Magnitude Systems *(or "what's the zeropoint?")*

Don't confuse magnitude systems with filter systems! – M Bershady

$$m_\lambda = -2.5 \log f + C_\lambda$$

Conceptually, the zeropoint (C) can either be based on physical units or on a reference star.
See Bessell (ARAA) 05 for review.

The Vega System

By definition, Vega (α Lyr): m = 0.00 *at all wavelengths*:

$$m_B = m_V = m_R = m_I \equiv 0.0$$

Therefore Vega has a color of 0.00 in all colors *by definition*:

$$B - V = V - I = I - R = 0.0$$

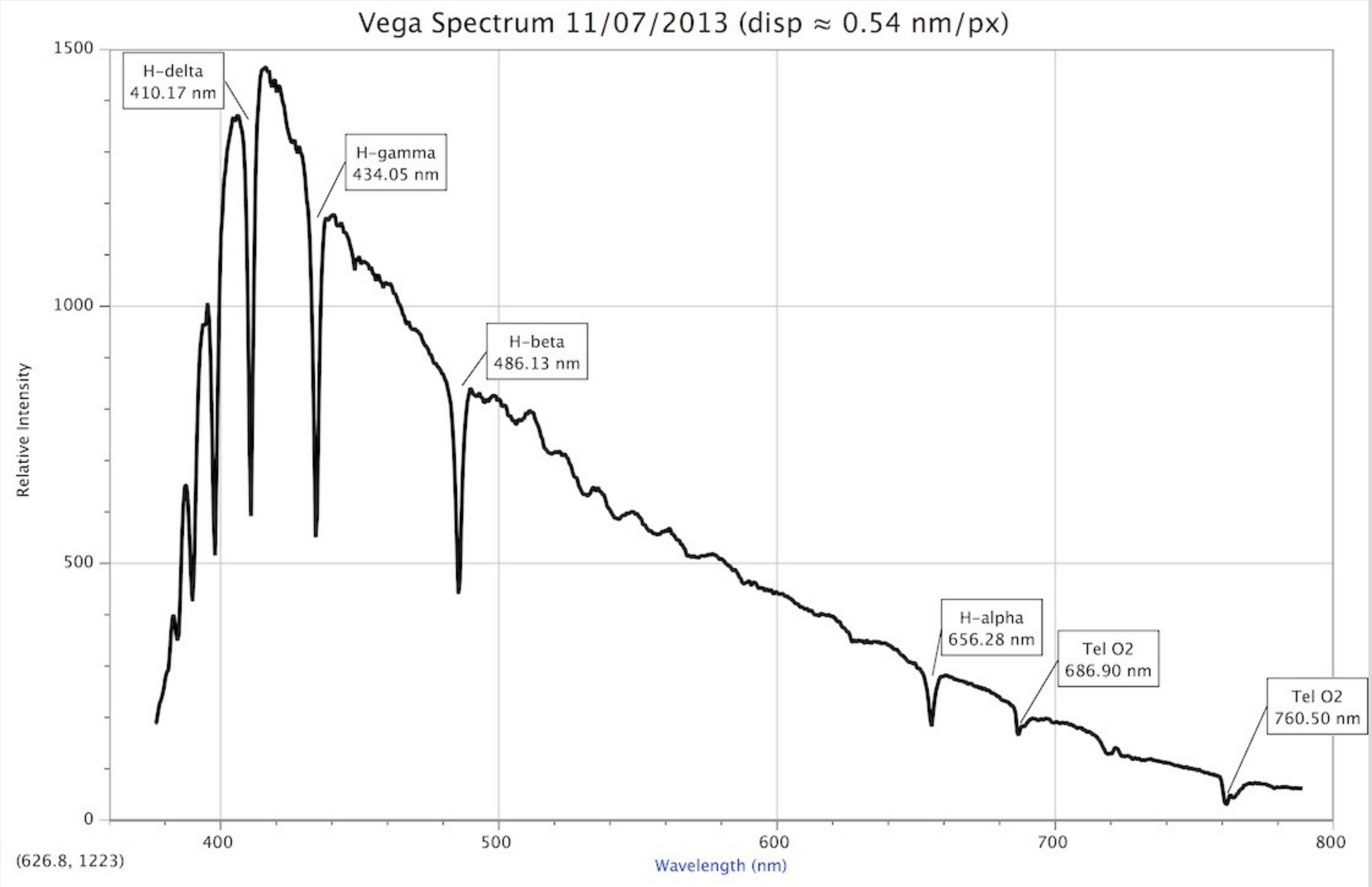
Therefore, in the Vega system, a color of 0.0 is ***NOT*** the same as equal flux at all wavelengths (a so-called "flat spectrum").

Magnitudes measure brightness ***relative to Vega*** and colors measure colors ***relative to Vega***.

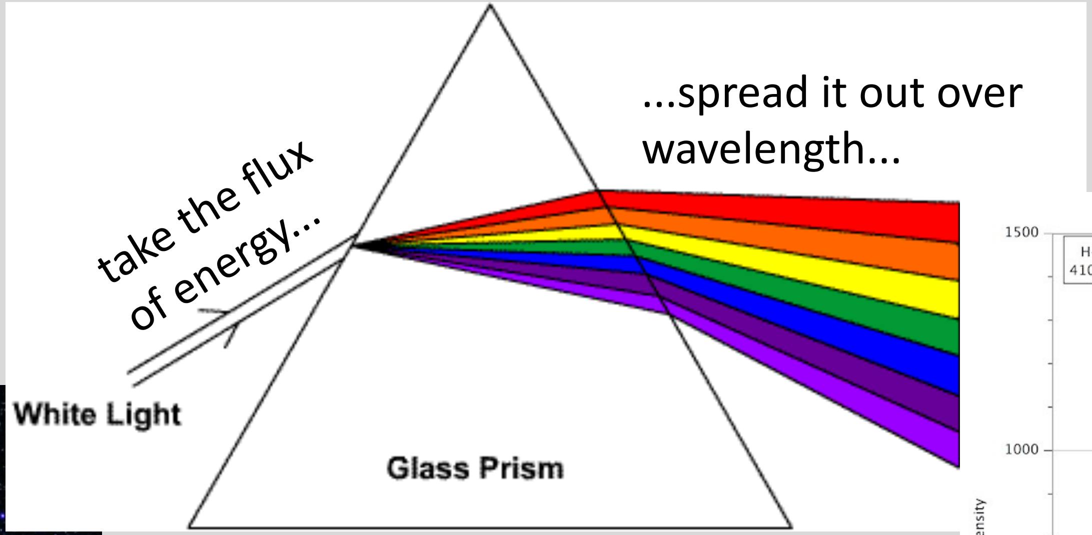
Vega is a very blue star!

Vega spectrum

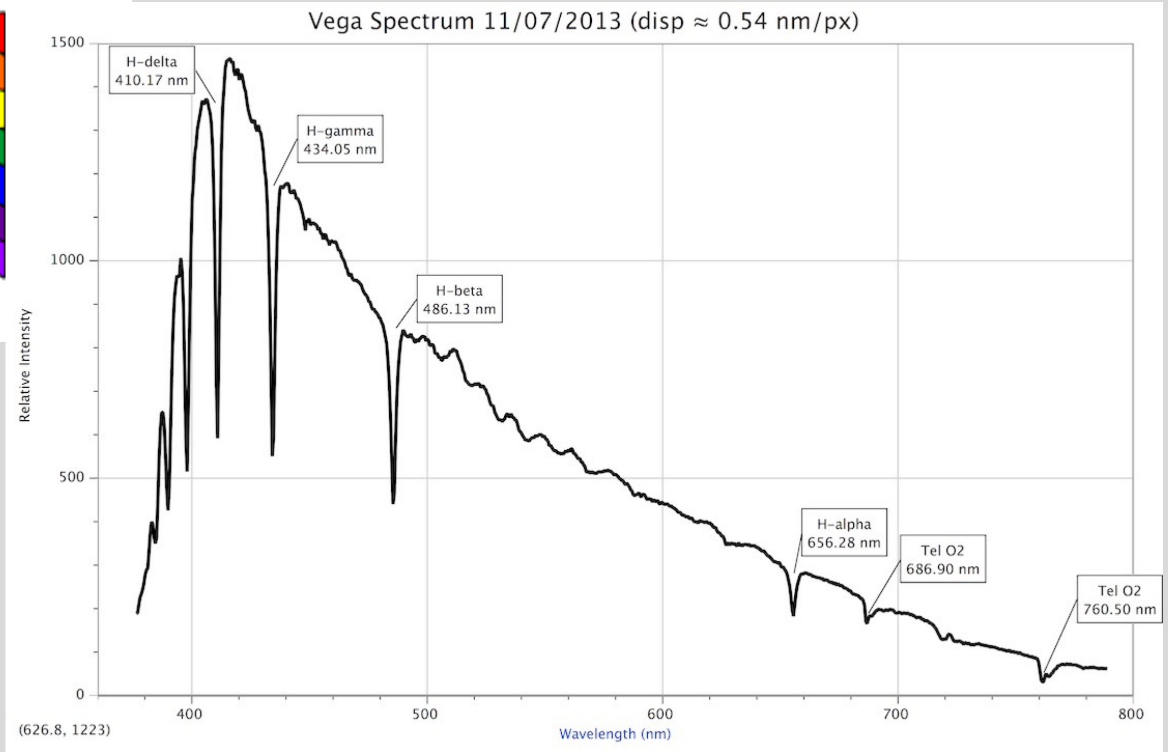
Courtesy KSU Astronomy



Physical Units: Flux and Flux Density



...to create a spectrum. Flux density is the intensity of the spectrum



Flux: Energy/area/time
Units: erg/s/cm^2
(where cm^2 refers to the area of your light collector)

Flux density: Energy/area/time/wavelength
Units: erg/s/cm^2/Angstrom

Magnitude Systems: the AB and STMAG systems

We can define the **monochromatic flux density** as

f_ν = Energy/area/time/frequency = erg/s/cm²/Hz

(1 Jansky = 10^{-23} erg/s/cm²/Hz)

or

f_λ = Energy/area/time/wavelength = erg/s/cm²/Å

Relating f_ν and f_λ

$$f_\nu d\nu = -f_\lambda d\lambda$$

or (since $\nu = hc/\lambda$)

$$f_\nu = \left(\frac{\lambda^2}{c}\right) f_\lambda$$

So there are two monochromatic magnitude systems where the zeropoint is in physical units of flux density:

AB system	STMAG system
$m_{AB} = -2.5 \log f_\nu - 48.6$	$m_{ST} = -2.5 \log f_\lambda - 21.1$
f_ν measured in erg/s/cm²/Hz	f_λ measured in erg/s/cm²/Å
color = 0 means constant f_ν	color = 0 means constant f_λ

Important points:

- Zeropoints are chosen so that in V band (≈5500Å), Vega has $m_{AB} \approx m_{ST} \approx 0.0$
- AB system more common than STMAG; SDSS *ugriz* mags are AB mags
- Constant f_ν is not the same as constant f_λ

Photometric Systems: Magnitude Zeropoints vs Flux Zeropoints

Think about the basic magnitude definition: $m = -2.5 \log f + C$

Written that way, C is a **magnitude zeropoint**, the magnitude of an object with $f = 1$ (in the appropriate units).

A different way of writing it would be: $m = -2.5 \log(f/f_0)$, where f_0 is the **flux zeropoint**, i.e., the flux of a zeroth magnitude object.

The two are related mathematically by $C = 2.5 \log f_0$

- In the AB system, the magnitude zeropoint is **the same at all wavelengths**: $\mathrm{C} = -48.6$. From this you can work out the flux zeropoint in erg/s/cm^2/Hz, and then convert that into Janskys.
- In the Vega system, the brightness of an object is measured relative to the brightness of Vega at each wavelength, **the zeropoints change with wavelength.** For example:

B (Vega)	V (Vega)
$f_0 = 4260$ Jy	$f_0 = 3640$ Jy

Remember: 1 Jy = 10^{-23} erg/s/cm^2/Hz

Handy table of zeropoints for different magnitude systems (Paul Martini, OSU)

Photometric Systems: Colors

Remember that a color is the difference between magnitudes at two wavelengths, for example B and V:

$$B - V = m_B - m_V = (-2.5\log(f_B) + C_B) - (-2.5\log(f_V) + C_V)$$

or equivalently

$$B - V = m_B - m_V = \left(-2.5\log(f_B/f_{0,B})\right) - \left(-2.5\log((f_V/f_{0,V})\right)$$

depending on whether you are using magnitude zeropoints or flux zeropoints.

Because these zeropoints are different in different magnitude systems (say Vega vs AB), a star will have a different color in different magnitude systems.

- In the Vega magnitude system, Vega has a color of $B - V = 0.00$, by definition.
- In the AB system, Vega has color of $B - V = -0.07$, its is slightly bluer than an object with constant f_ν

Moral of the story: always check to see what magnitude system is being used: Vega, AB, or STMAG.

Worked Example: Vega in different units

For Vega, the monochromatic flux density at 5492Å is

$f_\lambda = 3.63 \times 10^{-9}$ erg/s/cm^2/Å

which can also be written in terms of frequency:

$f_\nu = (\lambda^2/c)f_\lambda = 3.65 \times 10^{-20}$ erg/s/cm^2/Hz = 3650 Jy

careful with units on this step: Since f_λ was in "per Å" and f_ν is in "per Hz", λ and c should be in Å and Å/s respectively!

or AB magnitudes:

$m_{AB} = -2.5\log(f_\nu) - 48.6 = -0.006$

to convert to photon flux, divide by f_λ by the photon energy (hc/λ):

photon flux ≈ 1000 photons/s/cm^2/Å

and if the V filter has a width of ~ 900 Å, the total photon flux through a V filter bandpass is about 900,000 photons/s/cm^2.

Remember: these are all "top of the atmosphere" values, i.e., airmass X=0.

why do we care about photon flux? detectors count the number of photons received, not the amount of energy received!

Properties of a Detector

Quantum Efficiency

- fraction of photons detected
- wavelength and spatially dependent

Dynamic Range

- difference between lowest and highest measurable flux

Linearity

- detection rate should scale linearly with photon flux

Noise:

- low noise on measured signal
- low background noise

Stability

- repeatable measurements and calibration

Spatial dynamic range

- want to see fine detail but also want large field of view
- combination of pixel size and detector area

The Perfect Detector

- Counts every photon it receives.
- Notes the photon's position and energy.
- Has uniform wavelength and spatial response.
- Has a linear response.
- Has no noise.
- Has a high dynamic range.

Does such a thing exist?

The Perfect Detector

- Counts every photon it receives.
- Notes the photon’s position and energy.
- Has uniform wavelength and spatial response.
- Has a linear response.
- Has no noise.
- Has a high dynamic range.

Human Eye?

integration time: 1/30 second

The Perfect Detector

- Counts every photon it receives.
- Notes the photon’s position and energy.
- Has uniform wavelength and spatial response.
- Has a linear response.
- Has no noise.
- Has a high dynamic range.

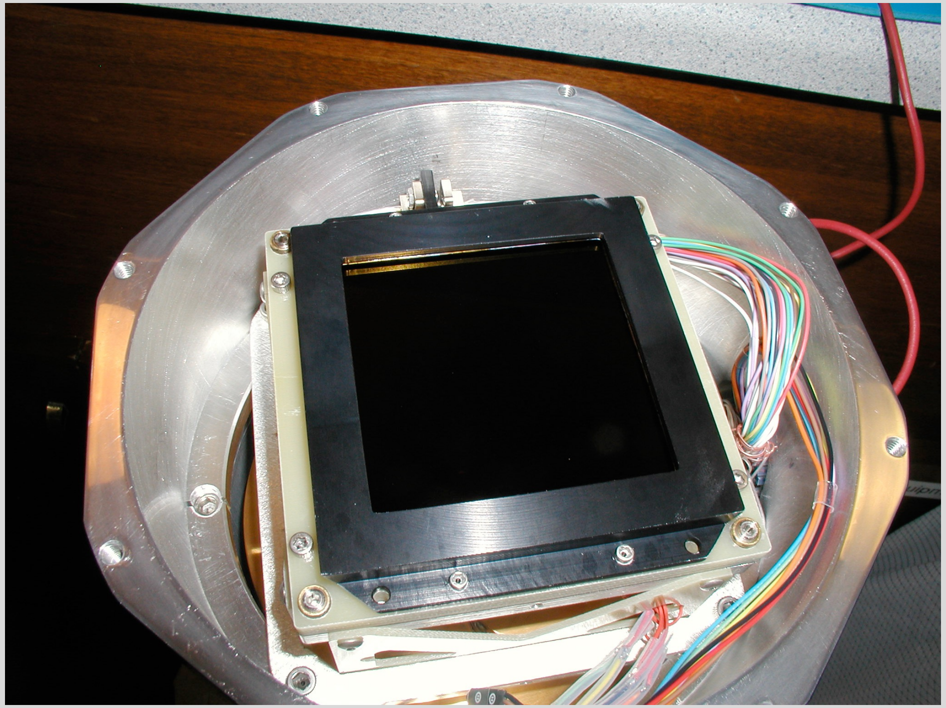
Photographic Film?

integration time: hours

The Perfect Detector

- Counts every photon it receives.
- Notes the photon’s position and energy.
- Has uniform wavelength and spatial response.
- Has a linear response.
- Has no noise.
- Has a high dynamic range.

Modern Solution:
Charge Coupled Device (CCD)



integration time: 15-20 min
but images can be stacked

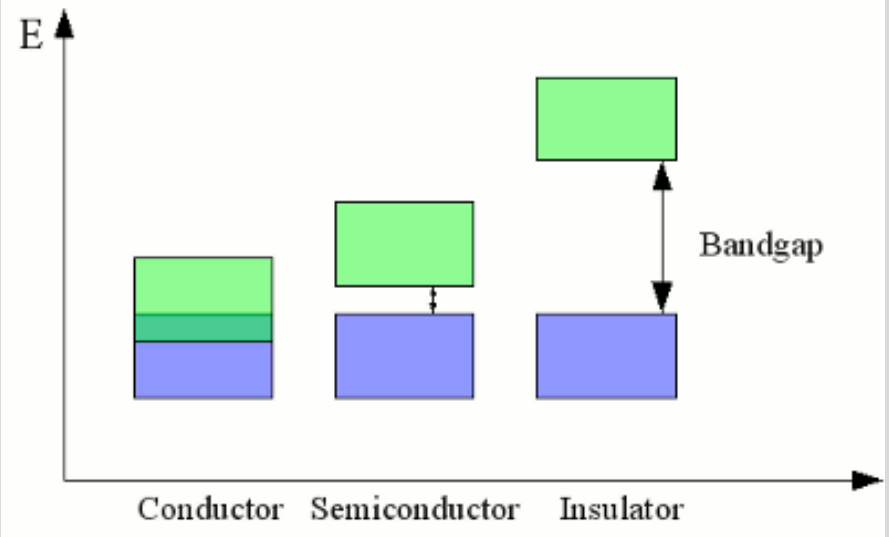
Charge Coupled Devices (CCDs)

Consider a silicon crystal semiconductor, where the electrons live in discrete energy bands.

Electrons in the low energy valence bands are locked in place in the crystal lattice and cannot move.

If you add energy (ie absorb a photon), an electron can jump into the conduction band, where it is free to move around the lattice.

Only photons above a minimum energy will be absorbed and detected.

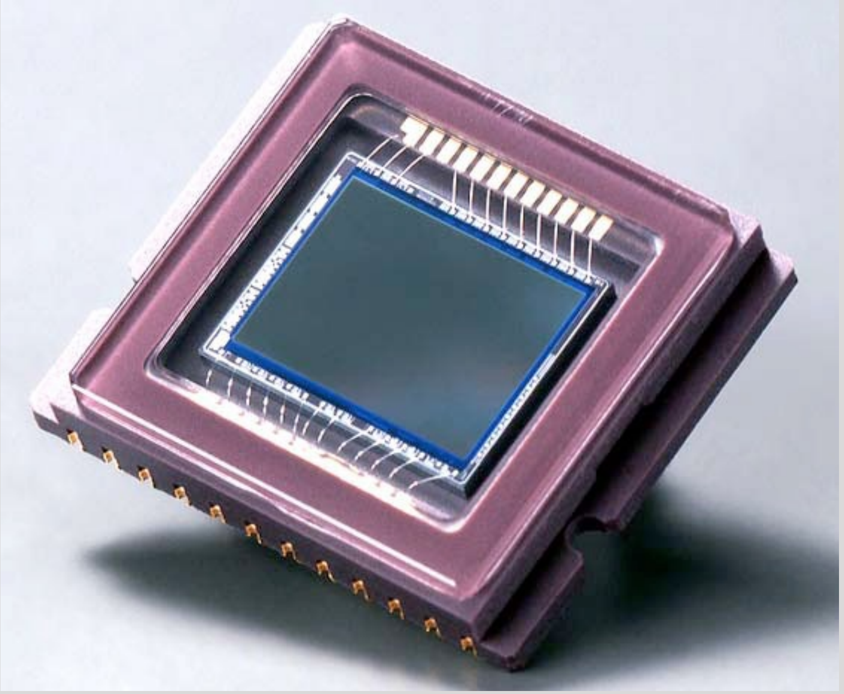


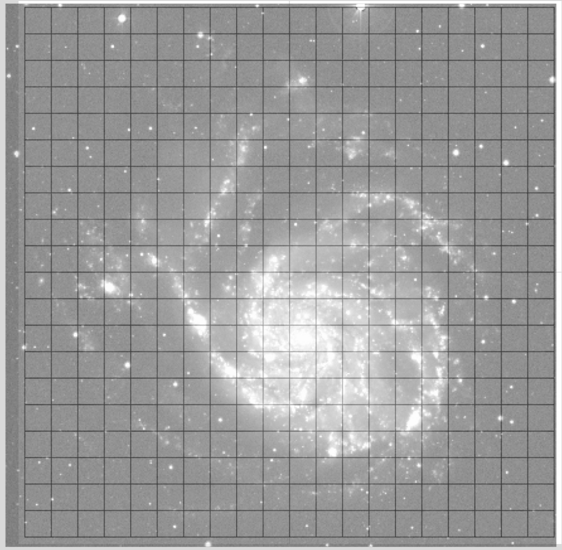
Material	Bandgap	λ_{max}
Silicon	1.1 eV	11,000 Å (1.1µ)
Germanium	0.67 eV	18,000 Å (1.8µ)
InSb (Indium Antimonide)	0.18 eV	6.7µ

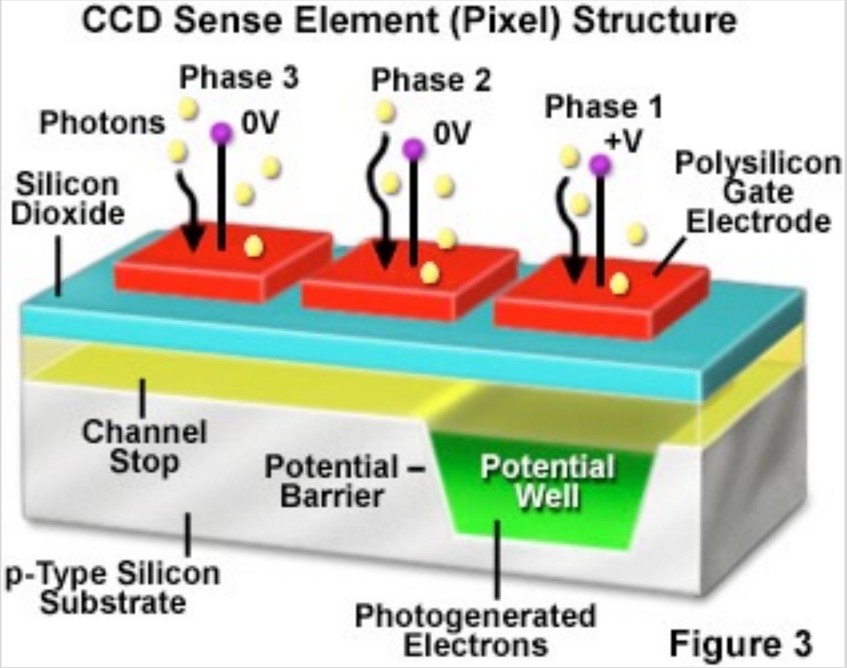
thermal noise: electrons can jump from the valence band to the conduction band on their own, depending on the temperature. CCDs are typically cooled to −125C or lower to reduce thermal noise.

So the material used sets the wavelength coverage and noise characteristics of the CCD.

CCD pixels







When a CCD is exposed to light, photons hit the detector and causing an electron to jump into the conduction band at the spot each photon was absorbed.

A CCD is divided into pixels, which consist of a set of gates where voltages are applied to keep the electrons in place during the exposure.

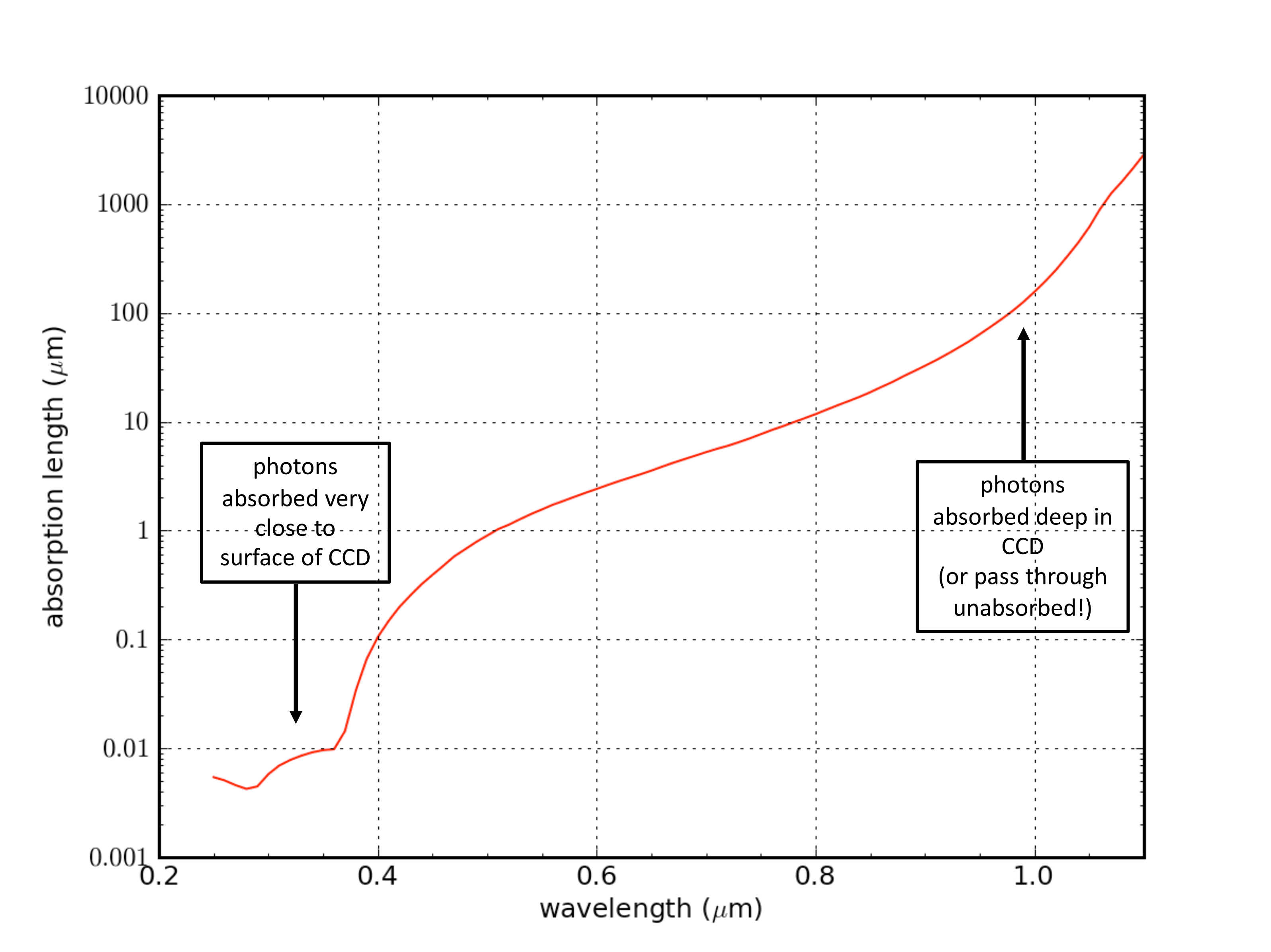
Silicon absorption

How far into the silicon CCD will photons travel before being absorbed?

Depends on the wavelength of the photon.

This determines **quantum efficiency** (the fraction of photons detected).

You want the photons absorbed close to the surface, where they can be captured and controlled by the pixel gates.

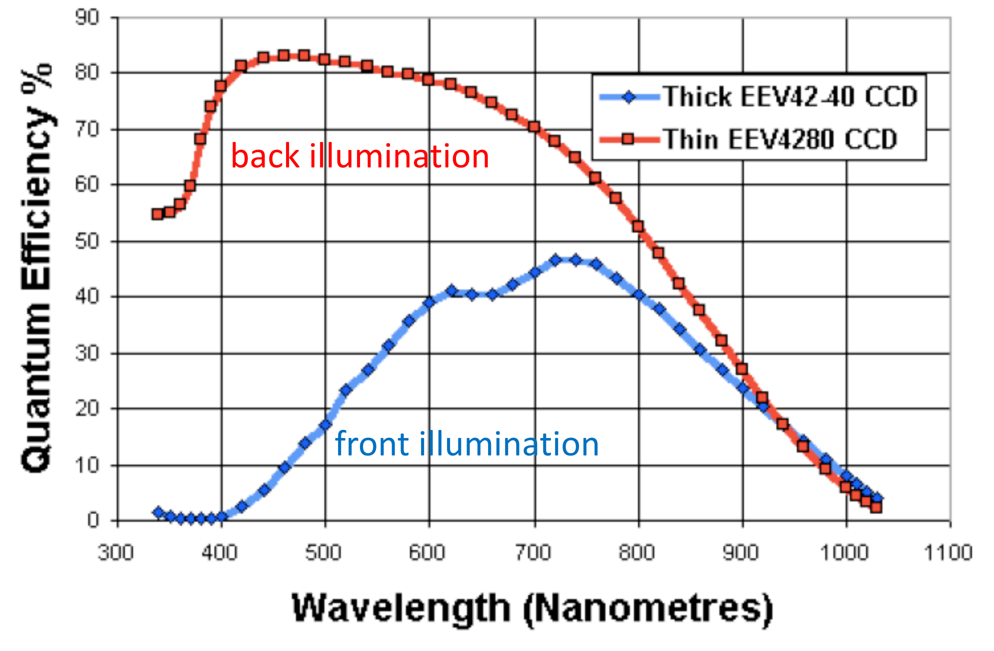


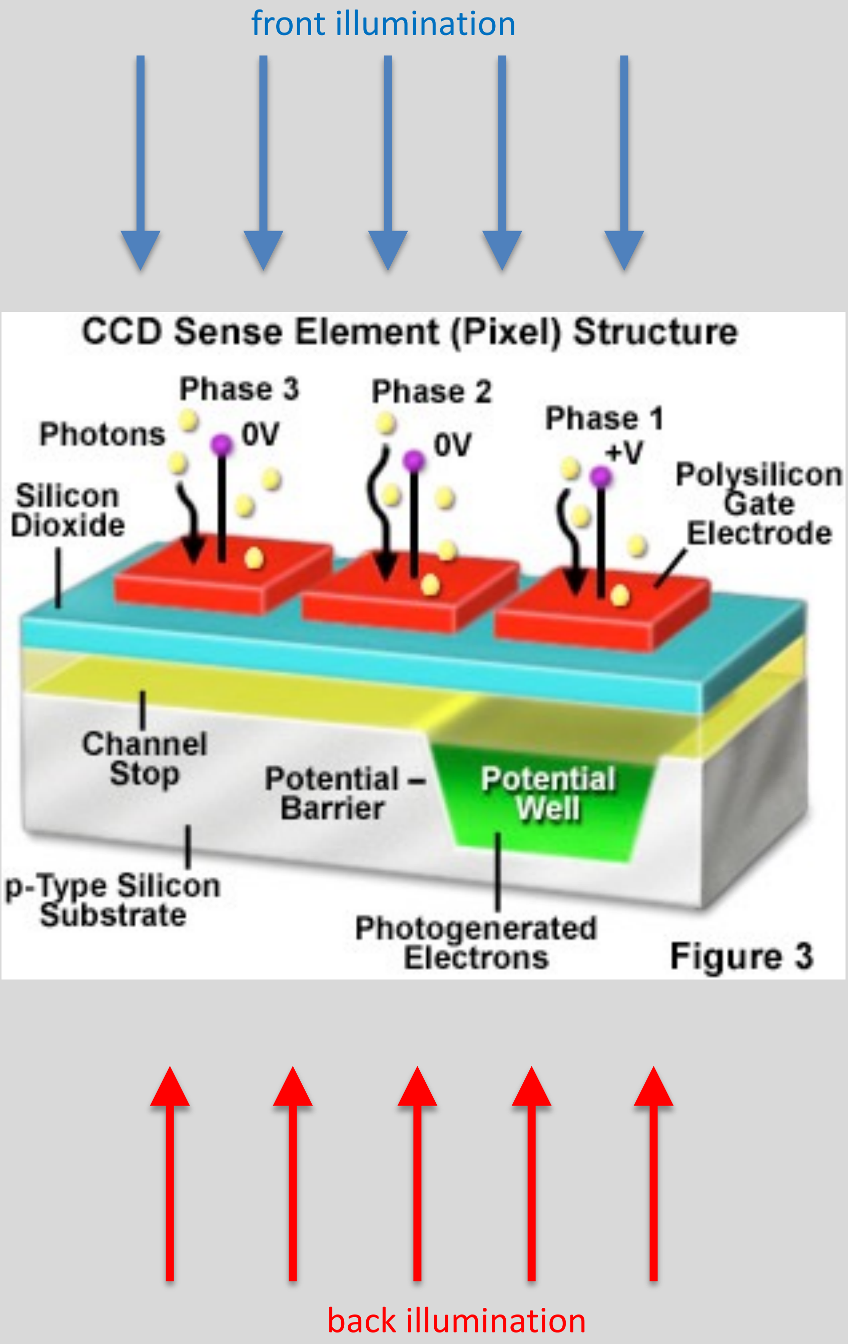
Front and Back Illuminated CCDs

CCD consists of a layer of nearly pure silicon covered on one side (front) by electronic gates that control the movement of the photoelectrons.

In front illuminated chips, the photons go through the gate structures before being absorbed. This lowers the quantum efficiency, particularly in the blue.

In back illuminated chips, the photons avoid the gates (raising QE), but they need to be thinned so that the absorption happens close to the gates.

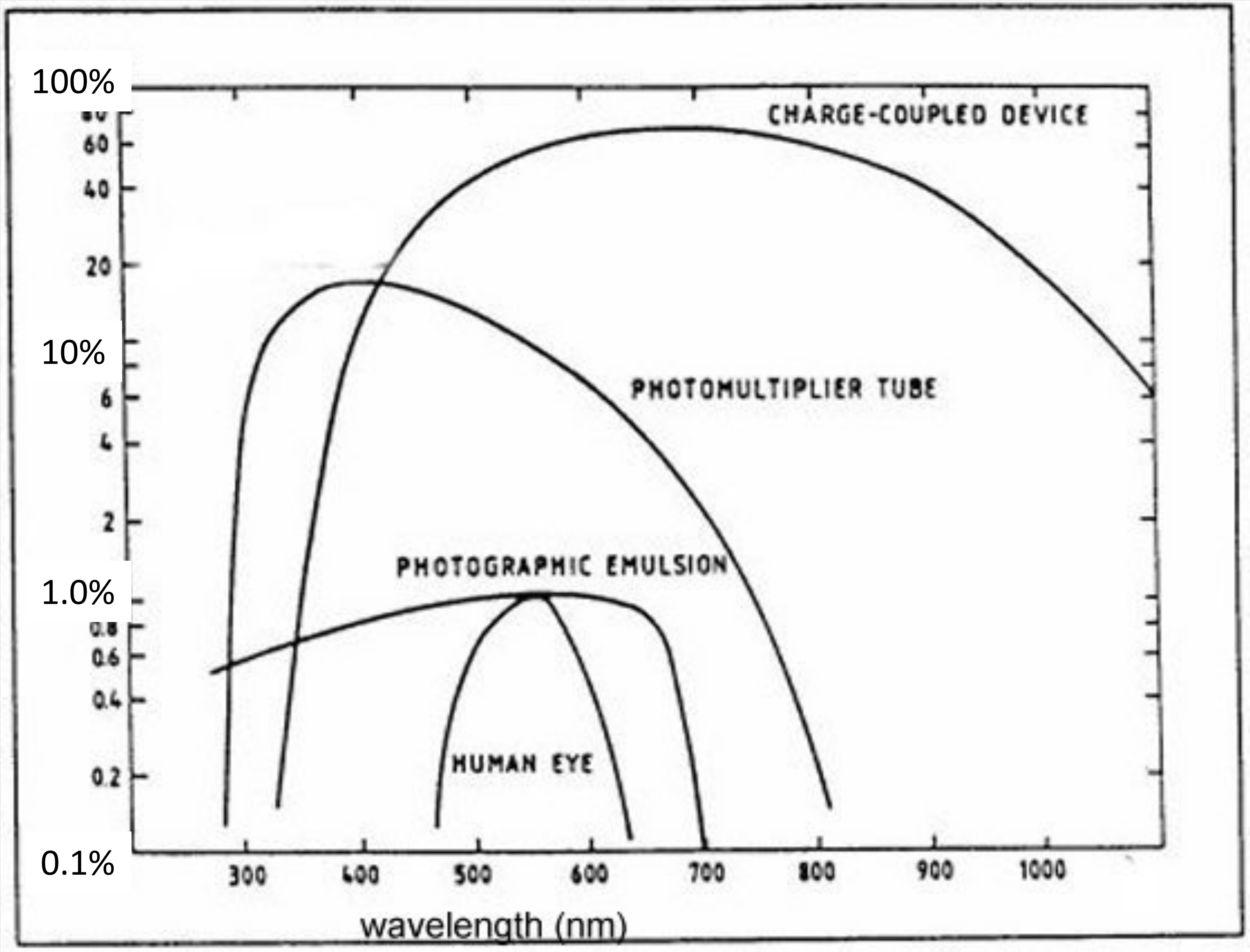




Quantum efficiency comparison

A factor of 10 in detection efficiency is like having a telescope that is 3x bigger!

However, you can't go above 100%.....



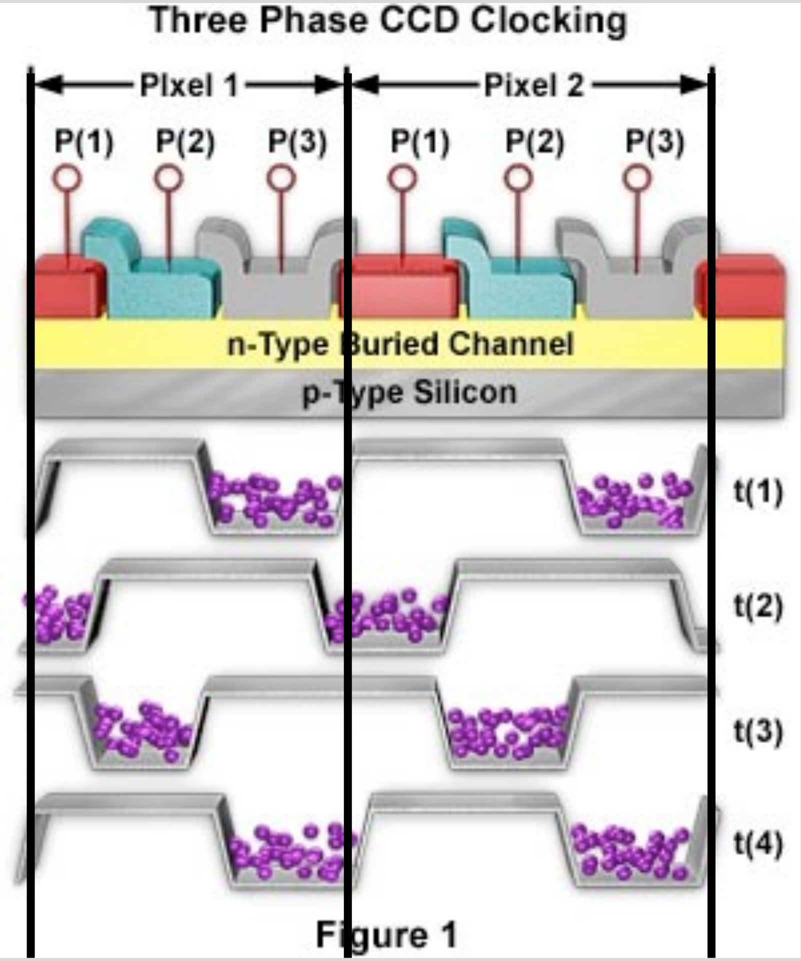
CCD “Read-out”

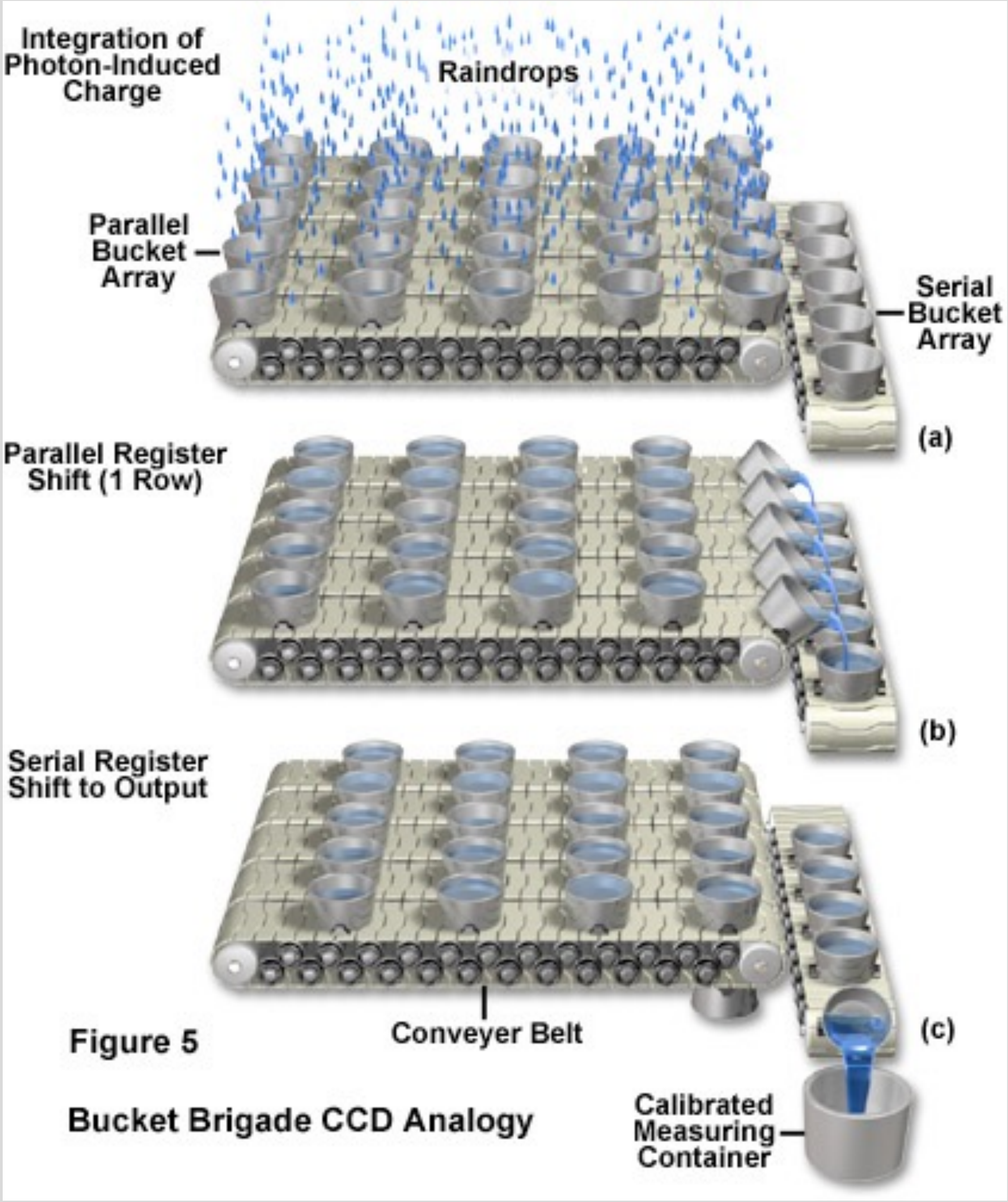
Once the exposure is over, the voltages on the pixel gates can be altered in a pattern that moves the charge across the CCD to be collected.

Reading out a CCD takes time. More pixels (bigger CCD), more time.

Schmidt 4Kx4K CCD: ~ 60 seconds

Readout can be done faster, but then more errors: higher **readout noise**.





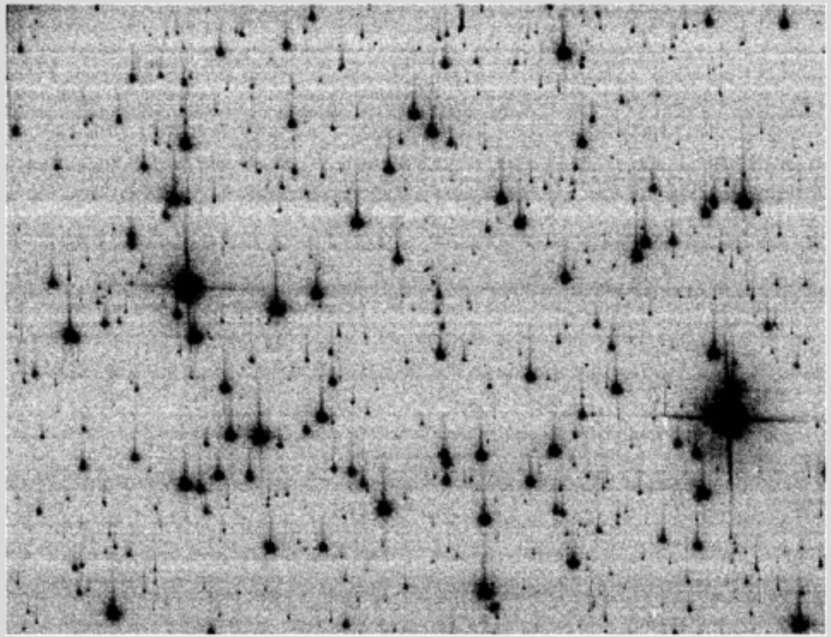
CCD pixel problems: misbehaving electrons

Charge transfer efficiency (CTE)

CTE: The fraction of electrons which are successfully transferred at each step. If you leave electrons behind (poor CTE)

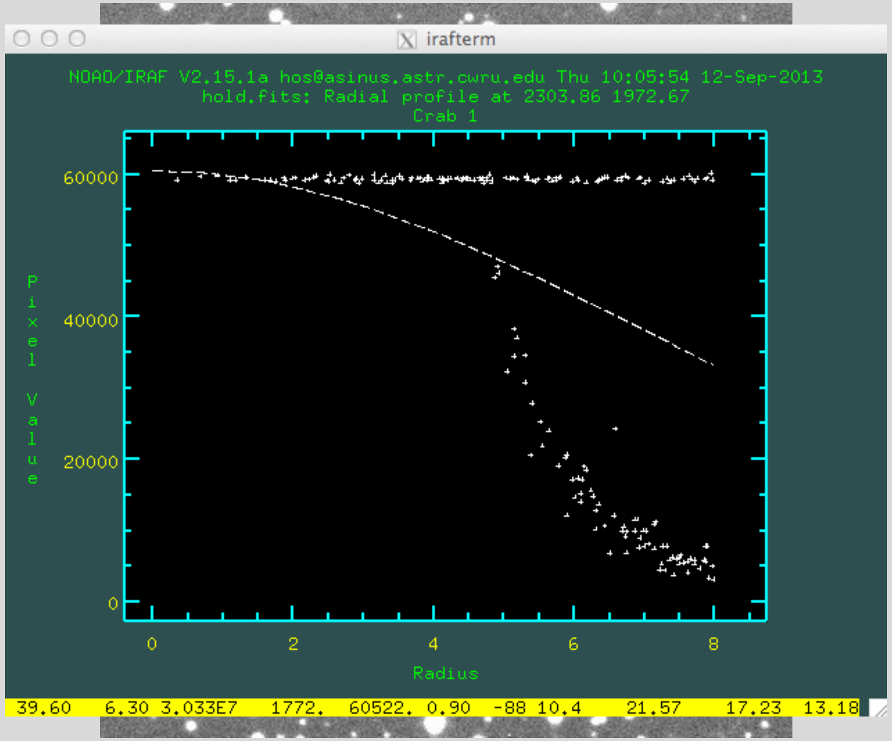
You want CTE ≥ 0.99999 or so!

Hubble ACS CTE effects (Anderson & Bedin 10)



Saturation/Bleeding

A pixel can hold a maximum accumulated charge (full well capacity or saturation). If exceeded, photons will no longer be accurately counted and charge will bleed out to adjacent pixels.



Cosmic rays

Charged particles hit the detector, freeing electrons. Limits exposure times to ~ 15-20 minutes.