

What was that? Did you see that??

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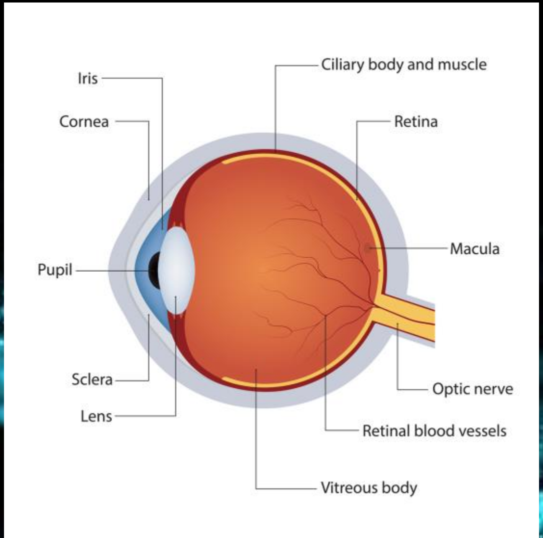
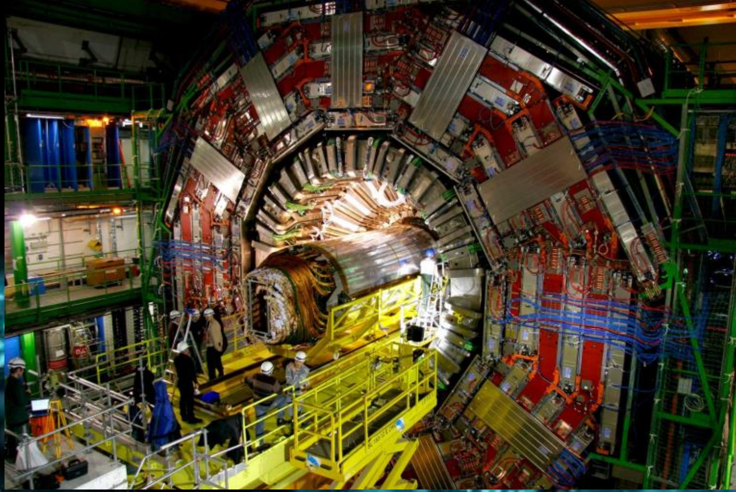
Why do we need particle detection?



- The human eye is a particle detector, capable of detecting photons of certain energies.
- As a result of the Cherenkov effect, we can also detect other particles with our eyes, but not without inflicting serious damage.
- Thus, we study the way particles interact with different materials such that we can detect their existence by observing their effect on a certain material.

Why do we need particle detection?



- An important application of particle detection is in Particle Physics.
- Particle Physics is concerned with discovering and studying fundamental particles and interactions and obtaining a unified theory that explains everything in the Universe.
- However, a theory can't be verified without experimental confirmation of it's predictions. This is where particle detectors come in.
- By colliding high-energy particle beams, we allow the creation of new particles whose properties we study using particle detectors, who track their trajectories, measure their energy, momentum and charge.

What are the applications of particle detection?

Fundamental Research

CMS Detector

Medical Imaging

MRI

Environmental Monitoring

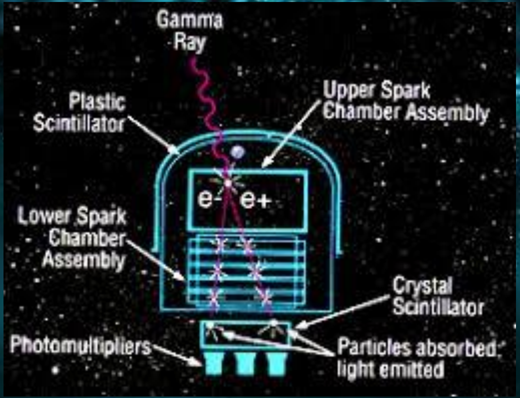
Dosimeter

What are the applications of particle detection?

Geological exploration

Geophysical Logging

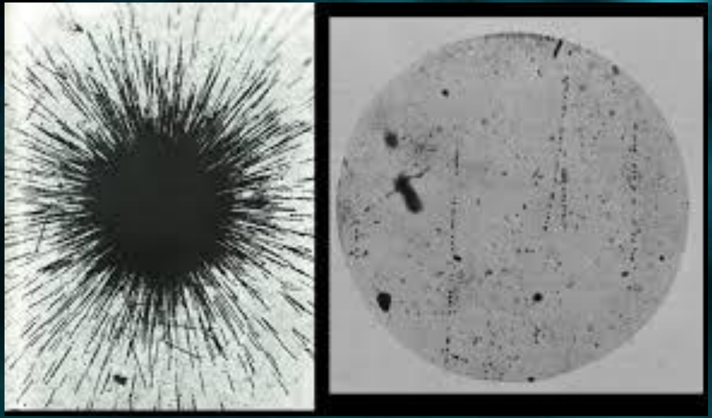
Astrophysics and Cosmology



Gamma-Ray Astronomy

How it was achieved in the past?

1. Early Methods:

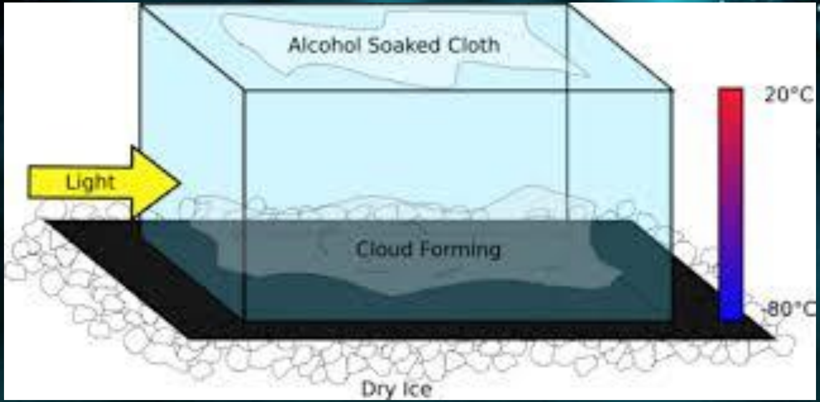


Photographic Plates

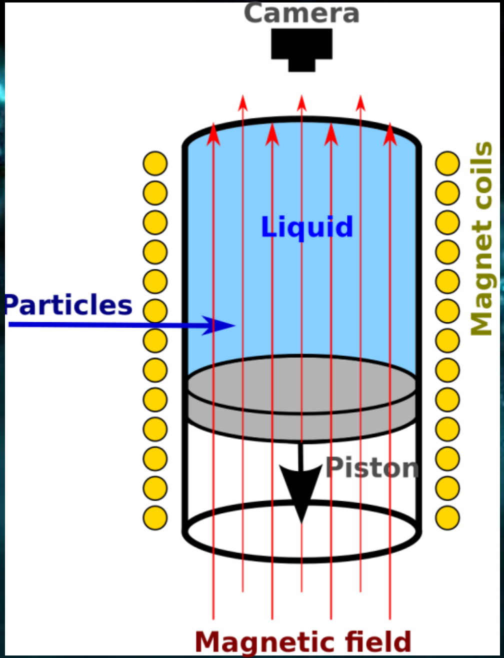
Scintillator material

How it was achieved in the past?

2. Mid 20th Century Methods



Cloud Chambers



Bubble Chambers

History of Particle Detection

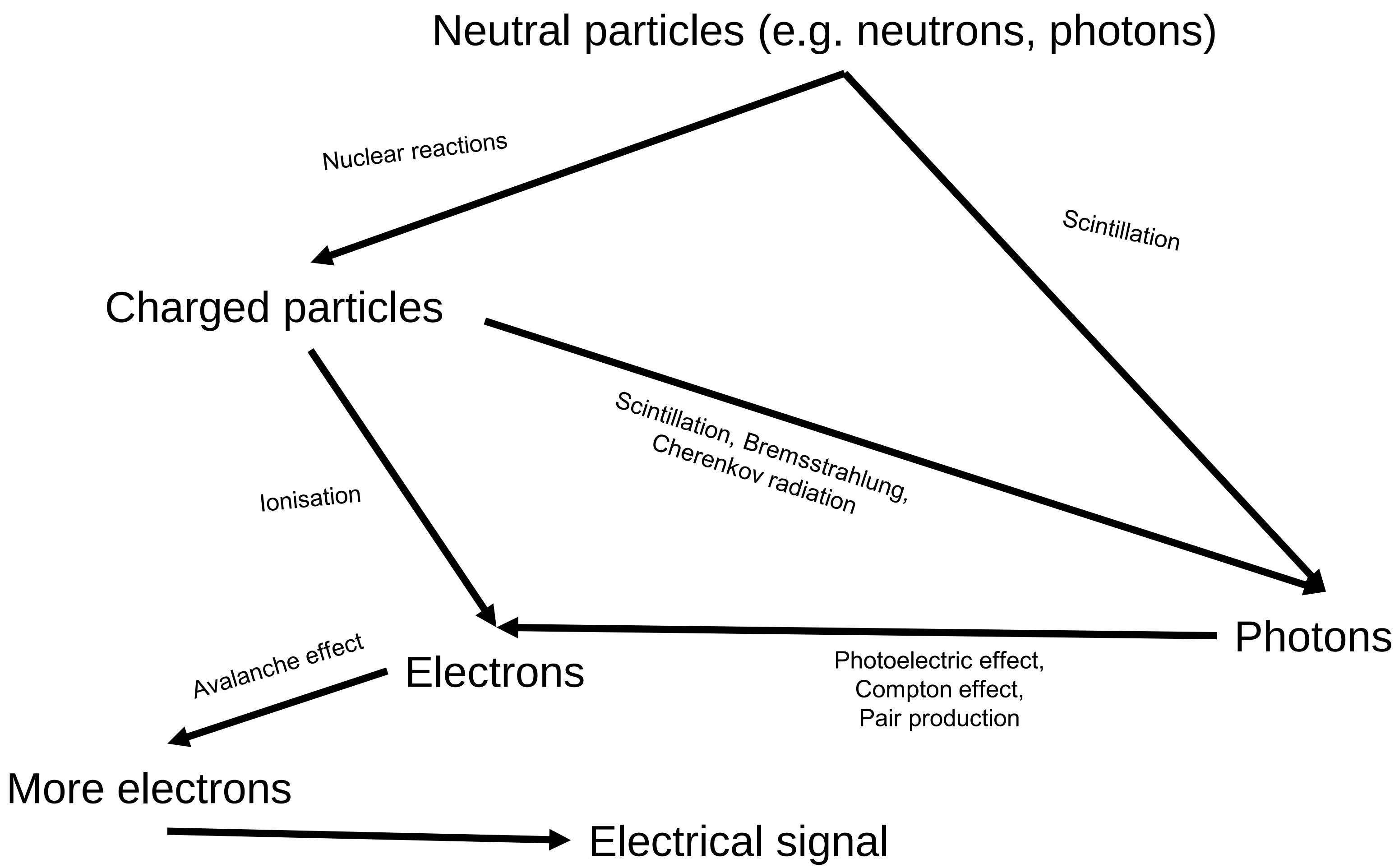
- ➢ Particle detectors have evolved over the past century from simple photographic films and scintillation screens to advanced electronic and semiconductor devices. Early detectors, like cloud and bubble chambers, made particle tracks visible and led to key discoveries like the positron and pion.
- ➢ The development of electronic detectors began with the Geiger-Müller tube and advanced to scintillation counters with photomultiplier tubes (PMTs), which increased sensitivity. Semiconductors later became high-precision tracking detectors.
- ➢ Today, hybrid systems like Silicon PMTs and Micropattern Gas Detectors are used, combining various technologies to enhance performance. This evolution supports future high-energy colliders and advances in particle physics.

How does modern particle detection work?

- **Basic detection principle**:

Electrical signal (which can be detected) ← moving electrons ← electrons need to be freed

- Lots of electrons need to be freed in order to detect them. Thus, we use the **Avalanche effect**: by applying a strong electric field, the already freed electrons gain kinetic energy which they use to free other subsequent electrons.



Neutral particles (e.g. neutrons, photons)
Nuclear reactions
Scintillation
Charged particles
Scintillation, Bremsstrahlung,
Cherenkov radiation
Ionisation
Photons
Electrons
Avalanche effect
Photoelectric effect,
Compton effect,
Pair production
More electrons
Electrical signal

Detection of charged particles

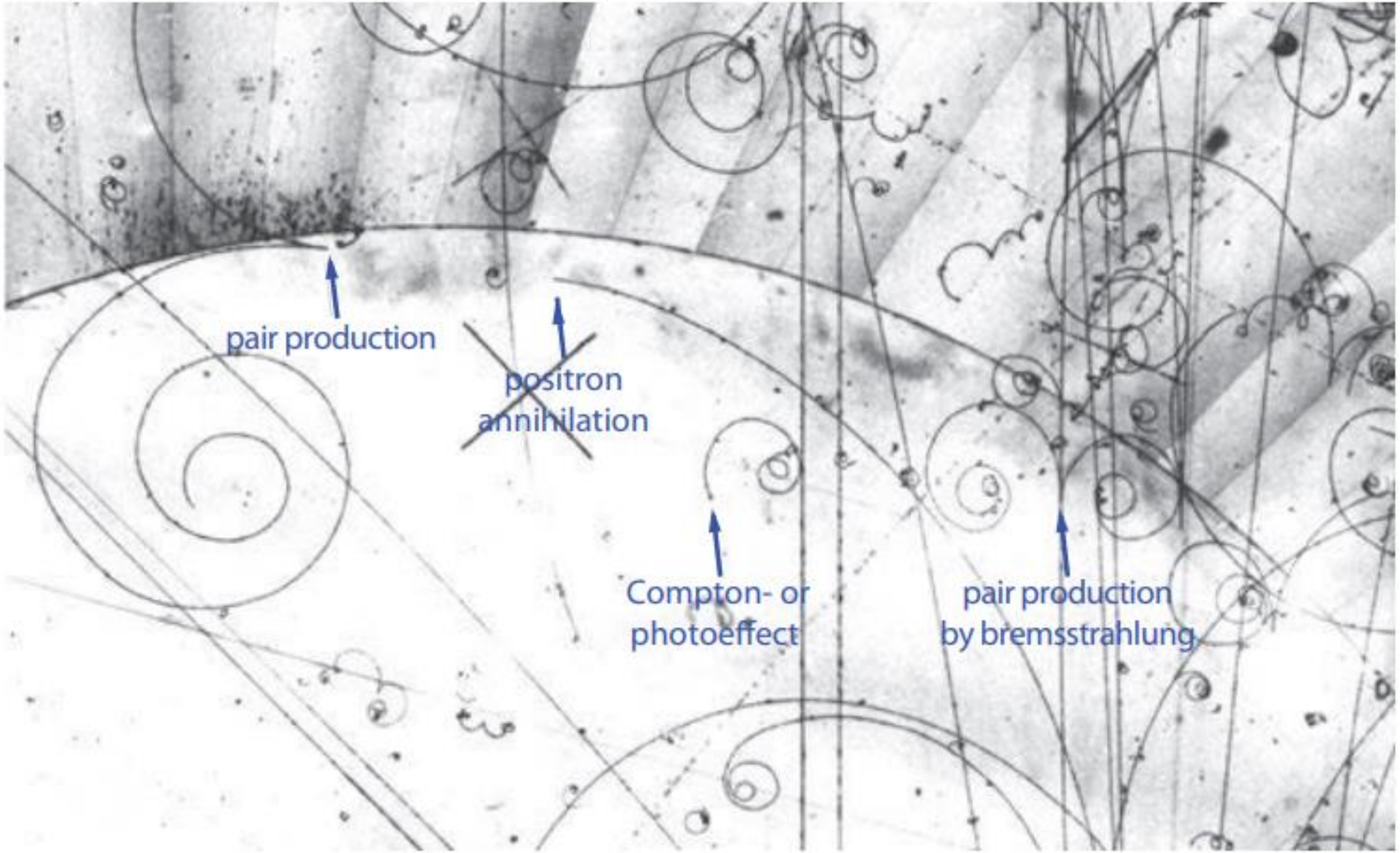
- **Ionisation**: some of its kinetic energy is transferred to an electron of the gas detector, thus freeing it.
- By creating **photons**:
  - Scintillation: the process where a material emits ultraviolet or visible light under excitation from high-energy photons or energetic particles like electrons, alpha particles, neutrons and ions.
  - Bremsstrahlung: is the electromagnetic radiation (i.e. photon) emitted as a result of the deceleration of a charged particle when deflected by another charged particle.
  - Cherenkov radiation: is the electromagnetic radiation (i.e. photon) emitted when a charged particle passes through a medium at a speed greater than the phase velocity of light in that medium.

Detection of neutral particles

- **Photon**: frees electrons as a result of the:
    - Photoelectric effect: the photon (around 1 keV) transfers its entire energy to an atom that emits a shell electron.
    - Compton effect: the photon (around 1 MeV) is scattered following the transfer of some of its energy to an electron, which is released from the outer valence shells.
    - Pair production: conversion of a photon into a positron-electron pair near a nucleus.

Detection of neutral particles

- **Neutron**: Using gases of large reaction cross section, the interaction between the neutron and the atomic nucleus results in charged particles.
- **Neutrino: only** via weak interaction (gravitational force caused by neutrinos is too weak).
    - By transferring energy to a target particle that subsequently emits Cherenkov radiation (no flavor information unfortunately)
    - By coupling with a W boson and as a result converting into a charged lepton which can be detected (flavor information)
    - By finding the decays in which the detected particles don't seem to respect energy conservation (the difference is the energy of the neutrino)



15-feet bubble chamber, Fermilab

Source: Hermann Kolanoski & Norbert Wermes, Particle Detectors

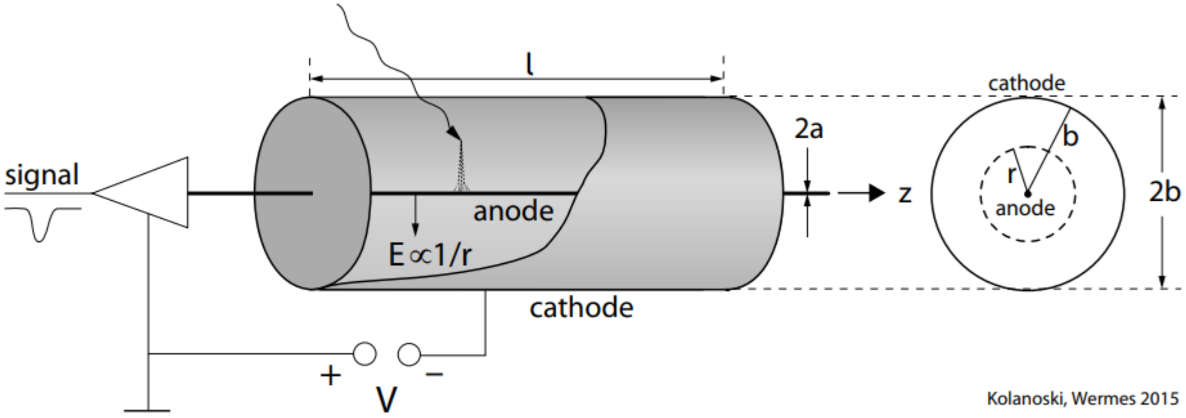
How many types of particles detectors exist?

The basic principle of particle detection can be implemented in machinery called particle detectors:

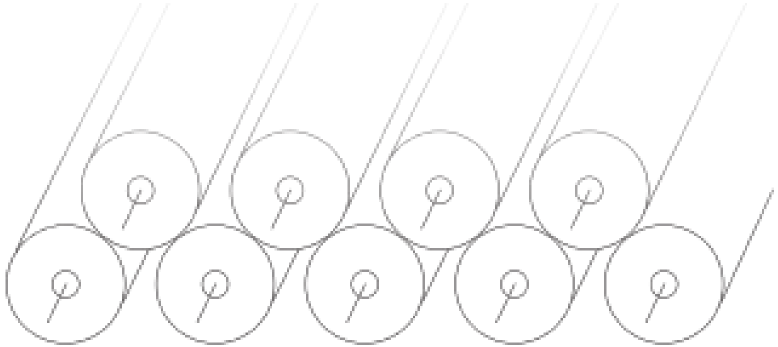
1. Gaseous Detectors
2. Semiconductor Detectors
3. Scintillation Detectors
4. Calorimeters

The Gaseous detector

- Consists in: a cathode and anode surrounded by a carefully selected gas.
- Mechanism:
  - Charged particles ionise the gas atoms.
  - The released electrons are attracted by the anode and the positive ions by the cathode.
  - The electrical signal is detected.
- Usually the anode is a wire and the cathode is a tube surrounding it. By multiplying these straw chambers we can effectively detect the points the charged particle has passed through, with a certain error margin (in this case the tube's radius).
- By connecting the dots we can determine the particle's trajectory.

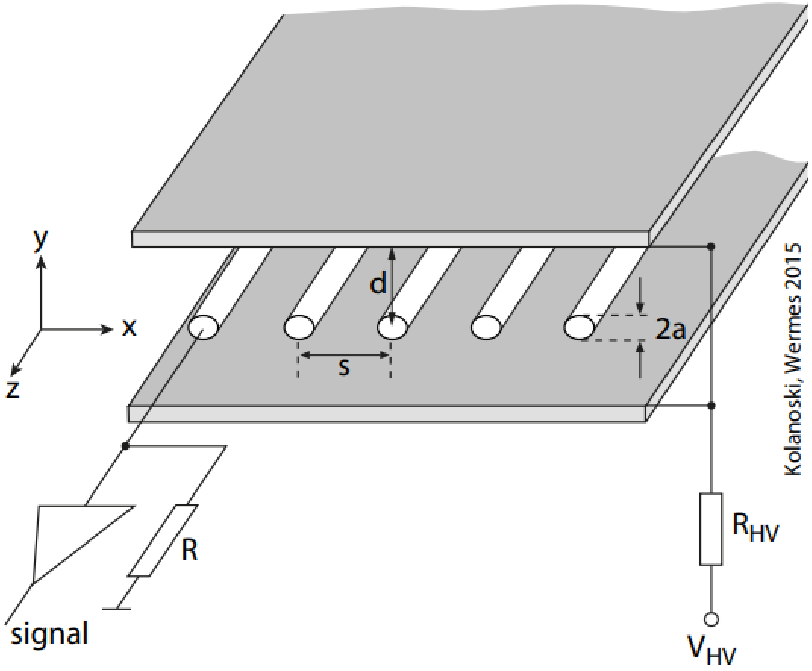


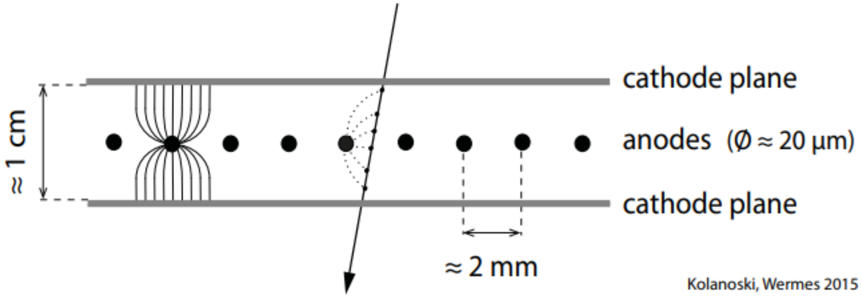
Kolanoski, Wermes 2015



The Gaseous detector

- Other layouts exist:
  - Multiwire proportional chamber (the tube being replaced by two parallel planar cathodes on each side of the wires)
  - Drift chambers (By measuring the drift time of the electron, a more precise measurement of the position of the charged particle is determined)
- By alternating the directions of the wires on multiple levels, a more precise tridimensional trajectory can be obtained.





Multiwire proportional chamber

The semiconductor detector

- Is based on a similar principle used in the gaseous detector.
- Mechanism:
  - The material is arranged between two electrodes.
  - The charged particles or photons hit the material (usually silicone), creating electron-hole pairs.
  - The electrons and holes travel to the electrodes, which results in an electrical signal that can be measured.
  - The energy of the particle can be determined by measuring the number of electron-hole pairs.
- This detector is more efficient than the gaseous detector because the energy necessary for the generation of an electron-hole pair is five times smaller than for the generation of an electron-ion pair in a gas.
- Therefore, a higher resolution can be achieved. The drawback is that silicone detectors are more expensive and require sophisticated cooling to reduce leakage currents.

Scintillation detector

- use scintillators, a material which emits photons when struck by an incoming particle, absorbing its energy.
- The scintillator is coupled with a photomultiplier tube (PMT), that absorbs the photons and re-emits them as electrons (photoelectric effect, compton effect, pair production)
- The multiplication of the electrons results in an electrical signal that can be measured, giving valuable information about the particle.

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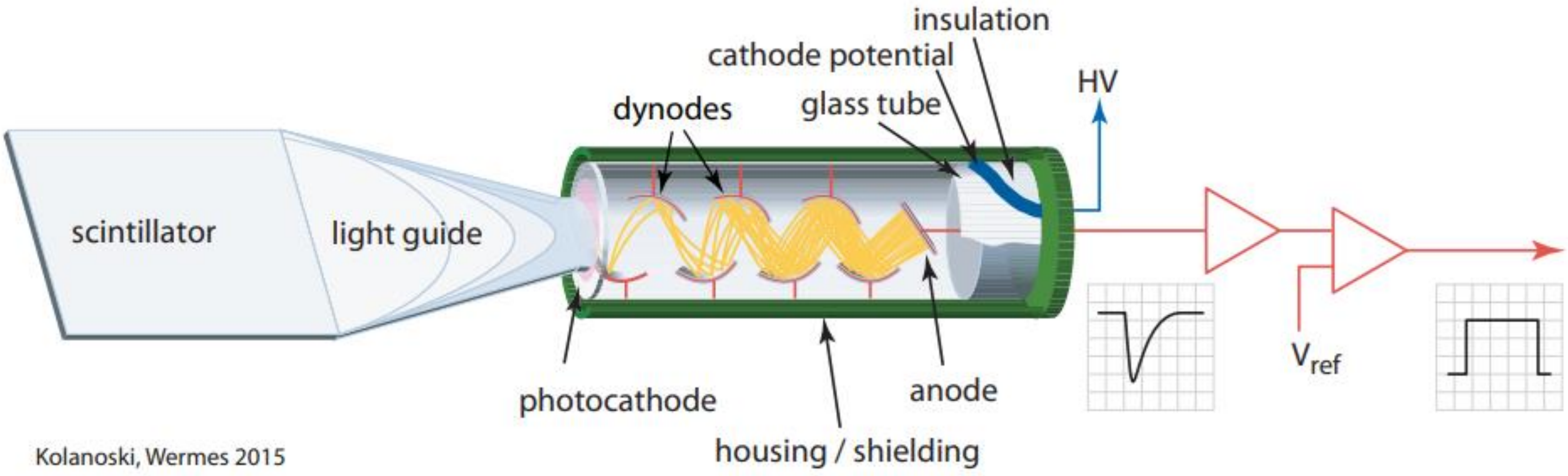
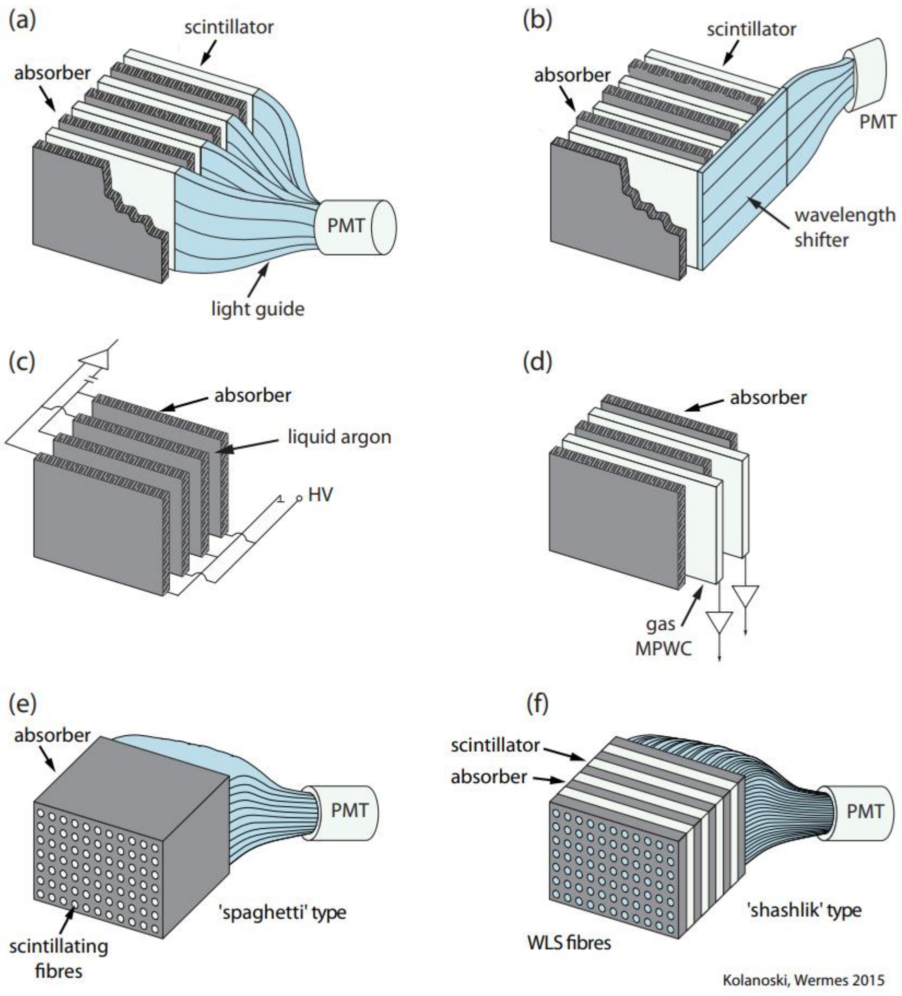
Scintillation detector



Calorimeter

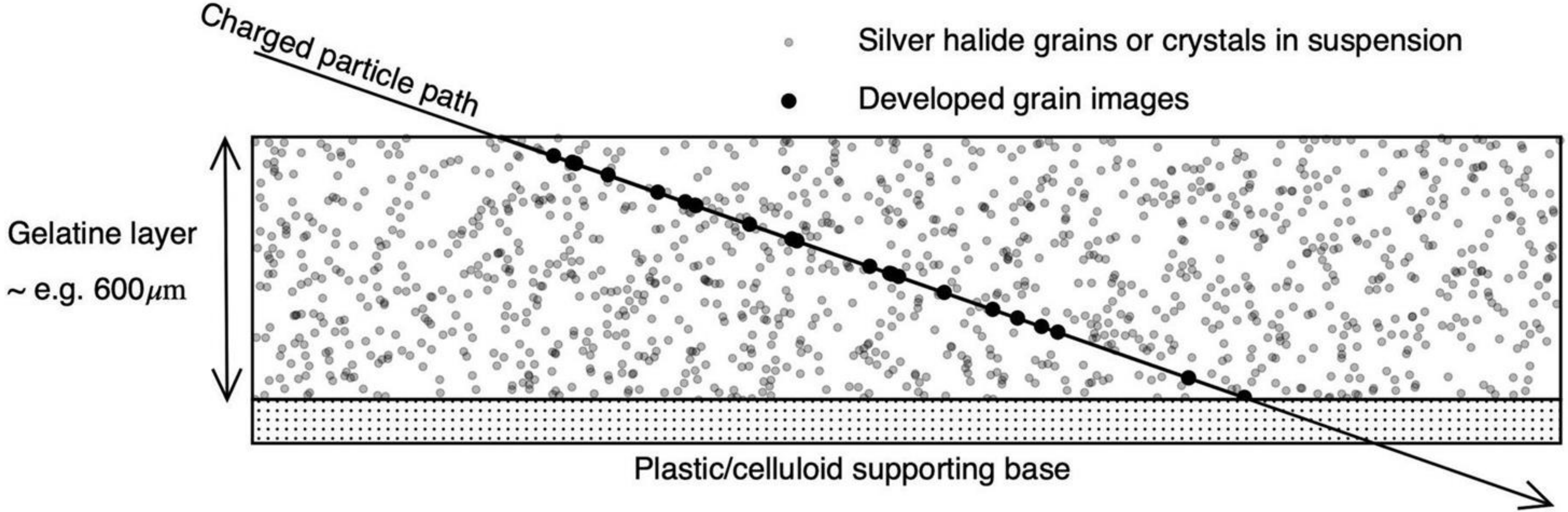
- As their name suggests ("calorie"), they measure a particle's energy as it passes through the detector.
- To measure a particle's full energy, it needs to deposit its entire energy in the calorimeter (this way stopping it).
- To do this, the calorimeter consists in alternating absorbing material (e.g. lead) and scintillation detectors or gaseous detectors.
- Two types: electromagnetic and hadronic.



Different calorimeter arrangements

Nuclear Emulsion

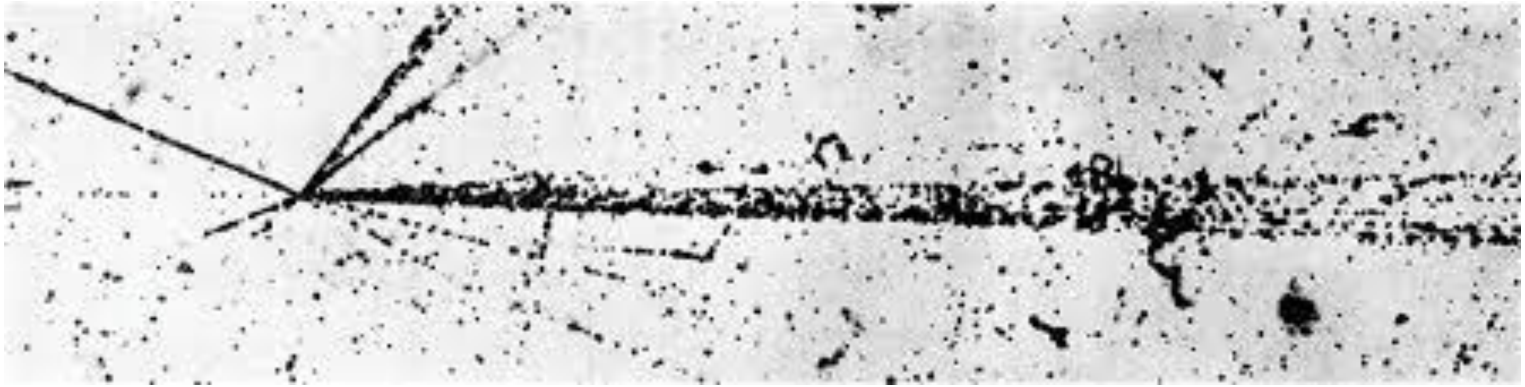
It uses photographic plates coated with a thick layer of gelatine sensitive to charged particles. When a particle passes through the emulsion, it creates a visible track of silver grains that can be examined under a microscope



Nuclear Emulsion

Nuclear emulsions have been used historically to discover particles like the pion. They are valued for their high resolution.

Although they are less common now due to the advent of electronic detectors, nuclear emulsions are still used in some experiments where high resolution is critical, such as in studying rare interactions or in astroparticle physics.



Where are these particle detectors used? (Examples)

- Mostly used in colliders at CERN, Fermilab, SLAC, Cornell
- For example:
    - ATLAS
    - CMS
    - ALICE
    - LHCb

Why do we need more powerful particle detectors?

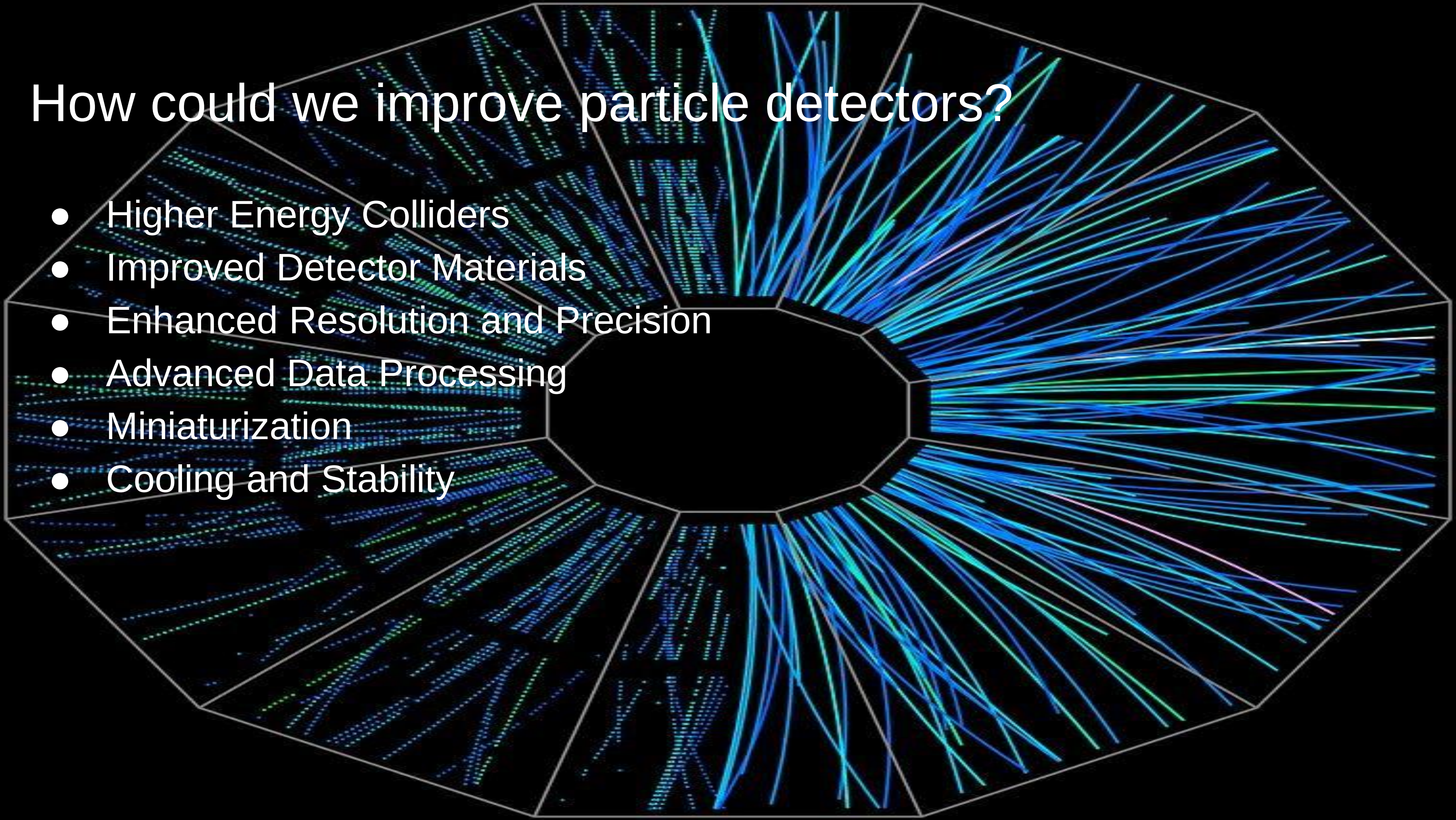
- Advancing Fundamental Physics
  - To deepen our understanding of the fundamental building blocks of the universe and the forces governing them.
- Probing Extreme Conditions
  - To recreate and study conditions similar to those just after the Big Bang, providing insights into the early universe.

Why do we need more powerful particle detectors?

- Precision Measurements
  - To make highly accurate measurements of particle properties and interactions
- Technological Advancements
  - To drive innovation and development in technology, benefiting both science and society

How could we improve particle detectors?

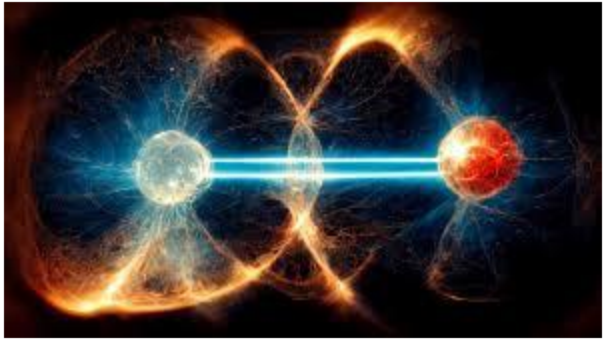
- Higher Energy Colliders
- Improved Detector Materials
- Enhanced Resolution and Precision
- Advanced Data Processing
- Miniaturization
- Cooling and Stability

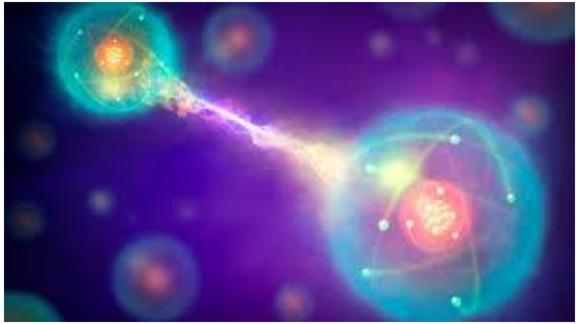


What new technologies could we use?

QUANTUM-ENHANCED PARTICLE DETECTOR

- **Quantum Sensors**
  - Much better sensitivity for weak signals
  - Smaller size but even better performance
  - Accuracy of measurements
- **Quantum entanglement**
  - Much higher sensitivity
  - Enhanced resolution.
  - More reliable





What new technologies could we use?

- **Quantum Computing for Data Analysis**
  - Faster data processing
  - Complex simulation
  - Machine learning integration
- **Graphene based detectors components**
  - Higher conductivity
  - Better durability
  - Thermal management

What new technologies could we use?

- **Adaptive Self Healing materials**
  - Longer operational life
  - Reduced Maintenance time and cost
- **Integrated Photonic Circuits**
  - Transmitting signals faster
  - Smaller size
  - Low energy consumption

Thanks for watching
and hope you enjoyed!

- And let’s not forget the people who helped us:
  - Roxana Zus
  - Sarah Zoechling
  - Calin Alexa
  - Elena Firu

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