TRIUMF

Present and Future of Silicon Photo-Multipliers (SiPMs) for Precision-Physics and Commercial Applications.

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TRIUMF
Physical Science Division

Rutherford Appleton Laboratory
17 - April - 2019

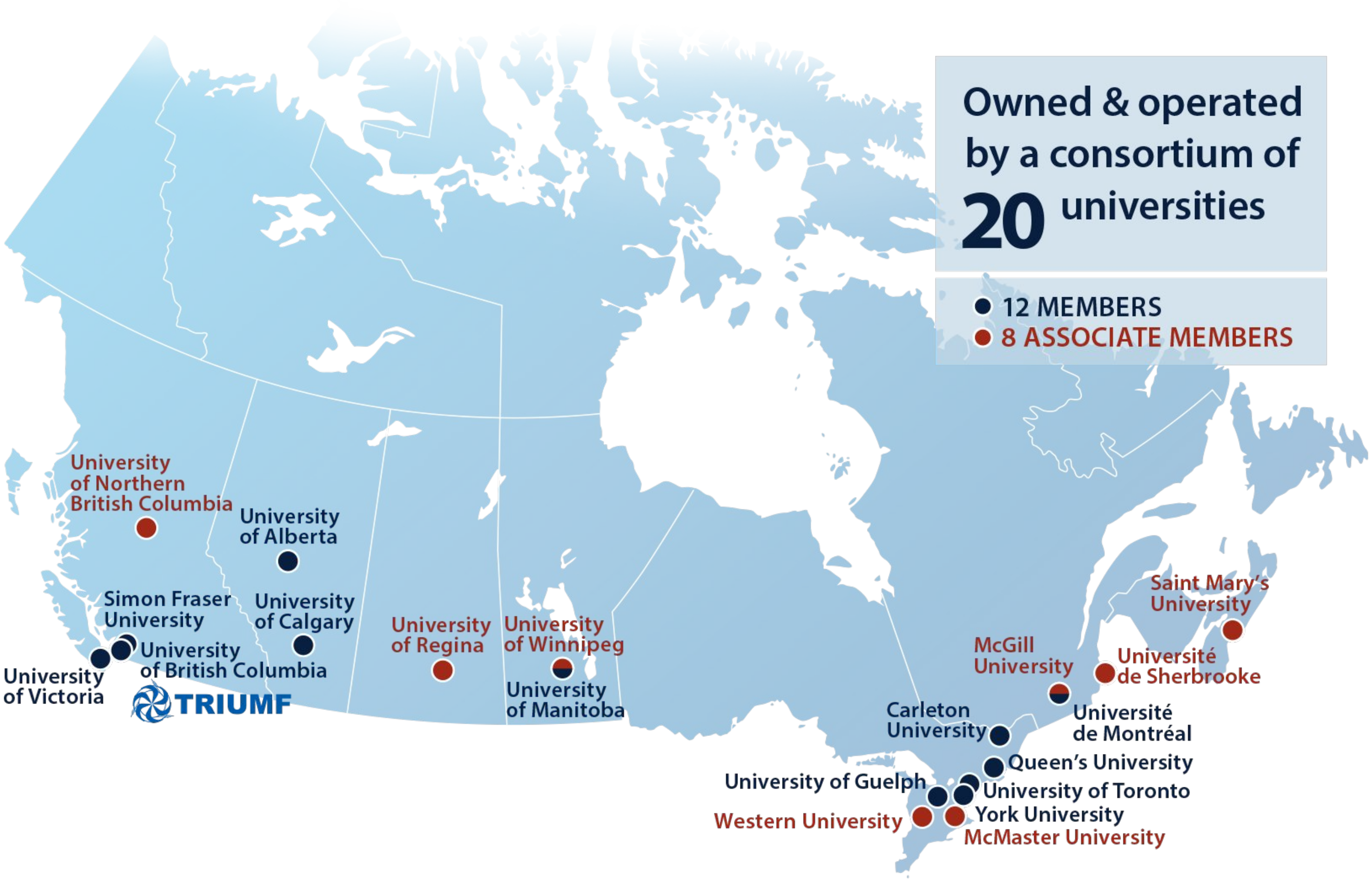
Discovery, accelerated

Outline

- TRIUMF Overview.
- Introduction / Motivation.
- How Do SiPMs Work.
- Characterization Model for SiPMs.
- Development of 3DSiPM.
- Boosting SiPMs VUV Efficiency.
- Precisions-Physics / Commercial Applications
- Conclusions.

TRIUMF Overview

Founded in 1968, TRIUMF is Canada particle accelerator centre (and much more).



Owned & operated by a consortium of 20 universities

- ● 12 MEMBERS
- 🟥 8 ASSOCIATE MEMBERS

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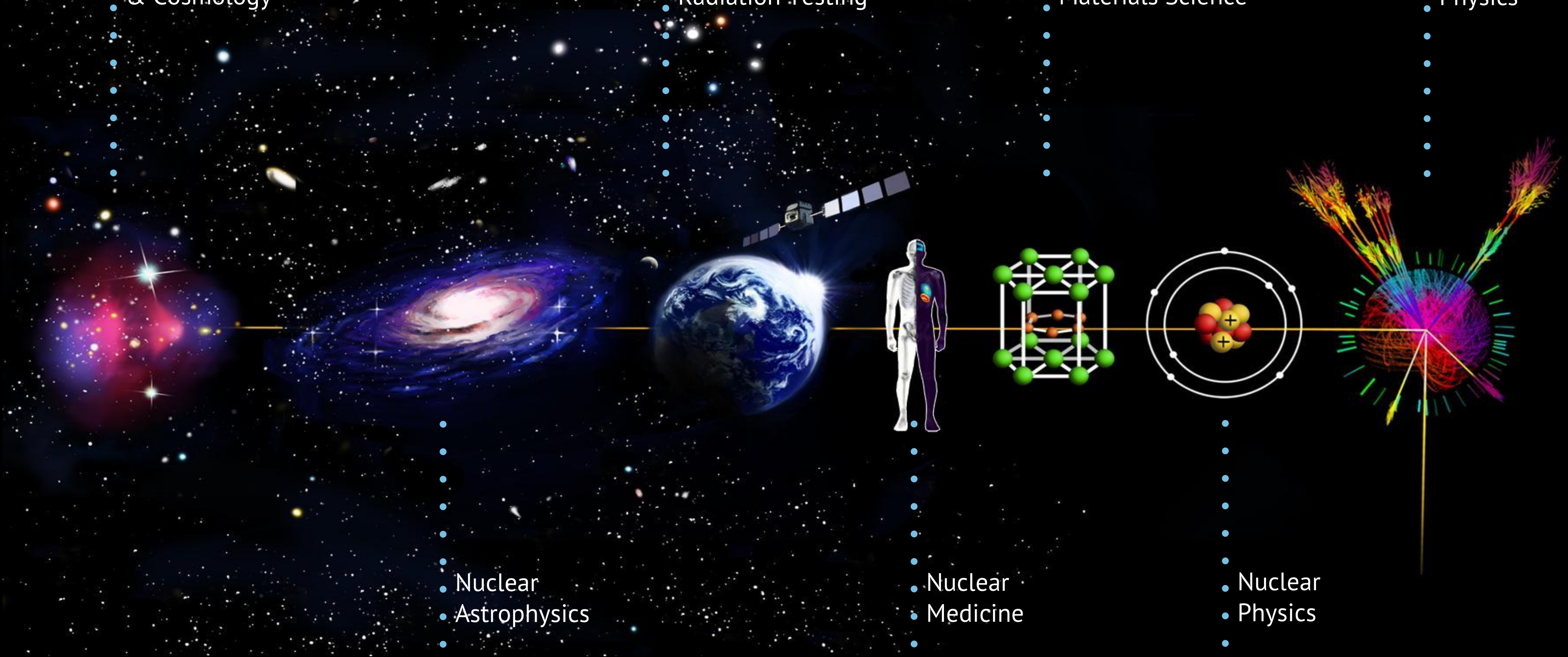
A Multidisciplinary Laboratory



Dark Matter & Cosmology

Electronics Radiation Testing

Molecular & Materials Science

Particle Physics

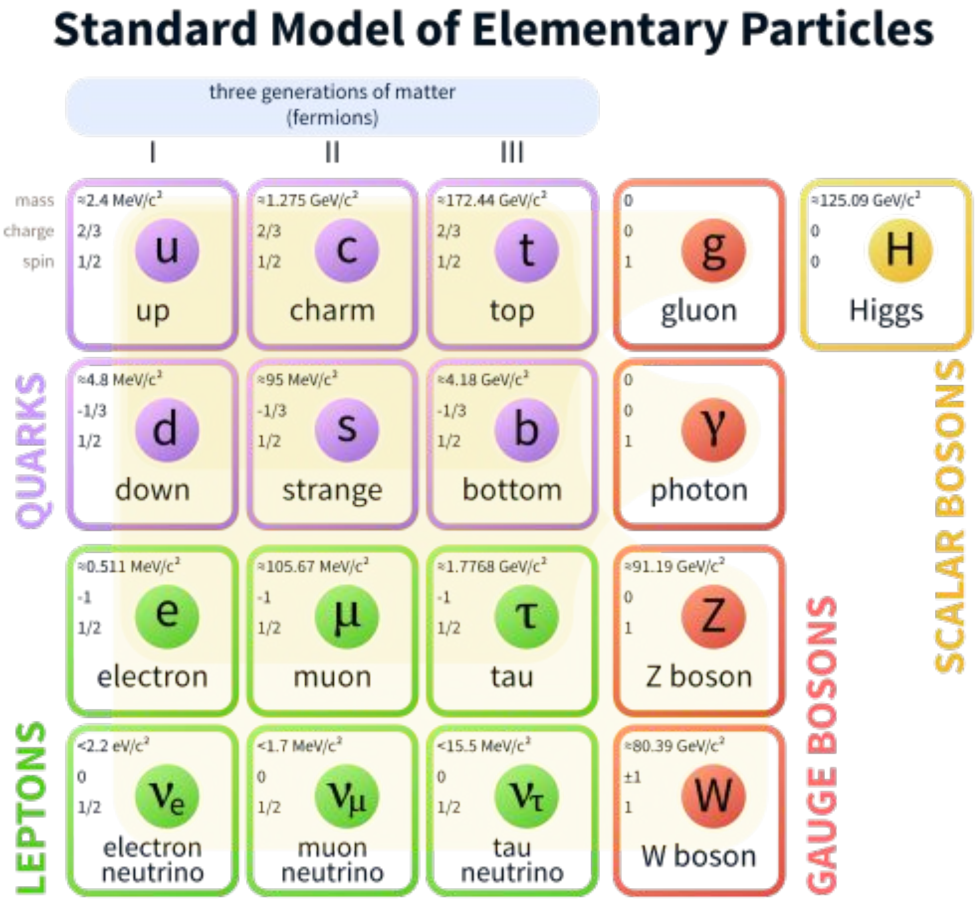
Nuclear Astrophysics

Nuclear Medicine

Nuclear Physics

Data Science

Introduction / Motivation



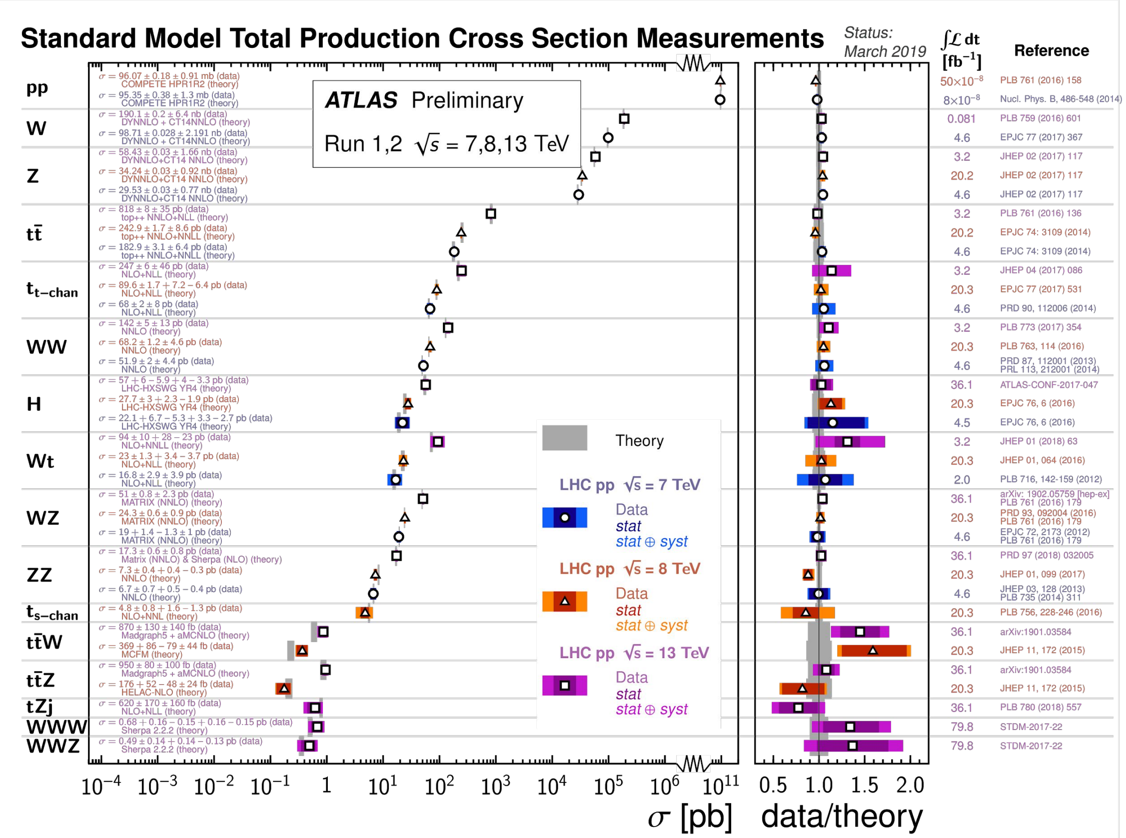
Standard Model of Elementary Particles

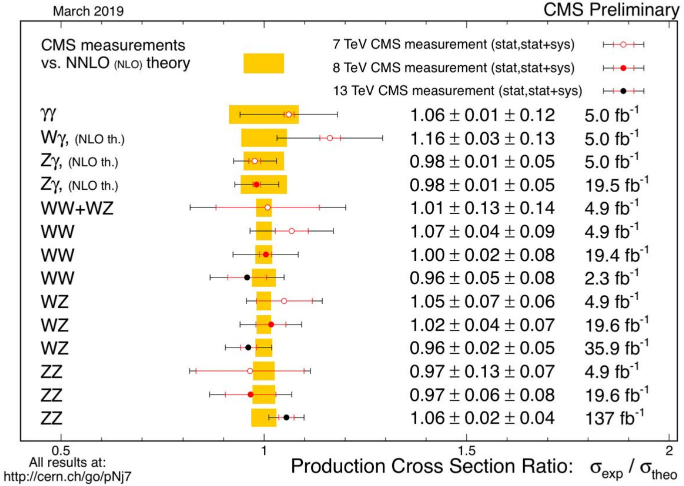
three generations of matter (fermions)

		I	II	III		
QUARKS	mass charge spin	≈2.4 MeV/c² 2/3 1/2 u up	≈1.275 GeV/c² 2/3 1/2 c charm	≈172.44 GeV/c² 2/3 1/2 t top	0 0 1 g gluon	≈125.09 GeV/c² 0 0 H Higgs
QUARKS		≈4.8 MeV/c² -1/3 1/2 d down	≈95 MeV/c² -1/3 1/2 s strange	≈4.18 GeV/c² -1/3 1/2 b bottom	0 0 1 γ photon	SCALAR BOSONS
LEPTONS		≈0.511 MeV/c² -1 1/2 e electron	≈105.67 MeV/c² -1 1/2 μ muon	≈1.7768 GeV/c² -1 1/2 τ tau	≈91.19 GeV/c² 0 1 Z Z boson	
LEPTONS		<2.2 eV/c² 0 1/2 ν_e electron neutrino	<1.7 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	≈80.39 GeV/c² ±1 1 W W boson	
					GAUGE BOSONS	

- **1897:** Discovery of the electron (J.J. Thomson).
- **1956:** Discovery of the electron neutrino (Cowan-Reines).
- **1962:** Discovery of the muon neutrino (Lderman-Schwartz).
- **1968:** Discovery of the up, down quarks (SLAC).
- **1974:** Discovery of the charm quark (SLAC and BNL).
- **1977:** Discovery of the bottom quark (FERMIlab).
- **1978:** Discovery of the gluon (DESY)
- **1983:** Discovery of the W and Z bosons (CERN).
- **1995:** Discovery of the top quark (CDF and D0).
- **2000:** Discovery of the tau neutrino (DONUT).
- **2013:** Discovery of the Higgs boson (CERN).

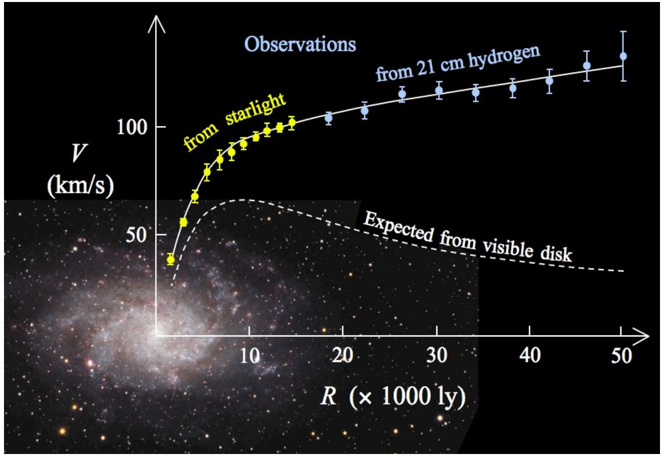
The Standard Model Works at an Extremely High Precision

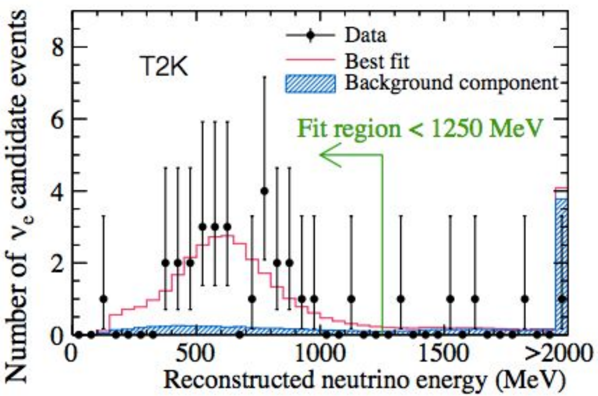


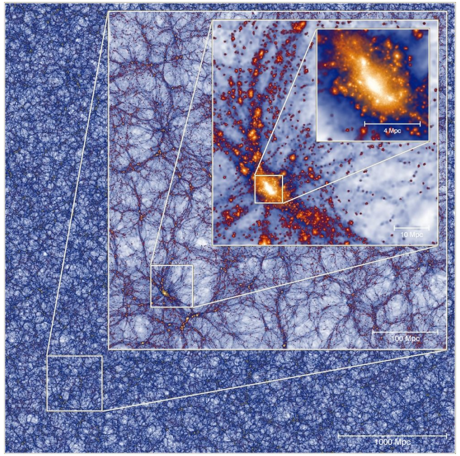


Discovery, accelerated

…. But There Are Still Open Questions



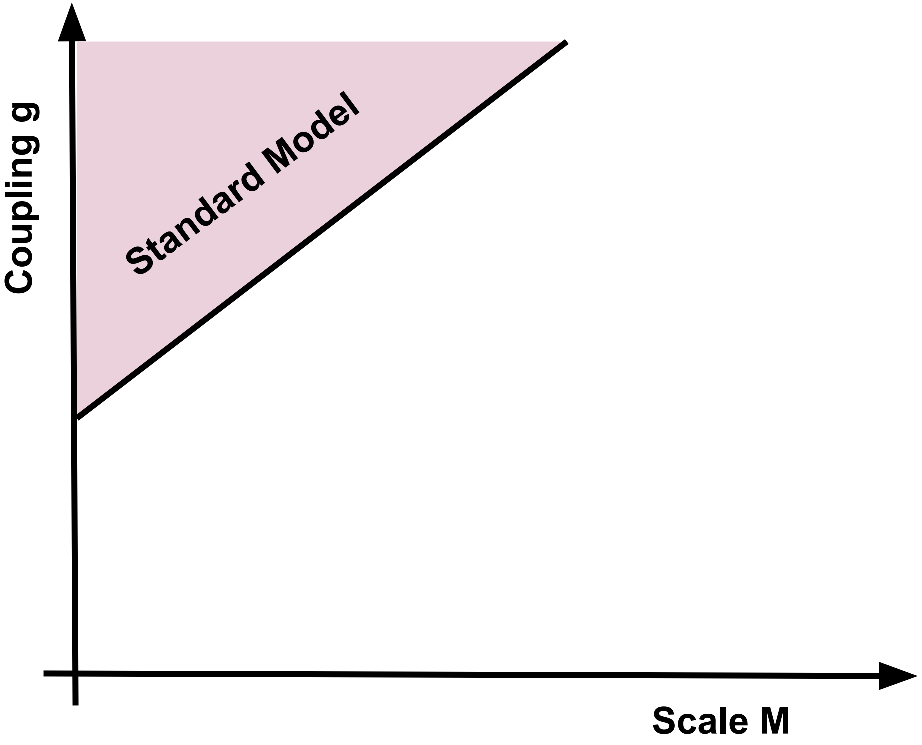




- What is Dark Matter?
- *Why Neutrinos have masses?*
- *What causes the Matter-AntiMatter Asymmetry?*
- *What drives large-scale Galaxies formations?*
- *What about Gravity?*
- *MORE …….*

Life at the Frontier of the Standard Model

We can generally parametrize new effects in terms of coupling (g) and energy distance^{-1} scale.



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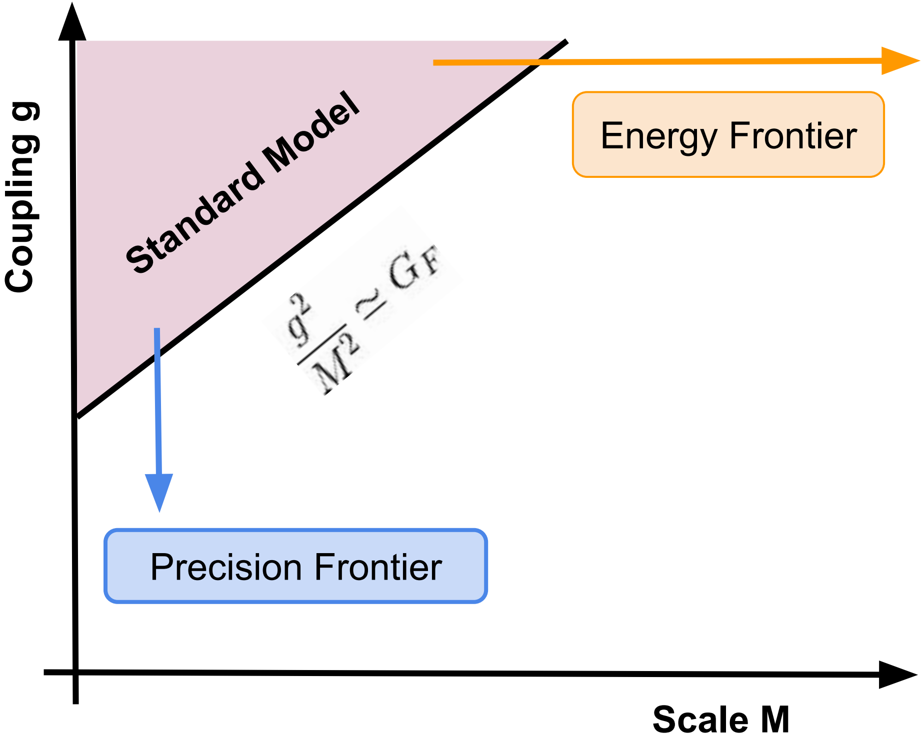

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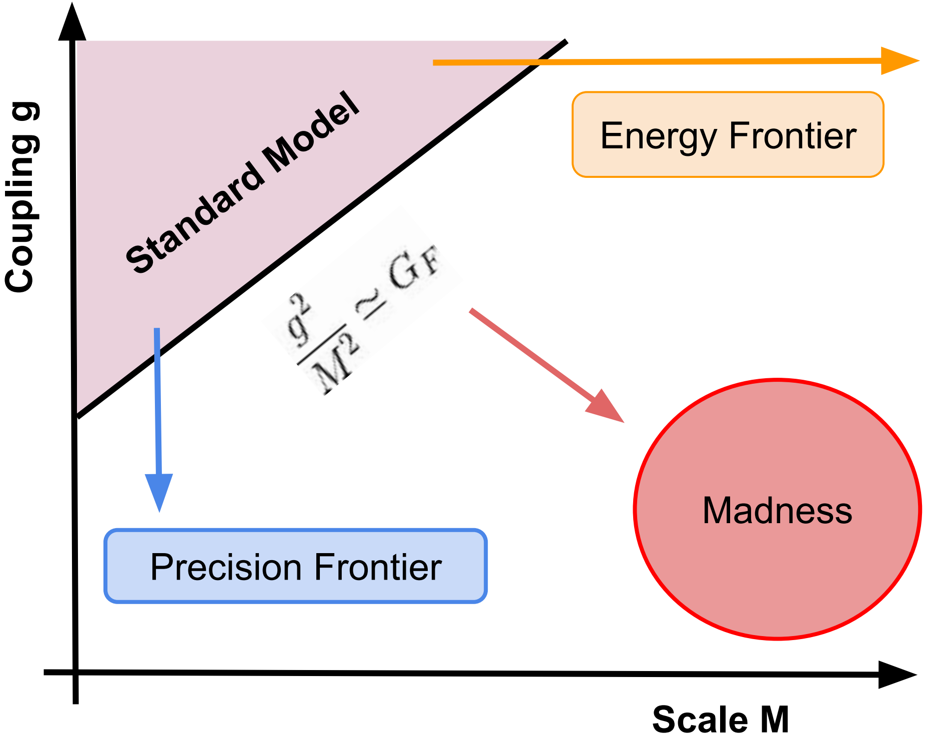
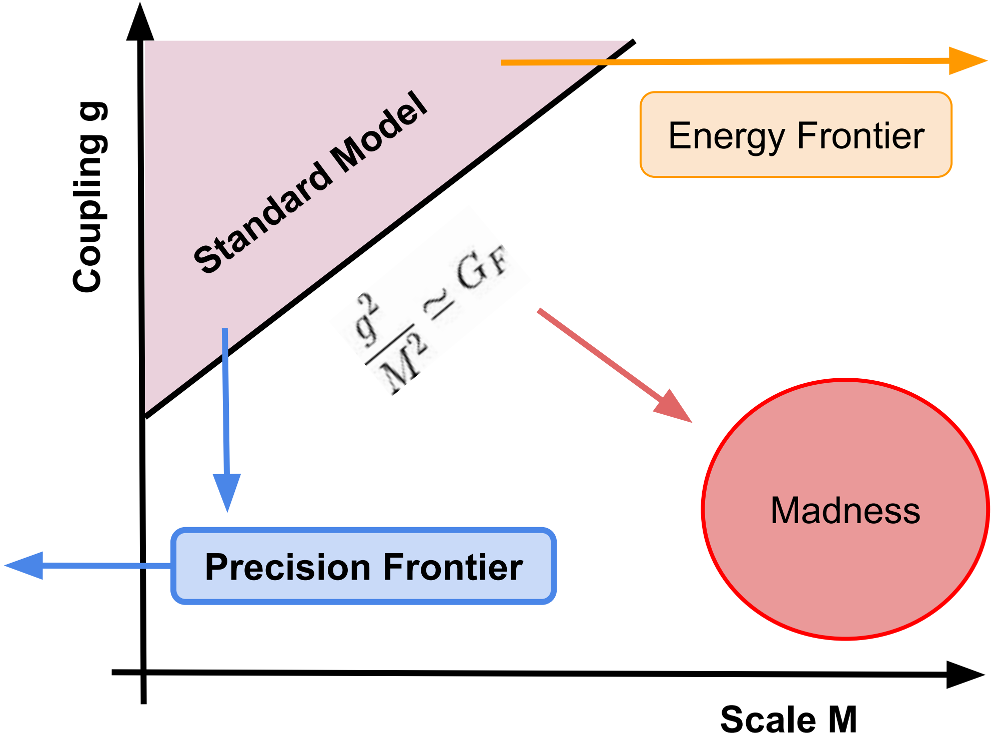


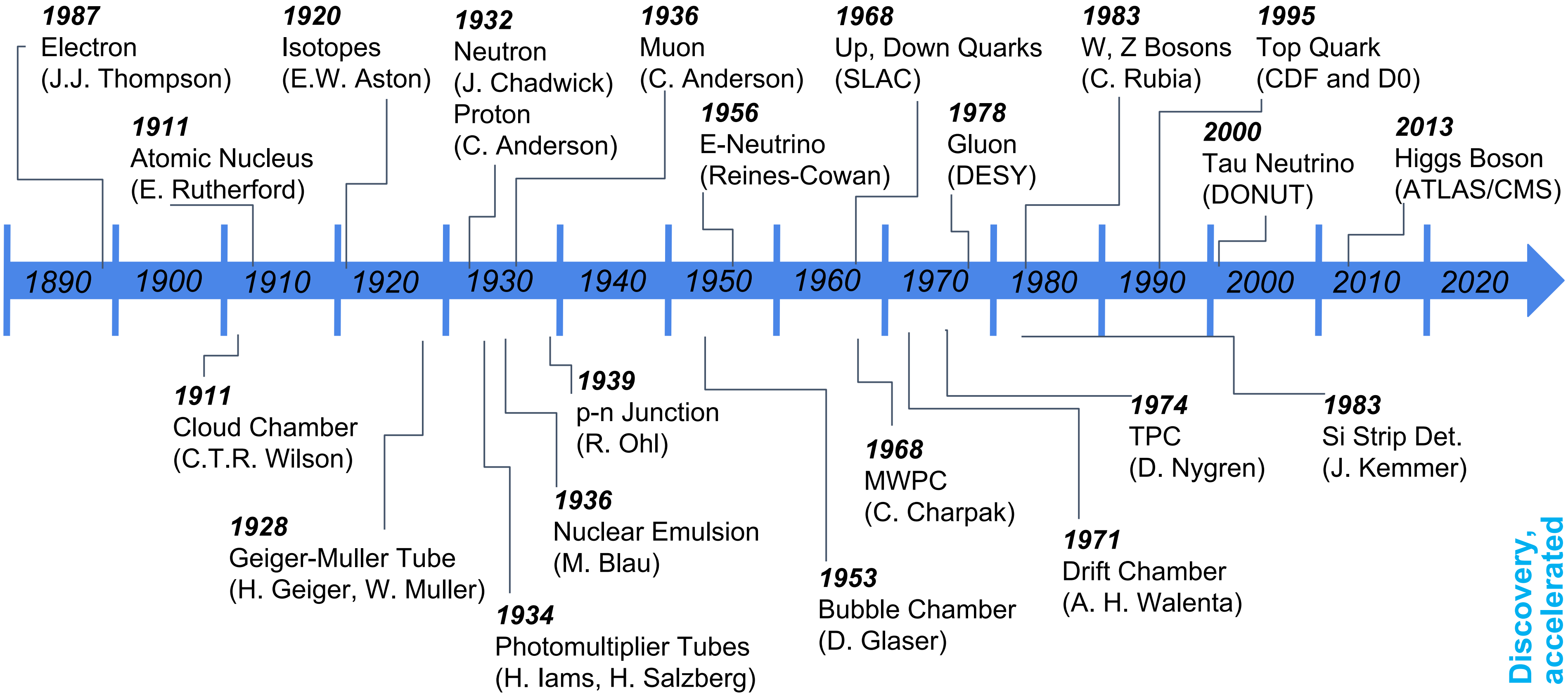
Life at the Frontier of the Standard Model

This requires new ideas and innovative technologies.

[Me: Dark Matter, Neutrino and Ultra-Cold Neutron]



Timeline of Particle Physics and Technology Development



1987
Electron
(J.J. Thompson)

1911
Atomic Nucleus
(E. Rutherford)

1920
Isotopes
(E.W. Aston)

1932
Neutron
(J. Chadwick)
Proton
(C. Anderson)

1936
Muon
(C. Anderson)

1956
E-Neutrino
(Reines-Cowan)

1968
Up, Down Quarks
(SLAC)

1978
Gluon
(DESY)

1983
W, Z Bosons
(C. Rubia)

1995
Top Quark
(CDF and D0)

2000
Tau Neutrino
(DONUT)

2013
Higgs Boson
(ATLAS/CMS)

1911
Cloud Chamber
(C.T.R. Wilson)

1928
Geiger-Muller Tube
(H. Geiger, W. Muller)

1934
Photomultiplier Tubes
(H. Iams, H. Salzberg)

1936
Nuclear Emulsion
(M. Blau)

1939
p-n Junction
(R. Ohl)

1953
Bubble Chamber
(D. Glaser)

1968
MWPC
(C. Charpak)

1971
Drift Chamber
(A. H. Walenta)

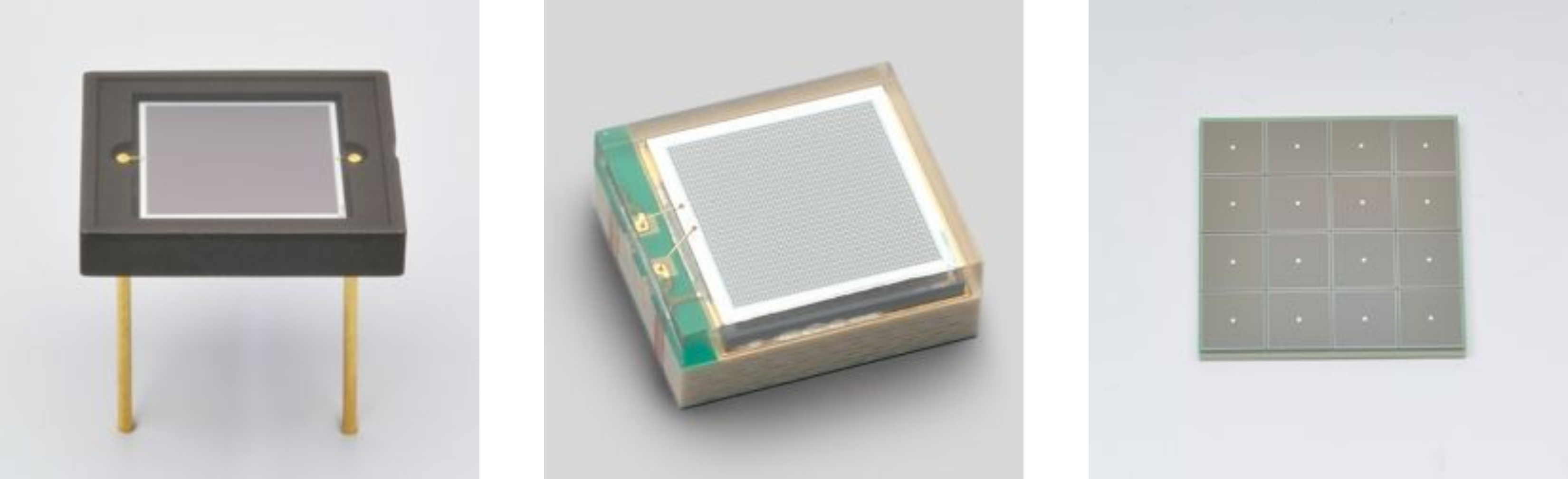
1974
TPC
(D. Nygren)

1983
Si Strip Det.
(J. Kemmer)

How Do SiPMs Work?

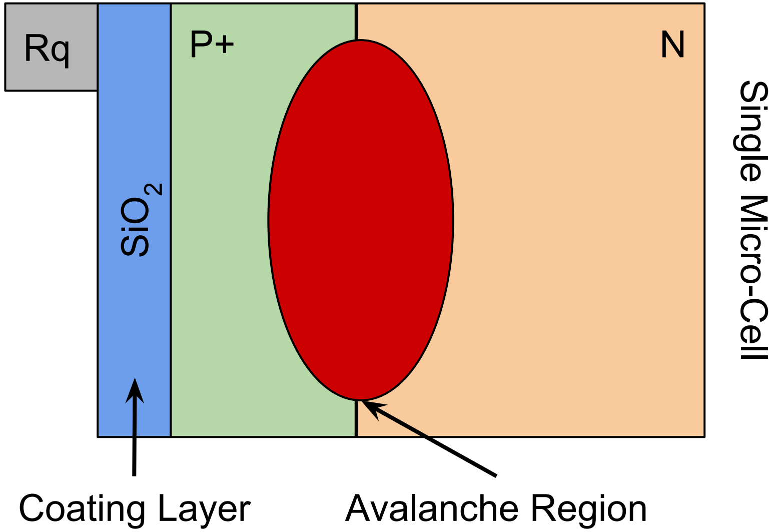
How Do SiPMs Work?

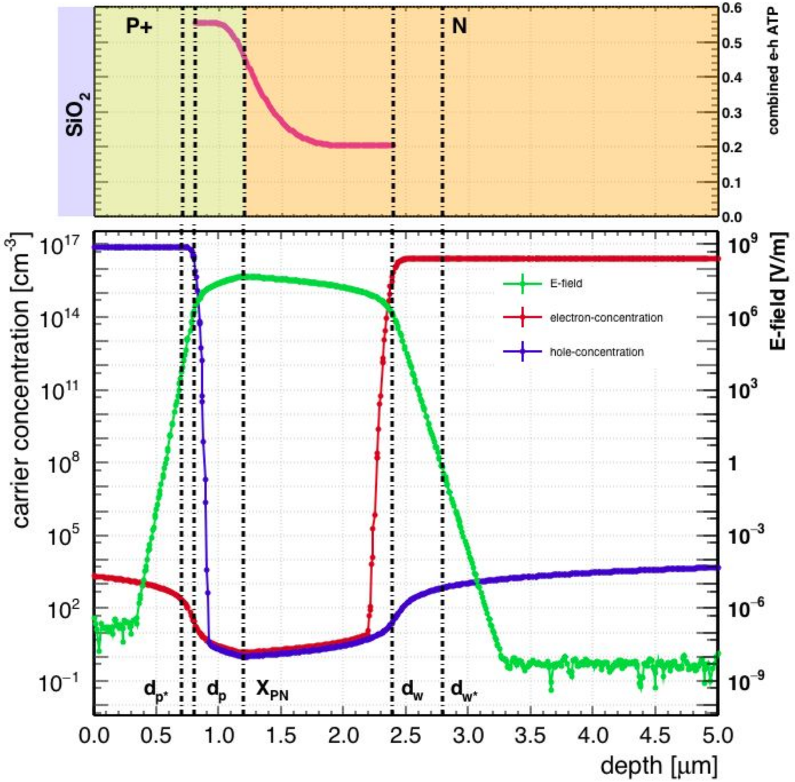
Silicon Solid State Devices, using the photoelectric effect to convert photons to electron/hole pair. Primarily, rely on p-n junctions for carrier amplification.



How Do SiPMs Work? Solid-State Approach

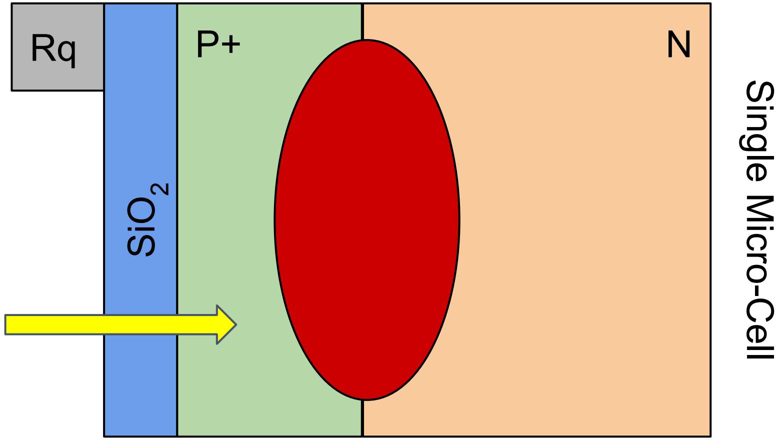
p-n junctions micro-cells operated in
Geiger-mode, with an added quenching resistor.
Each SiPM is composed by multiple micro-cells.

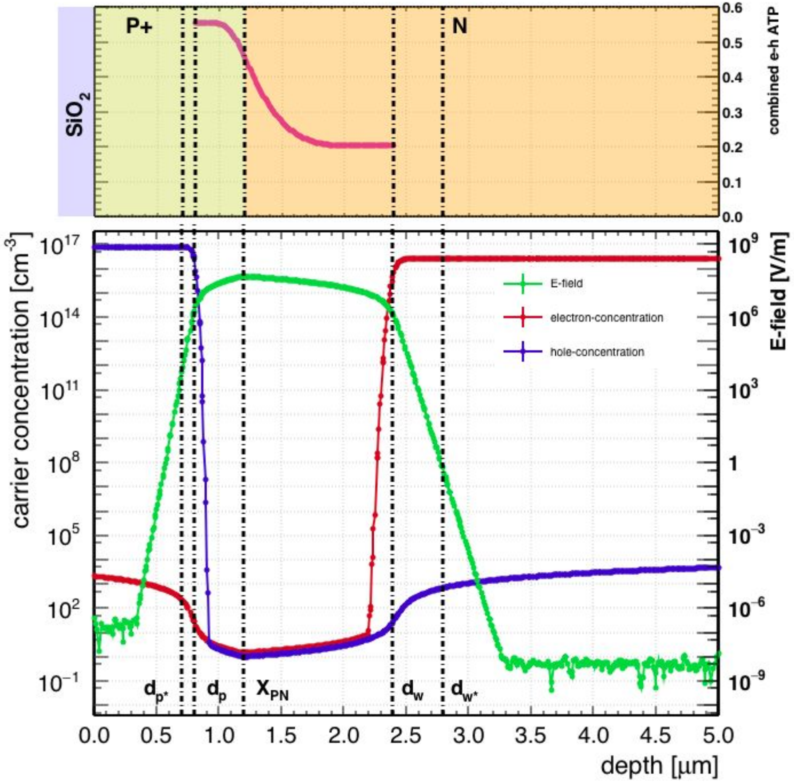




How Do SiPMs Work? Solid-State Approach

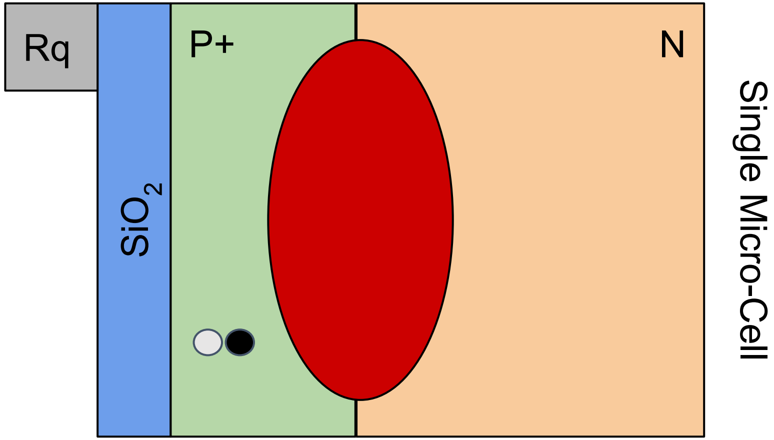
An incoming photon enters the junction and it is absorbed (wavelength dependent process).

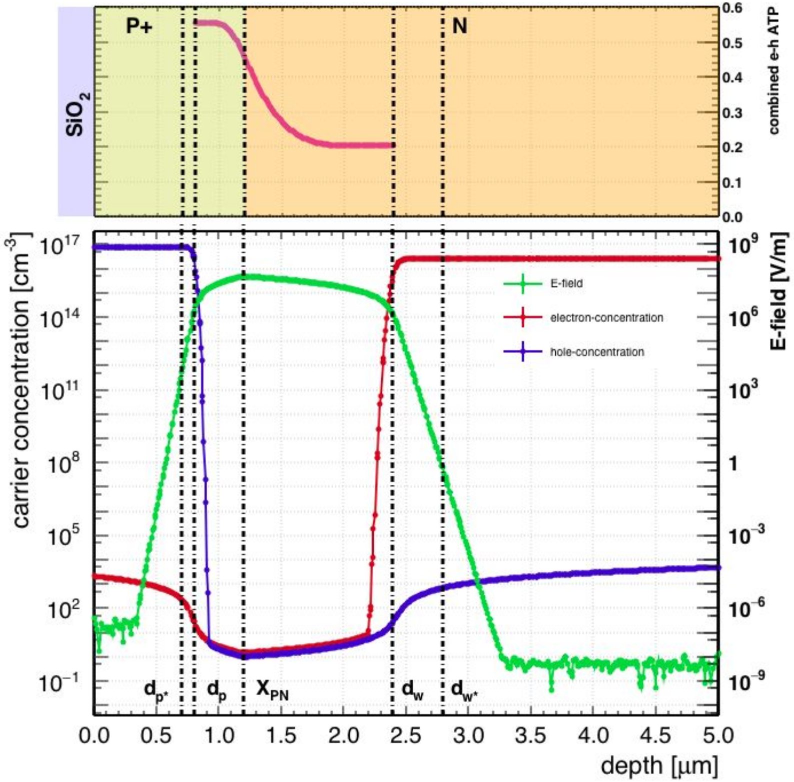




How Do SiPMs Work? Solid-State Approach

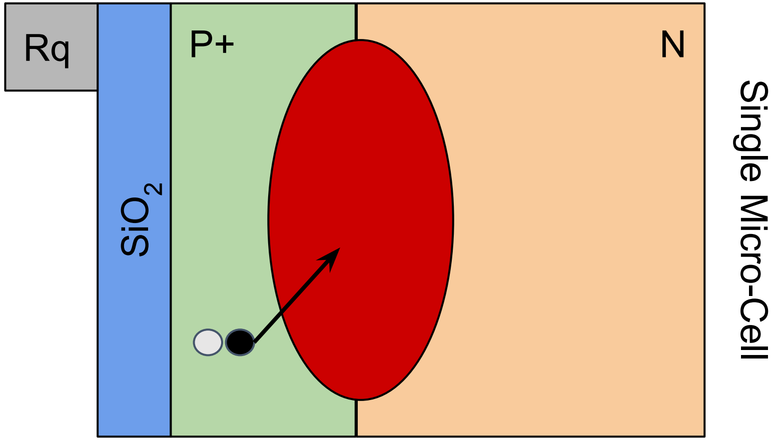
The absorbed photons generates an electron-hole pair in the absorption region.

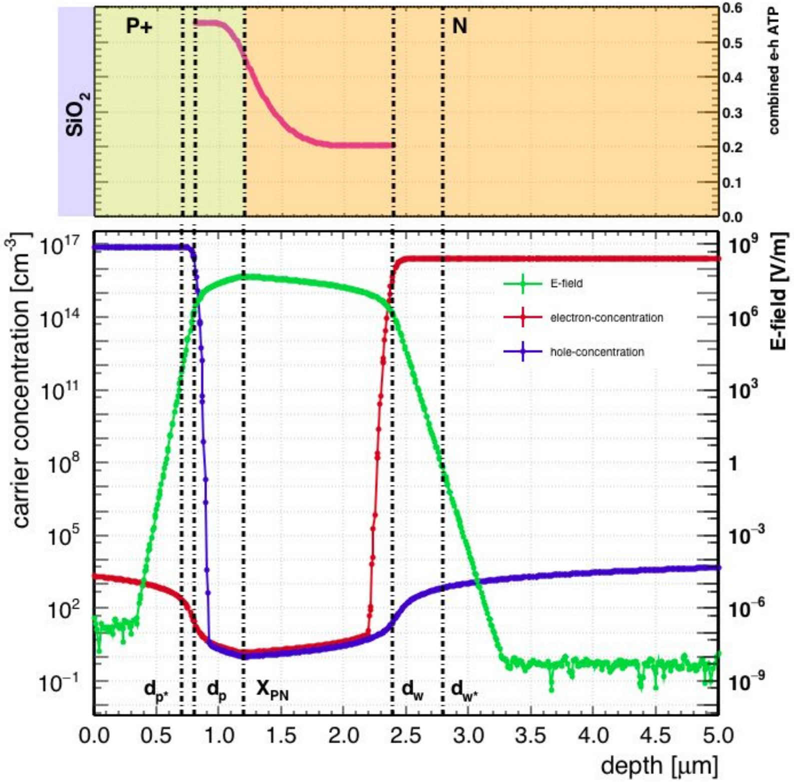




How Do SiPMs Work? Solid-State Approach

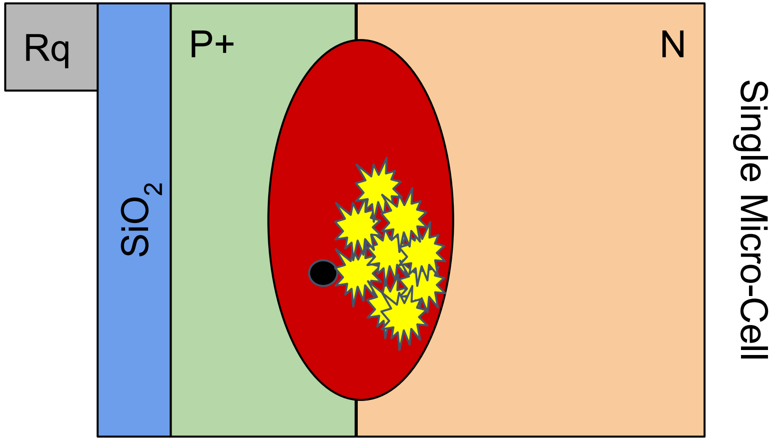
The internal field of the junction brings the generated carrier (e/h) to the avalanche region.

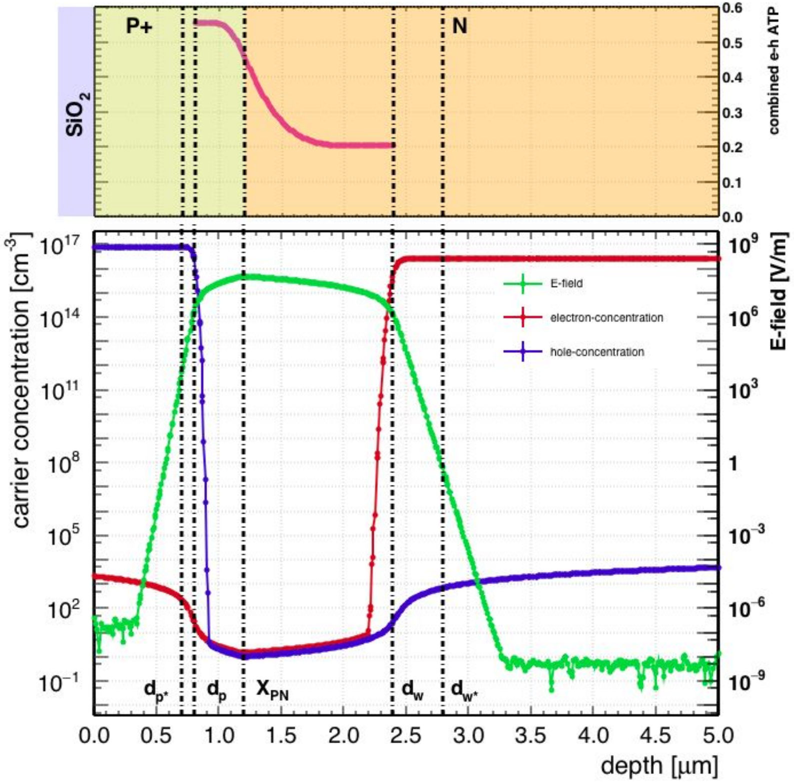




How Do SiPMs Work? Solid-State Approach

This triggers an avalanches, with gain ~10^6-10^7, which produces a readable signal.





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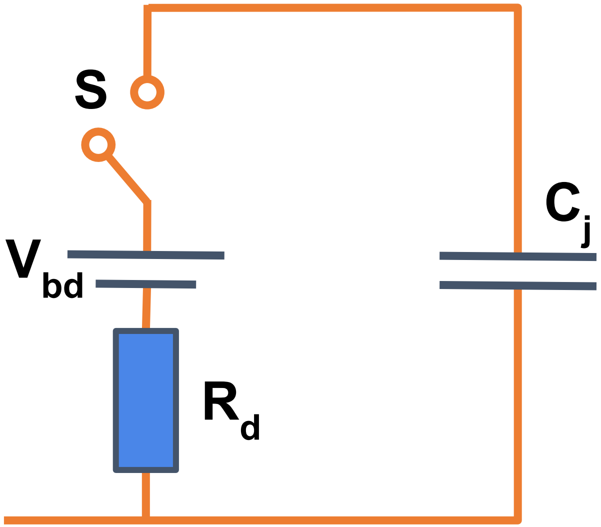
How Do SiPMs Work? Electronics Approach



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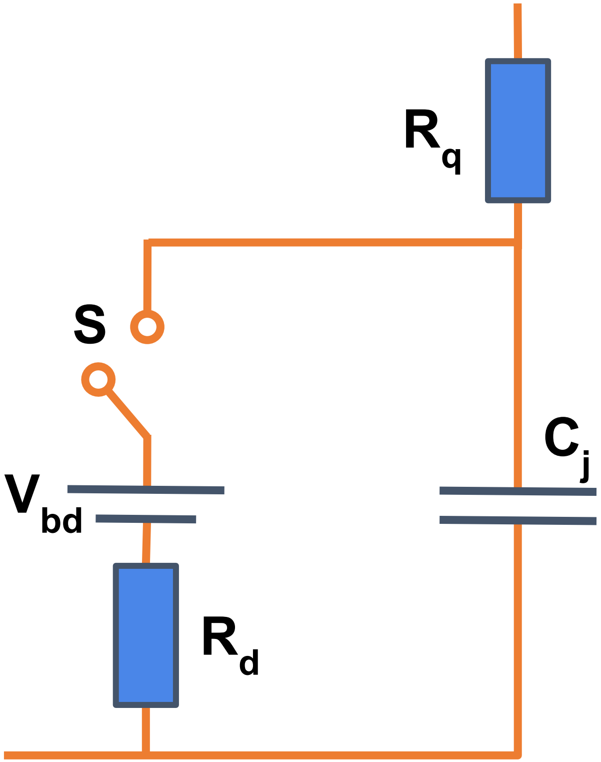

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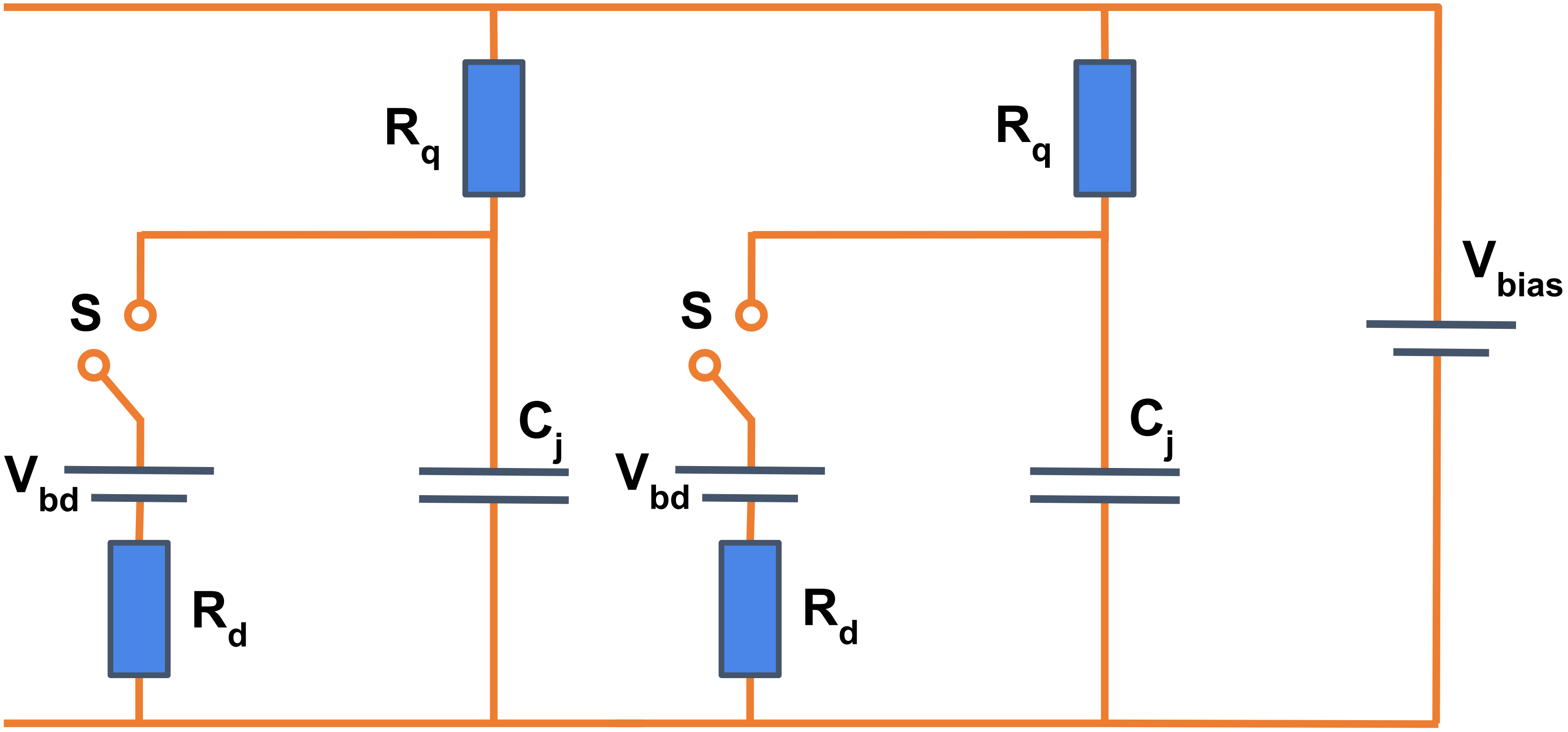

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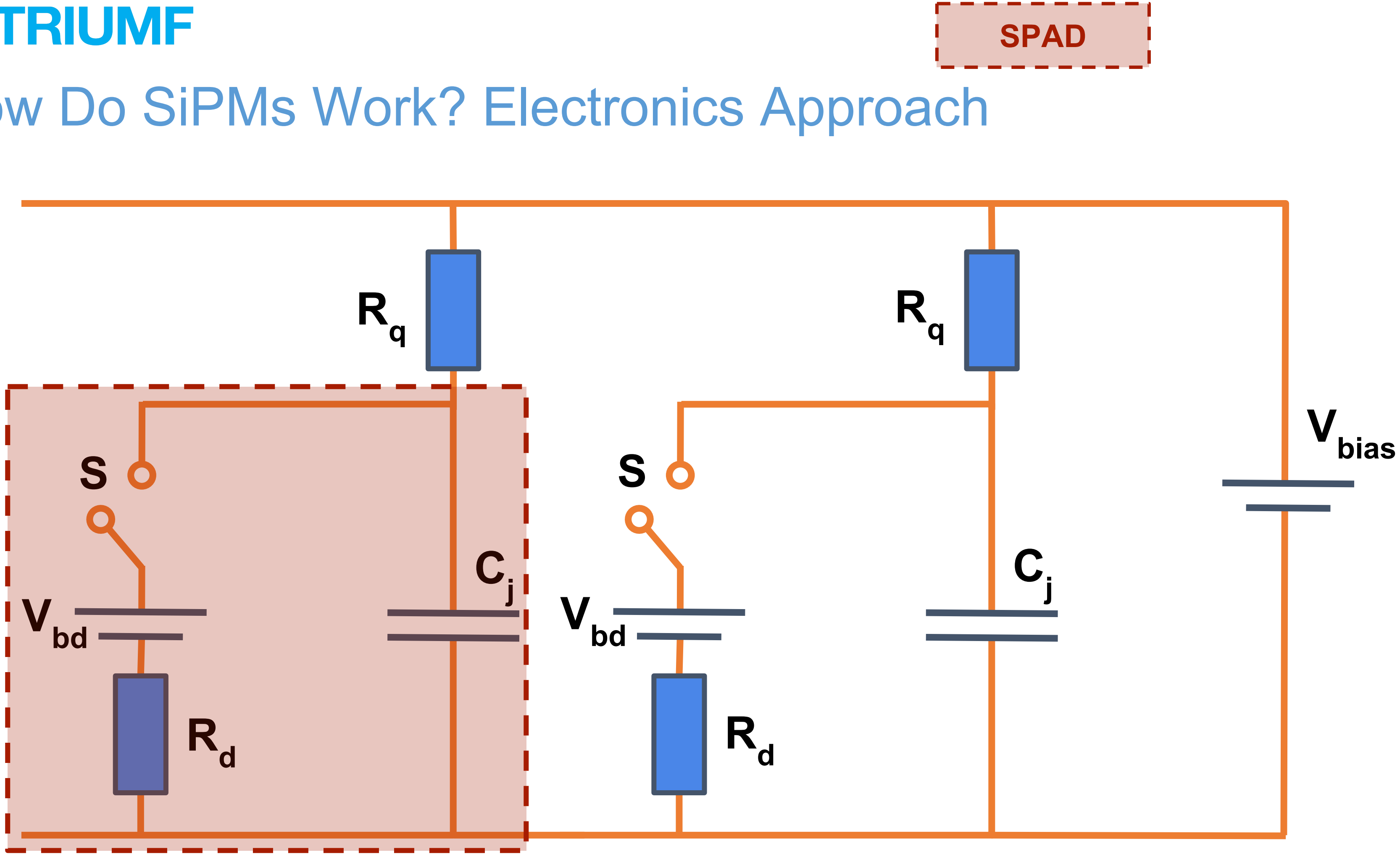
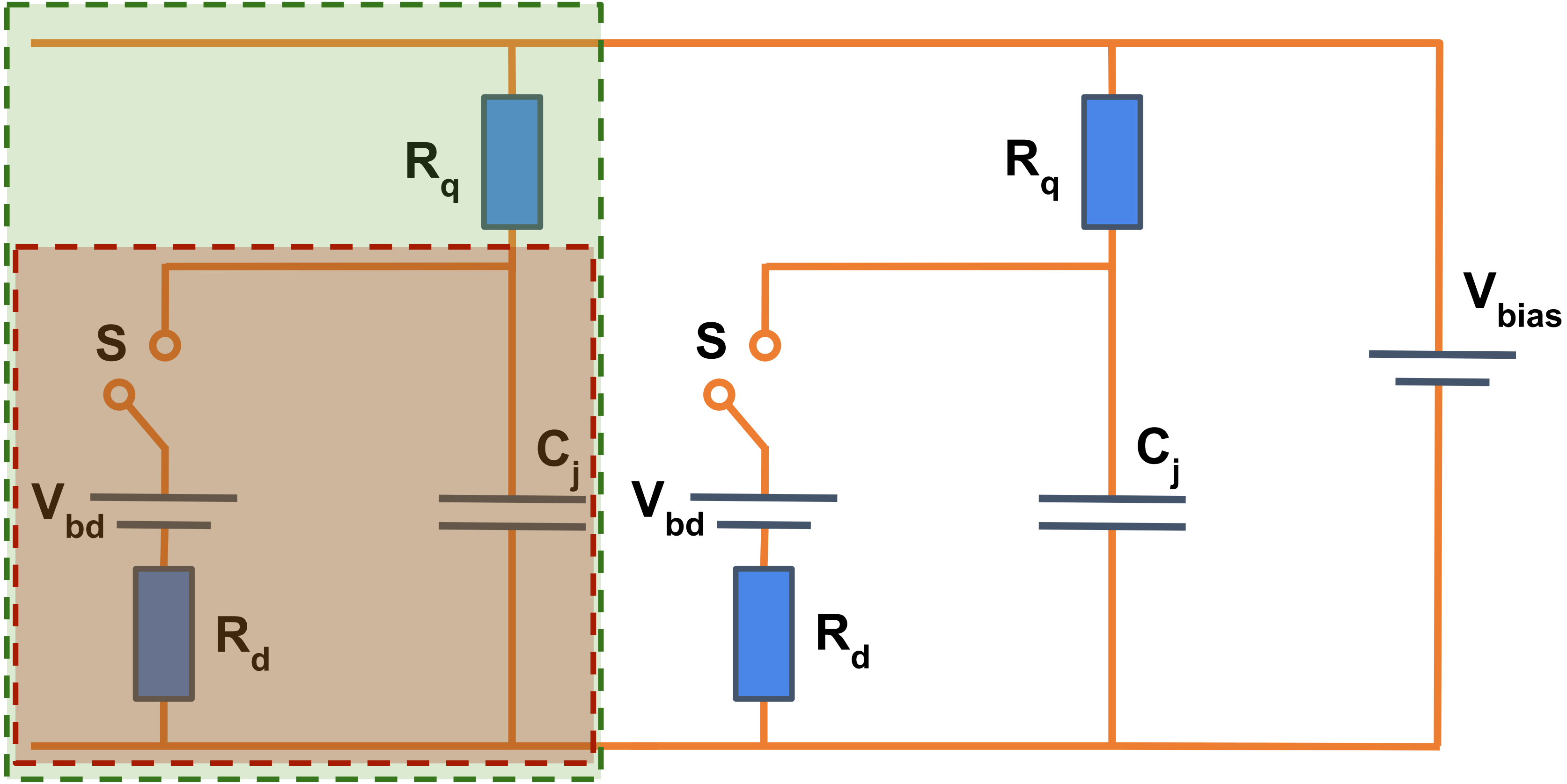


How Do SiPMs Work? Electronics Approach

🟥 SPAD

🟩 Microcell



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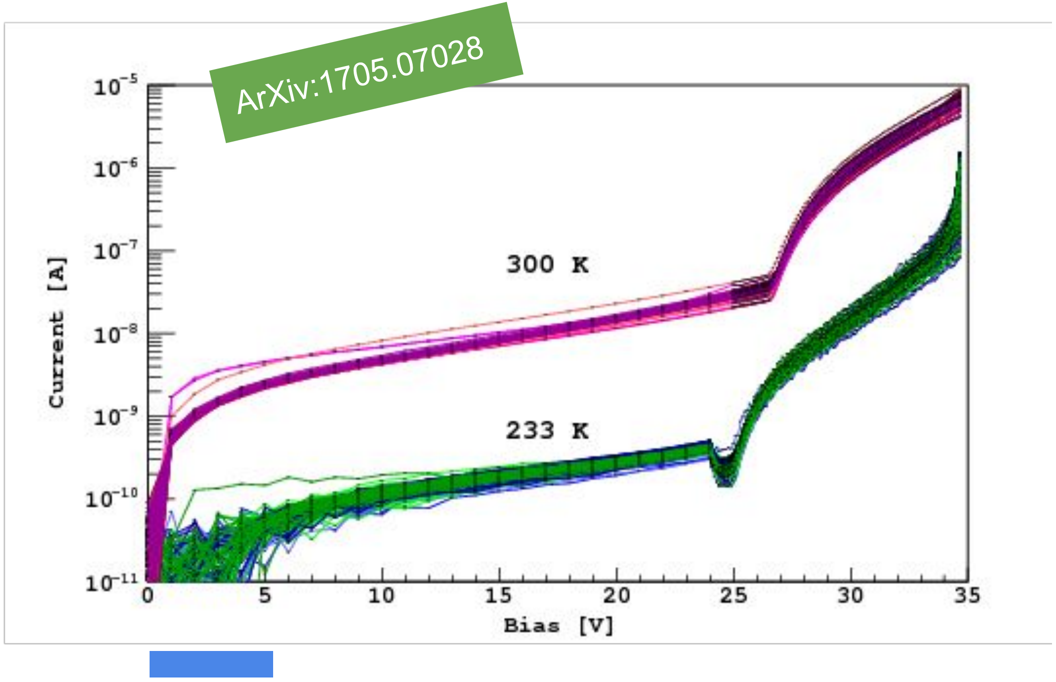
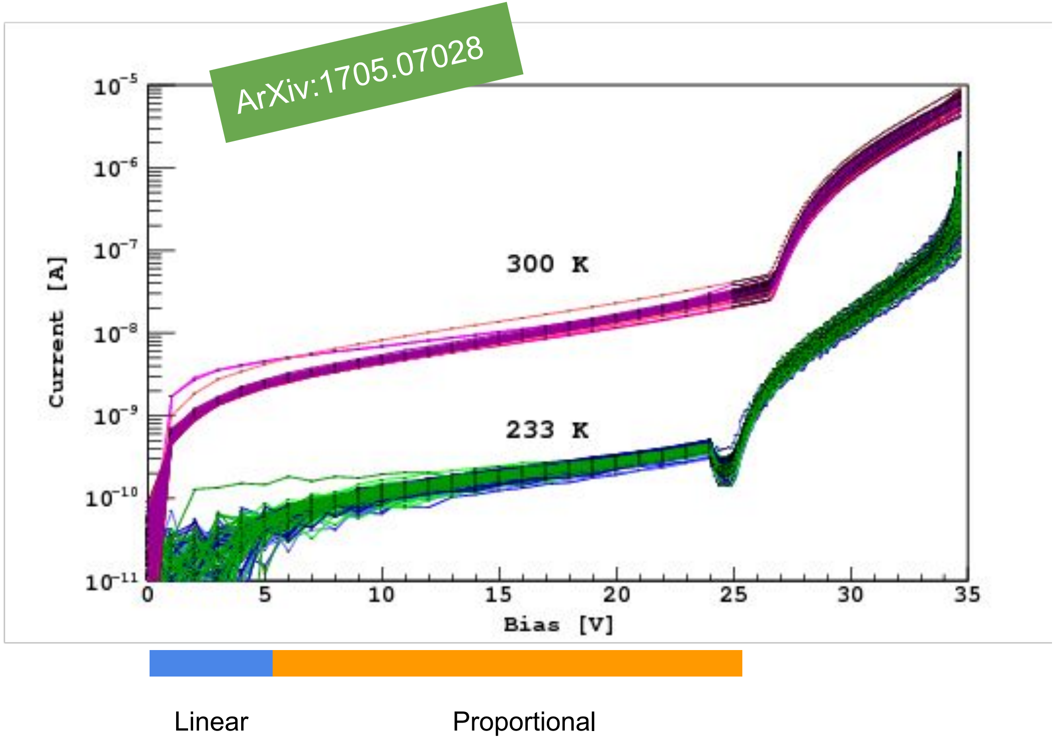


Linear

Linear Mode: Simple diode function, simply extract the generated carrier (e/h) after photon-absorption.

How Do SiPMs Work? Electronics Approach

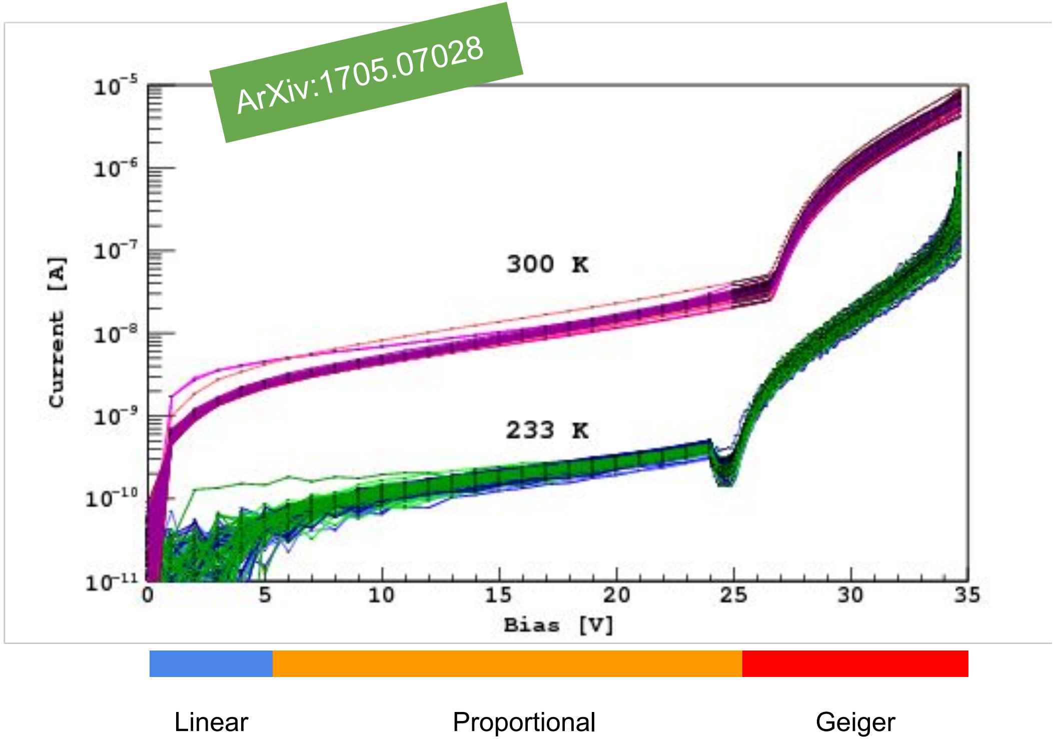


ArXiv:1705.07028

Linear Mode: Simple diode function, simply extract the generated carrier (e/h) after photon-absorption.

Proportional Mode: Simple Avalanche-Photo-Diode (APD), the generated carrier (e/h) undergoes gentle amplification (gain ~10-100).

How Do SiPMs Work? Electronics Approach



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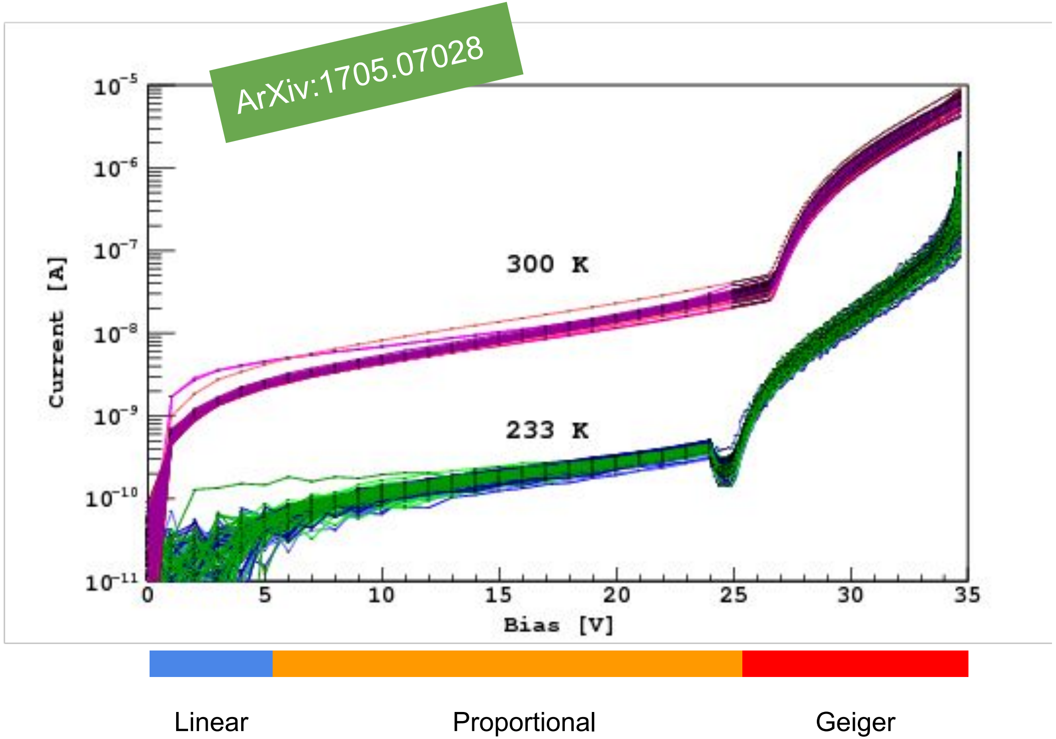
Geiger Mode: SiPM range. Here the generated carrier (e/h) is subject to strong amplification (gain ~10^6-10^7).

How Do SiPMs Work? Electronics Approach



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Breakdown Voltage: Corresponds to the bias voltage value at which the device switches from Proportional to Geiger mode.

SiPM vs Other Photo-Sensor Techniques

Technology	PMT	APD	SiPM
Gain	10^6 - 10^7	<100	10^6 - 10^7
Bias Voltage	~1200 V	~200 V	~50 V
Timing	Sub-ns	ns	Sub-ns (ps)
Photo Counting	Good	Good	Excellent
Temp Sensitivity	Low	High	Medium
Magnetic Fields	Shielding Needed	Immune	Immune
Warm Up Time	Required (min)	Instantaneous	Instantaneous
Ambient Ɣ Exposure	Can Cause Damage	No Damage	No Damage

SiPM Challenges

- **Radiopurity:** Easy to make very radiogenically pure SiPMs, but very difficult to package them with equally pure encapsulation and substrates.

- **Size:** Currently individual SiPM vary in size from 1x1 mm to 12x12 mm and more, challenge is to scale up to m^2 (without being limited by noise effects).

- **Timing:** Current SiPM are somewhat limited by the recovery time (comparable to fast PMTs), innovative approaches could get push timing to few ps.

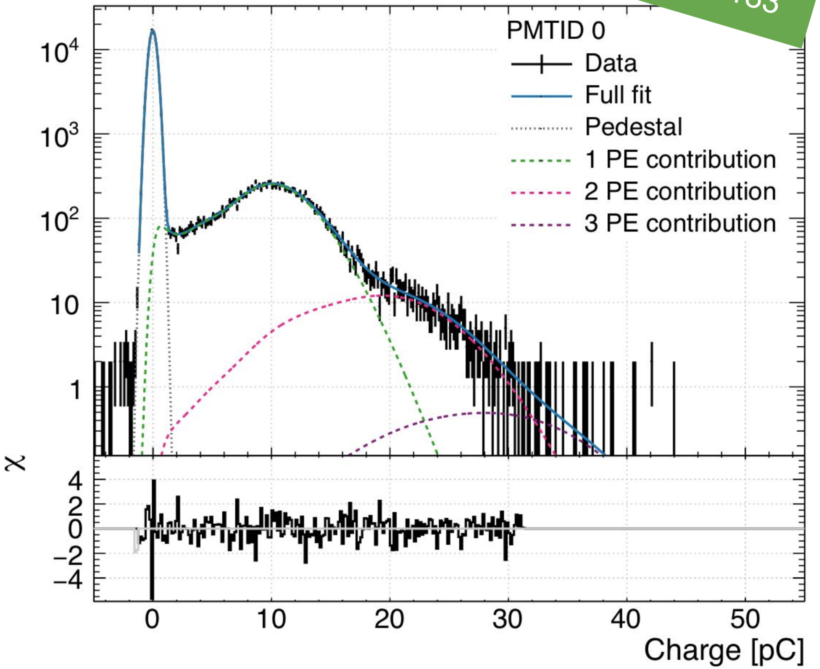
- **Noise:** At room temperature thermionic noise is still a limiting factor (reduced by several order of magnitudes at Cryogenics temperature). However, other correlated noise effect are also prominent in current SiPM.

Characterization Model for SiPMs

Photon Counting Abilities

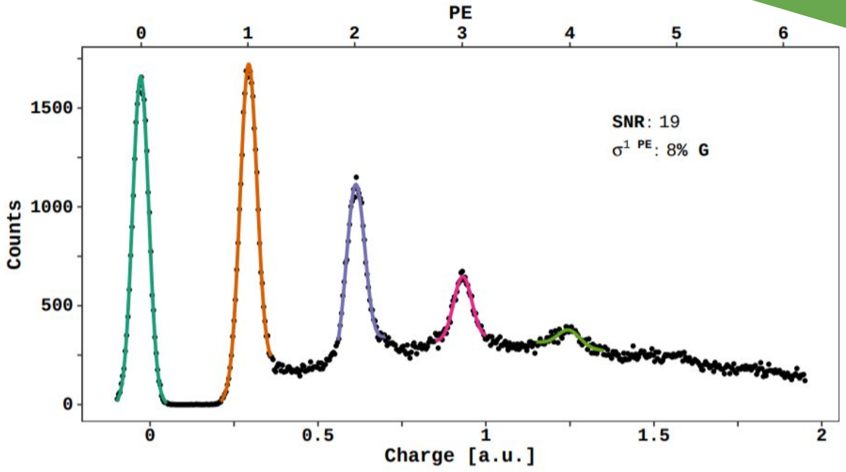
DEAP-3600 PMT:
Hamamatsu R5918 8” PMTs

ArXiv:1705.10183



DarkSide-20k SiPM:
Fondazione Bruno Kessler 1x1 cm

ArXiv:1705.07028



Because of their discrete structure SiPM are outstanding photo-counters. Well separated single to multiple Photo-Electrons Peaks.

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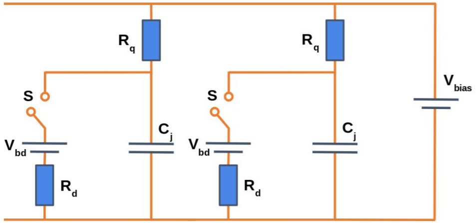
Output Signal and Pulse Shape

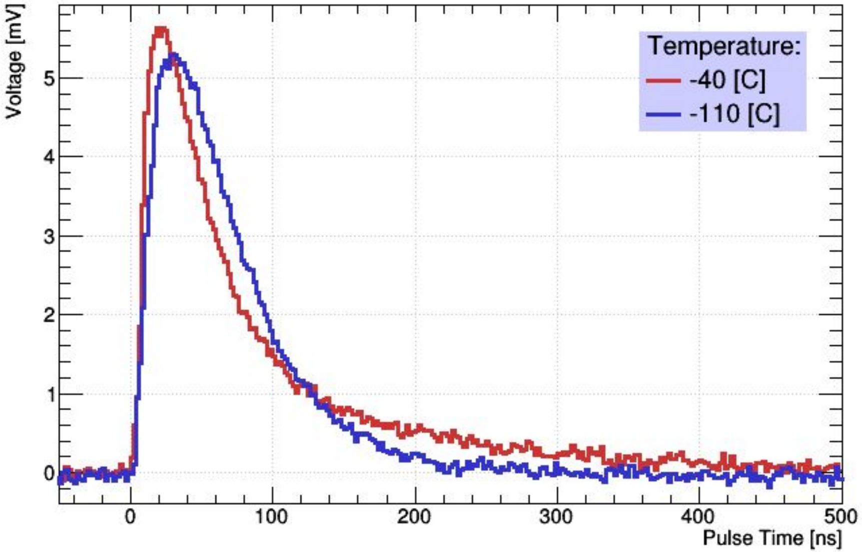
Rise Time: $\tau_r \propto (R_d \cdot C_j)$

Parasitic Spike: $\tau_S \propto (R_{tot} \cdot C_{tot})$

Recovery Time: $\tau_L \propto (R_q \cdot C_j)$

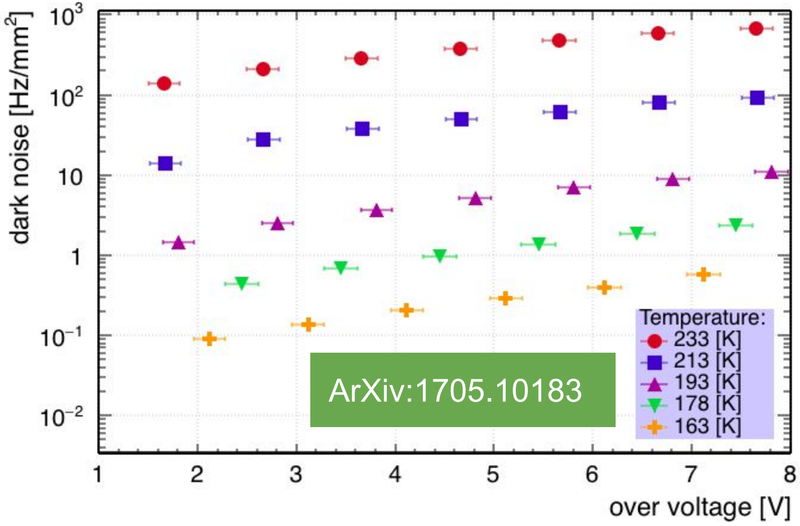
k: relative contribution of t_S and t_L.





$$V(t) = A \cdot \left[\left(\frac{1-k}{\tau_S} \right) \cdot \left(e^{-t/(\tau_S+\tau_r)} - e^{-t/\tau_r} \right) + \left(\frac{k}{\tau_L} \right) \cdot \left(e^{-t/(\tau_L+\tau_r)} - e^{-t/\tau_r} \right) \right]$$

SiPM Gain and Dark Noise



ArXiv:1705.10183

Over Voltage = Bias V - Breakdown V

Example using Hamamatsu VUV4 SiPMs.

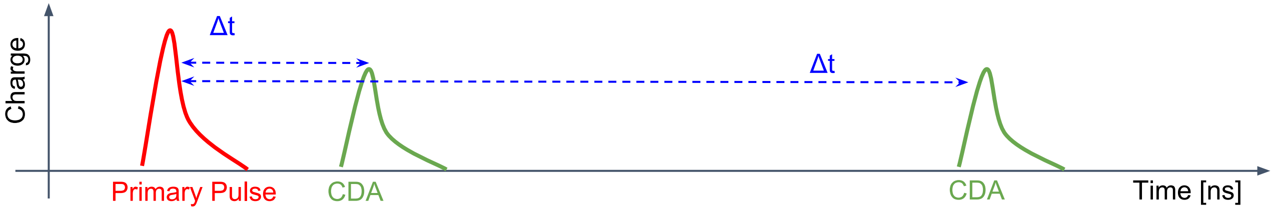
- Dark Noise pulses (DN) are charge signals generated by the formation of electron-hole pairs due to thermionic or field enhanced processes.
- Free carrier will undergo the standard avalanche process.
- Temperature dependent.
- Bias voltage dependent.
- DN Rate ~ 0.1 [Hz/mm^2] at LXe Temperatures (163 [K]).

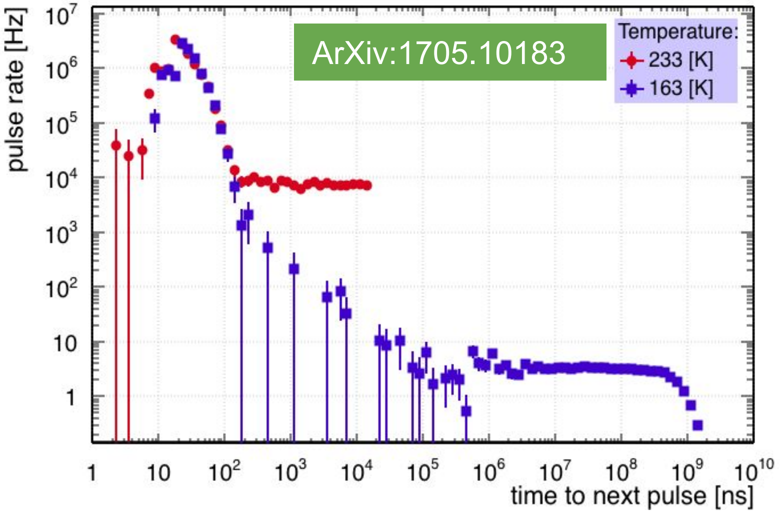
Correlated Avalanches Noise

Correlated Avalanche noise is due to at least two processes:

1. **Correlated Delayed Avalanches:** Trapping and subsequent release of charge carriers produced in avalanches (similar to the PMTs after-pulsing effect).
2. **Cross-Talk:** Production of secondary photons during the avalanche in the gain amplification stage detected in nearby cells or reflected back to the original cell for a secondary avalanche.

Correlated Delayed Avalanches (CDAs)

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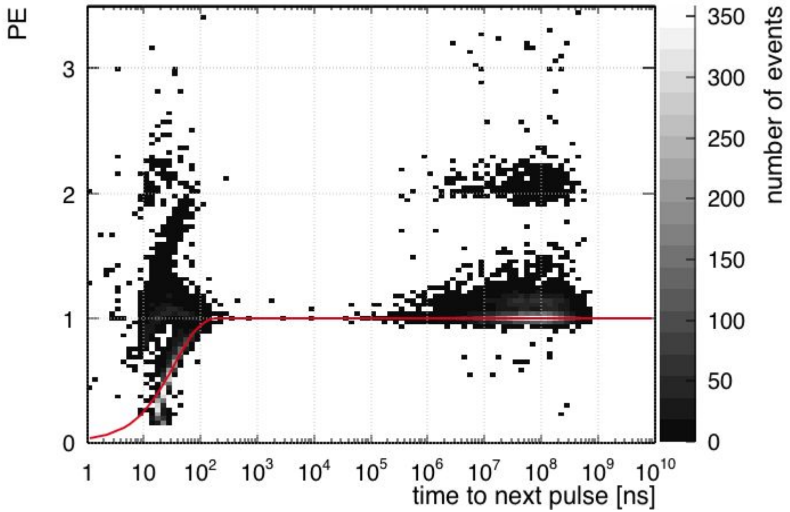
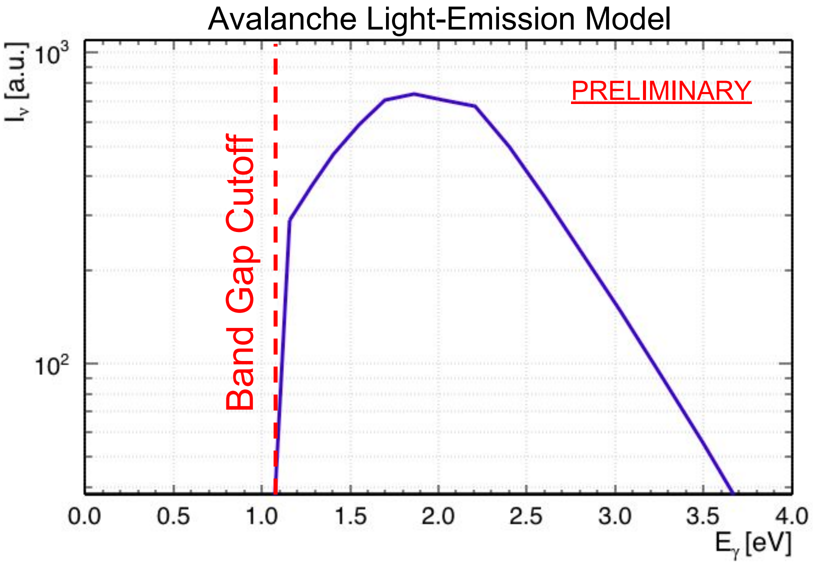
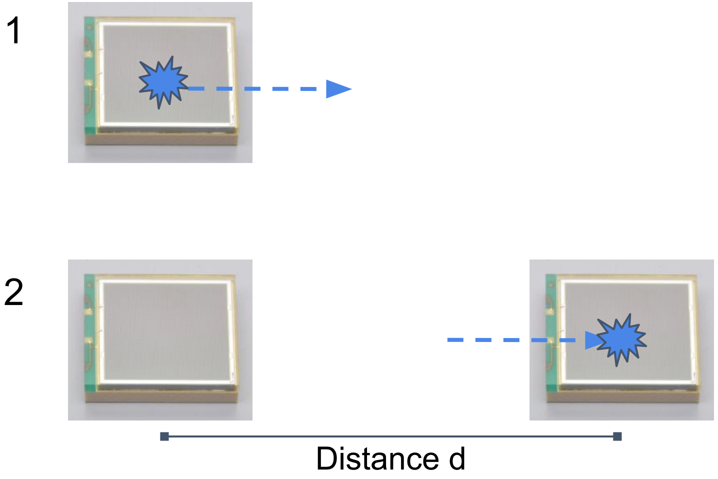


Cross-Talk

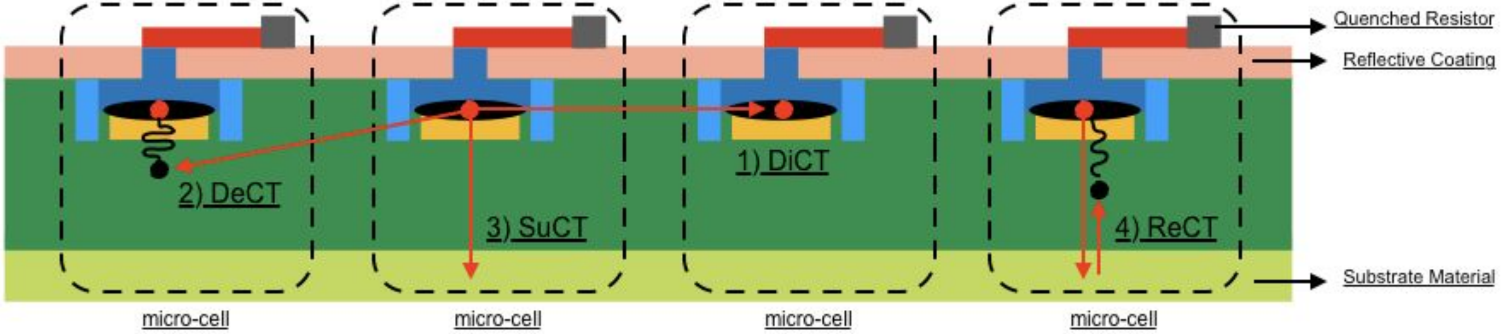
The carrier induced avalanche in the depleted region reaches high enough temperature to create a quasi-plasma, which can emit photons in a broad spectrum (Interband transition and bremsstrahlung radiation). The emitted radiation can reach and be detected a nearby SiPM.





Cross-Talk Effect

There are different types of Cross-Talk and they are heavily dependent on the structure of the micro-cell. Overall all there are four type of internal Cross-Talk: Delayed Cross-Talk, Substrate Cross-Talk, Direct Cross-Talk, Reflection Cross-Talk.



Delayed Cross-Talk

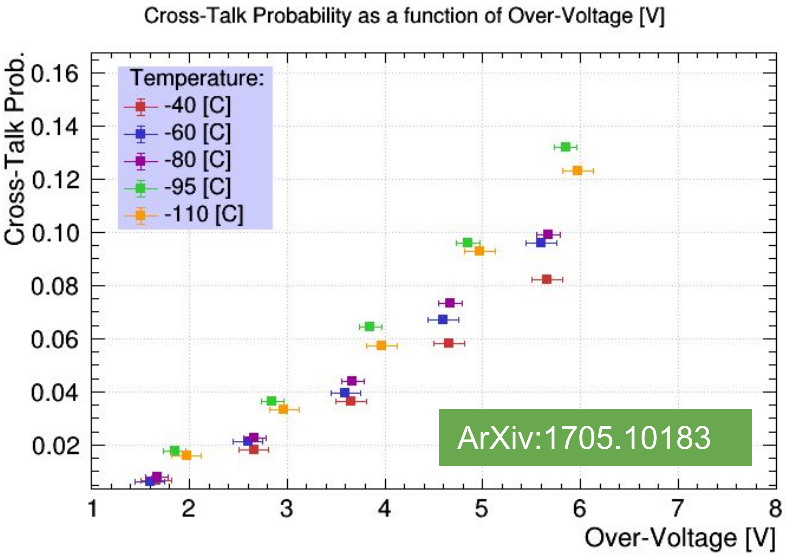
Substrate Cross-Talk

Direct Cross-Talk

Reflection Cross-Talk

Cross-Talk Effect

Different devices with different optical trenches and different substrate have very different Cross-Talk behaviour. Example with Hamamatsu VUV4 (Left) and FBK-RGB (Right).



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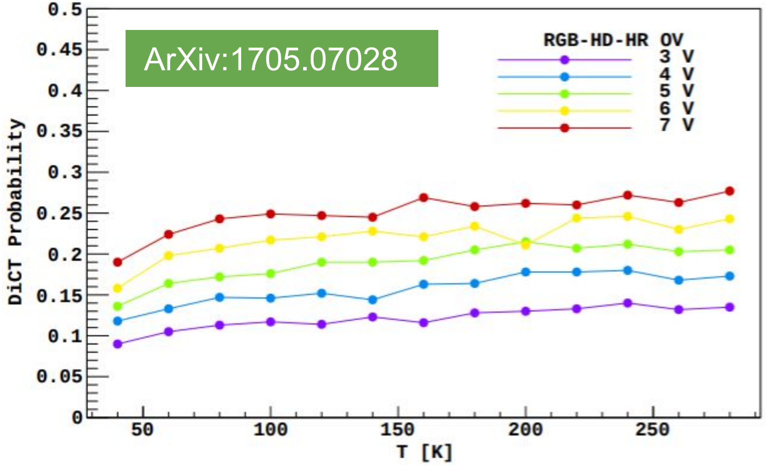


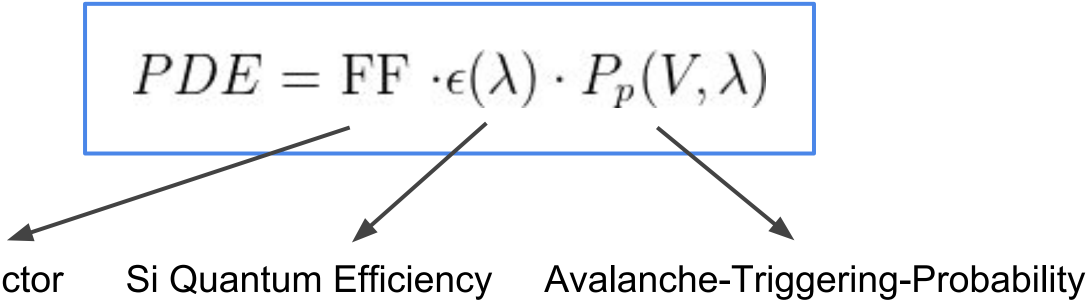
ArXiv:1705.07028

Photo-Detection-Efficiency

In general the Photo-Detection-Efficiency (PDE) is defined as the probability of a given photon (of a given wavelength) to be detected and produce a measurable signal in the SiPM.

Relative PDE measurements are “easy”, however, absolute PDE measurements are tricky.

In detail PDE depends not only on the device properties but also on the inpinning photon.
A more accurate definition of PDE can be given as the following:



$$PDE = \mathrm{FF} \cdot \epsilon(\lambda) \cdot P_p(V,\lambda)$$

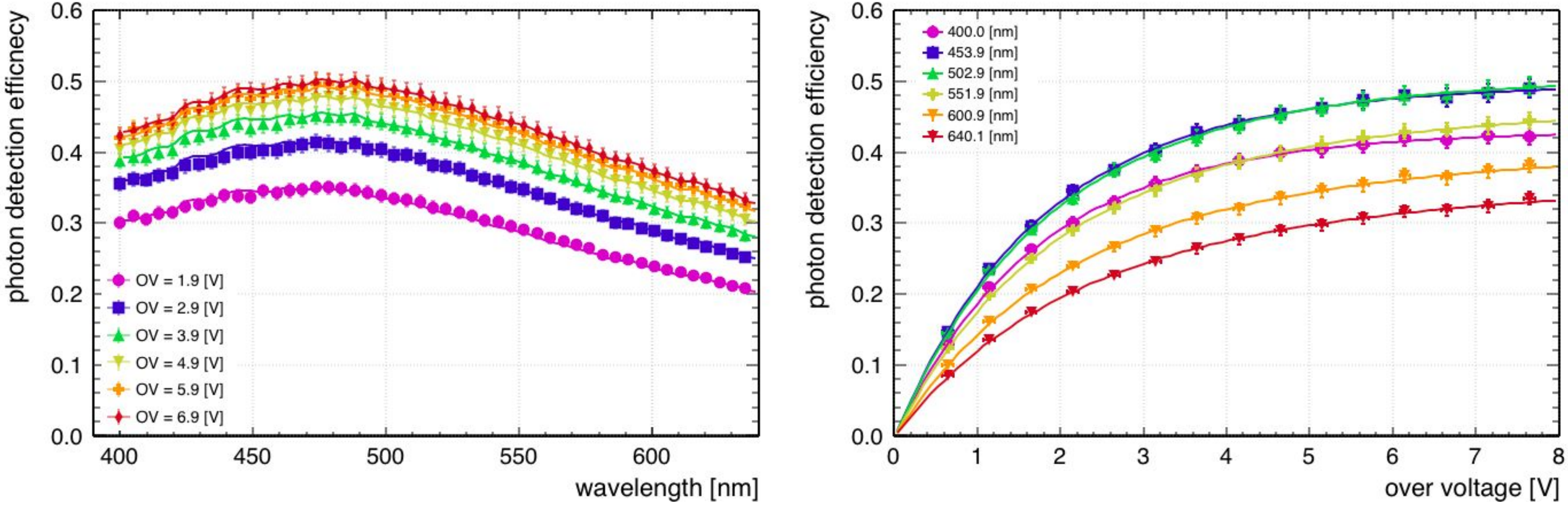
Fill-Factor

Si Quantum Efficiency

Avalanche-Triggering-Probability

Photo-Detection-Efficiency

As anticipated the PDE is dependent on the wavelength of the incoming photon and also on the bias voltage of the device. However, after a certain V value the PDE saturated (PDE_{max}).



Avalanche Triggering Probability

ArXiv:1904.05977

PDE needs to account for the fact that if the photon is absorbed outside of the active region, it will not be observed.

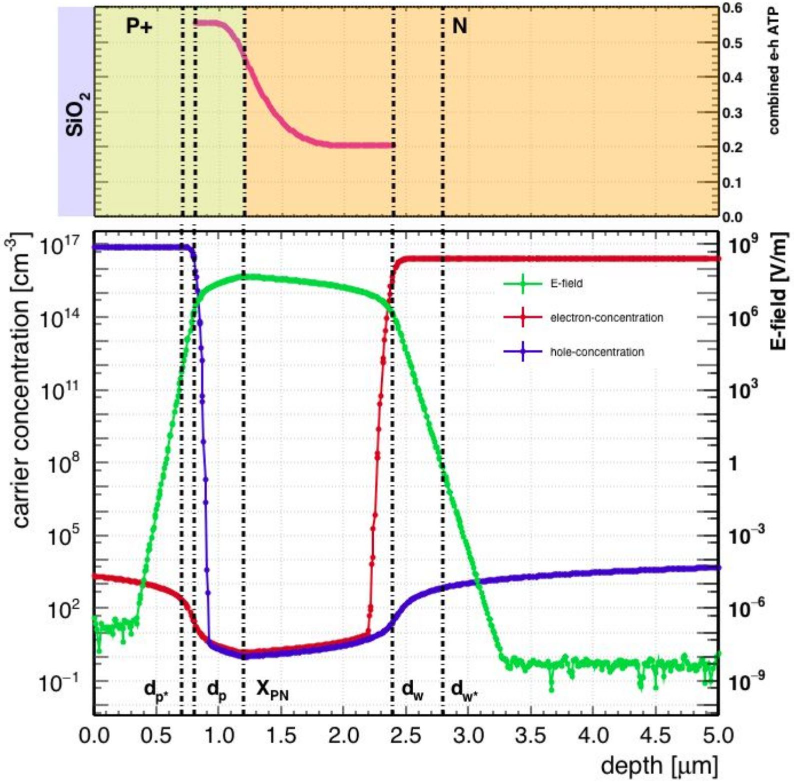
$$\mathrm{PDE} = \epsilon_0 \cdot \int_{d_P^*}^{d_W^*} \frac{1}{\mu} \exp\left(-\frac{x}{\mu}\right) \cdot \mathrm{P_P}(x,V)\ \mathrm{dx}$$

The Total Avalanche Triggering Probability has both an electron-driven and a hole-driven component

$$\mathrm{P_P}(x,V) \equiv \Big(\mathrm{P}_e(x,V) + \mathrm{P}_h(x,V) - \mathrm{P}_e(x,V)\cdot \mathrm{P}_h(x,V)\Big)$$

The fraction of electron-driven avalanches can be expressed as the following (depends on the size of the active region):

$$f_e^* \equiv \left[\frac{1-\exp\left(-\frac{(x_{PN}-d_P^*)}{\mu}\right)}{1-\exp\left(-\frac{W^*}{\mu}\right)}\right] \in [0-1]$$



Avalanche Triggering Probability

Redefine PDE to include the avalanche triggering probabilities for electron and hole driven avalanches, and to include the PDE$_{max}$ factor.

$$\mathrm{PDE} = \mathrm{PDE}_{\mathrm{MAX}} \cdot \left(\mathrm{P}_e(d_P) \cdot f_e^* + \mathrm{P}_h(d_W) \cdot (1 - f_e^*) \right)$$

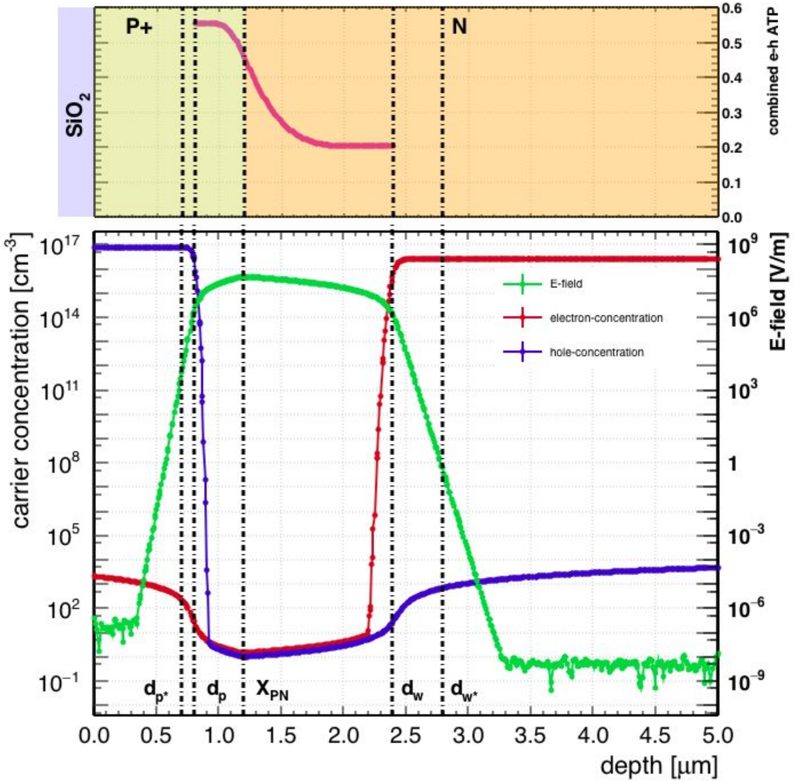
The probability to have an electron-driven avalanche is dependent on the size of the p+ active area.

$$\mathrm{P}_e(d_P) = \left[1 - \left(k_e \cdot V \cdot \exp\left(- k_{e2}/\sqrt{V} \right) \right)^{-2} \right]$$

The probability to undergo a hole-driven avalanche is dependent on P$_e$(d$_p$) and the field-strength factor in the junction k.

$$\mathrm{P}_h(d_W) = \left[1 - \left(1 - \mathrm{P}_e(d_P) \right)^{\mathrm{k}} \right]$$

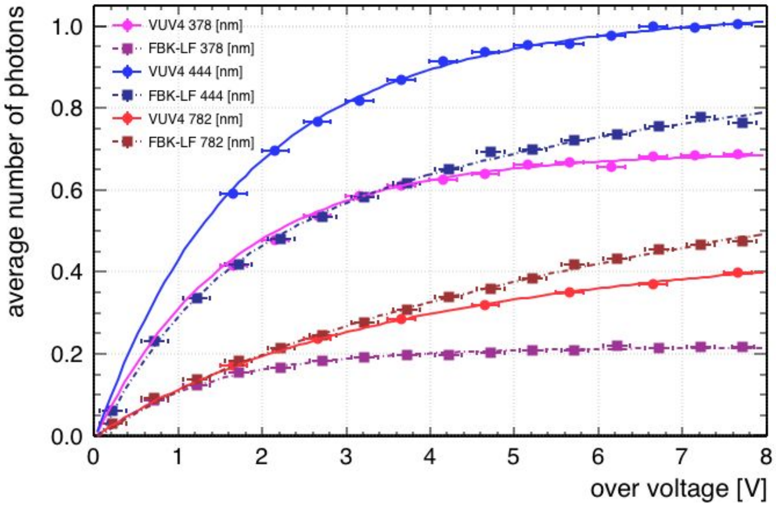
ArXiv:1904.05977



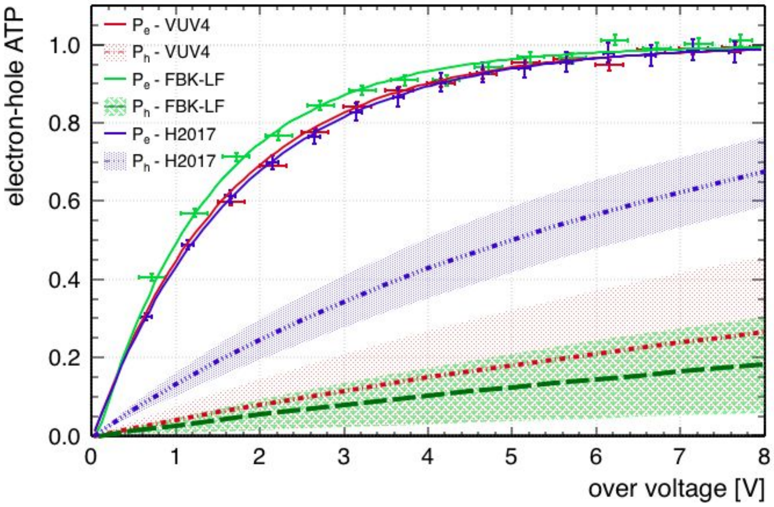
Avalanche Triggering Probability

This new characterization model was fully tested with multiple devices and at multiple wavelengths, with strong agreement across the full spectrum.

ArXiv:1904.05977



$$\mathrm{P}_e(d_P) = \left[1 - \left(k_e \cdot V \cdot \exp\left(-k_{e2}/\sqrt{V}\right)\right)^{-2}\right]$$



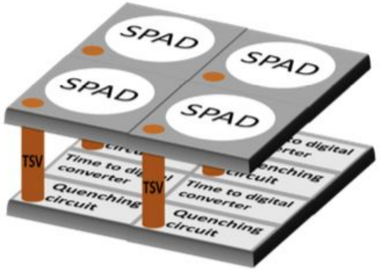
$$\mathrm{P}_h(d_W) = \left[1 - \left(1 - \mathrm{P}_e(d_P)\right)^{\mathrm{k}}\right]$$

Development of 3DSiPM

Why Digital Integration?

- Single Photon Avalanche Diodes (SPADs) are the basic unit cell of analog and digital SiPMs.
- But SPADs are effectively Boolean detectors, digital information is available at the sensor level.
- Analog SiPM sum boolean detectors (SPAD arrays) to get linear response
  [SPAD to Transimpedance Amplifier to ADC]

To Digitize the data …… AGAIN!



3D integration to fully take advantage of the SPAD’s digital nature:

- Independent optimization of detector layer and readout electronics
- One-to-one coupling minimizes digitization power, allows for CA noise mitigation, enabling/disabling cells
- One-to-one coupling between the SPAD and the Quenching circuit with uniform routing
- One-to-one coupling provides greater immunity to process, voltage and temperature variations and picoseconds timing Time-to-digital converter per pixel

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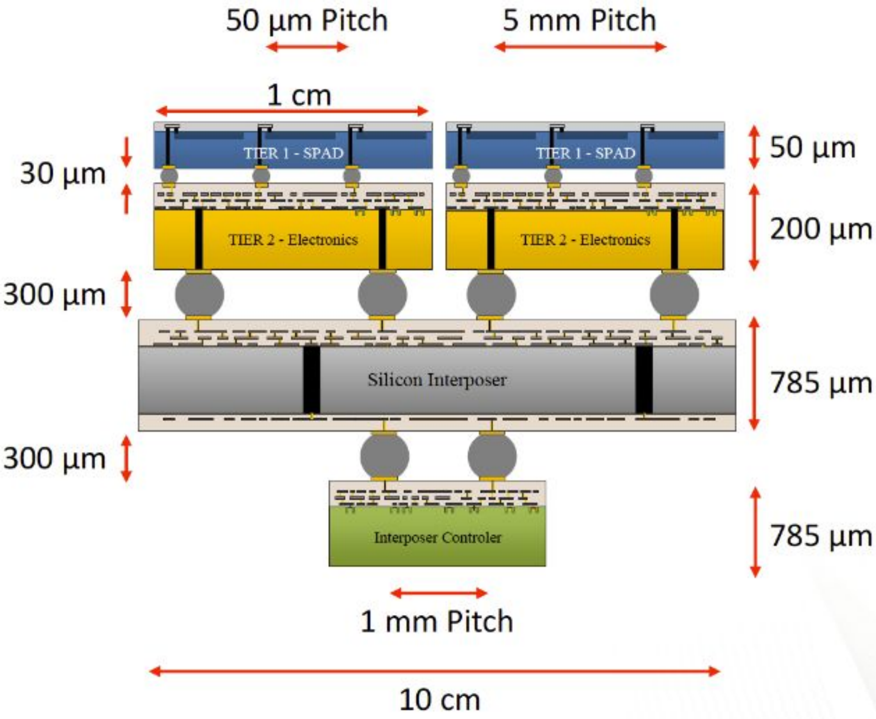
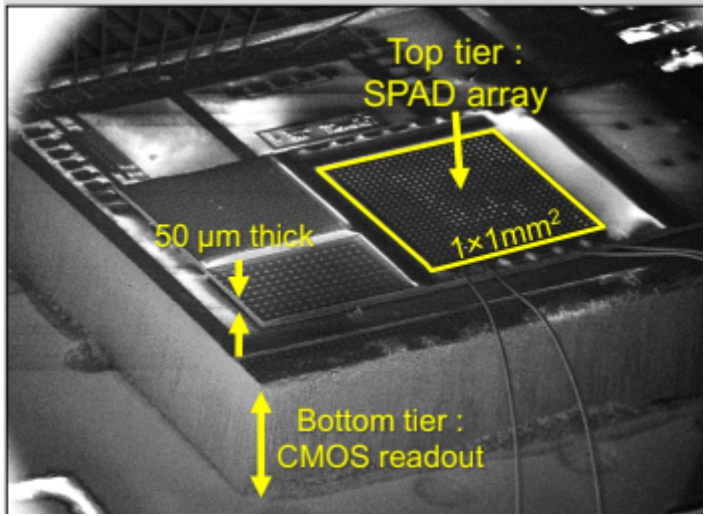
SiPM Digital Integration

S. Charlebois, CPAD 2018,
“3D Digital SiPM Development for Large Area Photodetectors”

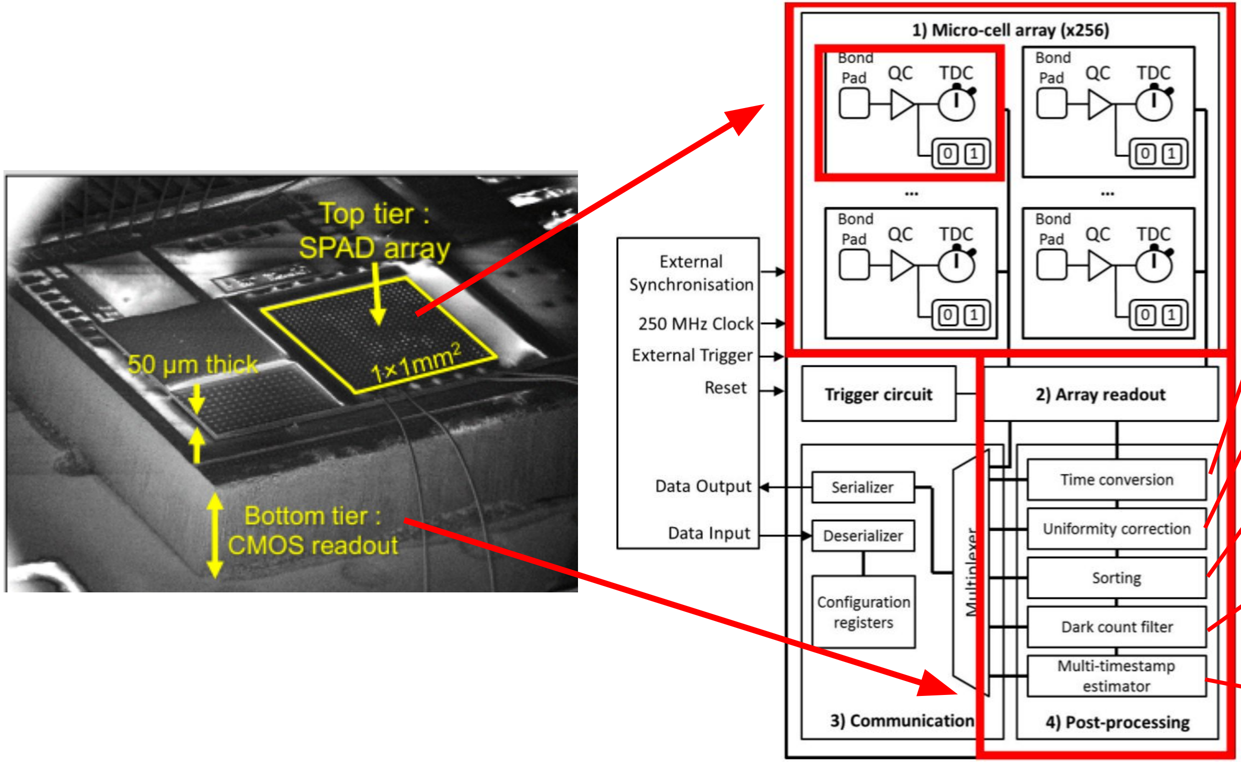




- Time-to-digital converter per pixel.
- No compromise between electronics and SPAD processes. Great photosensitive fill factor.
- Time Resolution 50-10 ps.

Discovery, accelerated

Digital Signal Processing



Time Conversion

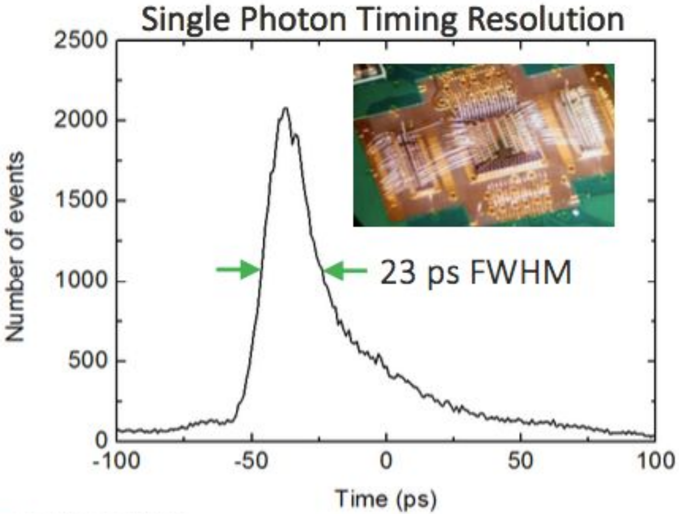
Uniformity Correction

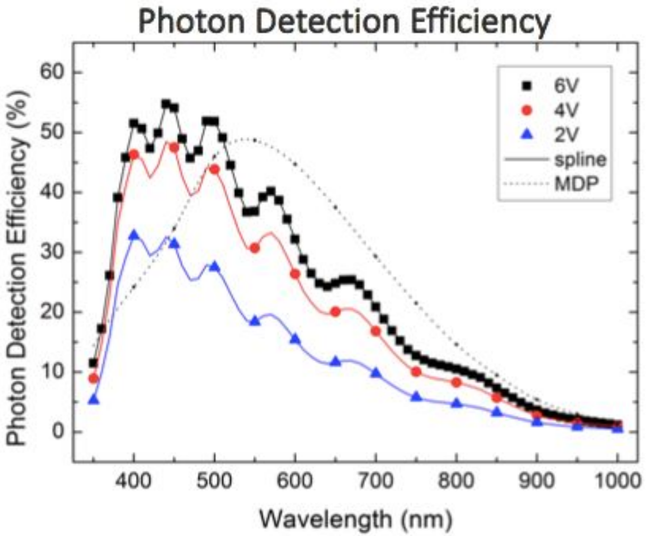
Sorting

Dark Noise Filter

Multi-Timestamp Estimator (BLUE)

PRELIMINARY Results from first Production





400-500 nm range :

- fast scintillators for PET scanners

VUV range (< 200nm):

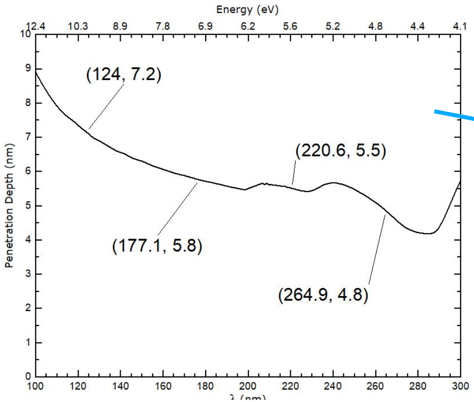
- liquid Xe : 178 nm
- liquid Ar : 128 nm

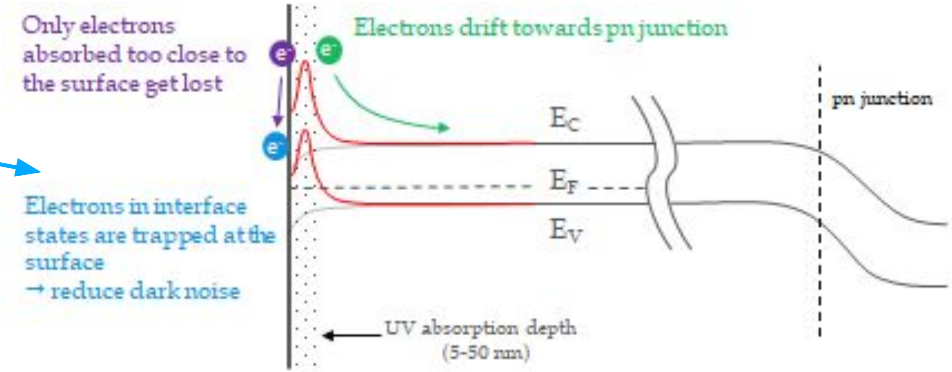
Very promising PRELIMINARY results from first production batch at the University of Sherbrooke (Quebec Canada). ~23 ps timing with standard CMOS integration (plenty of room for improvement)

Boosting SiPM VUV Efficiency

Boosting SiPM VUV Efficiency

Penetration Depth Challenge



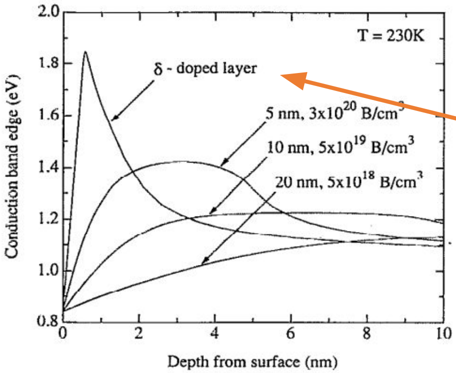


Only electrons absorbed too close to the surface get lost

Electrons drift towards pn junction

Electrons in interface states are trapped at the surface
→ reduce dark noise

UV absorption depth
(5-50 nm)

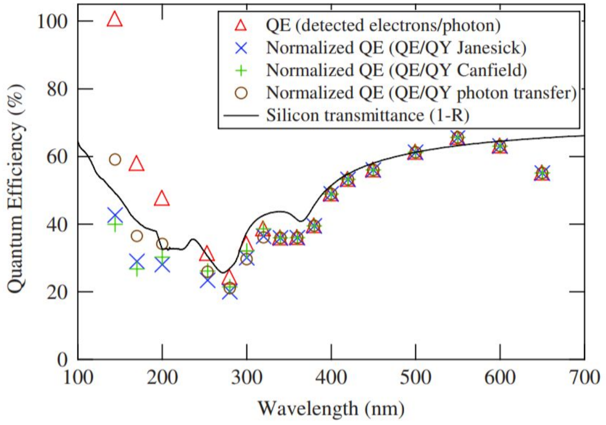


The delta-doping concept: Introduce an highly-doped layer at the surface of the SiPM, to modify the energy band profile. Electron generated below this barrier are drifted towards the p-n junction. Charges captured on the surface deflects and can not contribute to the device noise levels [1].

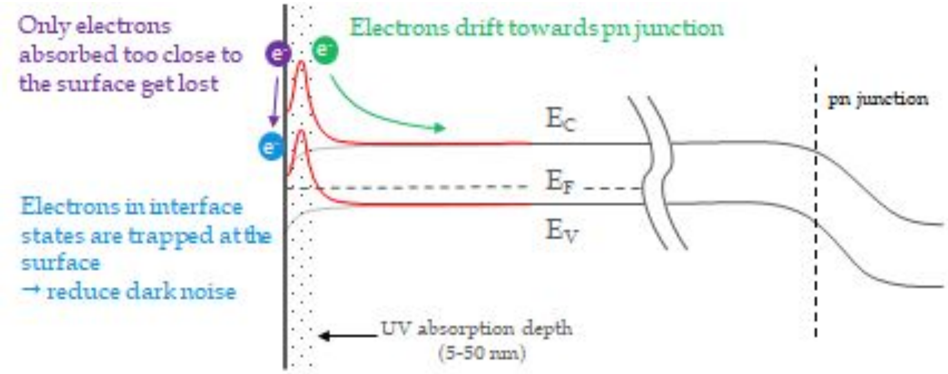
[1] App. Phys. Lett. 61, 1084 (1992) doi:10.1063/1.107675

Boosting SiPM VUV Efficiency

Previously demonstrated in CCD



Applied Optics, vol. 51, issue 3, p. 365



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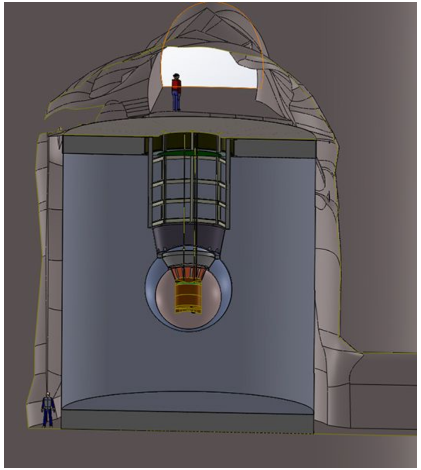
Precision-Physics Applications

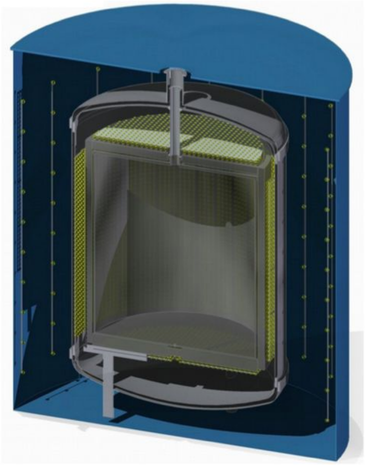
Precision-Physics Applications

Ultimate Goal: >50% PDE(VUV) 3DSiPM

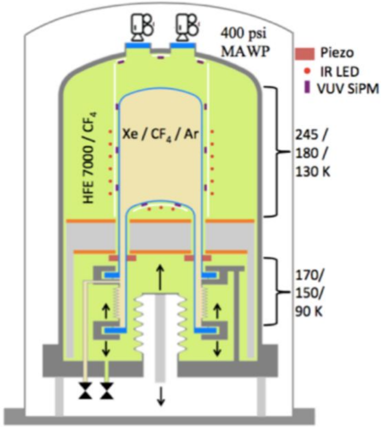
This work is primarily targeted towards low-background liquid noble experiments (Dark Matter & Neutrino) and precision measurements of ultra-cold neutrons (UCNs) properties like the nEDM.



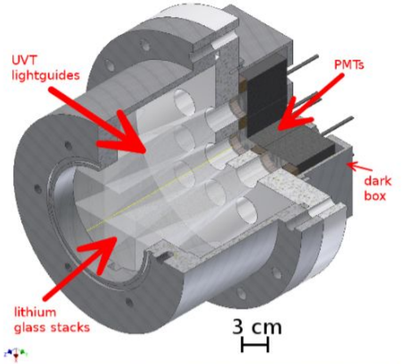
nEXO Experiment



300T Single-Phase LAr



LAr Bubble Chamber



Ultra-Cold Neutrons

Commercial Applications

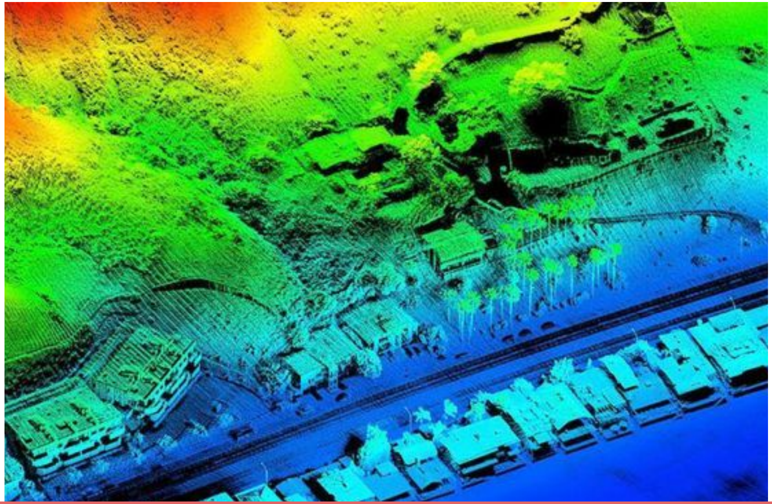
Commercial Applications

LXe PET Scanner (Medical Imaging)

LabPET/CT (2015)

Challenge: Pulse Timing < 15 [ps]

LiDAR Sensors with SiPM (3D Imaging)



Challenge: Good PDE (>30%) from 200-800 [nm]

Early-Fire Gas Analyzer: Use both Visible and UV light for particlets studies in area where fires are a considerable yearly problem (west-coast US, Canada).

Conclusions

Conclusions

- New technologies and ideas are fundamental for precision physics to search beyond the standard model of particle physics.
- SiPMs already provide a great option (compared to PMTs) for experiments dominated by scintillation and Cherenkov light detection.
- Analog SiPMs challenges include: size scalability, radiopurity, picoseconds timing, overall noise reduction.
- We have introduced a novel physics-driven method to characterize and fully understand SiPMs, including avalanche-triggering-probability (ArXiv:1904.05977).
- Described the progress on 3DSiPM and shown promising early results (timing ~23 ps).
- Introduced a new technique for boosting VUV efficiency via delta-doping.
- An ultimate device with electronics integration (3DSiPM) and boosted VUV sensitivity will be a game changer for multiple precision-physics experiments and multiple commercial applications.

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Thank you
Merci

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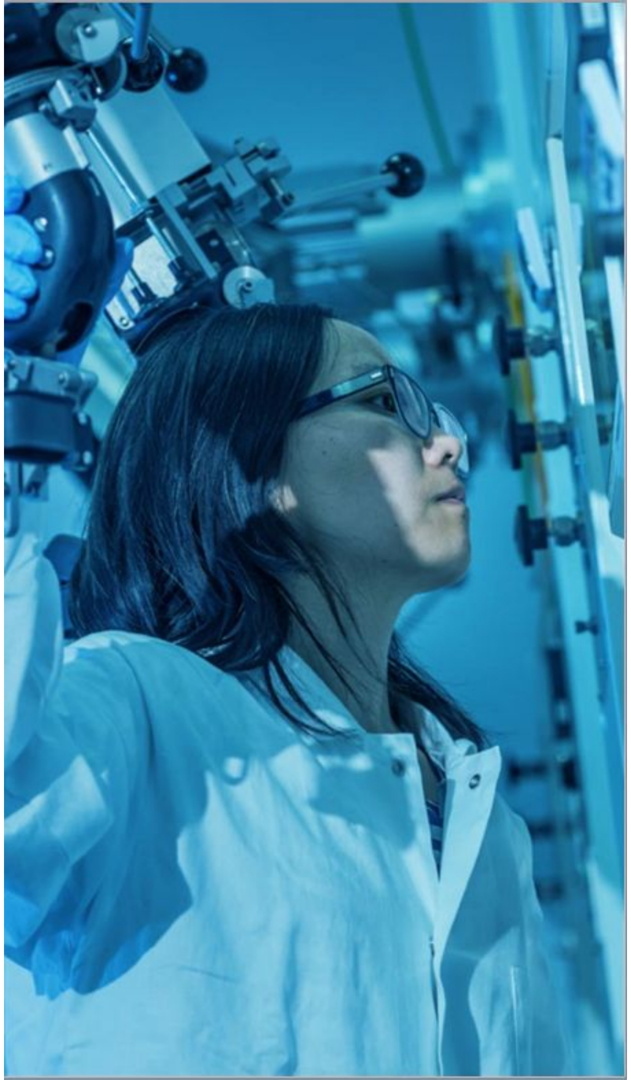

Discovery, accelerated

Backup Slides

From Technology Signals to Physical Information

- Ionization Electrons
- Scintillation Light
- Cherenkov Radiation
- Transition Radiation
- Magnetic Induction
- Phonons Propagation
- Acoustic Signals
- Heat Propagation
- ……. ???

→

- Energy
- Momentum
- Velocity
- Trajectory
- Particle ID
- Charge
- Patterns
- Timing
- Casuality

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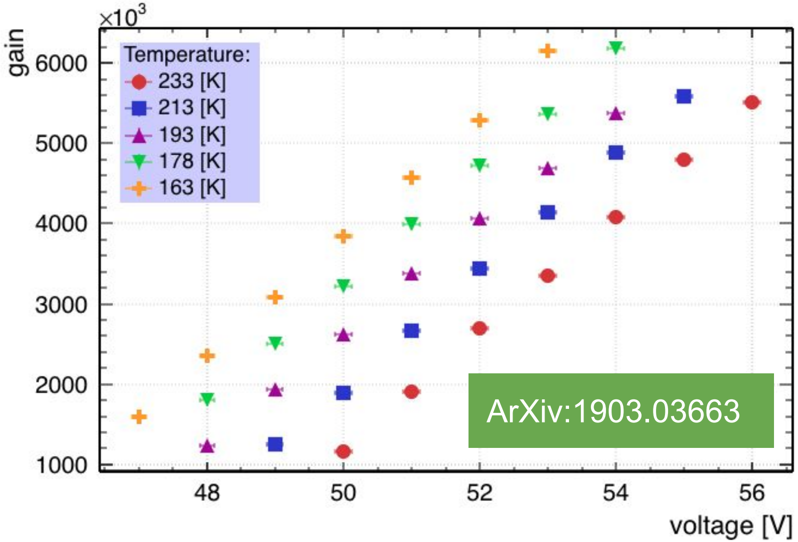
SiPM Gain and Dark Noise



Example using Hamamatsu VUV4 SiPMs.
The SiPM Gain can be defined as the following:

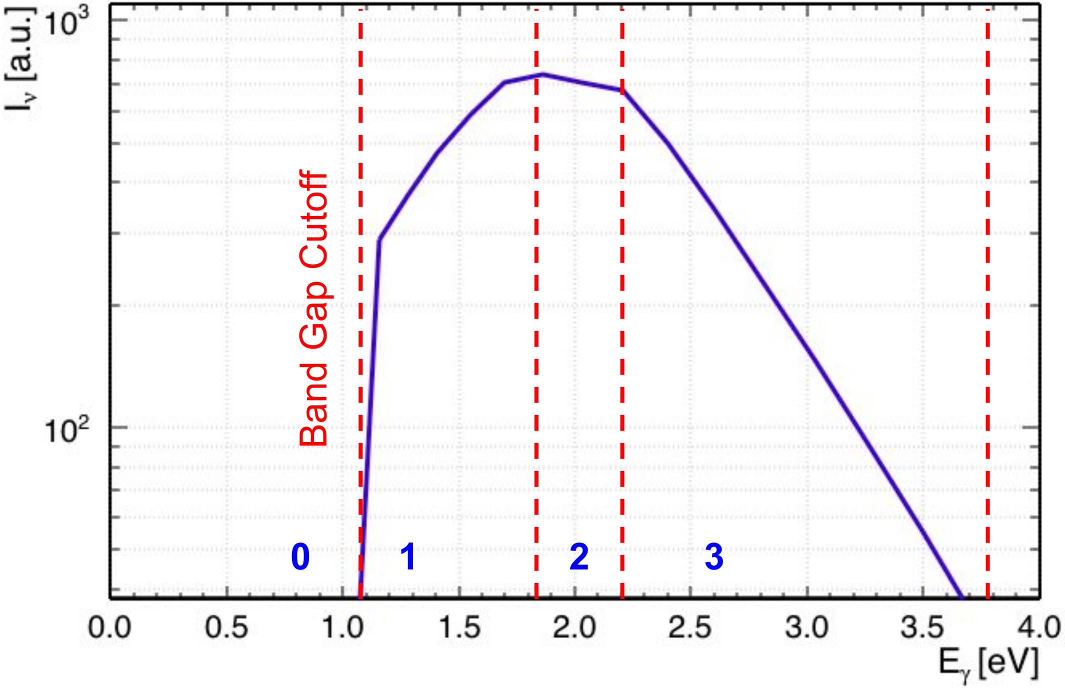
$$G = \left(\frac{I_{dr}}{2^{14}}\right) \cdot \left(\frac{< A_{1PE} > \cdot 10^9}{q_e \cdot g_{amp} \cdot R}\right)$$

I_{dr} = Input Dynamic Range of Digitizer
$<A_{1PE}>$ = Average 1PE Pulse Integral
R = Amplifier load resistance
g_{amp} = SiPM amplifier gain
q_e = electron charge.

Discovery,
accelerated

Physical Model for Light Emission

IEEE, DOI: 10.1109/16.760412



(Example using arbitrary values)
The model is divided in the following four components:

[0] Band-gap cutoff, 1.14 eV for Si at 330 [k]. Temperature dependent.

[1] Interband transitions of hot holes between different mass valence bands (phonon-assisted).

[2] Bremsstrahlung radiation by hot electron scatters.

[3] Direct-interband electron/hole transitions.

Physical Model for Light Emission

Direct Interband Transitions

Bremsstrahlung Radiation

Hot-h Interband Transitions

$$I_{di}(E_\gamma) = A \cdot E_\gamma^2 \cdot \left(\sqrt{E_\gamma - E_g}\right) \cdot exp\left(-\frac{E_\gamma}{W}\right) \cdot \left(1 + \frac{r_E E_\gamma}{W}\right)$$

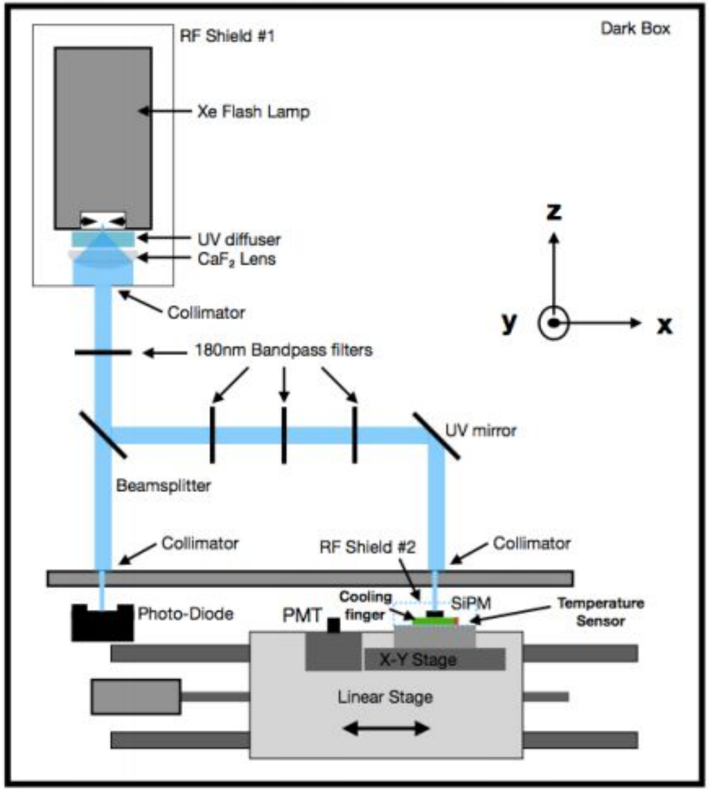
$$I_{di}(E_\gamma) = B \cdot exp\left(-\frac{E_\gamma}{k_0 T_e}\right)$$

$$I_{ib}(\nu) = C \cdot E_\gamma^{(3.5-a^*)} \cdot exp\left(-b \cdot (1.41 \cdot E_\gamma - E_g)\right) \qquad a^* = (1 - 3/\alpha)/(2 + 3/\alpha)$$

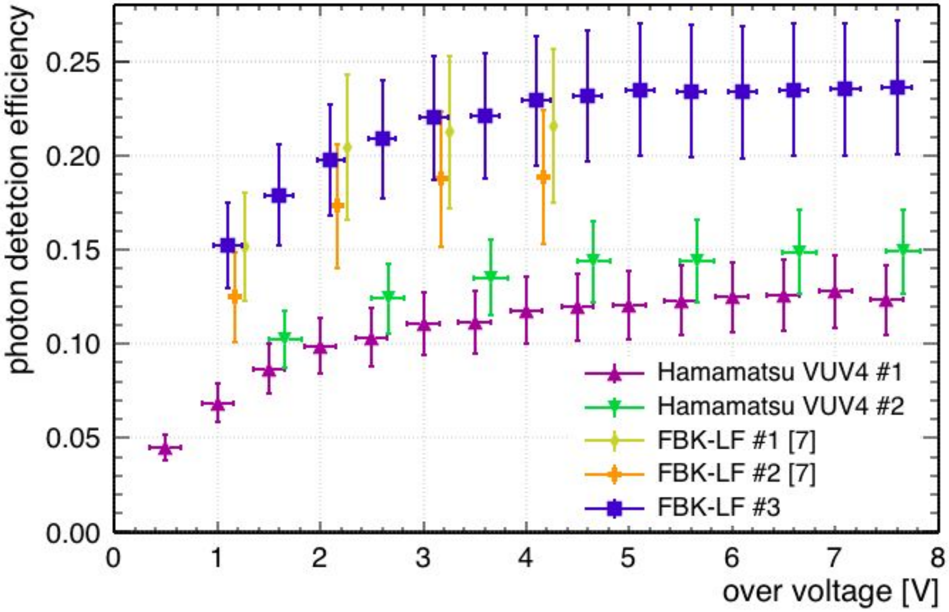
IEEE, DOI: 10.1109/16.760412

- ***A,B,C*** = Scaling factors
- **E_γ** = Photon Energy
- **E_g** = Band gap energy
- **r_E** = Energy integral correction factor.
- ***W*** = carrier temperature factor (electric field and ionization mean-free-path dependent).
- **T_e** = Electron temperature during avalanche.
- **α** = depleted region term (depends on e-field, ionization mean-free-path and optical phonon mean-free-path).
- ***b*** = mean-free-path for ionizing collisions.

Photo-Detection-Efficiency



arXiv:1903.03663



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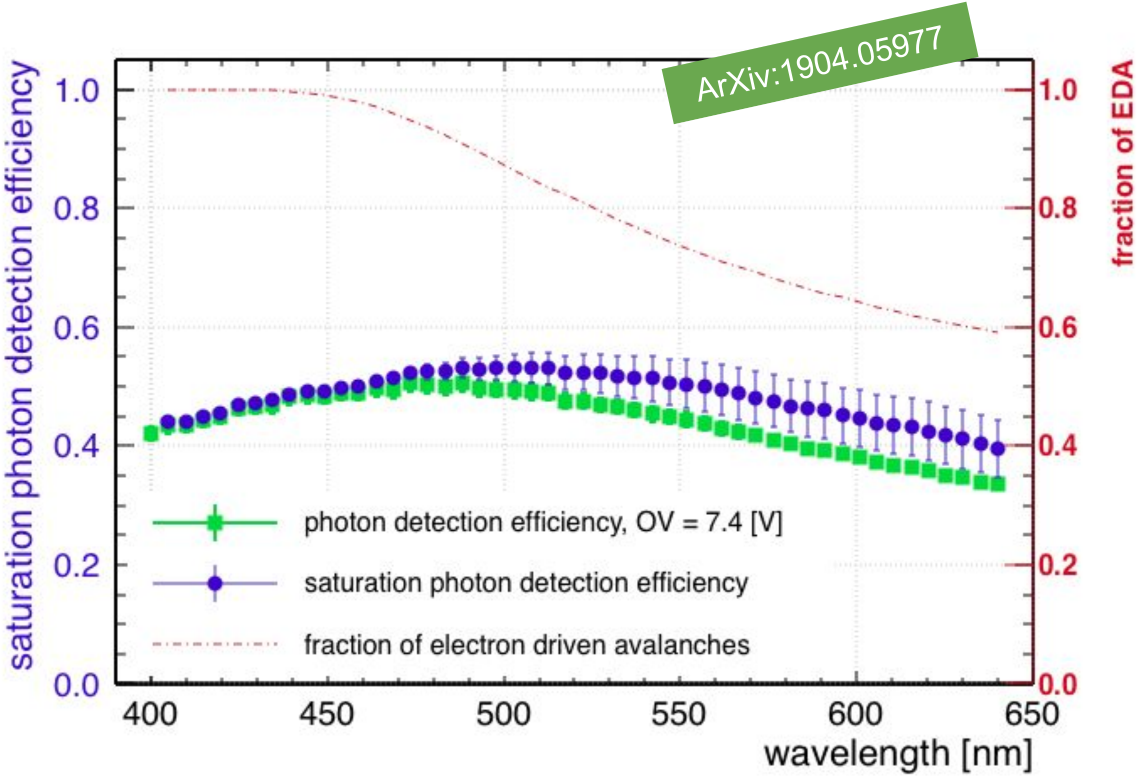
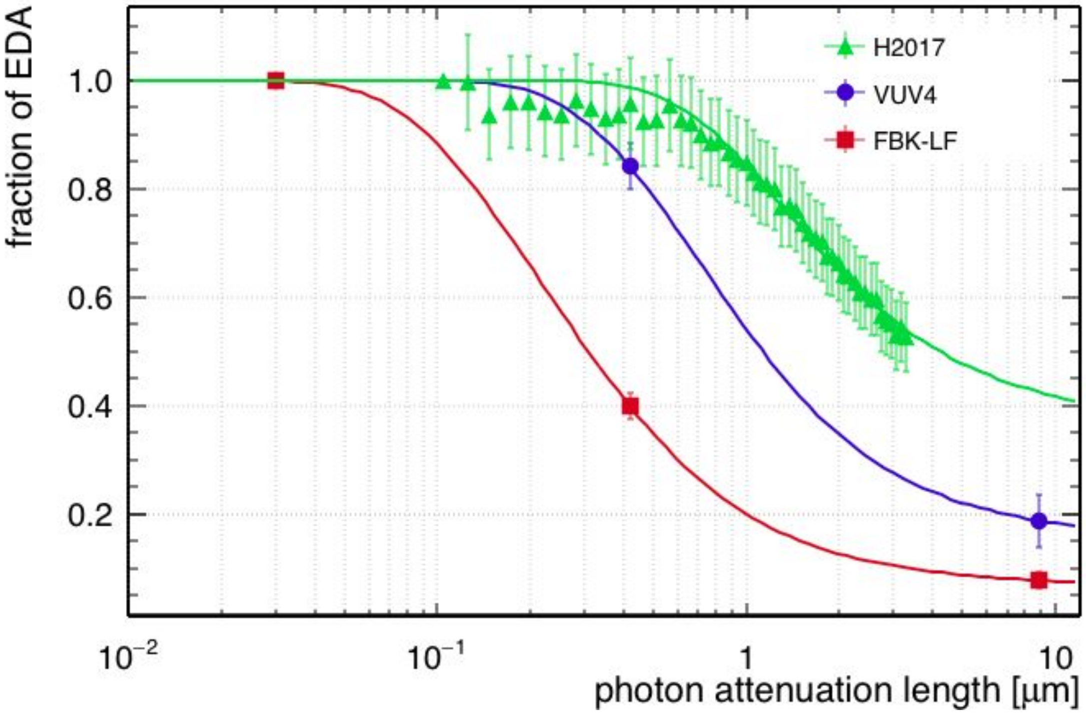
Avalanche-Triggering-Probability



Avalanche-Triggering-Probability

ArXiv:1904.05977



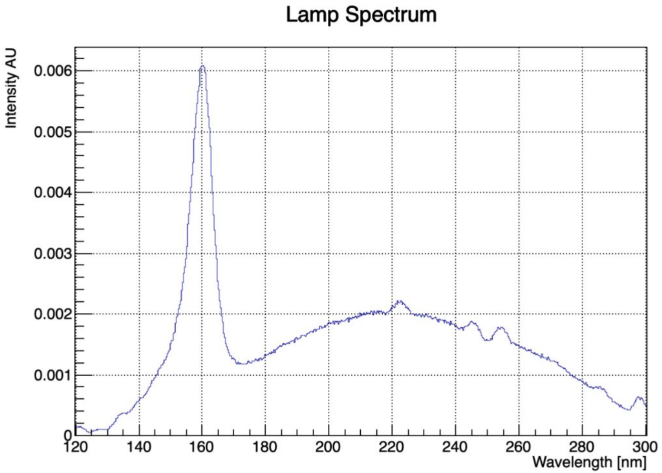
Boosting SiPM VUV Efficiency

Photo Detection Efficiency:

Transmittance

Reflectivity

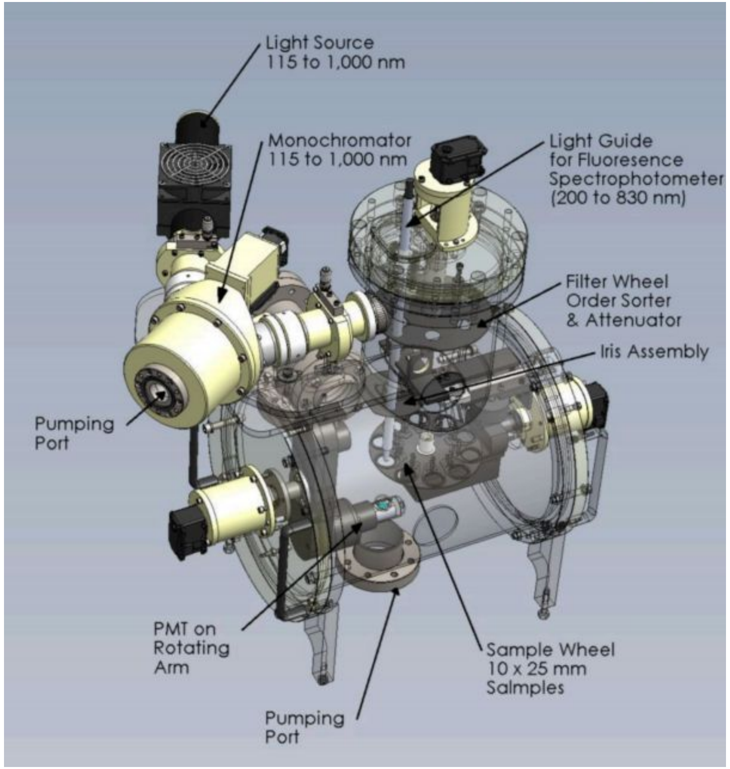
VUV Optics Game

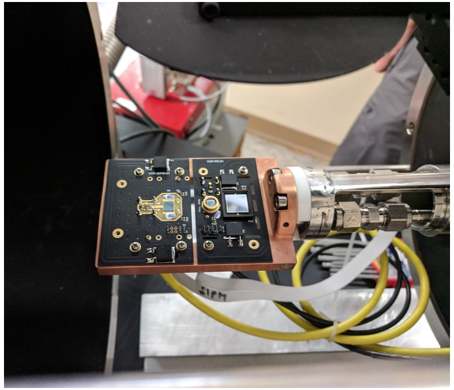


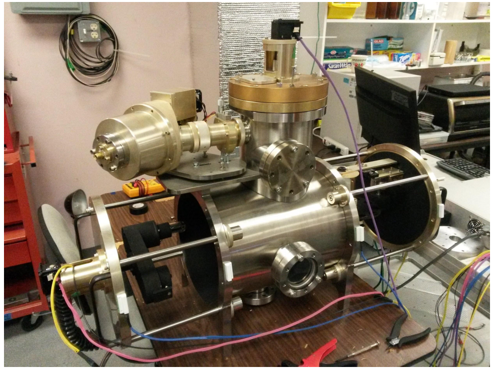
VUV Setup Design:

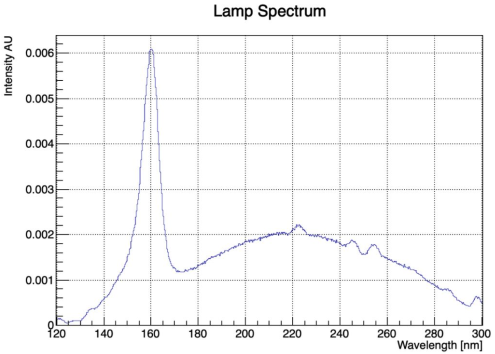
- Reflectance, Transmission, Fluorescence and more.
- Deuterium Lamp 100-400 nm continuous source spectrum.
- Advanced monochromator for precision wavelength selection.
- Ability to cool the sample to cryogenics temperatures.
- Ability to control the sample and readout position and tilt-angle.
- Reference PMT capable of sampling the beam via a parabolic mirror.
- Cryogenic sample holder with the ability to operate cold Diode/SiPM/PMTs.

VUV Optics and SiPM Characterization Setup









Early AR-Coating Results

AR Surface coating is critical for the ultimate VUV sensitive SiPM.
(Issue: Si reflectivity at ~175 nm is ~50%)
(SiO2 has poor transmission ~128 nm).

Important to balance transmission and reflectivity to identify the most optimal AR surface coating for 3DSiPM.

Optical Material Selection Campaign:
Currently Under Investigation:

- Al_2O_3
- MgF_2
- LiF
- LaF_3
- Pure Al