Rubin Observatory

Sensor Effects in CCDs

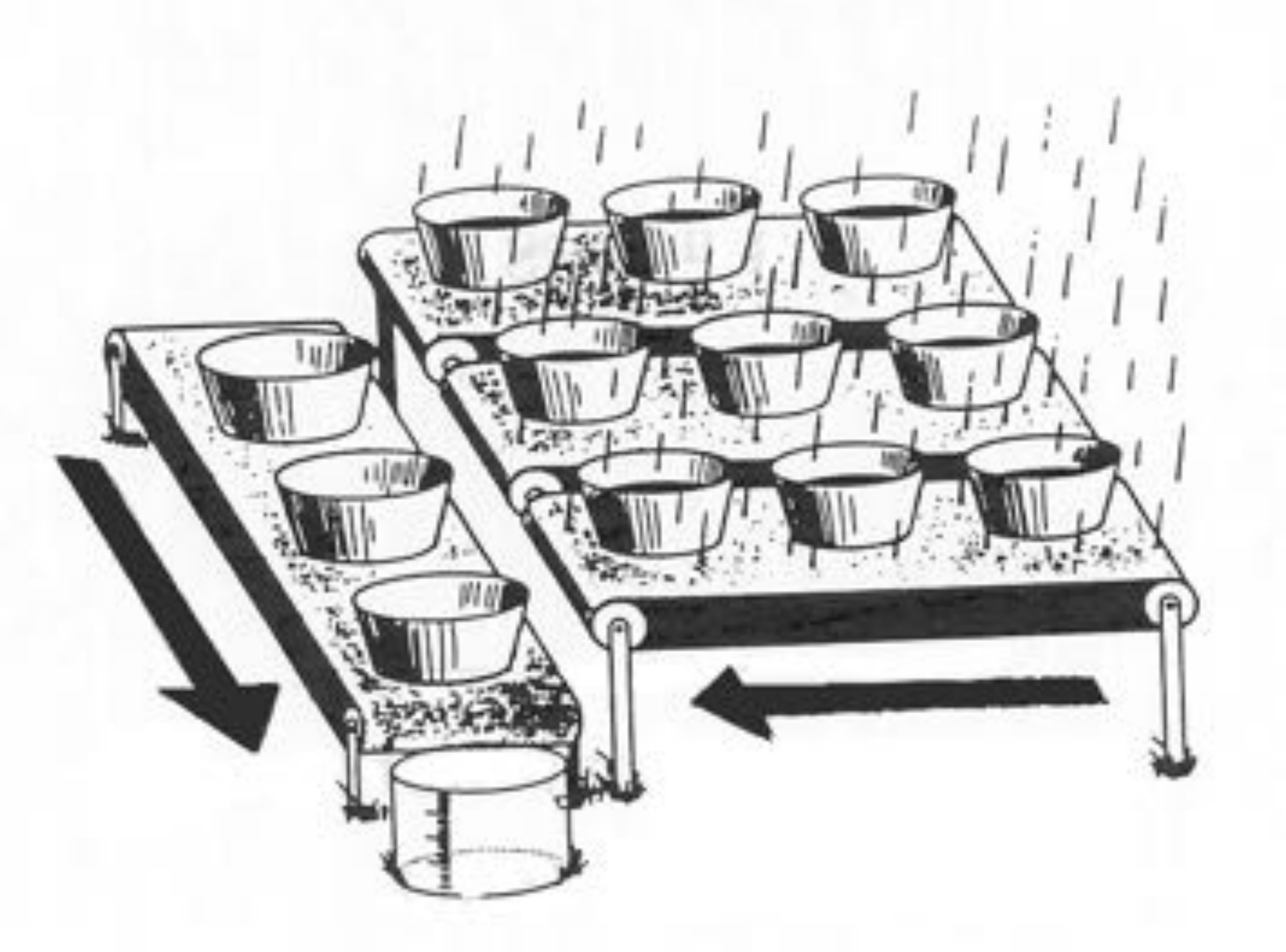
Colin Slater, University of Washington

LSSTC DSFP | The Internet | August 2020

- Before we can do science on images, we need to understand where those images came from.
- My most important message is: always think about the signal chain.
  - Between photons in space and an image on your computer, there's a long series of events that and measurements and transformations of those measurements, all of which contribute differently to the pixel values in your image
  - That is best thought of as a chain, since later steps in the process only know about their direct inputs. If an early step adds some noise or some problematic effect, later steps will act on that noise the same as any other signal.

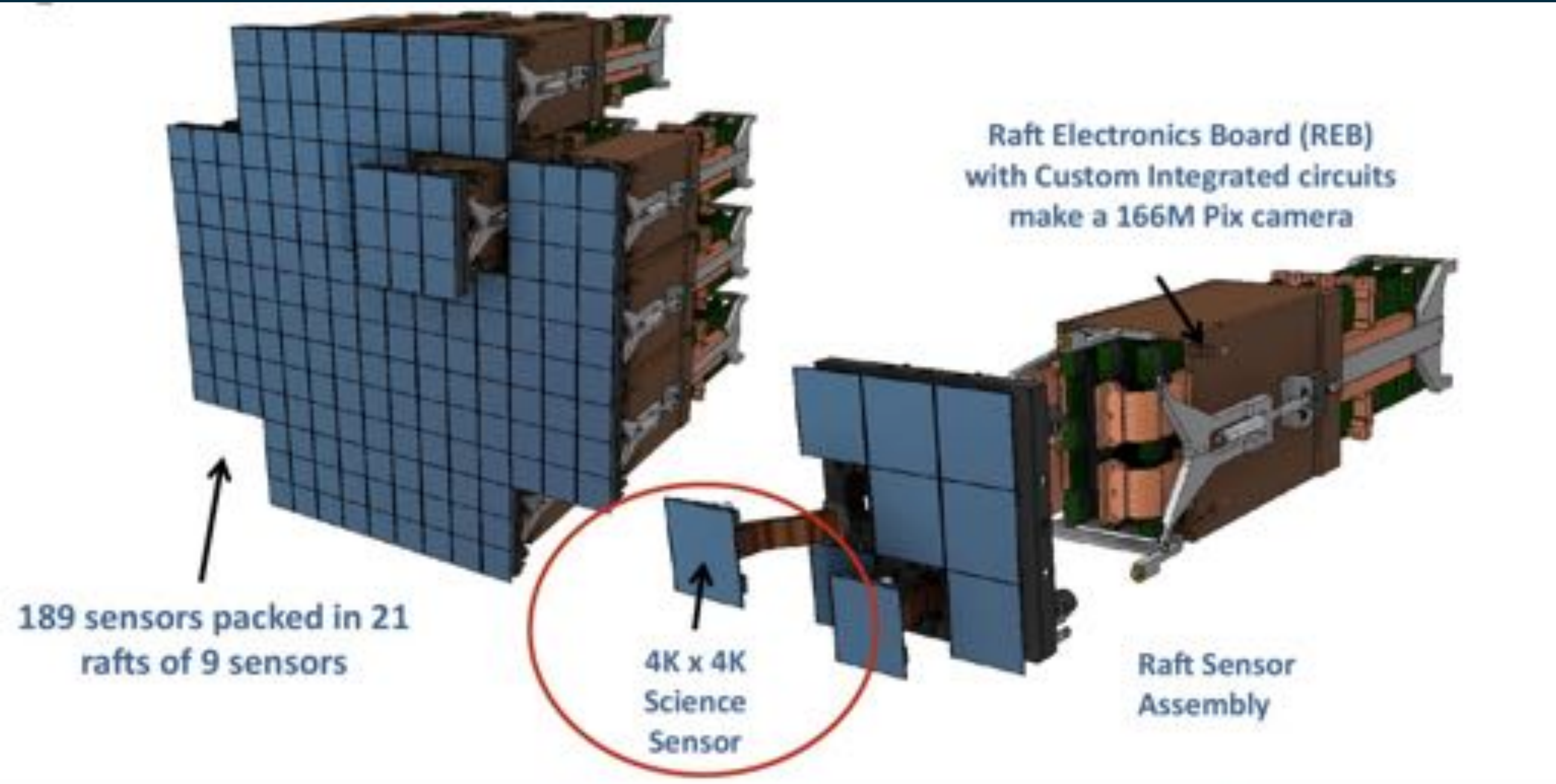
- The upside is that by understanding the different steps in the signal chain, you can more easily identify where some deleterious effect was introduced, and better know how to correct it.
- Much of image processing is concerned with "undoing" problematic effects in the signal chain.

Quick basics of CCDs

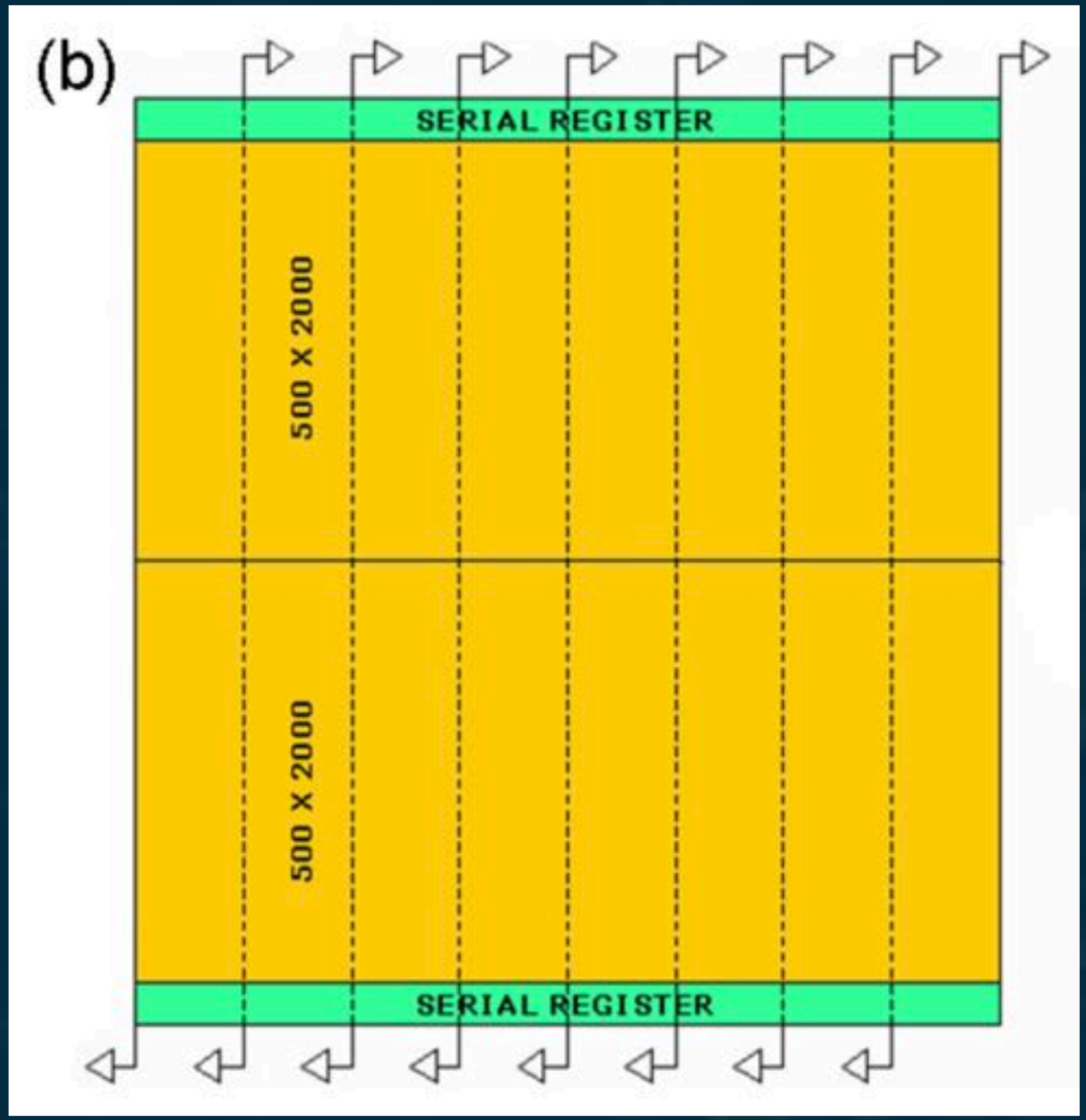


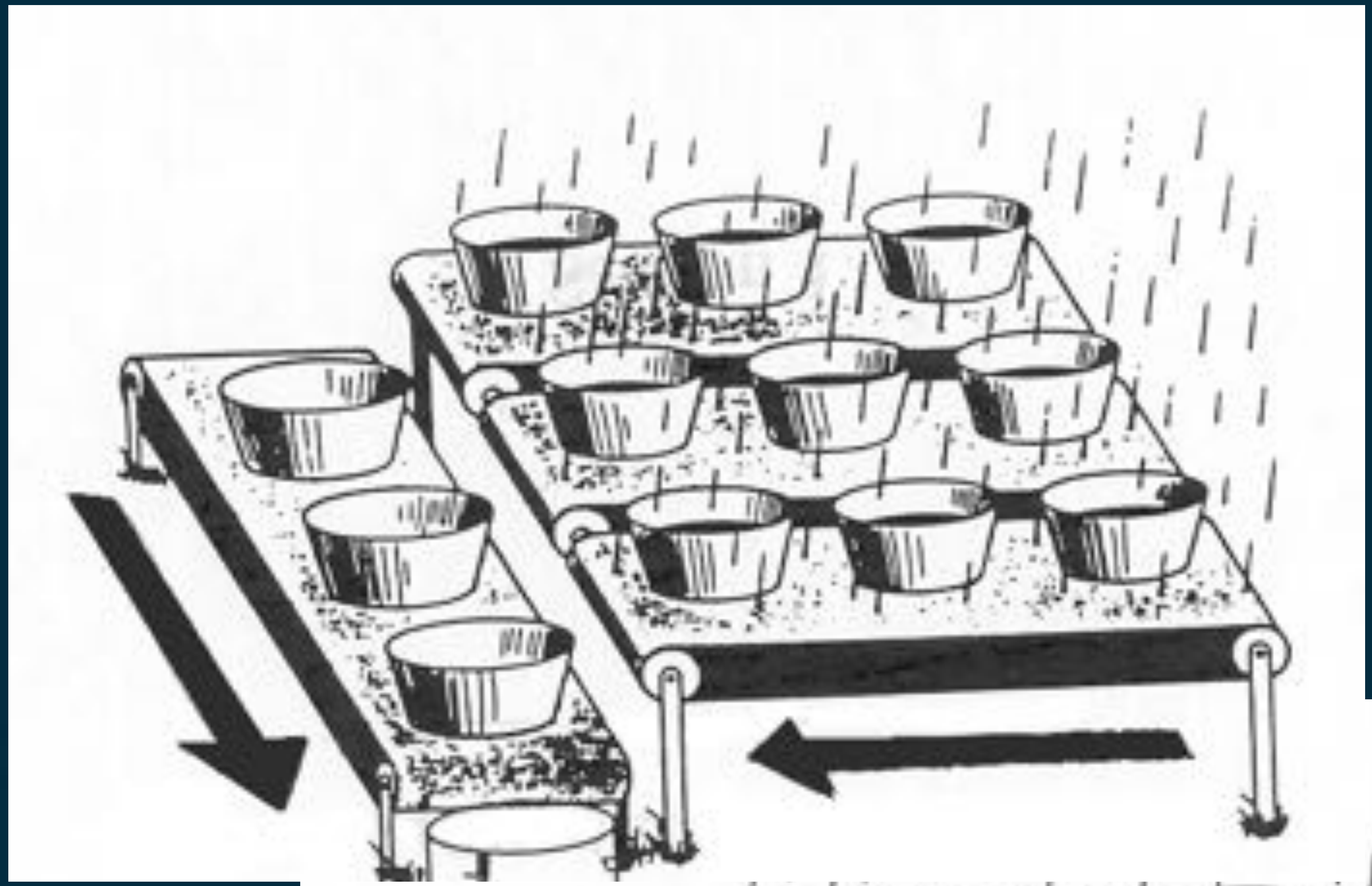
From Janesick 2001

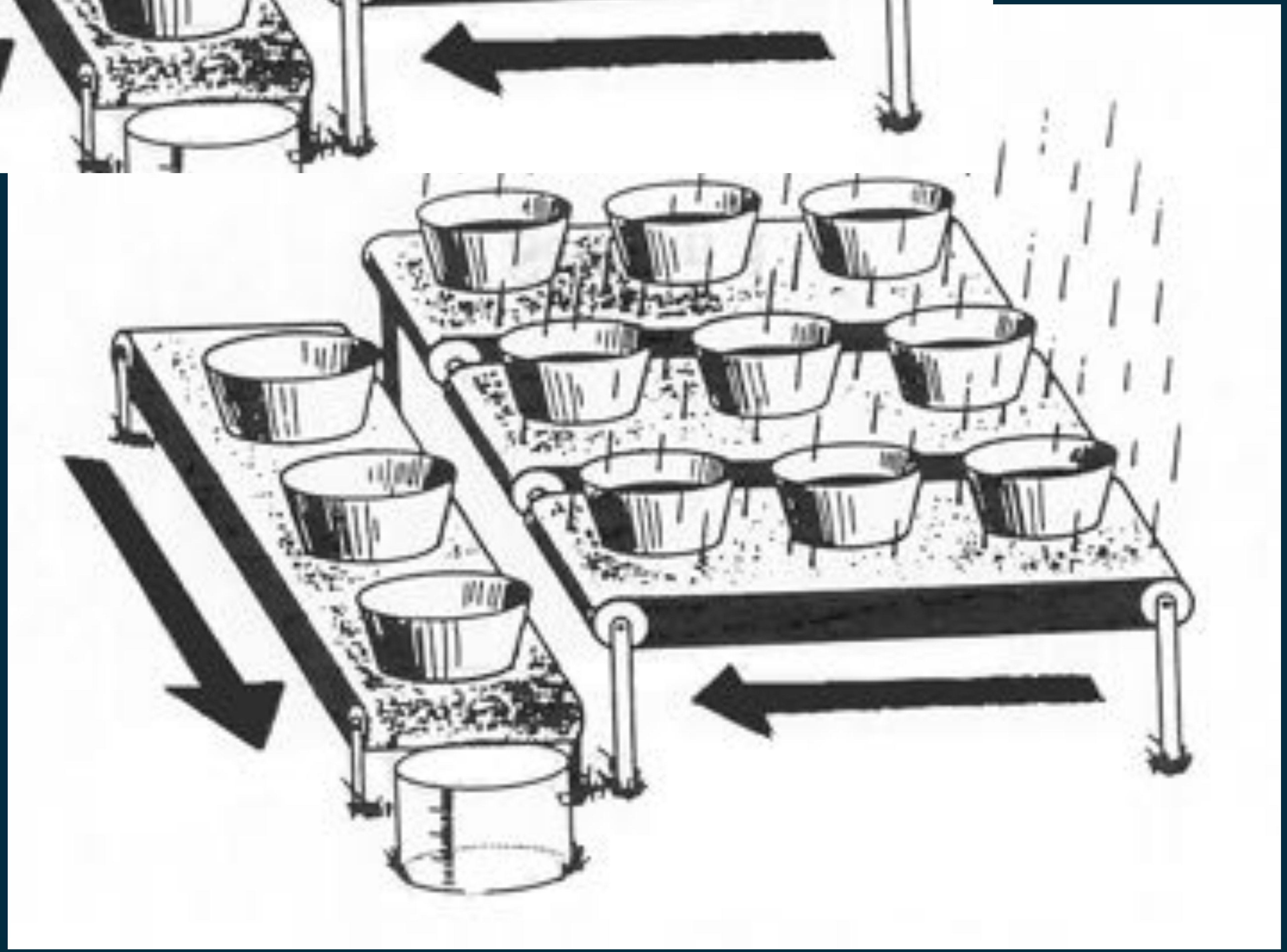
Quick basics of CCDs



- A single sensor (i.e. a single slab of silicon) may have multiple amplifiers







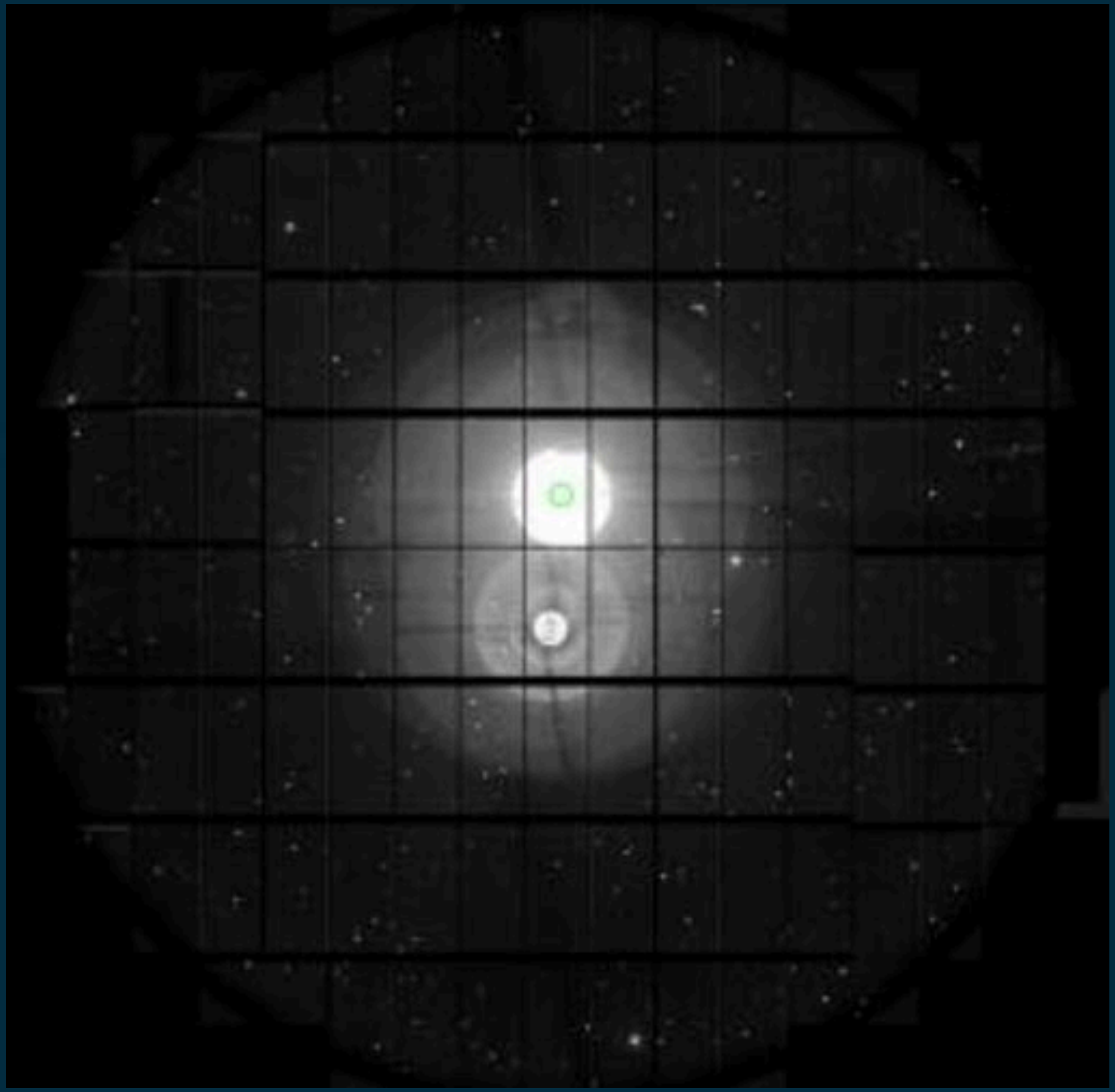
Stages in the signal chain

Rubin Observatory

- Atmosphere (going to skip this to focus on detectors)
- Optics
- Conversion of photons to electrons
- Charge collection
- Charge transfer
- Measurement, analog to digital conversion

Optics and Reflections

- Before we get into detectors, remember that the telescope also creates artifacts.
- Will mostly ignore these for today, but a lot of effort goes into mitigating them.
- Picture is the entire HSC focal plane; all the “halos” are internal reflections in the camera



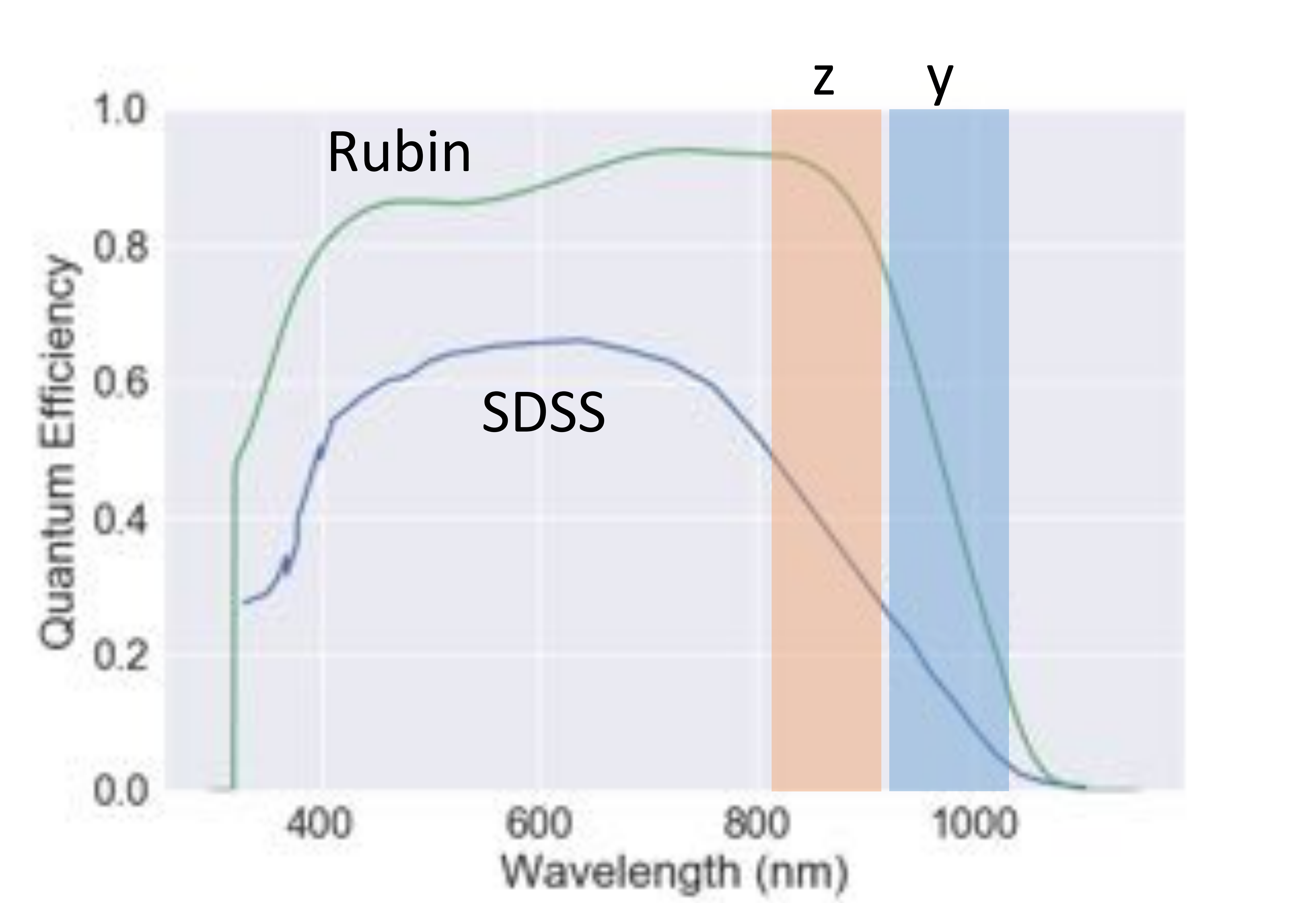
From Gunn & Lupton

Charge Conversion

- Once photons make it to the CCD, they need to be converted into electrons to be collected and measured.
- The fraction of photons that are successfully turned into electrons is called the quantum efficiency. Maximizing the quantum efficiency was a major effort in the development of astronomical CCDs

Improvements in QE

- The big difference between early 2000’s sensors and the latest surveys is in the red bands
- SDSS z-band was not very sensitive
- DES/HSC/Rubin Obs. now have much more sensitive z bands, and added an even redder band, y.



SDSS data from Doi et al. 2010

Charge Conversion, wavelength dependence

- At long wavelengths, more silicon is required to absorb all the photons.
- Rubin Observatory sensors are ~100 microns deep, compared to SDSS-era ~10-20 micron depth

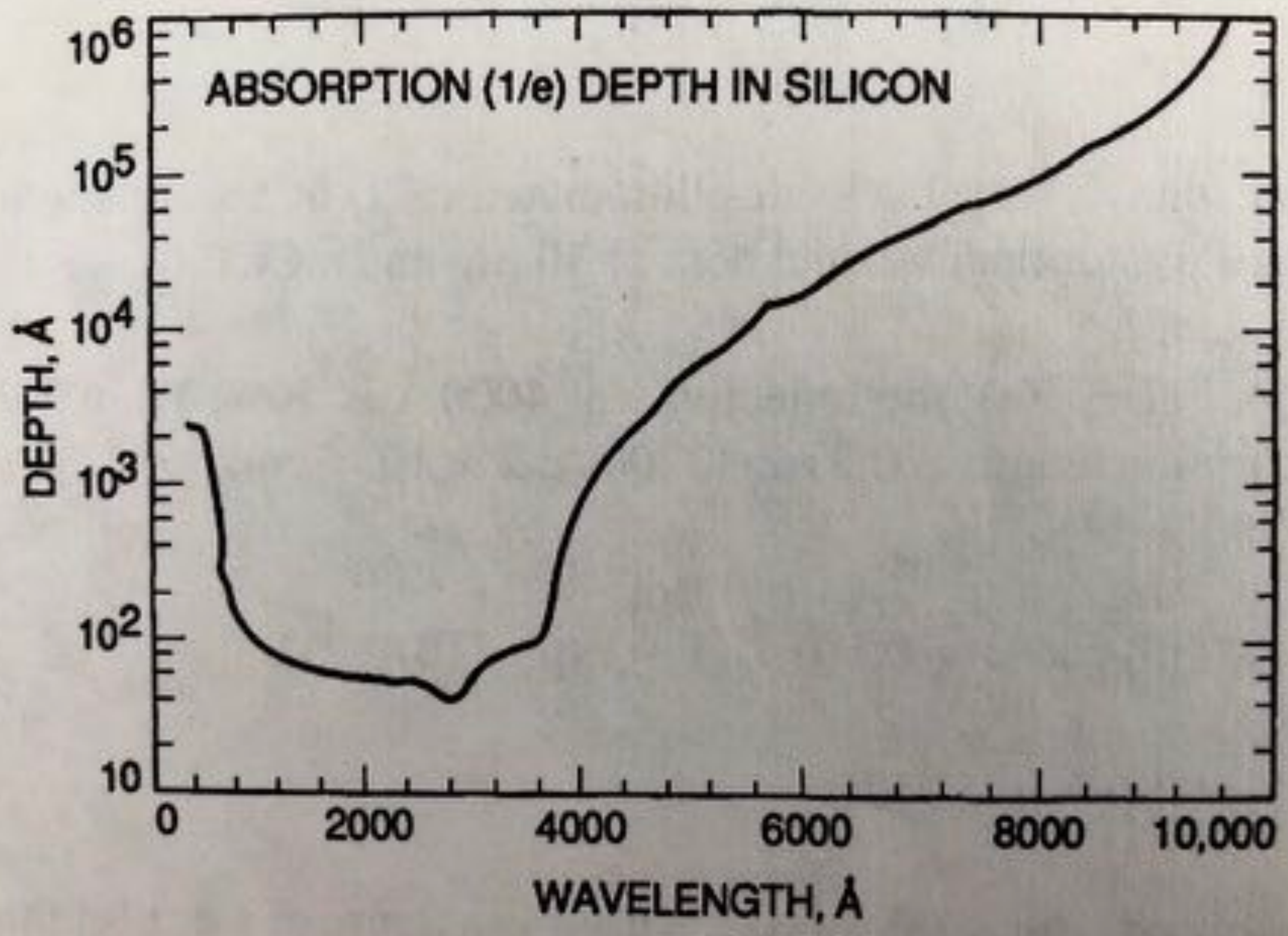


Figure 3.3(b) Silicon photon absorption characteristics.

From Janesick 2001

Charge conversion Pt. 2

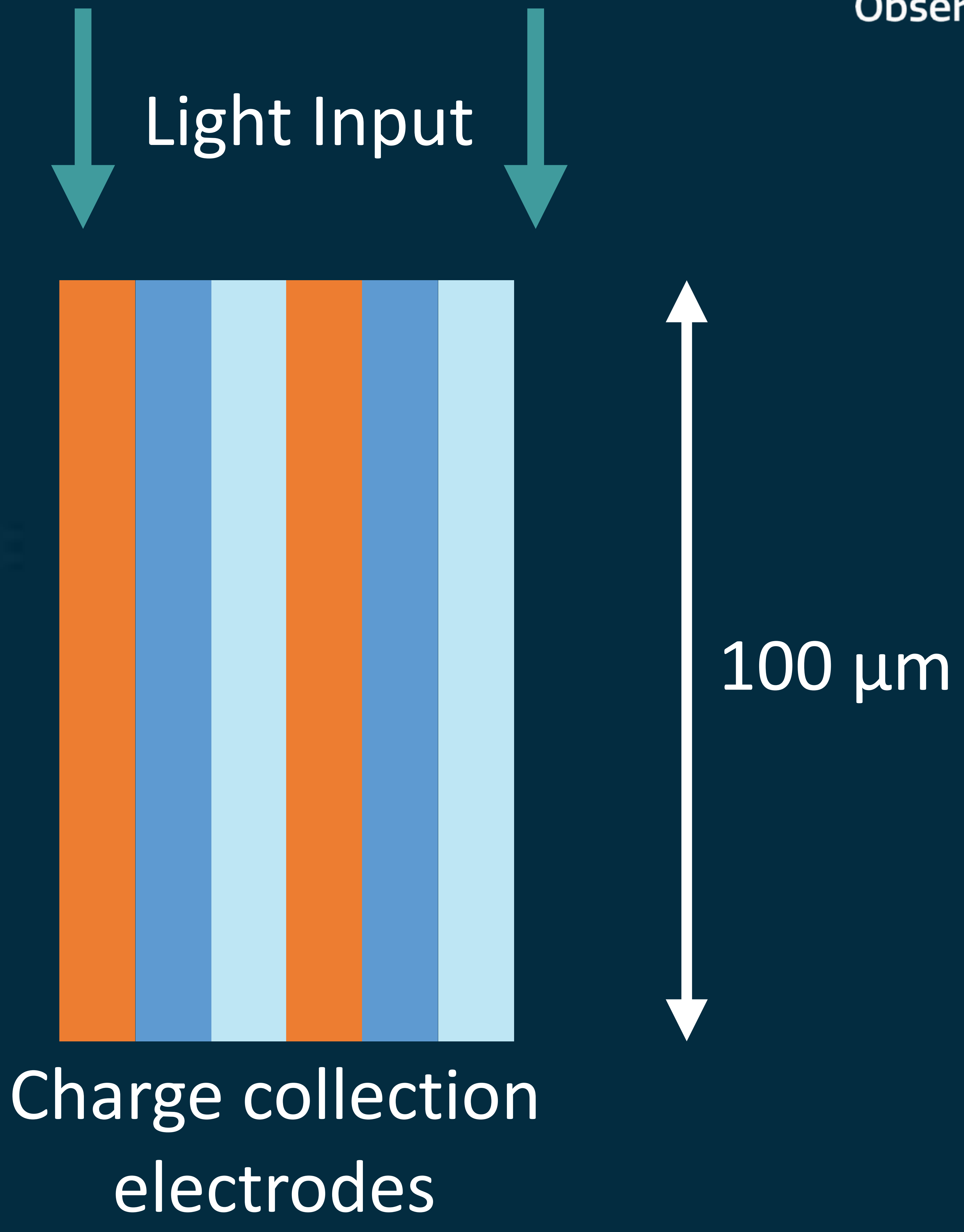
- Even with overall high QE, we think that there is some spatial variation in QE across the chip.
- Typically ~percent level or less.
- That’s part of why we apply a “flat field” correction, which multiplies each pixel by a number to “flatten” the sensor.
- The flat field might also include non-sensor things like specks of dust, so let’s not be too specific about it. More on this later.

Charge collection

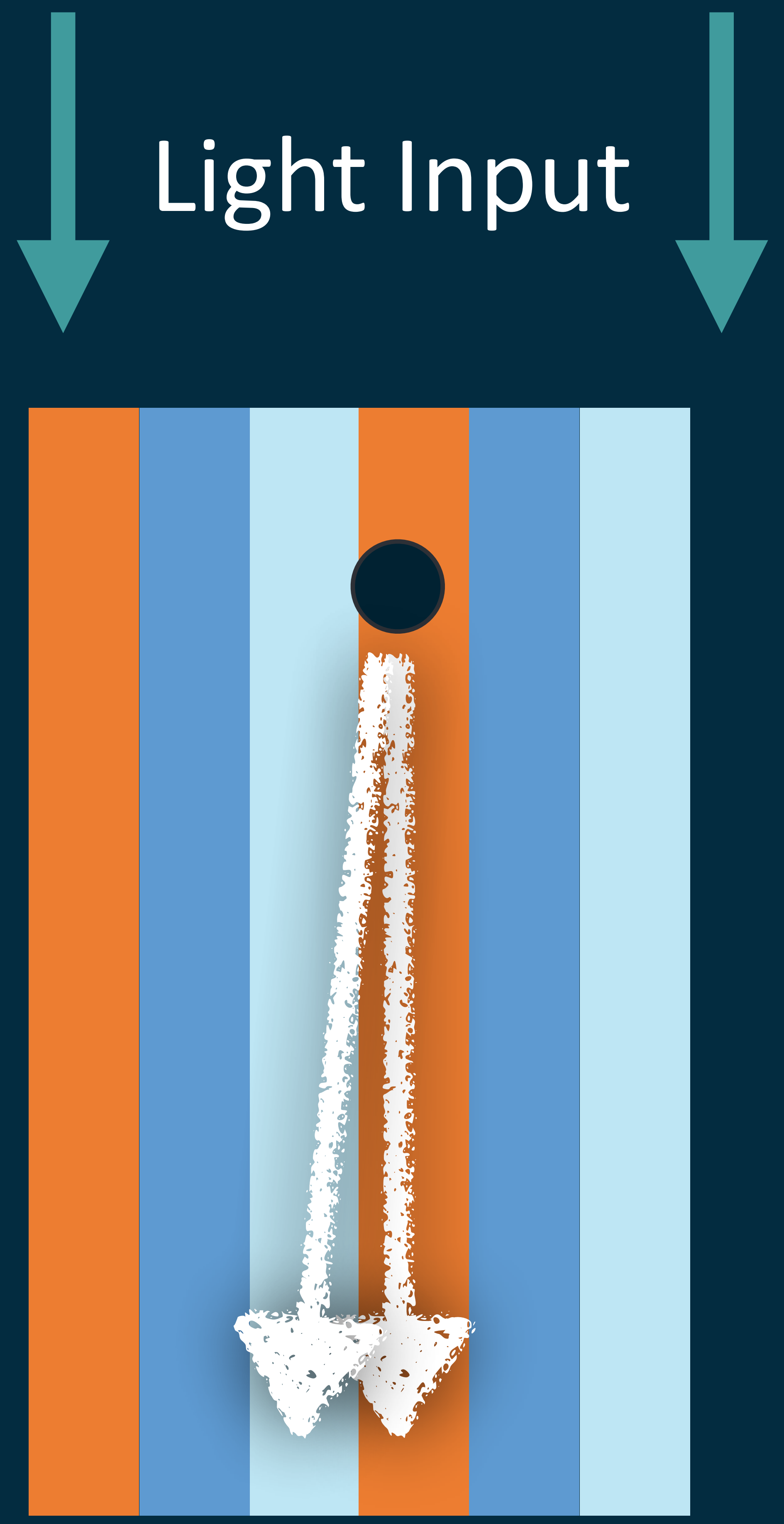
- Once a photon turns into an electron, it still has to be collected into a pixel.
  - The silicon where conversion happens doesn't know what a "pixel" is!
  - "Pixels" are only defined by electrodes on the opposite side of the CCD, away from the incoming light. (confusingly called the "front" side)
  - A "photoelectron" (a funny name!) has to drift from the place it originates to these electrodes, driven by electric fields
  - The dominant electric field is drawing electrons straight towards those electrodes, so all is well!

Charge Collection Pt 2

- But now, in the era of thick CCDs, pixels are very "tall"
- Rubin Obs. pixels are 10μm x 10μm, with 100 microns of silicon above them!
- The vertical electric field is pulling electrons down to the electrodes, but small lateral electric fields can interfere.
- We'll come back to this later.

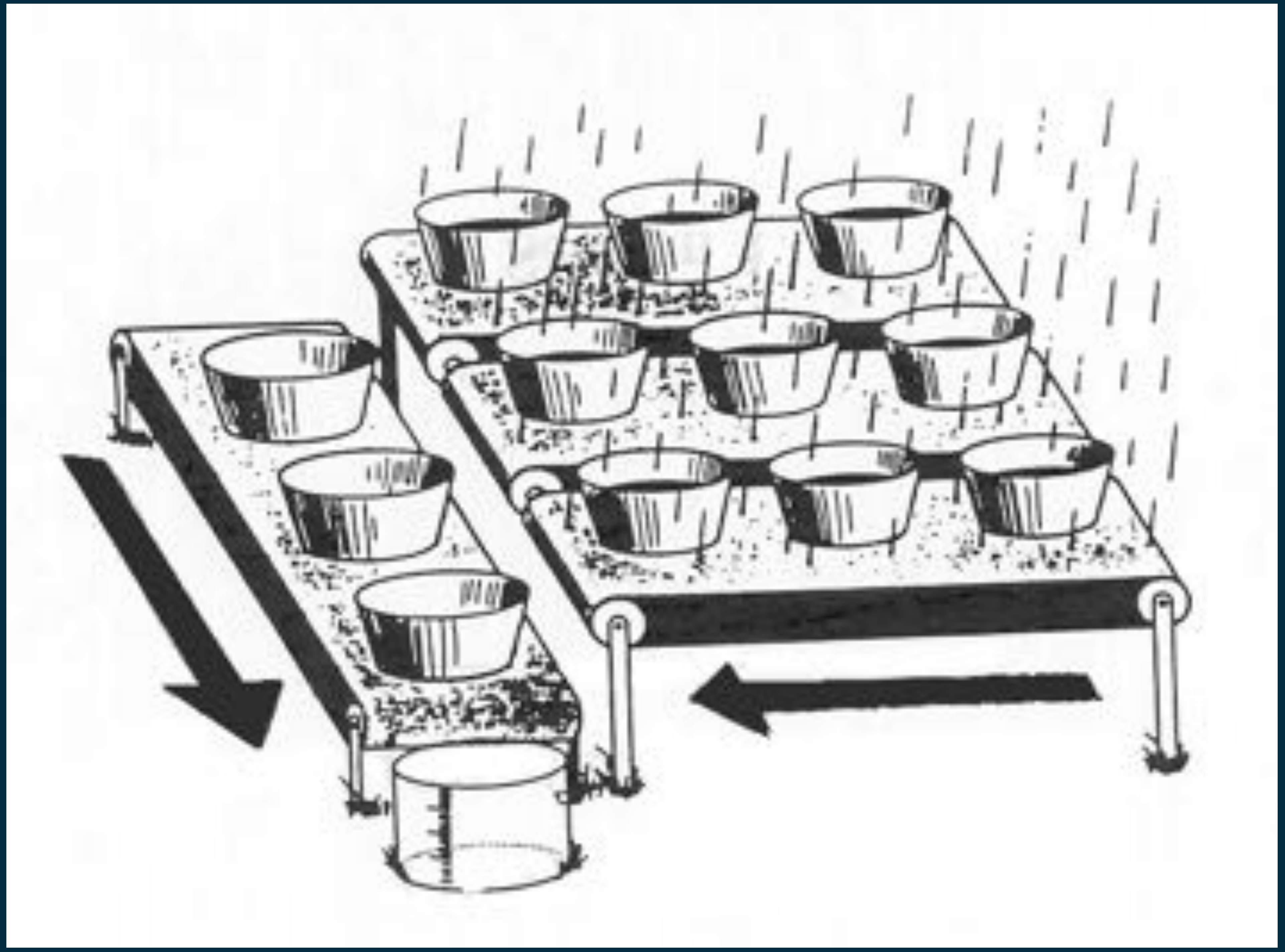


Charge Collection Pt 2



Small side-note

- There's one big problem with the "bucket brigade" image: CCDs do not have gaps between the pixels.
- Once a photon converts into an electron, it must end up in a pixel
- (as long as it's not near the edge of the detector)



Charge collection pt. 3

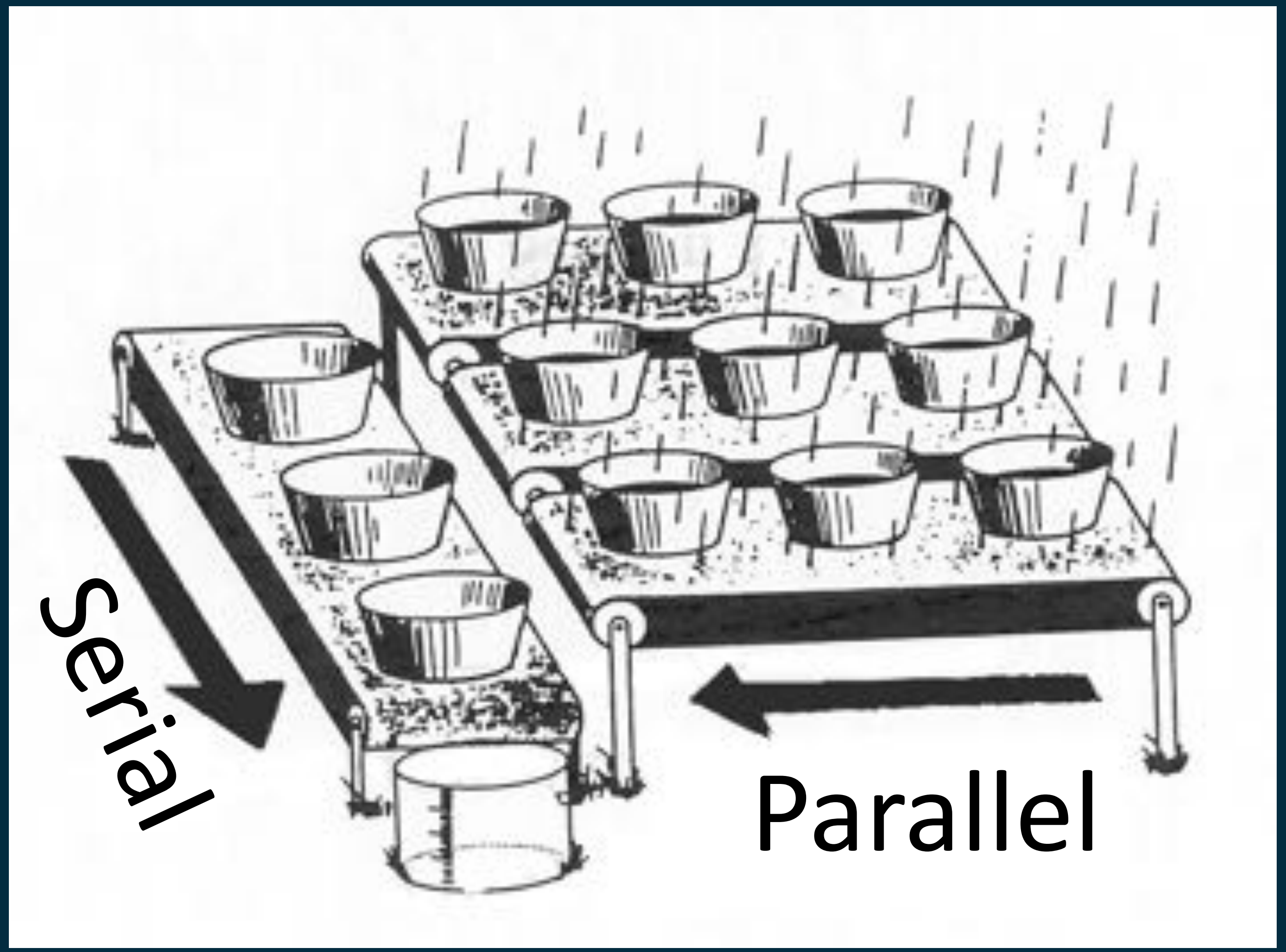
Rubin Observatory

- If you’ve looked at raw images, you’ve seen CCD “bleeds”.
- Only a limited amount of charge can collect in a given pixel; if too much is present, that photoelectron goes to the next-easiest location.
- There’s a big potential barrier between columns, so electrons are unlikely to flow that way. The barrier between different pixels along a single column is much less, easier to excess electrons to overcome

- Note that the photoelectrons are not “lost”, nor are photons deterred from converting into more photoelectrons.

Charge transfer

- Once the exposure is finished, the electrons sitting in their pixels need to be shifted around to the readout amplifier
- There are two parts to this:
  - “parallel transfer” which shifts entire rows to one edge
  - “Serial transfer”, which shifts one row on the edge to a single point, where the readout amplifier lives.
  - All data flows through one of these readout amplifiers. Early CCDs often had a single amplifier; LSST (e.g.) now has 16 per CCD.



Charge Transfer Pt 2

- Charge transfer is not perfect.
  - If you transfer 99.9% of charge, you still have to transfer it across hundreds to thousands of pixels, so that 0.1% adds up very severely.
  - Quantified as “Charge Transfer Efficiency”, or, confusingly, “Charge Transfer Inefficiency”
  - This was the dominant challenge of the 1990’s; still a concern for space-based sensors due to radiation damage.
  - In modern sensors, camera builders usually do so well on this that the software don’t have to worry about it.

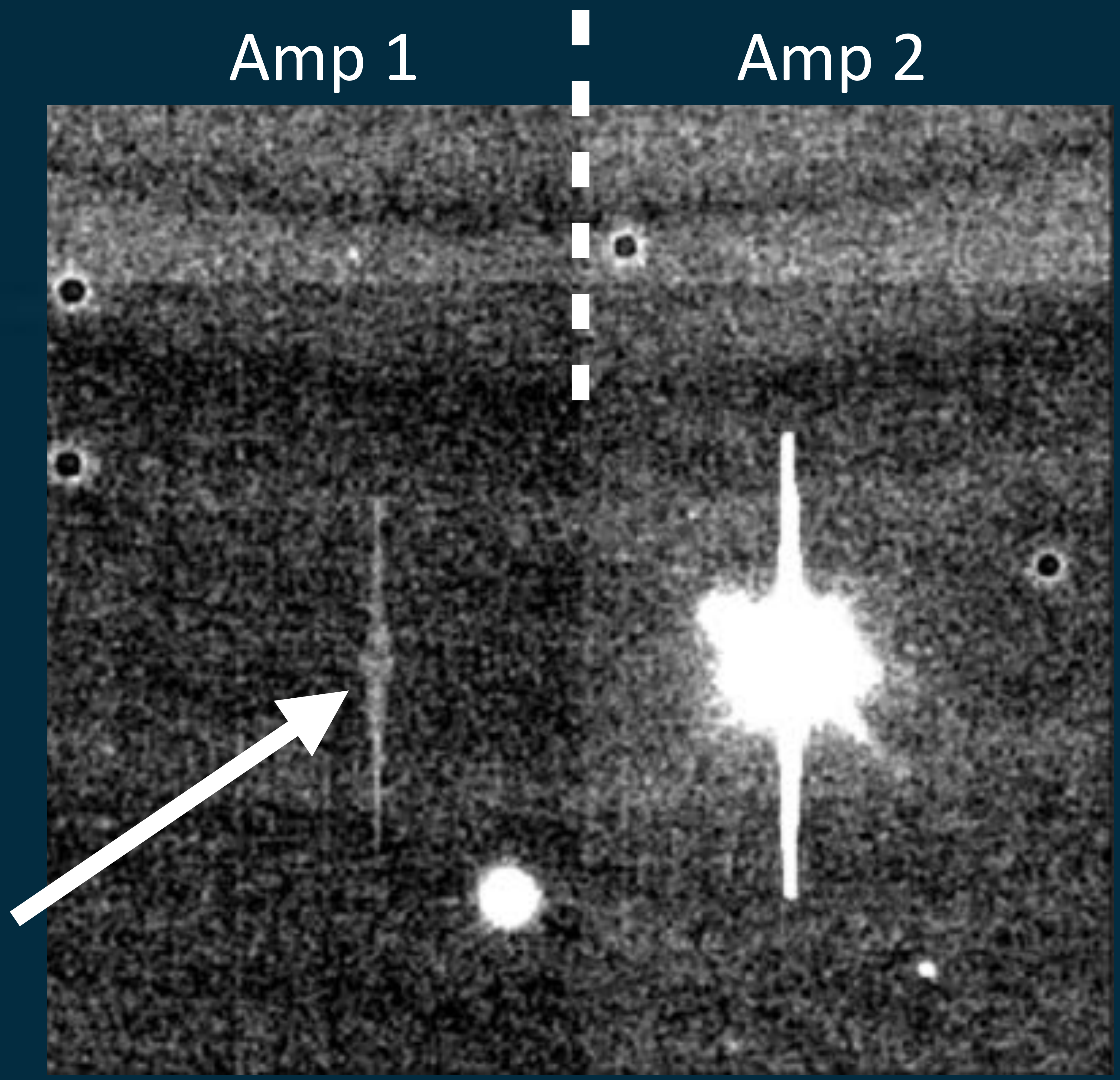
Charge Transfer Pt 3

Rubin Observatory

- A key consequence of the way CCDs are read out is the square array of pixels is transformed into a 1-dimensional sequence, which is read out over time.
- Some effects look like they're spatially correlated, but might actually be temporally correlated.

Crosstalk

- Looks spatial, but actually it's temporal
- Usually created by capacitive coupling between amplifiers on the same CCD, but there can be other causes also.



Charge Measurement

- We’re at the last step of the analog signal chain.
- The stored charge in the pixel need to be converted to a voltage, and amplified
- The amplified voltage is interpreted by an analog-to-digital converter (ADC). Look into correlated double-sampling if you’re interested.
- A small “bias” is added before measurement so that the ADC always sees a “positive” value.
  - We will remove the bias in software later.

“Readout noise”

- The measurement of charge introduces noise. Lots of camera engineering goes into minimizing this noise, so usually it’s very small in “finished” cameras.
- There are many physical mechanisms that cause this noise. To the user, they often just get lumped together.
- Often hear something like “a readout noise of 4 electrons”, i.e. 4 electron RMS scatter added to each pixel.

“Readout noise” Pt 2

- We can measure the readout noise by taking a “bias” frame.
- Take a zero second exposure, no light should get to the pixels.
- The readout is going to just measure the bias level (which we added at the amplifier), with some scatter corresponding to the readout noise.

Gain

Rubin Observatory

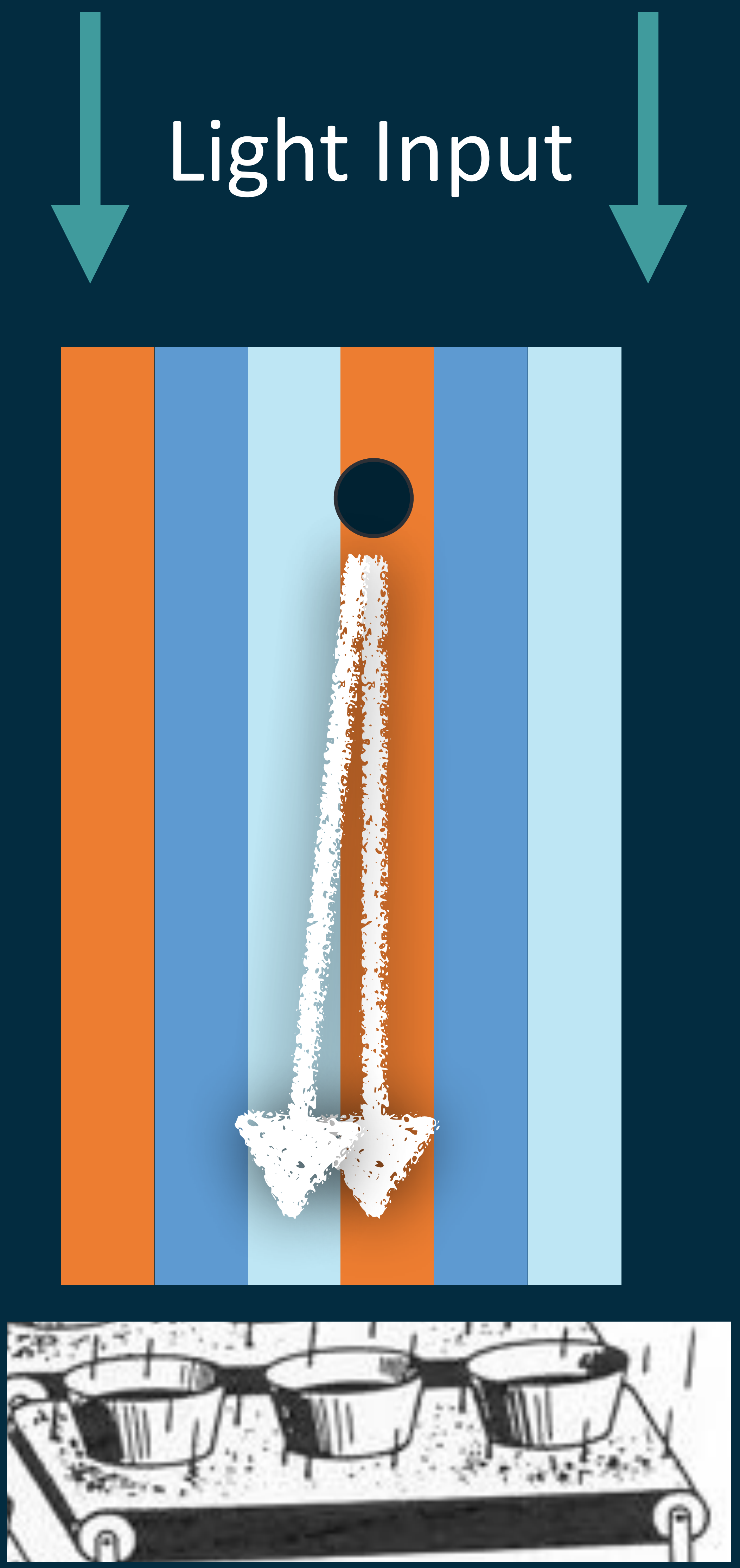
- When we read out the sensor, we translate the number of electrons in a pixel into a new "digital" number (a.k.a. "counts", "ADU" or "DN")
- There is a semi-arbitrary multiplicative factor between those two numbers, determined by the camera electronics. We call that the gain.
- The science user *mostly* doesn't need to know the gain value. We don't depend on it for calibration.
- At very high pixel values (usually), the relation between # of electrons and measured "counts" can become slightly nonlinear. Can be measured and corrected.

We made it through the signal chain.

Pause here if you need a break.

Challenges of thick sensors

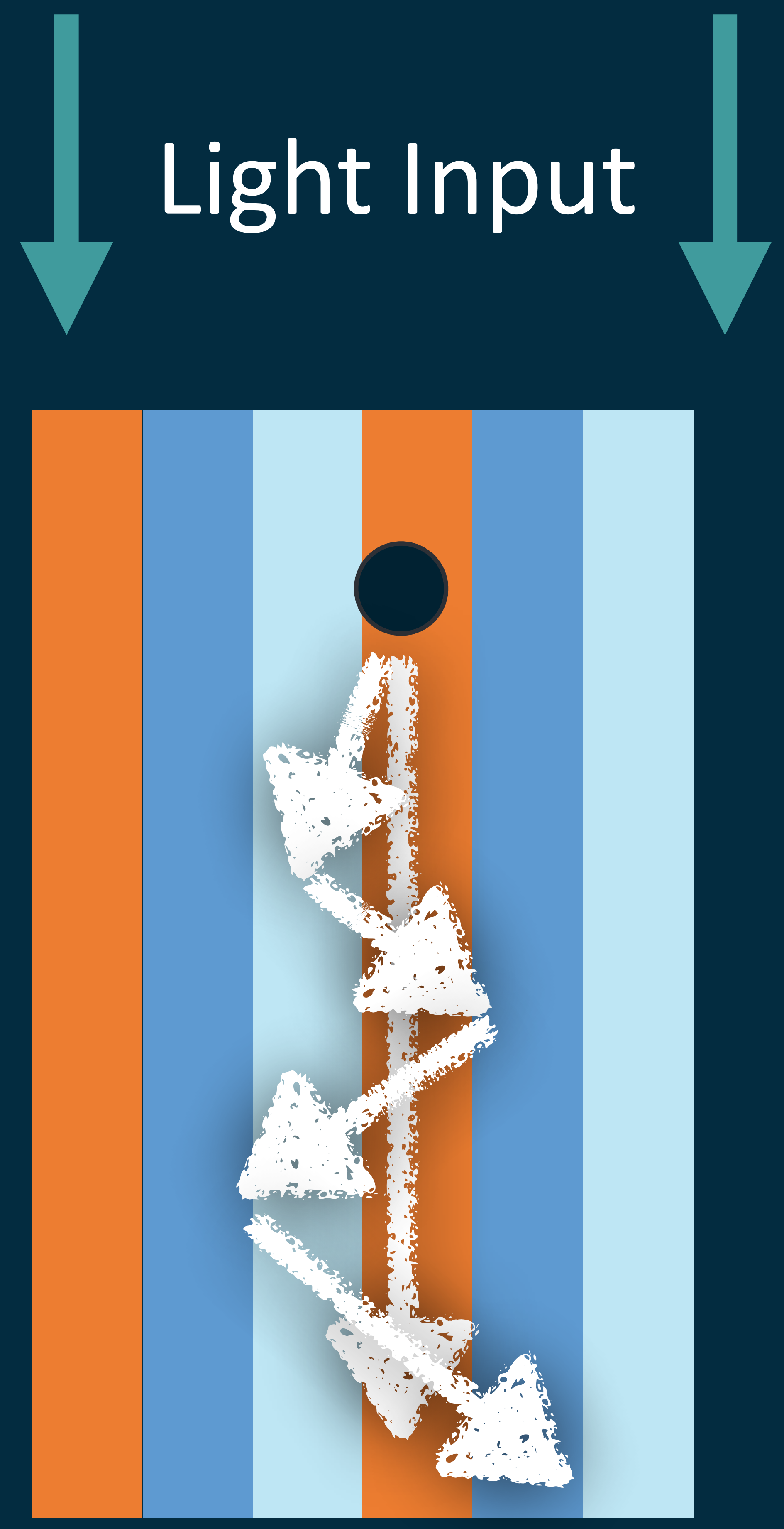
- Big cosmological surveys have all gone to "thick" sensors to gain red sensitivity.
- Thick sensors create an opportunity for all sorts of electric field mischief as photoelectrons travel to the electrodes
- Lots of recent work on understanding these effects.



Challenges of thick sensors - 1

- **Diffusion**: electrons can be scattered slightly as they interact with the silicon
- Typically much smaller than the optical PSF

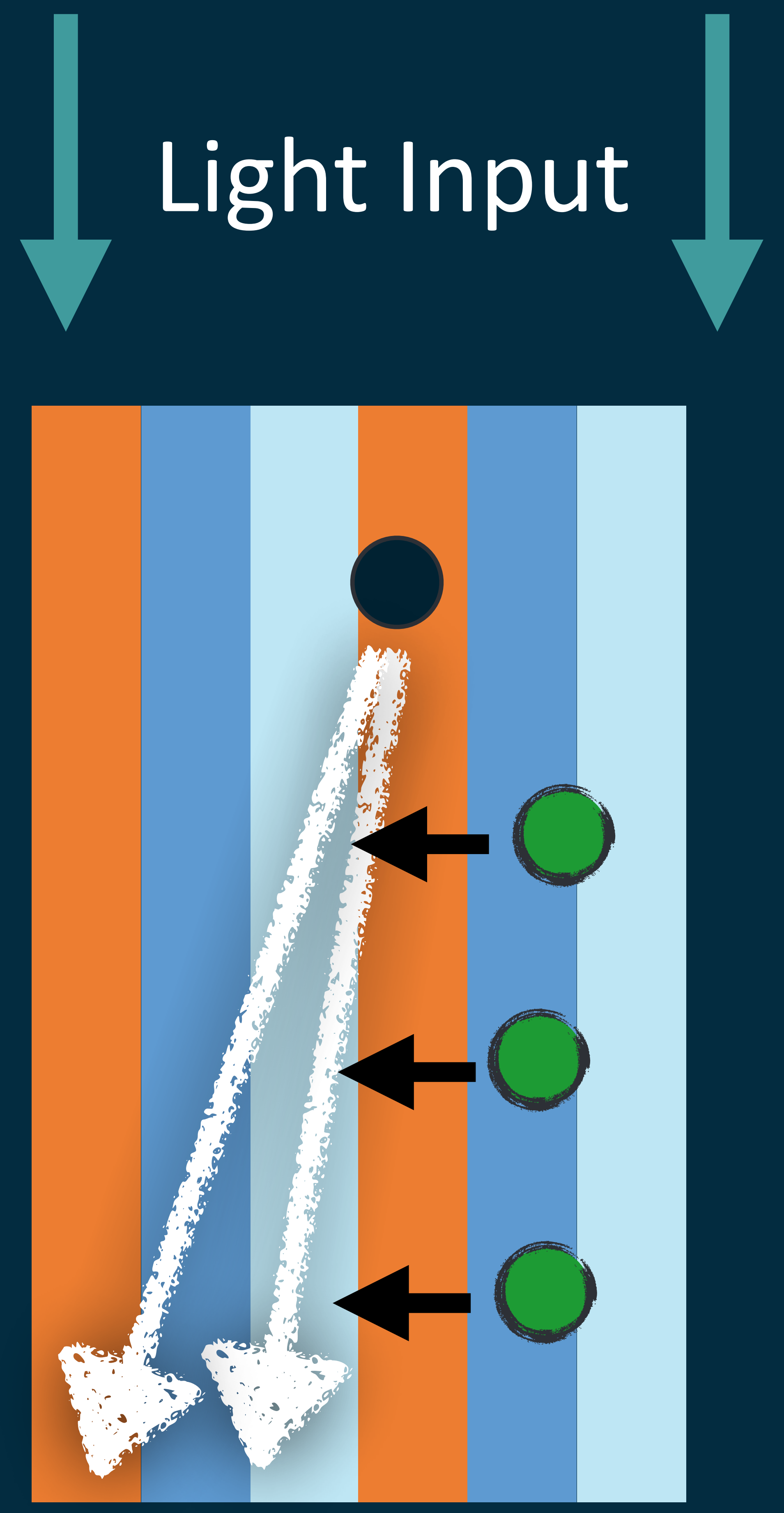
- Because blue photons convert to electrons (on average) closer to the top of the sensor, their photoelectrons have more path length to travel -> more diffusion
- Many thick sensor effects have a chromatic dependence



Rubin Observatory

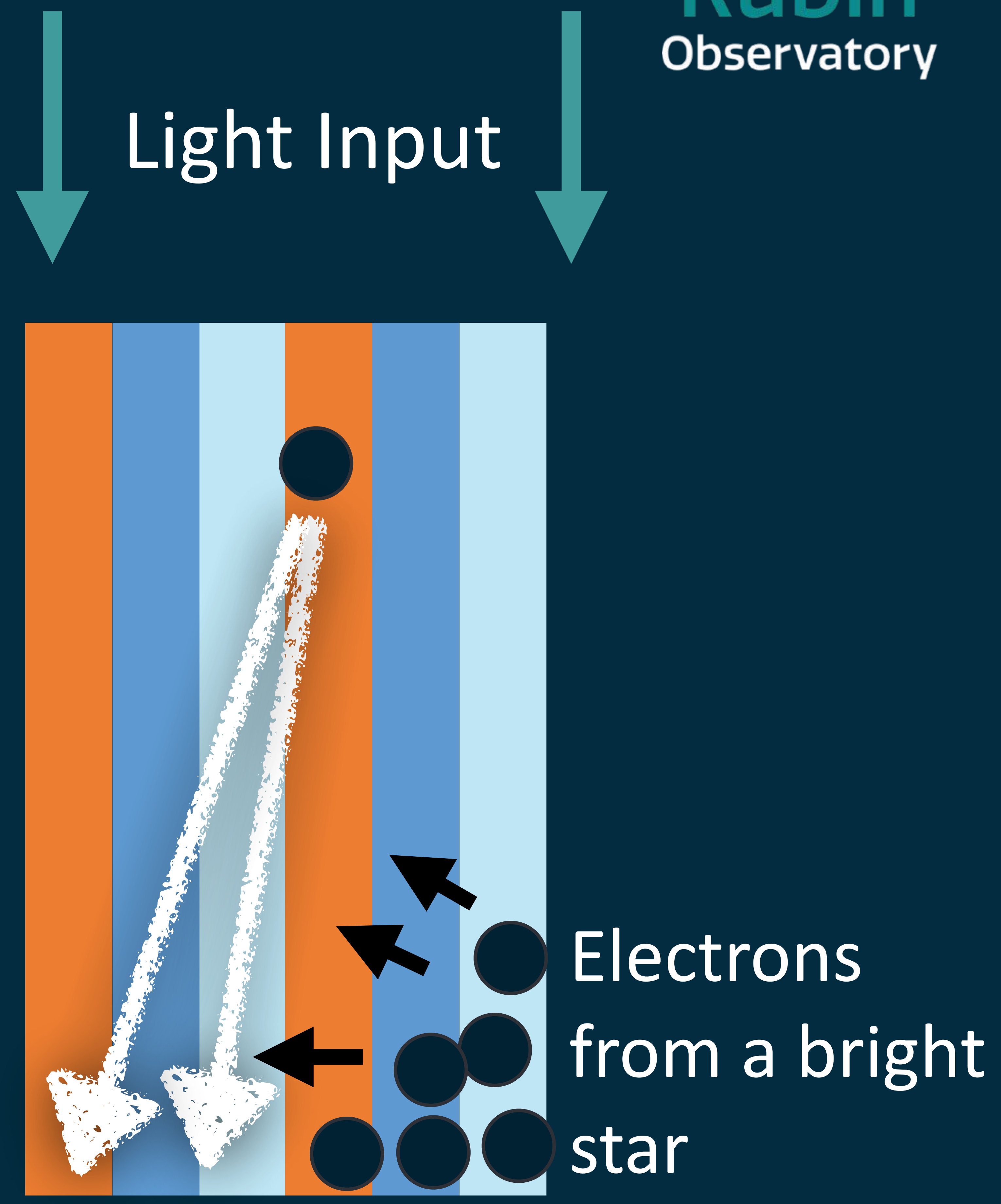
Challenges of thick sensors - 2

- **Si Impurities:** features of the silicon itself can create small electric field effects, pushing photoelectrons around
- This effectively makes some pixels "bigger" and some "smaller", commonly categorized as "pixel area variations"
- These are intrinsic features in a given detector, they don't change.



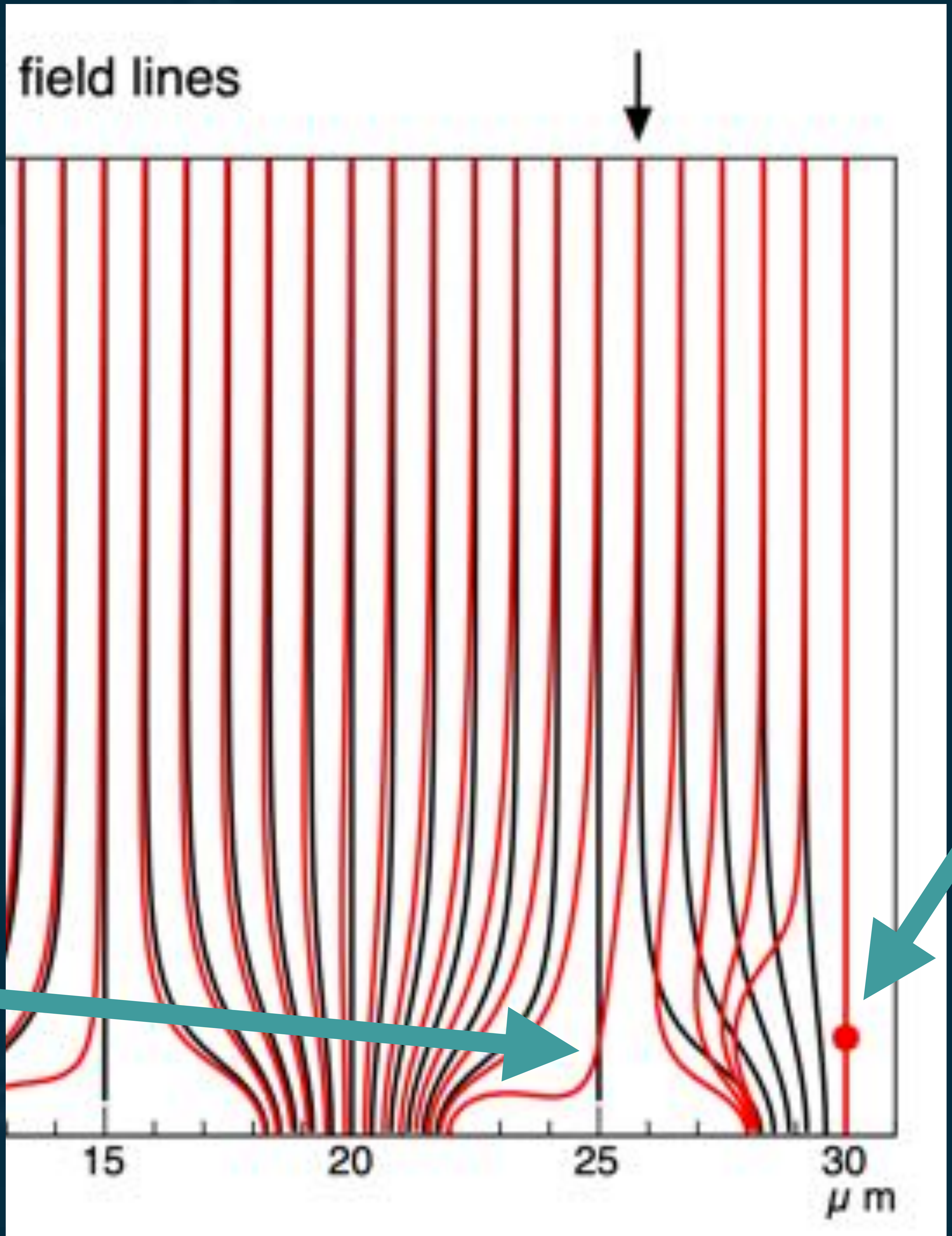
Challenges of thick sensors - 3

- **Other photoelectrons:** a pixel with a large stored charge tends to push incoming electrons away.
- This manifests as:
  - A flat field image tends to be slightly *more uniform* than Poisson noise predicts.
  - Stellar PSFs are intensity-dependent, slightly wider if the star is brighter
- The effect is small, but clearly distinguishable in large surveys.



Electrostatic simulations of a CCD

Rubin Observatory



- Simulation of the electric field lines
- red: with extra charge
- black: no extra charge

Charge from photoelectrons

Field lines are deflected into adjacent pixel

Antilogus et al. 2014, arXiv: 1402.0725

Mitigations for thick sensor effects

Rubin Observatory

- Careful sensor design
  - LSST sensors are only 100μm thick, half that of DES. Tradeoff between minimizing charge diffusion and maximizing red throughput.

- Careful calibration
  - Pixel area variations can "look like" QE variations, but correcting them with a normal flat field will make the problem **worse**

- Kernel-based corrections
  - Theoretically, the spreading of charge can be "undone". E.g., Coulton et al. 2017, but an ongoing (and not fully solved) problem.

An Aside: Where to learn more?

- The community of CCD specialists is pretty small, and it can be hard to stay up to date. CCD vendors are very protective of their sensor details.
- The best textbook is Janesick, but it's not up to date.
- The CCD community (and telescope engineering in general) tend to communicate via conferences, often with very useful written proceedings.
- SPIE holds a telescope engineering conference every two years.
- "Precision Astronomy with Fully Depleted CCDs" meeting has been on the cutting edge of thick sensors, see https://indico.bnl.gov/event/672/ and https://www.bnl.gov/paccd2016/