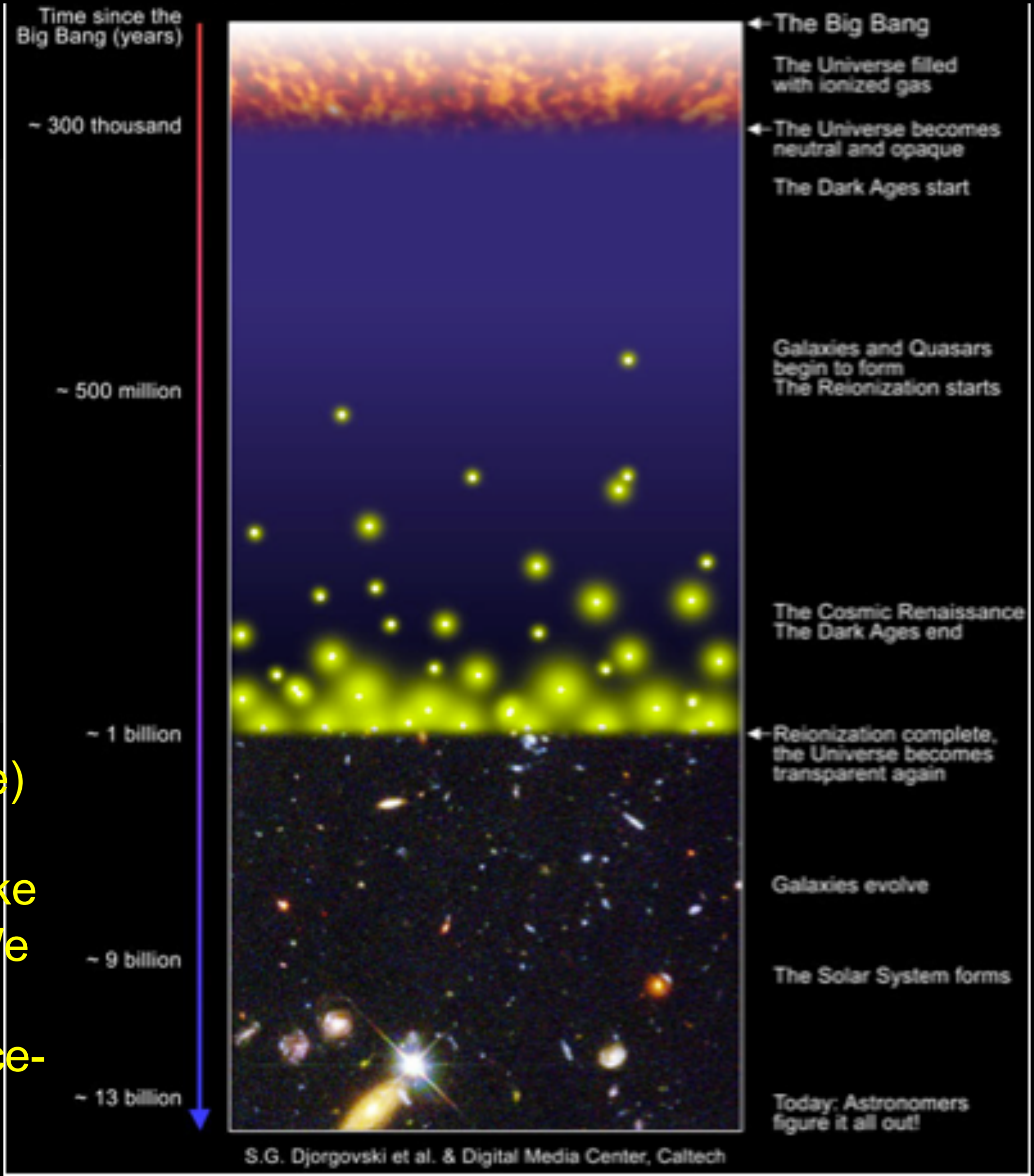
Astronomy is remote sensing

We cannot repeat (or change) the Universe in a controlled environment. We cannot make planets, stars, or galaxies. We cannot make the vacuum of space, nor the shape of space-time around a black-hole.



S.G. Djorgovski et al. & Digital Media Center, Caltech

Early Observatories

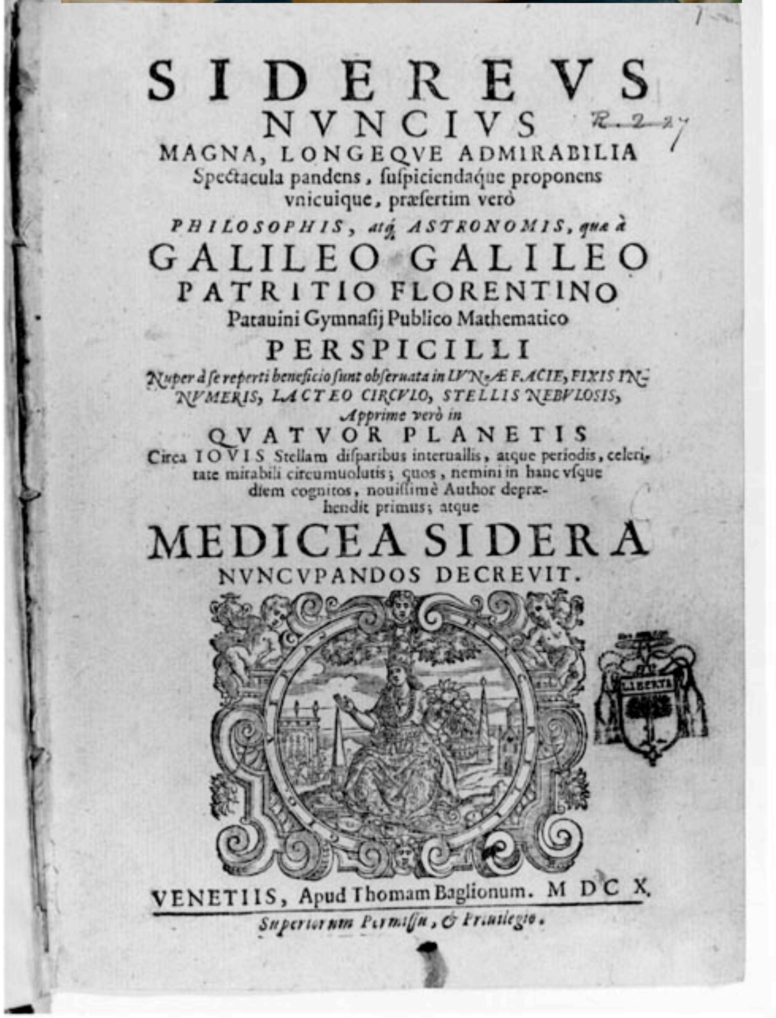
- The Incan Chankillo Observatory ~2400yrs old, “solar”

Galileo’s Telescope

The Starry Messenger (1610)

- SIDEREAL MESSENGER
  unfolding great and very wonderful sights
  and displaying to the gaze of everyone,
  but especially philosophers and astronomers,
  the things that were observed by
  GALILEO GALILEI,
  Florentine patrician
  and public mathematician of the University of Padua,
  with the help of a spyglass lately devised by him,
  about the face of the Moon, countless fixed stars,
  the Milky Way, nebulous stars,
  but especially about
  four planets
  flying around the star of Jupiter at unequal intervals
  and periods with wonderful swiftness;
  which, unknown by anyone until this day,
  the first author detected recently
  and decided to name
  MEDICEAN STARS

  (trans. A. van Helden, p. [26])

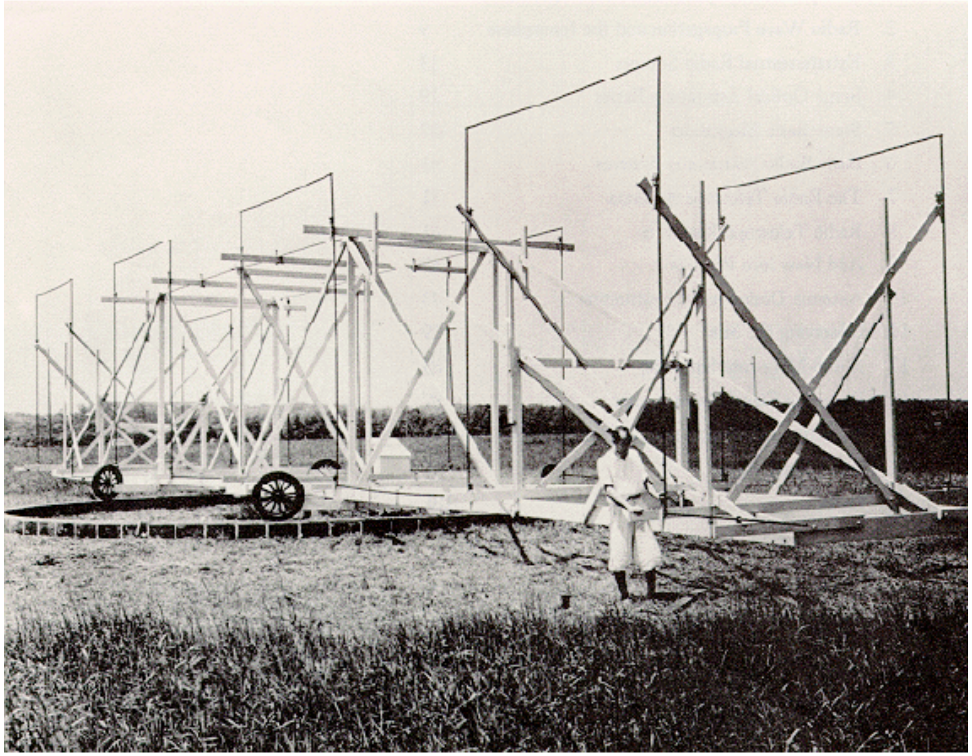


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, ſuſpiciendaque proponens
vnicuique, præſertim verò
PHILOSOPHIS, atq́ ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnaſij Publico Mathematico
PERSPICILLI
Nuper à ſe reperti beneficio ſunt obſeruata in LVNÆ FACIE, FIXIS INNVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam diſparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vſque diem cognitos, nouiſſimè Author depræhendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permiſſu, & Priuilegio.

Radio Astronomy “Discovered” in 1931
Jansky couldn’t get rid of the noise

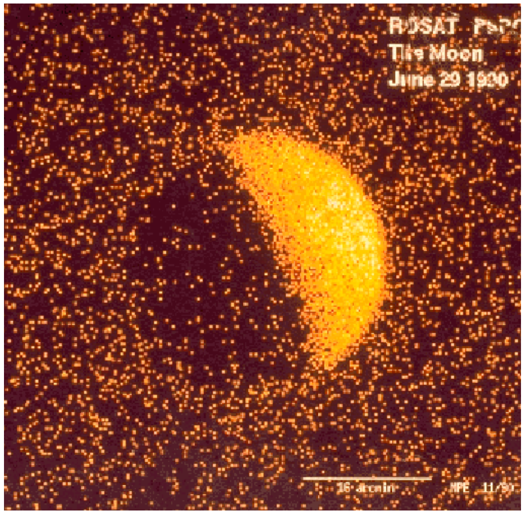
Jansky’s radio telescope



Reber’s radio telescope 1937

X-ray Astronomy

- “Discovered” in 1949
- Moon mapped in 1962
- Giacconi wins Nobel ‘92 prize for X-ray astronomy



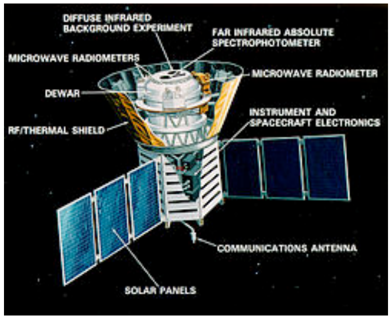
Microwave Astronomy “Discovered” in 1964

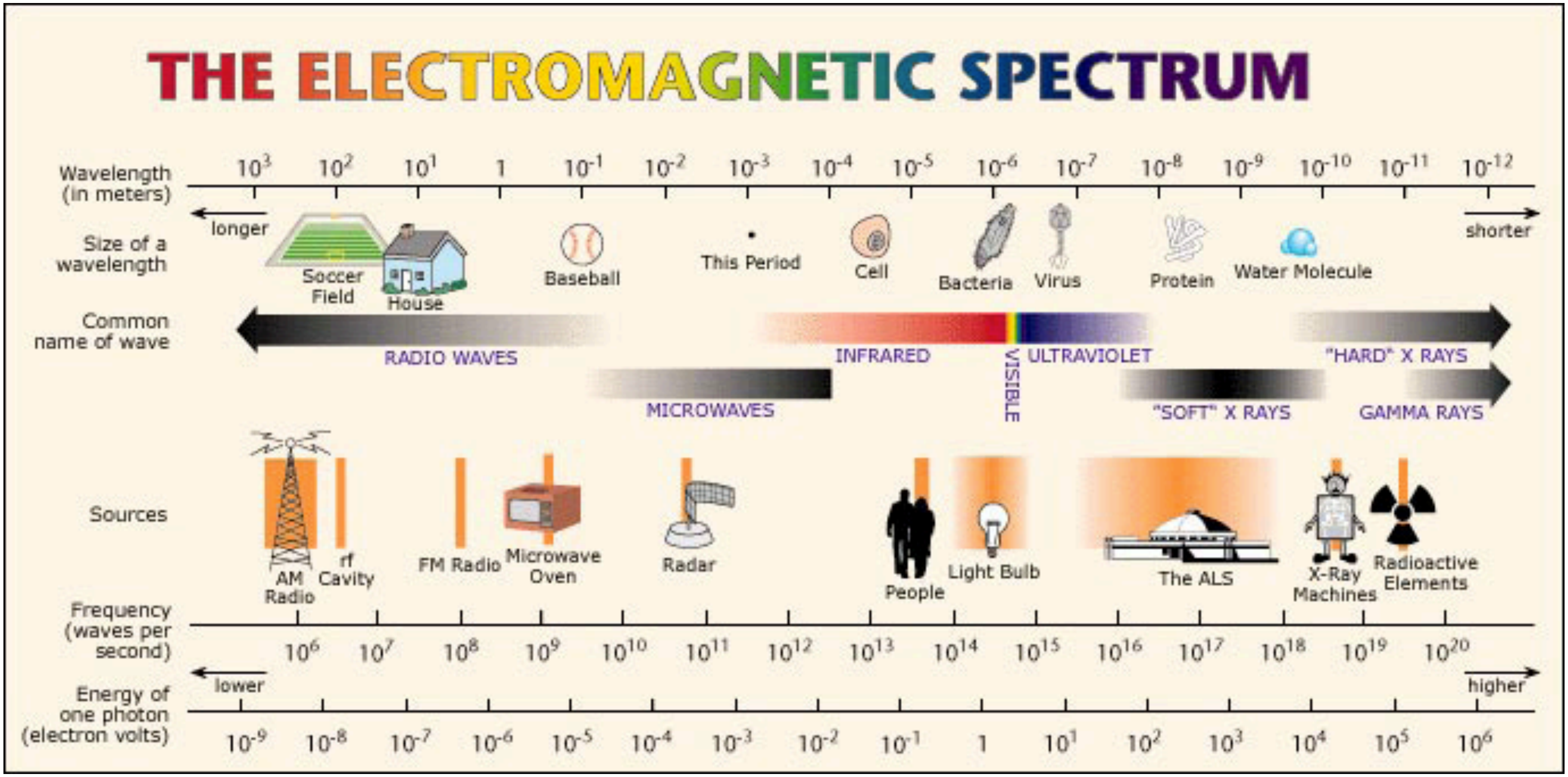
Penzias and Wilson

Discovered CMB

Mather and Smoot

Discovered CMB Anisotropies




THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^{3} 10^{2} 10^{1} 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
MICROWAVES
INFRARED
VISIBLE
ULTRAVIOLET
"SOFT" X RAYS
"HARD" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
lower
higher
Energy of one photon (electron volts)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}

Why a Telescope?

We have two telescopes, our eyes:

Collect Light

Form an Image

Interpret the Image

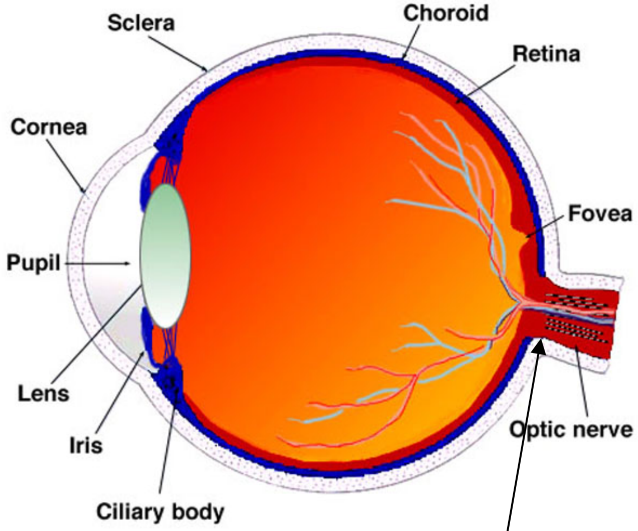


Fig. 6. Vertical sagittal section of the adult human eye.

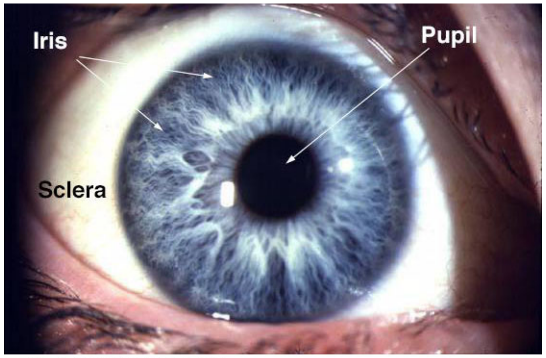
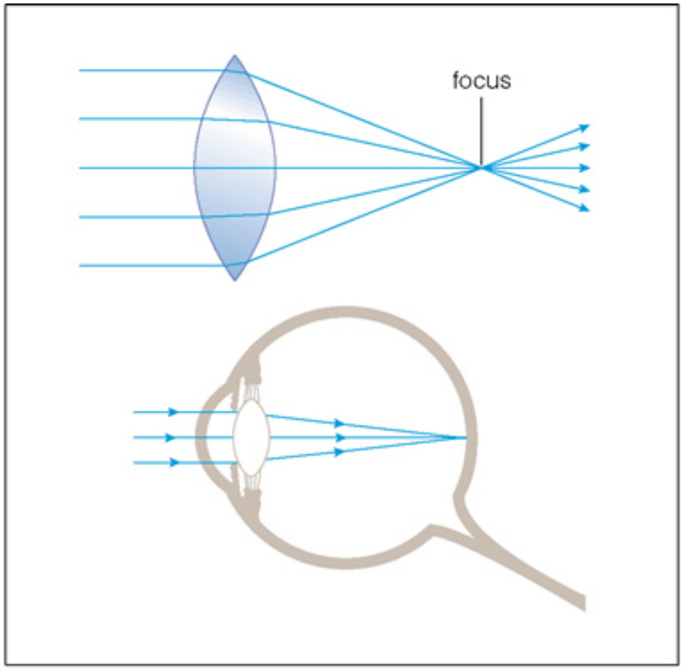
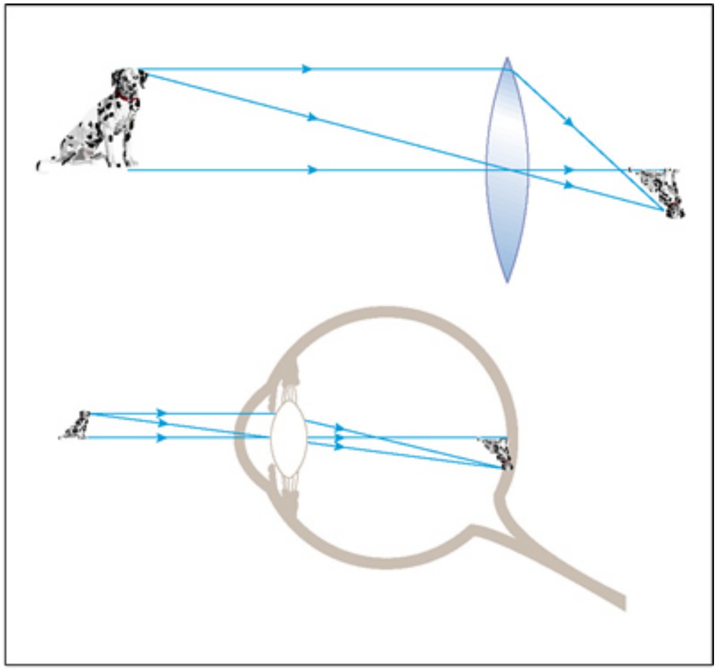


Fig. 1. View of the human eye

To Brain (interpretation)

The Role of Lenses



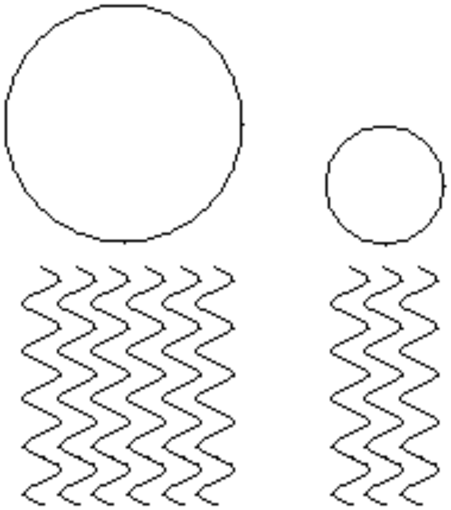


Lenses can bring light rays to a focus (increase intensity)

Light rays from different locations form an image (the dog)

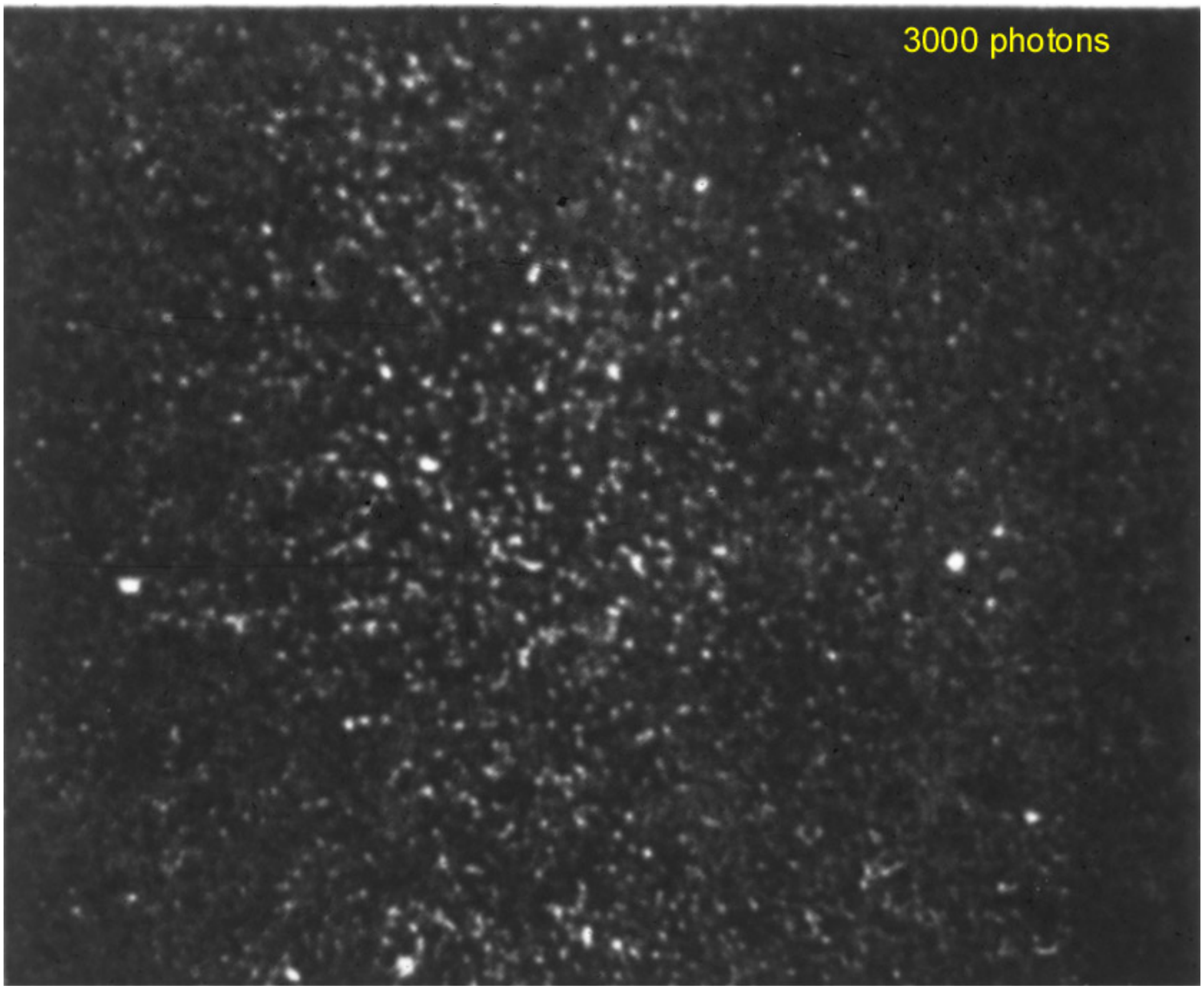
The Importance of Light-Gathering Power

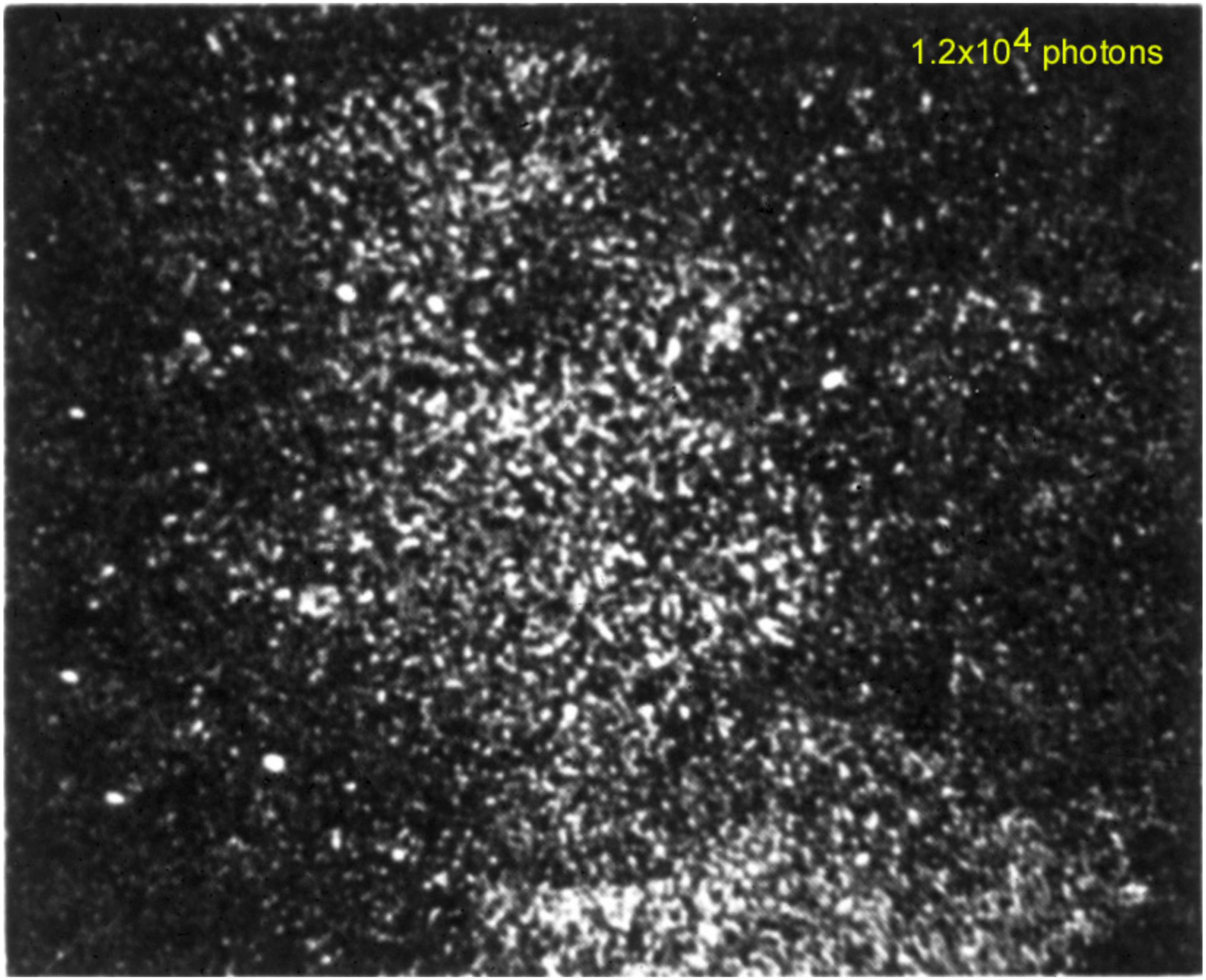
- Can only see to 6th magnitude by eye
- Limit due to not enough photons
- To see fainter things, we need Bigger eyes



Bigger objective gathers more light:
Brighter images
Flux depends on area of objective
$F \propto \pi (D/2)^2$
D= diameter

Example of how more photons give a more detailed image:




1.2x10^4 photons

9.3x10^4 photons


7.6×10^5 photons


3.6×10^6 photons

So you want a really big eye: a telescope with large collecting area

2 ways of collecting light**: lenses or mirrors (or both)**

Galileo’s telescope

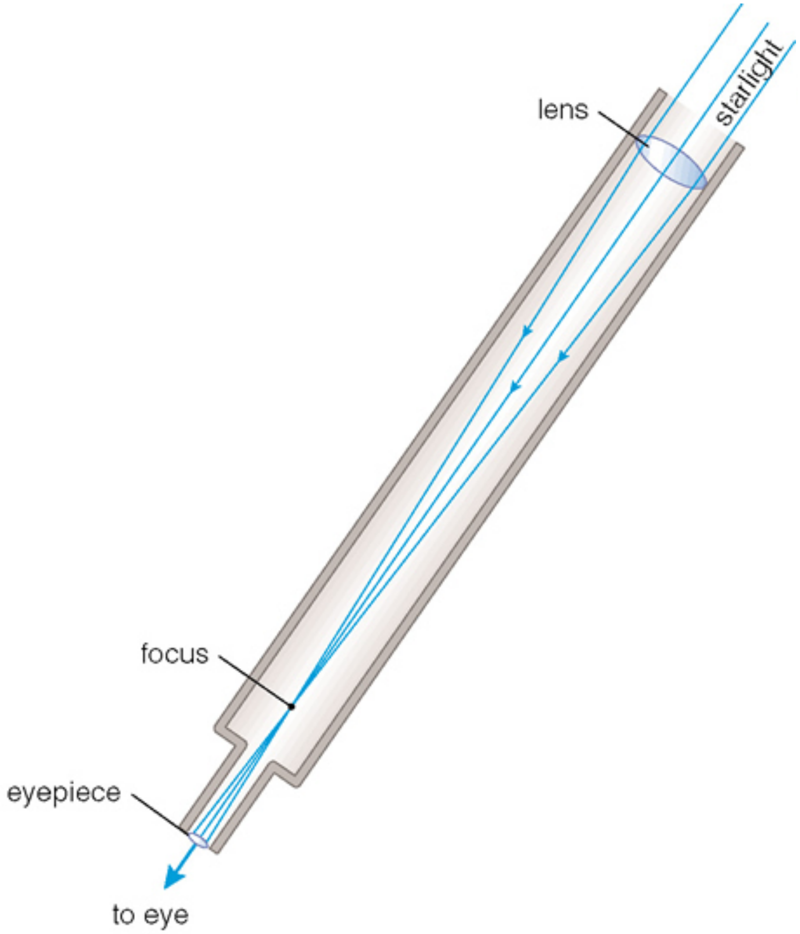
It is a **“refracting”** telescope (collects light with lenses)

Galileo’s telescope lens: 2.6 cm

Naked eye (pupil): 0.5 cm

Refractor

Yerkes 40-inch telescope; largest refractor in the world



(b)

Reflecting Telescopes: Mirrors

- Can make mirrors much larger than lenses
- Avoids chromatic aberration

Arrangements:

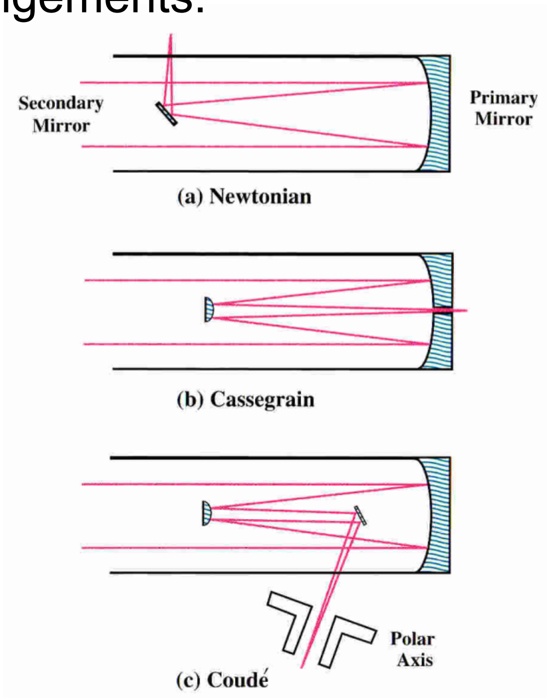


Fig 4.8. Focal arrangements in (a) Newtonian, (b) Cassegrain and (c) coudé telescopes. In each case the light enters the telescope from the left.

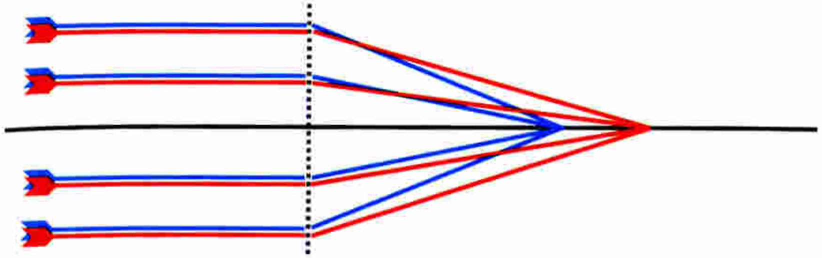
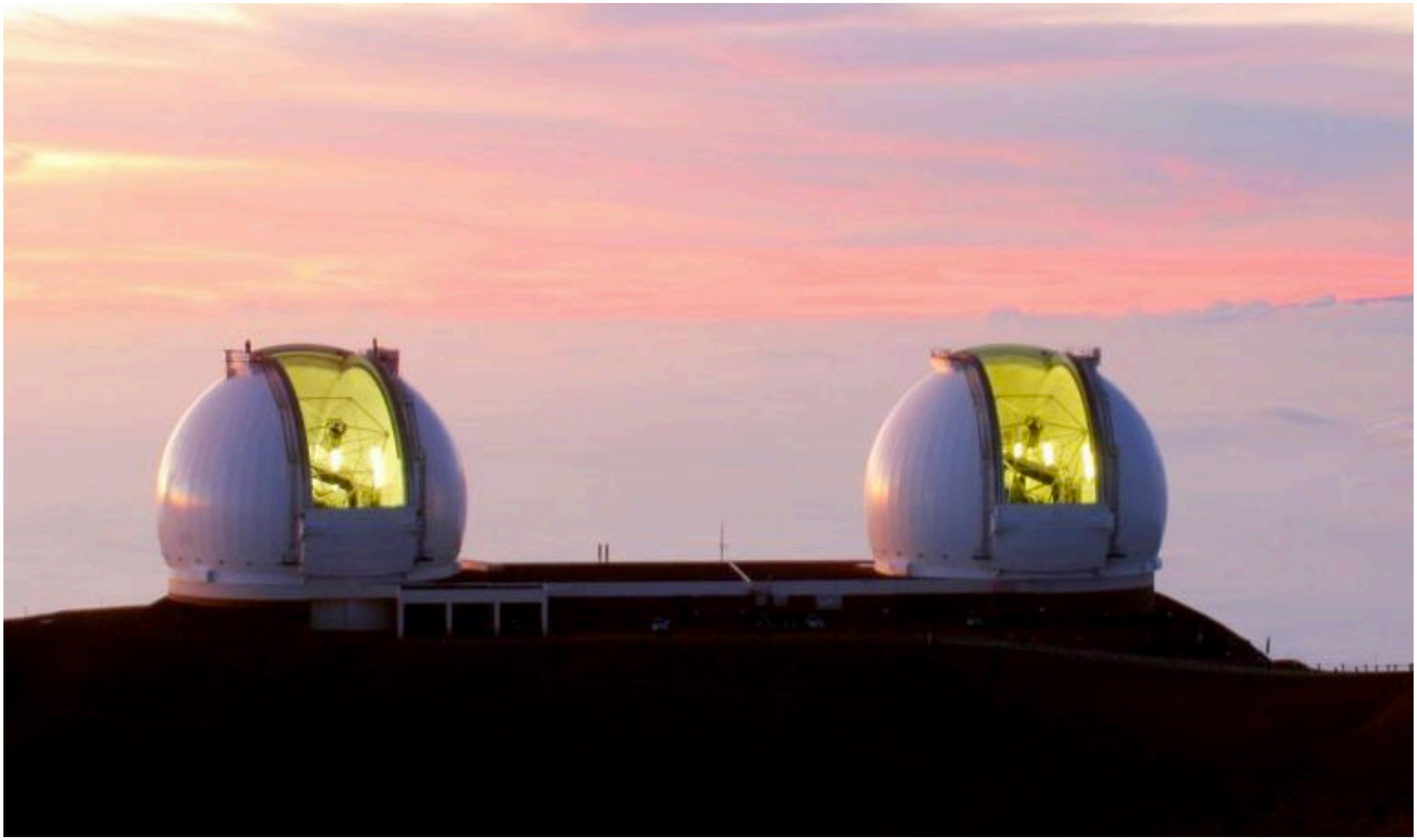


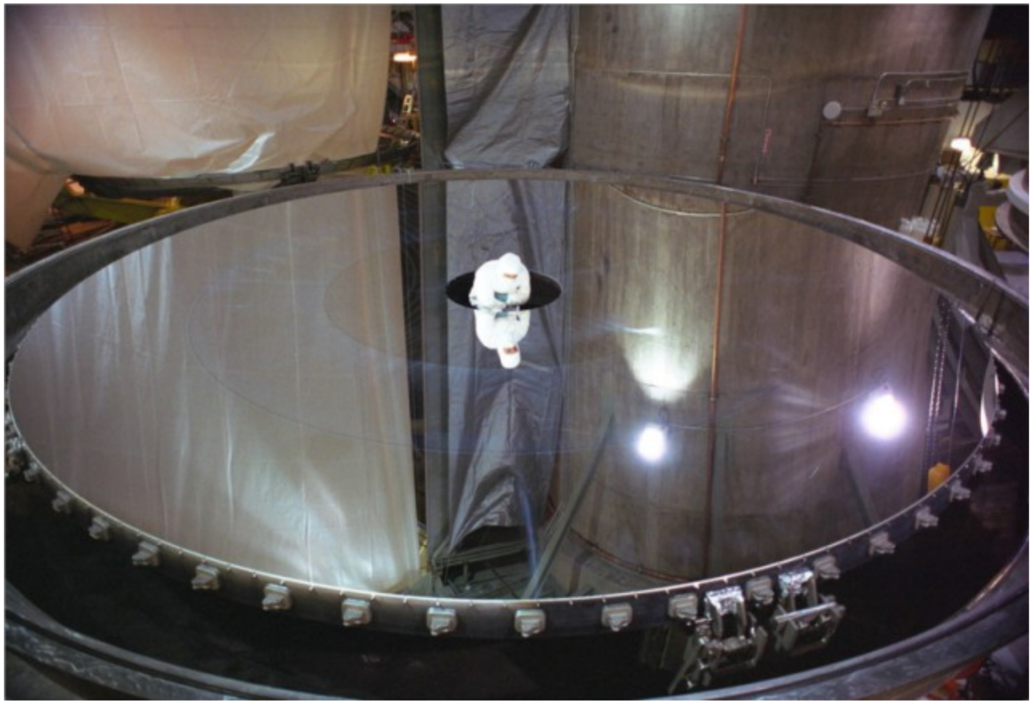
Fig 4.4. Chromatic aberration. The focal length is different for different wavelengths.

Keck telescopes

Submit of Mauna Kea, Hawaii



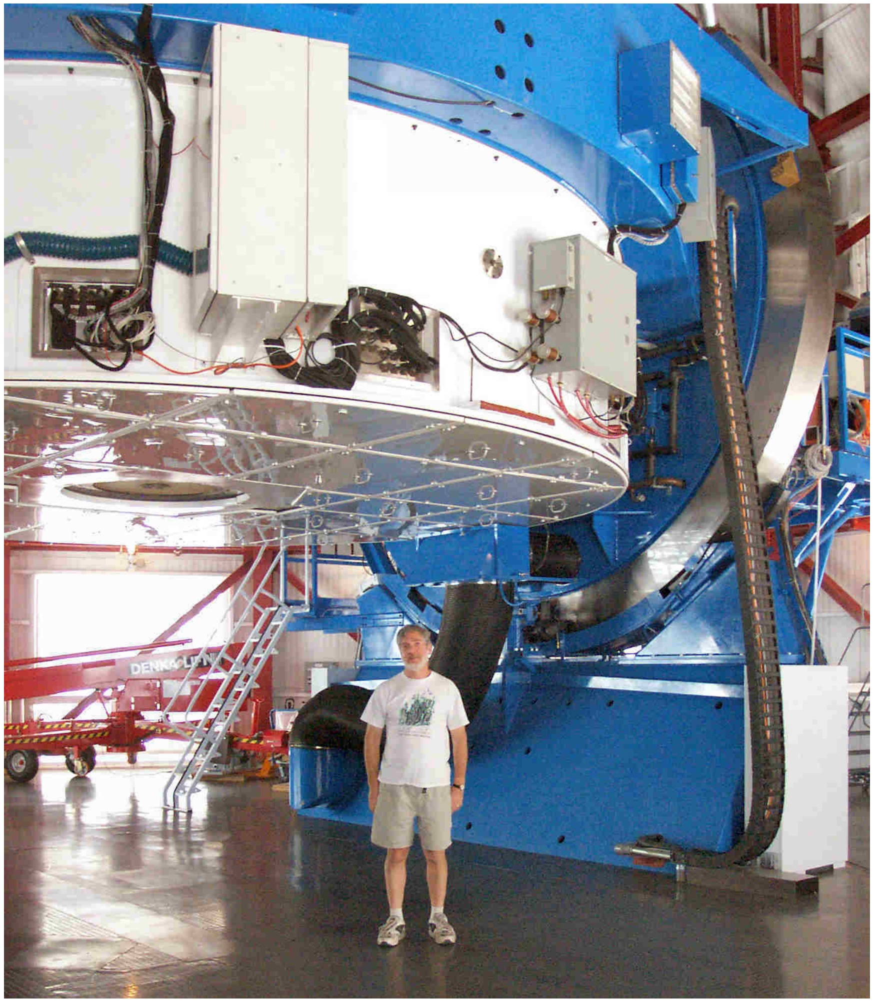
Gemini North/South (Hawaii/Chile)



Gemini North Telescope

8.1 mt

Magellan Observatory, Las Campanas, Chile



6.5 mt

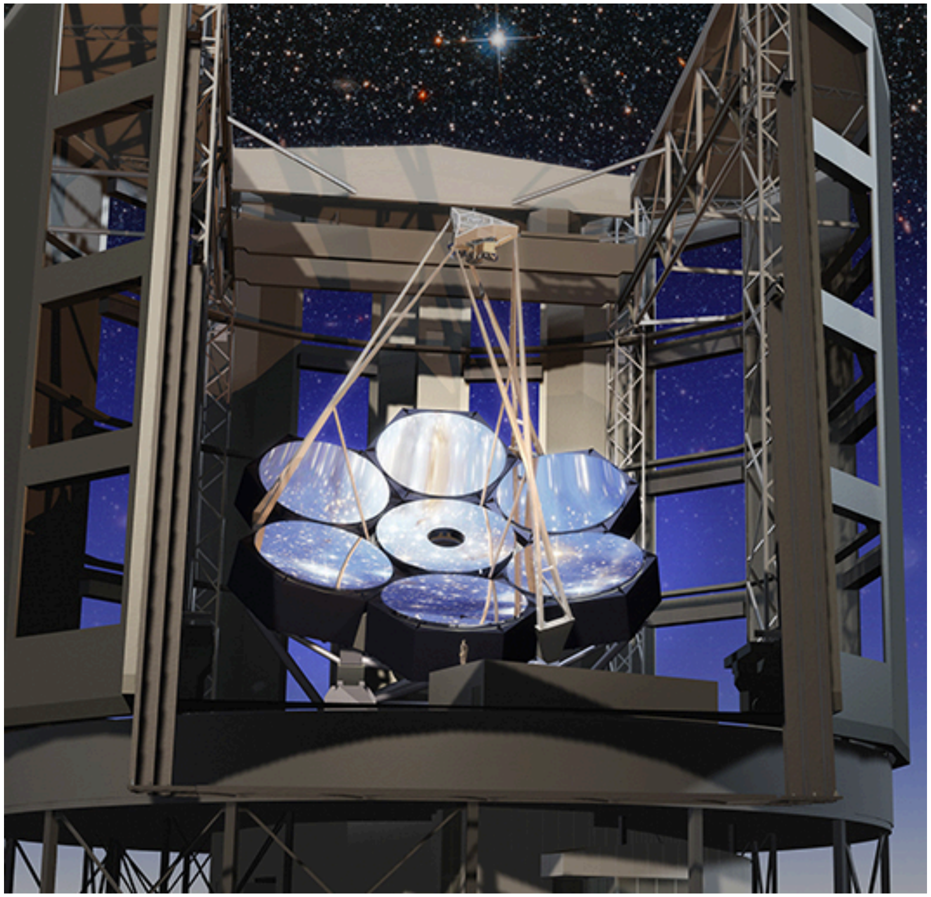
Very Large Telescope (ESO)

Each 8.2mt,equivalent area 16 mt

Secondary mirror adjusts itself to produce best images

http://www.eso.org/public/videos/vlttrailer2009/

In the future: **Giant Magellan Telescope**



Seven 8.4 meter or 27-foot segments, forming a single optical surface with a collecting area of 24.5 meters, or 80 feet in diameter.

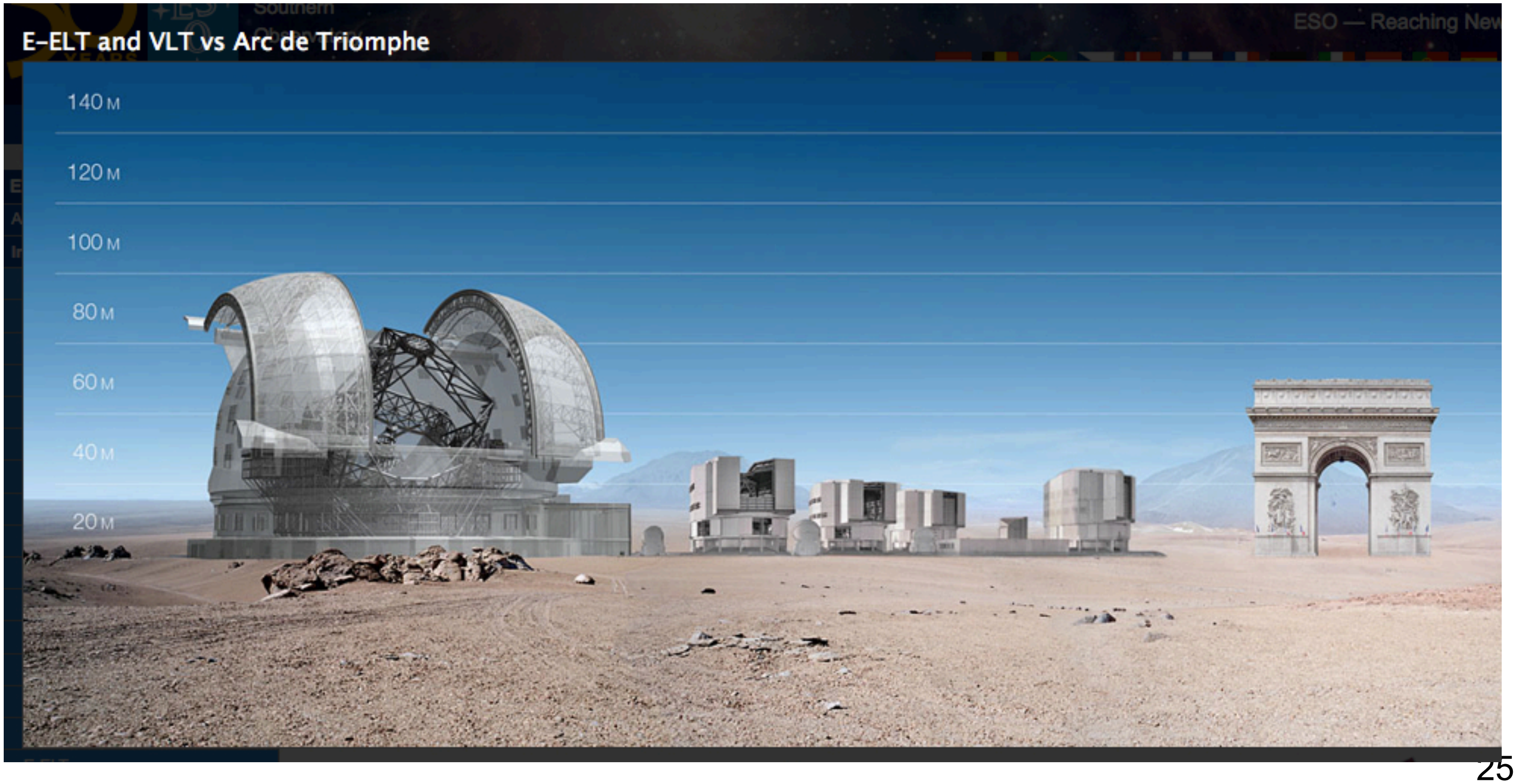
The GMT will have a resolving power 10 times greater than the Hubble Space Telescope.

Construction has started

http://www.gmto.org/index.html

Next decade: **European Extremely Large Telescope (E-ELT)**

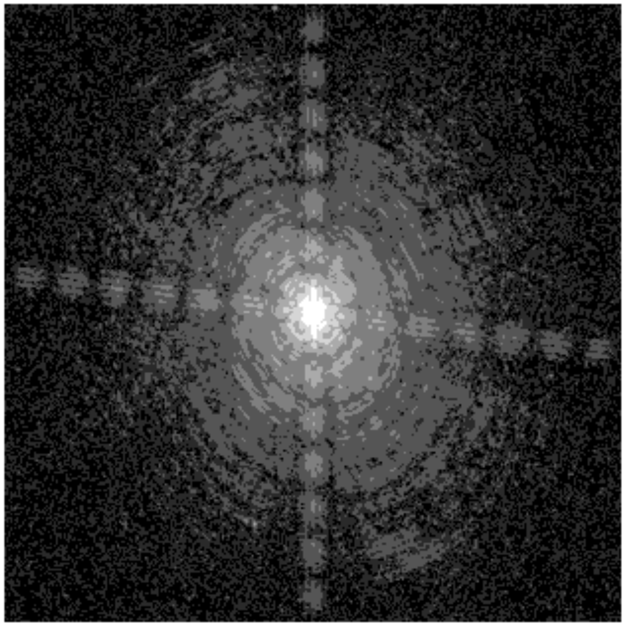
39 mt
800 segments, each 1.4 metres wide, but only 50 mm thick



Job #2: Angular Resolution

Resolution (detail you can image) is limited by the optics

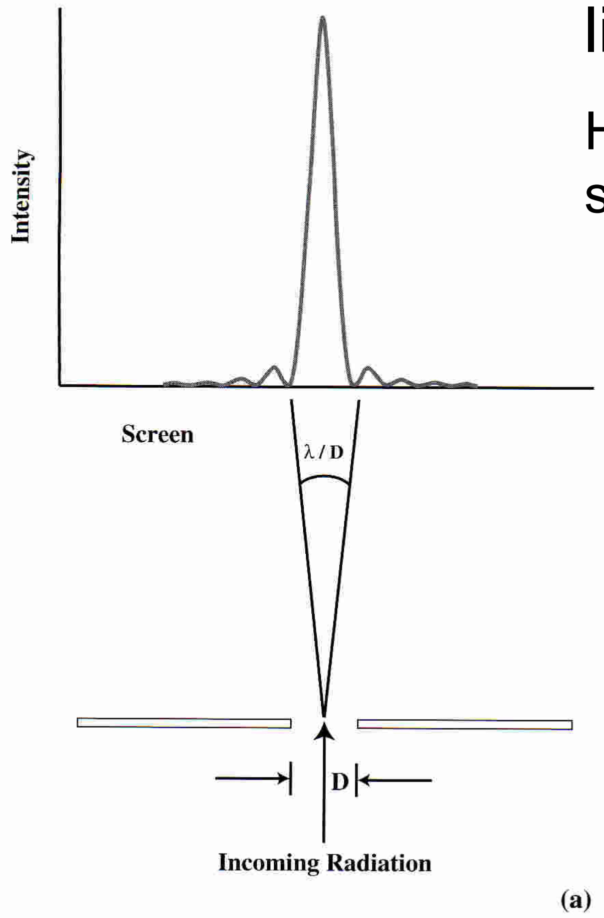
- smallest angle which can be seen
- **θ(rad) = 1.22 λ / D**
- due to diffraction



HST image of a point source
(structure due to telescope optics)

Diffraction of Light: Interaction of light waves and edges

Here, the edges are due to the telescope size (primary mirror)



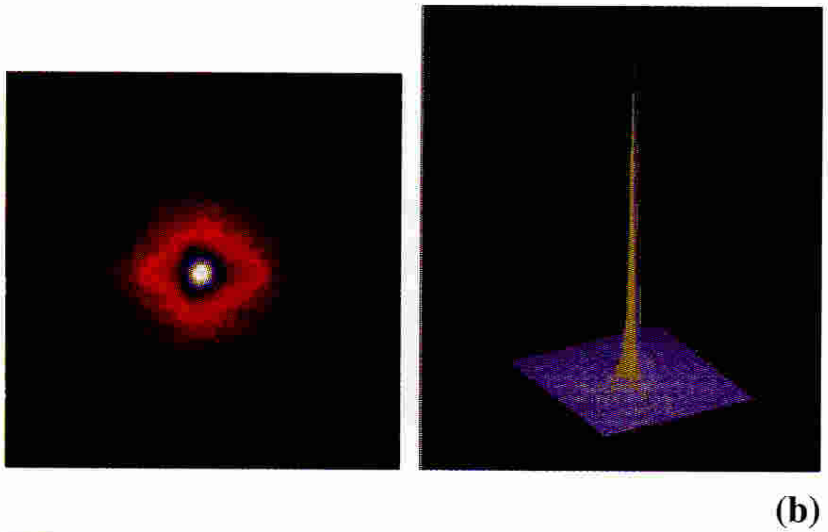


Fig 4.1. Diffraction. (a) A light ray enters from the bottom, and passes through a slit of length *D*. Diffraction spreads the beam out and it falls on a screen. The intensity as a function of position on the screen is shown at the top. Most of the energy is in the main peak, whose angular width is approximately λ/D (in radians). Smaller peaks occur at larger angles. The effect in a real image. (b) [ESO]

Most power in central maximum
Width of maximum $\propto \lambda/D$
For circular apertures, $\theta(\text{rad}) = 1.22\lambda/D$

Diffraction limit

θ(rad) = 1.22 λ / D

π rad = 180 degrees

=> 1 rad = 180x60x60/π = 2.05e5 seconds of arc (")

θ(") = 1.22x2.05e5 λ / D = 2.5e5 λ / D

For optical light λ = 5.5e-7m = 5.5E-5 cm is

θ(rad) = 1.22 x [5.5E-5 cm/D(cm)] = 6.7e-5 / D(cm)

θ(") = 2.0e5 x [5.5E-5 cm/D(cm)] = 13.8" / D(cm)

Example: Resolution Limit of Your Eye

Diffraction limit for optical light (λ = 5.5E-5 cm) is

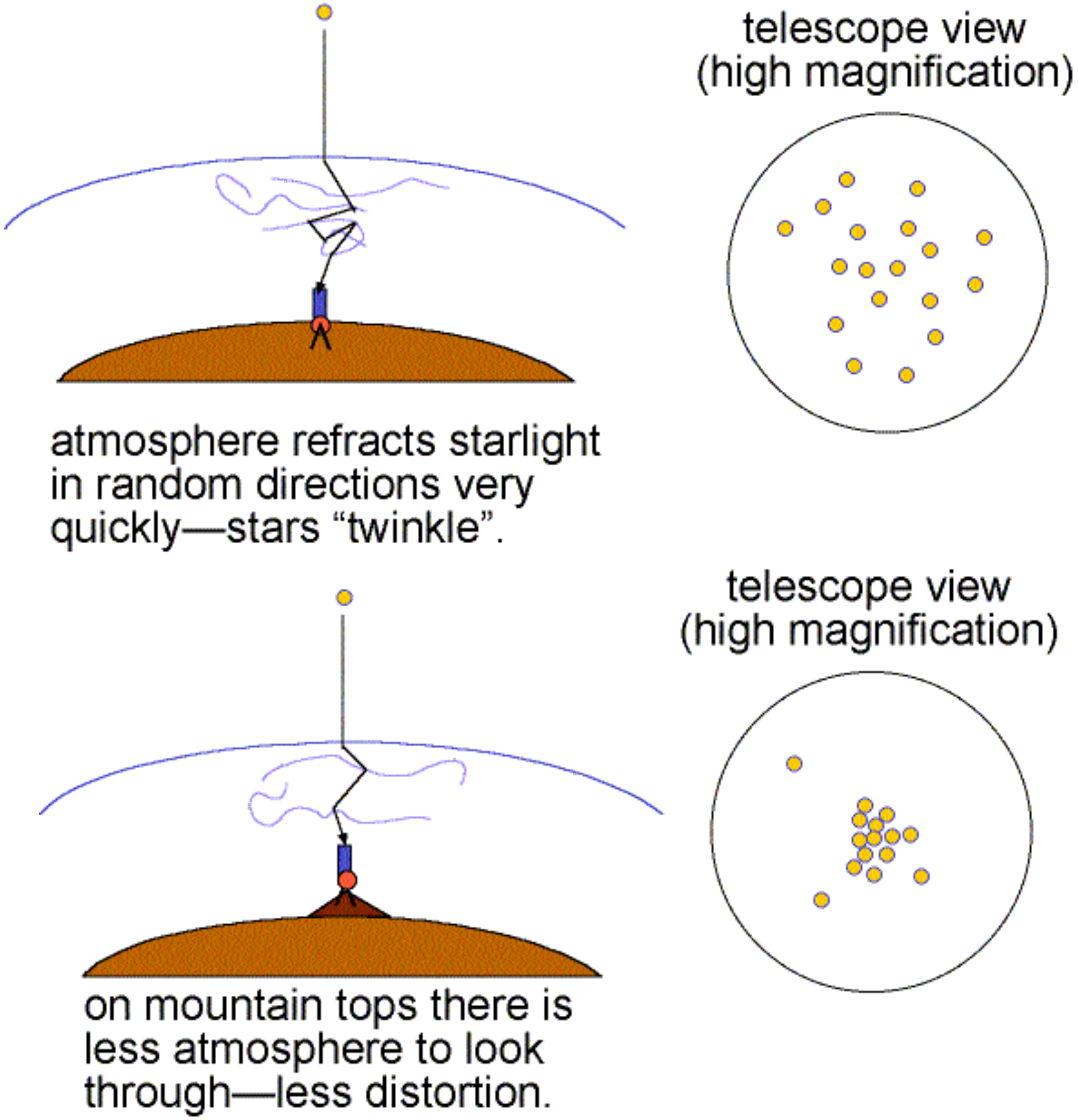
θ= 13.8”/D(cm)

θ= 6.7e-5 / D(cm)

The eye has D = 0.5 cm

So the limiting angle is about 28” (1.3E-4 radians)

Atmospheric Turbulence Also Messes Up Images (on Earth)



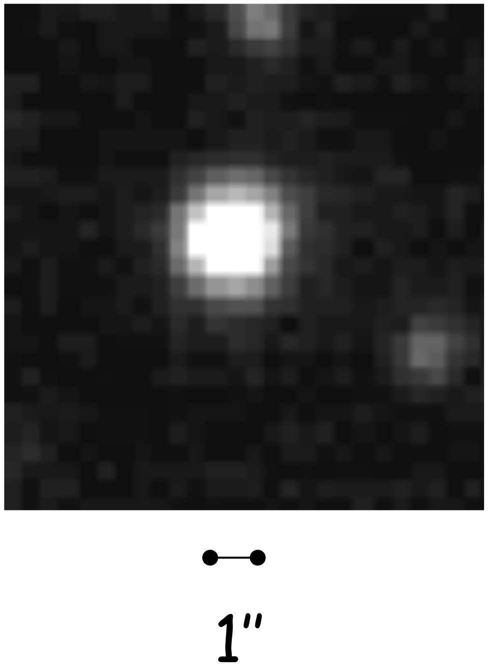
atmosphere refracts starlight in random directions very quickly—stars “twinkle”.

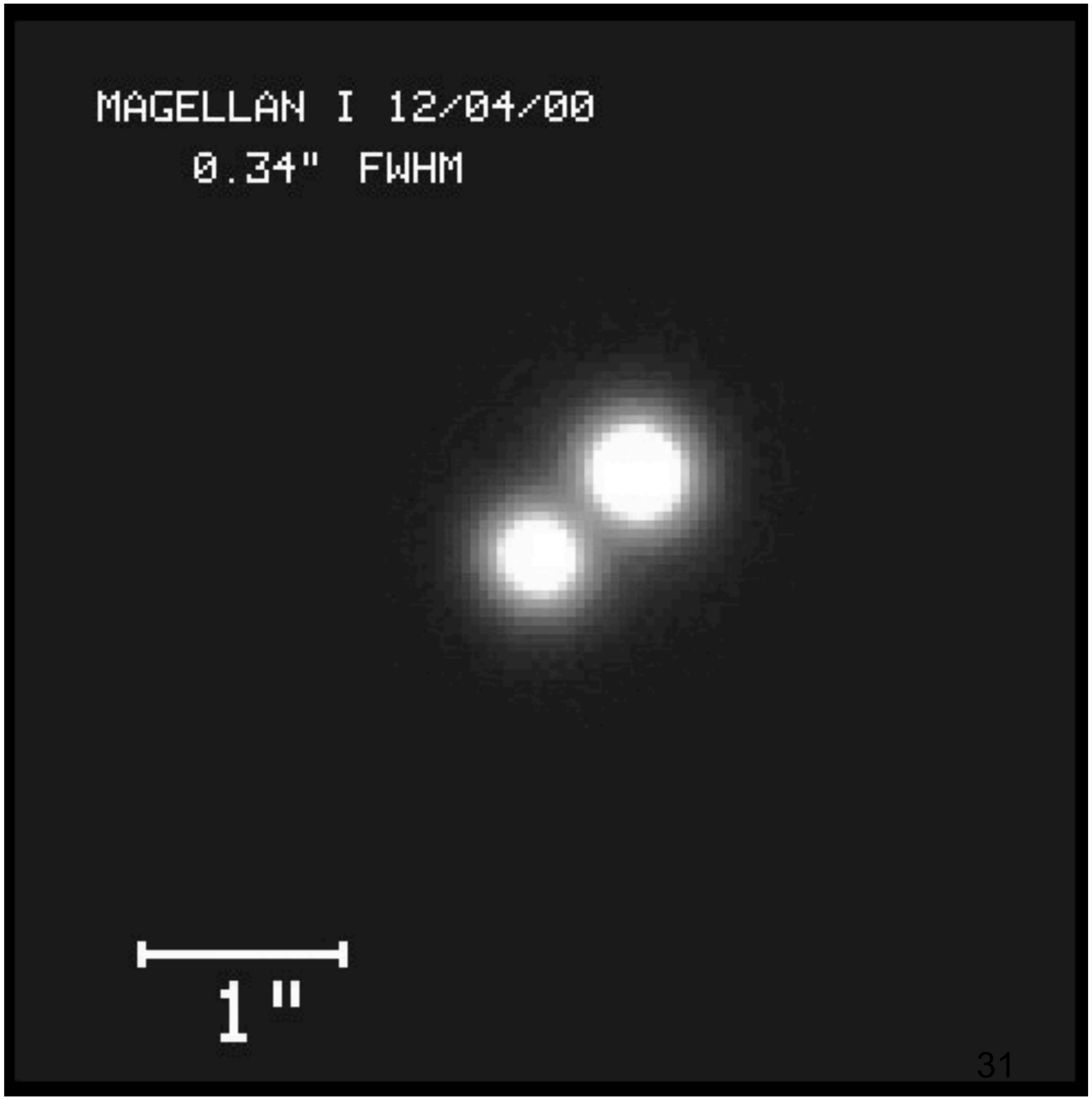
on mountain tops there is less atmosphere to look through—less distortion.

Actual images larger than diffraction limit

A better location + a better telescope = BETTER DATA!
Better resolution

Low resolution:





Atmospheric Blurring (“seeing”): 0.6” at an excellent site

Diffraction limit for optical light is 13.8”/D(cm)

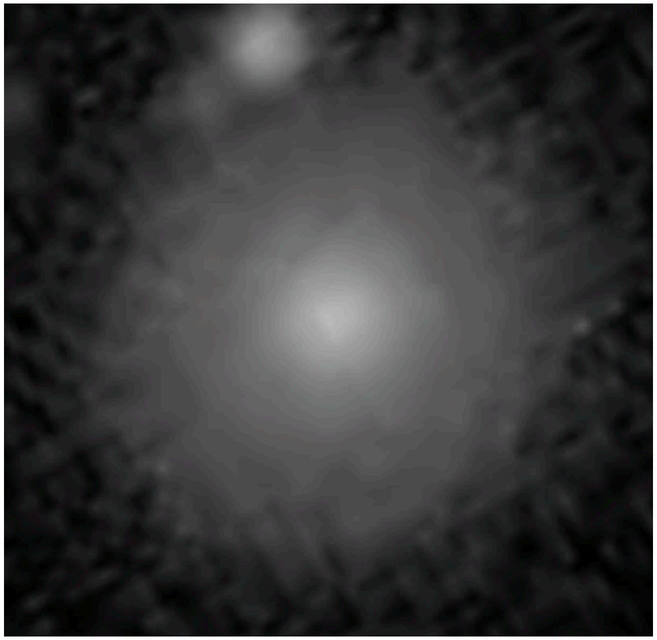
0.6” = 13.8”/D so **D = 13.8/0.6 = 23 cm** (9”, not very big)

So **all ground-based telescopes are “seeing” limited** unless you can do something special (adaptive optics).

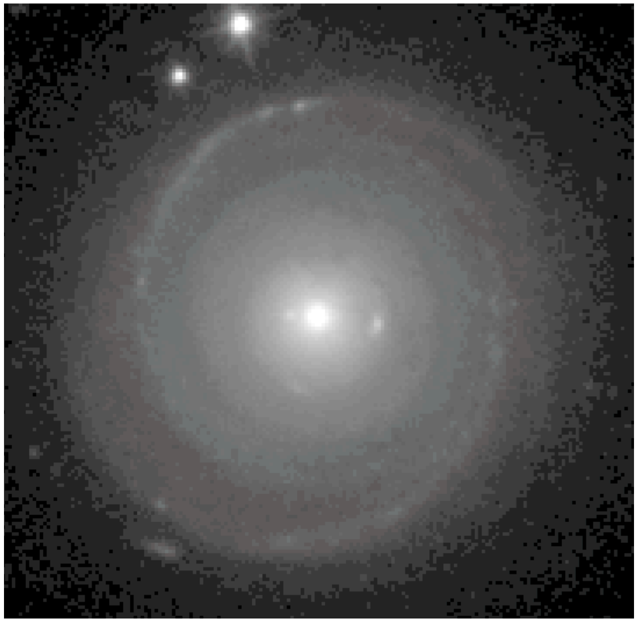
In space, you avoid this seeing problem and get the full diffraction limited resolution (0.05” for Hubble Space Telescope).

A better location + a better telescope = BETTER DATA!
Better resolution

SDSS



HST

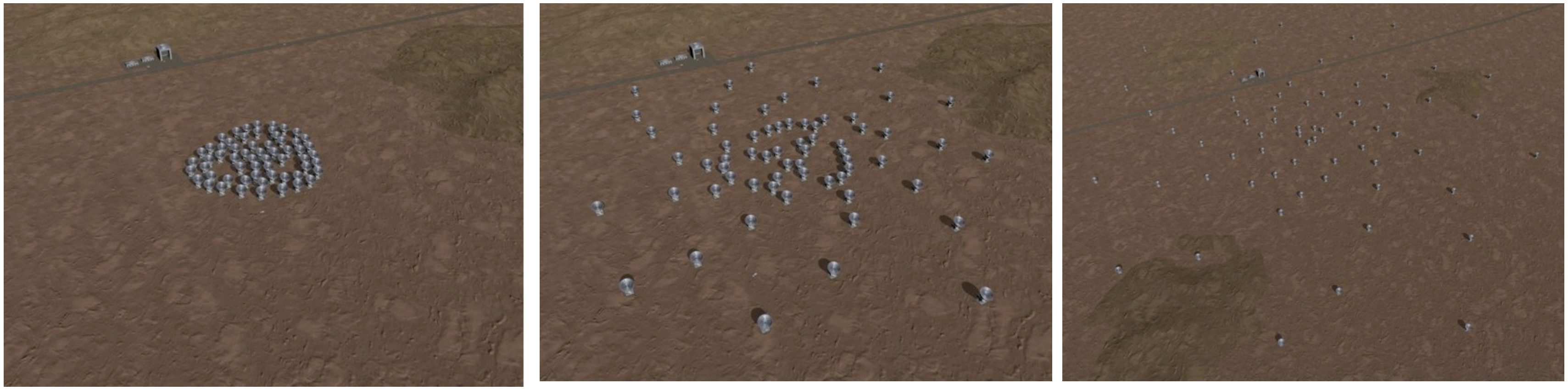


Atacama Large Millimeter Array, ALMA

Atacama dessert, Chile, international collaboration

64 antennas, 12 mt each
0.3 – 4 mm, resolution to 0.005”
Movable, at largest 14 km
The largest and most capable imaging array of telescopes in the world.

Three configurations



Detectors in the optical: **Eyes**, Film, CCD

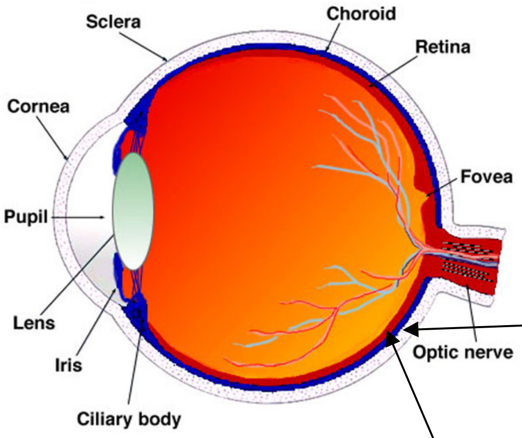


Fig. 6. Vertical sagittal section of the adult human eye.

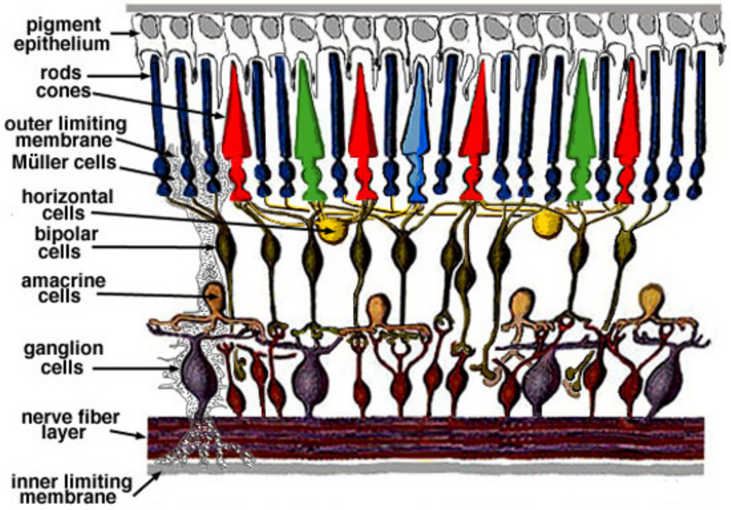


Fig. 2. Simple diagram of the organization of the retina.

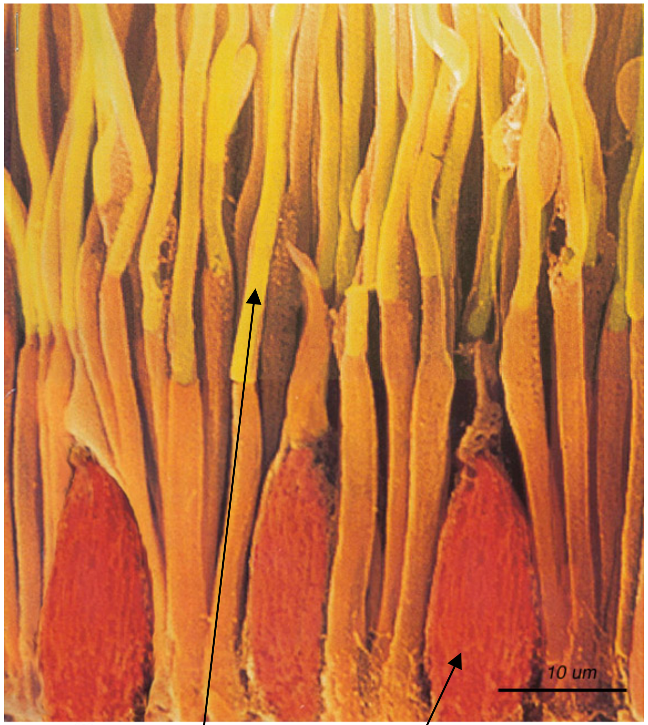
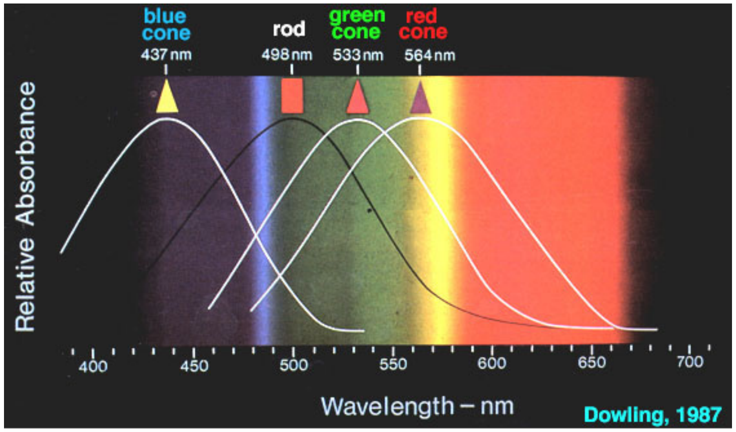


Fig1b. Scanning electron micrograph of the rods and cones of the primate retina. Image adapted from one by Ralph C. Eagle/Photo Researchers, Inc.

Rods: B&W detectors

Cones: Color detectors

Eyes as Detectors, cont.



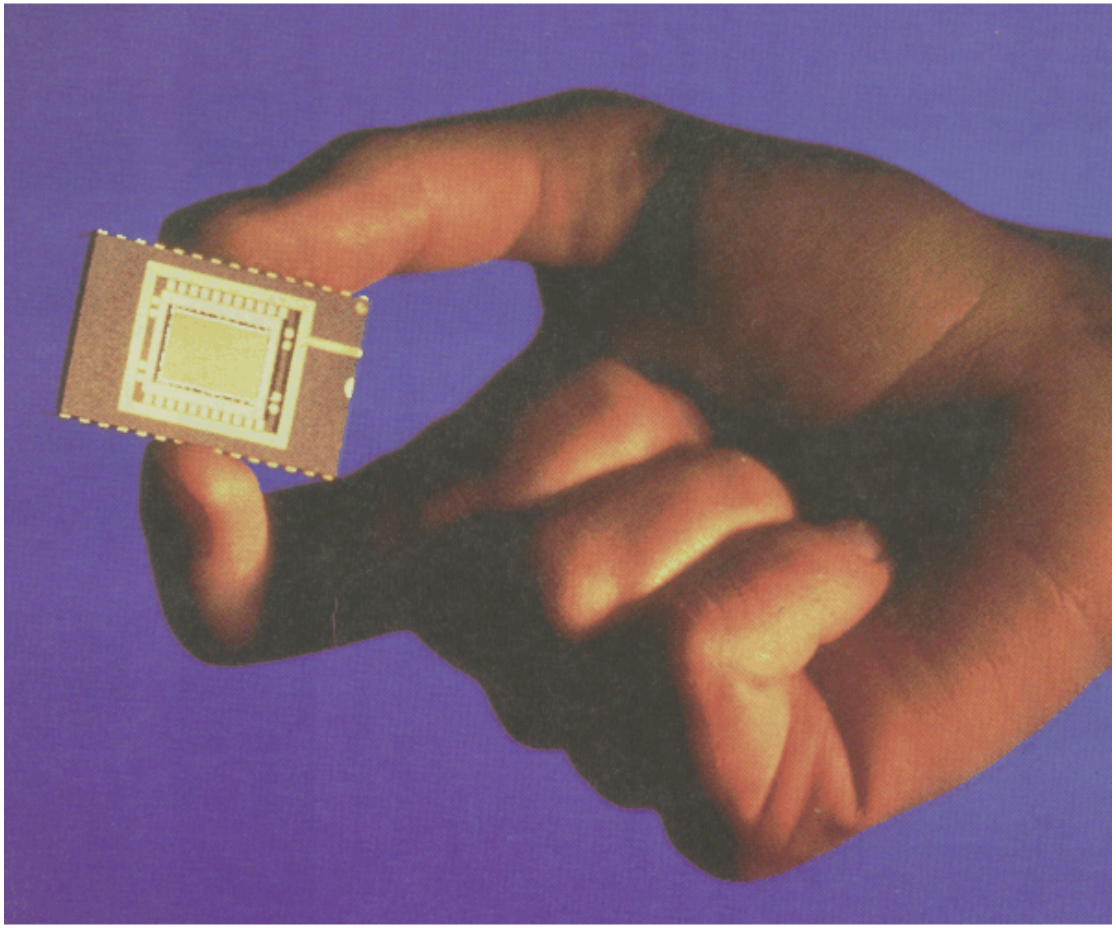
Dowling, 1987

Fig. 14.The peak spectral sensitivities of the the 3 cone types and the the rods in the primate retina (Brown and Wald, 1963). From Dowling's book (1987).

Rods: higher sensitivity, but not color (faint things all look white)

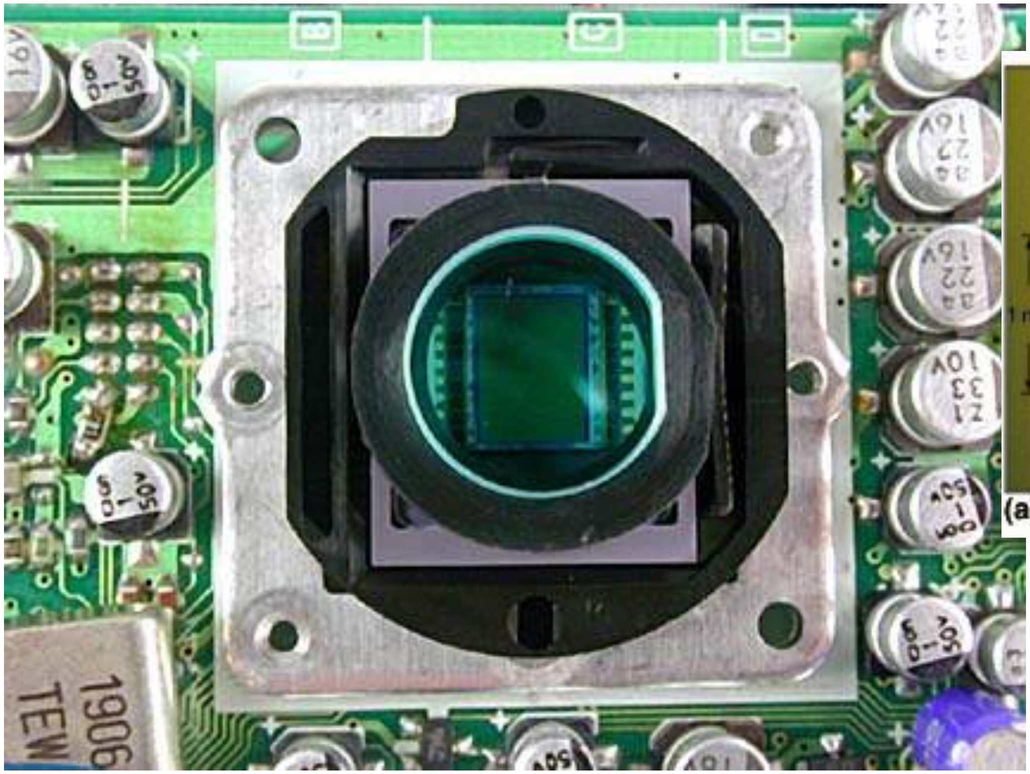
Cones: 3 color receptors (like filters): blue, green, red

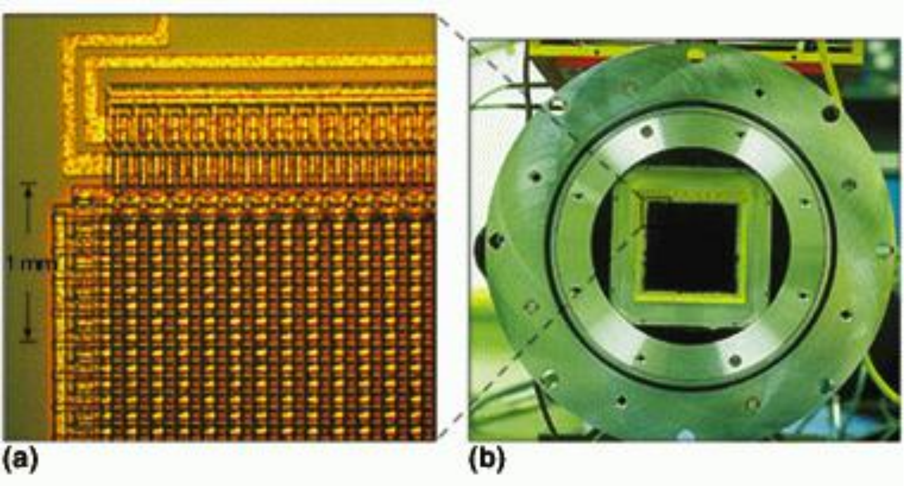
Detectors in the optical: Eye, Film, **CCDs**



CCDs take “black & white” pictures:
do <u>not</u> measure energy of photons

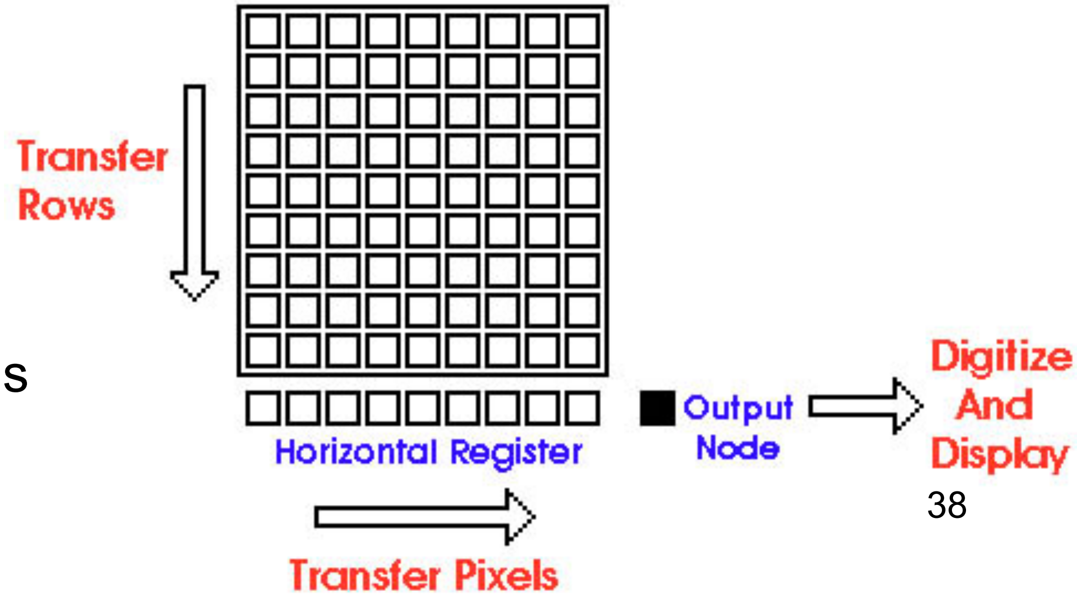
Charge-coupled device CCD





A CCD is an array of light-collecting buckets – signal proportional to intensity of light

“read out” the light buckets…
record how many photons
landed in each bucket

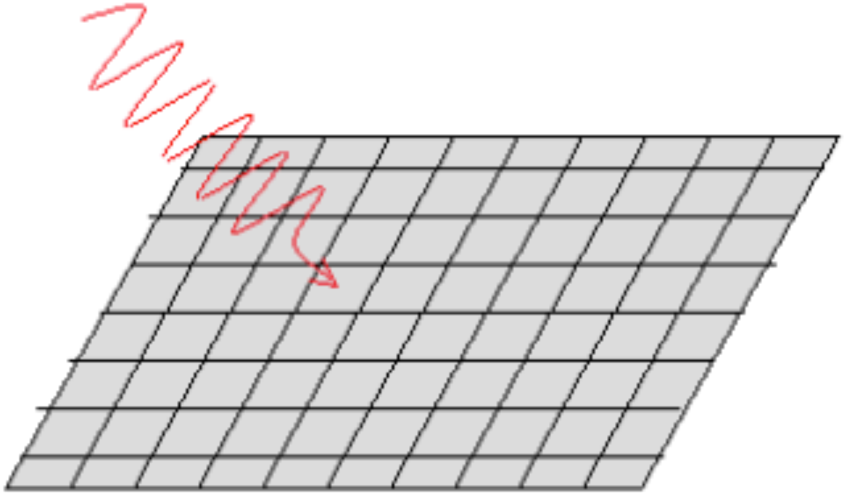


Instruments collect photons

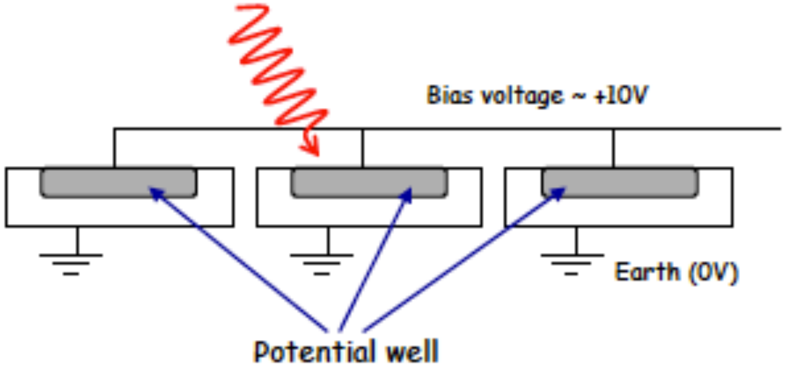
A CCD is a semiconductor array of light-sensitive pixels – typically about 20 μm across.

Image: direct 'map' of where photons arrive

Arrays of 10^7 pixels standard.

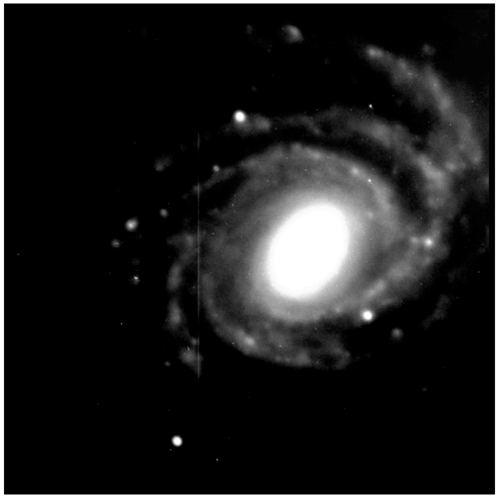


'State of the Art' – mosaics of CCDs, around 10^9 pixels in total

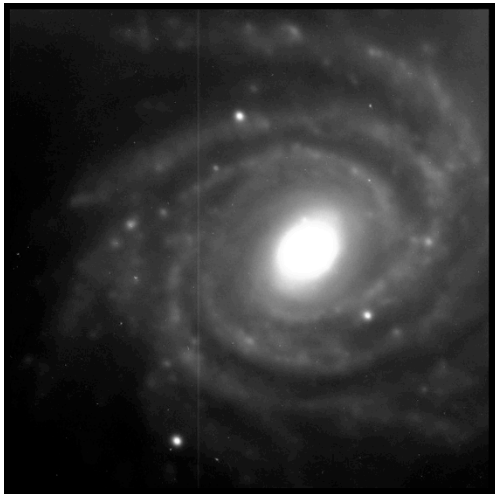


- Electron released when photon strikes semiconductor
- Bias voltage draws electron into potential well; stored there during exposure

So how do we see color?

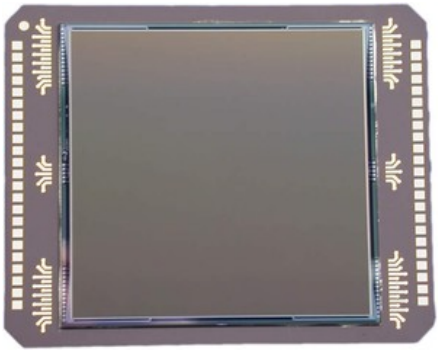


red light



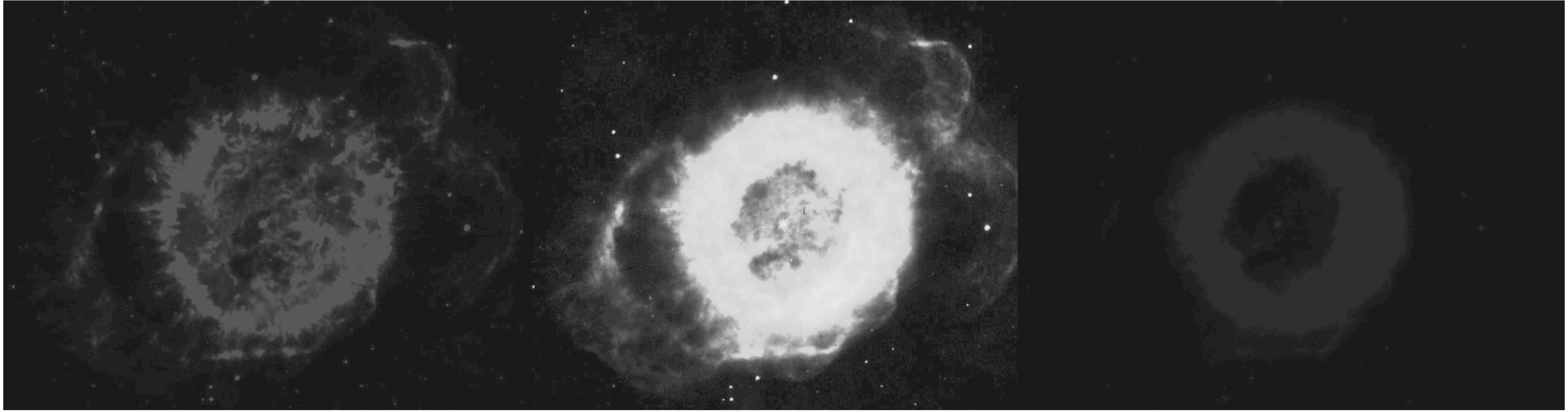
blue light

CCD



+ filters

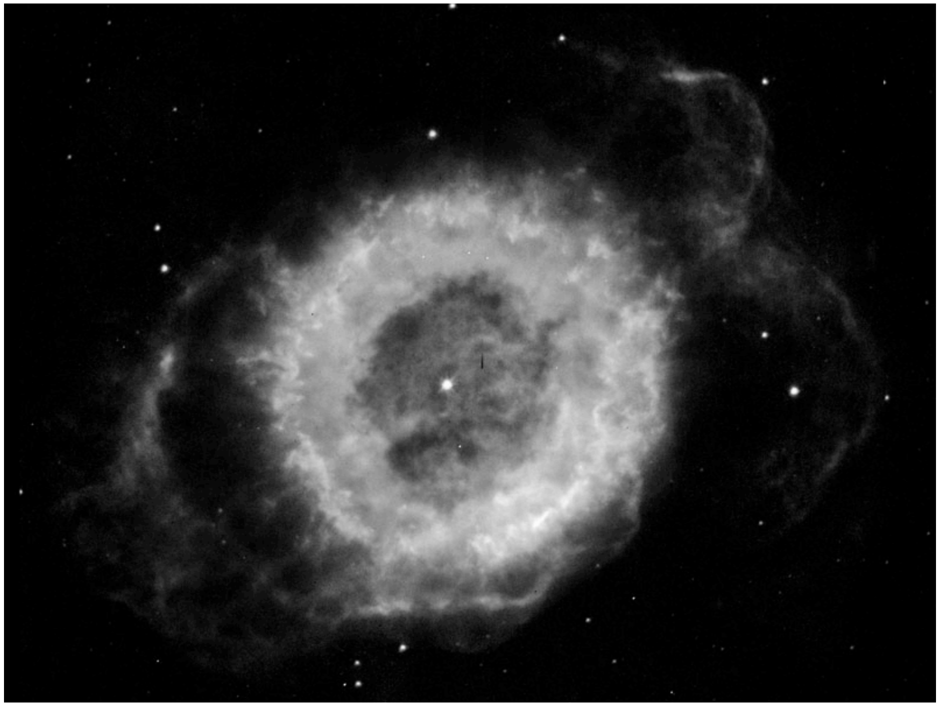
how do you get color pictures?

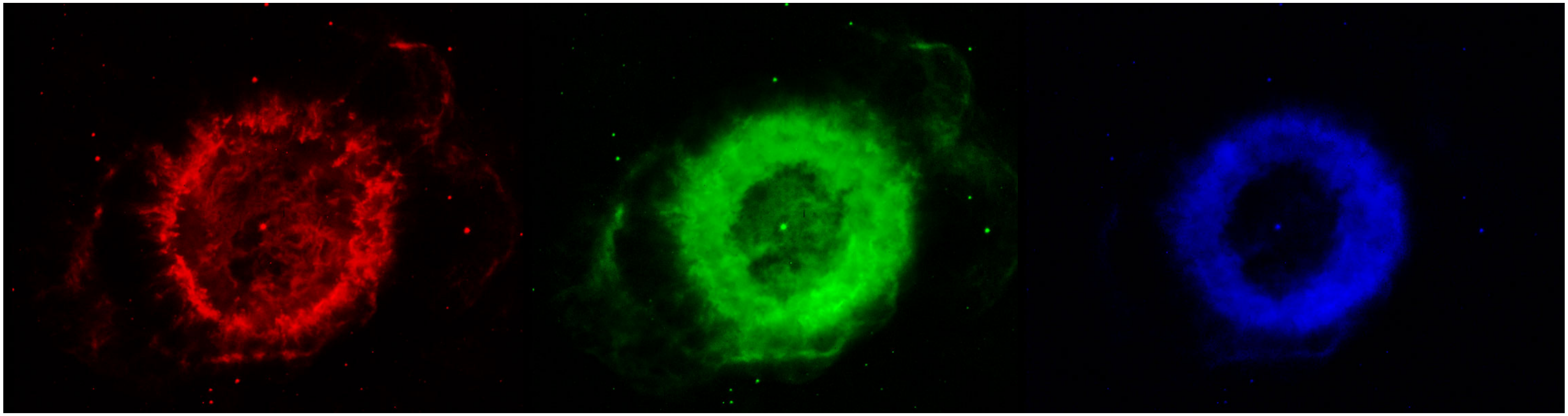


Red

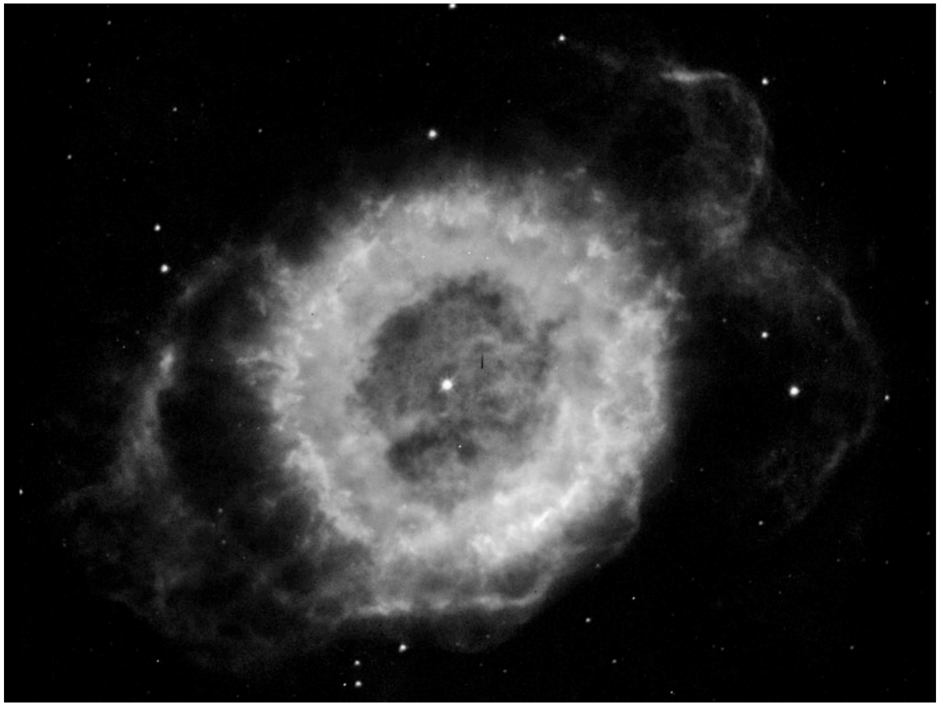
Green

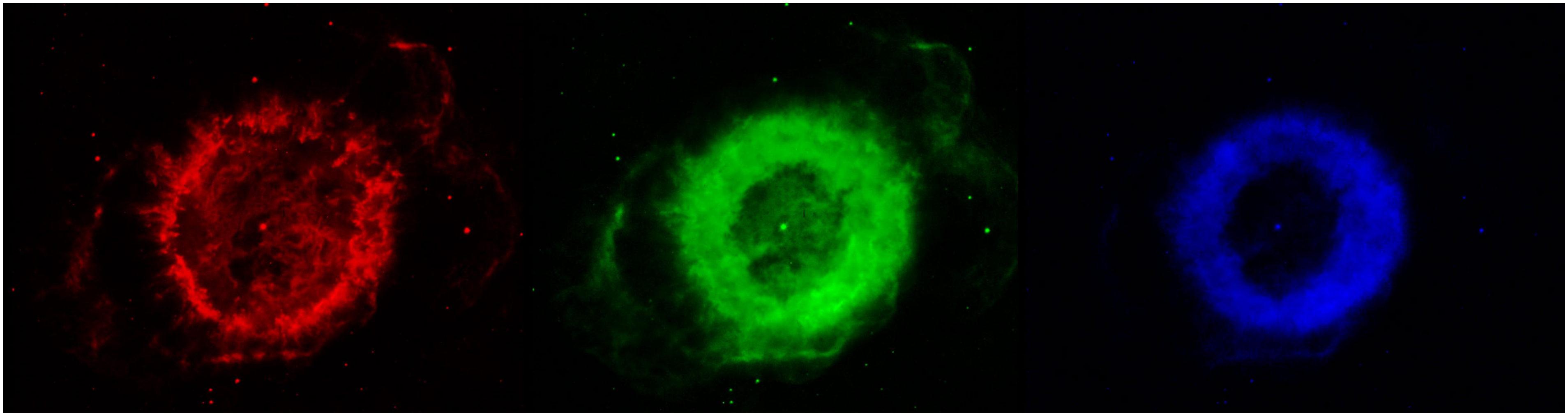
Blue



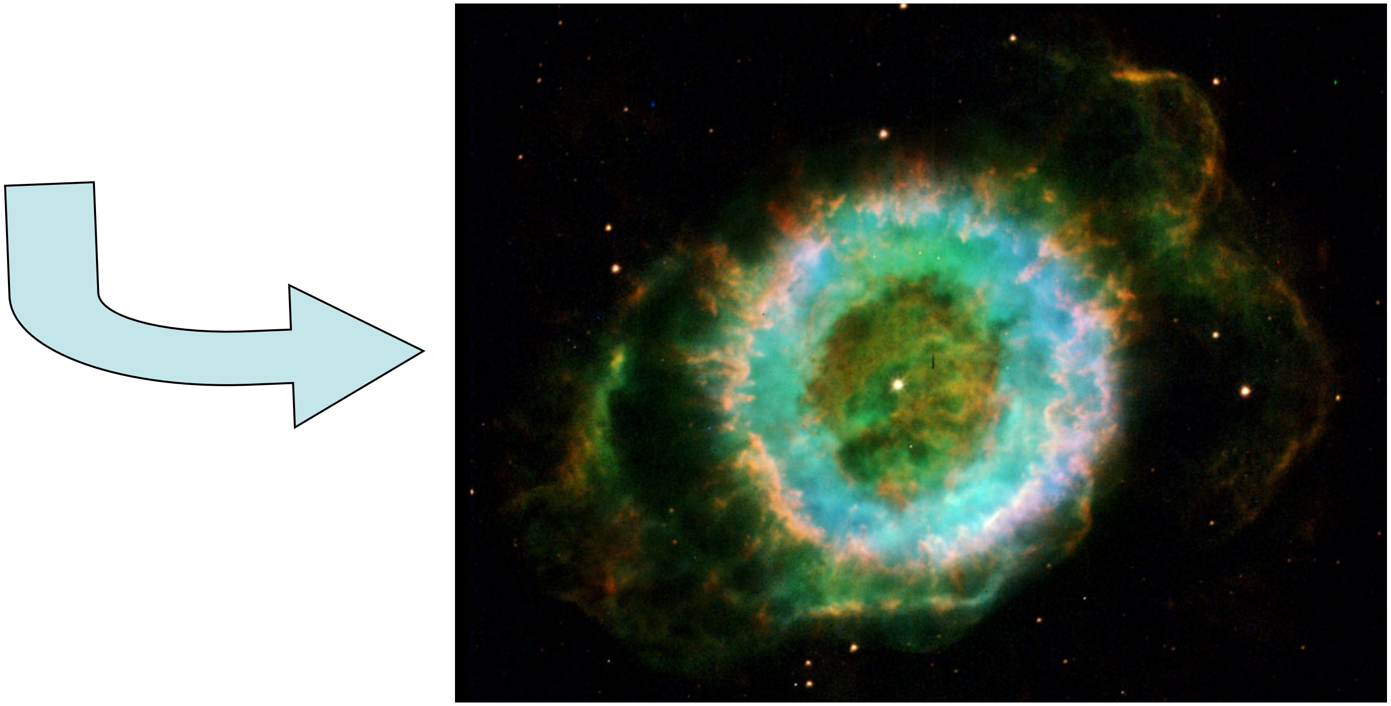


Red Green Blue





Red Green Blue



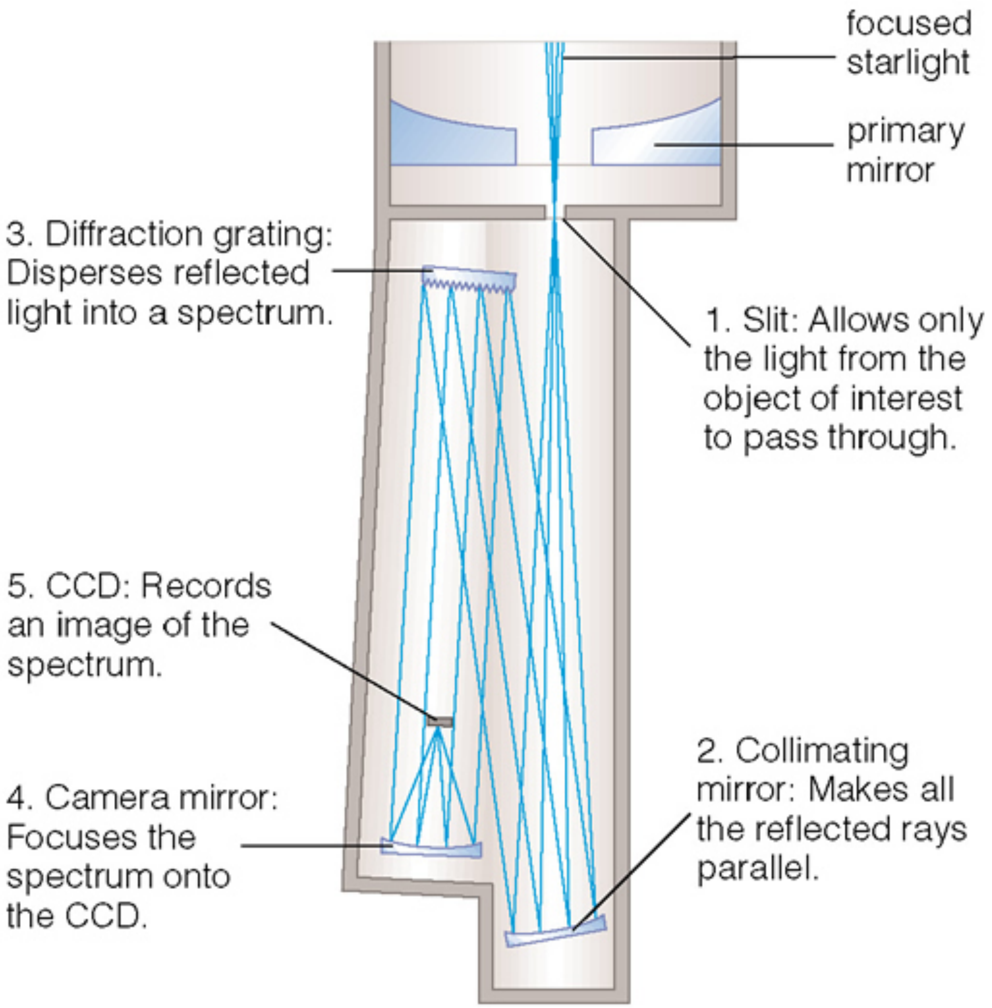
Imaging: A Primary Use of Telescopes

- use a camera to take pictures (images)
- Photometry → measure total amount of light from an object (apparent brightness) in a given wavelength band

Spectroscopy: The Other Primary Use of Telescopes

a spectrograph separates the light into its different wavelengths

Spectroscopy



- The spectrograph reflects light off a *grating*: a finely ruled, smooth surface
- Light interferes with itself and disperses into colors
- This *spectrum* is recorded by a digital CCD detector

Diffraction Grating: Dispersing the Light

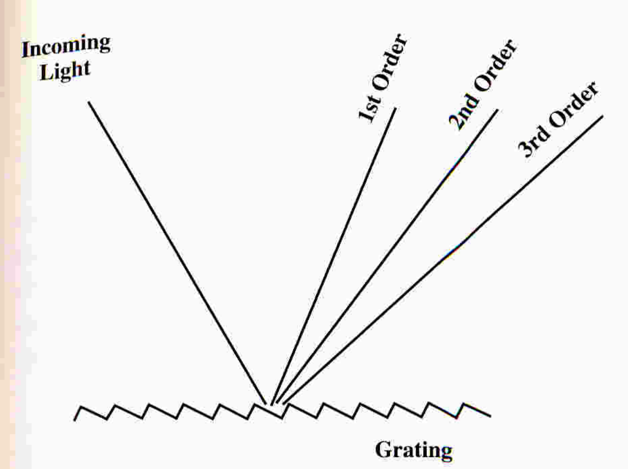
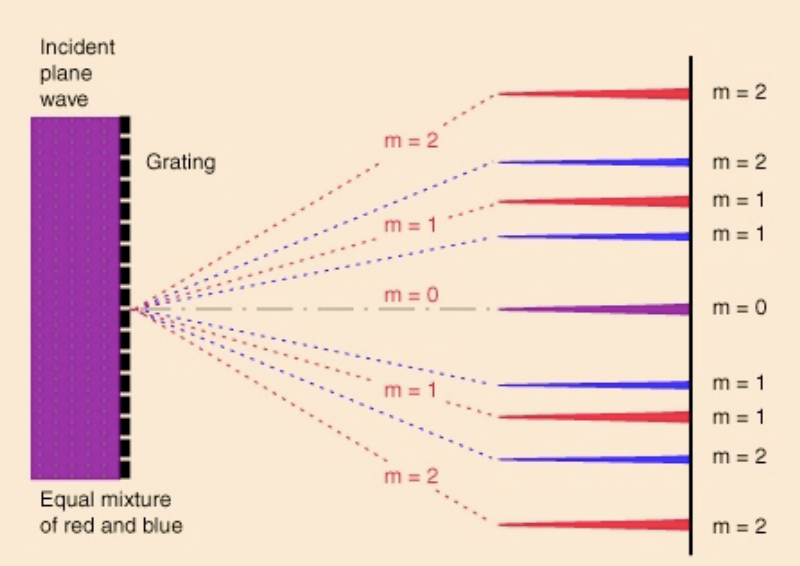


Fig 4.19. Diffraction grating. Light comes in from the upper left. The beam reflected off each step spreads out due to diffraction. However, interference effects result in maxima in the indicated directions. The angles of the steps can be adjusted (blazed) to throw most of the light into the desired order.

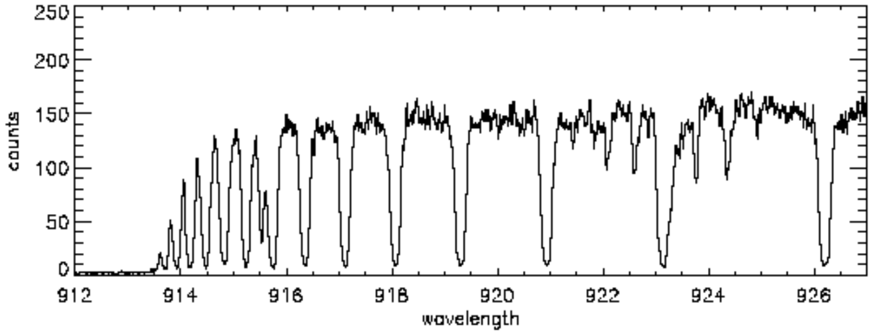


Maximum at angle sinθ = m λ / d

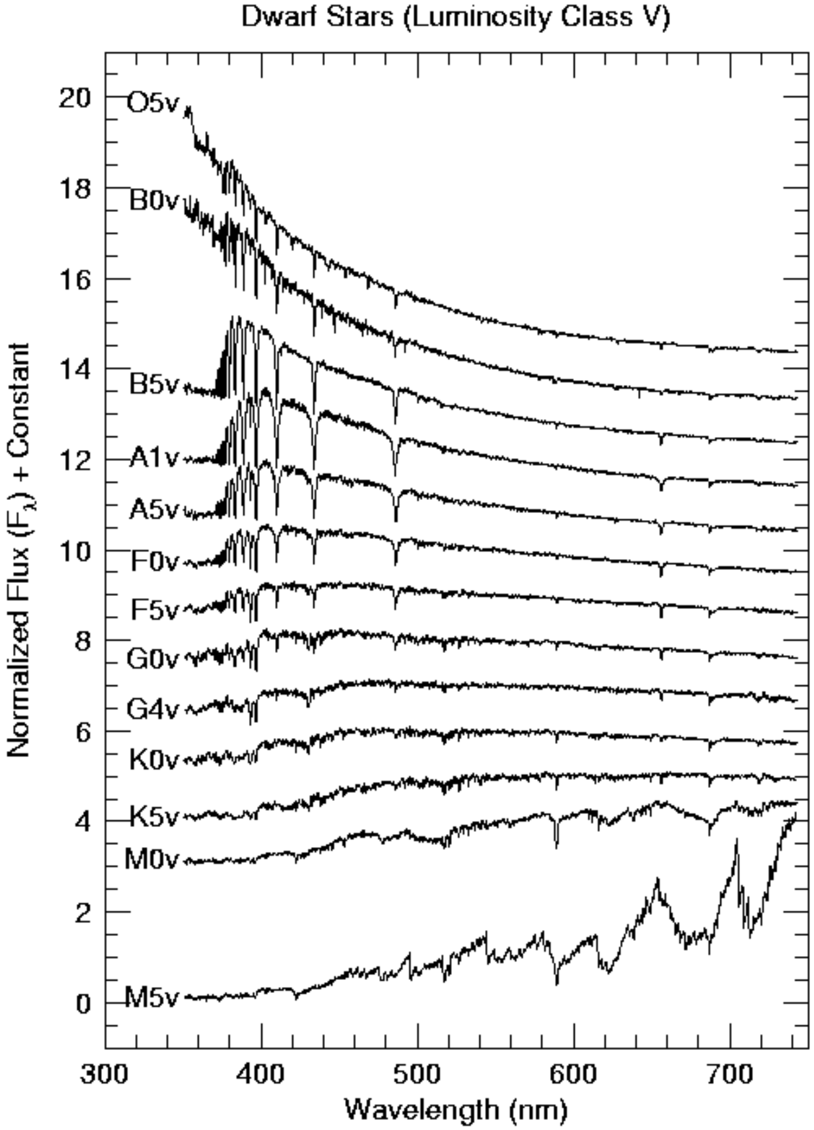
d = separation of slits or steps, m = order

Has the same effect as a prism, but technically better

Example of spectra

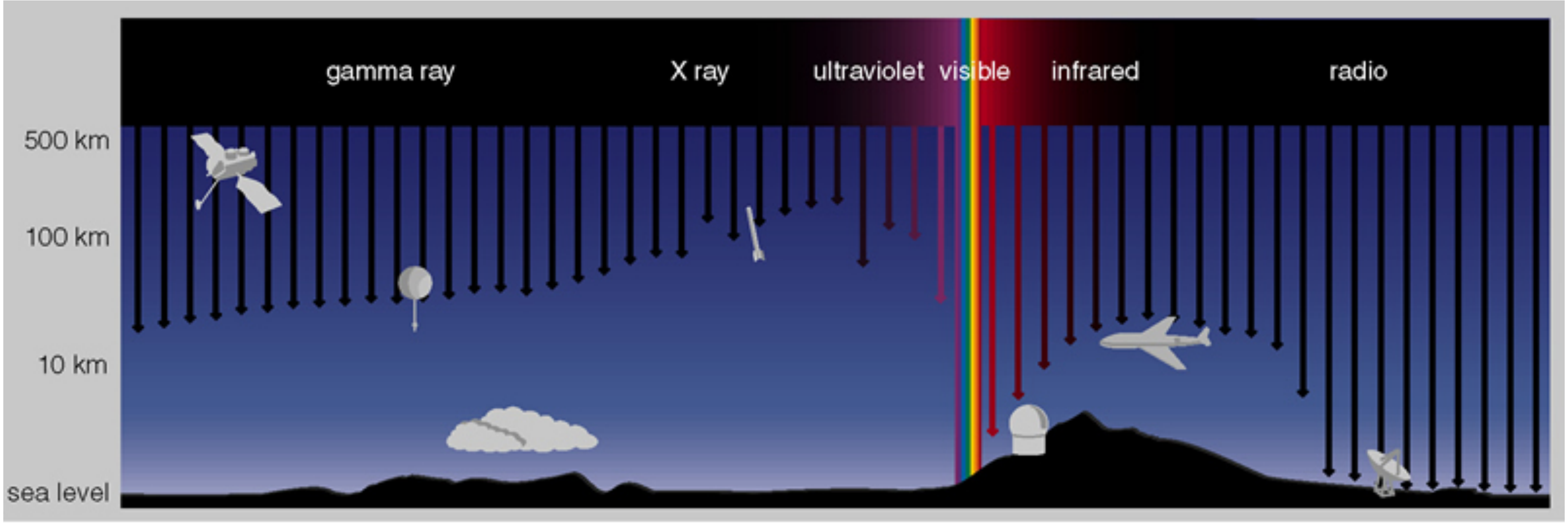


White Dwarf

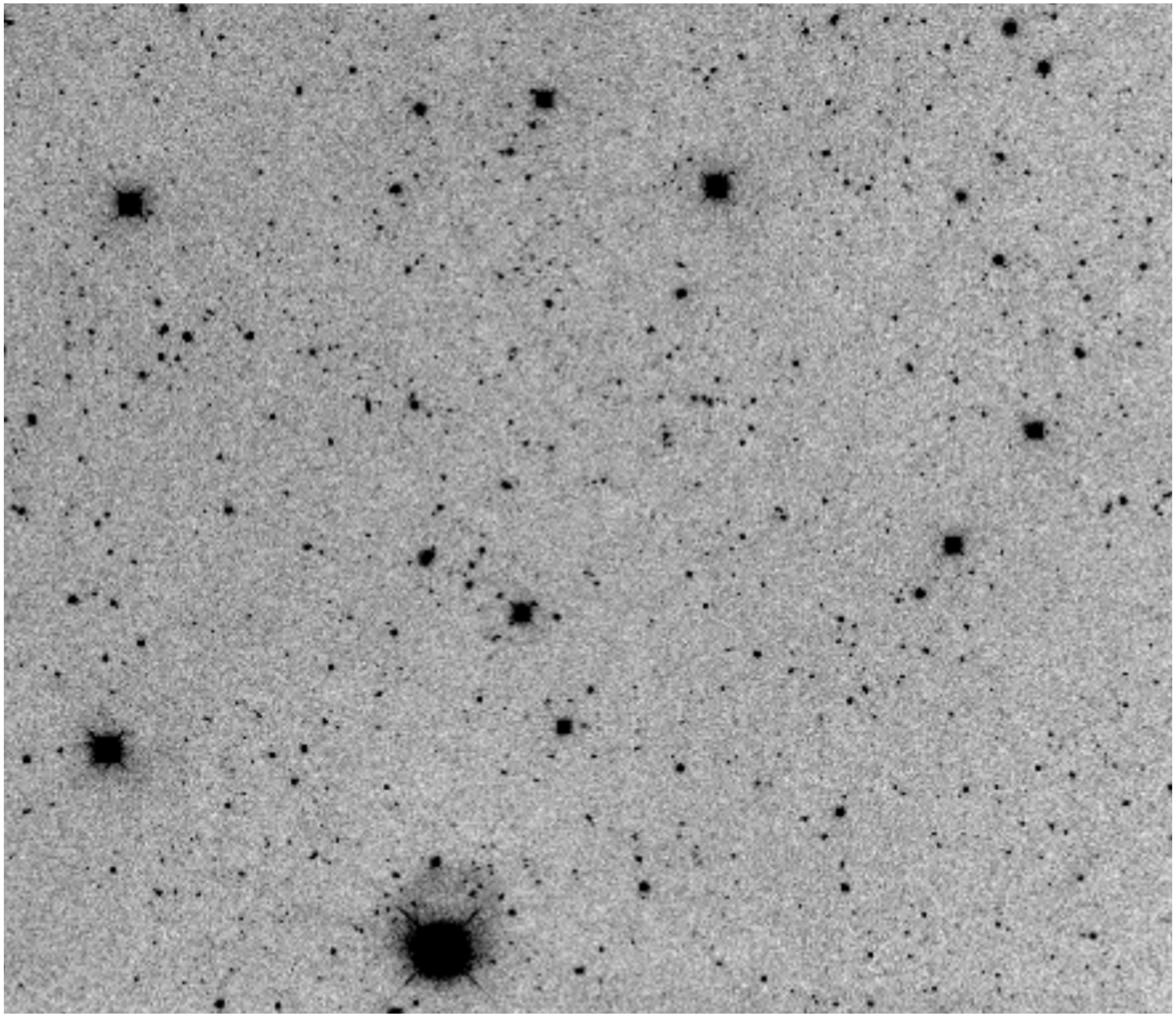


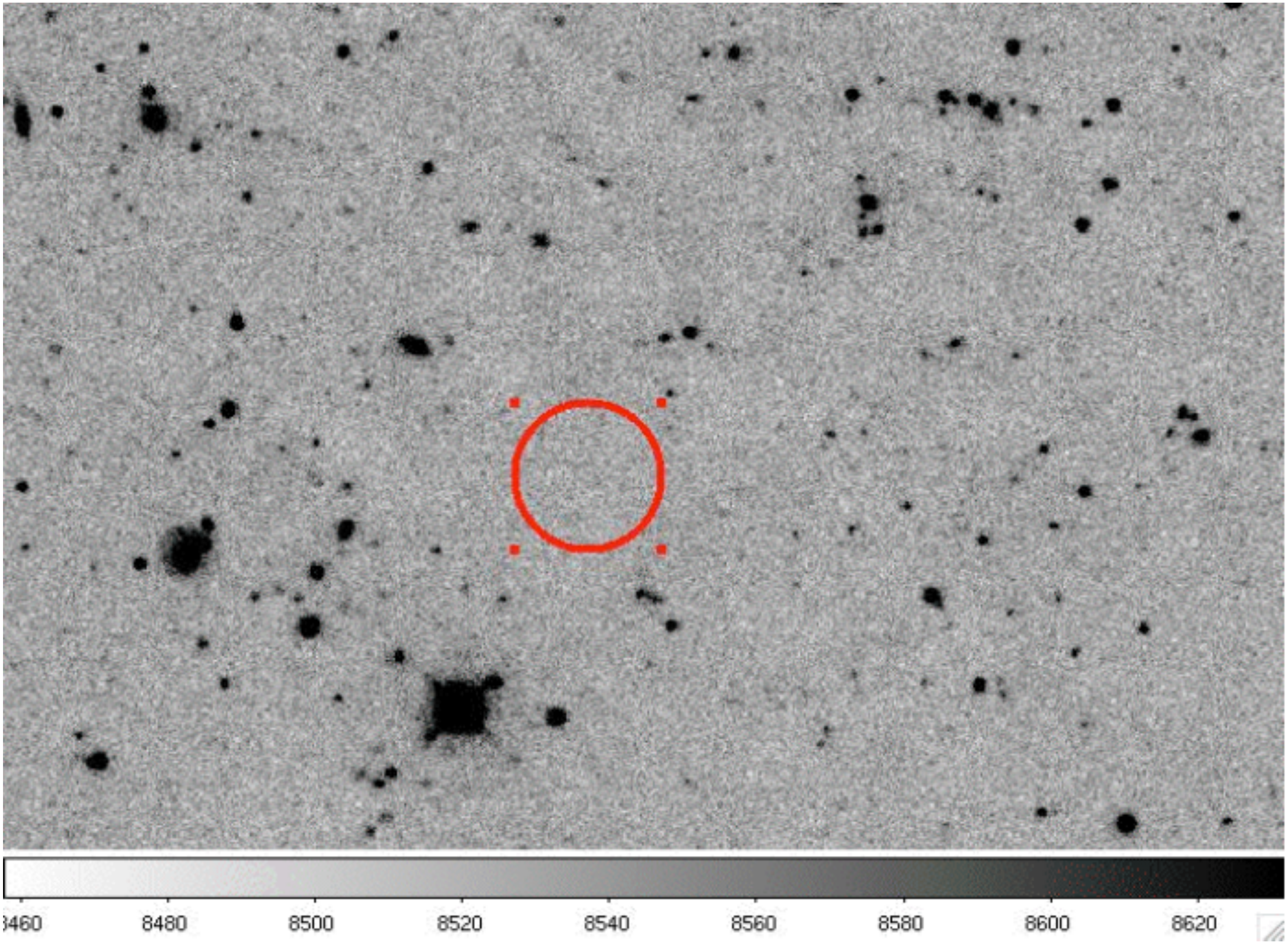
Atmospheric Absorption of Light

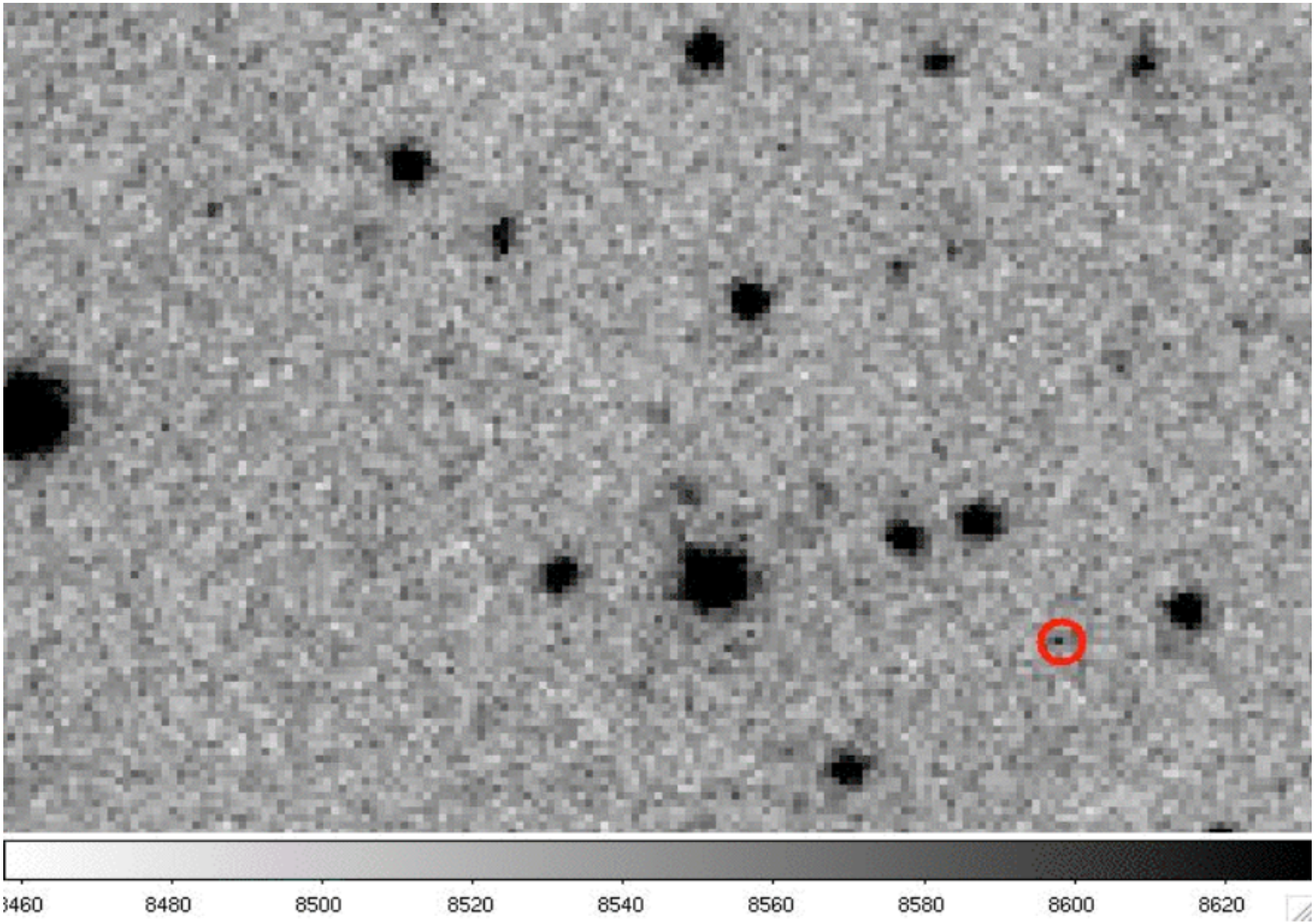
- Earth’s atmosphere absorbs most types of light
- Only visible, radio, and certain IR and UV light make it through to the ground
- To observe the other wavelengths, we must put our telescopes in space!



What about the light we see?




460
8480
8500
8520
8540
8560
8580
8600
8620


8460
8480
8500
8520
8540
8560
8580
8600
8620

From image to catalog

$$S/N = \frac{R_* \times t}{[(R_* \times t) + (R_{sky} \times t \times n_{\mathrm{pix}}) + (RN^2 + (\frac{\mathcal{G}}{2})^2 \times n_{\mathrm{pix}}) + (D \times n_{\mathrm{pix}} \times t)]^{1/2}}$$

$$\begin{aligned}
m \pm \sigma(m) &= C_0 - 2.5\log(S \pm N) \\
&= C_0 - 2.5\log[S(1 \pm \tfrac{N}{S})] \\
&= C_0 - 2.5\log(S) - 2.5\log(1 + \tfrac{N}{S}) \\
\sigma(m) &= \pm 2.5\log(1 + \tfrac{1}{S/N})
\end{aligned}$$

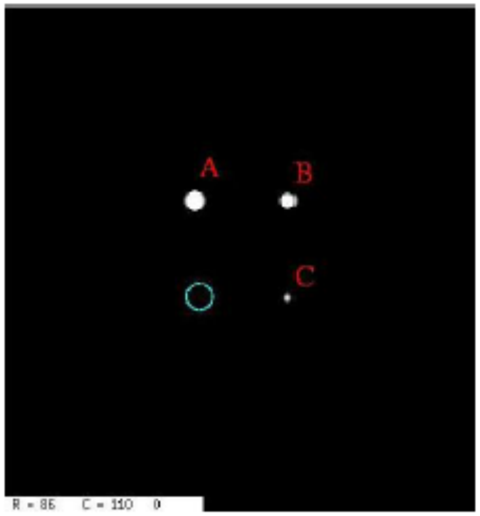
An example : Michael Richmond (Creative Commons License)

S/N typical astro-situation. Three stars with FWHM of 3 pixels.

bright (A), with peak value 8000 counts, total 80,800 counts

intermediate (B), with peak value 800 counts, total 8,080 counts

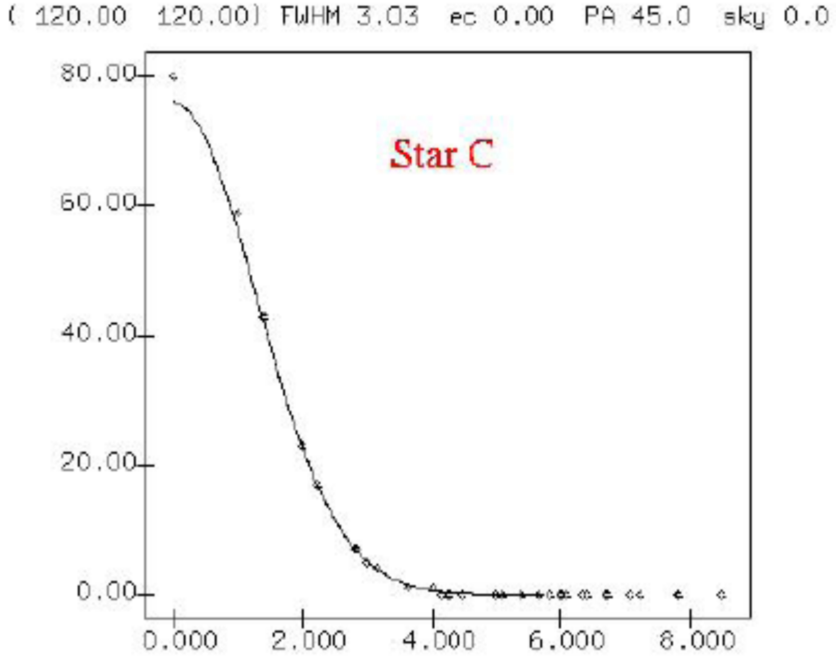
faint (C), with peak value 80 counts, total 808 counts



For simplicity, gain of 1 e/ADU. Aperture of radius **5** pixels, circle in the figure, to measure the light from each star. There are $\pi \cdot 5 \cdot 5 = 79$ pixels inside the aperture.

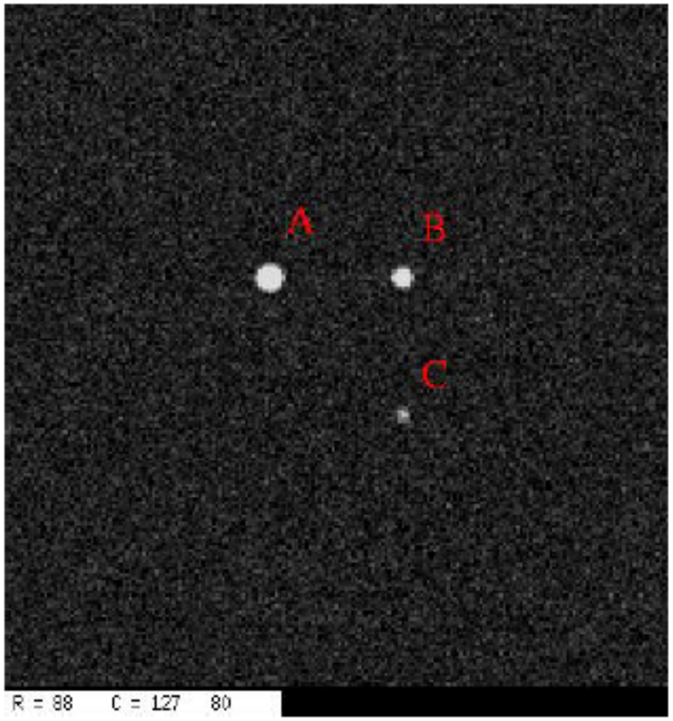
Bright stars: shot-noise limited

Suppose that the sky is very dark and the CCD's amplifier is nearly perfect; then light from the stars is the dominant source of both signal and noise. Even the faint star "C" shows up perfectly above its surroundings

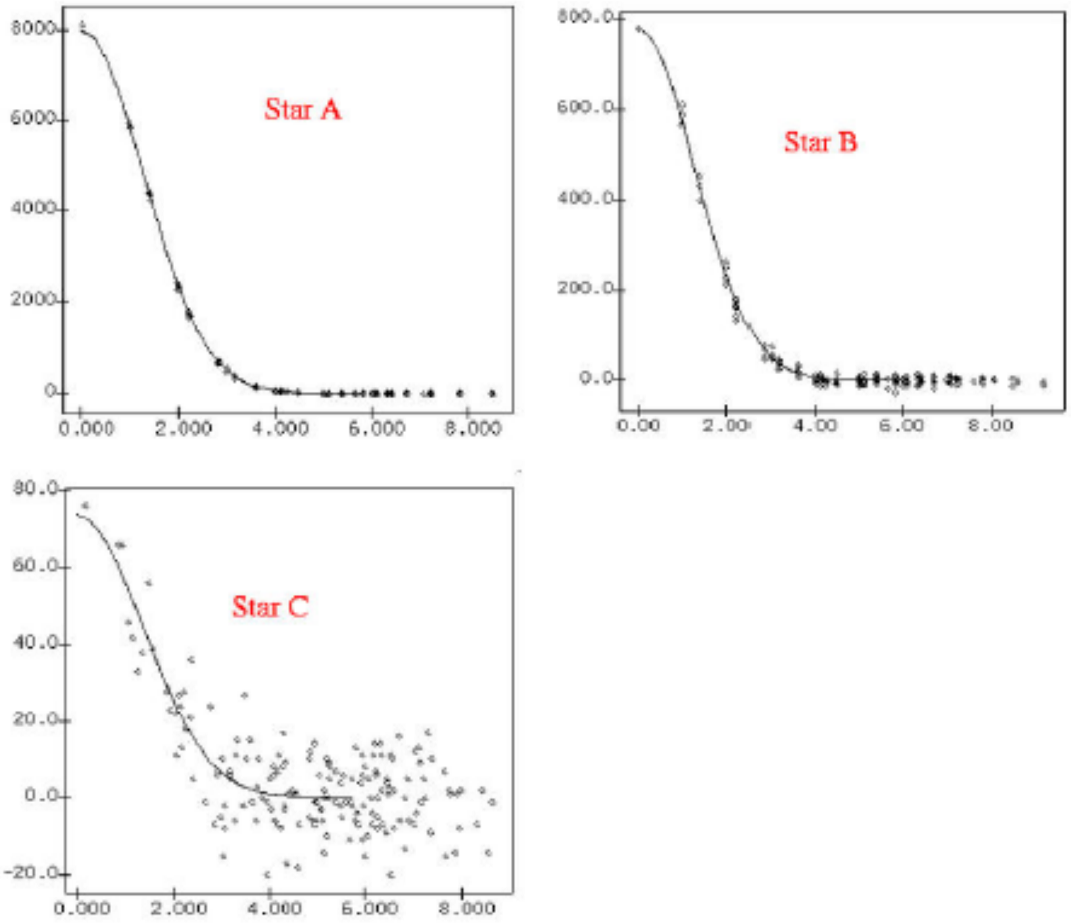


As the sky gets brighter ...

Now, let's increase the sky background from zero to a moderate value: 64 counts per pixel. An image of the field now shows mottling of the background, due to random fluctuations in the sky level from pixel to pixel.

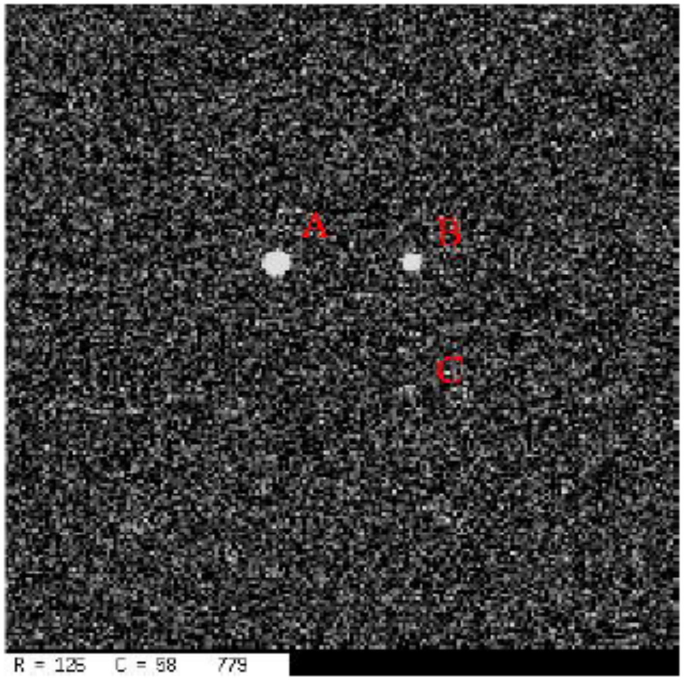


Radial profiles of the fainter stars show the noise in the background.

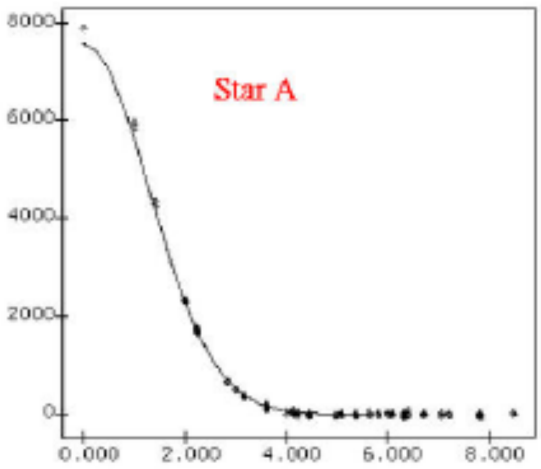


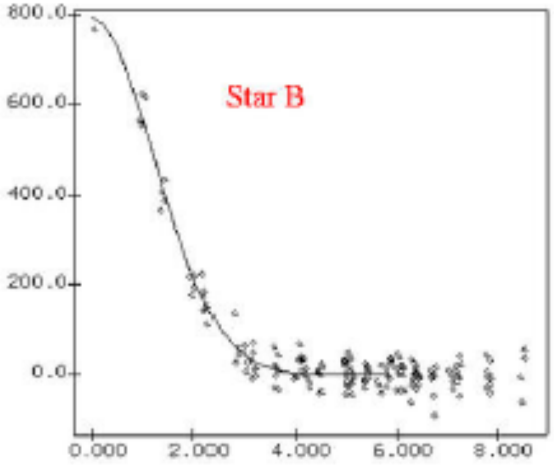
Bright sky: background-limited

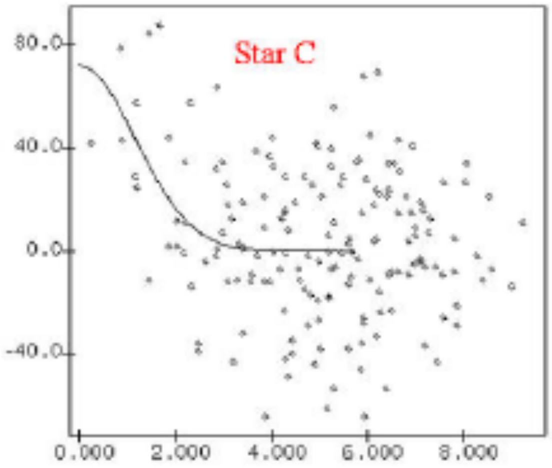
What if the sky is very bright compared to one's target object? That is, what if the sky background contributes many more electrons to a pixel than the star? Let's increase the average sky level in the simulation to 800 electrons.



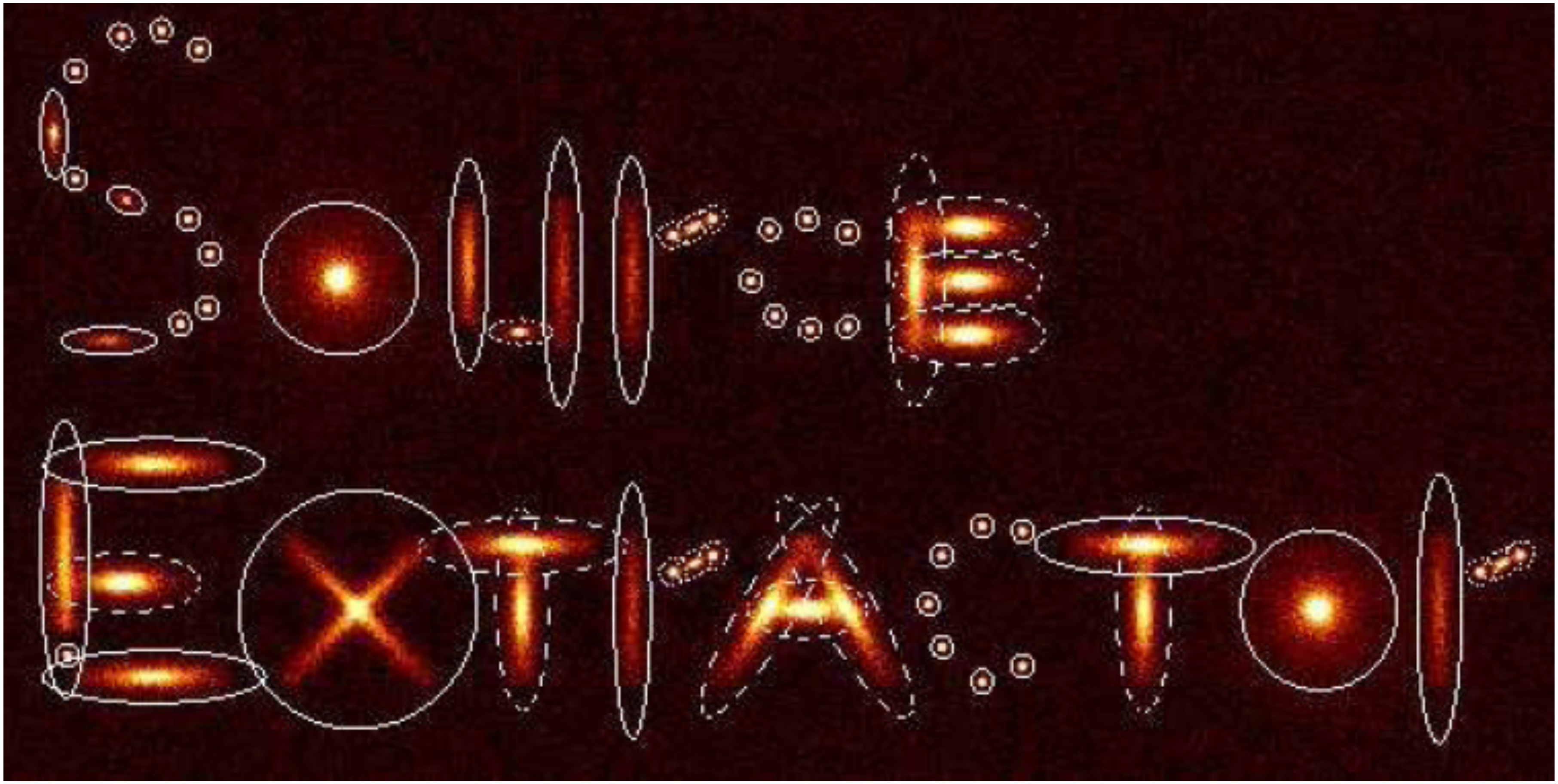
Radial profiles show the background now swamping the faint star "C"



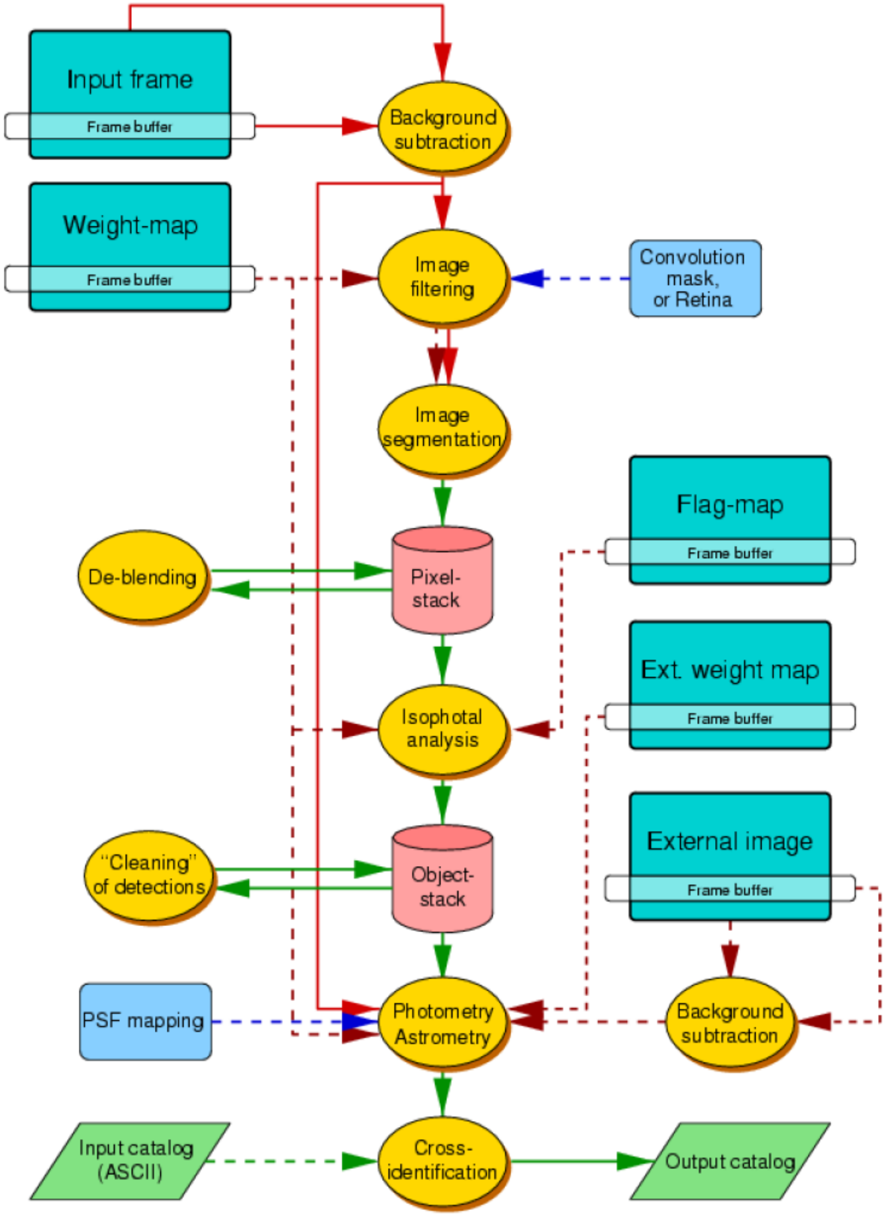




Source Catalog Creation: in practice

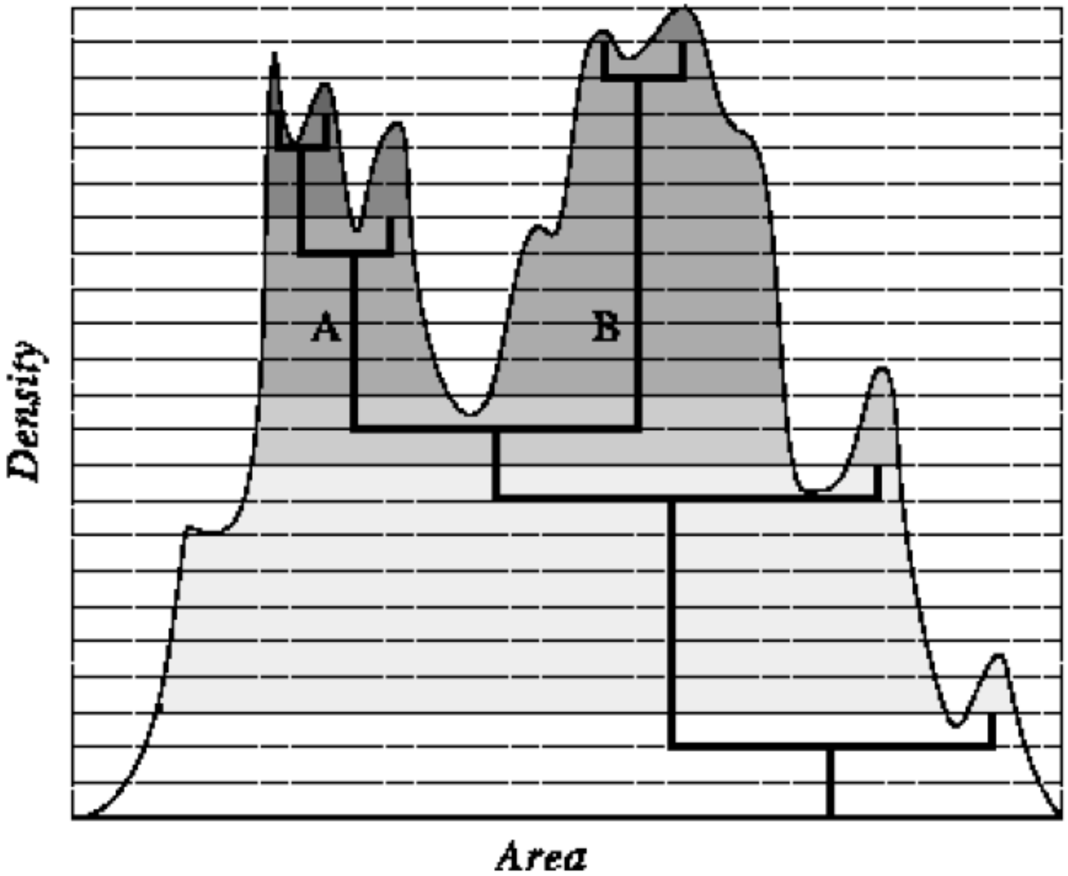


Bertin; Holwerda

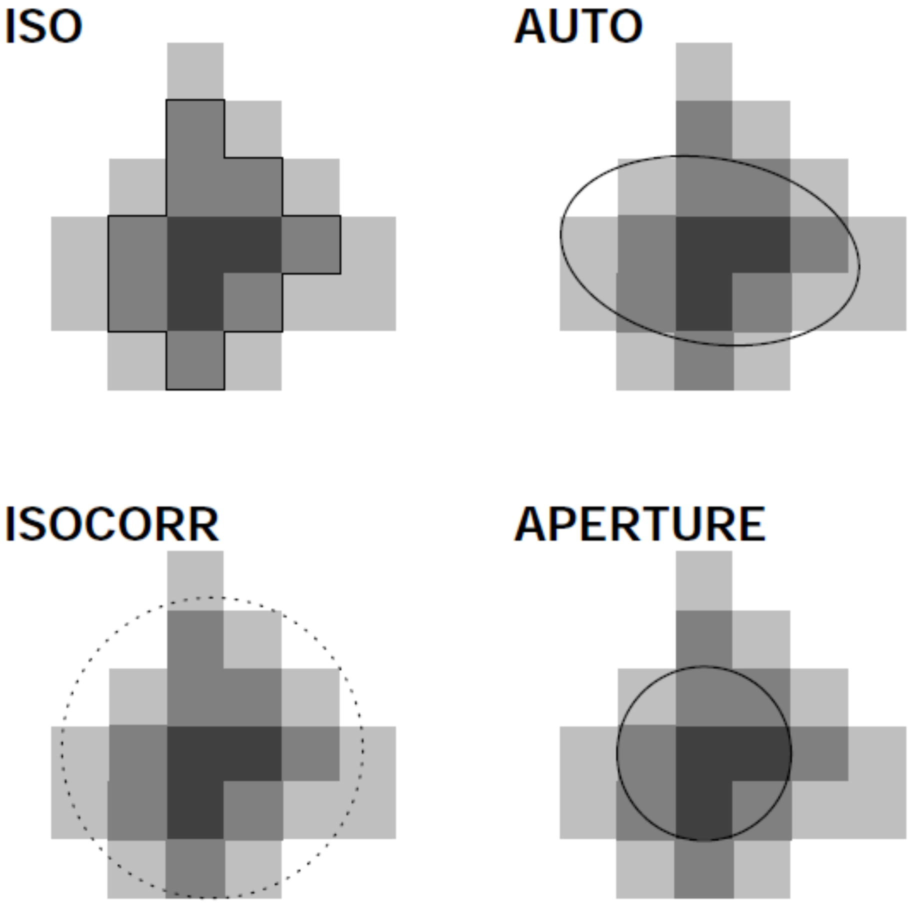


Source finding is hard and complicated

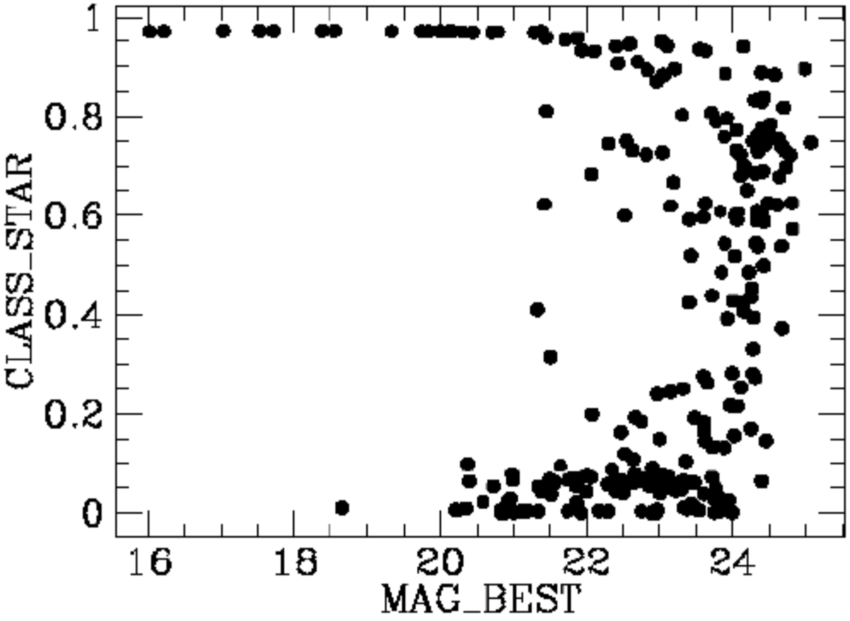
Defining parents and their children



Choosing apertures



Separating stars and galaxies



What do we do with the data?

- We use it to test models, make inferences about parameters.
- We need good data analysis methods to make this process:

objective	*same data, same analysis method ⇒ same results*
quantitative	*our data analysis should yield 'hard numbers' + uncertainties*
reliable	*not good if parameter estimates very sensitive to our assumptions; estimated uncertainties should be realistic*
informative	*we want to constrain physically meaningful parameters;* *our data analysis should help us understand "what is going on"*
predictive.	*the results of our data analysis should help us to make predictions with our models: i.e. future observations that could be made to better test the models.*