The discovery of the positron

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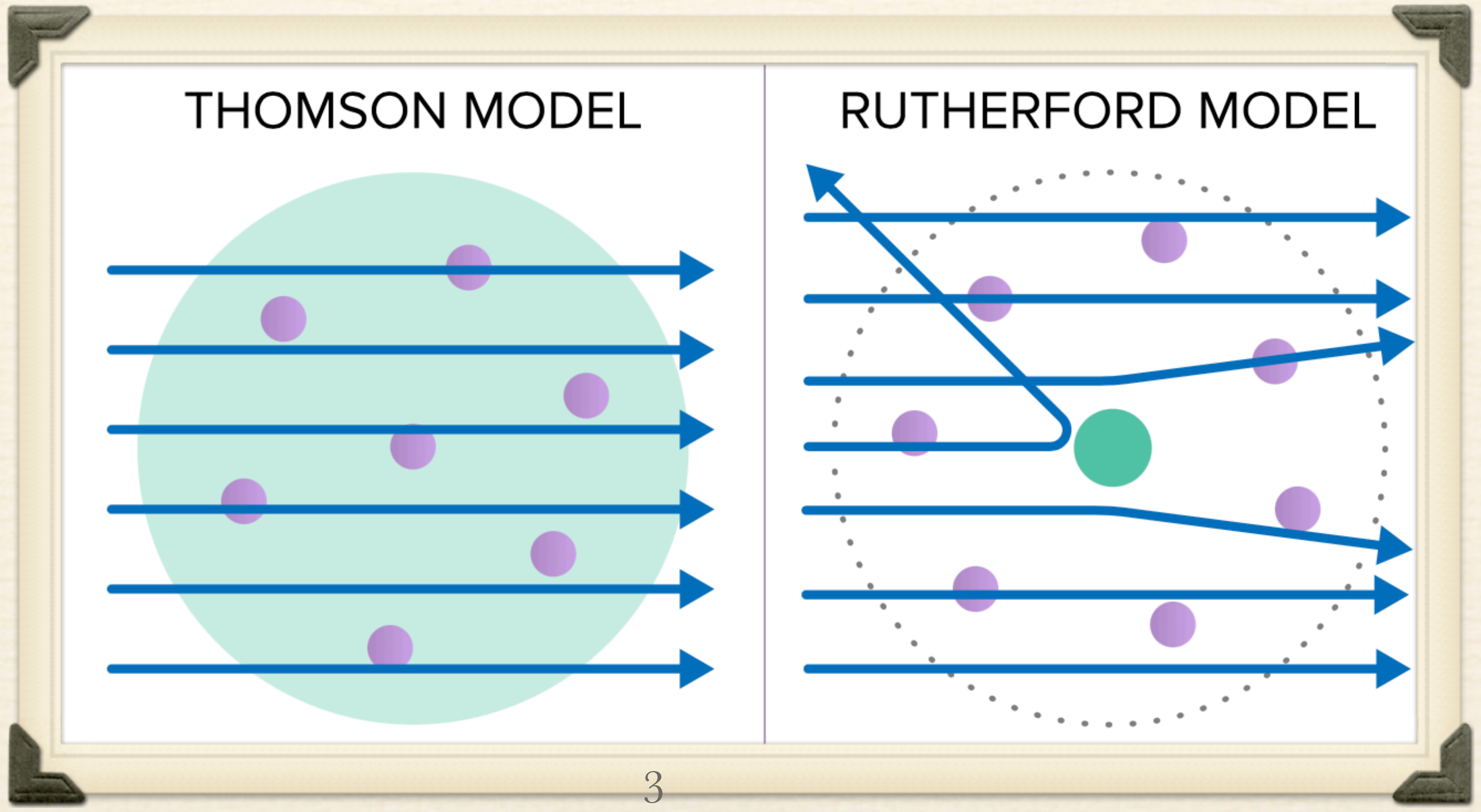
The historical background

- 1895: W. C. Rontgen discovers the X-rays.
- 1896: Henri Becquerel discovers that uranium emits radiation.
- 1897: J. J. Thomson discovers the electron.
- 1898: Marie Curie, with her husband, find two new radioactive elements, **polonium** and **radium**.

The historical background

- 1900: Planck discovers the blackbody radiation law, introducing his constant $\boldsymbol{h}$ and the concept of energy quantized in units of $\boldsymbol{h\nu}$.
- 1905: Einstein used Planck's constant to explain photoelectric effect.
- 1911: Rutherford found the real structure of the atom.



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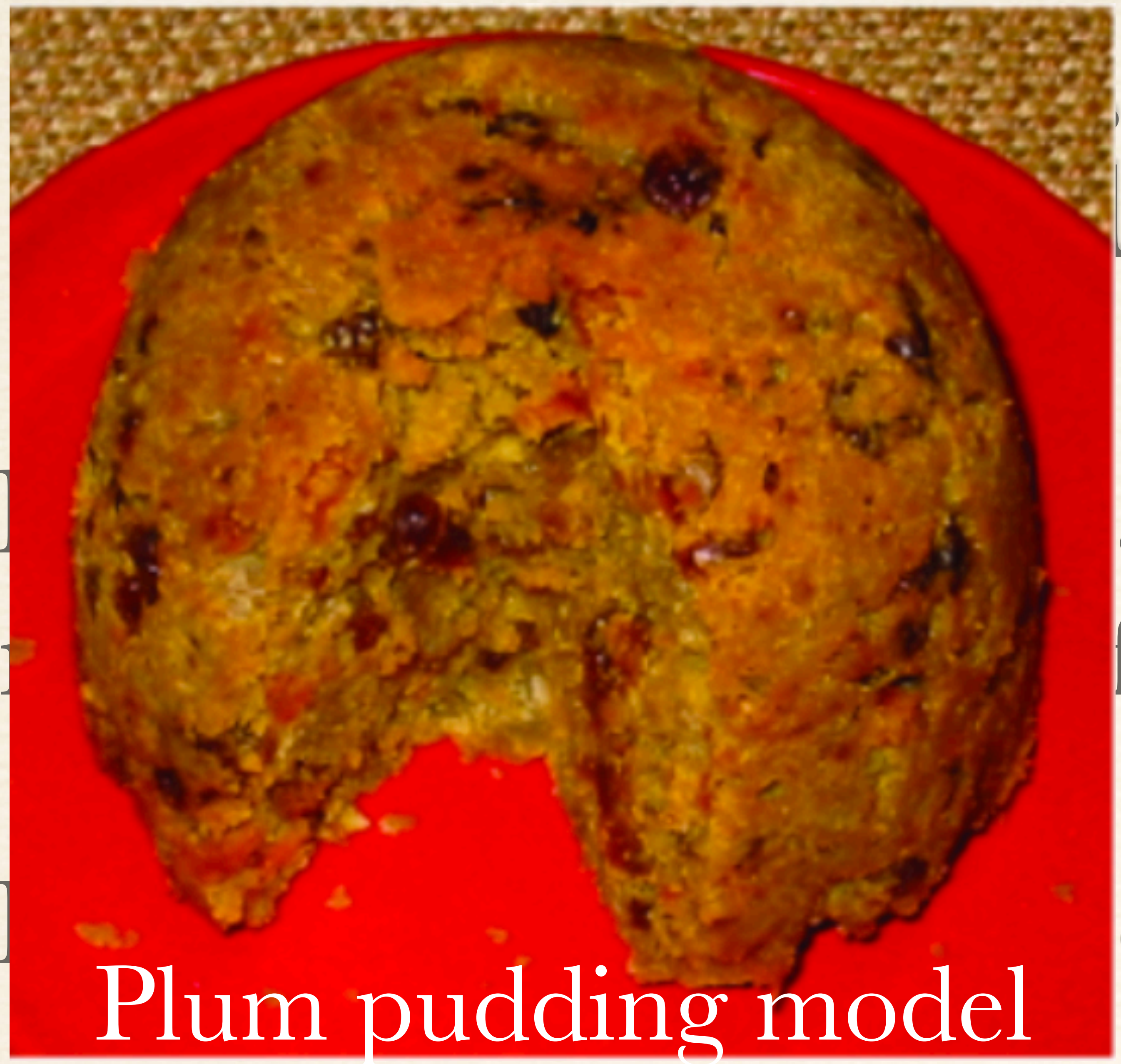

- 1900: I… …ackbody rad… …g his consta… …f energy qua…
- 1905: I… …constant to … …effect.
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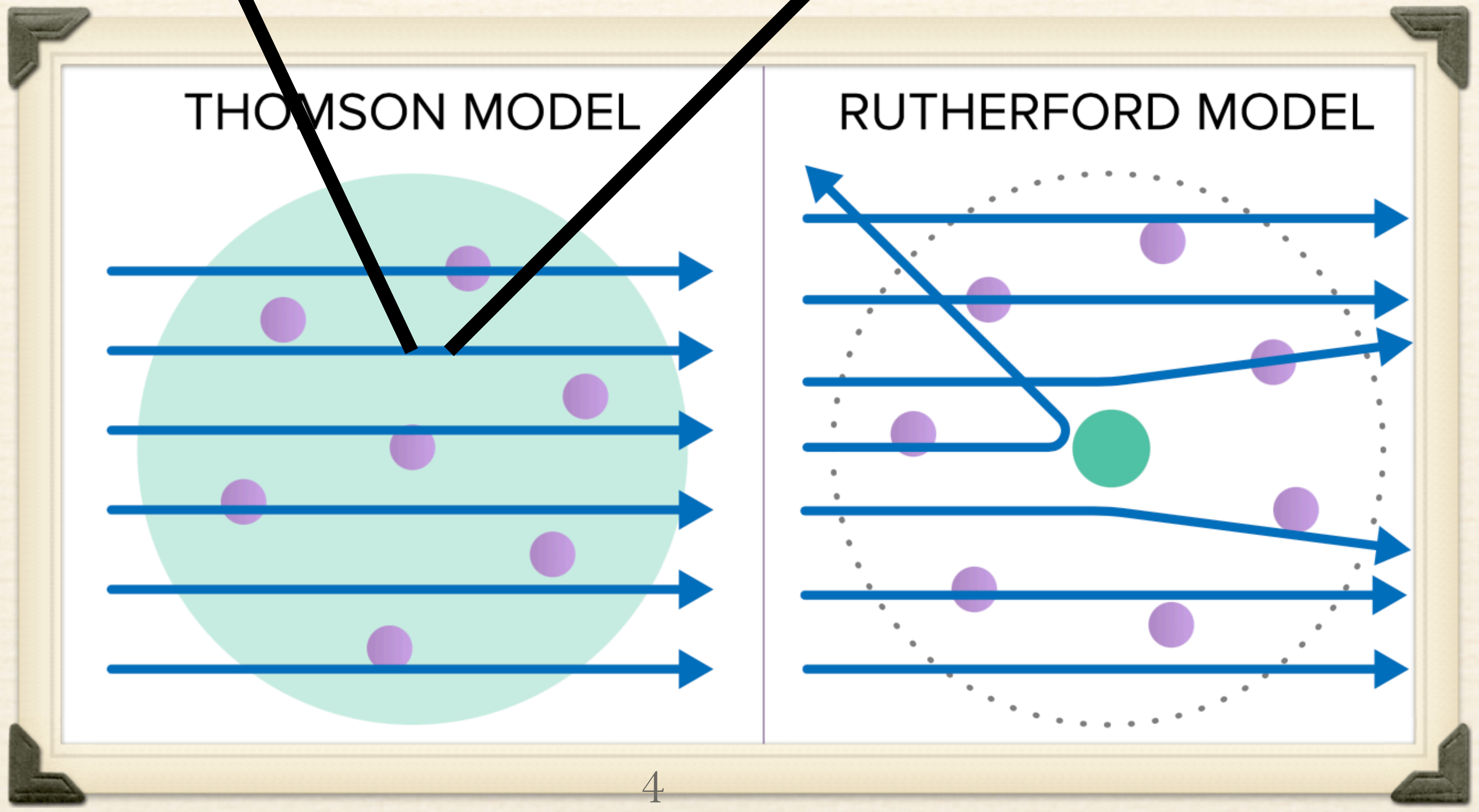


The historical background

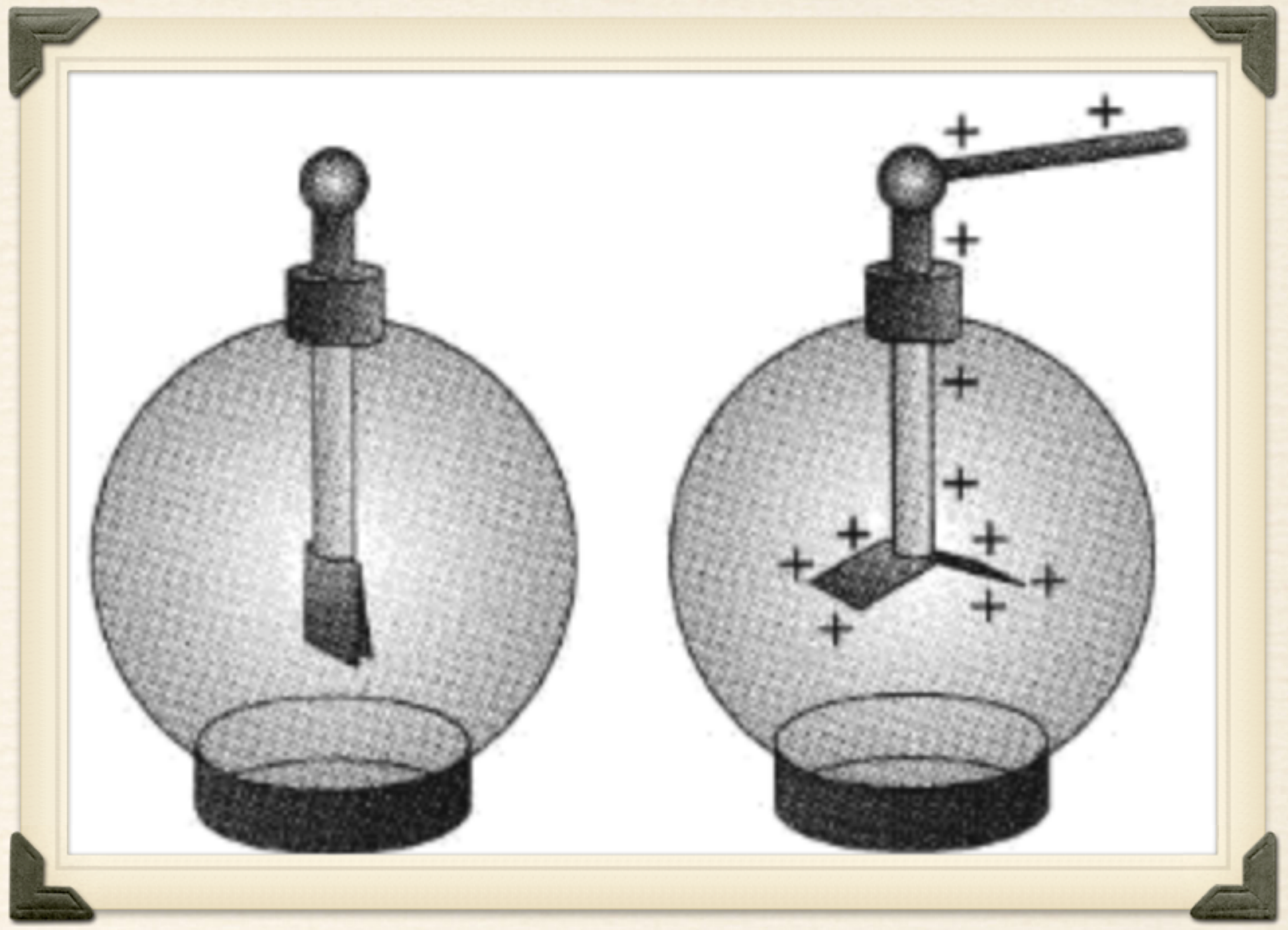
- 1913: H. Geiger invents the counter detector (which takes his name).
- 1913-1916: Bohr and Sommerfeld define the modern atom model.
- 1926: Particles are divided into two classes according to their angular momentum, ***fermions*** and ***bosons***.
- 1928: Dirac describes, for the first time, the electron from a relativistic point of view, deriving his famous equation.

The historical background

- 1930: W. Pauli theorizes the existence of the neutrino.
  - 1932: called in this way by E. Fermi during the Solvay Conference.
- 1930: H. Bethe formulates the equation of the energy loss for non-relativistic ionizing particle, in 1932 obtained the relativistic version.
- 1932: Chadwick discovers the neutral companion of the proton, the ***neutron***.

The cosmic rays discovery

- 1785: Coulomb observed an electroscope discharging spontaneously → air is not a good insulator.

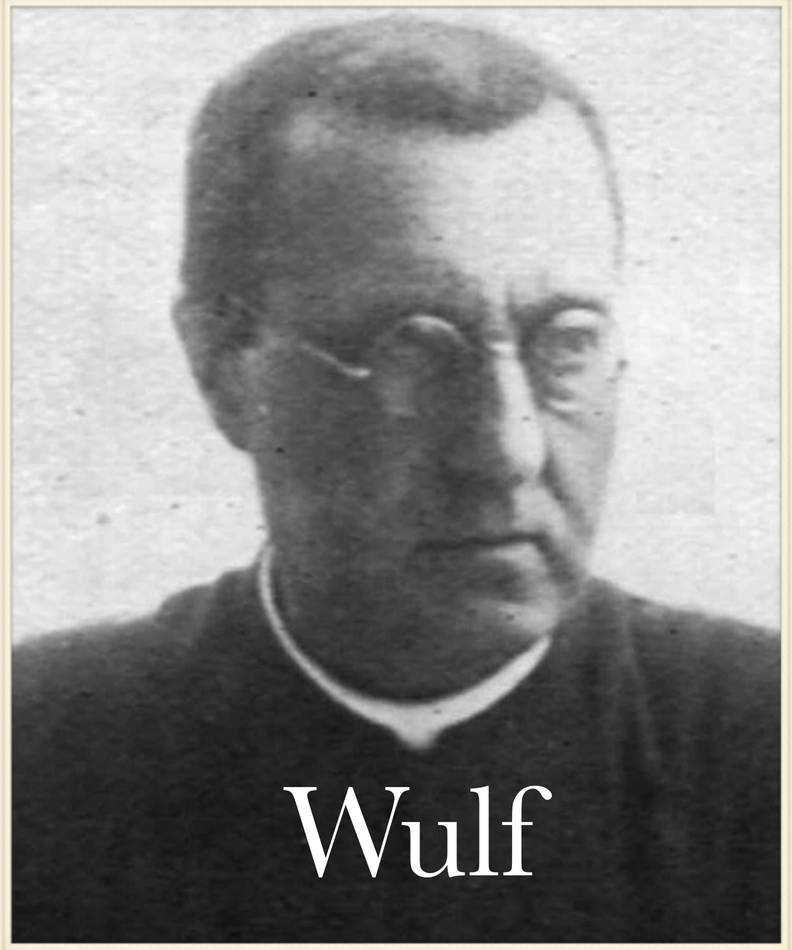


- 1900: Studying radioactive sources has been found that air conductivity changed under their influence.

- By shielding the electroscope they observed that the electroscope continued dis-charging, meaning the observed radiation was highly penetrating.

The cosmic rays discovery

- 1909: T. Wulf built a new electroscope for quantitive measurements.
- 1910: Wulf measured the flux on Eiffel Tower, founding an increasing of the ionization flux.
- 1910-11: Pacini measured the flux over Bracciano Lake and Livorno sea, finding a reduction of the flux under the water surface.

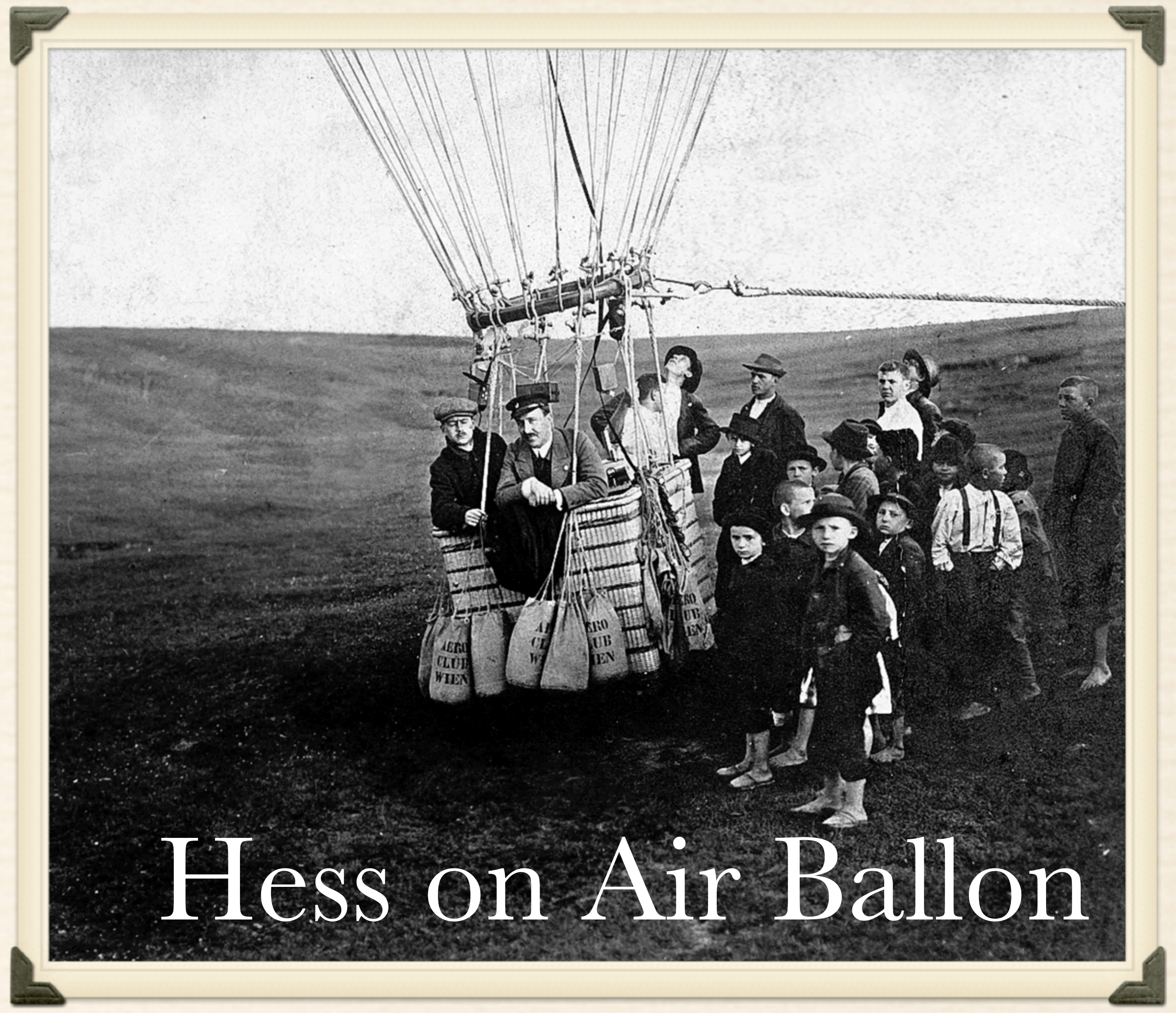

Wulf

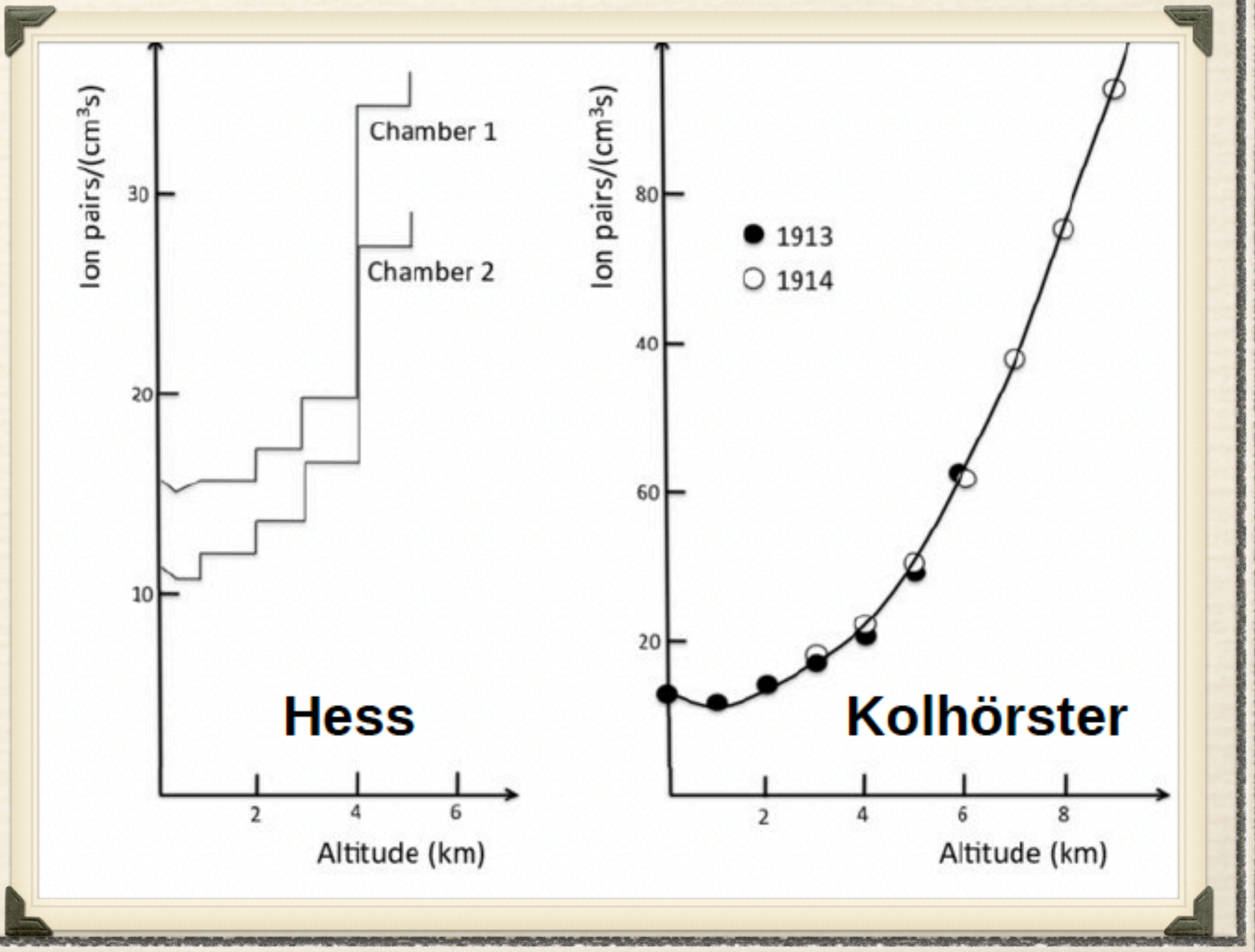

Pacini

Navy destroyers
Fulmine

The cosmic rays discovery

- 1912: F. Hess makes a heroic expedition, using a hot-air balloon, measuring the flux up to 5km height.
- Hess finds that the flux increases at higher heights.
- W. Kolhoster confirms his findings replicating the experiment.


Hess on Air Ballon

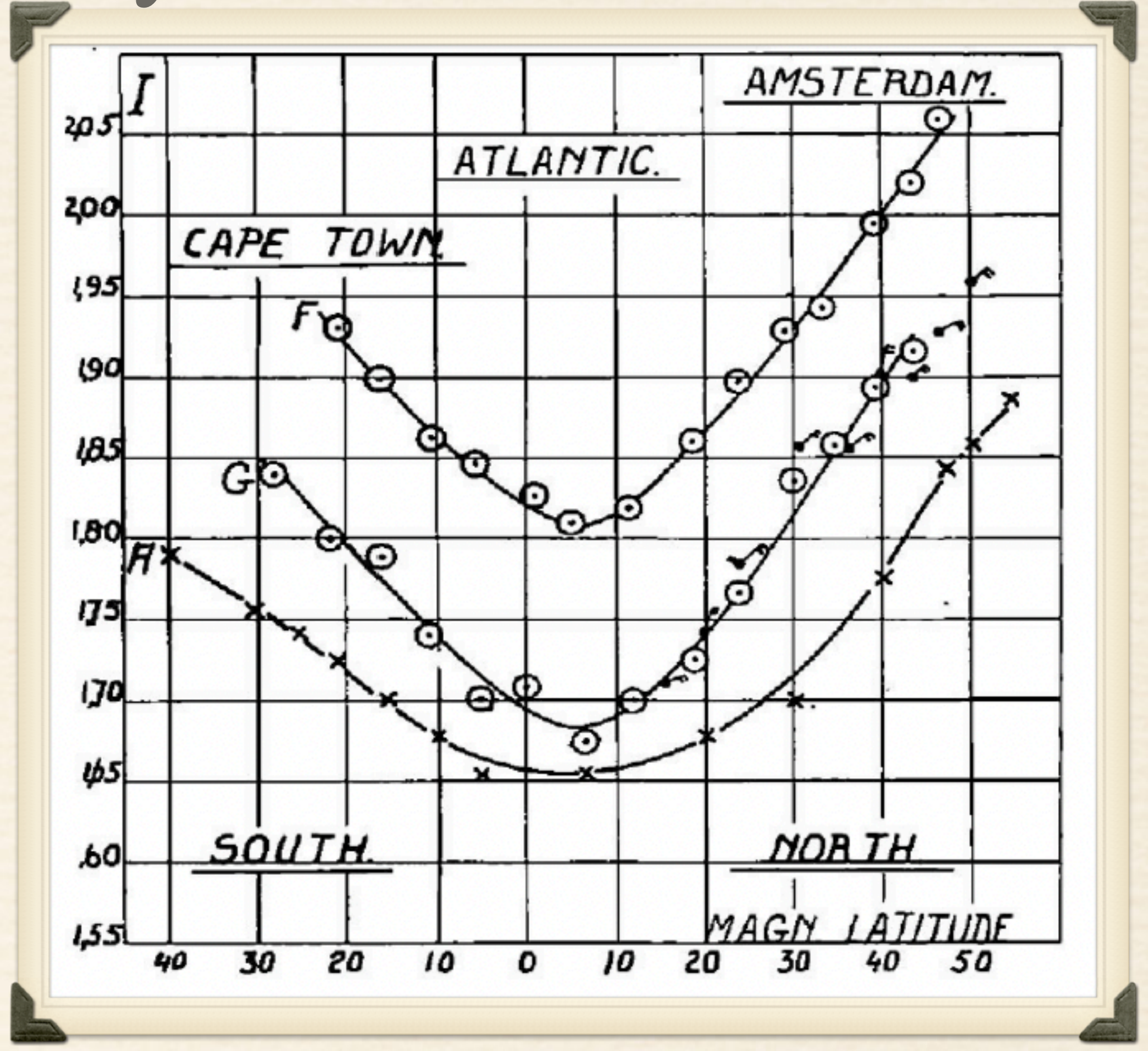


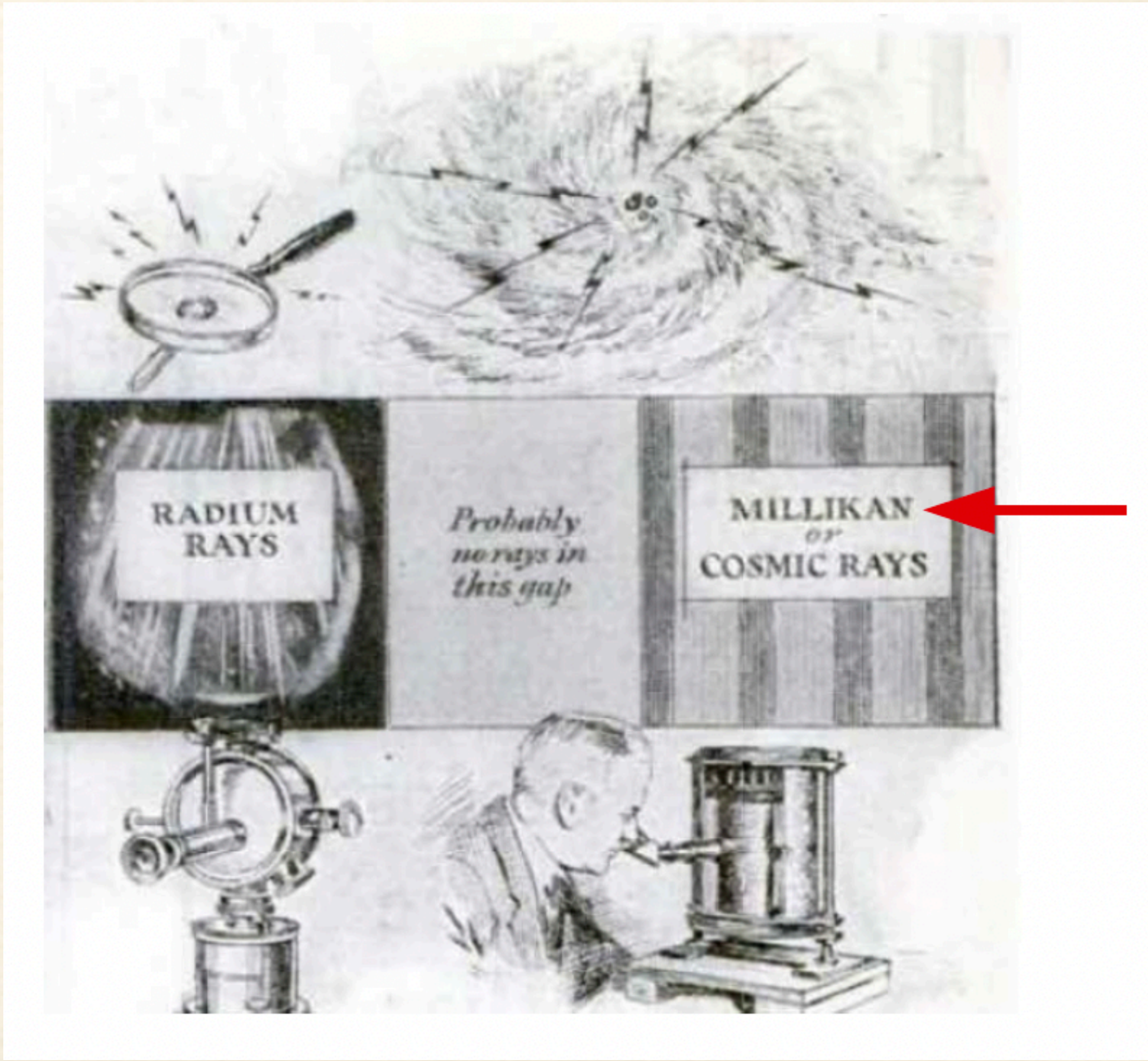
The cosmic rays discovery

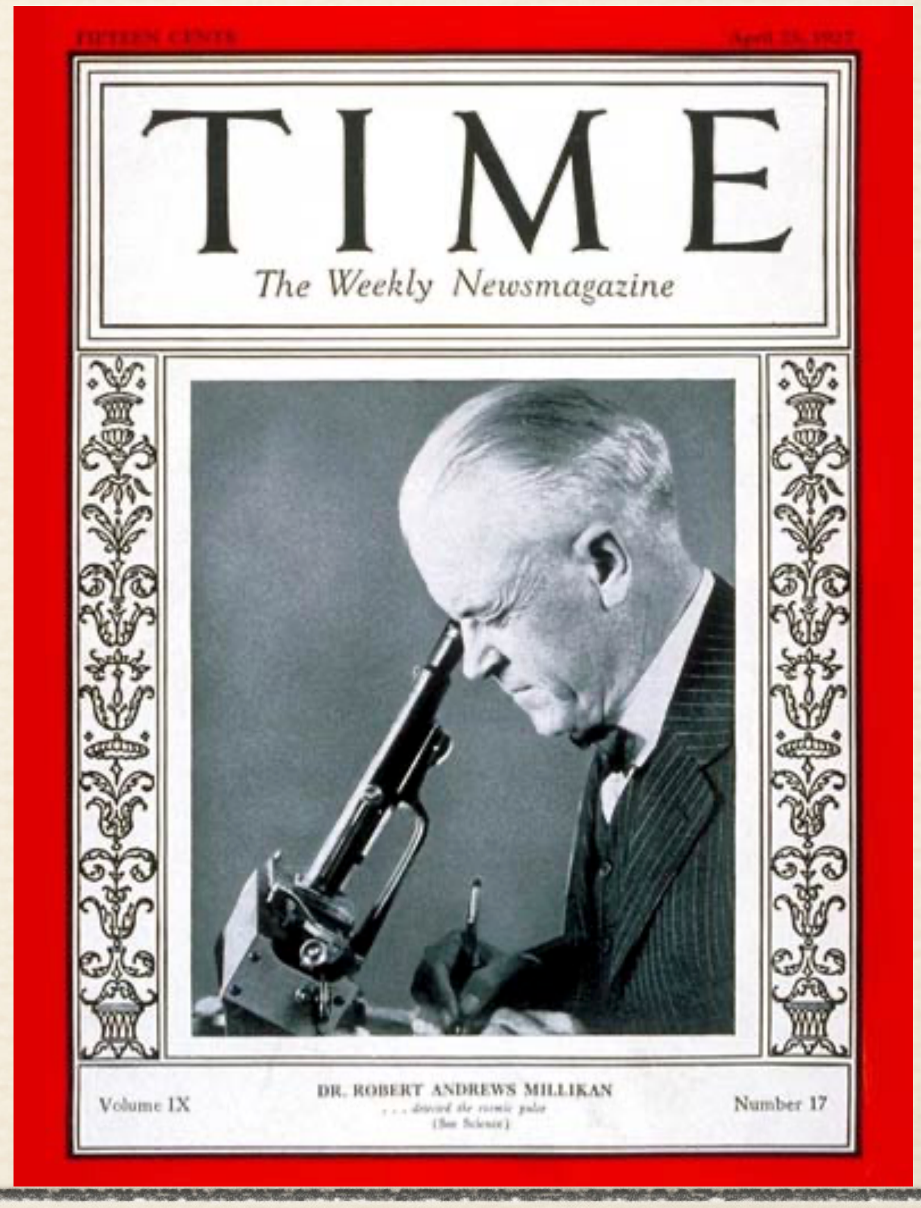
- 1925-26: Millikan replicates the Hess' measurement in Texas, founding a fourfold reduction in the flux.

- 1927: J. Clay explained this effect by geomagnetic changing as function of the latitude → charged particles.

- Millikan is convinced that this rays come from above and invents the name "cosmic rays".

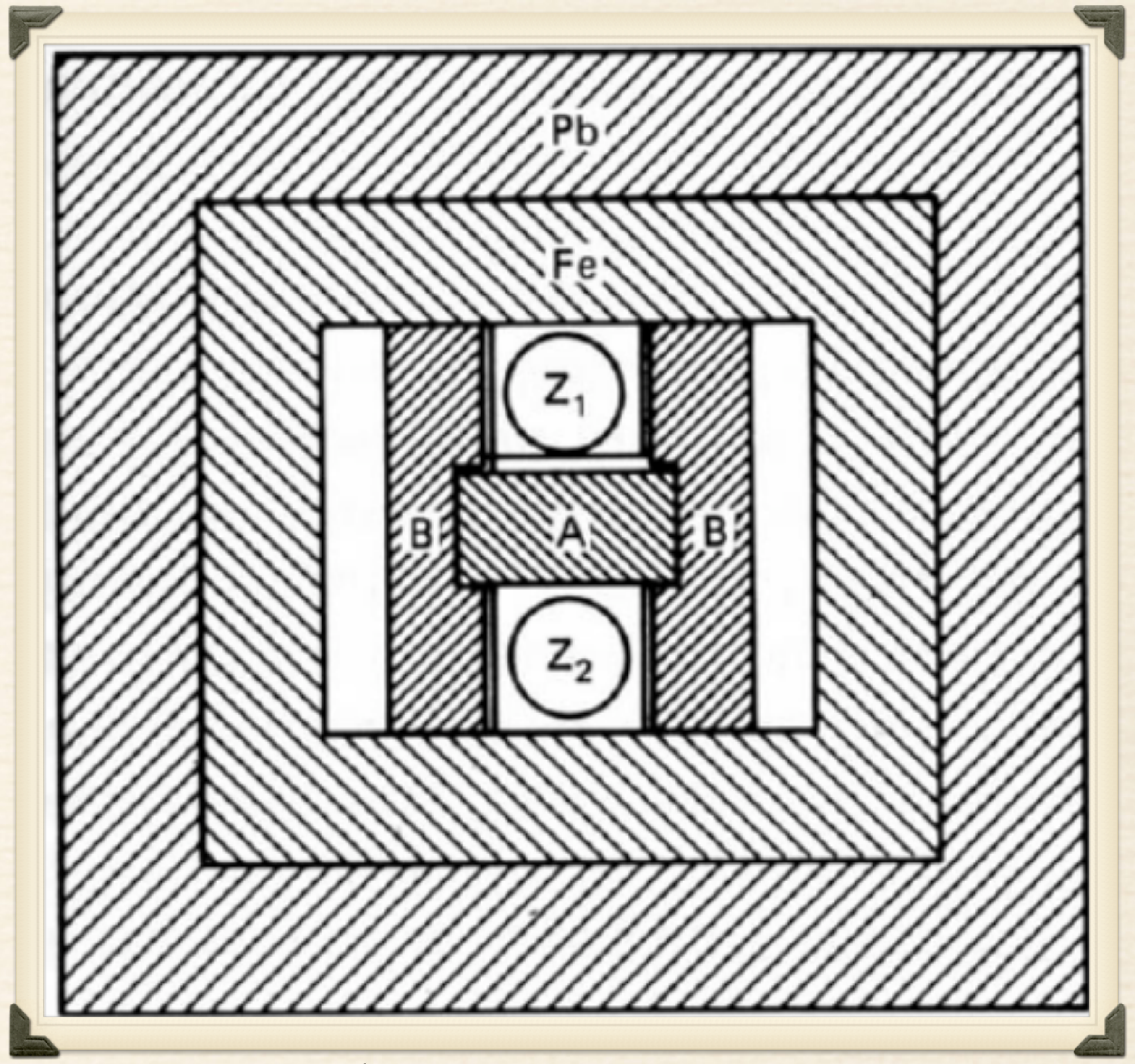






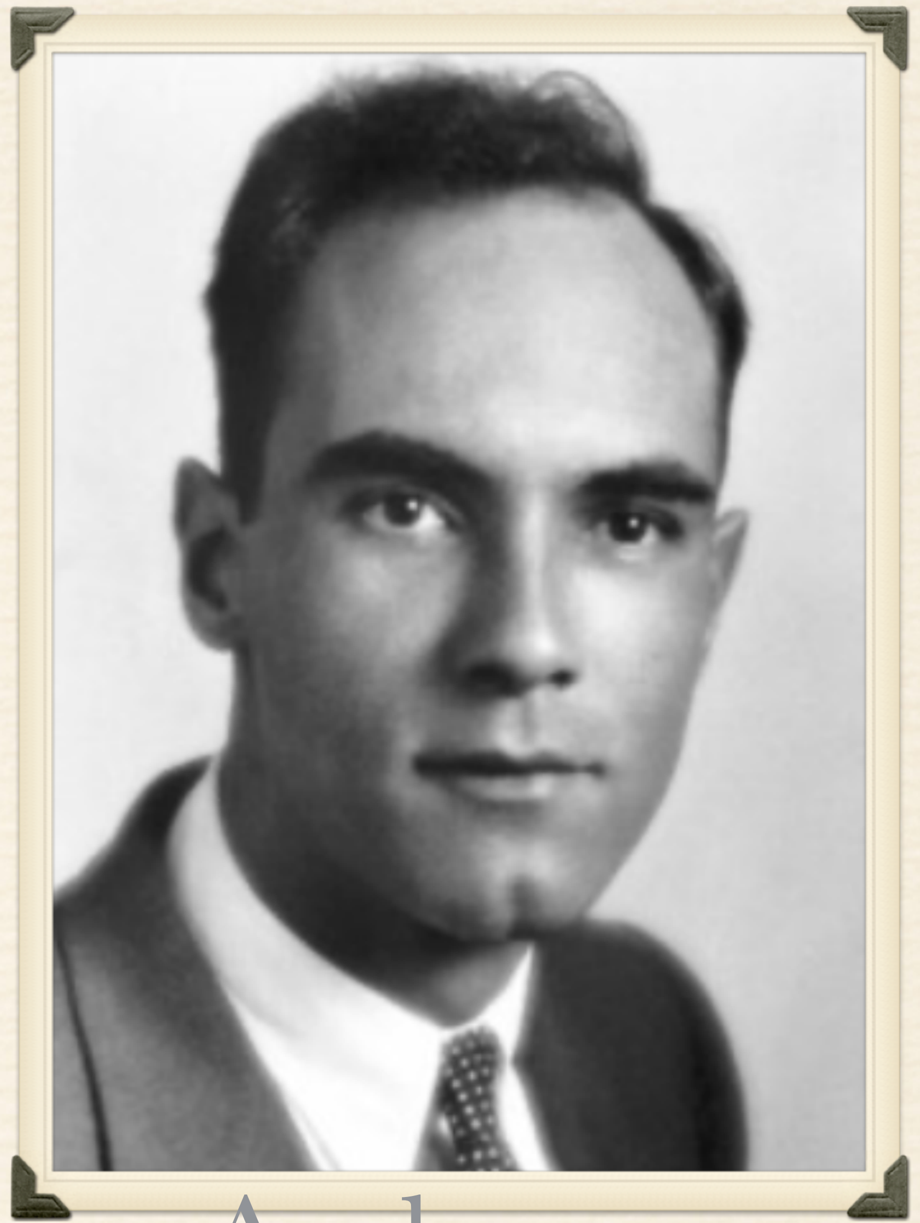
The cosmic rays composition

- After his first measurements Millikan thought that primary cosmic rays were γ-ray from interstellar fusion process.
- After Clay's measurements they understood were charged particle.
- 1929: Bothe and Kolhoster demonstrated that cosmic rays can go through 4cm of gold, they are **high energy particles** → first use of coincidences



The discovery of the positron

- Carl Anderson borns in 1905 in New York.
- He get his Ph.D from CalTech in 1930 studying the space distribution of photoelectrons ejected from various gases by X-rays.
- In 1930, with Millikan, starts studying the energy distribution of cosmic-ray particles.
- For his measurement Anderson developed a detector using a cloud chamber immersed in a magnetic field.



Anderson

The discovery of the positron: Detector

- The **cloud chamber** was invented by Wilson in ~1900.

Electric field to remove ions

- "**A**" is the chamber that contains saturated steam.

- "**C**" is a vacuum ampoule, when valve "**B**" is actuated, the piston go down and the region "**A**" expands adiabatically producing a supersaturated state.

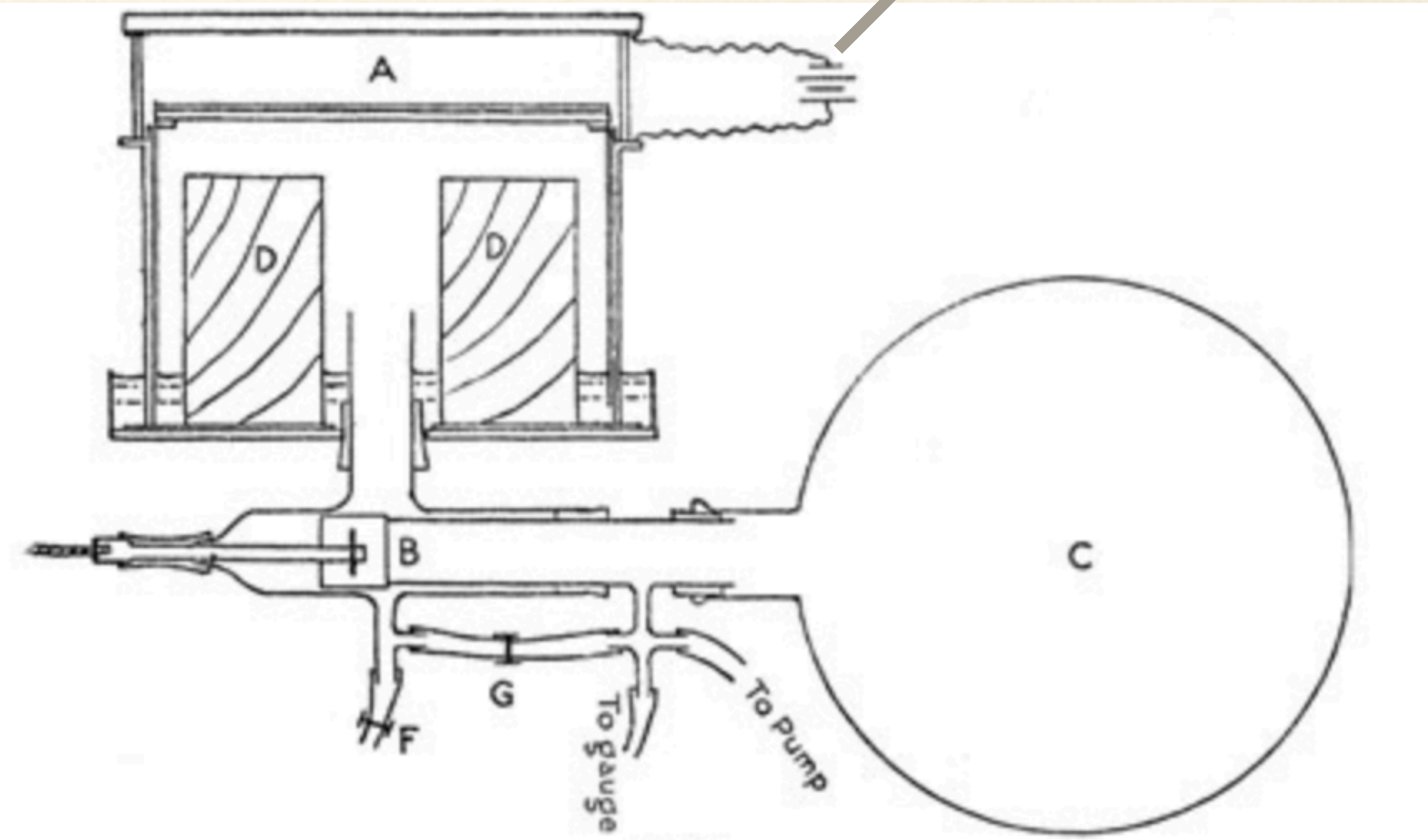


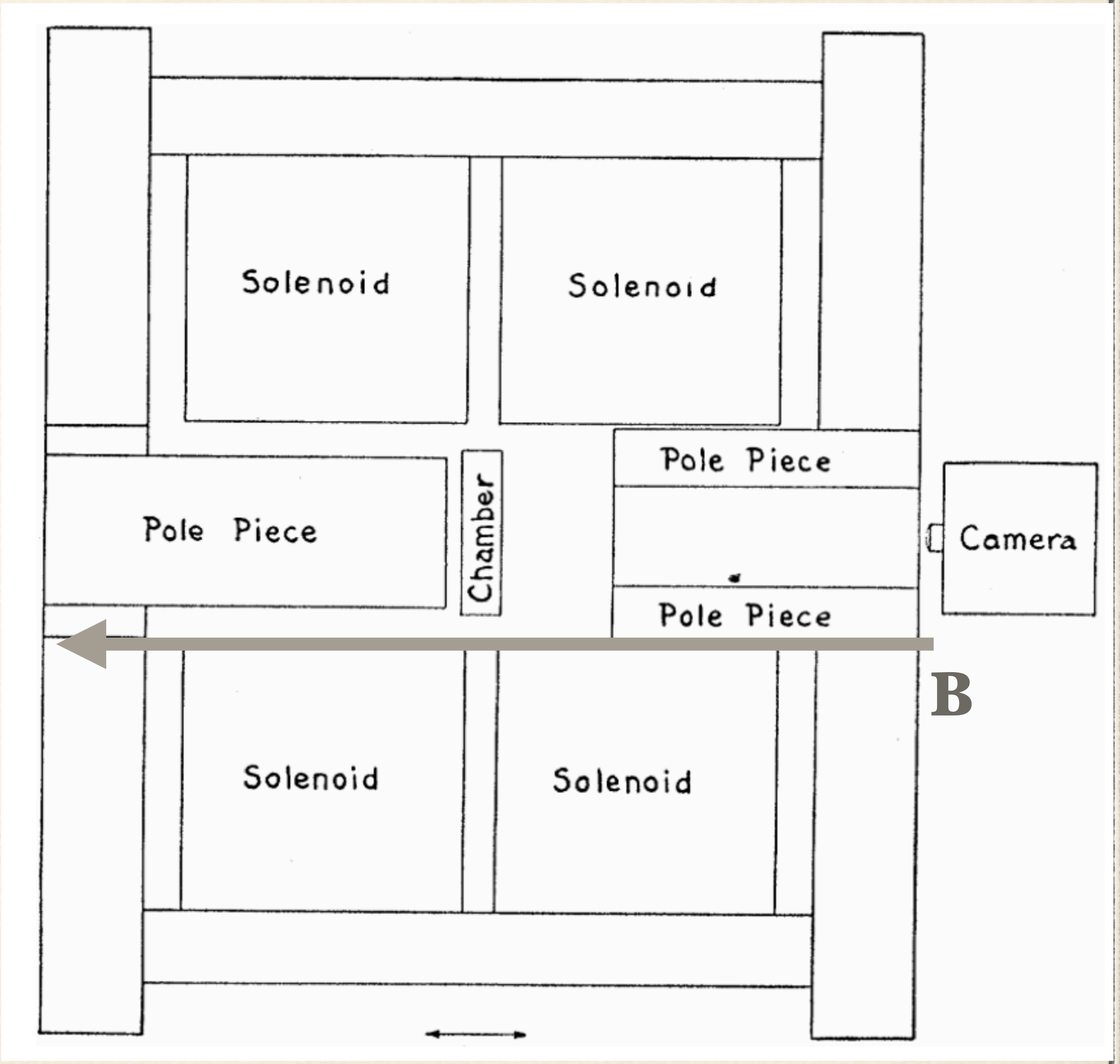
Fig. 1.

The discovery of the positron: Detector

- Ions in the supersaturated steam acts like condensation nucleus → produces drops.
- Spatial resolution of the tracks depends on:
  - Time of the expansion after the ionization, need 1/70s to become visible;
  - Energy of the incident particles;
  - Time occurred between the creation and the observation.

The discovery of the positron: Apparatus

- The chamber was 17x3 cm located between 2 coils with 1m diameter.
- The magnetic field used was 1.7 T.
- The power to feed the magnet was 425kW, 1/10 of the total energy required by the campus. For this reason they worked during the night!



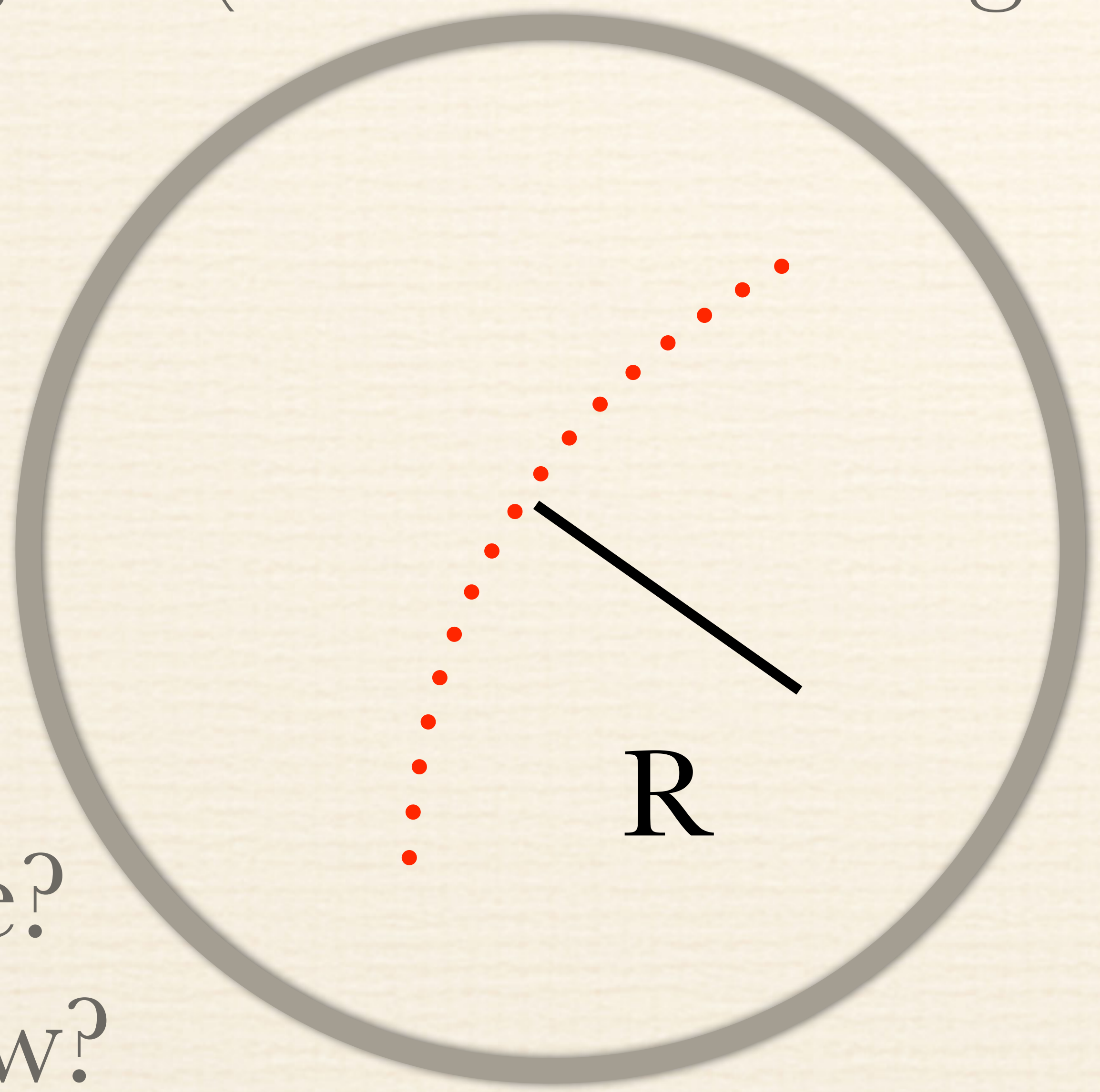
The discovery of the positron: Apparatus

- The camera was used to take picture of the tracks.
- The **time window** available was 0.025s (camera exposition).
- The **dead time** was ~10s to restore the apparatus for a new measurement.
- Anderson took 1600 pictures, during 4.5hrs of acquisition, for a total signal windows of ~40 seconds.
  - Only 1300 pictures contained events.

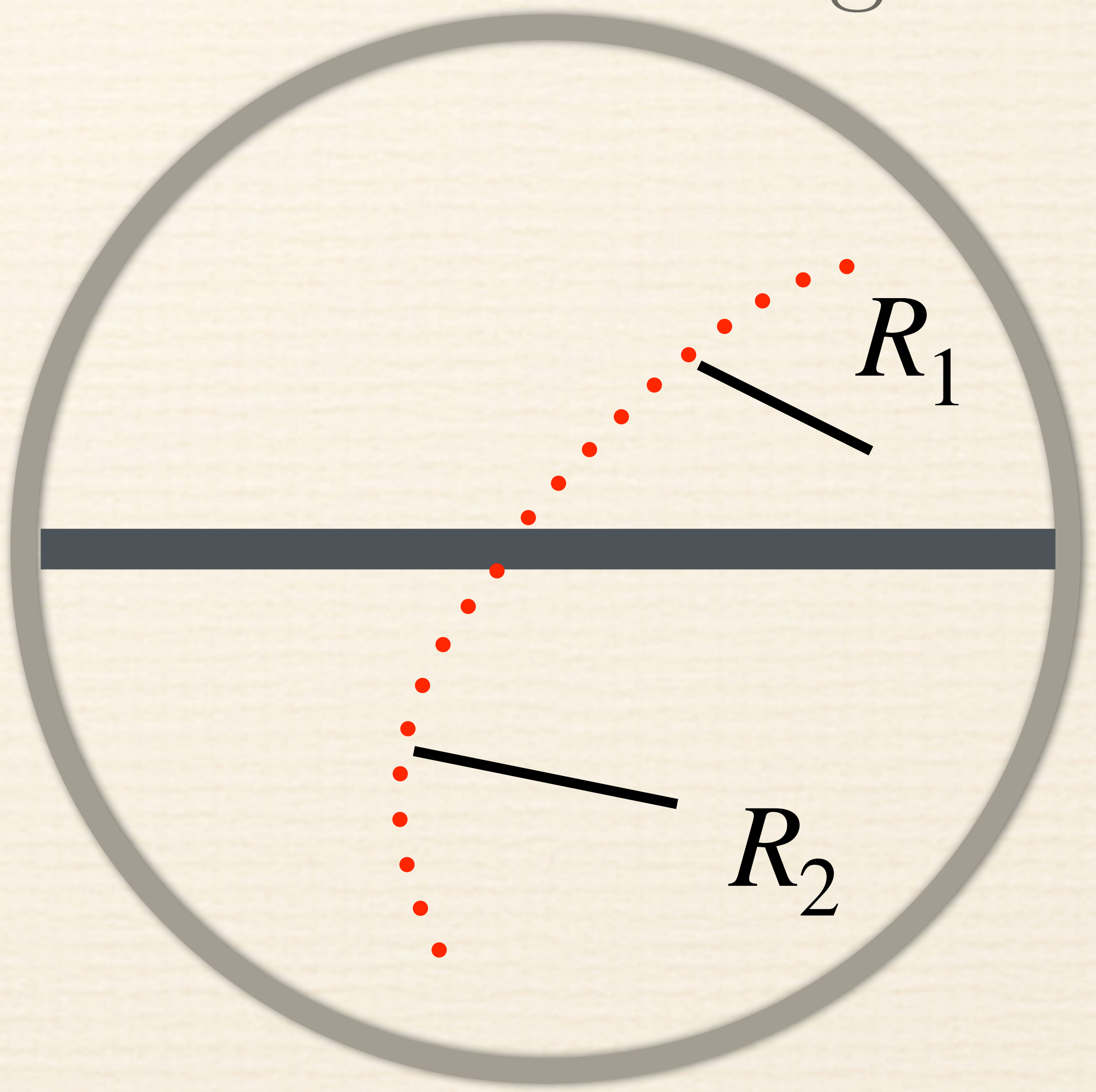
The discovery of the positron: Game changer idea

- From previous measurements they saw many tracks, but wasn't clear the direction, from above or from below? Knowing the direction you know also the charge.
- Anderson had a great idea, to locate a **lead thickness** (6mm, $\sim 1X_0$) in the middle of the chamber.
- Millikan didn't agree (he was a strong supporter of cosmic origin of these particles).

B $\otimes$



Proton from above?
Electron from below?



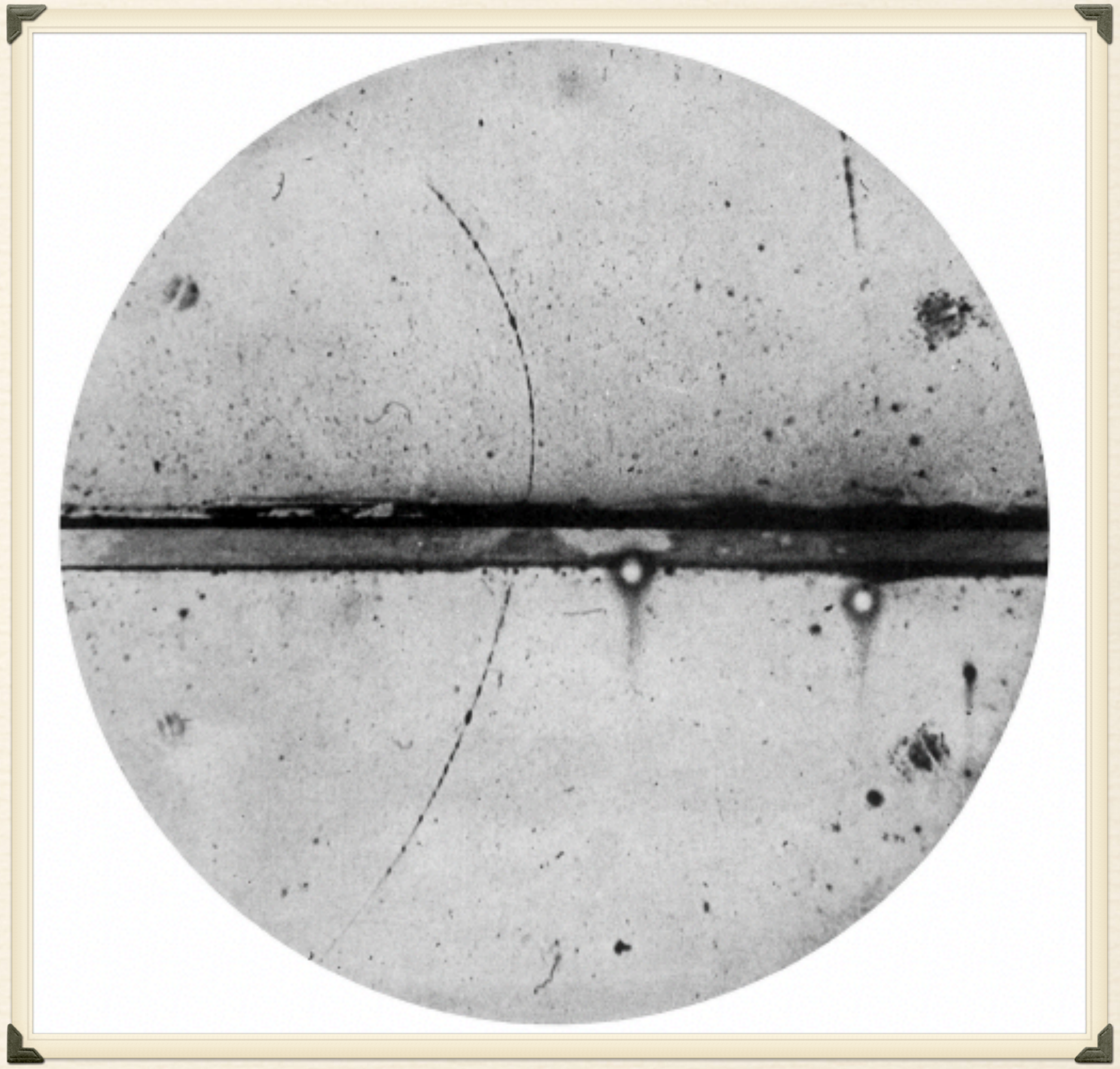
Negative particle from below

The discovery of the positron: Game changer idea

- Anderson had a winning idea, he found 15 tracks, over 1600, with positive charge, but mass close to the electron.

- The track shows a positive particle coming from below and able to cross the lead.

- He was able to distinguish proton from positive electron, named “positron” by Anderson, who proposed “negatron” for the electron.

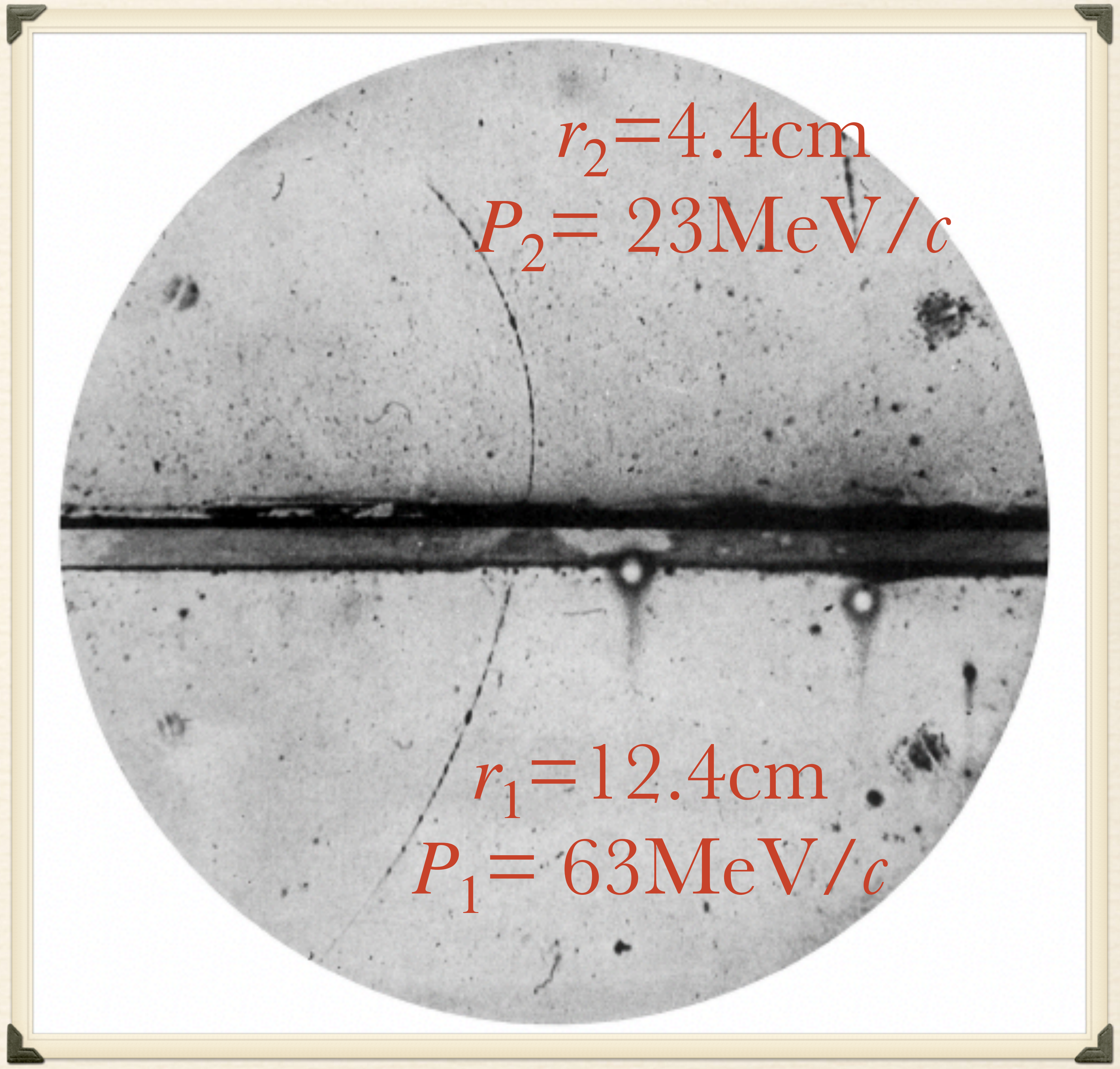


The discovery of the positron: Some calculation

- Measuring the radius of the tracks, Anderson computed the momentum (P) of the particle: $|\overrightarrow{P}| = eBr$

- The initial momentum of the particle is:
$$P_1 = 63\ \mathrm{MeV}/c$$

- While the momentum after the lead is:
$$P_2 = 23\ \mathrm{MeV}/c$$

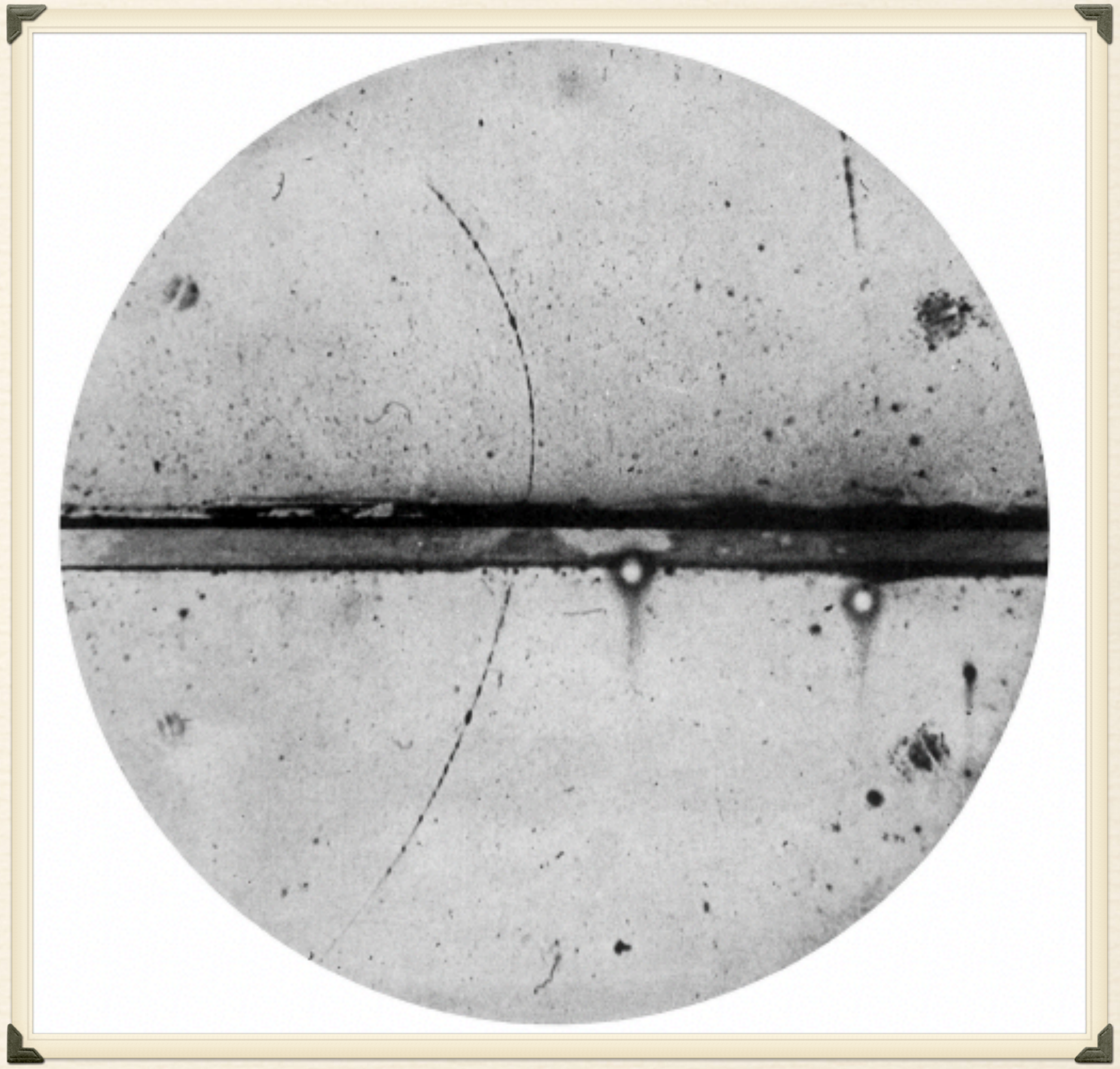


The discovery of the positron: Some calculation

- A non-relativistic proton with 63 MeV/c momentum would have:

$$T = \frac{P_1}{2m_p} \approx 300 \text{ MeV}$$

- With this energy the proton as a free range in air of 5mm, 1/10 of the track length.



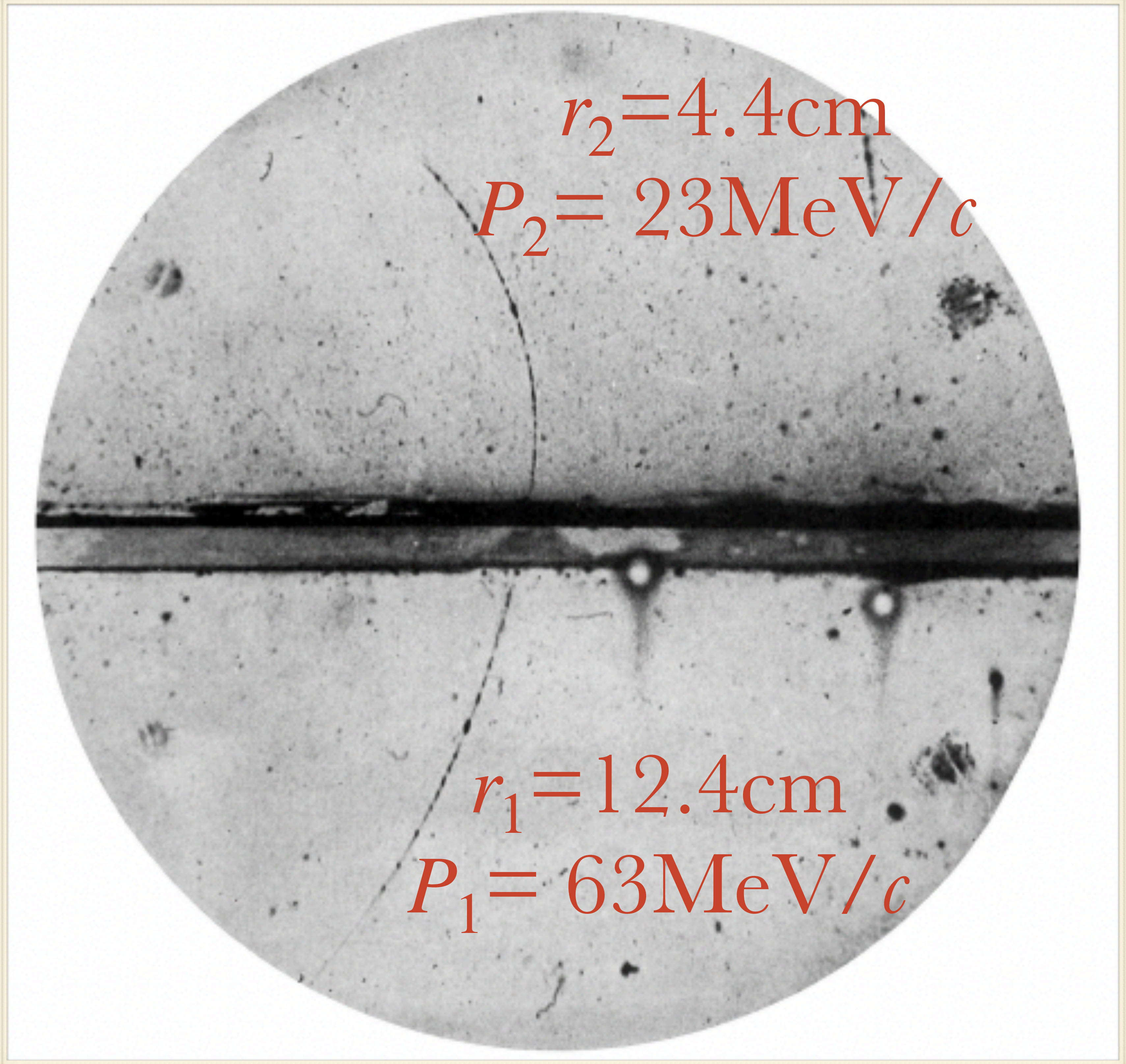
The discovery of the positron: Some calculation

- If instead we consider this particle with the mass of an electron, it is relativistic and the energy loss can be computed as:

$$\left(-\frac{dE}{dx}\right)_{rad} \sim \underbrace{4r_e^2\alpha\frac{N_A Z^2\rho}{A}ln(183Z^{-1/3})}_{\text{Radiation length}}E \sim \frac{E}{X_0}$$

- By solving the differential equation and considering $x \sim X_0$:

$$E_f = E_i \cdot e^{-x/X_0} = 23 \text{ MeV}$$



The discovery of the positron: The interpretation

- What did produce this event?
- The nature of proton and neutron wasn't clear at that time, the common sense was that neutron was a combination of electron and proton.
- So Anderson proposes that the proton is a combination of positron and neutron, so a γ-ray can interact with a proton producing the signal
- We know now this is not true, so what produced the event?

The discovery of the positron: The interpretation

- A bunch of possible positron production case are:
- $\pi^+ \rightarrow e^+ + \nu_e$ this is suppressed (0.01%) but possible, like K^+ meson decay (0.0016%) even more suppressed.
- $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ the most probable (~100%).
- $\gamma \rightarrow e^+ + e^-$ pair production ($E_{th} = 1.22$ MeV).

The discovery of the positron: The interpretation

- Dirac tried to explain it as 2 γ-rays interacting, but this was very unlikely in the laboratory.

- The true pair production and e.m. showers, were understood after Blackett-Occhiali measurements, using for the first time triggered cloud chamber with Geiger-Muller counter called "Counter Controlled Chamber"

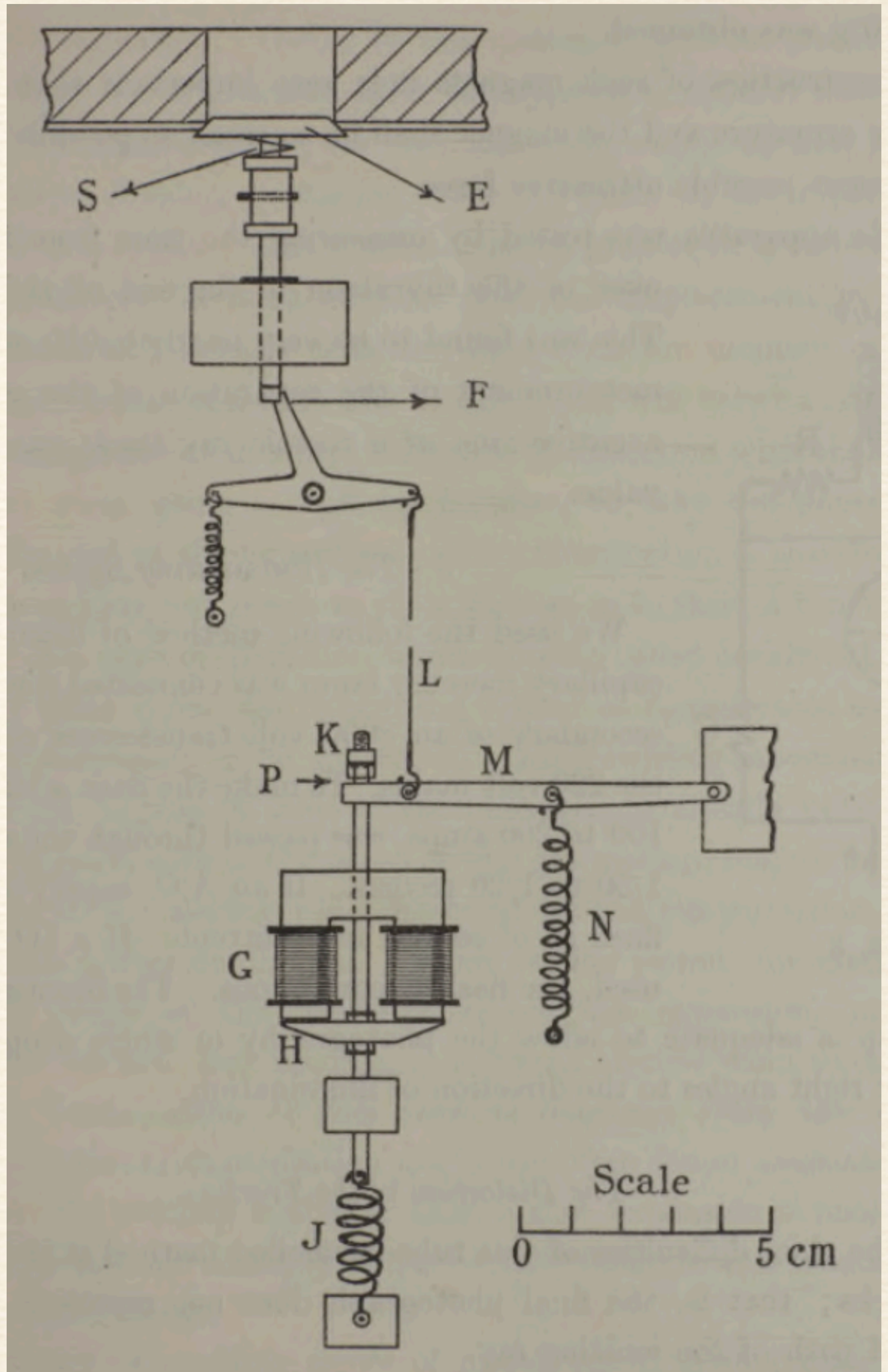


Fig. 2

The discovery of the positron: The impact

- It's interesting how Chadwick wrote in this article:

> The manner in which these positive electrons are produced is not yet clear, nor whether they arise from the action of the neutron emitted by the beryllium or from the action of the accompanying γ-radiation. It is hoped that further experiments now in progress will decide these questions.

- Physicist were thrilled and excited by these new measurements.

The discovery of the positron: The impact

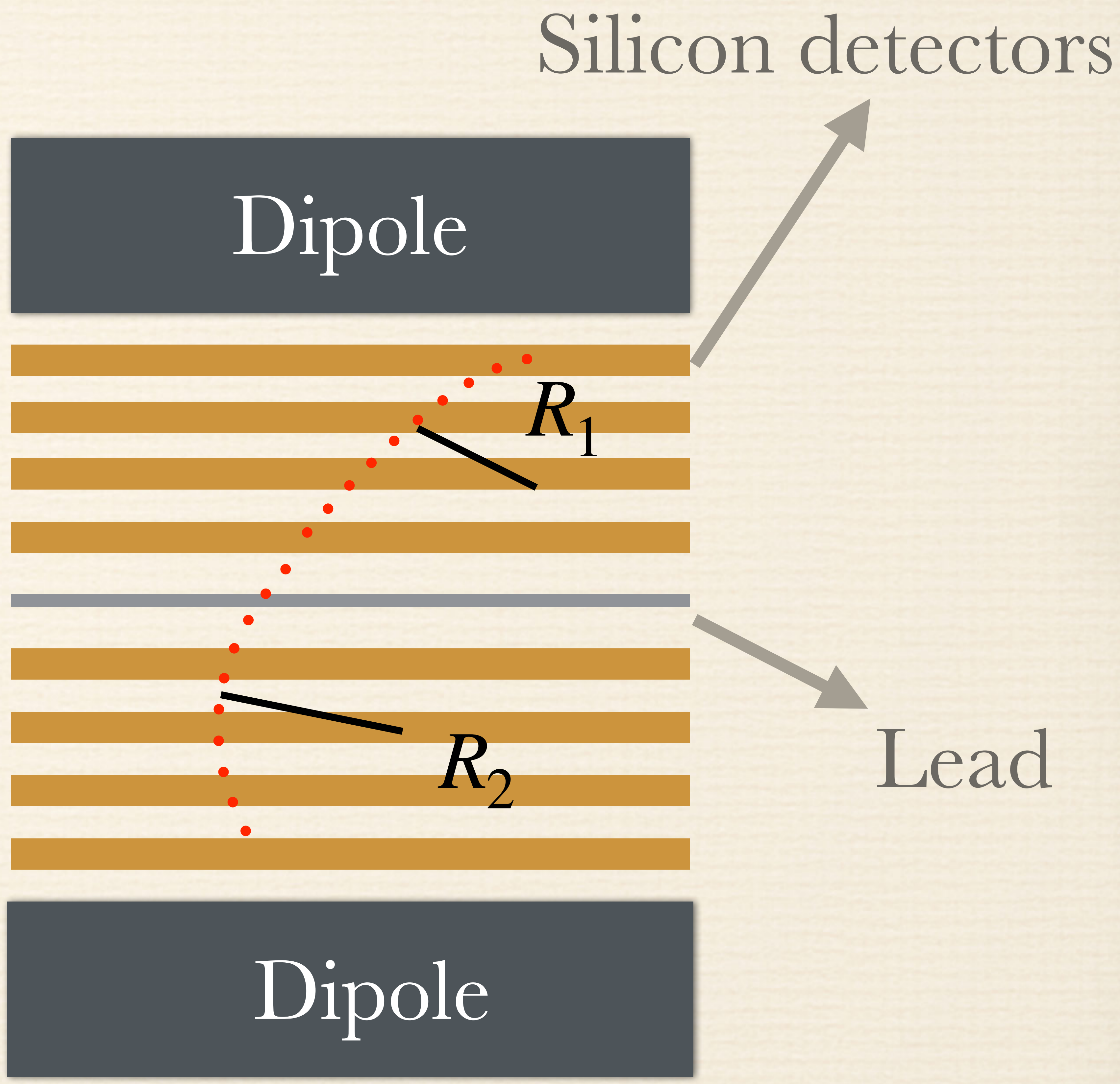
- The **theory of P. Dirac** in the famous article "The Quantum Theory of the Electron" were **confirmed**, showing that the positive particle as solution of Dirac equation is the electron antiparticle.
- The **discovery of anti-matter** opens a new scenario in particle physics and in the knowledge of nature.
- The technique used by Anderson, was improved by Occhialini-Blackett discovering **pair production** and e.m. showers (1933) and used to discover the muon (Anderson-Neddermeyer - 1936).
- It's maybe the beginning of the modern high energy particle physics.

The discovery of the positron: Today

The experiment can be replicated in the same way as Anderson but using modern detectors.

Tracker detector instead of cloud chamber:

- 50μm silicon pixel detector
- High spatial resolution - μm
- Negligible energy loss - 30KeV per layer



The discovery of the positron: Today

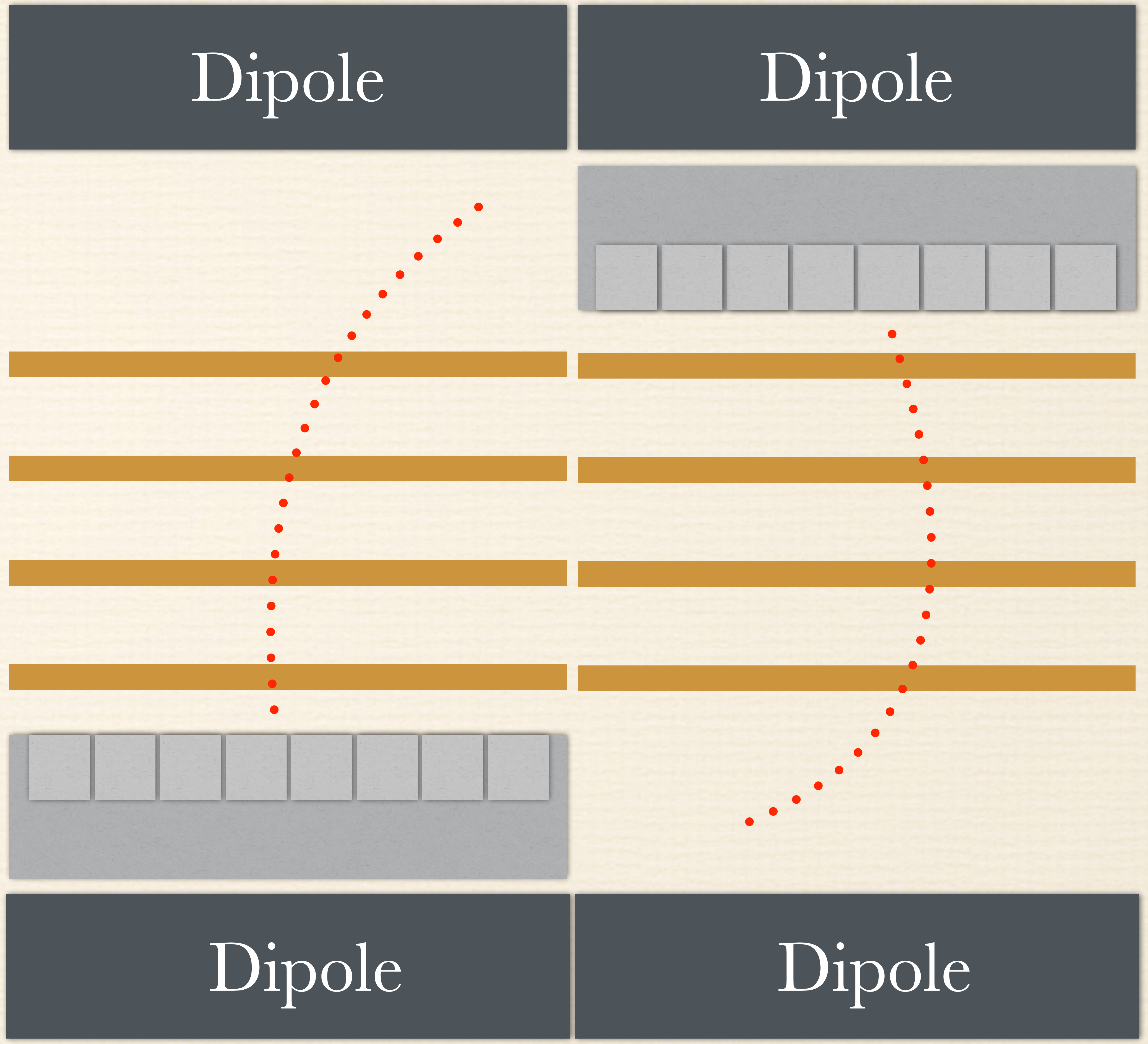
Other idea:

Tracker detector instead of cloud chamber:

- 50µm silicon pixel detector.
- High spatial resolution - µm.
- Negligible energy loss - 30KeV per layer.

E.m. calorimeter instead of lead:

- Segmented calorimeter with PbF_2 crystal.
- Resolution of MeV.



Thanks for the attention