DARTMOUTH

A Camera in Every Pocket

Science, Engineering and Entrepreneurship

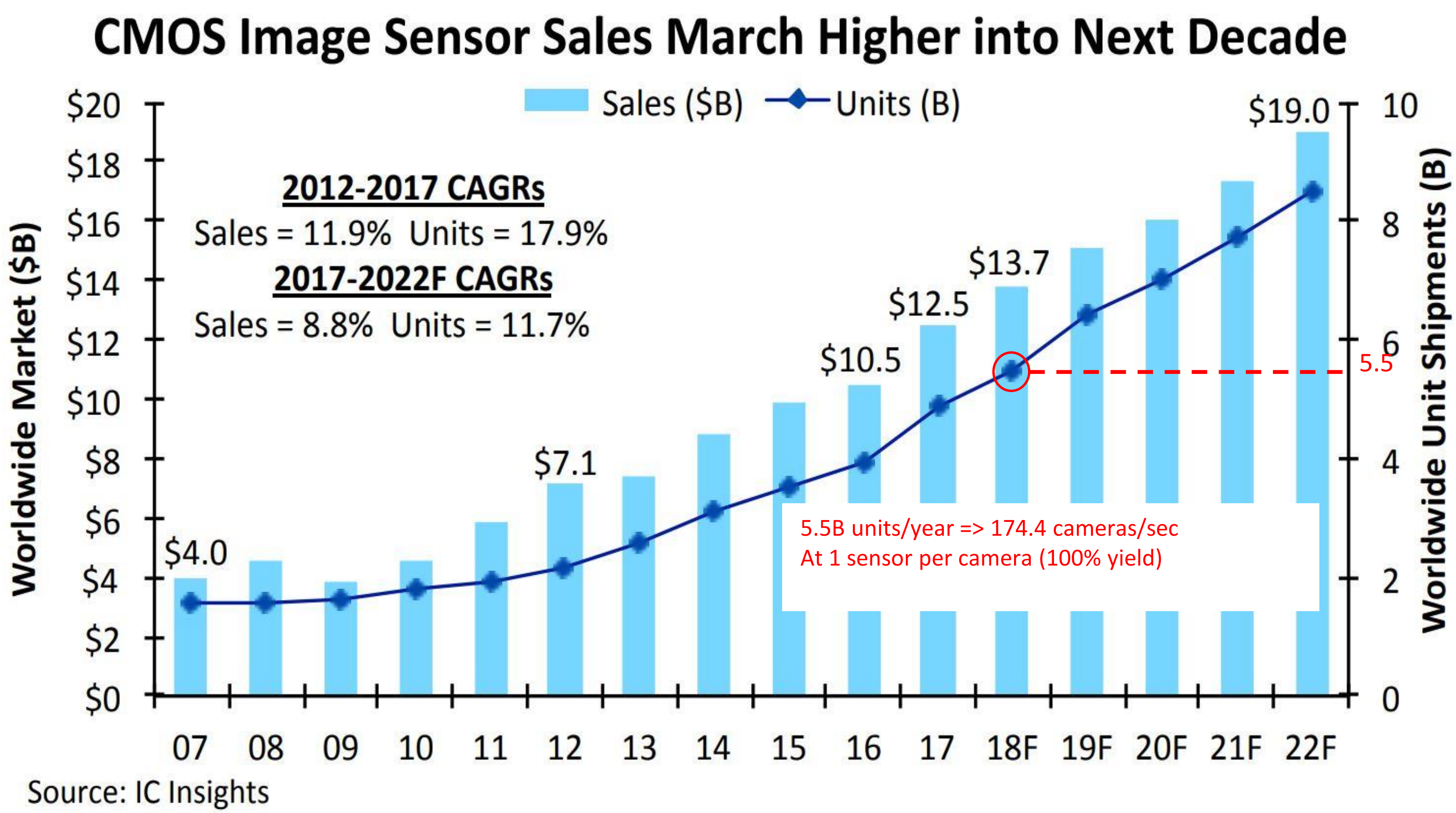
Eric R. Fossum

November 9, 2018

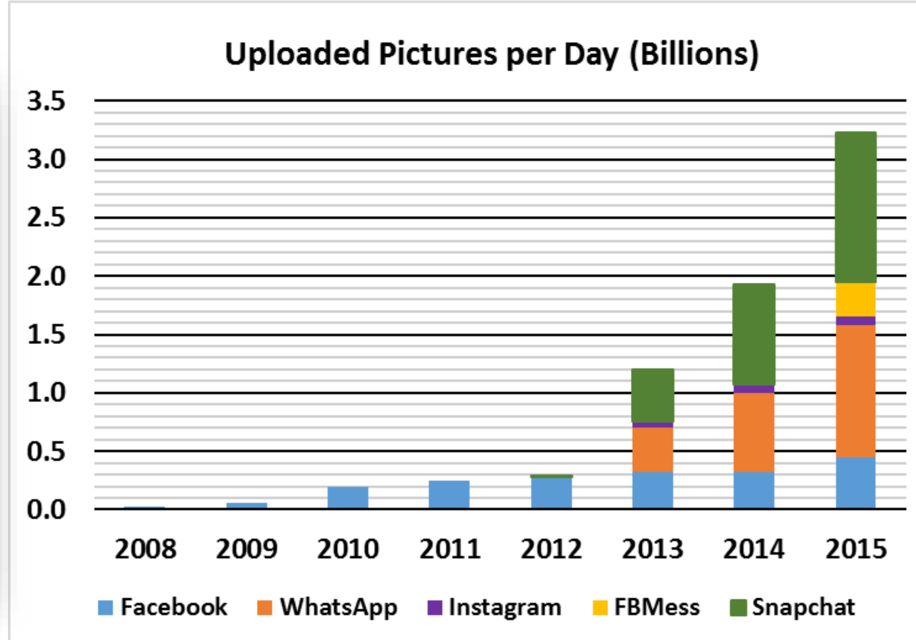
CMOS Image sensors enable billions of cameras each year

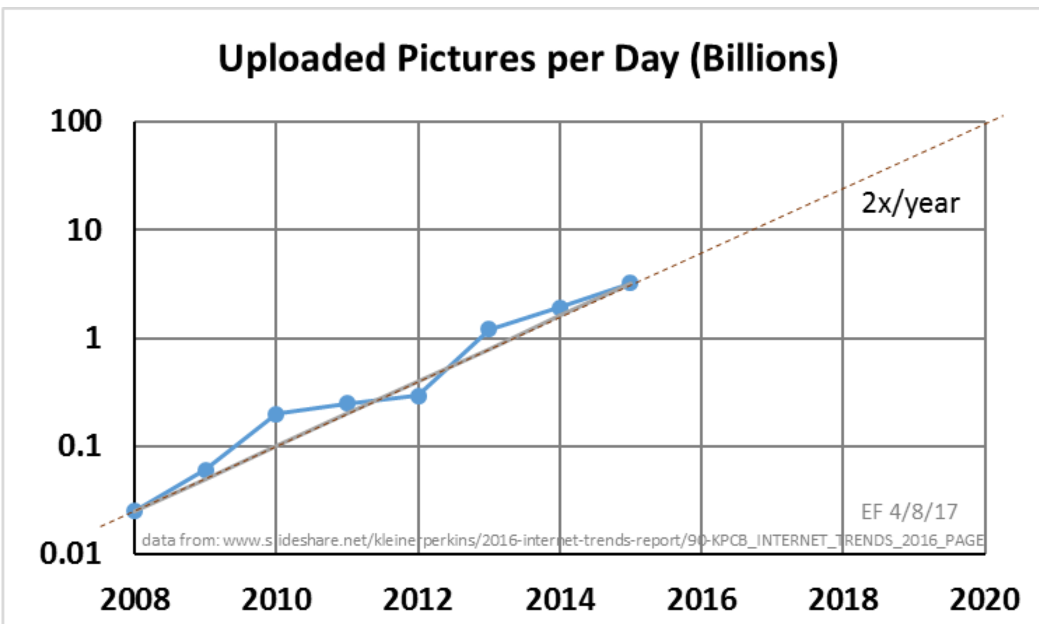
https://www.nytimes.com/2018/04/27/arts/design/mona-lisa-instagram-art.html

About 5 billion cameras made each year
(more than 150 per second)



http://image-sensors-world.blogspot.com/2018/05/cmos-sensor-sales-grow-at-record.html


Uploaded Pictures per Day (Billions)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2008
2009
2010
2011
2012
2013
2014
2015
Facebook
WhatsApp
Instagram
FBMess
Snapchat


Uploaded Pictures per Day (Billions)
100
10
1
0.1
0.01
2x/year
EF 4/8/17
data from: www.slideshare.net/kleinerperkins/2016-internet-trends-report/90-KPCB_INTERNET_TRENDS_2016_PAGE
2008
2010
2012
2014
2016
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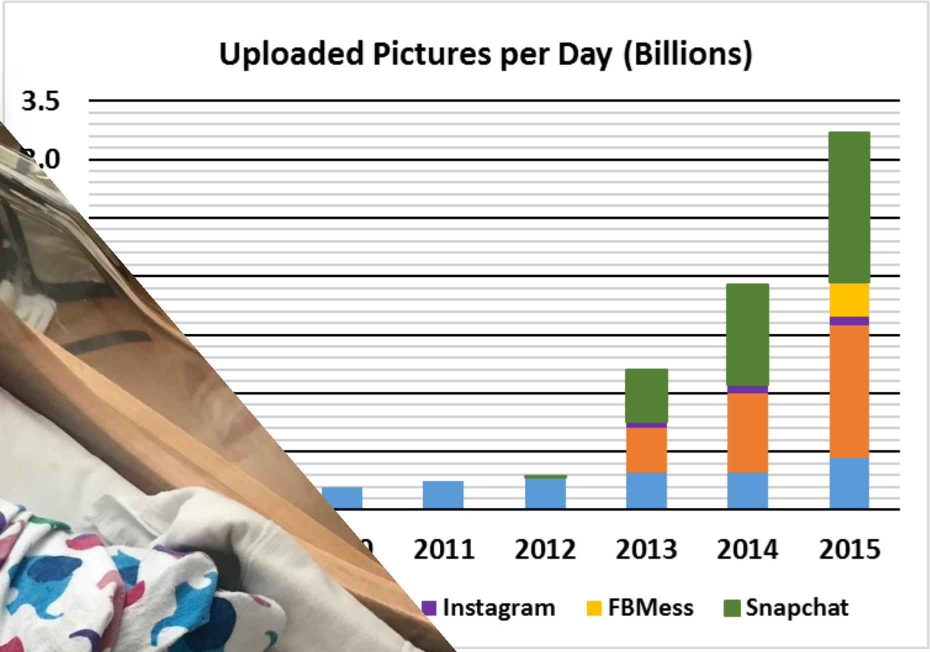
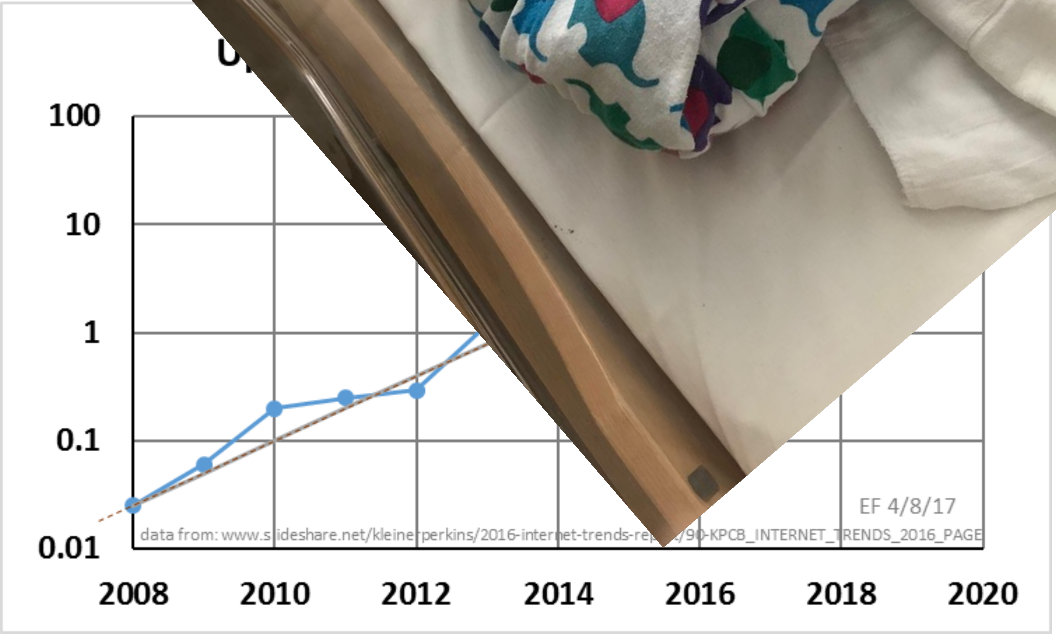
2020


Uploaded Pictures per Day (Billions)
3.5
2011
2012
2013
2014
2015
Instagram
FBMess
Snapchat


100
10
1
0.1
0.01
2008
2010
2012
2014
2016
2018
2020
EF 4/8/17

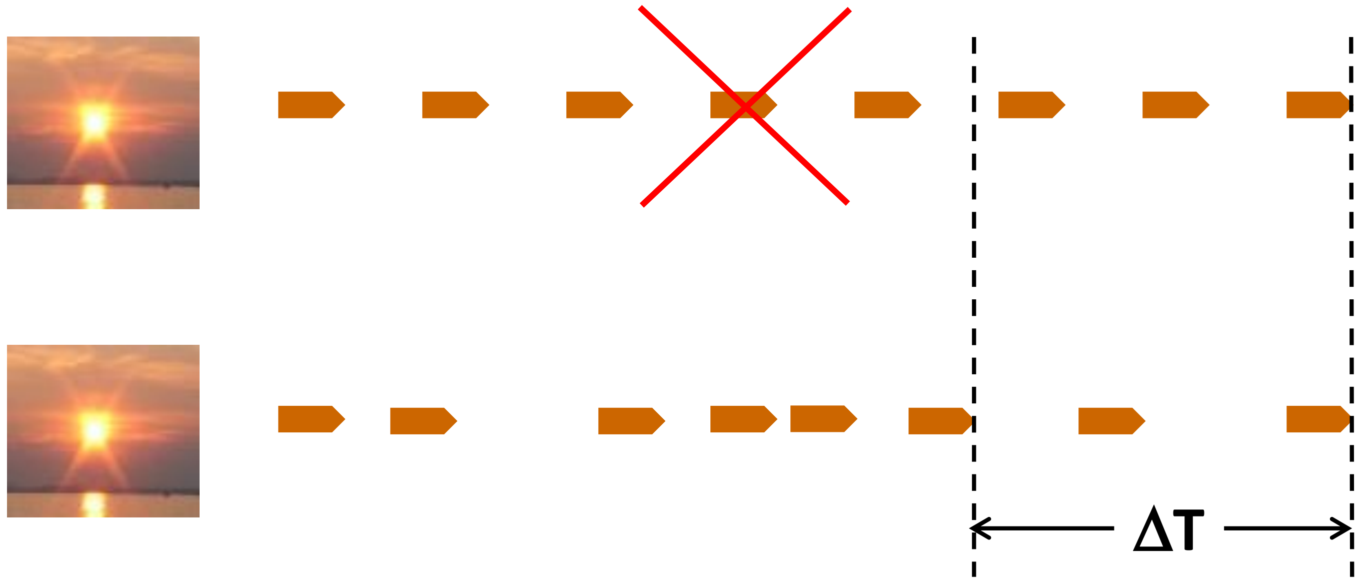
A little science

Photons of light are tiny quanta of energy

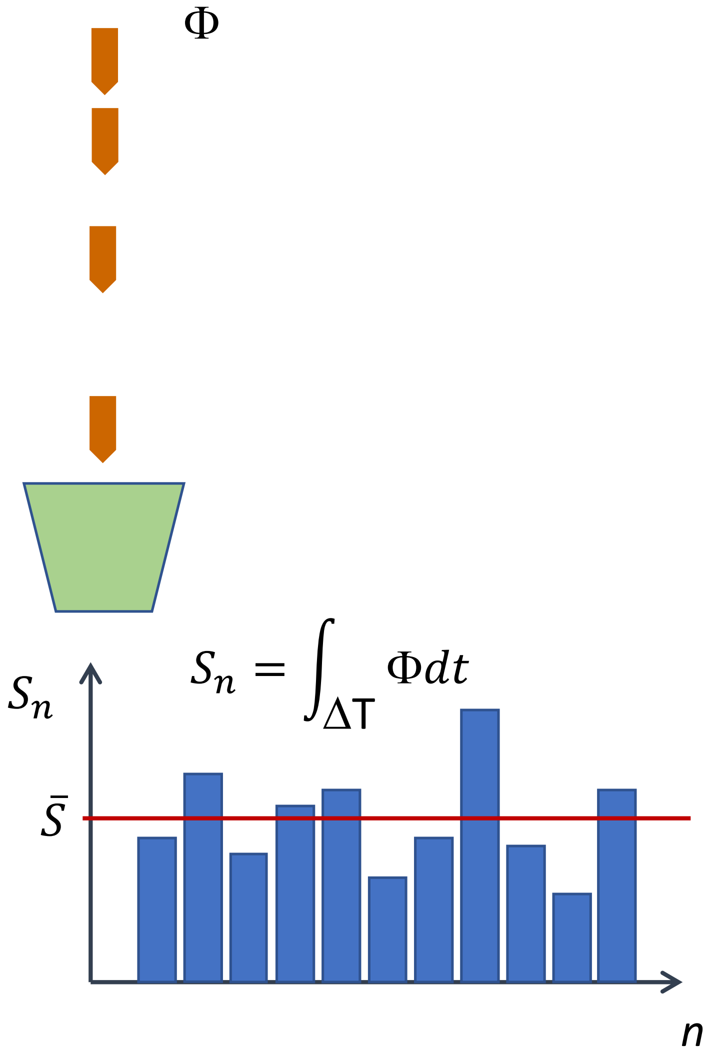
http://www.nktphotonics.com/

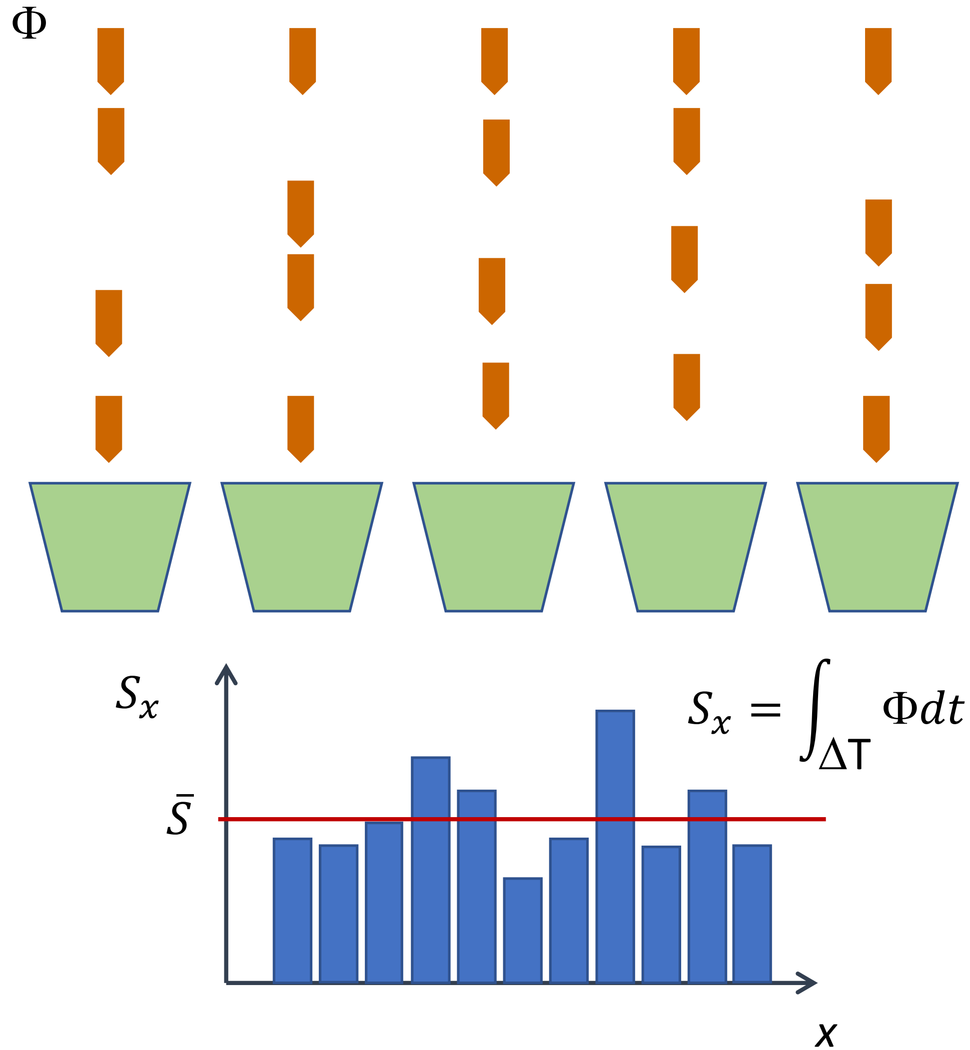
About 10 billion–billion (10^{19}) visible photons per second from a 60W light bulb

Photons are not evenly spaced

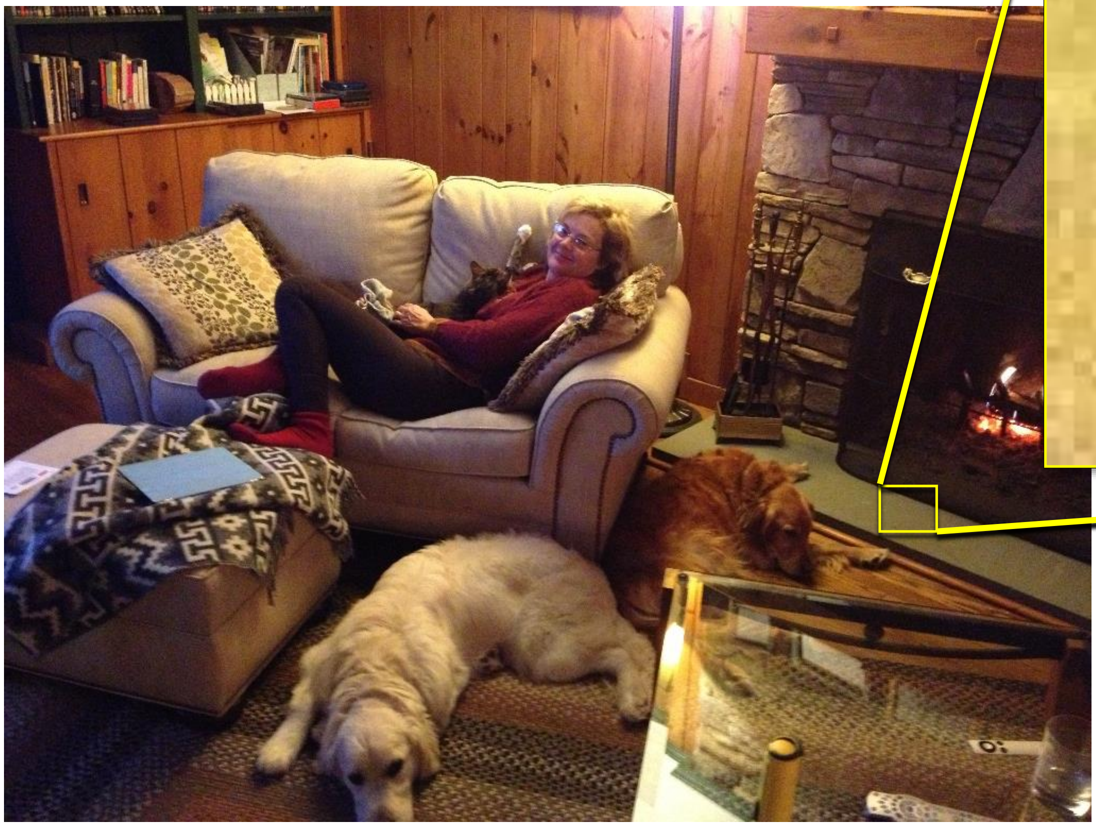


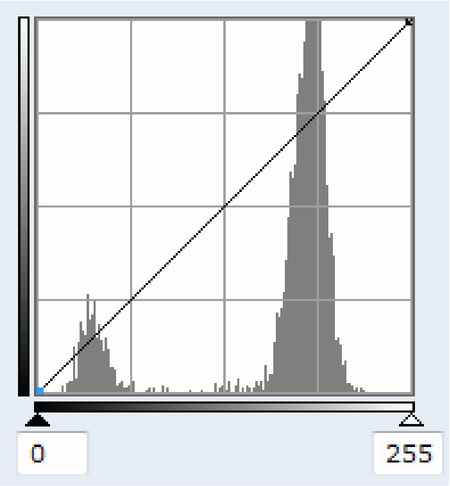
Noise can be temporal or spatial or both



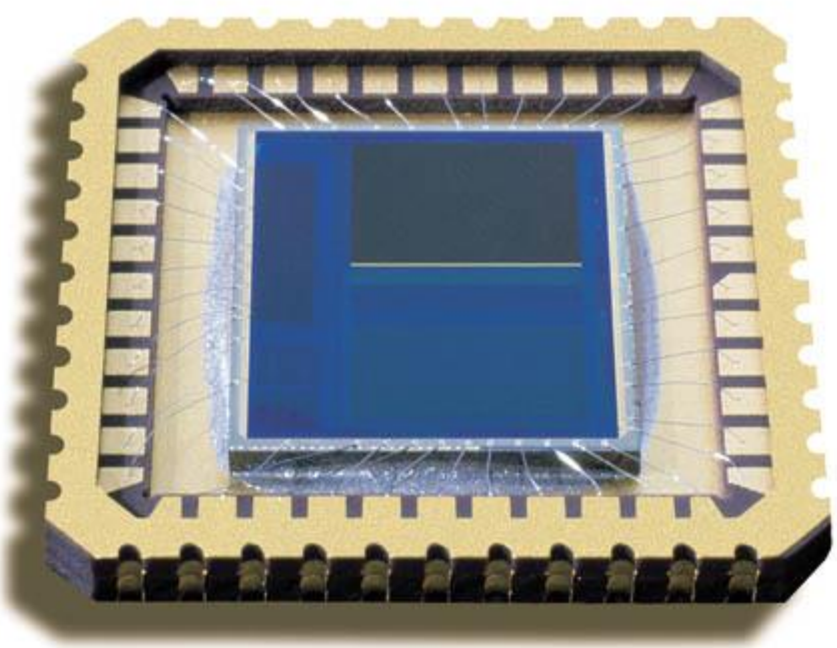


We can see photon shot noise in pictures

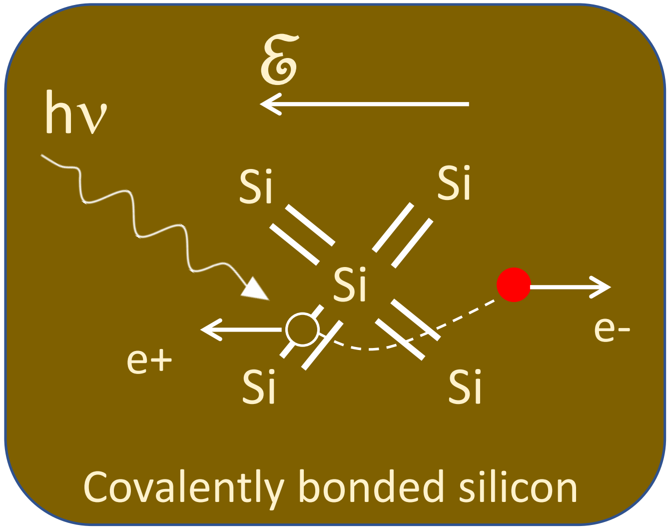


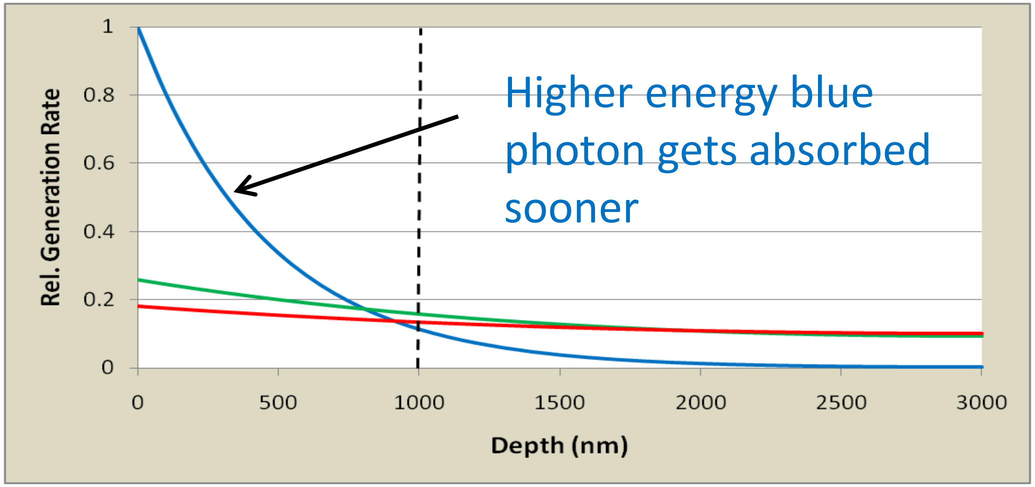


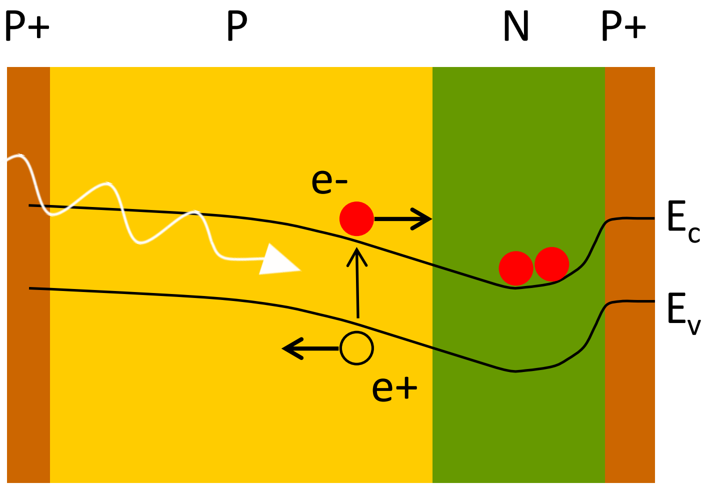
Photons generate photoelectrons in silicon



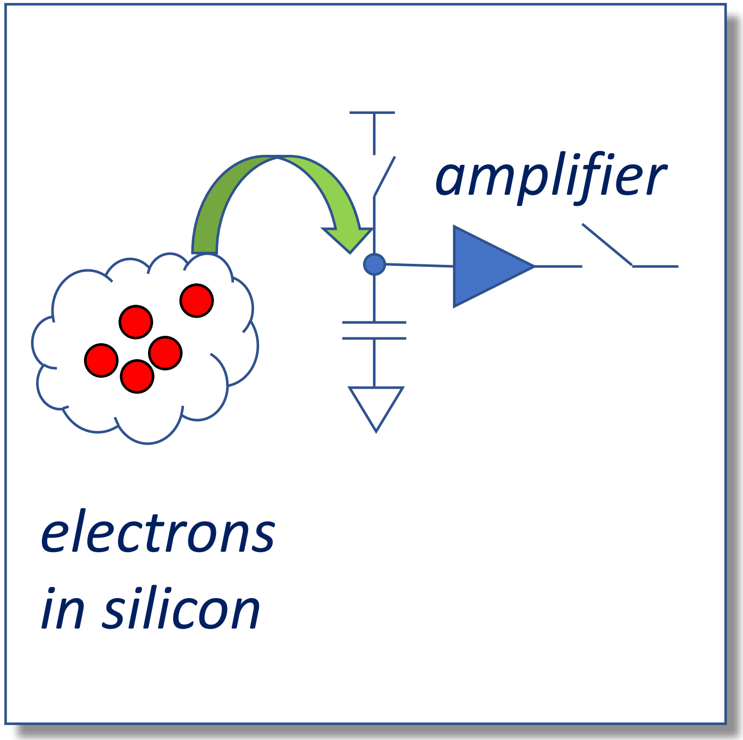
https://spinoff.nasa.gov/spinoff1999/ch2.htm



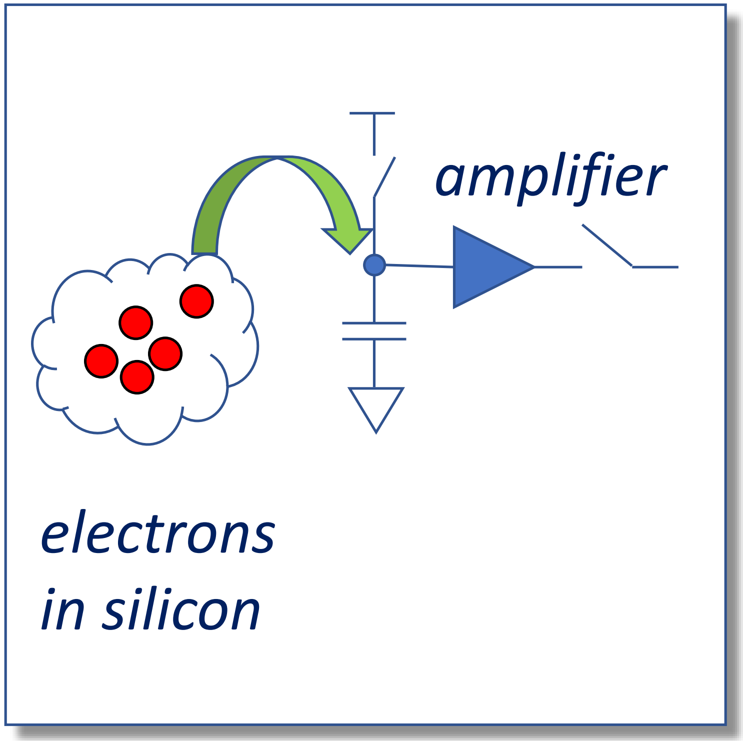




Suppressing thermal noise using correlated double sampling (CDS)



Suppressing thermal noise using correlated double sampling (CDS)

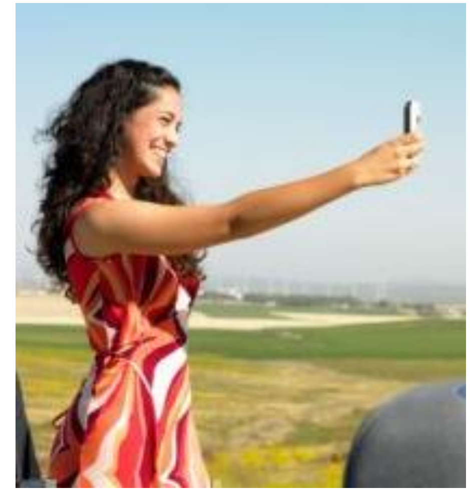


CDS

- Pulse reset switch
- Measure the reset voltage
- Transfer the electrons
- Measure the new voltage
- Signal $\Delta Q = C\ (V_2 - V_1)$

Image Sensors

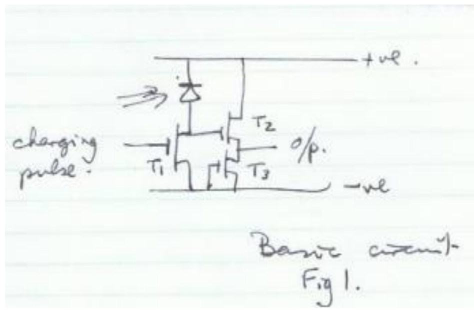
Many kinds of digital cameras



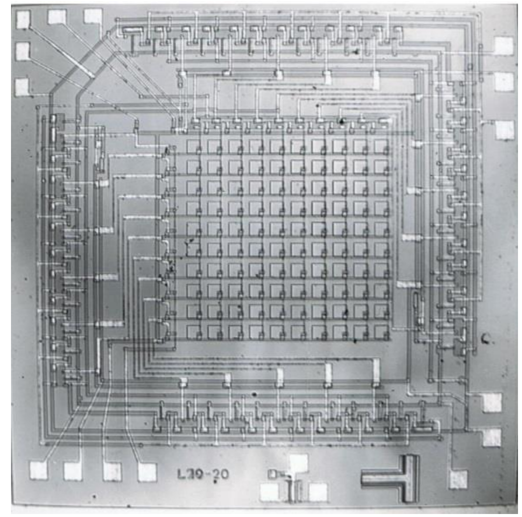
MOS "Photomatrices"
A zeroth generation image sensor

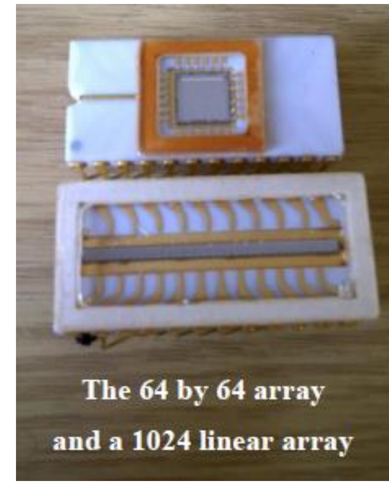
Peter JW Noble

~June 1966



First self-scanned →
Sensor 10x10 1966/67





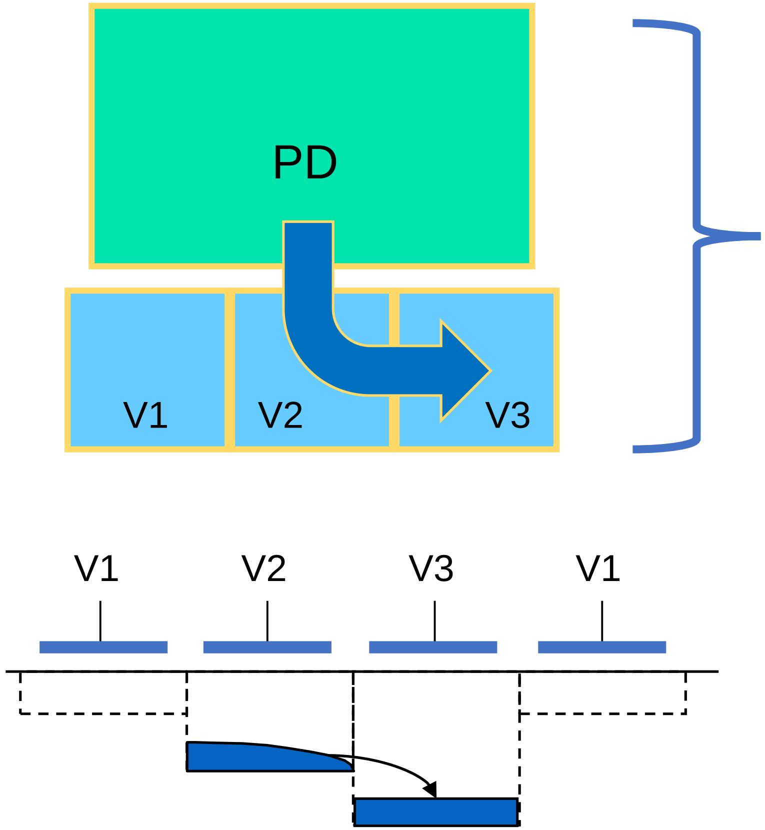
Gene Weckler

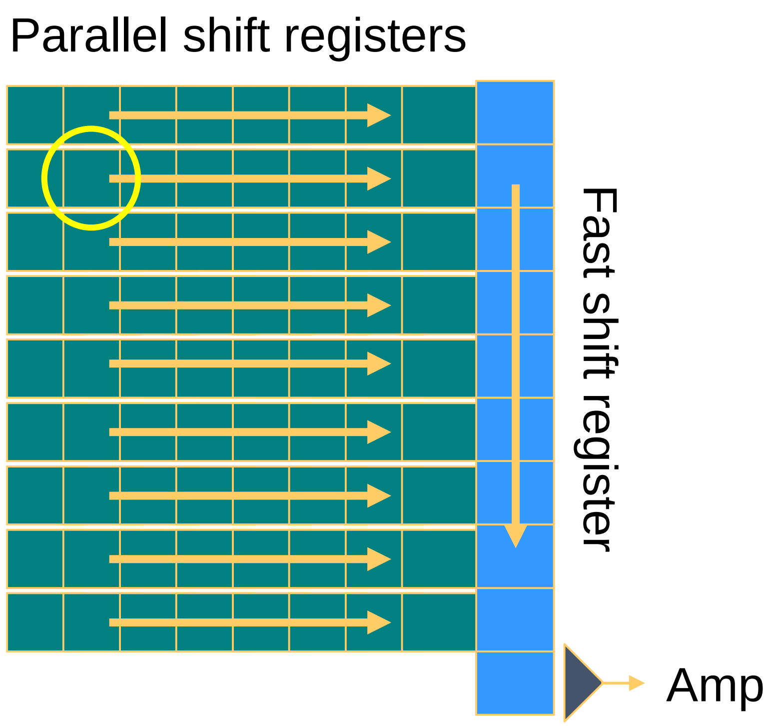
Mid-late 1960's
MOS arrays at Plessey
with startup Integrated Photomatrix Ltd. (IPL)

And Fairchild with startup Reticon

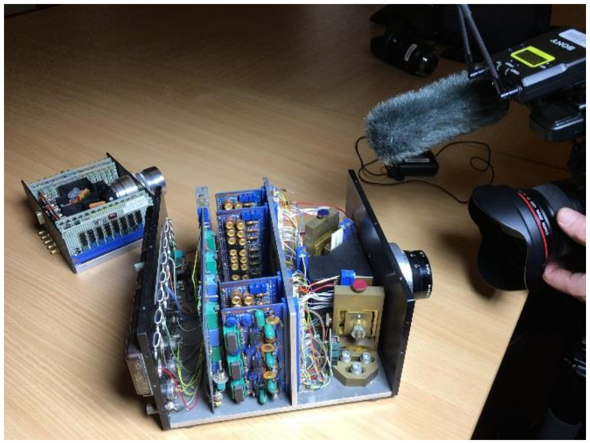
Charge-Coupled Device (CCD)

- CCD invented at Bell Labs 1969, then CCD image sensor in 1970.
- Perfected with mass production in Japan.
- Mainstay of digital cameras and camcorders in 1980’s and 1990’s.





CCD Cameras
1970's - 1990's

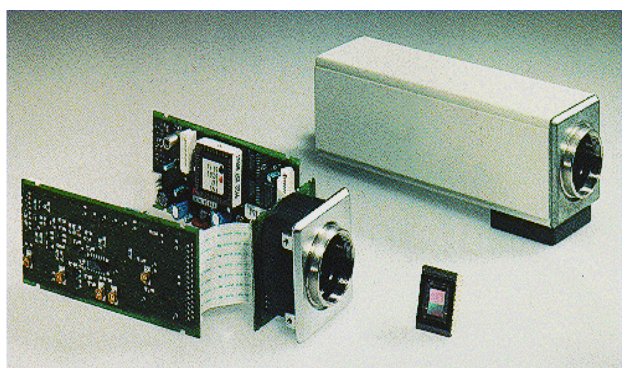


Early 70's Bell Labs CCD camera
by Mike Tompsett et al.

Steve Sasson with first
Kodak self-contained
digital camera (1975)

NASA Galileo Spacecraft CCD camera
(with optics) early '80s (800x800)

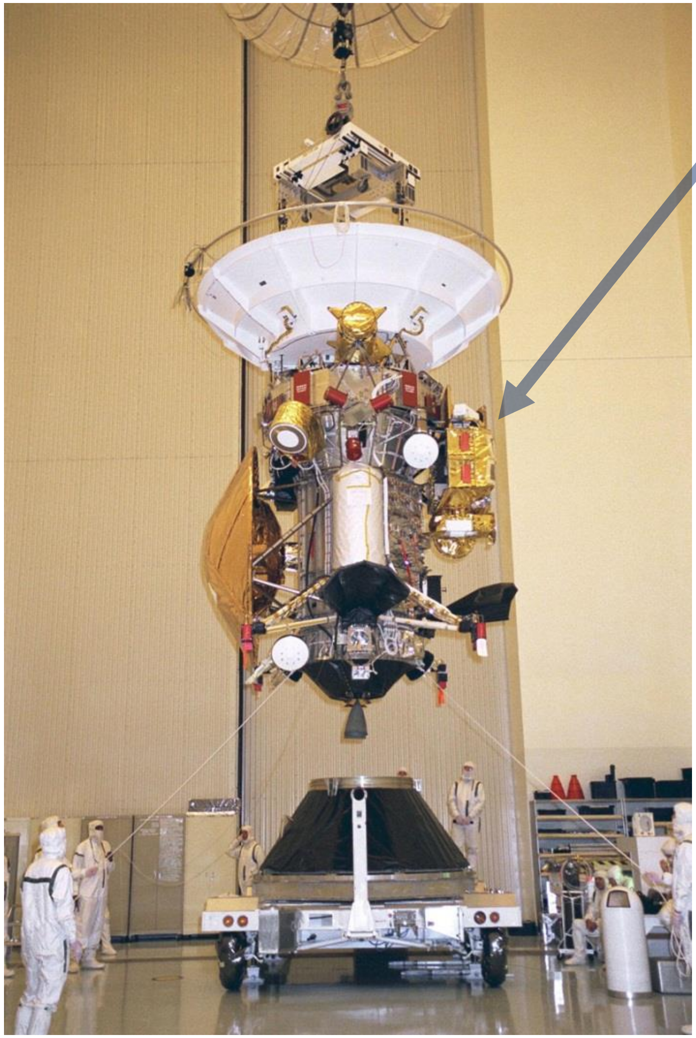
RCA Camcorder



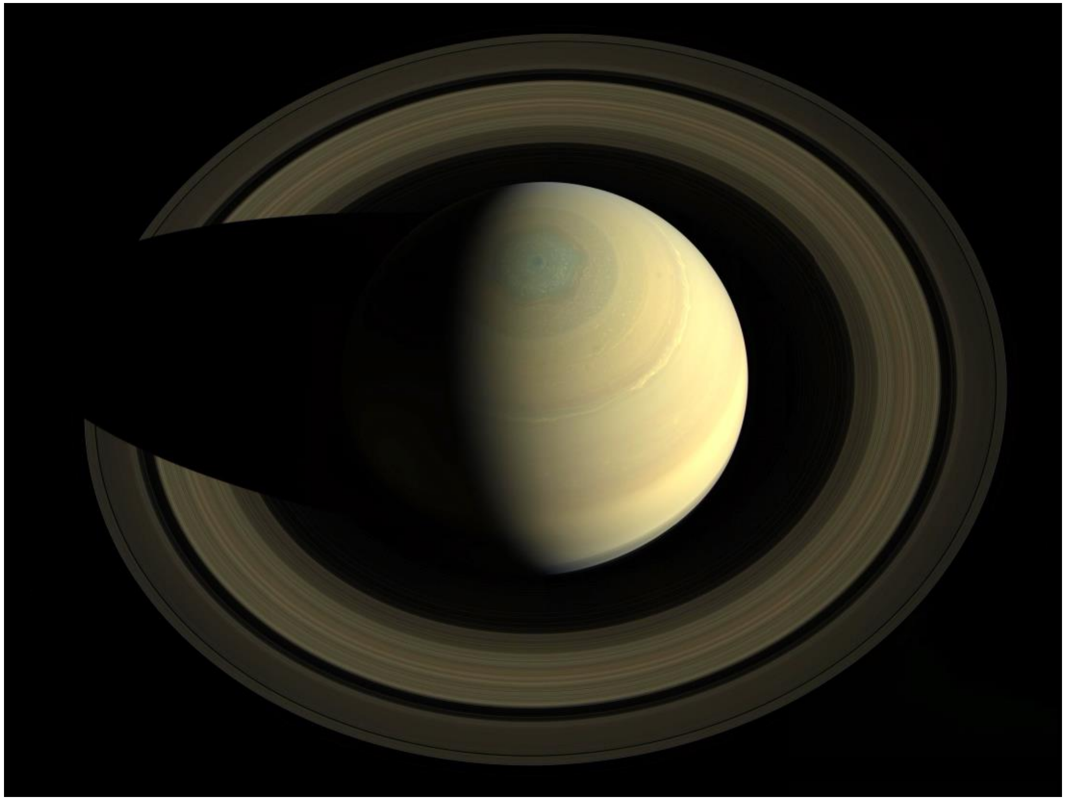
DALSA industrial CCD
camera late '80's

Sony Camcorder
early 90's

1990's NASA needs smaller cameras for smaller interplanetary spacecraft



Cassini CCD camera

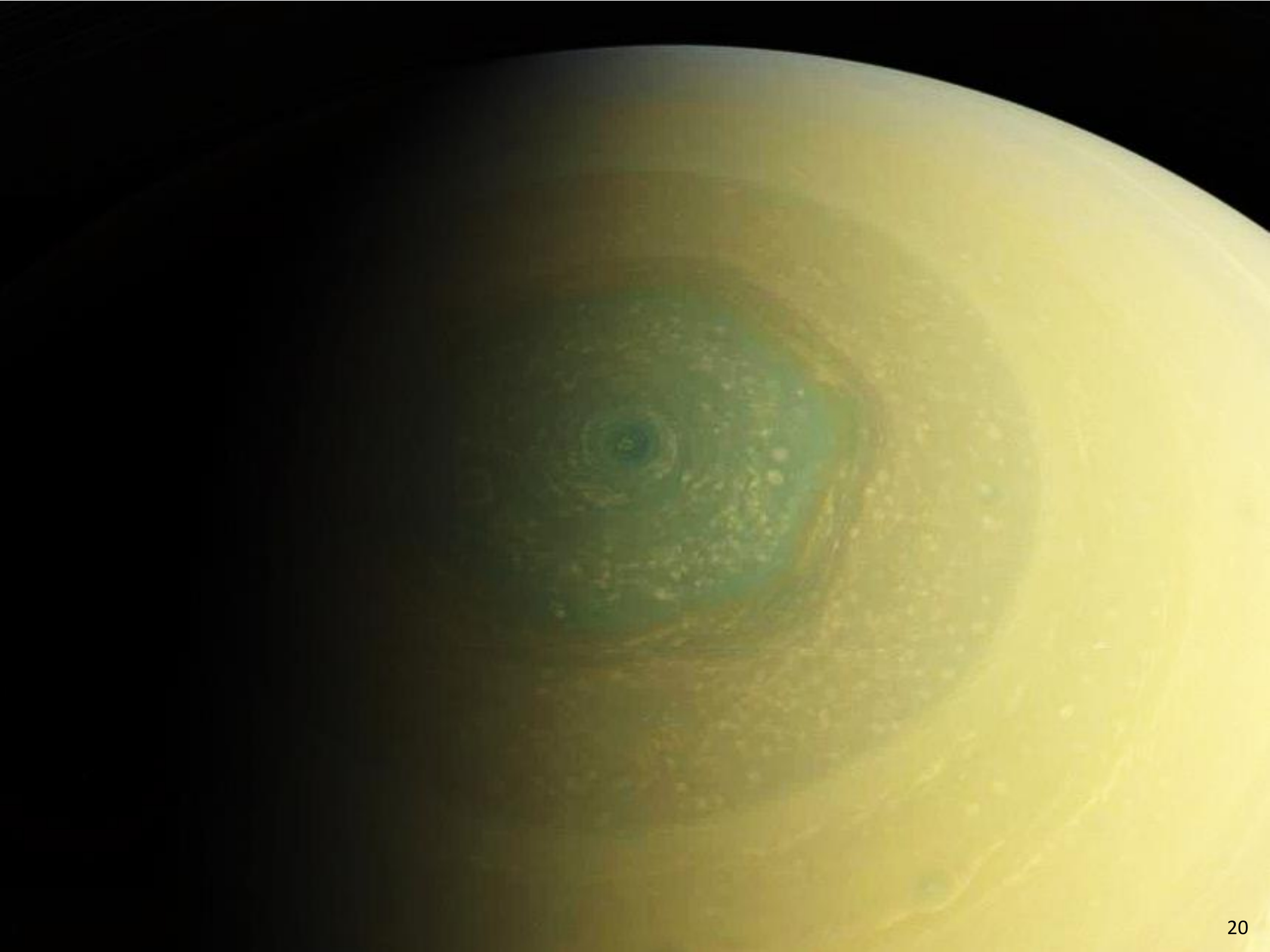


https://photojournal.jpl.nasa.gov/catalog/PIA17474

Saturn from above

Jet Propulsion Laboratory
California Institute of Technology

© ER Fossum 2018

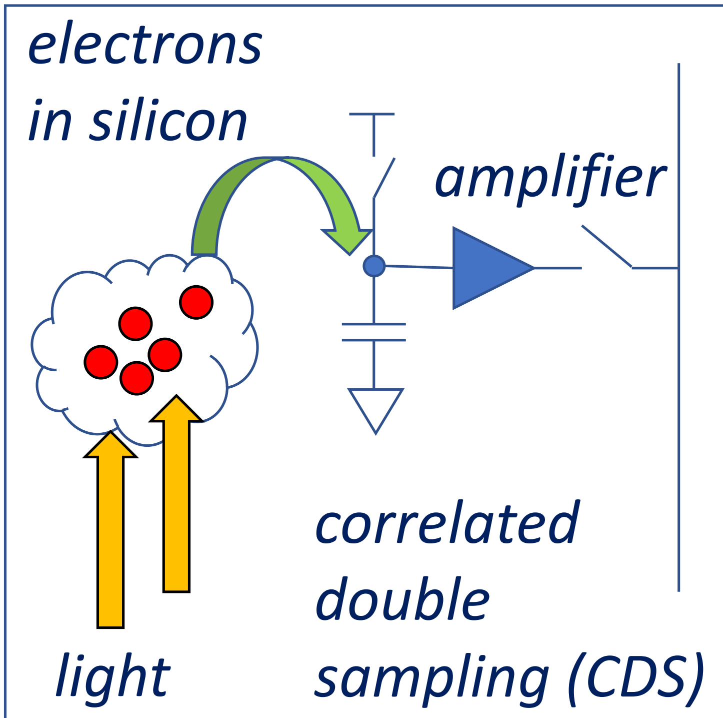


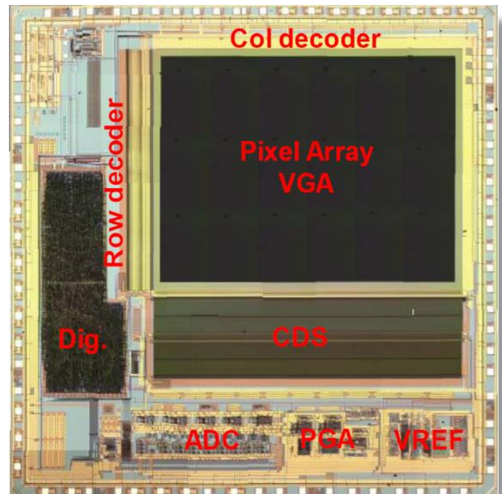
JPL

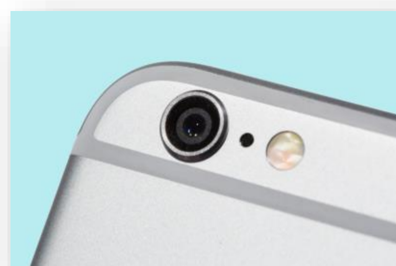
"Camera-on-a-Chip" enables much smaller cameras with lower battery power

Photobit

One Pixel







CMOS active pixel sensor
with intra-pixel charge transfer
US Patent 5,471,515

>5 billion cameras per year
>5 billion uploads per day

Technology Transfer

Entrenched industry moves slowly in adopting new technologies so in February 1995 we founded **Photobit Corporation** to commercialize the CMOS image sensor technology ourselves

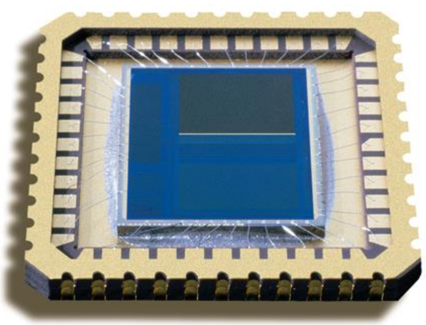
S.Kemeny, N. Doudoumopoulos, E. Fossum, R. Nixon

Perspiration Phase

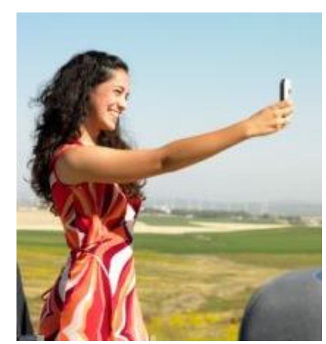
1995-2001 Photobit grows to about 135 persons

- Self funded with custom-design contracts from private industry
- Important support from SBIR programs (NASA/DoD)
- Later, investment from strategic business partners to develop catalog products
- Over 100 new patent applications filed

Nov 2001 Photobit acquired by Micron Technology



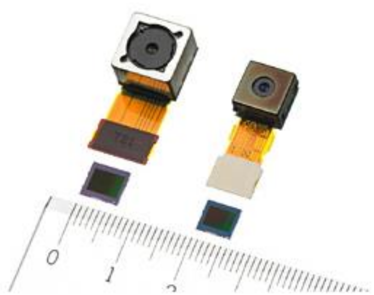


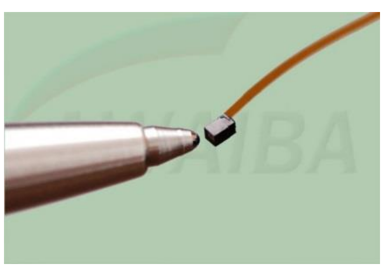



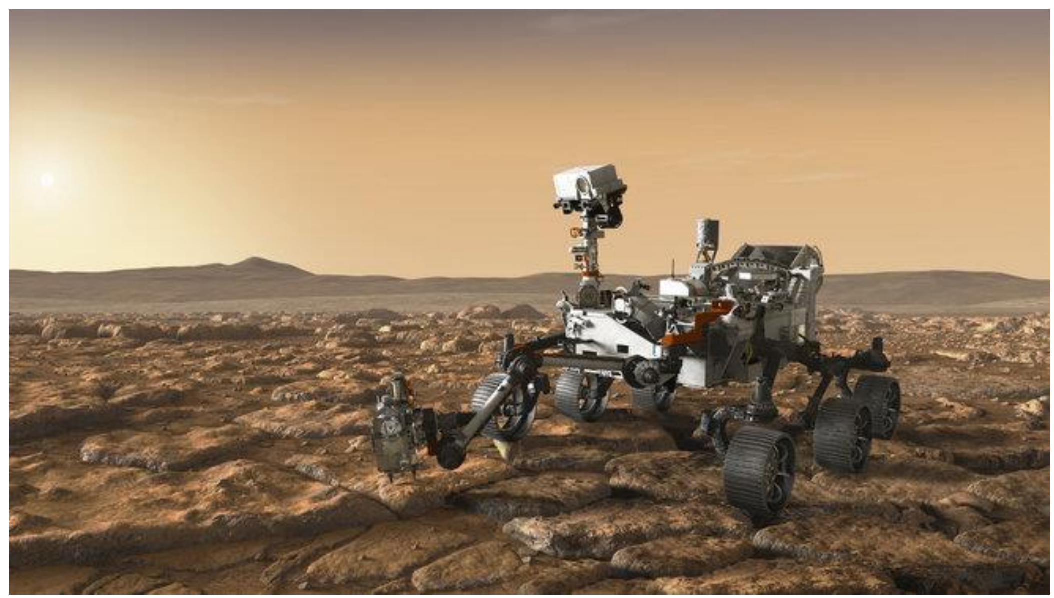
Photobit Corporation team (early 2000)

The technology develops a life of its own

- Thousands of engineers working on this around the globe.
- Today, about 5 billion cameras are manufactured each year that use the CMOS image sensor technology we invented at JPL, or more than 150 cameras per second, 24/365.
- Semiconductor sales of CMOS image sensors were over $12B/yr in 2017.
- Caltech successfully enforced its patents against all the major players.
- NASA is just now adopting the technology for use in space.







2017 Queen Elizabeth Prize for Engineering

For the creation of digital imaging sensors

Eric Fossum	Nobukazu Teranishi	Mike Tompsett

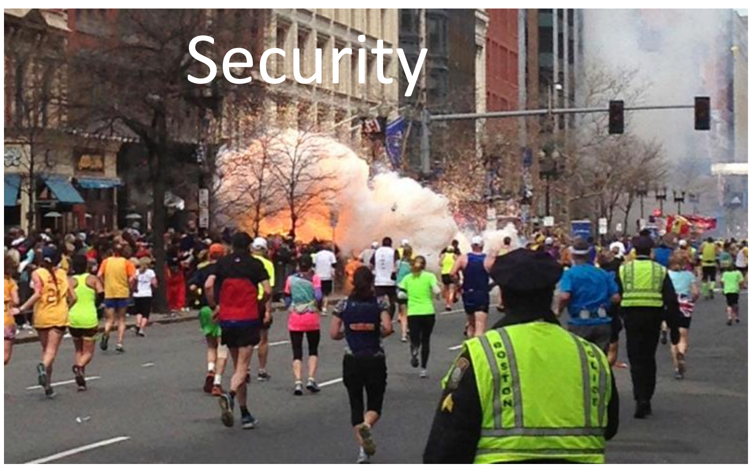
CMOS image sensor	Pinned photodiode	CCD image sensor

+ George Smith CCD

Buckingham Palace Reception
December 2017

New technology invariably brings new social issues

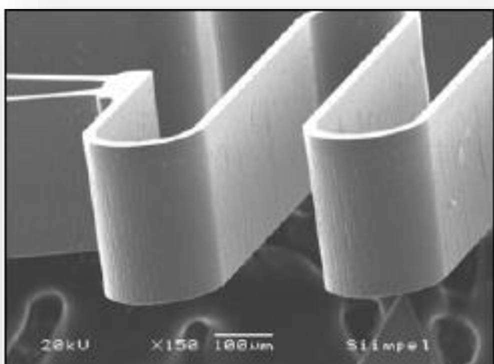
vs.

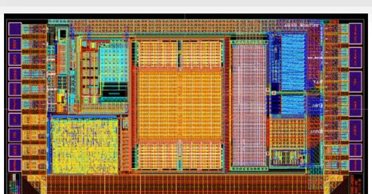


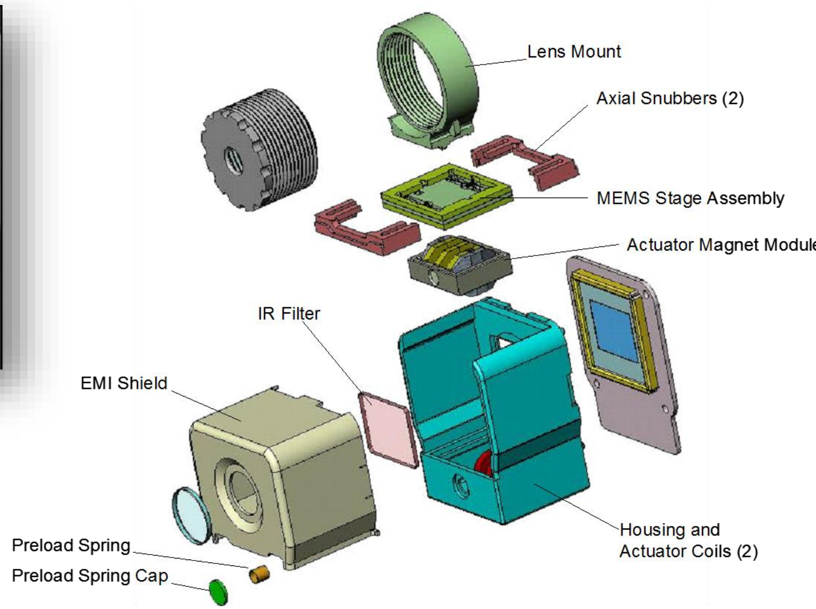
Police officers wearing A.I.-powered smart glasses in Luoyang. Reuters

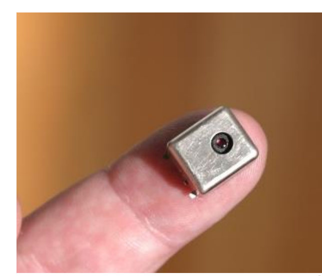
Image-driven Apps


SIIMPEL


20kU ×150 100µm Siimpel




Lens Mount
Axial Snubbers (2)
MEMS Stage Assembly
Actuator Magnet Module
IR Filter
EMI Shield
Housing and
Actuator Coils (2)
Preload Spring
Preload Spring Cap



Counting photons at Dartmouth

Photons of light are tiny quanta of energy

http://www.nktphotonics.com/

Quanta Image Sensor (QIS)
"Count Every Photon"

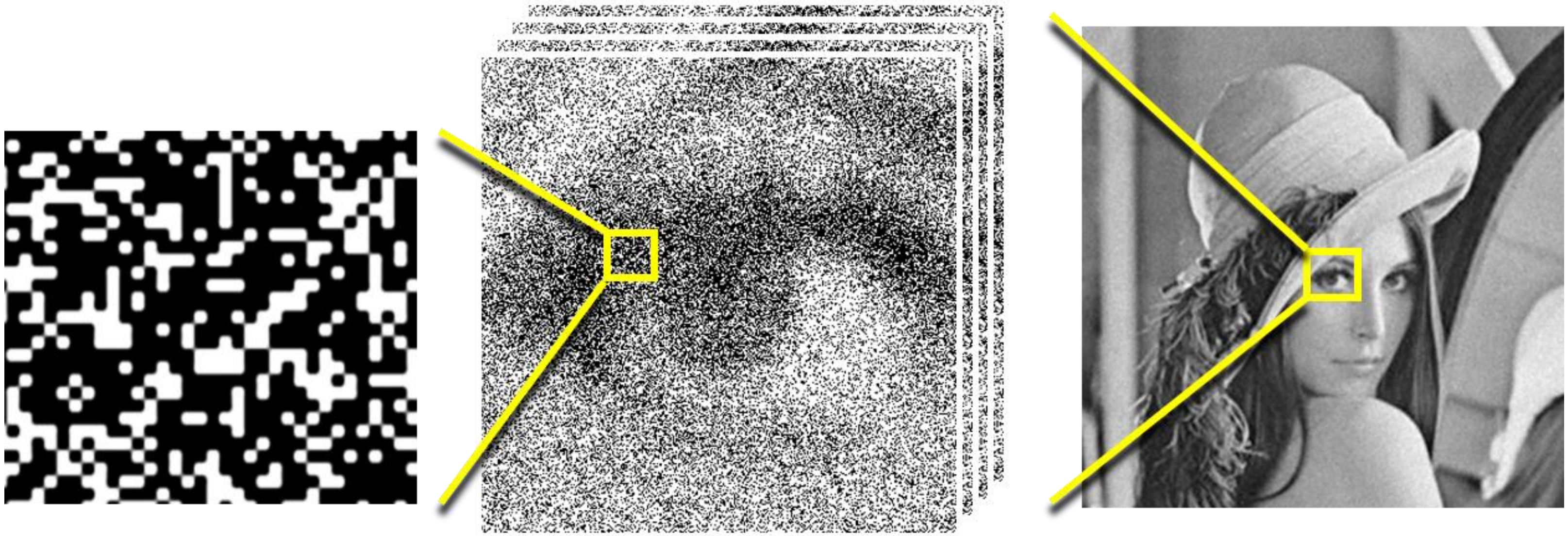
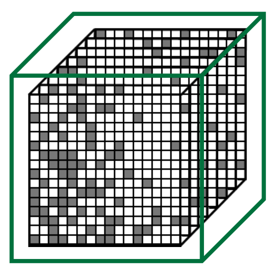


Image
reconstruction
X-Y-t Bit Density ➔ Gray Scale

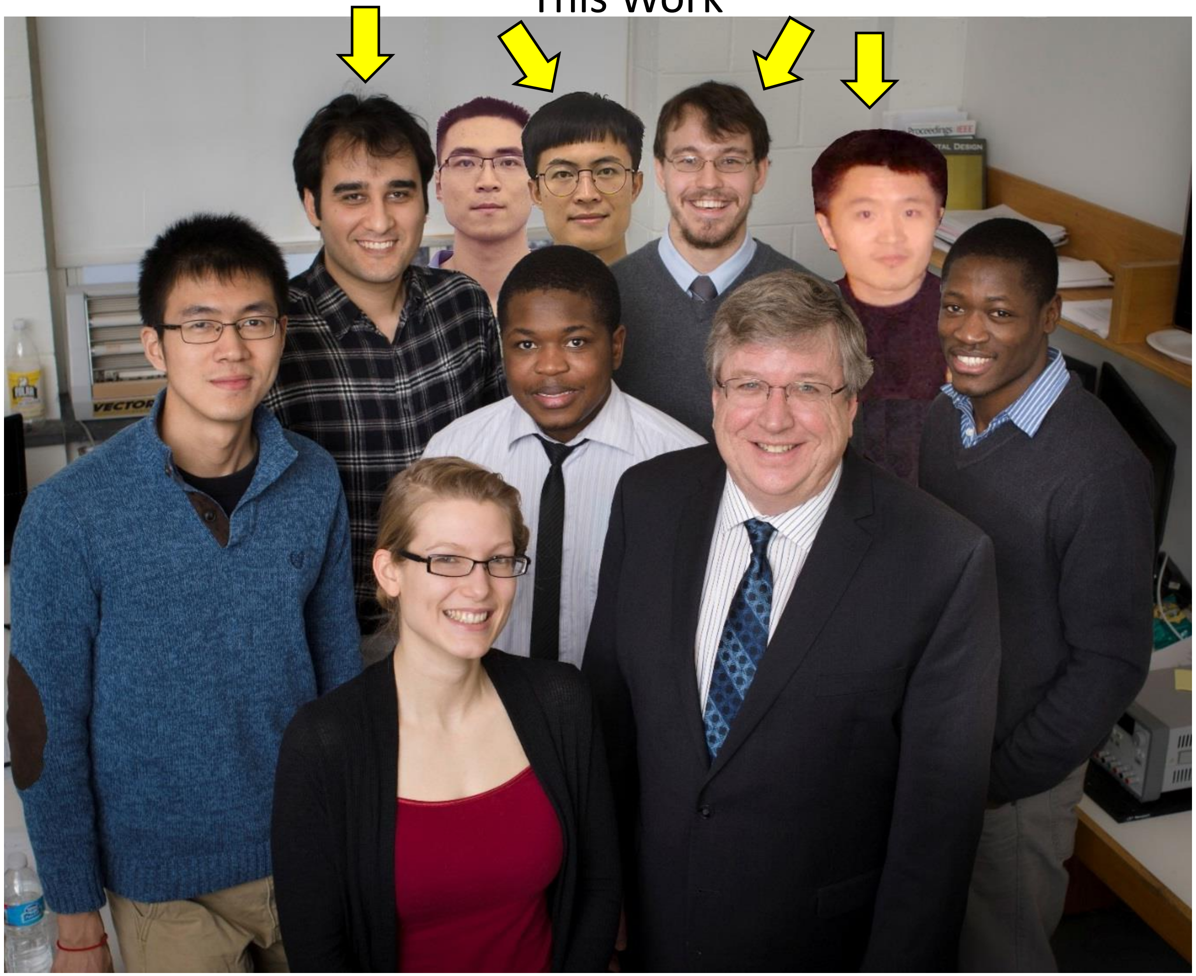


Cubicle

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

Group at Dartmouth

This Work



L-R: Song Chen, Saleh Masoodian, Rachel Zizza, Zhaoyang Yin, Donald Hondongwa, Wei Deng, Dakota Starkey, Eric Fossum, Jiaju Ma, Leo Anzagira

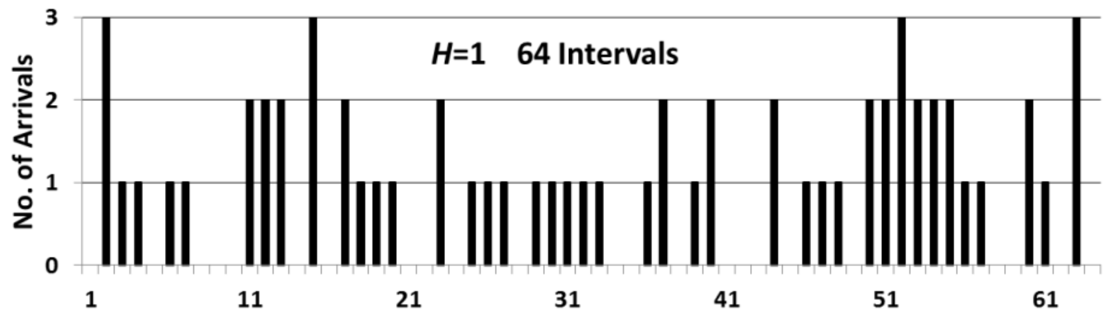
Photon and photoelectron arrival rate described by Poisson process

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

Probability of k arrivals

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

Monte Carlo



For 1b jot, only two states of interest

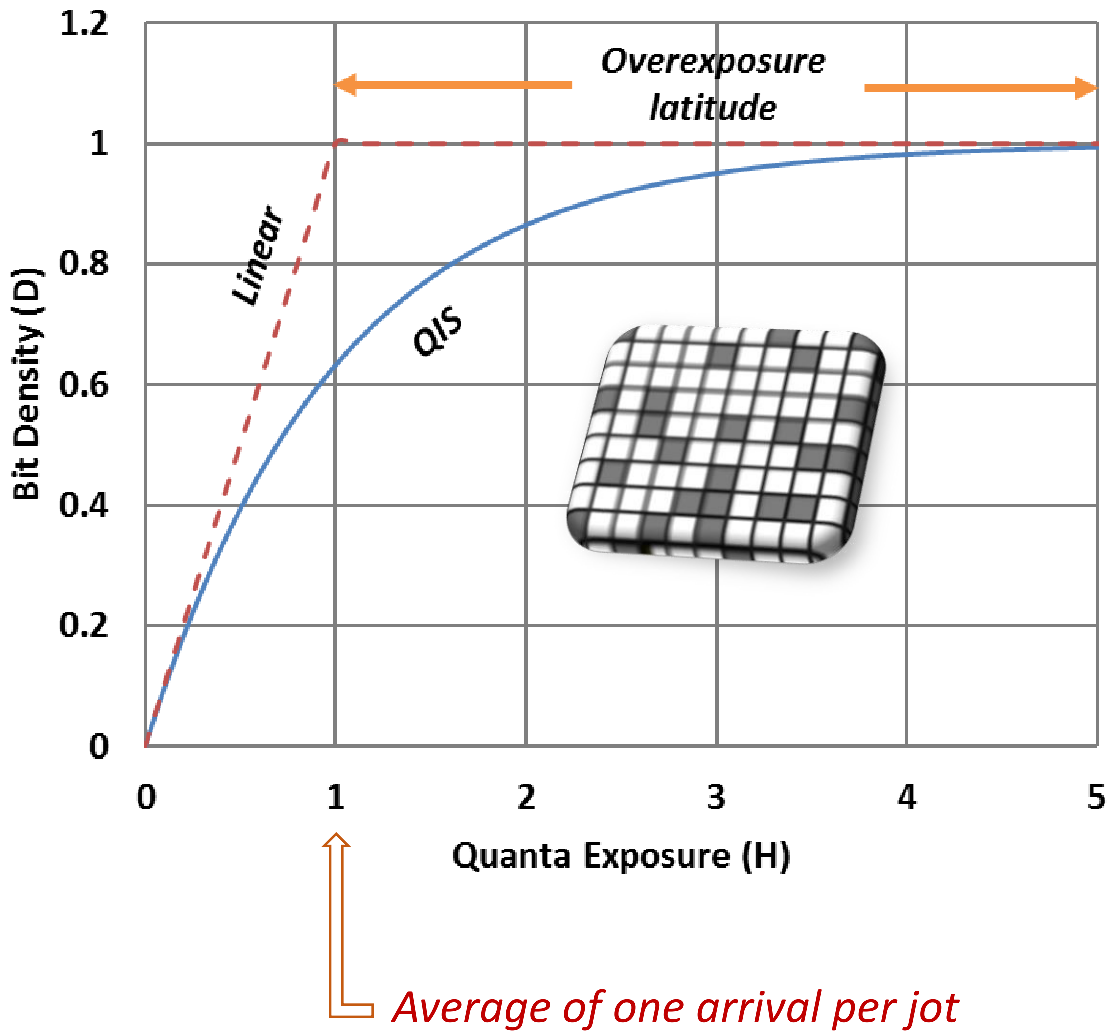
$$P[0] = e^{-H}$$

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

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

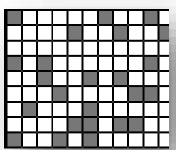
Photoresponse as bit density

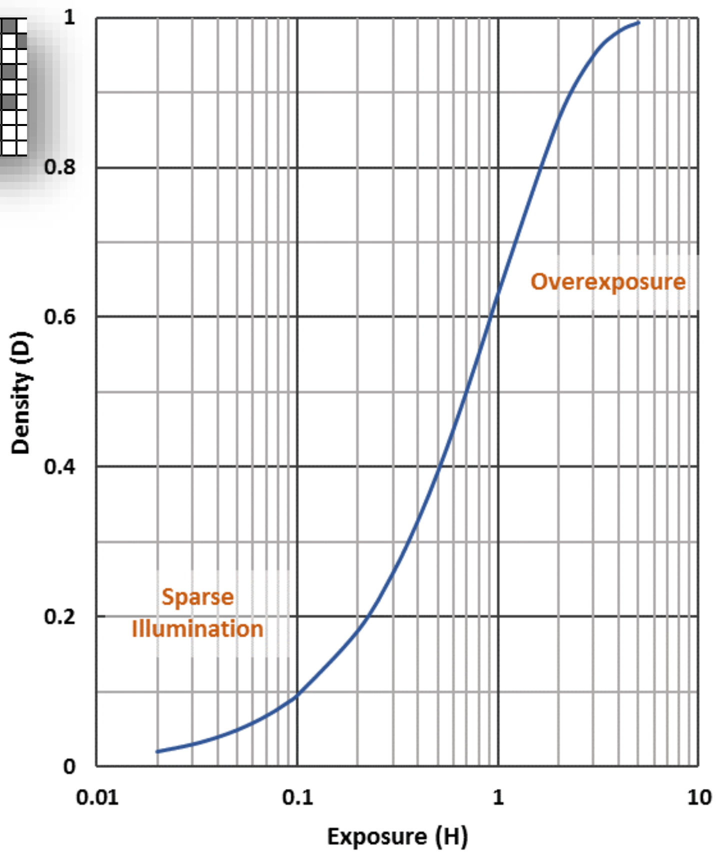
$$Bit\ Density\ D \triangleq \frac{M_1}{M} = 1 - e^{-H}$$



QIS responds to light

QIS D – log H

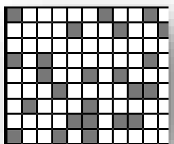


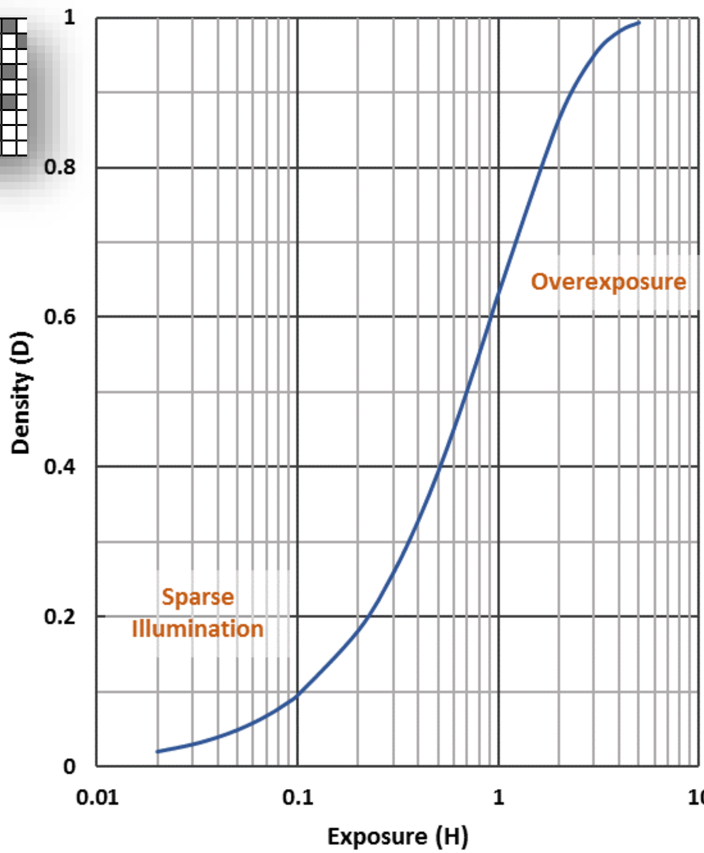


Bit Density vs. Exposure

QIS responds to light like film

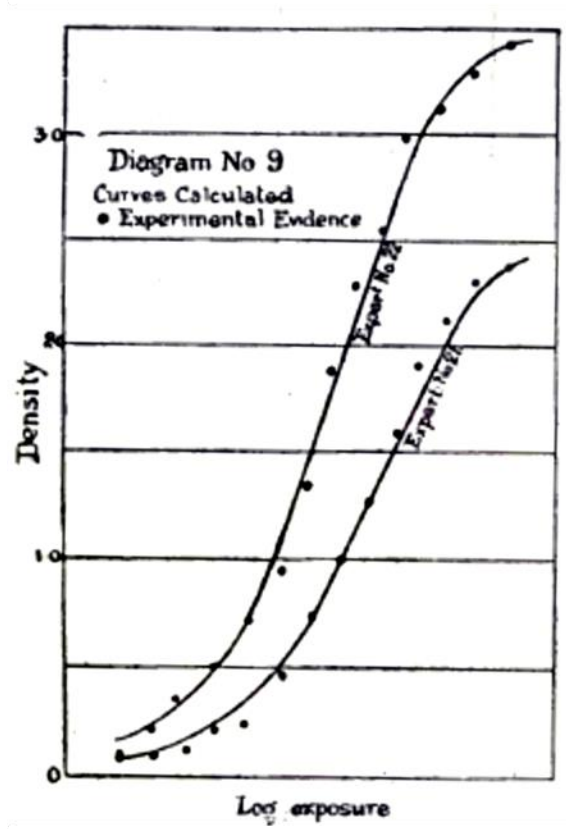
QIS D – log H



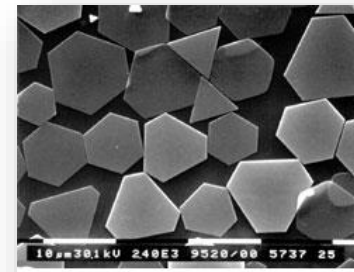


Bit Density vs. Exposure

Film D – log H



Film Density vs. Exposure
1890 Hurter and Driffield

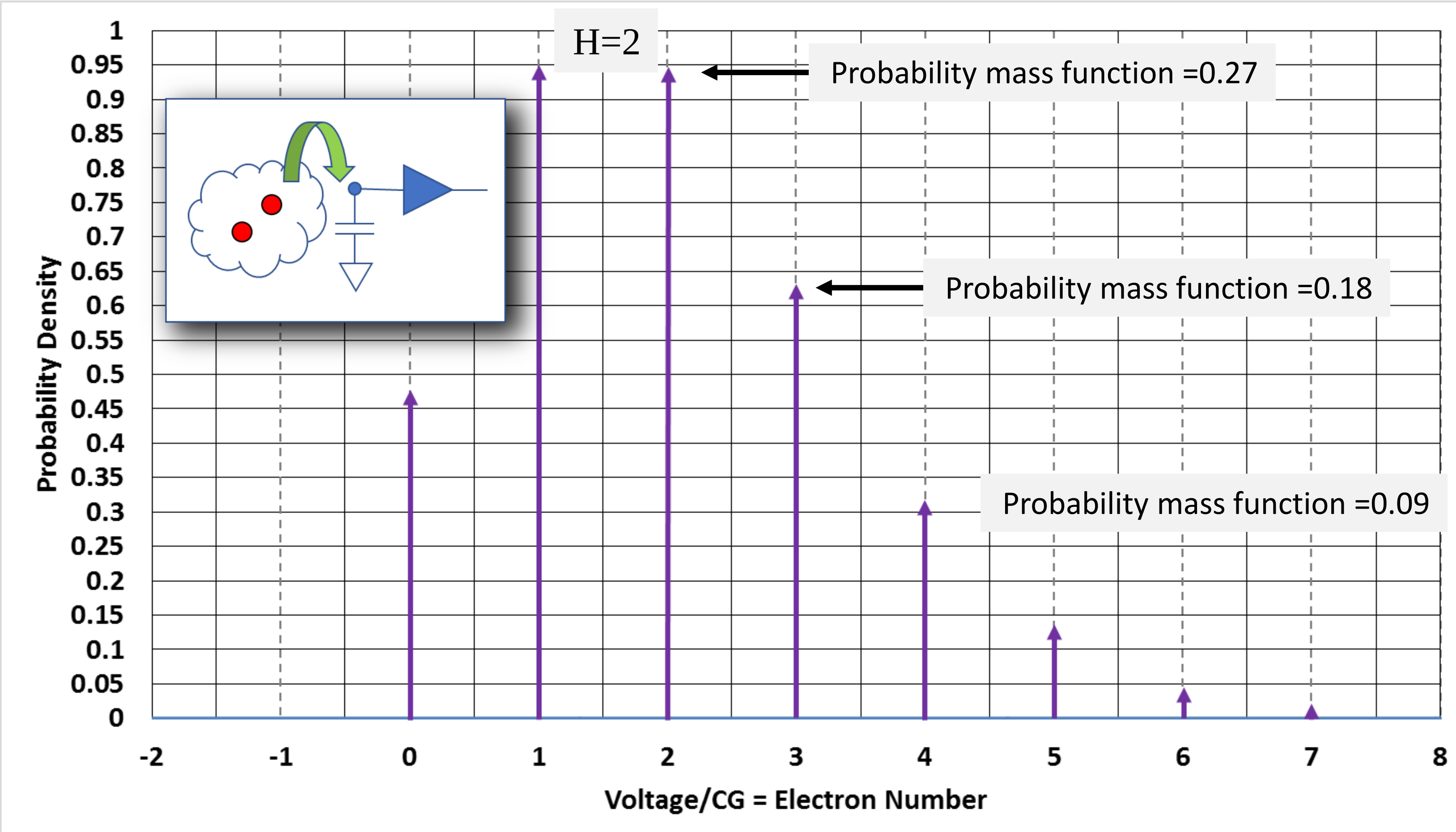


Electron micrograph of tabular grain emulsion

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

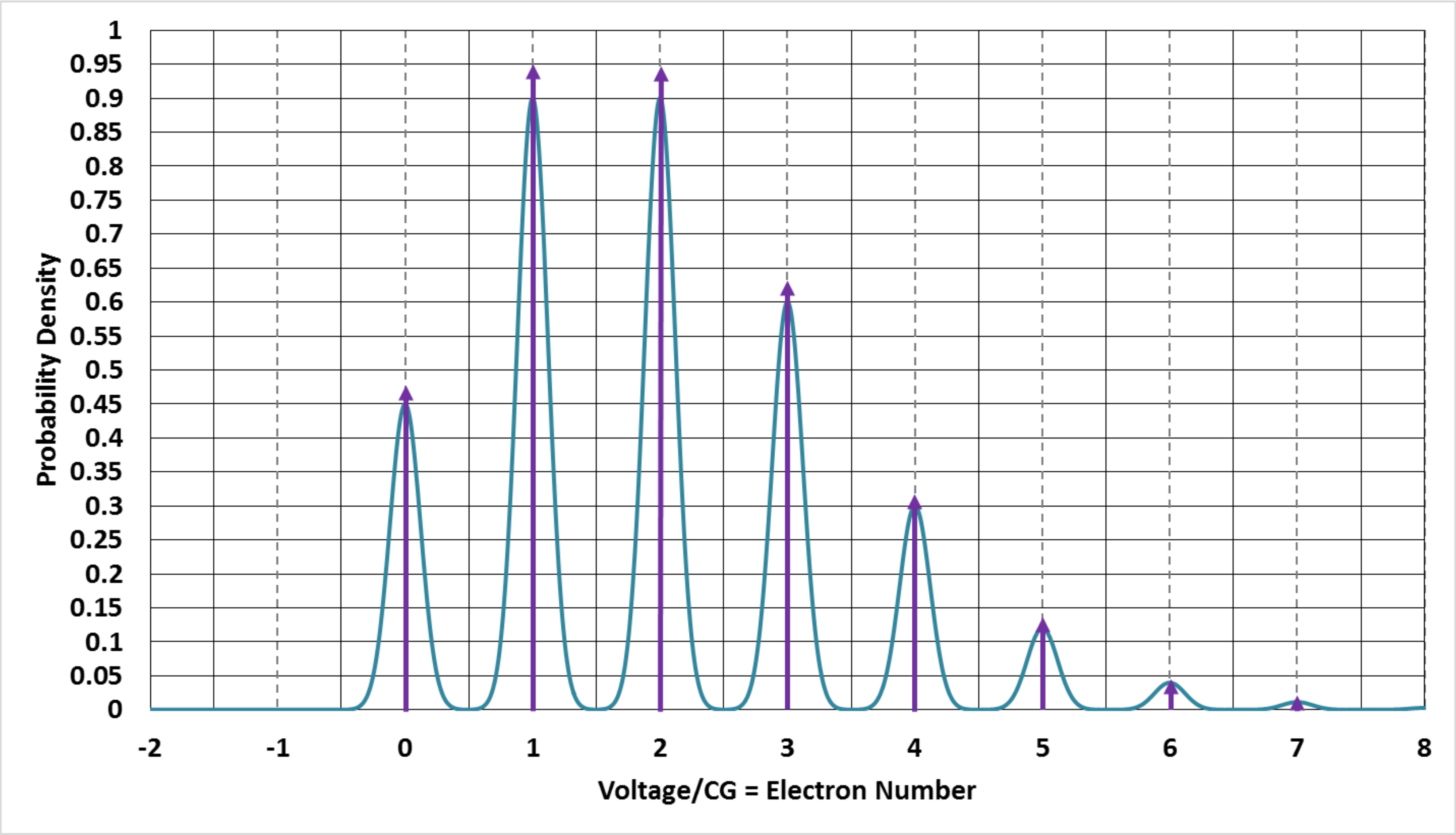
Voltage Output with No Electronics Noise

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

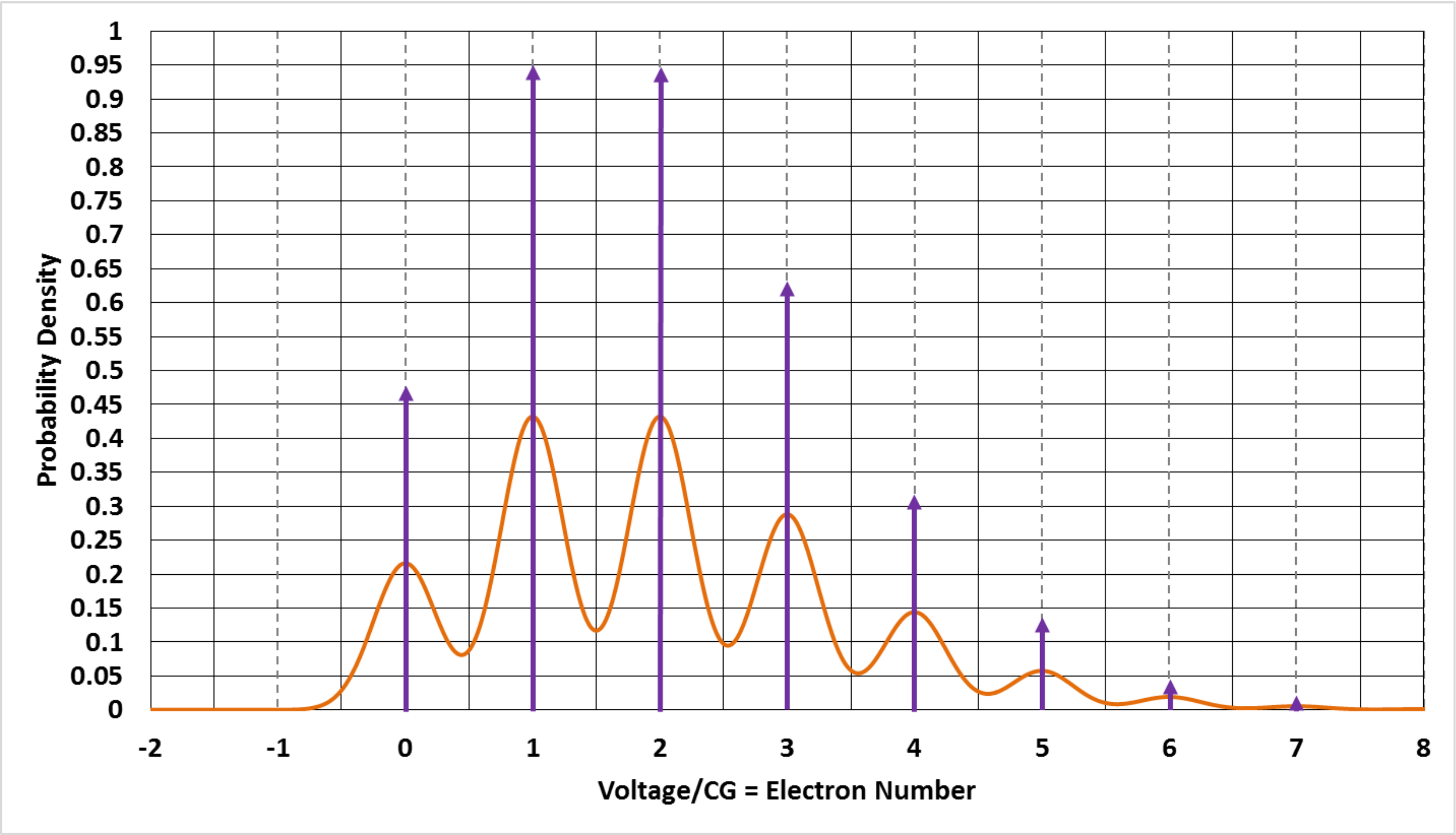


Broadened by 0.12e- rms read noise

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

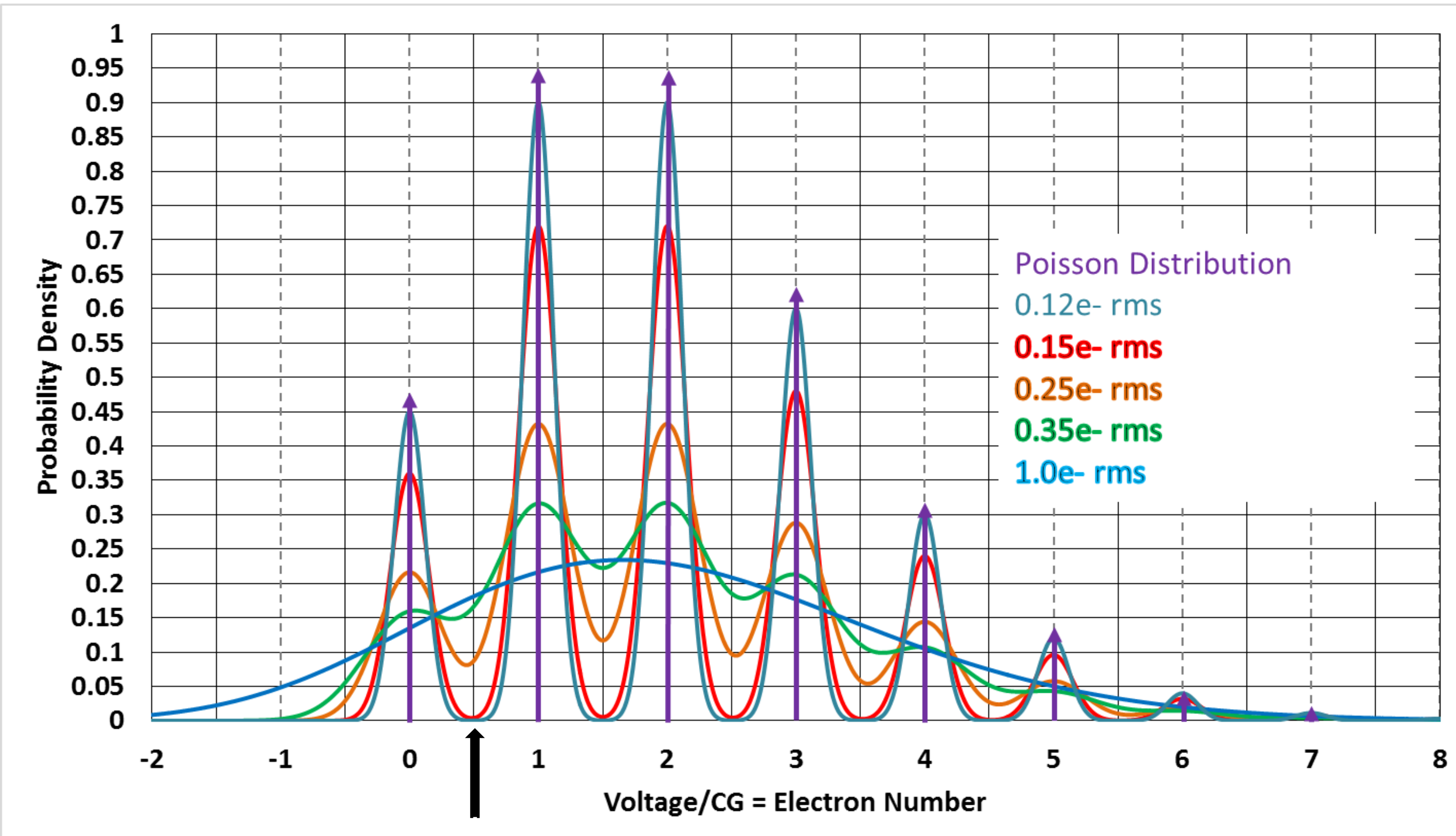


Broadened by 0.25e- rms read noise



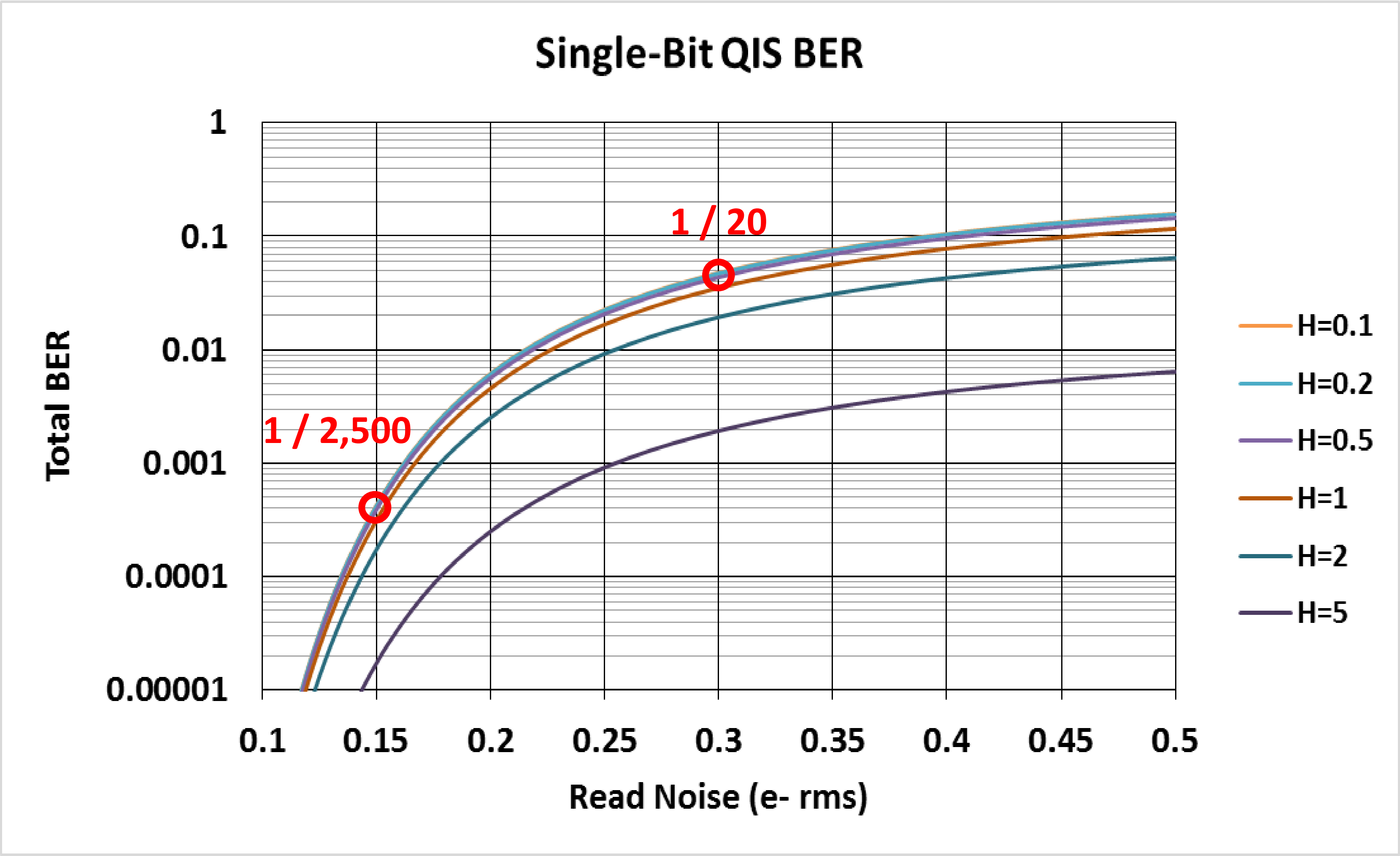
Model

Quantized Values Broadened by Readout Noise



“0” “1”

Bit error rate (BER) depends strongly on read noise

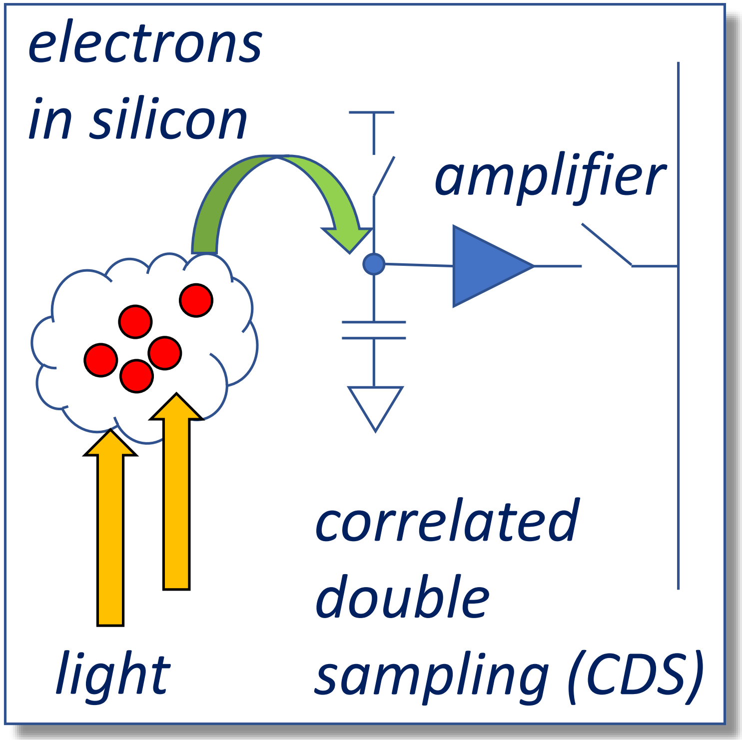


Our approach

Use very low capacitance sense node

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

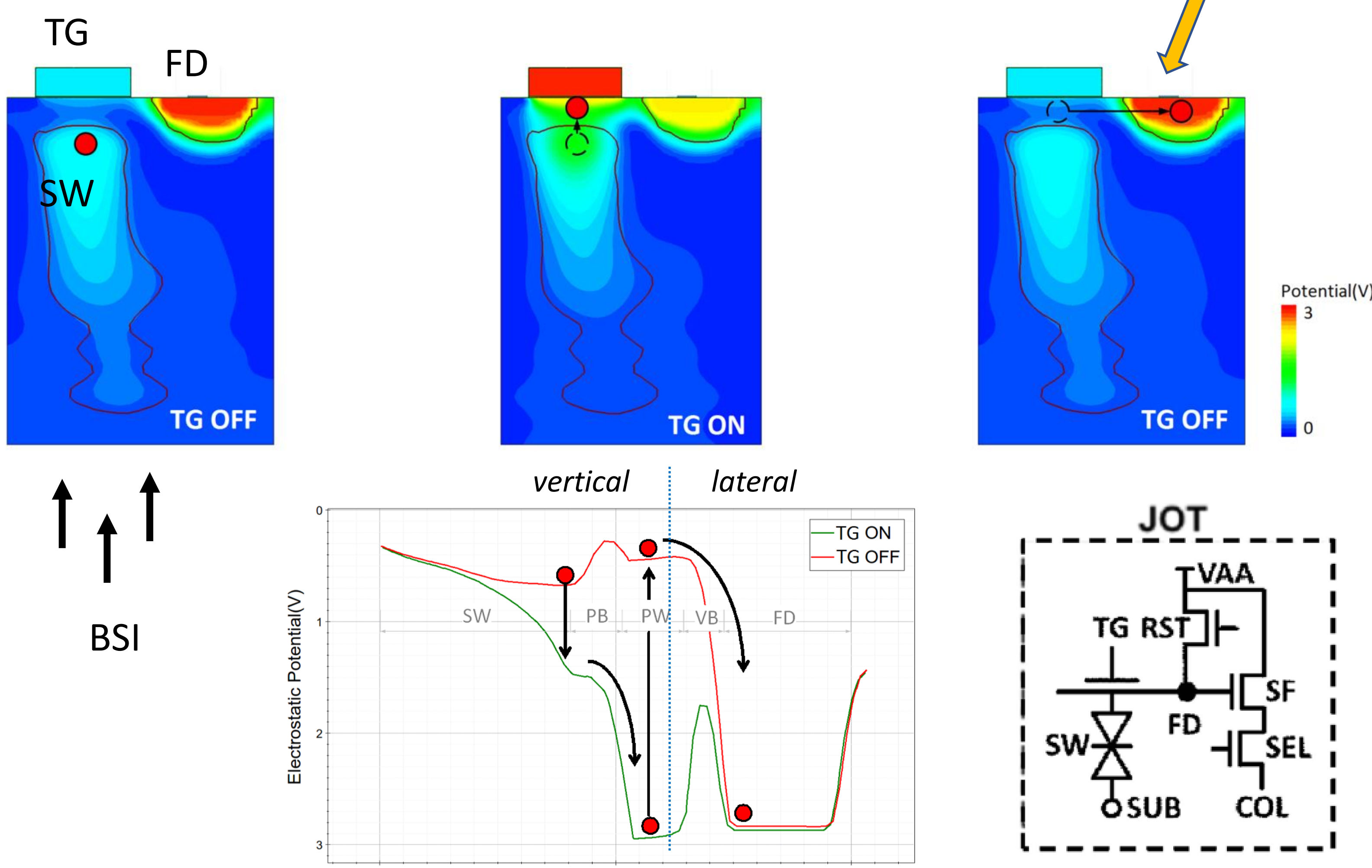
$$1mV = 1.6e\text{-}19 / 0.16fF$$



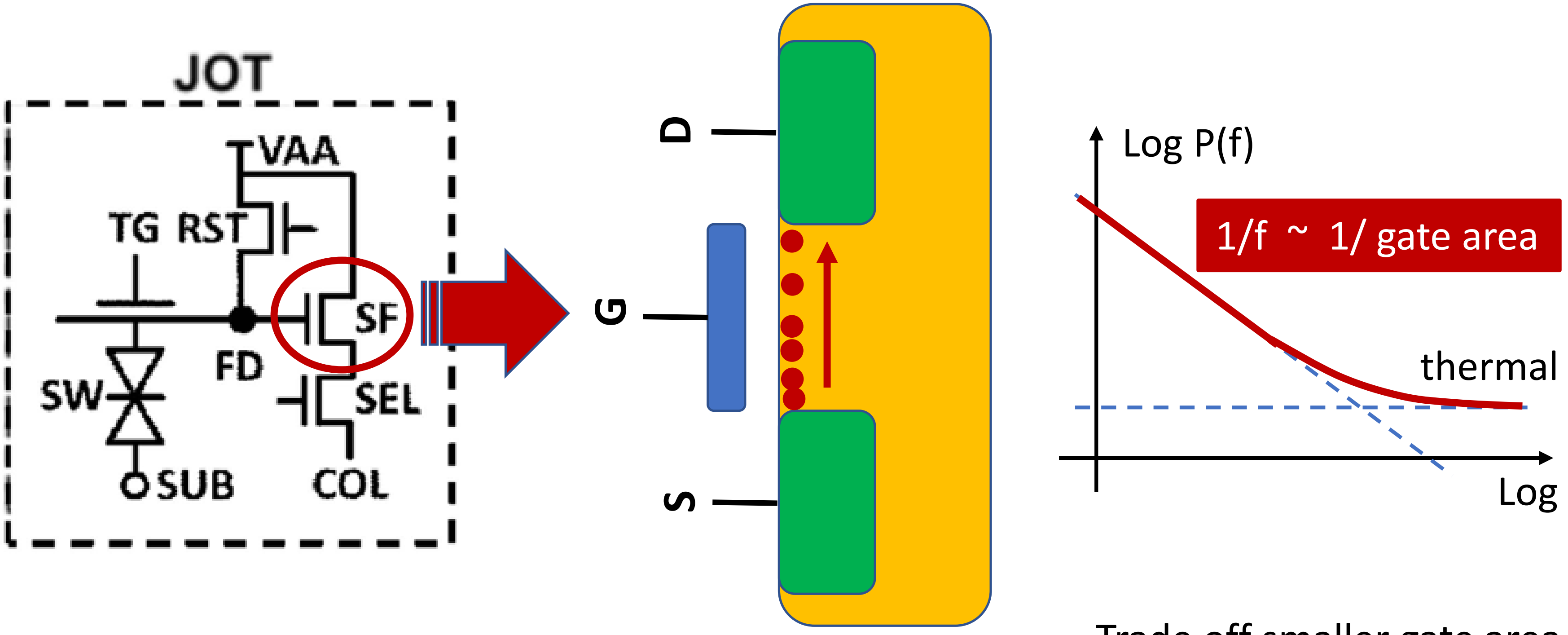
Pump-Gate Jot: Minimize TG-FD overlap capacitance

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

Highest possible CG
(Lowest possible cap.)

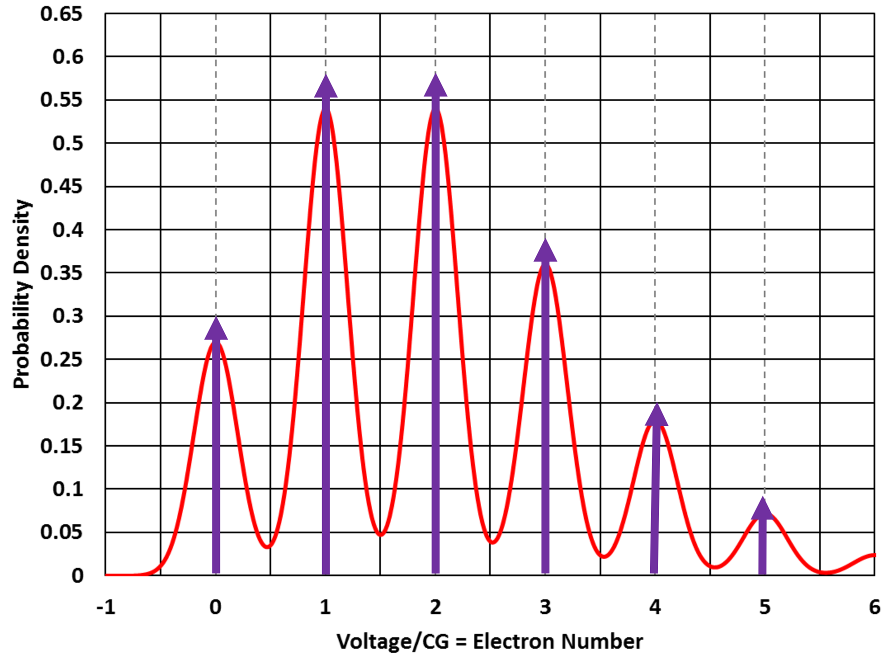


Noise in first transistor is critical



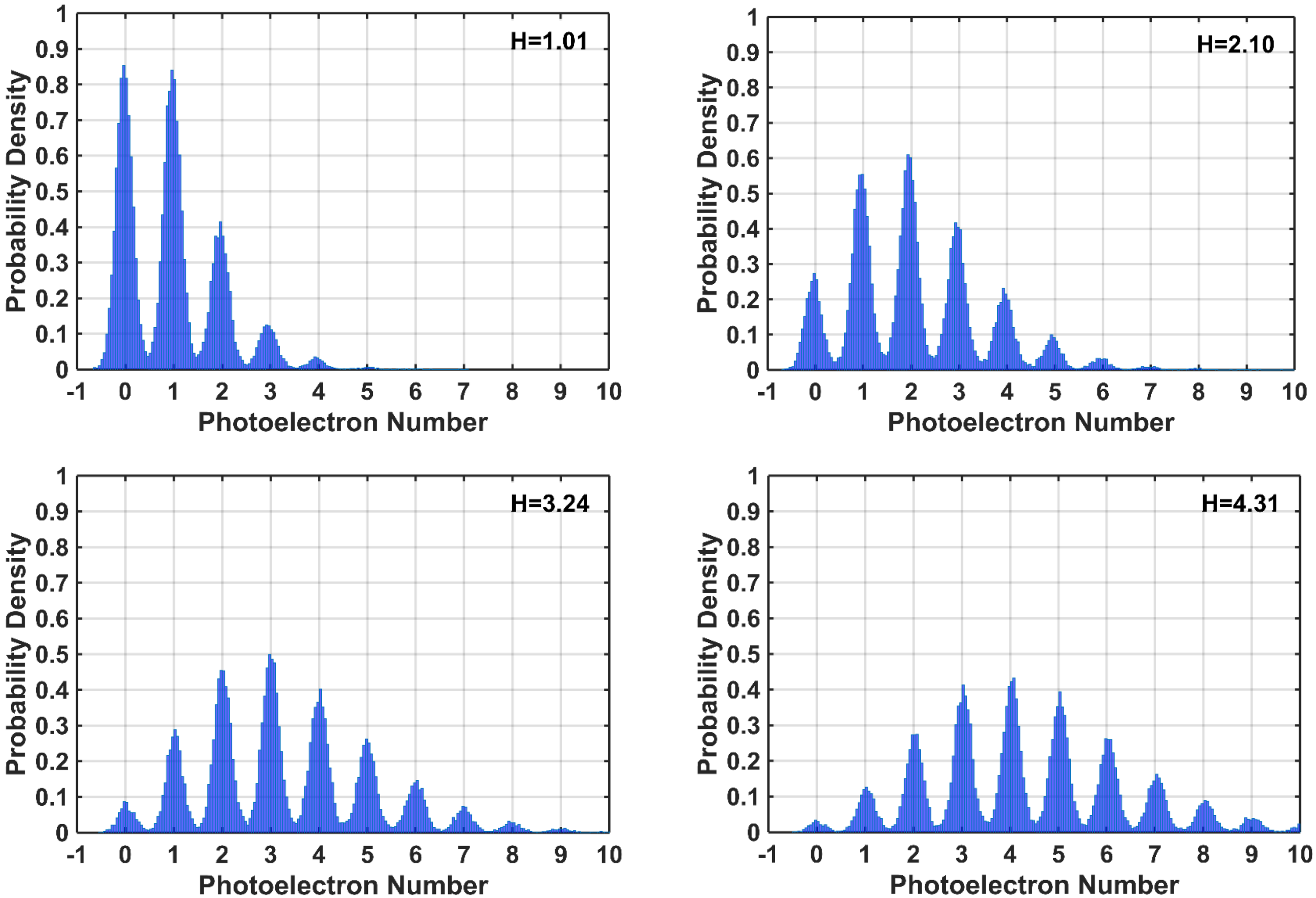
Trade off smaller gate area
for lower cap but more noise

Recall our Poisson probability mass function broadened by read noise



Experimental Data
Photon Counting Histograms

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



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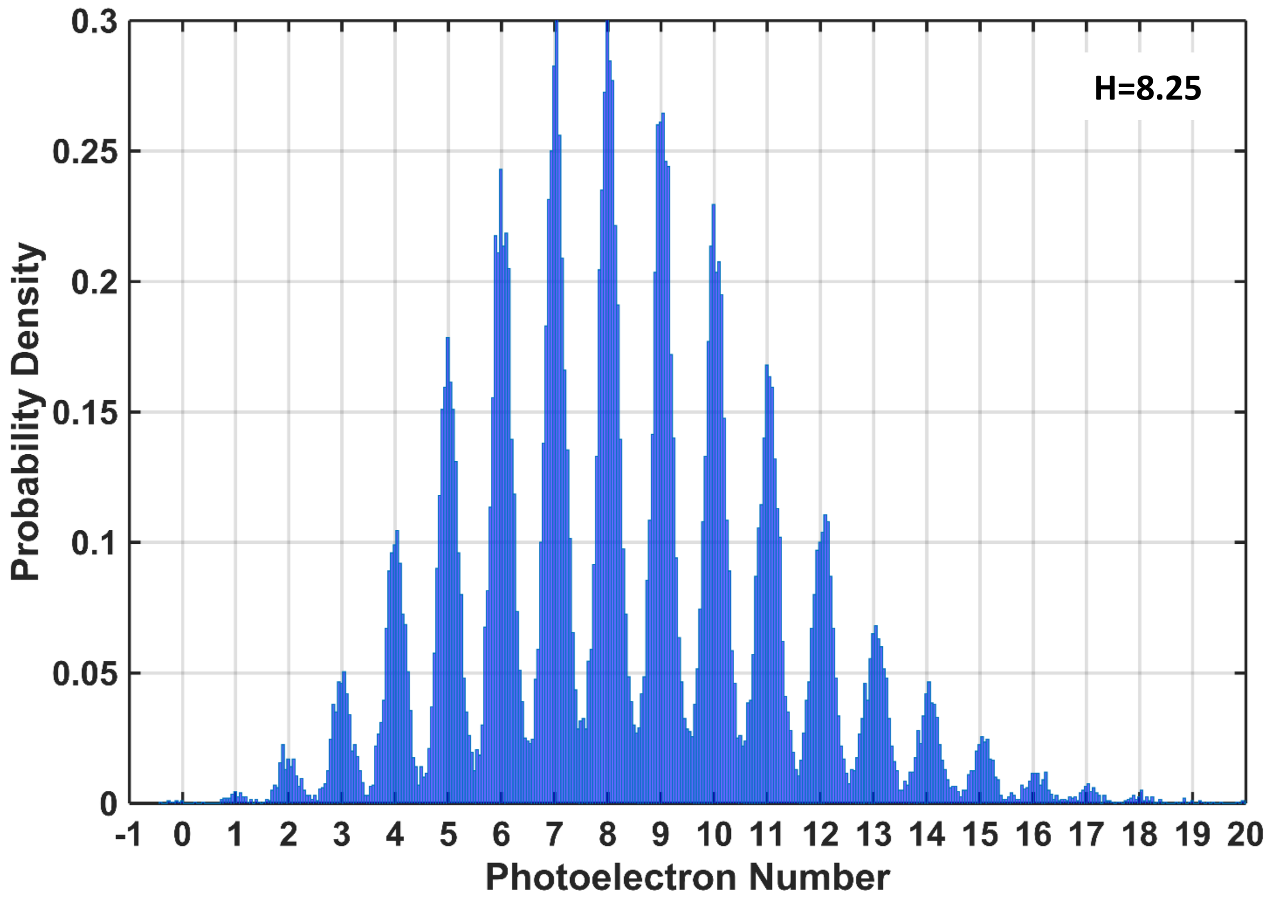
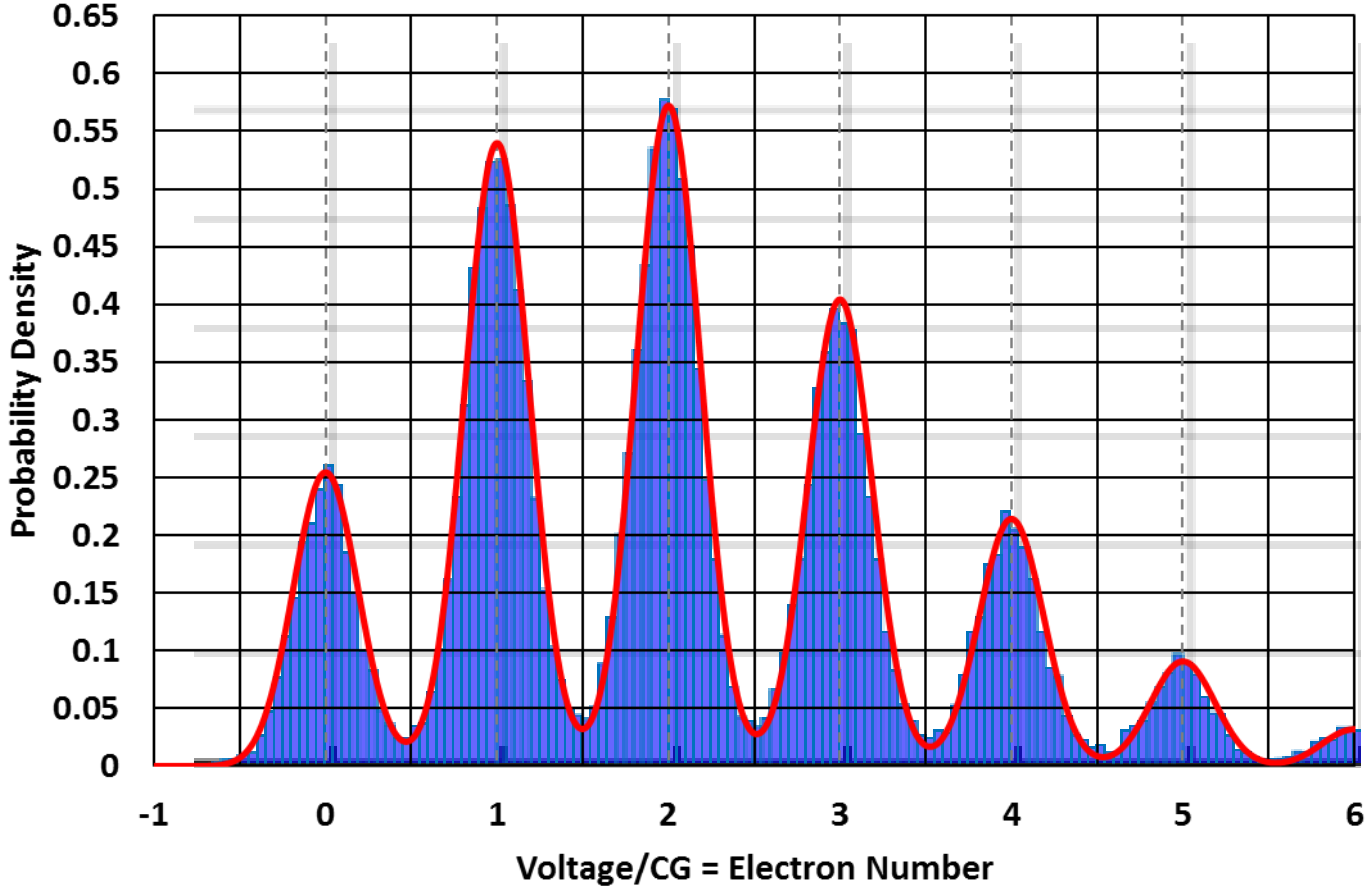
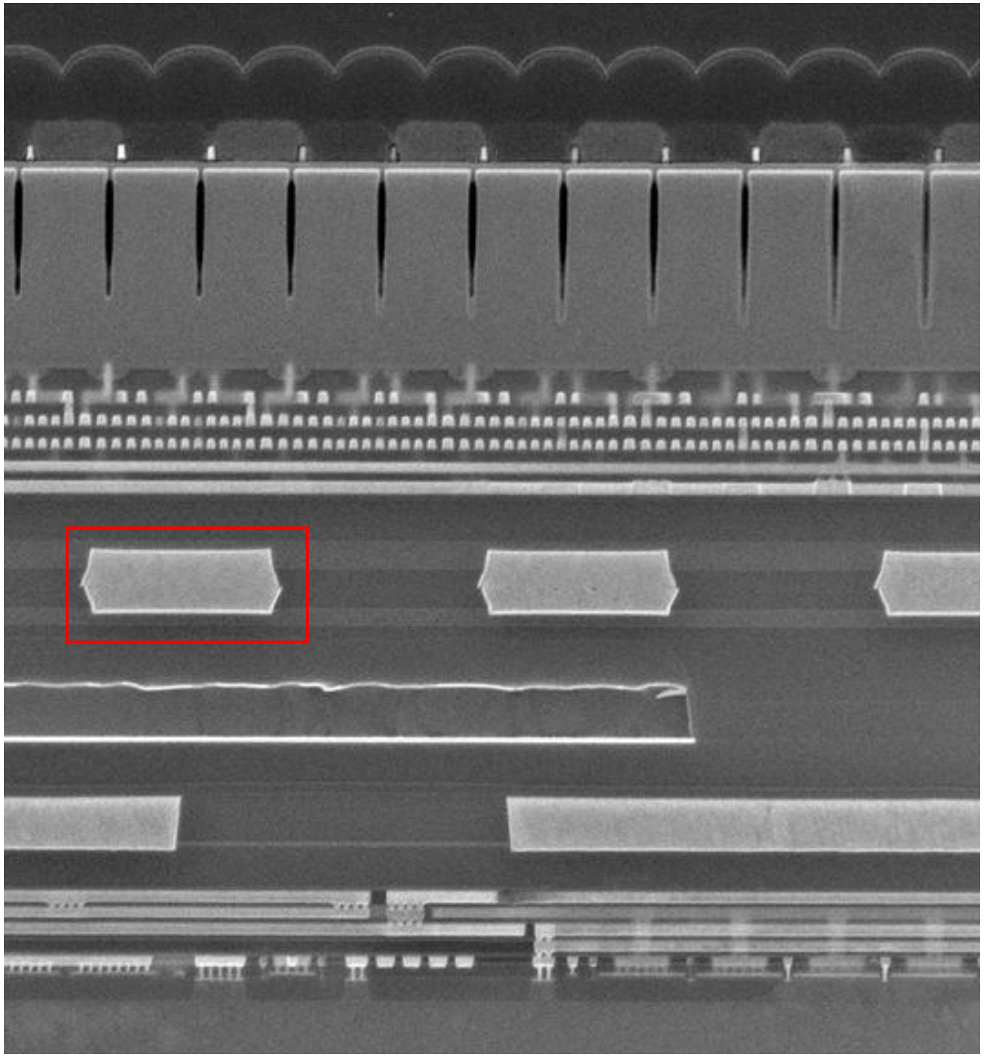


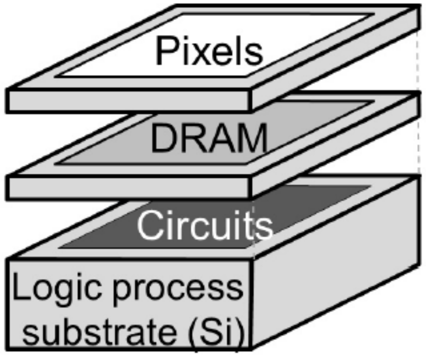
Model vs. Data



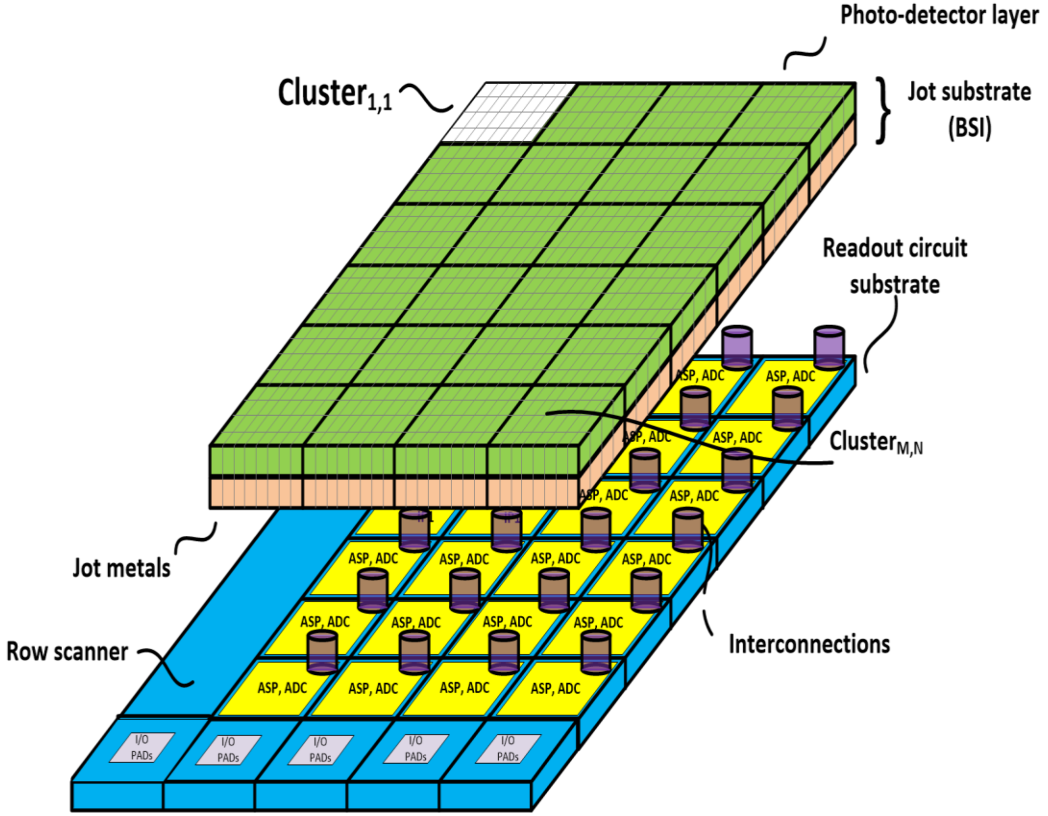
Stacked BSI CIS using wafer bonding



Newly developed
Stacked BI-CIS



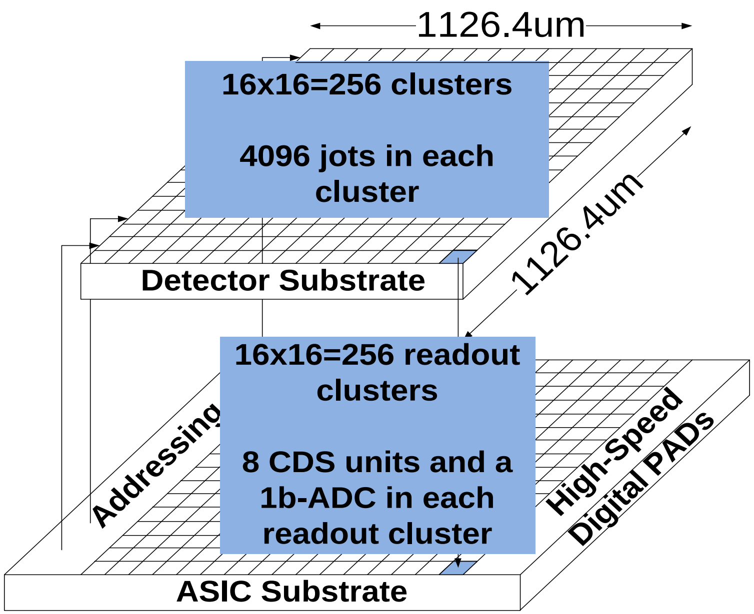
3D Stacked cluster-parallel readout to increase frame rate and reduce power



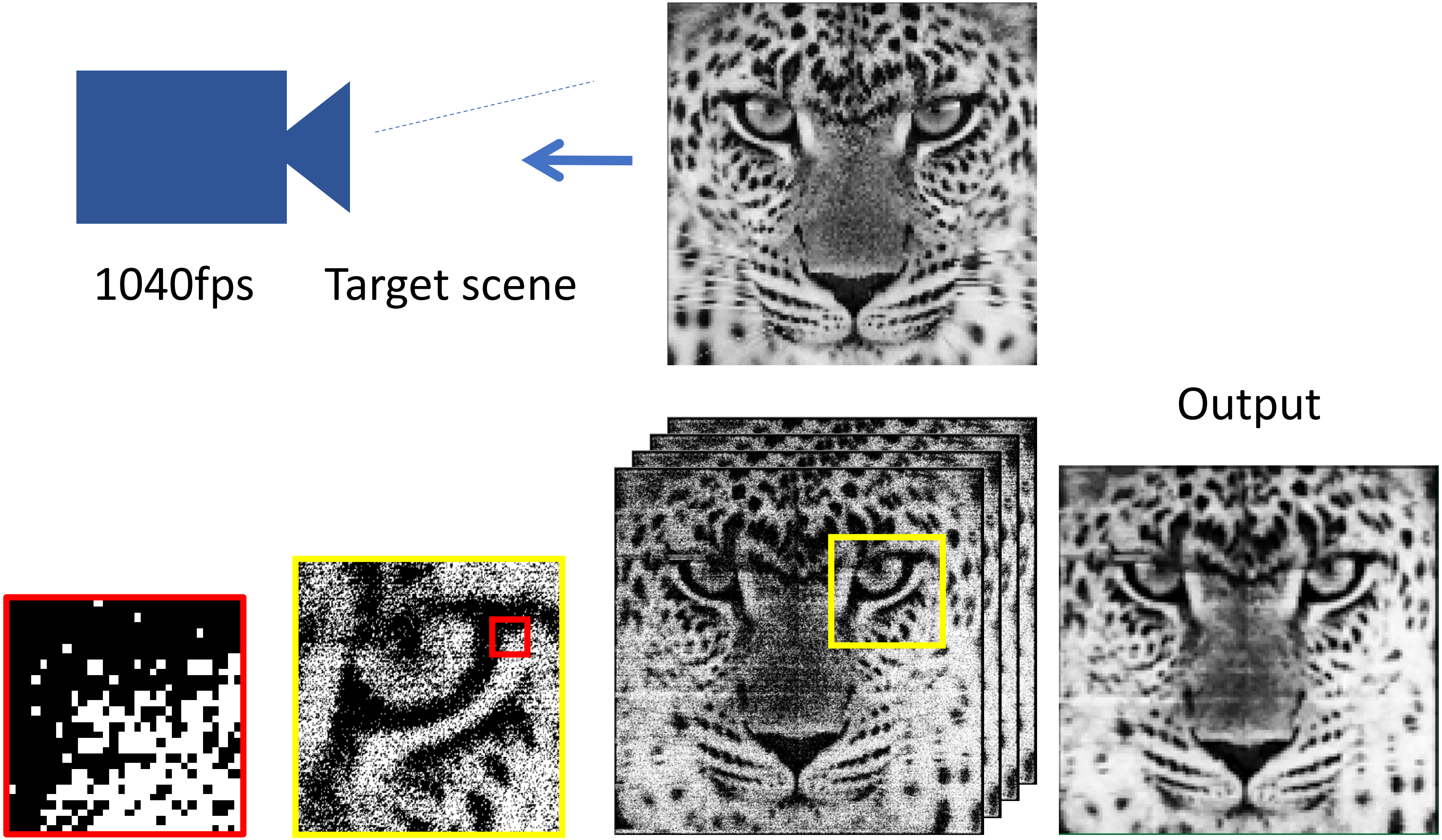
- Two or more stacked layers
- A group of jots form a cluster
- Readout circuits of a cluster of jots are located underneath cluster
- Clusters function in parallel
- Column line length is reduced, parasitics are reduced

Prototype 1Mjot 1040fps QIS (1b Digital Output)

- 20 different 1Mjot designs
- Process technology: CMOS BSI 45nm/65nm 2-layer Stacking
- Cluster-Parallel Architecture
- Readout Variation:
  - Analog
  - Single-bit Digital
- Resolution: 1024x1024
- Jot pitch size: 1.1µm
- Jot types:
  - Tapered-reset Pump-Gate
  - Punch-Through Reset
  - JFET SF



1Mjot prototype QIS experimental results



Gigajot spinoff (2017)

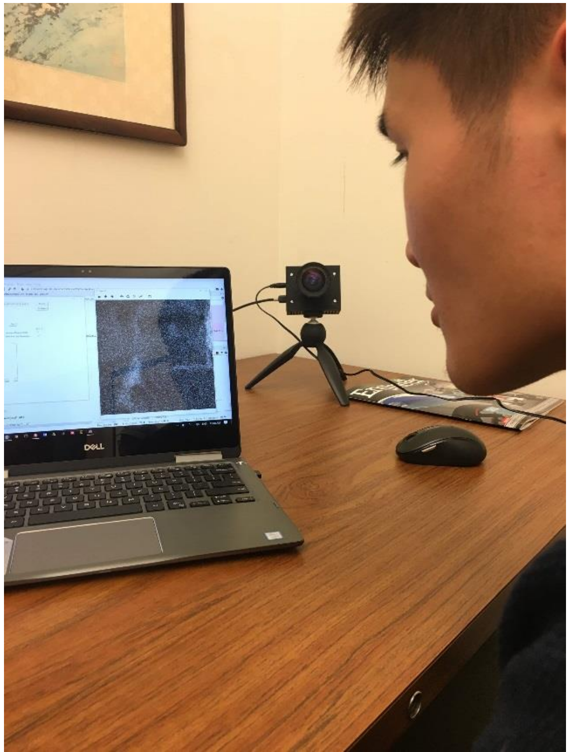
[Option 1.5]

Saleh Masoodian

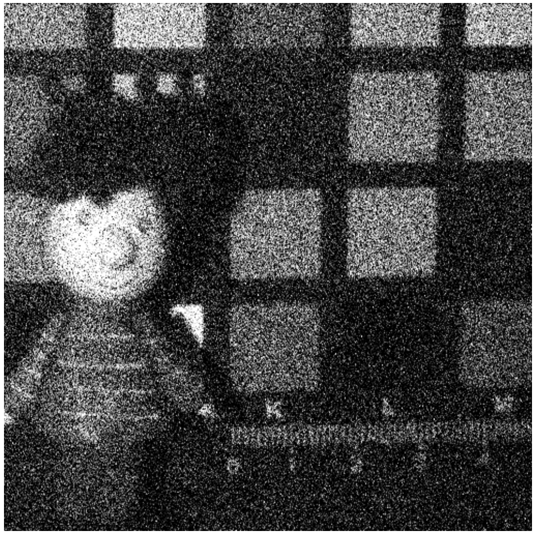
Jiaju Ma

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

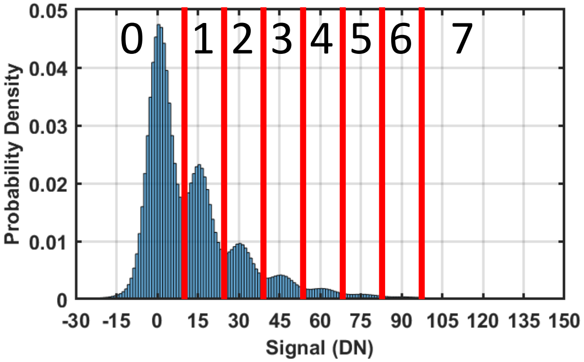
- Security systems
- Low light vision
- Internet of things (IOT)
- Biological imaging
- Astronomy
- Quantum Cryptography
- Photography
- Cinematography



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



Raw image and Histogram



1Mpixel 3b QIS Image
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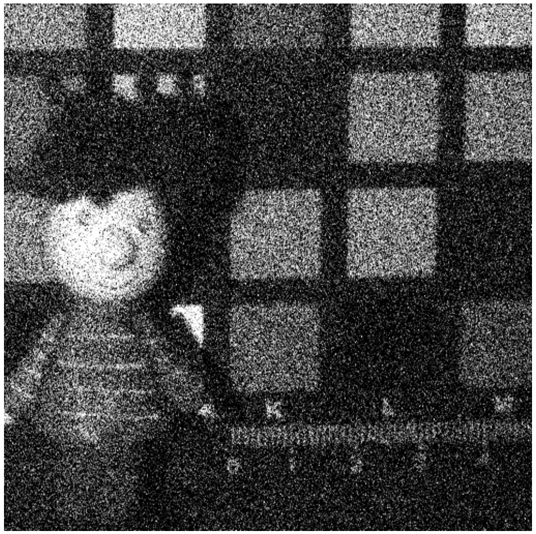
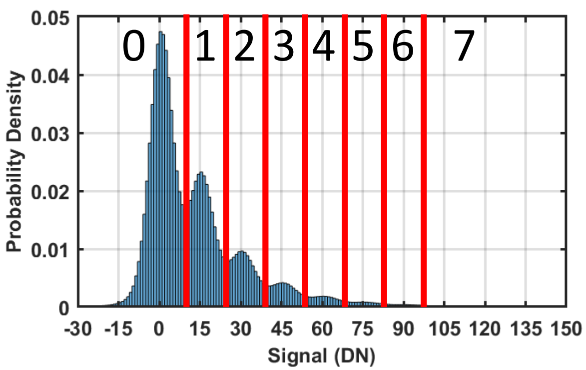


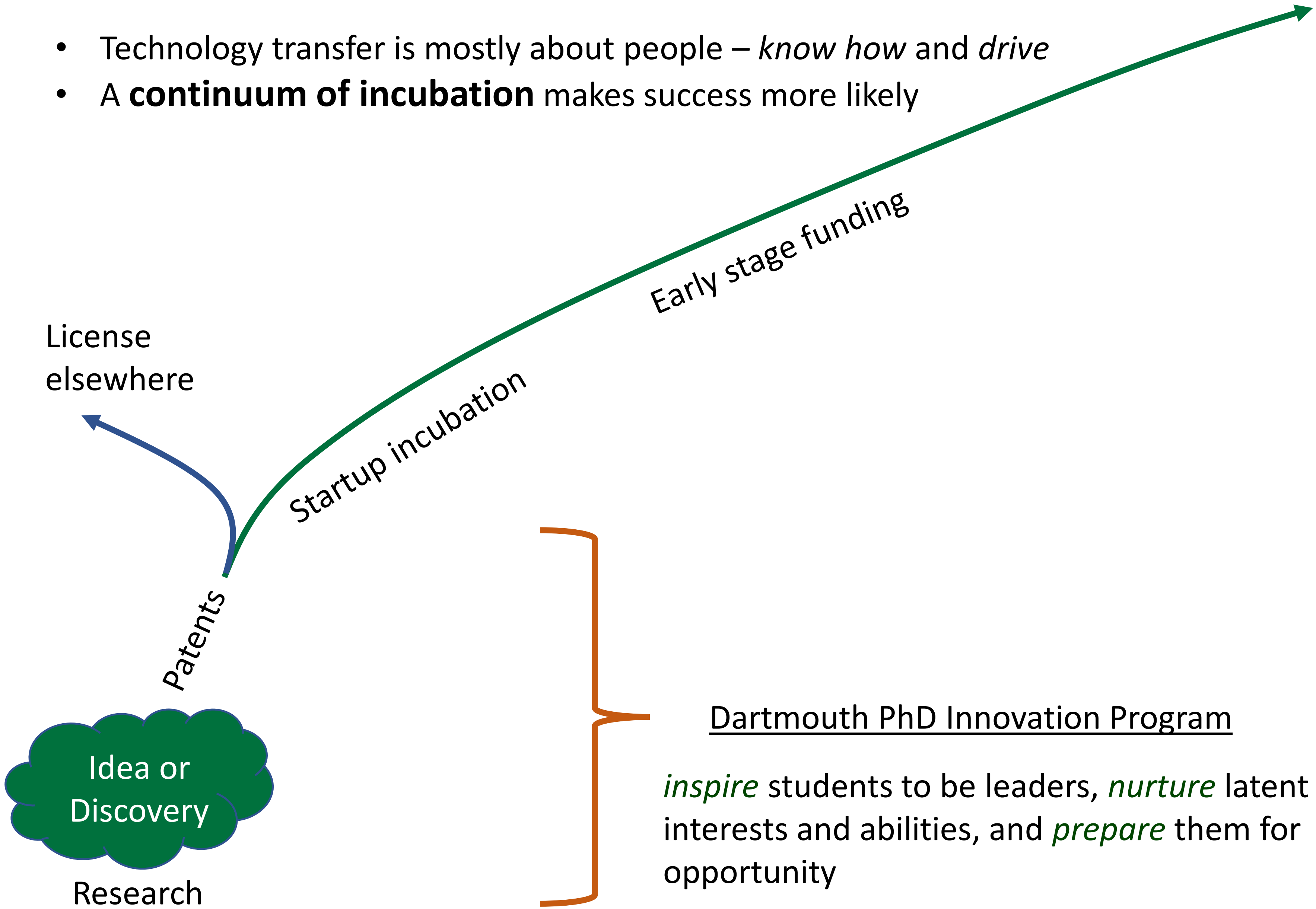
Raw image and Histogram



2x2x2 cubicle computation

Early arc of technology innovation

- Technology transfer is mostly about people – *know how* and *drive*
- A **continuum of incubation** makes success more likely



Dartmouth PhD Innovation Program

inspire students to be leaders, *nurture* latent interests and abilities, and *prepare* them for opportunity

Acknowledgments for QIS work

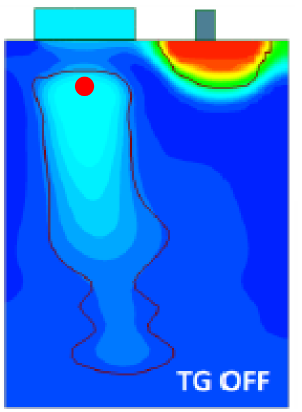
- Dartmouth graduate students
  - Ma, Masoodian, Starkey, Deng, Zizza, Anzagira, Hondongwa, Song
- Faculty colleagues
  - Hartov, Odame, Liu, Borsuk, Chan
- Rambus
  - Endsley, Stark, Guidash
- TSMC
  - Wei, Yamashita, Wang
- DARPA DETECT
- NSF, NASA and DOE SBIR (Gigajot)

The END

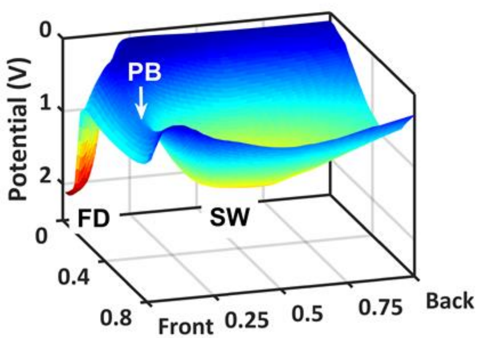
60

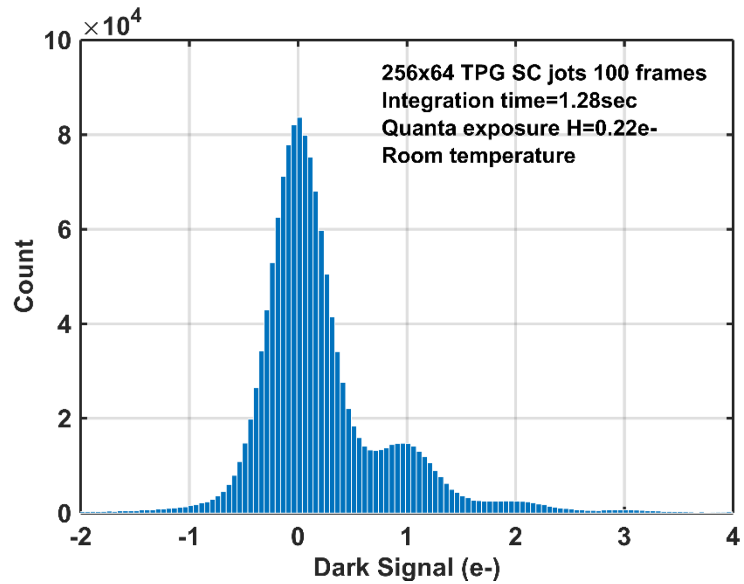
Dark Current

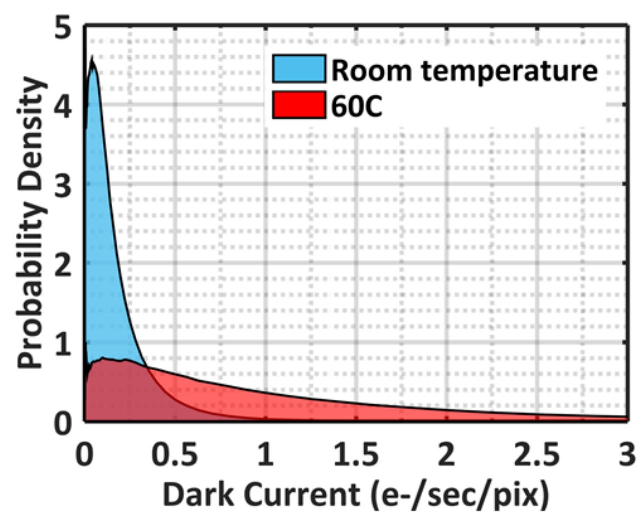
Room Temp: ~0.16e-/s avg. (~2pA/cm^2)
Previously measured ~2x every 10C



Storage well isolated from surface



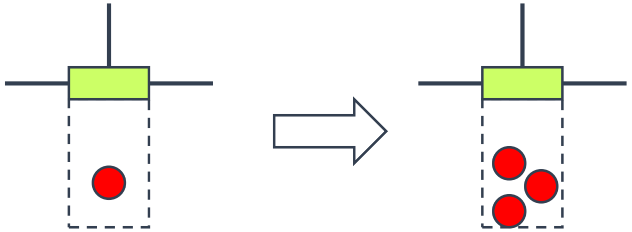




Multi-bit jot increases flux capacity

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

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



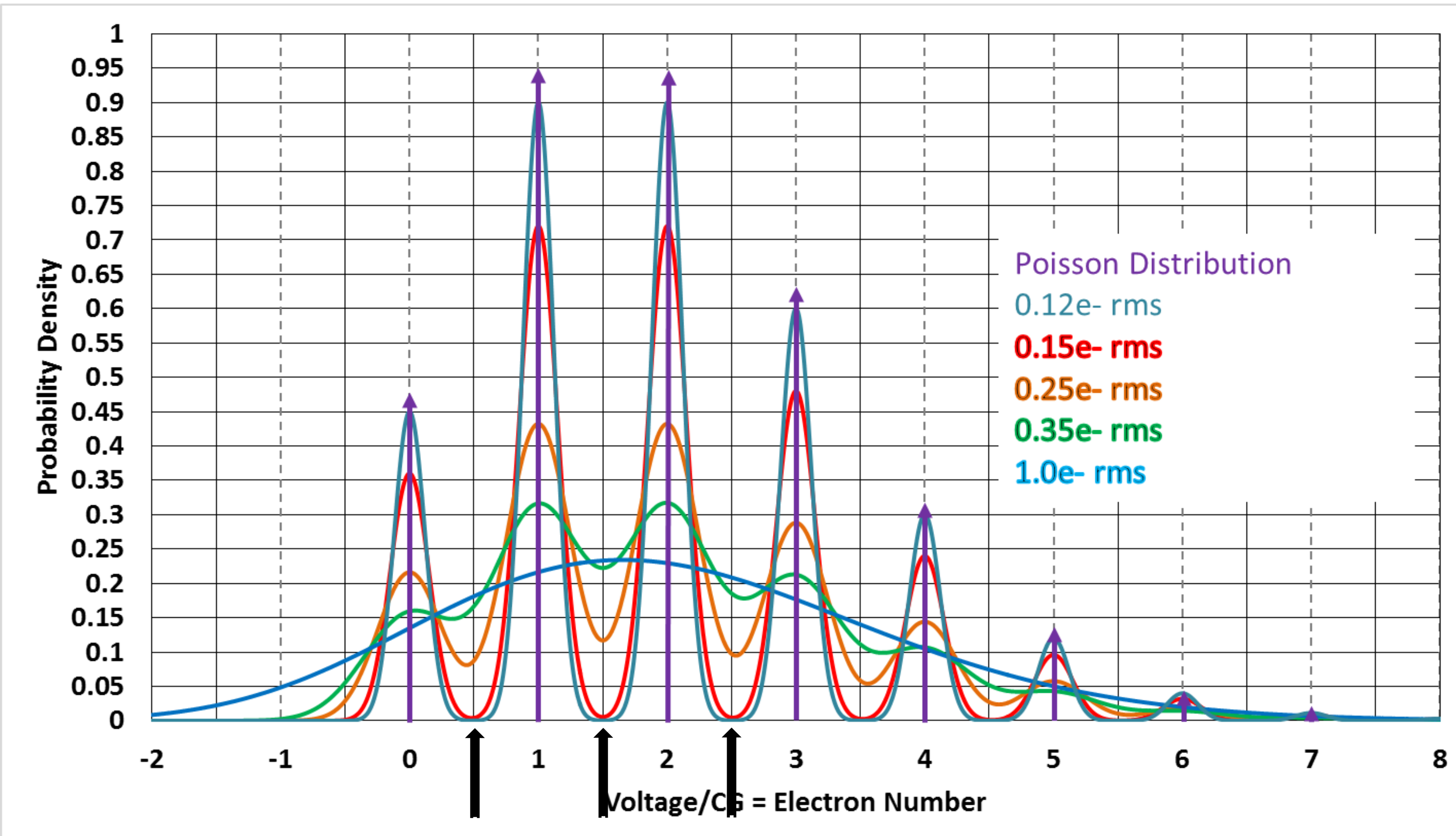
Single bit jot
0, 1 electrons

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

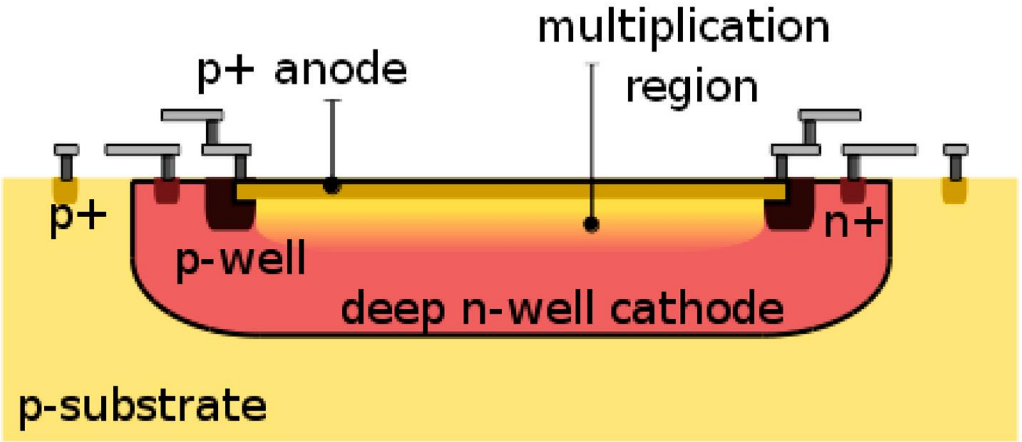
Little impact on detector and storage well. Little impact on FD CG or voltage swing (e.g. 1mV/e -> 31mV swing for 5b jot.

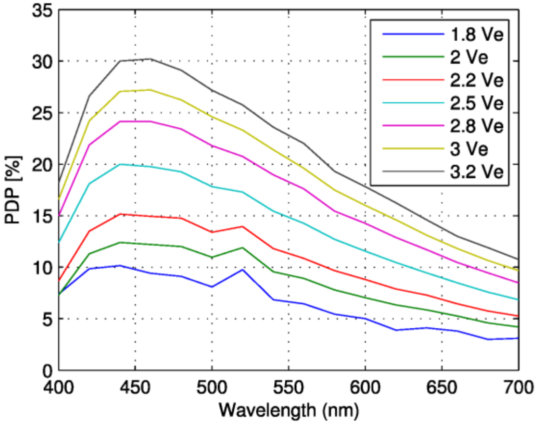
Multi-bit QIS for Photon Number Resolution
(e.g. 2-bit)



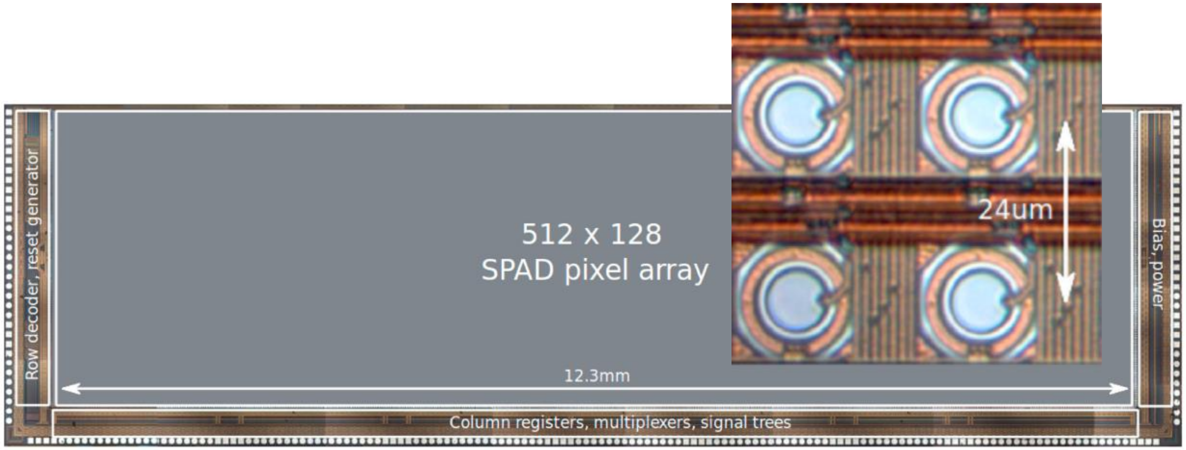
“00” “01” “10” “11”

Single Photon Avalanche Detectors (SPADS)

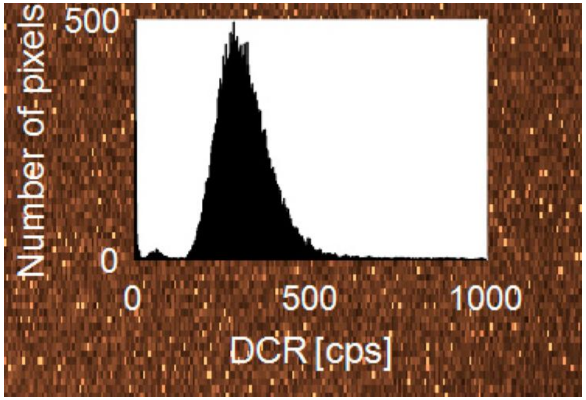




(a)



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



Room temperature

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)