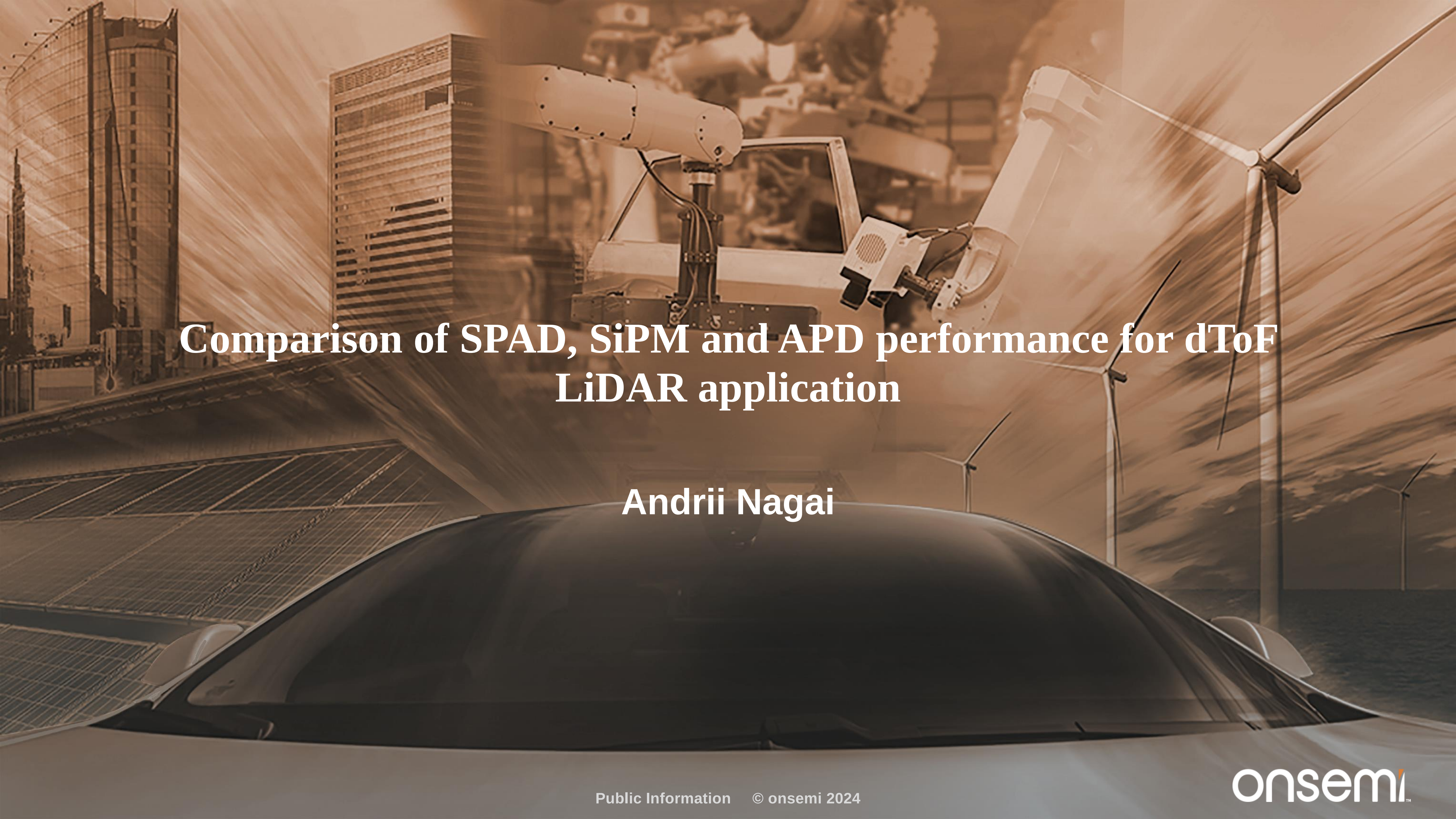
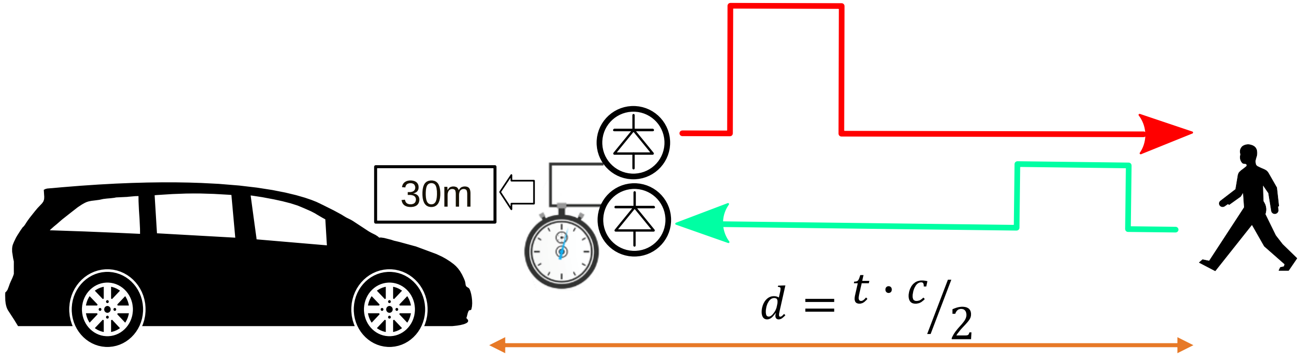


Comparison of SPAD, SiPM and APD performance for dToF LiDAR application

Andrii Nagai

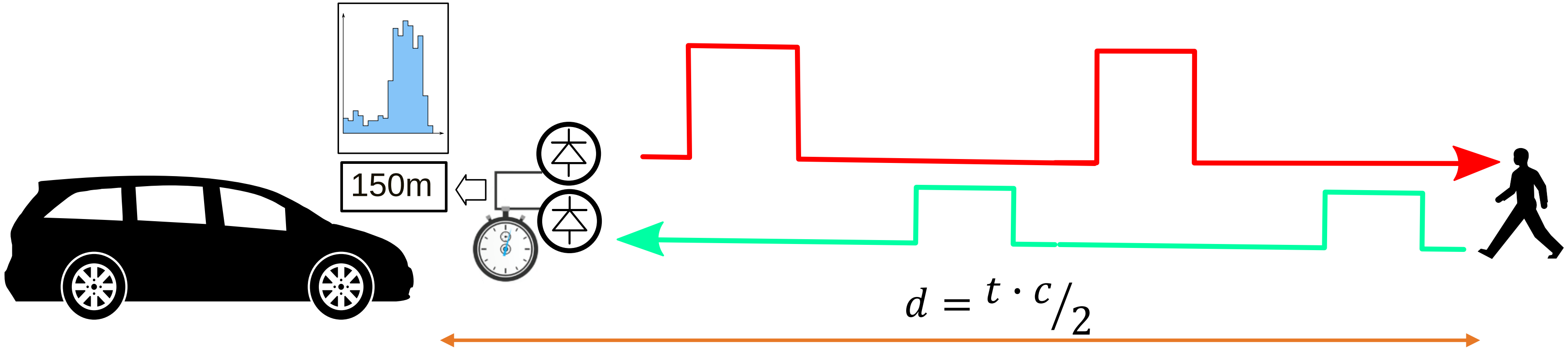
Direct ToF LiDAR – Simple Concept

- **Single Shot** laser pulse & photon arrival timestamp for Depth measurement

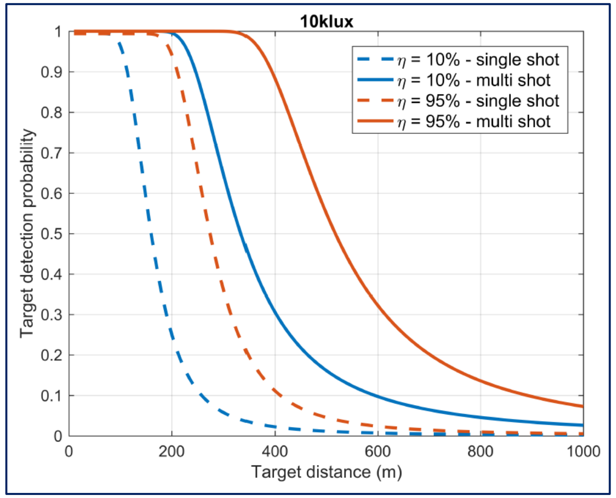


$$d = {}^{t \cdot c}/_{2}$$

- **Multi Shot** laser pulses & photon arrival timestamps to calculate **Depth** from histogram
  - Photon counting for **Intensity**

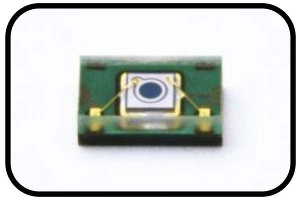


$$d = {}^{t \cdot c}/_{2}$$



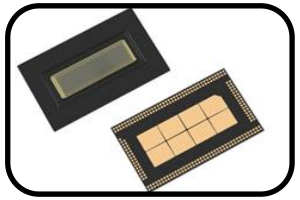
Typical photon detectors for LiDAR

Avalanche Photodiodes (APD)



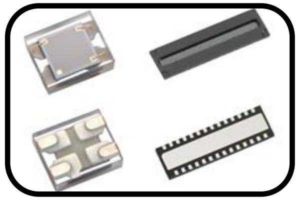
- ✗ High Voltage
- ✗ Poor Uniformity
- ✓ Moderate Gain (10^2)
- !! Linear Mode
- ↘ Market Adoption

Single Photon Avalanche Diode arrays (SPAD arrays)



- ✓ Low Voltage
- ✓ Excellent Uniformity
- ✓ Very High Gain (10^6)
- ✓ Geiger Mode – Single Photon
- ⇗ Market Adoption

Silicon Photomultipliers (SiPM)

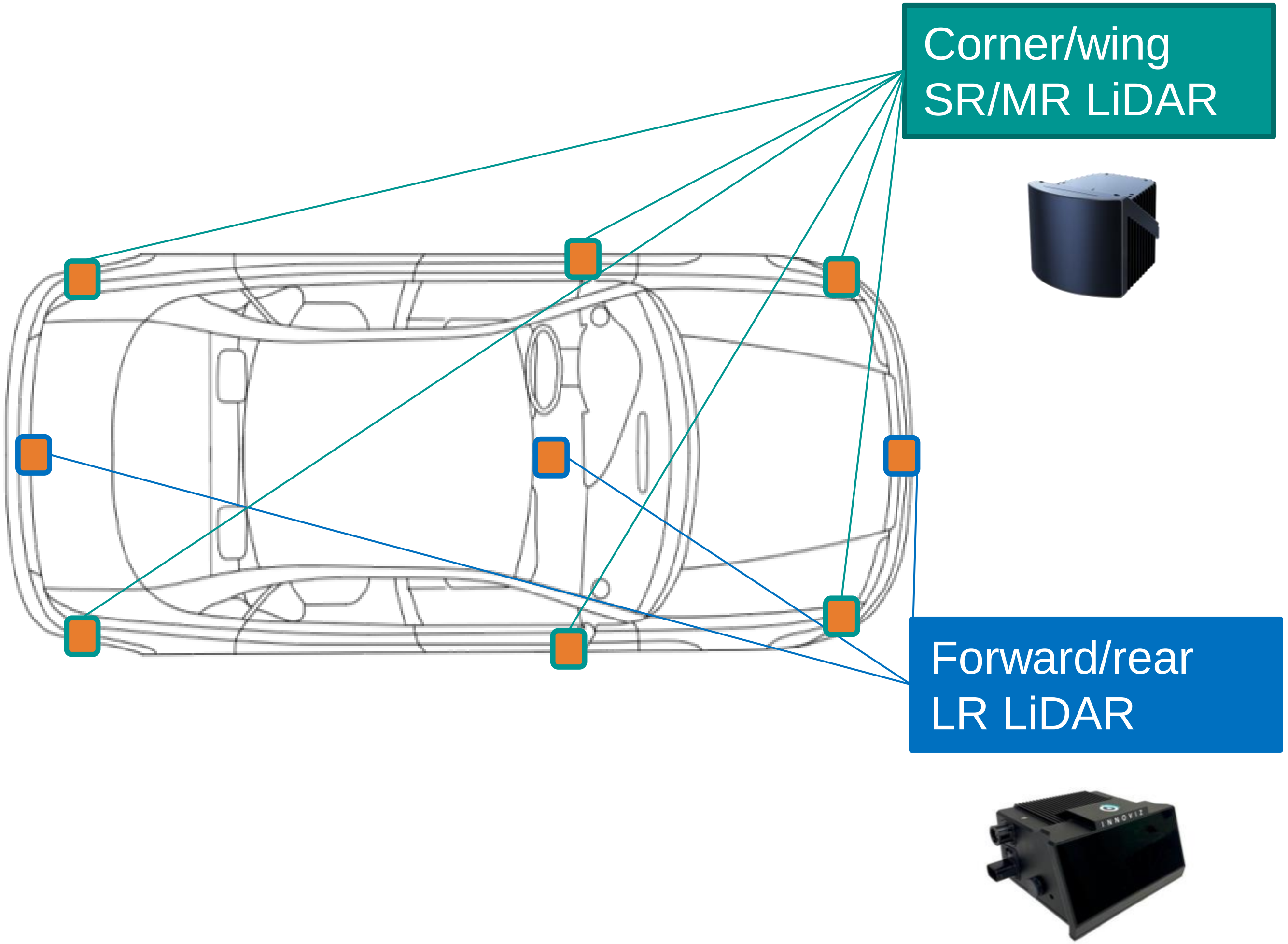


- ✓ Low Voltage
- ✓ Excellent Uniformity
- ✓ Very High Gain (10^6)
- ✓ Geiger Mode – Multi-Photon
- ⇗ Market Adoption

		APD	SPAD		SiPM
PDE @ 905 nm		N/A	30%		
QE @ 905 nm		55%	N/A		
N_{pixels}		N/A	2×2	7×7	2400
τ_{dead} ns		N/A	6		14
P_{XT} %		N/A	1		15
DCR MHz/mm²	25 C	N/A	0.025		0.15
	105 C		25		150
F		4	1.01		1.19
R_0 A/W		0.4	N/A		
M or G		100	1E5		
I_D, nA	25 C	0.05	N/A		
	105 C	102	N/A		

Calculations were performed for APD, SiPM and SPAD array (w/ 2×2 & 7×7 SPAD`s per macro-pixel) at 25 °C & 105 °C

LiDAR typical system specification:



Corner/wing SR/MR LiDAR

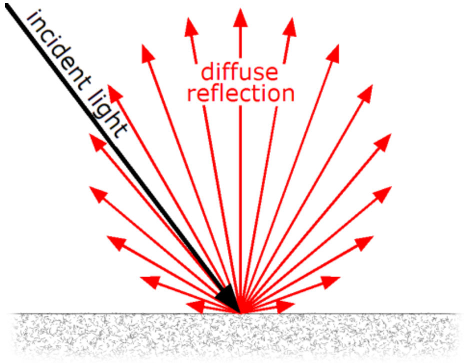
Forward/rear LR LiDAR

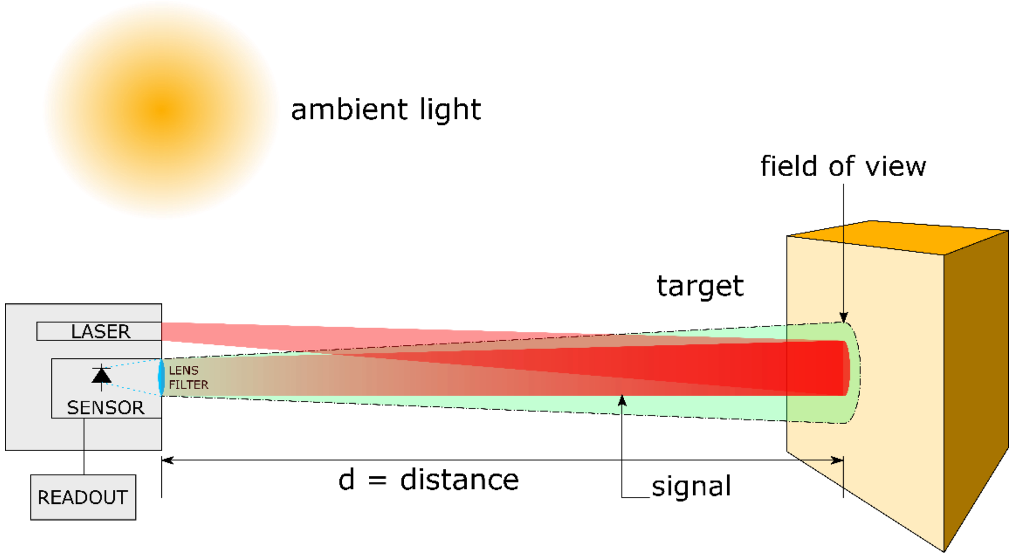
		Short	Long
System	*FoV* H×V	120° x 80°	120° x 25°
	$AoV_x \times AoV_y$	0.3° x 0.3°	0.05° x 0.05°
	P_{laser} per channel W	10	100
	N_{shots}	20	1
	d m	30	250
Optics	ε_{RX} %	90	
	ε_{TX} %	90	
	D_{lens} mm	1 to 50	
	λ nm	905	
	Δλ nm	±15	
	t_{laser} ns	5	
Readout	B_N MHz	1	
	R_f kΩ	10	
	$\langle V_{amp} \rangle$ nV/√Hz	28	
Condition	ambient light flux kLux	100	
	η %	10	

Calculations were performed for short & long range 905nm LiDAR`s, with different *FoV* and resolution

Some Initial Model Considerations

- Model assumptions:
  - Single point LiDAR
  - Lambertian target;
  - Laser spot:
    - within the sensor *AoV;*
    - Smaller than the target;
  - Ambient light power of 100 kLux





- Return laser power:

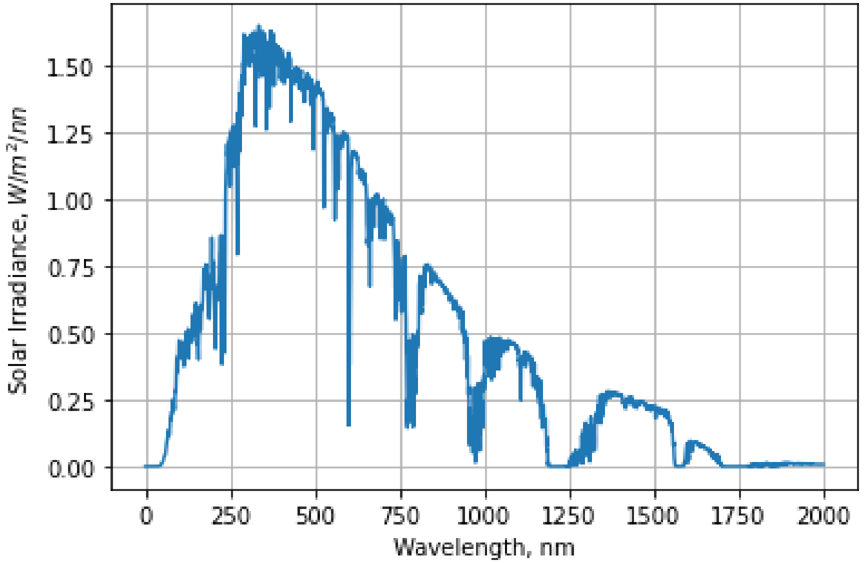
$$P_S(d) = P_{laser} \cdot \varepsilon_{RX} \cdot \varepsilon_{TX} \cdot \frac{1}{2\pi d^2} \times \eta \times A_{aperture}$$

- Background optical power:

$$P_B = \frac{1}{2\pi \cdot d^2} \cdot \Phi_{amb.} \cdot A_{FoV} \cdot \eta \cdot \varepsilon_{RX} \cdot A_{aperture}$$

- Aperture:

$$A_{aperture} = \pi \frac{D_{lens}^2}{4}$$



Aperture & Rx lens diameter D_{lens}

Return laser power:

$$P_S(d) = P_{laser} \cdot \varepsilon_{RX} \cdot \varepsilon_{TX} \cdot \frac{1}{8d^2} \times \eta \times D_{lens}^2$$

Background optical power:

$$P_B = \frac{1}{8 \cdot d^2} \cdot \Phi_{amb.} \cdot A_{FoV} \cdot \eta \cdot \varepsilon_{RX} \cdot D_{lens}^2$$

- Lens diameter D_{lens} defined the return laser power and collected ambient light;

- It should be optimized for each particular case:
  - Laser power;
  - Filter width;
  - Sensor performance;
  - Ranging;
  - etc.

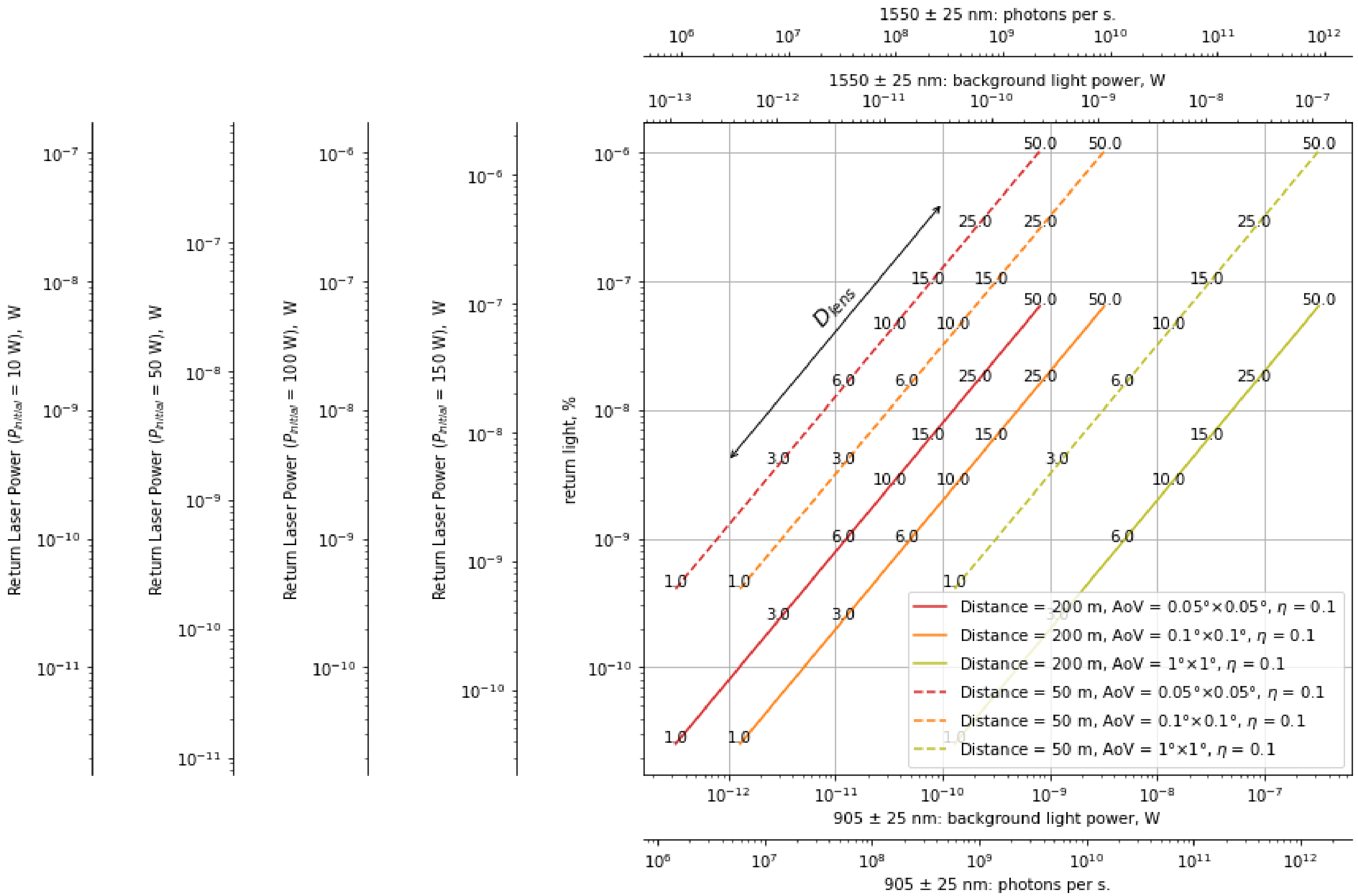
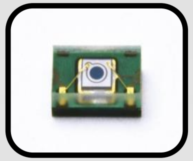


Figure 1 Return laser power (expressed in percentage and watts for initial laser power of 150, 100, 50 and 10 W) as a function of background light power (expressed in watts and photons per second) for 905 and 1550 nm systems. Results presented at different Dlens and AoV values and for two target distances of 200 m and 50 m.

SNR calculations:

APD:

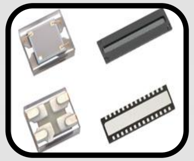


$$SNR_{APD} = \sqrt{N_{shots}}\frac{R_0 \times P_S}{\sqrt{2eB_N \times F \times (R_0 \cdot P_B + I_D) + \frac{B_N}{M^2}\left(\frac{4k_BT}{R_f} + \frac{\langle V_{amp}\rangle^2}{R_f^2}\right)}}$$

where:

- R_0 is responsivity without multiplication;
- F is excess noise factor;
- I_D is dark current, $I_D(T) = I_D(25℃) \times 1.1^{T\,-\,25℃}$
- M is multiplication factor or Gain;
- T is temperature in K,
- $<V_{amp}>$ is amplifier input voltage noise density;
- R_f is feedback resistance

SiPM & SPAD:



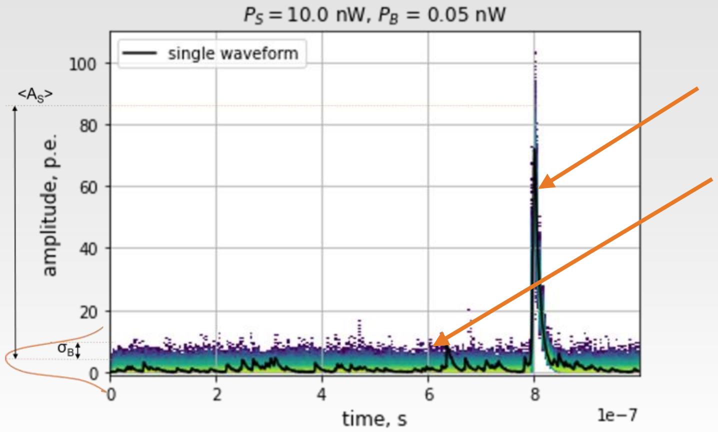
$$SNR = \sqrt{N_{shots}}\frac{N_{laser}}{\sqrt{N_{amb} + N_{elec.}^2}}$$

where:

- $N_{amb} = N_{cells} \cdot \left(1 - e^{-\left(\frac{P_B}{hc/\lambda}\cdot PDE+DCR\right)\frac{\tau_{dead}}{N_{cells}/(1-<XT>)}}\right)$
- $N_{laser} = (N_{cells} - N_{amb}) \times \left(1 - e^{-\left(\frac{P_S}{hc/\lambda}\cdot PDE+DCR\right)\frac{t_{laser}}{N_{cells}/(1-<XT>)}}\right)$
- $N_{elec.}^2 = \left(\frac{\tau_{dead}}{e\times G}\right)^2 \times B_N \times \left(\frac{4k_BT}{R_f} + \frac{\langle V_{amp}\rangle^2}{R_f^2}\right)$
- PDE is SiPM or SPAD photon detection efficiency;
- τ_{dead} is dead time;
- N_{cells} is number of microcells,
- DCR is dark count rate, $DCR(T) = DCR(25℃) \times 2^{T\,-25℃/8℃}$
- $\langle XT\rangle = -ln(1 - P_{XT})$ is an average number of crosstalk events per single avalanche, P_{XT} is optical crosstalk probability

SNR calculations: validation

Toy Monte Carlo:

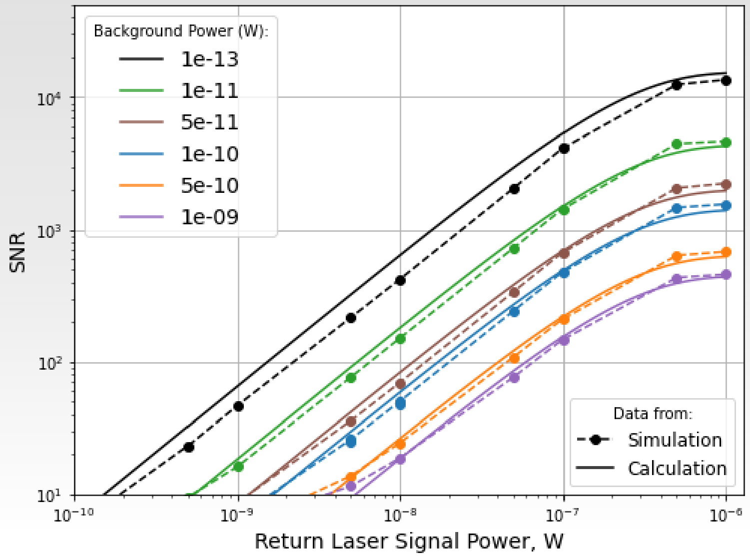


Returned laser signal

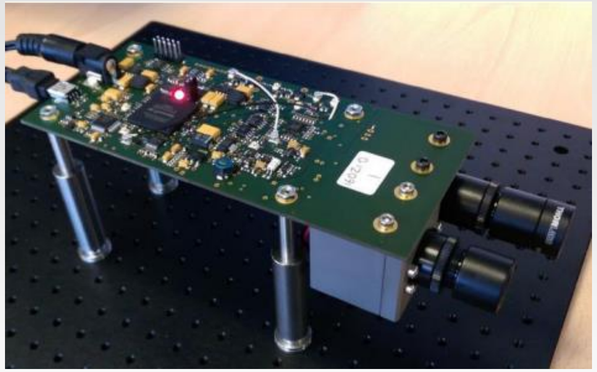
Ambient background

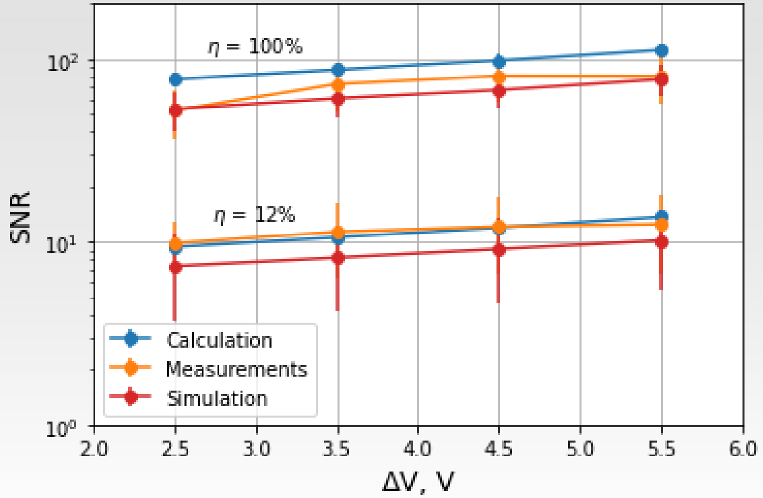
Signal to Nosie Ratio:

$$SNR = \frac{A_S}{\sigma_B}$$



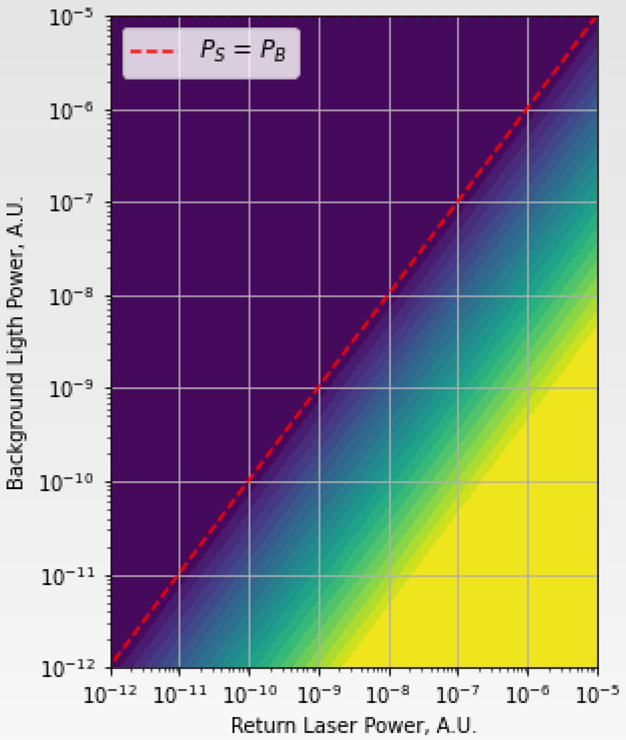
Single point Lidar





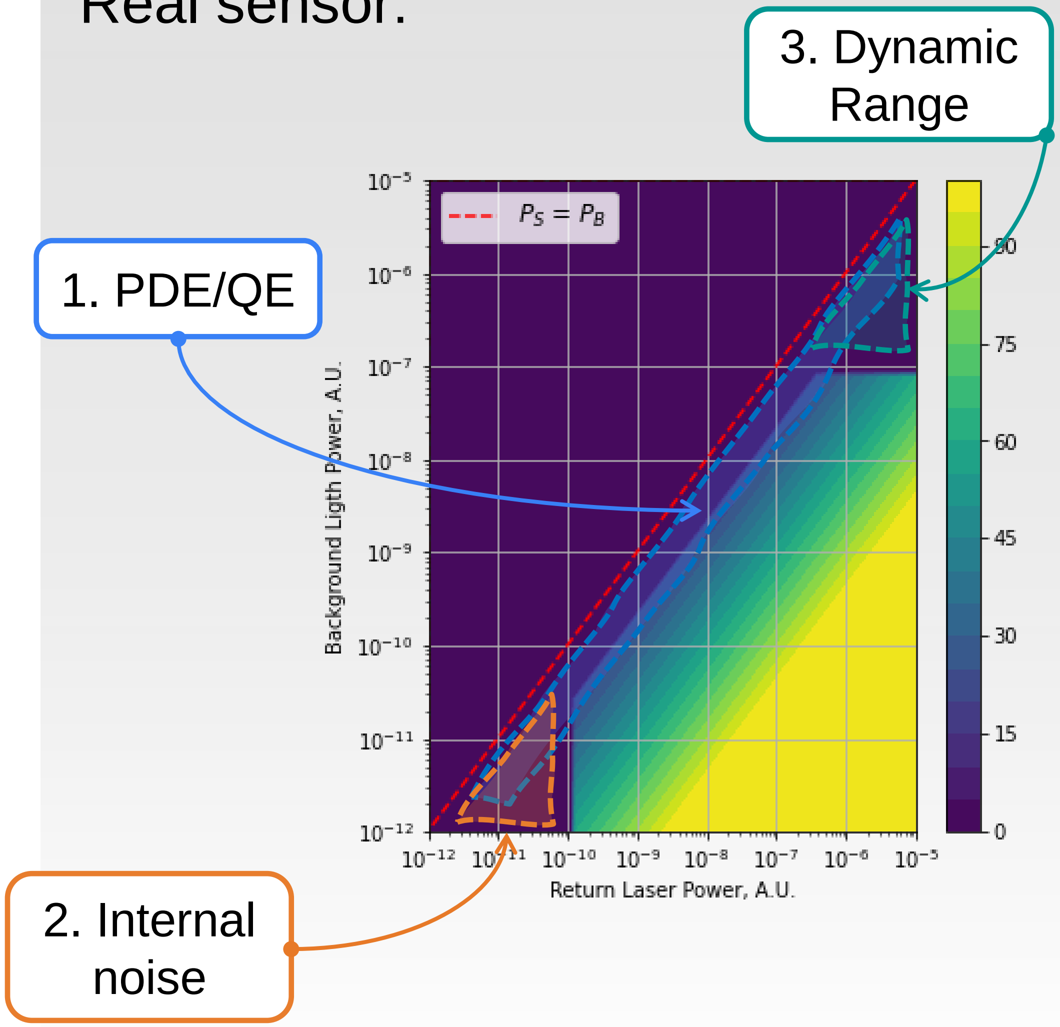
SNR results: from perfect to real sensor

Perfect sensor:



- SNR↘ with P_B ↗
- SNR↗ with P_S ↗

Real sensor:



1. PDE/QE

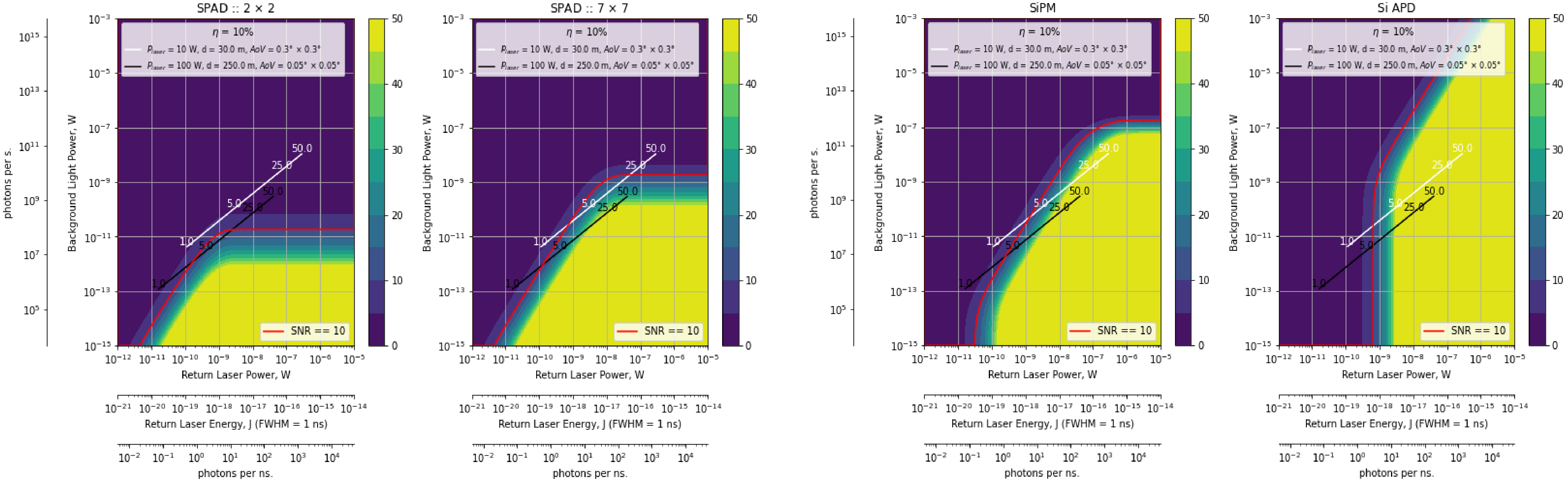
2. Internal noise

3. Dynamic Range

For real sensor, SNR↘ due to:
1. Detection probability
2. Internal noise
3. Dynamic range

SNR results: APD vs. SiPM vs. SPAD @ 25 °C

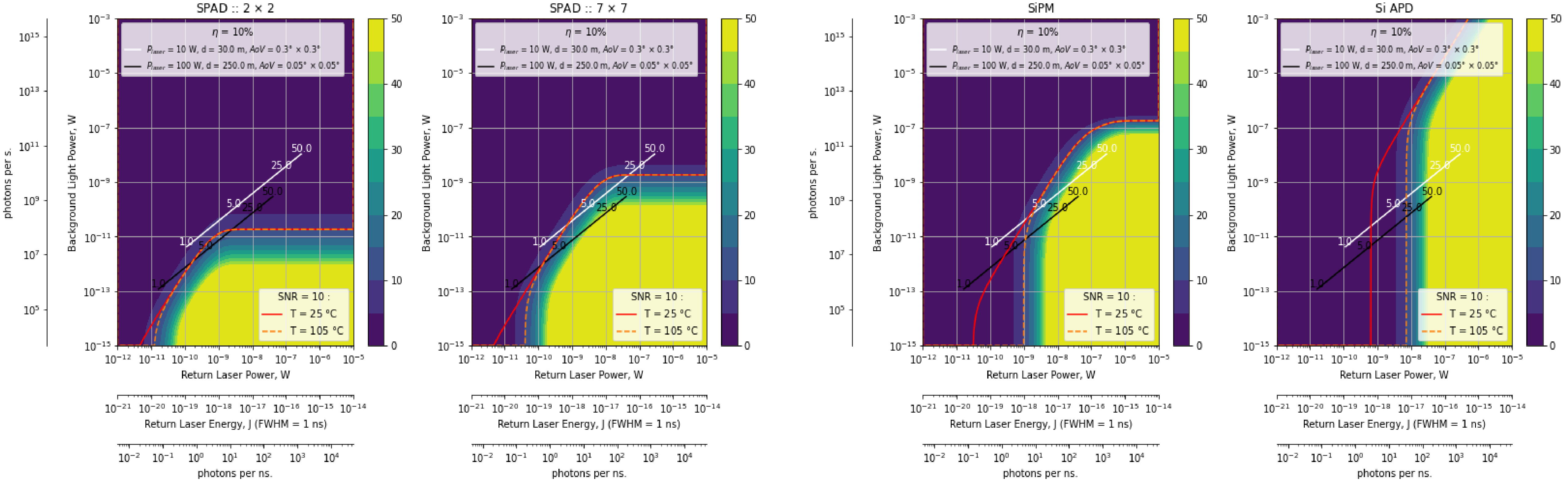
Detector Internal Noise ↗



Detector Dynamic Range ↗

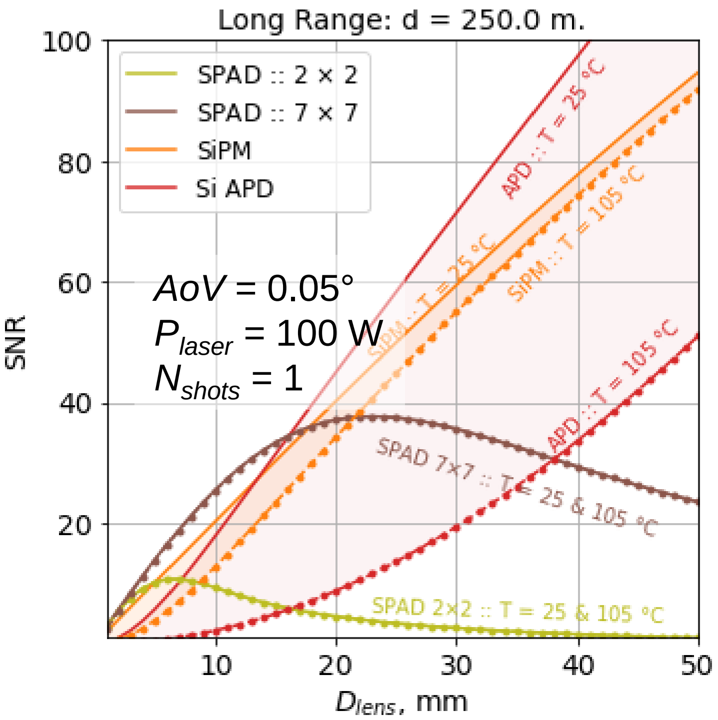
SNR results: APD vs. SiPM vs. SPAD @ 105 °C

Detector Internal Noise ↗

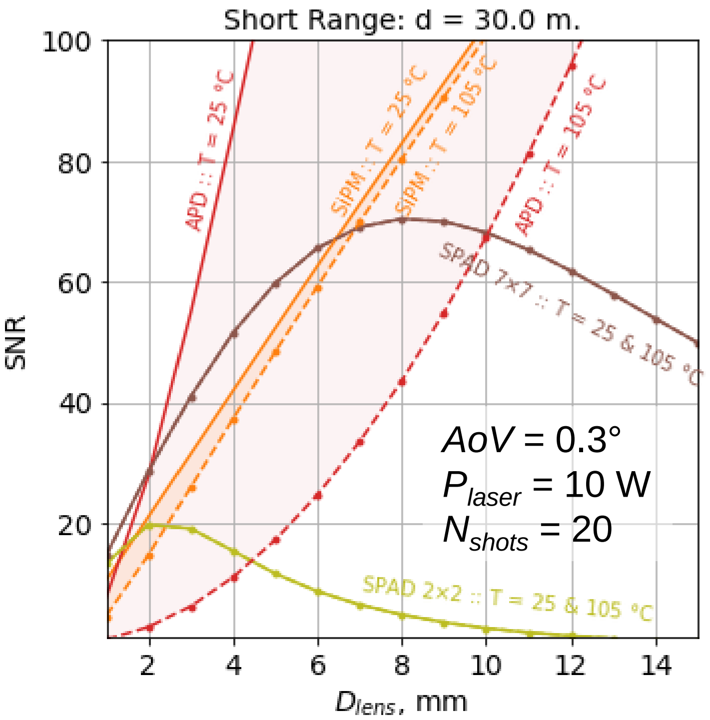


Detector Dynamic Range ↗

SNR vs. D_{lens}:



$AoV = 0.05°$
$P_{laser} = 100$ W
$N_{shots} = 1$



$AoV = 0.3°$
$P_{laser} = 10$ W
$N_{shots} = 20$

APD based system:

- Better performance with high D_{lens}
- High *SNR* fluctuation with *T* due to dark current

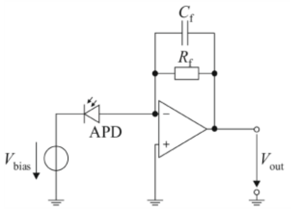
SiPM based system:

- Good performance over different D_{lens}
- *SNR* fluctuation with *T* due to *DCR*

SPAD based systems:

- Better performance at low D_{lens}
- No *SNR* fluctuation with *T* due to low *DCR*

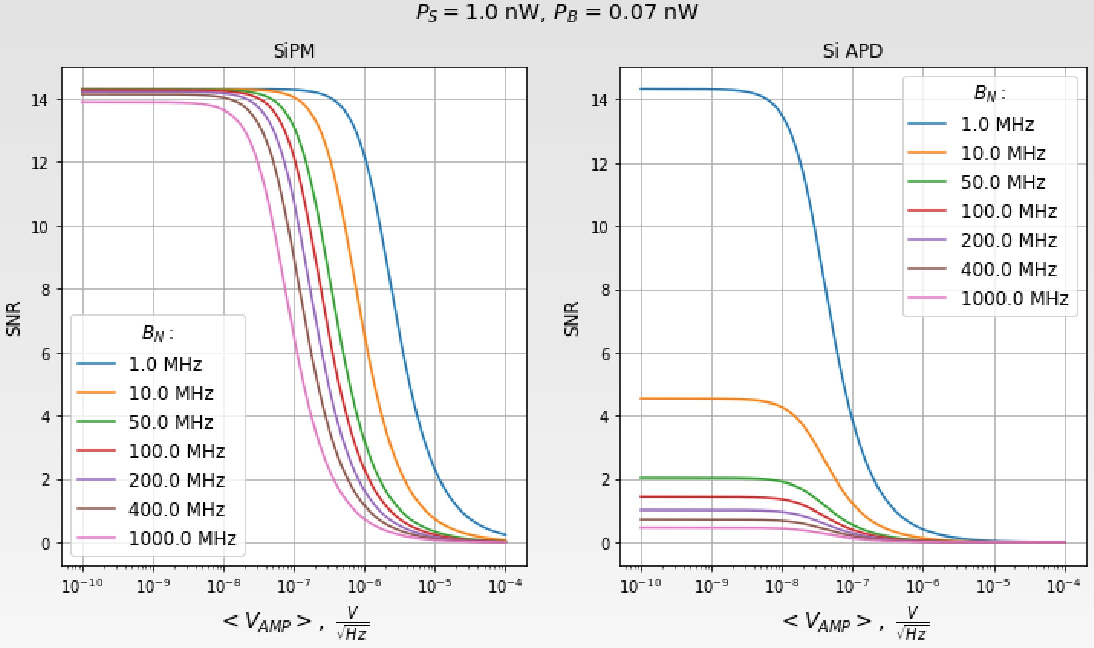
Effect of Read-out Electronics on *SNR*



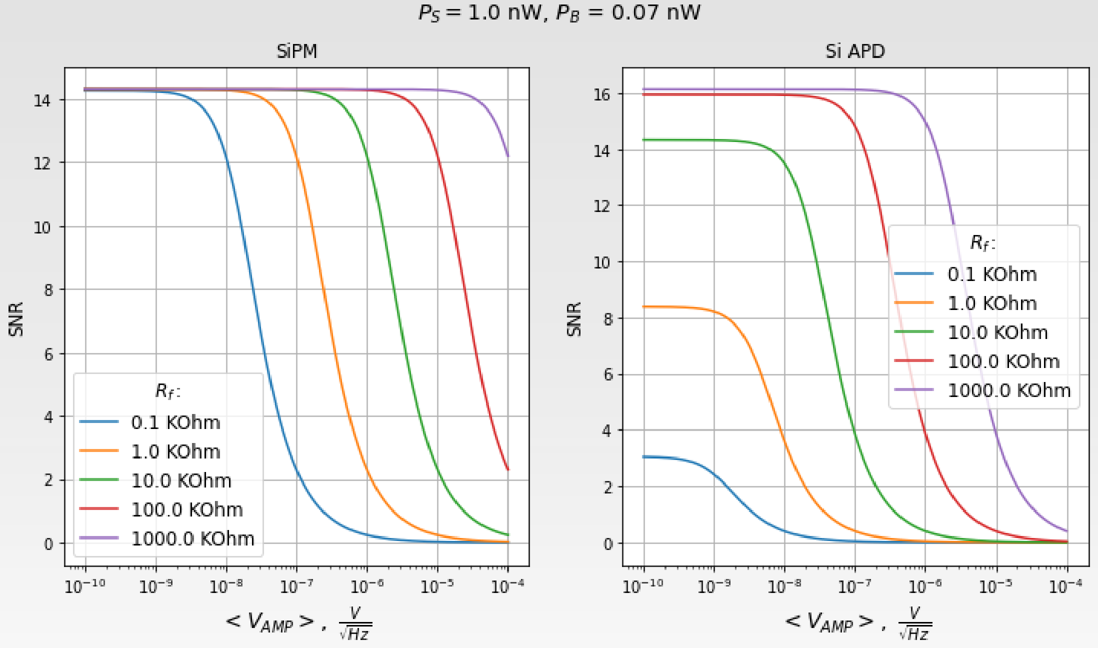
$$Noise^2 = \frac{B_N}{M^2}\left(\frac{4k_BT}{R_f} + \frac{\langle V_{amp}\rangle^2}{R_f^2}\right)$$

- $\boldsymbol{B_N}$ is defined as the frequency at which the gain of the amplifier becomes 0 dB;
- $\boldsymbol{\langle V_{amp}\rangle}$ is amplifier input voltage noise density;
- $\boldsymbol{R_f}$ is feedback resistor which set the gain of the transimpedance amplifier;

- SNR vs <V_{amp}> vs B_N:



- SNR vs <V_{amp}> vs R_f:



Due to much higher internal gain (i.e. 10^5 - 10^6) SiPM or SPAD devices less sensitive to electronics noise with respect to APDs which Gain (or multiplication ~ 10^2 - 10^3) is limited by dark current

Conclusions:

- To realize all the advantages the SiPM or SPAD could provide, the optical system should be designed to suppress unwanted interference from ambient background light (i.e. small D_{lens} and *FoV*);

- Due to relatively small internal multiplication *M*, the choice of read−out electronics is critical for APD−based LiDAR system, while SiPM & SPAD-based systems could tolerate much higher electronics noise due to high internal *Gain*

- SPAD vs. SiPMs → smaller number of micro-cells leads:
  - ☺ to smaller *DCR* as a result better sensitivity to return laser light ;
  - ☺ smaller *SNR* variation with temperature;
  - ☹ higher device nonlinearity and sensitivity to ambient light;

- “*Smart*” SiPM device:

  the possibility to activate (e.g. at high ambient or low *T*) or deactivate (e.g. at low ambient or high *T*) unused micro-cells on the fly will increase the LiDAR performance, and mitigate its performance degradation at high temperature.