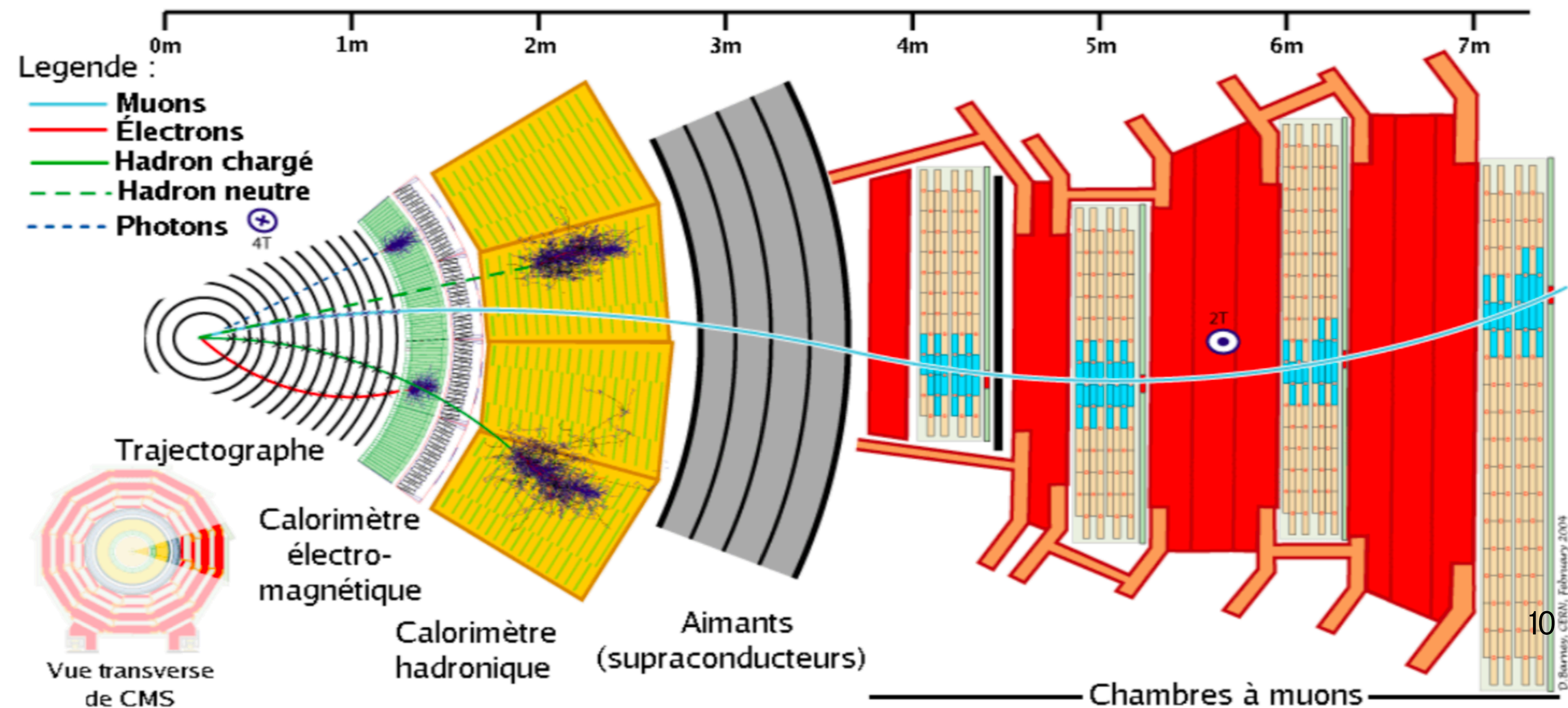
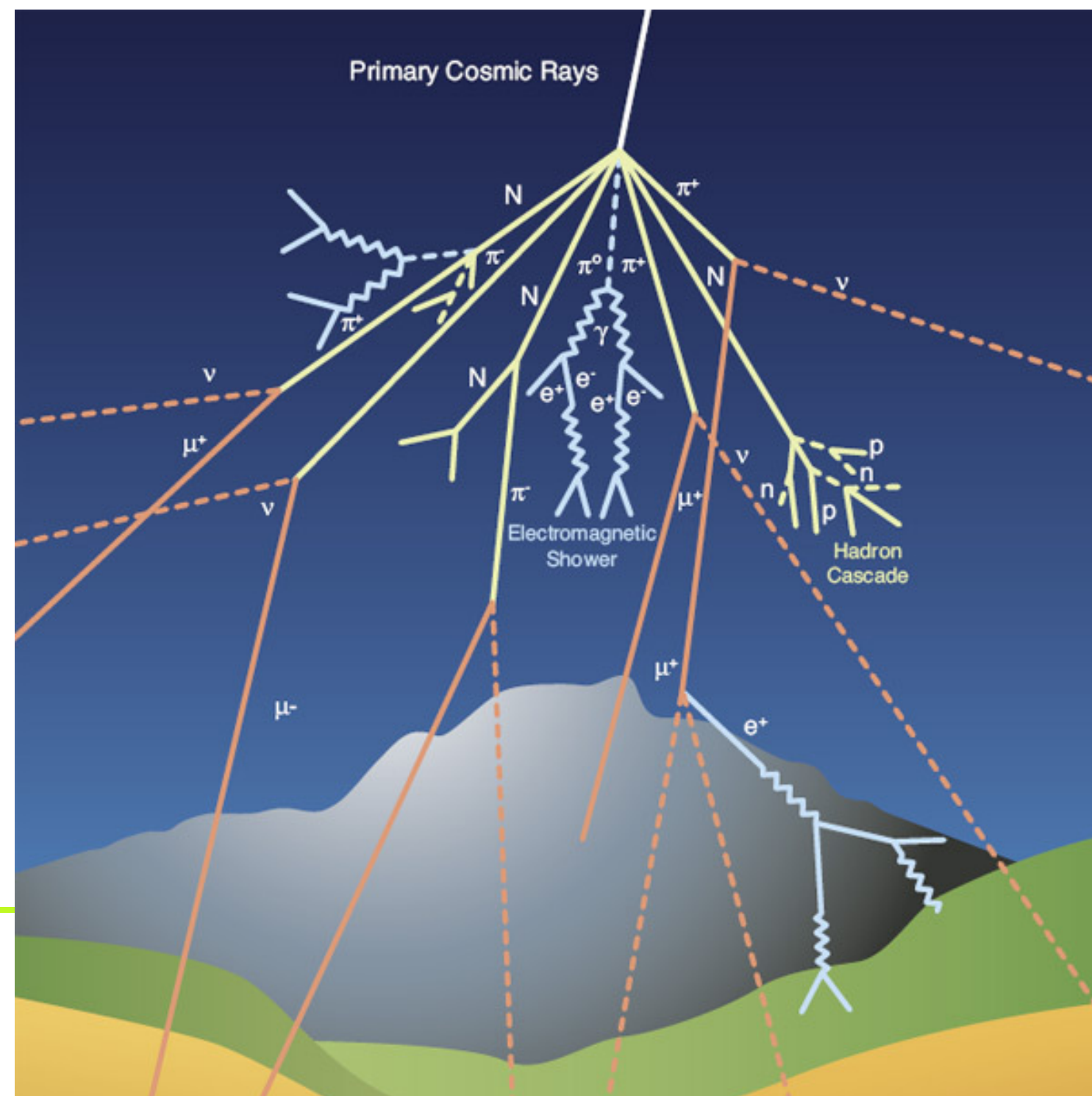


How do we detect particles ?

Most of these particles have very small lifetime !

- **Examples:**

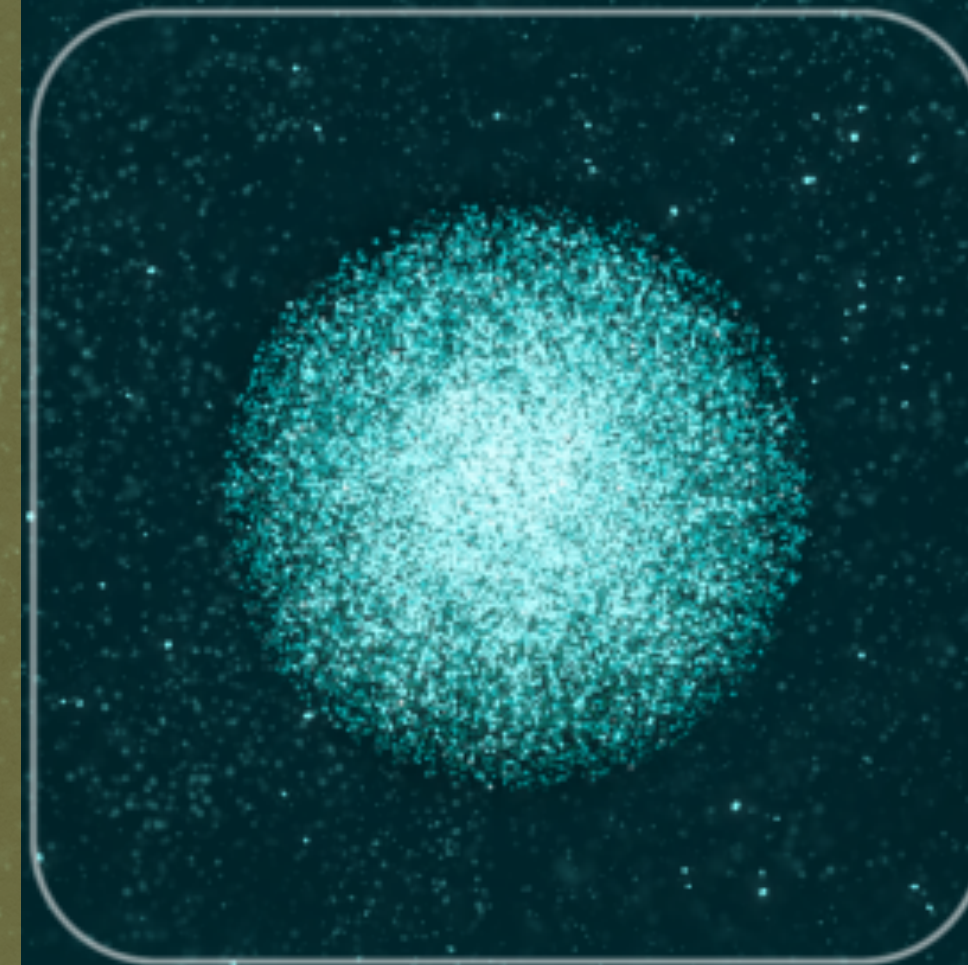
- cosmic particles interact with **atmosphere** (hydrogen, oxygen, azote,)
- accelerator particles interact with **detectors** (lead, tungsten, copper, silicium, ...)



Interaction : Electromagnetic

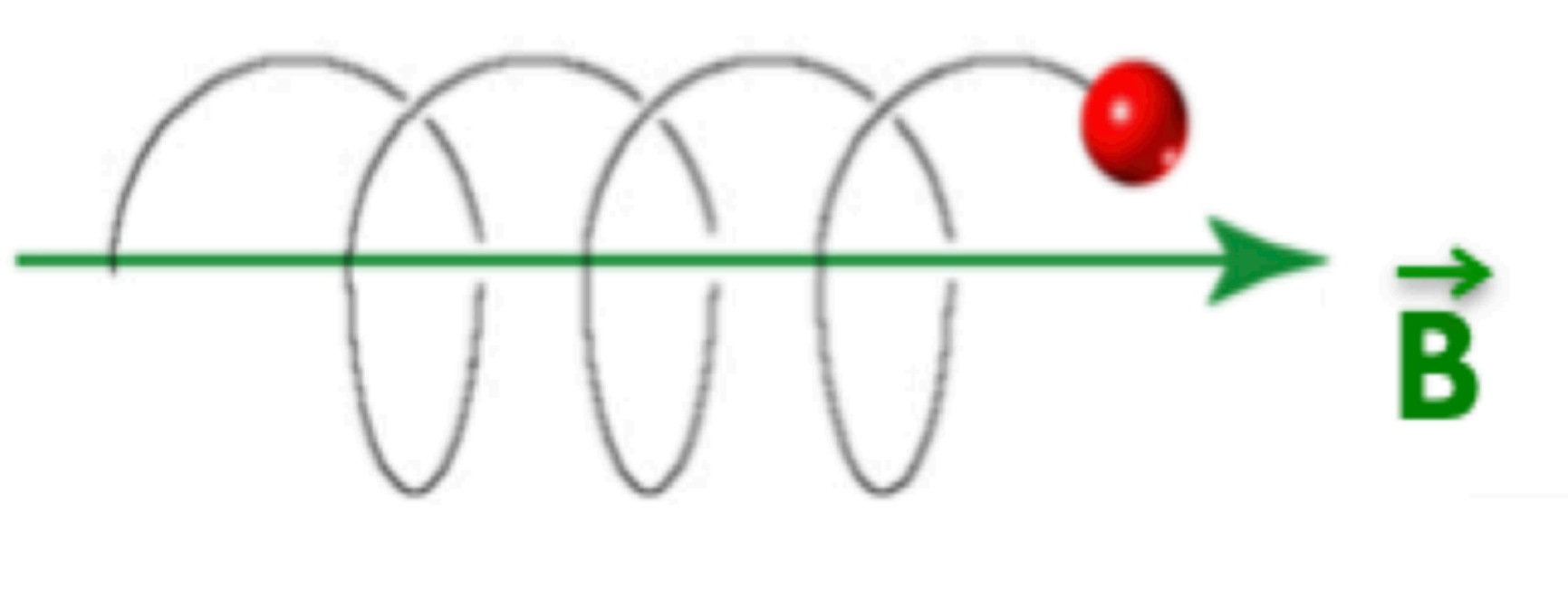


particles interacting electromagnetically



Charged particle in a magnetic field

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



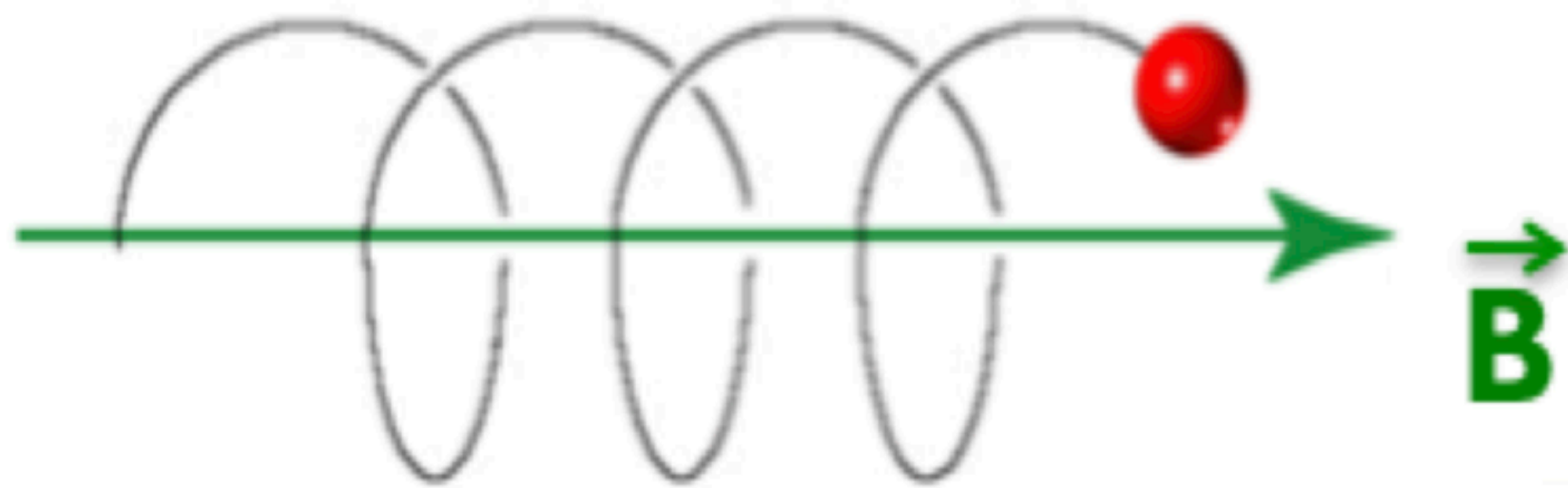
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

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

radius of curvature

Charged particle in a magnetic field

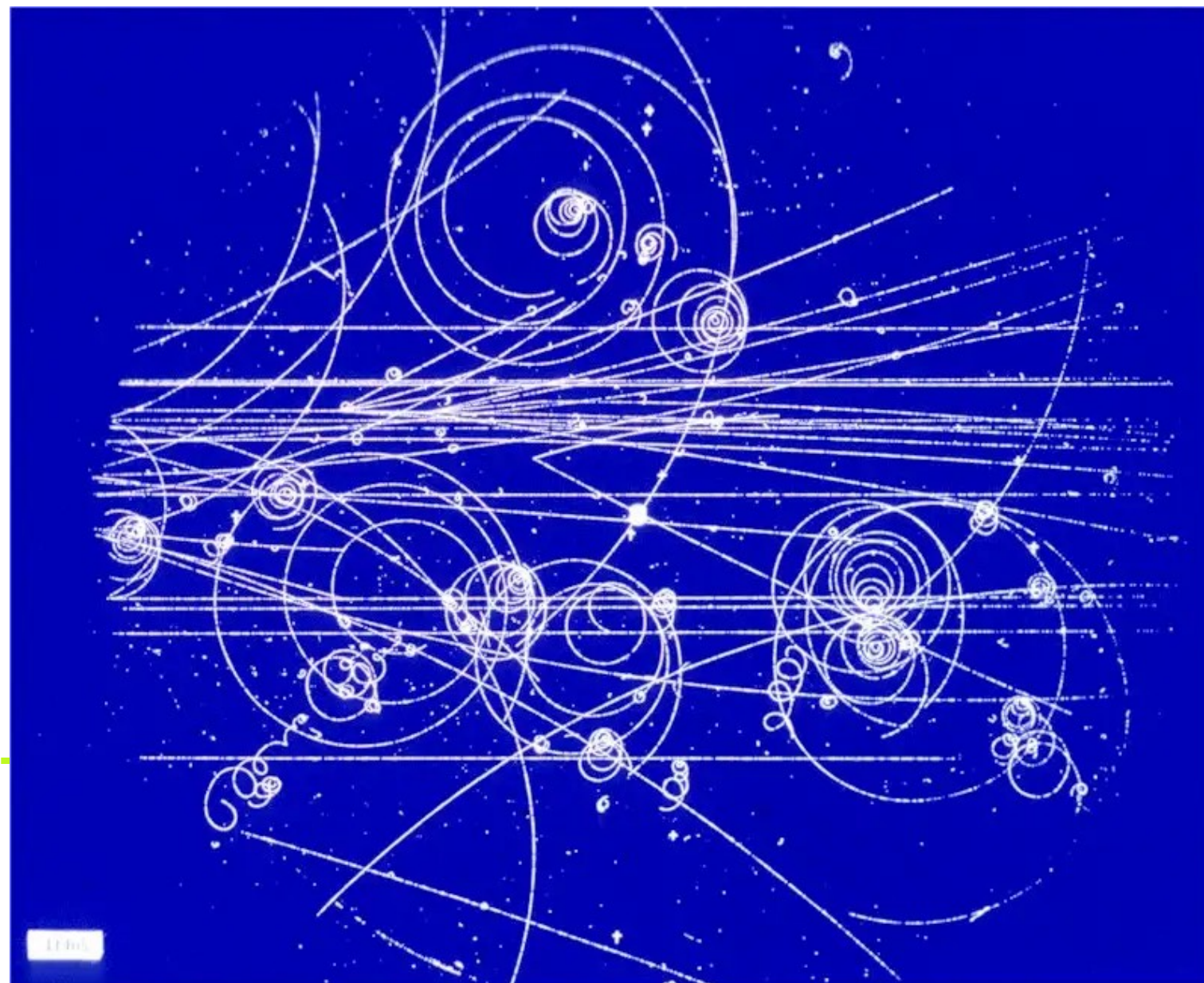
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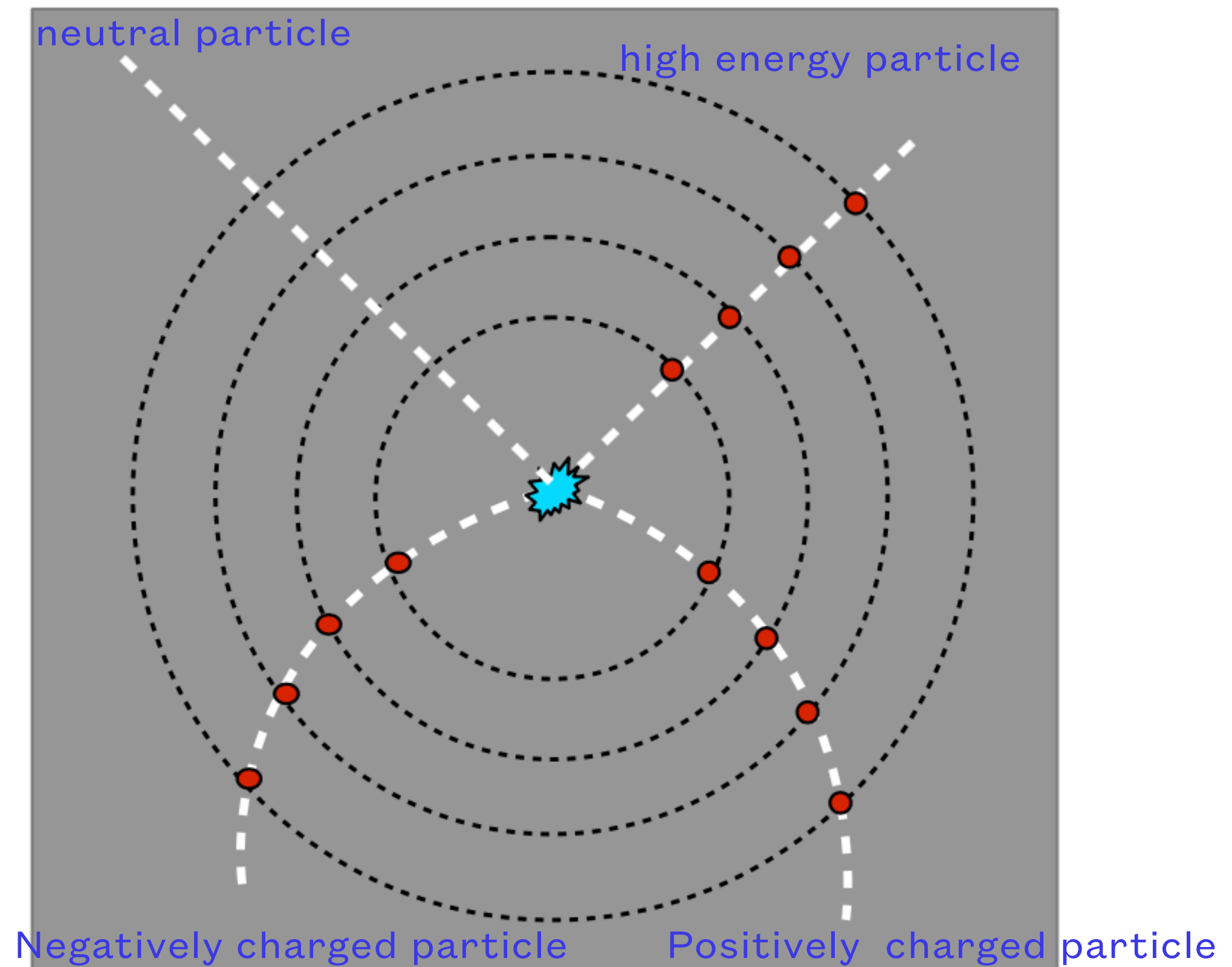
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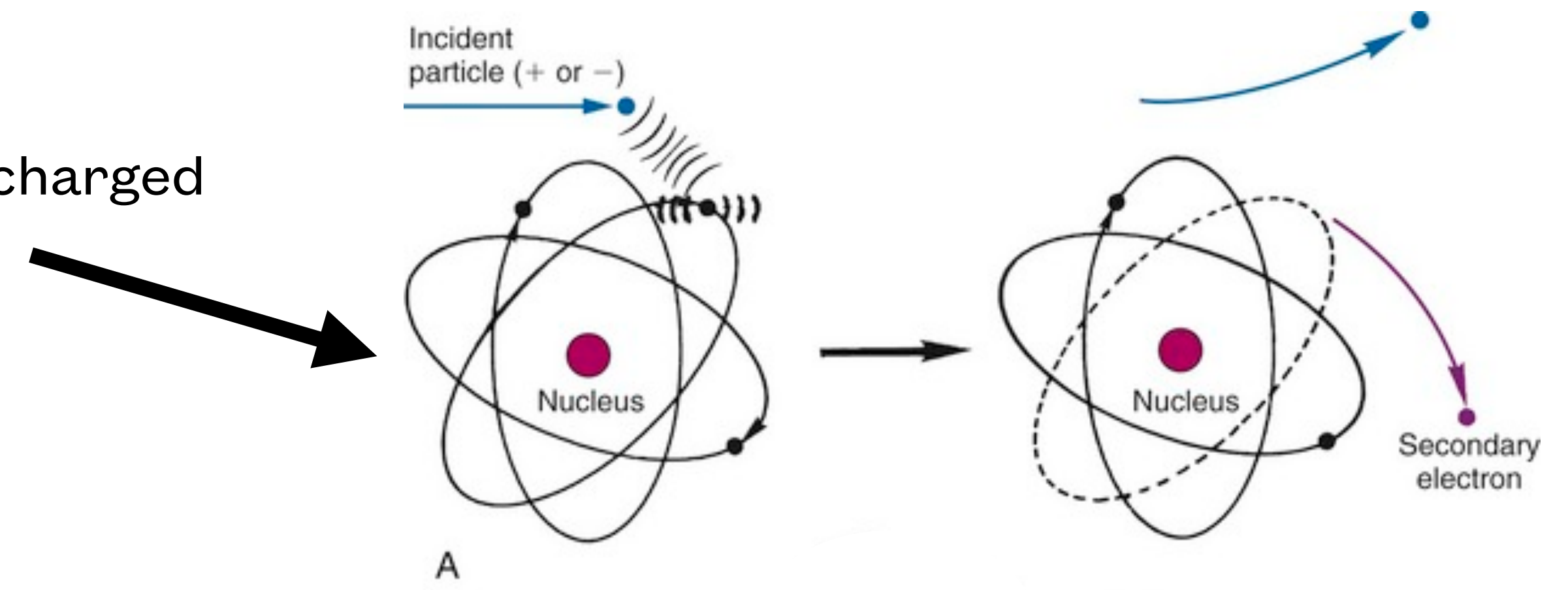


Bubble chamber



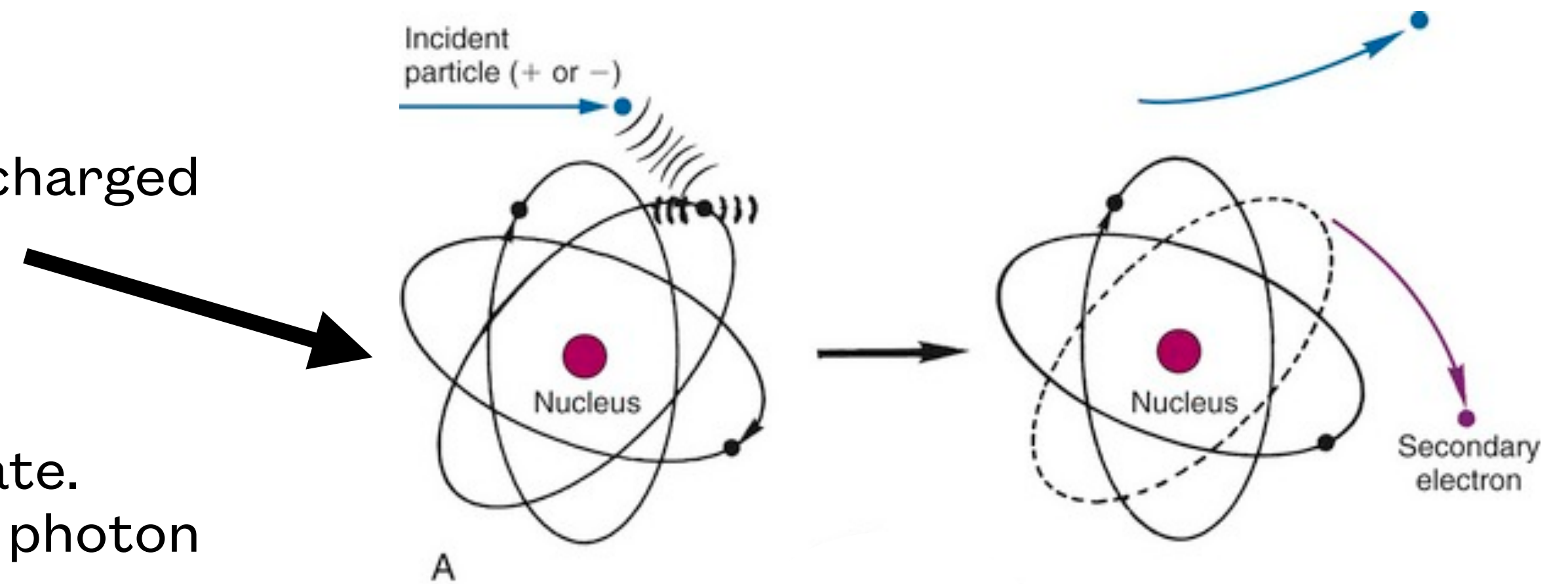
Interaction of charged particles with matter

- **Ionisation -> primary mechanism of energy loss**
 - remove one or more electrons from an atom near the charged particle's trajectory



Interaction of charged particles with matter

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 - promote one of atom's electrons to a higher energy state. Excited atom de-excite and emit low energy ultraviolet photon



Interaction of charged particles with matter

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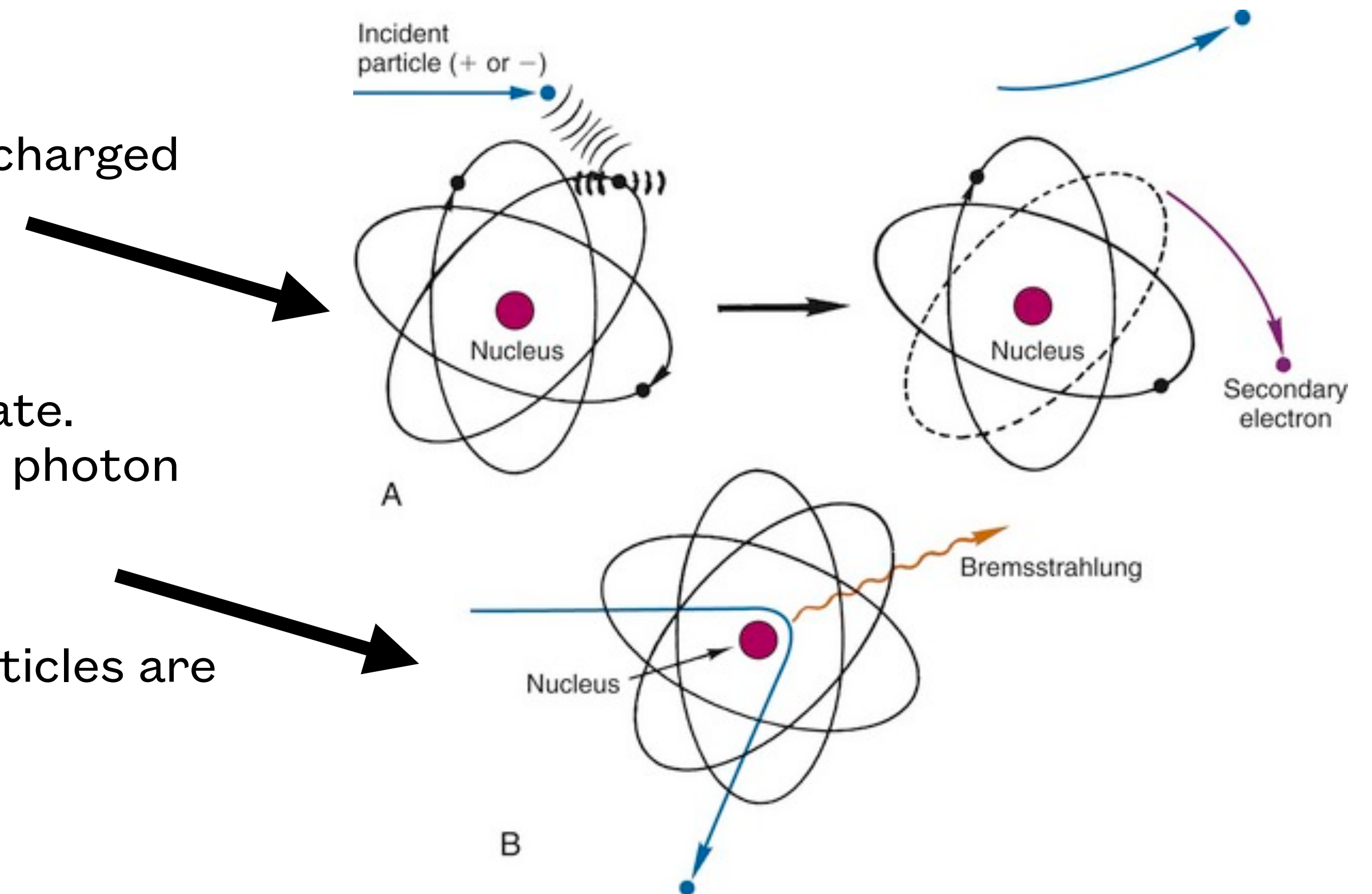
- remove one or more electrons from an atom near the charged particle's trajectory

- **Excitation**

- promote one of atom's electrons to a higher energy state. Excited atom de-excite and emit low energy ultraviolet photon

- **Bremstrahlung**

- electromagnetic radiation produced when charged particles are deflected



Interaction of charged particles with matter

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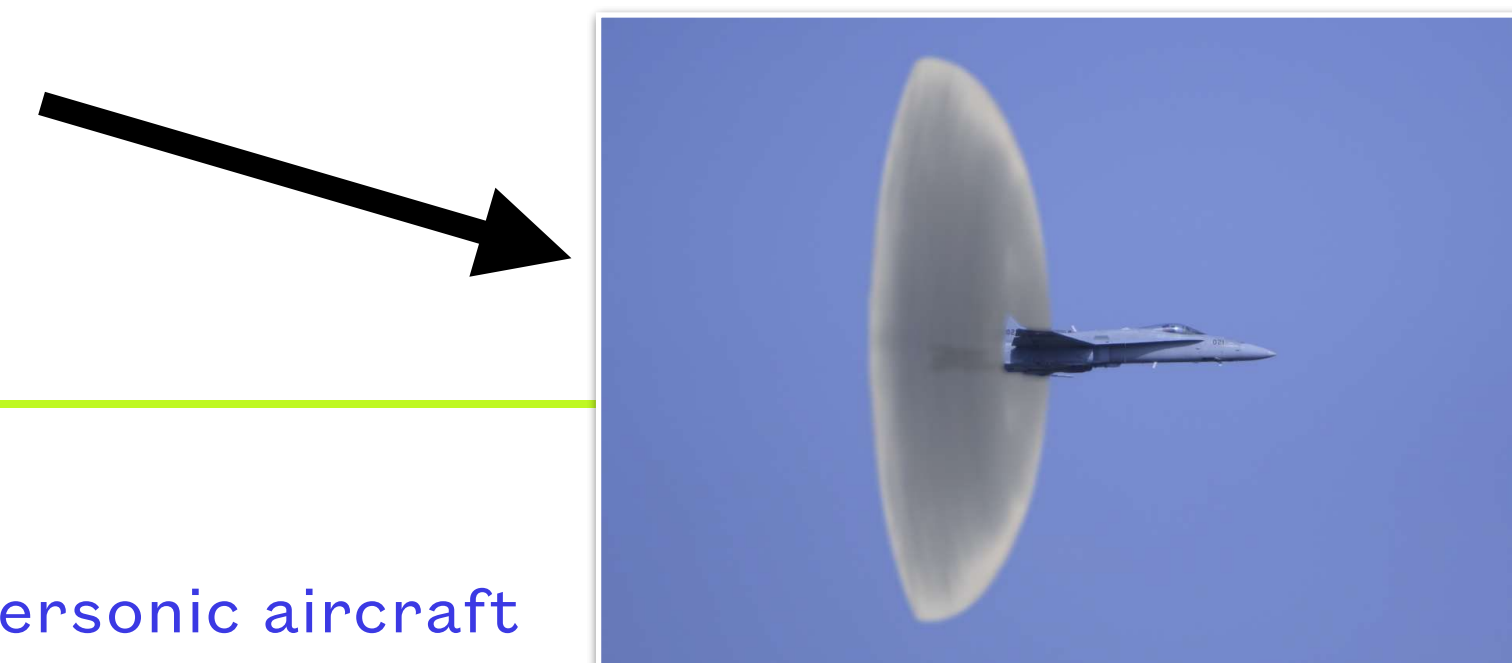
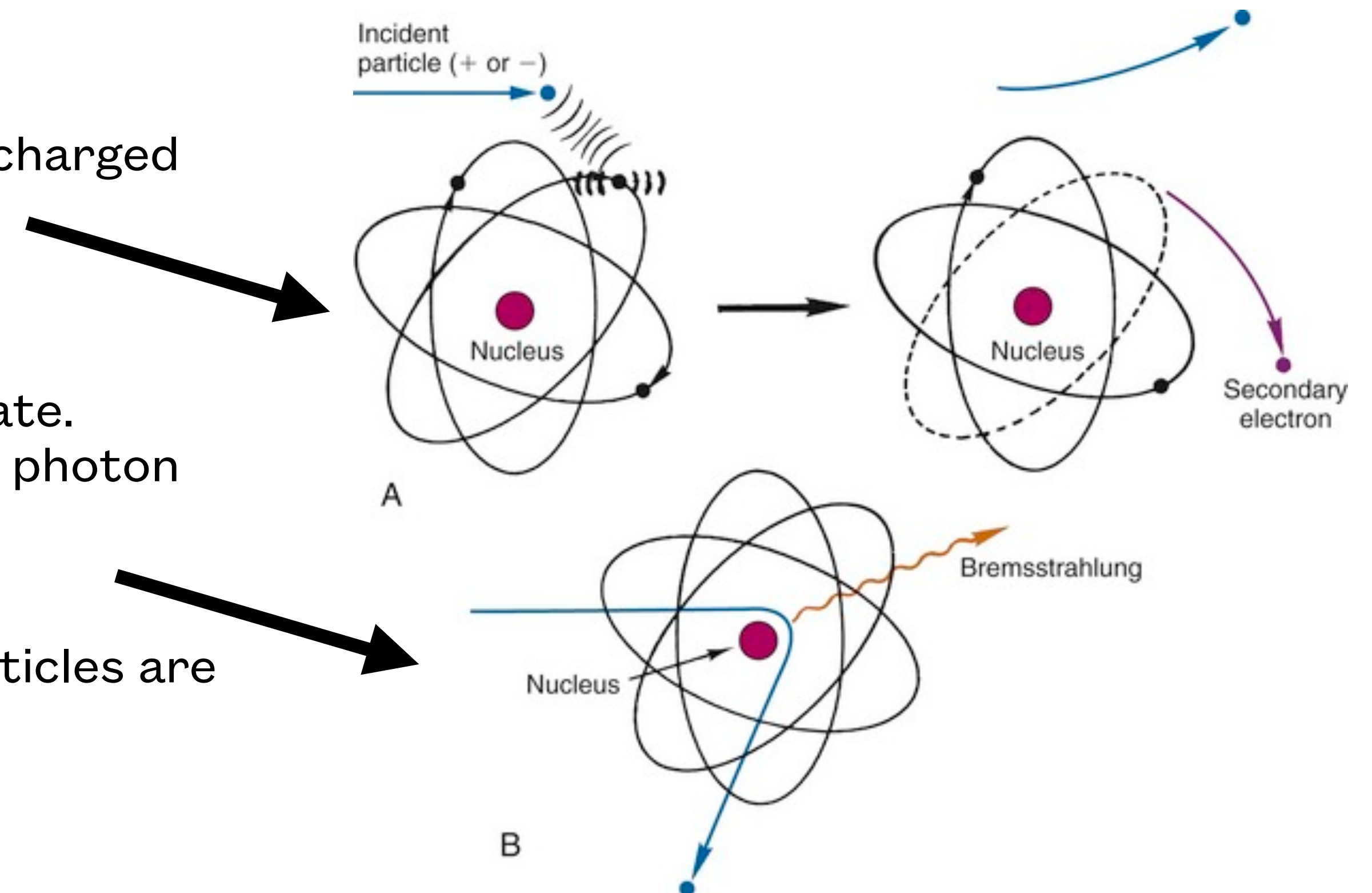
- promote one of atom's electrons to a higher energy state. Excited atom de-excite and emit low energy ultraviolet photon

- **Bremstrahlung**

- 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.

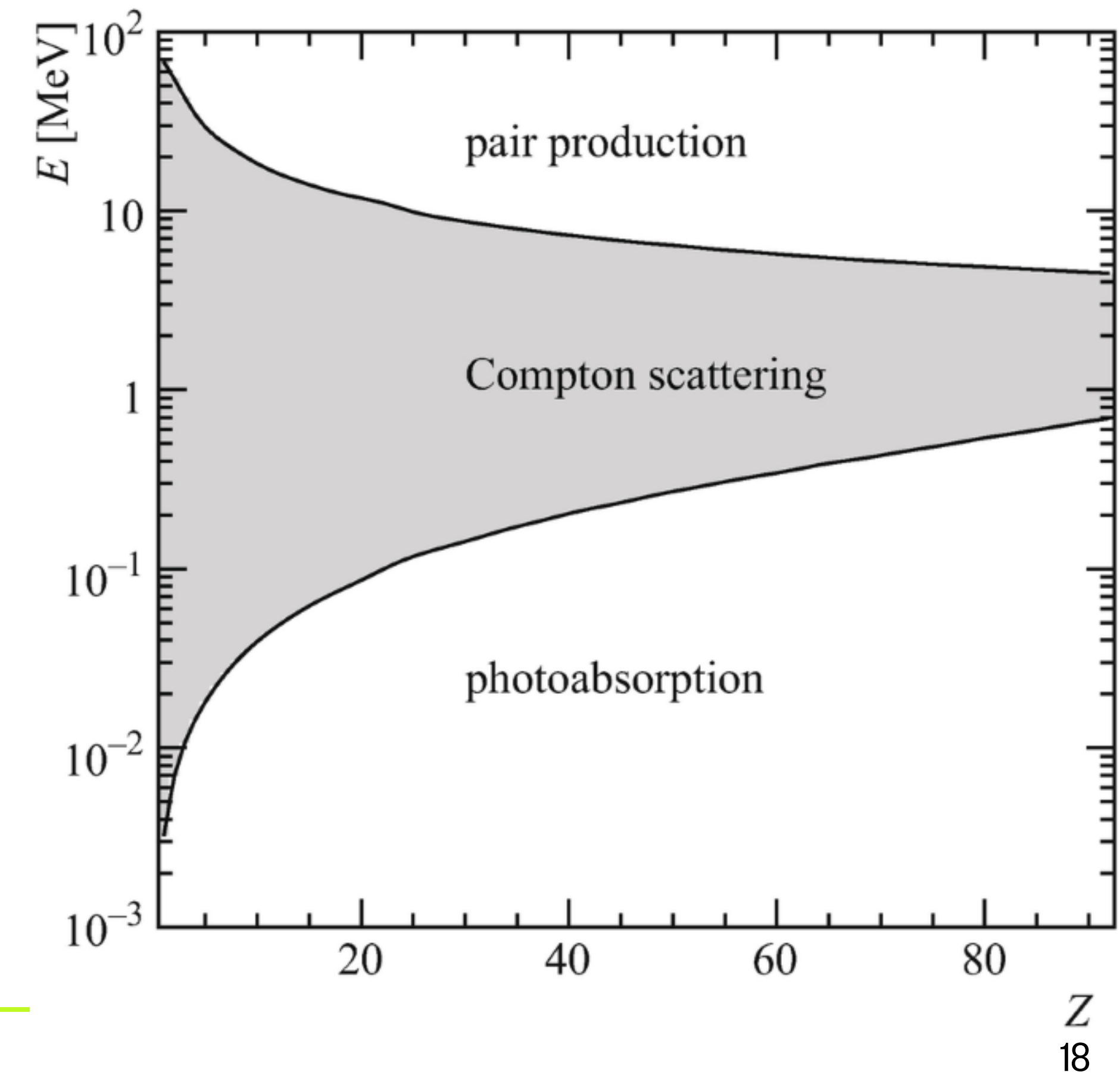
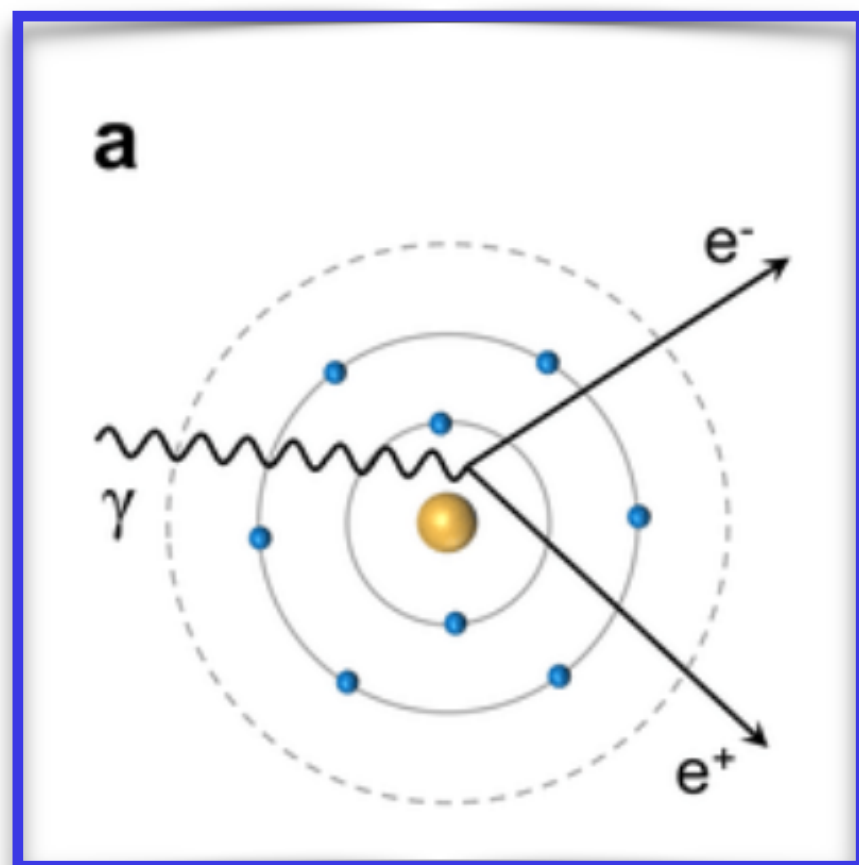


sonic boom of a supersonic aircraft

Interaction of photon with matter

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

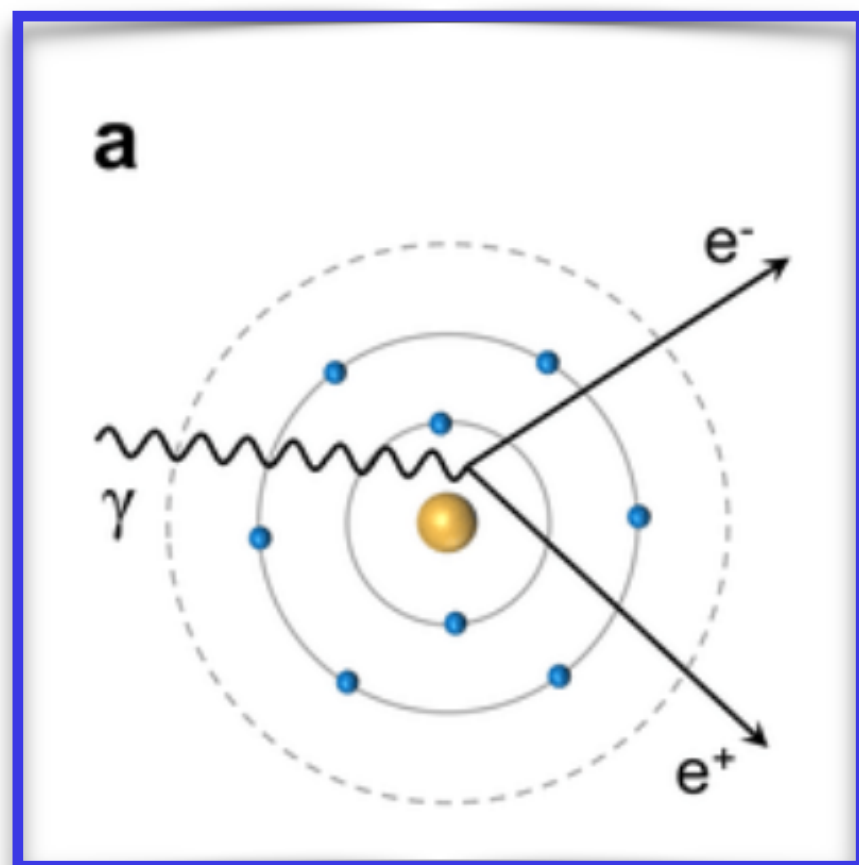
pair production



Interaction of photon with matter

- At high-energy it is essentially pair production

pair production



Compton Scattering

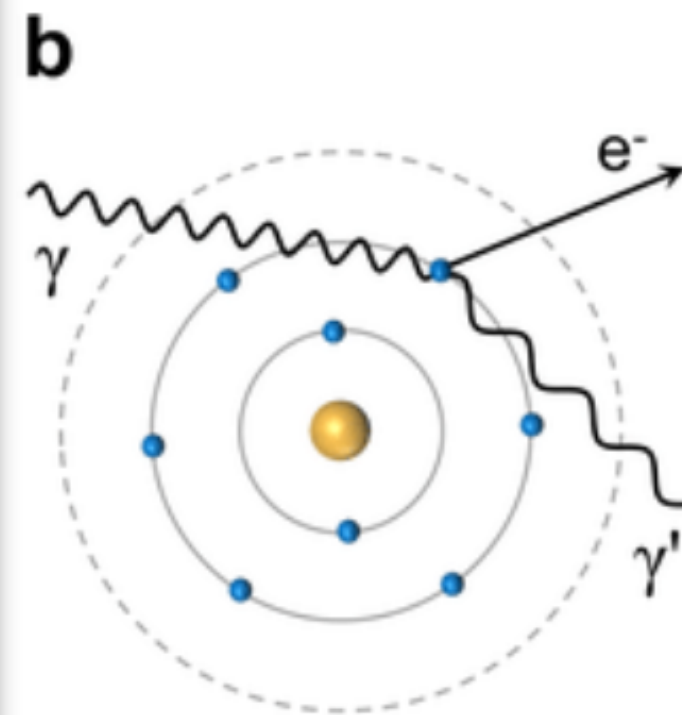
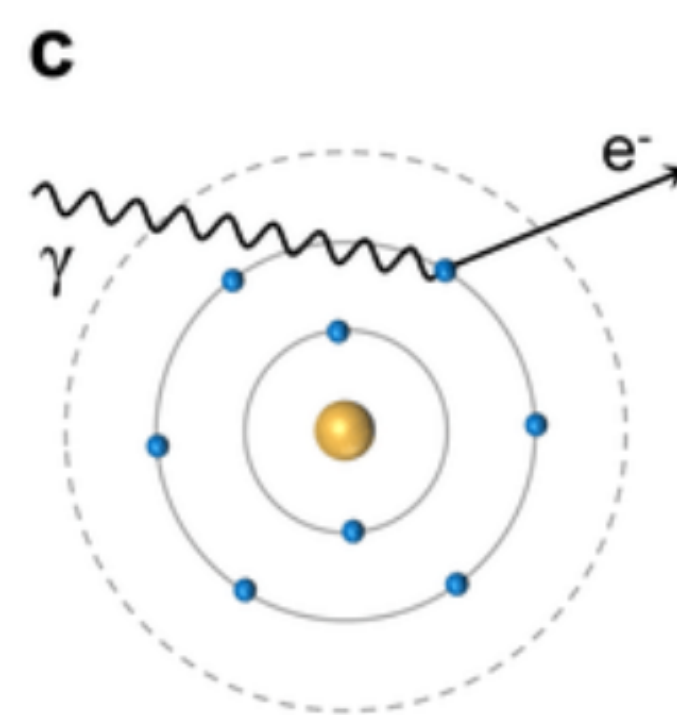
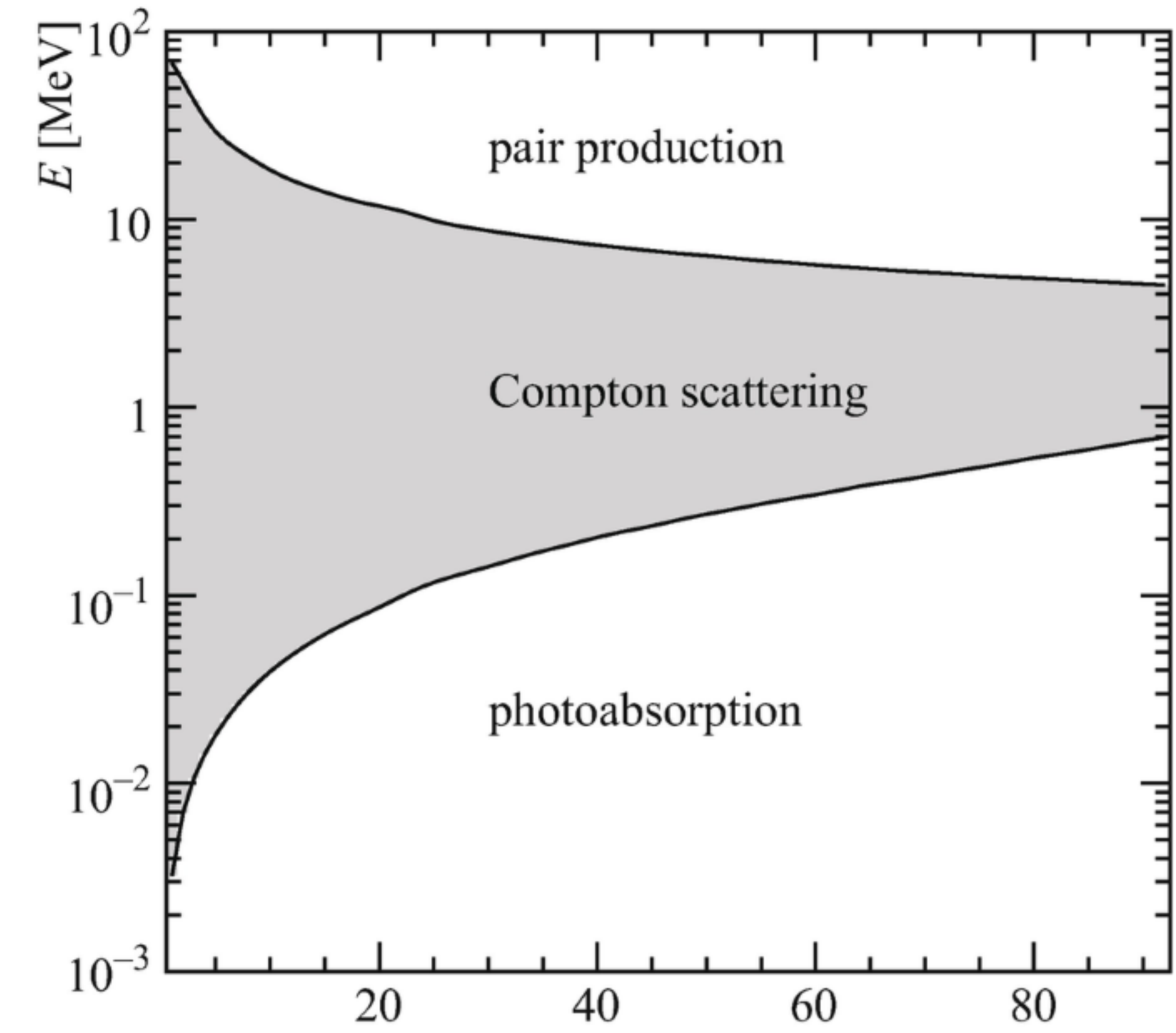
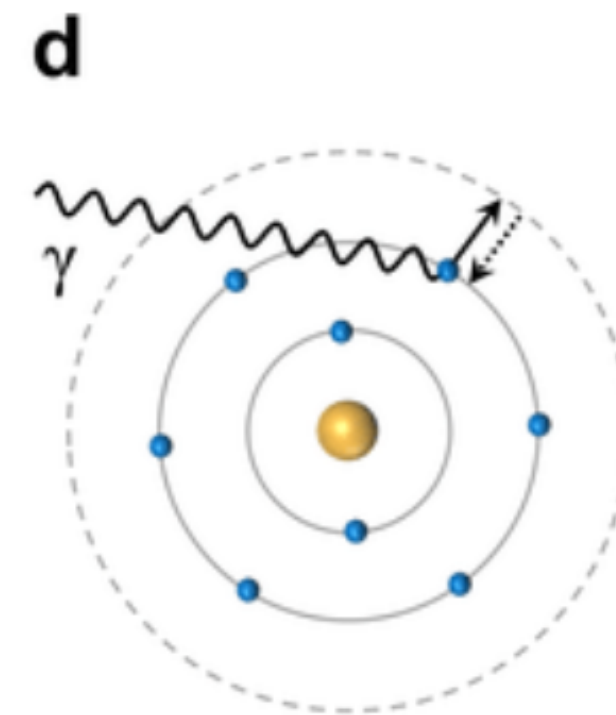


Photo-electric



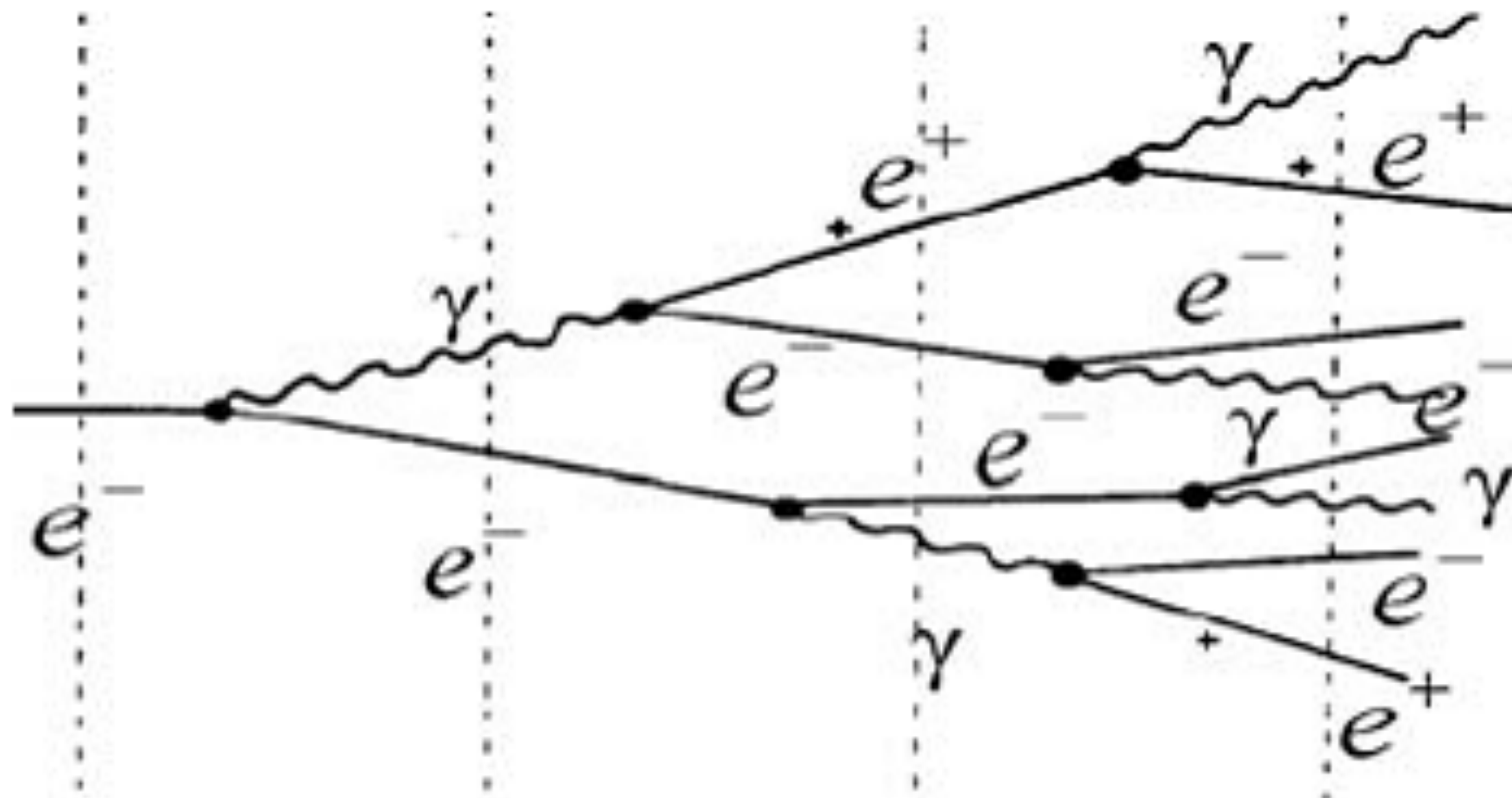
Excitation



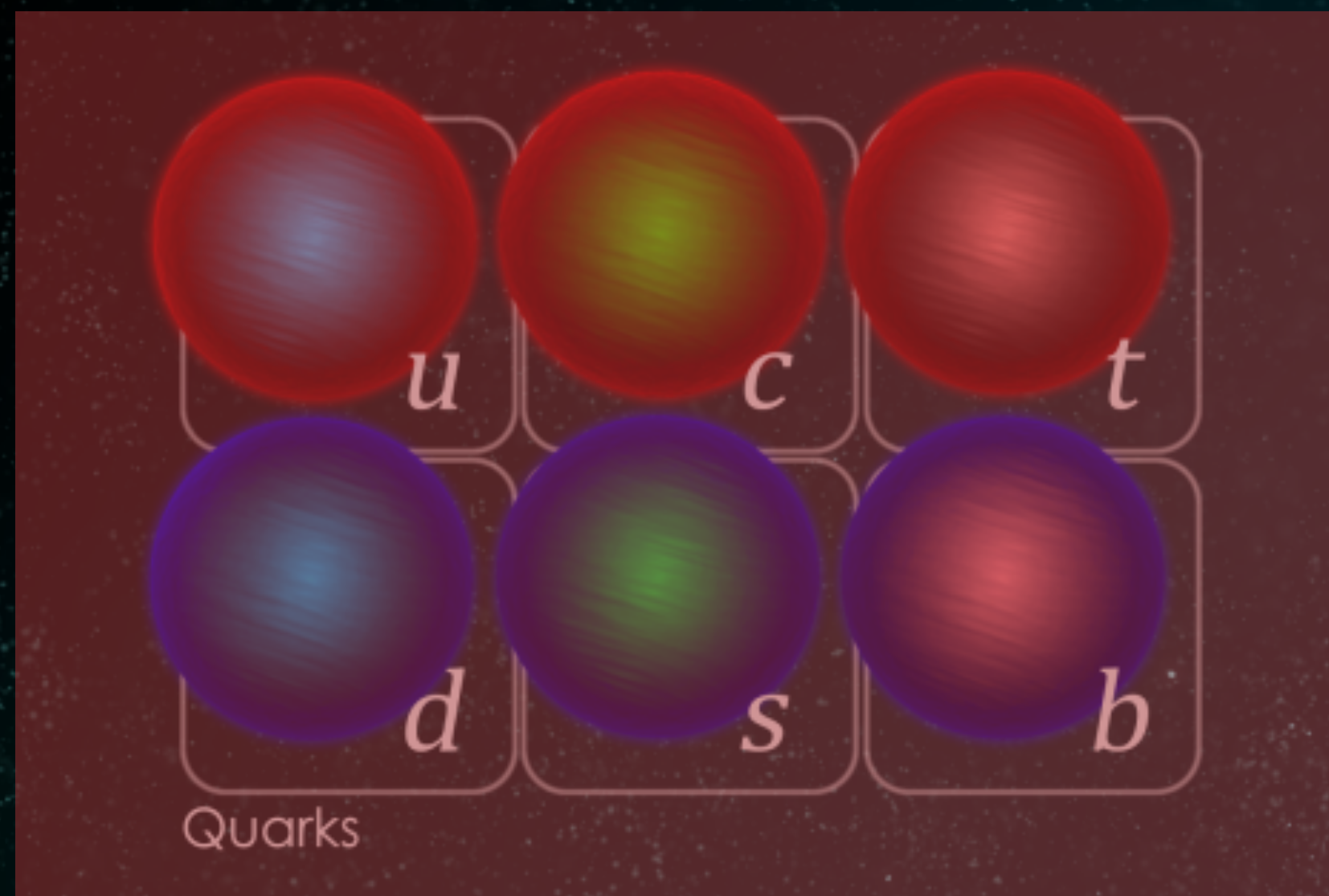
Electromagnetic shower

BREMSTRALLUNG
PAIR PRODUCTION
IONISATION

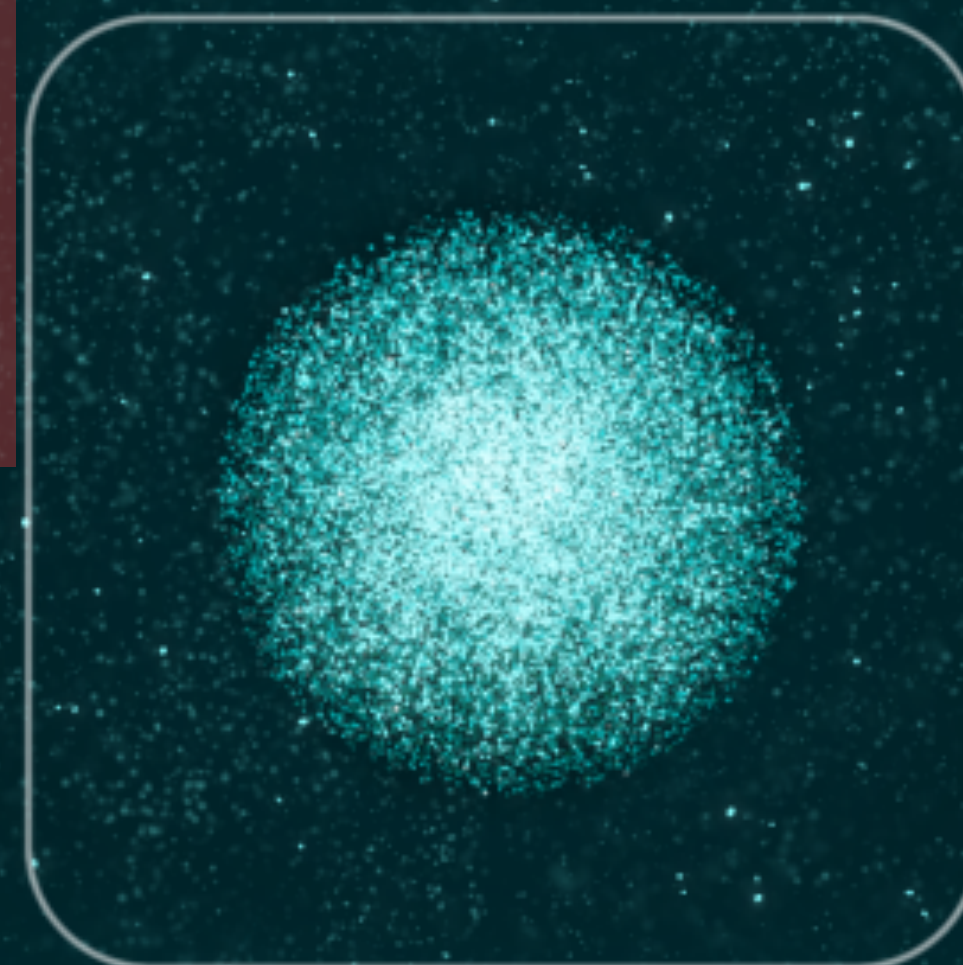
- Bremstrahlung + pair production
- **Ionisation of medium by final electrons play an important role in the detection**
 - ionization electrons drift in an electric field toward electrodes -> electrical signal proportional to total deposited energy



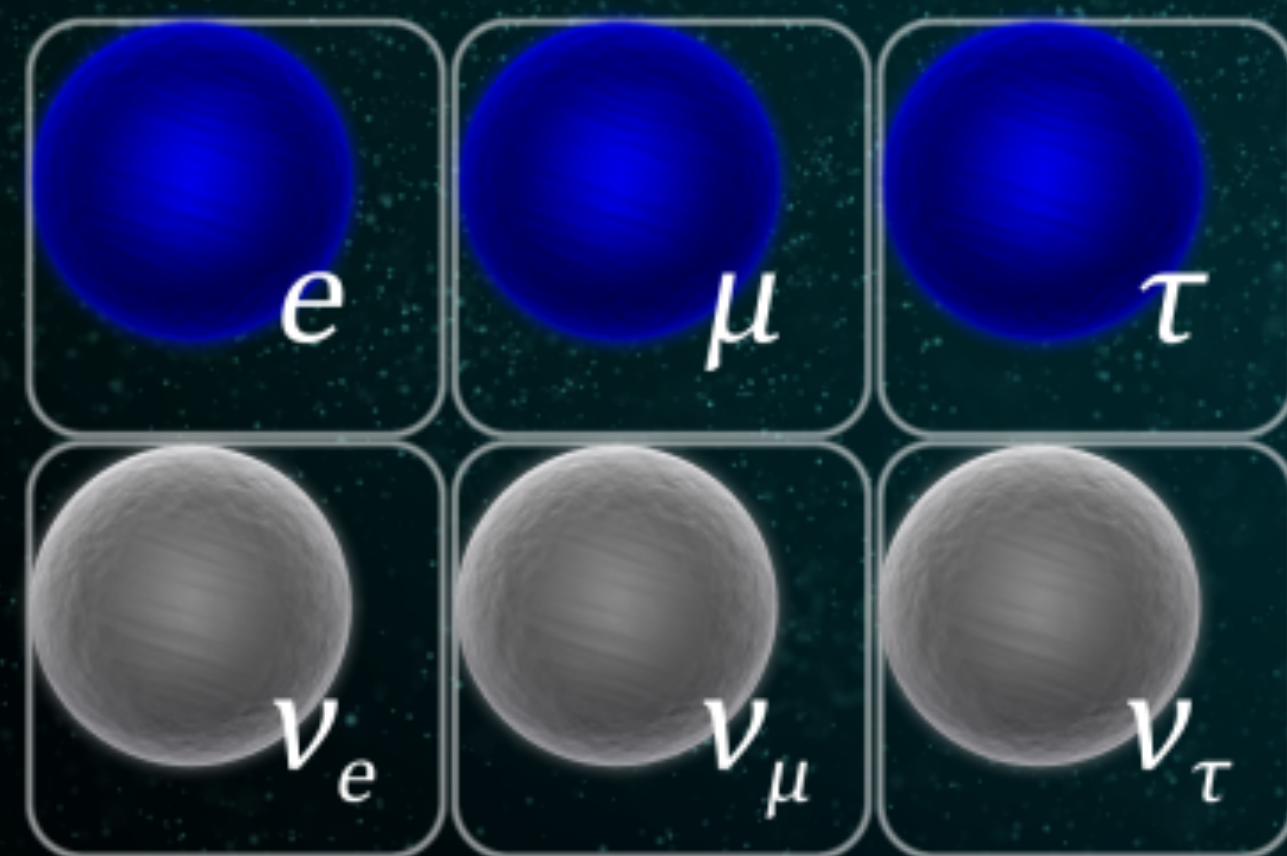
Strong interaction



Particules sensibles à l'interaction forte



Higgs boson

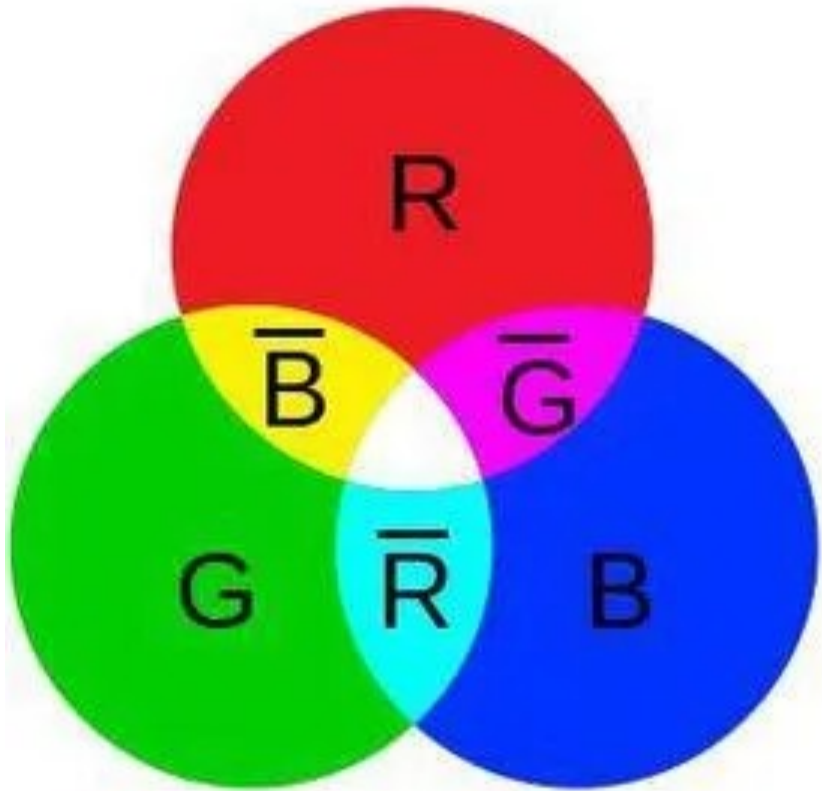


Leptons

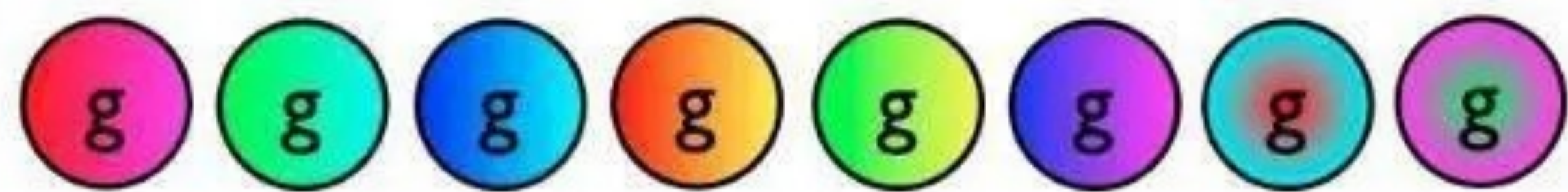
Strong force and color charge

3 colors

3 anti-colors



8 gluons



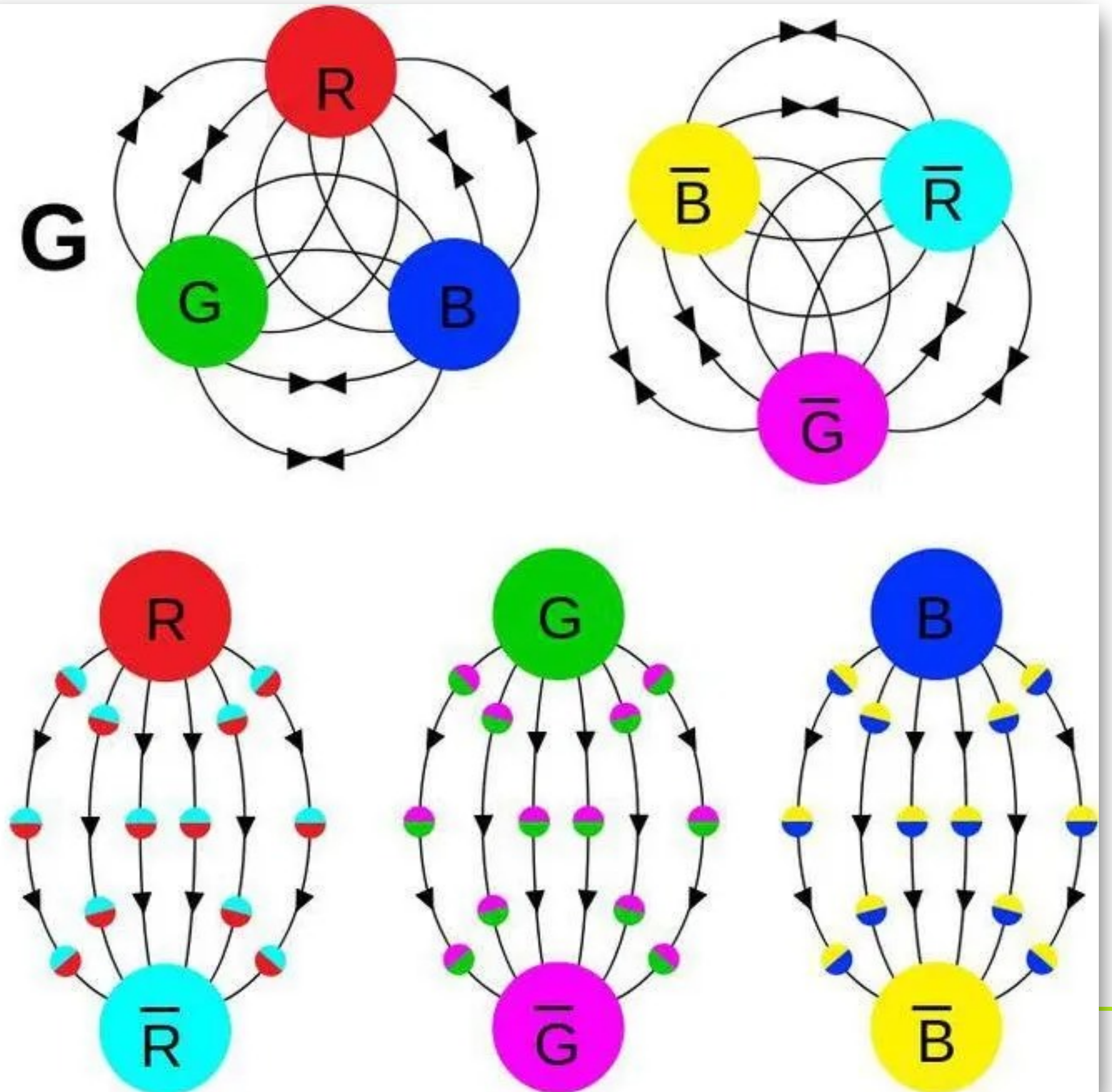
u d u d u d	c s c s c s	t b t b t b	Quarks
e^- ν_e	μ^- ν_μ	τ^- ν_τ	Leptons
$\bar{u}$ $\bar{d}$ $\bar{u}$ $\bar{d}$ $\bar{u}$ $\bar{d}$	$\bar{c}$ $\bar{s}$ $\bar{c}$ $\bar{s}$ $\bar{c}$ $\bar{s}$	$\bar{t}$ $\bar{b}$ $\bar{t}$ $\bar{b}$ $\bar{t}$ $\bar{b}$	Anti-Quarks
$\bar{e}^+$ $\bar{\nu}_e$	$\bar{\mu}^+$ $\bar{\nu}_\mu$	$\bar{\tau}^+$ $\bar{\nu}_\tau$	Anti-Leptons

-> THERE ARE THEN 36 QUARKS IN THE THEORY

Color confinement

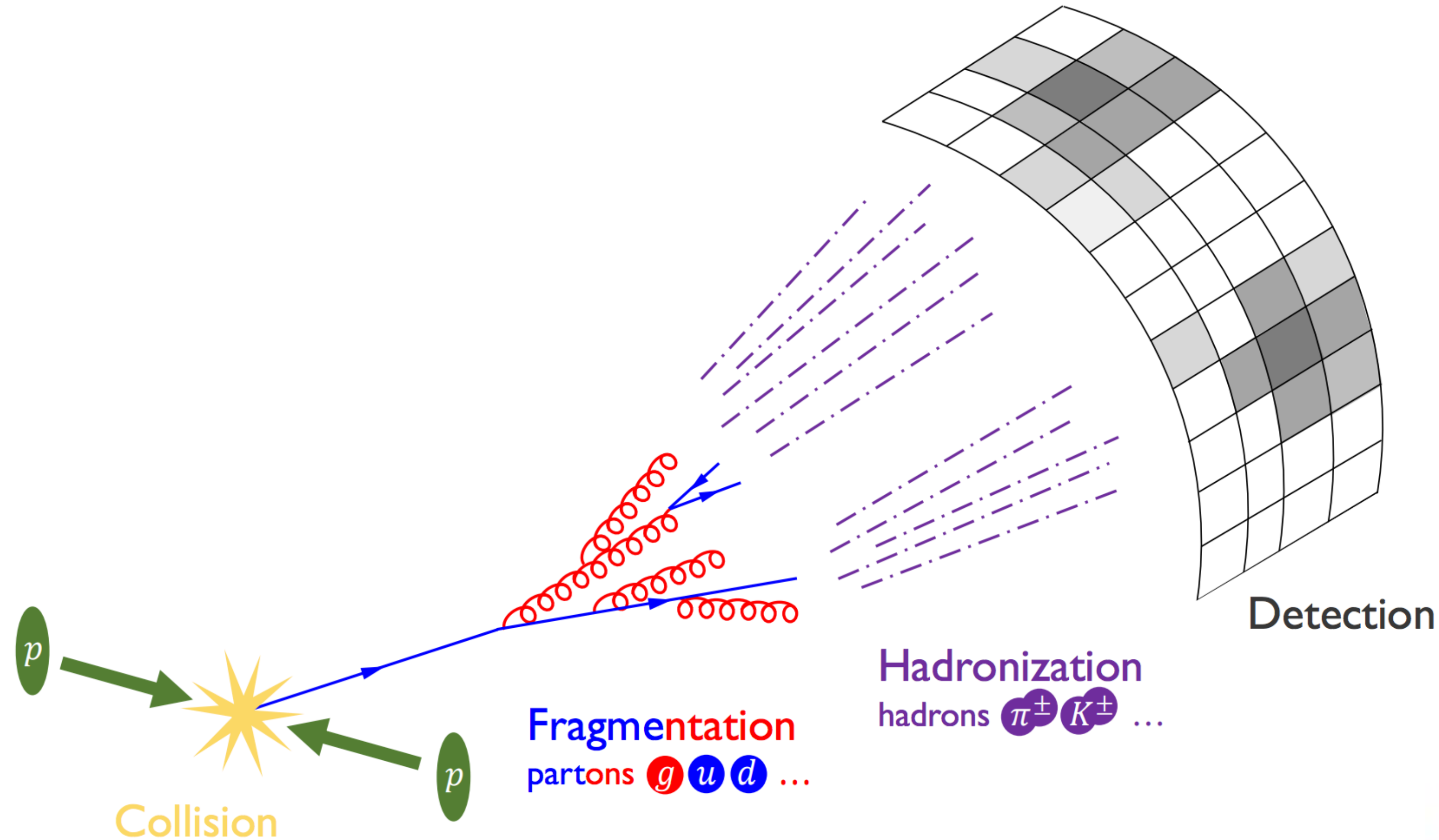
- Not possible to find a colored particle alone ! Only « white » particles allowed

Baryons

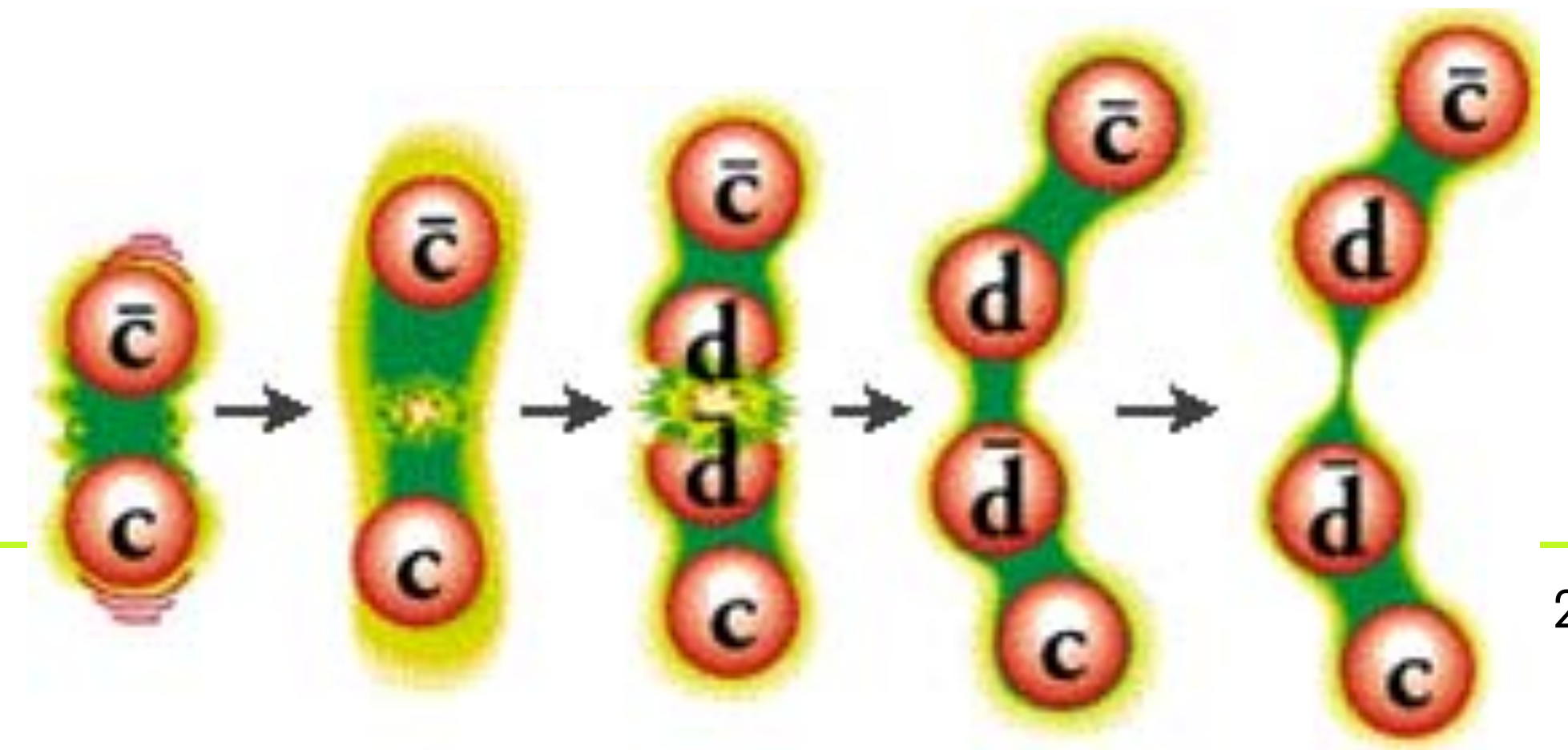


Mésons

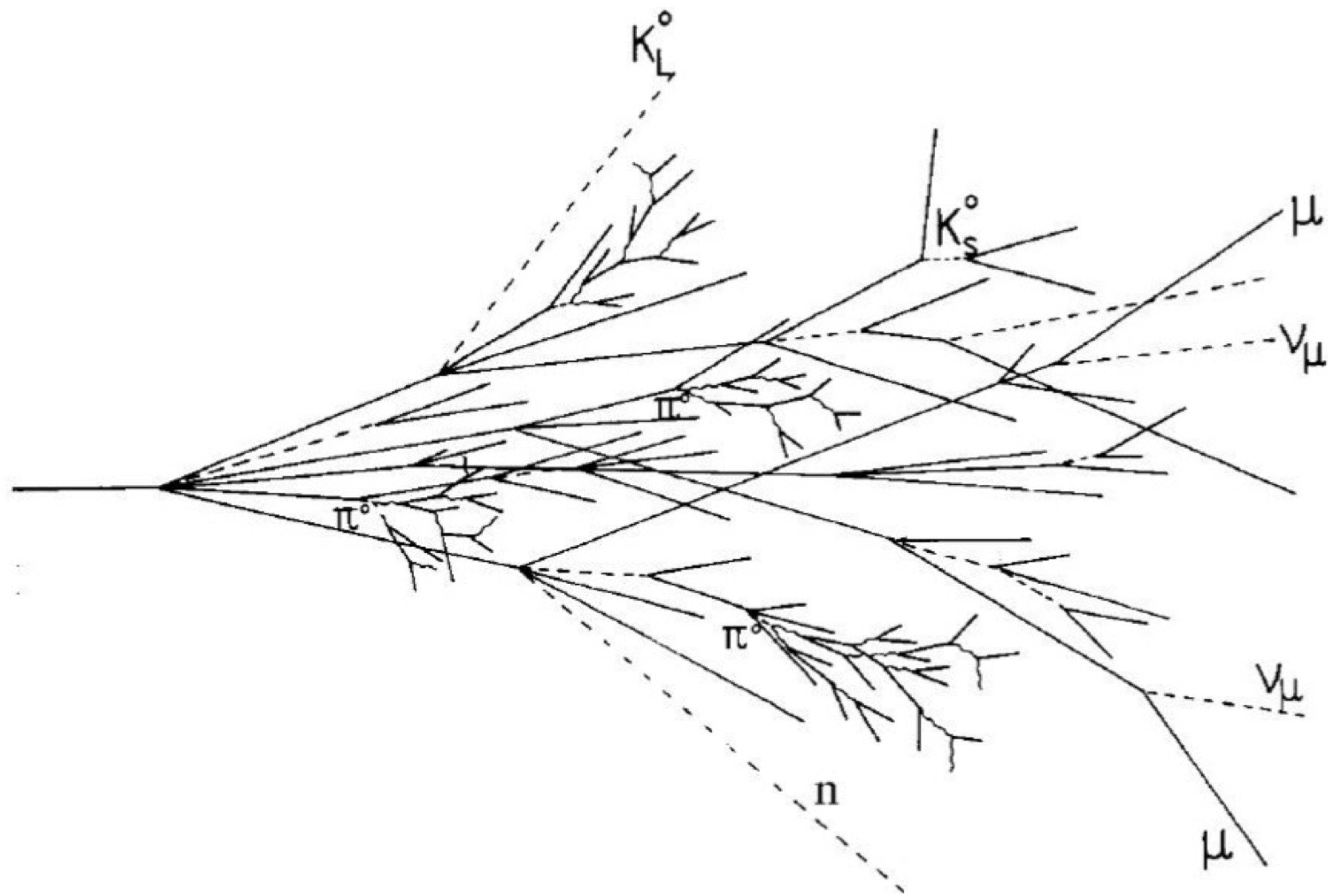
Fragmentation and hadronization



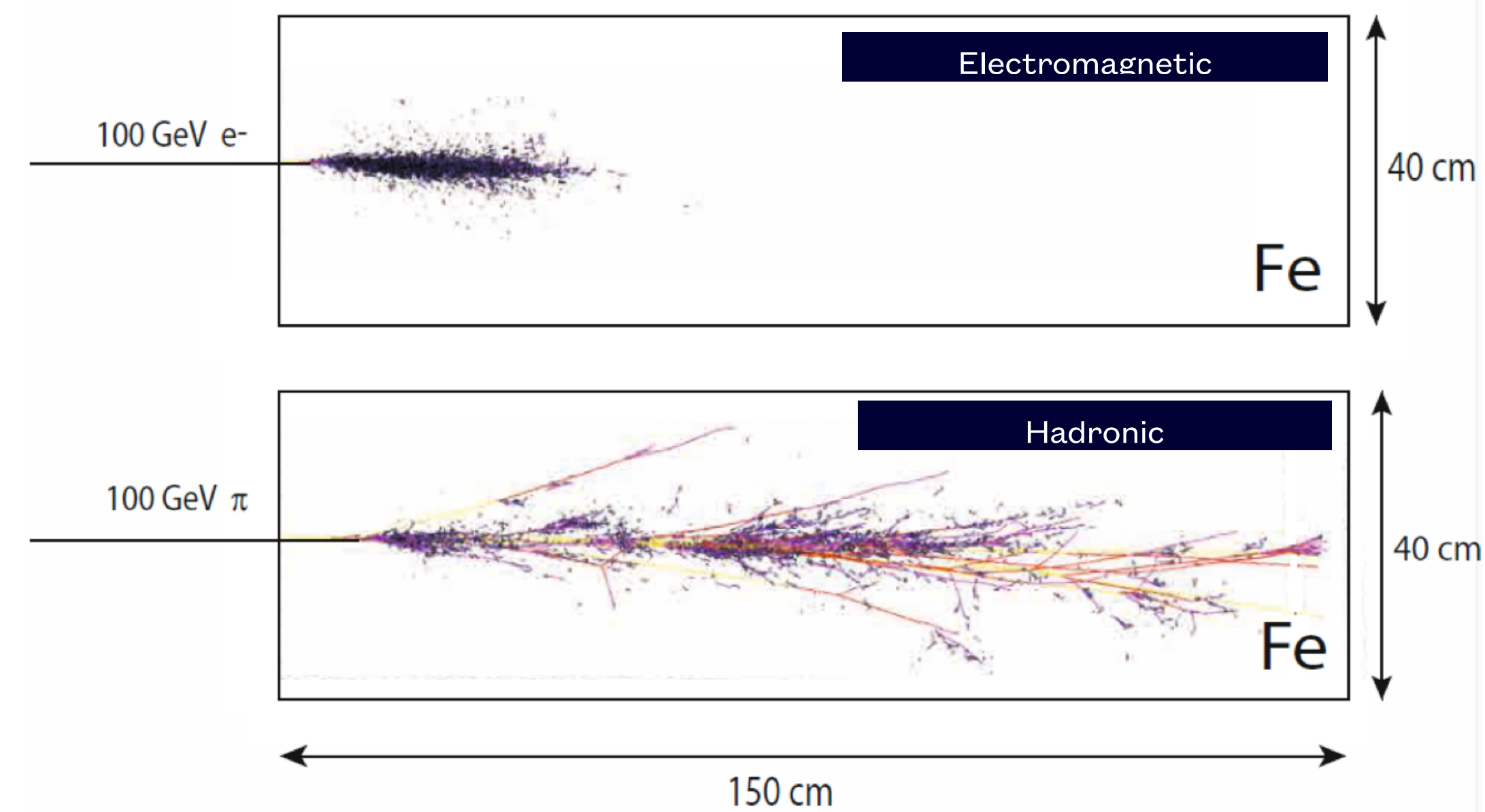
- When a single quark or gluon is emitted, process of fragmentation and hadronization occurs to «whiten» the particle
- Results in a hadronic shower -> a «jet»



Hadronic shower

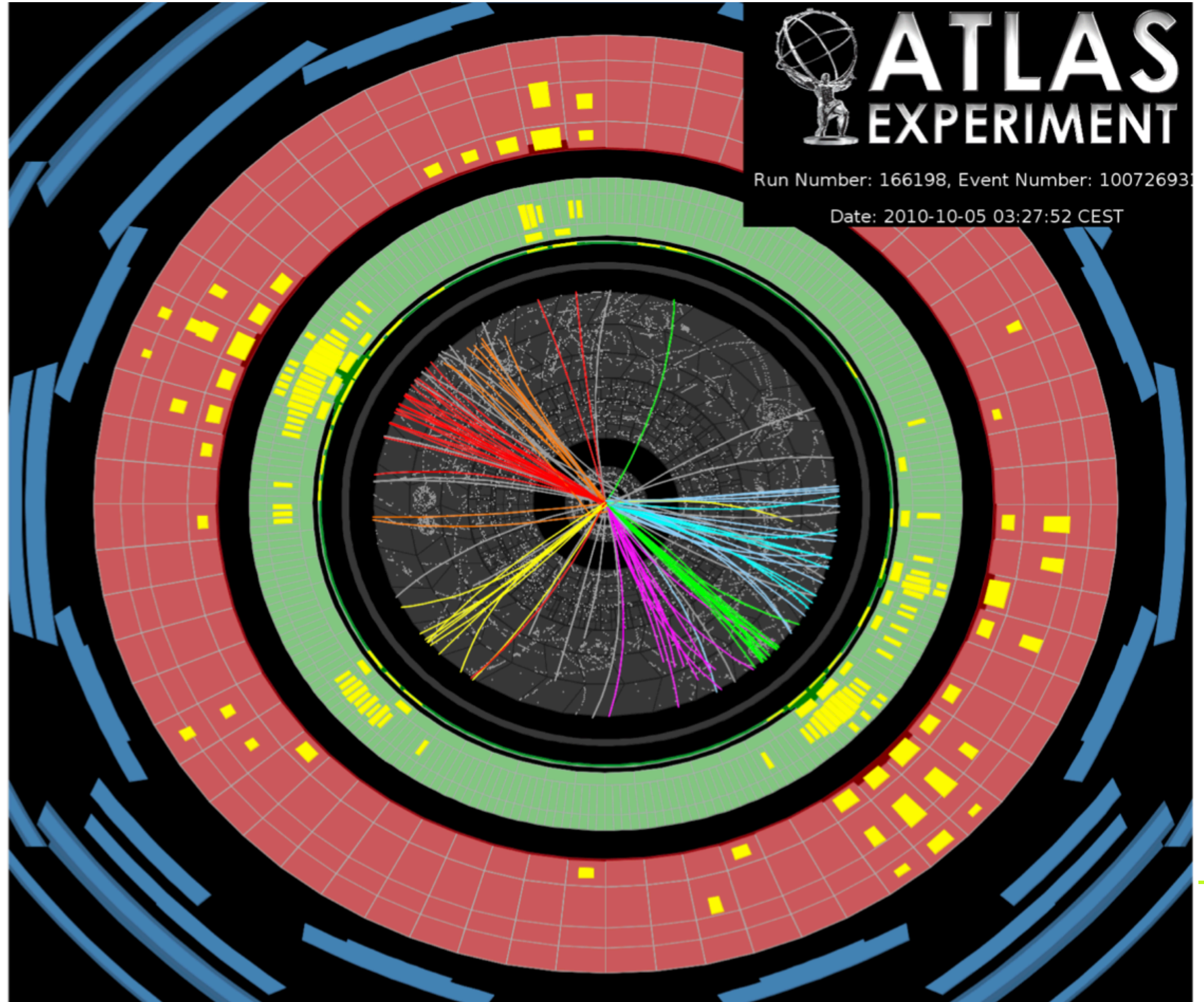


- **Larger showers**

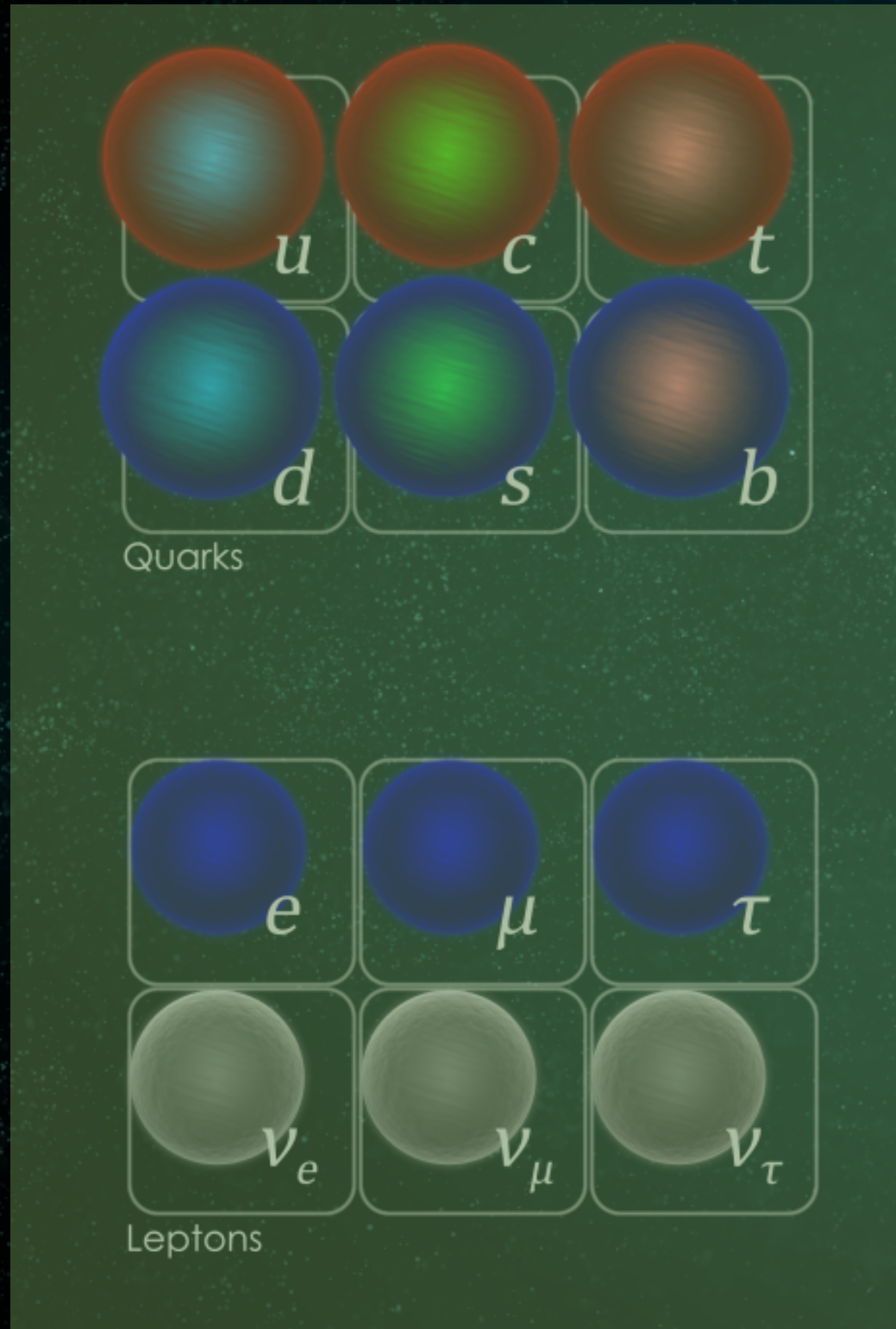


Jets of hadrons

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



Weak interaction



Particles sensitive to weak interaction



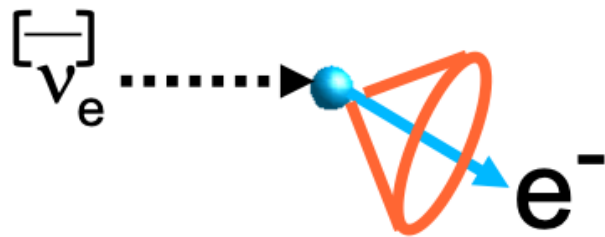
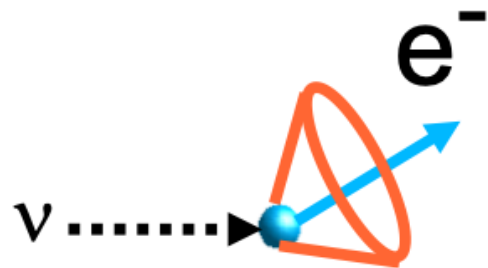
Higgs boson

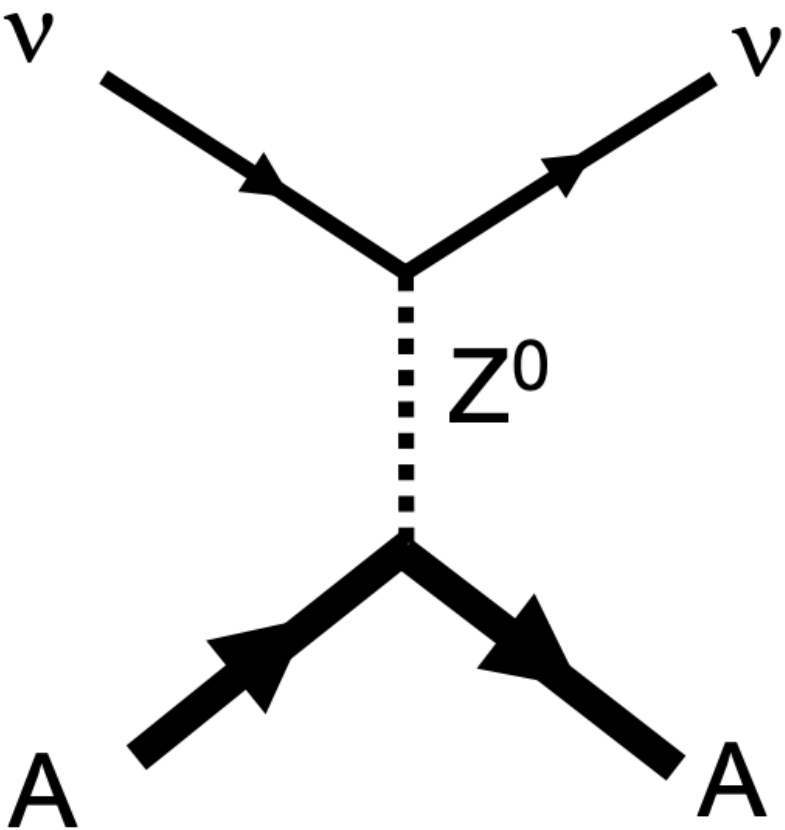


Unique force to which neutrinos are sensitive to !

Interaction of neutrinos with matter

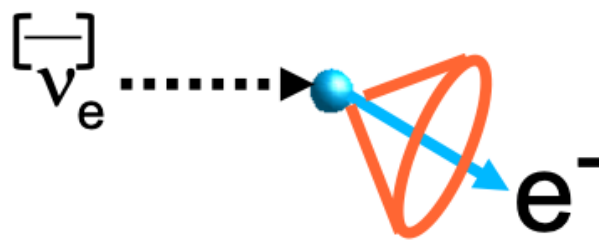
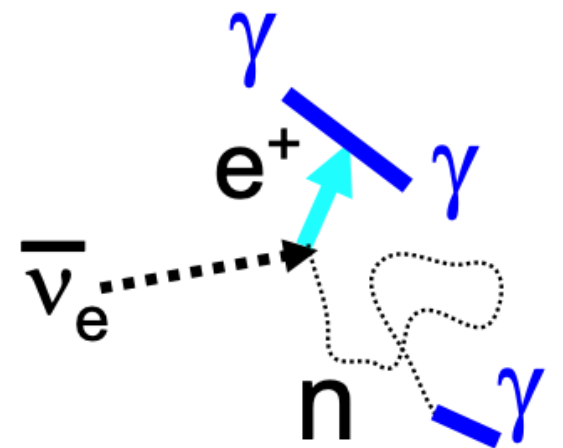
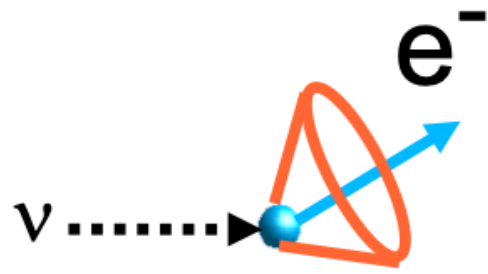
- Very rare interactions and tiny effects

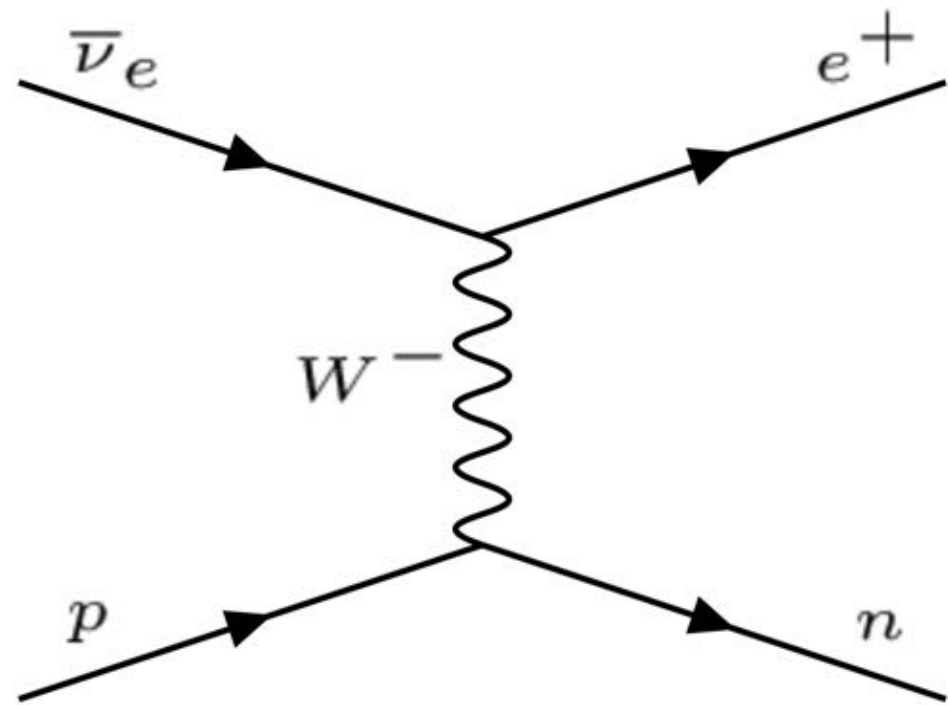
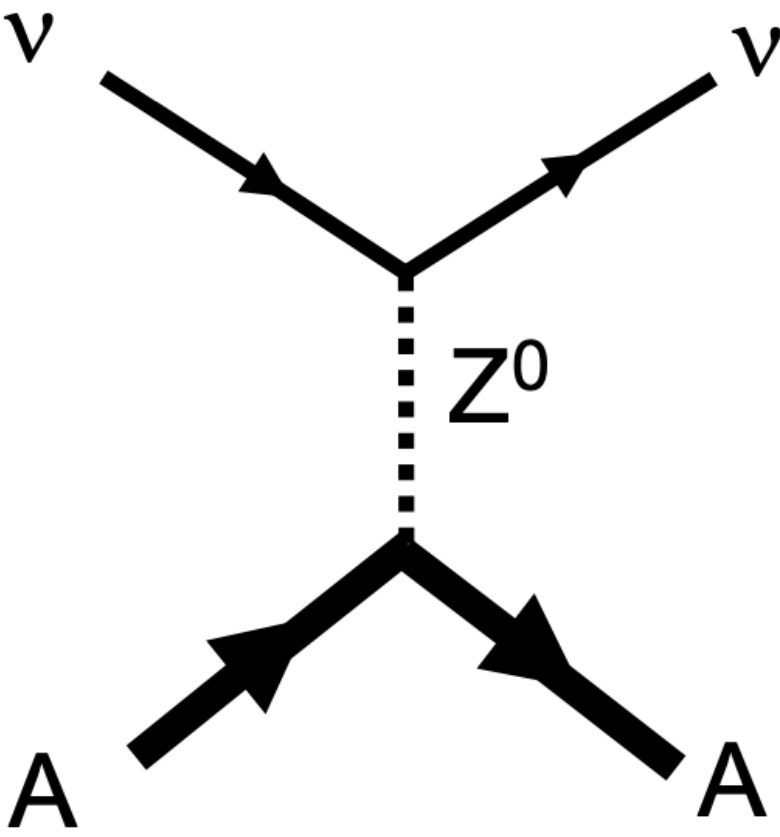
	Electrons
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 
Neutral current	 Useful for pointing



Interaction of neutrinos with matter

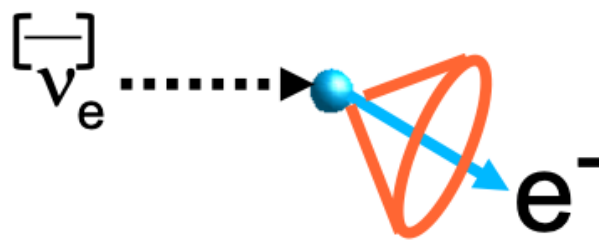
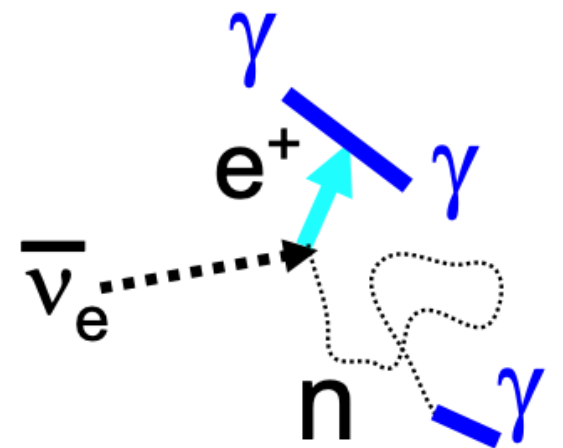
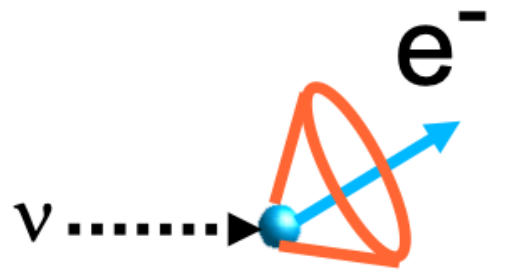
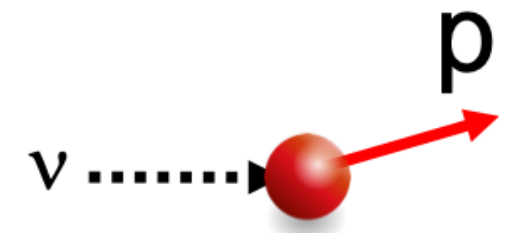
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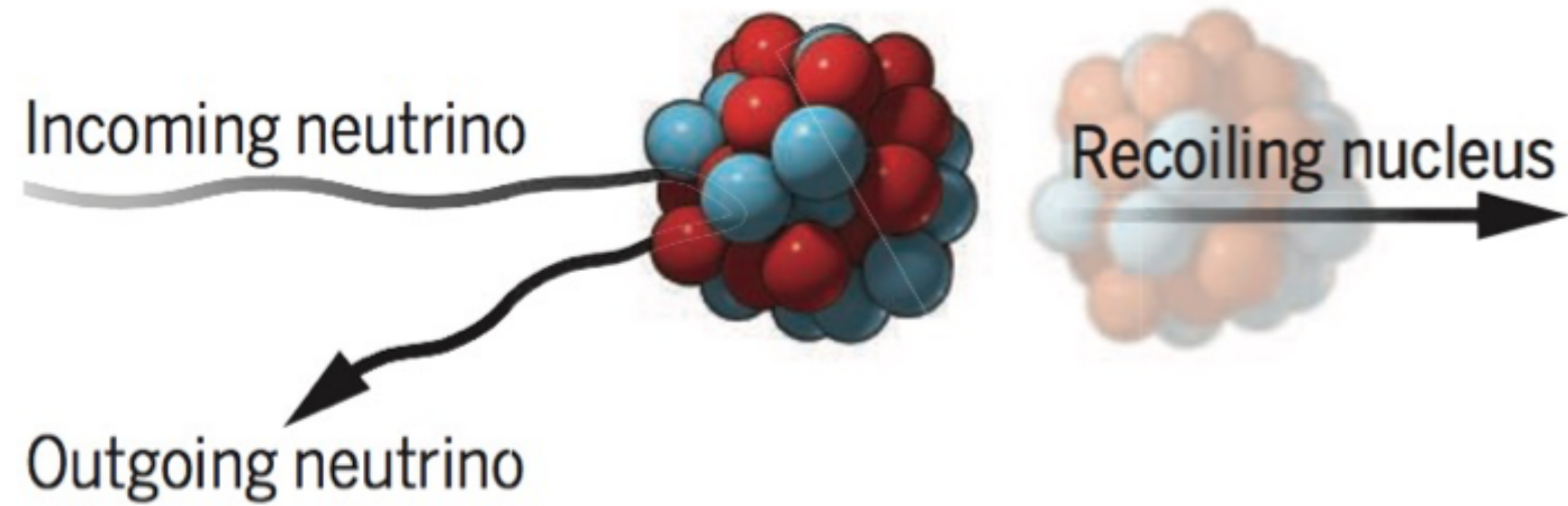
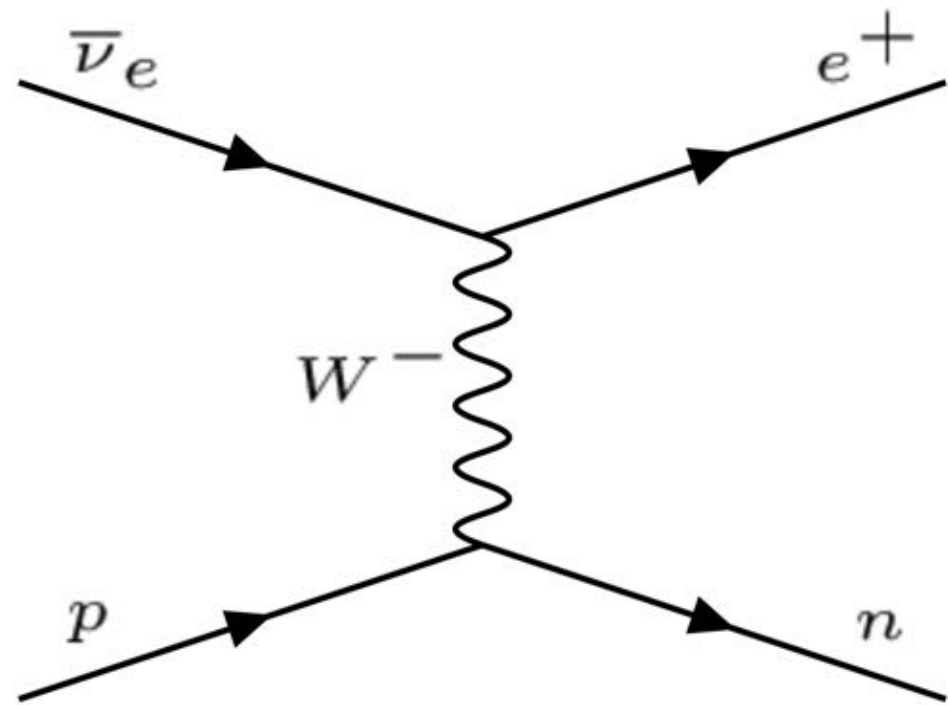
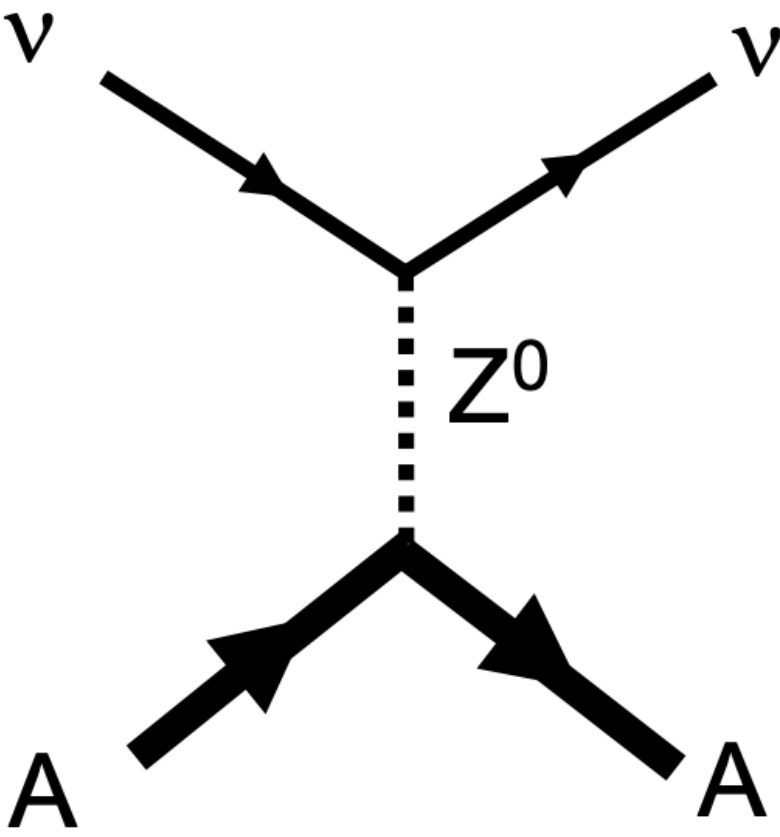
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Neutral current	 Useful for pointing	



Interaction of neutrinos with matter

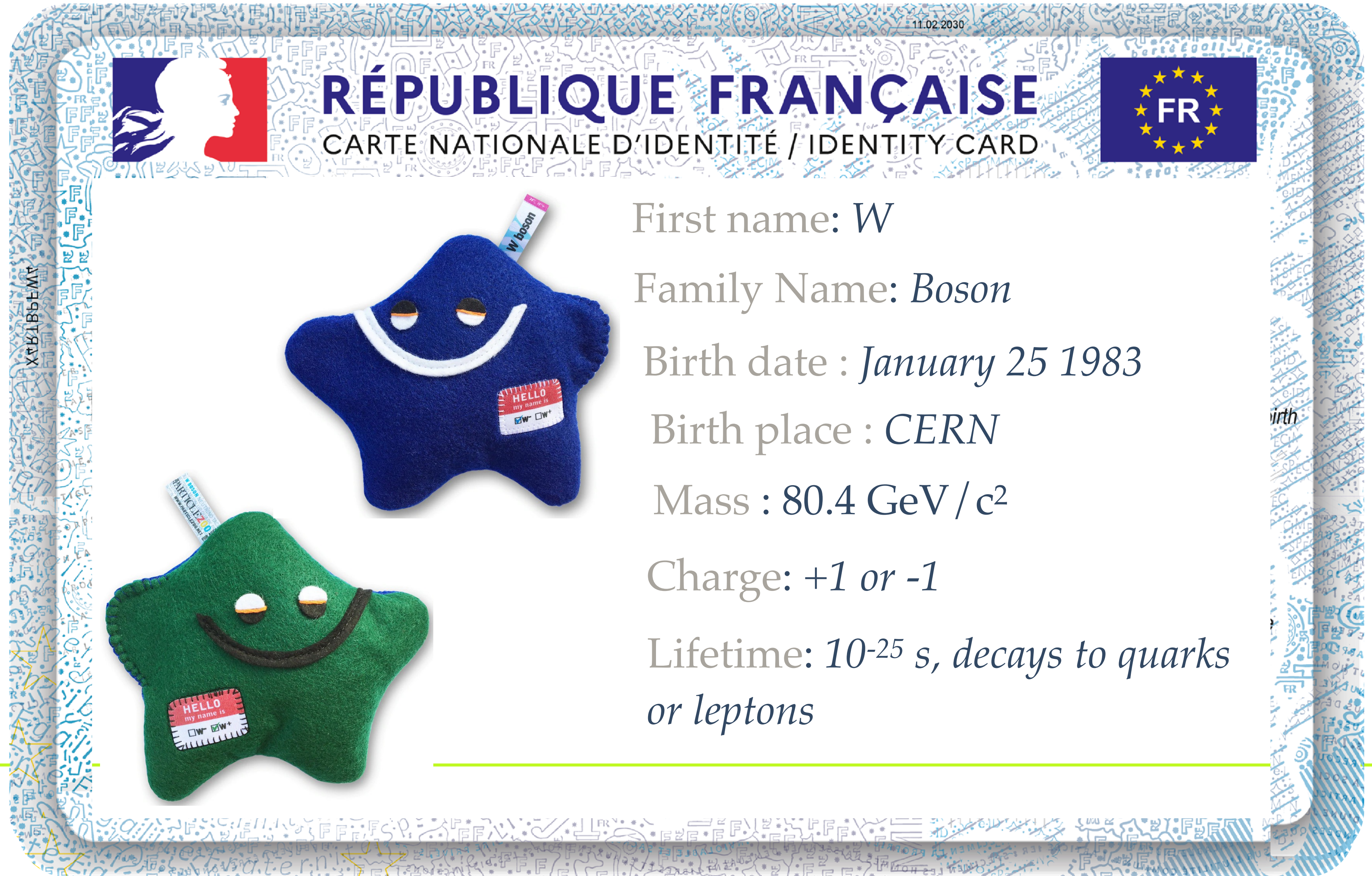
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	Electrons	Protons
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils



How do we identify particles ?

- The way they **interact with matter** tell us their main properties (mass, charge, lifetime, electromagnetic or hadronic particle, ...)



First name: W

Family Name: *Boson*

Birth date : *January 25 1983*

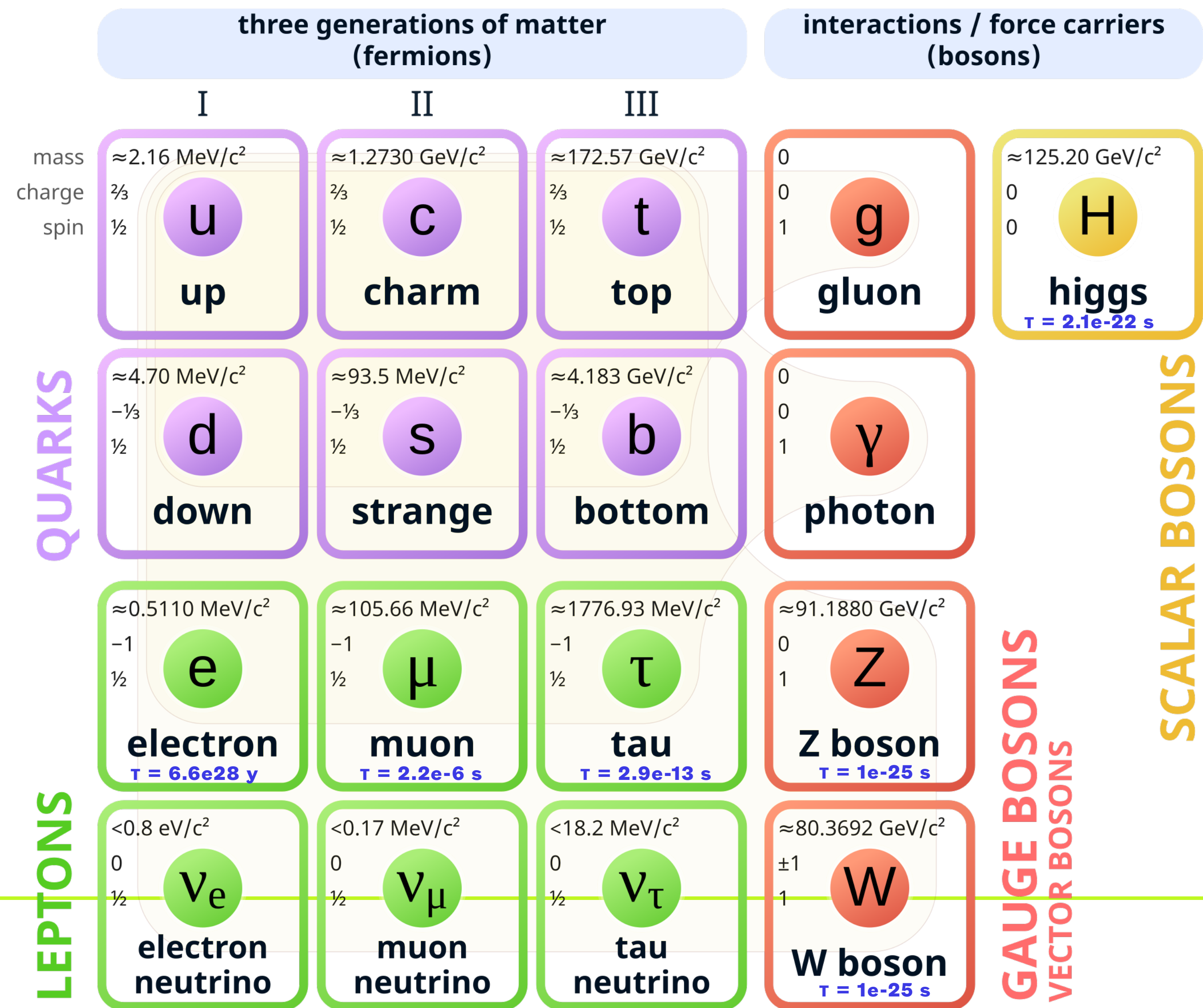
Birth place : *CERN*

Mass : $80.4 \text{ GeV} / c^2$

Charge: *+1 or -1*

Lifetime: 10^{-25} s , *decays to quarks or leptons*

Particle mass, charge and lifetime

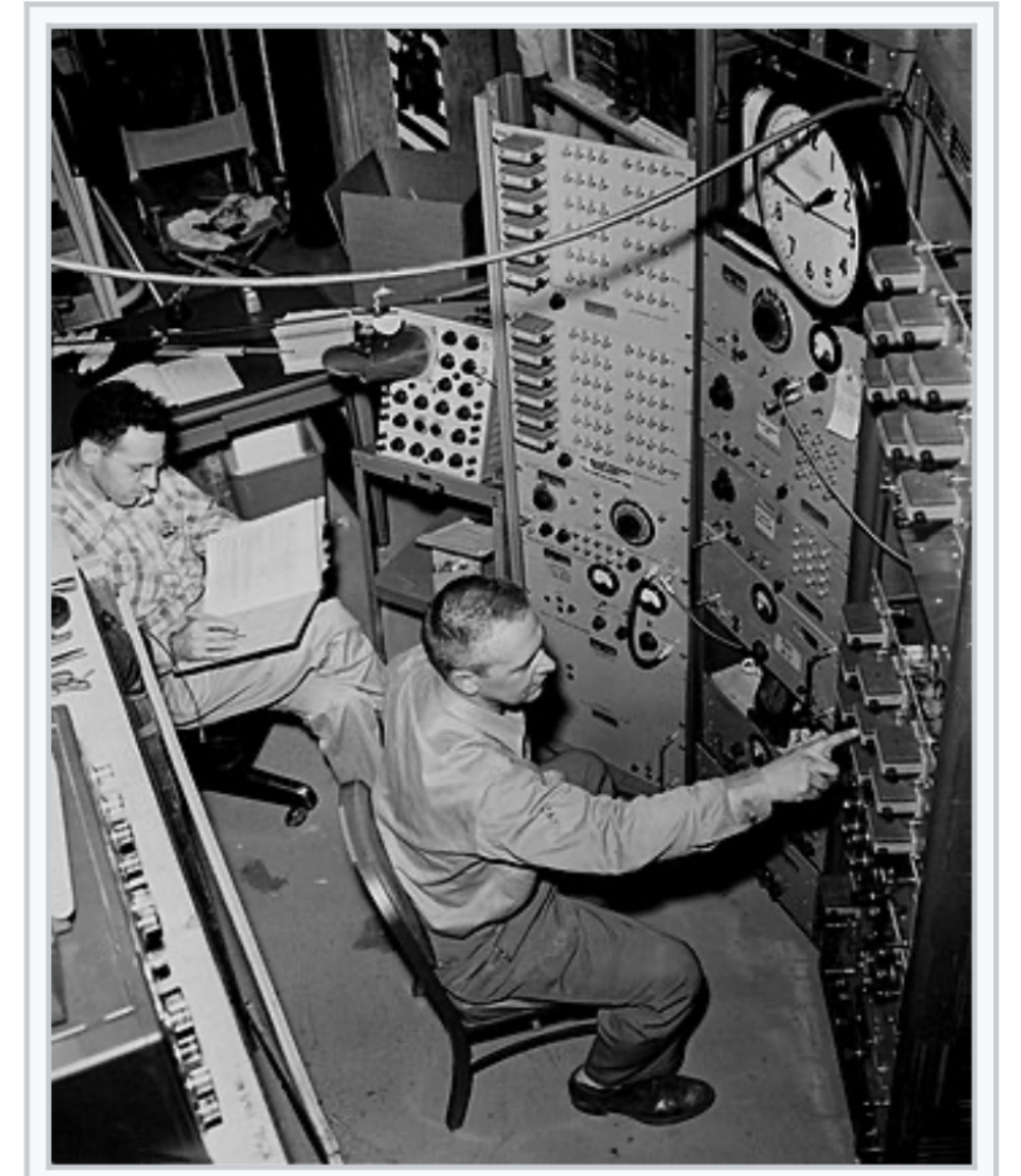
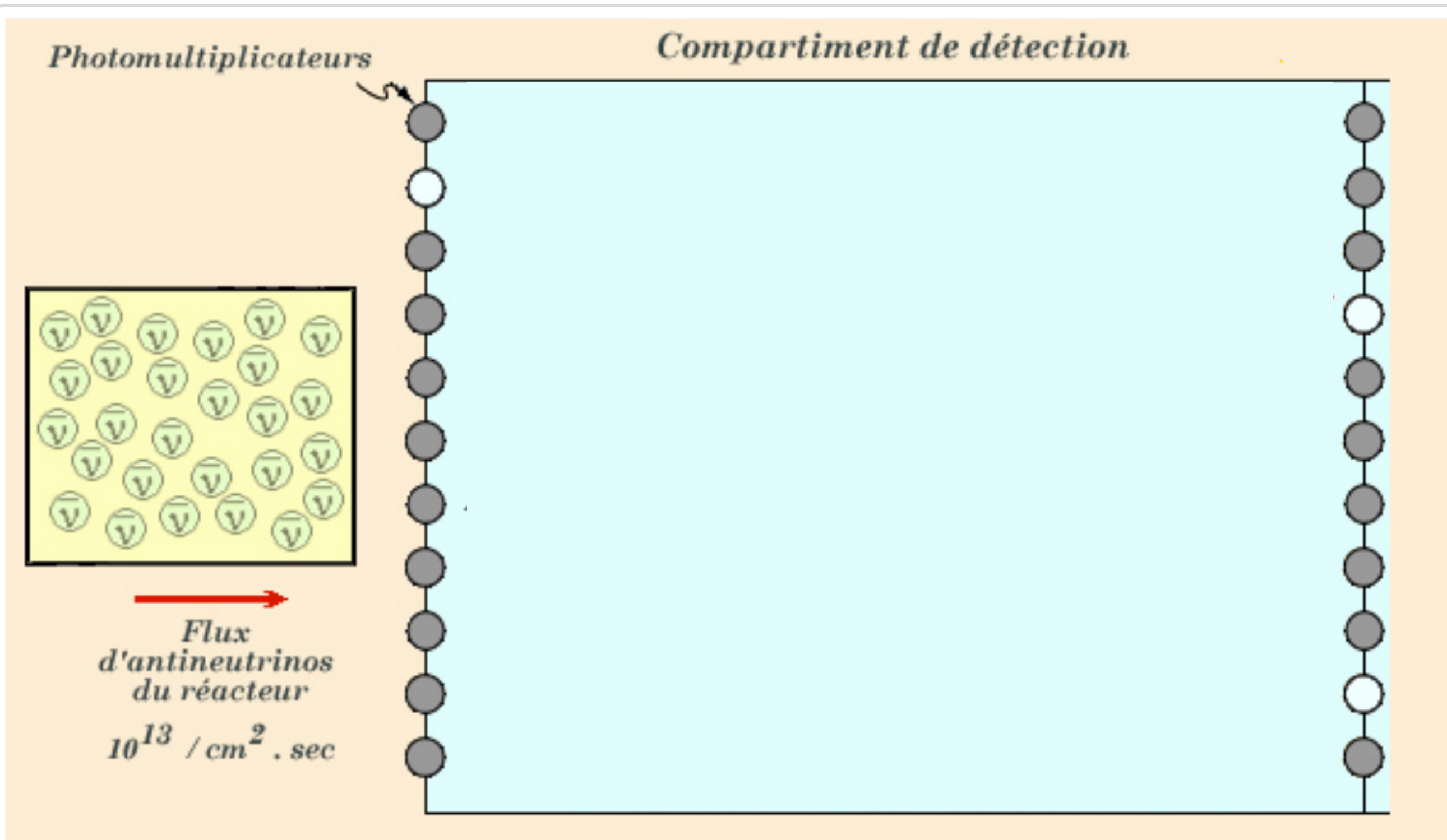


How were particles detected in the past ?

Some examples

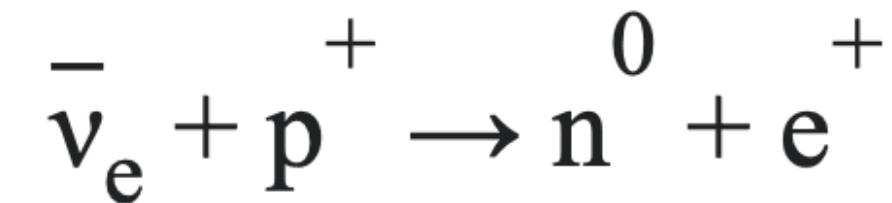
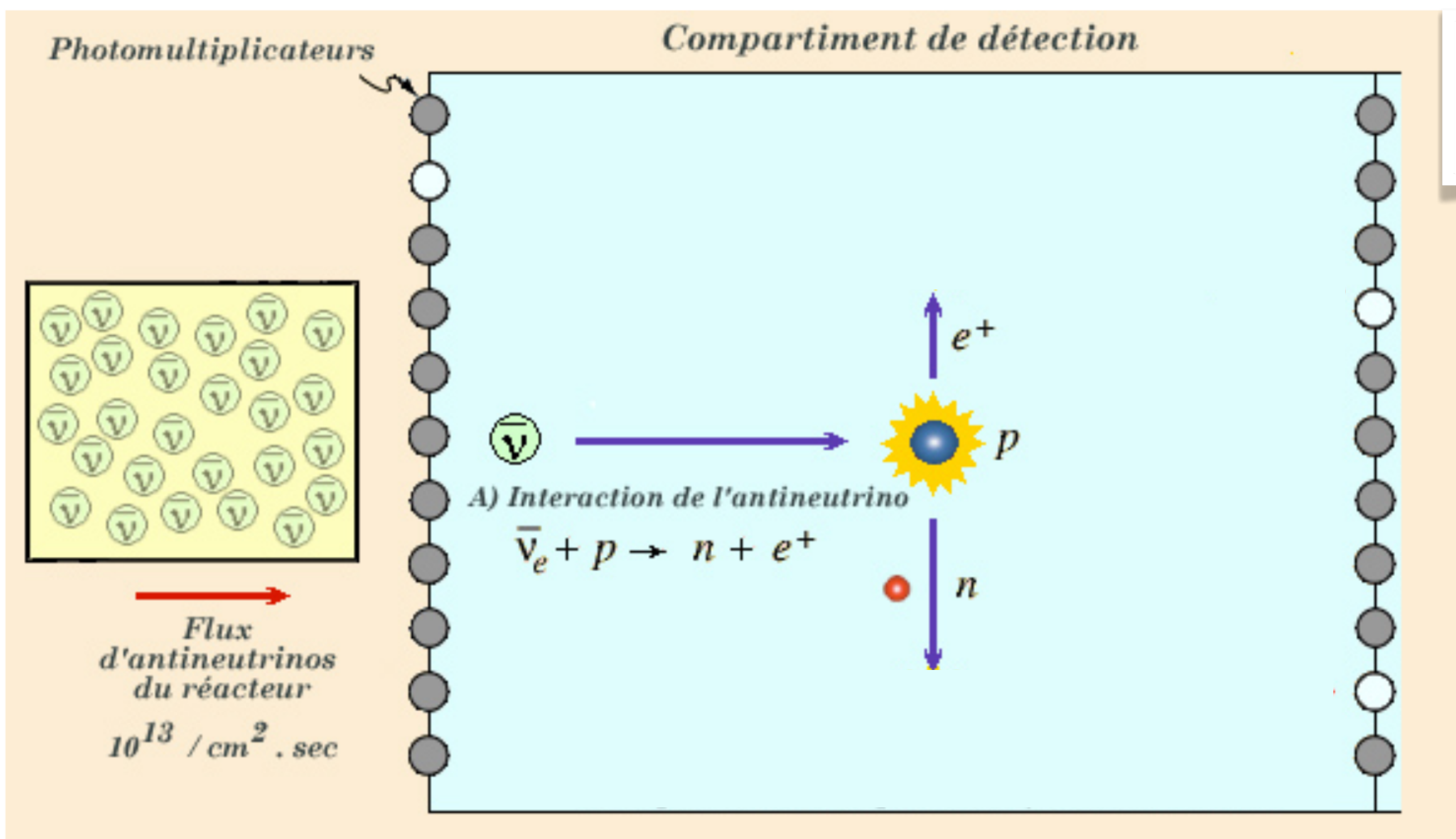
First neutrino detection - 1956

- 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).

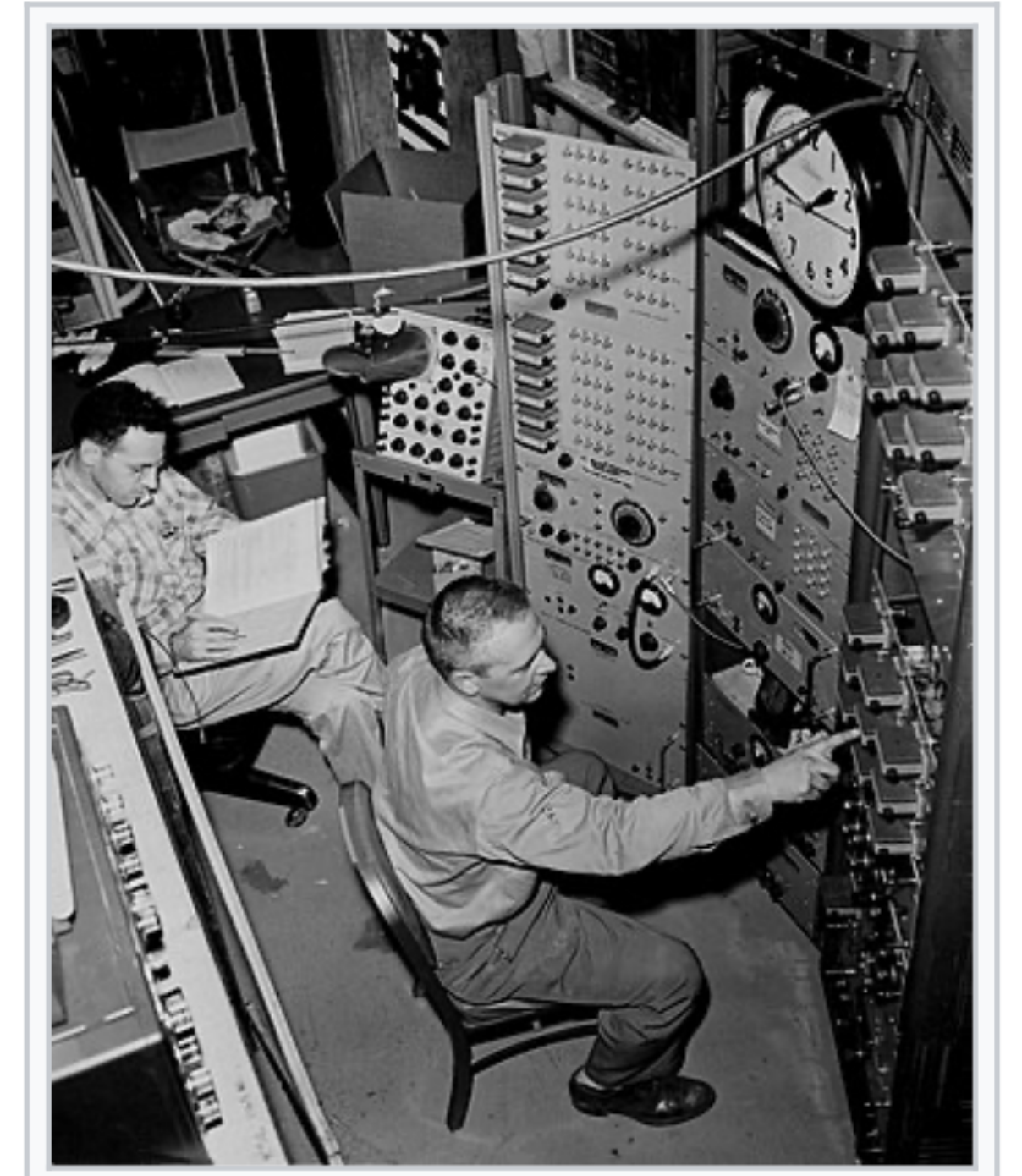


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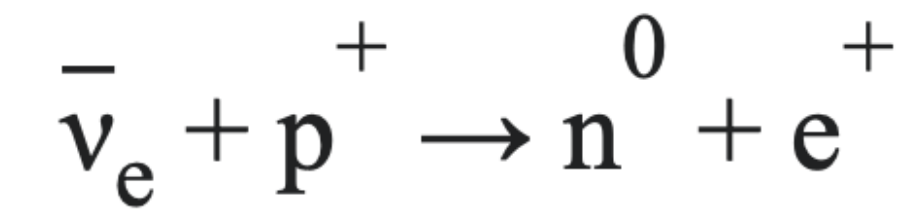
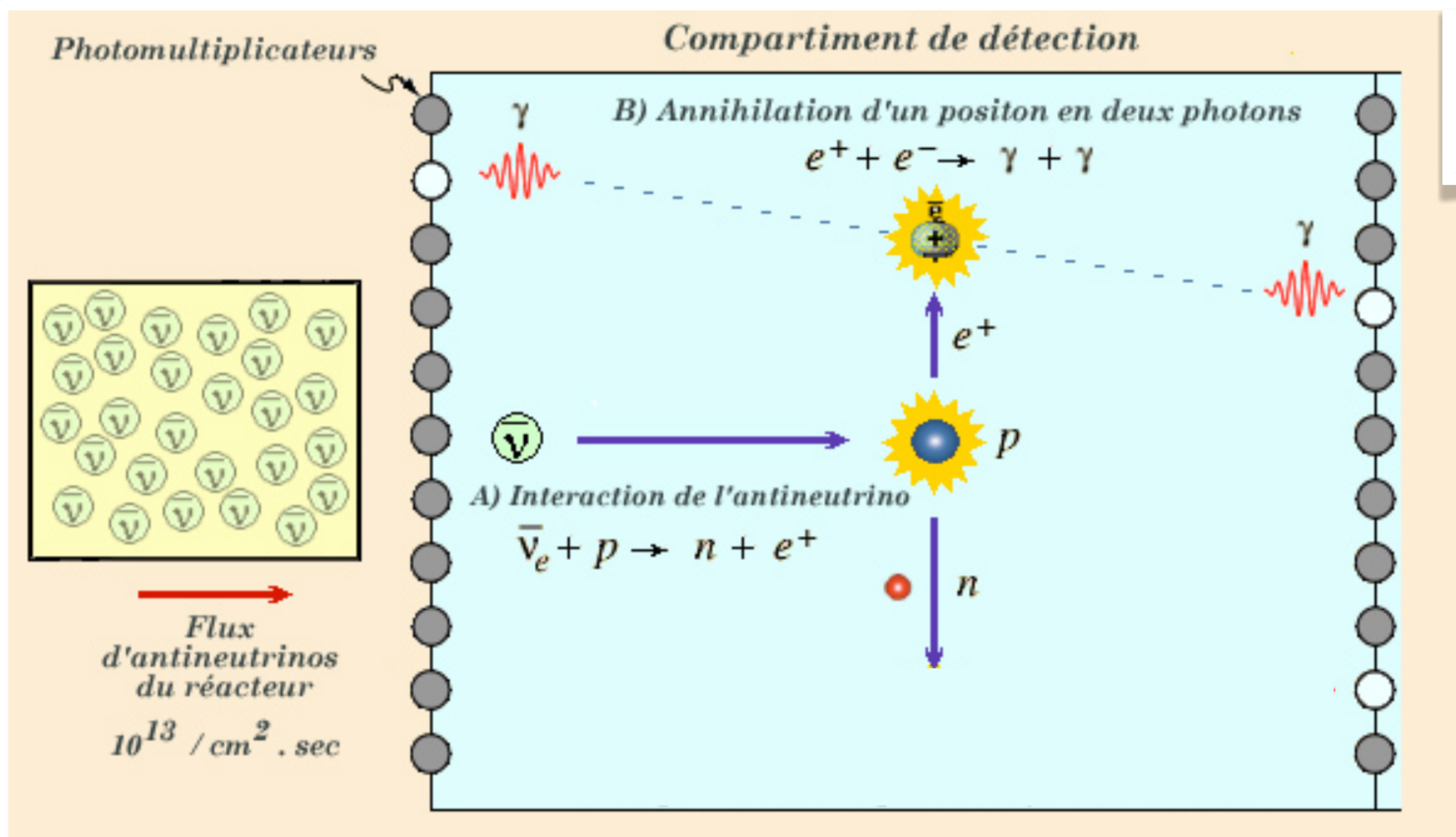


INVERSE BETA DECAY

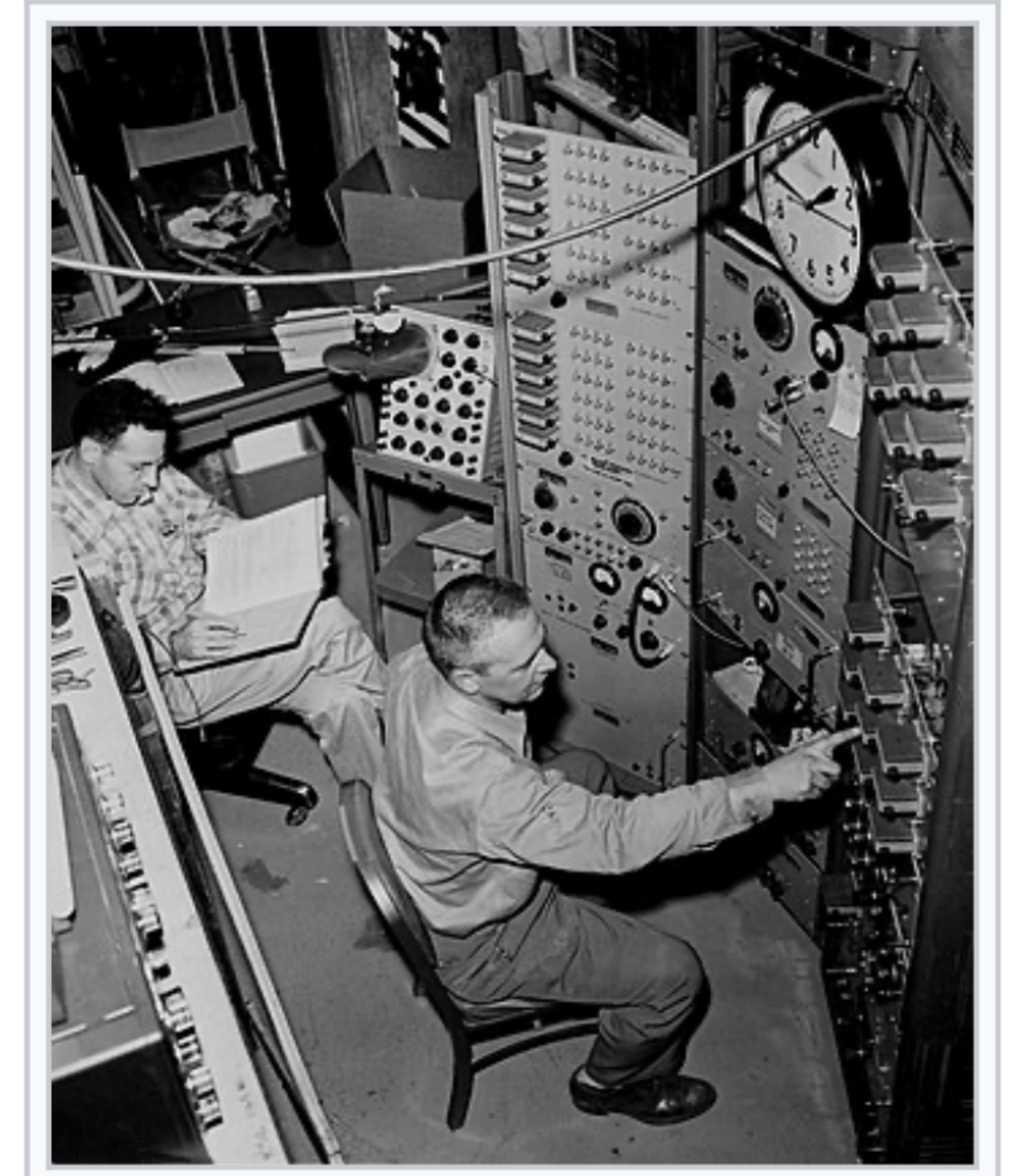


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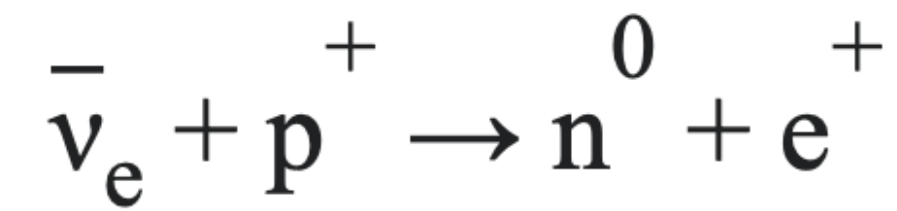
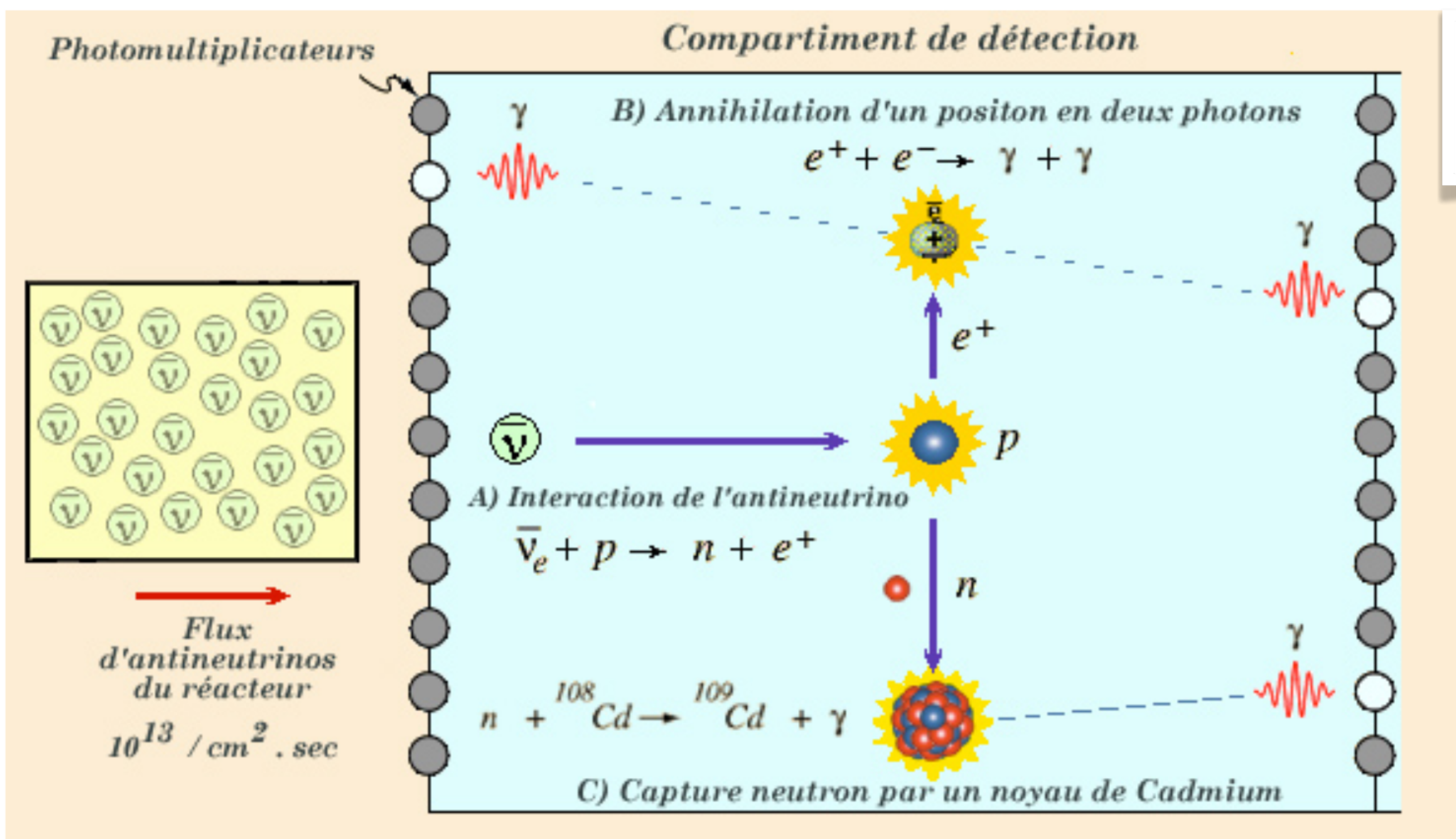


INVERSE BETA DECAY

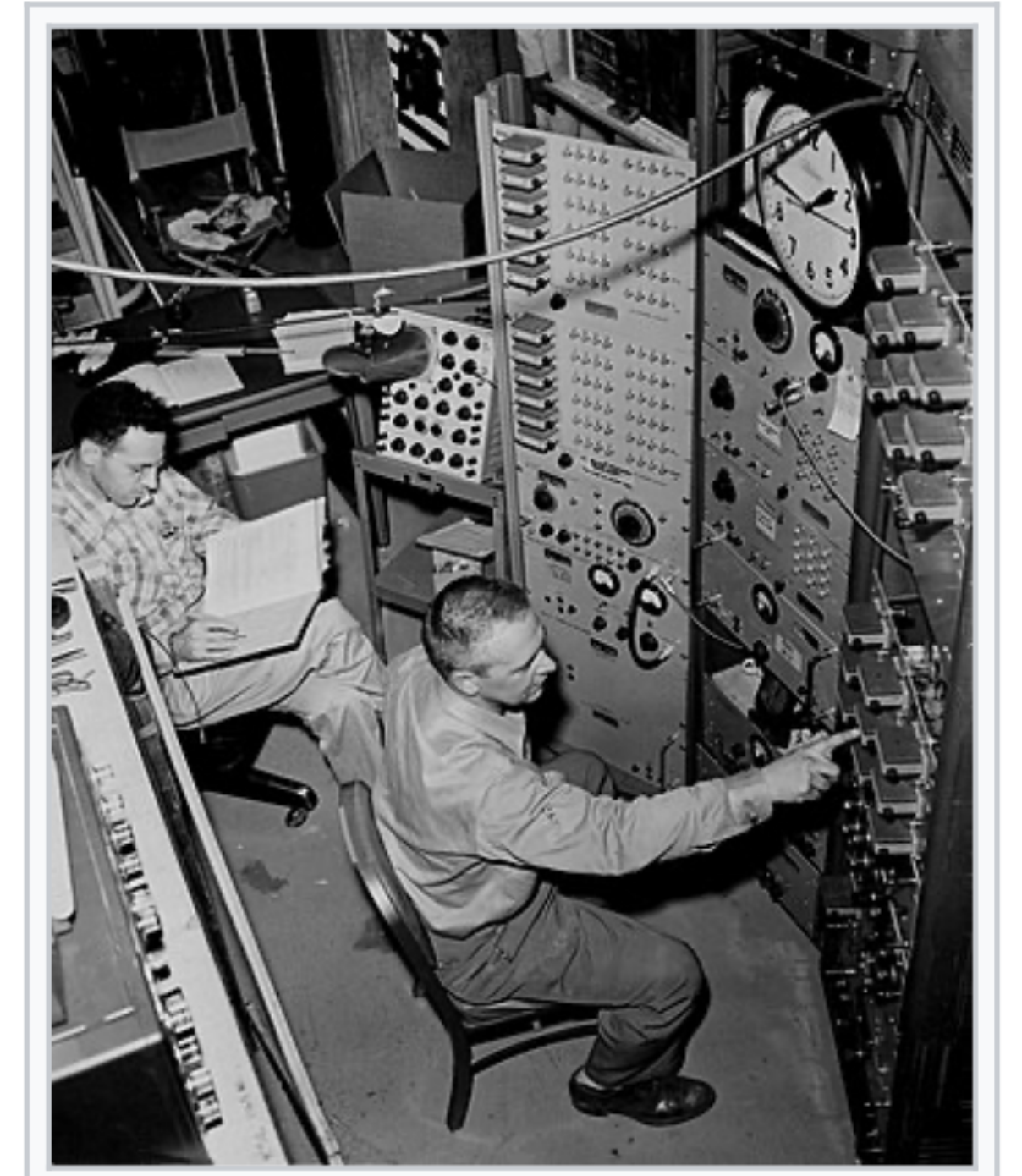


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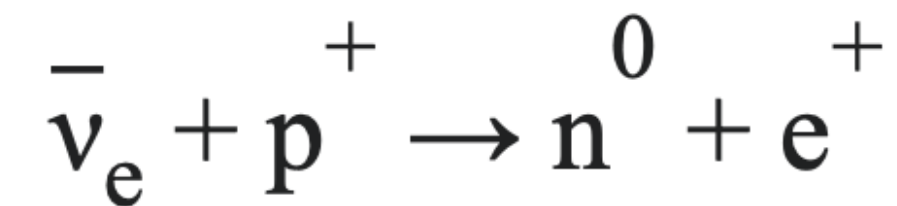
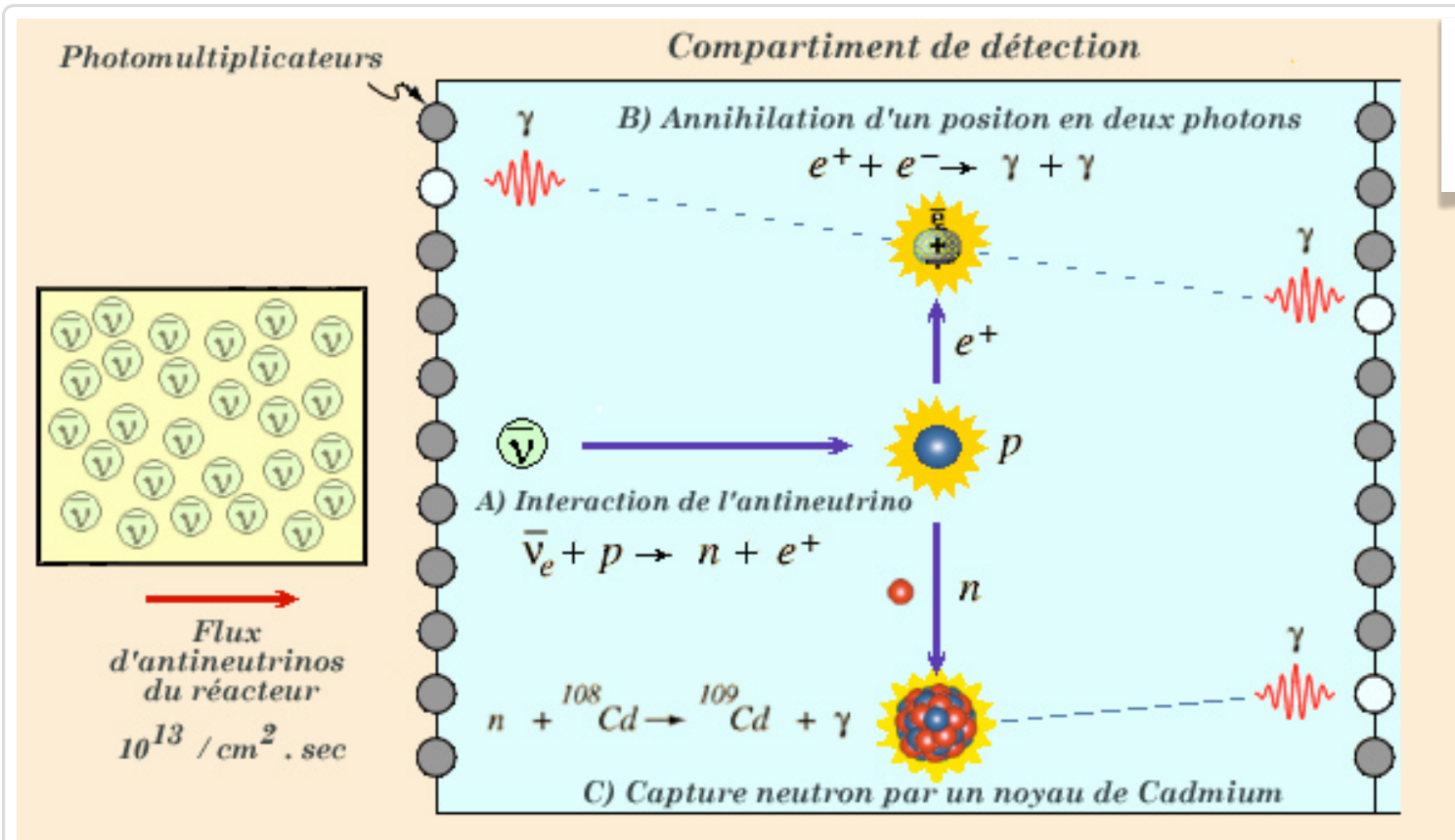


INVERSE BETA DECAY

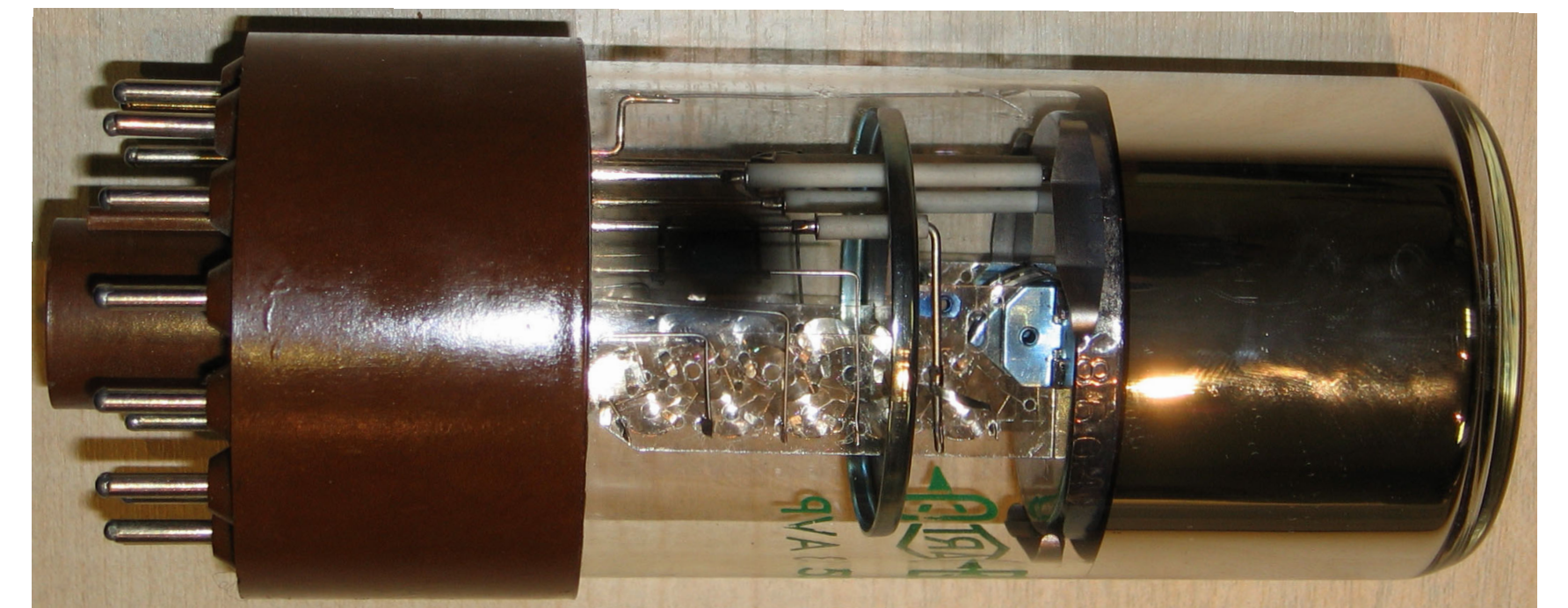
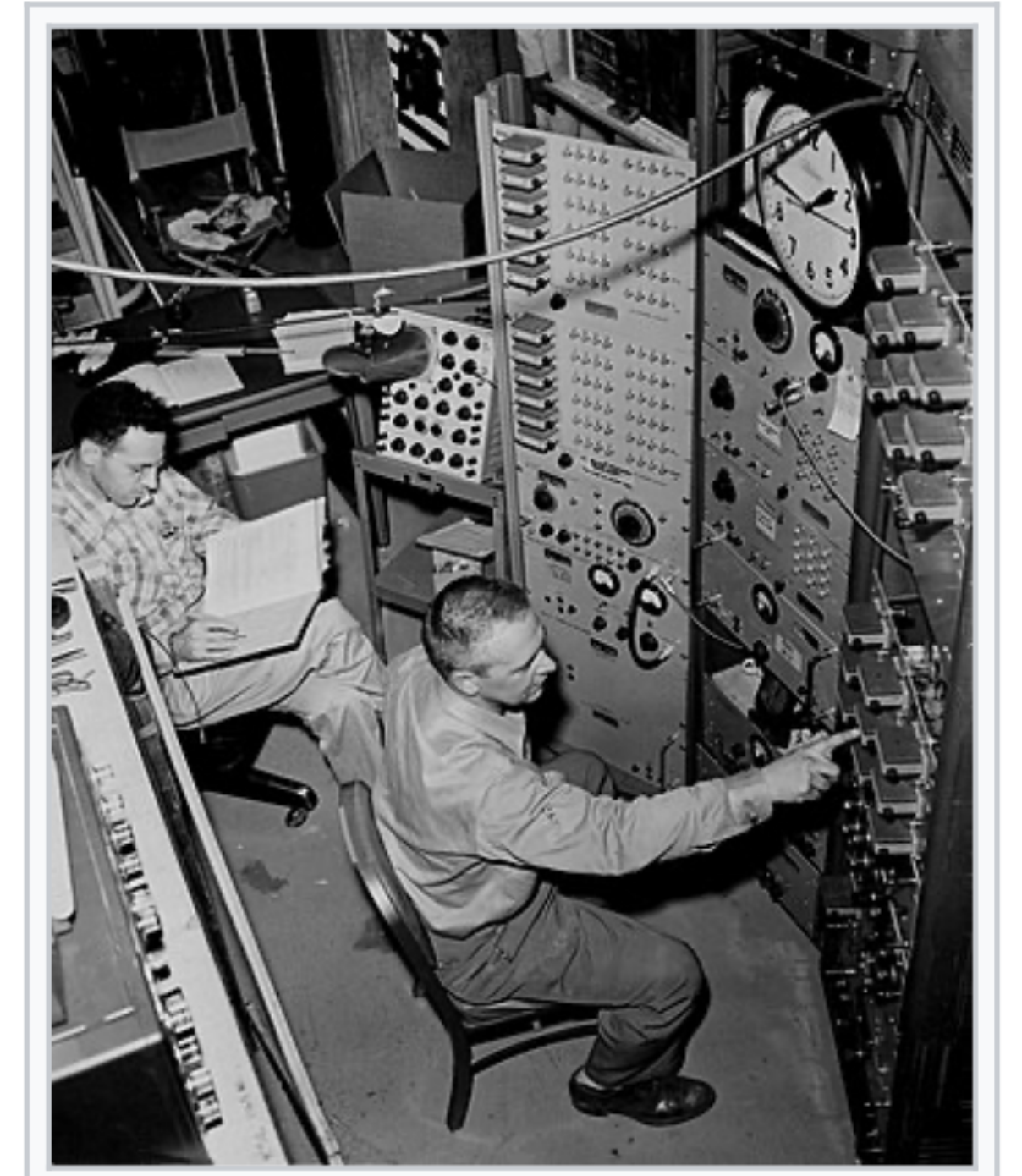


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- Water tanks sandwiched between **two layers of organic liquid scintillators** (just invented !) containing 110 photomultiplier tubes → **observation of neutrino**

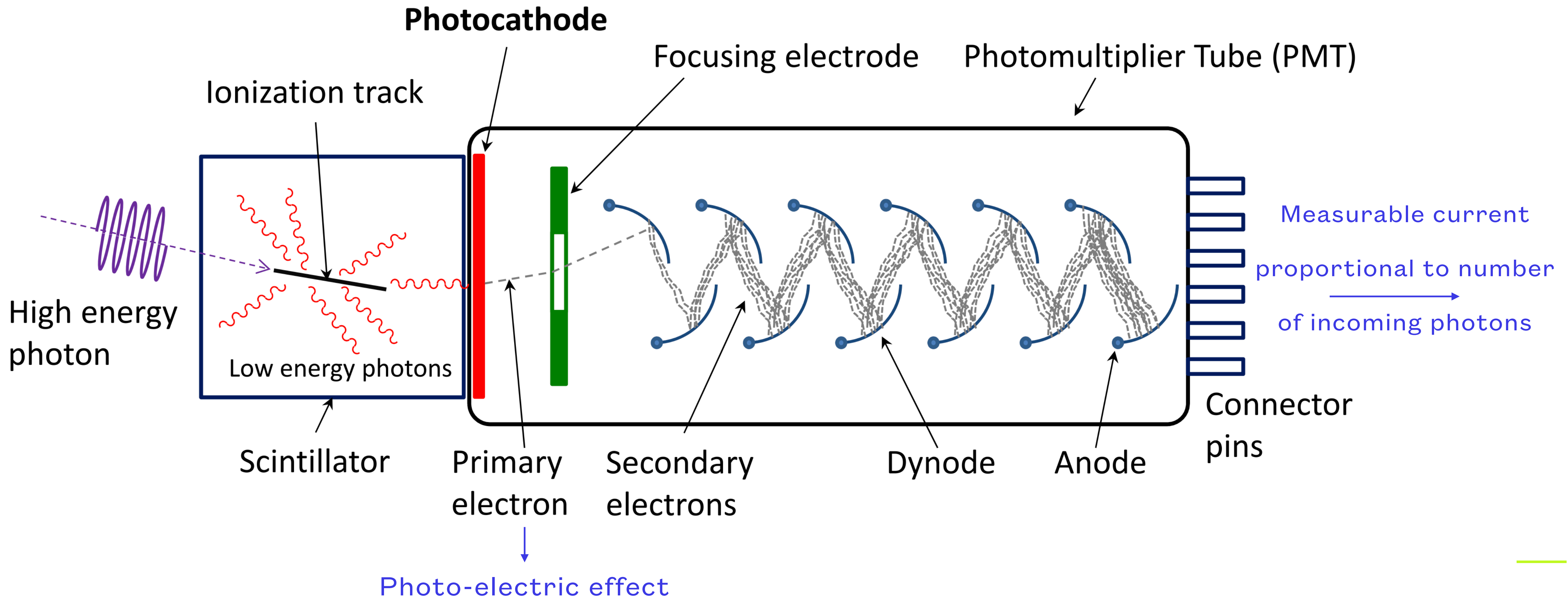


INVERSE BETA DECAY



Photomultiplier Tubes (PMT)

PHOTO-ELECTRIC EFFECT



Bubble chamber and neutral current - 1973

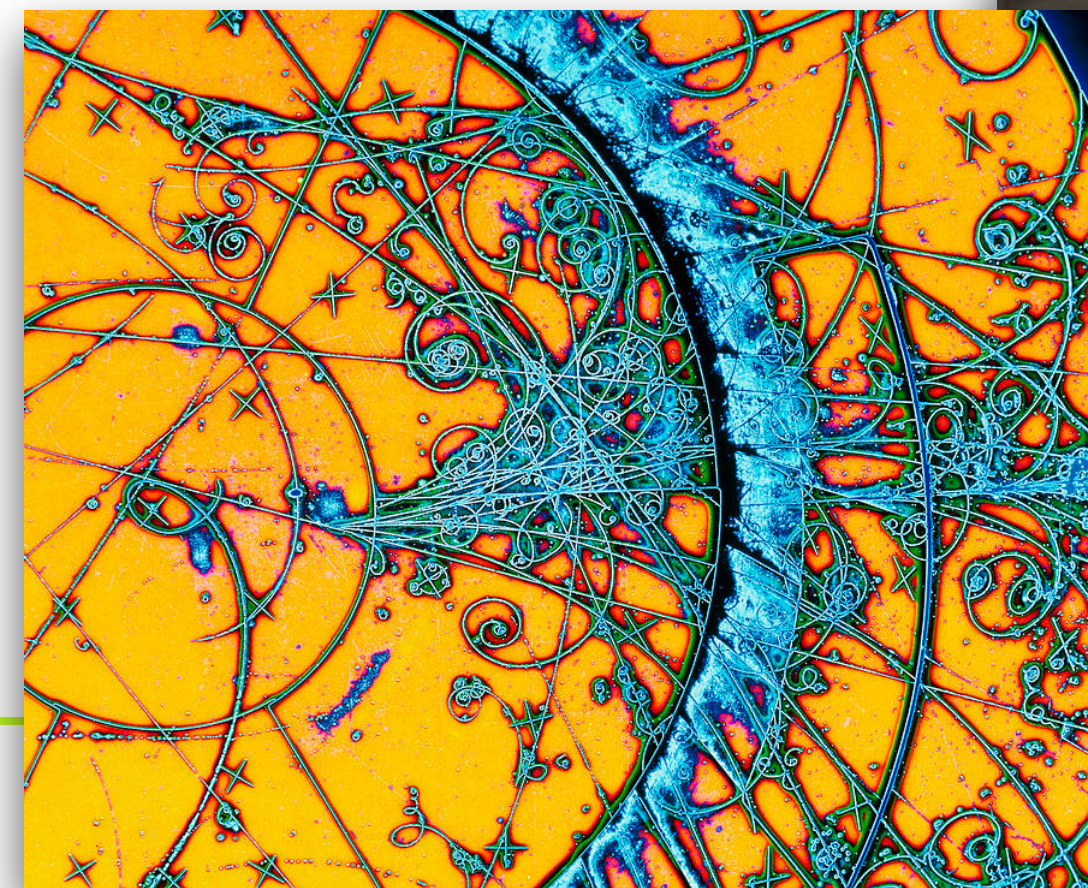
- **Bubble chamber (Donald Glaser)**: closed cavity filled with liquid (hydrogen) in metastable state, at precise limit of boiling. When external particle interacts $\rightarrow$ small bubbles form, trajectory curved thanks to magnetic field $\rightarrow$ pictures

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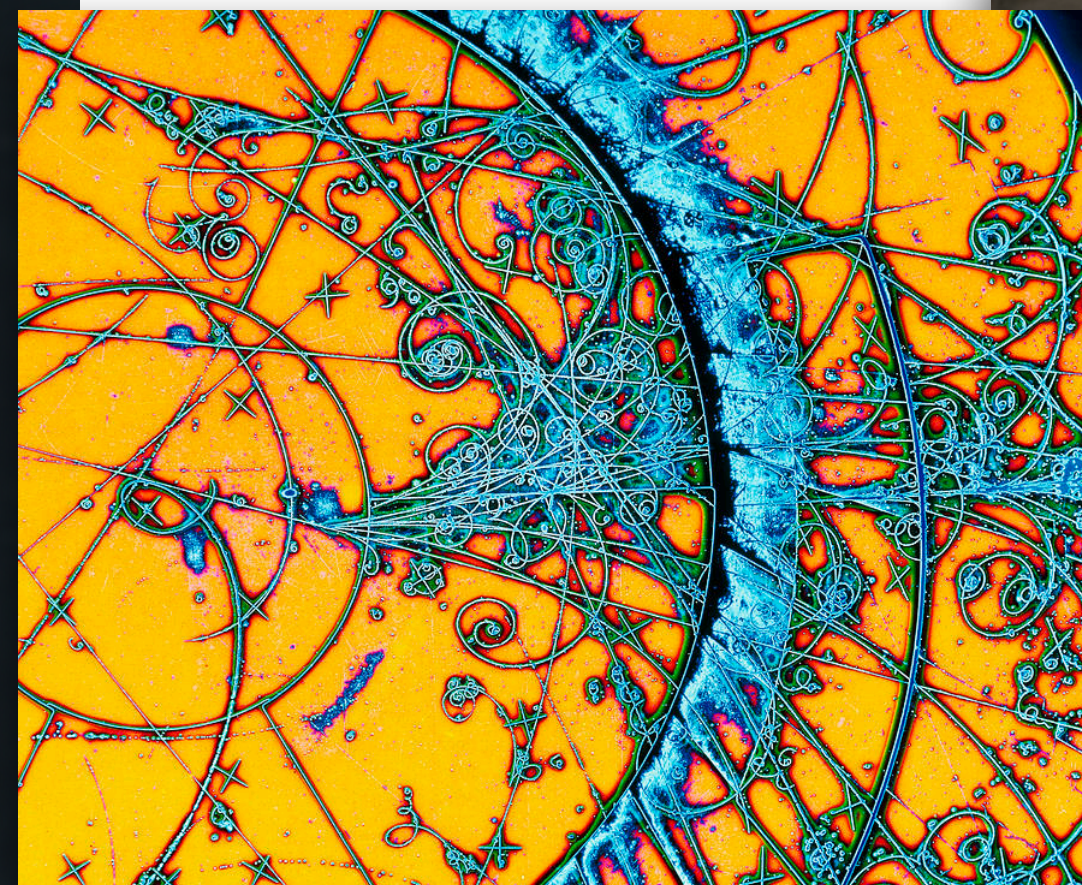
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- **need to examine thousands of photographs !**
- **Discovery of neutral currents**, Gargamelle (CERN), 1973



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** -> can reconstruct and record millions of particle tracks each second (resolution 100-300 μm)



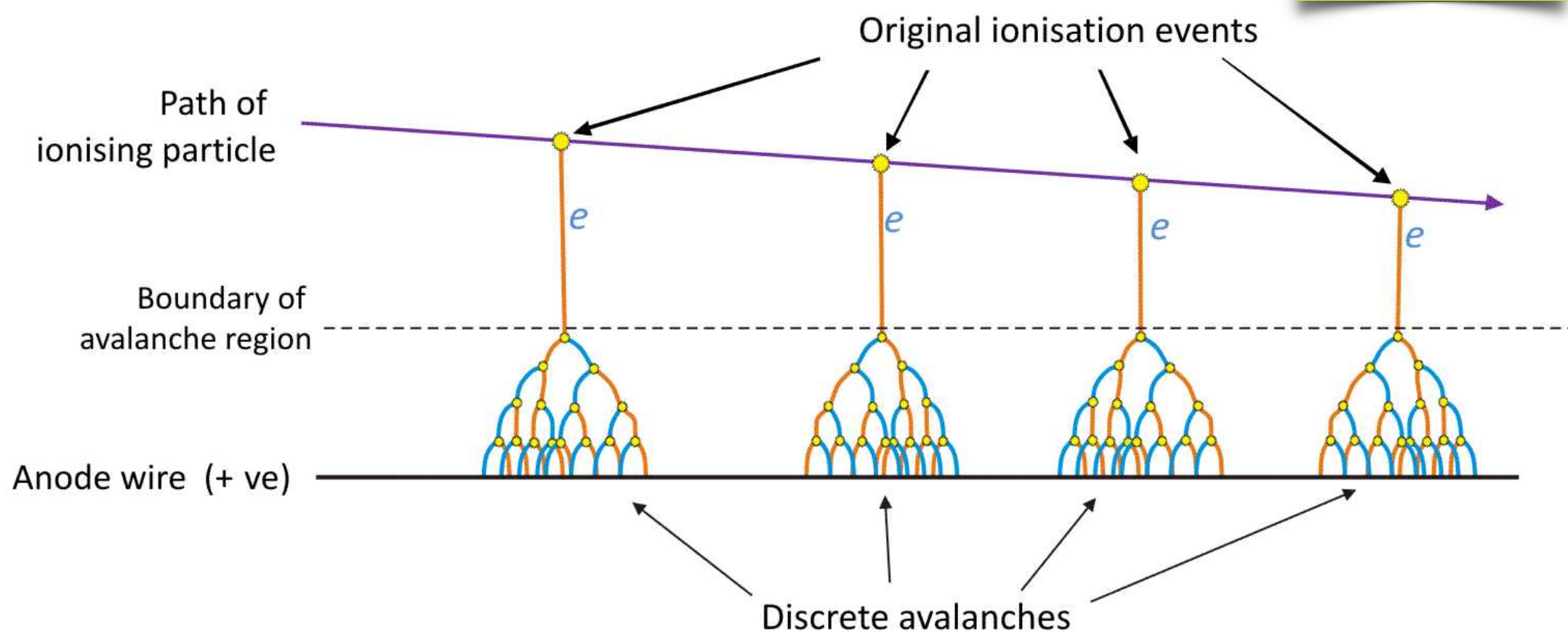
Georges Charpak's 'multiwire proportional chamber' particle detector consisted of many parallel wires, each connected to individual amplifiers. Linked to a computer, it could achieve a counting rate a thousand times better than before (Image: CERN)

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- Electrical voltage applied to a gas-filled tube with a wire running through its centre. Incoming charged particle ionizes the gas -> electron drift + avalanche

Creation of discrete avalanches in a proportional counter

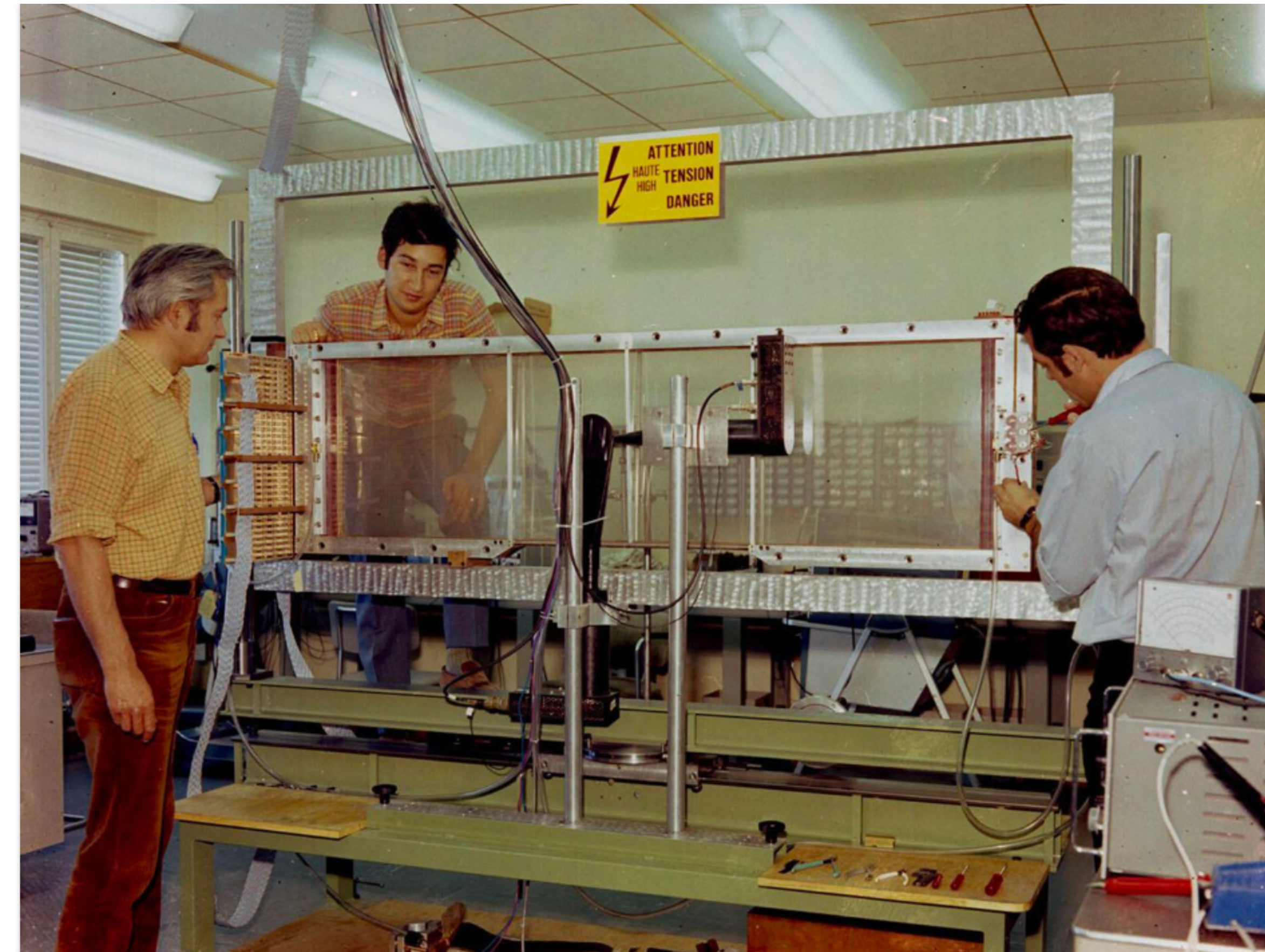
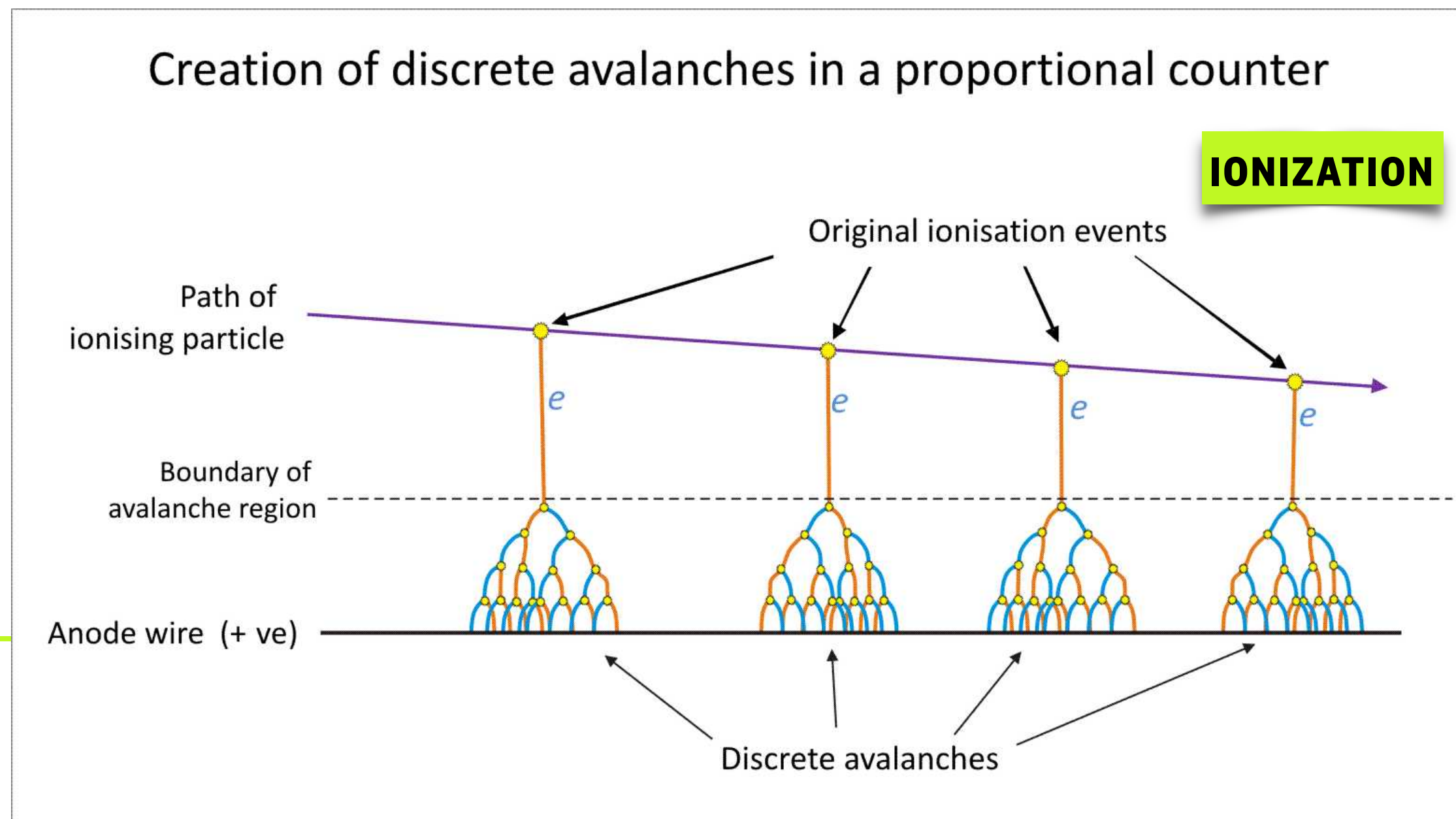
IONIZATION



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- Electrical voltage applied to a gas-filled tube with a wire running through its centre. Incoming charged particle ionizes the gas -> electron drift + avalanche
- Discovery of **charm quark** (BNL, SLAC - 1975), of **gluon** (TASSO in PETRA- DESY, 1979), and of **W and Z bosons** (UA1/UA2 -CERN, 1983)



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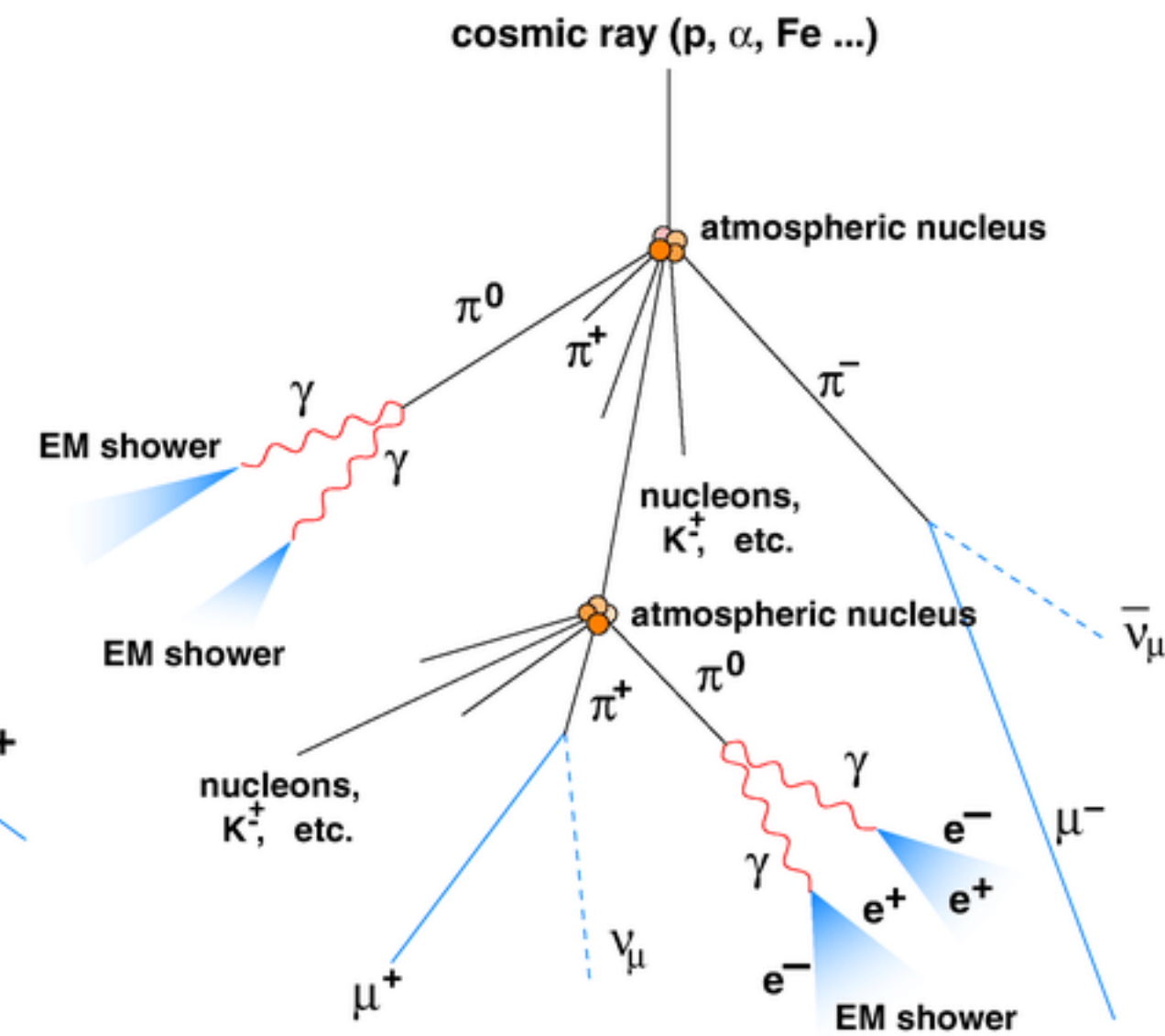
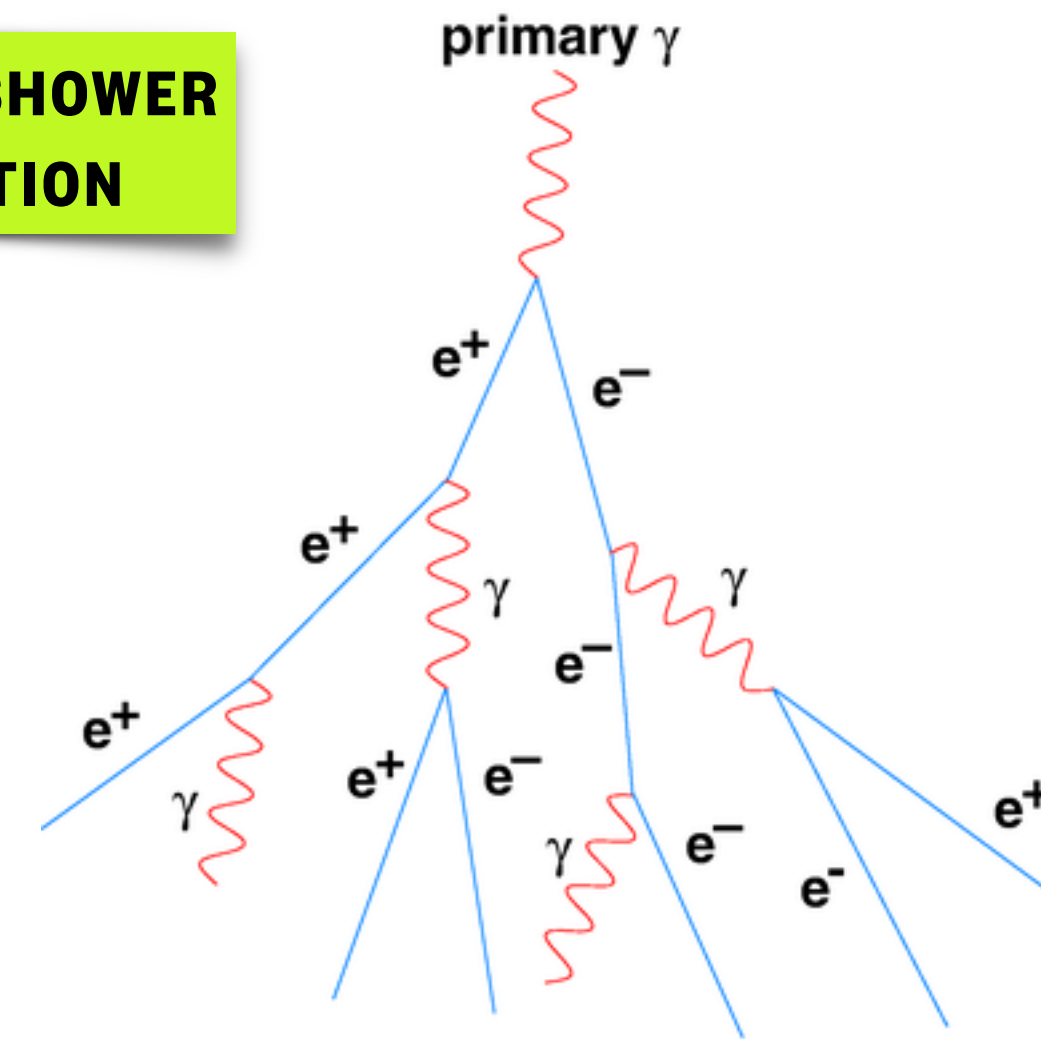
Current detection techniques

Some examples

Cosmic rays

- Cosmic particles entering in atmosphere -> cascade -> Cerenkov light cone of ~250 m for a few nanoseconds close to ground

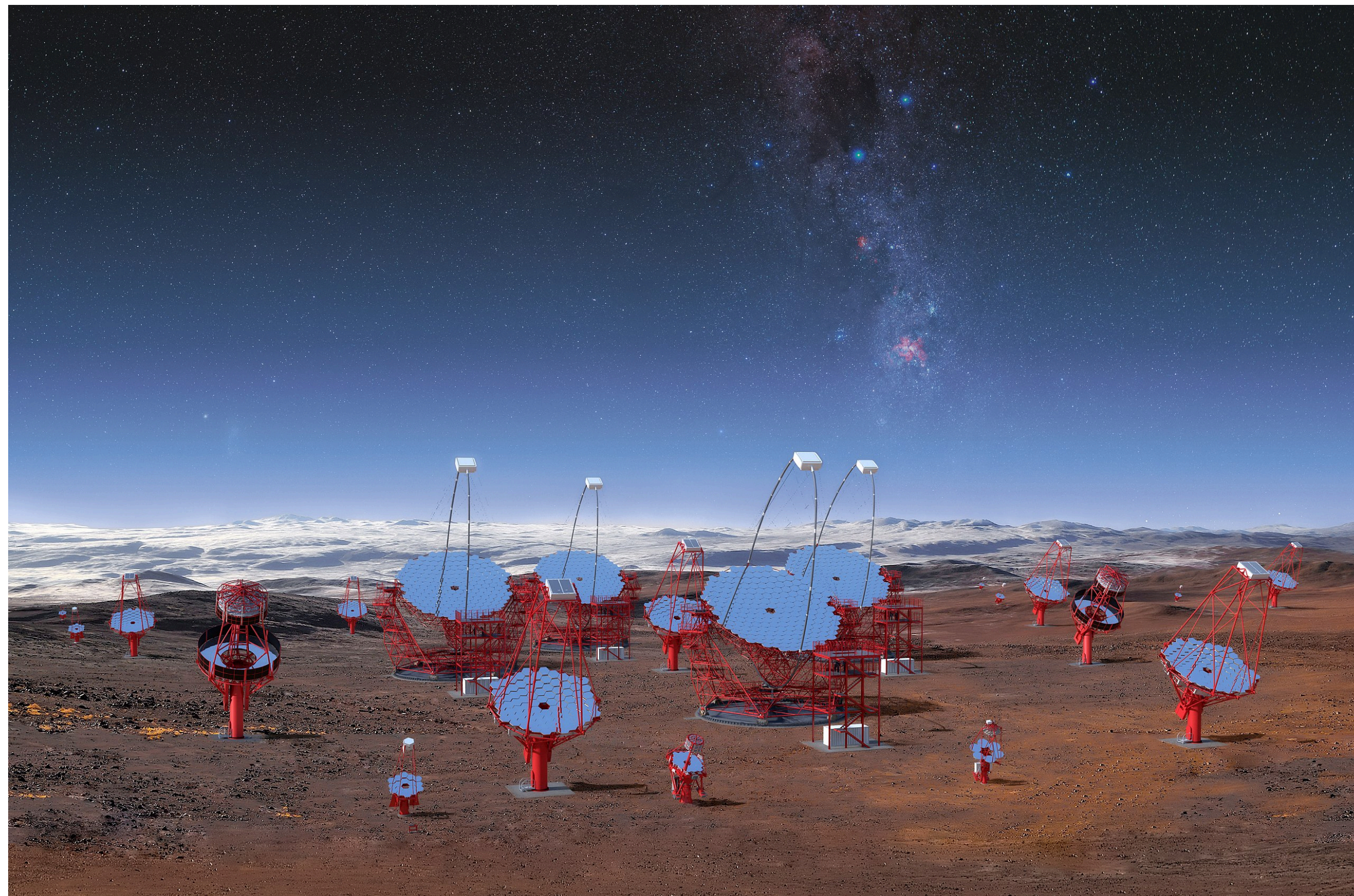
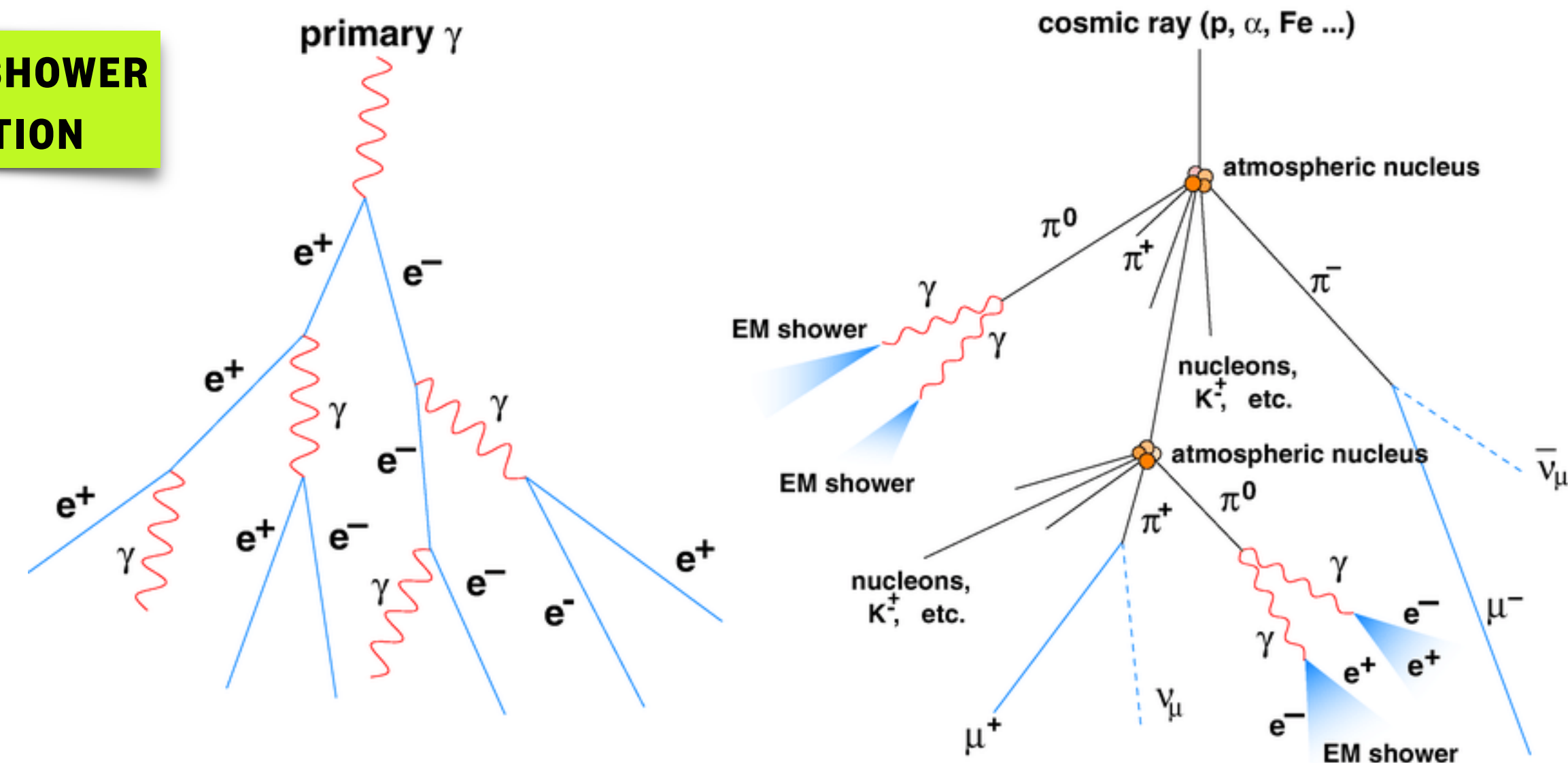
ELECTROMAGNETIC SHOWER CERENKOV RADIATION



Cosmic rays

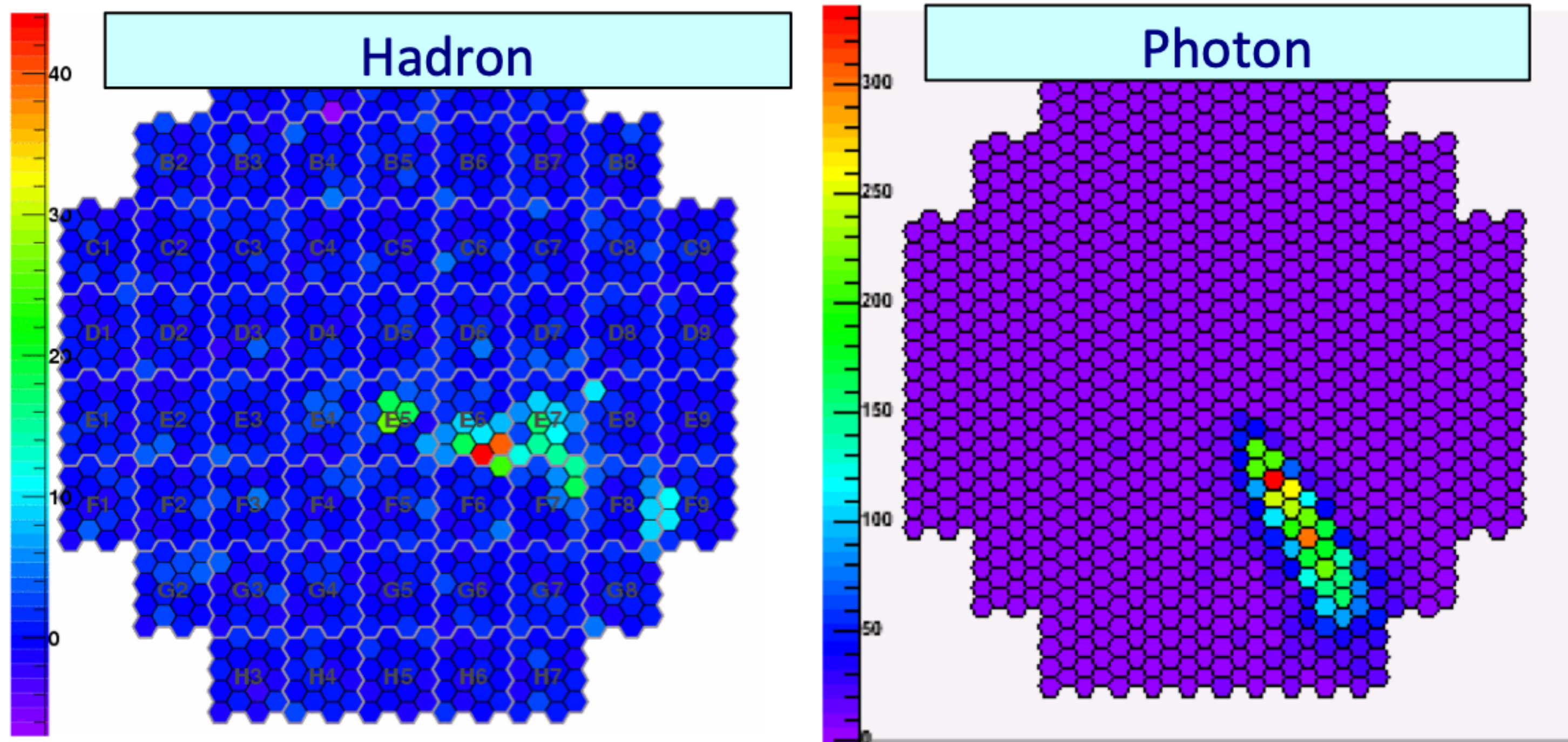
ELECTROMAGNETIC SHOWER CERENKOV RADIATION

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

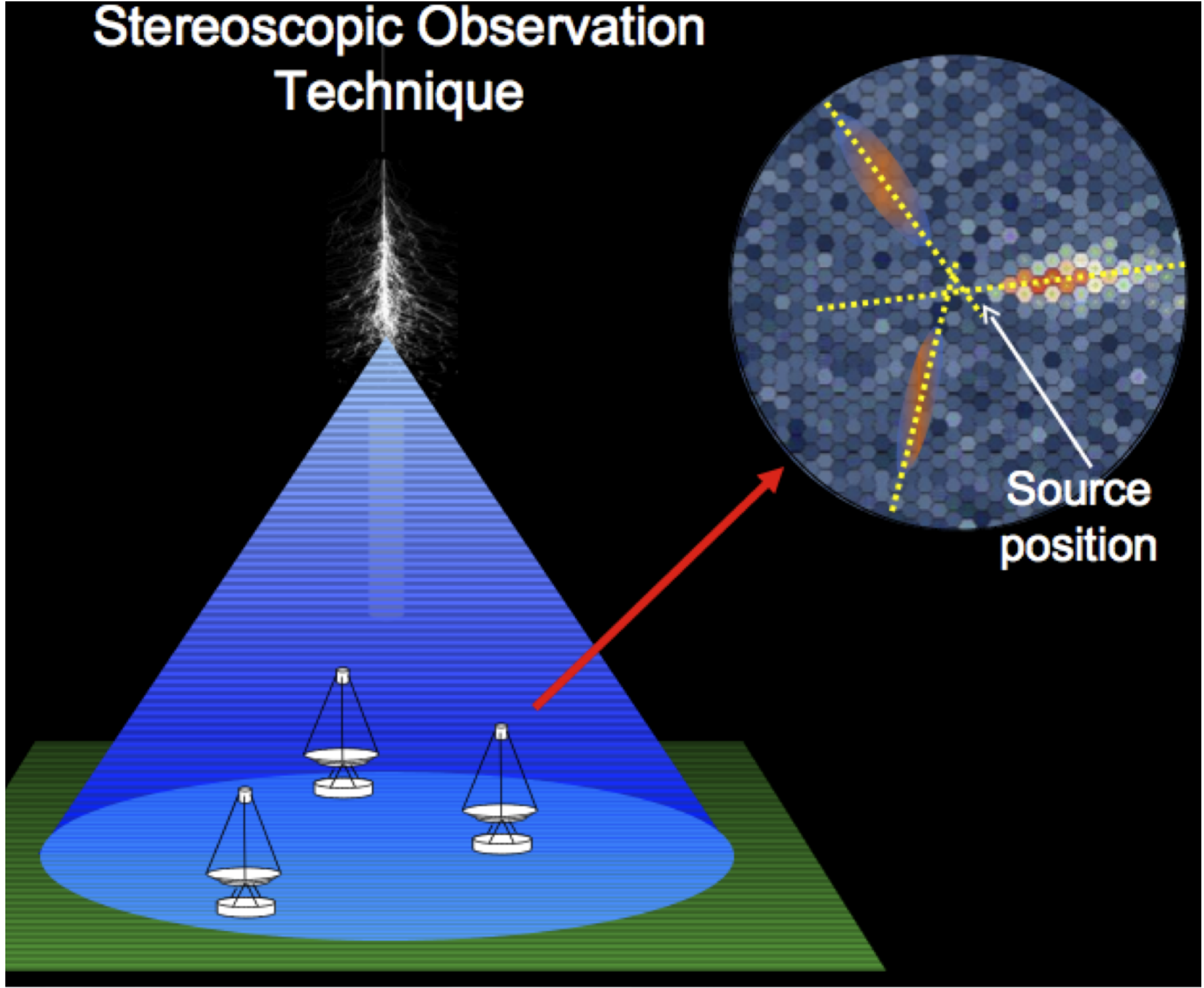
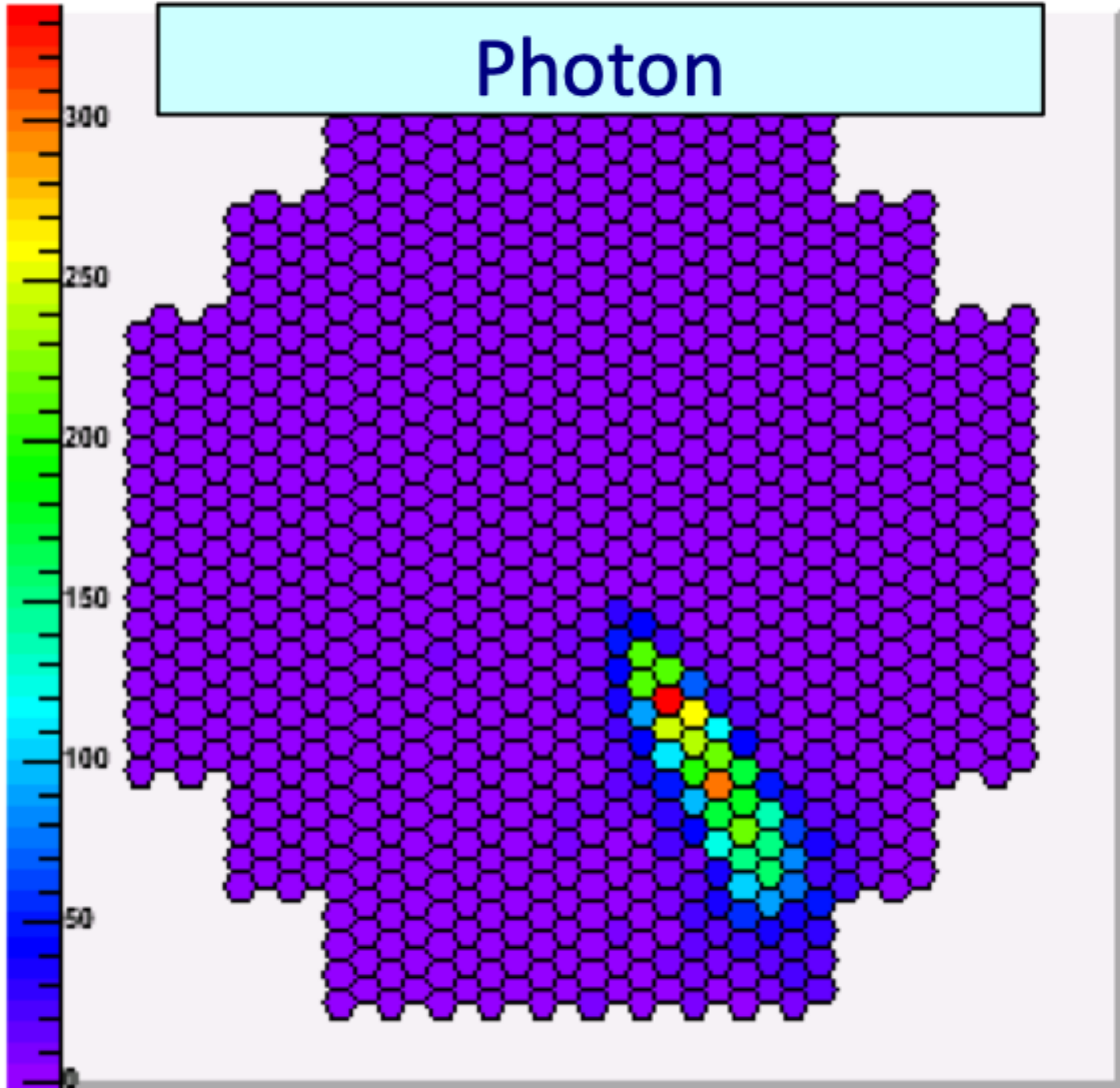
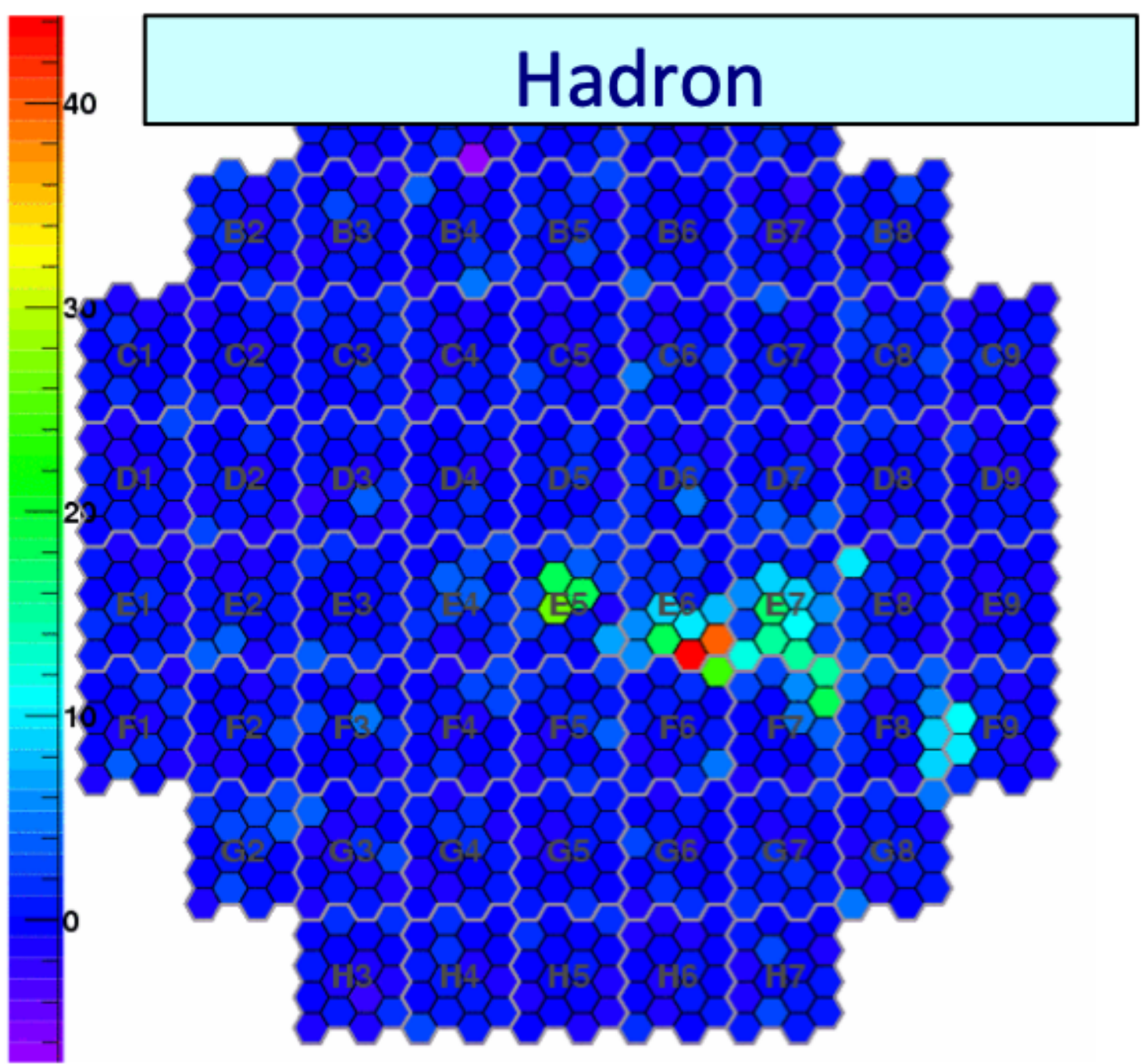


LST-1 and LST-2, La Palma, Canaries © Cyril FRESILLON / LAPP / CNRS Images.

Identifying particule



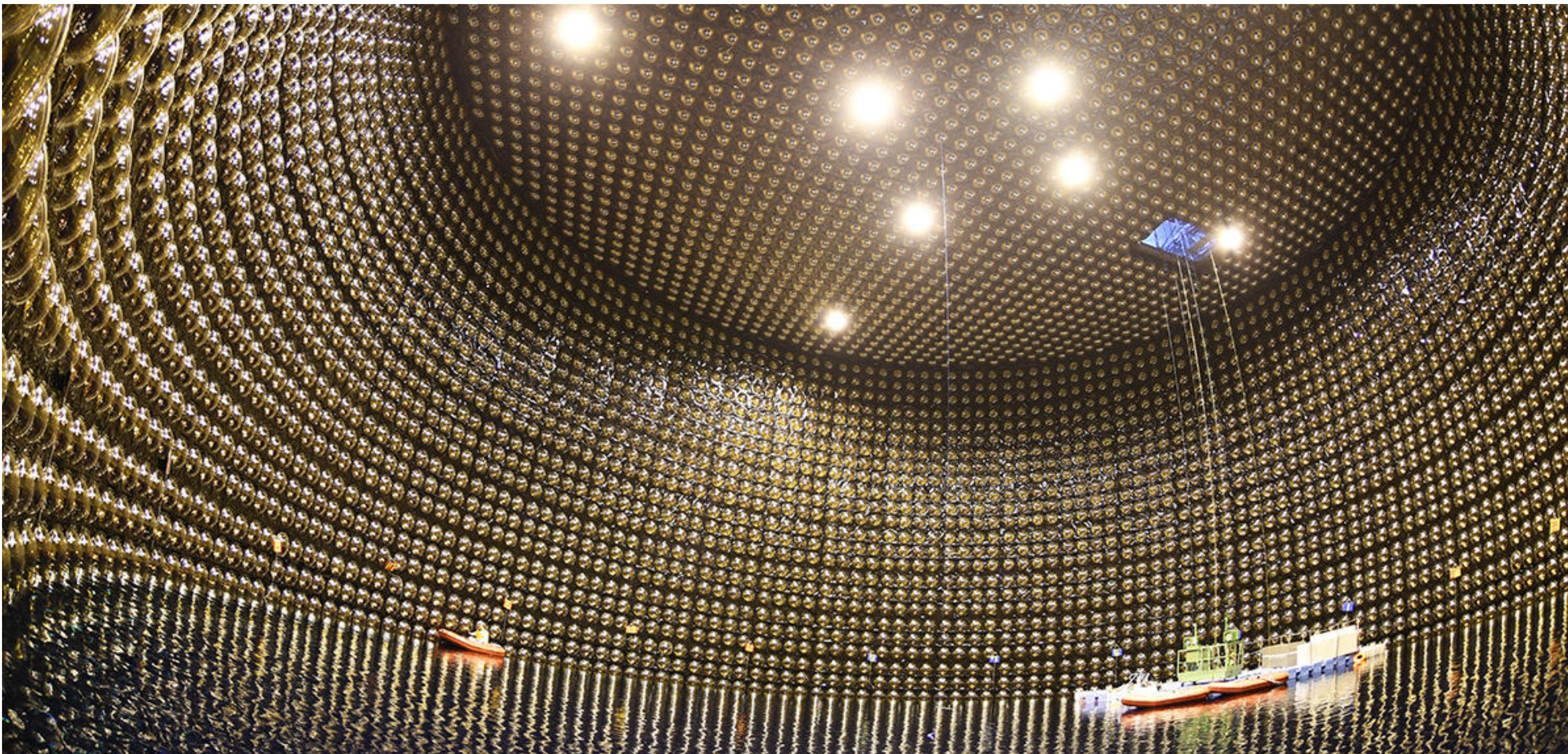
Identifying particule



Neutrinos detection

- **Super-Kamiokande (Japan, 1000 m underground):** 50 000 tons of pure water with ~11000 PMTs to detect Cerenkov light, 40m x 40 m.

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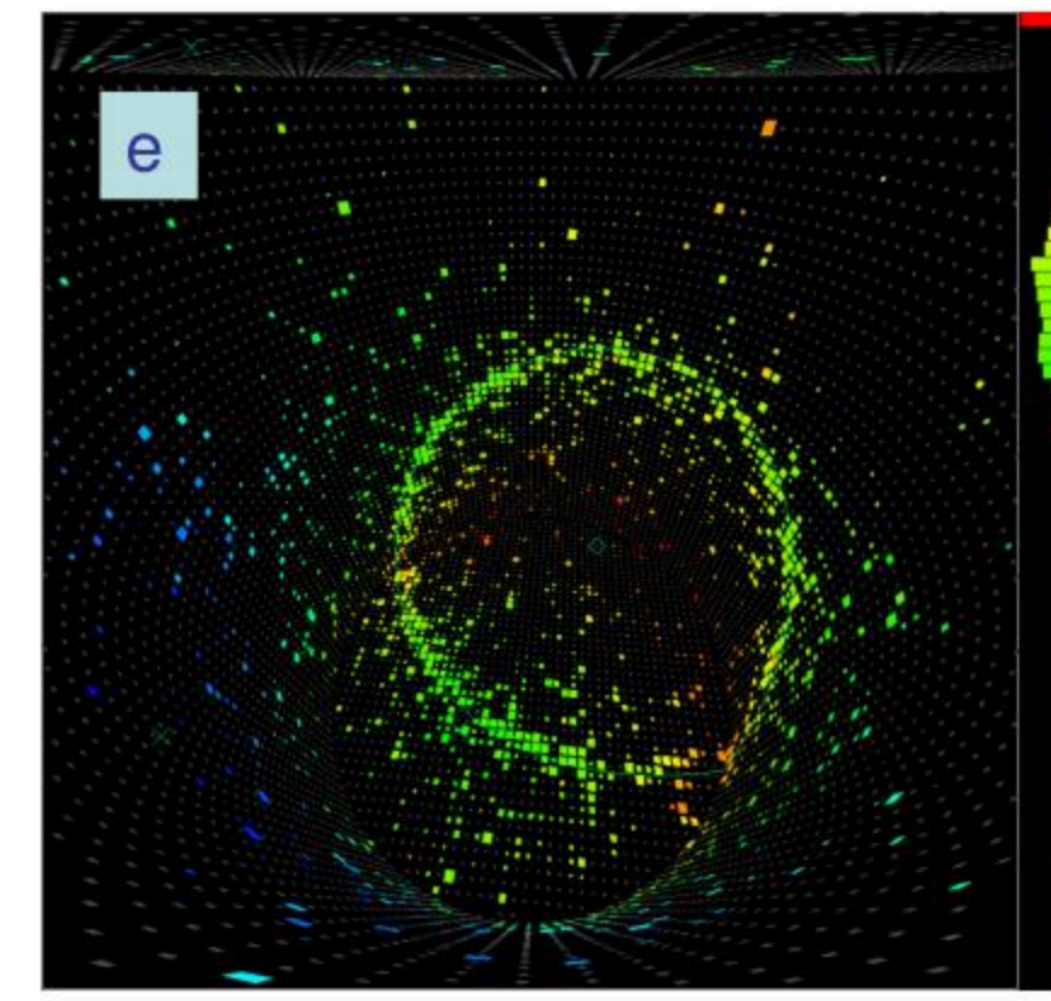
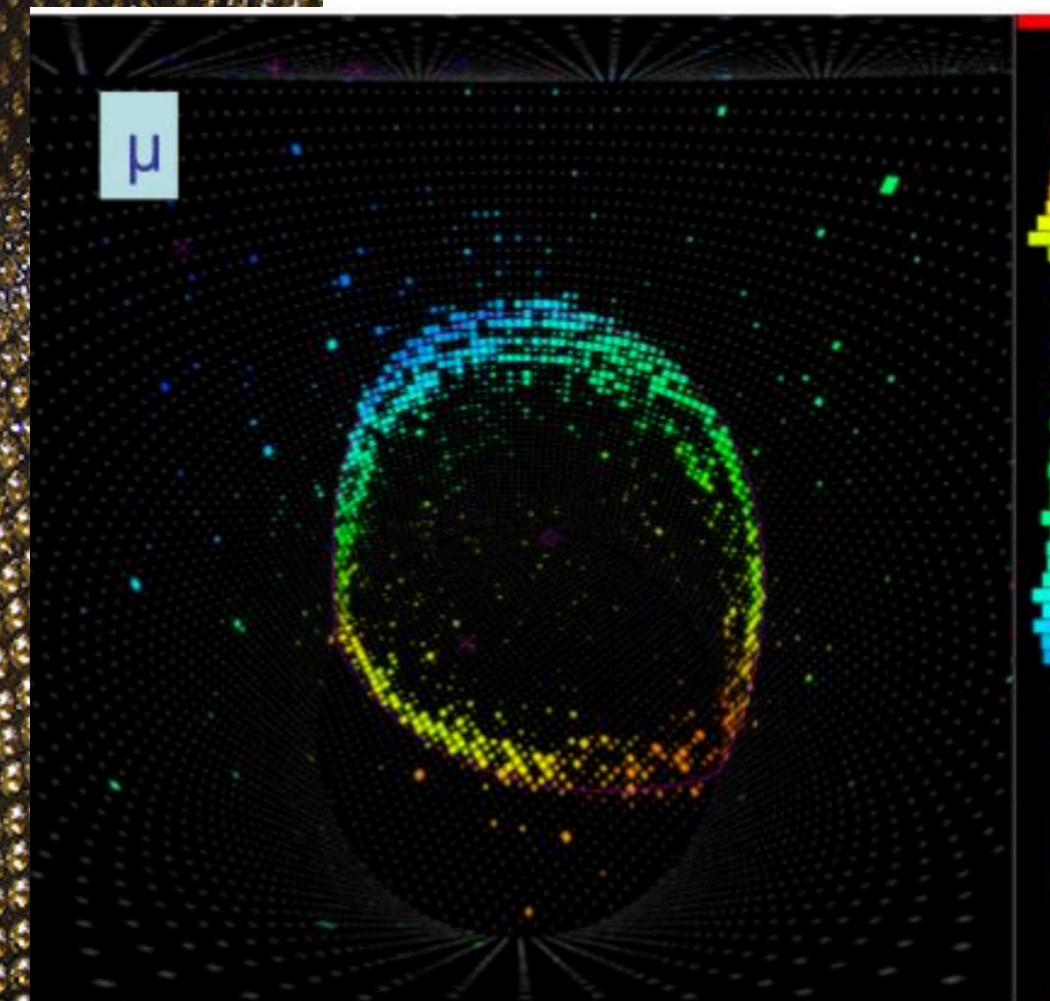
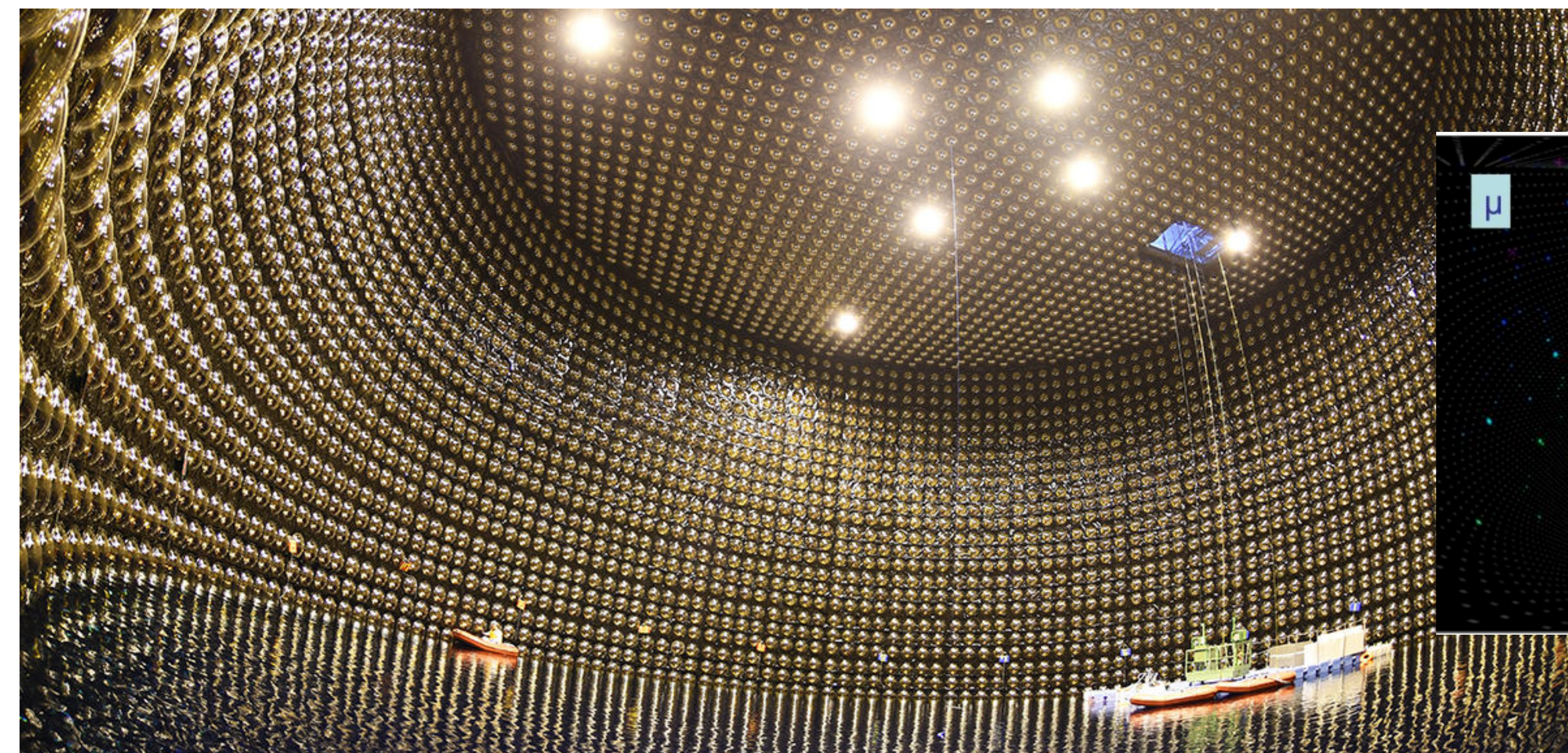
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$$\nu_e + n \rightarrow e^- + p$$

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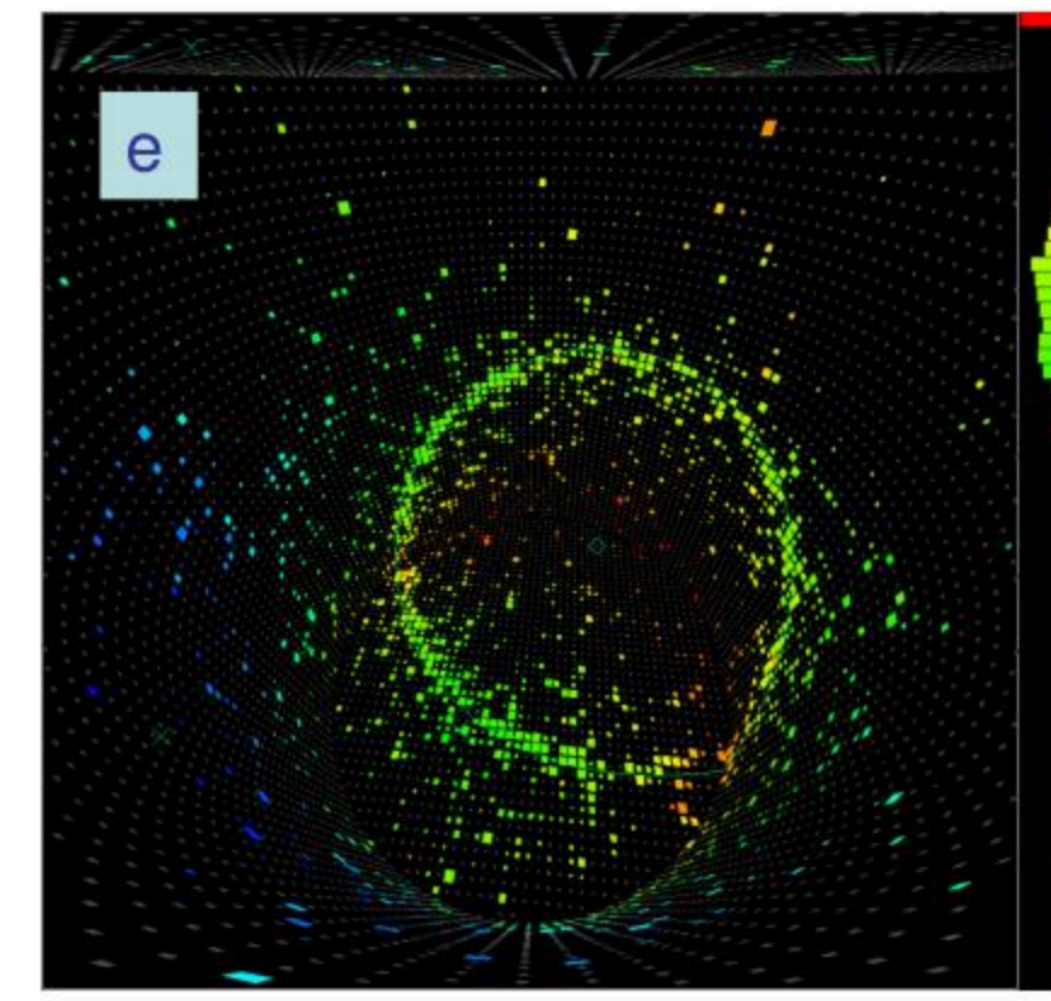
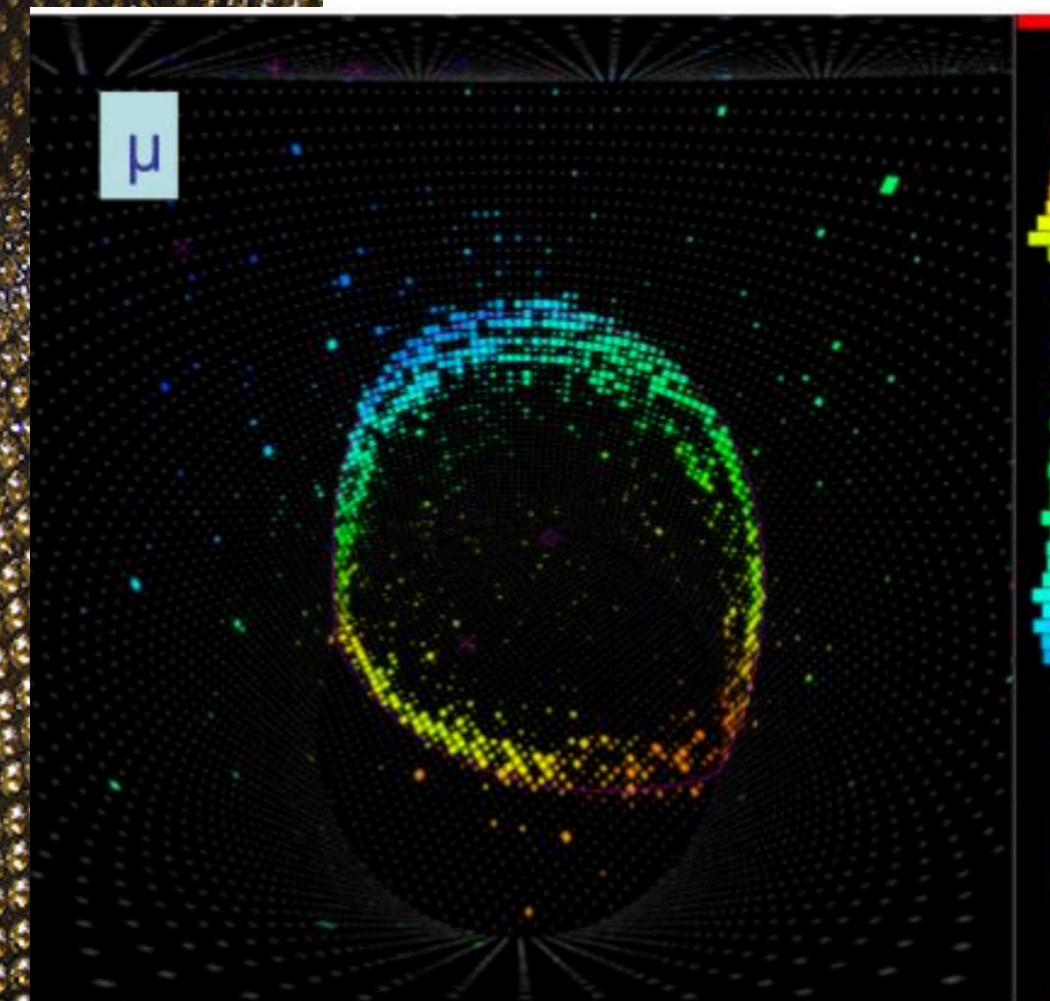
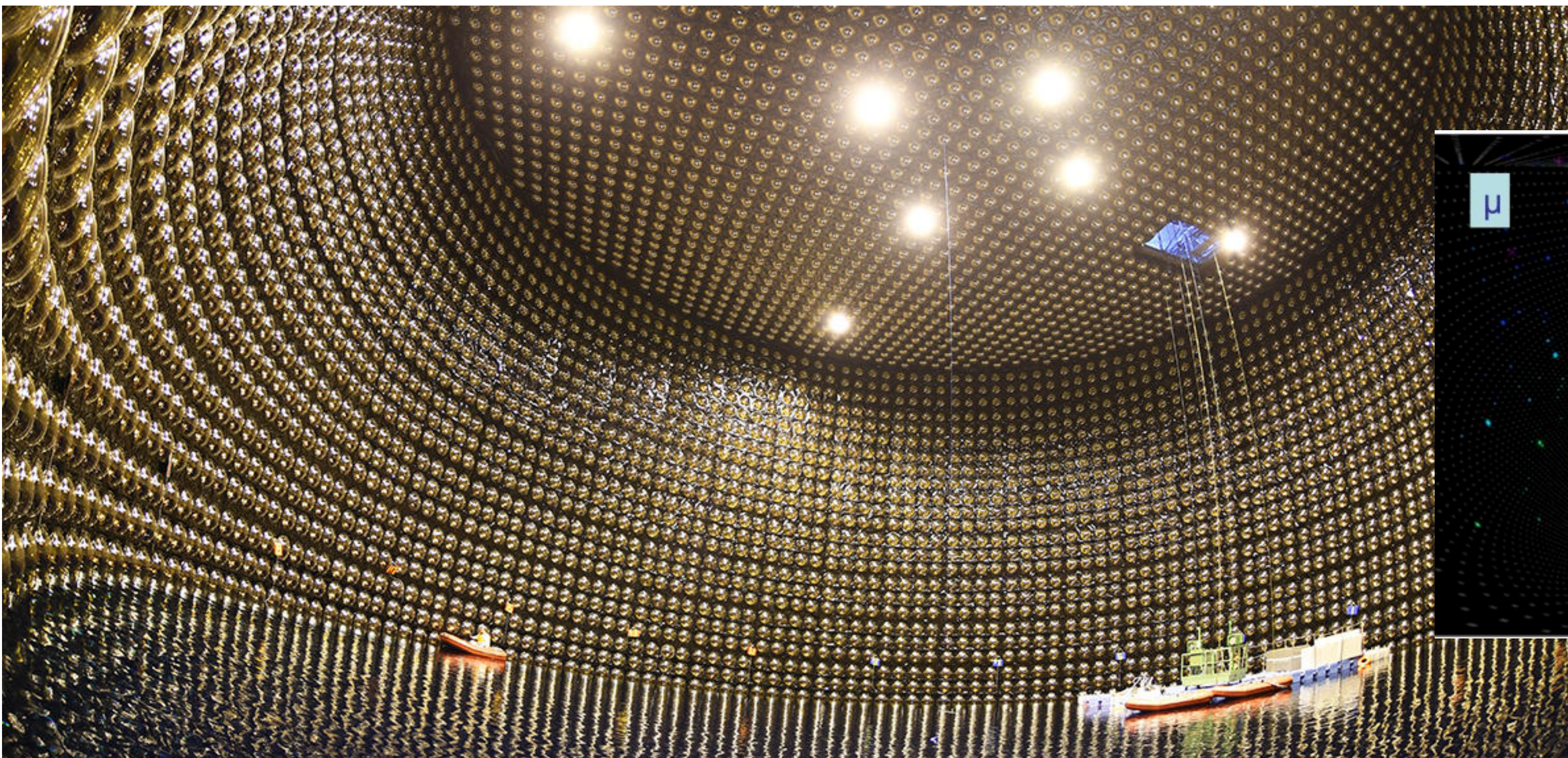
Neutrinos detection

CERENKOV RADIATION

- **Super-Kamiokande (Japan, 1000 m underground)**: 50 000 tons of pure water with ~11000 PMTs to detect Cerenkov light, 40m x 40 m.
- Extension (Hyper-Kamiokande) expected in ~2028 (260000 tons of pure water)

$$\nu_e + n \rightarrow e^- + p$$

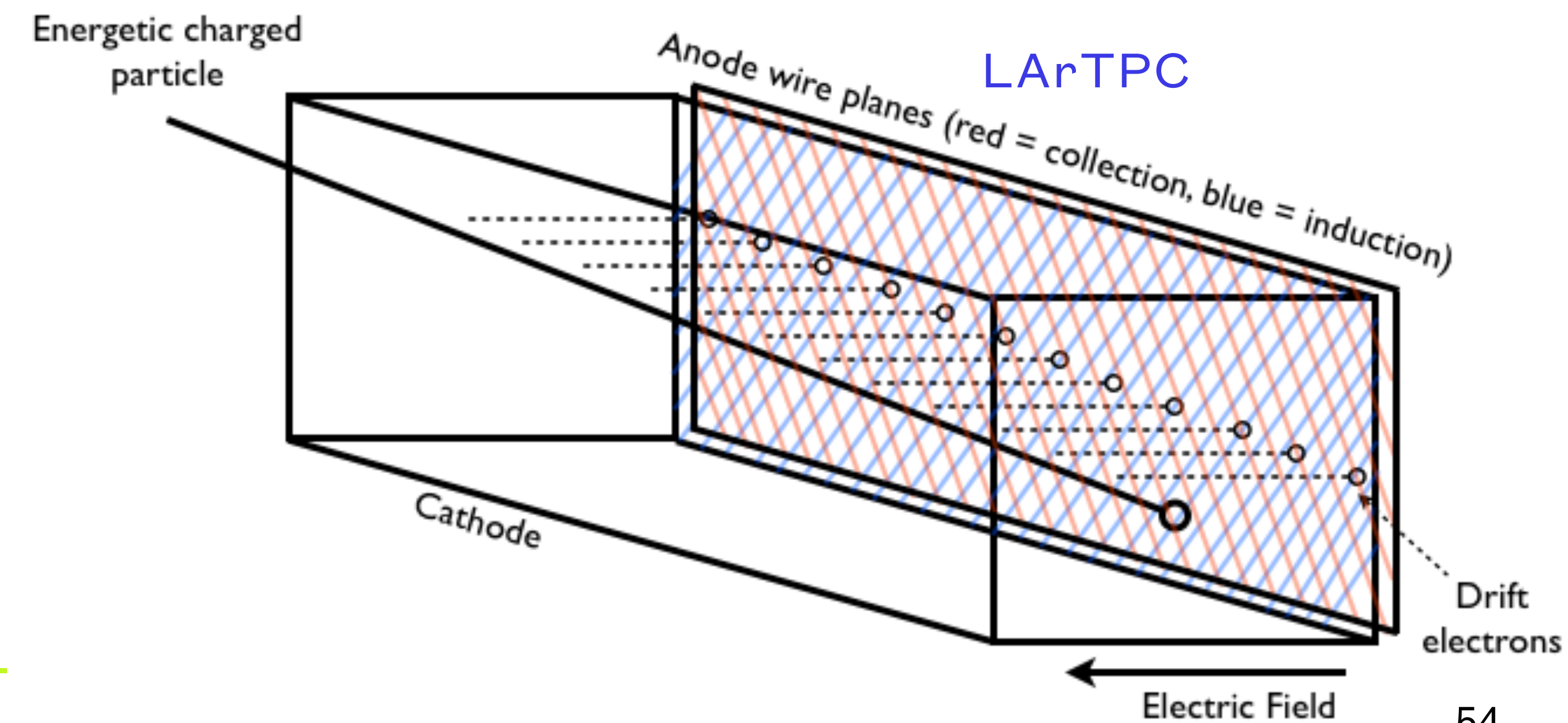
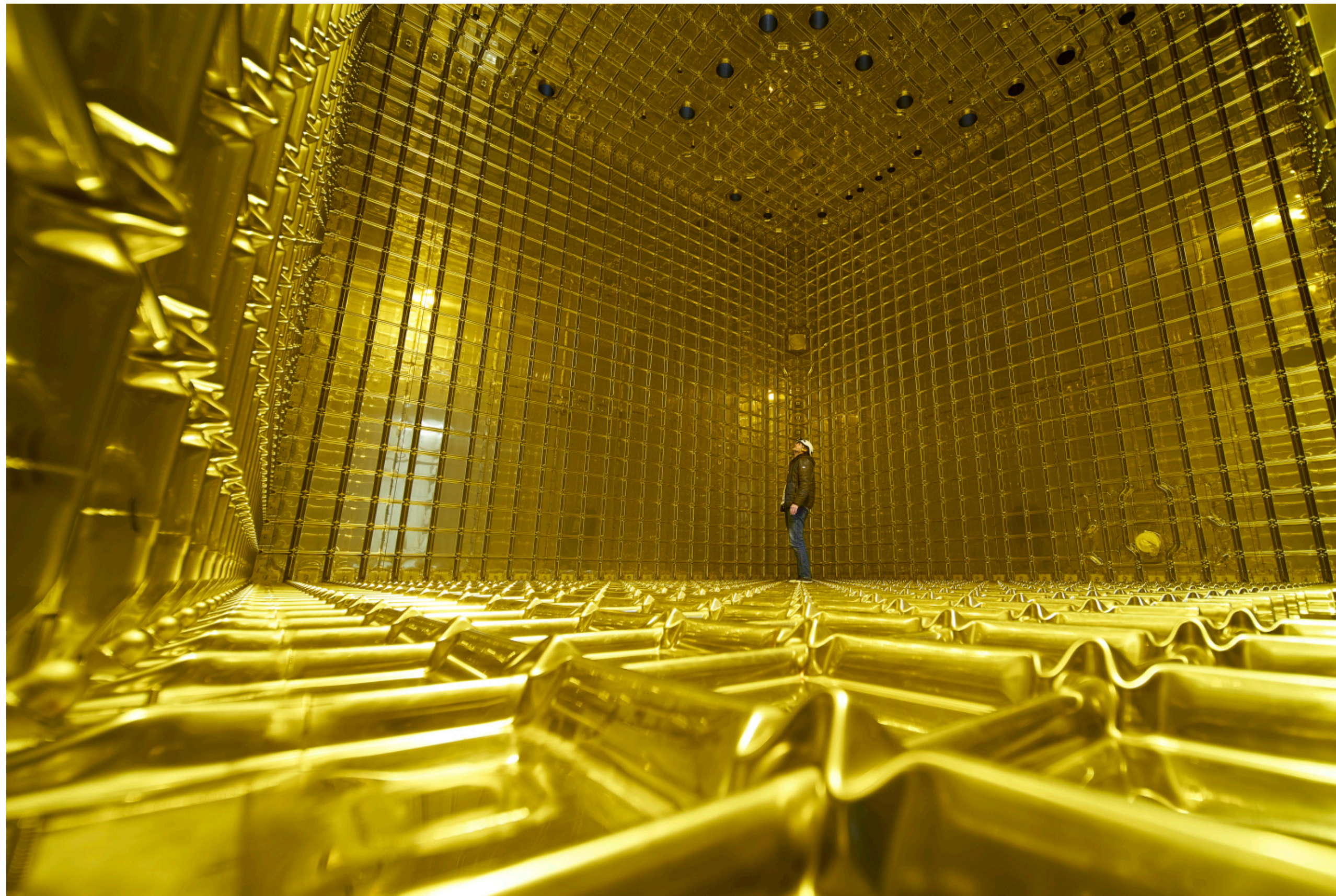
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Neutrinos detection

IONIZATION
EXCITATION -> SCINTILLATION

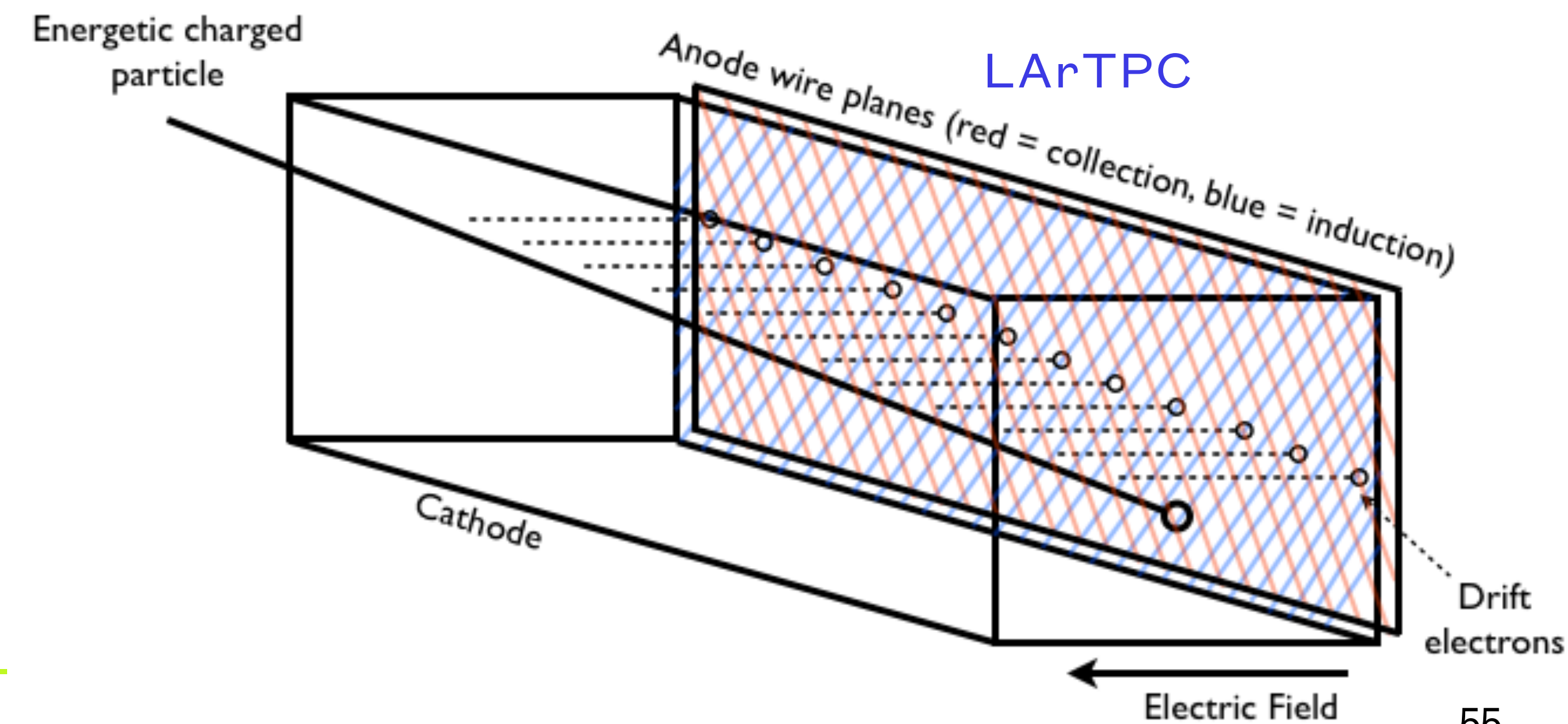
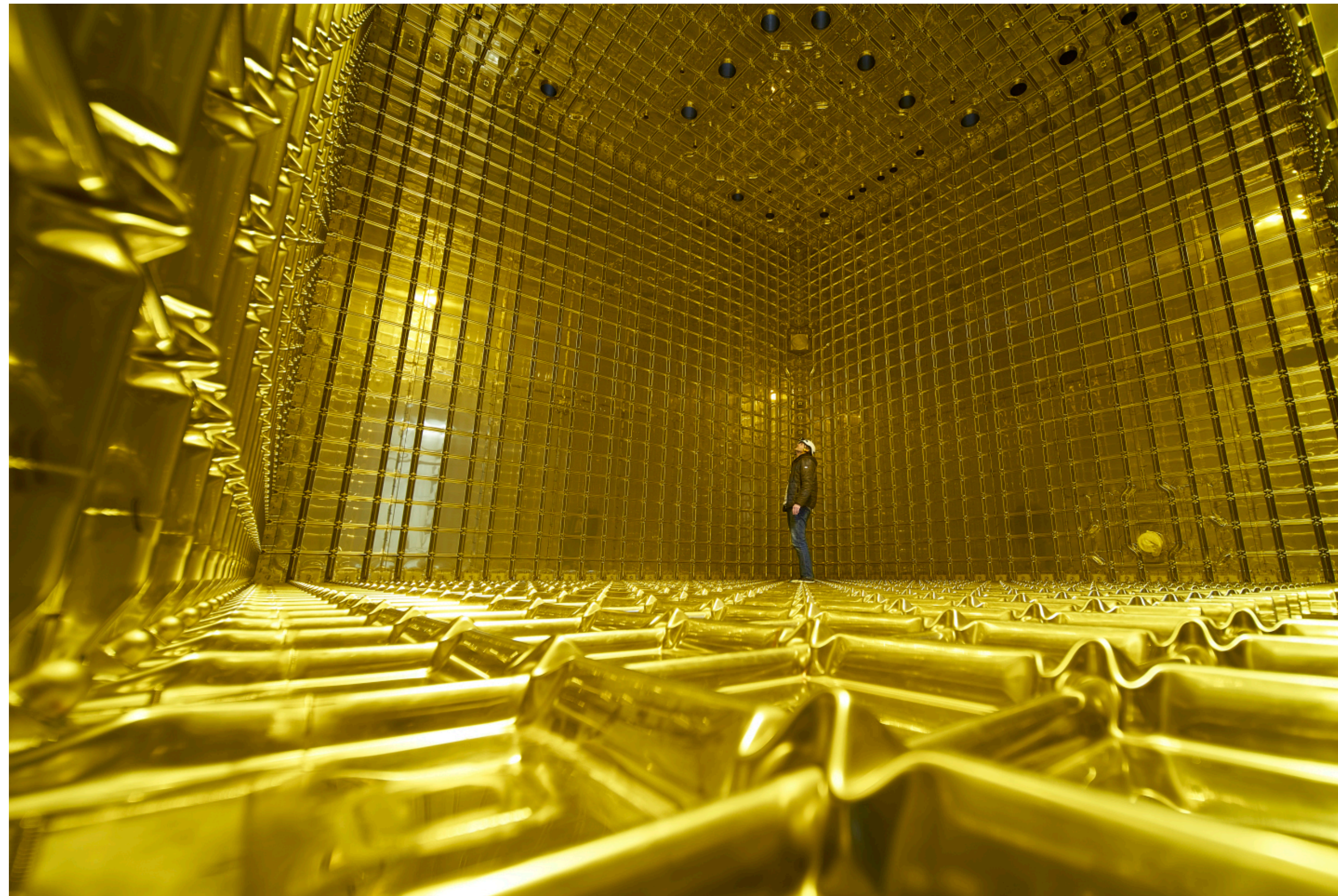
- **DUNE (>2030)**: 70 000 tons of liquid argon (LAr), 1.5 km underground, Time Projection Chambers (TPC) -> 3D images.
- Near detector at Fermilab (before oscillations), Far detector 1300 km away (after oscillations)



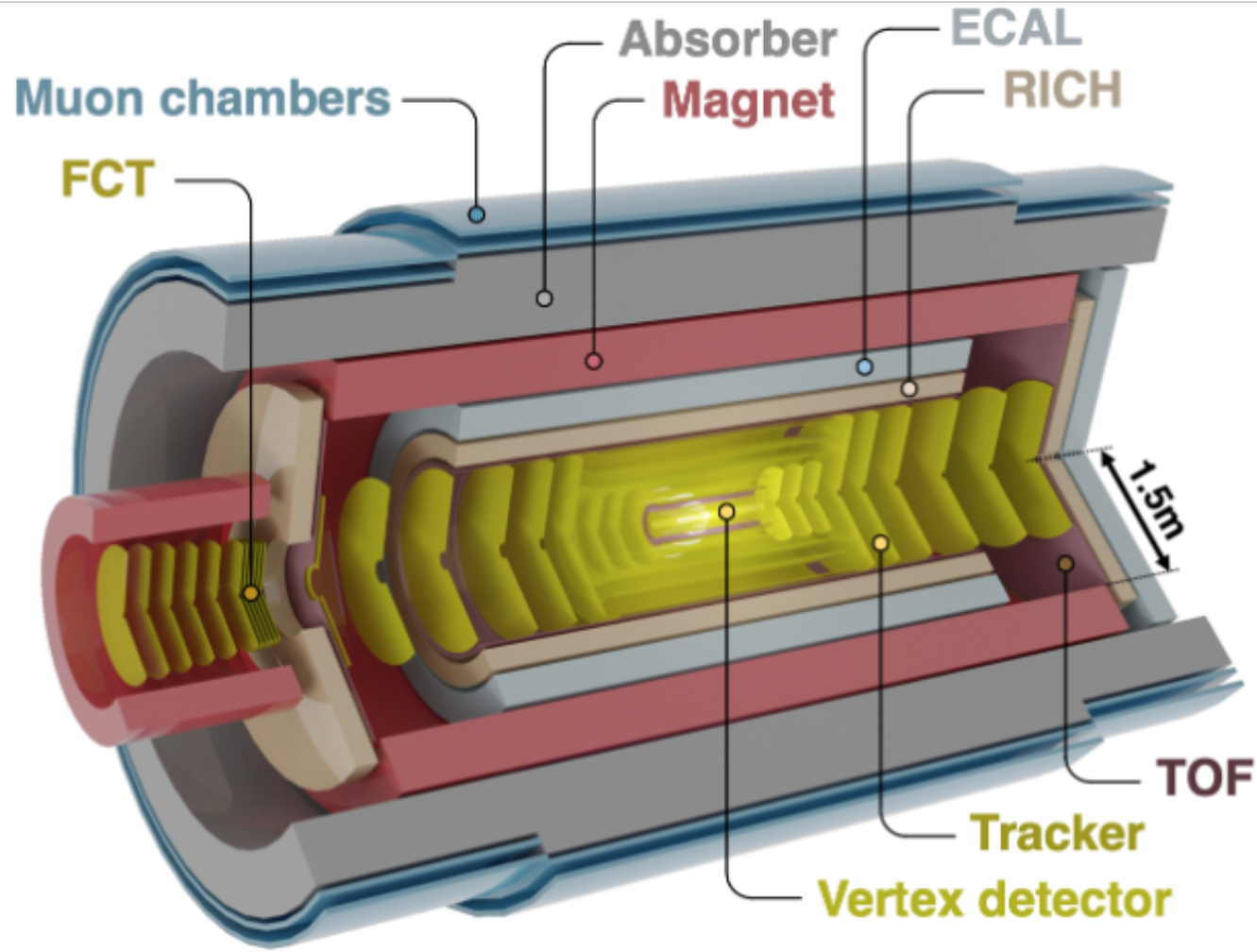
Neutrinos detection

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 - Near detector at Fermilab (before oscillations), Far detector 1300 km away (after oscillations)
- ProtoDune currently taking data at CERN, to prove feasibility (20 times smaller than DUNE) -> **LAPP team !**

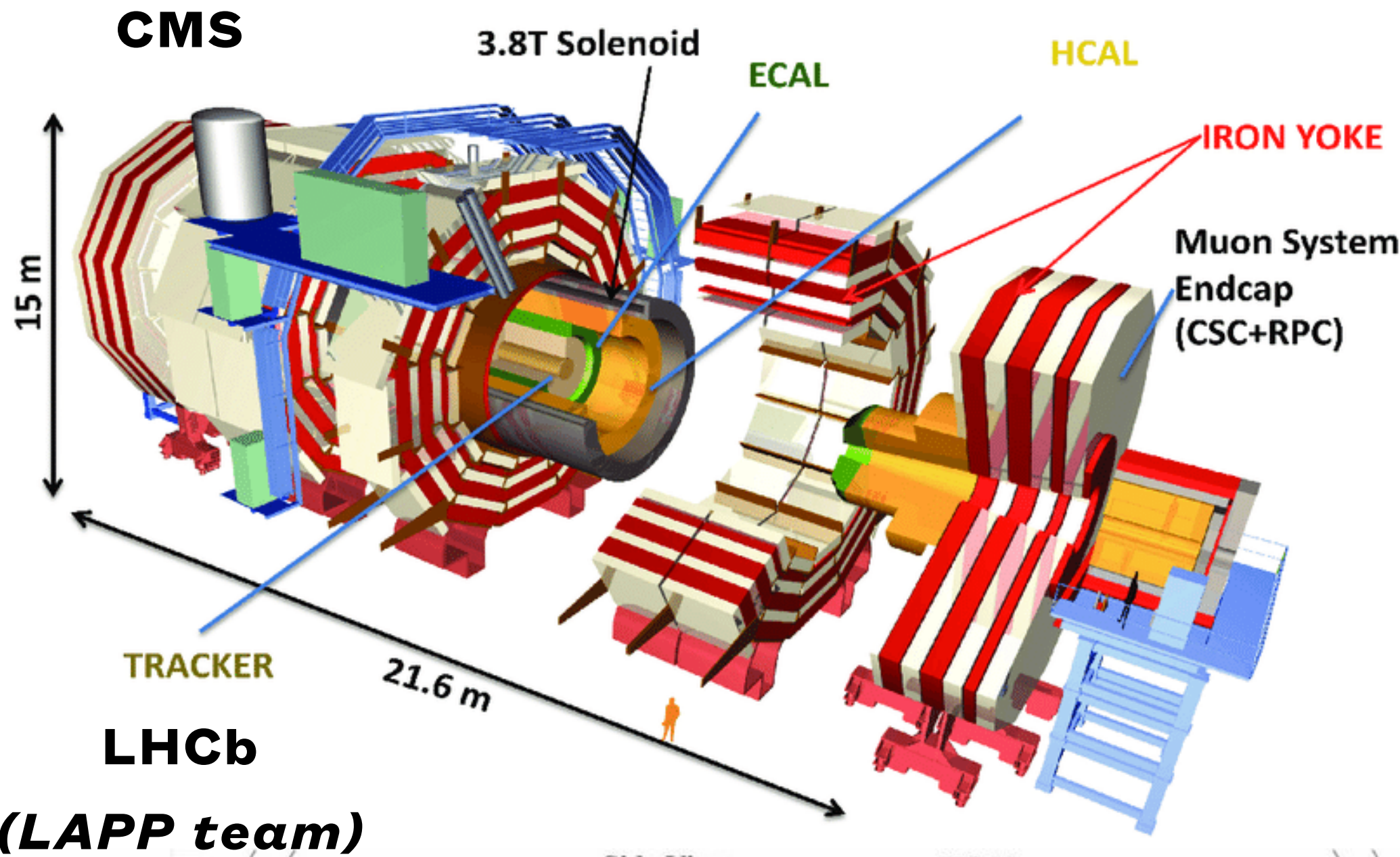
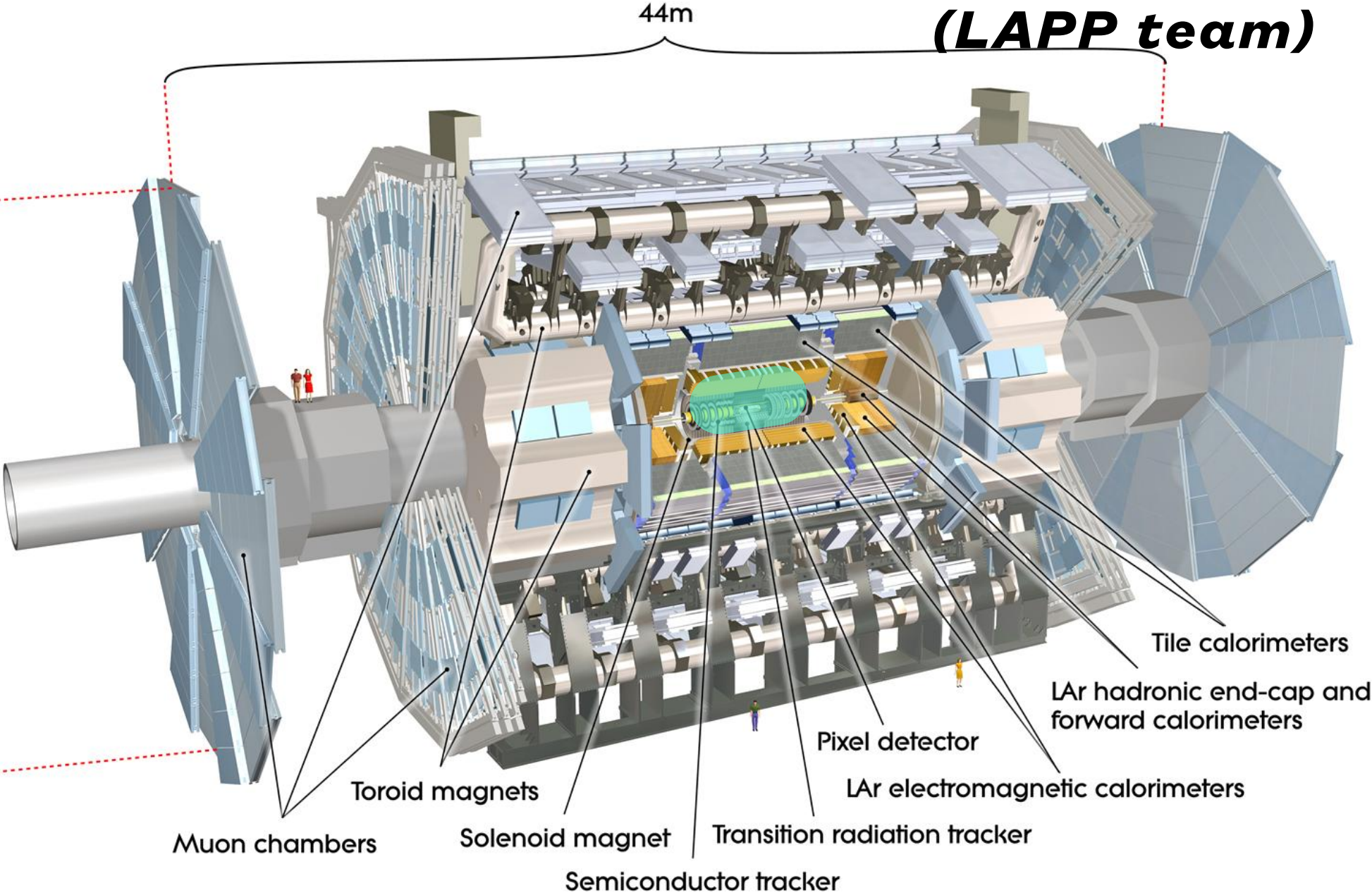


LHC detectors

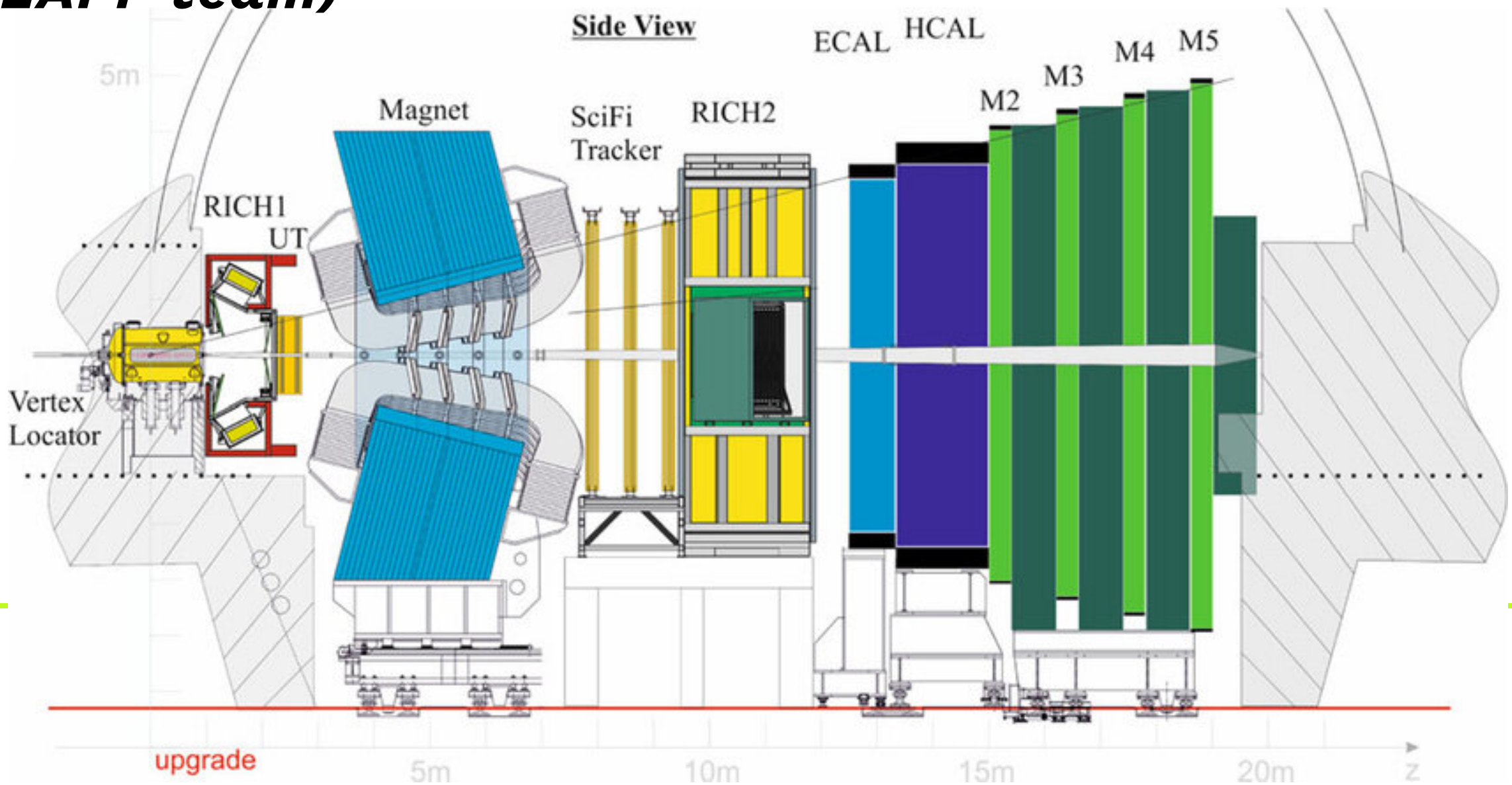


ALICE

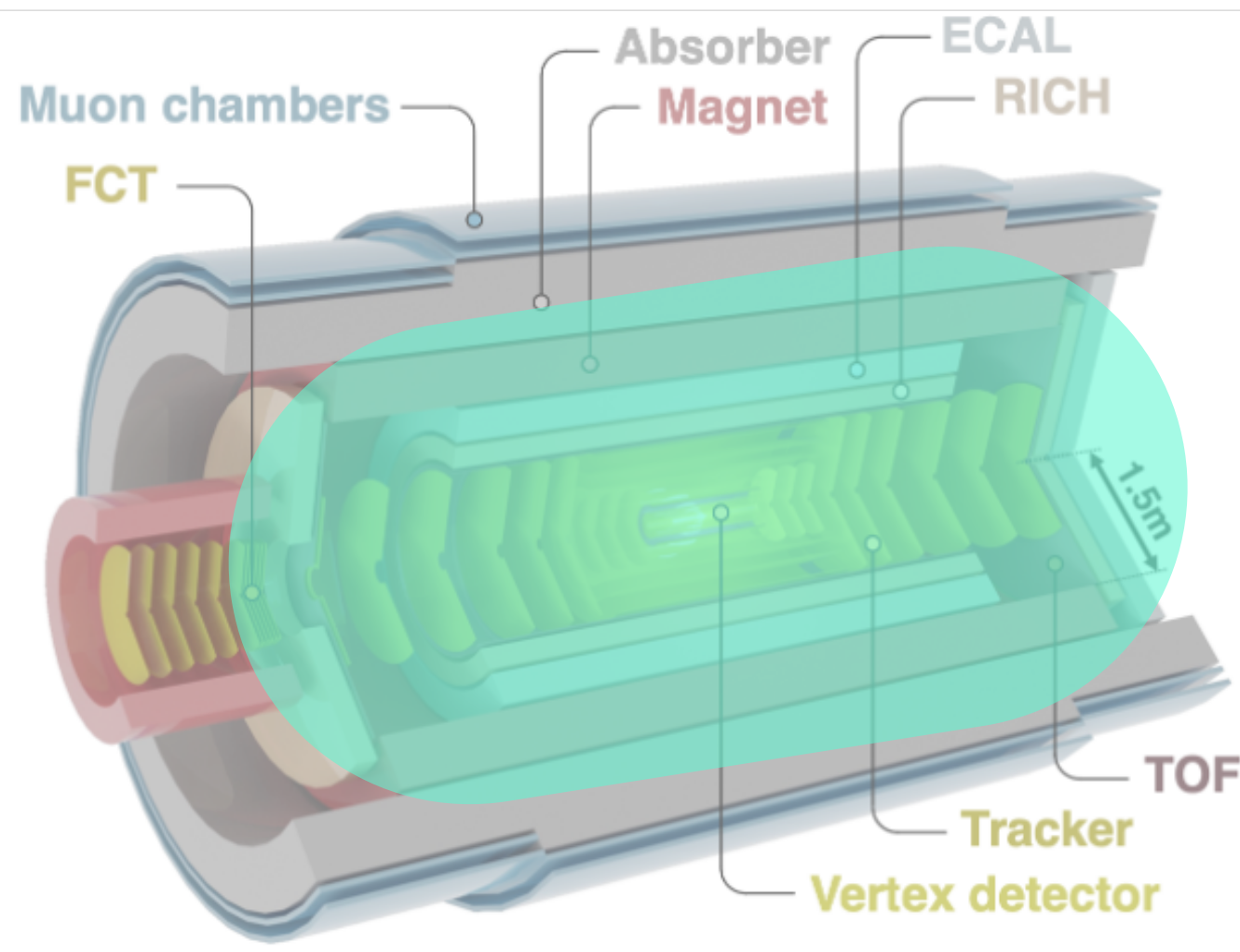
ATLAS
(LAPP team)



LHCb
(LAPP team)

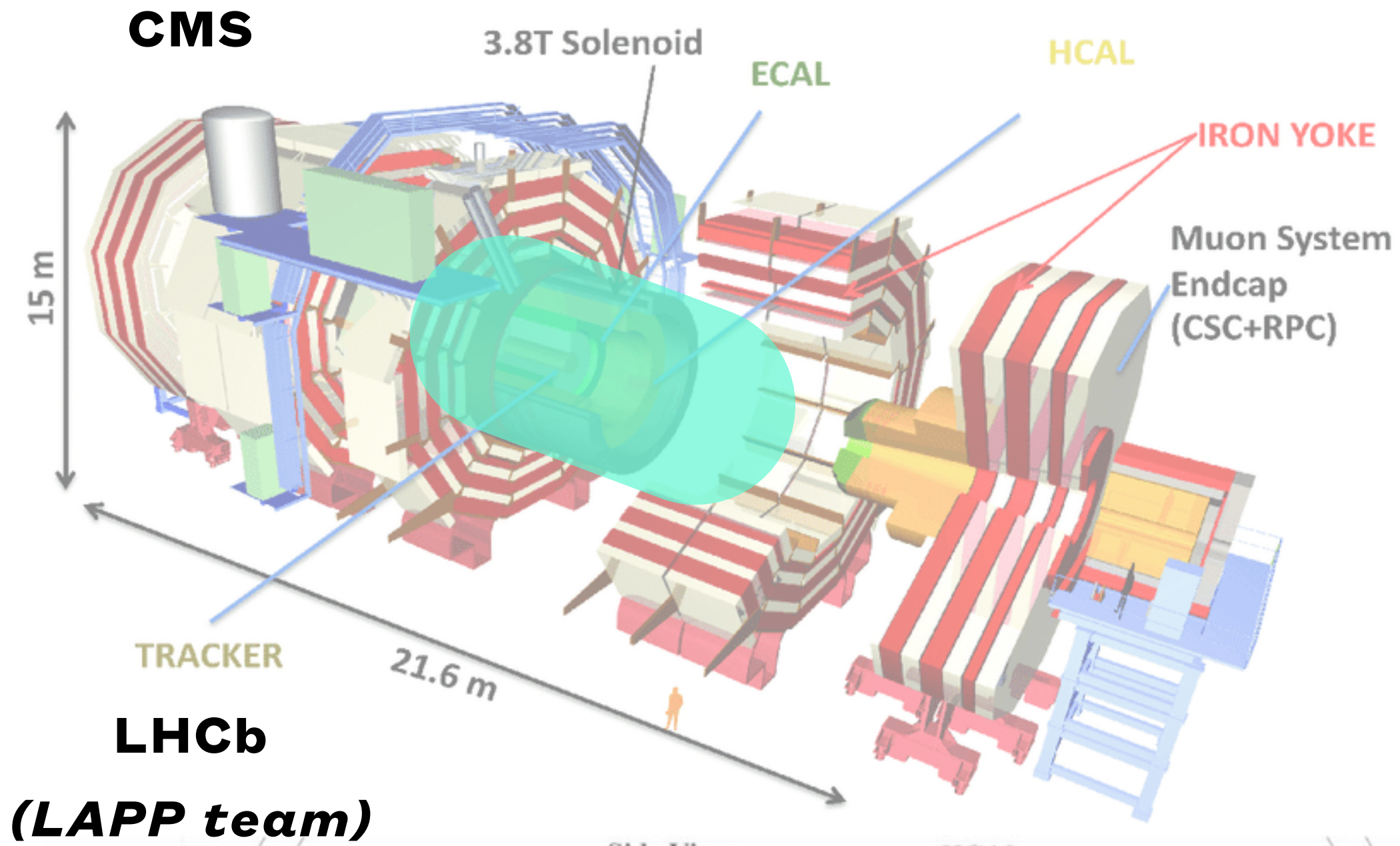
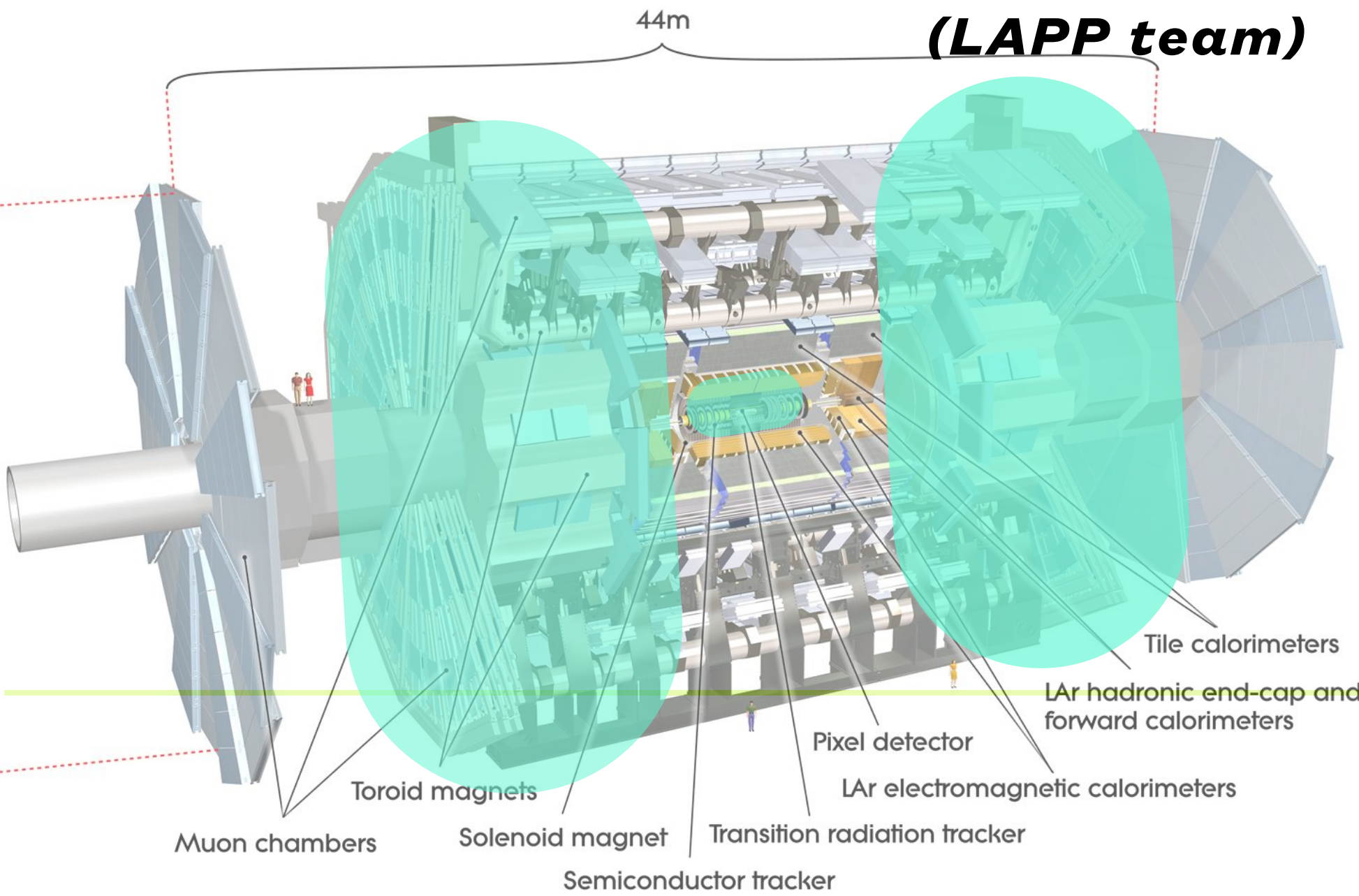


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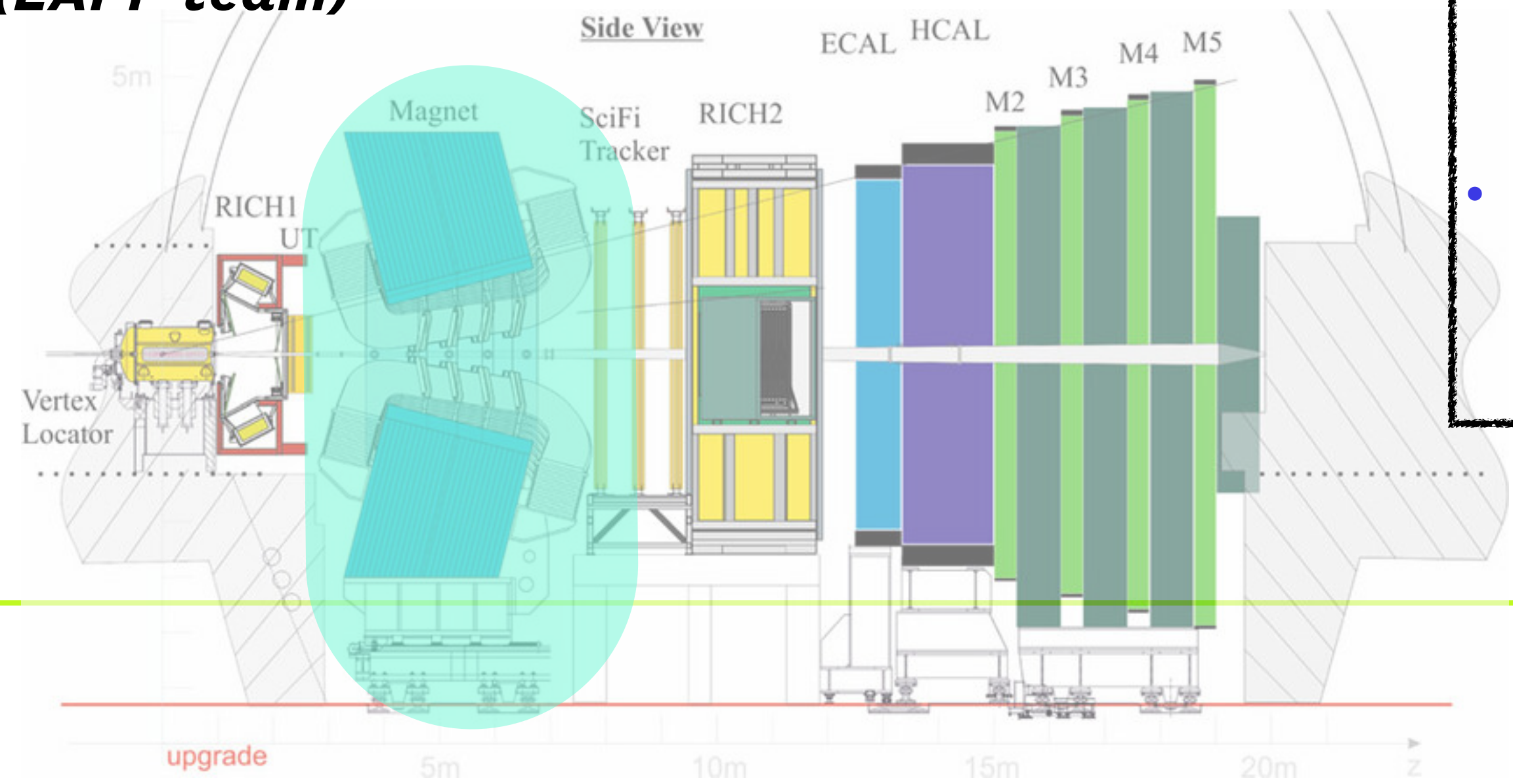
ALICE

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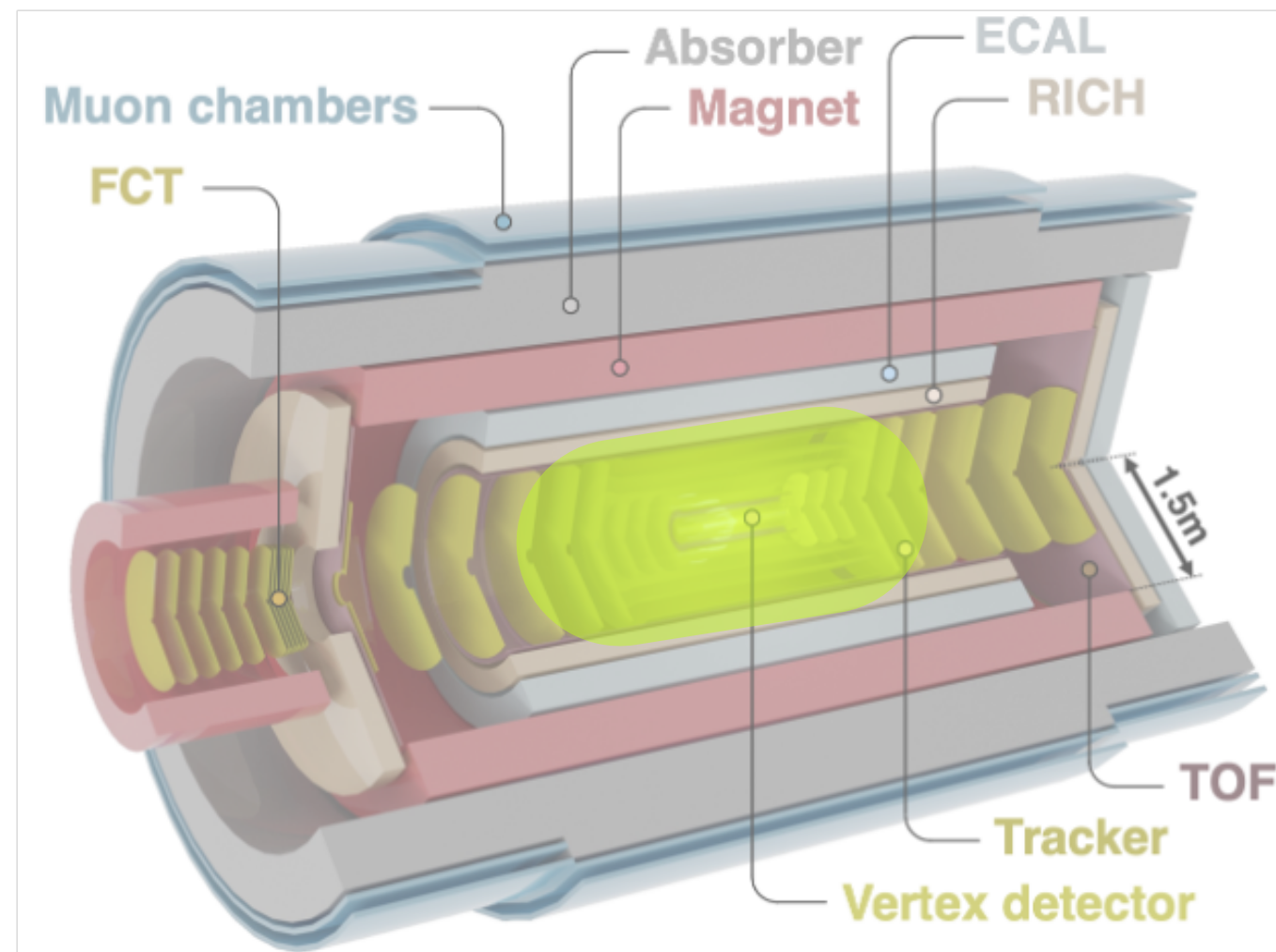
CMS

**LHCb
(LAPP team)**



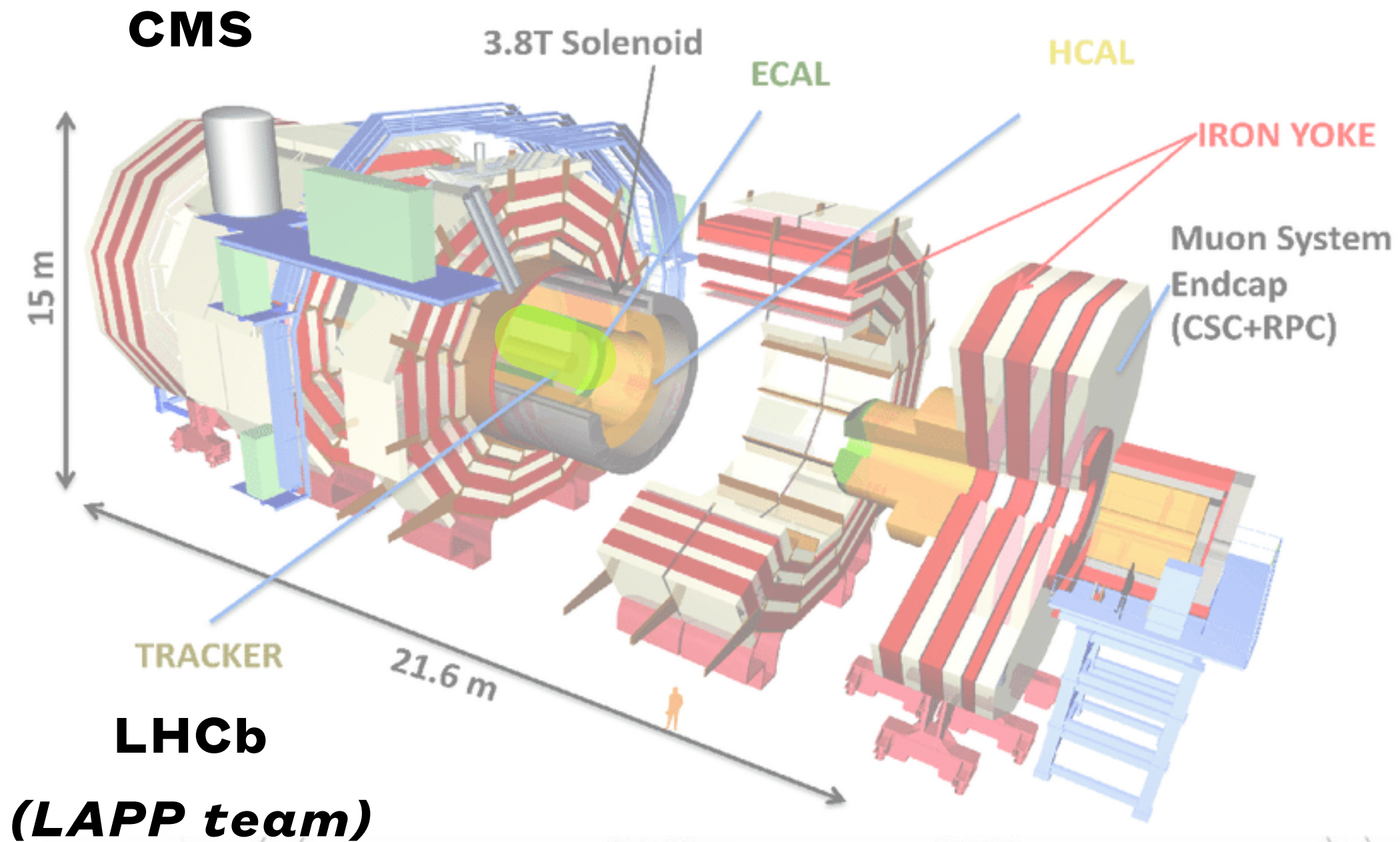
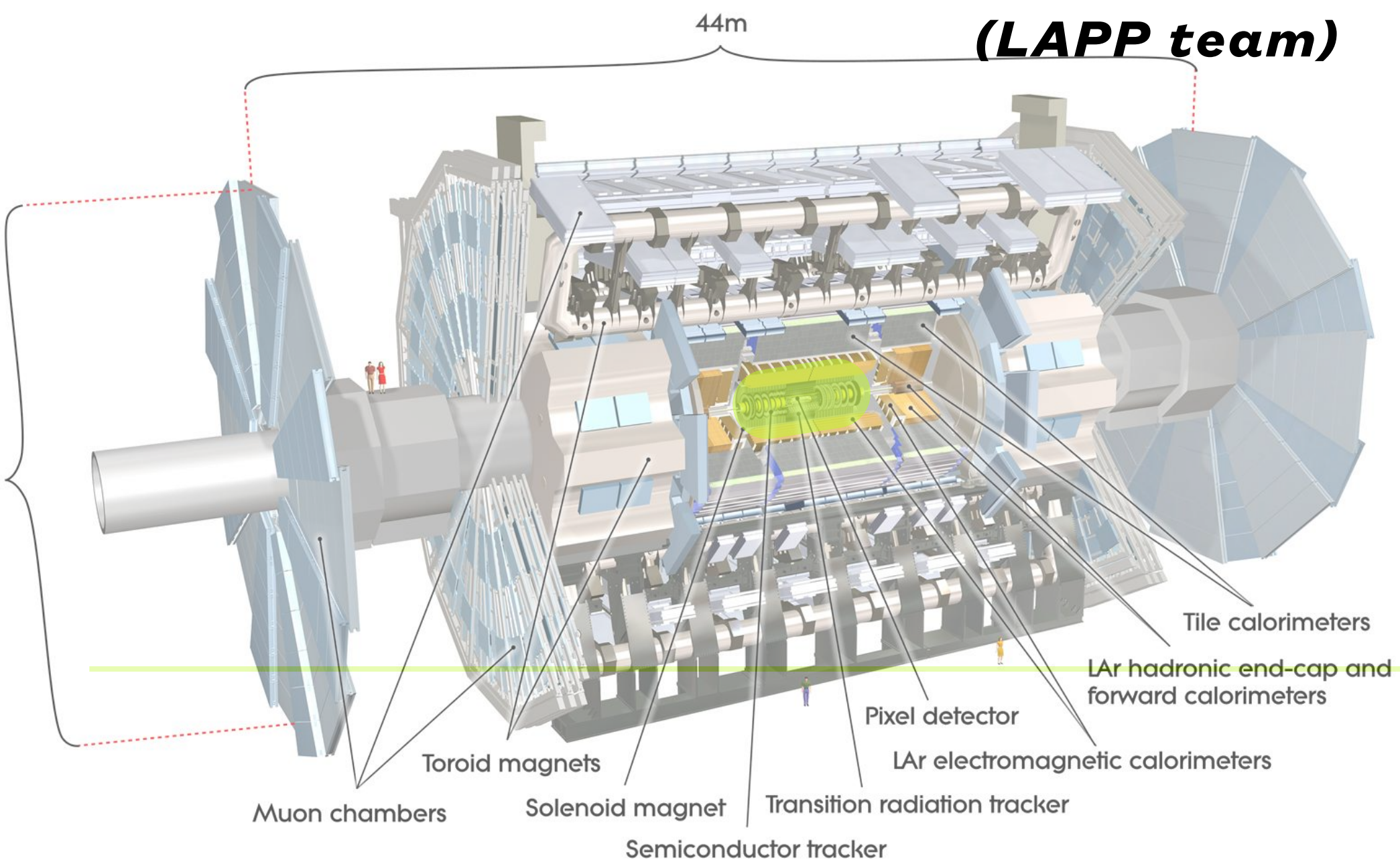
- High magnetic field to curve trajectories
- Tracker to reconstruct trajectory of produced particles
- Calorimeter to measure the energy
- Muon spectrometer for escaping muons

LHC detectors



ALICE

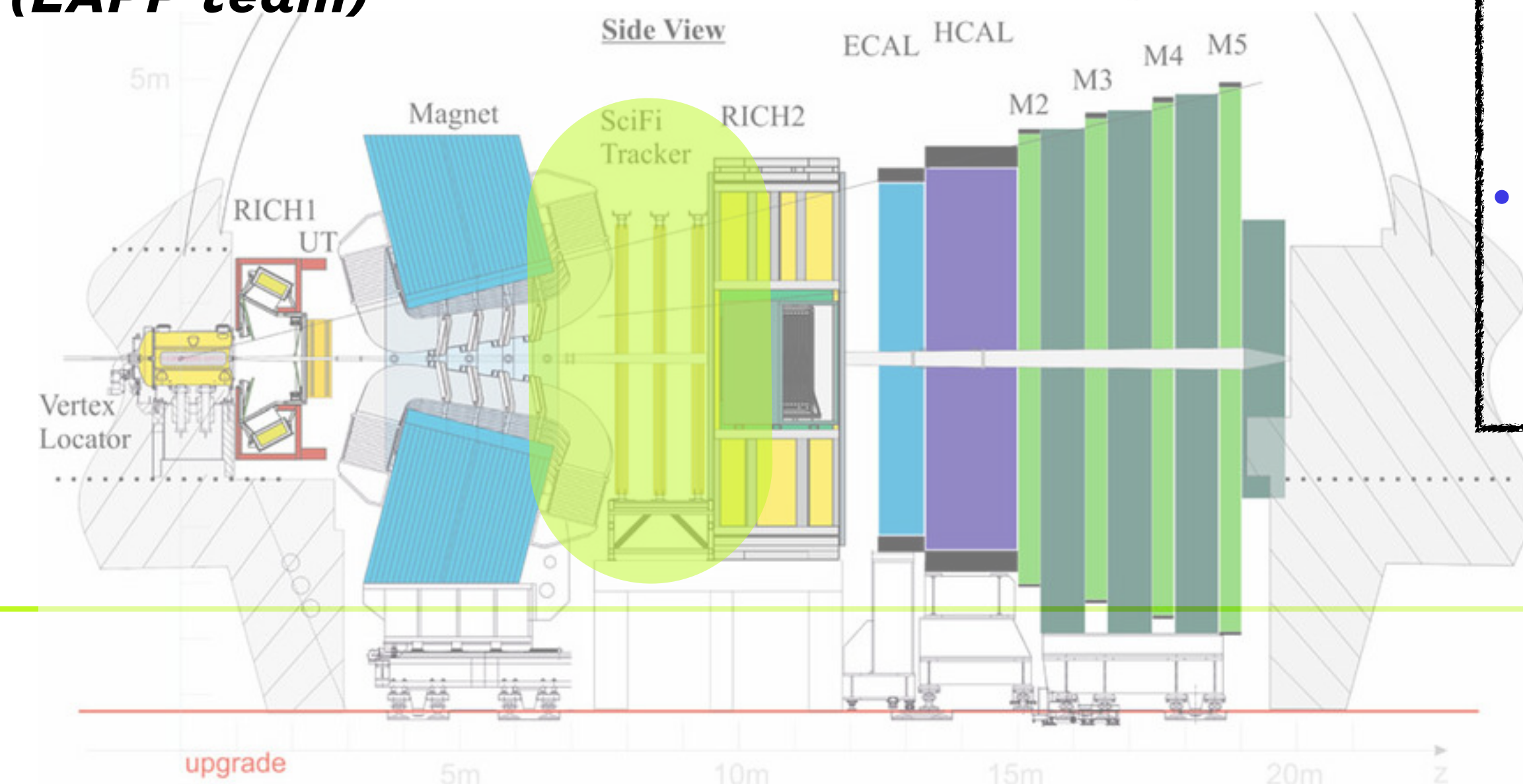
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CMS

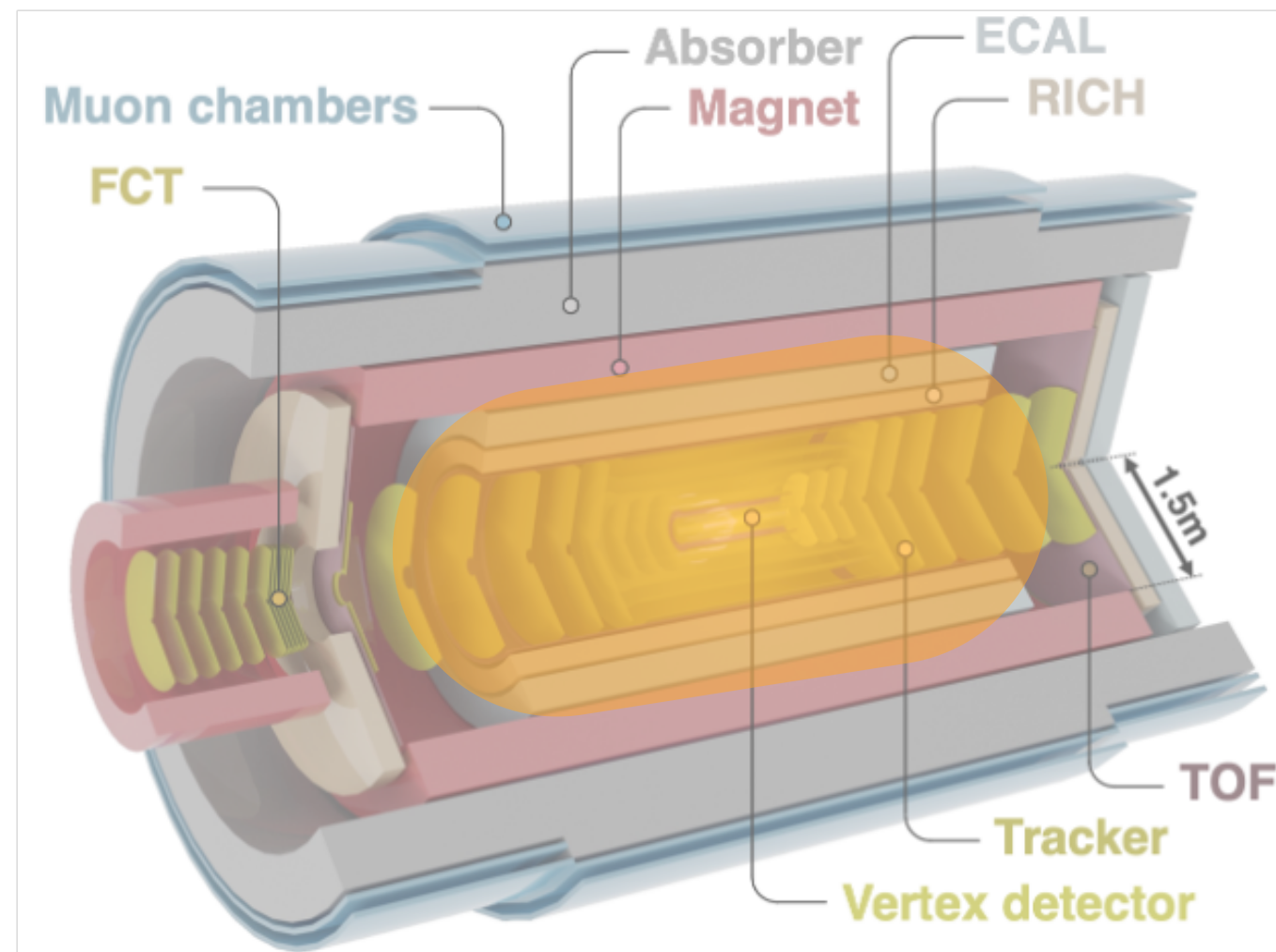
LHCb

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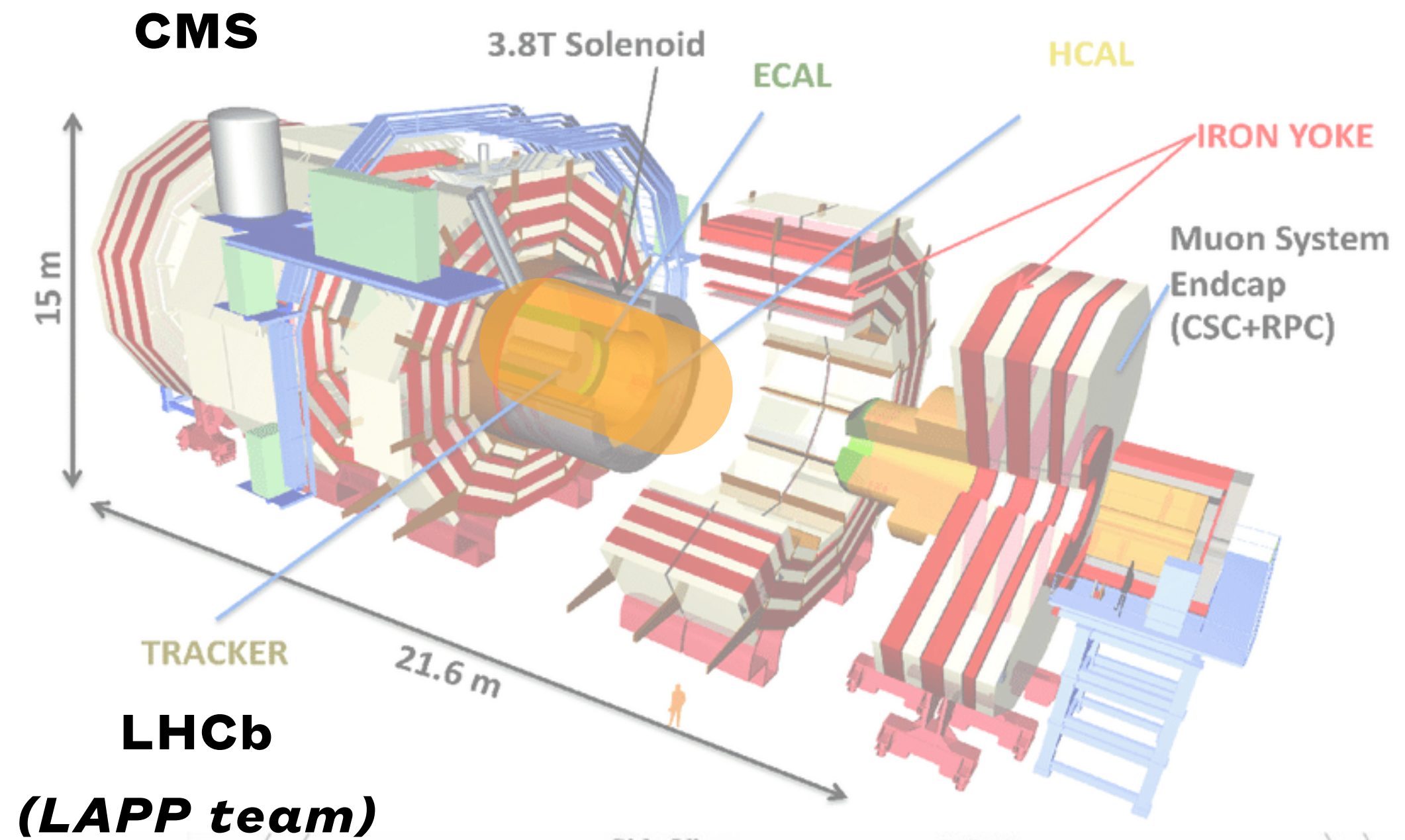
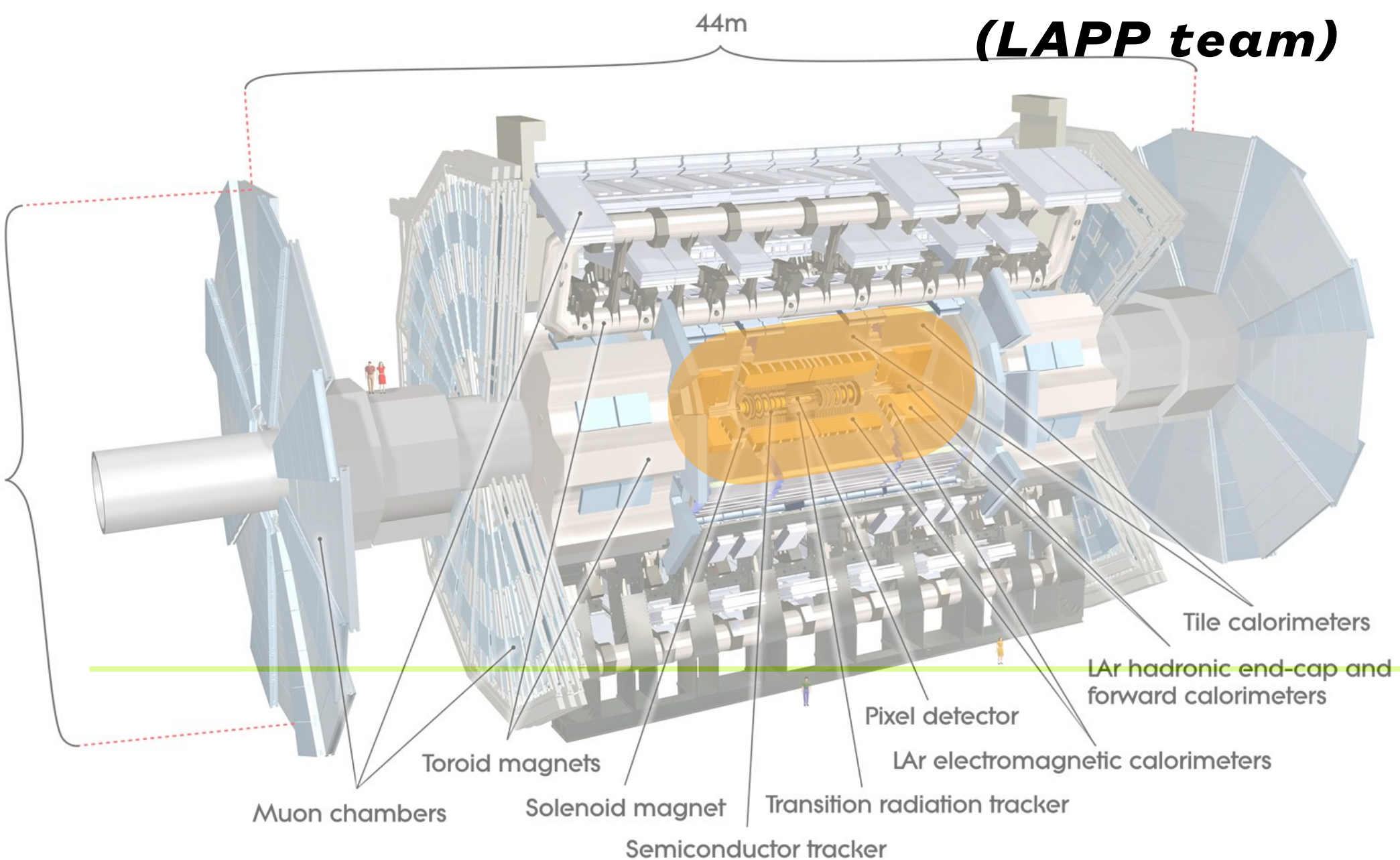
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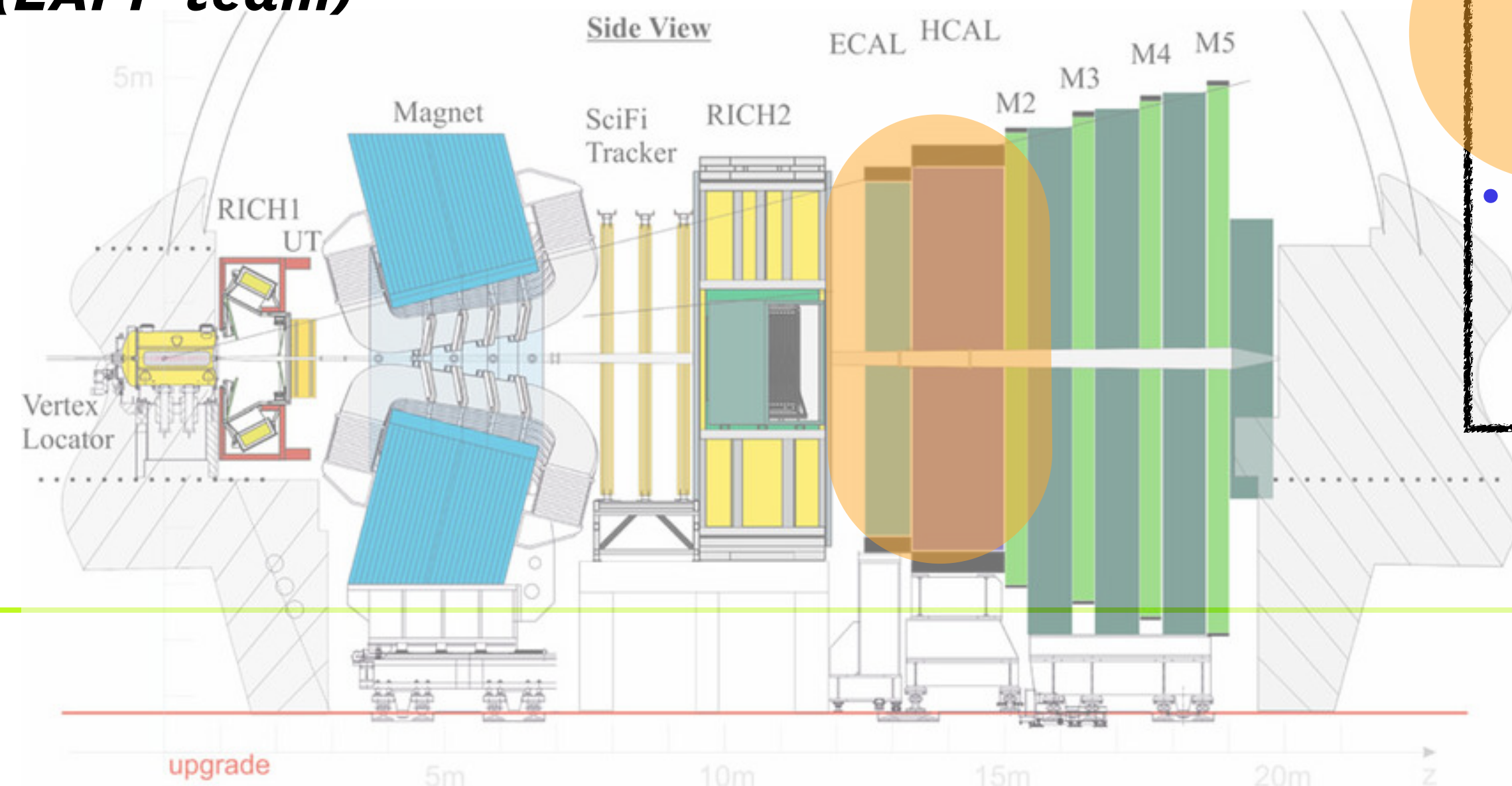
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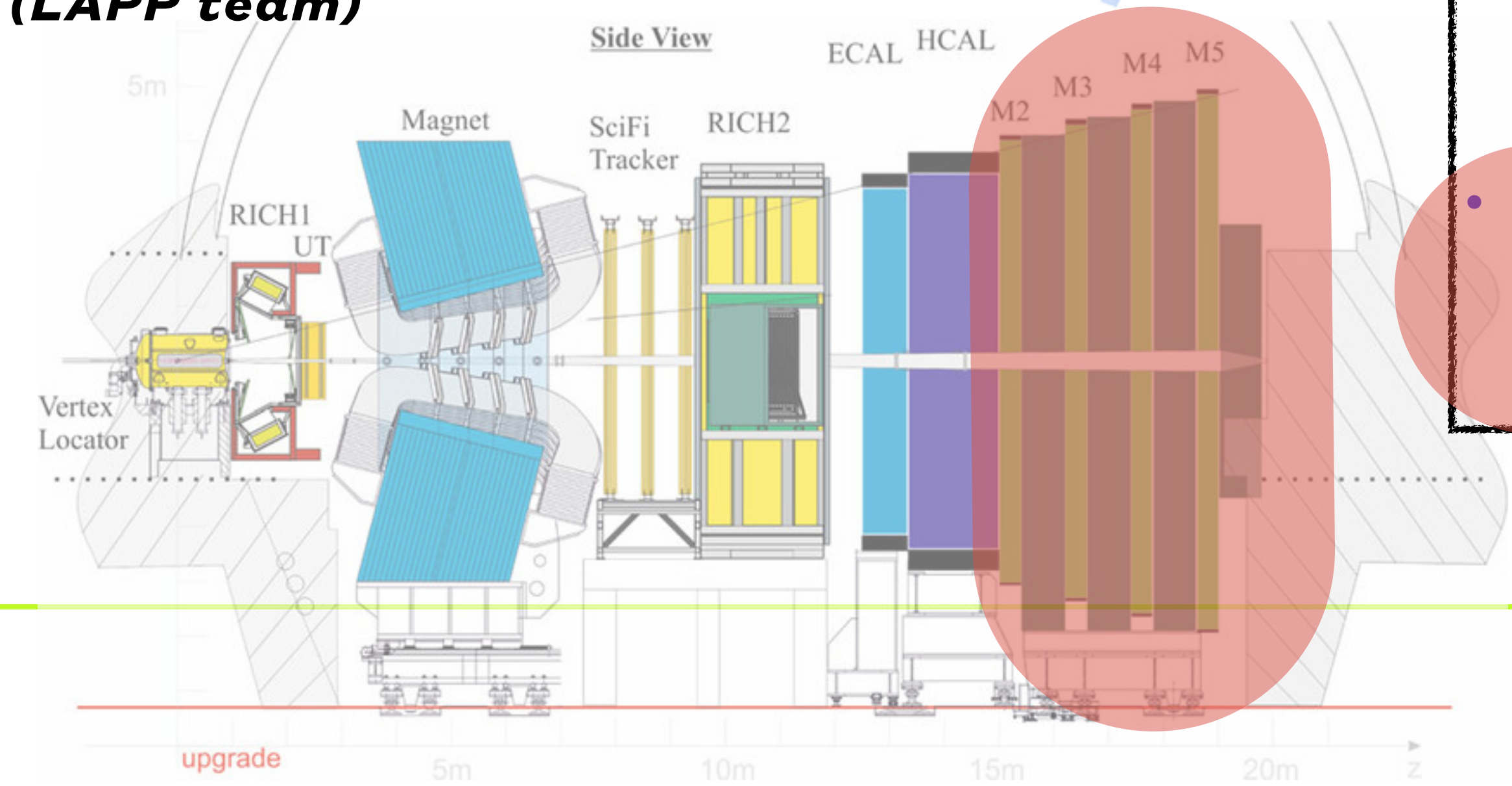
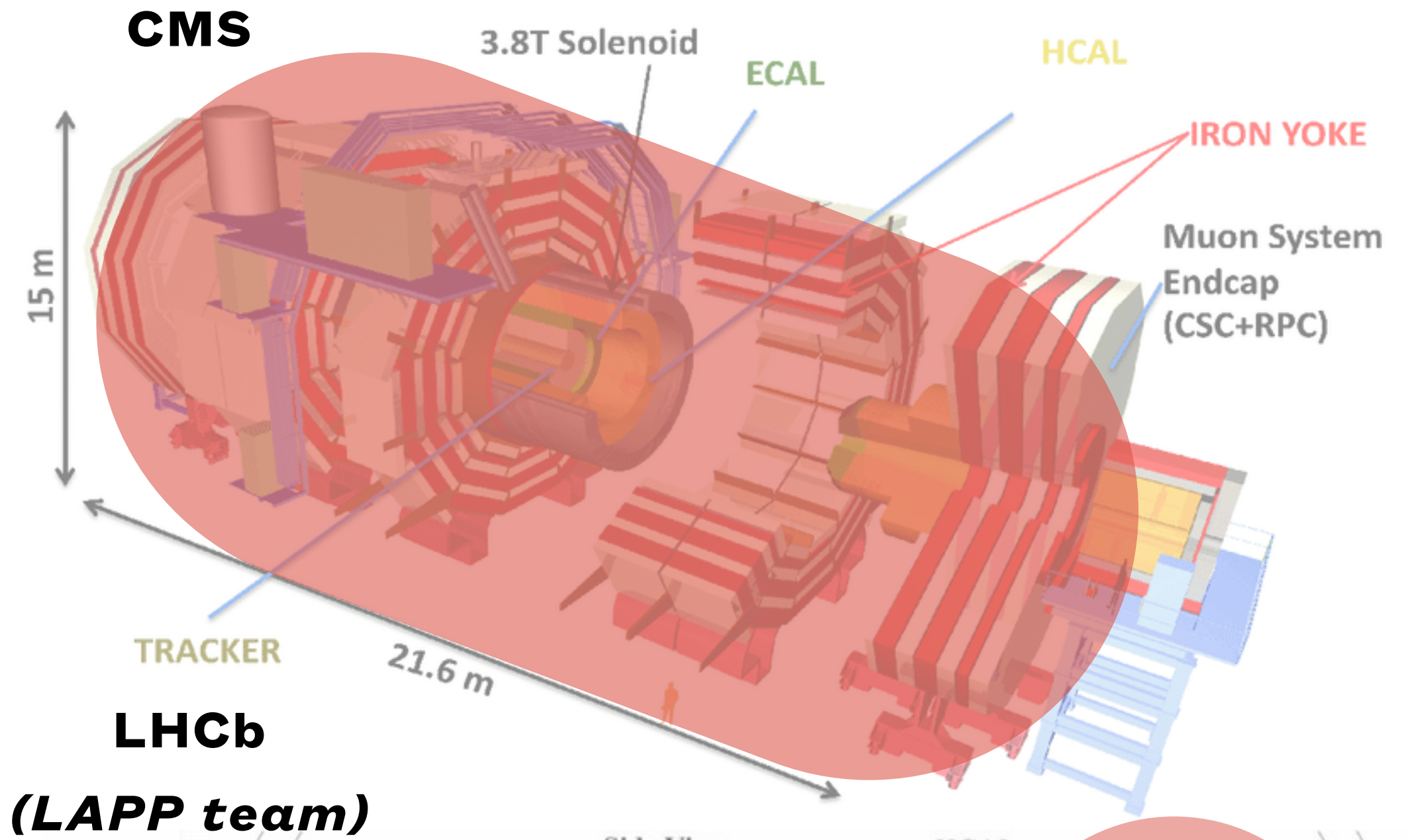
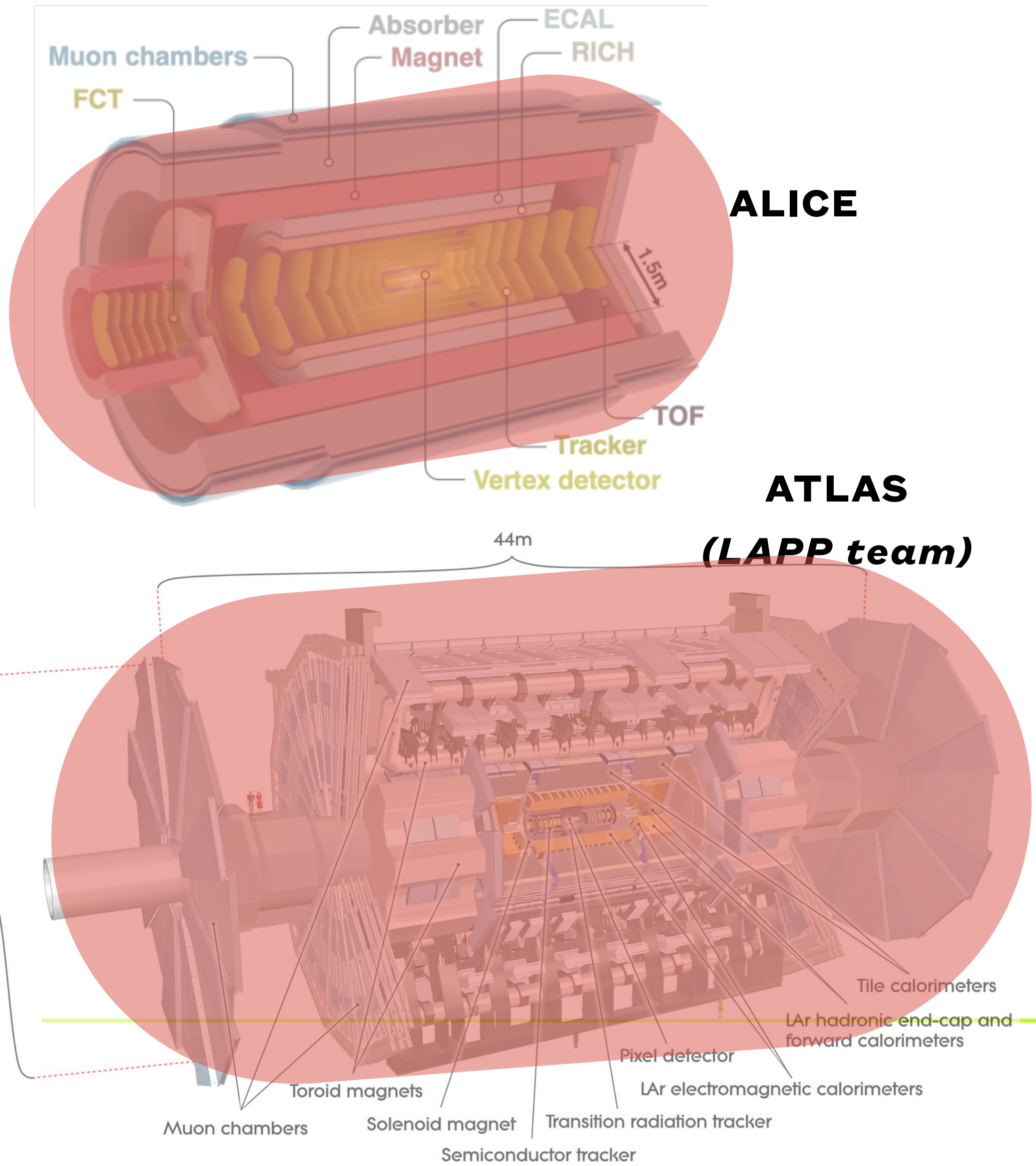
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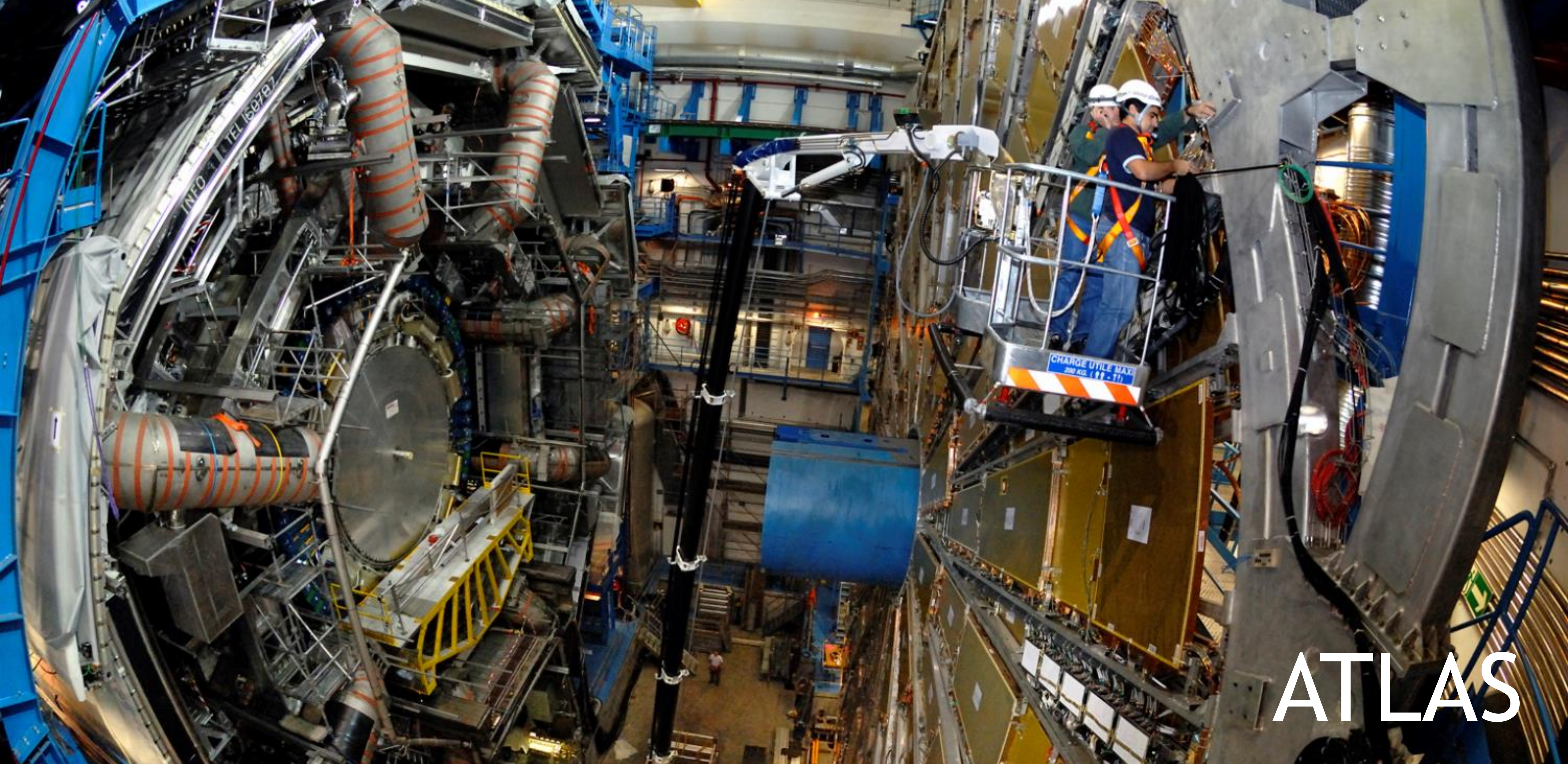


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LHC detectors



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Trackers

- **3 main technologies**

- **gaseous:** ionization in gas (electron-ion pair). Amplification needed

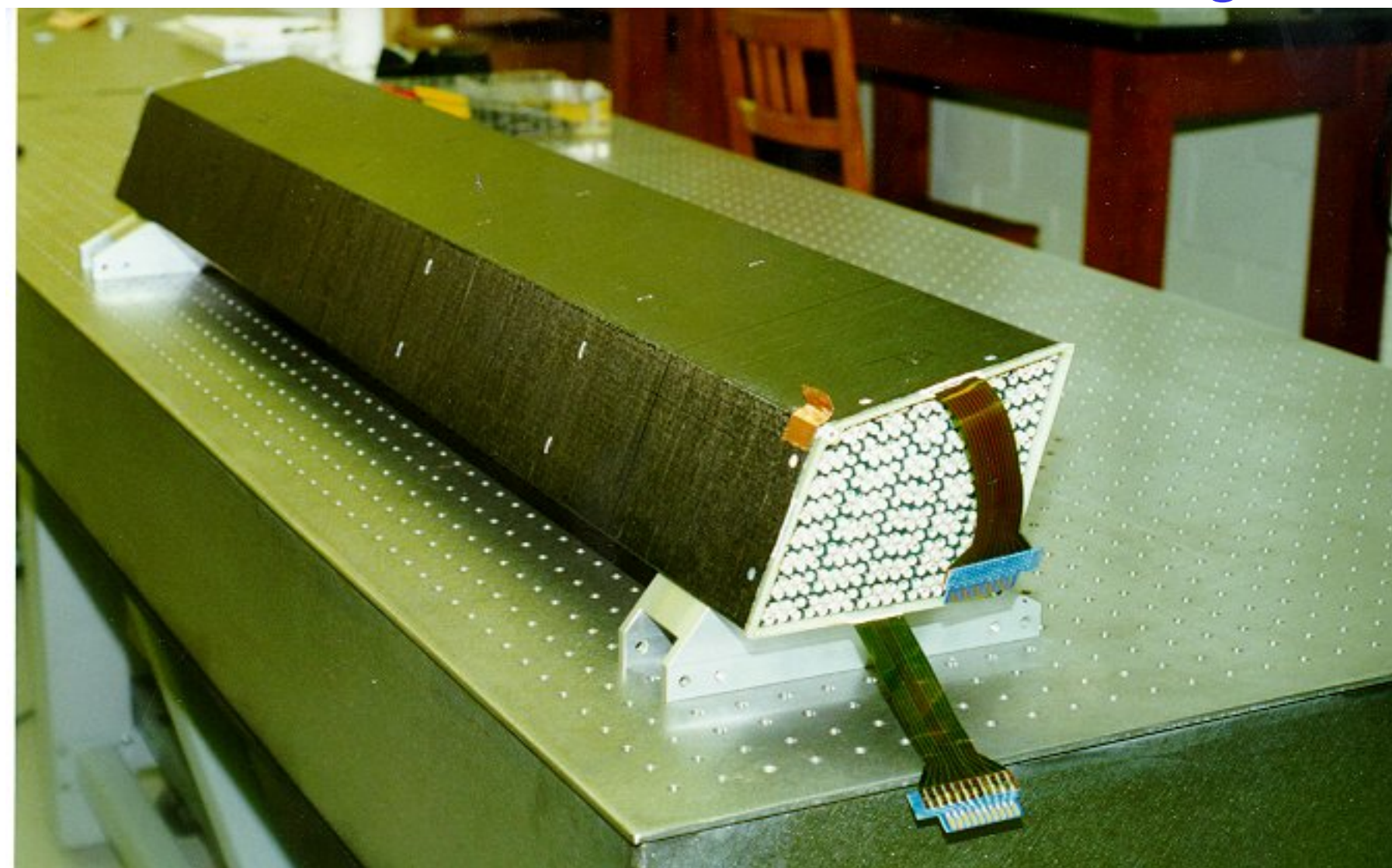
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Transition Radiation Tracker of ATLAS (gas)

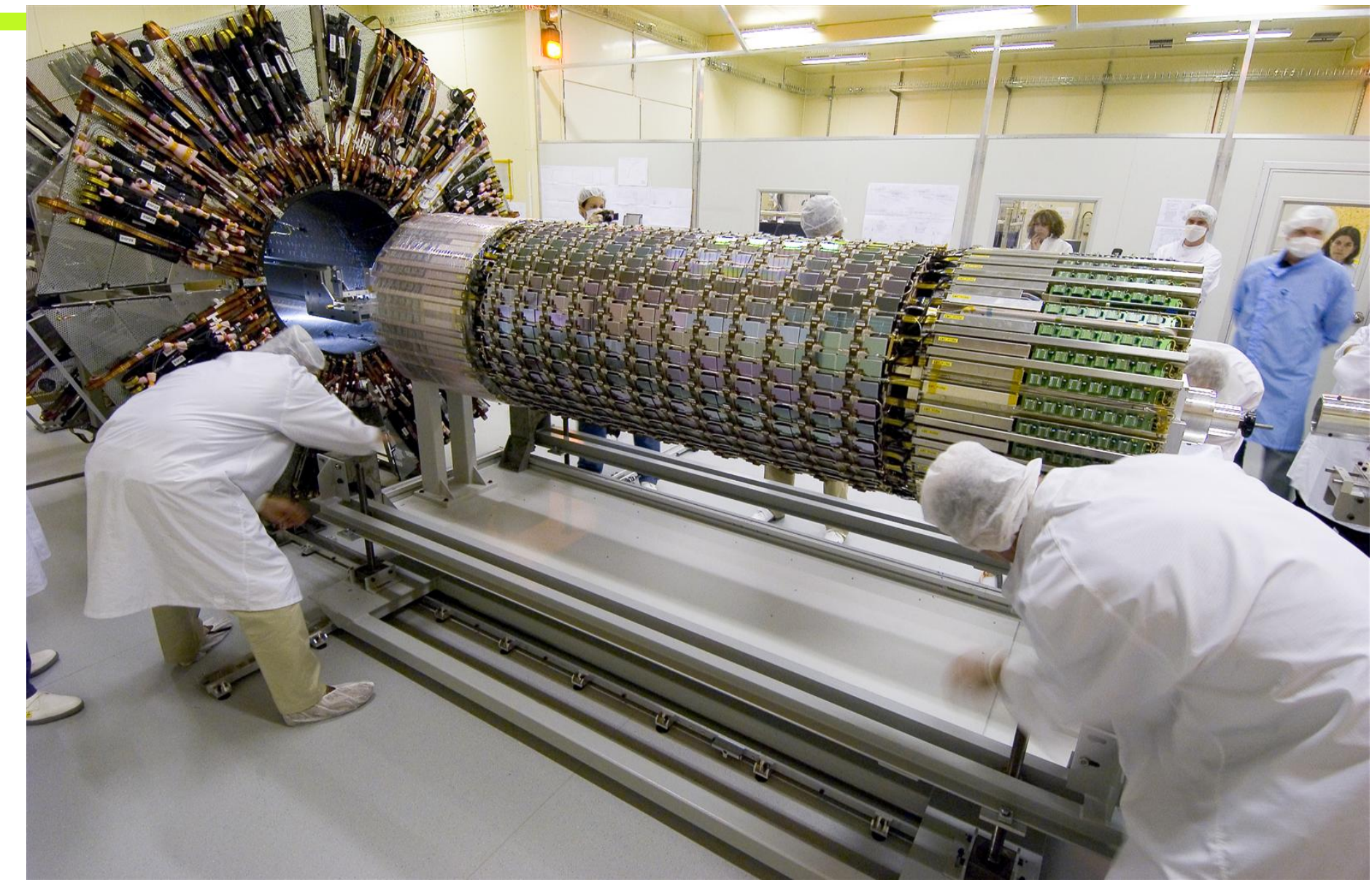
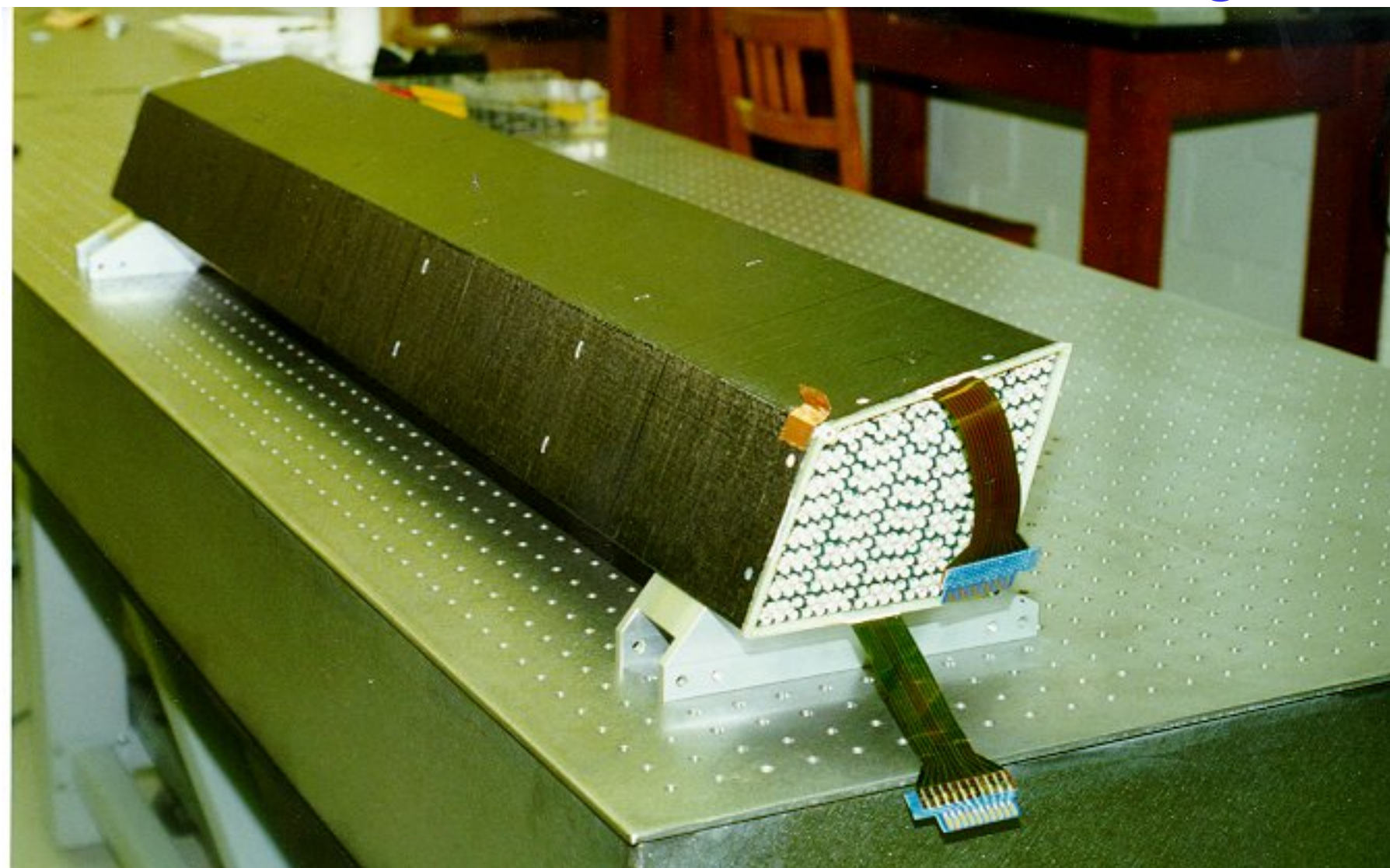


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- **silicon** : ionisation in solid material (electron-hole pair). No amplification needed

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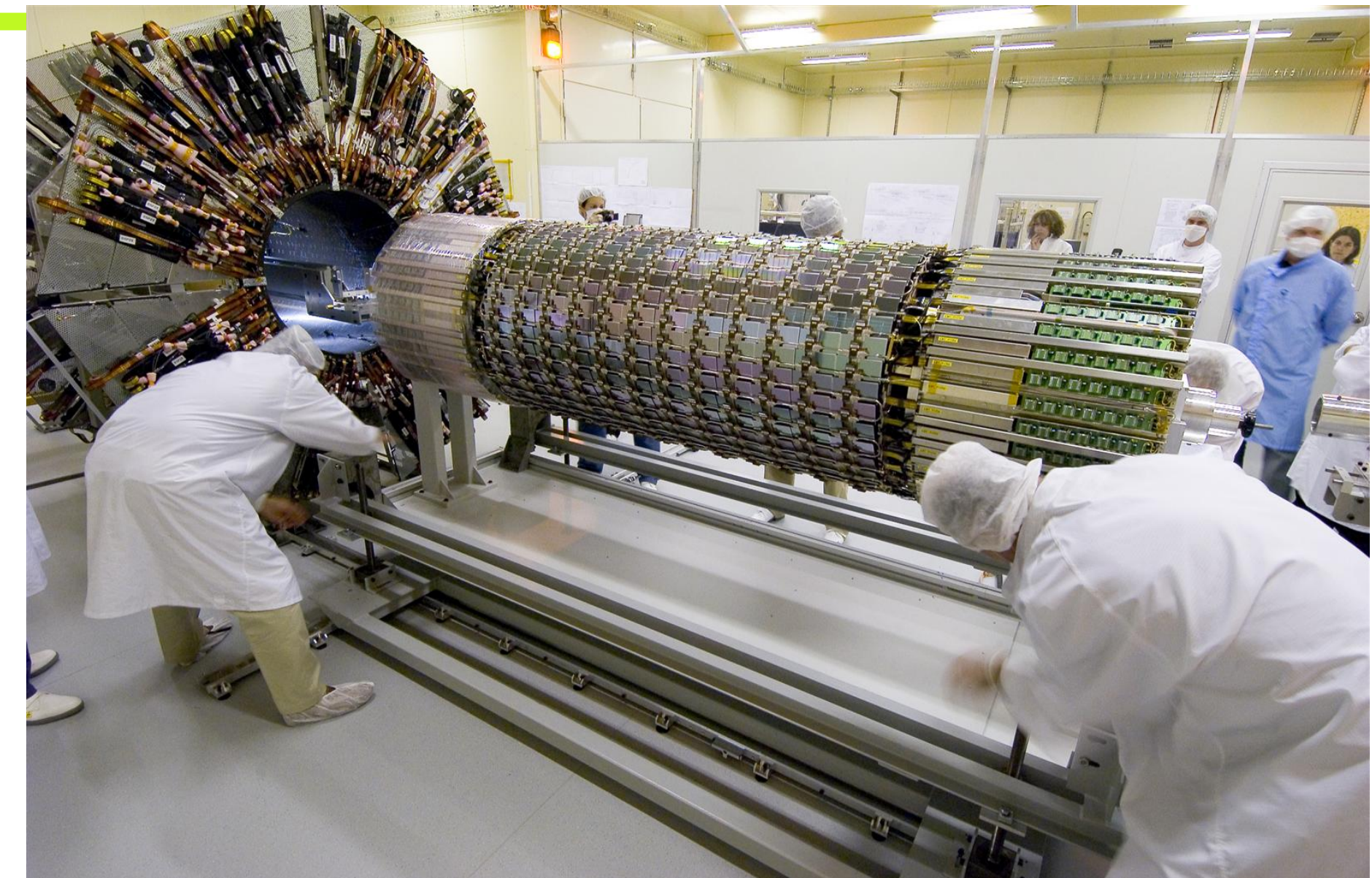
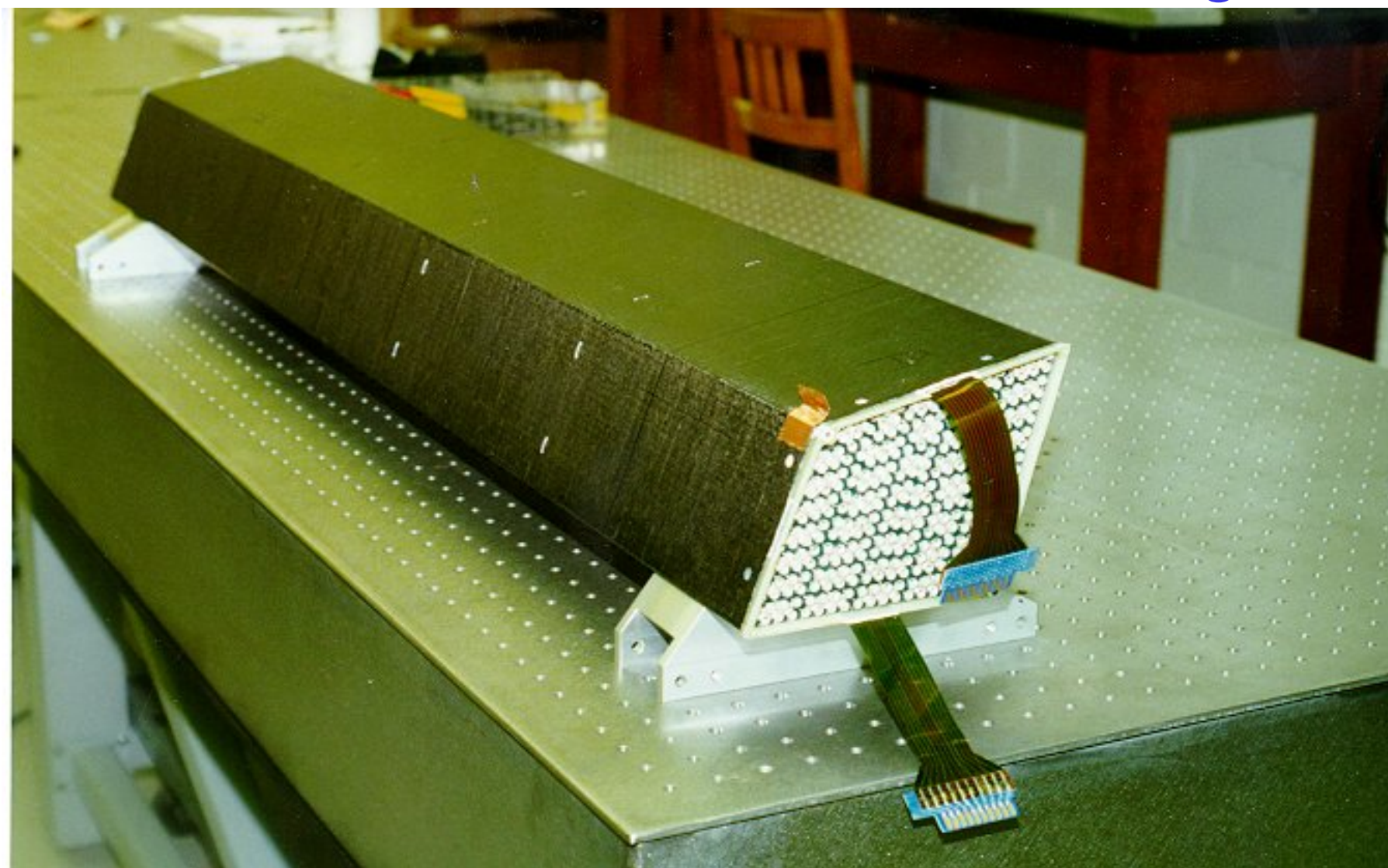
Semiconductor Tracker of ATLAS (silicon)

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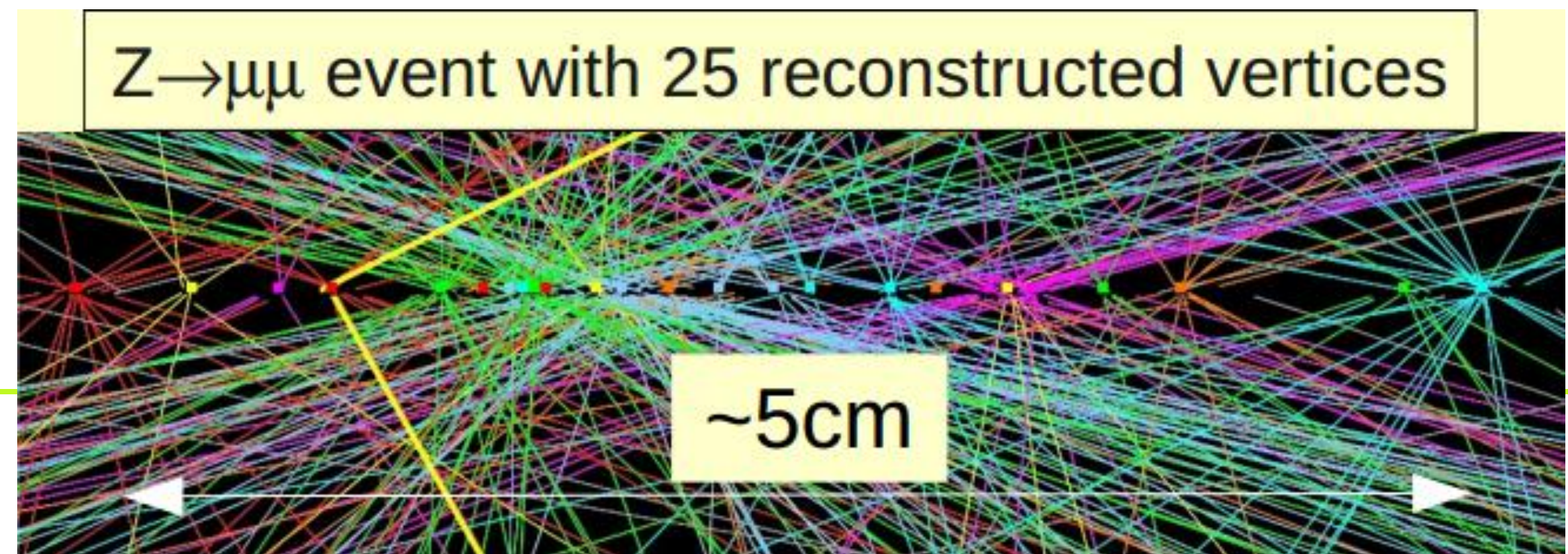
- **gaseous**: ionization in gas (electron-ion pair). Amplification needed
 - **silicon**: ionisation in solid material (electron-hole pair). No amplification needed
 - **scintillating fibers**: light detected with photodetectors
- Need very low density to avoid shower development
 - Measurement of particle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

Transition Radiation Tracker of ATLAS (gas)



Semiconductor Tracker of ATLAS (silicon)

Decay vertices



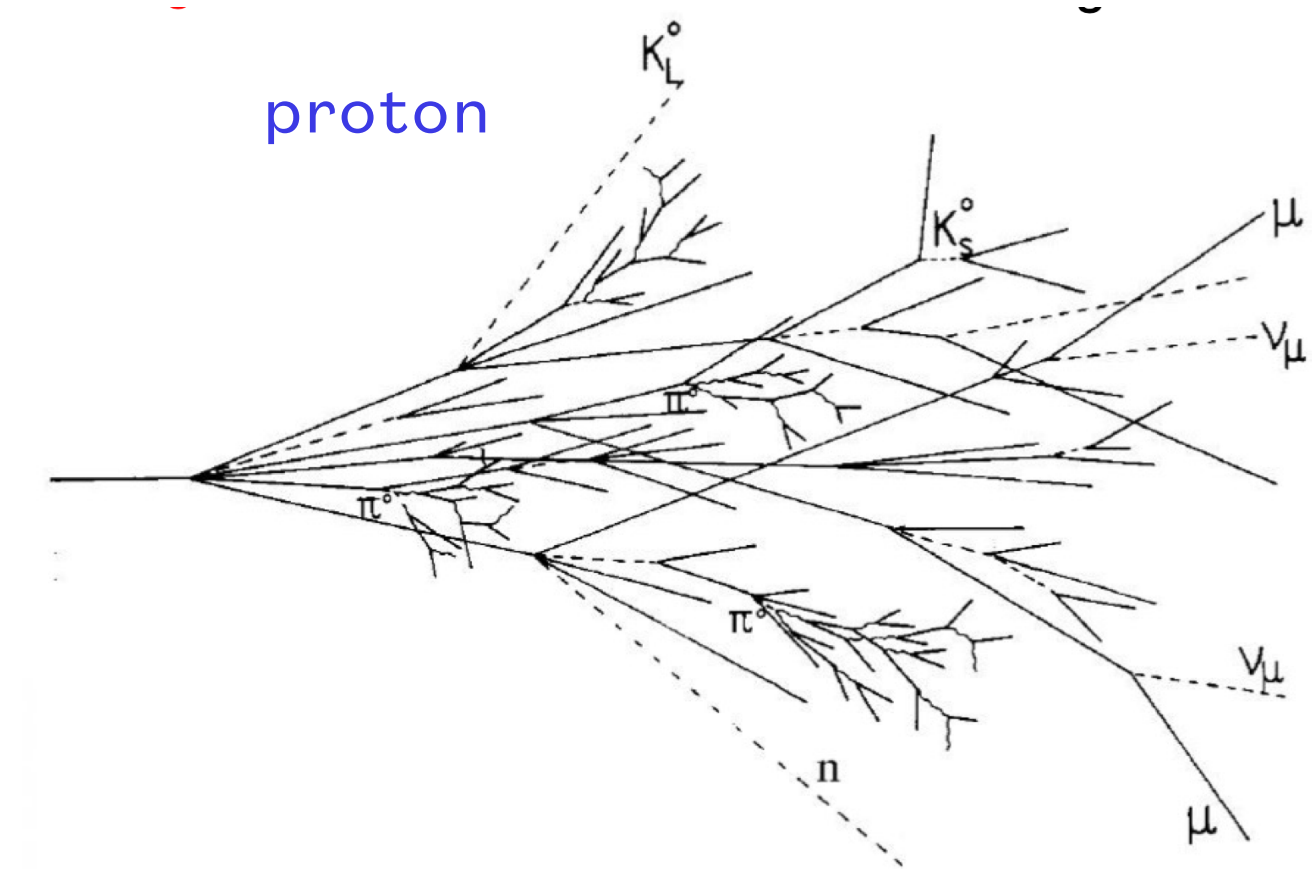
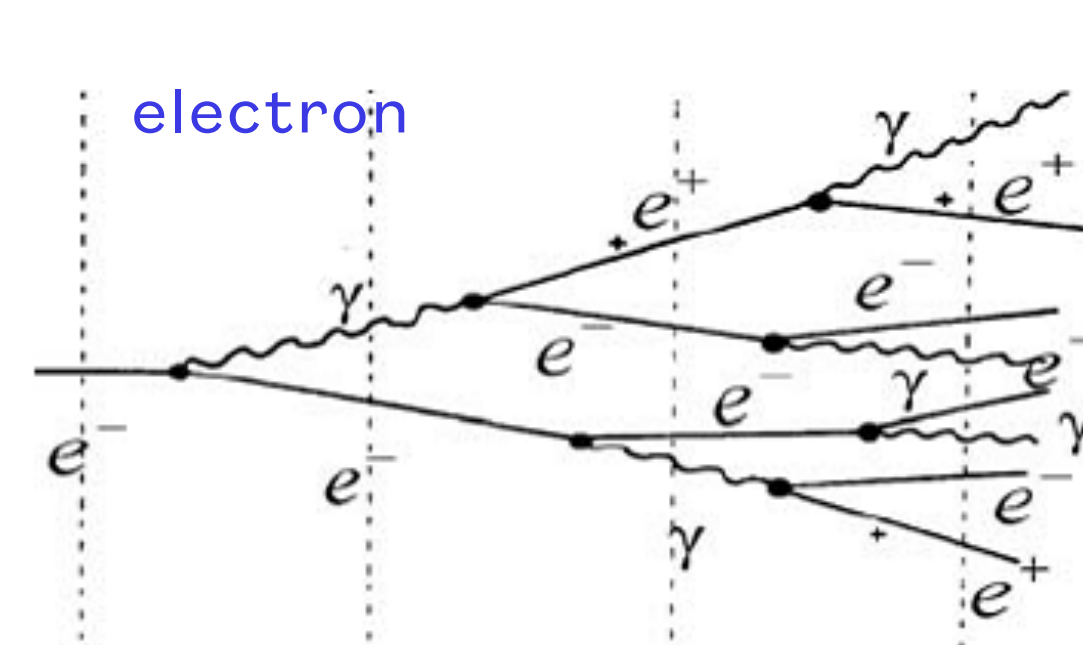
Calorimeters

- Electromagnetic or hadronic -> denser material to develop completely

-

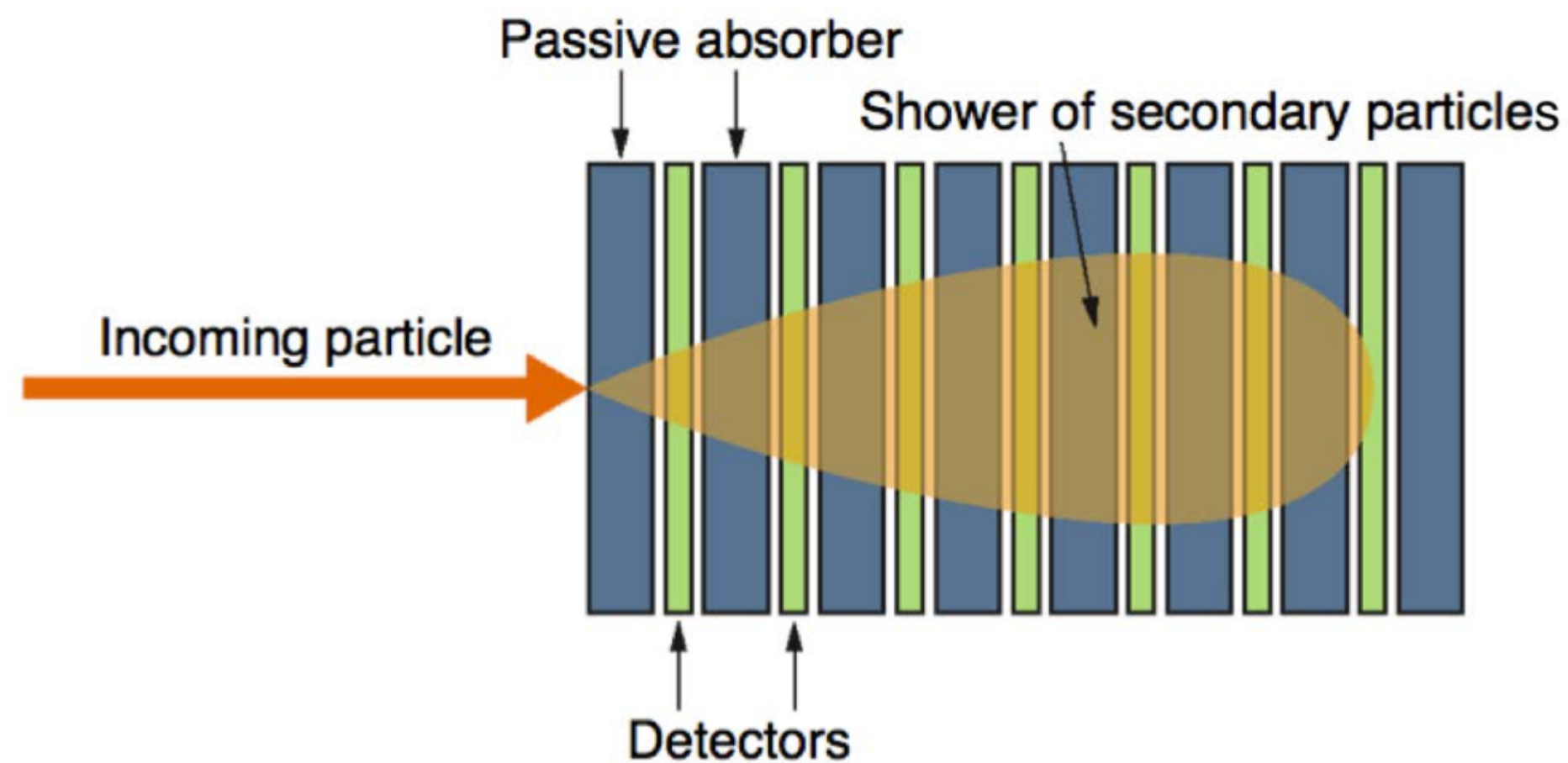
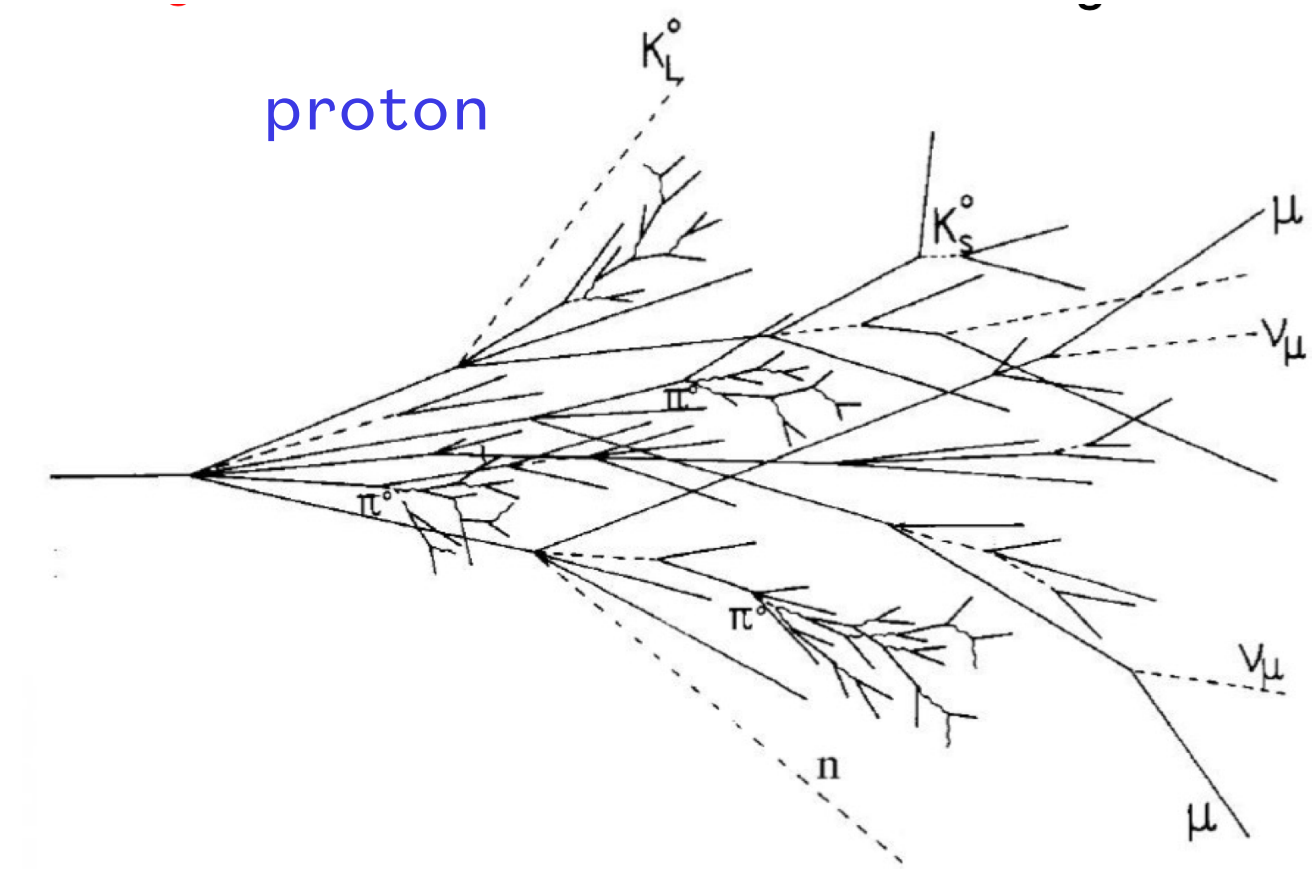
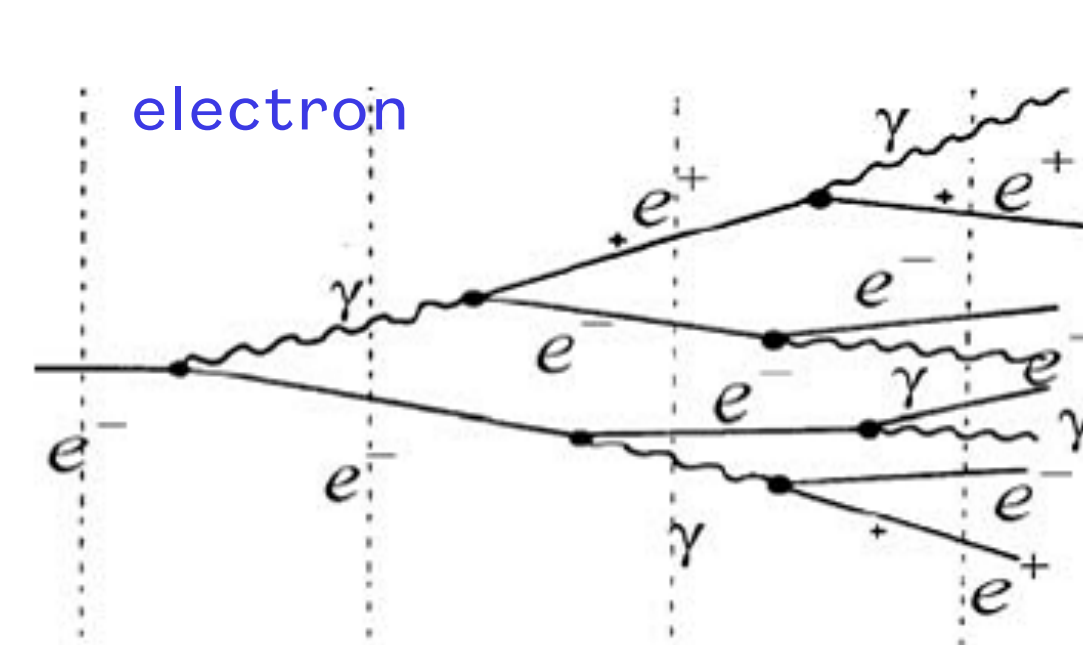
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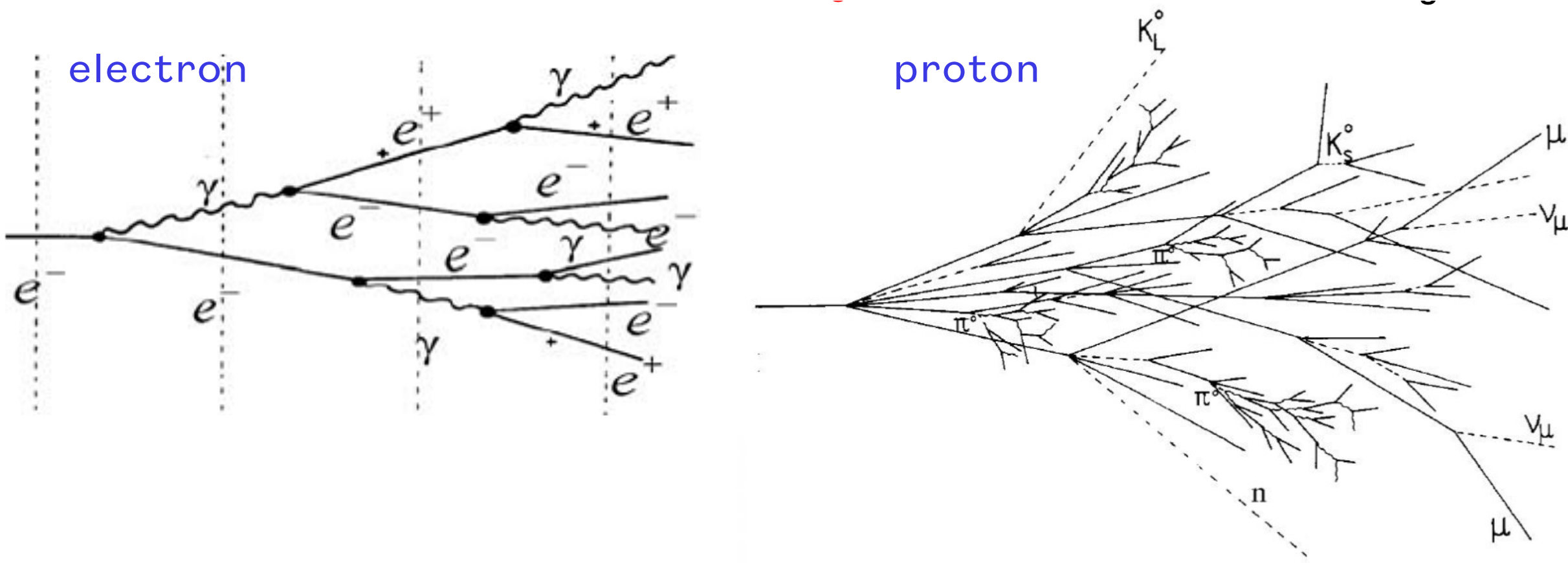
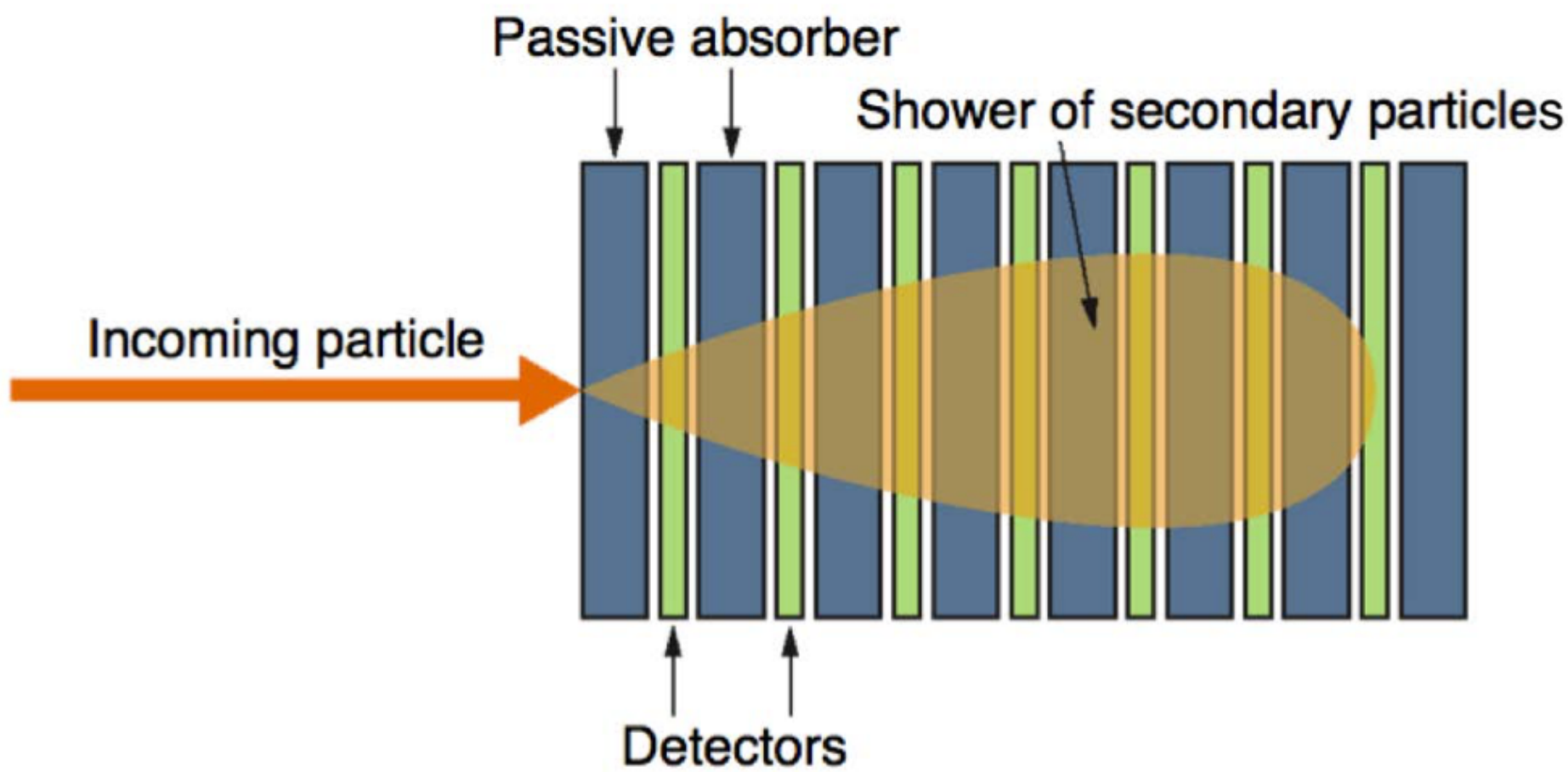
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- Shower is either contained **entirely** or **sampled** (dense material followed by active material)
- Shape of shower helps to identify the particle
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Calorimeters

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- Shower is either contained **entirely** or **sampled** (dense material followed by active material)
- Shape of shower helps to identify the particule
- Shower development scales with radiation length (distance in which energy of particle reduced by $1/e \approx 63.2\%$, 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 : $X_0 \approx \frac{(716 \text{ g cm}^{-2}) A}{Z(Z+1) \ln (287\sqrt{Z})}$

Calorimeters : energy resolution

- Intrinsic resolution $\sim 1/\sqrt{E}$
- Electronic noise : $1/E$
- Non-uniformities : constant term -> dominant at high energy

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

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Homogeneous calorimeters:

Experiment	Material	Energy resolution (E in GeV)
NA48	Liquid Kr	$4.8\%/\sqrt{E} \oplus 0.22\%$
BELLE	CsI(Tl)	$0.8\%/\sqrt{E} \oplus 1.3\%$
CMS	PbWO ₄	$2.7\%/\sqrt{E} \oplus 0.55\%^*$

[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	$15\%/\sqrt{E}$
SLD	liquid Ar	2.75	Pb	2.0	$8\%/\sqrt{E}$
DELPHI	Ar + 20% CH ₄	8	Pb	3.2	$16\%/\sqrt{E}$
ALEPH	Si	0.2	W	7.0	$25\%/\sqrt{E}$
ATLAS	liquid Ar		Pb		$10\%/\sqrt{E} \oplus 0.7\%^*$
LHCb	Scintillator		Fe		$10\%/\sqrt{E} \oplus 1.5\%^*$

* Design values

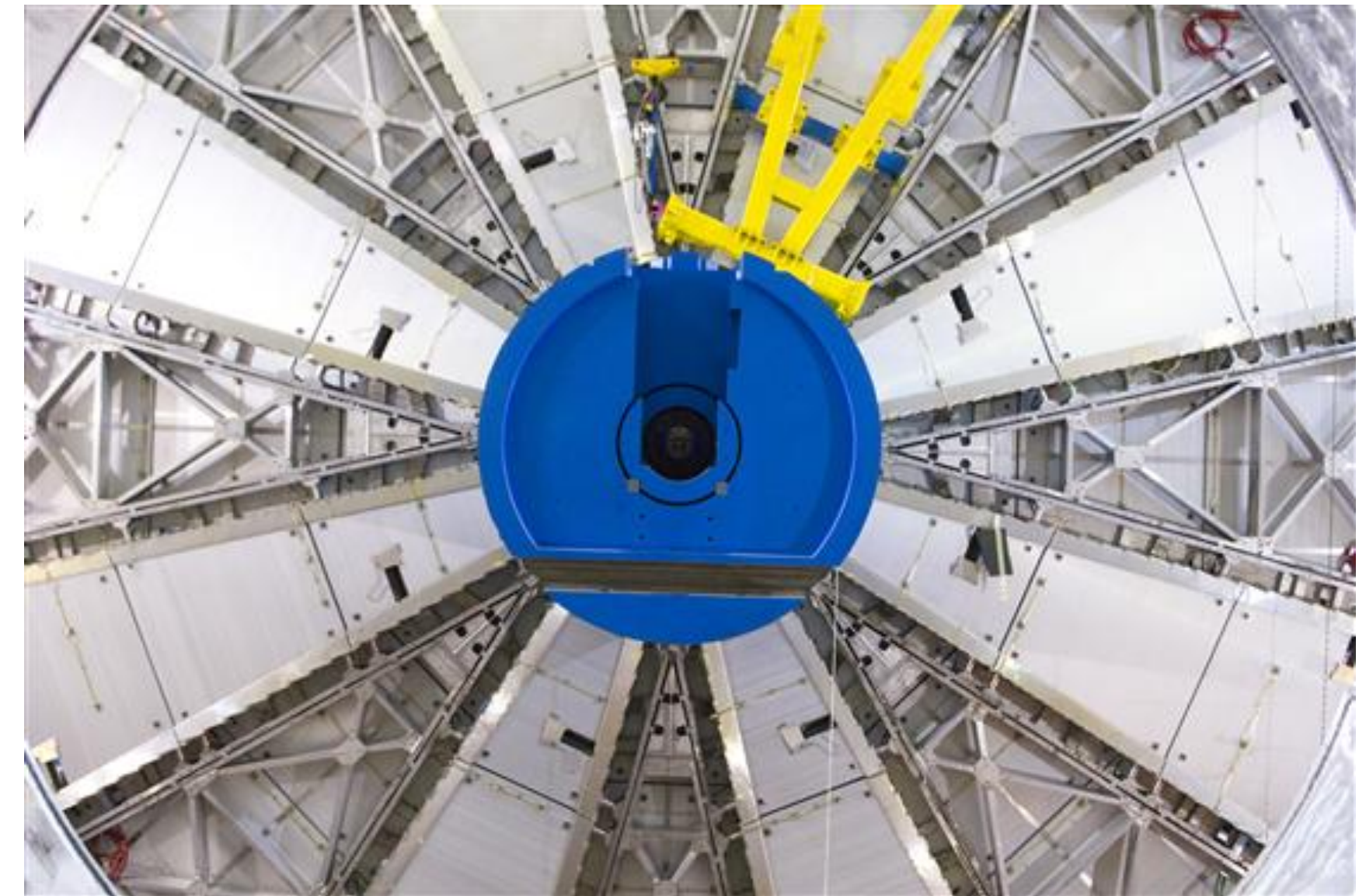
Muon spectrometers

- Identify and measures momentum of muons
- Thousands of chambers, big magnetic field to curve high-energy muons, biggest sub-detector
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 - **Drift Tubes** (0.1 mm precision but slow),

Monitored Drift Tubes



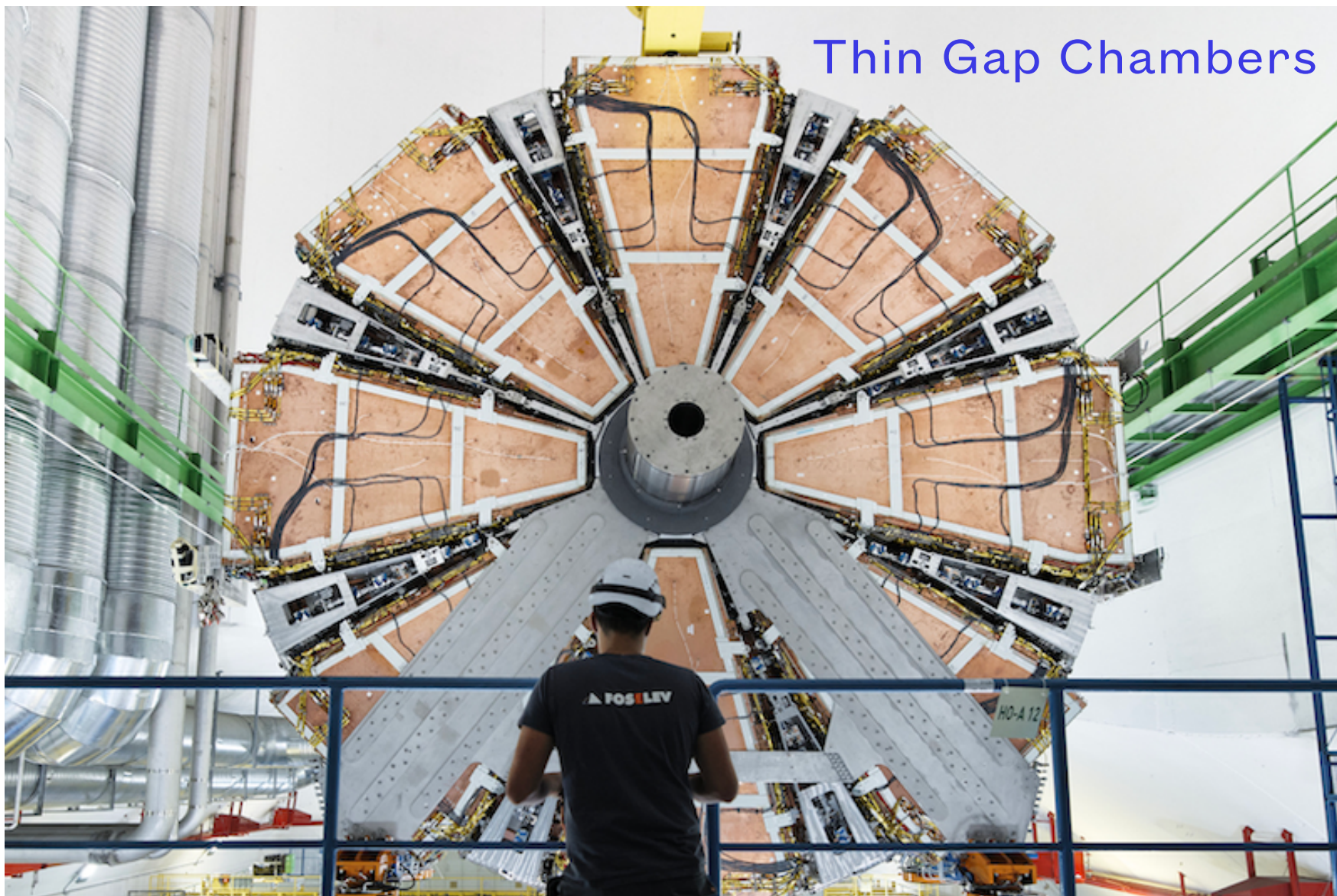
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Monitored Drift Tubes



Thin Gap Chambers



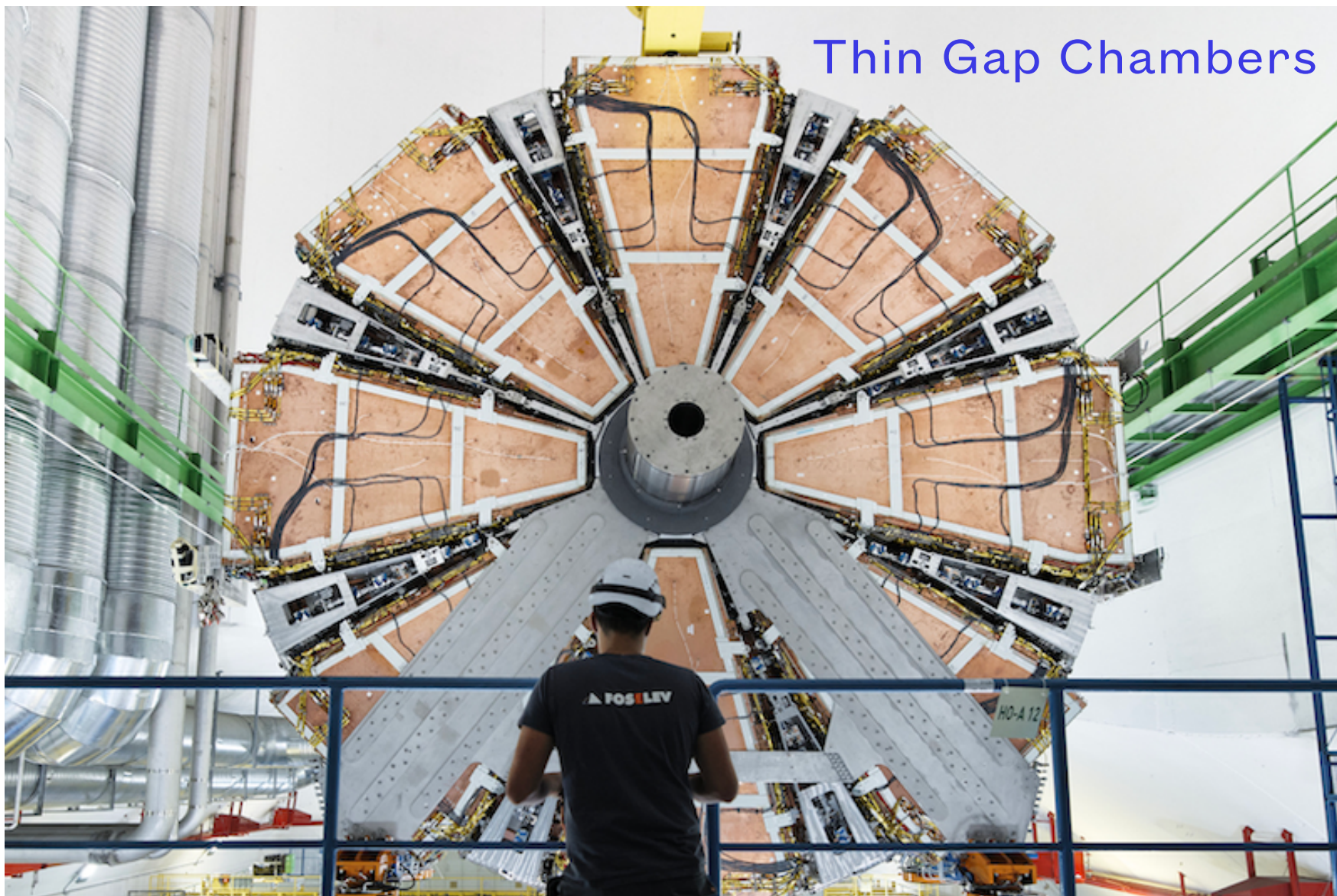
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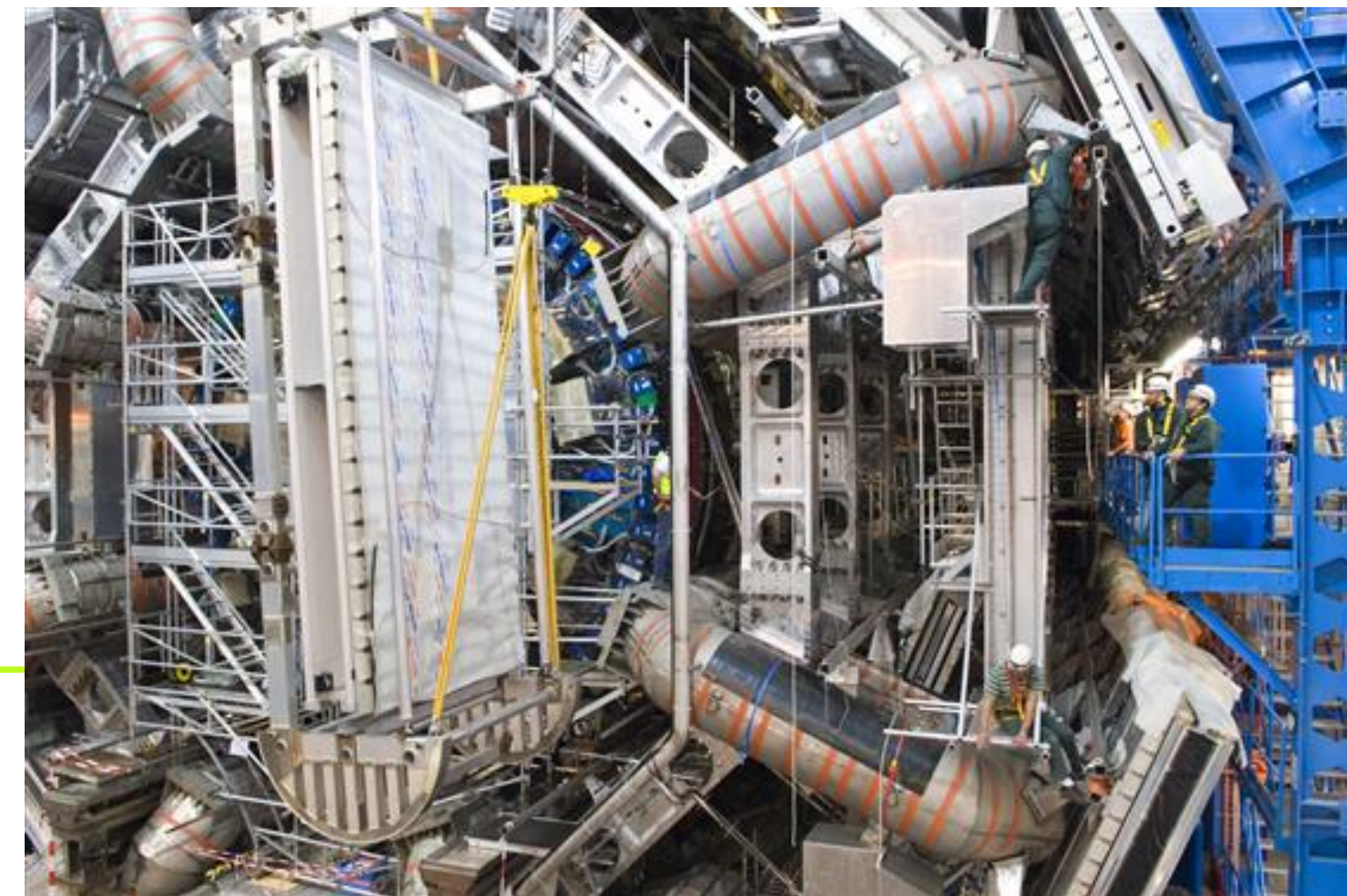
Monitored Drift Tubes



Thin Gap Chambers



Resistive Plate Chambers



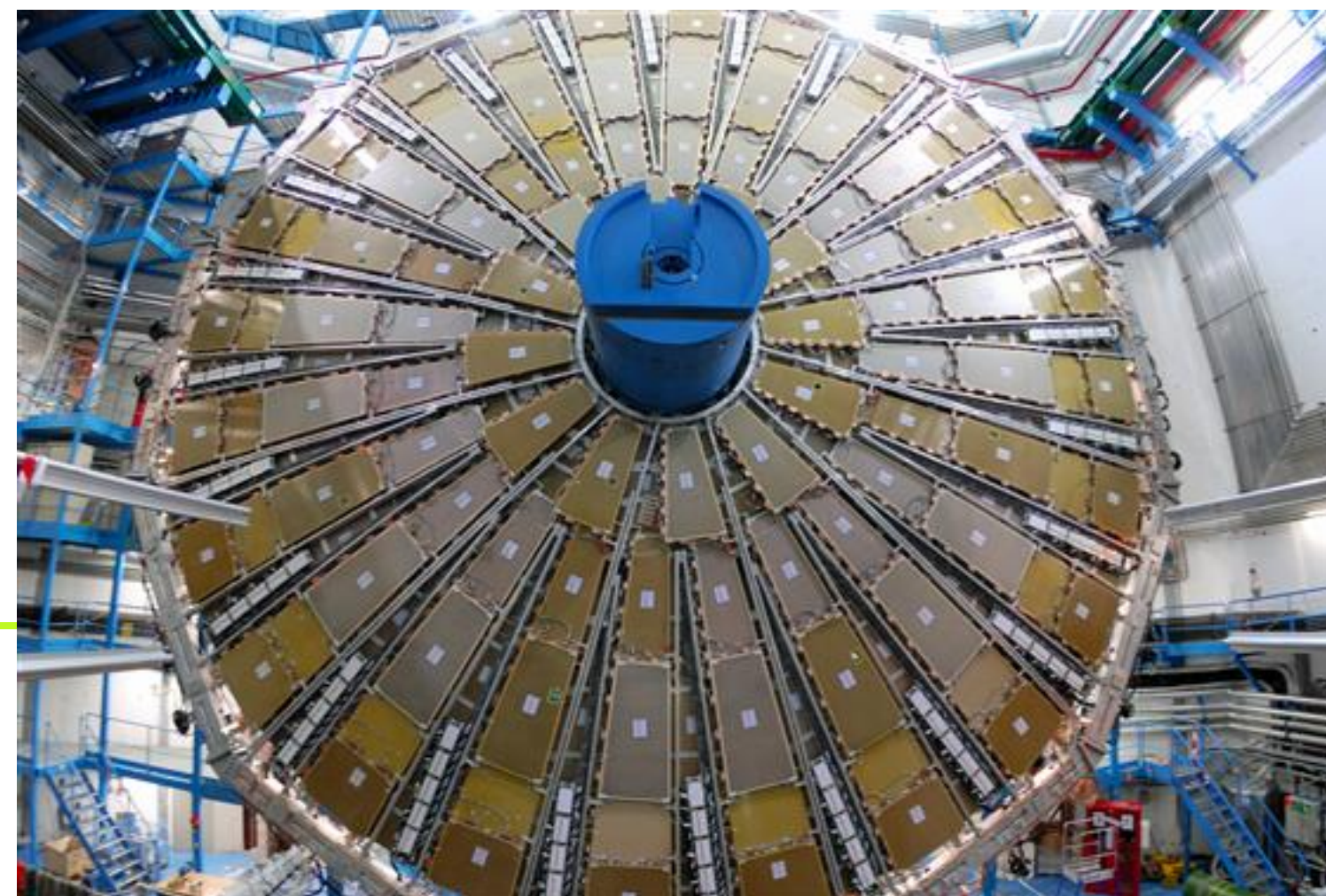
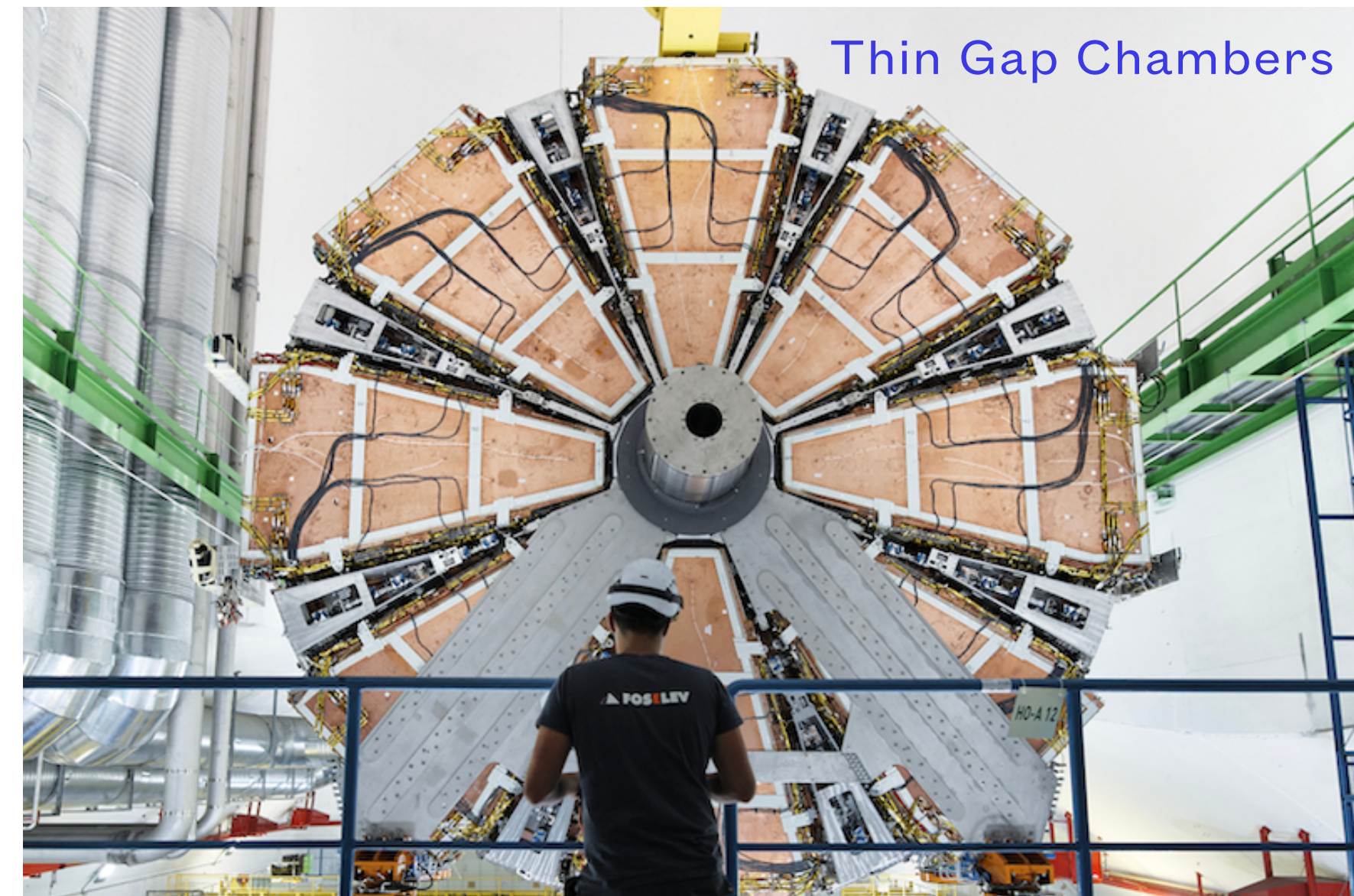
Muon spectrometers

- Identify and measures momentum of muons
- Thousands of chambers, big magnetic field to curve high-energy muons, biggest sub-detector
- Main technology : gas ionization detectors
 - **Drift Tubes** (0.1 mm precision but slow), **Thin-Gap Chambers** (fast signals), **Resistive Plate Chambers** (very fast, timing resolution within 2.5us), **Cathode Strips Chambers** (handle high rates), **Micromegas** (fast, precise, radiation resistant)

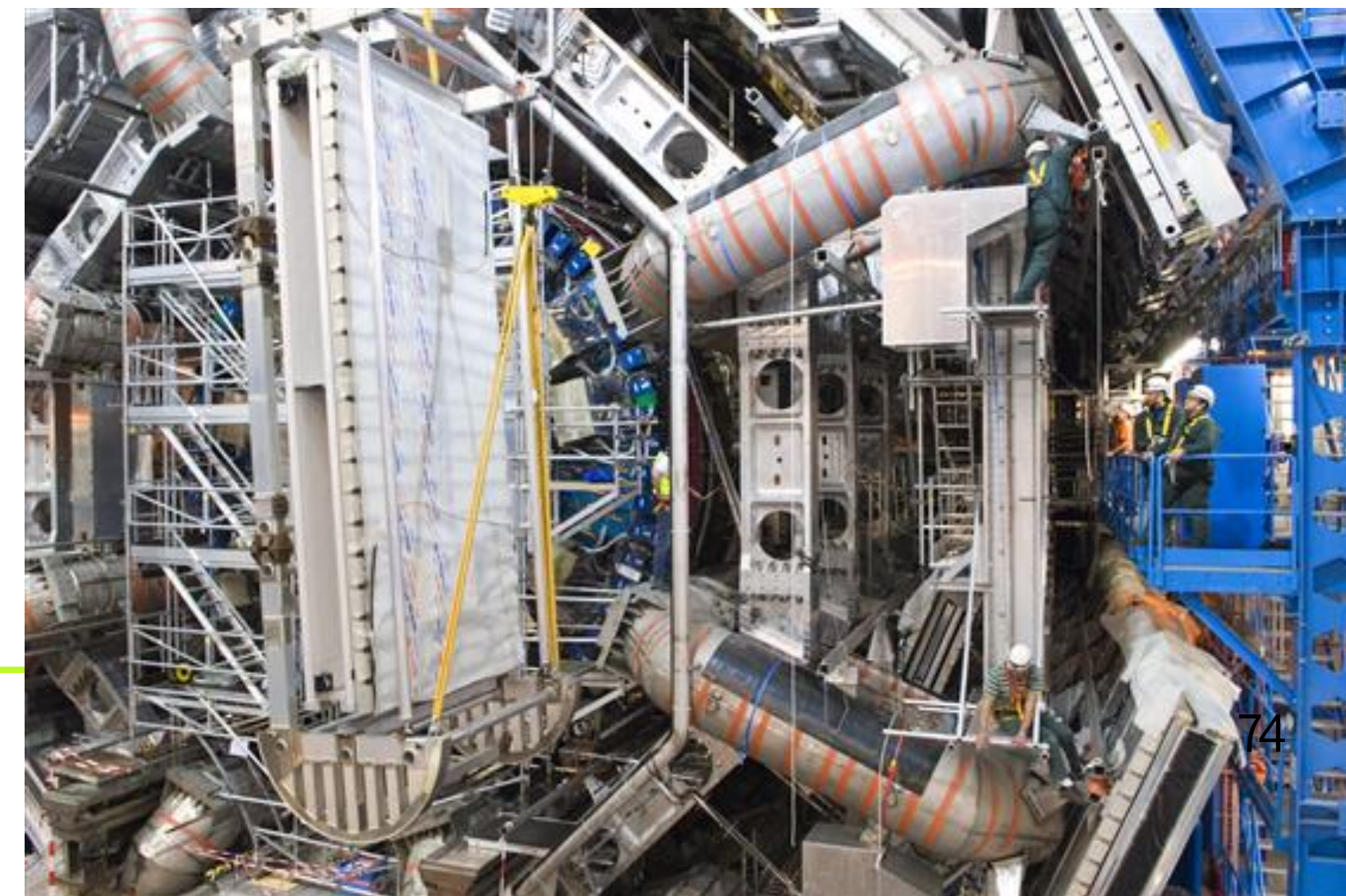
Monitored Drift Tubes



Thin Gap Chambers

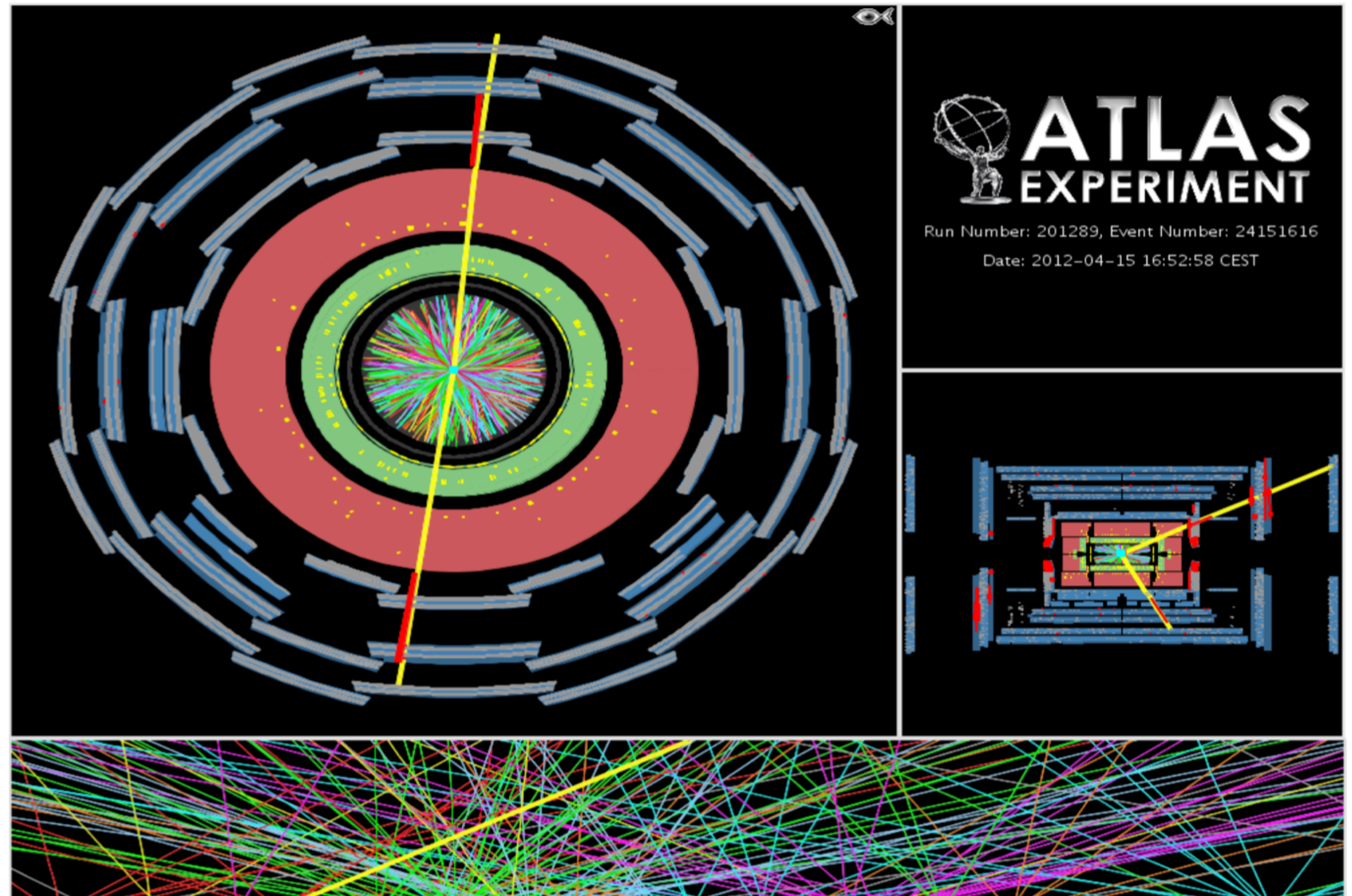


Resistive Plate Chambers

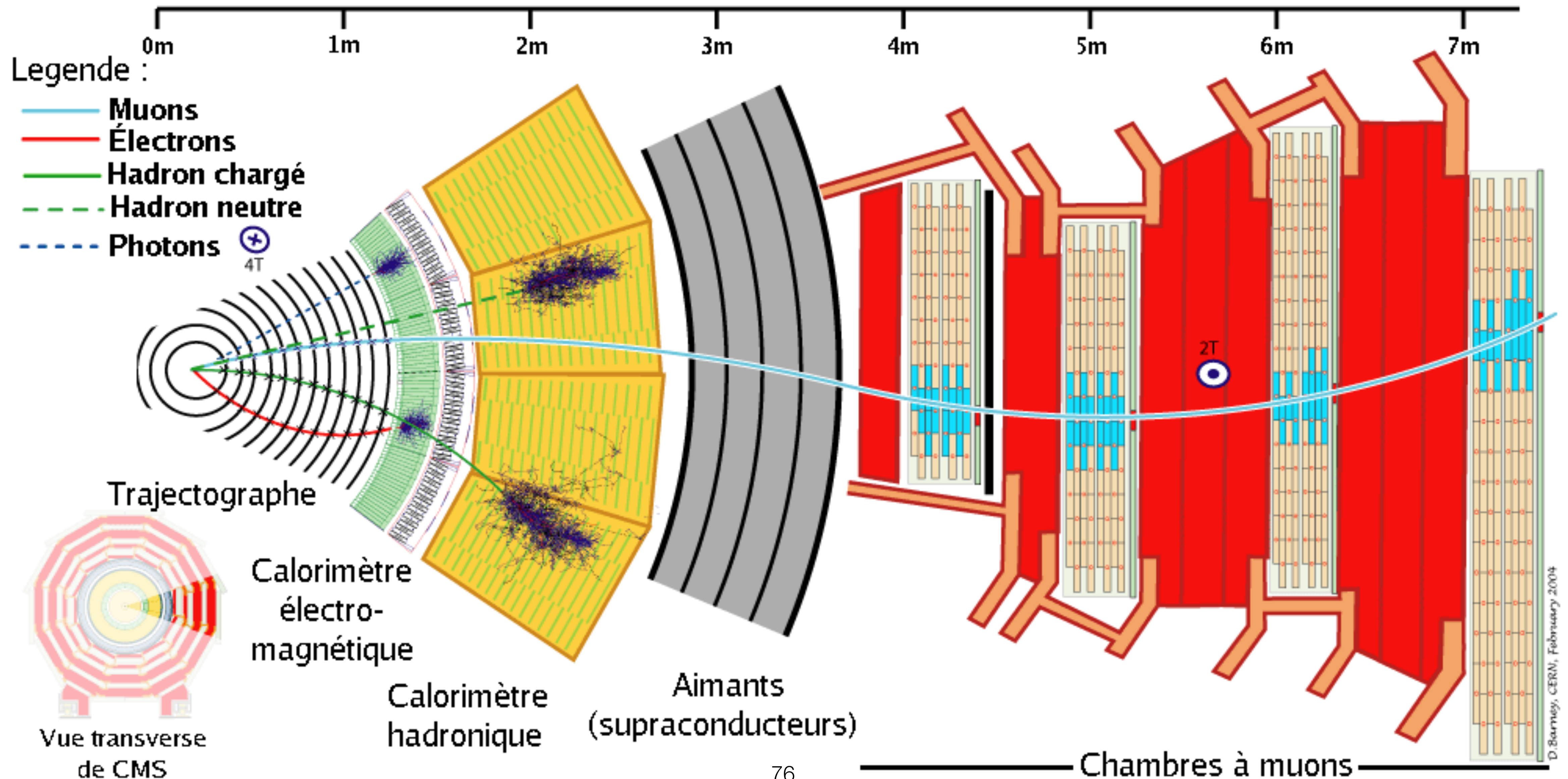


Muons in ATLAS

- Escape calorimeters, track recorded in spectrometer

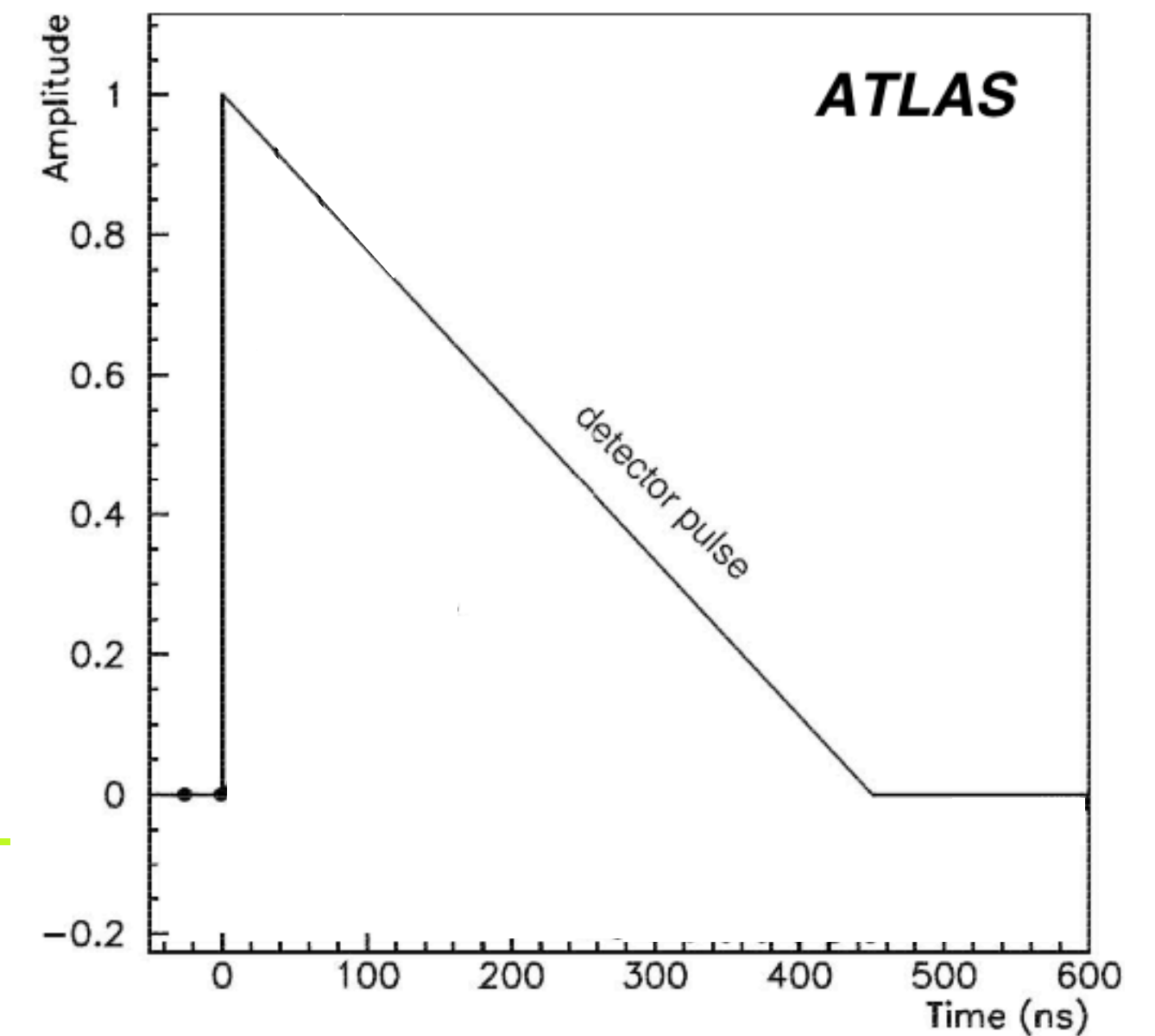
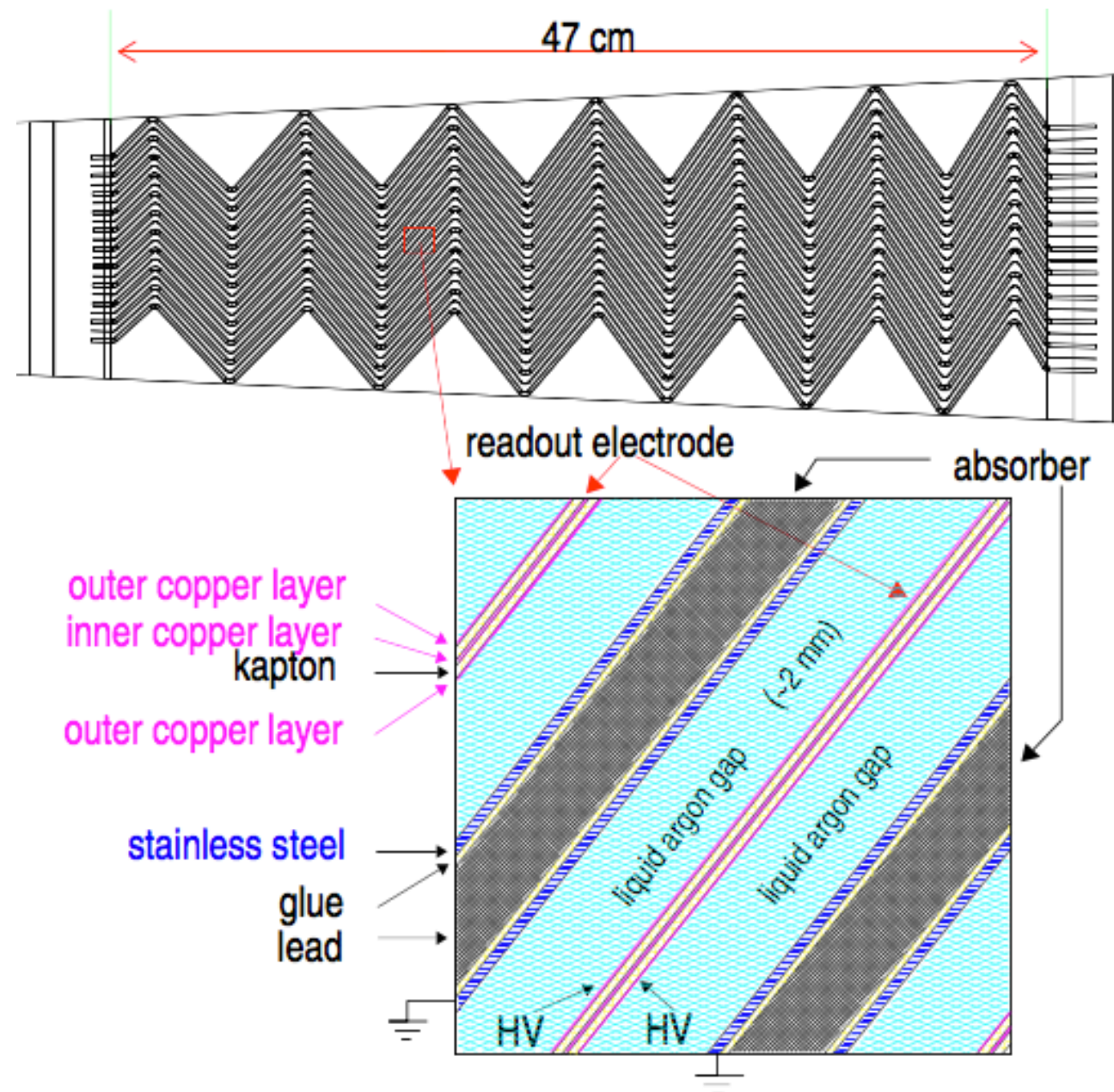


Particule identification



How to read the signal ?

- Example with ATLAS calorimeter :

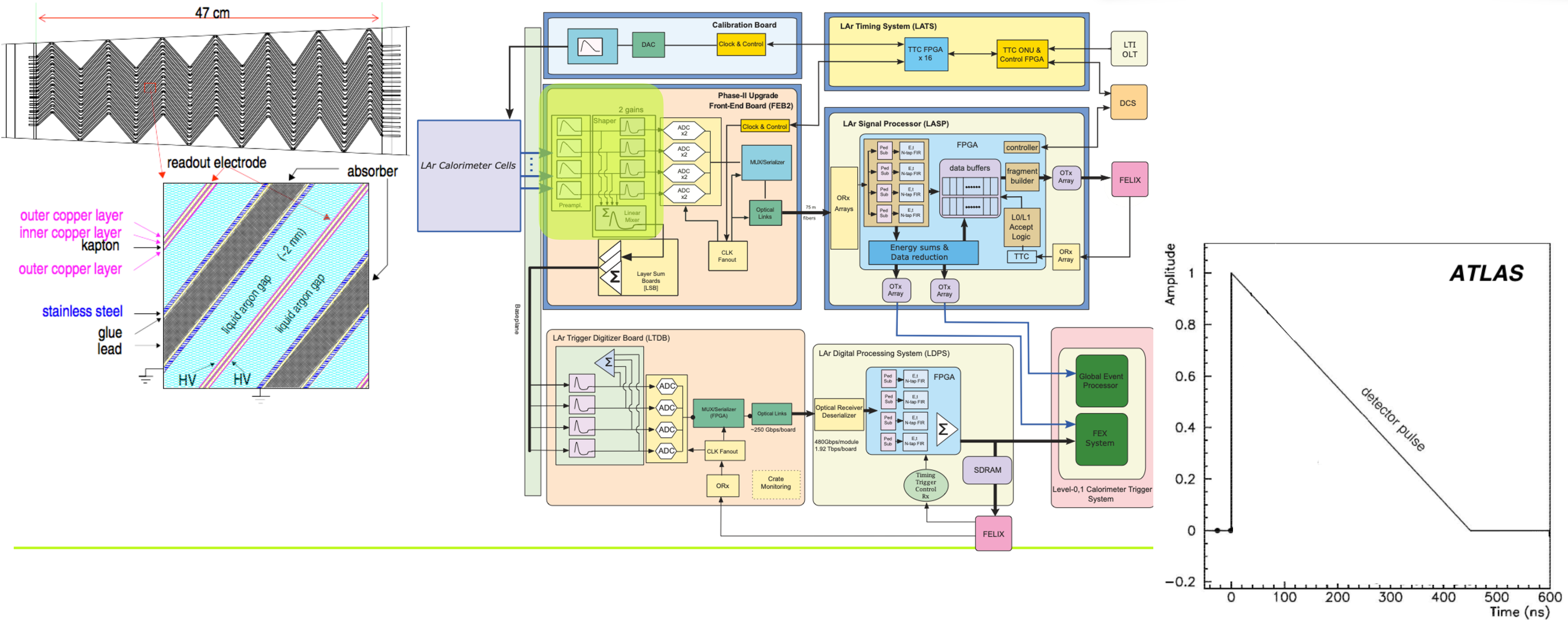


How to read the signal ?

- Example with ATLAS calorimeter :

IN DETECTOR :

- AMPLIFICATION AND SHAPING OF SIGNAL
-
-
-

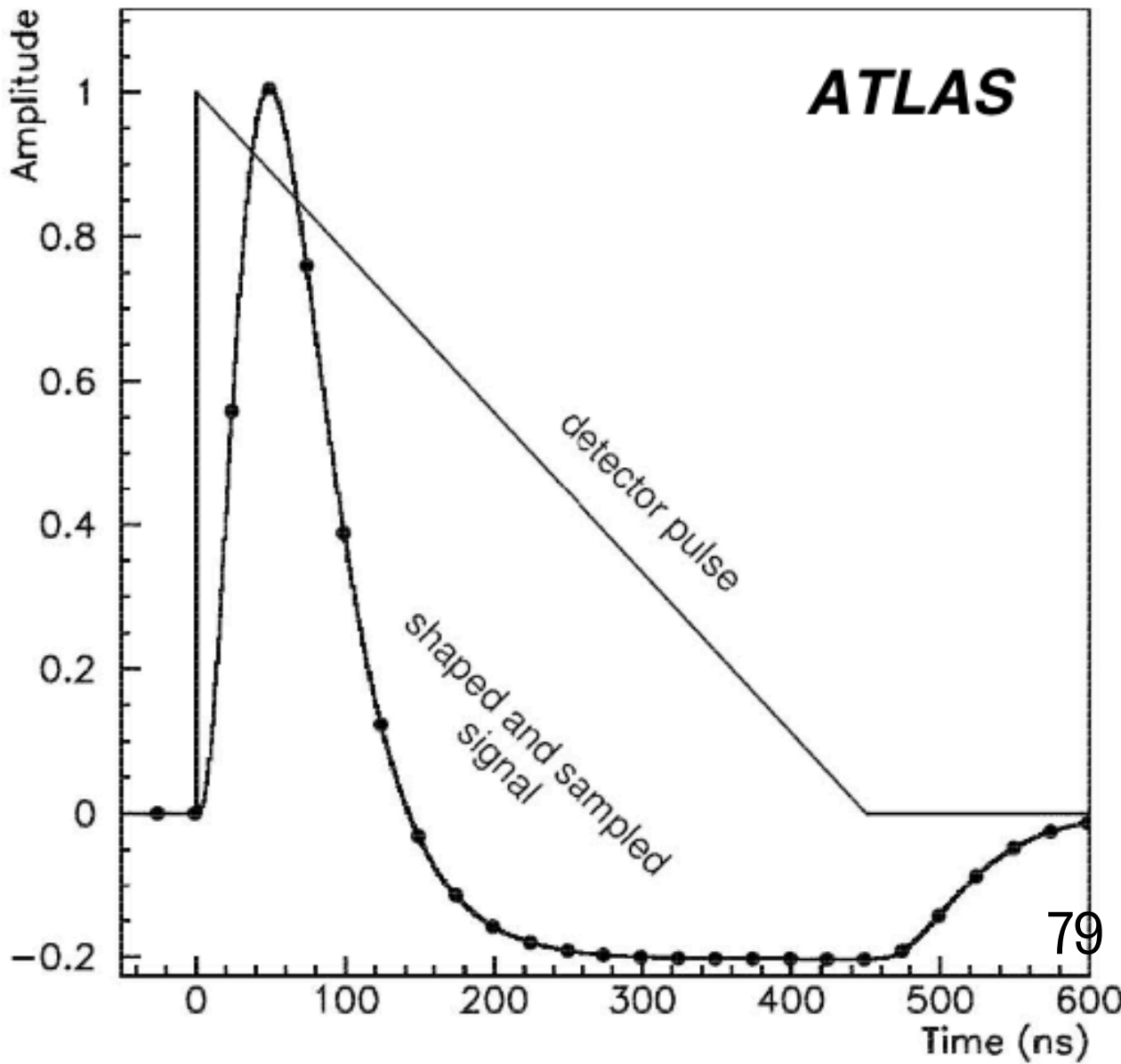
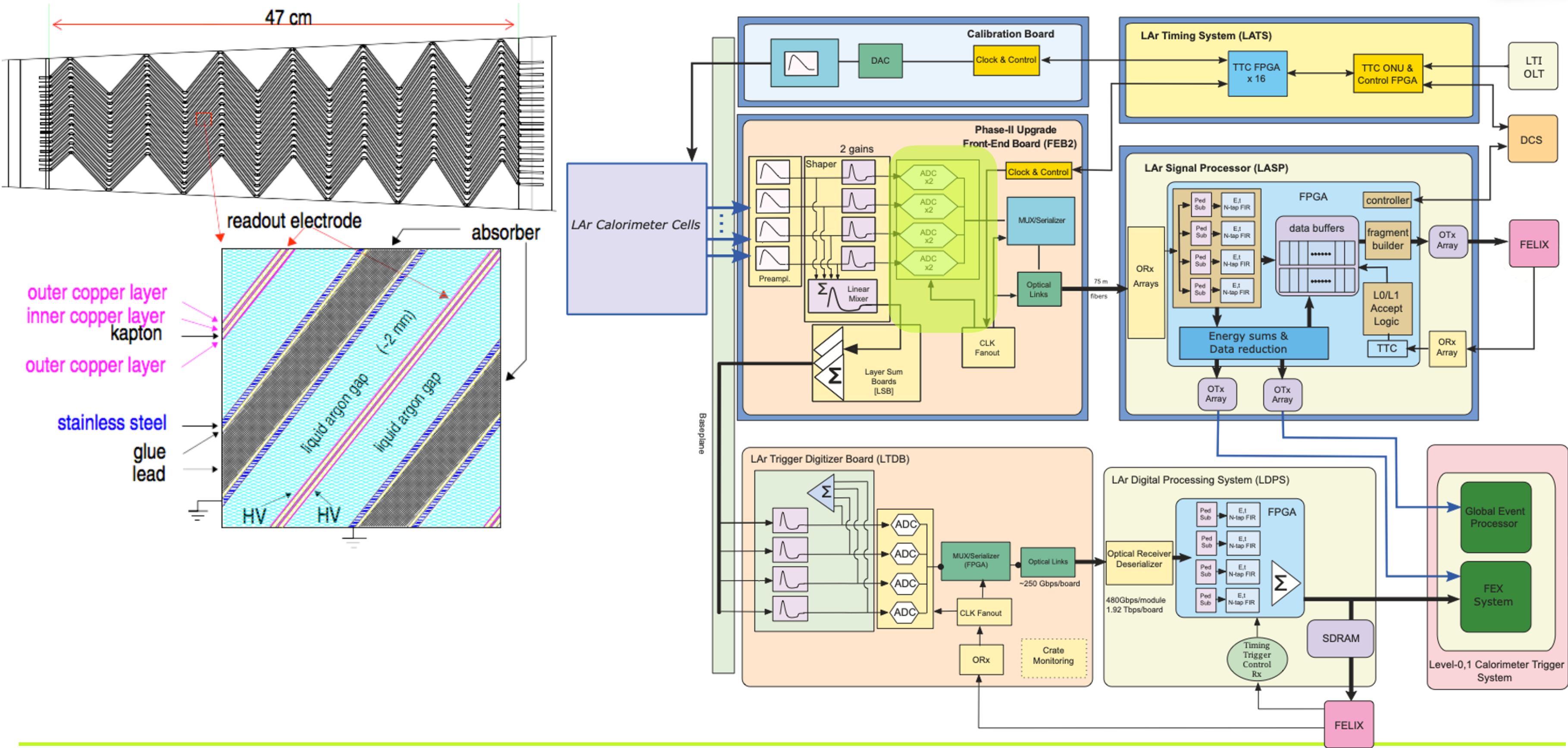


How to read the signal ?

- Example with ATLAS calorimeter :

IN DETECTOR :

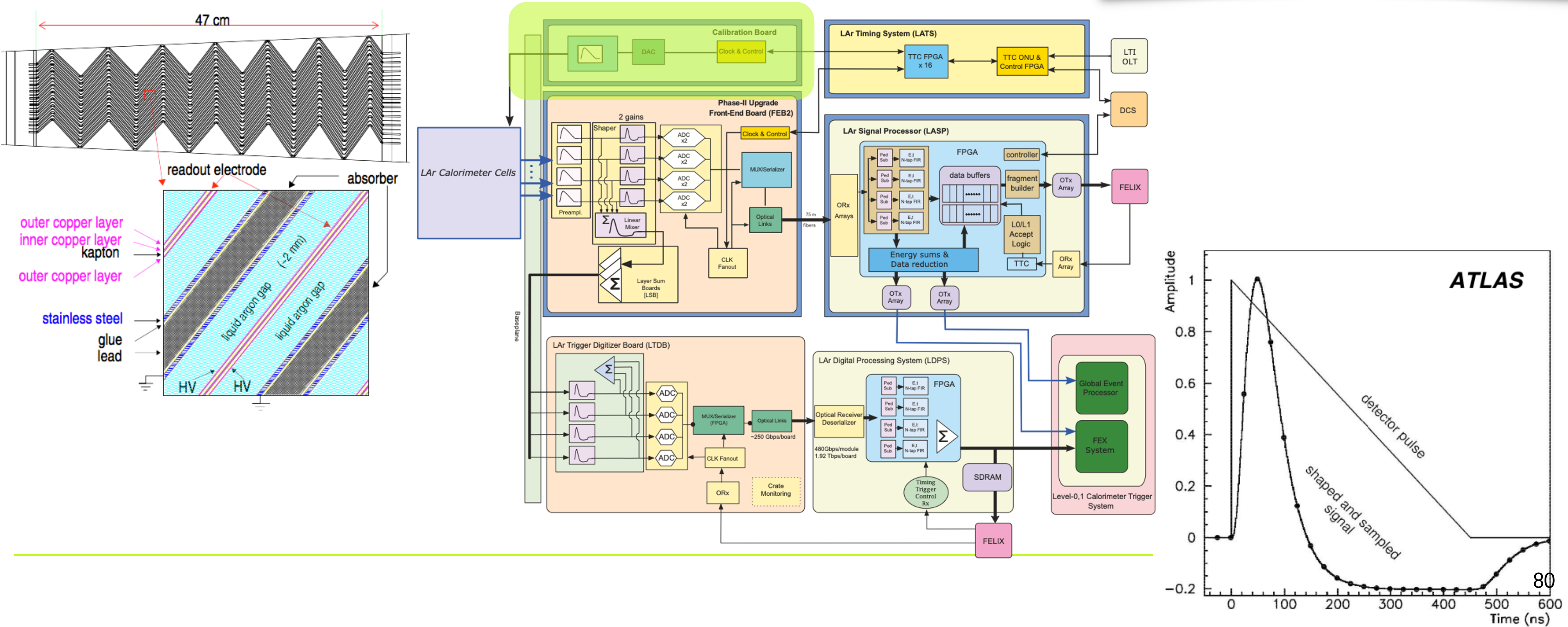
- AMPLIFICATION AND SHAPING OF SIGNAL
- DIGITIZATION (SAMPLING)
-
-



How to read the signal ?

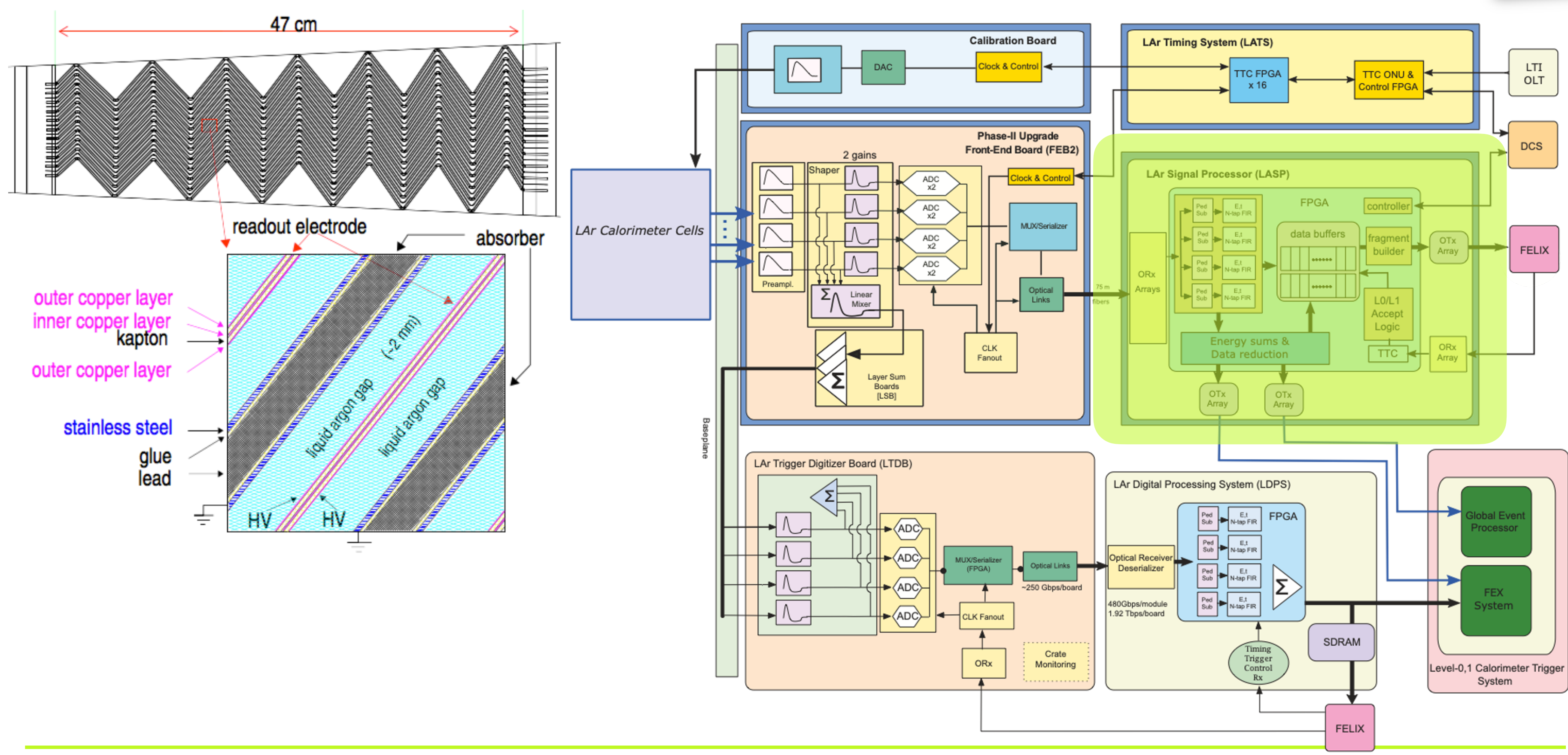
- IN DETECTOR :
- AMPLIFICATION AND SHAPING OF SIGNAL
 - DIGITIZATION (SAMPLING)
 - CALIBRATION OF THE CHAIN

- Example with ATLAS calorimeter :

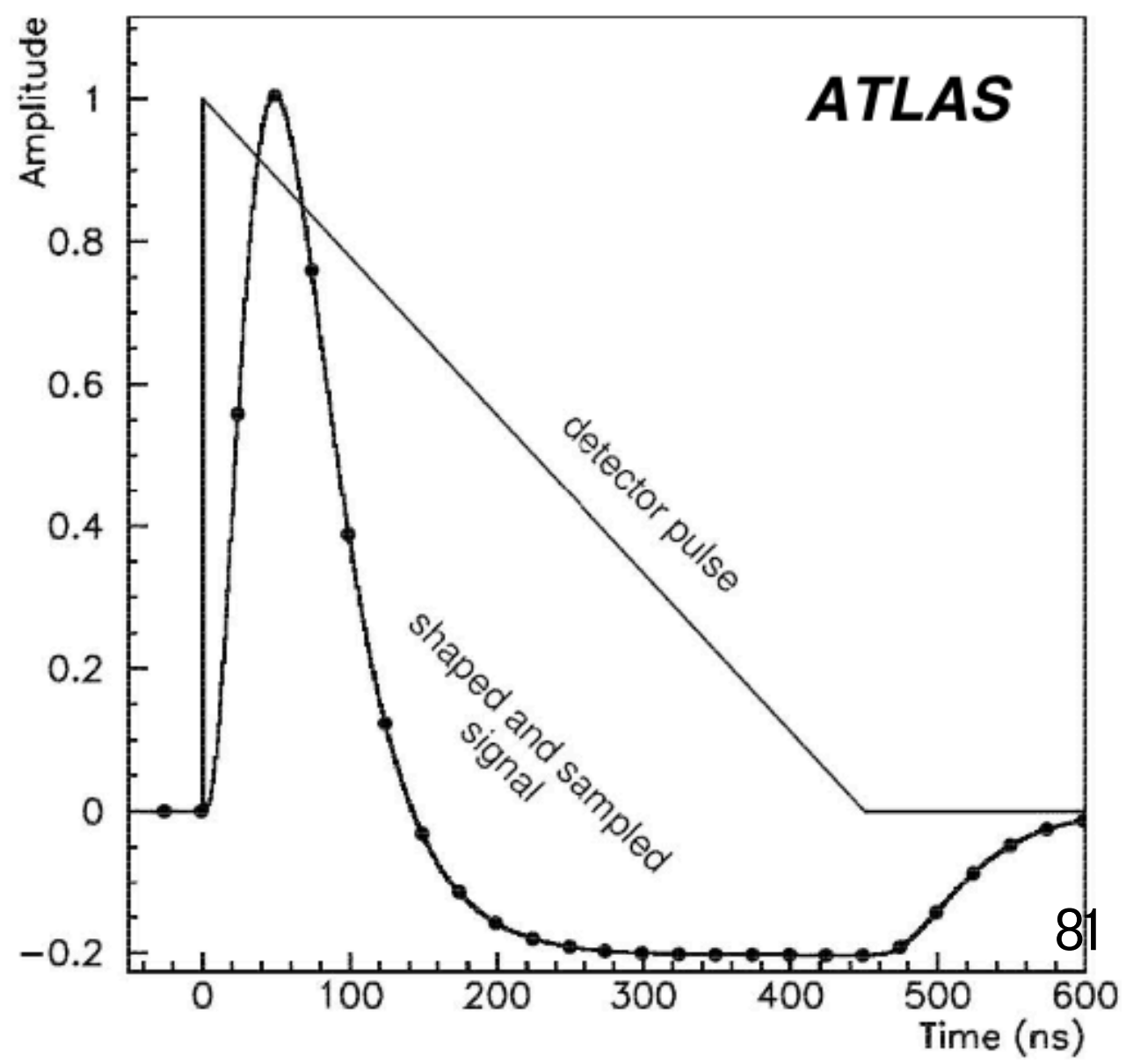


How to read the signal ?

- Example with ATLAS calorimeter :

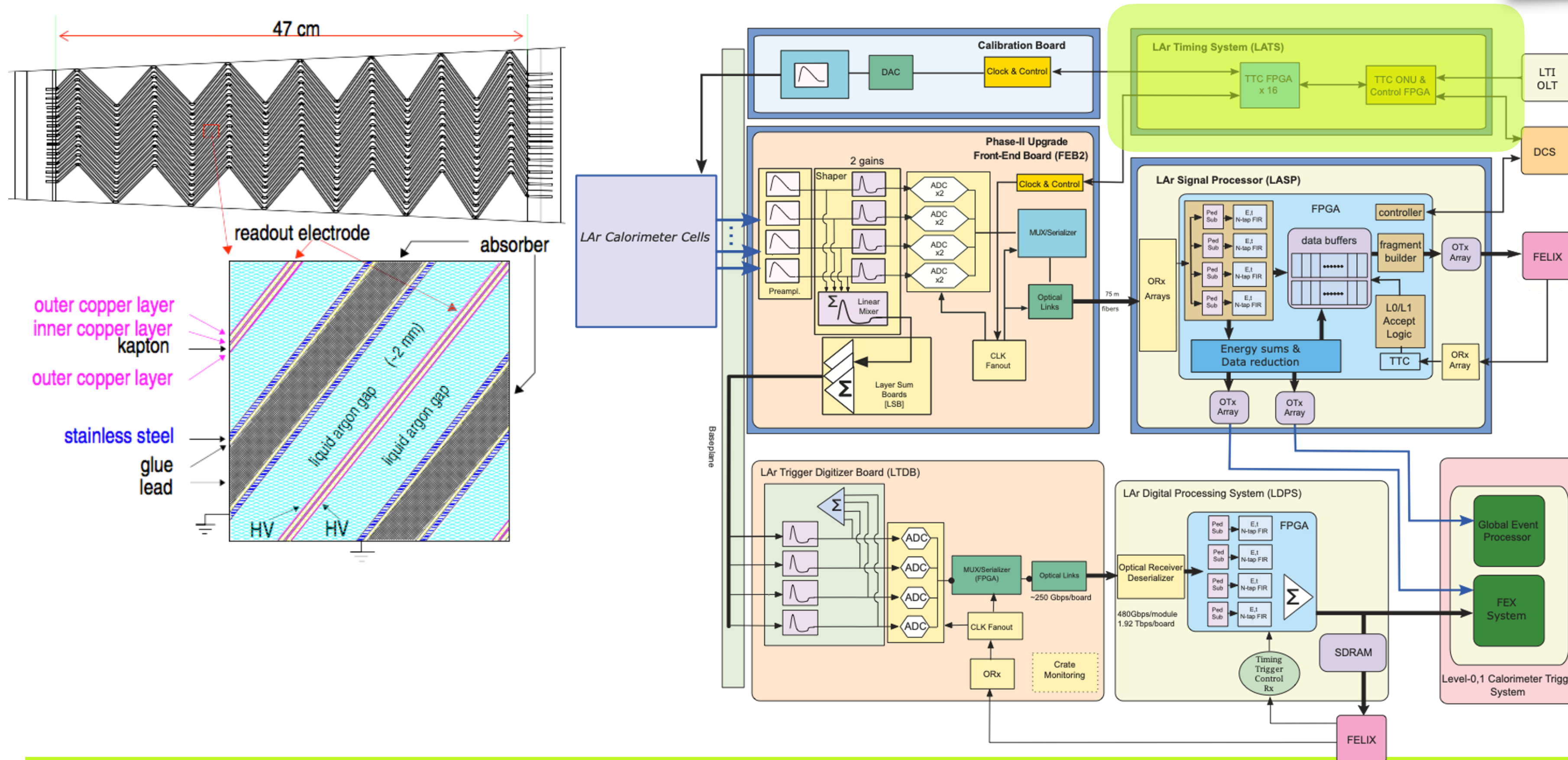


- IN DETECTOR :
- AMPLIFICATION AND SHAPING OF SIGNAL
 - DIGITIZATION (SAMPLING)
 - CALIBRATION OF THE CHAIN
- OFF-DETECTOR
- COMPUTATION OF ENERGY, QUALITY, TIMING
 -



How to read the signal ?

- Example with ATLAS calorimeter :

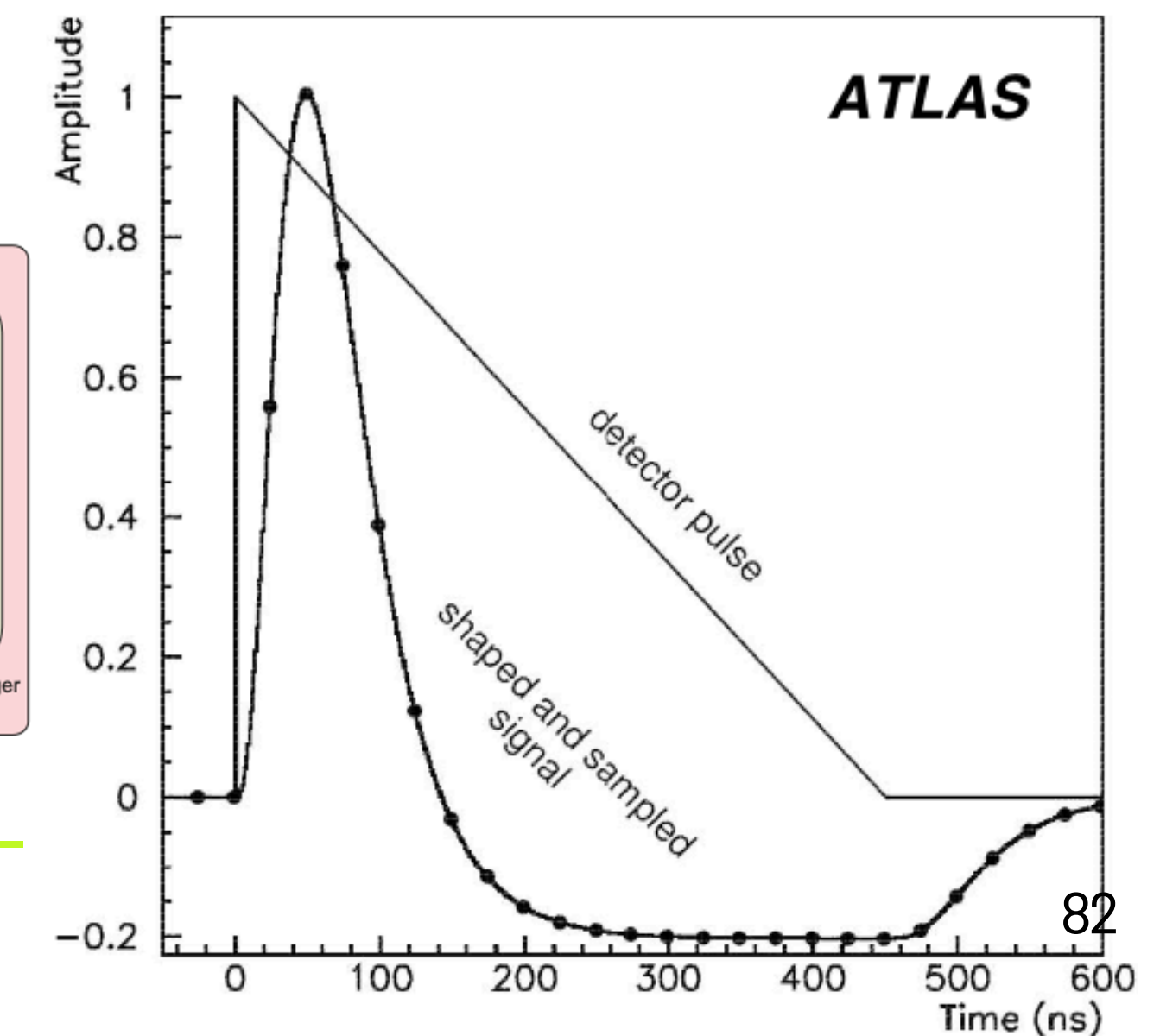


IN DETECTOR :

- AMPLIFICATION AND SHAPING OF SIGNAL
- DIGITIZATION (SAMPLING)
- CALIBRATION OF THE CHAIN

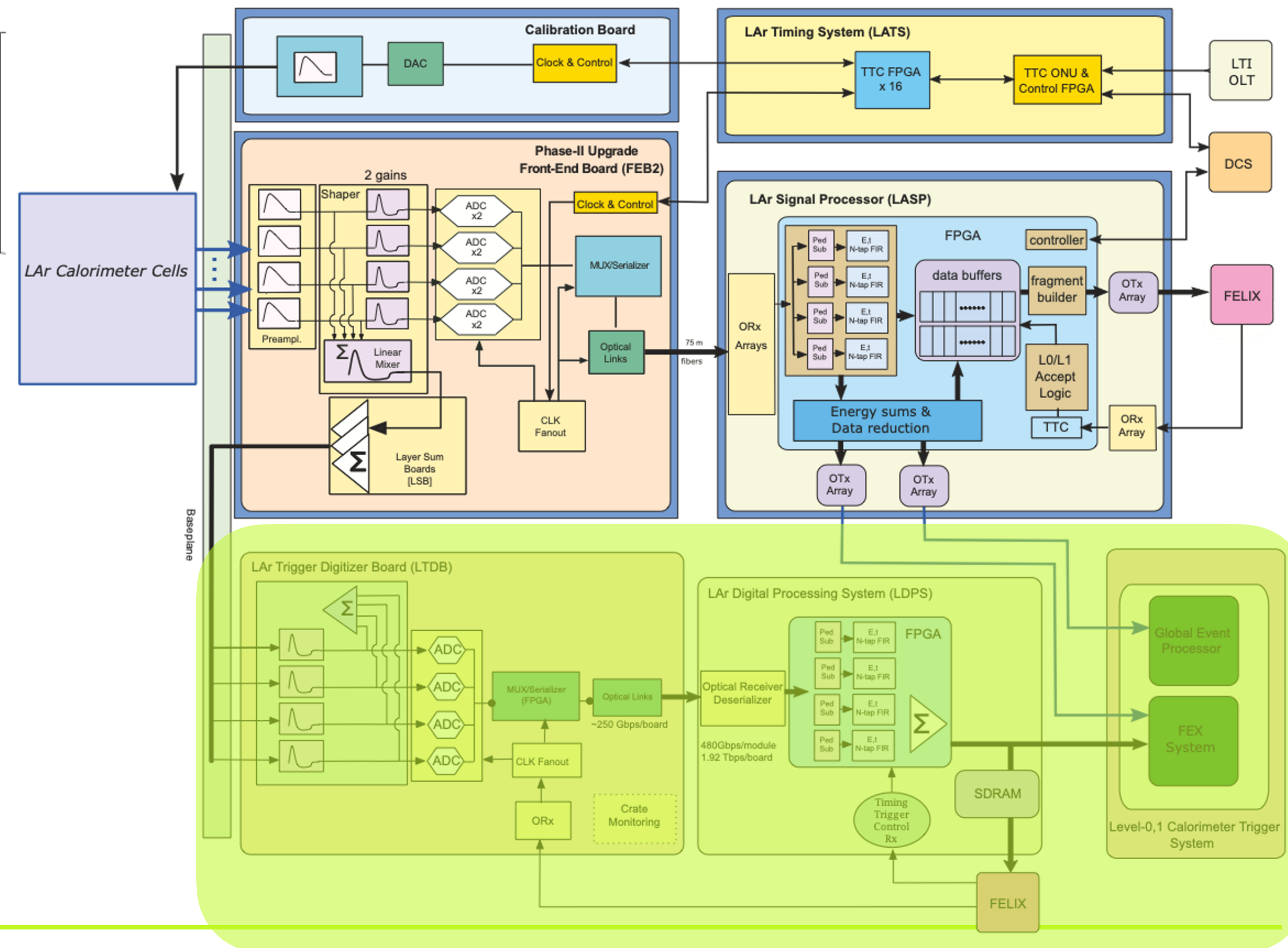
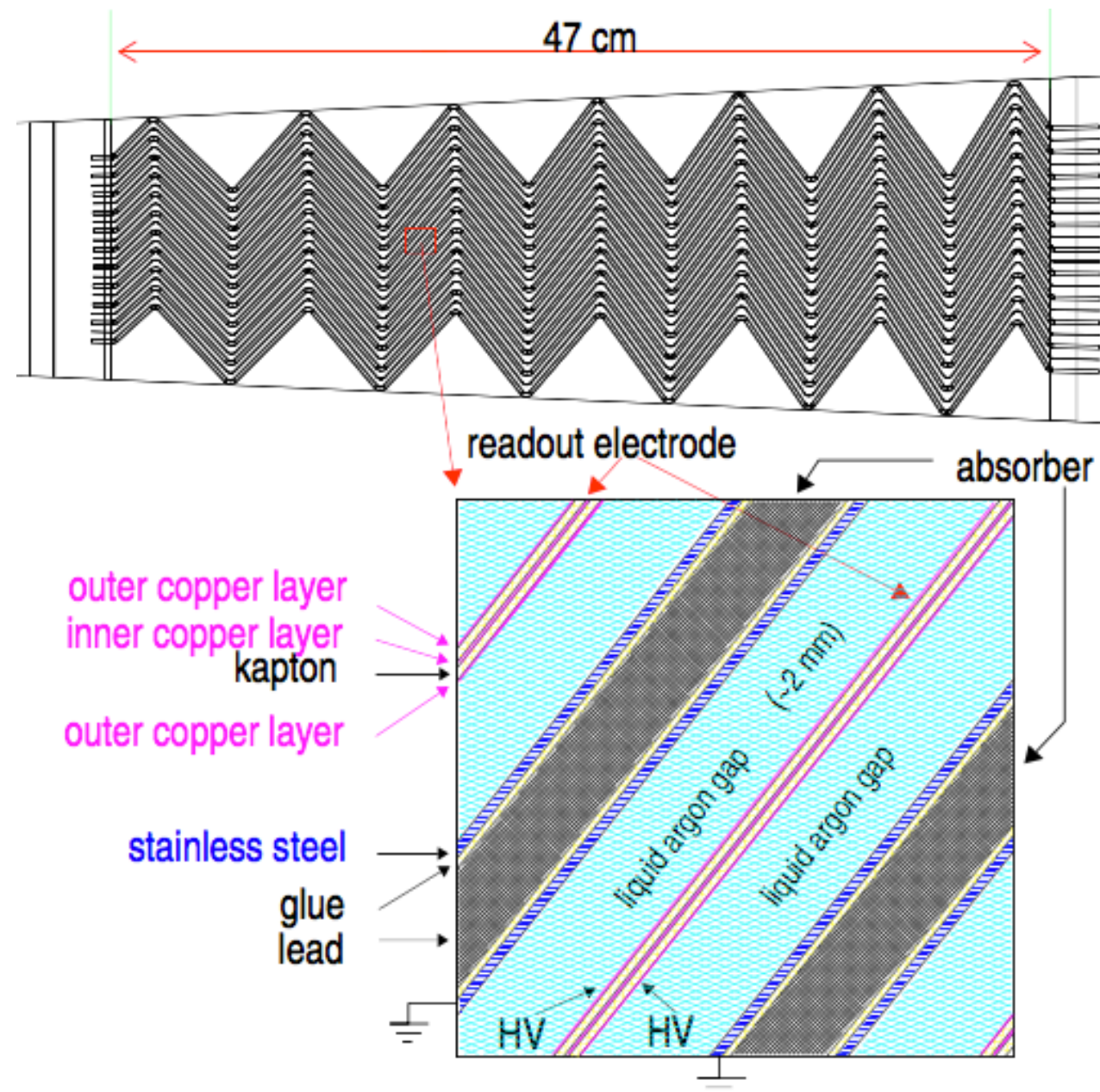
OFF-DETECTOR

- COMPUTATION OF ENERGY, QUALITY, TIMING
- TIMING, CONTROL AND CLOCK



How to read the signal ?

- Example with ATLAS calorimeter :

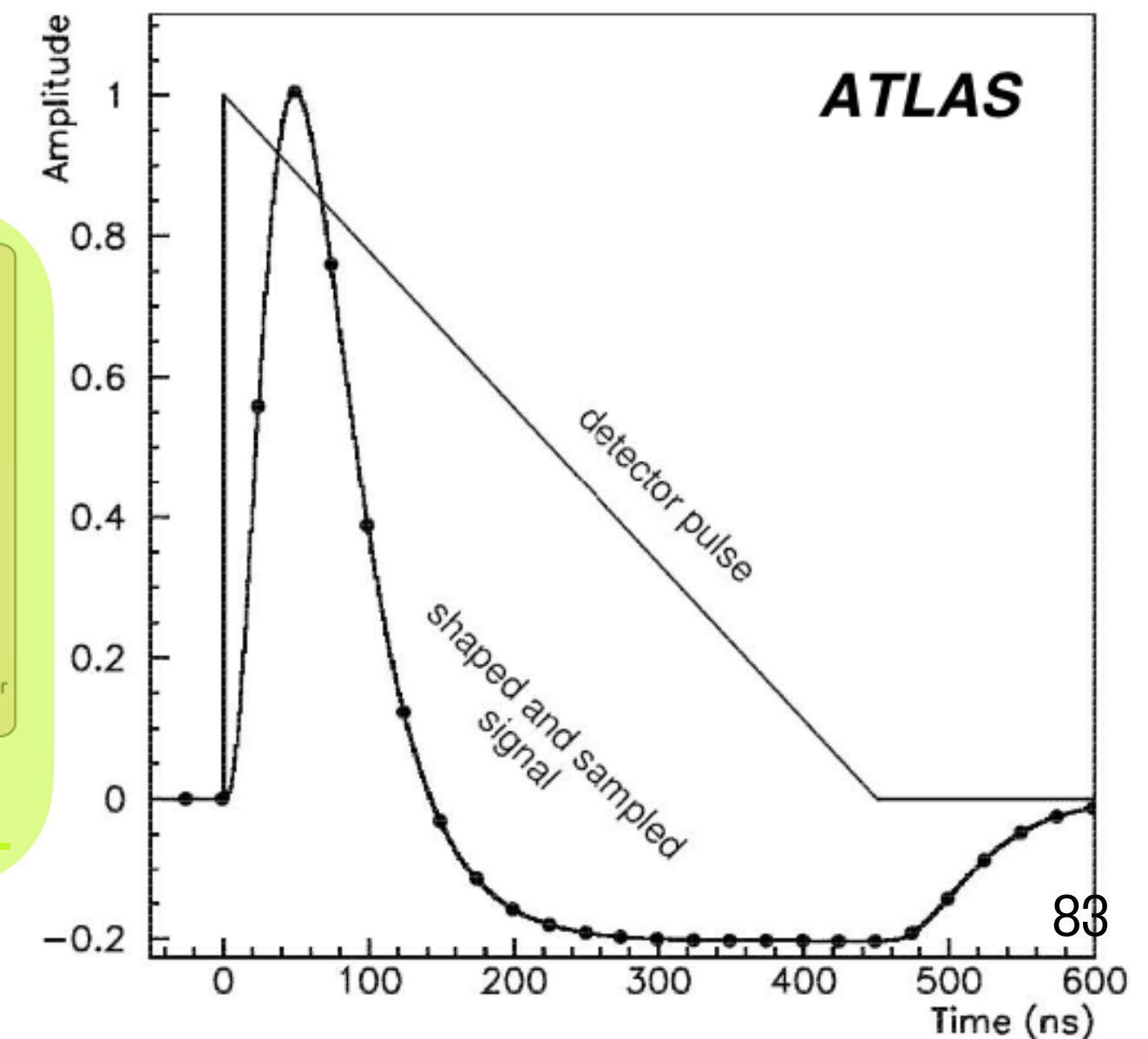


IN DETECTOR :

- AMPLIFICATION AND SHAPING OF SIGNAL
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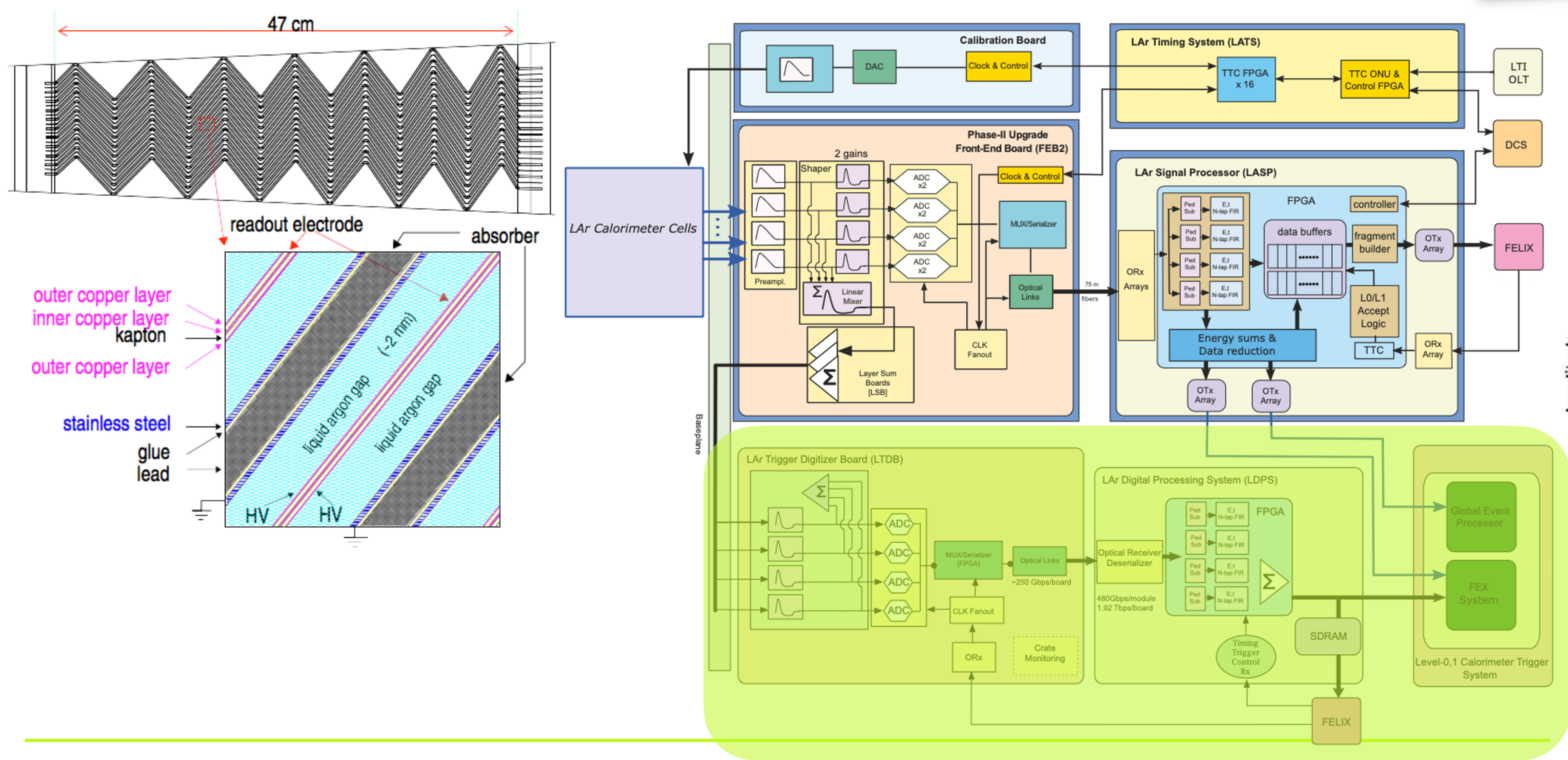
OFF-DETECTOR

- COMPUTATION OF ENERGY, QUALITY, TIMING
- TIMING, CONTROL AND CLOCK
- + TRIGGER SYSTEM



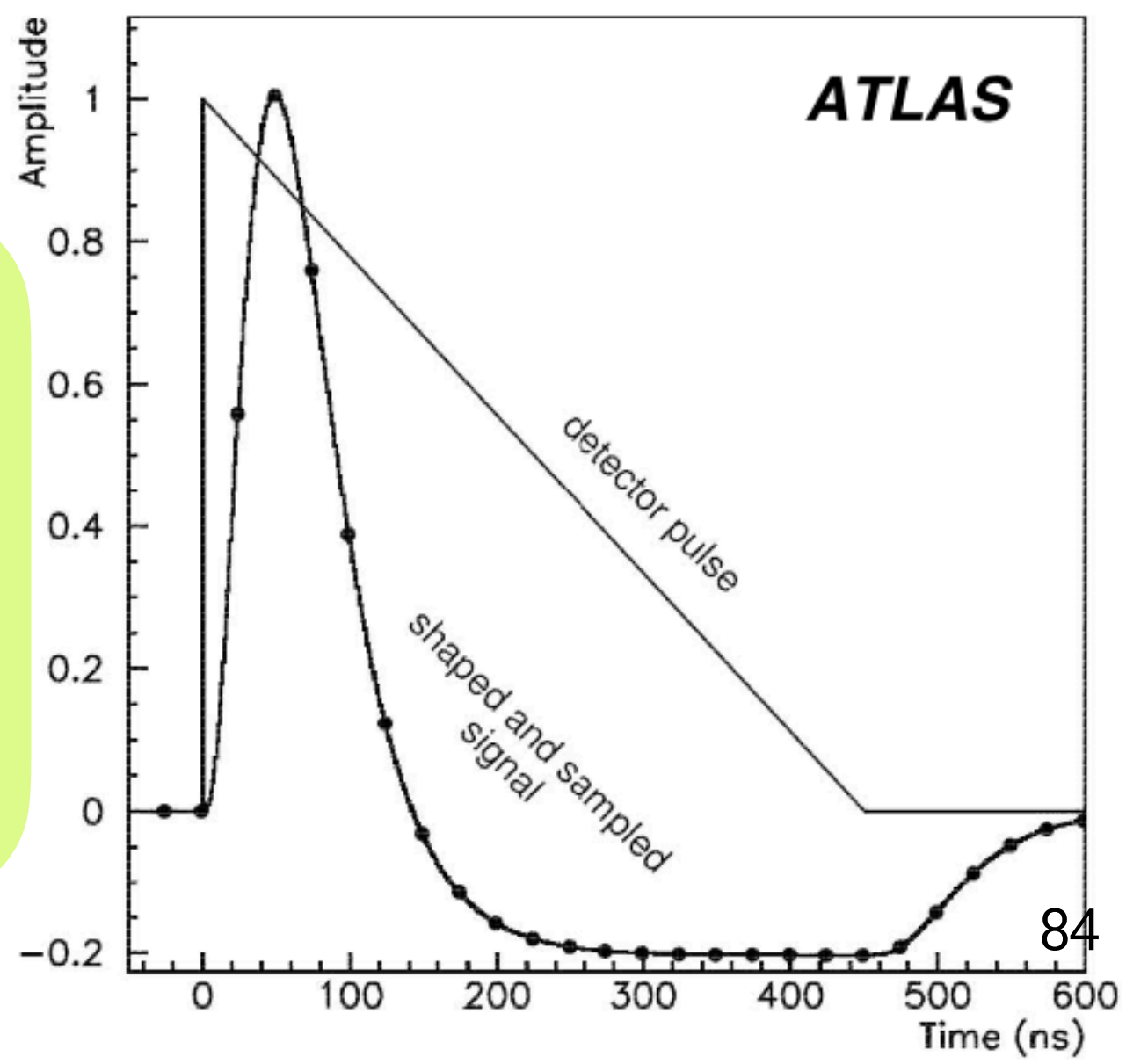
How to read the signal ?

- Example with ATLAS calorimeter :



- IN DETECTOR :**
- AMPLIFICATION AND SHAPING OF SIGNAL
 - DIGITIZATION (SAMPLING)
 - CALIBRATION OF THE CHAIN
- OFF-DETECTOR**
- COMPUTATION OF ENERGY, QUALITY, TIMING
 - TIMING, CONTROL AND CLOCK
- + TRIGGER SYSTEM**

Thousands of electronic boards !!



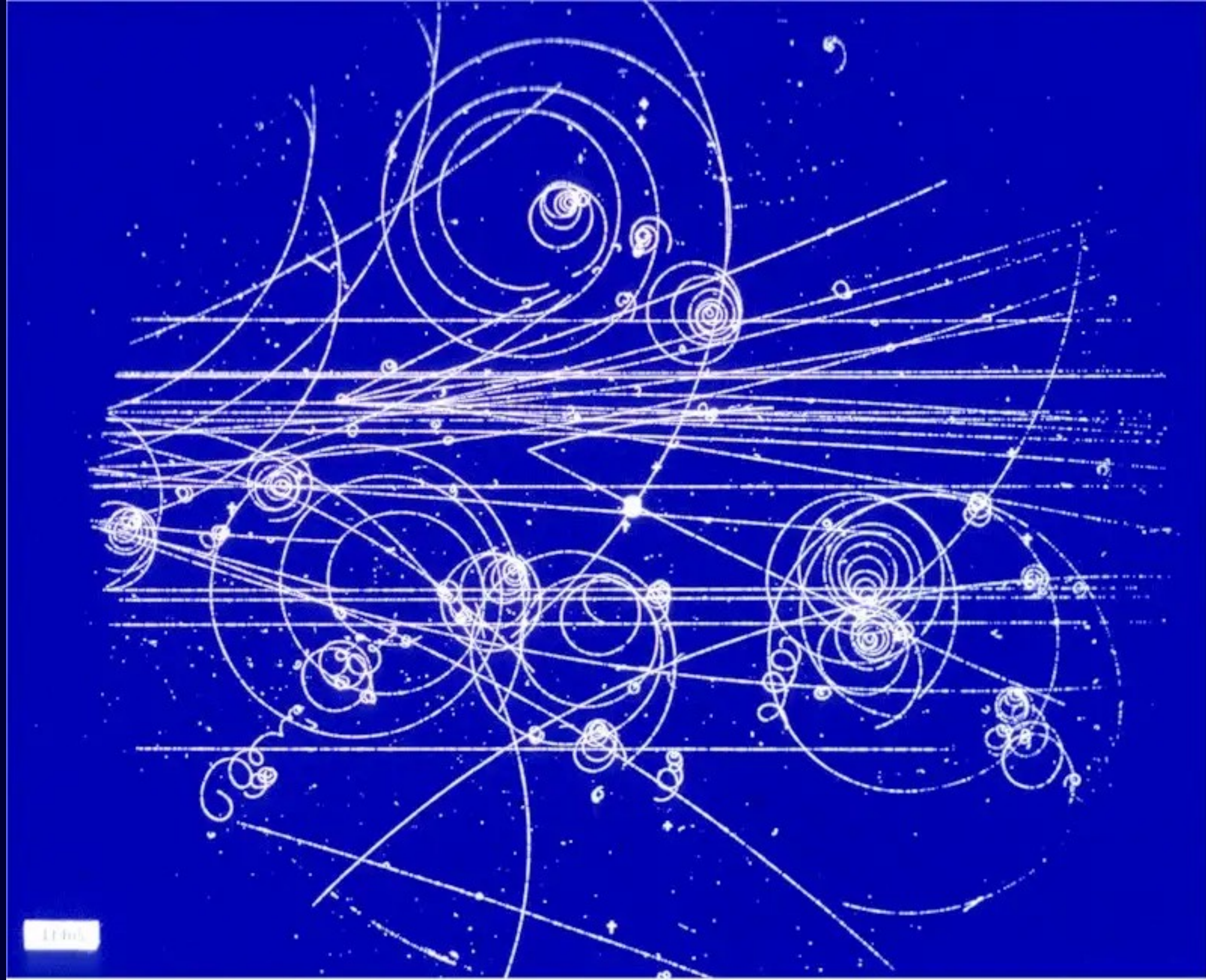
Building the future detectors - HL-LHC



Summary

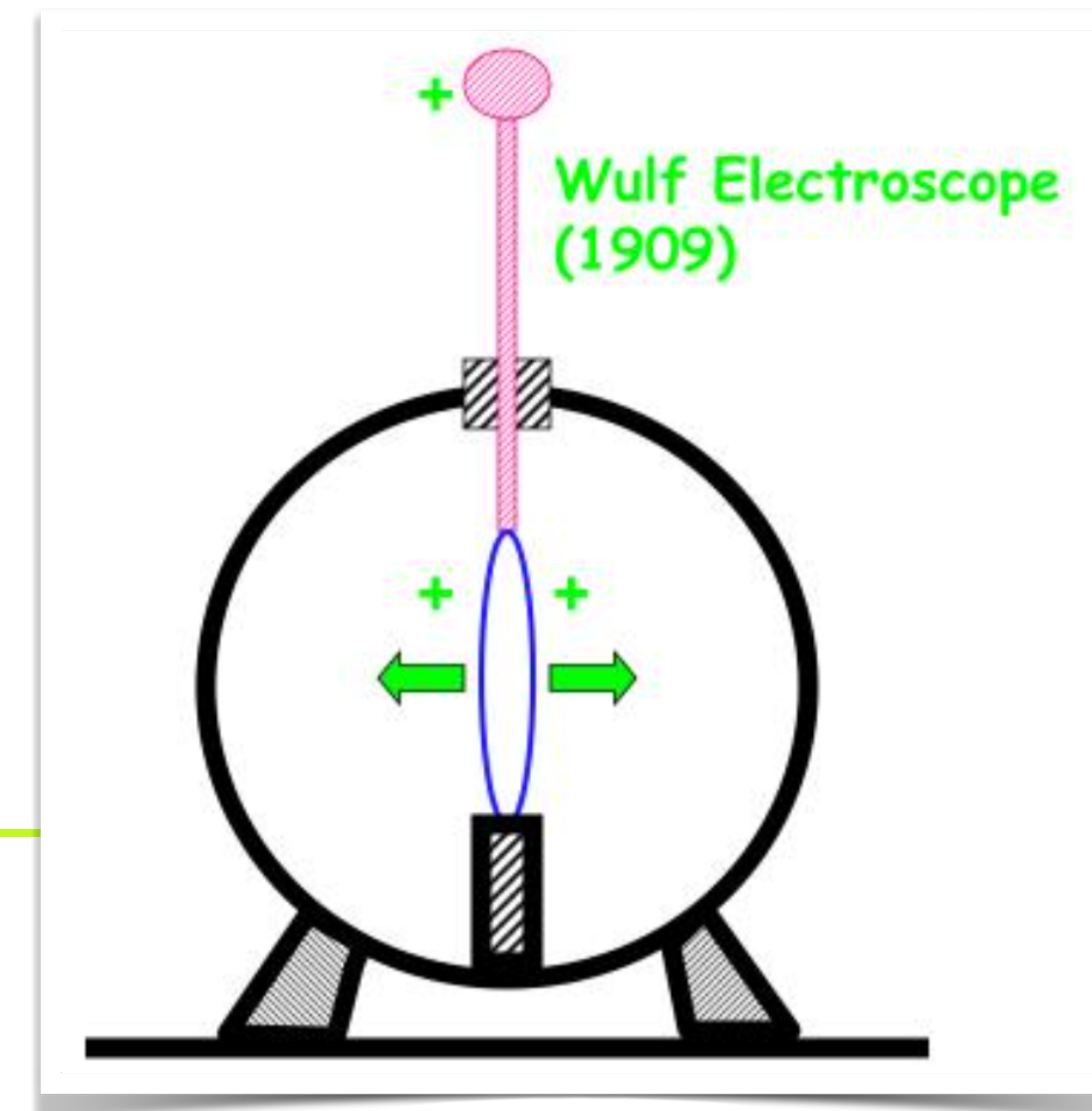
- Detection of particles essentially based on how they interact with matter
- With time, detectors techniques have improved : more precision, faster detection, better recording of signals
- Technologies will continue to improve, allowing us to see even deeper in fundamental laws

Thank you !



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



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**

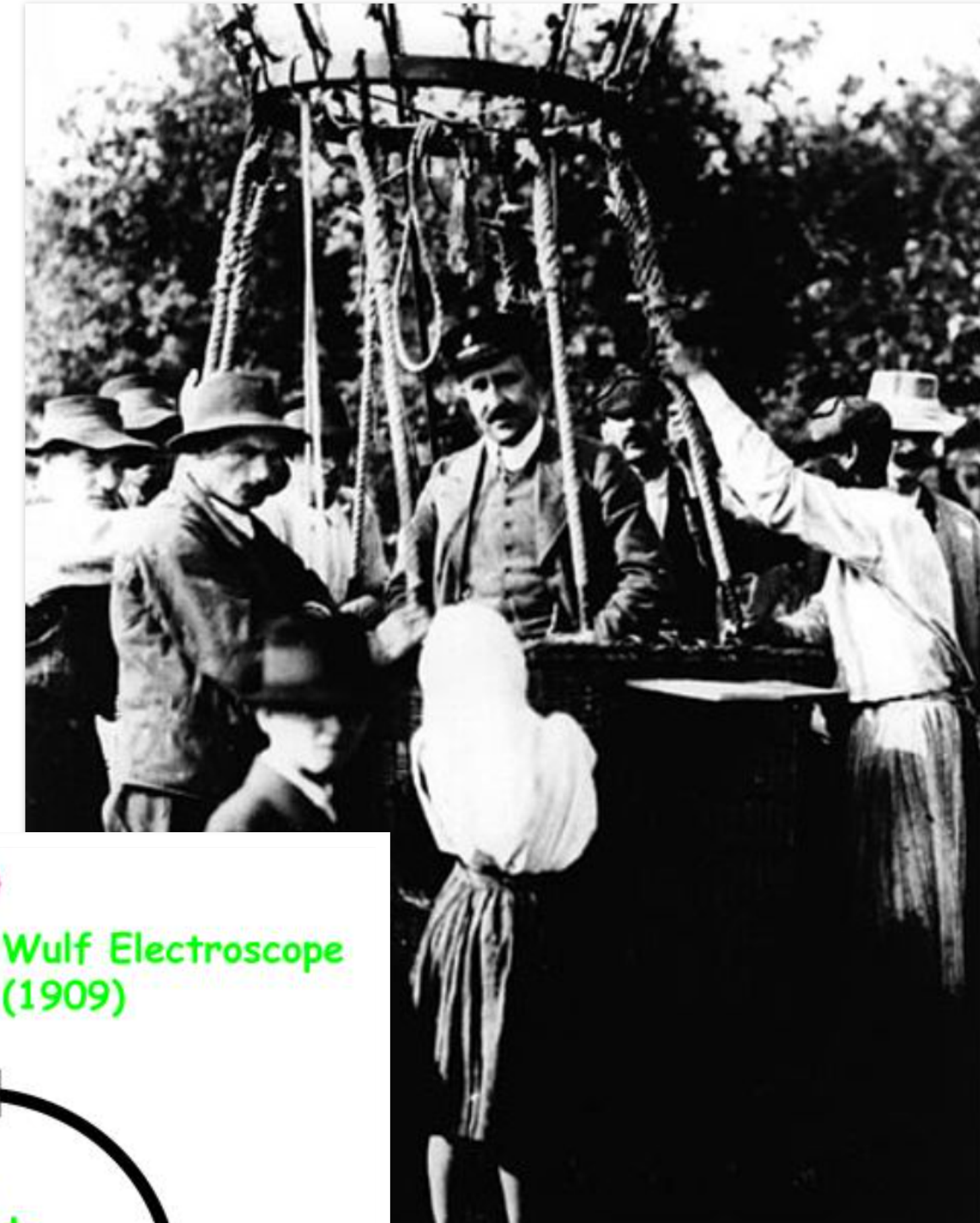
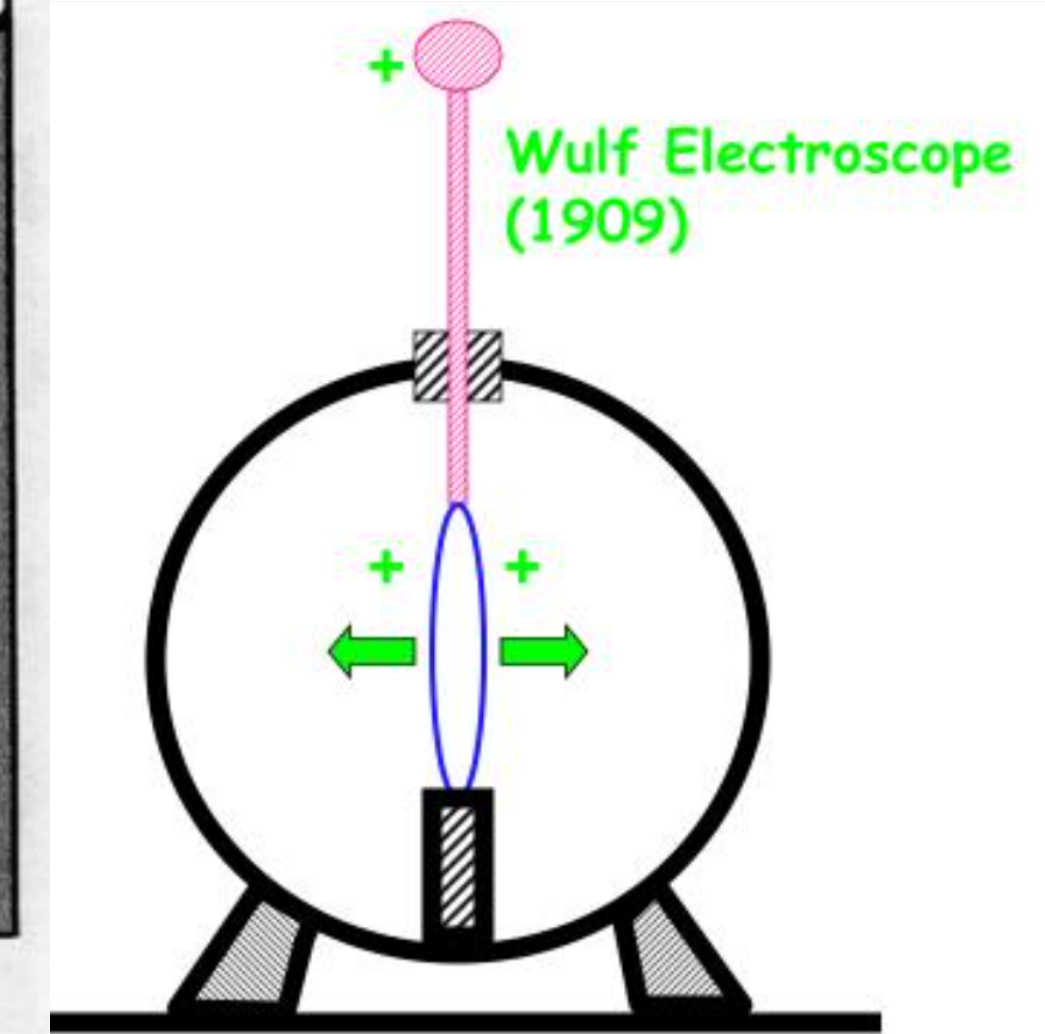
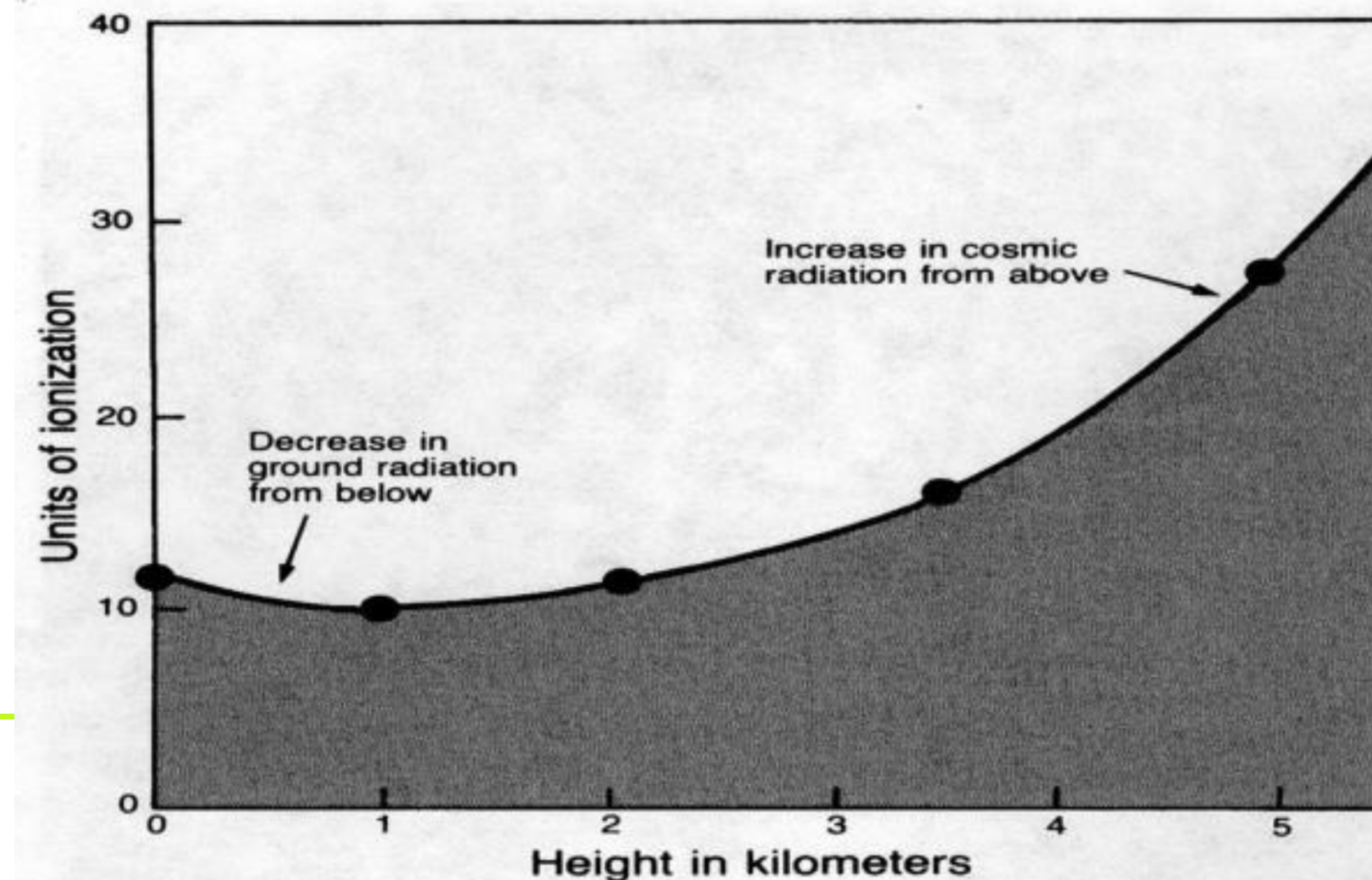


image:Wikimedia commons)