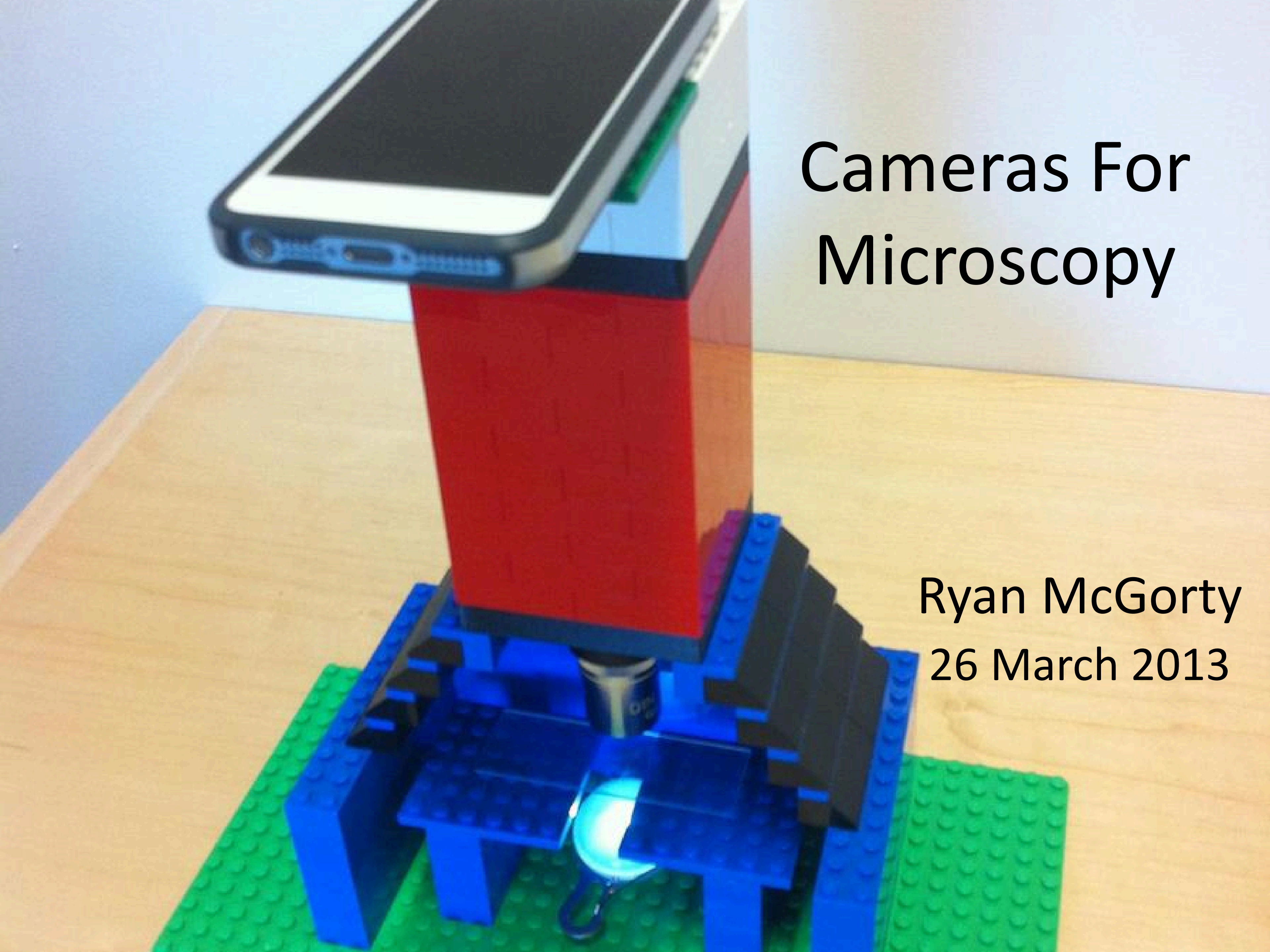


Cameras For Microscopy

Ryan McGorty

26 March 2013

Goals of this lecture

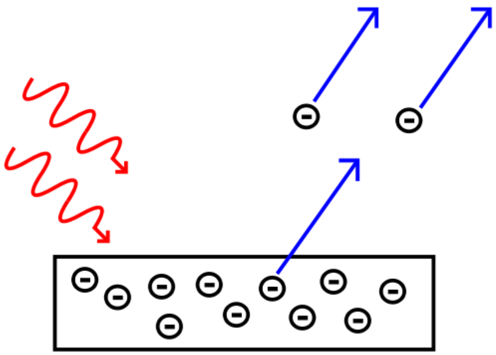
- Understand what prevents the ideal camera from being a realty
- Understand sources of noise in digital imaging
- Decipher meaning of camera specification sheets
- Understand basic architecture of digital sensors

How image sensors sense an image

1. Need way to detect photons

Hertz: observed in 1887

Photoelectric Effect



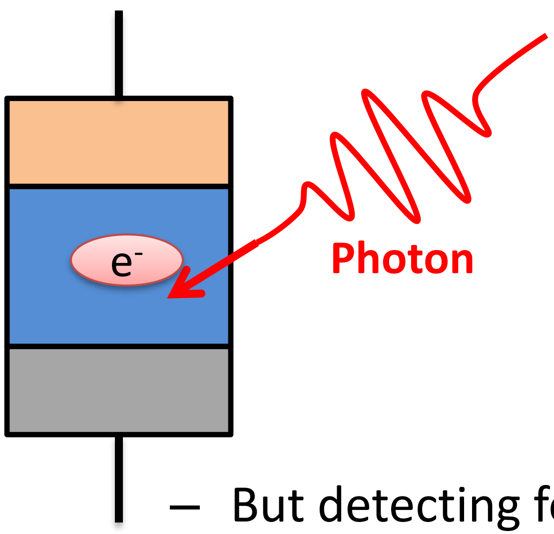
Einstein

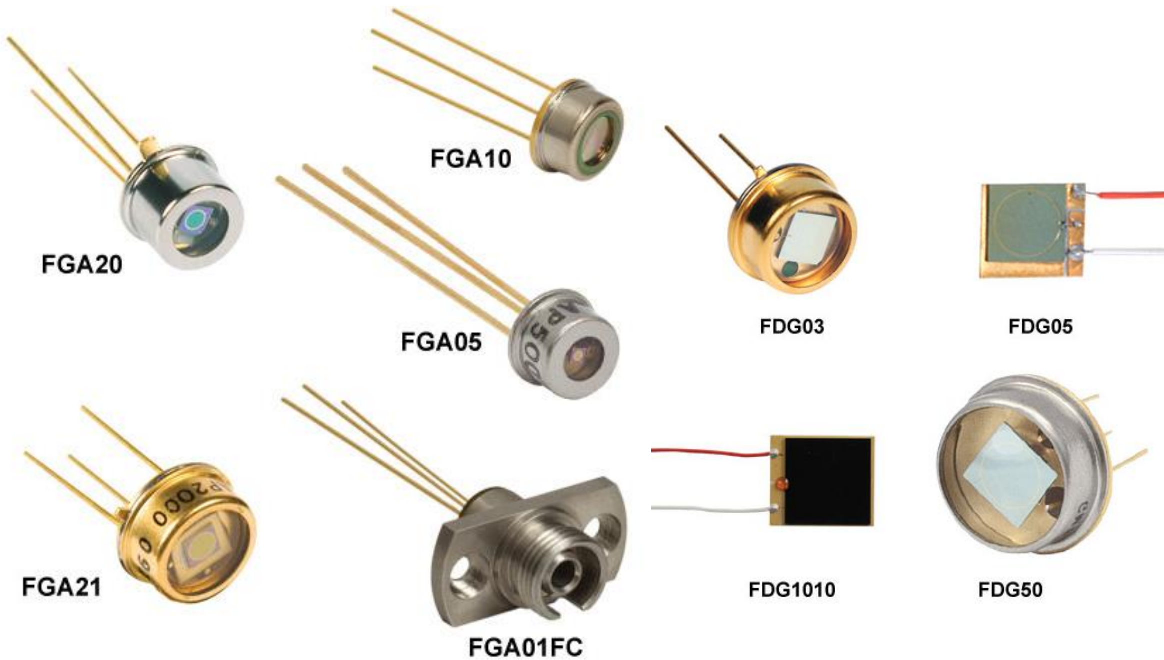
$E = \frac{hc}{\lambda}$

- For silicon, need ≈ 1.14 eV to release an electron
  - So need $\lambda < 1100$ nm

Point Detectors

- Photodiodes
  - Photons will generate electron (photoelectron)





  - But detecting few electrons is hard
  - Need way to amplify the signal

Point Detectors

- Avalanche Photodiode (APD)
  - Initial e^- becomes amplified through *impact ionization*
  - Gains of 100 to 1000

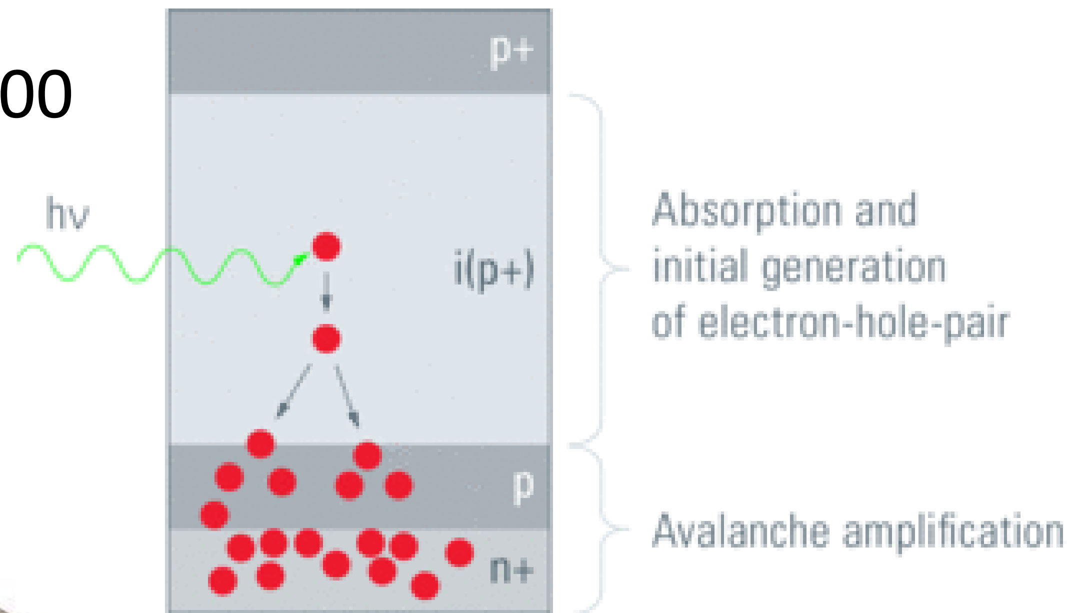


Image from http://www.leica-microsystems.com/science-lab/sensors-for-true-confocal-scanning/

Point Detectors

- Photomultiplier Tube (PMT)
  - Used widely in confocals
  - High linearity
  - Fast response
  - High gain

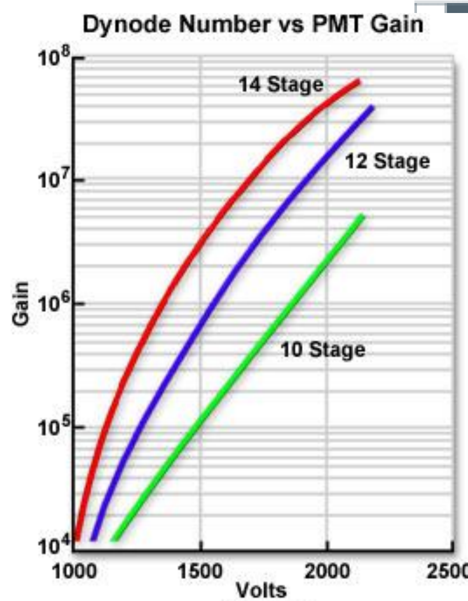


Figure 1

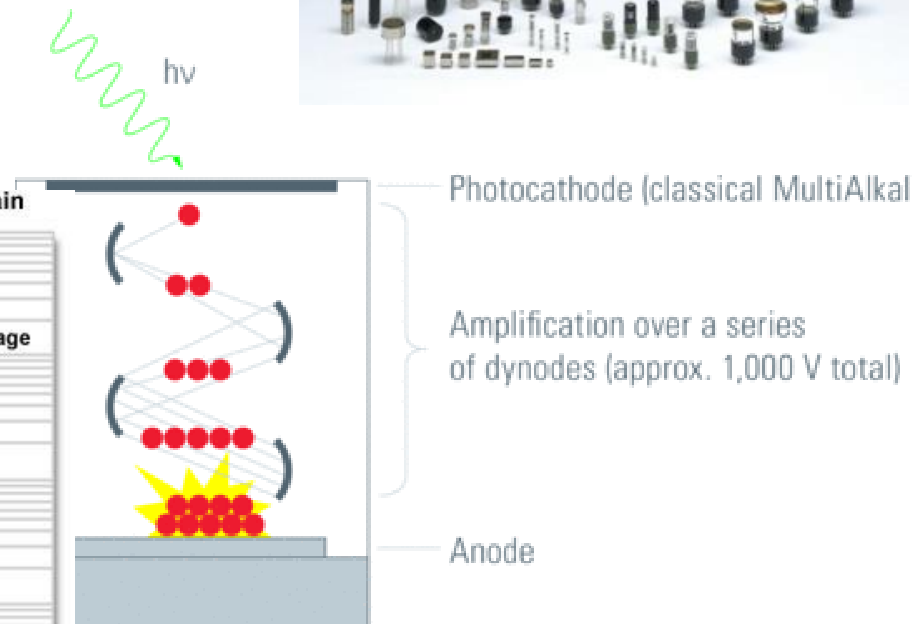
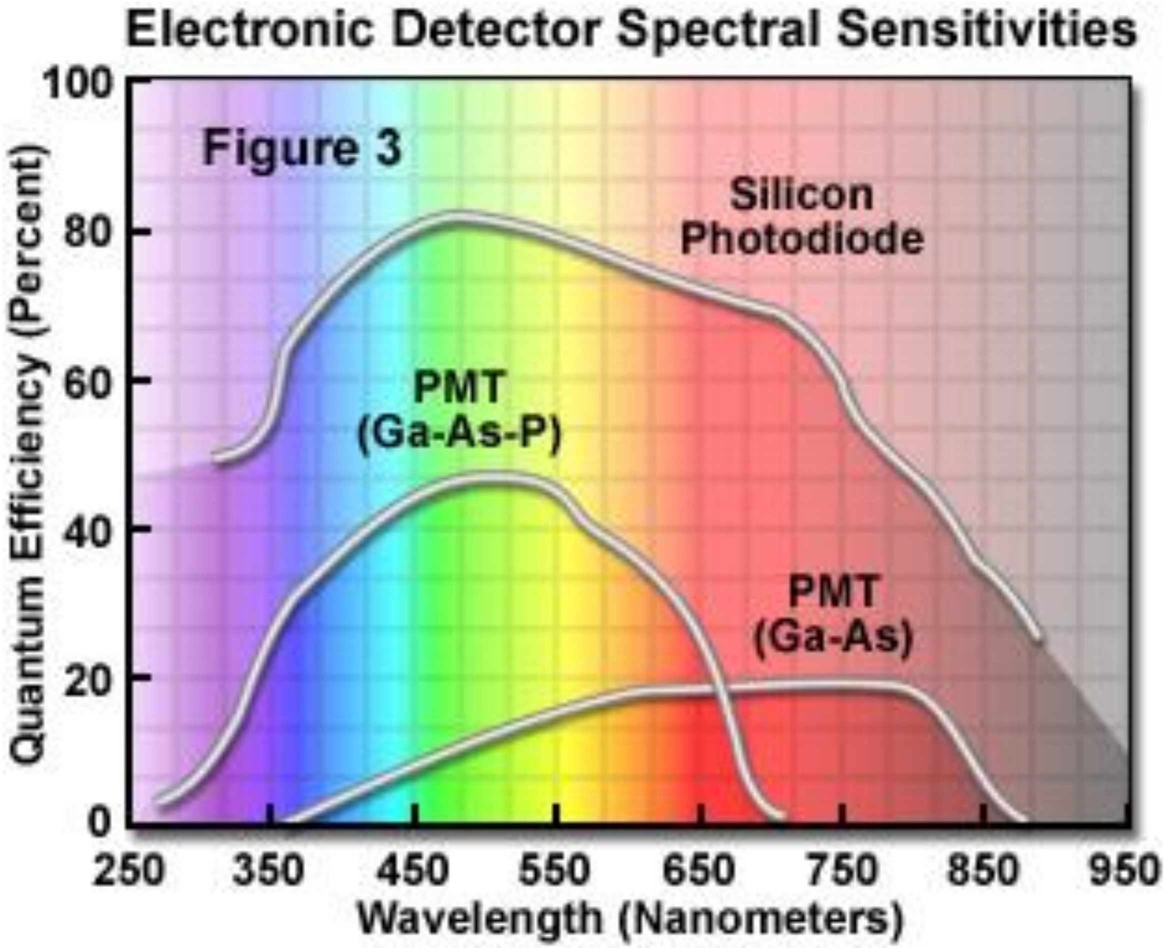


Image from http://www.leica-microsystems.com/science-lab/sensors-for-true-confocal-scanning/

How well are photons detected?

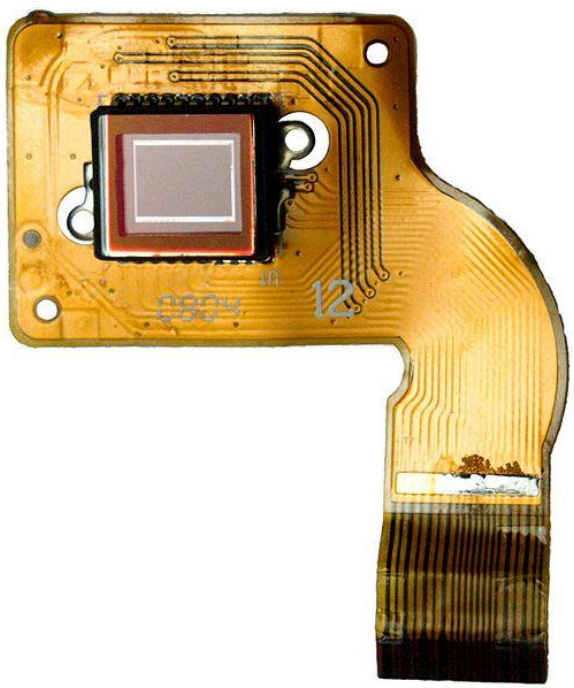
Quantum Efficiency



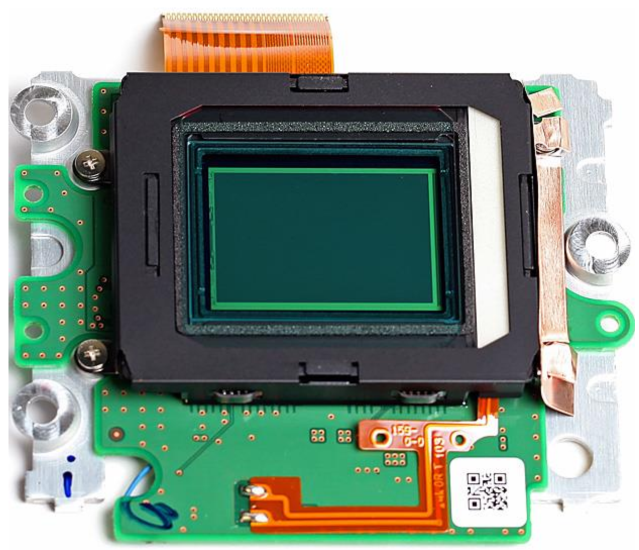
How image sensors sense an image

2. Must detect photons over an array of pixels

CCD



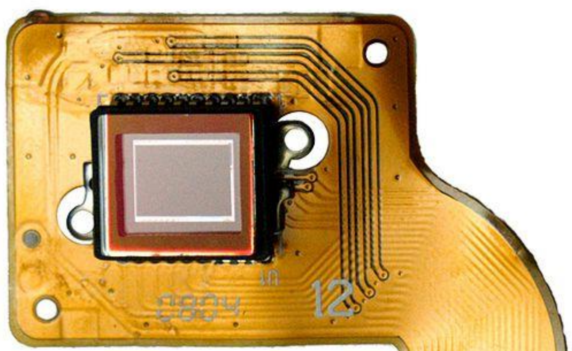
CMOS



How image sensors sense an image

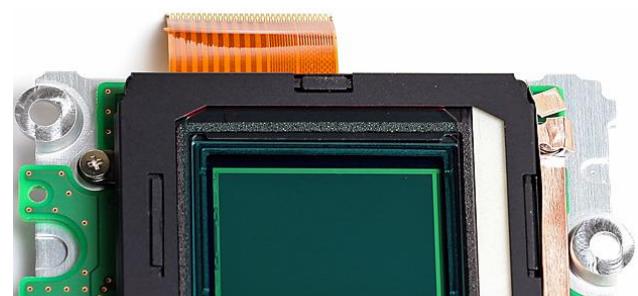
3. Electrons generated in each pixel must be read out

CCD



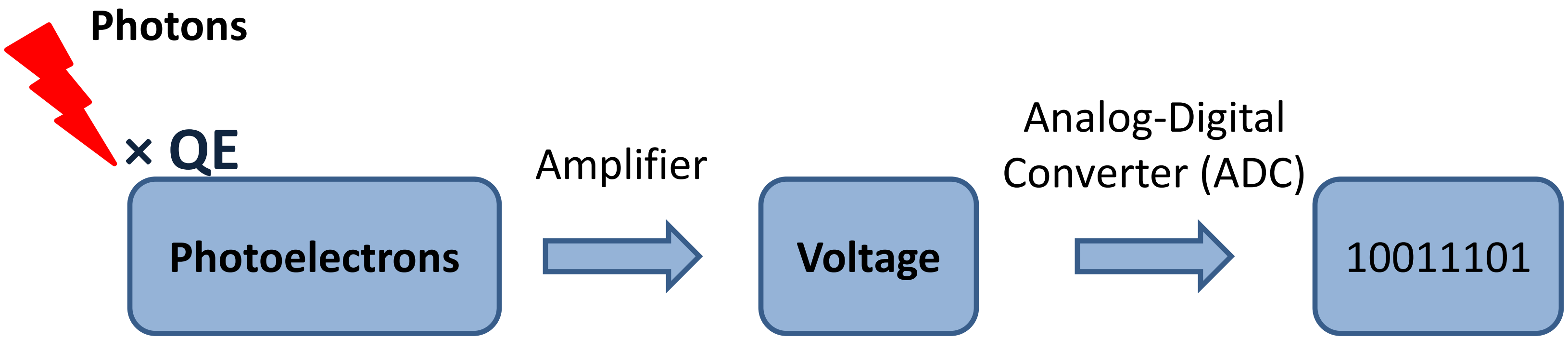
Serial devices where each pixel's charge is read out one at a time

CMOS



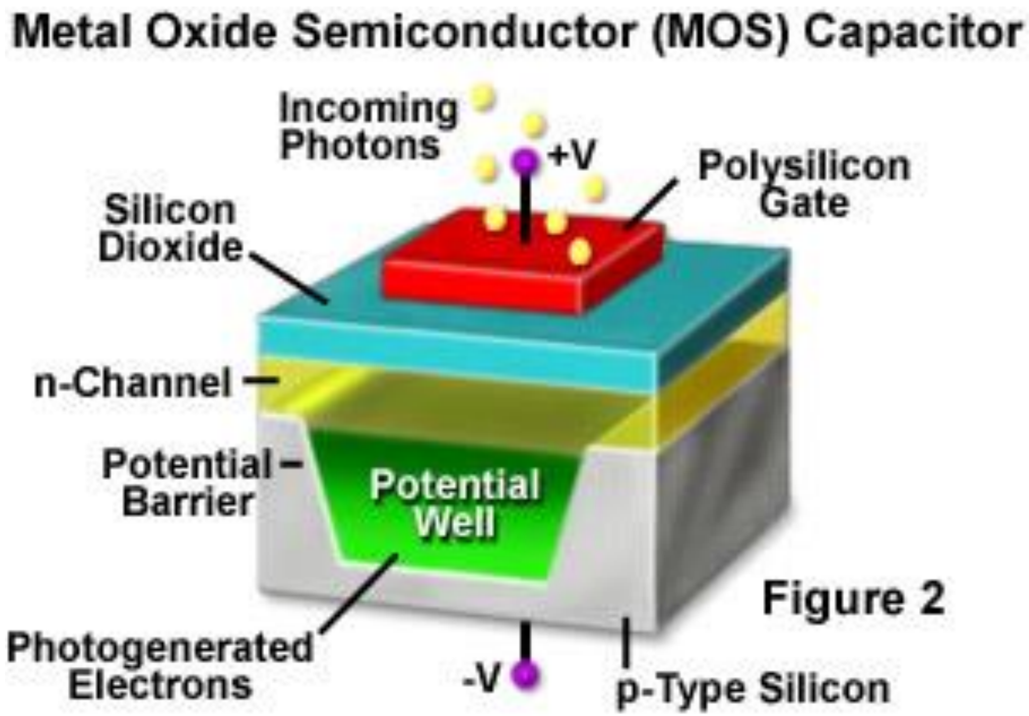
Each pixel contains amplifier electronics so read out can be much faster

What is meant by “read out”?



Bit Depth	Number of gray levels
8	2^8 = **256**
10	2^{10} = **1024**
12	2^{12} = **4096**
14	2^{14} = **16384**
16	2^{16} = **65536**

CCD Detectors

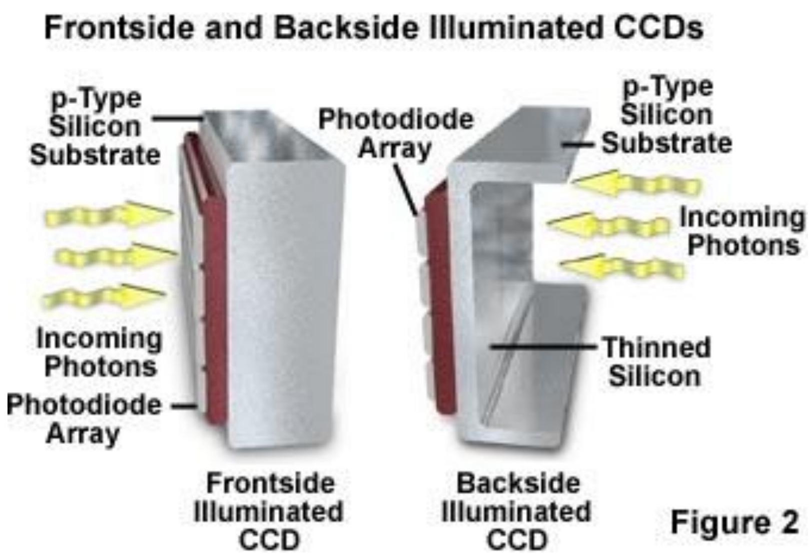


Charge-Coupled Device

- Invented at Bell Labs in 1970
- 2009 Nobel Prize in Physics
- Widely used in TV, medical, astronomy cameras
- Array of light sensitive MOS capacitors (pixels)
- Incoming light generates electrons which are captured in a potential well
- Electrodes, or gates, move the charge

Image from http://www.microscopyu.com/articles/digitalimaging/ccdintro.html

Front or Back Illuminated



Vertebrate

Octopus

Retina

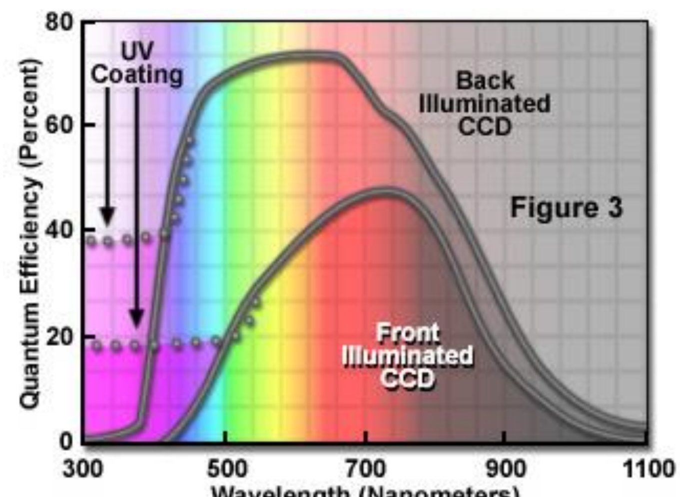
Nerves

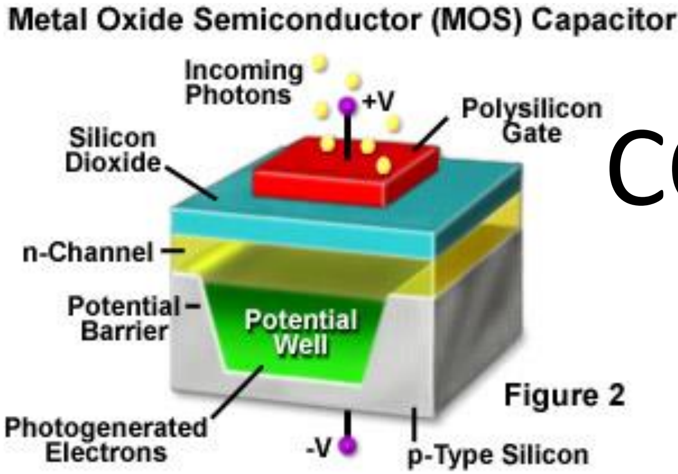
Optic nerve

http://en.wikipedia.org/wiki/Cephalopod_eye

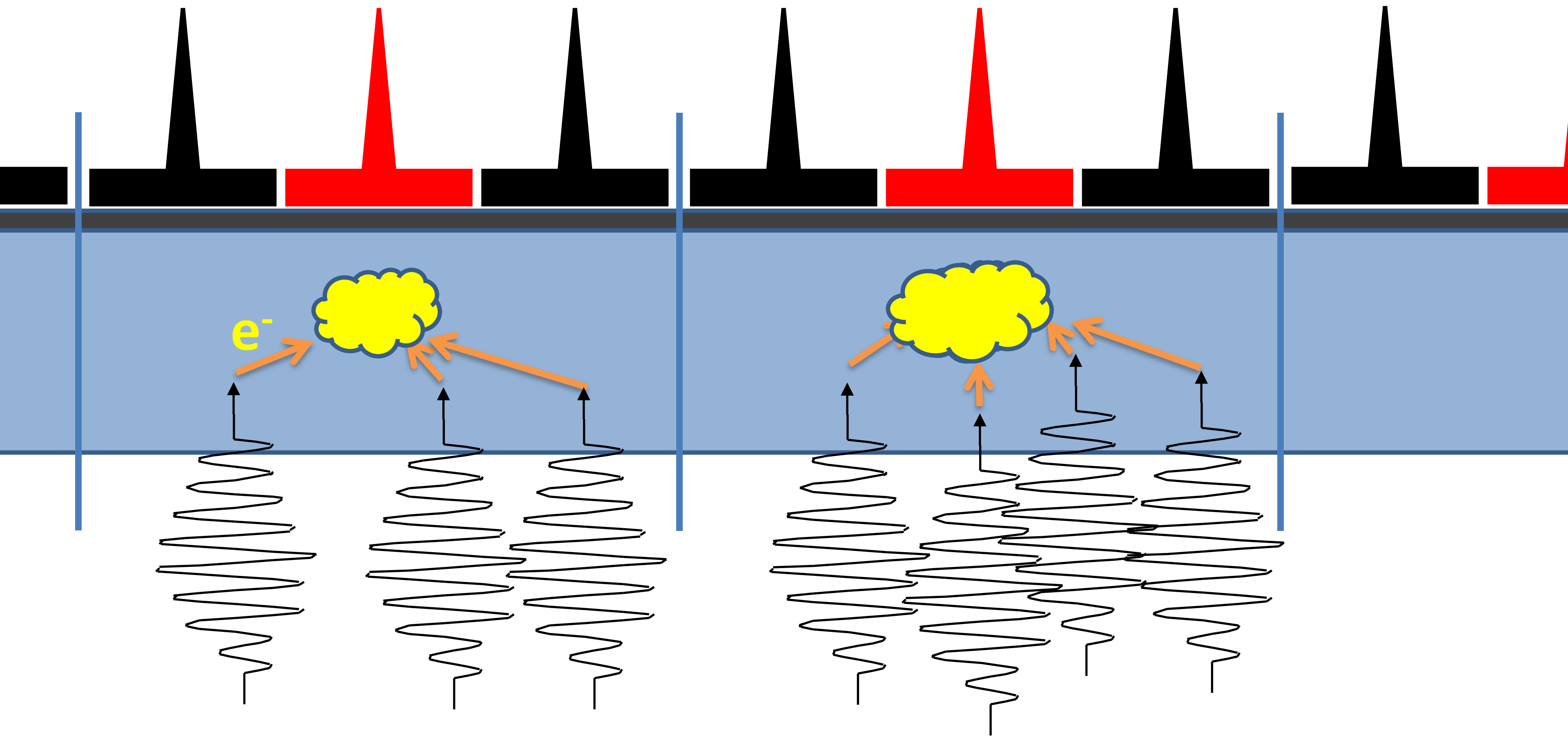
From http://learn.hamamatsu.com/articles/quantumefficiency.html

- Traditional, front-illuminated have **wiring in front** of photosensitive region
  - ➢ This blocks some light, reducing QE
- Back-illuminated CCDs:
  - ➢ Back side of the CCD is etched to 10-15 microns
  - ➢ More fragile and costly, but higher QE



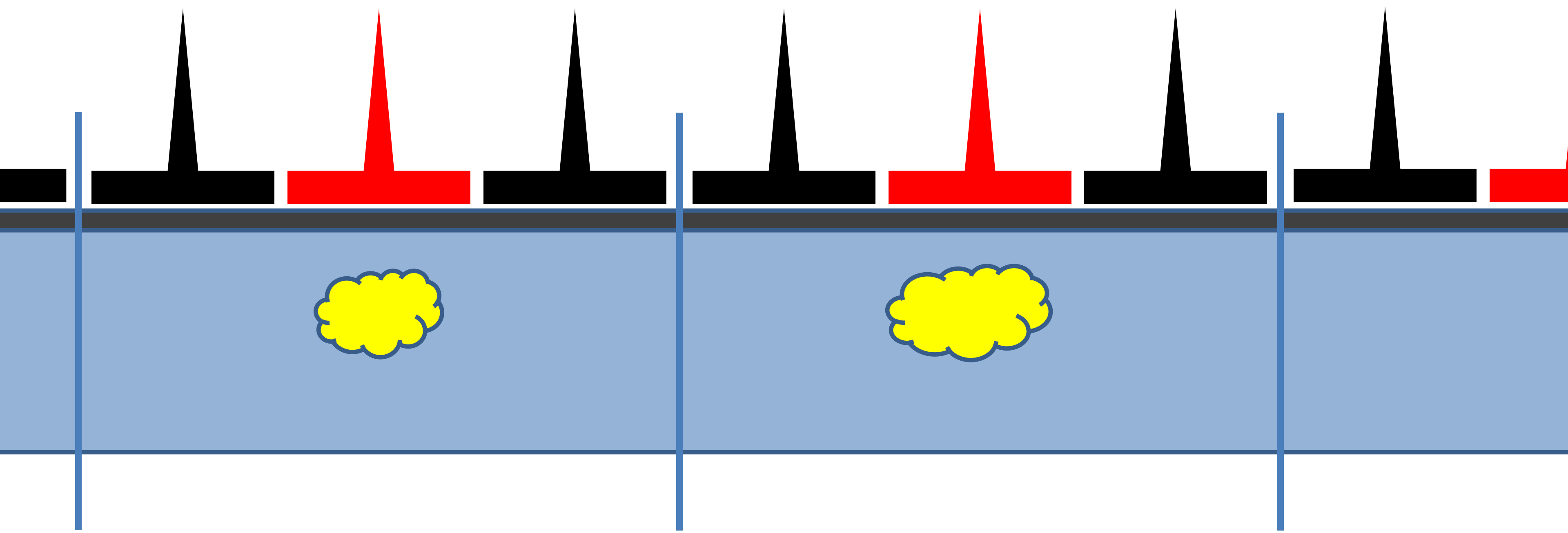


CCD Detectors



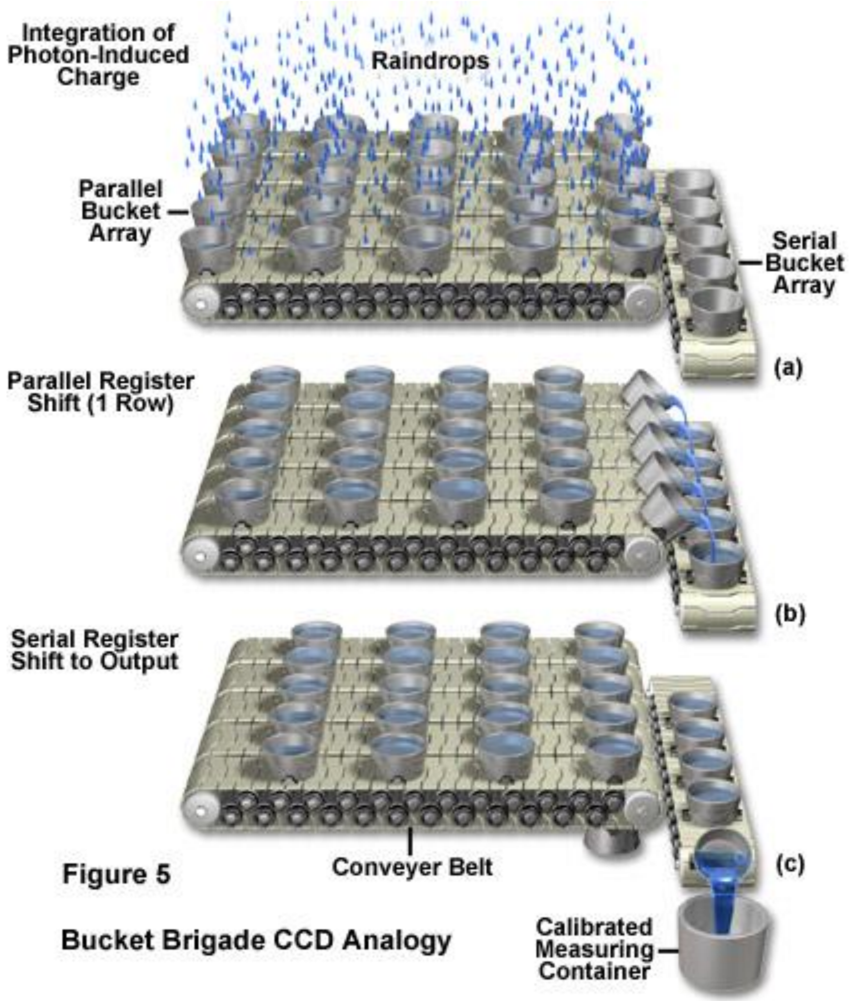
CCD Detectors

Three-phase clocking method



Photoelectrons from each pixel must be shuttled to the readout area to be amplified, converted to a voltage and then a digital number.

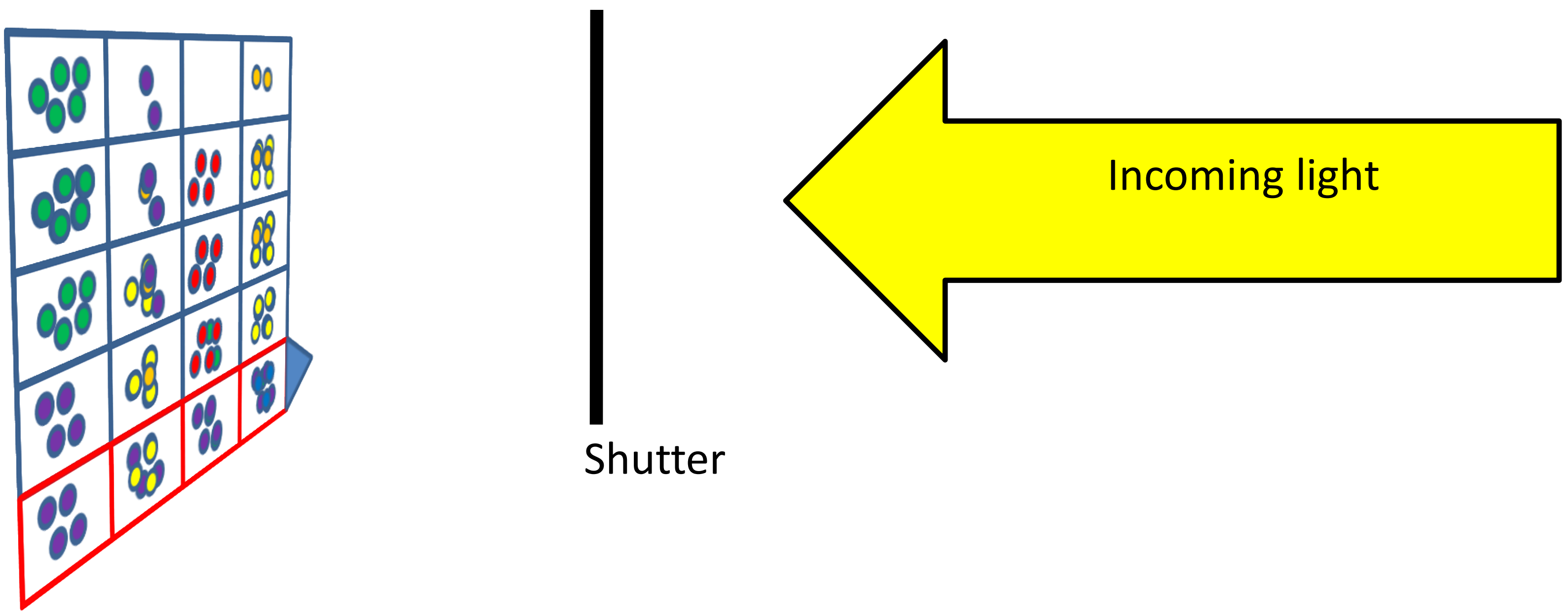
Bucket brigade analogy for read out



- Rain accumulates in buckets
- Rows of buckets shifted to readout row
- Readout row shifted bucket-by-bucket to measuring device
- Unless rain stops, last bucket to be read out will have much more water than the first

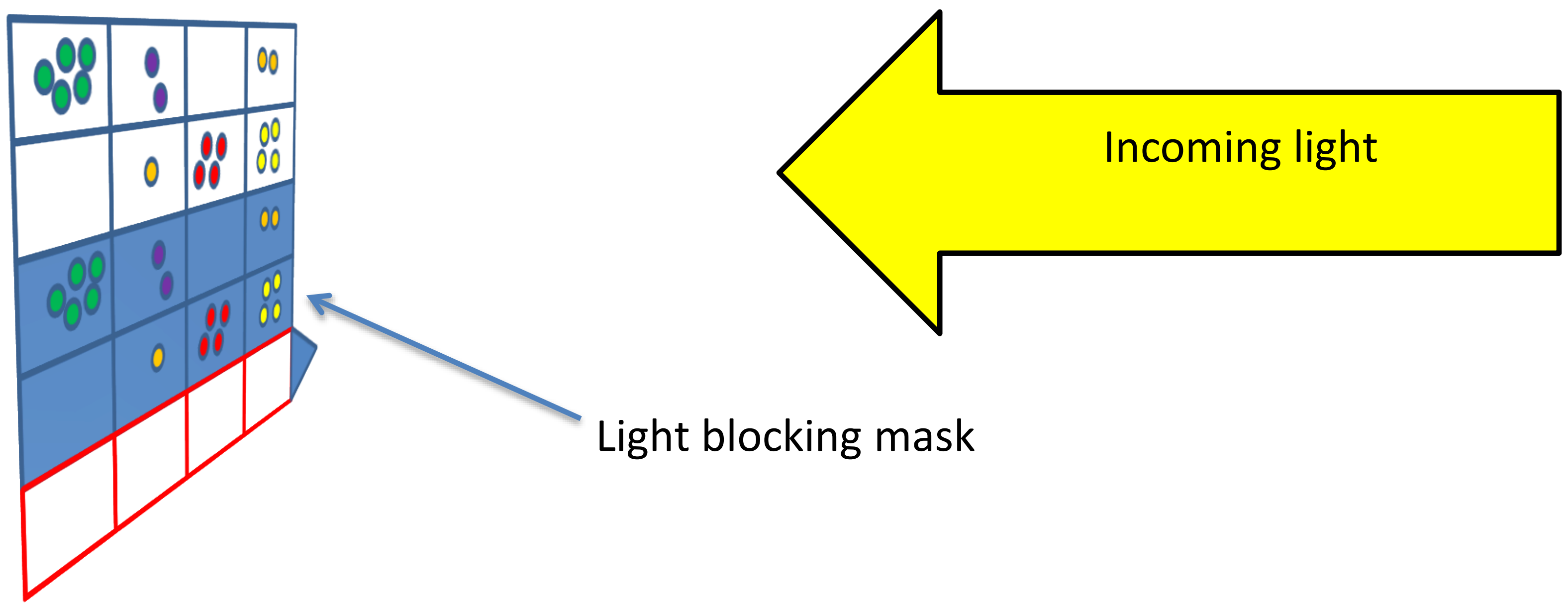
Transferring photoelectrons out

- Full frame
  - Full area of CCD collects light
  - During readout, shutter must block light



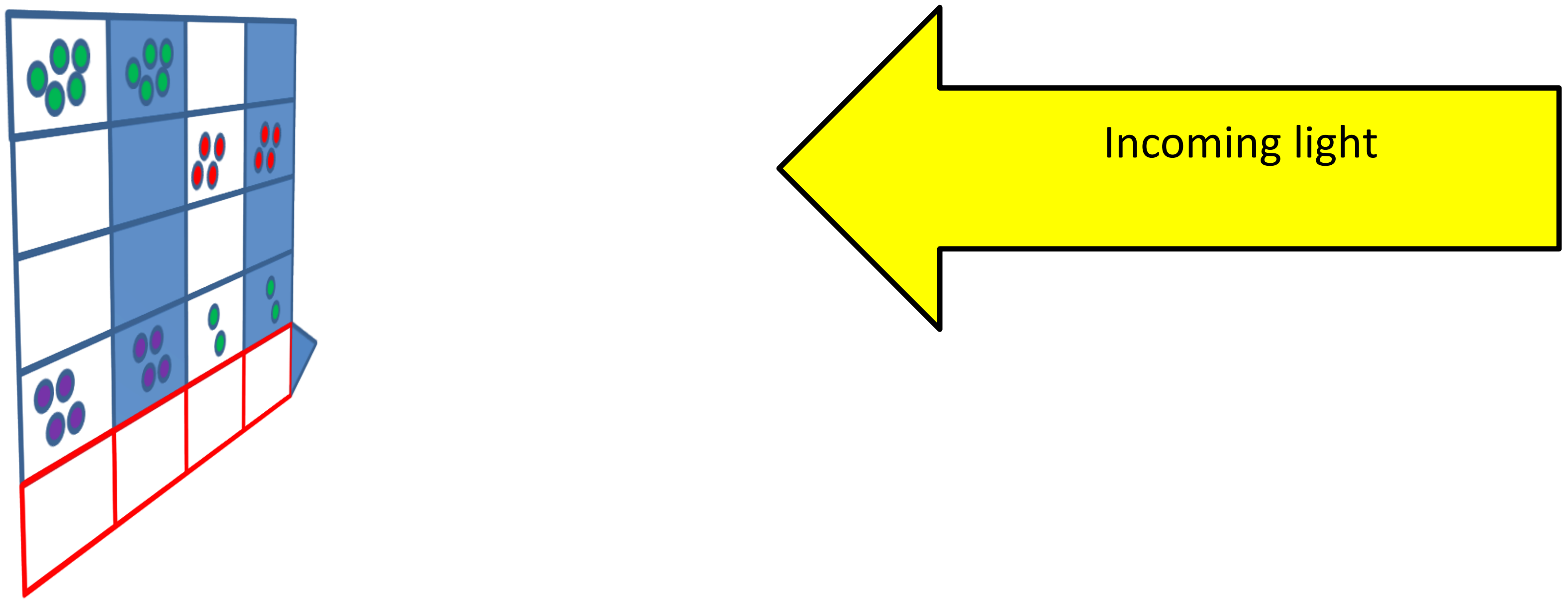
Transferring photoelectrons out

- Full frame
- Frame transfer
  - Half of CCD collects light; other half is for storage
  - After exposure, charge transferred to storage half and read out



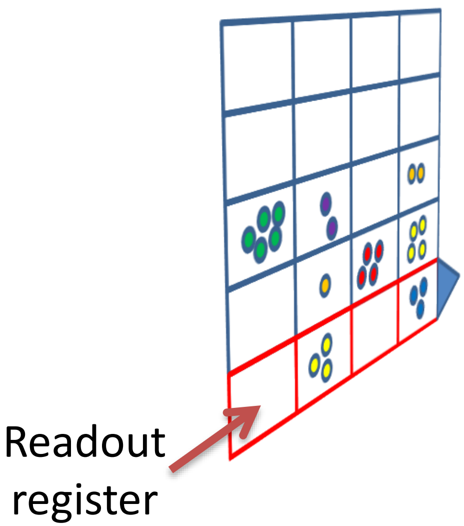
Transferring photoelectrons out

- Full frame
- Frame transfer
- Interline transfer
  - Alternating columns of light sensitive and storage/transfer pixels
  - Photosensitive pixels collect charge; charge shifted to neighboring columns and read out



Transferring photoelectrons out

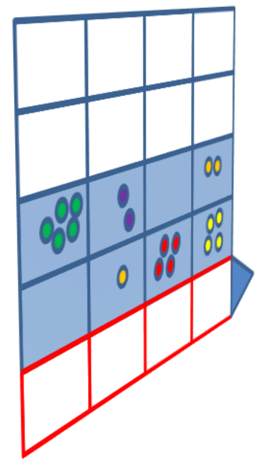
Full frame



Pros:
- Nearly all of CCD area is usable

Cons:
- Frame rates limited by shutter speed

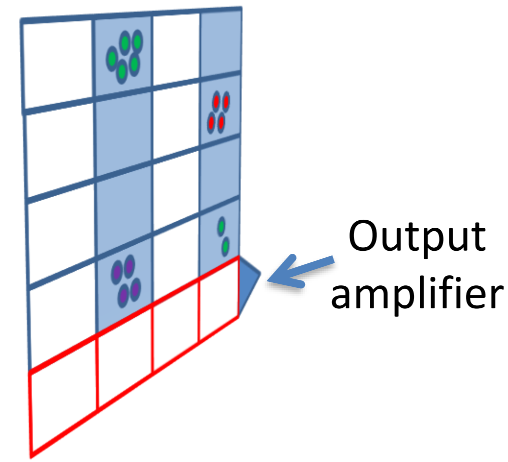
Frame-transfer



Pros:
- Fast: exposure and readout occur simultaneously

Cons:
- Half of CCD is not light sensitive

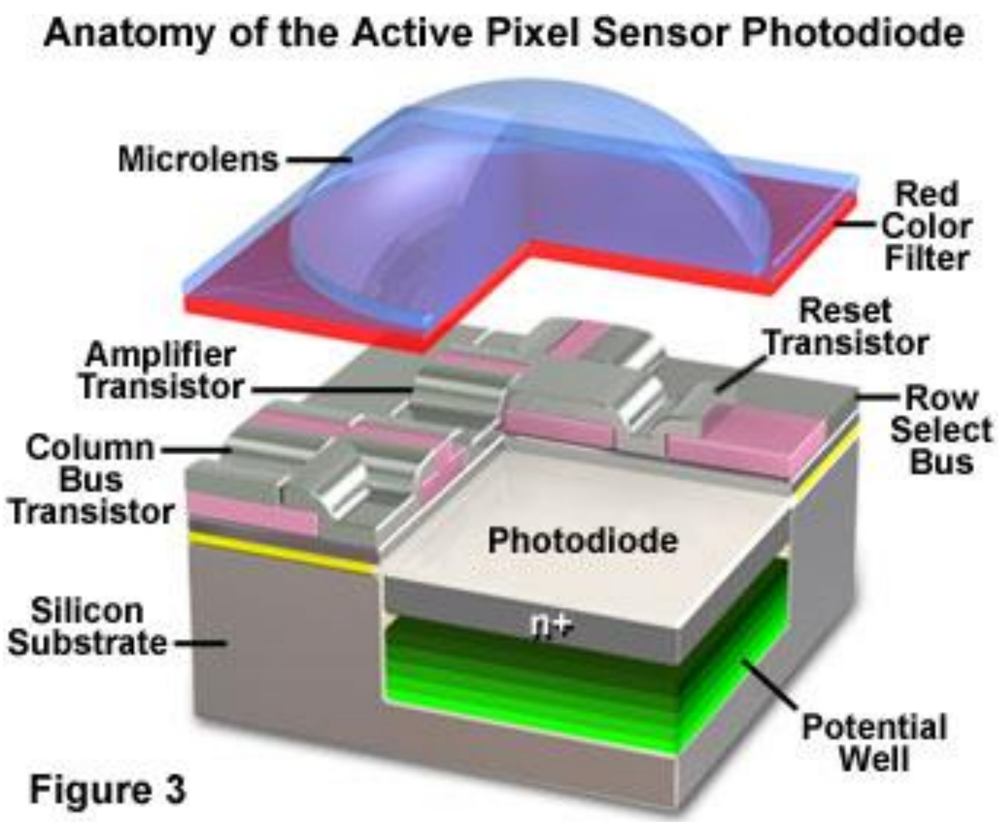
Interline



Pros:
- Fast: shift of only one pixel needed to store charge

Cons:
- Reduced fill factor (abated with microlenses)

CMOS Detectors



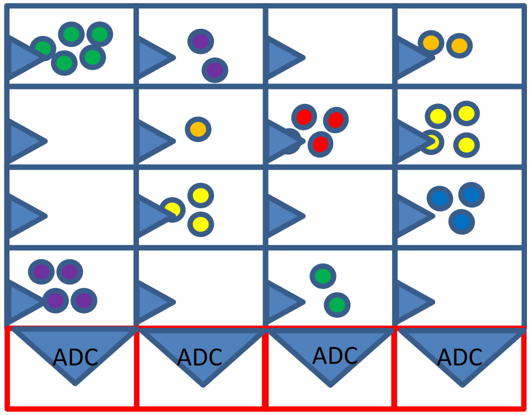
Complementary Metal Oxide Semiconductor

- Transistors in **each pixel** convert charge to voltage
- More can be done within a pixel meaning **frame read out can be faster**
- Fabricated much like microprocessors and RAM so are **cheaper to make**
- Used in webcams, phone cameras since they use **less power**

Image from http://www.olympusmicro.com/primer/digitalimaging/cmosimagesensors.html

CMOS read out

- Each pixel has at least 3 transistors
  - For converting charge to voltage; resetting pixel; transferring voltage
- Voltage transferred along columns to amplifiers and ADCs

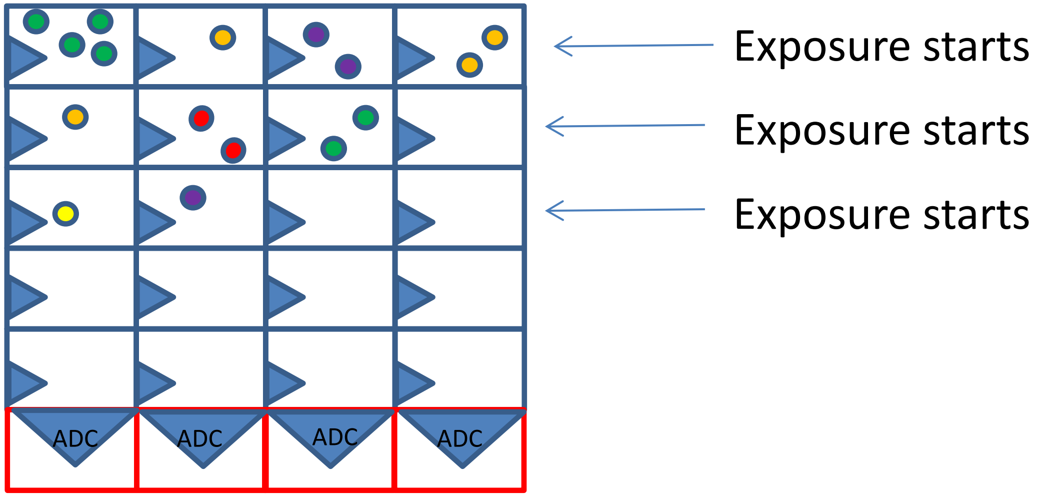


- Each row is then read out to memory

CMOS read out

Global vs. Rolling Shutter

- Rolling Shutter:
  - Exposure start is delayed between each row
  - Readout goes row by row
  - Offset time between rows as low as 10 µs



CMOS read out

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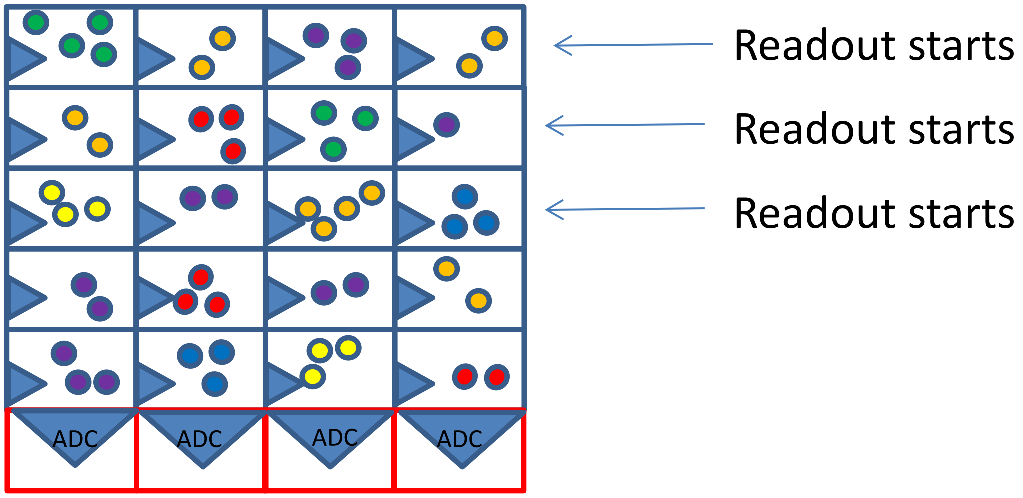

CMOS read out

Global vs. Rolling Shutter

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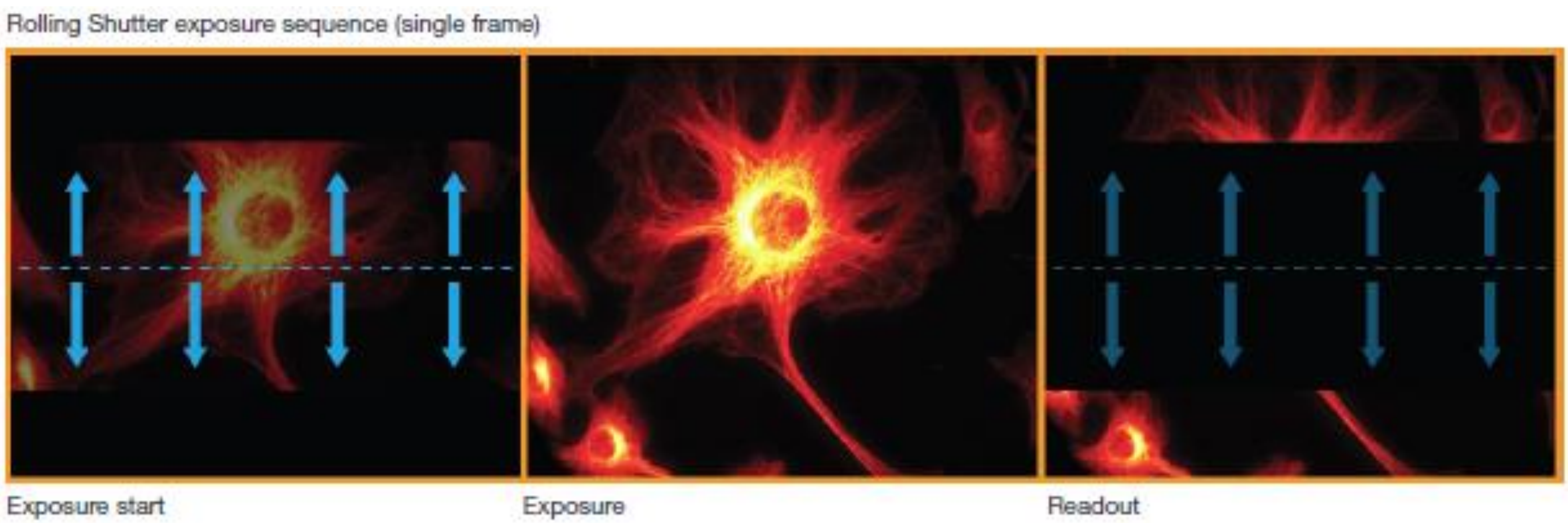


http://www.andor.com/pdfs/literature/Tech_Note_Rolling_Global_Shutter.pdf

CMOS read out

Global vs. Rolling Shutter

- Rolling Shutter:
  - Exposure start is delayed between each row
  - Readout goes row by row
  - Offset time between rows as low as 10 μs
- Global Shutter:
  - All pixels begin and end exposure at same time
  - Requires extra transistor in each pixel
  - Higher read noise
  - Half the maximum frame rate

Many options

CCD

CMOS

Camera Spec Sheets

System Specifications [2]

Model number	897
Sensor QE options	EX2: Back illuminated, dual AR coated BV: Back Illuminated, standard AR coated UVB: Back Illuminated, standard AR with additional lumogen coating
Fringe Suppression	Available on EX2 and BV sensor options
Active pixels	512 x 512
Pixel size	16 x 16 µm
Image area	8.2 x 8.2 mm with 100% fill factor
Minimum temperature, air cooled, ambient 20°C [3] Recirculator liquid cooling, coolant @ 22°C, >0.75l/min Chiller liquid cooling, coolant @ 10°C, >0.75l/min	-80°C -95°C -100°C
Thermostatic Precision	± 0.01°C
Digitization	
Triggering	
System window type	
Blemish specification	
PC Interface	
Lens Mount	
Direct Data Access	

Advanced Performance Spe

Dark current and background events [4,5] Dark current (e⁻/pixel/sec) @ -85°C Spurious background (events/pix) @ 1000x gain / -85°C	
Active area pixel well depth	
Gain register pixel well depth [6]	
Pixel readout rates	
Read noise (e⁻) [7] 17 MHz through EMCCD amplifier 10 MHz through EMCCD amplifier 5 MHz through EMCCD amplifier 1 MHz through EMCCD amplifier 3 MHz through conventional amplifier 1 MHz through conventional amplifier 80 kHz through conventional amplifier	
Linear absolute Electron Multiplier gain	
Linearity [8]	
Vertical clock speed	
Timestamp accuracy	

technical data

image sensor

type of sensor	CCD
image sensor	ICX285AL
resolution (h x v)	1392 x 1040 pixel (normal) 800 x 600 (center)
pixel size (h x v)	6.45 µm x 6.45 µm
sensor format / diagonal	2/3" / 11.14 mm
shutter mode	global (snapshot)
MTF	77.5 lp/mm (theoretical)
fullwell capacity	16 000 e⁻ (full frame) 24 000 e⁻ (binning)
readout noise	5 .. 7 e⁻ rms @ 12 MHz (typ.) 6 .. 8 e⁻ rms @ 24 MHz (typ.)
dynamic range	2 667 : 1 (68 dB, 12 MHz, full frame)
quantum efficiency	65 % @ peak
spectral range	290 nm .. 1100 nm
dark current	1 e⁻/pixel/s @ 23 °C
DSNU[1]	2 e⁻ rms
PRNU[2]	< 1 %

camera

max. frame rate	7.3 / 13.5 fps (12 / 25 MHz, normal) 11.7 / 21.6 fps (12 / 25 MHz, center)
exposure/shutter time	5 µs .. 60 s
dynamic range A/D	14 bit
A/D conversion factor	1.0 e⁻/count
pixel scan rate	12 MHz / 24 MHz
pixel data rate	19.5 Mpixel/s
binning (hor x ver)	1 x 1 .. 2 x 2
non linearity	< 1 %
smear	< 0.002 %
anti-blooming factor	> 400 (standard 100 ms exposure) > 4 (NIR enhanced 100 ms expos.)
interframing time[3]	1 µs
trigger input signals	software / TTL level
trigger output signals	3.3 V LVTTL level

[1] dark signal non-uniformity measured in a 90% center zone of the image sensor
[2] photo response non-uniformity
[3] time between two consecutive images for particle image velocimetry (PIV) applications

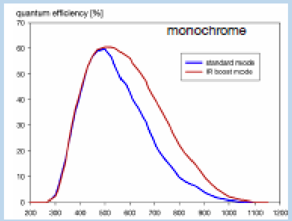
general

power supply	9 .. 28 VDC (12 VDC typ.)
power consumption	< 4 W
weight	0.25 kg
operating temperature	+ 10 °C .. + 45 °C
operating humidity range	10 % .. 80 % (non-condensing)
storage temperature range	- 20 °C .. + 70 °C
optical interface	C-mount
CE certified	yes

frame rate table[4]

resolution	normal		center	
pixelclock [MHz]	12	25	12	25
1392 x 1040	7.3 fps	13.5 fps	11.7 fps	21.6 fps
v2 binning	14.7 fps	27 fps	21.8 fps	40.4 fps

quantum efficiency



Specifications

Product number		C11440-22CU (ORCA-Flash4.0 V2)	
Imaging device		Scientific CMOS sensor FL-400	
Effective number of pixels		2048(H) × 2048(V)	
Cell size		6.5 µm × 6.5 µm	
Effective area		13.312 mm × 13.312 mm	
Full well capacity (typ.)		30 000 electrons	
Readout time	Standard scan (at 100 frames/s)	10 ms	
	Slow scan (at 30 frames/s)	33 ms	
Readout noise	Standard scan (at 100 frames/s, typ.)	1.9 electrons rms (1.3 electrons median)	
	Slow scan (at 30 frames/s, typ.)	1.5 electrons rms (0.9 electrons median)	
		33 000:1	
		Higher than 70 % at 600 nm and 50 % at 750 nm	
		Dark current (typ.)	Sensor temperature (nominal)
+20 ℃)		0.5 electrons/pixel/s	−10 ℃
		0.15 electrons/pixel/s	−20 ℃
		0.05 electrons/pixel/s	−30 ℃
		Camera Link	USB 3.0
		100 frames/s	30 frames/s
position)		200 frames/s	60 frames/s
ition)		25 655 frames/s	7894 frames/s
ion)		-	25 655 frames/s
de™ (Camera Link only)			
		Seamless readout	
		Top to bottom / Bottom to top	
		20 ms to 204.8 s (at full area readout)	
		Full area, Sub-array	
		16 bit output	
		Digital binning 2 × 2 / 4 × 4	
		Sub-array readout mode	
ger mode (at full resolution)		1 ms to 10 s	
ger mode with sub-array readout		38.96 µs to 10 s	
ger mode with sub-array readout		1 ms to 10 s	
		Camera Link full configuration Deca mode / USB 3.0	
		C-mount	
		AC 100 V to AC 240 V, 50 Hz/60 Hz	
		Approx. 70 VA	
		Edge, Level, Synchronous readout and Start trigger	
outing		SMA connector or Camera Link I/F	
inction		0 to 10 s in 10 µs steps	
		3 programmable timing outputs	
		Global exposure timing and Trigger ready output	
outing		SMA connector	
		PC-based acquisition package included	
		DCAM-SDK, commercially available software	

ut noise median in slow scan
internal trigger mode varies depending on sub-array setting. Minimum exposure time is in standard scan.

The Ideal Camera

- High resolution
  - Optically resolvable features span a couple pixels
- Large area
  - Covers field of view
- Linear response
  - Twice the photons gives twice the output
- Uniform response
  - Same response no matter where photon lands
- Fast
  - Can capture dynamic processes
- High sensitivity
  - All photons get measured

Going into the spec sheet

technical data

image sensor

type of sensor	CCD
image sensor	ICX285AL
resolution (h x v)	1392 x 1040 pixel (normal)

SONY Interline CCD chip

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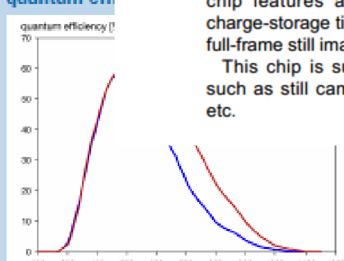
›perating temperature	
›perating humidity ran	
›torage temperature ra	
optical interface	
CE certified	

frame rate table[4]

resolution	nor
pixelclock [MHz]	12
1392 x 1040	7.3
v2 binning	14.

quantum effi



SONY **ICX285AL**

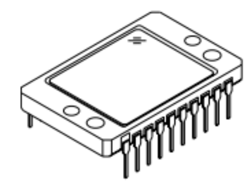
Diagonal 11 mm (Type 2/3) Progressive Scan CCD Image Sensor with Square Pixel for B/W Cameras

Description

The ICX285AL is a diagonal 11 mm (Type 2/3) interline CCD solid-state image sensor with a square pixel array. High sensitivity and low smear are achieved through the adoption of EXview HAD CCD technology. Progressive scan allows all pixel's signals to be output independently within approximately 1/15 second. Also, the adoption of high frame rate readout mode supports 60 frames per second. This chip features an electronic shutter with variable charge-storage time which makes it possible to realize full-frame still images without a mechanical shutter.

This chip is suitable for image input applications such as still cameras which require high resolution, etc.

20 pin DIP (Ceramic)



Going into the spec sheet

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shutter mode	global (snapshot)
MTF	77.5 lp/mm (theoretical)
fullwell capacity	16 000 e⁻ (full frame) 24 000 e⁻ (binning)
readout noise	5 .. 7 e⁻ rms @ 12 MHz (typ.) 6 .. 8 e⁻ rms @ 24 MHz (typ.)
dynamic range	2 667 : 1 (68 dB, 12 MHz, full frame)
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camera

max. frame rate	7.3 / 13.5 fps (12 / 25 MHz, normal) 11.7 / 21.6 fps (12 / 25 MHz, center)
exposure/shutter time	5 µs .. 60 s
dynamic range A/D	14 bit
A/D conversion factor	1.0 e⁻/count
pixel scan rate	12 MHz / 24 MHz
pixel data rate	19.5 Mpixel/s
binning (hor x ver)	1 x 1 .. 2 x 2
non linearity	< 1 %
smear	< 0.002 %
anti-blooming factor	> 400 (standard 100 ms exposure) > 4 (NIR enhanced 100 ms expos.)
interframing time[3]	1 µs
trigger input signals	software / TTL level
trigger output signals	3.3 V LVTTL level

[1] dark signal non-uniformity measured in a 90% center zone of the image sensor
[2] photo response non-uniformity
[3] time between two consecutive images for particle image velocimetry (PIV) applications

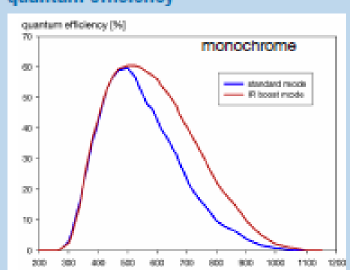
general

power supply	9 .. 28 VDC (12 VDC typ.)
power consumption	< 4 W
weight	0.25 kg
operating temperature	+ 10 °C .. + 45 °C
operating humidity range	10 % .. 80 % (non-condensing)
storage temperature range	- 20 °C .. + 70 °C
optical interface	C-mount
CE certified	yes

frame rate table[4]

resolution	normal		center	
pixelclock [MHz]	12	25	12	25
1392 x 1040	7.3 fps	13.5 fps	11.7 fps	21.6 fps
v2 binning	14.7 fps	27 fps	21.8 fps	40.4 fps

quantum efficiency



resolution (h x v)	1392 x 1040 pixel (normal) 800 x 600 (center)
pixel size (h x v)	6.45 µm x 6.45 µm

Suppose you want 3 pixels per resolvable unit of 300 nm:

$0.3\ \mu m \times M = 3 \times 6.45\ \mu m$

$M = 64.5\times$

Going into the spec sheet

technical data

image sensor

type of sensor	CCD
image sensor	ICX285AL
resolution (h x v)	1392 x 1040 pixel (normal) 800 x 600 (center)
pixel size (h x v)	6.45 µm x 6.45 µm
sensor format / diagonal	2/3" / 11.14 mm
shutter mode	global (snapshot)
MTF	77.5 lp/mm (theoretical)
fullwell capacity	16 000 e⁻ (full frame) 24 000 e⁻ (binning)
readout noise	5 .. 7 e⁻ rms @ 12 MHz (typ.) 6 .. 8 e⁻ rms @ 24 MHz (typ.)
dynamic range	2 667 : 1 (68 dB, 12 MHz, full frame)
quantum efficiency	65 % @ peak
spectral range	290 nm .. 1100 nm
dark current	1 e⁻/pixel/s @ 23 °C
DSNU[1]	2 e⁻ rms
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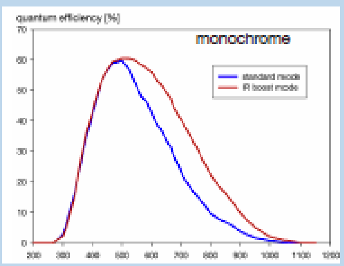
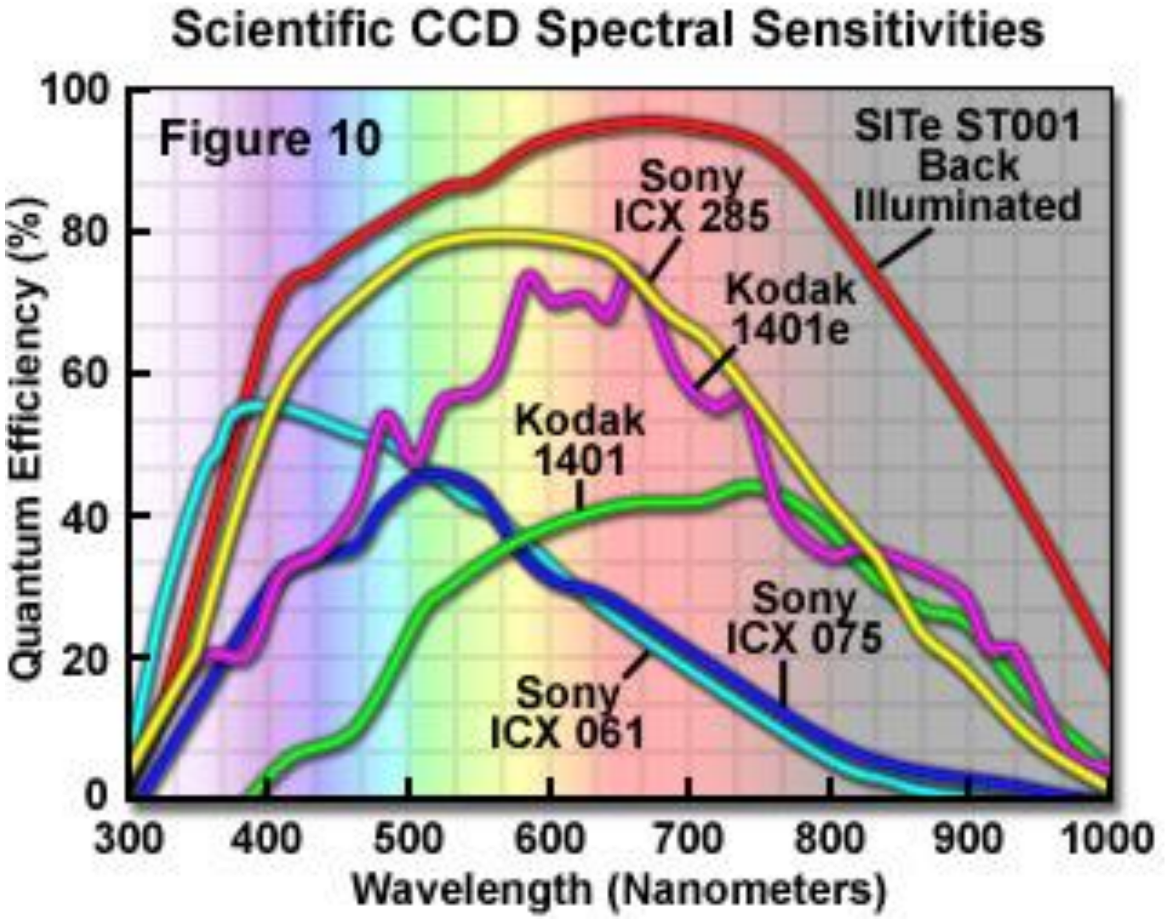


How well are photons detected?

Quantum Efficiency



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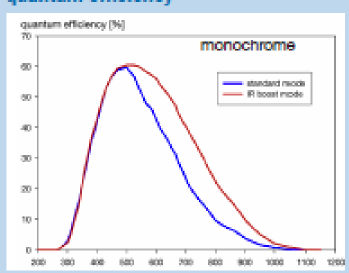
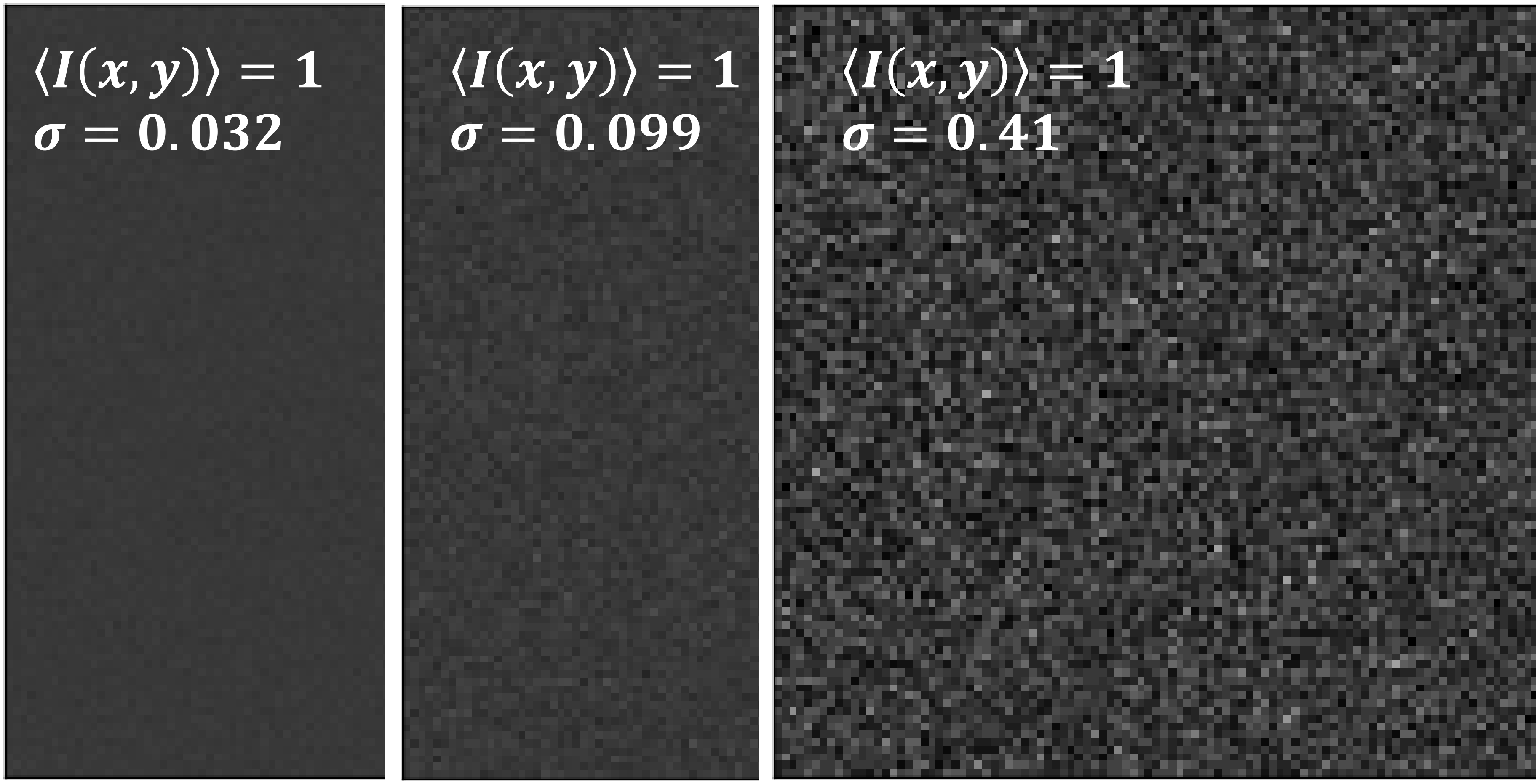


NOISE!

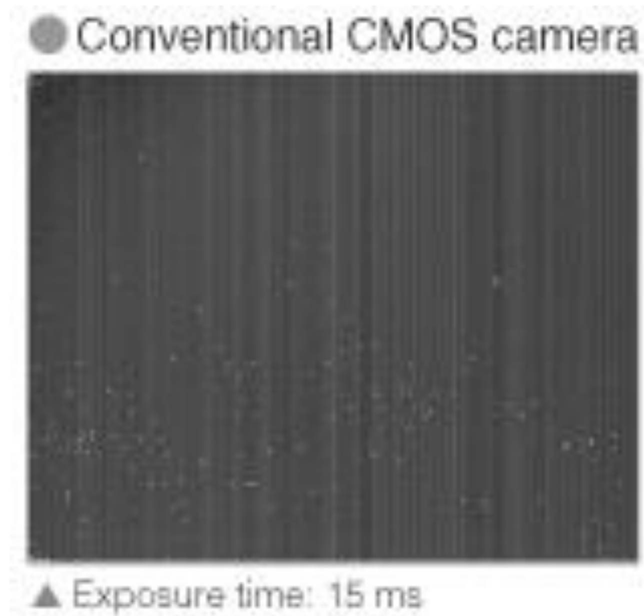
What is noise?

- Uncertainty in measured signal
- Looks like random fluctuations in intensity



NOISE!

- The different types of noise
  - Fixed Pattern Noise
    - Pixels respond to light or photoelectrons differently
      - [Perhaps because piece of dirt in front of some]
    - $\sigma_{FPN}\,(S) = \mathrm{P_N}S$ [$\mathrm{P_N}$ is the FPN quality factor]
    - Correctable through process of flat fielding
    - Can be an issue with CMOS since electronics associated with each pixel can be different



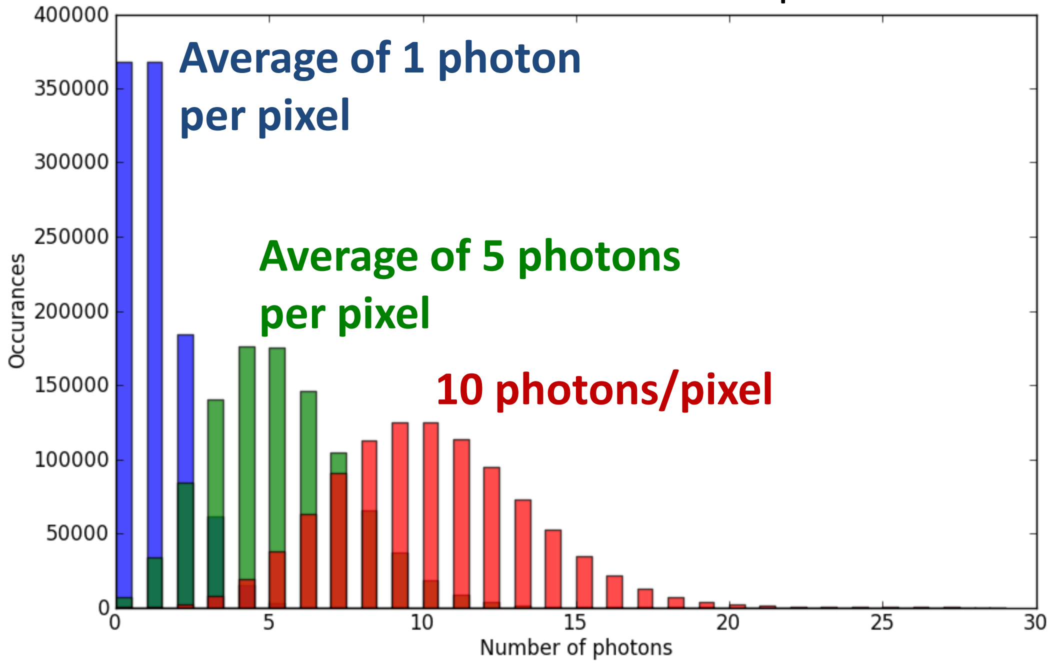
NOISE!

- The different types of noise
  - Fixed Pattern Noise
  - Dark Noise
    - Temperature dependent; reduced by cooling camera
  - Clock-induced Charge Noise
    - As charge gets moved around, new electrons can be generated

NOISE!

- The different types of noise
  - Fixed Pattern Noise
  - Dark Noise
  - Clock-induced Charge Noise
  - Shot Noise
    - Photons are discrete; follow Poisson distribution
    - Photon Shot Noise
      - $\sigma_{shot}\,(S) = S^{\frac{1}{2}}$

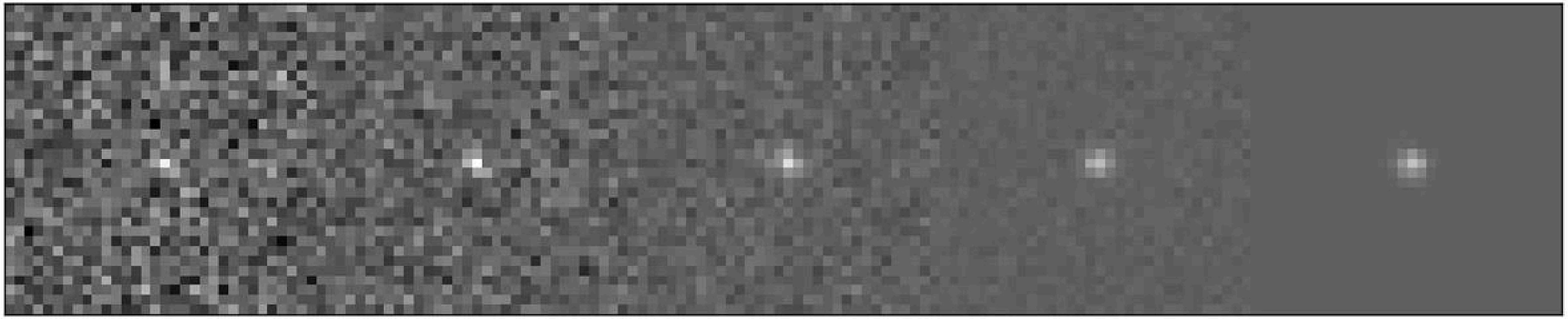
Photon distribution on 1 million pixels



NOISE!

- The different types of noise
  - Fixed Pattern Noise
  - Dark Noise
  - Clock-induced Charge Noise
  - Shot Noise
  - Read Noise
    - Not a function of signal. Due to electronics converting charge to voltage
    - Generally increases with increased readout speed
    - Sets the minimum signal that can be detected

Decreasing read noise



Same signal.

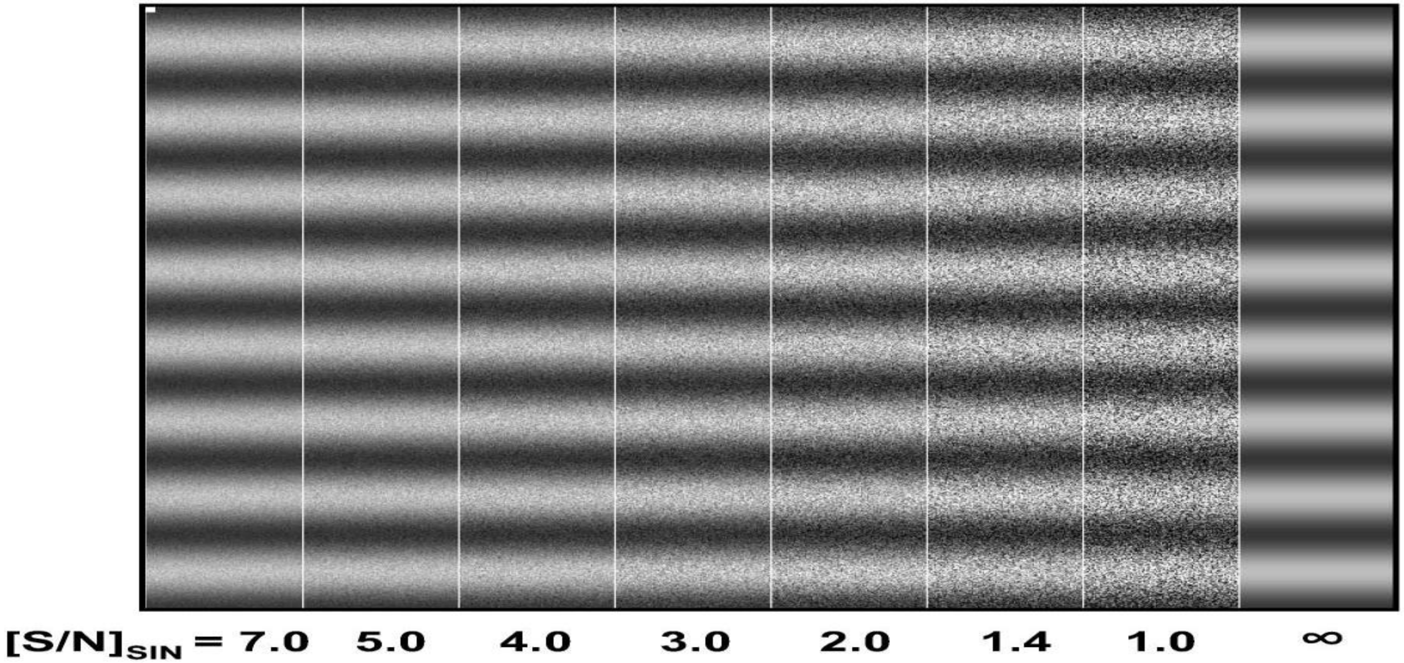
NOISE!

- The different types of noise
  - Fixed Pattern Noise
  - Dark Noise
  - Clock-induced Charge Noise
  - Shot Noise
  - Read Noise

- Signal to Noise Ratio

$$\mathrm{SNR} = \frac{\mathrm{QE} \times S}{\sqrt{\sigma_{READ}^2 + \mathrm{QE} \times S + (\mathrm{P_N} \times \mathrm{QE} \times S)^2}}$$

NOISE!

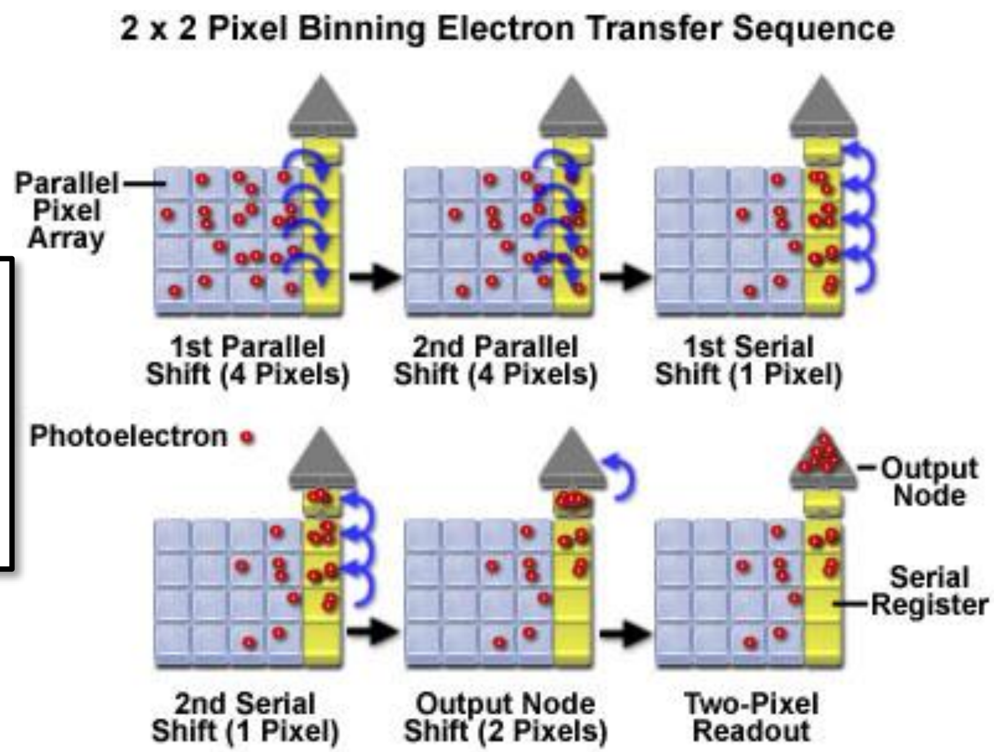


- Signal to Noise Ratio

$$\mathrm{SNR} = \frac{\mathrm{QE} \times S}{\sqrt{\sigma_{READ}^2 + \mathrm{QE} \times S + (\mathrm{P_N} \times \mathrm{QE} \times S)^2}}$$

How do you optimize SNR?

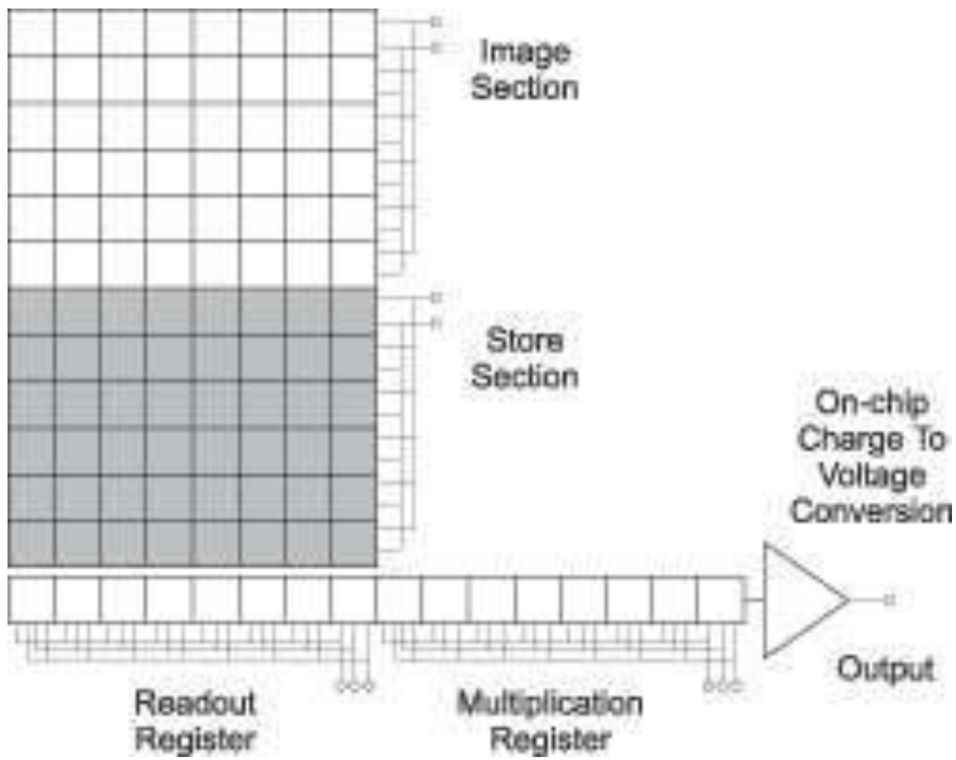
- Choose a camera that has:
  - High QE
    - Back illuminated
  - Low read noise
  - Cooling ability
  - Spatial uniformity
- When imaging:
  - Go at slowest speeds
  - Use largest pixel size
    - Binning



Binning increases the SNR by a factor of the sqrt of number of pixels binned

Nearly eliminating read noise: EMCCDs

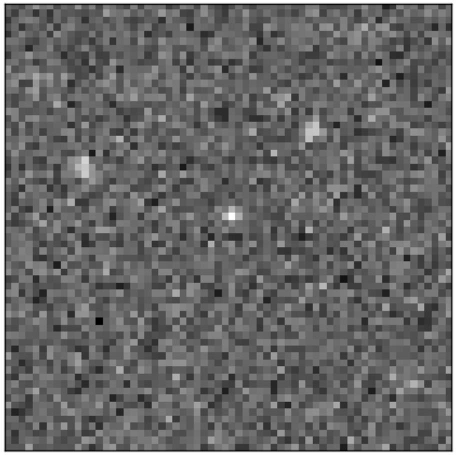
- Amplifies signal to push it well above read noise



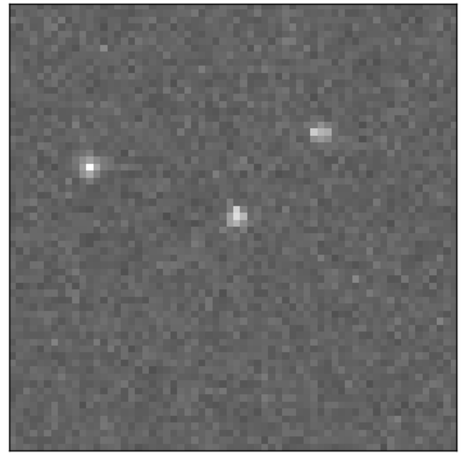
- In CCDs: rows gets transferred to edge to readout register
- EMCCDs add an **electron multiplication** (EM) register
- As charge is transferred through EM register, *impact ionization* increases charge on order of 100-1000×

Image from http://www.andor.com/learning-academy/electron-multiplying-ccd-cameras-the-technology-behind-emccds

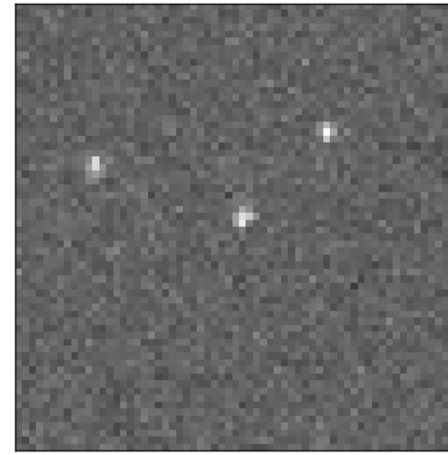
Noise in EMCCDs



Read noise = 10 e^-



Read noise = 0.5 e^-



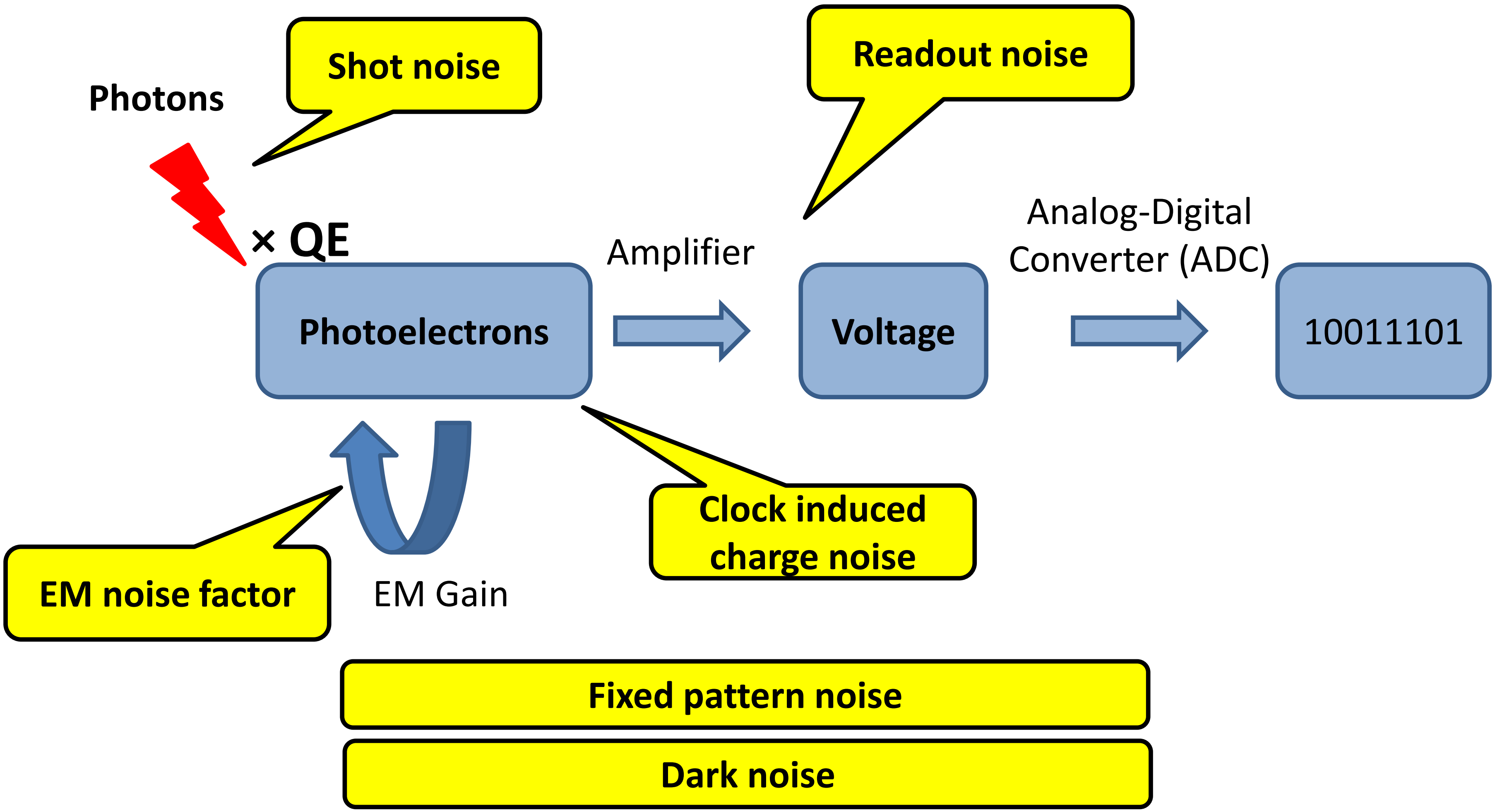
Read noise = 0.5 e^-
Plus EM associated noise, F_n

$$\mathrm{SNR} = \frac{\mathrm{QE} \times S}{\sqrt{\sigma_{READ}^2 / M^2 + F_n^2 \times \mathrm{QE} \times S}}$$

A new option for when photons are few: sCMOS

- “scientific” CMOS
  - Latest generation of CMOS cameras
  - Sensor split into top and bottom halves
    - Both are read out independently to increase speed
  - Each column as dual amplifiers and ADC
    - For high and low gain readout to maximize dynamic range

NOISE!

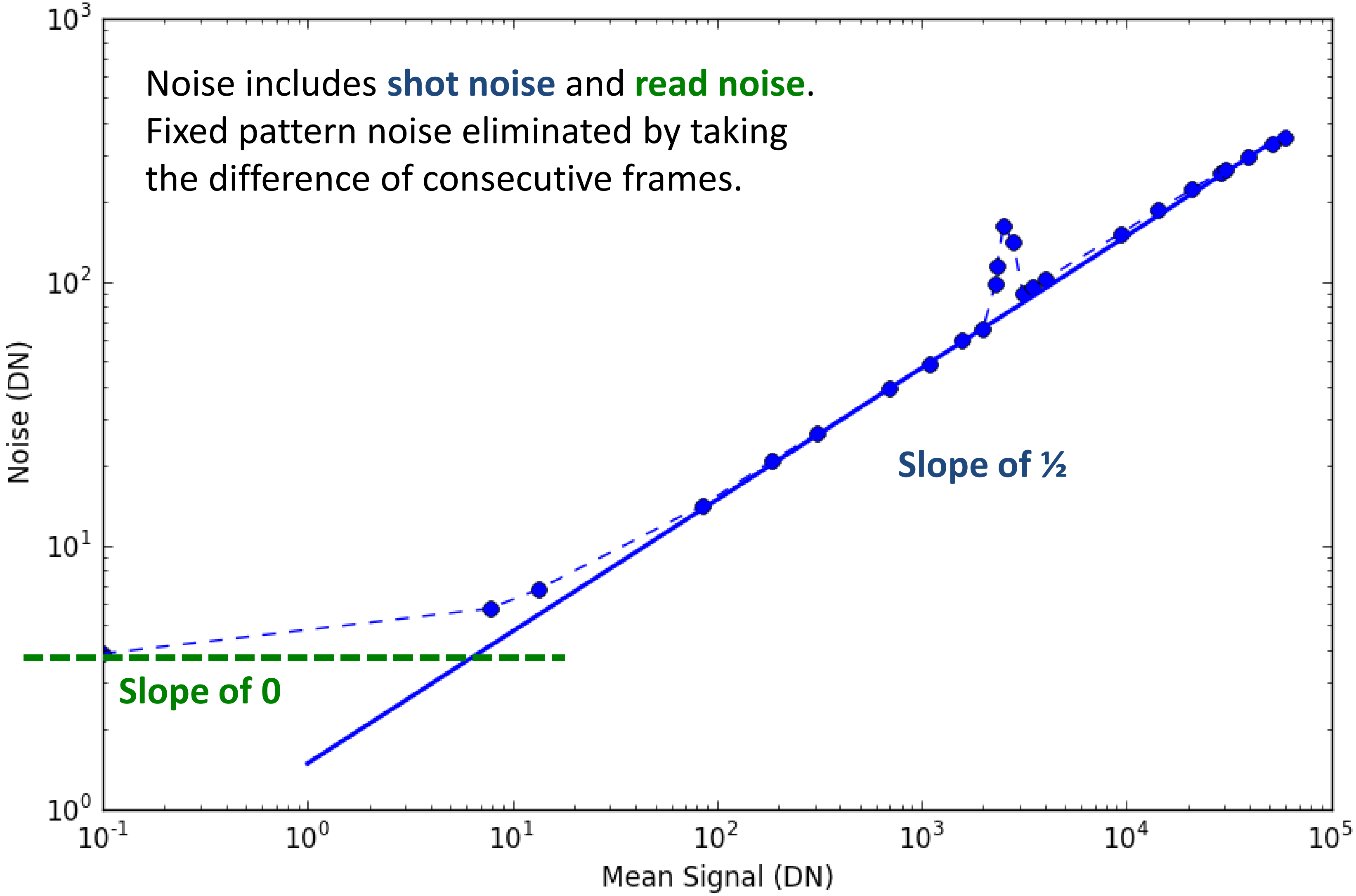

Shot noise
Photons
Readout noise
× QE
Amplifier
Analog-Digital
Converter (ADC)
Photoelectrons
Voltage
10011101
Clock induced
charge noise
EM noise factor
EM Gain
Fixed pattern noise
Dark noise

Measuring noise

- Steps to generate photon transfer curve:
  - Record several sequences of frames at various illumination levels starting with completely dark
  - Use homogenous illumination,
  - Or correct for inhomogeneity as well as fixed pattern noise by subtracted neighboring frames
  - Plot standard deviation of signal versus mean signal

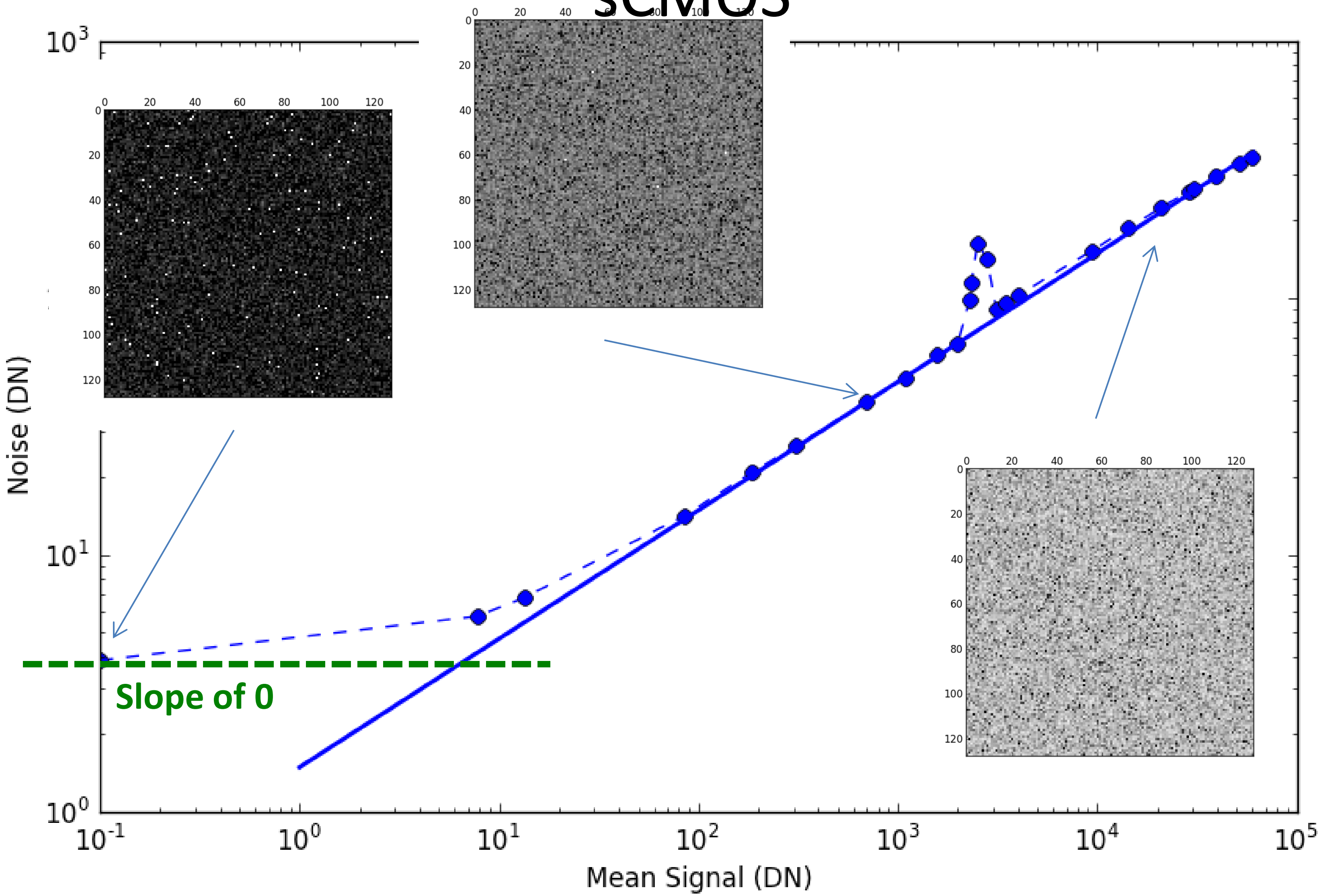
$$\sigma^2\big(\mathrm{I}(\mathrm{x},\mathrm{y})\big) = A\,\langle \mathrm{I}(\mathrm{x},\mathrm{y})\rangle + \sigma_{READ}^2$$

sCMOS



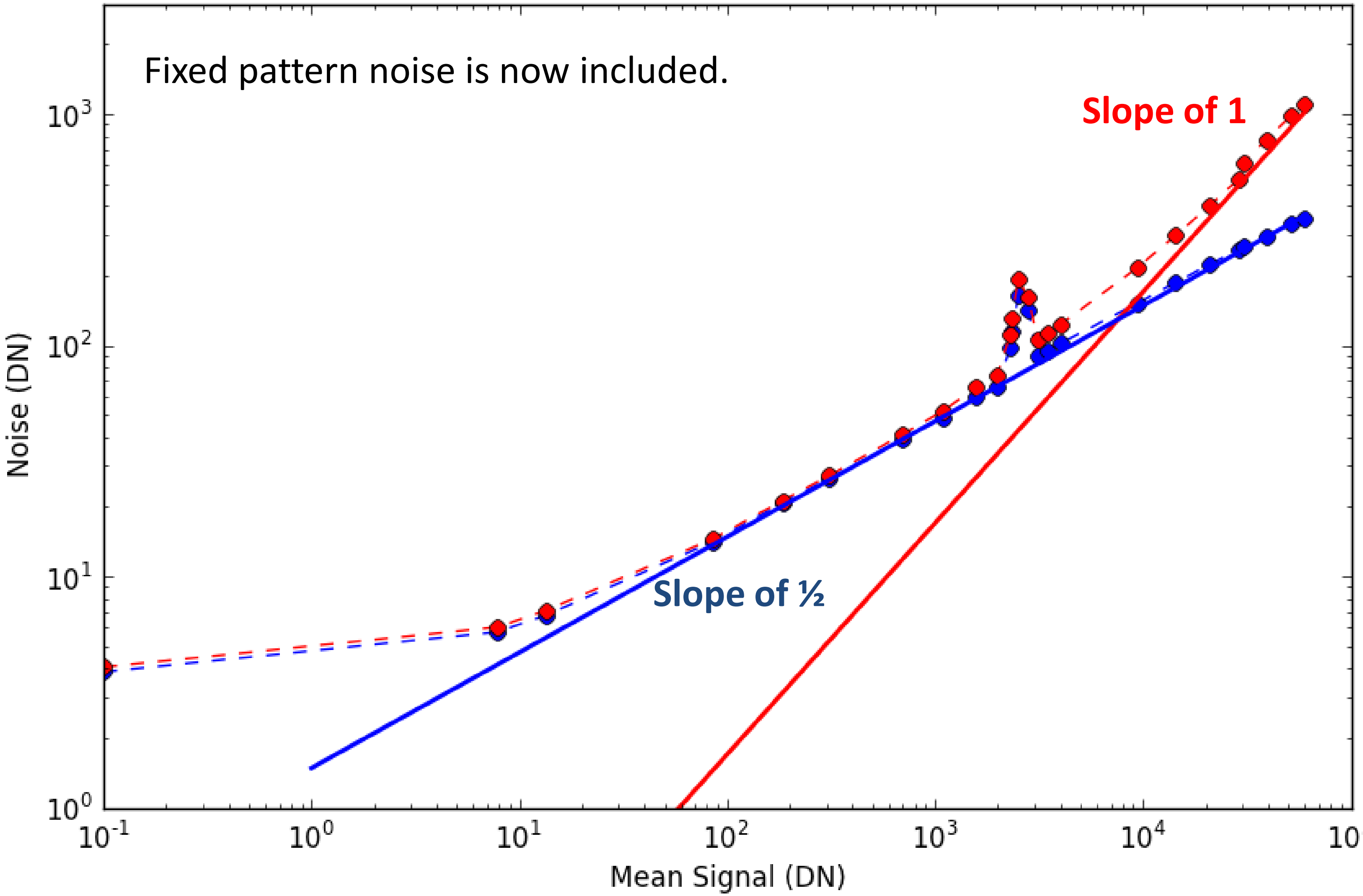
Noise includes shot noise and read noise.
Fixed pattern noise eliminated by taking
the difference of consecutive frames.
Slope of ½
Slope of 0
Noise (DN)
Mean Signal (DN)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

sCMOS

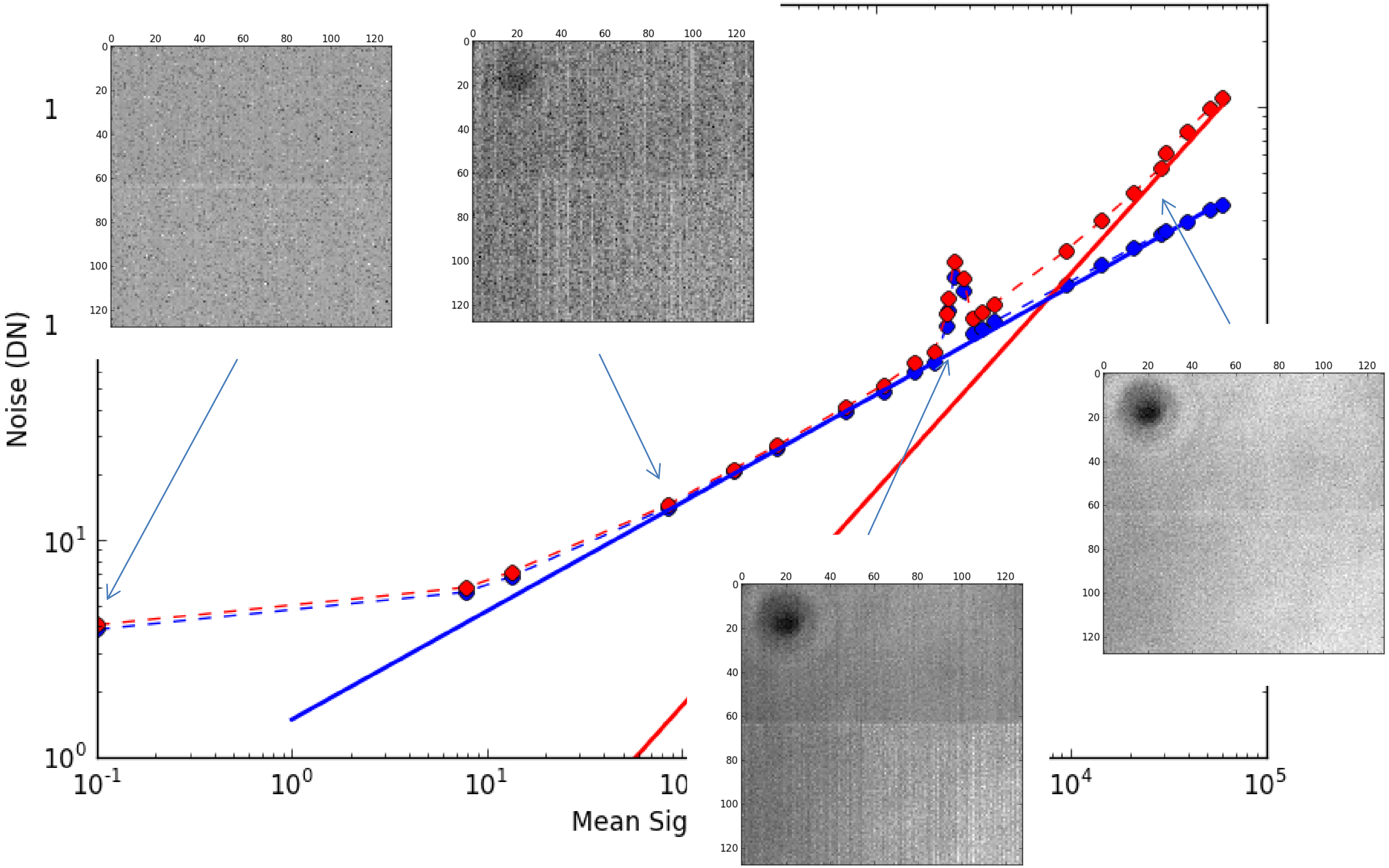


Images show variance on a log scale

sCMOS

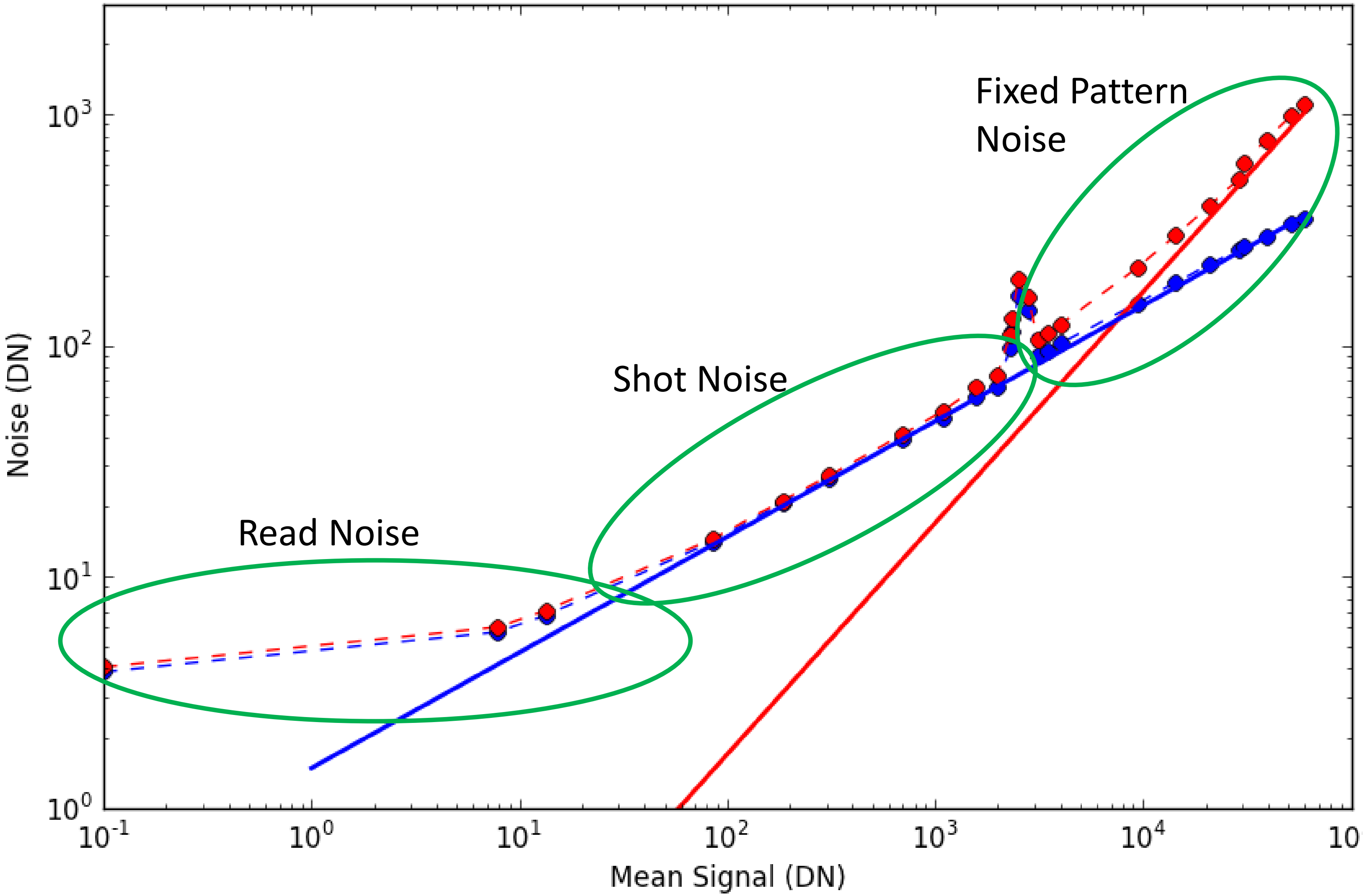

Fixed pattern noise is now included.
Slope of 1
Slope of ½
Noise (DN)
Mean Signal (DN)
10^3
10^2
10^1
10^0
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5

sCMOS



Images show average of 400 frames

sCMOS

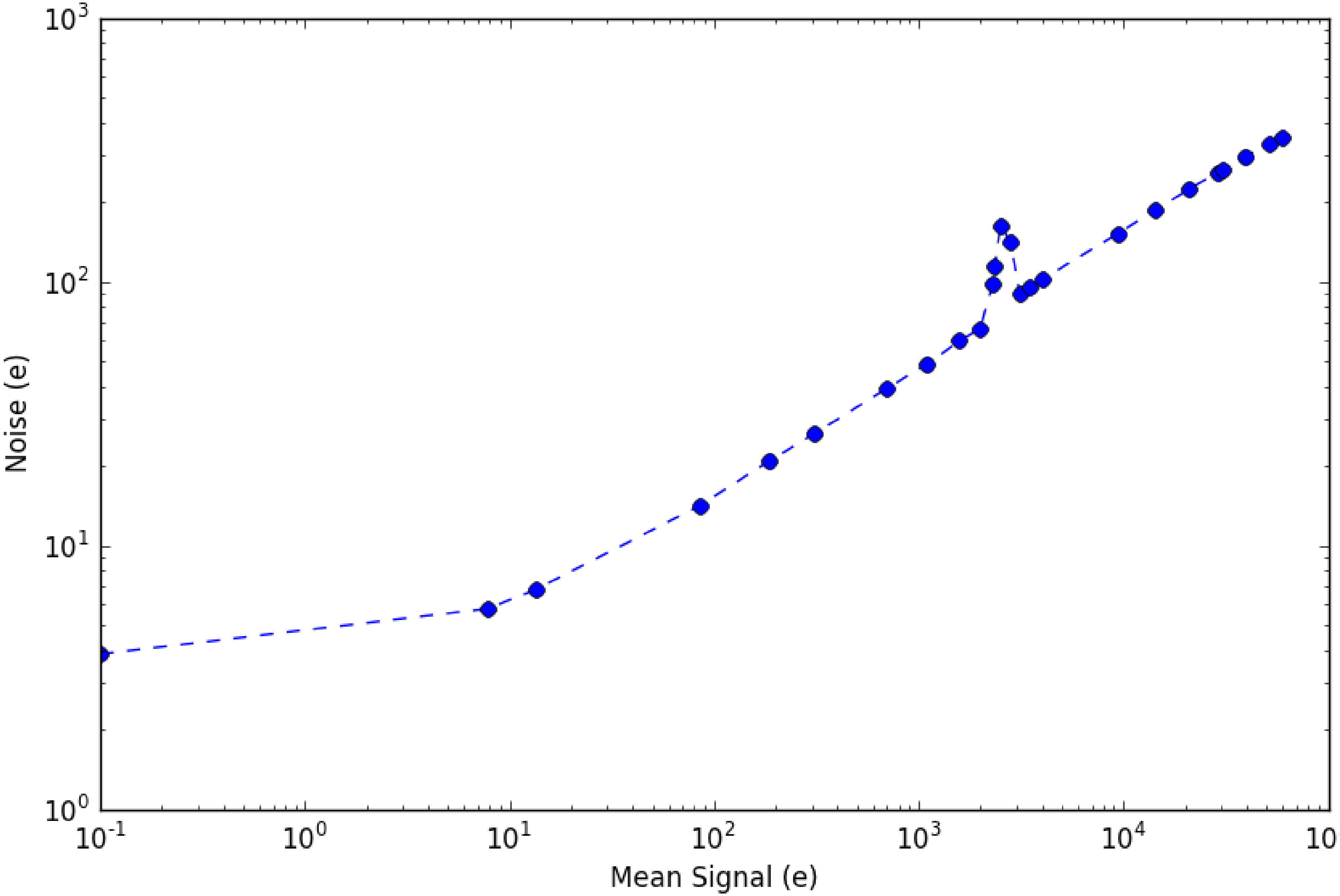


By looking at shot noise vs. signal: ADU conversion is about 2.2 DN/e$^-$

Read noise: noise vs. signal levels out around 3.8 DN = 1.7e$^-$

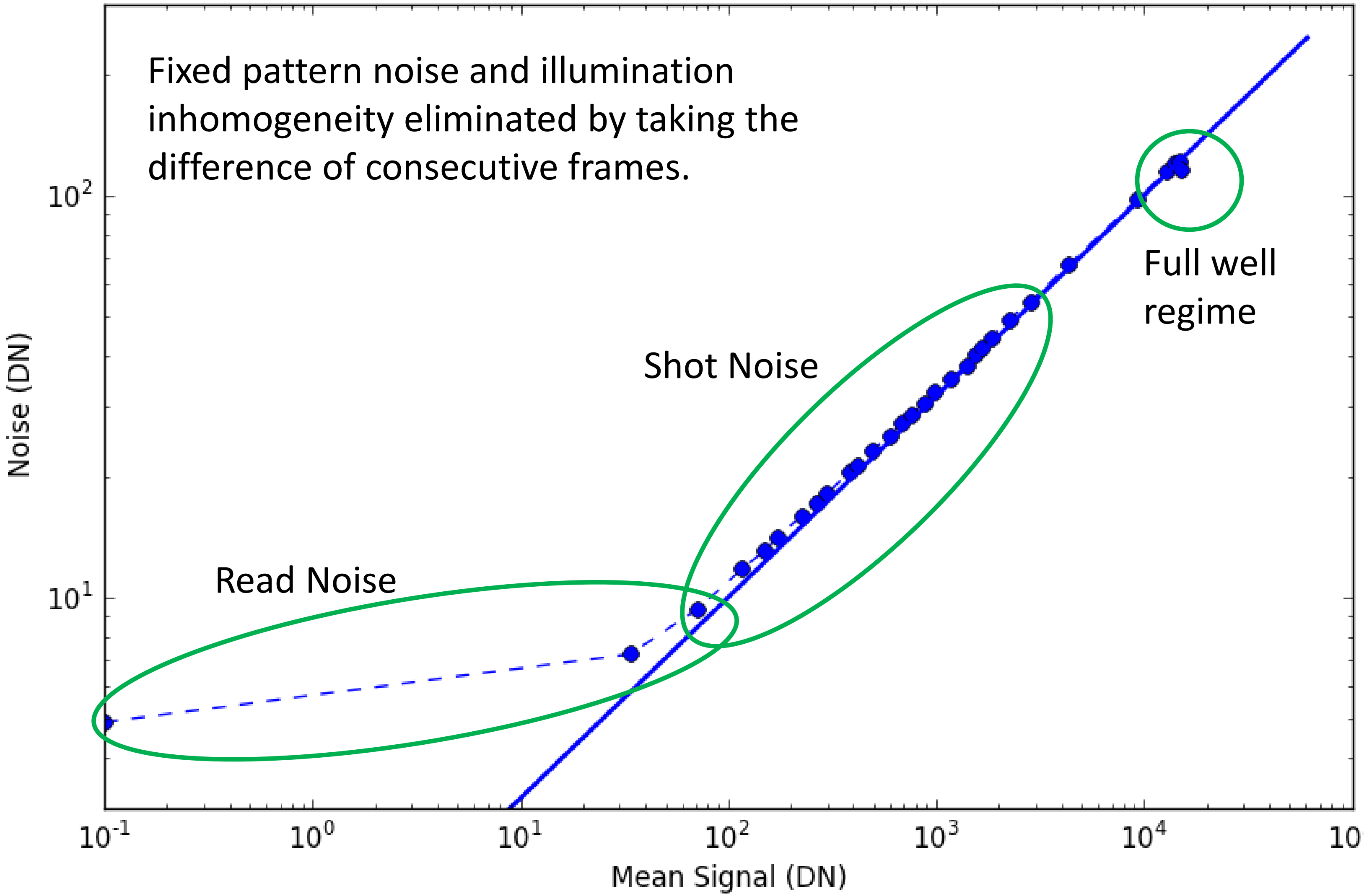
Fixed pattern noise: about 1.7% of signal

sCMOS



Read noise: noise vs. signal levels out around 1.7e$^-$

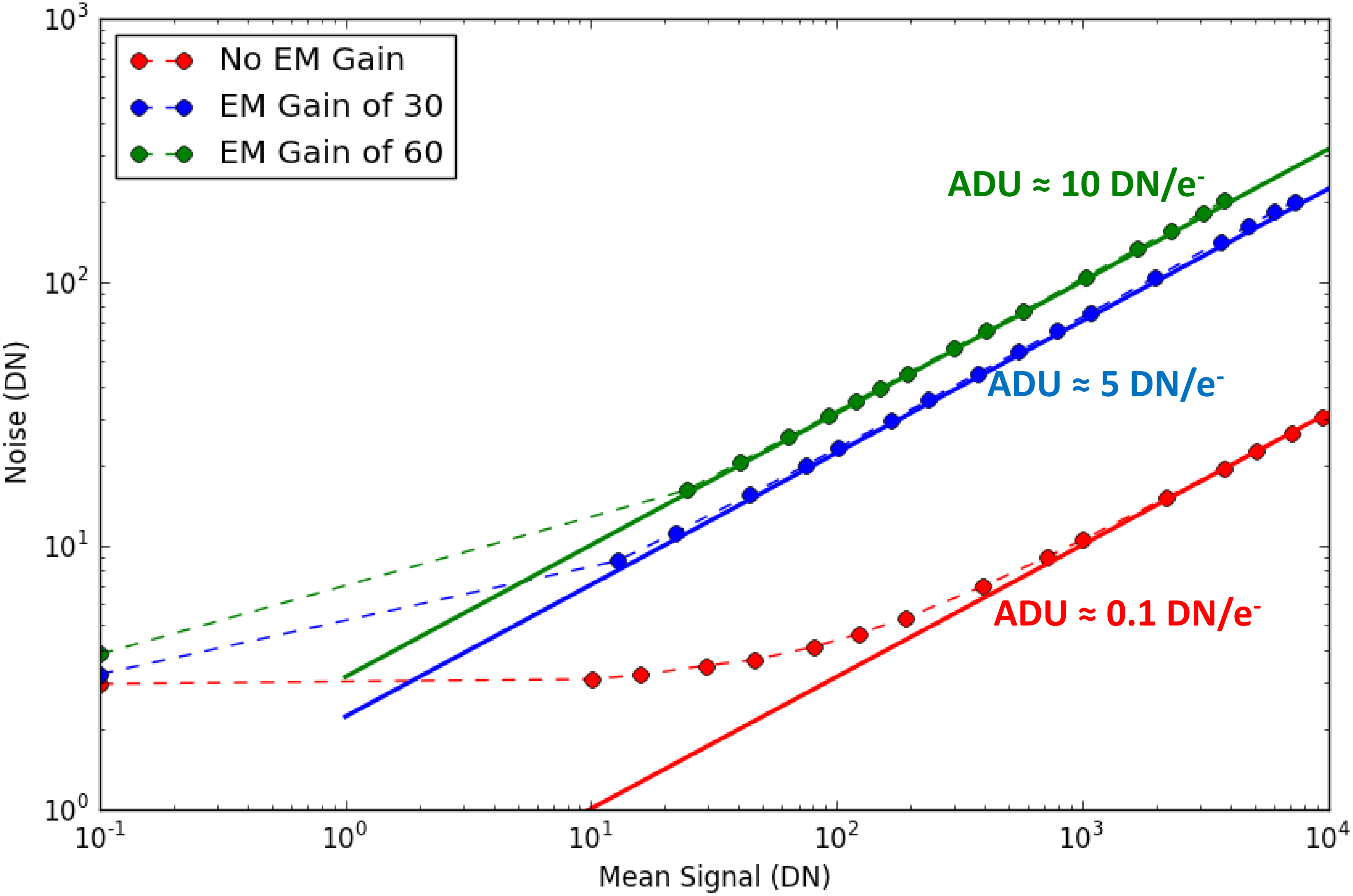
CCD



By looking at shot noise vs. signal: ADU conversion is about 1.0 DN/e^-

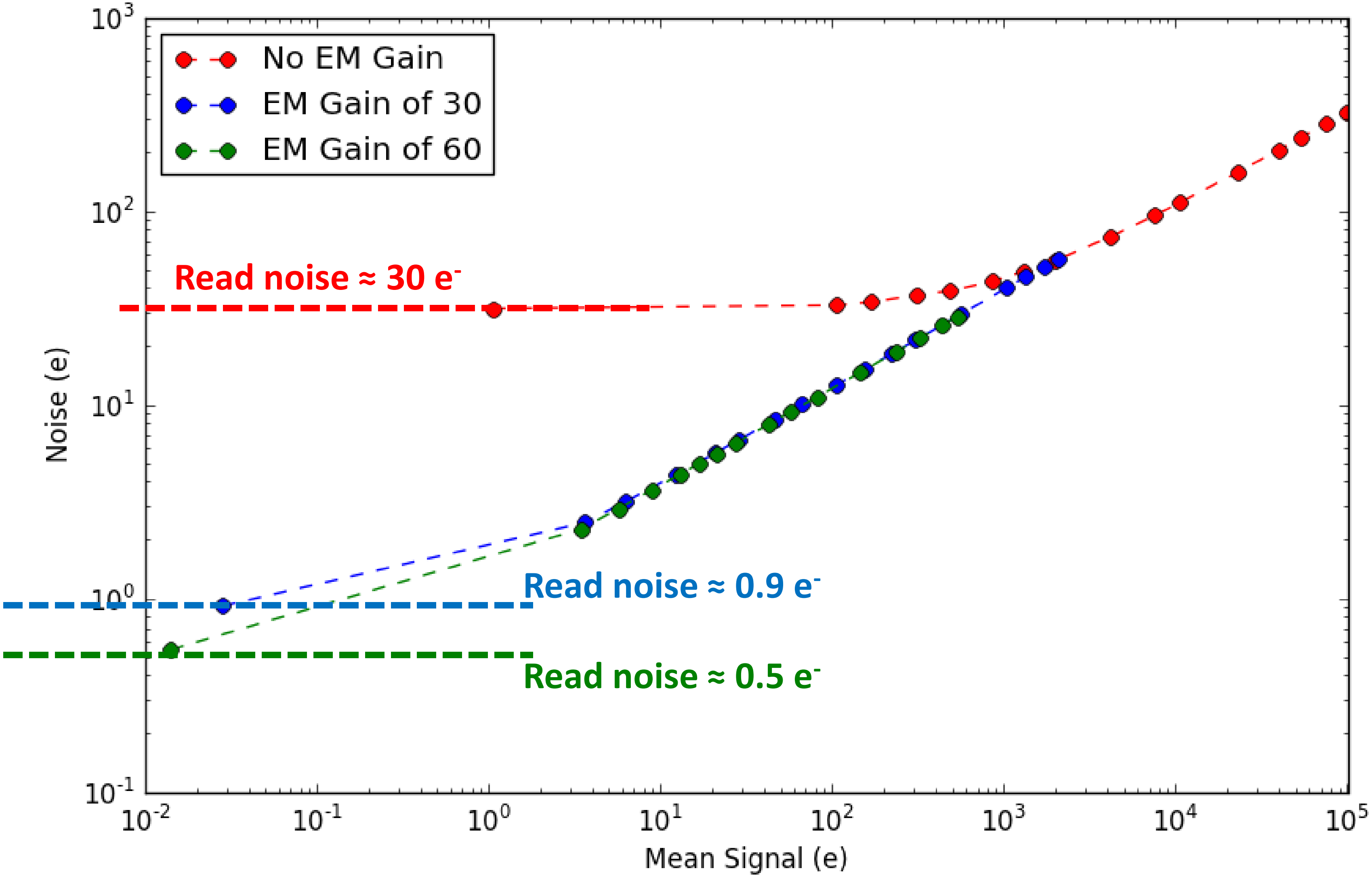
Read noise: noise vs. signal levels out around 5 DN = 5 e^-

EMCCD

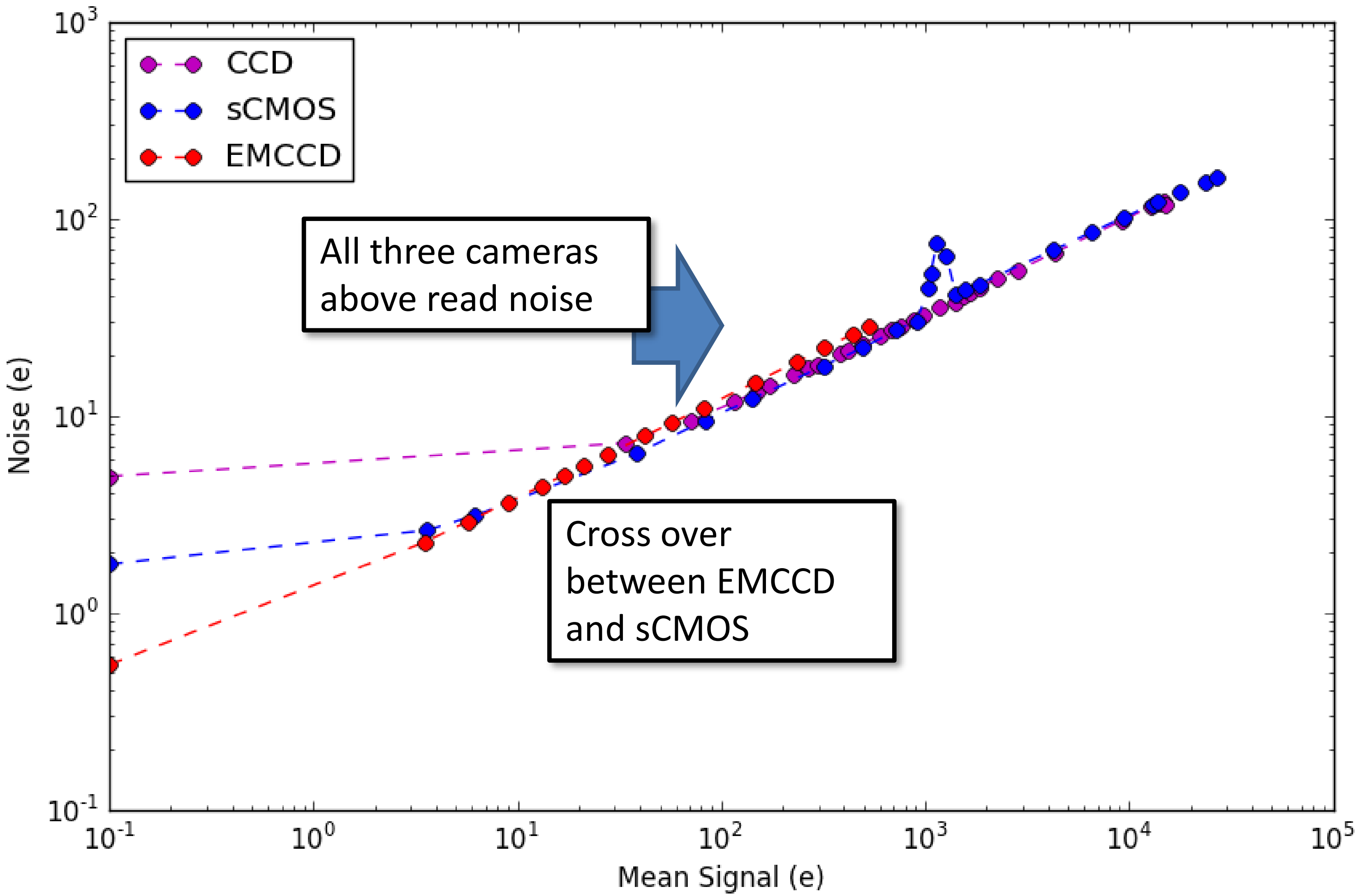


No EM Gain
EM Gain of 30
EM Gain of 60
ADU ≈ 10 DN/e-
ADU ≈ 5 DN/e-
ADU ≈ 0.1 DN/e-
Noise (DN)
Mean Signal (DN)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

EMCCD



When plotted in units of e^- rather than DN benefit of EM gain can be seen: **read noise is effectively reduced by the amount of gain**



CCD
sCMOS
EMCCD
All three cameras above read noise
Cross over between EMCCD and sCMOS
Noise (e)
Mean Signal (e)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-1}
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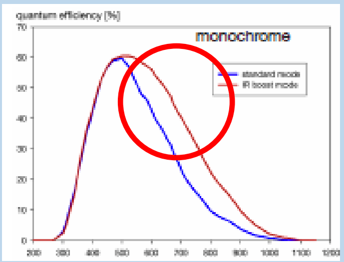
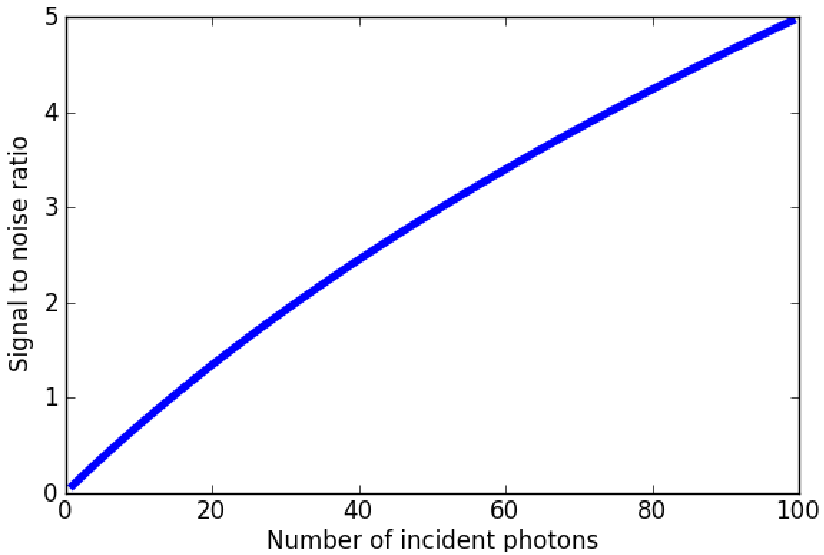


N_r = 6 e-
QE ≈ 45% at ≈ 700nm

$$\mathrm{SNR} = \frac{\mathrm{QE} \times P}{\sqrt{\mathrm{QE} \times P + \sigma_{READ}^2}}$$



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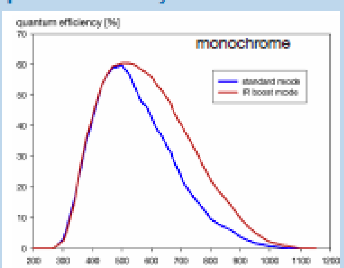
v2 binning	14.7 fps	27 fps	21.8 fps	40.4 fps

quantum efficiency



Dark current: 1 e^-/pixel/s @ 23 °C

Going back to the spec sheet

technical data

image sensor

type of sensor	CCD
image sensor	ICX285AL
resolution (h x v)	1392 x 1040 pixel (normal) 800 x 600 (center)
pixel size (h x v)	6.45 µm x 6.45 µm
sensor format / diagonal	2/3" / 11.14 mm
shutter mode	global (snapshot)
MTF	77.5 lp/mm (theoretical)
fullwell capacity	16 000 e⁻ (full frame) 24 000 e⁻ (binning)
readout noise	5 .. 7 e⁻ rms @ 12 MHz (typ.) 3 .. 9 e⁻ rms @ 24 MHz (typ.)
dynamic range	2 667 : 1 (68 dB, 12 MHz, full frame)
quantum efficiency	60 % @ peak
spectral range	290 nm .. 1100 nm
dark current	1 e⁻/pixel/s @ 23 °C
DSNU[1]	2 e⁻ rms
PRNU[2]	< 1 %

camera

max. frame rate	7.3 / 13.5 fps (12 / 25 MHz, normal) 11.7 / 21.6 fps (12 / 25 MHz, center)
exposure/shutter time	5 µs .. 60 s
dynamic range A/D	14 bit
A/D conversion factor	1.0 e⁻/count
pixel scan rate	12 MHz / 24 MHz
pixel data rate	19.5 Mpixel/s
binning (hor x ver)	1 x 1 .. 2 x 2
non linearity	< 1 %
smear	< 0.002 %
anti-blooming factor	> 400 (standard 100 ms exposure) > 4 (NIR enhanced 100 ms expos.)
interframing time[3]	1 µs
trigger input signals	software / TTL level
trigger output signals	3.3 V LVTTL level

[1] dark signal non-uniformity measured in a 90% center zone of the image sensor
[2] photo response non-uniformity
[3] time between two consecutive images for particle image velocimetry (PIV) applications

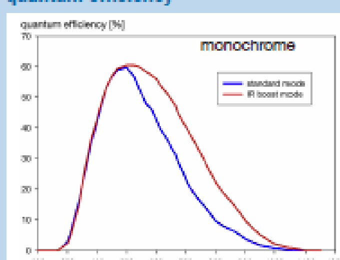
general

power supply	9 .. 28 VDC (12 VDC typ.)
power consumption	< 4 W
weight	0.25 kg
operating temperature	+ 10 °C .. + 45 °C
operating humidity range	10 % .. 80 % (non-condensing)
storage temperature range	- 20 °C .. + 70 °C
optical interface	C-mount
CE certified	yes

frame rate table[4]

resolution	normal		center	
pixelclock [MHz]	12	25	12	25
1392 x 1040	7.3 fps	13.5 fps	11.7 fps	21.6 fps
v2 binning	14.7 fps	27 fps	21.8 fps	40.4 fps

quantum efficiency



Dynamic range: 2,667:1

Read noise = 6 e^-
Full well capacity = 16,000 e^-
Dynamic range = 16,000/6 = 2667

Dynamic range A/D = 14 bit
Gray levels = 2^{14} = 16,384

Thanks!

- For more information:
  - http://learn.hamamatsu.com/articles
  - http://www.microscopyu.com/articles/digitalimaging/index.html/
  - *Photon Transfer* by James Janesick