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Using SNR Simulation to Select a Photodetector

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SNR as a Figure of Merit for Product Selection

The Challenge of Selecting a Detetor

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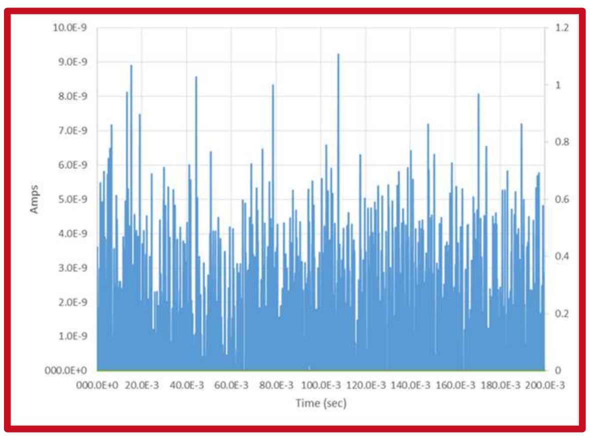
	Photodiode	APDs	MPPC	PMT
Quantum Efficiency	80 - 90%	80 - 90%	25 - 50% (PDE)	10 - 20% (QE_{eff})
Gain	1	<100	10^5~10^6	~10^6
Excess Noise Factor	1	~4	~1.05	~1.2
Spectral Range	Up to 1200 nm (Silicon) Up to 2.6 um (InGaAs)	Up to 1150 nm (Silicon) Up to 1700 nm (InGaAs)	320 to 900 nm (Peak 450-470 nm)	190 to 900 nm
Dynamic Range	Limited by amplifier	Limited by amplifier	Limited by number of microcells	Limited by divider current
Limit of Detection	nW Severly limited by readout noise	pW Limited by readout noise	fW Limited by dark noise ~ 100,000 cps (Noisy)	fW Limited by dark noise ~ 500 cps (Quiet)
Bias Voltage	-	~200 V	~ 50 V	~ 1000 V
Mechanical Robustness	Rugged	Rugged	Rugged	Good
Magnetic Field	Immune	Immune	Immune	Need protection
Design Complexity	Signal integrity	Signal integrity & temperature compensation	Temperature compensation	High voltage
Ambient Light Exposure	No damage	No damage	No damage	Can be damaged
Temperature Sensitivity	Low	High	Medium	Low
Warm Up Time	Instantaneous	Instantaneous	Instantaneous	Few minutes
Timing	Slow	Fast	Fast	Very fast
Price	Low	Medium	Low (<1/2'' Diameter)	High (<1/2'' Diameter)

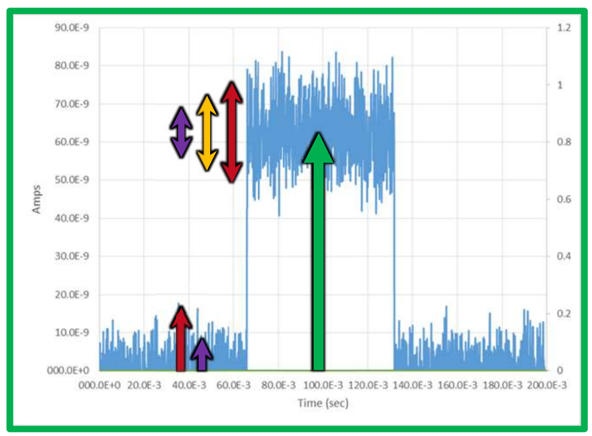
SIMULATION REFERENCE ONLY

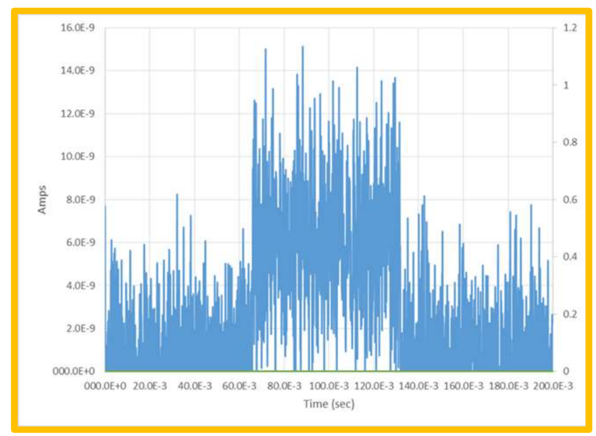
What is Signal to Noise Ratio (SNR)

- SNR can tell us the relative separation between the signal and the noise.

$$SNR = \frac{\textit{Signal}}{\sqrt{\textit{Dark Noise}^2 + \textit{Signal Noise}^2 + \textit{Readout Noise}^2}}$$







What SNR Value Do I Need?

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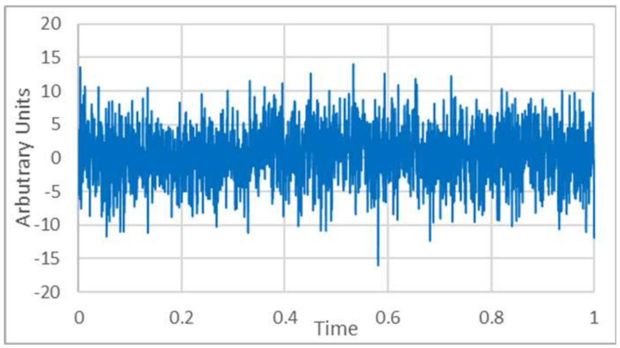
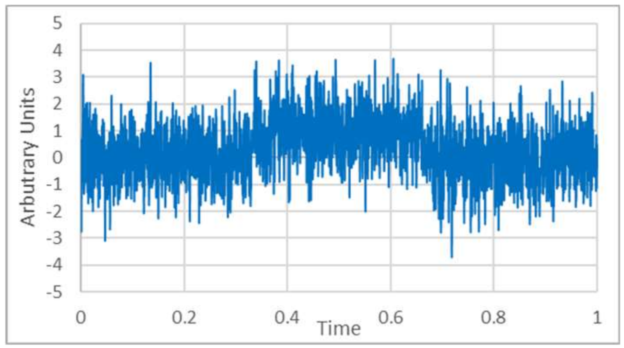
❖ SNR < 1 is unusable, and SNR < 3.3 is a challenge. Highest SNR is the goal.

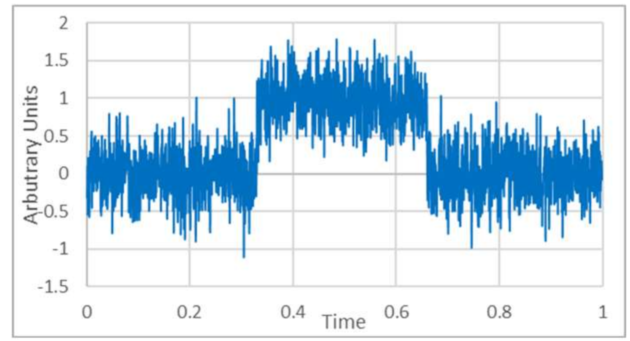
SNR < 1



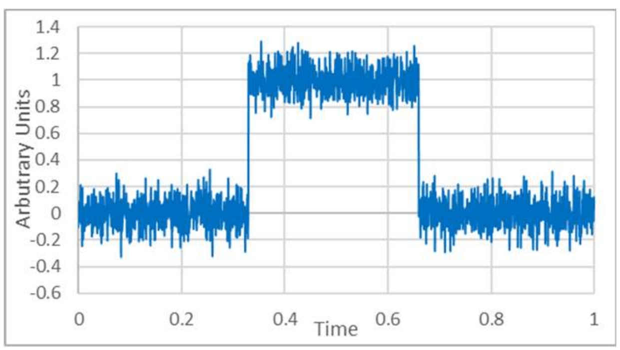
SNR = 1



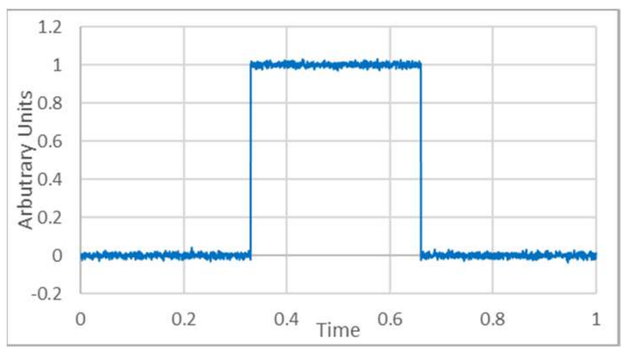
SNR = 3.3



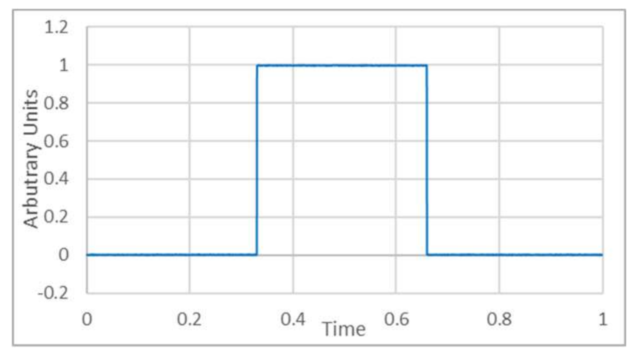
SNR = 10



SNR = 100



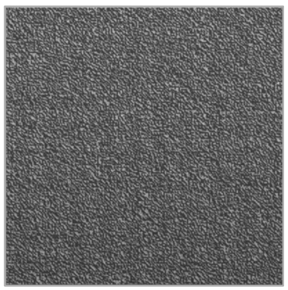
SNR = 1000



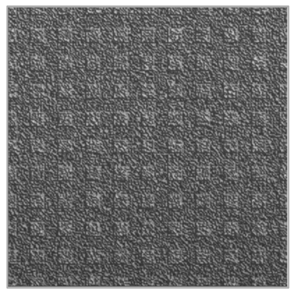
SNR in Other Forms: Image Quality

- SNR affects image quality.

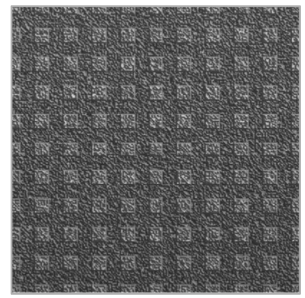
SNR = 1



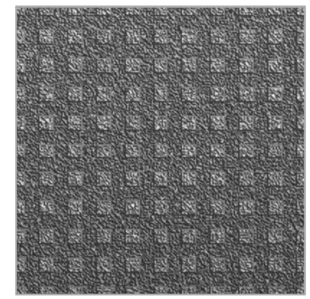
SNR = 3.3

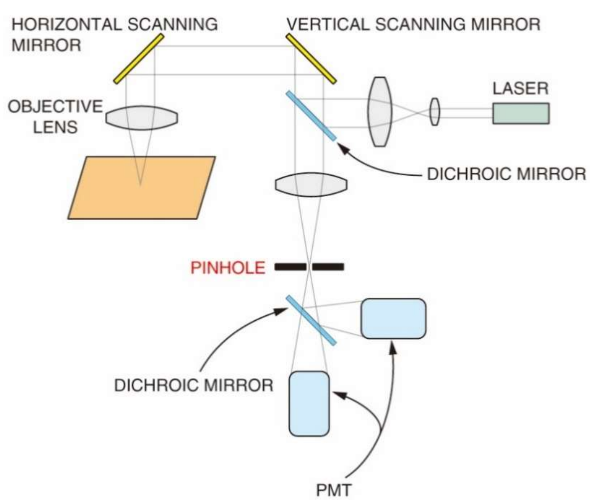


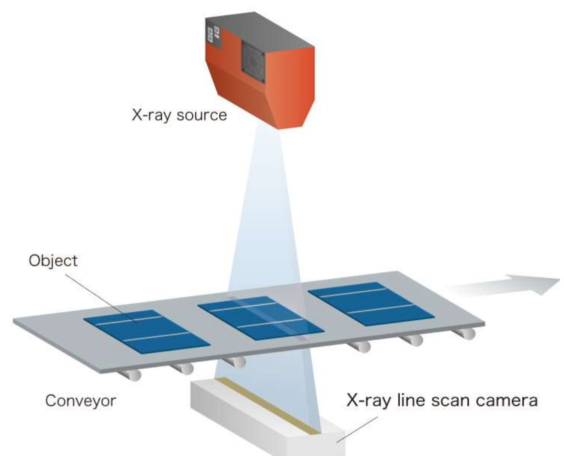
SNR = 10



SNR = 100







SNR in Other Forms: Position Sensitive Measurement

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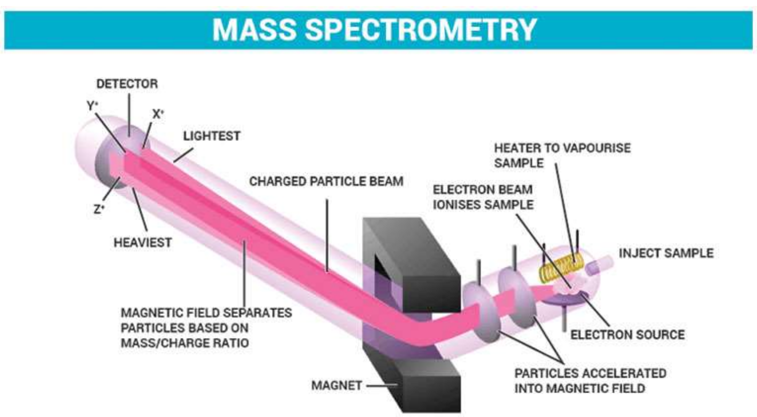
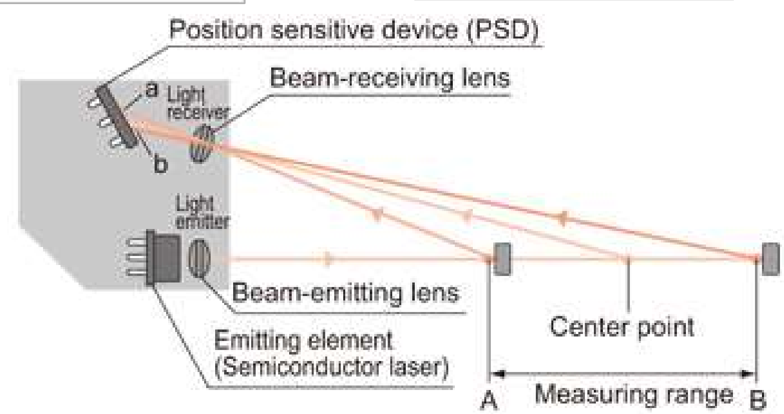
- “Location” of noise is generally evenly distributed.
- Center of gravity drifts towards center of active area with low SNR.

SNR = 1 | SNR = 3.3 | SNR = 10 | SNR = 100



https://microbenotes.com/mass-spectrometry-ms-principle-working-instrumentation-steps-applications/



https://www3.panasonic.biz/ac/ae/service/tech_support/fasys/tech_guide/measurement/laser/index.jsp

SIMULATION REFERENCE ONLY

SNR in Other Forms: Pulse Height Distribution (PHD)

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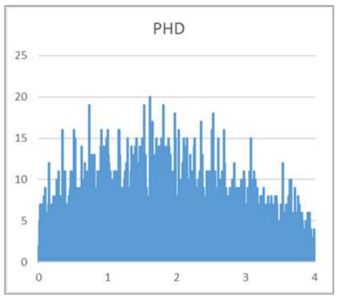
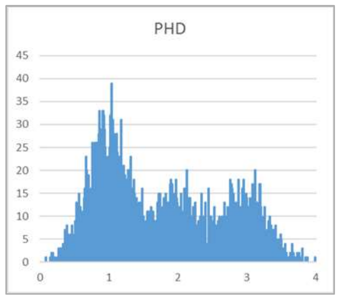
- Narrow PHD results from nearly identical pulse heights for identical input ▸▸ High SNR
- Broad PHD results from variation in pulses heights for identical inputs ▸▸ Low SNR

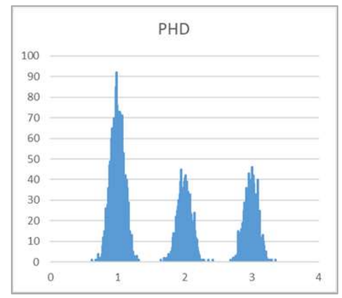
SNR = 1



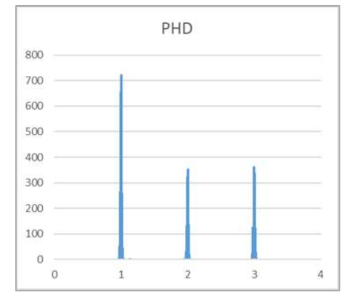
SNR = 3.3

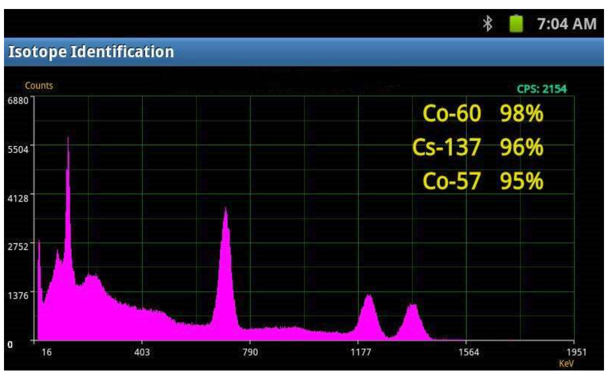


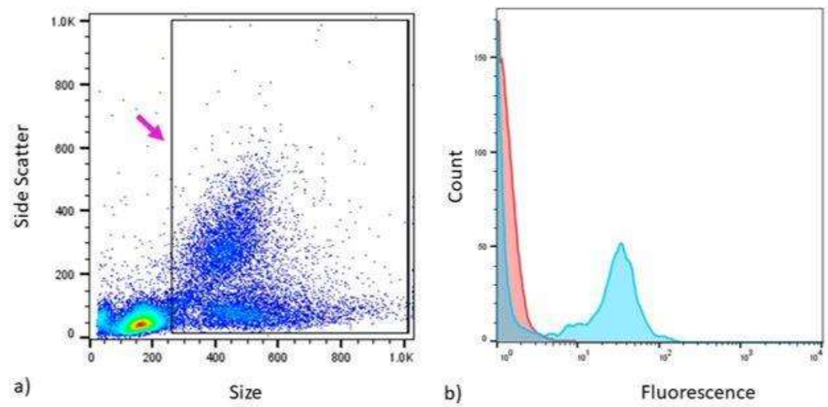
SNR = 10



SNR = 100







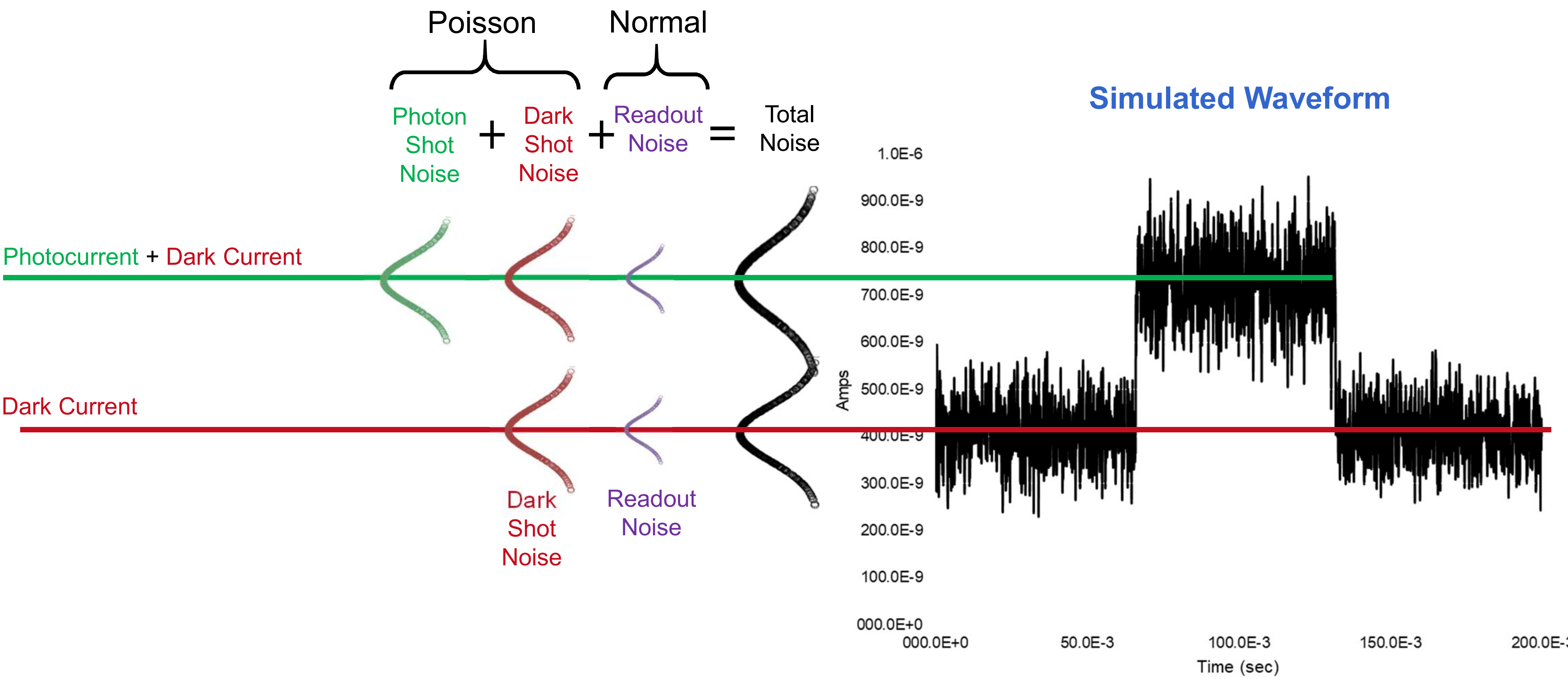
https://www.prweb.com/releases/2014/03/prweb11650449.htm

https://www.usgs.gov/media/images/flow-cytometric-dot-plot

SIMULATION REFERENCE ONLY

Simulating Signal and Noise

- Knowing the signal current, dark current, and noise allows us to simulate waveforms.



Generating Basic Waveforms

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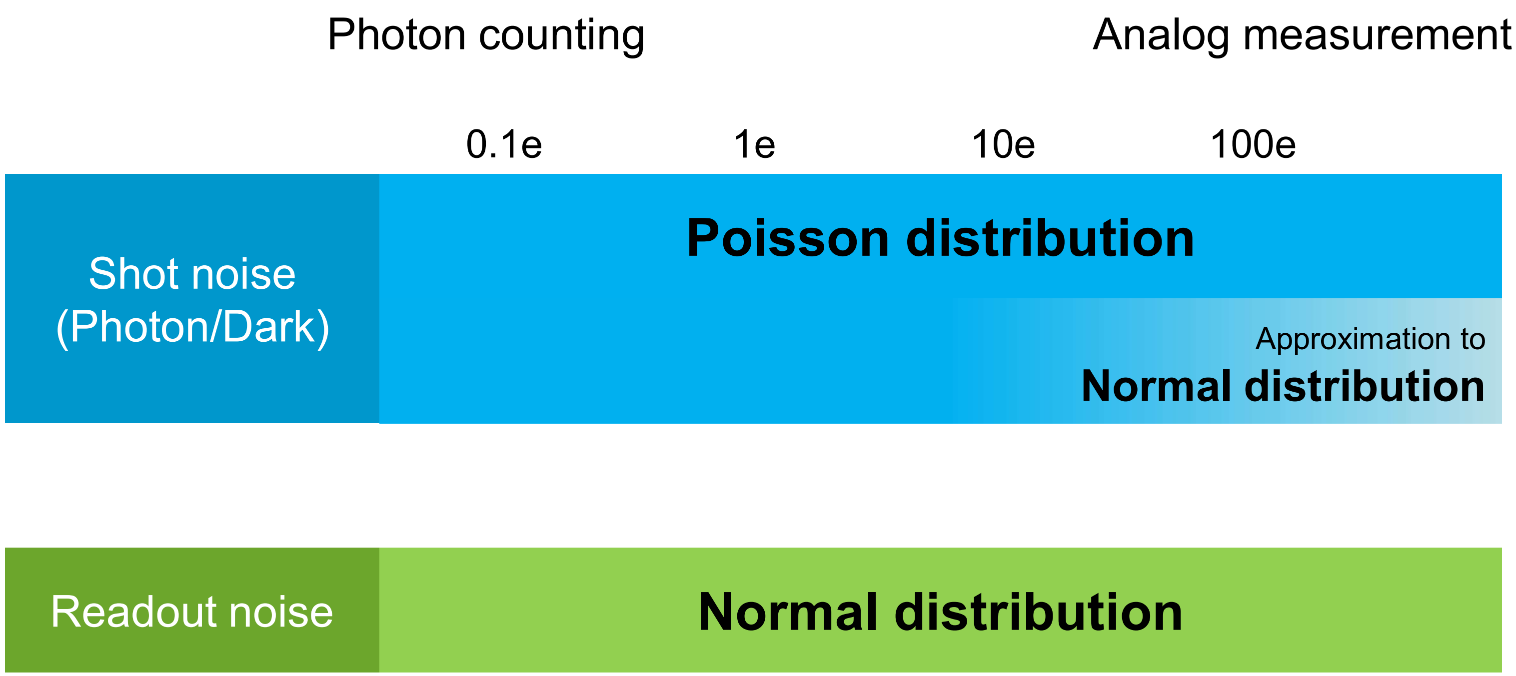
- Box-Muller Transform to convert uniformly distributed random number to normal distrubiton

$$x = \sqrt{-2\ln(RAND)} * \cos(2\pi RAND) * Std.Dev + Mean$$

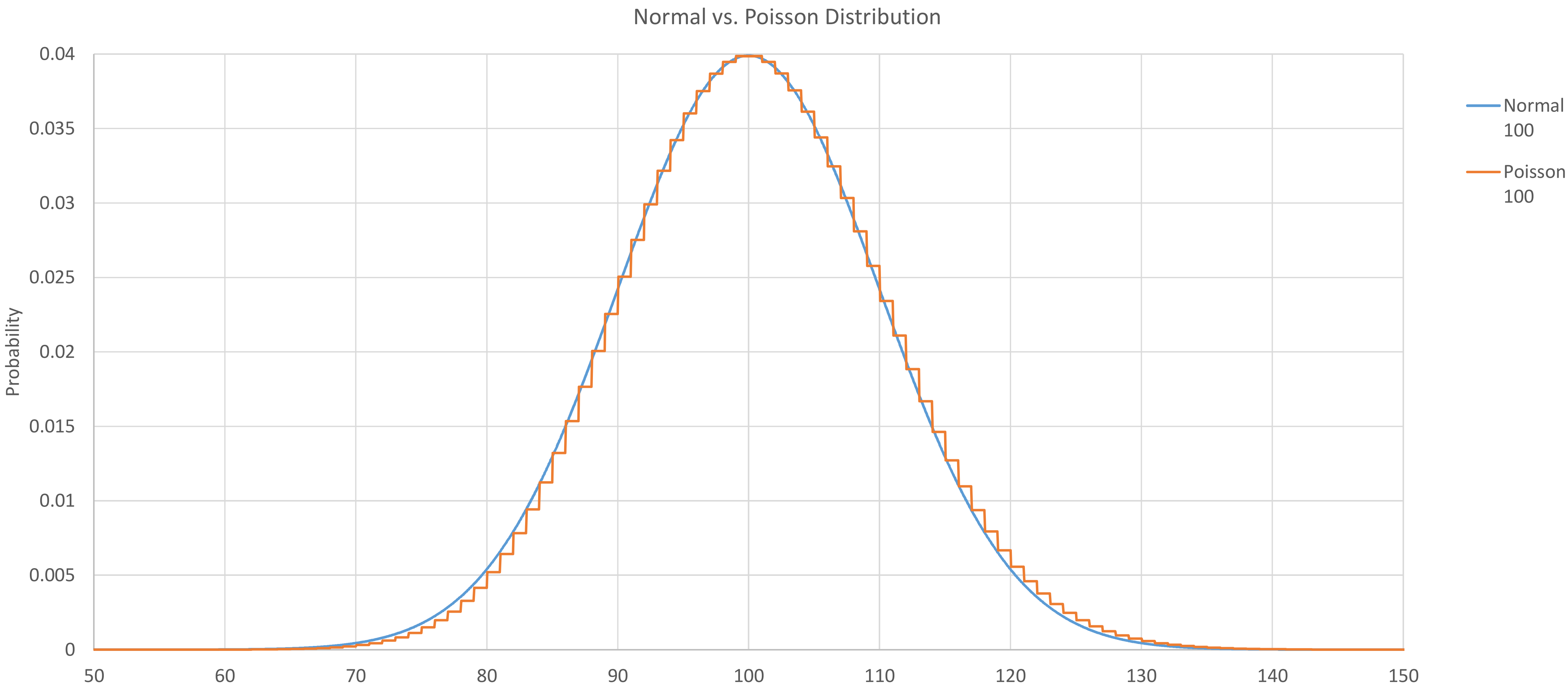
Noise

Average photocurrent
and dark current

Noise Distribution



Normal vs. Poisson Distribution



Generating Basic Waveforms

- Box-Muller Transform to convert uniformly distributed random number to normal distrubiton

$$x = \sqrt{-2\ln(RAND)} * \cos(2\pi RAND) * Std.Dev + Mean$$

Noise

Average photocurrent and dark current

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- Signal Shot Noise
- Dark Shot Noise
- Gain
- Excess Noise from Gain
- Readout Noise
- Dominant Noise Sources
- Detector Selection Process

Schematic View of Signal and Noise

Schematic View of Signal and Noise

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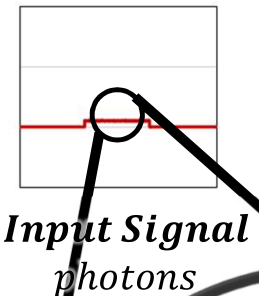
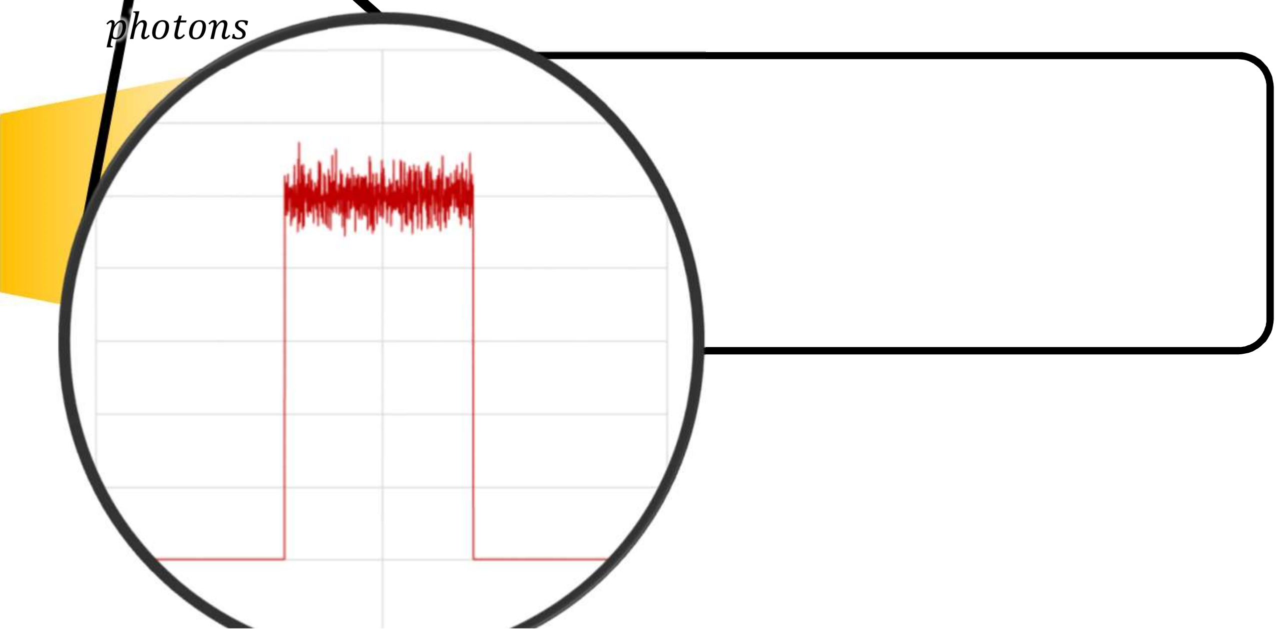
- Light itself has noise called photon shot noise due to random photon arrivals.



$$Signal = \frac{photons}{sec} * time$$

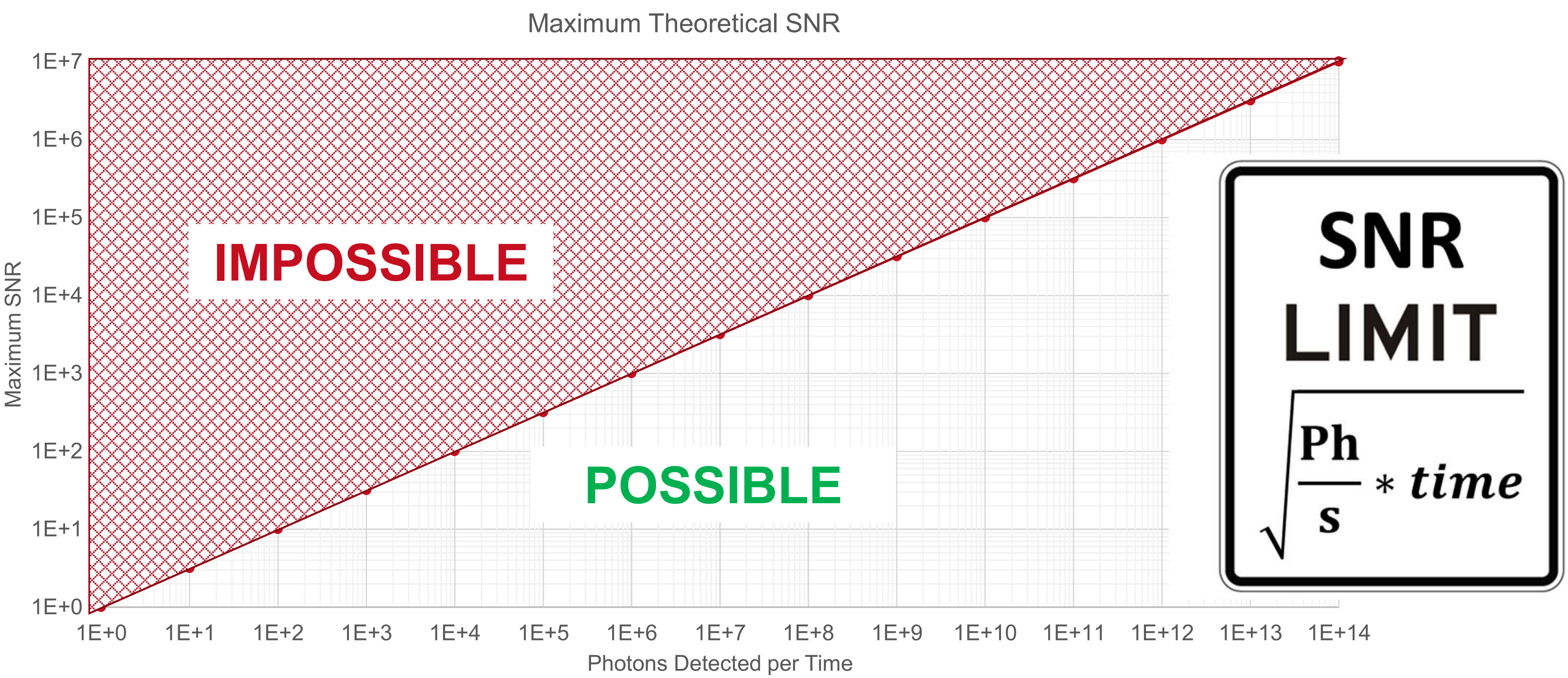
$$\sigma_{signal} = \sqrt{\frac{photons}{sec} * time}$$

$$time = \frac{1}{2 * bandwidth}$$



Statistical Limit of SNR

- The statistical limit of SNR is photon shot noise.



Sampling Time =/= Observation Time

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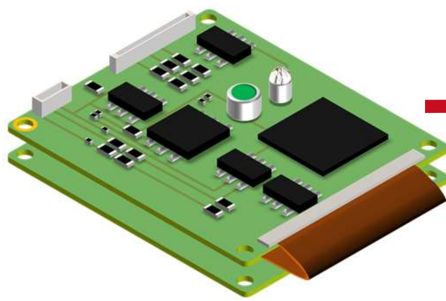
- Our definition of sampling time is ½ inverse of the detector & electronics bandwidth.
- Sampling time has no relationship to how long you obseve the detector output.



$$time = \frac{1}{2 * bandwidth}$$

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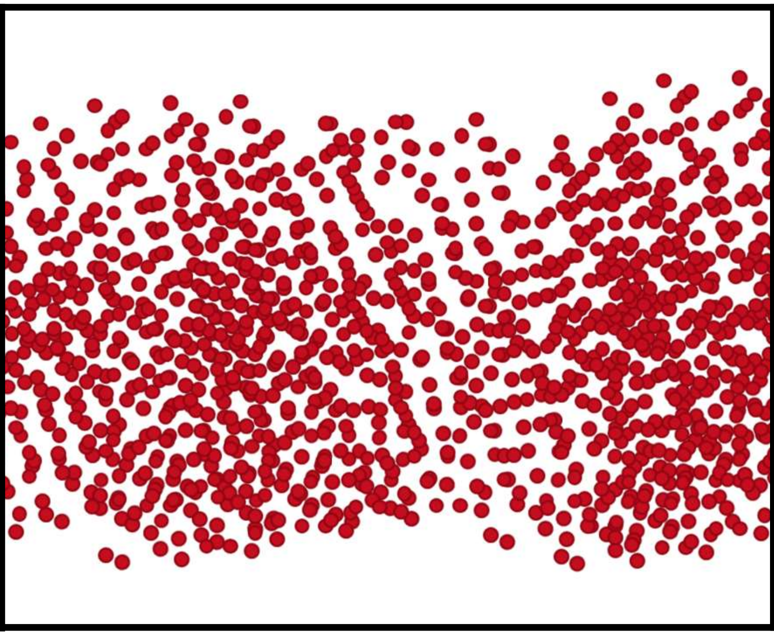
Integration Period

- Higher bandwidth results in more variation in each signal sample.

$$T = \frac{1}{2B}$$

Sampling Interval Decreased
Bandwidth Increased



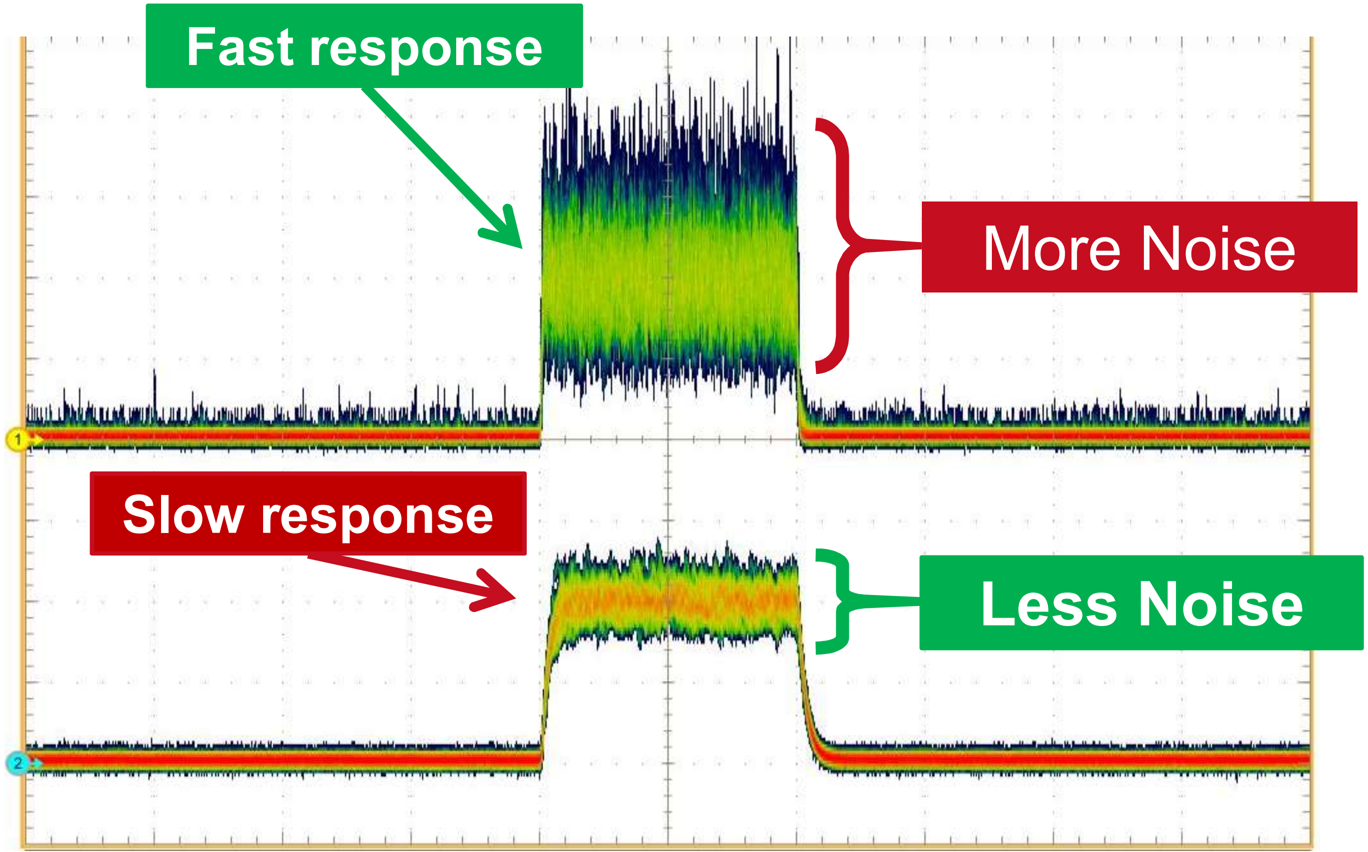
$$SNR = \frac{10{,}000\,\frac{ph}{s} * 0.1s}{\sqrt{10{,}000\,\frac{ph}{s} * 0.1s}} = \frac{1{,}000}{31.6} = 31.6$$

Bandwidth Optimization

❖ Higher bandwidth results in faster time response, but also more noise.

Amplifier
Fc = 4 MHz

Amplifier
Fc = 0.5 MHz



SIMULATION REFERENCE ONLY

Signal Degradation to Low BW

❖ Low bandwidth detector and readout circuit will distort fast input signals.

- Degradation can be caused by detector speed or readout circuit bandwidth and slew rate.

Describing incident light

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- Incident intensity can be described by Watts or photons per second.
- We can convert from Watts to photons per second by dividing by the energy of the photon

Radiant flux	Photons per second
Watts	**1/s**

Conversion:

Energy of a photon:

$$E[J] = \frac{h[Js]\ c\left[\frac{m}{s}\right]}{\lambda[m]}$$

Watts to Photons per second:

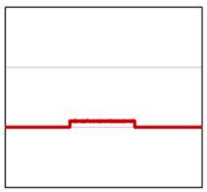
$$Photons\ per\ second\ \left[\frac{1}{s}\right] = \frac{Radiant\ flux\ \left[\frac{J}{s}\right]}{E[J]}$$

$h = 6.63 * 10^{-3}\ \ [Js] \rightarrow Planck's\ constant$

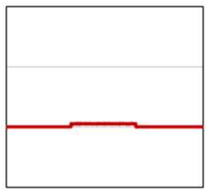
$c = 3 * 10^{8}\ \left[\frac{m}{s}\right] \rightarrow Speed\ of\ light\ in\ a\ vacuum$

Quantum Efficiency

❖ Higher QE improves SNR, lower QE reduces SNR.



$\times$ $\boldsymbol{QE}$ %

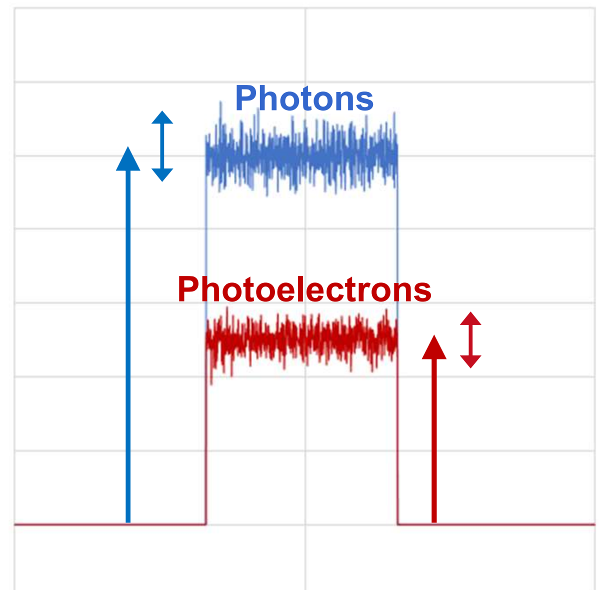


Input Signal
photons

Photoelectrons
e^{-}

$$Signal = \frac{photons}{sec} * \boldsymbol{QE}\% * time$$

$$\sigma_{signal} = \sqrt{\frac{photons}{sec} * \boldsymbol{QE}\% * time}$$



Quantum Efficiency and Photosensitivity

Detection Efficiency Terminology: Photodiode

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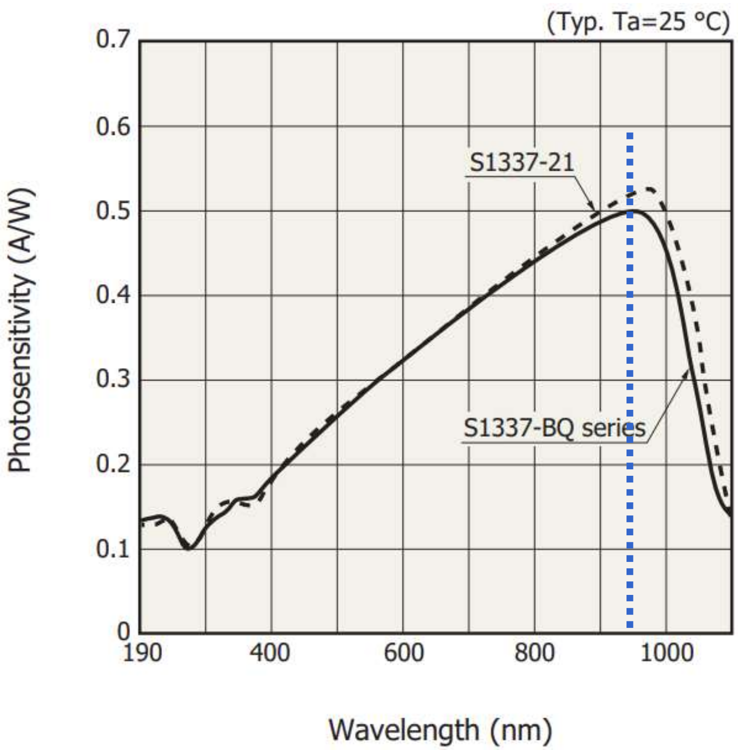
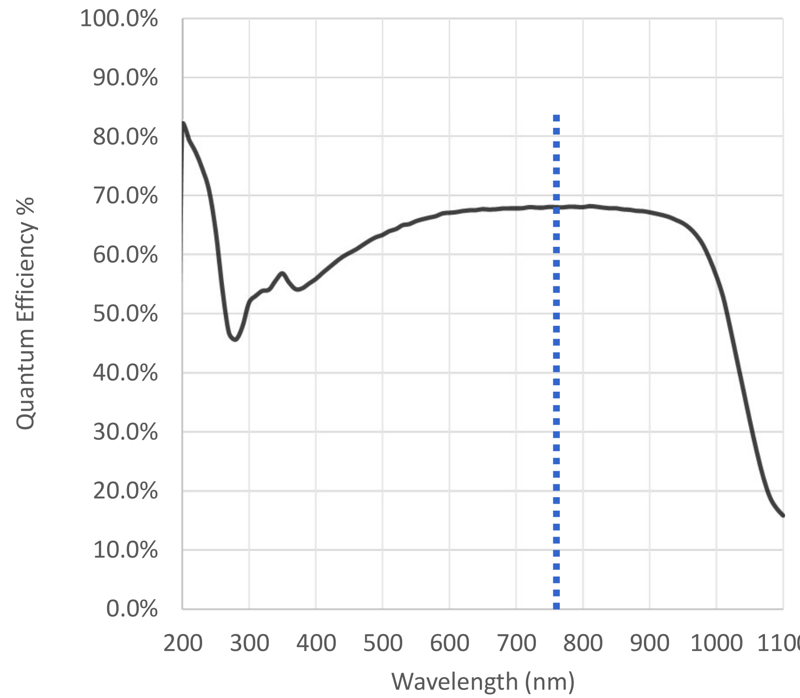
❖ Photosensitivity can be converted to Quantum Efficiency %.

$$Photosensitivity \left[\frac{A}{W}\right]$$

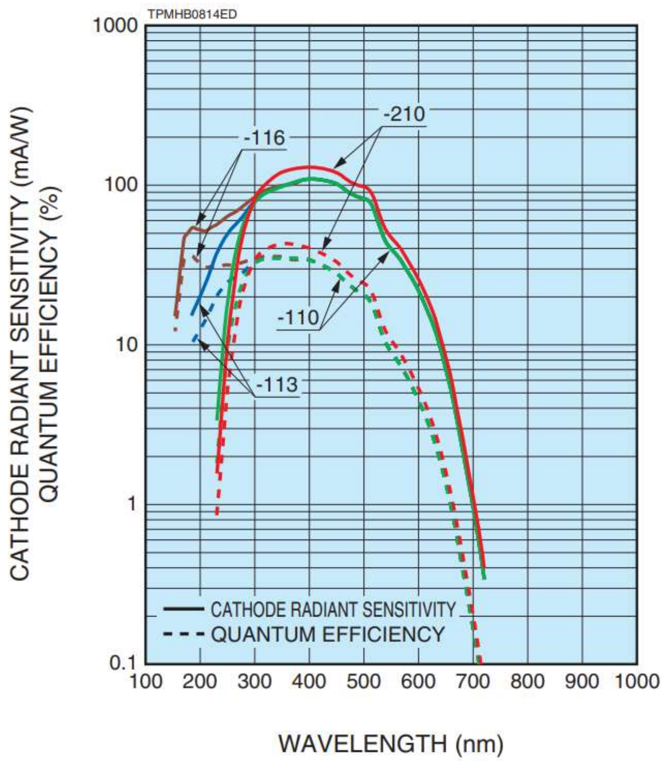


$$QE[\%] = Photosensitivity \left[\frac{C}{J}\right] * \frac{E[J]}{q[C]}$$



Detection Efficiency Terminology: PMT

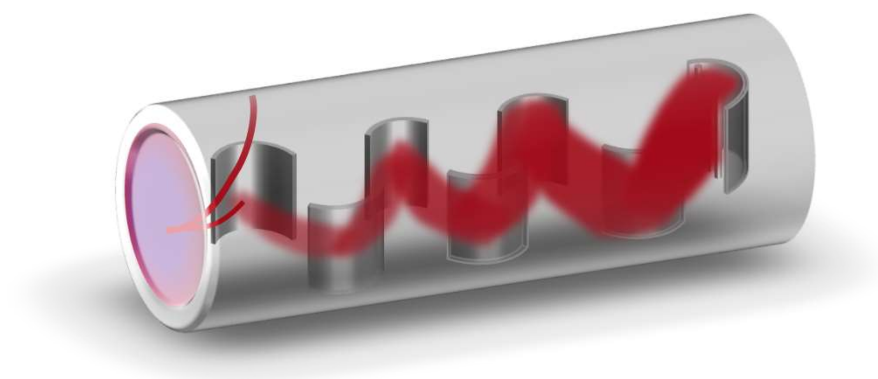
❖ PMT Collection Efficiency % should also be included to estimate signal.



$$QE_{eff}[\%] = QE_{cathode}[\%] * CE[\%]$$

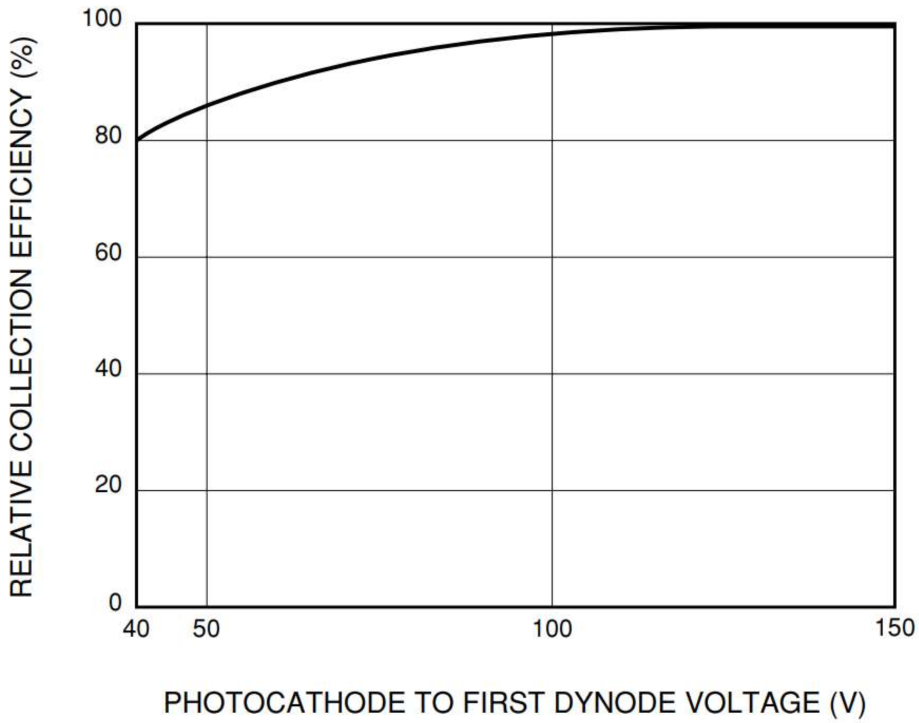
$$Signal = \frac{Photon}{sec} * QE_{eff}[\%] * Gain * time$$

$$CE[\%] = Dy_1\ Collection\ Efficiency \approx 70\% - 90\%$$



Collection Efficiency vs. Voltage

❖ Higher applied voltage to the PMT overall results in higher collection efficiency



Detection Efficiency Terminology: MPPC (SiPM)

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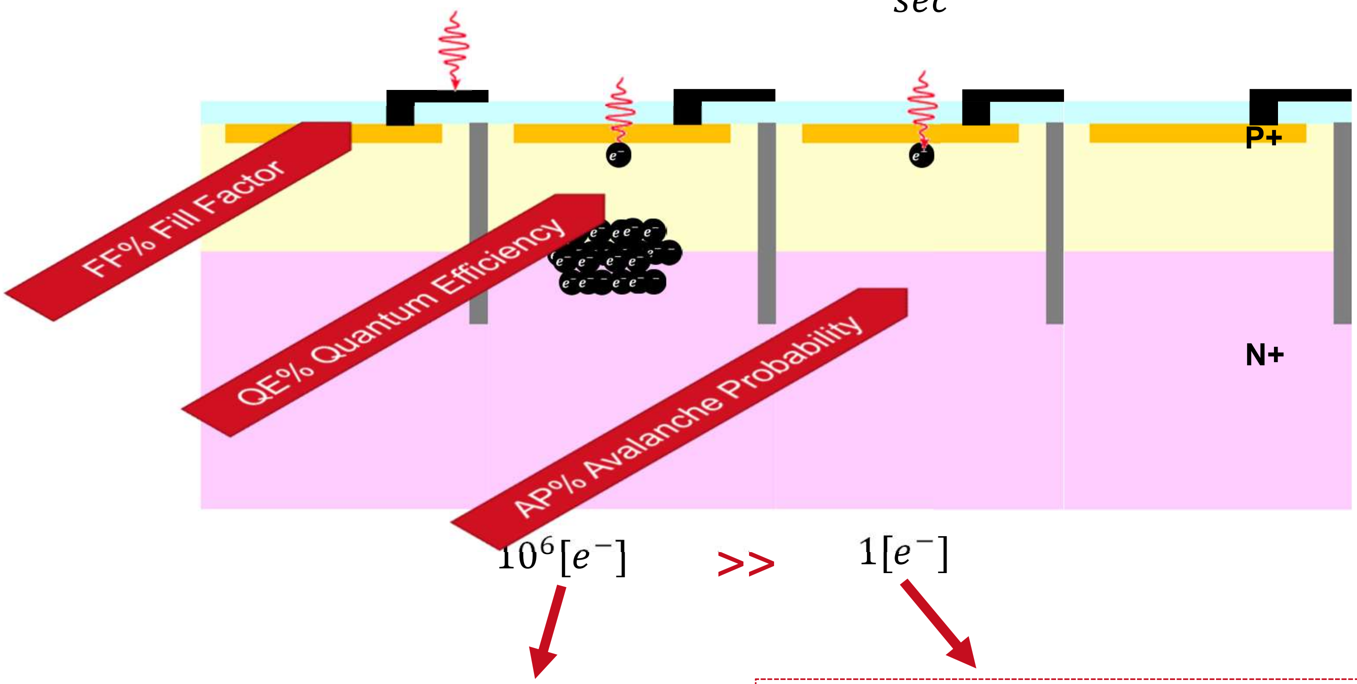
- PDE is used to calculate the output signal of MPPC(SiPM).

$$PDE[\%] = QE[\%] * AP[\%] * FF[\%]$$

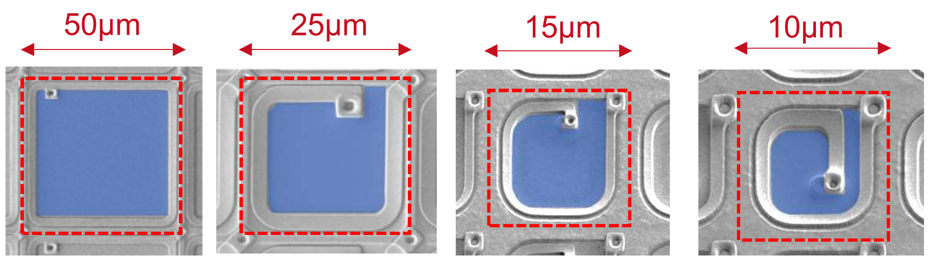
$$Signal = \frac{Photon}{sec} * PDE[\%] * Gain * time$$

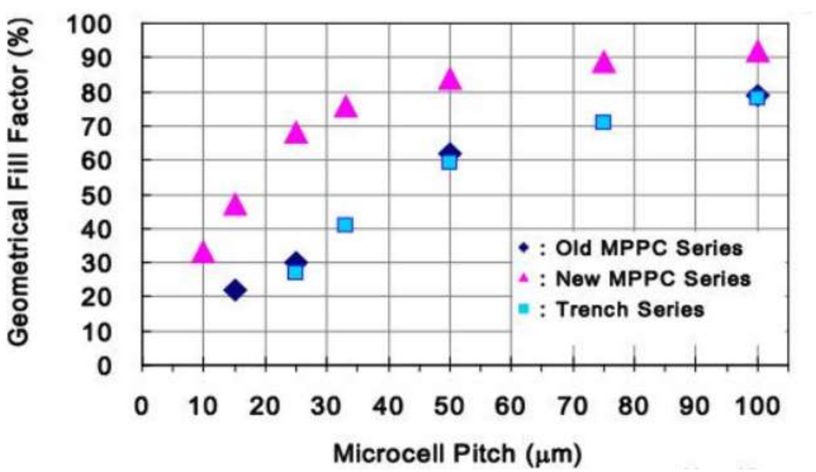


$$Signal = \frac{Photon}{sec} * QE[\%] * AP[\%] * Gain \boxed{+ \frac{Photon}{sec} * QE[\%] * (1 - AP[\%])}$$

Considerations for SiPM (MPPC) Photon Detection Efficiency

❖ Large microcells ▸ higher FF% ▸ higher PDE%





Considerations for SiPM (MPPC) Photon Detection Efficiency

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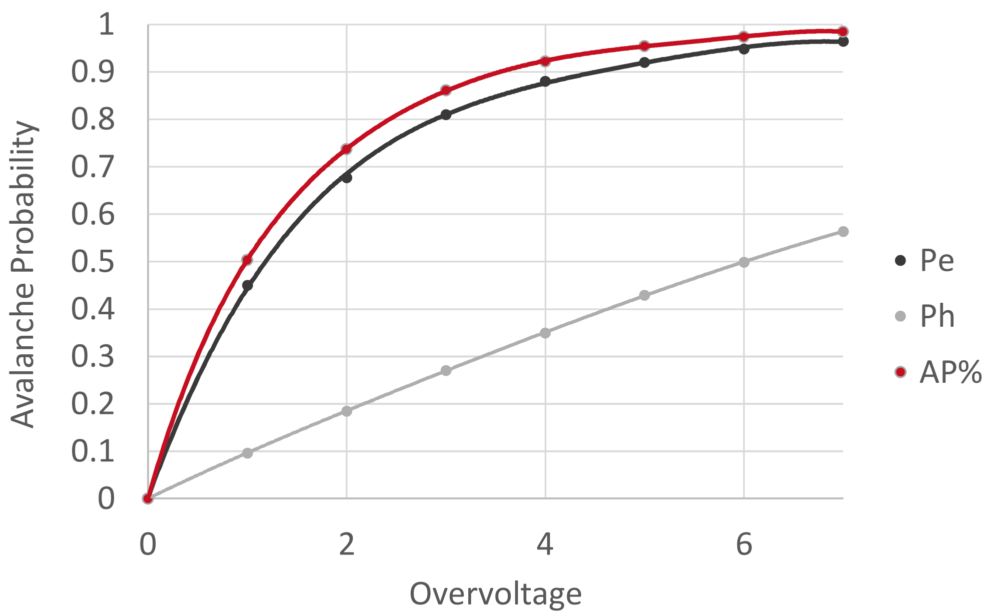
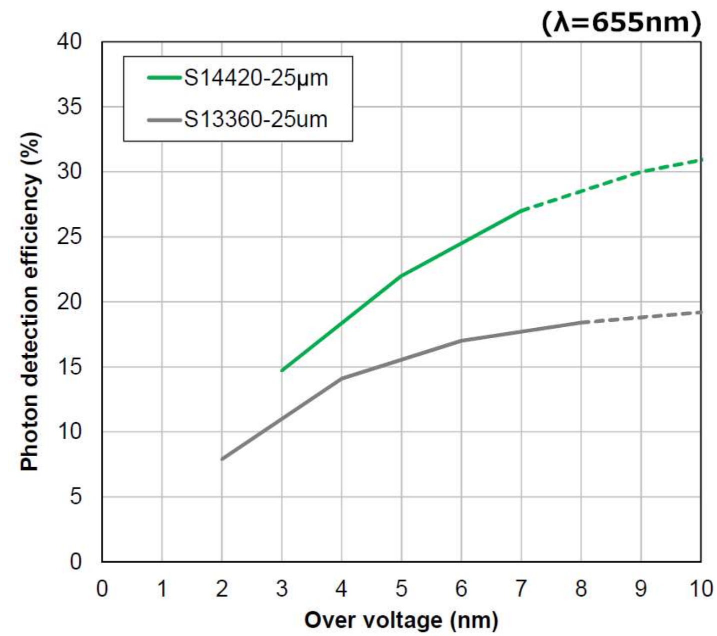
- AP% is increased with higher overvoltage
- Overvoltage = Applied Voltage – Breakdown Voltage

$$AP\%(V) = P_e + P_h - (P_e P_h)$$





Key Takeaways: Quantum Efficiency Photosensitivity

Phototube & Photodiodes

$$Signal = \frac{photons}{sec} * QE\% * time$$

APD

$$Signal = \frac{photons}{sec} * QE\% * Gain * time$$

PMT

$$Signal = \frac{photons}{sec} * QE\% * CE\% * Gain * time$$

MPPC (SiPM)

$$Signal = \frac{photons}{sec} * PDE\% * Gain * time$$

$$PDE\% = QE\% * FF\% * AP\%$$

Dark Current & Dark Noise

Dark Noise

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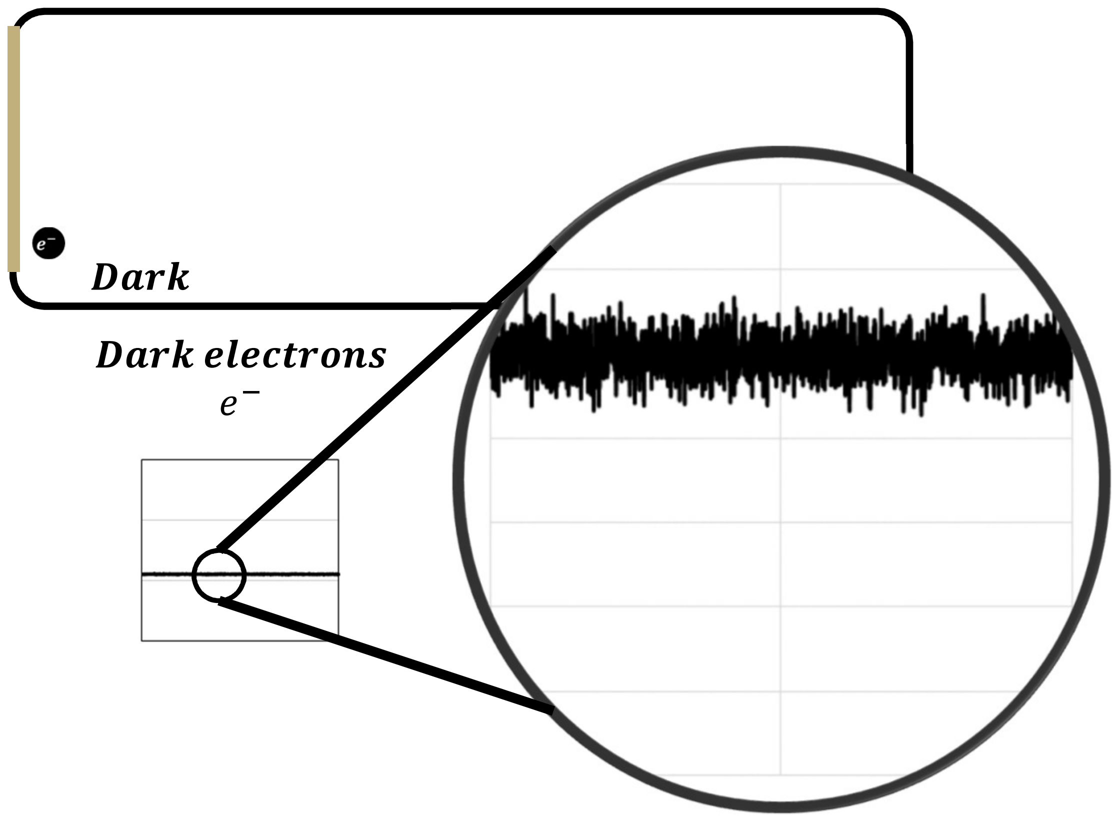
- Dark signal is the average value, its fluctuation is the dark noise.

$$Dark = \frac{dark\ electrons}{sec} * time$$

$$\sigma_{dark} = \sqrt{\frac{dark\ electrons}{sec} * time}$$



Dark Offset Subtraction

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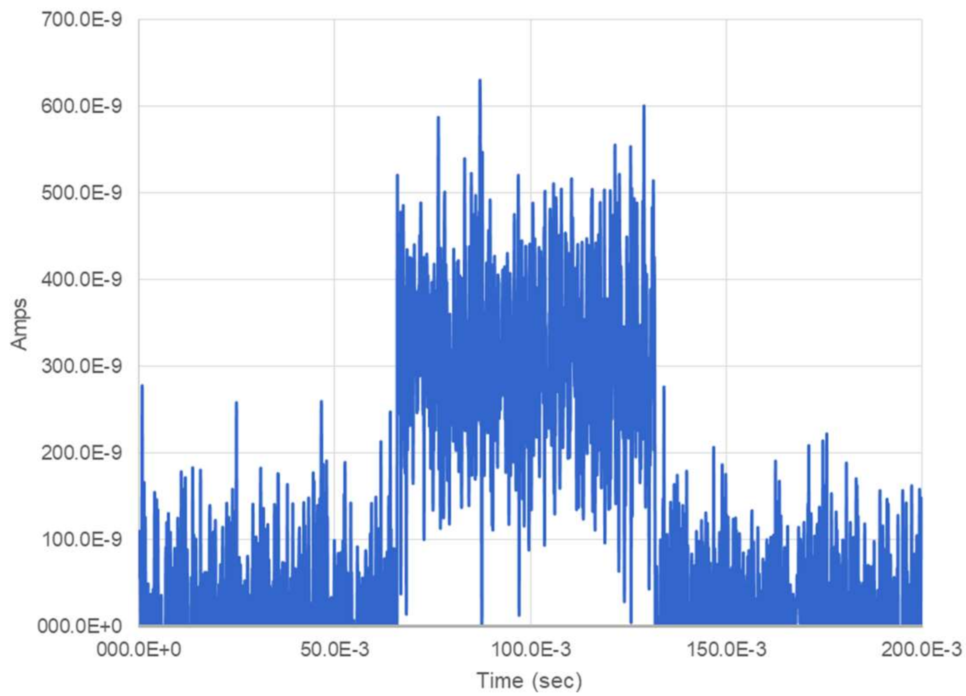
- We can subtract the offset ie. mean dark current, but noise remains.



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Dark Subtraction Increases Noise

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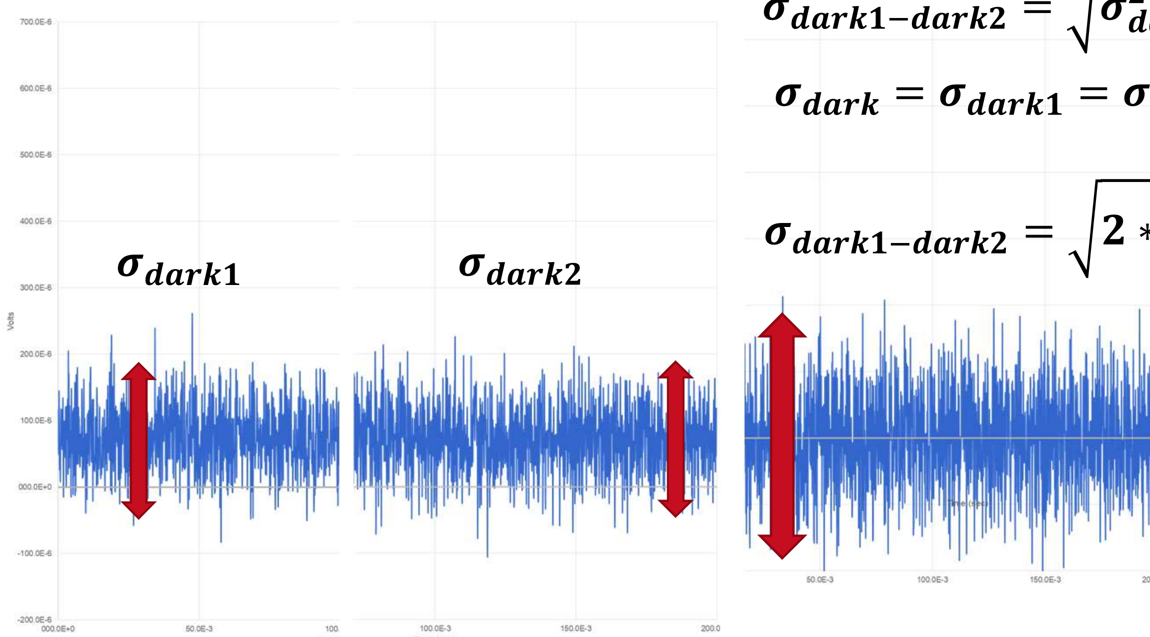
- Dark subtraction adds the noise from the dark reference measurement.

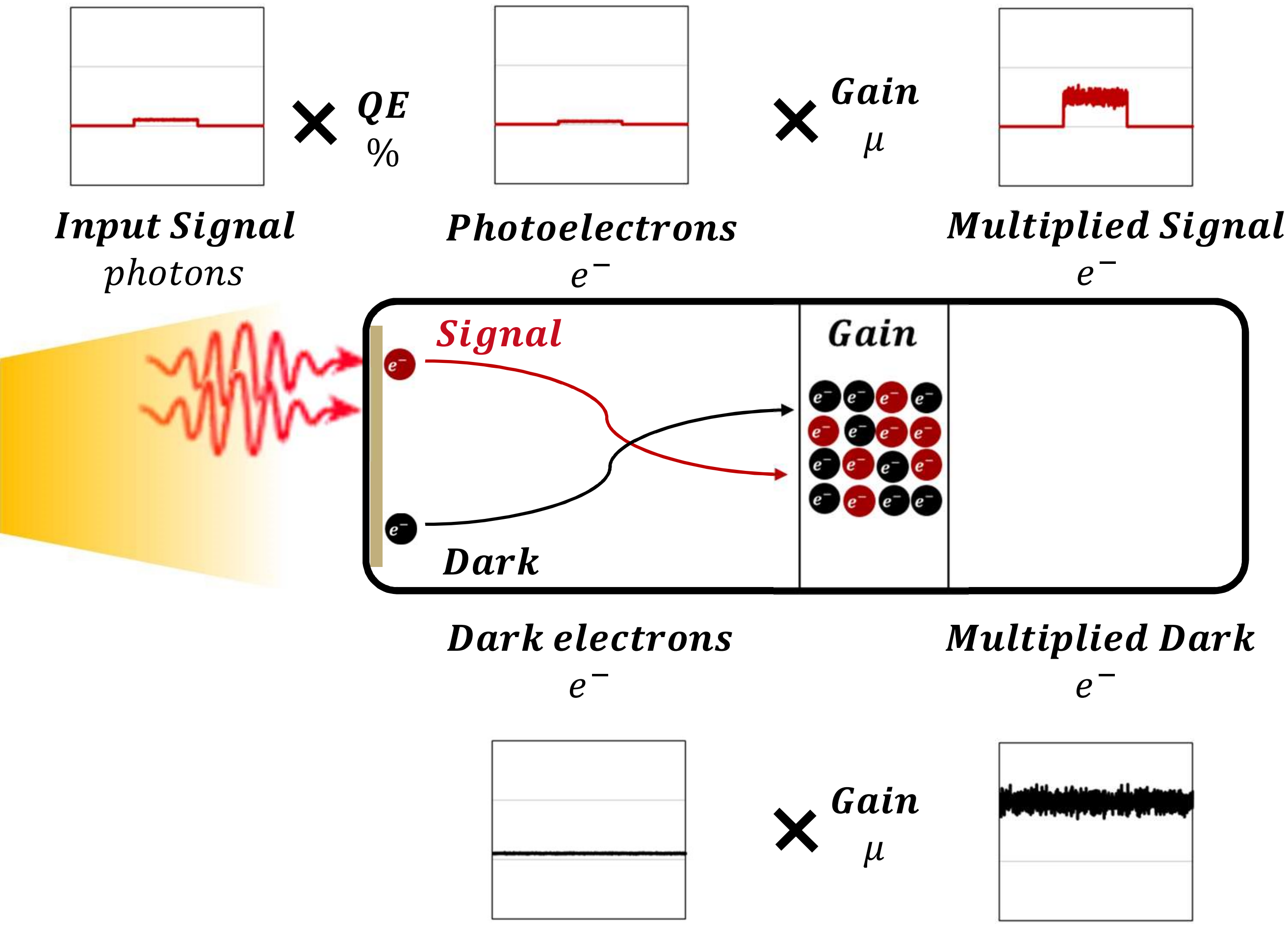
$$\sigma_{dark1-dark2} = \sqrt{\sigma_{dark1}^2 + \sigma_{dark2}^2}$$

$$\sigma_{dark} = \sigma_{dark1} = \sigma_{dark2}$$

$$\sigma_{dark1-dark2} = \sqrt{2 * \sigma_{dark}^2}$$



Intrinsic Gain (Ideal)



$$Signal = \boldsymbol{\mu} * \frac{photons}{sec} * QE\% * time$$

$$\sigma_{signal} = \boldsymbol{\mu} * \sqrt{\frac{photons}{sec} * QE\% * time}$$

- Gain amplifies signal and dark equally as well as the amplifying the noise.

$$Dark = \boldsymbol{\mu} * \frac{dark\ electrons}{sec} * time$$

$$\sigma_{dark} = \boldsymbol{\mu} * \sqrt{\frac{dark\ electrons}{sec} * time}$$

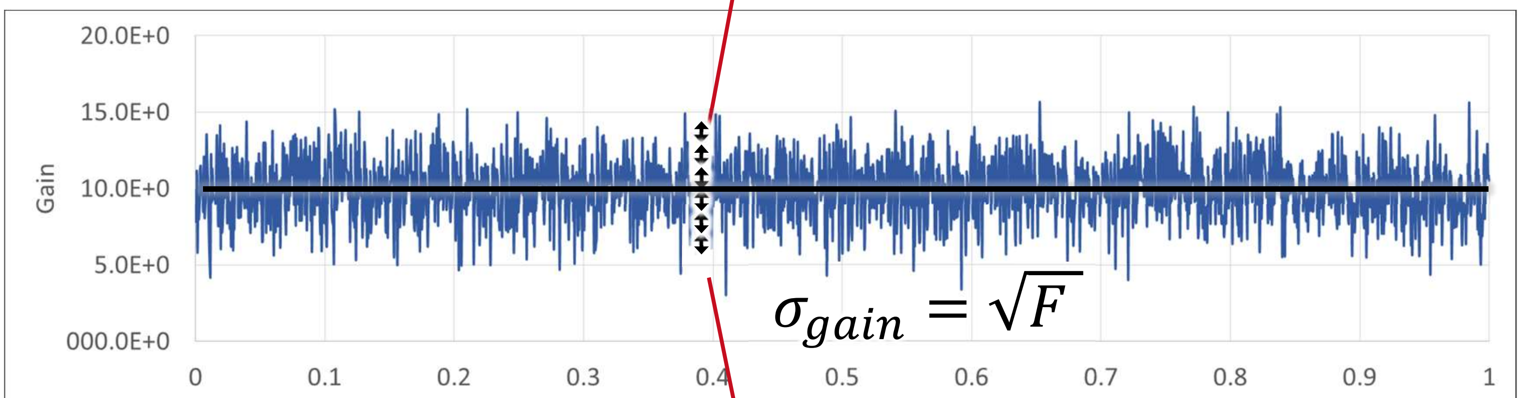
SIMULATION REFERENCE ONLY

Gain Fluctuation

- Gain randomly fluctuates
- Excess Noise Factor (F) describes the severity of gain fluctuation.

$$Signal = \boldsymbol{\mu} * \frac{photons}{sec} * QE\% * time$$

$$\sigma_{signal} = \sqrt{\boldsymbol{\mu}^2 * \boldsymbol{F} * \frac{photons}{sec} * QE\% * time}$$



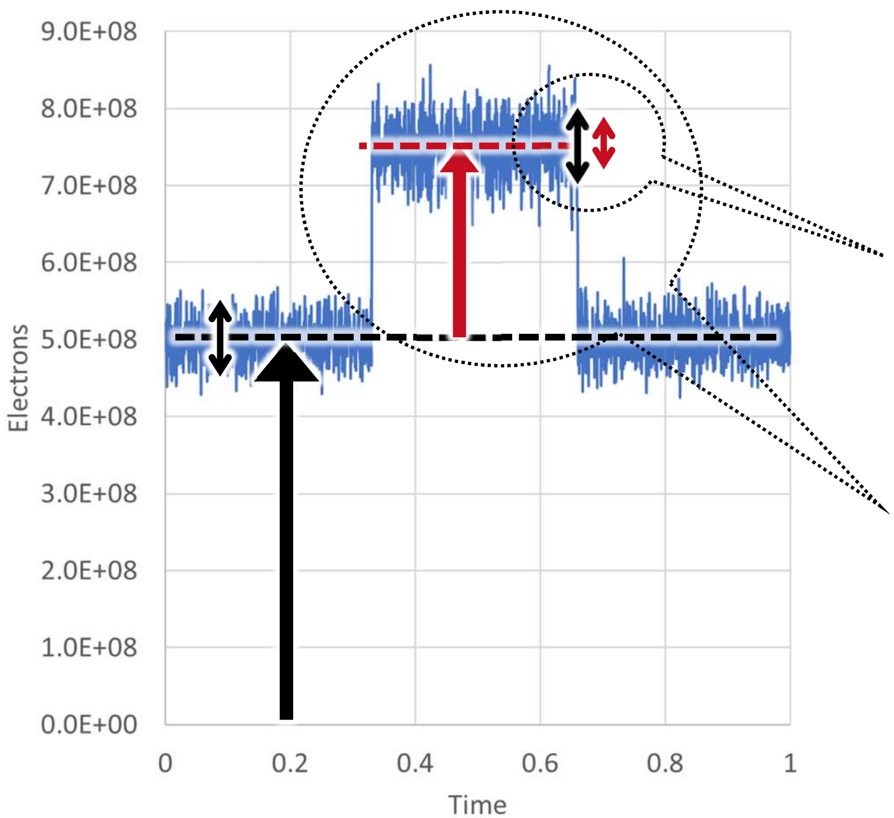
$$\sigma_{gain} = \sqrt{F}$$

$$Dark = \boldsymbol{\mu} * \frac{dark\ electrons}{sec} * time$$

$$\sigma_{dark} = \sqrt{\boldsymbol{\mu}^2 * \boldsymbol{F} * \frac{dark\ electrons}{sec} * time}$$

Signal and Noise from the Detector

- Noise terms can be combined by squaring the terms then taking the square root.
- Excess Noise caused by gain reduces the SNR from the detector



$$\sigma_{det} = \sqrt{\sigma_{signal}^2 + \sigma_{dark}^2}$$

$$\sigma_{det} = \sqrt{\mu^2 * F * \left(\frac{photons}{sec} * QE\% + \frac{dark\ electrons}{sec}\right) * time}$$

$$SNR_{det} = \frac{\mu * \frac{photons}{sec} * QE\% * time}{\sqrt{\mu^2 * F * \left(\frac{photons}{sec} * QE\% + \frac{dark\ electrons}{sec}\right) * time}}$$

Mechanism of Gain and Excess Noise

Cause of Excess Noise in Avalanche Photodiodes

❖ Impact ionization from both carriers makes APD gain very noisy.

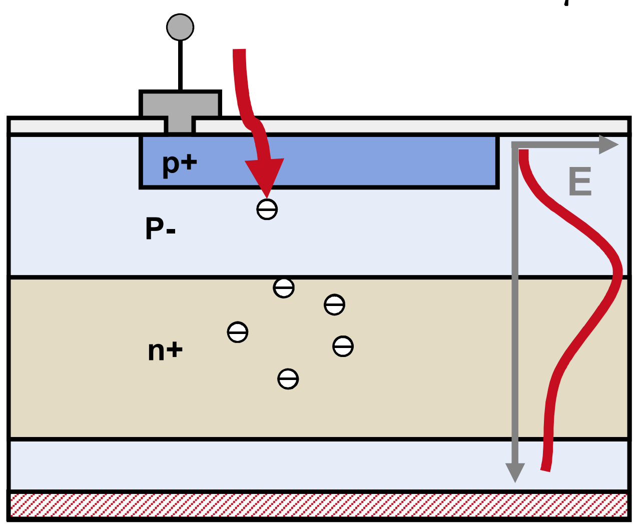
<u>APD</u>

- Low gain many times
- $F = Gain^{x}$
  - $x = Excess\ noise\ figure$
- $F \sim 2.0\text{-}4.0$
- $Gain: 10 - 100$

$\alpha: ionization\ rate\ of\ electrons$

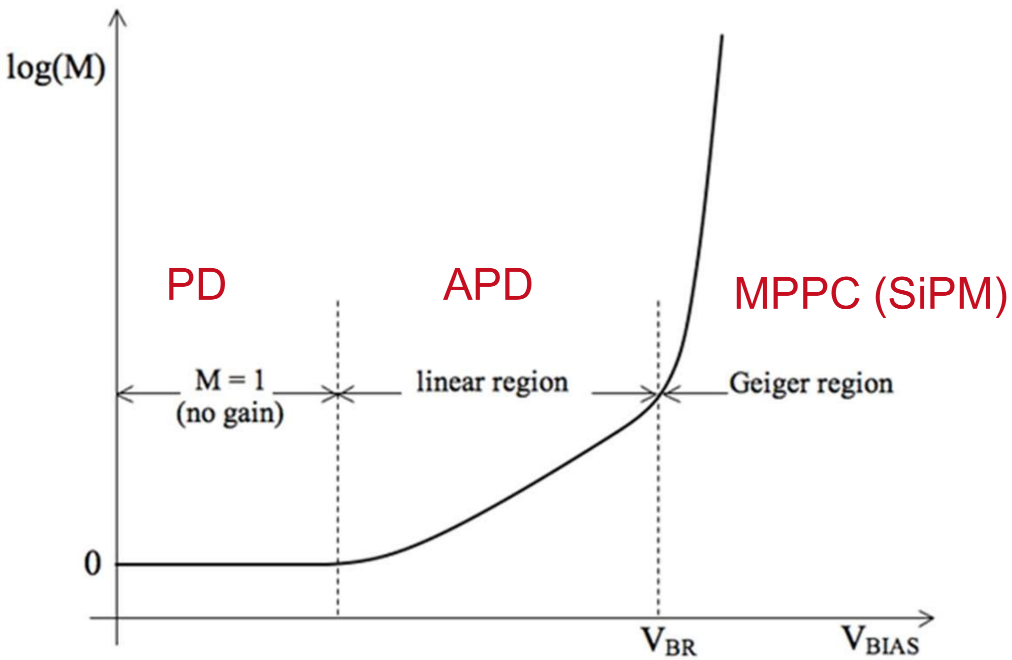
$\beta: ionization\ rate\ of\ holes$

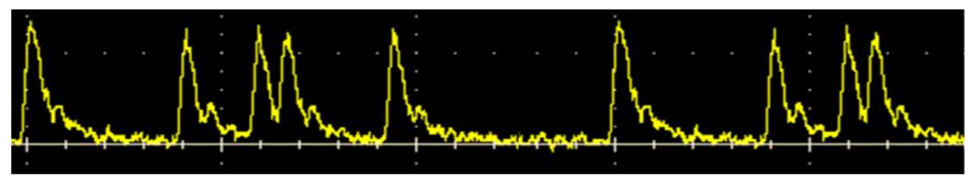
$$F = \mu\frac{\beta}{\alpha} + (2 - \frac{1}{\mu})(1 - \frac{\beta}{\alpha})$$



Geiger Mode APD (SPAD)

- Geiger mode causes the APD output to reach saturation chare.
- Geiger mode gain is almost perfectly uniform ie. low excess noise





Geiger Mode Array = MPPC (SiPM)

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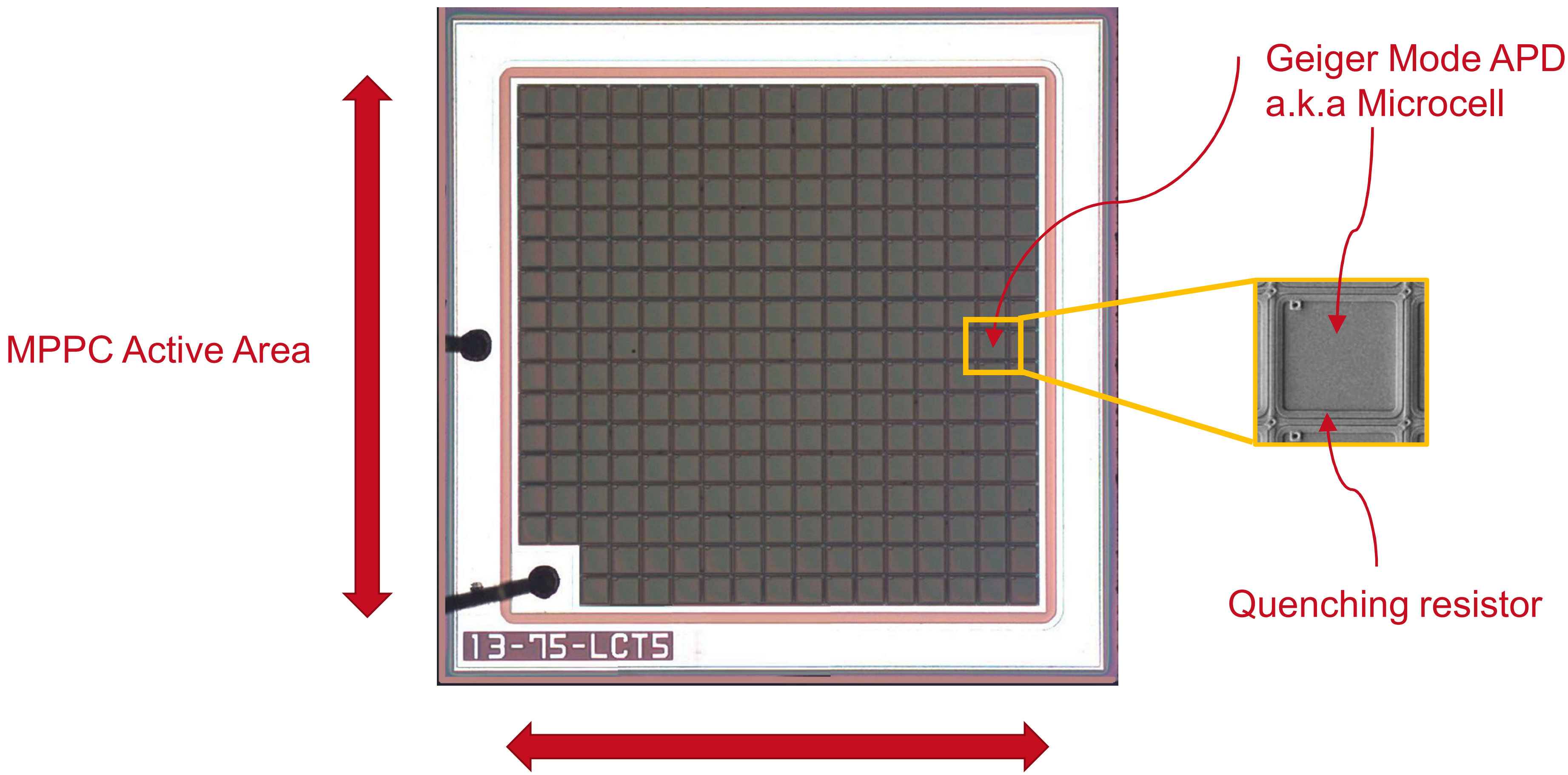
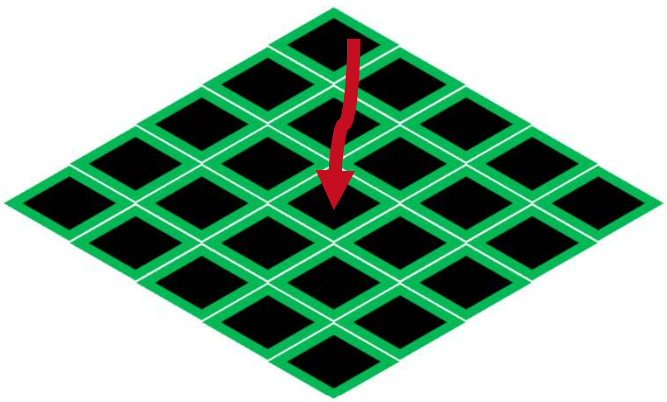


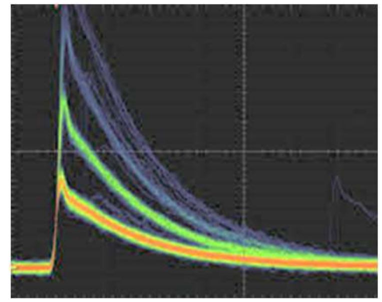
Cause of Excess Noise in MPPC (SiPM)

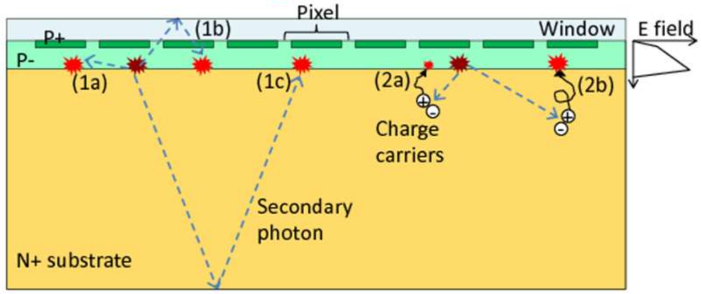
❖ Crosstalk can make gain appear higher than expected due to additional microcells firing.

MPPC (SiPM)

- Excess charge from crosstalk
- $F = \frac{1}{1+ln(1-P_{ct})}$
  - $\mathrm{P_{ct}}$ = Crosstalk probability
- $F \sim$ 1.05-1.1
- $Gain: 10^5 - 10^6$







J. Rosado (2015). *Characterization and modeling of crosstalk and afterpulsing in Hamamatsu silicon photomultipliers*

Cause of Excess Noise in MPPC (SiPM)

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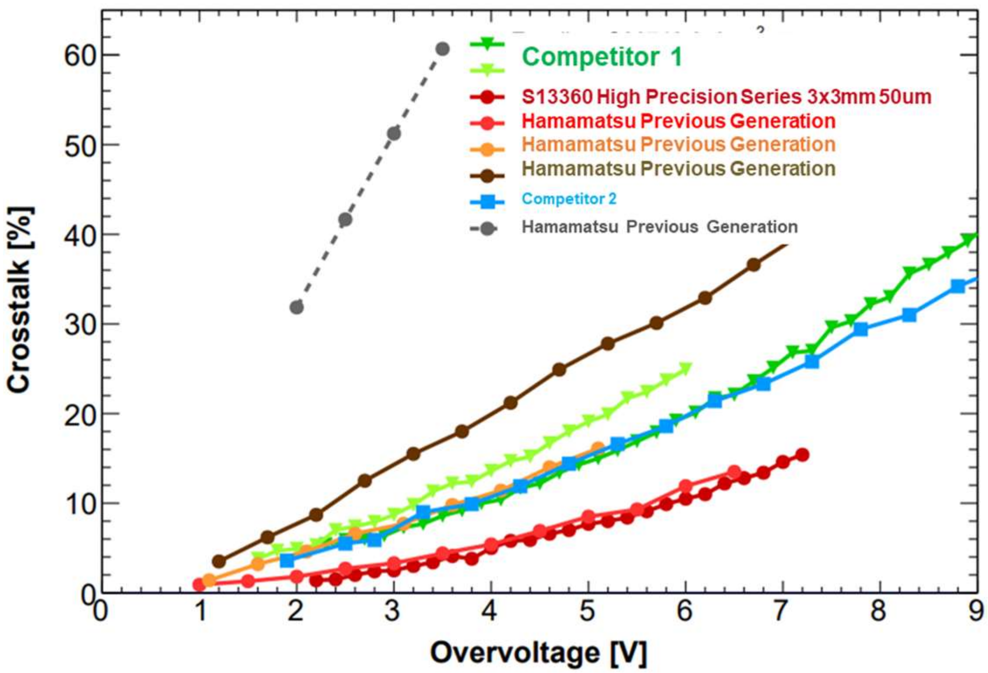
❖ Lower crosstalk MPPC achieves lower multiplication noise



$$F = \frac{1}{1 + ln(1 - P_{ct})}$$

- P_{ct} = Crosstalk probability

S. Vinogradov, 2011. *Analytical models of probability distribution and excess noise factor of Solid State Photomultiplier signals with crosstalk*

J. Biteau, 2015. *Performance of Silicon Photomultipliers for the Dual-Mirror Medium-Sizes Telescopes of the Cherenkov Telescope Array*

Crosstalk Reduction Development

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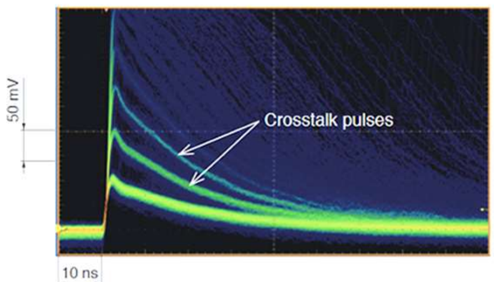
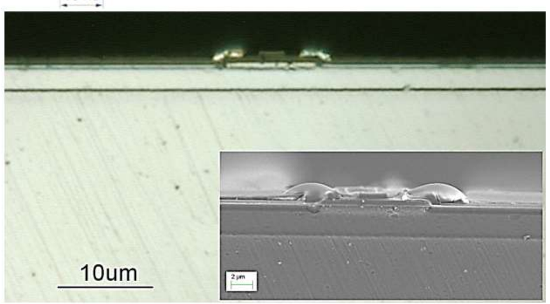
- Optical trenches reduce crosstalk by blocking the transmission of secondary photon.

<u>Previous Product</u>

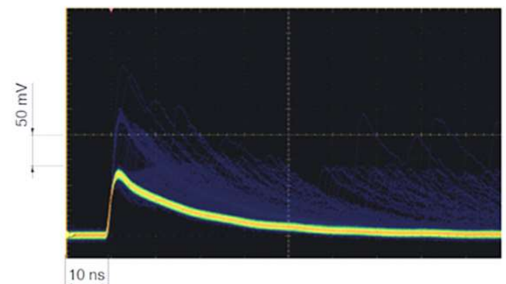
25% Crosstalk Probability

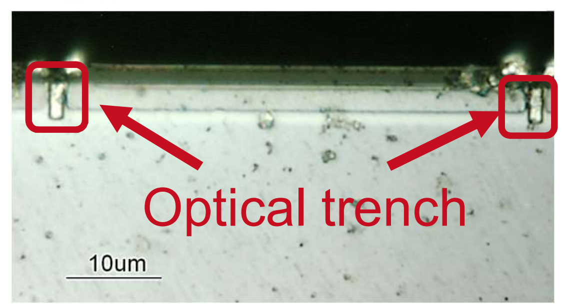




<u>S13360-3050CS</u>
(High Precision Series)

3% Crosstalk Probability





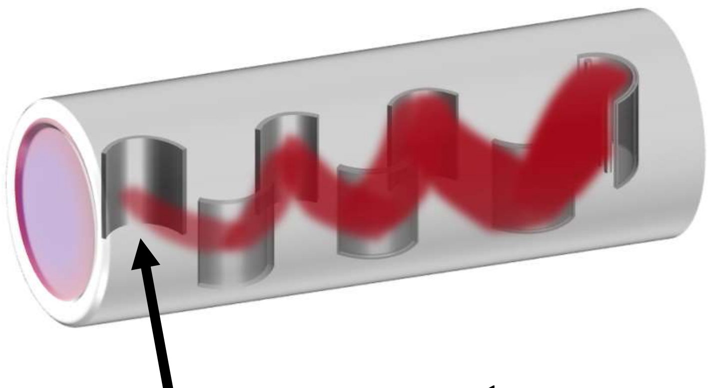
J. Rosado (2015). *Characterization and modeling of crosstalk and afterpulsing in Hamamatsu silicon photomultipliers*

Cause of Excess Noise in PMT

❖ Higher 1st dynode gain results in lower excess noise for PMT

PMT

- Variation in dynode emission
- $F = \frac{\delta}{\delta - 1}$
  - $\delta = Dy_1\ gain$
- $F \sim 1.1$ - 1.4
- $Gain: 10^4 - 10^6$



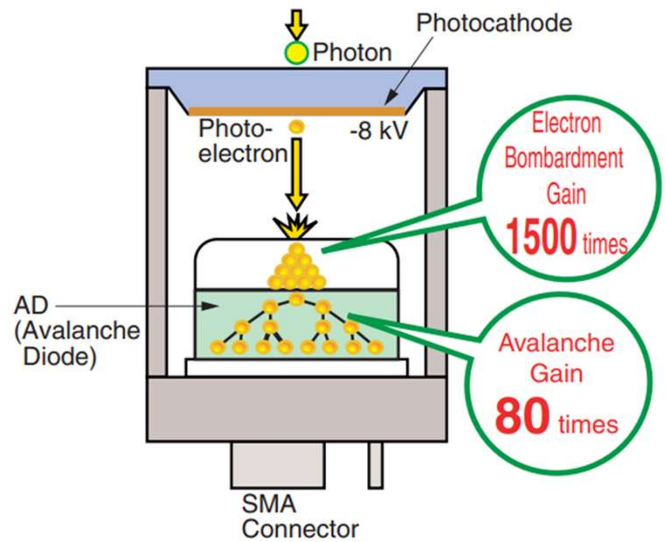
$$\delta = \mu^{\frac{1}{Number\ of\ Dynodes}}$$

Hybrid Photo Detector

❖ HPD gain is closest to ideal noiseless gain because of very high 1st stage gain.

HPD

- Electron bombardment x avalanche multiplication
- $F = \frac{\delta}{\delta - 1} = \frac{1500}{1499} \sim 1$



Operating Consideration for Excess Noise Factor

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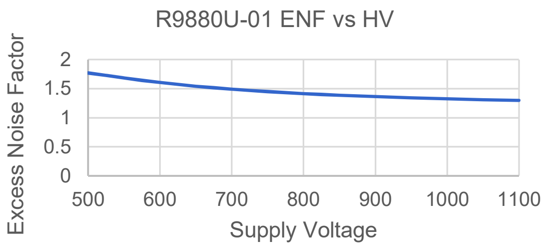
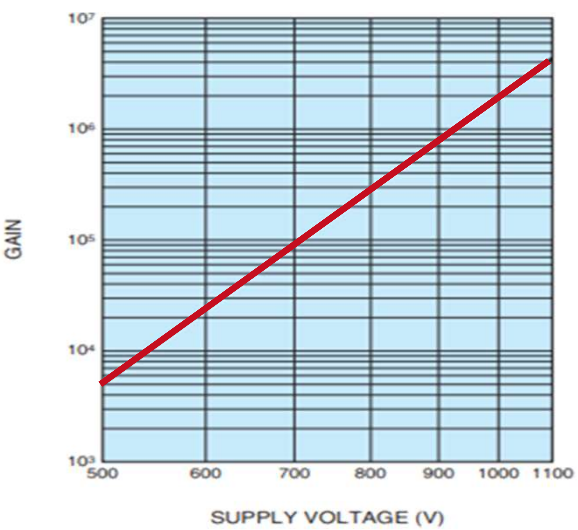
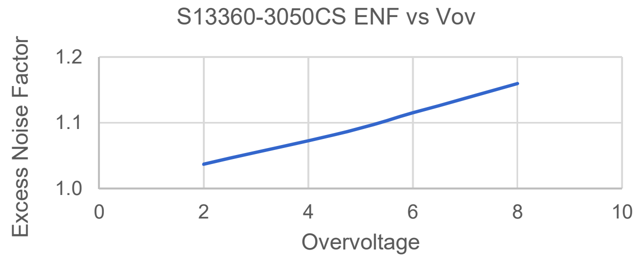
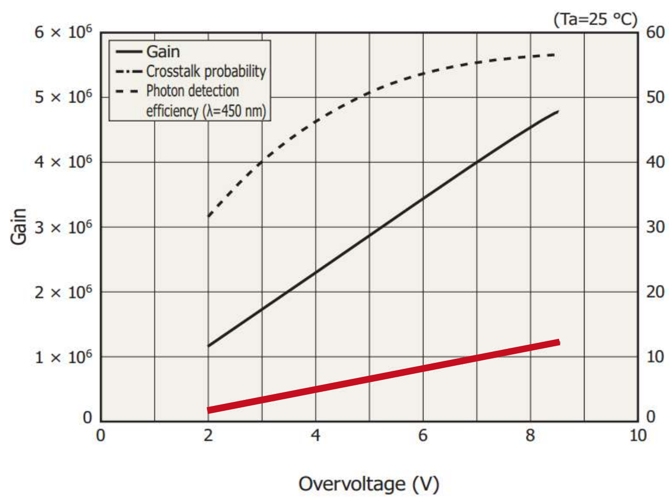
PMT



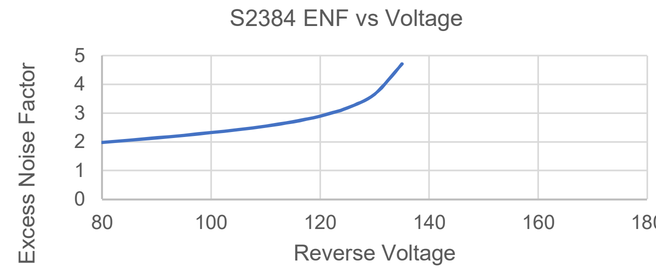


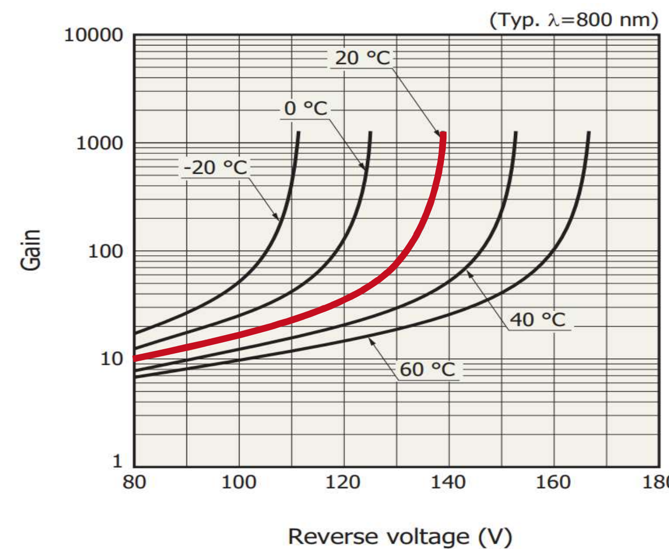
MPPC





APD





Excess Noise Factor Effect

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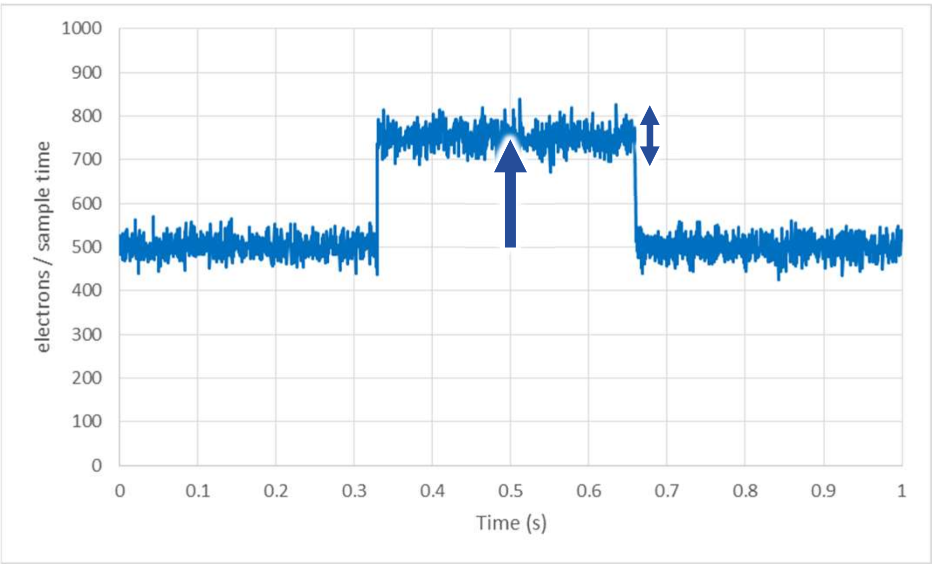
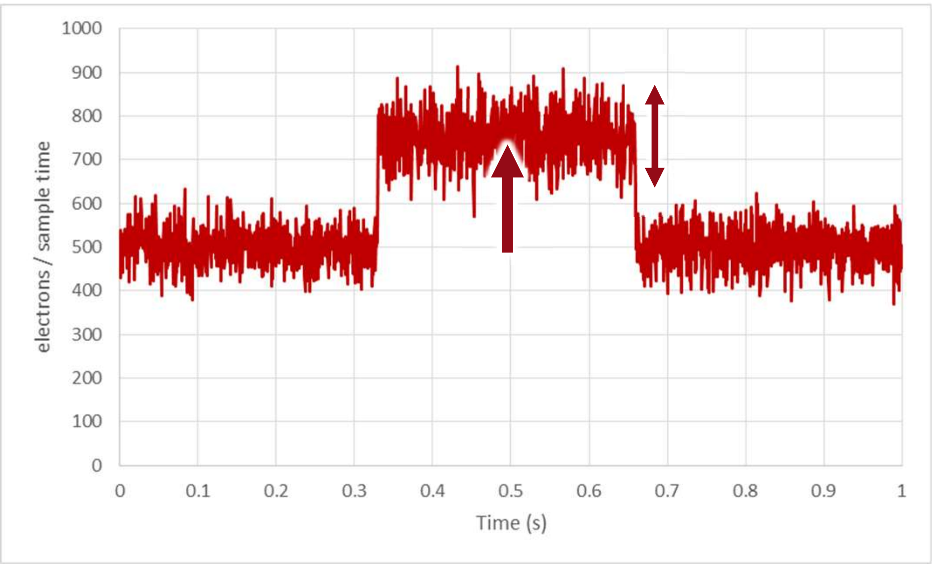
- Output with gain is just an enlarged copy, but noisier.

Cathode e^-



$\dfrac{\text{Anode } e^-}{\text{Gain}}$



Key Takeaways for Excess Noise

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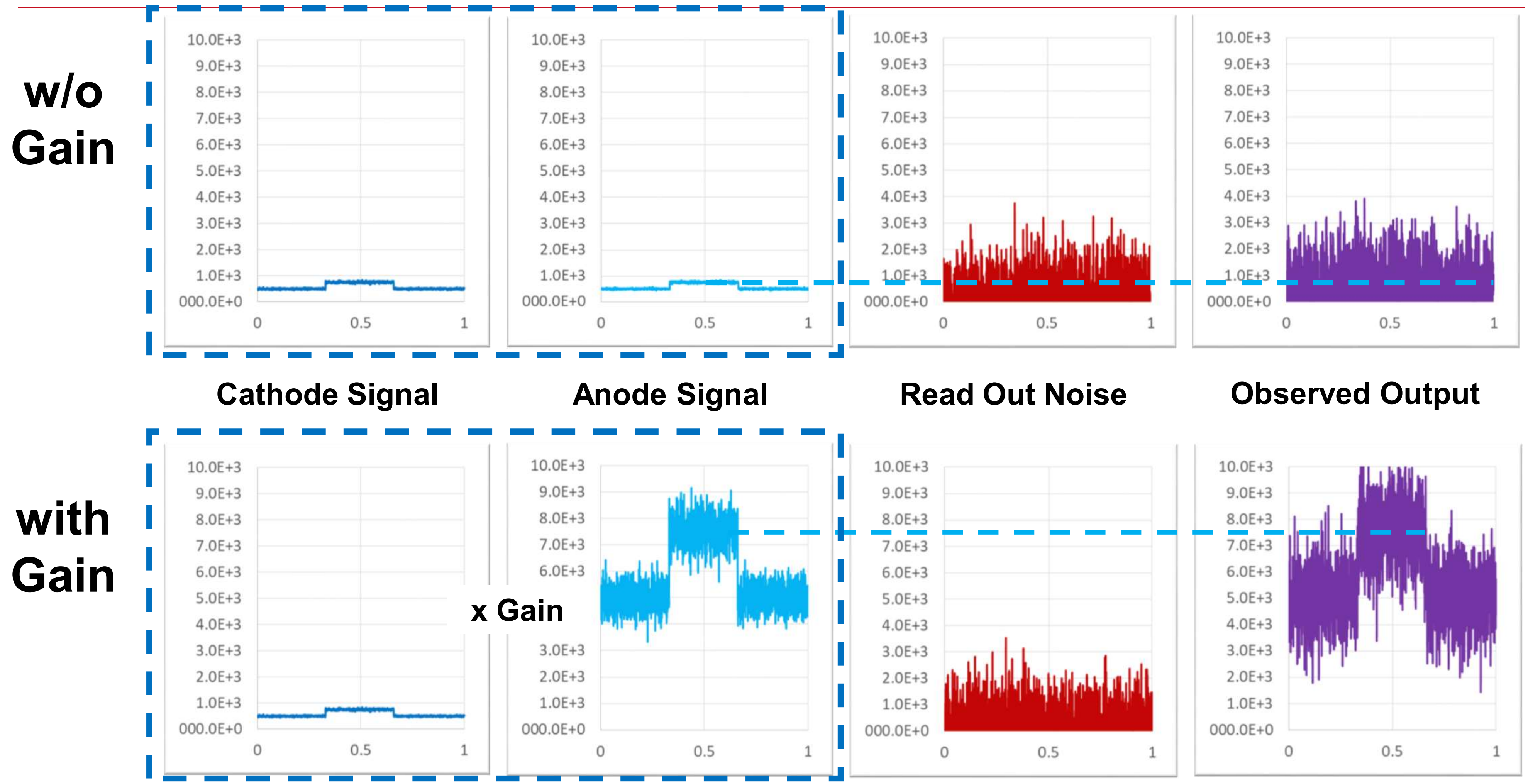
- Detectors with gain add excess noise to the signal which reduces the SNR of the detector output.
- Gain is simply enlarged copy, but noisier.

	MPPC	PMT	APD
Gain	10^5 - 10^7	10^4 – 10^7	10 - 100
Excess Noise Factor (F)	**1.05 – 1.1**	**1.1 – 1.2** **(HPD ~ 1.0)**	**2 - 4**
Cause of ENF	Crosstalk	Dynode secondary emission variation	Unpredictable ionization rate due to minority carrier ionization
Detector considerations for reducing ENF	Minimize crosstalk	Maximize 1st dynode gain	Minimize excess noise figure
Operating considerations for reducing ENF	Lower overvoltage	Higher voltage	Lower voltage

Benefits of Intrinsic Gain

Photodetector with and without Intrinsic Gain



Intrinsic Gain vs. External Gain

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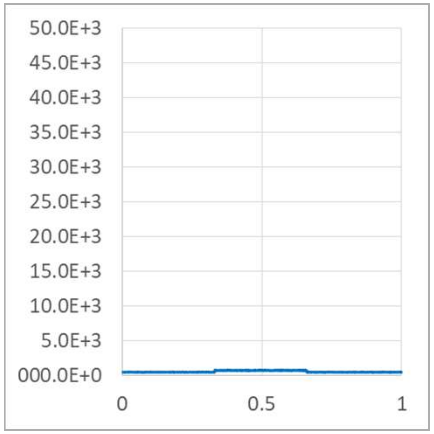
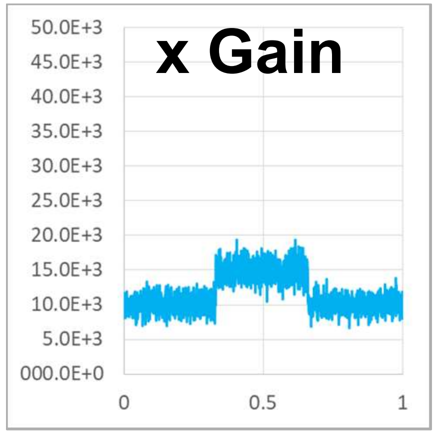
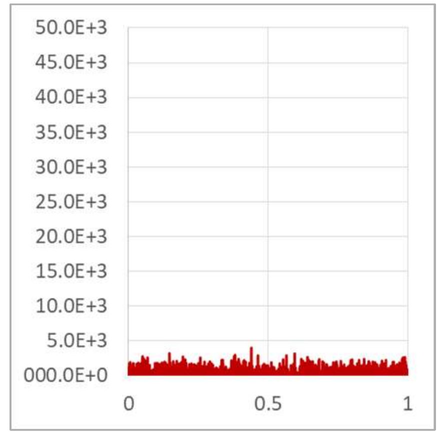
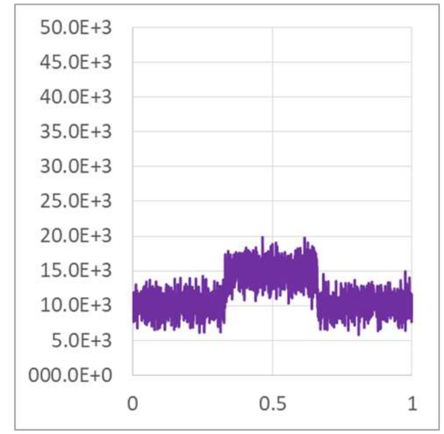
Intrinsic Gain



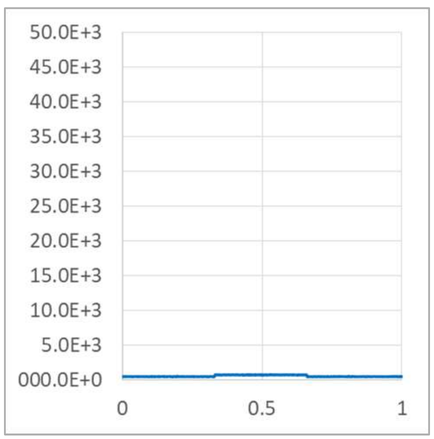


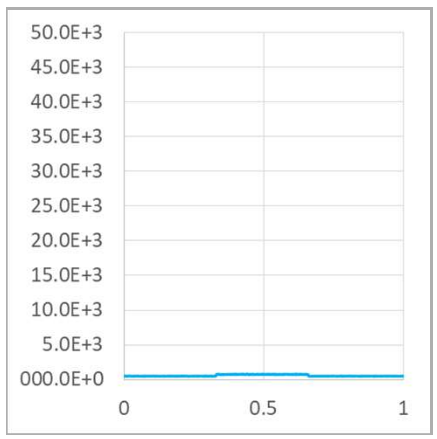


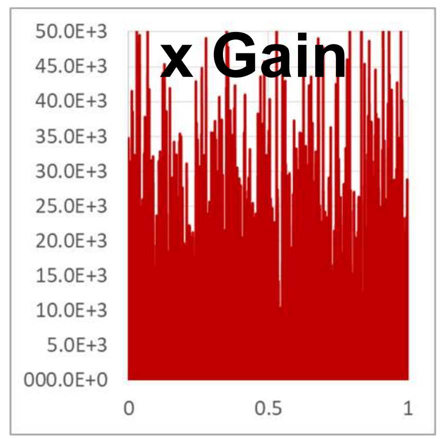


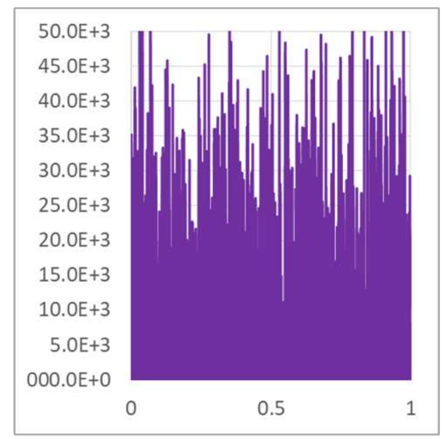
Cathode Signal | **Anode Signal** | **Read Out Noise** | **Observed Output**

External Gain







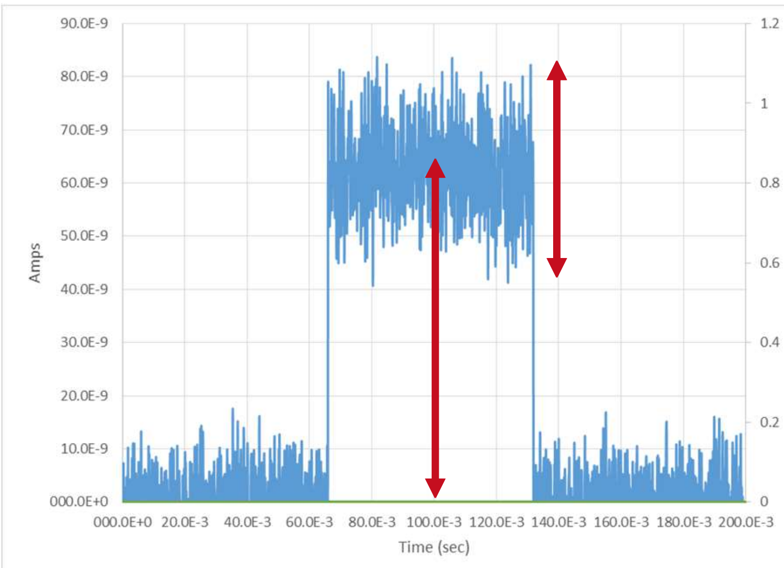


SIMULATION REFERENCE ONLY

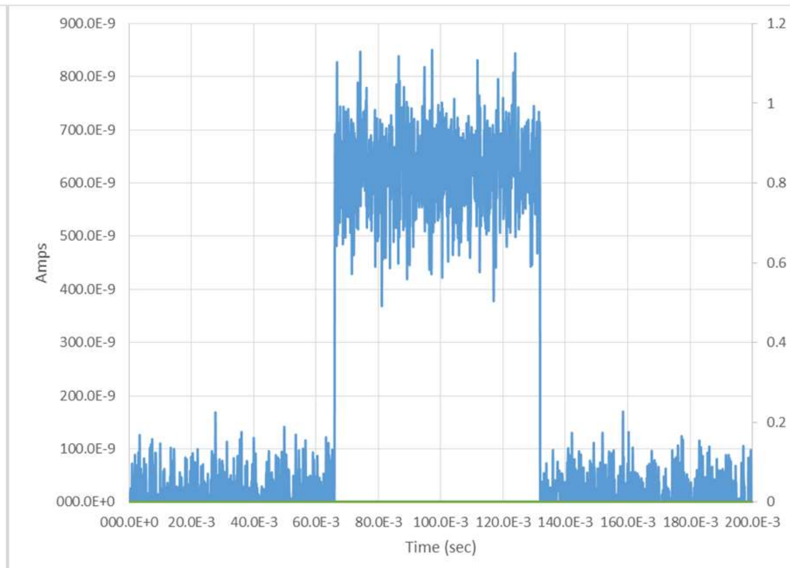
100k vs. 1M Gain

- Readout noise becomes insignificant with high intrinsic gain so adding extra gain has no improvement.

100,000 Gain



1,000,000 Gain



SIMULATION REFERENCE ONLY

QE%, Dark, and Gain Effect on Detector SNR

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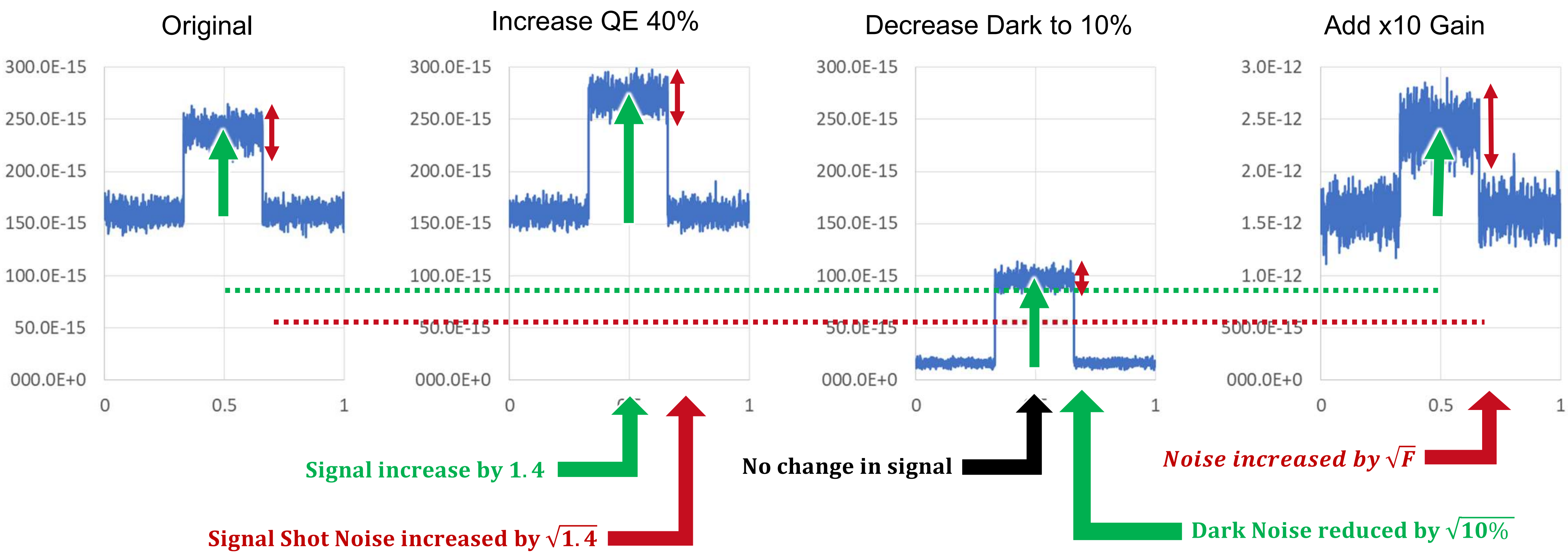
- Increasing QE and decreasing dark increases detector SNR, gain decreases detector SNR.



Unnecessary gain

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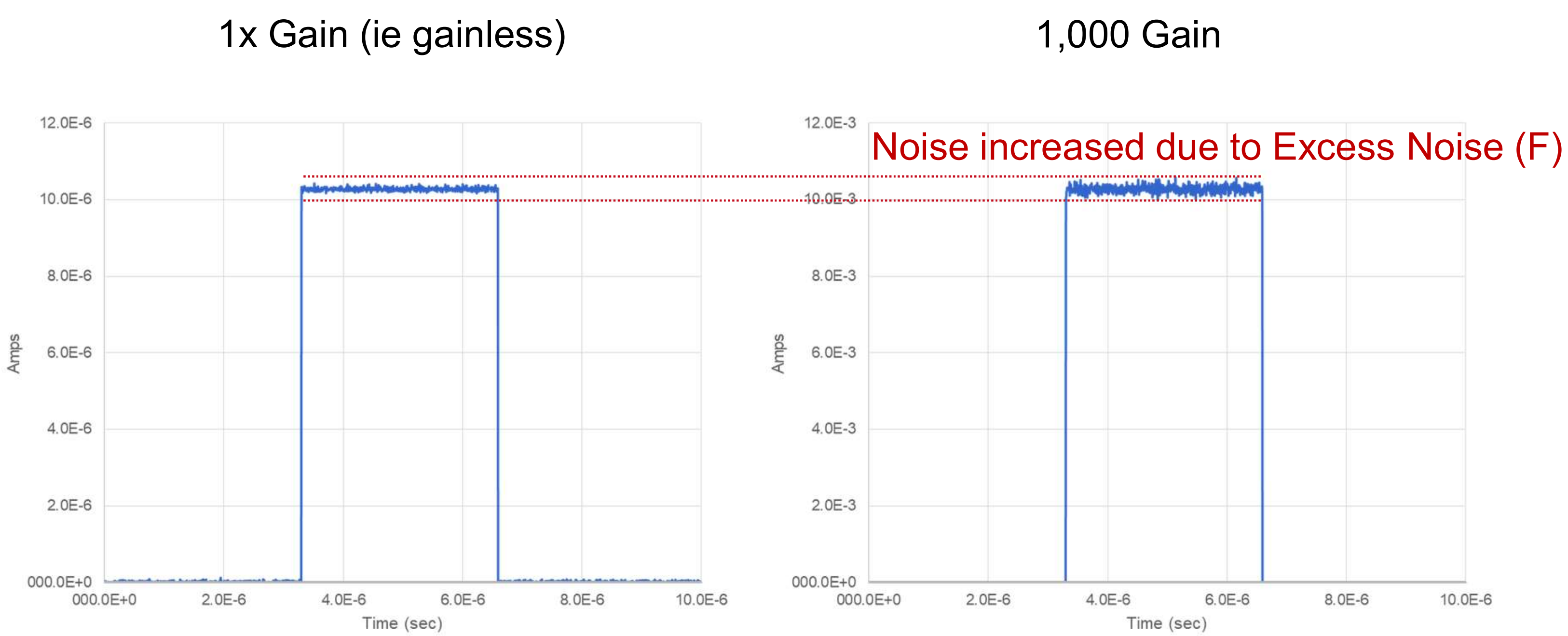
❖ Adding gain when not needed increases noise, and reduces SNR.



Key Takeaways: Benefits of Intrinsic Gain

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- Readout noise can make it impossible to measure weak signals without gain.
- Intrinsic gain raises the signal above readout noise.
- External (amplifier) gain does not raise signal above readout noise.
- With enough gain readout noise becomes insignificant.
- If readout noise is insignificant, then the system output SNR = detector output SNR
- Gain can only reduce detector output SNR.
- Increasing Quantum Efficiency % and reducing Dark Noise can improve detector SNR.

Readout Noise

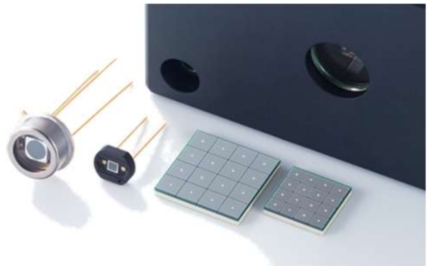
PD / PIN PD
1x

APD
$1 - 100$

Phototube
1x

PMT
$10^4 - 10^7$

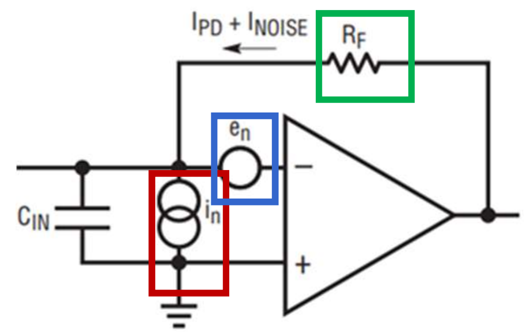
MPPC (SiPM)
$10^5 - 10^7$



Amplifier Noise

- Readout noise can come from voltage noise and current noise (amplifier), and Johnson noise (resistor).

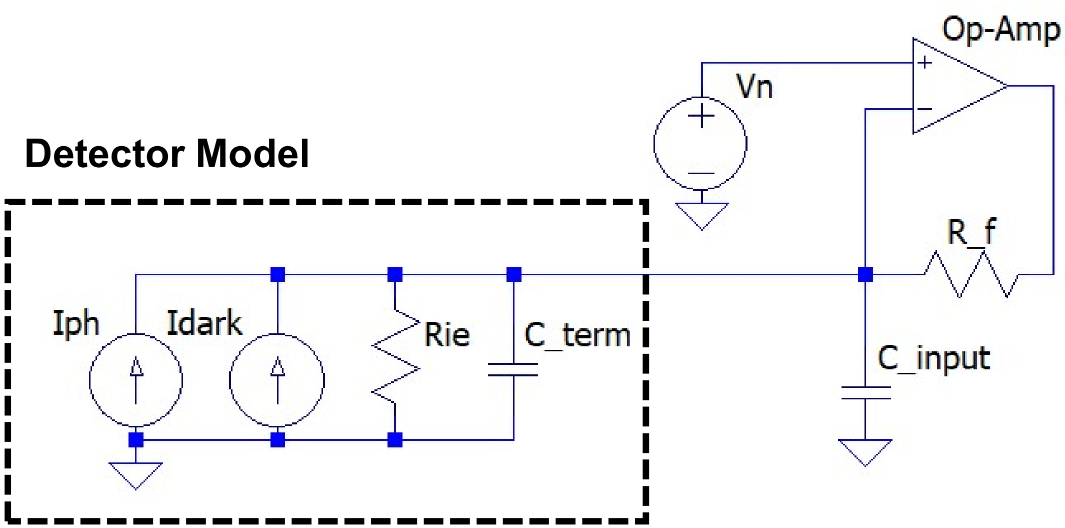
PARAMETER	CONDITIONS	OPA846ID, IDBV TYP +25°C	MIN/MAX OVER TEMPERATURE +25°C[1]	0°C to 70°C[2]	−40°C to +85°C[2]	UNITS	MIN/ MAX	TEST LEVEL[3]
AC PERFORMANCE (see Figure 1)								
Closed-Loop Bandwidth	G = +7, R_G = 50Ω, V_O = 200mV_{PP}	500				MHz	typ	C
	G = +10, R_G = 50Ω, V_O = 200mV_{PP}	400	270	250	225	MHz	min	B
	G = +20, R_G = 50Ω, V_O = 200mV_{PP}	110	82	80	75	MHz	min	B
Gain Bandwidth Product (GBP)	G ≥ +40	1750	1275	1245	1200	MHz	min	B
Bandwidth for 0.1dB Gain Flatness	G = +10, R_L = 100Ω, V_O = 200mV_{PP}	140	40	36	35	MHz	min	B
Peaking at a Gain of +7						dB	typ	C
Harmonic Distortion	G = +10, f = 5MHz, V_O = 2V_{PP}							
2nd-Harmonic	R_L = 100Ω	−76	−70	−68	−66	dBc	max	B
	R_L = 500Ω	−100	−89	−87	−85	dBc	max	B
3rd-Harmonic	R_L = 100Ω	−109	−95	−92	−90	dBc	max	B
	R_L = 500Ω	−112	−105	−101	−96	dBc	max	B
2-Tone, 3rd-Order Intercept	G = +10, f = 10MHz	44	41	40	38	dBm	min	B
Input Voltage Noise	f > 1MHz	1.2	1.3	1.4	1.5	nV/√Hz	max	B
Input Current Noise	f > 1MHz	2.8	3.5	3.6	3.6	pA/√Hz	max	B
Rise-and-Fall Time	0.2V Step	1.2	1.5	1.6	1.8	ns	max	B
Slew Rate	2V Step	625	500	425	350	V/µs	min	B
Settling Time to 0.01%	2V Step	15				ns	typ	C
0.1%	2V Step	10	12	14	16	ns	max	B
1%	2V Step	6	8	10	12	ns	max	B
Differential Gain	G = +10, NTSC, R_L = 150Ω	0.02				%	typ	C
Differential Phase	G = +10, NTSC, R_L = 150Ω	0.02				deg	typ	C



https://www.ti.com/lit/ds/symlink/opa846.pdf

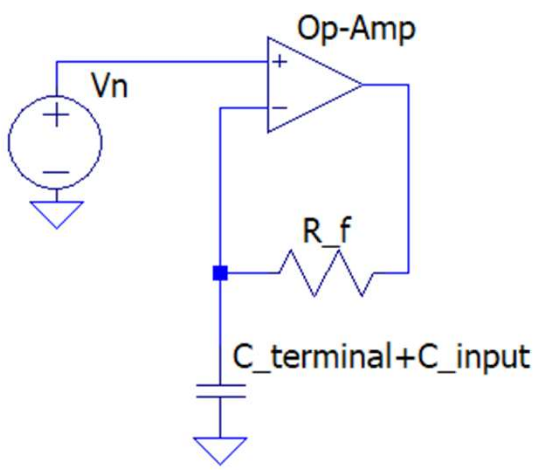
Effect of Terminal Capacitance on Voltage Noise Gain

- Detector capacitance, stray capacitance, and op-amp input capacitance contribute to the input capacitance.

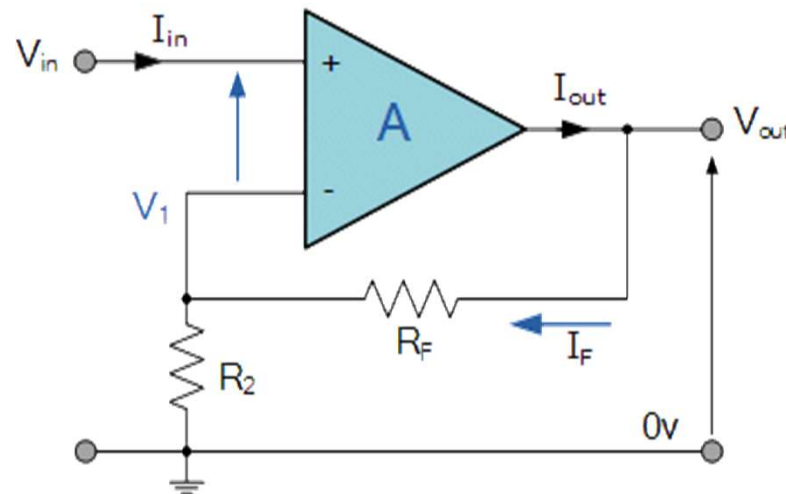


Effect of Terminal Capacitance on Voltage Noise Gain

- Input capacitance changes the gain applied to the voltage noise input.



$$Gain = \frac{R_f}{R_2}$$



Effect of Terminal Capacitance on Voltage Noise Gain

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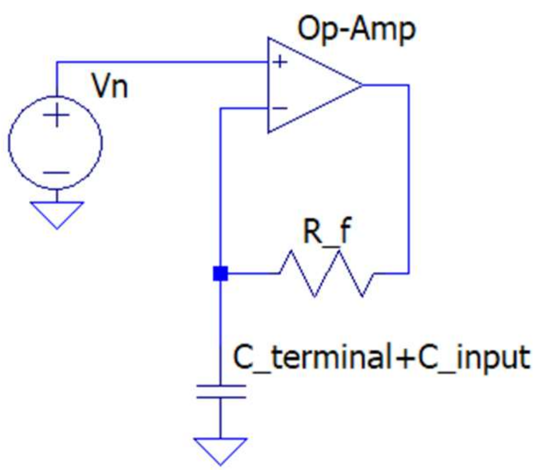
- Input capacitance increases the voltage noise gain.



$$Z_{cin} = \frac{1}{2\pi f C_{in}}$$

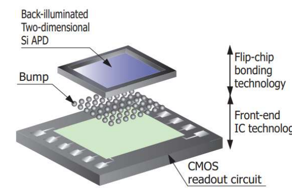
$$v_{out} = v_{Nrms}\left(1 + \frac{R_f}{Z_{Cin}}\right)$$

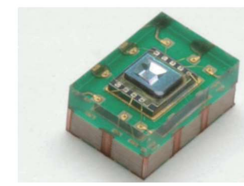
$$v_{out} = v_{Nrms}(1 + R_f 2\pi f C_{in})$$

Reducing Capacitance

$$v_{out} = v_{Nrms}\left(1 + R_f 2\pi f C_{in}\right)$$

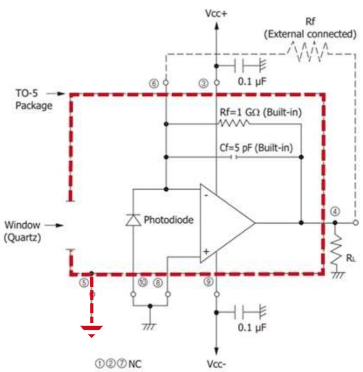
Output trace to op-amp as short and wide as possible

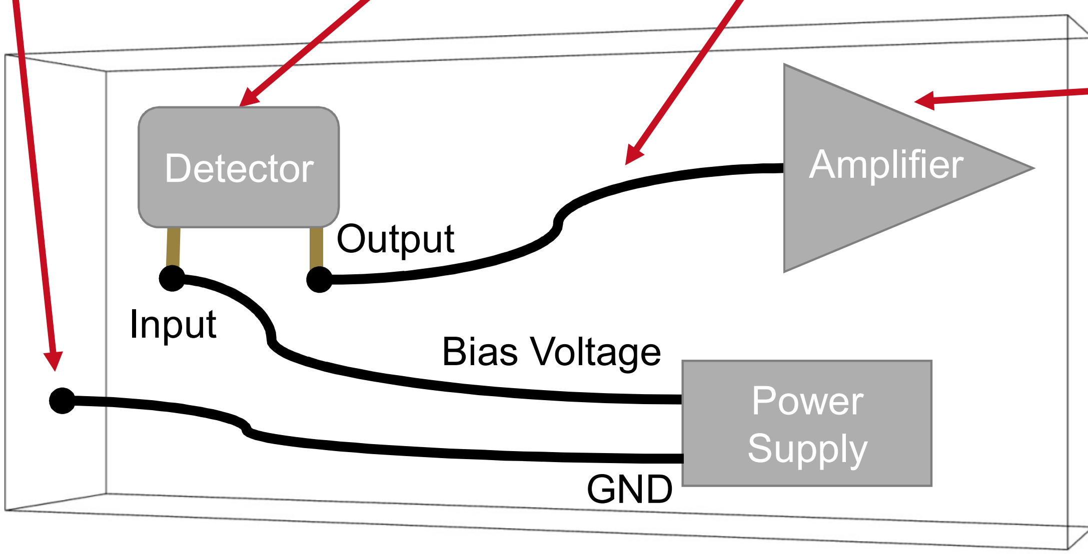




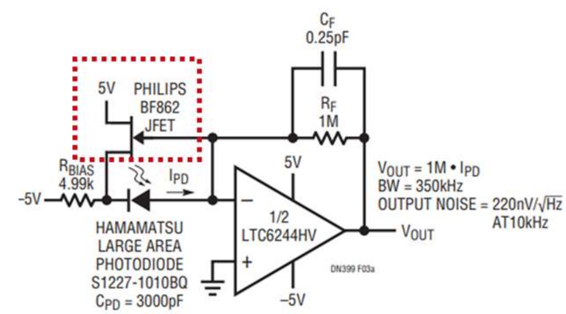
Grounded housing

Reduce detector terminal capacitance
eg. smaller area PD





JFET 'Bootstrap circuit' on the input



https://www.analog.com/media/en/reference-design-documentation/design-notes/dn399f.pdf

Standard Deviation and RMS

❖ We need the RMS of readout noise to calculate the overall SNR.

Shot Noise:

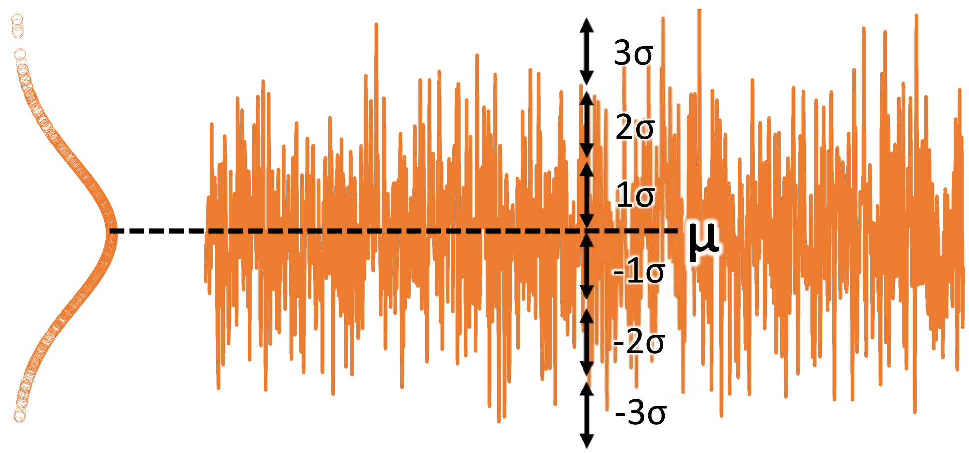
- Noise = Standard Deviation

Readout Noise:

- Noise = RMS = Standard Deviation when the Average is zero (μ=0)

Root Mean Squared

$$\sigma = \sqrt{\sigma^2} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i \qquad\right)^2}$$

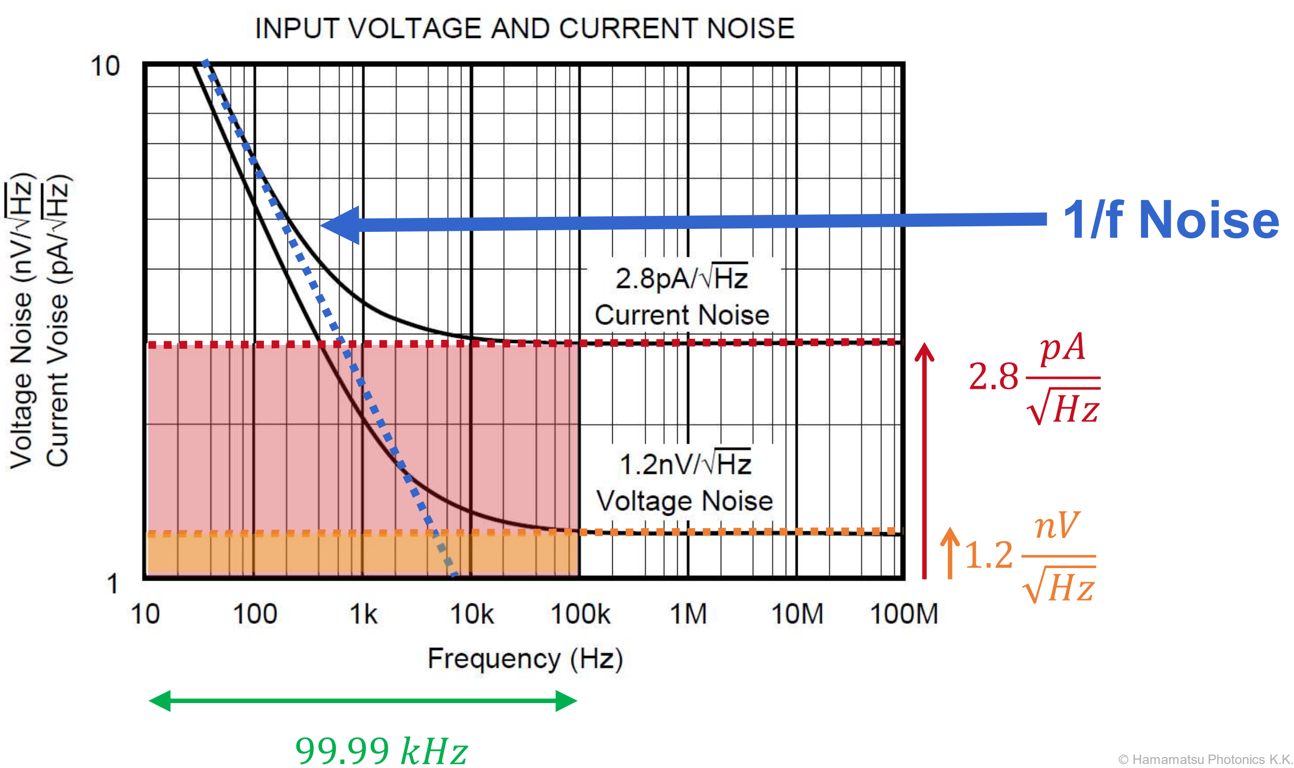


https://en.wikipedia.org/wiki/Standard_deviation

Calculating RMS from Noise Density

$$i_{Nrms} = 2.8\frac{pA}{\sqrt{Hz}} * \sqrt{99.99\ kHz} = 0.89\ nA$$

$$v_{Nrms} = 1.2\frac{nV}{\sqrt{Hz}} * \sqrt{99.99\ kHz} = 379\ nV$$



Noises Referred to the Input

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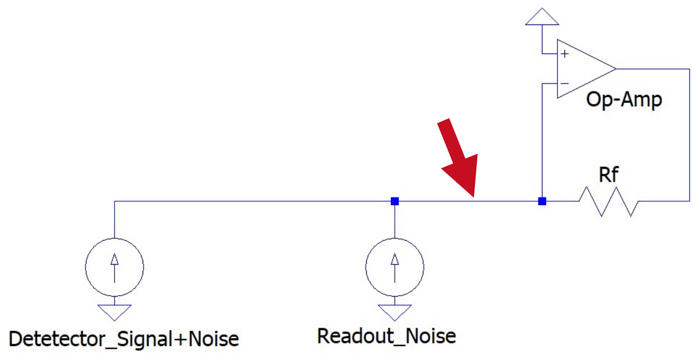
- Noise values converted to electrons at the input of the op-amp, can be compared easily to the detector noise.



Input Referred Noise Values:

Current Noise

$$v_{i_{Nout}} = i_{Nrms} R_f$$

$$i_{i_{Nin}} = i_{Nrms}$$

$$\sigma_{Current\ Noise}[e^-] = i_{Nin} \frac{time}{q}$$

Voltage Noise

$$v_{Nout} = v_{Nrms}(1 + R_f 2\pi f C_{in})$$

$$i_{v_{Nin}} = (\frac{v_{Nrms}}{R_f} + v_{Nrms} 2\pi f C_{in})$$

$$\sigma_{Voltage\ Noise}[e^-] = (\frac{v_{Nrms}}{R_f} + v_{Nrms} 2\pi f C_{in}) \frac{time}{q}$$

Johnson Noise

$$i_{Johnson} = \sqrt{\frac{4k_b T[K] f}{R}}$$

$$\sigma_{Johnson}[e^-] = \frac{time}{q} \sqrt{\frac{4k_b T[K] f}{R}}$$

Noise Sources Review

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Detector Noise

$$\sigma_{signal}[e^-] = \sqrt{\mu^2 * F * \frac{photons}{sec} * QE\% * Time}$$

$$\sigma_{dark}[e^-] = \sqrt{\mu^2 * F * \frac{dark\ electrons}{sec} * Time}$$

Readout Noise

$$\sigma_{Johnson}[e^-] = \frac{Time}{q}\sqrt{\frac{4k_b Temp[K]f}{R}}$$

$$\sigma_{Current\ Noise}[e^-] = I_{Nrms}\frac{Time}{q}$$

$$\sigma_{Voltage\ Noise}[e^-] = (\frac{V_{Nrms}}{R_f} + V_{Nrms}2\pi f C_{in})\frac{Time}{q}$$

$$\sigma_{Total} = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 \ldots}$$

$$\sigma_{Detector\ Noise} = \sqrt{\sigma_{signal}^2 + \sigma_{dark}^2}$$

$$\sigma_{Readout\ Noise} = \sqrt{\sigma_{Johnson}^2 + \sigma_{Current\ Noise}^2 + \sigma_{Voltage\ Noise}^2}$$

$$\sigma_{Total\ Noise} = \sqrt{\sigma_{signal}^2 + \sigma_{dark}^2 + \sigma_{Johnson}^2 + \sigma_{Current\ Noise}^2 + \sigma_{Voltage\ Noise}^2}$$

Gain Requirement

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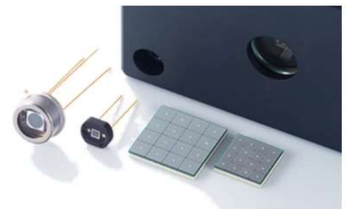
- The purpose of intrinsic gain is to raise the signal above readout noise.

$$\frac{photons}{sec} * QE\% * Time * \mu \quad > \quad \sigma_{Readout\ Noise}$$

$$\mu > \frac{\sigma_{Readout\ Noise}}{\frac{photons}{sec} * QE\% * time}$$

Detector Gain



	Photodiode	APDs	MPPC	PMT
Quantum Efficiency	80 - 90%	80 - 90%	25 - 50% (PDE)	10 - 20% (QE_{eff})
Gain	1	<100	10^5~10^6	~10^6
Excess Noise Factor	1	~5	~1.05	~1.2
Spectral Range	Up to 1200 nm (Silicon) Up to 2.6 um (InGaAs)	Up to 1150 nm (Silicon) Up to 1700 nm (InGaAs)	320 to 900 nm (Peak 450-470 nm)	190 to 900 nm
Dynamic Range	Limited by amplifier	Limited by amplifier	Limited by number of microcells	Limited by divider current
Limit of Detection	nW Severly limited by readout noise	pW Limited by readout noise	fW Limited by dark noise ~ 100,000 cps (Noisy)	fW Limited by dark noise ~ 500 cps (Quiet)
Bias Voltage	-	~200 V	~ 50 V	~ 1000 V
Mechanical Robustness	Rugged	Rugged	Rugged	Good
Magnetic Field	Immune	Immune	Immune	Need protection

Photon Counting

Photon Counting

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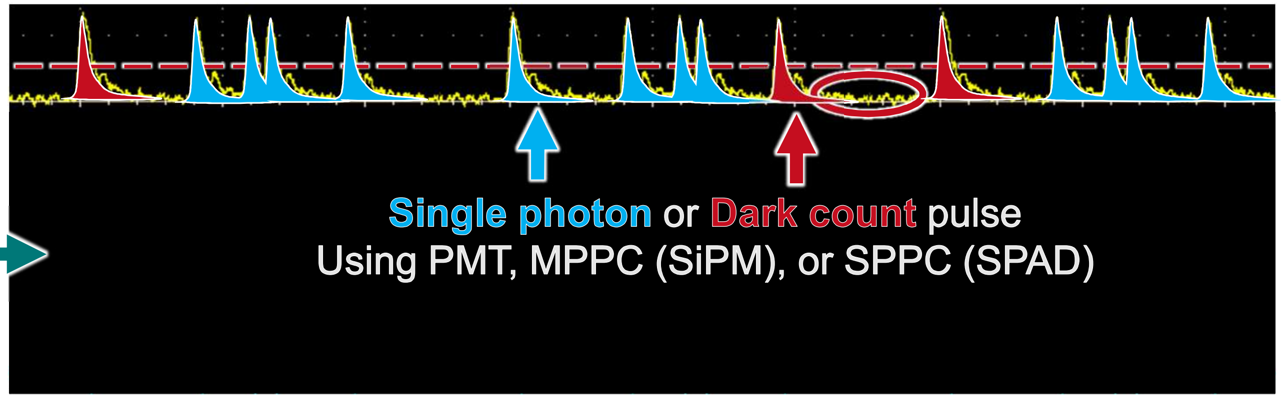
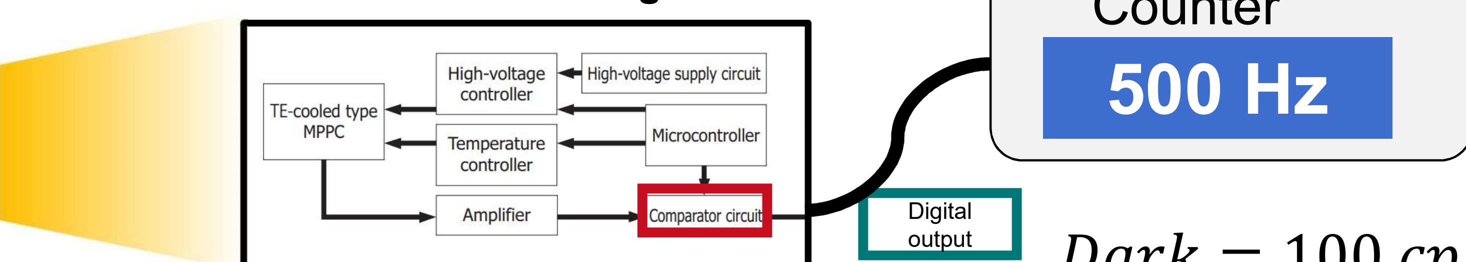
Comparator Threshold

Digital Output: (Count these pulses)



Photon Counting Module



$$Dark = 100\ cps$$

$$Signal = 500 - 100\ cps = 400\ cps$$

Photon Counting

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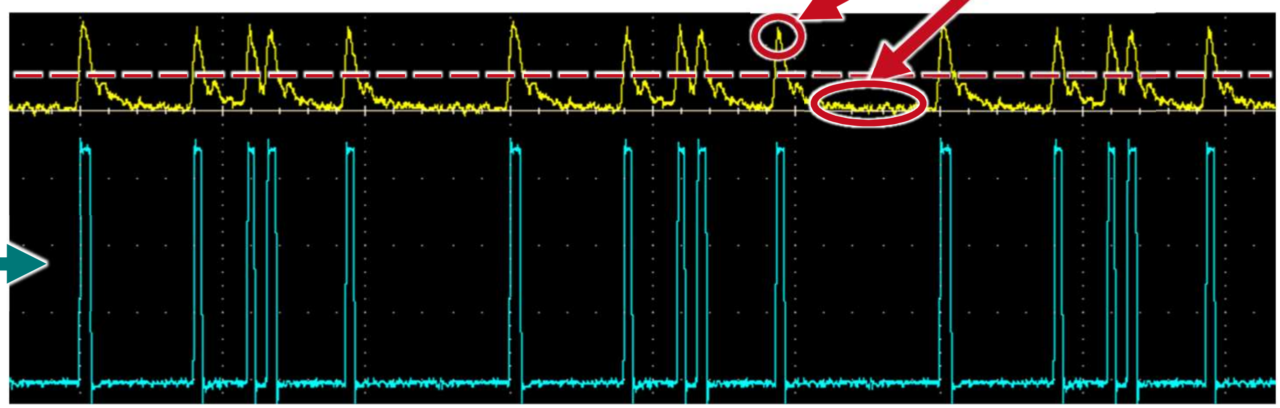
$$SNR_{PhotonCounting} = \frac{\frac{photons}{sec} * QE\% * time}{\sqrt{\frac{photons}{sec} * QE\% * time + 2 * \frac{dark\ counts}{sec} * time}}$$

Readout noise and excess noise are not a factor

Comparator Threshold

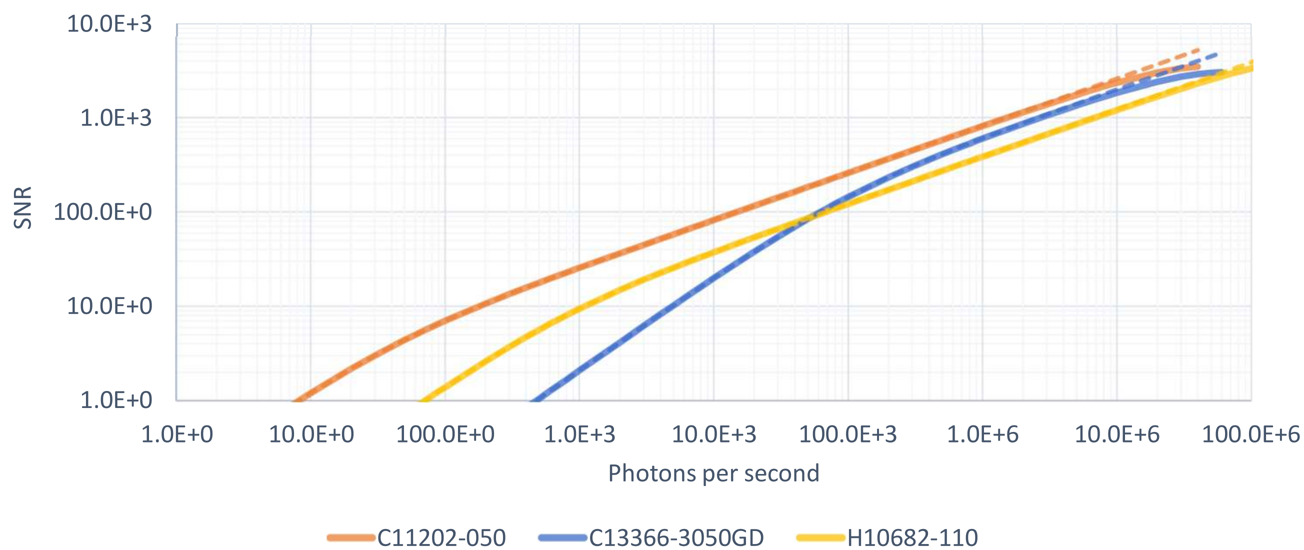
Digital Output:
(Count these pulses)



SIMULATION REFERENCE ONLY

Photon Counting Device

Family	Part Number	Active Area	Dark Count Rate (typ.)
SPPC Module (SPAD)	C11202-050 	Φ 0.05mm	7 cps
MPPC Digital Module (SiPM)	C13366-1550GD 	1.5 x 1.5 mm	2,500 cps
PMT Photon Counting Head	H10682-110 	Φ 8 mm	50 cps



SIMULATION REFERENCE ONLY

Photon Counting Device

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Family	Part Number	Active Area	Dark Count Rate (typ.)
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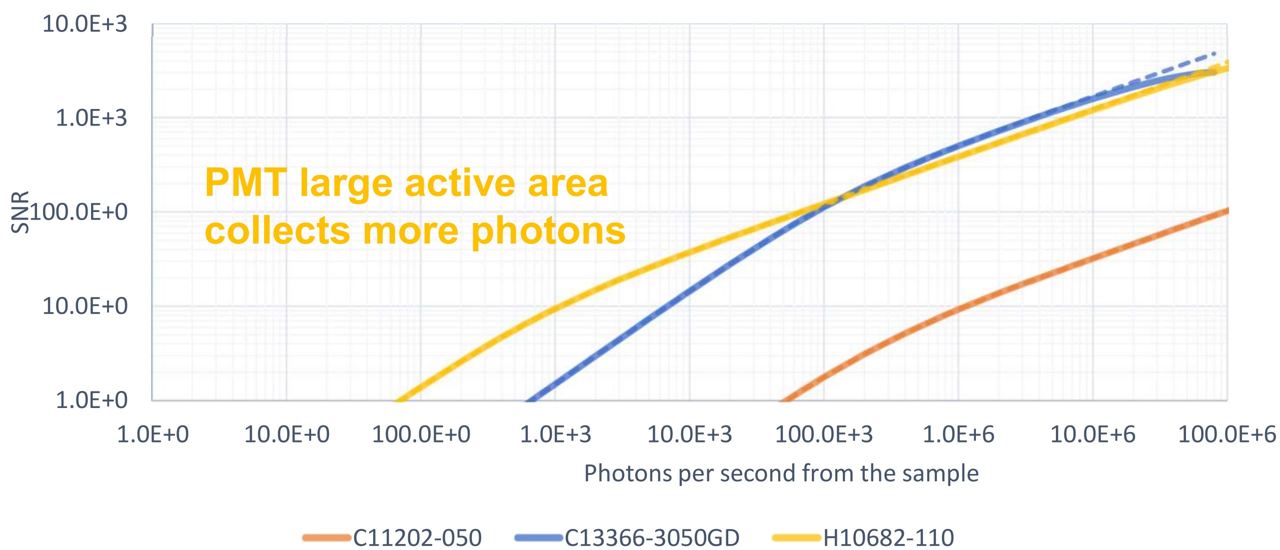

Limitations of Photon Counting

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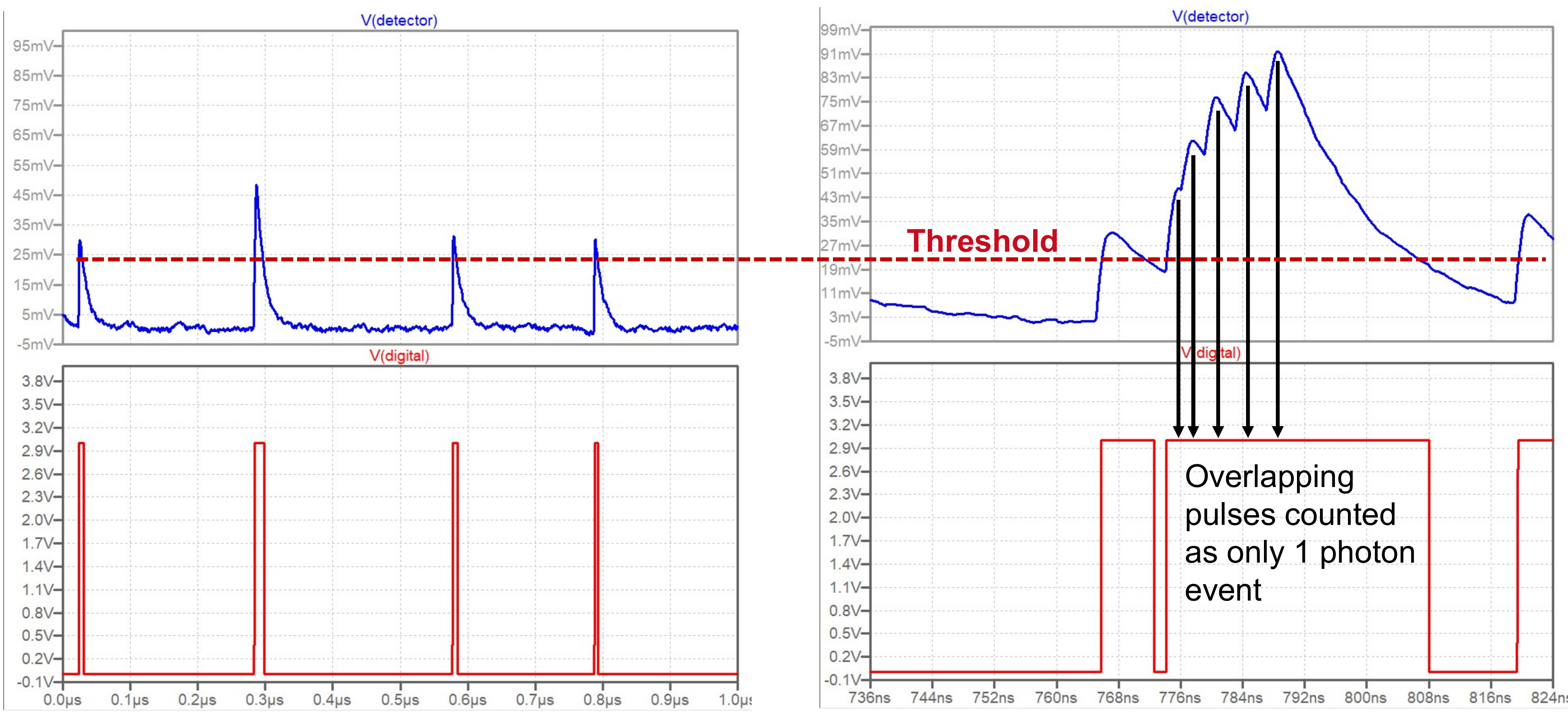
Ideal for Low Light Levels



SIMULATION REFERENCE ONLY

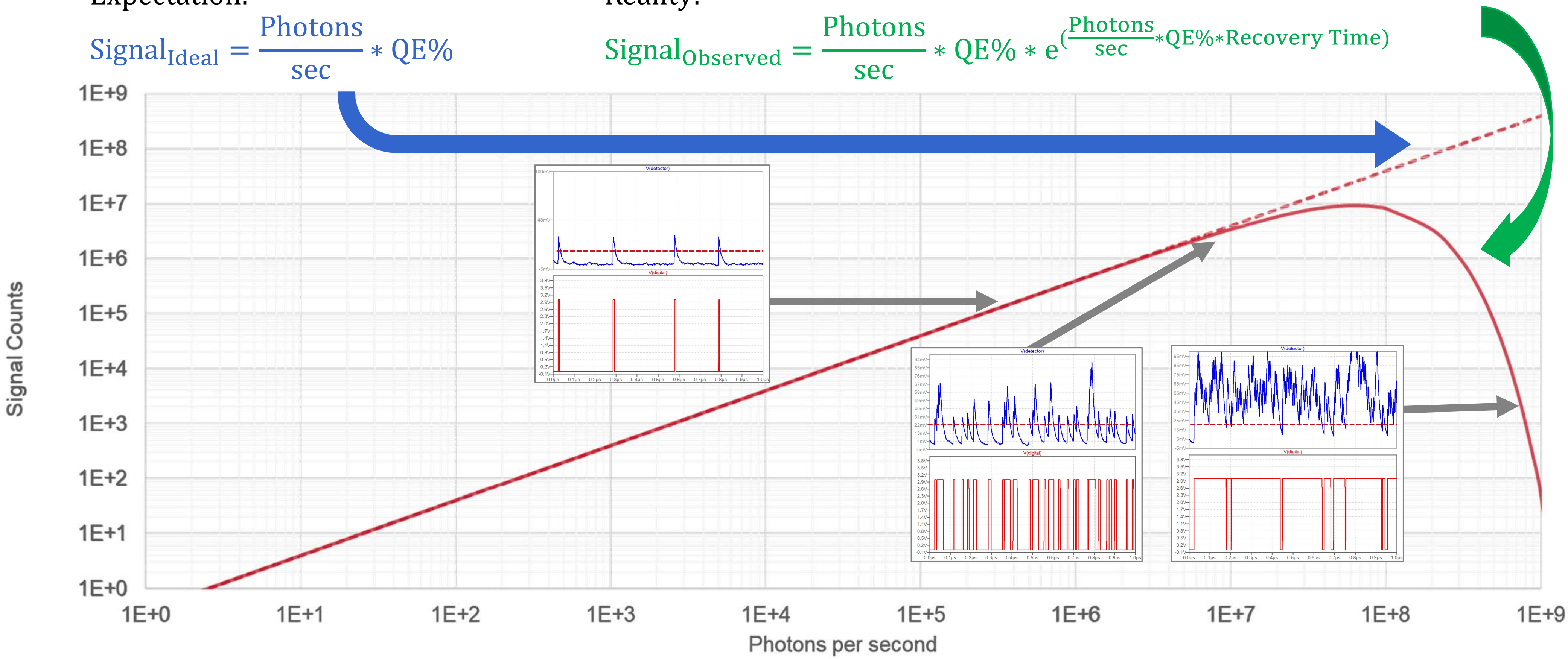
Count Rate Non-linearity

Expectation:

$$\text{Signal}_{\text{Ideal}} = \frac{\text{Photons}}{\text{sec}} * \text{QE\%}$$

Reality:

$$\text{Signal}_{\text{Observed}} = \frac{\text{Photons}}{\text{sec}} * \text{QE\%} * e^{(\frac{\text{Photons}}{\text{sec}} * \text{QE\%} * \text{Recovery Time})}$$



Upper Limit of Linearity for Photon Counting

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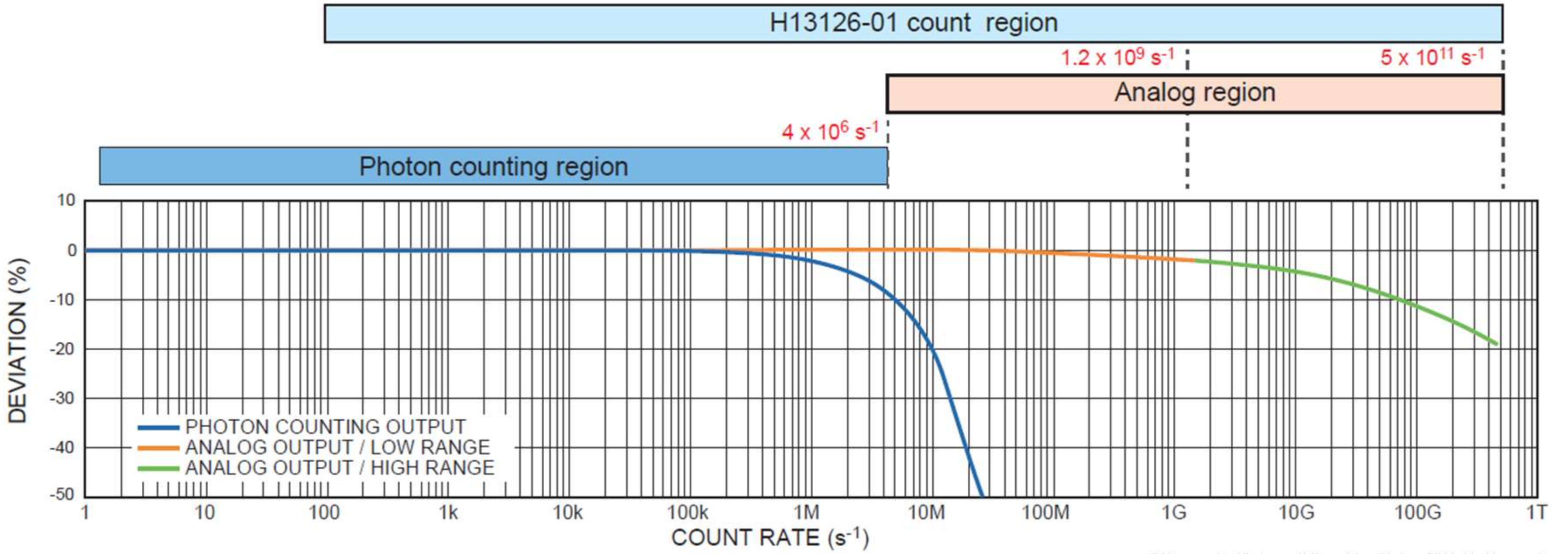
❖ Photon count rate

$$\text{Max. Count Rate} \approx \frac{-\ln(90\%)}{\text{Pulse Pair Resolution}}$$

Example:

$$\text{Max. Count Rate} \approx \frac{-\ln(90\%)}{20\text{ns}} = 5 * 10^6 \text{ cps max.}$$



Analog Measurement

SIMULATION REFERENCE ONLY

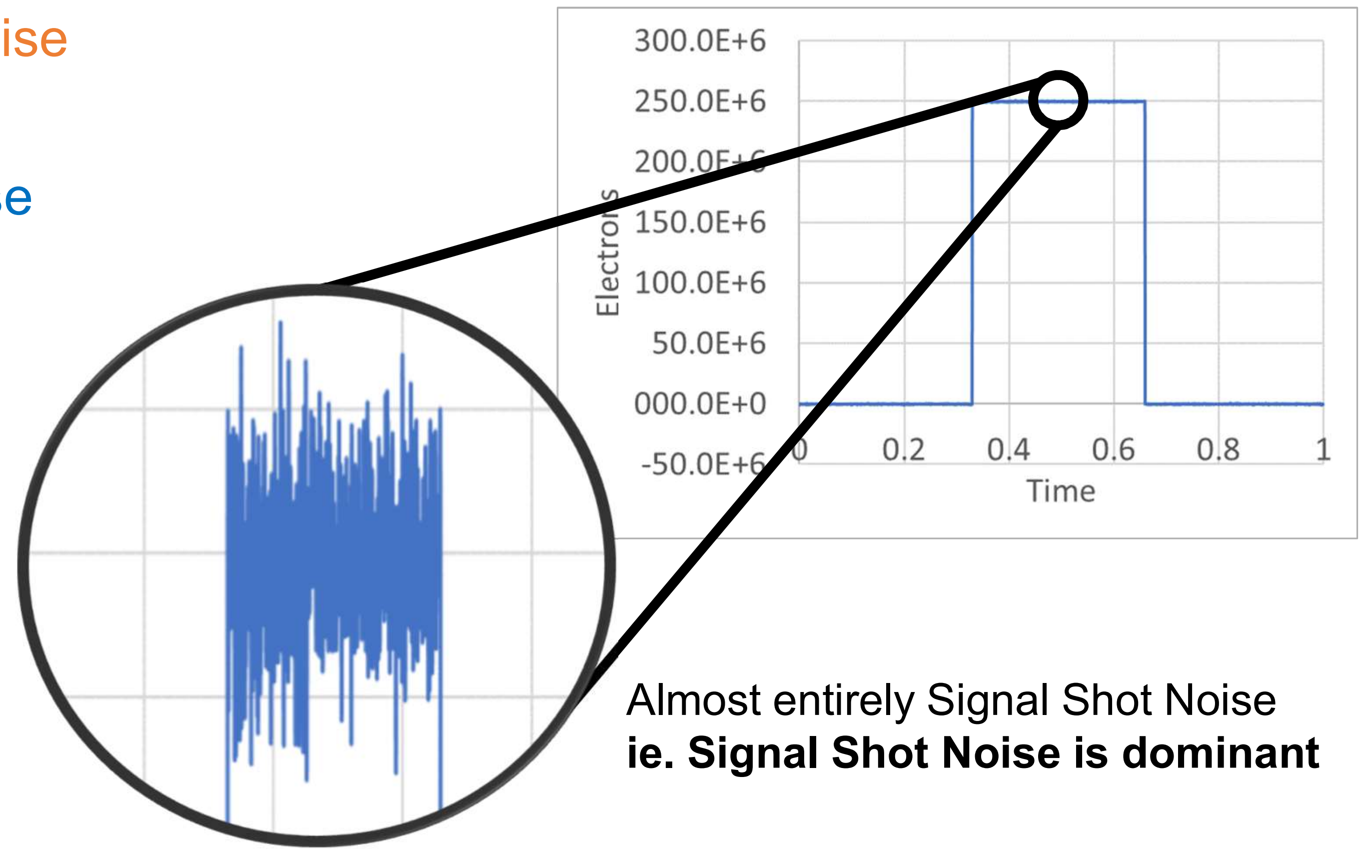
Dominant Noise Sources

Noise Sources:

Signal Shot Noise

Dark Shot Noise

Readout Noise



Almost entirely Signal Shot Noise
ie. Signal Shot Noise is dominant

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Dominant Noise Sources

Noise Sources:

Signal Shot Noise → $\sqrt{\frac{QE\%}{F}}$

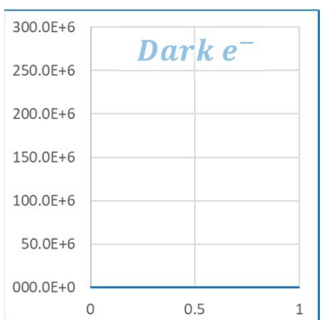
Dark Shot Noise

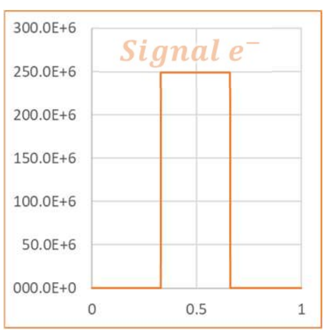
Readout Noise

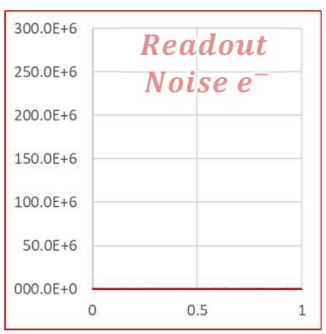
$$SNR = \frac{Signal}{\sqrt{\sigma^2_{Sign} + \sigma^2_{Dark} + \sigma^2_{Readout\ Noise}}}$$

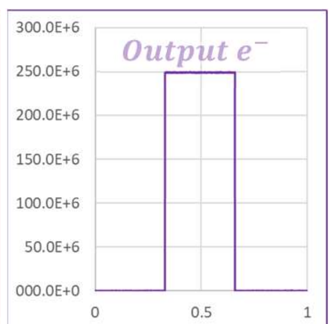
$$SNR \cong \frac{Signal}{\sqrt{\sigma^2_{Signa}}} = \frac{\mu * \frac{photons}{sec} * QE\% * time}{\sqrt{\mu^2 * F * \frac{photons}{sec} * QE\% * time}}$$

$$SNR \cong \frac{\frac{photons}{sec} * QE\% * time}{\sqrt{F * \frac{photons}{sec} * QE\% * time}}$$









SIMULATION REFERENCE ONLY

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Dominant Noise Sources

Noise Sources:

Signal + BG Shot Noise

$$\rightarrow \sqrt{\frac{QE\%}{F}}$$

$$NR = \frac{Signal}{\sqrt{\sigma^2_{Signal+BG} + \sigma^2_{Dark} + \sigma^2_{Readout\ Noise}}}$$

Dark Shot Noise

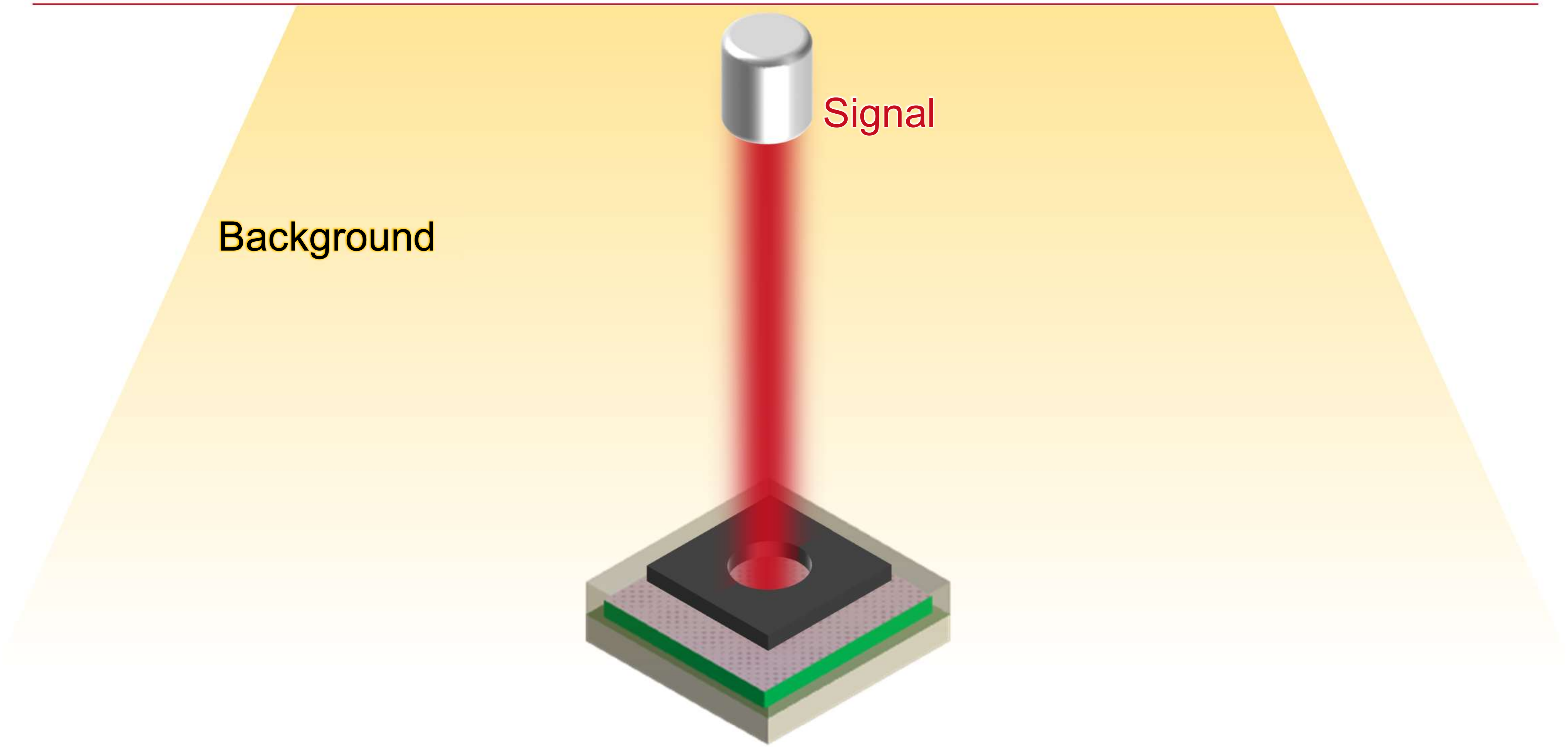
$$SNR \cong \frac{Signal}{\sqrt{\sigma^2_{Signal+B}}} = \frac{\mu * \frac{photons}{sec} * QE\% * time}{\sqrt{\mu^2 * F * \left(\frac{photons}{sec} + \frac{BG\ photons}{sec}\right) * QE\% * time}}$$

Readout Noise

$$SNR \cong \frac{\frac{photons}{sec} * QE\% * time}{\sqrt{F * \left(\frac{photons}{sec} + \frac{BG\ photons}{sec}\right) * QE\% * time}}$$

Background offset + BG Shot Noise

Optical Considerations for Reducing Background



Dominant Noise Sources

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Noise Sources:

Signal + BG Shot Noise → $\sqrt{\frac{QE\%}{F}}$

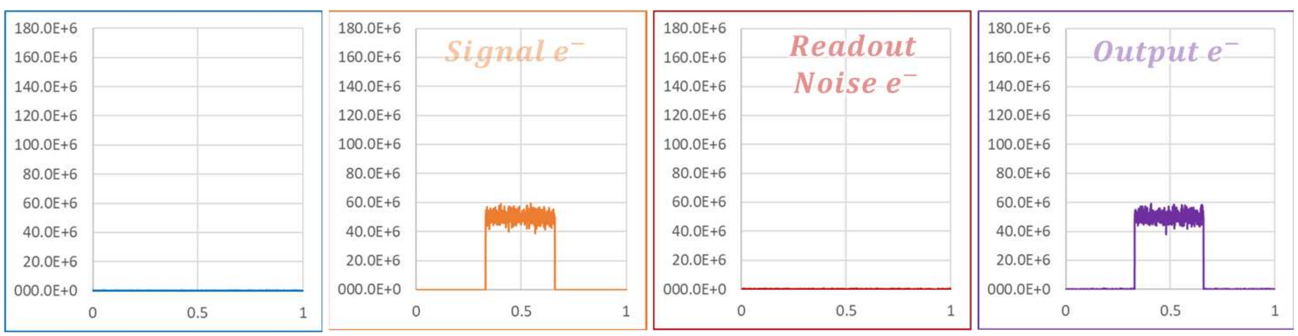
Dark Shot Noise

Readout Noise → *Gain*

$$NR = \frac{Signal}{\sqrt{\sigma^2_{Signal+Bg} + \sigma^2_{Da} + \sigma^2_{Readout\ Noise}}}$$

$$SNR \cong \frac{Signal}{\sqrt{\sigma^2_{Signal+B}}} = \frac{\mu * \frac{photons}{sec} * QE\% * time}{\sqrt{\mu^2 * F * \left(\frac{photons}{sec} + \frac{Bg\ photons}{sec}\right) * QE\% * time}}$$

$$SNR \cong \frac{\frac{photons}{sec} * QE\% * time}{\sqrt{F * \left(\frac{photons}{sec} + \frac{BG\ photons}{sec}\right) * QE\% * time}}$$



SIMULATION REFERENCE ONLY

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Dominant Noise Sources

Noise Sources:

Signal + BG Shot Noise

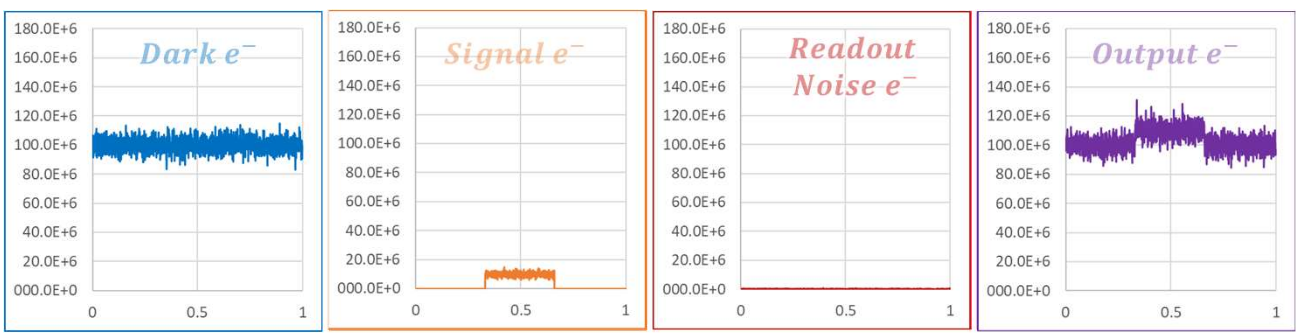
Dark Shot Noise → $\frac{QE\%}{\sqrt{F * \frac{dark\ e^-}{sec}}}$

Readout Noise → $Gain$

$$SNR = \frac{Signal}{\sqrt{\sigma^2_{Signal+Bg} + \sigma^2_{Dark} + \sigma^2_{Readout\ Noise}}}$$

$$SNR \cong \frac{Signal}{\sqrt{\sigma^2_{Dark}}} = \frac{\mu * \frac{photons}{sec} * QE\% * time}{\sqrt{\mu^2 * F * \frac{dark\ electrons}{sec} * time}}$$

$$SNR \cong \frac{\frac{photons}{sec} * QE\% * time}{\sqrt{F * \frac{dark\ electrons}{sec} * time}}$$



Dark Signal vs. Size

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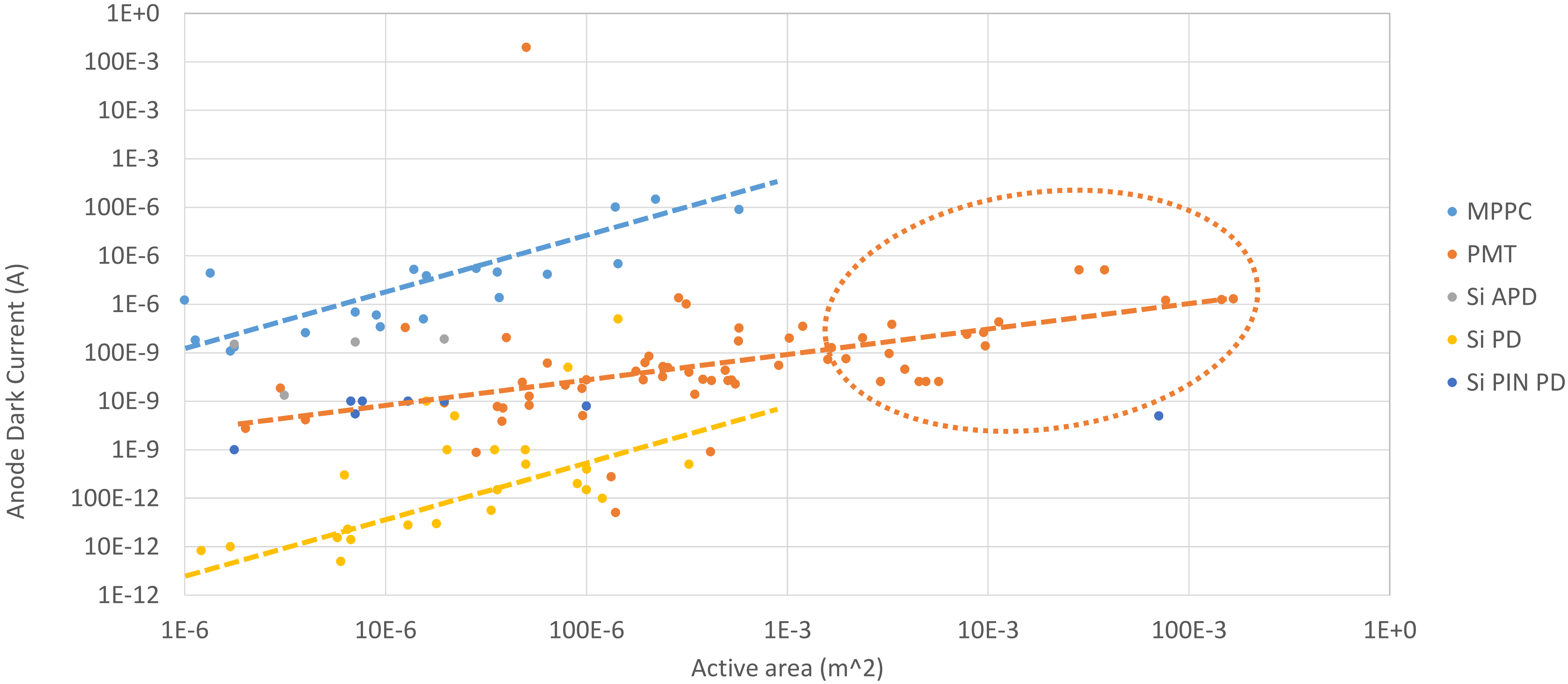

Reducing Dark Noise with Cooling

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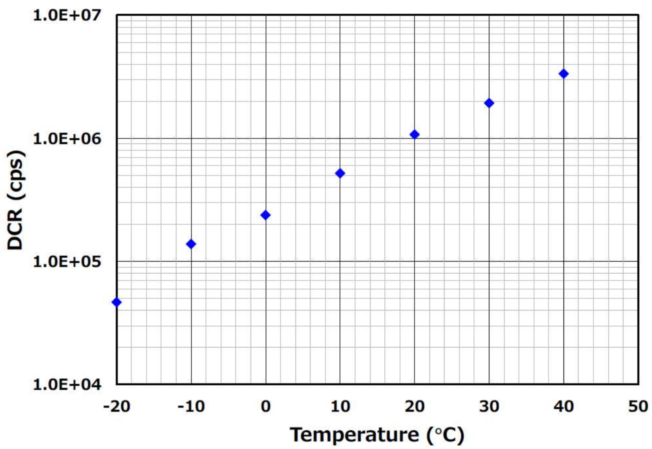
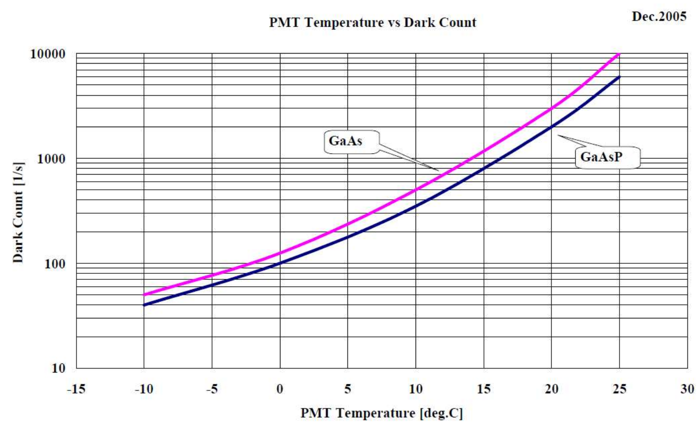
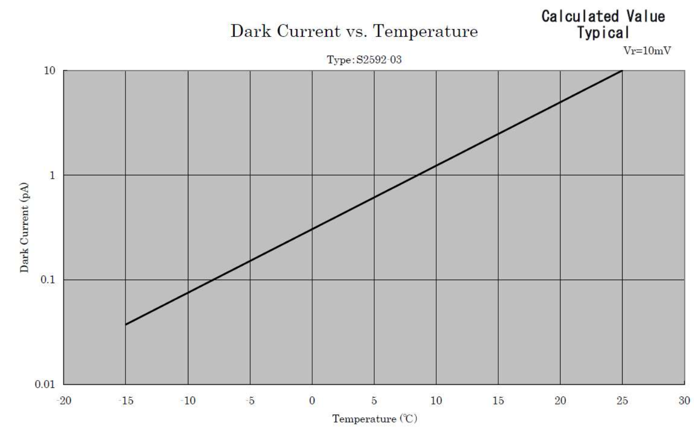
MPPC (SiPM)



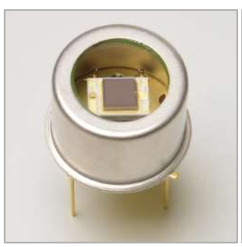
PMT



Photodiode



S13362
S14422



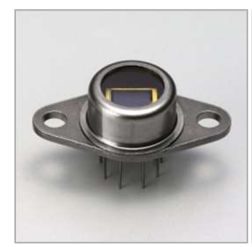
C13852
C14456

C13366
C14455

H7422
H7421

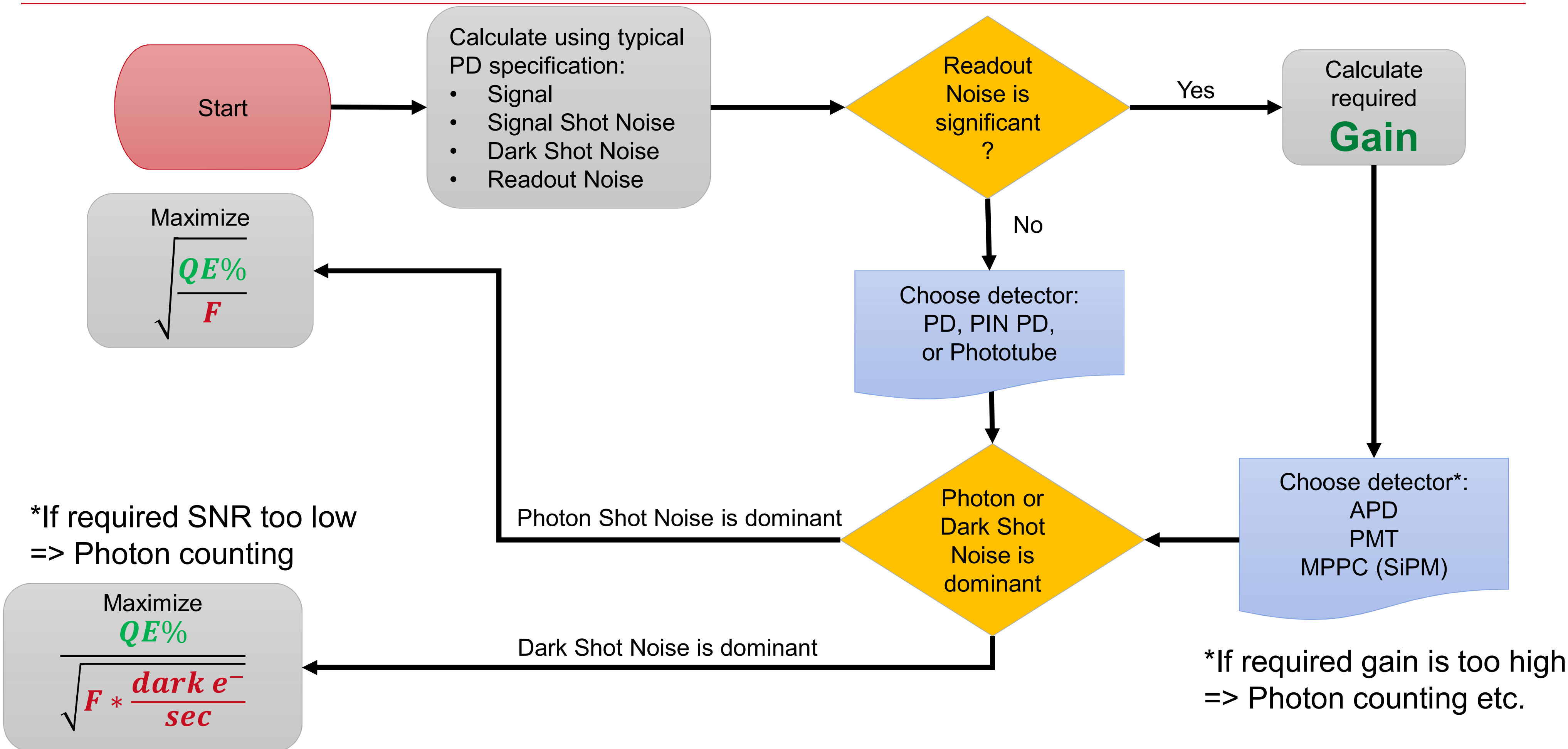
H10330C

S2592
S3477



C12843

Summary Detector Selection Process



SNR vs Input Light

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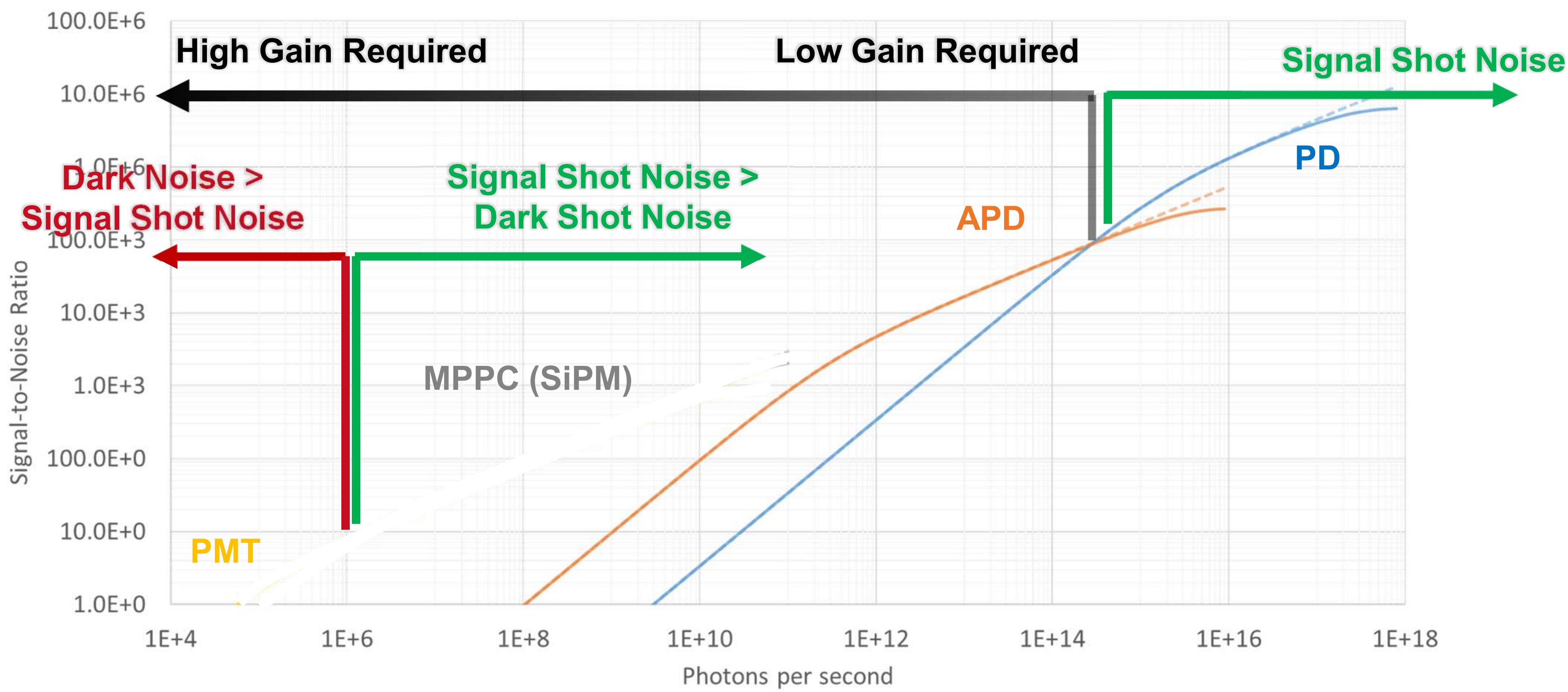

Other Things to Consider

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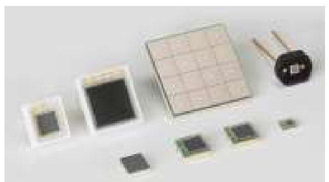
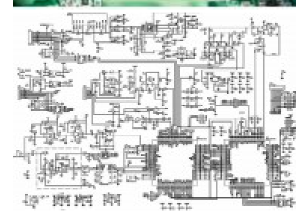
Photodetector
- QE%
- Dark Noise
- Speed
- Dynamic Range
- Size
- Cost

Electronics
- Noise
- Heat
- Speed
- Complexity
- Cost

Optics
- Efficiency
- Size
- Cost

Integration
- Enclosures
- Power consumption
- Reliability testing
- Supply-chain

Module Integration

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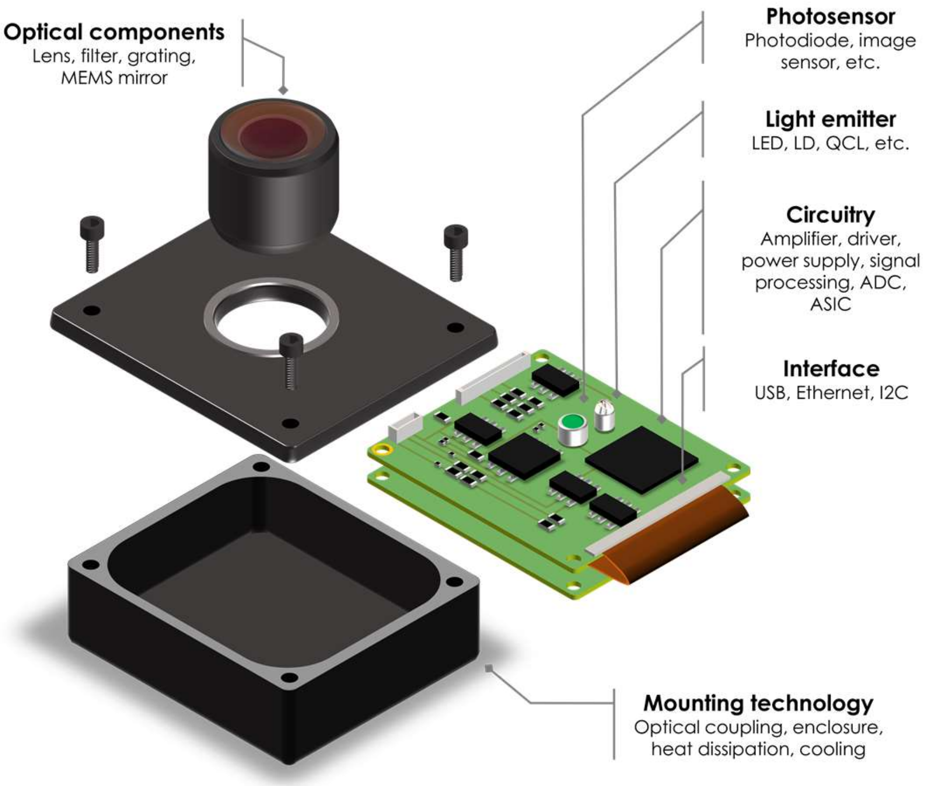
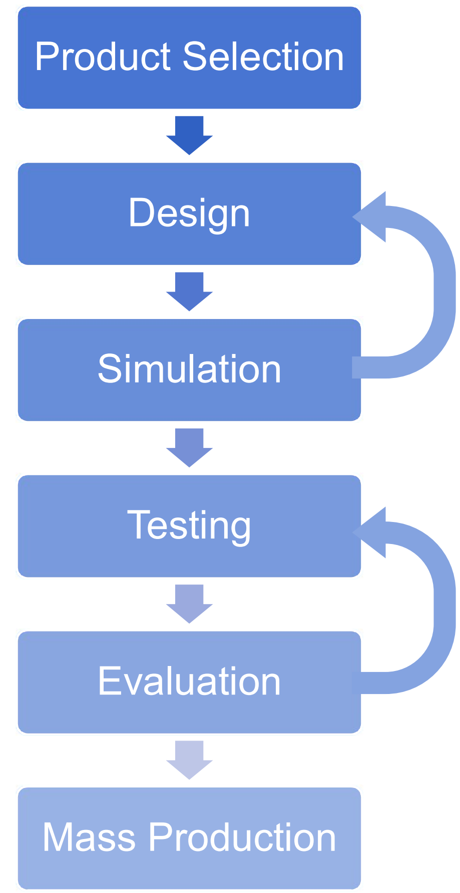
Hamamatsu Custom Module Capability



- ✓ Full product range of detectors & light sources
- ✓ Over 60 years in-house design design & manufacturing experience
- ✓ SNR, optical, and signal simulation
- ✓ One vendor responsible for product quality, focus on high-reliability
- ✓ Global company with local sales and applications support
- ✓ ISO certified, high-mix, low-volume production, optimized for custom-products



Additional Resources

Simulators	
Analog SNR	https://hub.hamamatsu.com/us/en/interactive_tools/analog-snr-simulator/index.html
Photon Counting SNR	https://hub.hamamatsu.com/us/en/interactive_tools/photon-counting-snr-simulator/index.html
Camera SNR & Image	https://www.hamamatsu.com/sp/sys/en/camera_simulator/index.html

Technical Notes	
Photomultipler Tube Handbook	https://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v4E.pdf
Opt-Semiconductor Handbook	https://www.hamamatsu-news.de/hamamatsu_optosemiconductor_handbook
Opto-Semiconductor Resources (App notes, tech notes, and selection guides)	https://www.hamamatsu.com/sp/ssd/doc_en.html
Hamamatsu Hub (Guides, webinars, and tech notes)	https://hub.hamamatsu.com/us/en/index.html#
MPPC Technical Note	https://www.hamamatsu.com/resources/pdf/ssd/mppc_kapd9005e.pdf

Technical Support	
Phone: 908-252-7225	https://www.hamamatsu.com/all/en/inquiry/index.html?inqtype=3&tcode=t_bh_ad&pt=Contact%20Information%20for%20the%20Americas

Summary

- **Upper limit of SNR is Photon Shot Noise** $\sqrt{\frac{photons}{sec} * T}$
- Sampling time: $T = \frac{1}{2B}$ (**Narrow Bandwidth improves SNR**)

- **Gain can improve overall SNR by making Readout Noise less significant.**
  - Gain multiplies dark and signal equally, so SNR is not improved if Readout Noise is not major source of noise.
  - Gain can only reduce SNR of the detector by introducing Excess Noise.
    - ENF: APD >> PMT > MPPC
      ~ 2 - 3 ~ 1.1 - 1.2 ~ 1.05 - 1.1

- **Photon counting** can be used to measure the lowest light levels by **making readout noise and excess noise less significant.**
  - Requires very high gain ~10^6
  - Counting linearity is limited by detector or electronics pulse pair resolution, typ. max count rate ~10^6 - 10^7

- **Signal Shot Noise limited** measurement can be improved by **increasing QE and reducing Excess Noise**
  - Reduce background light

- **Dark Shot Noise limited** measurement can additionally be improved by **reducing dark current/dark count**
  - Smaller active area (solid state detectors: PD, APD, MPPC (SiPM)
  - Use PMT (large active area, low dark counts)
  - Cooling the detector

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Contact Information

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dbutron@hamamatsu.com

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Week #	Weekly Topics	# of Talks	Talk #1 Date	Talk #2 Date
1	Introduction to Photodetectors	2	26-May-20	28-May-20
2	Emerging Applications - LiDAR & Flow Cytometry	2	2-Jun-20	4-Jun-20
3	Understanding Spectrometer	2	9-Jun-20	11-Jun-20
1 Weeks Break				
4	Specialty Products – Introduction to Light Sources & X-Ray	2	23-Jun-20	25-Jun-20
5	Introduction to Image Sensors	2	30-Jun-20	02-Jul-20
1 Weeks Break				
6	Specialty Products – Laser Driven Light Sources	2	14-Jul-20	16-Jul-20
7	Image Sensor Circuits and Scientific Camera	2	21-Jul-20	23-Jul-20
8	Mid-Infrared (MIR) Technologies & Applications	2	28-Jul-20	30-Jul-20
1 Weeks Break				
9	Photon Counting Detectors – SiPM and SPAD	1	11-Aug-20	
10	Using SNR Simulation to Select a Photodetector	1	18-Aug-20	

To register for other webinars or hear previous webinar recordings, please visit link below:

https://www.hamamatsu.com/us/en/news/event/2020/20200526220000.html