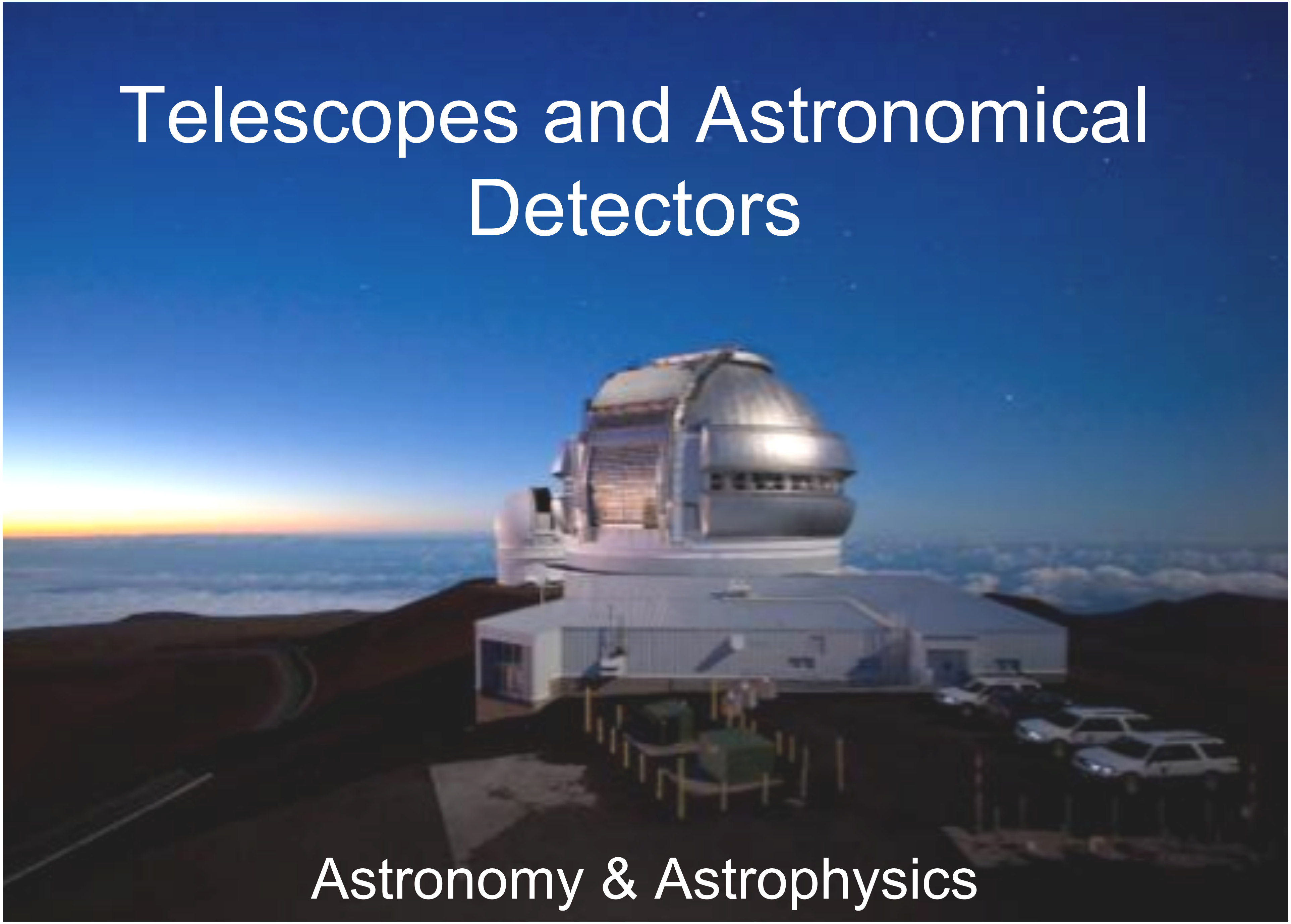
Telescopes and Astronomical Detectors



Astronomy & Astrophysics

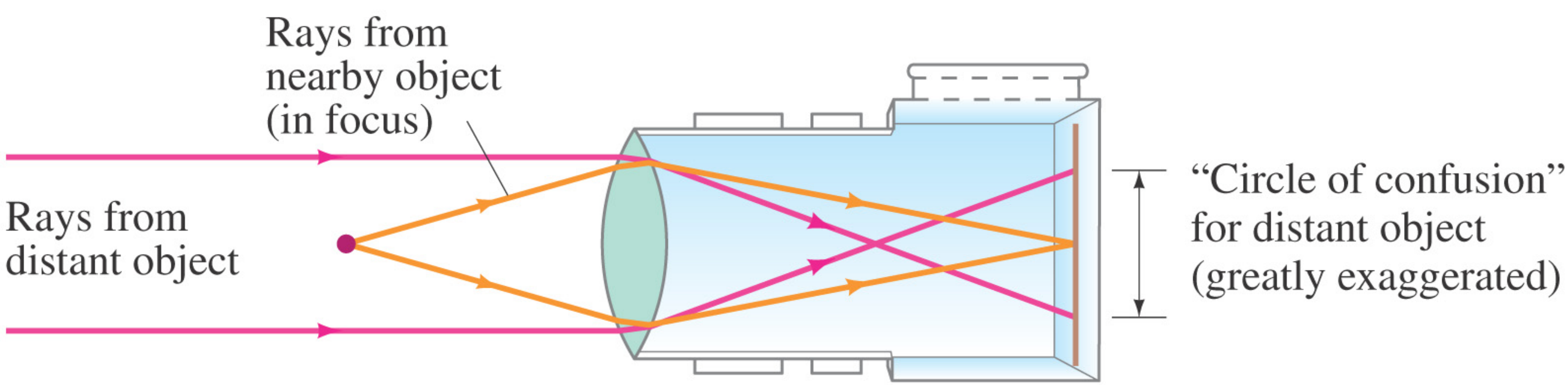
Telescopes & Detectors

- Telescope Collects and Focuses photons
- Detector Record incident photons that have been captured by the telescope.
- Intensity, Phase, Frequency, Polarization
- Difficulty of getting these 4 depends on wavelength regime.
- For now focus on nIR, Optical, UV, soft X-ray (below ~10 KeV)
- Telescope/Camera/Spectrograph sort out all but the intensity*, leaving the job of counting photons and registering their location.

*In x-ray usage the photon energy is also estimated

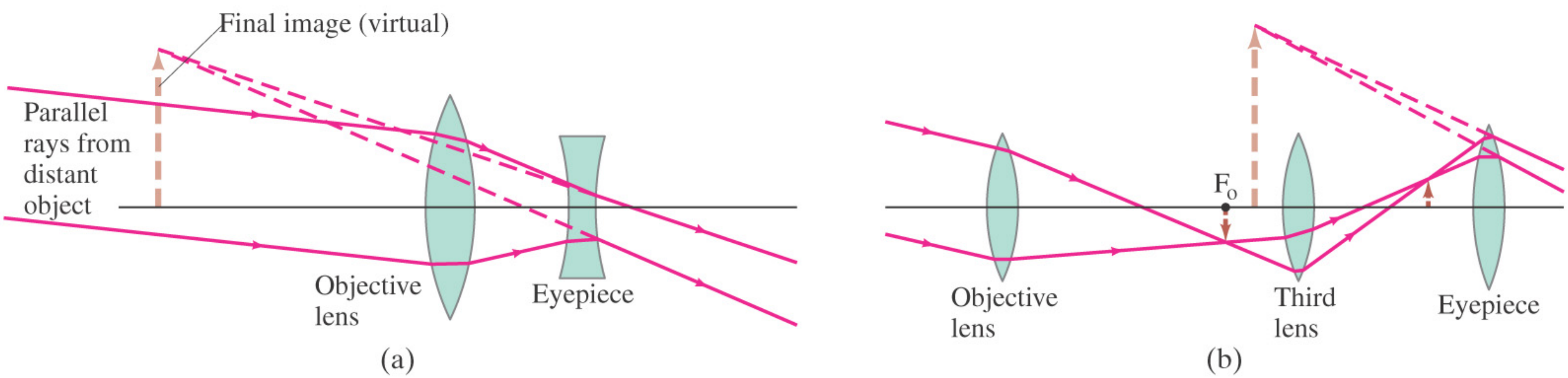
Cameras, Film, and Digital

There is a certain range of distances over which objects will be in focus; this is called the depth of field of the lens. Objects closer or farther will be blurred.



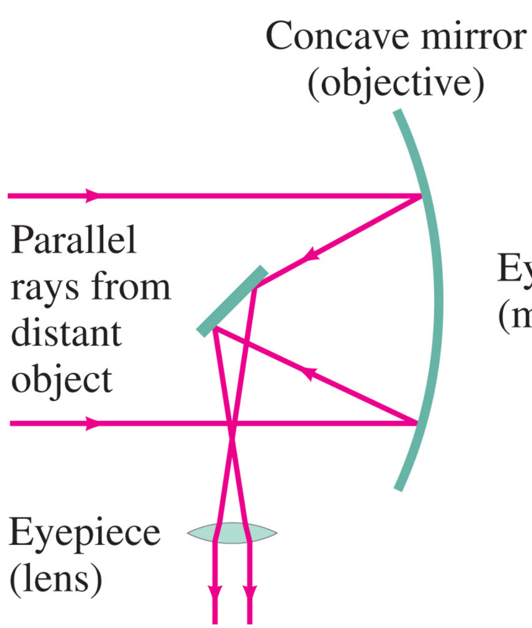
Refracting Telescopes

- Refractors consist of an objective lens and an eyepiece lens.
- Naturally produce upside down images
- A terrestrial telescope, used for viewing objects on Earth, should produce an upright image.
- Here are two models, a Galilean type and a spyglass:

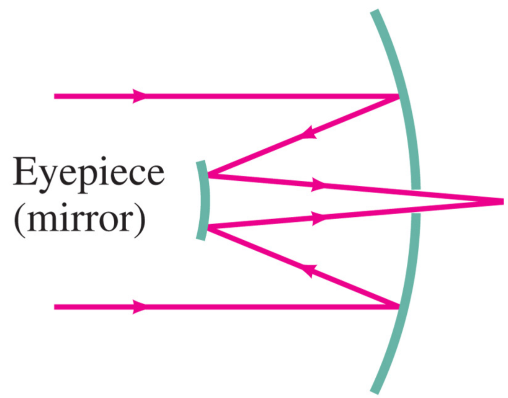


Reflecting Telescopes

- Astronomical telescopes need to gather as much light as possible.
- And obtain the sharpest view possible.
- The objective must be as large as possible.
- Mirrors are now used instead of lenses, as they can be made much larger.
- Mirrors focus all wavelengths of light equally (no chromatic aberration)



Newtonian

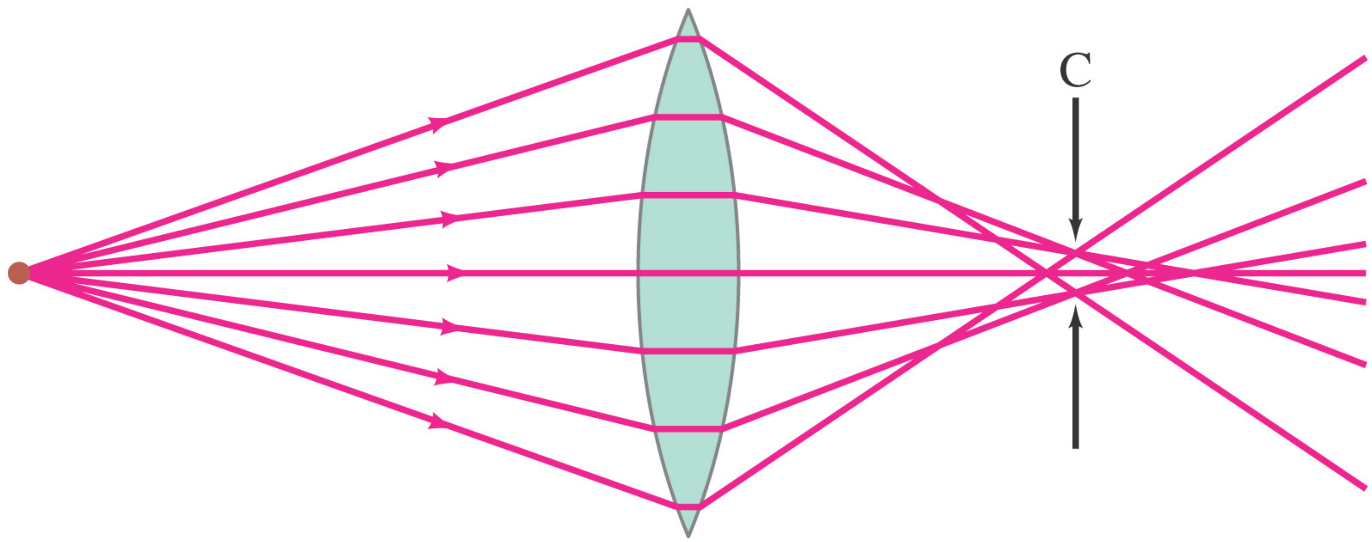


Cassegrain

$$M = \frac{\theta'}{\theta} = \frac{(h/f_e)}{(h/f_o)} = -\frac{f_o}{f_e}$$

Spherical Aberrations of Lenses

Spherical aberration: rays far from the lens axis do not focus at the focal point.



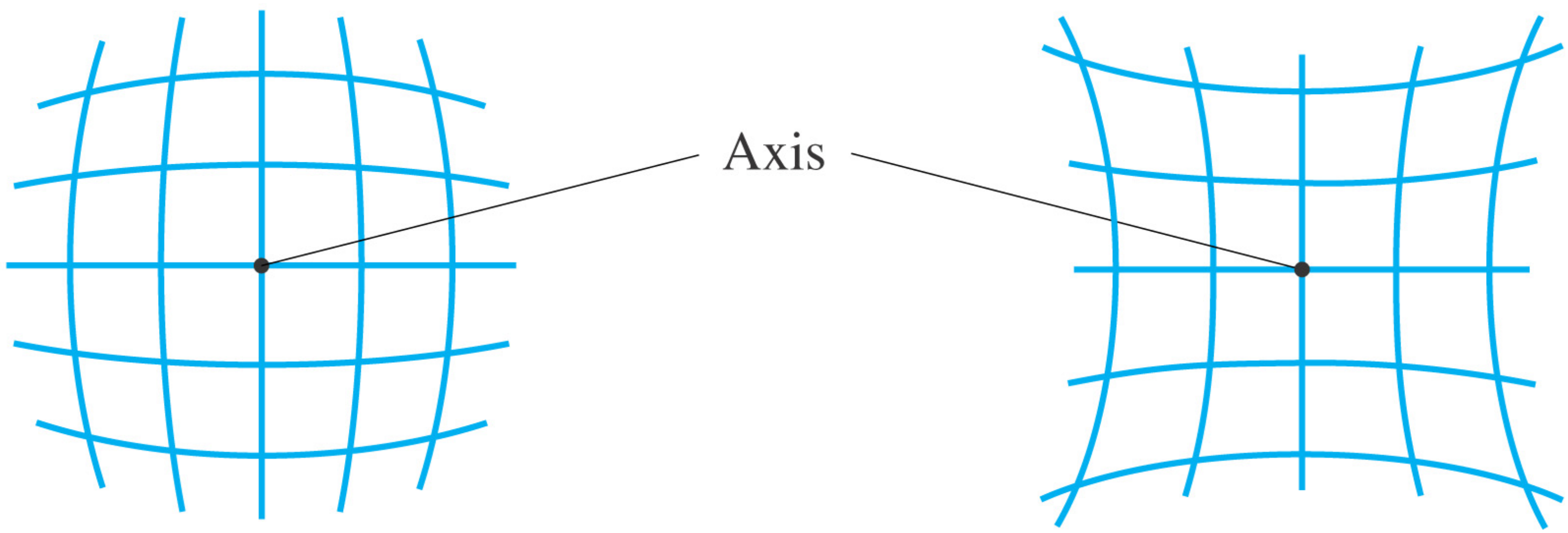
Solutions: compound-lens systems (camera lenses can have > 15 elements!)

use only central part of lens (e.g. by stopping it down)

Aspherical lens surfaces (expensive to produce)

Aberrations of Lenses and Mirrors

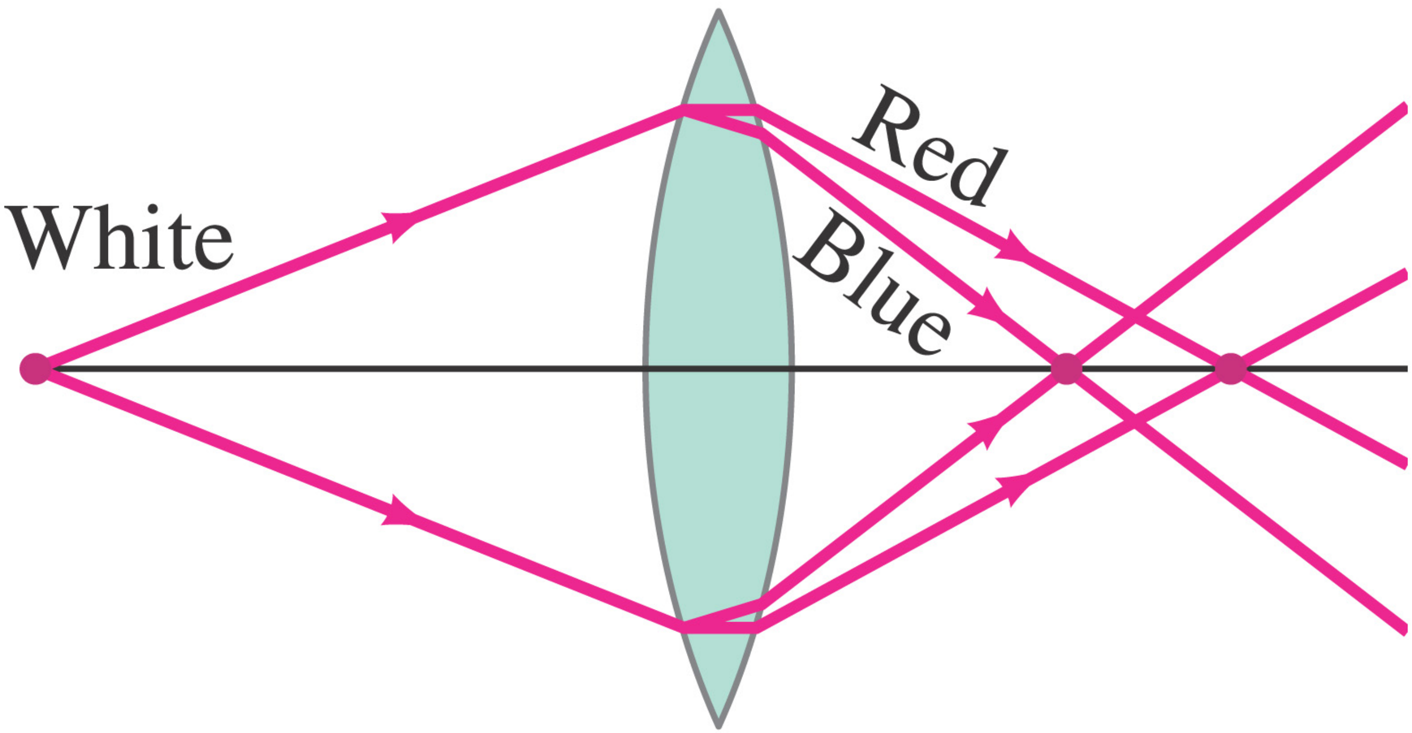
Geometric Distortion: caused by variation in magnification with distance from the lens. Barrel and pincushion distortion:



Solutions: multiple elements, aspheric curves, stopping down, image processing

Chromatic Aberration

Light of different wavelengths has different indices of refraction and focuses at different points



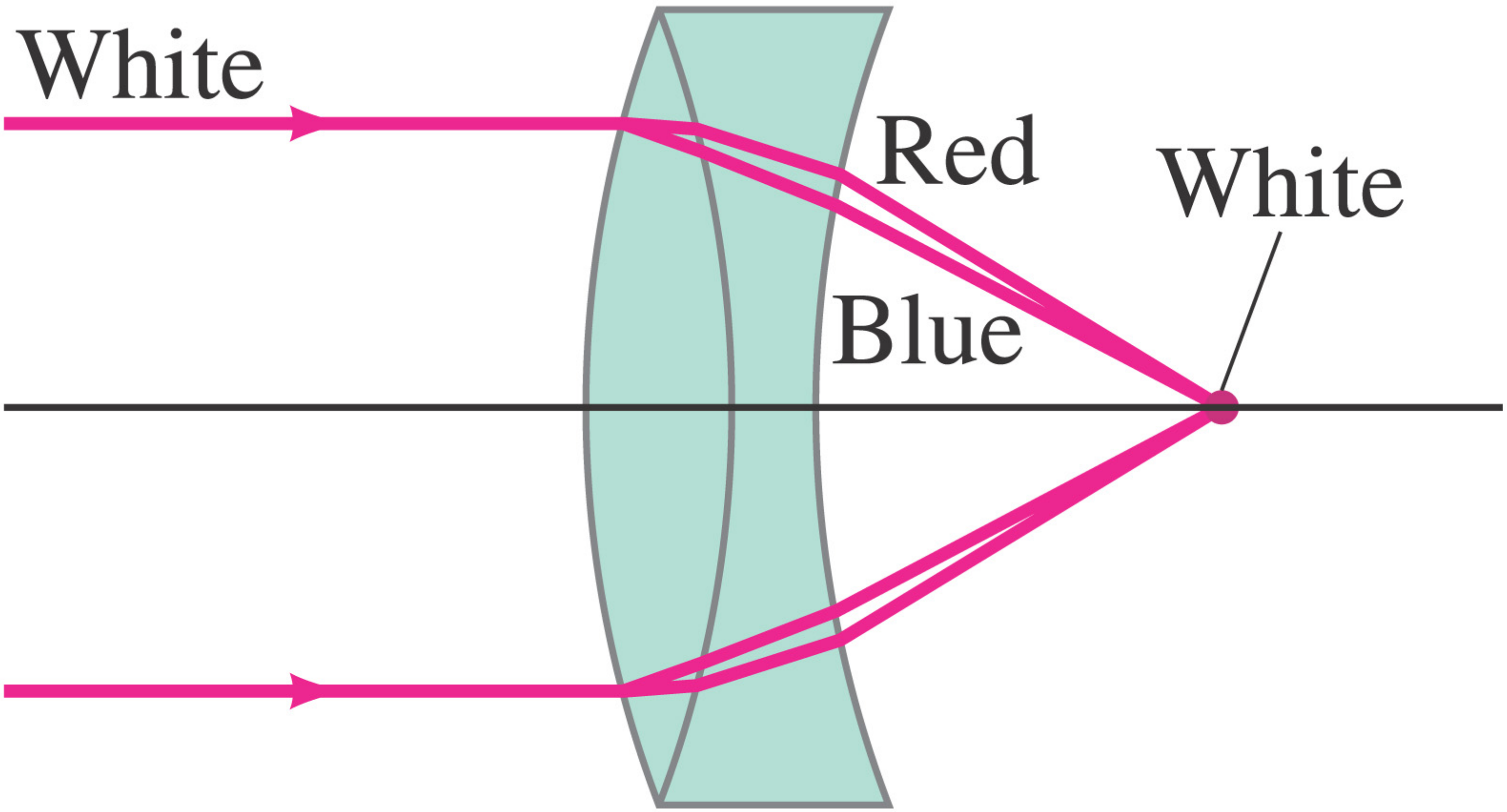
Solutions: Use only the center, stop down, use very long focal length, use colored filters, use multiple lenses

The Achromatic Doublet

• Achromatic doublet is a lens made of two lenses of different glass types that have different amounts of dispersion.

• Usually a Strong Converging lens made from a low dispersion glass, is glued to a Weaker Diverging lens (made from a higher dispersion glass)

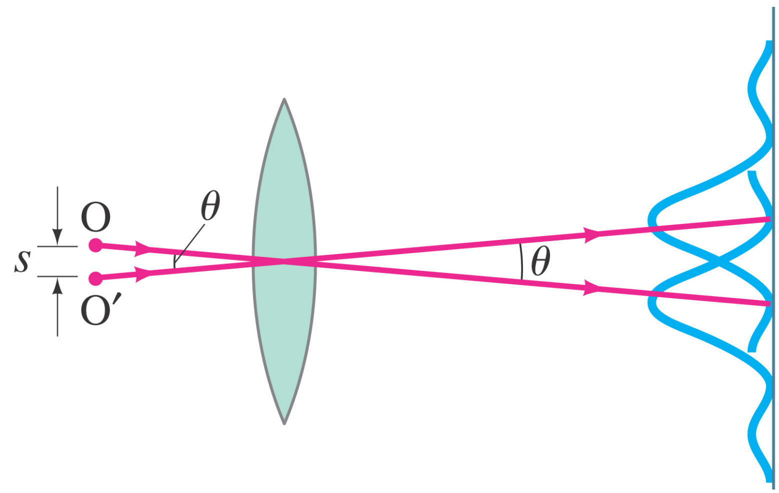
• The space between can be filled with glue, or oil.



• Anti-reflection coatings are required to prevent “ghost” images forming

Rayleigh Criterion, or the Diffraction Limit

The Rayleigh criterion states that two images are just resolvable when the center of one peak is over the first minimum of the other.



• The chief practical implication of Rayleigh's Criterion, is that ANY optical device (eye, camera, telescope, radio-telescope etc) cannot resolve details finer than θ (in radians) = $1.22\lambda/D$. Where D is the diameter (in meters) of the objective lens or mirror, and λ the wavelength (in meters) of the light in question.

• Similarly, light emitted from an aperture D will spread out with this angle (θ), due to diffraction. Even if the light rays start out perfectly parallel!

• Thus, the Wider the Aperture, the Sharper the Image. Remember this!

Light as a Wave

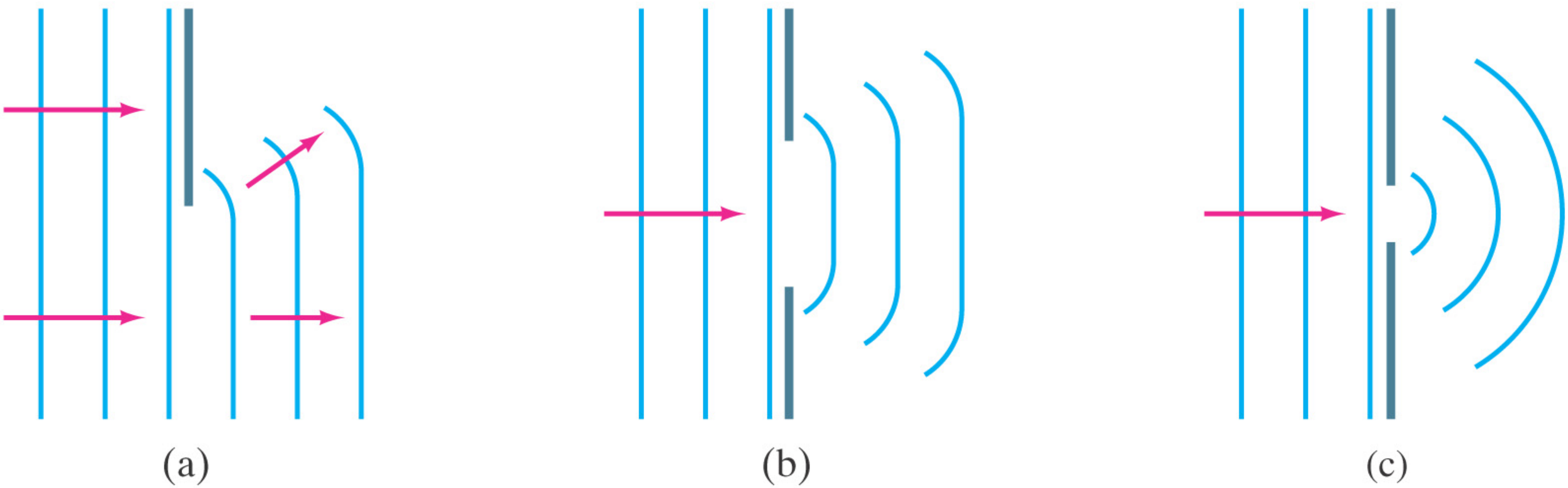
If Light is an electromagnetic wave, lets start by looking at how waves behave.

Ocean Waves entering a Cove

- Where the long ocean waves enter the opening of the cove, they spread out in rings, as if from a point.
- This phenomenon is called Diffraction
- Exactly the same thing happens to sound, and EM waves (light, radio, X-rays etc)

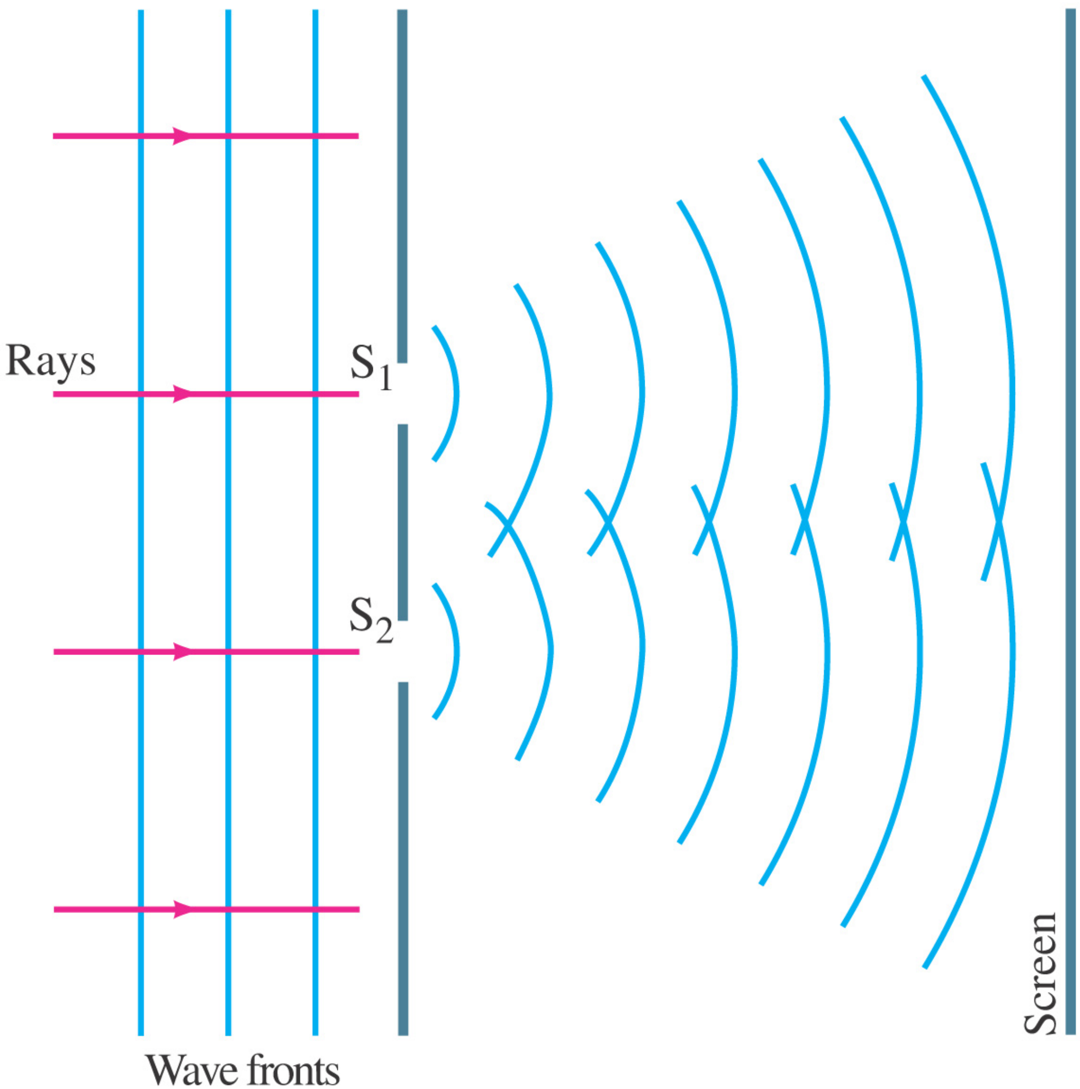
24.1 Huygens' Principle and Diffraction

Large aperture Small aperture



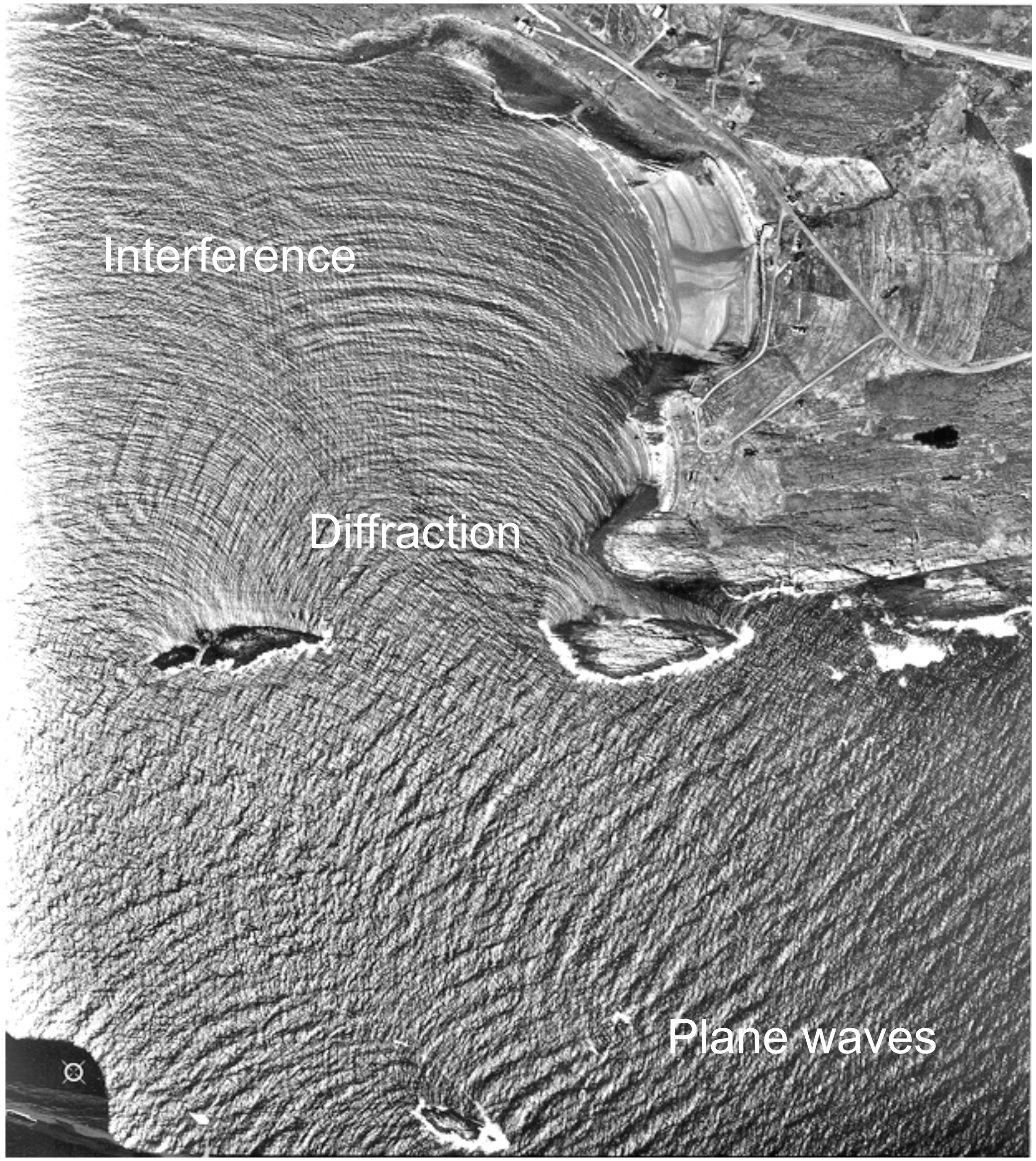
The smaller the aperture (or the more the waves are disturbed) the less information remains about the original direction of the waves.

24.3 Interference – Young's Double-Slit Experiment

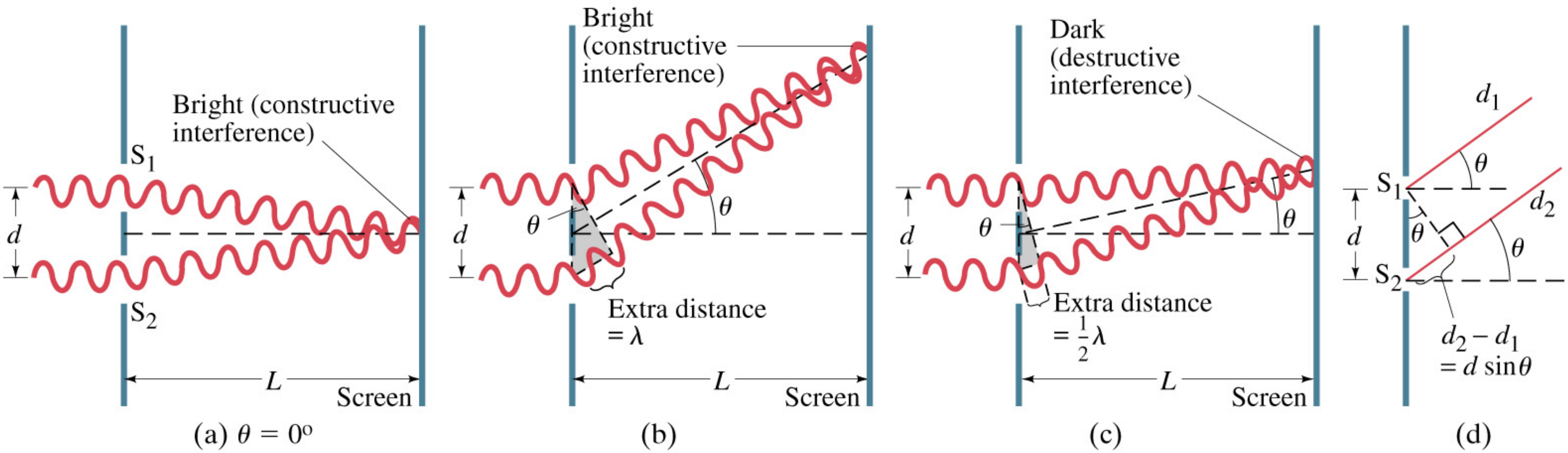


If light is a wave, there should be an interference pattern.

Need live demo
Or video followed by calculation

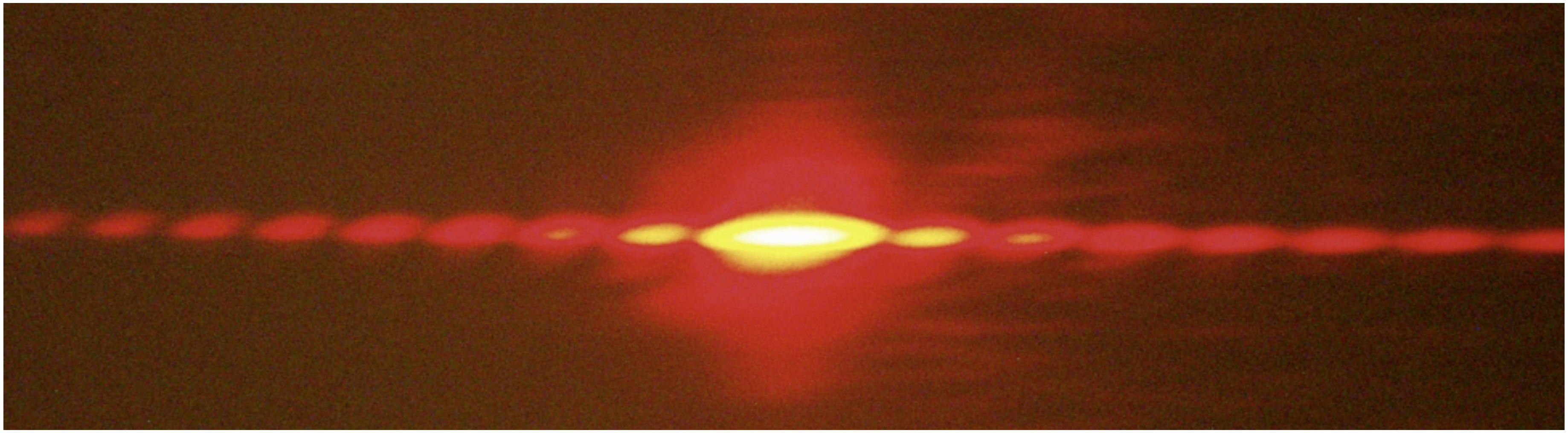

Interference
Diffraction
Plane waves

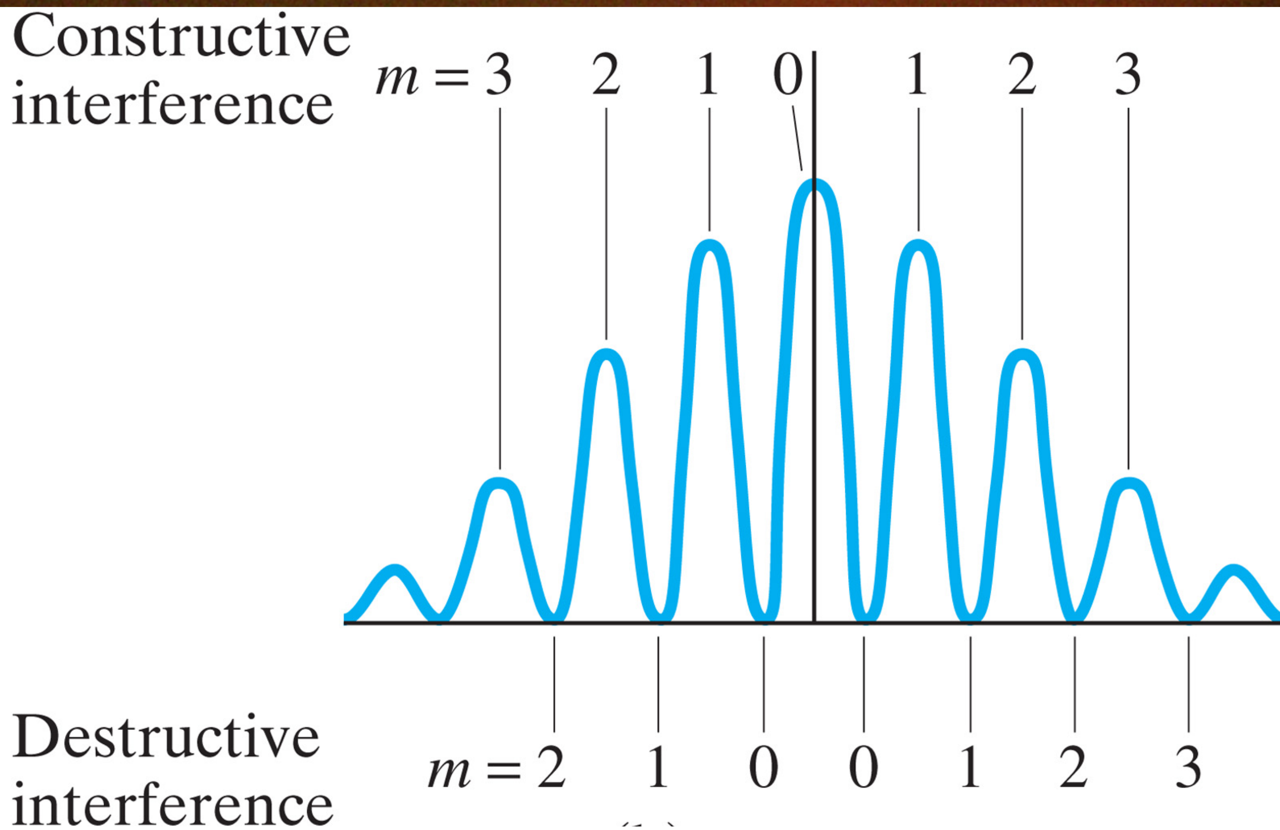
Constructive & Destructive Interference



- The interference occurs because each point on the screen is not the same distance from both slits.
- Depending on the path length difference, the wave can interfere constructively (bright spot) or destructively (dark spot).

Interference Pattern





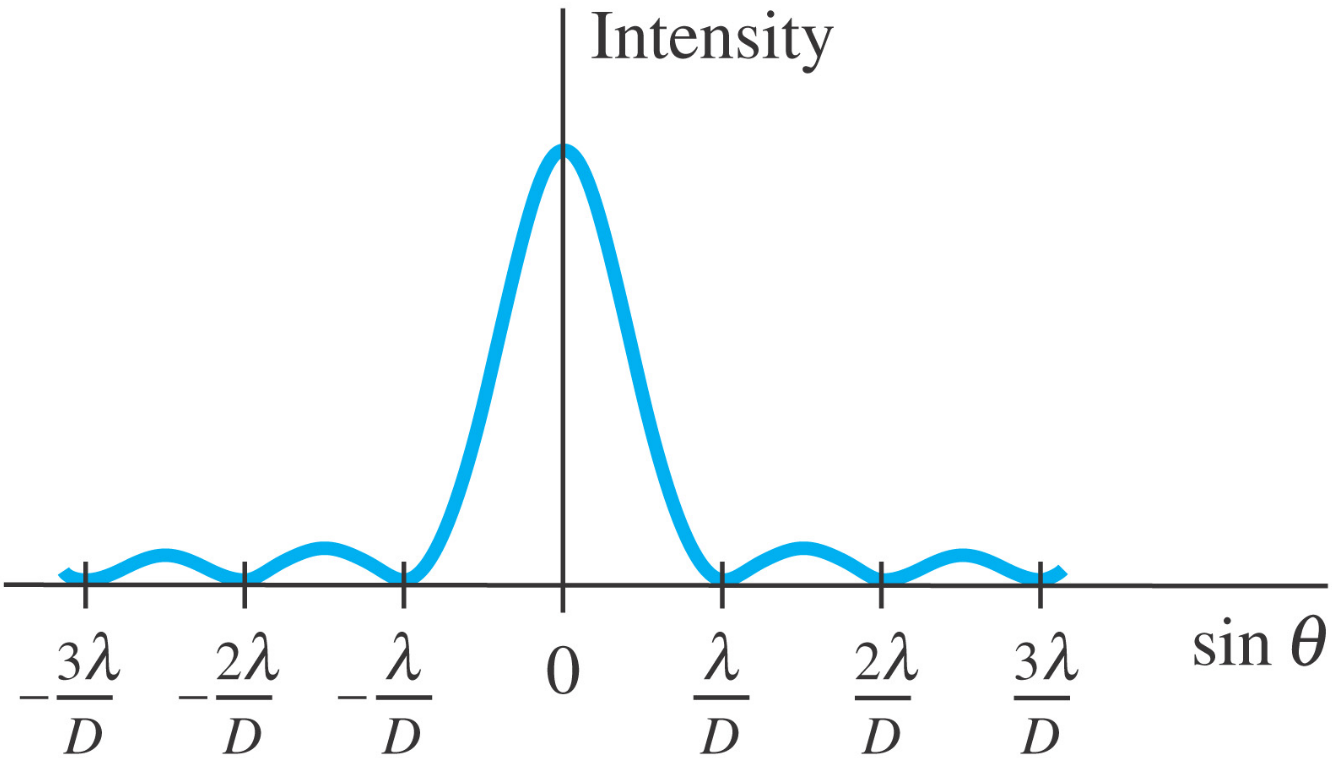
$$d \sin \theta = m\lambda,$$

Diffraction by a Single Slit

- A diffraction pattern still arises because different points along a slit create wavelets that interfere with each other just as a double slit would.
- The minima of the single-slit diffraction pattern occur when

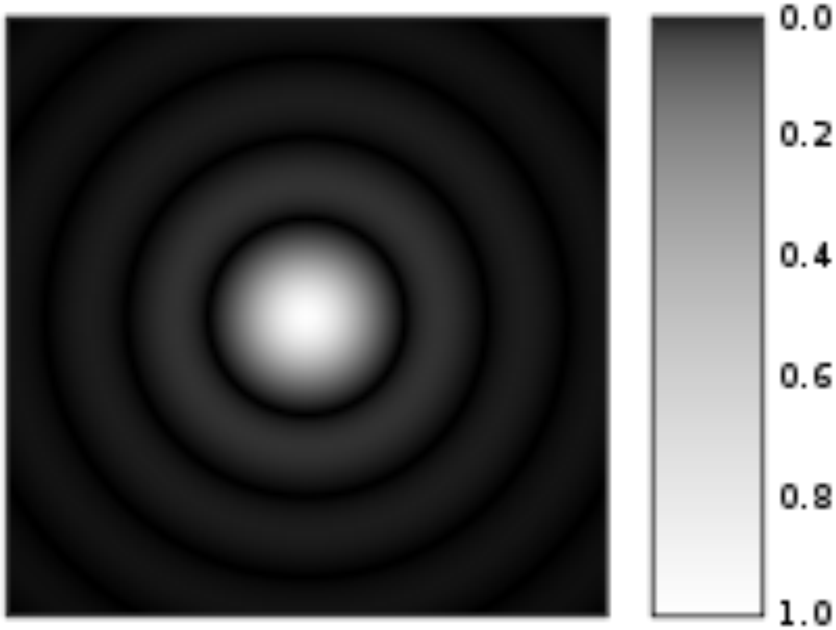
$$D \sin\theta = m\lambda, \qquad m = 1, 2, 3, \cdots$$

- Where D is now the diameter of the slit



Airey Pattern: Diffraction by a circular aperture

For a circular hole (for example your eye's pupil, or the aperture in a camera) the diffraction pattern is a central maximum, surrounded by concentric rings



The angular diameter of the central spot (in radians) is

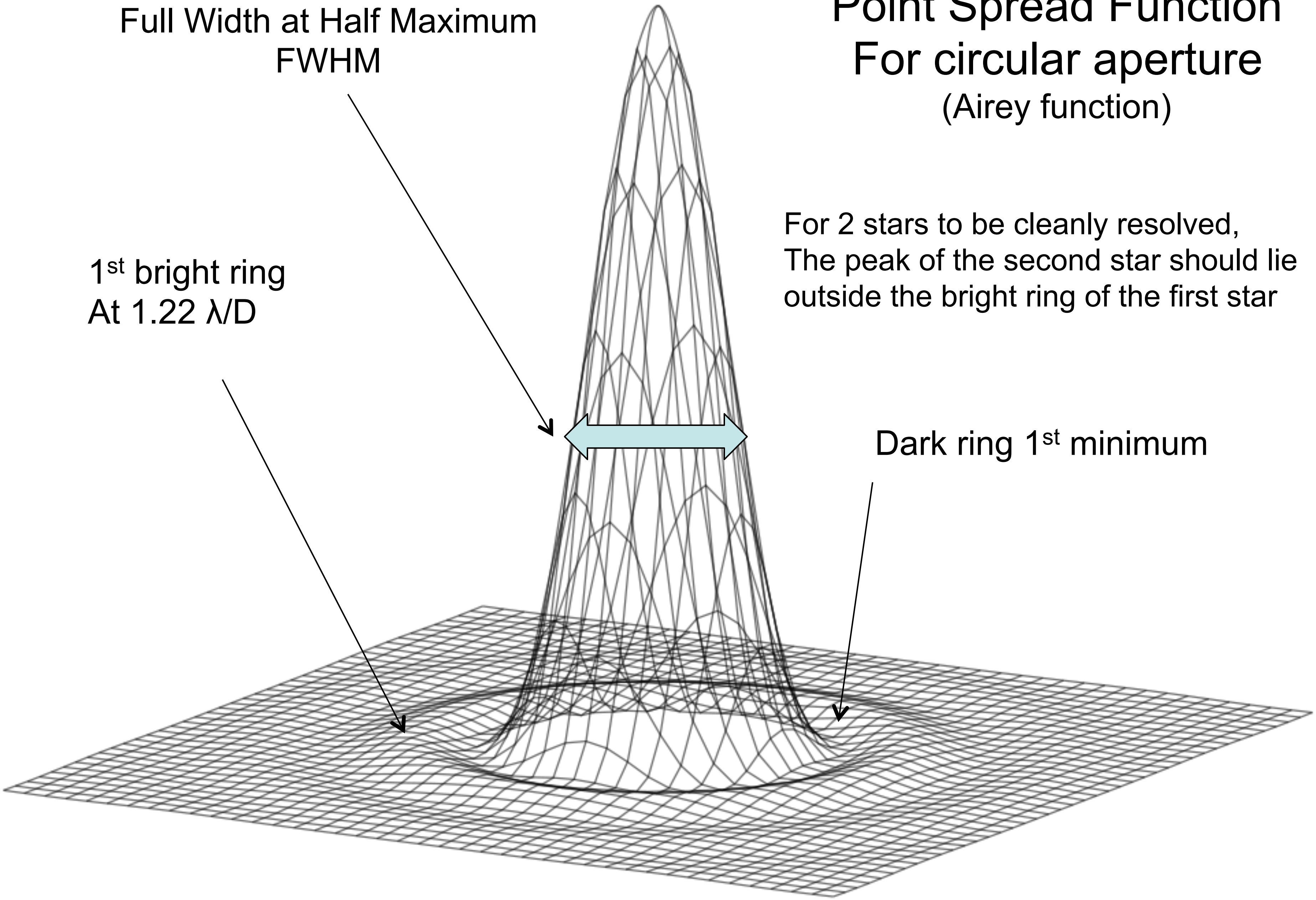
$$\theta_{min} = 1.22\lambda/D$$

Where D is the diameter of the aperture (in meters)

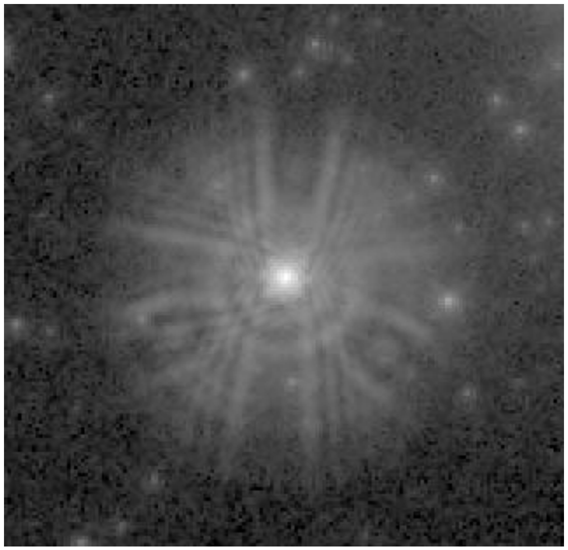
- **This fact is a fundamental limitation for ALL optical devices**
- **Nothing smaller than θ_{min} can be resolved, no matter what the magnification!**
- **The pattern is actually the Fourier transform of the Pupil**

Point Spread Function
For circular aperture
(Airey function)

For 2 stars to be cleanly resolved,
The peak of the second star should lie
outside the bright ring of the first star



Astronomical PSF's

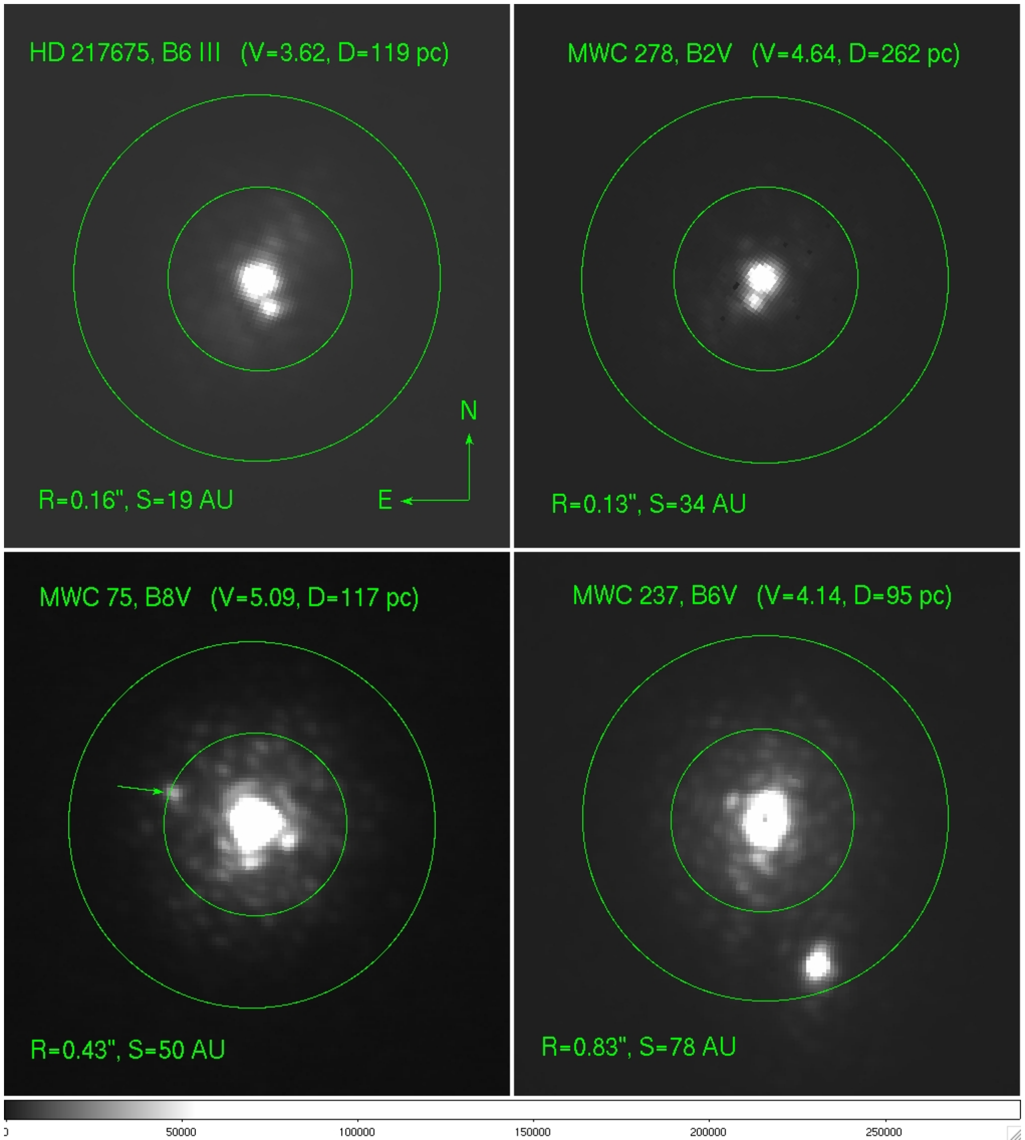


Hubble Space Telescope PSF
(with the original flawed optics)

- In reality the PSF is more complex than the Airey function, because of central obstructions in the telescope, optical abherations, seeing, telescope motion, scattered light, detector properties.
- Atmospheric Turbulence (seeing)

- Real PSF cannot be calculated analytically.
- Solutions:
  1) Direct measurement using stars
  2) Empirical model (e.g. multi-gaussians)
  3) Fourier Optics

Adaptive Optics Images of Close Binary Stars



- Images taken with Gemini North (8.5m) telescope
- *Altair* Adaptive Optics System
- Near Infrared (2 microns)
- PSF FWHM ~ 0.07" (measured)
- Pixel size = 0.02"
- This 0.07/0.02=3.5 samples per resolution element. Basically Nyquist optimum sampling
- Images are stacks of ~15-30 very short exposures, each with T~0.01 s
- Distance to these stars is known, so the actual separation of the binaries is calculated by the same method used in your HW
- Airey disk is discernible, which tells you the image is approaching the diffraction limit of the telescope ($1.22\lambda/D$)
- Note the "speckles"
- Circles plotted at r=0.5", 1"

CCDs in Astronomy

- CCDs (charge coupled devices)

  Photoelectric effect

  Linear Response

  Well depth

  ADC

  Gain

  Noise - Read noise

  - Dark Current & Temperature

  QE & Wavelength response

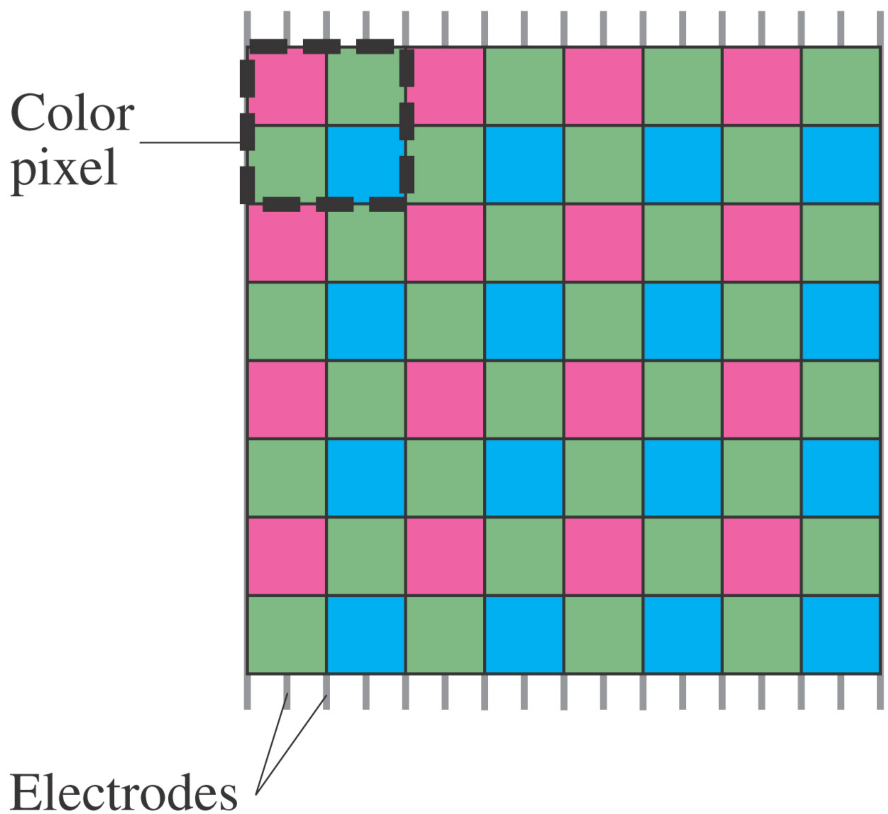
  Pixel Scale / Plate scale

  S/N Ratio - Poisson distribution

  Imaging vs Specroscopy

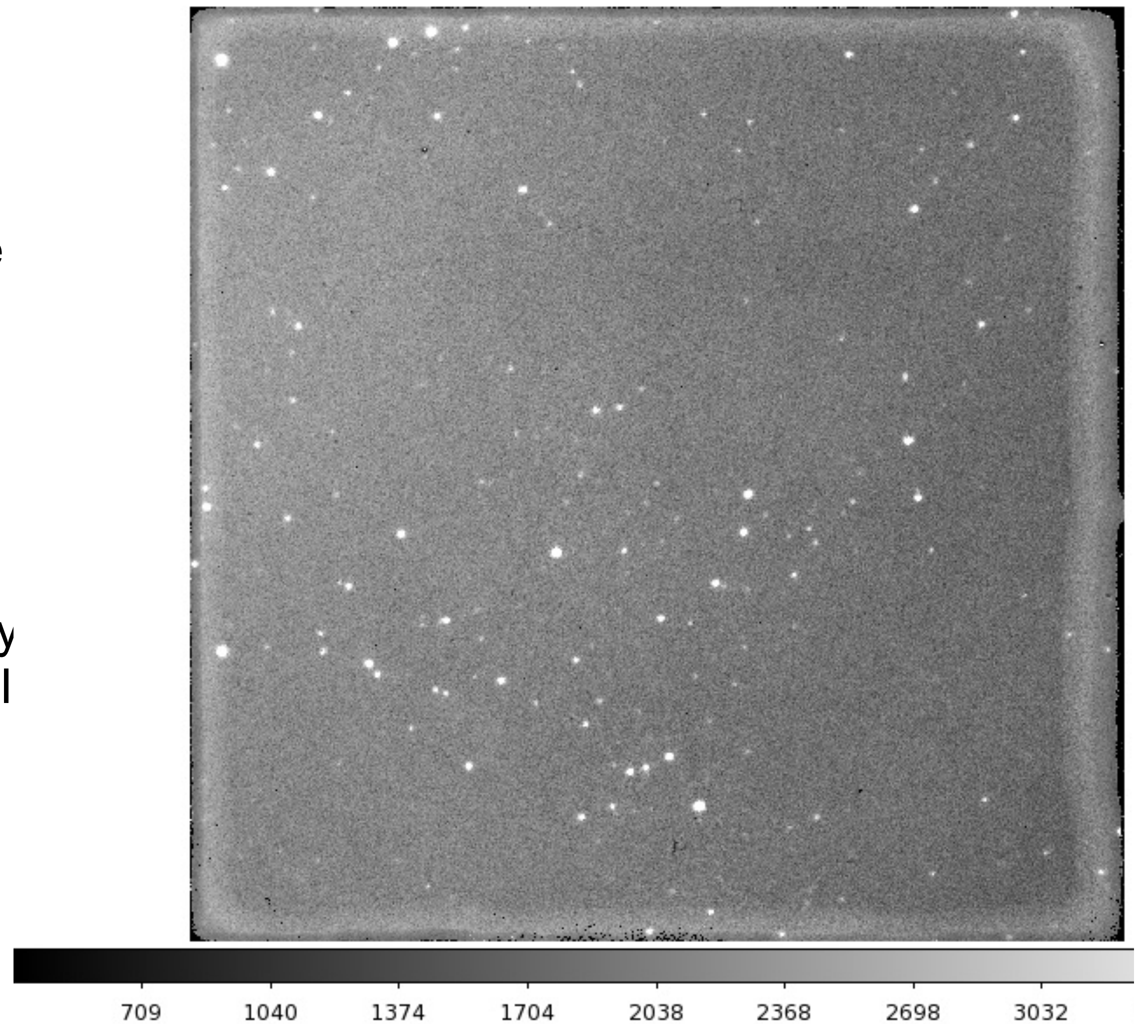
25.1 Cameras, Film, and Digital

A digital camera uses CCD sensors instead of film. The digitized image is sent to a processor for storage and later retrieval.



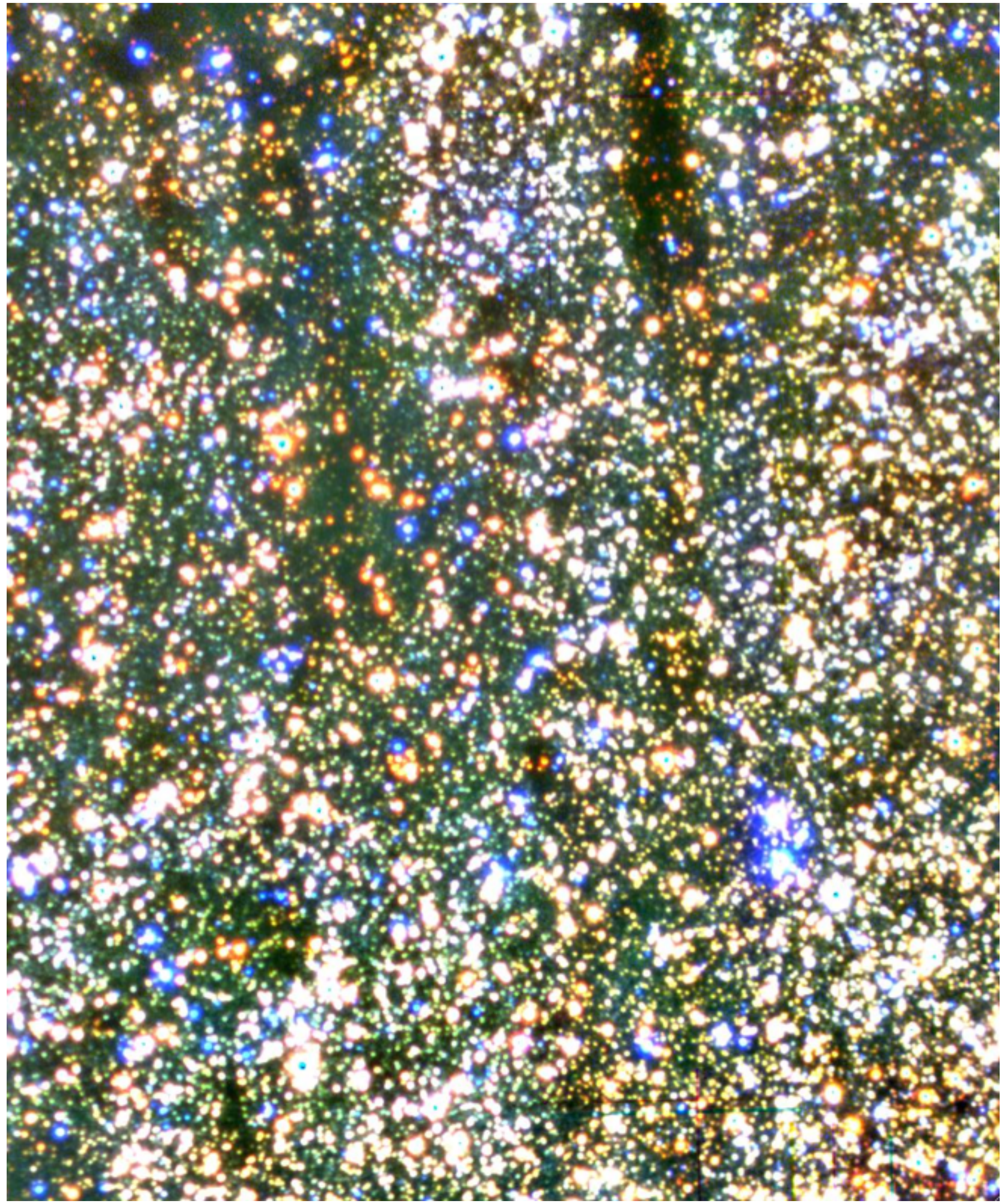
Raw data

- A raw 5 second exposure with the PANIC infrared imager on 6.5m the Magellan telescope in Chile
- No processing aside from selecting display scale
- Note all the image artifacts
- Dithering the telescope and combining many exposures which must be done anyway (to build dynamic range) will remove these artifacts.



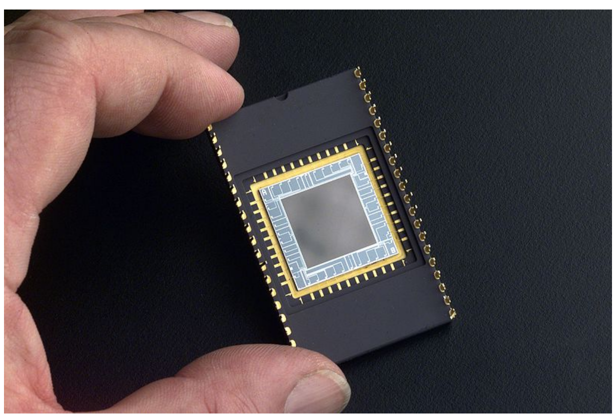
Processed Image

- This is the same data as the previous image.
- Stacked image composed from <u>dozens</u> of exposures taken in J,H,K filters
- Each frame processed to remove sky background, cosmic rays, detector artifacts etc.
- Representative color scale: 1.2μ=blue,
  1.6μ=green,
  2.2μ=red



What is a CCD ?

- Charge Coupled Device, is a pixellated semiconductor detector array.
- Each pixel is essentially a p-n photodiode, with millions of these fabricated on a single wafer, and connected by 'gate' transistors.
- Photoelectric effect -incoming photons free electrons, which accumulate in a "well".
- The number of electrons in the well increases linearly with increasing exposure. I.e. $N_e \propto N_{photon}$ (this is not true for photographic emulsions)

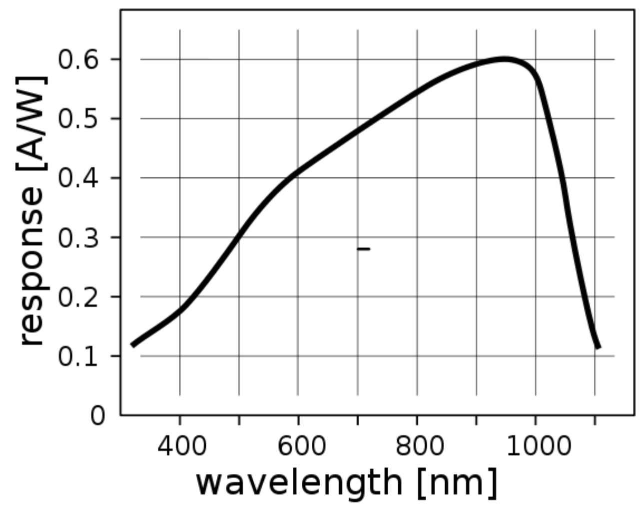


Material	Electromagnetic spectrum wavelength range (nm)
Silicon	190–1100
Germanium	400–1700
Indium gallium arsenide	800–2600
Lead(II) sulfide	<1000–3500

Various dopants are used to tune the bandgap to specific wavelength ranges

CCD Properties

- Highly efficient: QE can exceed 90%
- Broad wavelength response
- E = hf, but in the optical regime the value of E_e is totally masked by thermal fluctuations, and the sheer fact the there are too many incoming photons to register them individually.
- We do not typically operate the devices in photon-counting mode*.
- Read-out consists of shuffling the charges across the array and measuring them at an amplifier.
- Count the accumulated photoelectrons using an analog-to-digital-converter (ADC)
- ADC gain is chosen (e-/ADU) based on the inherent noisiness of the array.
- Typical gain value is 4.0
- 16 bit ADC gives 65K image ”levels”



* In X-rays the situation is reversed, and there is a new device called EMCCCD

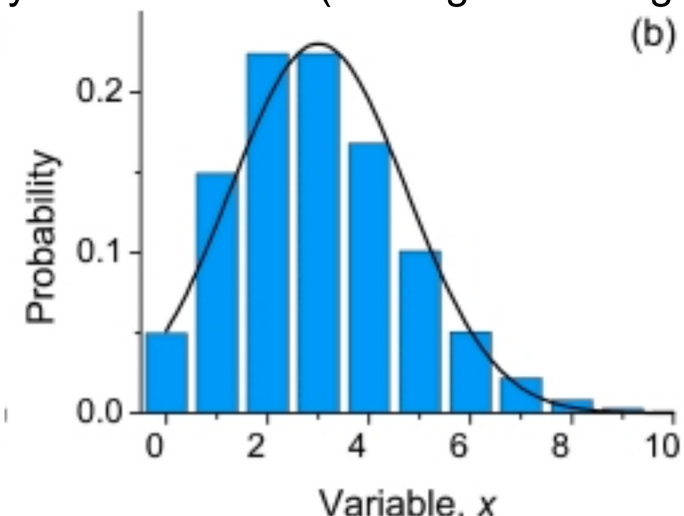
Limitations

- There is a maximum well capacity, after which the electrons leak into neighboring pixels, and the net charge inhibits further electron capture
- This process is called saturation, linearity breaks down somewhere around 90% of saturation. Generally operate at much lower levels.
- Dynamic range is limited primarily by well depth, but is obviously affected by noise (and hence gain) also.
- Full well is 100,000-200,000 electrons
- Consequently, very deep observations require multiple exposures. Sometimes numbering in the hundreds or more.
- Dark current (electrons liberated by thermal fluctuations) can limit exposure time, and increase noise. Simple solution - Liquid Nitrogen
- Read Noise: In the process of shuffling the charge clusters across the array, and sensing them at the amp, some noise is added. Can range from a few to tens of electrons per pixel.
- Read noise means that co-adding lots of exposures is not quite as good as one long exposure.

Photon Counting, Poisson Distribution & S/N Ratio

- The Poisson distribution expresses the probability of a given number of events occurring in a fixed interval of time (or space) if these events occur independently at a known average rate.
- Simeon Denis Poisson. published in 1838 in *Recherches sur la probabilite des jugements en matiere criminelle et en matiere civile*.
- If the expected number of occurrences in a certain interval is λ, then the probability that there are exactly k occurrences (k being a non-negative integer, k = 0, 1, 2, ...) is equal to

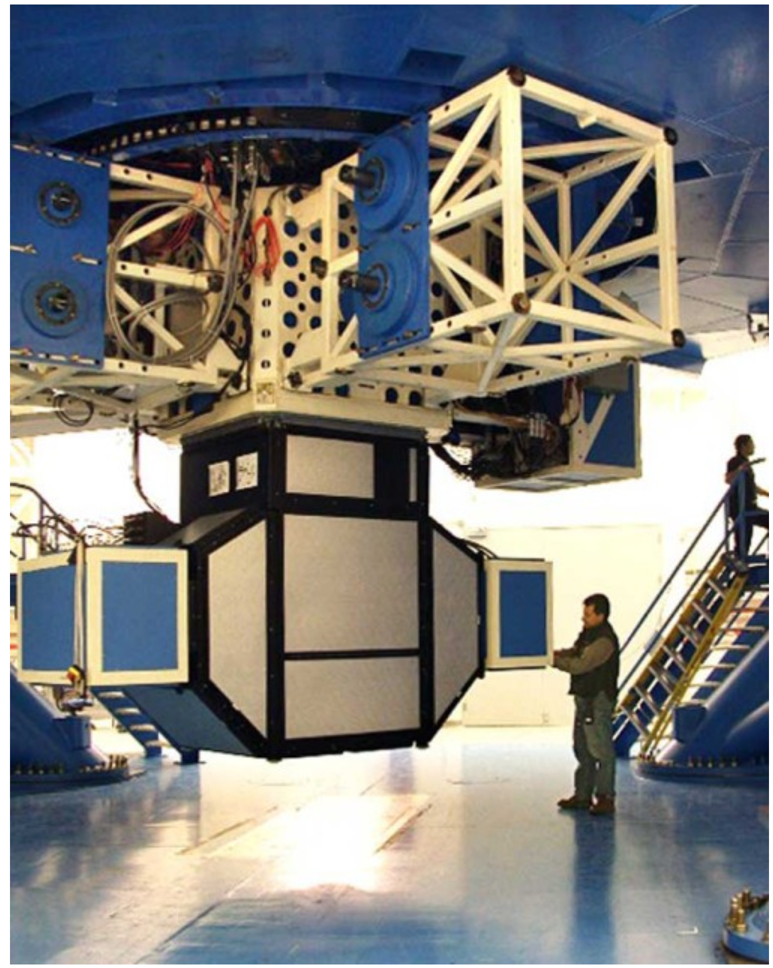
$$f(k;\lambda)=\frac{\lambda^k e^{-\lambda}}{k!}$$



- For instance, if photons arrive from a star on average 4 times per minute, and one is interested in the probability of an event occurring k times in a 10 minute interval, one would use a Poisson distribution as the model with λ = 10*4 = 40.
- The standard deviation of this distribution would then give the expected fluctuations either side of the mean.
- For Poisson distribution, the std error (uncertainty in the mean) = $\sqrt{N}$
- Hence the Signal-to-Noise Ratio (S/N) $= N_{signal} / \sqrt{N_{total}}$

Gemini Multi-Object Spectrograph (GMOS)

- 3 CCDs butted together to give ~8' FoV.
- 0.07 "/pix
- Typical MK seeing is 0.7" in the optical



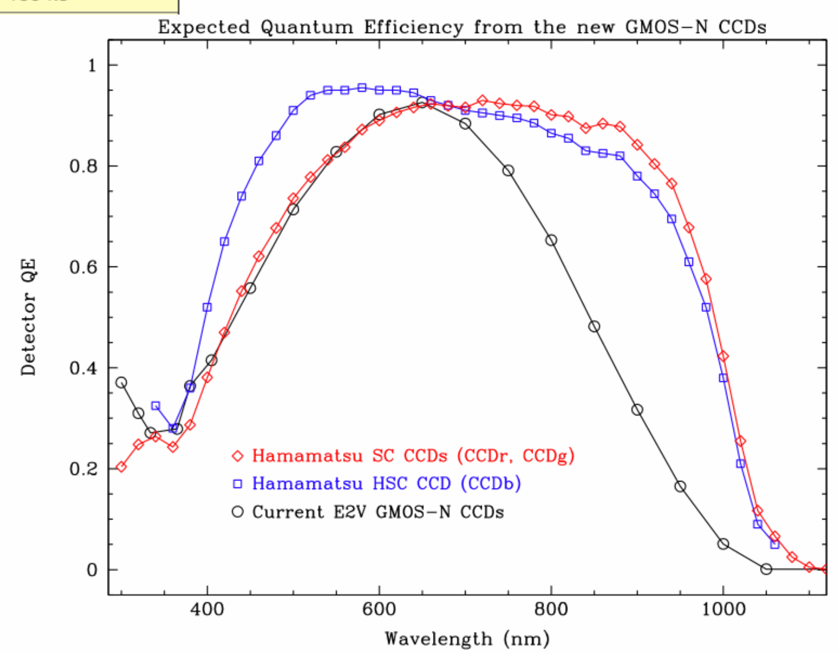
Gemini GMOS array characteristics

Array	EEV		
Pixel format	6144x4608 pixels		
Array layout	Three 2048x4608 chips in a row with ~0.5mm gaps		
Pixel size	13.5 microns square; 0.0727 arcsec/pixel		
Spectral Response	approx 0.36 to 0.94 microns [data / plot]		
Bias level	Bias image		
Flat field response	Fringe images Flat field images		
Readout time	See observing overheads page		
Chip	CCD 01	CCD 02	CCD 03
Chip ref no.	EEV 9273-16-03	EEV 9273-20-04	EEV 9273-20-03
Dark current*	0.8 e-/pix/hr	0.7 e-/pix/hr	0.5 e-/pix/hr
Full Well **	150 ke-	101 ke-	159 ke-

Pixel size, scale,

Read noise and
Dark current

- Quantum efficiency as a function of wavelength



Example S/N Calculation

What S/N do we get in a 1 minute exposure for a star that delivers 2,000 electrons per sec, on a night when the sky contributes 10 e^-/s/pix and the seeing is an exceptional FWHM=0.6” ?

GMOS parameters

Pixel size= 0.0727 ”/pix
Read Noise = 3.6 e^-/pix
Dark Current = 0.7 e^-/pix/hr

Method:

$$S/N = \frac{N_*}{\sqrt{N_{Total}}}$$

$$S/N = \frac{N_*}{\sqrt{\left(N_* + N_{Sky} + N_{Dark}\right) + N_{Read}}}$$

$$N_{Sky} = Pixels \times Sky = \pi R^2 Sky$$

$$N_{Dark} = Pixels \times Dark$$

$$N_{ReadNoise} = READNOISE\sqrt{Pixels}$$

$$N_{ReadNoise} = \sqrt{\left(n_1^2 + n_2^2 + \ldots . n_n^2\right)} = \sqrt{pixels \times n^2} = n\sqrt{Pixels}$$

1. Seeing FWHM=0.6”, so lets pick an aperture of say 1.2” diameter to collect essentially all of the Star’s flux but not so large as to gather excess Sky. So we set R=0.6 / 0.0727 = 8.25 pixels
2. Total counts form the star: Nstar= 60 x 2,000 = 120,000 (not quite a full well)
3. Find the number of pixels, so that we can calculate the total sky counts N_{sky}, the total read noise N_{Read}, and the total dark current $N_{dark.}$
   Area of Star on detector = πR^2 = 3.142 x 8.25^2 = 214 pixels
4. Calculate Sky counts in our aperture: N_{sky} = 214pix x 10e x 60s = 128,400
5. Dark counts in aperture: N_{dark} = 214 x 0.7/60 ≈ 3
6. Calculate Read Noise in aperture: N_{Read} = 3.6√214 = 53
7. Compute the S/N ratio:

$$S/N = \frac{120{,}000}{\sqrt{(120{,}000 + 128{,}400 + 3) + 53}}$$

$$S/N = 217$$

How many pixels are enough?

- Big blocky pixels are bad, because position and shape information are lost.
- Contrast is reduced if neighboring stars are blurred together.
- Poisson noise is increased due to additional sky background in a large pixel.

- On the other hand, the more pixels a given star's image is spread over, the more read noise will be introduced.

- Nyquist's theorem* states that all the information in an image is captured when there are 3 samples per resolution element.
- Thus, there is little point in packing pixels more densely than 1/3 the FWHM of the seeing disk. Conventionally defined as the FWHM of a stellar image.
- So in 1" seeing, you need 0.3" pixels for optimal sampling.

- Imagers (e.g GMOS) are usually designed with pixels small enough for the best seeing conditions that might occur, and are then binned to give effectively larger pixels for more "normal" or poorer conditions.

*Nyquist sampling theorem applies to all frequency analysis problems.

Film vs Electronic

- In days of yore (1880-1990) astronomers used photographic plates.
- Excellent wide-field coverage
- Good resolution
- Large dynamic range

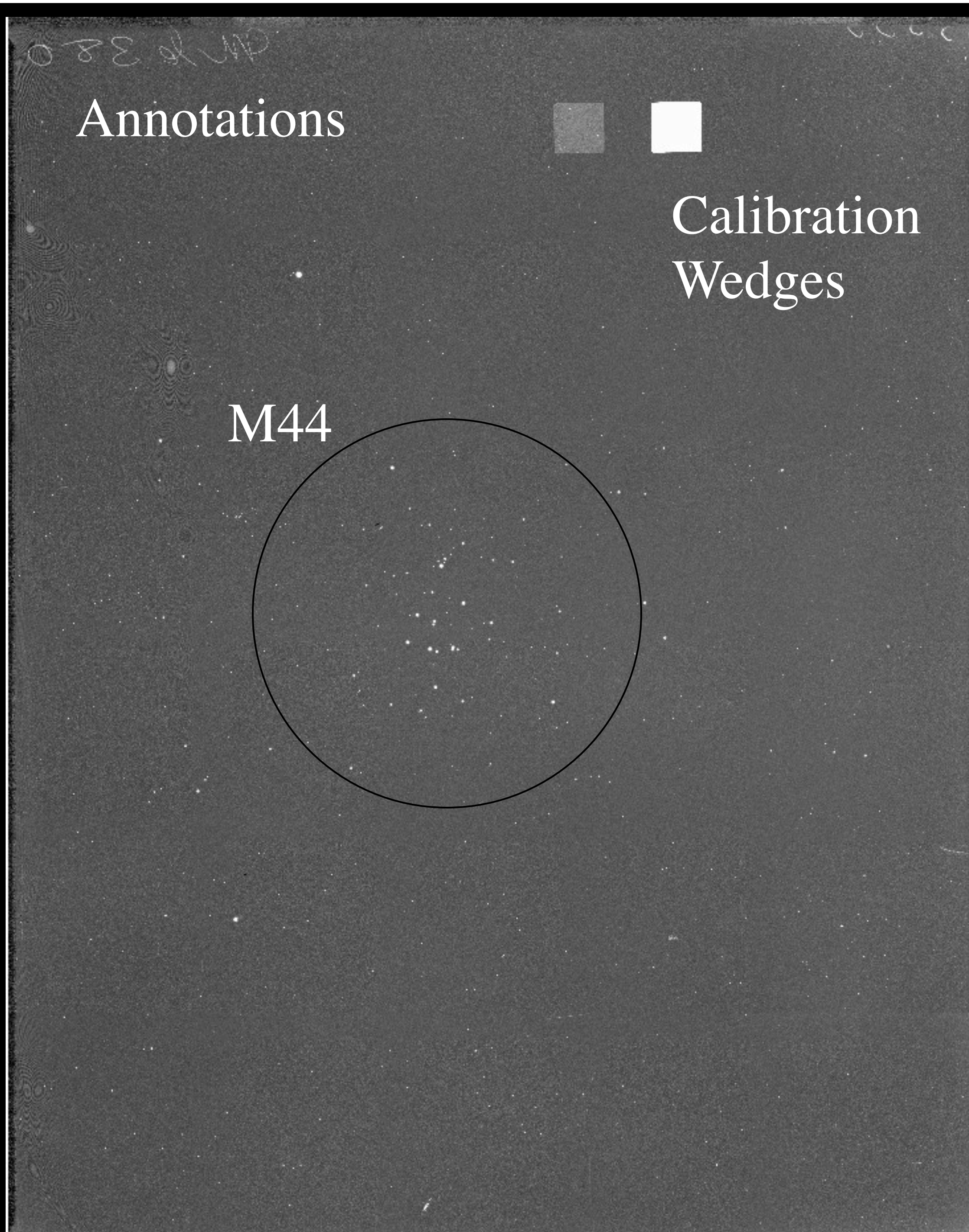
- Low sensitivity (~1%)
- Non-linear response to light
- Terrible to work with (messy, hazardous, laborious and difficult to analyze)

Today we use semiconductor devices

- Incredibly high sensitivity (90%)
- Linear response
- Data in digital form

- Operate at liquid Nitrogen temps
- Small size of devices, makes wide field instruments expensive

Scan of a photographic plate

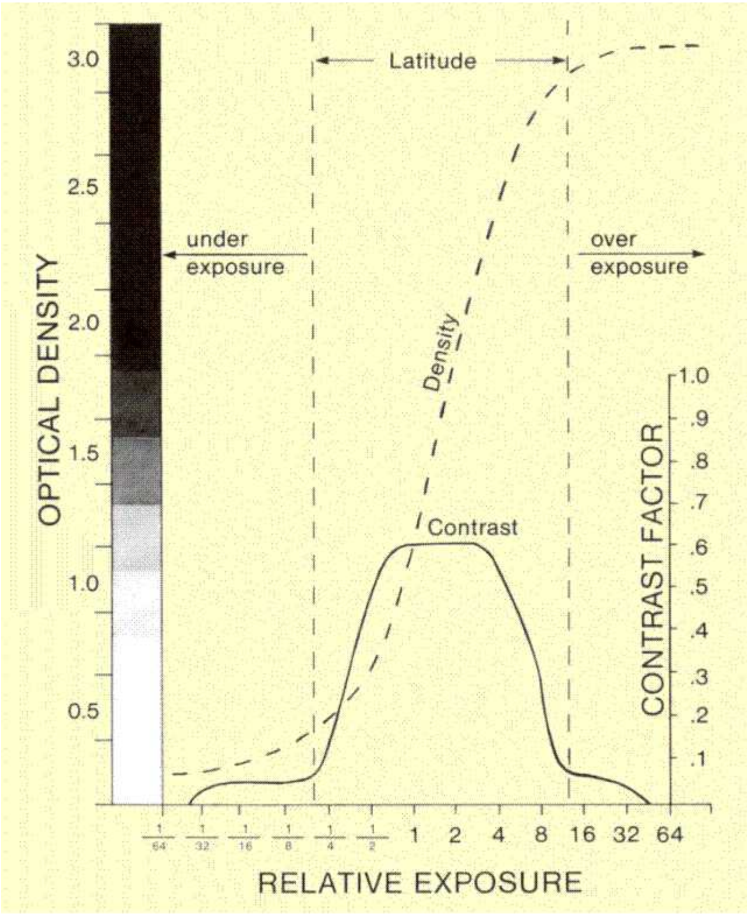


The open cluster M44. (Praseppe or "the Beehive", April 28, 1910, scanned by DASCH project.

5 min exposure

- Faintest stars visible are B~14

Photographic Emulsion Response to light

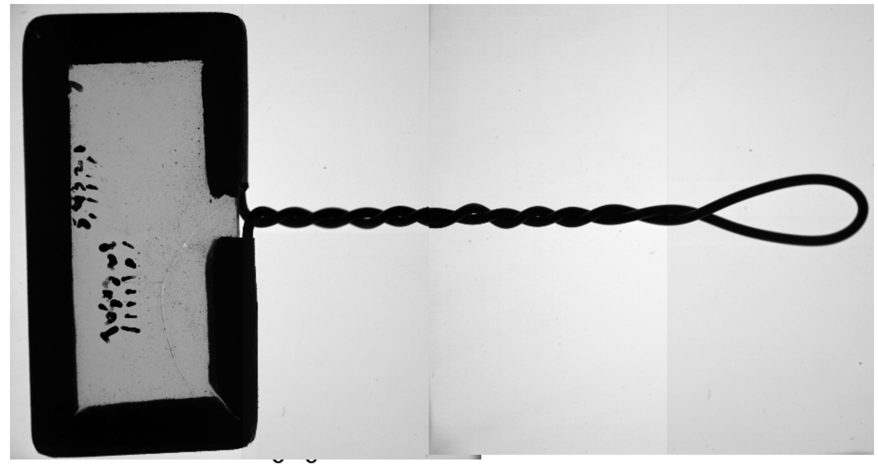


- Photographic Emulsion consists of microscopic silver halide grains suspended in gelatin.
- Light activates molecules (latent image)
- Development oxidizes the exposed grains causing them to become dark.
- Density of developed grains determines the darkness of the negative.
- Density increases with exposure (some product of aperture, time).
- Relation is log-linear, but only over a certain range.
- Results in effective PSF that is a convolution of the optical PSF (airey pattern+ seeing) with this non-linear response to light.
- Stars of different brightness have differing shape as well as differing density.

- On the Plus side. Photographic plates can be made very large, at minimal cost.

Measurements from Photographic plates

- Traditionally (and even today) measurements are made using a microscope, one star at a time
- Image diameter is compared against standard stars



- Plates can now be scanned, digitized and measured automatically.
- Calibration is performed by brute force using modern catalogs of photoelectric observations covering the same field.
- Non-linear response is fitted, and many other subtle effects can be calibrated out.