Photosensors For Particle Physics

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HEPCAT Summer School
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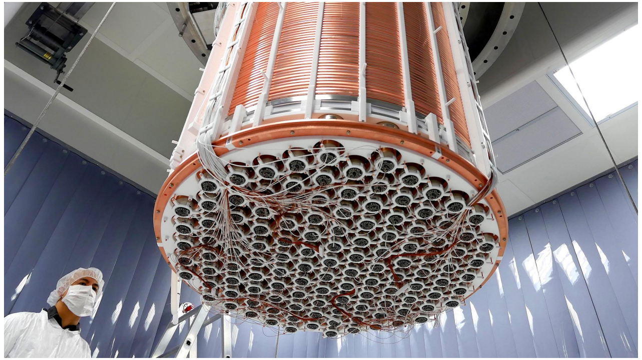
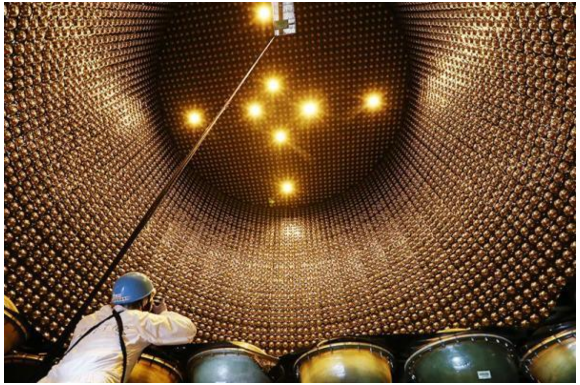
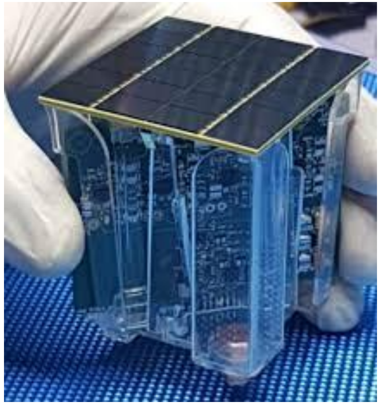
Introduction

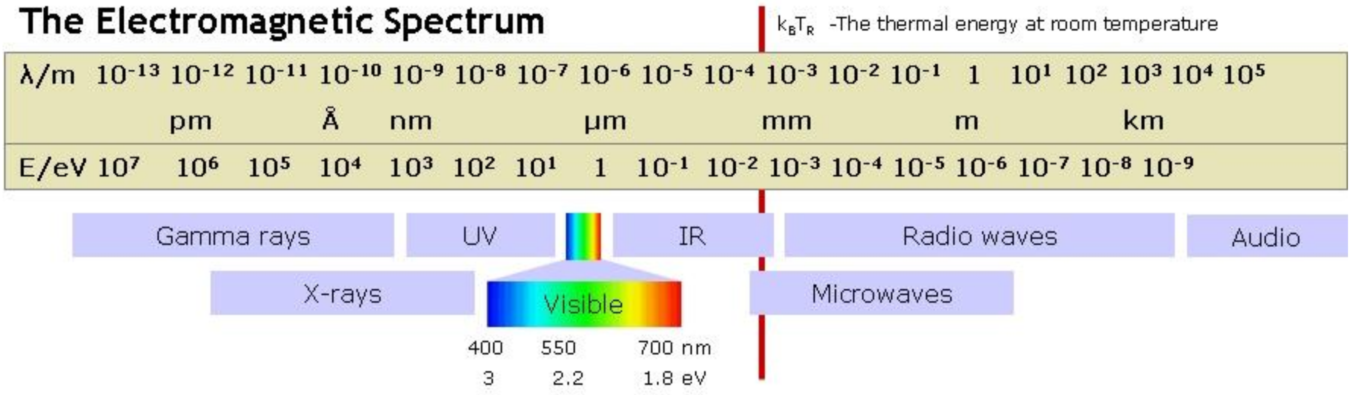
- Photosensors are the ”eyes” of particle physics experiments
- Brief discussion on the current technologies
- Discussion of the photosensors for future experiments







Detecting the electromagnetic spectrum

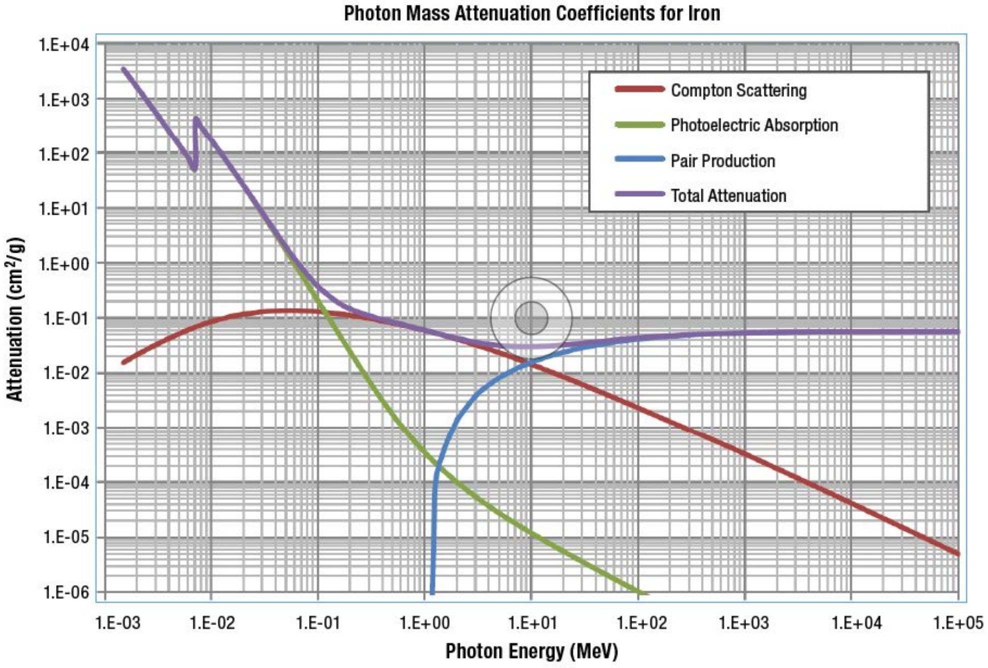


- Photosensors are designed to detect single photons from Microwave to UV range
- Photon signals are converted to electric signals (sometimes amplified)
- In particle physics, a common techniques to detect high energy particles (including gamma rays) is to convert them into a large number of photons or electroncs for detection.

Photodetection principles (IR to UV)

- Photon conversion to free electron
  - Photoelectric effect
  - PMT, microchannel plates
- Photon conversion to valence electron in materials
  - Semiconductor detectors
  - No intrinsic gain: photodiode, CCD
  - Amplified detectors: Avalanche photodiode, SiPM
- Photon conversion to heat (phonon)4
  - Bolometers
  - Superconducting detectors

Photodetection principles (x-ray to gamma)

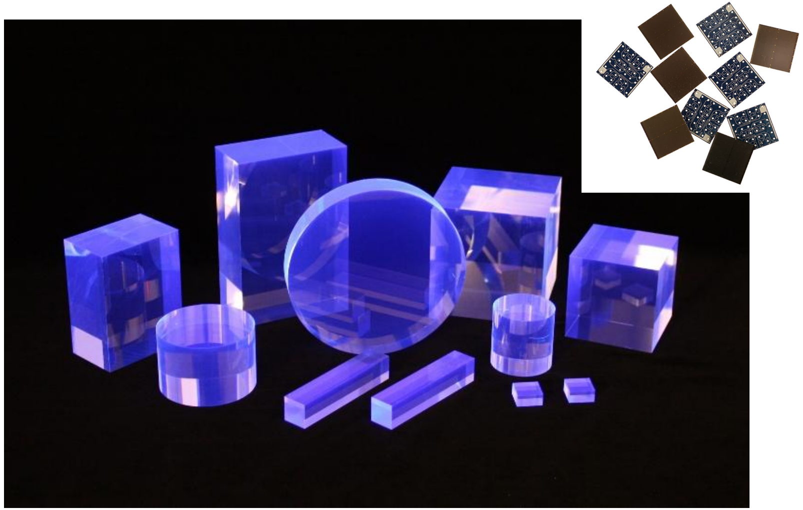


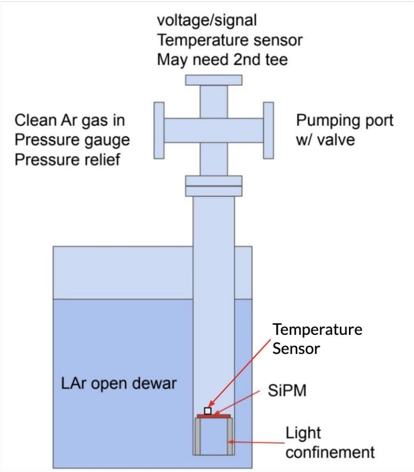
- Higher energy photons are more difficult to stop in materials
- The primary photon energy is converted into secondary quanta (photons or electrons)
- Many different detection techniques: scintillation detectors, semiconductor detectors, noble liquid detectors
- Similar detectors can be used for other high energy particles

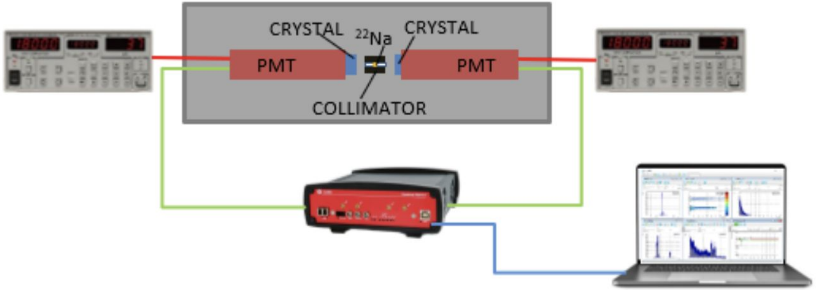
https://www.mirion.com/discover/knowledge-hub/articles/education/gamma-ray-absorption-in-matter-basic

Photosensors used in the Summer School

- Scintillator/SiPM Lab
- Liquid Argon Lab
- Inorganic Scintillator Lab

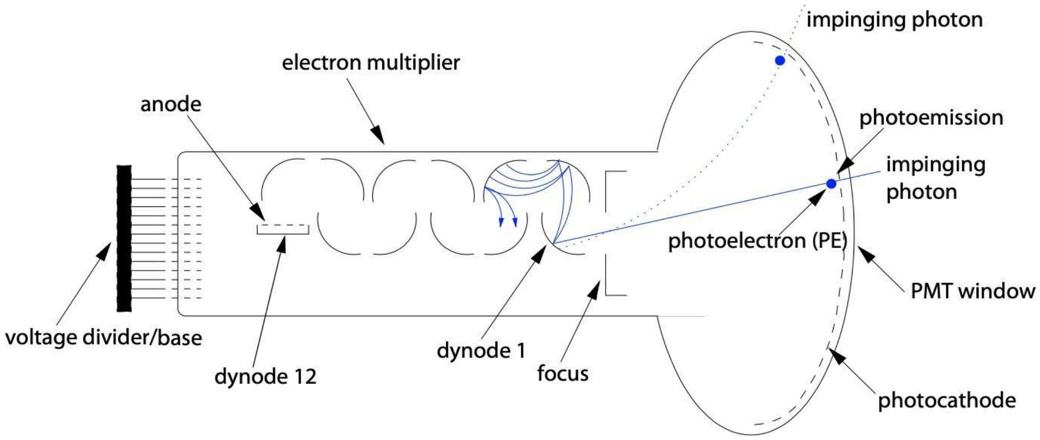


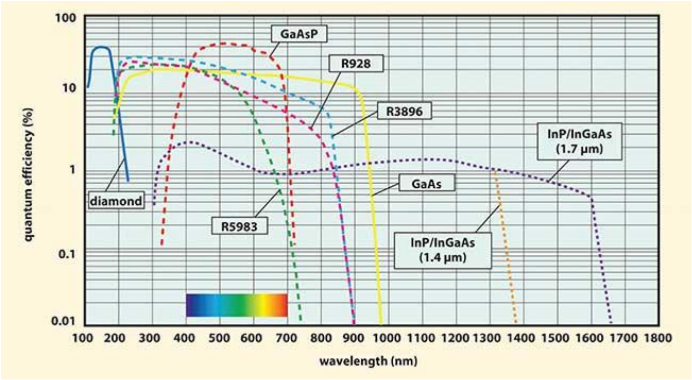




Photomultiplier Tubes (PMT)

- PMTs are vacuum-based devices with high gain and excellent timing resolution.
- They consist of a photocathode, dynodes, and an anode.
- PMTs are widely used in experiments requiring high sensitivity and single-photon detection.

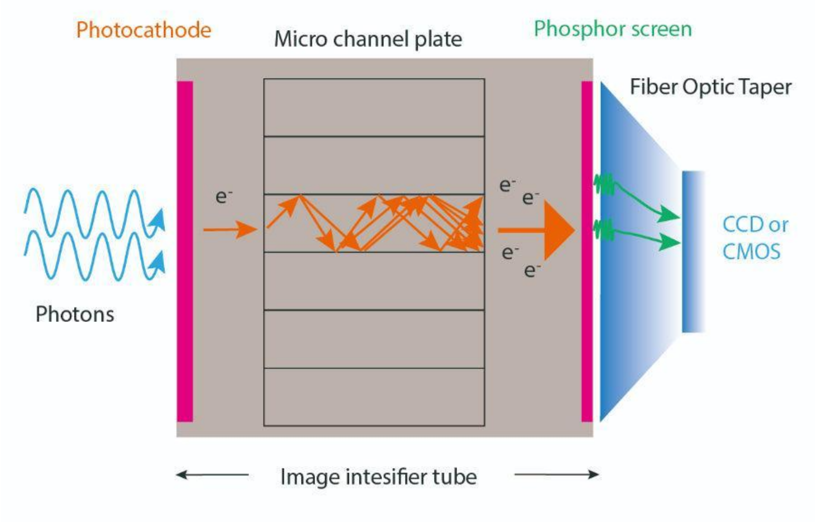


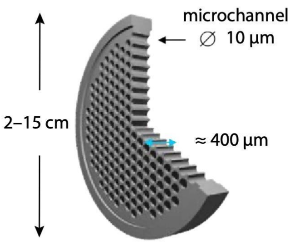


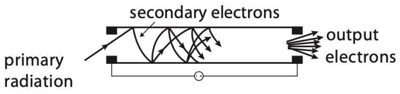
The spectral response of a photomultiplier covers a wide wavelength range.

https://www.photonics.com/Articles/Photomultipliers_Low-Light_High-Speed/a25145

Photon Counting Microchannel Plate (MCP)





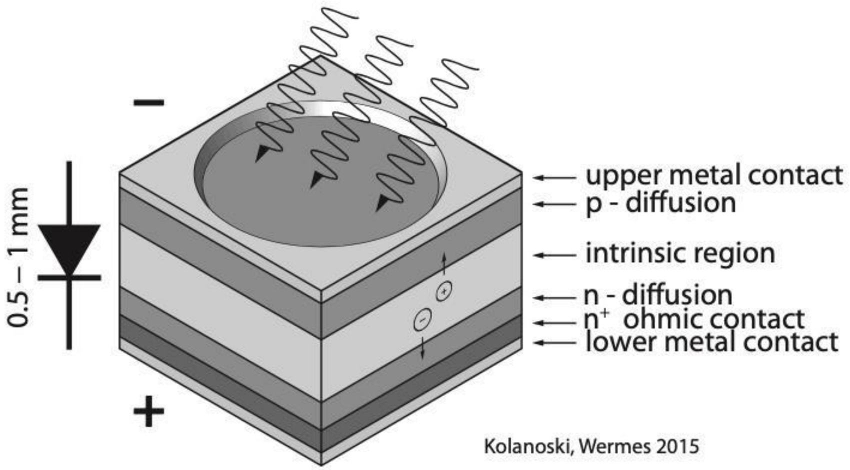


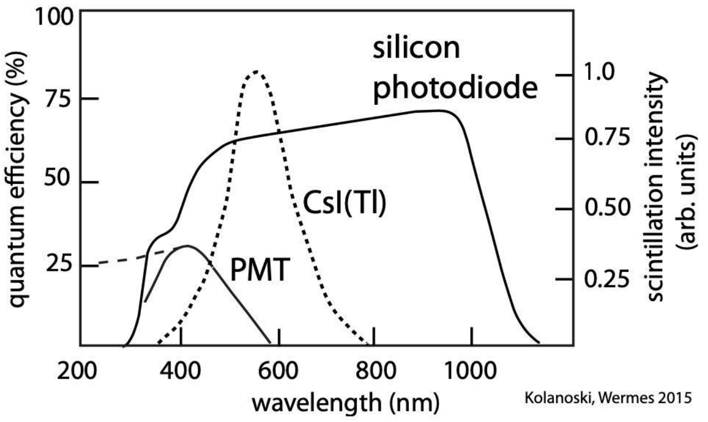
- Photo cathode similar to PMTs
- Electron amplification is replaced by microchannel plate.
- High position sensitivity, fast timing and insensitivity to magnetic field
- More expensive than PMTs in general

https://szphoton.com/products/mcp

Photodiodes

- Semiconductor device: absorbed photon creates an electron-hole pair
- PIN photodiode is most common
- Undoped region is placed between p- and n- doped regions
- Higher quantum efficiency than PMTs
- No intrinsic amplification

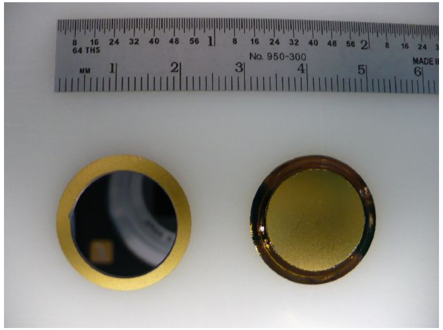




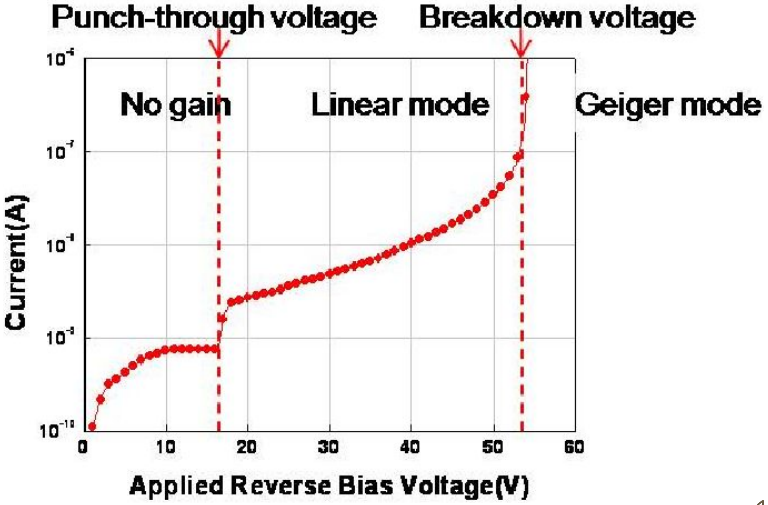
For comparison, a typical emission spectrum of a CsI (Tl) scintillation crystal (dotted line and right-hand y-axis).

Avalanche Photodiodes (APD)

- APDs are operated under a high reverse bias voltage, typically much higher than standard photodiodes.
- Electron signals amplified in high field regions
- Gain > 100 can be achieved.
- Can be run in linear mode (gain ~ 100) and Geiger mode (gain 10^5 – 10^6)

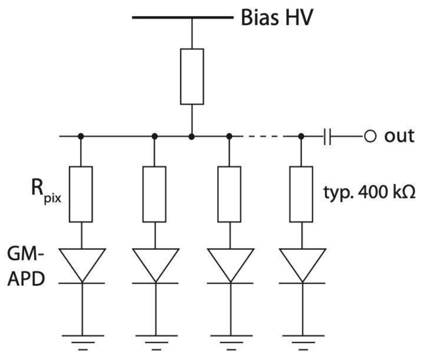


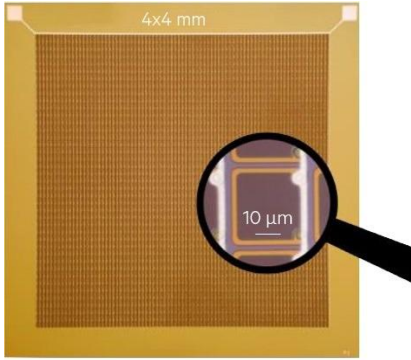
EXO-200 APDs

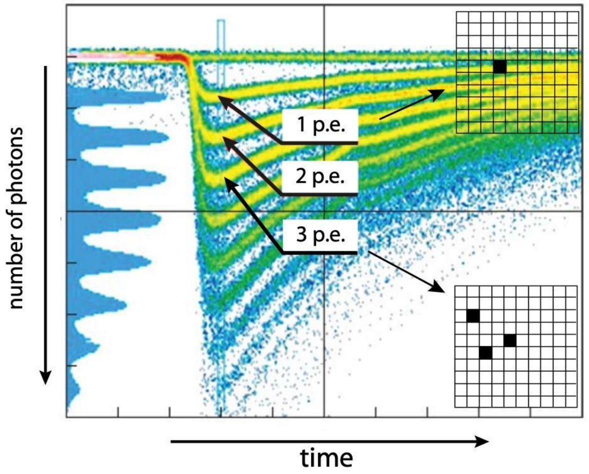


Silicon Photomultiplier (SiPM)

- SiPMs are solid-state devices with high photon detection efficiency and compact size.
- operated in (limited) Geiger mode at an amplification gain of about 10^6
- The pixel cells are small with typical dimensions in the range 15–70 µm
- Excellent photon counting ability
- High dark counts and correlated noise.

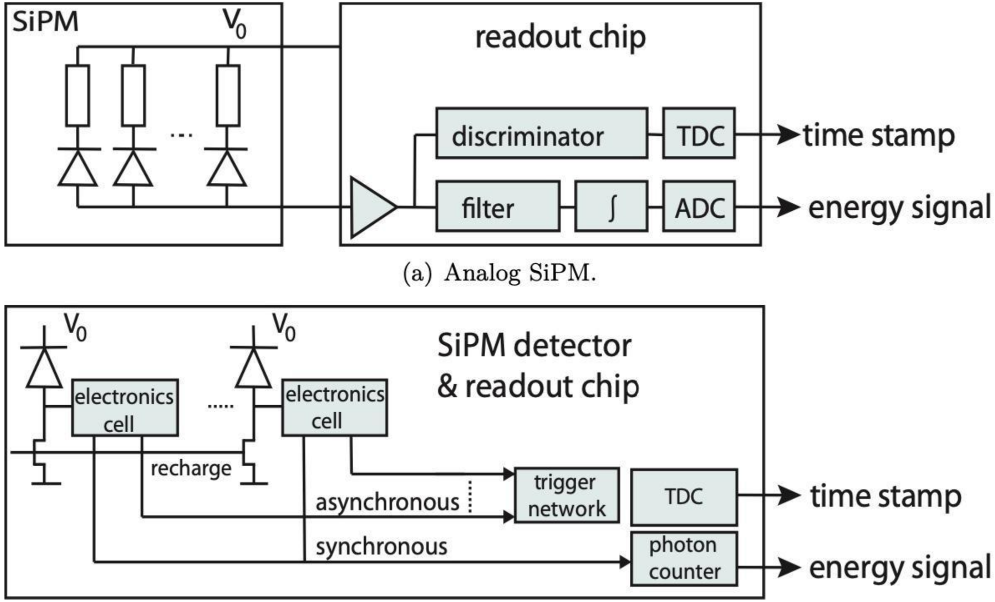






Digital SiPM

- Each cell is read individually
- **MOS transistor circuits** replace the passive quench resistors
- Allows for disabling individual noisy cells
- Could increase possible cross-talk
- First developed for high intensity, but can also detect single photons
- QE slightly smaller than analog due to transistors and other metals absorbing some photons

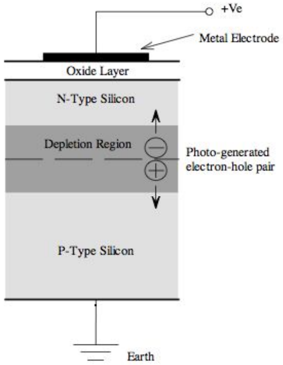


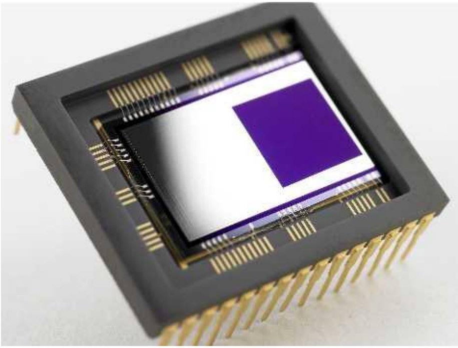
(a) Analog SiPM.

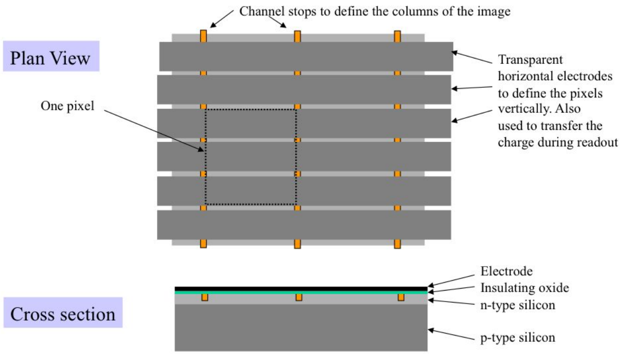
(b) Digital SiPM.

Charge Coupled Devices (CCDs)

- The electrons (or holes) are collected at each pixel capacitively
- Charge is integrated over a period of time
- Integrated charge signals are readout sequentially
- High quality image with Low noise, ~ 2 e, sub electron noise can be achieved in skipper CCD (multiple non-destructive reads)
- Dark matter detection and Astronomy spectrometer



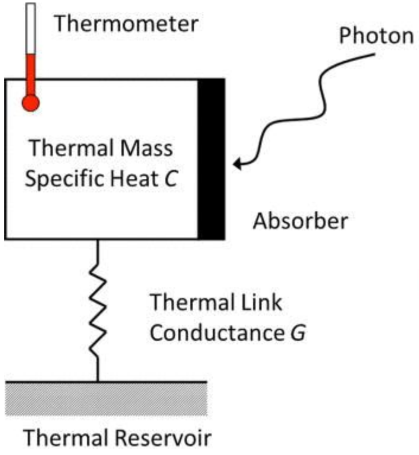


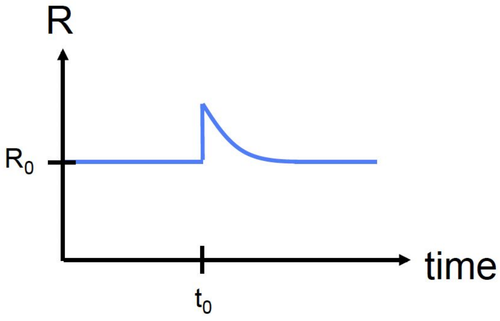


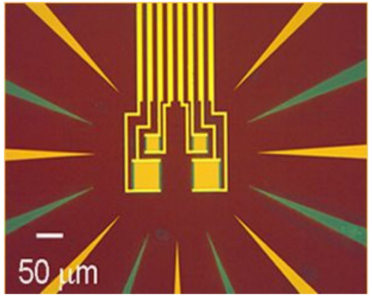
http://www.vikdhillon.staff.shef.ac.uk/teaching/phy217/detectors/phy217_det_structure.html

Bolometer (TES)

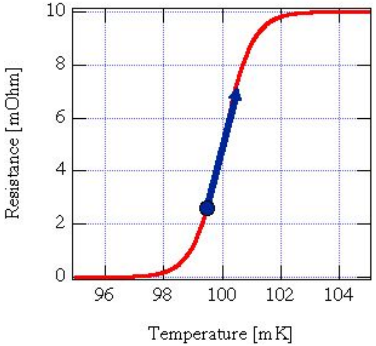
- Absorbed photon energy is converted into temperature change
- Transition Edge Sensor (TES) uses the sharp transition between normal and superconducting sates to measure temperature change
- Sensitive to a wide range of photon wavelength
- Slower response and requires low temperature operation







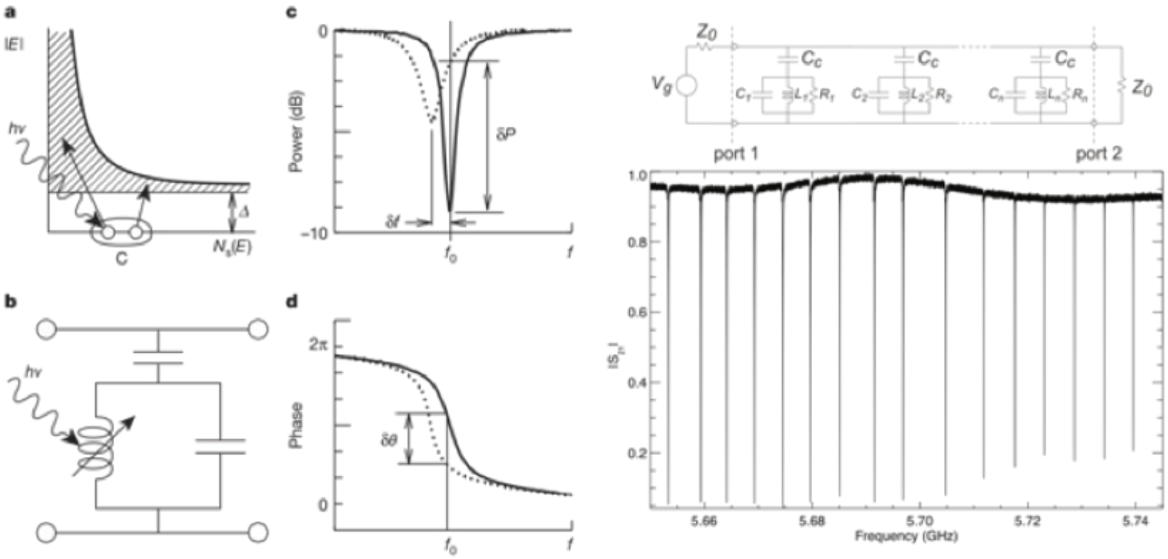
Transition Edge Sensor



https://en.wikipedia.org/wiki/Transition-edge_sensor

Kinetic Inductance Detectors (KIDs)

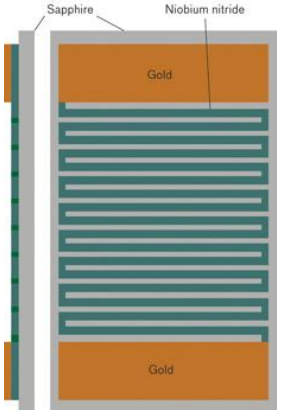
- Incoming photon breaks apart cooper pairs, causing the inductance of the detector changes
- The amplitude and phase of the resonance circuit changes can be measured to infer the energy of the incoming photon.
- Allowing high multiplexing capability in the frequency domain

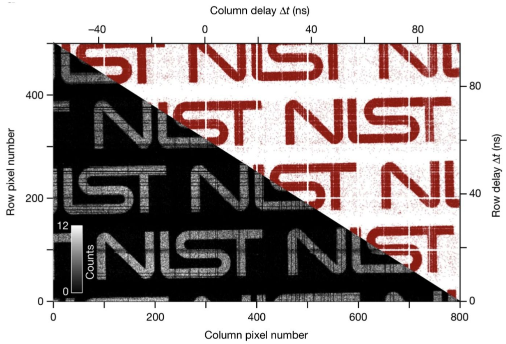


https://web.physics.ucsb.edu/~bmazin/mkids.html

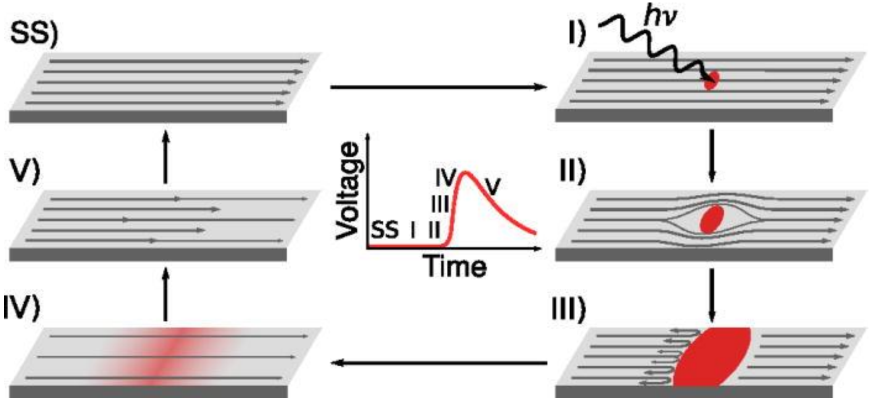
Superconducting nanowire

- When a single photon hits the nanowire, it locally breaks the superconducting state, creating a resistive "hotspot, ” and a voltage pulse.
- Can achieve near-unity efficiency in detecting single photons, especially in the infrared range.
- Very fast response and low dark rate
- A large array camera has been created by NIST in 2023





[A superconducting nanowire single-photon camera with 400,000 pixels]



Appl. Phys. Lett.. 2021;118(19). doi:10.1063/5.0045990

P5 Recommendation 2

New Exciting Initiatives for Particle Physics

a. **CMB-S4**, which looks back at the earliest moments of the universe to probe physics at the highest energy scales. It is critical to install telescopes at and observe from both the South Pole and Chile sites to achieve the science goals (section 4.2).

b. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

c. **An off-shore Higgs factory**, realized in collaboration with **international partners**, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined (see also Recommendation 6), the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US on-shore program in particle physics (section 3.2).

d. **An ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog, in coordination with international partners and preferably sited in the US (section 4.1).

e. **IceCube-Gen2** for study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter covering higher mass ranges using neutrinos as a tool (section 4.1).

Group exercise (Napkin designs)

a. CMB-S4

b. Re-envisioned second phase of DUNE

c. An ultimate Generation 3 (G3) dark matter direct detection experiment

d. IceCube-Gen2

Some suggested discussion points:

- What photosensor is the baseline design for the experiments?
- Are there alternative technologies that should be considered?
- What R&D should be conducted?
- If you building a new group, what prototypes would your build in your lab?

Group A: CMB-S4

Group B: DUNE, Far Detector 3

Group C: G3 Dark matter detector

Group D: Ice-Cube Gen2