Silicon Photomultipliers

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Materials

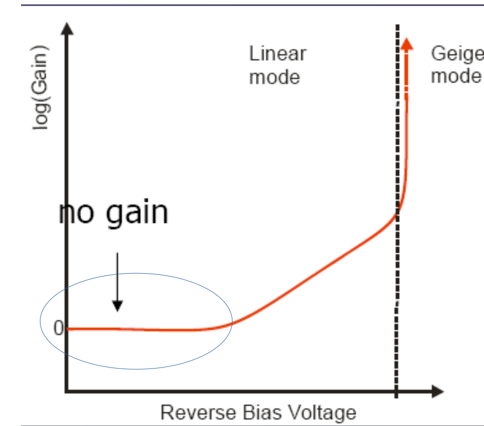
- I stole most of the contents of this presentation from:
- Lecture by Erika Garutti (Uni Hamburg):
  - https://www.desy.de/~garutti/LECTURES/SiPM.pdf
- Chen Xu PhD thesis (Uni Hamburg, in Erika’s group):
  “Study of the Silicon Photomultipliers and Their Applications in Positron Emission Tomography”
  - https://inis.iaea.org/collection/NCLCollectionStore/_Public/45/076/45076521.pdf
- My PhD thesis (DESY/Uni Wuppertal):
  ”Scintillator Calorimeters for a Future Linear Collider Experiment”
  - https://inis.iaea.org/collection/NCLCollectionStore/_Public/47/109/47109309.pdf
- Good search terms: CALICE AHCAL/ScECAL, Belle II KLM/CLAWS, CMS BTL/HGCAL, endotofpet-us
- Spec sheets of Hamamatsu, KETEK, SensL SiPMs

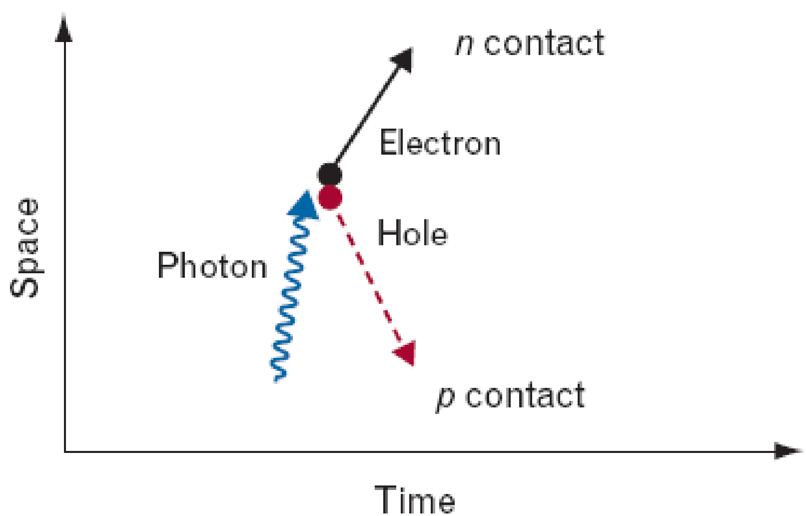
Contents

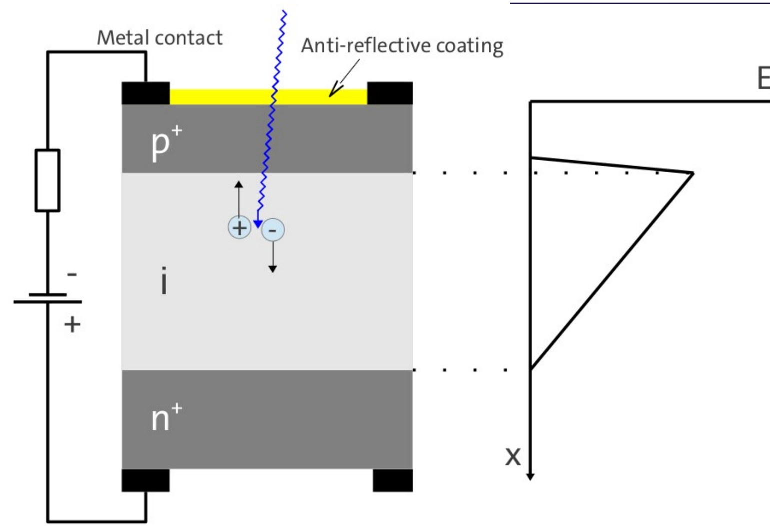
- Silicon diodes as photo sensors
- Silicon photomultipliers and their figures of merit
- Some applications and tips on simulation

Signal formation in Silicon Diodes

- Charge/hole separation from ionisation: photon or traversing charged particle
  - Drift towards electrodes, can be measured as charge current
- No inherent amplification:
  one photon → one e/h pair → signal of 1e and
  - Works for large photon fluxes (solar panels..)
- Revere bias adjusts thickness of active depletion layer
  - intrinsic (low-)doped layer increases active volume

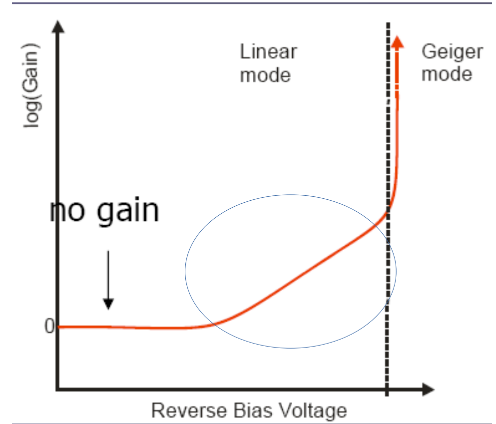


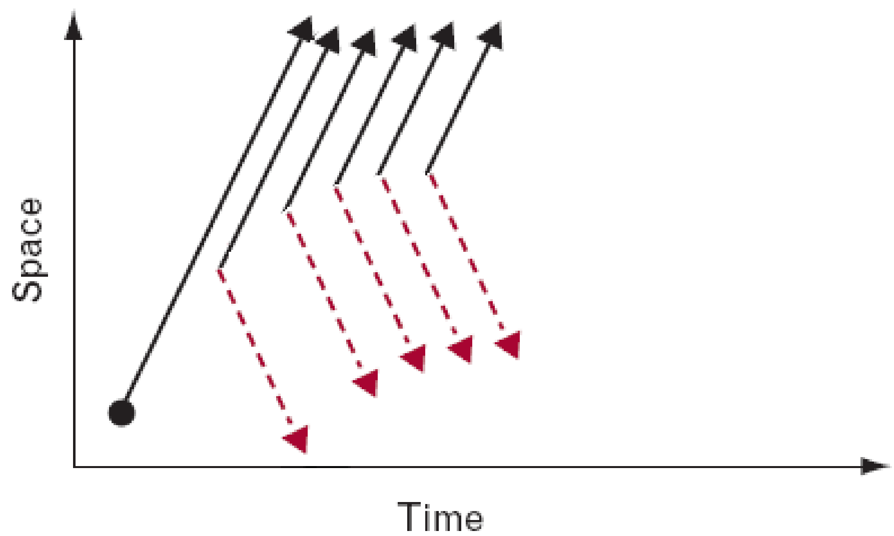


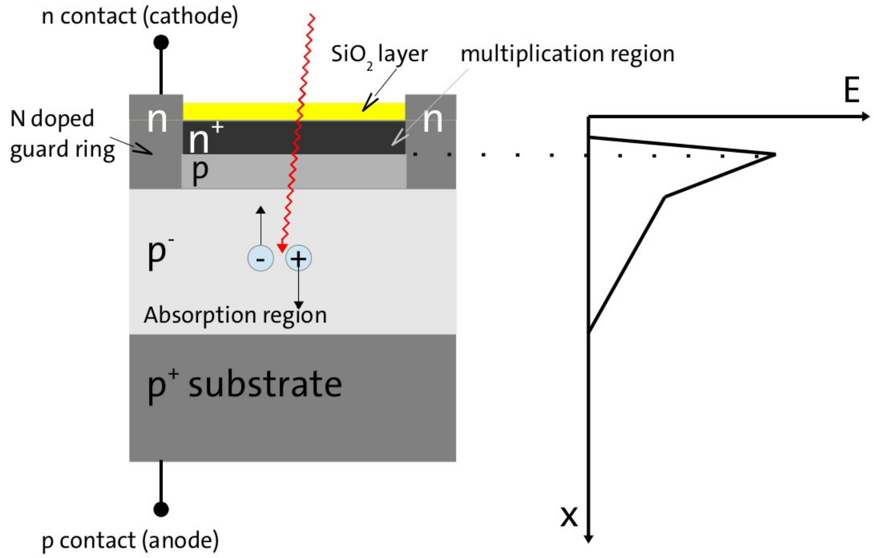


Avalanche (Photo) Diode - APD

- Increasing reverse bias beyond full depletion: Amplification from impact ionisation during drift
  - Gain ~10-1000, “linear mode”
  - Doping profile creates layer with strong field
- Characteristics strongly depend on temperature and bias, difficult to operate

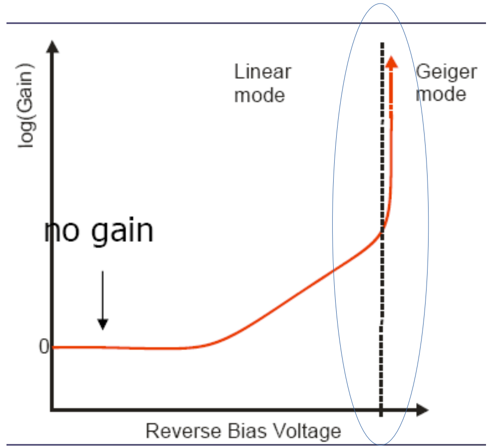


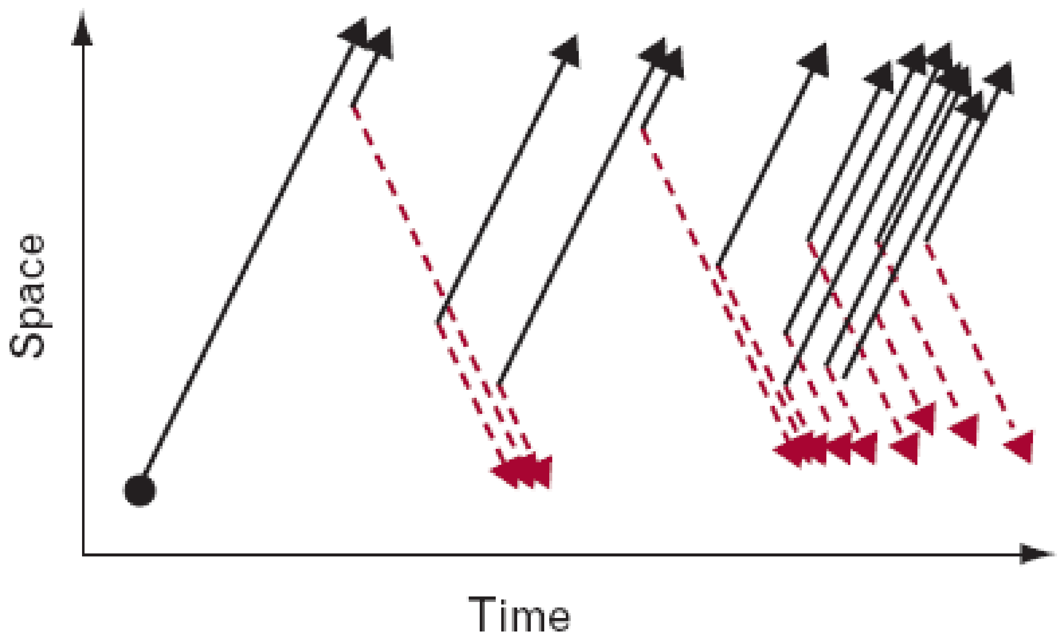




Single Photon Avalanche Diode - SPAD

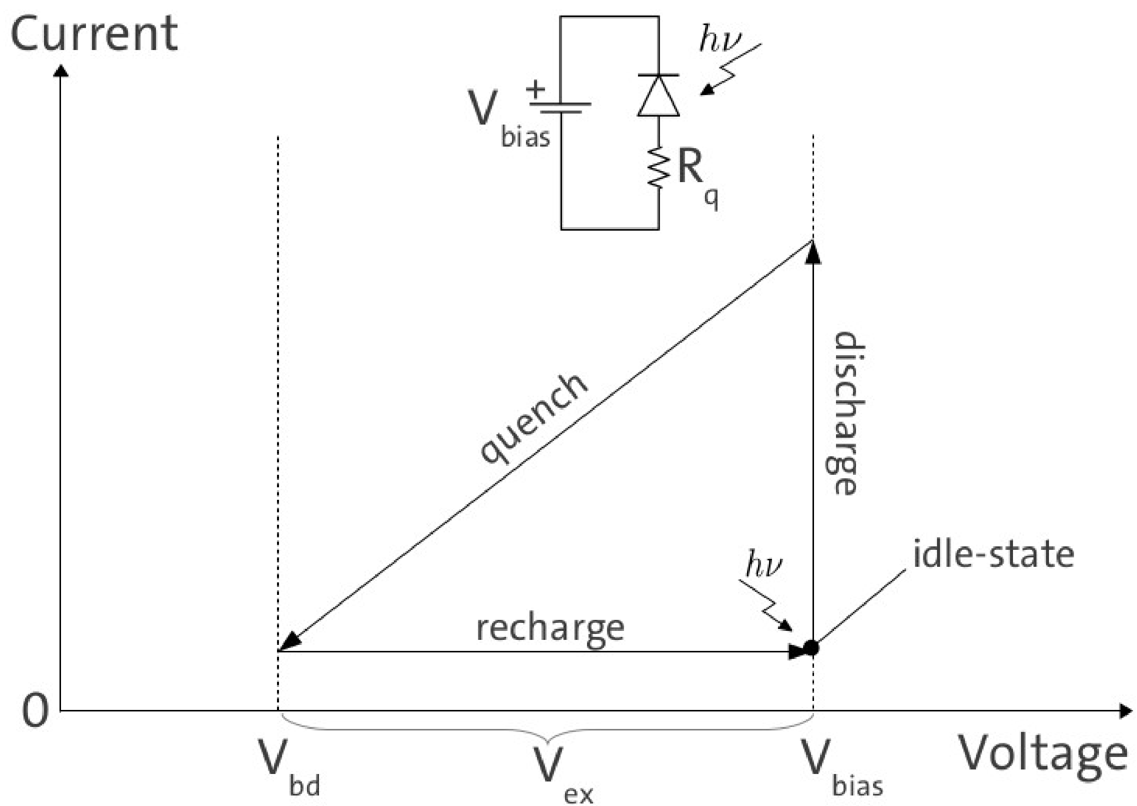
- Increasing bias beyond "breakdown" voltage: electrons and holes cause additional ionisations
  - Self supporting avalanche, infinite current, infinite gain: "Geiger mode"





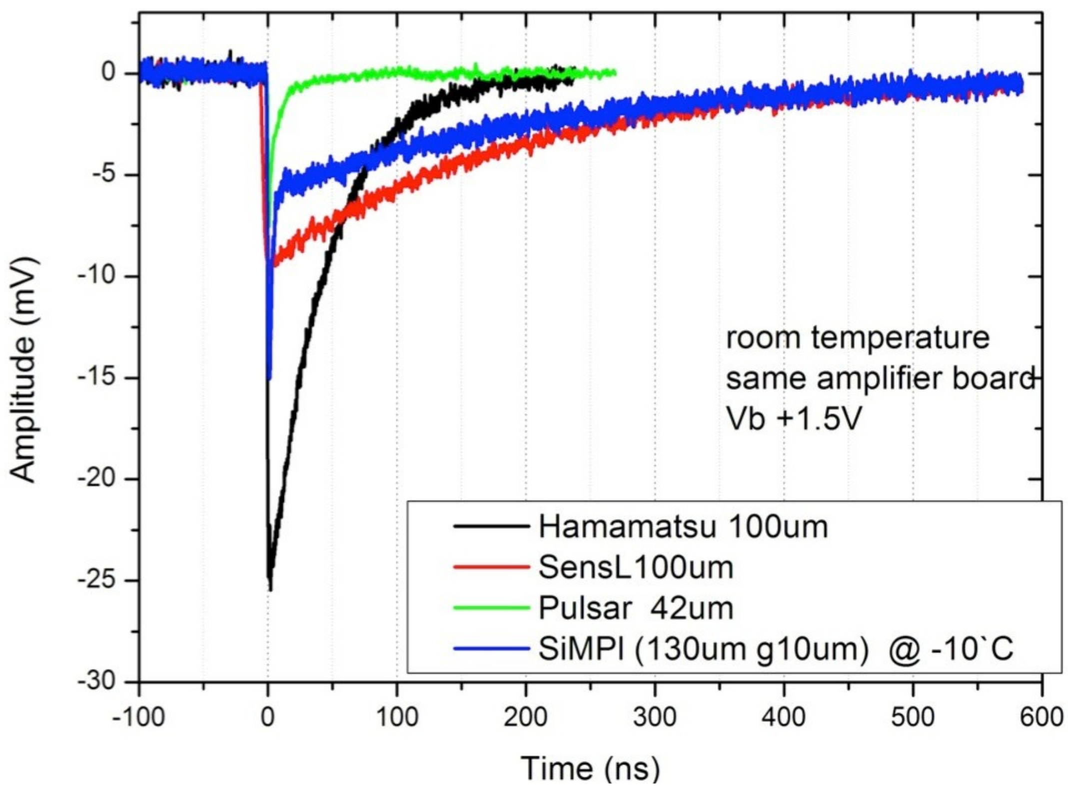
Single Photon Avalanche Diode - SPAD

- Adding quenching resistor (~MOhm) in series with diode interrupts avalanche
- Binary photon counter: signal is ~(voltage over breakdown * pixel capacitance)
  - “Gain” is number of electrons in output signal (but does not depend on input!)



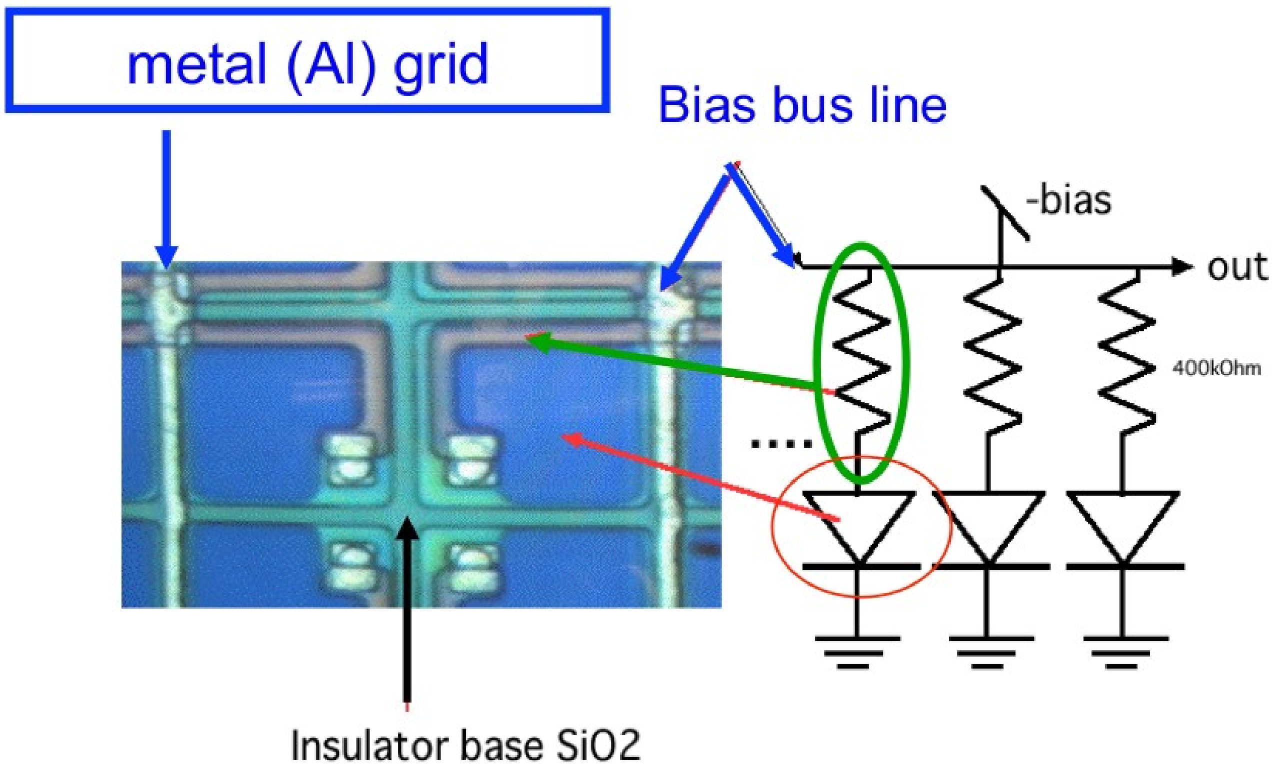
SPAD Signal

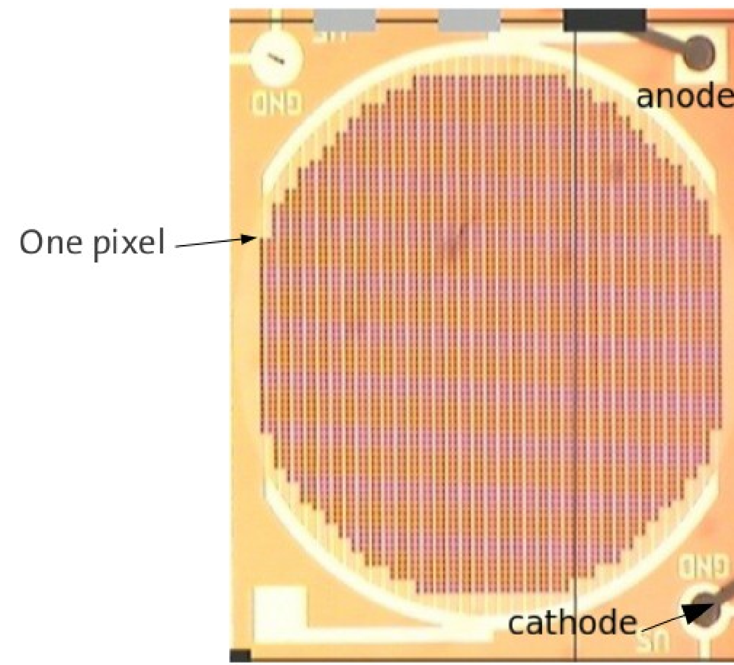
- Typical operation at 1-5V over breakdown, pixel capacitances 10-100fF: “gain” ~10^5-10^6
- Typically fast rise with “slow” fall (but lots of variation between types!)



Silicon Photomultipliers: SiPM

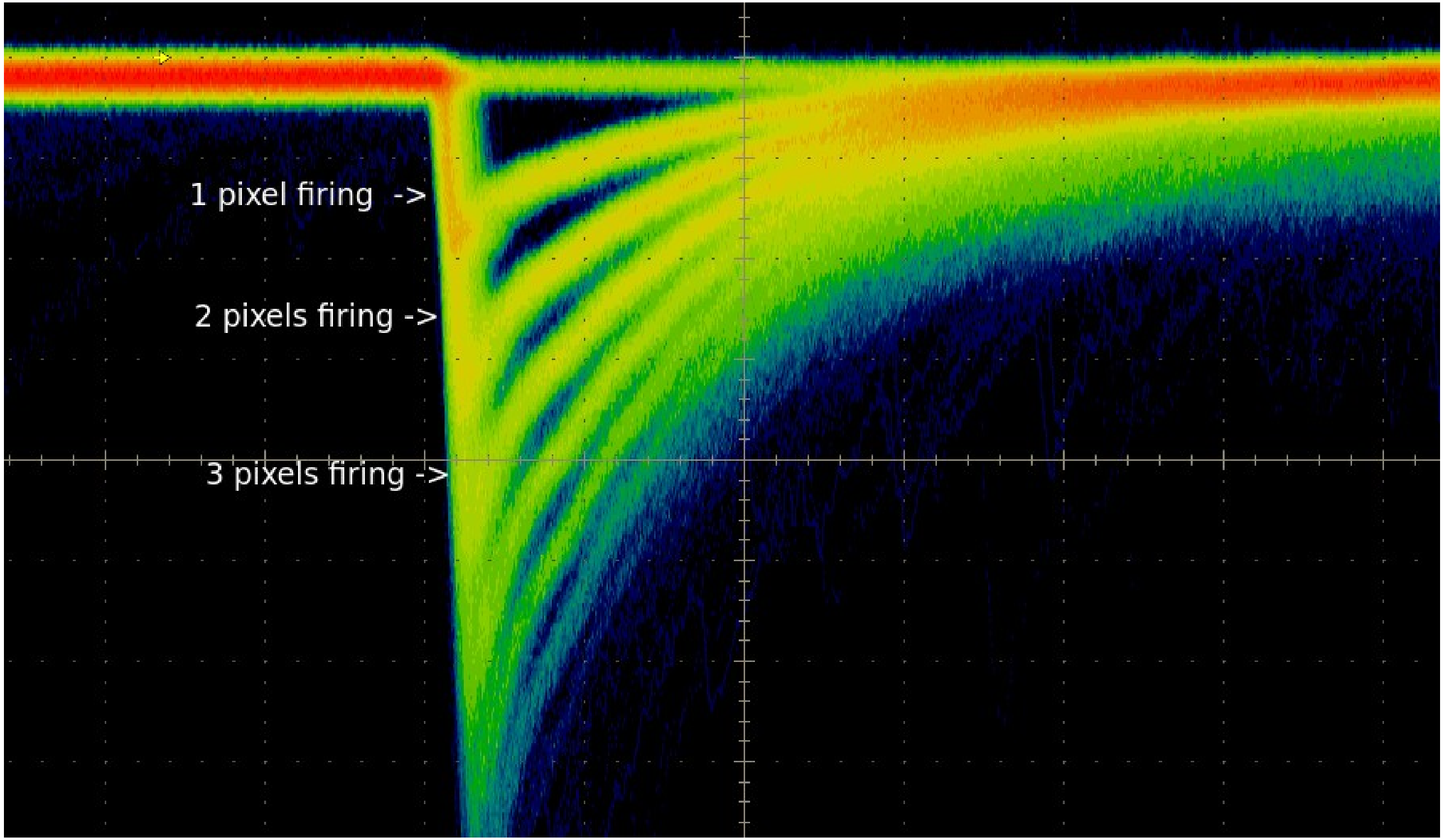
- SiPMs are arrays of SPAD on a single substrate
  - Hundreds to few thousand SPAD “pixels”, ~mm^2 total size





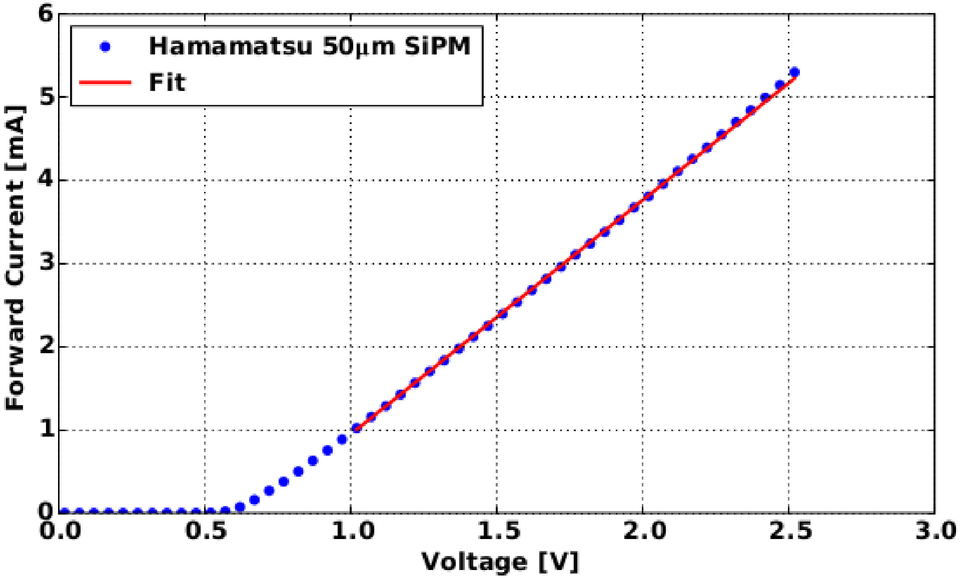
SiPM Signals

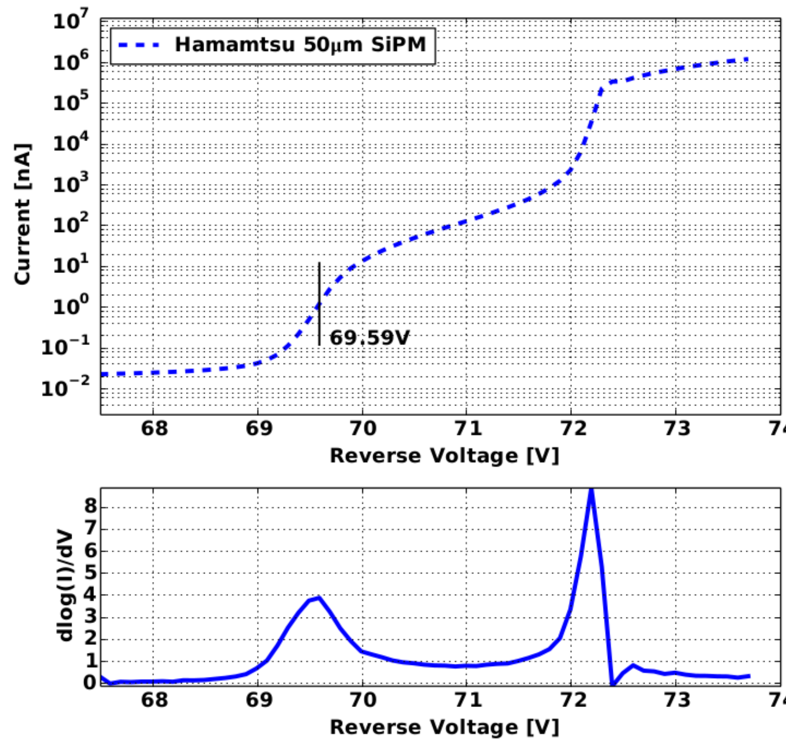
- Signal is sum of “fired” SPAD pixel charges: photon counting
- Can extract with waveform peak, integral (QDC)



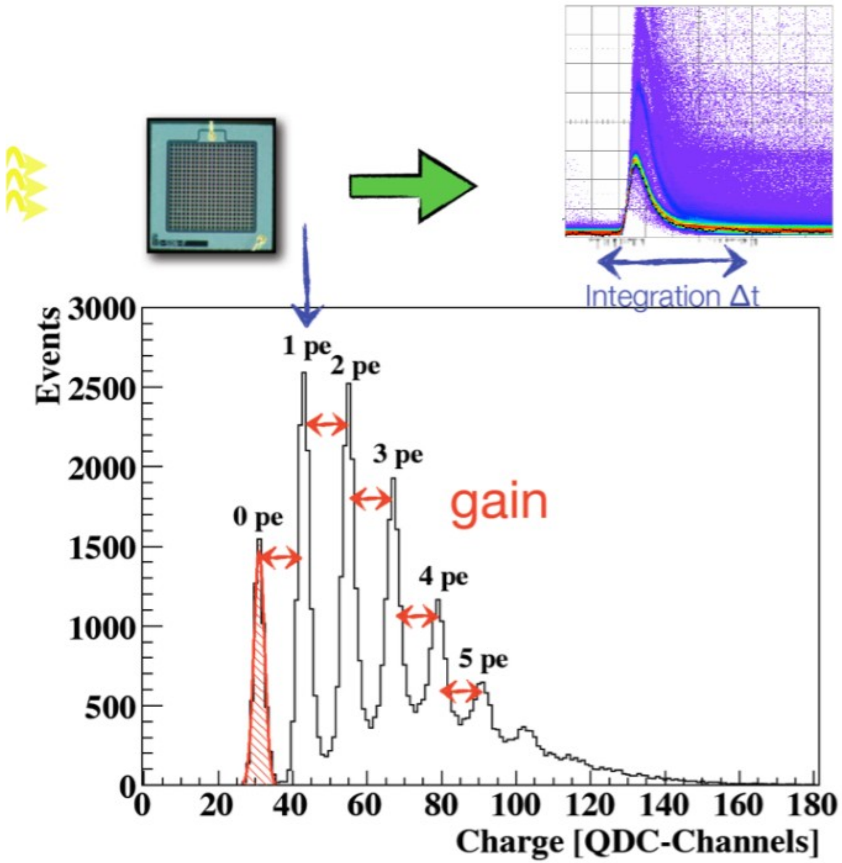
SiPMs: Breakdown and R_quench

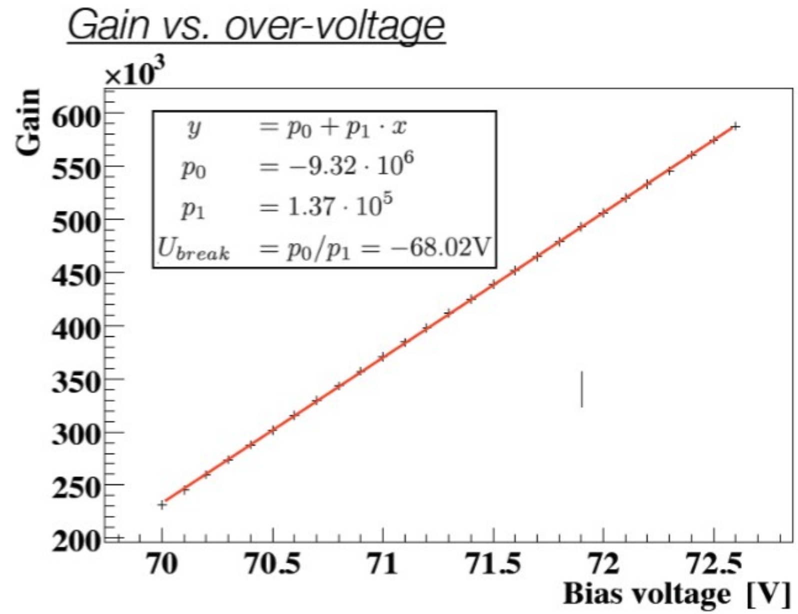
- Measure R_quench from forward bias current slope
- Various ways to measure breakdown:
  - Easy: Crank up reverse bias way above breakdown and see R_quench
  - Fancy: Fine scan of reverse bias and find first peak in dI/dV





SiPMs: Gain



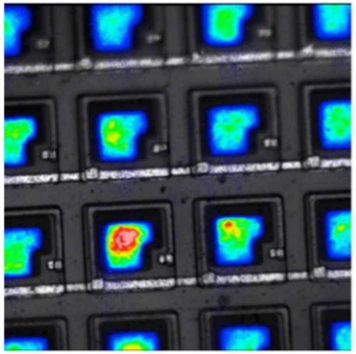


Fit function:

$$G = \frac{Q_{out}}{q_0} = \frac{C_{pix} \cdot (V_{bias} - V_{bd})}{q_0}$$

- Breakdown voltage effectively increases with temperature: Gain dependence around -1%/K
- n.b.: width of single photon peaks scales as sqrt(w_{ele} + n*w_{sipm})

SiPMs: Darkrate



A geiger discharge in a SiPM pixel can be initiated by an incoming photon or by free carries generated by thermal effects or tunneling (field-assisted generation)

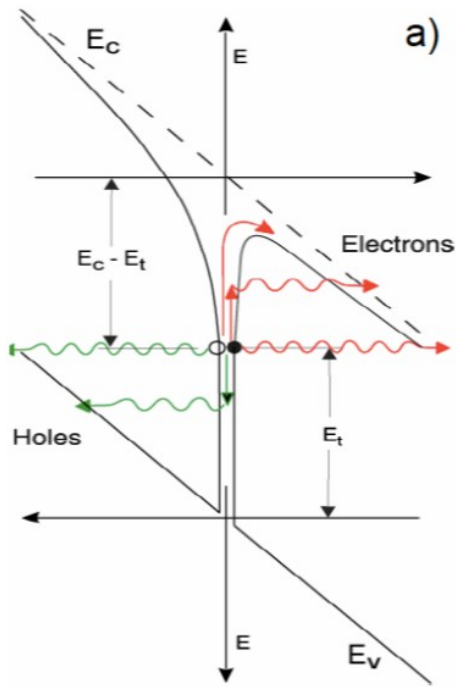
➔ dark count rate of 100 kHz – 10 MHz / mm² (@25°C) with threshold at half of one photo-electron amplitude

Free carrier generation by thermal effects

Depends on temperature (can be cooled away)

… charged impurities assist the emission of free carriers (Poole-Frenkel effect)

… depends on silicon quality



electron emission from a donor-like level enhanced by the Poole-Frenkel effect

Tunneling

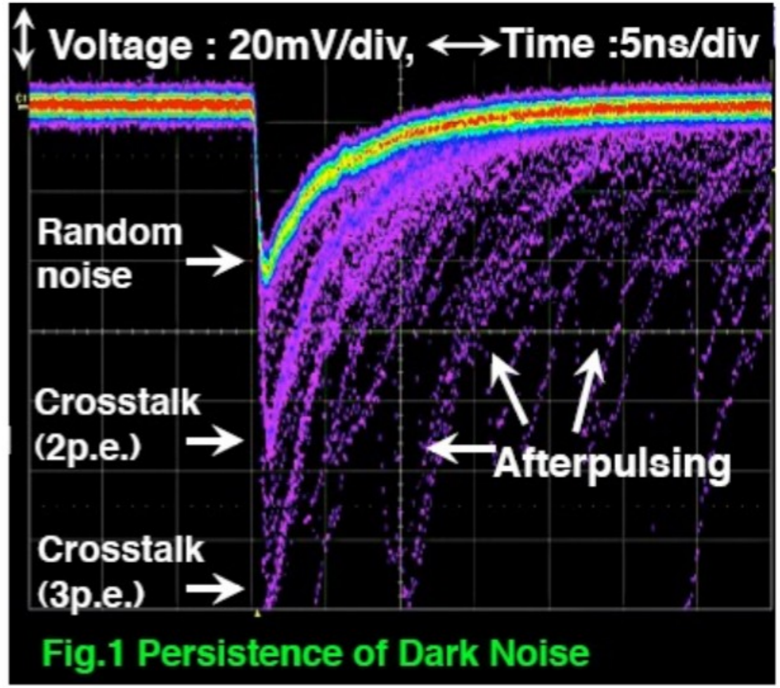
Depends on operation voltage (E field)
Influenced by technological design

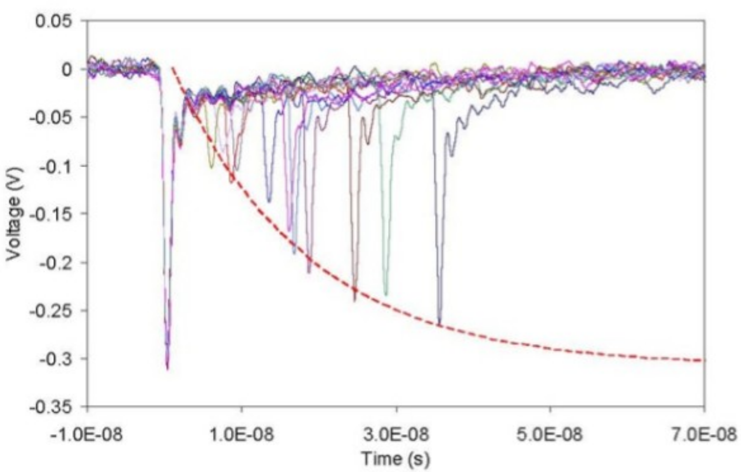
Note: Vacuum tubes inherently lower dark current per unit of sensitive area

SiPMs: Afterpulses

In the silicon volume, where a breakdown happened, a plasma with high temperatures (few thousand degree C) is formed and deep lying traps in the silicon are filled.
Carrier trapping and delayed release causes after-pulses during a period of several 100 ns after a breakdown.

The probability for after-puses increases with higher overvoltage (higher gain).

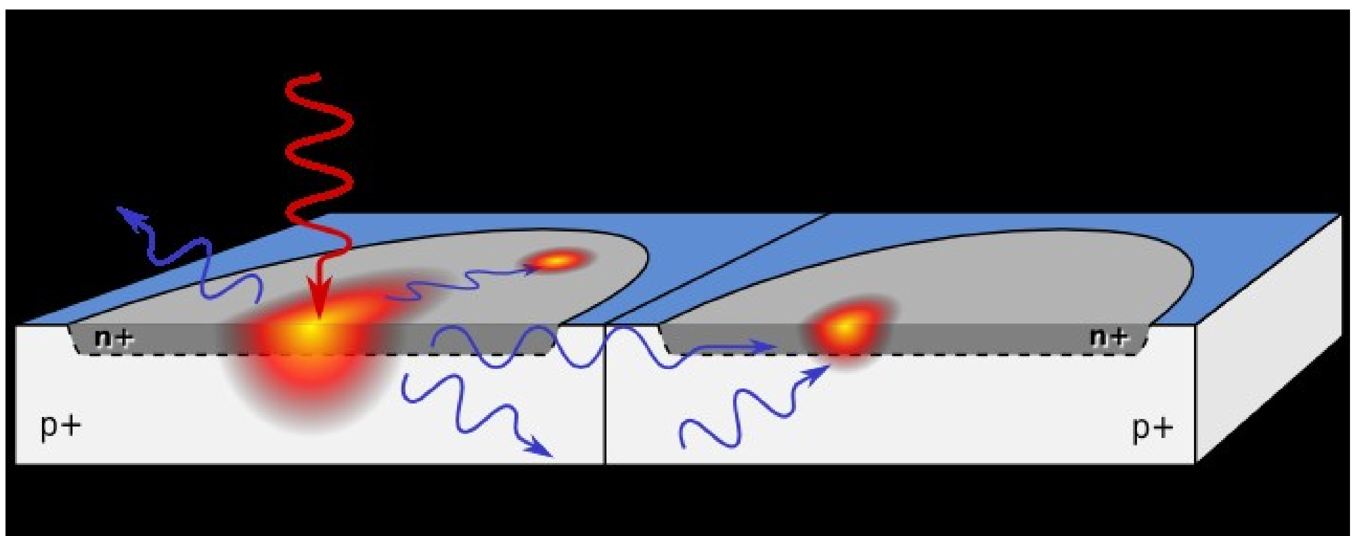




The amplitude of the after-pulse signals depends on the recovery stage of the pixel
➔ Use to determine recovery time

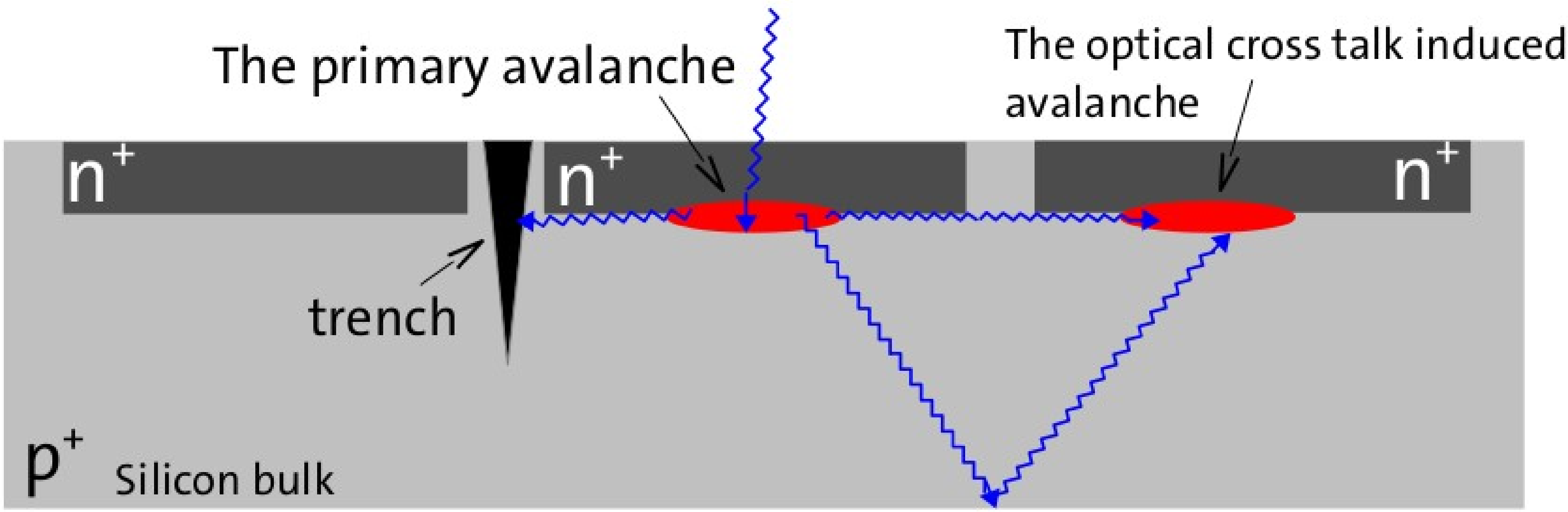
SiPM: Pixel Crosstalk

- Geiger avalanche emits 3photons/10^5 charge carriers with E>1.14eV [A. Lacaita et al, IEEE TED (1993)]
- Absorption length in silicon ~2um: can travel to neighbor pixel and start avalanche
  - more than one pixel fired from same initial photon

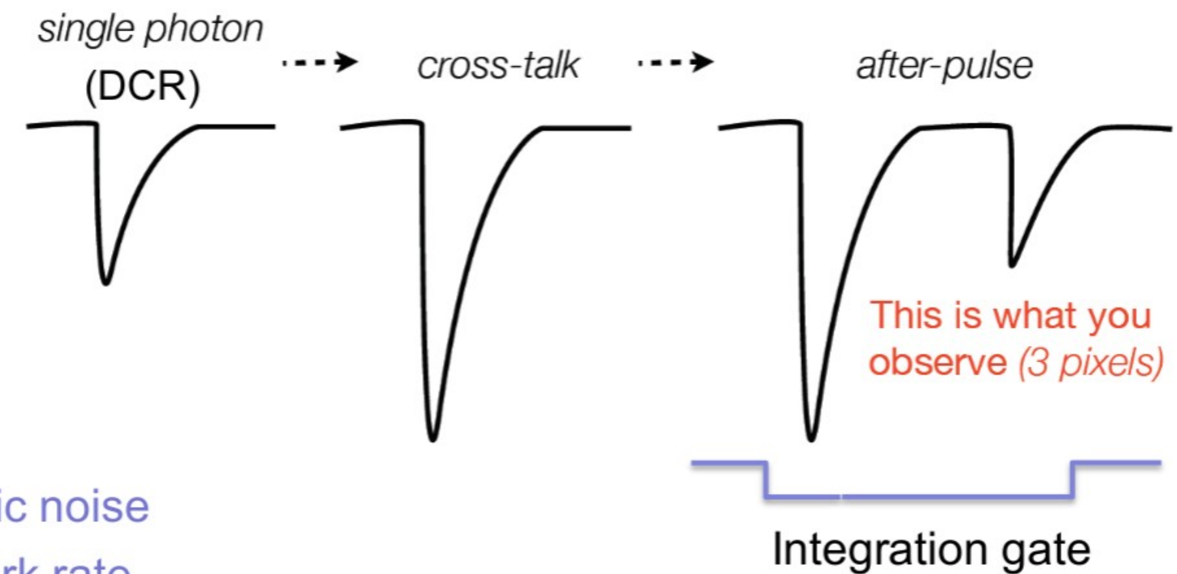


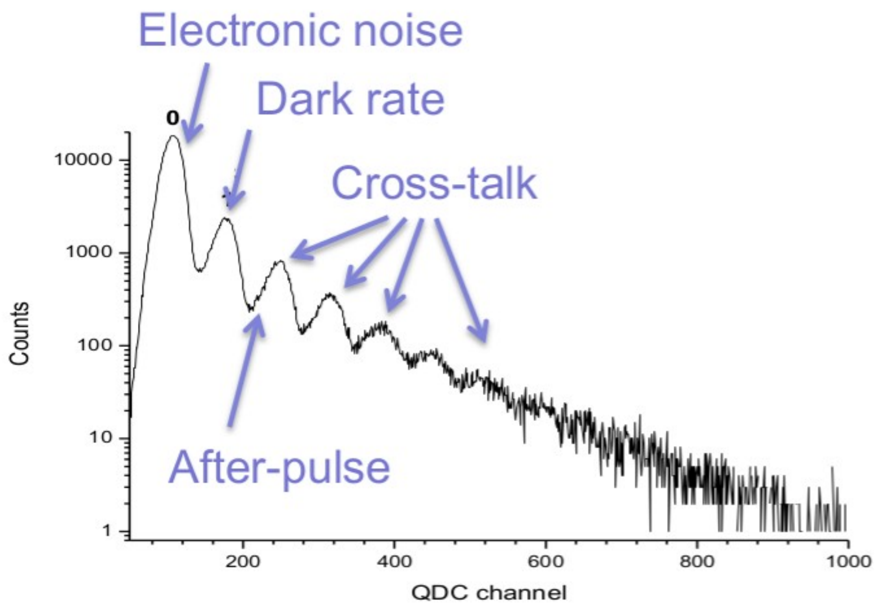
SiPM: Pixel Trenches

- Pixel crosstalk is greatly reduced by introducing physical trenches between pixels



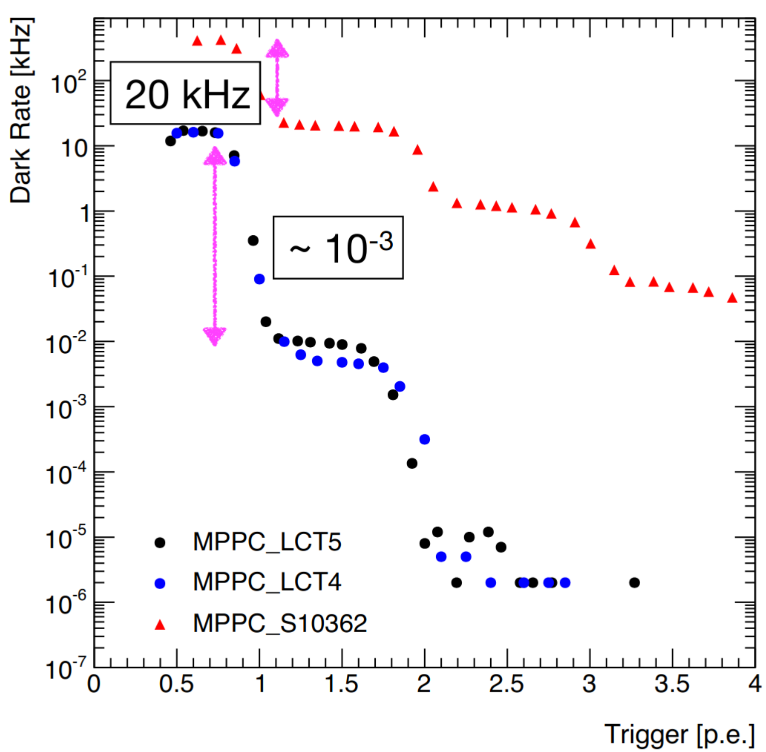
SiPMs: Noise w/ QDC

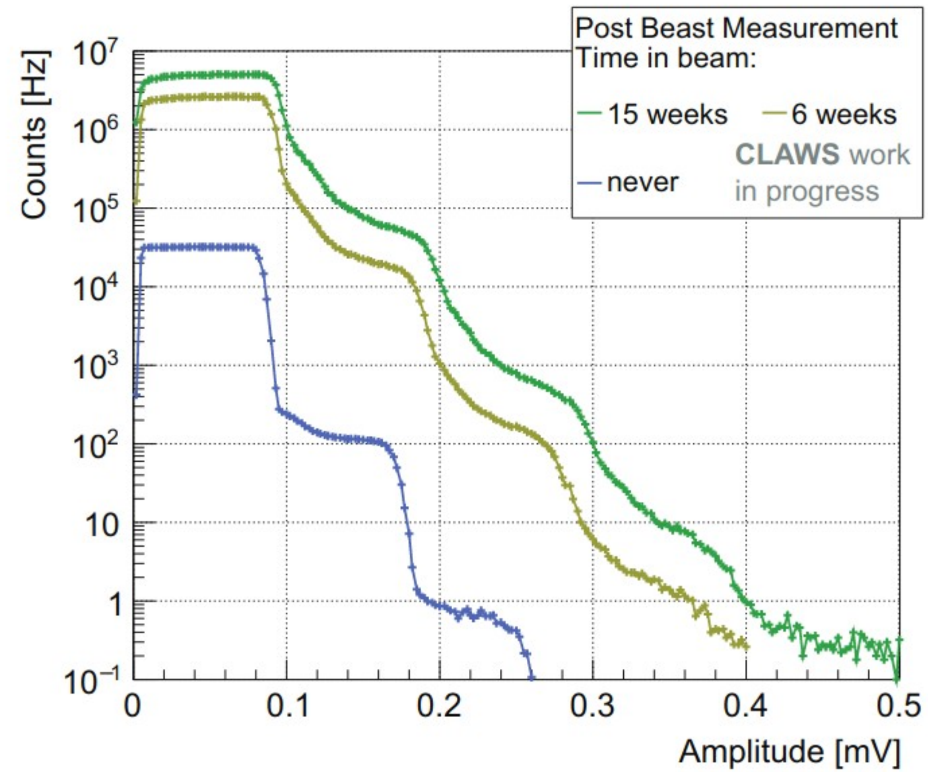




SiPMs: Noise w/ Threshold Counter

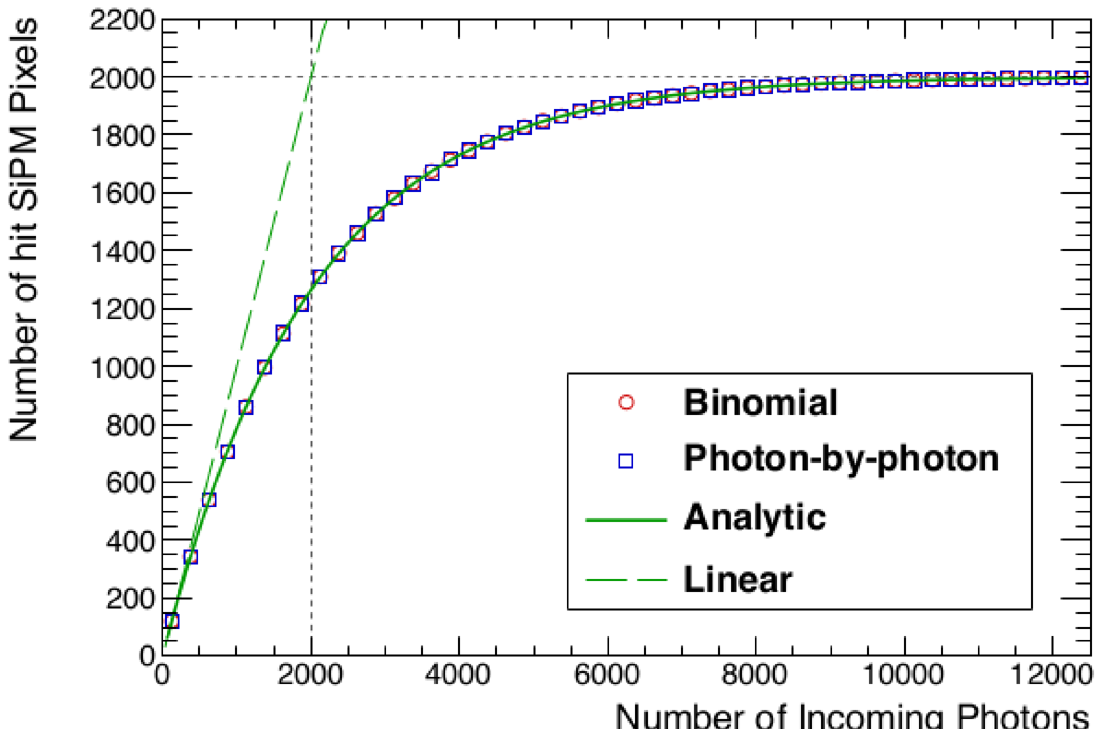
- Easier: Count rate of triggers vs. threshold
- Resulting curves contains everything: rates, crosstalk, gain
  - Can fit with integral of single photon spectrum





SiPMs: Saturation

- Two photons hitting the same pixel at same time will still only yield 1px signal
- Output signal will “compress” stochastically depending on number of photons hitting SiPM
- Easy to solve analytically for pixels with infinite recovery time
  - In practice, pixels can (partially) recover until next photon hits, K. Kotera “SiPM Response Functions Representing Wide Range Including Linear Behavior After Saturation” [arXiv:1510.01102]



SiPMs: Intermediate Summary

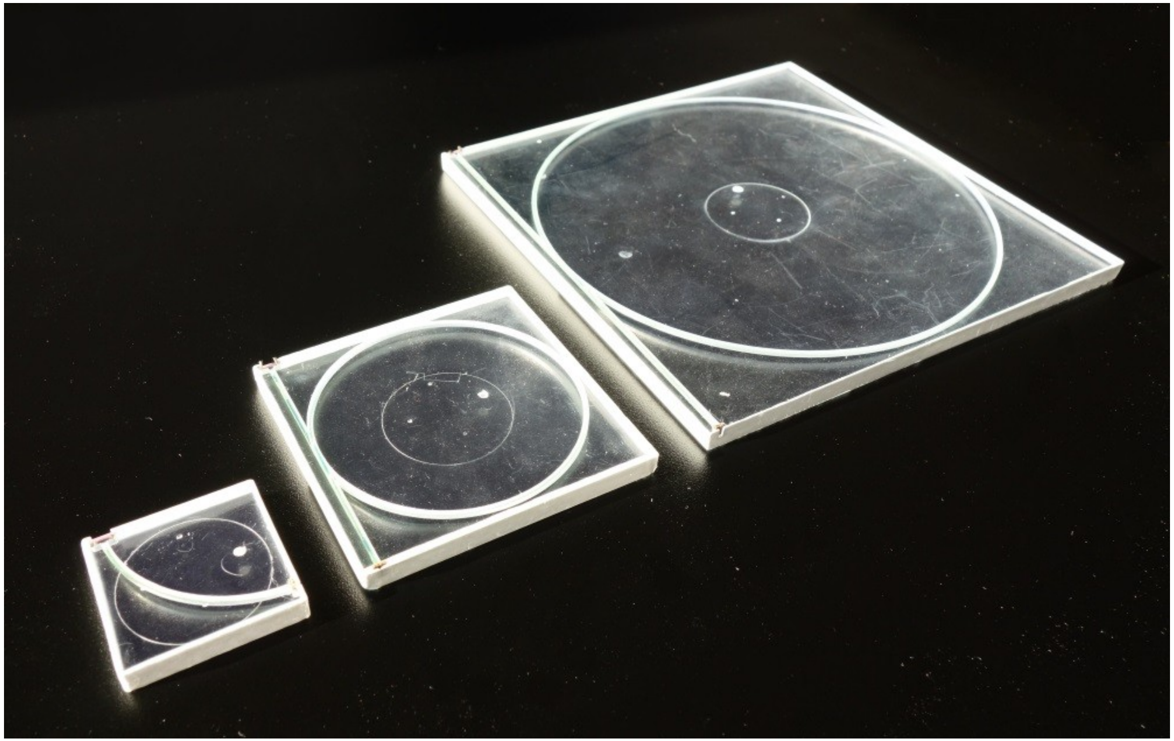
- SiPMs are arrays of binary photon counters
- Output signal is the sum of individual pixels
- Figures of merit (generally depend on voltage over breakdown)
  - Gain: output charge per fired pixel
  - Dark noise: rate of spontaneous thermal excitations
  - Pixel crosstalk: chance of firing neighbor pixel
  - [photon detection efficiency, not discussed here]
- For n_in approaching n_pixel, need to take SiPM saturation into account when reconstructing input signal

SiPM Applications

- SiPM as replacement for PMT: small, cheap, resistant to B-fields
- Usually coupled to scintillator (or Cherenkov radiator) to detect generated photons of ~optical wavelengths
- Plastic scintillator tiles: CALICE AHCAL/ScECAL (also used in CMS outer HGCAL upgrade)
  - 15-40 photons/MIP, depending on parameters
- crystal scintillator: LYSO+SiPM fast timing (if time)
  - Used for fast timing: HEP, PET scanners

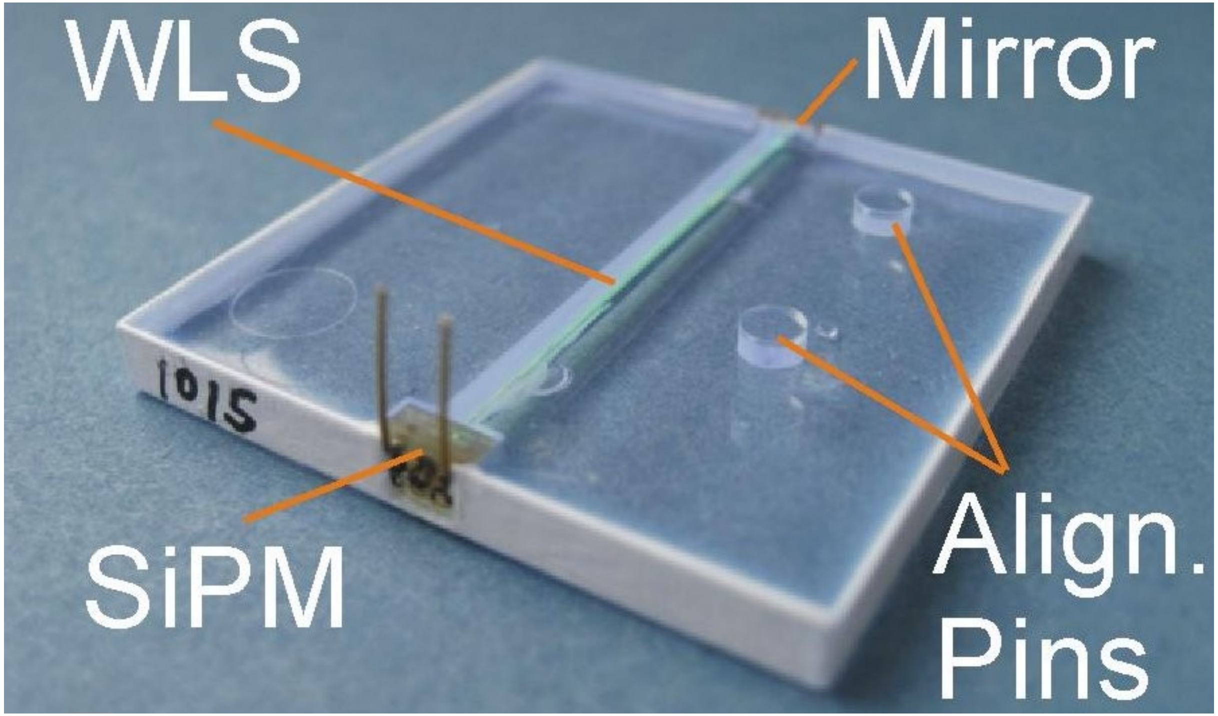
SiPM + Plastic Tiles: AHCAL 1st Gen

- 5mm thick plastic scintillator, wavelength shifting fiber
  - SiPMs used to be more sensitive in green wavelength range
  - Shifted photons are emitted isotropically inside WLS fiber, large fraction is confined along fiber



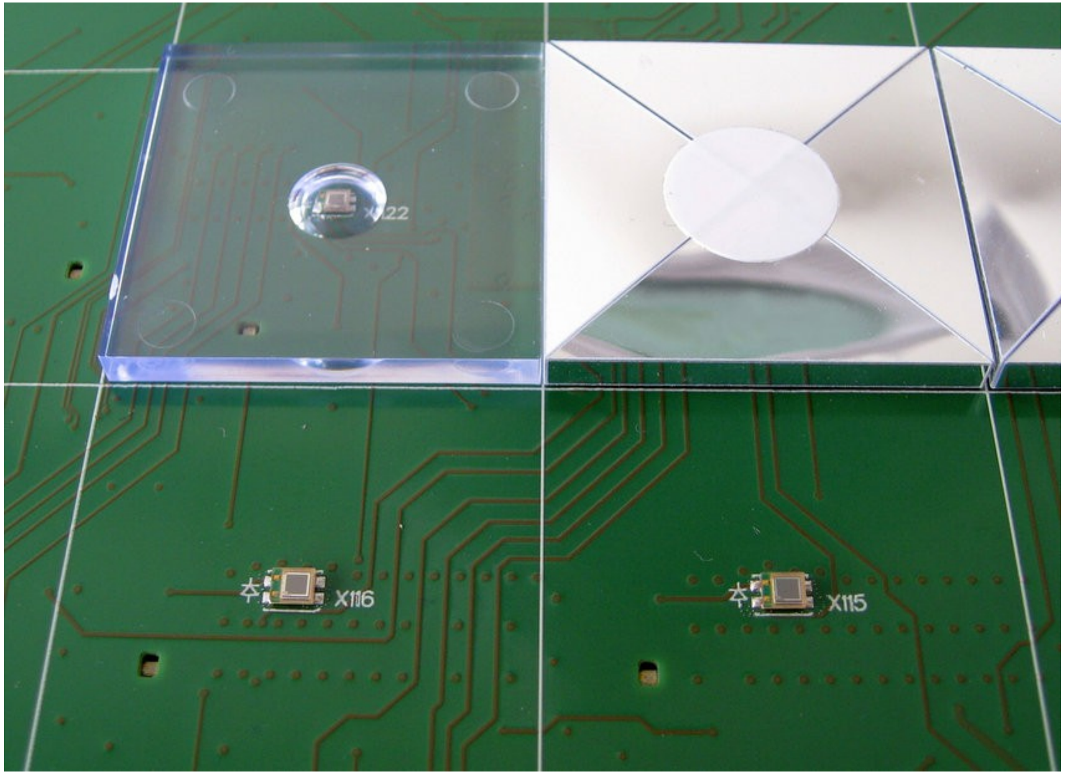
SiPM + Plastic Tiles: AHCAL 2nd Gen

- 3mm thick plastic scintillator, shorter wavelength shifting fiber



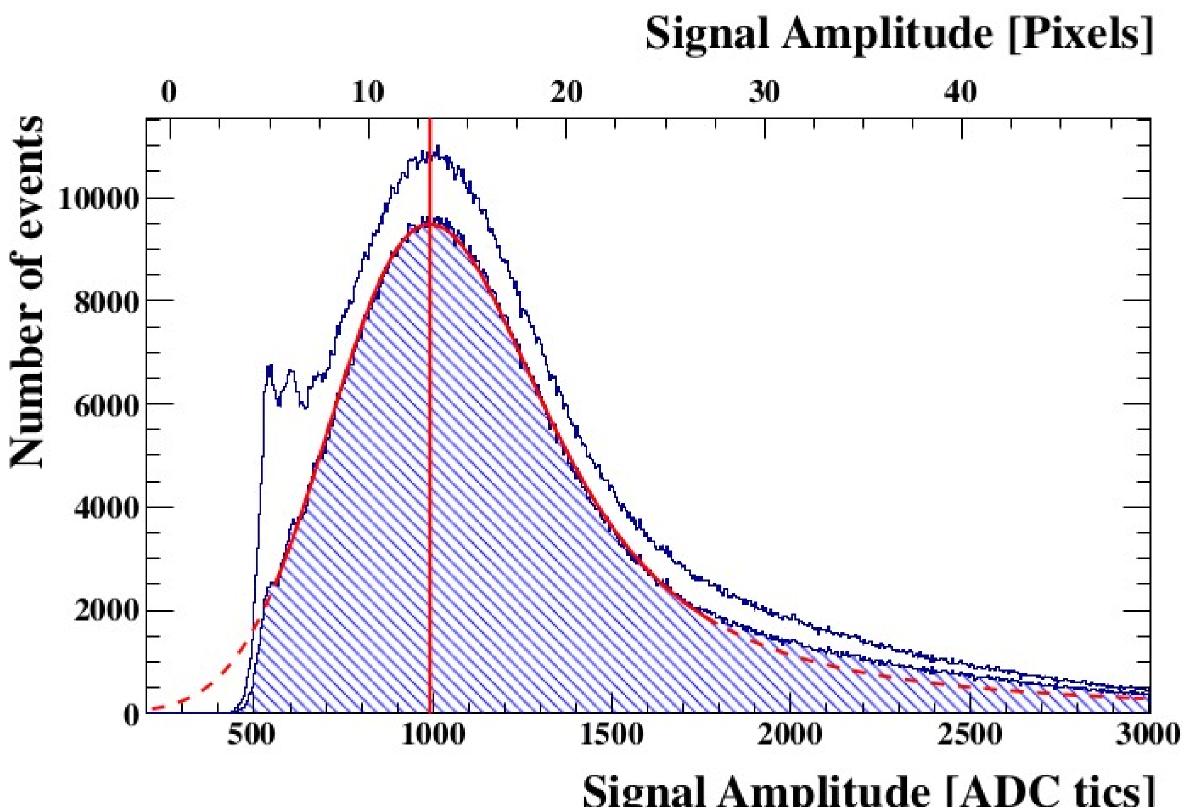
SiPM + Plastic Tiles: AHCAL 3rd Gen

- 3mm thick plastic scintillator, “dimple” design, individually wrapped
  - Current SiPMs don’t need WLS anymore
  - SiPM soldered to board, much simplified assembly



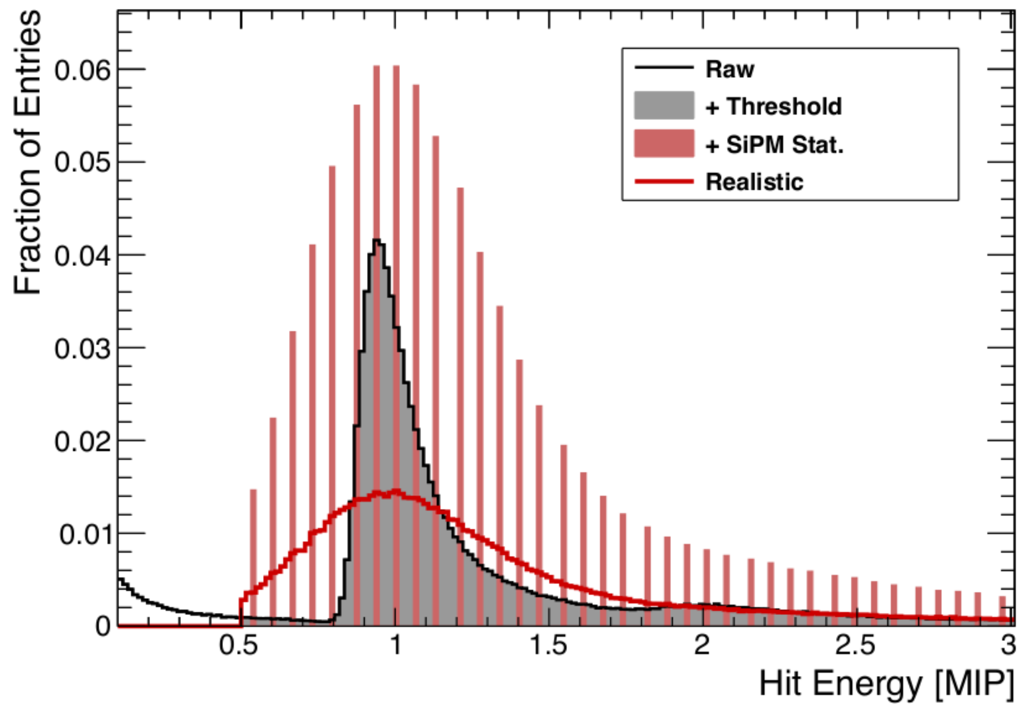
SiPM + Plastic Tiles: Lightyield

- Tile lightyield adjustable via wrapping material and dimple size to 10-40px/MIP, usually aiming for ~15px/MIP (MPV)
- MIP response is well modeled by Landau convoluted with Gaussian



Simulating Scintillator + SiPM Systems

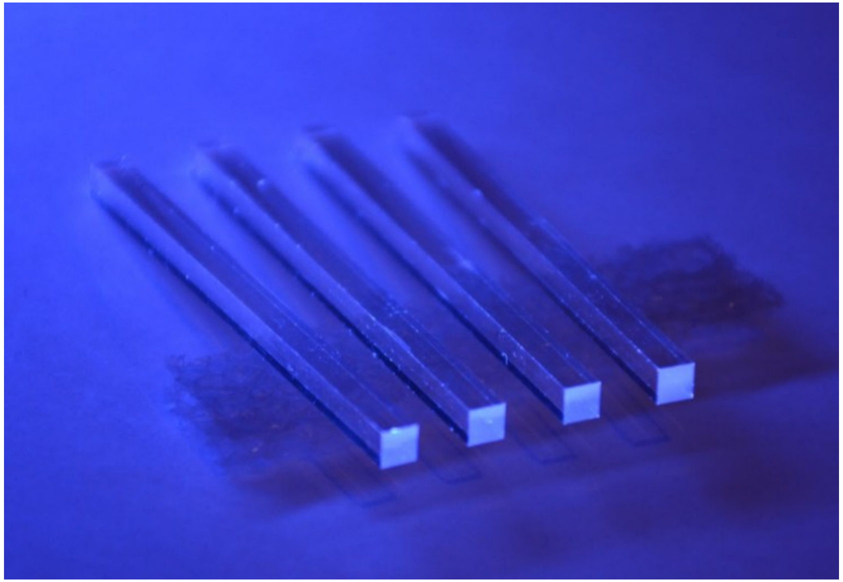
- Simulating optical propagation inside scintillator/WLS system is hopeless. We never got it to match in detail.
- Instead: measure tile lightyield in pixels/MIP, calibrate simulation to 1MIP peak, smear with Poisson statistics (check OH PhD thesis for recipe and algorithms)
  - Saturation effects are more complicated.



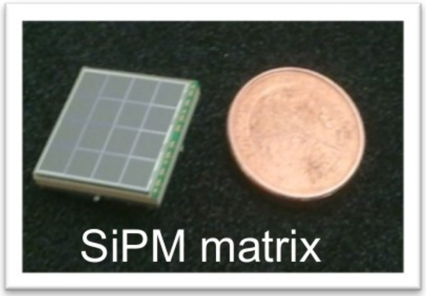
LYSO:Ce + SiPM Readout

- CMS Barrel Timing Layer: $3x3x50mm^3$ scintillator bars with SiPM on each end
- 30ps time resolution demonstrated for single MIPs
  - Driven by photon statistics, thousands of photons per MIP
  - SiPM matched to size of crystal

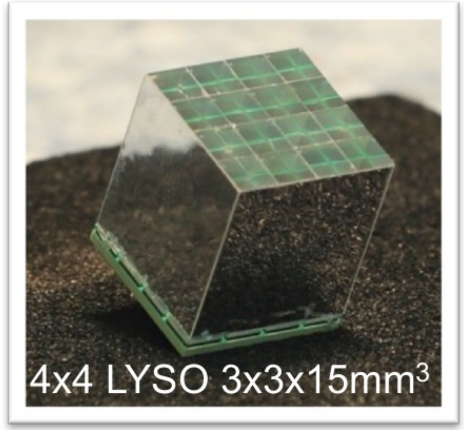
[CMS-TDR-020]

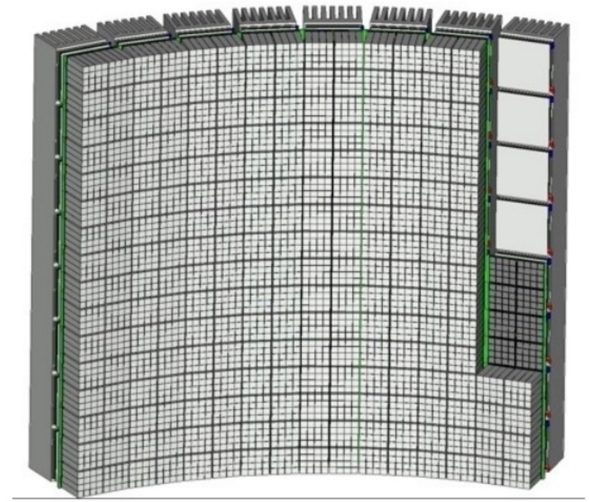


SiPM + LYSO Scint.: TOFPET

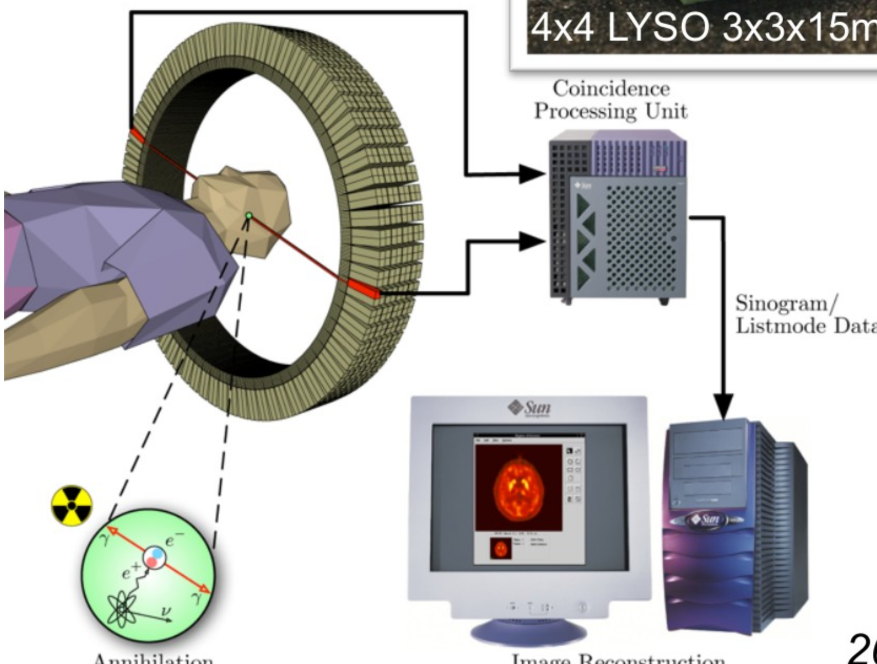


High granular Positron Emission Tomography detectors with Time-of-Flight information

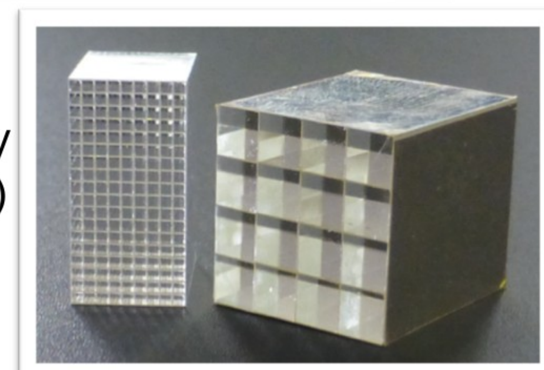




PET module with ~4000 channels



Higher granularity (0.75 mm) best with dSiPM



2013: Philips Vereos digital PET/CT