Gas-filled detectors
&
the Ecological transition

Marcello Abbrescia

Particle detectors: awesome devices!

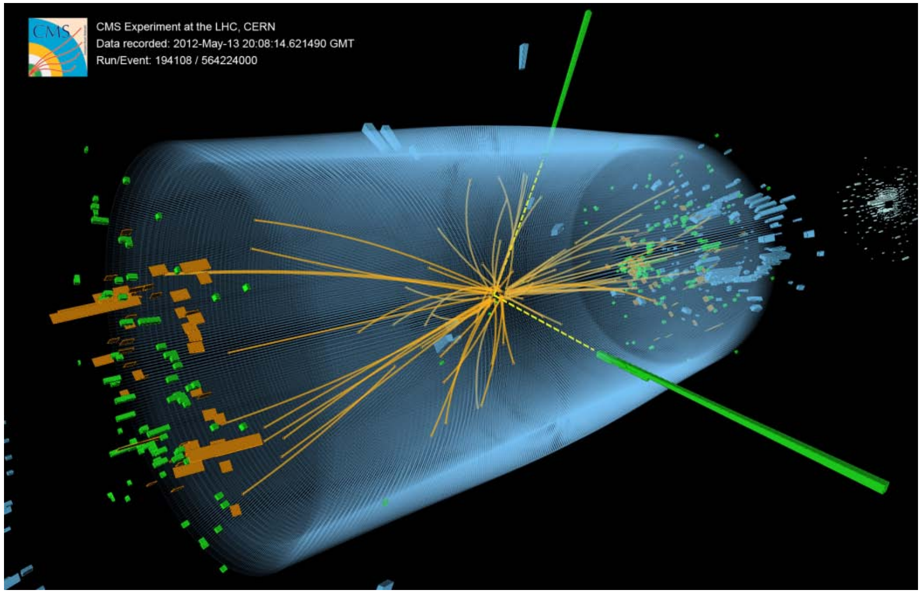
A particle (for instance a muon):

- ➢ we cannot feel it, we cannot touch it, we cannot see it
- ➢ has a mass of 0, 000 000 000 000 000 000 000 000 000 974 kg
- ➢ moves at a speed of: 299 792 458 m/s
- ➢ lives around: 0, 000 002 197 s
- ➢ has a charge of about: 0, 000 000 000 000 000 000 016 C

Nevertheless, we want to build devices – particle detectors- which detect them with:

- ✓efficiency close to 100%
- ✓temporal precision of about 0, 000 000 000 010 s
- ✓spatial precision of about 0, 01 m

(numbers given for MRPCs)



A Higgs boson candidate observed in CMS

A task for Nobel laureates

1927: Charles Thomson Rees Wilson, Cloud Chamber

1939: E. O. Lawrence, Cyclotron & Discoveries

1948: P.M.S. Blacket, Cloud Chamber & Discoveries

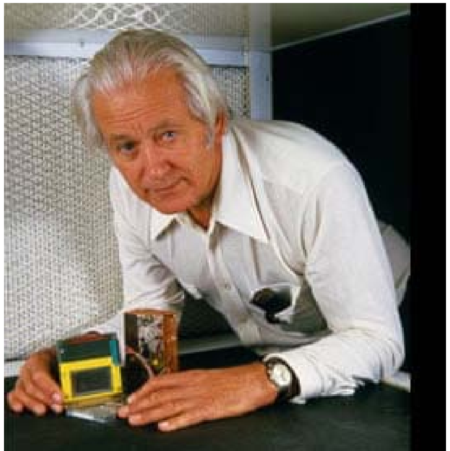
1950: C. Powell, Photographic Method & Discoveries

1954: Walter Bothe, Coincidence method & Discoveries

1960: Donald Glaser, Bubble Chamber

1968: L. Alvarez, Hydrogen Bubble Chamber & Discoveries

1992: Georges Charpak, Multi Wire Proportional Chamber



Gas-filled detectors

One of the most diffuse class of particle detectors is filled with gas → their sensitive medium ("core") is made out of gas

Basically, they are made out of one (or more) gas volumes, where an electric field is applied

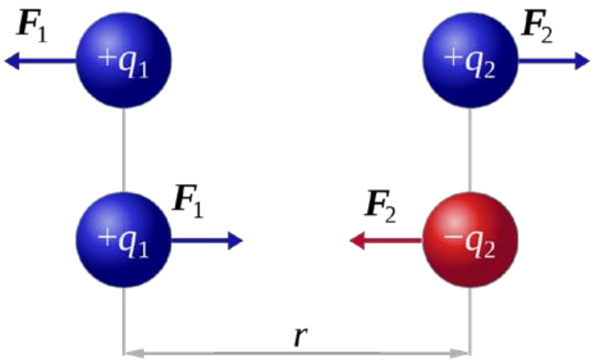
Now, image YOU are a muon entering a gas volume: what will YOU see?

Entering a gas-filled detectors

Basically: NOTHING!

- A gas is made out mainly of empty space.
- Even an atom is made out mainly of empty space
- An atom has typical dimensions of 10^{-10} m
  but practically all its mass is concentrated in its nucelus: 10^{-15} m
  (only a fraction 1/100000 of the space of an atom is occupied)

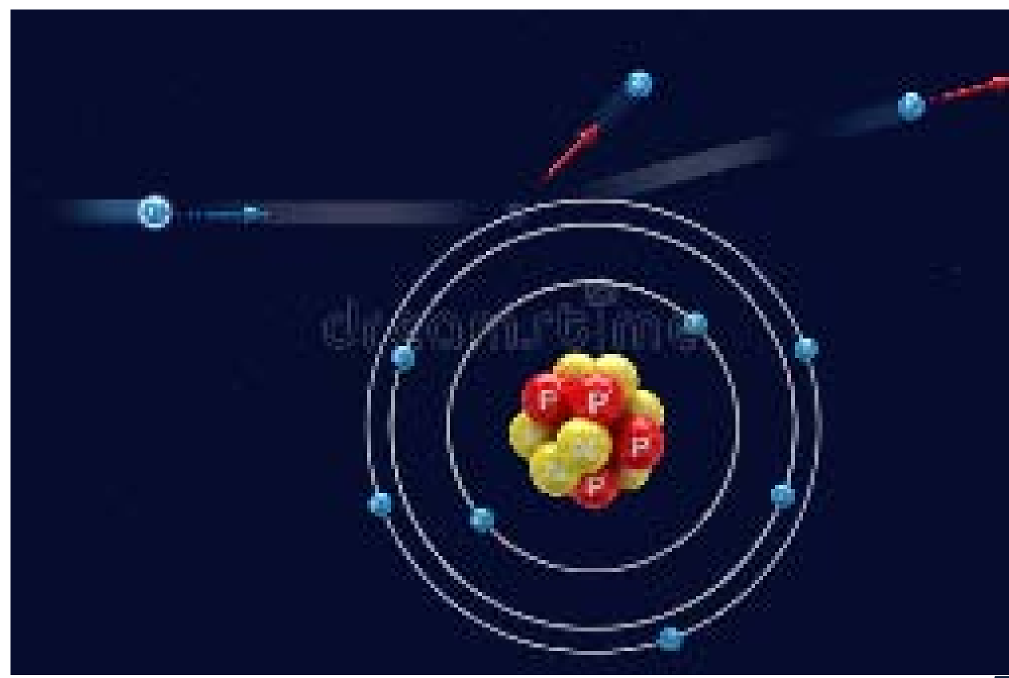
Sometimes…



$$|F_1| = |F_2| = k_e \frac{|q_1 \times q_2|}{r^2}$$

From time to time the impinging muon will pass close by an atom… and then… Coulomb interaction will do its job

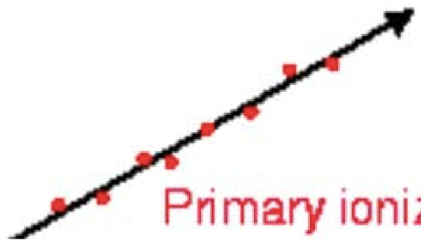
From time to time, the force on the electrons will be so intense that one or more electrons can be pulled away from the atom

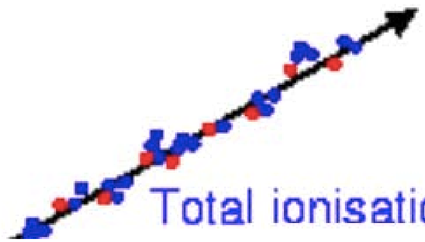


ion-electron pair formation
(gas ionization)

Secondary ionization

Quite often the extracted electrons have kinetic energy enough to generate secondary ionization: other ion-electron pairs are produced close to the track.





$$n_{total} \approx 3...4 \cdot n_{primary}$$

These processes have been studied by very famous physicists of the past: Niels Bohr (the one of the atom), Hans Bethe, and Felix Bloch

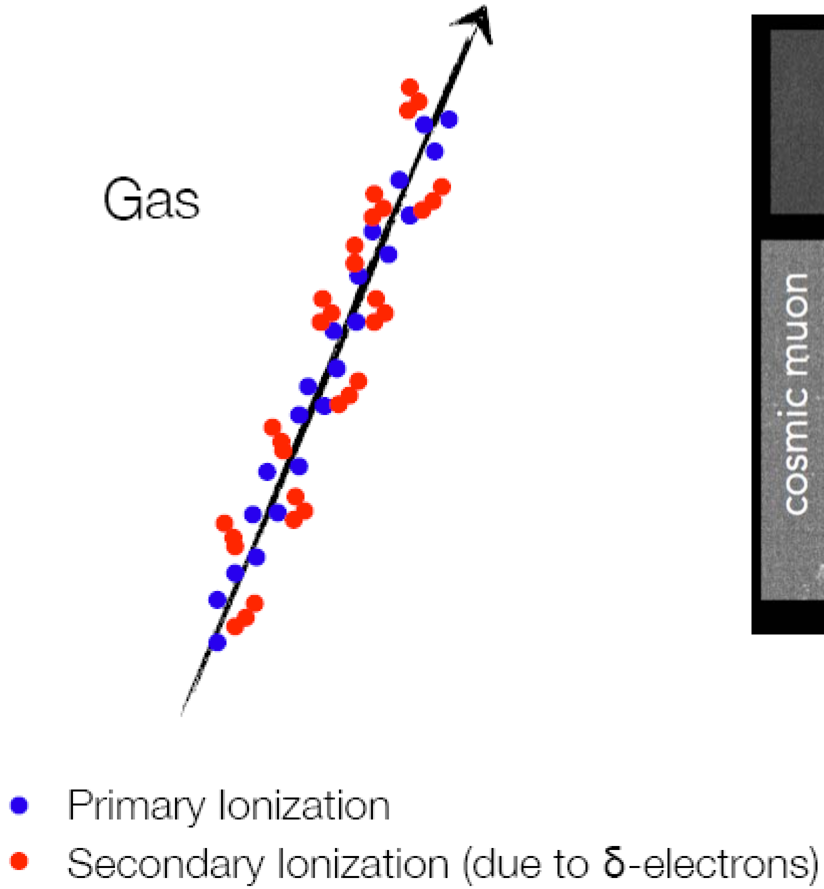
Zur Theorie des Durchgangs schneller Korpuskularstrahlen durch Materie

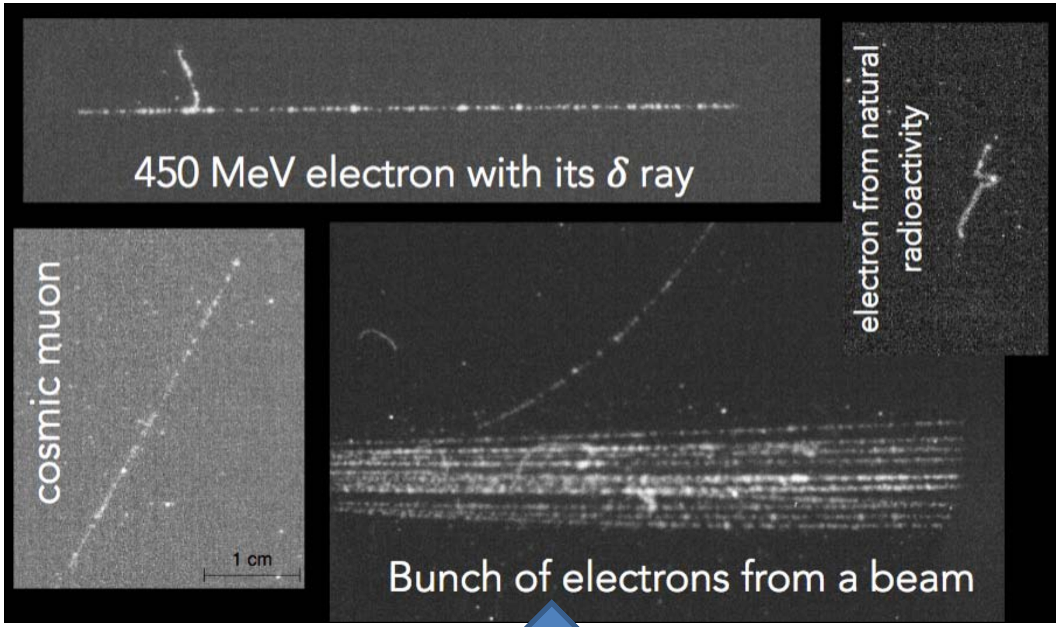
Von H. Bethe

Der unelastische Zusammenstoß einer schnellen geladenen Partikel (Elektron, Proton, α-Teilchen) mit einem Atom wird nach der wellenmechanischen Theorie von Born behandelt. Ein sehr einfaches Verfahren für die Auswertung der in die Theorie eingehenden Matrixelemente wird angegeben (§ 3) und die engen Beziehungen zur Intensität des Comptoneffekts festgestellt (§ 5). Die Theorie wird für Zusammenstöße mit Wasserstoffatomen im einzelnen und für kompliziertere Atome soweit wie möglich durchgeführt, es werden berechnet: die Winkelverteilung der unelastisch (§§ 6, 7 und 17) und der elastisch (§ 16) gestreuten Partikel, die Anregungsquerschnitte für die Anregung von optischen (§§ 9 und 17) und von Röntgenniveaus (§ 15) durch Elektronenstoß, die Gesamtzahl aller unelastischen und aller elastischen Stöße, sowie die Zahl der primär (§§ 10 und 18) und der sekundär (§ 19) gebildeten Ionen, die Geschwindigkeitsverteilung der Sekundärelektronen (§ 18) und schließlich die Bremsung der stoßenden Partikel durch die Gasatome (§§ 10, 12 und 13). Die Übereinstimmung mit der Erfahrung ist befriedigend bis gut. (Näheres vgl. die Zusammenfassung § 20.)

Ionization in gases

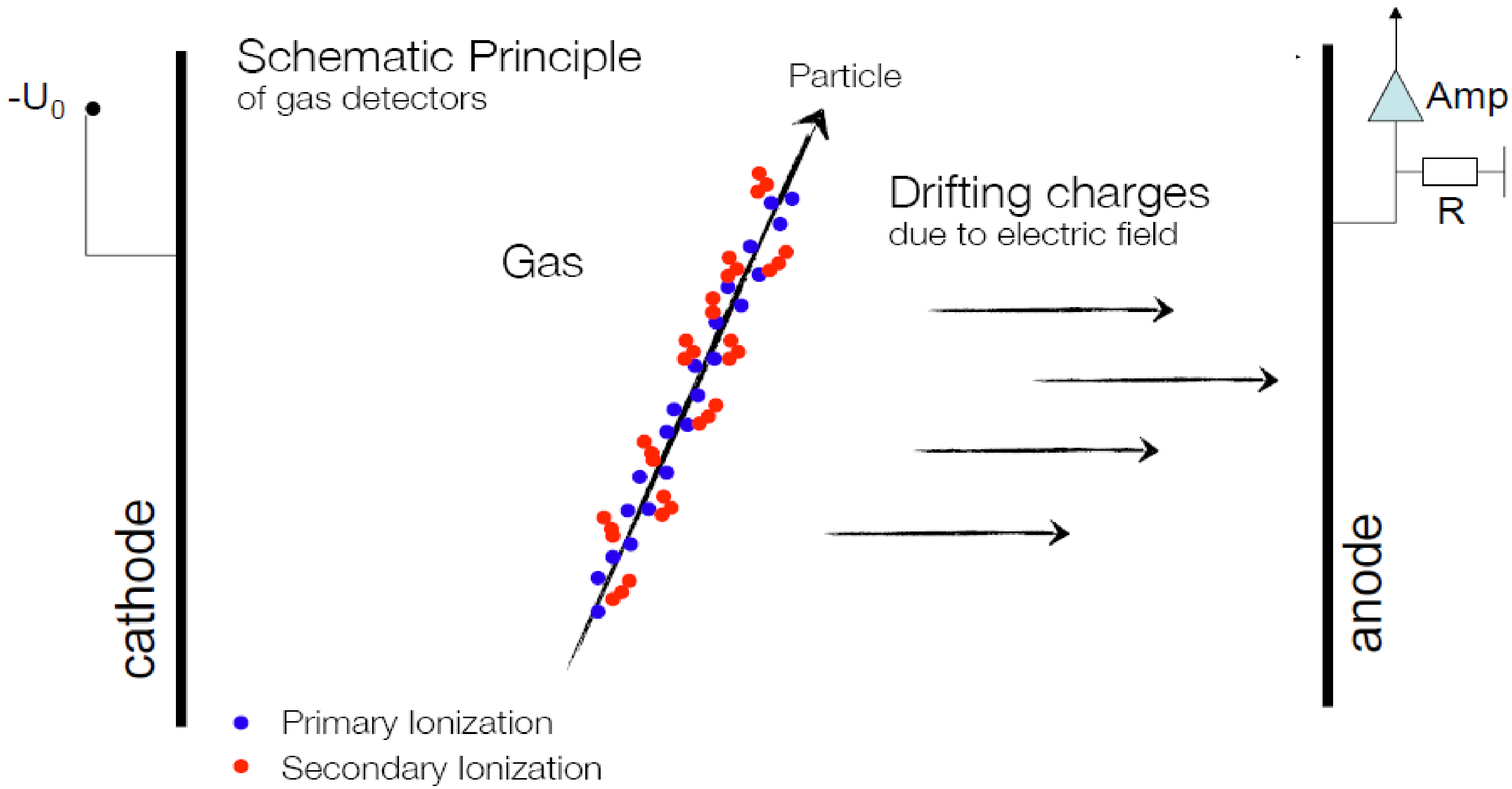
Therefore, an ionizing particle passing in a gas volume leaves a trail of ion-electron clusters behind it





Sometimes these trails are visible: electrons and ions (charged of opposite sign) recombine, emitting light

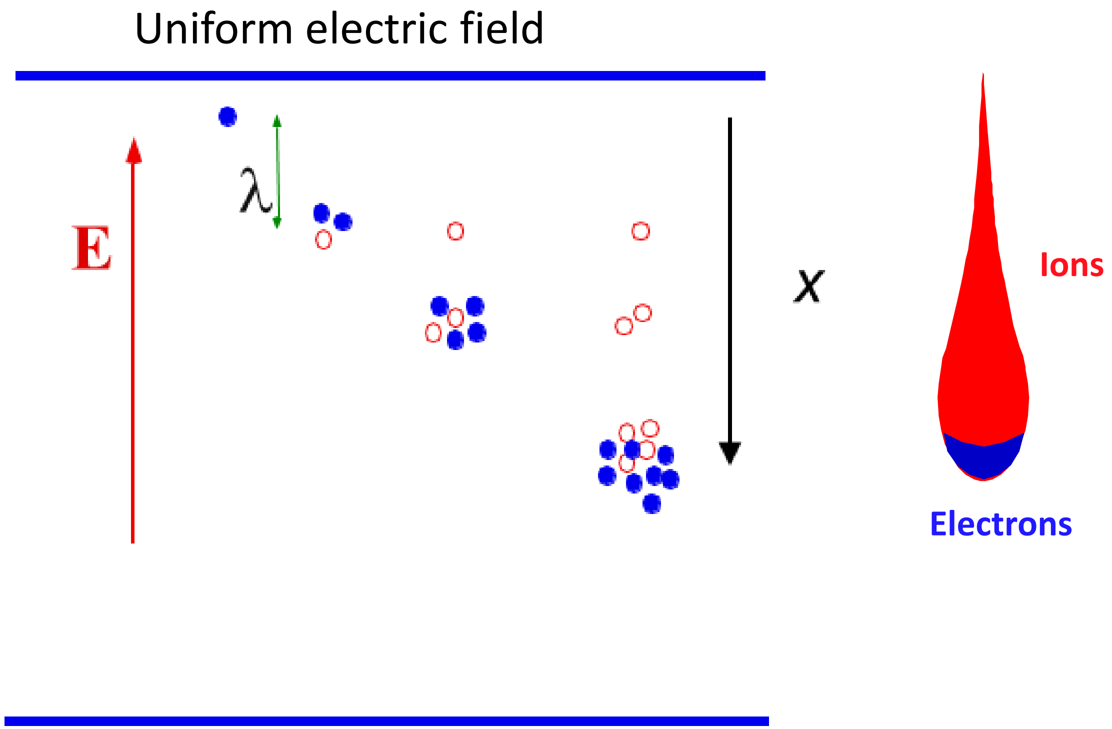
Principles of operation of gas-filled detectors

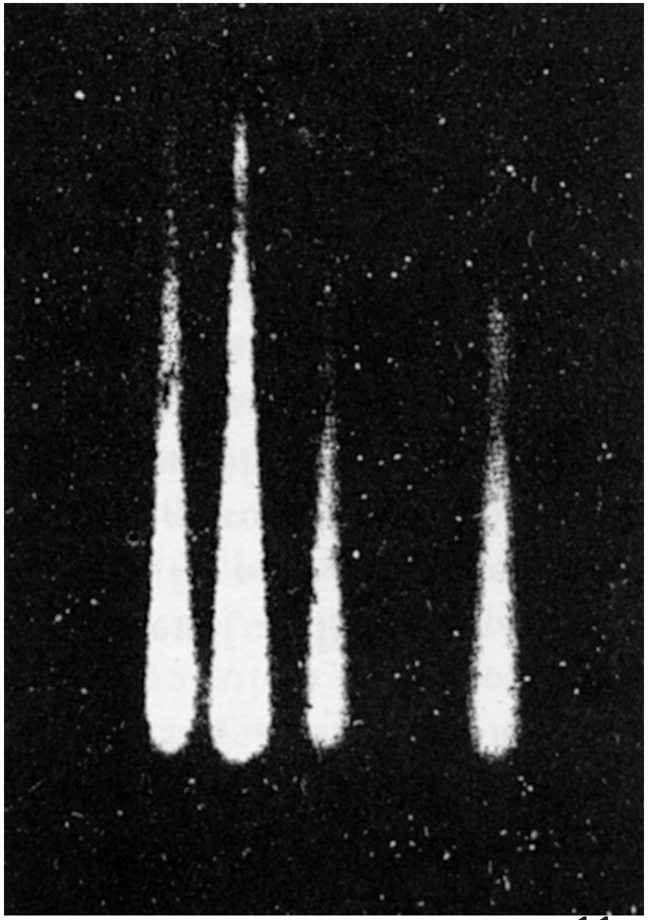


- **We need an electric field**: due to its presence, electrons and ions separate, and move toward anode and cathode, respectively.
- If the electric field is intense enough, **multiplication processes** take place
- Signal is produced by **induction** from the movement of charges in the gas

Multiplication processes in gases

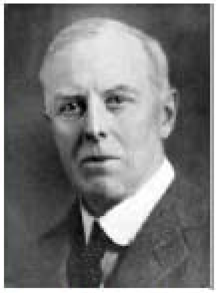
If the applied electric field is intense enough, electrons can gain sufficient kinetic energy to furtherly ionize gas atoms or molecules



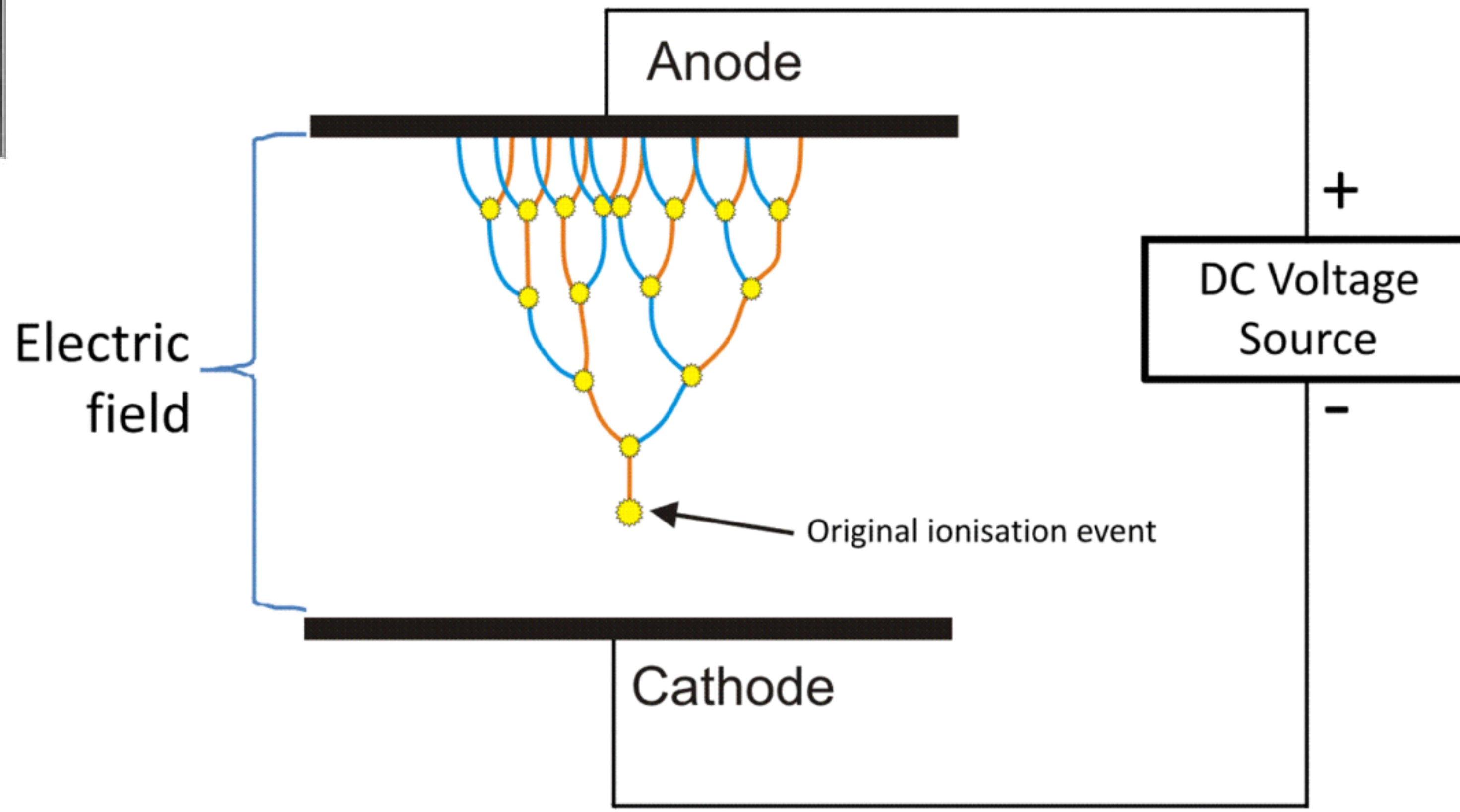


An "avalanche" is started. Since ions move much slower then electrons, they are left back.

Visualization of a Townsend avalanche



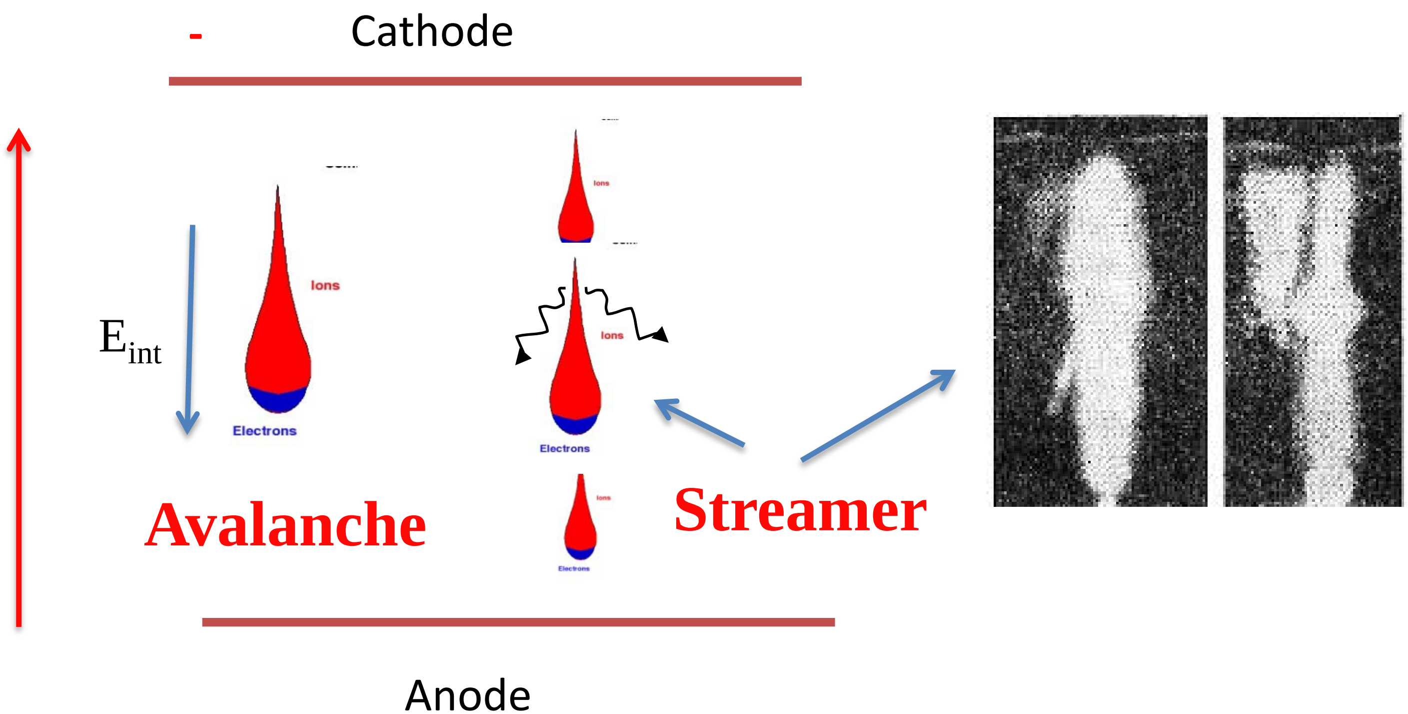
Sir John Sealy Edward Townsend (1868-1957)



The **key is the applied electric field**: the higher the potential difference, the higher the number of electrons arriving onto the anode

Streamers!

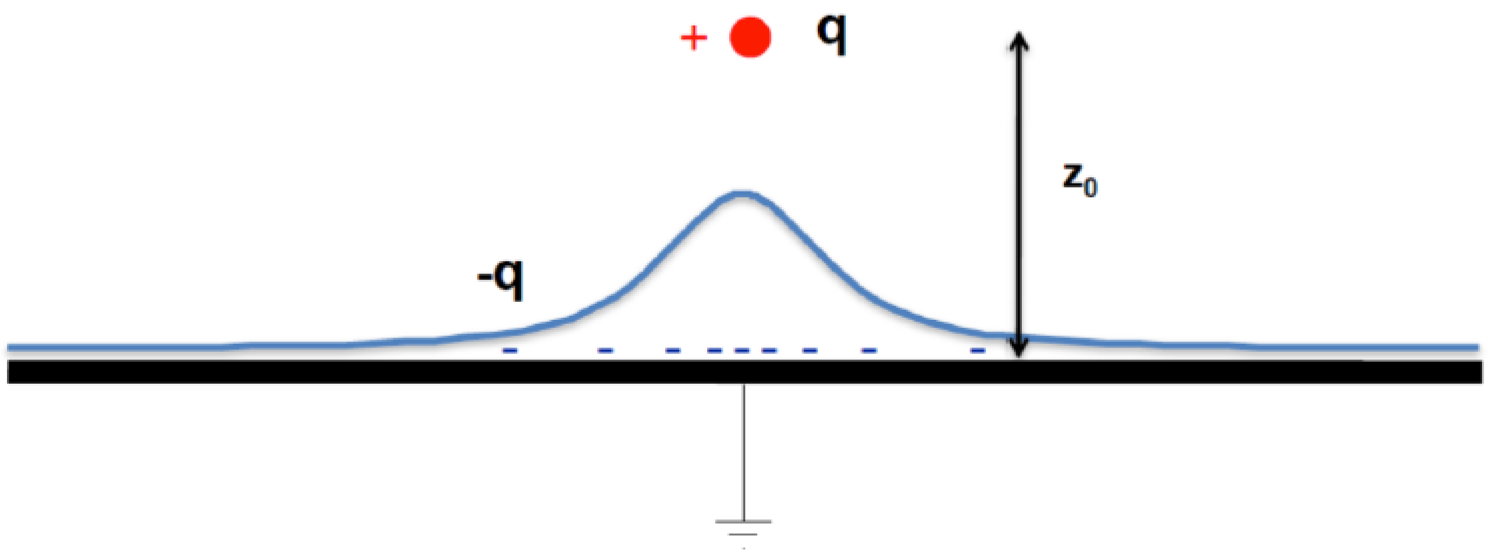
When an avalanche grows too much, space charge effects cause photon emission → new secondary avalanches can be produced,forming a streamline of charges: the "**streamer**"



When a streamer takes place, it gives origin to a huge signal, and usually all the readout strips are fired: we <u>do not want them</u>.

Next ingredient: charge induction

A free charge close to a metallic readout electrode attacts the electrons in it: **charge induction**



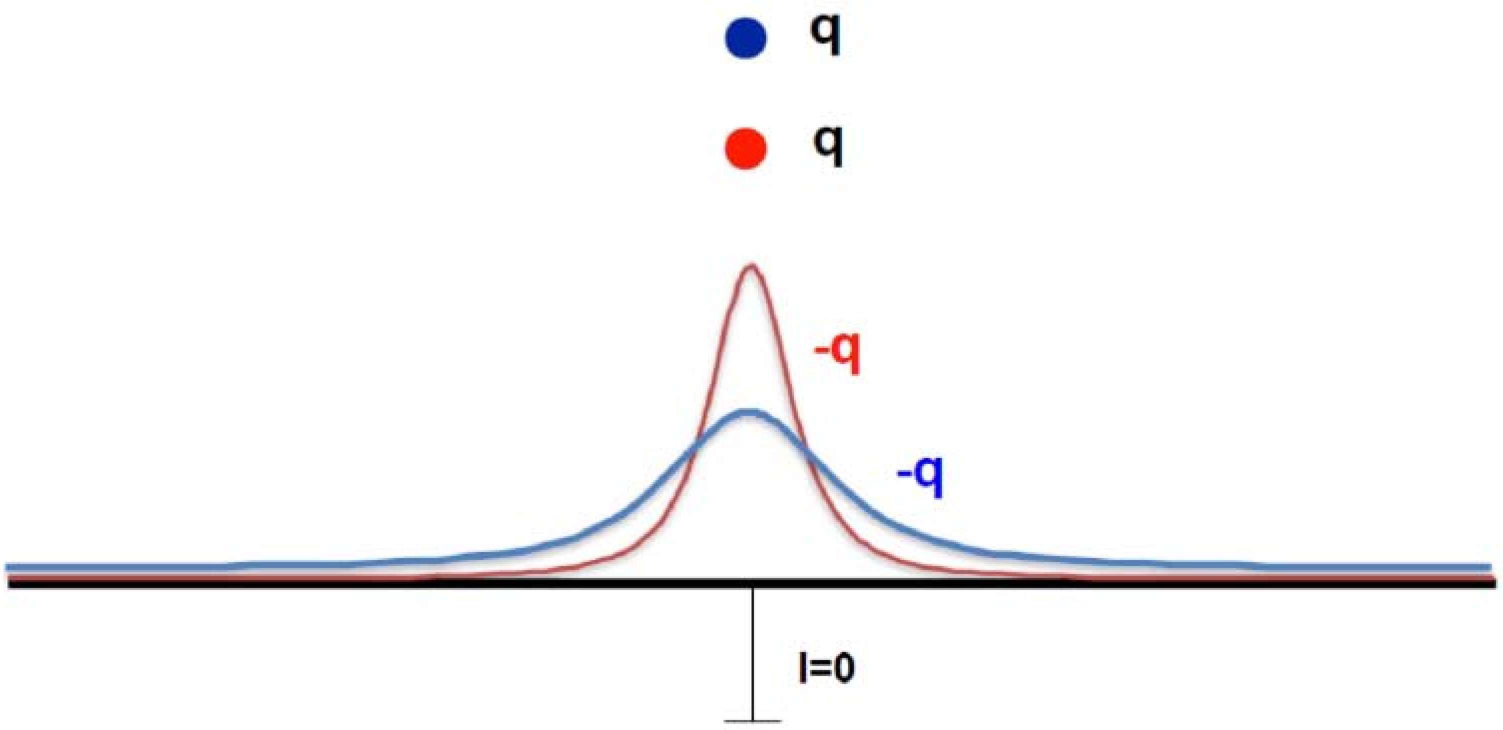
The charge distribution on the readout electrode can be described with a function similar to a Gaussian function → look for it!

Charge induction

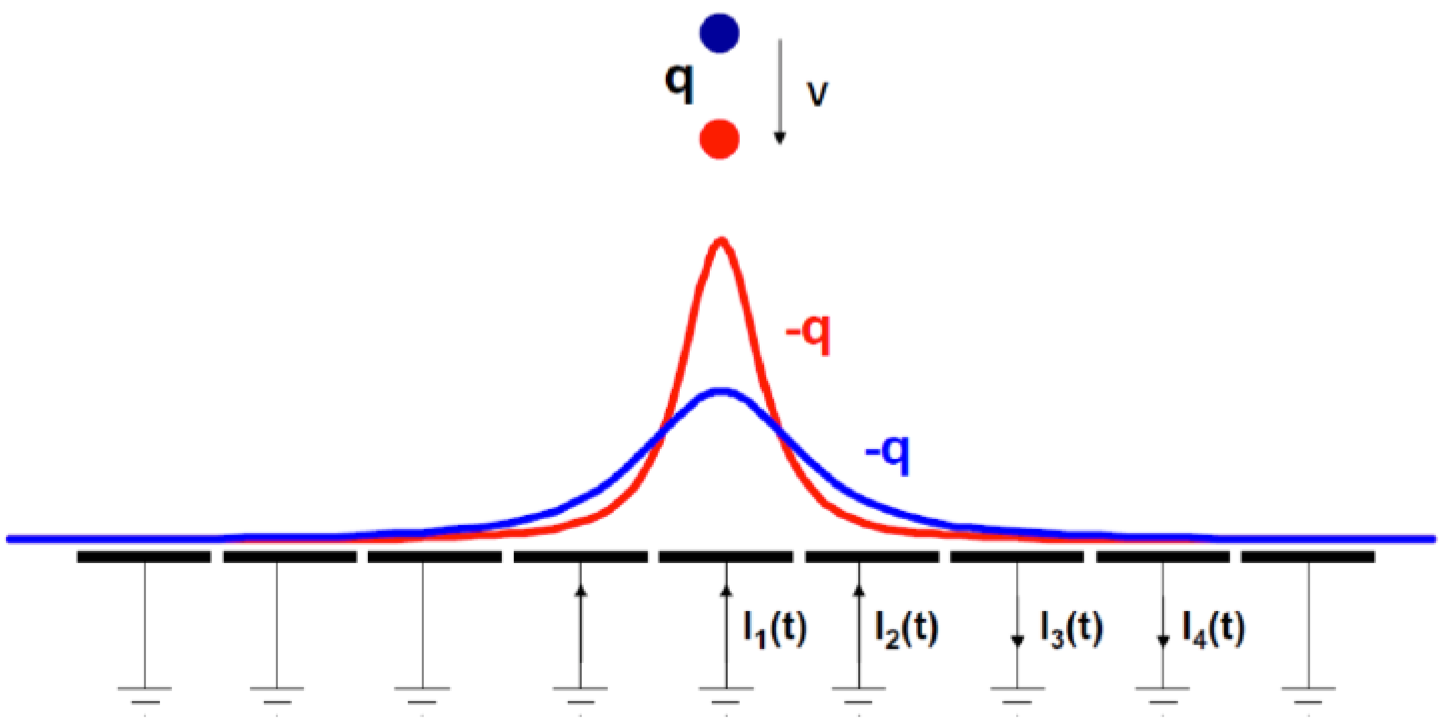
Of course, approaching the free charge to the electrode, the electric forces will be more intense:

→ the charge distribution will change (movement of charges)

→ it will be described by a narrower distribution



Signals, finally



- If instead of a plane we have many readout strips, we can read one signal from each strip
- Movement of charges on the readout electrode = current getting in or out of it = **signals!!!**
- Signals (=current) will be larger for strips closer to the particle

The most fundamental ingredient: the **GAS**

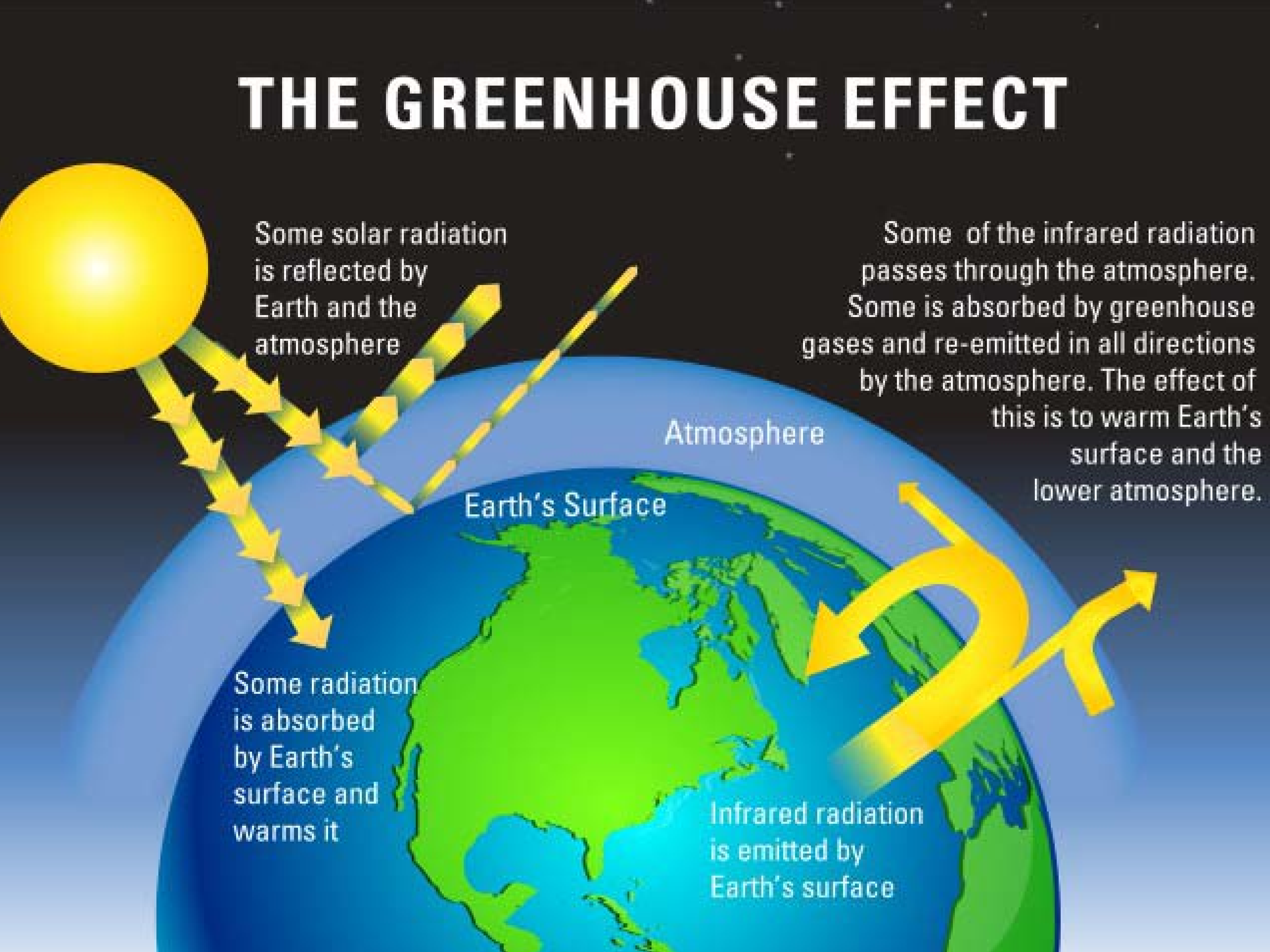
The gas mixture of the EEE detectors is made out of:
- $C_2H_2F_4$ = tetrafluoroethane = R134a
- SF_6 = sulfur exafluoride

R134a is a kind of Freon = commercial name for many various gases used mainly for refrigeration
- it is where **most ionization and multiplication processes** take place

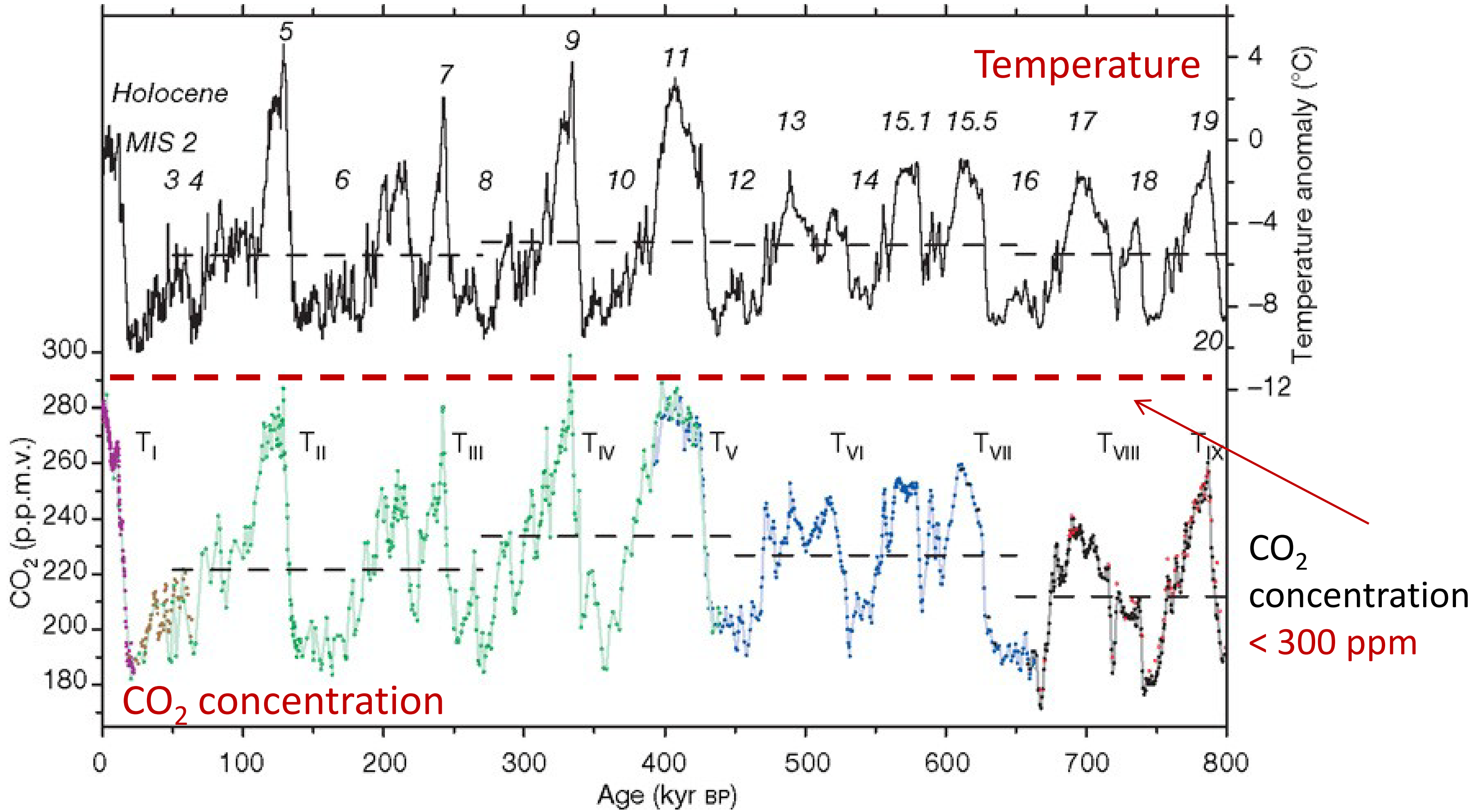
SF6 is used to "quench" the mixture, namely reduce (or avoid) the formation of streamers.

They have been selected after hundreds (literally) of tests!

What's the problem with them? They are greenhouse gases, and they have an effect similar to CO_2, but much larger.

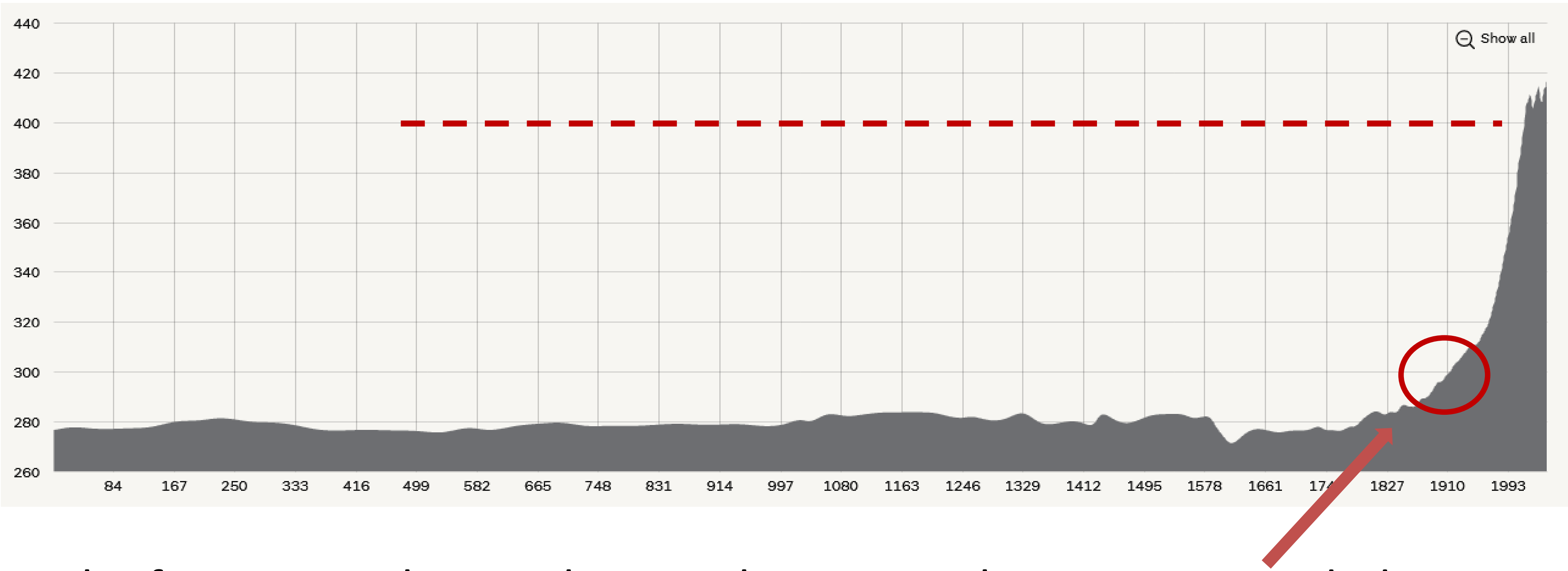

THE GREENHOUSE EFFECT
Some solar radiation is reflected by Earth and the atmosphere
Some of the infrared radiation passes through the atmosphere. Some is absorbed by greenhouse gases and re-emitted in all directions by the atmosphere. The effect of this is to warm Earth's surface and the lower atmosphere.
Atmosphere
Earth's Surface
Some radiation is absorbed by Earth's surface and warms it
Infrared radiation is emitted by Earth's surface

CO_2 concentration: last million year



We know that atmospheric CO_2 has ranged between 172 and 300 part per million (ppm) for the past 1 million years.

CO_2 concentration: last two thousand years



The first time in human history that atmospheric CO_2 exceeded 300 ppm was about the time the **Titanic sank (1912)** in the North Atlantic Ocean. Now, the crossover to concentrations that stay above 400 ppm CO_2 is nearly complete.

Global CO_2 emission from human activity

Most human-caused emissions of CO_2 into the atmosphere are from burning fossil fuels that had long been stored in the crust of the Earth. A small part of the fossil fuel total is from new cement usage.

86%

34.4 $GtCO_2$/yr

Fossil fuel emissions

14%

5.7 $GtCO_2$/yr

Emissions from land use change

(mostly deforestation)

Some numbers

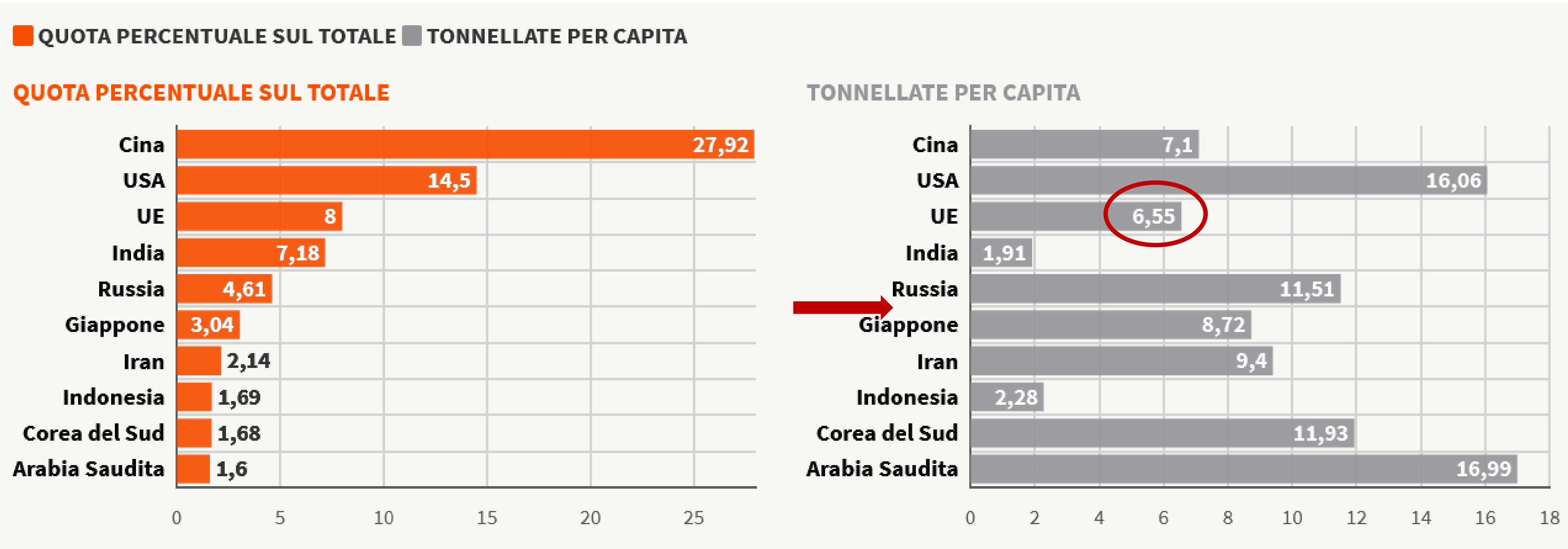
1 EEE telescope uses about 1 l/h of C_2H_2F4/SF_6 98/2 gas mixture
→**8760 liters per year** (when continuously operating, h24, even during August, Christmas, etc.)

Since the densities of $C_2H_2F_4$ = 4.25 kg/m^3 and of SF6 = 6.17 kg/m^3, this corresponds to inject into the atmosphere, each year:
36.5 kg of $C_2H_2F_4$ and 1.1 kg of SF_6

However, the Global Warming Power (GWP) of $C_2H_2F_4$ is 1430 the one of CO_2 (namely 1 ton of $C_2H_2F_4$ injected warms the Earth like 1430 of CO_2), and GWP(SF_6) = 23900

So, one EEE telescope injects into the atmosphere gas, for a GWP equivalent to **78.5 tonnes of CO_2 per year:**
36.5 kg x 1430 + 1.1 kg x 23900 = 52200 kg + 26300 kg = 78500 kg

Amount of CO_2 produced



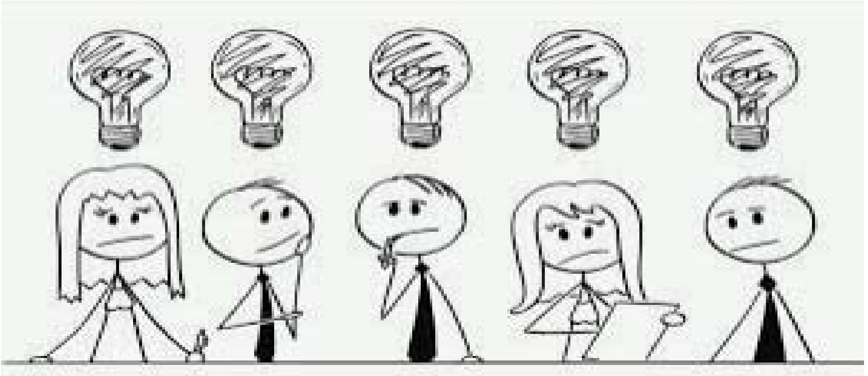
An EU citizen injects about 6.55 tons/year in the atmoshpere → One EEE telescope roughly emits the CO_2 equivalent to 12 **(twelve) people**

The problem

We need to replace the R134a and SF_6 with more ecological gases, namely with a much lower GWP.

Difficult problem: gases are **the core of gas-filled detectors**
-It's like I would ask you to replace silicon in electronic devices (including smartphones, computers, TV sets, etc.) with another material, BUT:

- with the **same performance**
- at the **same cost**
- without **changing anything** of the rest of electronic circuits



A BIG problem

For the EEE telescopes we are limited to:

-**Use binary mixtures,** since we have just two flowmeters

- cost= € 3000 per each EEE telescope
- cost = €180.000 per the whole network
- An easier solution could be found using ternary or quaternary mixtures

- Use mixtures that have a **working point** (=electric field to be applied to allow Towsend avalanches) **close to the present ,** < 20 kV

- The cost of the present HV power suppliers is about €4000 per EEE telescope (= € 240.000 for the whole network)

The new gas mixture must have:

✓a low GWP
✓guarantee the same spatial and time resolutions
✓must be safe (we cannot use hydrocarbons)
✓must have the same cost (for the whole EEE network ≈ 50 k€/year)

A green choice

Note that EU is progressively banning greenhouse gases:

- but they are still allowed for research applications (like EEE)

- $C_2H_2F_4$ and SF_6 are still allowed by law to be used in EEE telescopes

- nevertheless the green choice of the EEE community (and others) was to switch **NOW** to ecofriendly gas mixtures

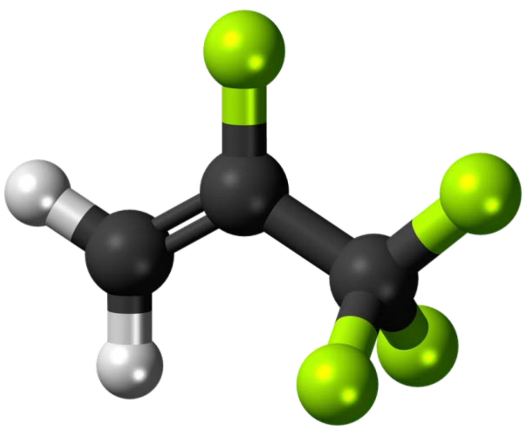
GREEN CHOICE

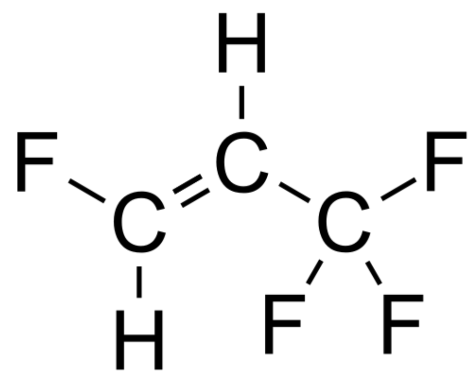
The smart (!?) idea

All high energy experiments (CMS, ATLAS, ALICE, LHCb, etc.) have started an intense R&D program to find suitable gas mixtures

-Practically all research trendlines are concentrated around the idea (by a smart guy) of replacing:

- $C_2H_2F_4$ (GWP=1430)→ $C_3H_4F_4$ze (GWP=4)
- SF_6 (GWP=23900) → CO_2 (GWP=1) or He (GWP<1)





$C_3H_4F_4$ze is the most similar molecule to $C_2H_2F_4$ but with a low GWP

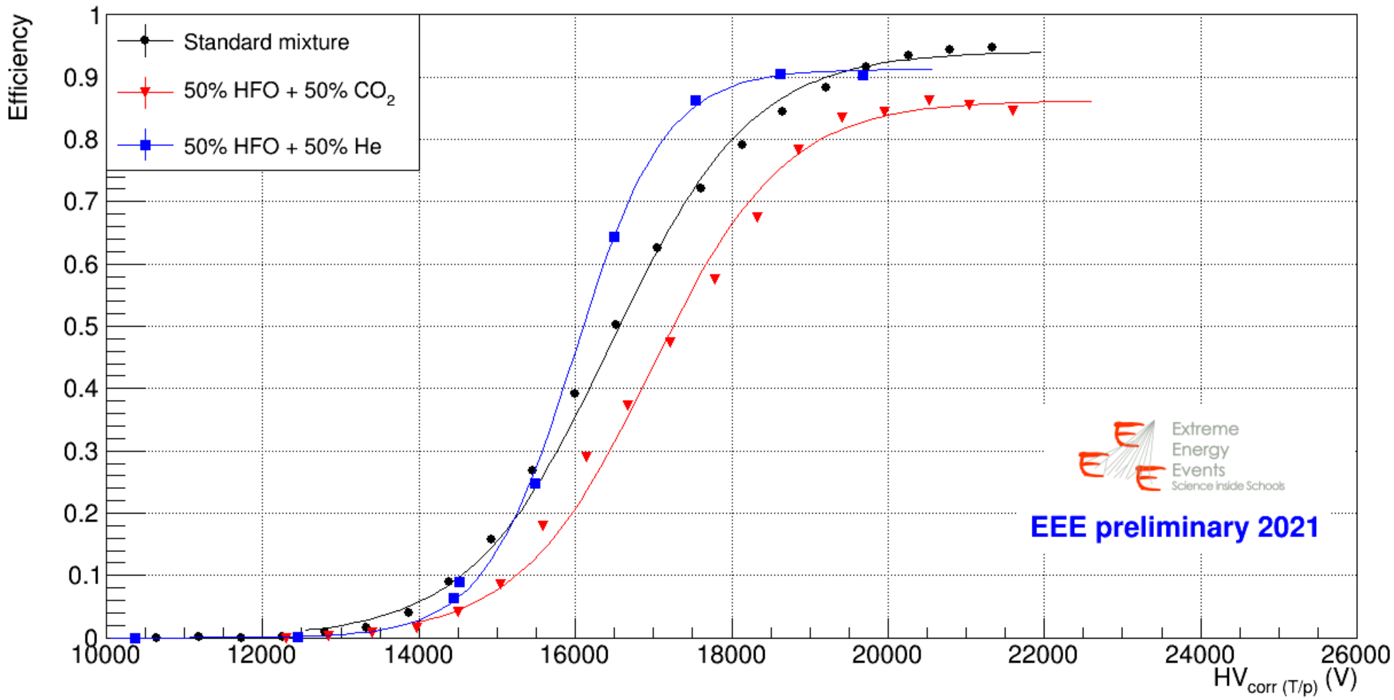
Would it be a solution?

A mixture made out of $C_3H_2F_4$ /CO_2 50/50 would have **GWP=2.5**
→ An EEE telescope would inject in the atmoshpere a gas whose GWP would be equivalent to **89.5 kg/year of CO_2**
→ This would roughly correspond to the CO_2 injected yearly by **0.014 human beings living in the EU**.

The EEE collaboration has started:
-a series of tests at the Bologna, CERN, Cosenza and Pisa sites
-A data analysis program in Cagliari, Lecce, Salerno

Promising results

Preliminary (unpublished) results indicate that this could be a suitable solution for the EEE telescopes.



BUT these results have to be confirmed, pass peer review, and these gas mixtures have to be proved suitable for **long term operation in EEE** without any performance degradation: still a lot of work to do.

Conclusions

- The EEE experiment is on the eve of a fundamental transition: **the ecological transition**
- It is a complex problem that has to be solved in the right way: **with the scientific method**
- Its solution will open the pathway to a **new phase of the EEE experiment**