Lecture 4:
Gamma-ray detection: From space to the ground

Lecturer: **Juan Cortina (CIEMAT, Madrid)**

General outline of the lecture:
- Detection basics -> Lesson 3.1
- Detection from the ground: introduction to atmospheric showers -> Lesson 3.2
- Detection from the ground: Cherenkov telescopes -> Lesson 3.2
- Detection from the ground: particle detector arrays -> Lesson 3.3
- Detection from space -> Lesson 3.3

Recommended reference:
"Handbook of X-ray and Gamma-ray Astrophysics", Springer, edit. Bambi & Santangelo (numerous sections available in arXiv)

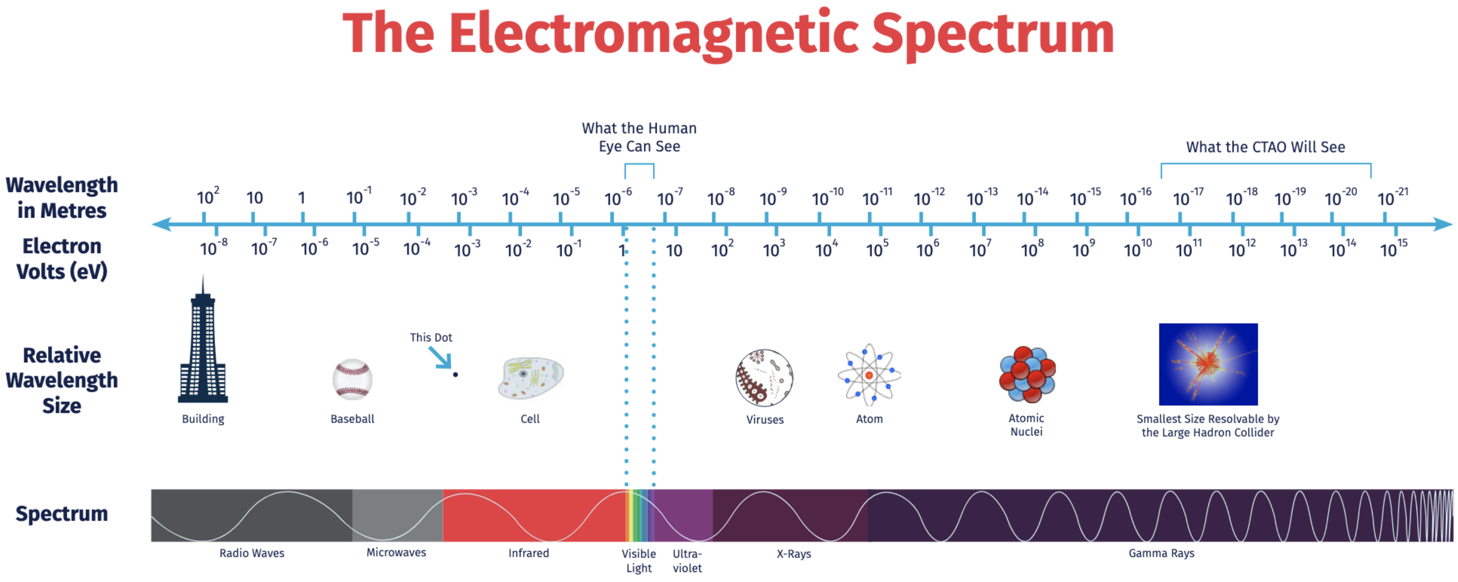
Lesson 4.1:
Basics of the detection

Credits for this lesson: **E. Lorenz (MPIfP Munich)**

Detecting photons

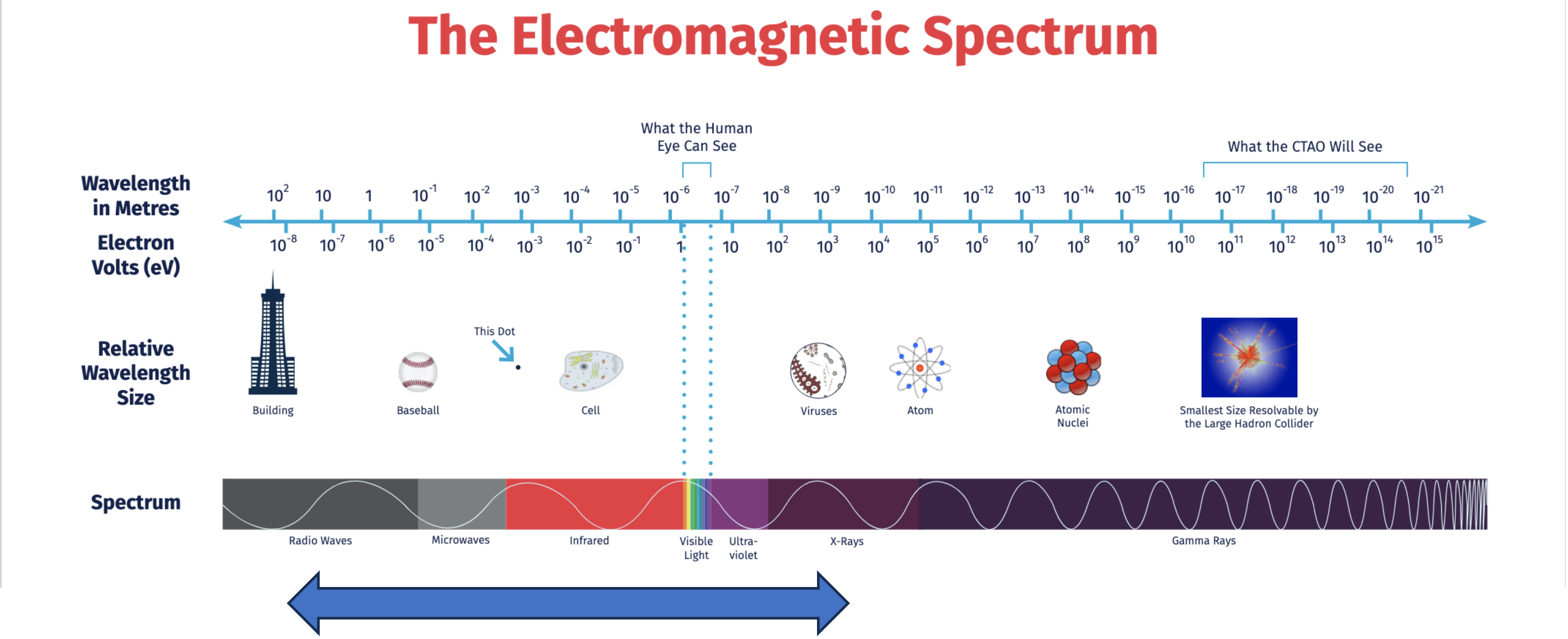
- We understand astrophysical objects through images and spectra at a given time.
- These are based on three observables: photon energy, arrival direction and time.
- How we measure these observables depends very much on photon energy / wavelength.

Detection technique depends on energy



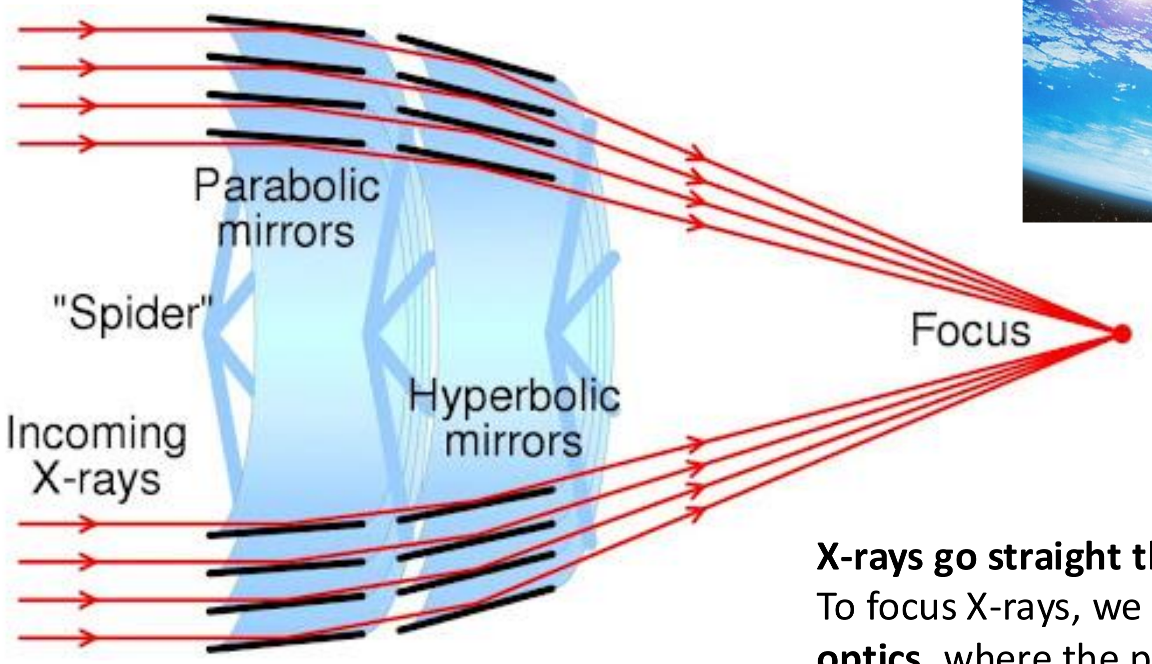
Credits: CTAO

1. Focusing



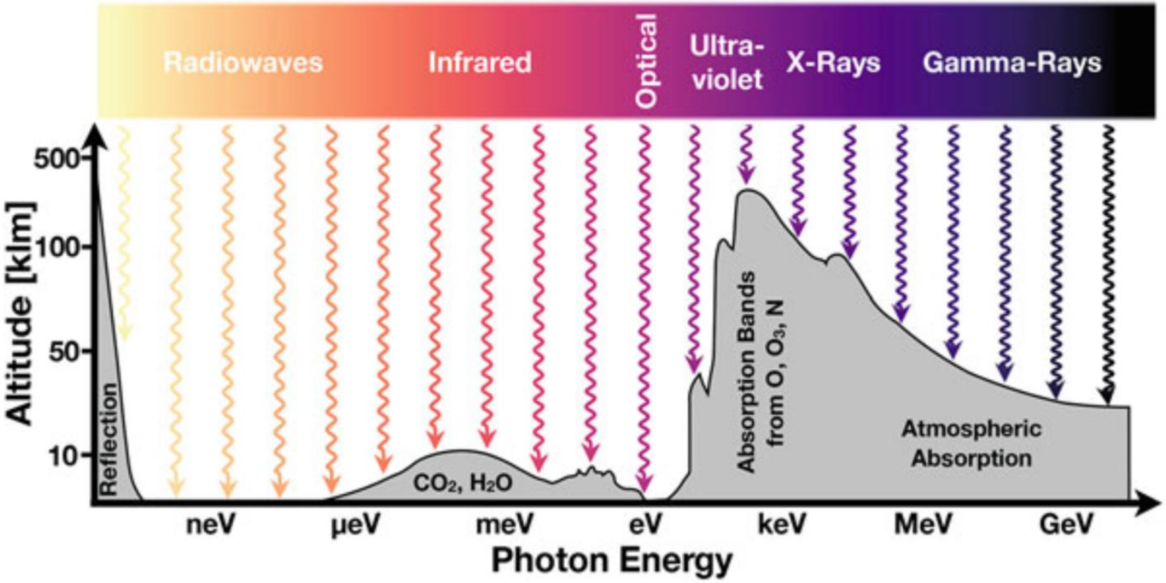
From <10 m radio to X-rays, we can focus light using lenses or mirrors. This makes life much easier because one can bring photons spreading over a very large area into a small detector.

Focusing limits: X-rays



X-rays go straight through them or are absorbed. To focus X-rays, we must use **grazing-incidence optics**, where the photons hit the mirror at a *very shallow angle* (typically 0.5–2°)

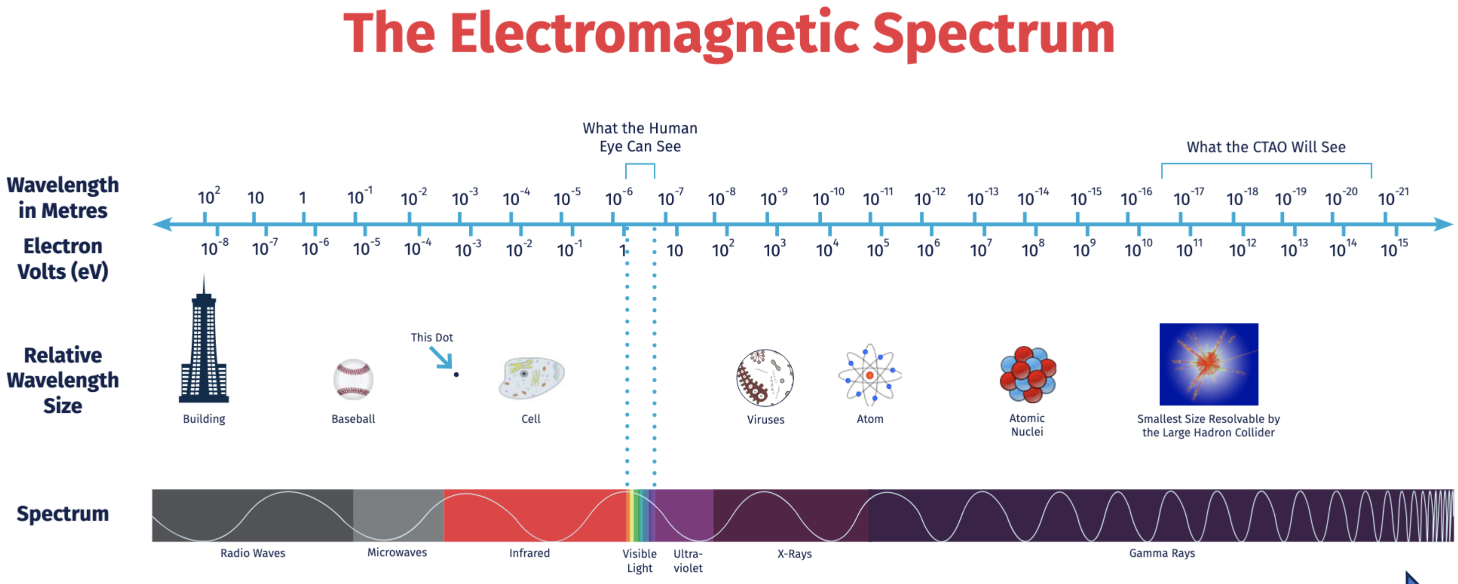
2. Atmospheric windows



Our atmosphere blocks light at many wavelengths…

Handbook of X-ray and γ-ray astrophysics, p. 1545

3. Wave vs particle



Starting at hard X-rays photon fluxes get very low and light starts to <u>behave like a particle</u>. We deal with individual photons, i.e. we get energy, direction and time for each photon.

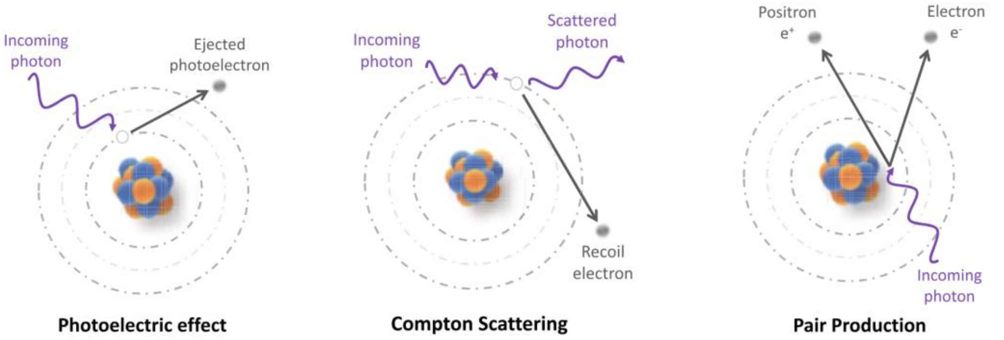
The γ-ray spectral range

- What's a γ-ray?
  - The magic photon energy is 2 x 511 keV = 1.022 MeV. At that energy a photon can produce an e^-e^+ pair.
  - We conventionally talk about γ-rays for photons above that energy.

- Putting together what we've learned: γ-rays behave like particles, they can't be focused and they are absorbed in the atmosphere.

Photon interaction with matter

The dominant physical process depends on photon energy:



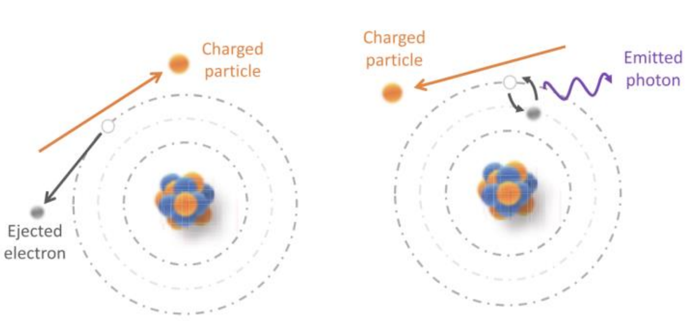
$E \lesssim 1$ MeV	$E \sim$ 1-10 MeV	$E \gtrsim 10$ MeV

Single-Event Effects, from Space to Accelerator Environments, Springer Nature

Typical secondary products are high energy electrons / positrons so must learn how they interact…

Electron/positron interaction with matter

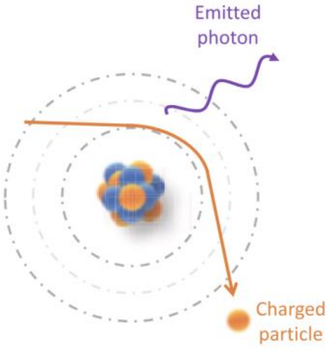
Single-Event Effects, from Space to Accelerator Environments, Springer Nature



Ionization

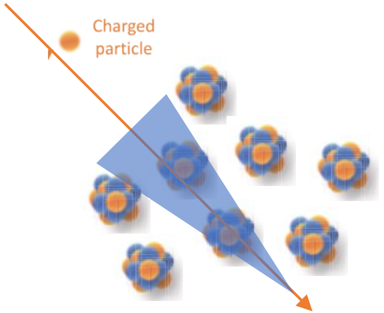
Excitation

E ≲ 10 MeV



Bremsstrahlung

E ≳ 10 MeV



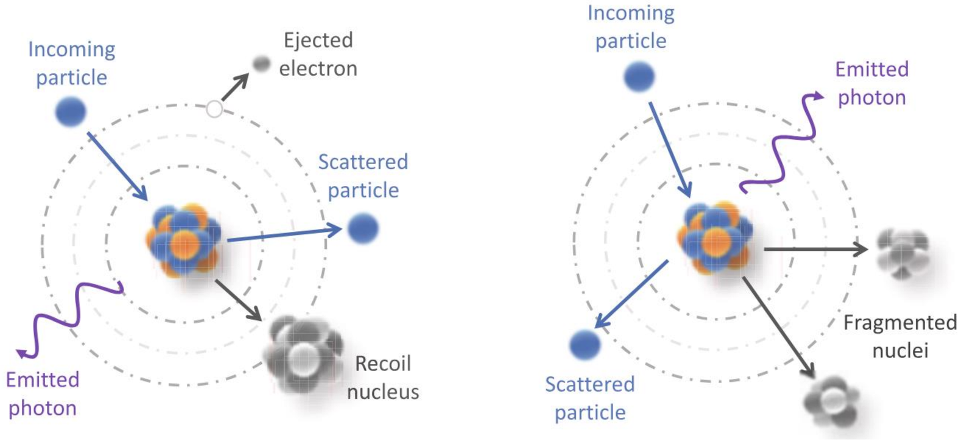
Cherenkov radiation

E ≳ 1 MeV in water
E ≳ 20 MeV in air..

Backgrounds

We are surrounded by high energy particles (electrons, protons, neutrons, nuclei…):

- In space: primary cosmic rays.
- In the atmosphere: primary or secondary cosmic rays.
- In the ground: natural radioactivity or cosmic rays.

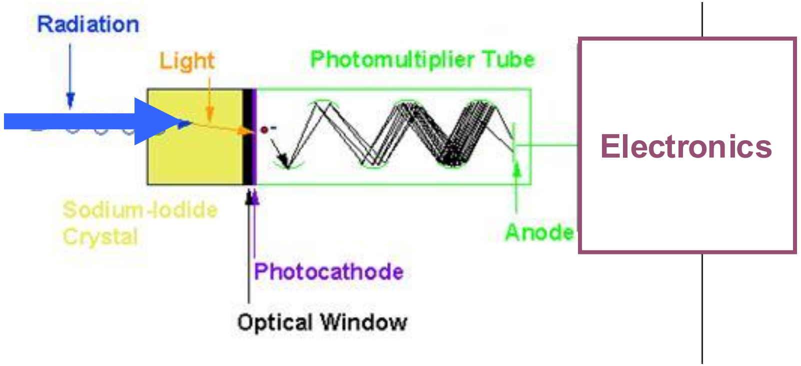


These particles also produce γ-rays or electrons when they interact with matter

Multi-stage detection

Particle detectors are **modular**:

- We make the electron/positron/muon/nucleus… interact with some material. This material **generates light** in the visible/IR/UV.
- We detect this light using PMTs, photodiodes, SiPM. These detectors **generate an electrical pulse**.
- We use electronic circuits to **process the electrical pulse**. That's the final signal which tells us that a particle has arrived and (in some detectors) what energy it carried.

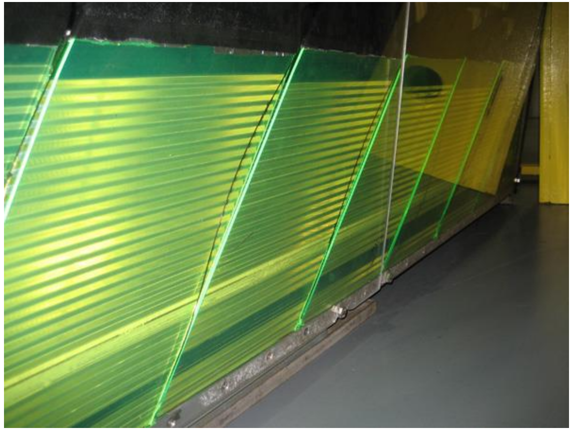


HOW TO DETECT ELECTRONS

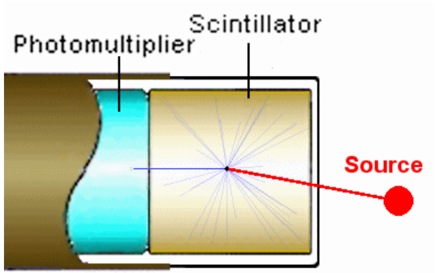
- Scintillators.
- Cherenkov detectors.
- Solid-state (silicon) detectors.
- Gas detectors.

Scintillators

- We use them to detect electrons and measure their energy.
- A charged particle traversing matter leaves behind it a wake of excited molecules.
- Certain types of molecules release a small fraction (3%) of this energy as **optical photons**.
- They "scintillate" = emit luminescence light which can be detected for instance by photomultipliers.
- Two types of scintillators:
    - Organic.
    - Inorganic.



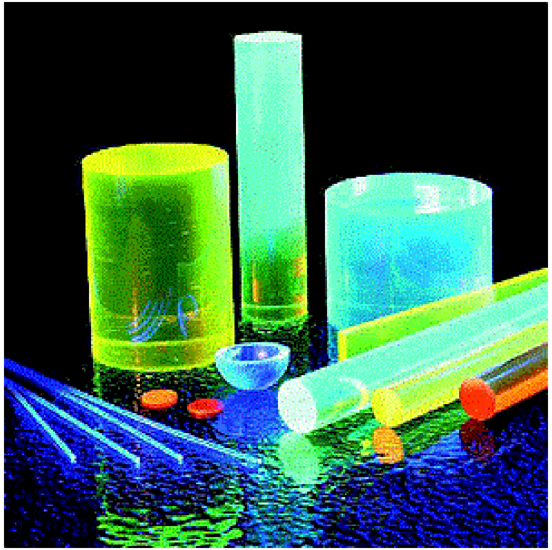
Scintillator sheets at Fermilab



Scintillator coupled to photomultiplier

Organic scintillators

- Crystalline, liquid or plastic. Most widely used: plastic.
- Density ~1 g/cm^3.
- Typical light yield ~ 1 photon/100 eV energy deposit.
- A "Minimum Ionizing Particle" (MIP, e.g. fast electron) crossing one cm of scintillator yields 20000 photons.
- Decay time in the ns range.
- Cheap and easy to fabricate in any shape.

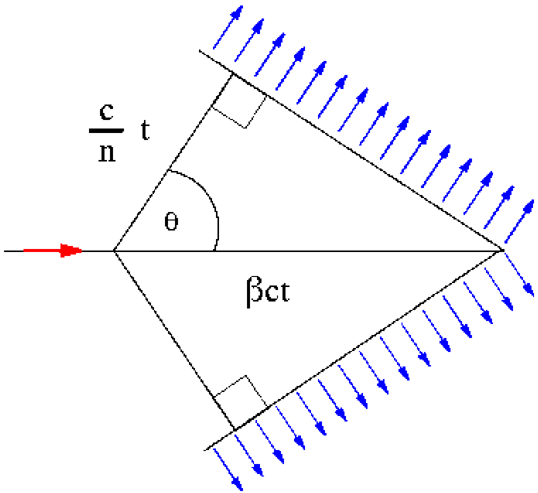


Inorganic scintillators

- Crystals: NaI(Tl), BGO,BaF_2, CsI(Tl), CsI(pure), $PbWO_4$, CeF_3
- High density: electrons lose their energy fast and produce many photons $\Rightarrow$ many photons means good energy resolution.
- NaI: density =3.67 g/cm^3. 1 MIP yields 190 000 photons after crossing 1 cm, 10 times more than plastic.

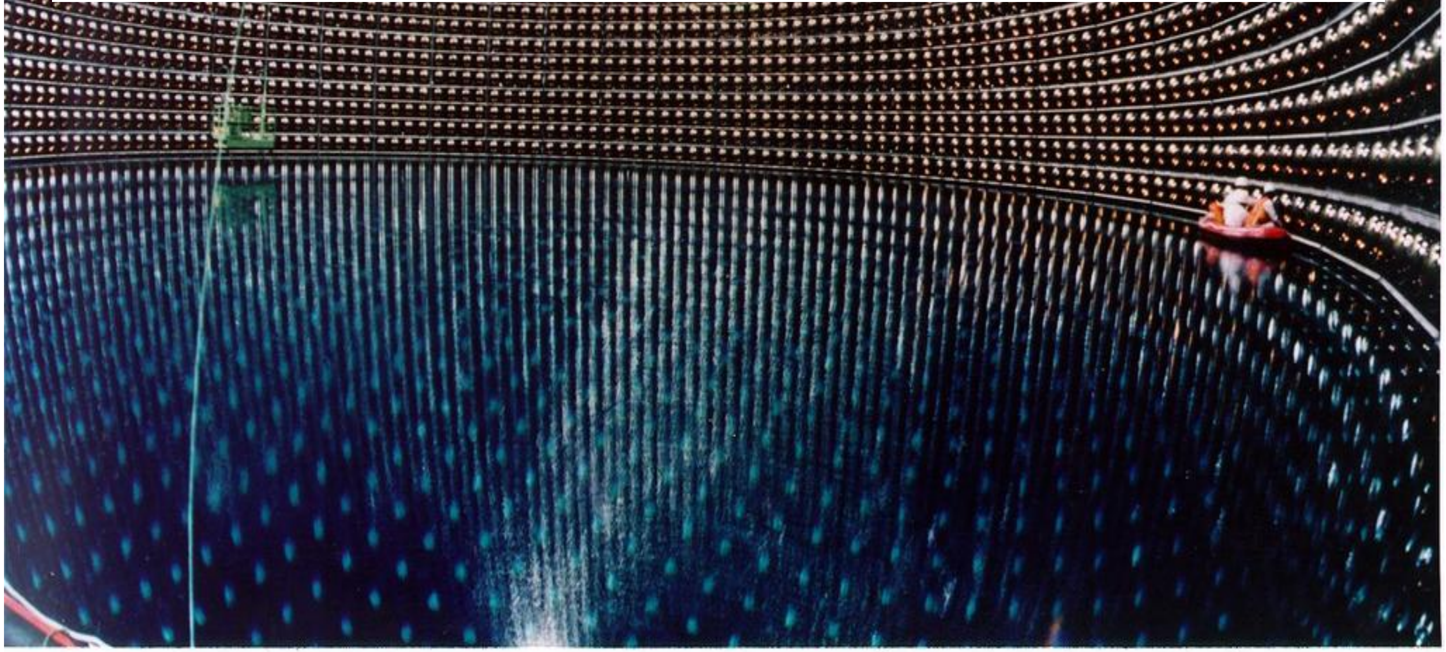
Cherenkov detectors

- They are based on the “Cherenkov effect”: a charged particle generates light in a medium when it travels faster than the speed of light in that medium.
- More details in the section about “Cherenkov γ-ray telescopes”.
- A cone of visible light along the trajectory of the electron, so we can use photon detectors to detect the Cherenkov light and know the electron’s energy.

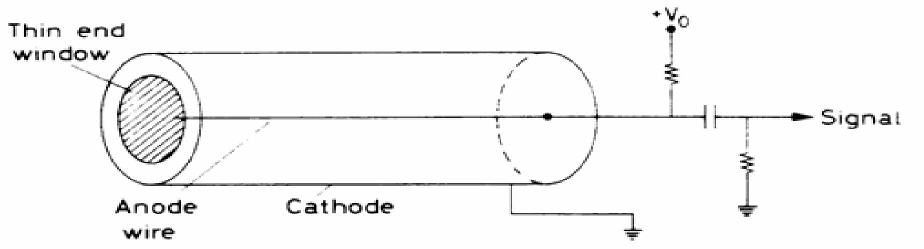


Cherenkov detectors

- The simplest detector is a tank of water whose walls are equipped with several PMTs.
- Many applications in astroparticle physics: cosmic rays, neutrino or gamma ray detectors. A huge example: Kamiokande.



Gas detectors



Basic principle:

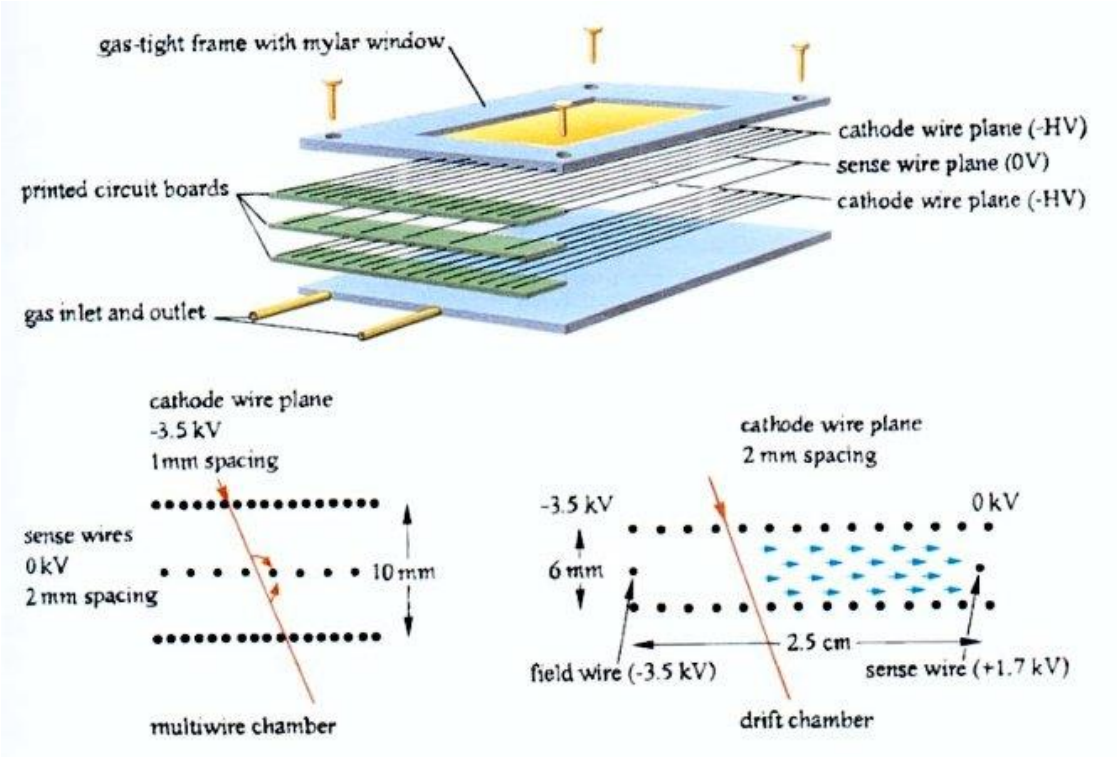
- Electrons also ionize a gas: each electron leaves a trace of free electrons along its trajectory in the gas.
- One adds an electric field to the gas and these free electrons fall in the potential towards the anode.
- They generate an electric current in the anode. One measures current and knows that an electron has entered the gas.

Gas detectors: Geiger counters

- The voltage in the gas is so high that the first electrons accelerate fast.
- They ionize other electrons which in turn accelerate and ionize others: an **avalanche** develops.
- The number of electrons in the anode is not proportional to the energy of the primary electron. This is the so-called “Geiger-mode”.
- A Geiger counter simply tells us that an energetic electron has arrived (0/1). Nothing about energy.
- It is used as a “radiation detector”.

Gas detectors: wire chambers

- Instead of one wire for the anode, we use many
- So we know where exactly the electron passes through the detectors, i.e. we "track" the electron.

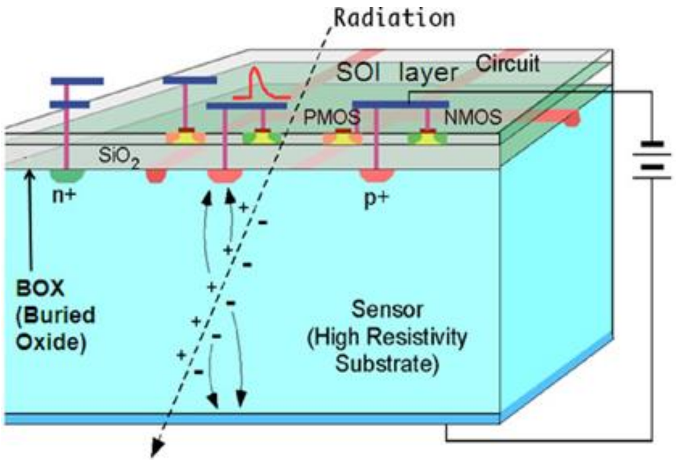


Gas detectors: multiwire proportional chamber

- We play all the tricks together: gas and many wires.
- But we keep the voltage drop low so that there's no avalanche.
- The number of electrons at the anode of the active wire is proportional to the energy of the primary electron.
- So we detect the electron, know its energy and track its direction.
- Nobel Prize for this idea: Georges Charpak in 1992.

Solid-state (silicon) detectors

- Electrons generate e-hole pairs when they traverse silicon.
- For minimum-ionizing particles, the most probable charge deposition in a 300 μm thick silicon detector is about 22000 electrons.
- This is a high current which can be measured: no need for extra photomultipliers like in scintillators.



Solid-state (silicon) detectors

- The most commonly used material is silicon, but germanium, gallium-arsenide, CdTe, CdZnTe, and diamond are also useful in some applications.
- Integrated circuit technology allows the formation of high-density micron-scale electrodes on large (10–15 cm diameter) wafers, providing excellent position resolution.
- Furthermore, the density of silicon and its small ionization energy result in adequate signals with active layers only 100–300 μm thick, so the signals are also fast (typically tens of ns).

Solid-state (silicon) detectors

They are cheaper and easier to operate than gas detectors, so they are slowly replacing them everywhere (as we will see in the lecture about space detectors).

Silicon detector in STAR: relativistic heavy ion collider in Brookhaven.

HOW TO DETECT OPTICAL PHOTONS, WITH A VIEW TO PARTICLE DETECTION

- Photomultipliers.

Solid-state (silicon) detectors:

- Photodiodes.
- CCDs.
- APDs.
- Silicon Photomultipliers.

General parameters

- **SPECTRAL RANGE (λ):** ≈ 200 nm TO ≈ 1.5 μm;
  -> visible spectrum + part of the UV and IR spectrum
  -> limits not sharply defined
  200nm : transmission cutoff of few meters of atmosphere
  1.5 μm: practical upper limit of single photon detection

- **QUANTUM EFFICIENCY:** IMPORTANT NUMBER THAT DESCRIBES THE CONVERSION PROBABILITY OF A PHOTON (PHOTONS) INTO ELECTRONS

  QE = #of photoelectrons /# of incident photons

  QE is wavelength dependent : QE = QE (λ)
  but the photoelectrons (PHE) do normally not carry info on the energy (color) of the photons!

  QE is normally < 1

General parameters

* **CONVERSION TIME**: CONVERSION PHOTON->PHOTOELECTRON IS PROMPT
ANY DELAY IS DETECTOR SPECIFIC
DELAY EXAMPLES: DIFFUSION OF A PHE IN MATERIAL DELAY IN SIGNAL PROCESSING ELECTRONICS

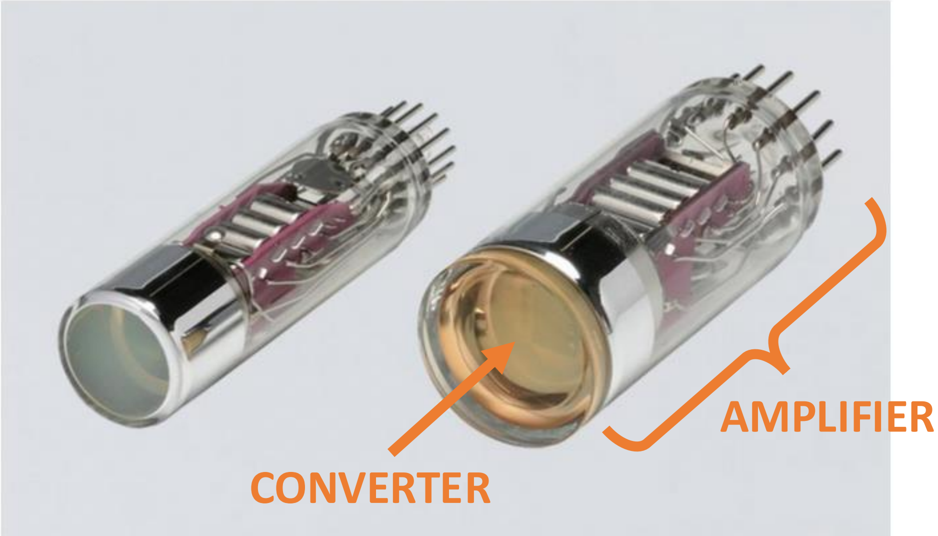
* THE ENERGY OF A PHOTON IS TOO LOW (typically eV) TO BE DETECTED/PROCESSED BY NORMAL ELECTRONIC CIRCUITS
$\Rightarrow$ NEEDS SPECIAL AMPLIFIERS

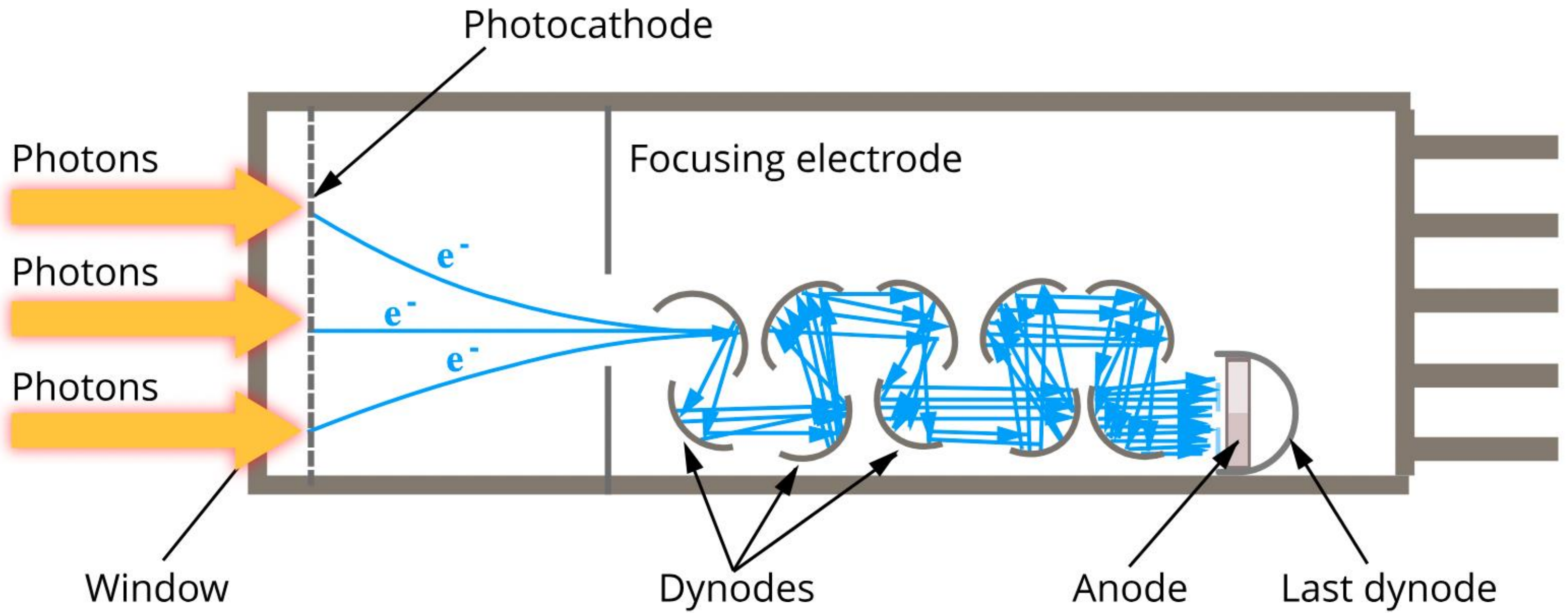
NORMAL SEMICONDUCTOR AMPLIFIERS HAVE THE NEEDED BANDWIDTH BUT ARE MUCH TOO NOISY ,
*BEST WIDEBAND AMPLIFIERS (Bandwidth ≈ 500 MHz) HAVE NOISE LEVELS $\sim$ FEW 1000 ELECTRONS AT INPUT
SINGLE PHOTONS

- IN VACUUM PHOTON DETECTORS: ELECTRON MULTIPLICATION BY DYNODE SYSTEM
- IN SOLID STATE DEVICES: AVALANCHE MULTIPLICATION IN SAME MATERIAL

Photomultipliers

- Photomultipliers were used by astronomers after photographic plates and before CCDs because they allowed for precise photometry.
- They are still the best devices to detect single photons.
- They are a combination of a **converter** from photon to electron ("photoelectron"=phe), and a high gain **amplifier** (electron multiplier).
- That's because a single phe needs large amplification.





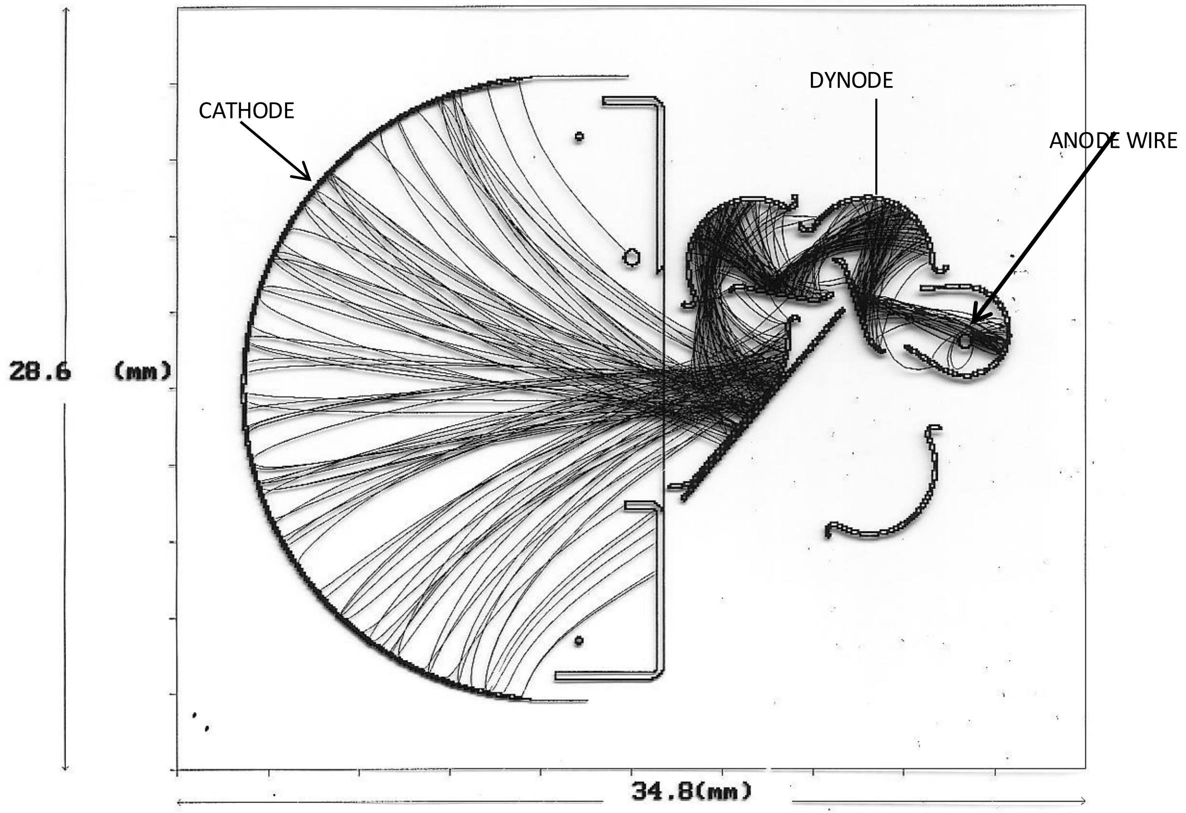
- Basic elements:
  - PHOTO CATHODE: PHOTONS GENERATE (PHOTO)ELECTRONS (PHE) THROUGH PHOTOELECTRIC EFFECT
  - ELECTRON FOCUSSING ELEMENT TO FOCUS PHE ON SMALL AREA AMP. SYSTEM
  - HIGH GAIN AMPLIFIER BY DYNODE SYSTEM
  - ANODE TO COLLECT SIGNAL AND COUPLE TO DAQ SYSTEM
  - AUXILIARY ELEMENTS: VACUUM CONTAINMENT, GLASS WINDOW, HT BIAS CIRCUITS….

PMTs: available at all sizes and shapes

From catalogue of Hamamatsu

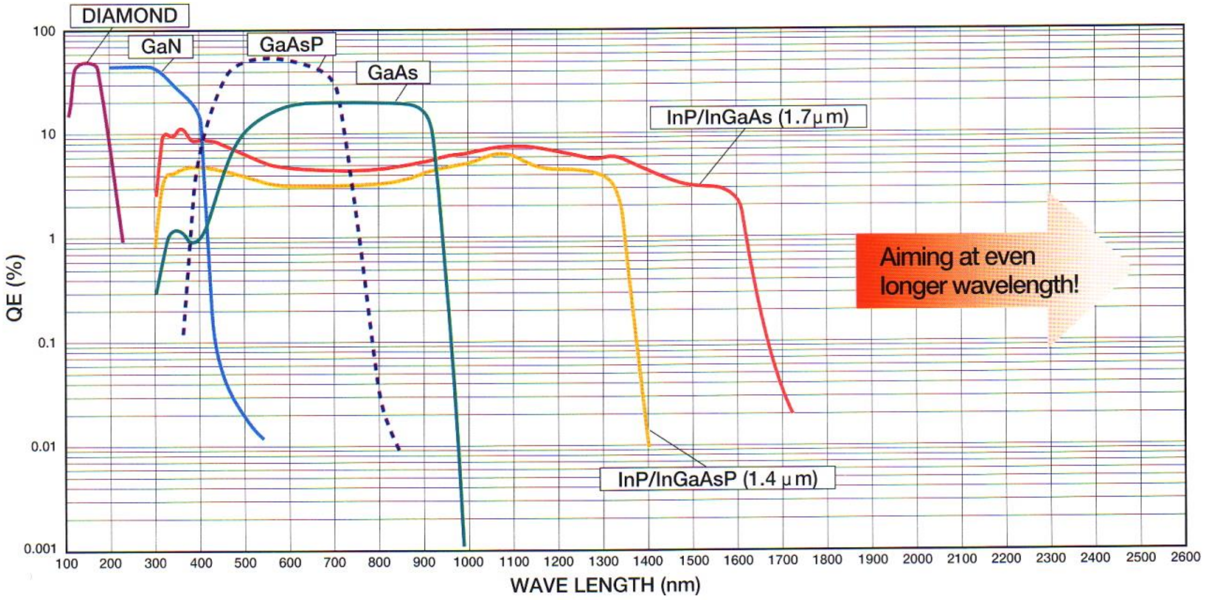
- From mm to tens of cm.
- Flat or curved photocathodes to match additional optics and optimize time response.

EXAMPLE: PHOTOELECTRON TRACKS AND DYNODE MULTIPLICATION IN A PMT 9116



The photocathode

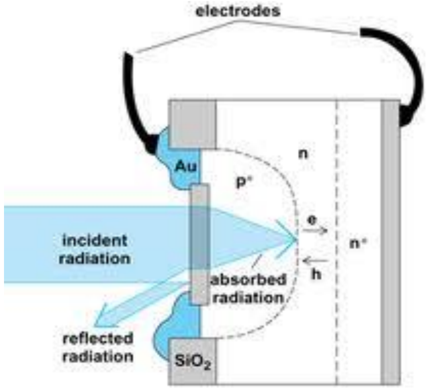
- BASICALLY A SEMICONDUCTOR WITH NEGATIVE ELECTRON AFFINITY
- CATHODES VERY THIN, FEW 10th Å -> SEMITRANSPARENT (partly reflecting, part of light not absorbed-lower QE)-
- VACCUM PRODUCTION TECHNIQUE
- Classical cathodes: mostly Cs- and/or Sb-based compounds such as CsI, CsTe, bi-alkali (SbRbCs, SbKCs), multi-alkali (SbNa2 KCs), GaAs(Cs), GaAsP, etc.



Solid-state photodetectors

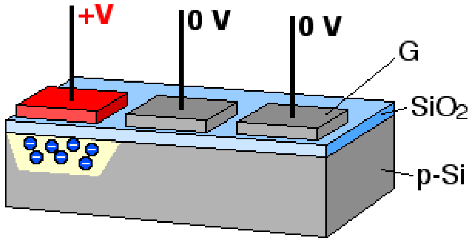
Silicon Photodiodes (PD)

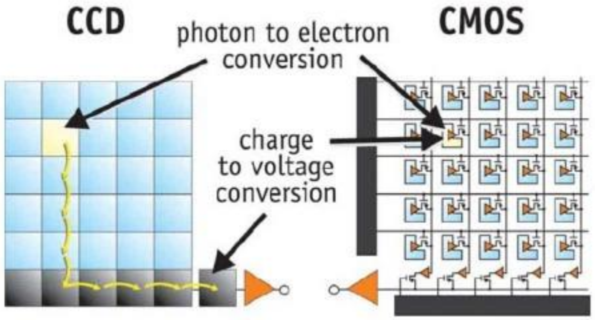
- **Silicon photodiodes** (PD) are widely used in high-energy physics as particle detectors and in a great number of applications as light detectors.
- Photons with energies above the indirect bandgap energy (wavelengths shorter than about 1050 nm, depending on the temperature) can create e-hole pairs (the “photoconductive effect”), which are collected on the p and n sides, respectively.



Silicon PD: CCD -> CMOS

- Very large arrays containing $O(10^7)$ of $O(10\ \mu m2)$-sized **PDs** pixelizing a plane are widely used to photograph all sorts of things from everyday subjects at visible wavelengths to crystal structures with X-rays and astronomical objects from infrared to UV.
- To limit the number of readout channels, these are made into charge-coupled devices (CCD), where pixel-to-pixel signal transfer takes place over thousands of synchronous cycles with sequential output through shift registers.
- In CMOS each pixel is read individually: faster (reaching 1 μs) and easier to integrate with readout electronics (now standard in cell phones!).





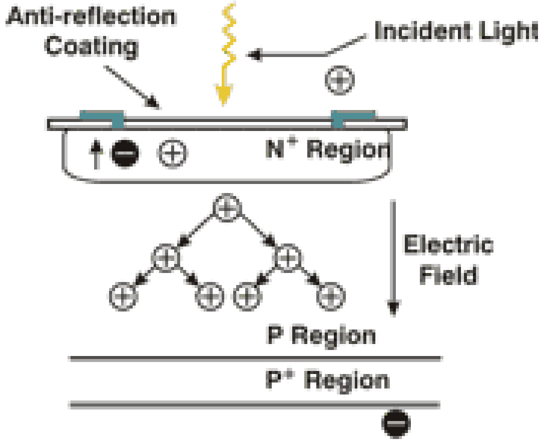
Silicon PD: CCD / CMOS

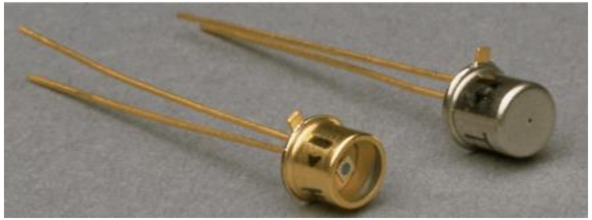
- Good:
  - High spatial resolution because we have thousands or millions of pixels.
  - High Quantum Efficiency: exceeds 90% over much of the visible spectrum.
- Bad:
  - Slow to process.
  - One doesn't know **when** the photon hit.
  - Lots of noise: one cannot detect individual photons.

- **This makes CCDs useless to detect particles, because particle detectors need precisely fast reaction and sensitivity to very few photons.**

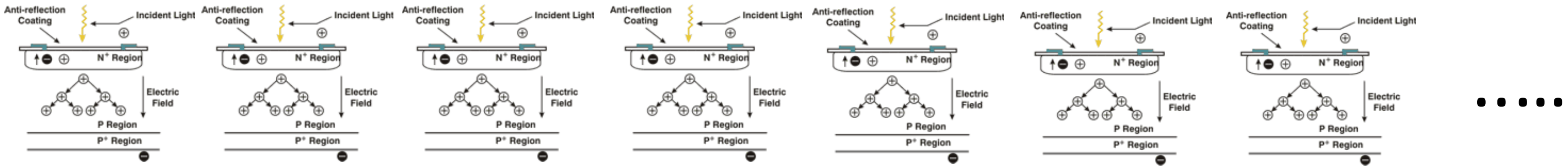
Silicon PD: Avalanche PD

- An exponential cascade of impact ionizations initiated by the initial photogenerated e-hole pair under a large reverse-bias voltage leads to an **avalanche** breakdown.
- As a result, detectable electrical response can be obtained from low-intensity optical signals down to single photons.





Silicon PM



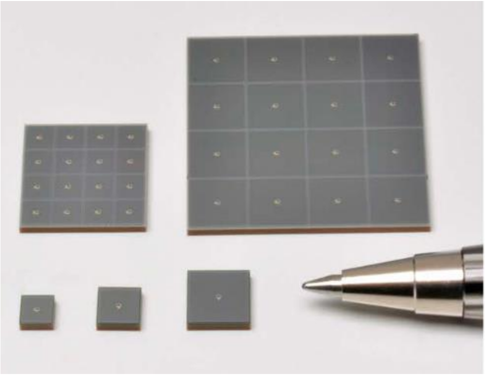
= “Geiger-mode multicell Avalanche PhotoDiode”

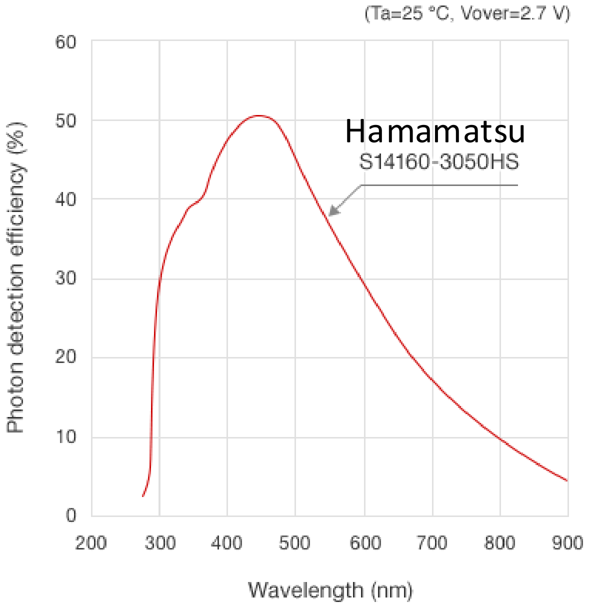
- An array of thousands of APDs.
- A photon falls in an APD and generate an avalanche of electrons-holes.
- We count how many APDs show an avalanche and we know how many photons have hit the SiPMT.
- Thus: a device to precisely measure number of photons with single photon response.

Silicon PM

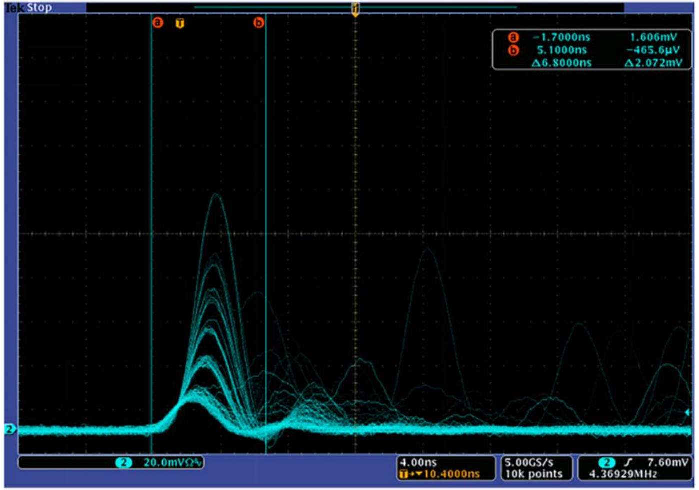
- GOOD SINGLE PHOTON RESPONSE
- HIGH QUANTUM EFFICIENCY (~50%)
- SIMPLE TO OPERATE: LOW VOLTAGE
- RELATIVELY CHEAP TO PRODUCE
- NOT AFFECTED BY MAGNETIC FIELDS
- ROBUST

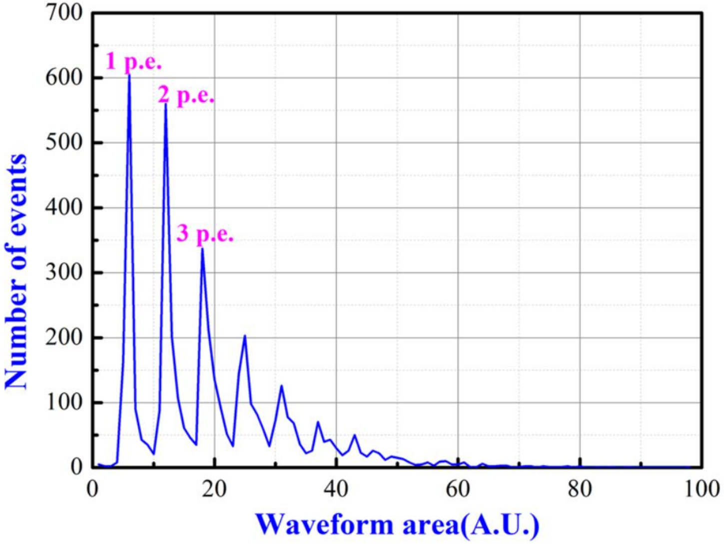
- HIGH NOISE RATE
- SMALL AREA





SiPM: Single photon resolution





Yang et al, Sci. Rep. 12, 15060 (2022)

- It is very useful to have a detector which can resolve the pulse produced by one single photon: allows to calibrate a signal in number of photons.
- SiPM have much higher single photon resolution than PMT or HPDs.

Summary

- Detecting a γ-ray implies making it interact with matter so that it generates lower energy secondary particles.
- We use these secondary particles to extract information (energy, direction, arrival time) about the primary γ-ray.
- We have learned how to detect these secondary particles: electrons and optical photons.

backup

Dynode voltage divider system

Photon in

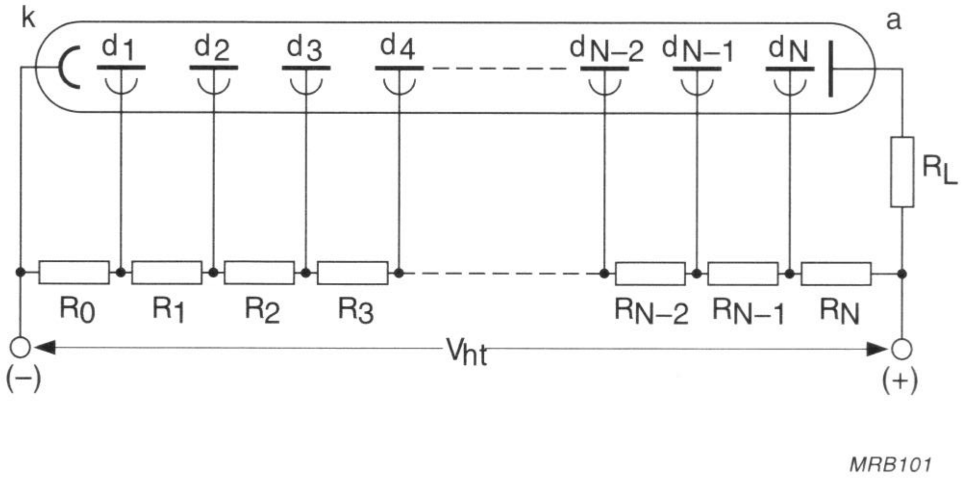
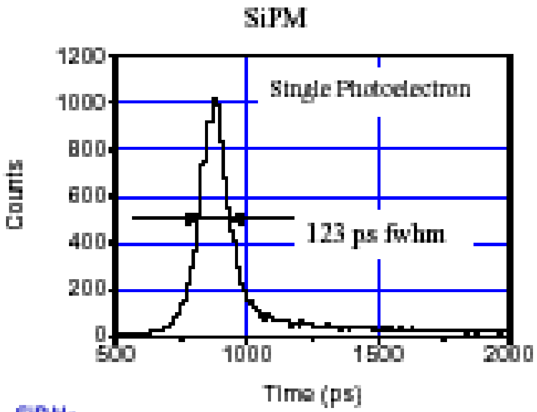
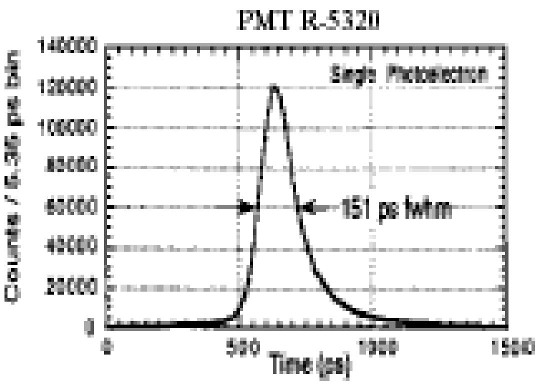


Fig.1.2 Voltage-divider high-tension supply

Electrical signal out

SiPM: fast time response





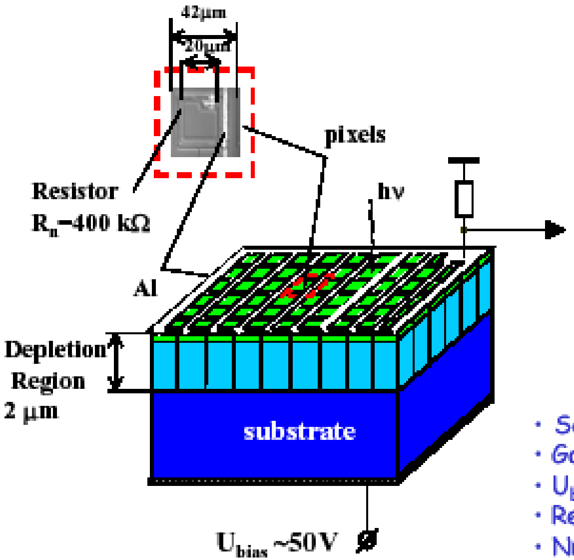
SiPM:

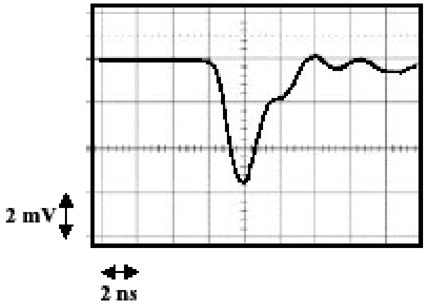
- position sensitive (~1 mm²)
- a single photon detection capability with background hits density : $2 \cdot 10^{-3}$ 1/ns·mm² (room temperature)
  $3 \cdot 10^{-4}$ 1/ns·mm² (-50°C)

- insensitive to magnetic field
- good time resolution (~50 ns rms)

FWHM: Laser (40 ps) + electronics (60 ps) => SiPM (100 ps)

SiPM: operating principle



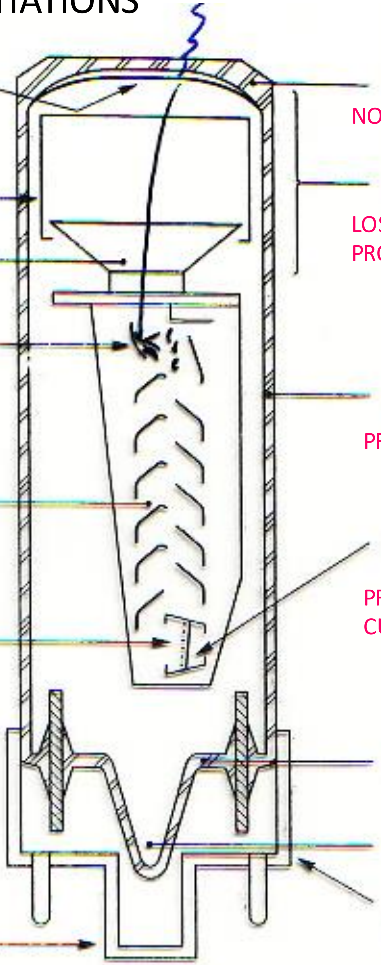


SiPM main features:

- Sensitive size 1x1mm² on chip 1.5x1.5 mm²
- Gain $2 \cdot 10^6$
- U_{bias}~50V
- Recovery time ~ 100 ns/pixel
- Number of pixels: 576
- Nuclear counter effect: negligible (due to Geiger mode
- Insensitive to magnetic field
- Dynamic range ~10^3/mm²

For further details see:
«Advanced study of SiPM»
http://www.slac.stanford.edu/pubs/icfa/fall01.html

A TYPICAL PMT: THE LIMITATIONS



photocathode: QE ≈ 25% IN PEAK REGION

window: NOT TRANSPARENT TO SHORT WAVE UV

input optics: LOSSY, EFF.≈ 30-90% (AT MOST)
PRONE TO EVEN WEAK MAGNETIC FIELDS

first dynode: INSUFFICIENT GAIN
LOSS OF SOME PHE (10-25%)

envelope: PRONE TO GAS DIFFUSION : HELIUM

multiplier: VERY HIGH GAINS POSSIBLE
VERY FAST, LOW NOISE
BUT NO FEEDBACK FOR GAIN STABILISATION

last dynode: PRONE TO AGEING, ION FEEDBACK
CURRENT LIMITATION

-BULKY

-EASILY DAMAGED BY HIGH LIGHT LEVELS

-NEEDS HV>~1000 V