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Progress Status on Quanta Image Sensors (QIS)

Eric R. Fossum

July 7, 2020

rit photonics for Quantum.2

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(Not much progress since SPW Milan Oct 2019)

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Contributors to this progress review

- Dr. Jiaju Ma – Dartmouth → Gigajot
- Dr. Saleh Masoodian – Dartmouth → Gigajot
- Dr. Dakota Starkey – Dartmouth → Gigajot
- Mr. Wei Deng – Dartmouth
- Ms. Kaitlin Anagnost – Dartmouth
- Prof. Stanley Chan – Purdue
- Mr. Abhiram Gnanasambandam – Purdue + Gigajot
- Dr. Omar Elgendy – Purdue → Gigajot
- EF – Dartmouth and Gigajot
- Rambus, TSMC, and also DARPA, NASA/JPL, NASA/RIT, Goodix

n.b. review data includes data taken by different people, different methods, different devices

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gigajot
WHERE EVERY PHOTON COUNTS

PURDUE
UNIVERSITY

Quanta Image Sensor (QIS)
"Count Every Photon"

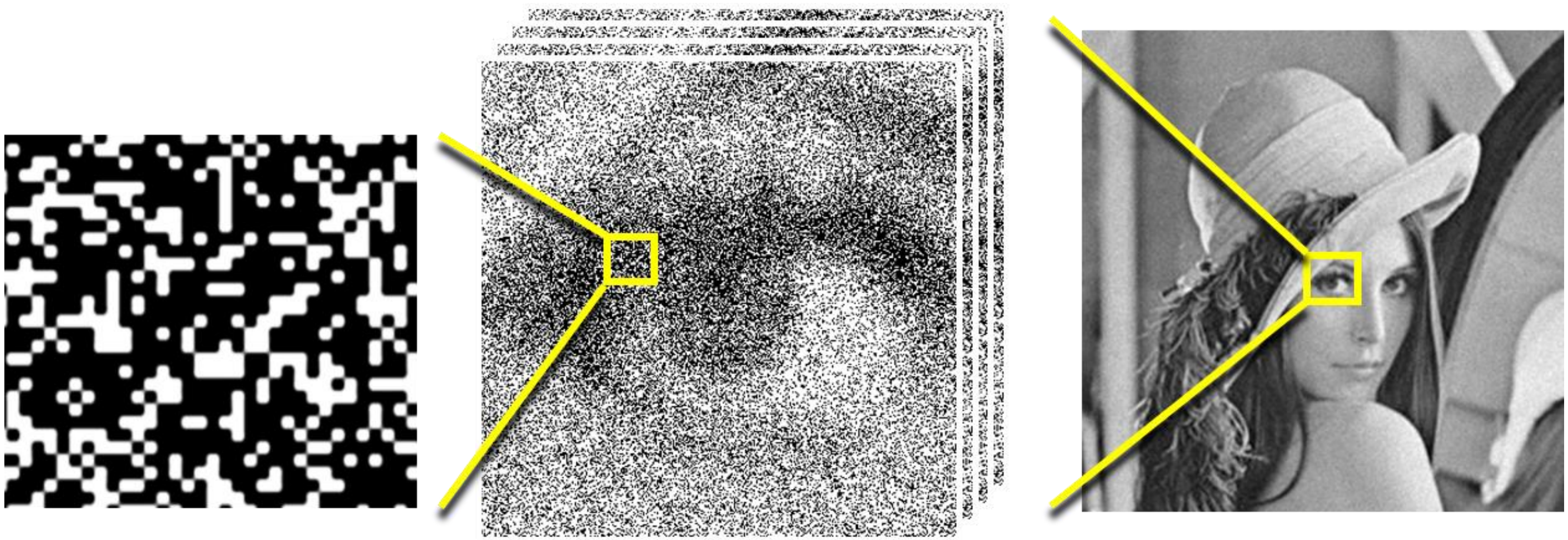
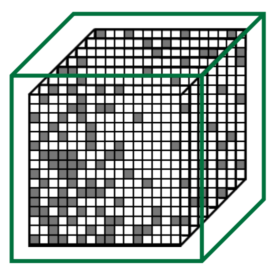


Image
reconstruction
X-Y-t Bit Density ➔ Gray Scale



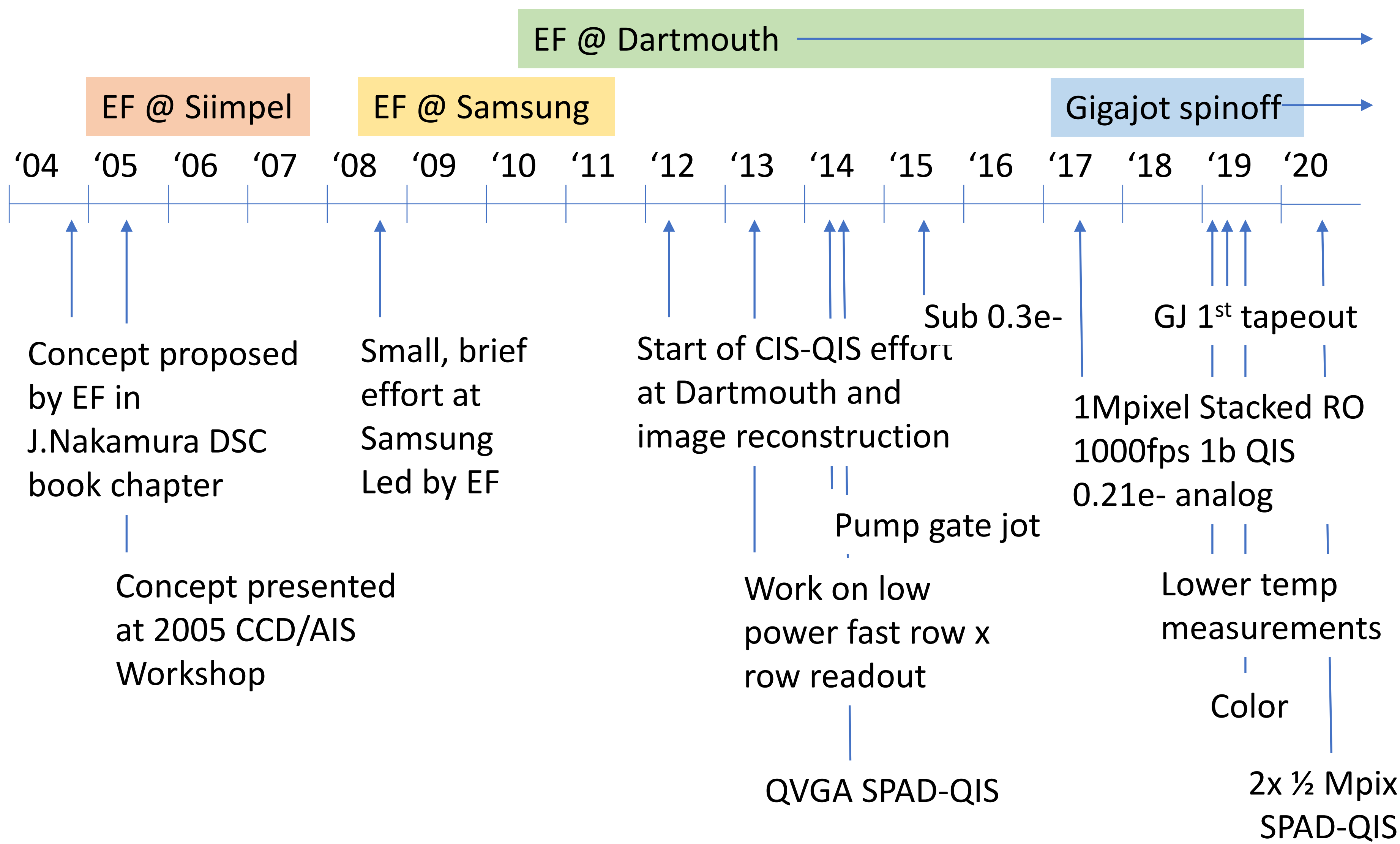
Cubicle

Vision: A billion jots readout at 1000 fps (1Tb/s) with single photon-counting capability and consuming less than a watt.

Imaging Paradigm Shift

- Might seem like a lot of extra work compared to an integrating bucket of charge in conventional CMOS image sensors (CIS).
- Counting every (visible) photon is about as sensitive as one can get for photography, security, defense, space, etc.
- Helps with small pixel vs. full-well capacity trade off.
- Allows new capabilities in computational imaging such as:
  - Trade off in sensitivity and resolution that can be scene-dependent or attention-dependent.
  - Permits time-delay and integration in multiple independent tracks and arbitrary directions.
  - Allows motion blur compensation for multiple targets.
  - Allows high apparent SNR for very low photon flux.

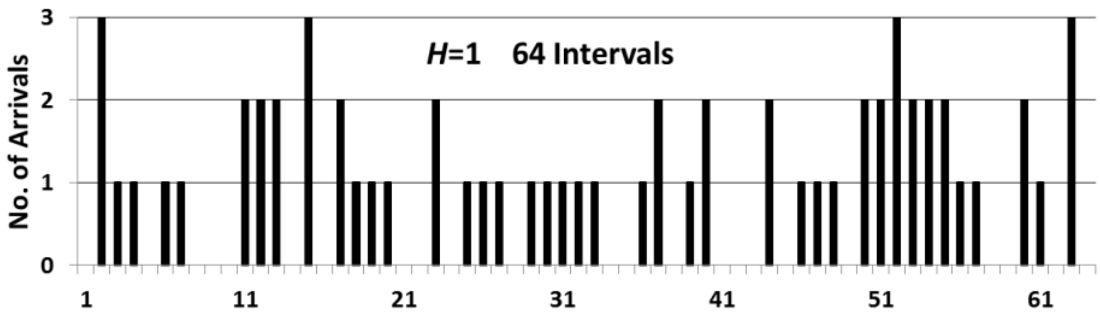
QIS Brief Timeline



Photon and photoelectron arrival rate described by Poisson process

Define *quanta exposure* $H = \phi\,\tau$ $\quad$ $H = 1$ means expect 1 arrival on average.

Monte Carlo



Probability of k arrivals

$$P[k] = \frac{e^{-H} H^k}{k!}$$

For jot, only two states of interest

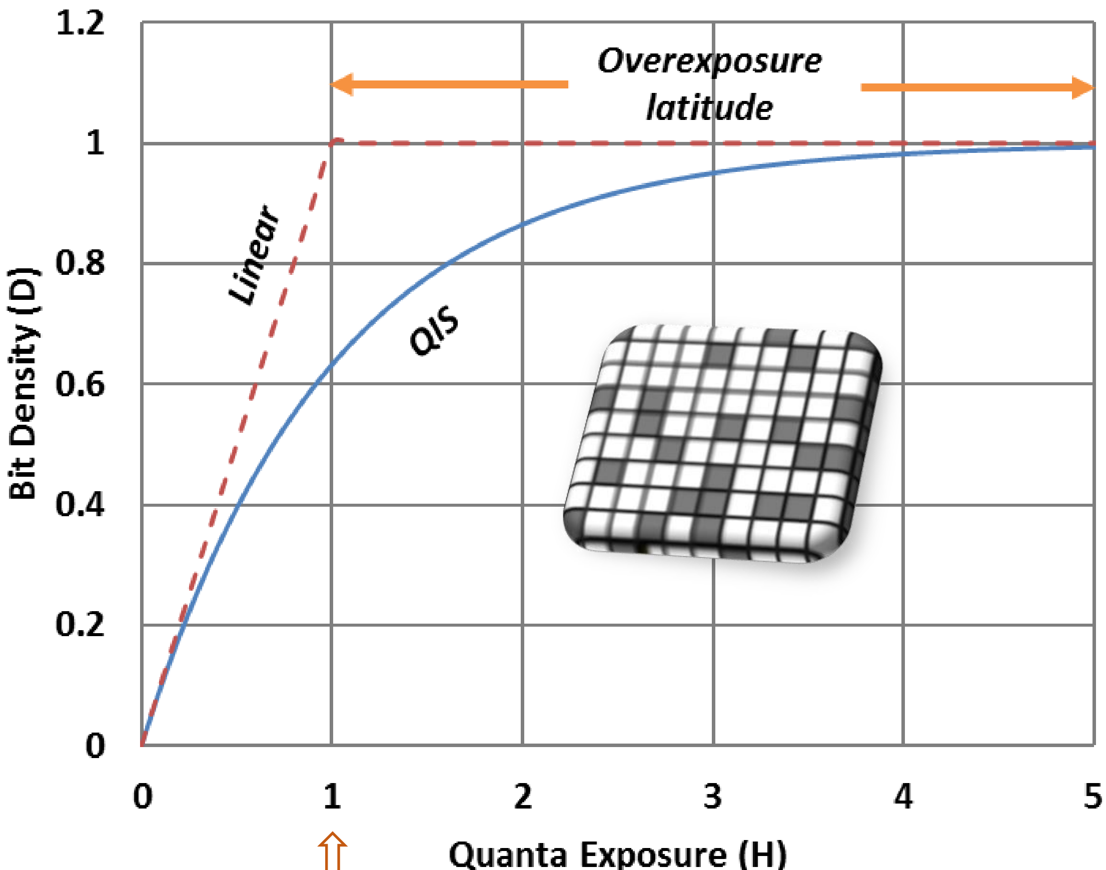
$$P[0] = e^{-H}$$

$$P[k > 0] = 1 - P[0] = 1 - e^{-H}$$

For ensemble of *M* jots, the expected number of 1's : $M_1 = M \cdot P[k > 0]$

Photoresponse as bit density

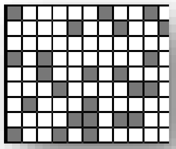
$$Bit\ Density\ D \triangleq \frac{M_1}{M} = 1 - e^{-H}$$

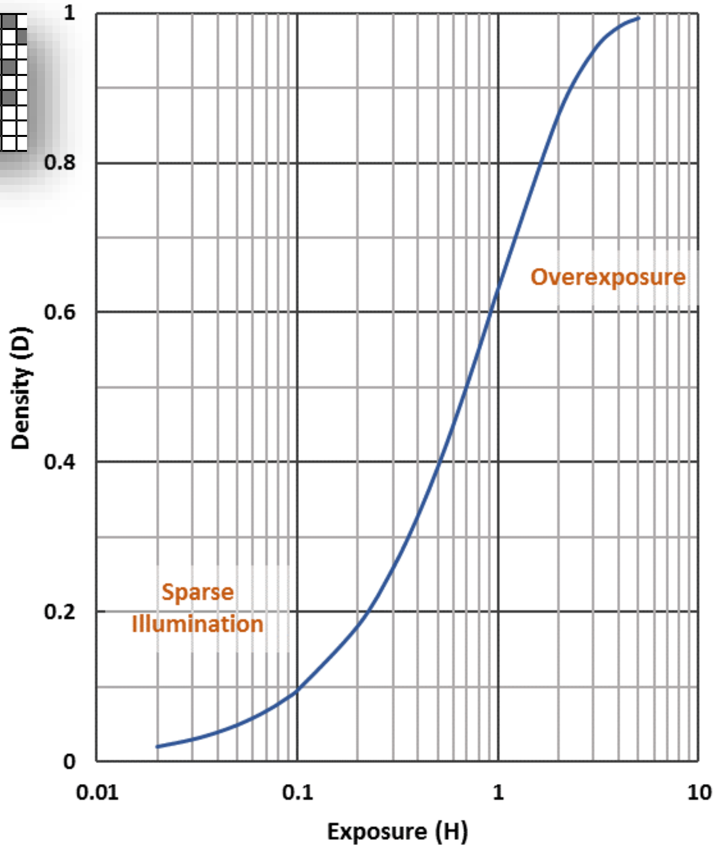


Average of one arrival per jot

QIS responds to light

QIS D – log H

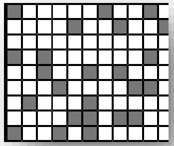


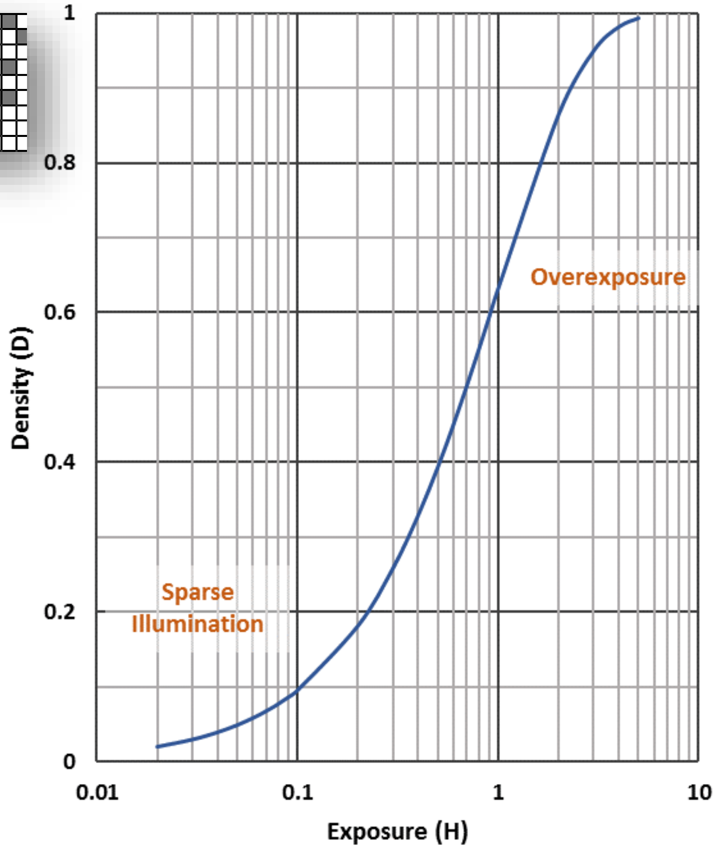


Bit Density vs. Exposure

QIS responds to light like film

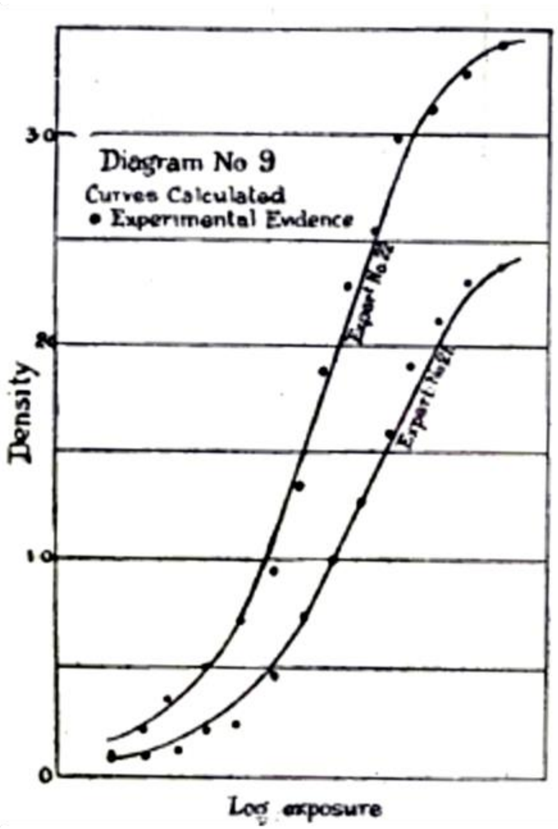
QIS D – log H



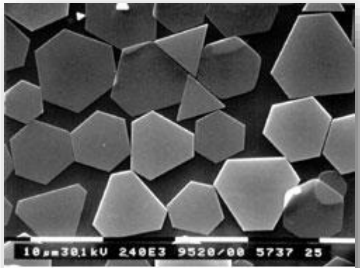


Bit Density vs. Exposure

Film D – log H



Film Density vs. Exposure
1890 Hurter and Driffield



Electron micrograph of tabular grain emulsion

Film grains are binary detectors

http://faculty.virginia.edu/ASTR5110/lectures/detectors/detectors_intro.html

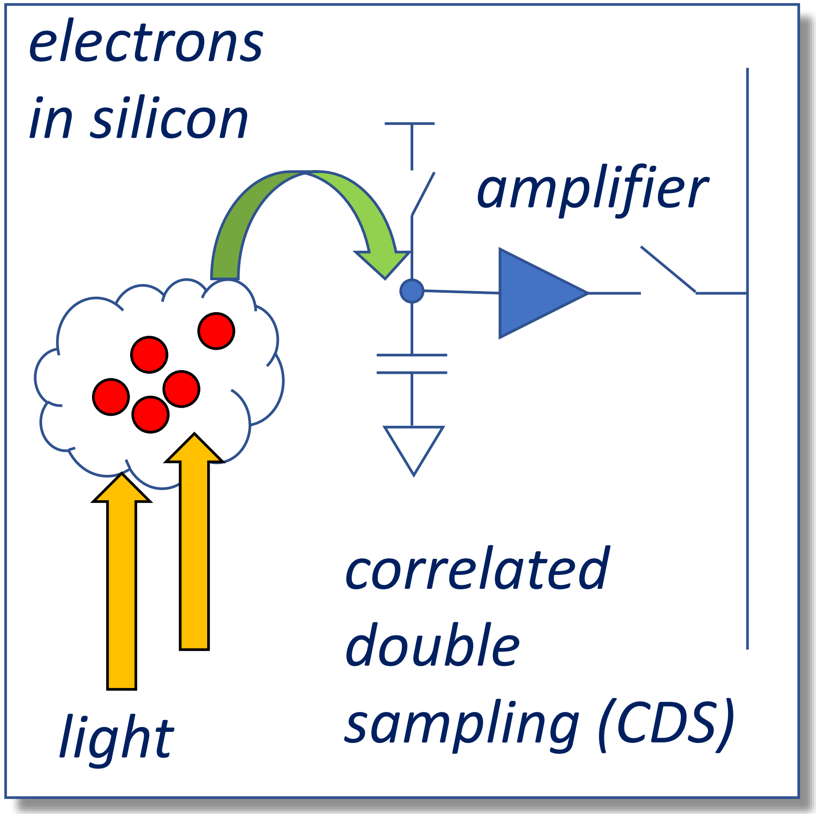
Our approach (CMOS QIS)

No avalanche multiplication, one electron per photon

Use very low capacitance sense node

$$\Delta V = \Delta Q / C$$

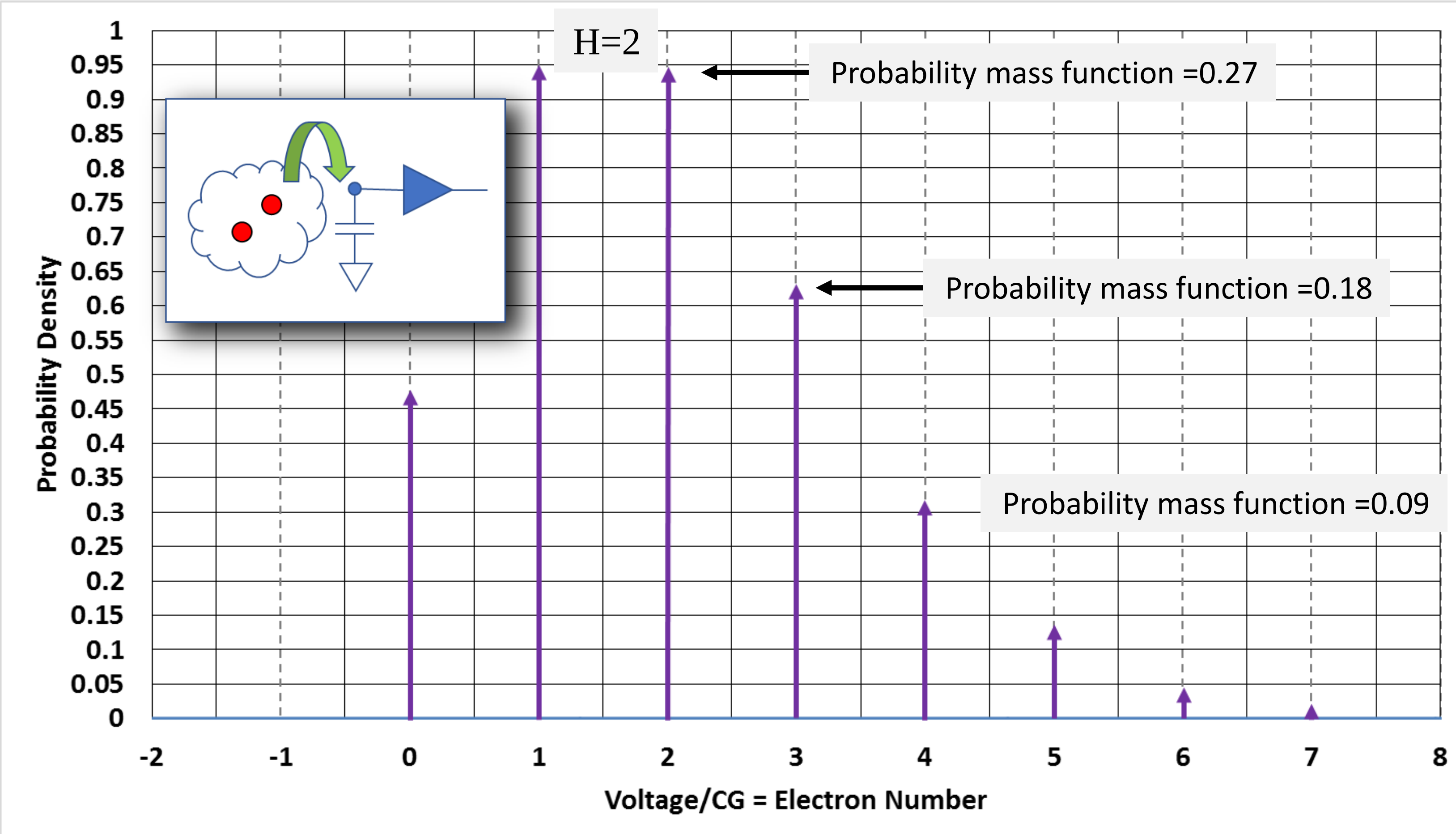
e.g. $1\text{mV} = 1.6\text{x}10^{-19}\text{C} / 160\text{aF}$



Conversion gain CG defined as q/C or volts/electron

Voltage Output with No Electronics Noise

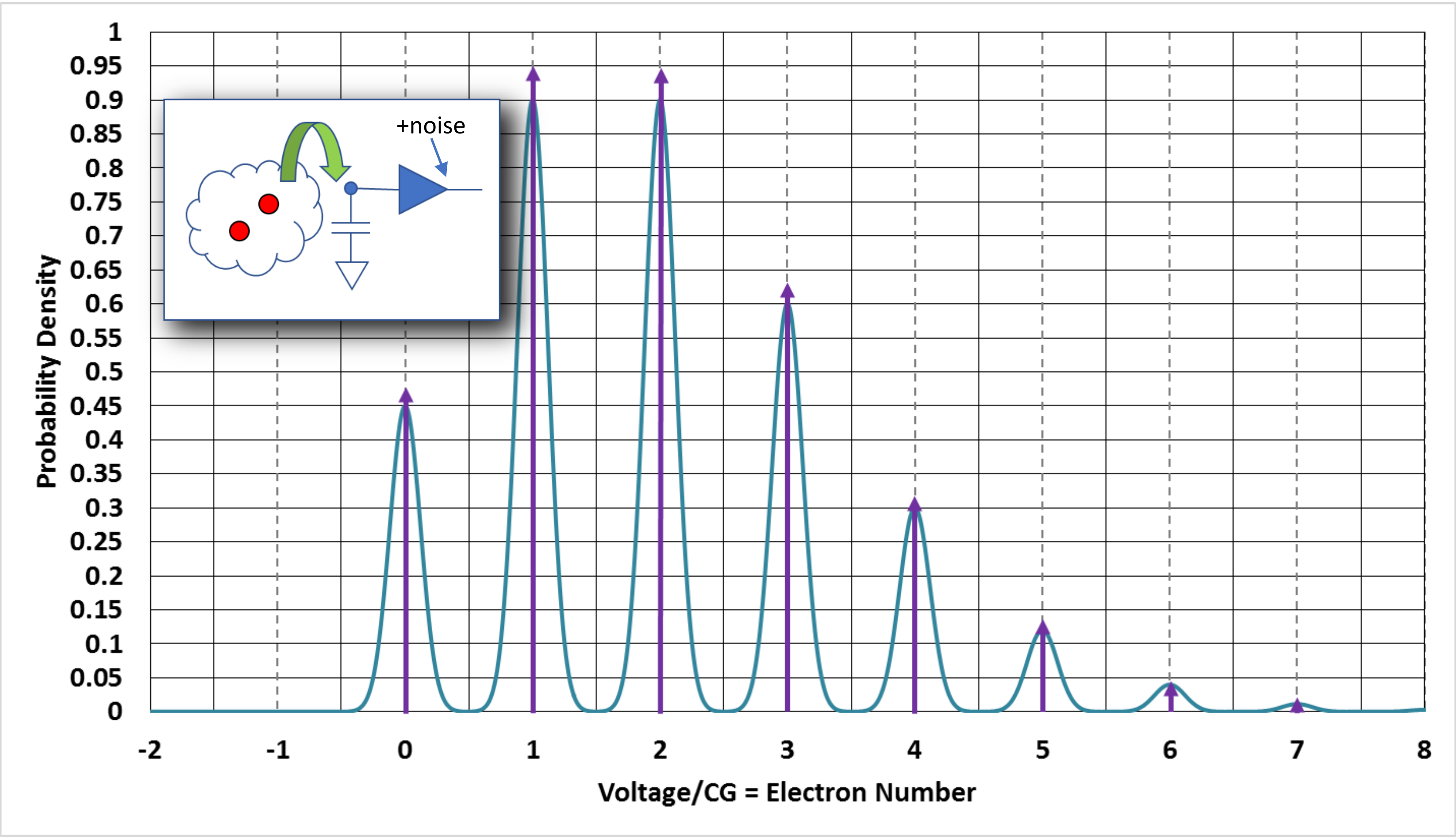
Poisson probability mass function $P[k] = \frac{e^{-H} H^k}{k!}, k = 0, 1, 2, 3 \ldots$



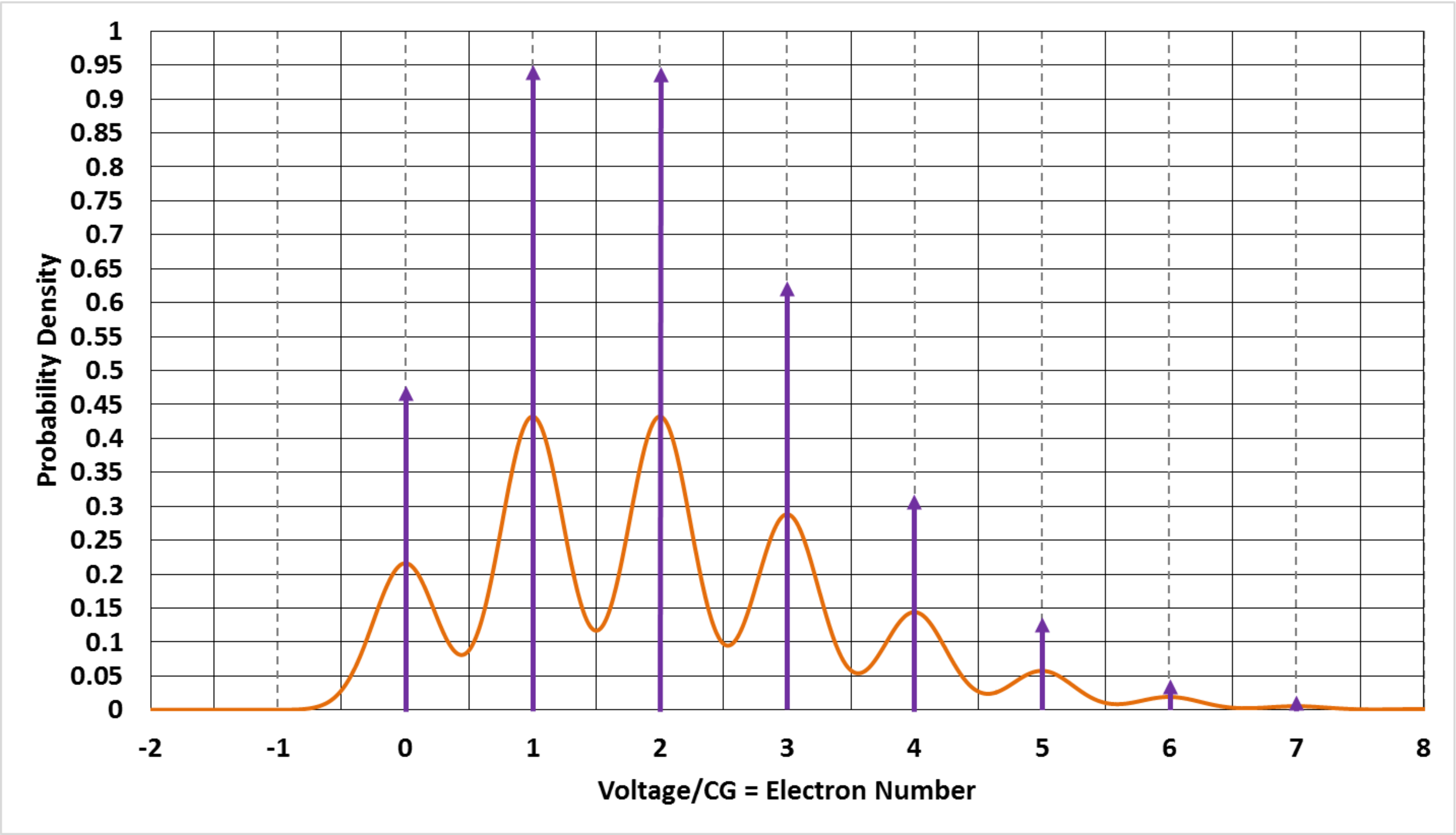
Without additive noise, voltage output should be very quantized

Broadened by 0.12e- rms read noise

$U_n = V_n / CG$ [e- rms]

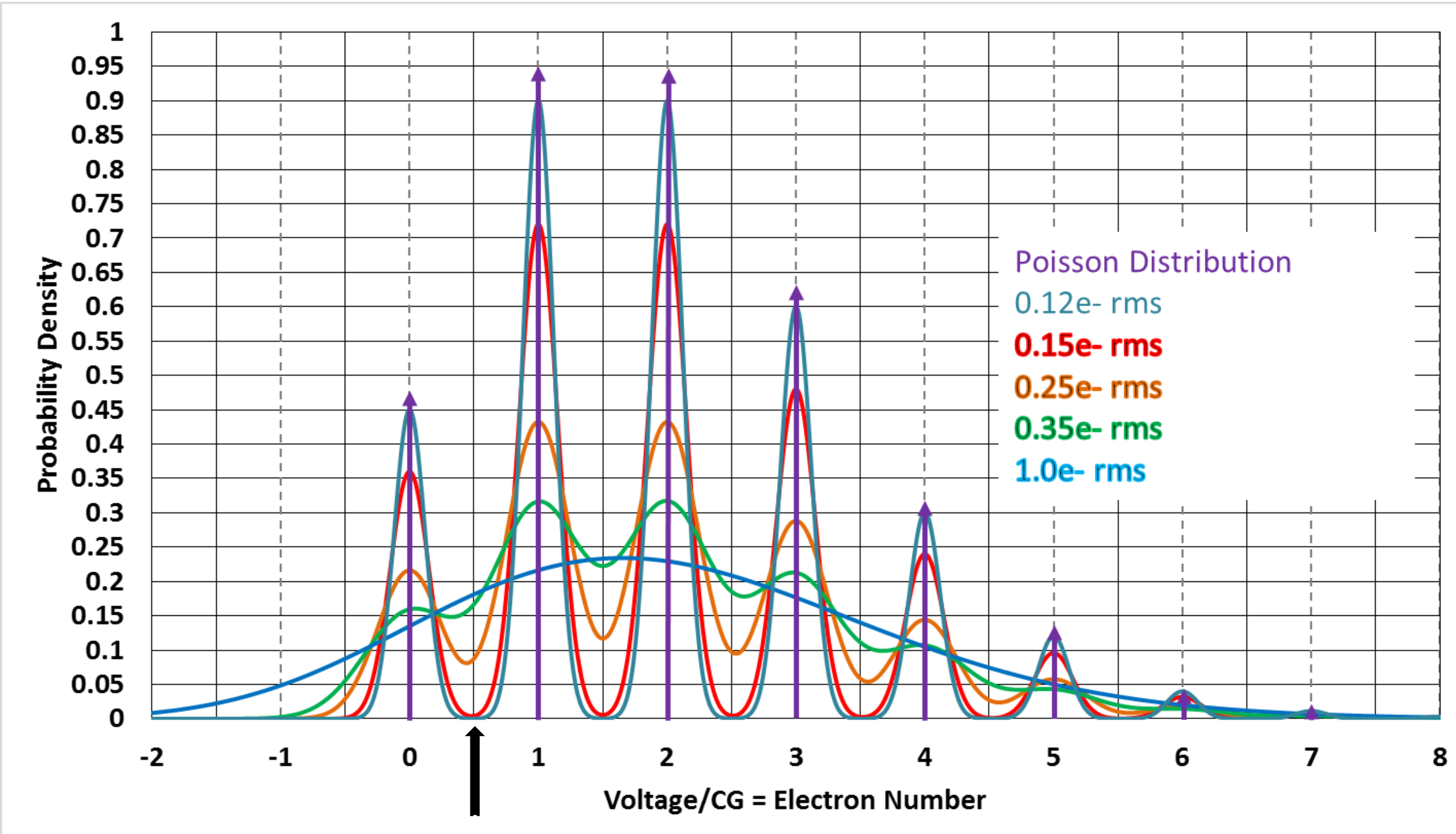


Broadened by 0.25e- rms read noise



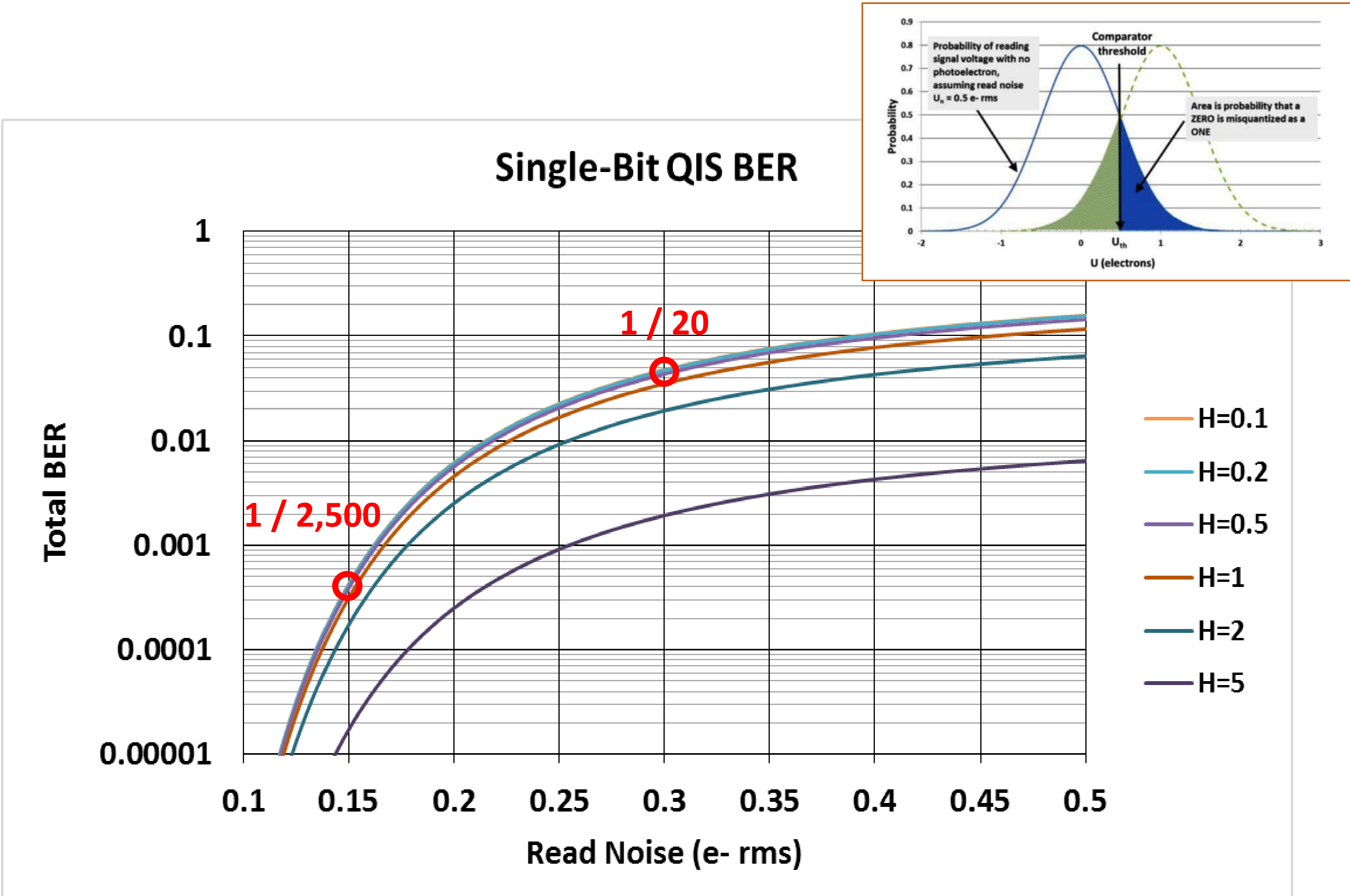
Model

Quantized Values Broadened by Readout Noise

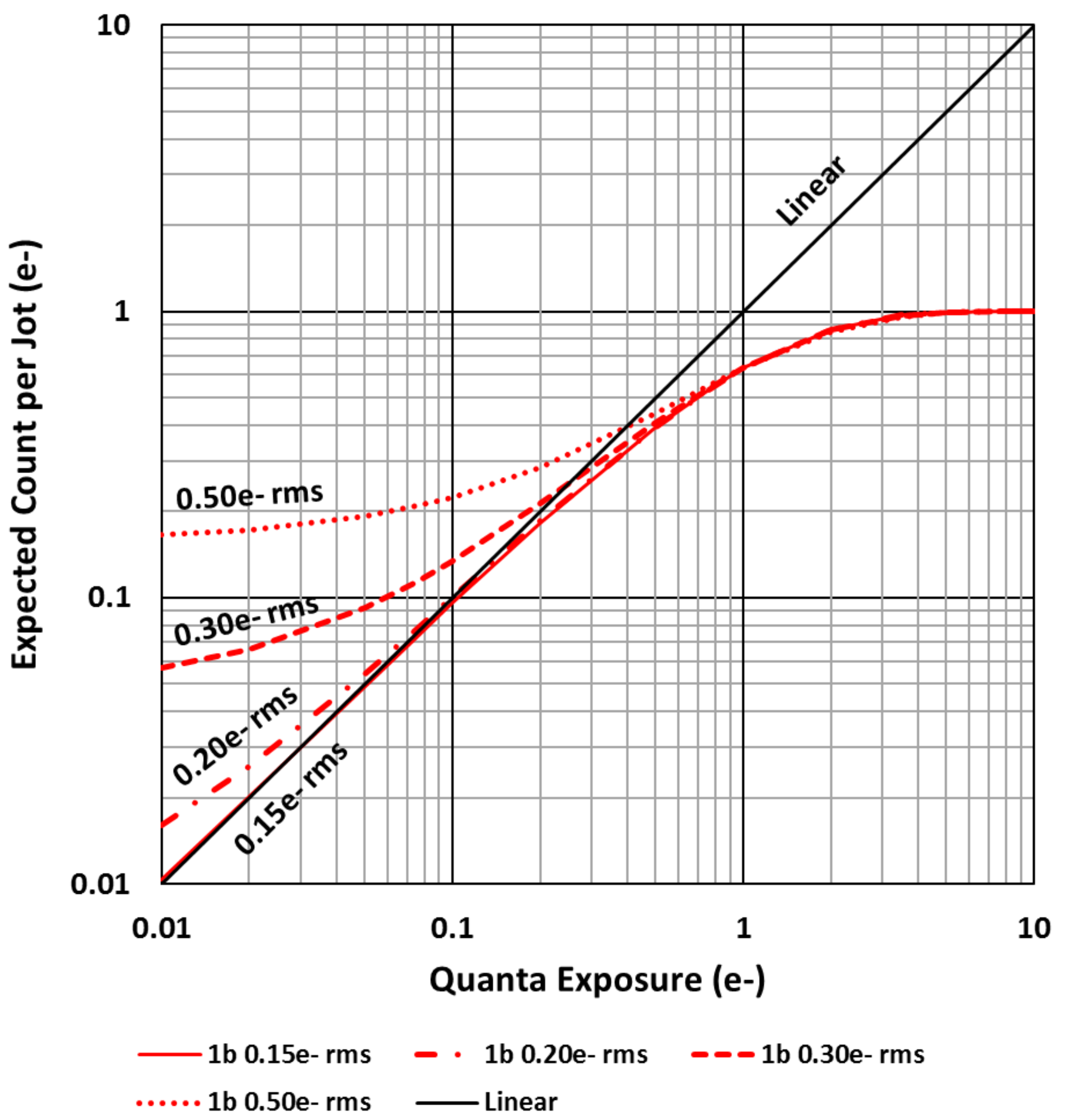


“0” “1”

Bit error rate (BER) depends strongly on read noise



Effect of Read Noise on Photon Counting Accuracy

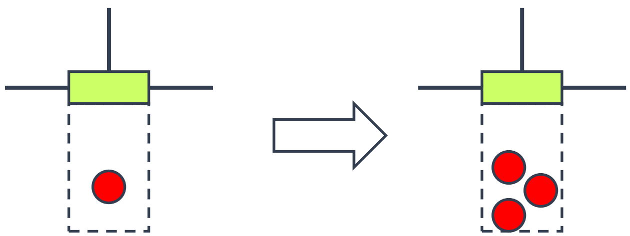


Quanta exposure is the avg. # of photons or photoelectrons that arrive per integration period

Multi-bit jot increases flux capacity

At the flux capacity, there is an average of $2^n - 1$ photoelectrons per *n*-bit jot

$$\phi_{wn} = jf_r(2^n - 1)/\delta\bar{\gamma}$$



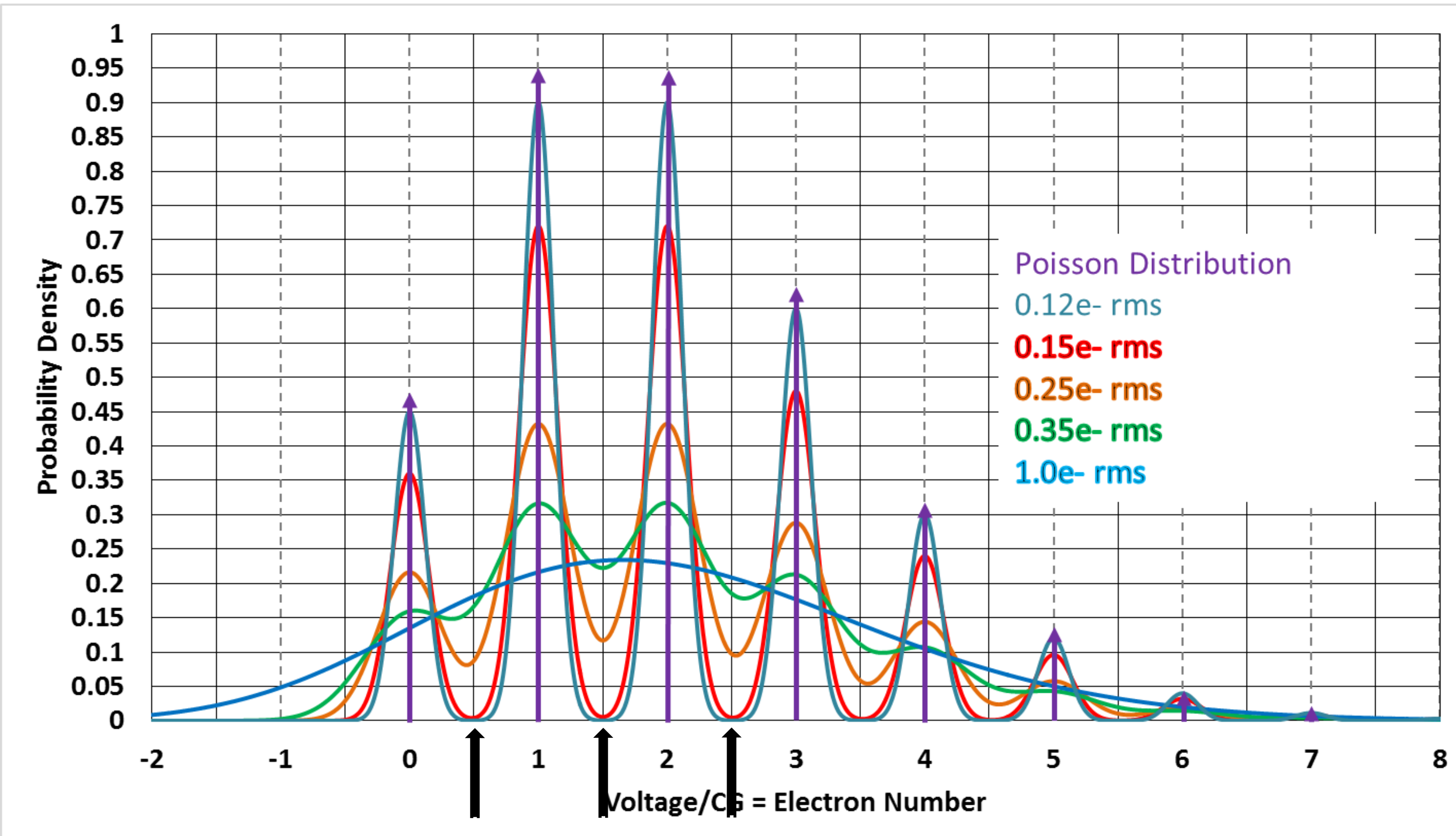
Single bit jot
0, 1 electrons

Multi-bit (2b) jot
0, 1, 2, 3 electrons

➔ Can increase flux capacity at same jot density and field readout rate
➔ Or, relax field readout rate and/or jot density for same flux capacity

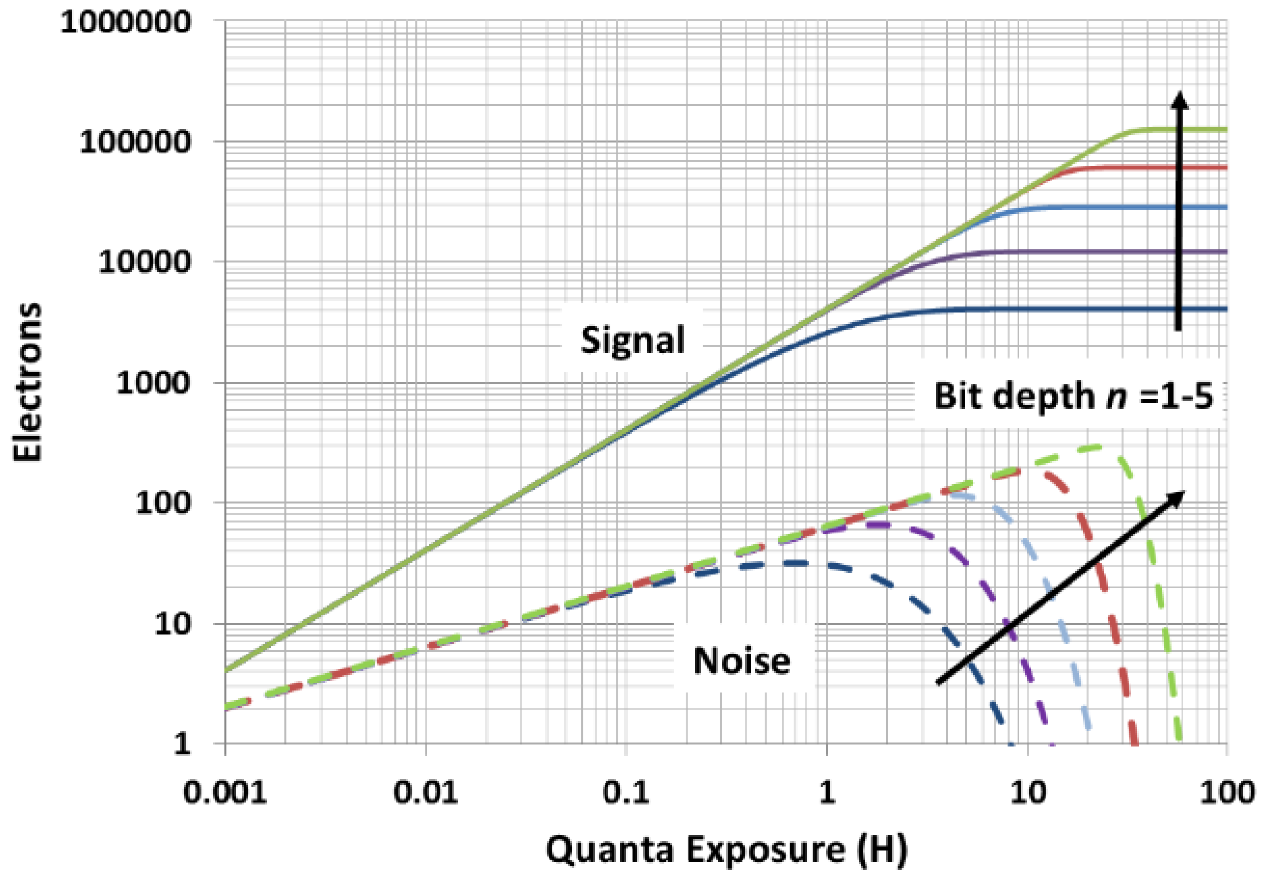
Little impact on detector and storage well. Little impact on FD CG or voltage swing (e.g. 1mV/e -> 31mV swing for 5b jot.

Multi-bit QIS for Photon Number Resolution (e.g. 2-bit)

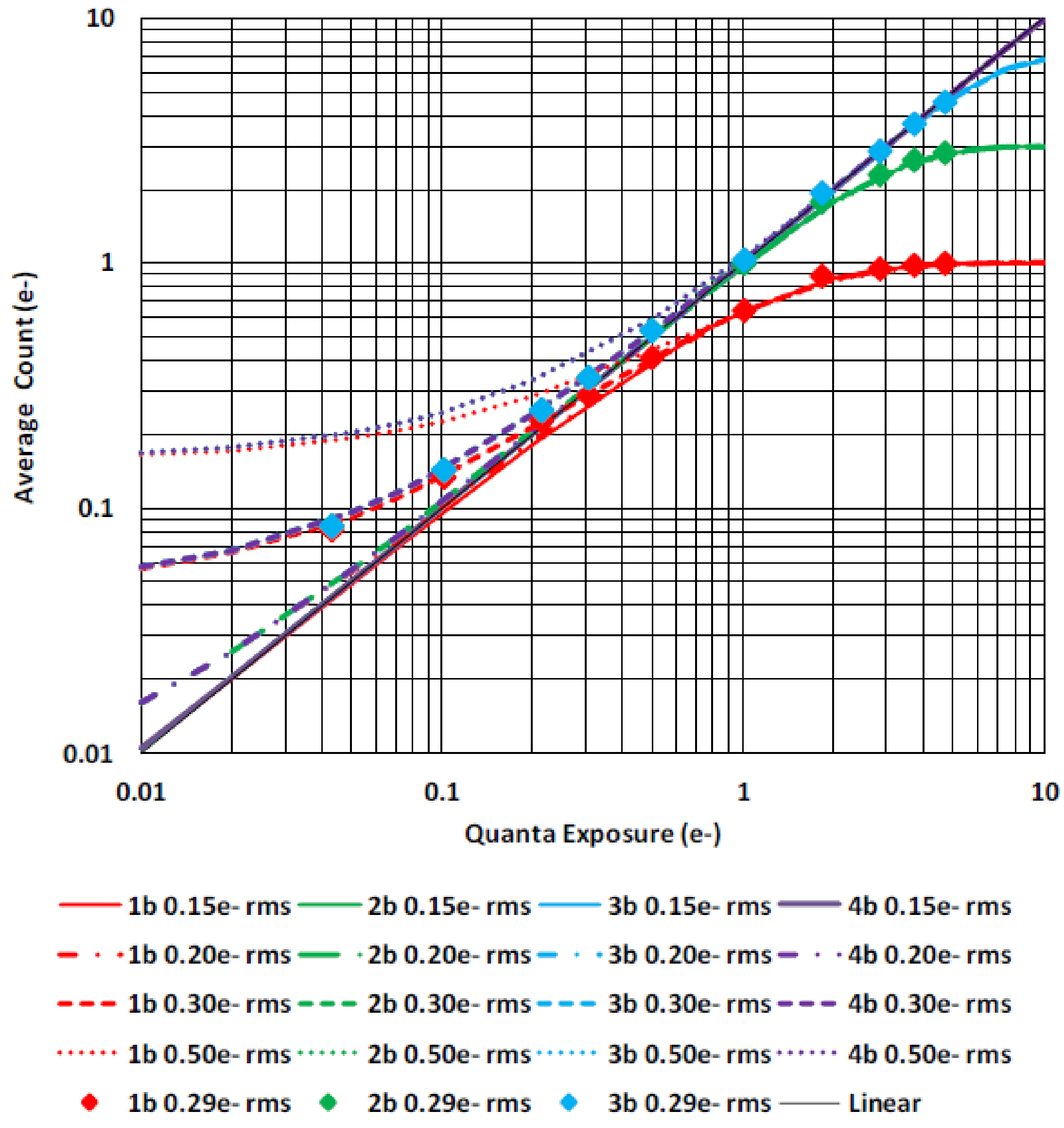


"00" "01" "10" "11"

Signal and Noise for Multi-bit QIS



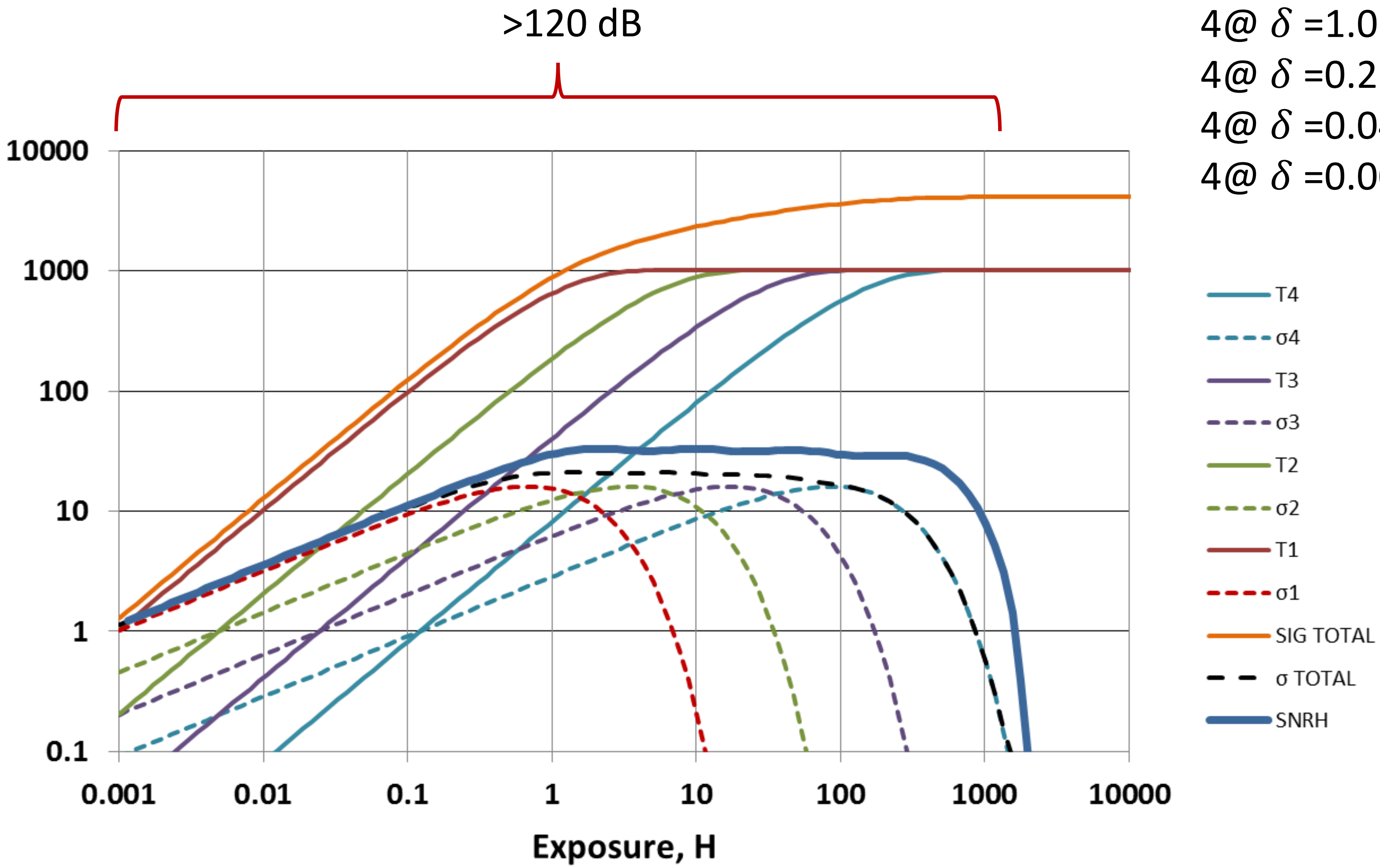
Noise Requirement for Photon Counting



High Dynamic Range with 1b QIS

16x16x16 cubicle

Sum of 16 fields
4@ δ =1.0
4@ δ =0.2
4@ δ =0.04
4@ δ =0.008



Fossum, IEEE JEDS vol 1(9) pp. 166-173 Sept 2013

High Dynamic Range with 1b & 3b QIS

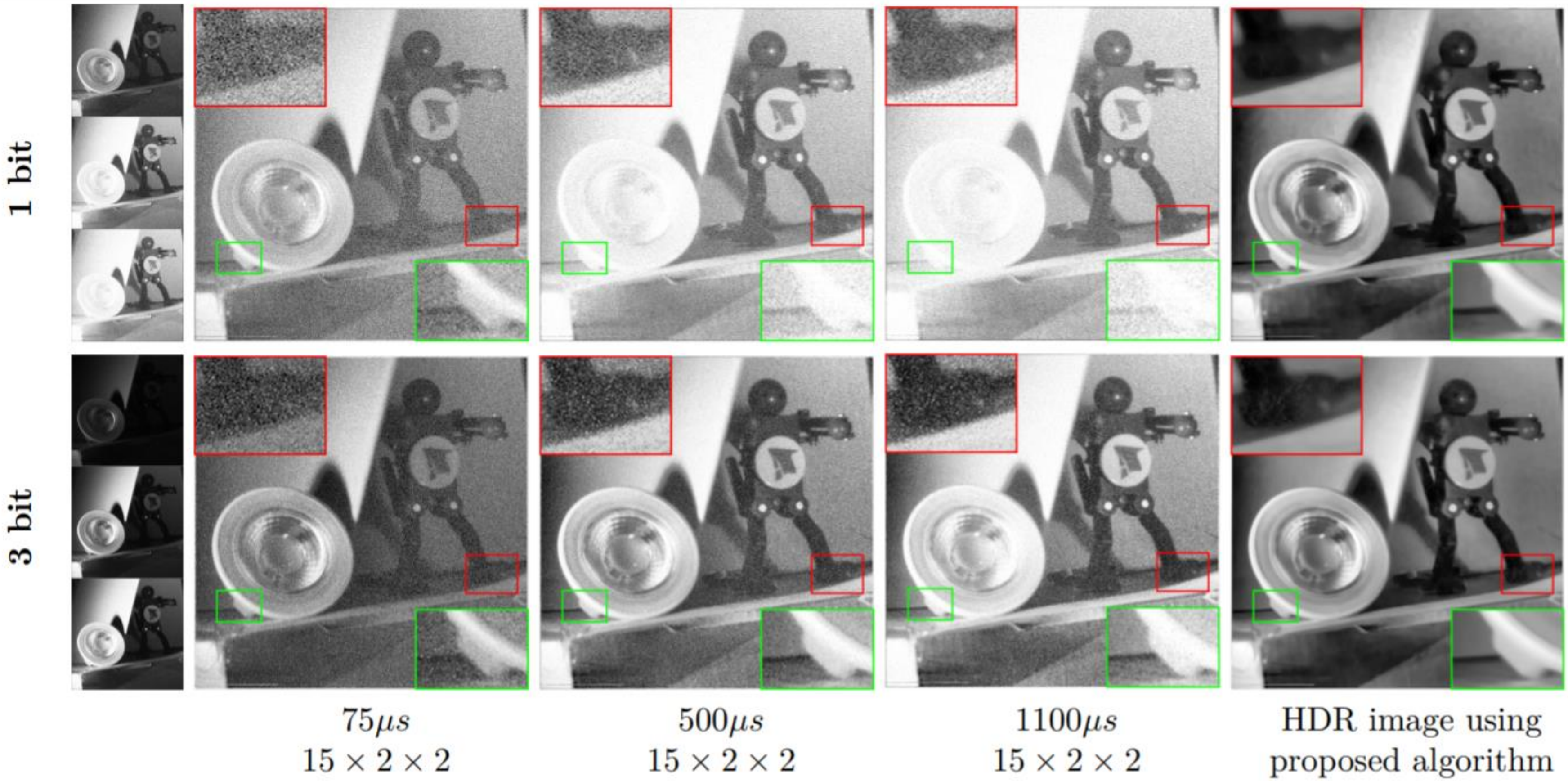


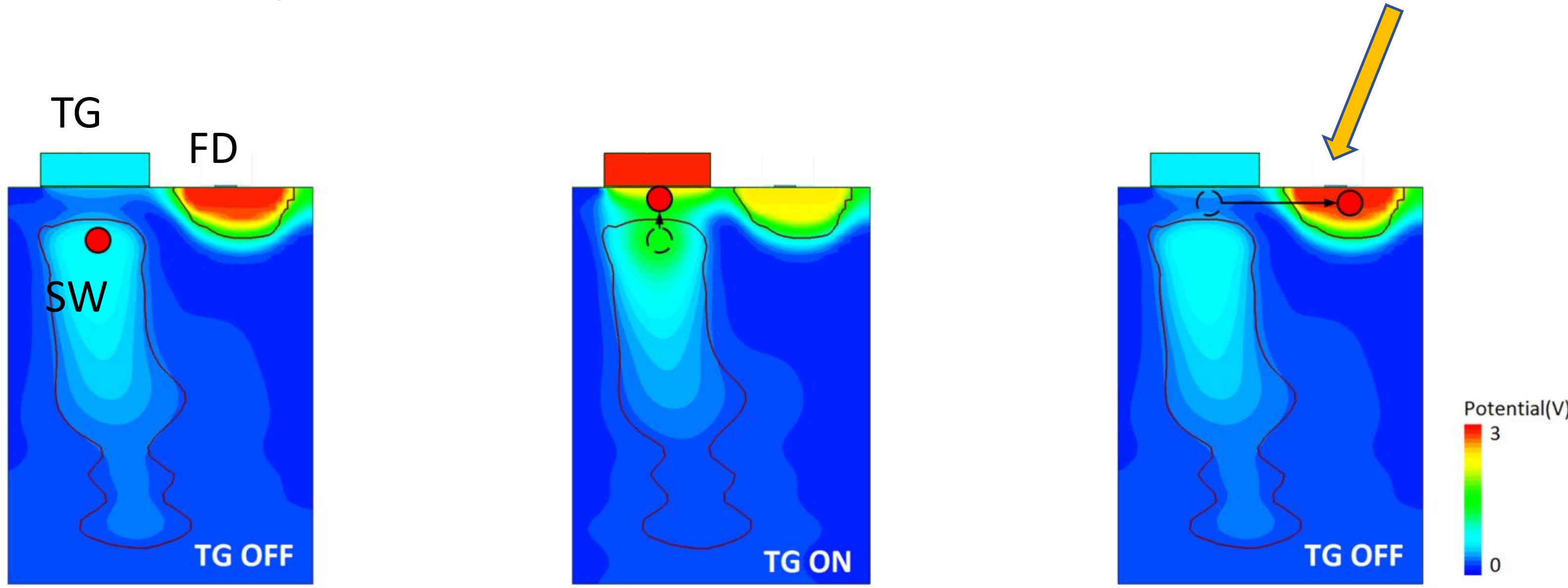
Figure 5. Real Data. In this experiment, we obtain 15 frames each at 3 different exposures - 75μs, 500μs, and 1100μs in 1 bit and 3 bit modes using a 1 Mpixel QIS image sensor. The average number of photons per pixel per frame are 0.5, 2.1 and 3.3 for the 3 exposures respectively. Spatial oversampling of 2×2 is used. The proposed HDR reconstruction algorithm is used to obtain the final HDR image. MATLAB's tonemap is used to display the images. The first column are images before tone-map.

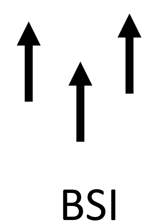
Gnanasambandam, Ma and Chan 2019
https://www.imagesensors.org/Past%20Workshops/2019%20Workshop/2019%20Papers/R23.pdf

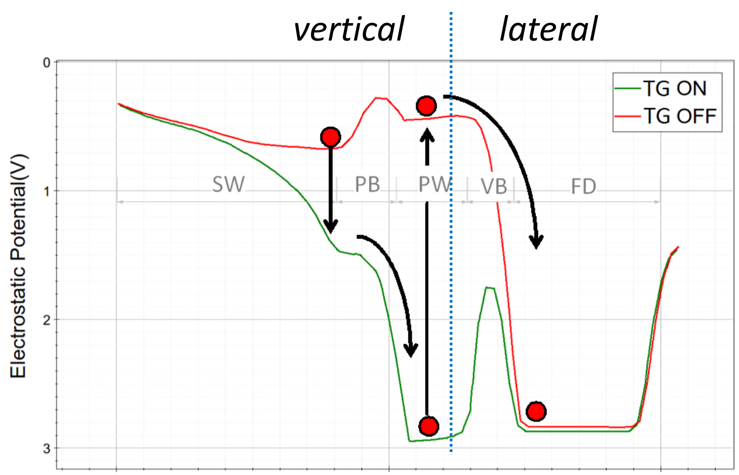
Pump-Gate Jot: Minimize TG-FD overlap capacitance

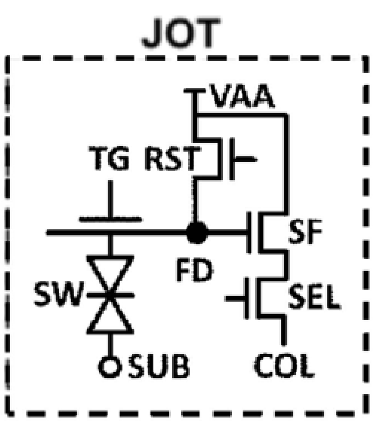
US Patent No. 9,728,565 B2
Fossum, Ma, Hondongwa

Highest possible CG
(Lowest possible cap.)

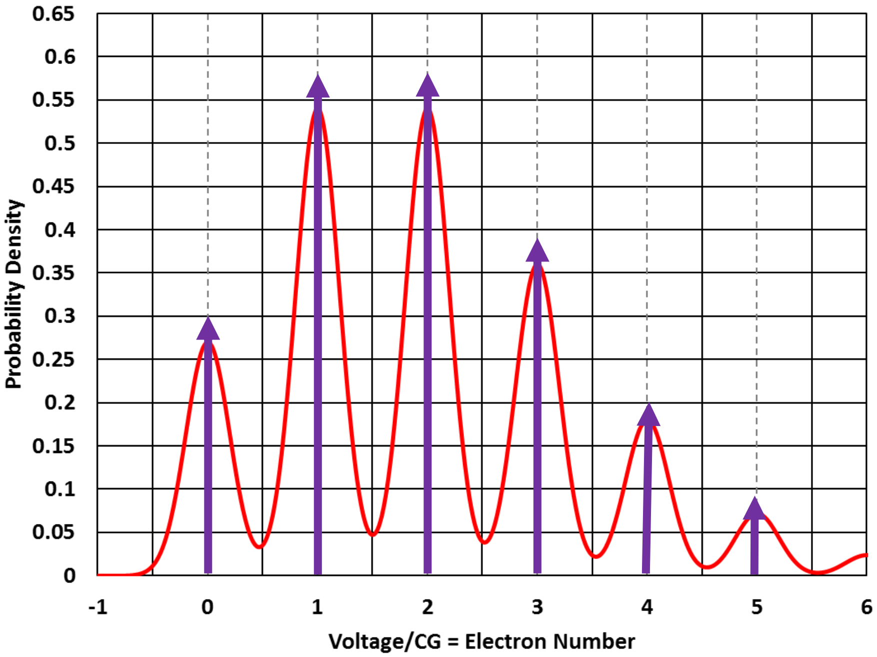






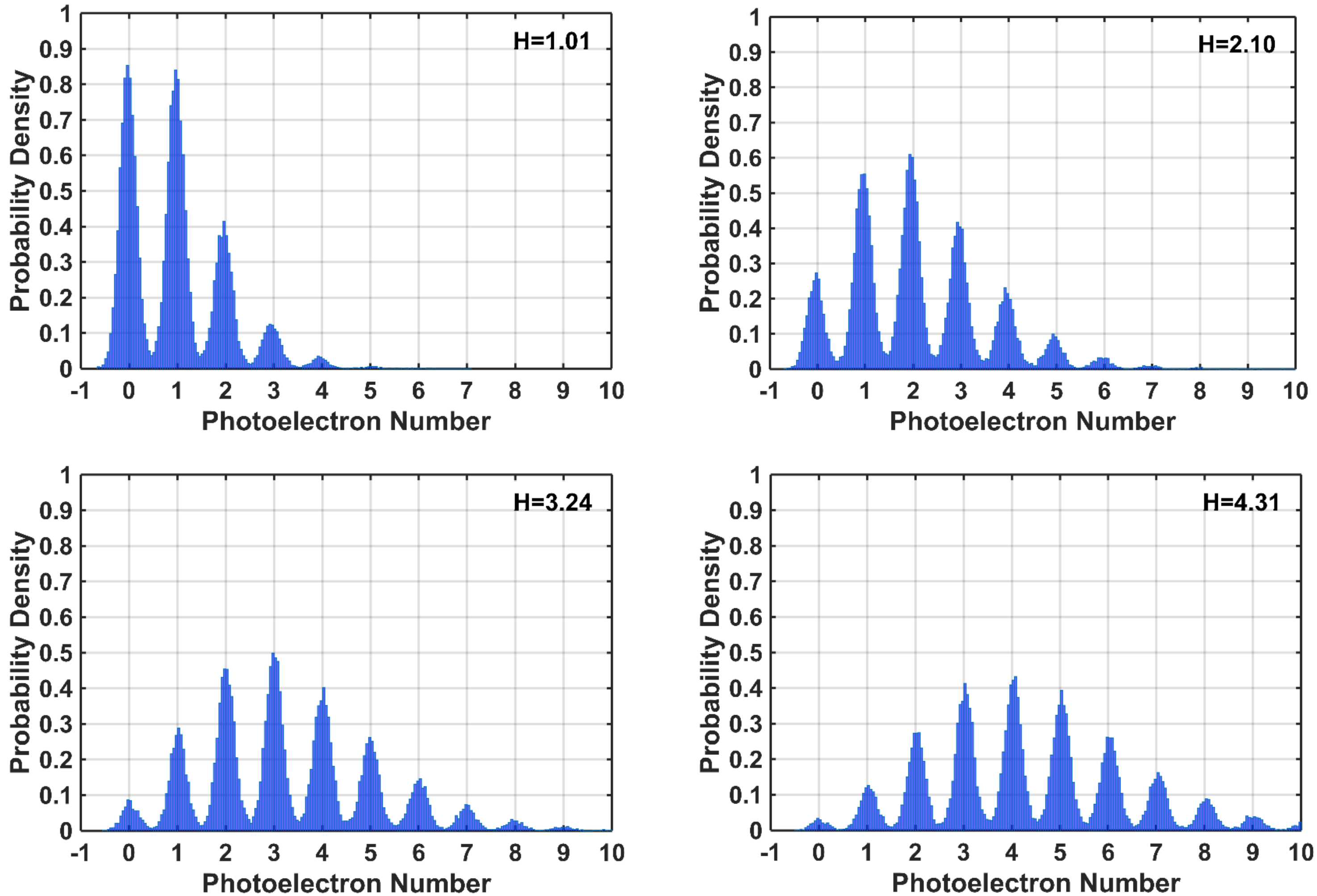


Recall our Poisson probability mass function broadened by read noise



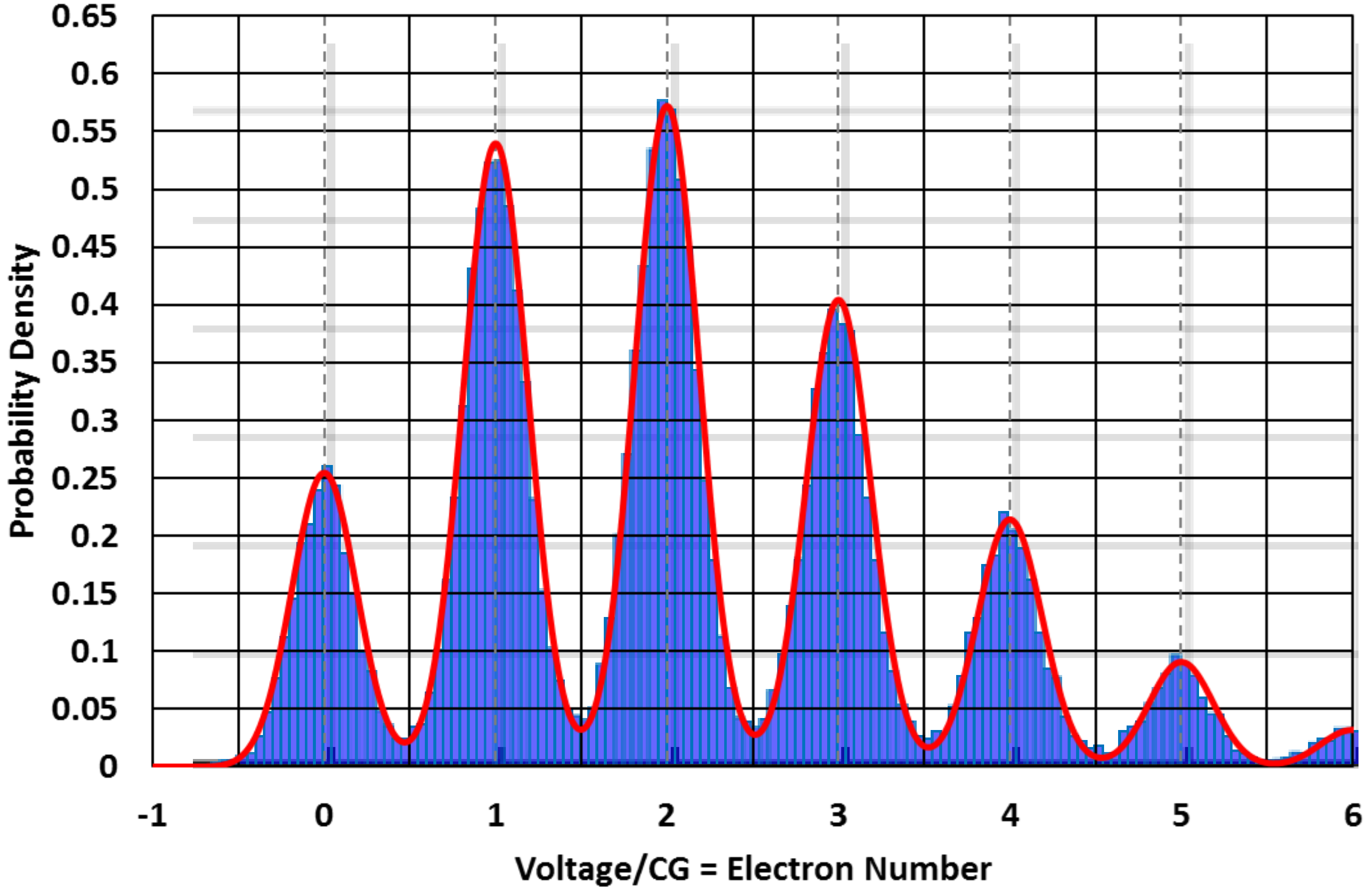
Experimental Data
Photon Counting Histogram for "a Golden Pixel"

20k reads of same jot, 0.175e- rms read noise ~21DN/e- (61.2uV rms 350uV/e- or 0.45fF)
Room temperature, no avalanche, 20 CMS cycles, jot:TPG PTR BC



Model vs. Data = New characterization tools

Conversion gain from peak spacing

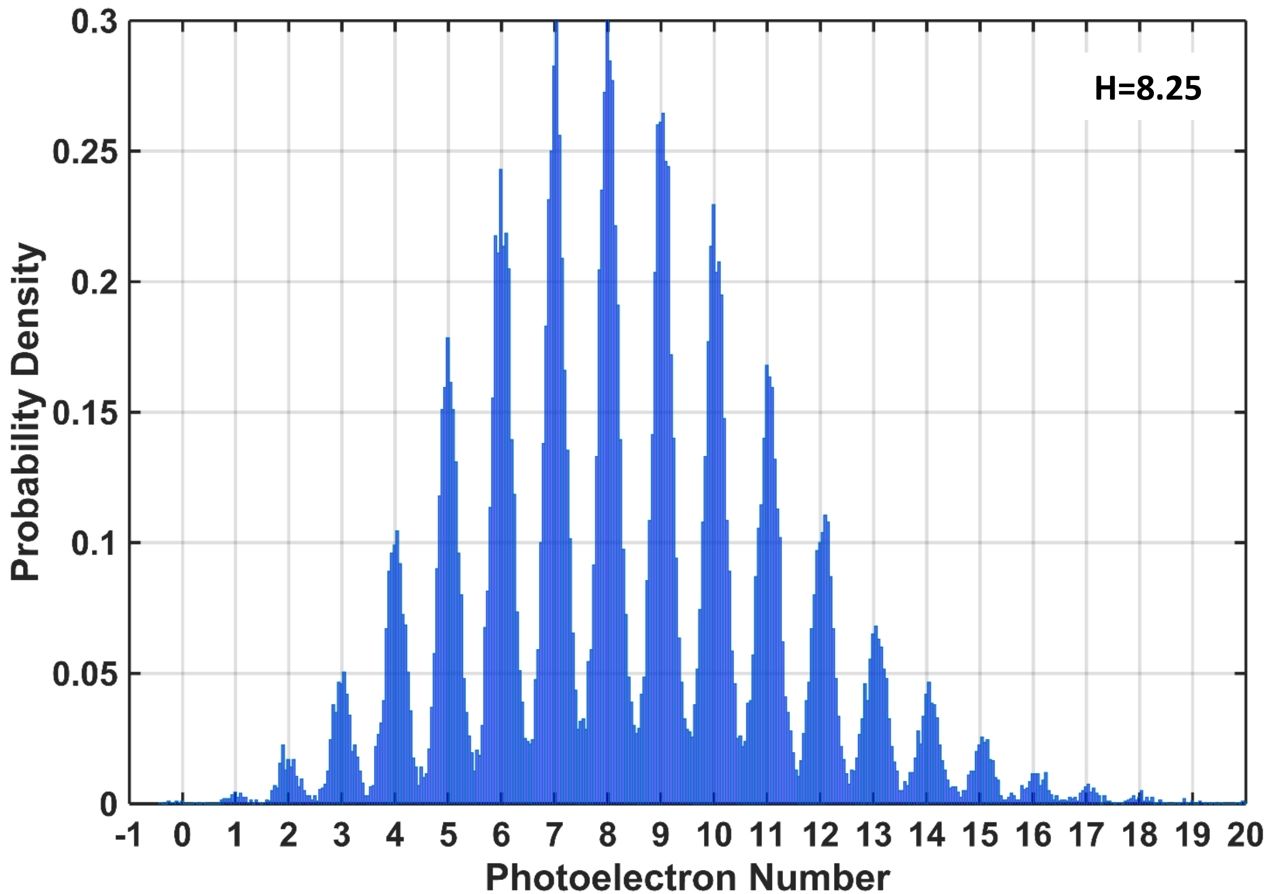


Quanta exposure from relative peak heights

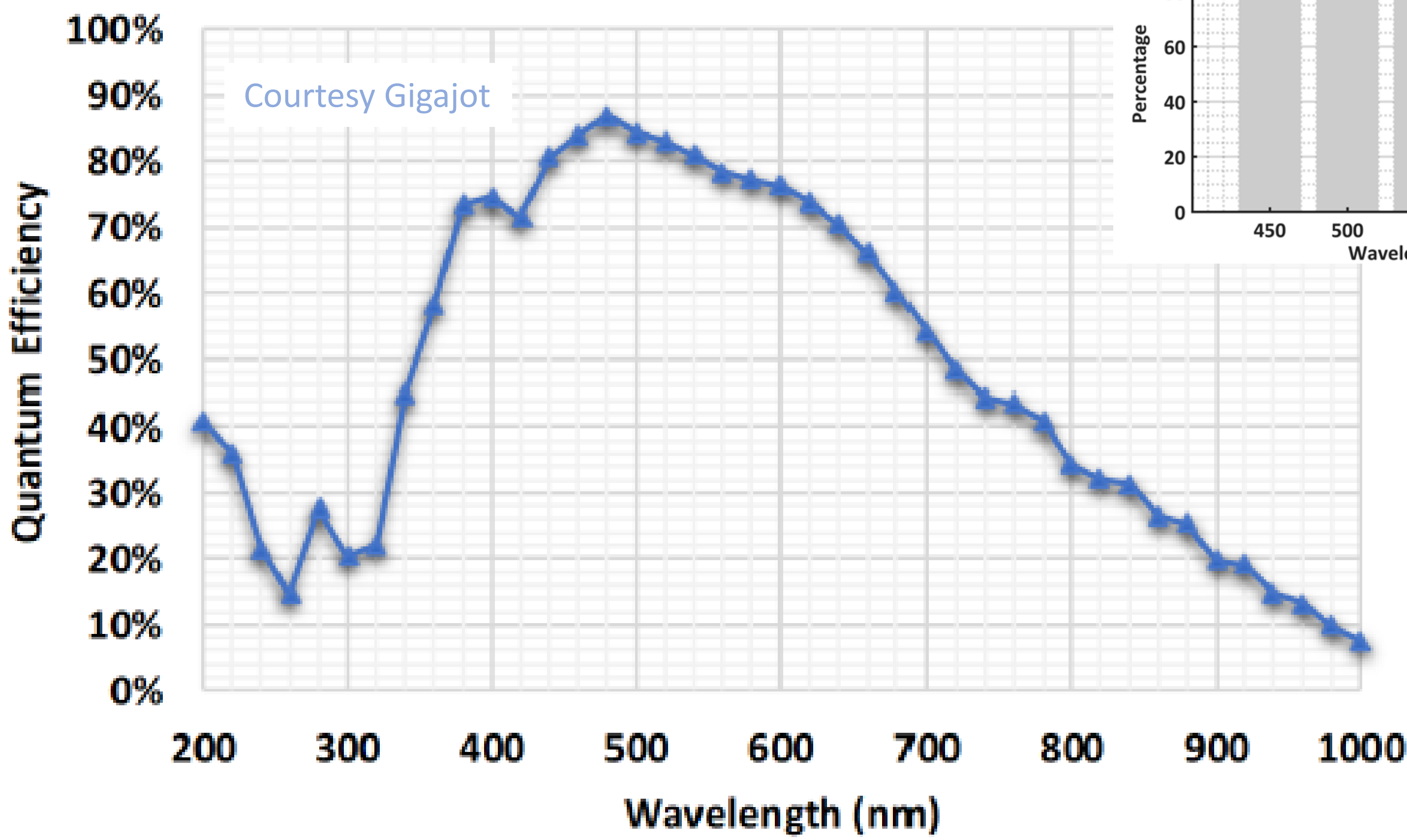
Read noise from valley-peak modulation value

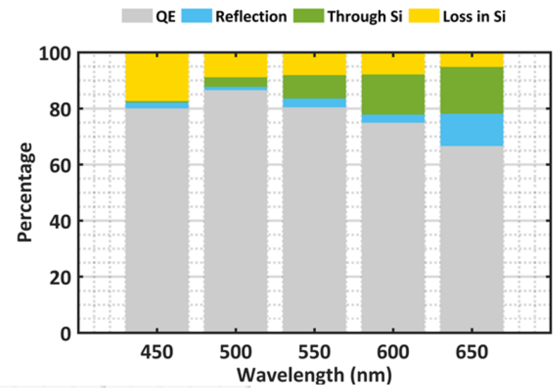
Experimental Data
Photon Counting Histograms

20k reads of same jot, 0.20e- rms read noise ~21DN/e-
Room temperature, no avalanche, 20 CMS cycles, jot:TPG PTR BC



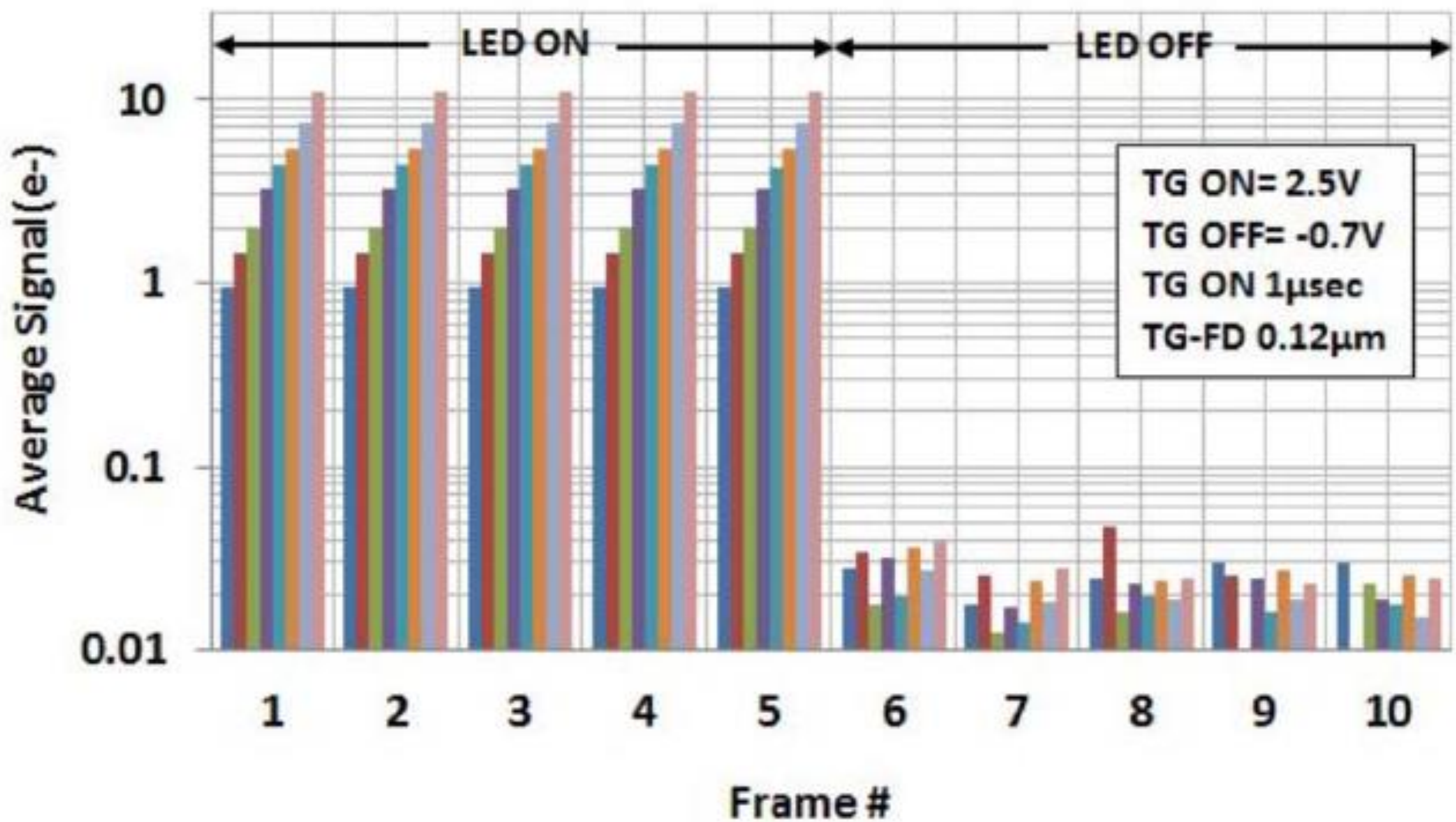
Quantum Efficiency





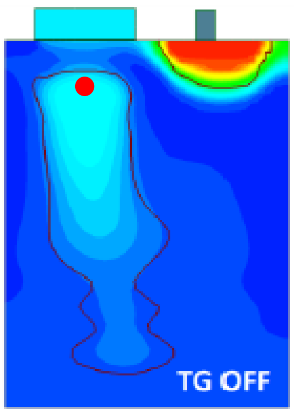
Quantum Efficiency 200nm to 1000nm

Lag

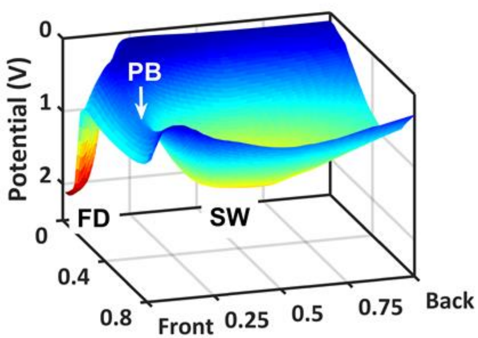

LED ON
LED OFF
10
1
0.1
0.01
Average Signal(e-)
TG ON= 2.5V
TG OFF= -0.7V
TG ON 1µsec
TG-FD 0.12µm
1
2
3
4
5
6
7
8
9
10
Frame #

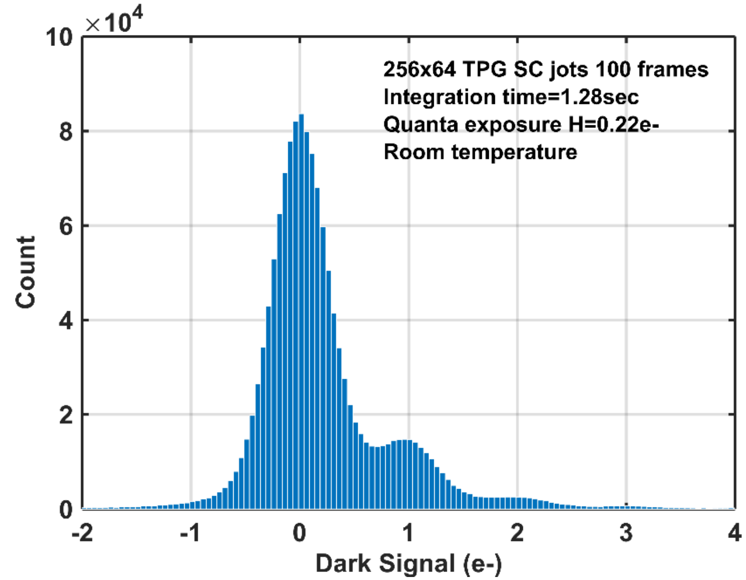
Very Low Dark Current (0.07 cps at RT)

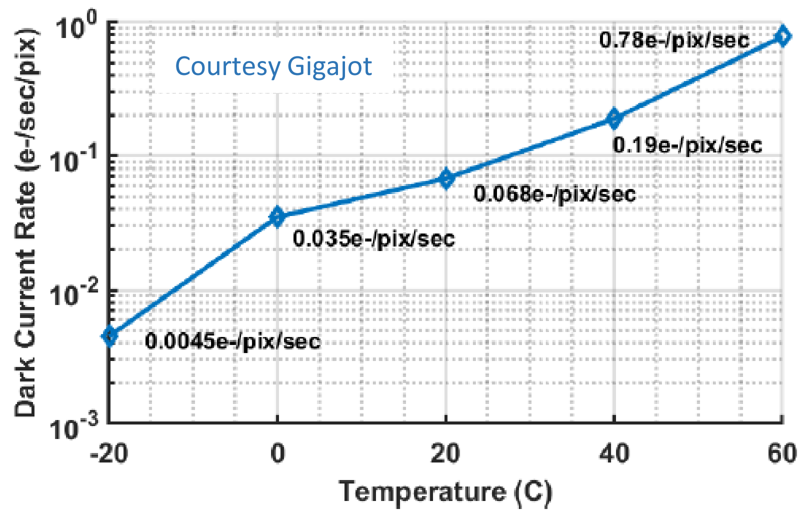
Room Temp: ~0.07e-/s avg. (~1pA/cm^2)
Previously measured ~2x every 10C



Storage well isolated from surface



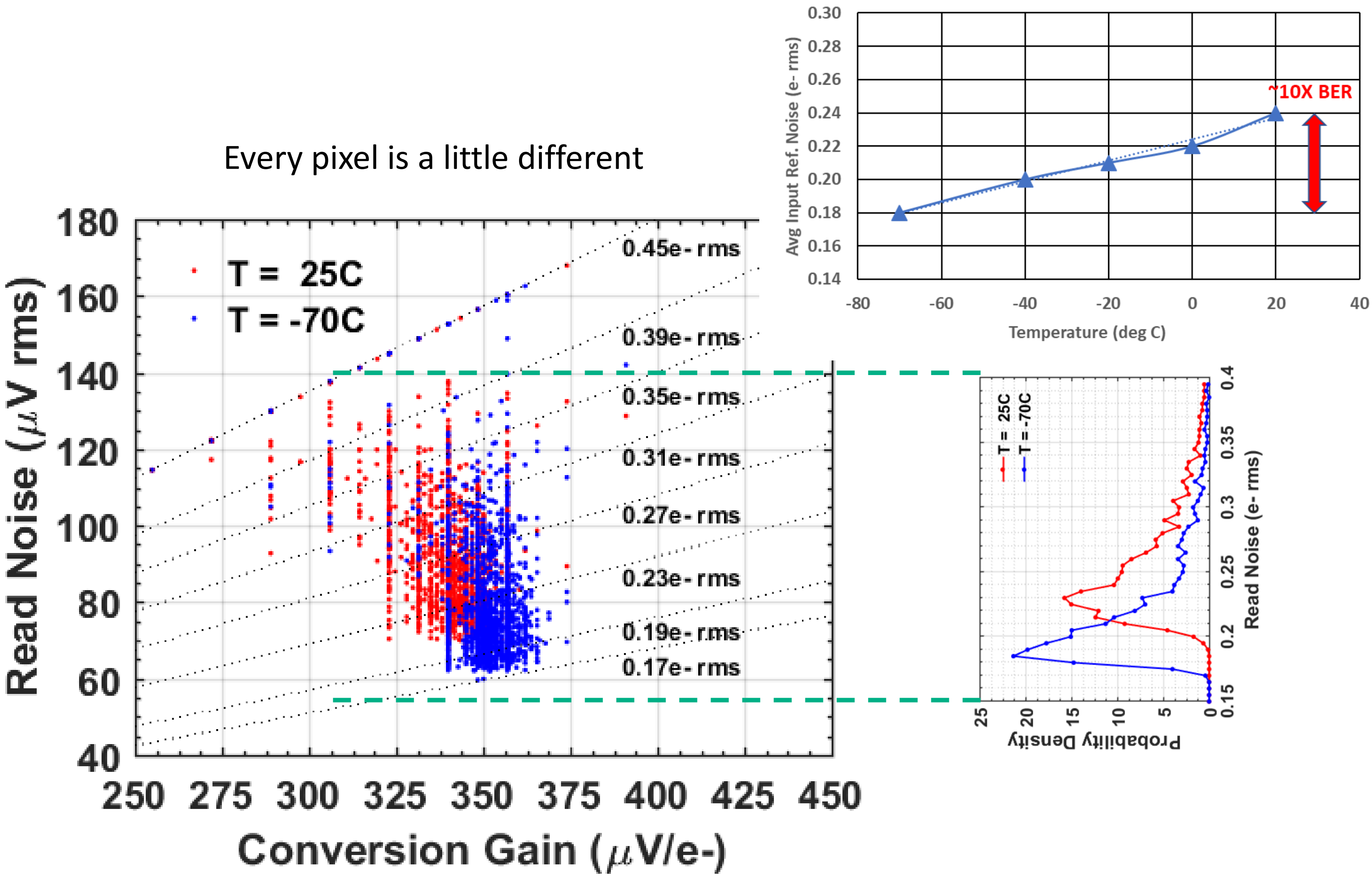




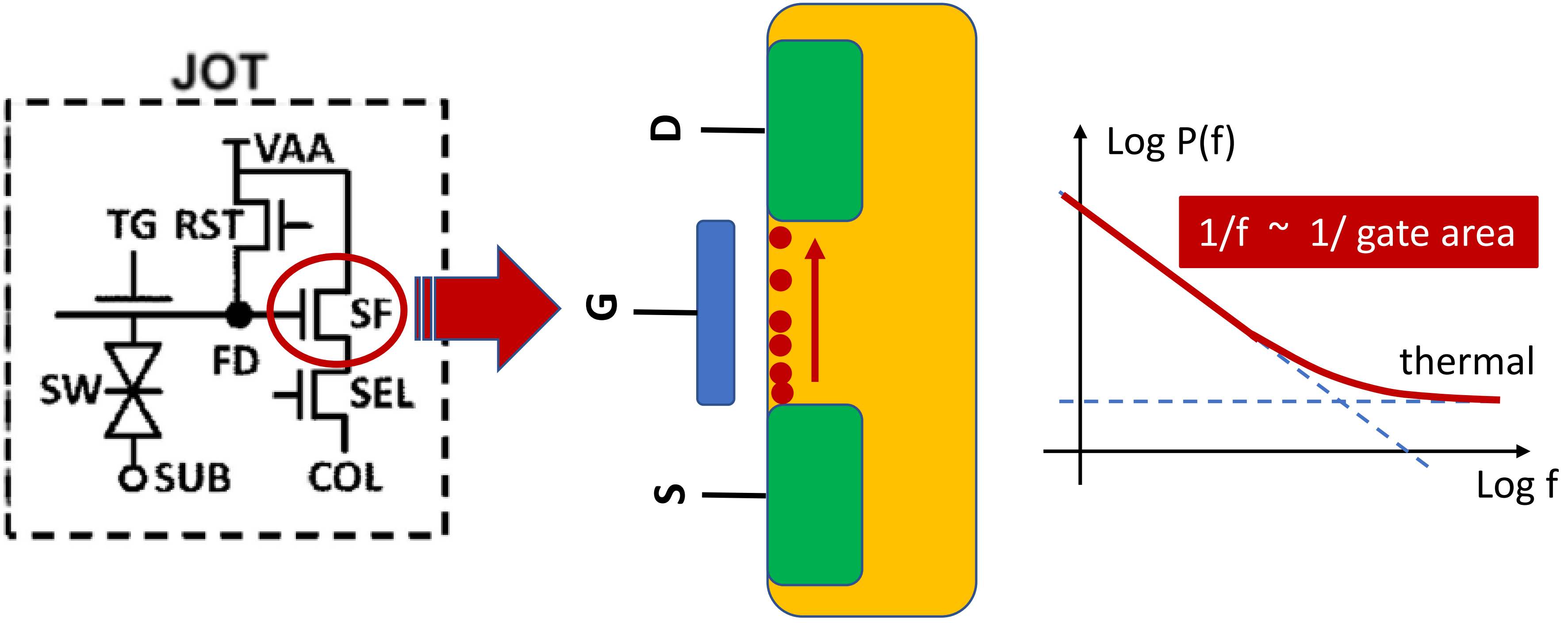
Average Dark Current -20C to 60C

Cooling to -70C
Reduces Read Noise and Improves CG

Every pixel is a little different



Noise in first transistor is critical



1/f Noise Modelling Review

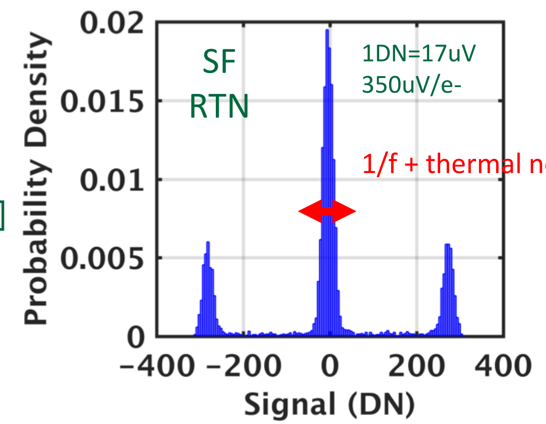
- Hooge's mobility fluctuation model
  Phonon-scattering-induced mobility fluctuation.

Empirical and bulk

- McWhorter's number fluctuation model
  Carrier number fluctuation, interface traps.

- Berkeley unified model
  Number fluctuation and the correlated mobility fluctuation at surface

Probability of occurrence: ~2%

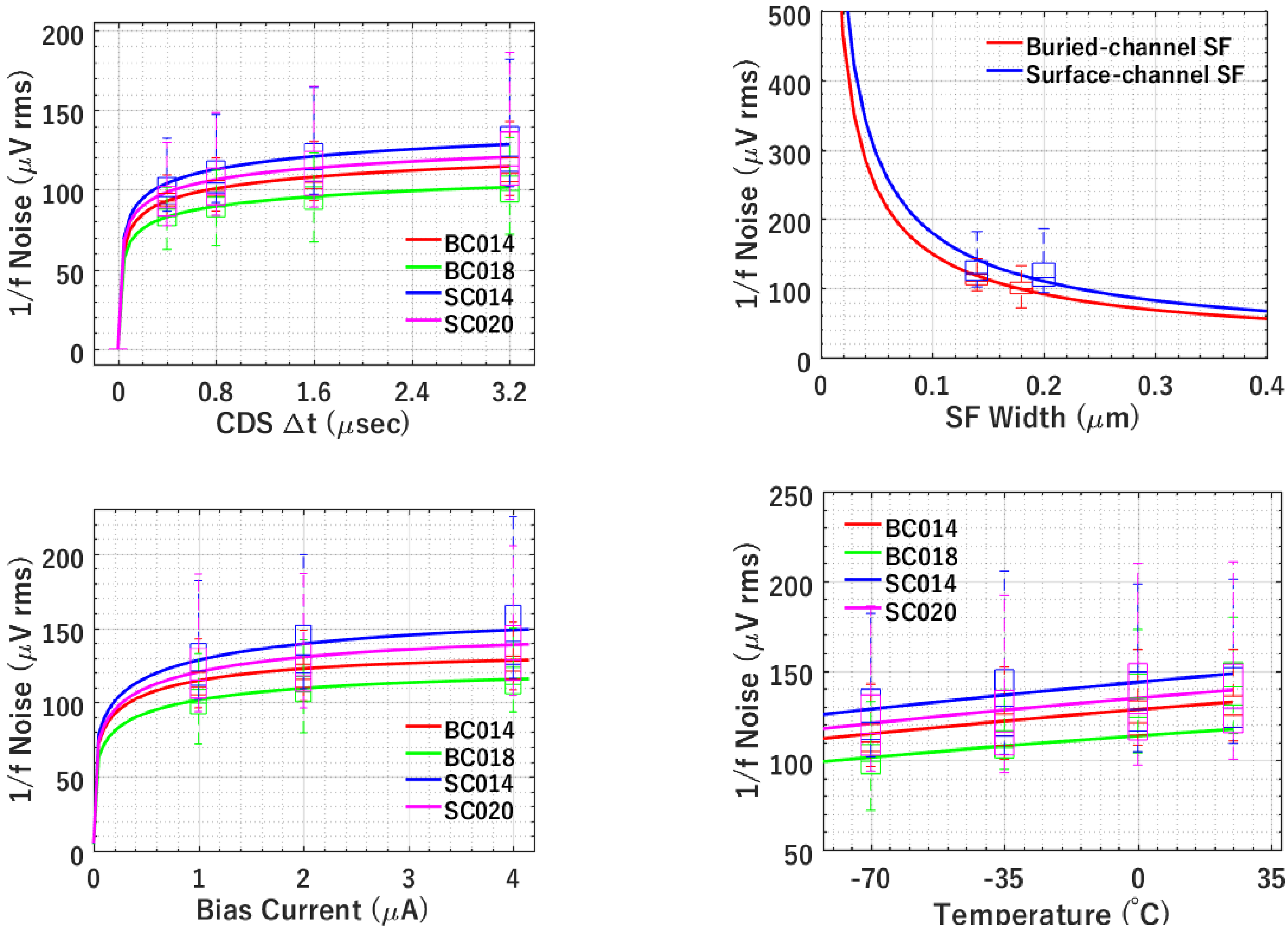


13e-
input referred

1e- trapped at Si-SiO_2 equiv. to 13e- on gate!

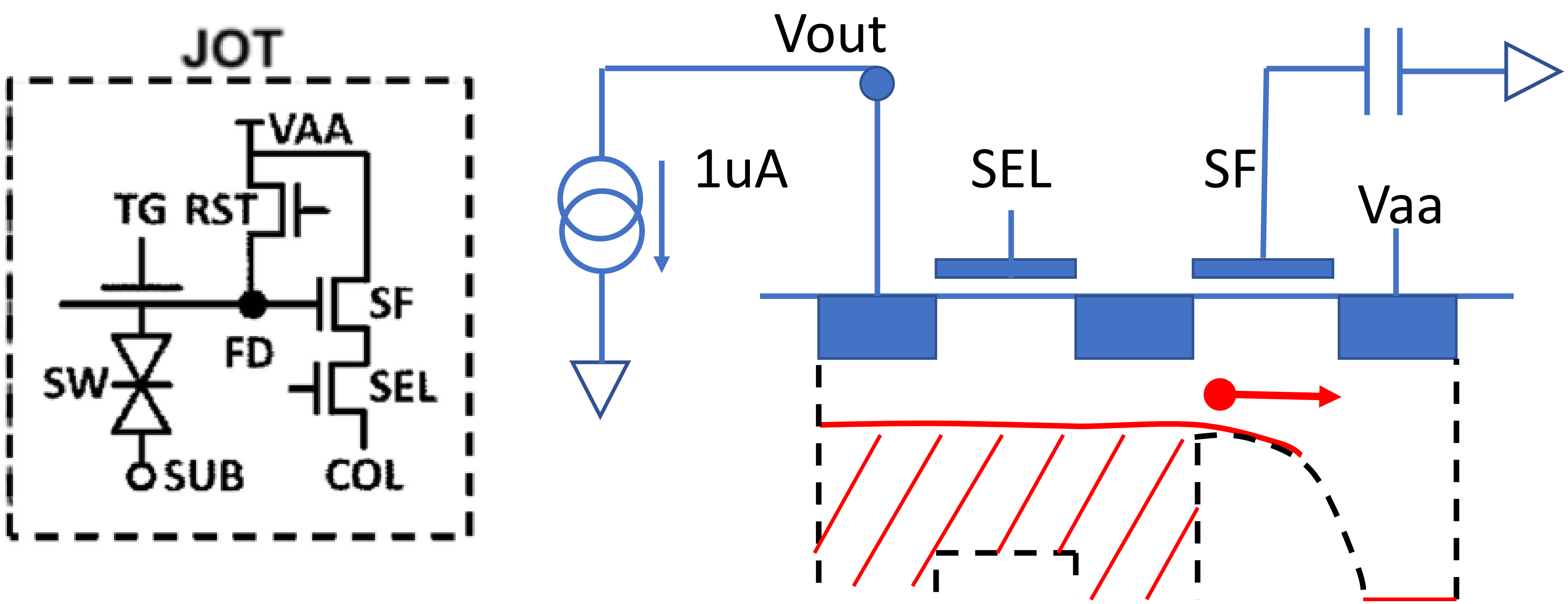
At 0.14x0.27um gate area, expect 1-5 traps per MOSFET if $N_{IT} \cong 1\text{x}10^{10}$ traps/cm^2

1/f Noise versus CDS, Bias Current, SF Size, and Temperature and Model (mostly Hooge)



Deng et al, 2019

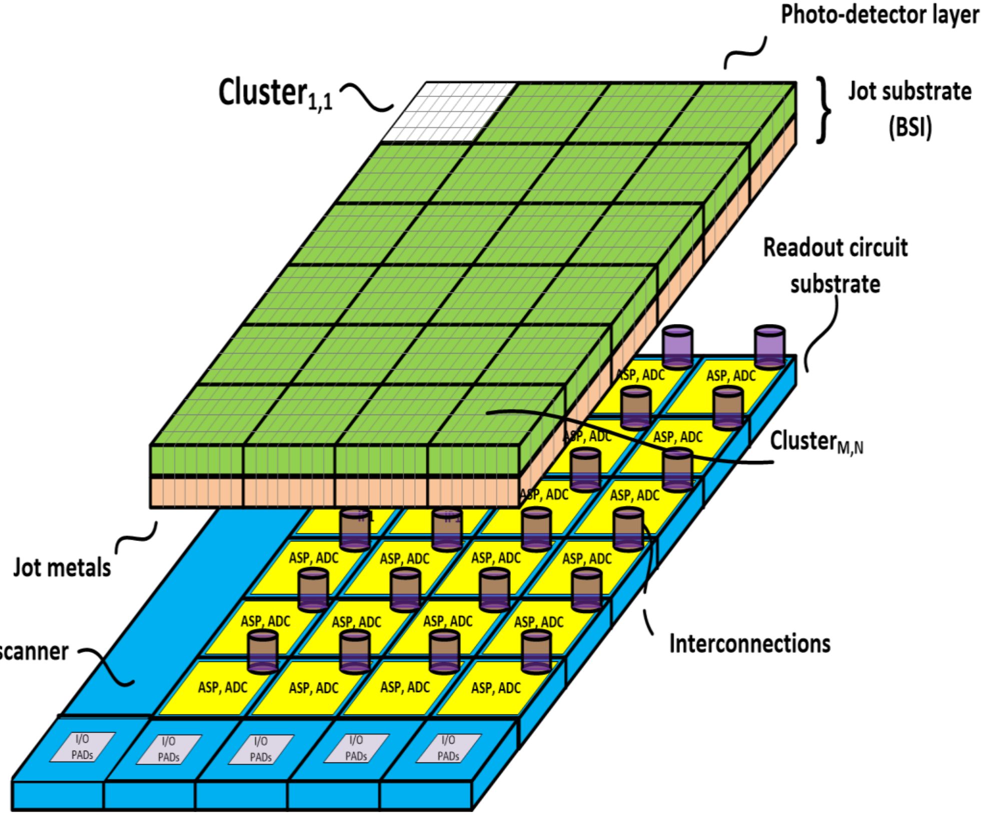
Physical Origin of Noise Discussion

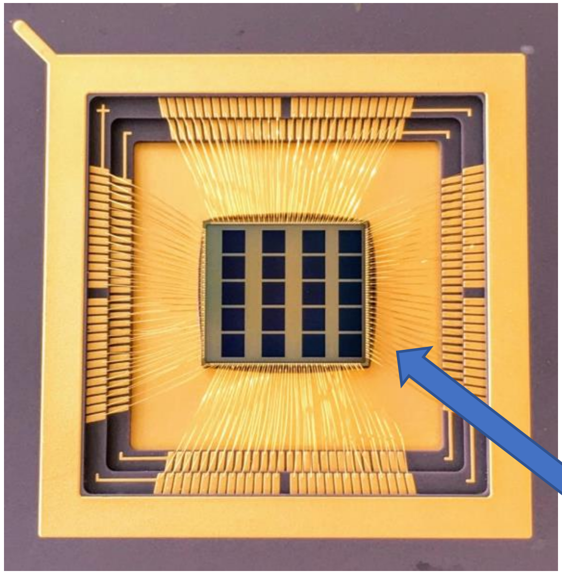


- Changing SF transistor type and size changes 1/f noise
- Number fluctuation? almost no traps, and RTN huge
- Mobility fluctuation? ~< 10 psec transit time, ballistic?
- Once carriers enter SF at source, how is Vout impacted?
- What mechanism gives rise to microsecond fluctuations?
- Why sharp cutoff of noise histogram at lower “bound?”

20 Mpixel single-photon detector array

- Process technology: TSMC CMOS BSI 45nm/65nm 2-layer stacking
- Cluster parallel readout architecture for low power and modularity
- 20 different 1Mpixel arrays on test chip
- Readout Variation:
  - ➢ Analog
  - ➢ Single-bit Digital
- Pixel: 1.1µm 1024x1024
- Pixel variation: TPG, PTR, JFET





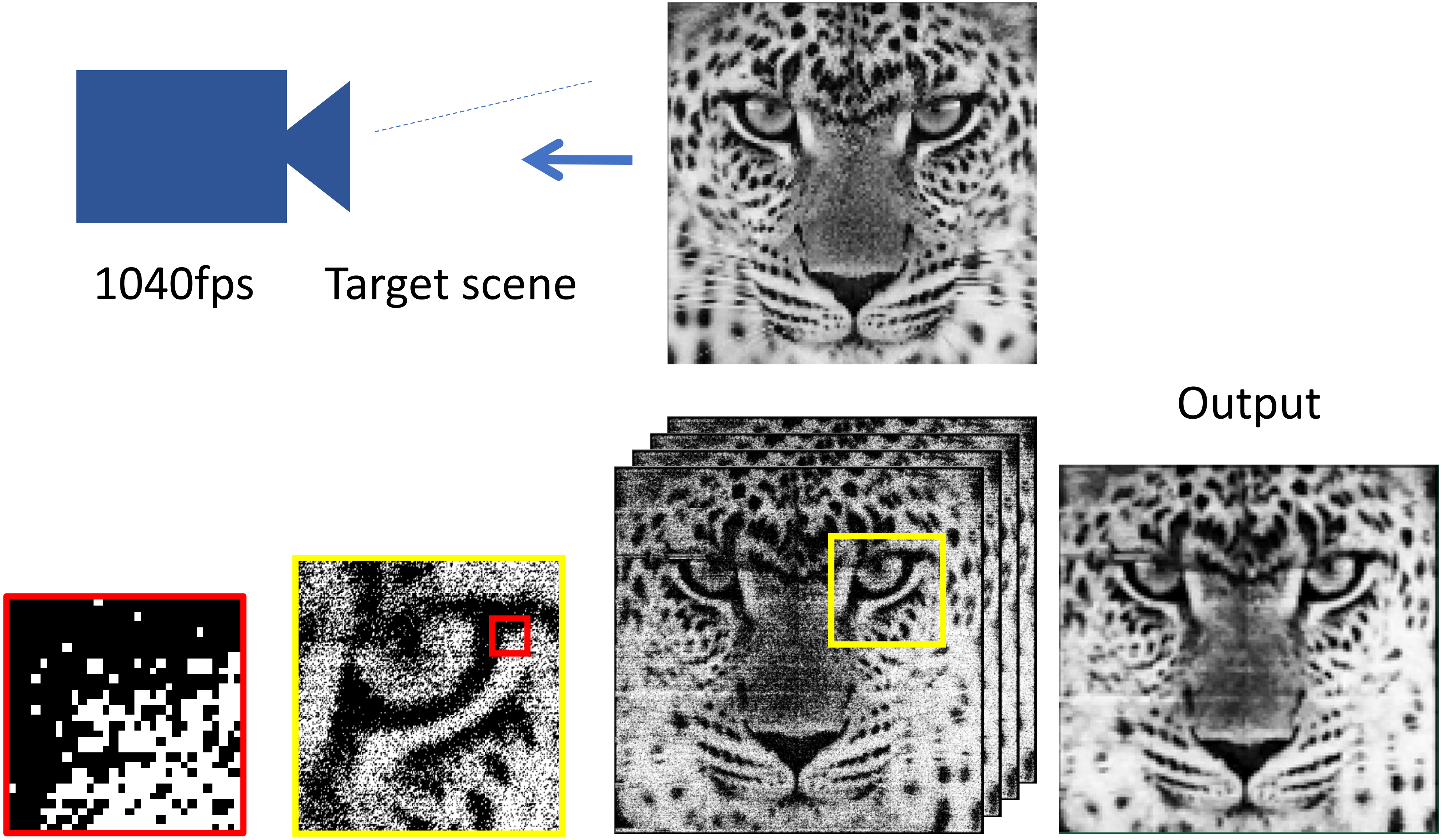
20 Mpixel single photon detector array

Summary of Measured Results
1Mpixel 1b QIS Digital Subarray at Room Temp

Process	45nm (jot layer), 65nm (ASIC layer)
VDD	1.8V & 2.5V (Analog, digital and array), 3V & 2.2V (I/O pads)
Jot type	BSI Tapered Pump Gate 2-Way Shared RO
Jot pitch	1.1µm
BSI Fill Factor	~100%
Quantum Efficiency	79% @ 550nm
Conversion gain on column	345µV/e-
Input Referred Noise	0.22e- r.m.s.
Corresponding BER	~1%
Avg. Dark current (RT)	0.16e-/s
Equiv. Dark Count Rate (RT)	0.07Hz/jot

Equiv. PD Dead Time		<0.1%
Array		1024 (H) x 1024 (V)
Field rate		1040fps
ADC sampling rate		4MSa/s
ADC resolution		1 bit
Output data rate		32 (output pins) x 34Mb/s = 1090Mb/s
Package		PGA with 224 pins
Power	Array	2.3mW
	256 ADCs	7.5mW
	Addressing	4.1mW
	I/O pads	3.7mW
	Total	17.6mW
FOM ADC		6.9pJ/b

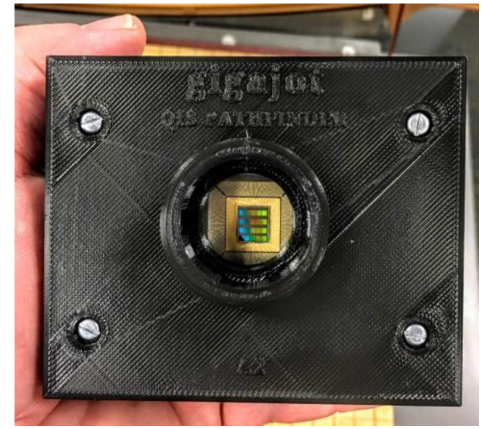
1Mjot prototype QIS experimental results



Gigajot spinoff (2017)

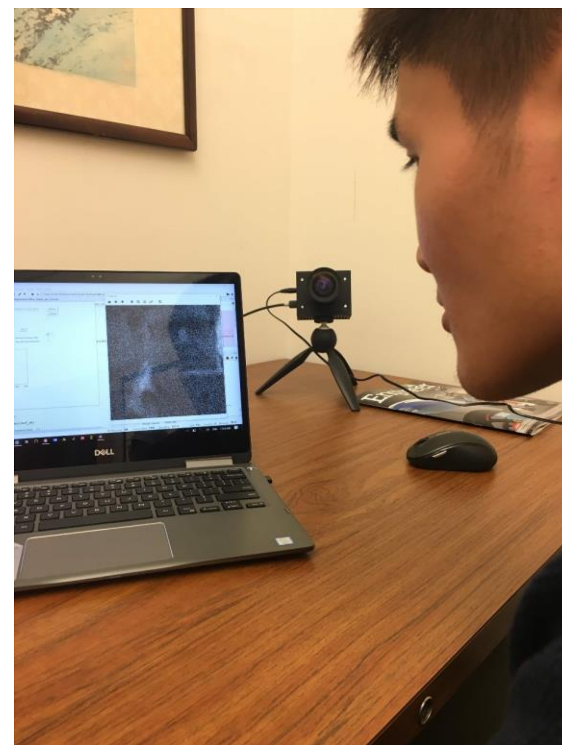

Saleh Masoodian


Jiaju Ma

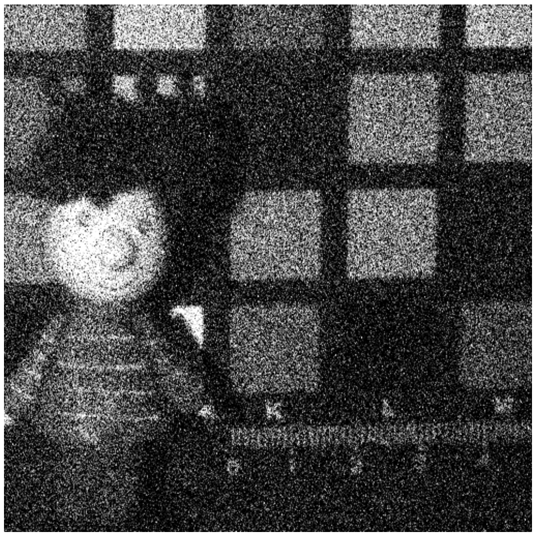


QIS great for low light, high resolution imaging and photon-number resolving systems

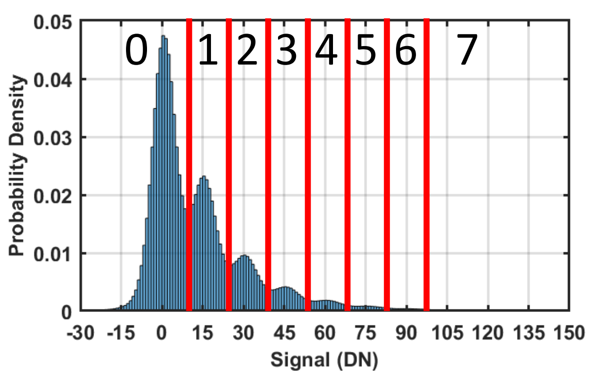
- Security systems
- Low light vision
- Internet of things (IOT)
- Biological imaging
- Astronomy
- Quantum Cryptography
- Photography
- Cinematography

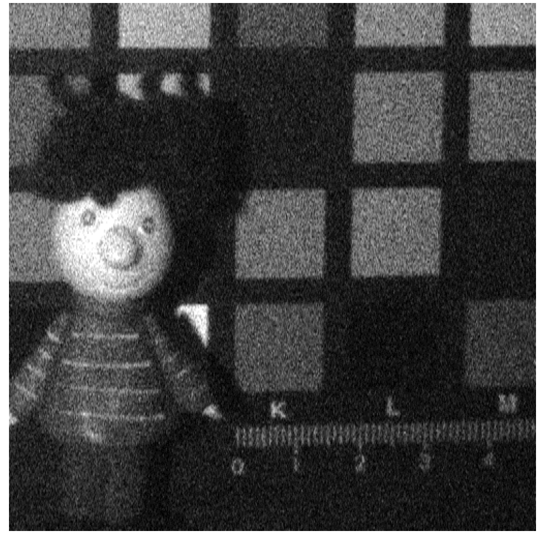


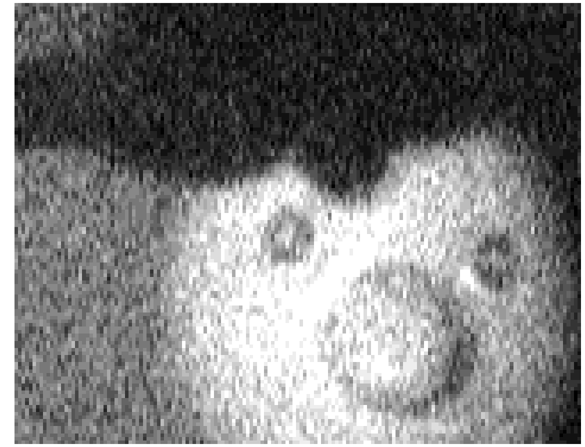
1Mpixel 3b QIS Image
Exposure of 0.87e-/pixel average



Raw image and Histogram



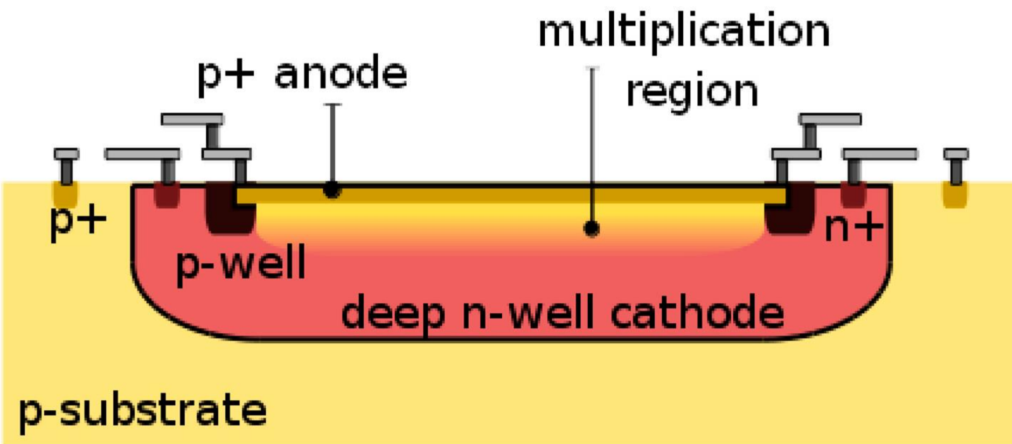


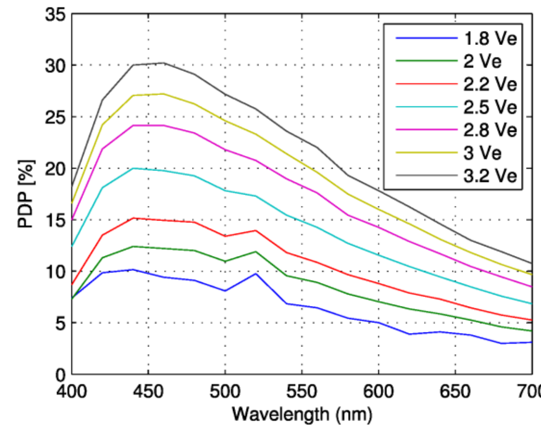


2x2x2 cubicle sum only

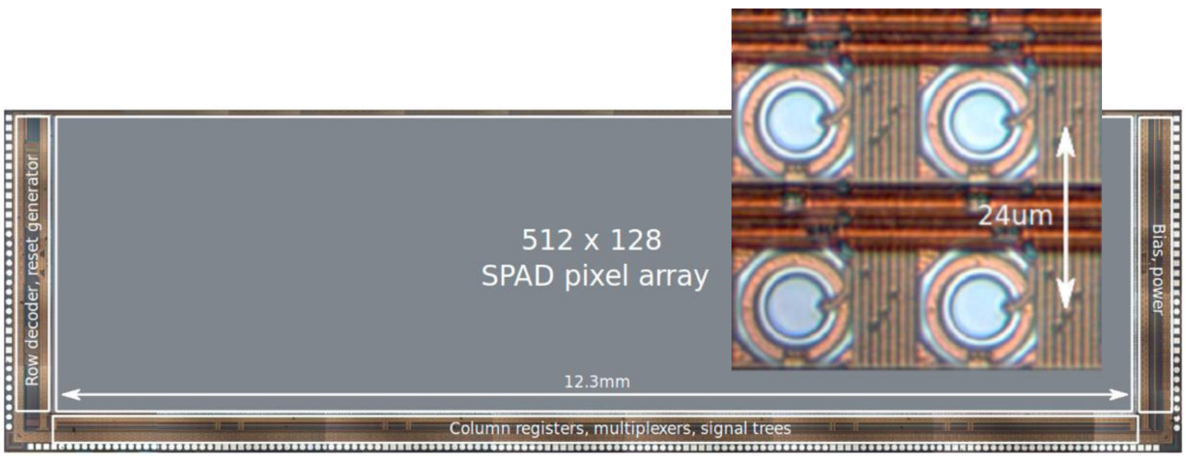
2x2x2 cubicle denoise

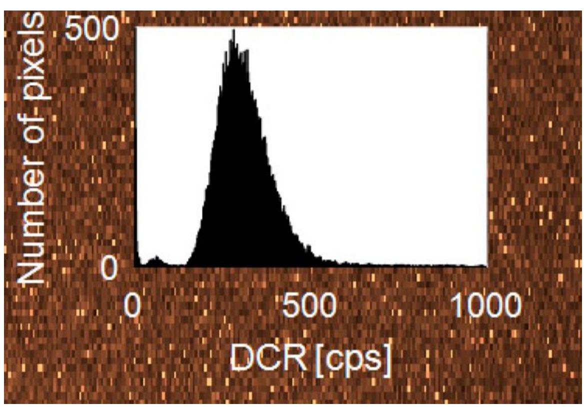
Single Photon Avalanche Detectors (SPADS)





(a)





Room temperature

Photon-Counting Arrays for Time-Resolved Imaging
by I. Michel Antolovic, Samuel Burri, Ron A. Hoebe, Yuki Maruyama, Claudio Bruschini and Edoardo Charbon
Sensors 2016, 16(7), 1005; doi:10.3390/s16071005

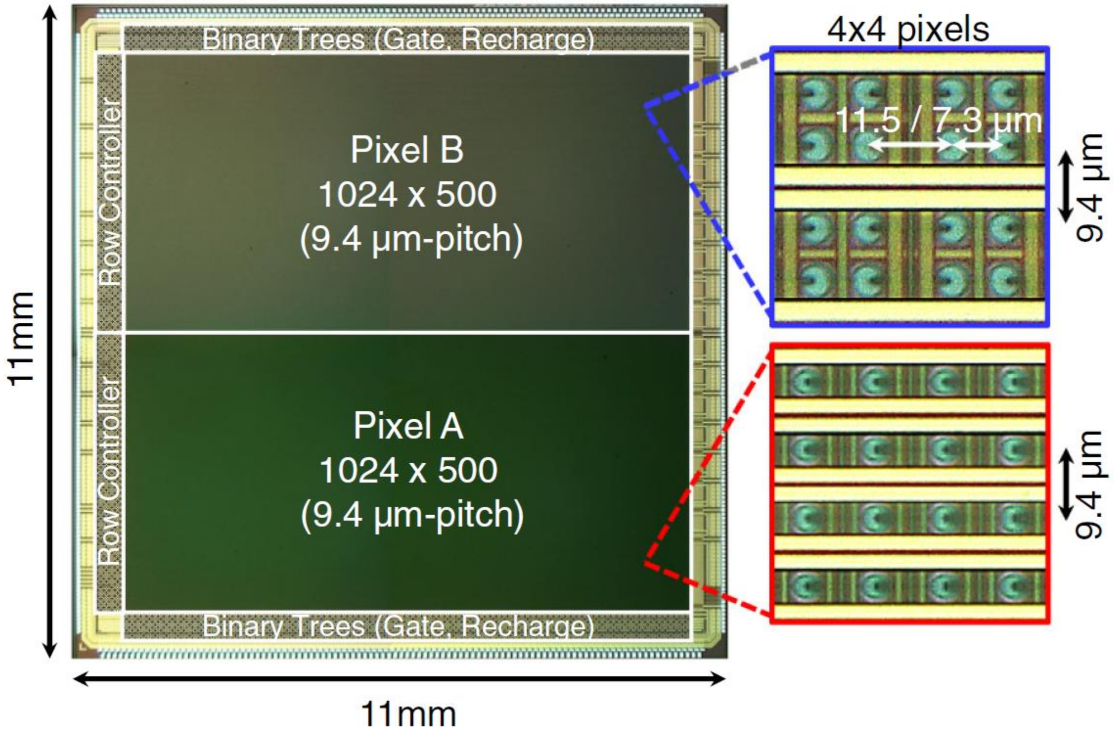
Issues with SPADs for QIS application

SPADs use avalanche multiplication for gain

- High internal electric fields
- Higher operating voltages (15-20V)
- Larger pixels (8-25um)
- High dark count rates (100-1000Hz)
- Dead time
- Low fill factor (low PDE <50%)
- Low manufacturing yield
- Small array sizes (below 0.1M jots)

But, SPADS are excellent for time resolved photon detection

"1/2 Mpix" SPAD-QIS by Canon



	This Work (Pixel A/B)
Process technology	180 nm CMOS
Chip size (mm^2)	11 × 11
Sensor resolution	1024 × 1000
Pixel size (µm)	9.4
Fill factor (%)	7.0/13.4
Pixel output bit depth	1b
No. of pixel transistors	7/5.75
Median DCR (cps)	0.4/2.0 (V_{ex} = 3.3 V)
Max. PDP (%)	10.5/26.7 (V_{ex} = 3.3 V)
Max. PDE (%)	0.7/3.6 (V_{ex} = 3.3 V)
Cross talk (%)	0.17/0.39 (V_{ex} = 3.3 V)
Min. gate length (ns)	3.8
Frame rate (fps)	24,000 (1b)
Power dissipation (W)	0.284/0.535

Kazuhiro Morimoto, Andrei Ardelean, Ming-Lo Wu, Arin Can Ulku, Ivan Michel Antolovic, Claudio Bruschini, and Edoardo Charbon, "Megapixel time-gated SPAD image sensor for 2D and 3D imaging applications," Optica 7, 346-354 (2020)

Comparison

Metric	CIS-QIS Actual to date	CIS-QIS Estimated +3 years	SPAD-QIS Actual to date	SPAD-QIS Estimated +3 years
Pixel Size	1.1um	1.1-10um	9.4um	3um
Array Size	20x1Mpix	>100Mpix	2x(1/2)Mpix	1-10Mpix
1Mpix size	1.2mm^2	1.2mm^2	121.0mm^2	9mm^2
Fill Factor	>90%	>90%	13%	>13%
PDE	>70%	>70%	3.6%	>3.6%
Frame Rate	1000fps	~1000fps	24,000fps	24,000fps
Read Noise	0.22e- rms	<0.22e- rms	<0.15e- rms	<0.15e- rms
Multibit	Yes (slower)	Yes (fast)	No	No
Flux Capacity	0.8ke-/s/um^2	800ke-/s/um^2	0.3ke-/s/um^2	3ke-/s/um^2
Dark Current	<0.1 e-/s	<0.1e-/s	2.0e-/s	>2.0e-/s
Power	20mW 1b	<200mW 1b	535mW 1b	>535mW 1b
Color	Yes	Yes	No	Yes

Estimates by EF   CIS-QIS based on Gigajot publications   SPAD-QIS based on Canon/EPFL publications

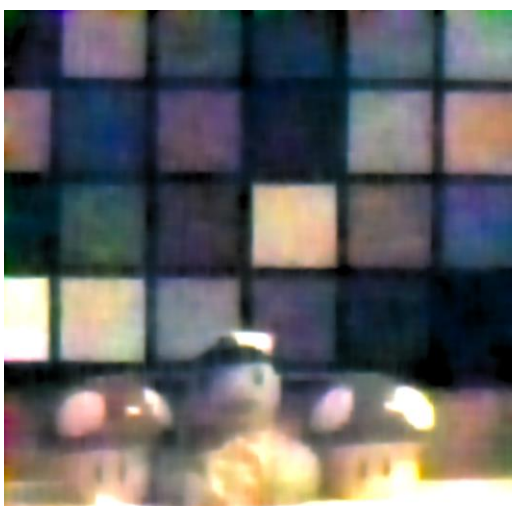
Color Progress

1Mpix, 1x1x1 cubicle

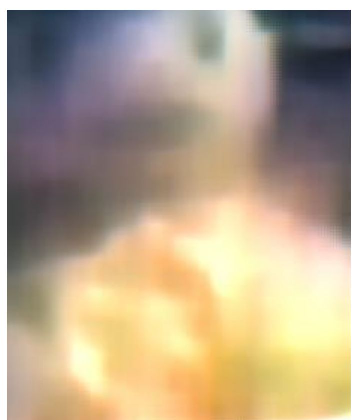
Standard Pipeline

Neural Network

Average light
1.8e- /pixel



Average light
0.7e- /pixel



Elgendy 2019

Image Classification in the Dark using Quanta Image Sensors

Abhiram Gnanasambandam, and Stanley H. Chan, *Senior Member, IEEE*

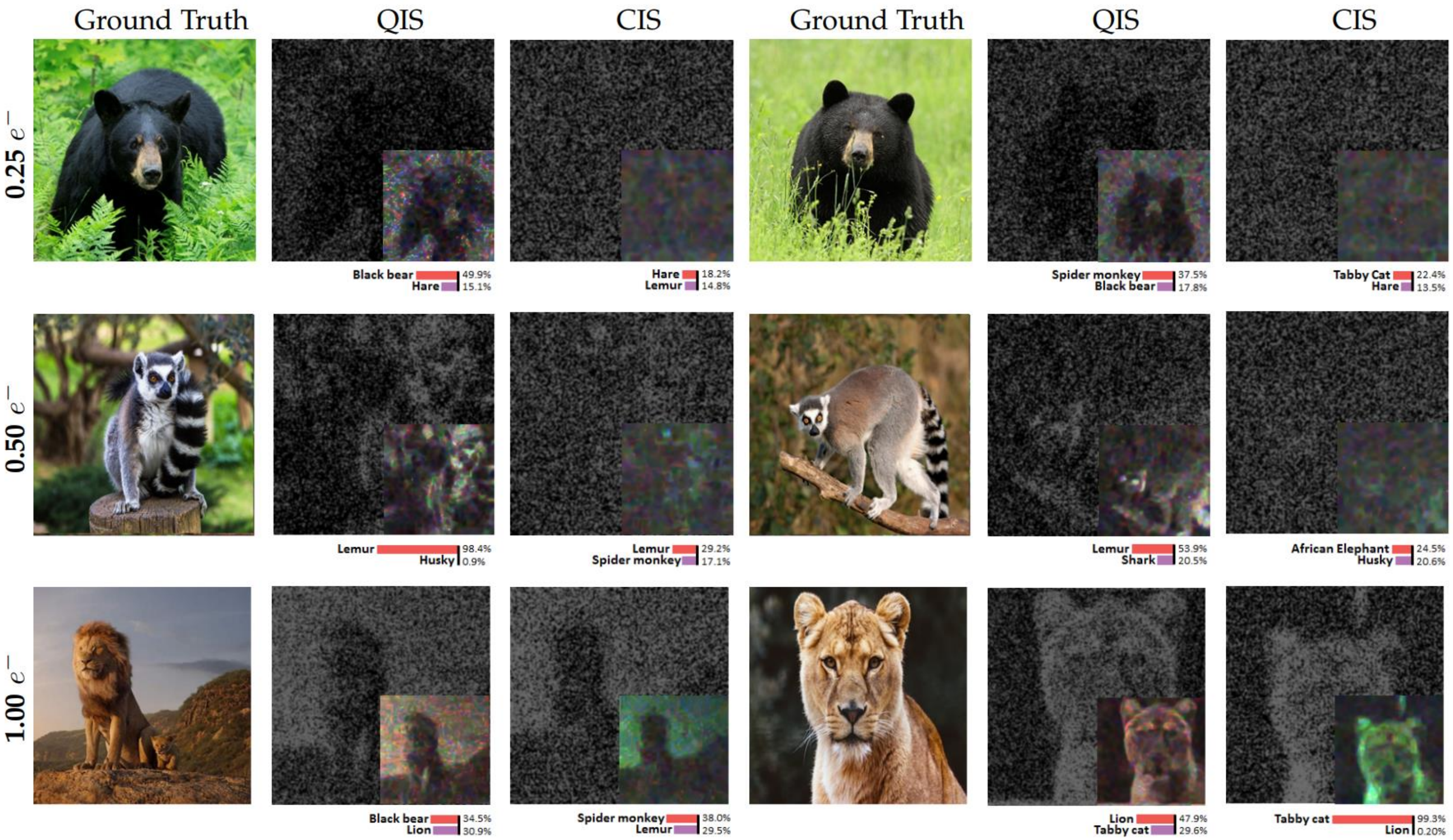


Fig. 10. **Real Image Results**. This figure shows raw Bayer data obtained from a prototype QIS and commercially available CIS, and how they are classified using our proposed classifier. The inset images show the denoised images (by [42]) for visualization. Notice the heavy noise at 0.25 and 0.5 ppp, only QIS plus our proposed classification method can produce the correct prediction.

https://arxiv.org/pdf/2006.02026.pdf

Quanta Burst Photography

SIZHUO MA and SHANTANU GUPTA, University of Wisconsin-Madison, USA
ARIN C. ULKU, CLAUDIO BRUSCHINI, and EDOARDO CHARBON, EPFL, Switzerland
MOHIT GUPTA, University of Wisconsin-Madison, USA

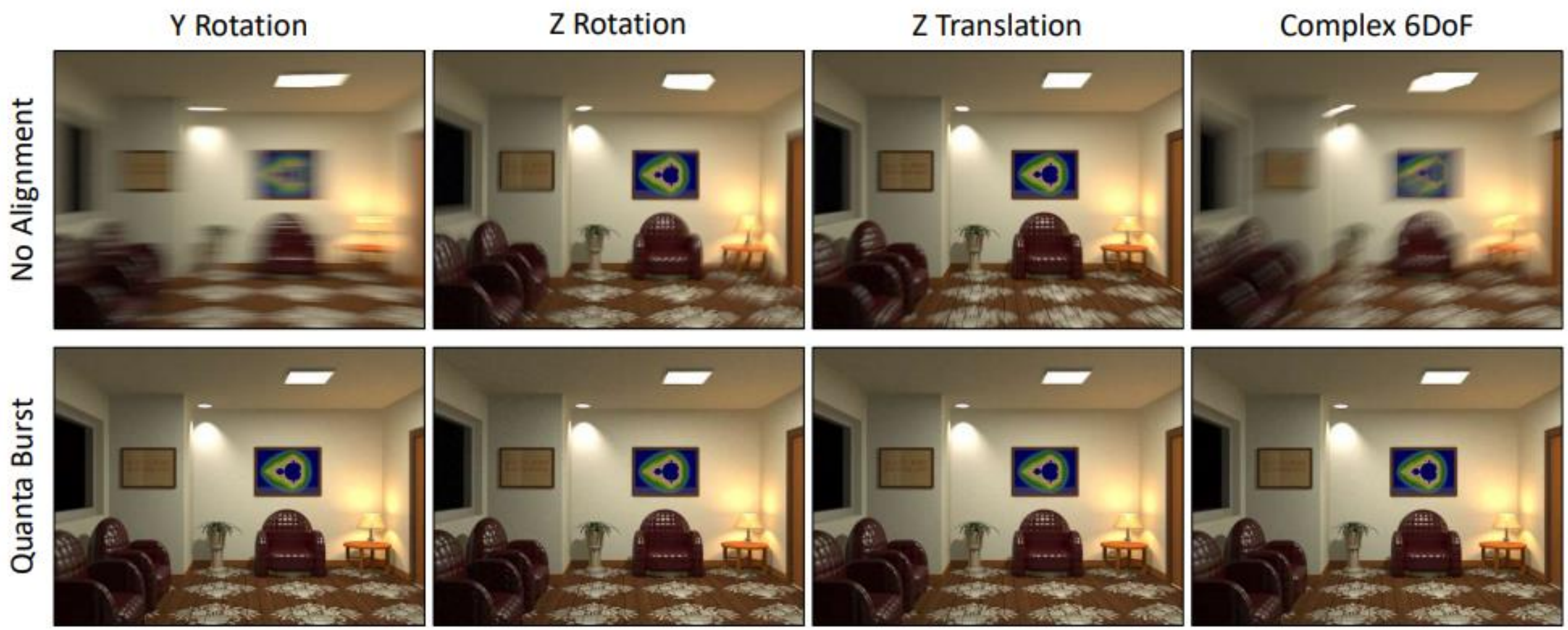
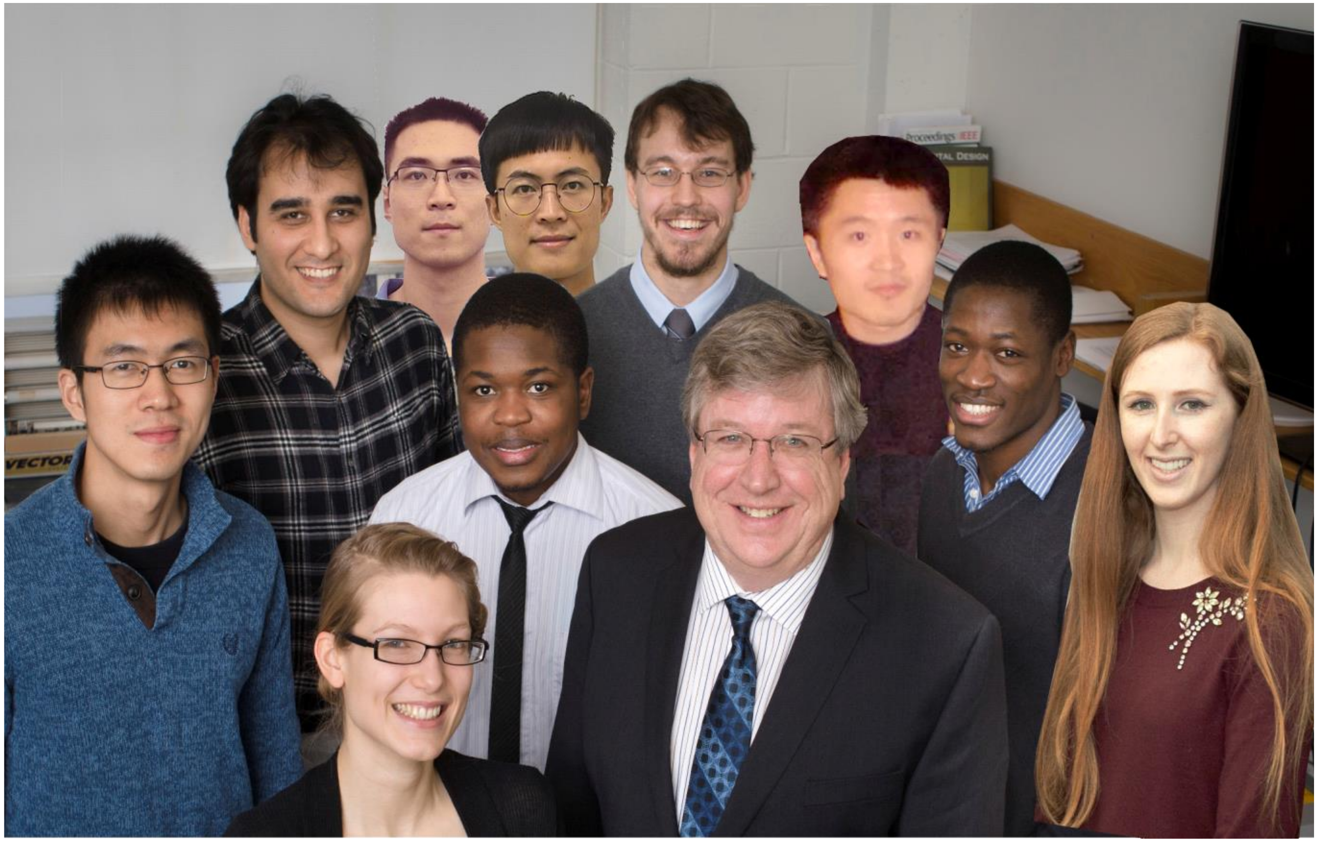


Fig. 8. **Performance for different types of camera motion.** We simulate four different types of motion for the same scene: rotation around y-axis, rotation around z-axis, translation along z-axis and a random 6 degrees-of-freedom (DoF) trajectory. In all cases, the proposed algorithm is able to align the binary images and generate high-quality images.

July 2020 ACM Transactions on Graphics, https://doi.org/10.1145/3386569.3392470.

Graduate Student Group at Dartmouth



L-R: Song Chen, Saleh Masoodian, Rachel Zizza, Zhaoyang Yin, Donald Hondongwa, Wei Deng, Dakota Starkey, Eric Fossum, Jiaju Ma, Leo Anzagira, Kaitlin Anagnost
(not pictured: Xin Yue)