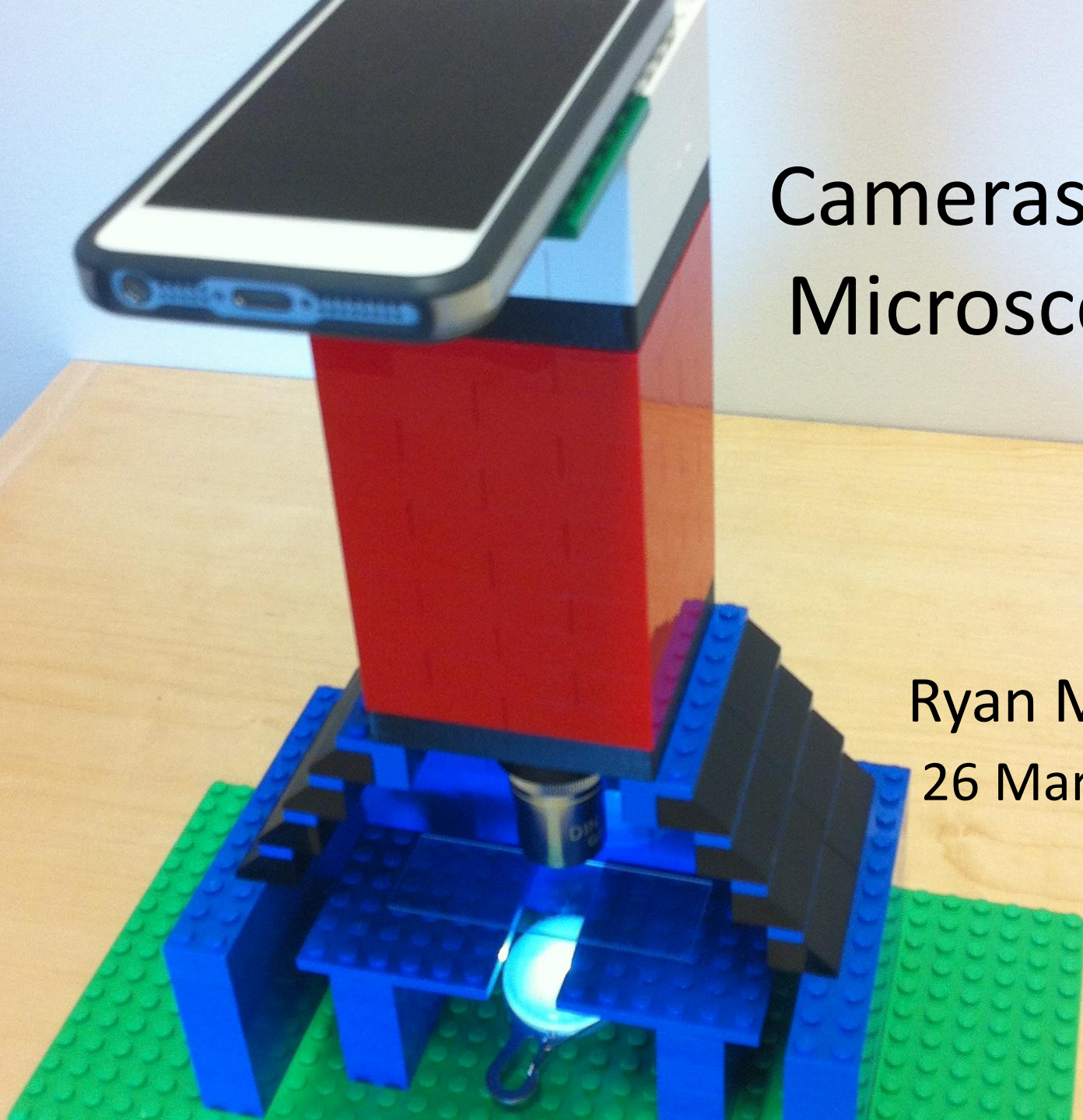


Cameras For Microscopy

Ryan McGorty
26 March 2013



Goals of this lecture

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

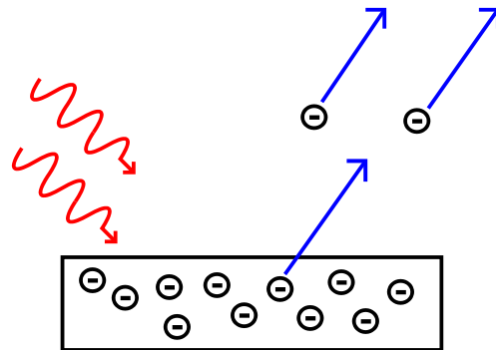
How image sensors sense an image

1. Need way to detect photons



Hertz: observed
in 1887

Photoelectric Effect



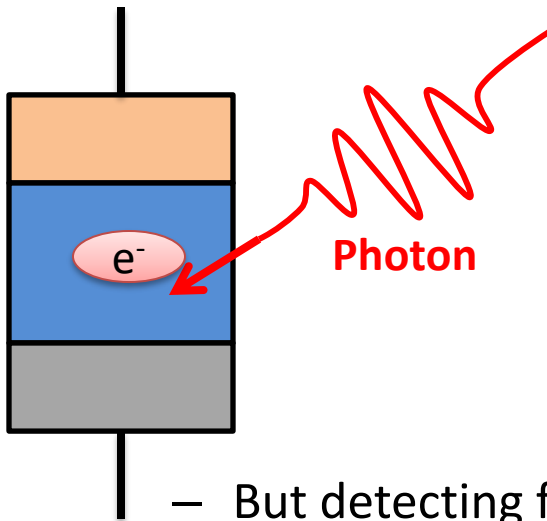
Einstein
 $E = \frac{hc}{\lambda}$

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

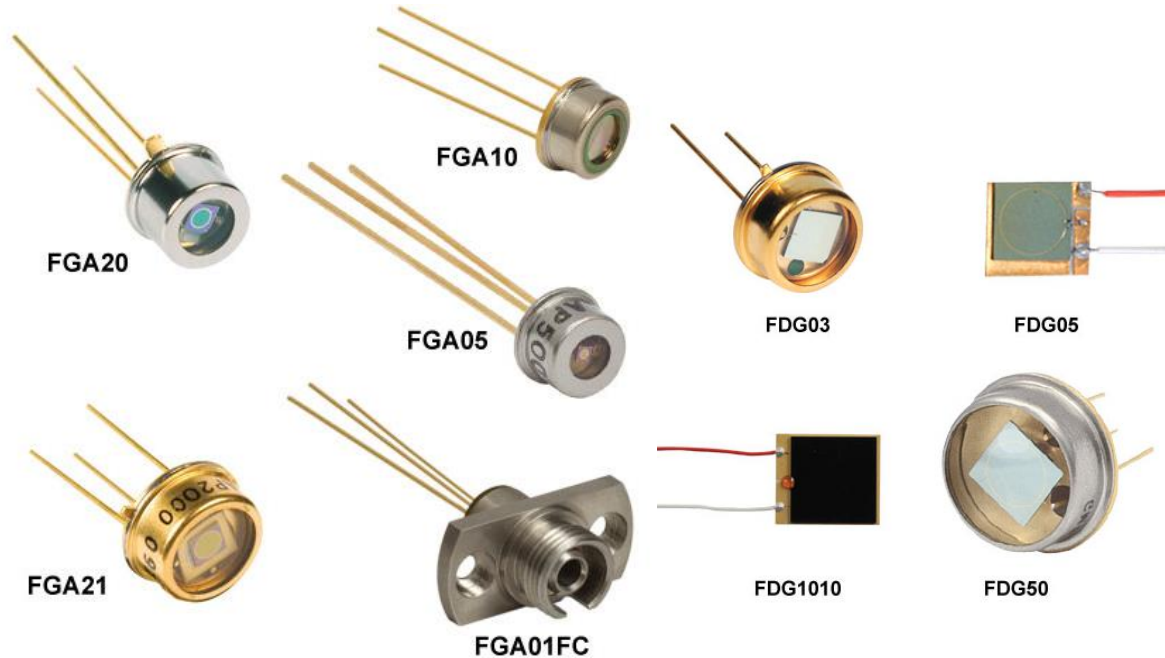
Point Detectors

- Photodiodes

- Photons will generate electron (photoelectron)

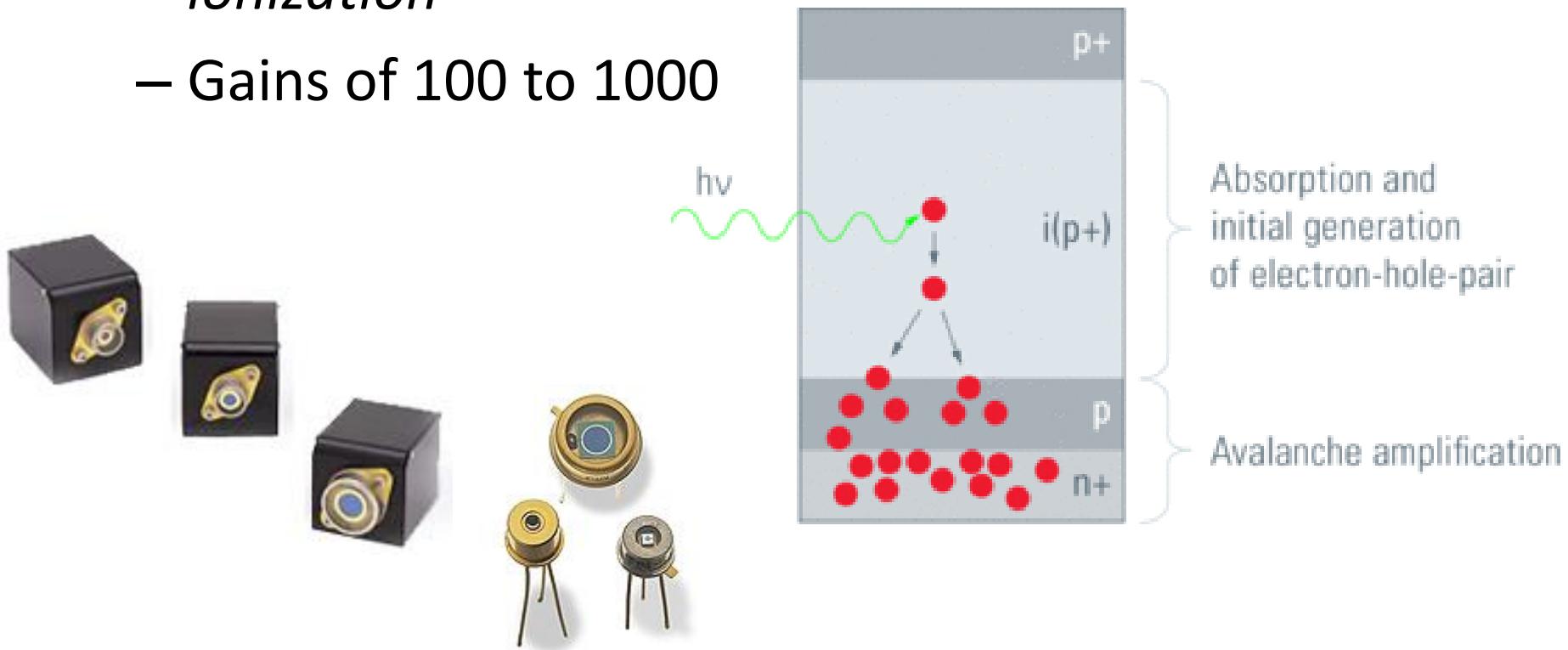


- But detecting few electrons is hard
- Need way to amplify the signal



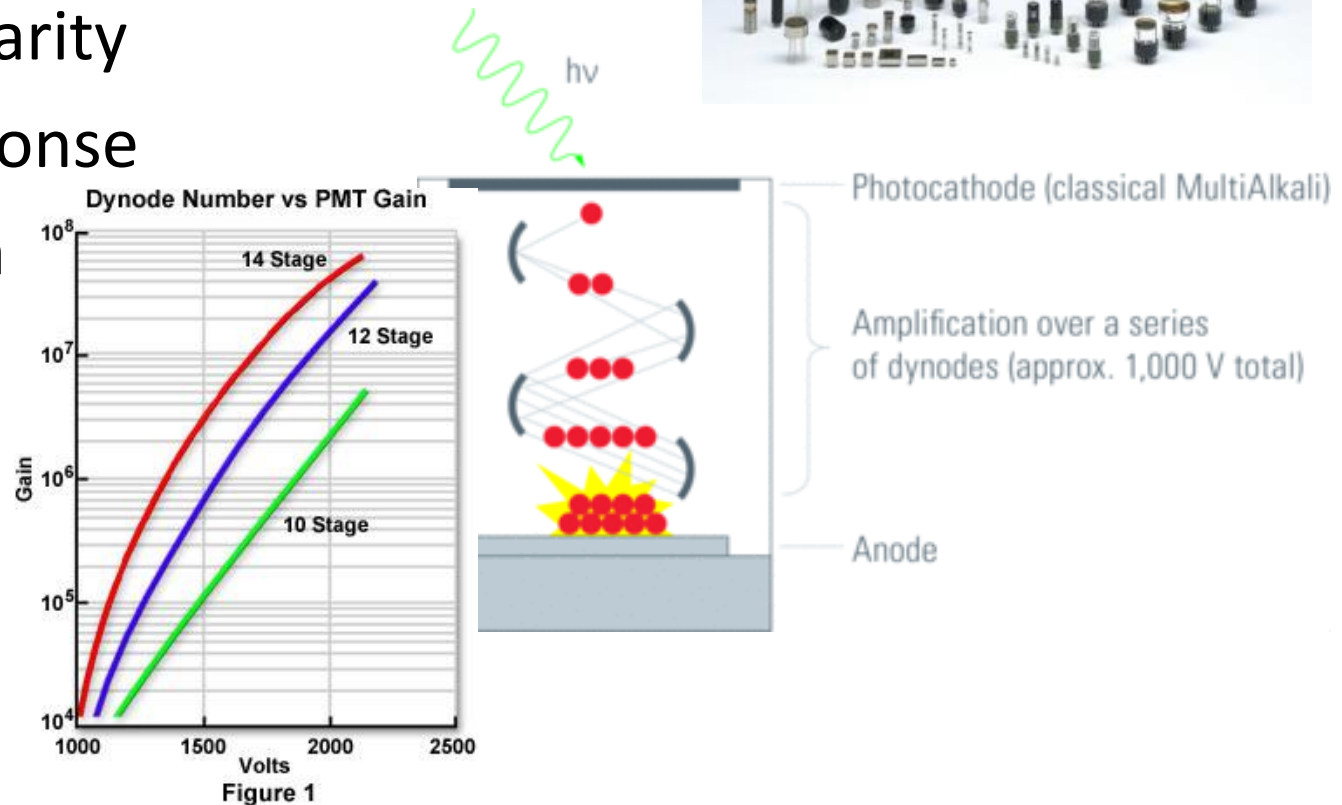
Point Detectors

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



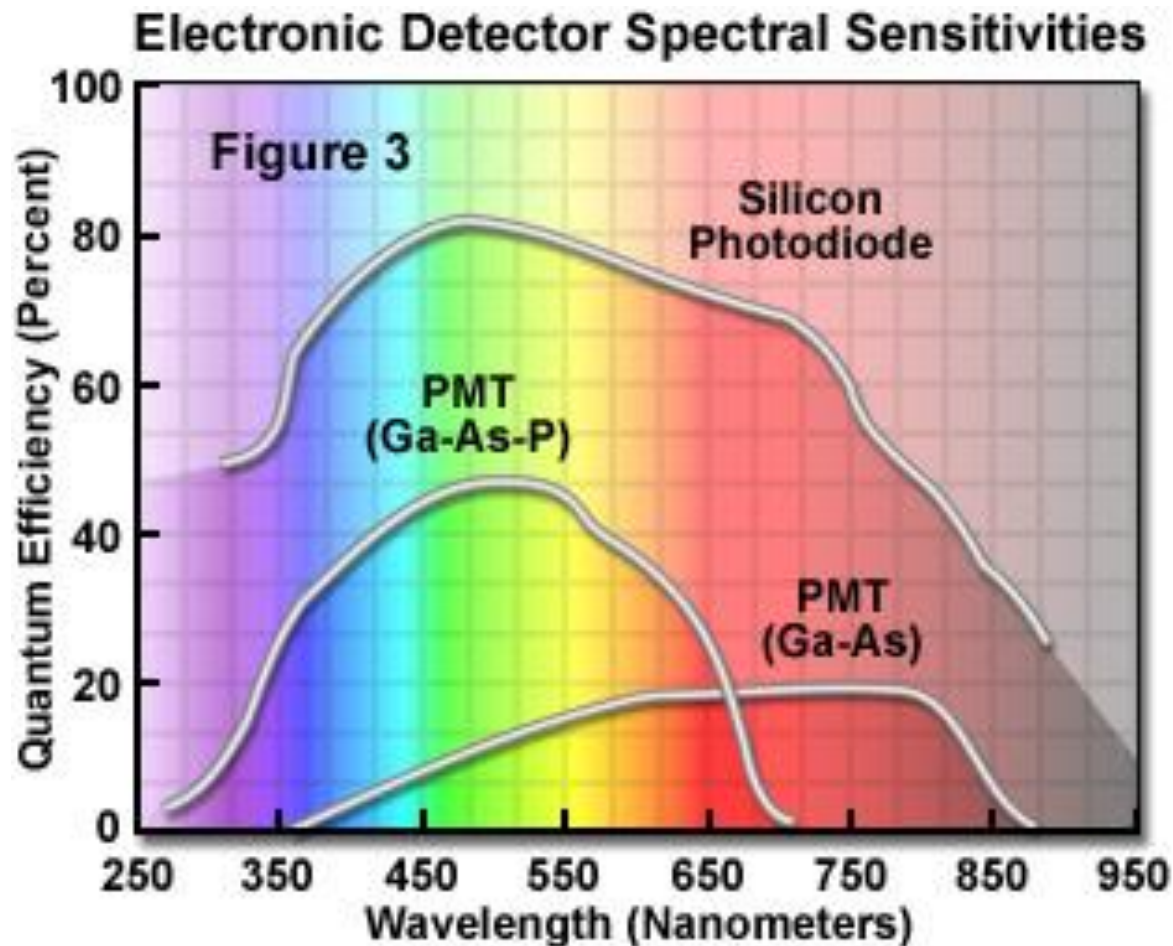
Point Detectors

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



How well are photons detected?

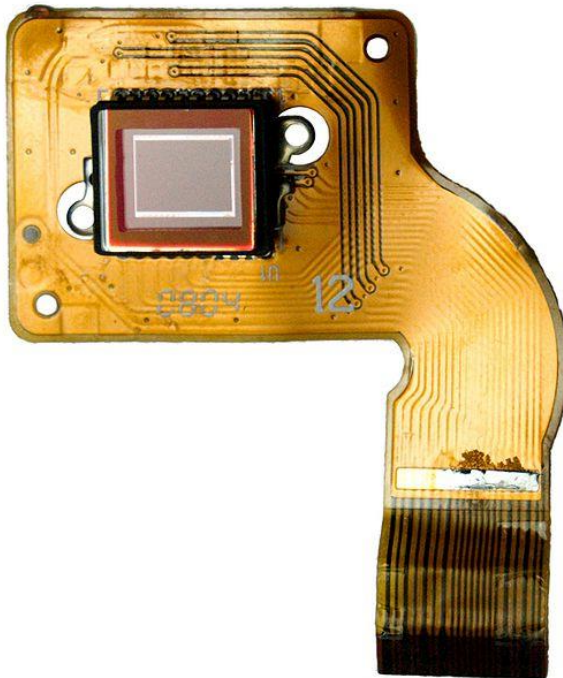
Quantum Efficiency



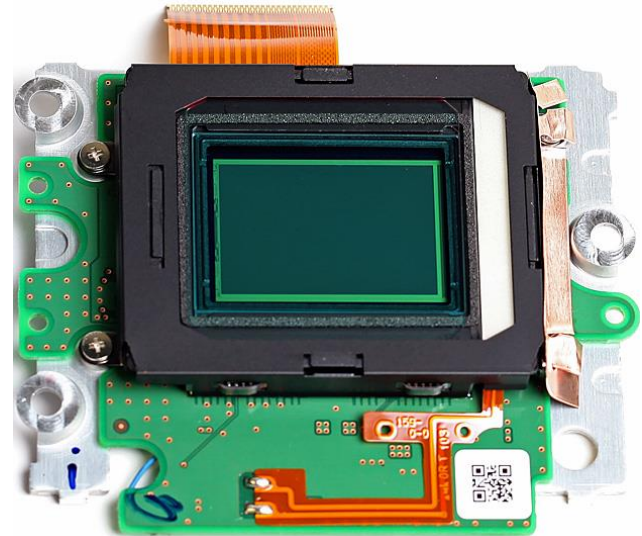
How image sensors sense an image

2. Must detect photons over an array of pixels

CCD



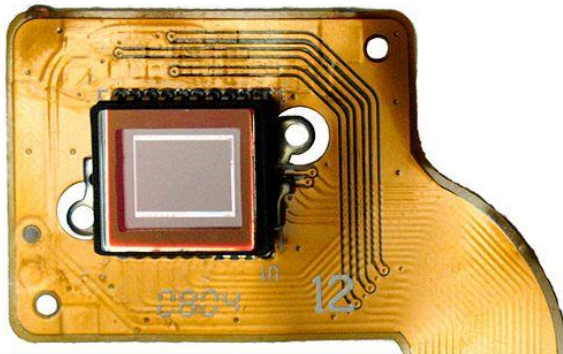
CMOS



How image sensors sense an image

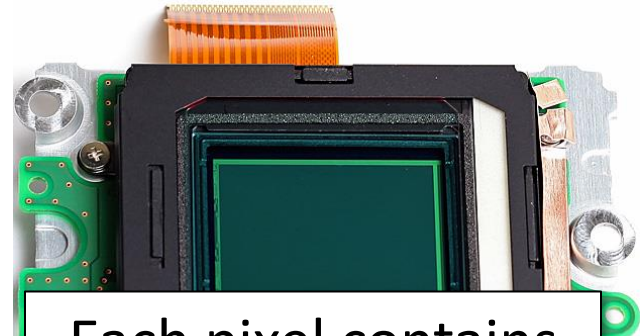
3. Electrons generated in each pixel must be read out

CCD



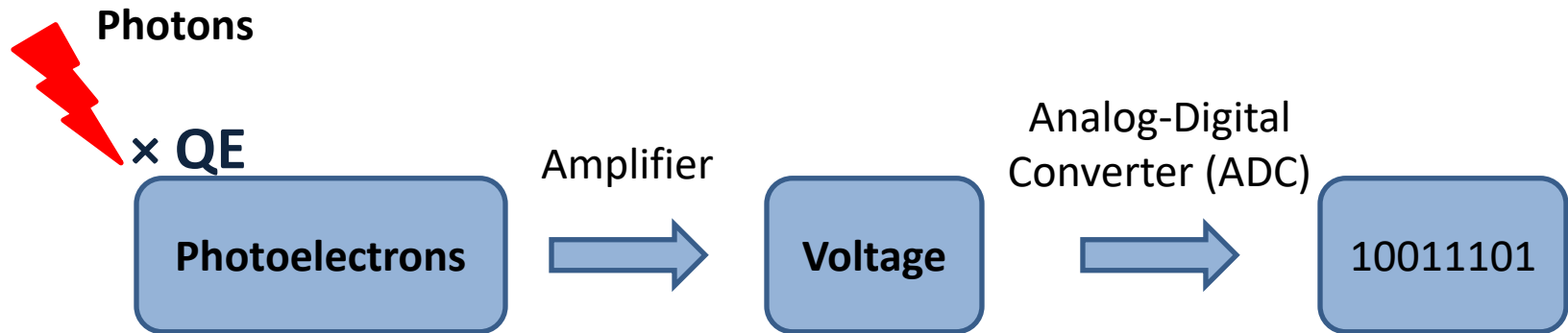
Serial devices
where each pixel's
charge is read out
one at a time

CMOS



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

What is meant by “read out”?

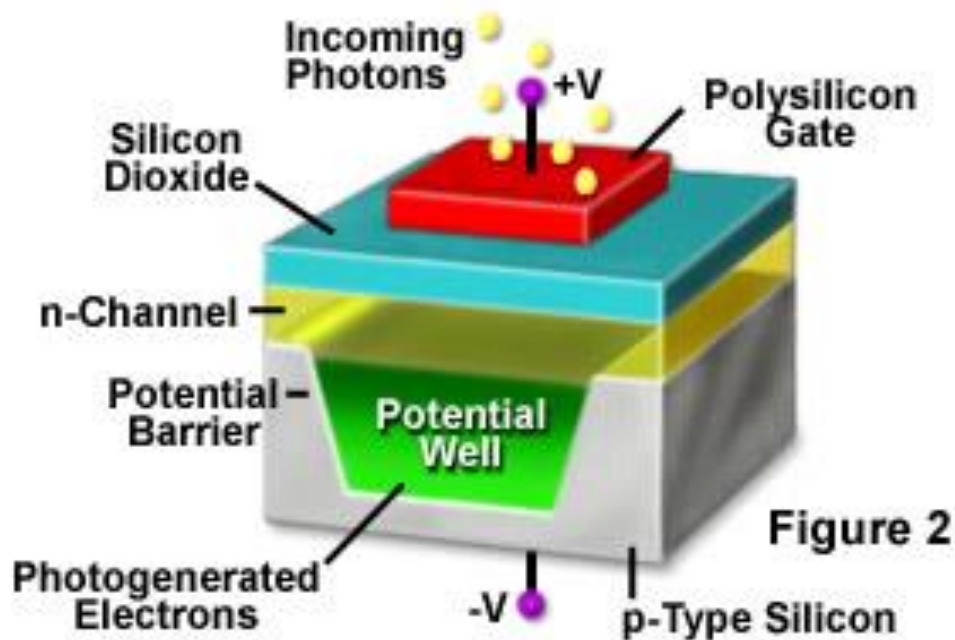


| Bit Depth | Number of gray levels |
|-----------|-----------------------|
| 8 | $2^8 = 256$ |
| 10 | $2^{10} = 1024$ |
| 12 | $2^{12} = 4096$ |
| 14 | $2^{14} = 16384$ |
| 16 | $2^{16} = 65536$ |

CCD Detectors

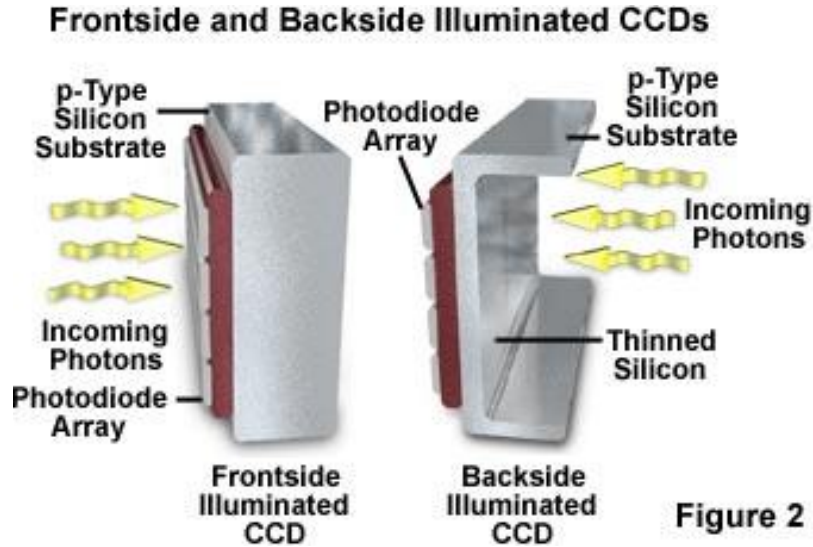
Charge-Coupled Device

Metal Oxide Semiconductor (MOS) Capacitor



- 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

Front or Back Illuminated



- 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

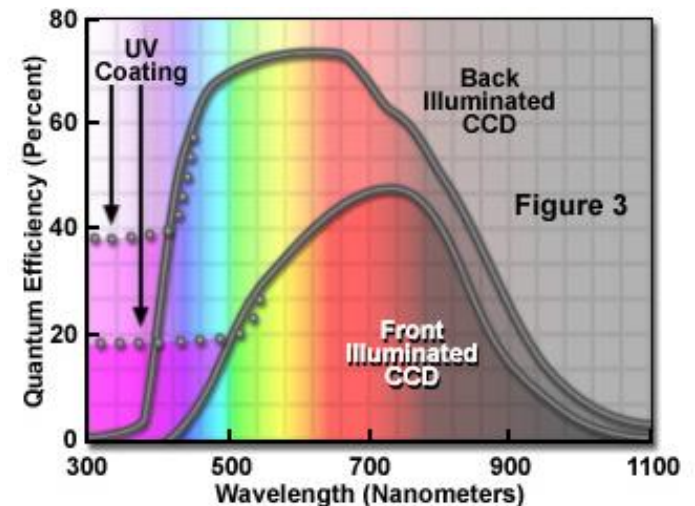
Vertebrate

Octopus

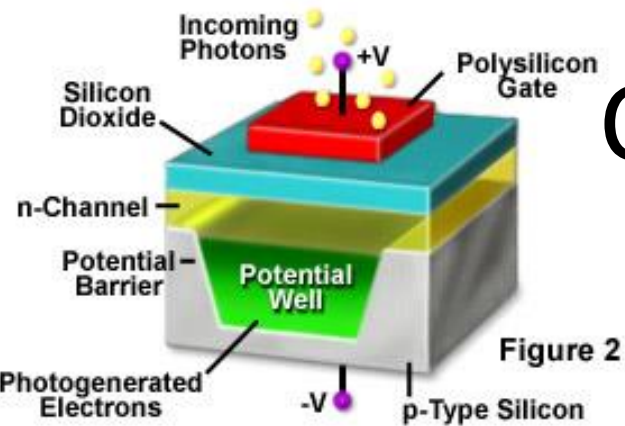
Retina
Nerves

Optic nerve

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

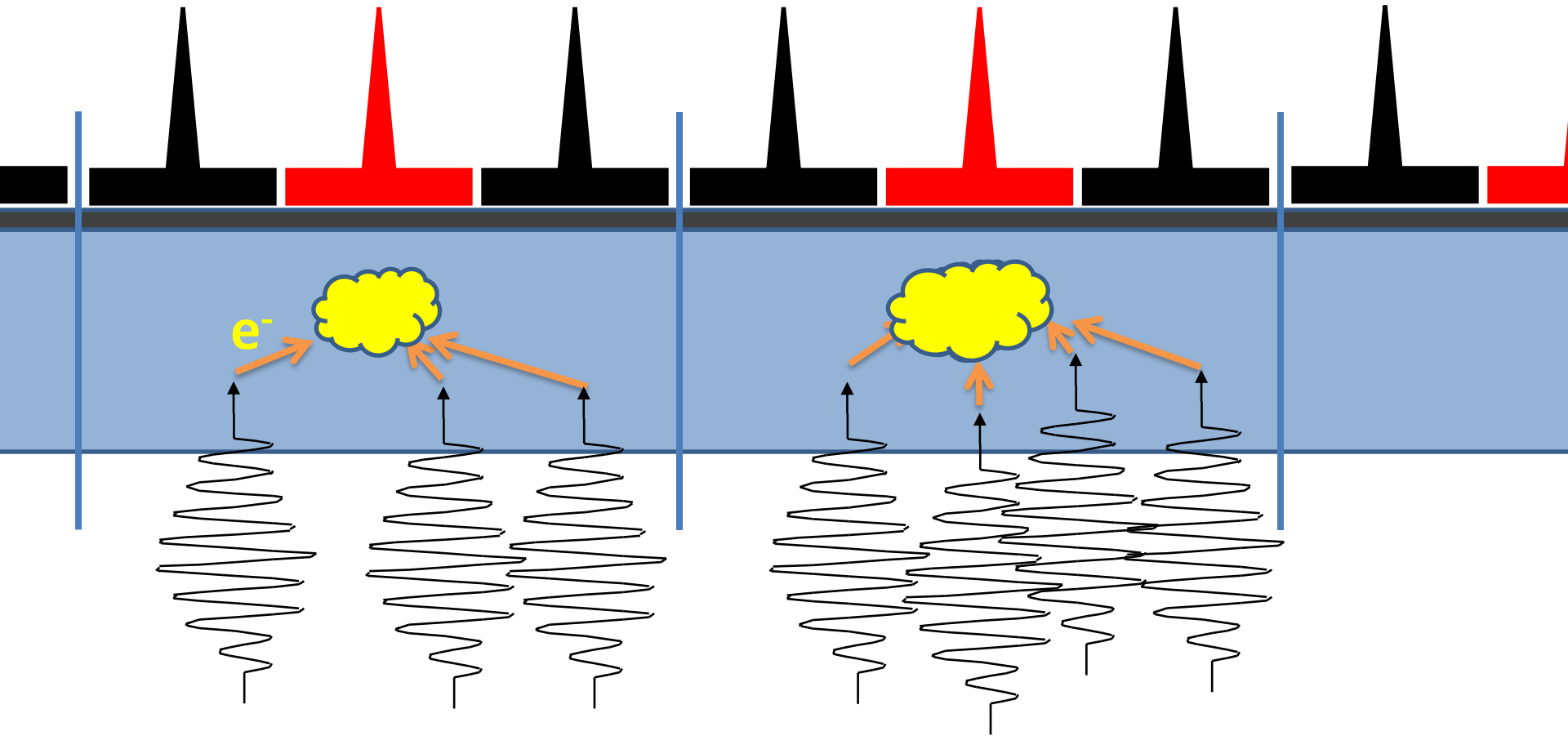


Metal Oxide Semiconductor (MOS) Capacitor



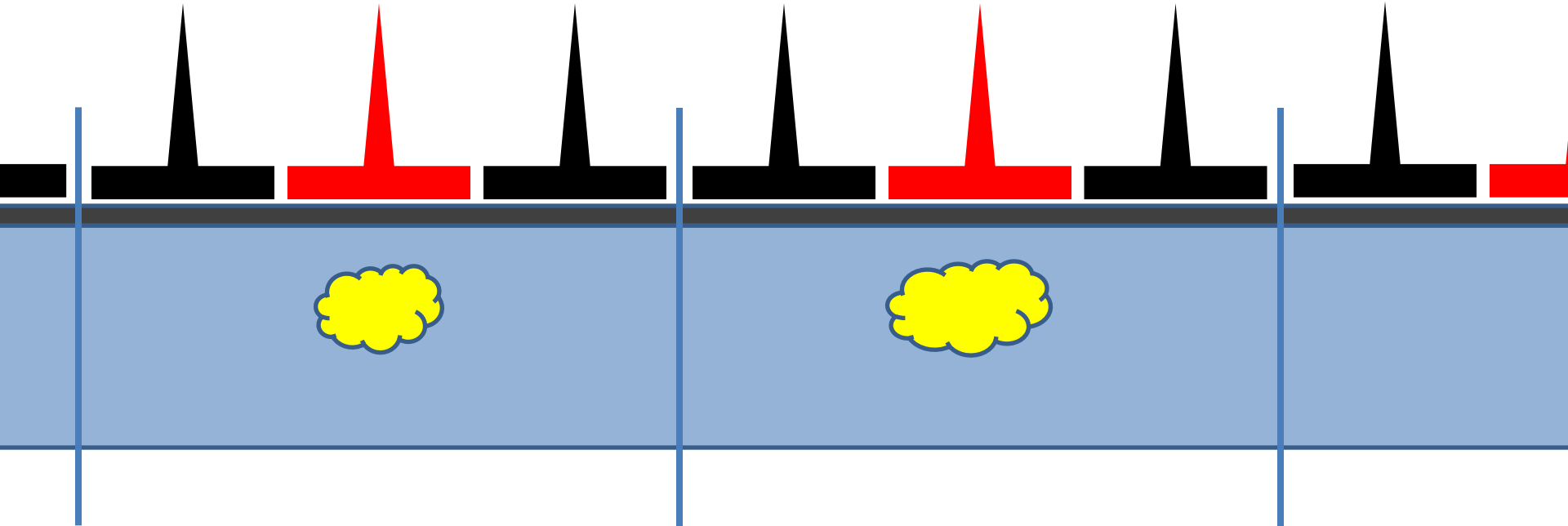
CCD Detectors

Figure 2



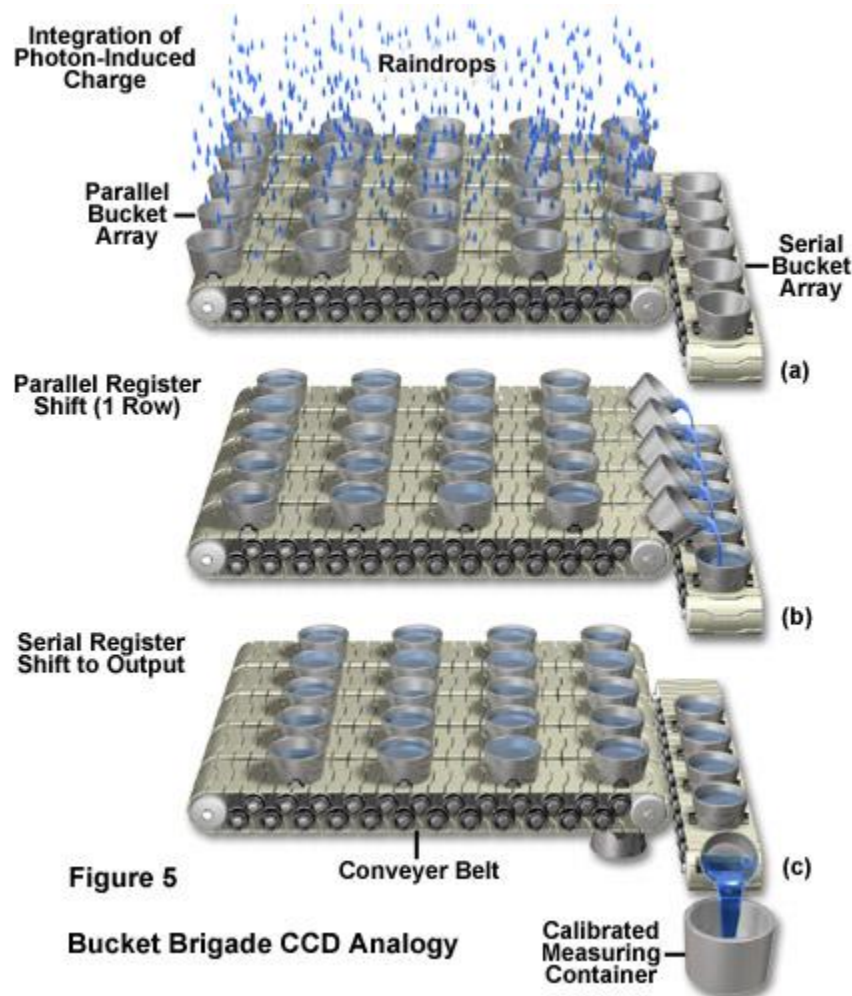
CCD Detectors

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.

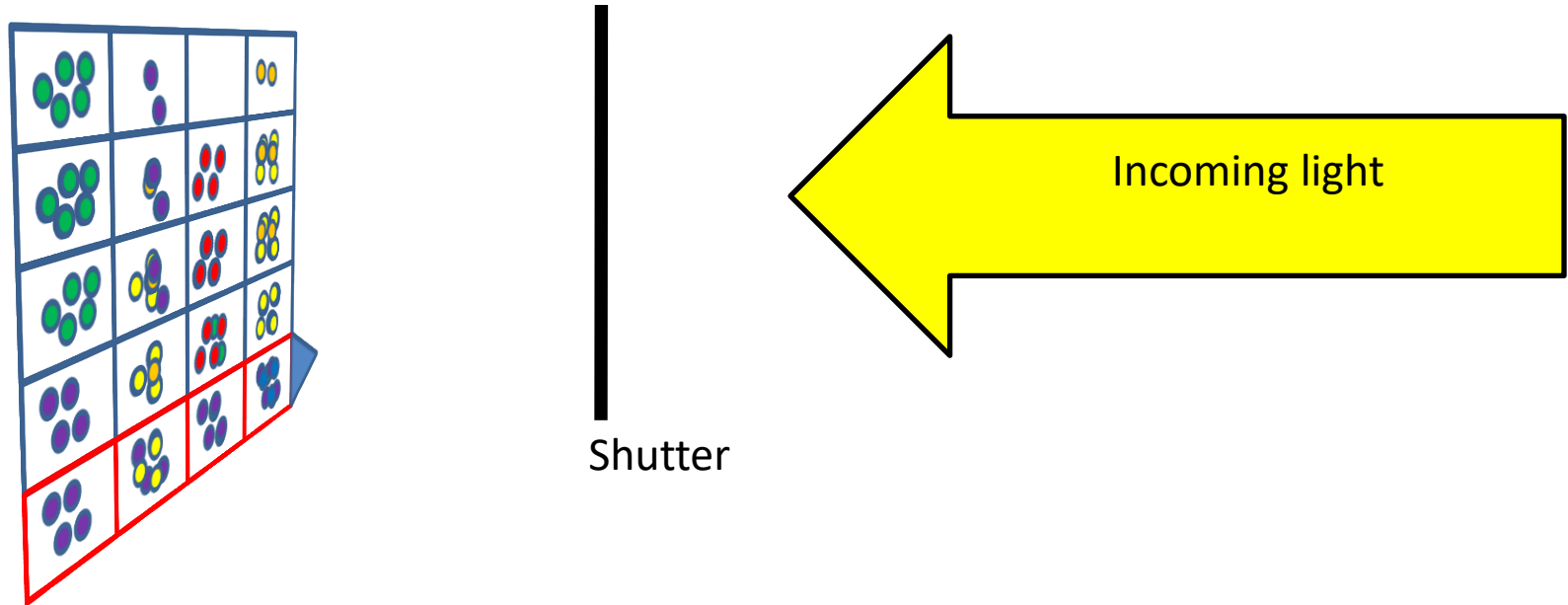
Bucket brigade analogy for read out



- 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

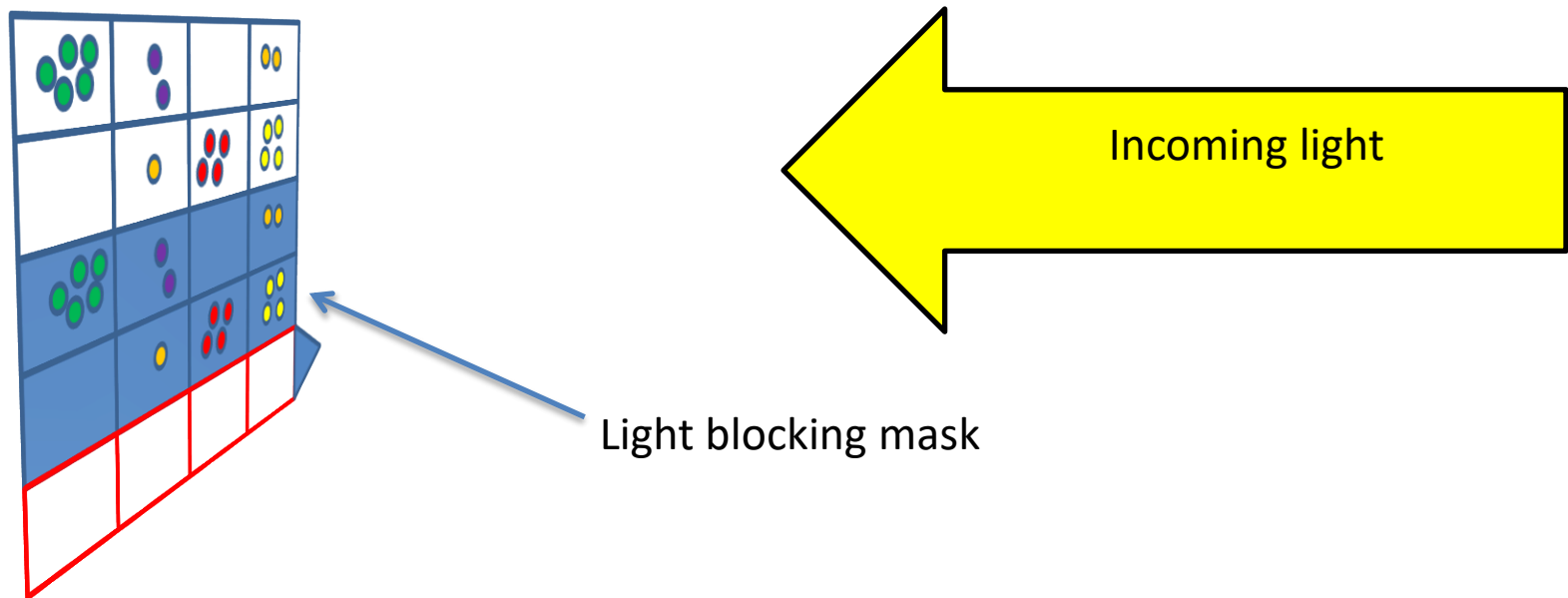
Transferring photoelectrons out

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



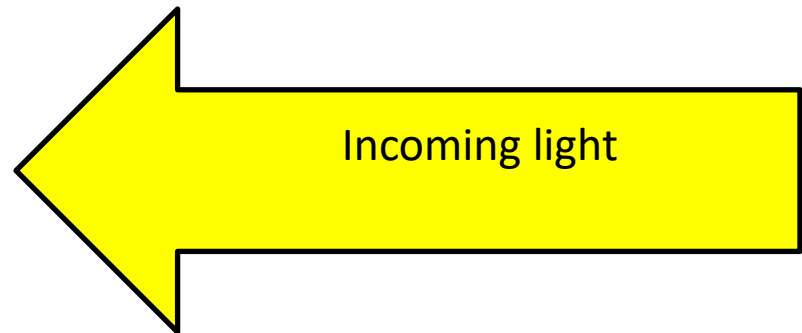
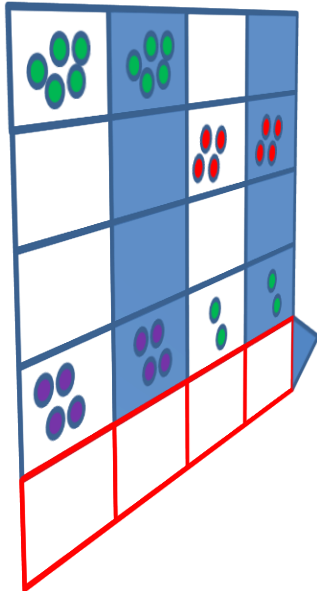
Transferring photoelectrons out

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



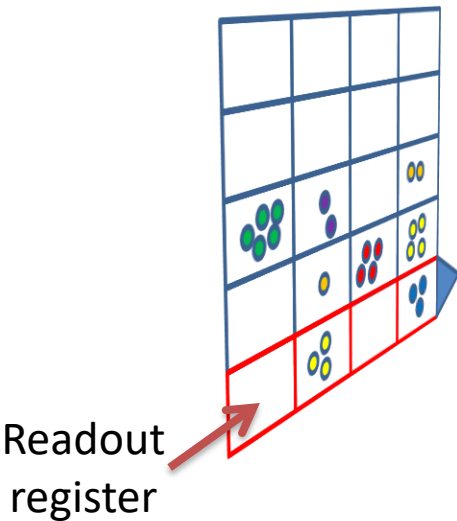
Transferring photoelectrons out

- 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



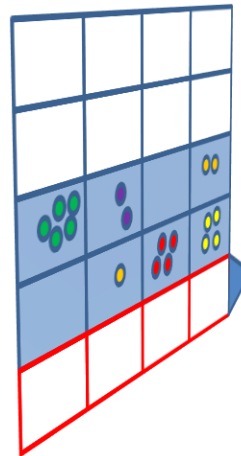
Pros:

- Nearly all of CCD area is usable

Cons:

- Frame rates limited by shutter speed

Frame-transfer



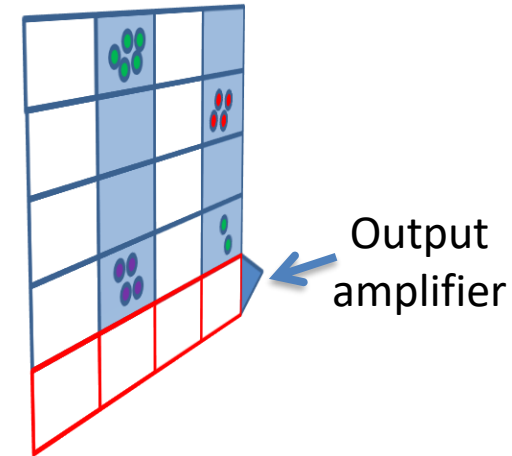
Pros:

- Fast: exposure and readout occur simultaneously

Cons:

- Half of CCD is not light sensitive

Interline



Pros:

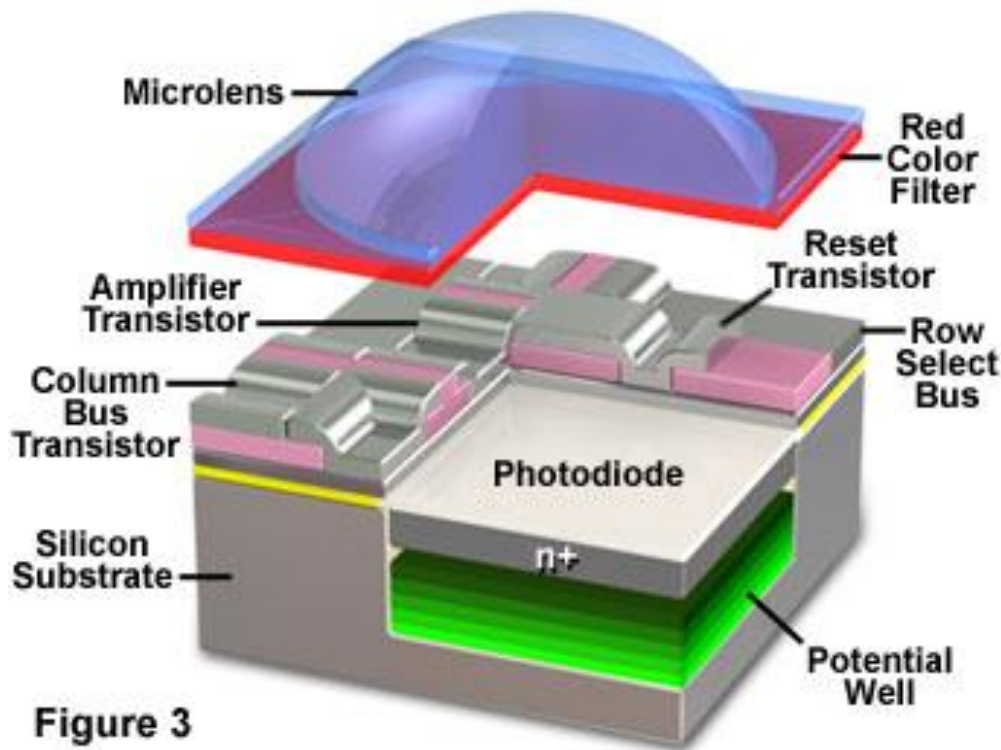
- Fast: shift of only one pixel needed to store charge

Cons:

- Reduced fill factor (abated with microlenses)

CMOS Detectors

Anatomy of the Active Pixel Sensor Photodiode

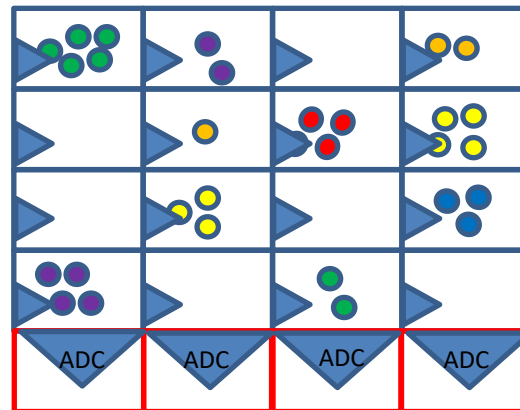


Complementary Metal Oxide Semiconductor

- 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**

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

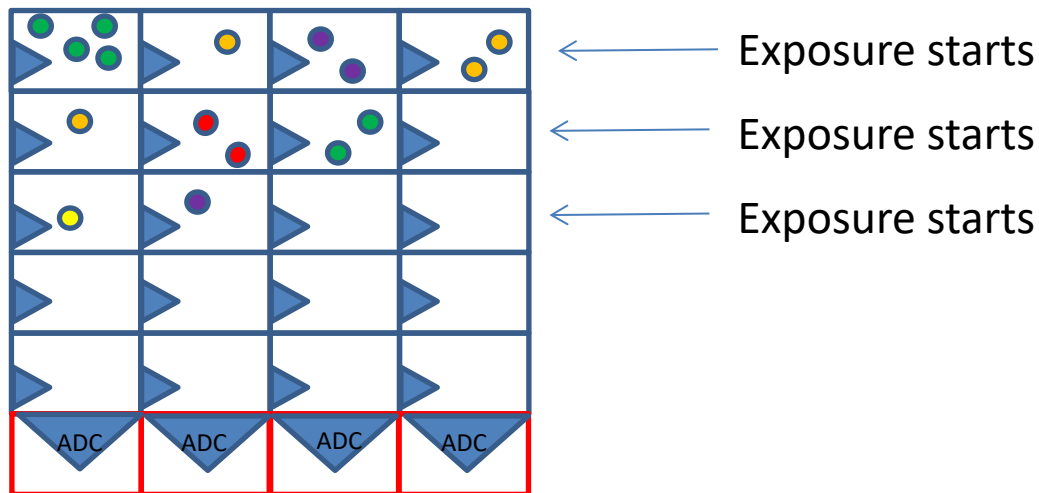


- Each row is then read out to memory

CMOS read out

Global vs. Rolling Shutter

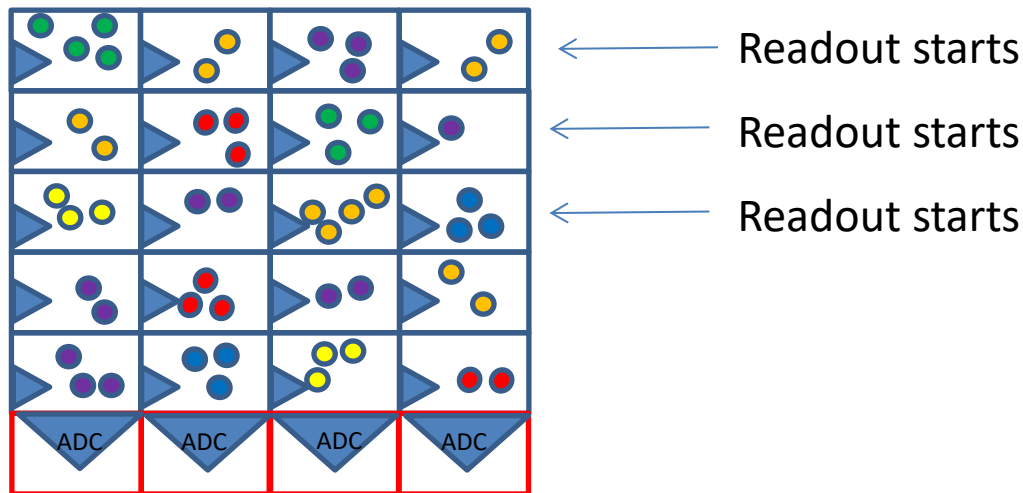
- Rolling Shutter:
 - Exposure start is delayed between each row
 - Readout goes row by row
 - Offset time between rows as low as $10\ \mu\text{s}$



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 $10\text{ }\mu\text{s}$

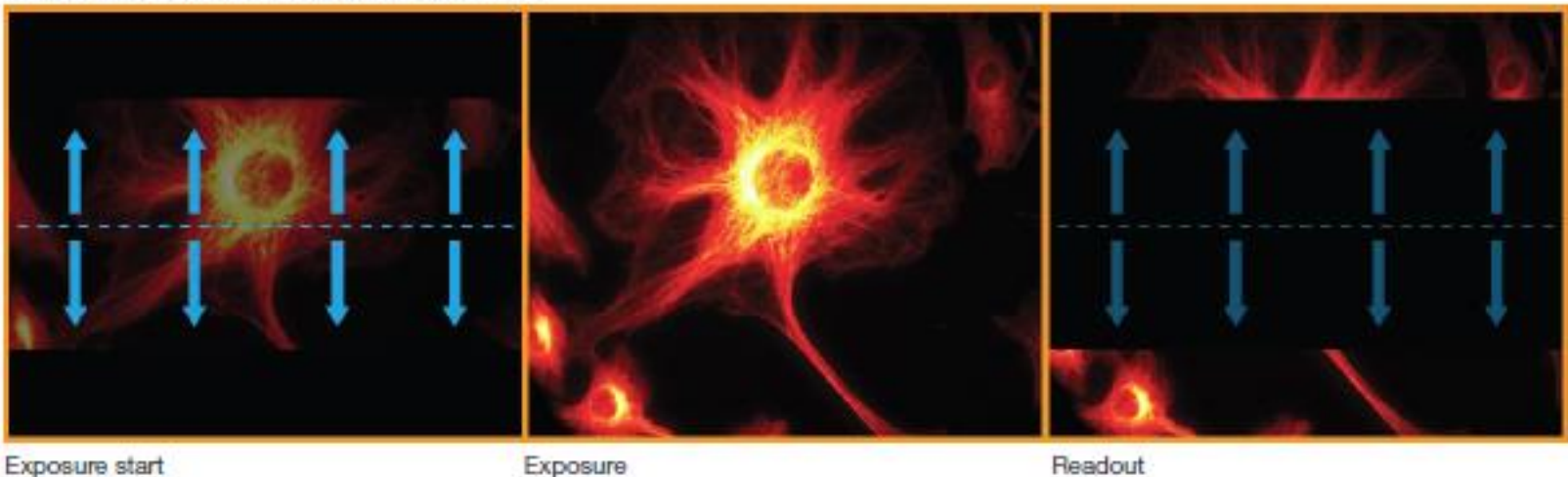


CMOS read out

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 $10\text{ }\mu\text{s}$

Rolling Shutter exposure sequence (single frame)



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 $10\ \mu\text{s}$
- 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 ¹

| | |
|---|---|
| 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 ¹ 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 Specifications

| |
|---|
| Dark current and background events ^{1,2} |
| 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 ³ |
| Pixel readout rates |
| Read noise (e ⁻) ¹ |
| 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 ⁴ |
| Vertical clock speed |
| Timestamp accuracy |

technical data

Image sensor

| | |
|--------------------------|--|
| type of sensor | OCD |
| image sensor | ICX285AL |
| resolution (h x v) | 1392 x 1040 pixel (normal) 800 x 800 (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 | 2 687 : 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 LVTTTL 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



Specifications

| | |
|----------------------------|--|
| Product number | C11440-22CU (ORCA-Flash4.0 V2) |
| Imaging device | Scientific CMOS sensor FL-400 |
| Effective number of pixels | 2048(H) x 2048(V) |
| Cell size | 6.5 µm x 6.5 µm |
| Effective area | 13.312 mm x 13.312 mm |
| Full well capacity (typ.) | 30 000 electrons |
| Readout time | Standard scan (at 100 frames/s) Slow scan (at 30 frames/s) |
| Readout noise | Standard scan (at 100 frames/s, typ.) Slow scan (at 30 frames/s, typ.) |
| | 1.9 electrons rms (1.3 electrons median) 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 °C | 0.5 electrons/pixel/s | -10 °C |
| | 0.15 electrons/pixel/s | -20 °C |
| | 0.05 electrons/pixel/s | -30 °C |

| | | |
|-----------|-----------------|-----------------|
| | Camera Link | USB 3.0 |
| | 100 frames/s | 30 frames/s |
| position) | 200 frames/s | 60 frames/s |
| tion) | 25 655 frames/s | 7894 frames/s |
| on) | - | 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 x 2 / 4 x 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 |

¹ noise median in slow scan
internal trigger mode varies depending on sub-array setting. Minimum exposure time is in standard scan.

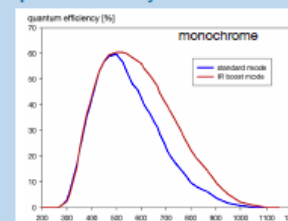
general

| | |
|---------------------------|--------------------------------|
| 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 table⁴

| resolution | normal | center |
|------------------|----------|----------|
| pixelclock [MHz] | 12 | 25 |
| 1392 x 1040 | 7.3 fps | 13.5 fps |
| v2 binning | 14.7 fps | 27 fps |

quantum efficiency



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

| | |
|--------------------|--|
| 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 | 85 % @ 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 LVTTTL level |

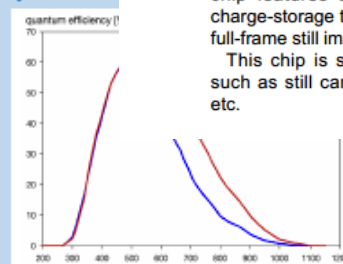
general

| | |
|---------------------------|---------------------------|
| power supply | 9 .. 28 VDC (12 VDC typ.) |
| power consumption | < 4 W |
| weight | 0.25 kg |
| operating temperature | |
| operating humidity range | |
| storage temperature range | |
| optical interface | |
| CE certified | |

frame rate table⁴

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

quantum eff



SONY

ICX285AL

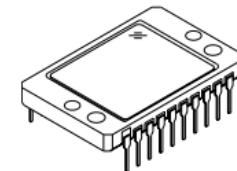
Diagonal 11 mm (Type 2/3) Progressive Scan CCD Image Sensor with Square Pixel for B/W Cameras

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)



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

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 |
| 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 LVTTTL level |

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 table⁴

| resolution | normal | center |
|------------------|----------|----------|
| pixelclock [MHz] | 12 | 25 |
| 1392 x 1040 | 7.3 fps | 13.5 fps |
| 800 x 600 | 11.7 fps | 21.6 fps |
| v2 binning | 14.7 fps | 27 fps |
| | 21.8 fps | 40.4 fps |

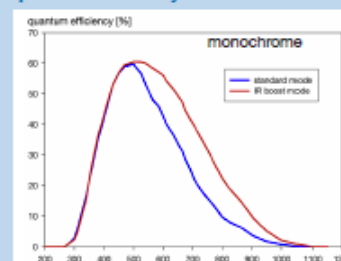
| | |
|--------------------|--|
| resolution (h x v) | 1392 x 1040 pixel (normal) 800 x 600 (center) |
| pixel size (h x v) | 6.45 µm x 6.45 µm |

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

$$0.3 \mu\text{m} \times M = 3 \times 6.45 \mu\text{m}$$

$$M = 64.5 \times$$

quantum efficiency



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

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 |
| 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 LVTTTL level |

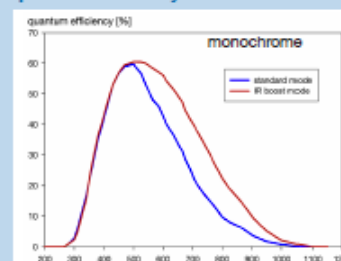
general

| | |
|---------------------------|-------------------------------|
| 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 table⁴

| 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 | 21.6 fps | 40.4 fps |

quantum efficiency



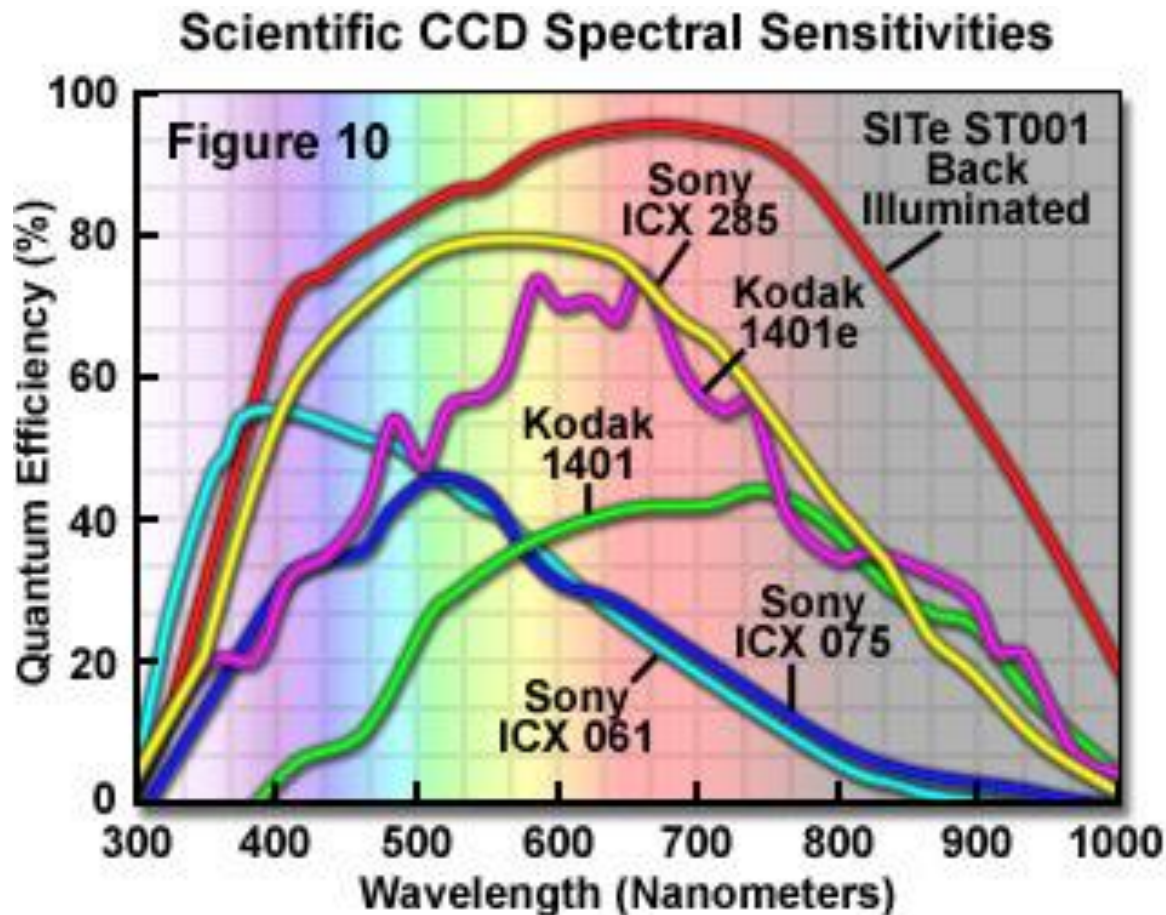
¹ dark signal non-uniformity measured in a 90% center zone of the image sensor

² photo response non-uniformity

³ time between two consecutive images for particle image velocimetry (PIV) applications

How well are photons detected?

Quantum Efficiency



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 (58 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 LVTTTL level |

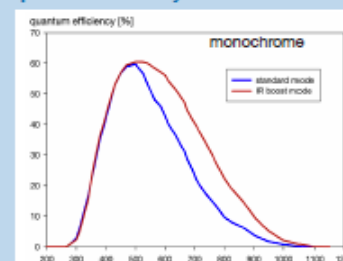
general

| | |
|---------------------------|-------------------------------|
| 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 table⁴

| 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 | 21.6 fps | 40.4 fps |

quantum efficiency



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


NOISE!

What is noise?

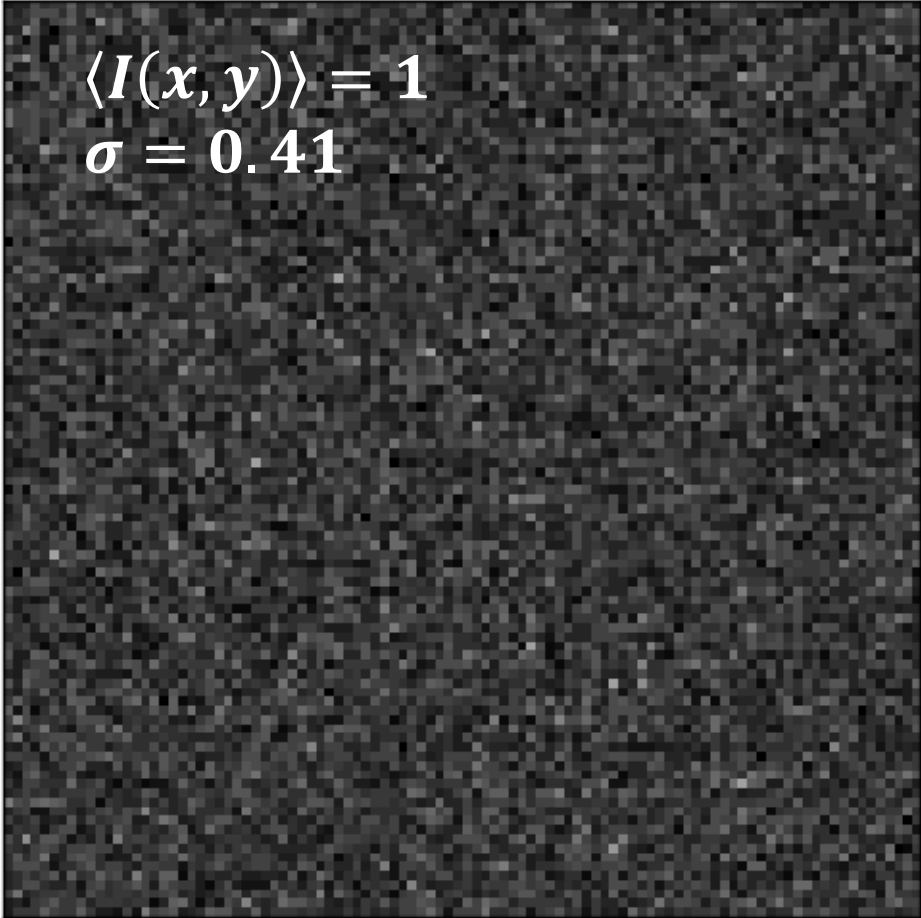
- Uncertainty in measured signal
- Looks like random fluctuations in intensity



$\langle I(x, y) \rangle = 1$
 $\sigma = 0.032$



$\langle I(x, y) \rangle = 1$
 $\sigma = 0.099$

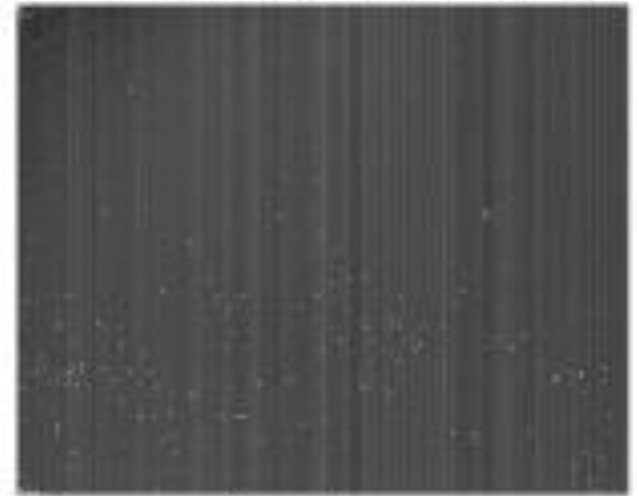


$\langle I(x, y) \rangle = 1$
 $\sigma = 0.41$

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]
 - $\sigma_{FPN}(S) = P_N S$ [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

● Conventional CMOS camera



▲ Exposure time: 15 ms

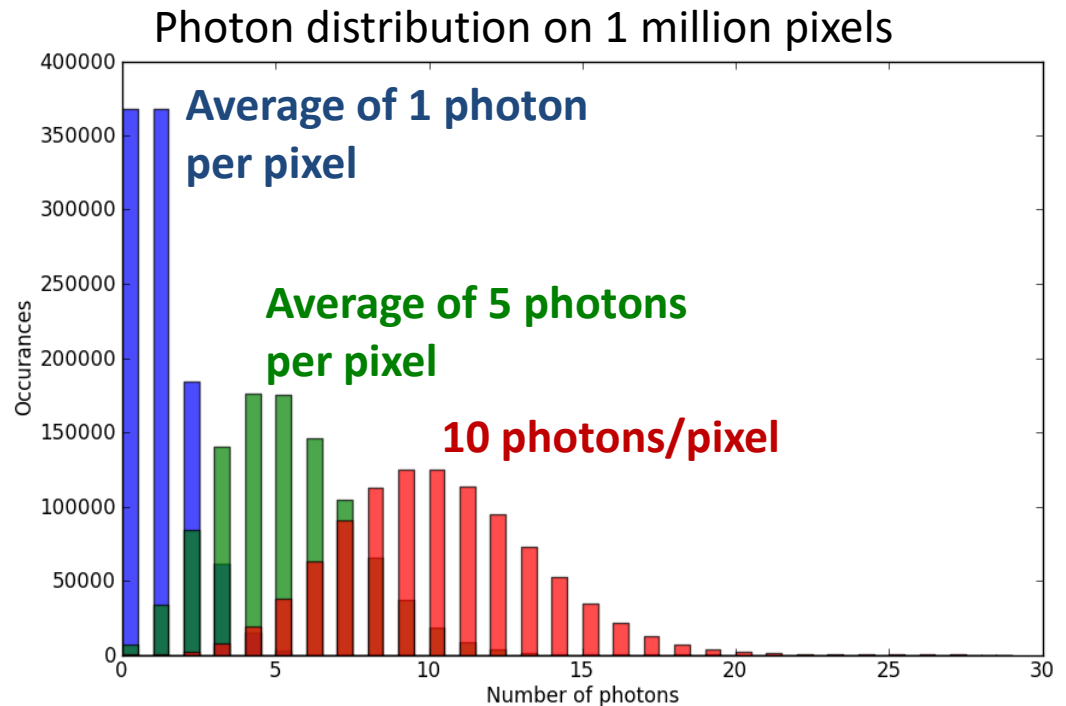
NOISE!

- 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

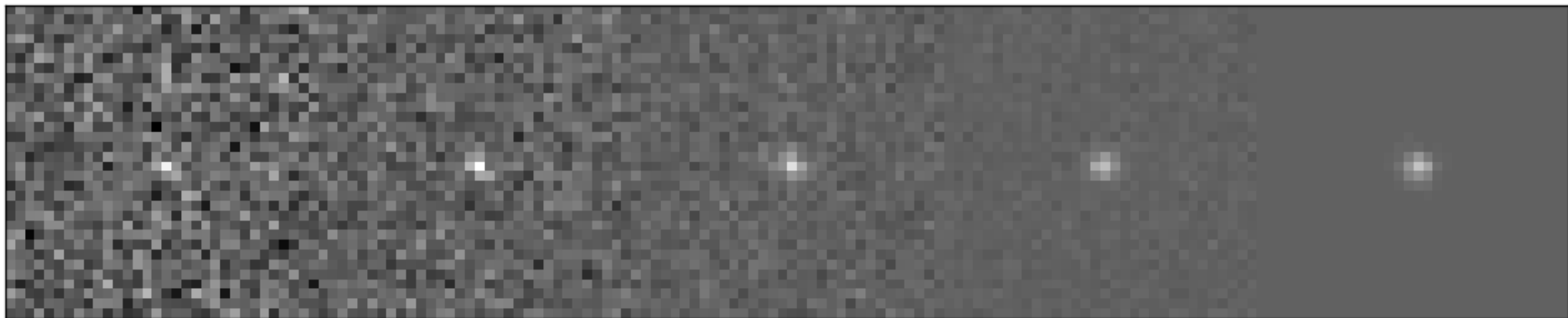
$$\sigma_{shot}(S) = S^{\frac{1}{2}}$$



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.

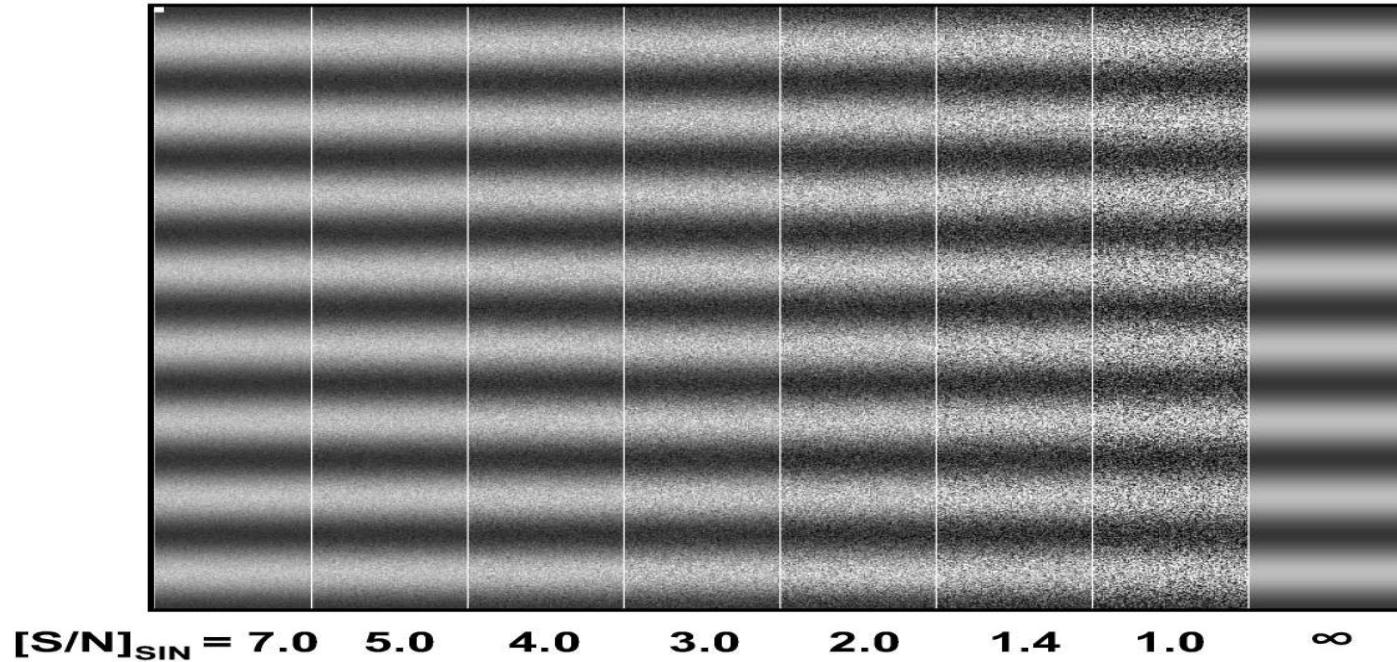
NOISE!

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

- Signal to Noise Ratio

$$\text{SNR} = \frac{\text{QE} \times S}{\sqrt{\sigma_{\text{READ}}^2 + \text{QE} \times S + (\text{P}_\text{N} \times \text{QE} \times S)^2}}$$

NOISE!



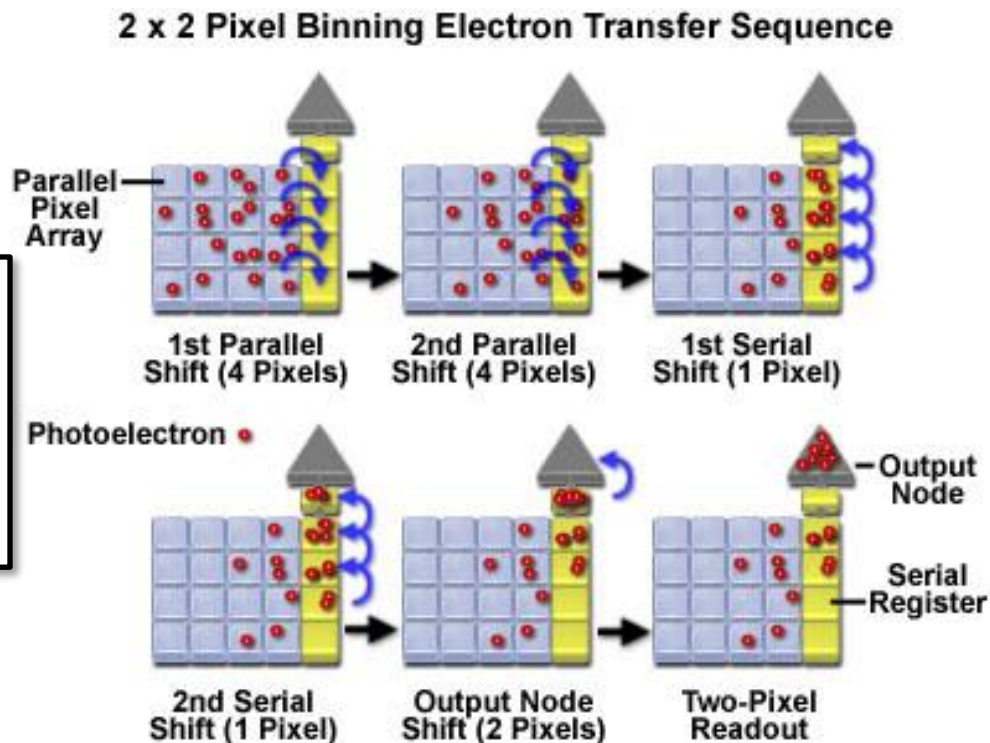
- Signal to Noise Ratio

$$\text{SNR} = \frac{\text{QE} \times S}{\sqrt{\sigma_{\text{READ}}^2 + \text{QE} \times S + (\text{P}_\text{N} \times \text{QE} \times S)^2}}$$

How do you optimize SNR?

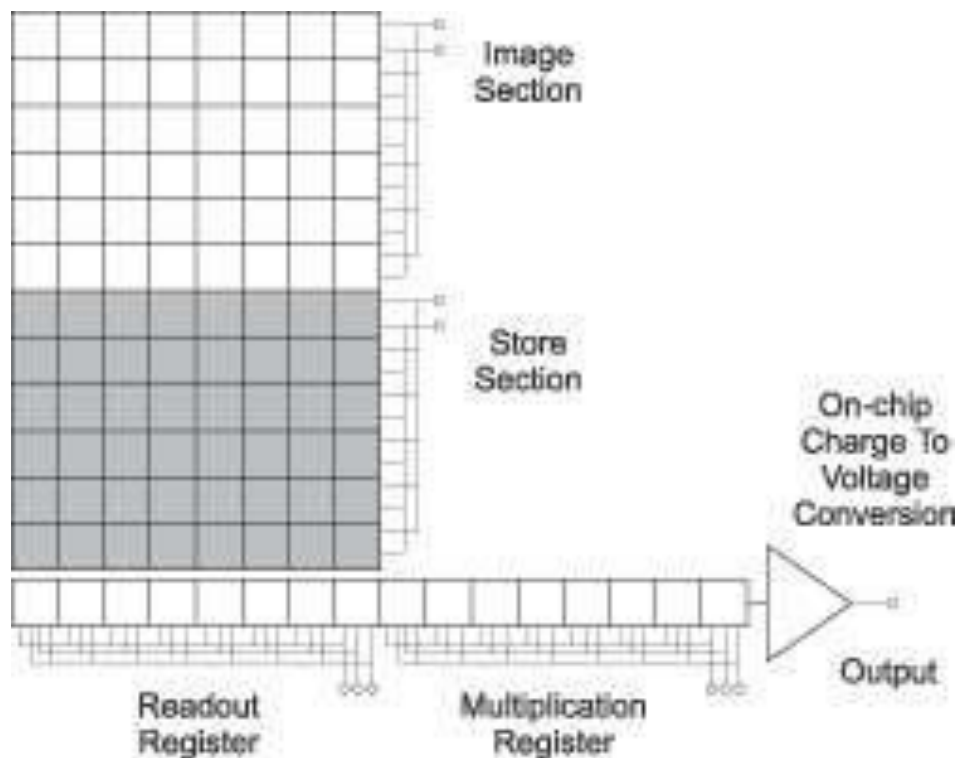
- Choose a camera that has:
 - High QE
 - Back illuminated
 - Low read noise
 - Cooling ability
 - Spatial uniformity
- When imaging:
 - Go at slowest speeds
 - Use largest pixel size
 - Binning

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



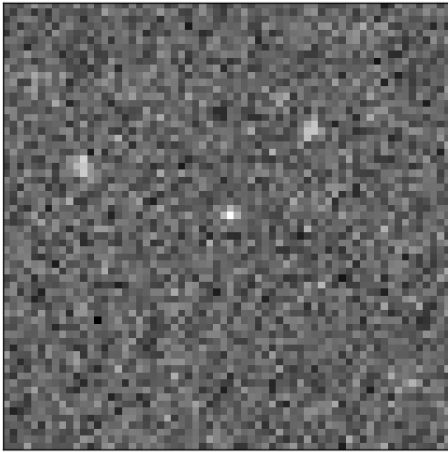
Nearly eliminating read noise: EMCCDs

- Amplifies signal to push it well above read noise

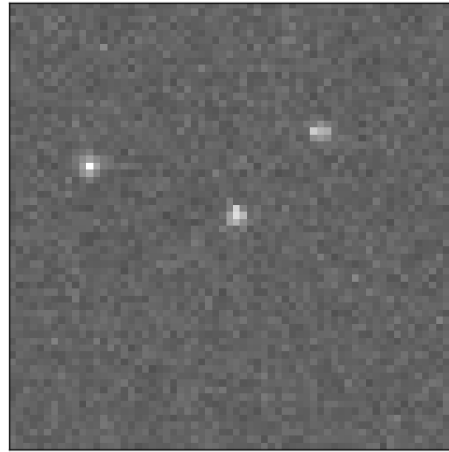


- In CCDs: rows gets transferred to edge to readout register
- EMCCDs add an **electron multiplication (EM)** register
- As charge is transferred through EM register, *impact ionization* increases charge on order of 100-1000×

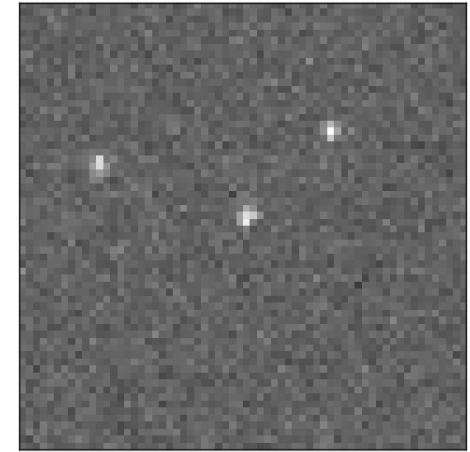
Noise in EMCCDs



Read noise = 10 e⁻



Read noise = 0.5 e⁻



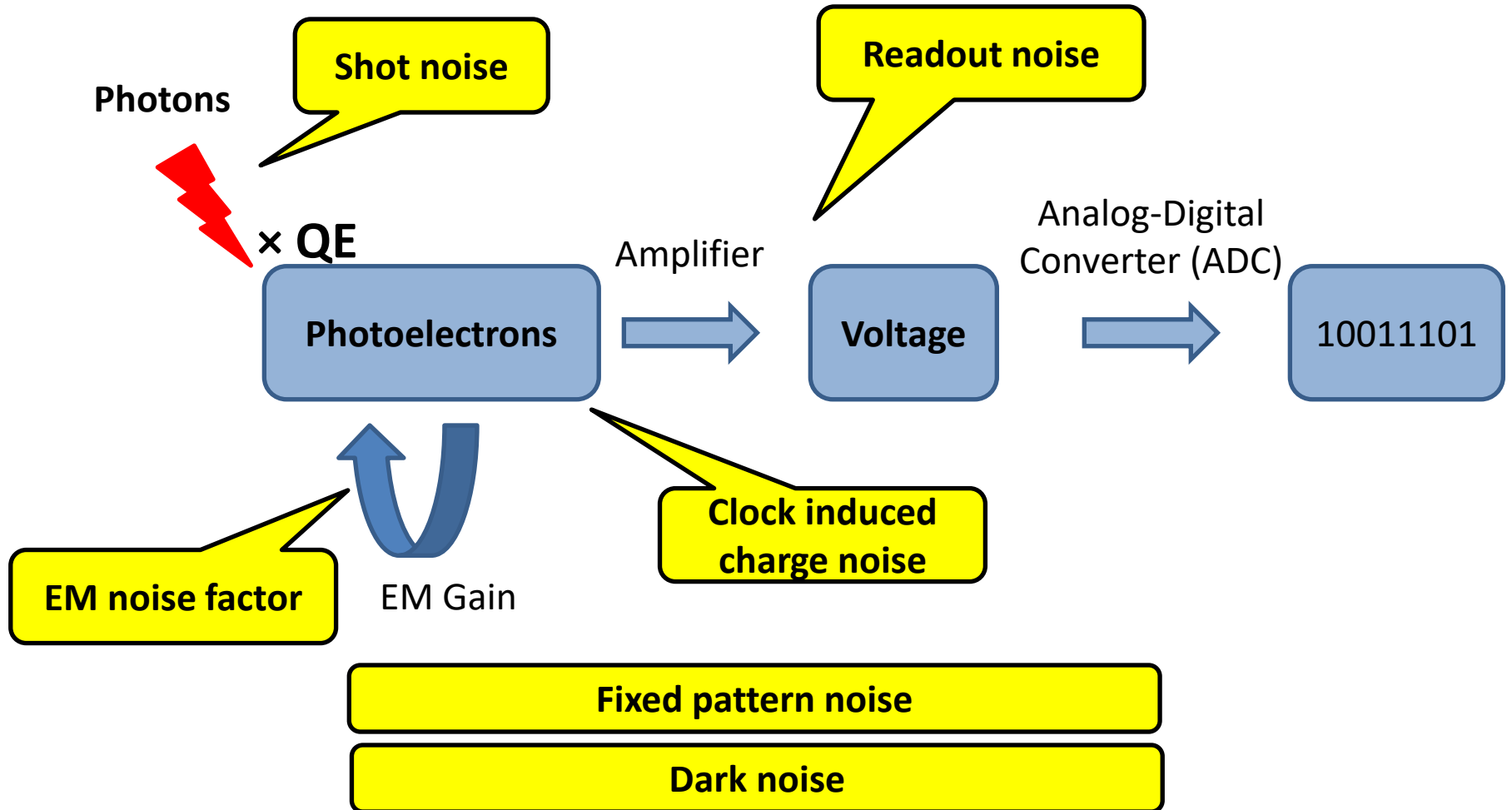
Read noise = 0.5 e⁻
Plus EM associated
noise, F_n

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

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!

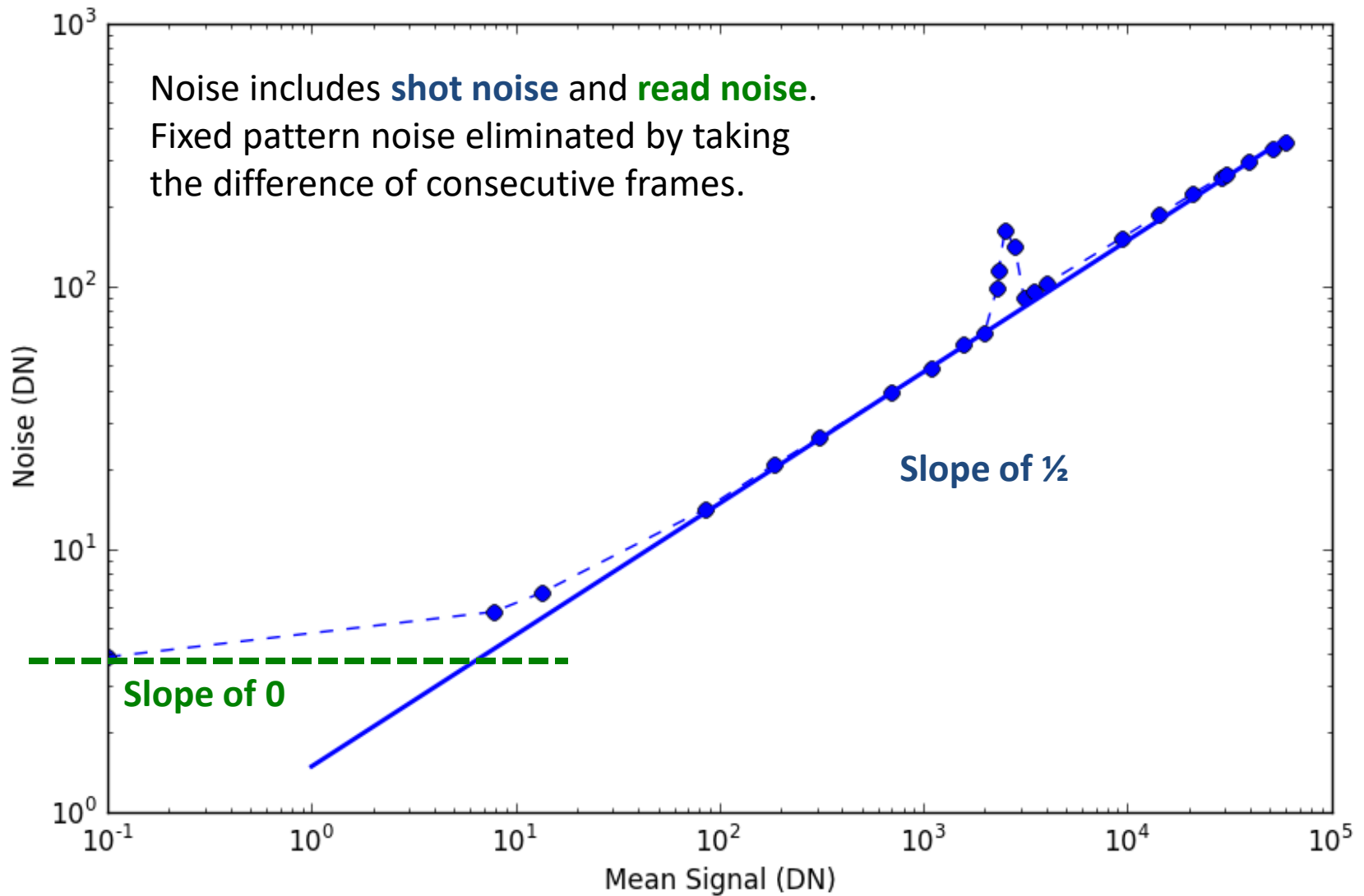


Measuring noise

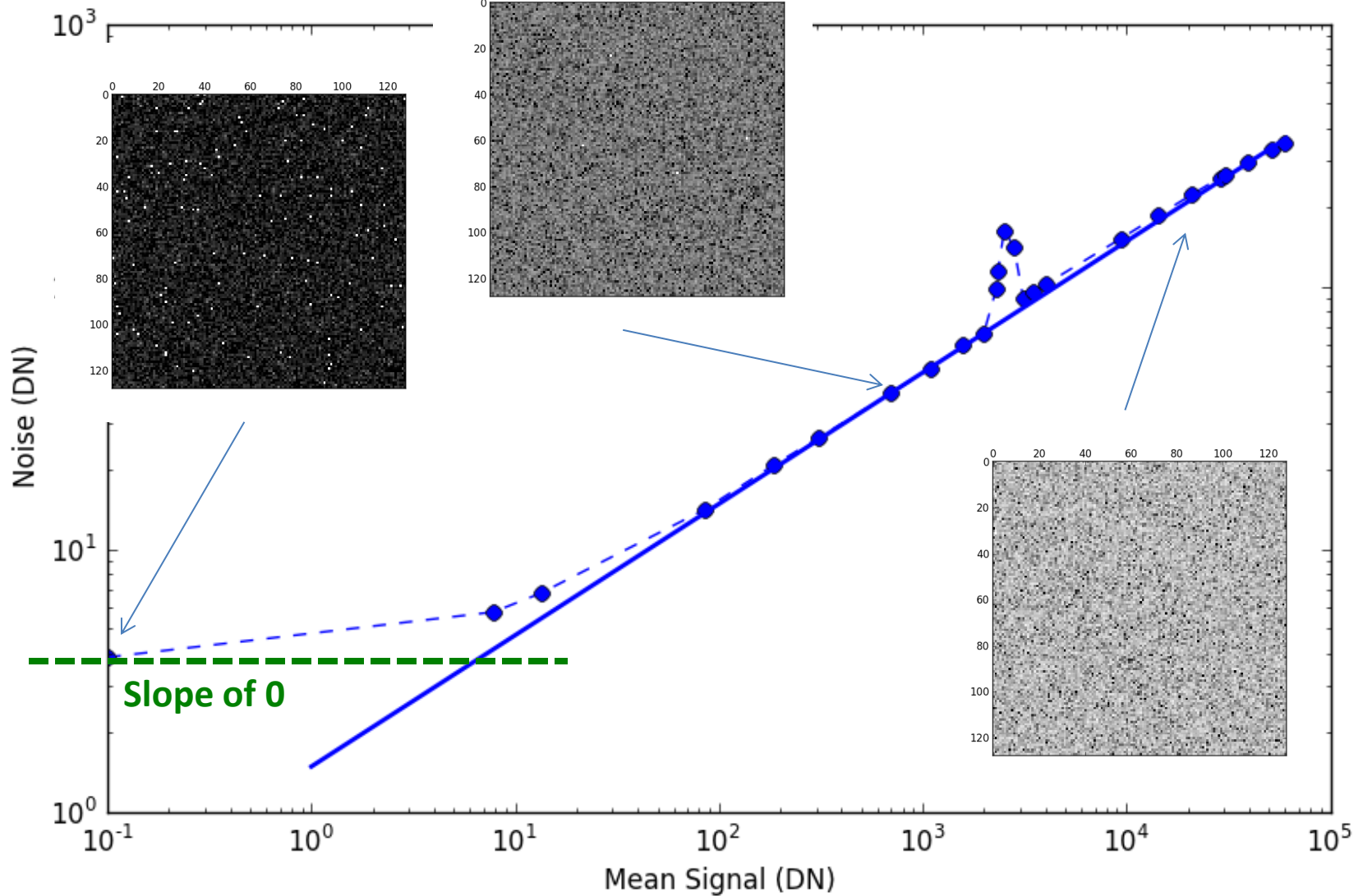
- Steps to generate photon transfer curve:
 - Record several sequences of frames at various illumination levels starting with completely dark
 - Use homogenous illumination,
 - Or correct for inhomogeneity as well as fixed pattern noise by subtracted neighboring frames
 - Plot standard deviation of signal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

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

sCMOS

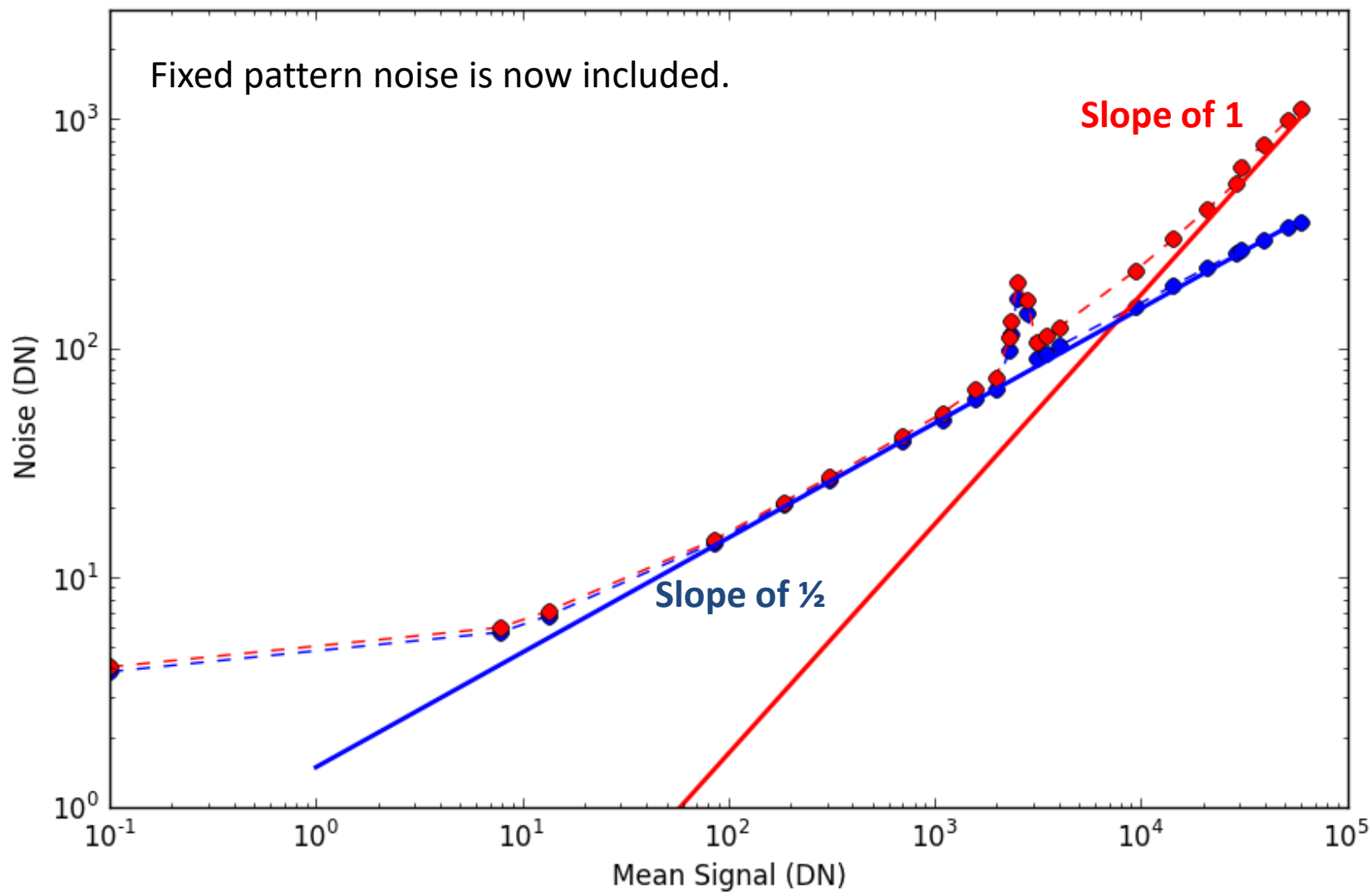


sCMOS

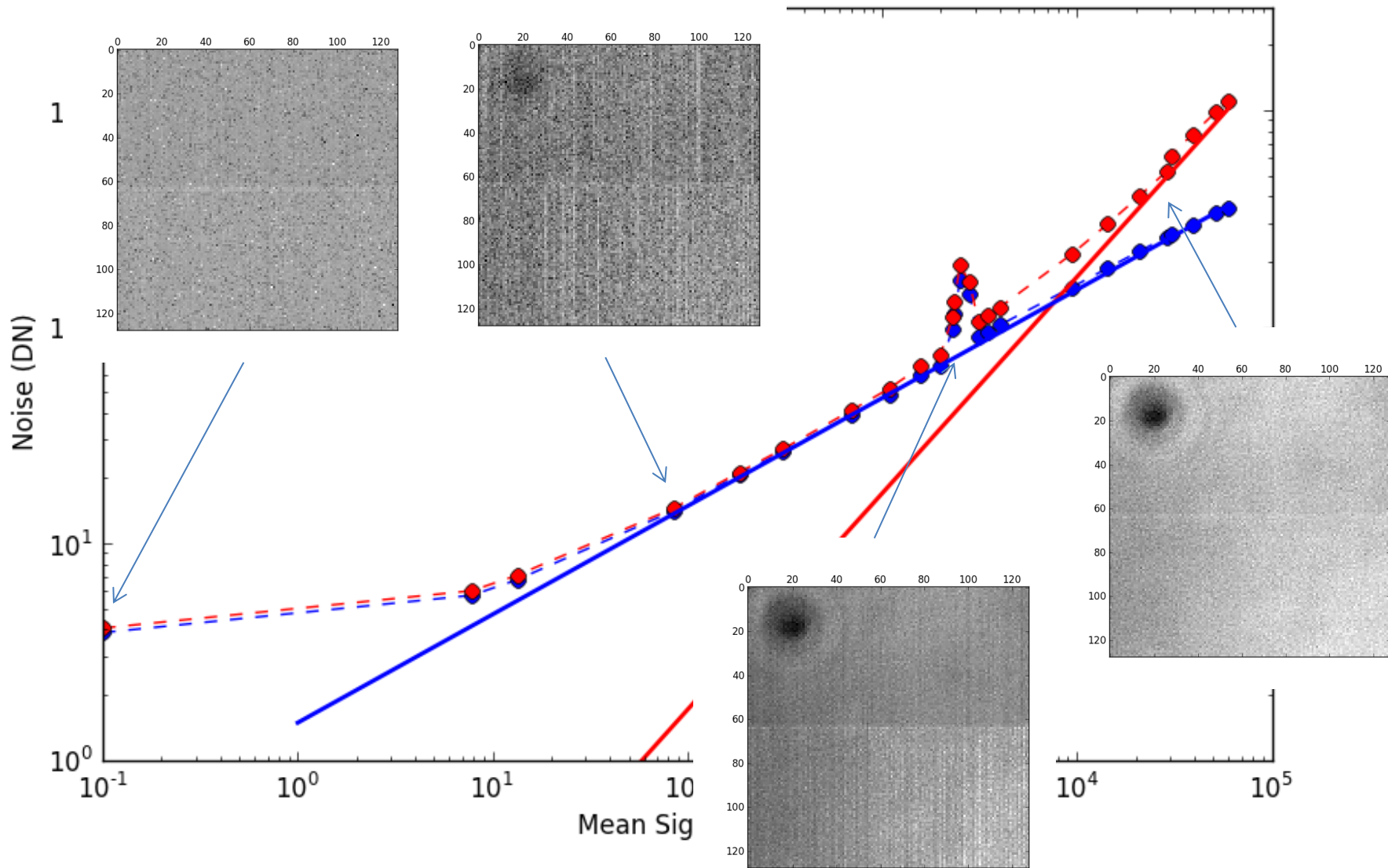


Images show variance on a log scale

sCMOS

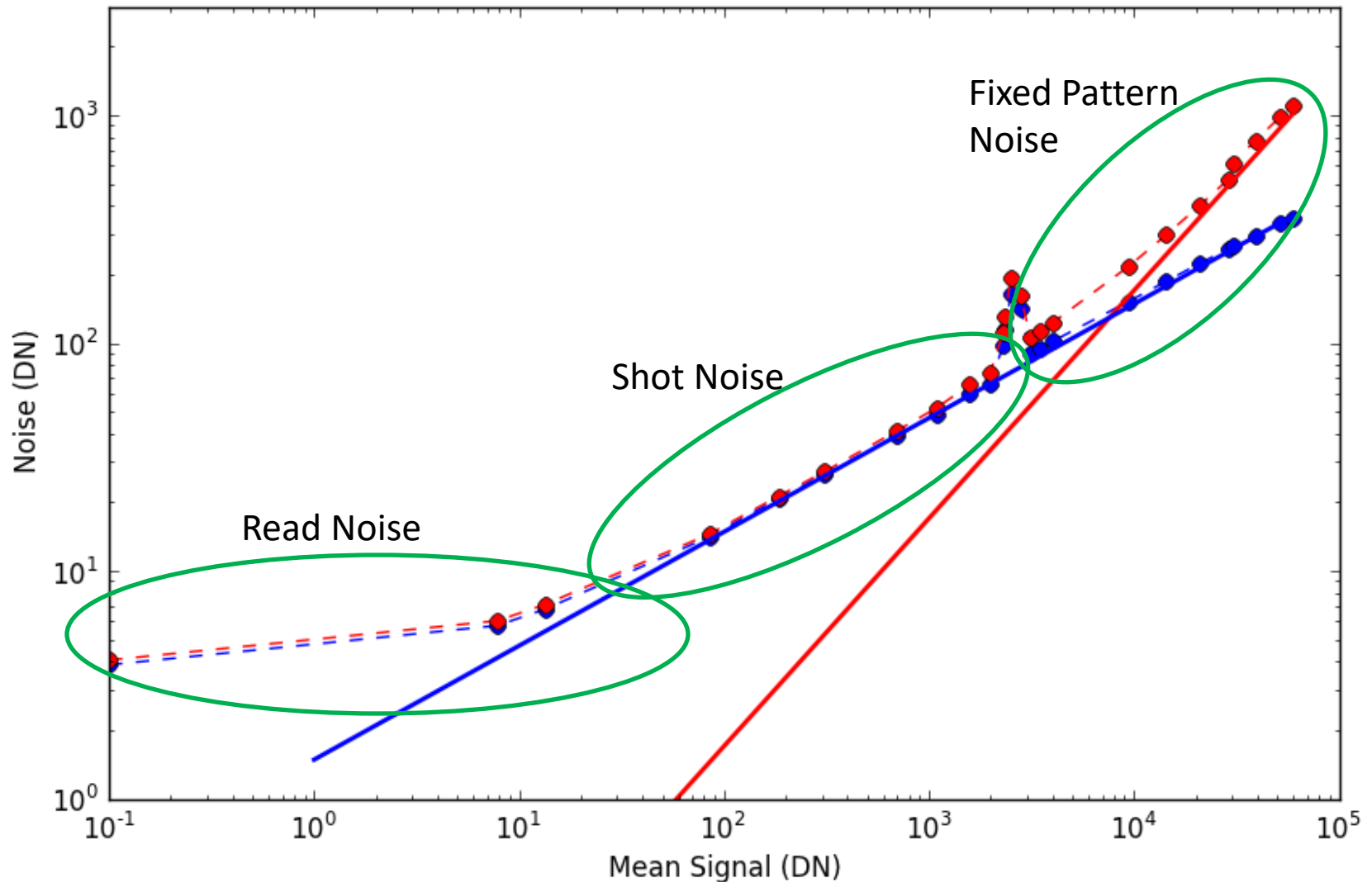


sCMOS



Images show average of 400 frames

sCMOS

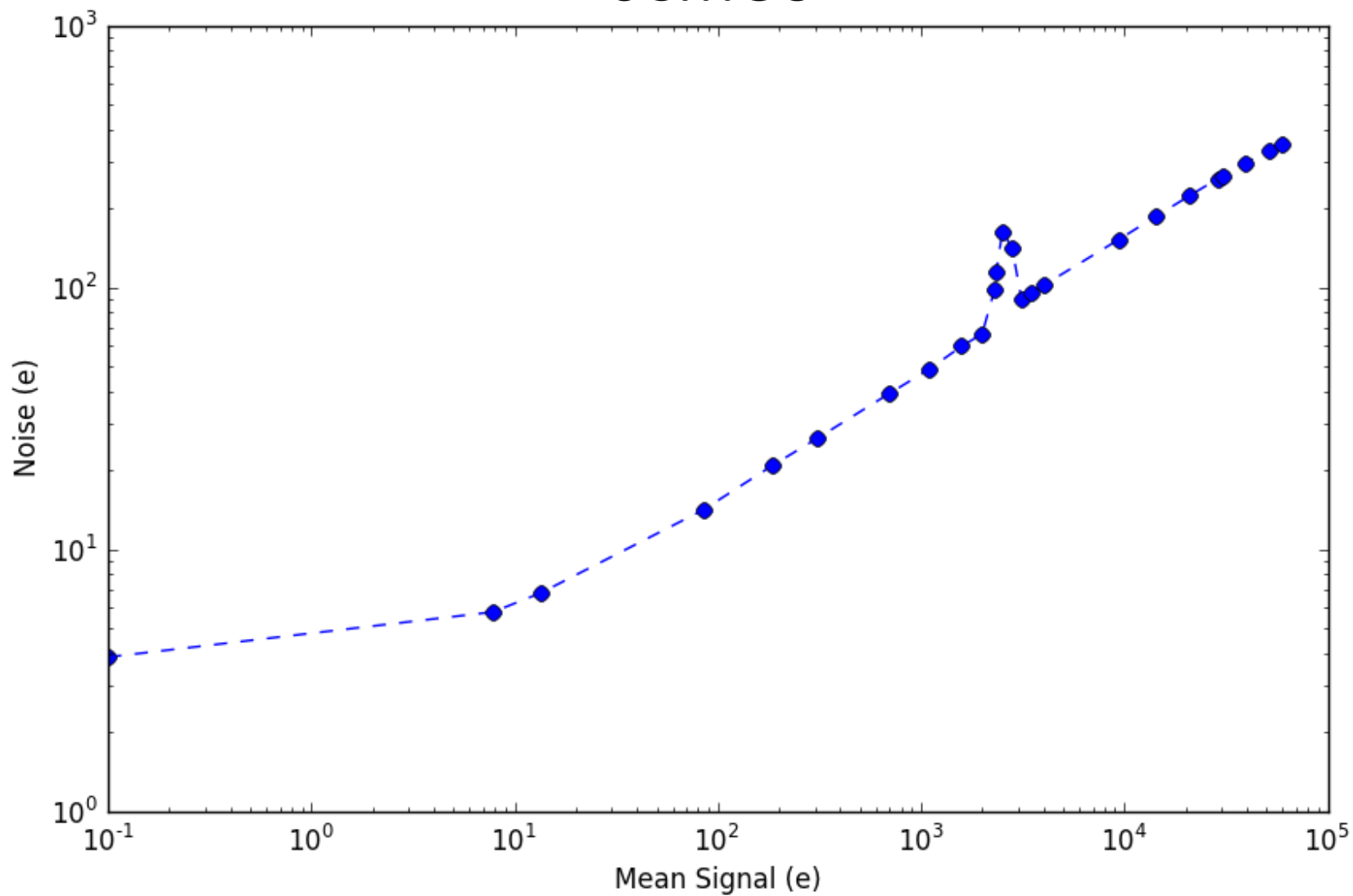


By looking at shot noise vs. signal: ADU conversion is about 2.2 DN/e^-

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

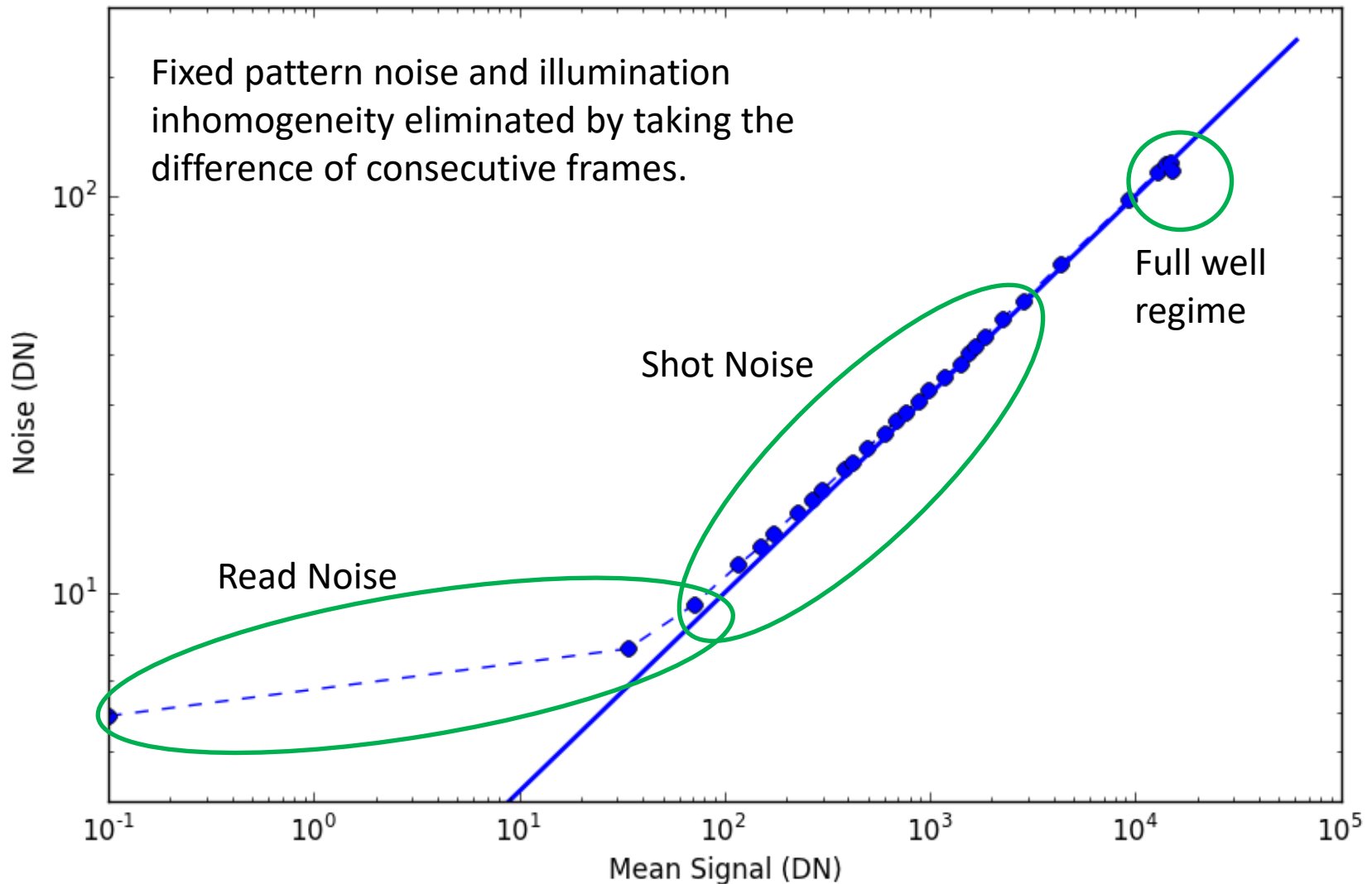
Fixed pattern noise: about 1.7% of signal

sCMOS



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

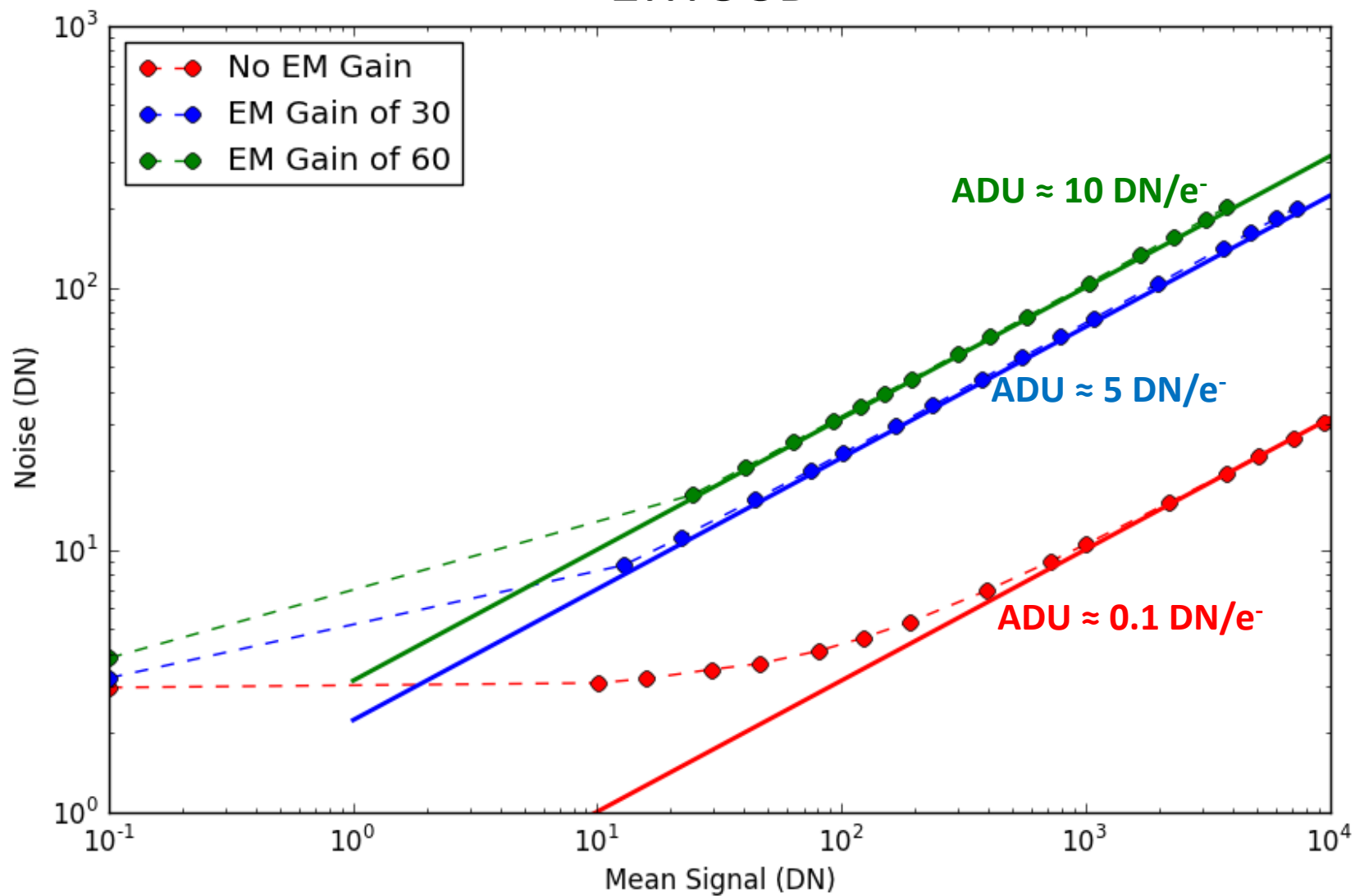
CCD



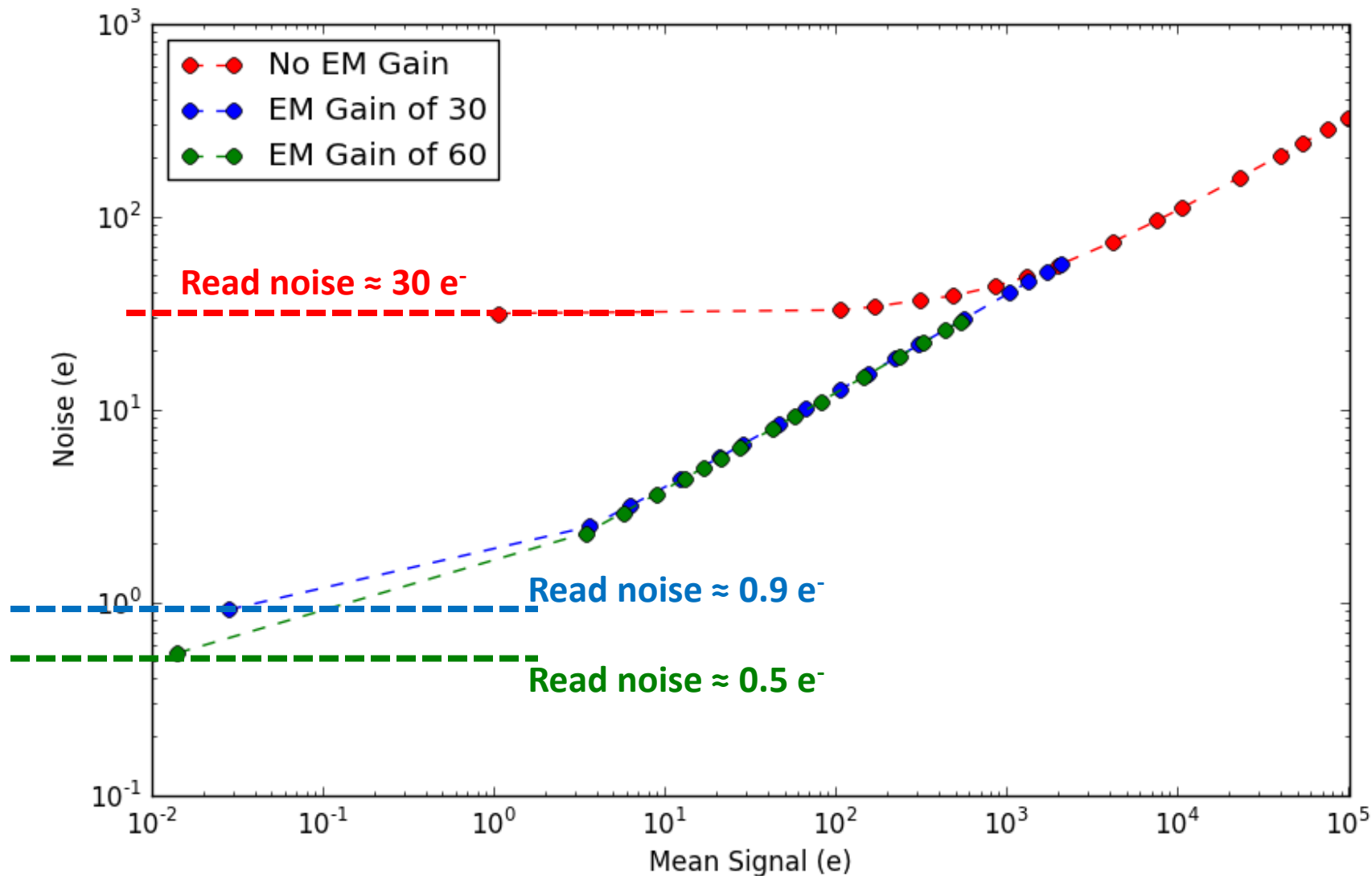
By looking at shot noise vs. signal: ADU conversion is about 1.0 DN/e⁻

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

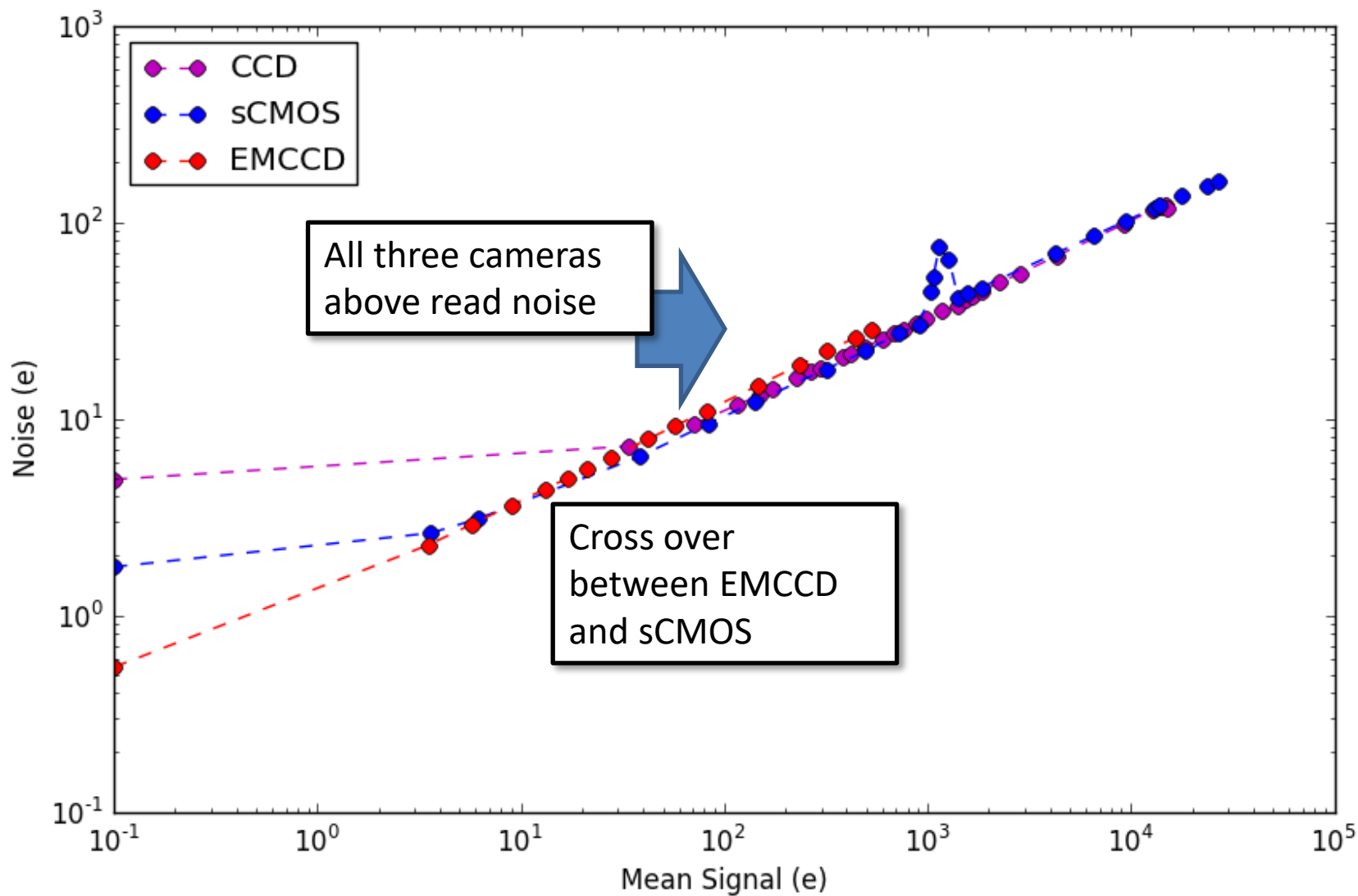
EMCCD



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



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.) 6 .. 8 e ⁻ rms @ 24 MHz (typ.) |
| dynamic range | 2 667 : 1 (60 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

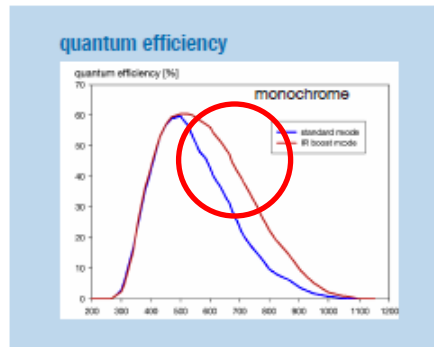
| | |
|--------------------------------|--|
| max. frame rate | 7.3 / 13.5 fps (12 / 25 MHz, normal) 11.7 / 21.6 fps (12 / 25 MHz, center) |
| exposure/shutter time | 5 µs .. 60 s |
| dynamic range A/D | 14 bit |
| A/D conversion factor | 1.0 e ⁻ /count |
| pixel scan rate | 12 MHz / 24 MHz |
| pixel 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 |

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 table⁴

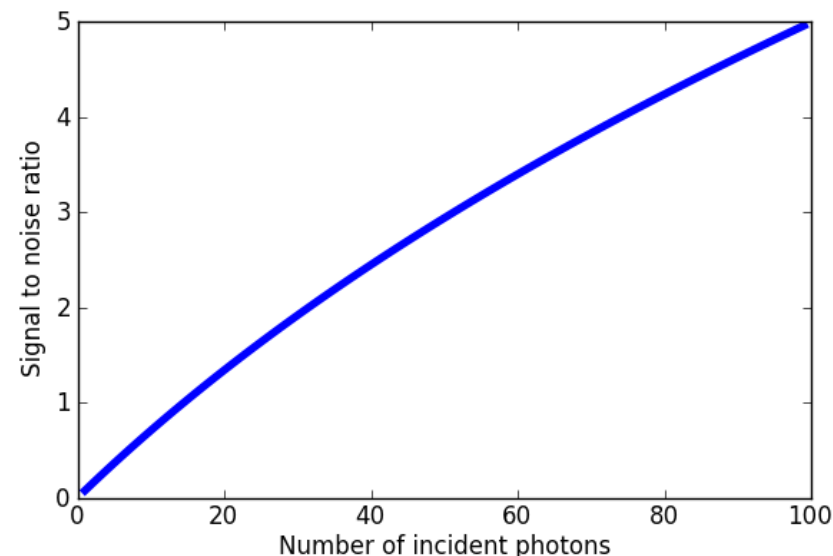
| resolution | normal | center |
|-------------------|----------|----------|
| pixeldclock [MHz] | 12 | 25 |
| 1392 x 1040 | 7.3 fps | 13.5 fps |
| 800 x 600 | 11.7 fps | 21.6 fps |
| v2 binning | 14.7 fps | 27 fps |
| | 21.6 fps | 40.4 fps |



$$N_r = 6 \text{ e}^-$$

$$QE \approx 45\% \text{ at } \approx 700\text{nm}$$

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



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

Going back to the spec sheet

technical data

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| | |
|--------------------------|--|
| type of sensor | CCD |
| image sensor | ICX285AL |
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| 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 | 200 nm .. 1100 nm |
| dark current | 1 e ⁻ /pixel/s @ 23 °C |
| DSNU ¹ | 2 e ⁻ rms |
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camera

| | |
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| max. frame rate | 7.3 / 13.5 fps (12 / 25 MHz, normal) 11.7 / 21.6 fps (12 / 25 MHz, center) |
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| 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 LVTTTL level |

general

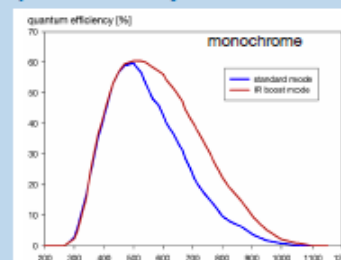
| | |
|---------------------------|-------------------------------|
| power supply | 9 .. 28 VDC (12 VDC typ.) |
| power consumption | < 4 W |
| weight | 0.25 kg |
| operating temperature | + 10 °C .. + 45 °C |
| operating humidity range | 10 % .. 80 % (non-condensing) |
| storage temperature range |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

frame rate table⁴

| 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 | 21.6 fps | 40.4 fps |

Dark current: 1 e⁻/pixel/s @ 23 °C

quantum efficiency



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

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| | |
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| 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 | 85 % @ 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 ⁻ /Vcode |
| 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 LVTTTL level |

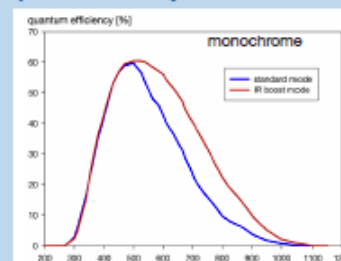
general

| | |
|---------------------------|-------------------------------|
| 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 table⁴

| 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 | 21.6 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 = 2¹⁴ = 16,384

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

Thanks!

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

