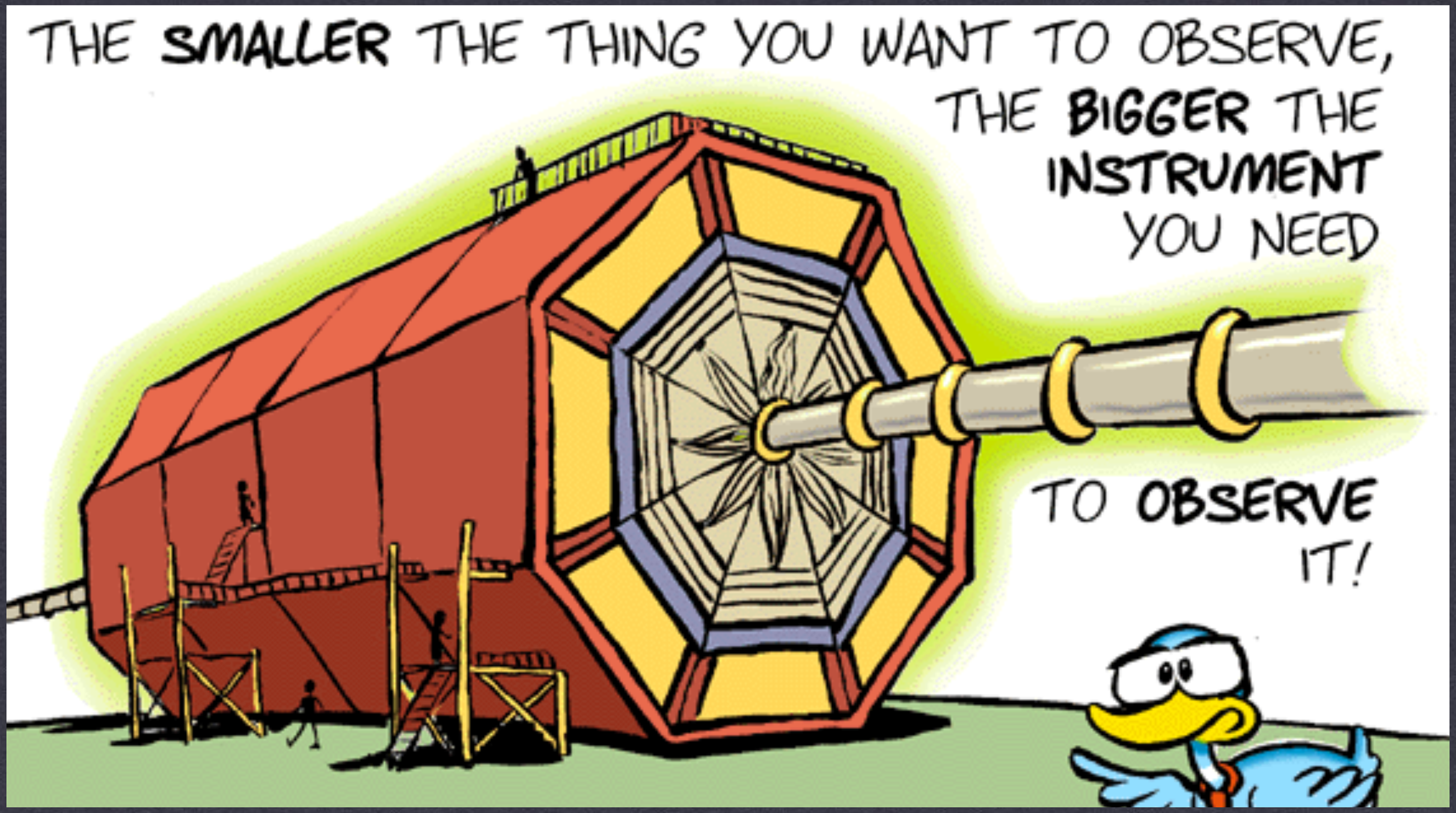

PARTICLE DETECTORS

Tools for discovery

February, 18th 2017

ANGELA FAVA

Theory or Experiment?

- Progress in Physics is the result of a symbiosis between theory and experiment.
- Is the majority of Nobel Prizes awarded for experimental work or theoretical work?

A. experiment

B. theory

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- Is the majority of Nobel Prizes awarded for experimental work or theoretical work?

experiment

As of 2013, experimental discoveries outnumbered theoretical ones at about 5-2!

- Which fraction of the Nobel Prizes were awarded specifically for technical innovation?

A. 5% B. 15% C. 20% D. 30%

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experiment

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- Which fraction of the Nobel Prizes were awarded specifically for technical innovation?

20%

Almost as many as all the theoretical contributions!

https://quantumcoffee.wordpress.com/2014/06/08/nobel-prizes-in-physics-theorists-vs-experimentalists/

Origin of the scientific method

- The basis of the experimental investigation of nature dates back to the XVI century, with the actions of G. Galilei.
- Einstein named Galileo the "**father of modern science**". Galileo's great contribution: science based on careful observation, measurement, and controlled experiment, and made accessible to a wide audience.

" Io stimo più il trovar un vero,

benché di cosa leggiera,

che 'l disputar lungamente delle massime questioni

senza conseguir verità nissuna."

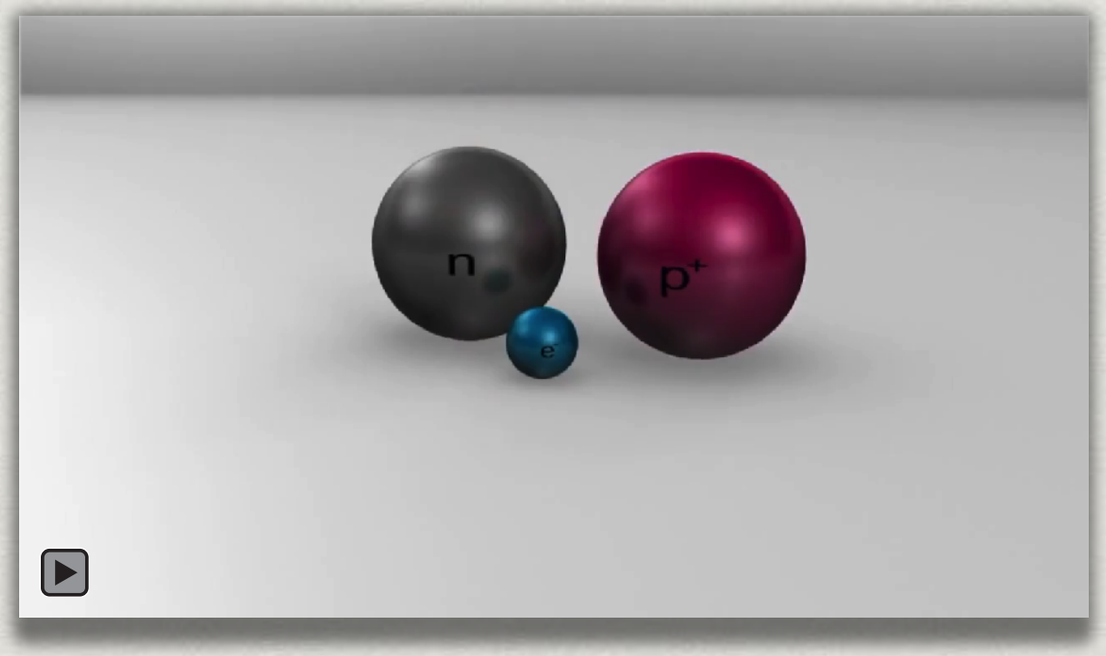
"I appreciate more discovering some truth,
although of minor relevance,
rather than abundantly discussing major topics
without getting to any results."

- Galilei's many discoveries were possible thanks also to the many instruments he invented, the telescope in primis.

A UNIVERSE OF PARTICLES

The particle zoo

- The situation became much more complicated since the beginning of the XX century. Observation of cosmic rays lead to the discovery of a multitude of particles!



From "CERN: The Standard Model Of Particle Physics" _ film produced as part of the CERN/ATLAS multimedia contest internship

- How many particles have been observed up to now?

A. 100 ÷ 200

B. 200 ÷ 300

C. 300 ÷ 400

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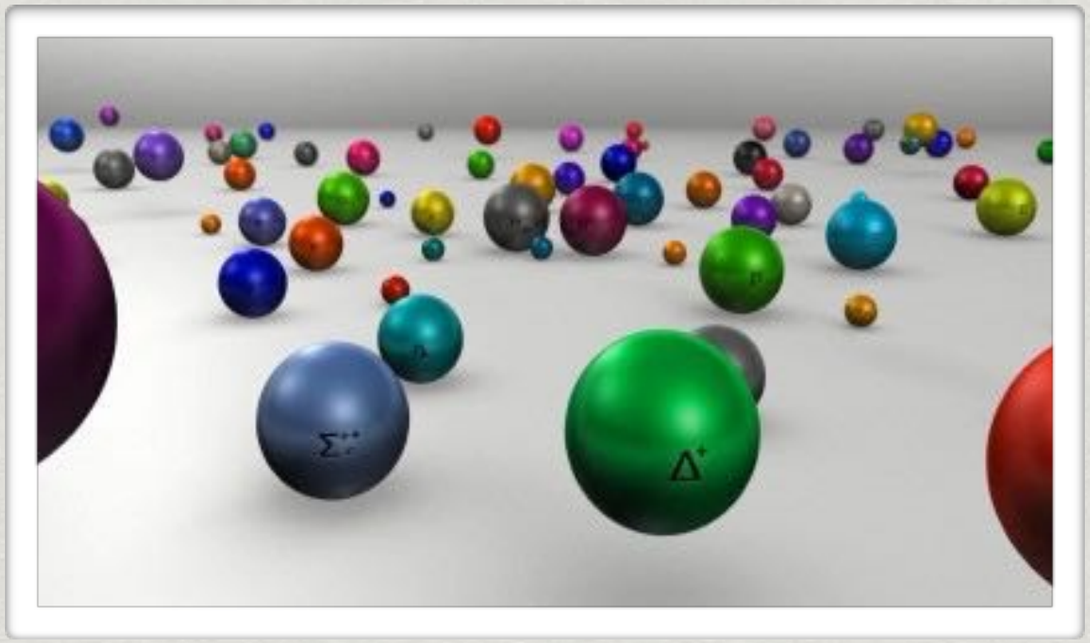

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- How many particles have been observed up to now?

200 ÷ 300

They are named after greek letters: we have almost run out of symbols!
And there might even exist many more than these...

- This is just for ordinary matter. Numbers double accounting for anti-matter.

Particle Data Group (www.pdg.lbl.gov): the bible of Particle Physics!

Tidying up the mess: the Standard Model

These are fundamental!

Special particles: they carry the information in the interaction!

What about protons & neutrons? They are made of quarks!!!

Unit of measurement in Particle Physics

- **Electronvolt (eV)**: energy acquired by an electron accelerating through a potential difference of one volt.

$$1\ \text{eV} = q_e \cdot V = (1.6 \times 10^{-19}\ \text{C}) \cdot (1\ \text{V}) = 1.6 \times 10^{-19}\ \text{J}$$

- Commonly adopted for masses as well.
  From the mass-energy equivalence $E = mc^2$, in the "natural units" framework ($c = 1$).

- 1 eV

511 keV = electron mass

200 MeV

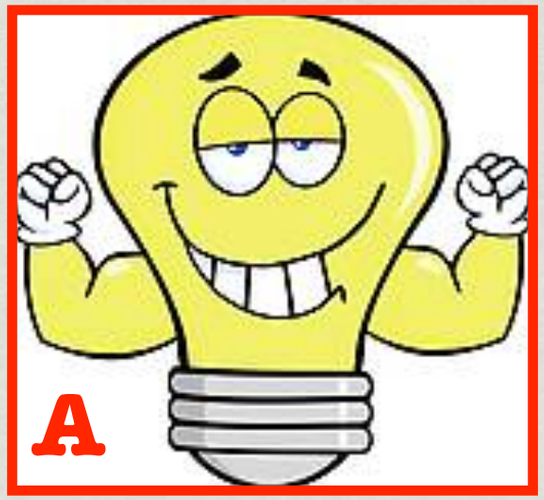
125 GeV = mass of the Higgs boson

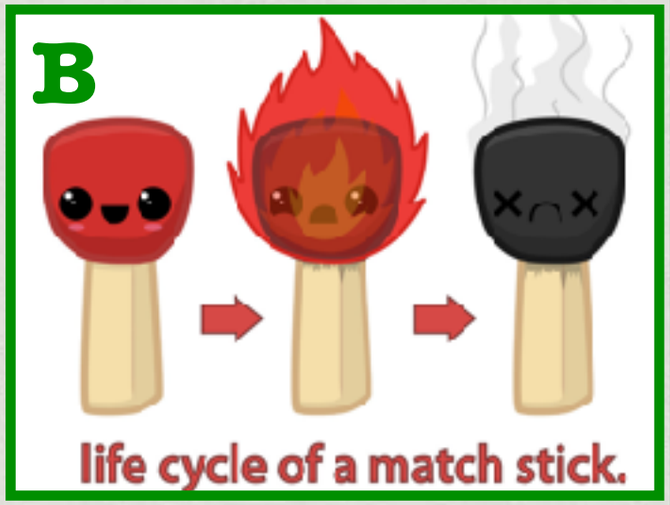
1 TeV

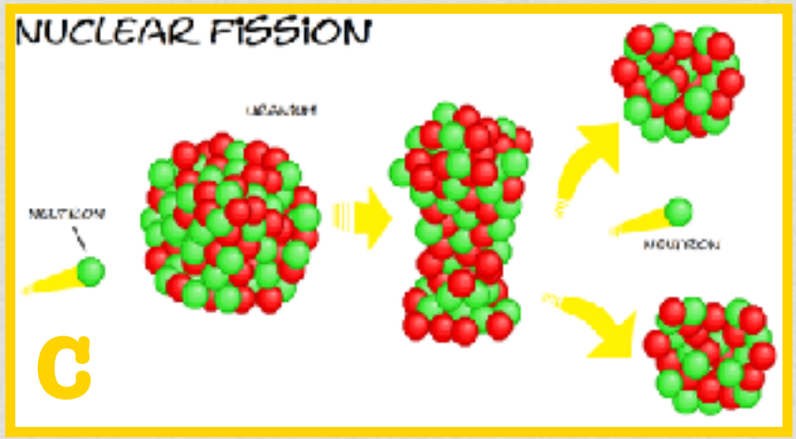
13 TeV = collisions at LHC

624 EeV

10^{88} eV = estimated total mass-energy of the observable Universe







By the way… particles travel fast!

- Velocity of elementary particles is close to the speed of light
  ➟ relativistic effects cannot be neglected

- Relativistic correction factor for a particle with velocity v

$$\gamma = \frac{1}{\sqrt{1+\beta^2}}, \quad \beta = \frac{v}{c}$$

- Einstein equation, as a function of the rest mass m_0 of the particle:

$$E = \gamma m_0 c^2$$

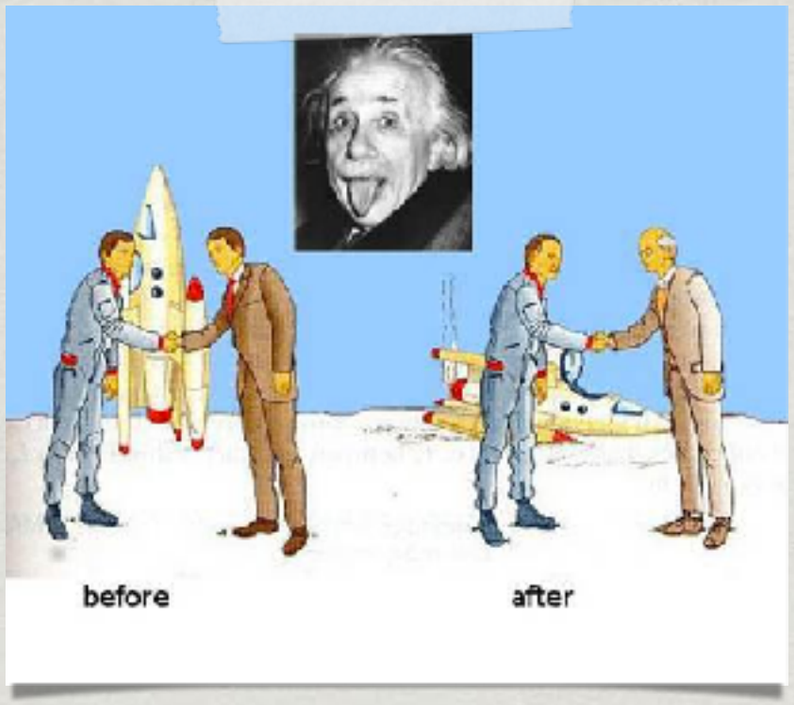
- **Time dilation**: from the point of view of inertial observers, as we are, times are longer ("Twin paradox").

  Example. In classical kinematics we wouldn't expect that cosmic-ray muons (m_0 = 105 MeV, τ = 2.2 μs) cross the 10 km depth of the atmosphere:

  $$s = v\,\tau = 600 \text{ m}$$

  But at typical energies (E = 2GeV)

  $$\gamma = \frac{E}{m_0} \sim 19 \quad ➟ \quad s = v\,\gamma\,\tau = 12 \text{ km!}$$



Particle Sources

NATURAL

Cosmic rays

- The first source for Particle Physics experiments.
- broad energy spectrum, up to 3 x 10^8 TeV ("Oh-My-God" particle).
- Interesting for cosmological studies.

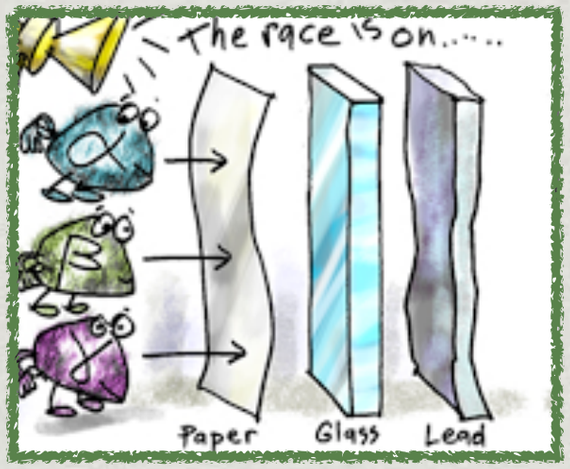
ARTIFICIAL

Accelerators

- Developed since 1930.
- Maximum energy obtained up to now: 13 TeV at LHC (CERN).
- Excellent for studies of rare particles thanks to very high intensity.

Radioactive decays.

- Low energies, in the keV - MeV range.
- Most famous applications in Particle Physics with neutrinos



Who is going to win the race?

A. ^{4}He nuclei

B. Electrons

C. Photons

Particle Sources

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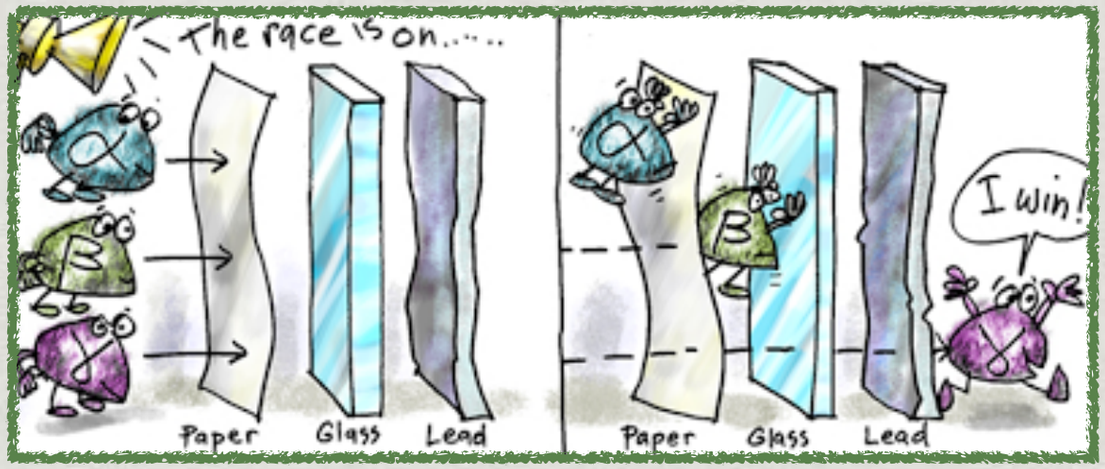


Who is going to win the race?

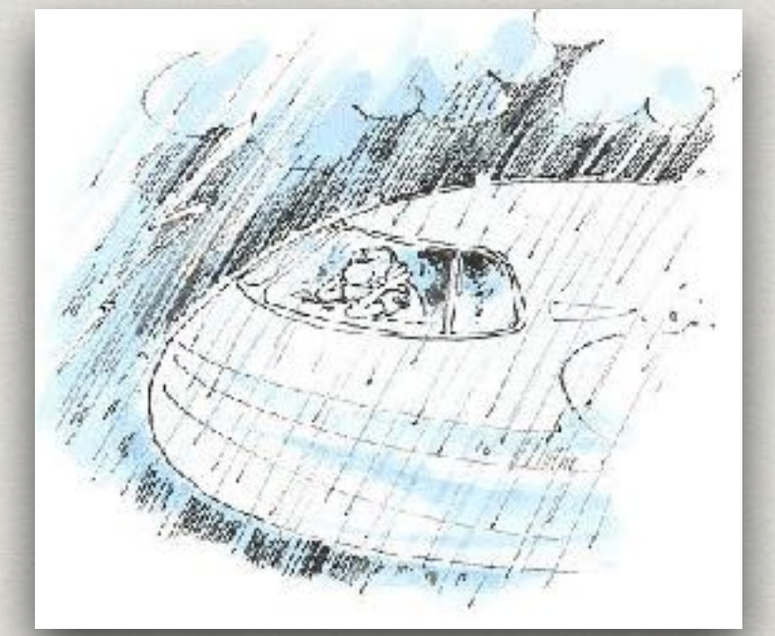
Photons

Cosmic rays: an invisible rainfall

100000 particles

cross the human body

in 1 hour!



At 33000 ft

almost **1 million particles**

cross one human body

in 1 hour!

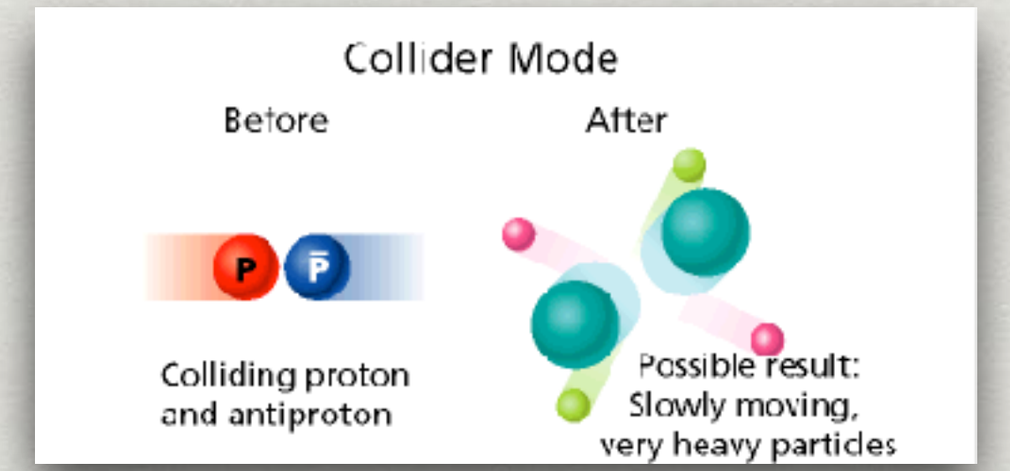
In the Gran Sasso National Laboratories (Italy),
at 1400 m depth,
human body is crossed by
only **1 particle every 10 hours!**

Who is hiding under the invisibility cloak?

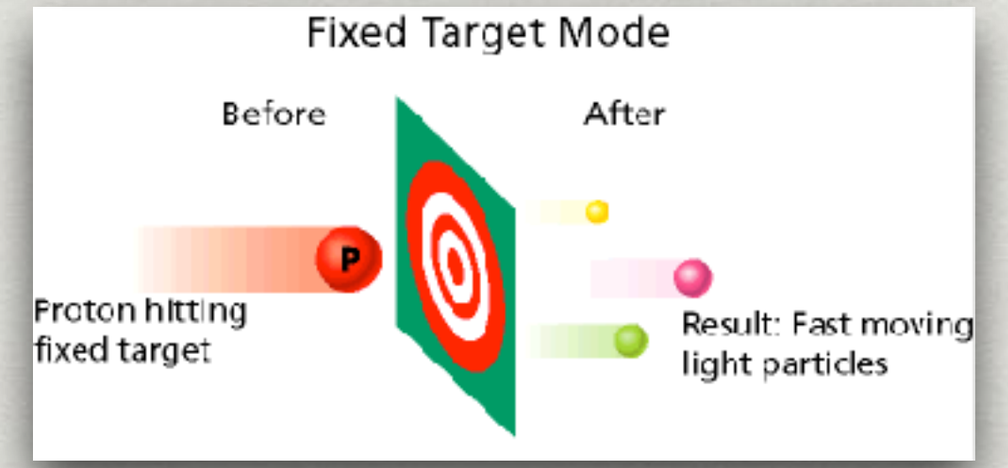
From “The fantastic voyage of Nino the neutrino” _
film produced by INFN (National Institute of Nuclear Physics), Italy

Particle production at accelerators

- **Colliding beams**.
  Maximisation of energy transfer.
  Most powerful: LHC (Large Hadron Collider)
  at CERN (Switzerland), 13 TeV!



- **Fixed target**.
  Production is forward with limited energy transfer.

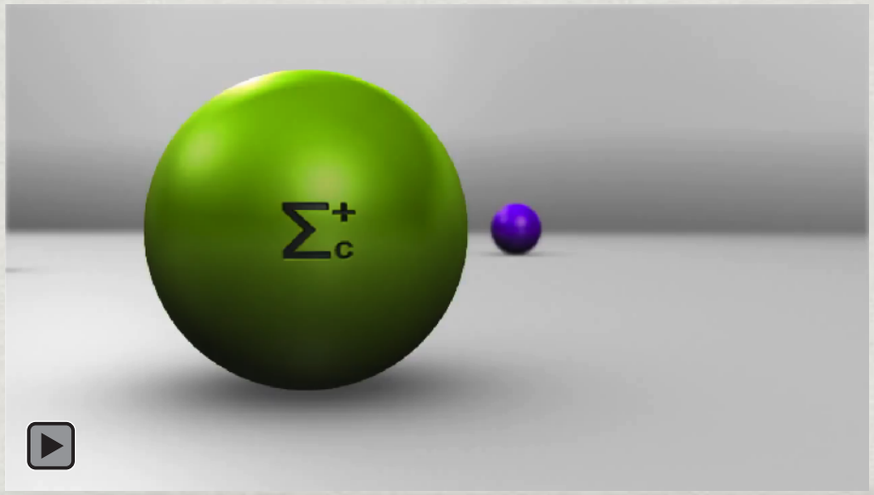


Neutrino beams examples of fixed target.
At Fermilab: BNB and NuMI!

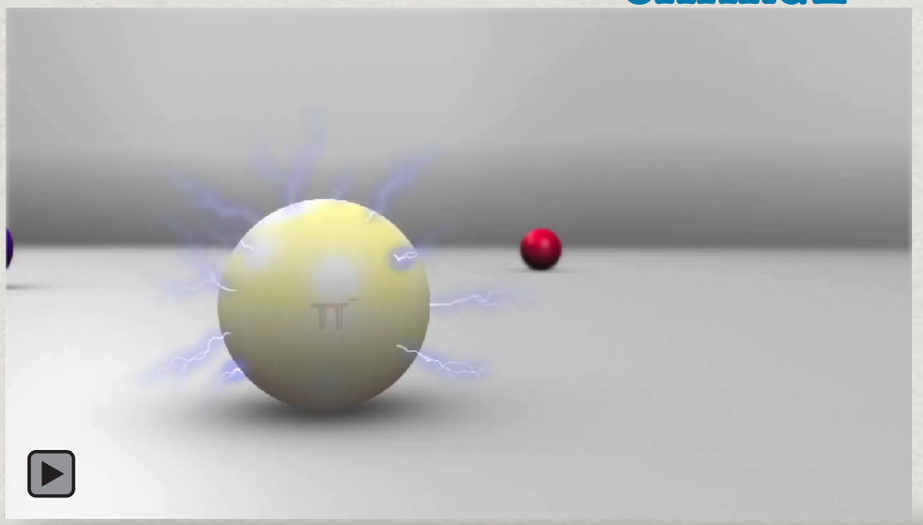
What to look for...

- PARTICLE (for theorist) = irreducible representation of Poincare group 😱
- PARTICLE (for experimentalist) = entity recognisable by measurable properties 👌

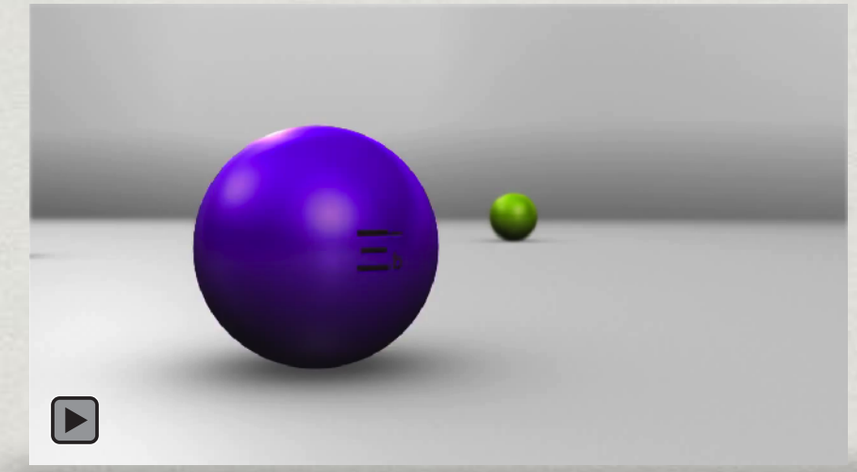
MASS



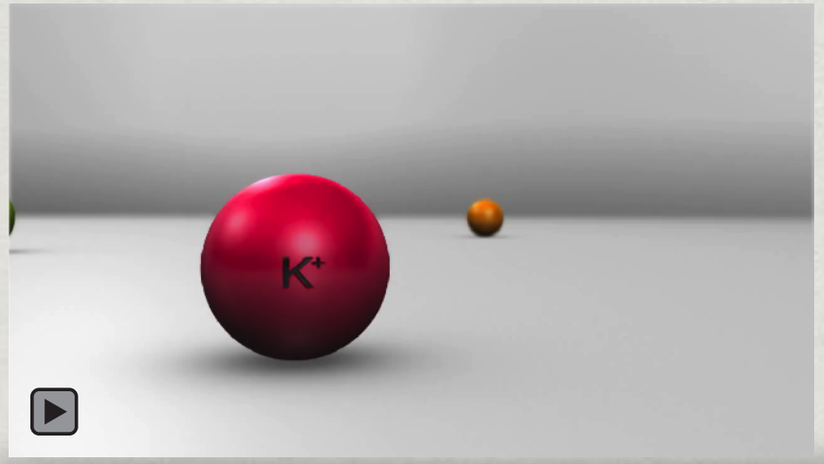
CHARGE



SPIN



LIFETIME



- Energy, momentum (mass x velocity) and position are additional handles.

IT'S ALL ABOUT FORCE

Interaction of particles with matter

- Measurement of particles and their properties is based on their interaction with matter.
- Only a small fraction of particles is actually detectable: the "stable" ones ($c\tau$ > 500 μm).

γ , $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $k^{\pm}$, $p^{\pm}$, k^{0}, n, ν → Weak interaction

Electromagnetic interaction

Strong interaction

- Electromagnetic interaction of charged particles = photon exchange with the atoms:
  - heavy particles ($\mu^{\pm}$, $\pi^{\pm}$, $k^{\pm}$, $p^{\pm}$) = virtual photon
    ionisation (electron emission) and excitation;

    → Followed by emission of real photons
    scintillation

  - light particles ($e^{\pm}$) = real photons
    bremsstrahlung radiation;
  - all particles in particular circumstances = additional real photons
    Cherenkov radiation.
- Electromagnetic interaction of photons = electrons production
  photoelectric effect, **Compton scattering** and **pair production**.

Ionisation & Scintillation

- Progressive energy loss by means of multiple interactions with the atomic electrons. If the absorber is thick enough, the incoming particle finally stops.
- Measured quantity: $\Delta E/\Delta x$, i.e. number of electrons/ions or de-excitation photons.
- It depends on:

A. Fundamental constants

B. Features of the incident particle

C. Properties of the absorber medium

- Which is the only set of unknown parameters?

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Features of the incident particle

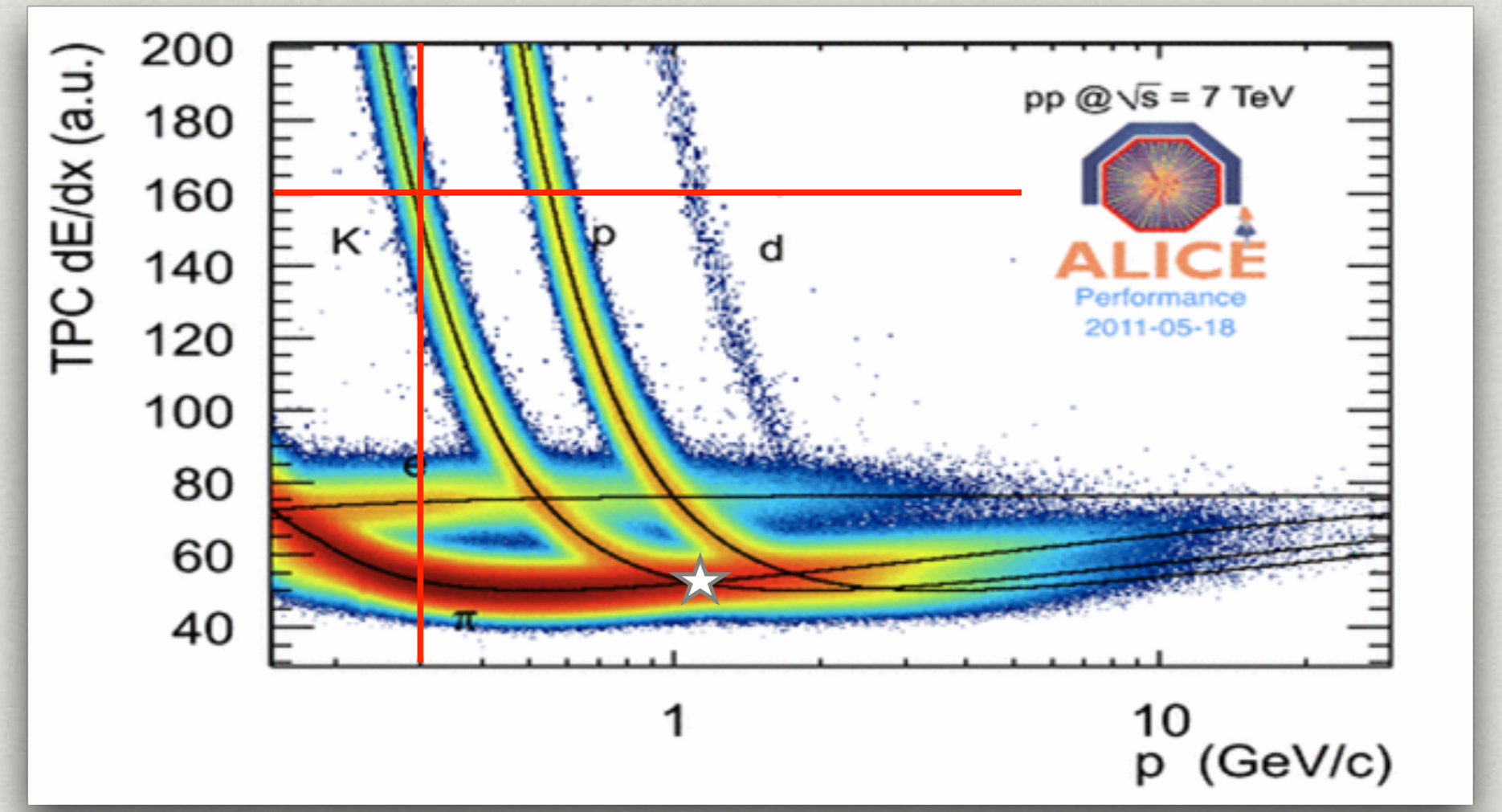
- Which is the only set of unknown parameters?

  Measurement of dE/dx allows inferring the velocity of the incoming particle.

Particle identification with dE/dx

- Assuming to have independently determined the momentum, the value of the mass can be extracted, thus allowing for PID (Particle Identification).
  Ex: knowing dE/dx = 160… k, p, d cannot be distinguished
  having also the info p = 300 MeV/c… the particle is identified as a kaon!

- This is especially true at low energies.
  Ex: even assuming to know both dE/dx = 50 and p ≃ 1 GeV/c…
  It is impossible to determine if the particle is a k or a π!

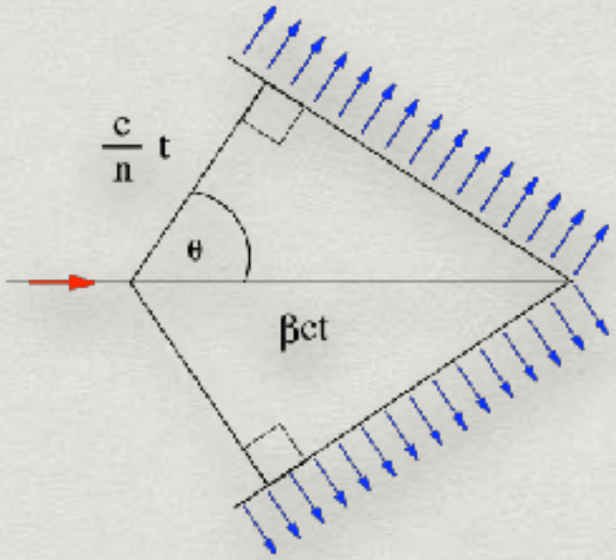


Cherenkov radiation

- **Sonic boom** = sound associated with shock waves caused by objects travelling through air faster than the speed of sound.

- Photons in a medium are typically slower than in vacuum. Quantified by refractive index n.

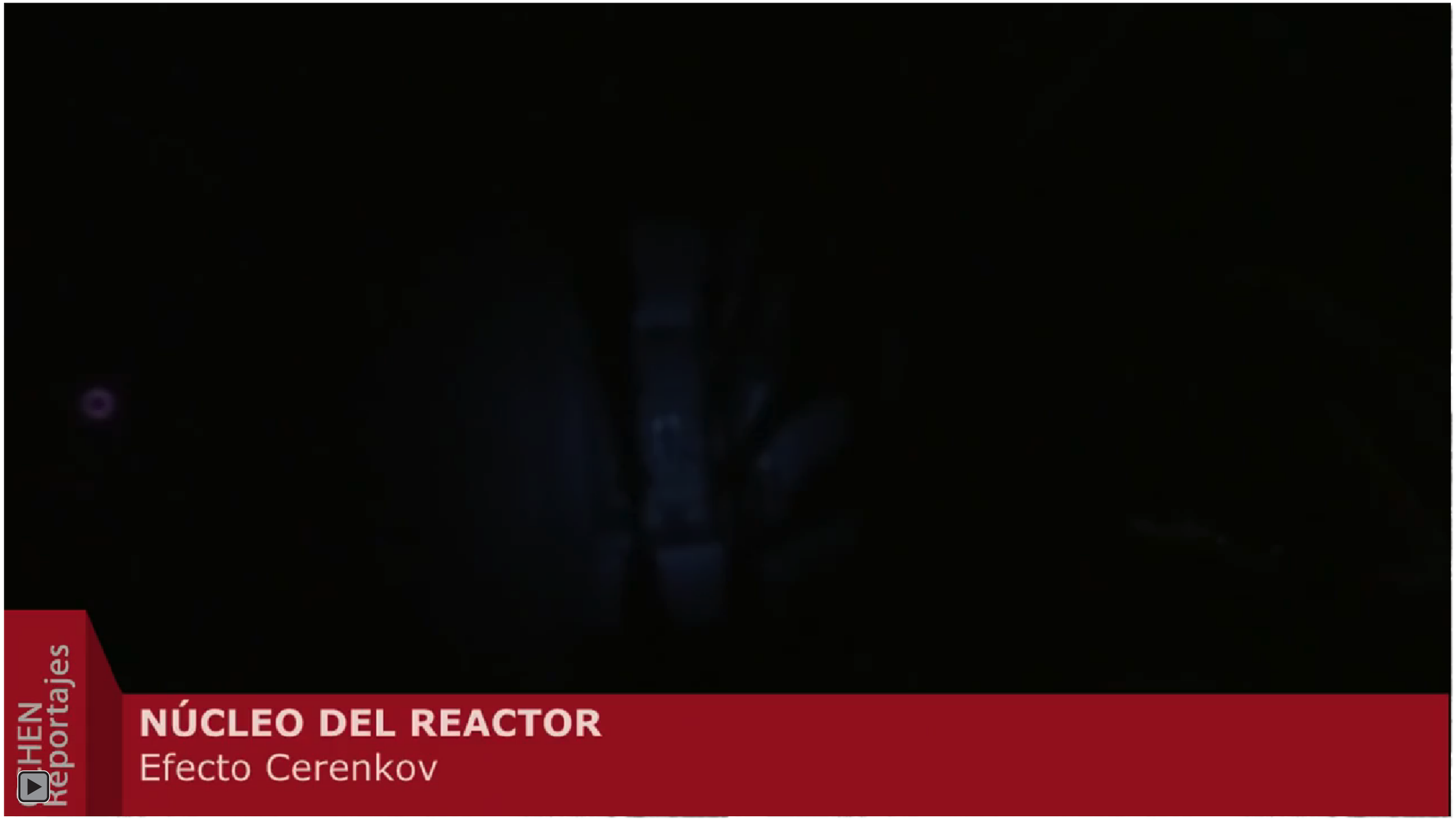
$$cos\theta_C = \frac{1}{n(\nu)\beta}$$



- **Cherenkov light** = light associated with electromagnetic shockwave caused by charged particles travelling in a medium with a velocity higher than light ($\beta > 1/n$).

Photons are emitted in a cone. Aperture angle depends only on particle velocity and refraction index.

A “sonic boom of light”



Particle identification with ϑ_C

- Being the refraction index of the material known, the measurement of ϑ_C allows inferring the velocity of the incoming particle.
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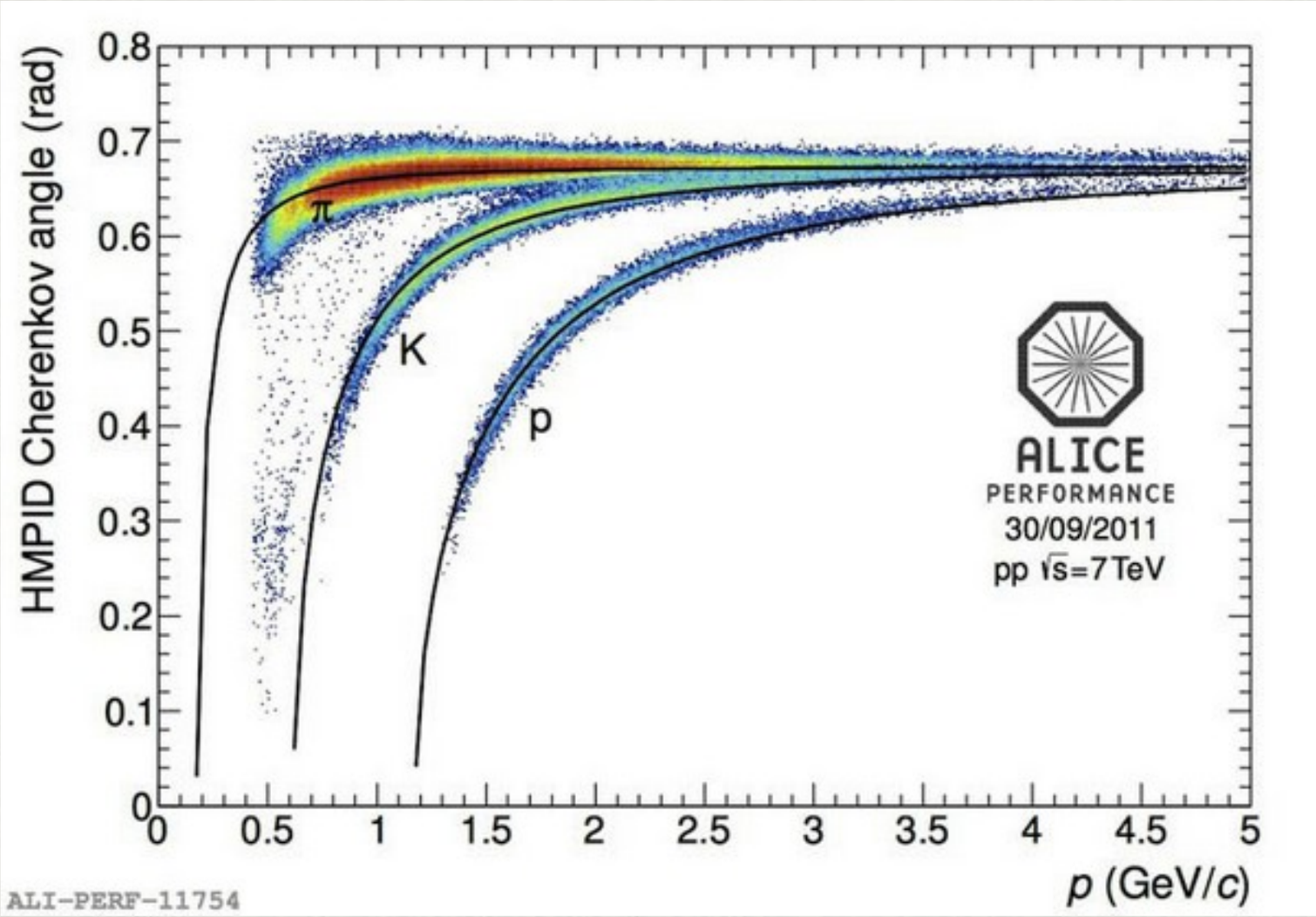

- A particle at 1.5 GeV/c emits a Cherenkov cone at 0.4 rad.
  What can be said on the particle?

A. π

B. k

C. p

D. Unidentified

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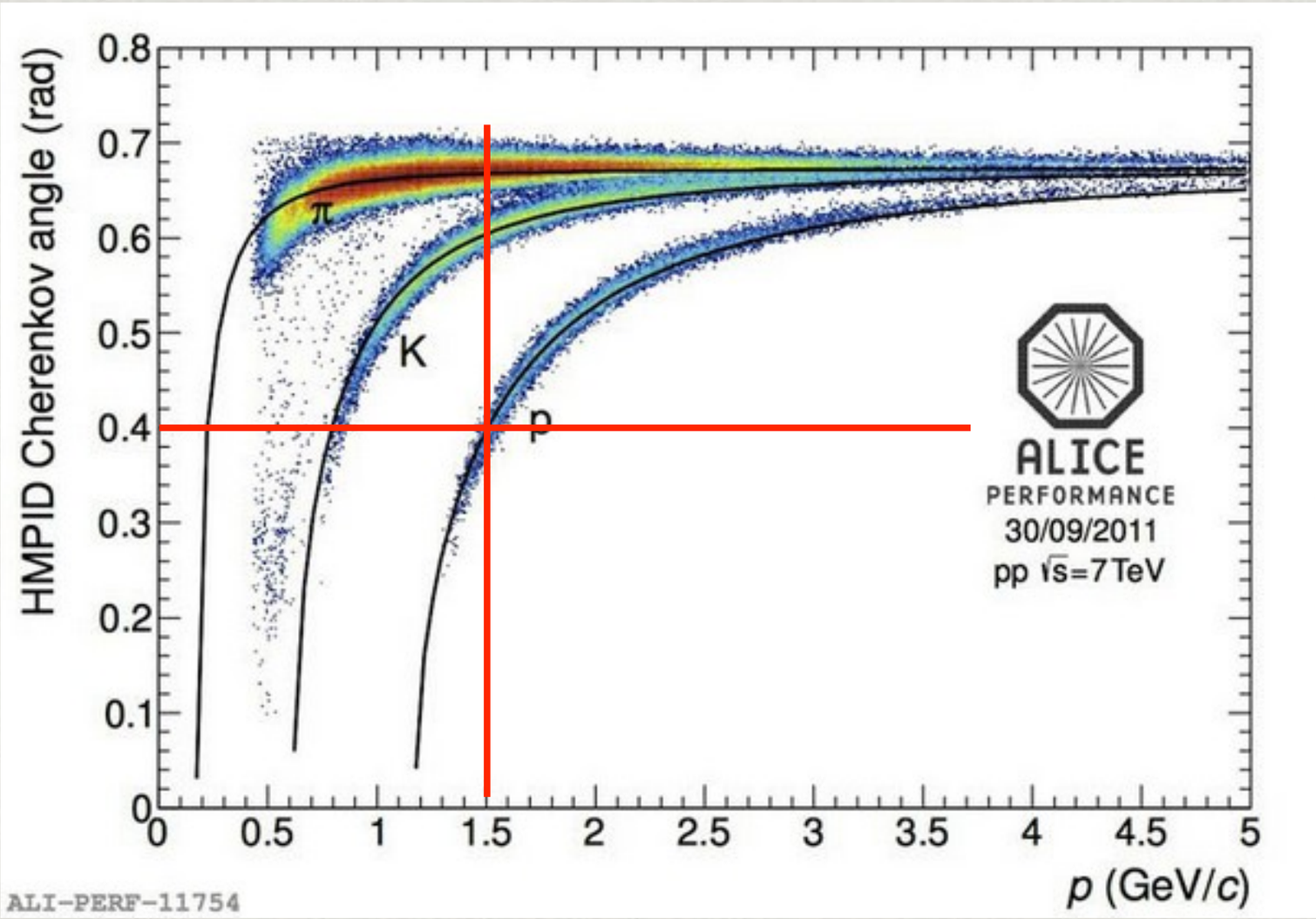

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  What can be said on the particle?

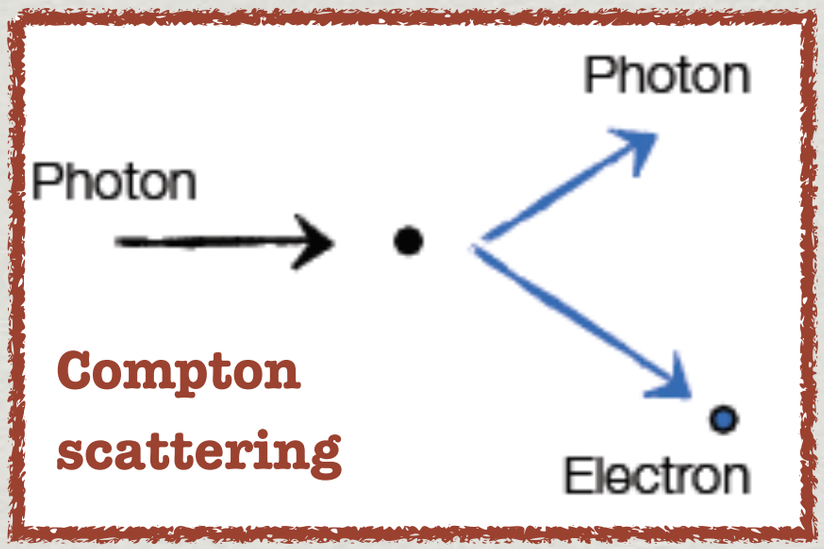
p

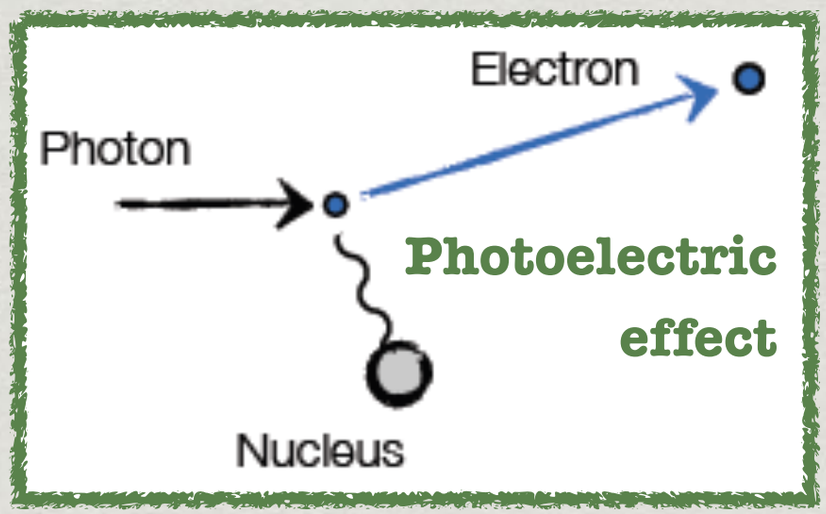
Photons

"**One shot**": everything happens in one single interaction.

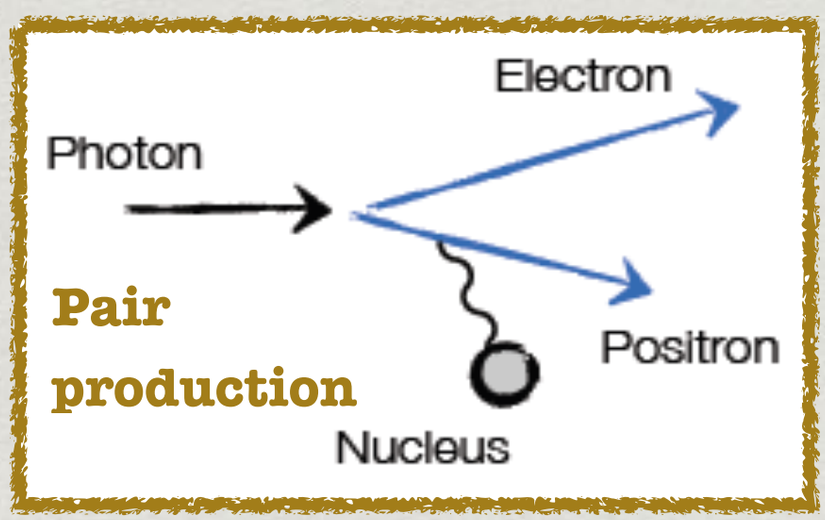
Partial energy loss,
with emission of 1 electron.

Total energy loss.





Emission of
1 electron.



Emission of
an electron-
positron pair.

Charged particles in magnetic fields

- How do charged particles in motion in a magnetic field behave?

A. Slow down

B. Bend

C. Speed up

Charged particles in magnetic fields

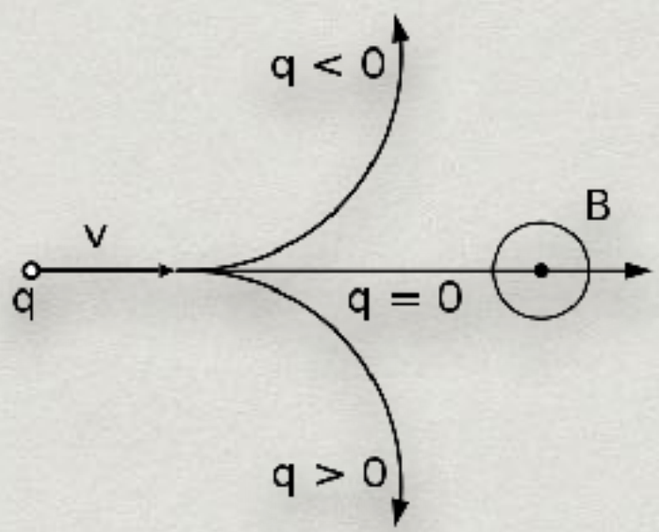
- How do charged particles in motion in a magnetic field behave?

B. Bend

- Because of the Lorentz force $\vec{F} = q\vec{v} \times \vec{B}$, they describe a circular motion in the plane perpendicular to the direction of the magnetic field, with a curvature radius

$$R = \frac{p_T}{qB}$$

- Particles of opposite charges are bent in opposite directions.
  This makes the measurement of the sign of the charge of the particle very easy!



- By measuring the amount of bending, the transverse momentum can be determined.

HERE COMES THE FUN

Scintillation

- Prompt ($\simeq 10^{-9}$ s) or delayed (up to hours!) de-excitation of the atoms/molecules of the medium back to their ground state.

- What does the response time depends on?

A. Medium

B. Incoming particle

C. Both

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Medium

Depends on "stability" of the excited state.

- What does the total number of emitted photons depends on?

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Different from the **light yield** = efficiency of conversion of the incoming particle energy into scintillation photons. This depends on the medium only.

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- What does the wavelength of emitted photons depends on?

Medium

It corresponds to the energy difference between the initial excited and the ground state. Typically in the UltraViolet range.

Scintillating materials

- Possibility to choose among a huge variety of materials.

- ORGANIC
  - **plastic**
  - liquid
  - crystal
- INORGANIC
  - **liquid**/gas
  - crystal
- GLASS

Pro	Cons
Fast (1 ns)	Low light yield (< 5%)
Easily shaped	Radiation damage
Small T dependence	
Cheap	

Pro	Cons
High light yield (< 15%)	Complicated crystal growth
High density	Large temperature dependence
Good energy resolution	Expensive

- Why aren't the scintillation photons re-absorbed by others atoms/molecules?.

  De-excitations through intermediate energy levels before the final return to the ground state ⇒ Energy of the scintillation photon isn't enough for additional excitation.

Light detection

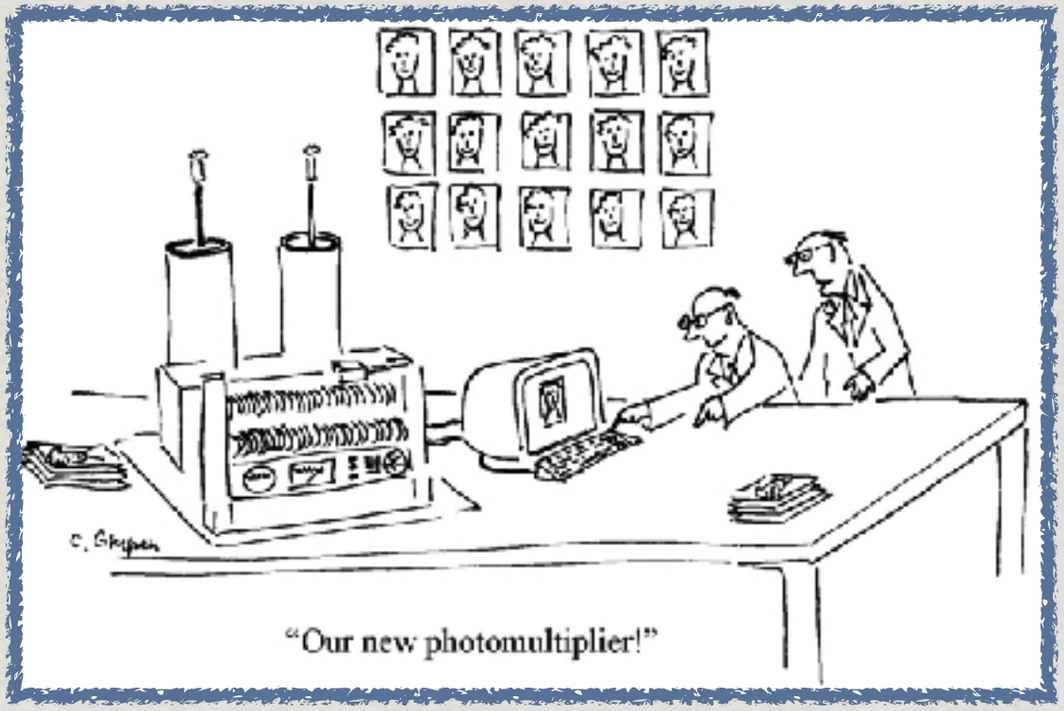
- A light detector everybody knows...
  The EYE!!!!
- Indeed a primordial technique was the observation of the light flashes produced by charged particles hitting a screen made of zinc sulphate.

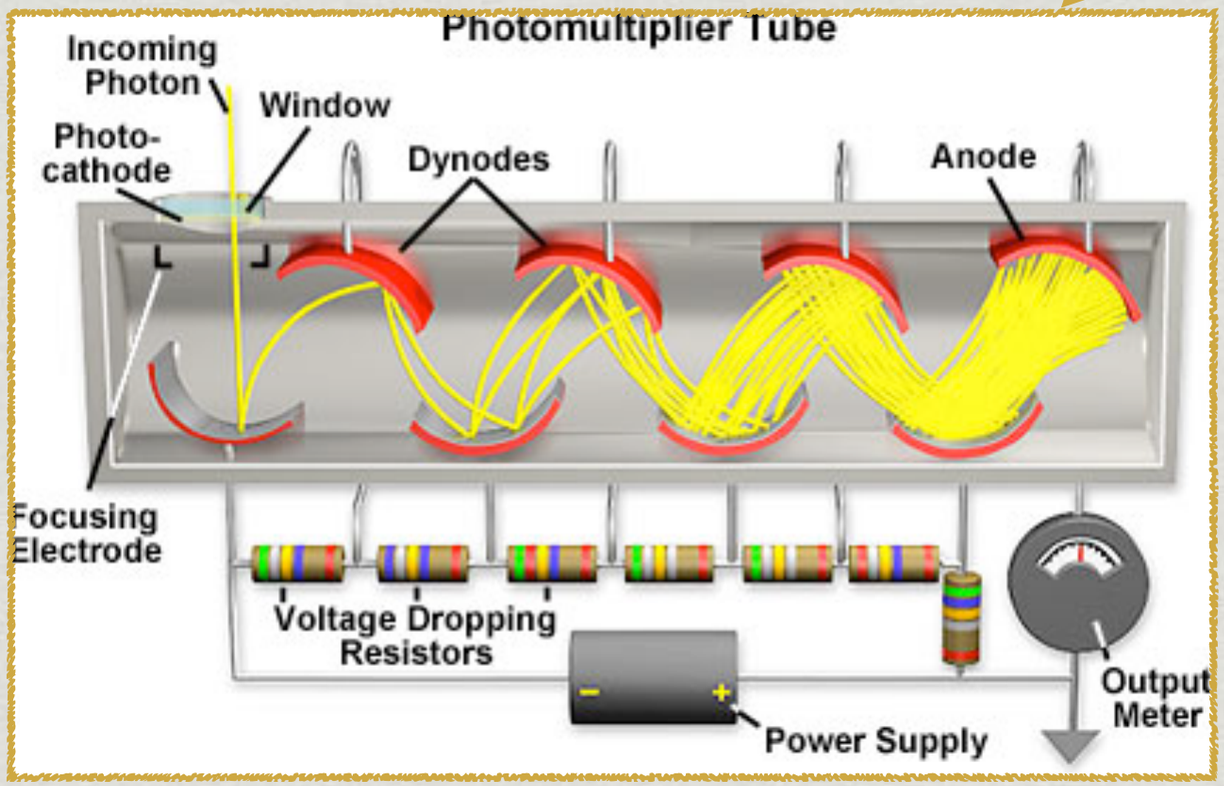
- With a good training human eye can see al low as 15 photons if emitted in a time interval shorter than 1/10 seconds (persistency of the image in the retina) in the **green**.
  It seems that the sensitivity improves with a good cup of coffee...
  better if it is a strong one!
- Many limitations in the human eye (at least for particle detection):
  - very narrow range of wavelengths;
  - impossibility to quantify the intensity of light;
  - imprecise timing;
  - low efficiency;
  - frustration 😫

  Better to have an instrument doing this job!

Photo-detectors

- Purpose: convert light into a detectable electrical signal
- Several types of devices:
  - vacuum —> PMT (PhotoMultiplier Tube),
    MCP (MicroChannel Plate),
    HPD (Hybrid PhotoDetector);
  - solid state —> PD (PhotoDiode),
    APD (Avalanche PhotoDiode),
    SiPM (Silicon
    PhotoMultiplier)





- For each photon entering through a transparent window onto the photocathode, 1 electron is extracted.
- Photoelectron is accelerated towards following electrode (dynode), where it is multiplied.
  Process repeated in cascade.

1 photon in ⟹ > 1 million electrons out!

More on PMT's

- Dozens of types, different in size, shape and performances.

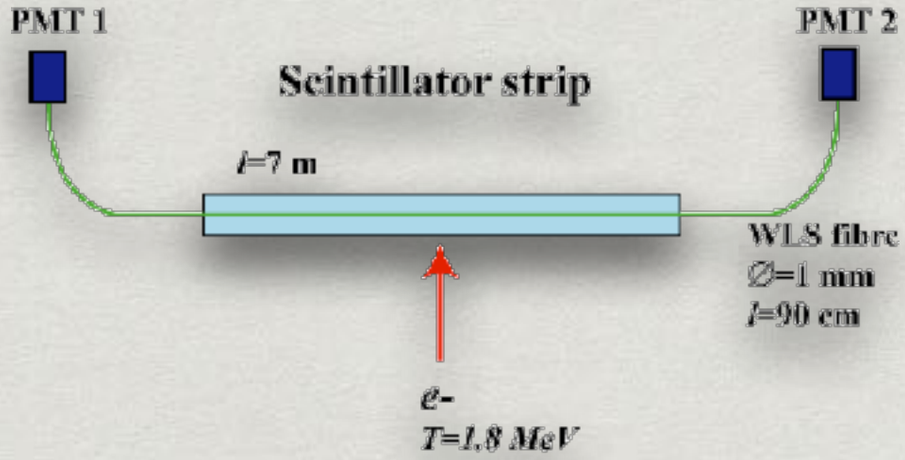
- The internal PMT volume is in vacuum.

  In SuperKamiokande (a detector of Cherenkov light operate in Japan for studying neutrino oscillations) one PMT imploded in the Super-Kamiokande, generating a shock wave that broke half of the 11000 PMT's!

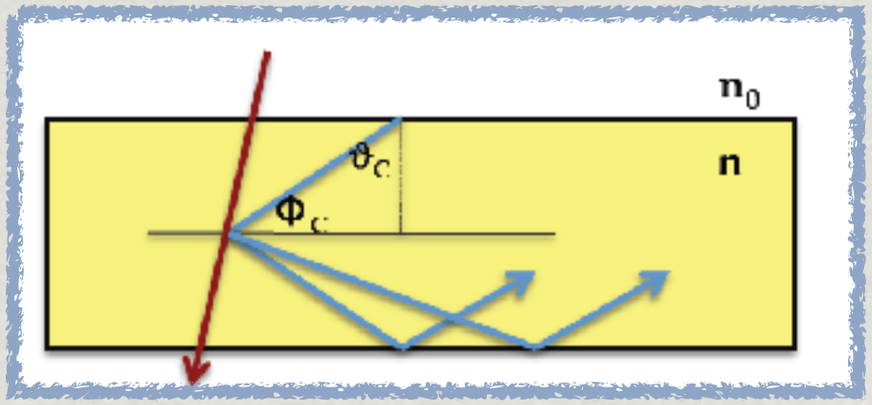
Combined high-speed camera images of a PMT implosion in the Naval Undersea Warfare Center's Propulsion Noise Test System

Coupling with the photodetectors

- Scintillation light typically needs to be conveyed to the photodetector, for instance for coupling different geometries or because the scintillator is immersed in a magnetic field that would damage the photodetector.



Optical fibers



- Light in plastic scintillator propagates by means of total reflection.

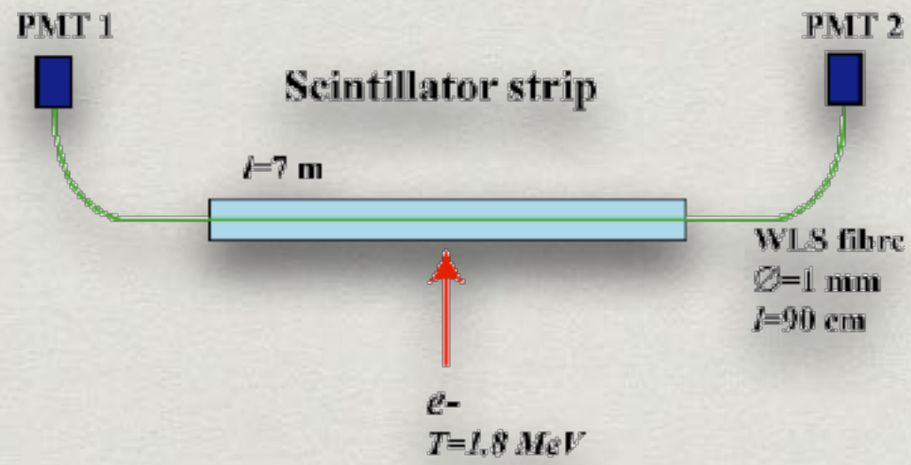
- Combining scintillator, light guide and photodetector, is an electric signal available?

A. Yes

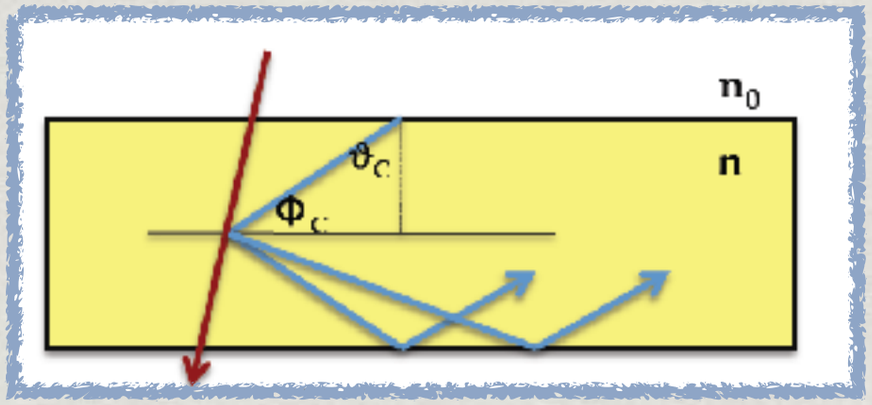
B. No

Coupling with the photodetectors

- Scintillation light typically needs to be conveyed to the photodetector, for instance for coupling different geometries or because the scintillator is immersed in a magnetic field that would damage the photodetector.



Optical fibers



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B. No

Scintillation light wavelength (UV) not matched to that of photodetectors (visible).
Wavelength shifters: absorb scintillation photons and re-emit them at longer wavelength.

Ionisation

- How to detect the ionisation charge?

- Several techniques, based on:
  - **PHASE-TRANSITION**
    - photographic emulsions;
    - cloud chambers;
    - bubble chambers
  - **DRIFT IN ELECTRIC FIELDS**
    - wires (MultiWire Proportional Chambers, Time Projection Chambers, Geiger counters..);
    - micro-patterns (Gas Electron Multiplier, Micro Strip Gas Chamber, Micromegas...);
    - Resistive Plate Chambers.
  - **SEMICONDUCTORS**
    - strips;
    - pixels
    - 3D.

Bubble chambers

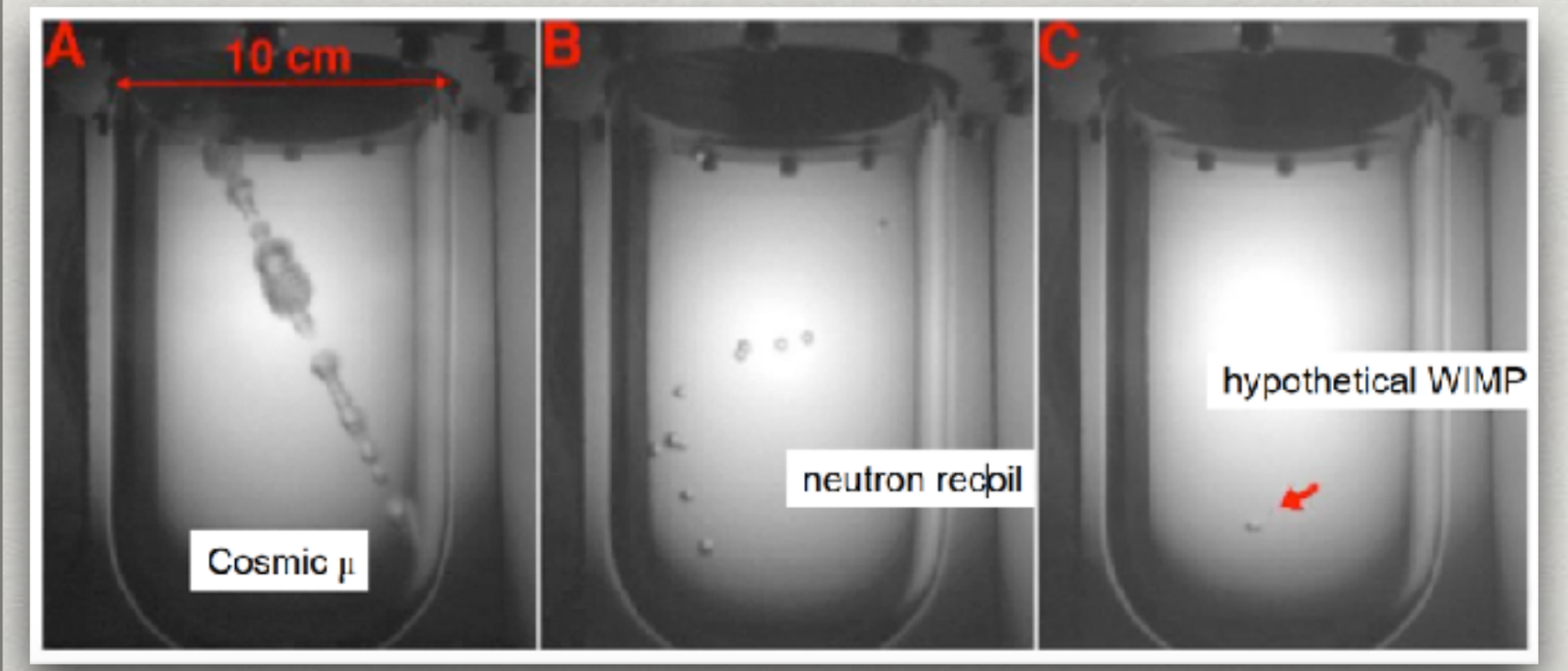
- Invented in 1952 by Donald Glaser (Nobel prize 1960).
- Sealed chamber filled with pressurised gas (H_2, D_2, Ne, ...) close to the boiling point.

Quick expansion
↓
Superheated liquid
↓
Ionisation due to charged particles
↓
Bubbling
↓
Photographs
↓
Quick pressurisation

- Medium is at the same time target and detector.
- The system is usually completed by a magnetic field in the active volume.

Particle identification in bubble chambers

- dE/dx is measured by counting the number of bubbles.
  Momentum is extracted by the curvature radius in the magnetic field.
  Charge sign is determined by the direction of the bending in the magnetic field.
  Putting everything together, particles are identified.



- Discovery of many particles and
  detailed studies of the interaction mechanisms. 👍🏼 🎉
- But huge scanning effort! 👎🏼 😰

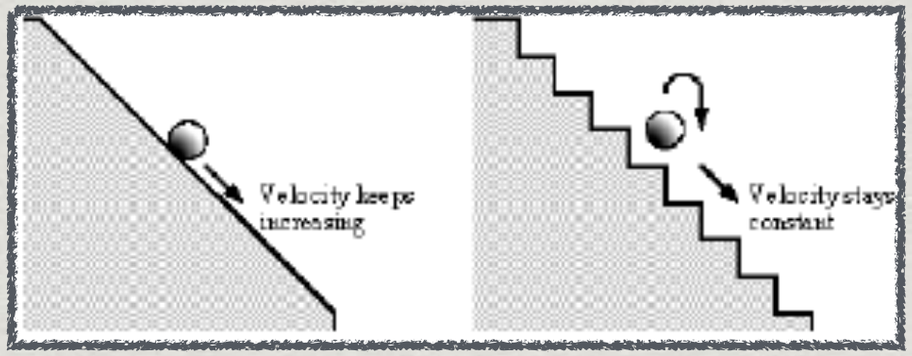
Ionisation: charge transportation

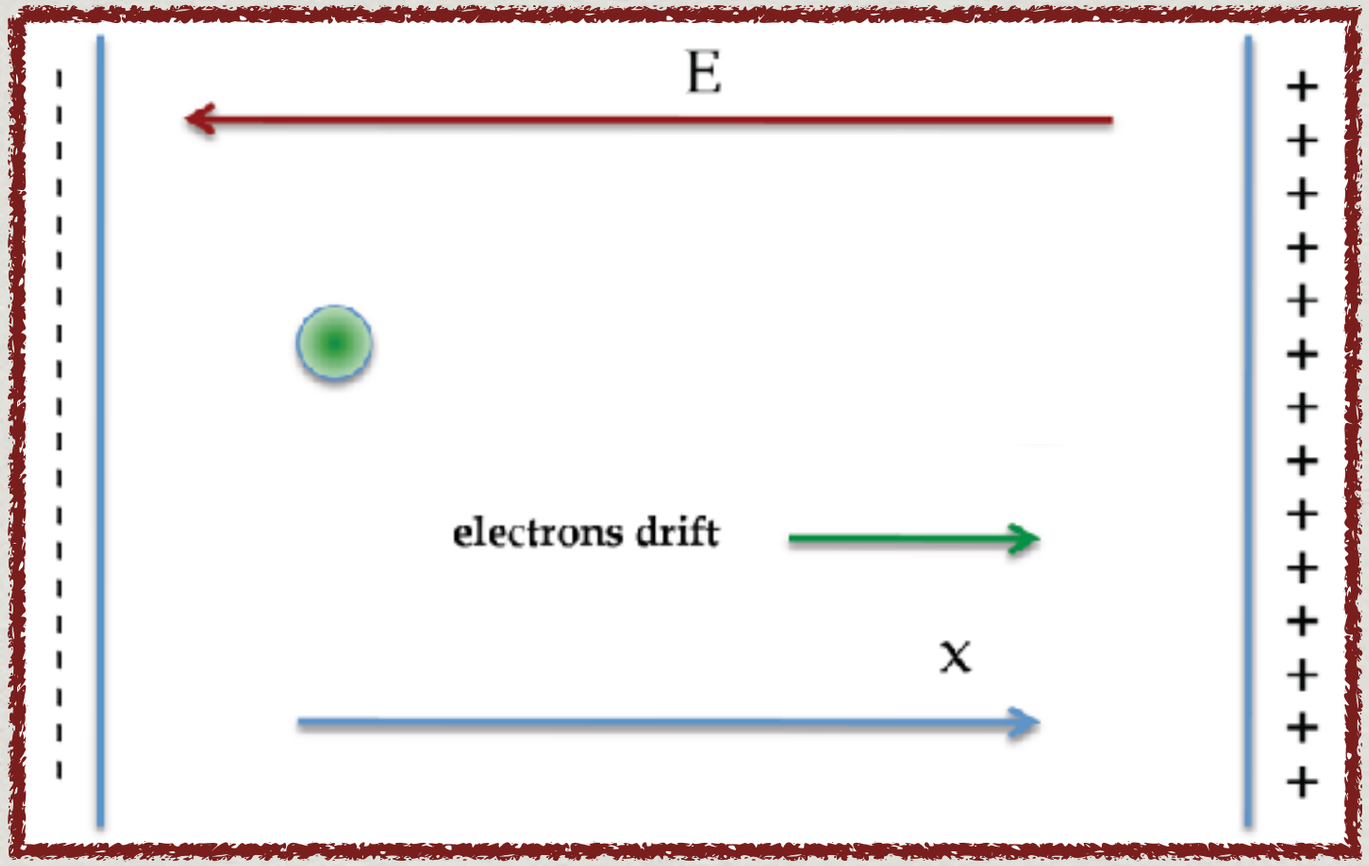
Under the application of an external electric fields, electrons drift towards the anode

- **Drift** velocity v_D is CONSTANT... Why???

  The electrons are accelerated only in the average free path between two collisions with the atoms in the medium, and than re-start from rest.

  Same as electrons flowing in an electric circuit!





Does the signal on the anode start when the ionisation occurs or when the electrons get to the anode?

A. ionisation

B. e^- arrival

Ionisation: charge transportation

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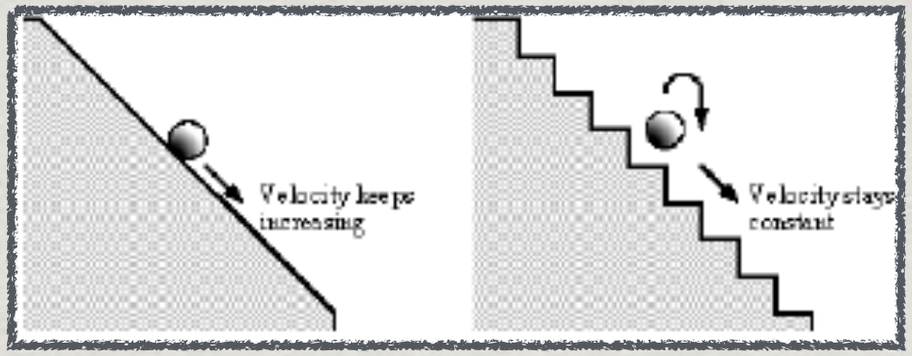
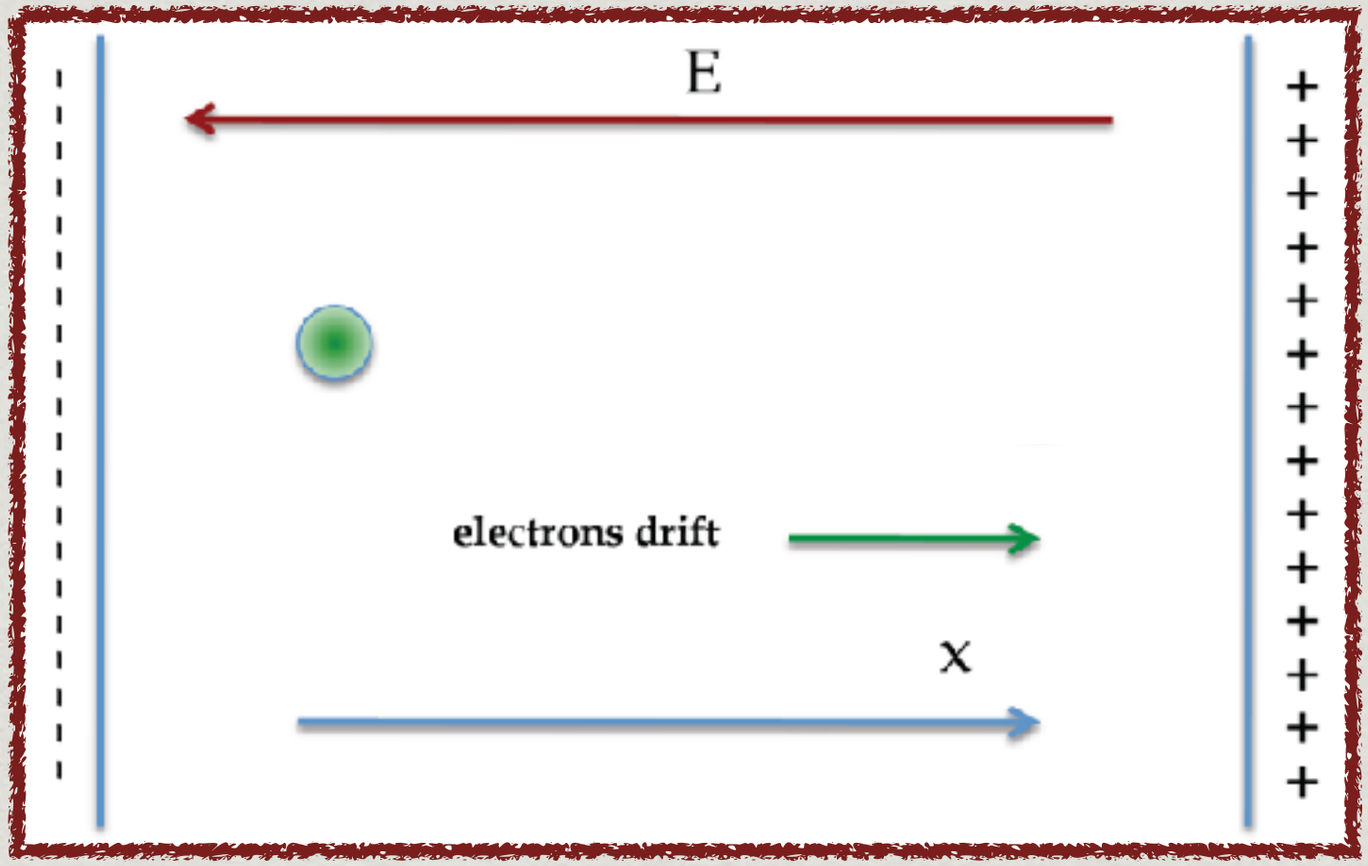
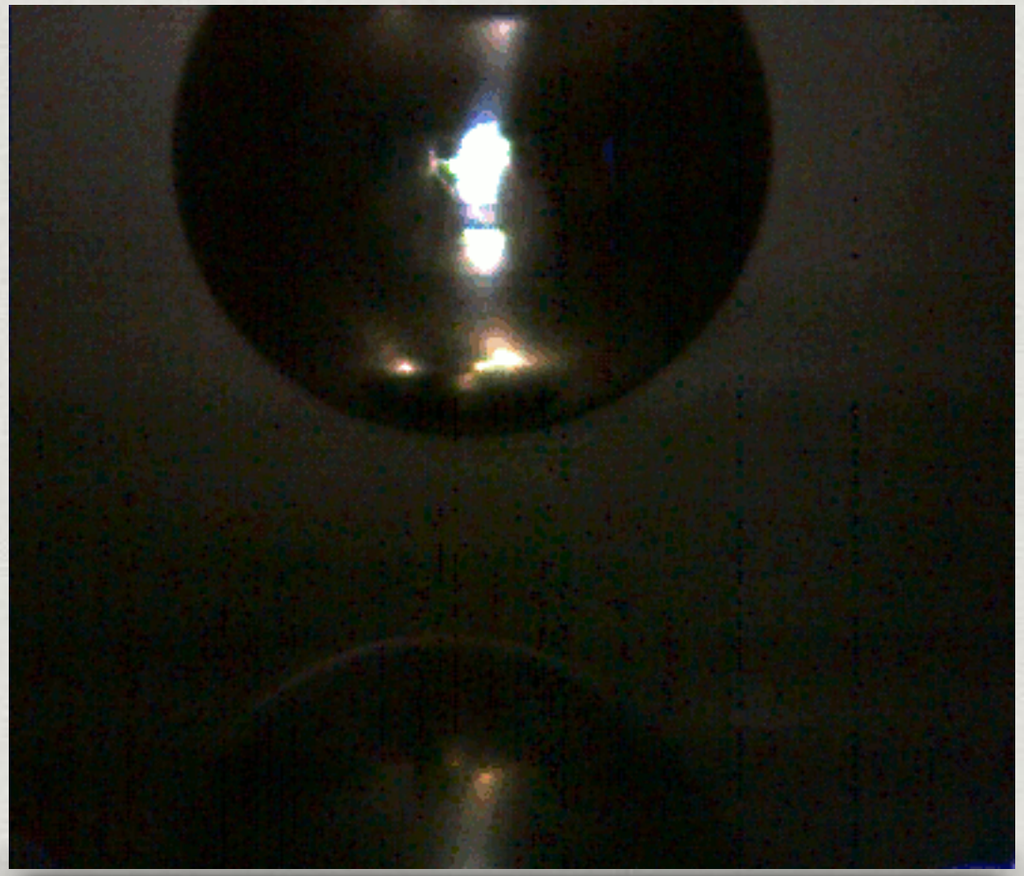




Does the signal on the anode start when the ionisation occurs or when the electrons get to the anode?

ionisation

Breakdown



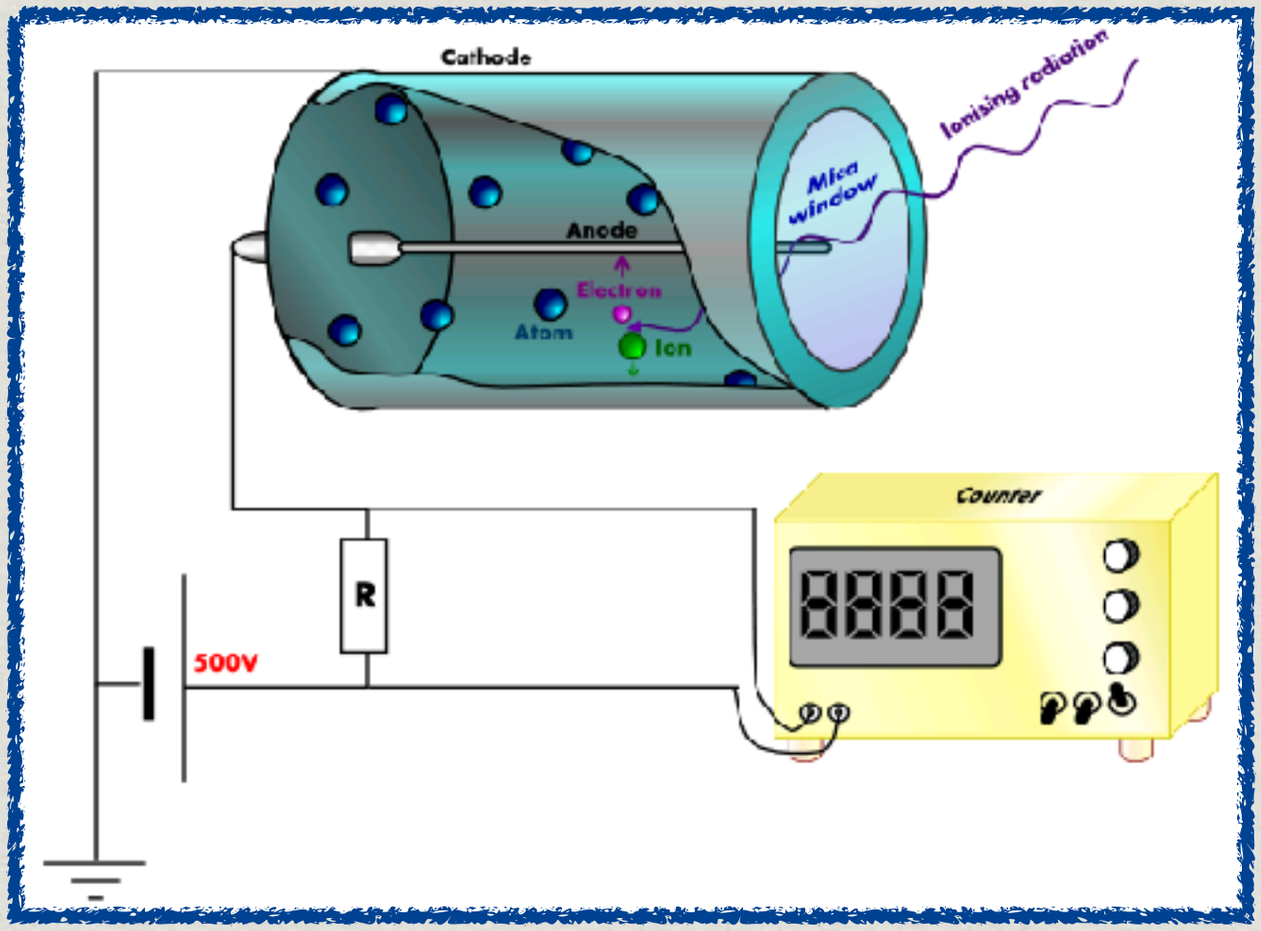
High-speed camera footage of streamer development in LAr
from J. Sinclair talk at CPAD2016

Geiger - Müller counter

- Fine wire along the axis of a cylindrical cathode filled with gas.
  Very intense electric field.
- Saturated avalanche at the passage of a charged particle.
- The current causes a counter to chirp.
  How many chirps per incoming particle?

A. One

B. Depends on particle energy



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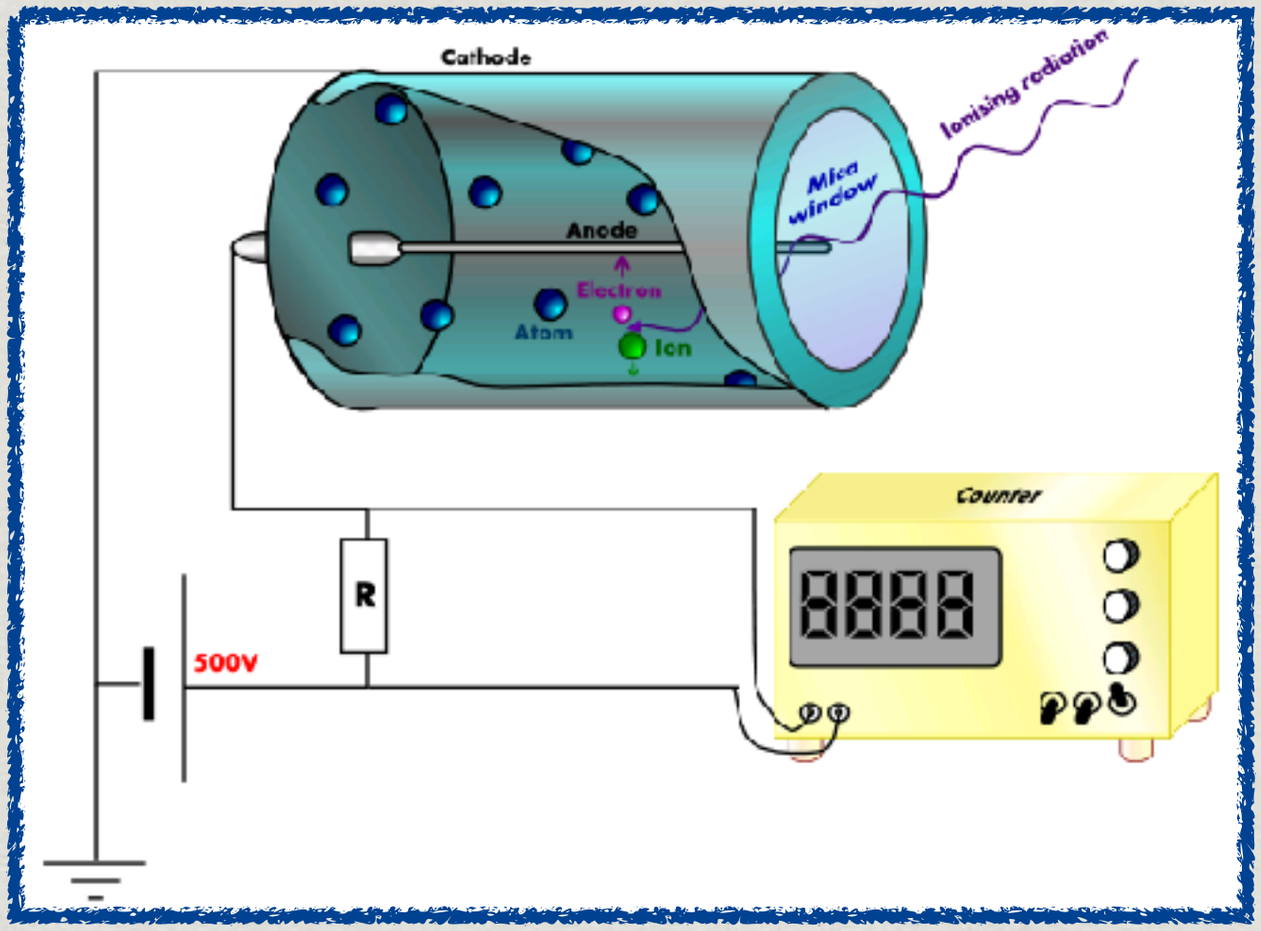
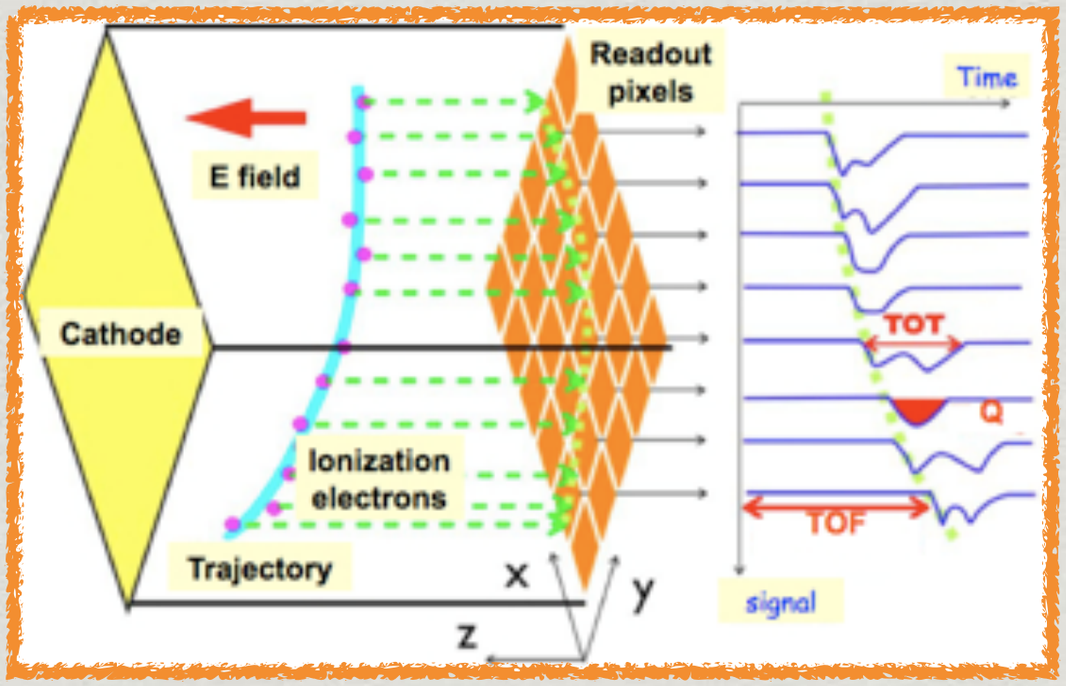
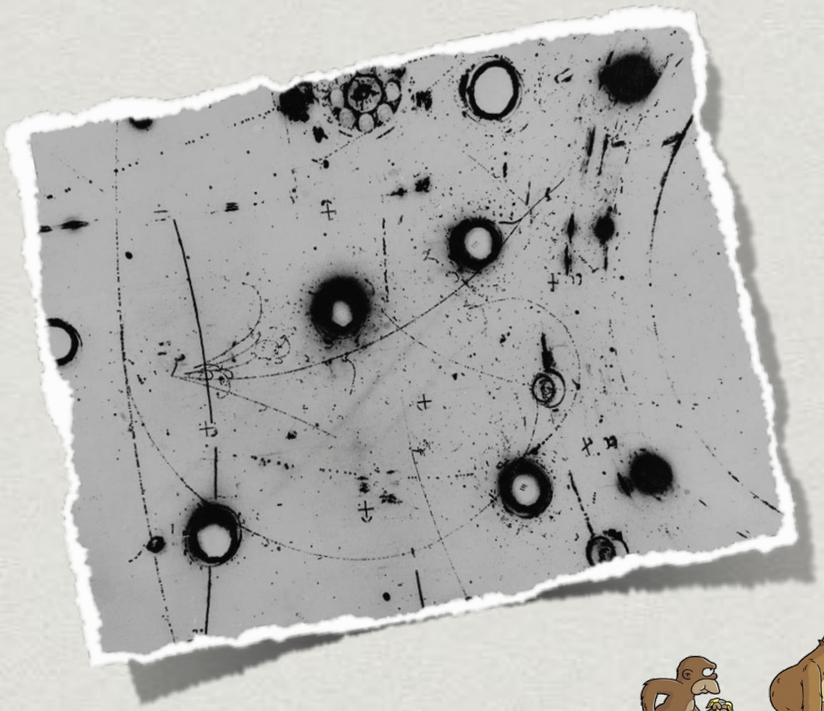


- Frequently used to verify radioactivity.

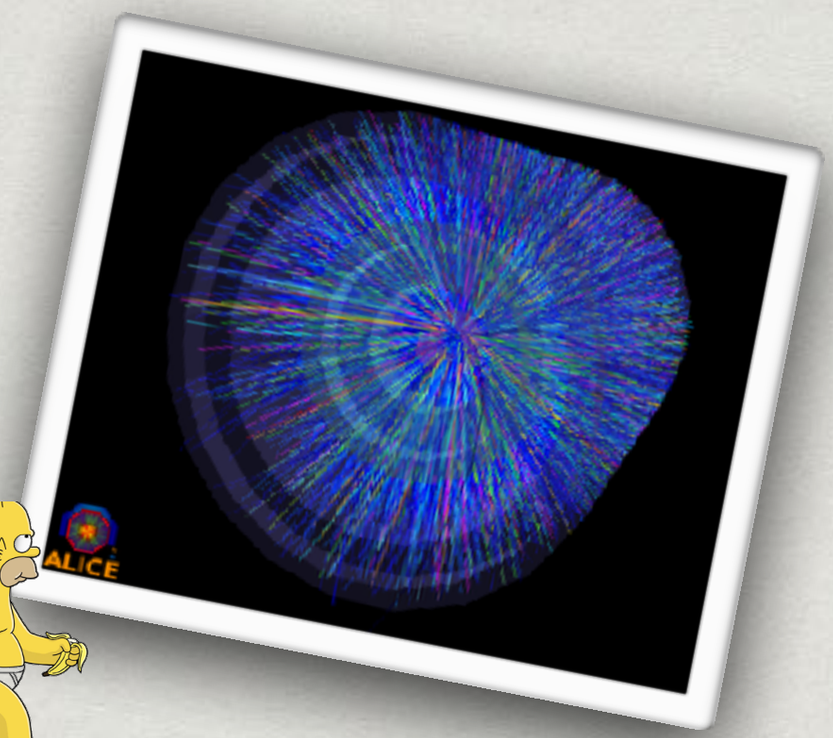
Time Projection Chambers

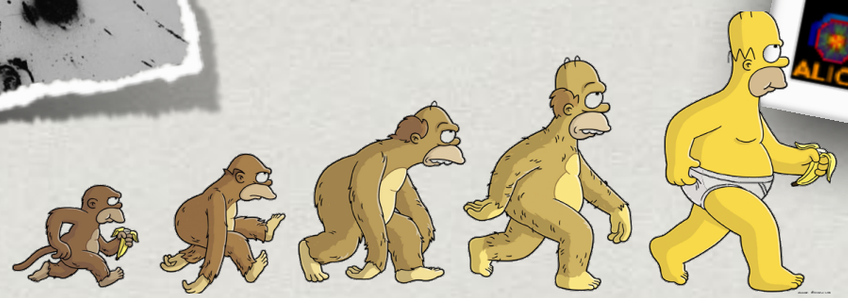
- Large gas/liquid filled cylinder with a thin central plane (cathode).
- Ionisation electrons to the anode (readout plate) by electric field.
  Position along the drift direction extracted from drift time.
- Pulse size distribution ➟ dE/dx measurement.

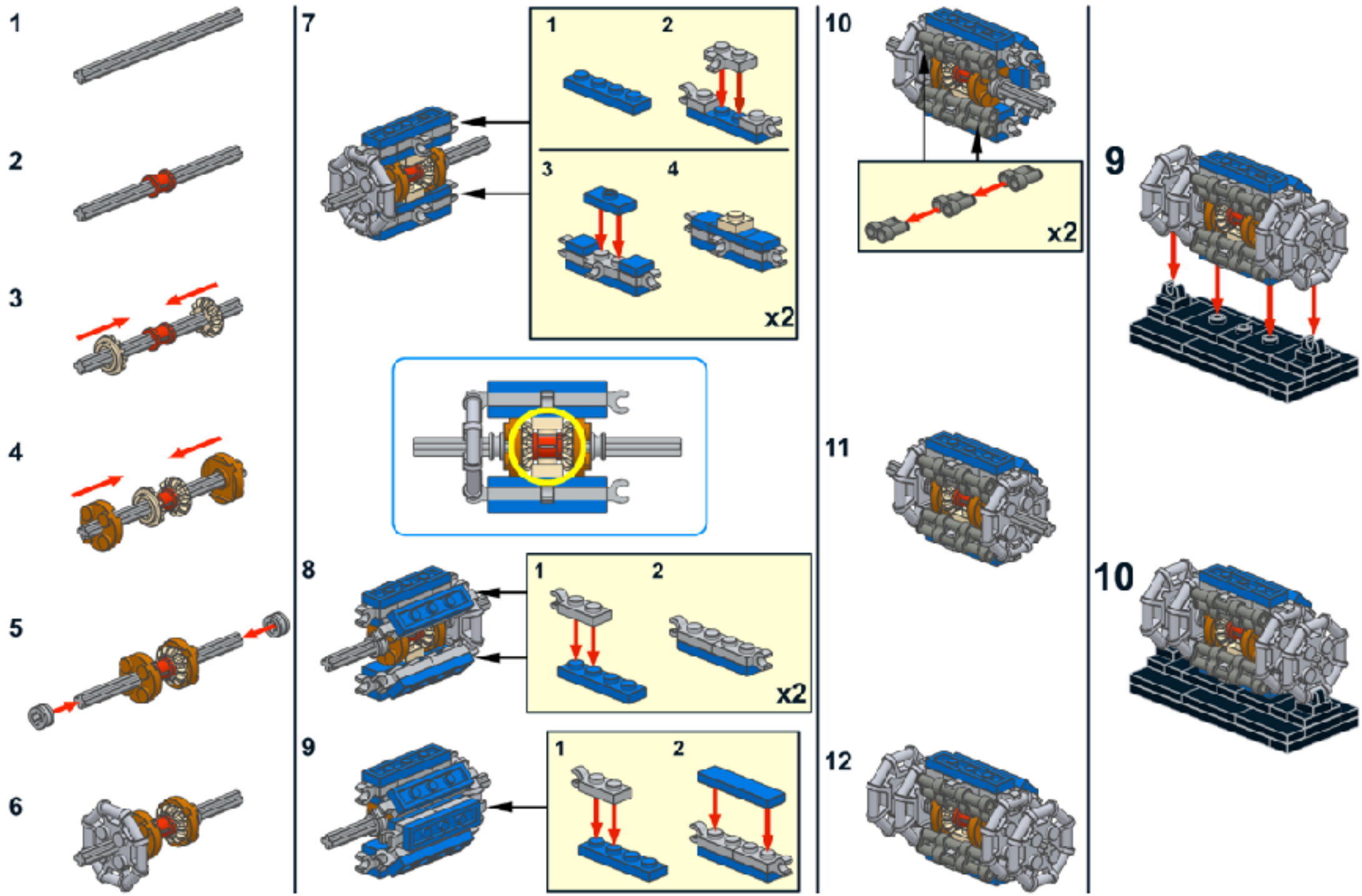




Electronic bubble chambers!





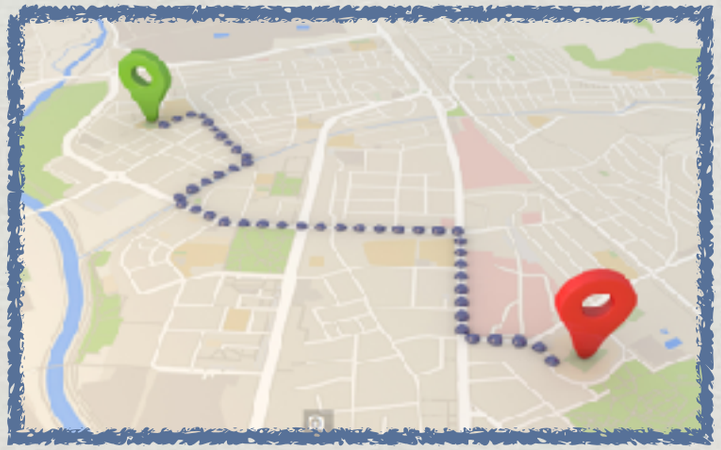


BUILDING A REAL DETECTOR

Detectors functionalities

- **TRACKING**

  High resolution measurement of the particle tracks.
  Ex: charge sign and momentum measurement by
  track curvature in a magnetic field.



- **PID (Particle Identification)**

  Measurement of β, γ, v or dE/dx that, combined with the momentum, allow to reconstruct the mass and therefore to identify the particle.

- **CALORIMETRY**

  Energy measurement by completely absorbing it.

- **TRIGGER/VETO**

  Selection of interesting events / background rejection.

The right tool for the job

- Is there a one-to-one relation between detector technique and functionality?

A. Yes

B. No

The right tool for the job

- Is there a one-to-one relation between detector technique and functionality?

No

- The same functionality can be pursued with different techniques.

Ex: PID can be realised with... bubble chambers

A. Yes

B. No

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Cherenkov detectors

A. Yes

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TPC's — A. Yes — B. No

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TPC's — Yes

Scintillators — A. Yes B. No

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- Different functionalities can be combined into one same technique.

Ex: TPC's can be used for... tracking — A. Yes — B. No

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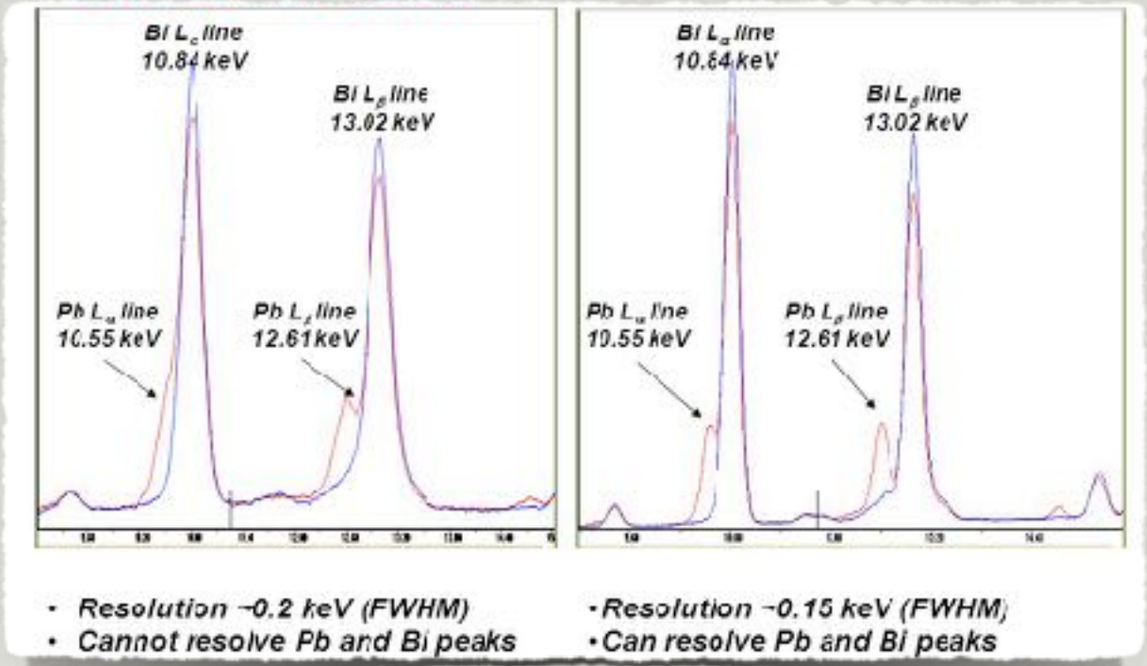
calorimetry — Yes

trigger — No

Performance

- **RESOLUTION**

  Accuracy in the measurements (energy, time, position, etc).
  Expressed in terms of width of the distribution, usually Gaussian, of measured values around the average.



- **EFFICIENCY**

  Probability of detecting the signal of each incoming particle.

- **RESPONSE TIME**

  Time needed for generating a signal since the primary interaction.

- **DEAD TIME**

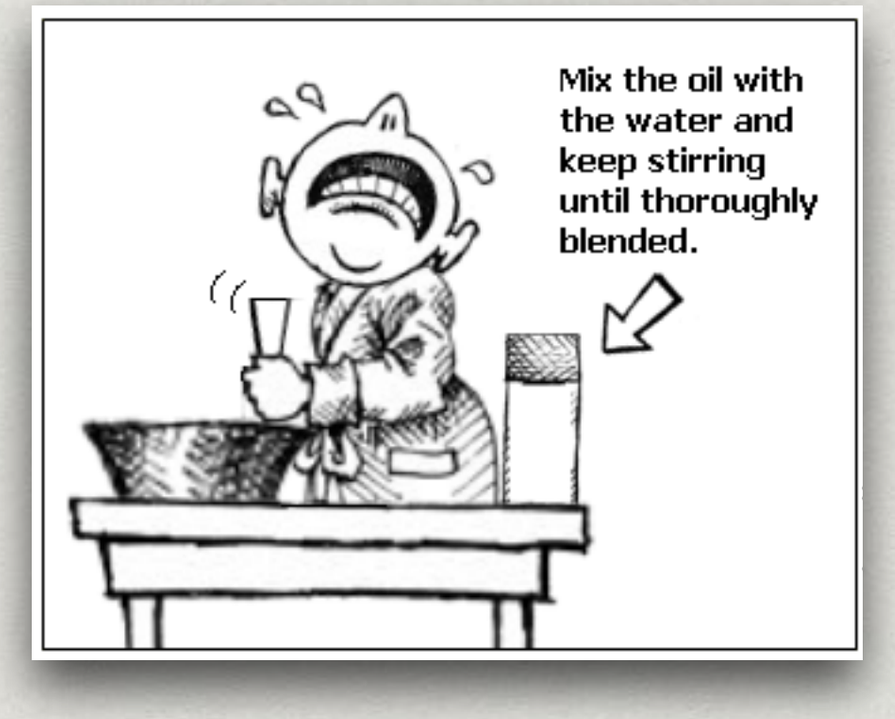
  Period of time after each signal in which no other signals can be generated.

- **STABILITY IN TIME**

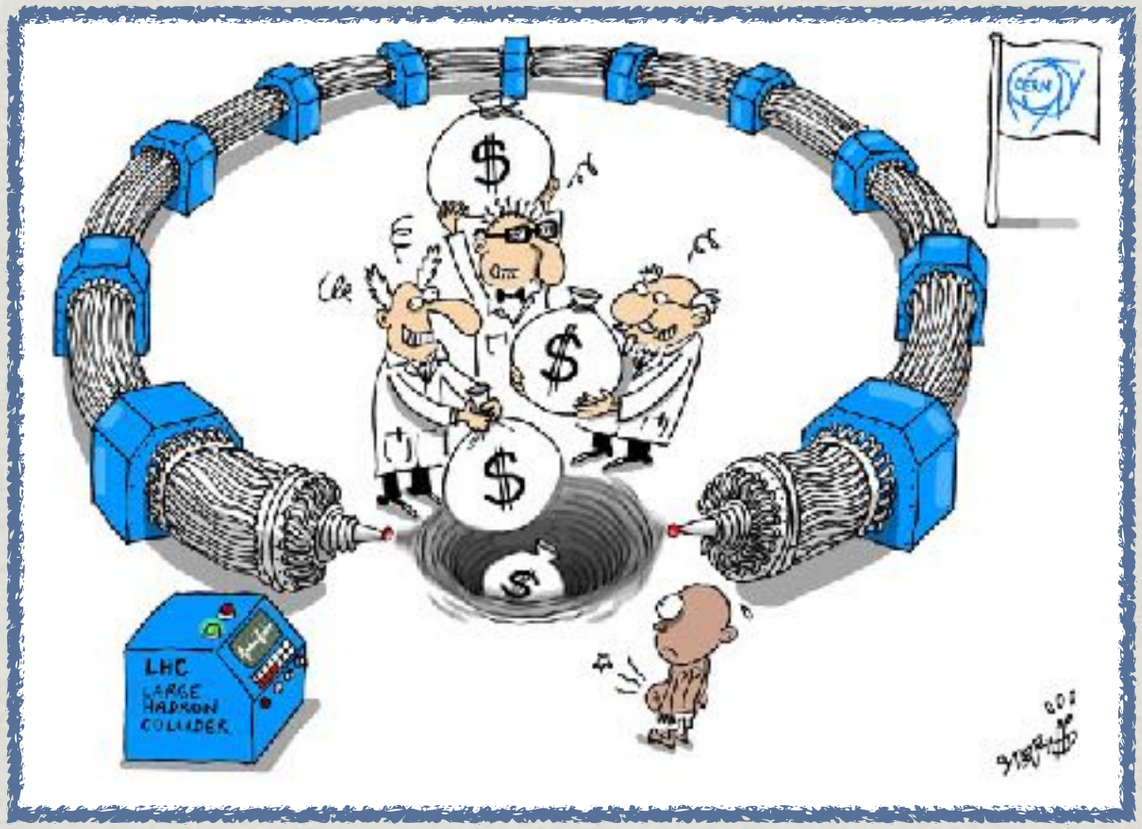
- **RADIATION HARDNESS**

- etc...

The recipe for the perfect detector... 🤔



... doesn't exist 😧

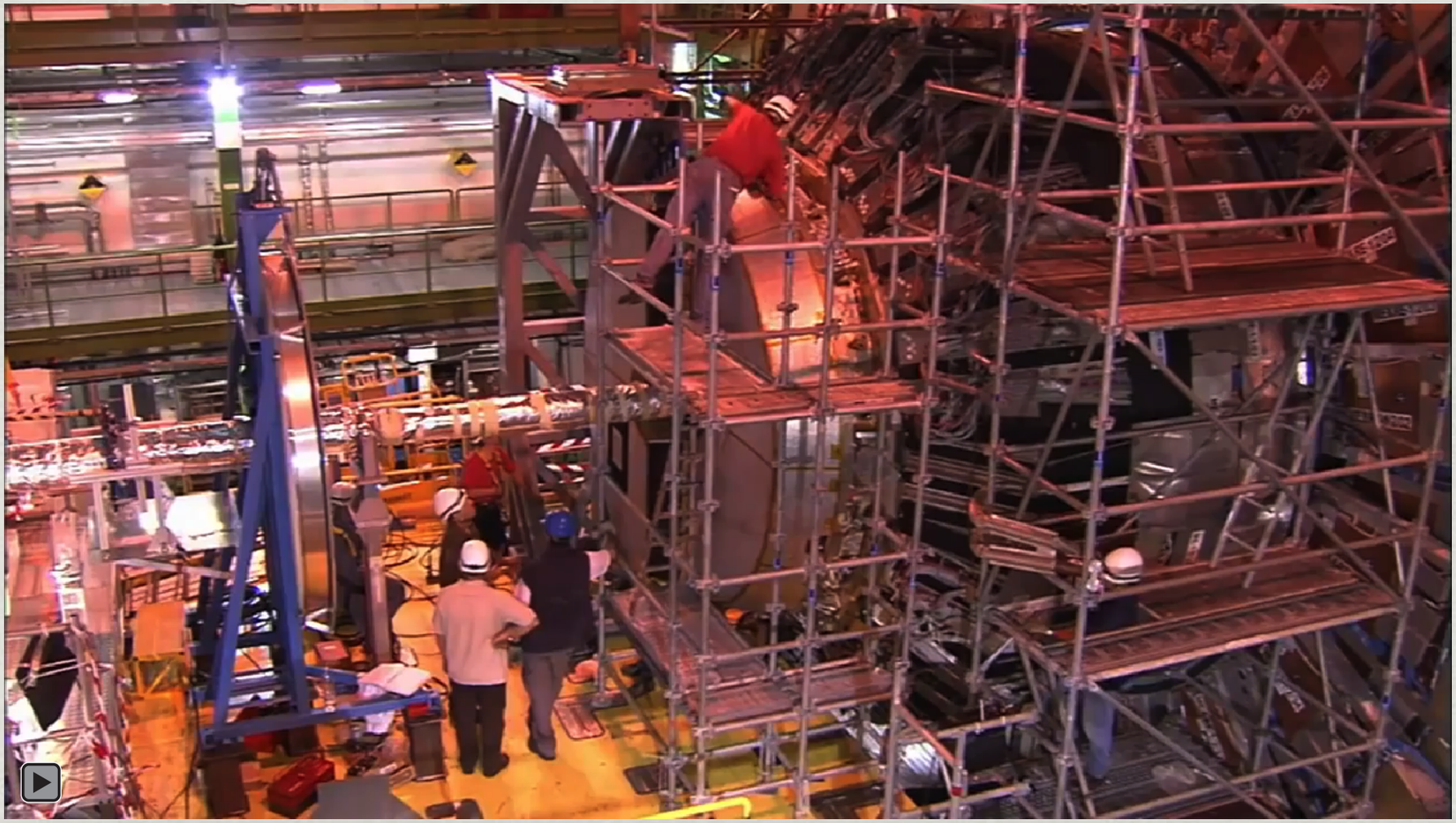


- The choice for the detector design is driven by the PHYSICS CASE:
  Which functionalities are needed?
  Which performance is required?
  But also by the COST $$$

- Usually detectors, especially nowadays, are made of several sub-detectors.

The Big Friendly Giants

- The two biggest detectors installed at the LHC accelerator: ATLAS and CMS.
  - **ATLAS** is 45 m long and 25 m wide, but weighs "only" 7000 t;
  - **CMS** is smaller, 21 meters long and 15 meters wide, but heavier, 12500 t.
- Installed in shafts at 100 m depth: big technological challenges for the installation!



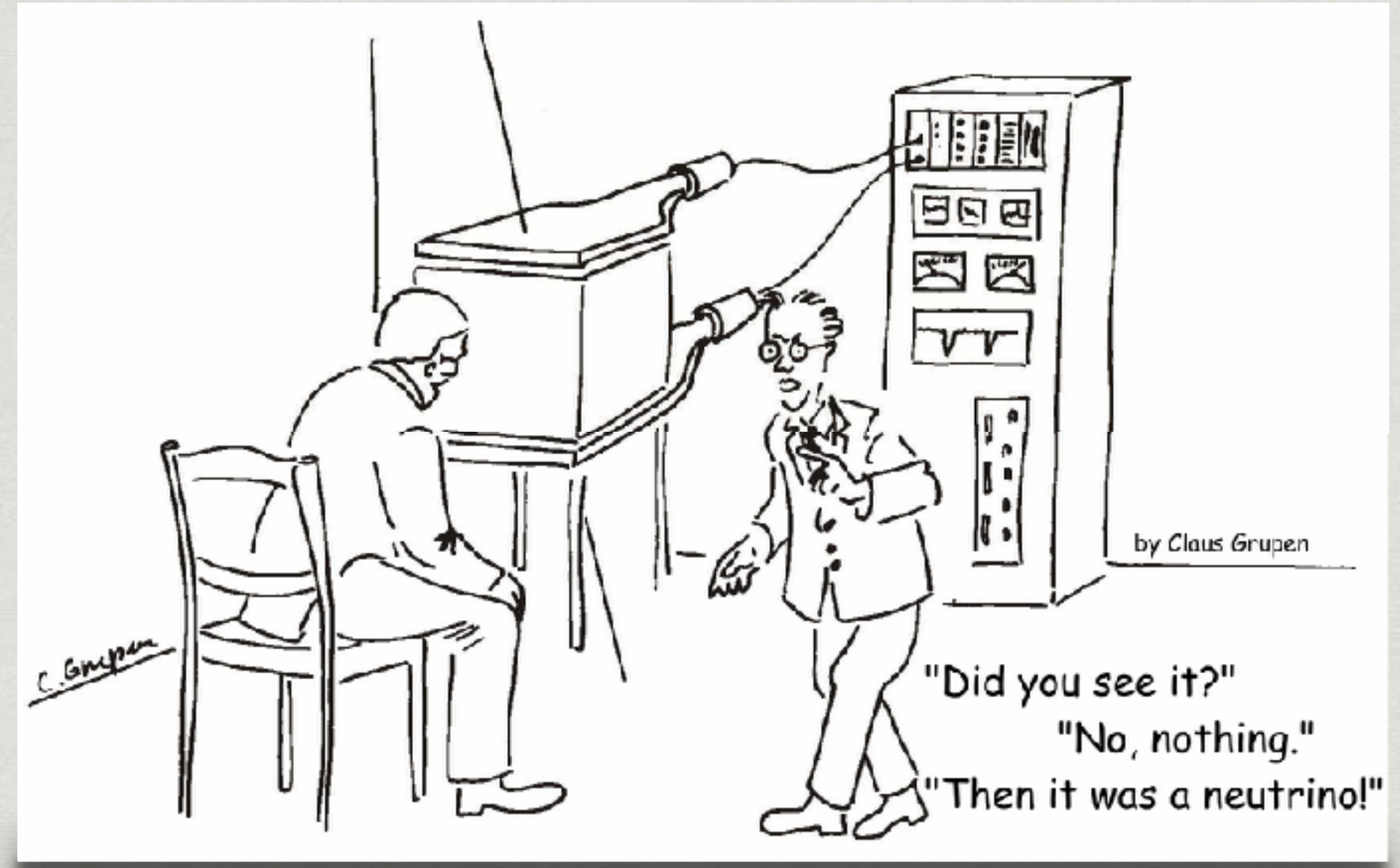
from "An introduction to CMS experiment at CERN"

An insight into ATLAS detector

from “ATLAS - Episode 1 -A New Hope”

The ghosts catchers

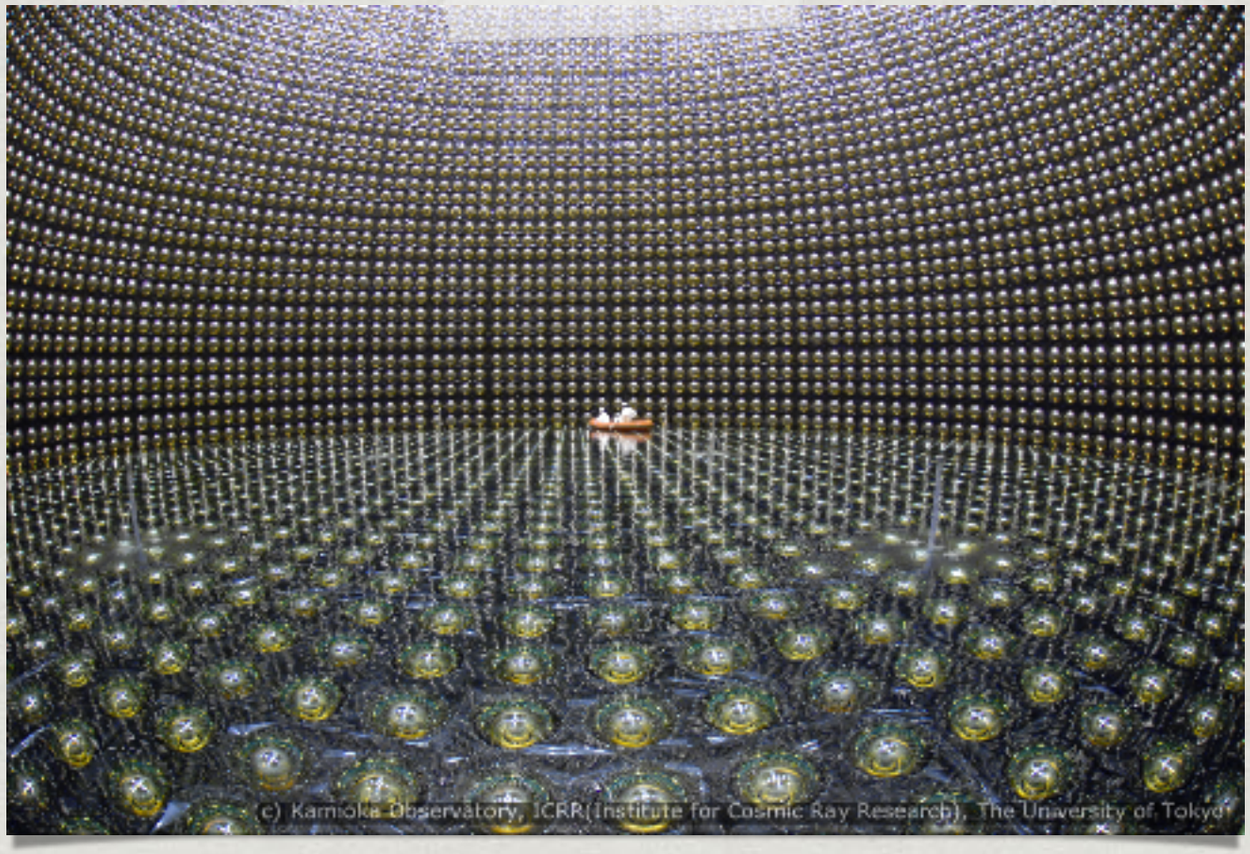
- Another big challenge is the search for rare events: neutrino interactions, dark matter, neutrino less double beta decay, proton decay, etc.



- The trick consists in exploiting extremely massive detectors, still with excellent tracking and calorimetric properties.
- Typically installed deep underground for shielding the cosmic radiation.

Cherenkov detectors

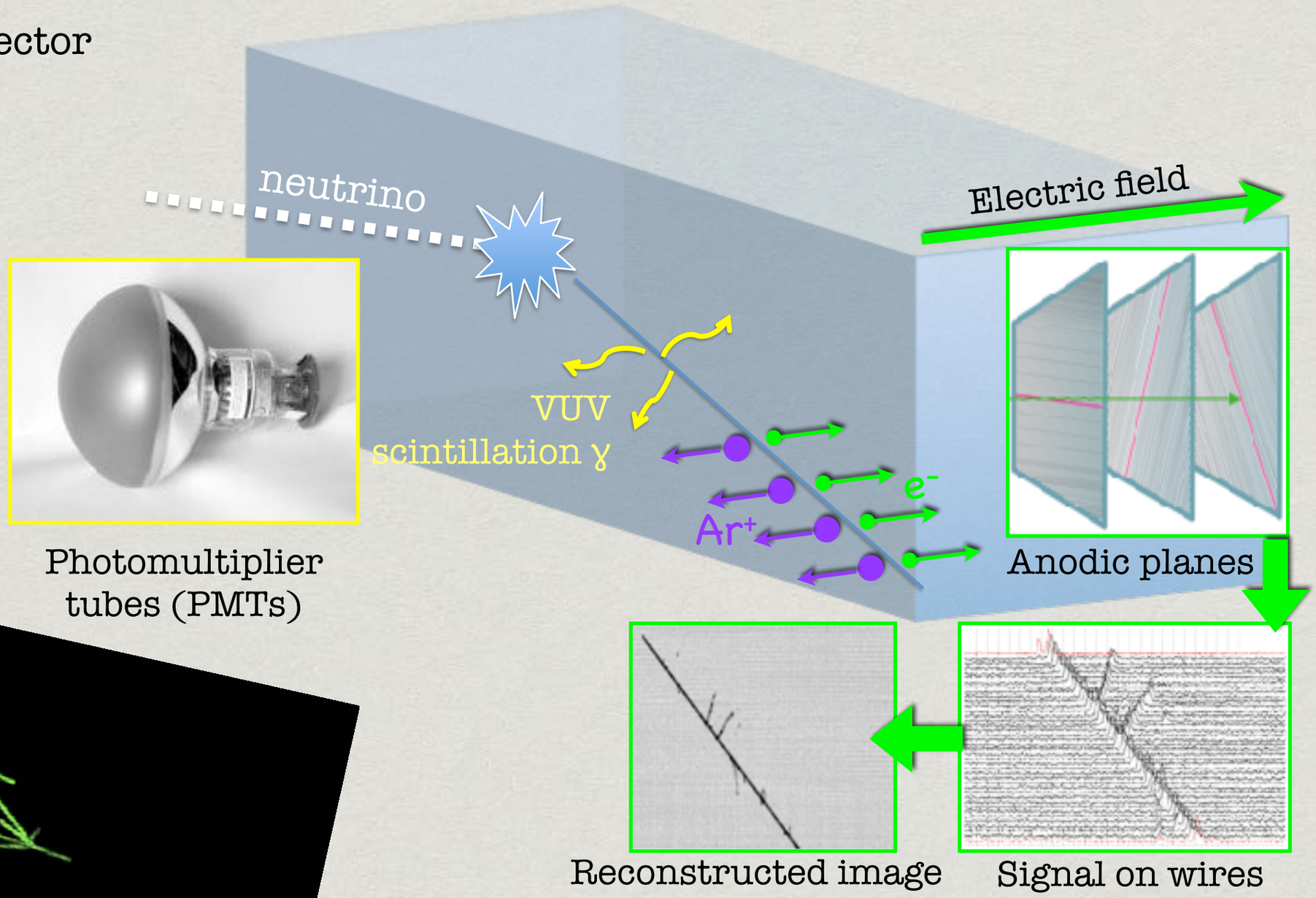
- **Super-Kamiokande** (Japan):
  - 40 m diameter, 41 m high tank, filled with 55 kt of ultra pure water;
  - light detected by 11200 PMTs;
  - Nobel Prize in 2015 “for the discovery of neutrino oscillations, which shows that neutrinos have mass”

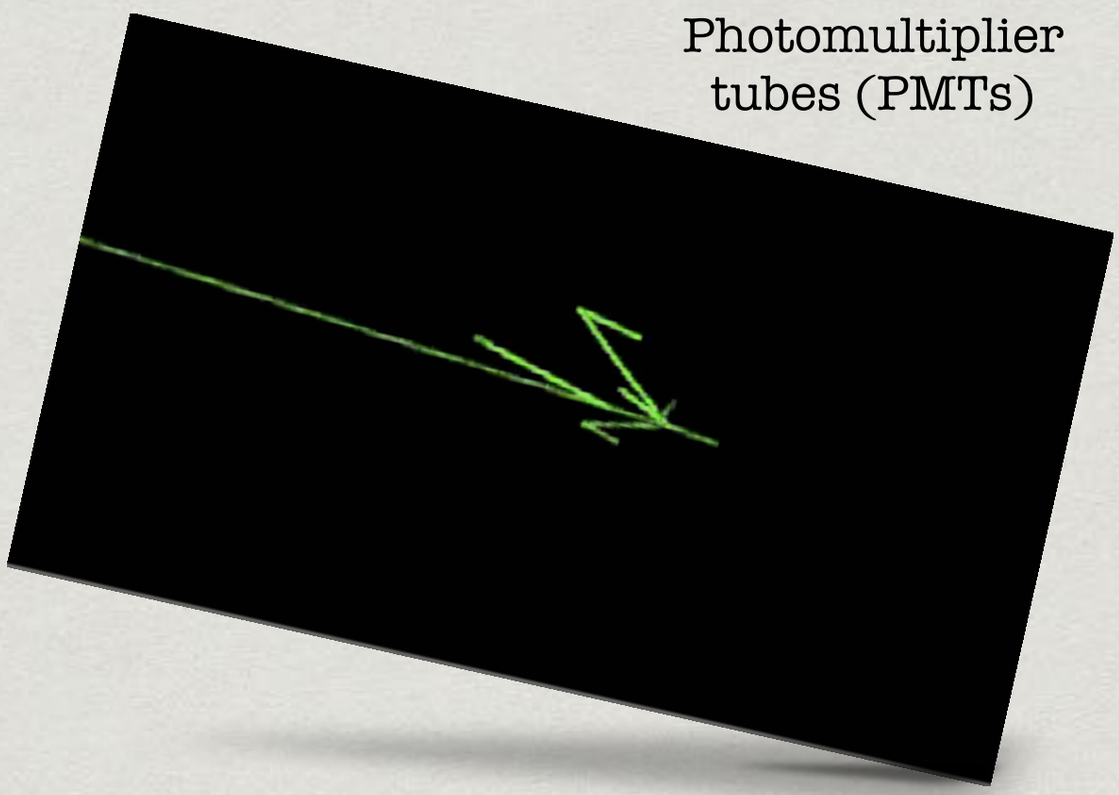


- **IceCube** (South Pole):
  - 1 cubic kilometer of ice as the target/detector down to 2,500 meters depth;
  - light detected by 5160 PMTs;
  - In 2015 it recorded the highest energy neutrino ever: 3 PeV (3×10^{15}).

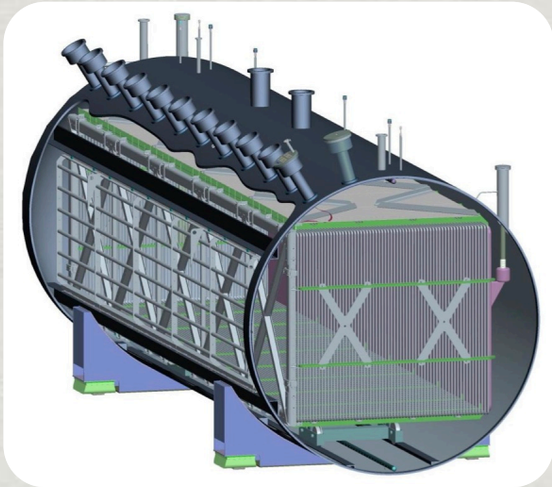
Liquid argon TPC

- "New" technique: H. Chen (1976) [FNAL P-496], C. Rubbia (1977) [CERN-EP/77-08]
- Both scintillation detector and TPC



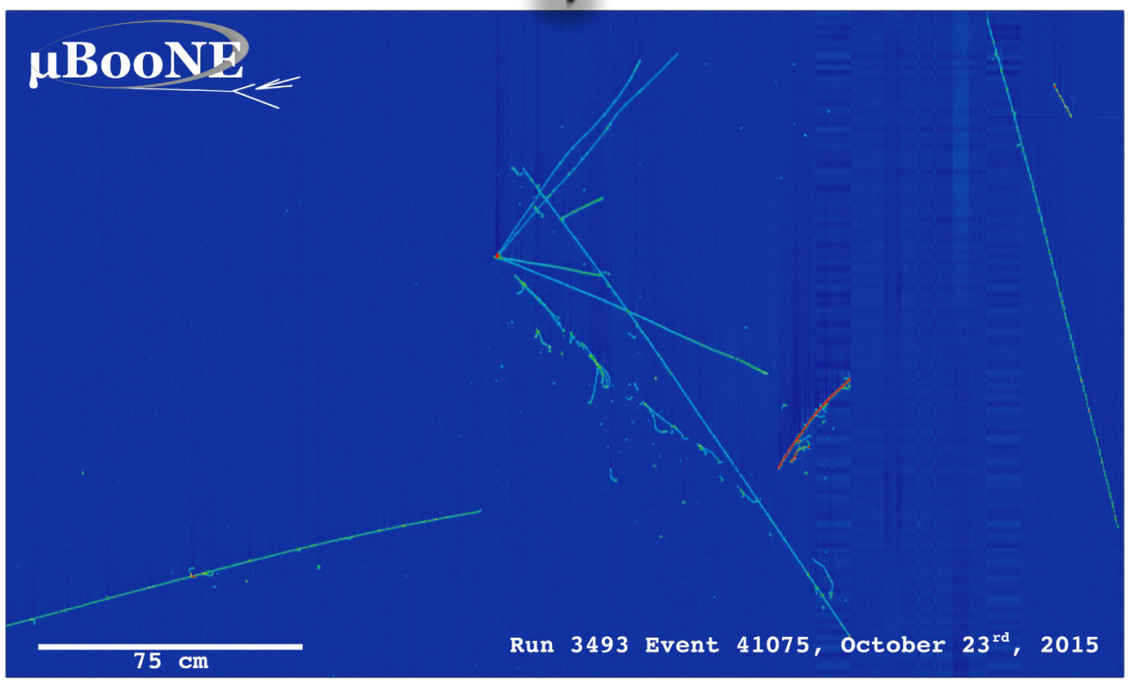


MicroBooNE



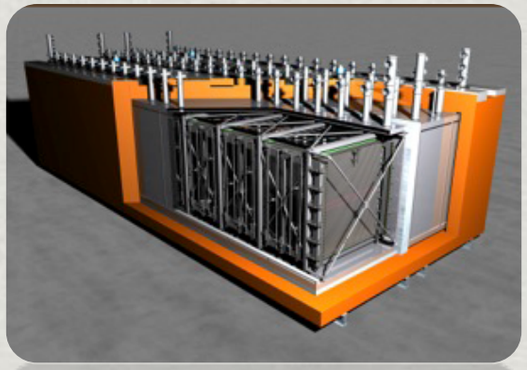
- 170 t of LAr, 87 t active mass
- 1 TPC with 2.5 m drift
  and 3 wire planes with 3 mm pitch.
  32 8” PMTs.

- Installed at Fermilab
  since December 2014.
- Exposed to BNB ν beam,
  470 m from target.
- First ν interactions
  on October 2015.



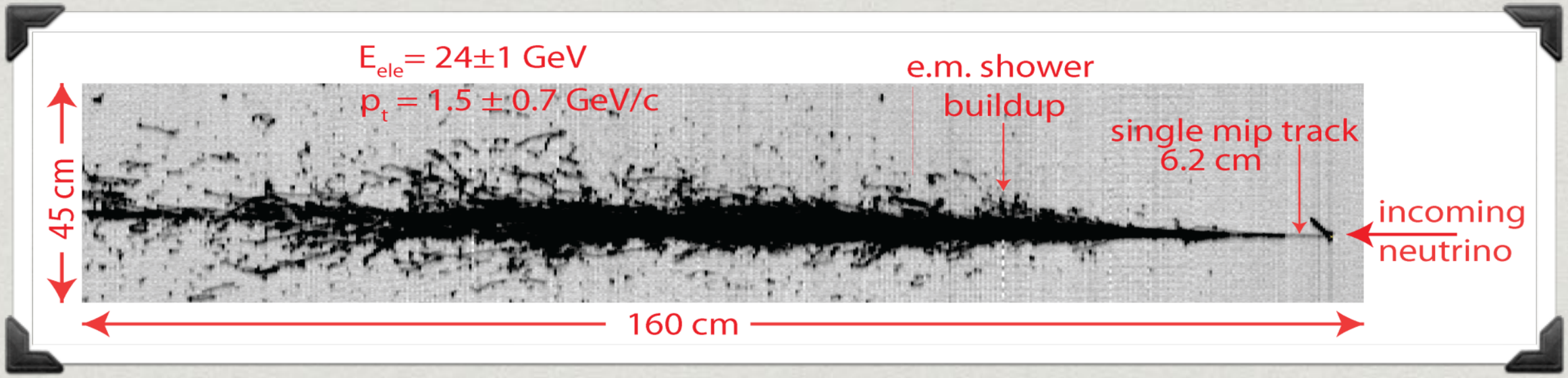
ICARUS

[ICARUS Collaboration]



- 760 t of LAr, 476 t active mass
- 4 TPCs with 1.5 m drift
  and 3 wire planes with 3 mm pitch.
  360 8” PMTs.

- Operated underground in Italy in 2010 ÷ 2012 with CNGS ν beam.
- Now being overhauled at CERN. It will be moved to Fermilab in May this year!
  It will be exposed to the BNB beam (same as MicroBooNE) at 600 m from target.



DETECTING @ FERMILAB