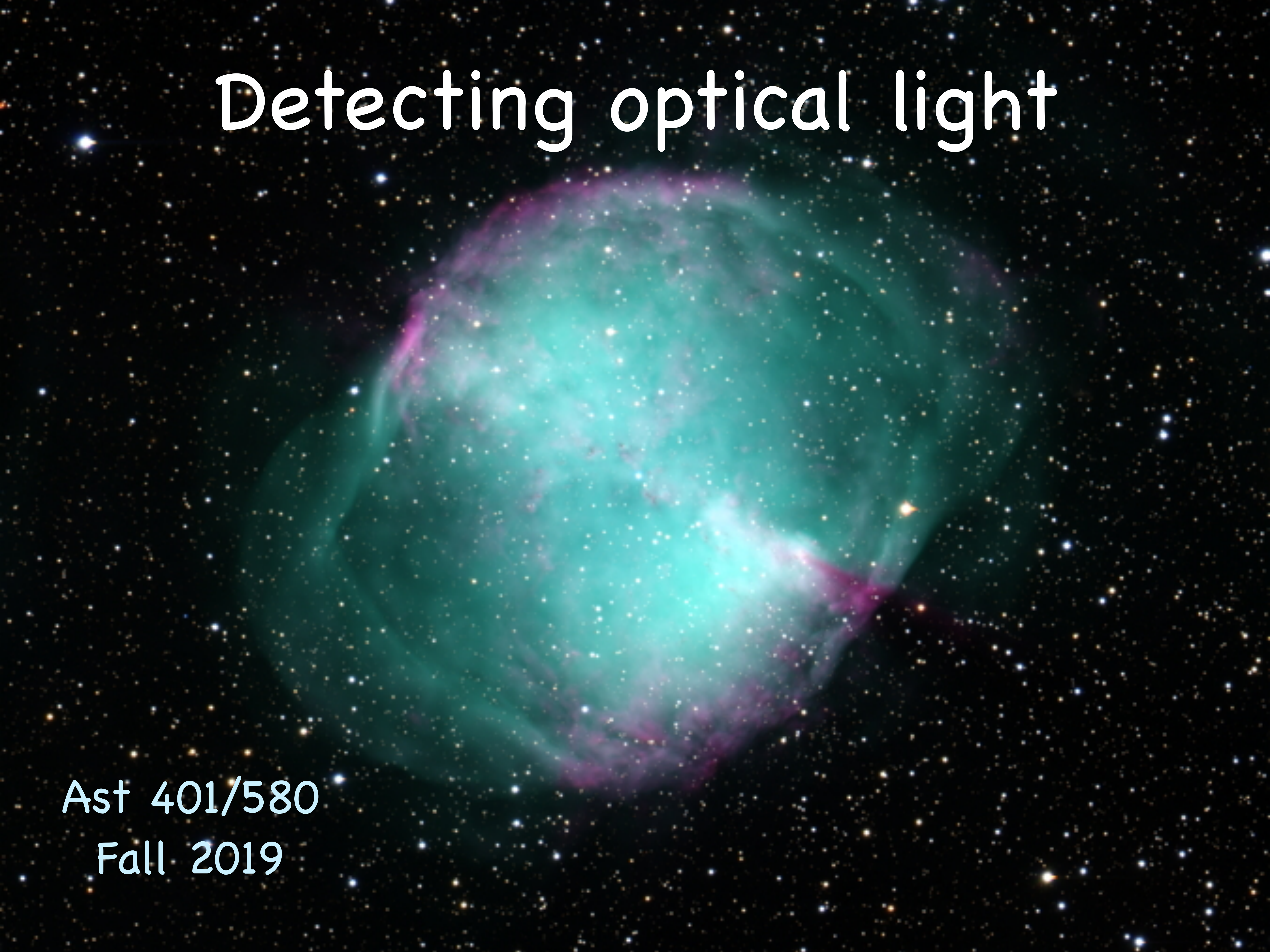
# Detecting optical light



Ast 401/580

Fall 2019

# Requirements of the "optimal" detector

- Area: The larger the detector, the greater the field of view.
- Resolution: The "pixel size" needs to sample the seeing: i.e., there should be about >= 2.5 pixels for the FWHM of a point source to satisfy Nyquist sampling.
- Quantum efficiency: Astronomers are nearly always photon-starved. We'd like to detect the few we get.
- Integration: want to be able to collect photons over a period of time!

# Requirements of the "optimal" detector

- Spectral response: we'd like to be able to observe what gets through the atmosphere, from 3200Å to 10,000Å. (Going further into the NIR would have its drawbacks as well as advantages).
- Linearity: Astronomers like to MEASURE what we see! Having an output that is proportional to input nice!
- Dynamic range: Be able to observe bright and faint stuff in the same field.

# Requirements of the "optimal" detector

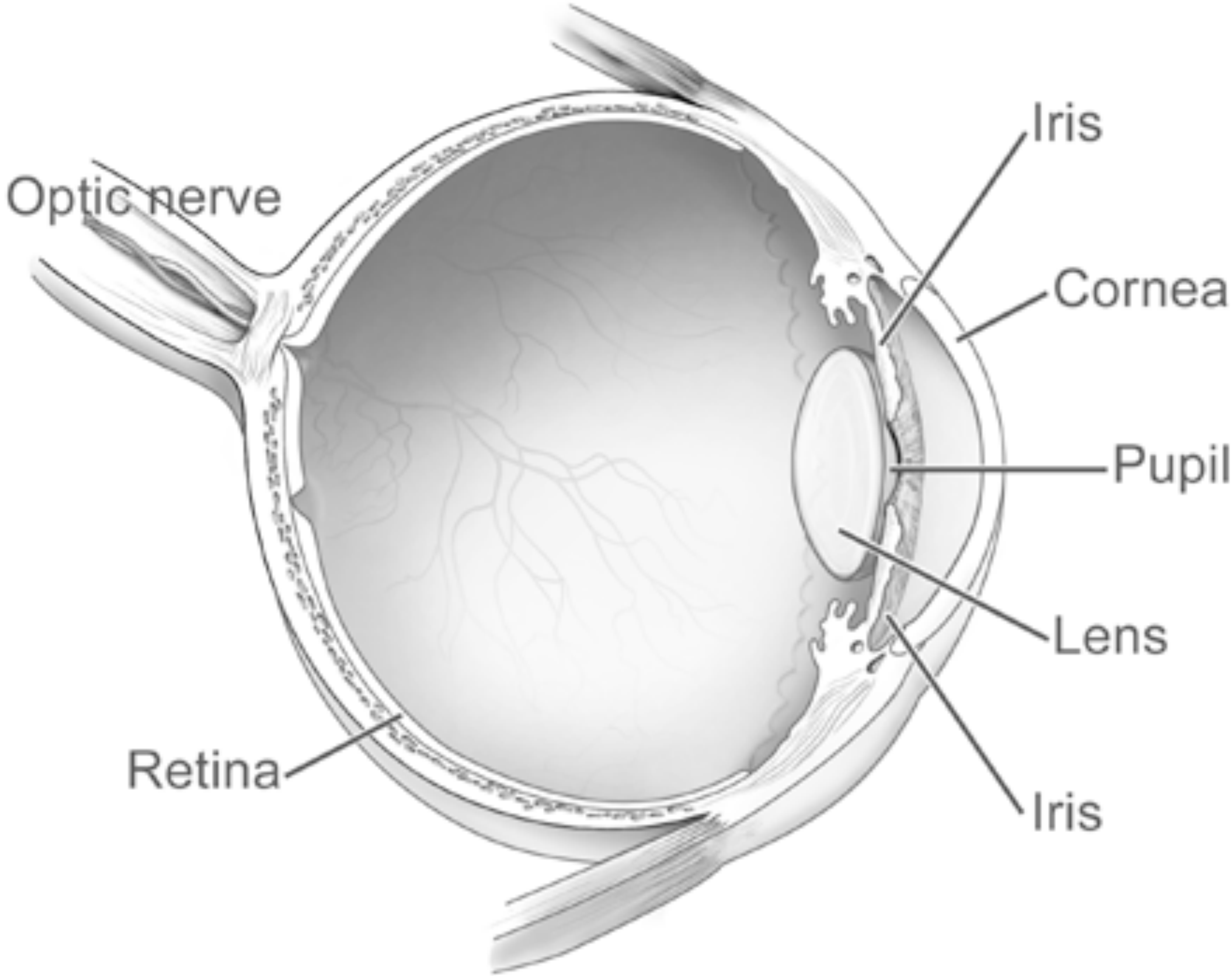
- Noise: Low noise good! Would optimally like to be limited by photon statistics $N^{0.5}$.
- Time resolution: Sometimes you want to measure things that change rapidly (occultations, for instance).

# Detectors: some optimal, some not

- The Eye
- Photographic plates
- Photoelectric photometers
- CCDs
- The future

# The Eye

# The Eye



# The Eye

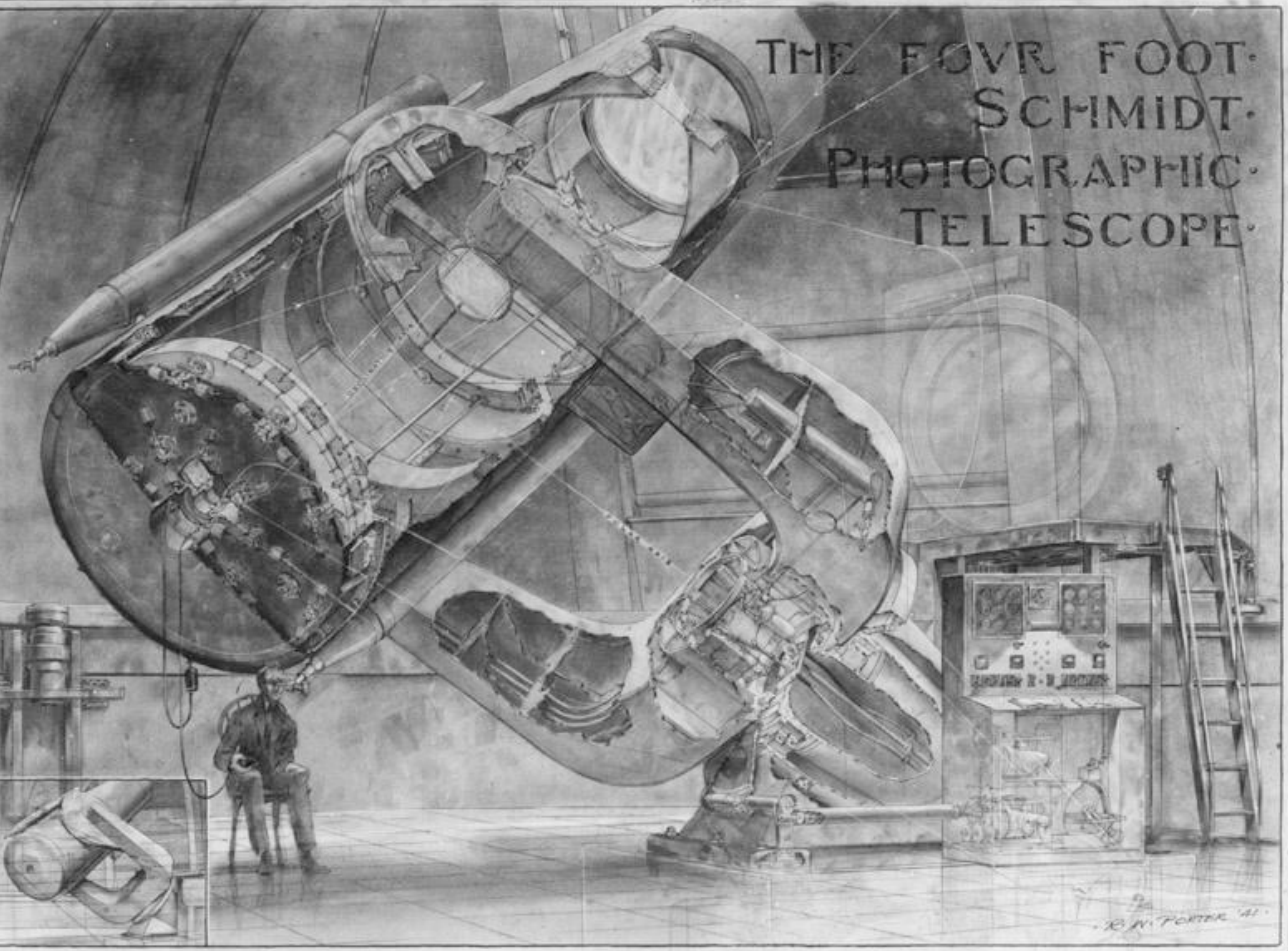
- Pretty amazing!
  - Focal length changes in order to be able to focus close up and far away: muscles squeeze the lens!
  - Brightness dynamic range of 10 billion to 1. Iris changes from 2mm in bright sunlight to 8mm when dark adapted.
  - Spatial resolution about 1′

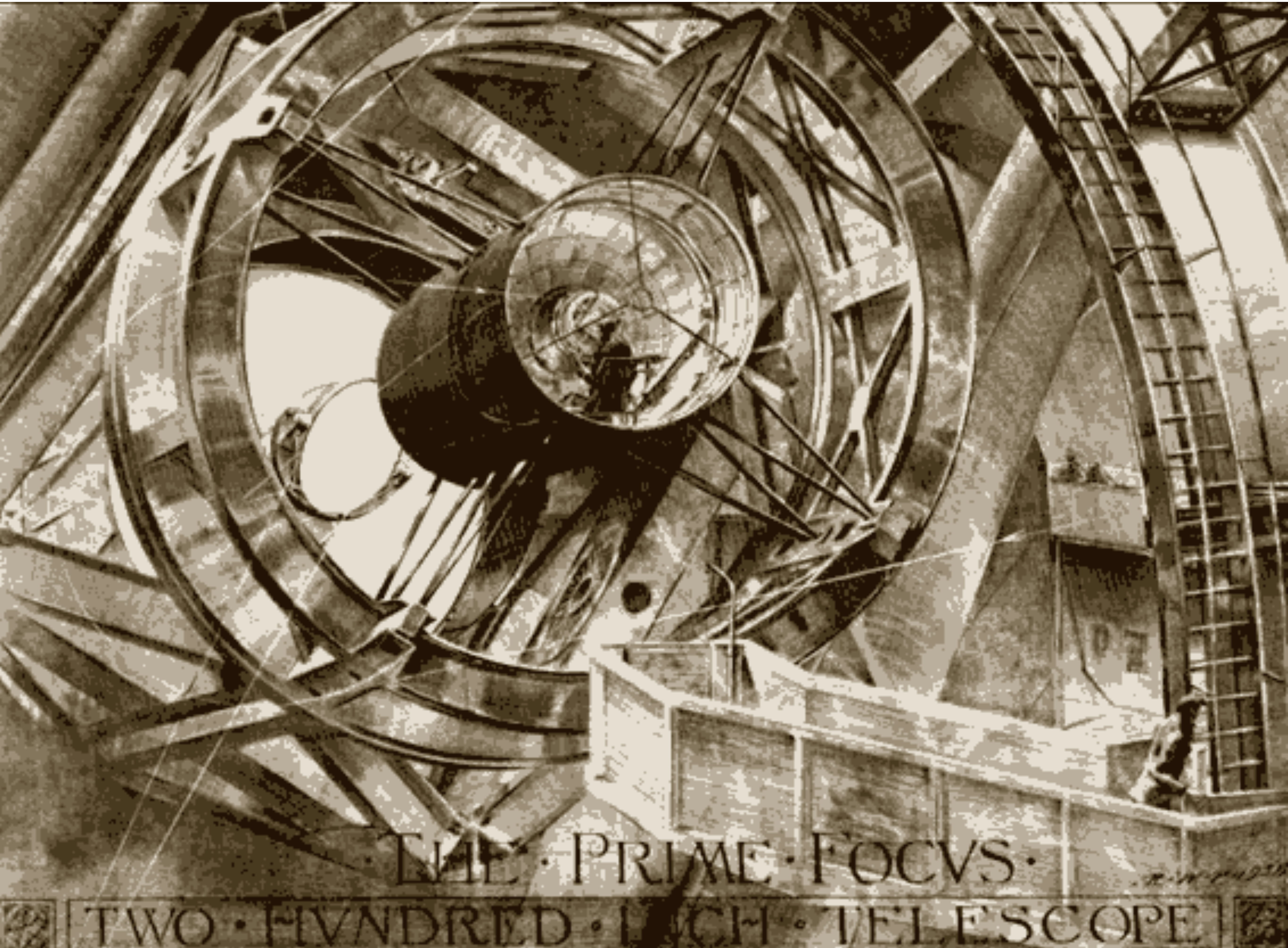
# The Eye

- The eye contains two types of cells: cones and rods. Both are sensitive to light, but rods are more efficient with faint light. Cones are the only color-sensors. Cones are centered; rods are distributed found everywhere else. So, can see faint stuff at night better out of the corner of your eye: “averted vision”

# Photographic plates

- Very large area: 14"x14" or even 20"x20"
- Not linear, but could convert density-->intensity by calibration spots, accuracy about 10%
- Could integrate, but "reciprocity failure". Surface not as sensitive to low light levels as high.
- Resolution good (about 6-10 μm).
- Permanent record going back to roughly 1900.


THE FOVR FOOT SCHMIDT PHOTOGRAPHIC TELESCOPE
R. W. PORTER '41


· THE · PRIME · FOCVS ·
TWO · HVNDRED · INCH · TELESCOPE

# Photoelectric photometers

- Used simple "photomultiplier". An aperture defined the amount of light that entered the instrument (say 5"). The light then passed through a filter (U, B, or V, usually, as they weren't very sensitive to red light), a Fabry lens then spread the light out so it lit uniformly the photocathode surface. Amount of signal out was proportional to the amount of light falling on it. Would measure the signal for a star, and then measure the signal for a nearby star.

# Photoelectric photometers

- VERY accurate: could do milli-mag photometry without batting an eye. Very low (no) noise. But intrinsically 1-D. Could measure one object at a time, and you could not measure the flux of blended stars. Sky subtraction was never simultaneous, unless you used a two-tube photometer. Still in occasional use today.

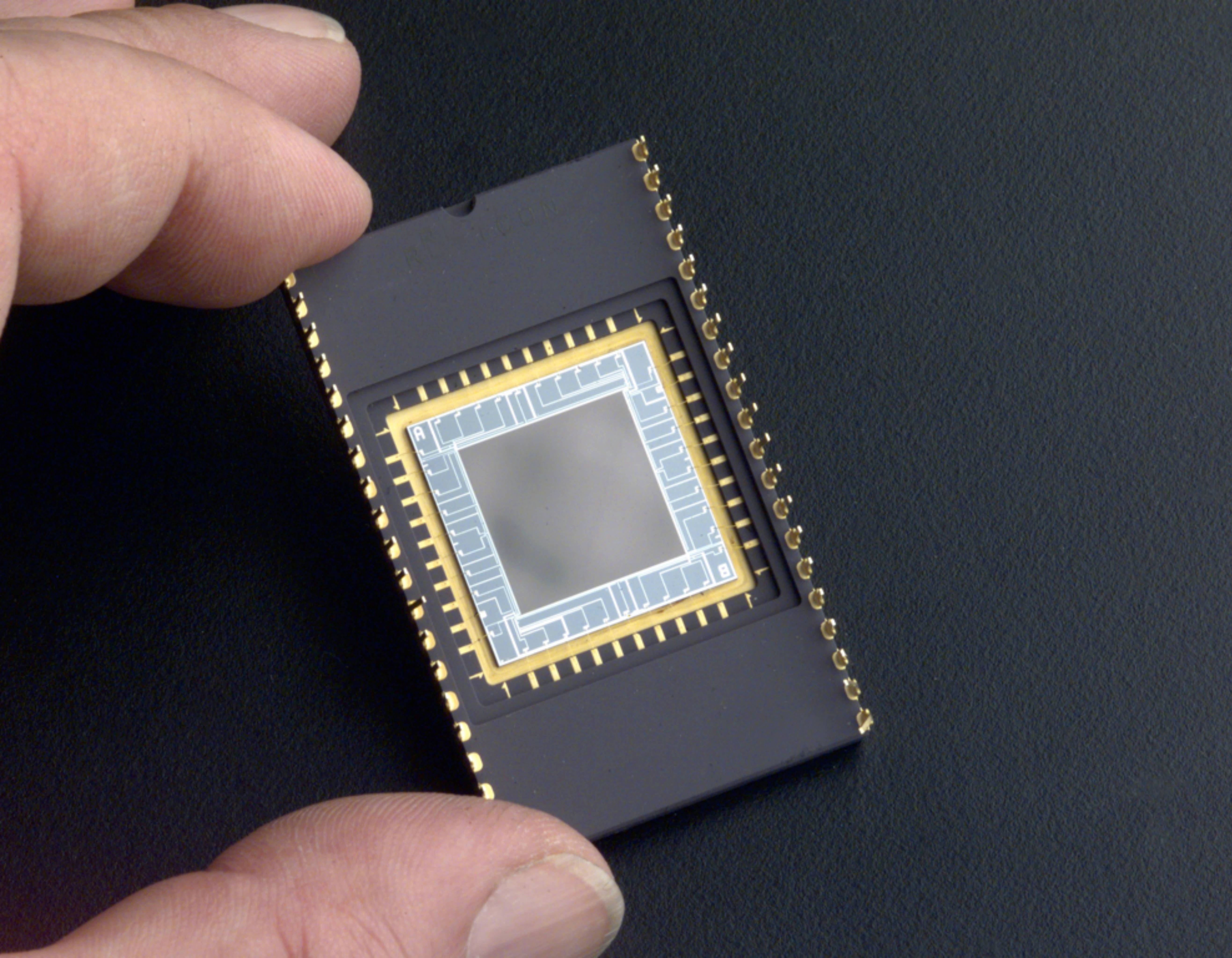
# CCDs

The Charge Coupled Device (CCD)

- This is **the** detector used for optical work today.
- Two-dimensional array of $10^6$–$10^7$ photosensitive capacitors.

# CCDs

- The Charge Coupled Device (CCD) was invented in 1969 by Boyle and Smith at AT&T Bell Labs. The intent was to transfer charge along the surface of a semiconductor from one capacitor to the next, which would make it very useful as a shift register memory device. They were eventually awarded the Noble Prize for this.
- The first astronomical image was taken with a CCD in 1975, and changed everything.


A
B

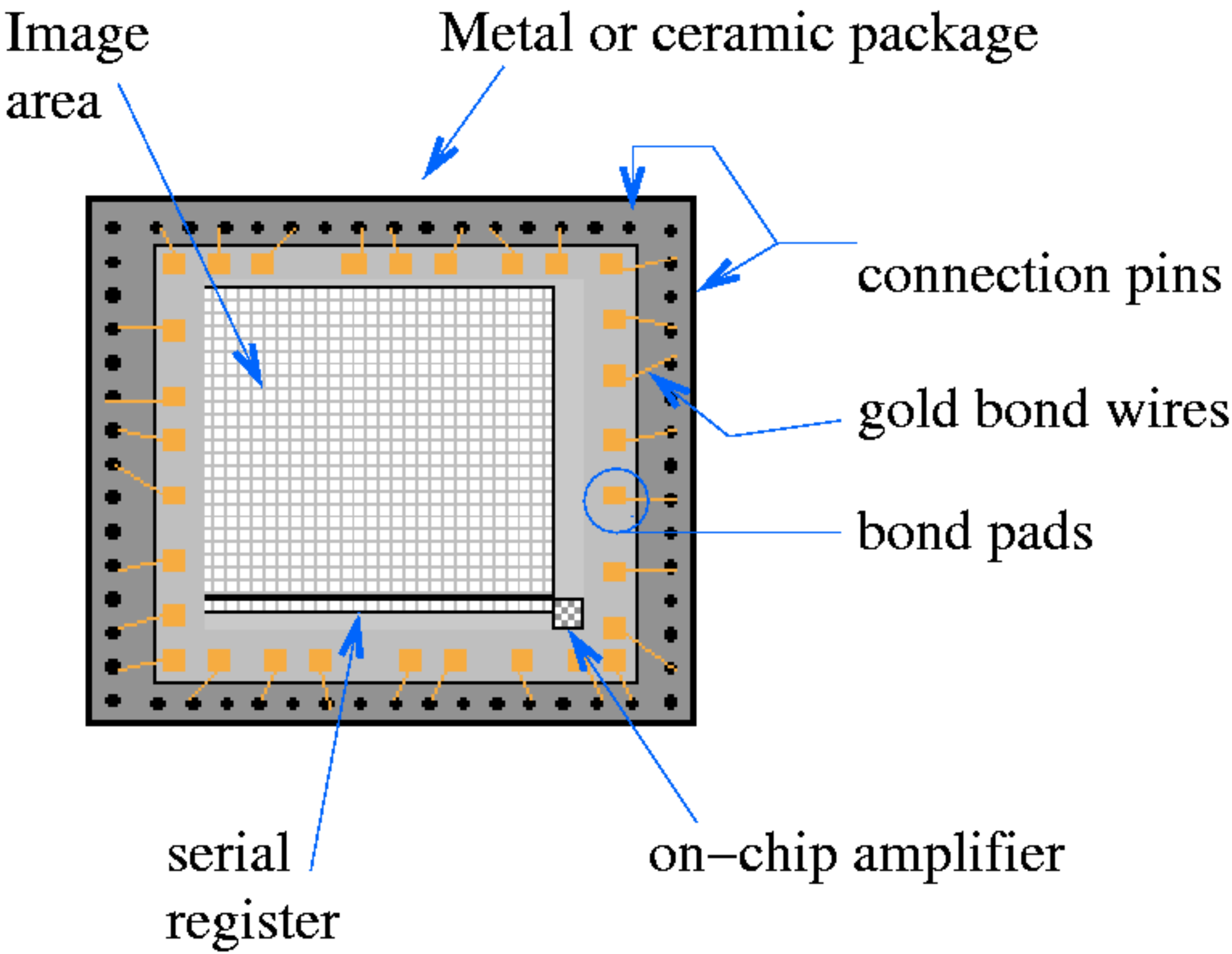
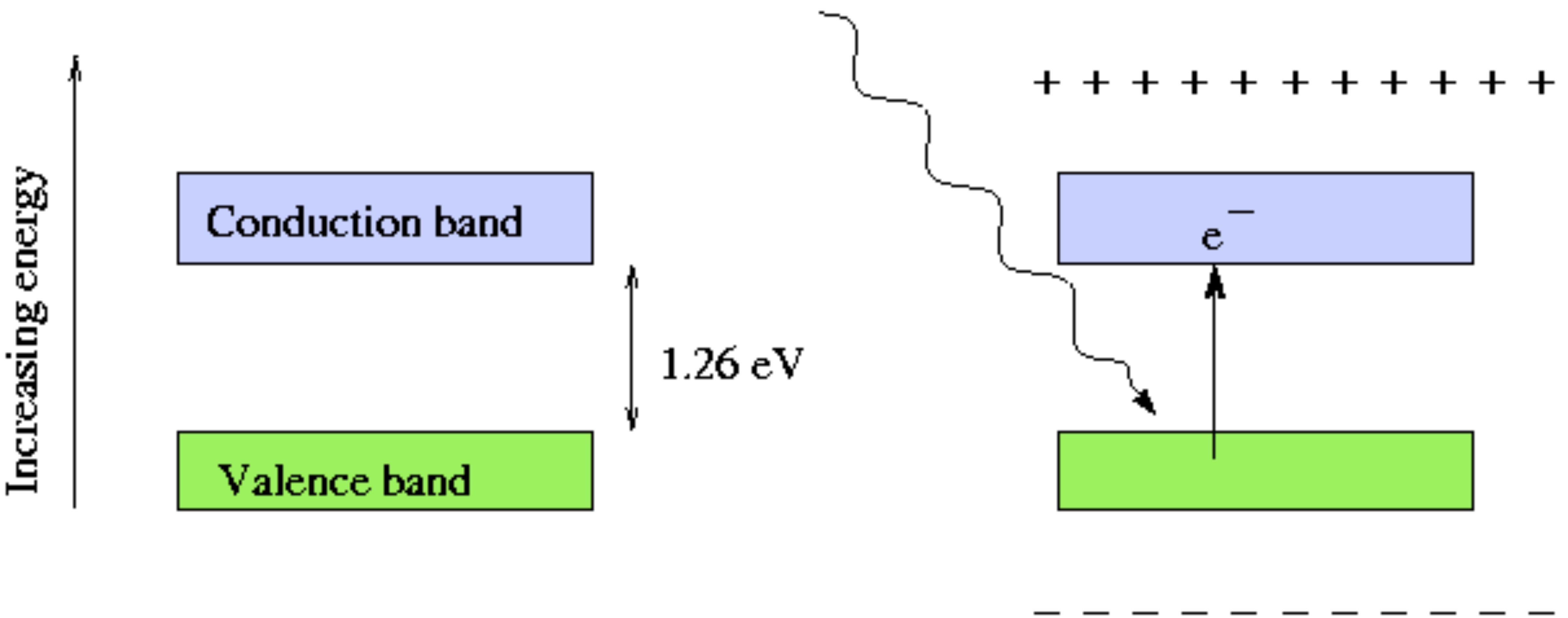


Image
area
Metal or ceramic package
connection pins
gold bond wires
bond pads
serial
register
on–chip amplifier

# CCDs

- Atoms in a silicon crystal have electrons arrayed in two discrete energy bands. Most of them are in the lower energy "valence band", but can be excited to the upper "conduction band" by a photon with wavelength shorter than about 1 μm. (That wavelength corresponds to about 1.26eV, the difference between the two bands.)

# CCDs



# CCDs

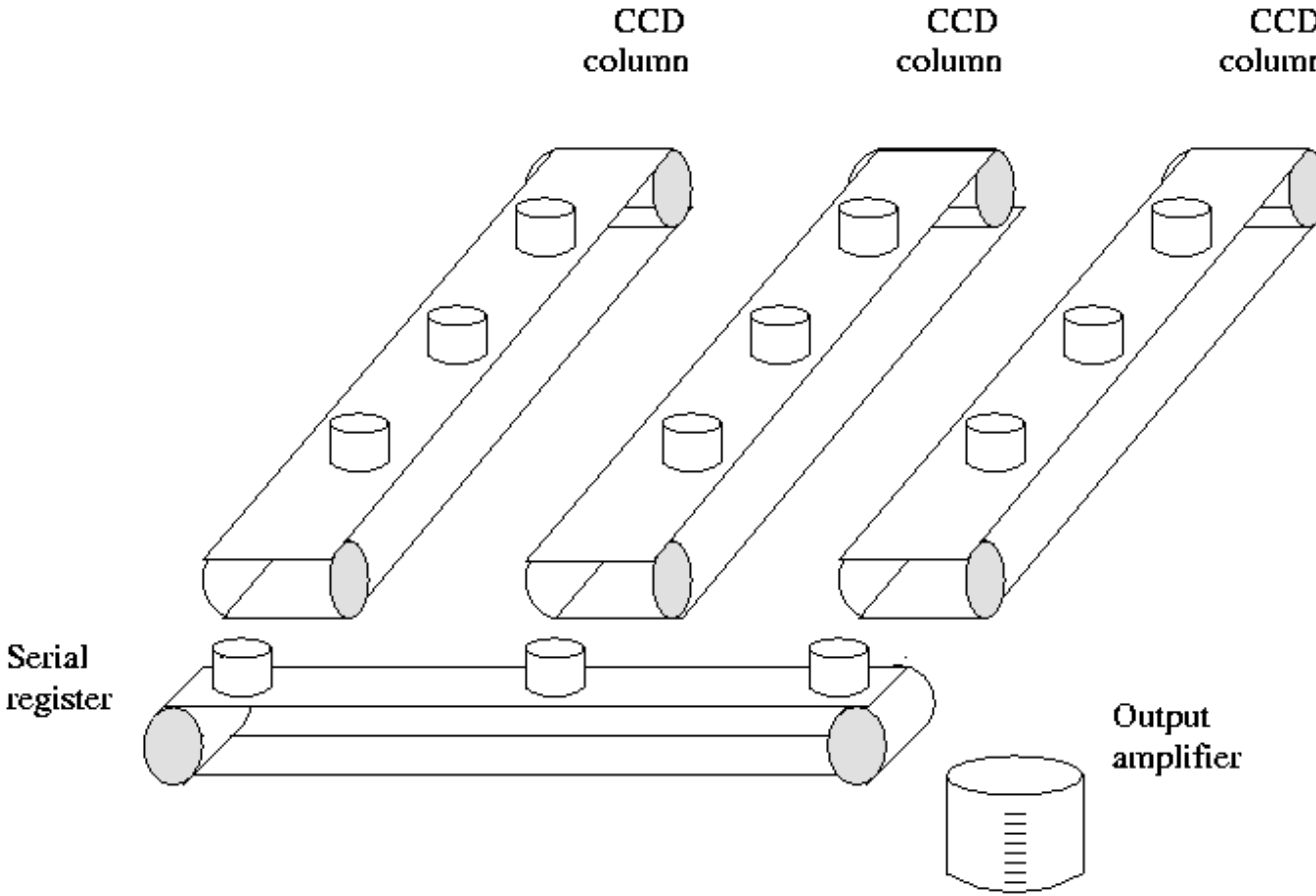
- Electrons can also be knocked up into the upper level by thermal jittering. This is why CCDs used in astronomy are kept cold, typically -120 C (-184$^{o}$F).

# CCDs

- A photon comes in and (with about an 80% probability) creates an electron-hole pair. During the course of the integration more and more electrons go up into the conduction band. Think of a CCD as a zillion little capacitors.

# CCDs

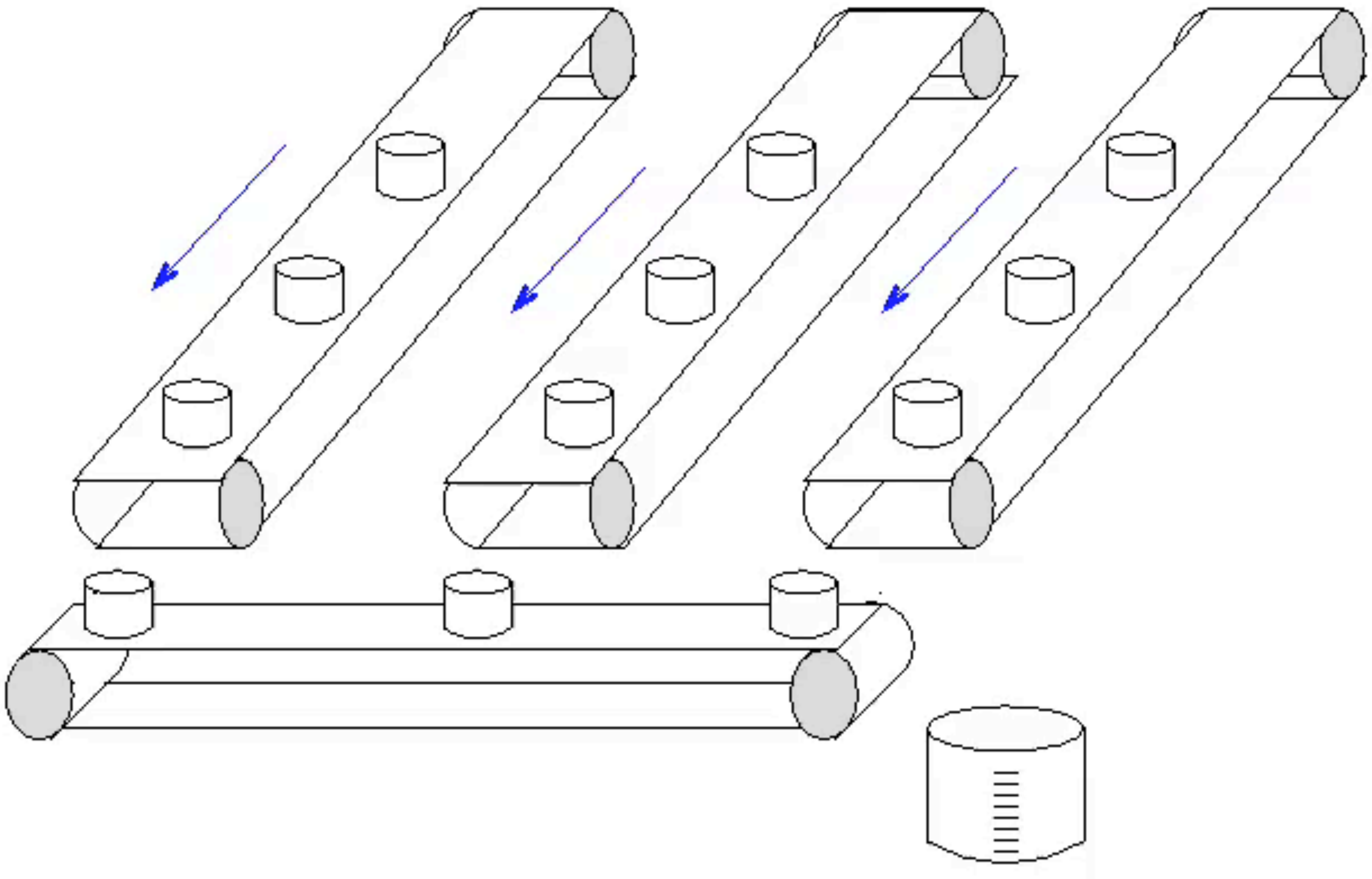
- Or better, think of buckets on stationary conveyer belts.  We open the shutter and let rain (light) fall on the array, filling the buckets (pixels) by varying amount. We then close the shutter and start the conveyor belts:



CCD
column
CCD
column
CCD
column
Serial
register
Output
amplifier

# CCDs

- The buckets are clocked down the column conveyor belt  onto a special conveyer belt, the "serial register", which moves them to output amplifier, one row at a time.



# CCDs

- The amplifier converts the charges to voltages and adds a small bias offset. The signal then goes into a 16-bit analog-to-digital (A/D) converter which outputs a number between 0 and 65,536 that is proportional to the signal. That output number is what we refer to as an "ADU" (A/D unit).

- Incidentally, the "gain" has to do with the conversion of the number of the voltage to the number you get out. Can determine the number of $e^-$ per ADU from first principles

# CCDs

Summary of what happens:

(1) Charge is clocked down along a column, shifting a row of pixels off the array and onto the serial register.

(2) Each pixel on the serial register is shifted to the readout amplifer.

(3) Charge in each pixel is read as a voltage and amplified.

(4) An analog-to-digital converter converts this voltage to a digital count (ADU).

(5) Number of electrons needed to produce 1 ADU is termed the gain. Typically 1-3 e/ADU.

# CCDs

- How long does this readout process take? If you read it out too fast, you add read-noise. If you read it out slowly, it takes forever. Example: LMI is read out at about 0.5Mpx/sec (2μsec/pixel). Thus the 6K x 6K chip takes about a minute and a half to read out.

# CCDs

The CCD we used on the Swope in 2013 was formatted to 2K x 3K. It took 127 seconds to read out (>2 minutes!). How fast were the conveyor belts moving?

6 million pixels / 127 sec = 0.05 Mpix/sec or 20 μsec/pixel

About 10x more slowly than with a modern controller.

The current chip (2014+) is formatted to 4Kx4K and took 20 seconds using 4 amplifiers: 1 million pixels / 20 seconds. Same speed, but 4 amplifiers!

# CCDs

One way to reduce read-out time is to use multiple amplifiers. Most CCDs come with four, one at each corner. But, their gains and bias levels are slightly different, complicating the reduction process. Joining things up along the seams afterwards never works extremely well.

# CCDs

Another way around long read-out times is to BIN the CCD. Typically binning is 2x2, so every 4 original pixels now becomes 1 binned pixel. Will speed out the readout time by a factor of 4. But you will loose resolution. Sometimes this doesn't matter. LMI on the DCT has 0.12"/unbinned-pixel. Our seeing is good, but not THAT good. So, we bin 2x2 and have 0.24"/binned-pixel. That still satisfies the Nyquist criteria if the seeing is 0.7" FWHM. For the LMI, the readout time then becomes about 20 sec, and you're not losing anything. In fact, you're gaining in dynamic range.

# CCDs

How much water do the buckets hold? This depends (in part) of how large the buckets are. But for a typical 15μm pixel, the answer is about 100,000 e-. This is known as the "full-well". Beyond that you SATURATE, and you don't know anything about the brightness of a star. In practice CCDs become non-linear shortly before you fill up the well. If you bin the CCD 2x2 you don't make the bucket 4 times bigger, though...more like 2-3 x bigger.

# CCDs

The first CCDs that were in common use in the early 1980s were 320x512 devices with 30μm pixels (so, 9.6mm x 15mm, or 0.4-in x 0.6-in). Compare these to a 14-in x 14-in photograph plate! But the thing was...they were linear. Twice as much light produced twice as much signal. And the signal was ready and you didn't have digitize the photographic plate to get it into the computer.

# CCDs

These output amplifiers weren't all that great back then. They added about 100 $e^-$ "read-noise". In other words, rather than just getting the photon-noise for a star ($N^{0.5}$) you ALSO got an extra 100$e^-$ "jitter" for your troubles. If you had a signal of only 100 $e^-$ to start out with, you'd expect a noise of 10 $e^-$. But instead you'd be getting 100+ $e^-$ noise.

# Side-bar: Adding errors

Noise terms usually add in quadrature:

$\sigma^2_{tot}=\sigma^2_A + \sigma^2_B$

$\sigma_A = N^{0.5}$

$\sigma_B = R$

where N=number of electrons, and R is the read-noise.
If N=100, and R=100...

$\sigma^2_{tot}=100+10000$ or

$\sigma = 100.5$

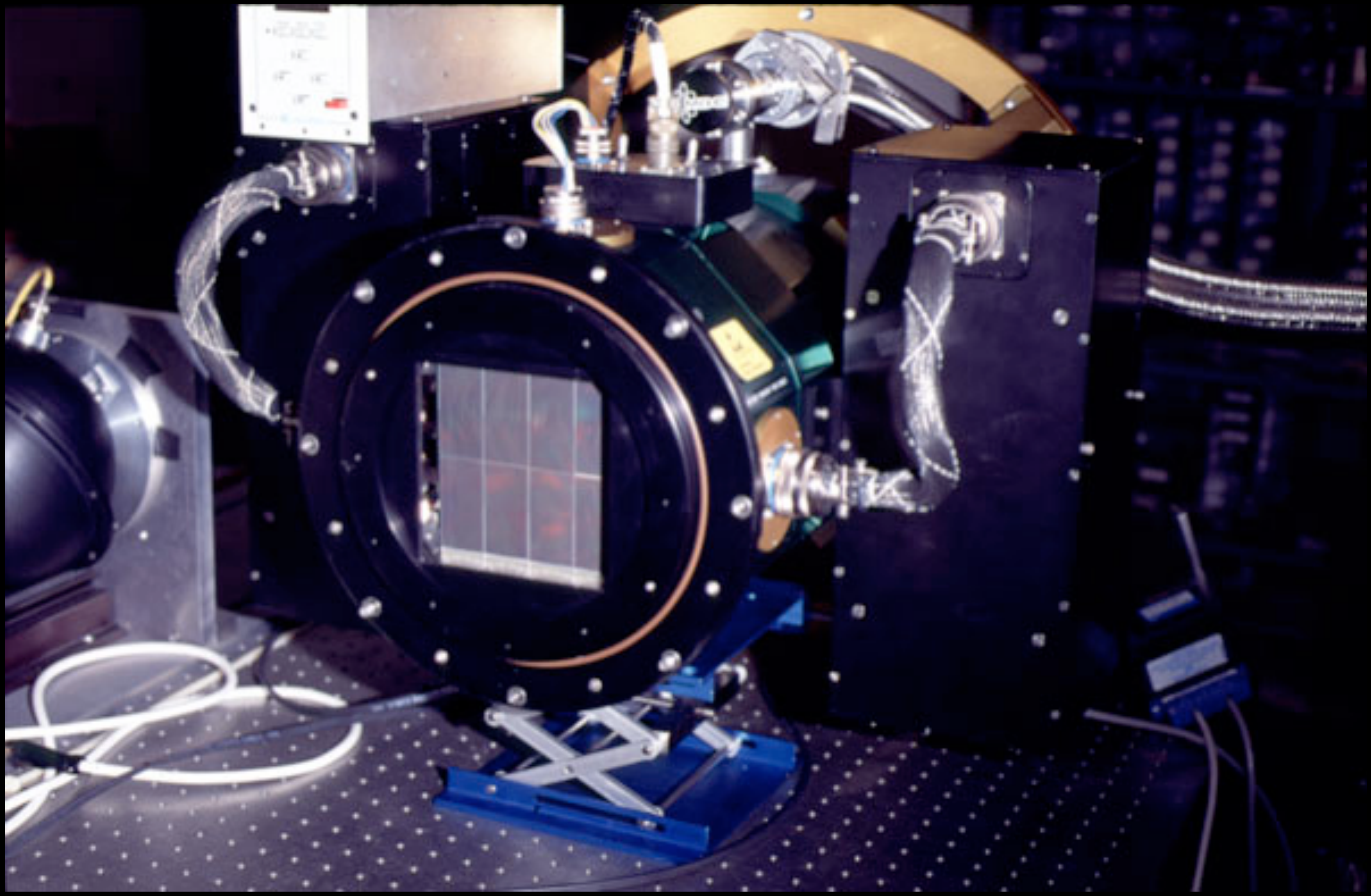
# CCDs

Modern CCDs have 2048x4096 15-$\mu$m pixels (30.7mm x 61.4 mm or 1.2-in x 2.4-in), read-noise of 6 $e^-$ , and QEs of 80% or better. The largest CCD in the world is located in the Large Monolithic Imager (LMI) on the 4.3-m DCT! But it's still only 91.5mm x 91.5mm (3.6-inches on a side), PUNY compared to the 14-in x 14-in photographic plates.

# CCDs

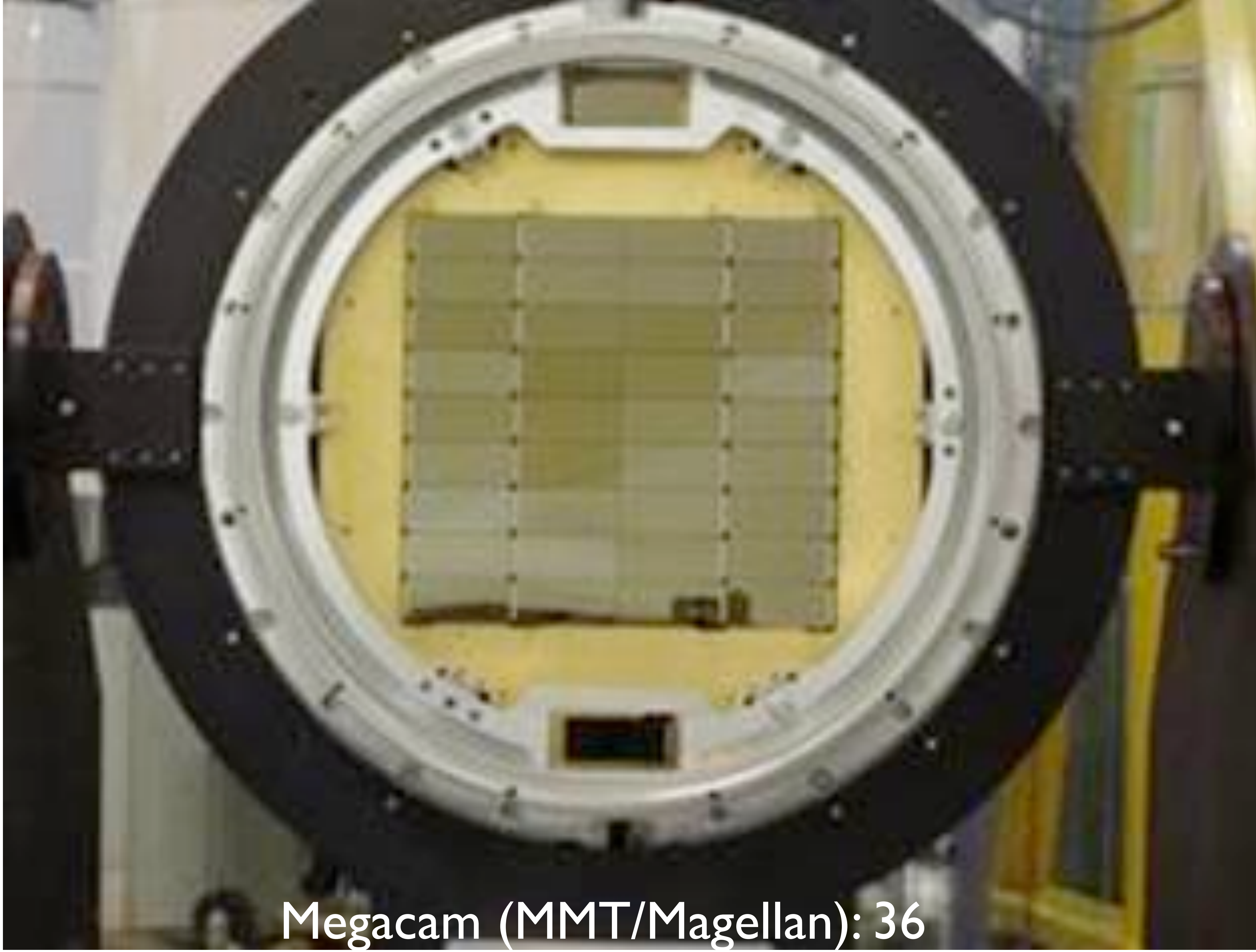
The way around this limitation is to make mosaics of MANY CCDs.

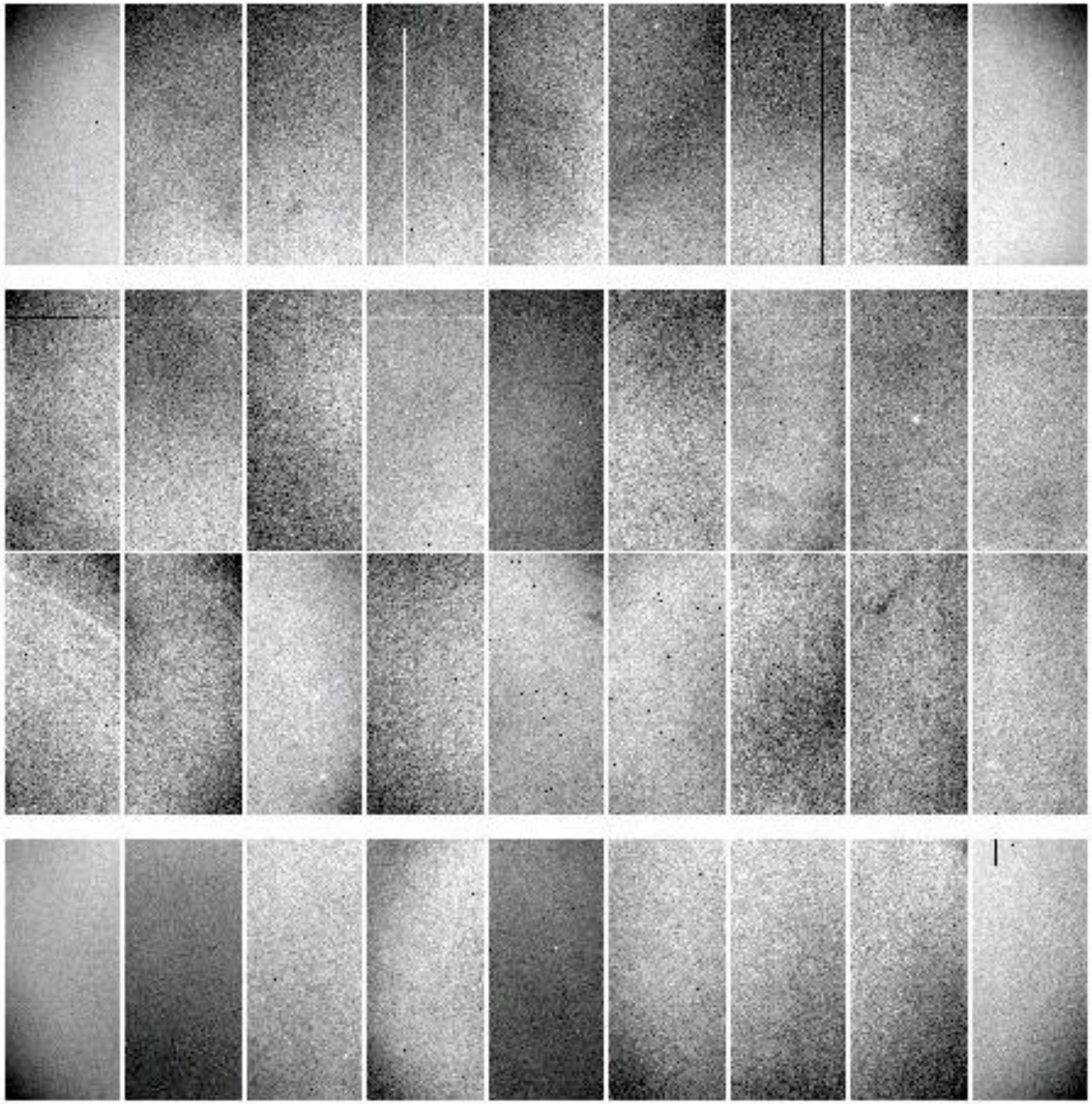
# Most modern astronomical cameras are mosaics of 8 or more CCDs



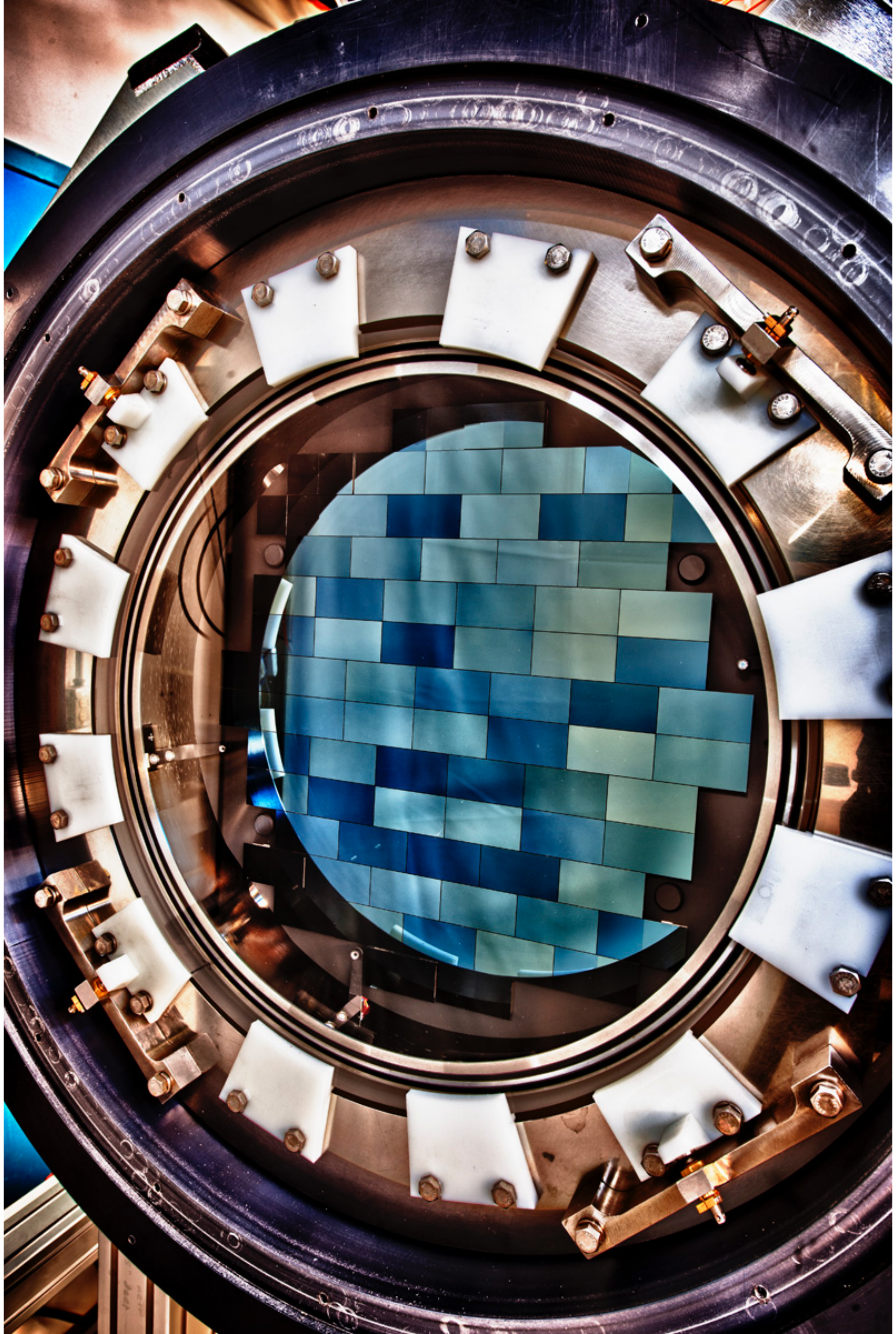
# Mosaics

That has about the same area as the LMI CCD (8 2048x4096 detectors) but it has GAPS that need to be filled in. (That's why we went the expensive route with LMI.) But you can make even bigger mosaics.


Megacam (MMT/Magellan): 36



Each CCD
responds
to light
differently!
Yikes!



DECam focal plane
74 CCDs

# The Future

Although CCDs are used for all critical applications (medical imaging, etc.) chances are that the thing in your digital camera is actually a CMOS device. (Surprise!) Someday CMOS devices will replace CCDs and even bigger ones will be possible.