Observational Astronomy - Lecture 3
Telescopes and the Electromagnetic Spectrum

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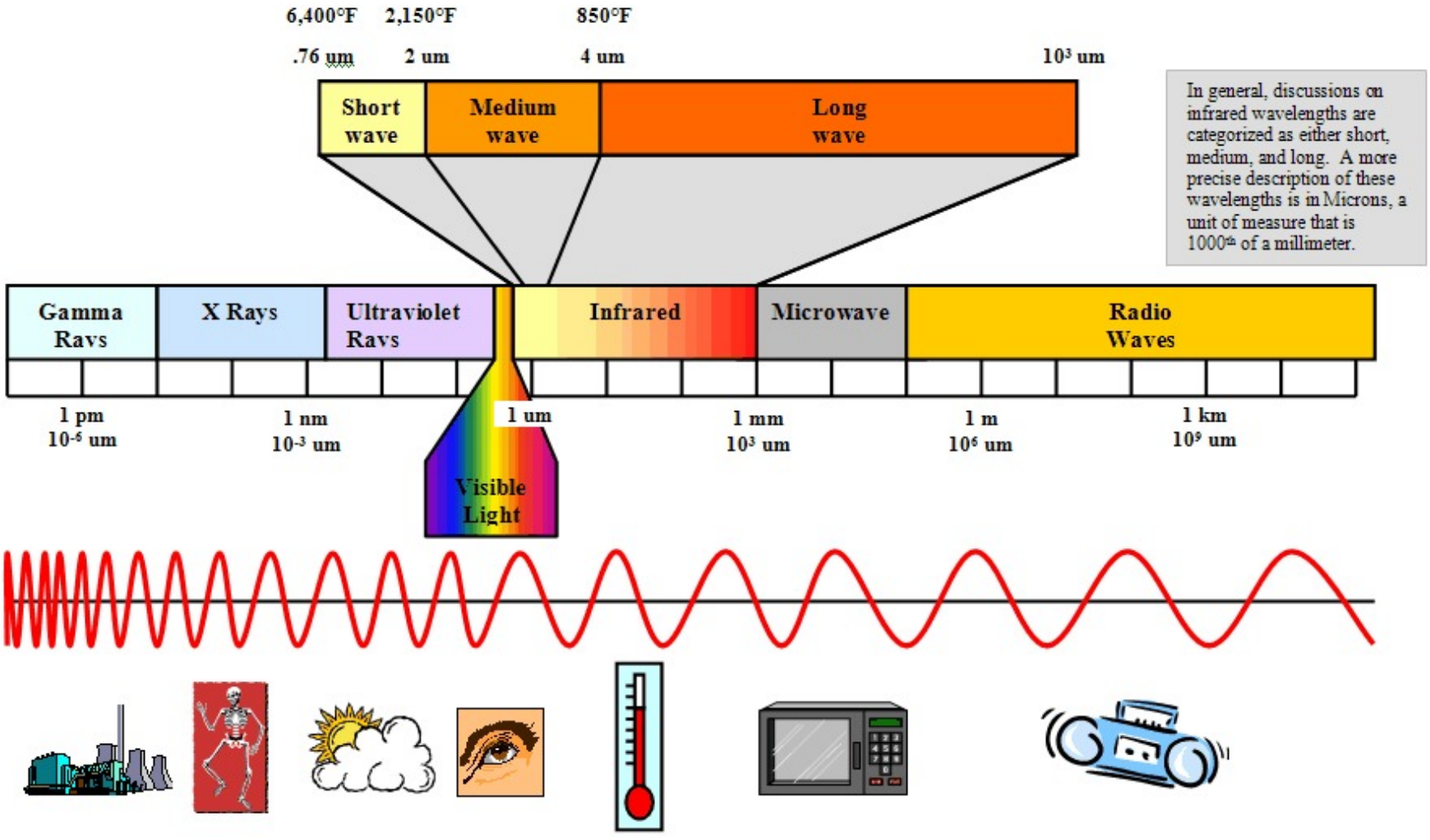
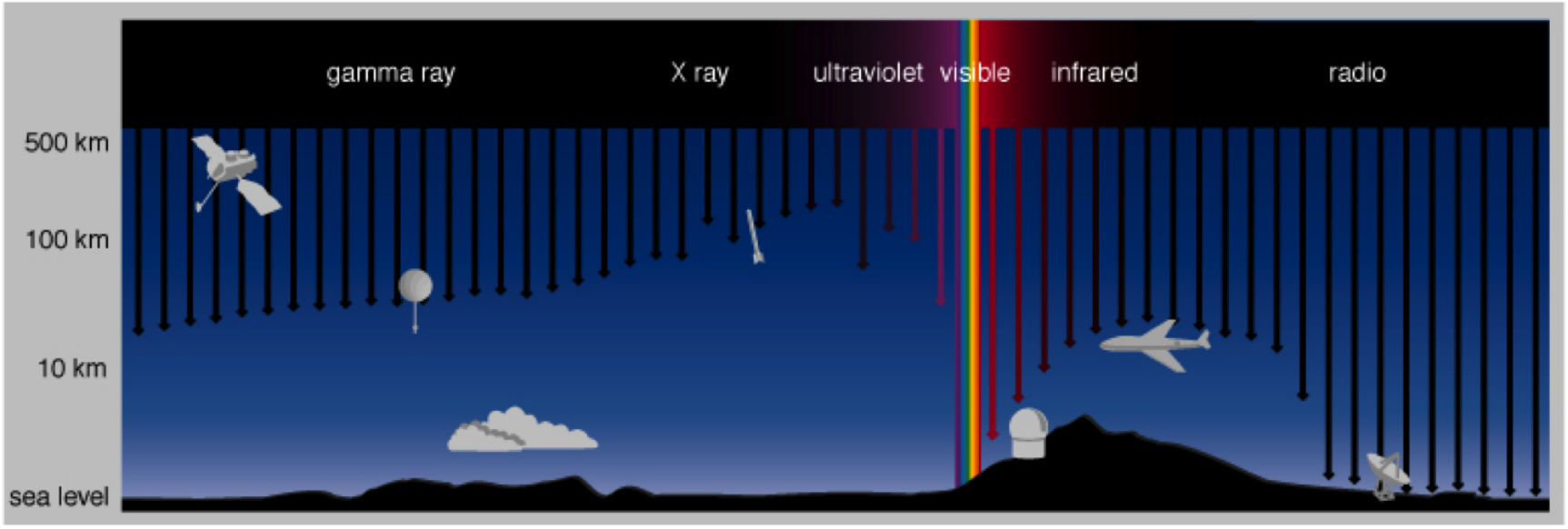
The Electromagnetic Spectrum



The Observational "Windows" at the Earth's Surface



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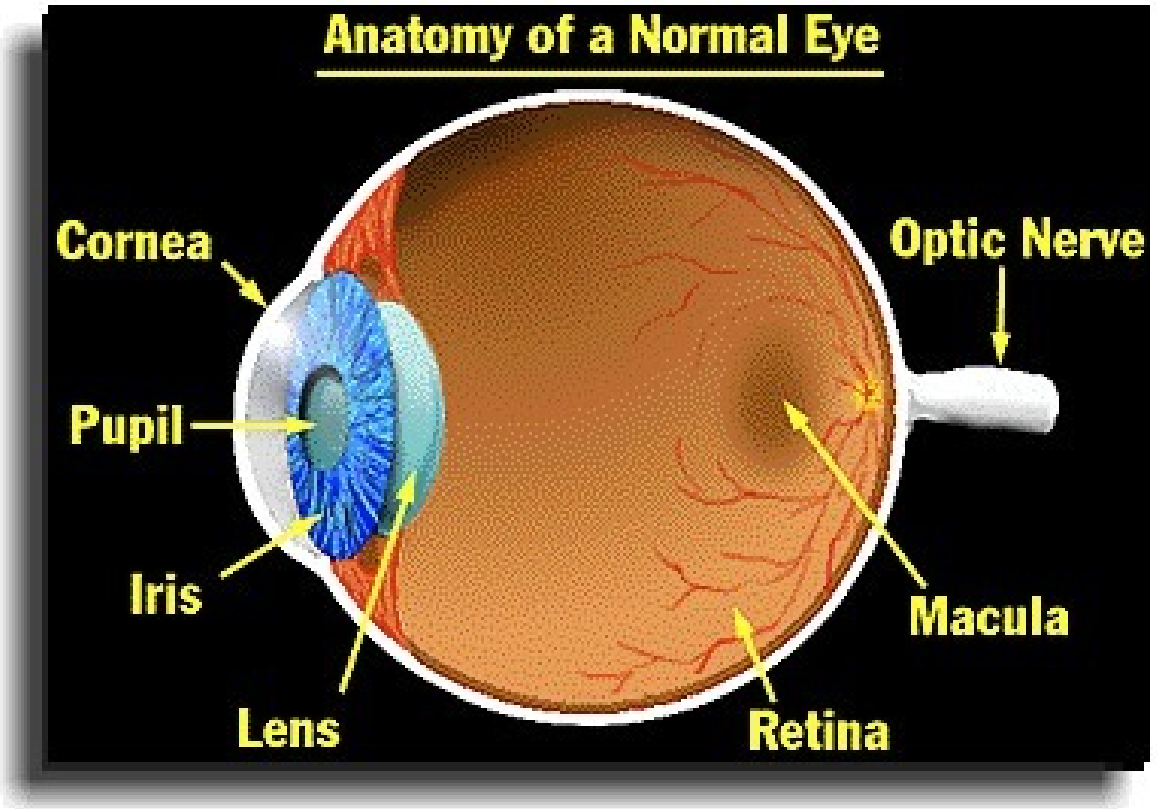
The Human Eye



Response of the Human Eye

- The retina of your eye contains both rods and cones to detect the light.
- Cones are sensitive to color, rods are more sensitive to low light levels.
- This is why only the brightest stars show colors.

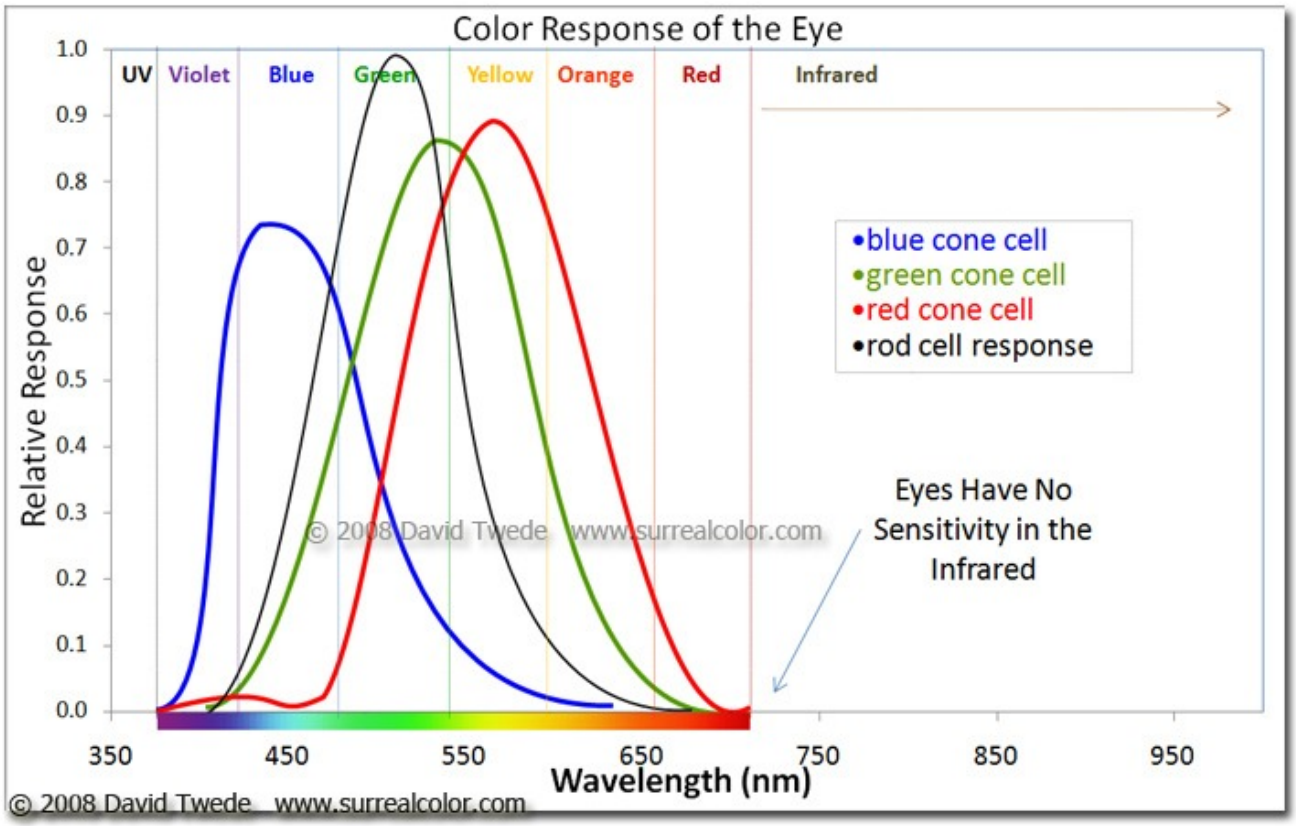
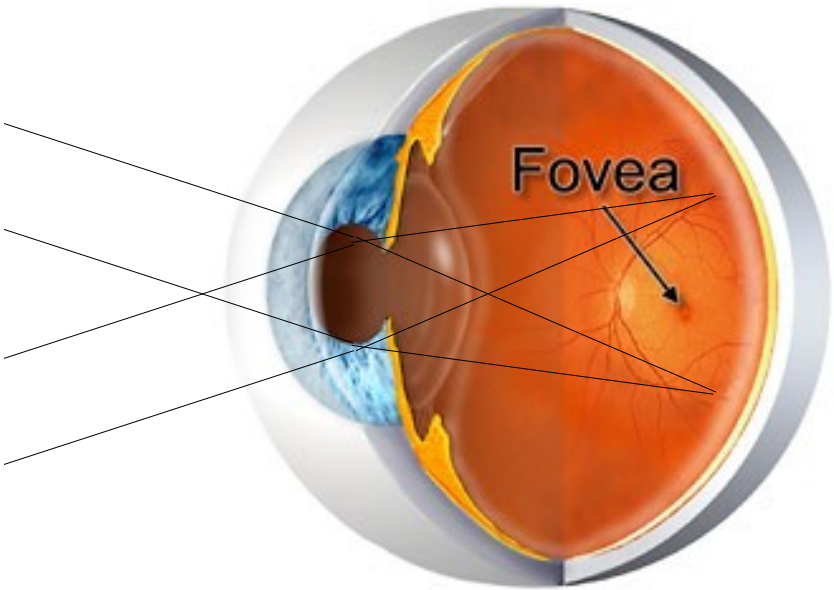
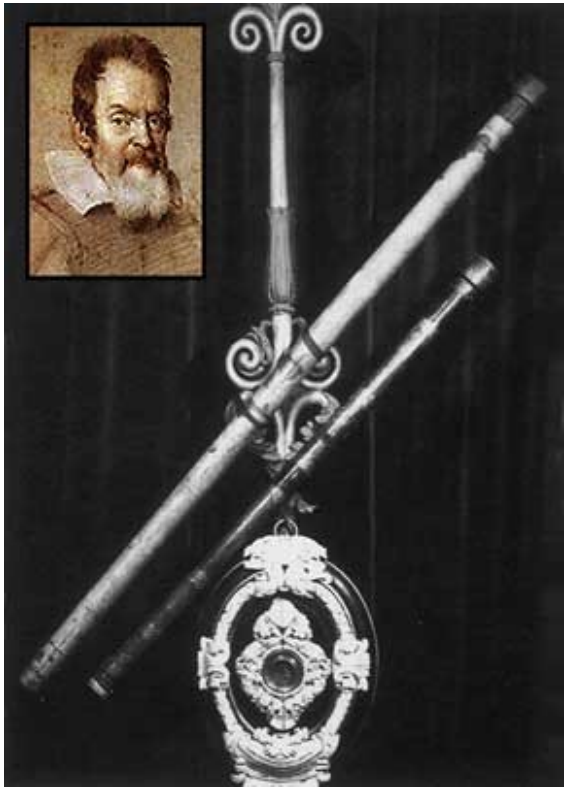


Image Formation by the Eye.

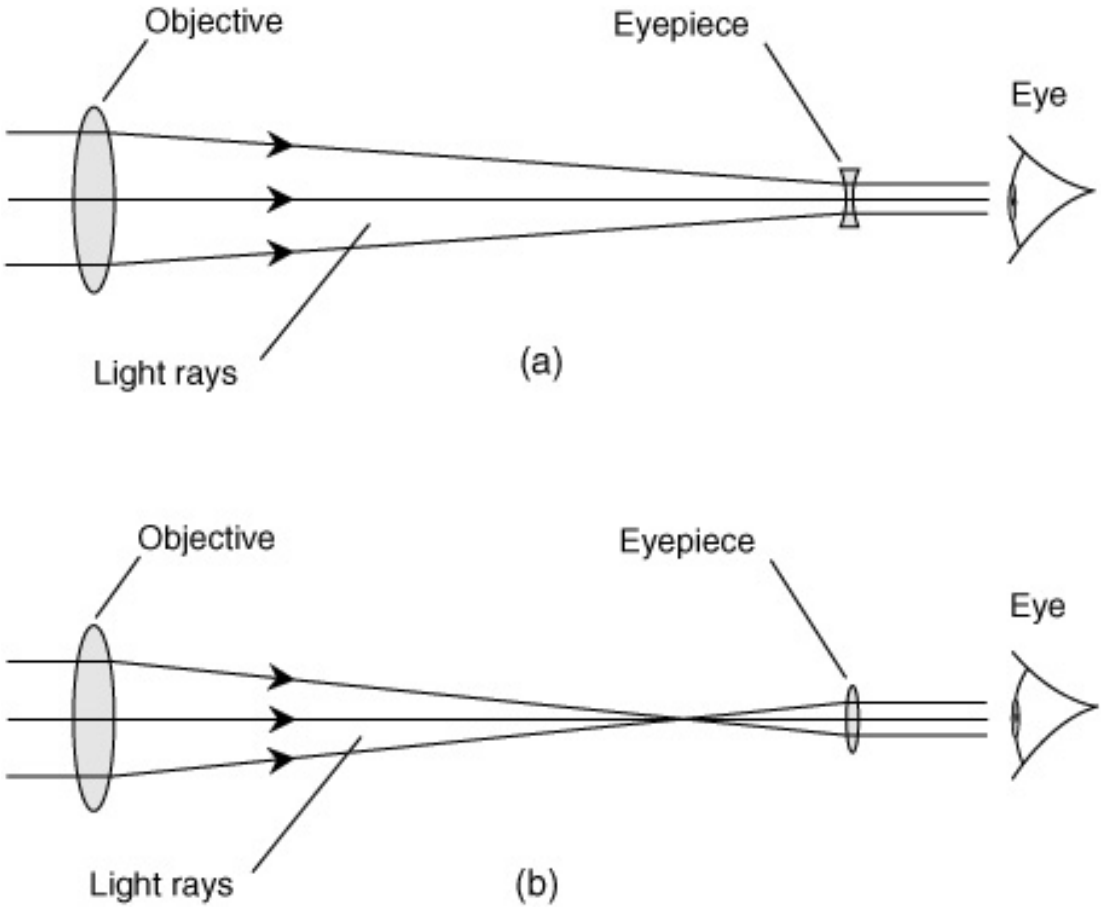


- The lens focuses light from different directions onto different parts of the retina, forming an image.
- The fovea has a much higher density of cones, and a smaller density of rods, so it is less sensitive to dim light.
  - Averted vision (looking off to the side) allows you to see fainter objects.
- In dim light, the iris opens almost completely, and the opening in the pupil is about 7mm in diameter.

Refracting Telescopes

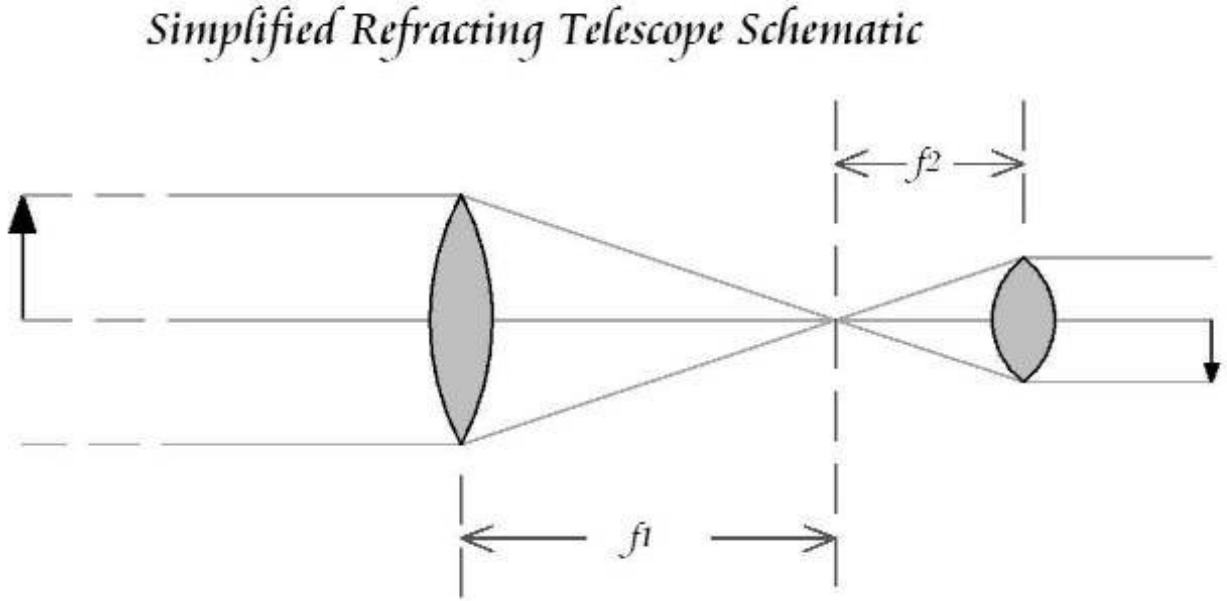


Galileo's Telescope



(a) Galilean Telescope - Upright Image
(b) Keplerian Telescope - Inverted Image

A Keplerian Telescope

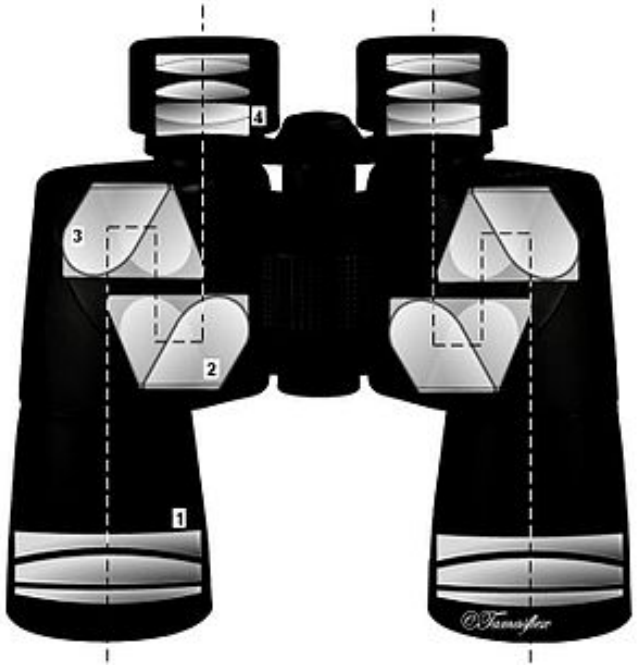


- Objects are inverted.
- Magnification $\mathrm{M} = \mathrm{f}_1/\mathrm{f}_2$. Often written $\mathrm{M} = \mathrm{f}_\mathrm{o}/\mathrm{f}_\mathrm{e}$.

Binoculars

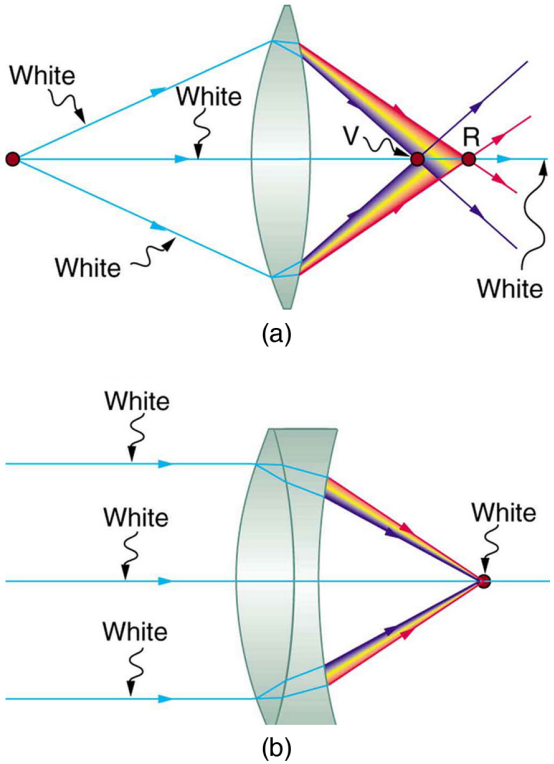
Binoculars are typically referred to with a pair of numbers such as 7 X 50: 7X magnification; 50mm aperture.

Typical binoculars



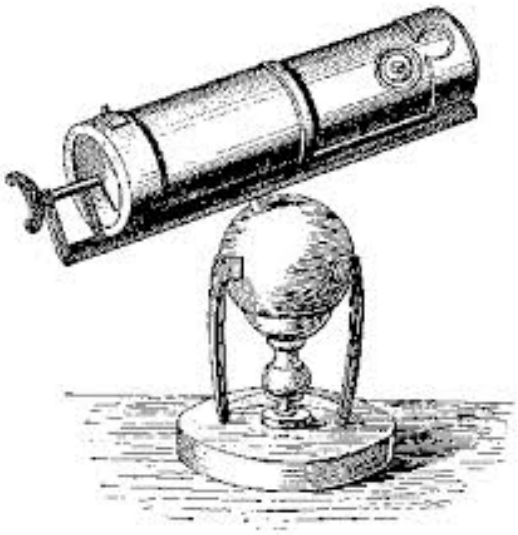
Binoculars are Keplerian telescopes with a pair of prisms which turn the image right side up.

Chromatic Aberration

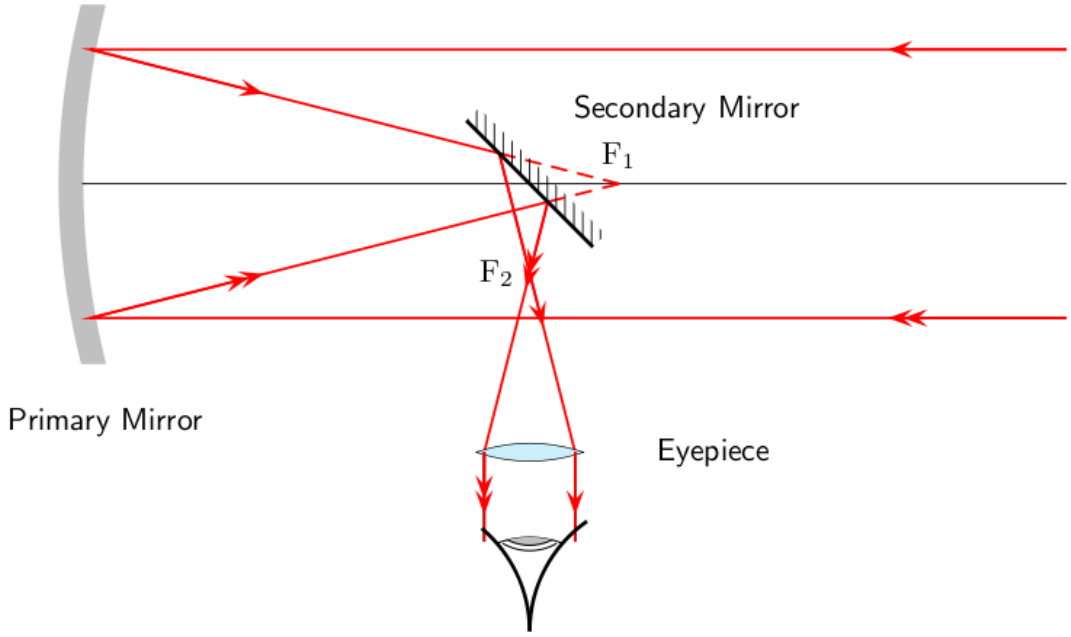


- Uncorrected lenses act like prisms and split the light into different colors.
- Making the lens from two different types of glass can correct for this.
- Reflecting telescopes are also free from this *chromatic aberration*.

Reflecting Telescopes

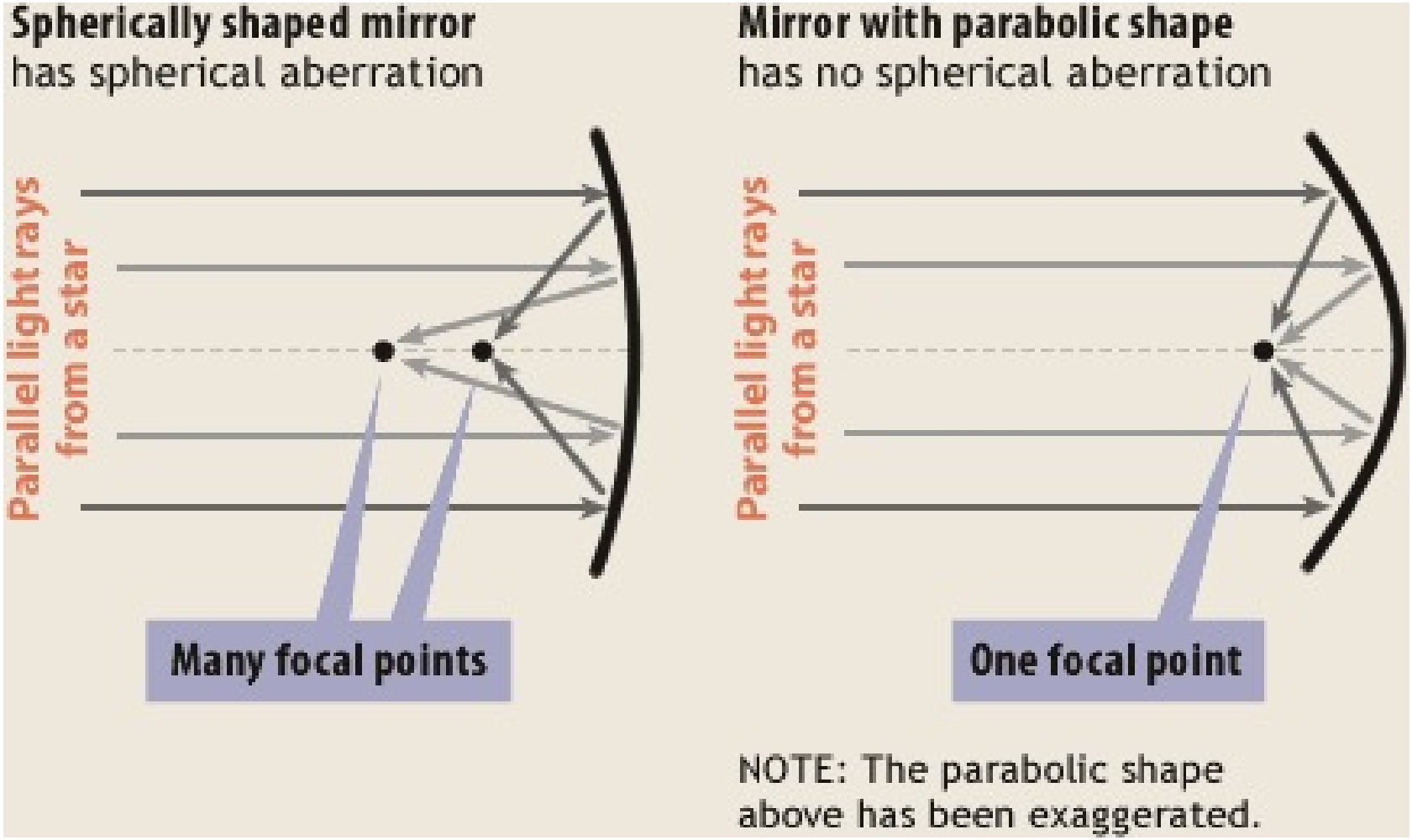


Newton's Telescope



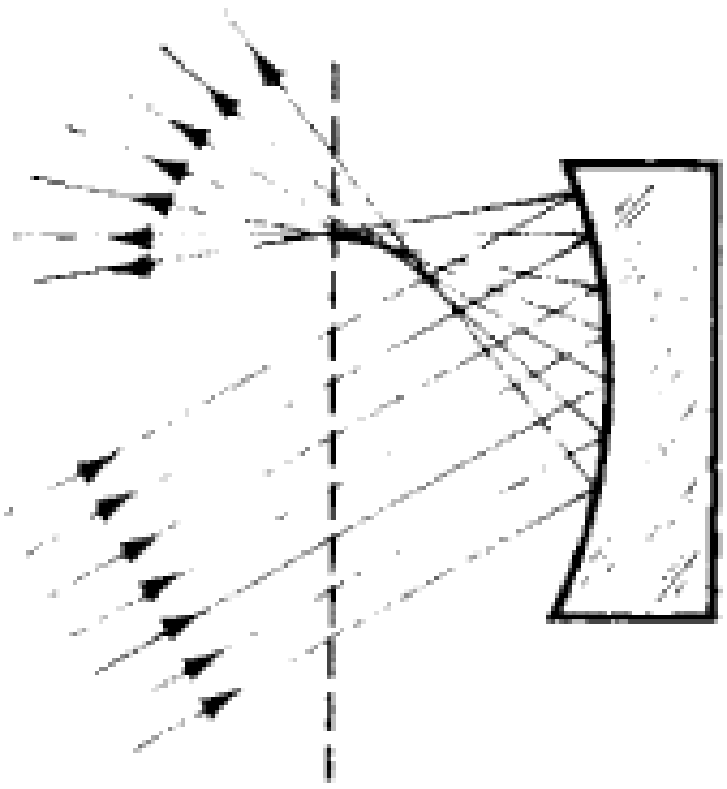
The alt-az telescopes we will use are of this type.

Spherical Aberration



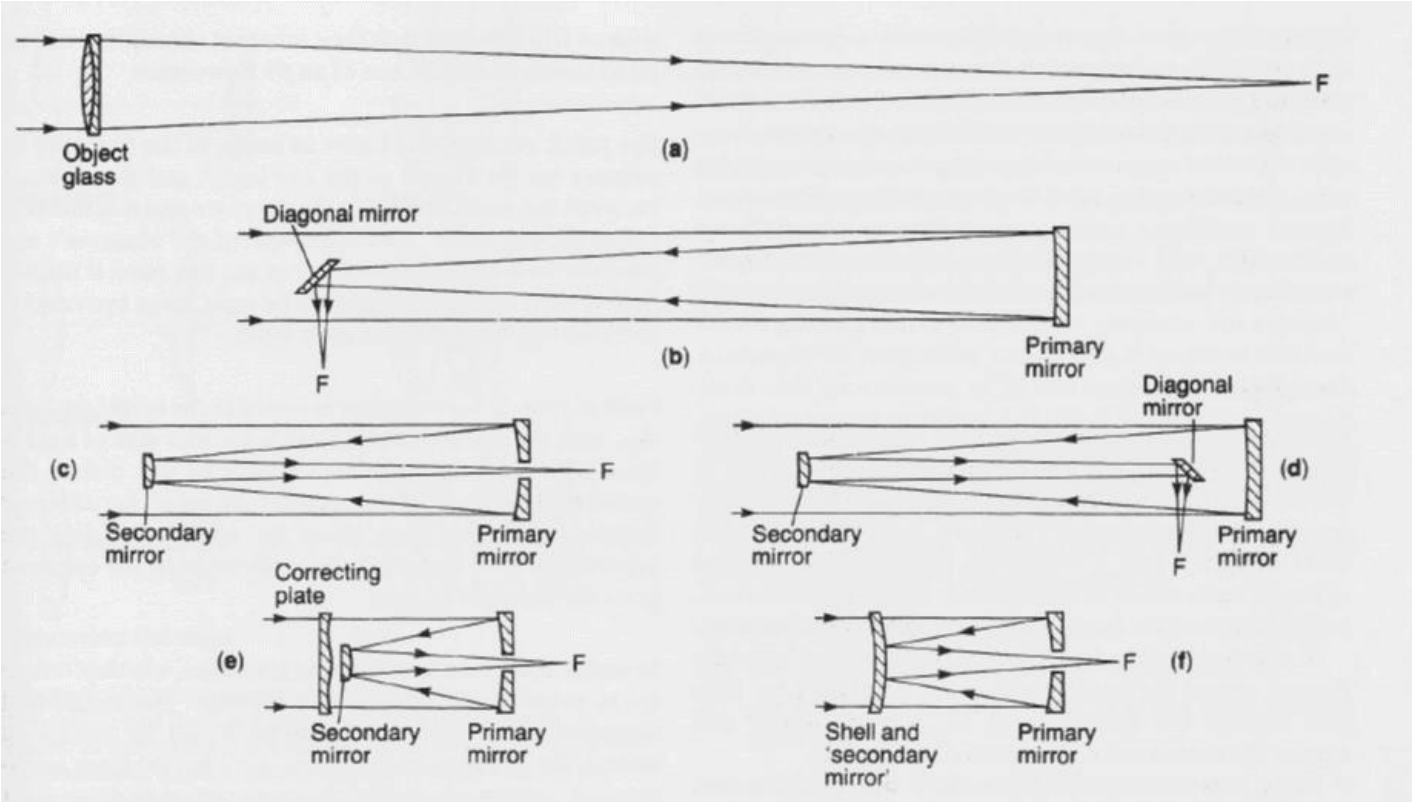
- Spherical mirrors suffer from *spherical aberration*.
- Parabaloidal mirrors focus the light to a point.

Coma



- While parabaloidal mirrors are free from spherical aberration, they suffer from *coma*, where images off the central axis are degraded.
- Modern telescope designs correct for both spherical aberration and coma.

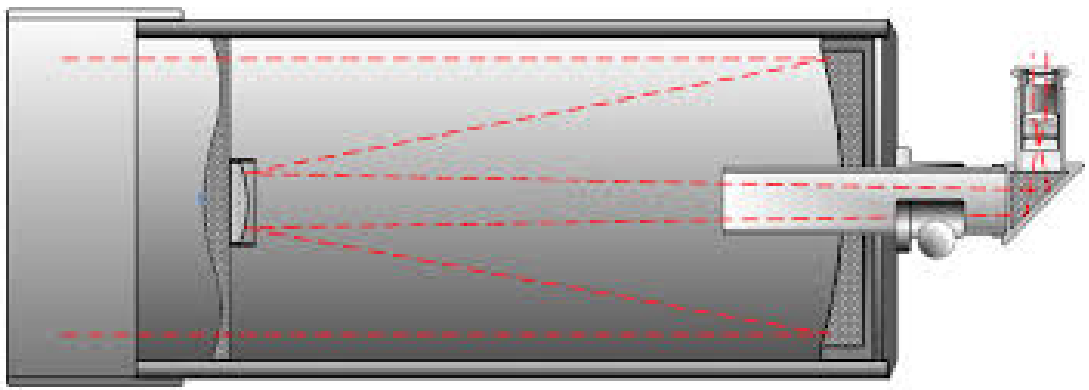
Types of Telescopes



- (a) Refracting
- (b) Newtonian
- (c) Cassegrain
- (d) Cassegrain-Newtonian
- (e) Schmidt-Cassegrain
- (f) Maksutov

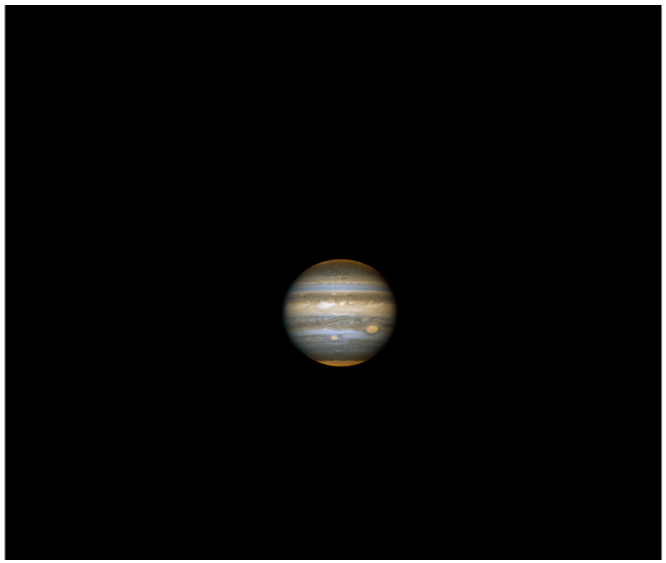
Schmidt-Cassegrain Reflecting Telescopes

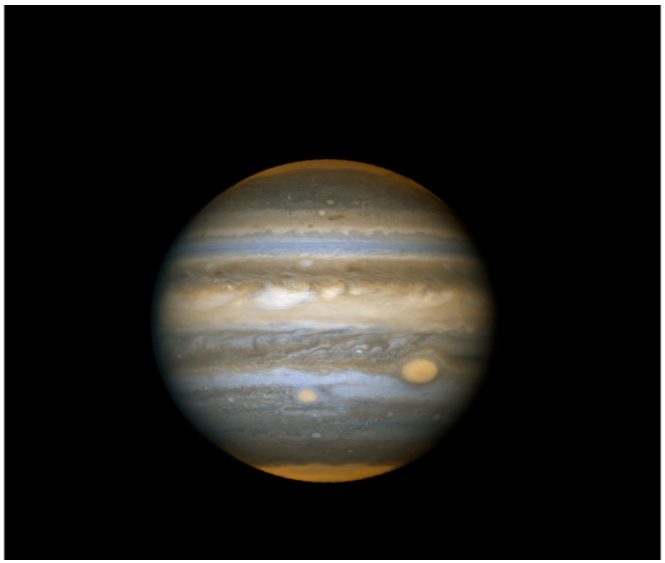
Meade Telescope



The Meade telescopes we will use are of this type.

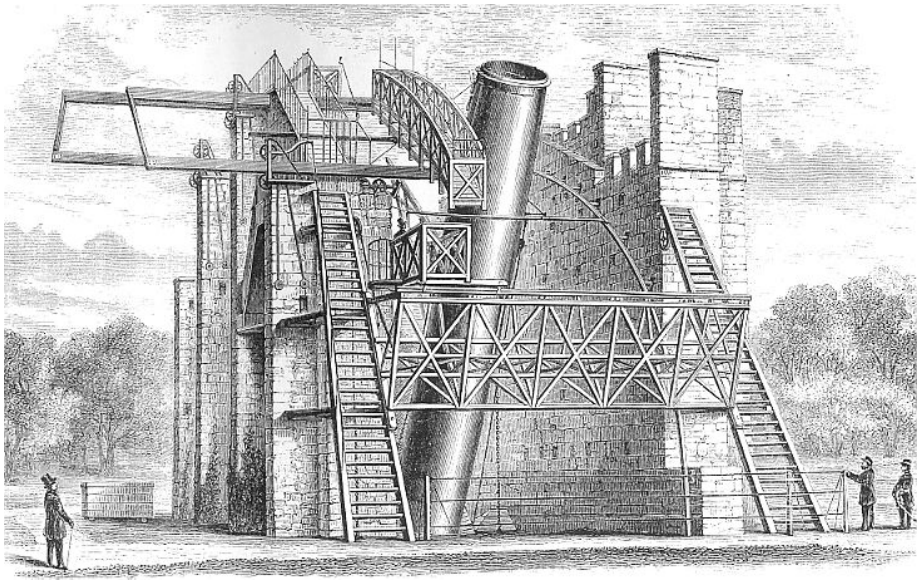
Magnification and Field of View (FOV)



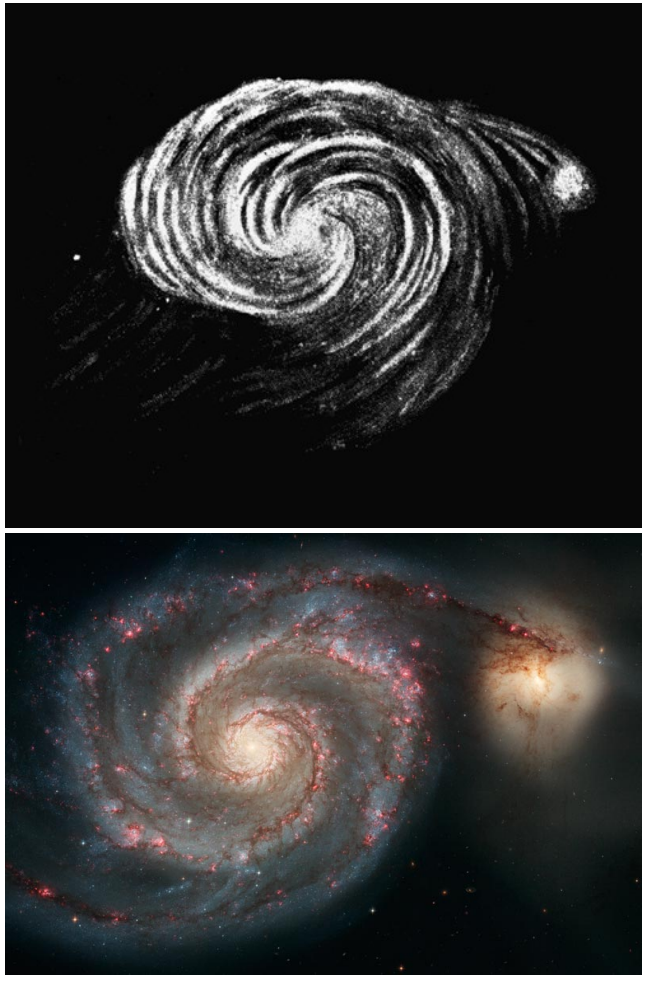


- A higher magnification results in a smaller field of view (FOV).
- $\text{True FOV} = (\text{Apparent FOV})/\text{M}$. Most eyepieces have an apparent FOV of $40° - 50°$.
- Typical True FOV of binoculars is $\approx 6° - 8°$.

Lord Rosse and "The Leviathan of Parsonstown"



Lord Rosse's 48" telescope
ca 1850



Lord Rosse's sketch of M51 and a Hubble photo

Professional Telescopes

Keck twin 10 meter telescopes on Mauna Kea

The 2.5 meter SDSS automated telescope at Apache Point observatory in Arizona

The 2.4 meter Hubble space telescope

Why Bigger and Bigger Telescopes - 1?

- There are two main reasons why a bigger telescope is better.
- One - increased light gathering power:
  - A telescope gathers light in proportion to its area.
  - Pupil of eye $\approx 7\mathrm{mm}$ in diameter in dim light.
  - How much more light does the Keck 10 meter telescope gather?

$$\mathrm{Area\ \ ratio} = \frac{\pi(10000\ \ \mathrm{mm})^2}{\pi(7\ \ \mathrm{mm})^2} = 2.0 \times 10^6$$

  - How does this translate into seeing fainter objects?

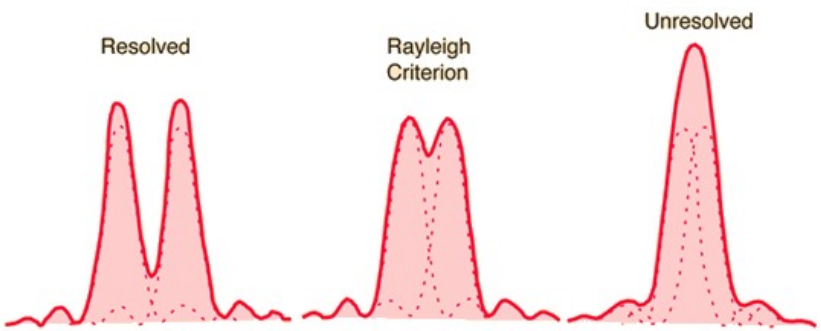
$$\mathrm{m_{Keck}} - \mathrm{m_{Eye}} = 2.5\ \ \log_{10}(\frac{\mathrm{I_{Eye}}}{\mathrm{I_{Keck}}}) = 2.5\ \ \log_{10}(2.0 \times 10^6) = 15.8$$

  - Since the eye can see to about magnitude 6, since means that the Keck can see to about magnitude 22.
  - In practice, Keck can see even fainter (to around m = 27), since it uses CCD detectors which are more sensitive than the eye and store light over long periods.

Why Bigger and Bigger Telescopes - 2?

- Two - increased resolution:
  - The resolution of a telescope is its ability to separate two closely spaced objects.
  - The resolution of a circular aperture is limited by *diffraction*, caused by the wave nature of light.
  - The Rayleigh criterion gives the resolution of a telescope. Here:
    - θ in the angular resolution in radians
    - λ is the wavelength of light
    - D is the diameter of the telescope

$$\theta = 1.22\frac{\lambda}{\mathrm{D}}$$



Resolution Examples - 1

- Example 1 - Human Eye in visible light:
  - λ is the wavelength of visible light = 500 nm = $5.0 \times 10^{-7} m$
  - D is the diameter of the eye = 7 mm = $7.0 \times 10^{-3} m$

$$\theta = 1.22 \frac{5.0 \times 10^{-7} \mathrm{m}}{7.0 \times 10^{-3} \mathrm{m}} = 8.7 \times 10^{-5} \text{ radians}$$

$$\theta = 8.7 \times 10^{-5} \text{ radians} \times \frac{360}{2\pi} \times 60 \times 60 = 18 \text{ arcseconds}$$

- Example 2 - Keck Telescope in visible light:
  - λ is the wavelength of visible light = 500 nm = $5.0 \times 10^{-7} m$
  - D is the diameter of the mirror = 10 m

$$\theta = 1.22 \frac{5.0 \times 10^{-7} \mathrm{m}}{10 \mathrm{m}} = 6.0 \times 10^{-8} \text{ radians}$$

$$\theta = 6.0 \times 10^{-8} \text{ radians} \times \frac{360}{2\pi} \times 60 \times 60 = 0.012 \text{ arcseconds}$$

Resolution Examples - 2

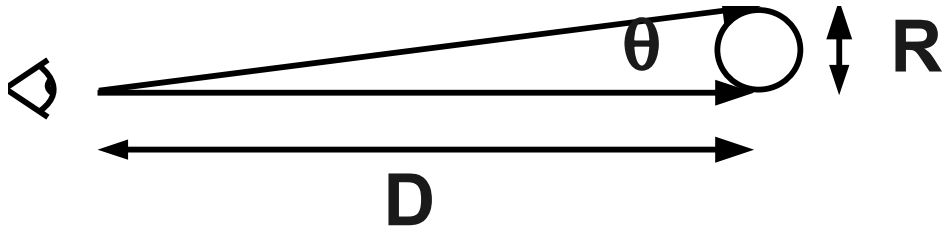
- Example 3 - Hubble Telescope in visible light:
  - λ is the wavelength of visible light = 500 nm = $5.0 \times 10^{-7} m$
  - D is the diameter of the mirror = 2.4 m

$$\theta = 1.22 \frac{5.0 \times 10^{-7}\text{m}}{2.4\text{m}} = 2.5 \times 10^{-7} \text{ radians}$$

$$\theta = 2.5 \times 10^{-7} \text{ radians} \times \frac{360}{2\pi} \times 60 \times 60 = 0.05 \text{ arcseconds}$$

- In practice, atmospheric turbulence limits the resolution of the eye to about 60 arcseconds (1 arcminute), and the resolution of the Keck telescope to about 0.5 - 1.0 arcseconds, while the Hubble, since it is in space, comes very close to achieving its theoretical resolution of 0.05 arcseconds.

Resolution Examples - 3



- What are the implications of angular resolution in terms of resolving physical objects?
- Let's calculate the smallest objects we can see on the moon. Remember, for small angles:

$$\theta = \frac{\mathrm{R}}{\mathrm{D}}$$

$$\mathrm{R} = \theta \mathrm{D}$$

Resolution Examples - 4

- The distance to the moon D is about 380,000 km, so $\mathrm{D} = 3.8 \times 10^8 \mathrm{m}$.
- For the eye:

$$\theta = \frac{1.0\mathrm{arcminute}}{60} \times \frac{2\pi}{360} = 2.9 \times 10^{-4} \text{ radians}$$

$$\mathrm{R} = 2.9 \times 10^{-4} \times 3.8 \times 10^8 \mathrm{m} = 1.1 \times 10^5 \mathrm{m} = 110\mathrm{km}$$

- For the Keck:

$$\theta = \frac{1.0\mathrm{arcsecond}}{3600} \times \frac{2\pi}{360} = 4.8 \times 10^{-6} \text{ radians}$$

$$\mathrm{R} = 4.8 \times 10^{-6} \times 3.8 \times 10^8 \mathrm{m} = 1.8 \times 10^3 \mathrm{m} = 1.8\mathrm{km}$$

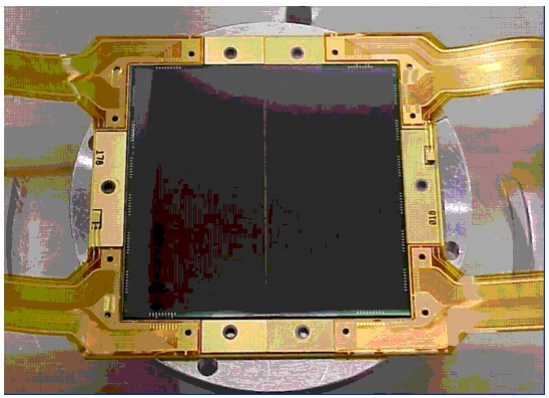
- For the Hubble:

$$\theta = \frac{0.05\mathrm{arcsecond}}{3600} \times \frac{2\pi}{360} = 2.4 \times 10^{-7} \text{ radians}$$

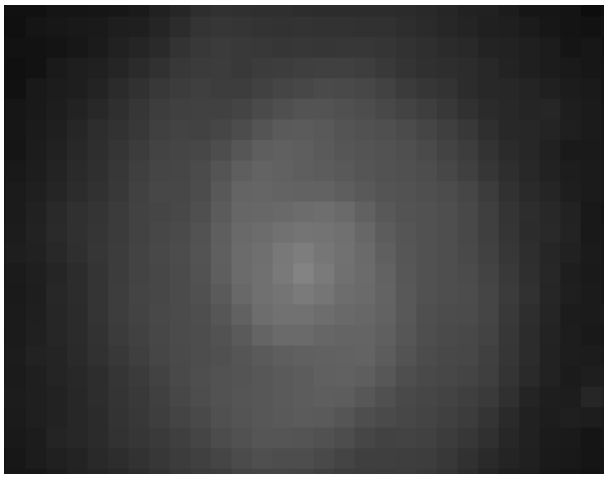
$$\mathrm{R} = 2.4 \times 10^{-7} \times 3.8 \times 10^8 \mathrm{m} = 92\mathrm{m}$$

Detectors

- The first telescopes used the human eye as detectors.
- In the 20th century, photographic plates proved much better.
  - They are more sensitive than the eye.
  - They can collect light for long periods of time.
- Today, the CCD (Charged-Coupled Device) imager is the preferred detector.
  - They produce a digitized image that can be read out electronically.

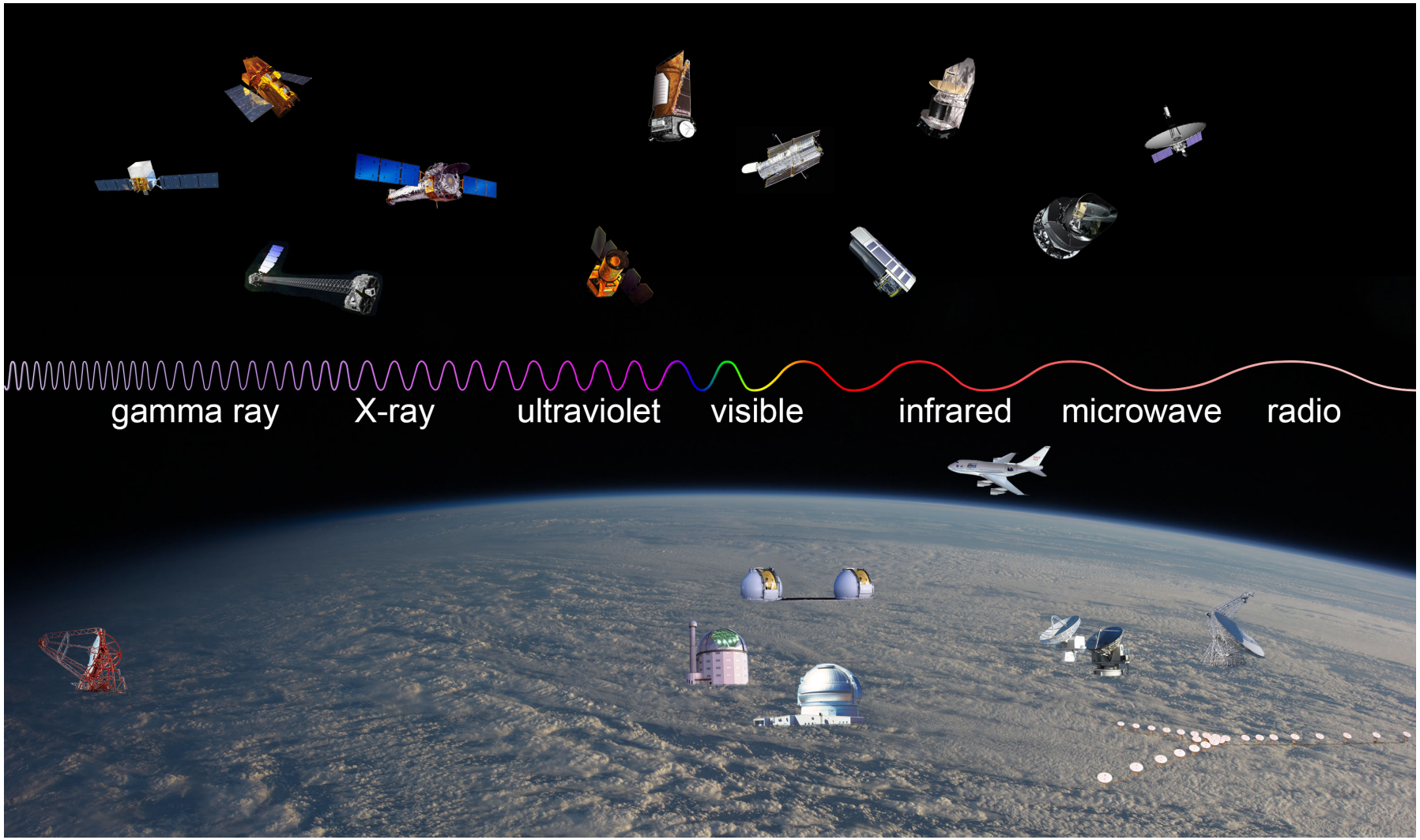


A CCD imager (4096x4096) from the Hubble space telescope.

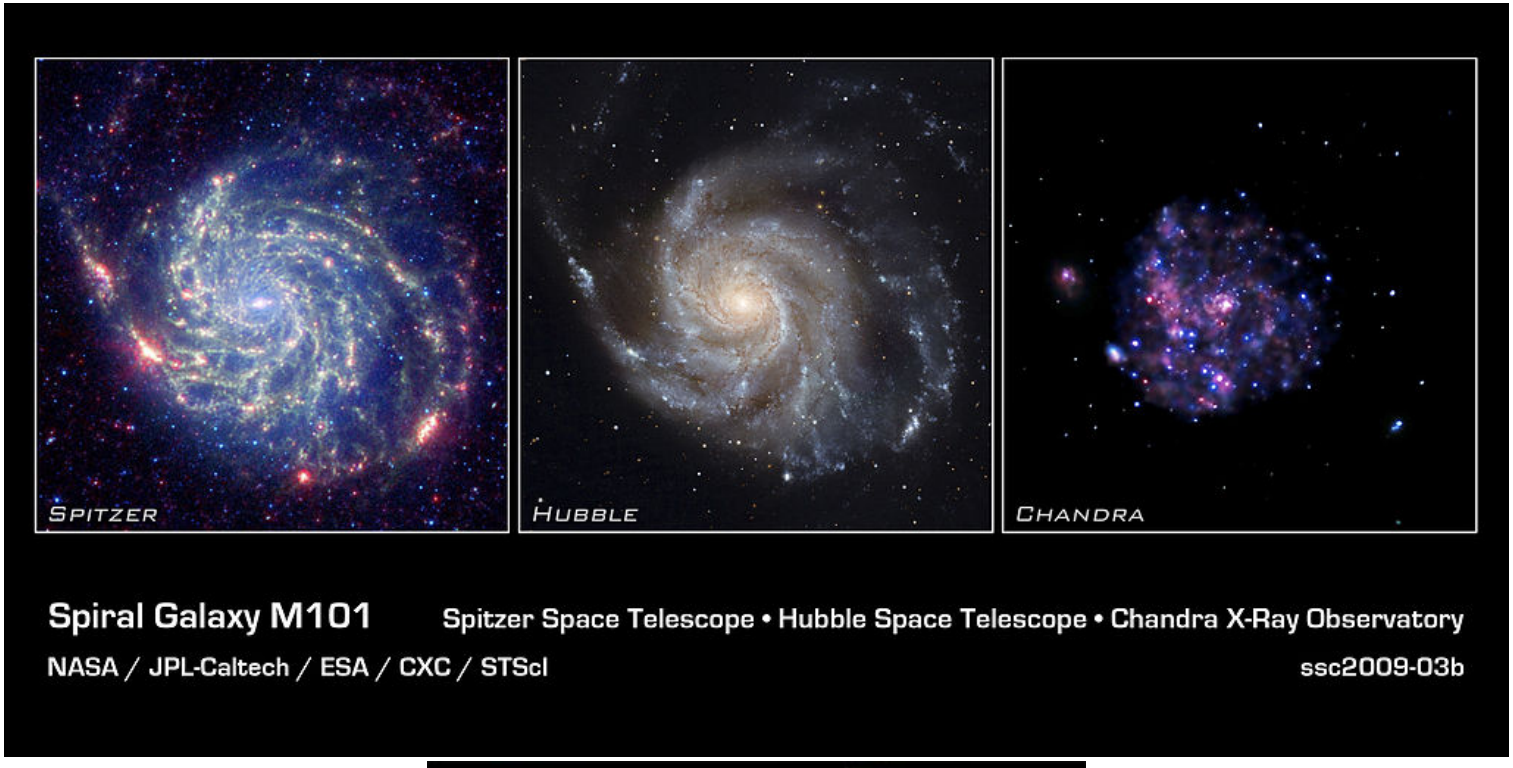


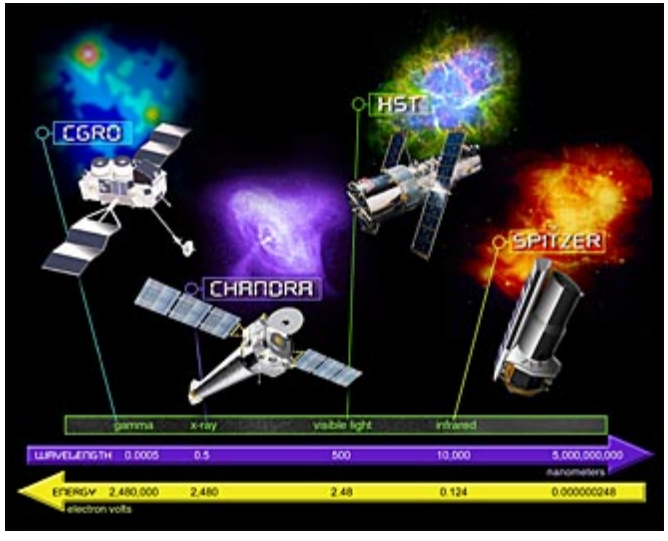
A portion of a Hubble image showing pixels.

Observatories Across the EM Spectrum

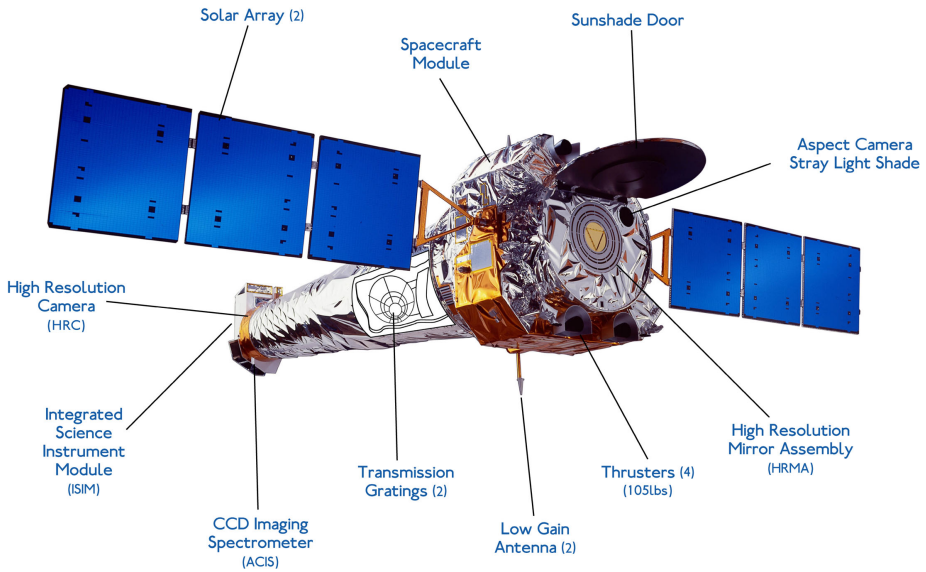


NASA's "Great Observatories"

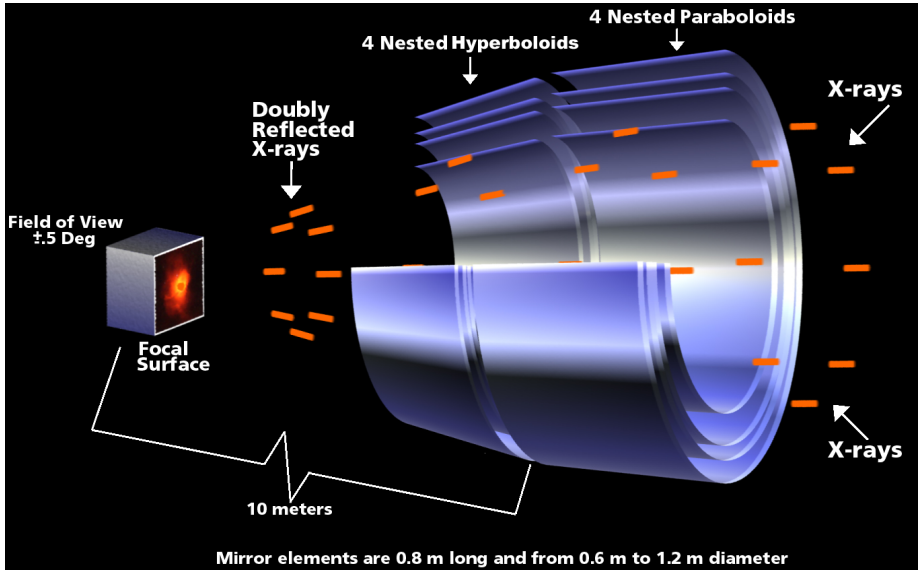




The Chandra X-ray Telescope



The Chandra spacecraft



How the grazing incidence mirrors achieve a focus.

The ATC Radio Telescope Array in Australia

Six 22 meter dishes.

Radio Telescope Resolution

- Rememeber, angular resolution is given by:

$$\theta = 1.22\frac{\lambda}{\mathrm{D}}$$

- What does this mean for radio telescopes?
  Suppose f = 1GHz, D = 22m

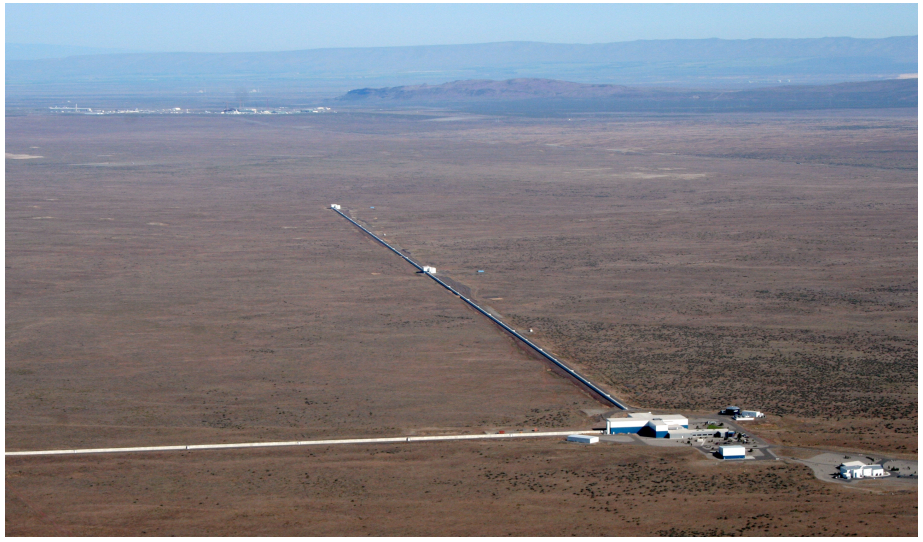
$$\lambda = \frac{\mathrm{c}}{\mathrm{f}} = \frac{3.0 \times 10^8 \mathrm{m}}{10^9 \mathrm{Hz}} = 30\mathrm{cm}$$

$$\theta = 1.22\frac{0.3\mathrm{m}}{22\mathrm{m}} = .014 \text{ radians} = 0.8^\circ$$

- So this huge radio dish, 22 meters across, has a resolution about 50 times worse than your eye in visible light!

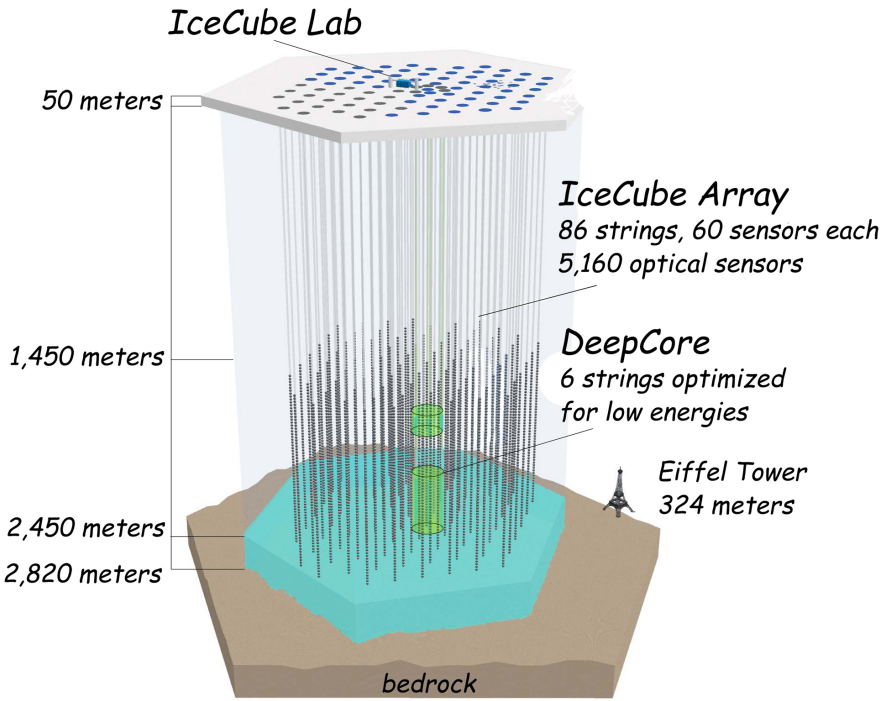
LIGO Gravitational Wave Telescope

LIGO Observatory in Louisiana.

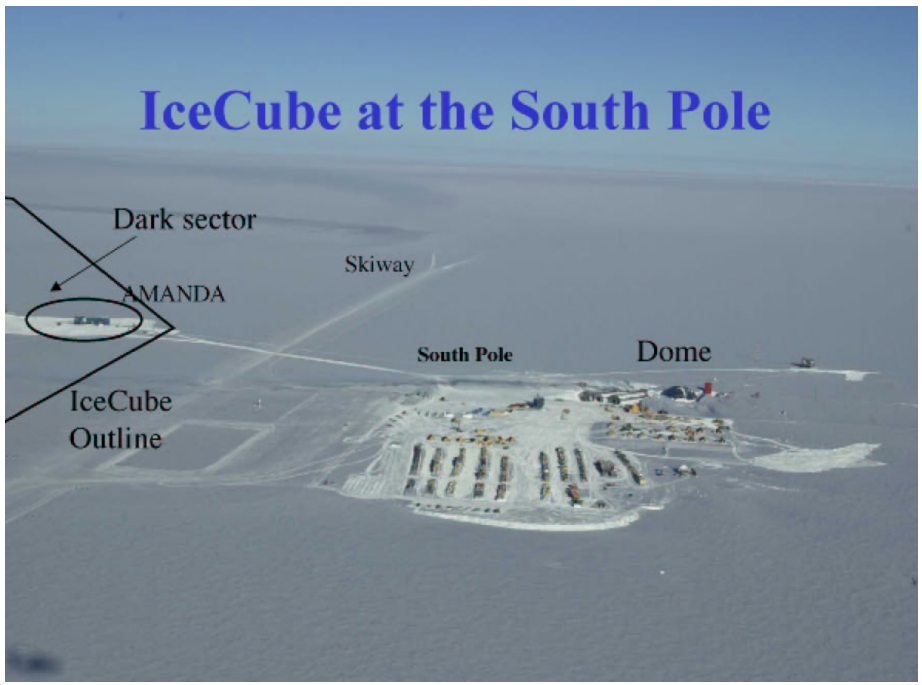


LIGO Observatory in Washington state.

The IceCube Neutrino Telescope



IceCube covers a cubic kilometer of ice in Antarctica.



An aerial view of the surface.

Summary

1. The Electromagnetic Spectrum covers a huge range - from radio waves to gamma rays.
2. Our eyes are only sensitive to a small part of the EM spectrum.
3. Telescopes gather much more light, and have much higher resolving power than our eyes.
4. Telescopes in space are probing much more of the EM spectrum, since most radiation does not reach the ground.
5. We are beginning to probe the universe in other ways than just EM waves.