PMTs and SiPM In High Energy Physics

A Abhishek
Cycle 38
University of Siena

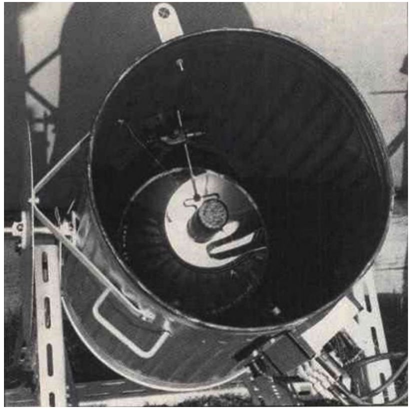
UNIVERSITÀ DI SIENA 1240

Contents:

- Cherenkov Astronomy - MAGIC Telescopes
- PMTs and SiPMs
- Points of comparison
- Conclusions from literature
- Summary

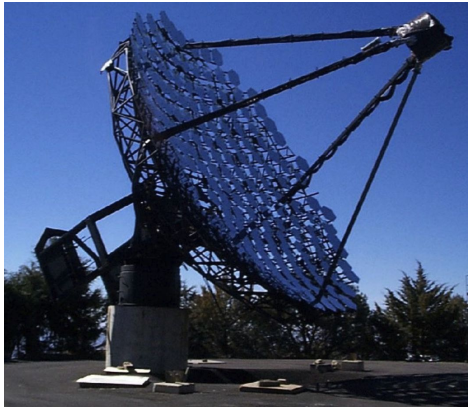
Cherenkov Astronomy - A quick history

- 1937 - Pavel Cherenkov, Igor Tamm, Ilya Frank:
  - Charged particle moving at a high speed inside a medium emits anisotropic radiation in the forward direction.
- 1953 - Galbraith and Jelley
  - Tested and confirmed the Cherenkov pulses coming from air shower in the atmosphere. Marked the beginning of atmospheric air Cherenkov technique.
- 1960s - First generation Cherenkov telescopes:
  - Set up many telescopes with mirrors [~O(meters)] and PMTs.
- 1968 - Second generation telescopes:
  - 10m Whipple telescope which played a major role in gamma-ray astronomy. Stereoscopic imaging system, parametrization of measured Cherenkov images.
- Late 1990s - Third generation telescopes:
  - MAGIC, CANGAROO, HESS, VERITAS and the future CTAO



Detector of Galbraith and Jelley

10m Whipple Telescope



Chudakov’s telescopes in Crimea

HEGRA Array, La Palma

Image source: Wikipedia

Img credits:
https://www.mdpi.com/2218-1997/8/4/219

MAGIC Telescope

- La Palma, Canary Islands
- Two 17m diameter telescopes (85m apart)
- Imaging Cameras consisting of PMTs

To study:

- Cherenkov light radiated in Extensive Atmospheric Showers (EASs)
- EASs occur in Earth's atmosphere at the height of 10–20 kms
- EASs are produced by energetic cosmic rays or gamma rays impinging the Earth.
- Cherenkov radiation is peaked in the blue-UV, has a duration of few nanoseconds

PMTs and SiPMs

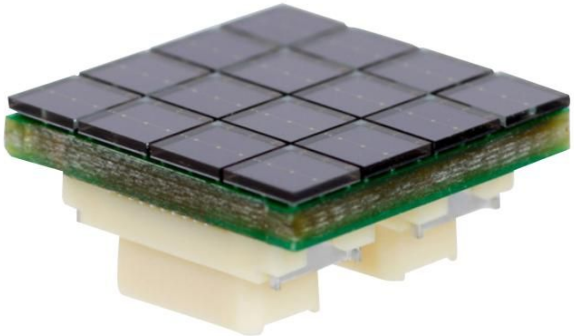


Image source: Wikipedia

Photomultiplier tubes

- Detectors of light in the range of ultraviolet, visible and near-IR.
- These detectors multiply the current produced by incident light by a very high number, enabling individual photons to be detected even when the incident flux is very low.

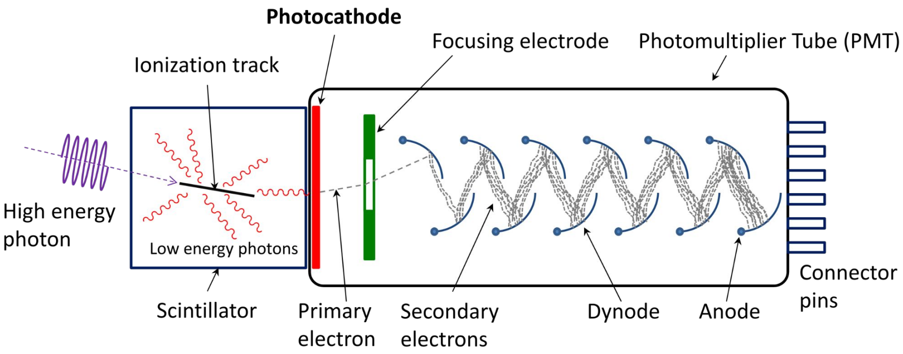


Image source: Wikipedia

PMT structure

- Photocathode emits phe-
- Dynodes amplifies number of e-
- Anode captures the amplified e- and produce the output current signal.

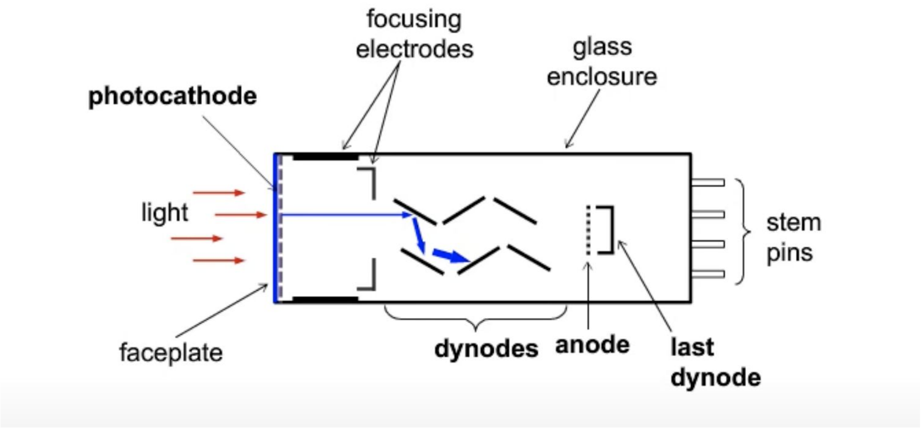
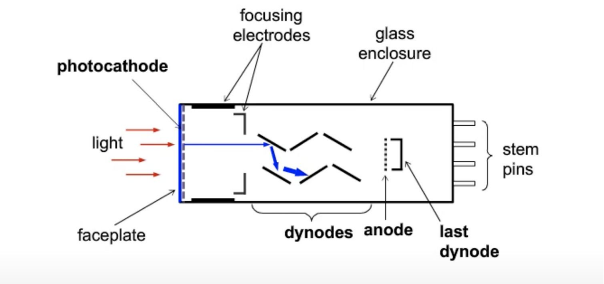


Image source: Wikipedia

Photomultiplier tubes

- The amount of Cherenkov photons reaching the pixels is reconstructed from the signal charge in the PMTs
- Reconstruction is done by analysing the ultra-fast sampled signal pulse.
- Extraction: summing the ADC counts in a certain time-window.
- This provides a rough signal charge per readout channel.
- After calibration process, these are converted into the number of photons at the camera plane.



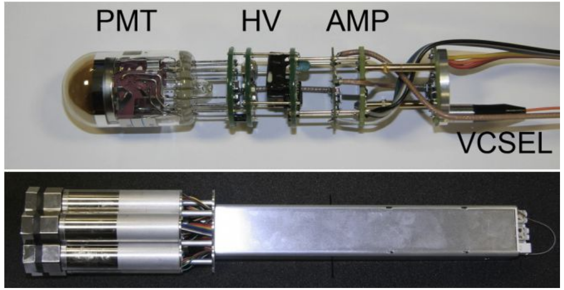


Image credit: A.Hahn et al

ADC: analog-to-digital converter

Silicon Photomultipliers

- SiPMs are being considered for the next generation of cameras for telescopes.
- Some smaller-size IACTs like FACT or proposed SST and SCT prototypes use SiPMs.

Image source: Wikipedia

SCT: Schwarzschild-Couder Telescope

Silicon Photomultipliers

- SiPMs are photosensors composed of microscopic diode cells assembled in matrices.
- These SiPMs are based on single-photon avalanche diodes
  Implemented on common silicon substrate.

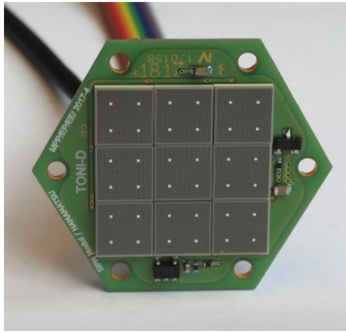


Image source: Wikipedia

SiPM structure

- Avalanche photodiodes and Rq (Quenching resistors)
- $\Delta V = V_{BIAS} - V_{BD}$
- ΔV - **Overvoltage**

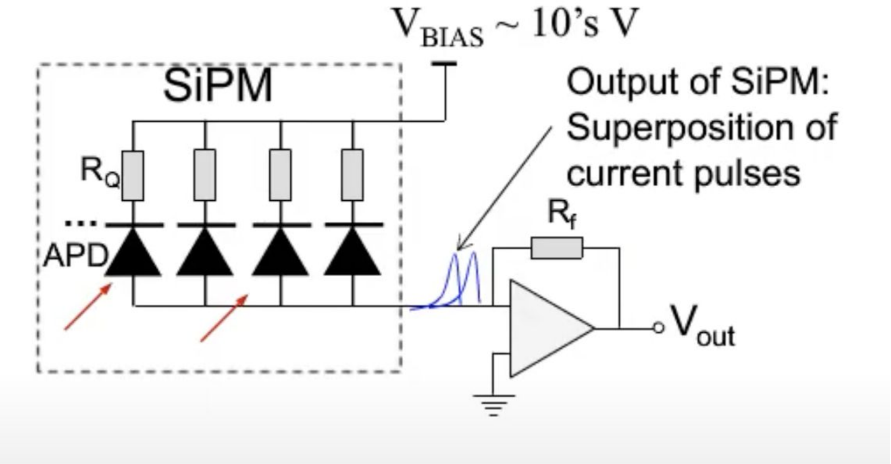


Image source: Hamamatsu resources

MAGIC Telescope

- We will look at the difference between PMTs and SiPM based on studies done with MAGIC. [A. Hahn et al]

  "Direct Comparison of SiPM and PMT Sensor Performances in a large-size imaging air Cherenkov telescope"

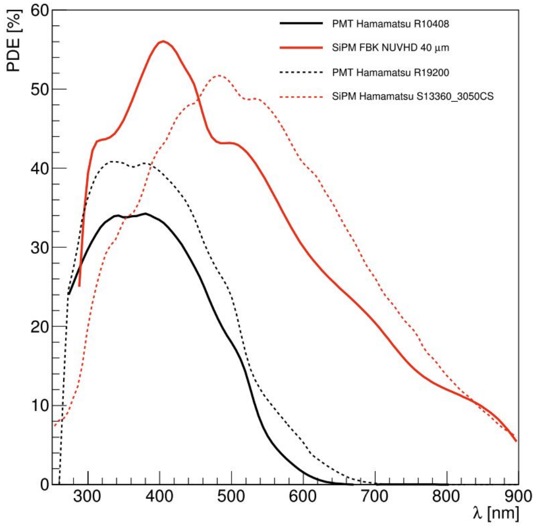
- Studies done by developing a SiPM prototype detector module and installing in the MAGIC telescope camera

Points of comparison:

- Spectral coverage
- Noise
- Signal to noise ratio

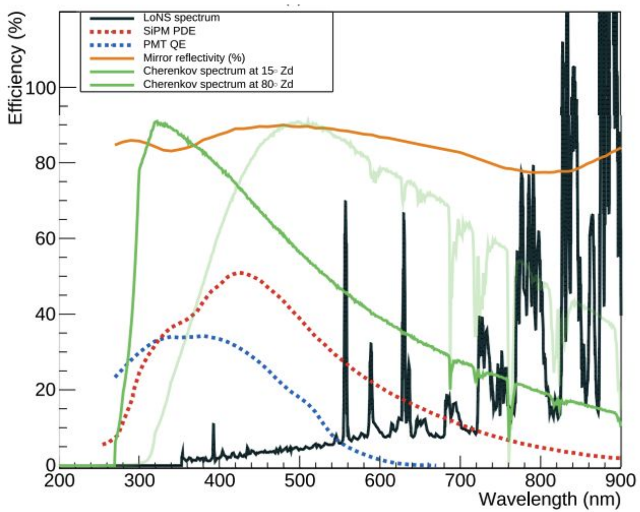
Peak photon detection efficiency

- The overall conversion factor from photons to the number of detectable photoelectrons is called photon detection efficiency (PDE)
- In C.Arcaro et al. They studied the PDE for current PMTs and proposed SiPMs.
- Implies SiPMs have peak PDE at larger wavelengths than that of PMTs.



Peak photon detection efficiency

- In A.Hahn et al. They performed similar studies and compared with spectra of light of night sky and Cherenkov from air showers reaching the camera.
- They found the new SiPMs will detect 60-70% more Cherenkov Photons than MAGIC PMTs.



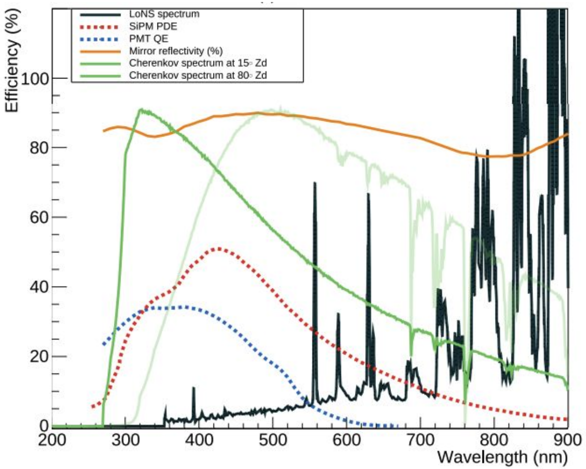
Spectral coverage

PMT

- Cover smaller range, we need to use different kinds of PMTs for different wavelengths.

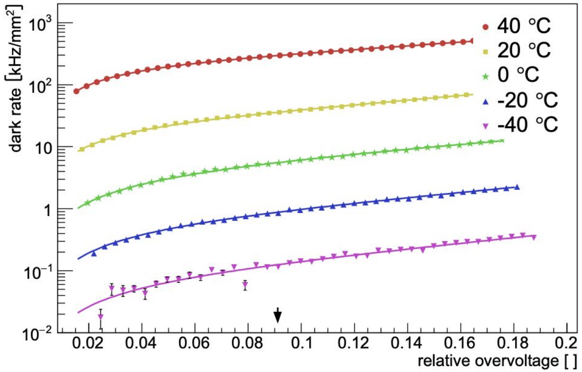
SiPM

- Have a larger range. Unique SiPM can cover from UV to NIR.



Noise - Dark counts

- Dark counts: Output current when there is no input light are called as to be produced by dark counts.
- PMTs: thermally emitted electrons from the photocathode (also from dynodes but less significant) can cause dark counts, which increases with temperature.
- SiPMs: dark counts rate depends on Temperature and also the overvoltage.



Otte et al.

Noise: Afterpulsing

- PMTs: the afterpulsing can be caused by ion-feedback or by scattering of electrons at the first dynode. Resulting in a second avalanche. Creates issues with timing measurements.

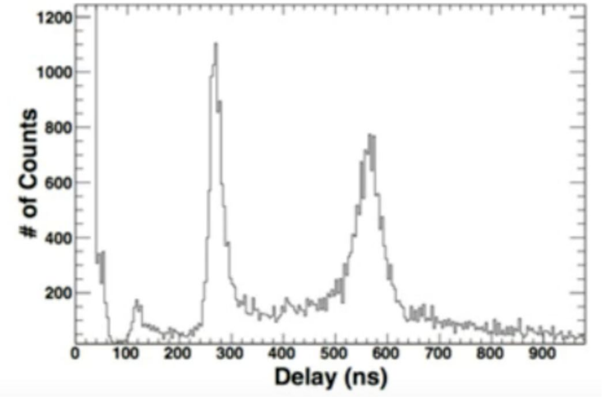


Image source: Hamamatsu resources

Noise: Afterpulsing

- SiPM: During the discharge, some e- are trapped, when gets released they can create a secondary avalanche.
- SiPMs also have optical cross-talks contributing to noise. The discharge can sometimes produce photons capable of triggering neighbouring microcells.

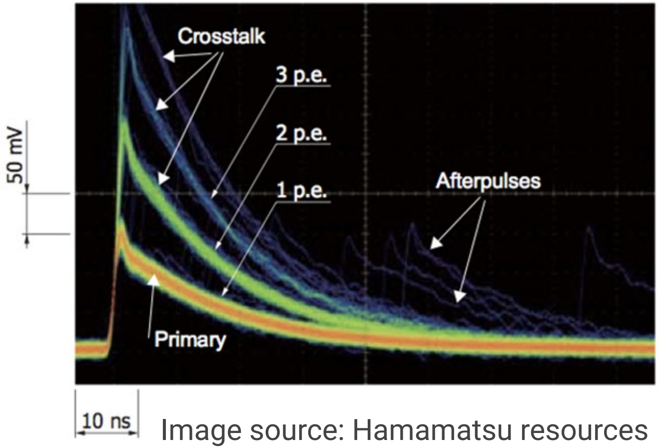
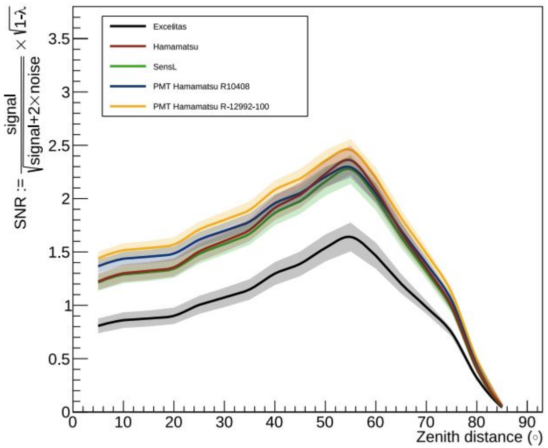


Image source: Hamamatsu resources

Signal-to-Noise ratio (SNR)

- Comparison between PMTs and the new SiPMs w.r.t altitude above the horizon (90 - Zd) of observations
- At low Zd PMTs show slightly higher SNR.
- At medium to high Zd, the SNR of the new PMT and SiPMs is comparable.
- SNR of SiPM also needs to account for the optical cross-talk, modelling which could be tricky.



C.Arcaro et al.

Conclusions of A. Hahn et al.

- SiPMs have comparable or even better peak PDE than the best classical PMTs, due to the strong background from LoNS (noise) and spectral differences between the sensors, this alone is not an indication of their better performance
- SNR is mostly comparable PMTs and SiPMs demonstrate very similar SNRs across all zenith distances, except for marginally higher SNR of SiPMs in the range between ~ 45° and ~ 65°

MAGIC Telescope

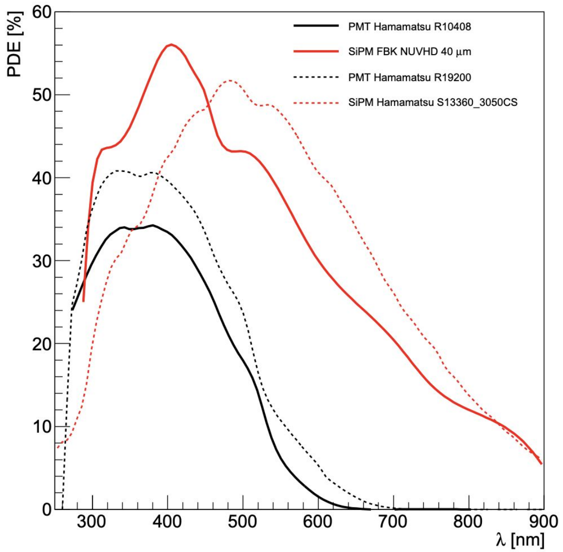
- We will look at the difference between PMTs and SiPM based on studies done with MAGIC. [Arcaro et al]

  “Performance Boost of a 17 m class Cherenkov telescope with a SiPM-based camera”

- Investigated the performance of IACTs like MAGIC by applying generalized simulations

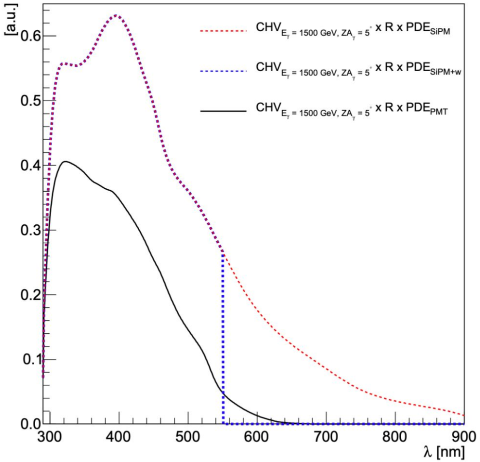
Conclusions of C. Arcaro et al.

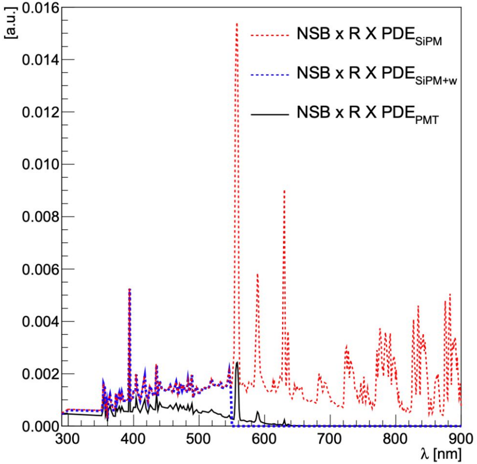
- Shown exemplary PDEs of PMTs and SiPMs showing that the typical sensitivity of SiPMs to red photons is higher w.r.t. that of PMTs



Conclusions of C. Arcaro et al.

- SiPMs would allow for a factor 2.2 to 2.5 higher light yield regardless of the energy of the primary. This strong signal boost is also accompanied by an even stronger factor of 5.3 of more light from the NSB

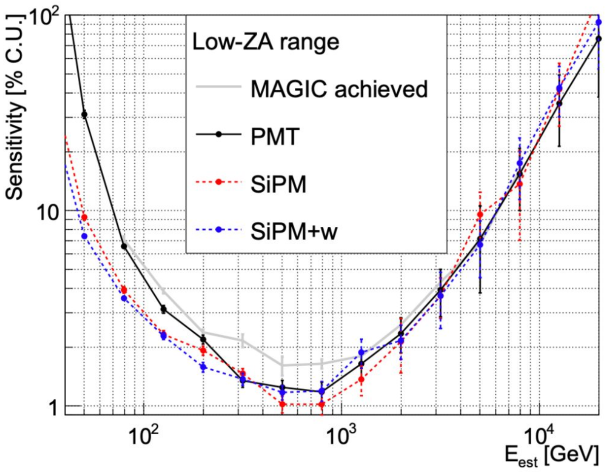


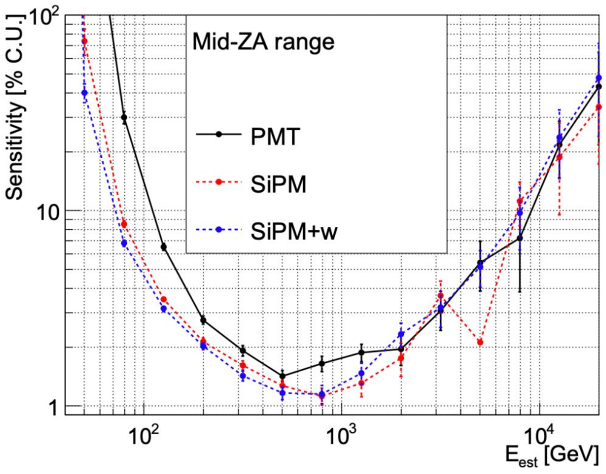


R: mirror reflectivity term

Conclusions of C. Arcaro et al.

- A SiPM based camera would grant a factor of about three higher sensitivity at 50 GeV (for low zenith-angle observations), with decreasing improvement for higher energies

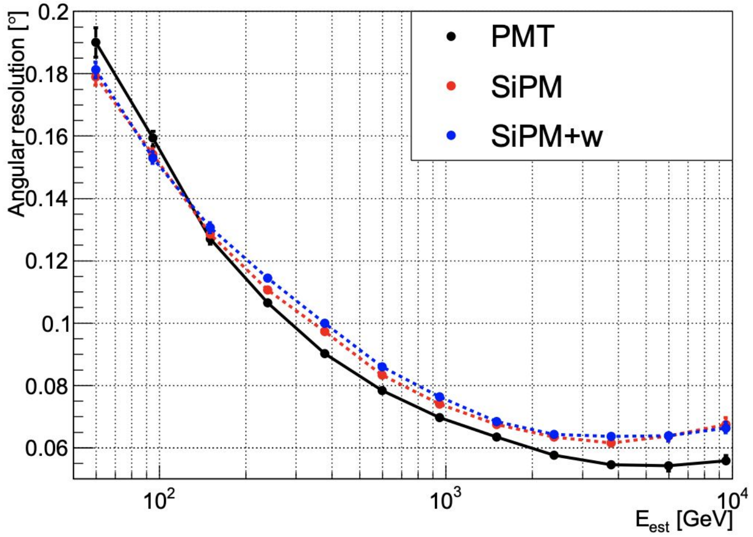




R: mirror reflectivity term

Conclusions of C. Arcaro et al.

- A SiPM camera will also display slightly better at low energies, angular resolution, however at higher energies the effect is inverted



There is a very little difference in the angular resolution with or without using filters. This shows that, except of the lowest energies, the reconstruction of the shower direction is still not strongly limited by the amount of light received by the telescopes (first conclusion), or the ”cleaningness” of the image, but by other factors (such as geomagnetic field deflection of the shower, optical PSF of the instrument, pixelisation of the camera, . . .)

R: mirror reflectivity term

Summarizing:

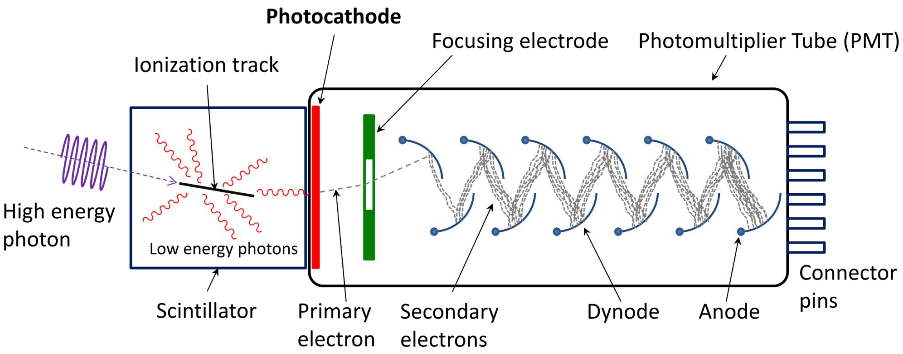
- Though SiPM has better peak PDE than PMT but we also have to consider the strong background from LoNS and spectral coverage of both.
- Signal to noise ratio is more or less comparable, slightly higher for the new generation SiPM at large zeniths
- Increased background counts from LoNS due to wider spectral coverage of SiPM could create issues if not modelled well.
- Further studies based on SiPM usage in smaller telescopes and differences compared to the large telescope would be helpful.

Thank you.

Backup slides →

Photomultiplier tubes

- Detectors of light in the range of ultraviolet, visible and near-IR.
- These detectors multiply the current produced by incident light by a very high number, enabling individual photons to be detected even when the incident flux is very low.



MAGIC uses Hamamatsu PMTs with 6 dynodes and hemispherical photocathode.

Issues with SiPM

- Cell-recharging: At high background rates, G-APDs can be triggered before fully recovering from a previous discharge.
- This would increase the gain variance and lower the mean gain of the device.
- They calculated Poissonian probability of another LoNS photon hitting the same cell within the recharging time - around 0.5 - 1.5%
- This will result in reduced charge resolution and increased systematic uncertainties for observations under strong moonlight.
- Comparing the trigger rates of the Hamamatsu SiPMs and neighboring PMTs we found that the SiPMs measure 4.3 times more LoNS. From the shower image analysis, we found that 2.08 ± 0.09 times more Cherenkov photons were detected by the SiPMs.

Defn:

- Optical crosstalk: When a pixel is fired by either an incoming photon or by a thermally generated electronhole pair, hot carriers in the avalanche breakdown induce emission of IR photons that in turn may trigger further avalanches in nearby pixels. This stochastic process, called optical crosstalk, is characterized by being nearly instantaneous, and its probability is proportional to the SiPM gain.
- Operating at low bias voltage would diminish significatively crosstalk effects, but at the expense of degrading the photon-detection efficiency.
- The incorporation of isolation trenches around each pixel, successfully reduces optical crosstalk.

- At conditions where only one pixel is expected to be excited simultaneously (e.g., dark counts), crosstalk results in output pulses with amplitudes twice or several times the amplitude of a single triggered pixel
- The crosstalk probability ε is usually defined as the rate of dark counts with crosstalk (two or more fired pixels) divided by the total dark-count rate.

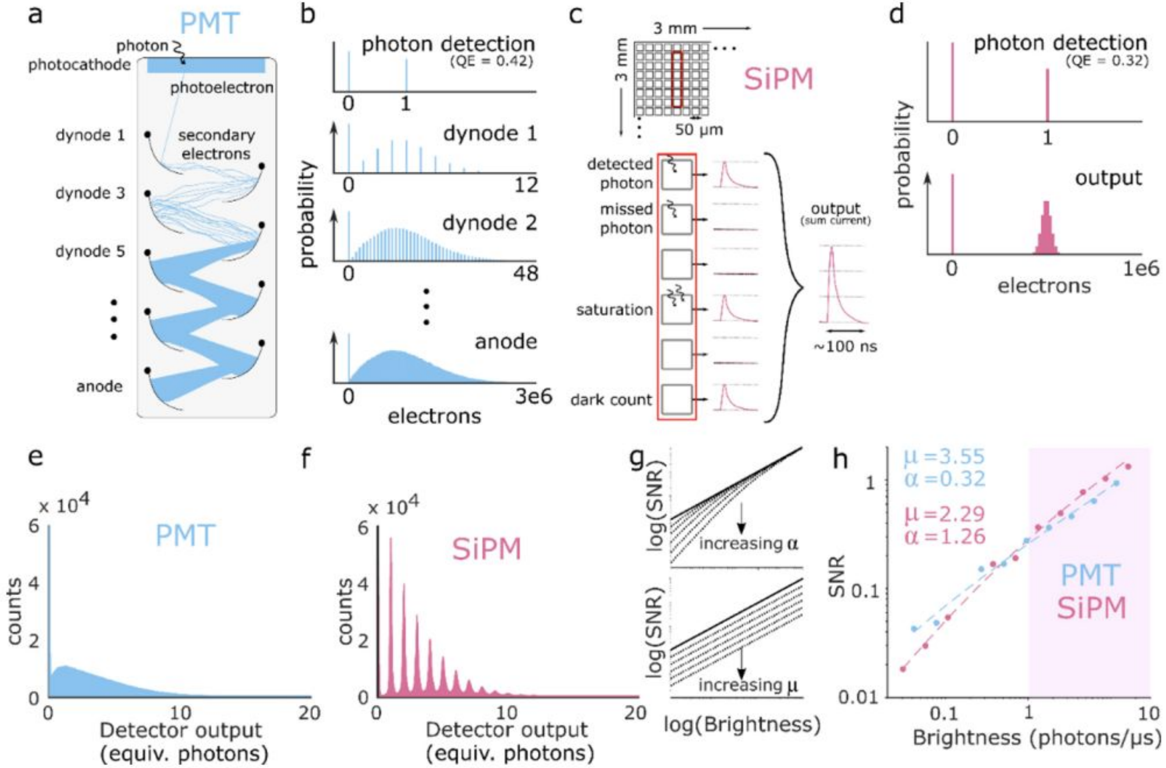
Defn:

Quantum efficiency (QE, or ρ) is the most obvious way to describe cathode photoemission. It is defined as the ratio of the number of photoelectrons emitted by the cathode to the number of photons incident on the window, and is usually expressed as a percentage.

The gain or current amplification, G, of a PMT is the ratio of the anode current to the photocathode current. It varies as a power of the supply voltage (usually >5) and: G2/G1 = (V2/V1)^{alpha N} where G2 and G1 are the gains at supply voltages V2 and V1 respectively, alpha is a coefficient (0.6 to 0.8) set by the dynode material and geometry, and N is the number of dynodes.

The ratio of the number of incident photons to the number of electrons collected at the anode is called charge linearity. The proportionality between incident flux and anode current is called current linearity.

Working principle



Working principle

PMT operating principle. The photocathode converts a photon into a single electron with high efficiency. The electron is accelerated under high voltage, striking a series of dynodes. Each collision releases several more electrons, exponentially amplifying the signal. b. PMT gain variability. Simulated electron count distributions at different stages of PMT amplification. Stochastic variation in small integer numbers of electrons collected from the first dynode produces large variance in pulse heights, a form of multiplicative noise. Gain was modeled as Poisson. c. SiPM operating principle. An array of SPADs make up the SiPM. Each SPAD behaves like an ‘all or none’ switch, producing a stereotypical current pulse when one or more photons are absorbed. The output is the sum of the individual SPAD currents. Avalanches also occur without photon absorption, producing dark counts, a form of additive noise. d. SiPM gain variability. Simulated electron count distribution for a SiPM. Saturating amplification in each SPAD makes SiPM pulse heights highly uniform, with low multiplicative noise.