An Introduction to Detectors

Why Understanding CCDs is Crucial for Modern Surveys

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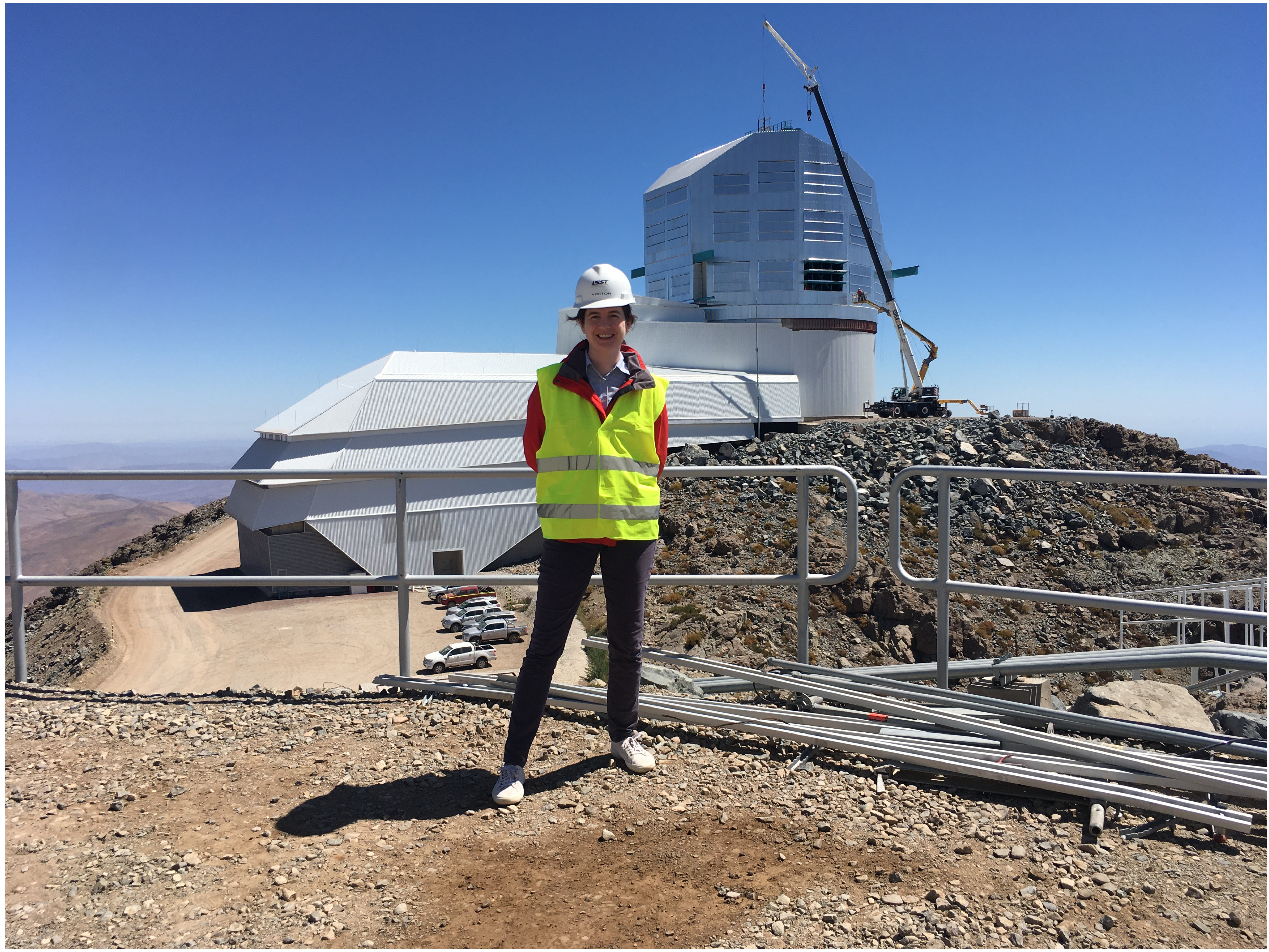
June 12, 2023, University of Washington

Quick Personal introduction

- Member of Rubin Data Management since 2019
  - Data Release Production team
- Officially based at Princeton University (but physically based in Montreal)
- Background in SNIa Cosmology (imaging and spectrophotometric surveys)
- Currently focused on astrometric calibration

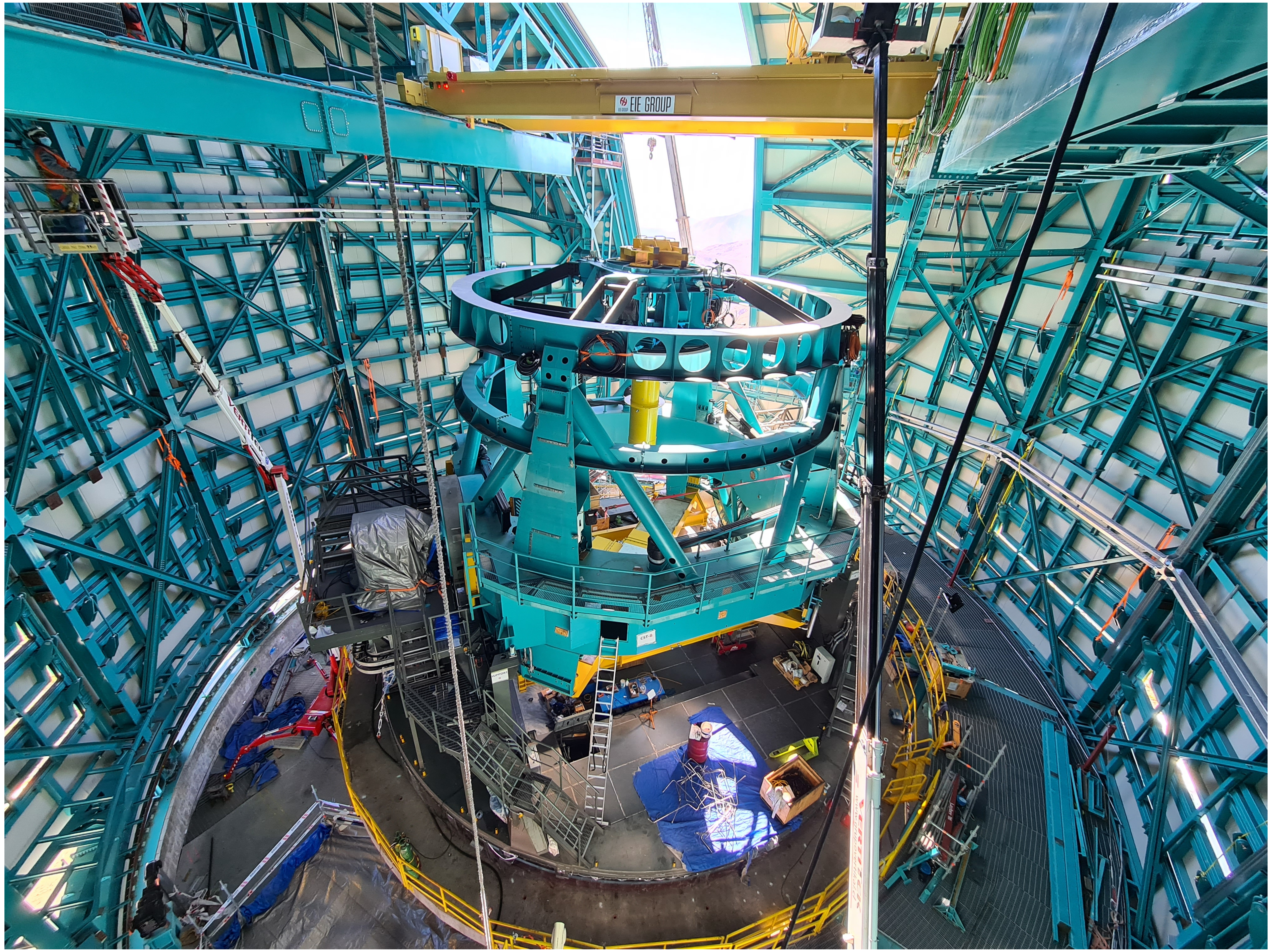


Outline

1. Quick telescope overview
   - Situating detectors in the big picture
2. How do CCDs work?
   - Following the signal chain
3. Fun side-effects
   - Saturation, the brighter-fatter effect, tree rings.

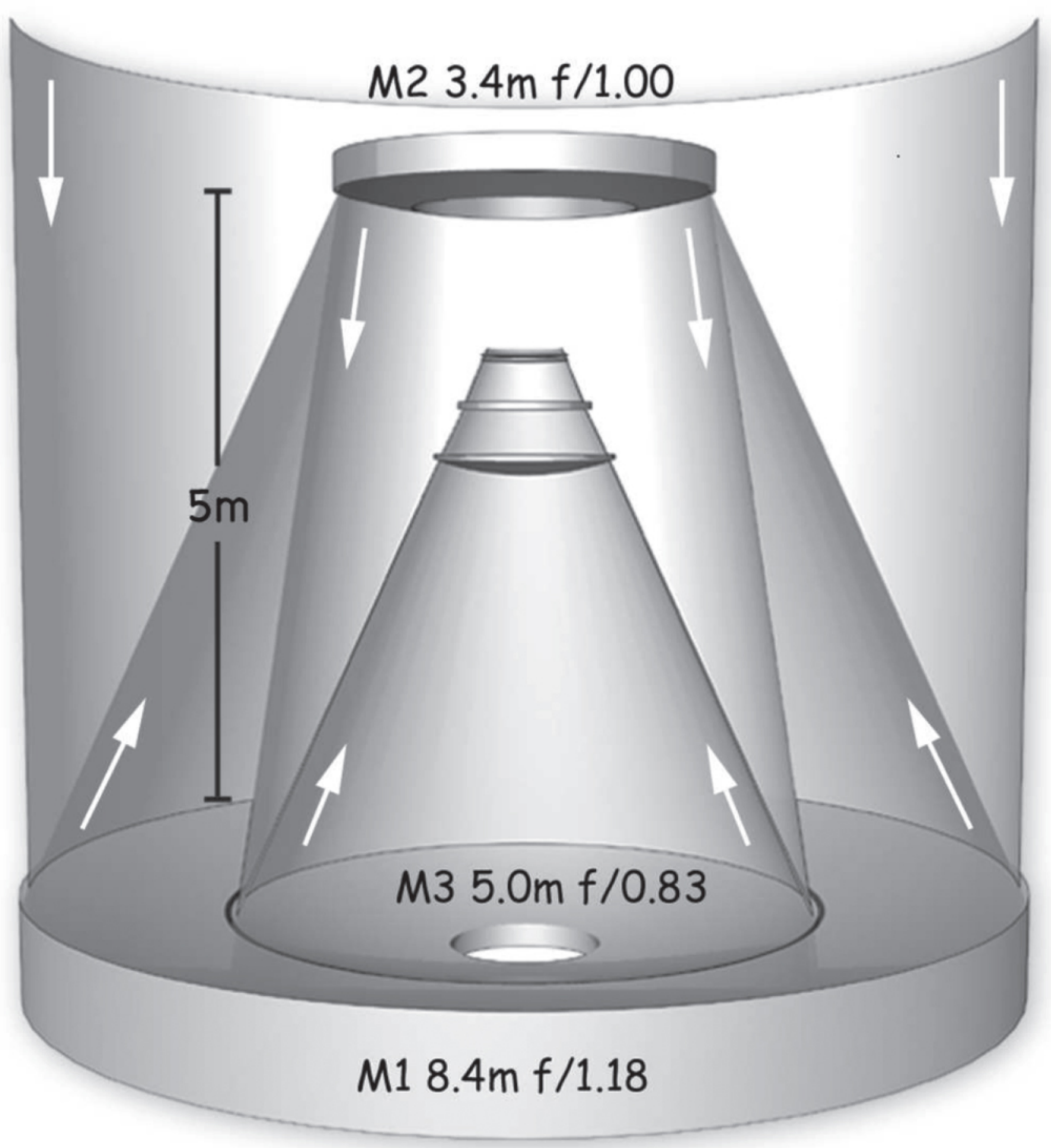
The Path of a Photon

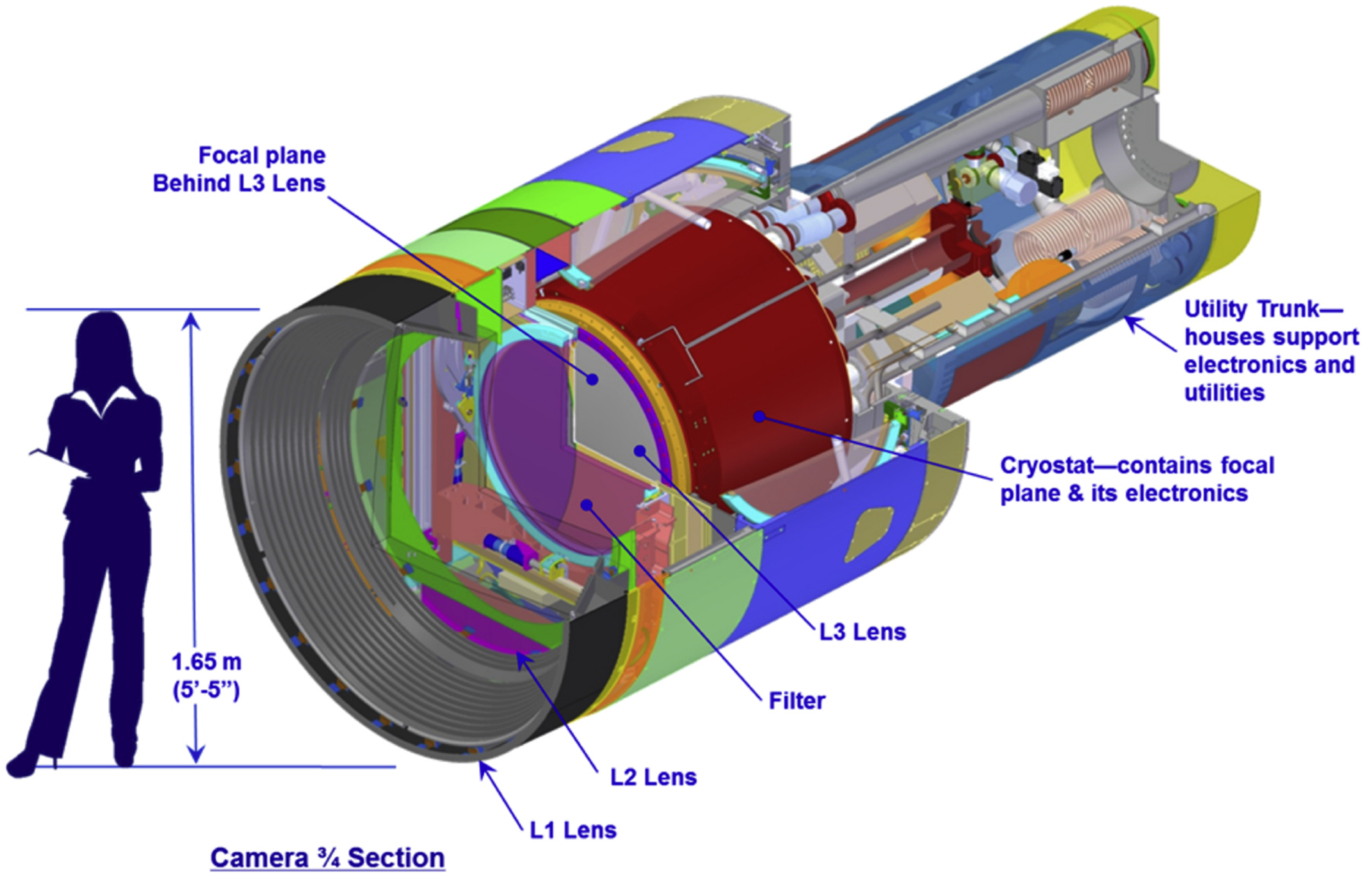
The telescope mount assembly



The Path of a Photon

Mirrors, Lenses, and Camera

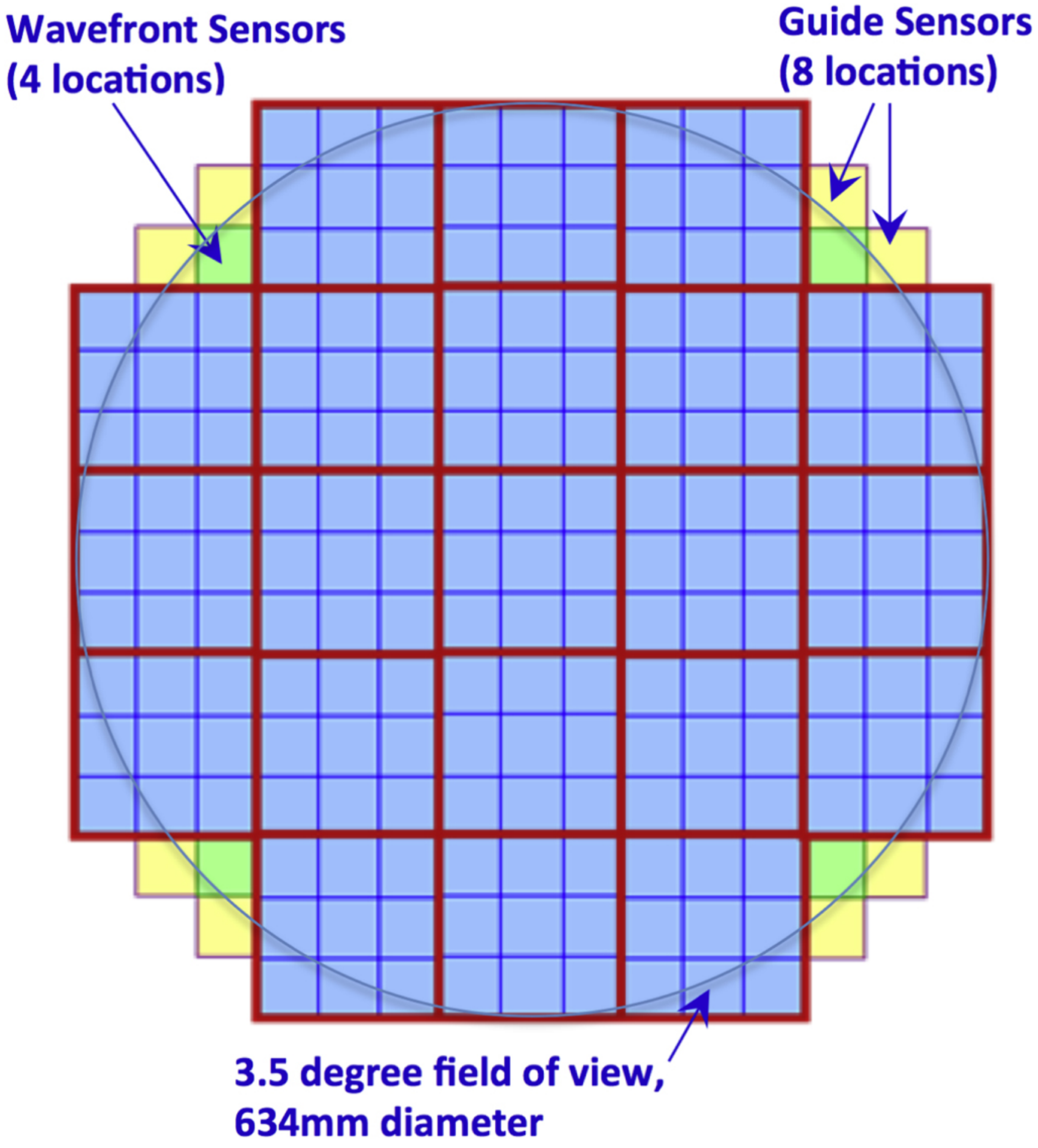




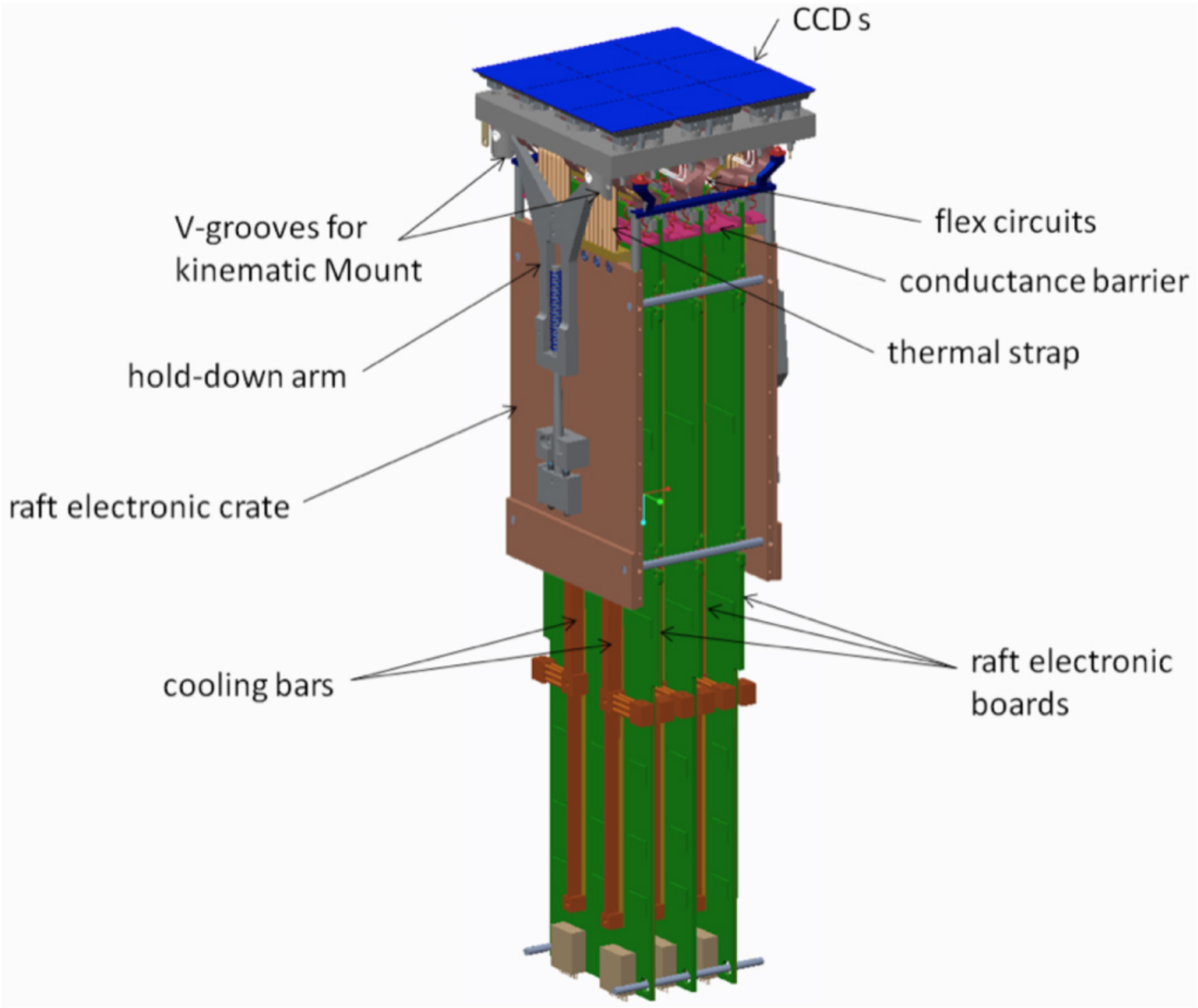
The Path of a Photon

The detectors

LSSTCam Focal Plane Array



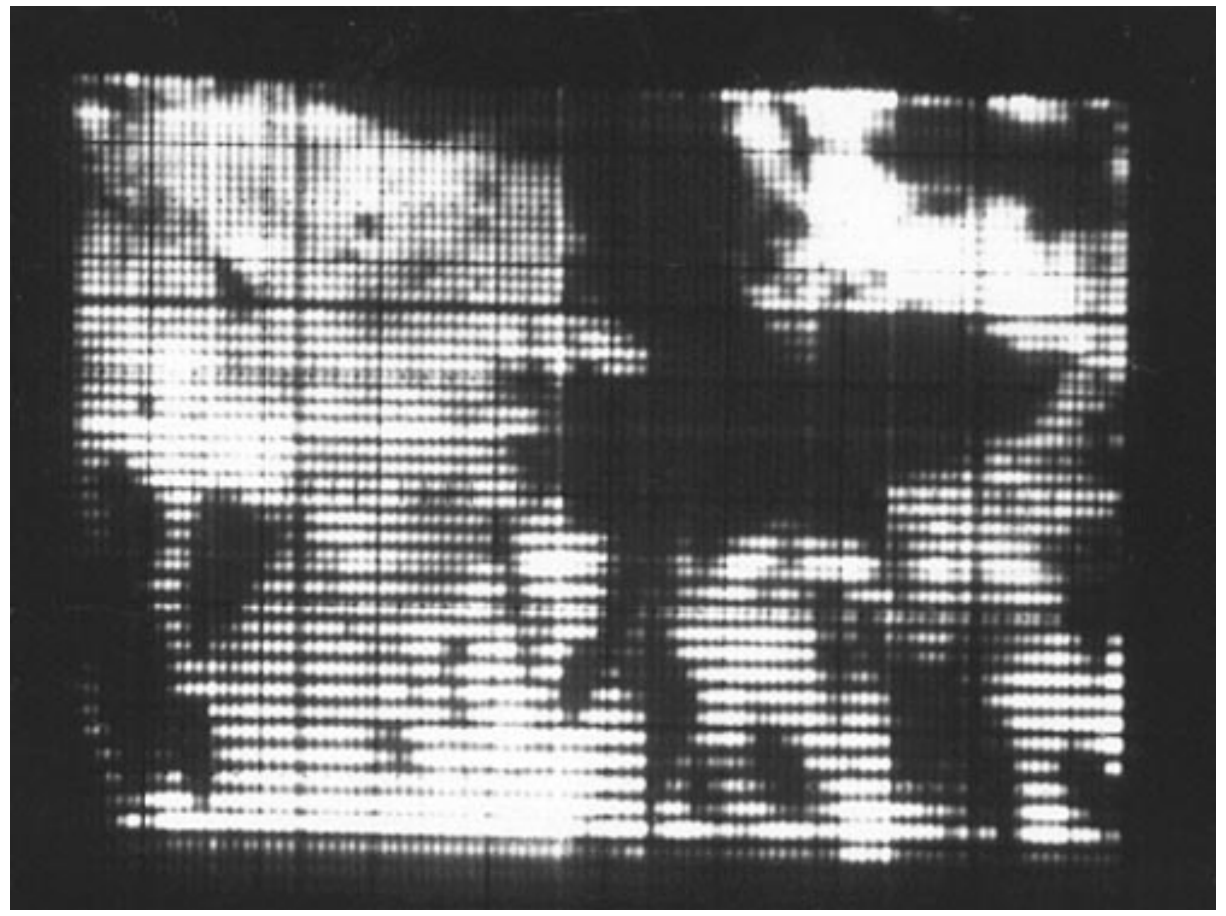
LSSTCam Raft Module (one of the red squares at left)



A brief history of Charge-coupled devices (CCDs)

- The CCD was invented at Bell Labs in 1969
- Became the standard for astronomical imaging in the 1980s.
- Different than the detector in you phone camera, which is a Complementary Metal Oxide Semiconductor (CMOS) imager.
- Improvements in the past 50 years have led to devices with over 100 million pixels, low read noise, and high quantum efficiency (discussed later).
    - Developments in CCDs are closely tied to advancements in the field!

Very Early Astronomical Images from CCDs



Craters of the moon, taken by Jim Janesick in 1974 (100 x 100 pixels)

Uranus, taken in 1976 (400 x 400 pixels)

Recent Image with Modern CCDs

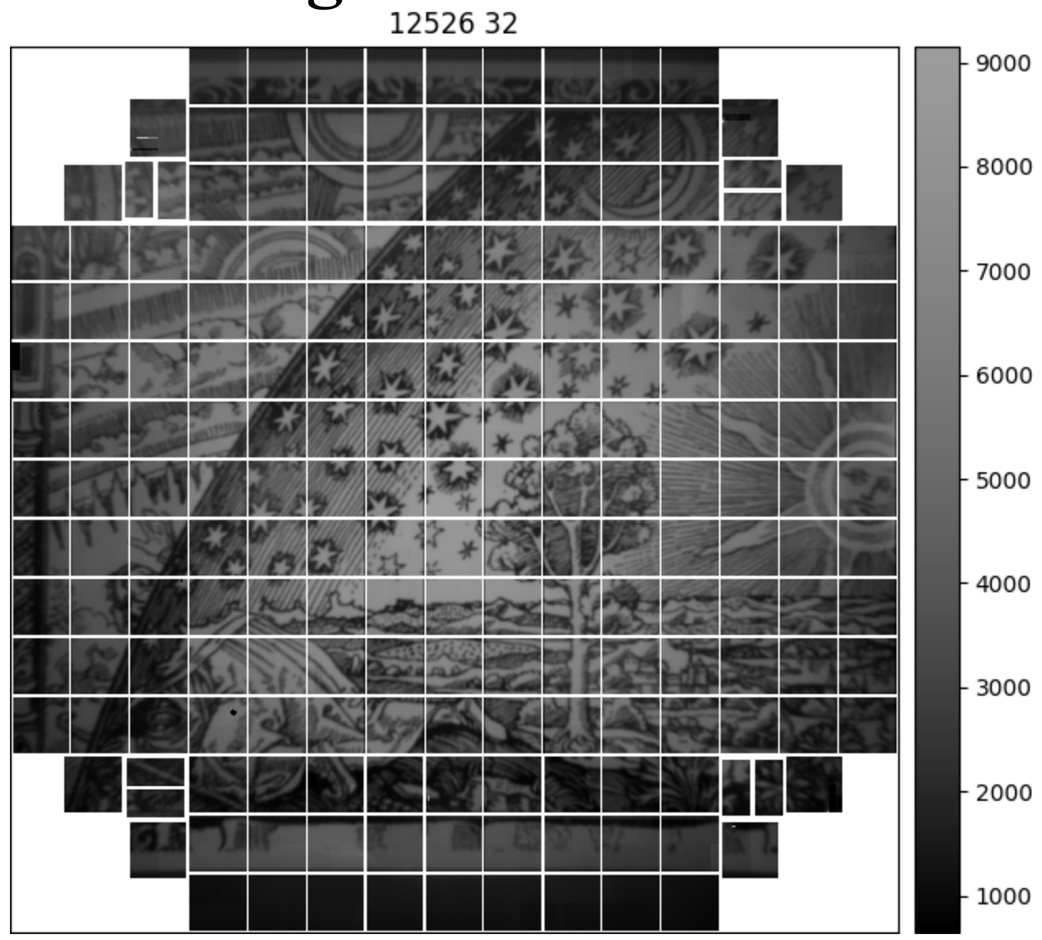
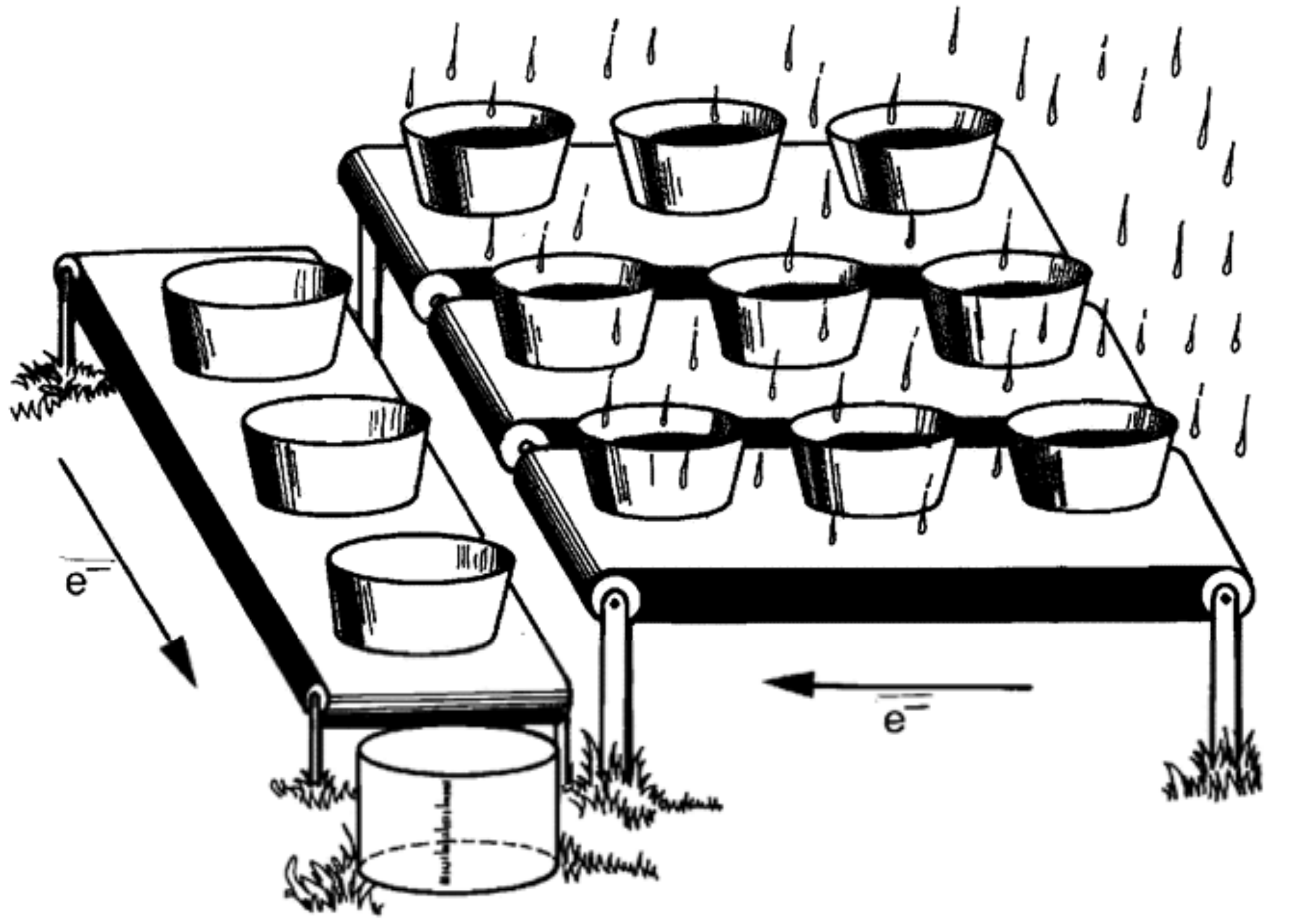


Image of the Flammarion wood engraving taken by the LSST camera at SLAC (197 4k x 4k CCDs + 8 2k x 4k CCDs)

The signal chain

- What happens between a photon hitting the detector and the image on your computer?
- A series of measurements and transformations contribute to the pixel values of an image.
- Understanding the steps of the signal chain allows us to identify problematic effects
- To get back to the signal of the incoming photons, we try to undo these effects.
- Stages in the signal chain:

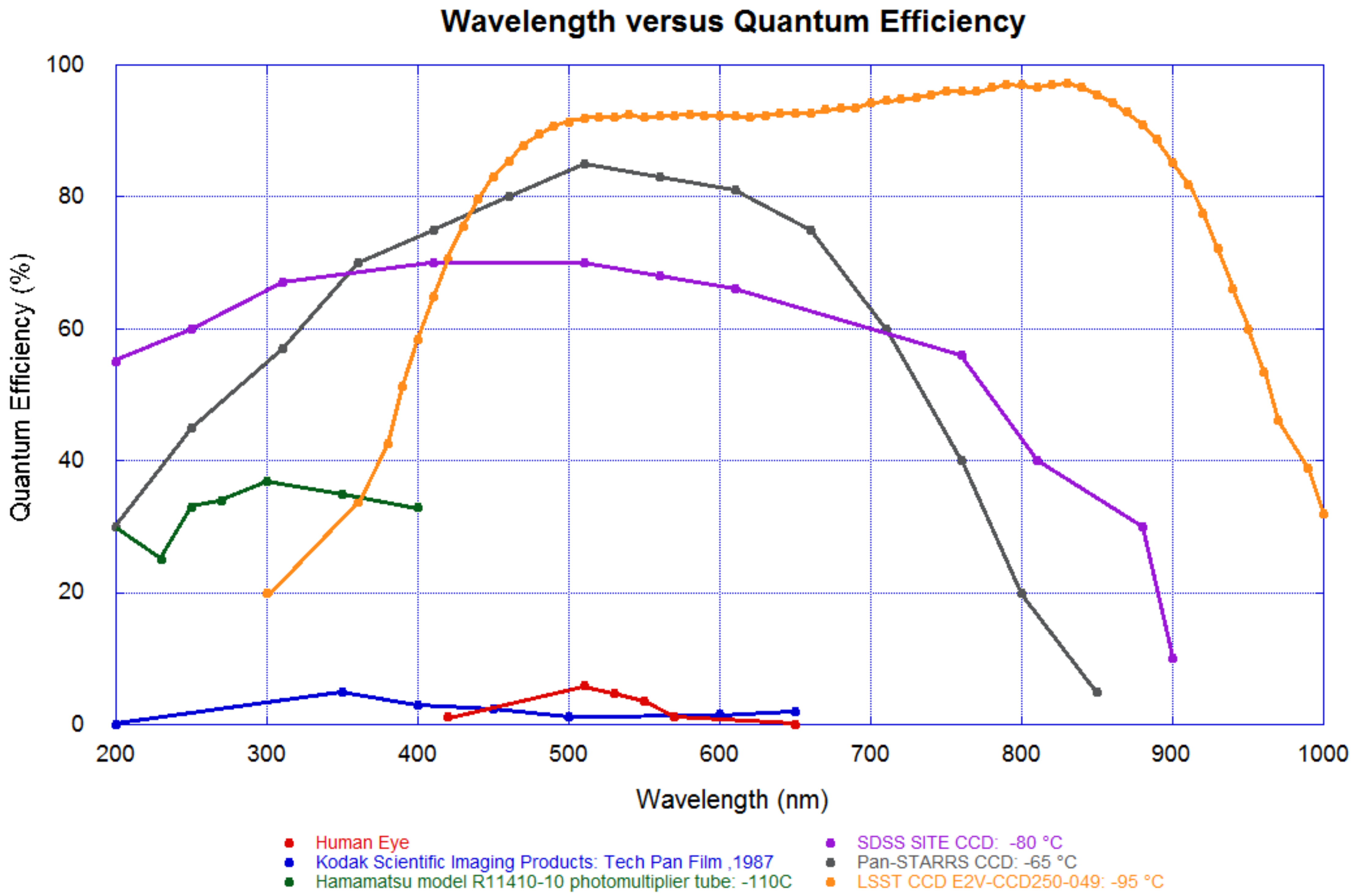
  1. Conversion of photons to electrons
  2. Charge collection
  3. Charge transfer
  4. Measurement/analog-to-digital conversion



The “Bucket Brigade” (Janesick 2001)

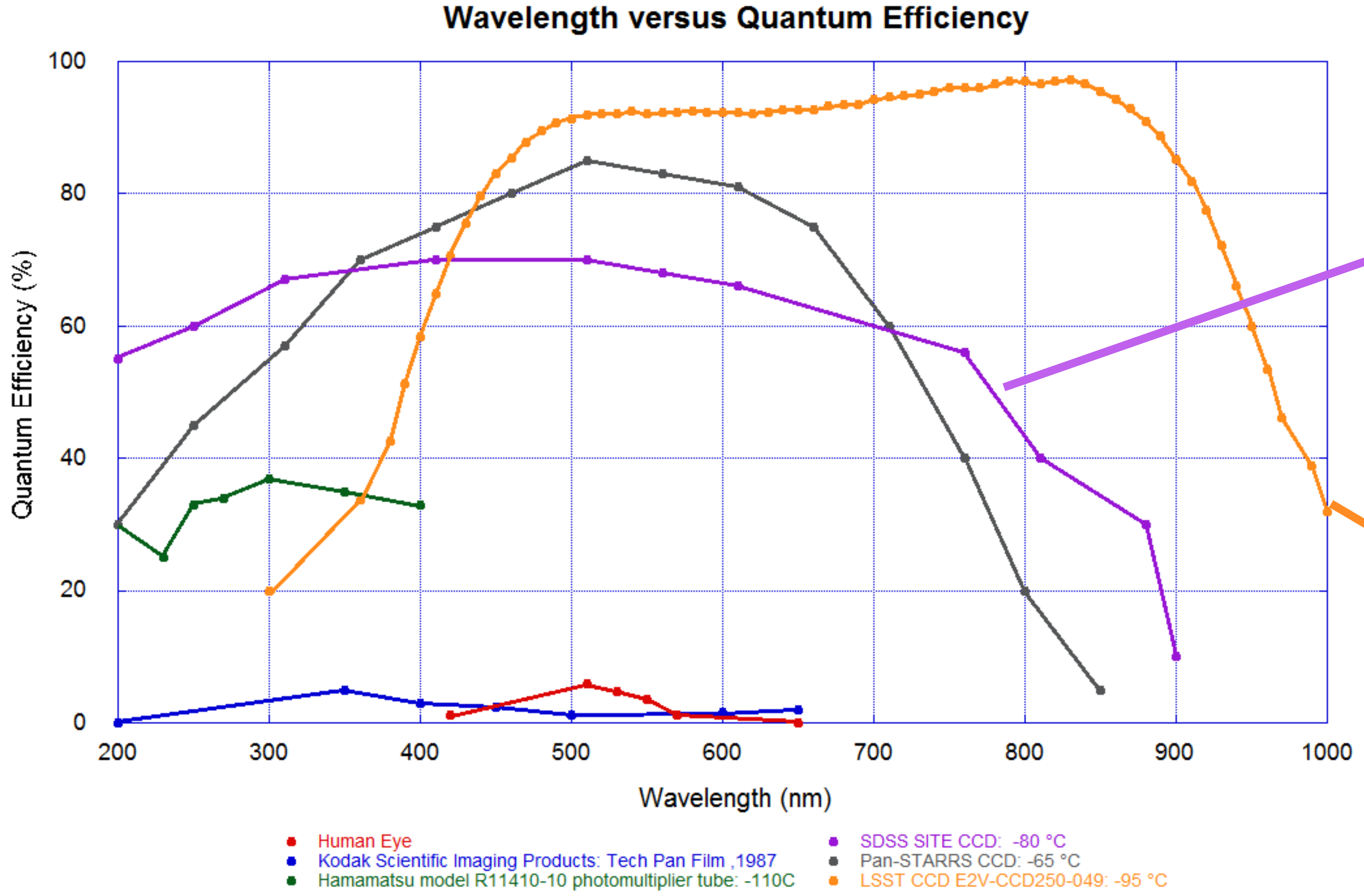
Step 1. Conversion from photons to electrons

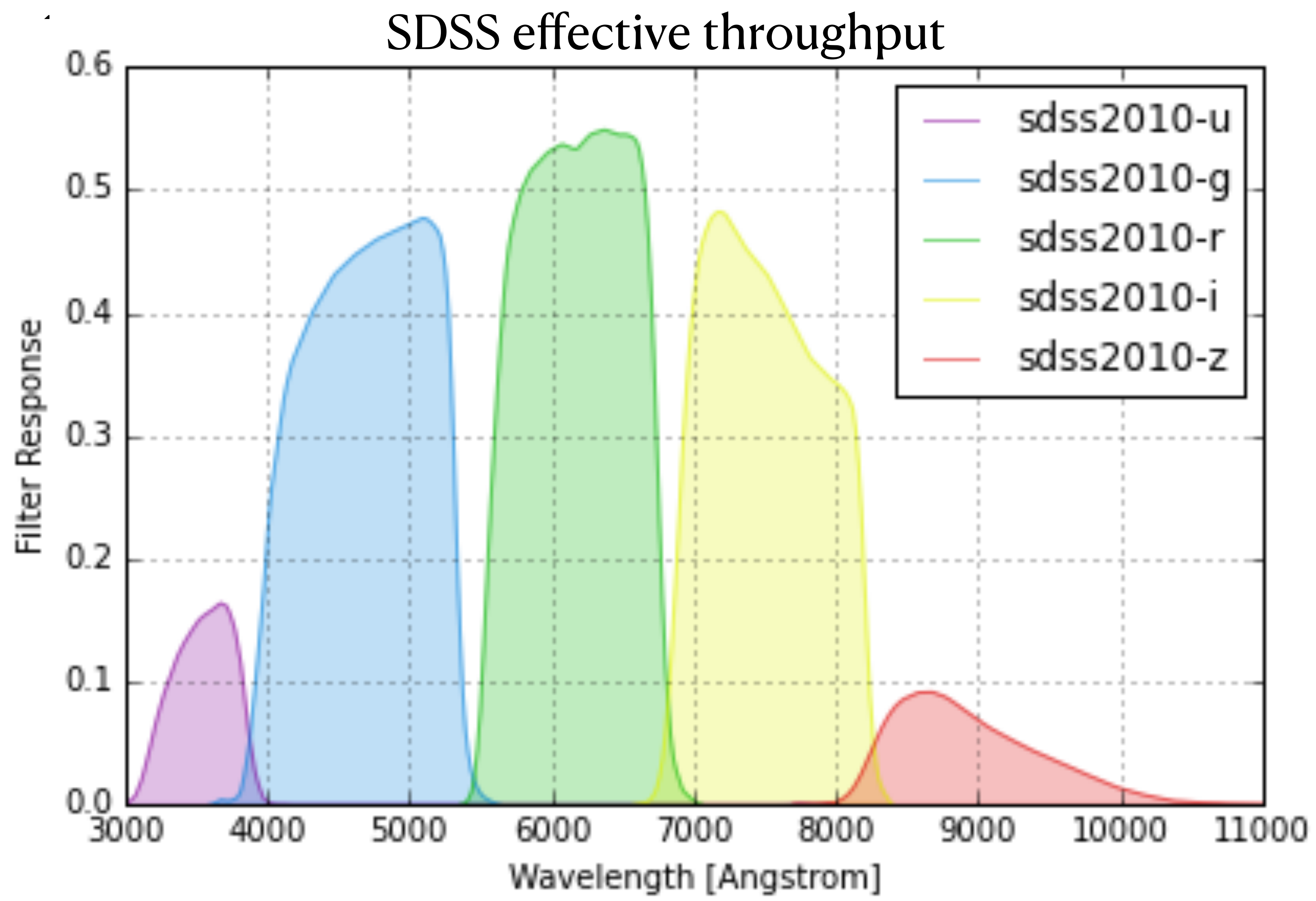
- When photons hit the CCD, they need to be converted into electrons.
- This happens through the photoelectric effect — a photon hits a Silicon atom, and an electron absorbs that energy and becomes mobile
- The fraction of photons that are converted is called the quantum efficiency
    - (Maximizing this efficiency was a major step in the development of astronomical CCDs.)

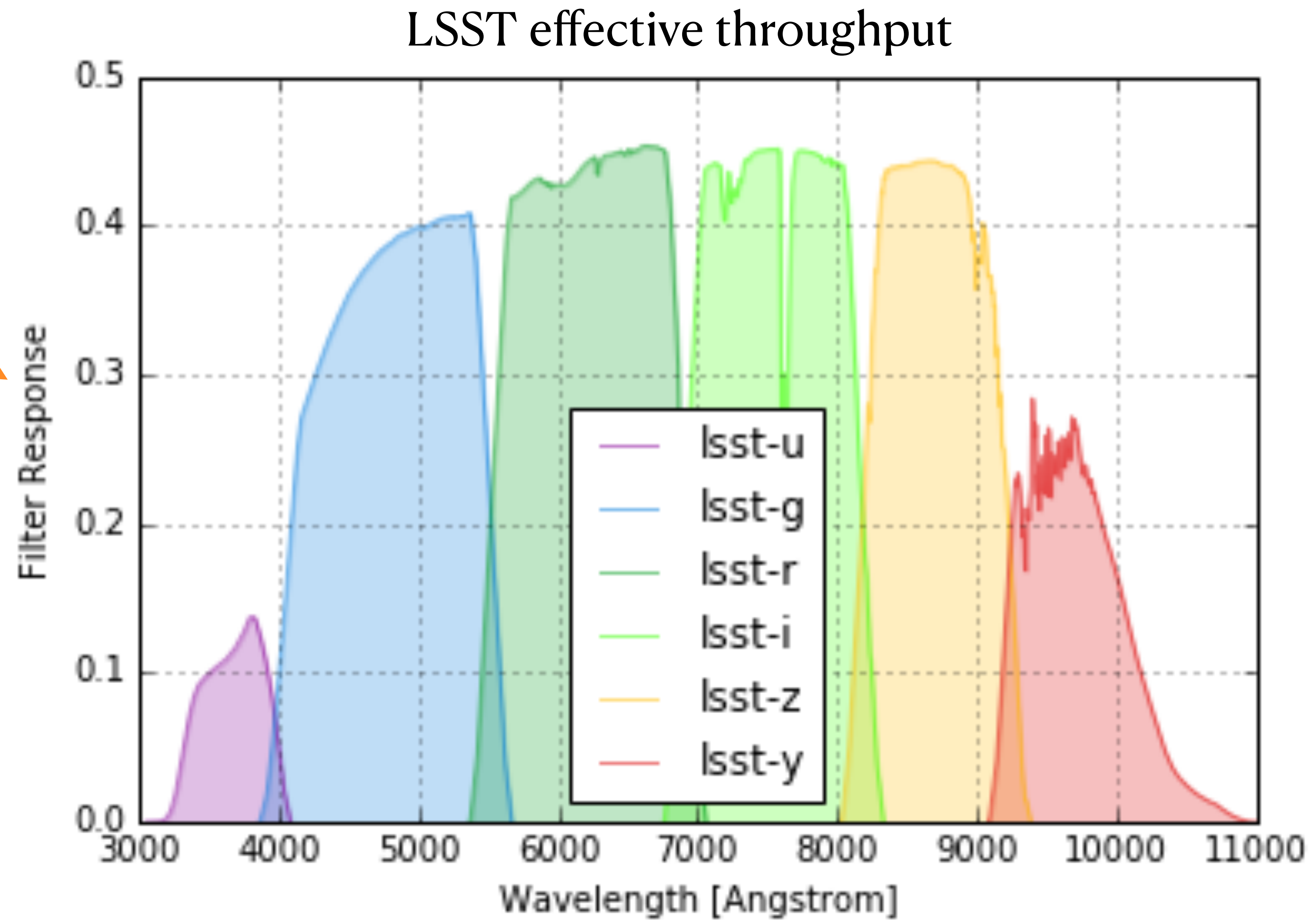


Coles+ 2017

- Side note: this has a big effect on the effective throughp







Charge conversion as a function of wavelength

- Thicker silicon is needed to absorb all the photons at higher wavelengths.
- SDSS-era sensors were ~10-20 microns deep, but Rubin's are ~100 microns.
- Thick sensors have side-effects! We'll come back to this.

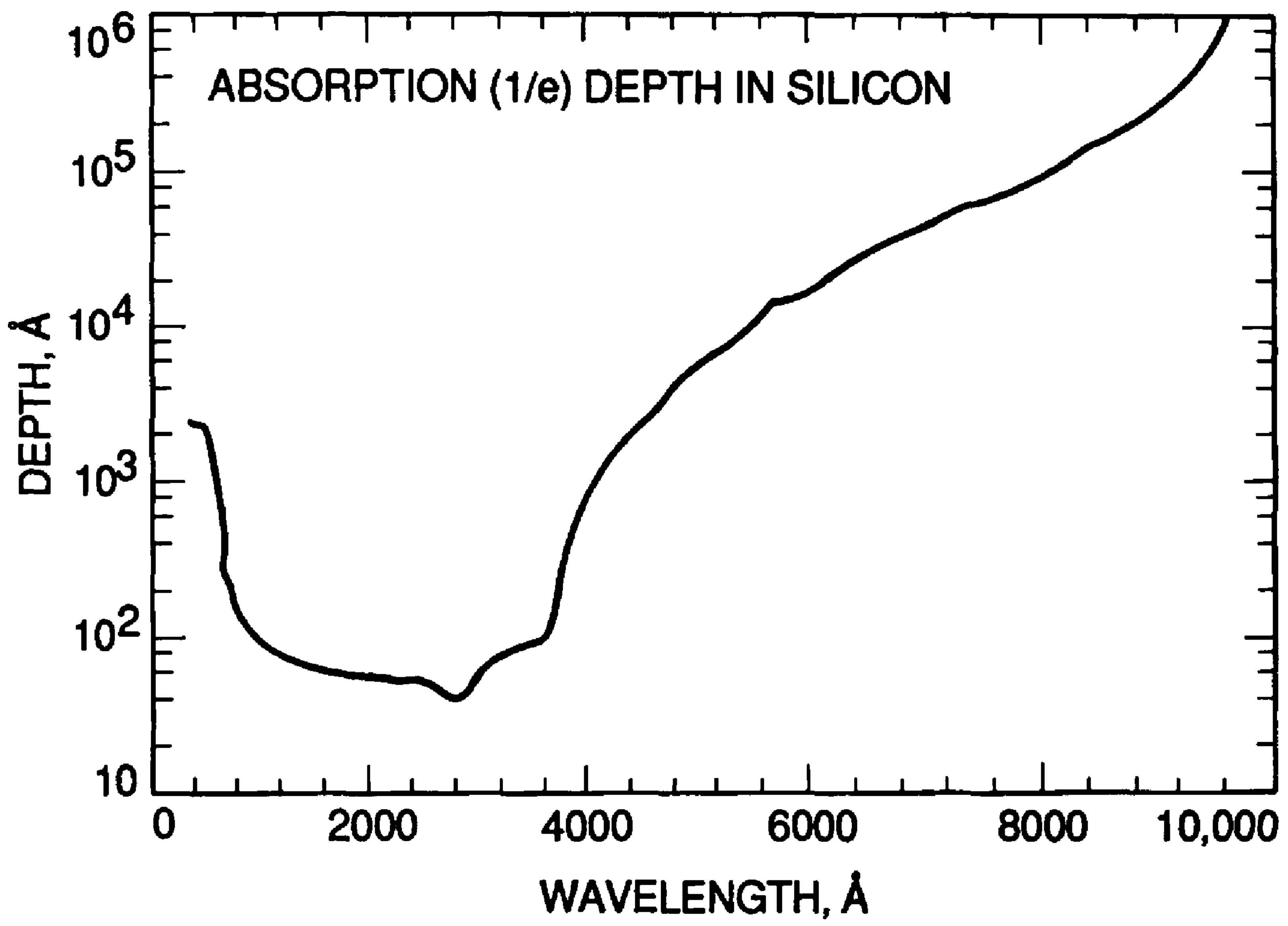
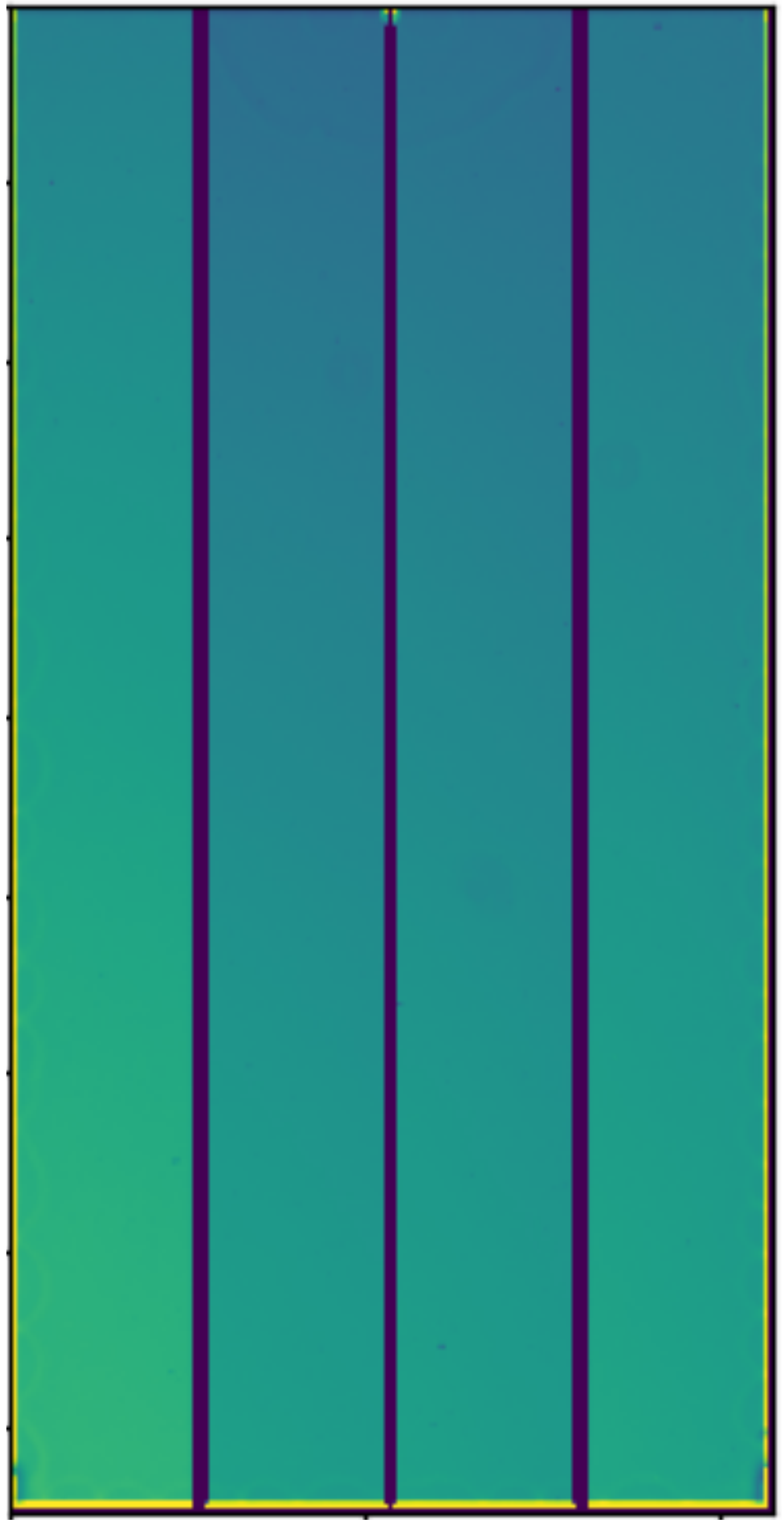


Figure 3.3(b) Silicon photon absorption characteristics.

- There can be spatial variation in QE across the chip. (around ~1 percent)
- This is one of the reasons to do a 'flat field' correction.
- Flat fields correct for non-uniform response over the focal plane, so it also accounts for other effects.



Flat field image from HSC

Step 2. Charge Collection

- “Pixels” are created by electric field potential wells
- The spacing of the potential wells (combined with the telescope optics) determines the pixel scale (angle on the sky per pixel, also called pixel pitch).
- These potential wells are defined by potential barriers that are either static (i.e. from doping) or external and variable (from applied voltages) — which is used depends on how charge is read off CCD (see next section).

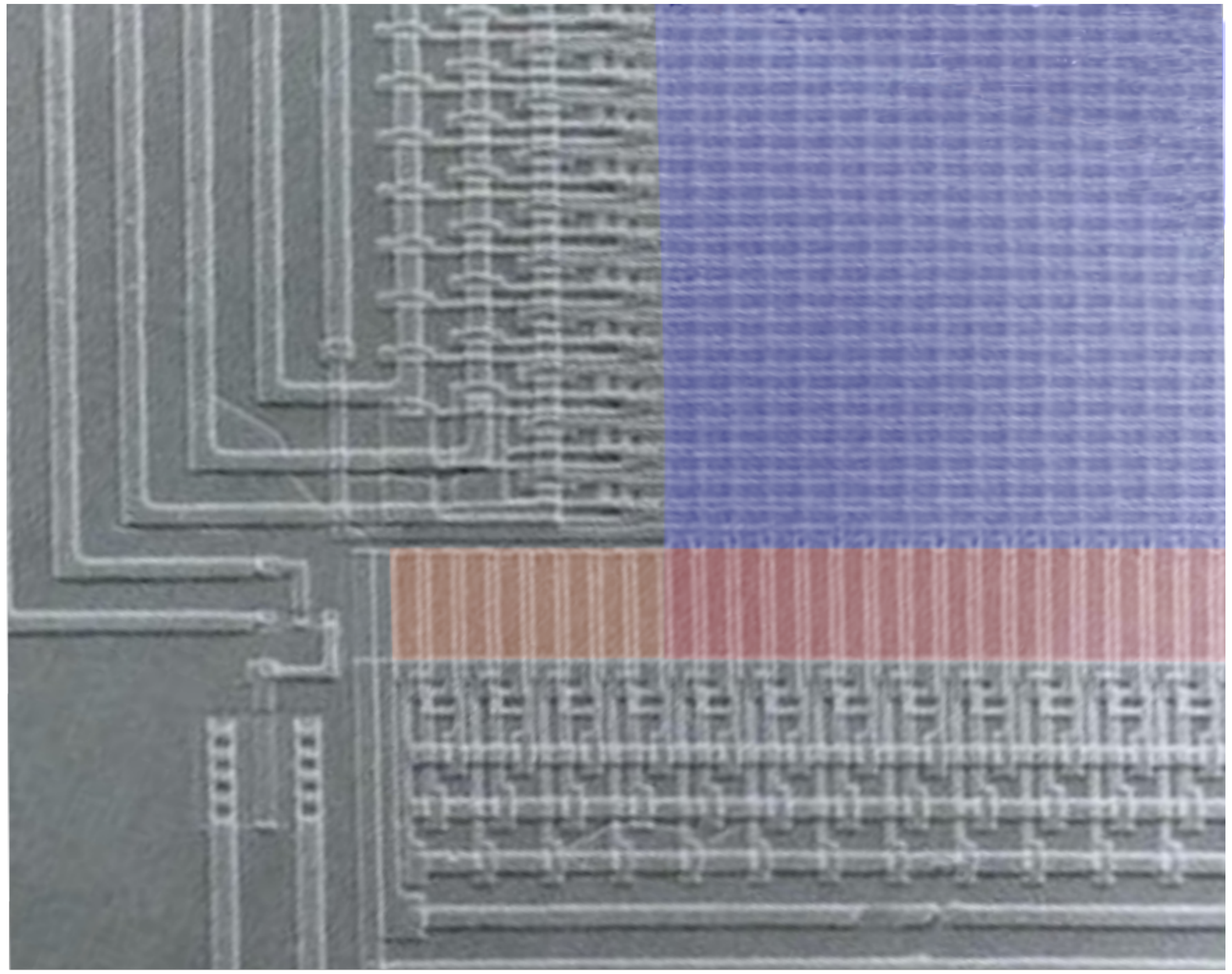


Figure A.5: SEM image of a corner of a Hubble WF/PC II CCD, modified from Janesick 2001, Fig 1.12i. The colours correspond to Figure A.3a, with the serial register in red, the eight extended register pixels in orange and the imaging area in blue. The square-with-spots in the bottom-left corner is the output amplifier. The structures below the serial and extended registers are the gates which enable serial clocking (shown in more detail in Figure A.6), and those to the left of the imaging area control the parallel clocks. If you look carefully at the blue region you can see the horizontal parallel gates and vertical ridges of SiO_2 (“field oxide”) covering the channel stops.

- Each pixel of a CCD is a tiny capacitor
- A photoelectron drifts from where it originated to the potential wells.
- The predominant electric field draws electrons straight across the detector.
    - Stray (small) electric fields can interfere with this, particularly in thick detectors
- Even just a few electrons can be measured because of very small capacitance:
    - A 20 μm x 20 μm capacitor with thickness of 10 μm has capacitance of ~4 fF — a single electron results in a voltage of ~ 40 μV.

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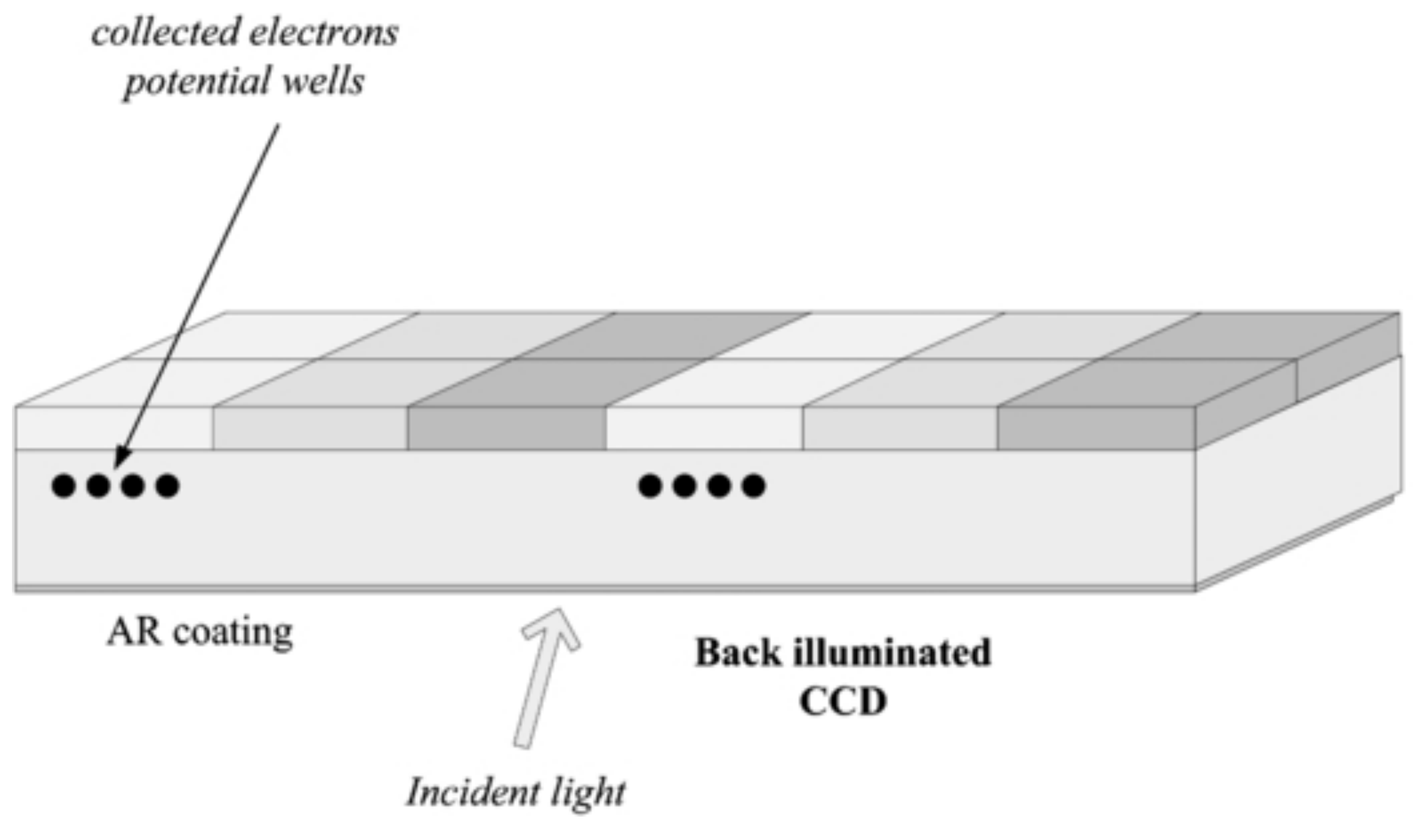
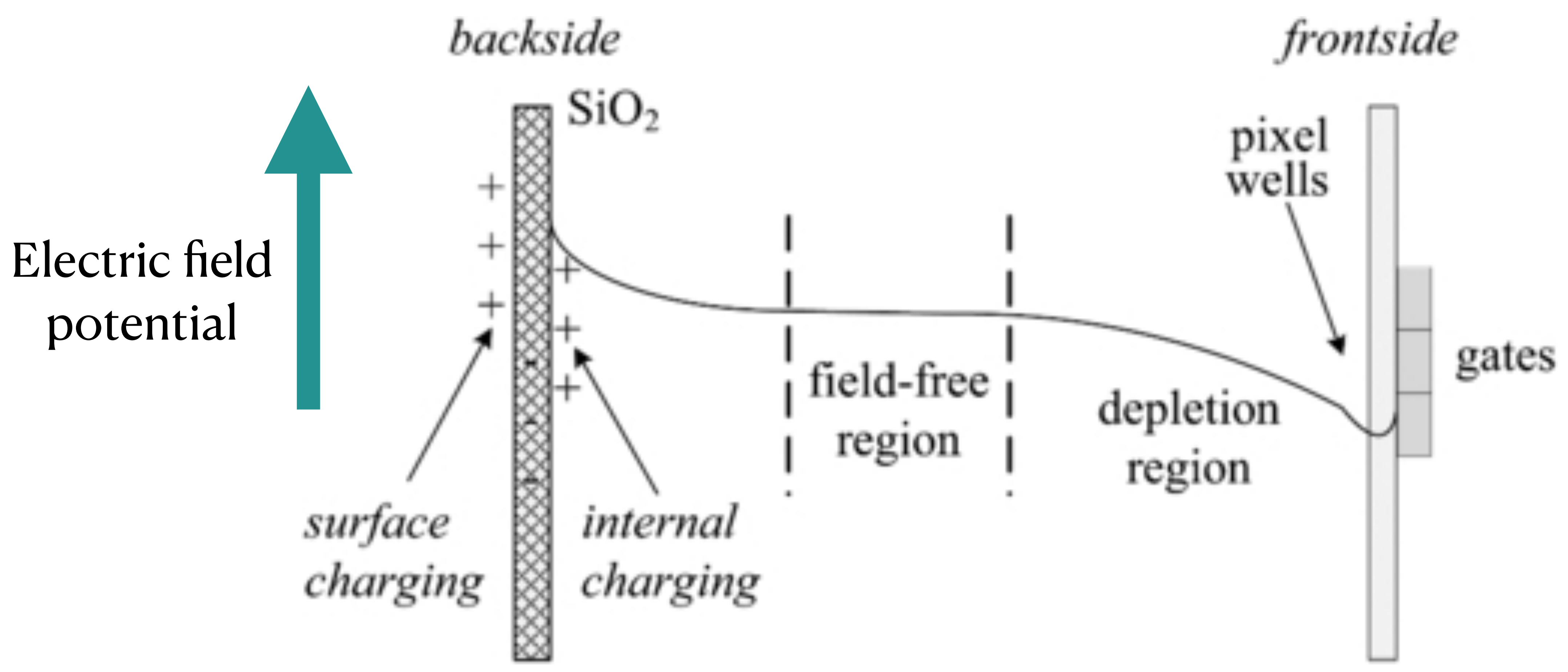




Complications of Charge collection

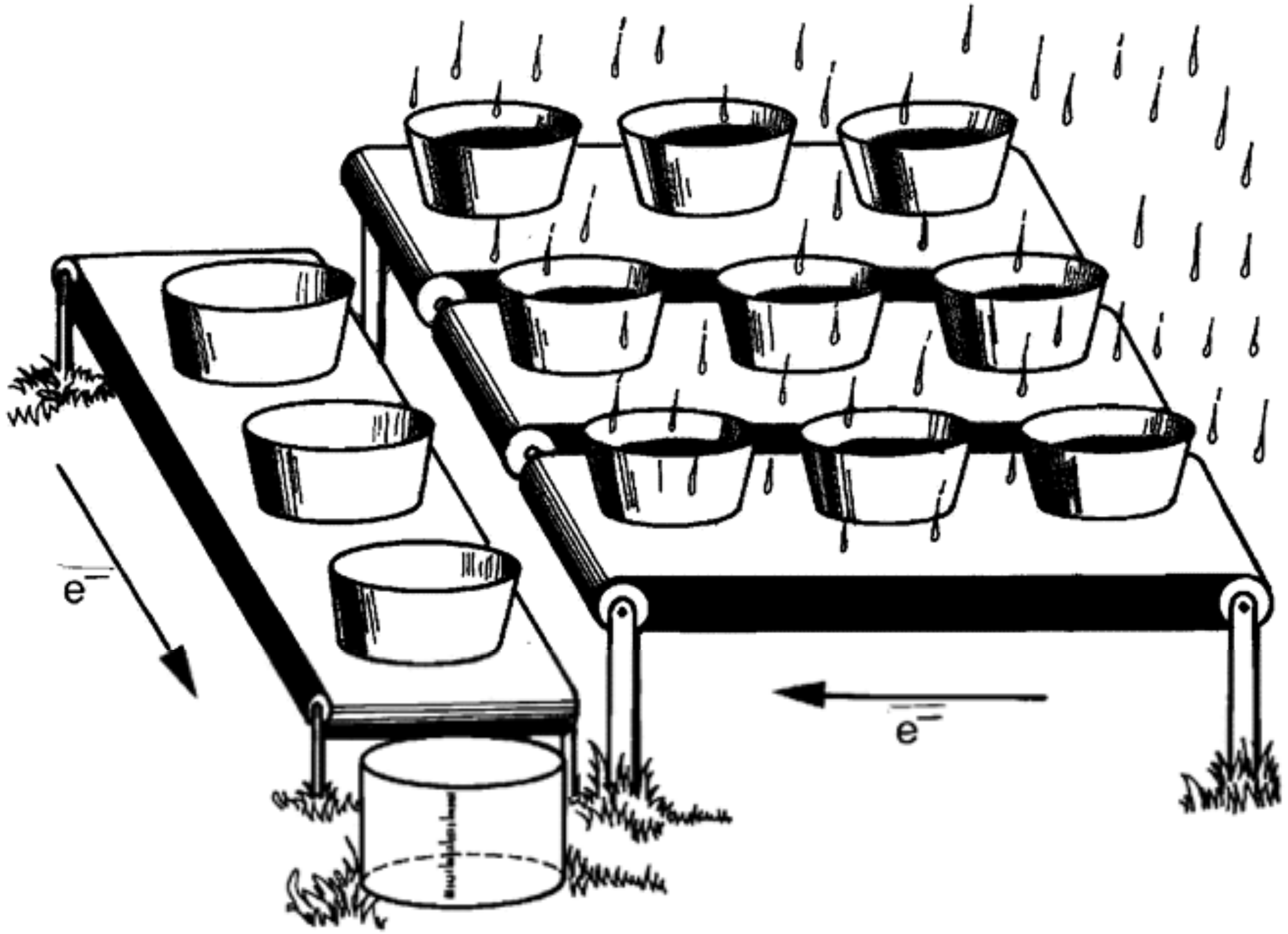
- Each pixel has a limited capacity (the full-well capacity).
- If too much charge is present, a photoelectron goes to the next-easiest location.
- There is a lower potential between rows than between columns, so electrons are more likely to move up and down a column — this is the cause of pixel “bleeds”.
- Pixels aren’t lost, but it becomes much harder/impossible to accurately measure the bright source in question. (In practice saturated objects are masked or flagged in some way.)

Step 3. Charge Transfer

CCD pixels are like an array of buckets

- Electrons need to be shifted the the readout amplifier.

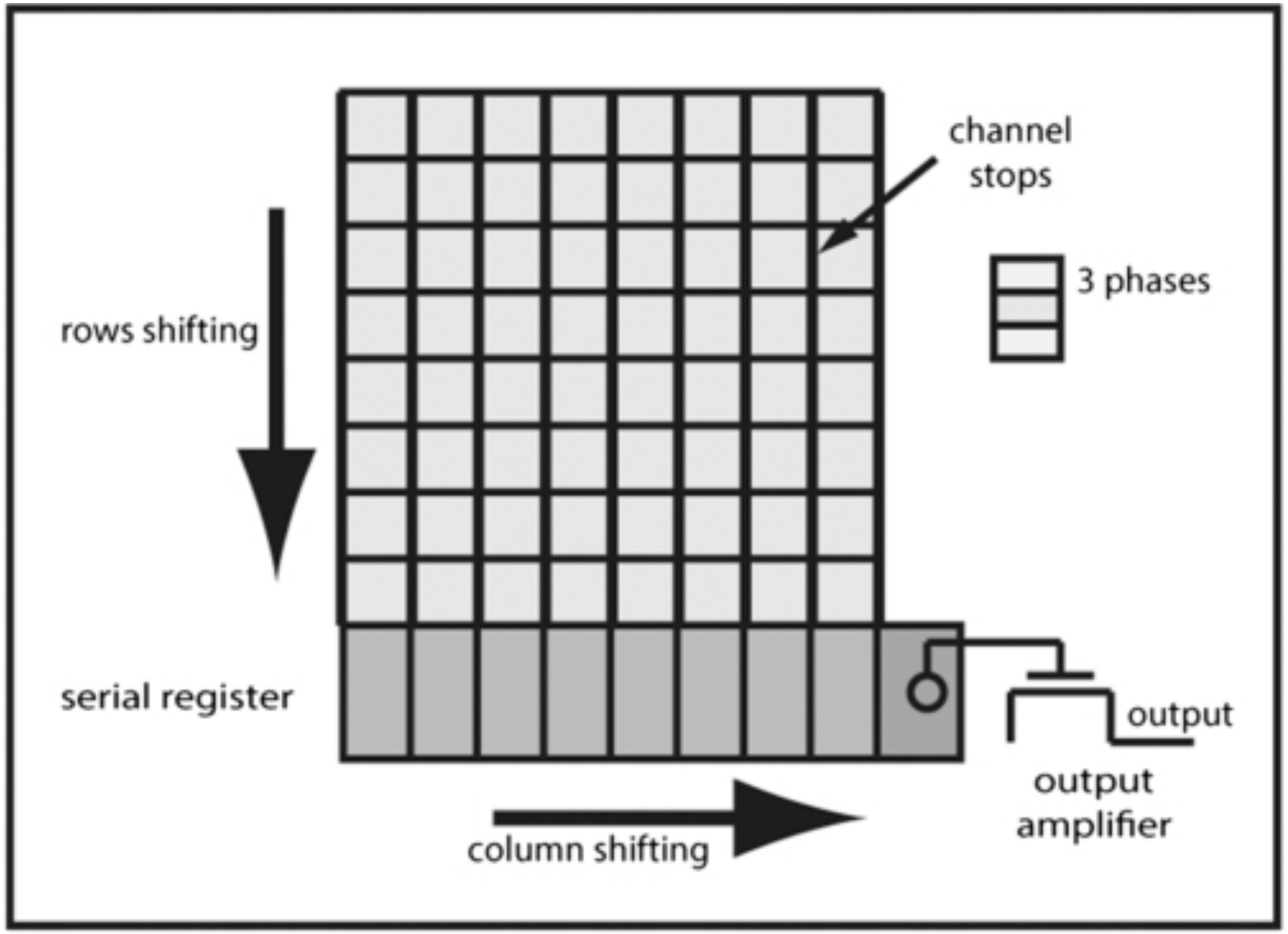
- This happens in two steps:
  - Parallel transfer - rows are shifted to one edge
  - Serial transfer - the row on the edge is shifted to the readout amplifier.
- Important caveat — real CCDs don't have gaps like in the bucket analogy!



Janesick, 2001

Simple CCD layout

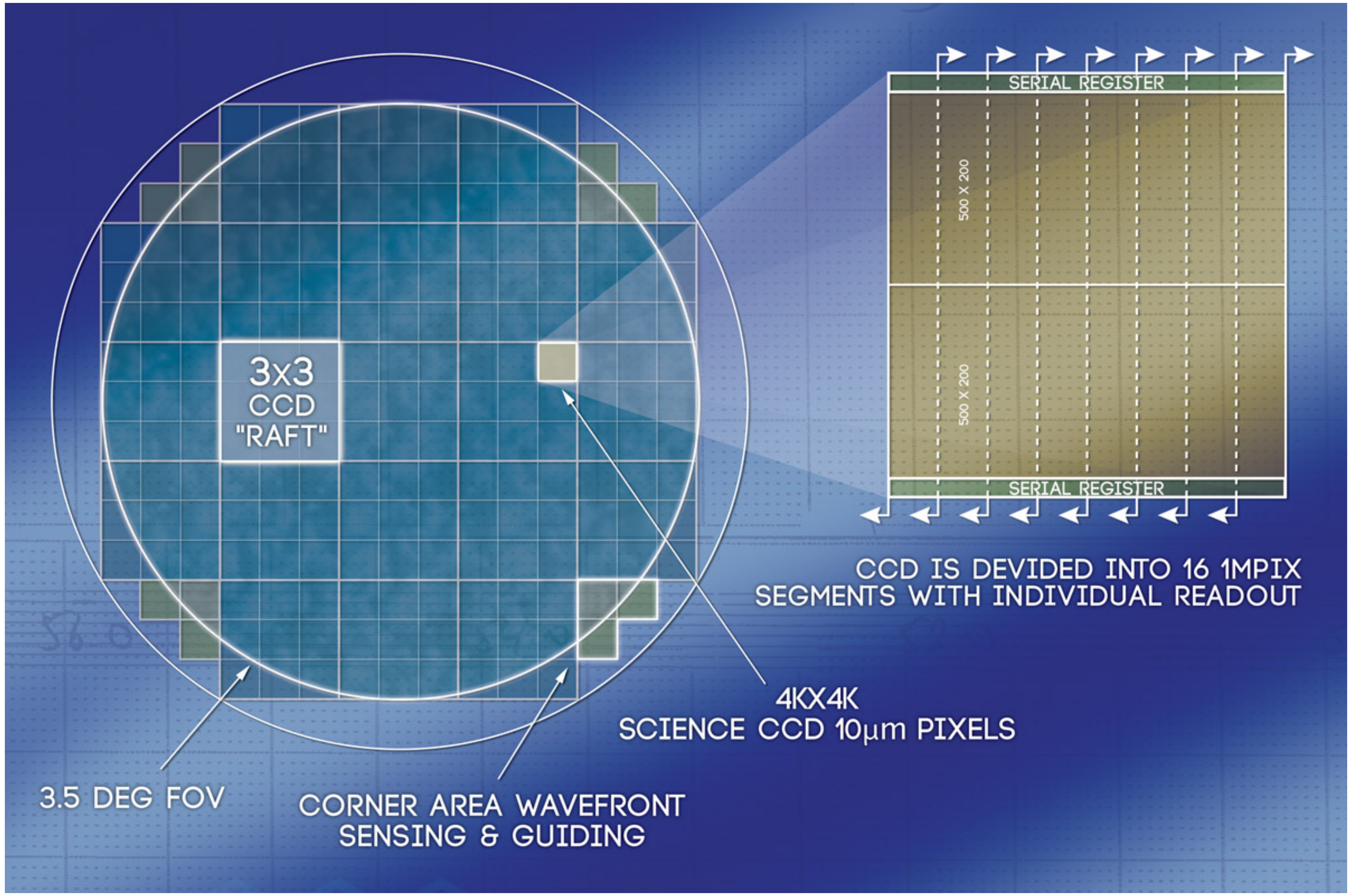
- Manipulating the applied voltages shifts electrons off the imaging area onto the serial register.
- They are then shifted to the readout amplifier.



Lesser, 2015

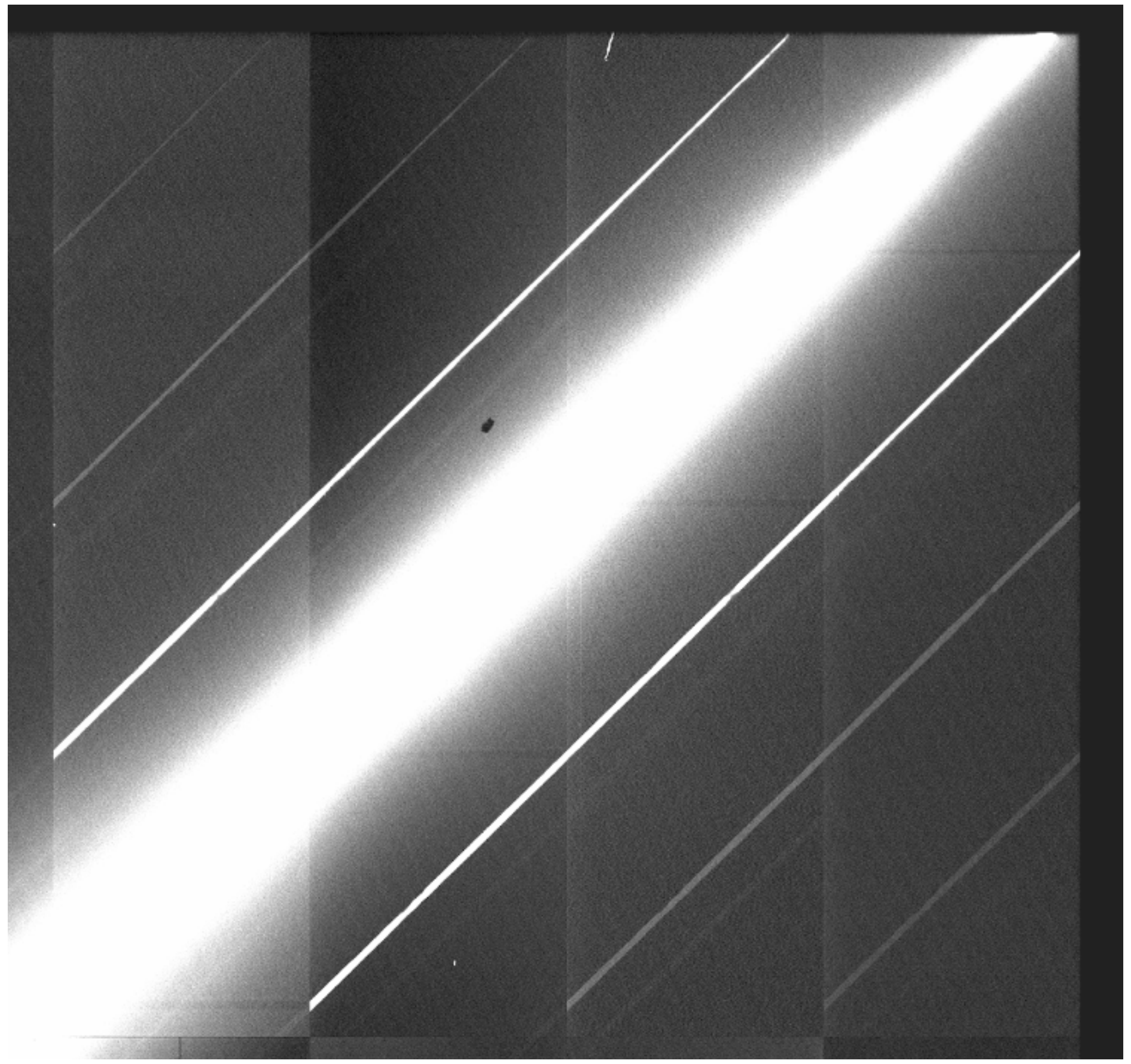
CCDs are now split into segments, each with its own amplifier

- Splitting the ccd into several segments is necessary to meet the readout time requirement of 2 seconds.



Complications with Charge Transfer

- Charge transfer efficiency (CTE) refers to the amount of charge successfully transferred off the CCD.
  - Modern CCDs have CTE values of 0.999995 or better.
  - With imperfect CTE, pixels further from the amplifier are measured to have fewer electrons than closer pixels.
  - Don't really need to worry about this in modern sensors, but it can be an issue for space-based sensors because of radiation damage.
- Crosstalk is another side effect of charge transfer.
  - Usually caused by capacitive coupling between amplifiers.
  - Amplitude of crosstalk is ~1e-4 of the primary source.



Crosstalk from a bright satellite-like source in an LSSTCam detector, from talk by Andrew Bradshaw

Step 4. Charge Measurement

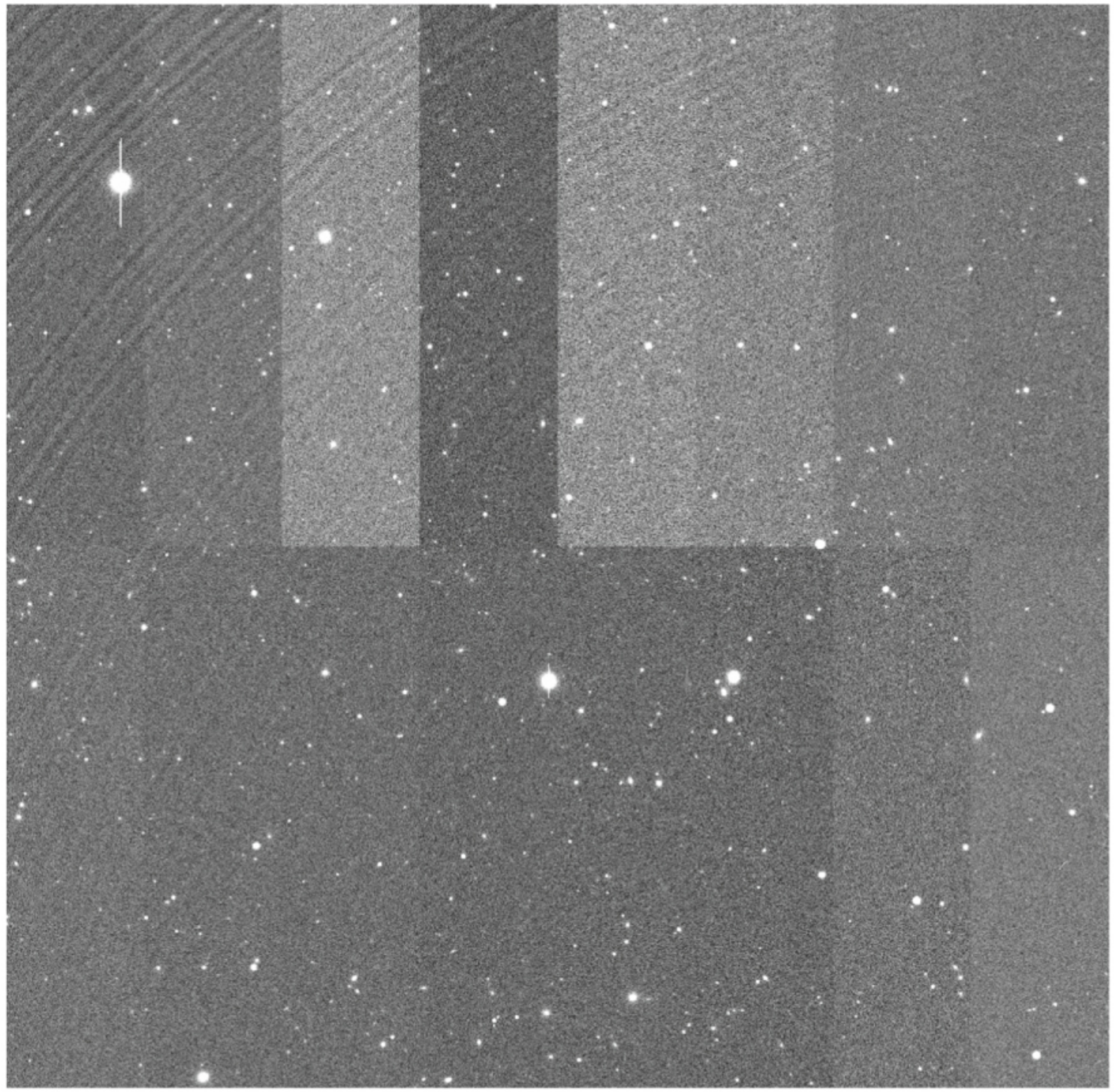
- The electrons are shifted off the end of the serial register to the output amplifier.
- Charge is converted to voltage because of the capacitance of the output voltage
    - Follows the equation $V = Nq / C$, where C is capacitance of the node, N is the number of electrons on the node, and q is the electronic charge.
- The voltage is buffered by the output amplifier to create a measurable signal.
- The analog signal is converted to digital by an analog-to-digital converter (ADC).
    - This digital signal is called the digital number (DN, also called counts or ADU)
- Finally, the node is reset before the next pixel is read.

Complications of Charge Measurement

- Bias - a small bias is added so that the ADC always sees a positive value.
  - This gets removed in software instrument signature removal.
- Read Noise - This term lumps together all the sources of noise from the measurement of charge
  - This can be measured by taking a zero-second exposure (a “bias” frame) — the readout should just be the bias level with some scatter corresponding to the read noise.
- Gain - this is a multiplicative factor between the number of electrons in a pixel and the counts.
  - Measured by comparing the signal to the noise from the pixels.
  - Can be nonlinear at very low and and very high pixel values—should be measured and corrected for.
  - The value is needed to convert quantities back into electron units.

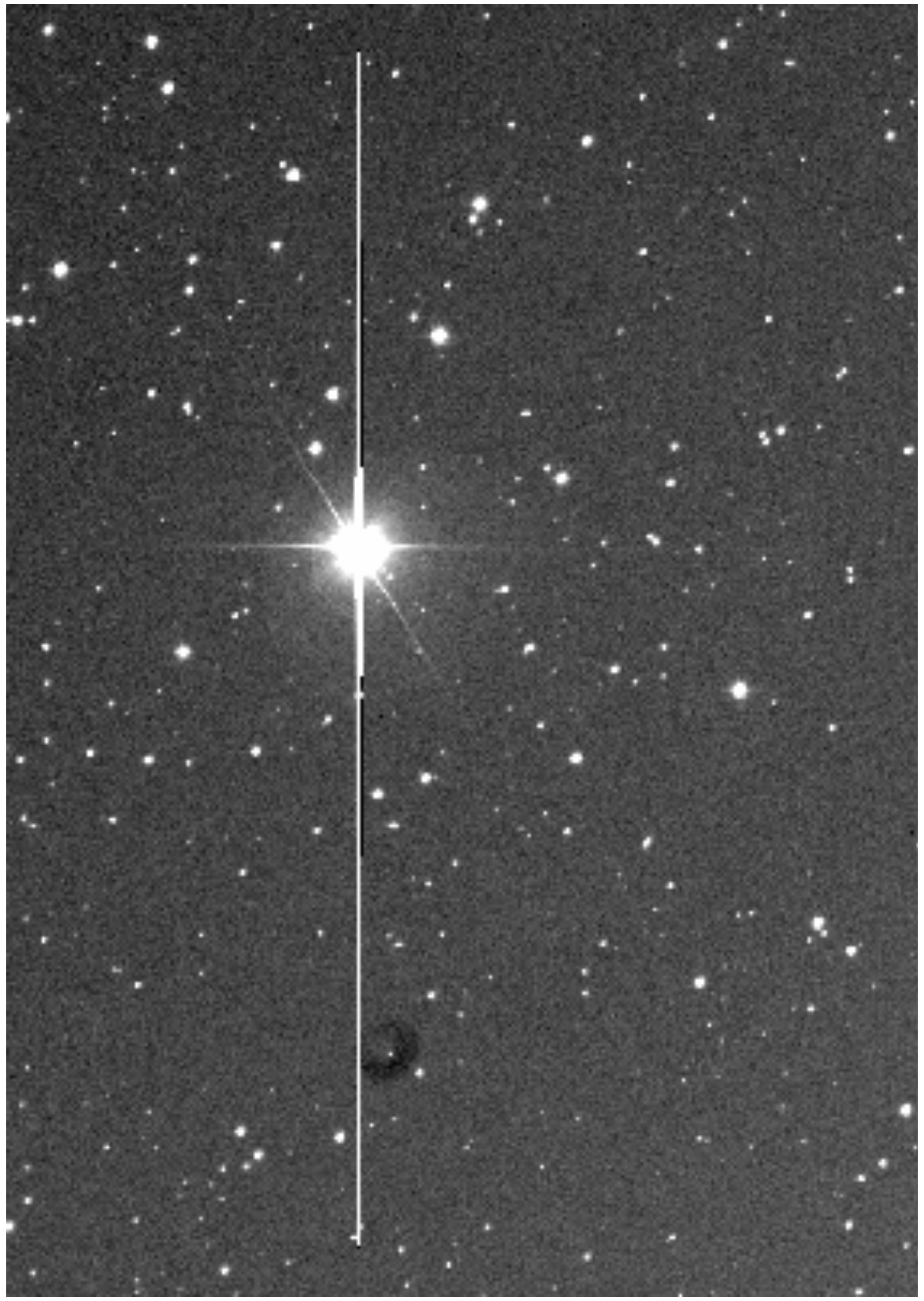
Onto the fun side effects...

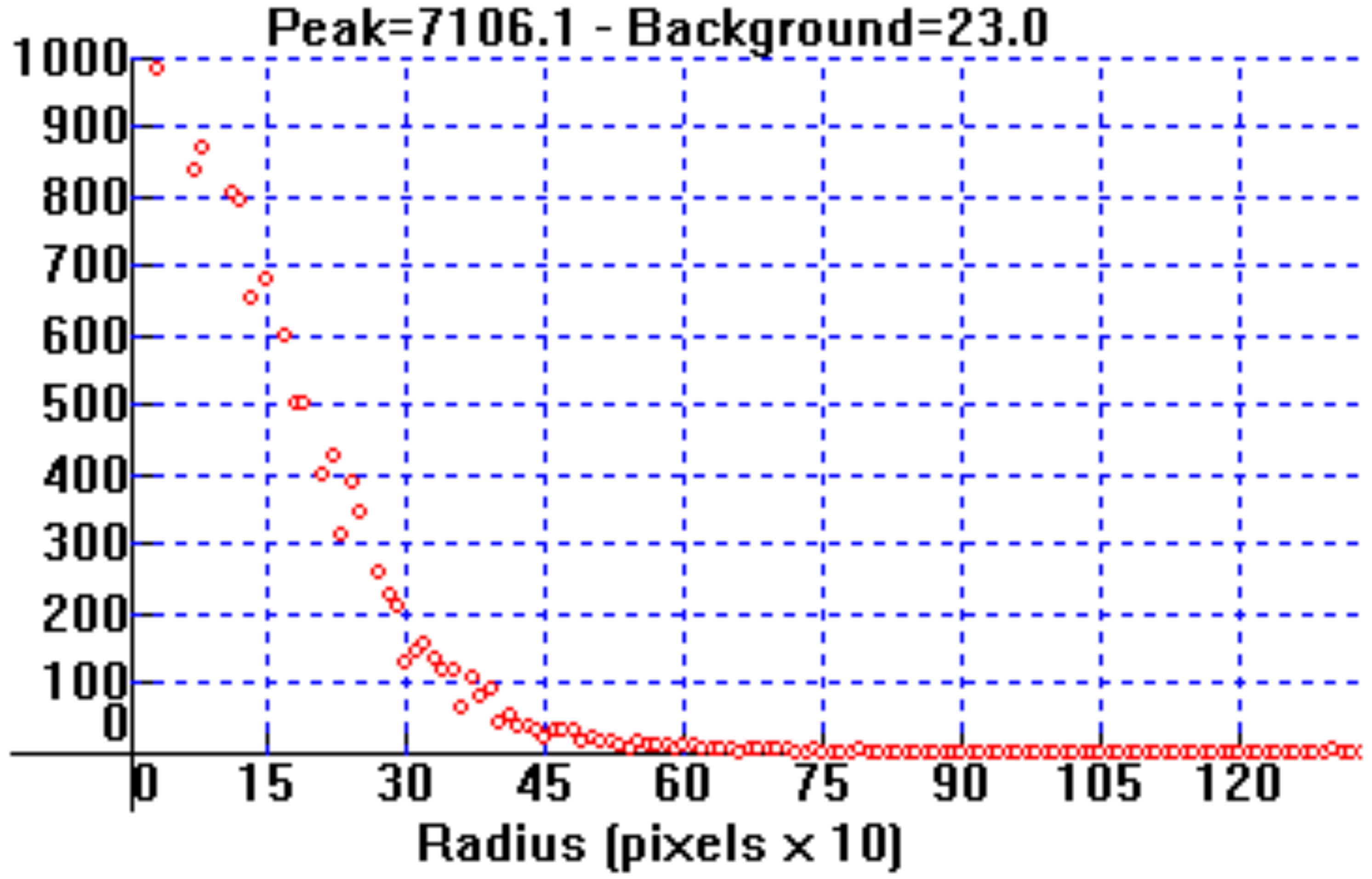
- Perfect CCDs would have pixels that could hold an infinite amount of charge, with electric fields pulling electrons straight from the detector surface to the pixel wells.
- Departures from this situation cause problems/fun challenges!



Simulated LSSTCam Image from DC2, LSST DESC 2021

Saturation




Peak=7106.1 - Background=23.0
1000
900
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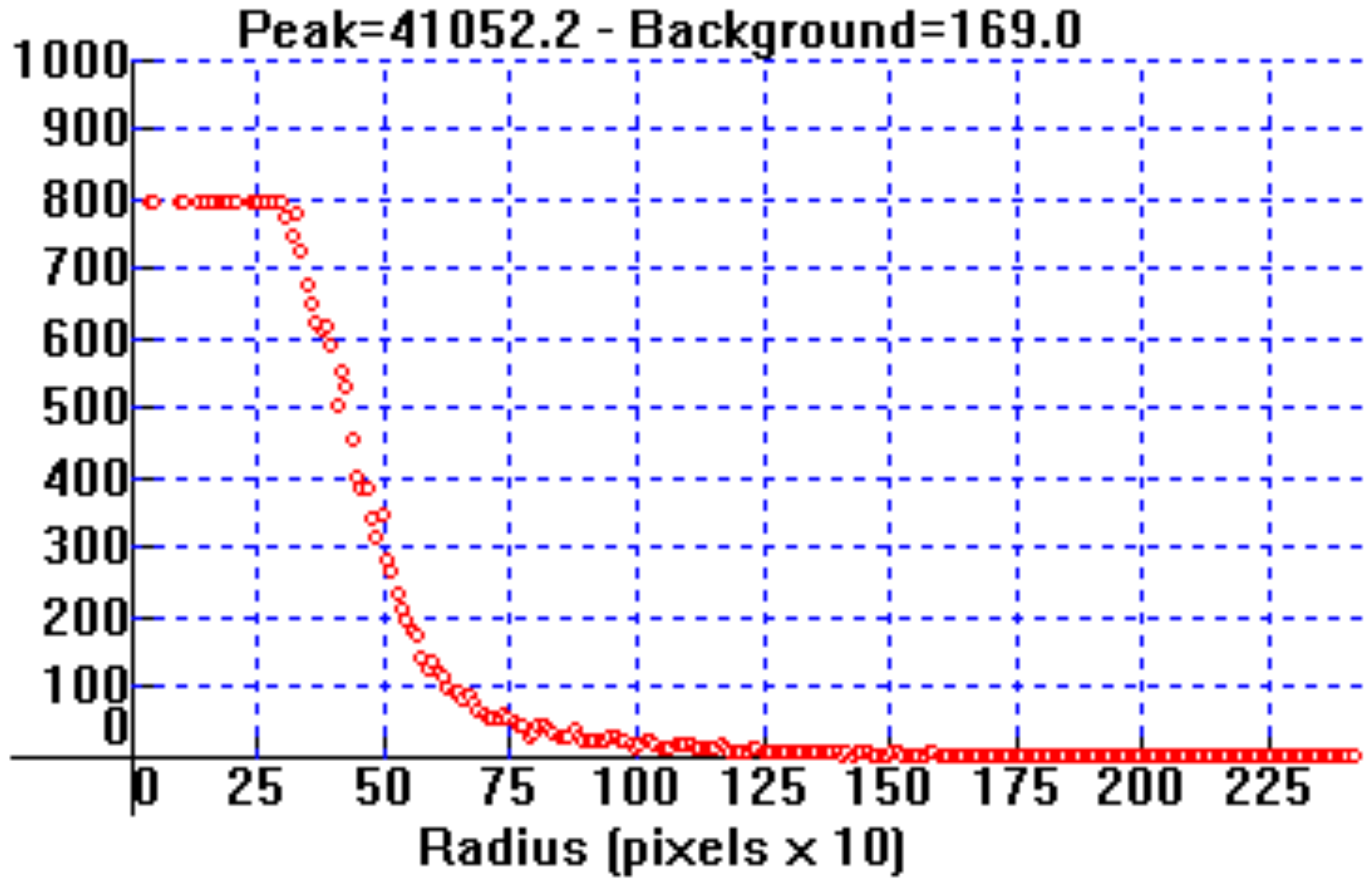
0 15 30 45 60 75 90 105 120
Radius (pixels x 10)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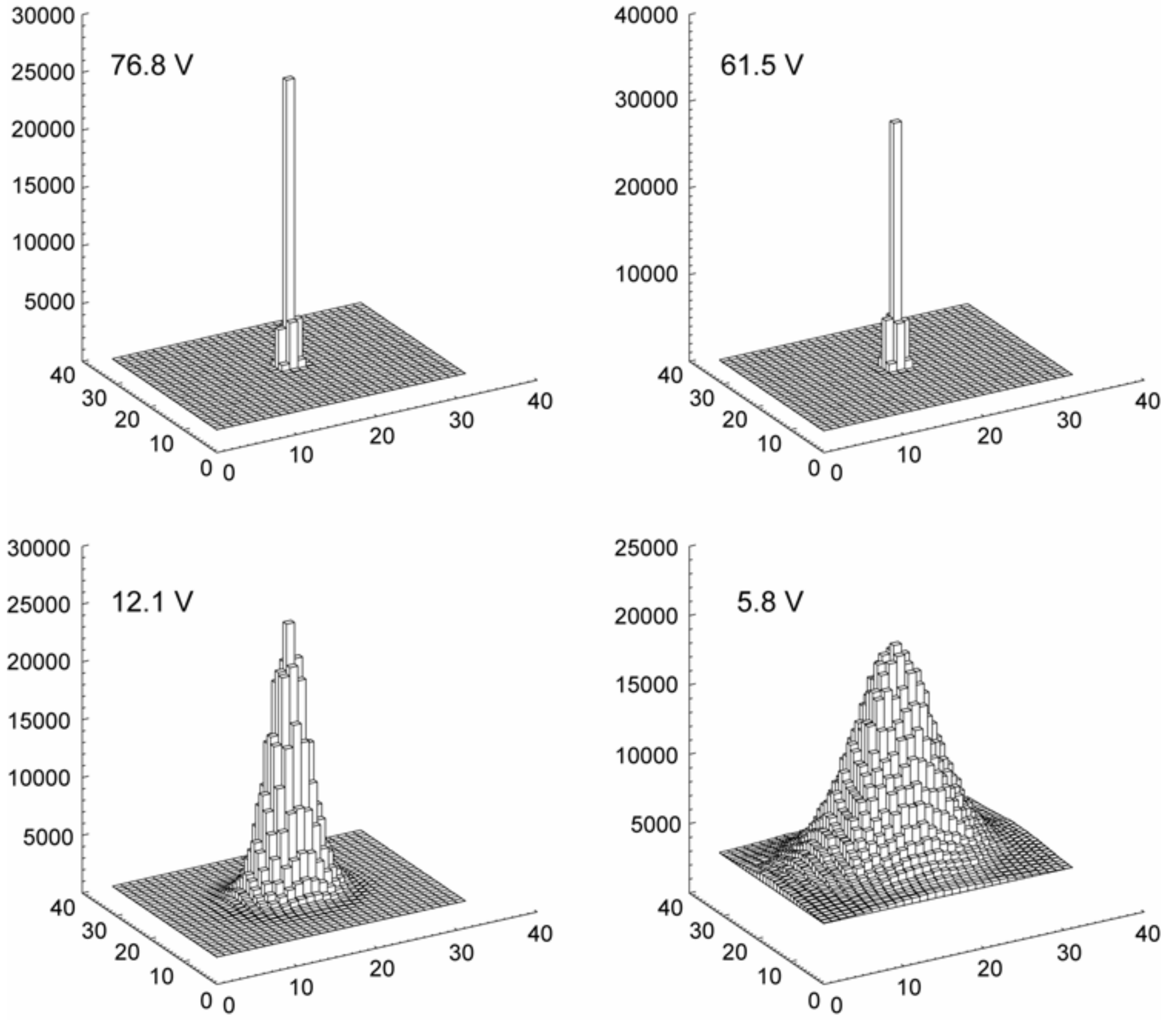
0 25 50 75 100 125 150 175 200 225
Radius (pixels x 10)

Thick sensors: diffusion

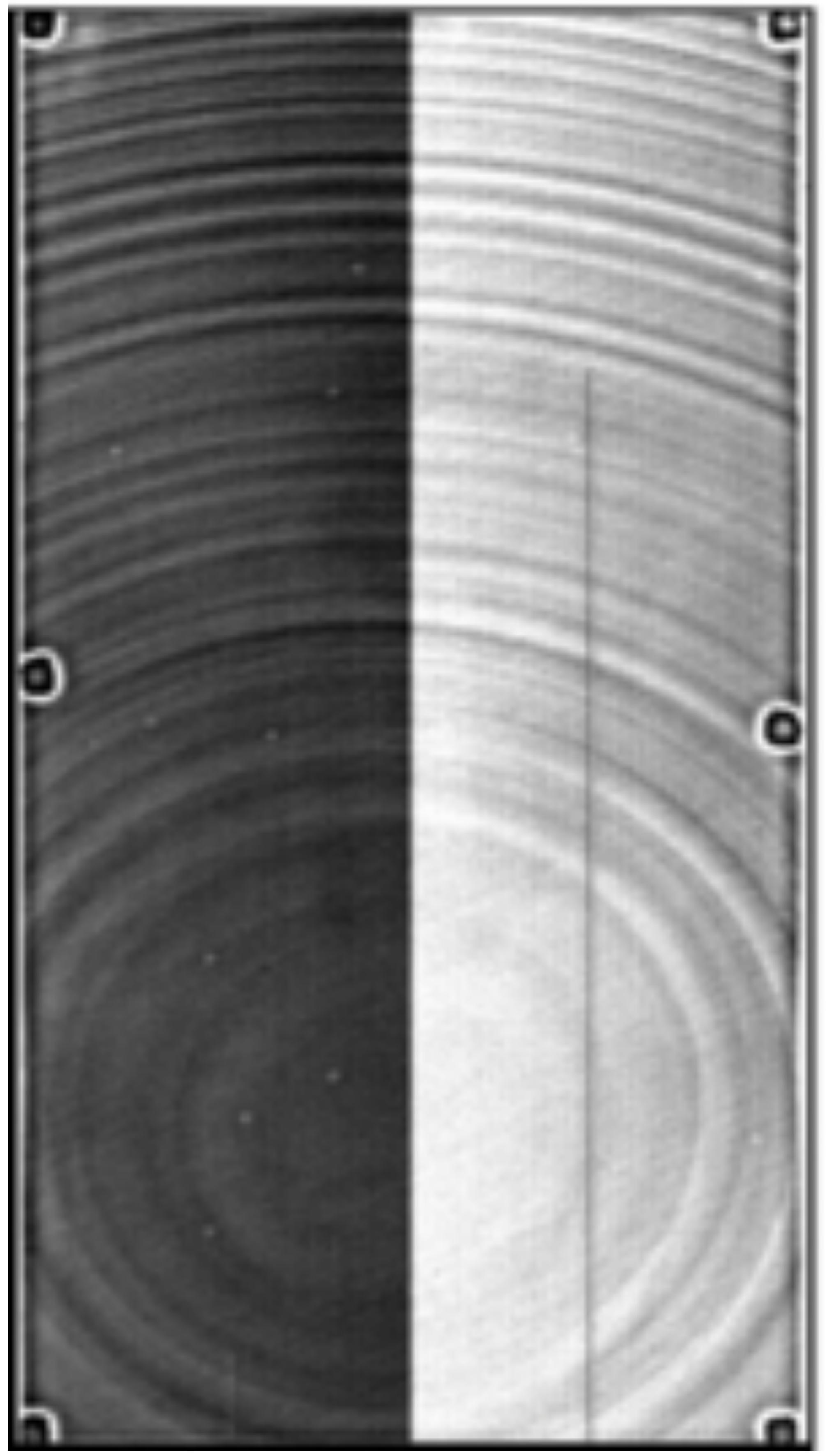
- Electrons scatter slightly as they interact with the silicon.
- Creates a spreading effect (much smaller than the PSF typically).
- Dependent on electric potential in the sensor.
- There can be a chromatic dependence because bluer photons convert to electrons closer to the top of the sensor.

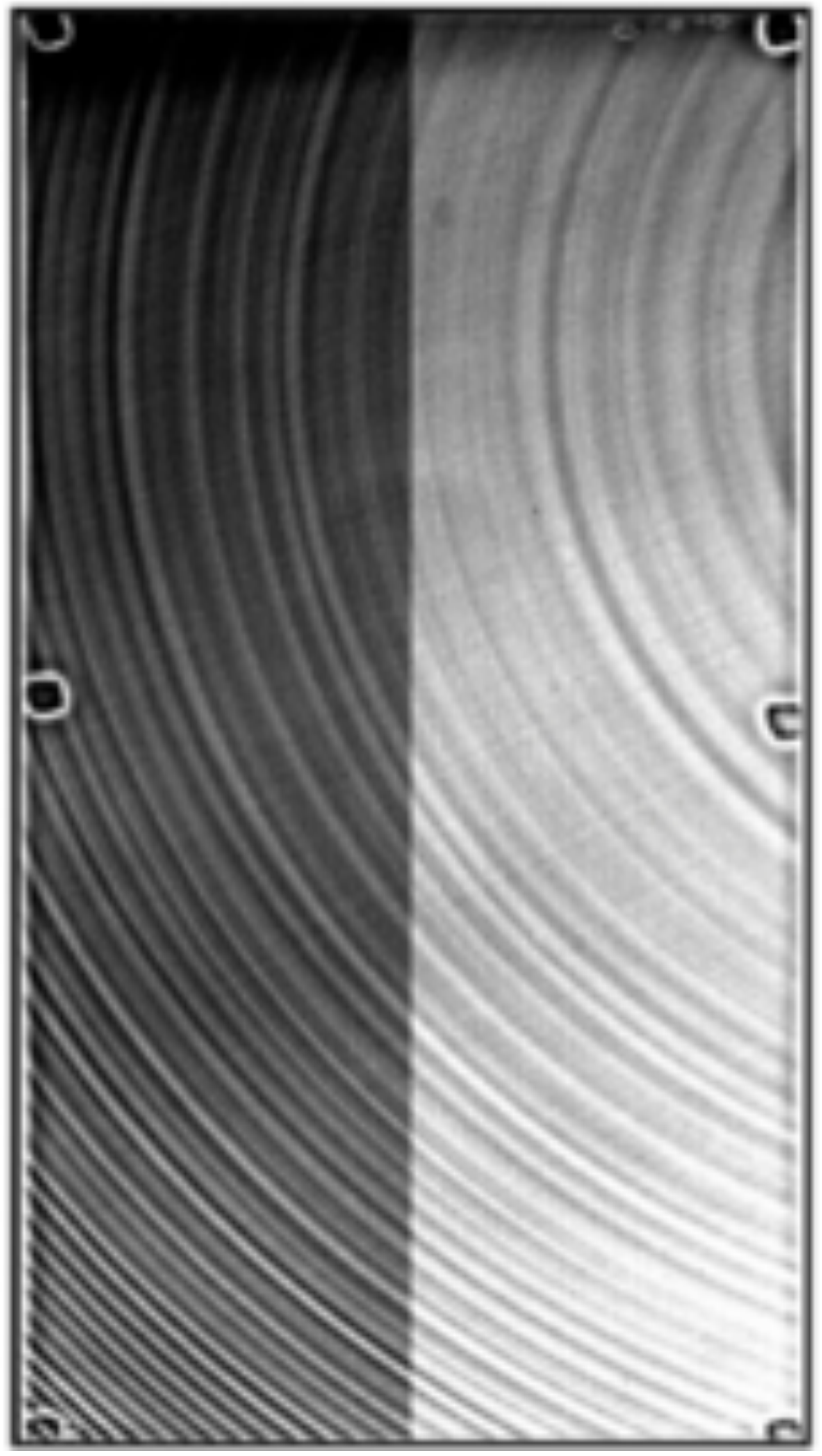


Karcher+ 2004

Thick sensors: Si Impurities

- Pixel area variation / tree rings
- Will talk about this more in Intro to Astrometry talk

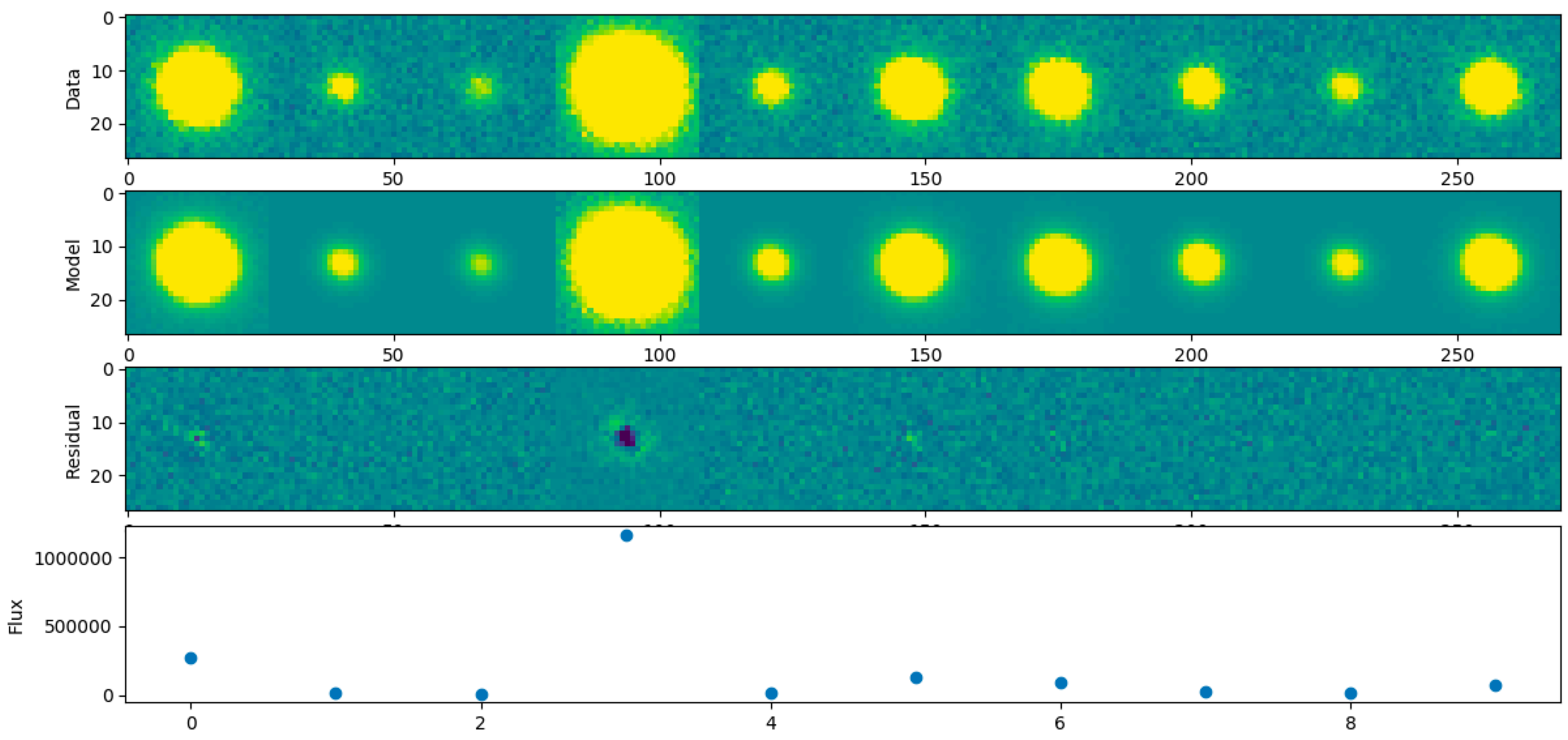




Plazas+ 2014

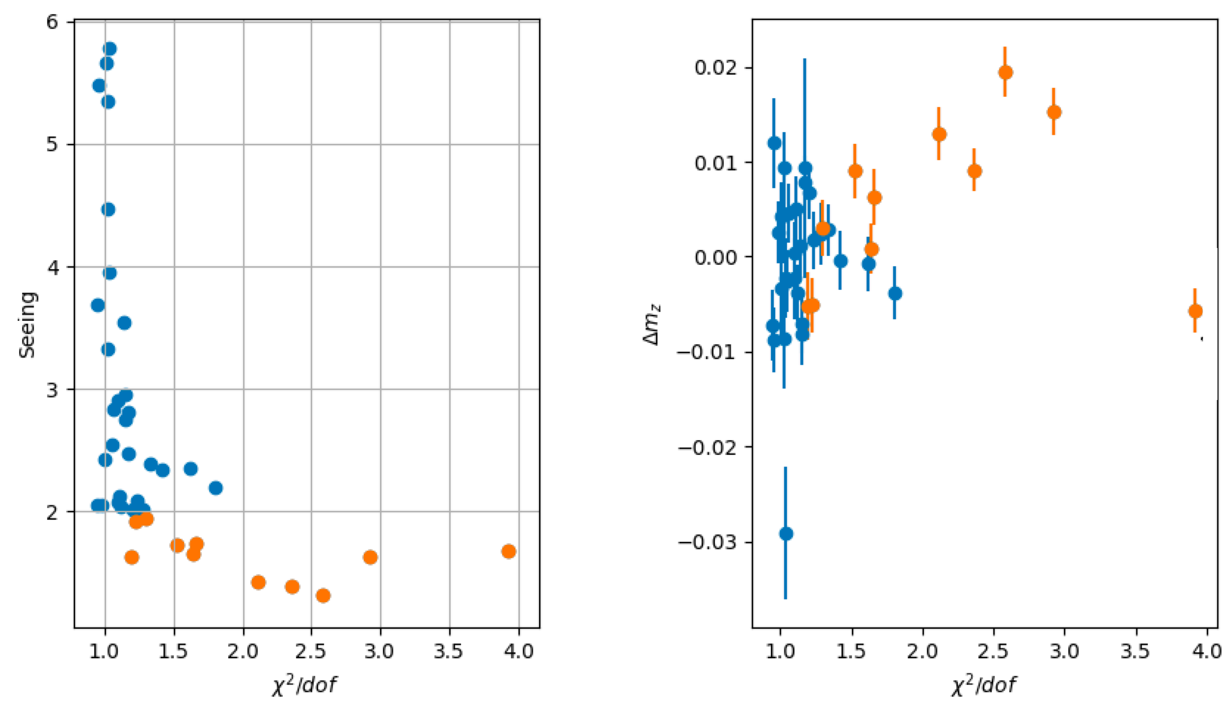
Thick sensors: the brighter-fatter effect

Bright stars are measured to have wider point-spread-functions (PSFs)



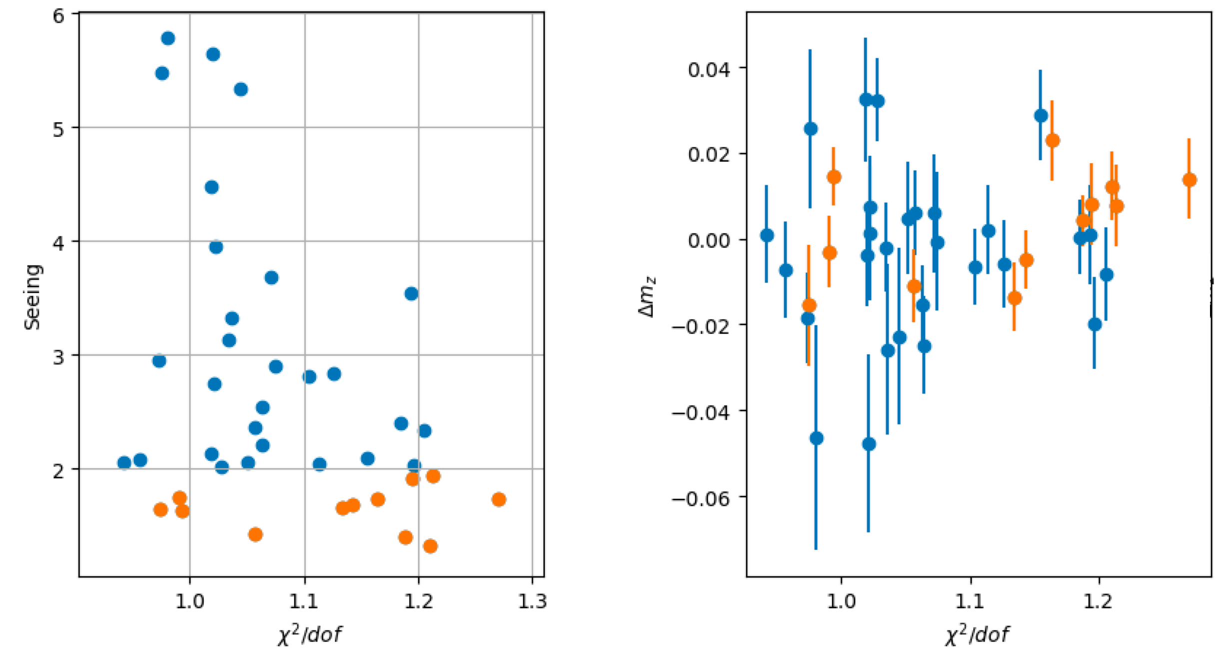
Bright star:

(flux~10^6)

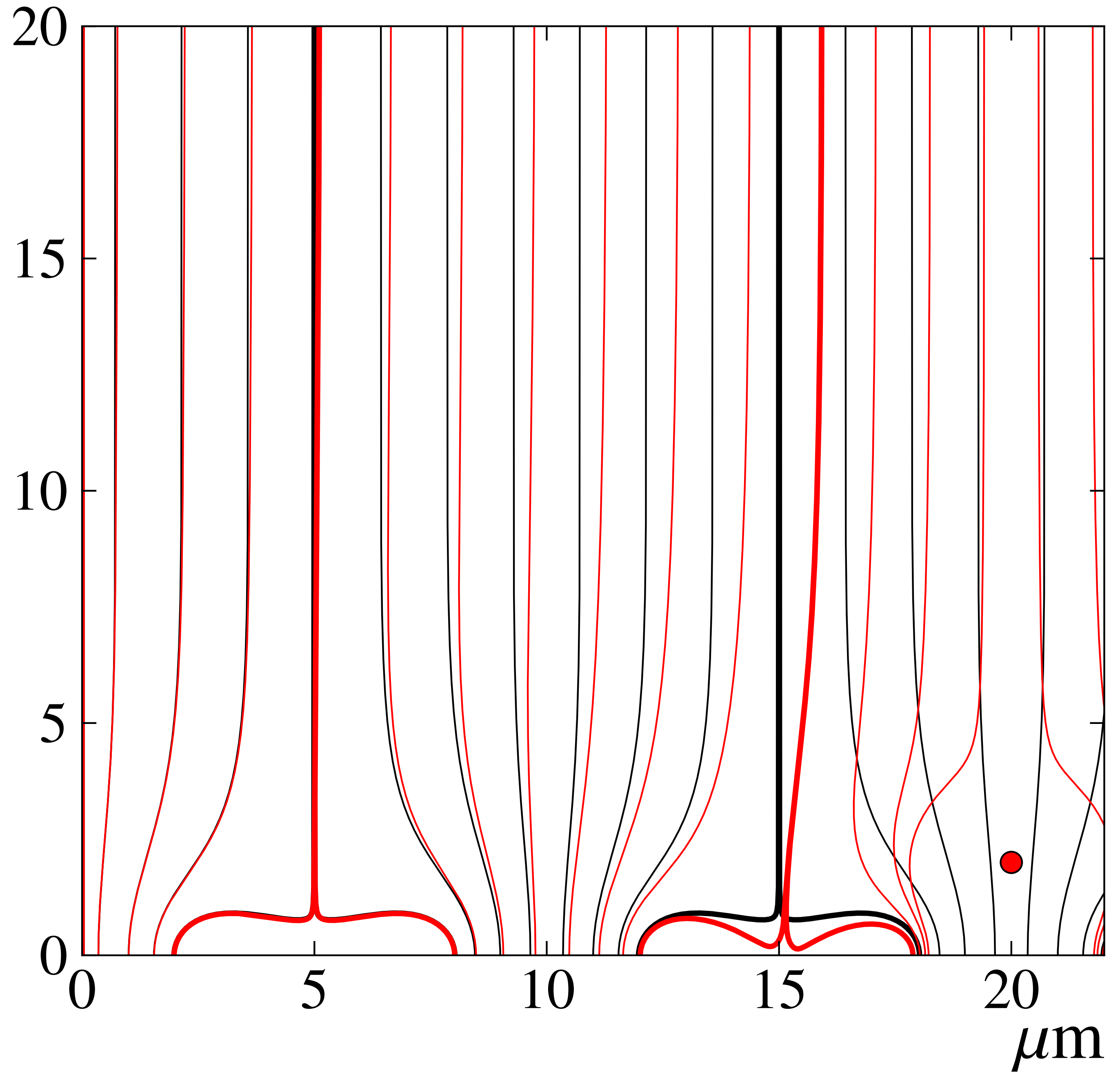


Dim star:

(flux~10^5)



- Charges accumulating in a given pixel well start to affect the electric field
- Subsequent arriving electrons are actually deflected away slightly.
- The resulting PSF is broader than it should be.
- Can be corrected for (but not perfectly) using a kernel-based correction (see Coulton 2017).



Guyonnet+, 2015

Conclusion

- CCDs are a foundational part of modern survey astronomy.
- A basic understanding of CCDs can go a long way in helping you to recognize sensor anomalies in your data.

Further Reading:

- *A Summary of Charge-Coupled Devices for Astronomy*, M. Lesser, 2004 — A concise basic overview.
- *Scientific Charge-Coupled Devices*, J. Janesick, 2001 — A full text book, but out of date
- Papers from the "Precision Astronomy with Fully Depleted CCDs" meeting