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Photon Counting Without Avalanche Multiplication - Progress on the Quanta Image Sensor

Eric R. Fossum

March 16, 2016

Image Sensors 2016 Europe

London, England, UK

Group at Dartmouth

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  - Prof. Kofi Odame
  - Mike Guidash (Rambus)
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  - Prof. Yue Lu (Harvard)
  - Prof. Atsushi Hamasaki (Hiroshima)
  - Mr. Ryohei Funatsu (NHK)
- QIS work supported, in large part, by
  - Rambus Inc.

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Quanta Image Sensor
"Count Every Photon"

- Original goal for QIS was to take advantage of shrinking pixel size and make a very tiny, specialized pixel ("jot") which could sense a single photoelectron.
- Jots would be readout by scanning at a high frame rate to avoid likelihood of multiple hits in the same jot and loss of accurate counting.
- Image pixels could be created by combining jot data over a local spatial and temporal region using image processing.
- The first proposed algorithm was the "digital film sensor" using a "grain" and "digital development" construct.

E.R. Fossum, *What to do with Sub-Diffraction-Limit (SDL) Pixels? – A Proposal for a Gigapixel Digital Film Sensor (DFS),* Proc. Of the 2005 IEEE Workshop on Charge-Coupled Devices and Advanced Image Sensors, Karuizawa, Japan, June 2005

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Quanta Image Sensor Architectural Elements

- Photon counting pixels
  - Actually photoelectron counting pixels
  - Accurately discriminate between 0 and 1 photoelectron – single-bit QIS
  - Or, between 6 and 7 photoelectrons – multibit QIS
- Oversampled sub-diffraction-limit pixel size
  - 500nm pixel pitch or smaller is target
- Large number of pixels
  - 100’s Mpixels or Gpixels per sensor.
- High speed readout
  - Example, 1000 fps

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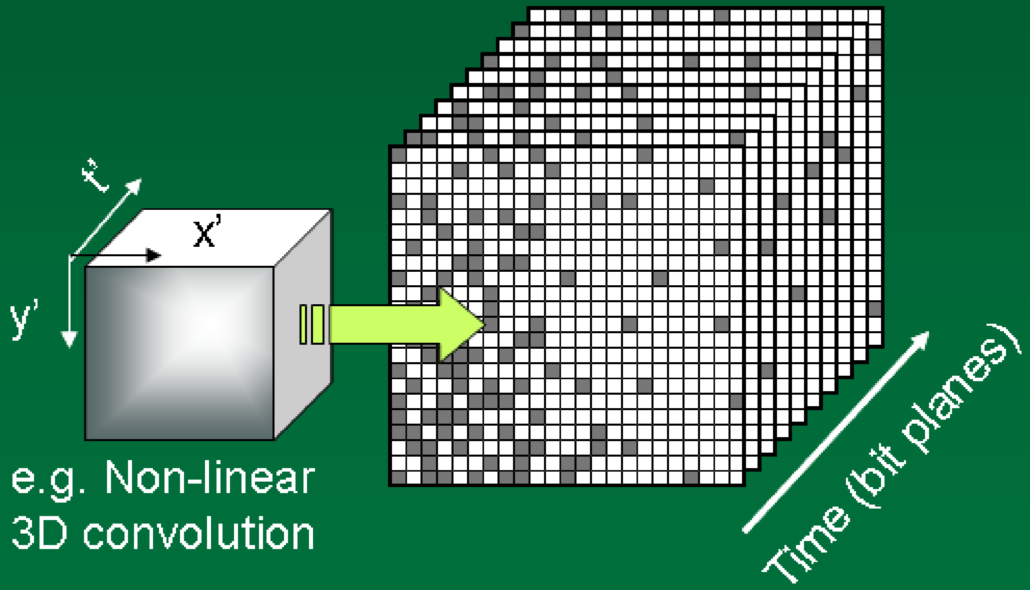
Quanta Image Sensor

- Specialized sensor pixel called “jot” for convenience
- One output image pixel formed from a “cubicle” of sensor jots
- Cubicle size (X, Y and time) flexible and programmable
- Binning can be nearly noiseless



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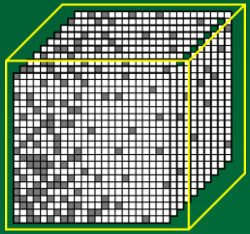
Pixels from Jots (Simulation)

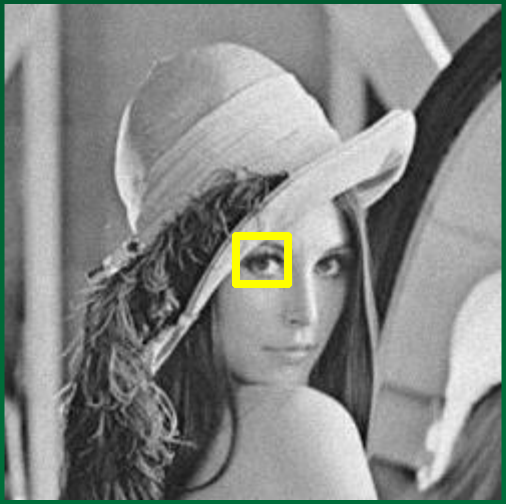


Simplest

$$\sum_{X'Y't'} j(X,Y,t)$$

16x16x16 “cubicle”

$$0 \leq S \leq 4096$$



R. Zizza, *Jots to Pixels: Image Formation Options for the Quanta Image Sensor*, (Dartmouth, 2015)

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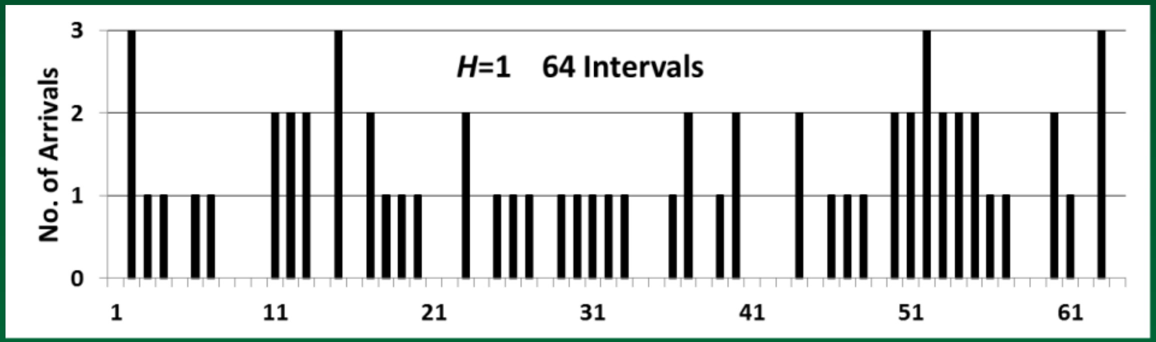
Photon and photoelectron arrival rate described by Poisson process

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 : $M_1 = M \cdot P[k>0]$

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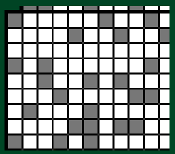
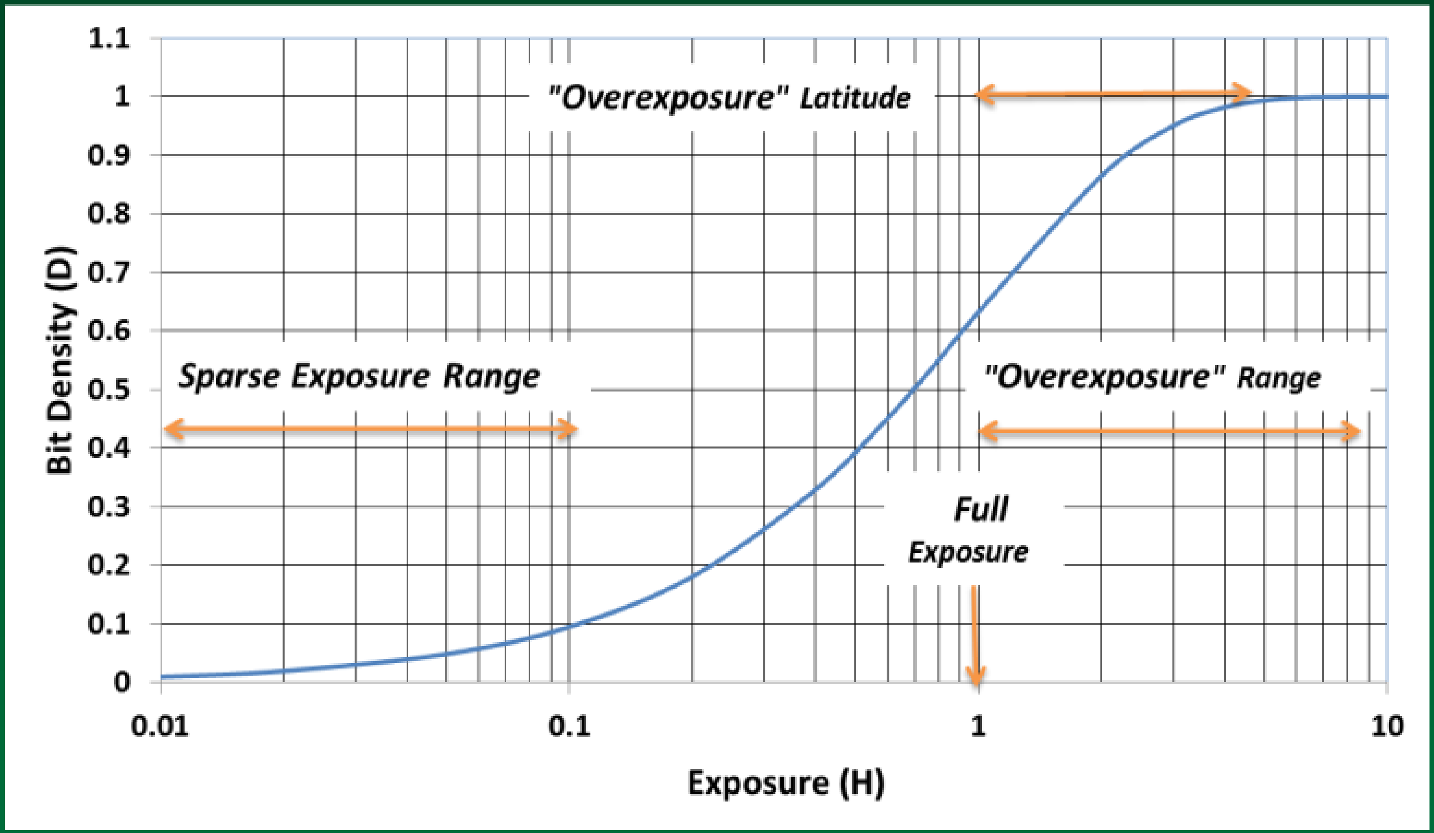
Bit Density



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



$$D \cong H \quad \text{(linear)}$$

Can determine H from measured D

$$\mathrm{H} = \ln\left[\frac{1}{1-D}\right]$$

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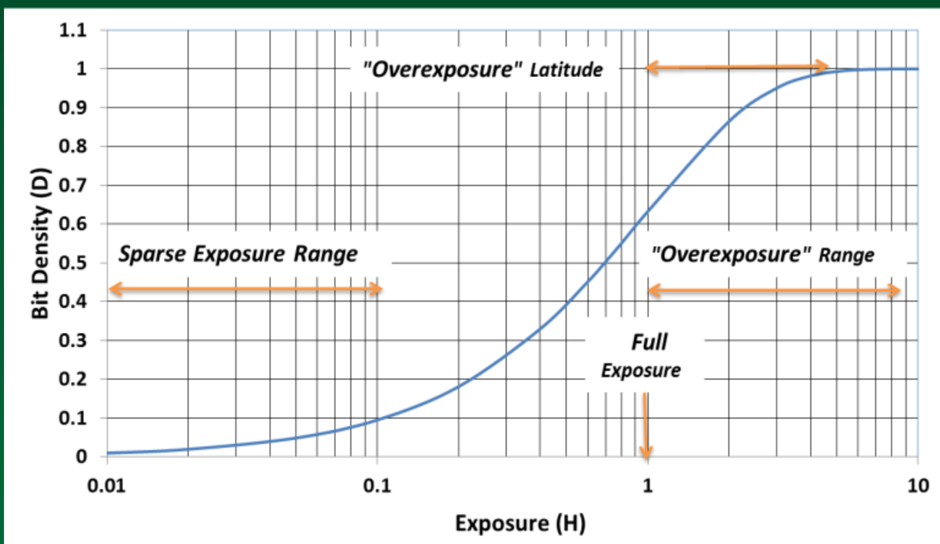
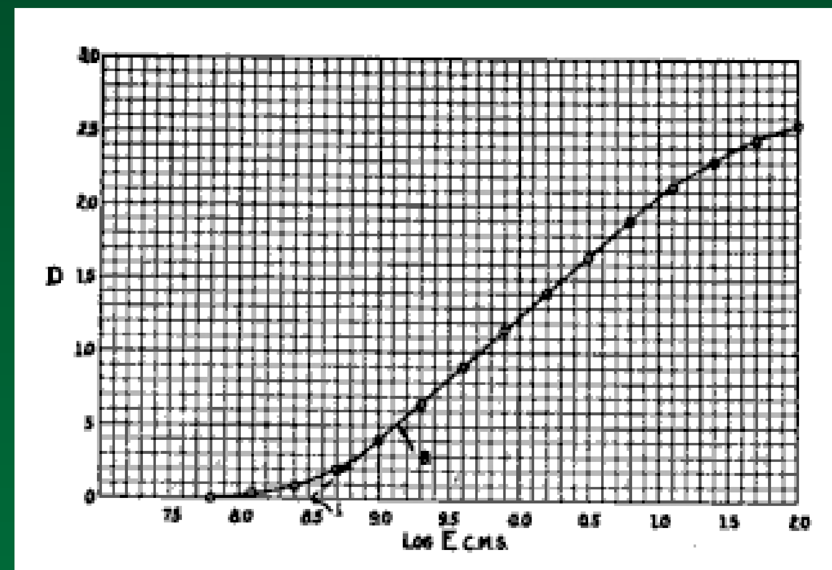
Film-like Exposure Characteristic for Single-Bit QIS

QIS D – log H



Bit Density vs. Exposure

Film D – log H



Film Density vs. Exposure
1890 Hurter and Driffield

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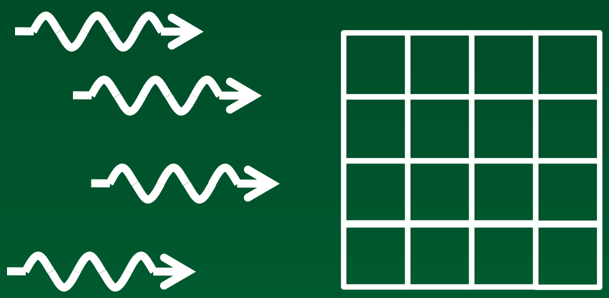
Figure of Merit: Flux Capacity ϕ_w



At the flux capacity, there is an average of one photoelectron per jot

$$\phi_w = jf_r/\sigma\bar{\gamma}$$

$j = jot\ density\ (per\ cm^2)$

$f_r = field\ readout\ rate\ (per\ sec)$

$\sigma = shutter\ duty\ cycle$

$\bar{\gamma} = average\ quantum\ efficiency$

- At 500nm jot pitch, 1000fps, 100% duty cycle and 35% QE, $\phi_w \cong 10^{12}/cm^2s$
- Corresponds to ~100lux (555nm, F/2.8, RT=80%)

➔ Drives high jot density and field readout rate so can handle normal lighting conditions

➔ And improve SNR per sq. cm of sensor area.

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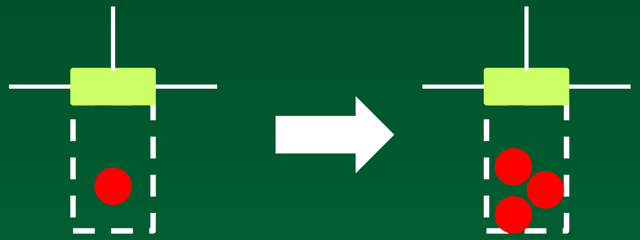
Multi-bit Jot Increases Flux Capacity

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

$$\phi_{wn} = j f_r (2^n - 1)/\sigma \bar{\gamma}$$



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.

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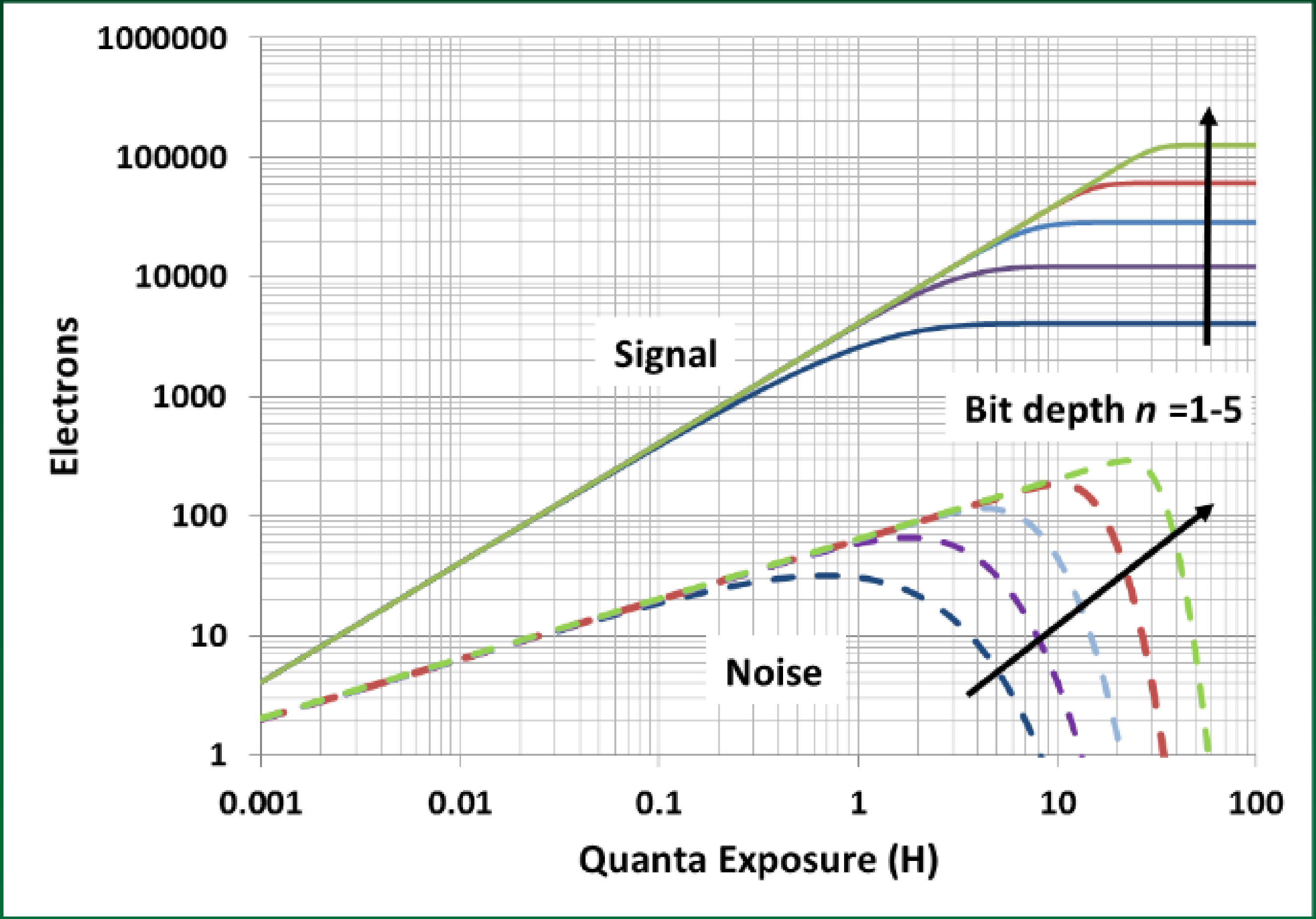
Signal and Noise for Multi-bit QIS



Log signal and noise as a function of log exposure for multi-bit QIS jots with varying bit depth. The signal is the sum over 4096 jots (e.g. 16x16x16). Saturation signal is $4096 \cdot (2^n - 1)$.

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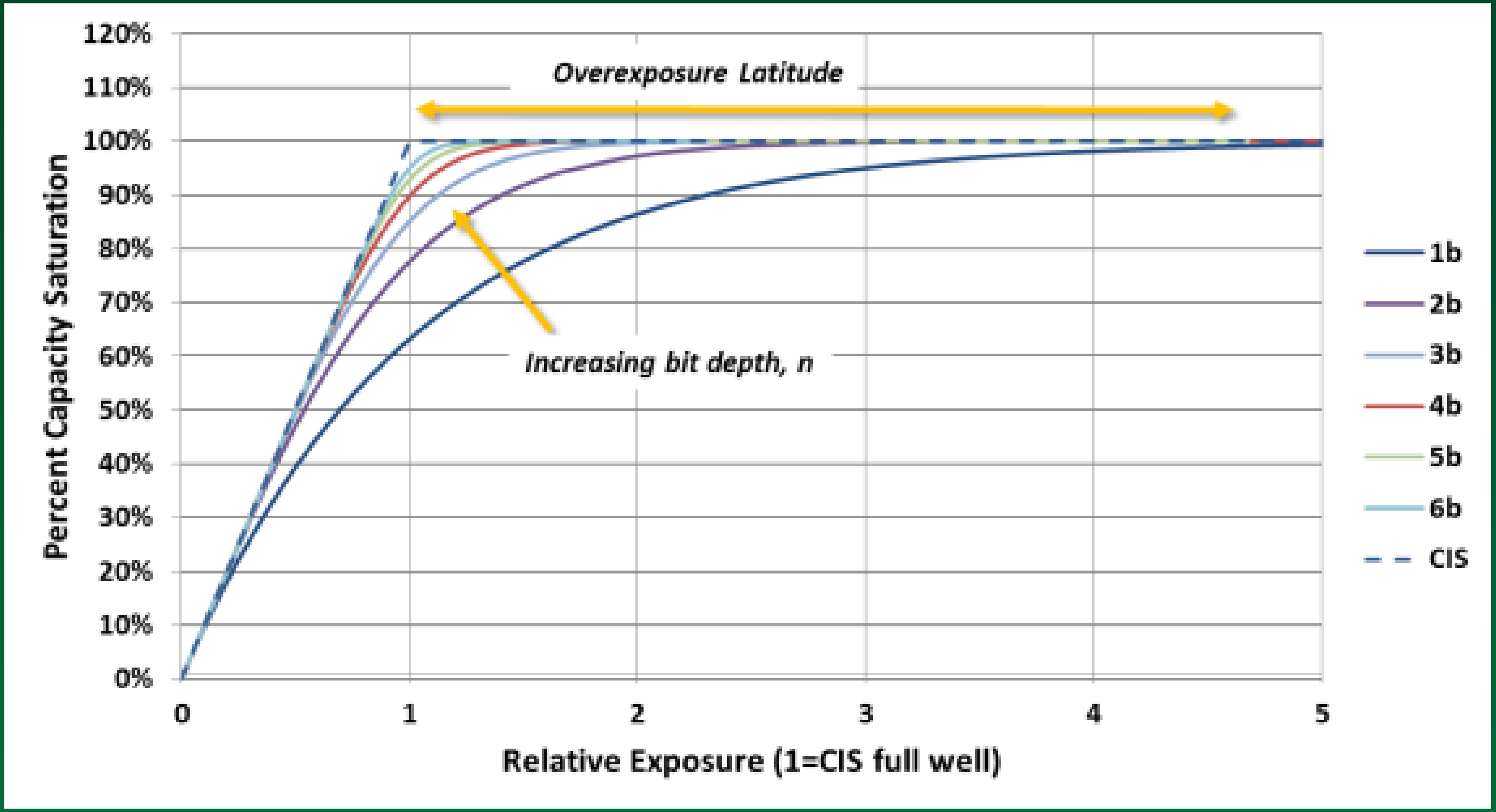
Signal Non-Linearity for Multi-bit QIS



Non-linearity and saturation characteristics of single-bit and multi-bit QIS for 1≤n≤6 bits. For the QIS, the capacity of the full well is given by FW=2^n-1. The relative exposure is the quanta exposure H (in photoelectrons) divided by the full well, and the percent saturation is calculated from the expected number of photoelectrons in the photosite. Generally for the QIS, a “cubicle” in x,y, and t might be summed.

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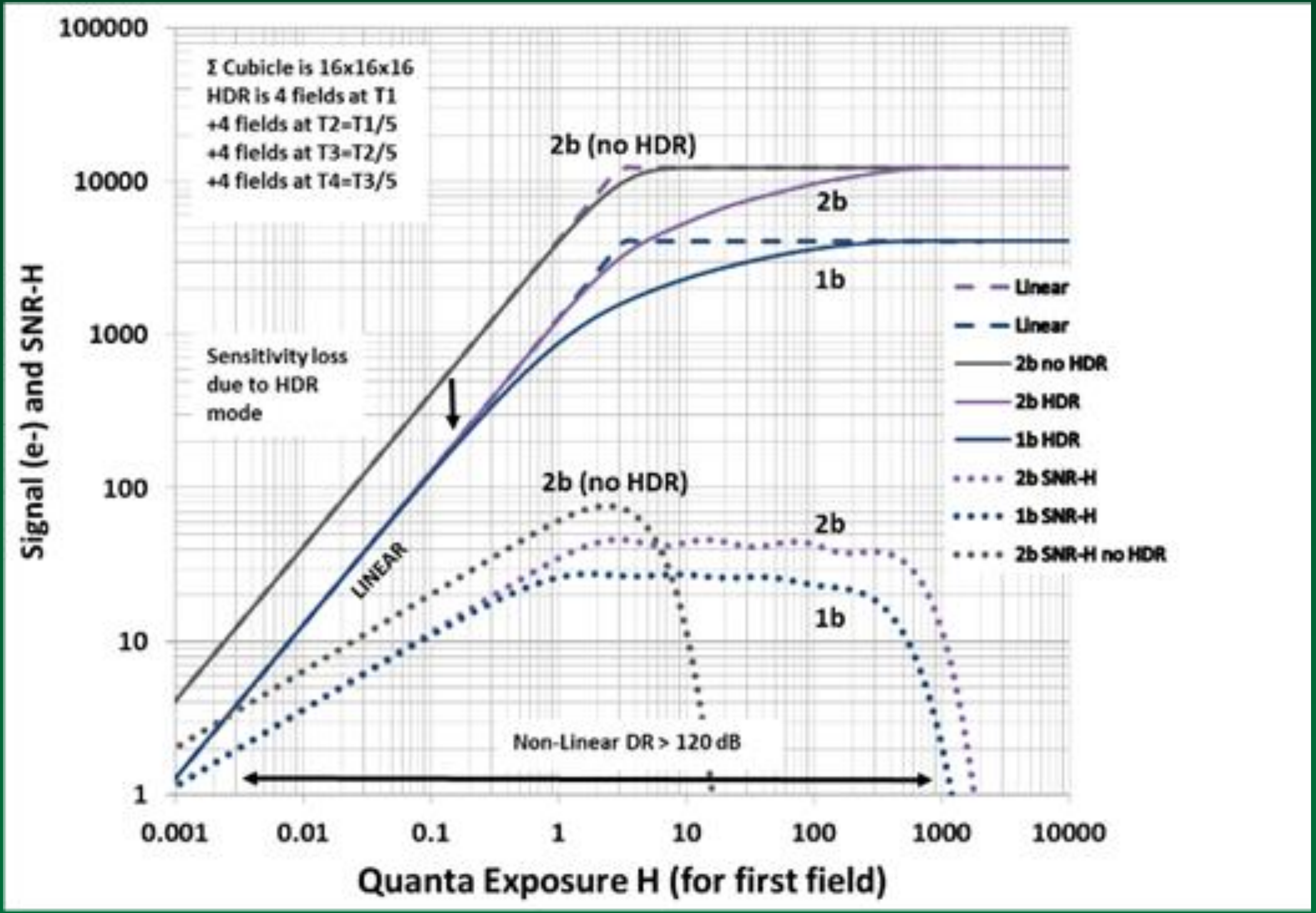
HDR mode for Multi-bit QIS



Comparison of an HDR mode for 1b and 2b QIS. Cubicle is 16x16x16 fields, with 4 different shutter duty cycles. First 4 fields duty cycle is unity, next is 1/5, next is 1/25, and last group of 4 fields is 1/125. Signal is sum of cubicle data

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Possible QIS Applications

- Scientific low light applications
  - Life sciences
  - Astronomy
- Defense and Aerospace
- Encryption
- Consumer photography
- Cinema
- Automotive?
- Mobile? – the billion dollar question
- *“You don’t find killer apps, they find you”*

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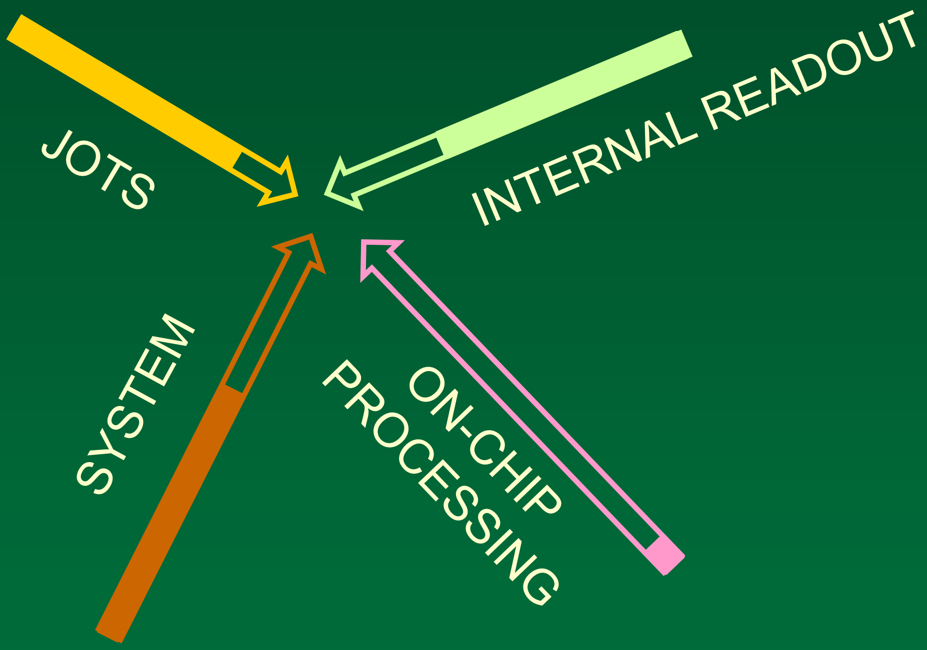
QIS implementation requires Devices, Circuits, and System

Strawman numbers

- <500 nm jot pitch
- Gigajot QIS (10^9 jots)
- 1000 fps
- 1 Tb/s data rate
- 1 Watt or less (<1pJ/b)



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Low Power Readout Progress

Lead: Saleh Masoodian

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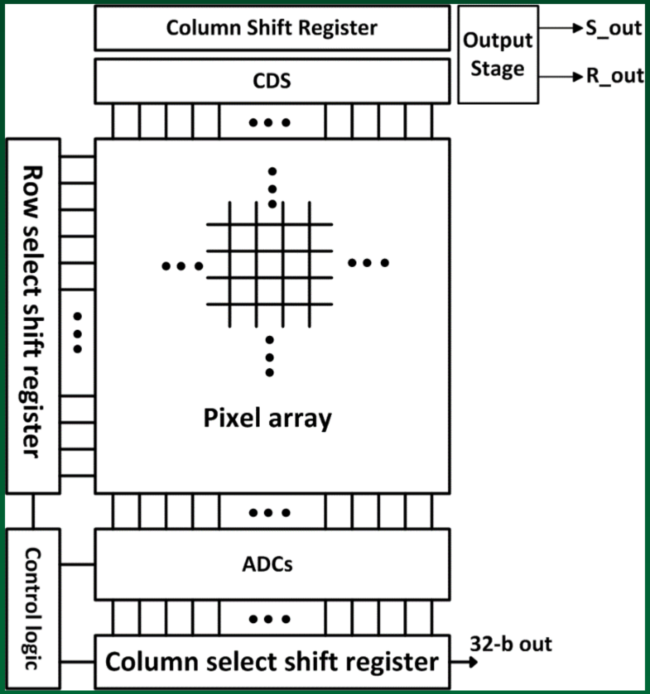
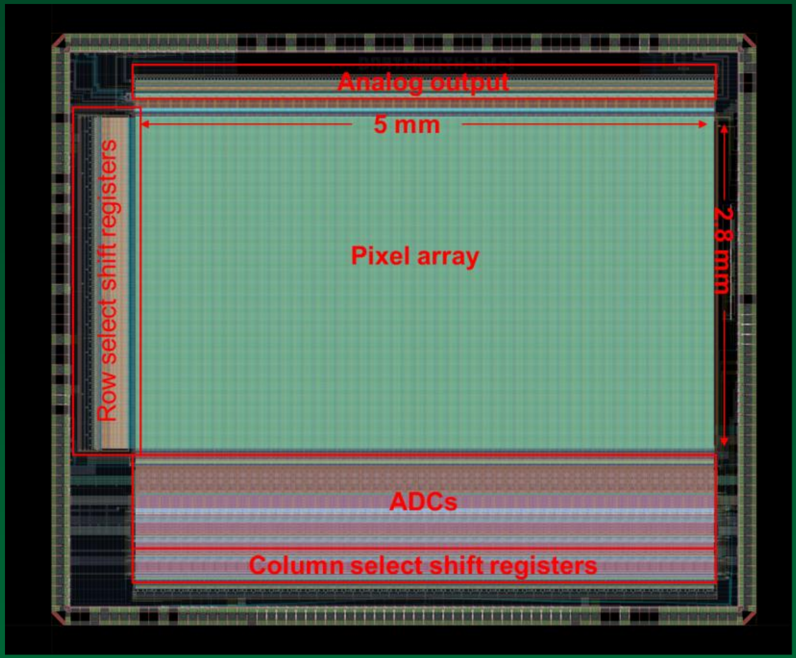
23mW 1000fps 1 Mpix binary image sensor





1 captured frame,≲10e-

- XFAB 0.18um 1.8V
- 1376(H) x 768(V) 3.6um 3T CDS
- 119uV/e- , 2e- rms, ~5.2e- threshold
- 768KSa/s
- 1 Gb/s data rate
- Whole chip incl. pads 20mW
- ADCs 2.6mW
- Energy 2.5pJ/b

Masoodian, Rao, Ma, Odame, Fossum 2015 IISW

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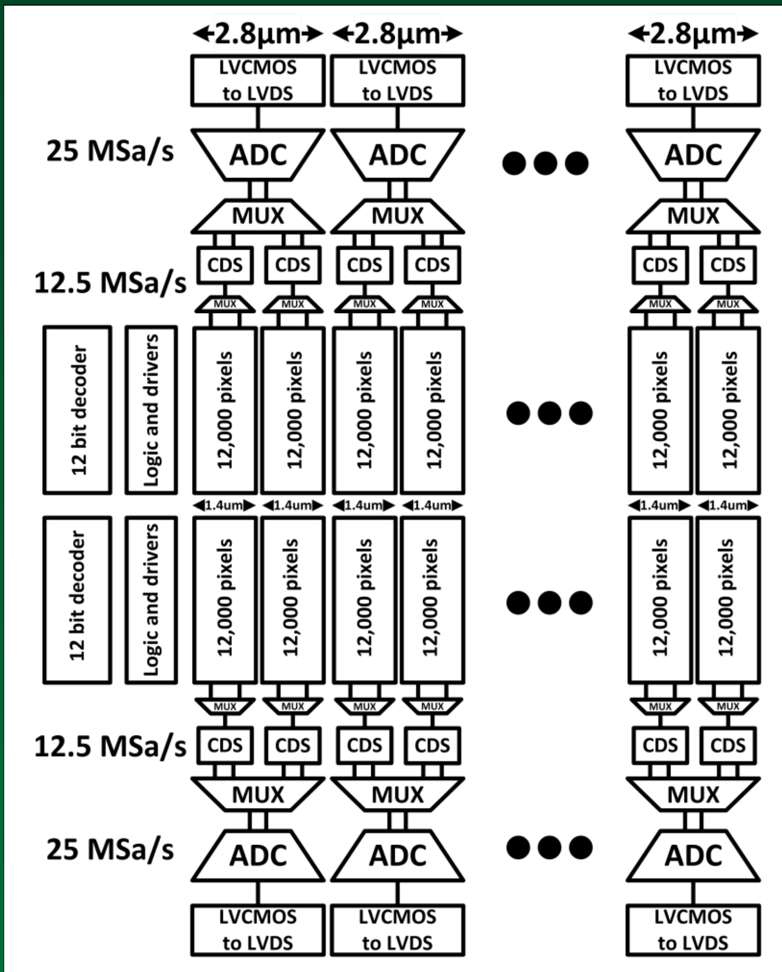
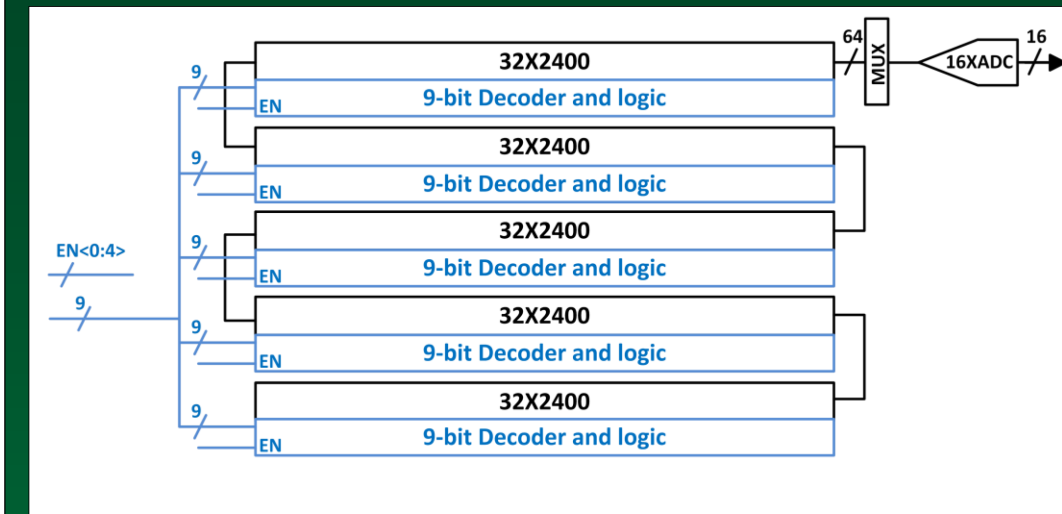
Pathfinder for 1Gjot 65nm BSI CIS (TSMC)





1.4um, 1.75T PPD pixels, 65uV/e-
1.2e- rms

Scaled to Gjot QIS:
42,000x24,000, 1040 fps
=2.85W internal readout

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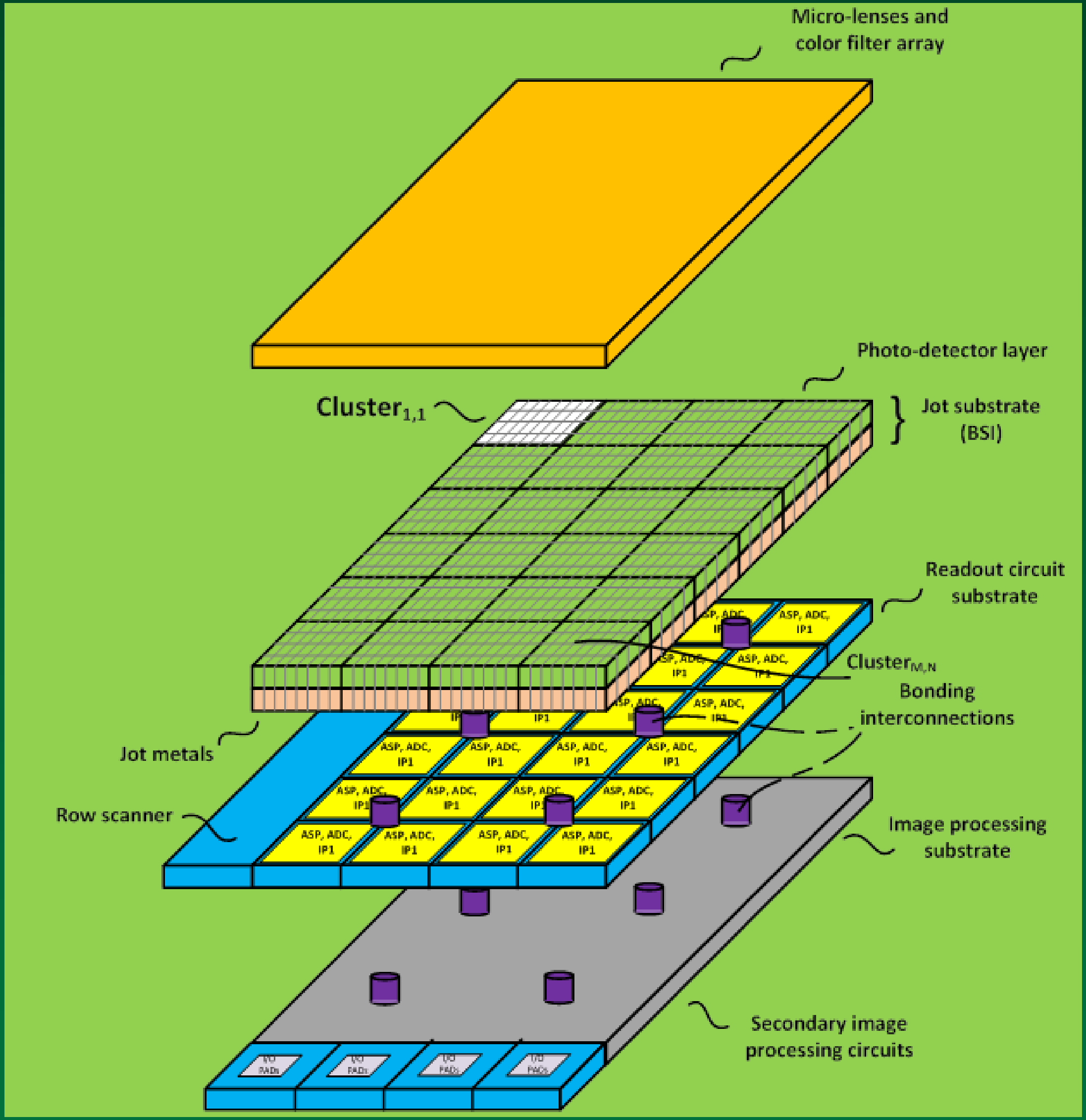
 Saleh Masoodian et al. 2016

Stacked QIS with Cluster-Parallel Readout



>10x reduction in power due to lower capacitance and slower operation

Fossum and Masoodian 2015 unpublished

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Read Noise and Photon-Counting Histogram

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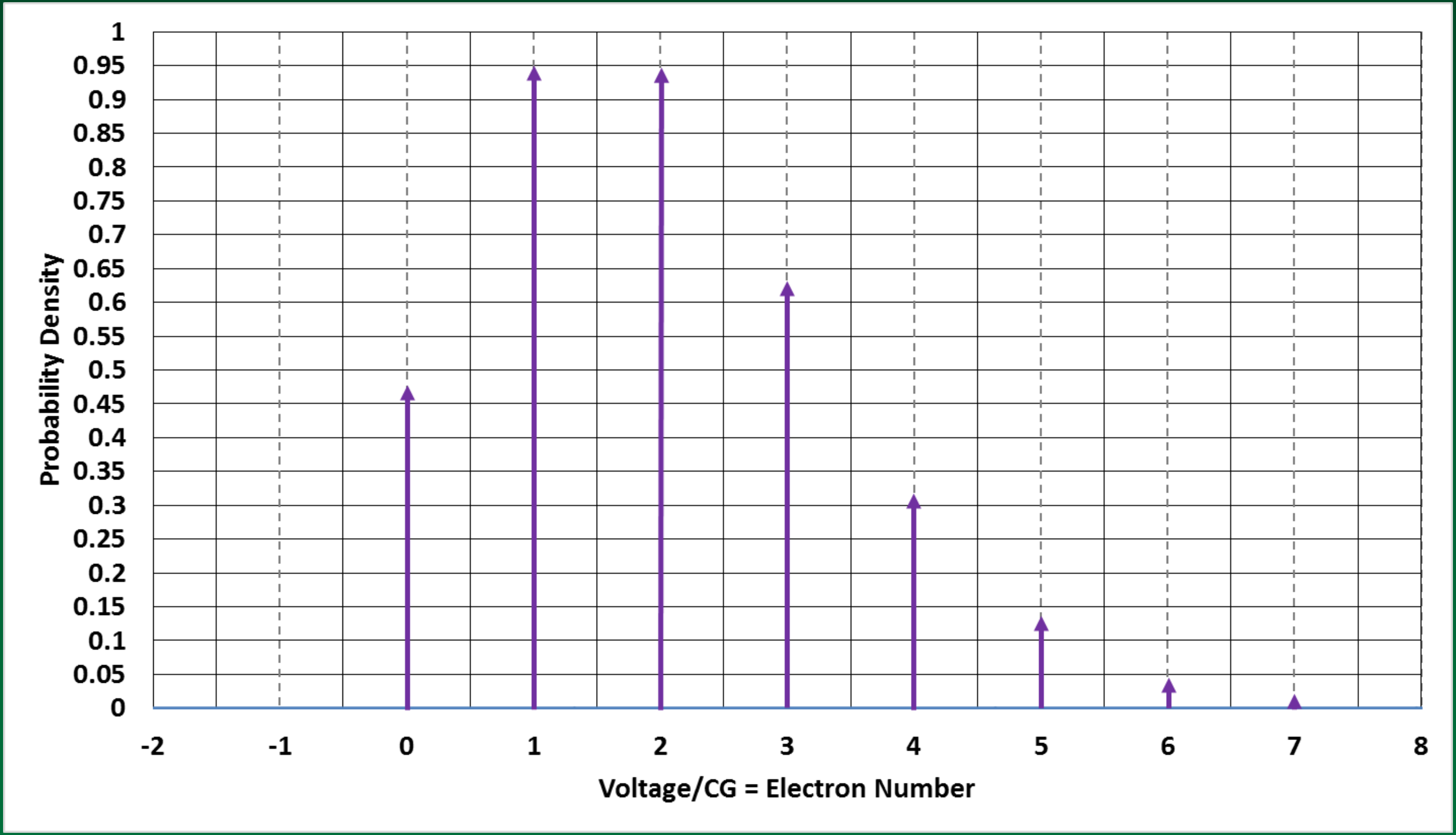
Poisson Distribution (scaled)

H=2



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

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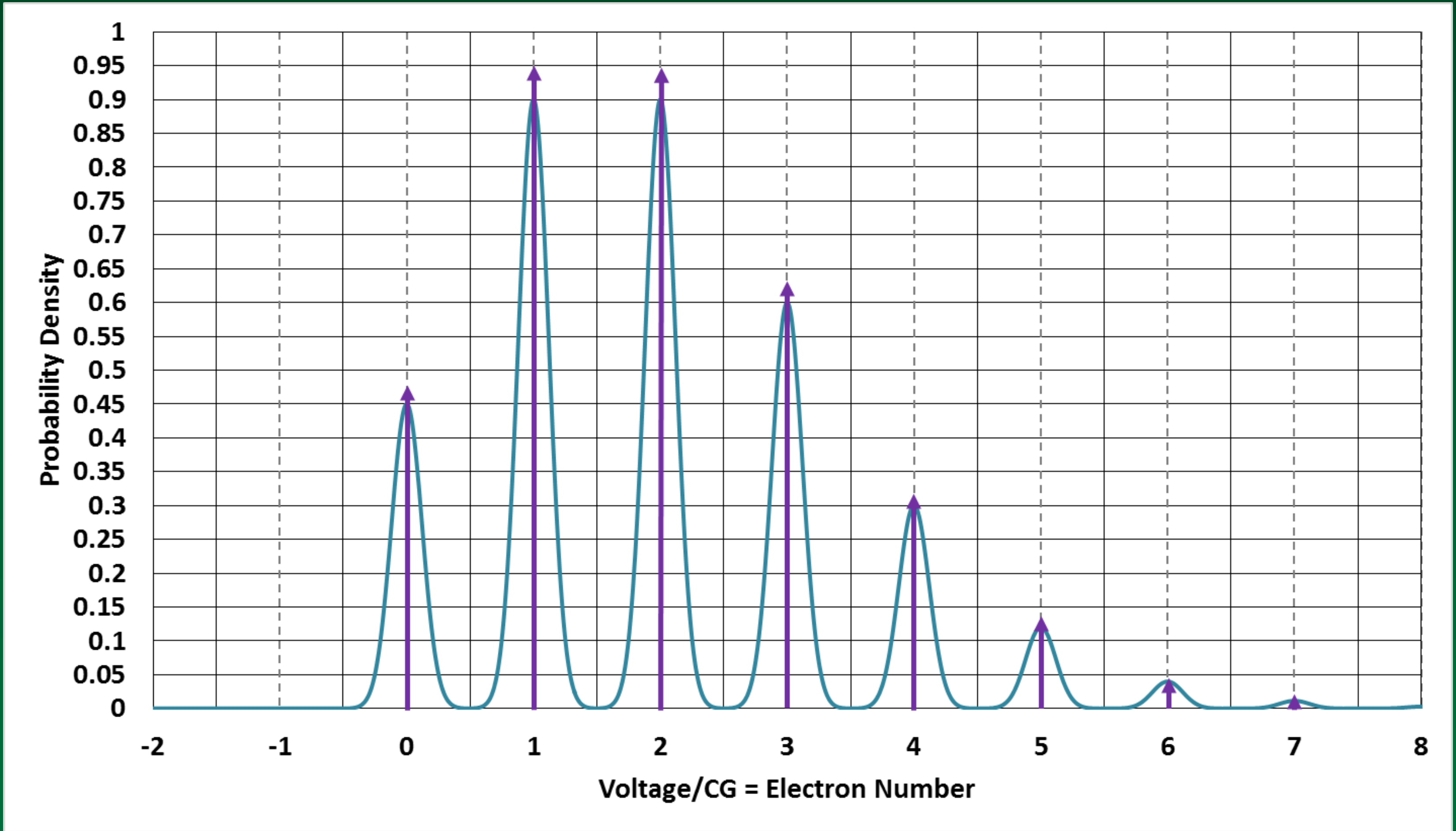
Broadened by 0.12e- rms read noise



Model

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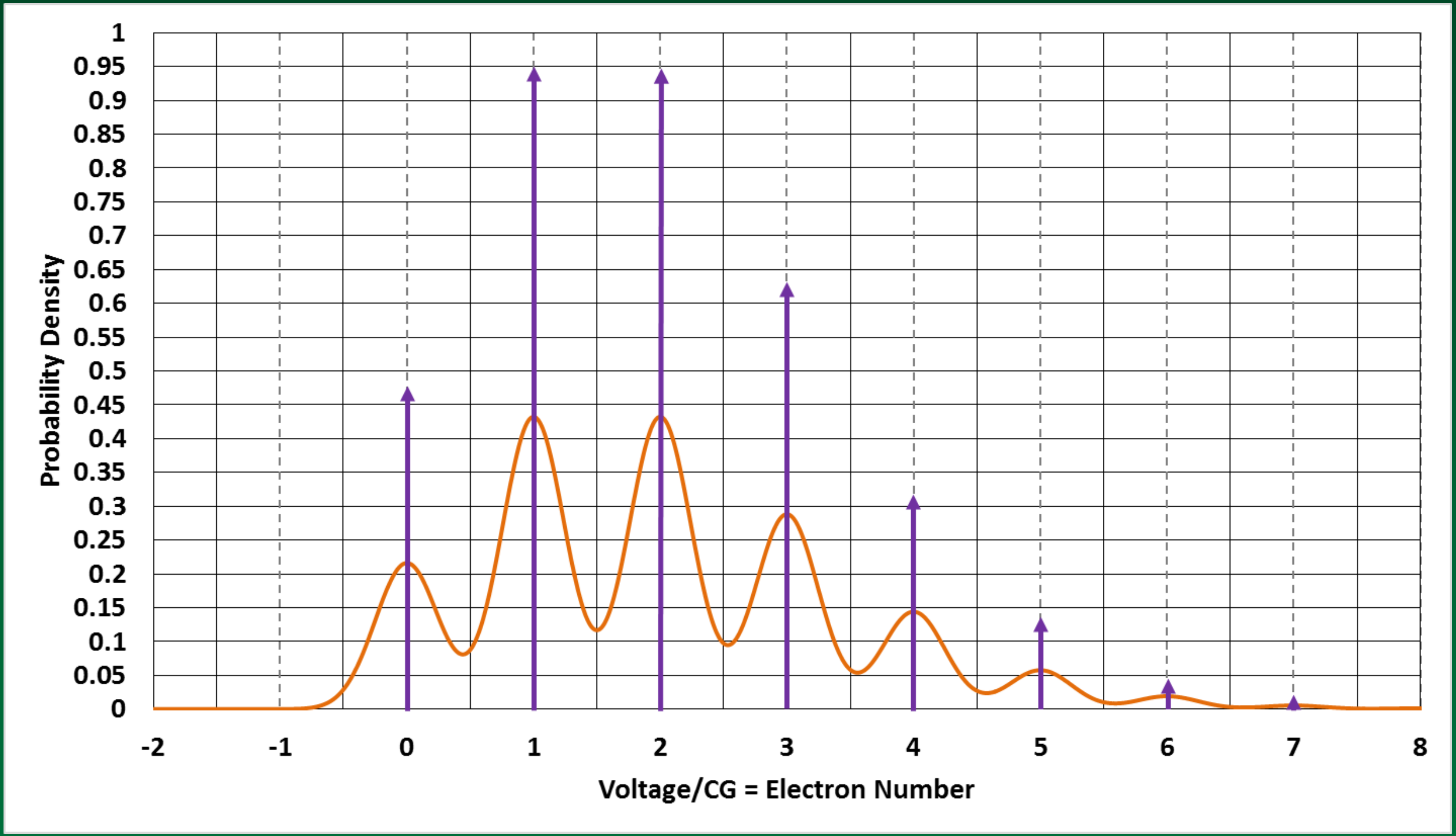
Broadened by 0.25e- rms read noise



Model

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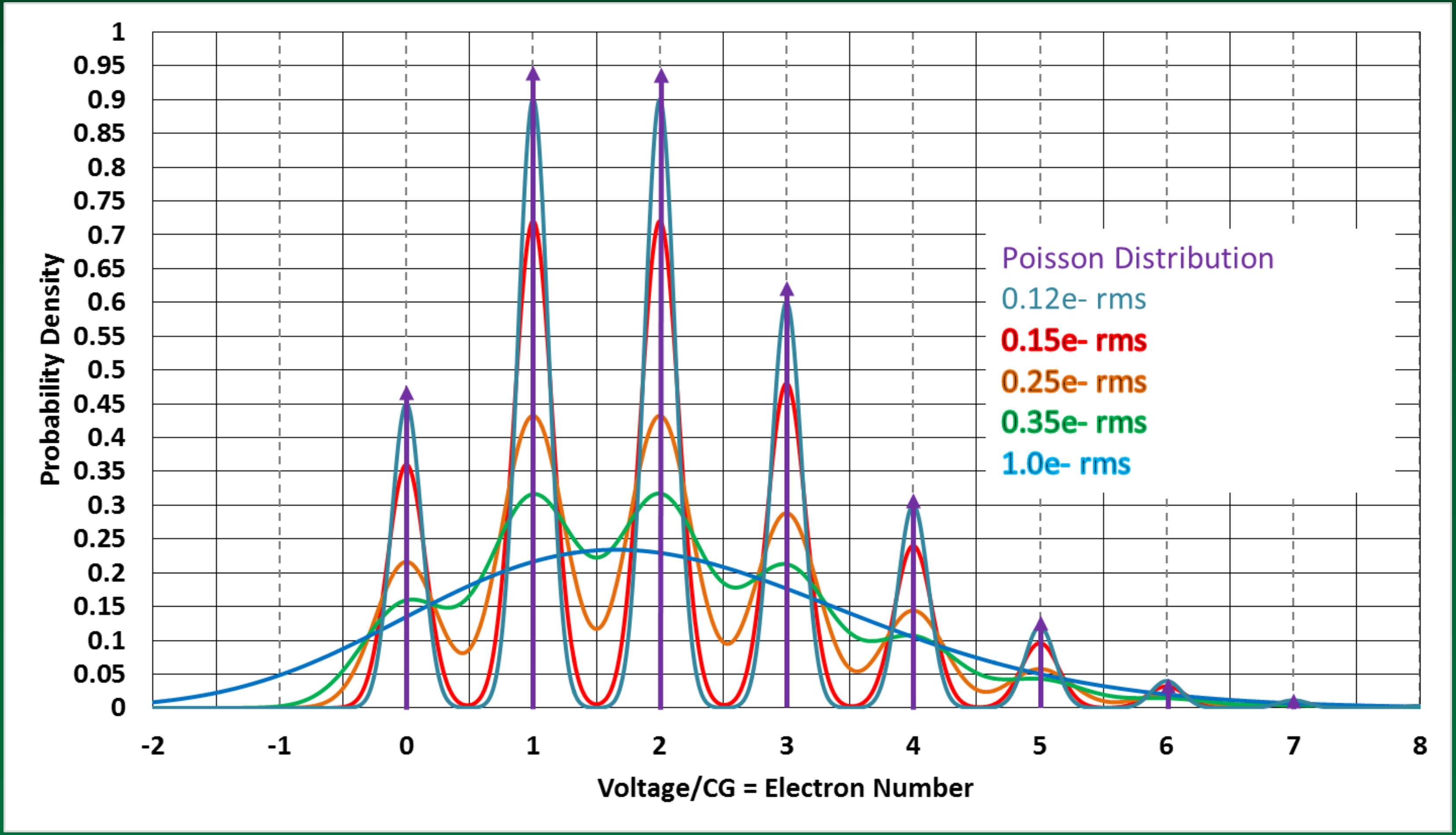
Probability Distribution for Various Levels of Read Noise



Model

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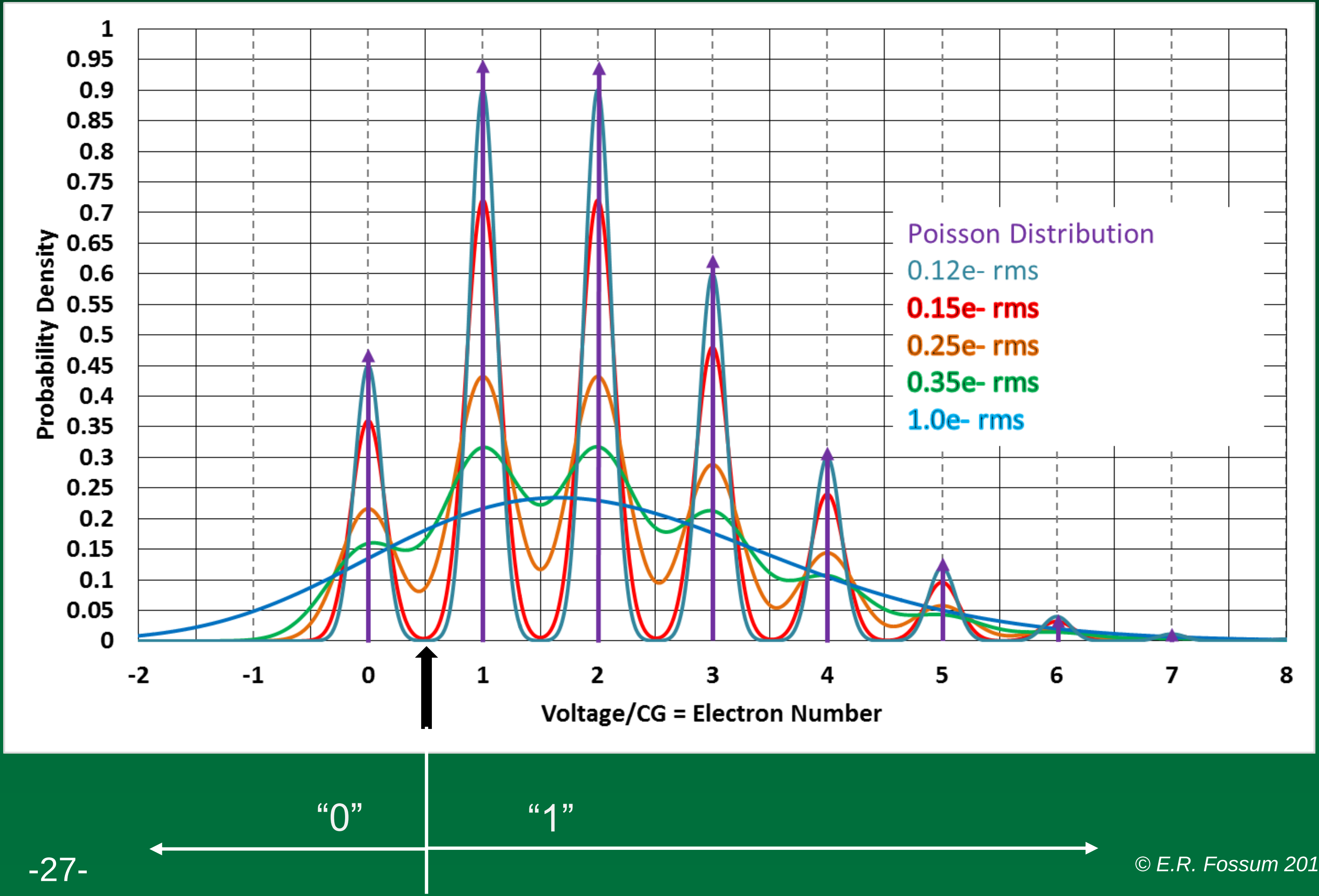
Single-bit QIS



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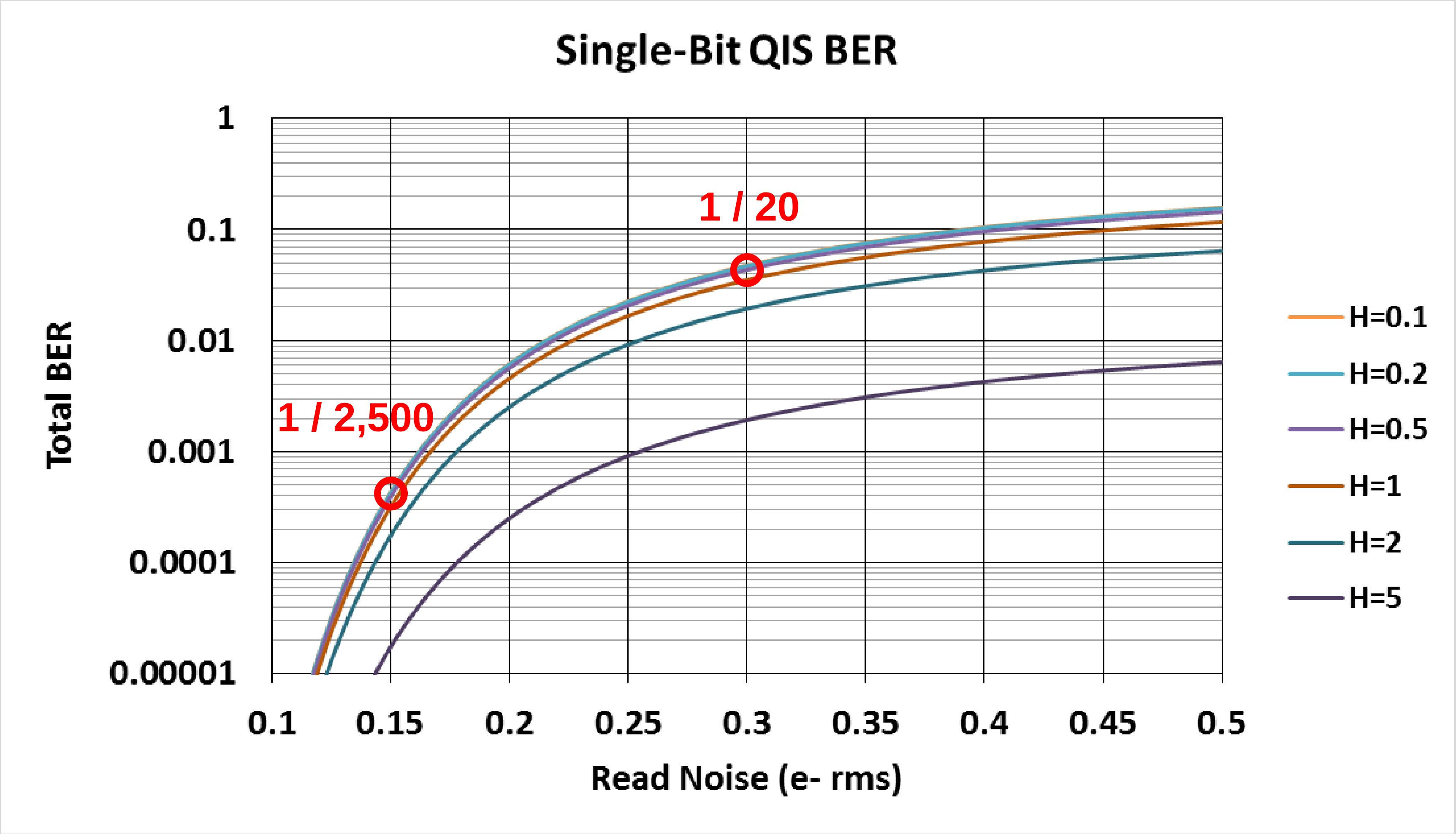
BER vs. Read Noise



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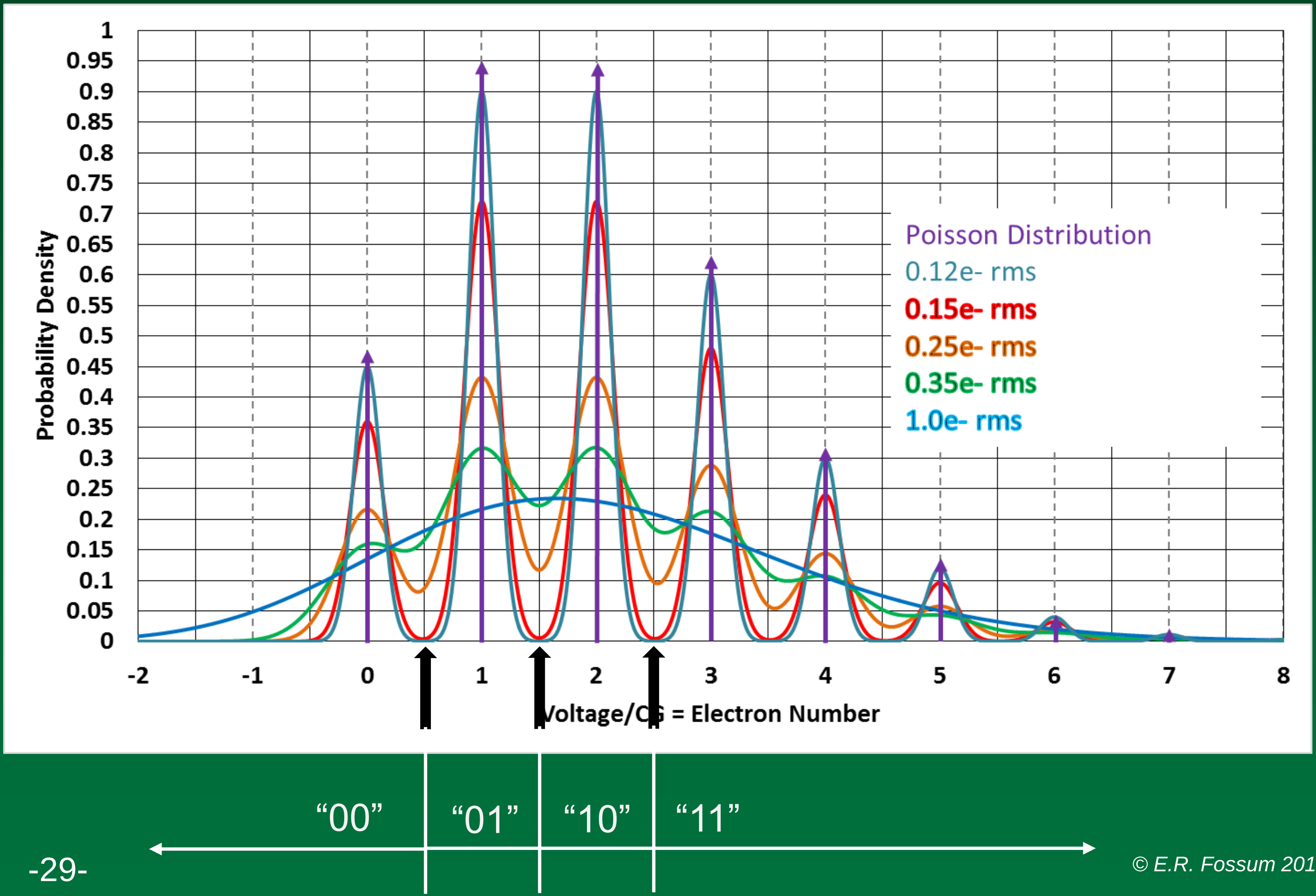
Multi-bit QIS (e.g. 2-bit)



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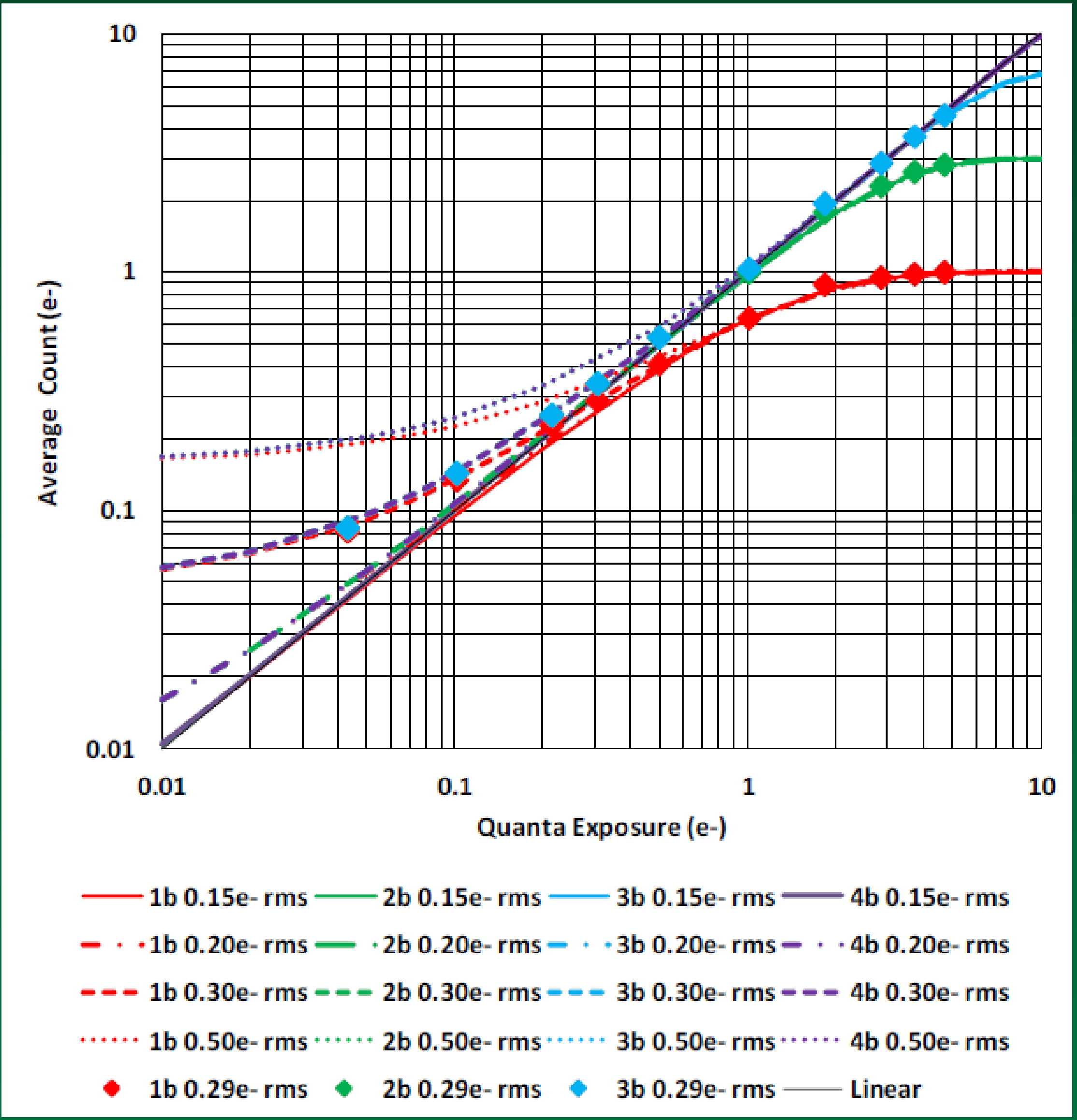
Noise Requirement for Photon Counting



Fossum, IEEE JEDS on-line March 2016

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Jot Progress

Lead: Jiaju (JJ) Ma

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Jot Device Considerations

General targets:

- 200 nm device in 22 nm process node (“10L”)
- 0.15e- rms read noise or less
- High conversion gain > 1 mV/e- (per photoelectron)
- Low active pixel transistor noise <150 uV rms
- Small storage well capacity ~1-100 e-
- Complete reset for low noise
- Low dark current ~ 1 e-/s
- Not too difficult to fabricate in CIS line

Candidate devices

- Single photon avalanche detector (SPAD)
- Single electron FET
- Bipolar jot
- Pump gate jot
- JFET jot

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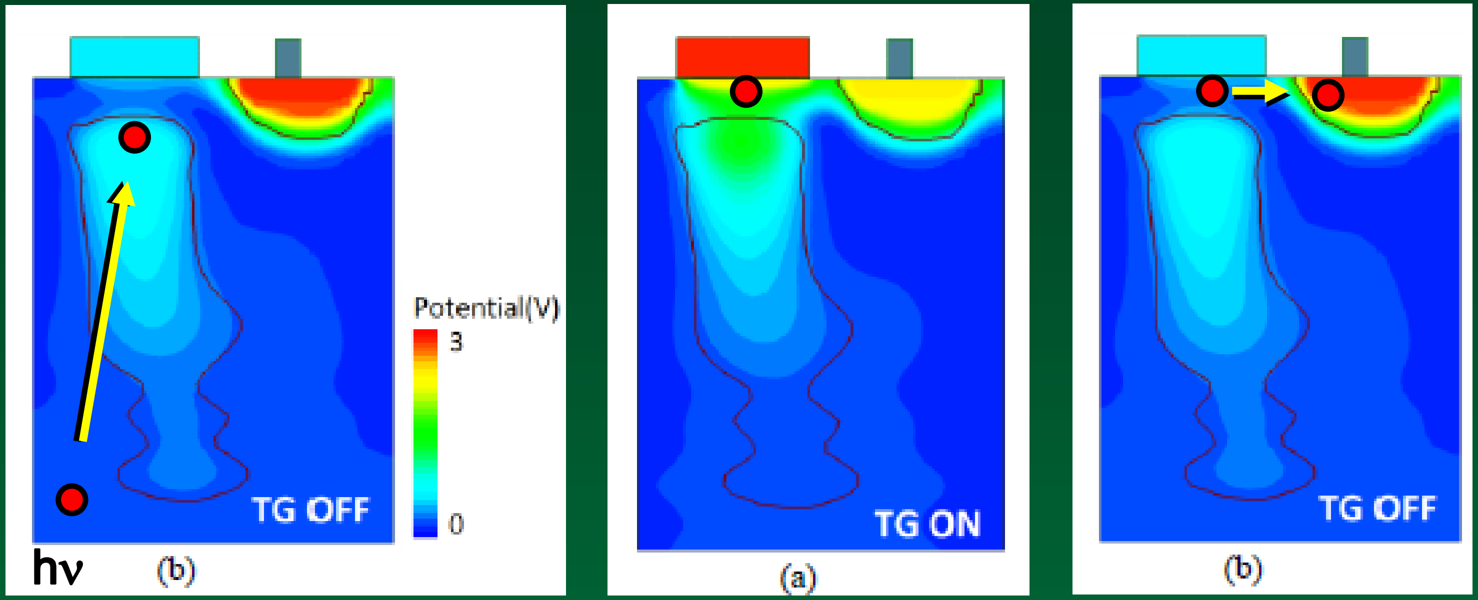
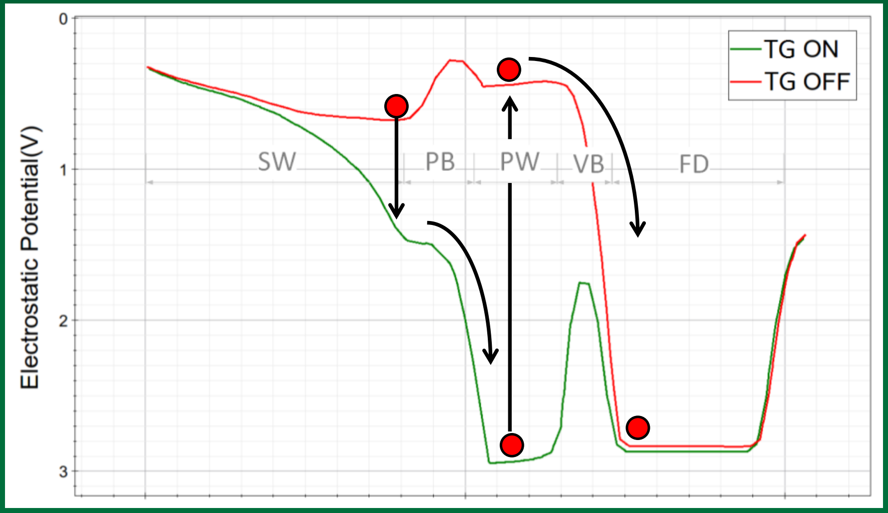
Pump-Gate Jot





Fabricated in
TSMC 65nm
BSI CIS

1.4um pitch

Ma and Fossum
2014 IEDM, 2015 JEDS, 2015 EDL

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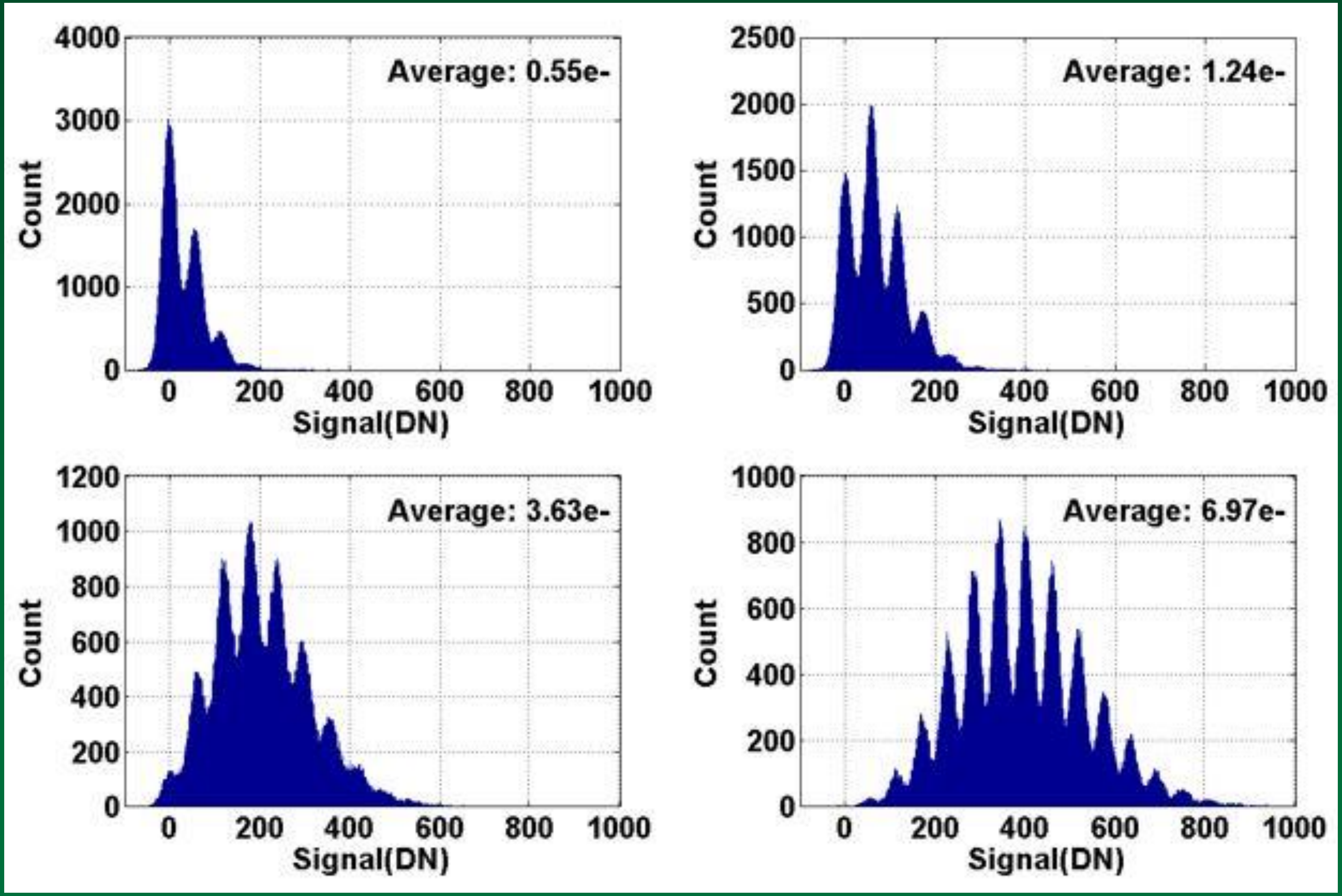
Experimental Data
Photon-Counting Histograms

200k reads of same jot, ~0.28e- rms read noise, 120uV rms, 430uV/e-, ~60DN/e-
Room Temperature, No Avalanche, Single CDS readout



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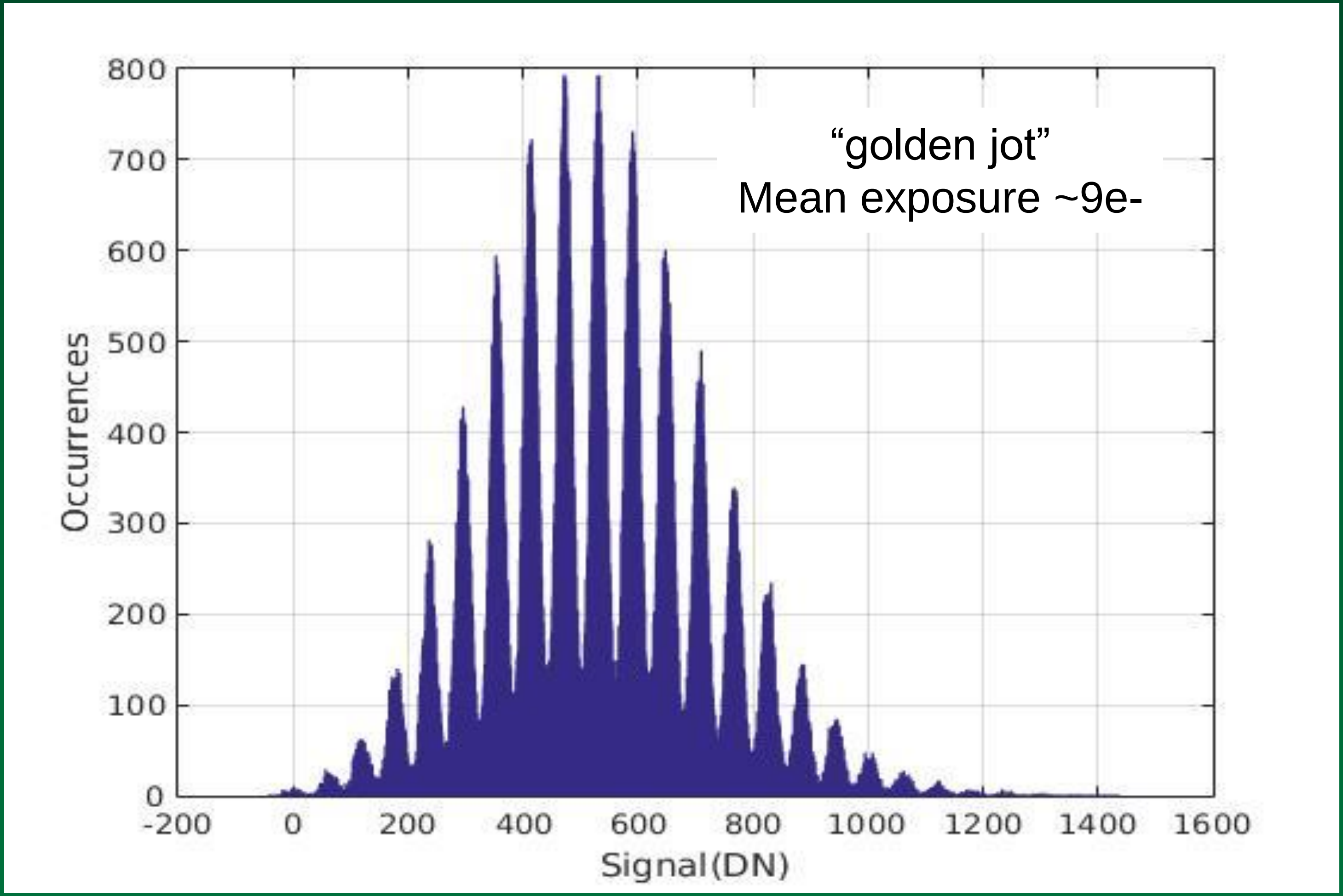
Ma, Starkey, Rao, Odame and Fossum IEEE JEDS 3(6) 2015.

Experimental Data
Photon-Counting Histograms

200k reads of same jot, ~0.22e- rms read noise, 93uV rms, 423uV/e-, ~60DN/e-
Room Temperature, No Avalanche, Single CDS readout



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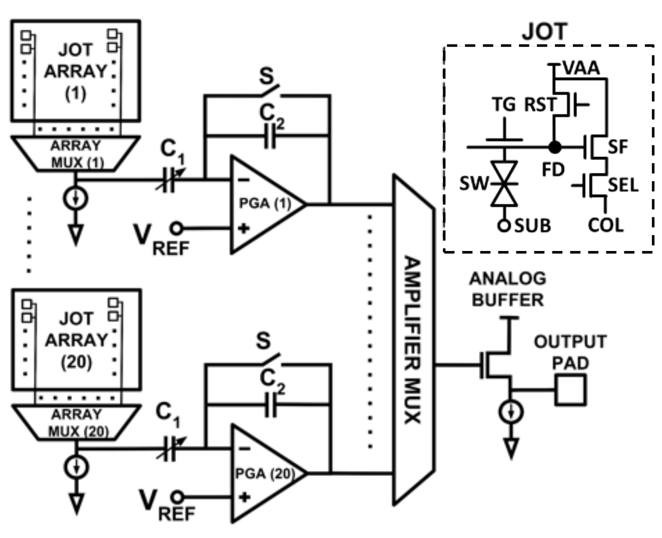
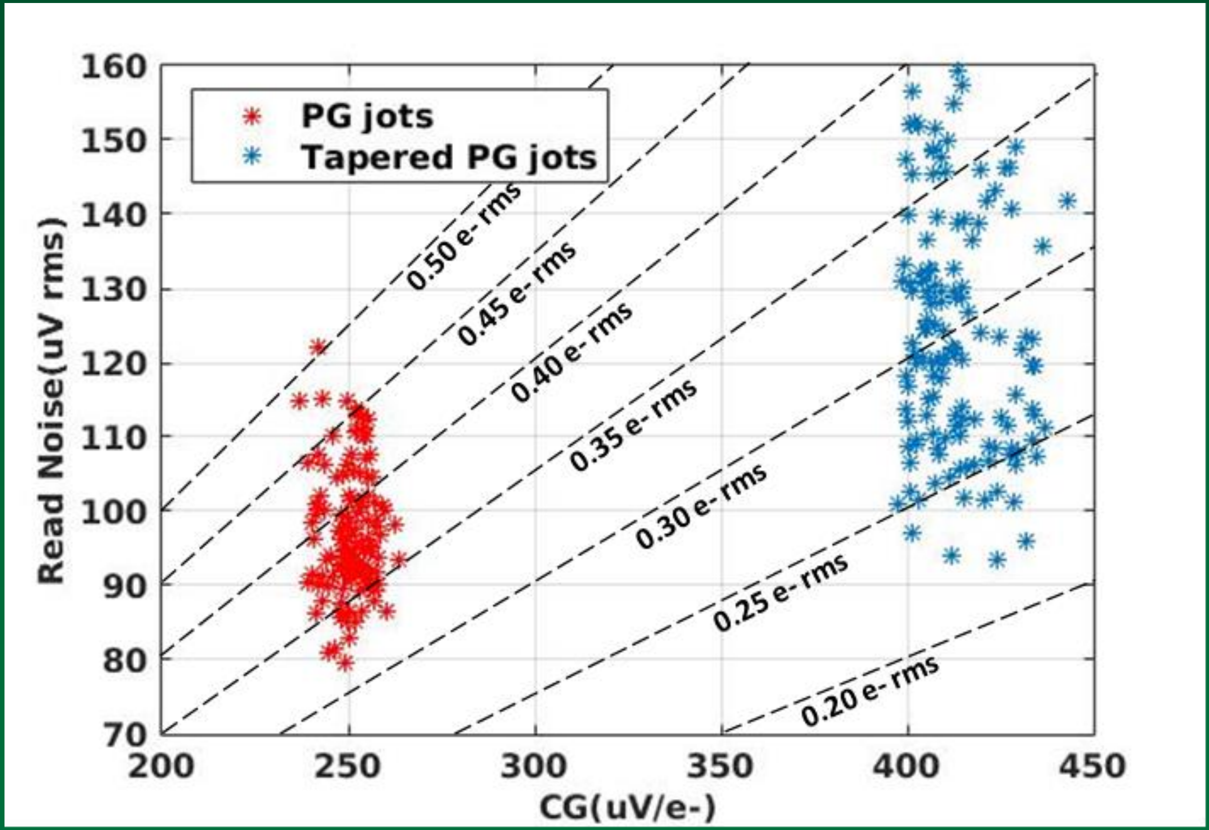
Ma, Starkey, Rao, Odame and Fossum IEEE JEDS 3(6) 2015.

CG and Read Noise Scatter





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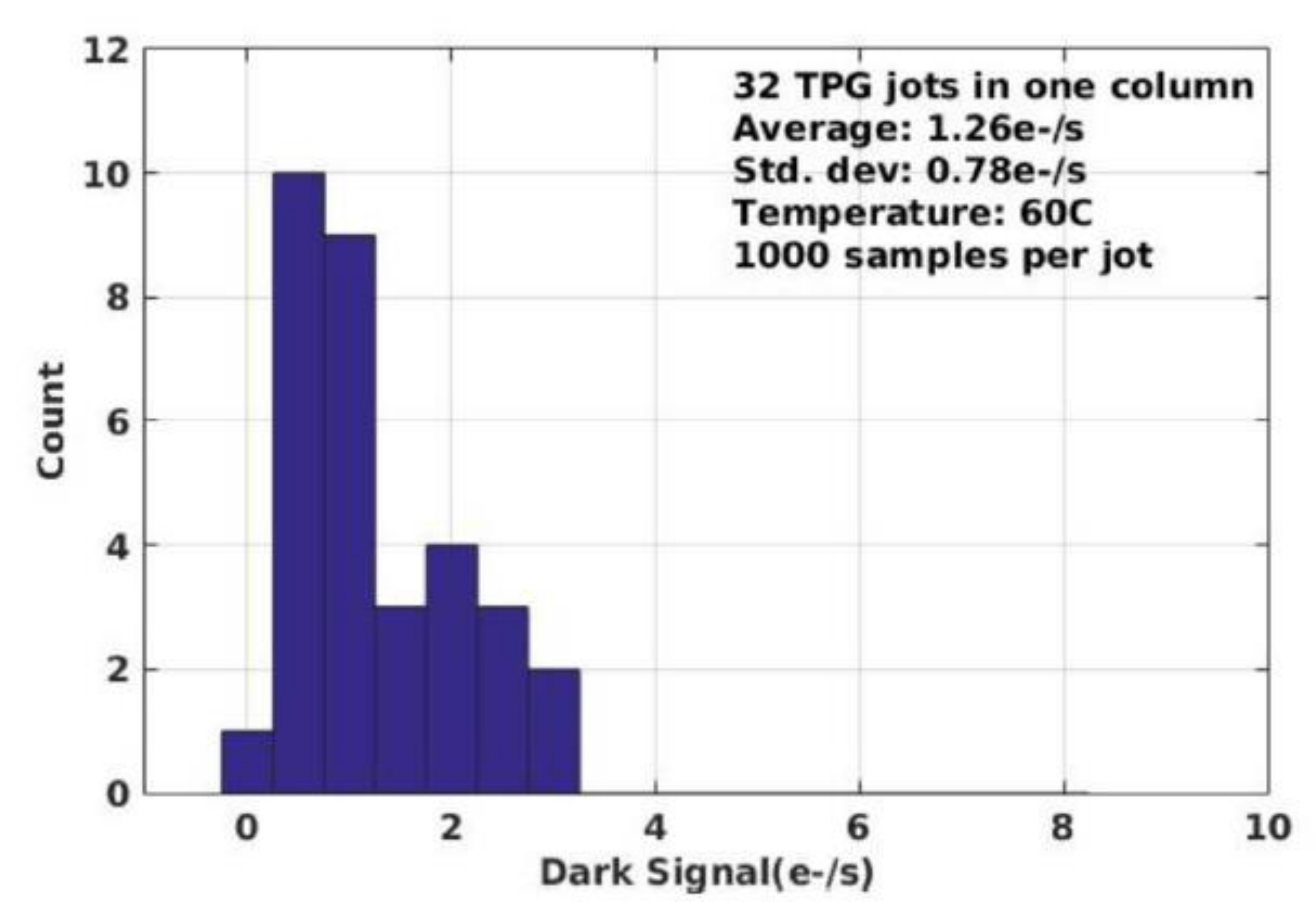
Ma, Starkey, Rao, Odame and Fossum IEEE JEDS 3(6) 2015.

Dark Current



Ma, Starkey, Rao, Odame and Fossum, submitted to IEEE JEDS Aug 2015

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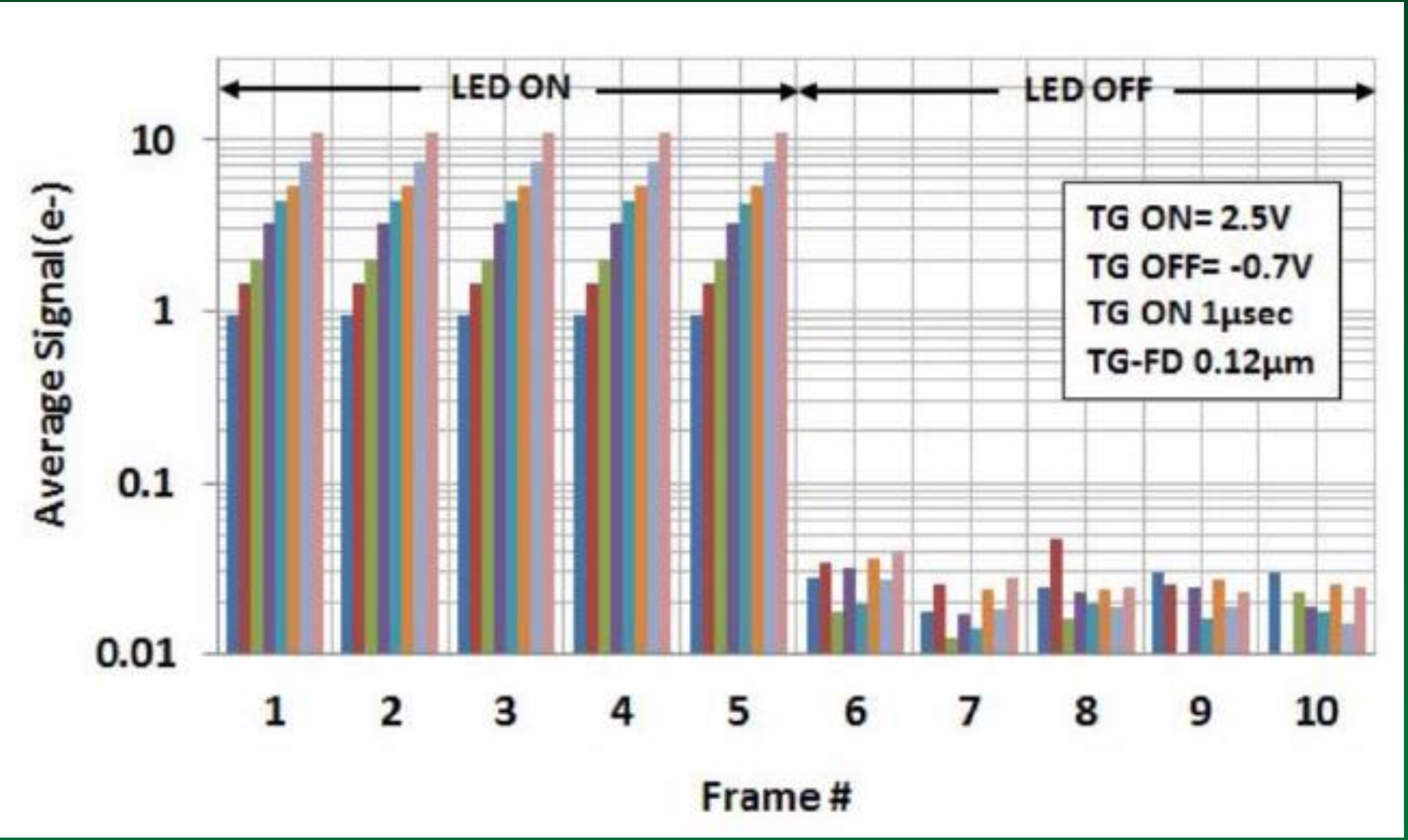
Ma, Starkey, Rao, Odame and Fossum IEEE JEDS 3(6) 2015.

Lag



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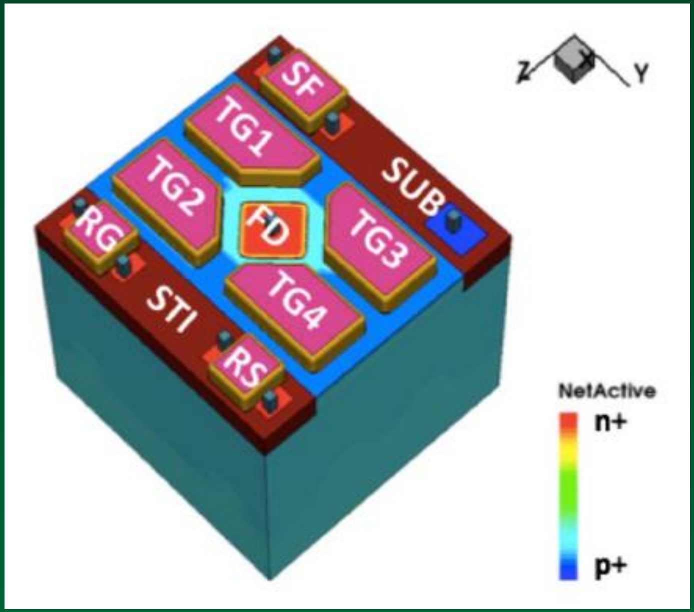
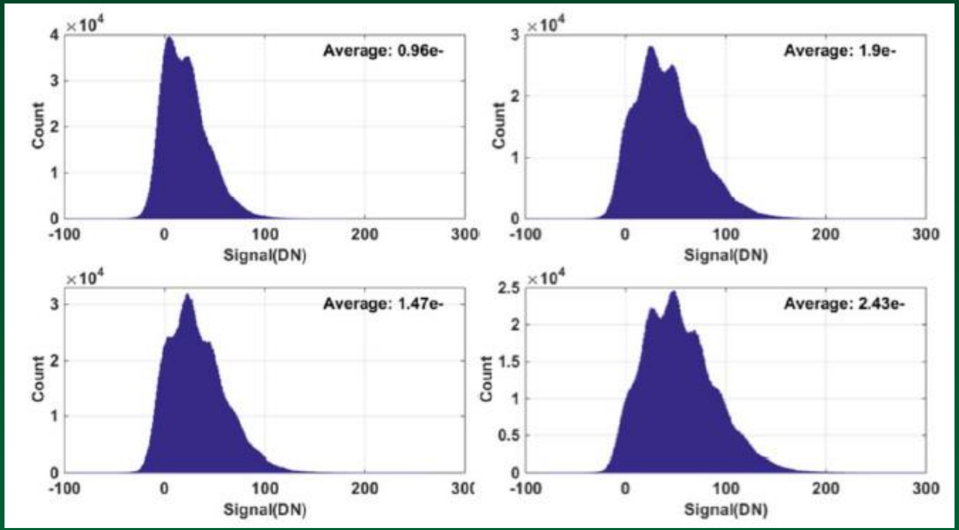
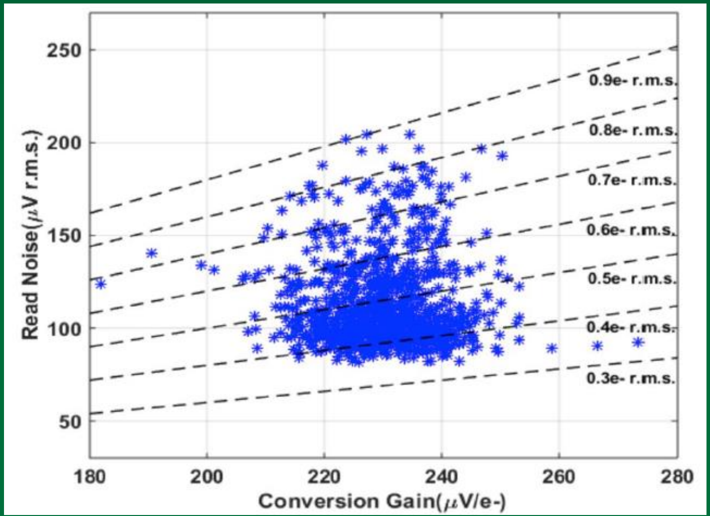
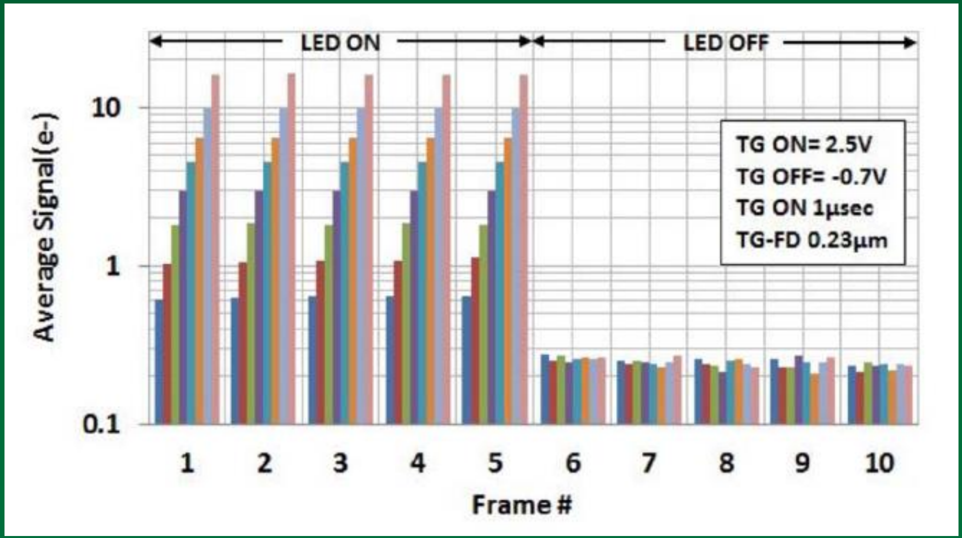
1 um Shared RO Jot









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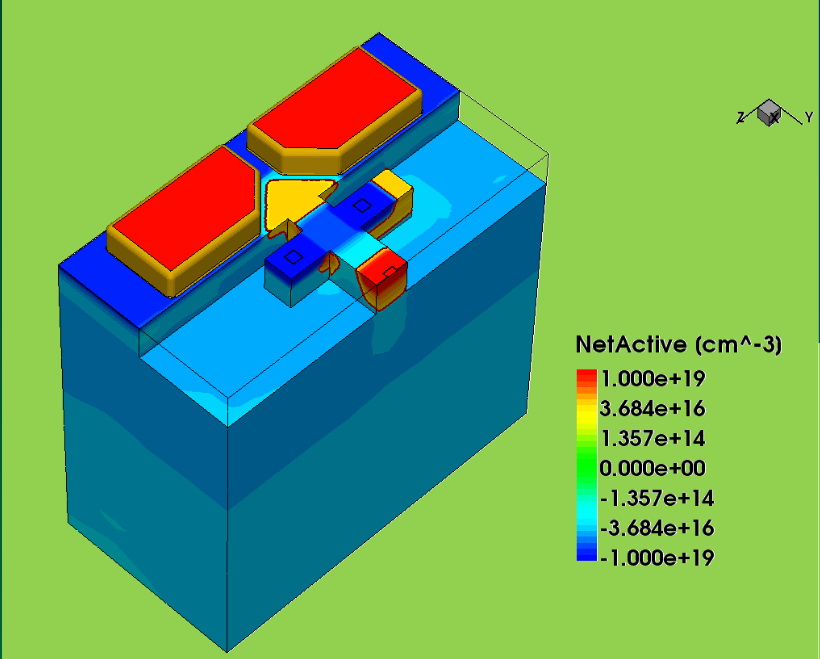
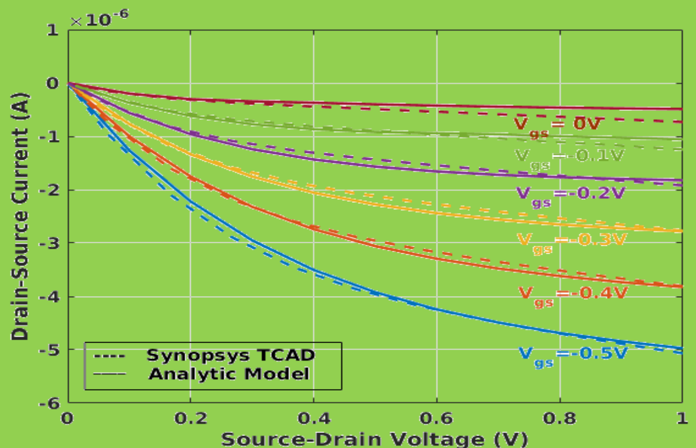
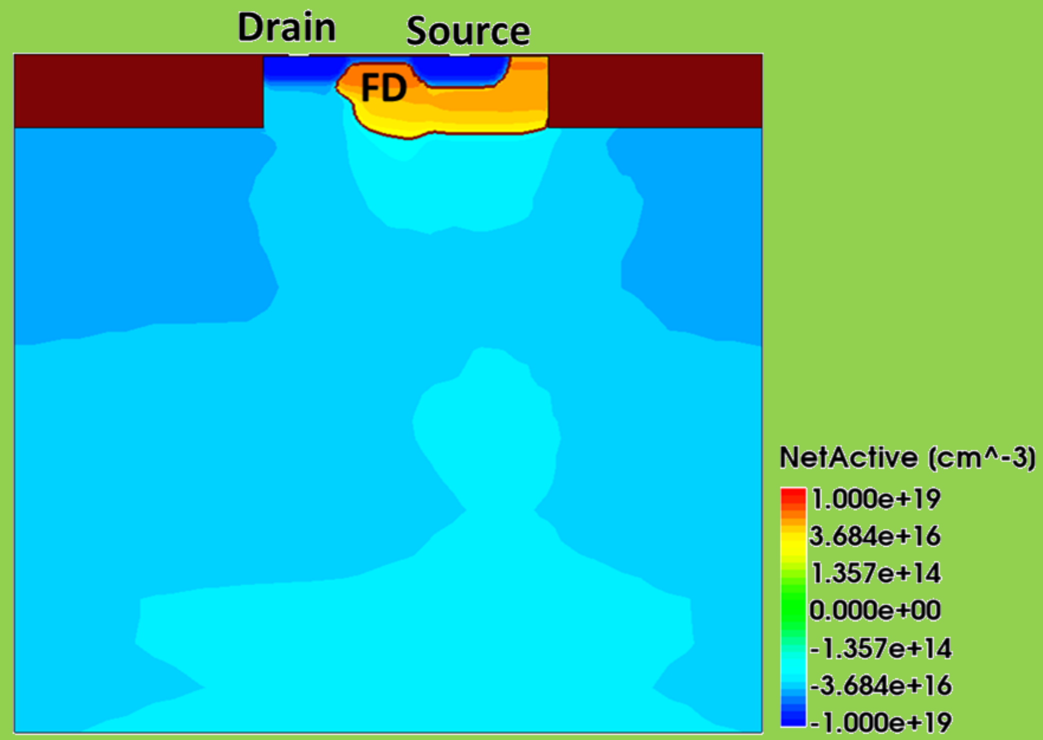
Proposed JFET Jot

CG: ~ 1.35mV/e-
FWC: ~200e-
Drive: ~1uA
Pitch: ~1um 65nm BSI CIS







Ma and Fossum 2015 unpublished

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Closing Remarks

- Photon-counting without avalanche gain is coming.
  - Work in Dartmouth, Shizuoka, Sarnoff, Caeleste have demonstrated deep sub-electron read noise without avalanche gain. Others working on it.
- May come to consumer devices, even mobile.
  - D-logH is very attractive to photographers and cinematographers
  - Computer science community very excited about QIS due to image generation possibilities.
- SPADs remain dominant for time-resolved photon counting
  - Big pixels, high electric fields, high dark count rate, low resolution, but excellent time resolution

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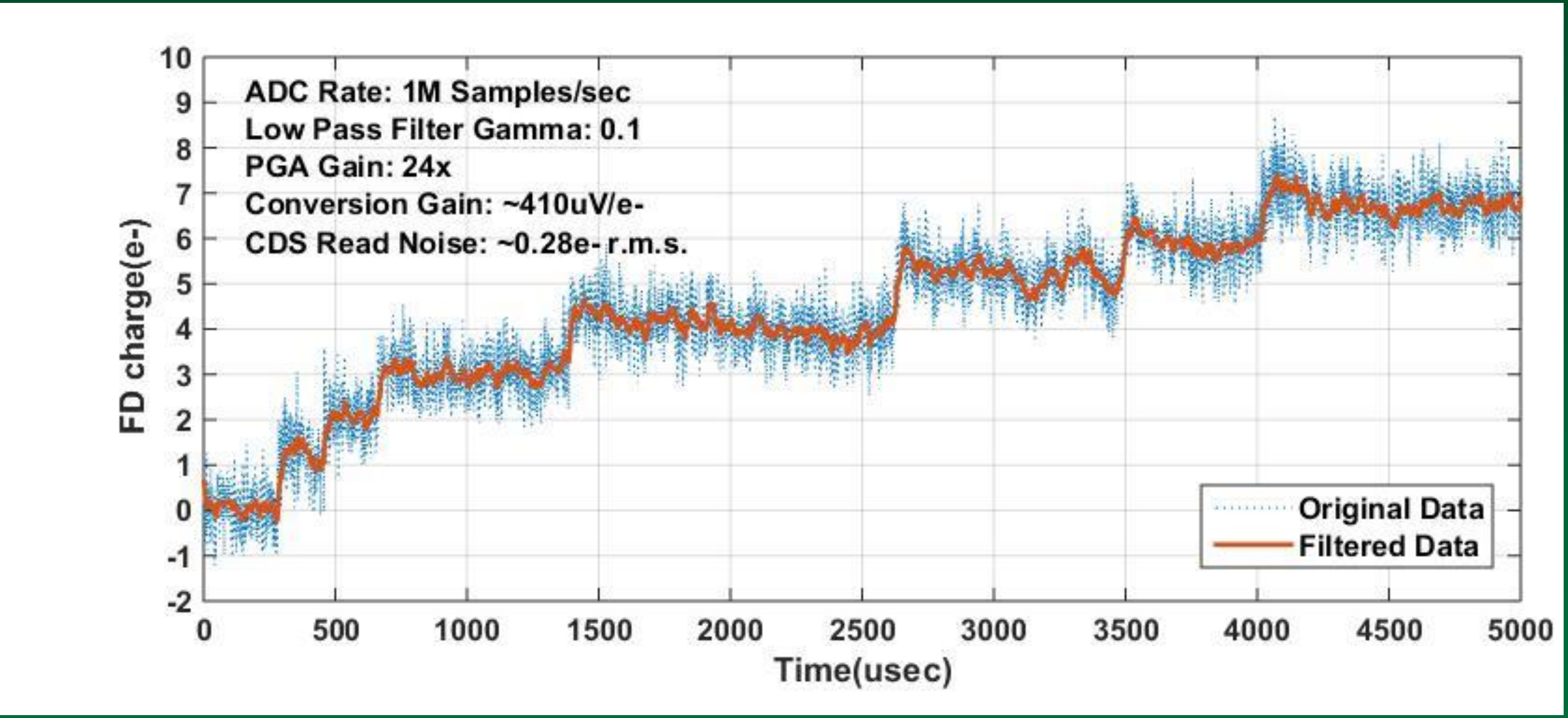
RTS and Single Electron Integration Steps



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