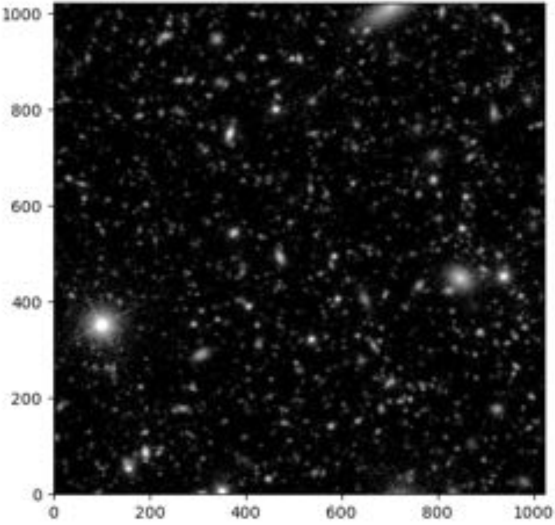
The Imperfection of Optical/NIR Astronomical Data

Robert Lupton

2018-01-22

Data



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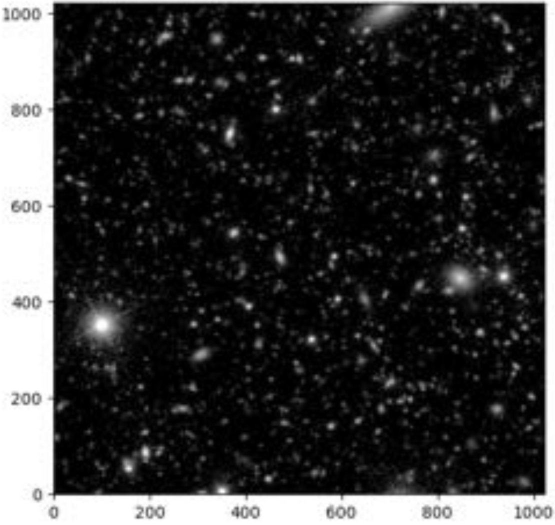

This image is noisy.

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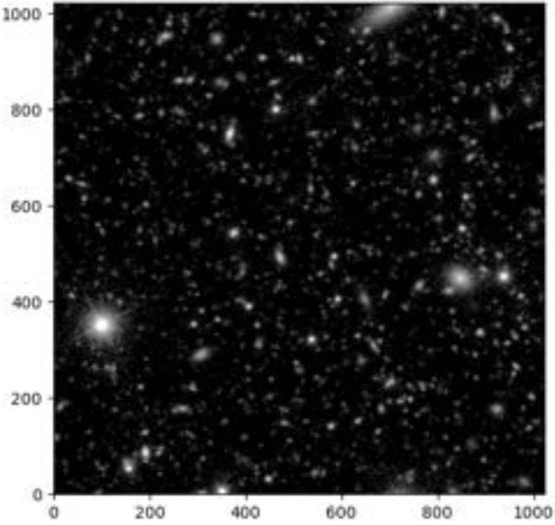

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Probability Distributions

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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.

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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

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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):

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

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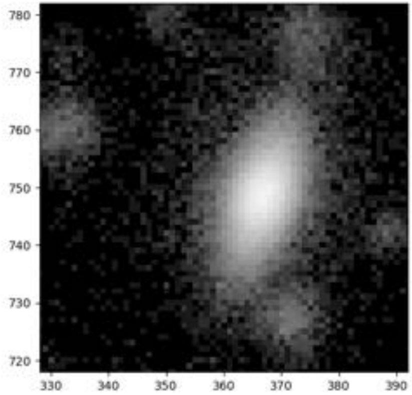
It's traditional to visualize data as uniformly illuminated squares, but this is just a convention.

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 $\sqrt{\mu}$.

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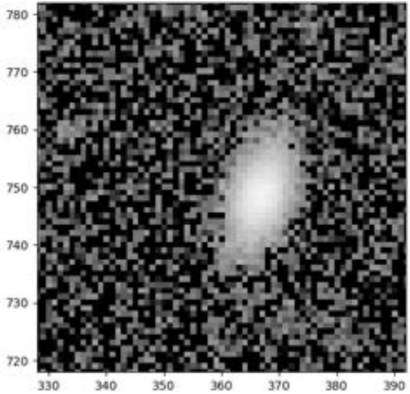

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Most of the photons don't come from the objects.

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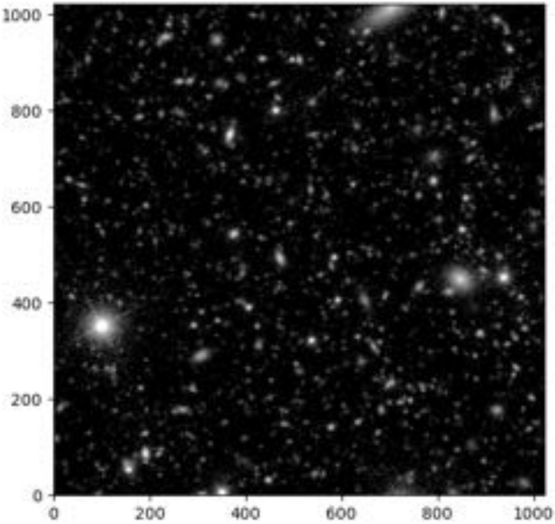

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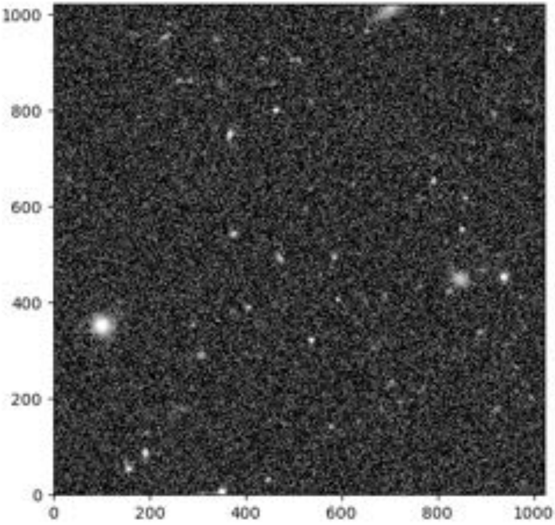

Question 1: Whence comes the background (`sky') level?

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

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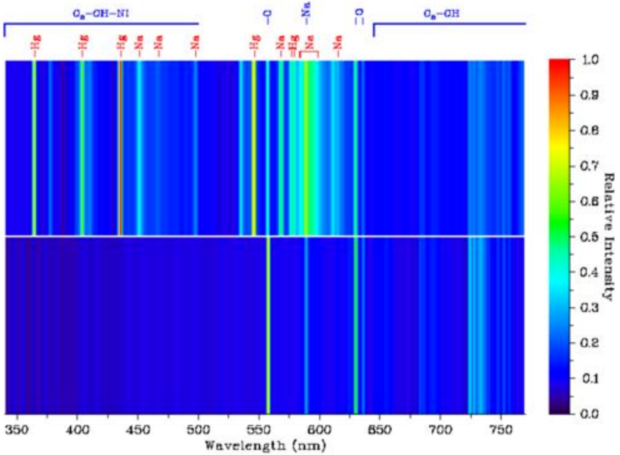
- Night sky emission (*Na*, *Hg*, …)
- Scattered and Ghost light from the telescope
- Dark current in the CCDs
- Glow from the ion pumps

Answer 1



C_a–CH–Ni
C_a–CH
Hg
Na
O
Relative Intensity
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
350
400
450
500
550
600
650
700
750
Wavelength (nm)

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} \left(I_0(x) \otimes \phi\right)\,dx \\
&= \int_{-\infty}^{\infty} P(x-x_p)\left(I_0(x) \otimes \phi\right)\,dx \\
&= \left(P \otimes \phi \otimes I_0\right)(x_p)
\end{aligned}
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where

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P(x) = \begin{cases} 1 & |x| \le 0.5 \\ 0 & |x| > 0.5 \end{cases}
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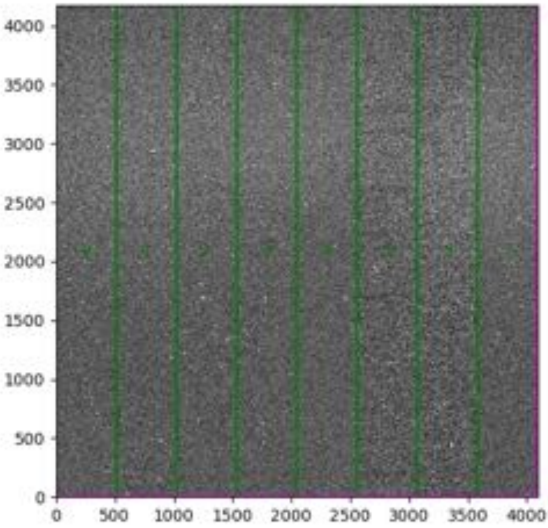
i.e. We replace the PSF ϕ by $P \otimes \phi$; but the latter is the function that we measure.
So the sampling causes no fundamental problems for the PSF, although it can make it (much) harder to measure if the data is not at least Nyquist sampled.

What does real CCD data look like?

Examples of CCD Images (all from PFS)



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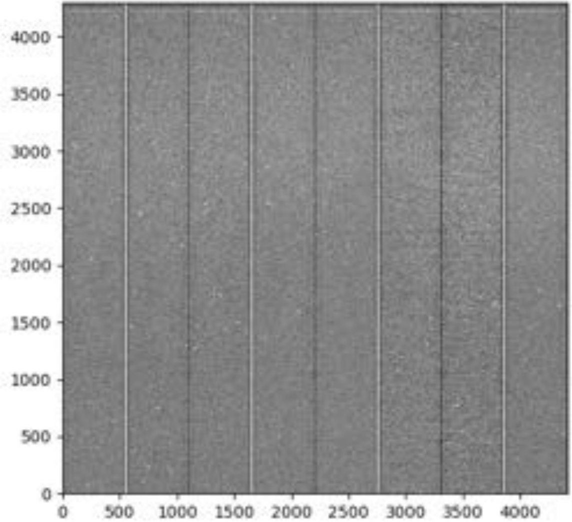

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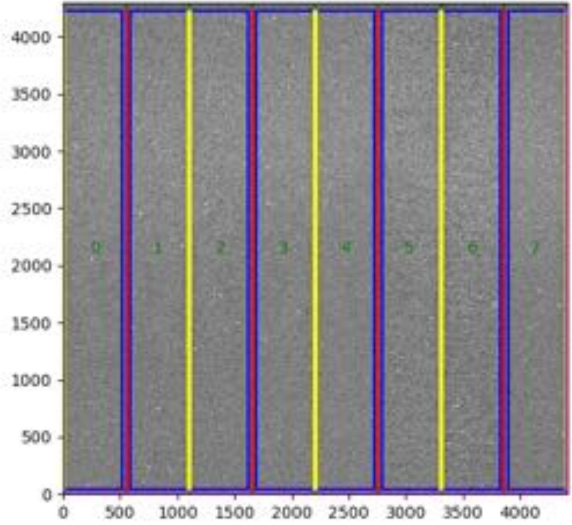

Overscan, Data, Extended register

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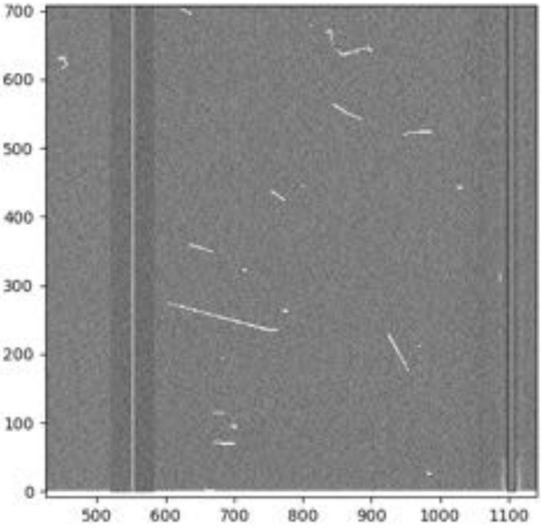

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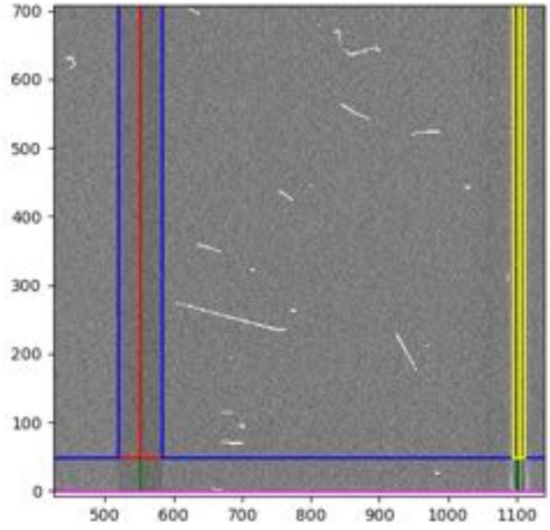

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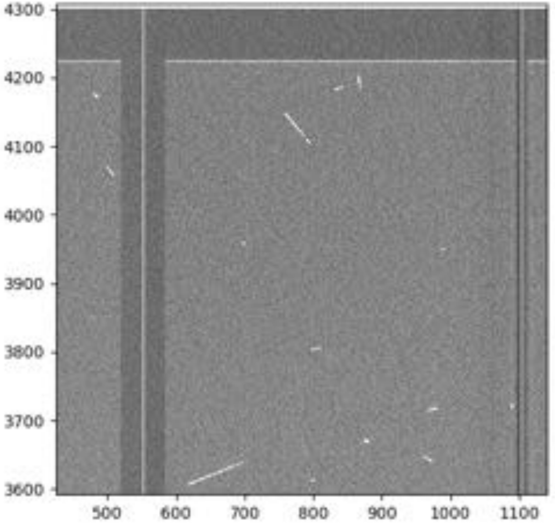

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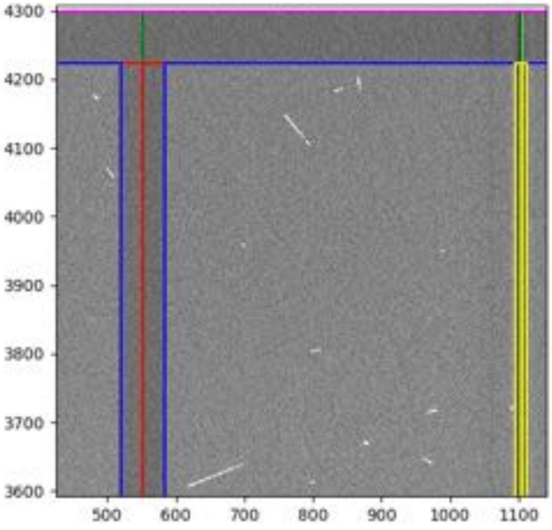

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Question 3: How do CCDs detect light?

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

Question 5: How do CCDs detect light?

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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 $\lambda < 1.08\mu m$.

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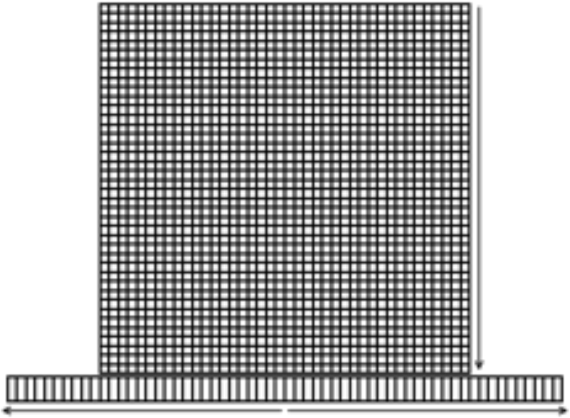
I remember 1.1 eV; 1.1 μ m

CCDs

What do those pretty colours mean?



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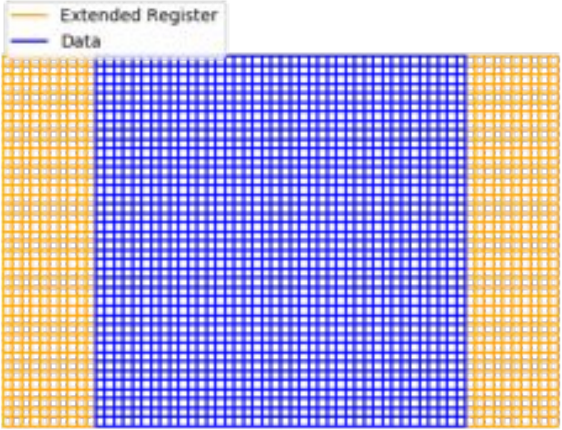

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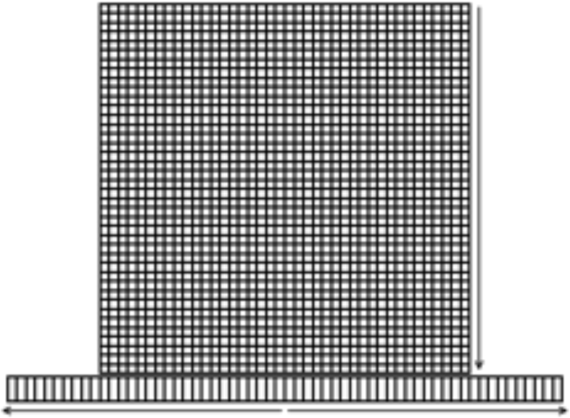

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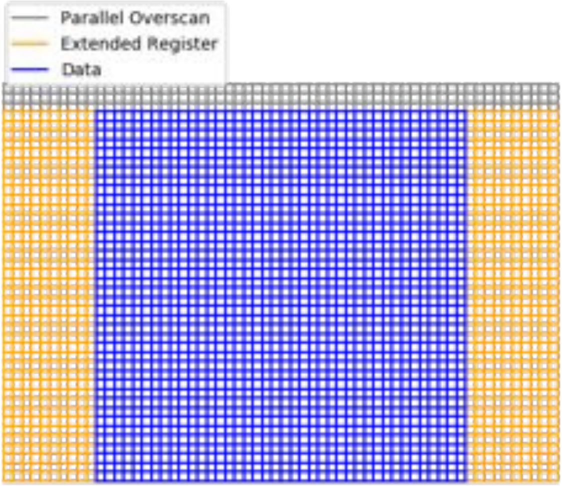

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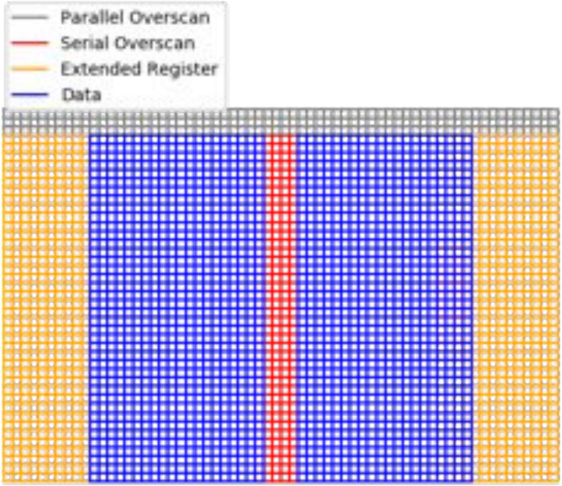

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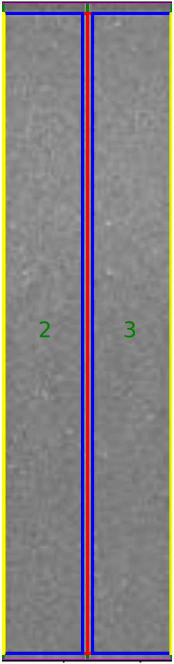
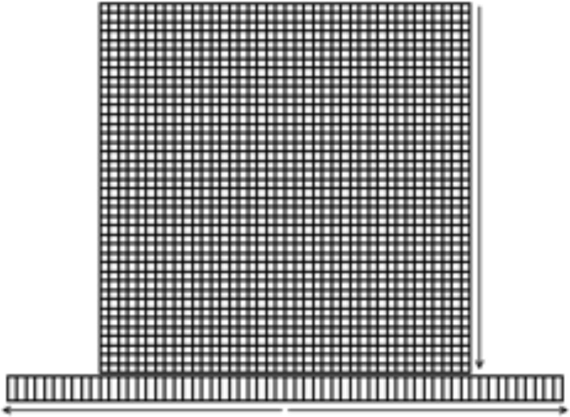


A 1024×4096 CCD

CCD Readout



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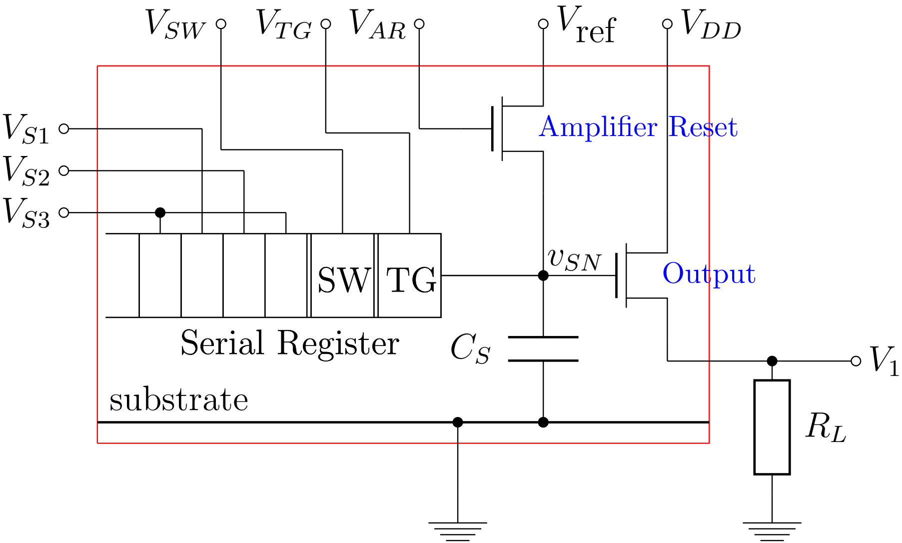
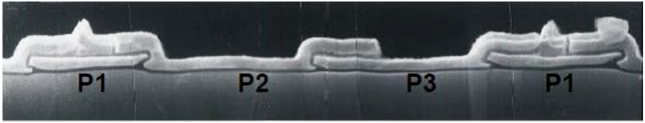


V_{SW}
V_{TG}
V_{AR}
V_{ref}
V_{DD}
V_{S1}
V_{S2}
V_{S3}
Amplifier
Reset
SW
TG
v_{SN}
Output
Serial Register
C_S
V_1
substrate
R_L

Real CCDs (a Tektronix CCD; Janesick)



Parallel transport gates

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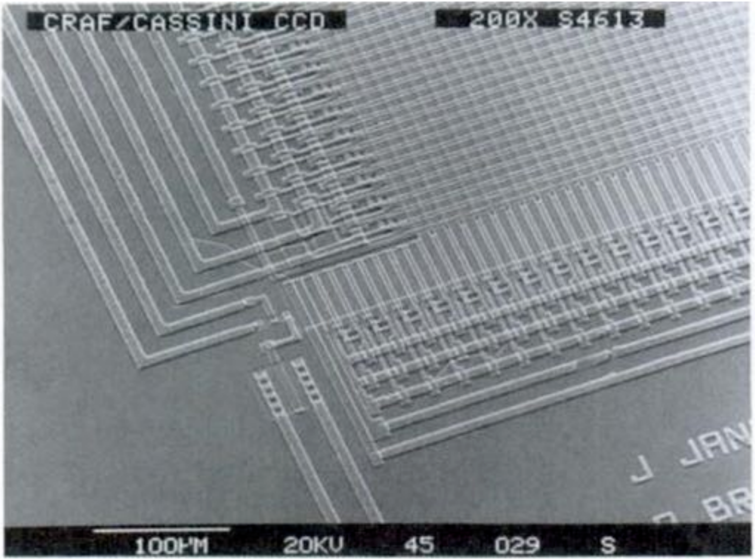

Corner of active area, parallel gates, serial register, and output capacitor

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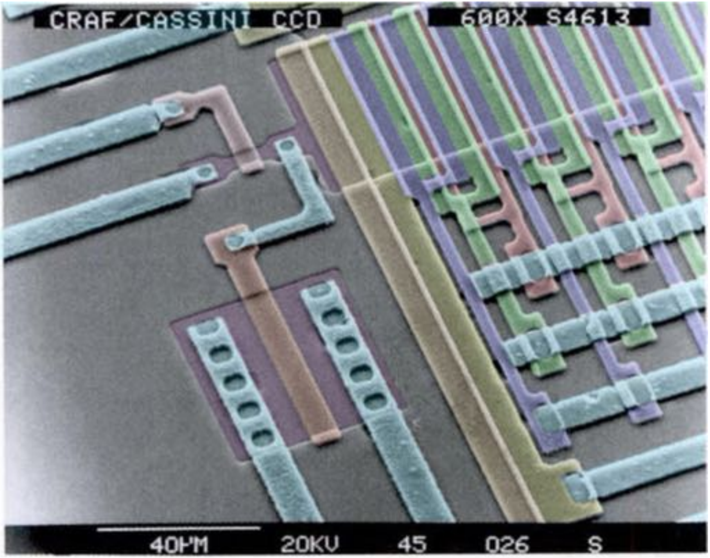

Serial register, reset gate, and output capacitor

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 $1/2CV^2$, so the probability of seeing that voltage is given by a Boltzman distribution.

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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 $T \sim 160K$ we have $\langle Q^2 \rangle \sim 1.5 \times 10^{-17}$ or 100 electrons.

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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; $\tau = 1/(RC)$.

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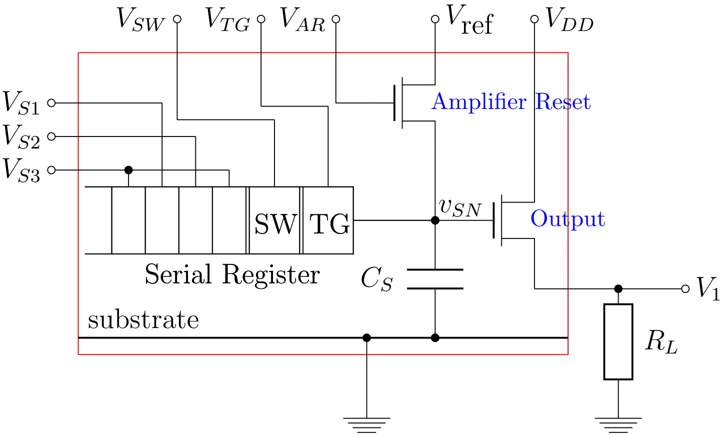
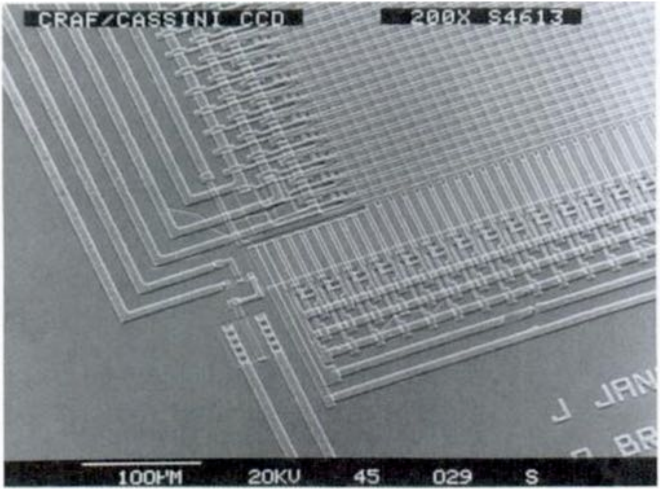


Real CCDs



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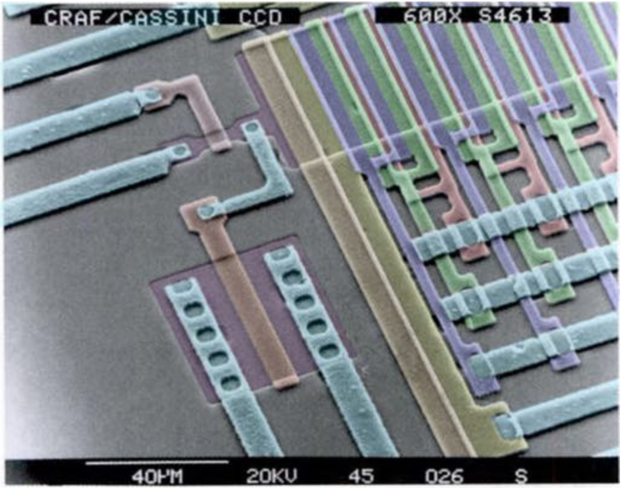
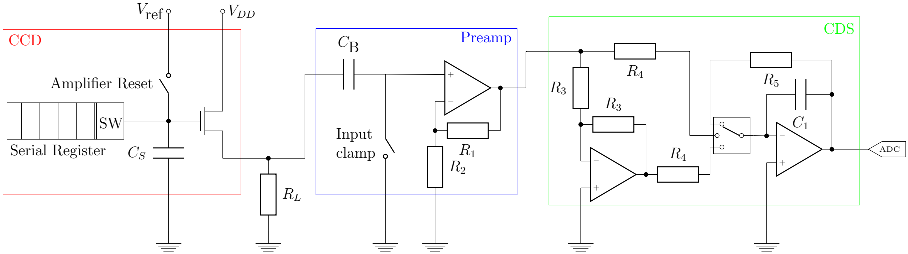


CCD Video Chain



Correlated Double Sampling

We can exploit this by measuring the capacitor *twice* but only resetting it *once*: *D*ouble *C*orrelated *S*ampling (CDS)

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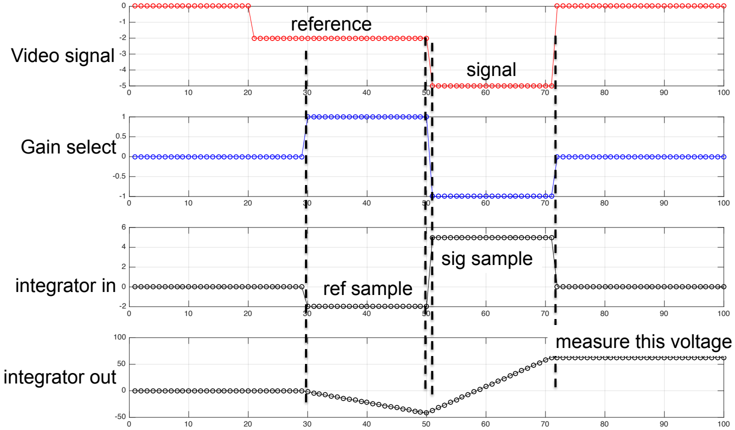
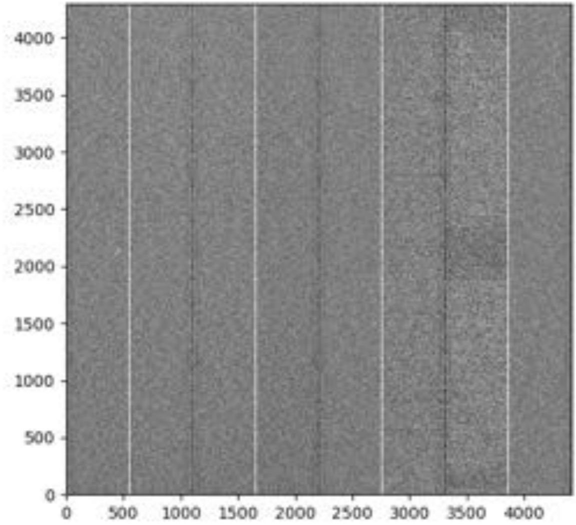


(Credit: Chris Stubbs)

More Examples of CCD Images (all from PFS)



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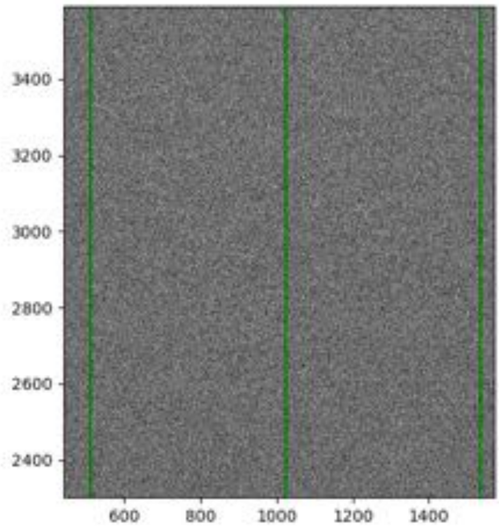

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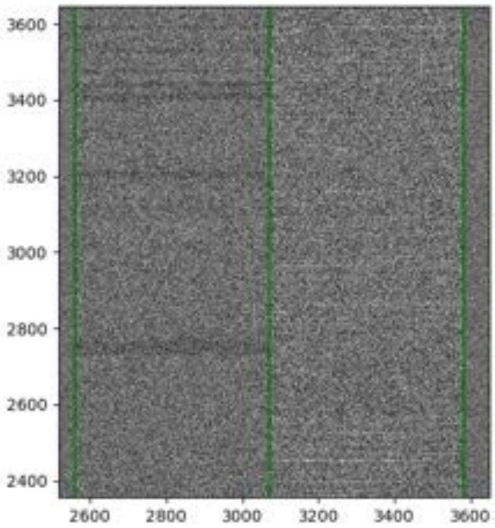

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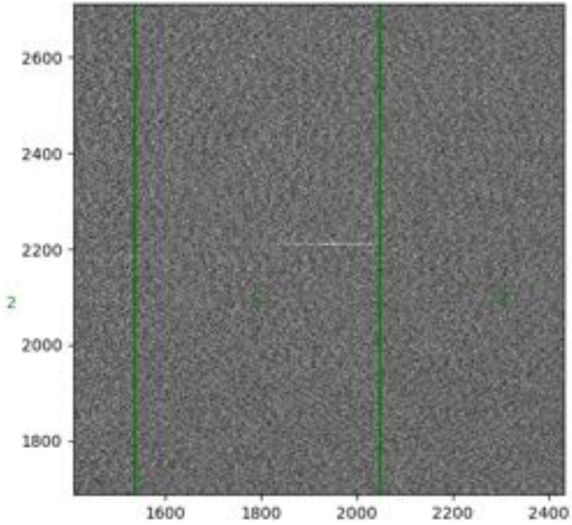

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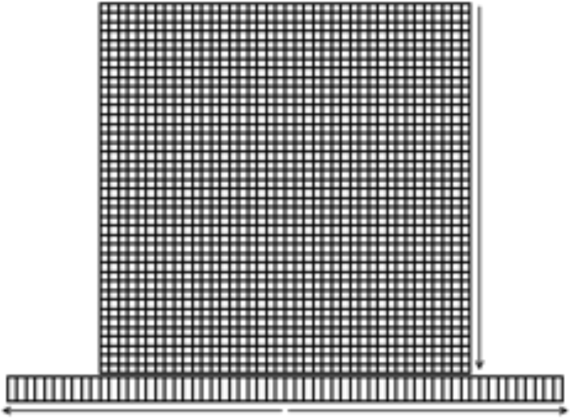
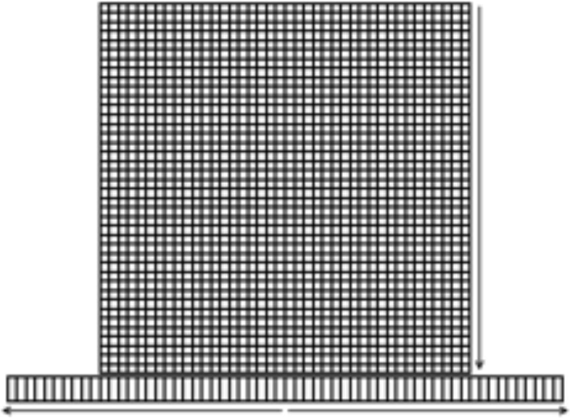
Crosstalk

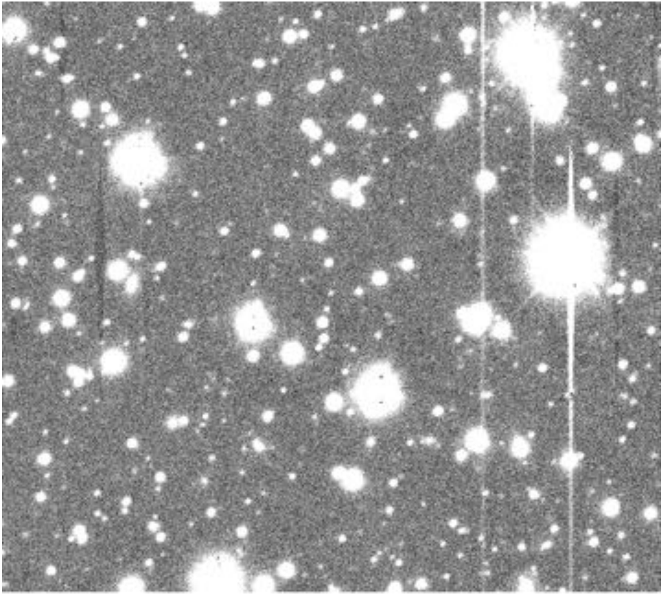


Crosstalk



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

Crosstalk in HSC



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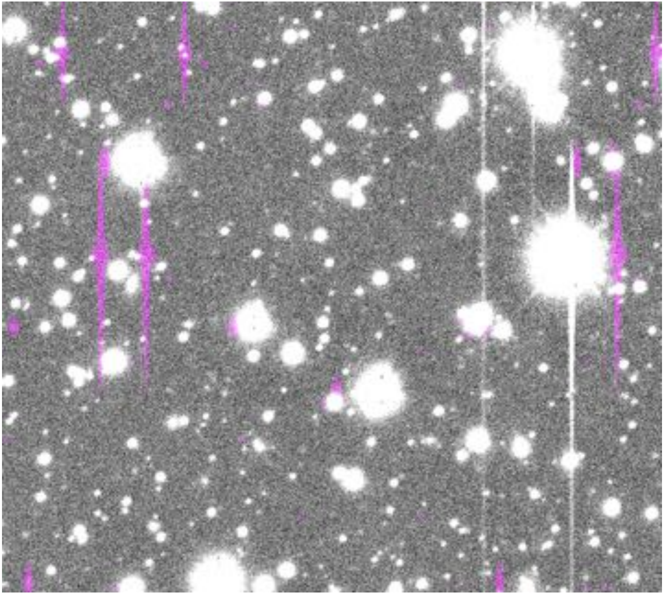

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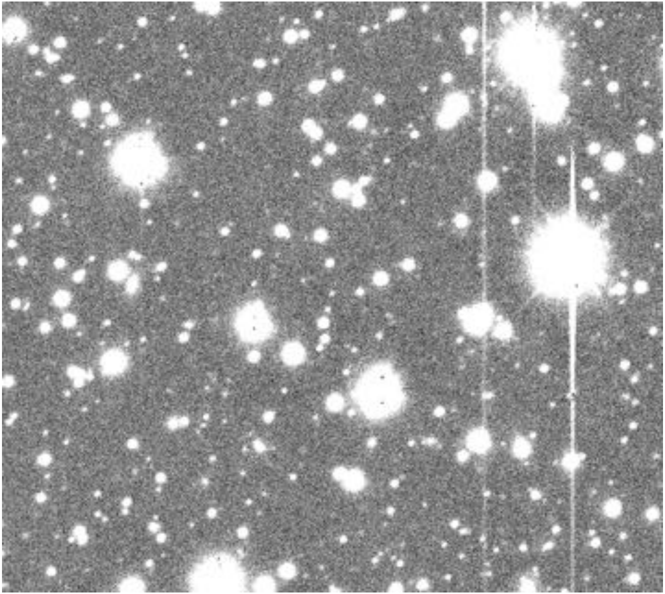

Crosstalk Coefficients for HSC

ampIn	ampOut			
	0	1	2	3
0		-125 $\pm$ 12	-149 $\pm$ 3	-156 $\pm$ 1
1	-124 $\pm$ 17		-132 $\pm$ 2	-157 $\pm$ 3
2	-171 $\pm$ 2	-134 $\pm$ 13		-153 $\pm$ 13
3	-157 $\pm$ 6	-151 $\pm$ 5	-137 $\pm$ 2	

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

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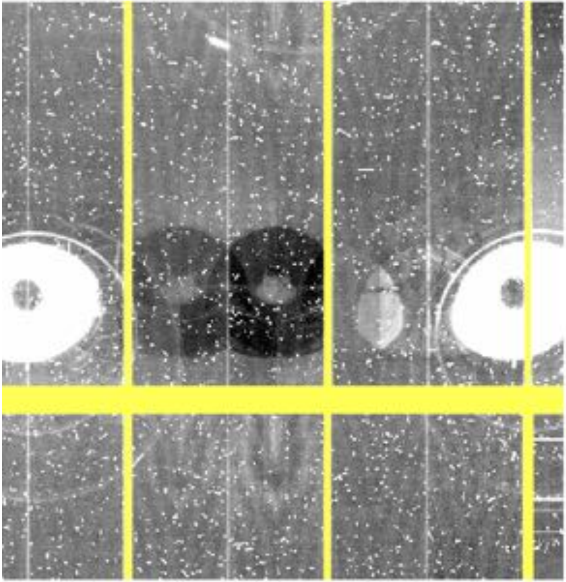
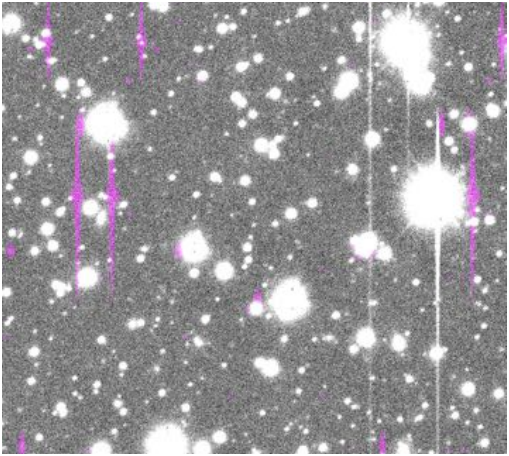


Saturation



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

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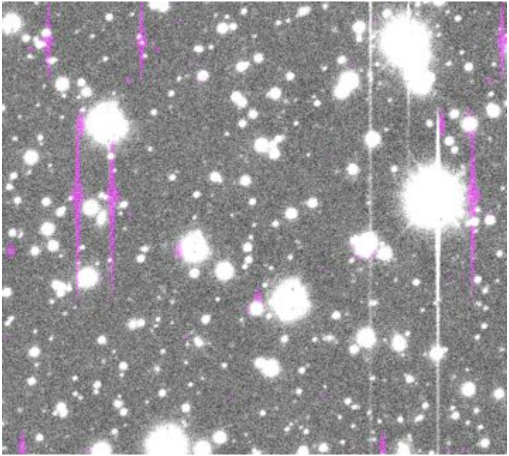
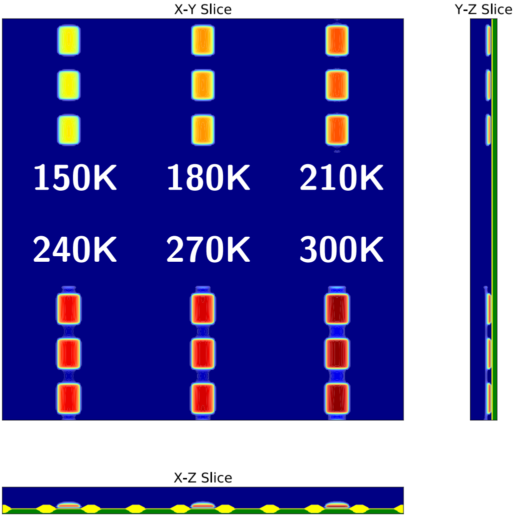


The bright stars have streaks up-and-down the detector. The pixels are unable to keep the electrons that they are given localised.

Saturation



The electrons escape once there are more than *c.* 2e5 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, to the variance is 10200, right?

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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?

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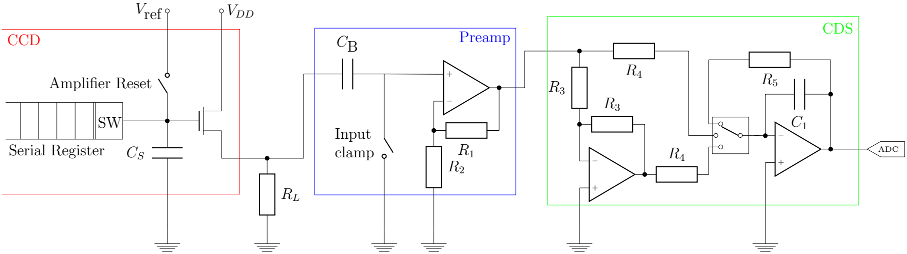
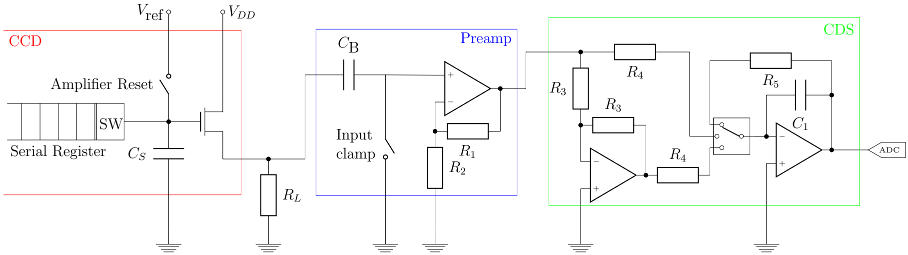


At least 3 parts of that circuit have some gain, *g*. So the variance is 10000/g.

Non-linearity

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



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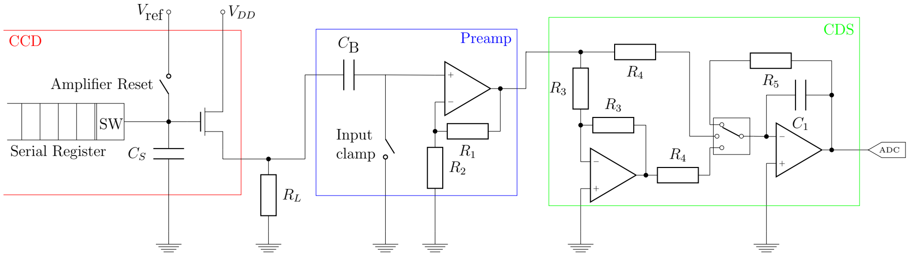

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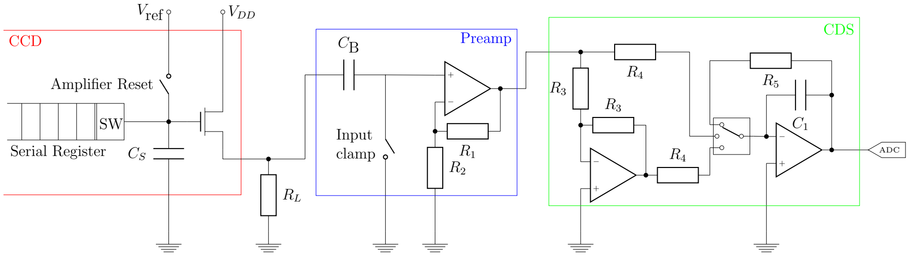

Actually they're usually pretty good. The problem is the transconductance of the output FET and the varying capacitance of the sense node. These are both c. 1% and have opposite signs -- but the result is that CCDs do show non-linear behaviour (i.e. the gain is a function of intensity).

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%.

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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)
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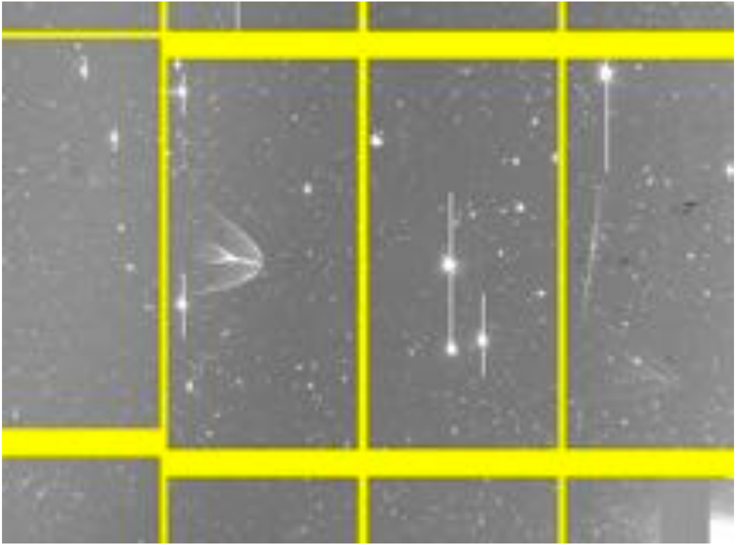
Ghosties and Ghoulies



Arcturus (i $\sim$ -0.6)

Jim Gunn and I imaged the Hokule`a with HSC

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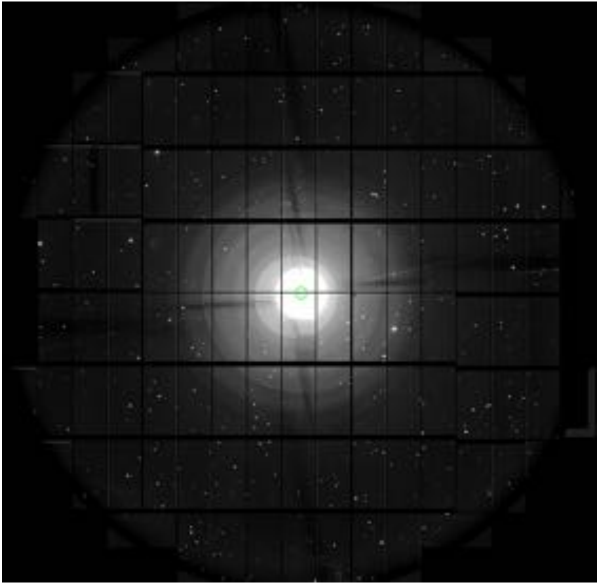

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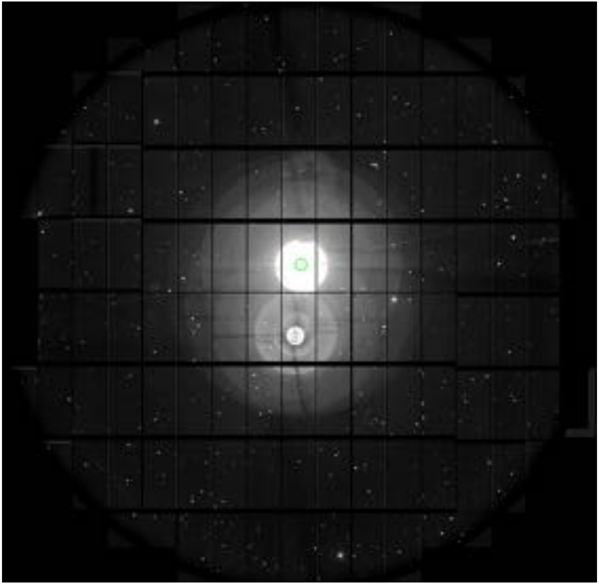

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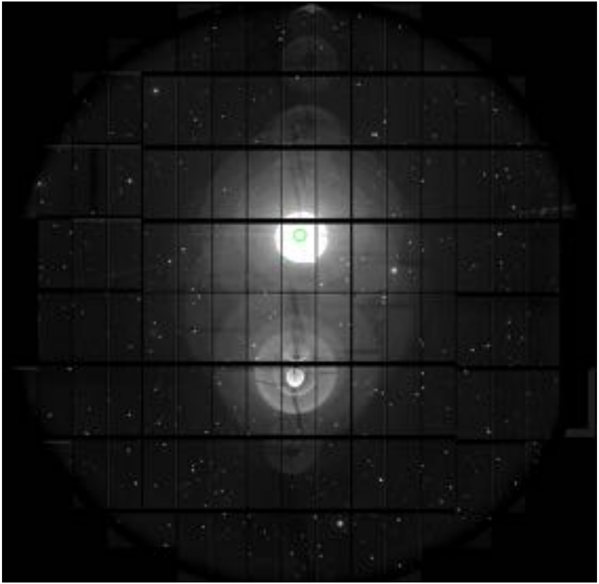

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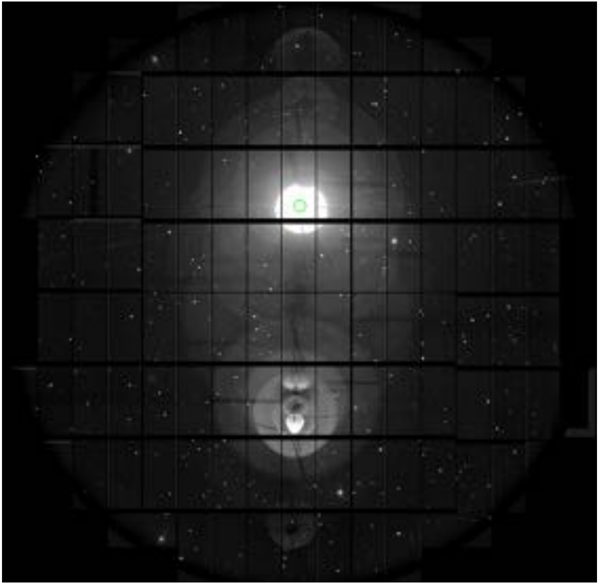

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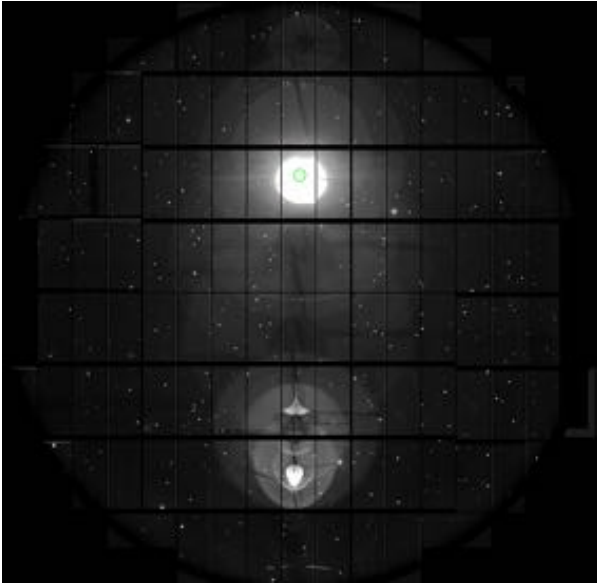

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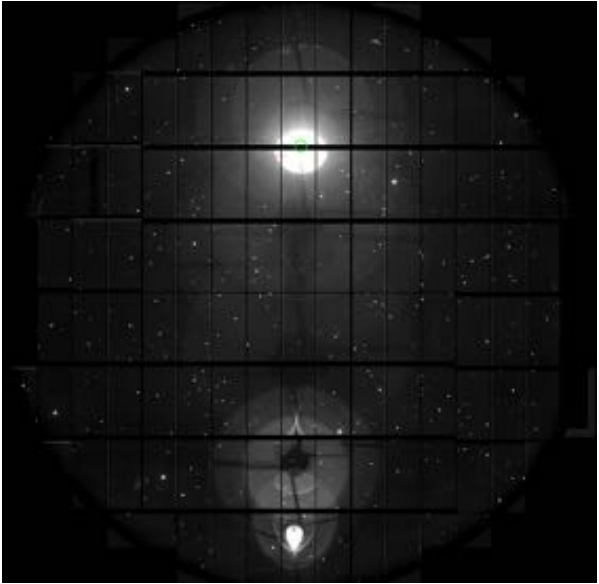

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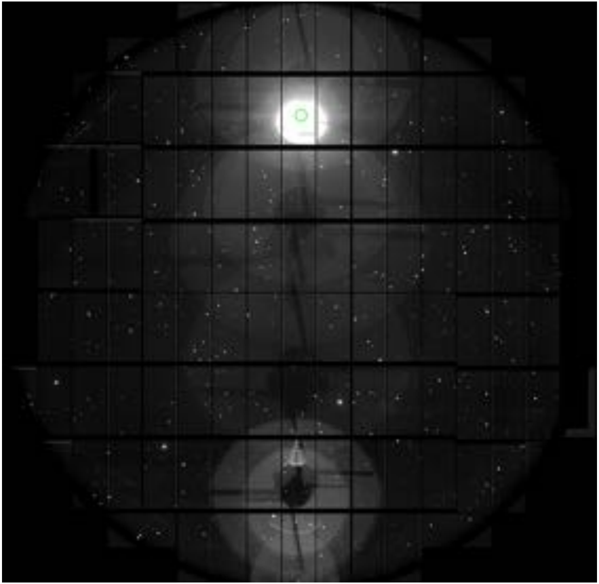

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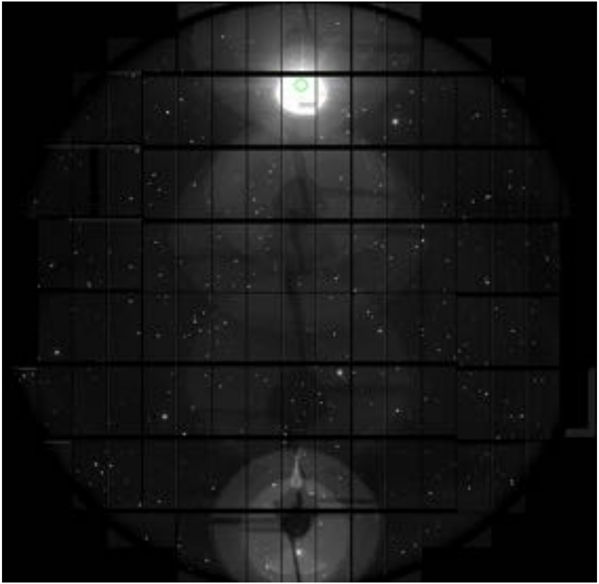

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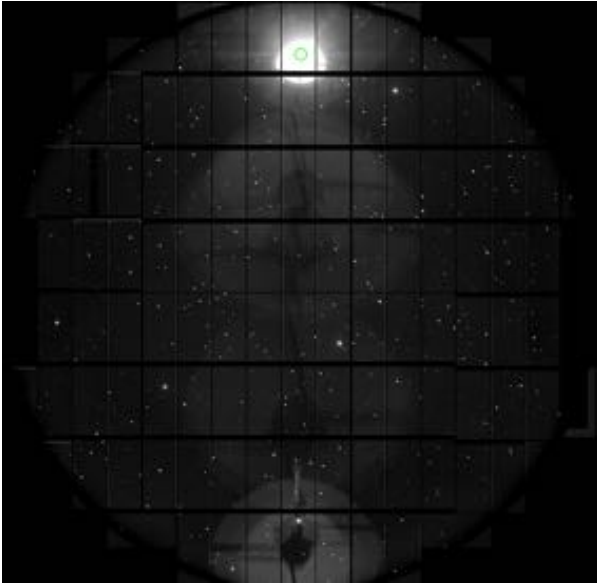

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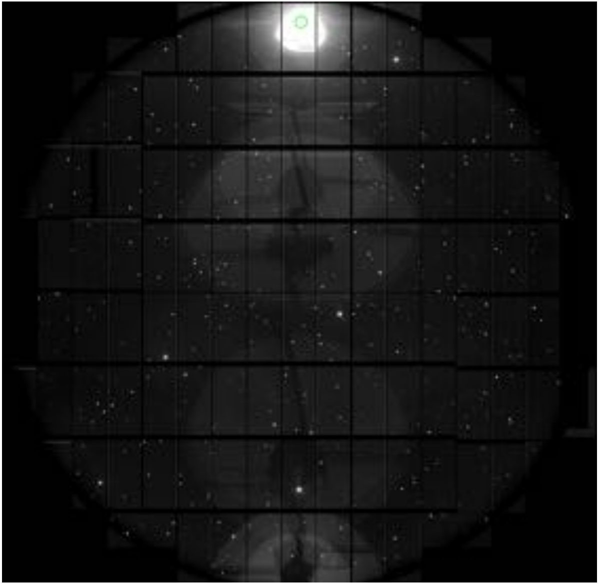

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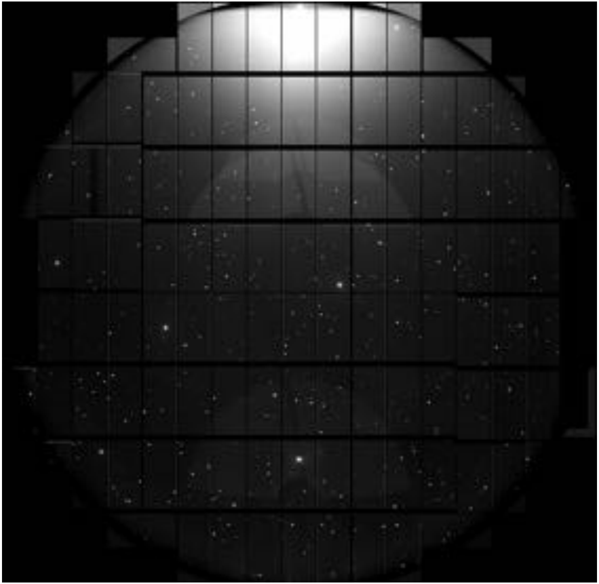

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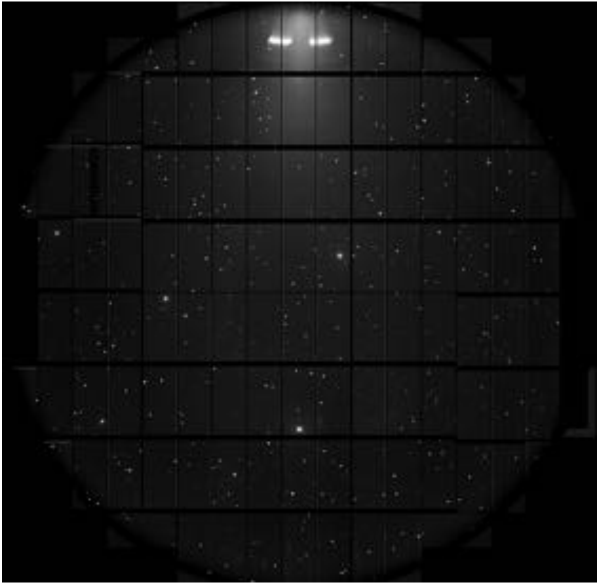

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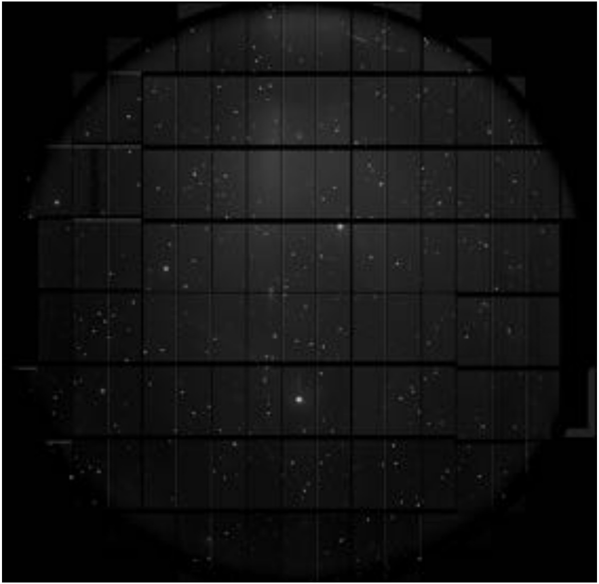

Question 11: How should we measure the gain?

Answer 11

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

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

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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
...		

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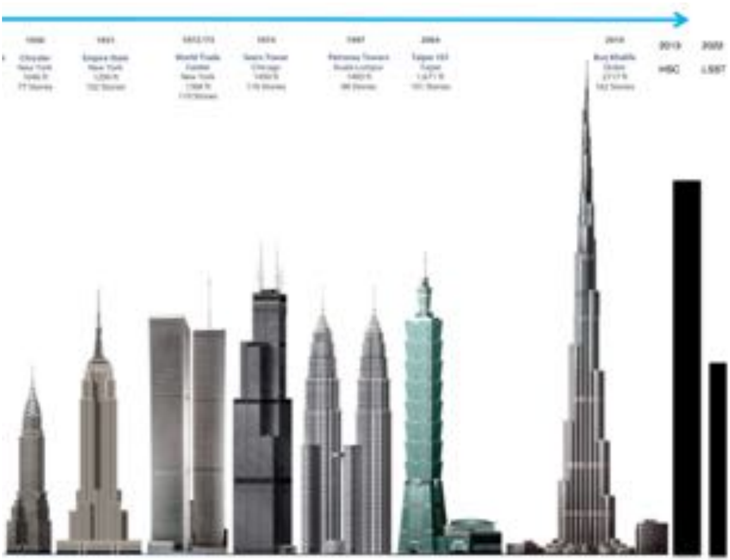
1_54	3	2.93	3.14	3.15	3.26
1_54	4	2.99	3.21	3.24	3.35
1_55	1	3.68	3.92	3.94	4.08
1_55	2	3.52	3.74	3.78	3.91
1_55	3	3.44	3.70	3.72	3.86
1_55	4	3.46	3.69	3.73	3.87
1_56	1	3.15	3.35	3.37	3.46
…					

What went wrong?

Modern CCDs



(pixels have correct aspect ratios, but not size)

Flat Field Statistics

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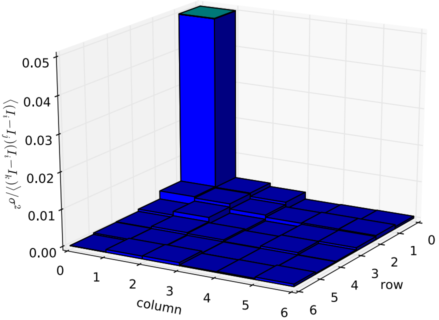

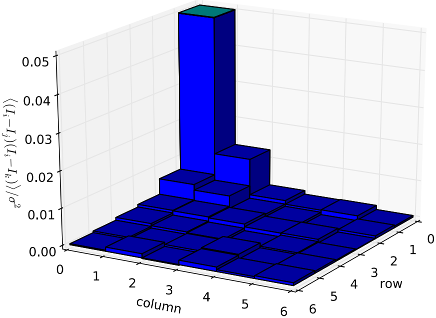

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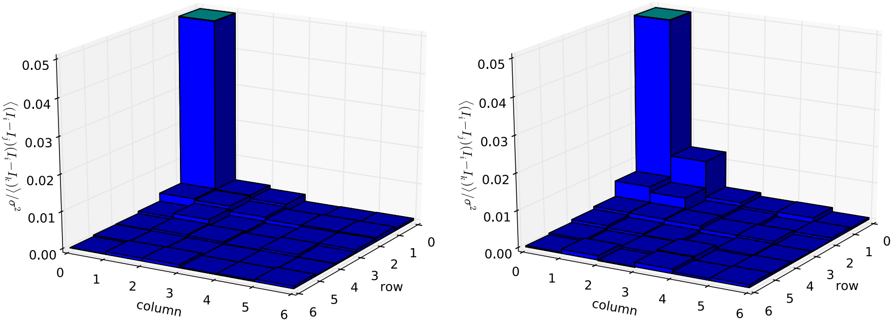

Correlations in the differences between pairs of flat fields. On the left the mean level is *c.* 7500e$^-$, on the right 90000e$^-$.

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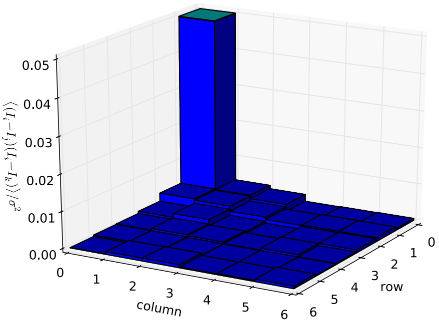
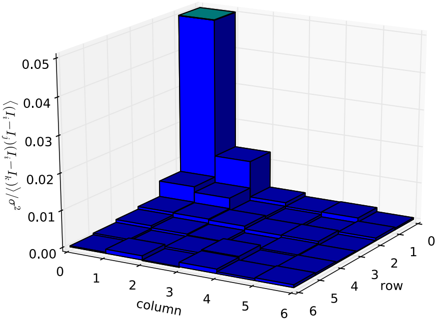
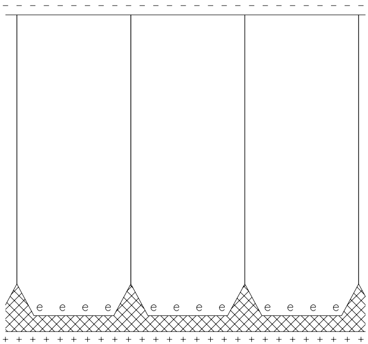




Correlations in the differences between pairs of flat fields. On the left the mean level is *c.* 7500e$^-$, on the right 90000e$^-$.

How did the photons know about each other?

Pixel Correlations



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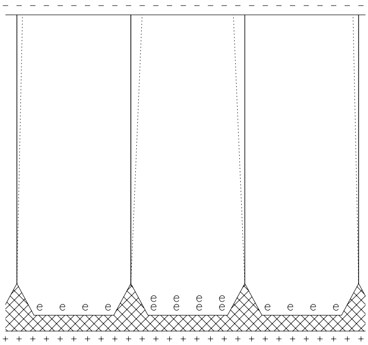

The effective pixel boundaries depend on the charges already in the pixels, and this leads to correlations which increase with flux level; this is why the gain was apparently a function of intensity.

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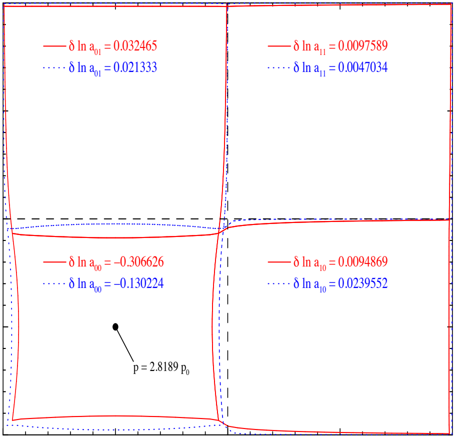

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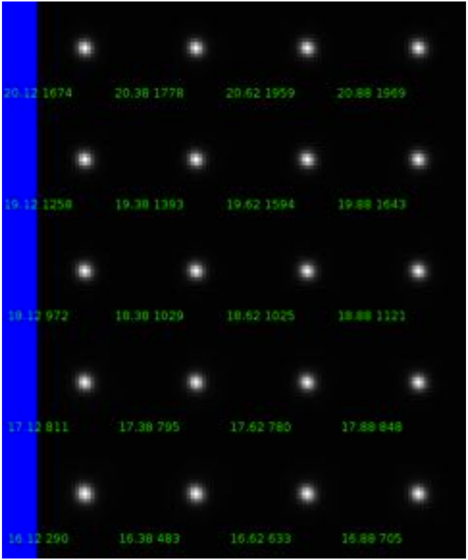

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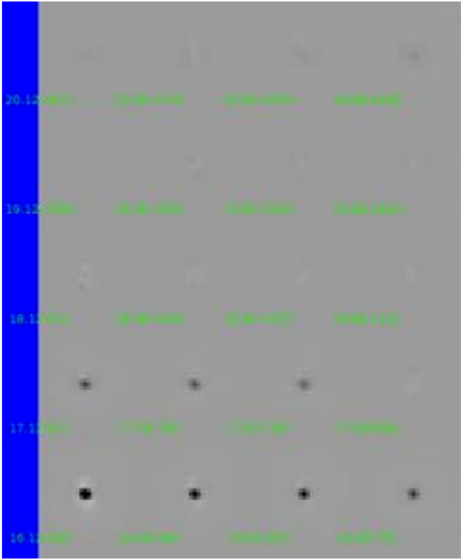
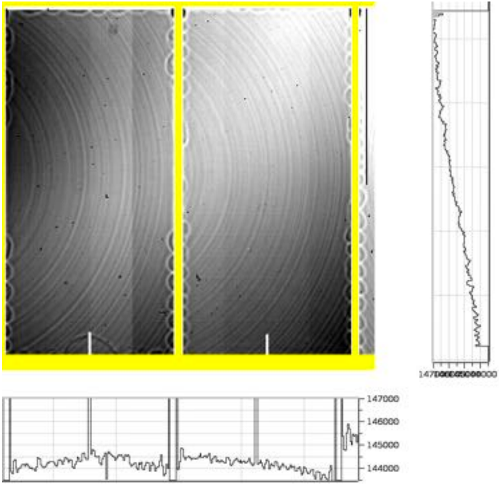


Tree Rings



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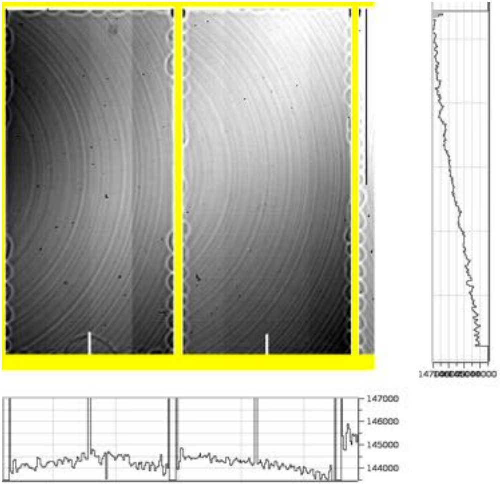
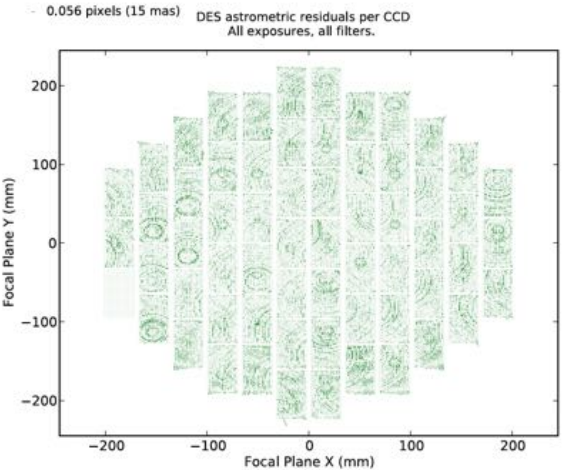


Pixel distortions due to doping gradients in the Si.

Tree Rings



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

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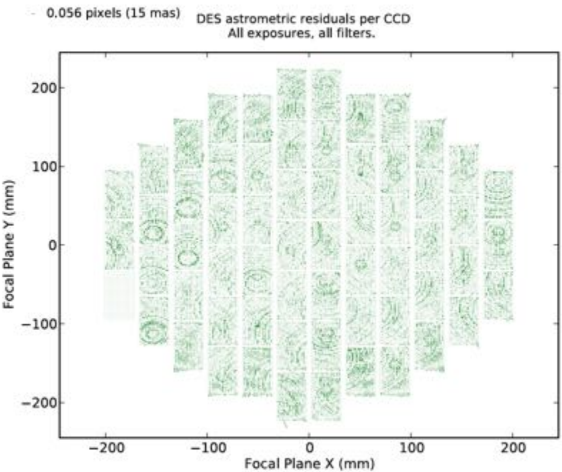

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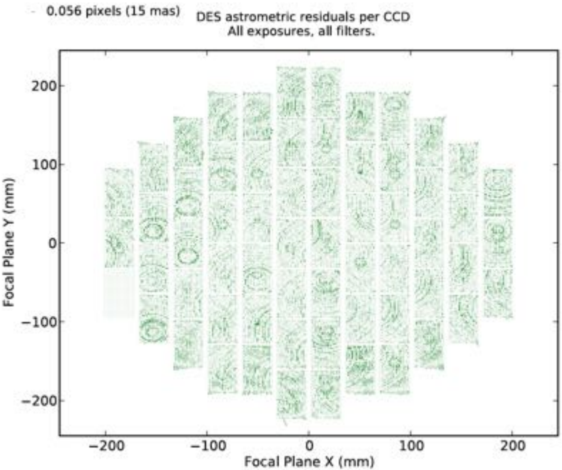
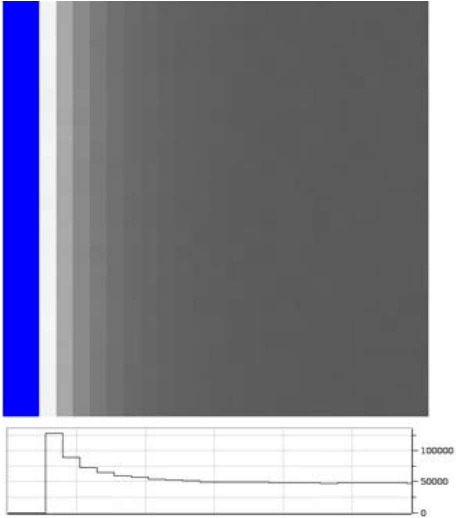


DES sees c. 1% treerings, and they affect the astrometry (at the few mas level). We don't see significant problems in HSC. We don't expect significant problems in LSST.

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).

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- 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
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  - so do CMOS devices (nowadays)

HgCdTe Detectors

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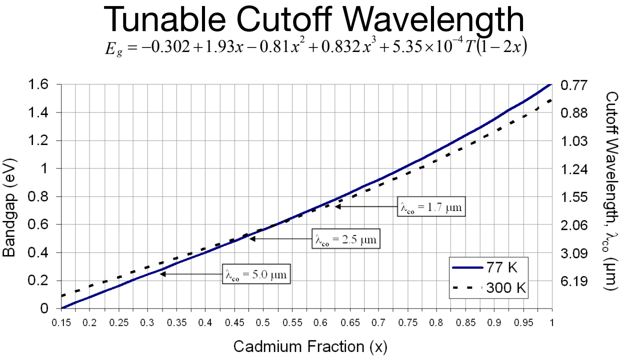
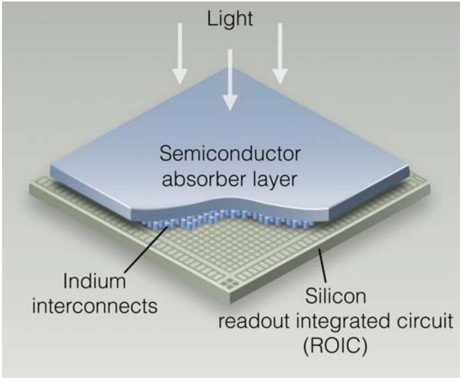
In practice, we turn to Hg_{1-x} Cd_x Te:



Bandgap and cutoff wavelength of $Hg_{1-x}Cd_xTe$ 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 (0.6μm -- 2.5+μm) 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