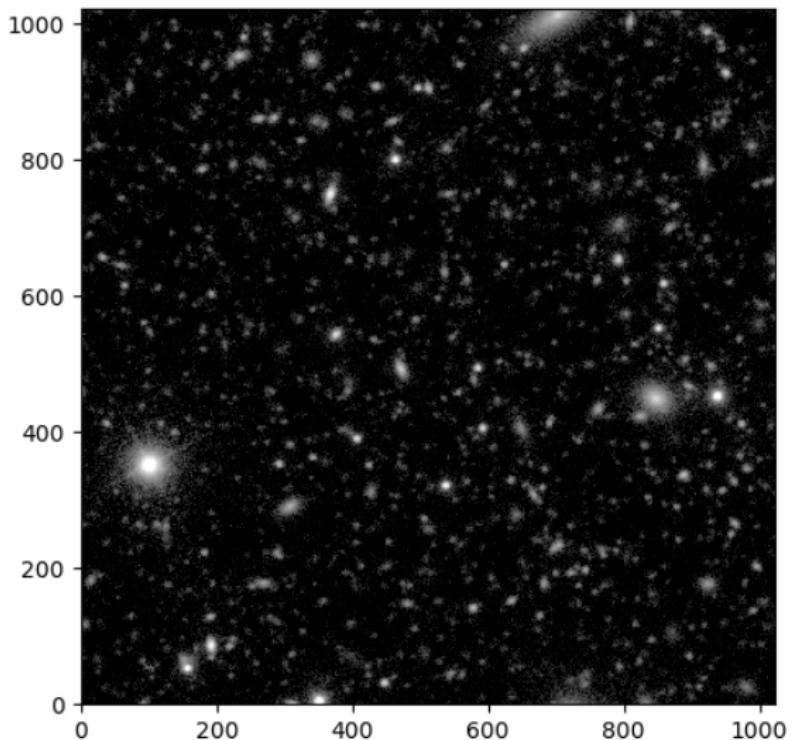


The Imperfection of Optical/NIR Astronomical Data

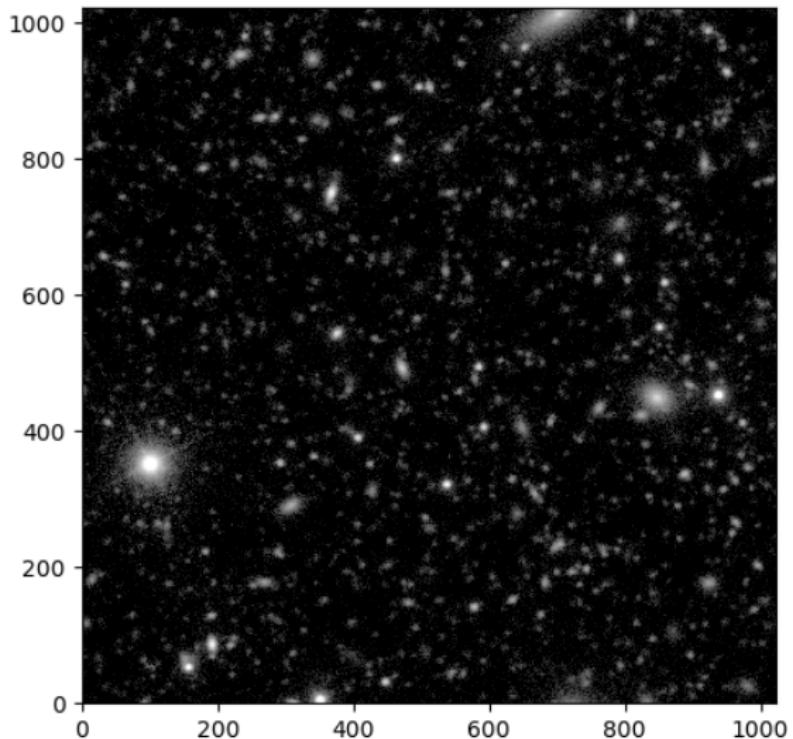
Robert Lupton

2018-01-22

Data

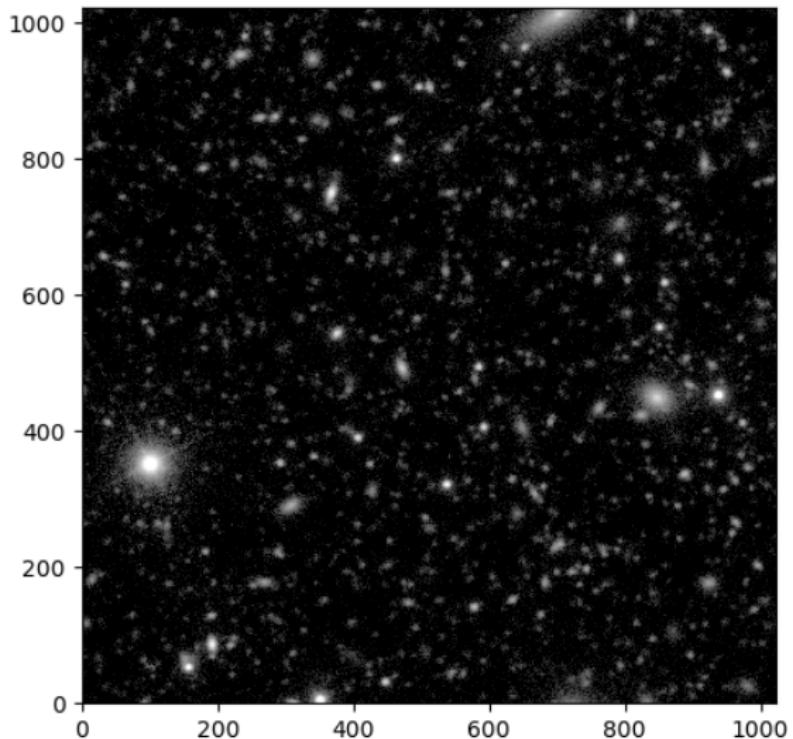


Data



This image is noisy.

Data



This image is noisy; all images are noisy

Probability Distributions

Probability Distributions

As you all remember, if the probability of something happening is p and you make n attempts, the probability of r successes is:

$$p(r) = \frac{n!}{r!(n-r)!} p^r (1-p)^{n-r}$$

with mean np and variance npq ; this is the *binomial* distribution.

Probability Distributions

As you all remember, if the probability of something happening is p and you make n attempts, the probability of r successes is:

$$p(r) = \frac{n!}{r!(n-r)!} p^r (1-p)^{n-r}$$

with mean np and variance npq ; this is the *binomial* distribution.

In the limit $n \rightarrow \infty$, $p \rightarrow 0$, and $np \rightarrow \mu$, the probability of seeing r events is:

$$p(r) = \frac{\mu^r}{r!} e^{-\mu}$$

with mean μ and variance μ ; this is the *Poisson* distribution $P(\mu)$.

Probability Distributions

As you all remember, if the probability of something happening is p and you make n attempts, the probability of r successes is:

$$p(r) = \frac{n!}{r!(n-r)!} p^r (1-p)^{n-r}$$

with mean np and variance npq ; this is the *binomial* distribution.

In the limit $n \rightarrow \infty$, $p \rightarrow 0$, and $np \rightarrow \mu$, the probability of seeing r events is:

$$p(r) = \frac{\mu^r}{r!} e^{-\mu}$$

with mean μ and variance μ ; this is the *Poisson* distribution $P(\mu)$.

In the limit $\mu \gg 1$, this becomes:

$$p(r) = \frac{1}{\sqrt{2\pi\mu}} e^{-(r-\mu)^2/(2\mu)}$$

also with mean μ and variance μ ; this is the *Gaussian* distribution, $N(\mu, \mu)$.

Definitions

Let us assume that the star's profile, the PSF, is given by $\phi(\mathbf{x})$, normalised such that

$$\sum_i \phi(\mathbf{x}_i) = 1$$

Definitions

Let us assume that the star's profile, the PSF, is given by $\phi(\mathbf{x})$, normalised such that

$$\sum_i \phi(\mathbf{x}_i) = 1$$

Modern optical and IR detectors are made out of pixels, so the values that we measure are the integrals of our signal over a pixel (here of size 1×1):

$$I(\mathbf{x}_p) = \int_{y_p - 0.5}^{y_p + 0.5} \int_{x_p - 0.5}^{x_p + 0.5} I(x, y) dx dy$$

Definitions

Let us assume that the star's profile, the PSF, is given by $\phi(\mathbf{x})$, normalised such that

$$\sum_i \phi(\mathbf{x}_i) = 1$$

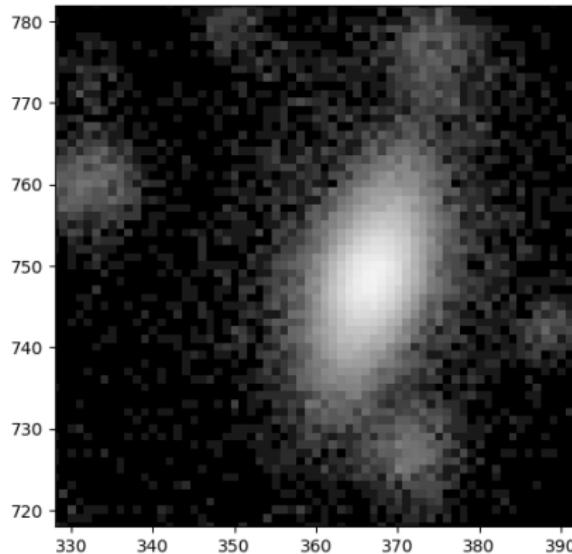
Modern optical and IR detectors are made out of pixels, so the values that we measure are the integrals of our signal over a pixel (here of size 1×1):

$$I(\mathbf{x}_p) = \int_{y_p - 0.5}^{y_p + 0.5} \int_{x_p - 0.5}^{x_p + 0.5} I(x, y) dx dy$$

It's traditional to visualize data as uniformly illuminated squares, but this is just a convention.

Poisson Noise

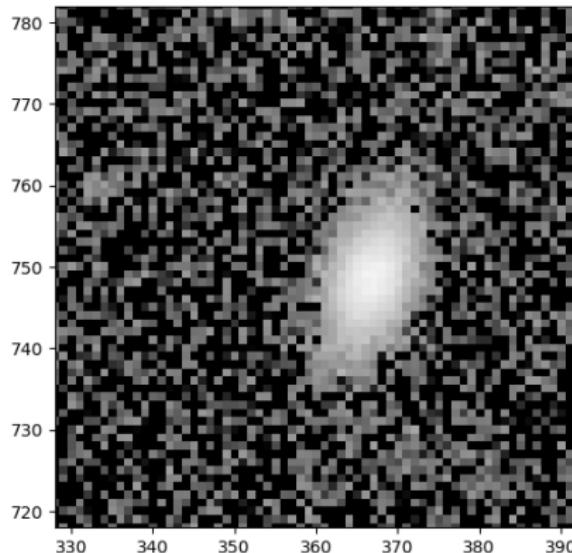
The arrival of photons from a far-off galaxy is an example of a Poisson process.



If the mean number of photons in a pixel is μ then the standard deviation of our estimate of the flux in that pixel is $\sqrt{\mu}$.

Poisson Noise

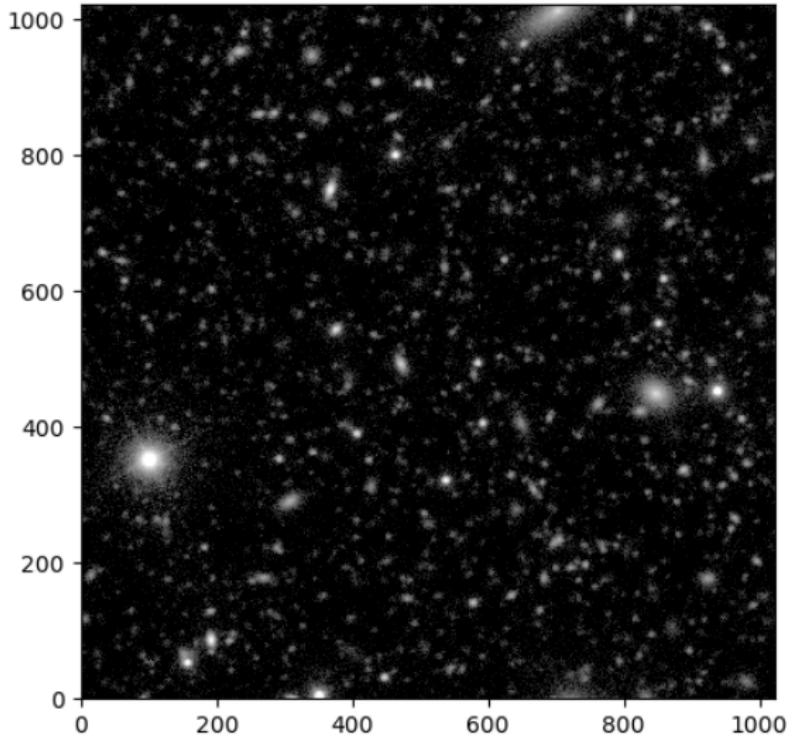
The arrival of photons from a far-off galaxy is an example of a Poisson process.



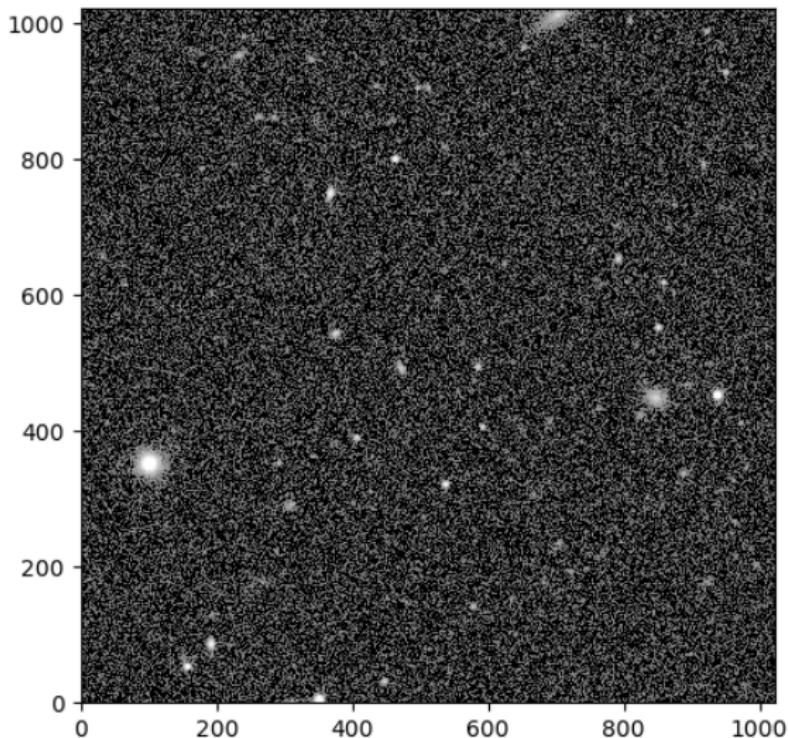
If the mean number of photons in a pixel is μ then the standard deviation of our estimate of the flux in that pixel is $\sqrt{\mu}$.

Most of the photons don't come from the objects.

Data



Data



Question 1: Whence comes the background ('sky') level?

List as many contributions as you can to the 'sky' level.

Answer 1

Things I thought of were:

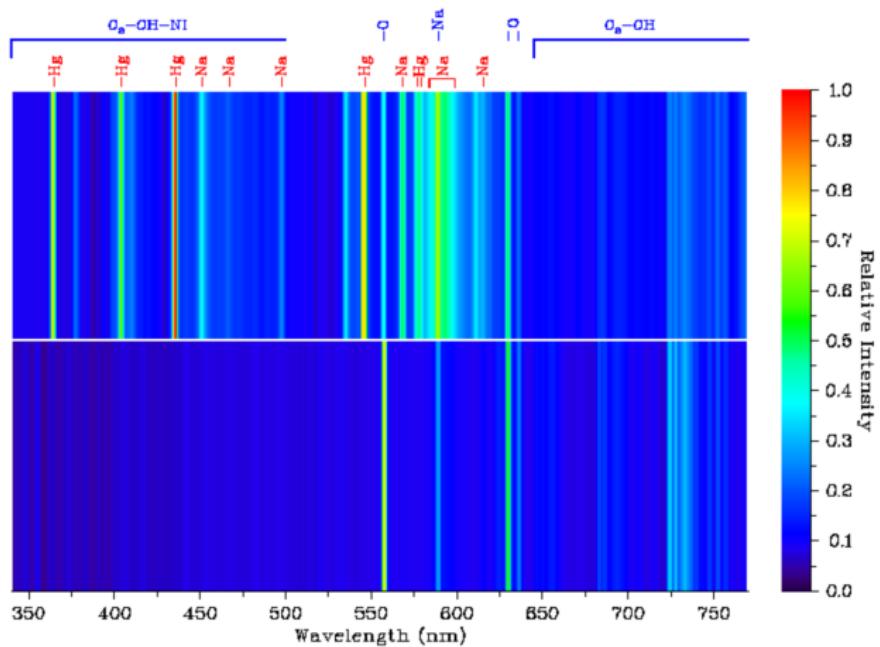
- Night sky emission (O_2 , OH)
- Zodiacal light/Gegenschein
- Starlight scattered from the atmosphere
- Moonlight scattered from the atmosphere
- Galactic cirrus
- Extra-Galactic background

Answer 1

Things I thought of were:

- Night sky emission (O_2 , OH)
- Zodiacal light/Gegenschein
- Starlight scattered from the atmosphere
- Moonlight scattered from the atmosphere
- Galactic cirrus
- Extra-Galactic background
- Night sky emission (Na , Hg , ...)
- Scattered and Ghost light from the telescope
- Dark current in the CCDs
- Glow from the ion pumps

Answer 1



Question 2: Does the pixelisation matter?

Our image is continuous, but we only measure its integral over a pixel.

How does this affect the PSF?

Answer 2:

Let the image above the atmosphere be $I_0(x)$, so we see $I(x) \equiv I_0(x) \otimes \phi$.

We measure

$$\begin{aligned}I_p &= \int_{x_p - 0.5}^{x_p + 0.5} I(x) dx \\&\equiv \int_{x_p - 0.5}^{x_p + 0.5} (I_0(x) \otimes \phi) dx \\&= \int_{-\infty}^{\infty} P(x - x_p) (I_0(x) \otimes \phi) dx \\&= (P \otimes \phi \otimes I_0)(x_p)\end{aligned}$$

where

$$P(x) = \begin{cases} 1 & |x| \leq 0.5 \\ 0 & |x| > 0.5 \end{cases}$$

i.e. We replace the PSF ϕ by $P \otimes \phi$

Answer 2:

Let the image above the atmosphere be $I_0(x)$, so we see $I(x) \equiv I_0(x) \otimes \phi$.

We measure

$$\begin{aligned}I_p &= \int_{x_p - 0.5}^{x_p + 0.5} I(x) dx \\&\equiv \int_{x_p - 0.5}^{x_p + 0.5} (I_0(x) \otimes \phi) dx \\&= \int_{-\infty}^{\infty} P(x - x_p) (I_0(x) \otimes \phi) dx \\&= (P \otimes \phi \otimes I_0)(x_p)\end{aligned}$$

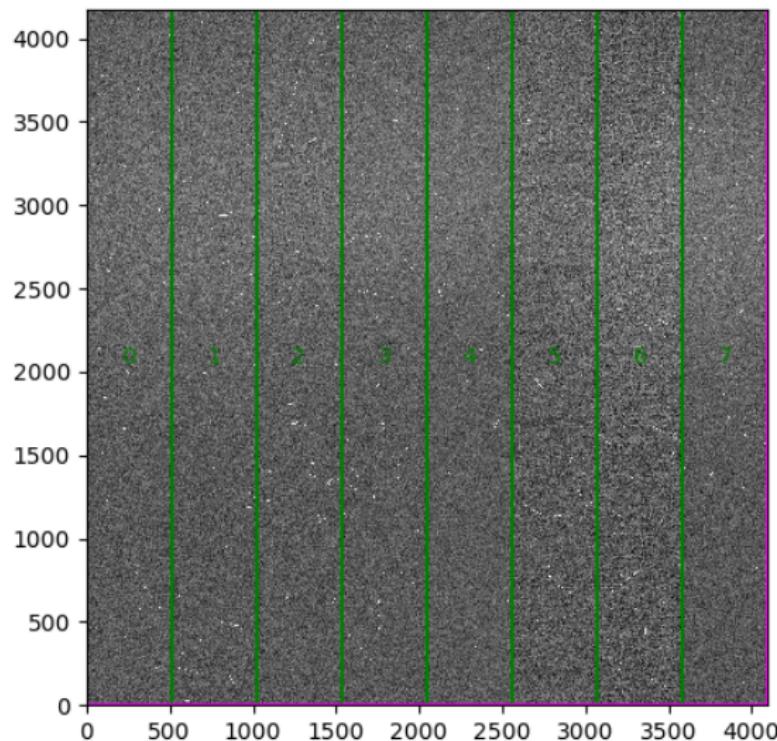
where

$$P(x) = \begin{cases} 1 & |x| \leq 0.5 \\ 0 & |x| > 0.5 \end{cases}$$

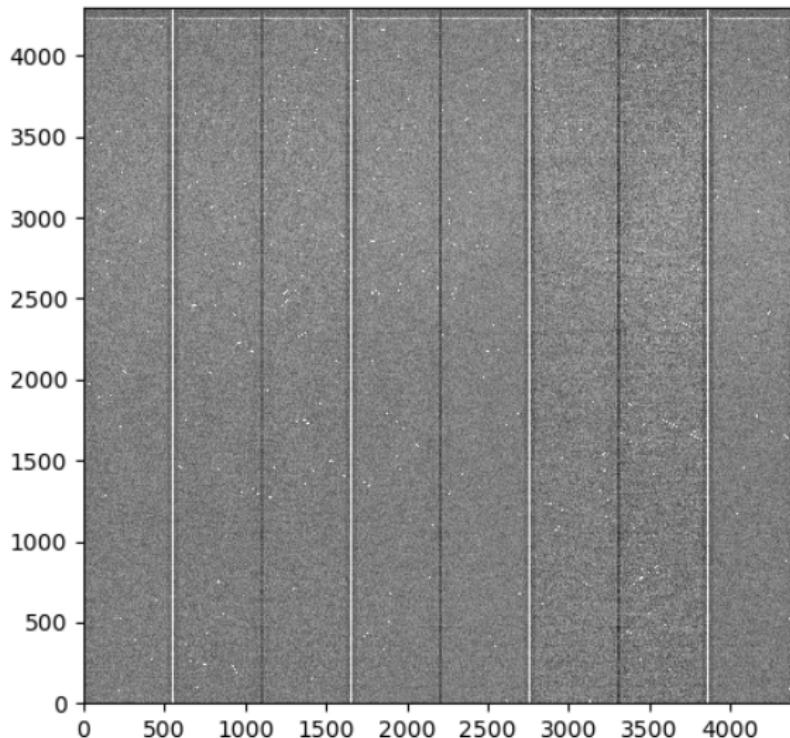
i.e. We replace the PSF ϕ by $P \otimes \phi$; but the latter is the function that we measure.
So the sampling causes no fundamental problems for the PSF, although it can make it
(much) harder to measure if the data is not at least Nyquist sampled.

What does real CCD data look like?

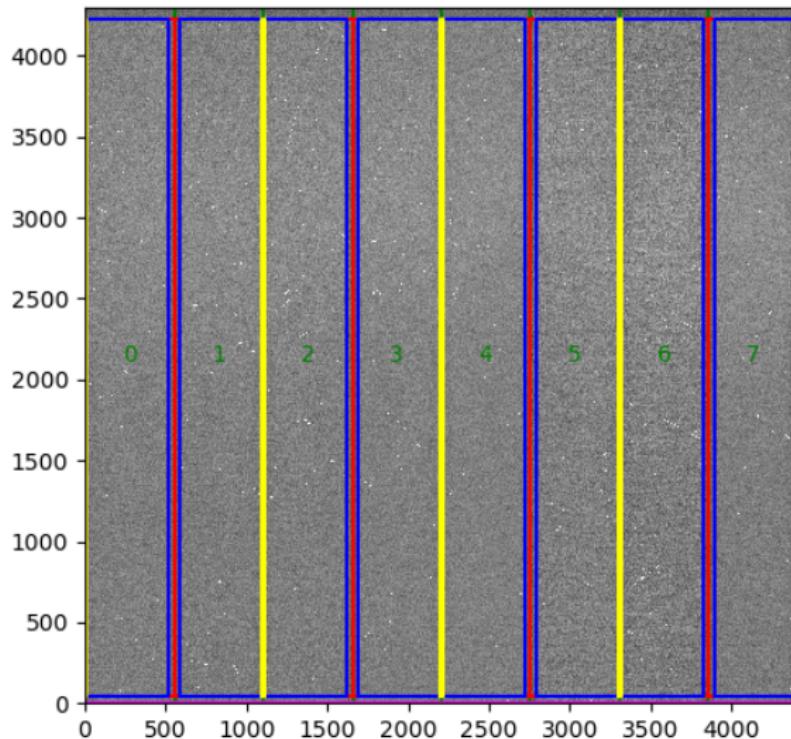
Examples of CCD Images (all from PFS)



Examples of CCD Images (all from PFS)

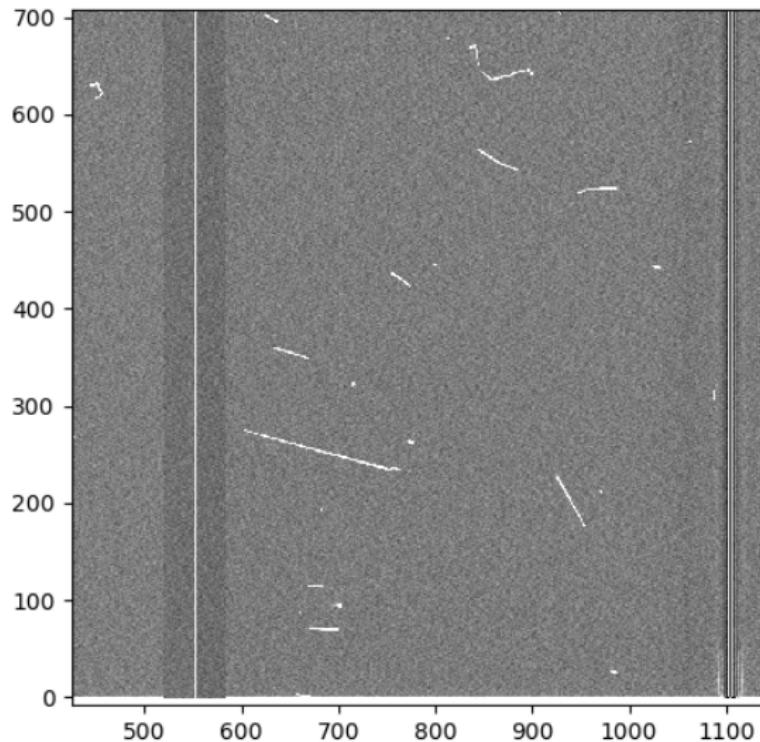


Examples of CCD Images (all from PFS)

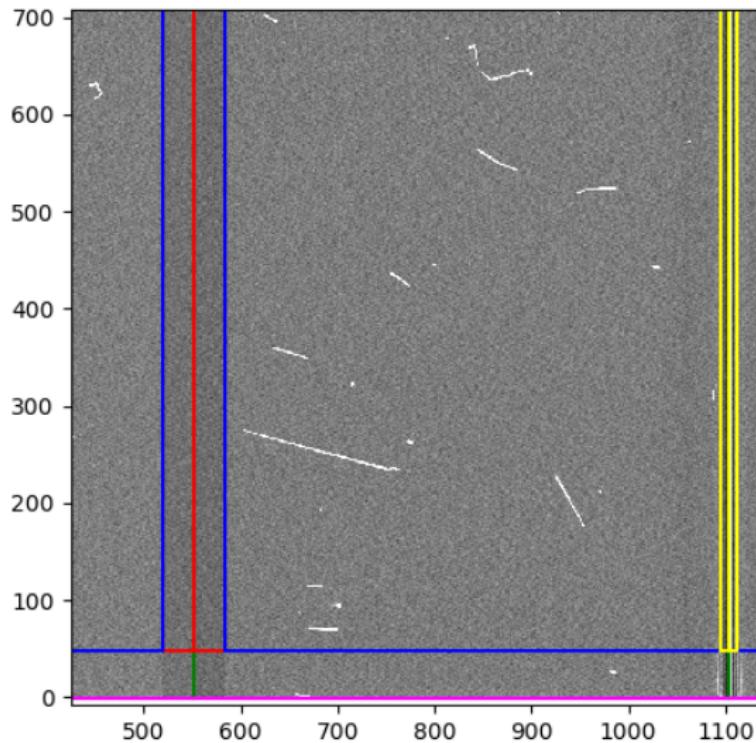


Overscan, Data, Extended register

Examples of CCD Images (all from PFS)

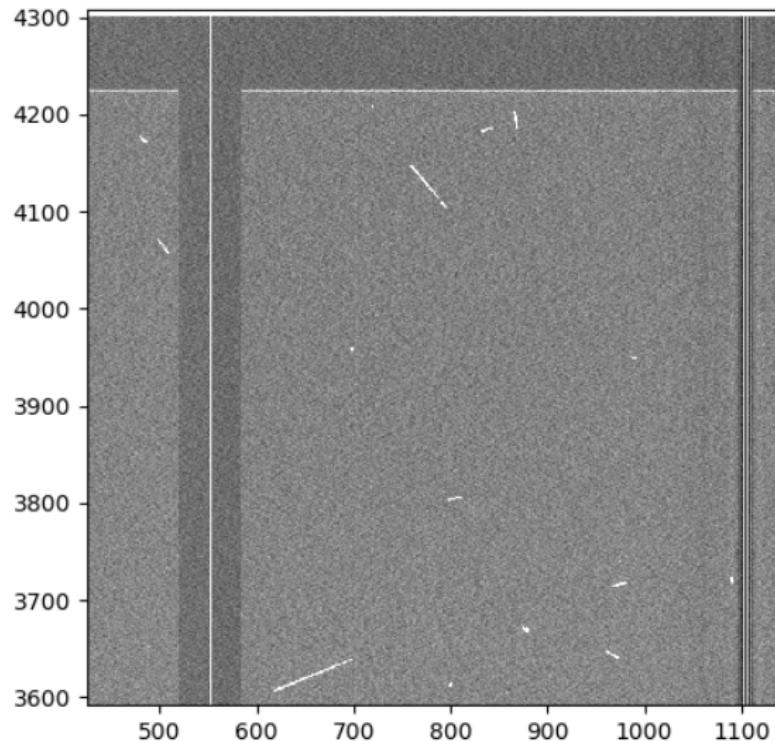


Examples of CCD Images (all from PFS)

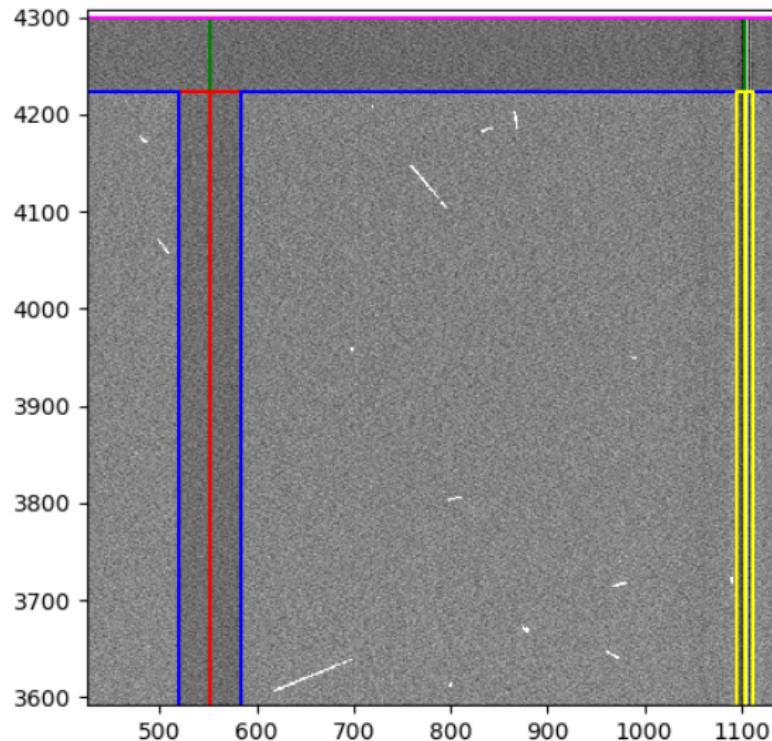


Overscan, Data, Extended register

Examples of CCD Images (all from PFS)



Examples of CCD Images (all from PFS)



Overscan, Data, Extended register

Question 3: How do CCDs detect light?

Question 4: How do CCDs detect light?

Too Easy: photons excite electrons from the valence band to the conduction band.

Question 5: How do CCDs detect light?

Too Easy: photons excite electrons from the valence band to the conduction band.
So the question is: what is the reddest photon that a CCD can detect?

Answer 5

The (indirect) bandgap of *Si* is 1.15 eV at 170K, so the photon must have $\lambda < 1.08\mu m$.

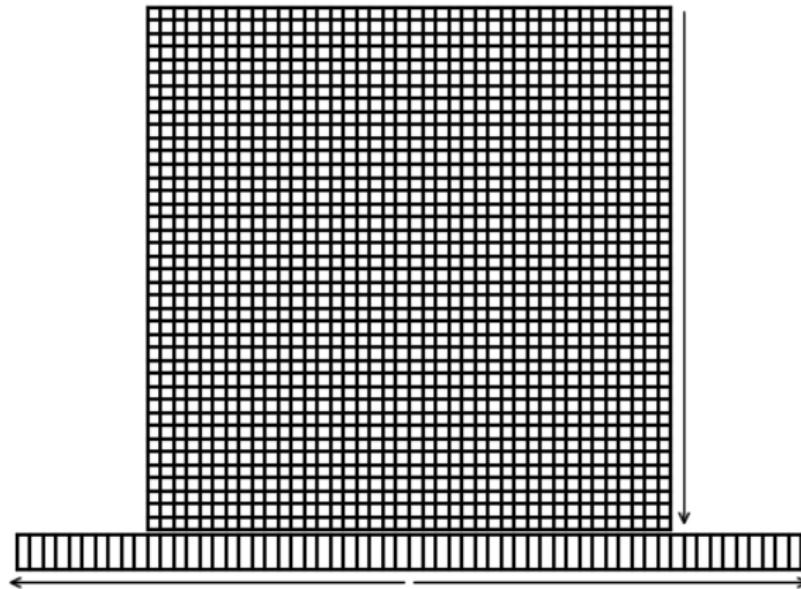
Answer 5

The (indirect) bandgap of *Si* is 1.15 eV at 170K, so the photon must have $\lambda < 1.08\mu m$.

I remember 1.1 eV; 1.1 μm

CCDs

What do those pretty colours mean?



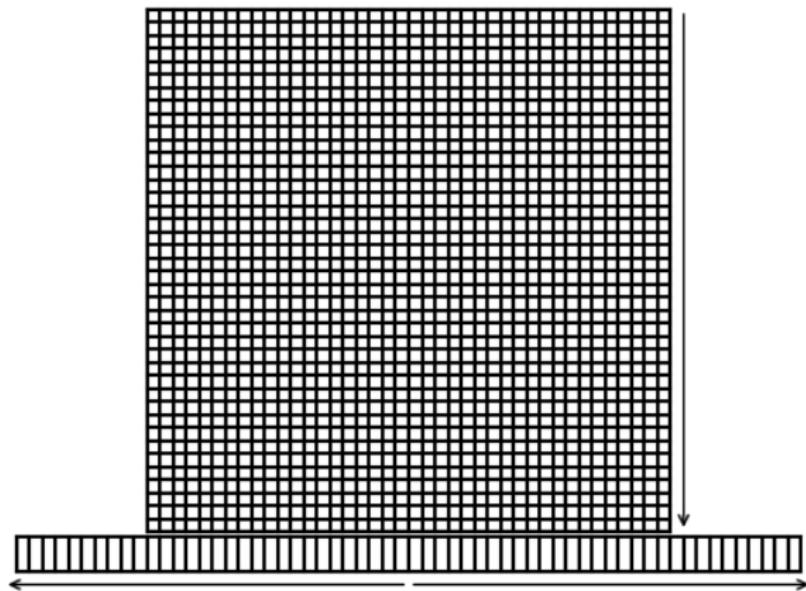
CCDs

What do those pretty colours mean?



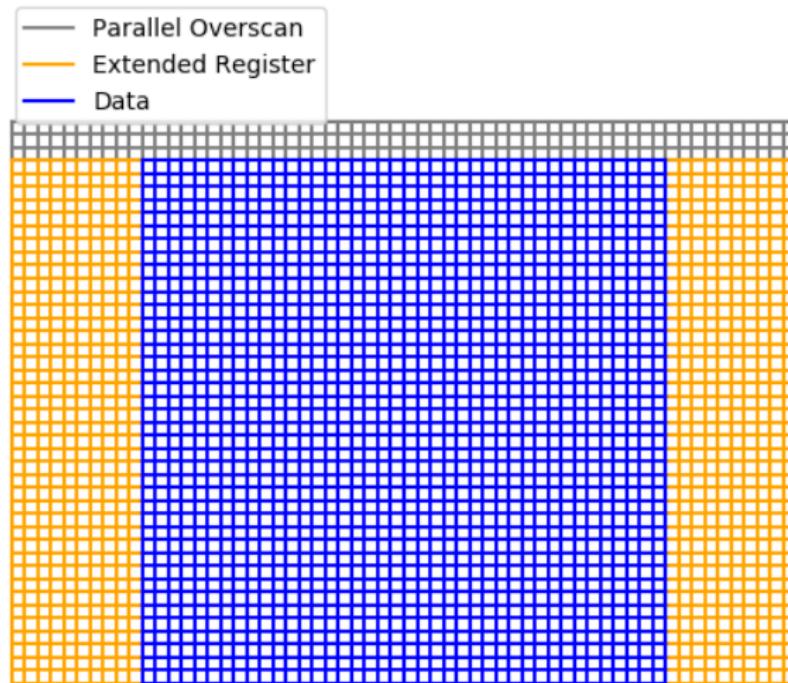
CCDs

What do those pretty colours mean?



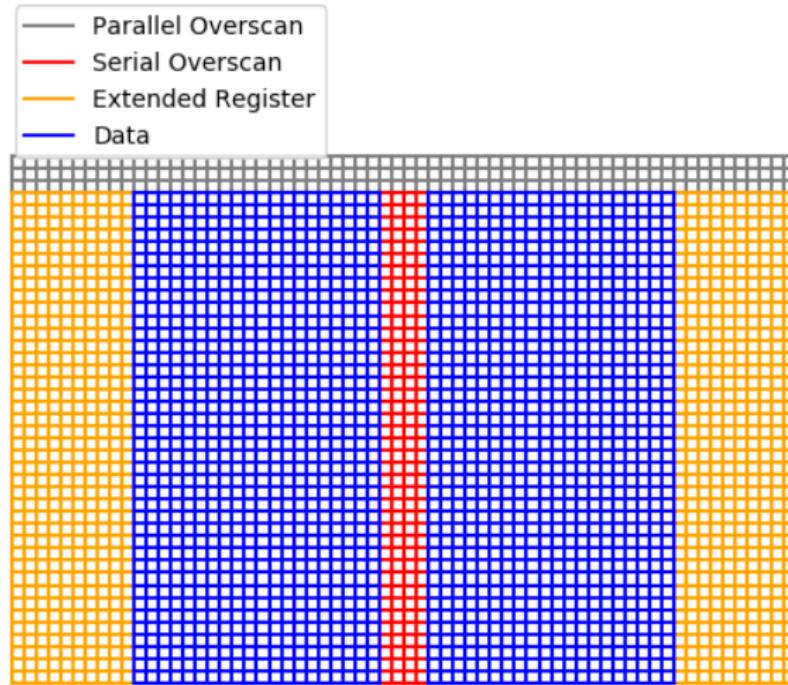
CCDs

What do those pretty colours mean?

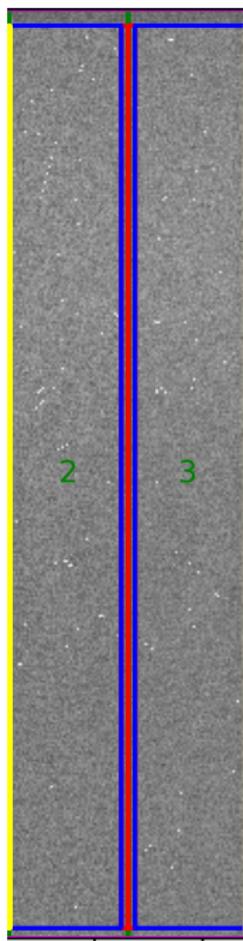


CCDs

What do those pretty colours mean?

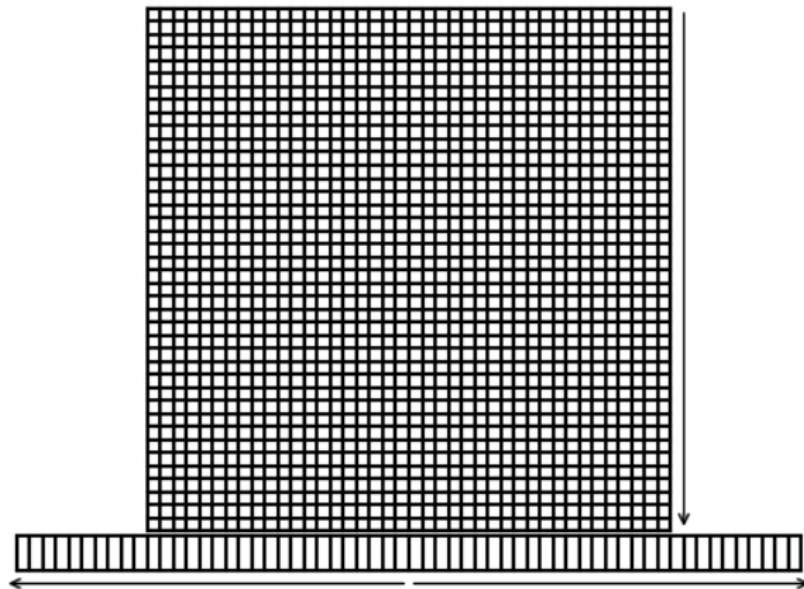


CCDs

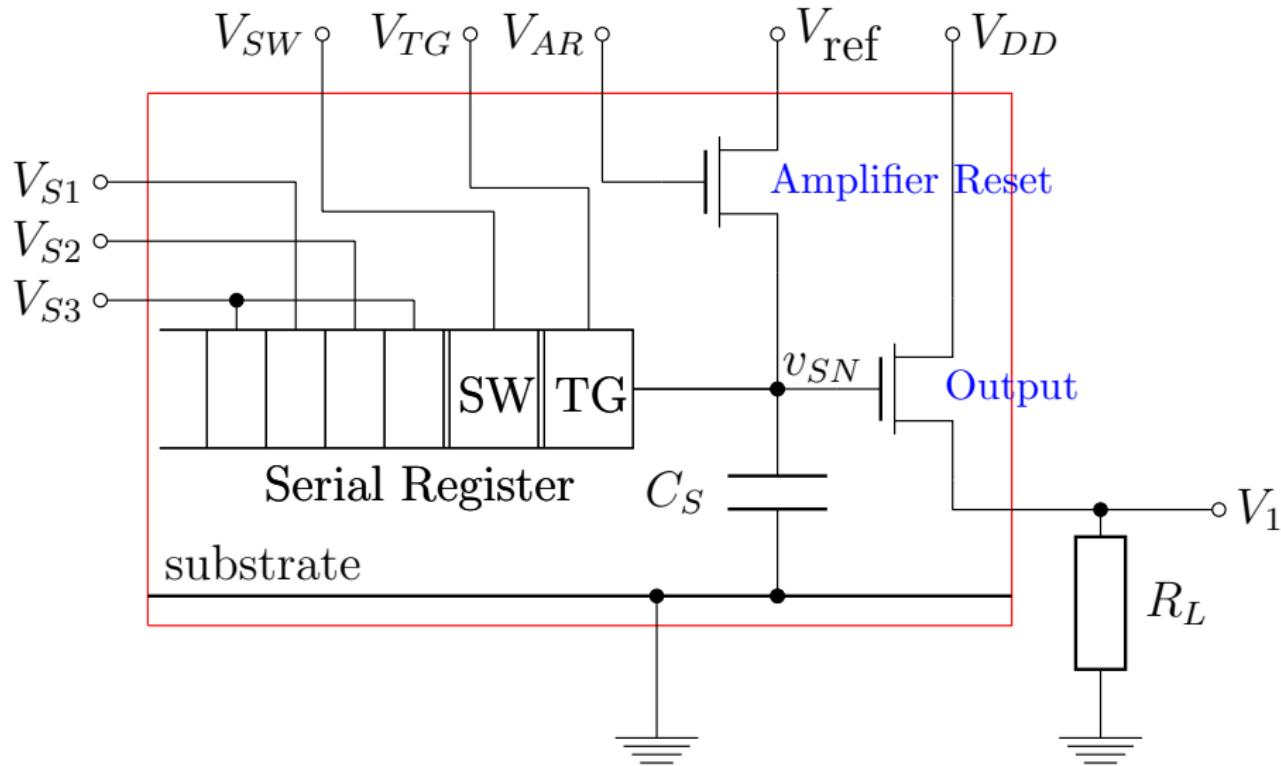


A 1024×4096 CCD

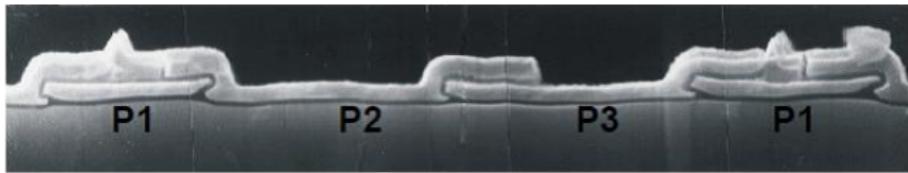
CCD Readout



CCD Readout

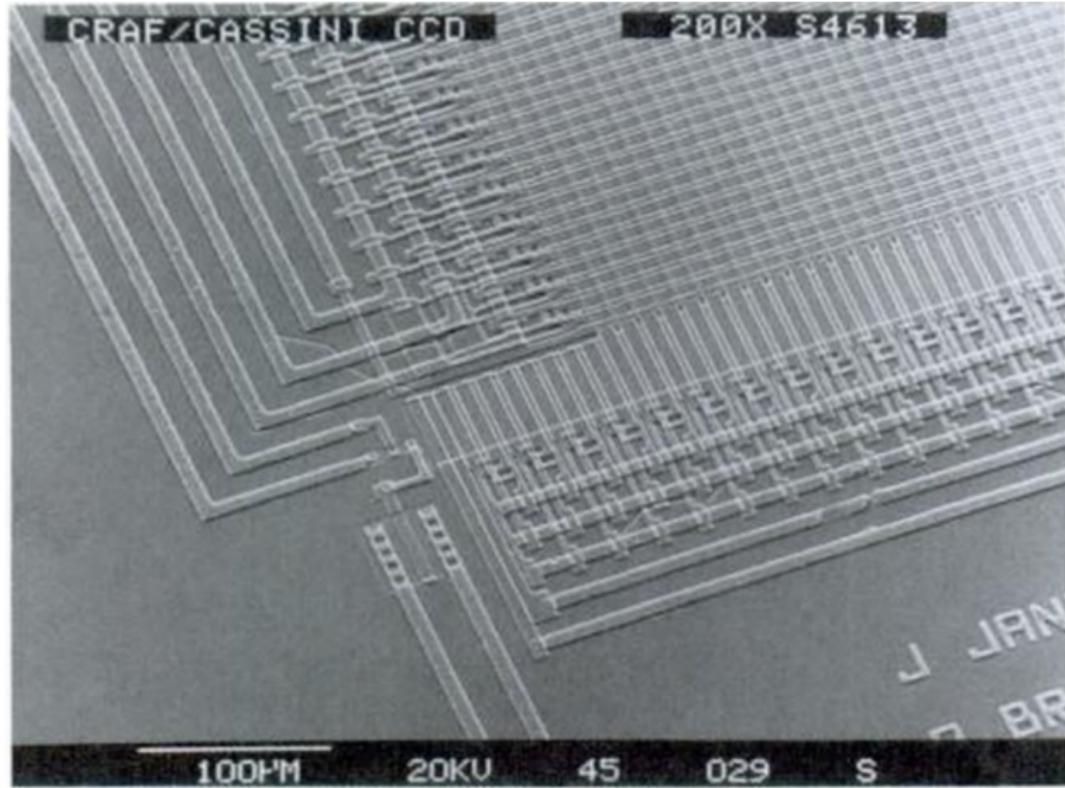


Real CCDs (a Tektronix CCD; Janesick)



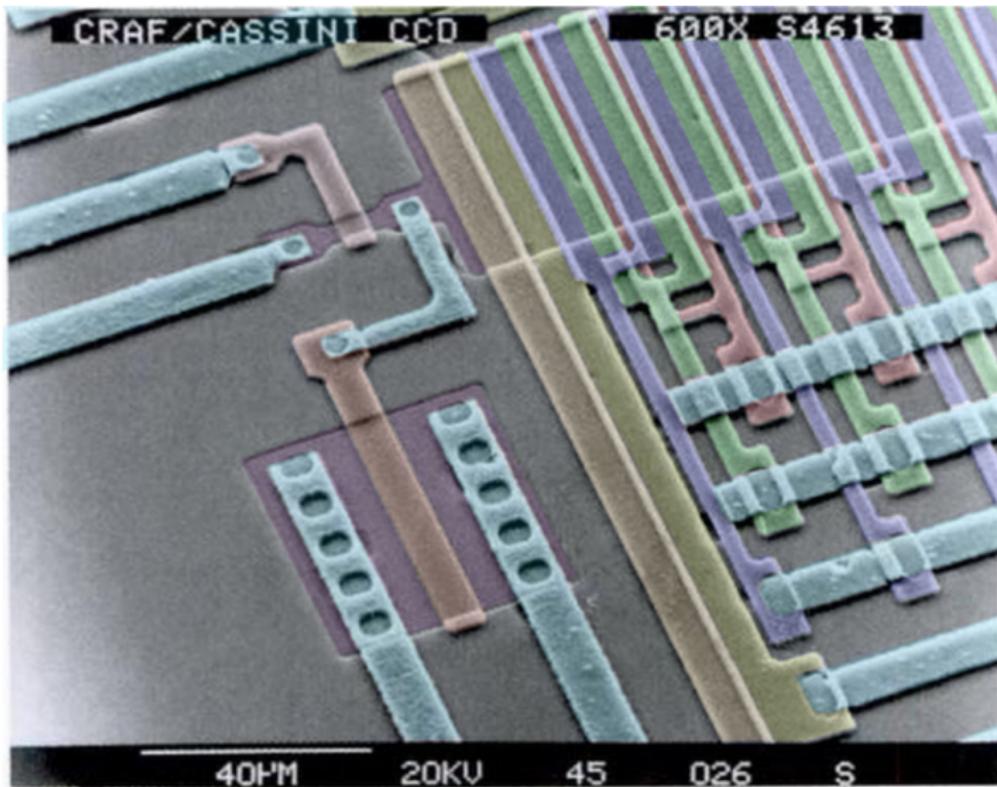
Parallel transport gates

Real CCDs (a Tektronix CCD; Janesick)



Corner of active area, parallel gates, serial register, and output capacitor

Real CCDs (a Tektronix CCD; Janesick)



Serial register, reset gate, and output capacitor

Question 6: kT/C Noise

If you have a partially charged capacitor of capacitance C at temperature T , how well can you measure the charge, Q ?

Question 7: kT/C Noise

If you have a partially charged capacitor of capacitance C at temperature T , how well can you measure the charge, Q ?

Let's actually ask a slightly easier question: What voltage do you measure if you connect a voltmeter across a discharged capacitor of capacitance C at temperature T ?

Answer 7

If the voltage is V then the stored energy is $1/2C V^2$, so the probability of seeing that voltage is given by a Boltzman distribution.

Answer 7

If the voltage is V then the stored energy is $1/2C V^2$, so the probability of seeing that voltage is given by a Boltzman distribution.

$$\begin{aligned} p(V) &\propto e^{-E/kT} \\ &= e^{-CV^2/2kT} \end{aligned}$$

i.e.

$$\begin{aligned} \langle V^2 \rangle &= \frac{kT}{C} \\ \langle Q^2 \rangle &= kTC \end{aligned}$$

Answer 7

If the voltage is V then the stored energy is $1/2C V^2$, so the probability of seeing that voltage is given by a Boltzman distribution.

$$\begin{aligned} p(V) &\propto e^{-E/kT} \\ &= e^{-CV^2/2kT} \end{aligned}$$

i.e.

$$\begin{aligned} \langle V^2 \rangle &= \frac{kT}{C} \\ \langle Q^2 \rangle &= kTC \end{aligned}$$

You might prefer this argument:

Answer 7

If the voltage is V then the stored energy is $1/2C V^2$, so the probability of seeing that voltage is given by a Boltzmann distribution.

$$\begin{aligned} p(V) &\propto e^{-E/kT} \\ &= e^{-CV^2/2kT} \end{aligned}$$

i.e.

$$\begin{aligned} \langle V^2 \rangle &= \frac{kT}{C} \\ \langle Q^2 \rangle &= kTC \end{aligned}$$

You might prefer this argument: The capacitor C is just like any other thermodynamic degree of freedom so the expectation value of its energy is $1/2kT$:

$$\frac{1}{2}C\langle V^2 \rangle = \frac{1}{2}kT$$

which gives the same result but isn't strictly honest.

Orders of Magnitude

The *sense node* C_s has a capacitance of c. 0.1pF (so 300000 e^- produce a 0.5V signal). At $T \sim 160\text{K}$ we have $\langle Q^2 \rangle \sim 1.5 \times 10^{-17}$ or 100 electrons.

Orders of Magnitude

The *sense node* C_s has a capacitance of $c. 0.1\text{pF}$ (so 300000 e^- produce a 0.5V signal). At $T \sim 160\text{K}$ we have $\langle Q^2 \rangle \sim 1.5 \times 10^{-17}$ or 100 electrons. The noise we'd get from 10^4 e^- .

Orders of Magnitude

The *sense node* C_s has a capacitance of $c. 0.1\text{pF}$ (so 300000 e^- produce a 0.5V signal). At $T \sim 160\text{K}$ we have $\langle Q^2 \rangle \sim 1.5 \times 10^{-17}$ or 100 electrons. The noise we'd get from 10^4 e^- . Bad.

Question 8: How fast does that voltage vary?

We know that the voltage on our capacitor has a variance of ktC , but how fast does it change?

Answer 8

It depends on the resistance; $\tau = 1/(RC)$.

Answer 8

It depends on the resistance; $\tau = 1/(RC)$.

If $C \sim 0.1\text{pF}$ and $R \gg 100M\Omega$, $\tau \gg 10\mu\text{s}$.

Answer 8

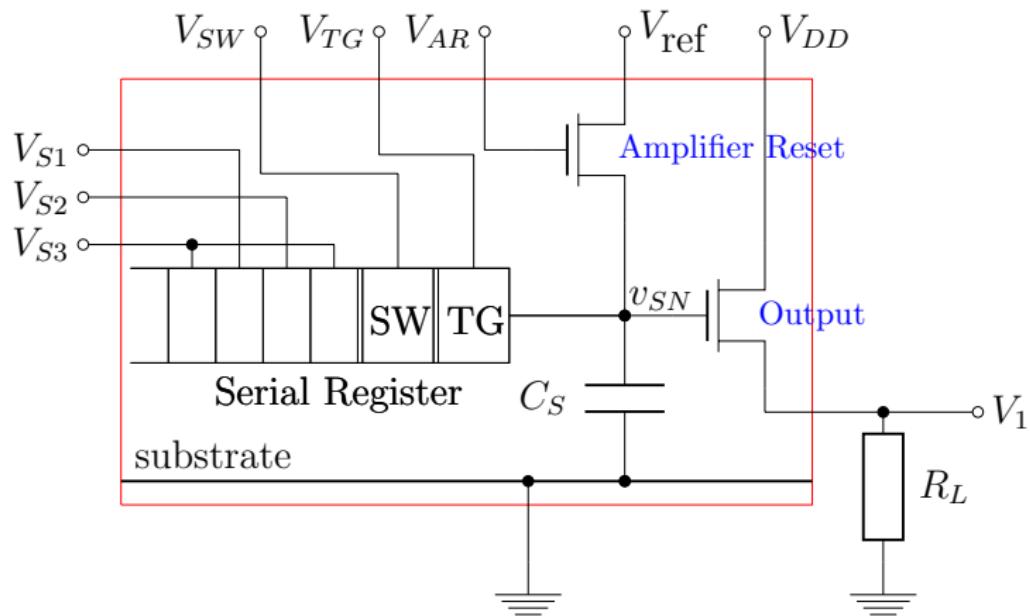
It depends on the resistance; $\tau = 1/(RC)$.

If $C \sim 0.1\text{pF}$ and $R \gg 100M\Omega$, $\tau \gg 10\mu\text{s}$. So if we use a **large** resistor we can "freeze" the kTC noise.

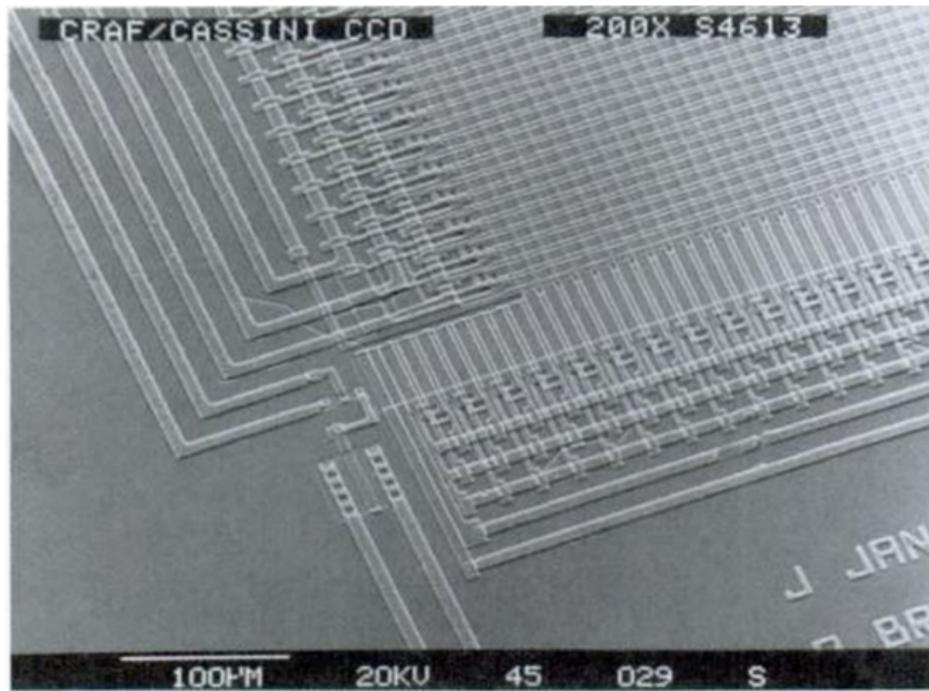
Answer 8

It depends on the resistance; $\tau = 1/(RC)$.

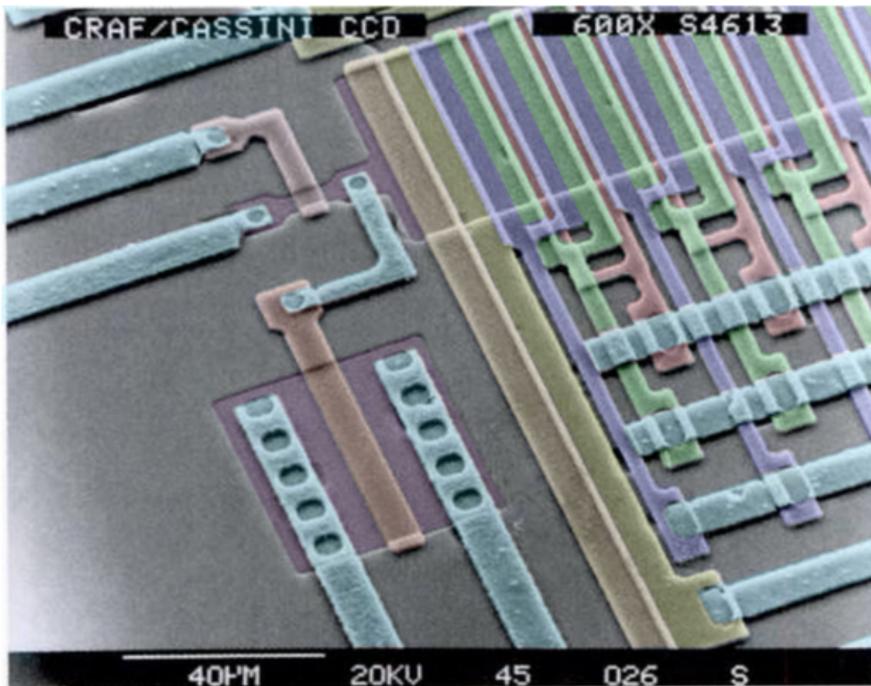
If $C \sim 0.1\text{pF}$ and $R \gg 100M\Omega$, $\tau \gg 10\mu\text{s}$. So if we use a **large** resistor we can "freeze" the kTC noise.



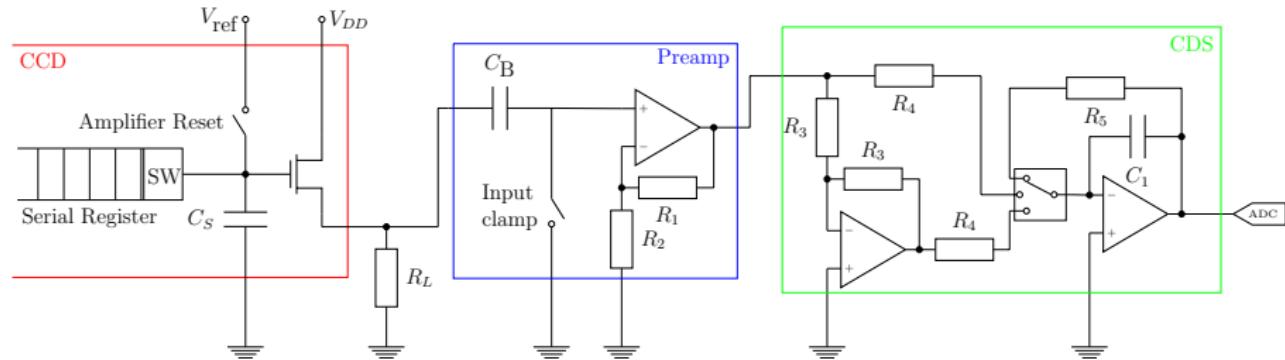
Real CCDs



Real CCDs



CCD Video Chain

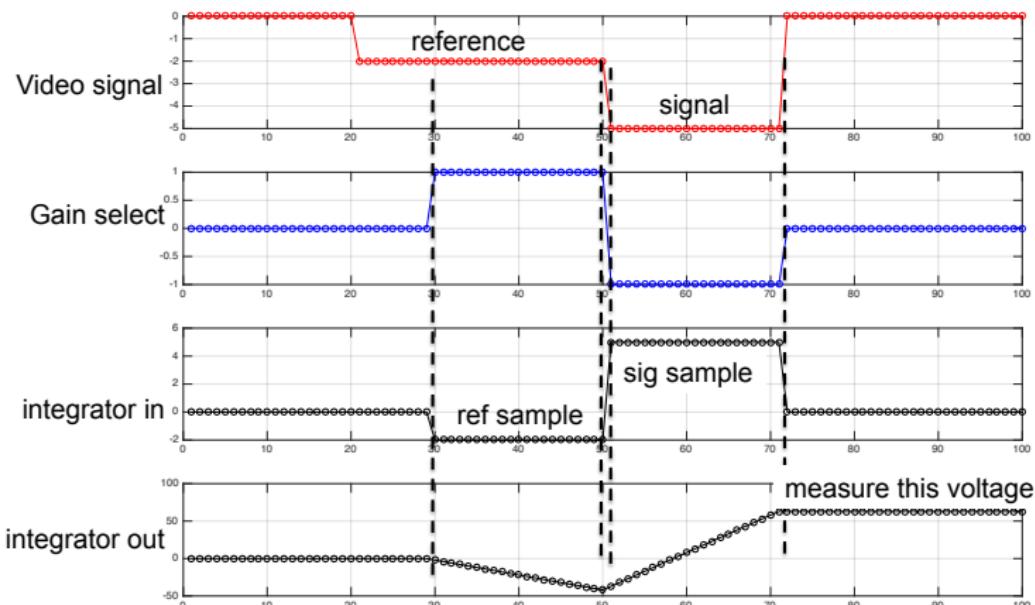


Correlated Double Sampling

We can exploit this by measuring the capacitor *twice* but only resetting it *once*:
Double Correlated Sampling (CDS)

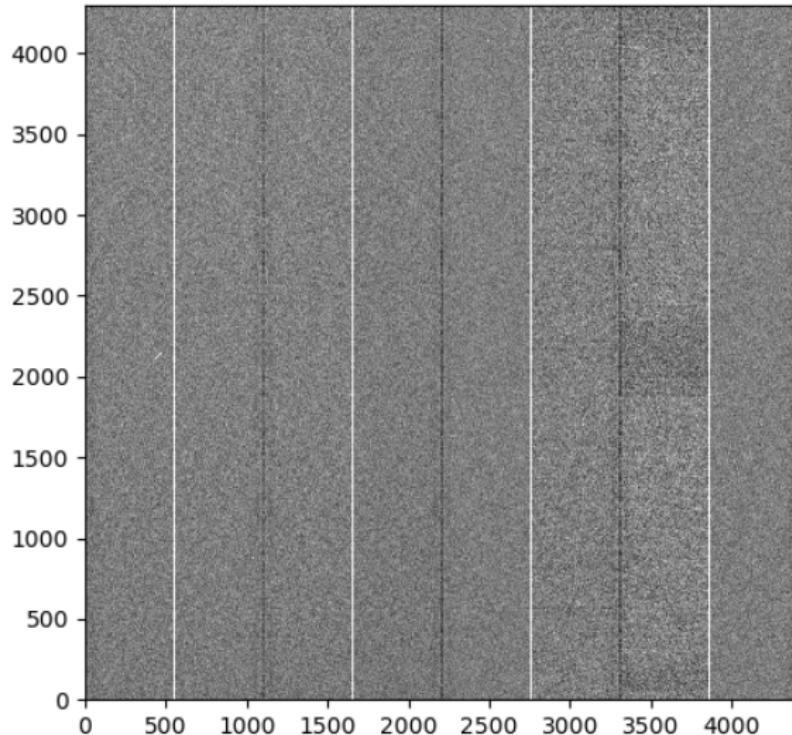
Correlated Double Sampling

We can exploit this by measuring the capacitor *twice* but only resetting it *once*:
Double Correlated Sampling (CDS)

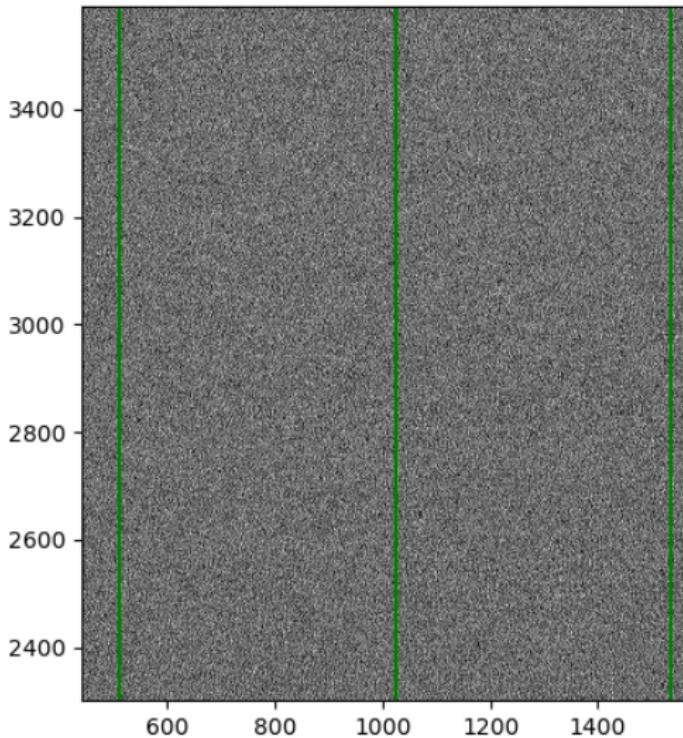


(Credit: Chris Stubbs)

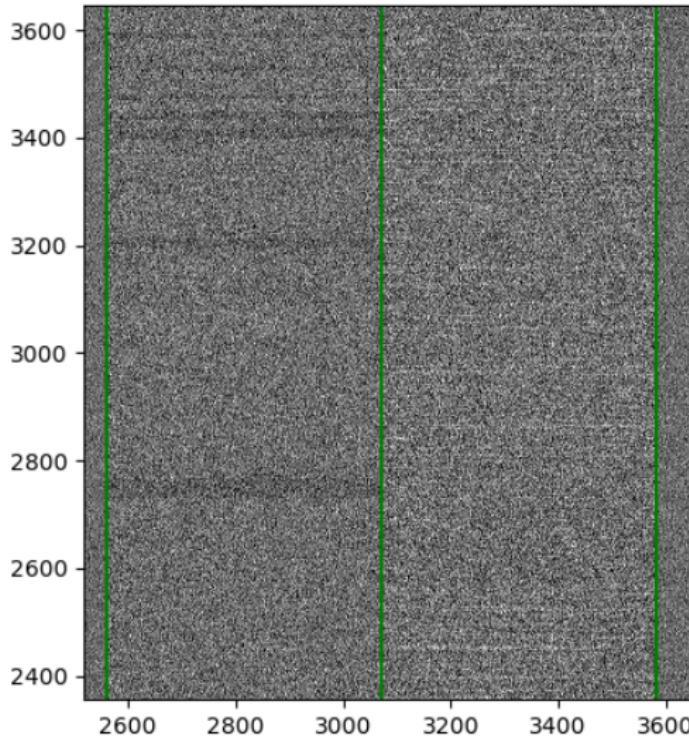
More Examples of CCD Images (all from PFS)



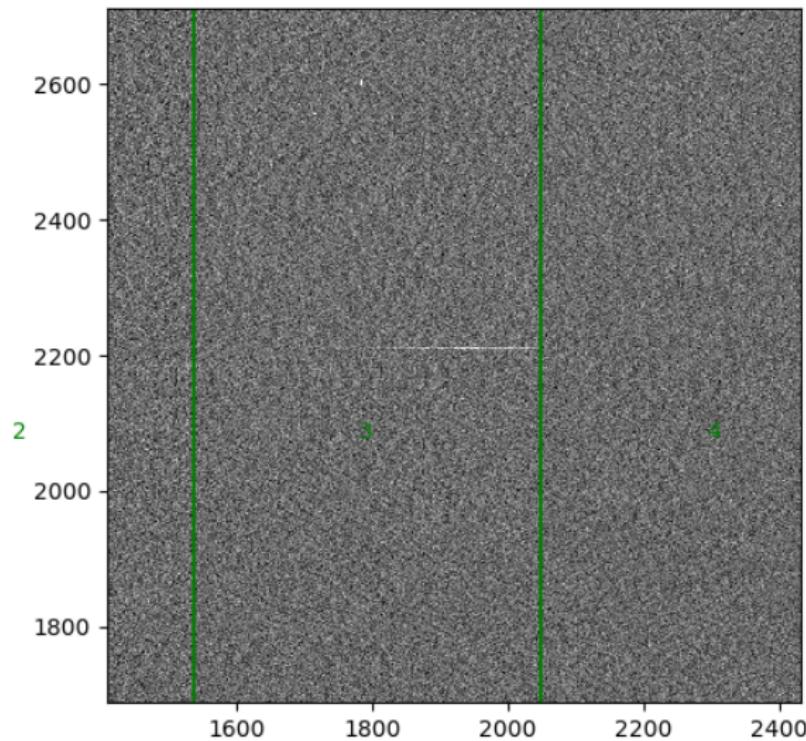
More Examples of CCD Images (all from PFS)



More Examples of CCD Images (all from PFS)



More Examples of CCD Images (all from PFS)



$1/f$ Noise and other non-Thermal Noise

There kTC noise is c. $100e^-$ but fortunately CDS removes almost all of it from our signals.

$1/f$ Noise and other non-Thermal Noise

There kTC noise is c. $100e^-$ but fortunately CDS removes almost all of it from our signals.

There is also (white, Gaussian) Johnson noise ($\sqrt{4kTR}$ per $\sqrt{\text{Hz}}$) from resistors.

$1/f$ Noise and other non-Thermal Noise

There kTC noise is c. $100e^-$ but fortunately CDS removes almost all of it from our signals.

There is also (white, Gaussian) Johnson noise ($\sqrt{4kTR}$ per $\sqrt{\text{Hz}}$) from resistors.

Physical processes related to trap density and location within the output FET's channel generate noise with a power spectrum falling as $\sim 1/f$.

$1/f$ Noise and other non-Thermal Noise

There kTC noise is c. $100e^-$ but fortunately CDS removes almost all of it from our signals.

There is also (white, Gaussian) Johnson noise ($\sqrt{4kTR}$ per $\sqrt{\text{Hz}}$) from resistors.

Physical processes related to trap density and location within the output FET's channel generate noise with a power spectrum falling as $\sim 1/f$.

The horizontal features in the PFS devices are due to some weirdness in the electronics.

$1/f$ Noise and other non-Thermal Noise

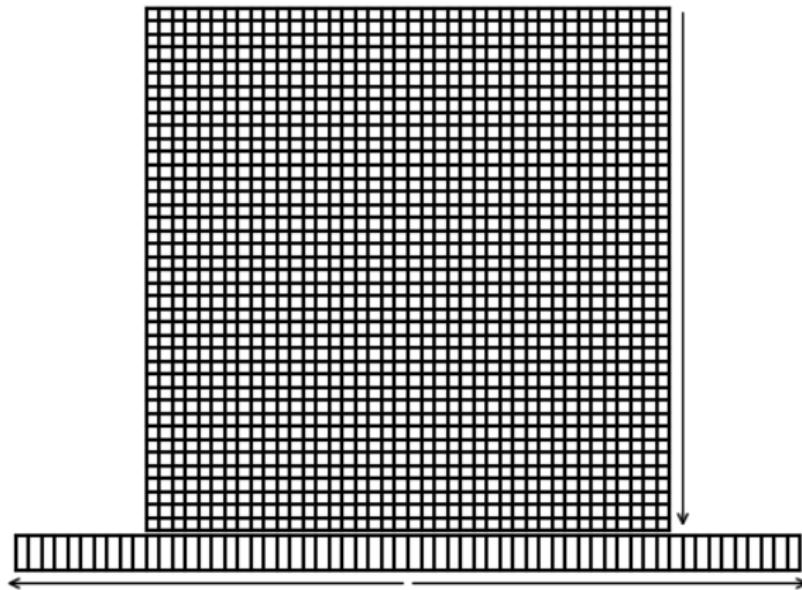
There kTC noise is c. $100e^-$ but fortunately CDS removes almost all of it from our signals.

There is also (white, Gaussian) Johnson noise ($\sqrt{4kTR}$ per $\sqrt{\text{Hz}}$) from resistors.

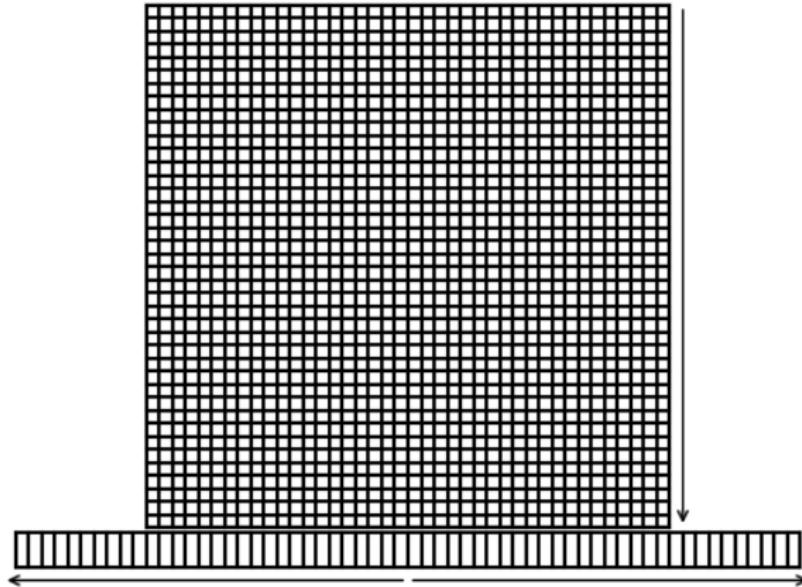
Physical processes related to trap density and location within the output FET's channel generate noise with a power spectrum falling as $\sim 1/f$.

The horizontal features in the PFS devices are due to some weirdness in the electronics. Jim Gunn says he's going to fix it...

Crosstalk

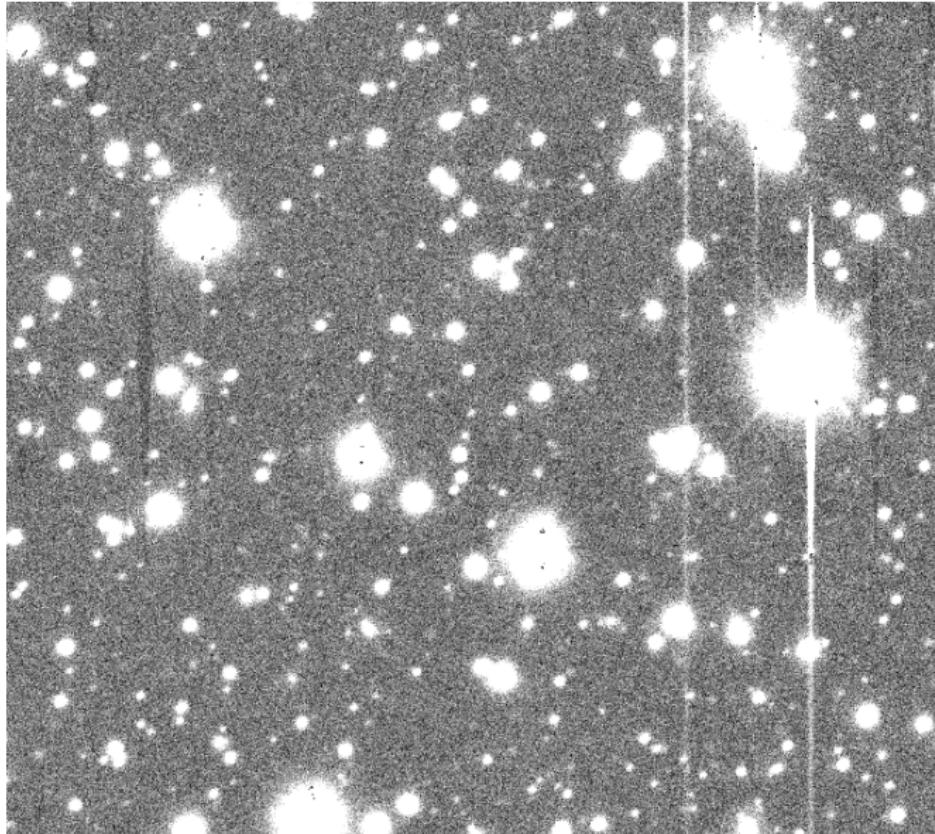


Crosstalk

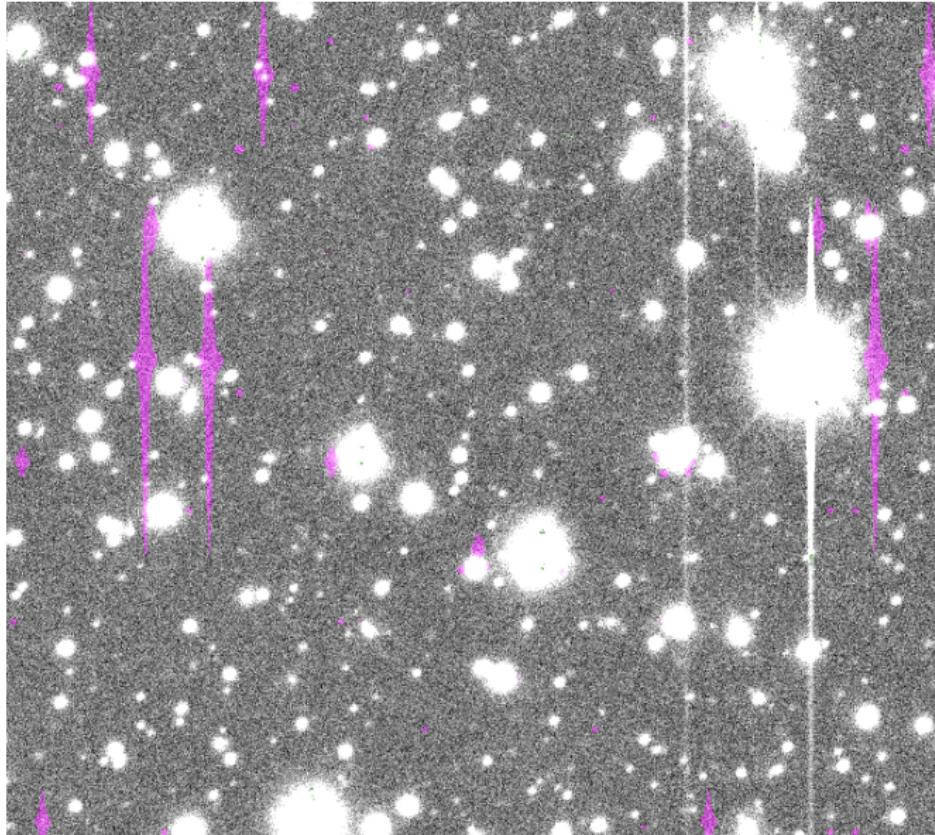


One might worry that the two amplifiers would affect each other.

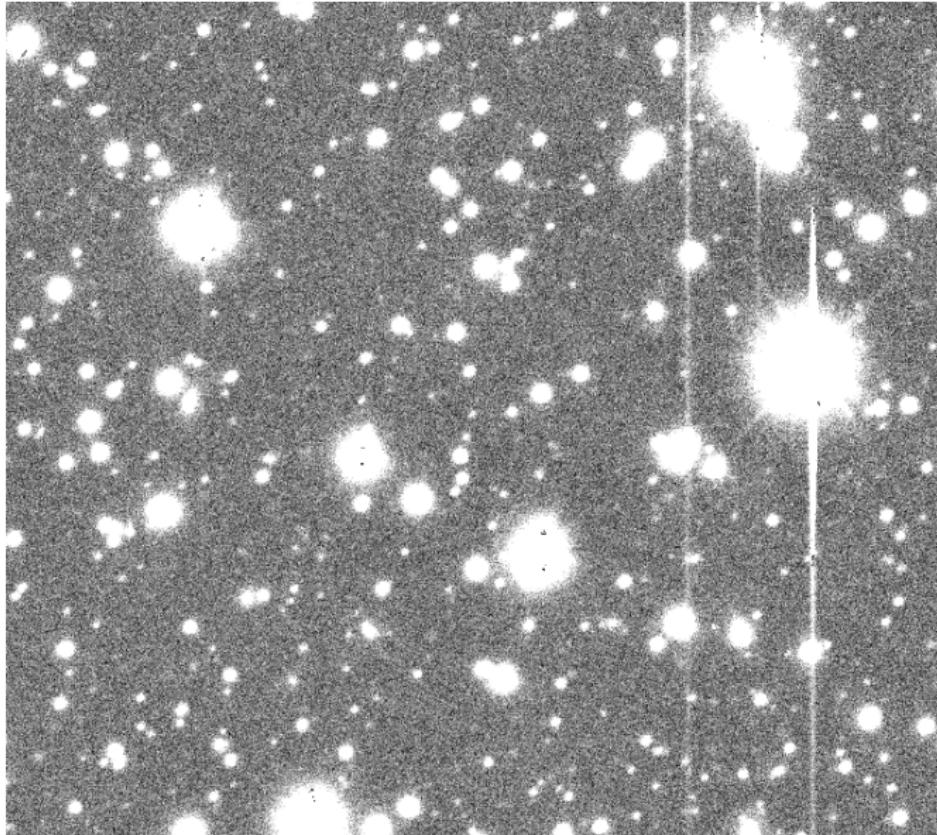
Crosstalk in HSC



Crosstalk in HSC



Crosstalk in HSC

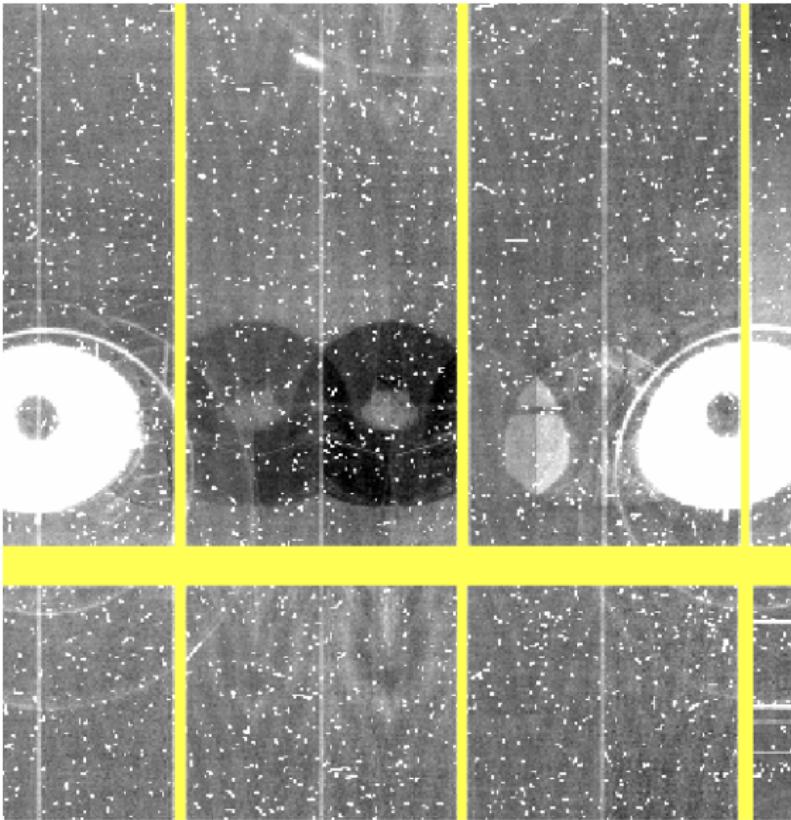


Crosstalk Coefficients for HSC

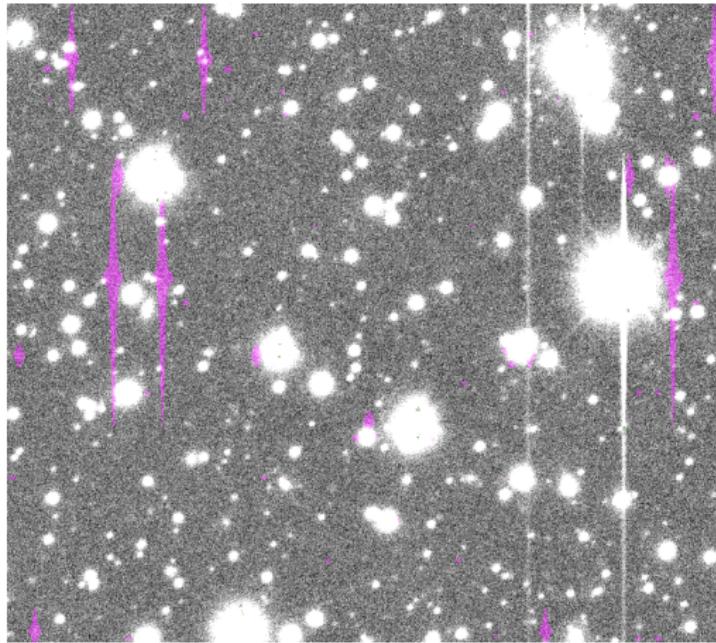
amplIn	ampOut			
	0	1	2	3
0		-125 ± 12	-149 ± 3	-156 ± 1
1	-124 ± 17		-132 ± 2	-157 ± 3
2	-171 ± 2	-134 ± 13		-153 ± 13
3	-157 ± 6	-151 ± 5	-137 ± 2	

Table: Crosstalk estimated from visits HSC 902476 and 902478 (in ppm, i.e. $\times 10^6$).

Crosstalk in HSC

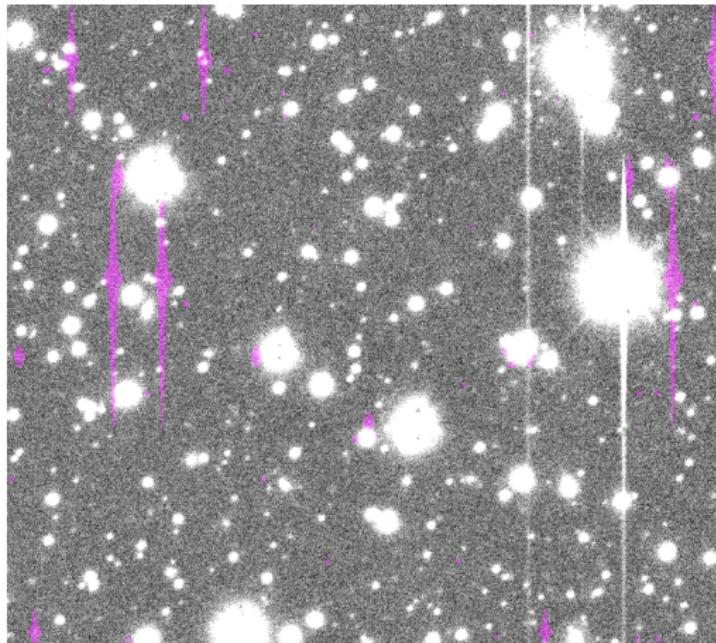


Saturation



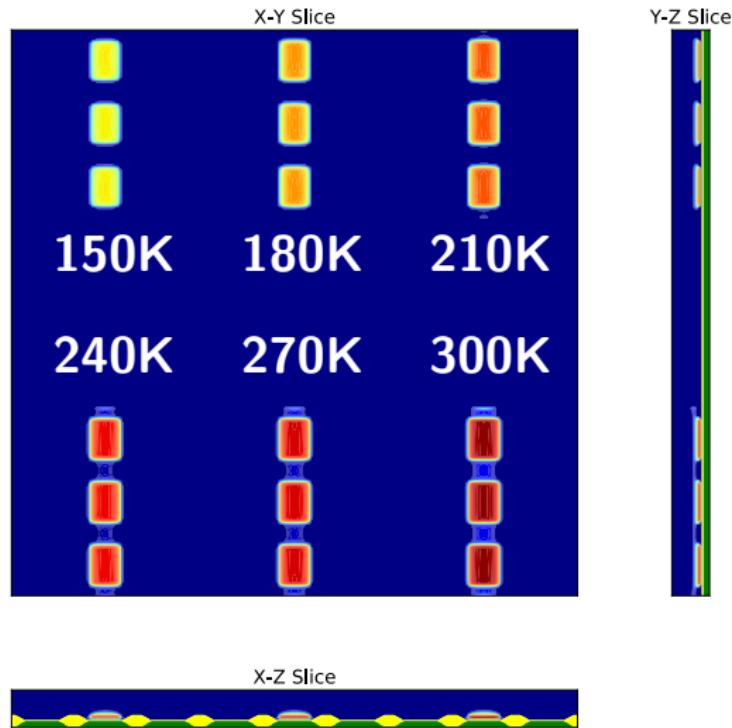
The bright stars have streaks up-and-down the detector.

Saturation



The bright stars have streaks up-and-down the detector. The pixels are unable to keep the electrons that they are given localised.

Saturation



The electrons escape once there are more than c. $2\text{e}5$ in a pixel.

Question 9: Are electrons lost?

Do the electrons disappear? Why can't I just add them up to recover the star's flux?

Answer 9

- They don't usually disappear (unless you push charge up to the surface)
- If the bleed column extends to the top or bottom of the CCD you have problems
- The amplifier non-linearity may be badly characterised at high flux levels
- If the gain is set too low you may saturate the A/D

Question 10: Poisson Noise

If someone gives me a raw CCD image with a mean level of 10200 DN/pixel what will the variance be?

Answer 10

It's a Poisson process, so the variance is 10200, right?

Answer 10

It's a Poisson process, so the variance is 10200, right? Wrong. The raw data has a smallish offset (bias) added to the video signal.

Answer 10

It's a Poisson process, so the variance is 10200, right? Wrong. The raw data has a smallish offset (bias) added to the video signal. An offset also results from stray capacitances between the serial register and the sense node.

Answer 10

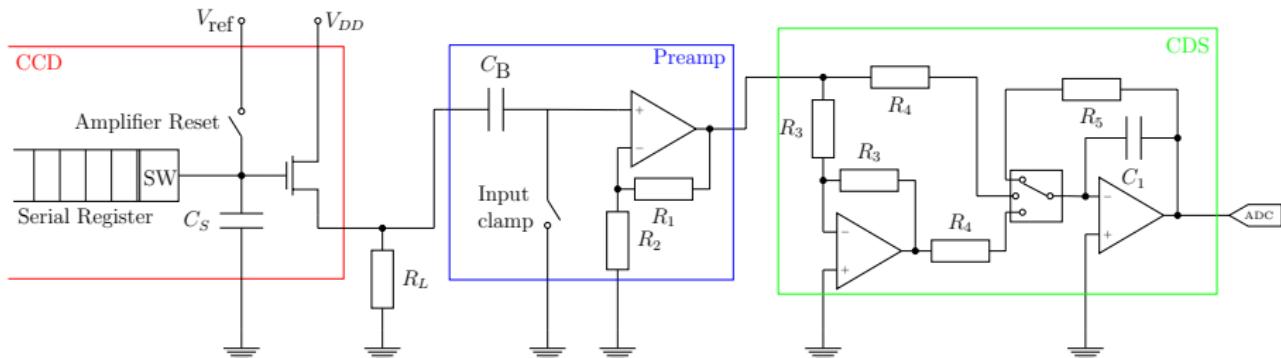
It's a Poisson process, so the variance is 10200, right? Wrong. The raw data has a smallish offset (bias) added to the video signal. An offset also results from stray capacitances between the serial register and the sense node.

OK, so we subtracted an estimate of the bias level. If the image has a level of 10000 DN/pixel, the variance will be 10000, right?

Answer 10

It's a Poisson process, so the variance is 10200, right? Wrong. The raw data has a smallish offset (bias) added to the video signal. An offset also results from stray capacitances between the serial register and the sense node.

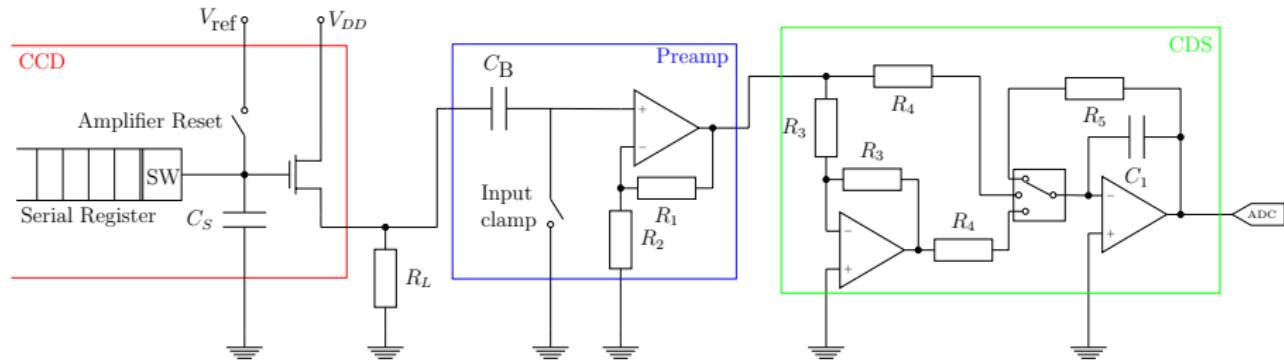
OK, so we subtracted an estimate of the bias level. If the image has a level of 10000 DN/pixel, the variance will be 10000, right? Wrong.



At least 3 parts of that circuit have some gain, g . So the variance is $10000/g$.

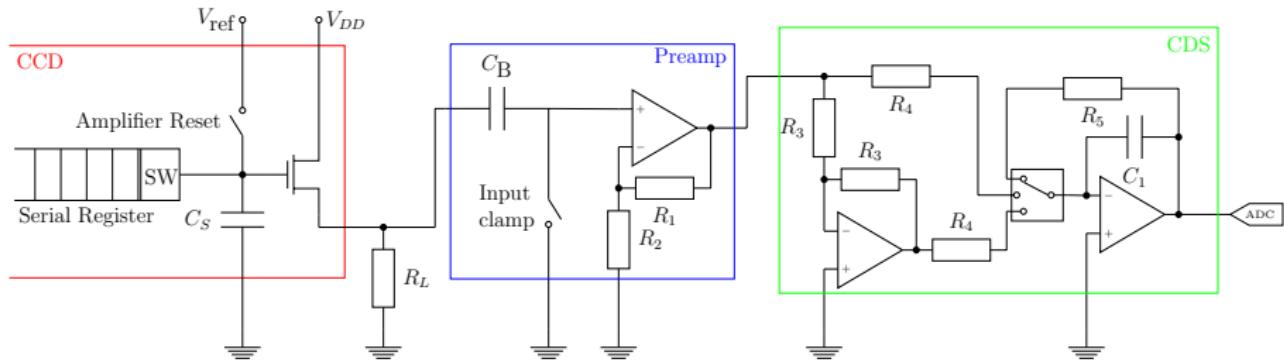
Non-linearity

You might also be worrying about the linearity of all those electronics.



Non-linearity

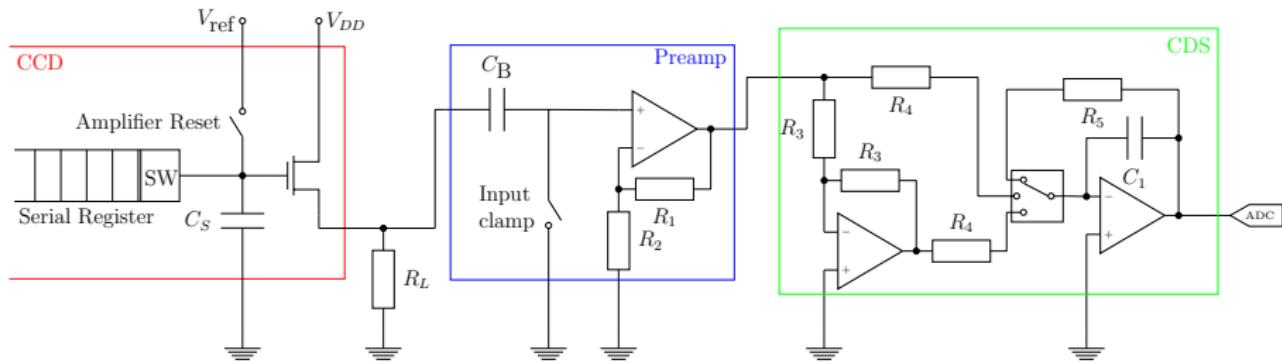
You might also be worrying about the linearity of all those electronics.



Actually they're usually pretty good.

Non-linearity

You might also be worrying about the linearity of all those electronics.



Actually they're usually pretty good. The problem is the transconductance of the output FET and the varying capacitance of the sense node. These are both c. 1% and have opposite signs -- but the result is that CCDs do show non-linear behaviour (i.e. the gain is a function of intensity).

Fixed Pattern Noise

What do we do if all the pixels are not equally sensitive (say $N(1, 0.01^2)$)? If we measure the fractional variance of an image there will be a floor of 1%.

Fixed Pattern Noise

What do we do if all the pixels are not equally sensitive (say $N(1, 0.01^2)$)? If we measure the fractional variance of an image there will be a floor of 1%. The usual solution is to divide your data by a *flat field* image of a screen uniformly illuminated with a bright light. Now the fractional variance goes to zero as you beat the photon noise.

Fixed Pattern Noise

What do we do if all the pixels are not equally sensitive (say $N(1, 0.01^2)$)? If we

measure the fractional variance of an image there will be a floor of 1%.

The usual solution is to divide your data by a *flat field* image of a screen uniformly illuminated with a bright light. Now the fractional variance goes to zero as you beat the photon noise.

But what happens if the pixels are actually all really equally sensitive, but have different sizes?

Fixed Pattern Noise

What do we do if all the pixels are not equally sensitive (say $N(1, 0.01^2)$)? If we measure the fractional variance of an image there will be a floor of 1%. The usual solution is to divide your data by a *flat field* image of a screen uniformly illuminated with a bright light. Now the fractional variance goes to zero as you beat the photon noise.

But what happens if the pixels are actually all really equally sensitive, but have different sizes?

Answer: Using a flat field gets you the right answer for surface brightness measurements, but you get object measurements *wrong*.

Fixed Pattern Noise

What do we do if all the pixels are not equally sensitive (say $N(1, 0.01^2)$)? If we measure the fractional variance of an image there will be a floor of 1%. The usual solution is to divide your data by a *flat field* image of a screen uniformly illuminated with a bright light. Now the fractional variance goes to zero as you beat the photon noise.

But what happens if the pixels are actually all really equally sensitive, but have different sizes?

Answer: Using a flat field gets you the right answer for surface brightness measurements, but you get object measurements *wrong*.

You can imagine forward modelling to deal with this but it's nasty/expensive --- my whole discussion of why the PSF includes the pixel breaks down if every pixel is special.

Summary: Noise in Images

- Detector noise
 - ▶ reset noise (removed by CDS)
 - ▶ Johnson noise (sub-dominant by careful circuit design)
 - ▶ Analogue-Digital Converter (ADC) noise (buy a better ADC)
 - ▶ $1/f$ noise from the output FET (buy a better CCD)
- Photon noise
- Crosstalk (buy a better electronic engineer and fix the rest in software)
- Fixed-pattern noise

Summary: Noise in Images

- Detector noise
 - ▶ reset noise (removed by CDS)
 - ▶ Johnson noise (sub-dominant by careful circuit design)
 - ▶ Analogue-Digital Converter (ADC) noise (buy a better ADC)
 - ▶ $1/f$ noise from the output FET (buy a better CCD)
- Photon noise
- Crosstalk (buy a better electronic engineer and fix the rest in software)
- Fixed-pattern noise

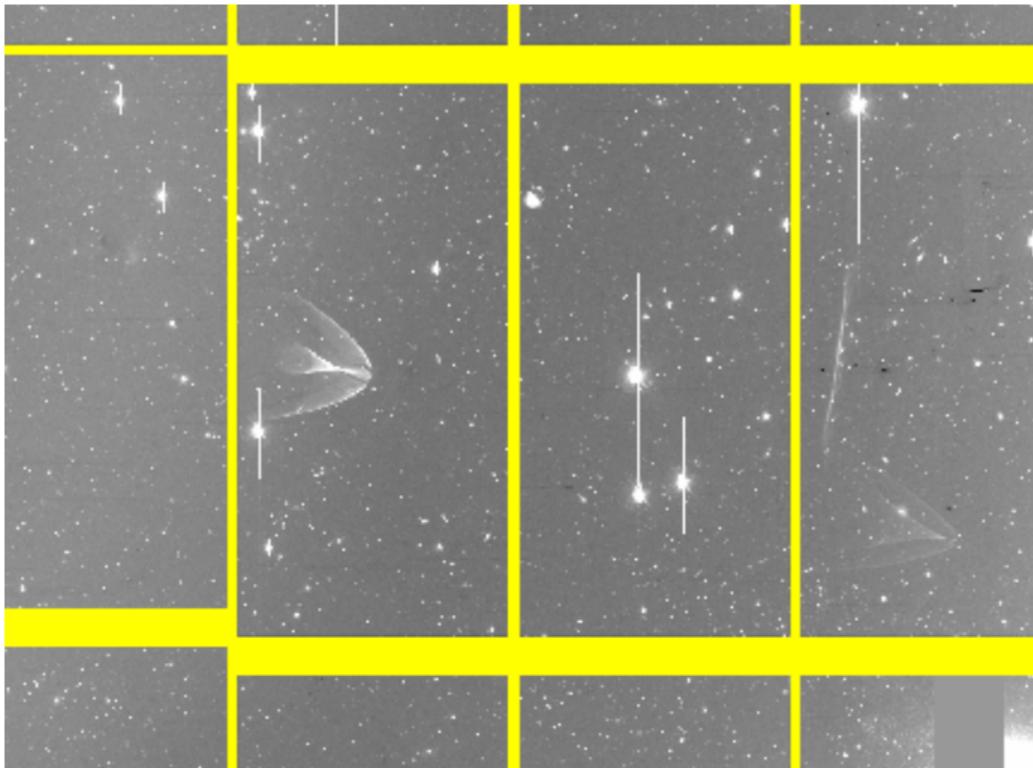
With careful circuit design we can keep the detector noise down to a few electrons ($8e^-$ for LSST; $2-3e^-$ for PFS). We then choose exposure times long enough that the photon noise dominates.

Summary: Noise in Images

- Detector noise
 - ▶ reset noise (removed by CDS)
 - ▶ Johnson noise (sub-dominant by careful circuit design)
 - ▶ Analogue-Digital Converter (ADC) noise (buy a better ADC)
 - ▶ $1/f$ noise from the output FET (buy a better CCD)
- Photon noise
- Crosstalk (buy a better electronic engineer and fix the rest in software)
- Fixed-pattern noise

With careful circuit design we can keep the detector noise down to a few electrons ($8e^-$ for LSST; $2-3e^-$ for PFS). We then choose exposure times long enough that the photon noise dominates. *N.b.* this doesn't work in the X-ray; but you get lots of electrons/photon.

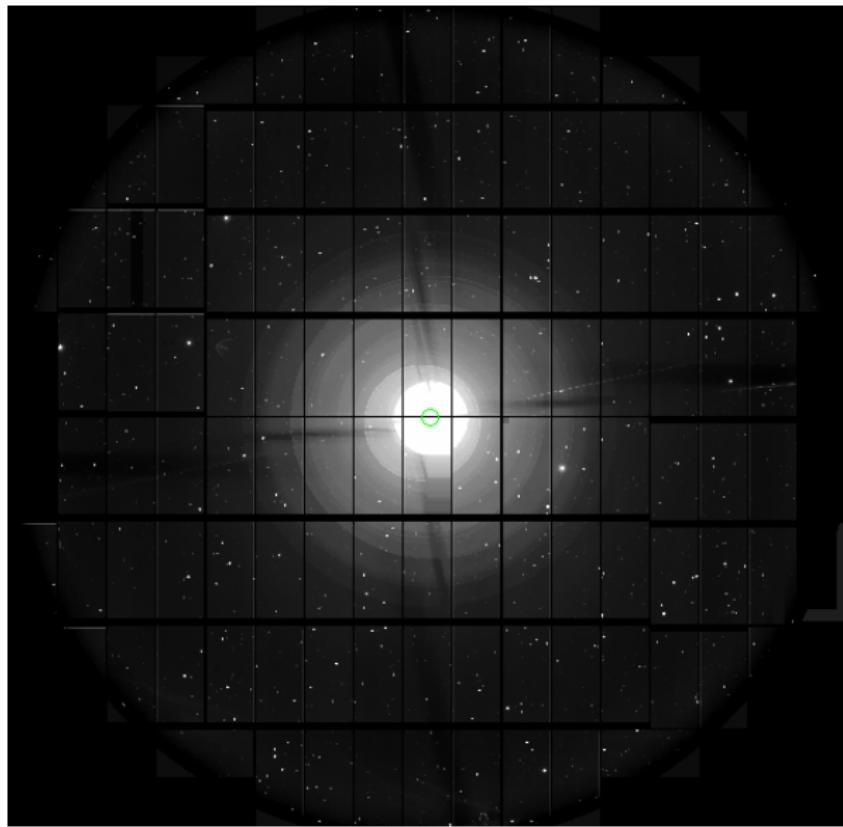
Ghosties and Ghoulies



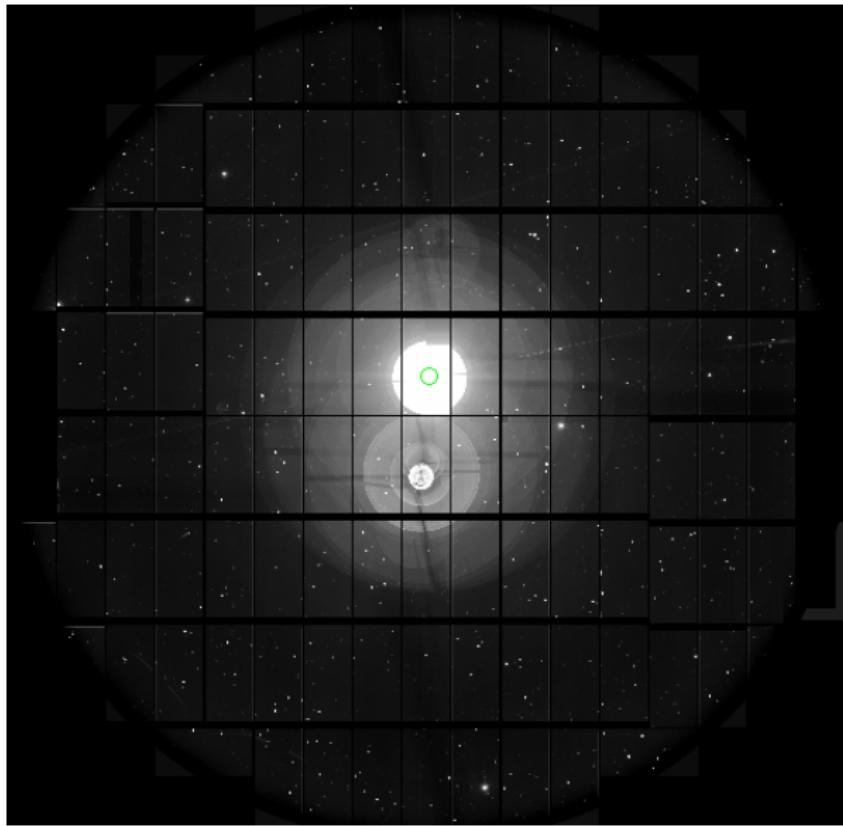
Arcturus (i \sim -0.6)

Jim Gunn and I imaged the Hokule`a with HSC

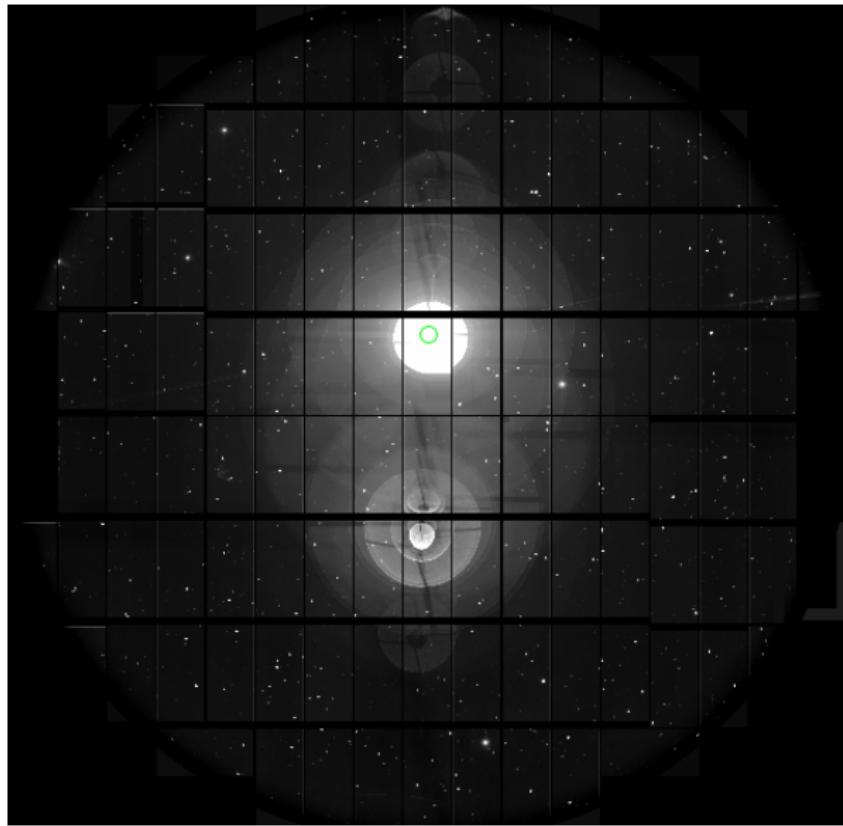
Arcturus ($i \sim -0.6$)



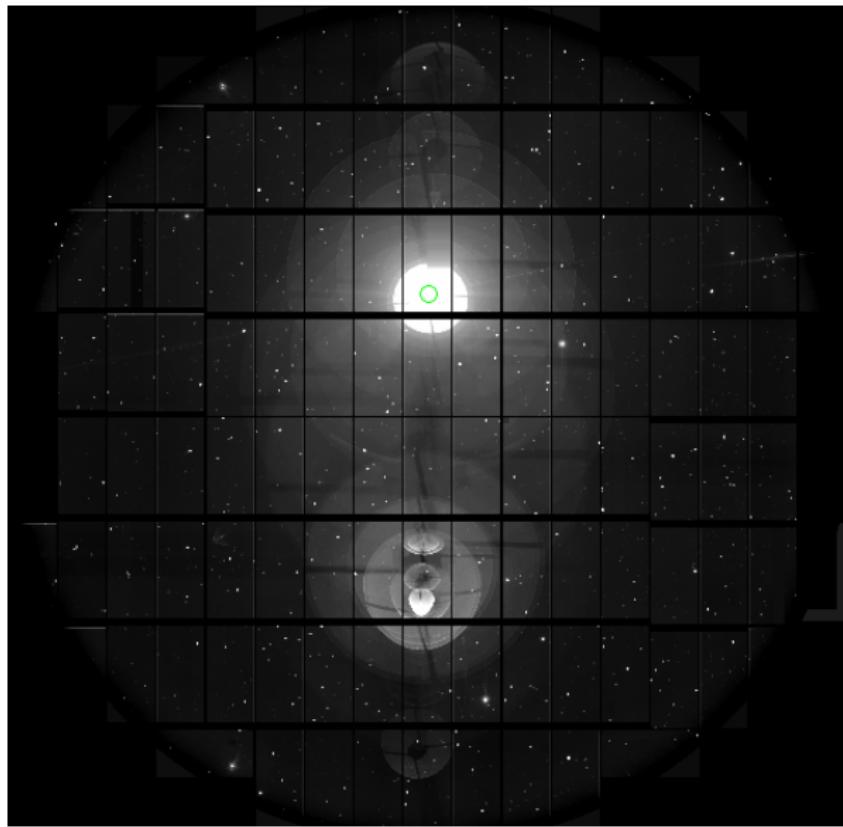
Arcturus ($i \sim -0.6$)



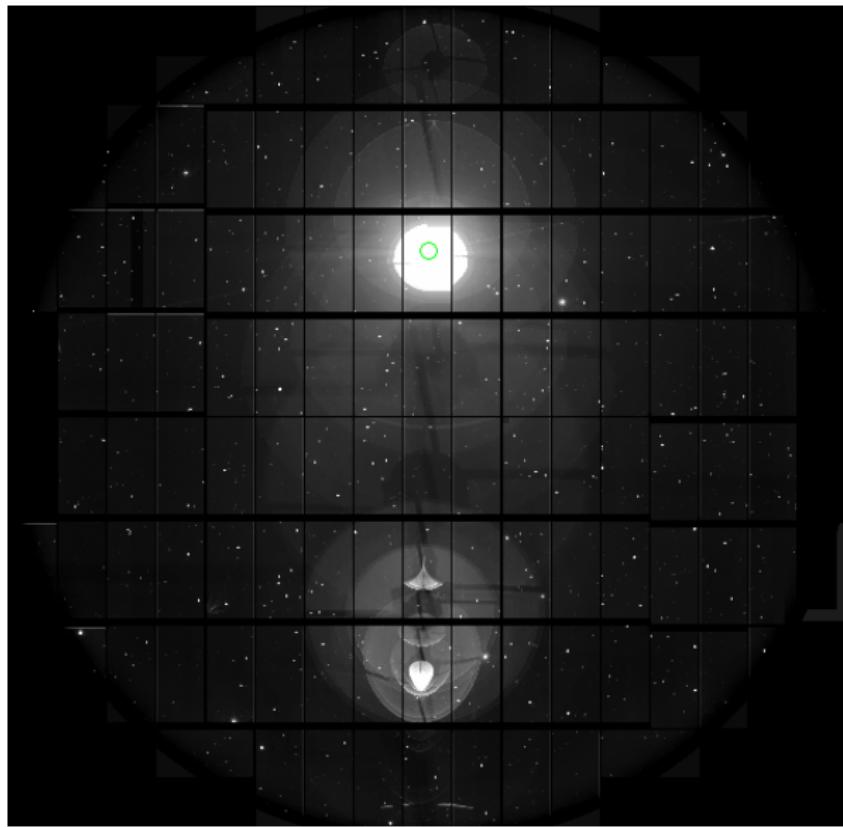
Arcturus ($i \sim -0.6$)



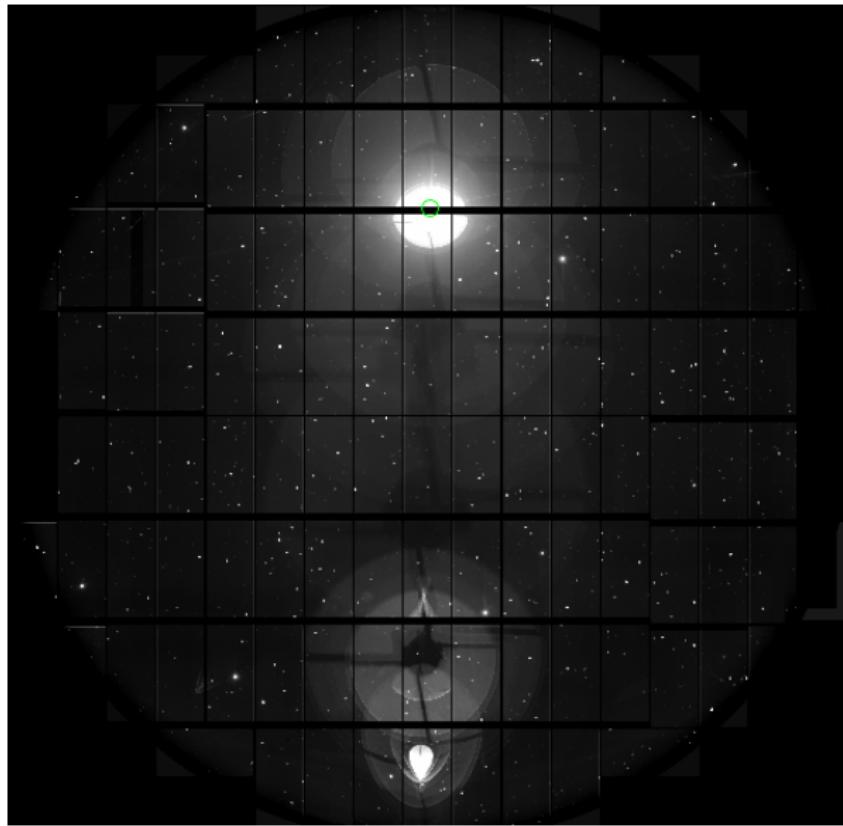
Arcturus ($i \sim -0.6$)



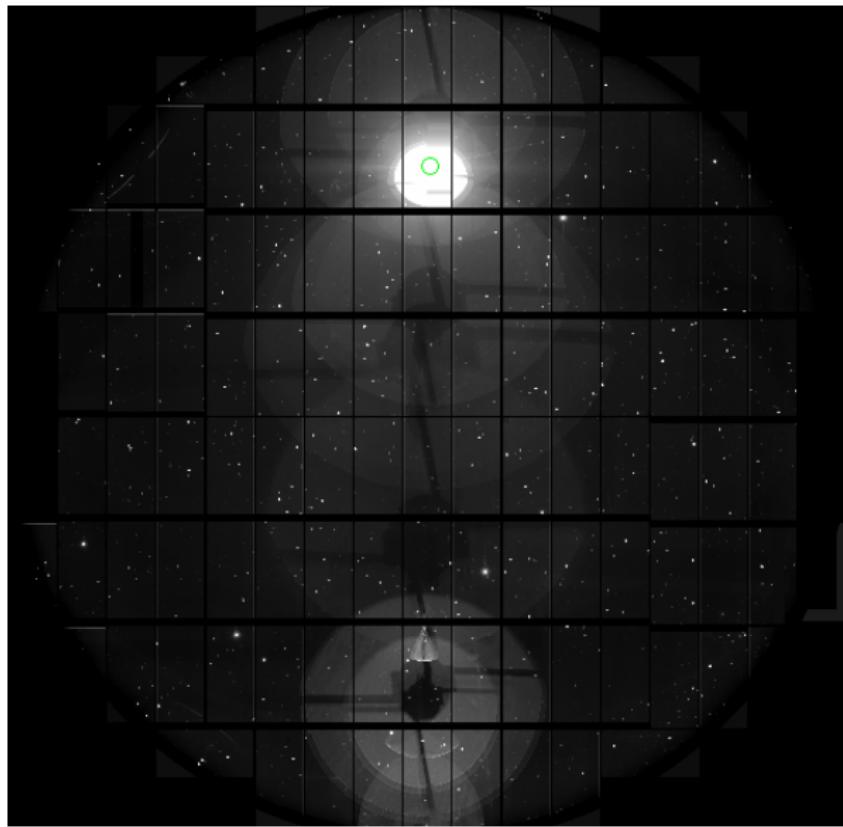
Arcturus ($i \sim -0.6$)



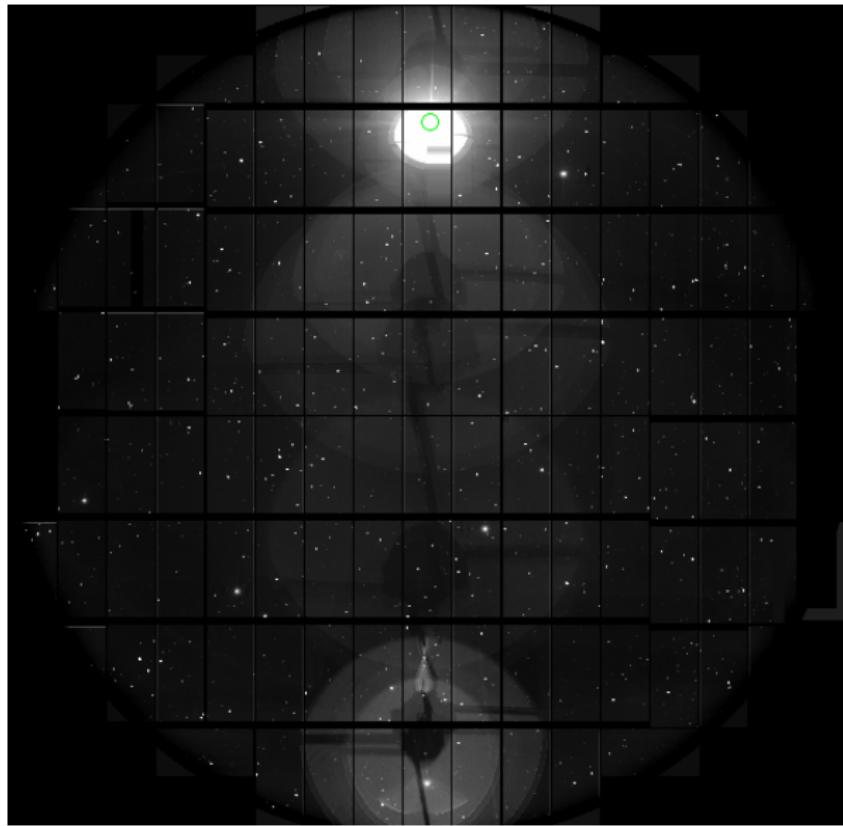
Arcturus ($i \sim -0.6$)



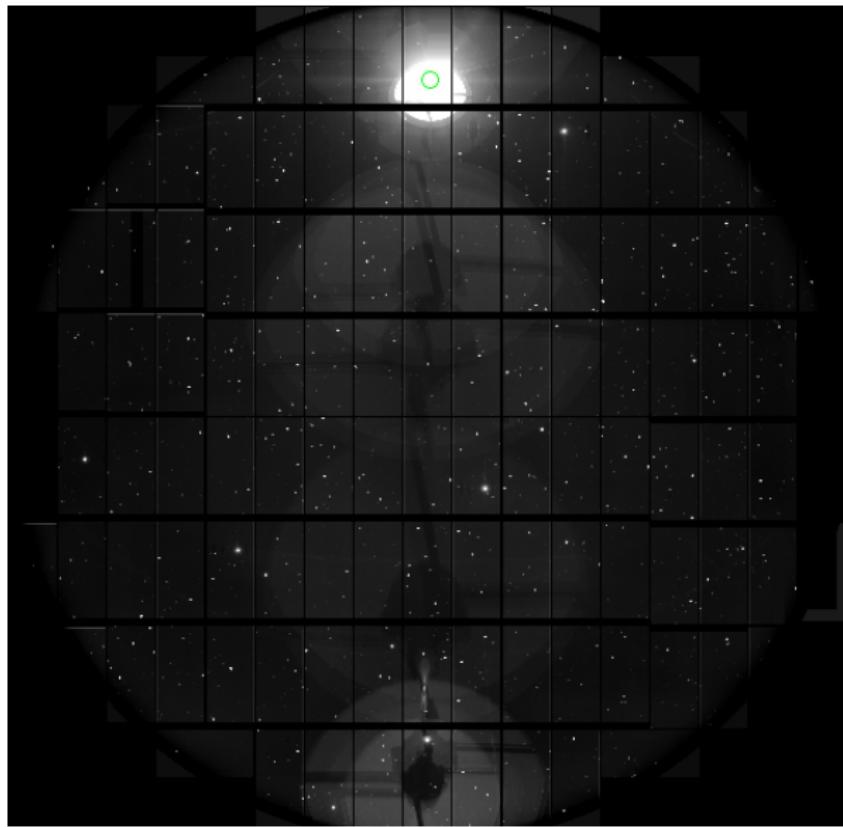
Arcturus ($i \sim -0.6$)



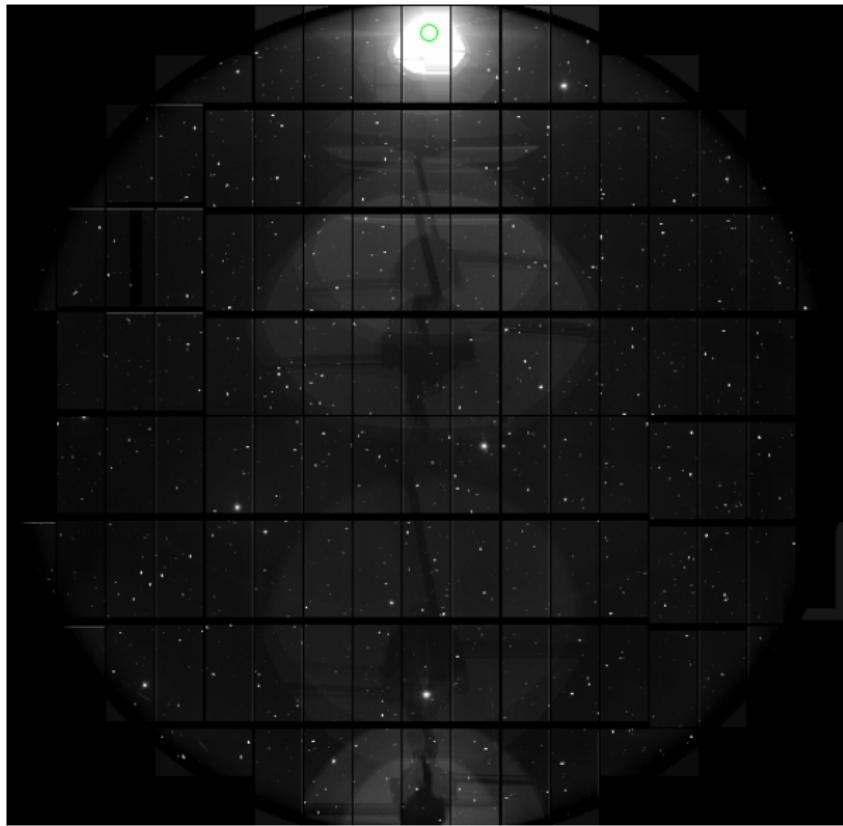
Arcturus ($i \sim -0.6$)



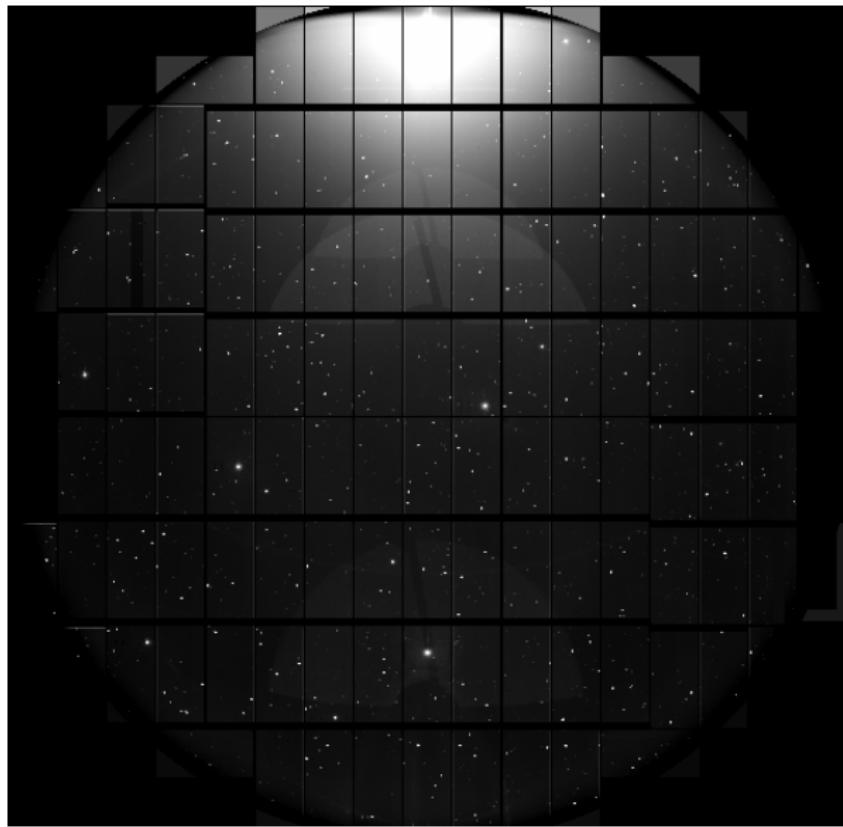
Arcturus ($i \sim -0.6$)



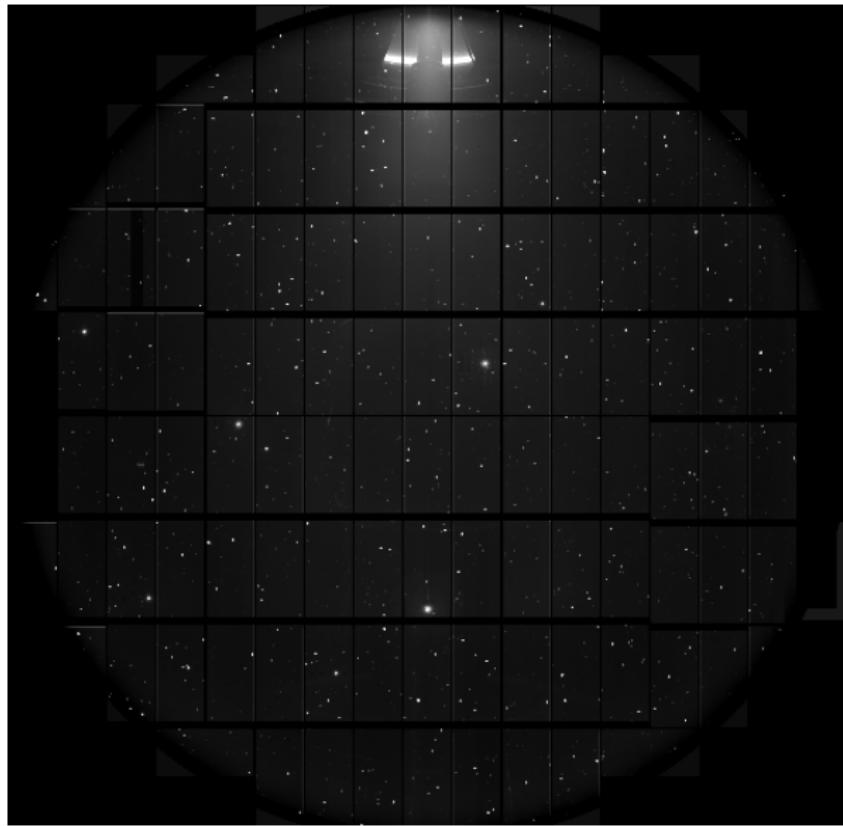
Arcturus ($i \sim -0.6$)



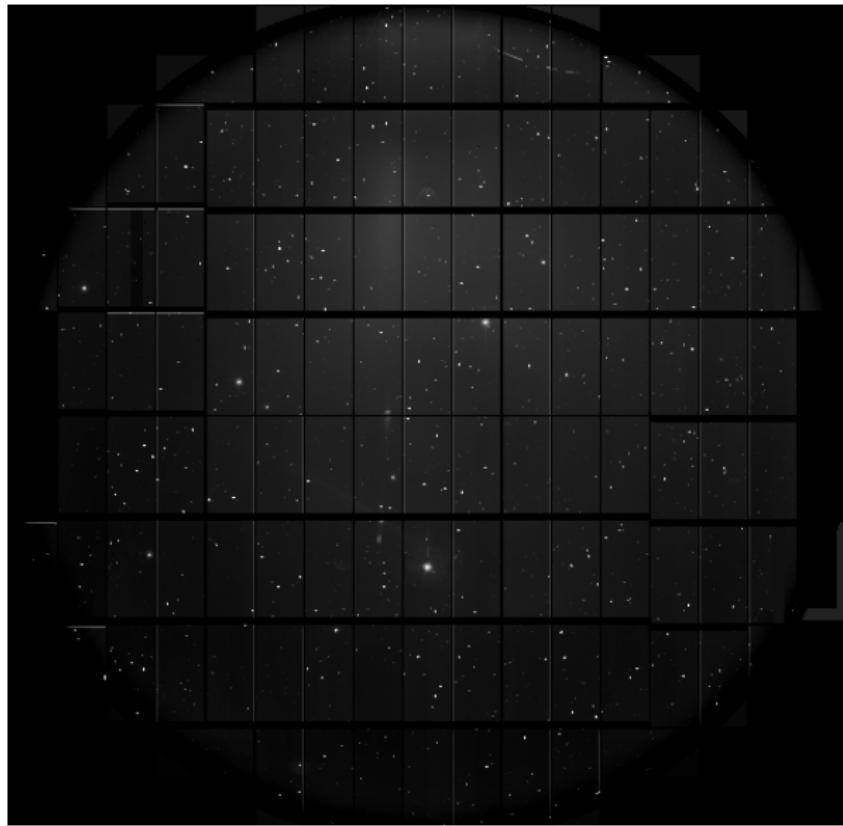
Arcturus ($i \sim -0.6$)



Arcturus ($i \sim -0.6$)



Arcturus ($i \sim -0.6$)



Question 11: How should we measure the gain?

Answer 11

Take two images with the same flux level, I_1 and I_2 , and calculate

$$\frac{1}{g} = \left\langle \frac{(I_1 - I_2)^2}{I_1 + I_2} \right\rangle$$

Answer 11

Take two images with the same flux level, I_1 and I_2 , and calculate

$$\frac{1}{g} = \left\langle \frac{(I_1 - I_2)^2}{I_1 + I_2} \right\rangle$$

We did this for the HSC detectors:

Level		1850
CCD	Amp	g
1_54	1	2.87
1_54	2	3.02
1_54	3	2.93
1_54	4	2.99
1_55	1	3.68
1_55	2	3.52
1_55	3	3.44
1_55	4	3.46
1_56	1	3.15
...		

Answer 11

Take two images with the same flux level, I_1 and I_2 , and calculate

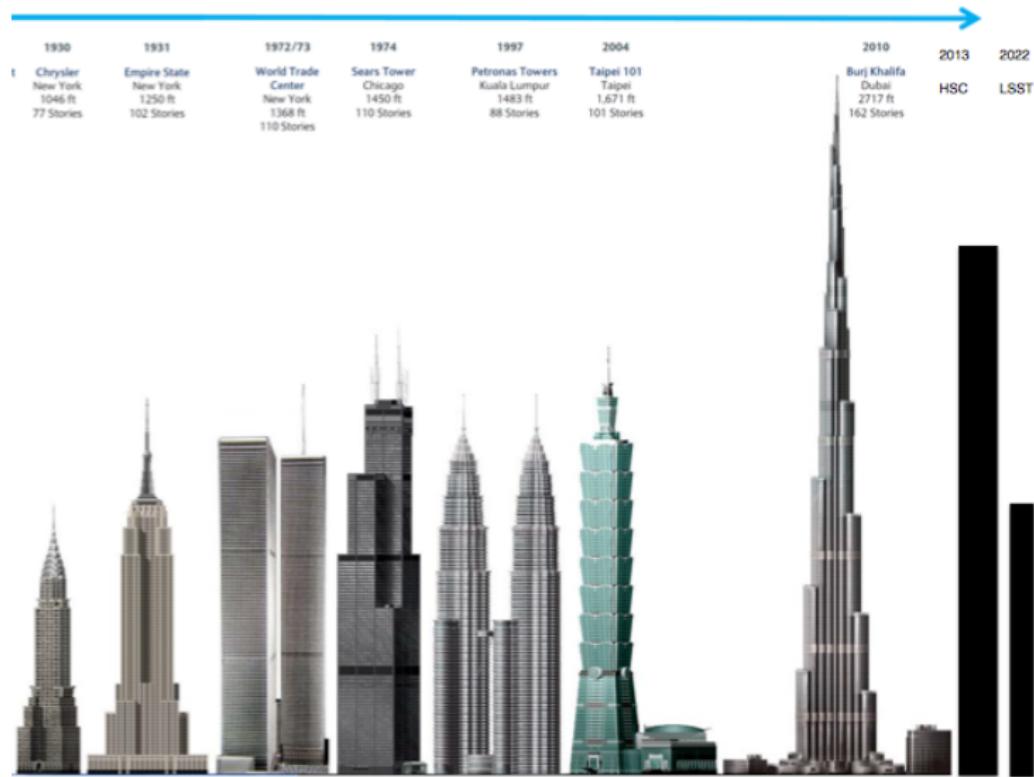
$$\frac{1}{g} = \left\langle \frac{(I_1 - I_2)^2}{I_1 + I_2} \right\rangle$$

We did this for the HSC detectors:

Level CCD	Amp	1850	23500	32500	65000
		<i>g</i>	<i>g</i>	<i>g</i>	<i>g</i>
1_54	1	2.87	3.19	3.21	3.35
1_54	2	3.02	3.20	3.22	3.34
1_54	3	2.93	3.14	3.15	3.26
1_54	4	2.99	3.21	3.24	3.35
1_55	1	3.68	3.92	3.94	4.08
1_55	2	3.52	3.74	3.78	3.91
1_55	3	3.44	3.70	3.72	3.86
1_55	4	3.46	3.69	3.73	3.87
1_56	1	3.15	3.35	3.37	3.46
...					

What went wrong?

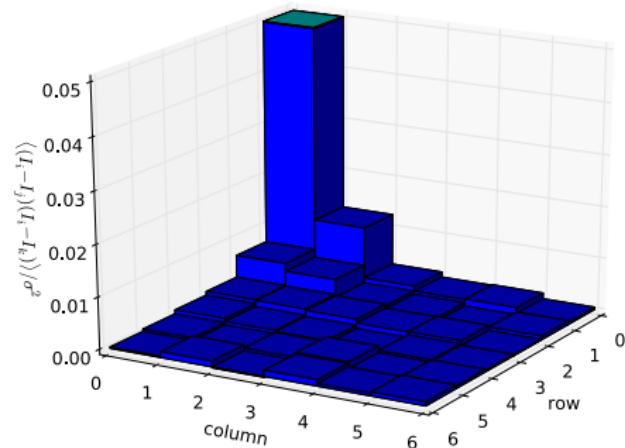
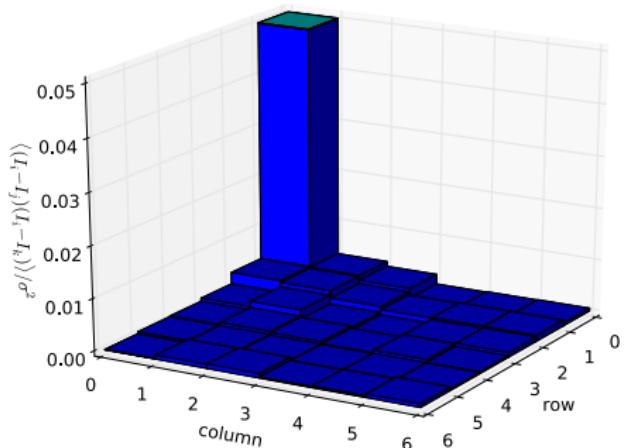
Modern CCDs



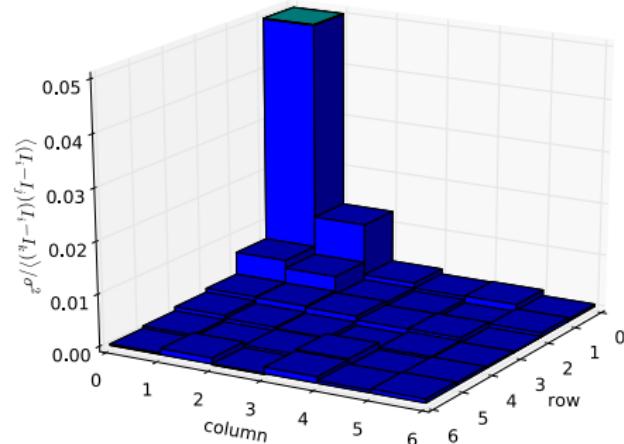
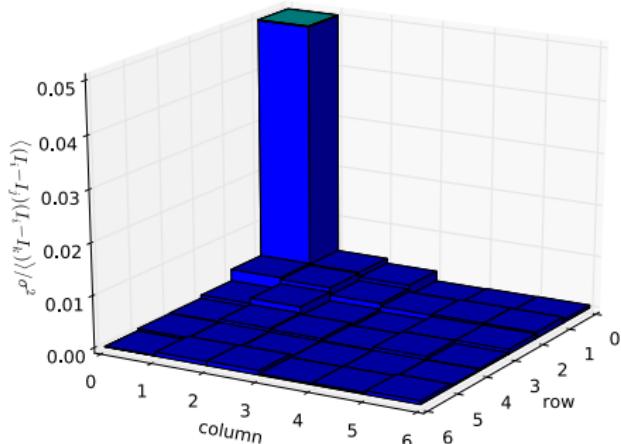
(pixels have correct aspect ratios, but not size)

Flat Field Statistics

Flat Field Statistics

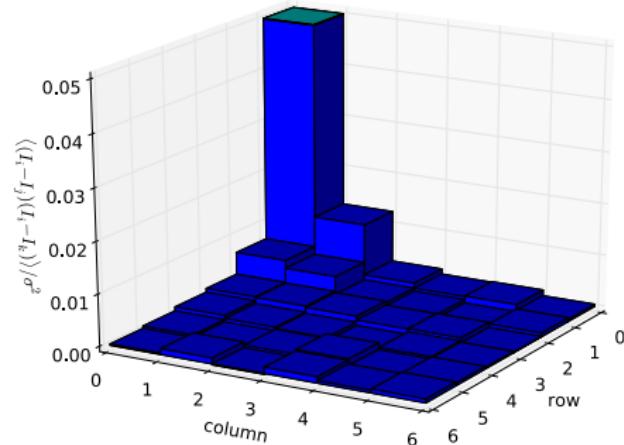
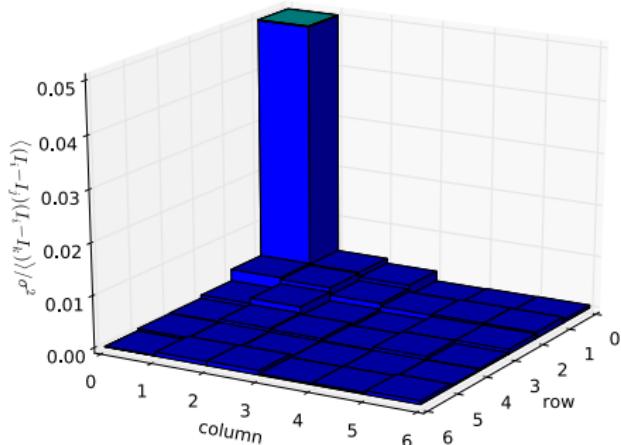


Flat Field Statistics



Correlations in the differences between pairs of flat fields. On the left the mean level is $c. 7500e^-$, on the right $90000e^-$.

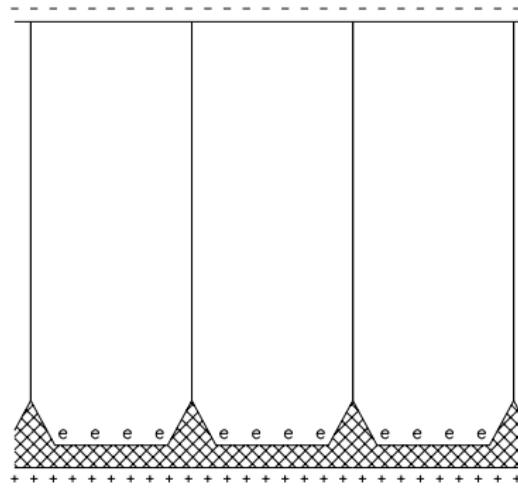
Flat Field Statistics



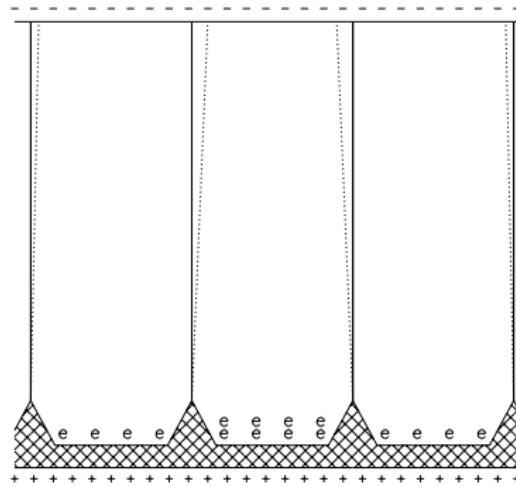
Correlations in the differences between pairs of flat fields. On the left the mean level is $c. 7500e^-$, on the right $90000e^-$.

How did the photons know about each other?

Pixel Correlations

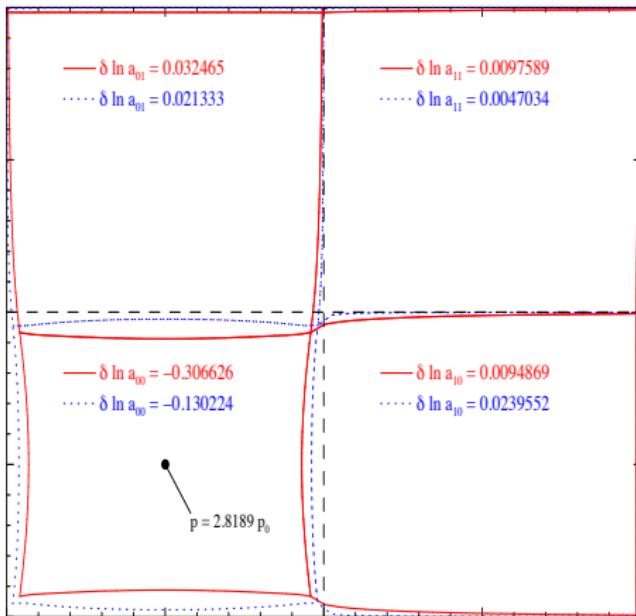


Pixel Correlations



The effective pixel boundaries depend on the charges already in the pixels, and this leads to correlations which increase with flux level; this is why the gain was apparently a function of intensity.

Pixel Correlations



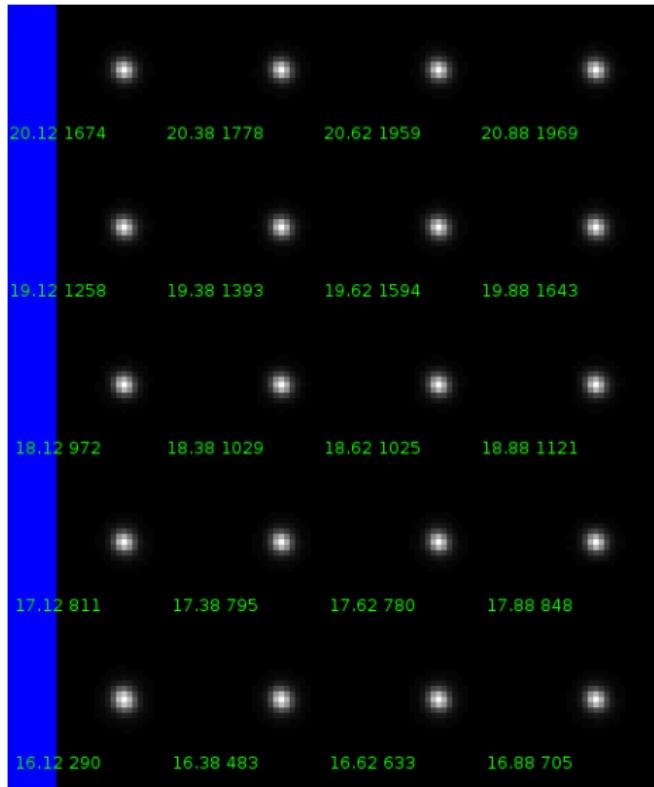
The effective pixel boundaries depend on the charges already in the pixels, and this leads to correlations which increase with flux level; this is why the gain was apparently a function of intensity.

PSF

Those electrostatic effects also affect the PSF.

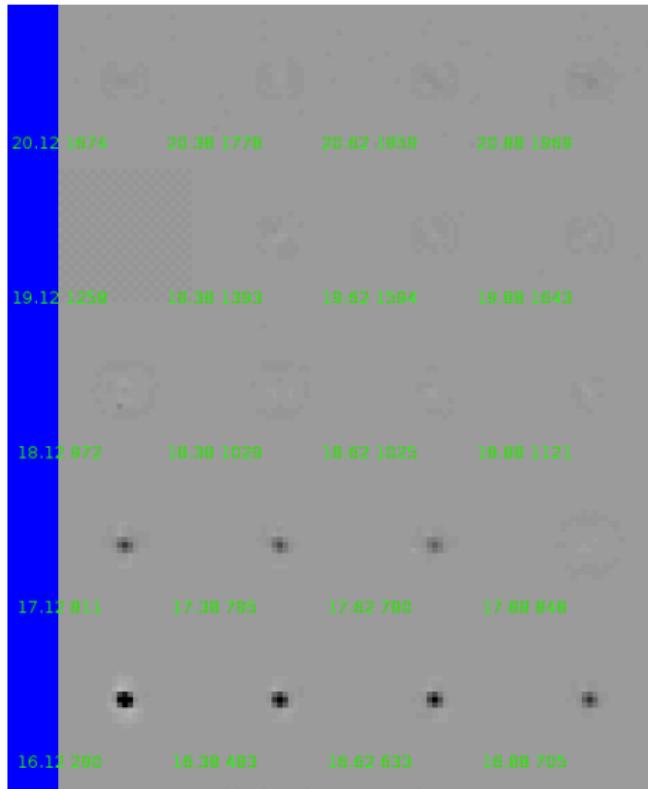
PSF

Those electrostatic effects also affect the PSF.

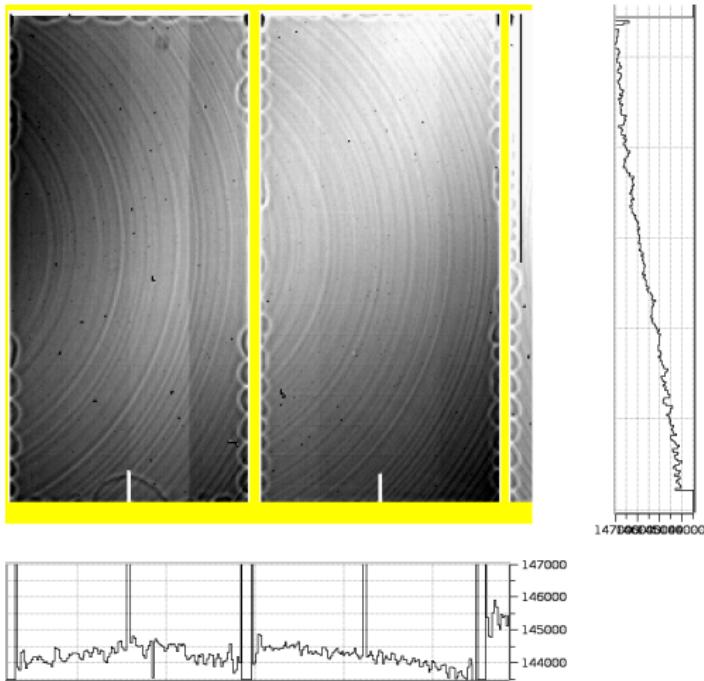


PSF

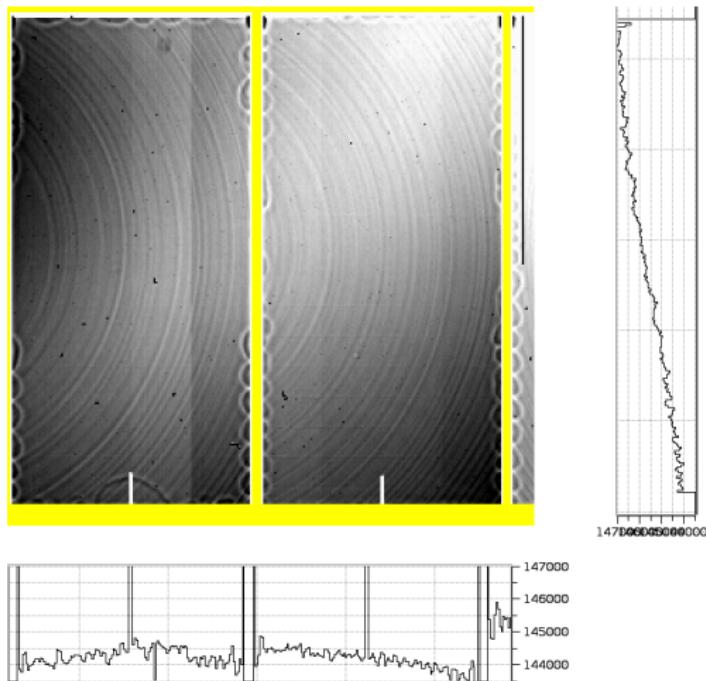
Those electrostatic effects also affect the PSF.



Tree Rings

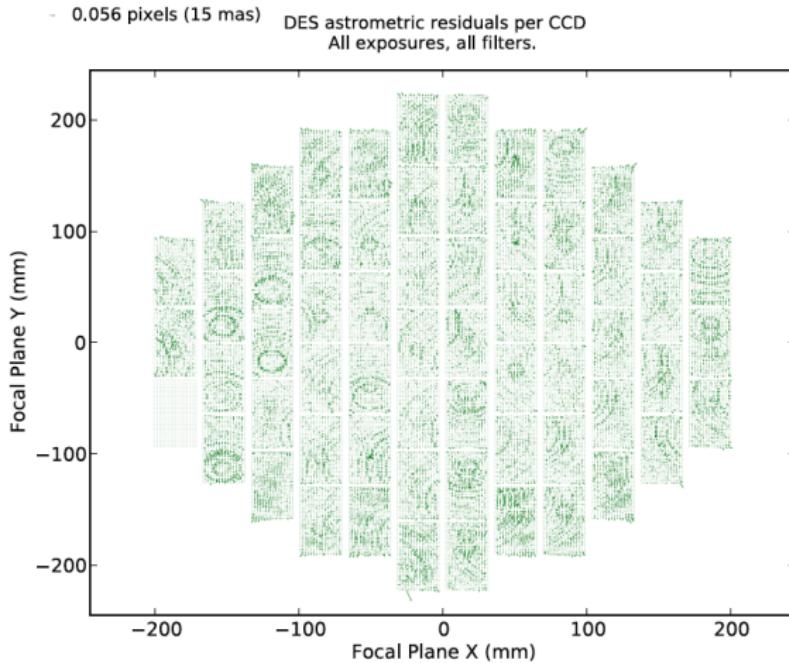


Tree Rings



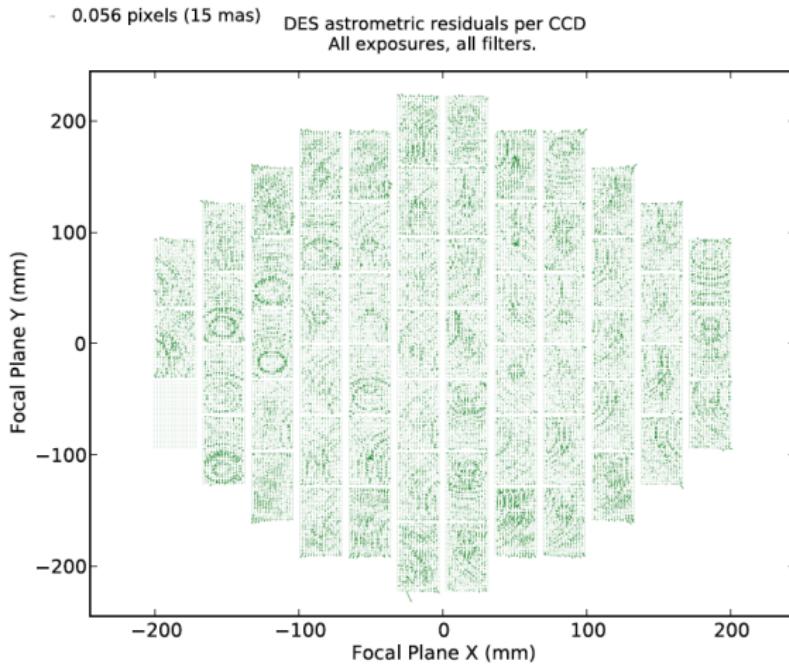
Pixel distortions due to doping gradients in the Si.

Tree Rings



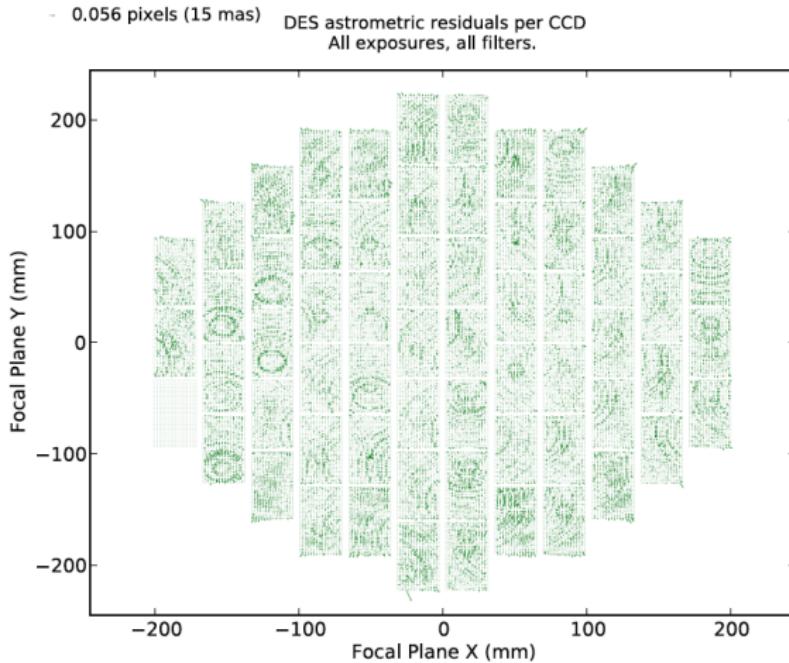
DES sees c. 1% treerings, and they affect the astrometry (at the few mas level).

Tree Rings



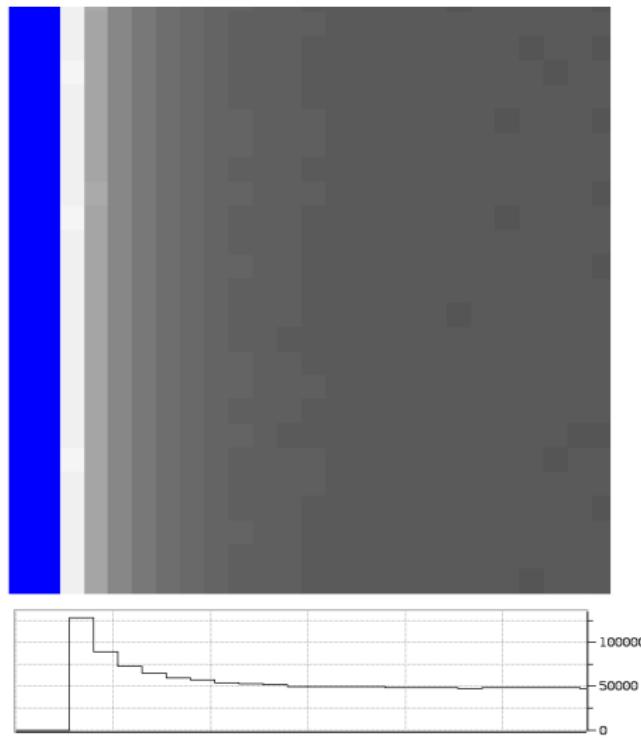
DES sees c. 1% treerings, and they affect the astrometry (at the few mas level). We don't see significant problems in HSC.

Tree Rings



DES sees c. 1% treerings, and they affect the astrometry (at the few mas level). We don't see significant problems in HSC. We don't expect significant problems in LSST.

Pixel Size Variation at the Device Edges



The electric field diverges near the edge of the CCD, and this leads to larger pixels (by a factor of c. 200% at the very edge of an HSC device).

CMOS Detectors

CMOS detectors have a bad reputation in astronomy, but they're getting really good.

CMOS Detectors

CMOS detectors have a bad reputation in astronomy, but they're getting really good.

- CCDs and CMOS devices both detect photons in separate pixels

CMOS Detectors

CMOS detectors have a bad reputation in astronomy, but they're getting really good.

- CCDs and CMOS devices both detect photons in separate pixels
 - ▶ CCDs transport the photo-electrons (or holes) to a small number of readouts

CMOS Detectors

CMOS detectors have a bad reputation in astronomy, but they're getting really good.

- CCDs and CMOS devices both detect photons in separate pixels
 - ▶ CCDs transport the photo-electrons (or holes) to a small number of readouts
 - ▶ CMOS devices convert the carriers to voltages within the pixels

CMOS Detectors

CMOS detectors have a bad reputation in astronomy, but they're getting really good.

- CCDs and CMOS devices both detect photons in separate pixels
 - ▶ CCDs transport the photo-electrons (or holes) to a small number of readouts
 - ▶ CMOS devices convert the carriers to voltages within the pixels
 - ▶ The read can be done non-destructively

CMOS Detectors

CMOS detectors have a bad reputation in astronomy, but they're getting really good.

- CCDs and CMOS devices both detect photons in separate pixels
 - ▶ CCDs transport the photo-electrons (or holes) to a small number of readouts
 - ▶ CMOS devices convert the carriers to voltages within the pixels
 - ▶ The read can be done non-destructively
- CCD pixels are passive; CMOS pixels each have at least three transistors

CMOS Detectors

CMOS detectors have a bad reputation in astronomy, but they're getting really good.

- CCDs and CMOS devices both detect photons in separate pixels
 - ▶ CCDs transport the photo-electrons (or holes) to a small number of readouts
 - ▶ CMOS devices convert the carriers to voltages within the pixels
 - ▶ The read can be done non-destructively
- CCD pixels are passive; CMOS pixels each have at least three transistors
 - ▶ CCD amplifiers are individuals; CMOS pixels are individuals

CMOS Detectors

CMOS detectors have a bad reputation in astronomy, but they're getting really good.

- CCDs and CMOS devices both detect photons in separate pixels
 - ▶ CCDs transport the photo-electrons (or holes) to a small number of readouts
 - ▶ CMOS devices convert the carriers to voltages within the pixels
 - ▶ The read can be done non-destructively
- CCD pixels are passive; CMOS pixels each have at least three transistors
 - ▶ CCD amplifiers are individuals; CMOS pixels are individuals
- CCD cameras need shutters; CMOS cameras don't

CMOS Detectors

CMOS detectors have a bad reputation in astronomy, but they're getting really good.

- CCDs and CMOS devices both detect photons in separate pixels
 - ▶ CCDs transport the photo-electrons (or holes) to a small number of readouts
 - ▶ CMOS devices convert the carriers to voltages within the pixels
 - ▶ The read can be done non-destructively
- CCD pixels are passive; CMOS pixels each have at least three transistors
 - ▶ CCD amplifiers are individuals; CMOS pixels are individuals
- CCD cameras need shutters; CMOS cameras don't
- Reset kTC noise is important

CMOS Detectors

CMOS detectors have a bad reputation in astronomy, but they're getting really good.

- CCDs and CMOS devices both detect photons in separate pixels
 - ▶ CCDs transport the photo-electrons (or holes) to a small number of readouts
 - ▶ CMOS devices convert the carriers to voltages within the pixels
 - ▶ The read can be done non-destructively
- CCD pixels are passive; CMOS pixels each have at least three transistors
 - ▶ CCD amplifiers are individuals; CMOS pixels are individuals
- CCD cameras need shutters; CMOS cameras don't
- Reset kTC noise is important
 - ▶ CCDs ameliorate this with CDS

CMOS Detectors

CMOS detectors have a bad reputation in astronomy, but they're getting really good.

- CCDs and CMOS devices both detect photons in separate pixels
 - ▶ CCDs transport the photo-electrons (or holes) to a small number of readouts
 - ▶ CMOS devices convert the carriers to voltages within the pixels
 - ▶ The read can be done non-destructively
- CCD pixels are passive; CMOS pixels each have at least three transistors
 - ▶ CCD amplifiers are individuals; CMOS pixels are individuals
- CCD cameras need shutters; CMOS cameras don't
- Reset kTC noise is important
 - ▶ CCDs ameliorate this with CDS
 - ▶ so do CMOS devices (nowadays)

HgCdTe Detectors

The problem in the IR is the bandgap; CCDs are unable to detect photons with wavelengths greater than around $1.1\mu\text{m}$.

HgCdTe Detectors

The problem in the IR is the bandgap; CCDs are unable to detect photons with wavelengths greater than around $1.1\mu\text{m}$. One option would be to use Ge with a bandgap of 0.66eV ($1.9\mu\text{m}$), but Ge O₂ is not easy to work with.

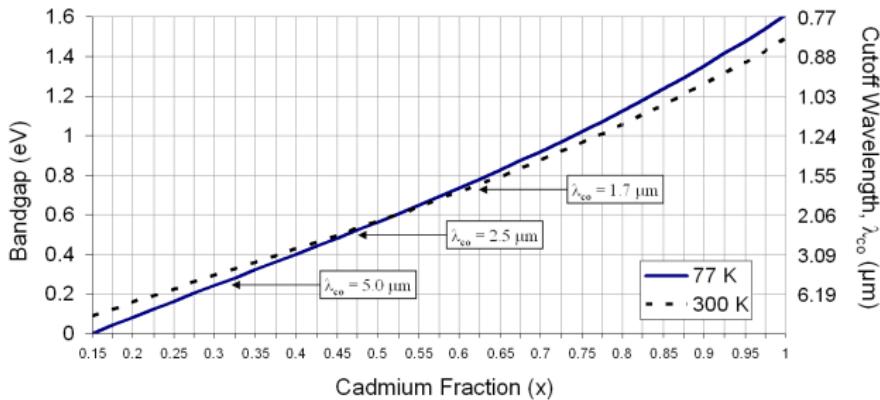
HgCdTe Detectors

The problem in the IR is the bandgap; CCDs are unable to detect photons with wavelengths greater than around $1.1\mu\text{m}$. One option would be to use Ge with a bandgap of 0.66eV ($1.9\mu\text{m}$), but Ge O₂ is not easy to work with.

In practice, we turn to $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$:

Tunable Cutoff Wavelength

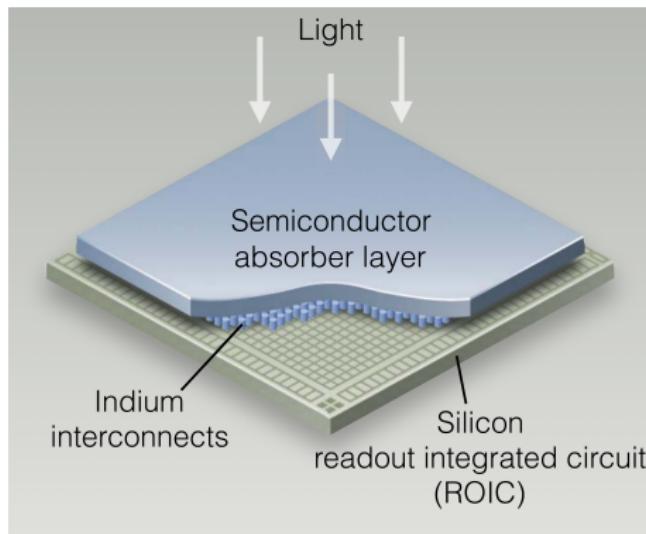
$$E_g = -0.302 + 1.93x - 0.81x^2 + 0.832x^3 + 5.35 \times 10^{-4}T(1-2x)$$



Bandgap and cutoff wavelength of $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ as a function of cadmium fraction, x . Credit: Beletic, J. et al. 2008, Proc SPIE, 7021, 70210H-70210H-14.

HgCdTe Detectors

In many ways our NIR ($0.6\mu\text{m} \text{ -- } 2.5+\mu\text{m}$) detectors are very similar to CCDs, but structurally they are much more similar to CMOS devices:



(Jim Beletic via Bernie Rauscher)

HgCdTe Detectors

Problems with HgCdTe include:

- Correlated noise (probably largely due to the readout electronics, the "Sidecar")
- Inter-Pixel Capacitance
- Persistence
- Sensitivity to wavelengths you don't care about
- Export restrictions