

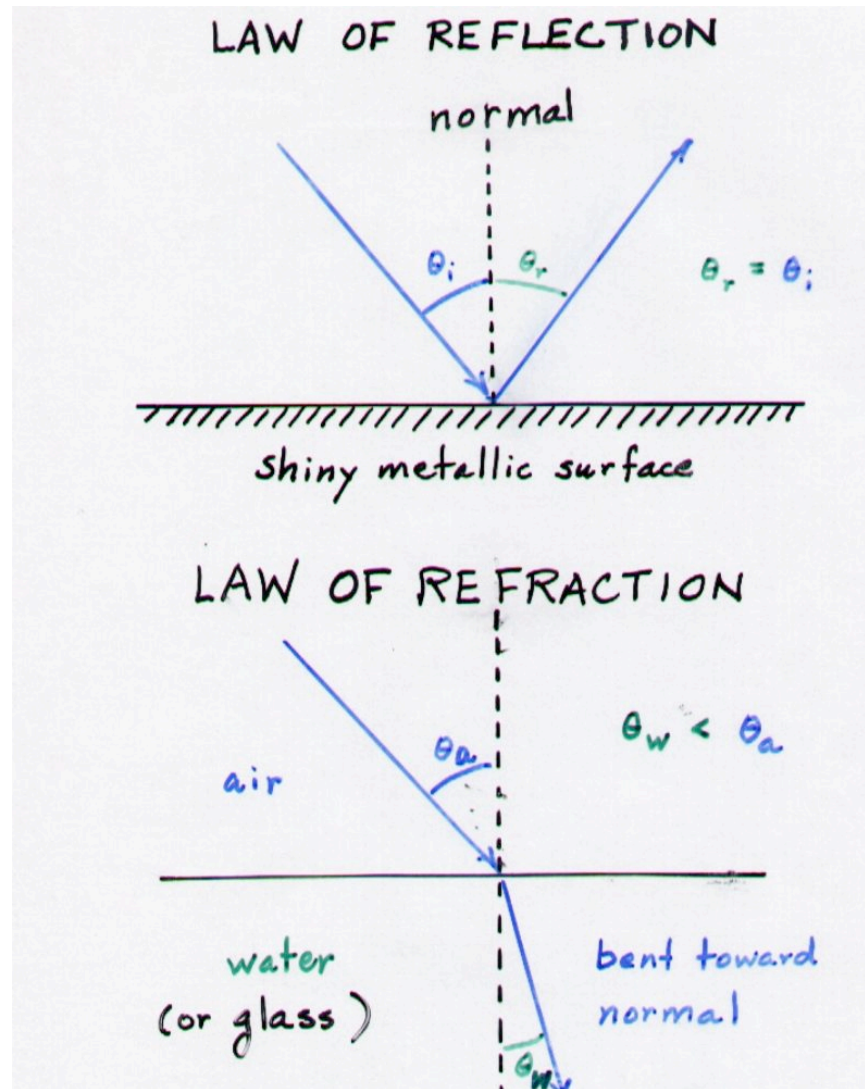
# Lecture 9

## Telescopes & Light

# Outline of Lecture 9

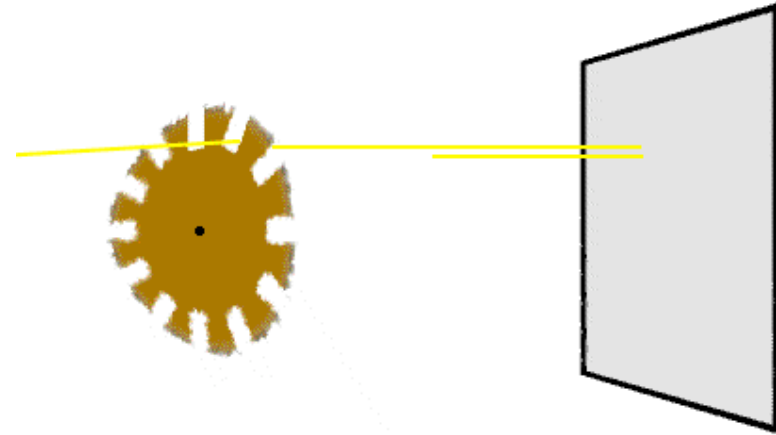
- Nature of Light:
  - Laws of refraction and reflection.
  - Wave versus particle picture of light.
  - The speed of light & Roemer's observations of Galilean satellites
- Refracting versus reflecting telescopes:
  - Newton's dissatisfaction with chromatic aberration of refracting telescopes.
  - Newton's discovery of dispersion of white light into spectrum of colors.
  - Newton's invention of a reflecting telescope.
- Angular resolution:
  - Astronomical seeing and diffraction limit.
  - Adaptive optics.
  - Aperture synthesis.

# Reflection & Refraction

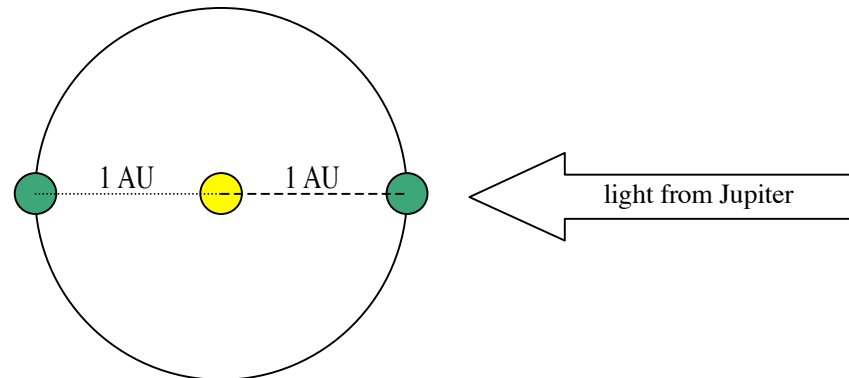


# Speed of Light & Value of AU

- Galileo attempts to measure the speed of light. Eventual success with Fizeau in 1849:  
 $c = 3.00 \times 10^8 \text{ m s}^{-1}$  (in vacuum).
- Galileo suggests using transits/eclipses of moons of Jupiter as clock for determining longitude at sea (cf. concept of time zones).
- Ole Roemer (1644-1710) tries to get very accurate predictions of when transits/eclipses will occur. Find discrepancies of about 1000 s depending on whether Jupiter is in conjunction or opposition from the Sun. Concludes diameter of circular orbit of Earth around Sun = 1000 lt-sec (i.e., light takes 1000 s to traverse 2 AU).
- With Fizeau's value for  $c$ ,  $1 \text{ AU} = 500 \text{ lt-sec} = 1.50 \times 10^{11} \text{ m}$ .



Prentice-Hall

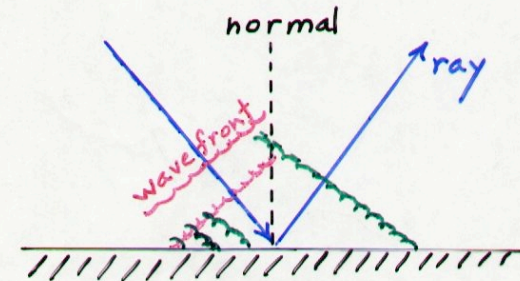




# Nature of Light

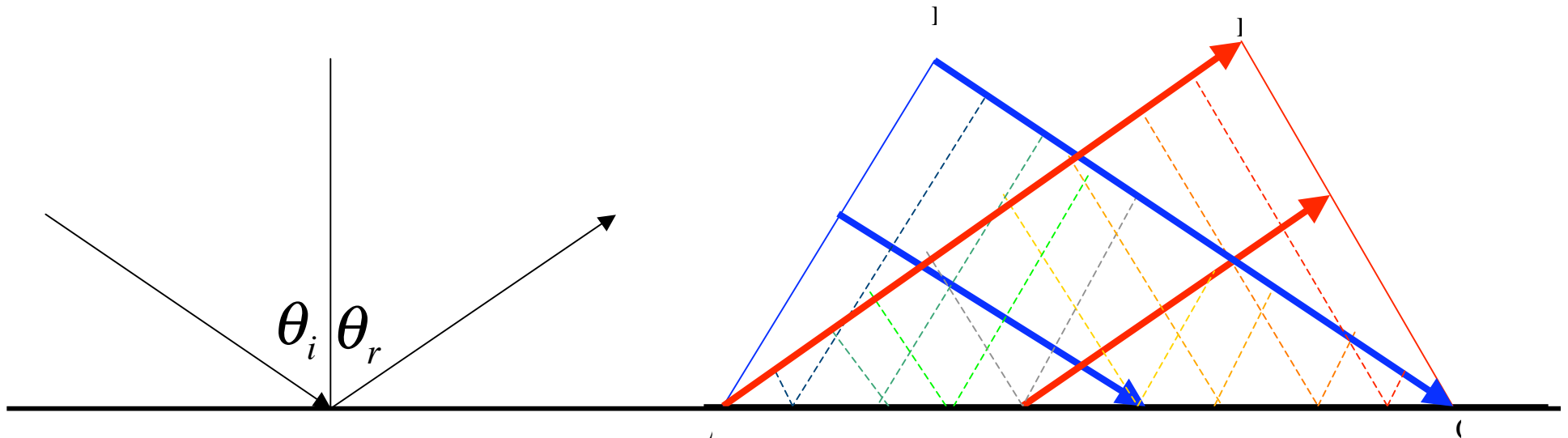
- Huygens: Light is a *wave*, whose influence propagates by spreading from point to point, reinforcing or destroying the influence of other waves.
- Newton: Light is a *particle* (termed by Newton, a *corpuscle*), which propagates in a straight line from point to point, unless it *reflects* from obstacles, or *refracts* upon entering a different medium inside of which it slows down or speeds up. Rays are paths traced by particles of light.

Huygen's principle and the law of reflection



Propagation of wavelets to new points, which act as sources of new wavelets. Wavefront = locus where wavelets' crests add constructively. Rays are directions perpendicular to wavefronts (apparent directions of propagation).

# Reflection



Corpuscular reflection

$$\theta_r = \theta_i$$

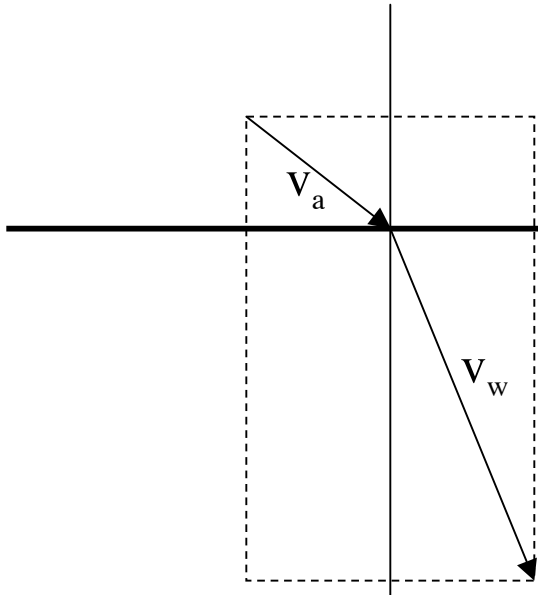
for an elastic bounce in which perpendicular velocity is reversed.

Wave reflection from (infinite) mirror according to Huygen's principle also gives

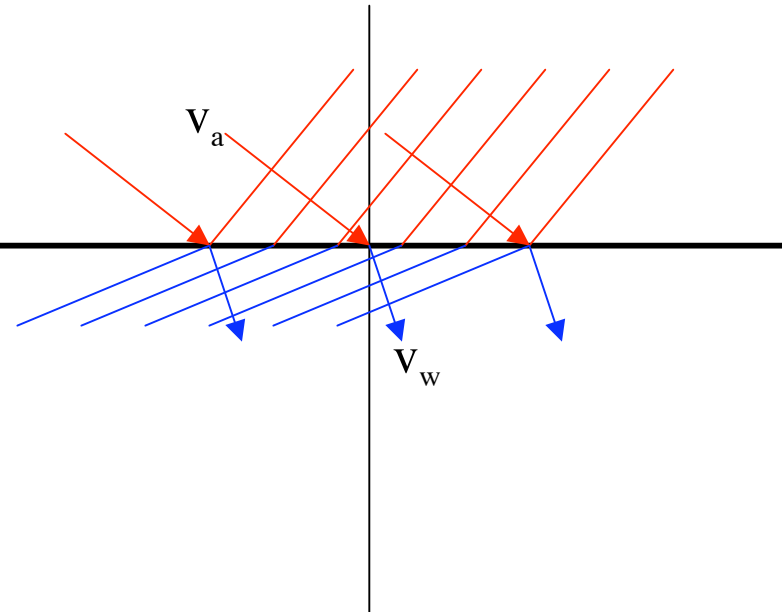
$$\theta_r = \theta_i$$

No difference because of light is propagating in same medium (air) before and after reflection.

# Refraction



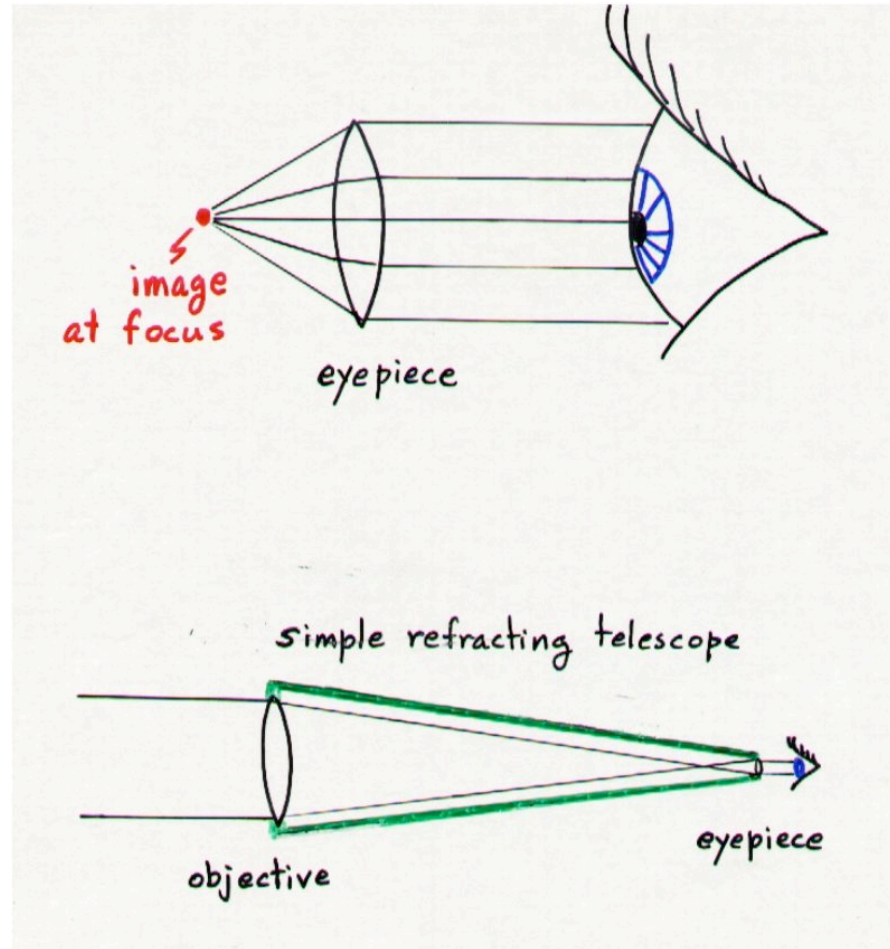
To explain observed behavior, speed of **light corpuscle** in water  $v_w$  must be greater than its speed in air  $v_a$ .



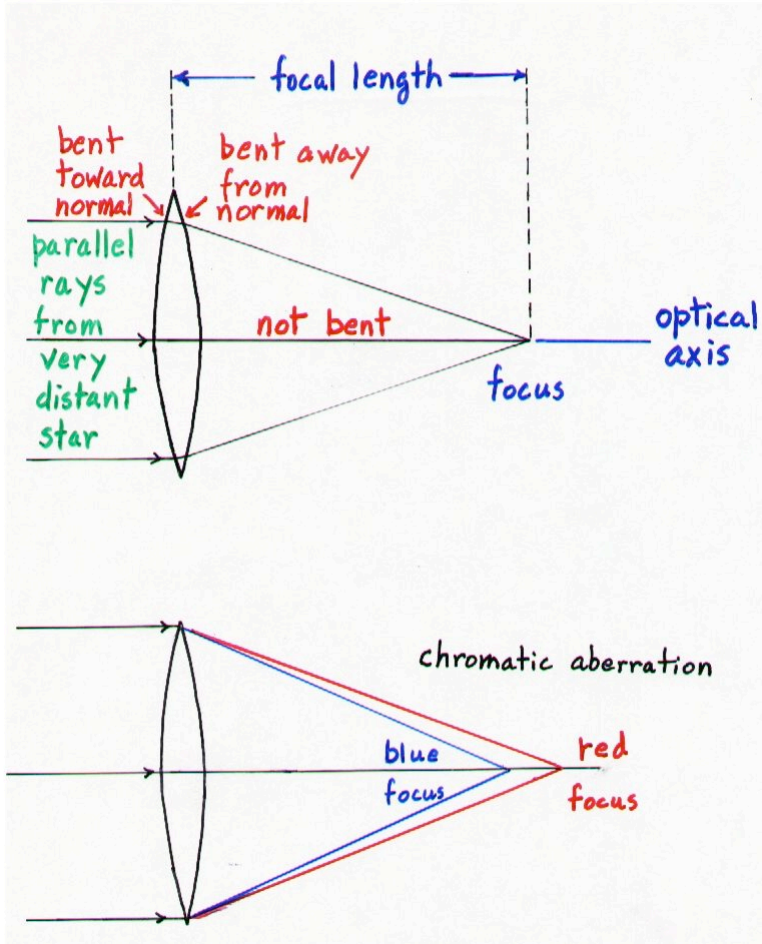
To explain observed behavior, speed of **light wave** in water  $v_w$  must be smaller than its speed in air  $v_a$ .

Now known that  $v_w < v_a$ , which favors wave theory of light

# Lens as Eyepiece and Simple Refracting Telescope

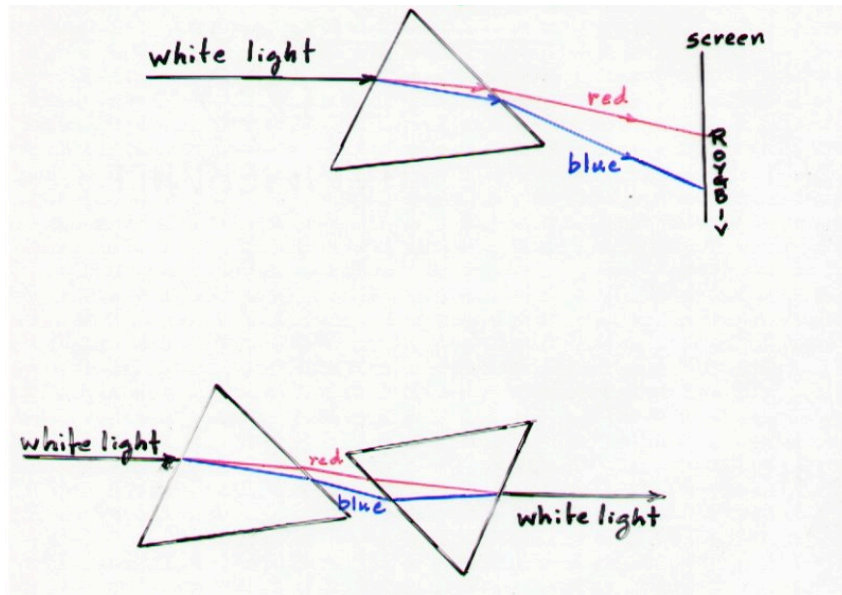


# Principle of Lens



# Natural Light Is Made of Spectrum of Colors

Dispersion of white light by a prism:

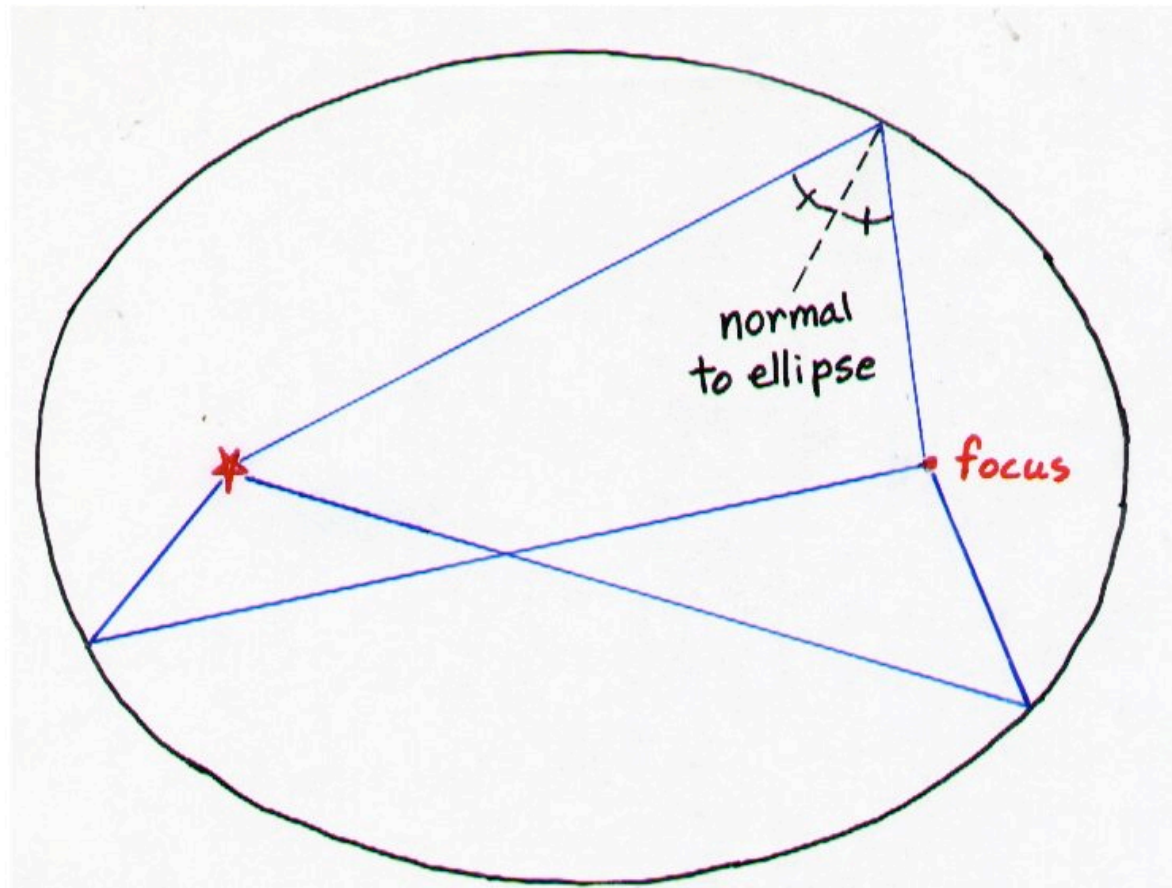


Newton's use of two prisms shows that colors were not added by prism to colorless (white) light. Instead color is an intrinsic part of the different components of light. (Natural light contains a *spectrum*.)

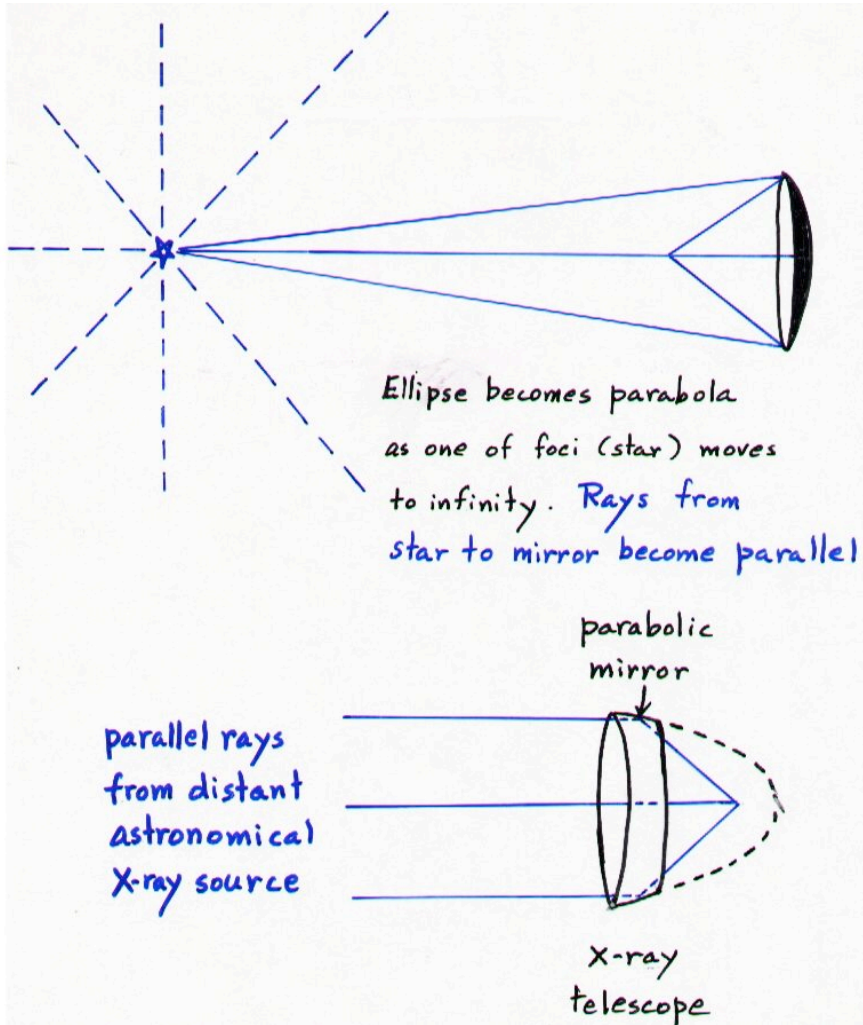




# Alhazen (965-1040): Ellipse Brings Light from One Focus to Other Focus

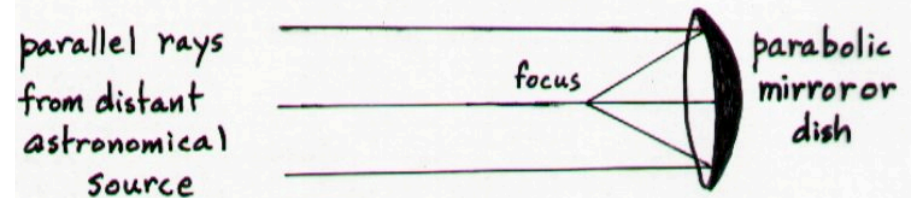


# When Source Moves to Infinity, Needed Ellipse Becomes Parabola



Parabolic mirror focuses light from point source at infinity

## Reflecting Telescope

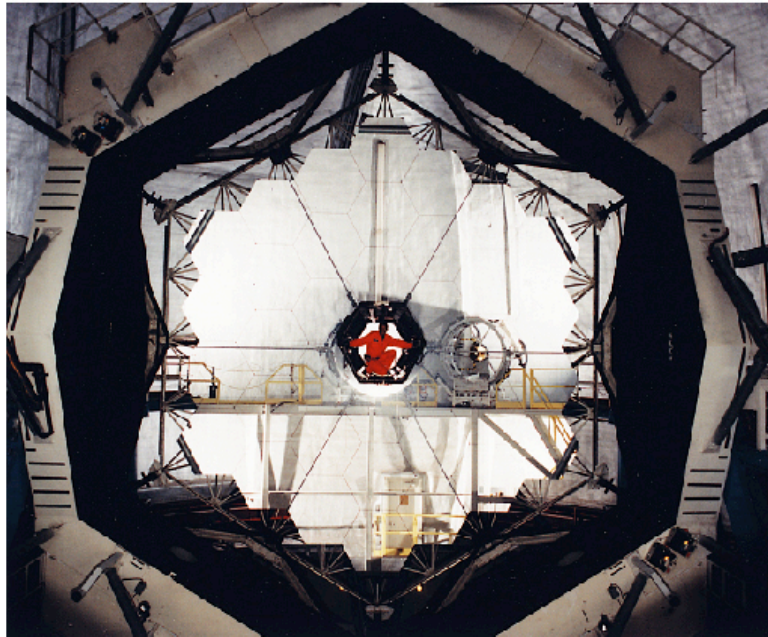


Note viewing is at Newtonian focus

Newton's reflector

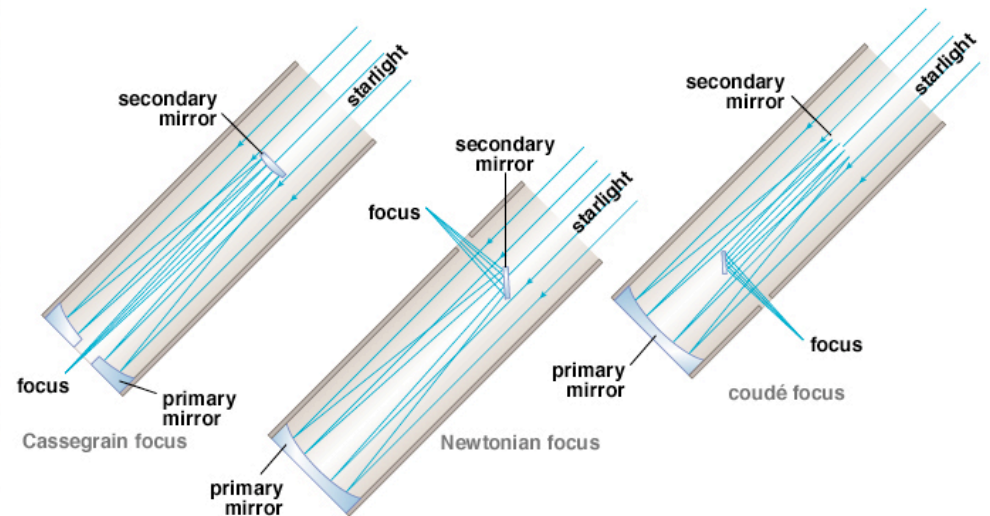


# All Large Telescopes Built Today Are Reflectors



(b)  
Copyright © Addison Wesley

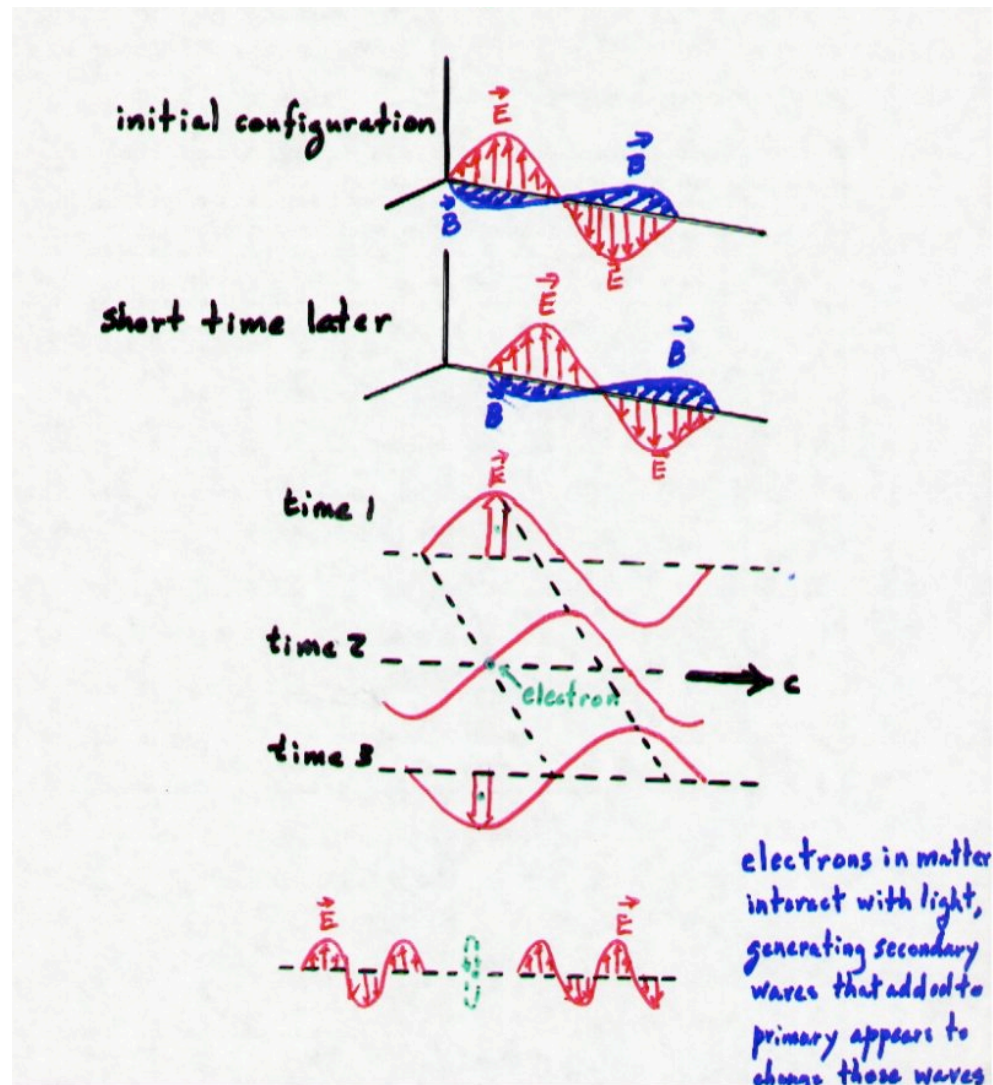
Keck telescope with 36  
parabolic segments =  
10 m mirror



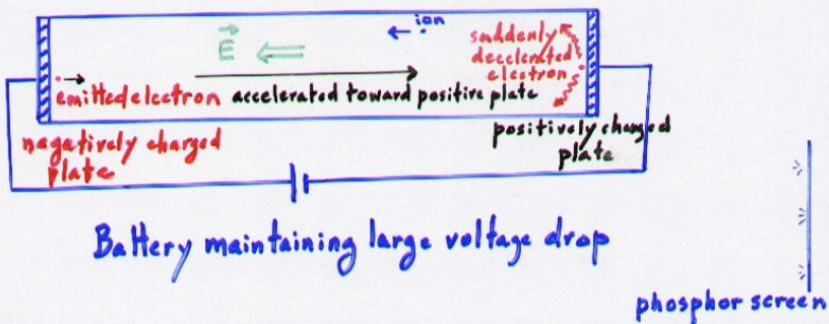
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Possible focal arrangements,  
apart from prime focus in front,  
for a modern telescope

# Huygen's Principle from How a Charged Particle Interacts with Light (extra material)



# Discovery of X-Rays by Roentgen (1845-1928)



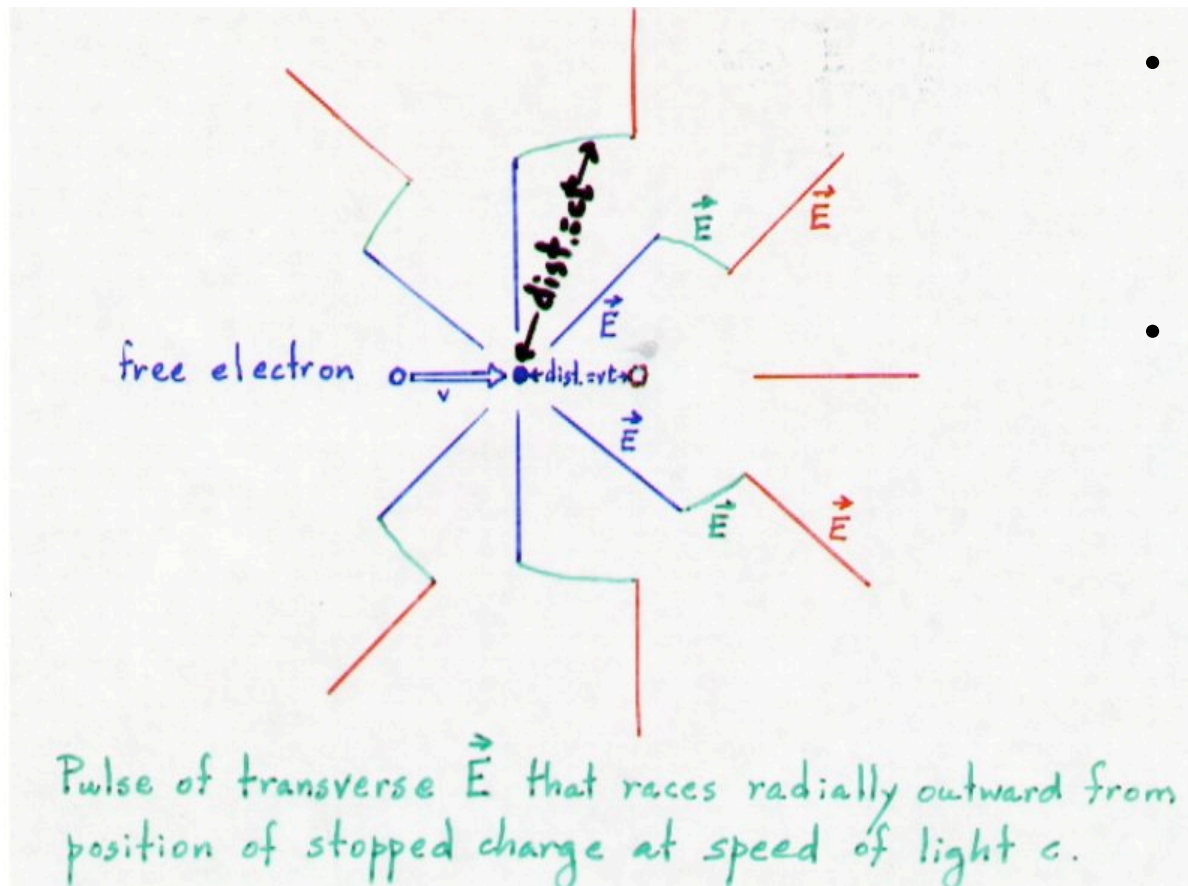
- Put hand between cathode-ray tube and phosphor screen to block stray light or particles - see bones of hand! Penetrating rays of unknown nature: X-ray
- Modern CRT (TV, Computer monitor)



Harvard Medical School

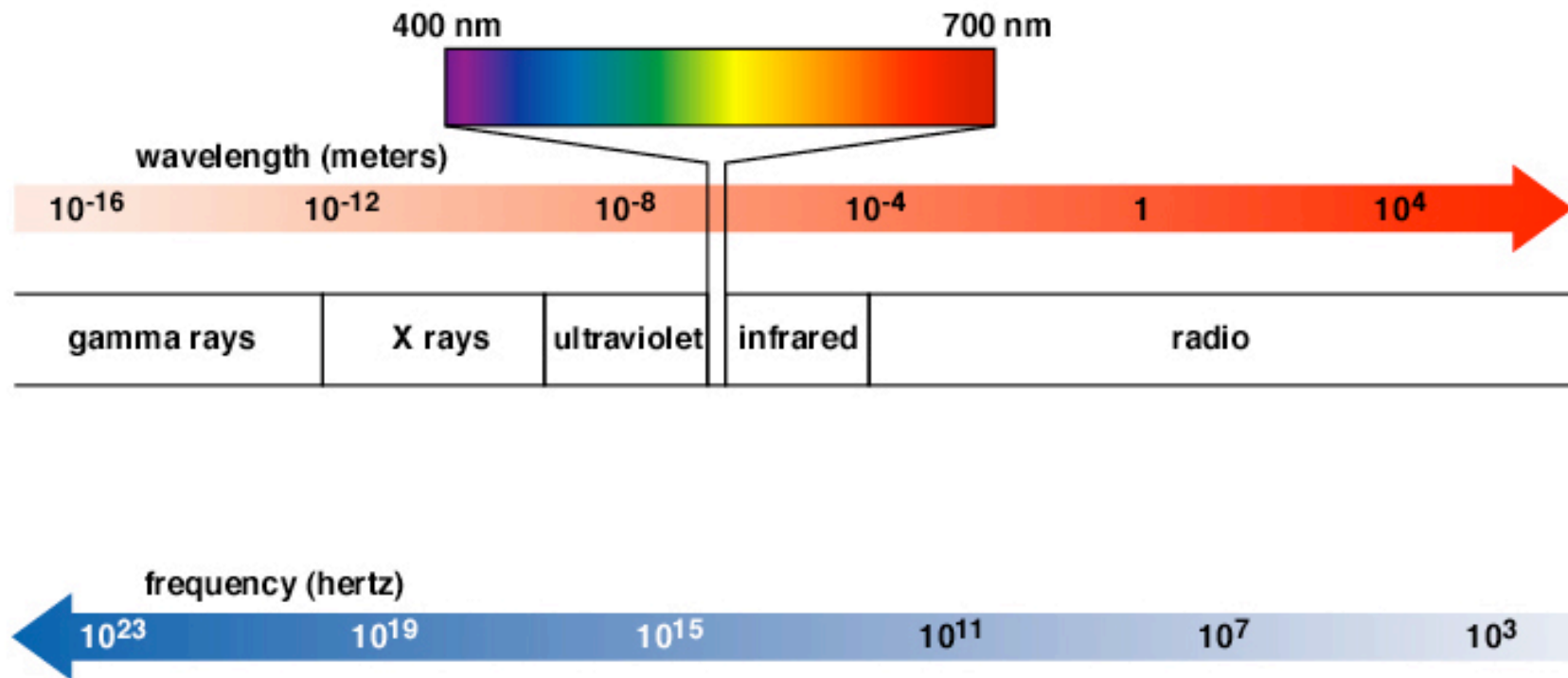


# Radiation from a Suddenly Stopped Charge (extra material)



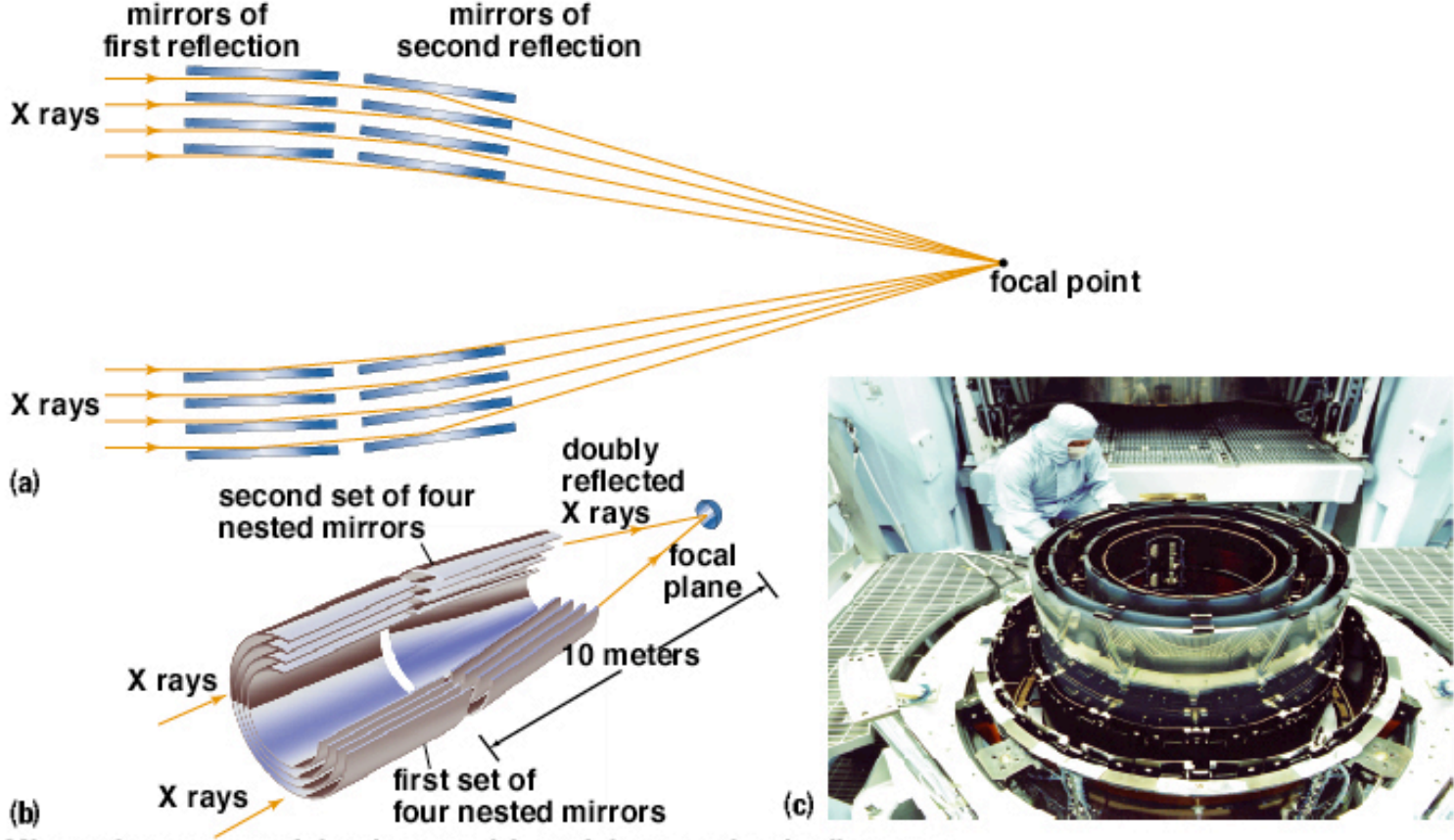
- Classically, a charged particle will emit radiation whenever it is accelerated or decelerated.
- The more violently a moving charge is accelerated or decelerated, the more kinked is the resulting transverse  $\vec{E}$ , i.e., the shorter is wavelength and period of the emitted radiation associated with the pulse of light.

# The Electromagnetic Spectrum



Addison-Wesley

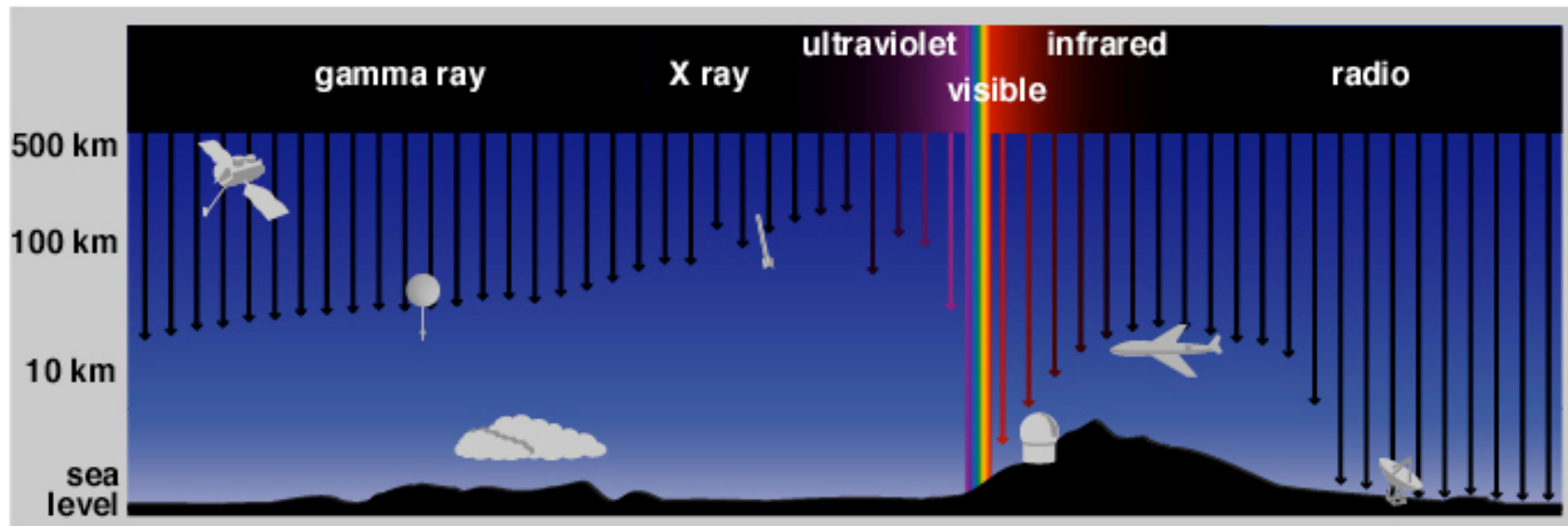
# Principle of X-Ray Telescopes (extra material)



Mirror elements are 0.8 m long and from 0.6 m to 1.2 m in diameter.

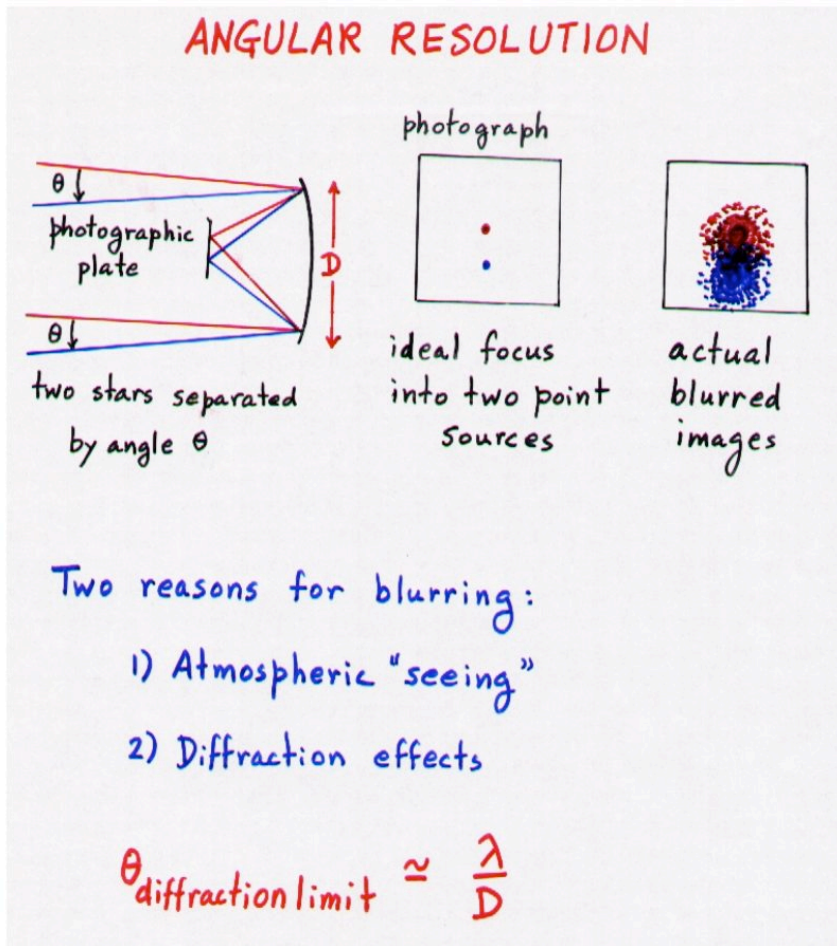
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# Transparency of Atmosphere at Different Wavebands

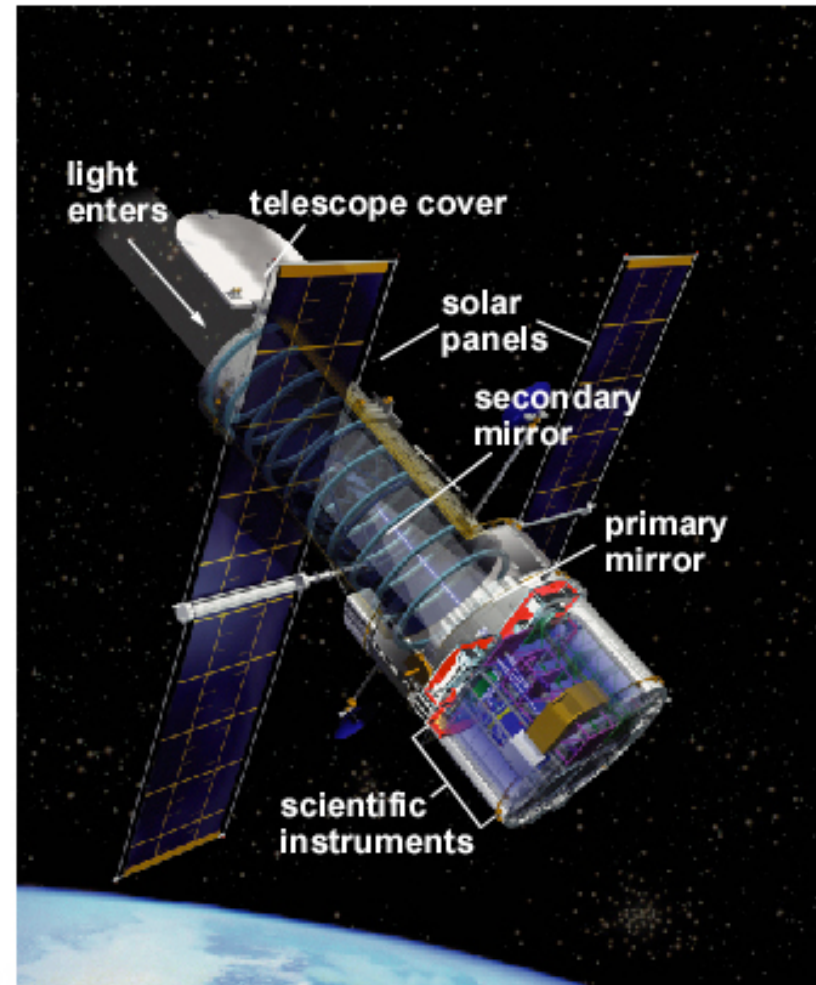




# Why Human Eyes and Telescopes Do Not Form Perfect Images



At visible wavelengths, for human pupil,,  
 $\lambda / D \approx 5 \times 10^{-4}$  rad = 1.5 arcmin.



(b) Hubble telescope gets above atmospheric turbulence.

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# Correction for Atmospheric Turbulence by Adaptive Optics (extra material)

### Adaptive Optics

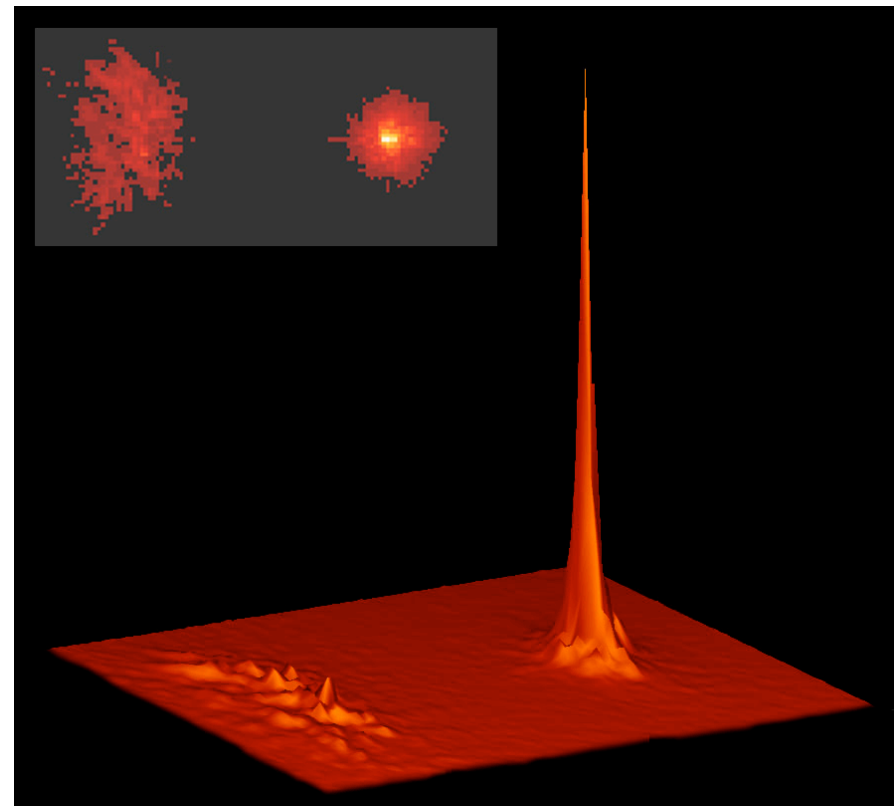
The diagram illustrates the principle of Adaptive Optics. On the left, 'incident wavefront in space' is shown as a flat blue line with downward arrows. A 'fixed flat mirror' (represented by a hatched blue line) reflects it as a 'reflected wave' (red line with upward arrows). On the right, 'starlight through turbulent air' is shown as a distorted blue line with downward arrows. An 'actuated deformable mirror' (represented by a blue line with vertical bars of varying heights) reflects it as a 'corrected plane wave' (red line with upward arrows).

### Image of Star

The image shows two star images. The one on the left is labeled 'without AO' and is a blurry, multi-colored cluster of pixels. The one on the right is labeled 'with AO' and is a sharp, single red dot.

- Everything in small field of view about star is also corrected for atmospheric turbulence (light passes through the "same air").
- Natural guide star versus artificial guide star.

Stellar Image with and without AO



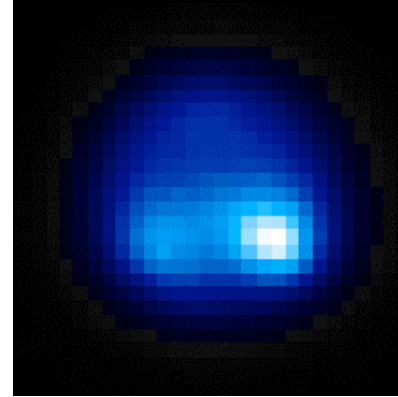
Center for Adaptive Objects

# Adaptive Optics in Action (extra material)

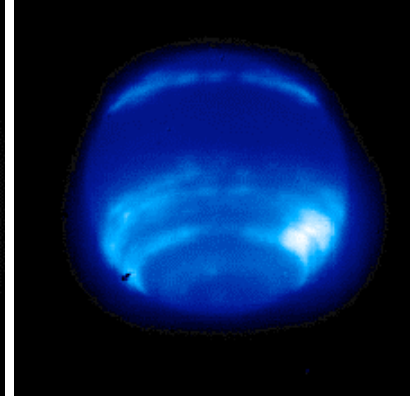
Laser guide star



Neptune without AO



Neptune with AO



Example of adaptive optics on globular cluster M13

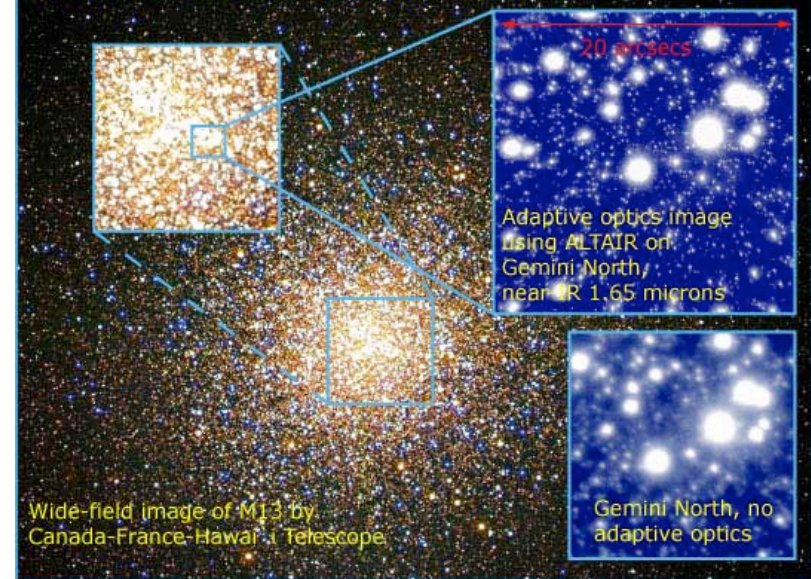
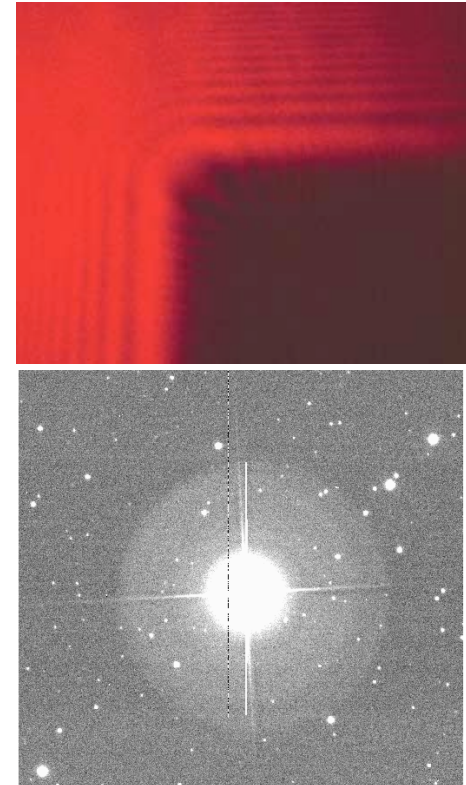


Photo Credits: Center for Adaptive Optics

# Diffraction

- Sound is a wave (alternating regions of high and low pressure).
- Light is a wave (alternating directions of electric and magnetic fields).
- Sound diffracts around corners, so we can hear a person through an open door even if we cannot see her.
- Why doesn't light bend around corners (of the door)? Answer: it does, but the effect is too subtle to notice unless we perform careful experiments.

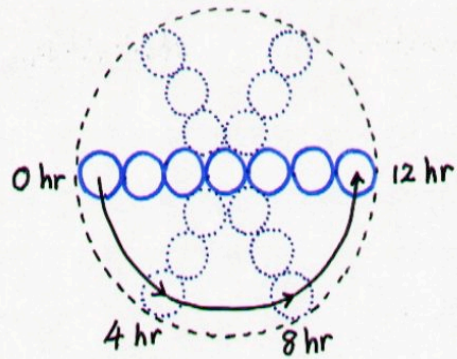
Diffraction rings as well as chromatic aberration seen through a 1 inch refractor.



Diffraction patterns formed by corner of a razor blade and by circular aperture of a reflecting telescope and its struts.



# Simulating a Large Telescope with an Array of Small Ones



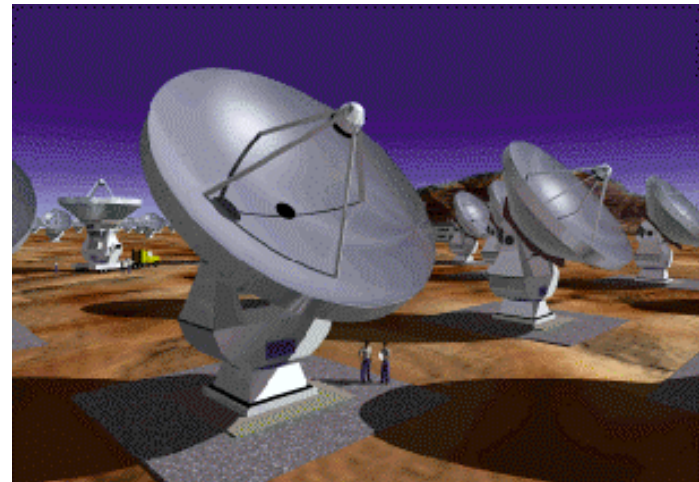
aperture synthesis

$$\theta_{\text{diffraction limit}} \approx \frac{\lambda}{D}$$

Can achieve  $10^{-3}$  arcsecond resolution  
if have radio telescopes that span continents.



VLA  
(Very  
Large  
Array)



ALMA  
(Atacama  
Large  
Millimeter  
Array)

NRAO

# Summary

## Light: Wave or Particle?

- Newton's controversies:
  - With Hooke: Who first discovered certain phenomena in optics, and who discovered  $1/r^2$  law of gravitation?
  - With Leibniz: Who first discovered calculus?
  - With Huygens: Is light a wave or a particle?
- With Maxwell's theory of light discussed in lecture 8 and experiments involving interference and diffraction, the issue seems decisively settled in favor of Huygen's wave picture.
- However, it is unwise to discount the ideas of a genius completely. In a future lecture on quantum mechanics, we will see how Einstein -- the greatest opponent of Newtonian concepts in mechanics because of its conflicts with Maxwell's electromagnetic-wave theory of light -- comes to Newton's aid in the question of whether light is, after all, also a *particle*!