Part 1: The Sky; History of Astronomy; How Science Works

- Tuesday, January 17 Reading: Chapters 1 & 2.1, Appendix A
  - Introduction, syllabus, class rules; units, scales,
  - rotation of the Earth, time zones, constellations; tour – where we go in the course
- Thursday, January 19 Reading: Chapters 2, 3 HW 1 assigned
  - The sky: Rotation of Earth, seasons, phases, eclipses
- Tuesday, January 24 Reading: Chapter 4-1, 4-2, 4-3
  - History of Astronomy: Greeks, Copernicus, Tycho, Kepler
- Thursday, January 26 Reading: Chapter 4-4, 4-5
  - History of Astronomy: Galileo, Newton
- Tuesday, January 31 Reading: "Windows on science" sections or
  - How science works "How do we know?" sections in Chapters 1, 2, 3, 4
- Thursday, February 2 Reading: Chapter 5 HW 1 due
  - The nature of light, telescopes, spectra
- Monday, February 6 Help session from 4 — 6 PM in RLM 4.102
- Tuesday, February 7 Exam 1

Exam 1

All exams consist of 50 multiple choice questions with no penalty for wrong answers.

So, if you are not sure, do your best to guess.

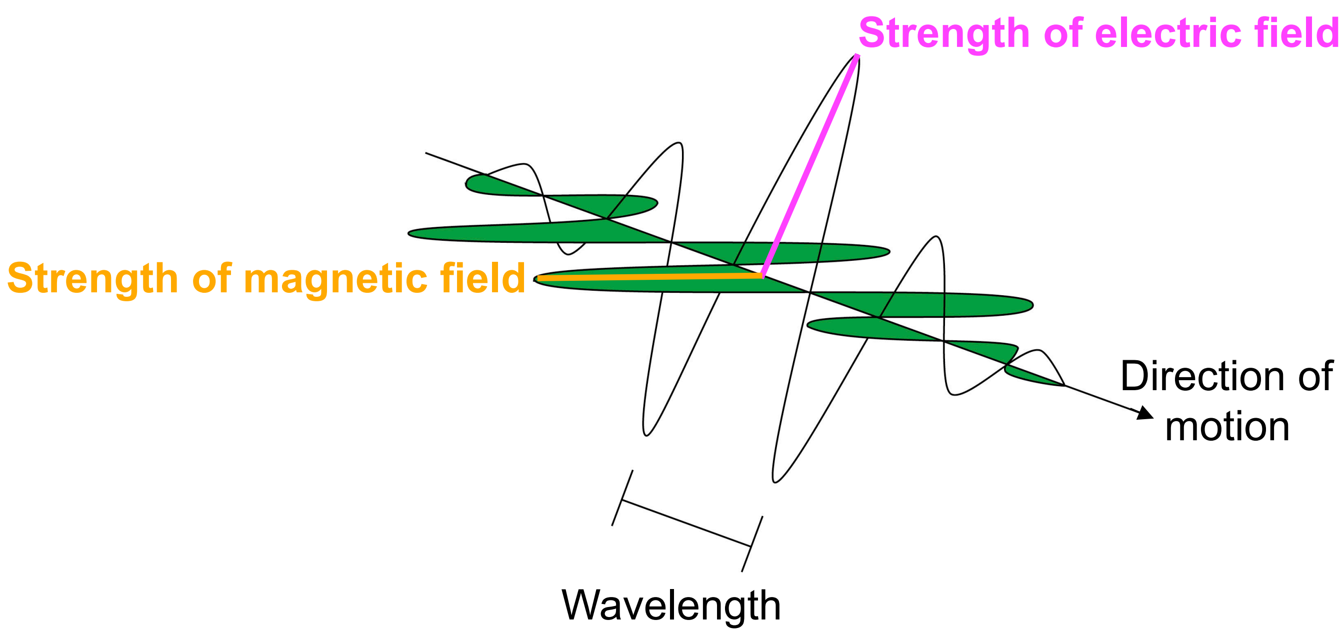
Please bring pencil(s) so that you can fill out the scantrons.

No other accessories (calculators, cell phones, …) are allowed.

Important: Anything in the posted slides that I did not cover in class could be on the exam.

Light is made of photons

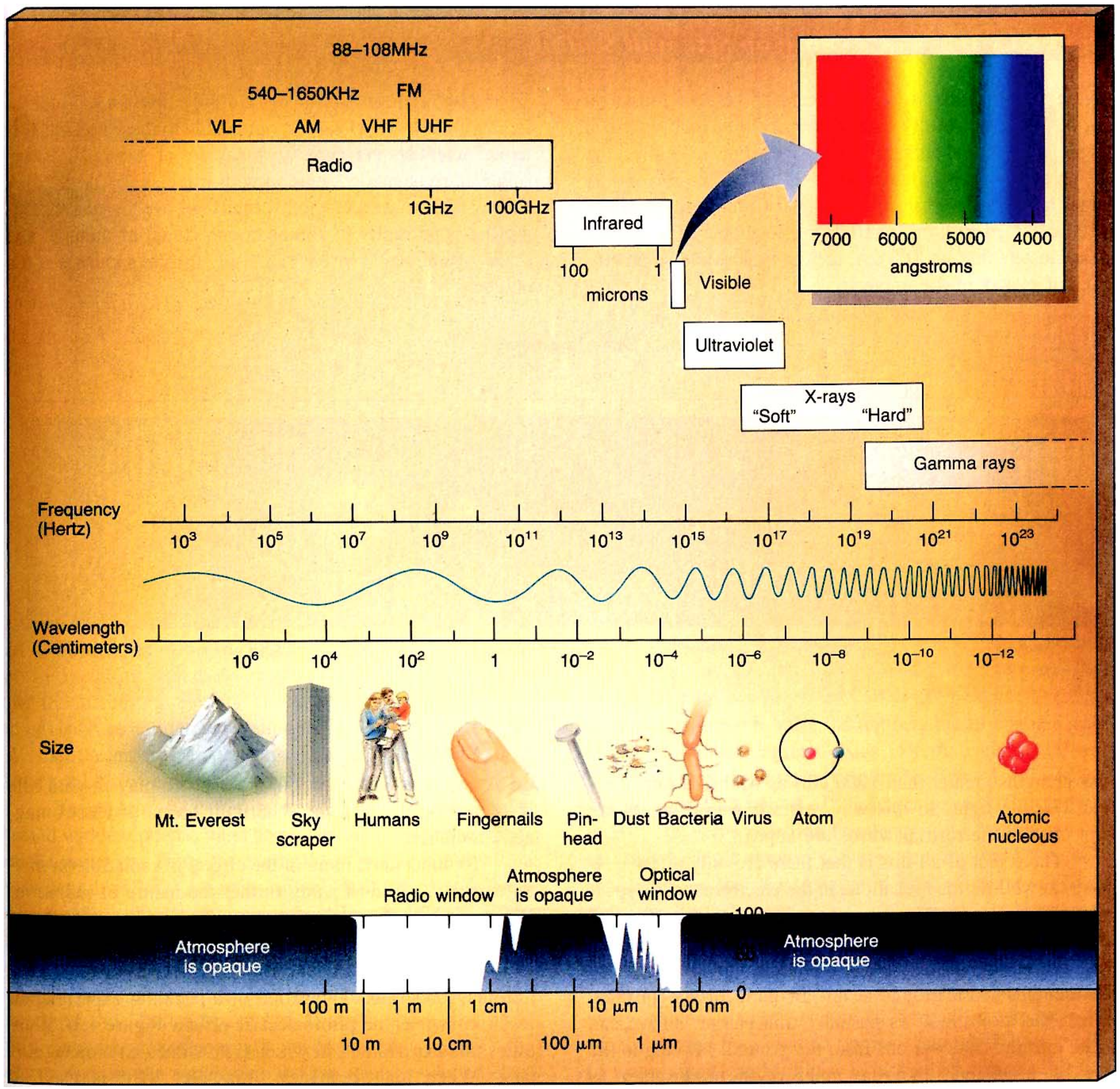
Light travels as packets of electromagnetic waves called photons.

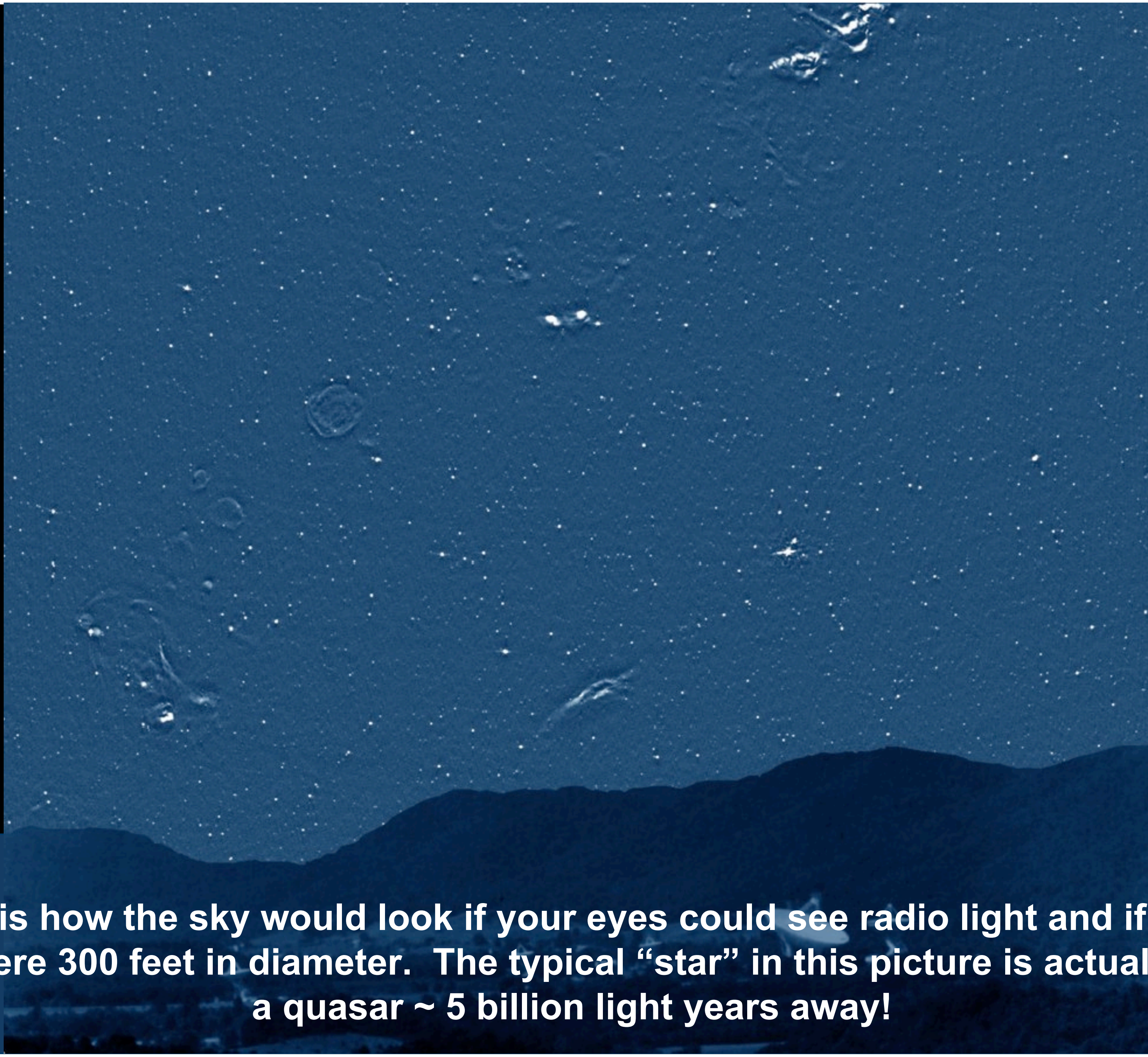


Shorter waves are bluer. Longer waves are redder.

Radio; Microwaves; Infrared, Visible & Ultraviolet Light; X-rays; Gamma Rays

Are All Light





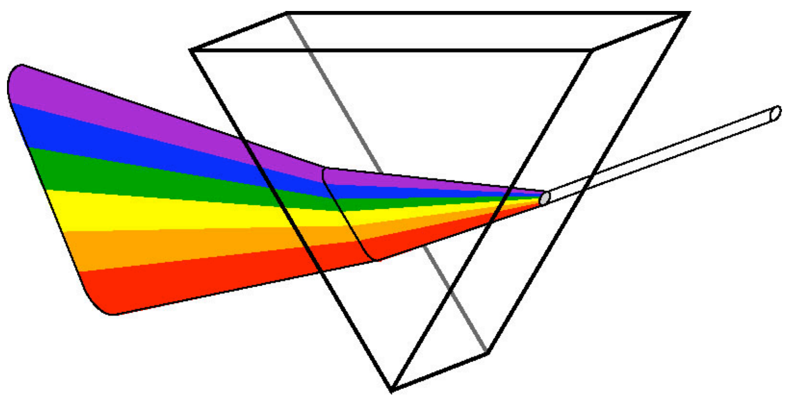
This is how the sky would look if your eyes could see radio light and if they were 300 feet in diameter. The typical “star” in this picture is actually a quasar ~ 5 billion light years away!

Light and Color

Light has two complementary aspects: waves and particles.

By passing light through a prism, Newton showed that **white light** is made of a rainbow of different colors. These colors can be recombined to get white light.

But each individual color is “pure” — when passed through a second prism, it remains unchanged.

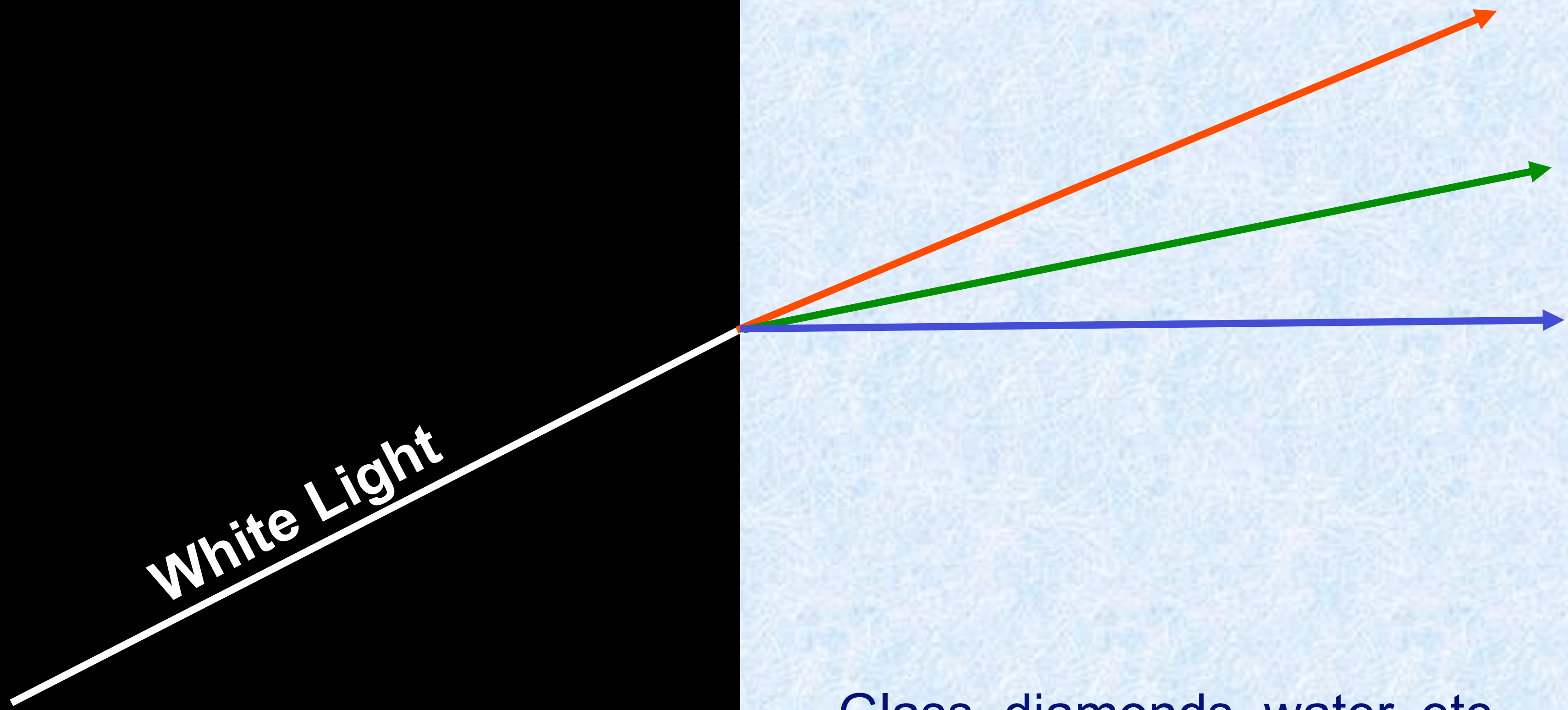


Note: 1 Å = 1×10^{-10} m.

Violet	≈	4100 Å
Blue	≈	4600 Å
Green	≈	5000 Å
Yellow	≈	5700 Å
Orange	≈	6000 Å
Red	≈	6500 Å

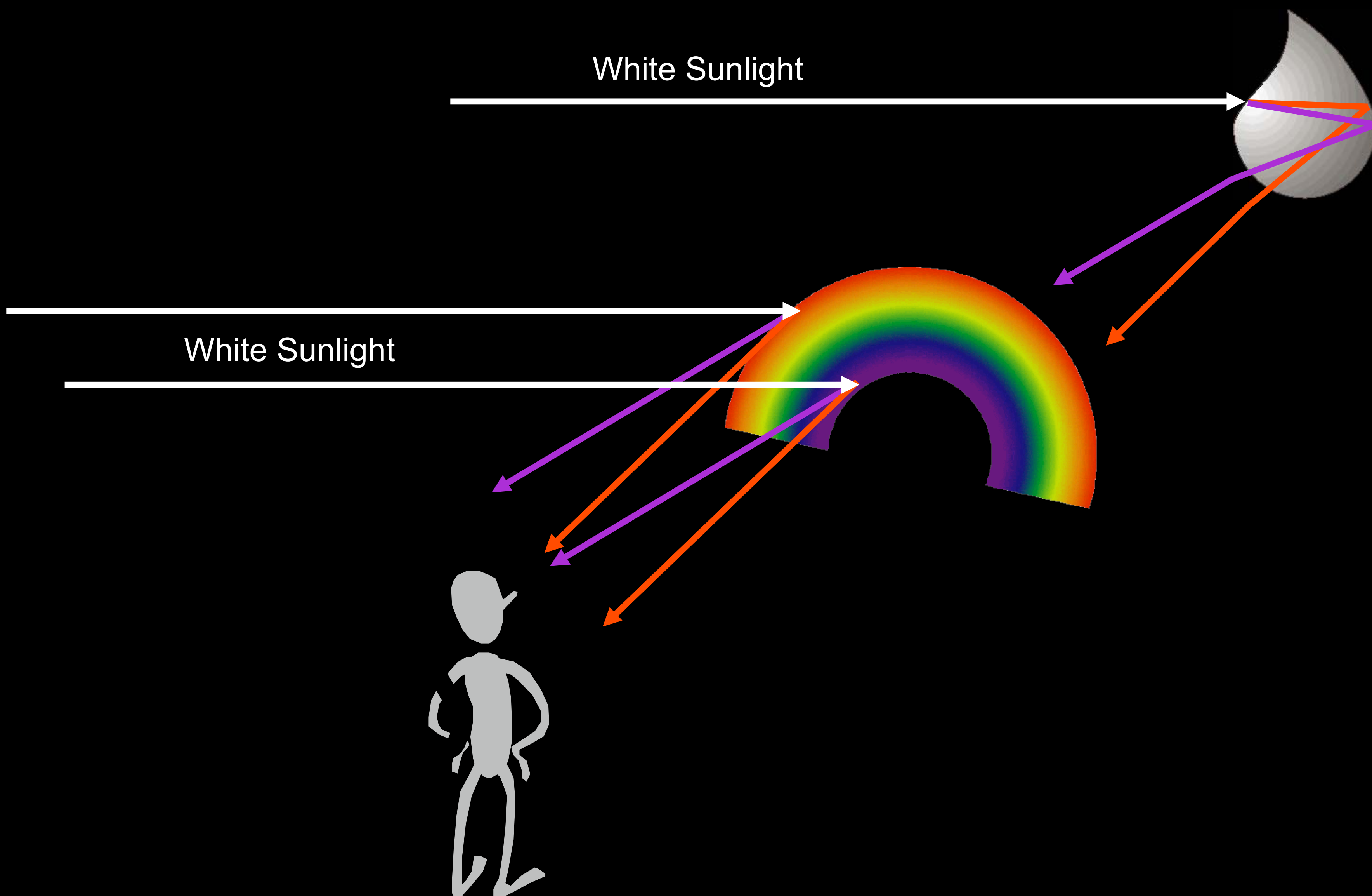
What property of light distinguishes one color from another? Answer: Wavelength.

Refraction of Light

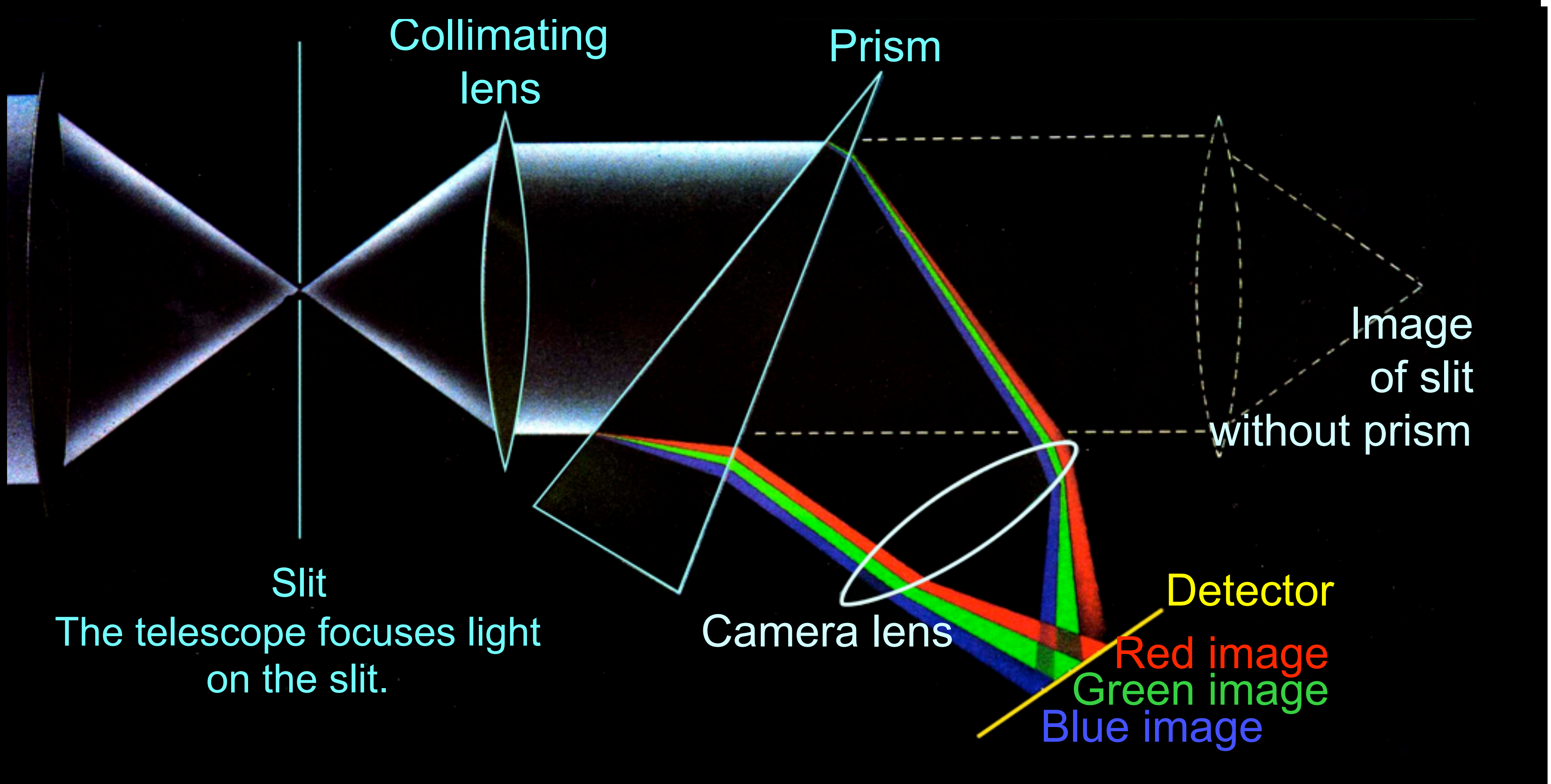


Glass, diamonds, water, etc.
bend blue light more than red light.

How A Rainbow Works



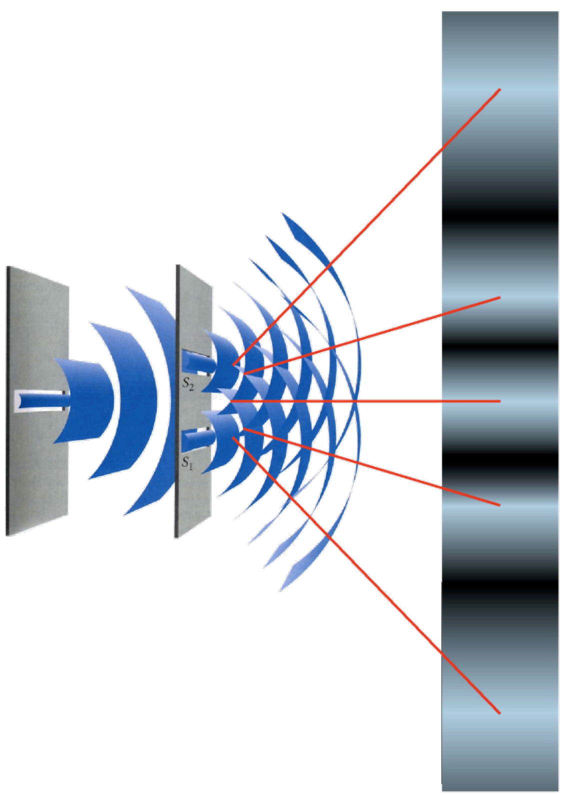
Simple Spectrograph

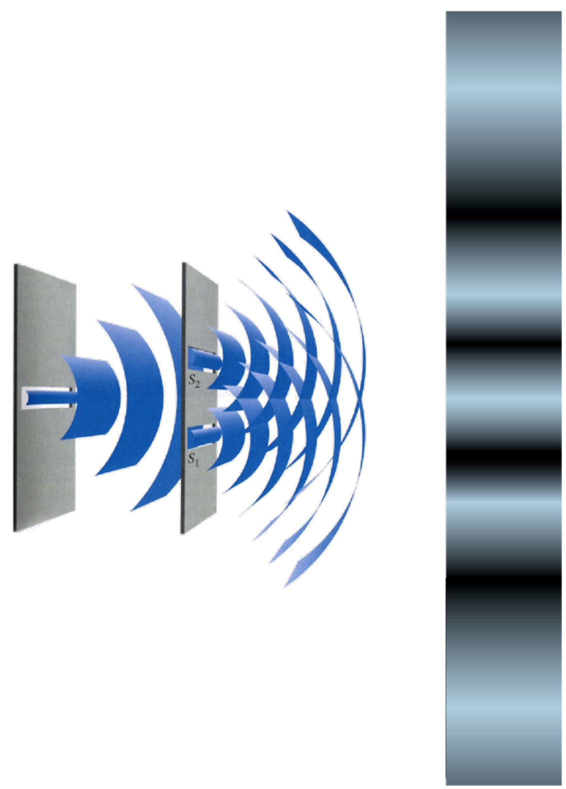


Light is a Wave

What is light? Answer 1: light is a wave. It consists of vibrating electric and magnetic fields. A changing electric field generates a changing magnetic field, and *vice versa*. The color of the light is related to the wavelength of the waves: bluer light has shorter wavelengths; redder light has longer wavelengths.

Evidence for the wave-like nature of light came from studies of diffraction effects:

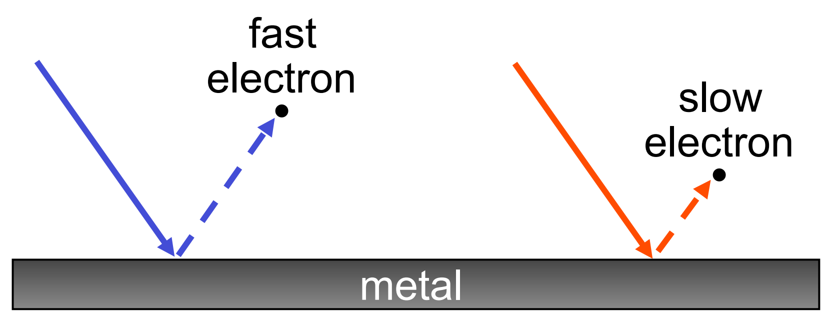




Light is a Particle

What is light? Answer 2: Light is a kind of particle. Light rays are like streams of tiny bullets. The color of the light is related to the energy of the particles: bluer light particles have higher energies; redder light particles have lower energies.

Evidence for the particle nature of light is provided by the photoelectric effect:



If the light gets brighter,

the number of electrons emitted gets bigger, but

the speed of the electrons is unchanged.

The speed of the electrons depends only on the color of the light.

Is Light a Wave or a Particle?

Experiments say

Yes!

Sometimes light acts like a wave;
Sometimes it acts like a particle.

Photons Are Both Waves And Particles

Is light a wave or a particle? Each answer agrees with some experiments and disagrees with others. So neither answer completely describes the observed properties of light. Both answers are partly correct, but never at the same time:

We now believe that light is composed of photons. They behave either like waves or like particles but never like both at once. Roughly speaking, photons

behave like waves when they travel through space, and they
behave like particles when they interact with matter.

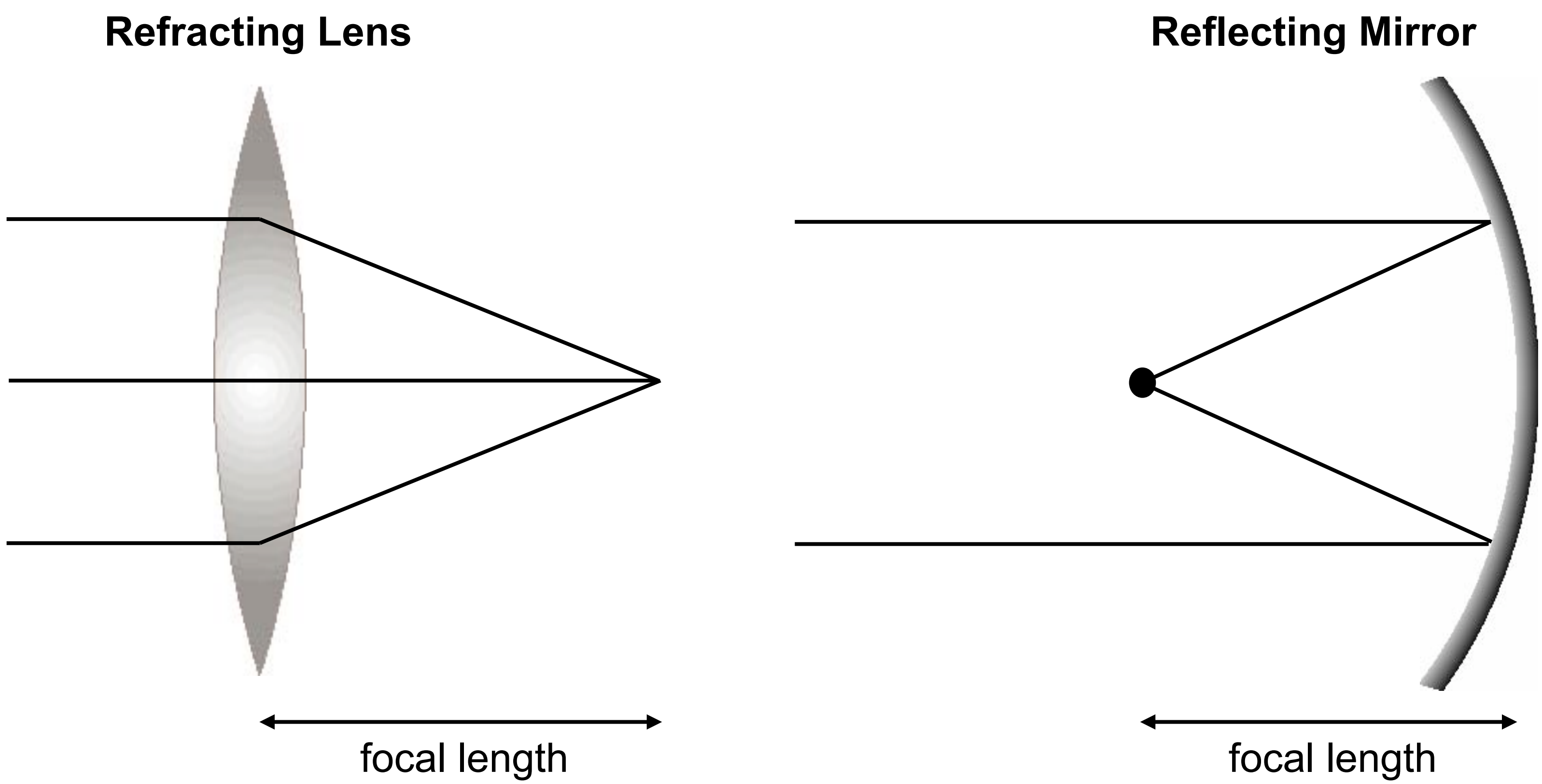
The connection between these two descriptions is given by Planck's law:
The energy *E* of a photon is related to its wavelength λ by

$$E = \frac{hc}{\lambda}.$$

Here *c* is the speed of light and *h* = 6.63 x 10^{-34} kg m^2 / s is Planck's constant.

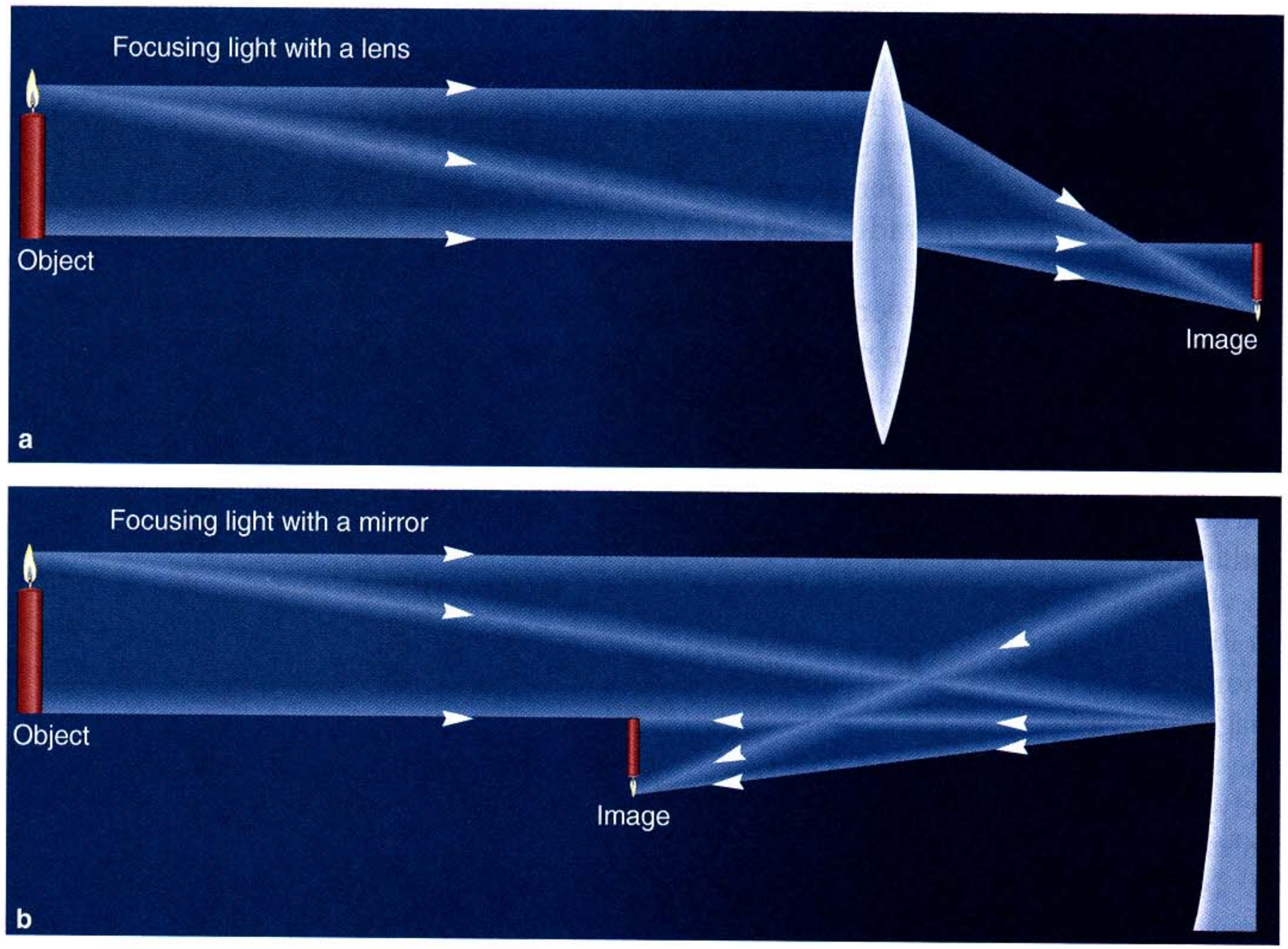
Bluer light has more energy per photon. Redder light has less energy per photon.

How to Make a Telescope: Start by Focusing Light



Focusing an Image

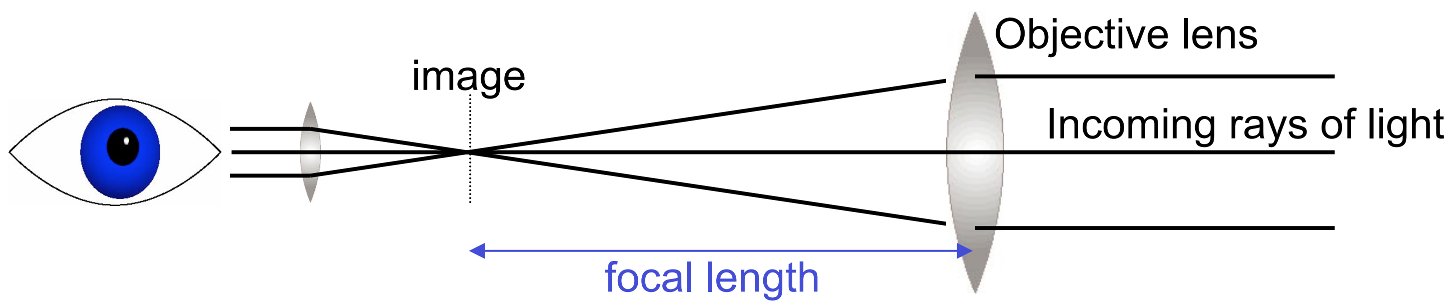
Figure 5-3
(a) To see how a lens can focus light, we trace three light rays from the flame and base of a candle through a lens, where they are refracted to form an inverted image. (b) A mirror forms an image by reflection from a concave surface. Notice that the light is reflected from the aluminized front surface of the mirror and does not enter the glass. Thus, mirrors do not produce chromatic aberration.



Telescope Design

Telescopes are giant cameras. A camera has an objective lens or mirror that focuses an image of the scene onto a detector. If the subject of the photo is very far away, then the image is sharp ("in focus") when the distance between the objective and the detector is equal to the focal length of the objective.

The longer the focal length, the larger the image on the detector. Long focal lengths are needed to make large images of astronomical objects. For example, the Palomar 200 inch telescope has a focal length of 660 inches and produces an image of the Moon about 6 inches in diameter. For comparison, a typical camera produces an image of the Moon only 0.017 inches in diameter.



To look through a telescope, you use an eyepiece to enlarge the focused image. Magnification of the telescope = focal length of the objective divided by focal length of the eyepiece. Magnification is not the most important of feature of a telescope.

Refracting Telescopes

Like an ordinary camera, a refracting telescope uses a lens to focus the image. **Early lenses were made of only one kind of glass and had a serious problem: the focal length depends on the color of the light*.** So when red light from an object is sharply focused, the blue light is fuzzy, and vice versa.

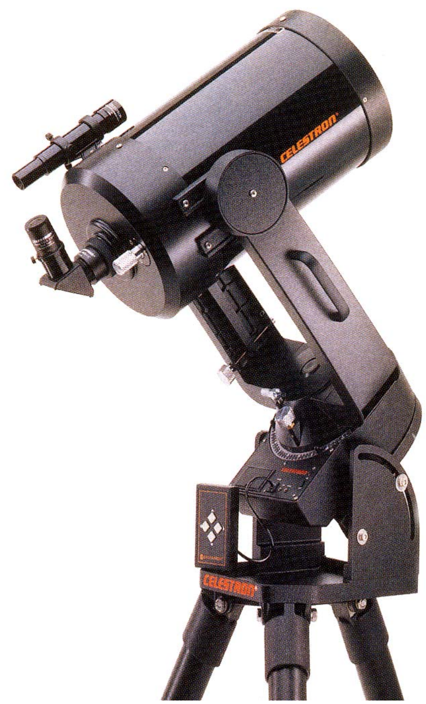
Compound lenses solve this problem by using two kinds of glass. Telescopes with compound lenses make very clear images. But a big lens bends under its own weight, so it is almost impossible to make a good lens that is more than 40 inches in diameter.

***Why?**

Reflecting Telescopes

A <u>reflecting telescope</u> uses a curved mirror instead of a lens. It is easy to make a mirror with a spherical surface, but spherical mirrors don't bring all light to the same focus. This problem is solved by giving the surface of the mirror a parabolic shape.

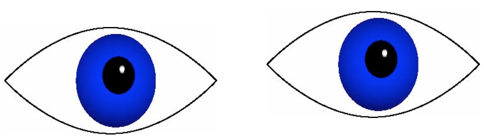
A parabolic mirror brings light of all colors to the same sharp focus. Also, mirrors can be supported from behind, so they do not bend under their own weight. Mirrors can be very big. For these reasons, most modern telescopes are reflectors.

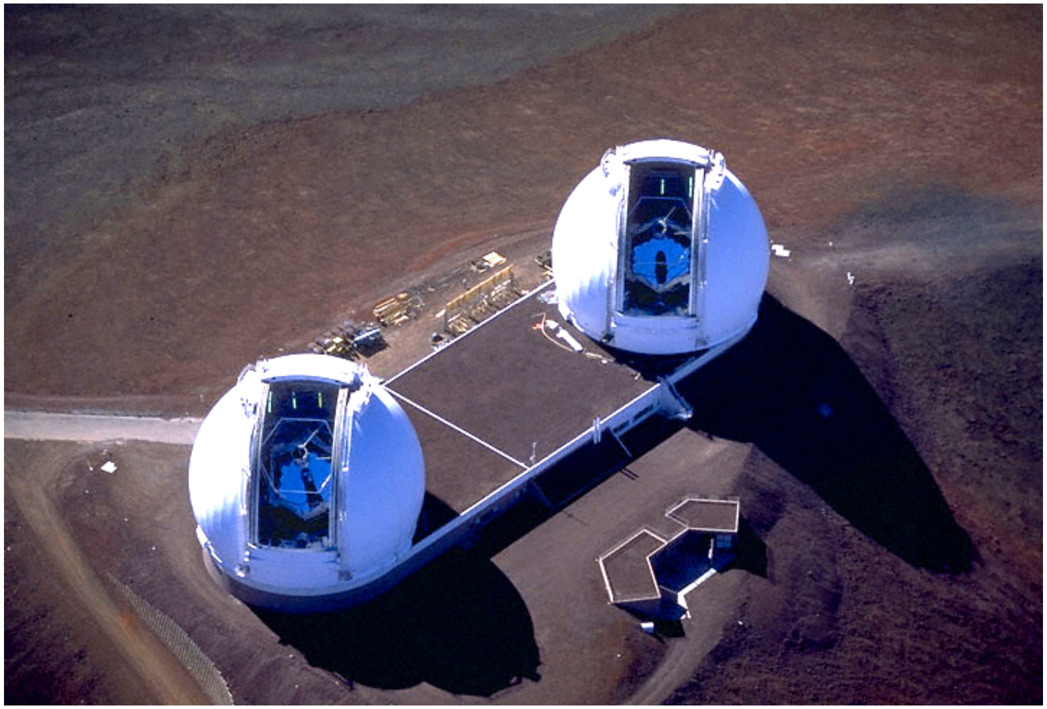


Light Gathering Power

Light from a star spreads out in all directions; we collect only a tiny fraction of it. The bigger the area of the objective, the more light it can collect. So the light gathering power of a telescope is proportional to the square of its diameter.

For example, the lenses in your eyes, when dark-adapted, have an area of 35 mm^2. The mirrors of the Keck telescopes have an area of almost 78 m^2 = 78 million mm^2, so they collect about 2 million times more light than the eye.





Angular Resolution

Two stars very close together in the sky may look like a single point of light regardless of the magnification. This is partly due to the wave-like nature of light. The angular resolution of a telescope is proportional to the diameter of the objective divided by the wavelength of the light. The better the angular resolution, the closer two stars can be and just be separated. Bigger telescopes make sharper images.

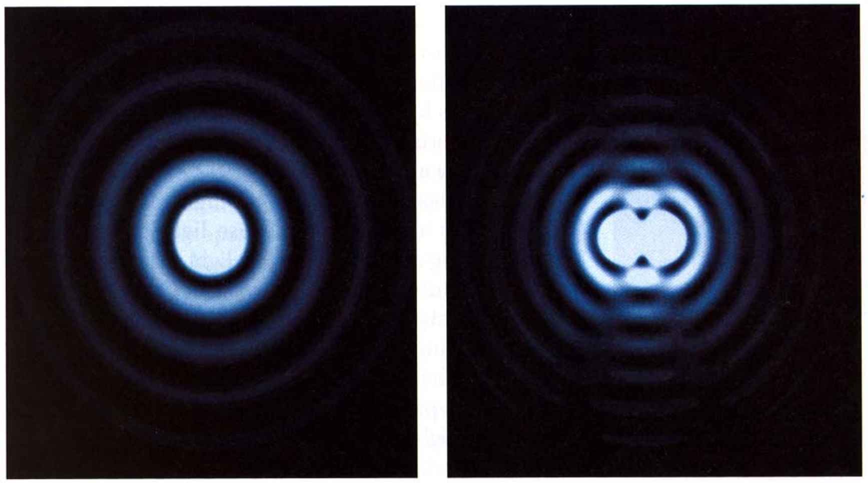


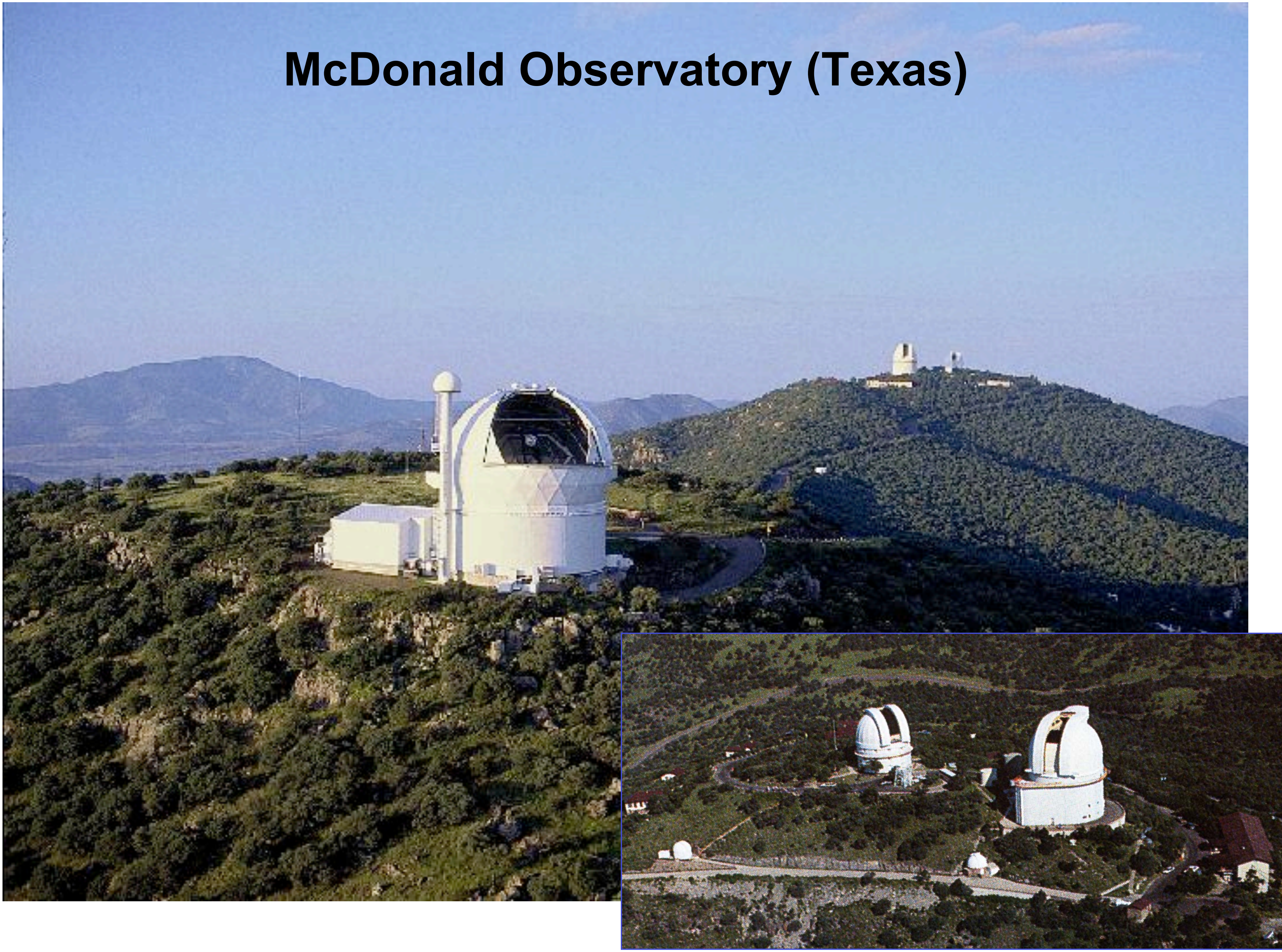
Figure 5-11
(a) Stars are so far away that their images are points, but the wave nature of light surrounds each star image with diffraction fringes (much magnified in this computer model). (b) Two stars close to each other have overlapping diffraction fringes and become impossible to detect separately. *(Computer model by M. A. Seeds)*

In practice, the angular resolution of a telescope is limited by air turbulence, which blurs the images of stars. Without special equipment, the best ground-based telescopes can resolve stars that are separated by as little as 0.4 arcseconds. Astronomers have developed "rubber mirrors" whose shapes can be controlled rapidly and accurately to correct some of the blurring produced by the atmosphere.

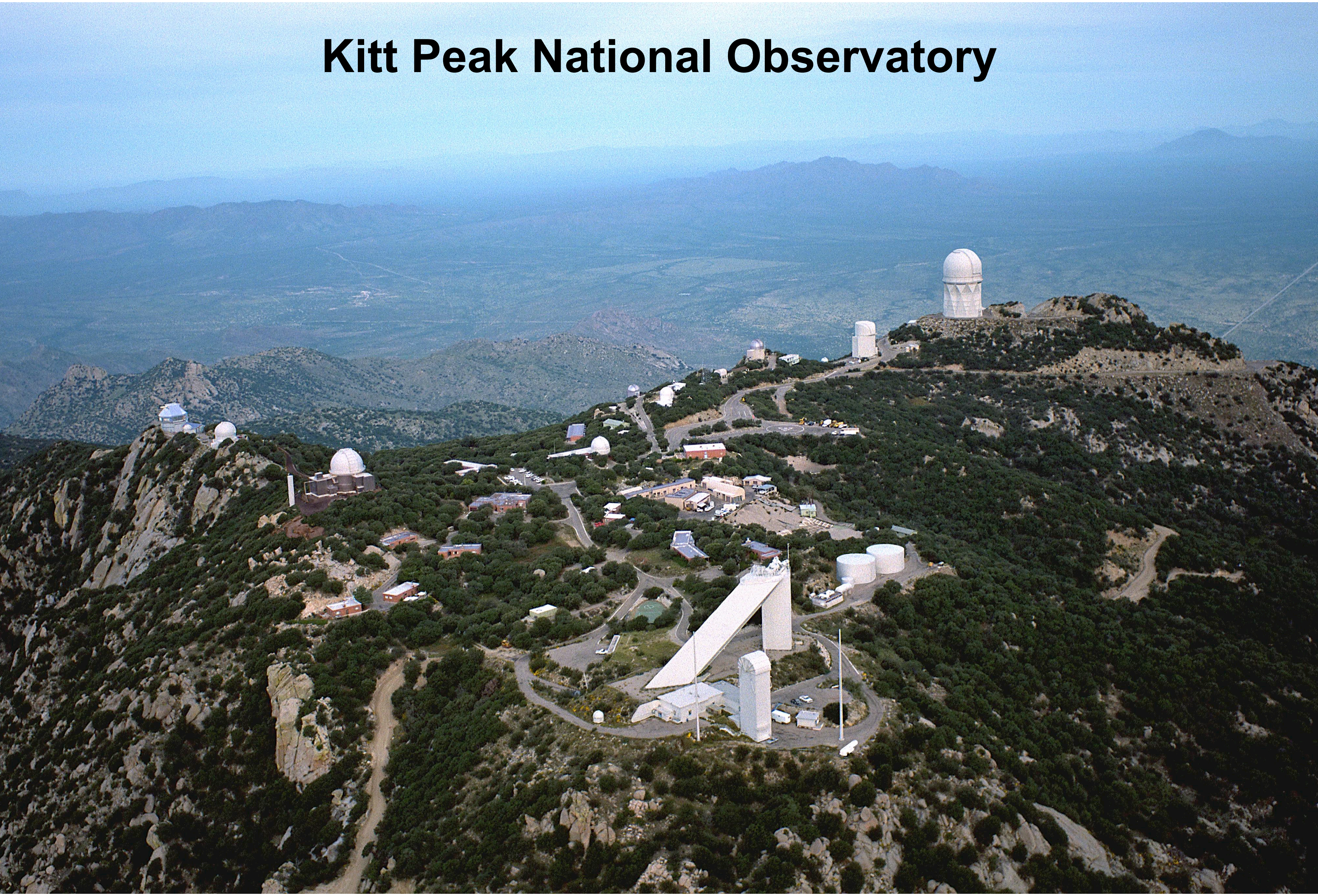
A Demonstration of Resolution

Hubble Space Telescope Image
0.1”

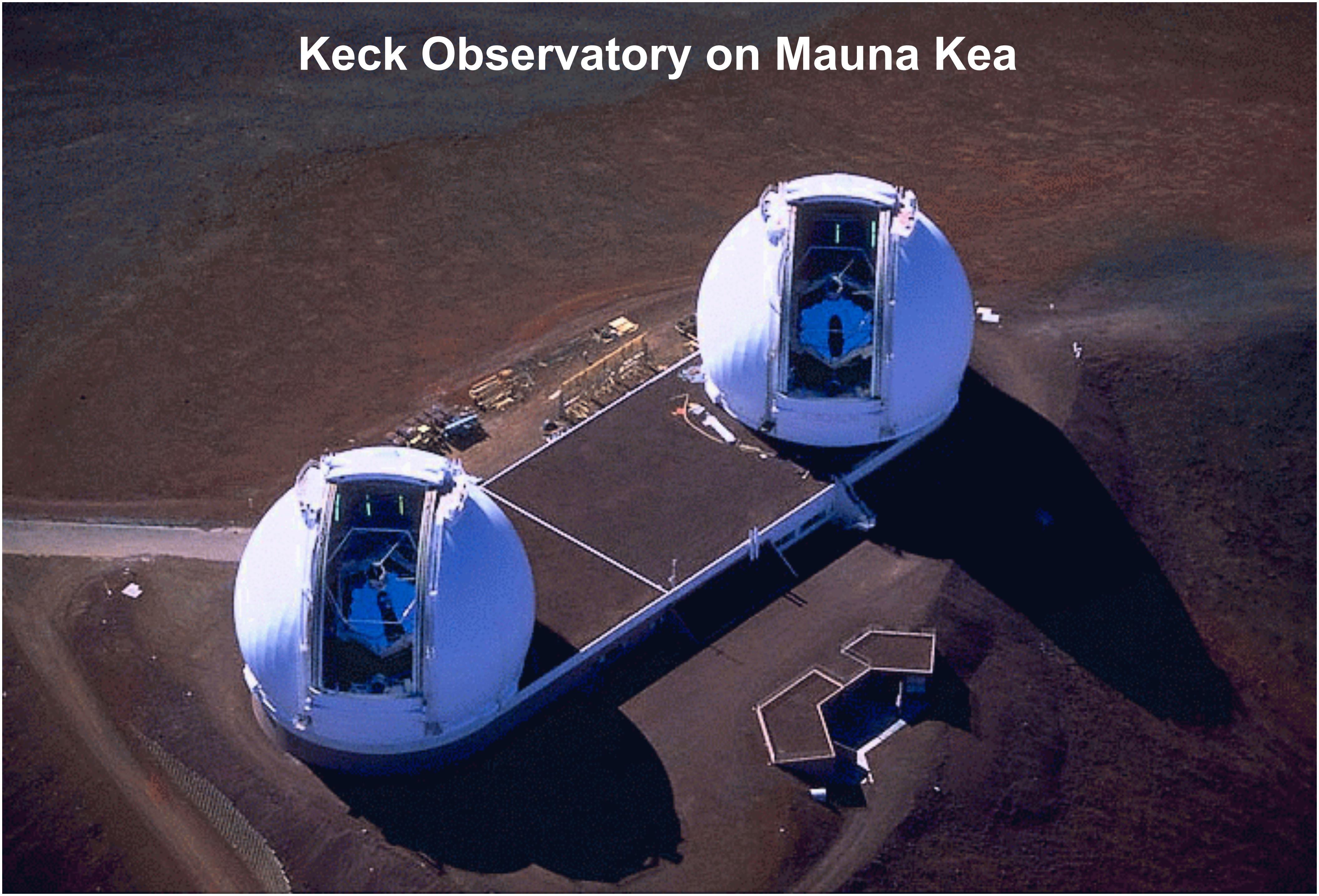
McDonald Observatory (Texas)



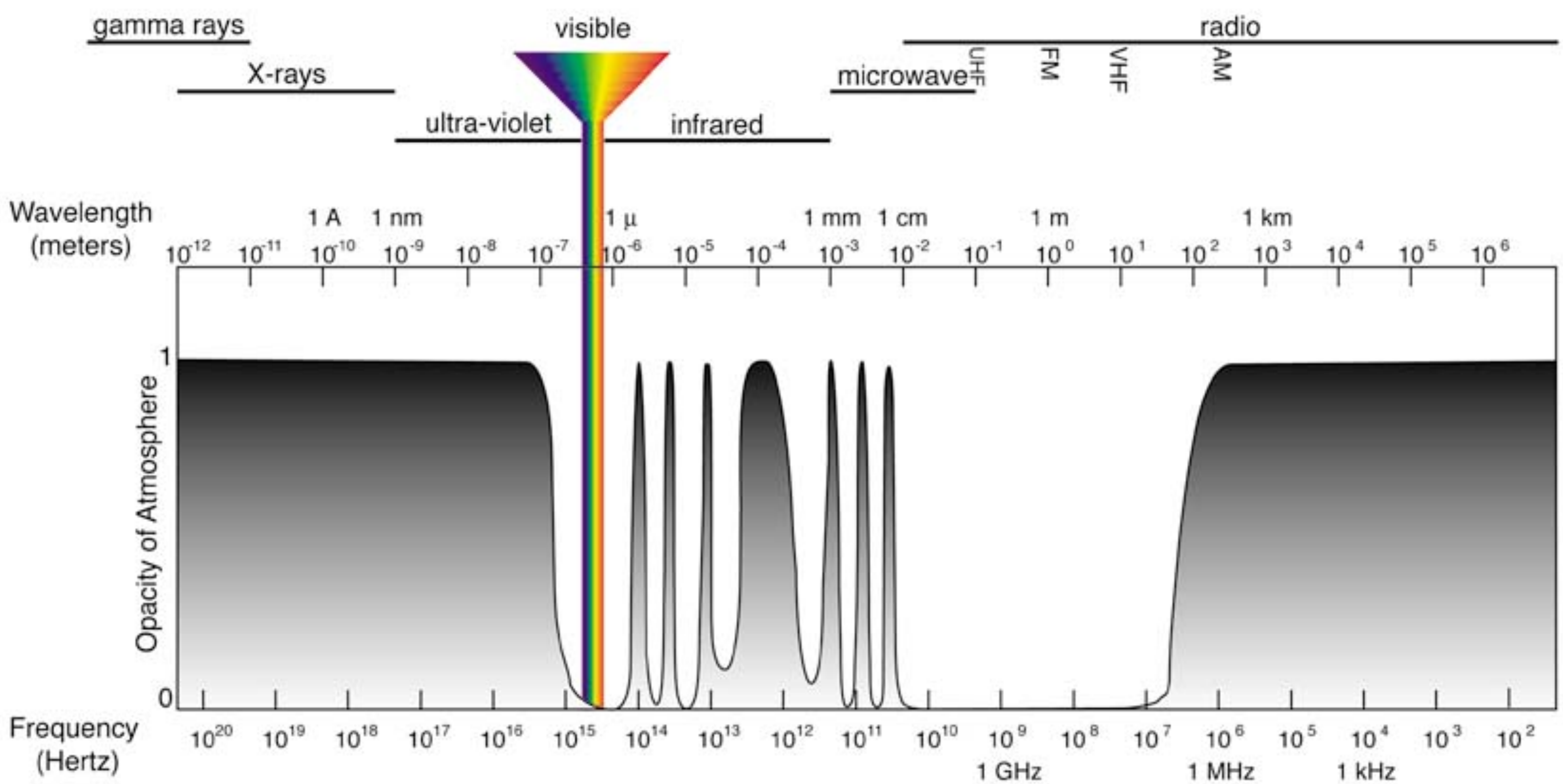
Kitt Peak National Observatory



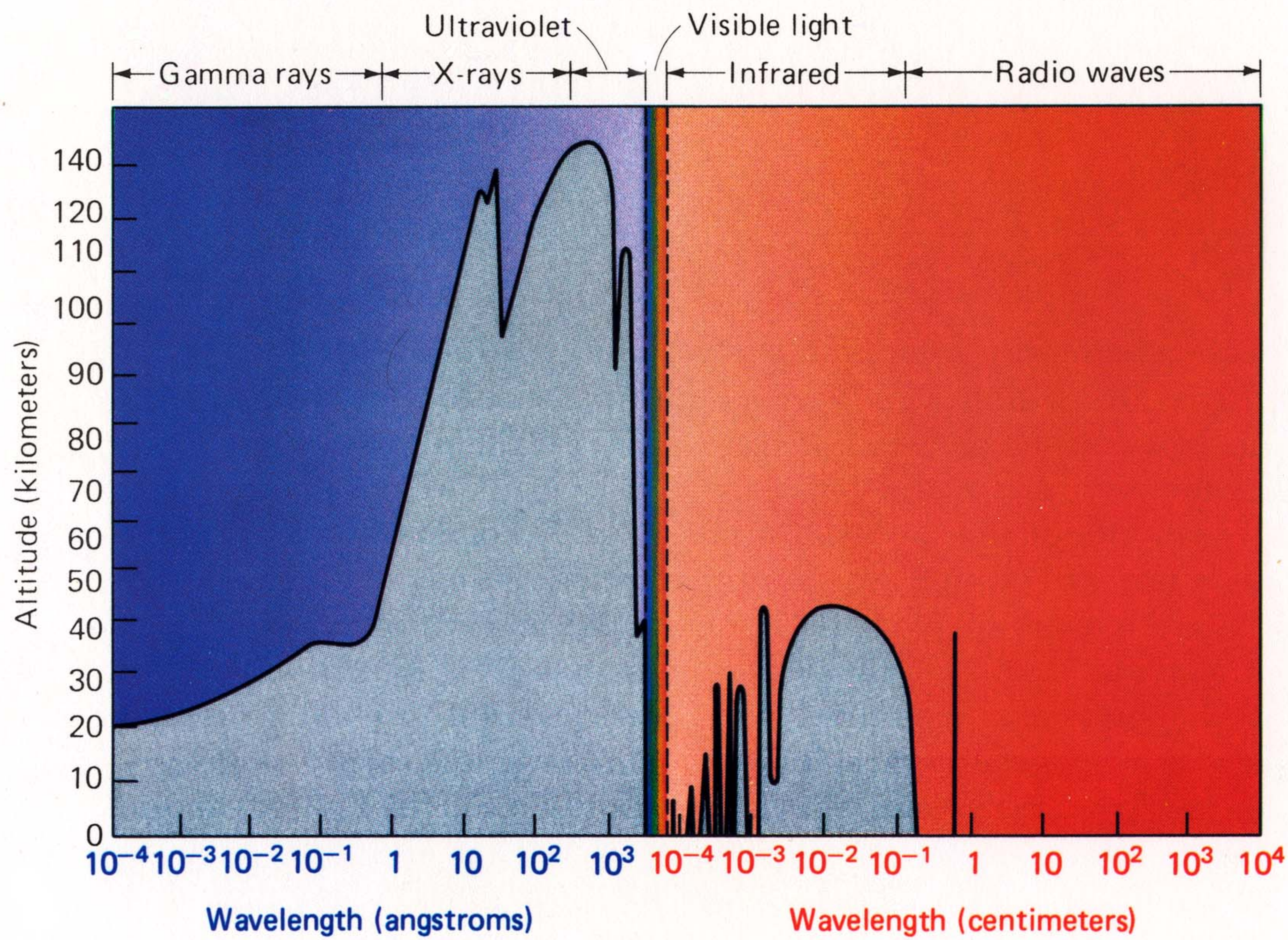
Mauna Kea Observatory


Keck Observatory on Mauna Kea

Atmospheric Transparency



Altitude Where Light Is 50% Absorbed By The Atmosphere

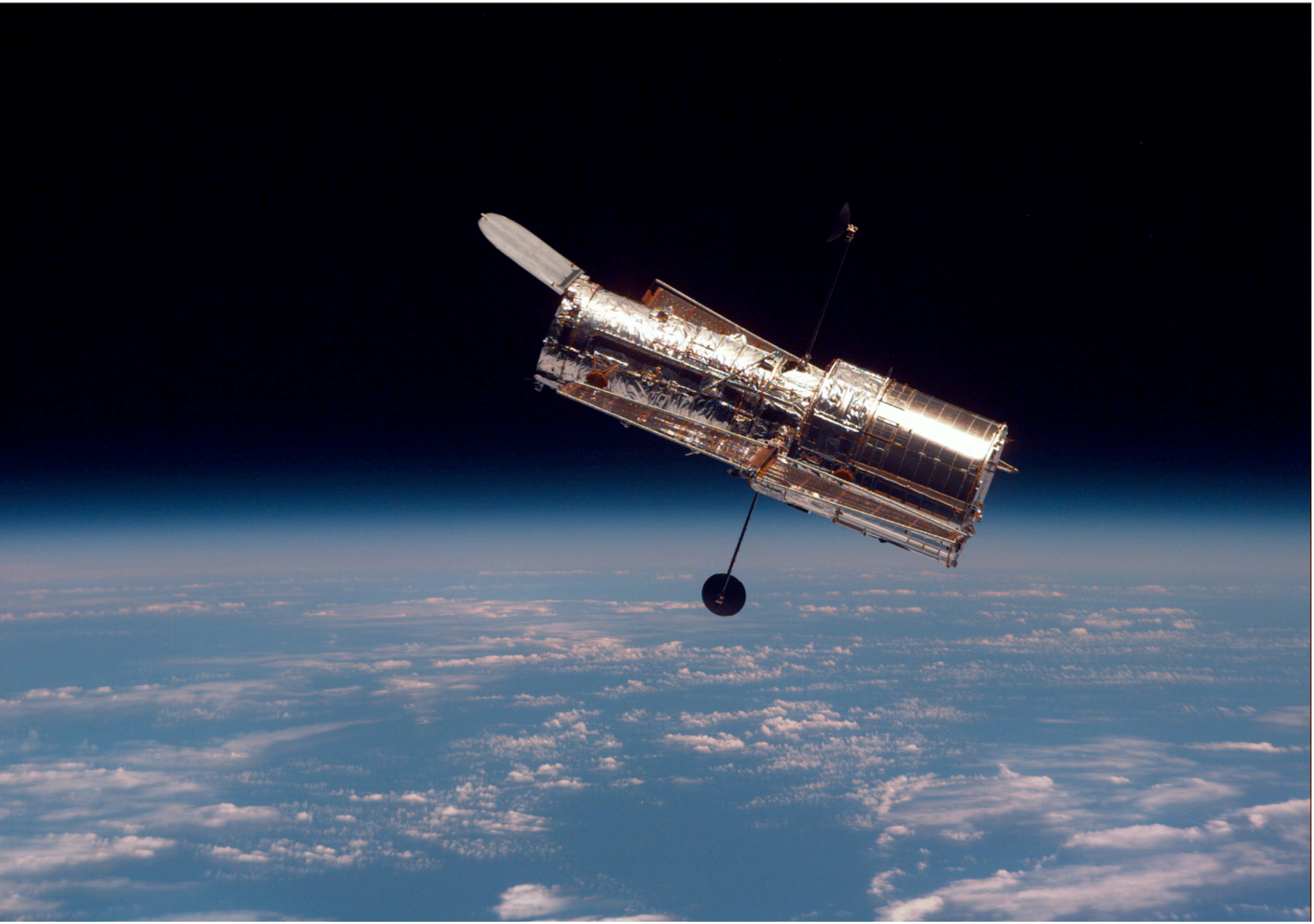


Why we put telescopes in space despite the cost !

No atmospheric turbulence ⇒ better resolution.

We can observe wavelengths that are absorbed by Earth's atmosphere.

Minor reason: It is never cloudy.
We would never pay the high cost of putting telescopes in space if the only reason were to avoid cloudy weather!



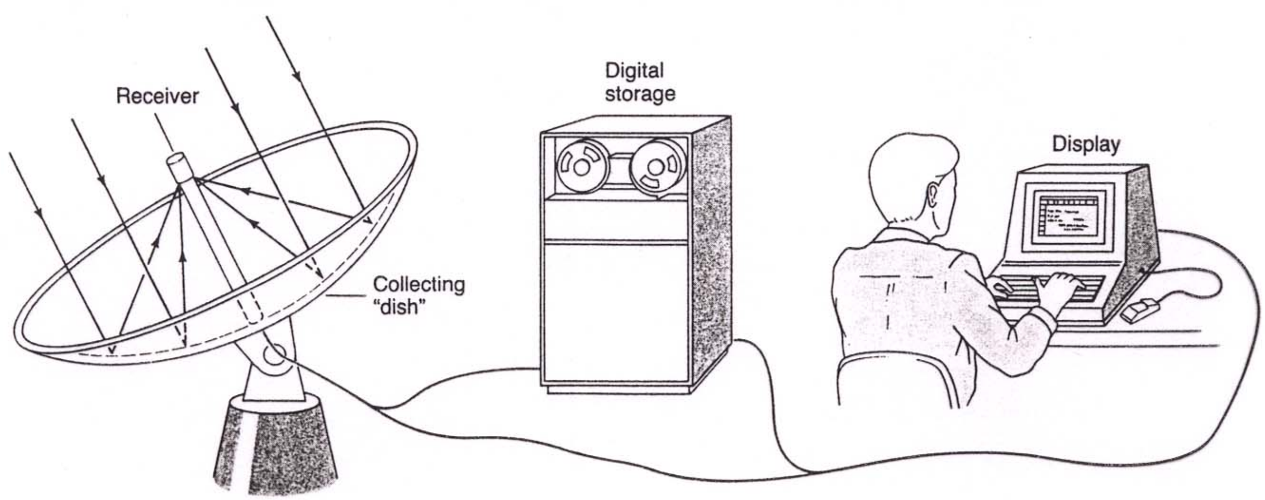
Radio Telescope

Visible light is a tiny part of the electromagnetic spectrum. We can observe other colors of light, too, including radio and submillimeter waves, infrared and ultraviolet light, X-rays, and gamma rays.

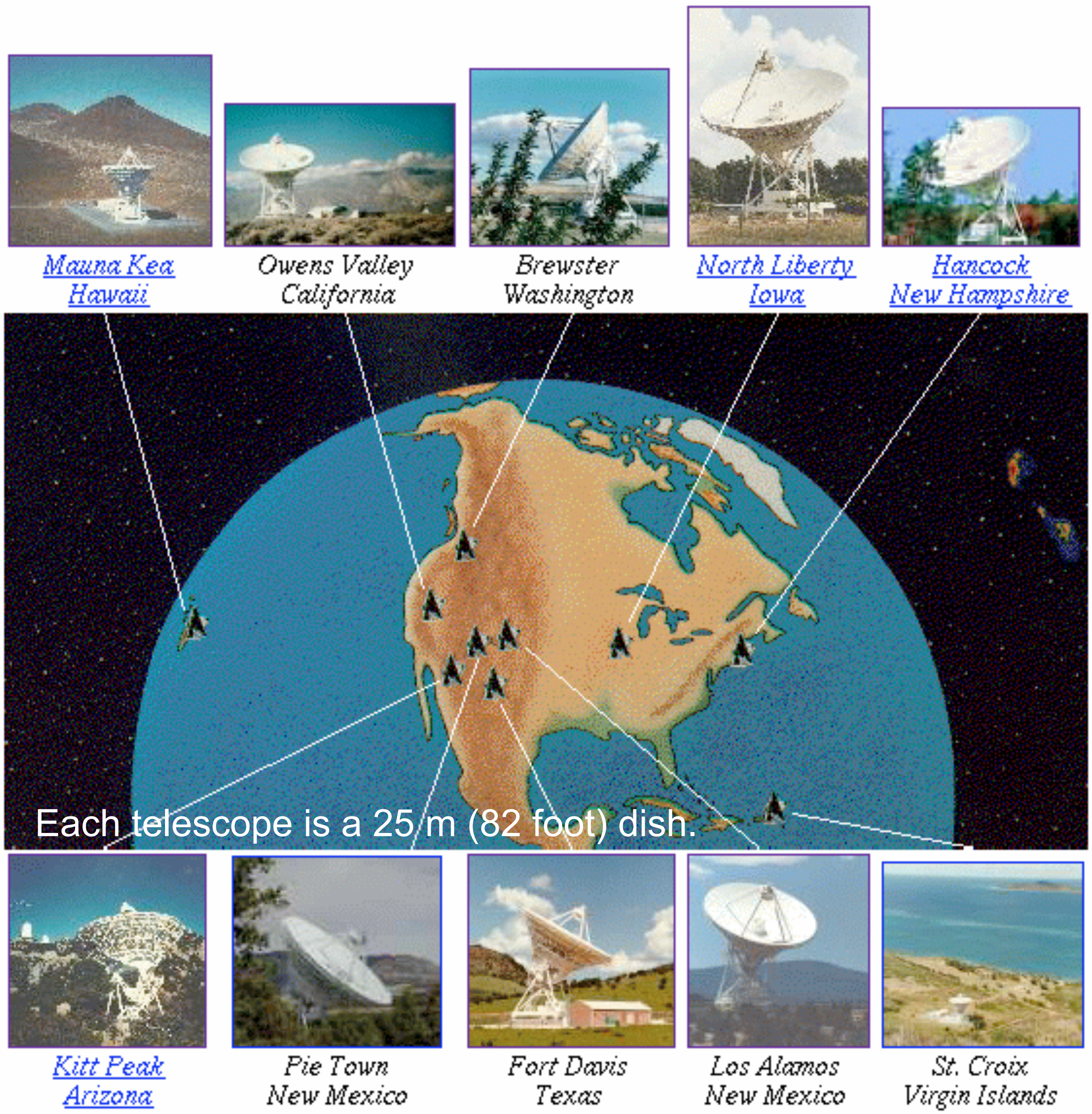
Radio Telescopes

Radio waves from outer space surround us. Much of the snow that you see on a TV tuned between stations is due to astronomical sources. How do we learn something useful from this signal?

Because radio waves have wavelengths of cm — km, that is, thousands to millions of times longer than those of visible light, radio telescopes must be very large to get good angular resolution. The largest single-dish radio telescope has a mirror 1000 ft in diameter. For better resolution, separate radio telescopes can be linked together.

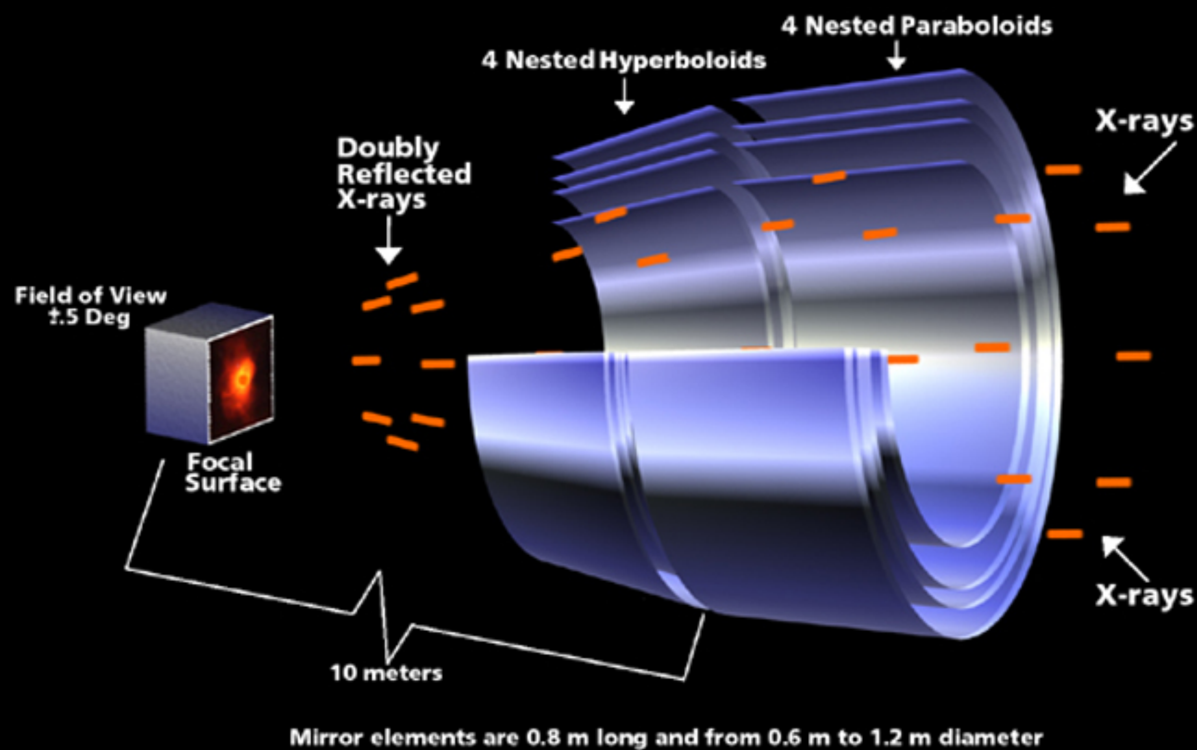


Very Long Baseline Array



Best resolution is < 1/1000 arcsec.

X-Ray Telescopes Use Grazing-Incidence Mirrors



X-ray telescope cannot use ordinary mirrors, because X-rays pass through mirrors instead of bouncing off of them. However, X-rays reflect off of a metal surface if they strike it at a very shallow angle.

So X-ray telescopes are made of nested arrays of funnel-like mirrors. Such telescopes must be put in space, because our atmosphere absorbs X-rays.

Chandra X-Ray Observatory

The Kelvin Temperature Scale

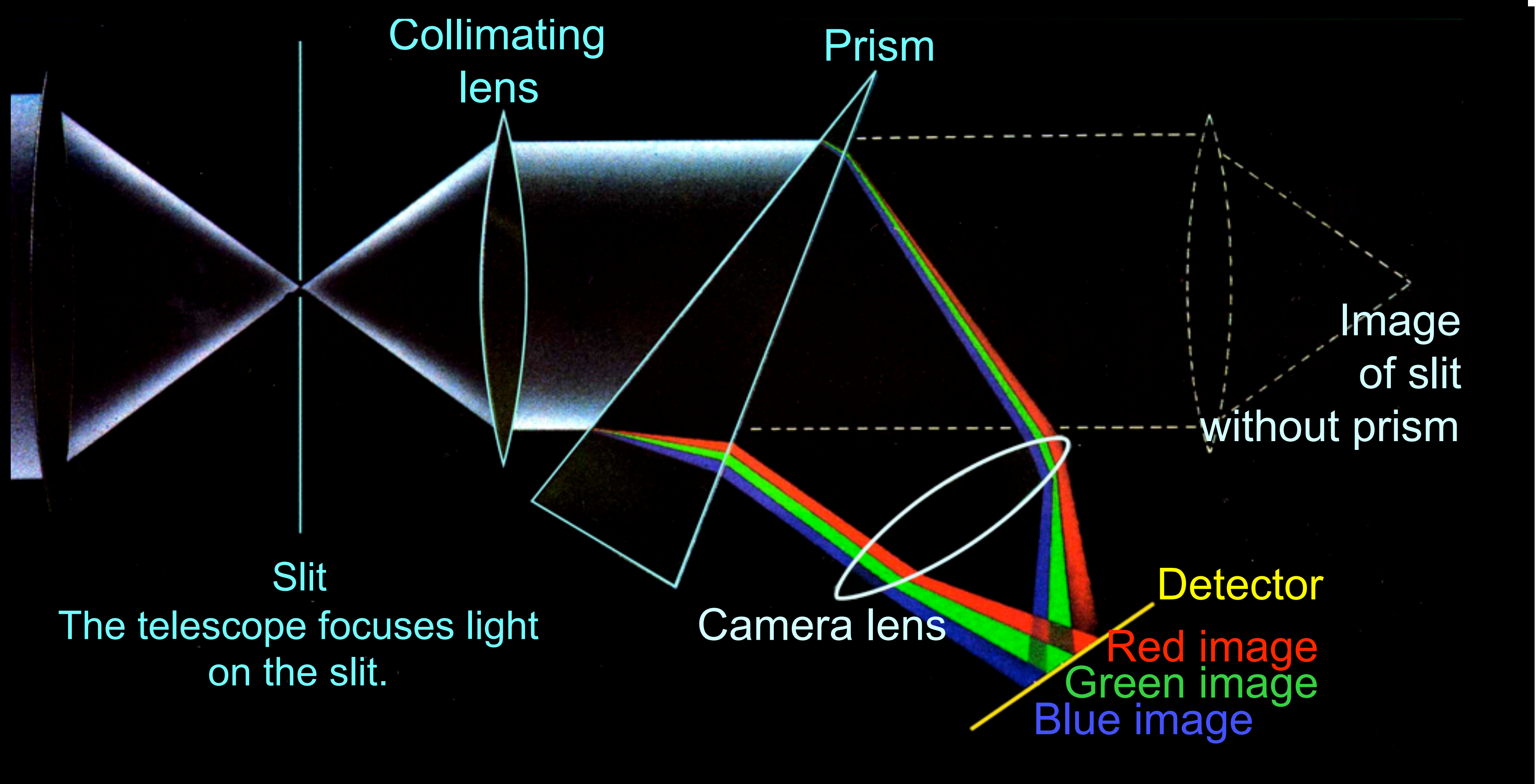
	ºF	ºC	K
Coldest possible temperature	-459.7	-273.2	0
Temperature where ºC and ºF cross	-40	-40	233.2
Water freezes at 1 atmosphere pressure	32	0	273.2
Water boils at 1 atmosphere pressure	212	100	373.2

$$\mathrm{K} = {}^{\circ}\mathrm{C} + 273^{\circ}.2$$

$${}^{\circ}\mathrm{C} = \frac{5}{9}\left({}^{\circ}\mathrm{F} - 32^{\circ}\right)$$

(see Appendix A)

Simple Spectrograph



Spectra

The spectrum of an object is the amount of energy that it radiates at each wavelength.

Much of what we know about the Universe comes from spectra.
They are much more instructive than images.

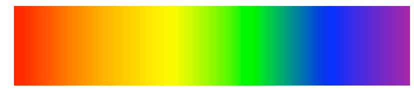
Continuous Spectra

All macroscopic objects emit radiation at all times. Their atoms move around by an amount that increases with temperature. Accelerated charged particles radiate. So:
Everything radiates with a spectrum that is directly related to its temperature.

For example: people are warm; they glow brightly in the infrared. Similarly, a warm iron glows in the infrared but not in visible light. Then, as it is heated to higher and higher temperatures, it glows red, then white, then blue.

Continuous Spectra

An idealized object that absorbs all radiation that hits it is called a **black body**.
In equilibrium with its surroundings, it emits exactly as much radiation as it absorbs.
Then it emits a spectrum as described in Figure 6-6 of (most editions of) the text.
This **black body** or **thermal radiation** has the following properties:

- It is continuous radiation (there are no emission or absorption lines): 

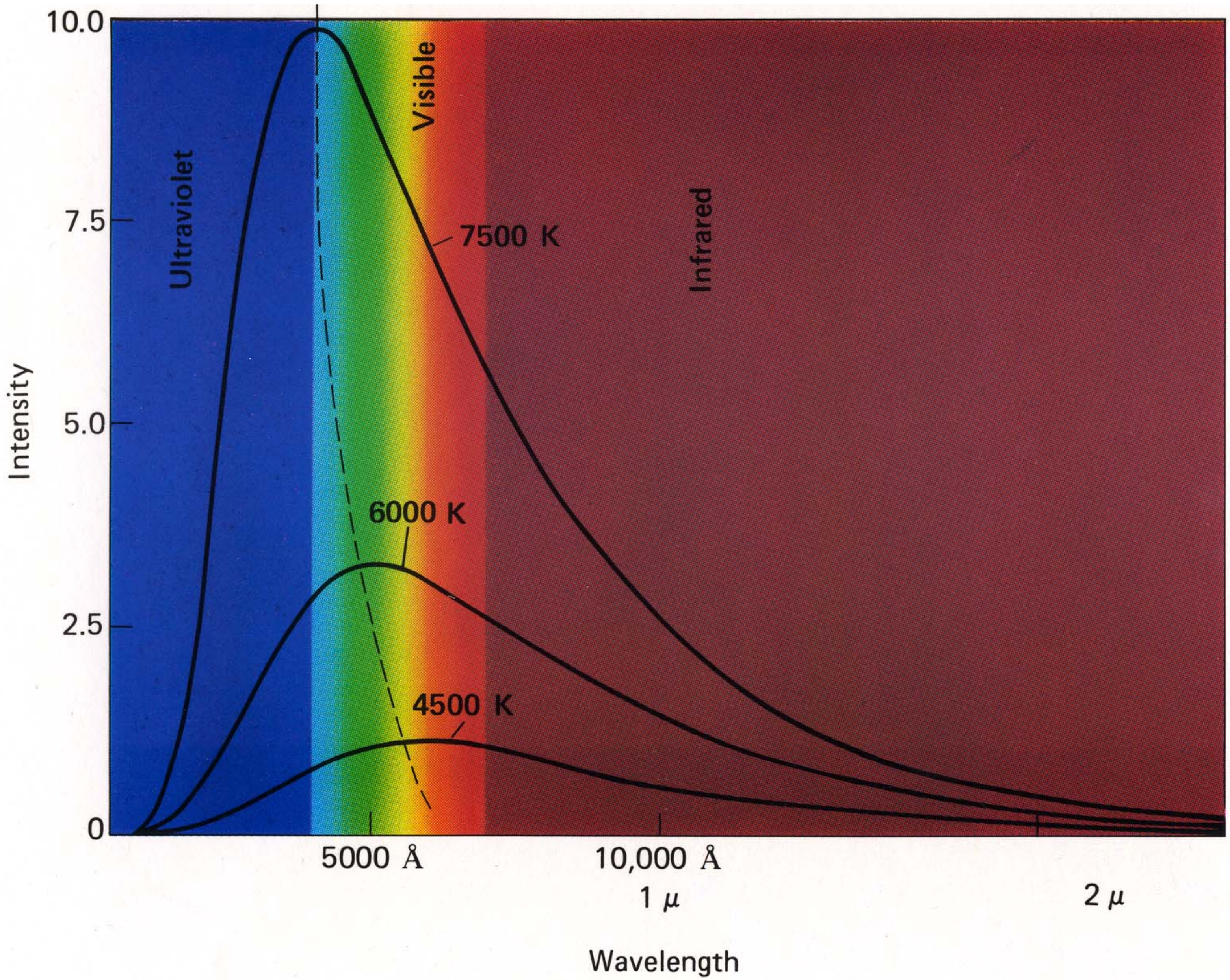
- Its spectrum is brightest at a wavelength that depends on temperature, and the brightness falls more quickly toward the blue than toward the red. Specifically:

- **Wien's Law**: The wavelength of maximum brightness in Å is 30,000,000 K divided by the temperature in K. That is, $l_{max} = 3.0 \times 10^{7}$ Å / T(K). Hotter things radiate bluer light. If the temperature doubles, the wavelength of maximum brightness gets 2 times shorter.

- **Stefan-Boltzmann Law**: The total energy emitted varies as the 4th power of temperature: $E = sT^4 = s \times T \times T \times T \times T$. The Stefan-Boltzmann constant s is given in Box 6 — 1.

A black body is an idealized concept, but for many objects (including stars), the above are useful approximations.

Black Body Spectra



How Hot Is The Sun?

The Sun is a yellow star.

So the maximum energy emitted
ought to be at ~ 5700 Å.

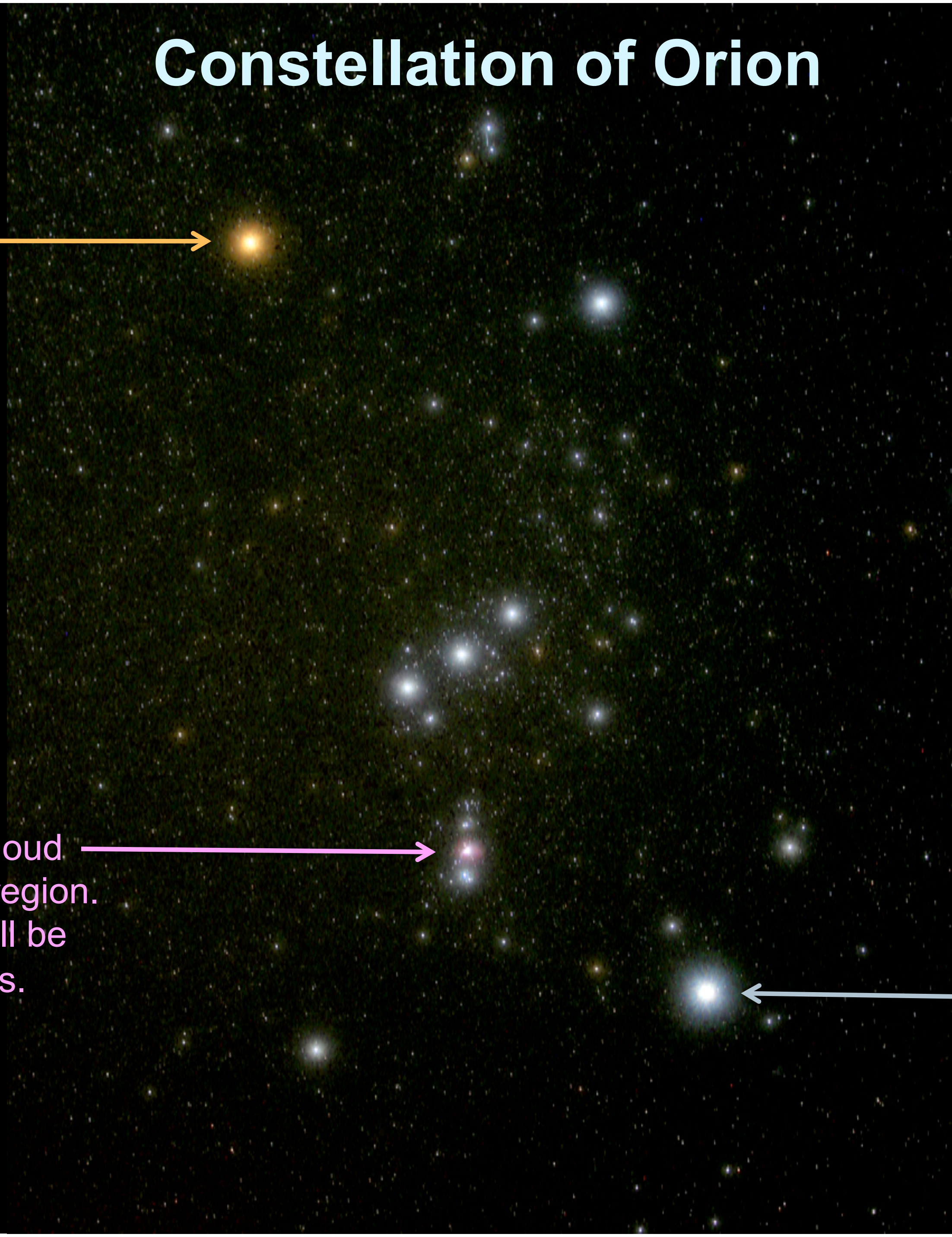
From Wien's Law,
$(5700\ \text{Å}) \times T = 3.0 \times 10^7\ \text{Å K}.$

Therefore $T \approx 5260$ K.

This is pretty close to correct. The correct answer is 5800 K. We missed slightly because the spectral energy drops more rapidly toward the blue than toward the red. In fact, the maximum energy emitted by the Sun is at about 5000 Å.

Constellation of Orion

Betelgeuse is a red supergiant star (T = 3500 K).



Orion Nebula gas cloud and star-formation region. Why it looks pink will be discussed next class.

Rigel is a blue supergiant star (T = 12,130 K).