

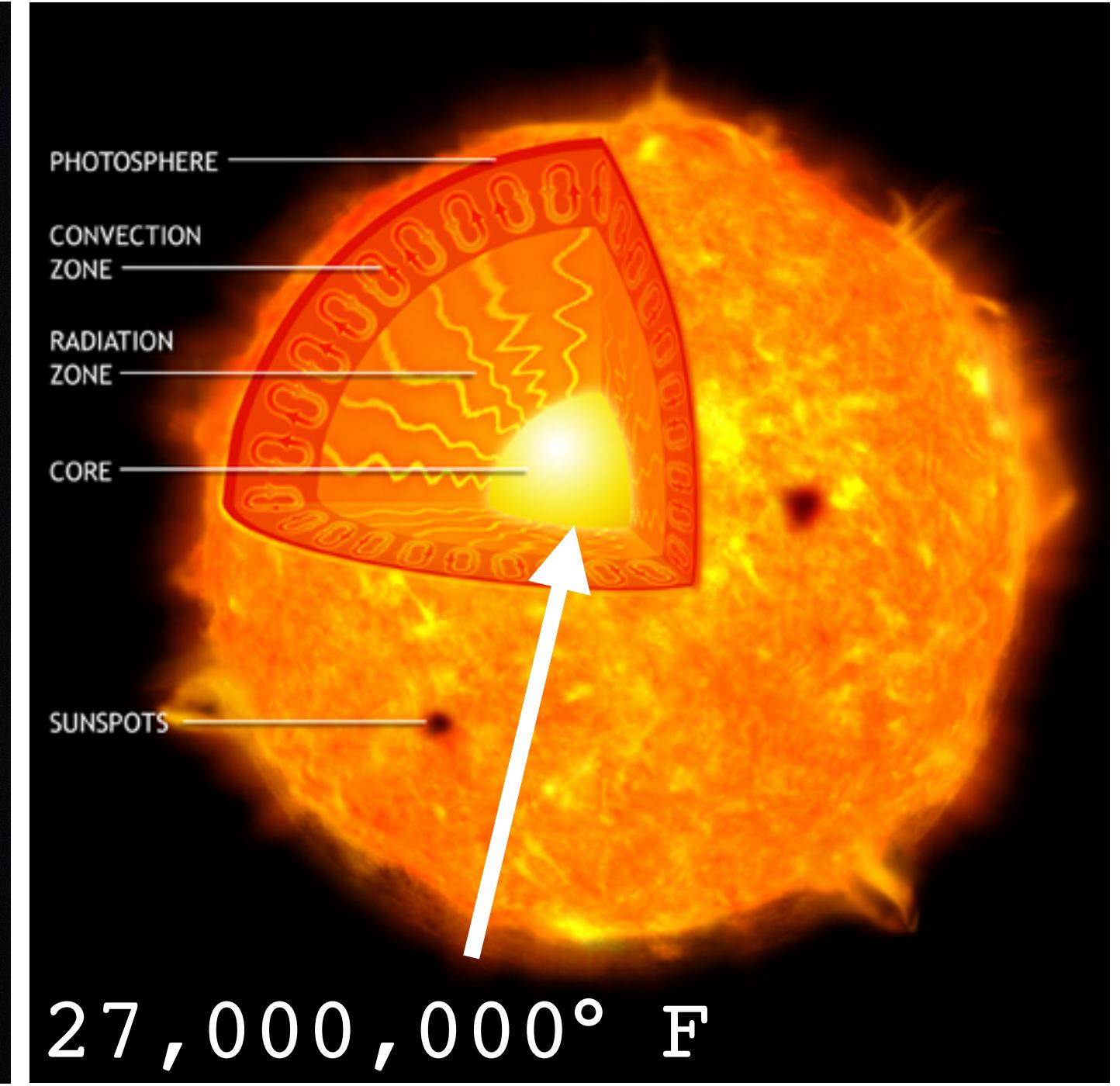
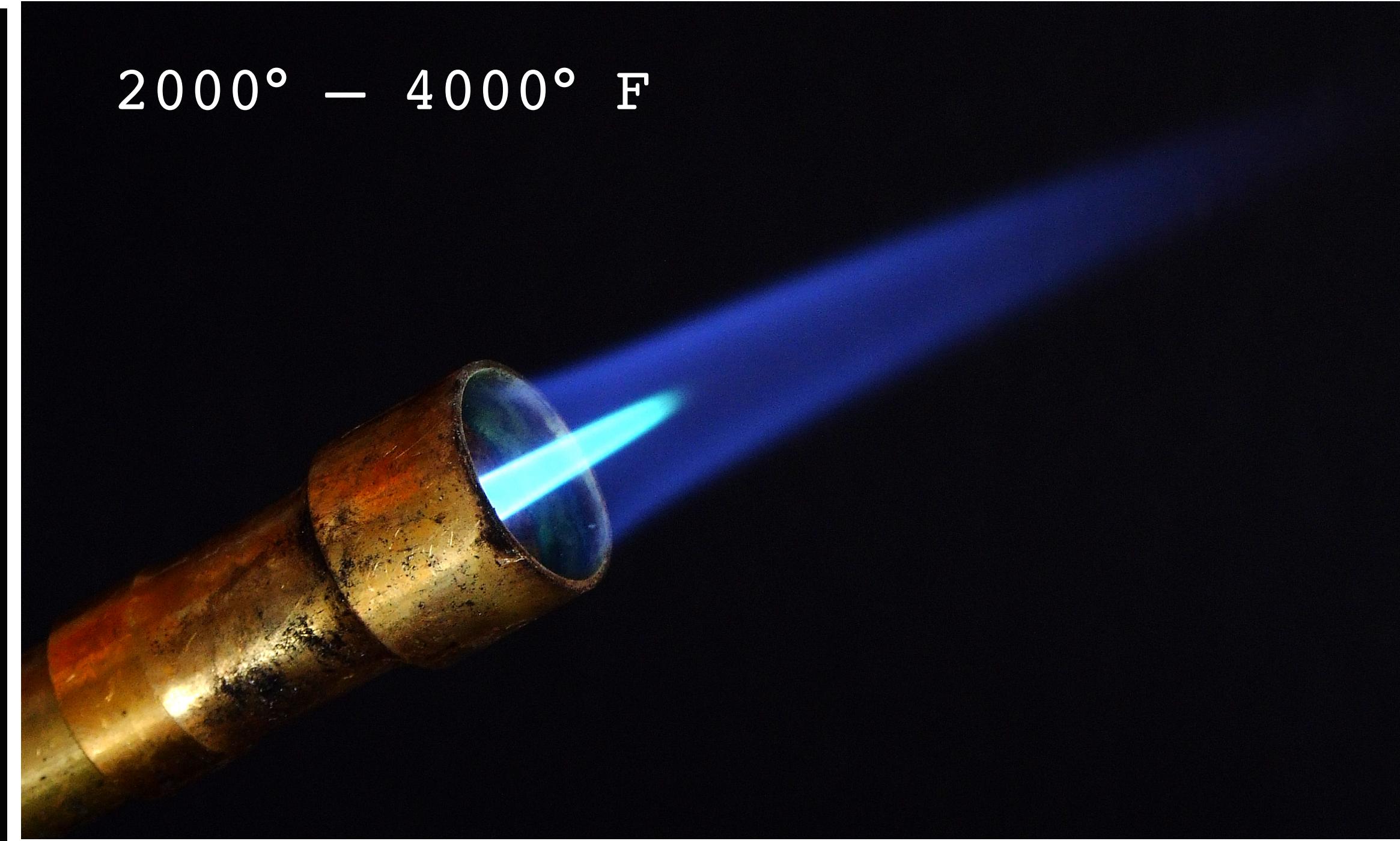
How the LHC makes (and ALICE measures) mini-Big Bangs



Anthony Timmins

UNIVERSITY of
HOUSTON

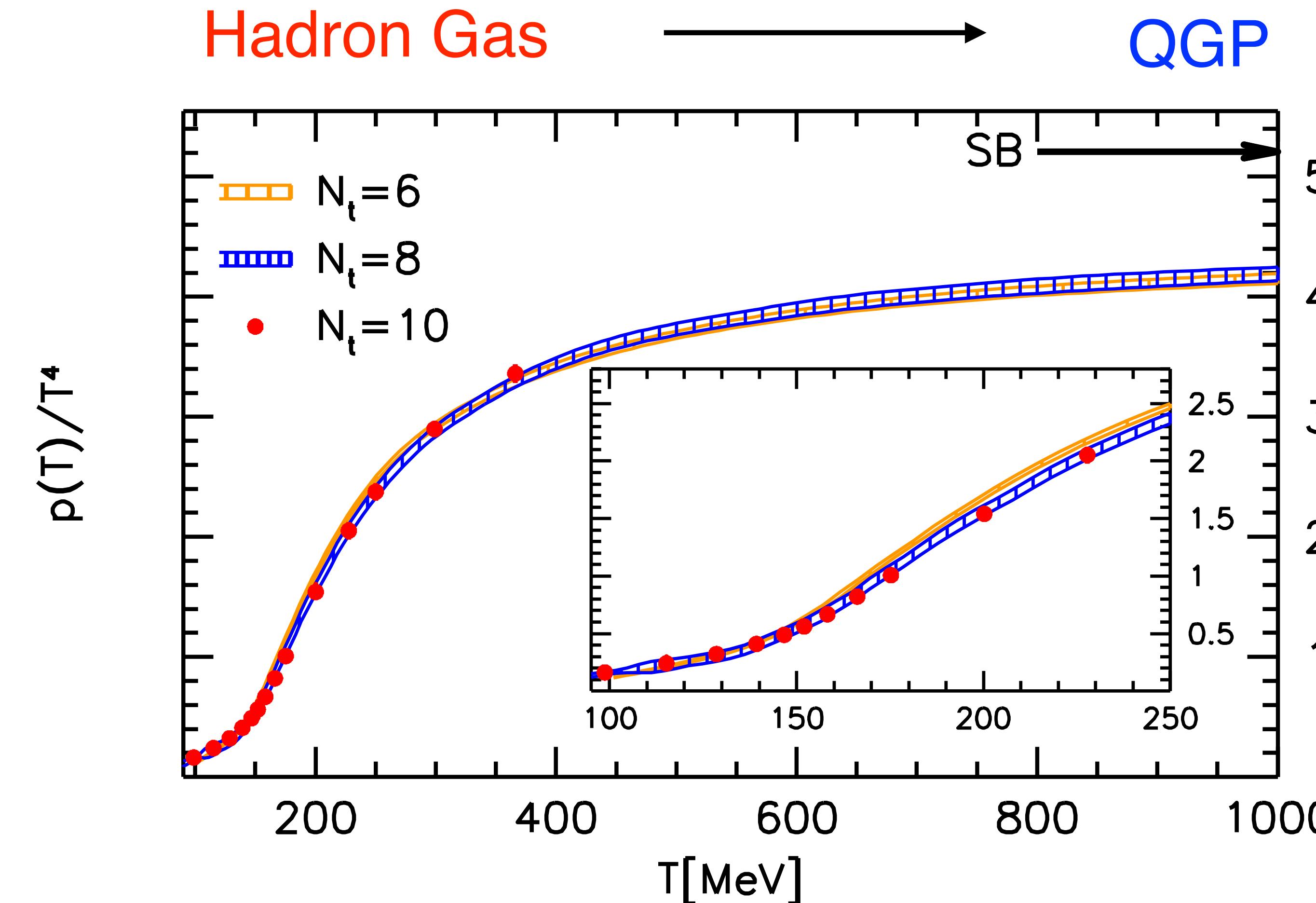
1. How much heat do we need to create a QGP?



► **5,000,000,000,000° F!!!**

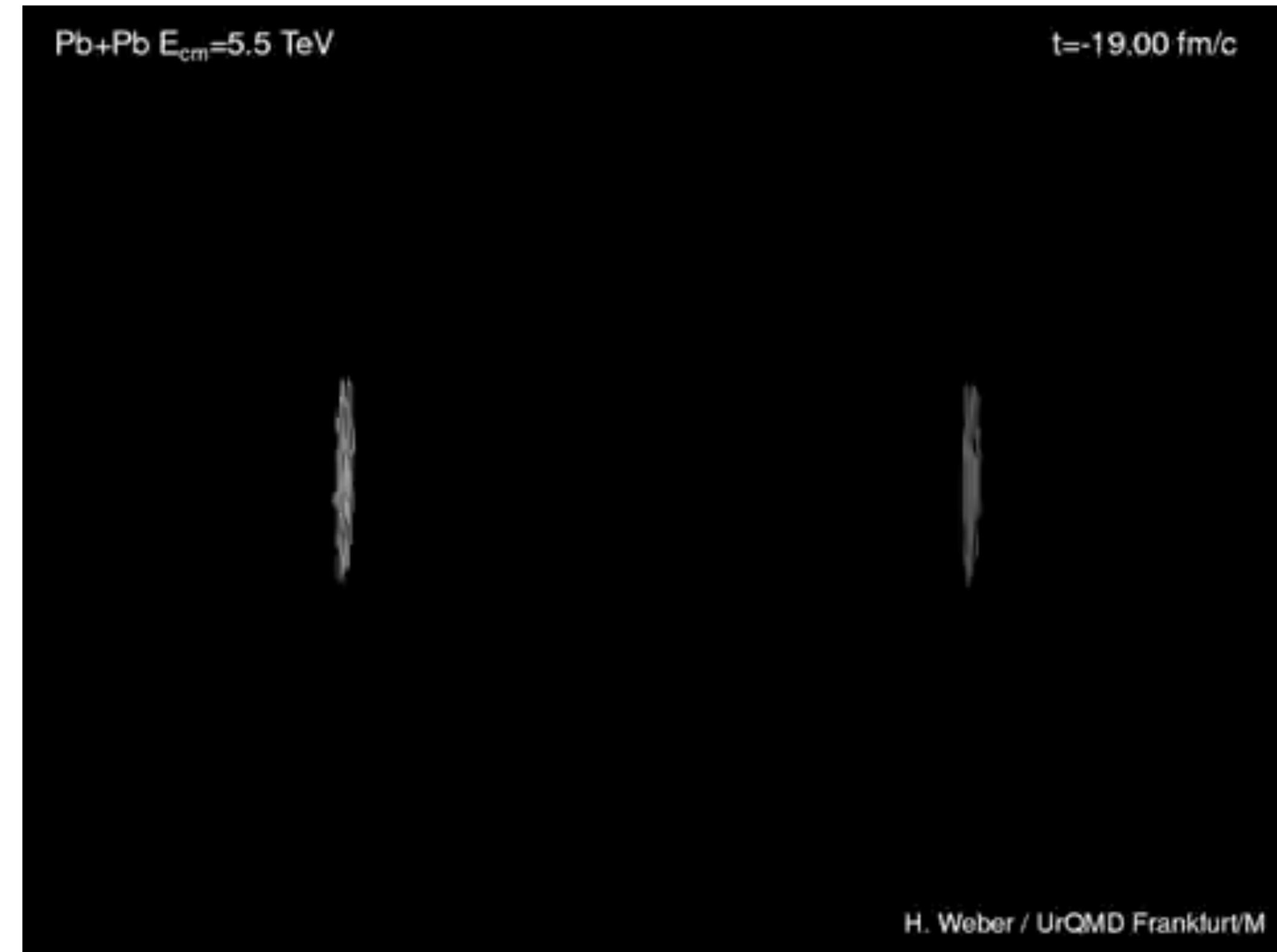
- ✓ Roughly a million times higher temperature than center of sun
- ✓ At such temperatures, half the “F” value to get Celcius “C” or Kelvin “K”

1. How much heat do we need to create a QGP?



- See Wilke's talk and **phase transition temp of 150 MeV** corresponds to $\sim 2,500,000,000,000$ K

1. How much heat do we need to create a QGP?



<https://videos.cern.ch/record/1304862>

- Crude but highly effective: collisions!
- To make the QGP, we collide Pb-Pb heavy ions (nuclei) at the LHC

2. Accelerators and Beams

- › All accelerators use **electromagnetic fields to increase the energy of charged particles**
- › Two types: **DC accelerators** have a steady electric field (i.e., time independent), **AC accelerators** use radio frequency electric fields.
- › Modern-day large accelerators in particle/nuclear physics are AC.

2. Accelerators and Beams

- First type of DC accelerator was the Cockcroft–Walton machine, which used aligned electrodes with successively higher potentials.
- Could accelerate charged particles to **1 MeV**, and still used as injectors for other accelerators.
- The most important DC machine in current use is the **van de Graaff accelerator**

2. Accelerators and Beams

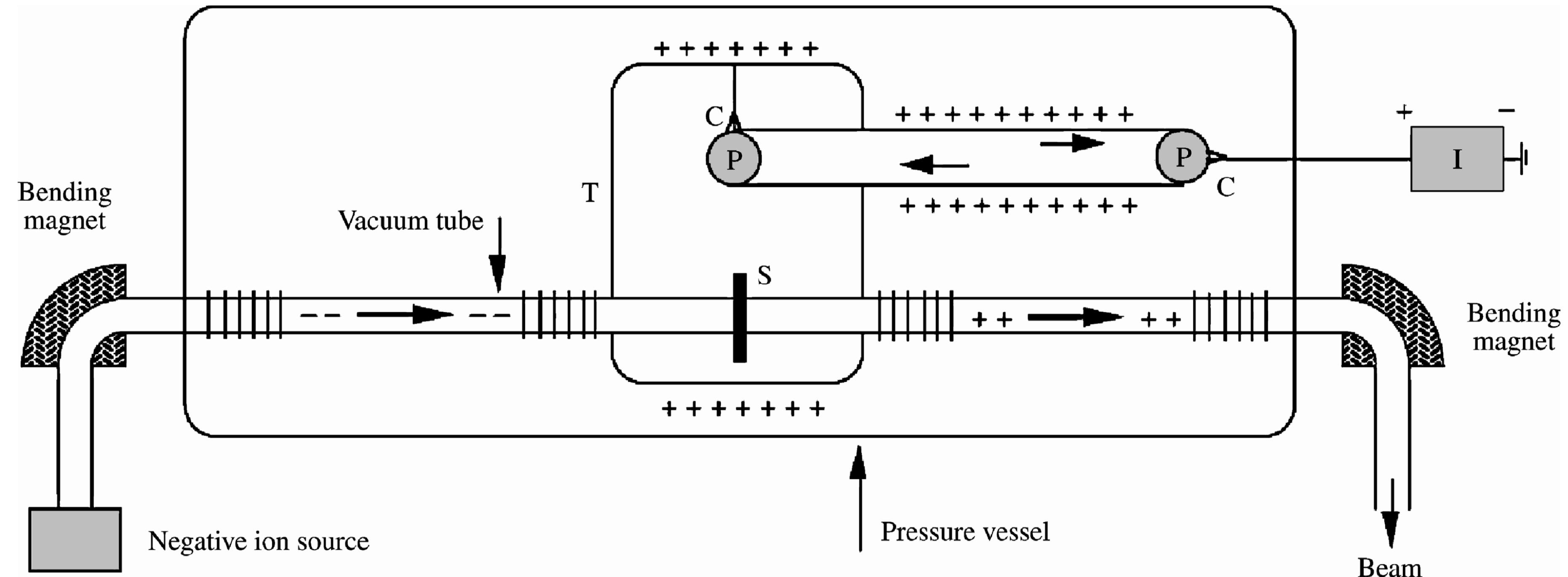


Figure 4.1 Principle of the tandem van de Graaff accelerator

- › Negative ions are attracted to S, then stripped (thin carbon foil) to remove electrons to produce positive ions

2. Accelerators and Beams

- ▶ The pulleys transfer ions via the Comb (C) to a hollow metal sphere that provides the electric field to accelerate the beam.
- ▶ Beam energies achieved **30-40 MeV**.



Robert J. Van de Graaff



John G. Trump

2. Accelerators and Beams

- Two types of AC accelerators: Linear (linac) and Cyclic

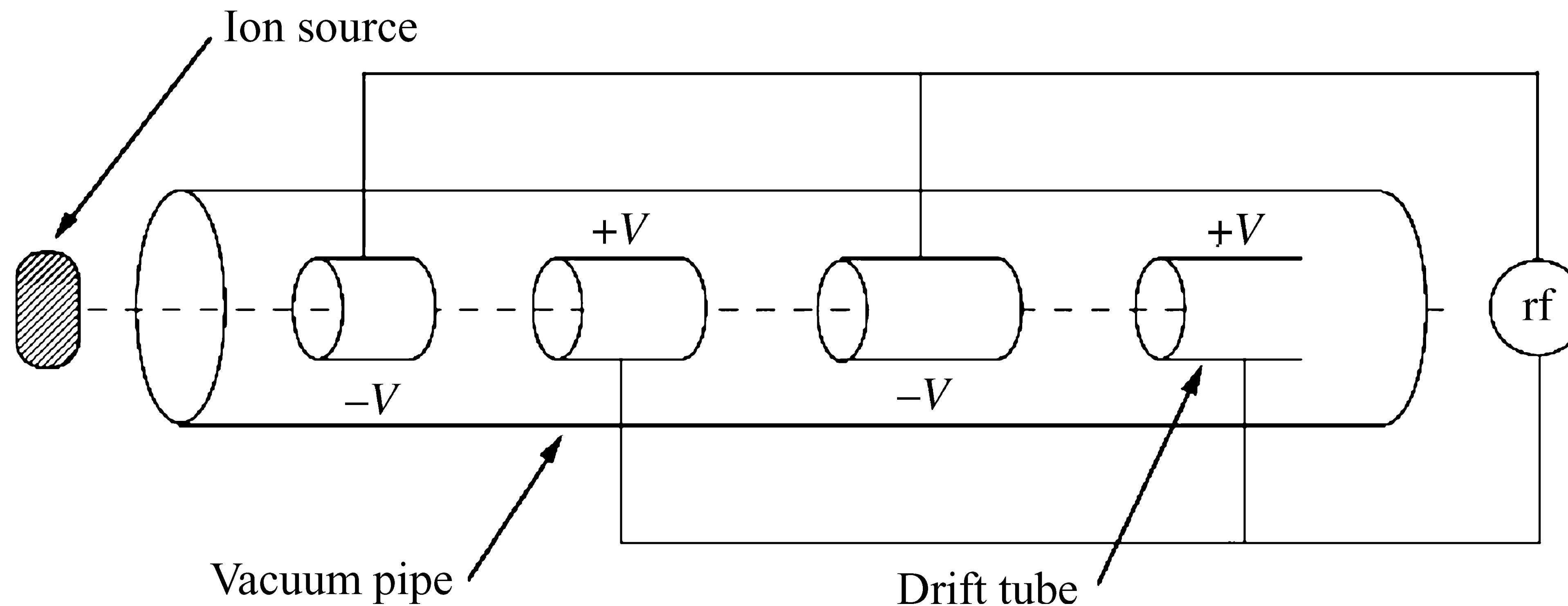


Figure 4.2 Acceleration in a linear ion accelerator

2. Accelerators and Beams

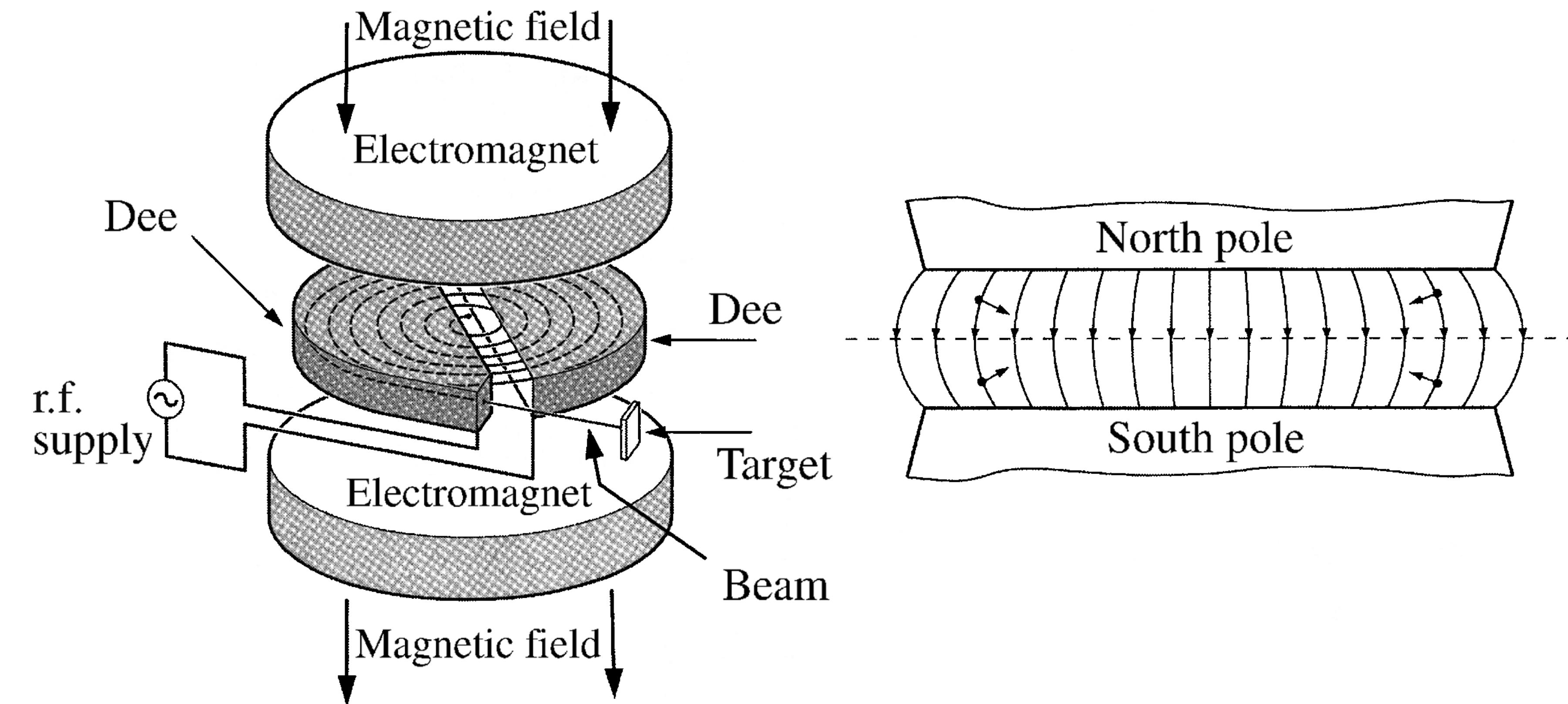
- ▶ Charged particles travel to the first terminal - potential flips, sending them to the next terminal.
- ▶ Form bunches when doing so
- ▶ The largest **Linac** is at the SLAC Laboratory in Stanford, USA. The maximum energy of the beam particles is **50 GeV**. Over 3 km long



2. Accelerators and Beams

- ▶ Cyclic accelerators used for low-energy nuclear physics experiments are of a type called **cyclotrons**.
- ▶ Cyclic accelerators used for high-energy particle/nuclear physics called **synchrotrons**
- ▶ In a **cyclotron**, charged particles are constrained to move in near-circular orbits by a magnetic field during the acceleration process.

2. Accelerators and Beams

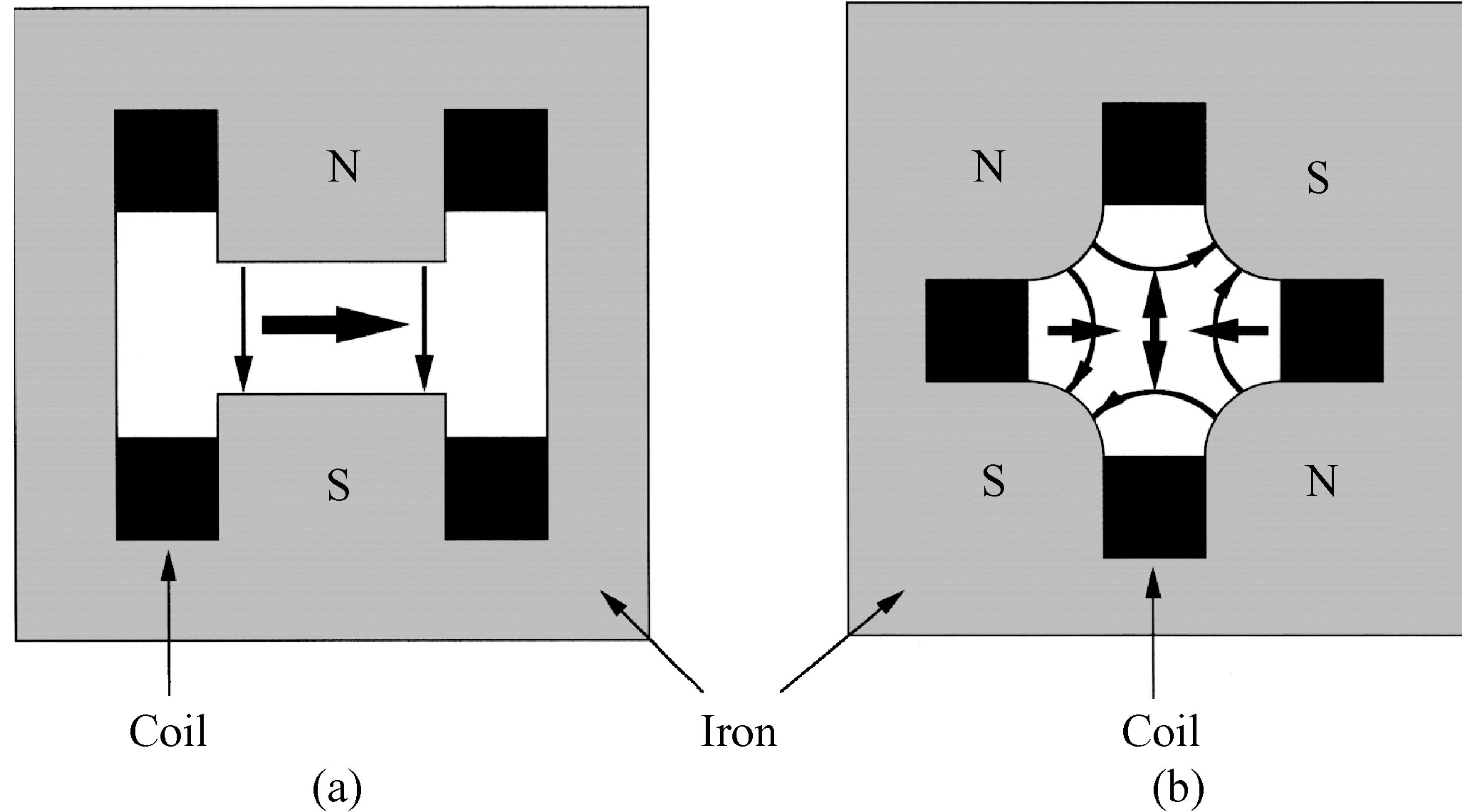


- ▶ Ions are accelerated each time they pass through the Dee
- ▶ The shape of magnetic fields keeps the ions in a stable orbit i.e. in the middle

2. Accelerators and Beams

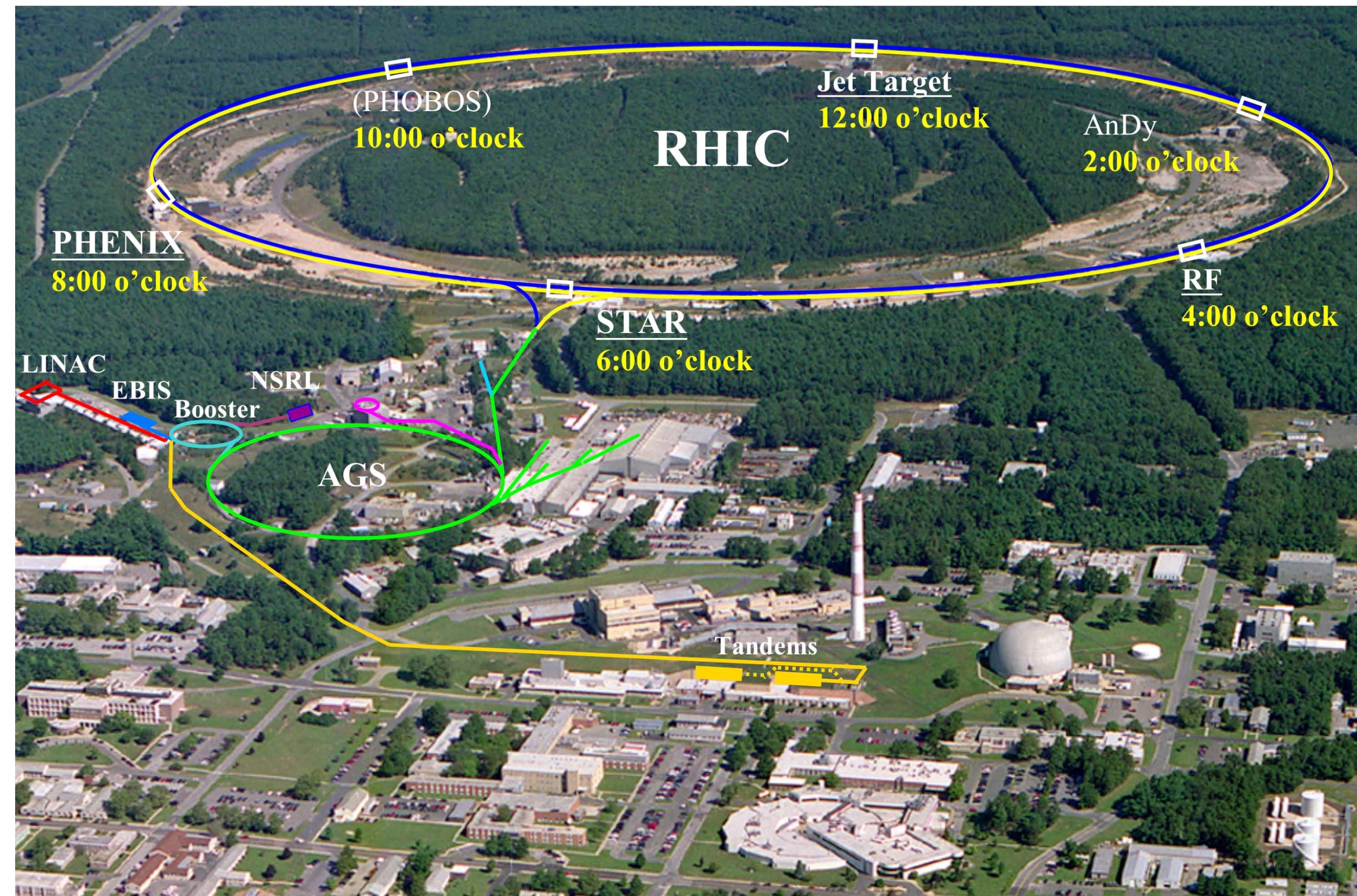
- A **synchrotron** works similarly to a linac, but the beam pipe is circular.
- Since particles travel in a circular orbit, they **emit radiation called synchrotron radiation**.
- Amount of energy lost goes as $1/m^4$
- In units of GeV/c , the momentum of an orbiting particle is **$p=0.3B\rho$** , where ρ is the radius of curvature (m), and B is the magnetic field (T).

2. Accelerators and Beams



- Beam magnet (left) ensures circular orbit. Up to 7 T at LHC (superconducting).
Quadrupole magnetic (right) keeps the beam focused

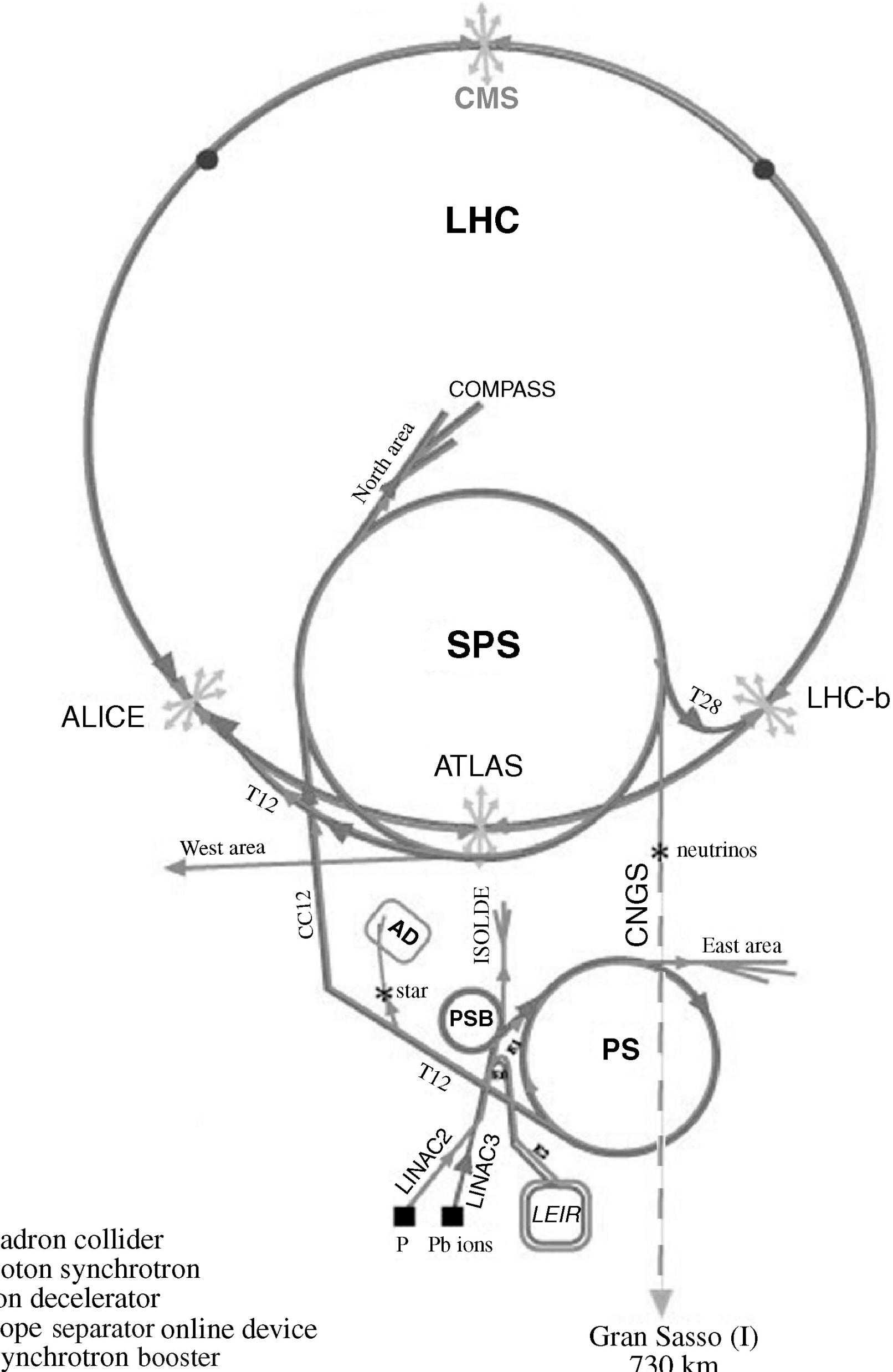
2. Accelerators and Beams



- The relativistic heavy-ion collider (RHIC) in New York is 4km in circumference with maximum energy of **500 GeV**.

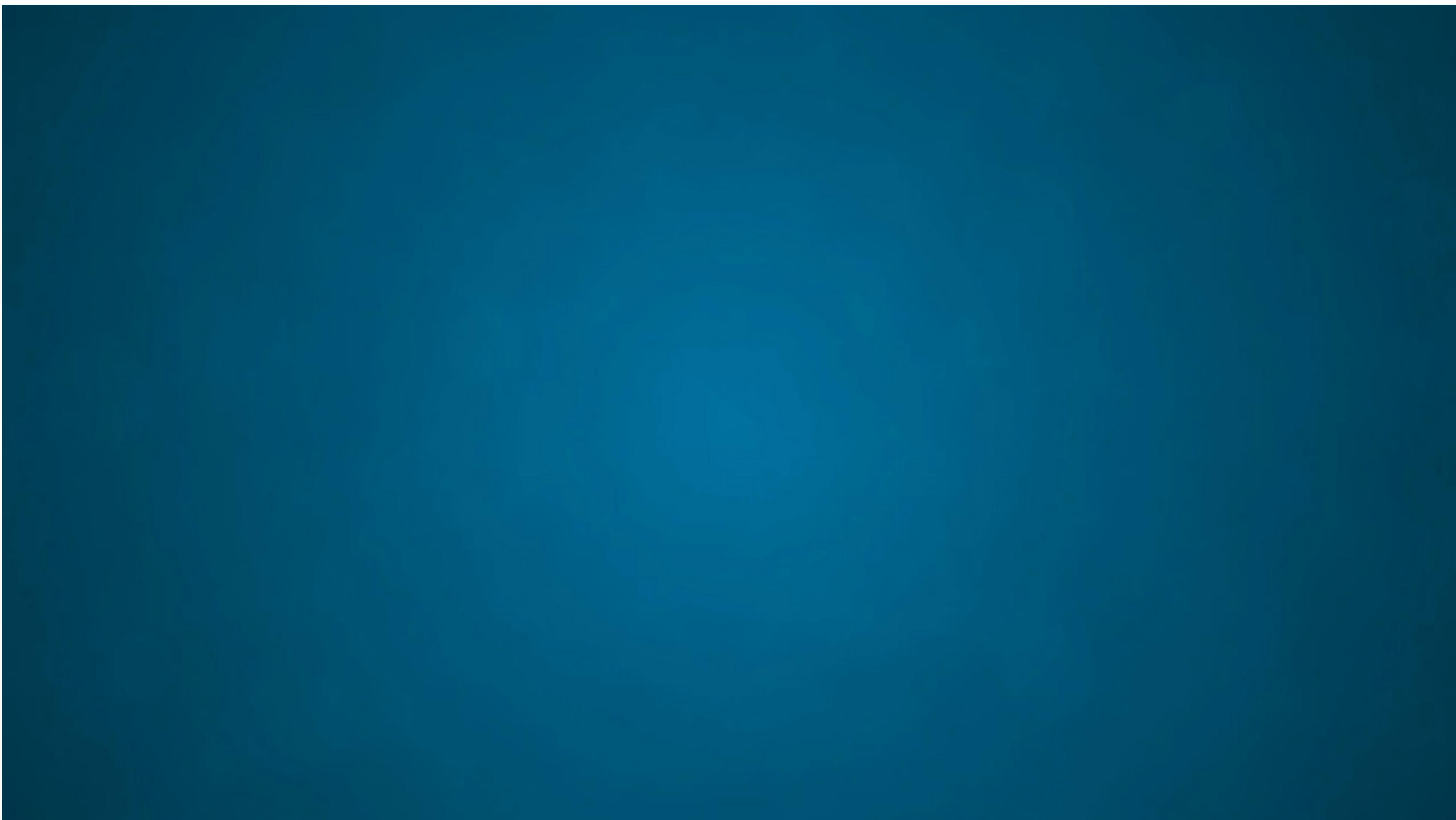
2. Accelerators and Beams

- ▶ LHC (Geneva, Switzerland) collides beams with maximum particle energies of **6.5 TeV**
- ▶ Ring is 27 km in circumference and most powerful in the world
- ▶ Can collide p-p, p-A and A-A ions.



LHC: Large hadron collider
SPS: Super proton synchrotron
AD: Antiproton decelerator
ISOLDE: Isotope separator online device
PSB: Proton synchrotron booster
PS: Proton synchrotron
LINAC: Linear acceleration
LEIR: Low energy ion ring
CNGS: Cern neutrinos to Gran Sasso

2. Accelerators and Beams

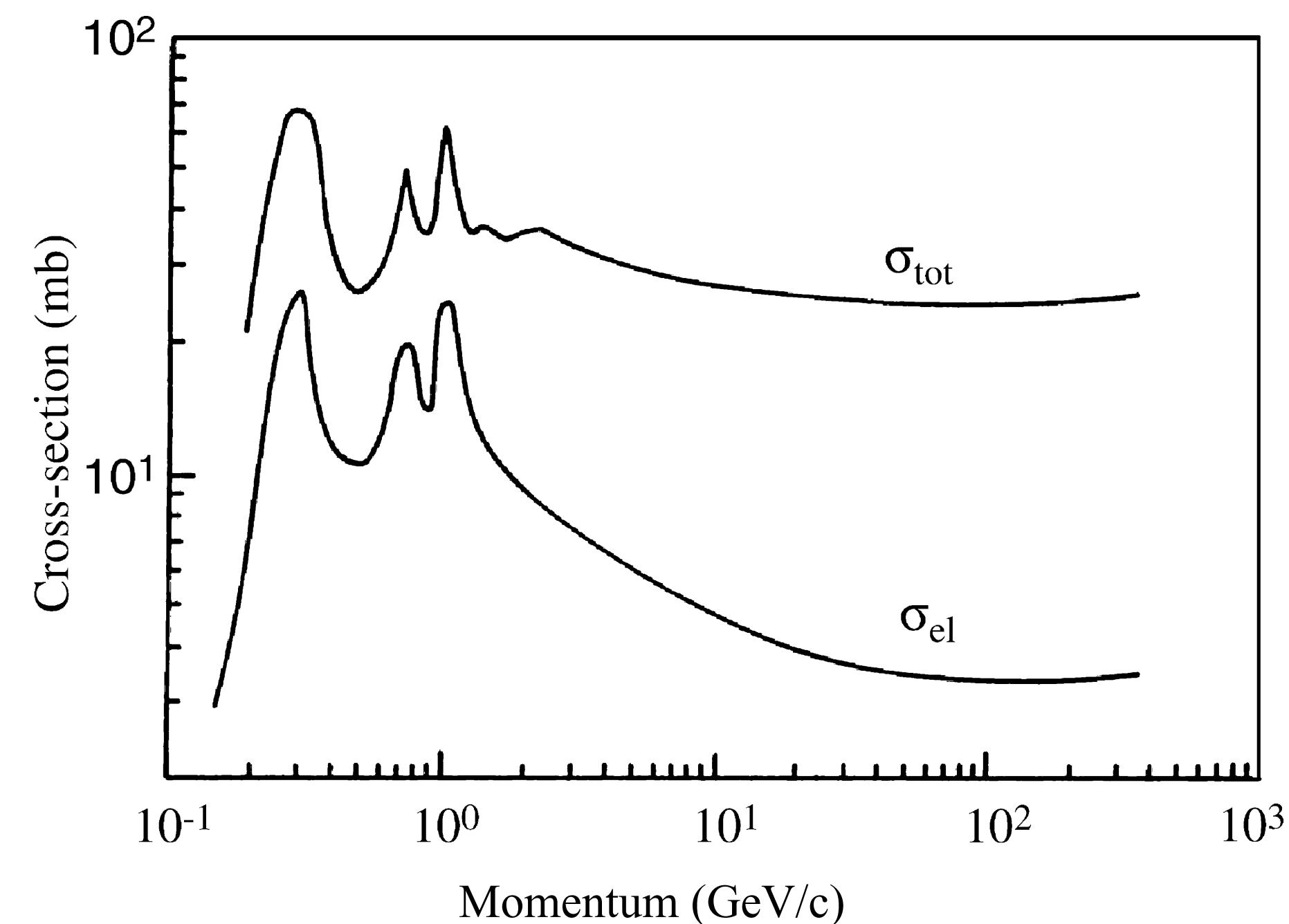


3. Particle Interactions with Matter

- In order to be detected, a **created particle from a collision must undergo an interaction with the material of a detector.**
- The **first possibility is that the particle interacts with an atomic nucleus**, e.g., via a strong (hadronic) or weak interaction (neutrino). Sometimes new particles are made, which can then be detected.
- Second is **charged particles may excite/ionize atoms via interactions with electrons**, leading to ionization energy losses and also leading to radiation energy losses.
- Most detectors utilize second process

3. Particle Interactions with Matter

- Many hadronic cross-sections (short range) show interesting structure at low energies due to hadronic resonances.
- At energies above about 3 GeV, **total cross-sections** are usually slowly varying.



3. Particle Interactions with Matter

- ▶ The probability of a hadron-nucleus interaction occurring as the hadron traverses a small thickness dx of material is given by:
 - ▶ $dp = n\sigma_{\text{tot}} dx$
- ▶ where n is the number of nuclei per unit volume in the material. Mean distance travelled before interaction
 - $$\ell_c = 1/n\sigma_{\text{tot}}$$
- ▶ Often called collision length.

3. Particle Interactions with Matter

- ▶ An analogous quantity is the absorption length, defined by:

$$\ell_a = 1/n\sigma_{\text{inel}},$$

- ▶ governs the probability of an inelastic collision. At high energies $l_c \approx l_a$. Finally, the basis for studying neutrinos is (hard particle to detect!):

$$\bar{\nu}_\ell + p \rightarrow \ell^+ + X,$$

- ▶ and they typically have very long absorption lengths.

3. Particle Interactions with Matter

- Ionization energy losses are used for the detection of all charged particles. The Bethe-Bloch formula describes this process:

$$-\frac{dE}{dx} = \frac{D q^2 n_e}{\beta^2} \left[\ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I}\right) - \beta^2 \right],$$

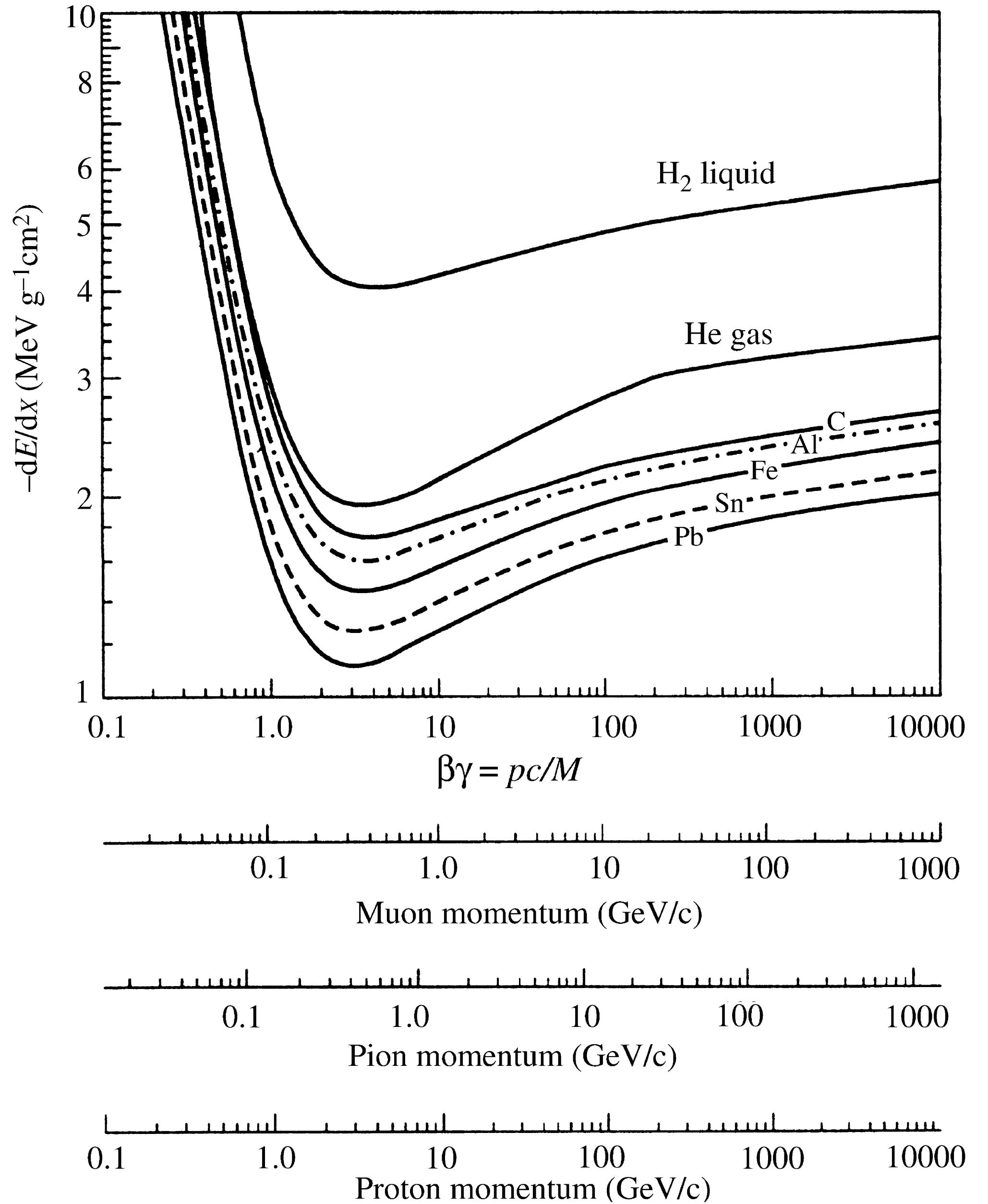
- If v is the velocity of the particle, $\beta=v/c$, $\gamma=(1-\beta^2)^{-1/2}$. It depends on the charge q of the particle traveling through the material. The constant

$$D = \frac{4\pi\alpha^2 \hbar^2}{m_e} = 5.1 \times 10^{-25} \text{ MeV cm}^2,$$

- and the other constants are due to the material's properties.

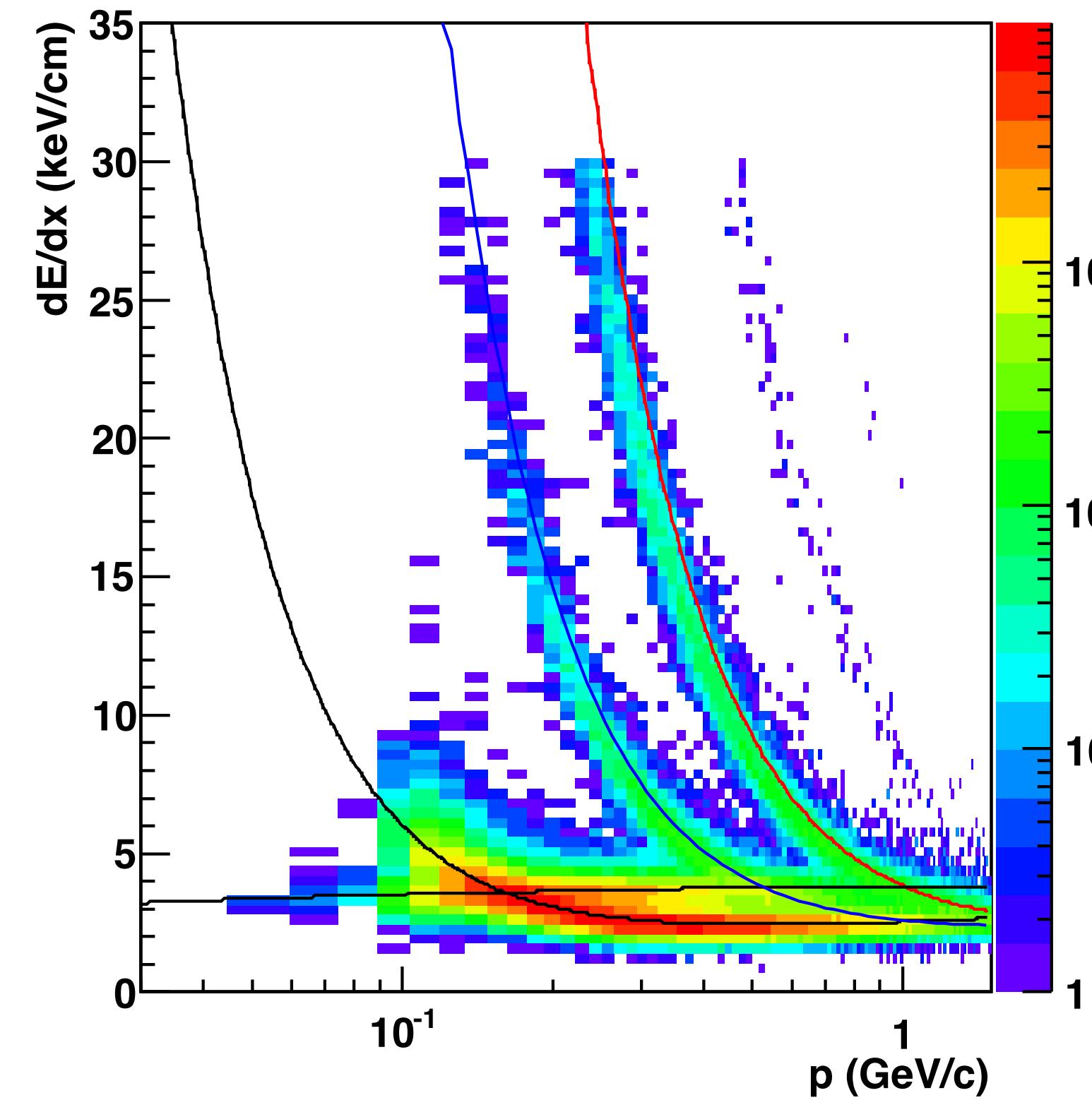
3. Particle Interactions with Matter

- Sometimes dE/dx is divided by the density.
- Left shows ionization loss for muons, pion, protons for different materials.

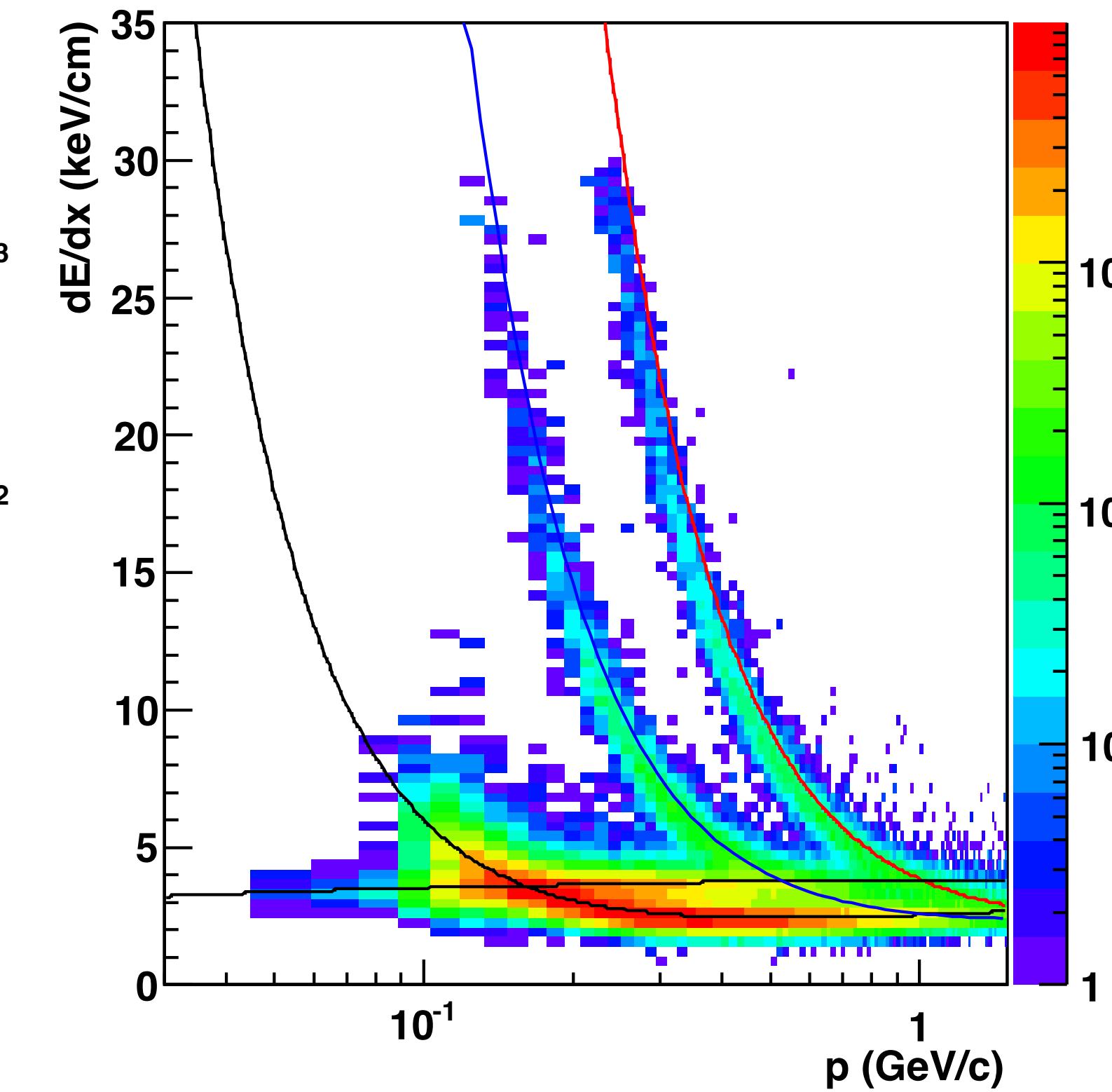


3. Particle Interactions with Matter

- From my thesis - detected particles from STAR experiment



Positive particles



Negative particles

3. Particle Interactions with Matter

- The minimum ionization occurs at $\beta\gamma \approx 3-4$. Factoring out the material density for particles with unit charge:

$$\left(-\frac{dE}{dx} \right)_{\min} \approx 3.5 \frac{Z}{A} \text{ MeVg}^{-1} \text{cm}^2.$$

- The distance a particle will travel before losing all of it's energy is:

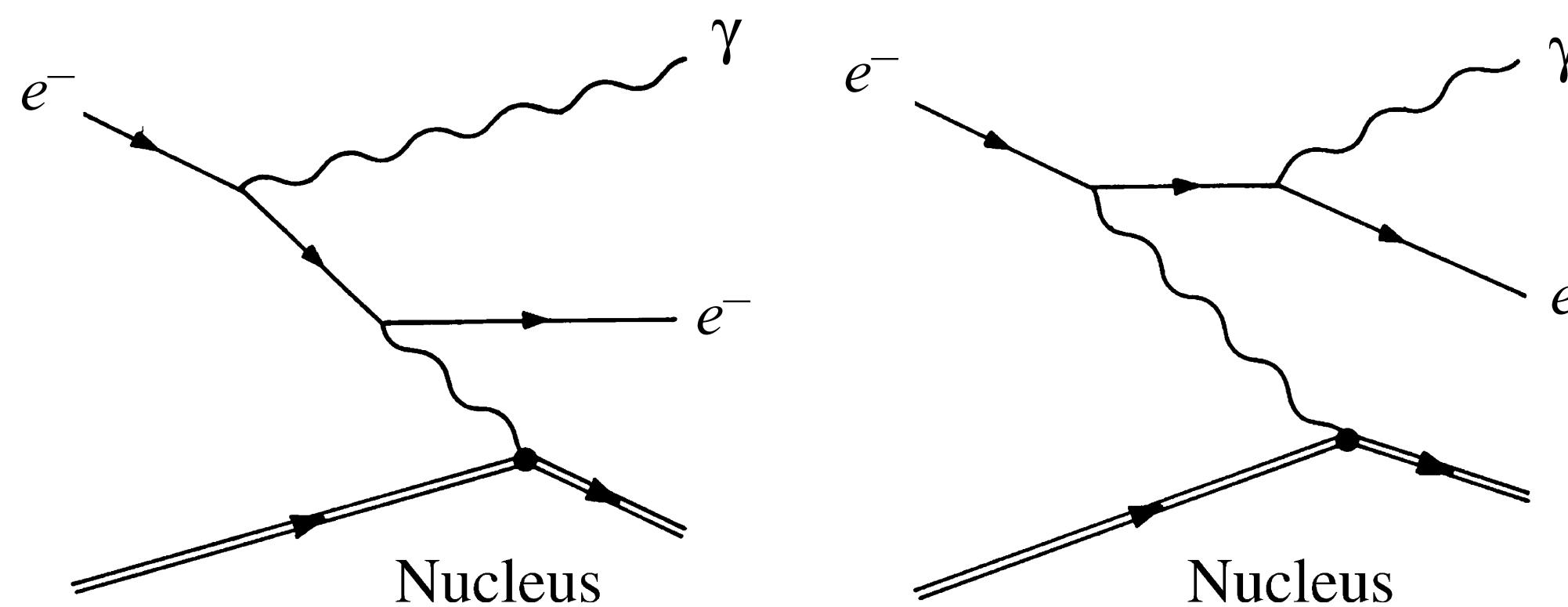
$$R = \int_0^{\beta_{\text{initial}}} \left[-\frac{dE}{dx} \right]^{-1} \frac{dE}{d\beta} d\beta = \frac{M}{q^2 n_e} F(\beta_{\text{initial}}),$$

3. Particle Interactions with Matter

- When a charged particle traverses matter, it can also lose energy by radiating photons through collisions with nuclei, known as **bremsstrahlung**.

$$e^- + (Z, A) \rightarrow e^- + \gamma + (Z, A),$$

- The Feynman diagrams associated with this process are:



3. Particle Interactions with Matter

- For relativistic electrons, the radiative energy loss is given by:

$$-dE/dx = E/L_R.$$

- where L_R is a constant, known as the **radiation length**, which depends on Z and n_a (number of atoms per unit volume). Integrating:

$$E = -E_0 \exp(-x/L_R),$$

- where E_0 is the initial energy. Generally $-dE/dx = CE/m^2$

3. Particle Interactions with Matter

- Photons will also have a probability of being scattered/absorbed by matter

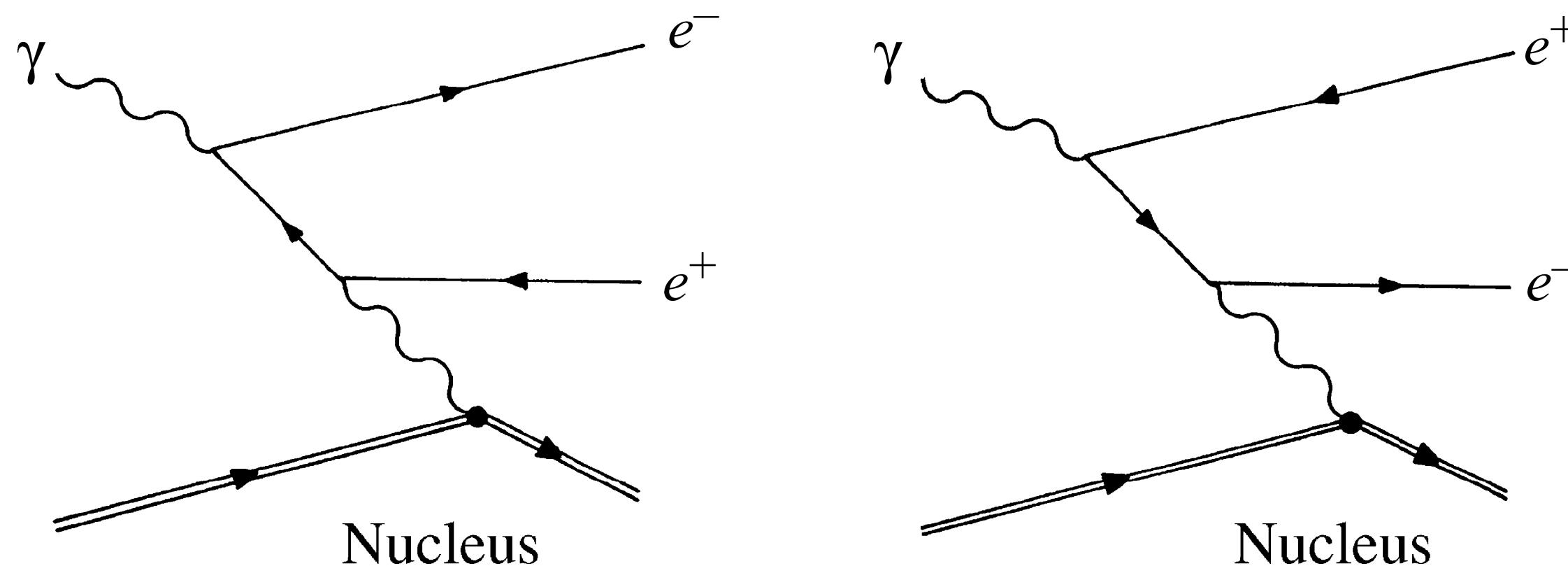


Figure 4.11 The pair production process $\gamma + (Z, A) \rightarrow e^- + e^+ + (Z, A)$

- For a beam with I photons per second traversing a small thickness of matter:

$$dI = -I \frac{dx}{\lambda}$$

3. Particle Interactions with Matter

- ▶ The mean free path before absorption is:

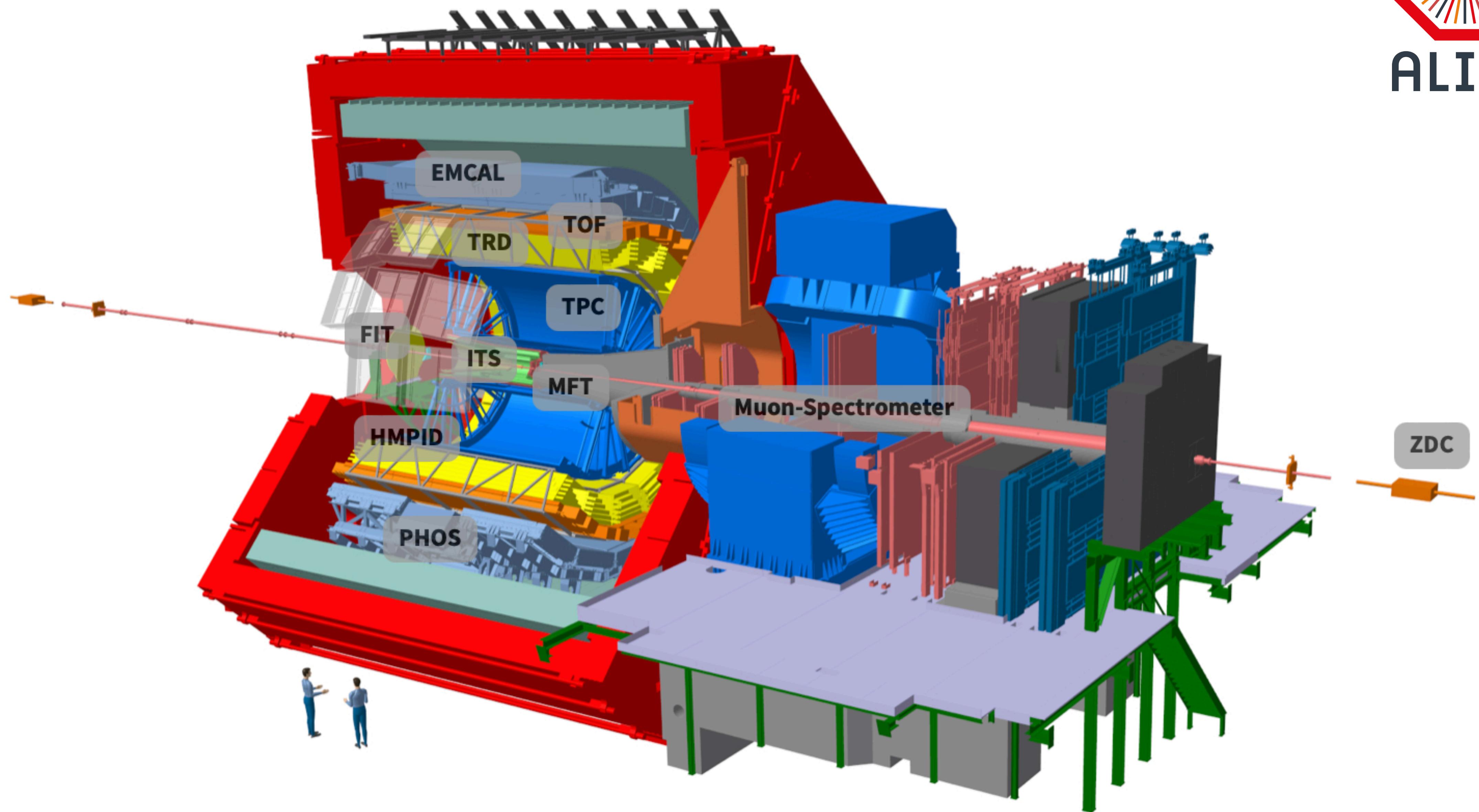
$$\lambda = (n_a \sigma_\gamma)^{-1}$$

- ▶ where σ_γ is the cross section for such a process. Integrating:

$$I(x) = I_0 e^{-x/\lambda}$$

- ▶ where I_0 is the initial intensity.

4. Particle Detectors

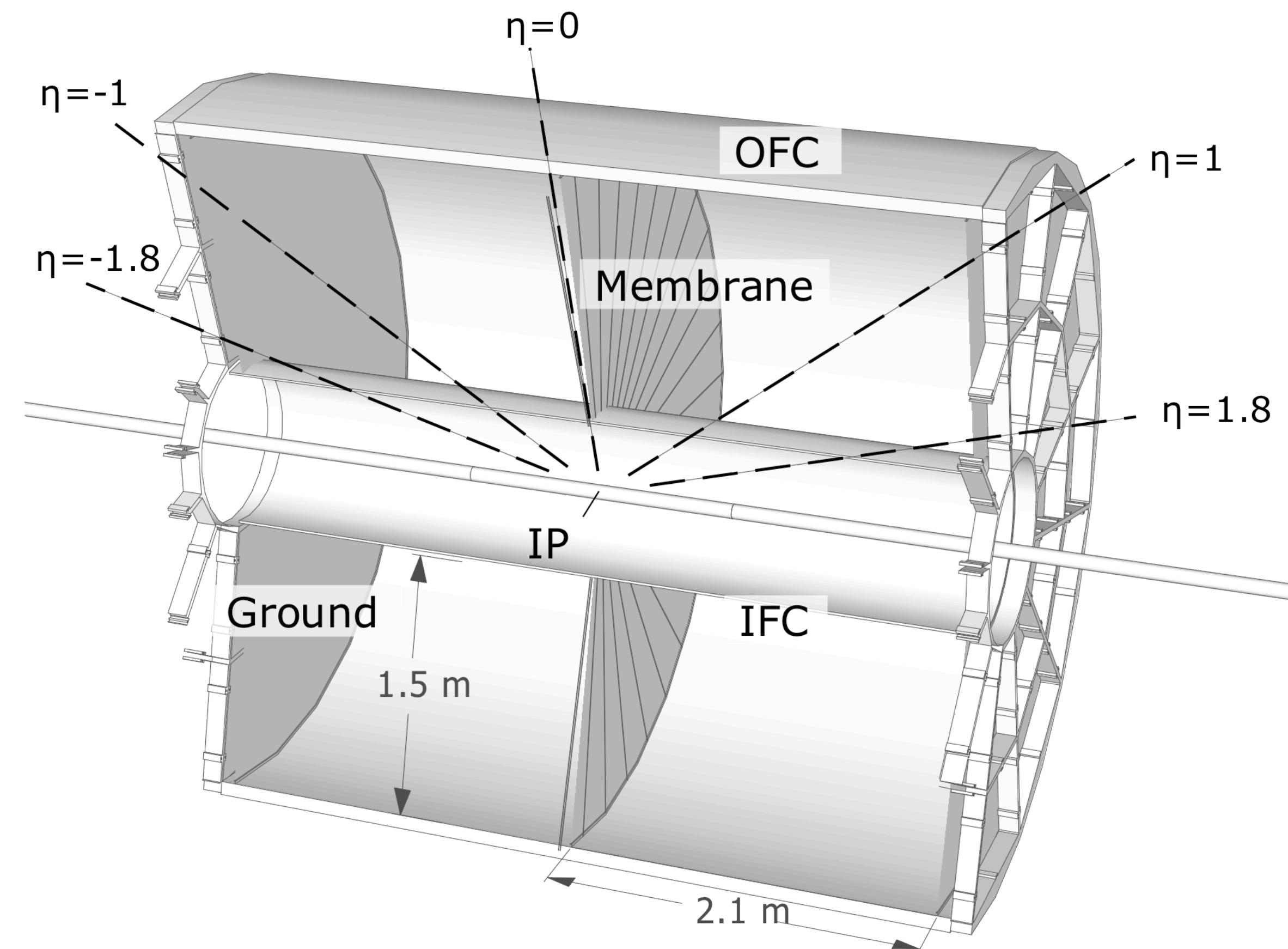


4. Particle Detectors

- **Gas detectors** detect the ionization produced when a charged particle passes through a gas.
- Typical energy needed to produce an electron–ion pair is 30 ± 10 eV
- The ionized particles are then made to drift to regions where their signal can be detected.
- ALICE Time Projection Chamber (TPC) is the world's largest gas detector!

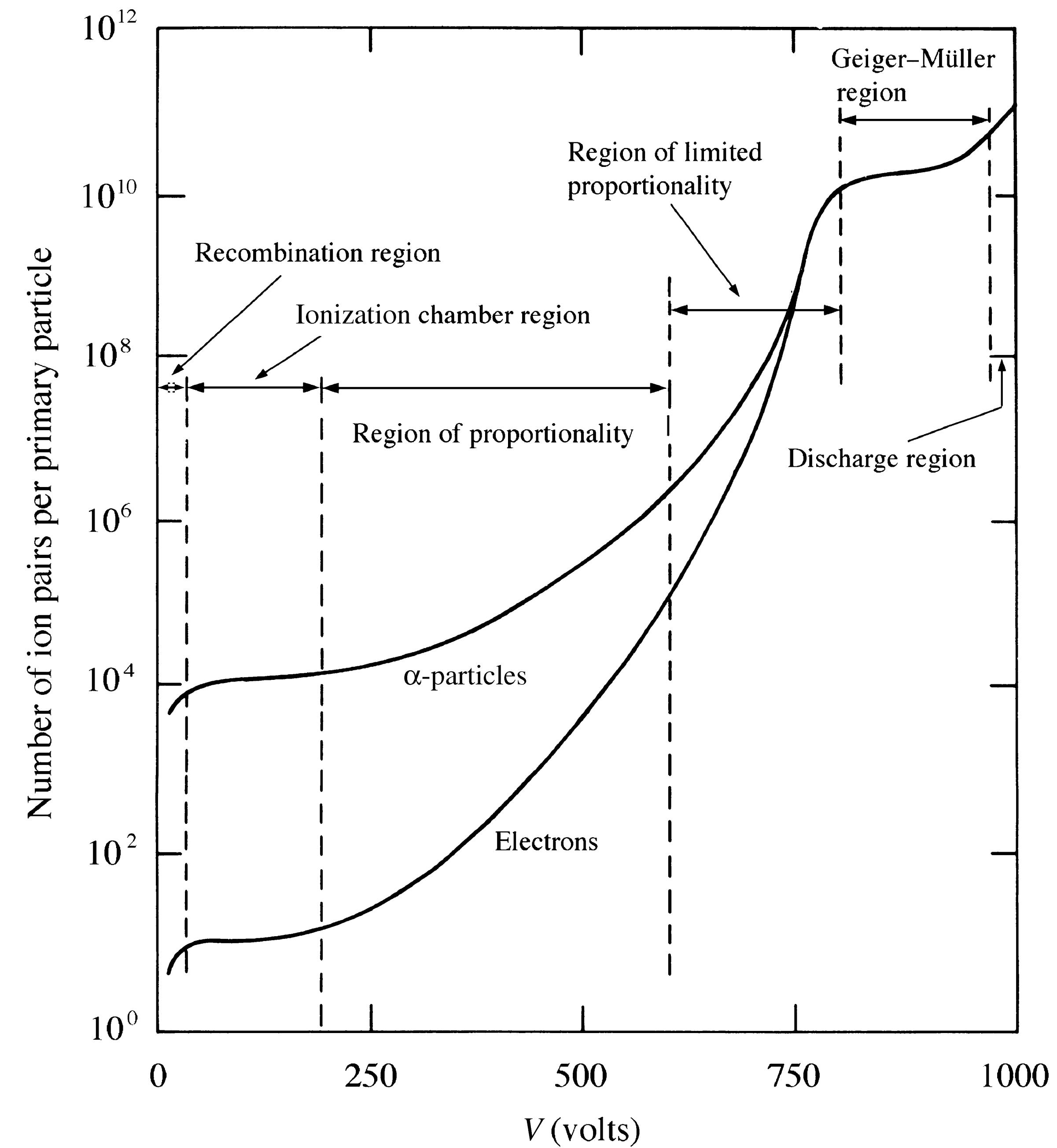
4. Particle Detectors

- ▶ In the **ionization chamber**, voltages are small, they typically have a uniform electric field e.g. **1.4 kV/m**. Ionized particles will drift towards the proportional region.



4. Particle Detectors

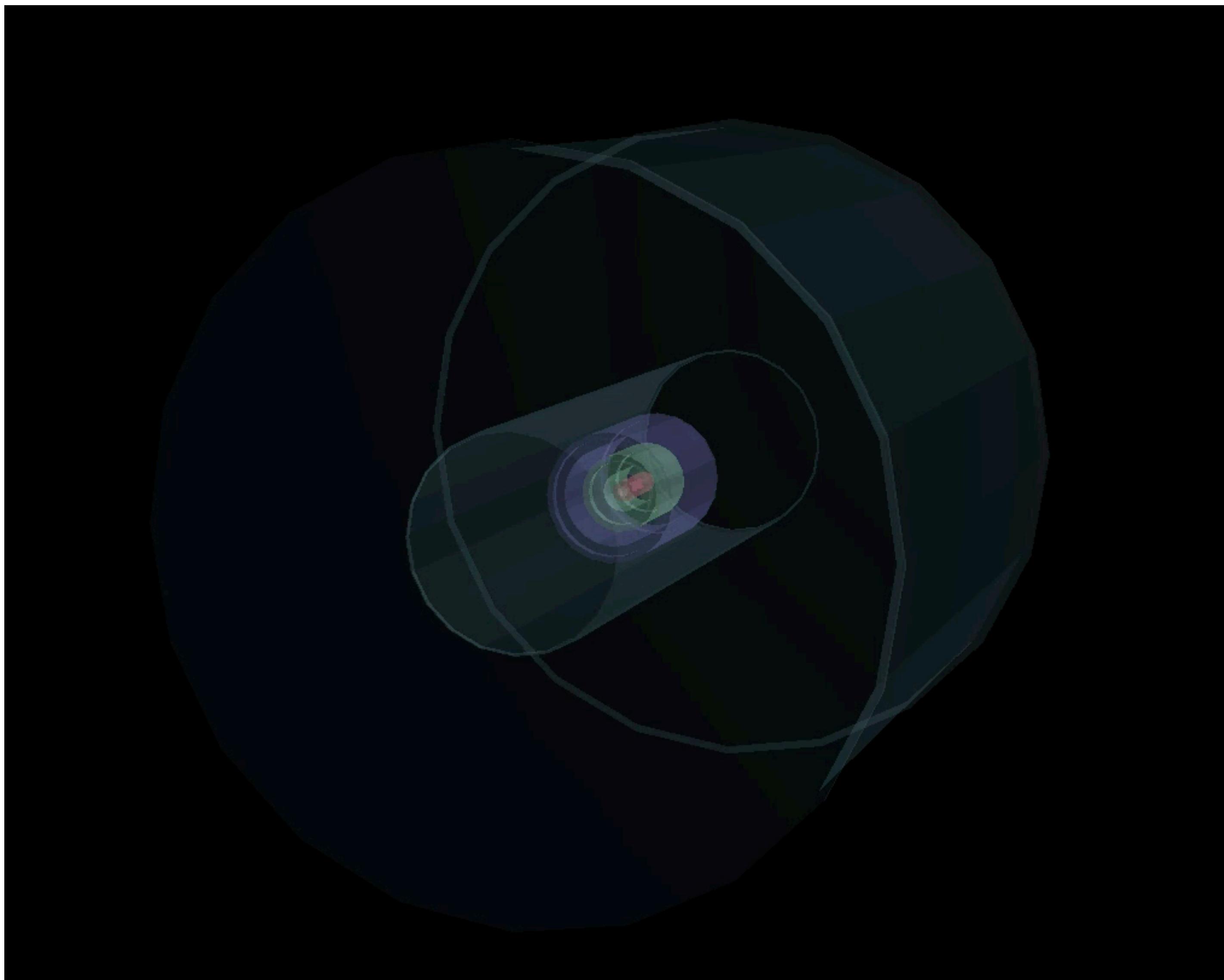
- ▶ Voltages are needed to amplify number of ionized particles



4. Particle Detectors

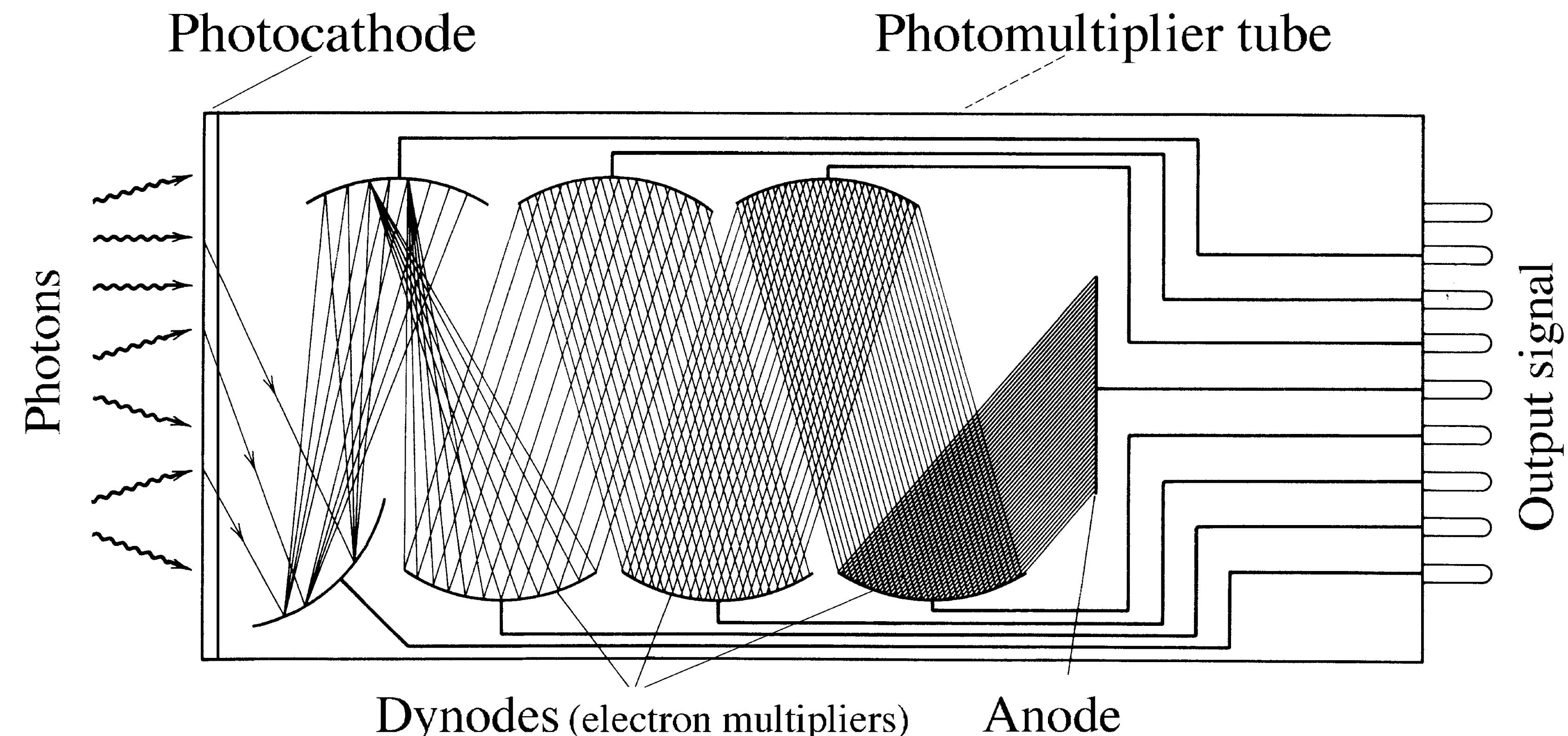
- ▶ In the **proportional region**, the electric field is much greater (**10^7 V/m**)
- ▶ The ionized particles accelerate rapidly and produce secondary ionizations.
- ▶ The readout pads then collect these electrons, producing a measurable voltage pulse, which is recorded as a function of time

4. Particle Detectors



4. Particle Detectors

- In some materials, the interaction of charged particles produces many photons. **Scintillators** can be used to detect these.

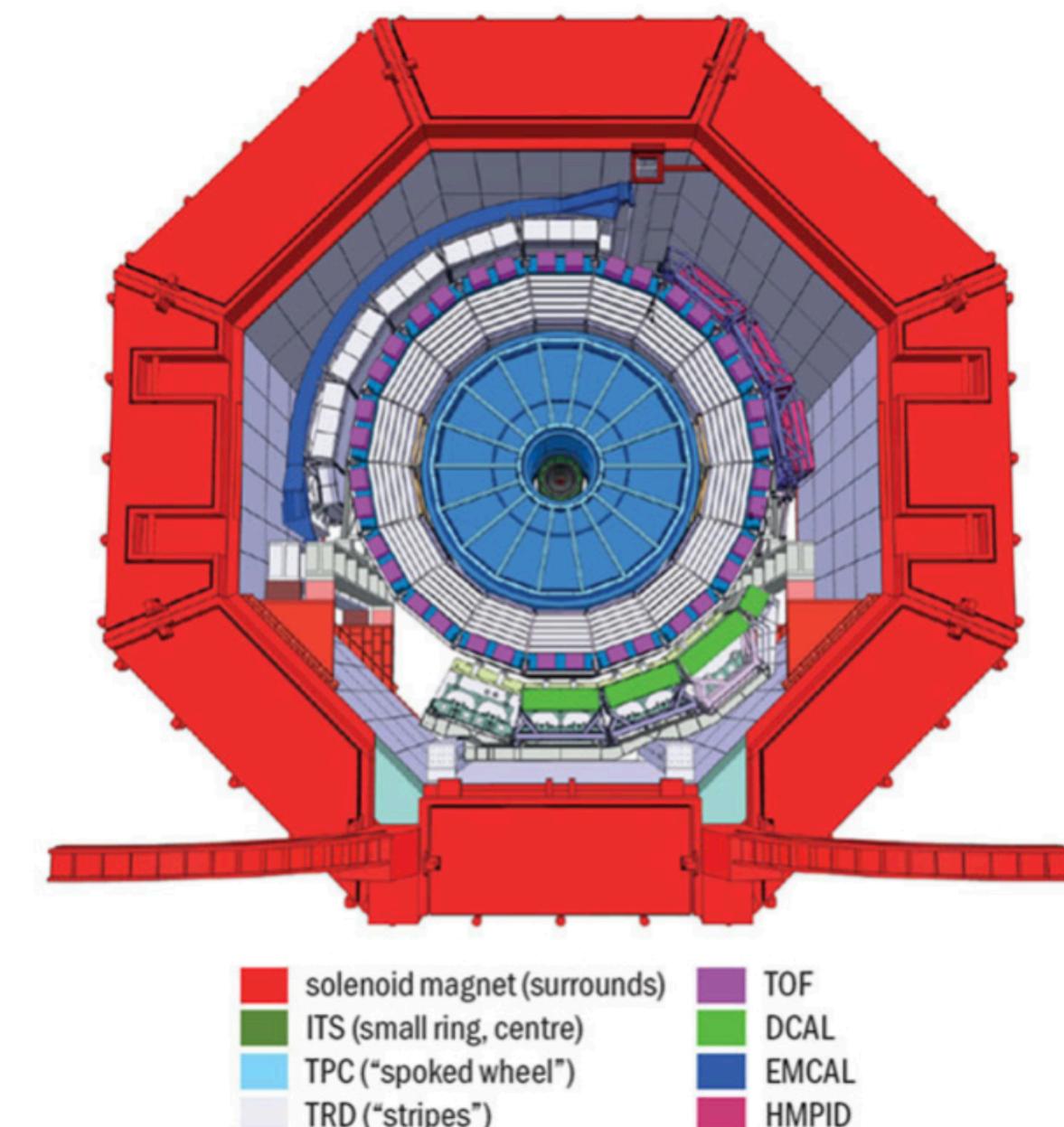


4. Particle Detectors

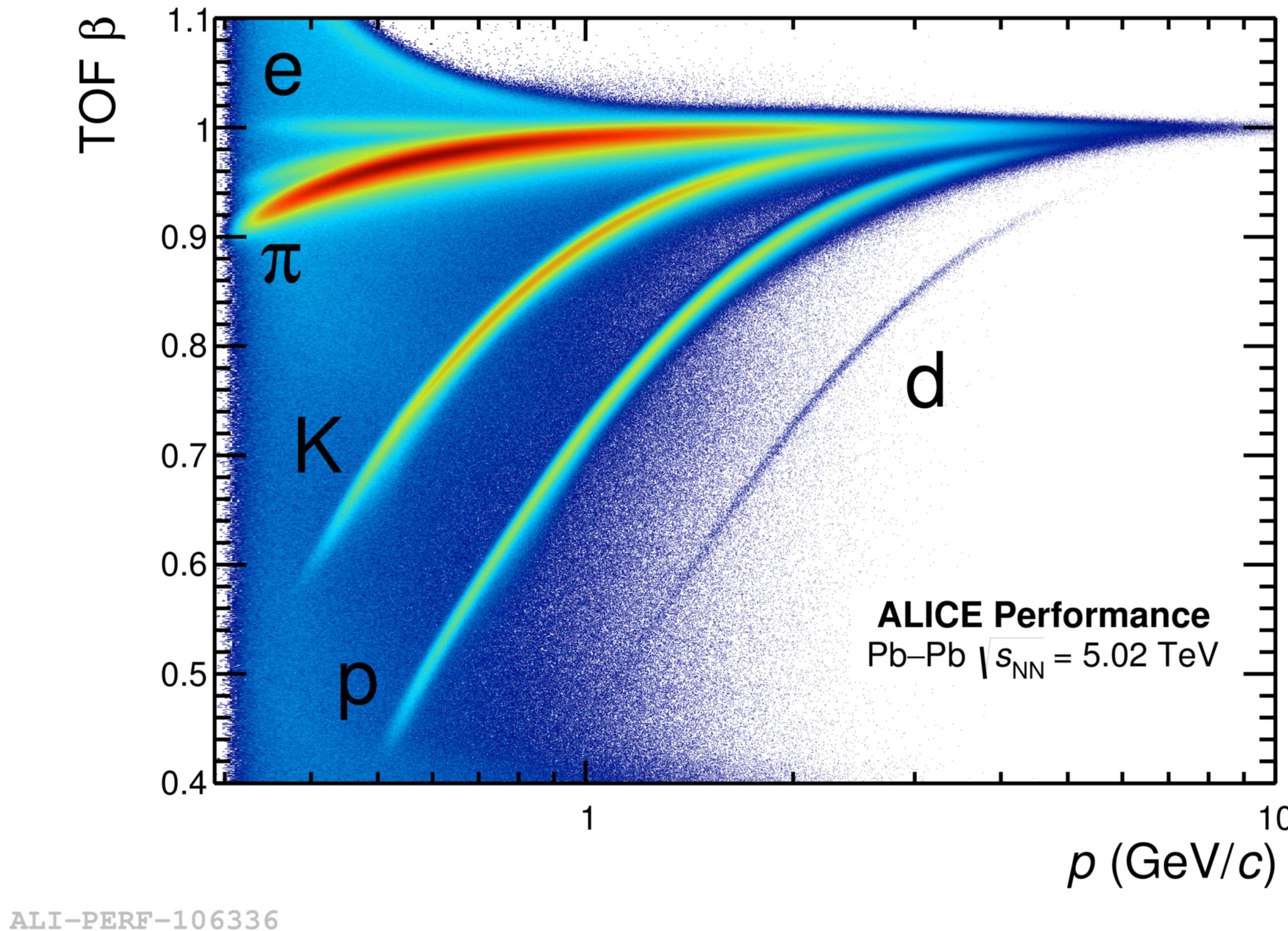
- ▶ Semiconductor detectors, e.g., ALICE ITS, involve the detection of electron-hole pairs created by the passage of a charged particle.
- ▶ Voltage is applied across the detector (creating an electric field), and the electrons and holes drift to the electrodes, producing a measurable current or pulse
- ▶ Have advantage of being **fast**, but are more complex to build compared to gas detectors.

4. Particle Detectors

- ▶ Charged particles leave **tracks** either via ionization trails and/or hits in multiple semiconductor detectors.
- ▶ A magnetic field is almost always used to determine the momentum of a track via $p=0.3B\rho$, since its radius of curvature is known.
- ▶ ALICE uses a warm magnetic field with 0.5 T



4. Particle Detectors

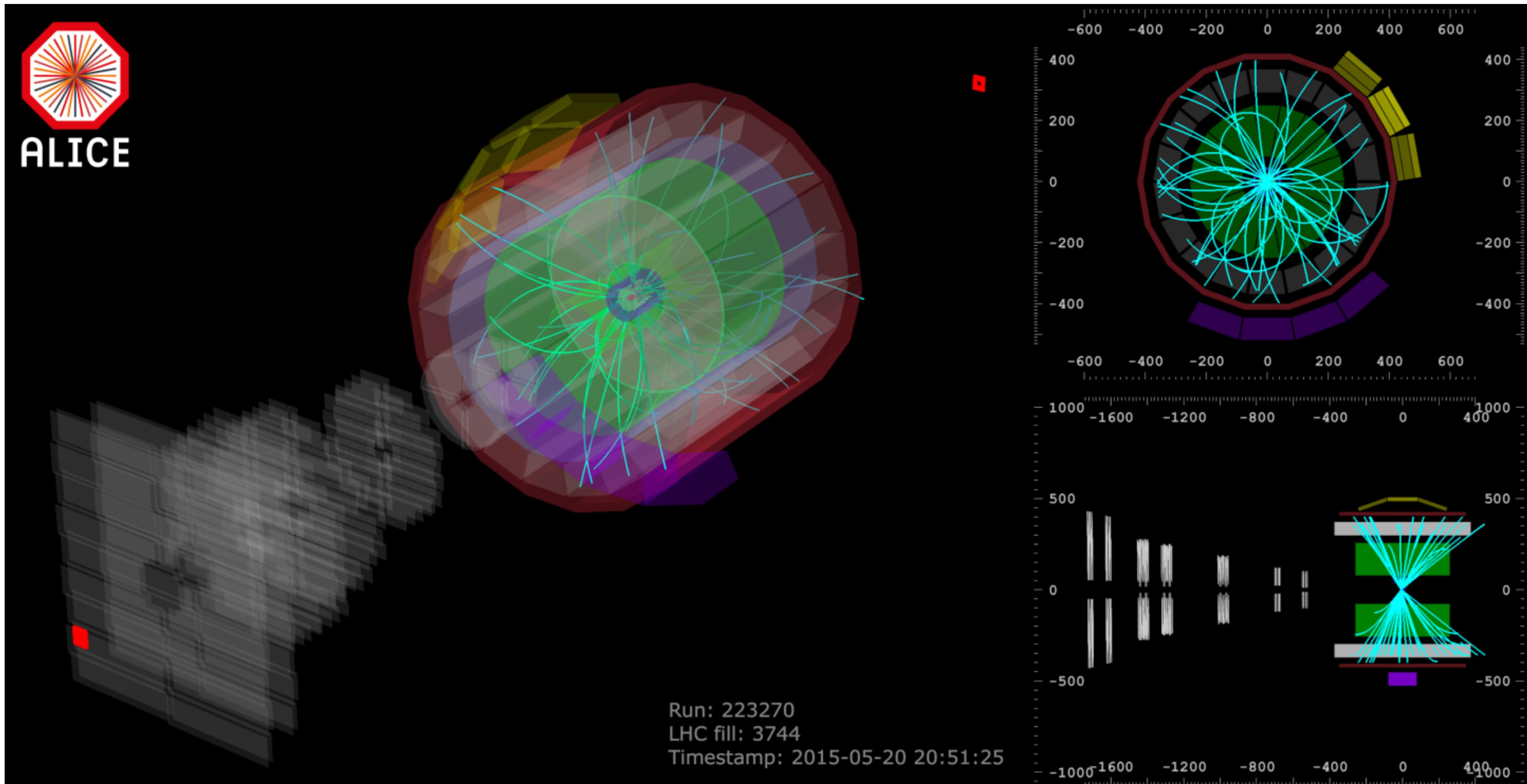


- Timing detectors (ALICE TOF) can be used to determine mass of charged particle via a measurement of the track velocity ($\beta = v/c$).

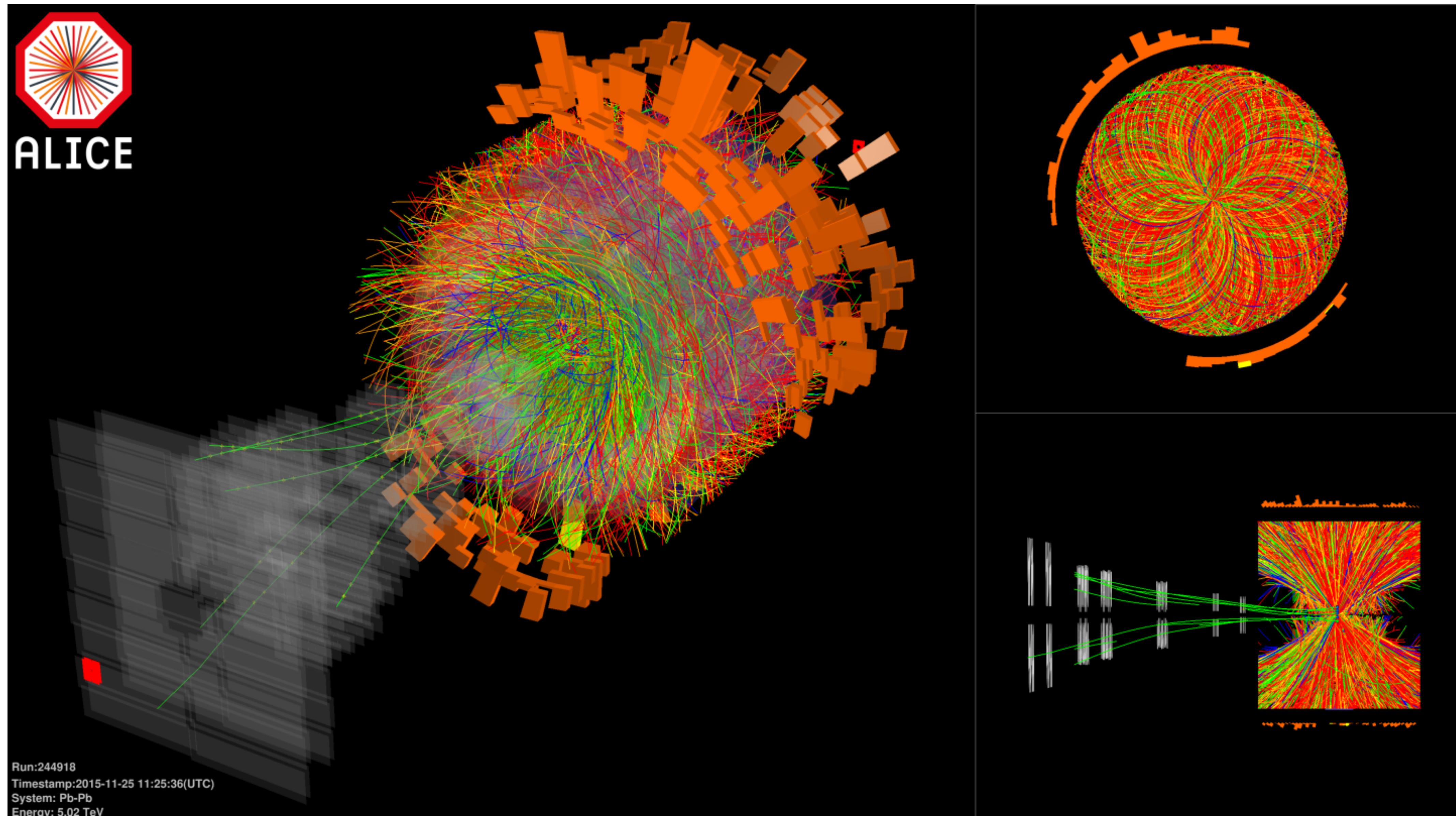
4. Particle Detectors

- **Calorimeters** are detectors used to measure the **energy** and **position** of particles. They are capable of detecting **neutral particles** indirectly, by measuring the charged secondary particles produced in interactions, and they respond very quickly.
- **Electromagnetic calorimeters (ECAL):** Measure electrons, positrons, and photons. Detect the **particle showers** produced by bremsstrahlung, pair production, or absorption
- **Hadronic calorimeters (HCAL):** Measure hadrons (protons, neutrons, pions) by detecting **hadronic showers** produced in the detector material.

4. Particle Detectors

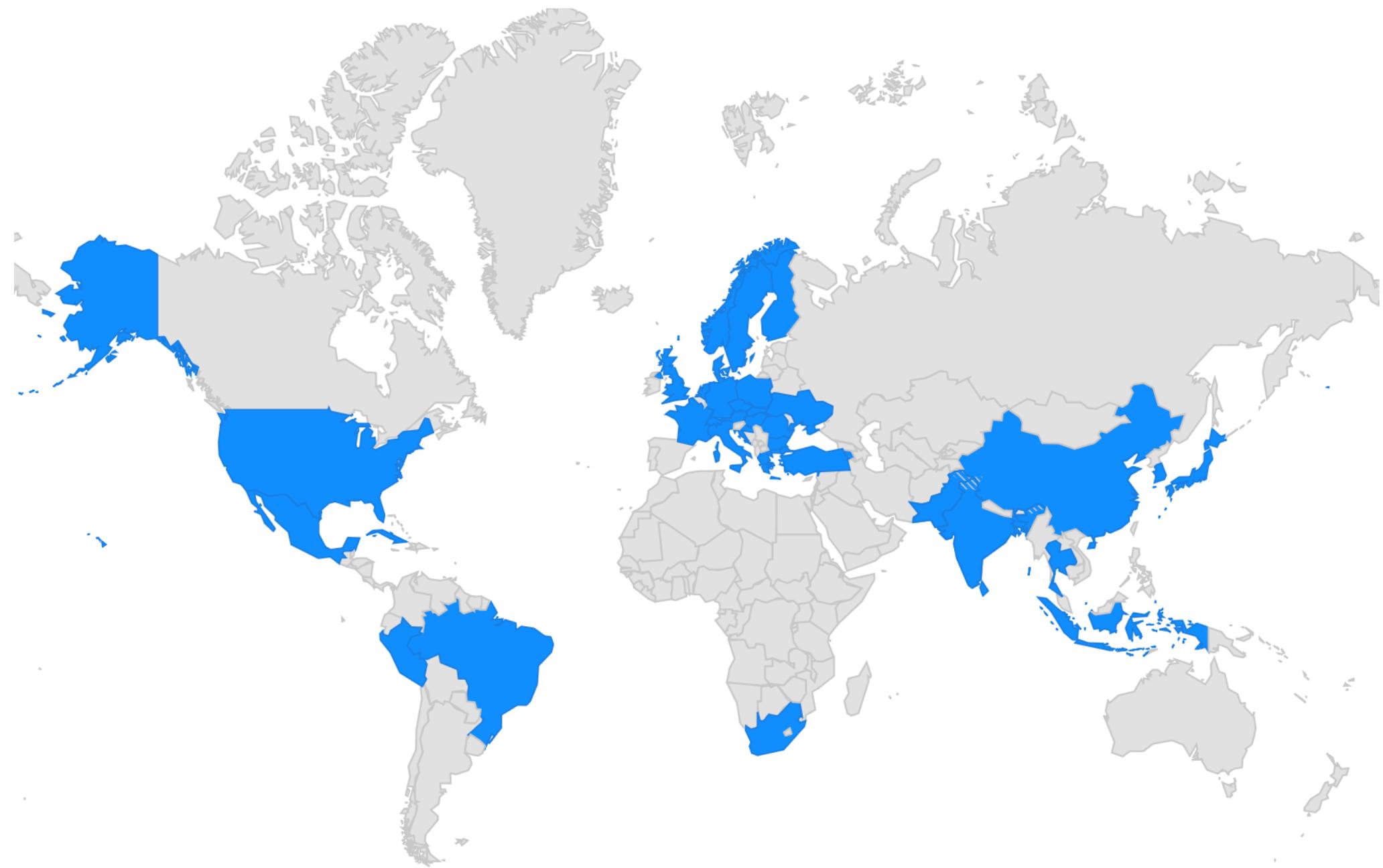


4. Particle Detectors



4. Particle Detectors

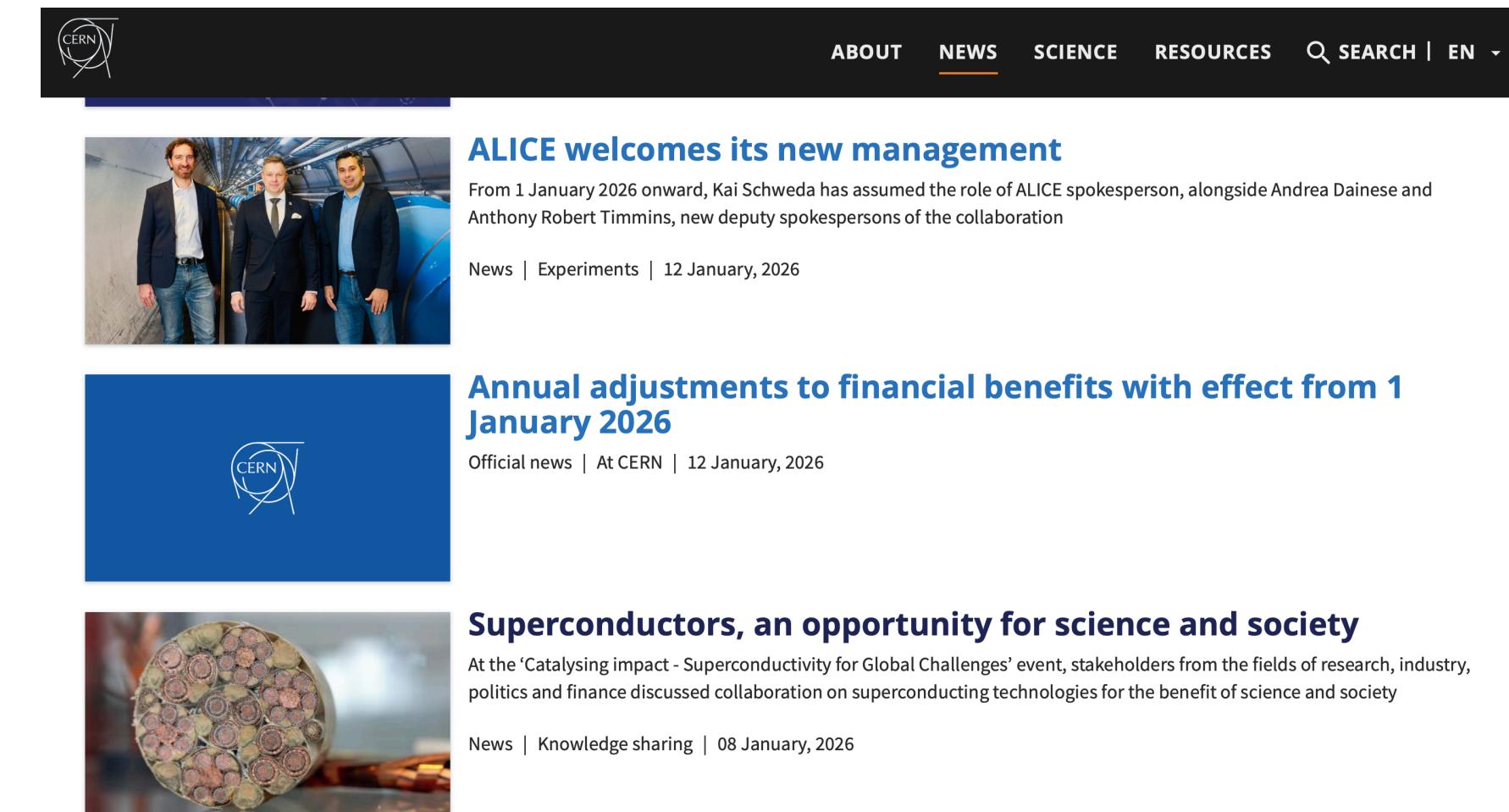
38 countries, 169 institutes, 1837 members



- ▶ ALICE is the largest nuclear physics experiment in the world in terms of collaboration membership...

5. Summary and fun facts

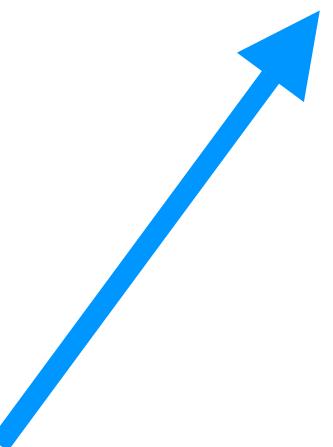
Type	Experiment	Title of CERN Physics news article	Social media shares
HI	ALICE	ALICE detects the conversion of lead into gold at the LHC	667
HI	ALICE	ALICE solves mystery of light-nuclei survival	421
	CMS	First observation of single top quark production with W and Z bosons	352
	CMS	Deciphering the heavyweights of the tetraquark world	270
	CMS	AI enhances Higgs boson's charm	267
	CMS	Clocking nature's heaviest elementary particle	155
HI	ALICE	First evidence of heaviest anti-nucleus	150
HI	ALICE	ALICE eyes the cosmos	144
	ATLAS	ATLAS gets under the hood of the Higgs mechanism	138
HI	NA61	Symmetry between up and down quarks is more broken than expected	129
HI	ALL	Shape-shifting collisions probe secrets of early Universe	128
	CMS	CMS finds unexpected excess of top quarks	105
	ATLAS	Observing triplets of weak bosons	100
HI	ALL	The other 99%	98
	LHCb	Searching for new physics with beauty particles	58
	ALL	A bestiary of exotic hadrons	27



ALICE welcomes its new management
From 1 January 2026 onward, Kai Schweda has assumed the role of ALICE spokesperson, alongside Andrea Dainese and Anthony Robert Timmins, new deputy spokespersons of the collaboration
News | Experiments | 12 January, 2026

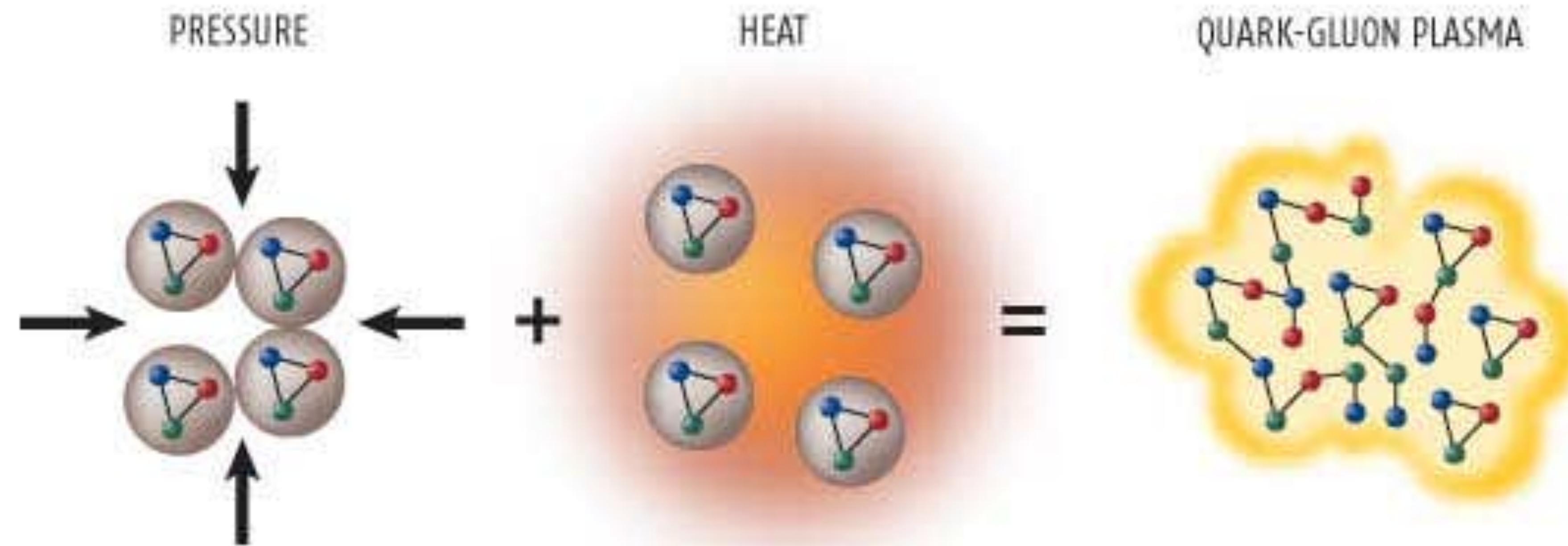
Annual adjustments to financial benefits with effect from 1 January 2026
Official news | At CERN | 12 January, 2026

Superconductors, an opportunity for science and society
At the 'Catalysing impact - Superconductivity for Global Challenges' event, stakeholders from the fields of research, industry, politics and finance discussed collaboration on superconducting technologies for the benefit of science and society
News | Knowledge sharing | 08 January, 2026



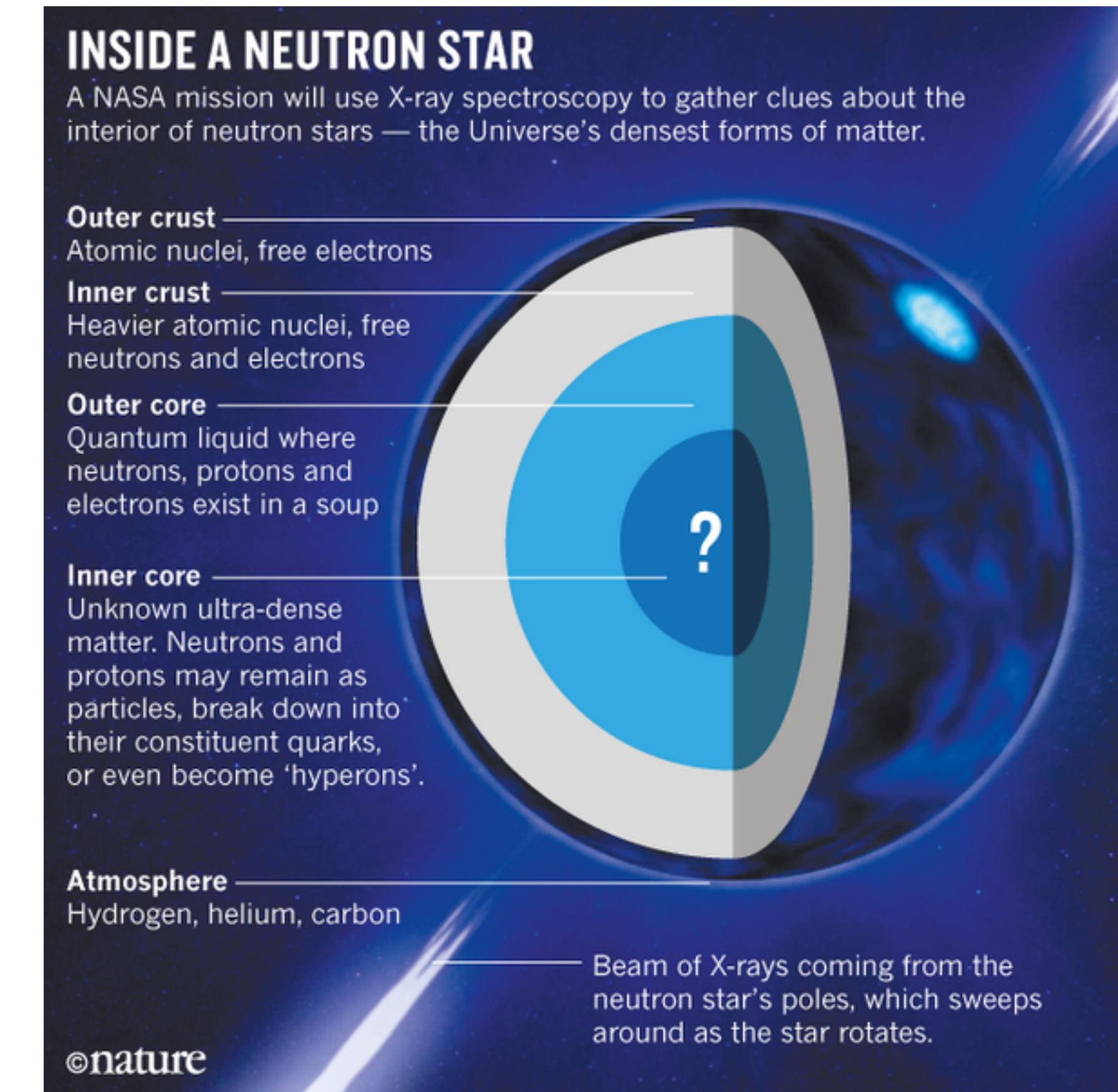
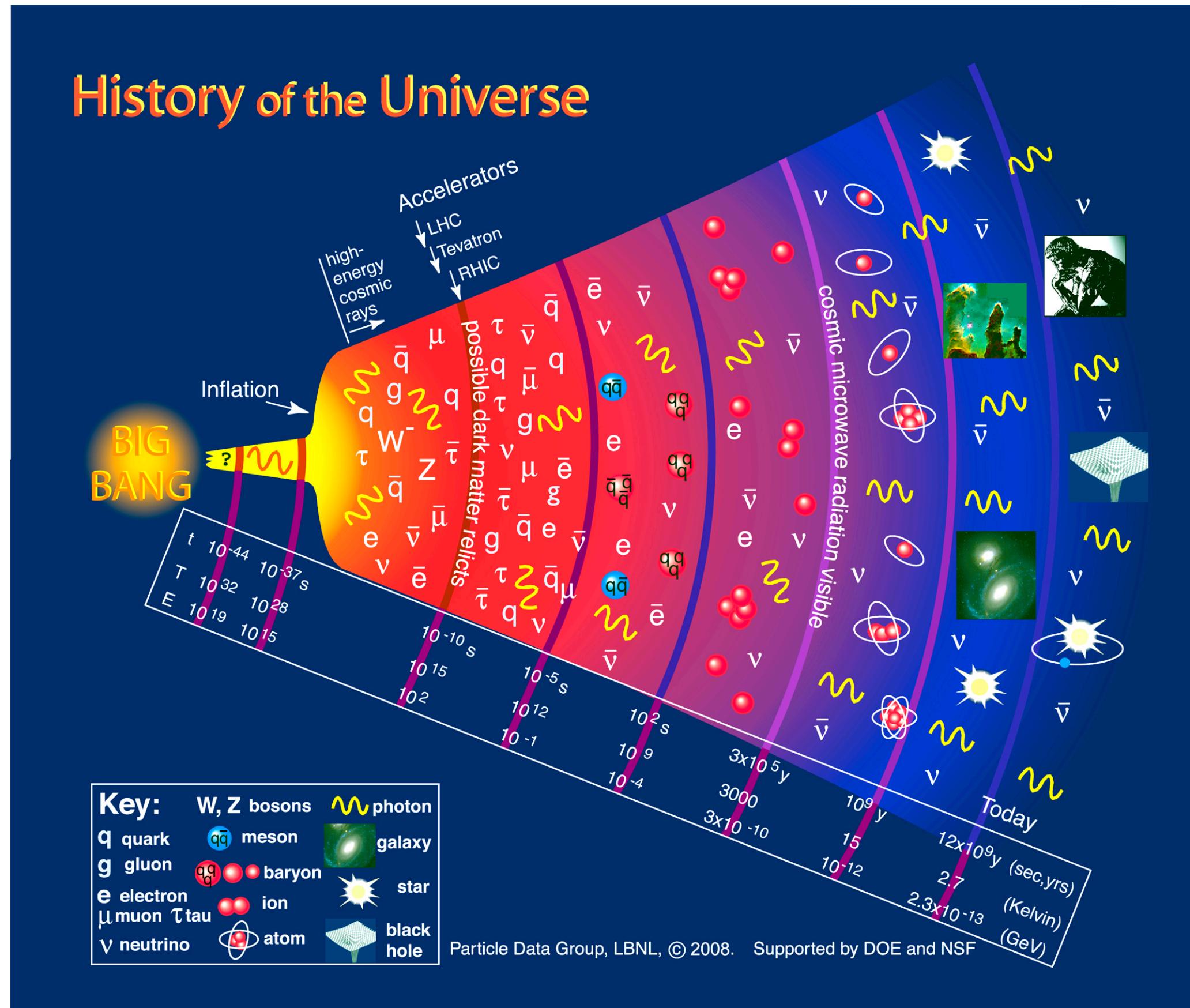
- Discoveries by heavy-ion physics are **very prominent at CERN in 2025.**
- Almost **half the articles** come from **17% of the heavy-ion physicists** at LHC

Back-up: The Quark Gluon Plasma (QGP)



- When a nucleus is compressed and heated, a QGP forms
- ✓ Quarks are no longer localized within protons and neutrons

Back-up: Why is the Quark Gluon Plasma (QGP) interesting?



- ▶ Early universe would have been in the QGP state
- ▶ The core of neutron stars may contain a QGP