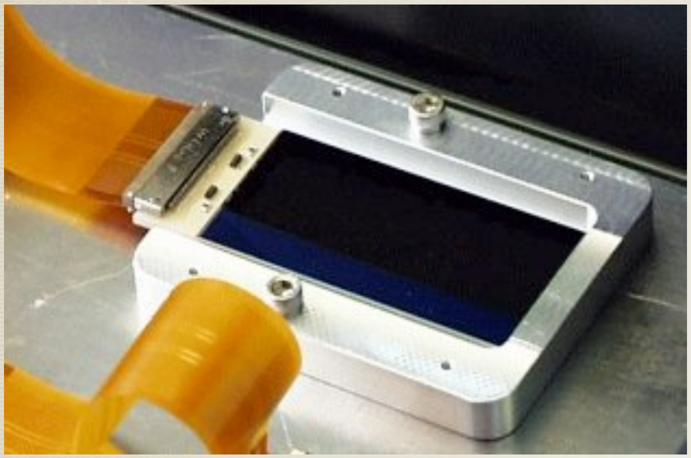
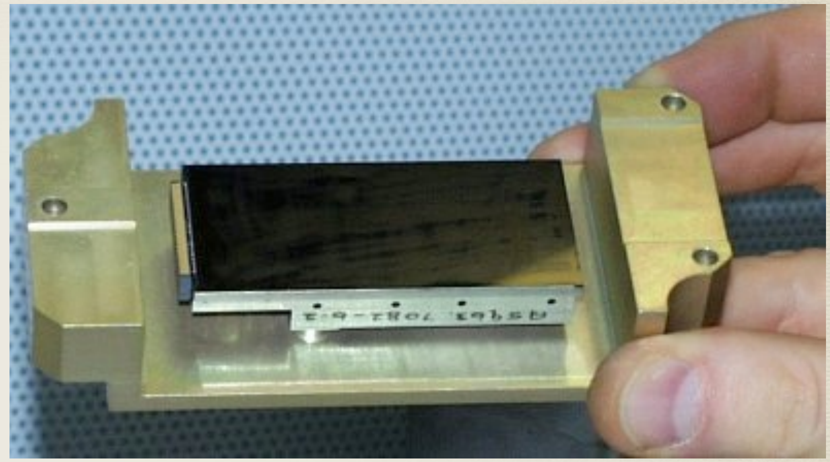
CCDs

- From the near-UV to the near-IR, a single type of detector is almost universally used, called a *charge-coupled device* or CCD





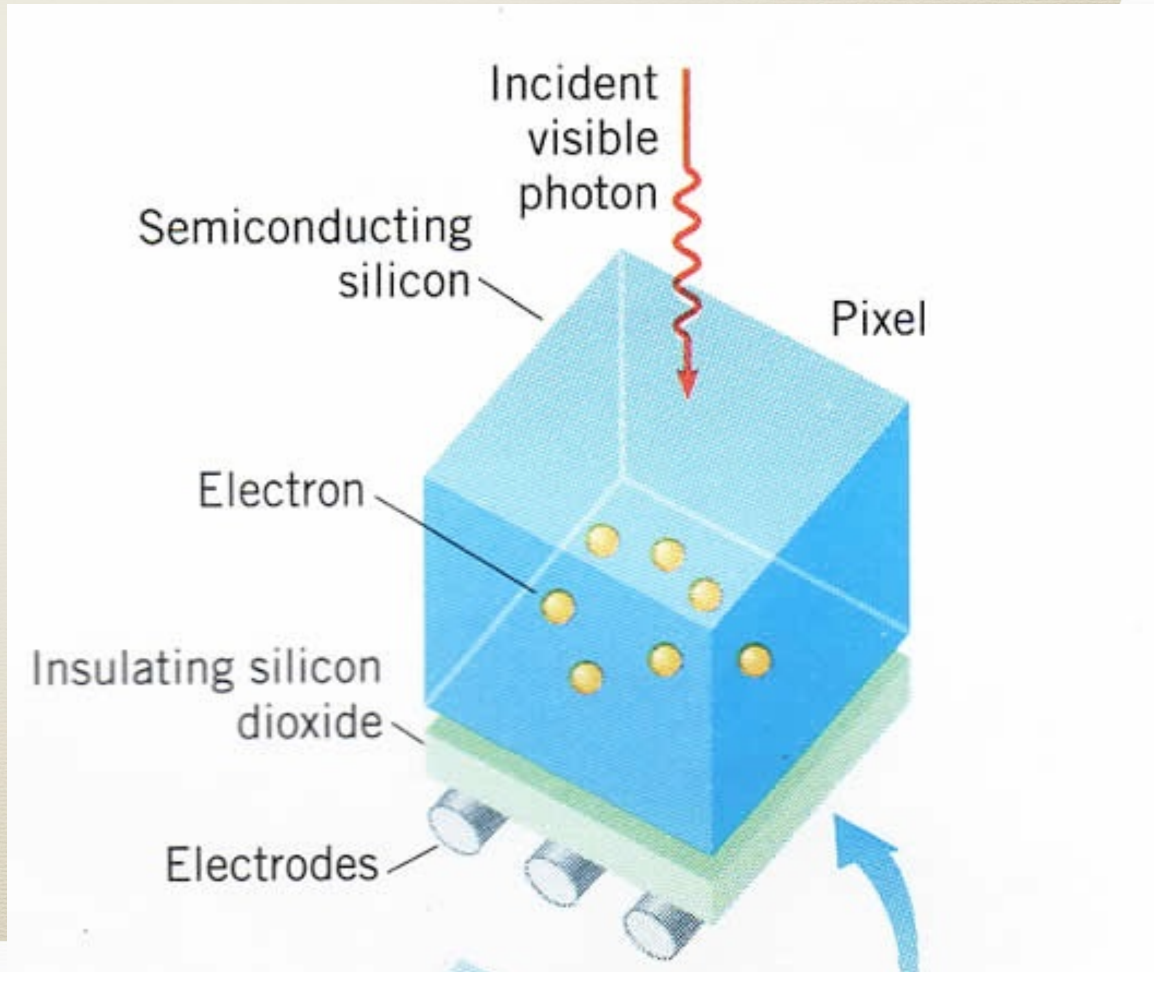
- CCDs have many advantages:
  - High QE, approaching 100%
  - High linearity: output counts almost perfectly $\propto$ # of photons over a wide range in count levels
  - Low noise, high uniformity, digital output format (2kx2k-10kx10k pixels)

Basic idea

- CCDs are made from silicon (with tiny amounts of boron, phosphorus, etc. to contribute extra electrons or 'holes'), just like computer chips (and are manufactured by similar techniques)

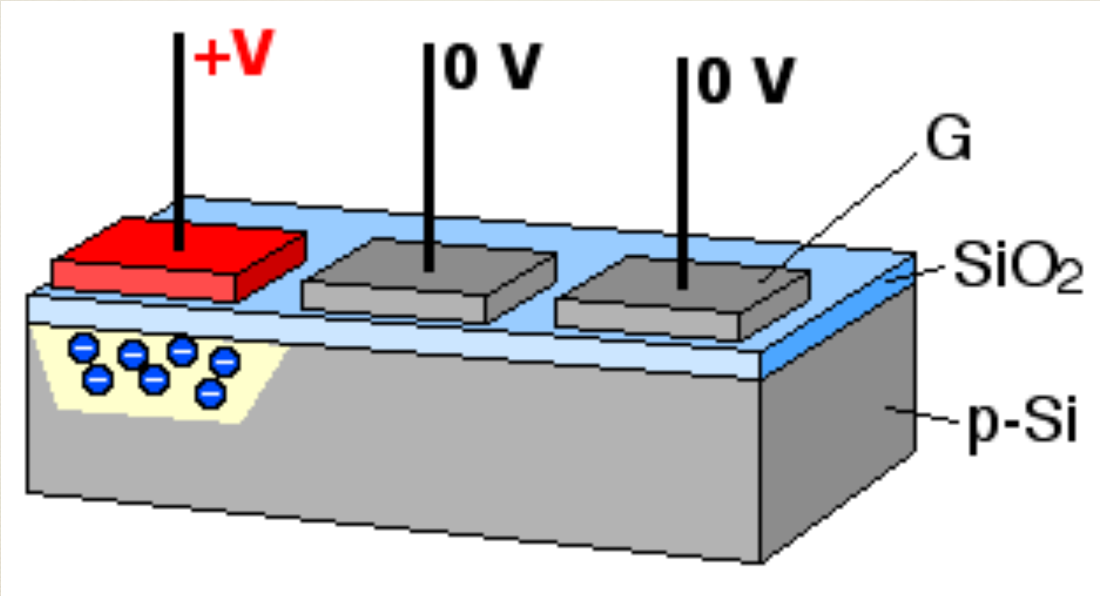
- Photons with energy above 1.14 eV (wavelength <1.1 μm) can liberate electrons from silicon via the photoelectric effect

- The electrons are held in an individual, ~10μm pixel by an applied voltage. Depending on design, $>10^5$ electrons can be held in a pixel - basically a tiny capacitor

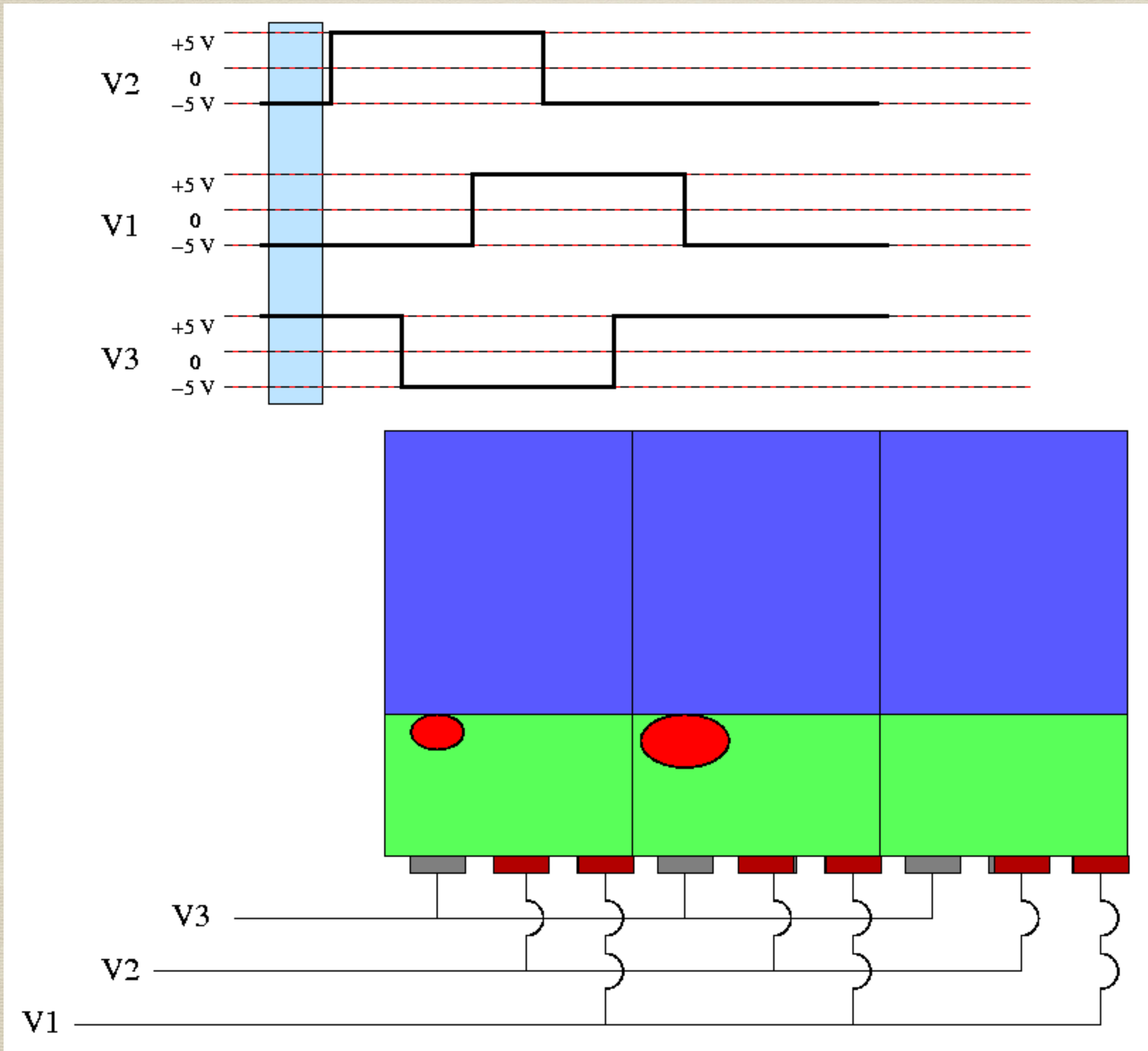


Charge transfer in a CCD

- CCDs are differentiated from other detectors in how they are read out. Charge is transferred from one pixel to the next by cyclically changing the voltages applied to 3 sets of electrodes



Charge transfer in a CCD

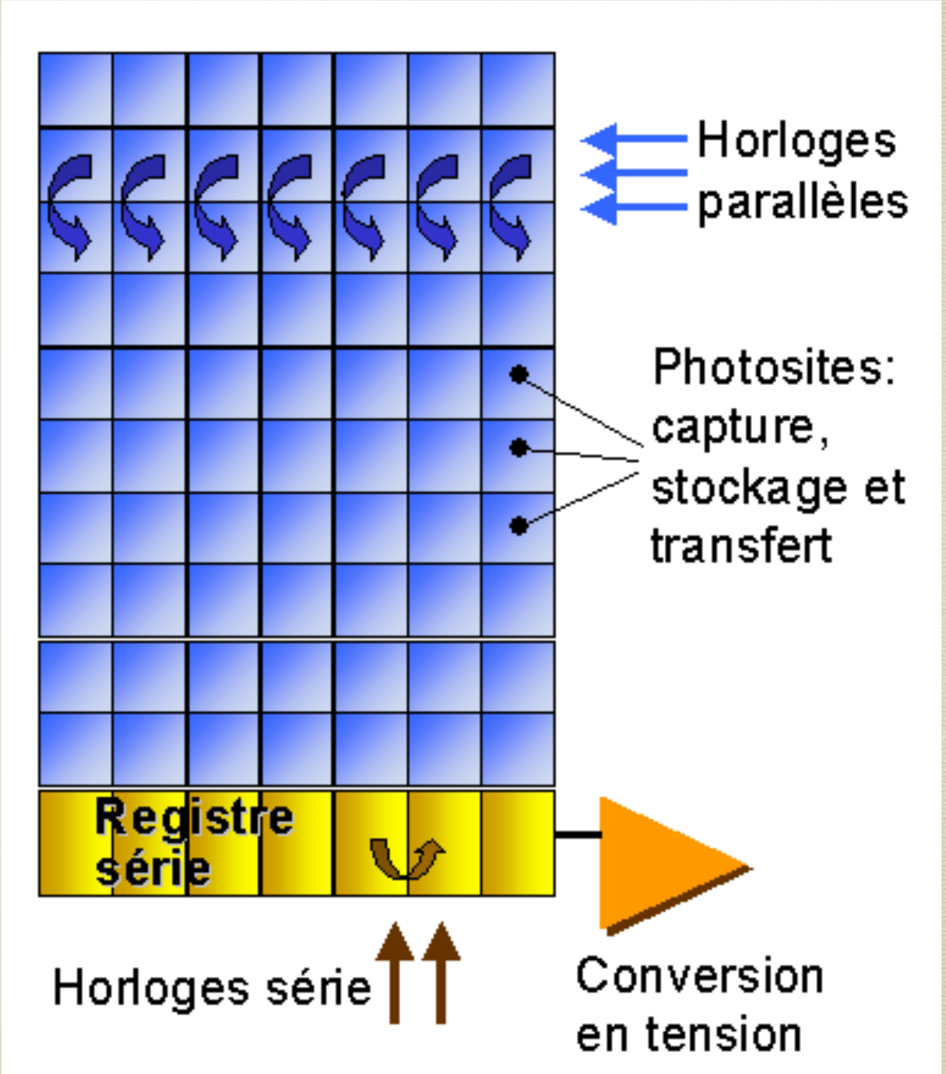


Reading out a CCD

- Charge is moved from one row to the next row, then moved horizontally to an amplifier built into the same chip.

- So all the pixels that share an amplifier are read out in series

- Moves may occur at up to ~20kHz (faster moves result in more noise). So a 2kx2k block of pixels reads out in 200 sec - >3 minutes

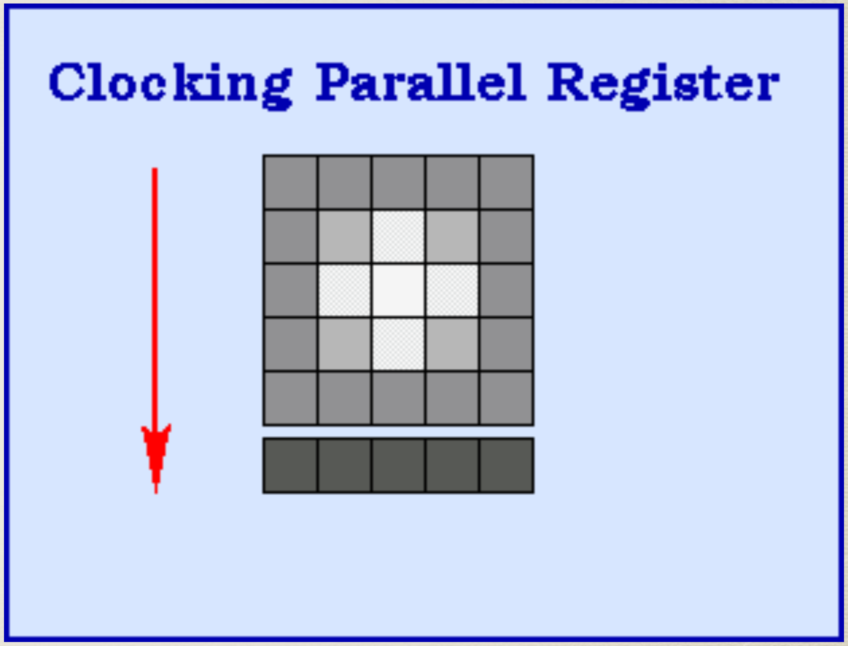


Charge Transfer Efficiency

- There's a small chance that an electron doesn't move; the probability it does is the Charge Transfer Efficiency (CTE).

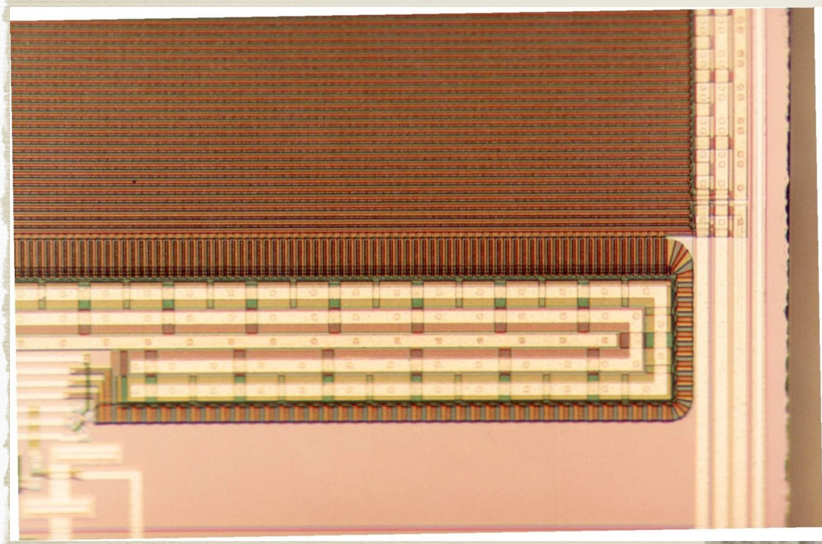
- In a 2kx2k detector, charge can go through 4k moves; CTEs approaching 99.9999% are necessary (1 - 1E6)

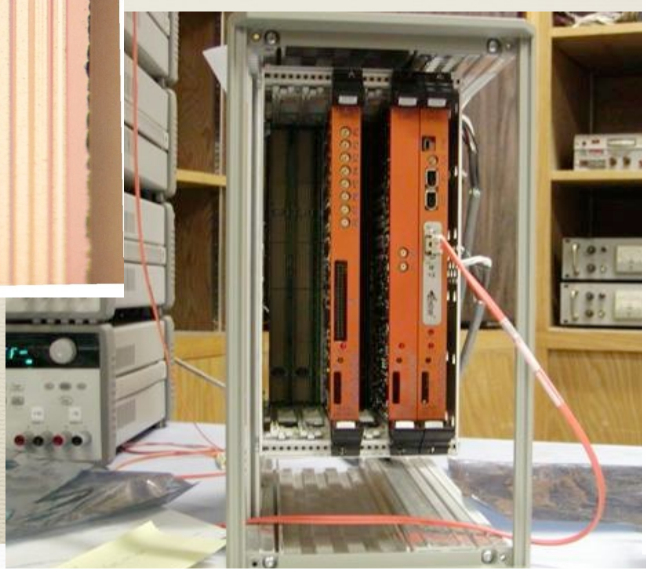
- CTE tends to degrade over time with radiation damage, a problem for CCDs in space



Reading out a CCD

- The amplified signal goes to a set of signal-processing electronics. The analog signal (a measured voltage) gets turned into a digital number for each pixel (a measurement in ADU, or analog-to-digital units)





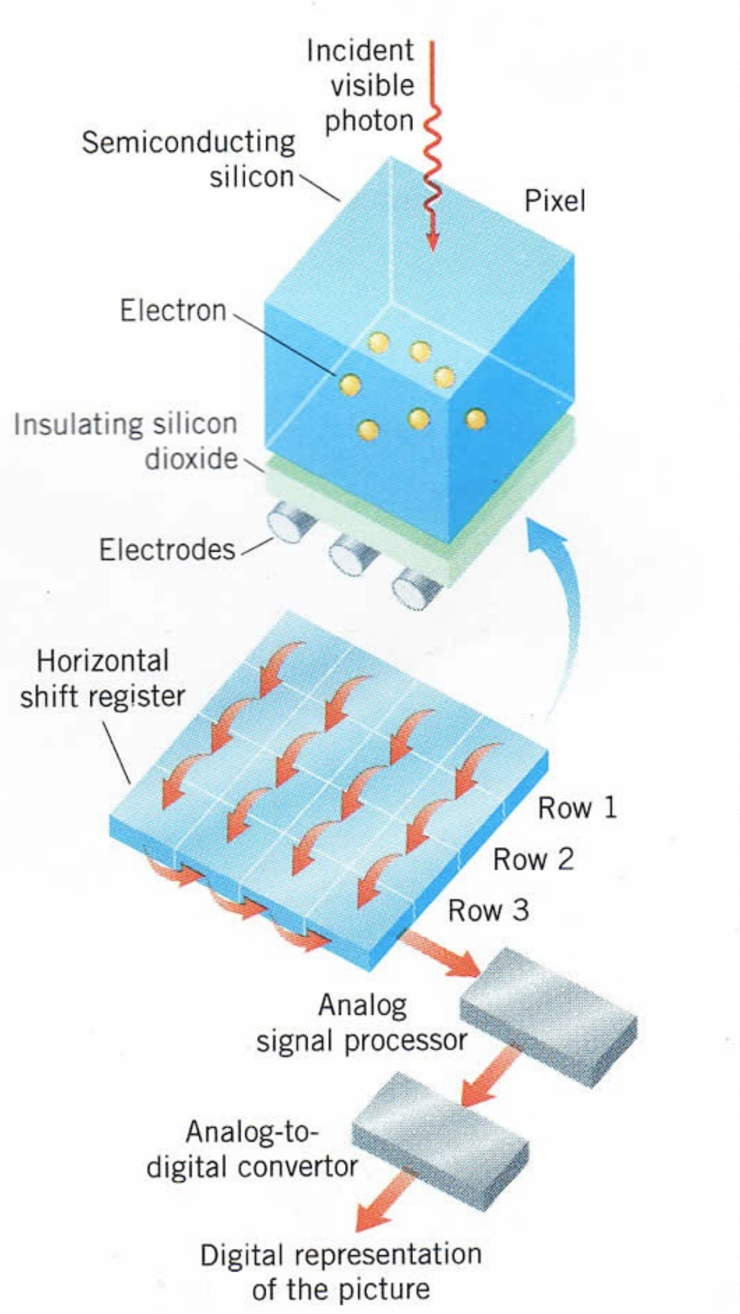
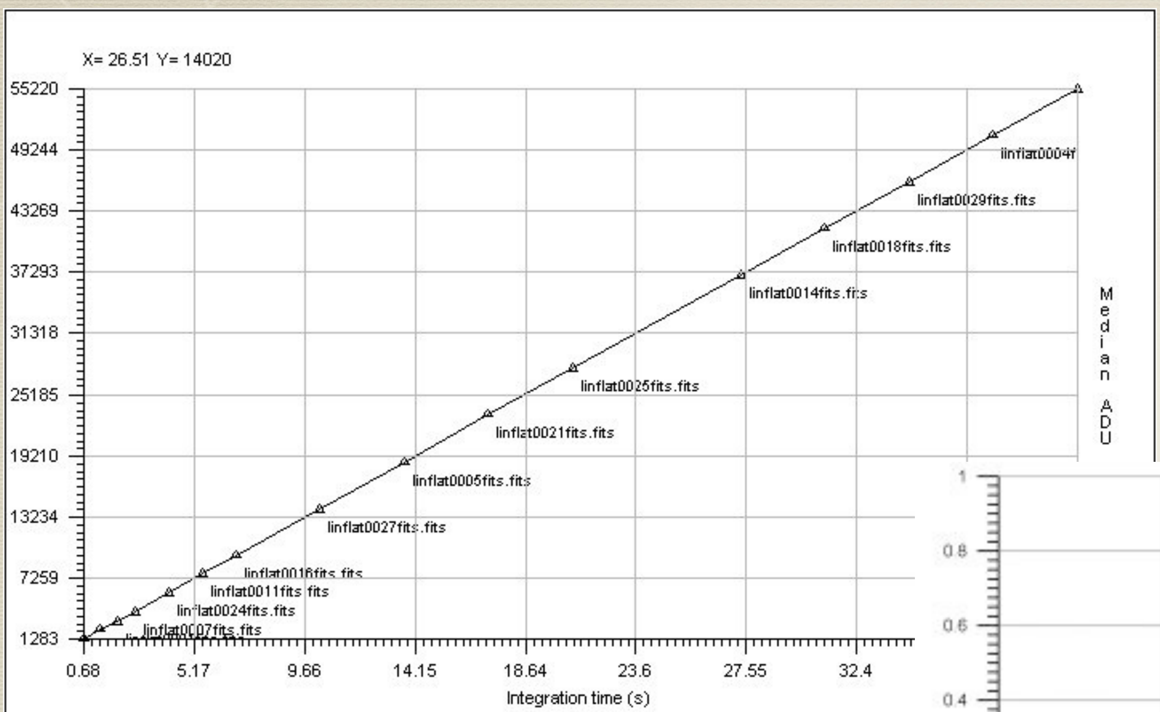
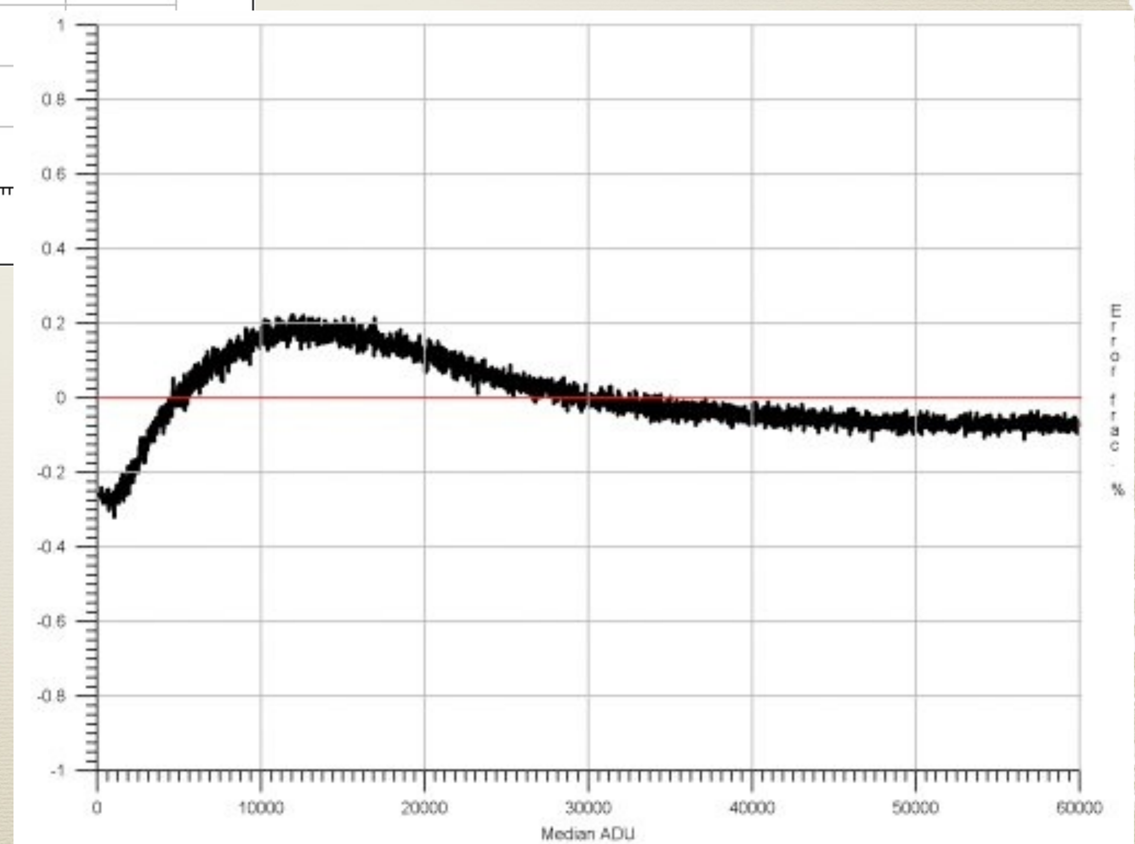


Figure 29.7 A CCD array can be used to capture photographic images using the photoelectric effect.

Linearity of CCDs

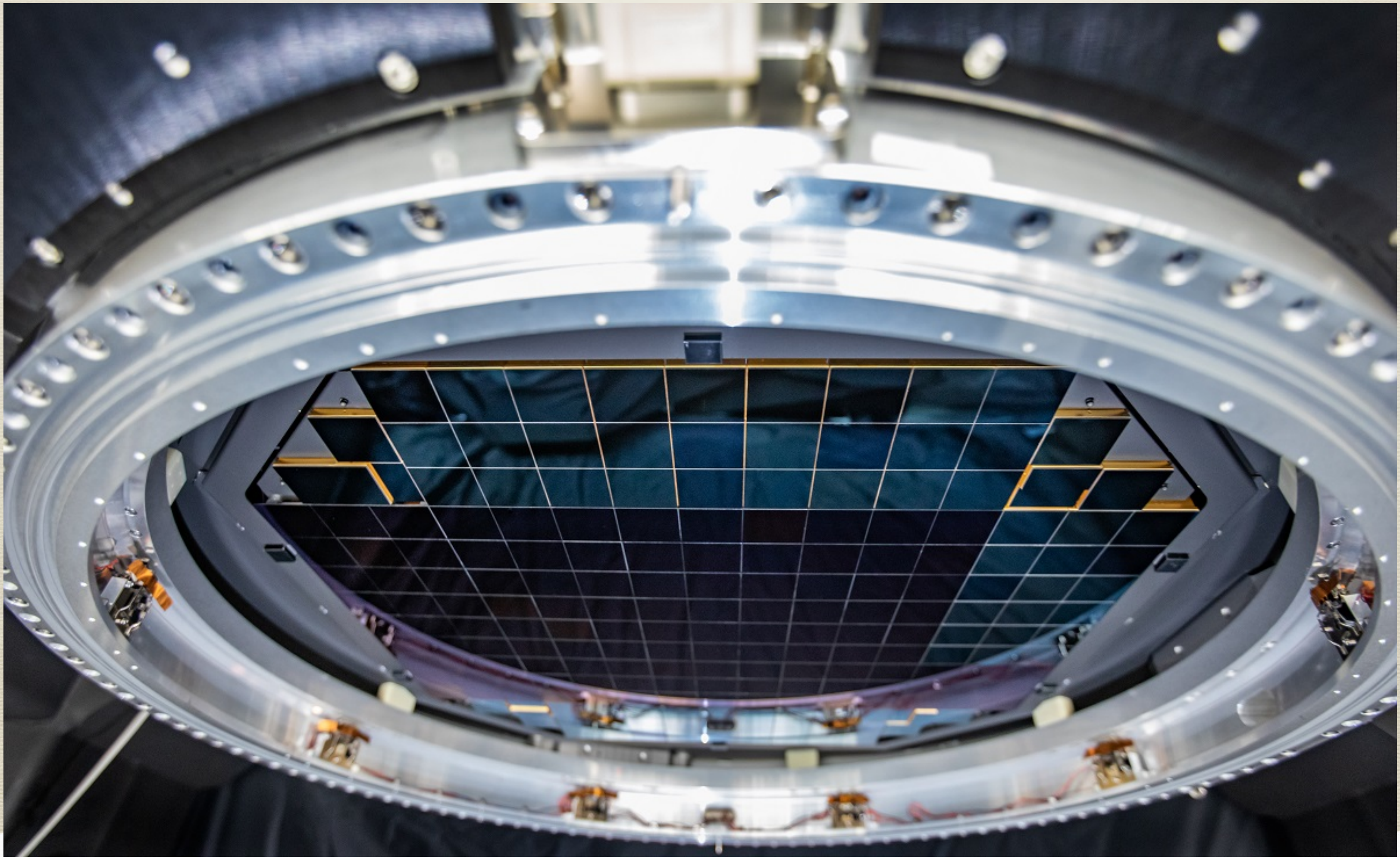




- CCDs are generally highly linear detectors, though there can be deviations when pixels contain extremely few or extremely many electrons

Large field-of-view instruments use many CCDs

- Example: Rubin Observatory LSST Camera
  - 189 4k x 4k CCDs $\Rightarrow$ 3.2 Gigapixels



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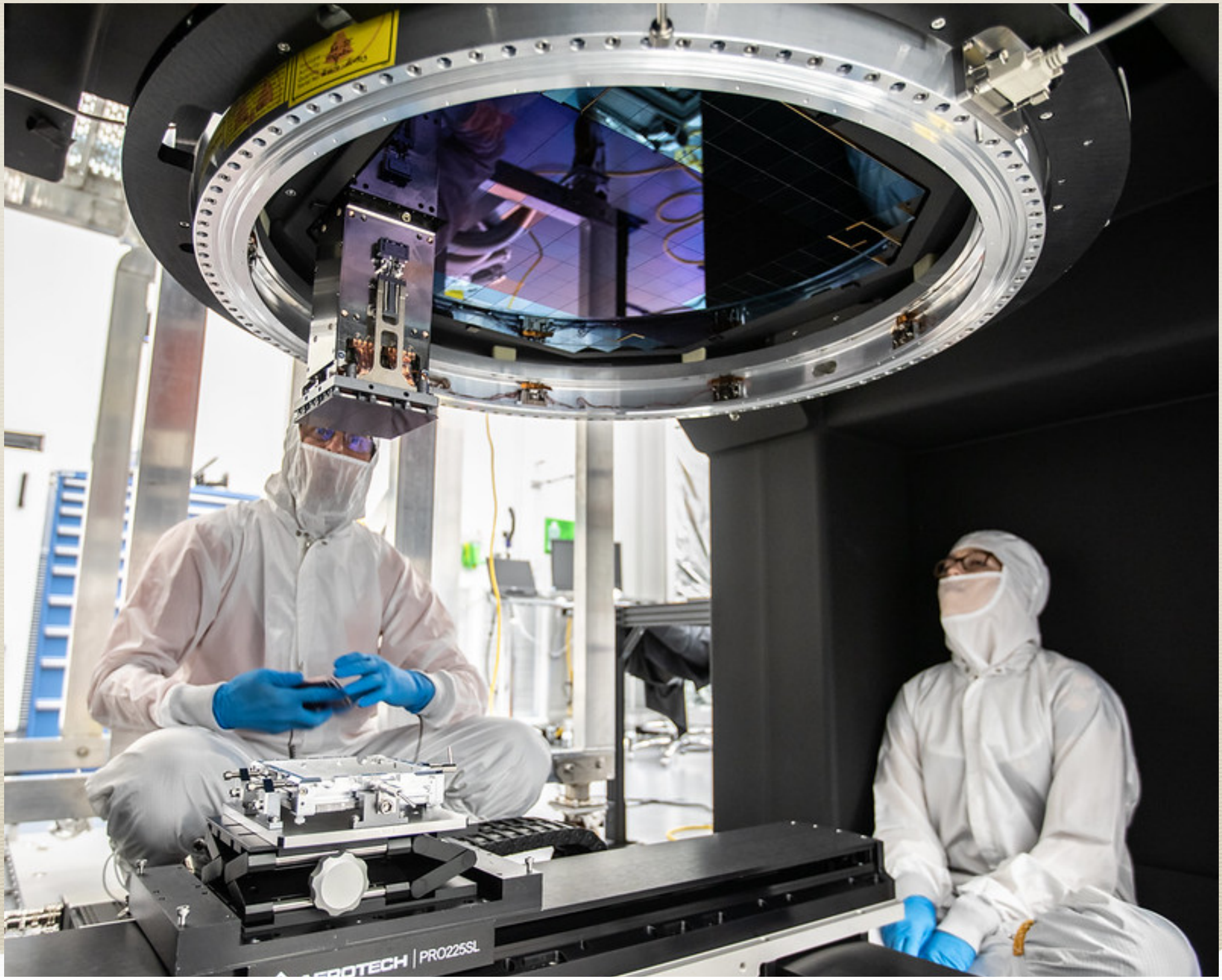

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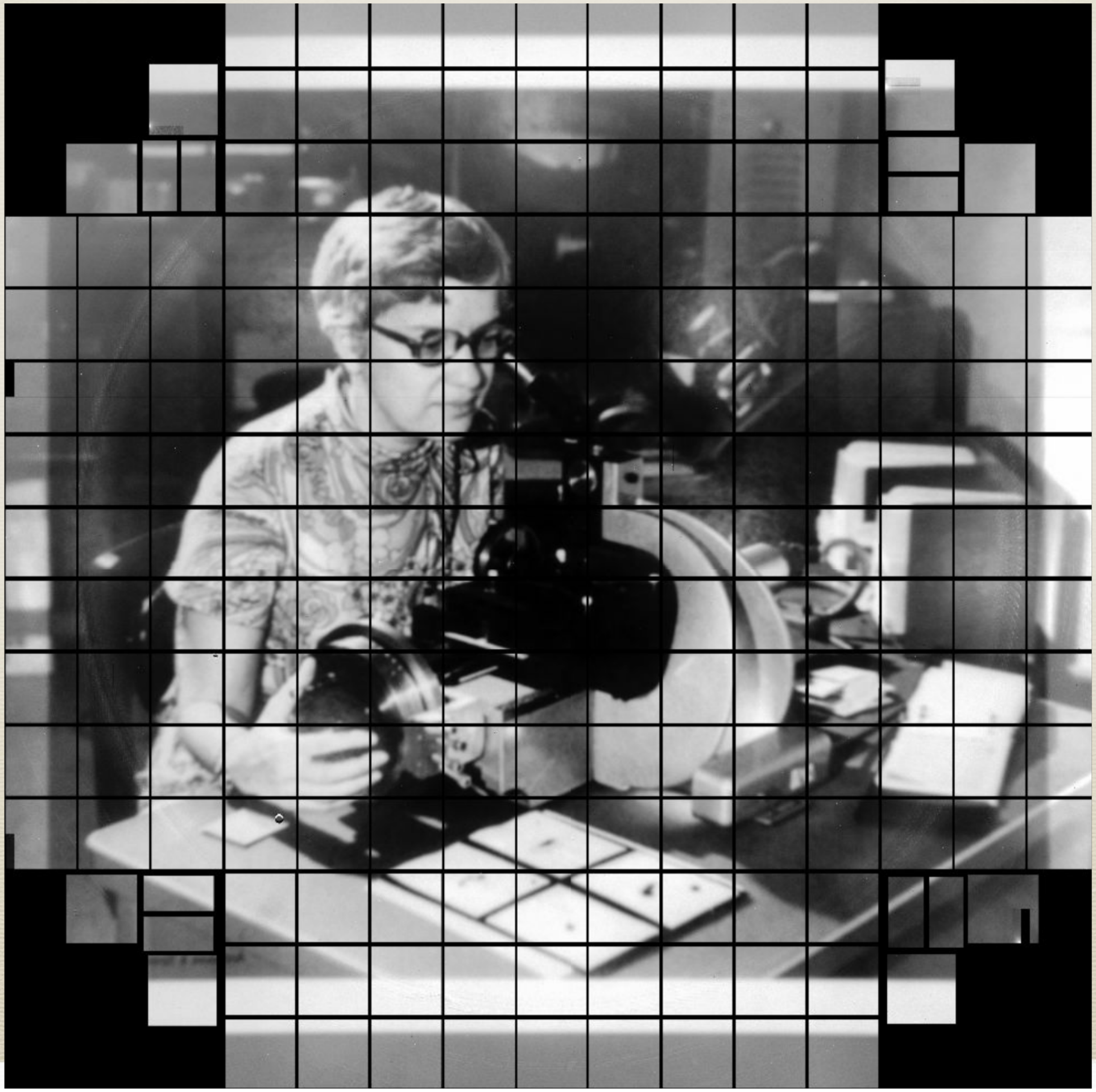
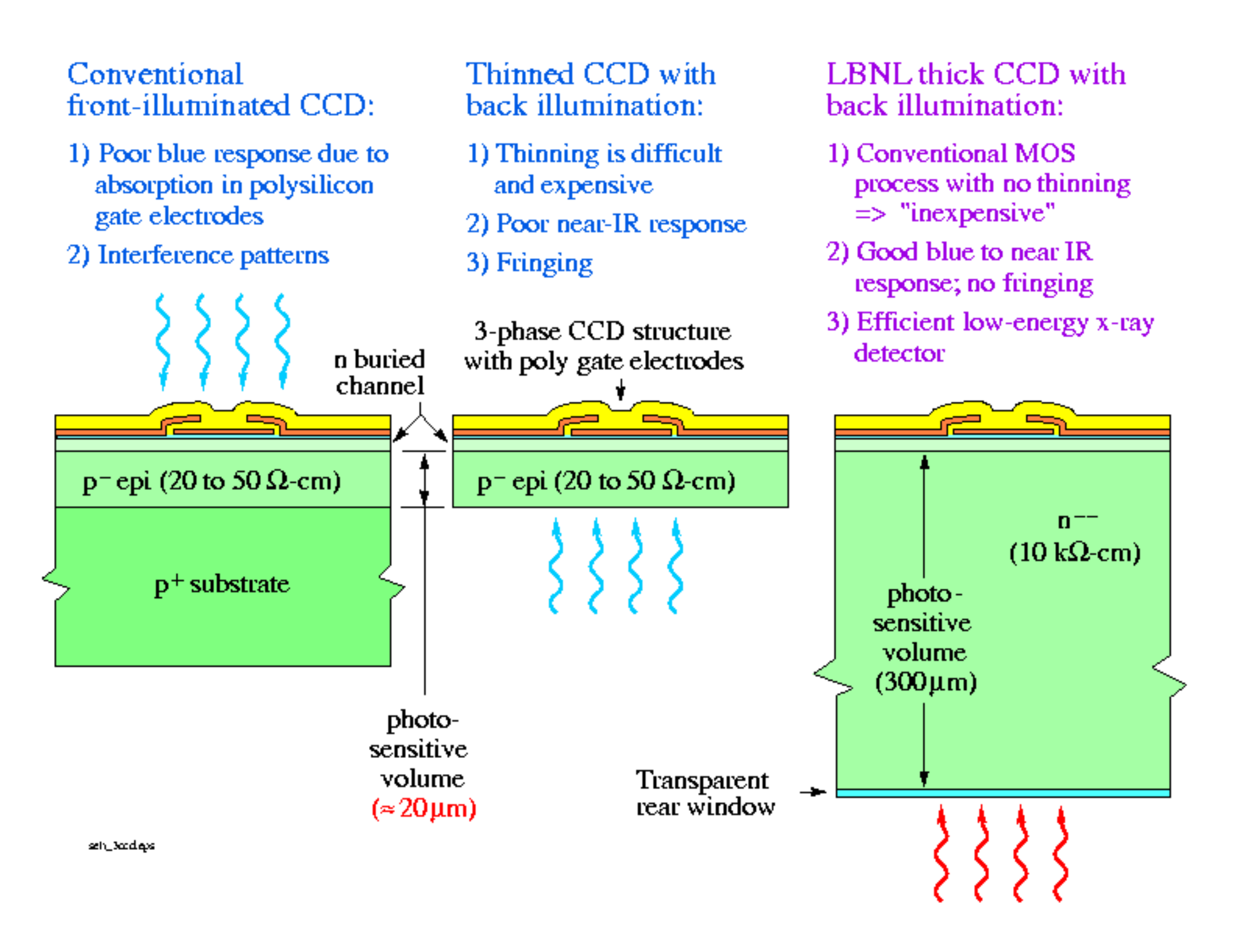


Types of CCDs

- CCDs are either *front-side-illuminated* (so all the photons travel through the electrodes, etc. etched on top), which impedes sensitivity especially in the UV; or *back-side illuminated* (in which case they normally need to be made thinner by etching, lowering yields)



Gain & read noise

- The digital value for each pixel in ADU is not the same as the number of electrons recorded; e.g. if we have two bytes (0-65535) to encode each pixel, and pixels can hold up to 100k electrons, we might read out the CCD with a *gain* of 2 e^-/ADU.

- One component to the noise from each pixel is the *shot noise*: this is simply the Poisson error in the number of electrons that a pixel will record (as each photon is an independent event, this obeys Poisson statistics). Not that this noise will be $N_{e^-}^{1/2}$, NOT $N_{ADU}^{1/2}$. Noise (in ADU) = Noise (in e^-) / g, where g is the gain.

- Additionally, there is a small amount of noise inherent in the readout electronics: the *read noise*. It is generally specified in RMS electrons; this is the standard deviation in the counts from a single pixel that contains the same number of electrons. Good detectors today have read noise <5 e^-.

Bias

- ADU values are generally only >=0; this will bias the errors from read noise when signal is close to 0

- To get around this, the output electronics apply a bias voltage to all measurements, e.g. 400 or 1000 ADU

- We can then determine the bias level either with:

  1) a *bias frame*: observe for 0 seconds, then readout the CCD. This can be useful if some pixels have accumulated charge so have different bias levels than others; but multiple bias frames may be needed to limit noise

  2) an *overscan region*: read out, say, 32 rows of data after the data is all read out. We can then take the average of those measurements as our mean bias level

Dark current

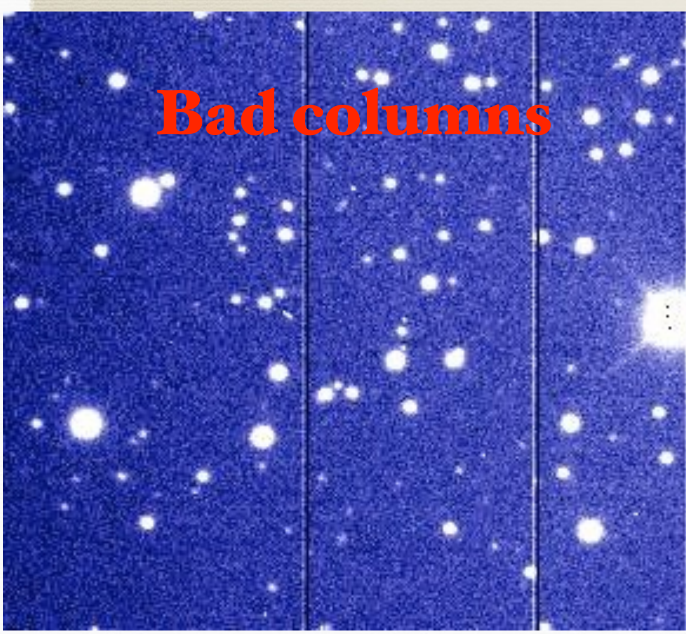
- Some CCDs will accumulate charge over time due to electrons knocked loose thermally; this signal is called *dark current*

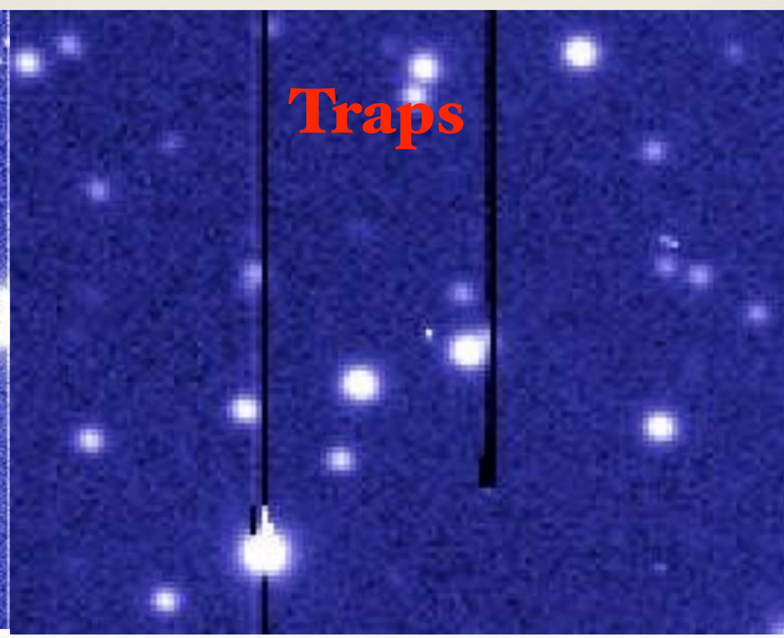
- Research CCDs are generally kept in liquid nitrogen dewars, ~-100 C, to minimize this.

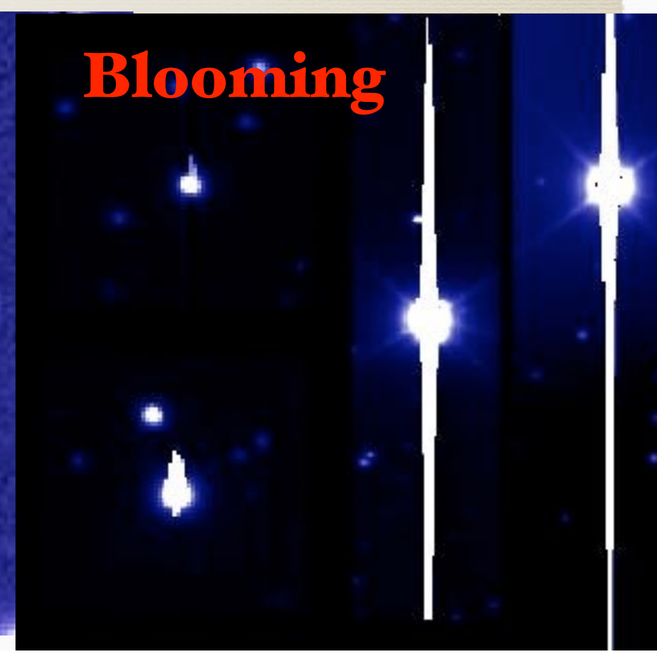
- If dark current is significant, we can remove its effects by observing with the shutter closed exactly as long as we observe with it open, and remove it pixel-by-pixel (may need multiple dark frames to minimize noise); this is called a *dark frame*

Bad pixels

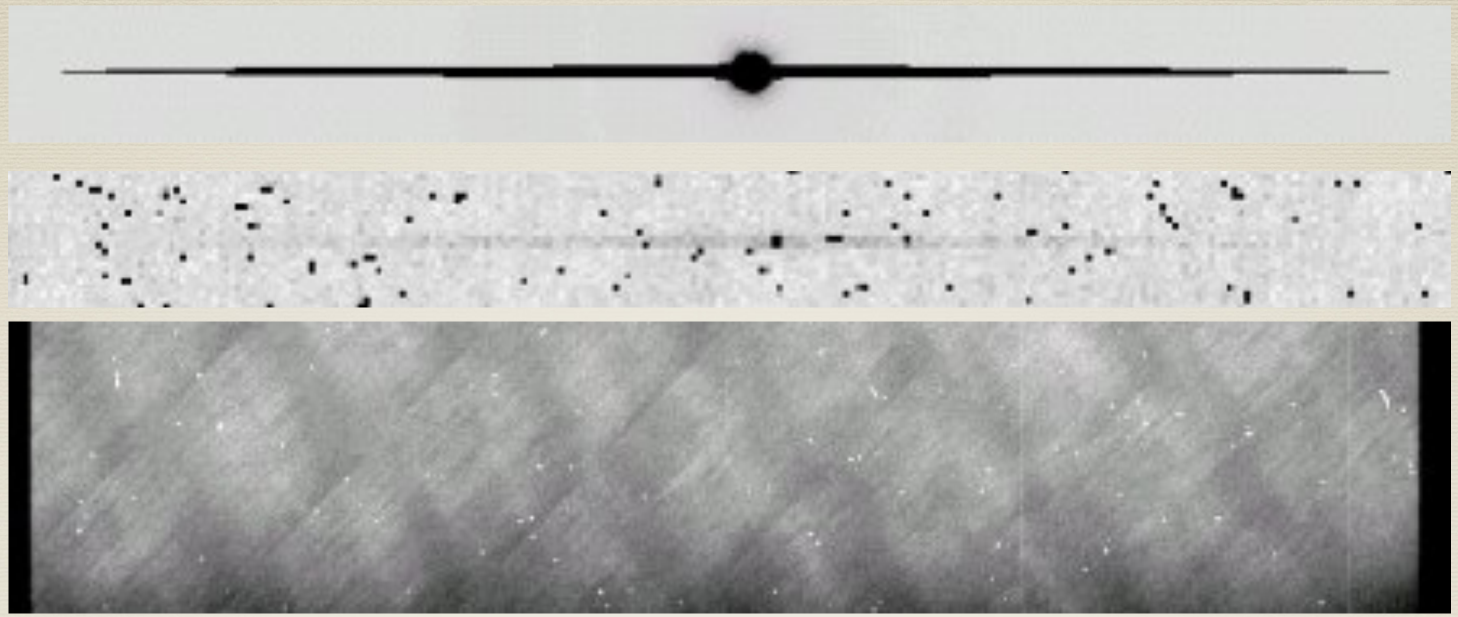
- All silicon chips have defects. Sometimes a whole column may not be able to be read out, or a single pixel may 'trap' all charge coming from behind it
- There are also 'hot pixels' which have strong dark current, depending on temperature. We deal with these problems by 'dithering': taking images with multiple-pixel shifts between them
- In other cases, data in a pixel may be overcome by electrons spilled over from pixels with bright objects, or there can be afterimages left in the CCD



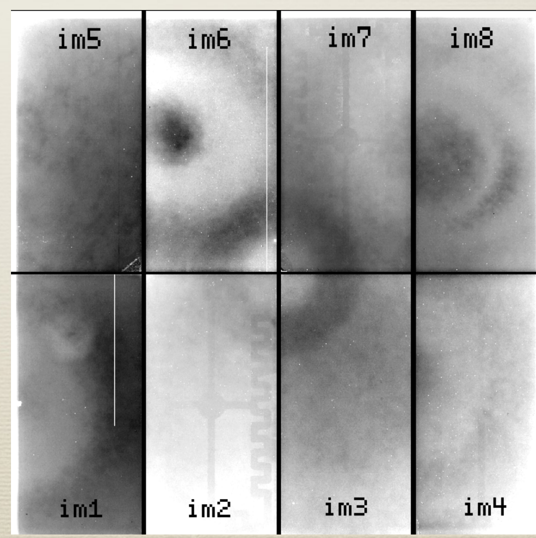




Afterimages



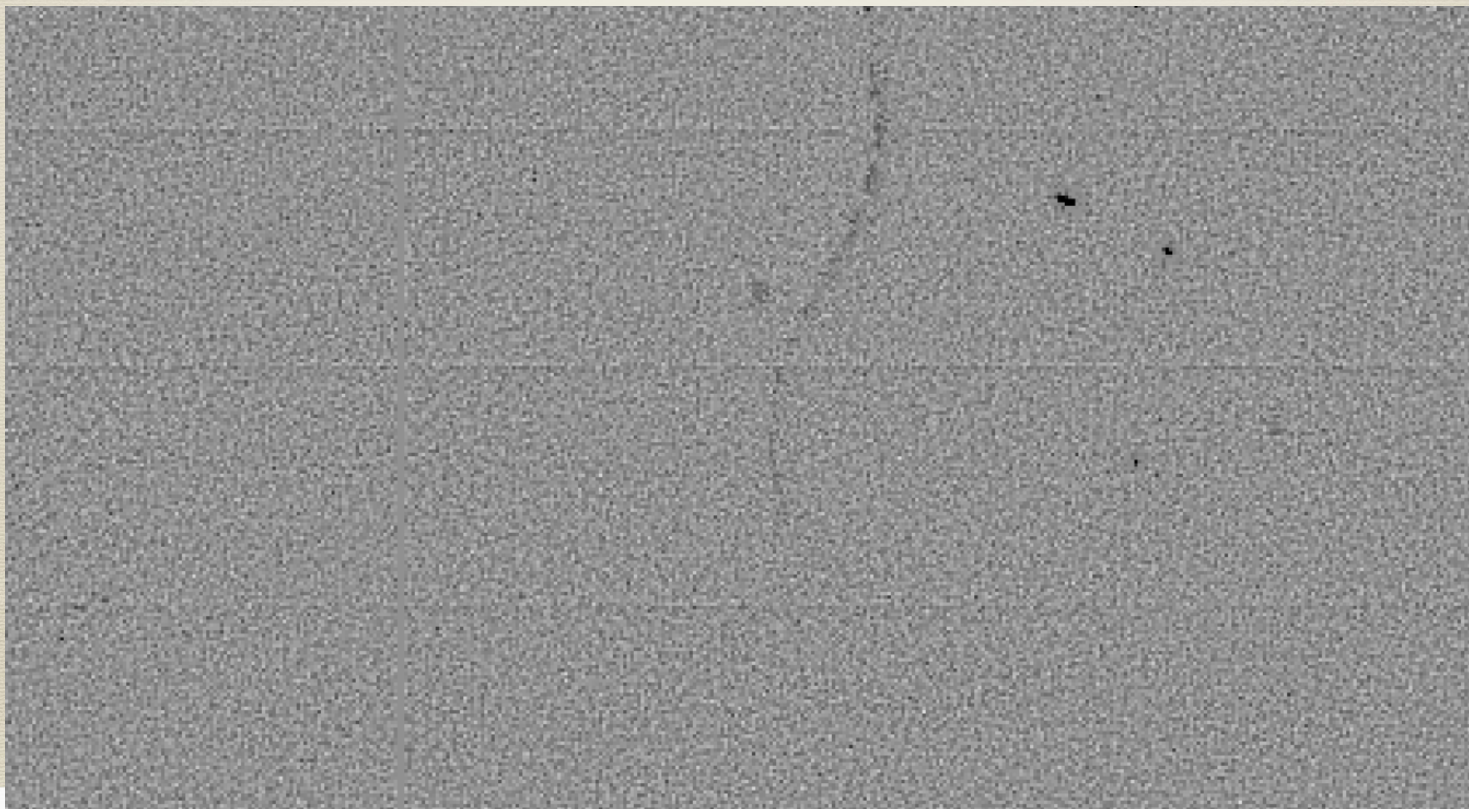
- Every CCD has its own idiosyncracies, generally only learned from years of experience. It's only worse when we have 'mosaics' of multiple CCDs...



Response variations

- Pixels will typically vary in their QE by 1-5%; also some pixels may be obstructed by dust or lie on imperfections in the silicon

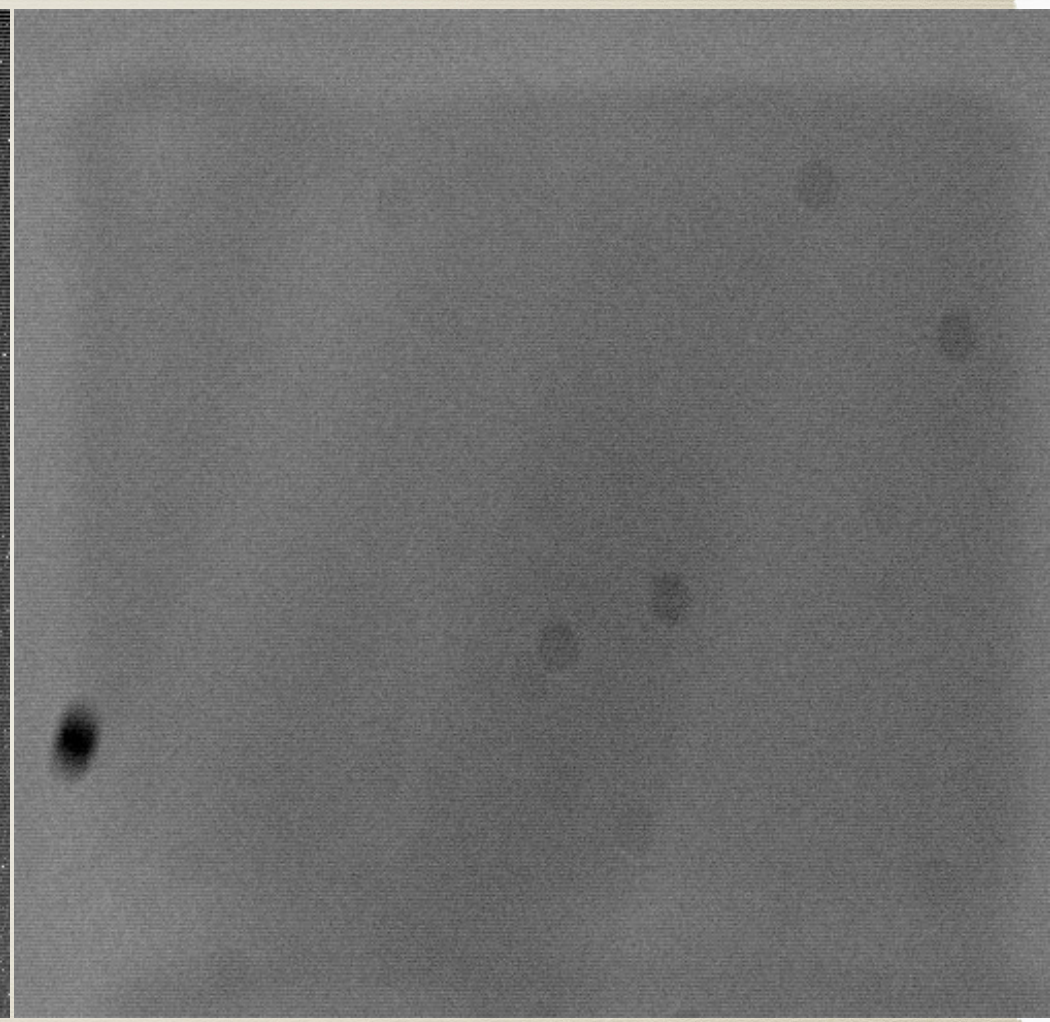
- We'd further like to correct for variations in sky area, fringing, etc.



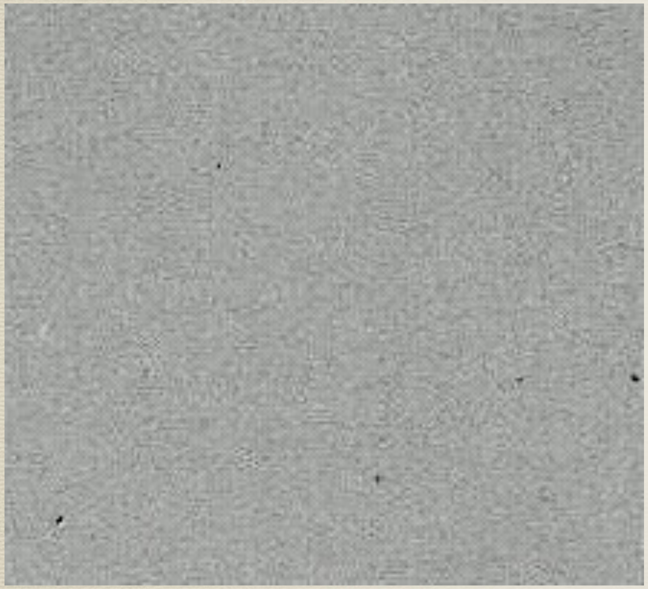
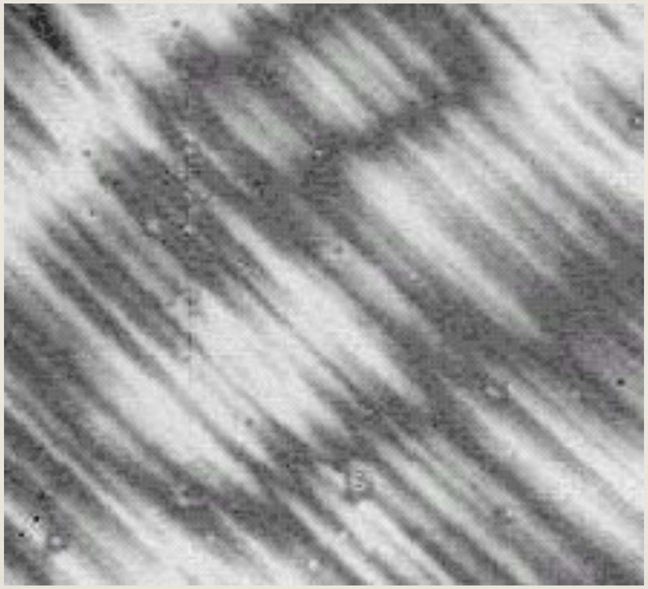
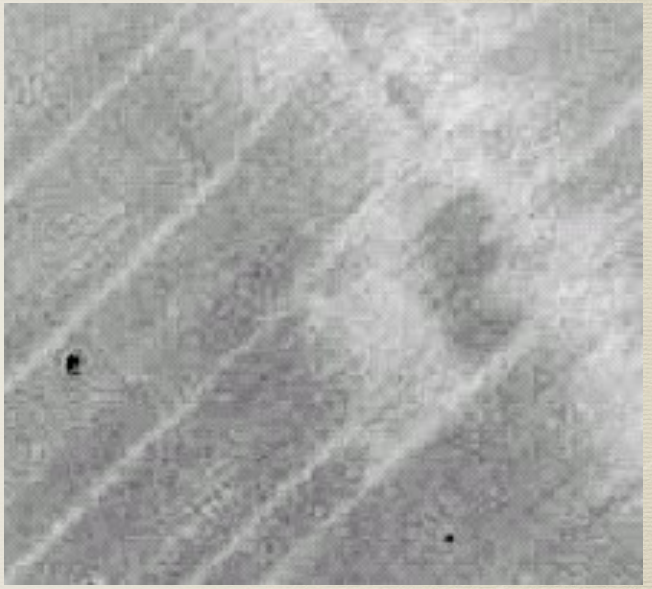
Flat-field frames

- If we know how every pixel responds to light, we can correct for all these variations
- So we observe a uniform, diffuse source of light and measure how strongly each pixel responds; then we can divide by that to correct for variations in QE, etc. T
- Suitable light sources include:
  - Twilight sky
  - The telescope dome (illuminated by lamps)
  - Internal lamps
  - Median of a big stack of sky images
  - There will be Poisson noise in the flat fields. If we want to measure 1% variations to 0.2% accuracy, say, we need 250,000 counts total!

Data vs. flat



Flat fields can depend on wavelength, operating temperature, etc.

Basic data processing

- In addition to your images of the sky, obtain multiple flat fields, and bias and dark frames as necessary, hopefully during daylight/twilight hours
- Combine multiple darks, flats, etc. together. to minimize noise
- Manipulate the flat:

  flat -> (flat-bias); correct for nonlinearity & gain; then

  flat -> flat/mean(flat); i.e., normalize to have mean 1
- Read in the data, correct for bias & dark current:

  data -> (data - [bias or dark])

  - Correct for linearity & gain, then for pixel response variations, fringing, etc.:

  data -> data/normalized flat
- At the same time, we generally keep a 'noise' or 'weight' image which gives the uncertainty in the measurement at each pixel. If we multiply the data by a constant *a*, the noise gets multiplied by *a* too.