Announcements

- Quiz 8 on Chapter 12 due tonight, practice problems in Problem Set 8A
- Next Monday: Quiz 8B, Problem Set 8B
- Midterm is Wednesday March 26 in class
  - Will cover Chapter 3, 9-12
  - Problems will be similar to those on quizzes
    - 45 problems
    - Includes parts of quiz 4, up to quiz 8
  - No book, notes or calculator
    - Sheet of formulas will be given
    - Calculations will be doable without a calculator
  - Bring #2 pencil!
  - Review in class today

The New York Times

SPACE & COSMOS

Space Ripples Reveal Big Bang's Smoking Gun

By DENNIS OVERBYE MARCH 17, 2014

Alan Guth was one of the first physicists to hypothesize the existence of inflation, which explains how the universe expanded so uniformly and so quickly in the instant after the Big Bang 13.8 billion years ago.
Rick Friedman for The New York Times

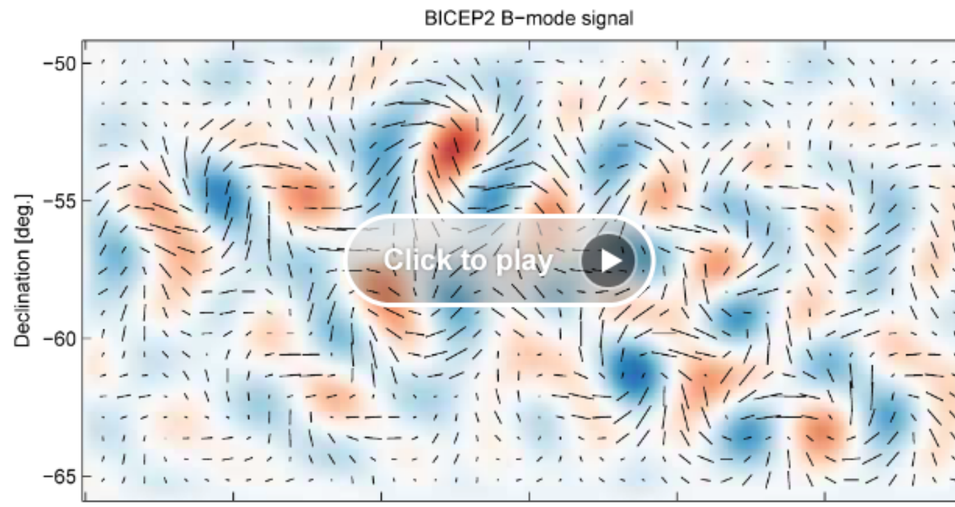
CAMBRIDGE, Mass. — One night late in 1979, an itinerant young physicist named Alan Guth, with a new son and a year's appointment at Stanford, stayed up late with his notebook and equations, venturing far beyond the world of known physics.

He was trying to understand why there was no trace of some exotic particle that should have been created in the Big Bang. Instead he discovered what might have made the universe bang to begin with. A potential hitch in the presumed course of cosmic evolution could have infused space itself with a special energy that exerted a repulsive force, causing the universe to swell faster than the speed of light for a prodigiously violent instant.

If true, the rapid engorgement would solve paradoxes like why the heavens look uniform from pole to pole and not like a jagged, warped mess. The

Big Bang breakthrough announced; gravitational waves detected

By **Elizabeth Landau**, CNN
updated 10:37 AM EDT, Tue March 18, 2014 | Filed under: Innovations



Ripples in space-time revealed

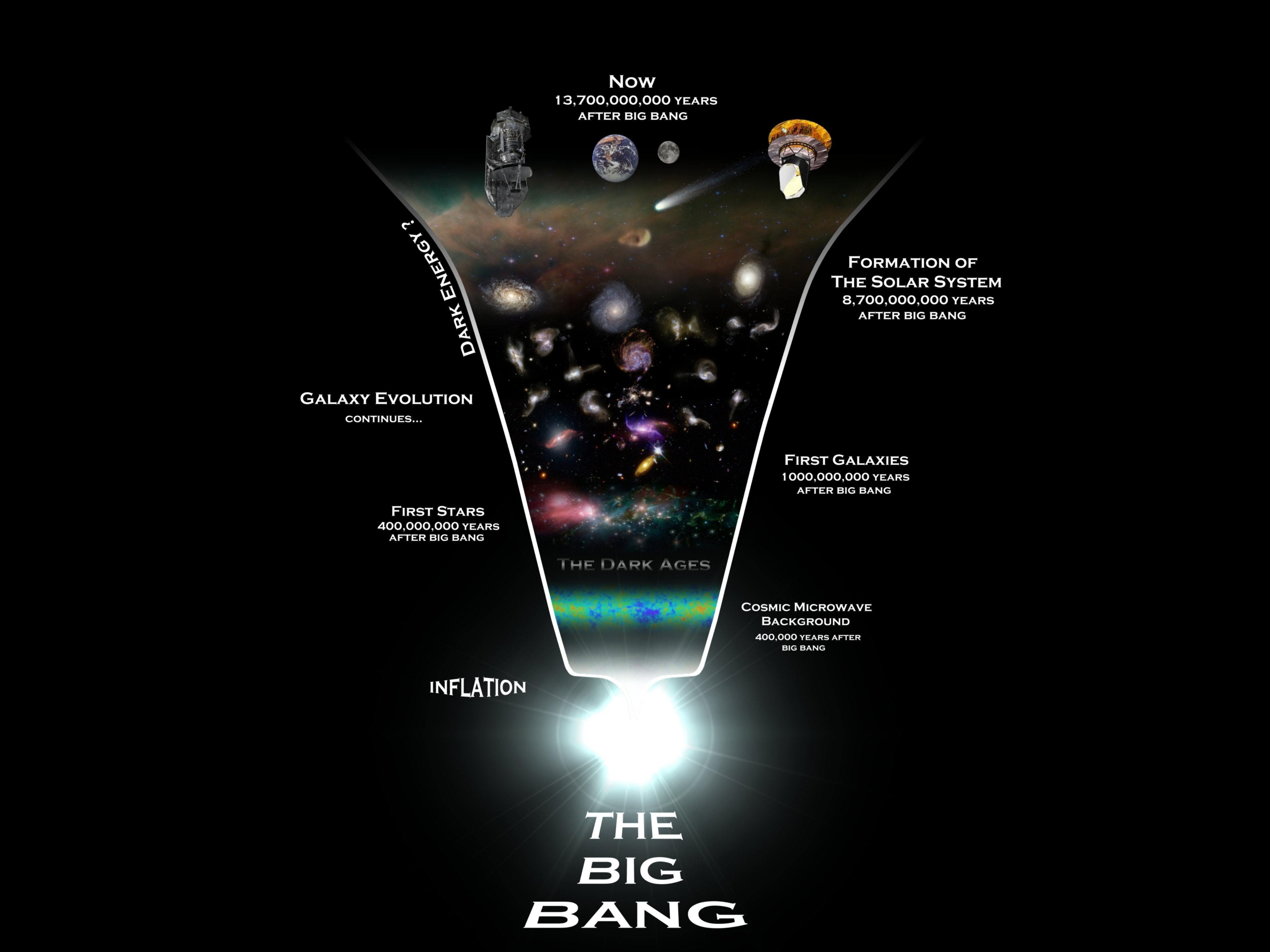
STORY HIGHLIGHTS

- Gravitational waves were predicted by Albert Einstein
- New results from BICEP2 are 'smoking gun for inflation'
- During inflation, the universe expanded faster than the speed of light

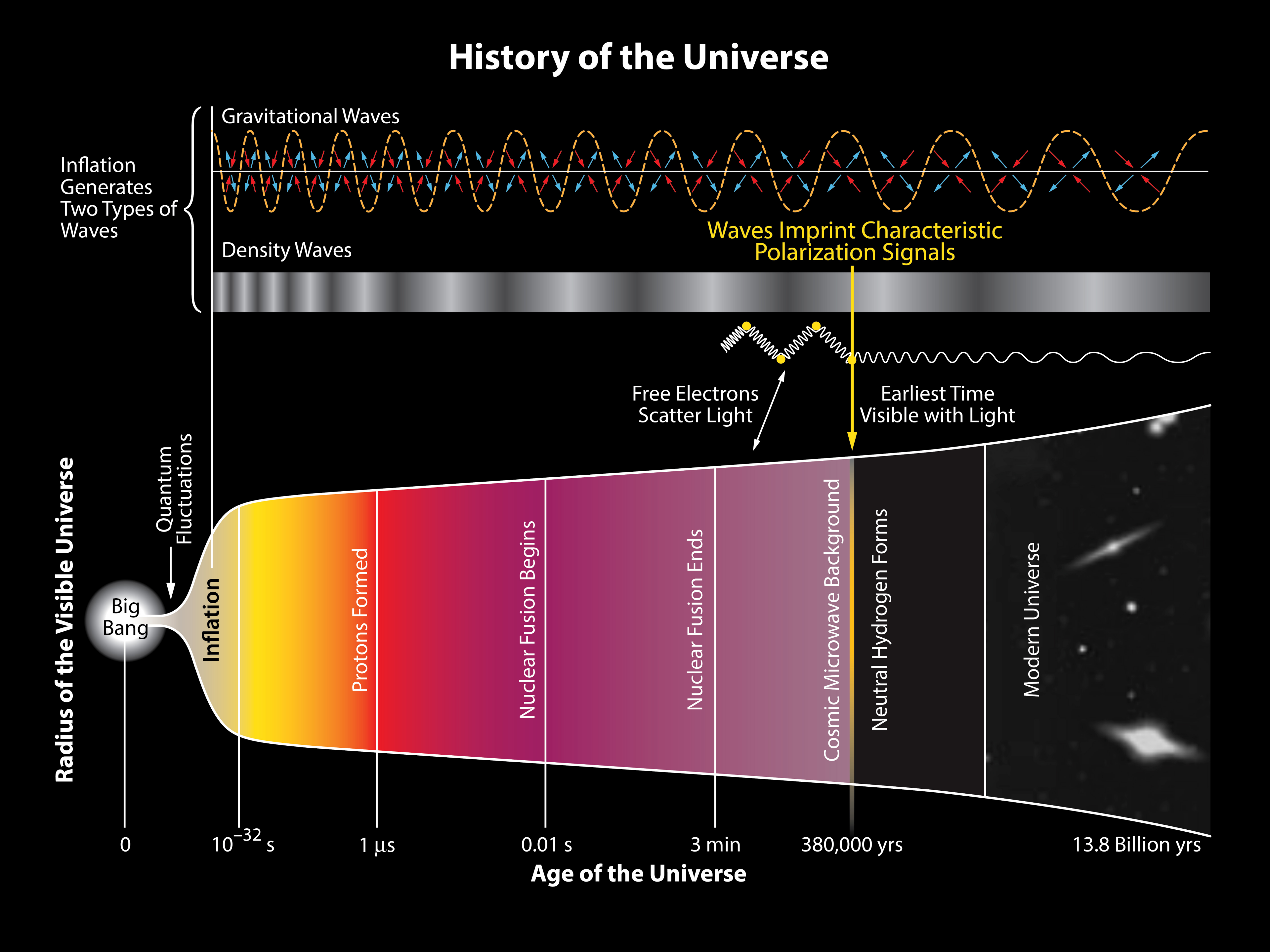
(CNN) -- There's no way for us to know exactly what happened some 13.8 billion years ago, when our universe burst onto the scene. But scientists announced Monday a breakthrough in understanding how our world as we know it came to be.

If the discovery holds up to scrutiny, it's evidence of how the universe rapidly expanded less than a trillionth of a second after the Big Bang.

"It teaches us something crucial about how our universe began," said Sean Carroll, a physicist at California Institute of Technology, who was not involved in the study. "It's an amazing achievement that we humans, doing science systematically for just a few hundred years, can extend our understanding that far."

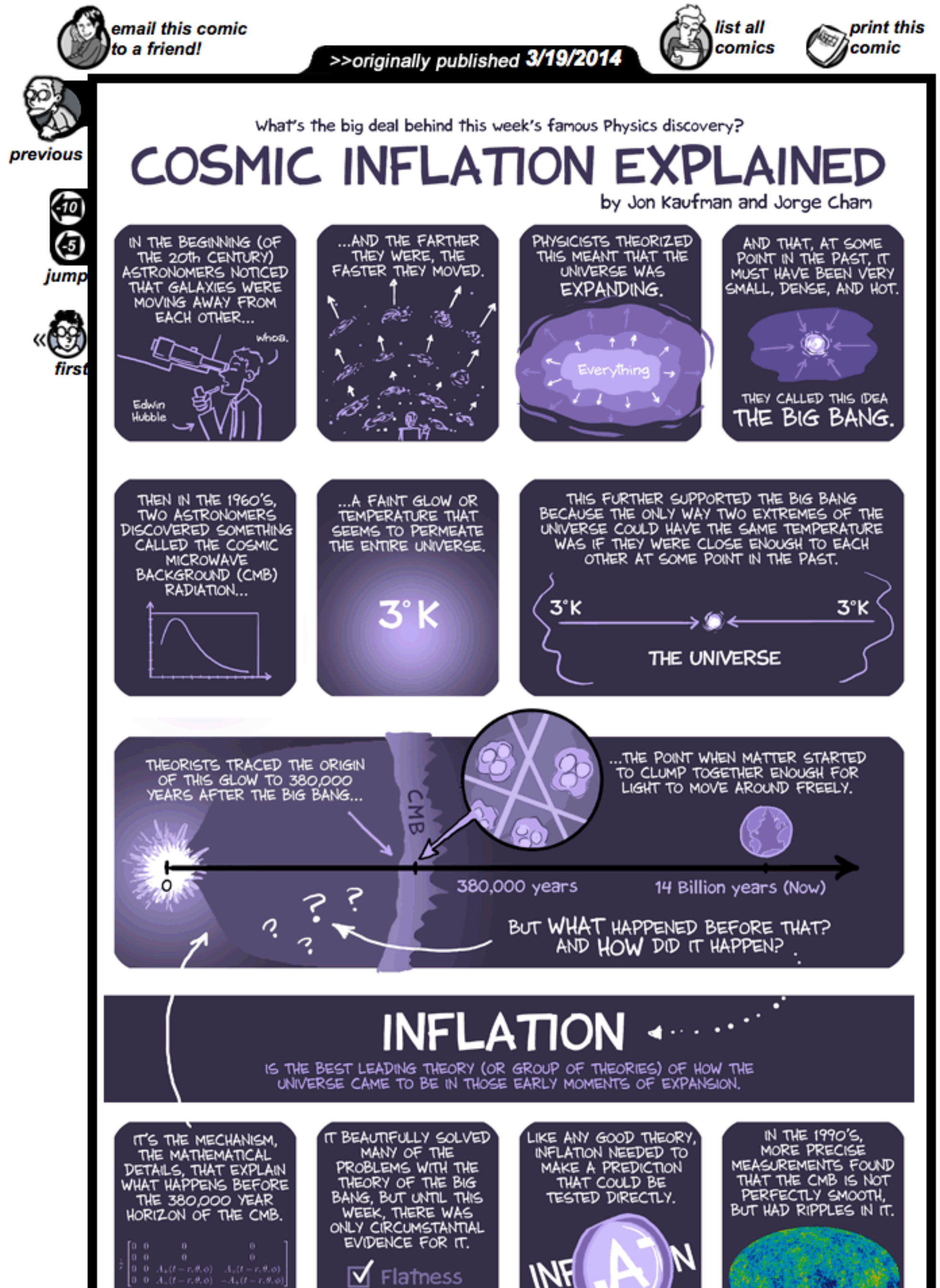


Now
13,700,000,000 years
after Big Bang
Dark Energy ?
Formation of
The Solar System
8,700,000,000 years
after Big Bang
Galaxy Evolution
continues...
First Galaxies
1000,000,000 years
after Big Bang
First Stars
400,000,000 years
after Big Bang
The Dark Ages
Cosmic Microwave
Background
400,000 years after
Big Bang
Inflation
THE
BIG
BANG



History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10^{-32} s
1 μs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

http://phdcomics.com/comics/archive.php?comicid=1691



Information provided on midterm:

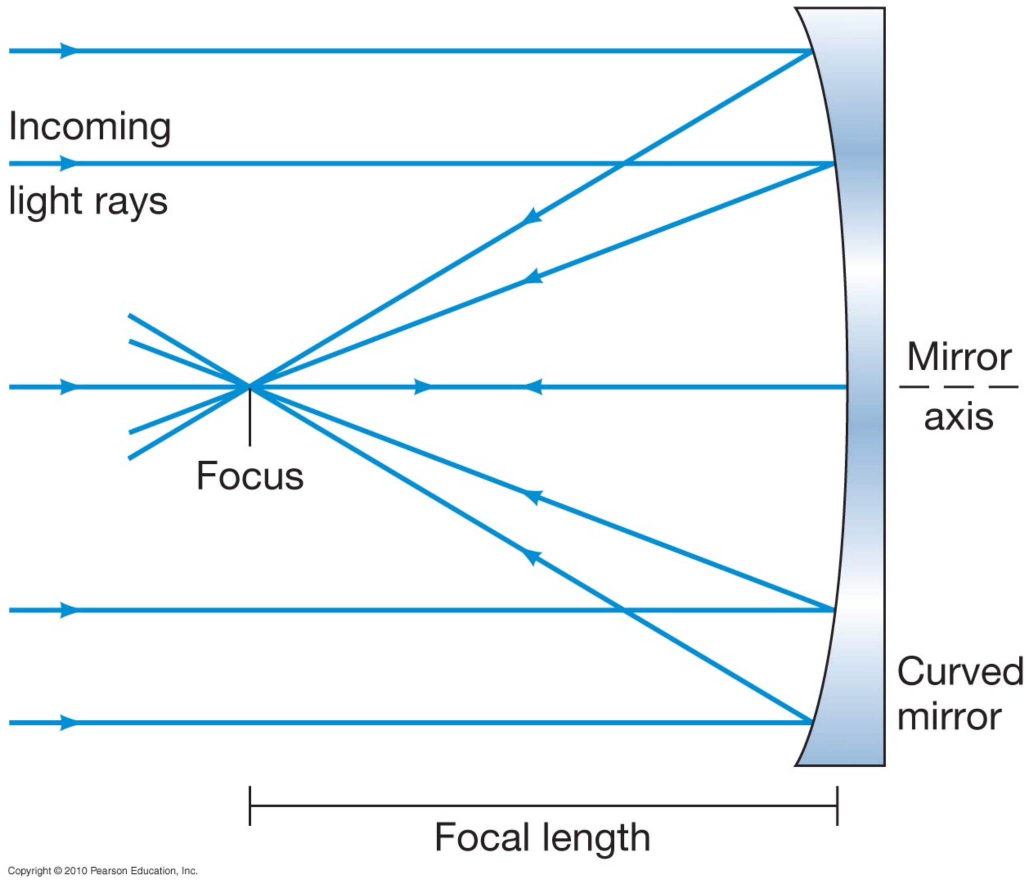
- 1 AU $= 3 \times 10^8$ km
- speed of light $= 3 \times 10^8$ m/s
- Kepler's 3rd law:
$$a^3 = P^2$$
with the period P in years and semi-major axis a in AU.
- Newton's law of gravity:
$$F = \frac{GMm}{r^2}$$
- Peak wavelength and temperature of blackbody radiation:
$$\lambda = \frac{3 \times 10^6}{T} \text{ nm}$$
with wavelength λ in nm (1 nm = 10^{-9} m) and temperature T in Kelvin.
- Conversion of mass into energy: $E = mc^2$
- Relationship between brightness B and distance d:
$$B_2 = B_1 \times \frac{d_1^2}{d_2^2}$$
- Relationship between luminosity L, temperature T and radius R of stars:
$$L = 4\pi\sigma T^4 R^2$$
where $4\pi\sigma$ are constants.

Figure 3.1

Optical Telescopes

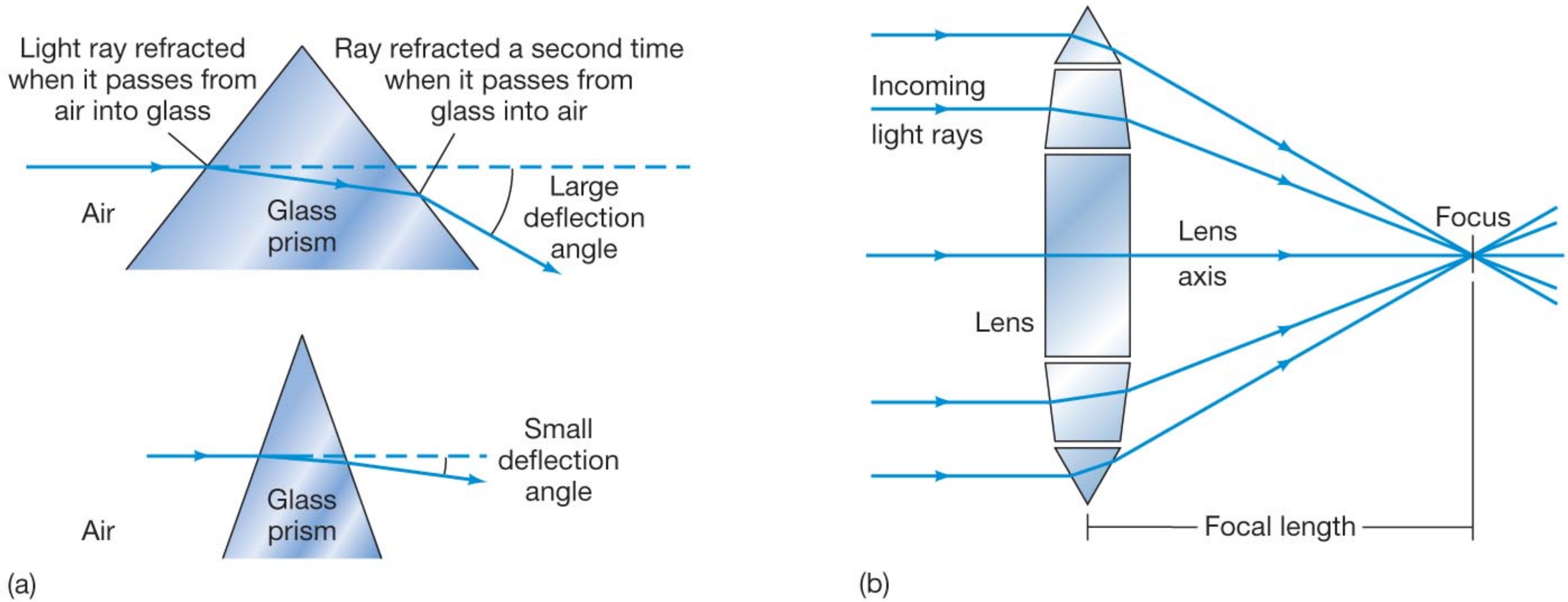
Images can be formed through reflection or refraction.

Reflecting mirror



Note that the incoming light rays are parallel. This is because astronomical objects are so far away.

Refracting lens



Modern telescopes are all reflectors:

- Light traveling through a lens is refracted differently depending on wavelength (chromatic aberration). Mirrors don't suffer from this.

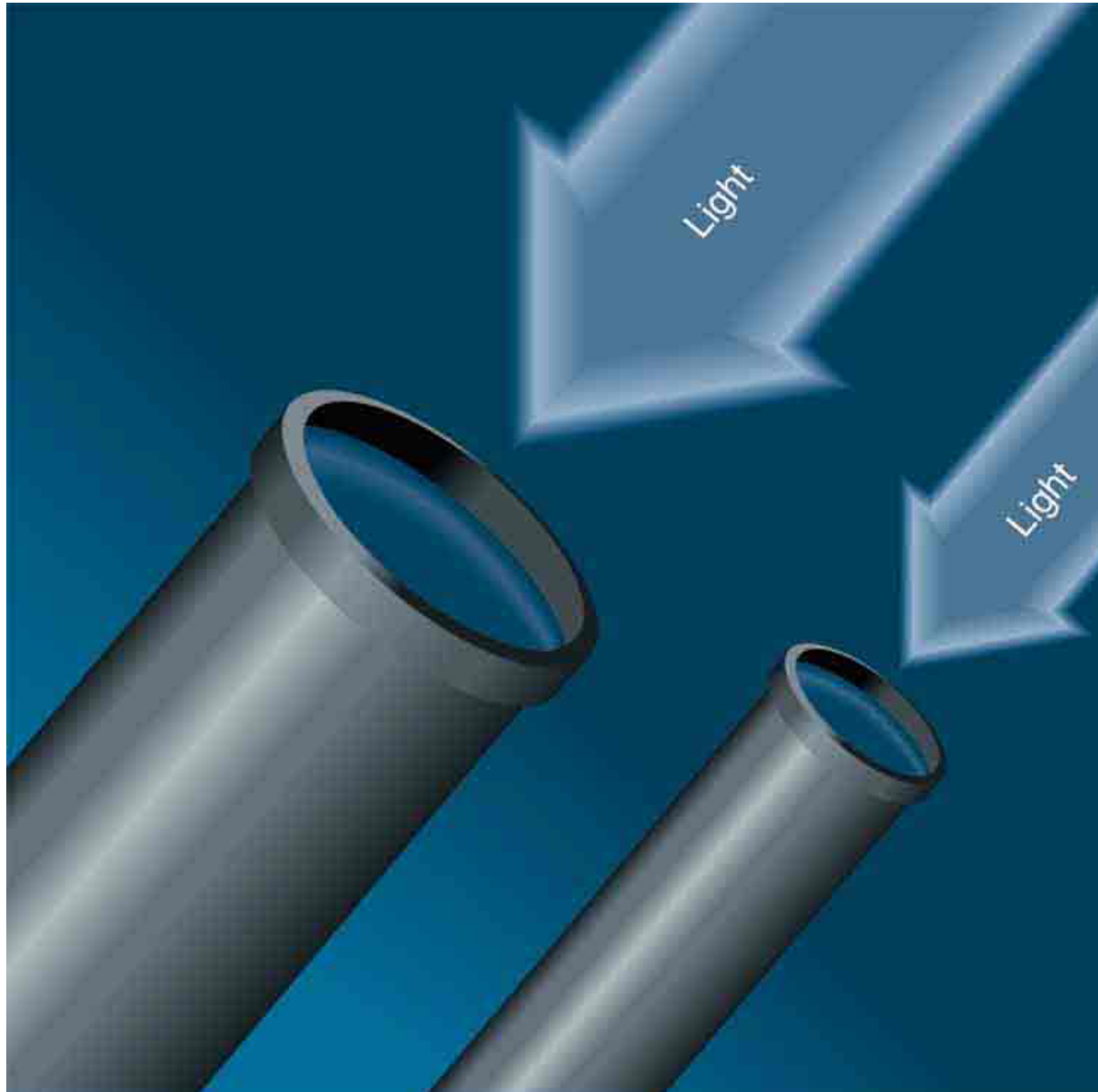
- Some light traveling through lens is absorbed (especially IR and UV light). Mirrors can be made to reflect this IR and UV.

- Large lens can be very heavy, and can only be supported at edge. Mirrors are supported at the back.

- Lens needs two optically acceptable surfaces, mirror only needs one, though mirror surfaces have to be more precise.

Bigger is Better in Astronomy

A larger telescope gathers more light and so can see dimmer objects.

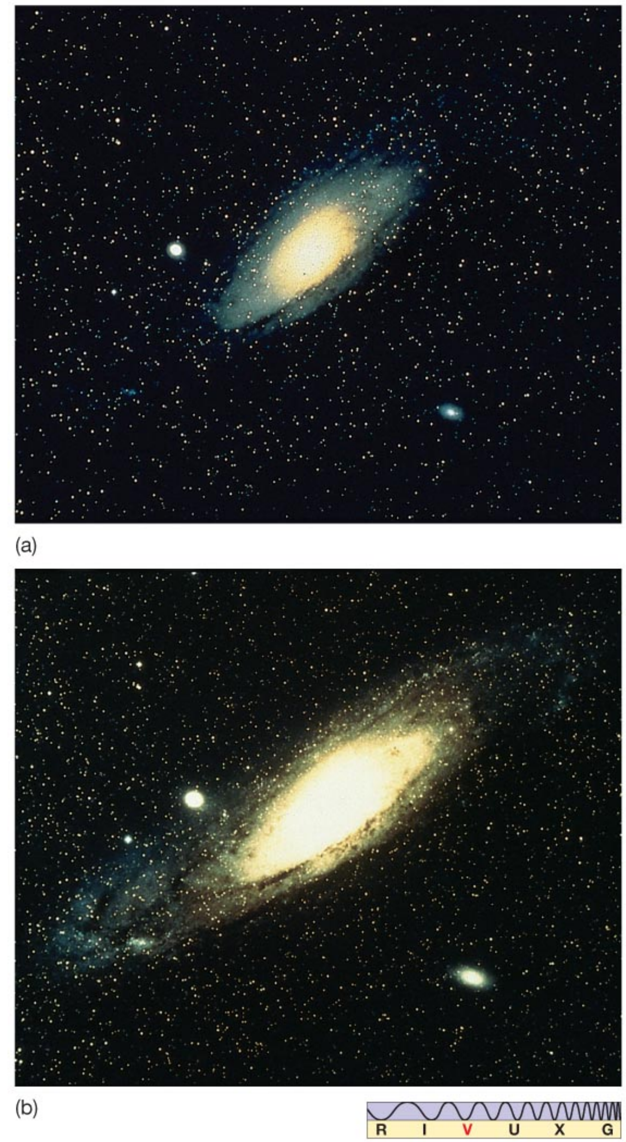


Light-gathering power:

Improves detail

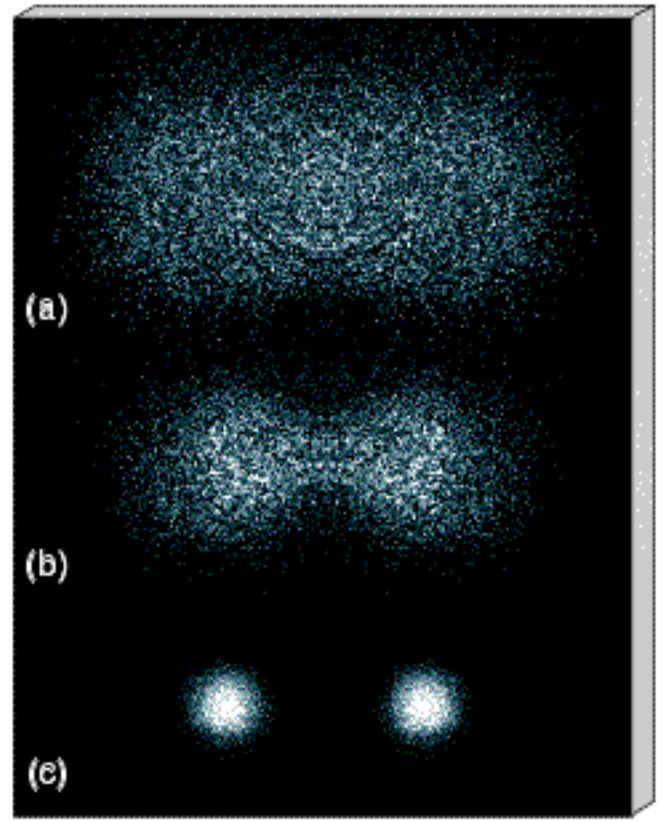
The figure, part (b) was taken with a telescope twice the size of (a).

Twice the diameter means four times the light, since the area of the telescope is four times larger.

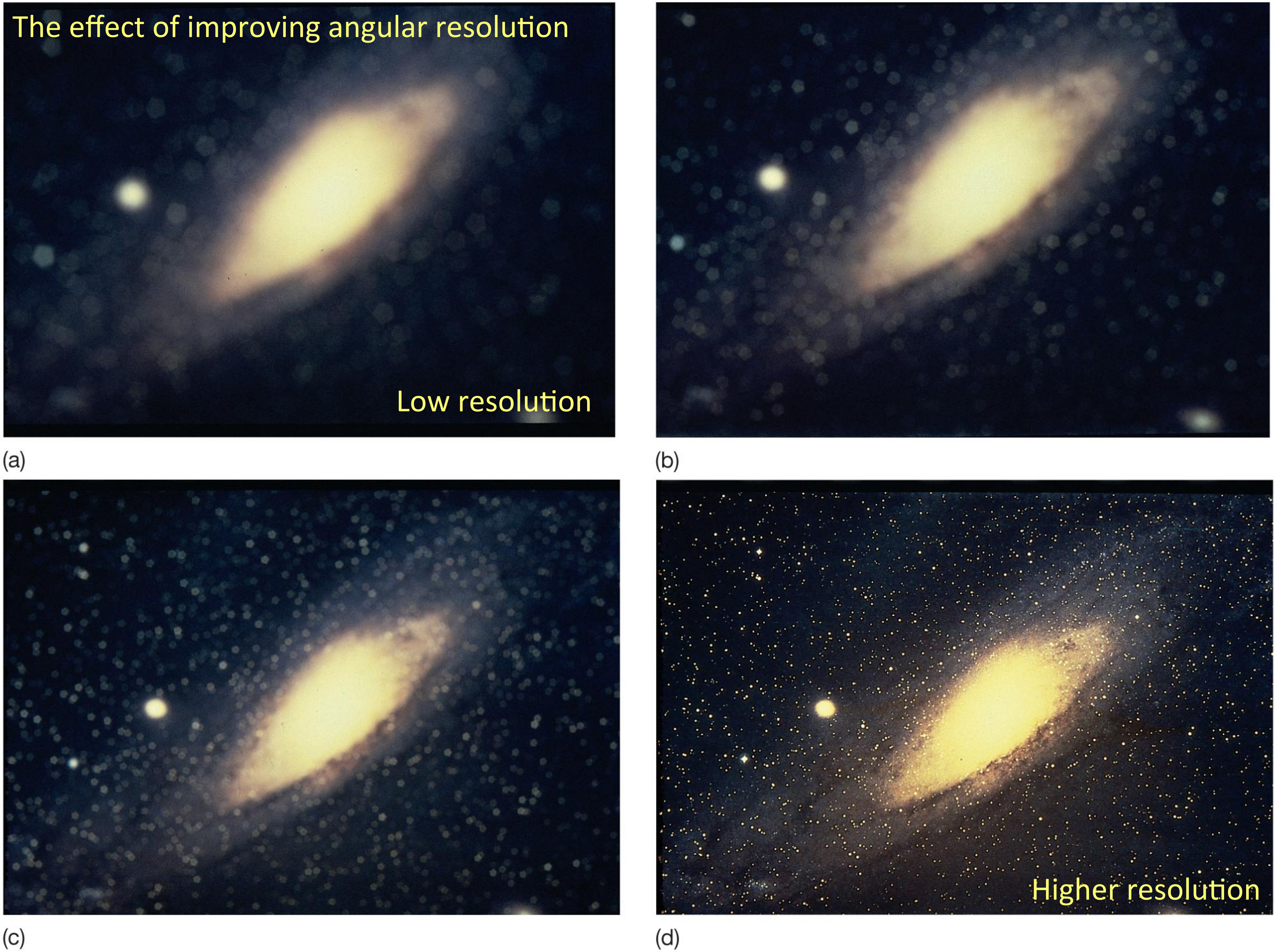


Angular resolution

The second major advantage of a large telescope is its ability to see a **separation between two objects that are nearly in the same direction**. In optical astronomy, one typically wants to see two distinct stars when looking at a binary system in which the two stars orbit their common center of mass. The resolving power is the smallest angle one can see with a given telescope.



Large telescopes have greater resolving power than small telescopes, but the resolving power of all earthbound optical telescopes is limited by the turbulence of the air.


The effect of improving angular resolution
Low resolution
(a)
(b)
(c)
(d)
Higher resolution

The resolving power of all ground-based optical telescopes is limited by the blurring effect of turbulence in the atmosphere.

To avoid the problems with turbulence one places optical telescopes on mountains to get above most of the atmosphere, or, more expensively, on satellites.

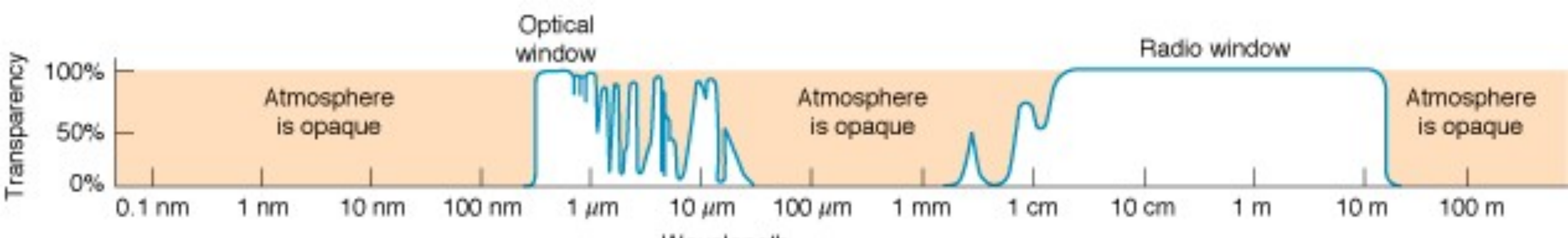
Go to space

The Hubble Space Telescope

One of the main advantages of a telescope in space is that its images are not blurred by the atmosphere

So far we have been talking about optical telescopes that observe visible light. We also observe other parts of the electromagnetic spectrum.

The atmosphere is opaque to light of most wavelengths, marked by tan shading in the diagram. **Optical** and **radio** wavelengths can be seen from the ground. For γ-rays, X-rays, most ultraviolet and most infrared light,
one uses satellite telescopes.



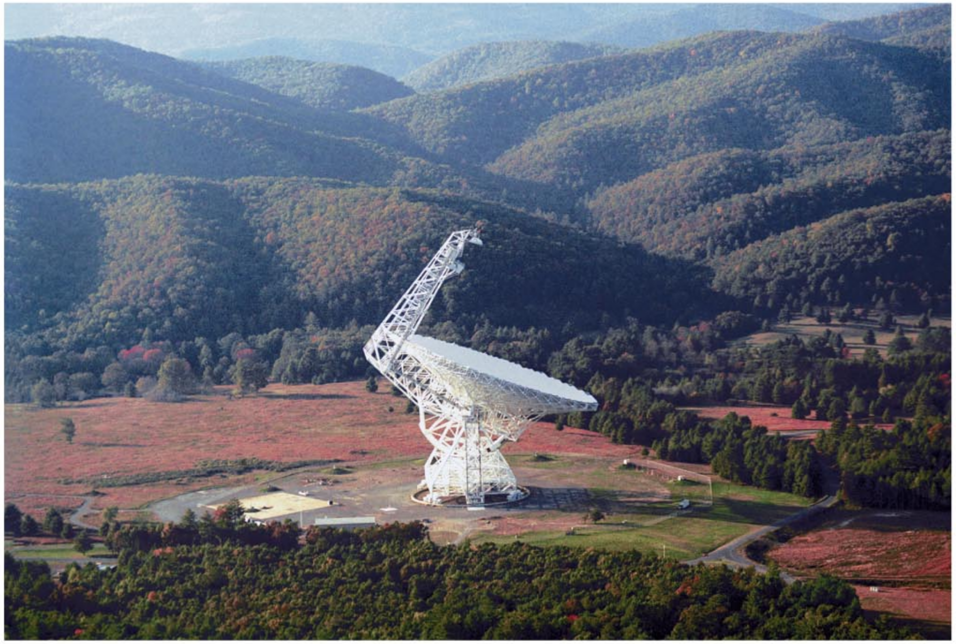
γ-rays X-rays UV visible infrared microwave RADIO

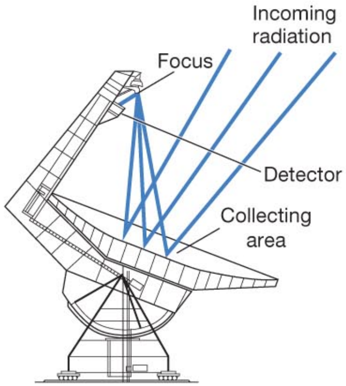
Radio telescopes:

- **Similar to optical reflecting telescopes**
- **Less sensitive to imperfections due to longer wavelengths – surface has to be smooth on the scale of wavelengths of light observed**
- **Can be made very large**

Green Bank Telescope, 105 m diameter

National Radio Astronomy Observatory, West Virginia


(a)



(b)

Longer wavelength means poorer angular resolution

- Atmospheric blurring isn't an issue in radio
- The *diffraction limit* is
  - Ultimate limit in angular resolution comes from **diffraction**, the spreading of light as it passes a corner or opening

$$\text{angular resolution (arc seconds)} = 0.25\,\frac{\text{wavelength }(\mu\text{m})}{\text{mirror diameter (m)}}$$

  - Longer wavelength: poorer resolution
  - Larger telescope: better resolution

(a)

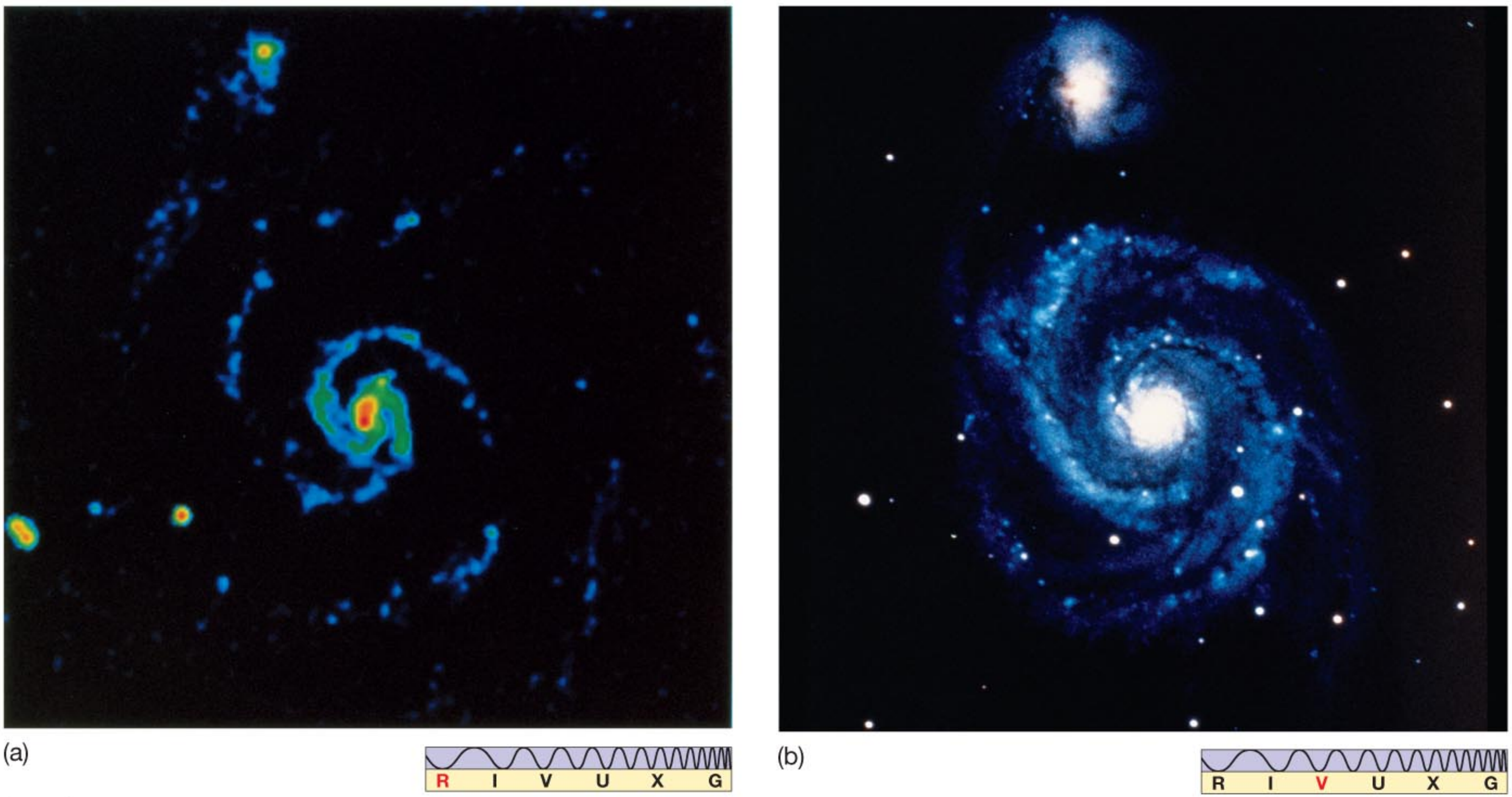
(b)

Interferometry

• Combines information from several widely spread radio telescopes as if it came from a single dish.

• Resolution will be that of dish whose diameter = largest separation between dishes.

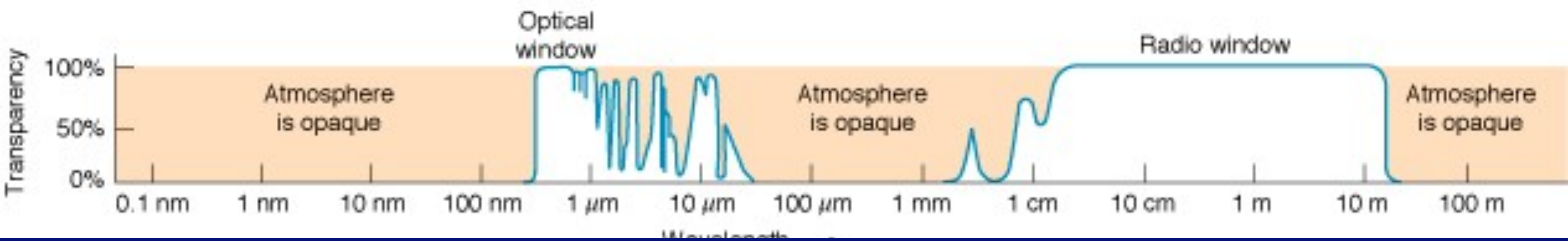
With interferometry we can get radio images whose resolution is close to optical.



There are still other wavelengths of light we would like to observe!

Optical and radio wavelengths can be seen from the ground.

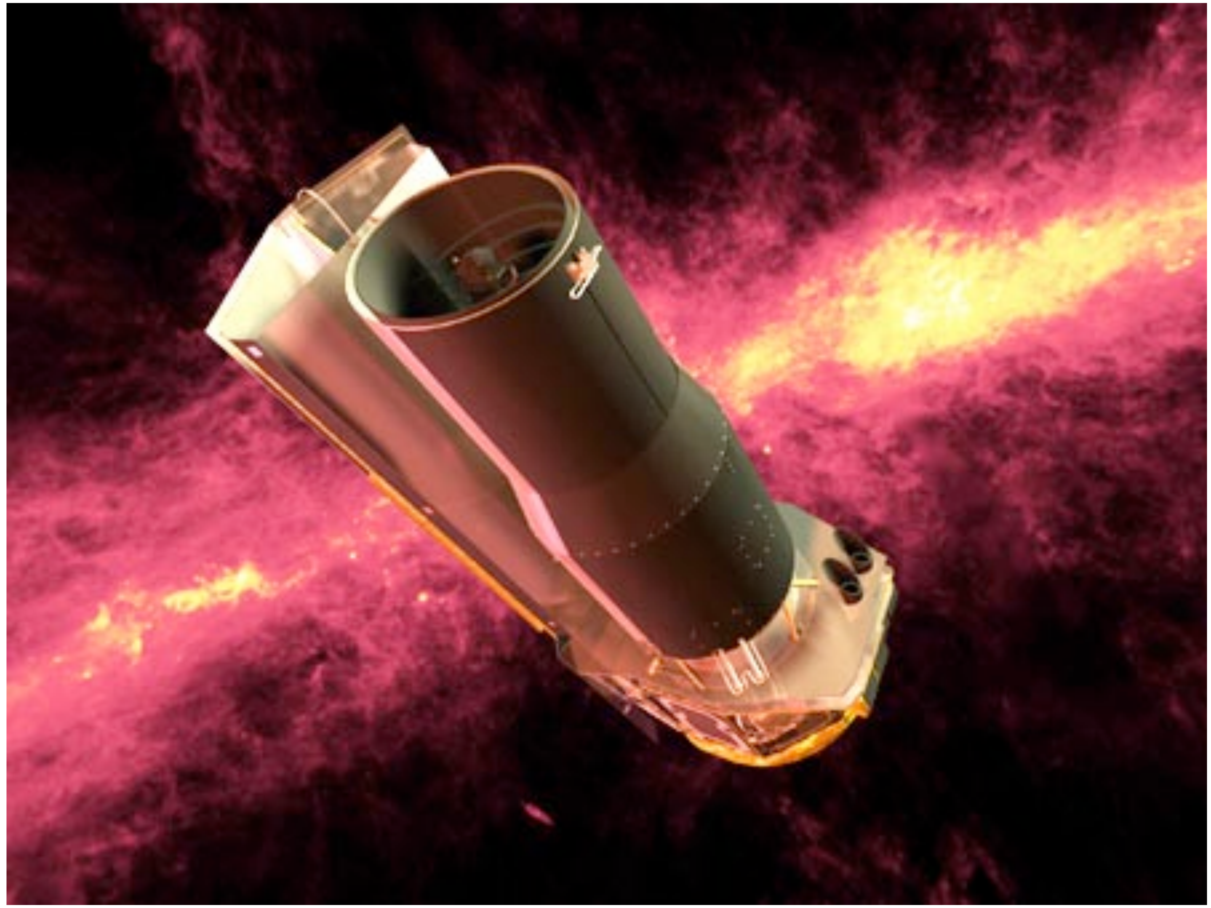
For γ-rays, X-rays, most ultraviolet and most infrared light, one uses satellite telescopes.



γ-rays X-rays UV visible infrared microwave RADIO

The **Spitzer Space Telescope**, an infrared telescope in space

Everything emits radiation because of its temperature. Cold things emit in the infrared, so to observe in the infrared our telescope must be very very cold, or else it will be much brighter than what we're trying to look at!

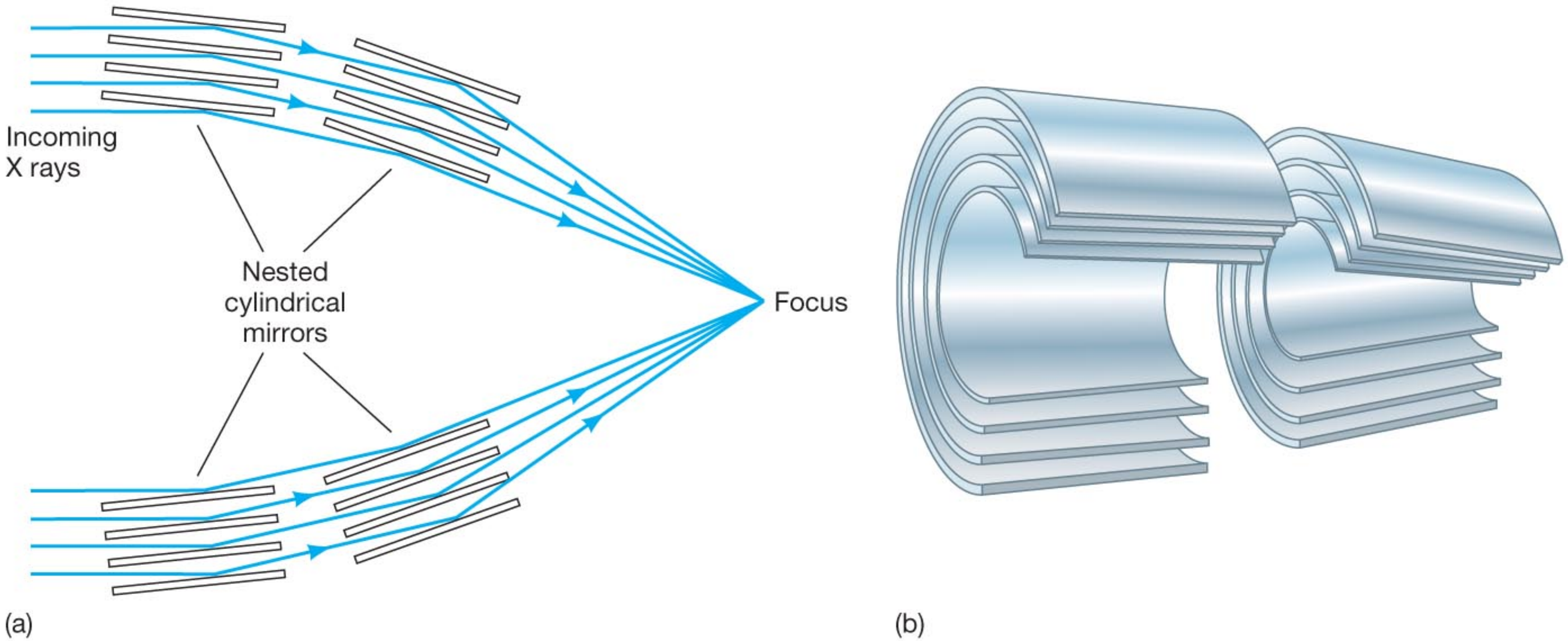


Cooled to 4 K by liquid helium (until it ran out) – must be very very cold to keep thermal background low

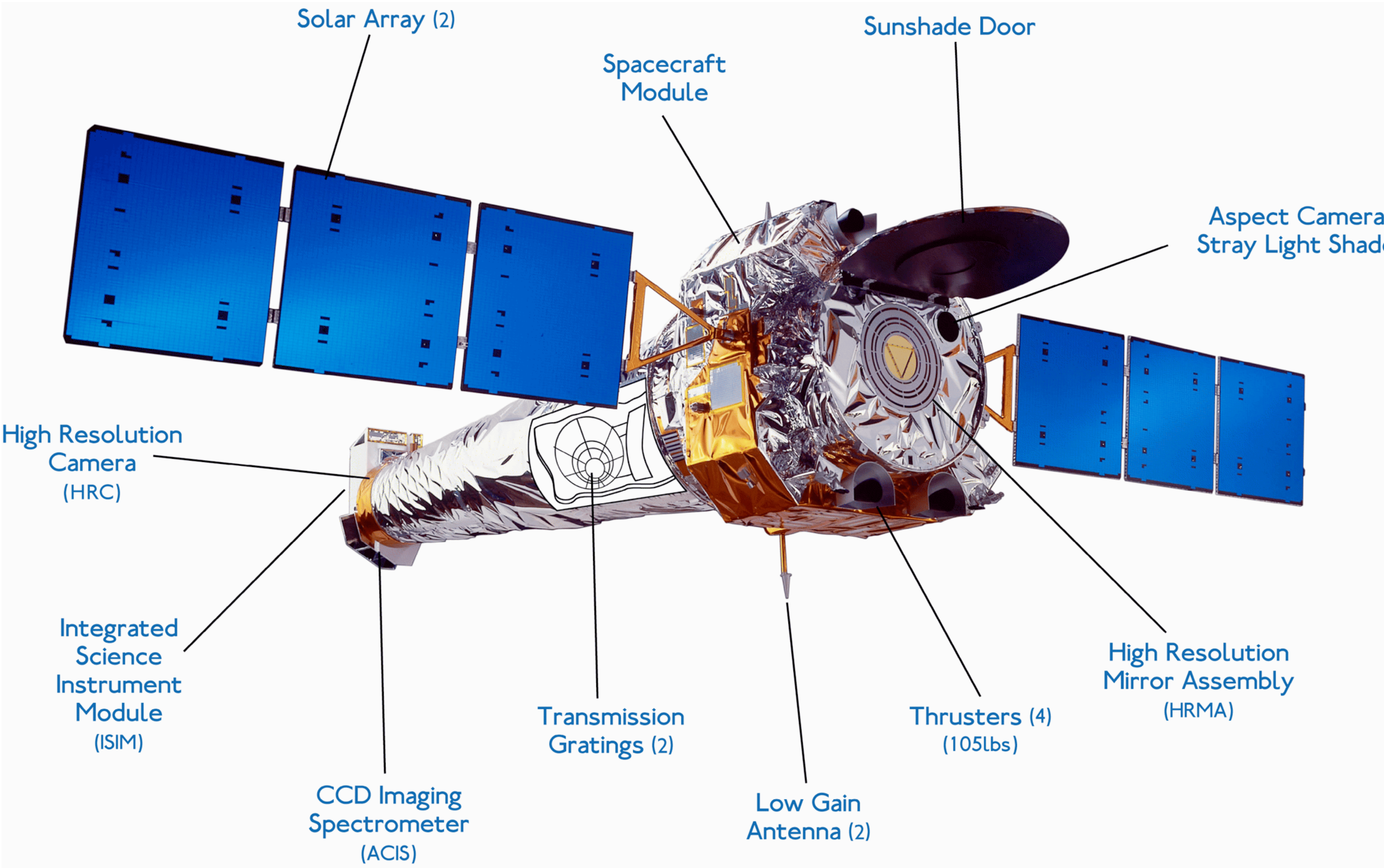
What about shorter wavelengths?

X rays and gamma rays will not reflect off mirrors as other wavelengths do; need new techniques.

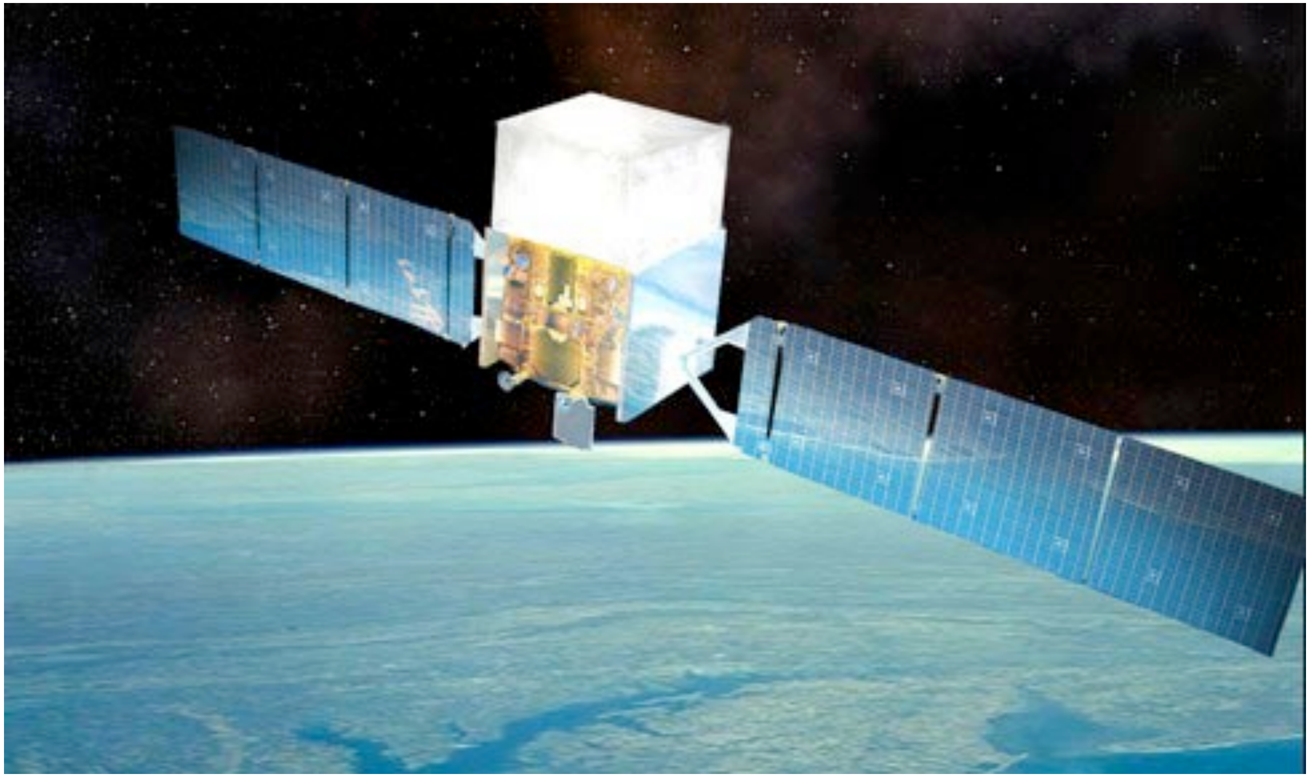
X rays will reflect at a very shallow angle, and can therefore be focused.



The Chandra X-ray Observatory



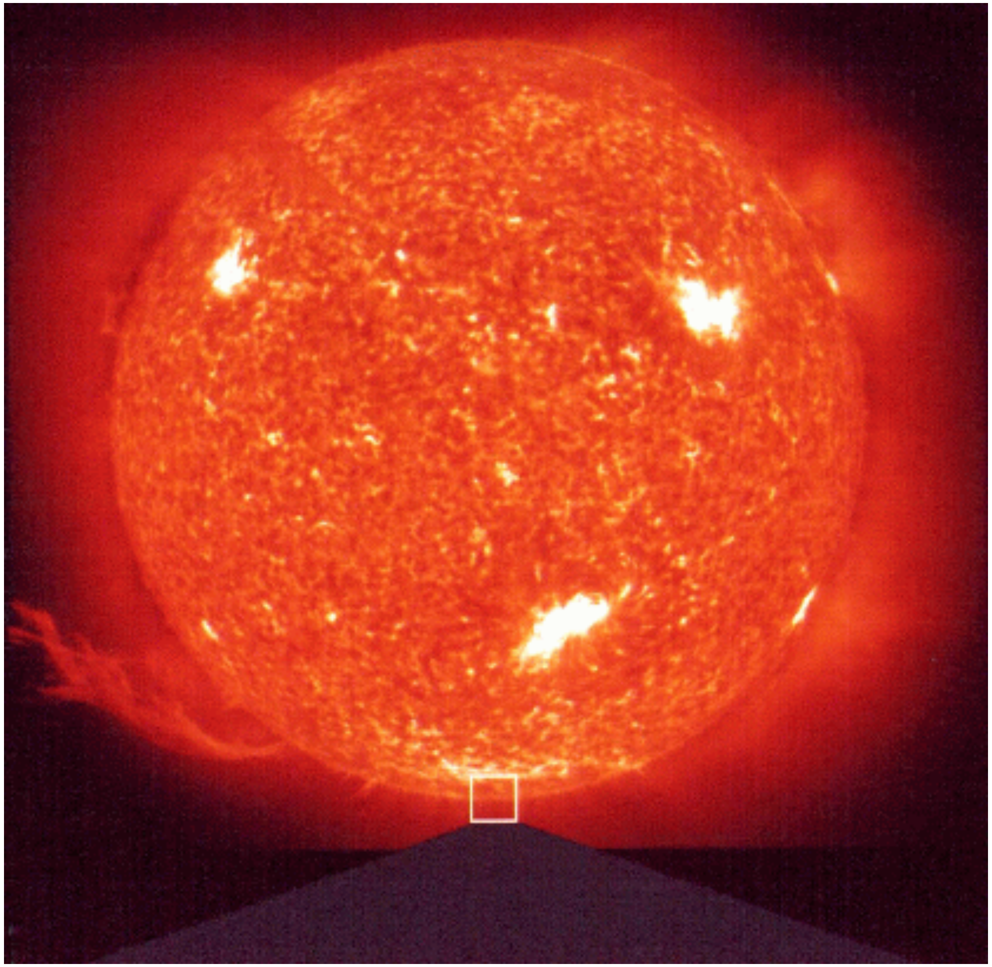
The Fermi Gamma Ray Telescope in Earth orbit



Fermi
Gamma-ray
Space Telescope

Gamma rays can’t be focused. We just put a detector in space and wait for them.

The Sun



The Sun is a star – the closest and most important star to us.

TABLE 9.1 Some Solar Properties

Radius	696,000 km
Mass	1.99×10^{30} kg
Average density	1410 kg/m^3
Rotation period	25.1 days (equator); 30.8 days (60° latitude) 36 days (poles) 26.9 days (interior)
Surface temperature	5780 K
Luminosity	3.86×10^{26} W

The radius of the Sun is more that 100 times the radius of the Earth, and the mass of the Sun is more than 300,000 times the mass of the Earth.

We know A LOT about the Sun - perhaps more than we know about the center of the earth.

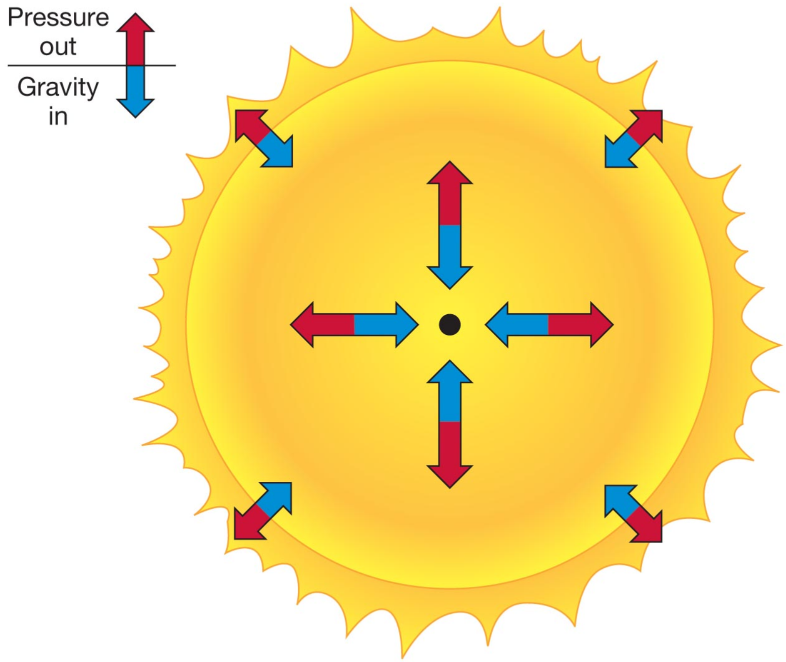
The Solar Interior

(core, radiation zone, and convection zone)

We cannot see inside the Sun. We use models and simulations to tell us what's going on inside it.

Models start from the idea of **hydrostatic equilibrium**:

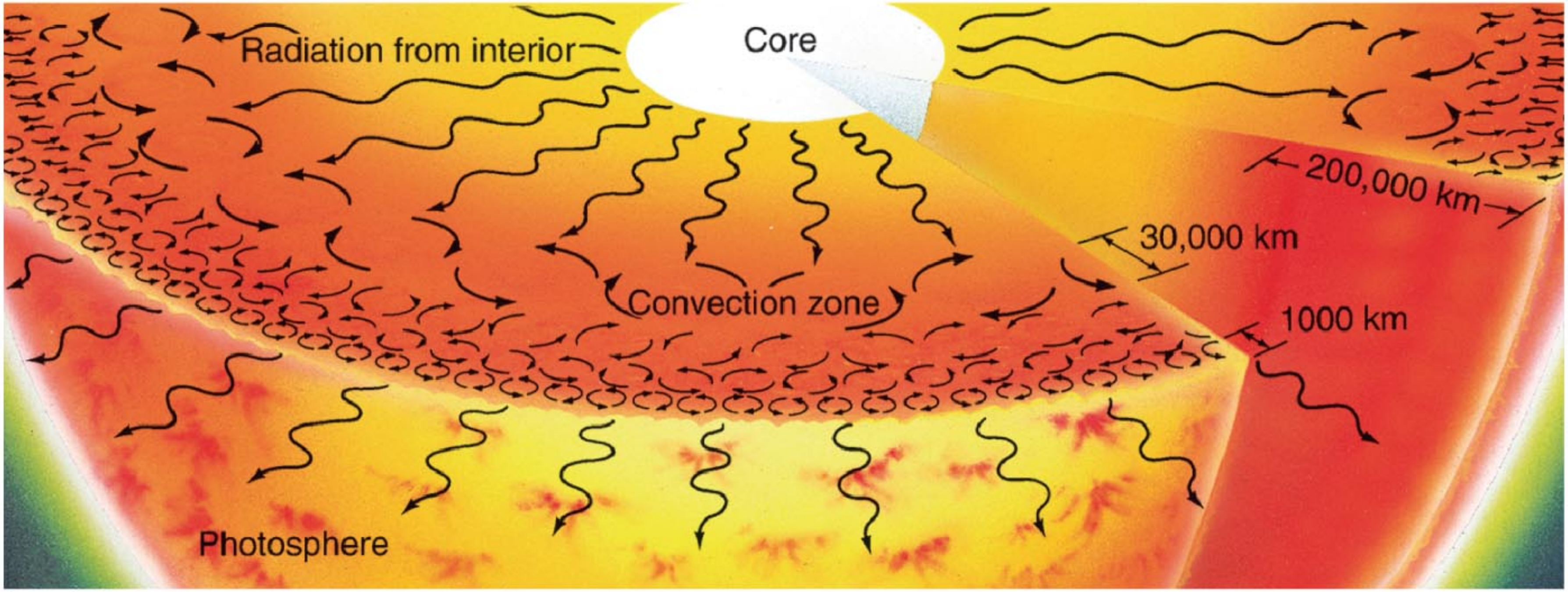
The pressure of gas exactly balances the gravitational pull of gravity.



Because the Sun is very massive, very high temperatures and pressures are needed to balance gravity.

How does Energy get out of the Sun? Radiation and Convection

The radiation zone is relatively transparent; the cooler convection zone is opaque.

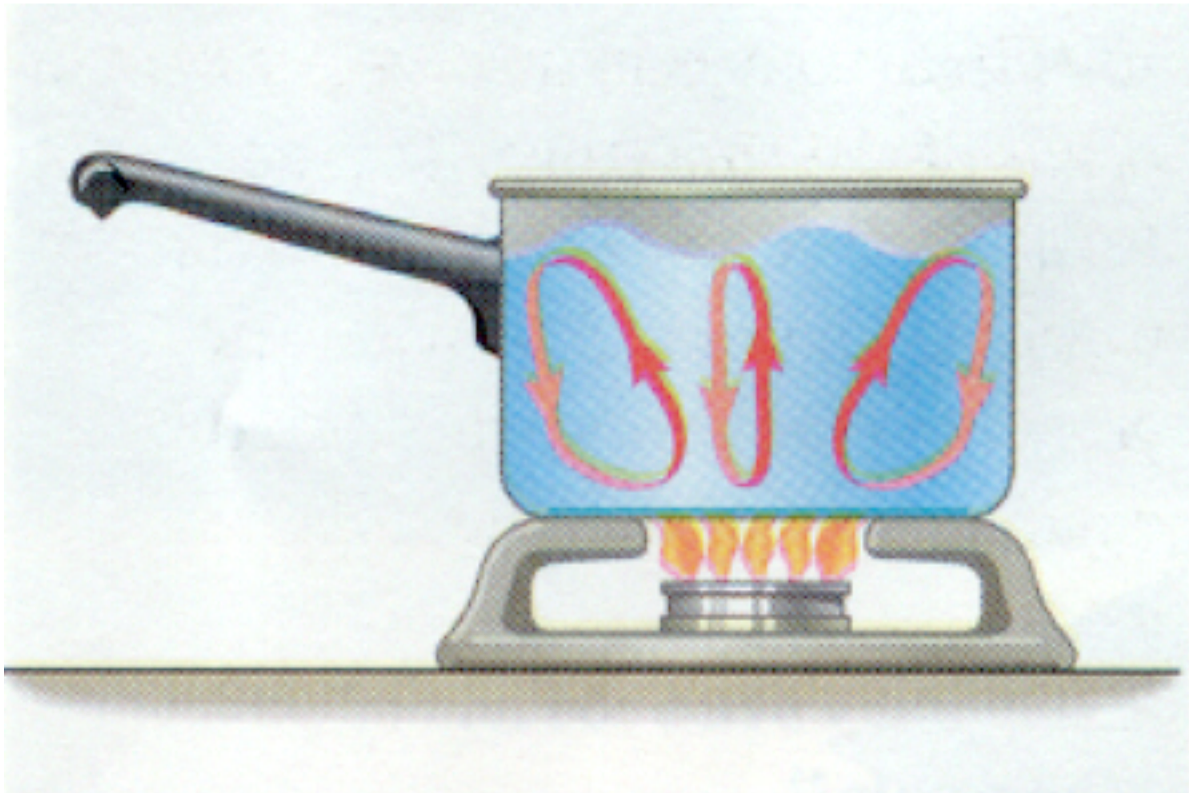


What is radiation?

All objects give off and absorb electromagnetic radiation.

But hotter objects gives off more than cooler objects.

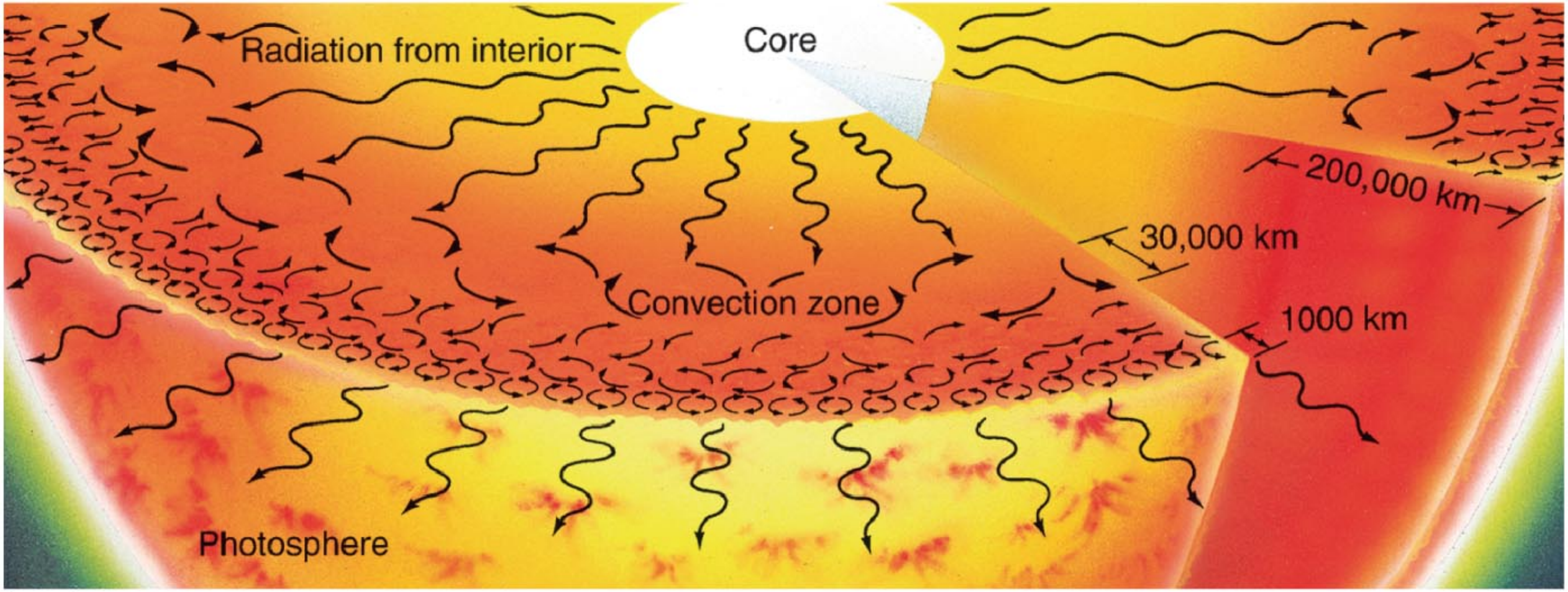
What is convection?



Convection transfers heat by moving stuff around. Hot stuff rises, cool stuff sinks.

The sun transports energy by radiation in certain parts and convection in others.

This is due to the different transparency of hydrogen and helium as a function of temperature.



The Solar Atmosphere

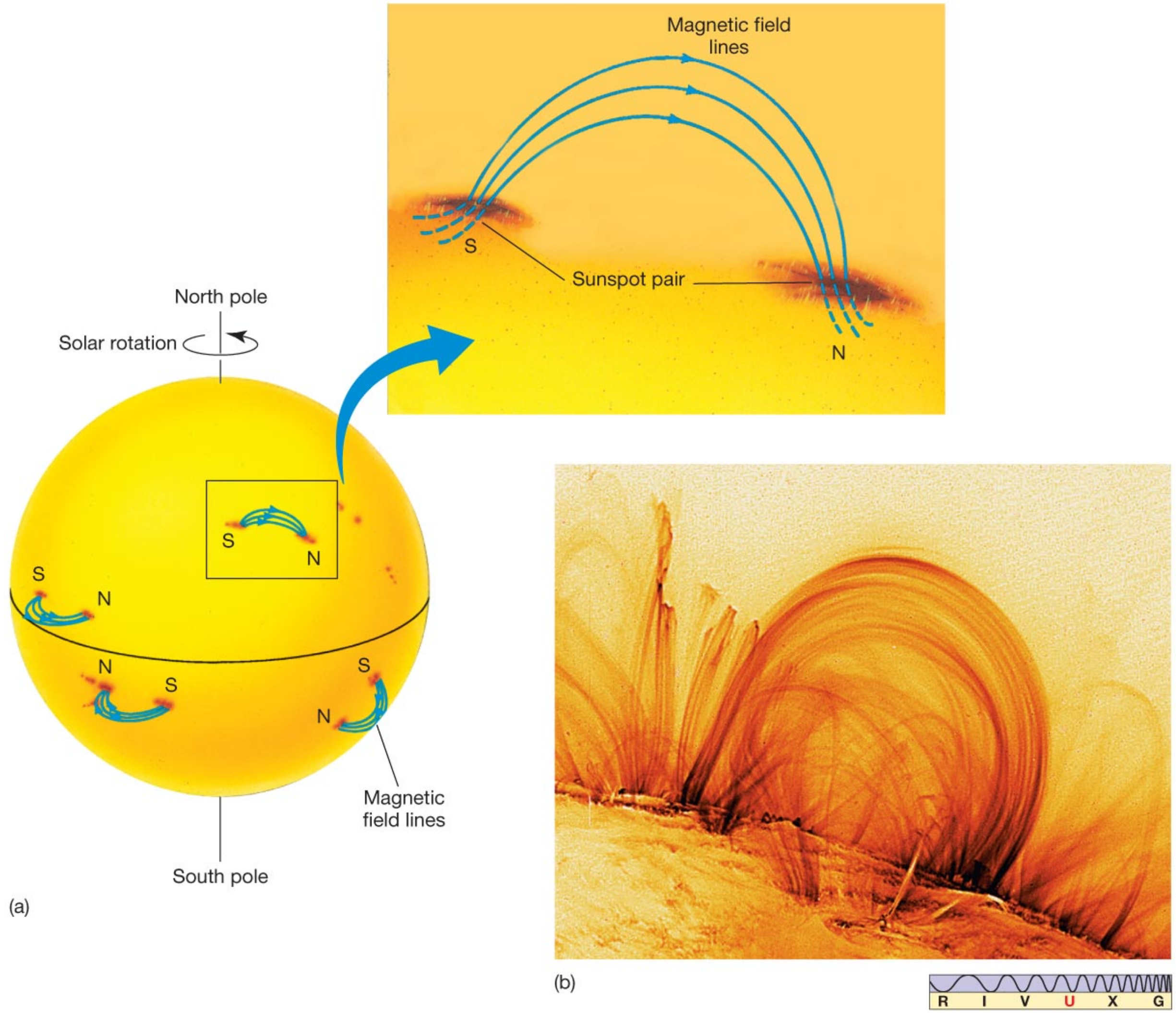
Photosphere with **sunspots**

What are Sunspots?

Sunspots come and go, typically in a few days.

Sunspot pairs are linked by magnetic field lines, which drain energy from the photosphere

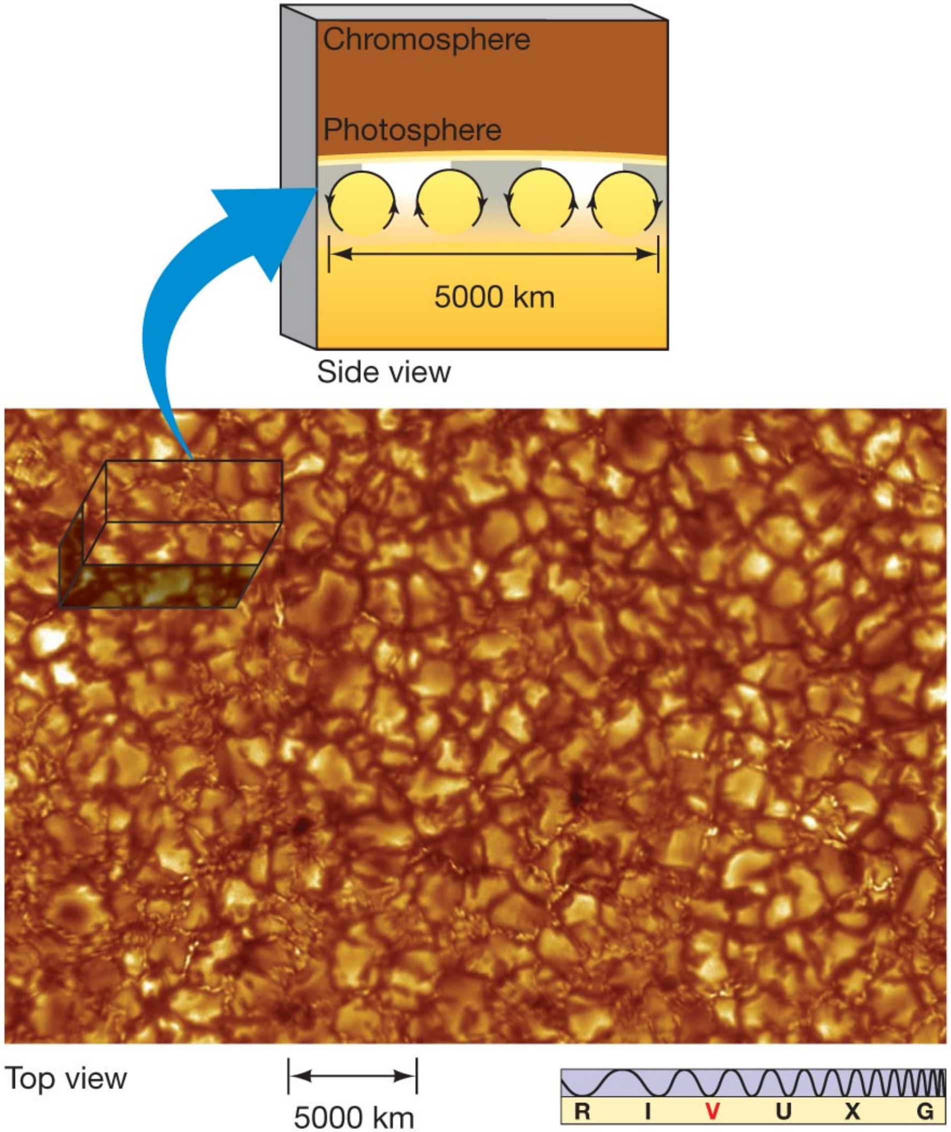
They are dark because they are **cooler** than the surrounding photosphere



Looking closer at the photosphere

Convection on the photosphere is granulated, with areas of upwelling material surrounded by areas of sinking material.

These spots are called granules.



Summary: Features of the Photosphere

Heat from the interior moves by convection (hot hydrogen gas rising) to the photosphere

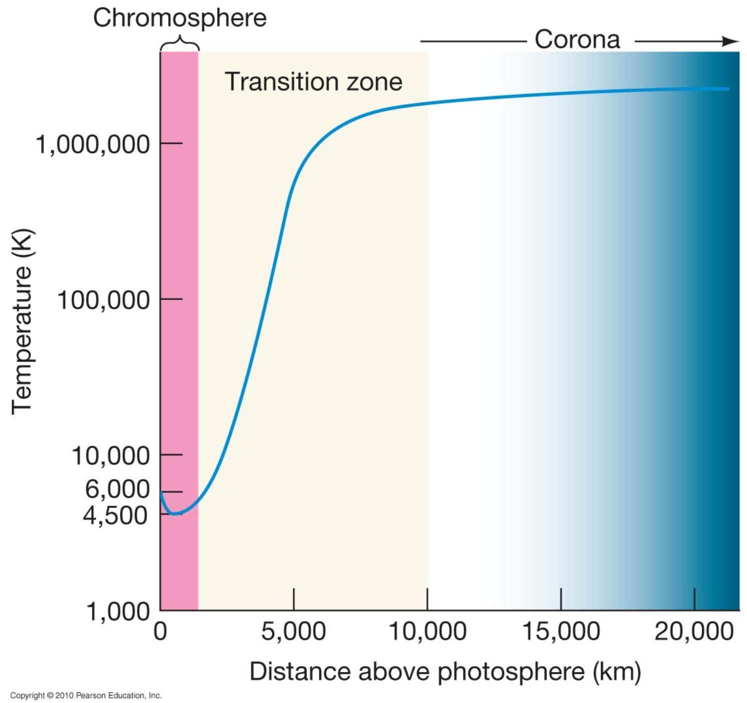
The tops of convection cells are called granules

Sunspots are the result of strong magnetic fields going in or out of the Sun's surface

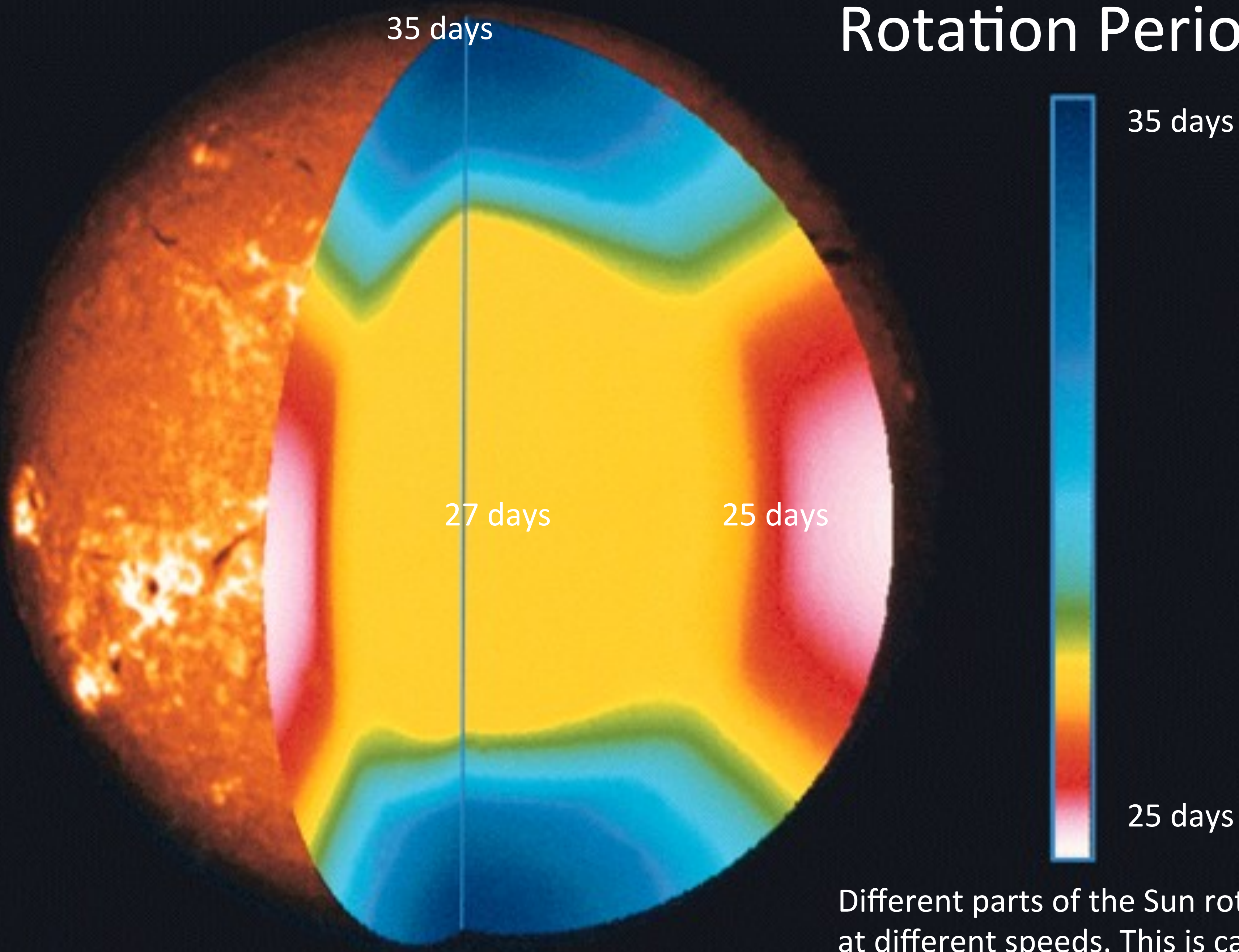
The magnetic field drains energy from the surrounding photosphere, cooling it; because the cooler gas is darker, it is seen as a dark spot.

The temperature of the photosphere is about 6,000 K.

But outside the photosphere, the temperature (surprisingly) increases, reaching 3 million K in the Corona.

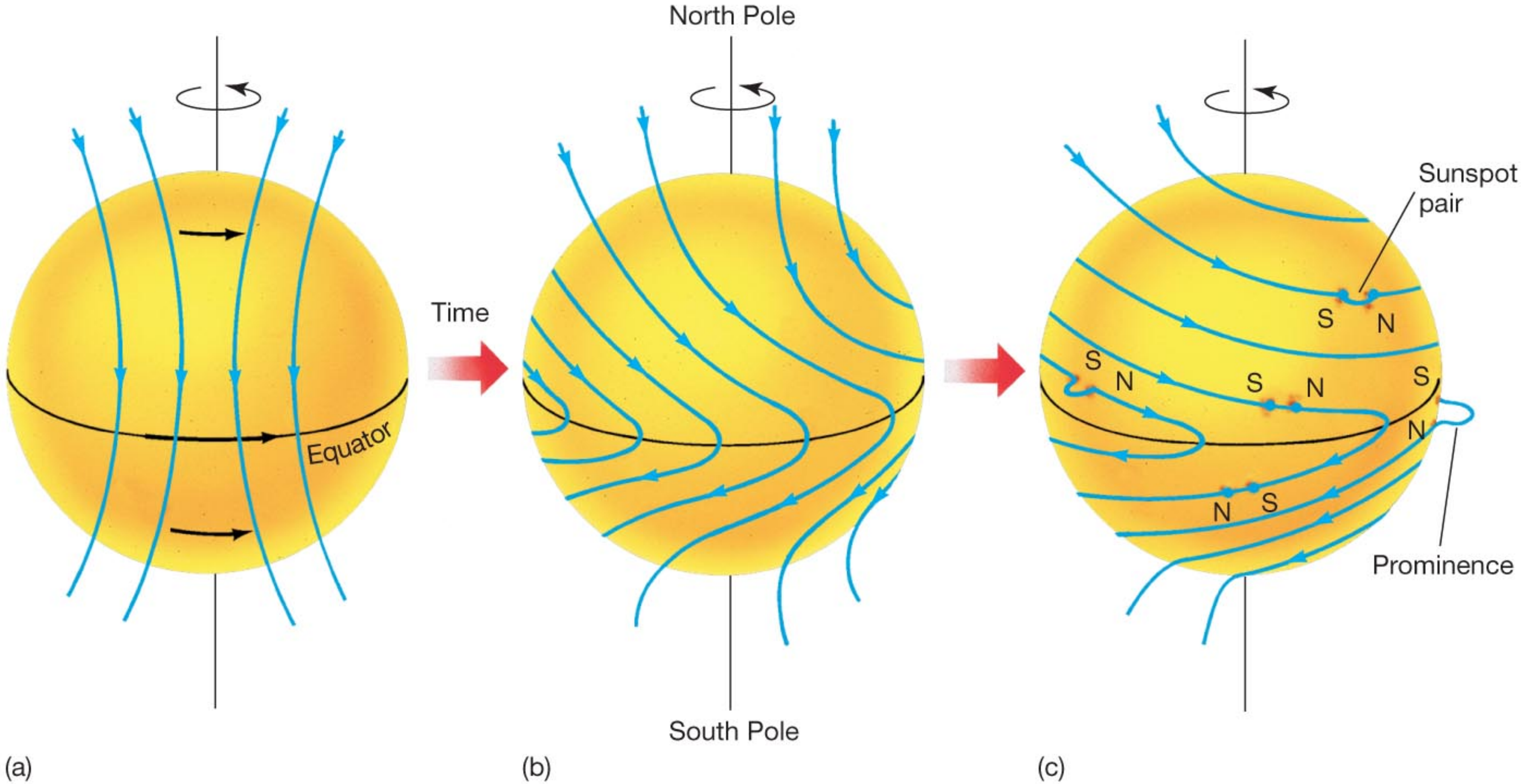


Rotation Period



Different parts of the Sun rotate at different speeds. This is called **differential rotation**.

The rotation of the Sun drags magnetic field lines around with it, causing kinks in the field lines.



The sun spins faster at the equator than the poles

Why does the Sun shine?

- Only one known process can account for the huge amount of energy generated by the Sun:

Conversion of mass into energy via **nuclear fusion**

$$\mathbf{E = mc^2}$$

Energy = mass x (speed of light)^2

$E=mc^2$

Mass m given in kg

Speed of light c is 3×10^8 meters/second

Example: How much energy do you get if you can change 1 kg of matter entirely to energy?

$$E = mc^2 = (1)(3\times10^8)(3\times10^8)$$

$$= 9\times10^{16} \text{ watt-seconds}$$

This is more than 200 times the energy released by the most powerful nuclear bombs

Example 2: (Luminosity of the Sun)

If the Sun changes 4 x10^9 kg to energy each second, how much energy does it produce each second?

$$E = mc^2 = (4\times10^9)(3\times10^8)(3\times10^8)$$

$$= 36\times10^{25}$$

$$= 4\times10^{26}\,\text{watt - seconds}$$

The Energy of Starlight

The Sun turns hydrogen into helium, and the mass of a helium atom is slightly less than the mass of 4 hydrogen atoms (by 0.7%=0.007)

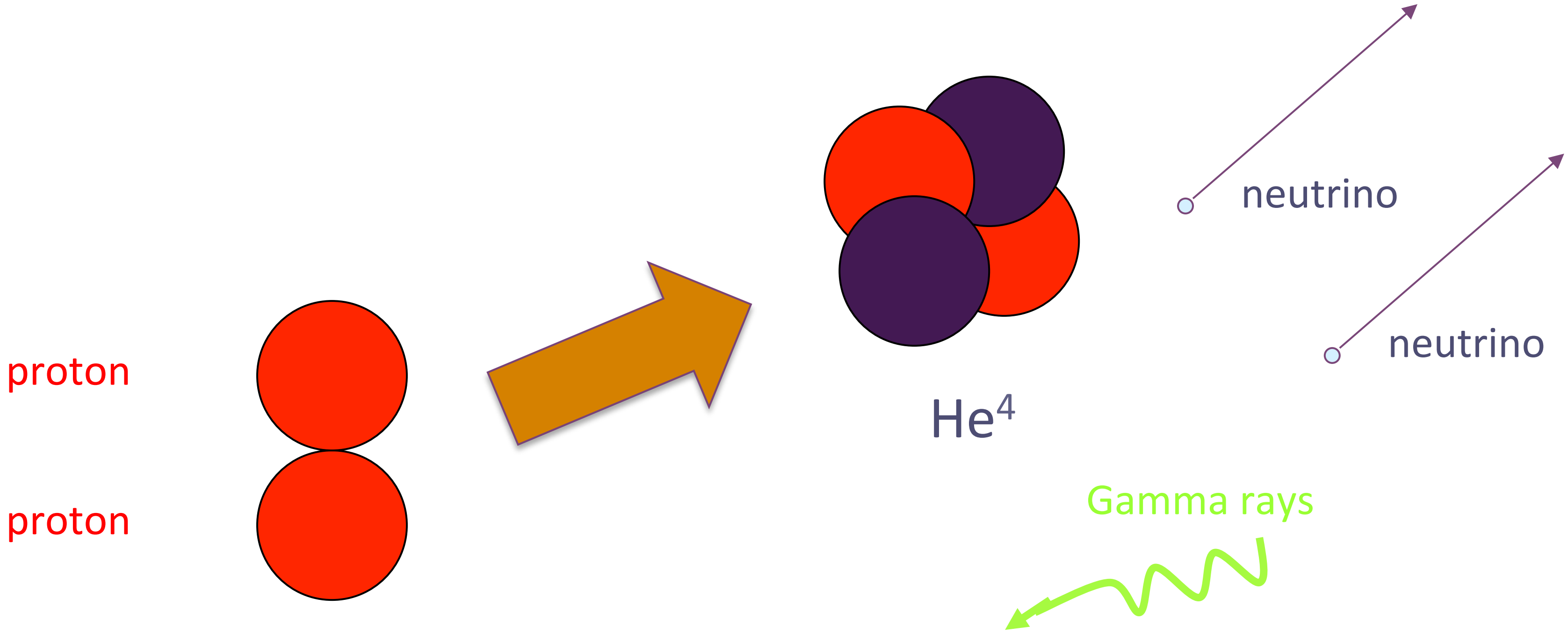
$$4m_H - m_{He} = .007m_H$$

Hydrogen can turn into helium, and when it does, 0.7% of its mass changes to energy, and **that energy powers the Sun**

Fusion of H to He in stars like the Sun

Basic process, neglecting intermediate steps:

4 protons → helium-4 + 2 neutrinos + energy



Stars

What do we need to know?

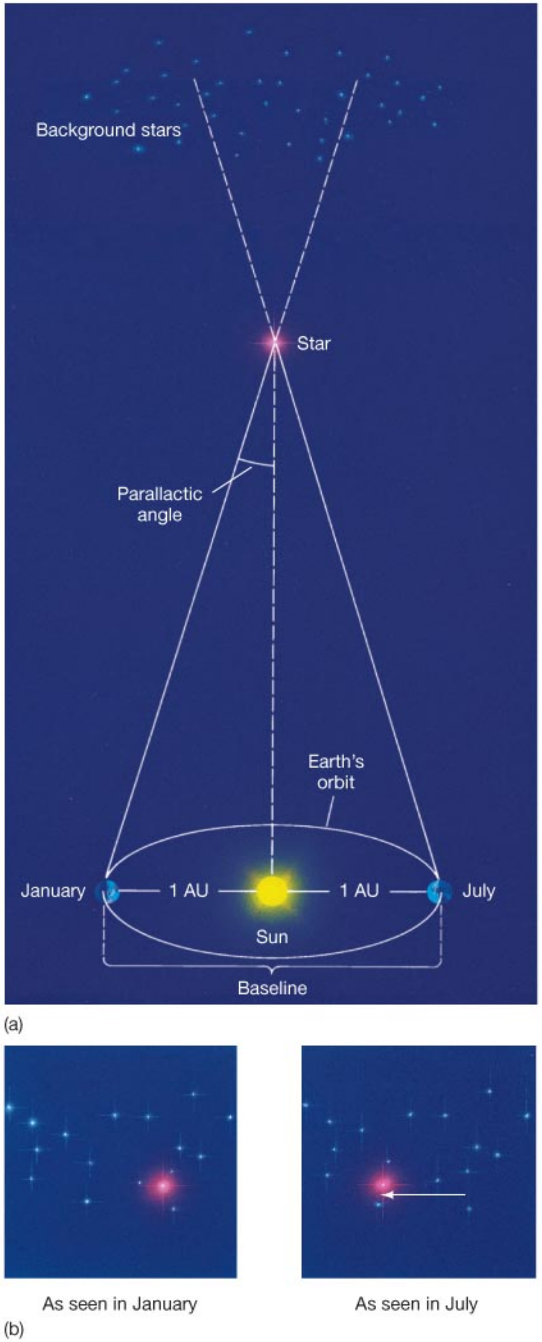
- How big are they? **Mass** and **Size**
- How **bright** do they shine?
- How do they shine? – we sort of know this already, at least for the Sun

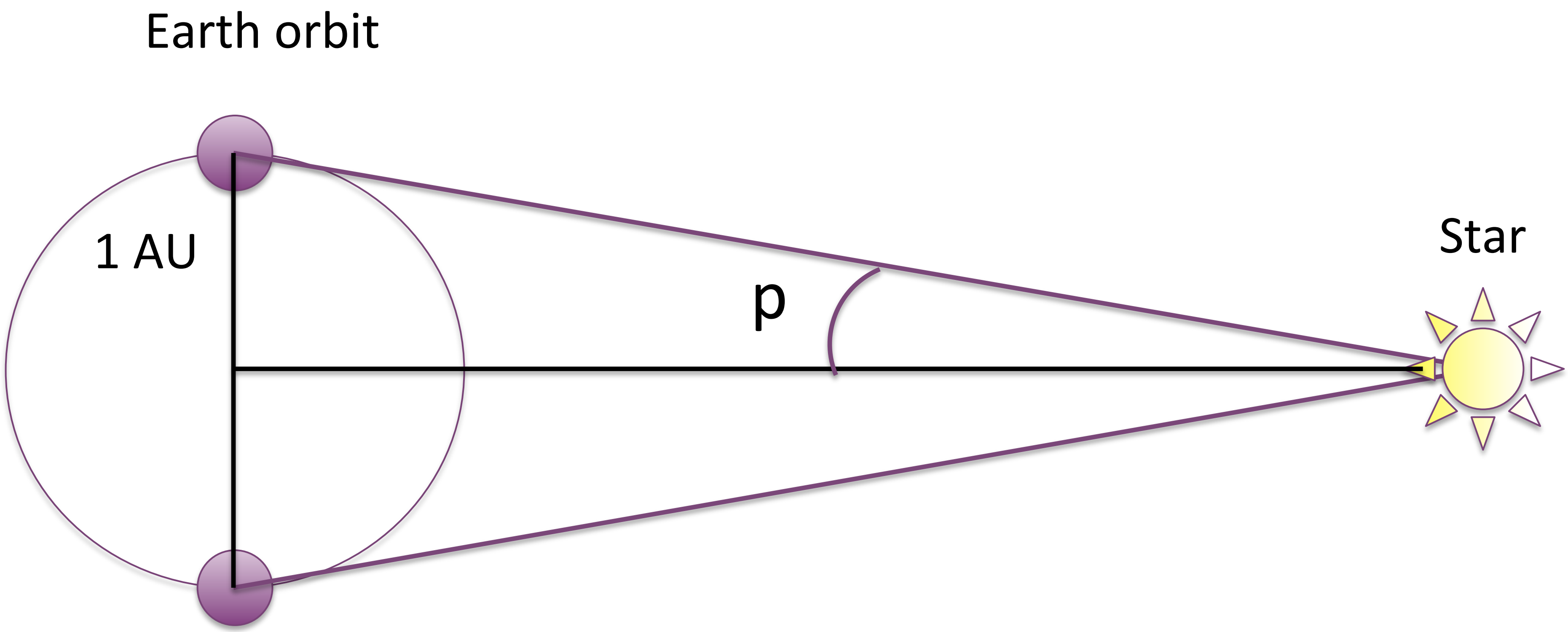
To tackle this, we must first know how far away they are. How do you measure the distances to the stars?

Method 1: **Stellar Parallax**

For the very closest stars you can measure how much they shift against more distant stars over the course of six months – the time it takes for the earth to move from one side of its orbit to another.

- Shift is about 1/3600 of a degree or 1 arcsecond.





- The parallax angle, p of a star is the angle formed by the star and the radius of the Earth's orbit. (i.e. the angle subtended at a star by the radius of the Earth's orbit is the parallax angle, p, of the star)
- This is the apparent shift in the star's position due to the Earth's motion about the Sun.

When the angle is 1", the star's distance is 210,000AU or 3.26 ly.

This distance is called one **parsec** (for parallax second), or pc for short: 1 pc = 3.26 ly = 3.09 $\times 10^{13}$ km

Method 2: Spectroscopic Parallax

How bright something seems depends on the distance

apparent brightness = luminosity/($4\pi\ d^2$)

How bright it seems

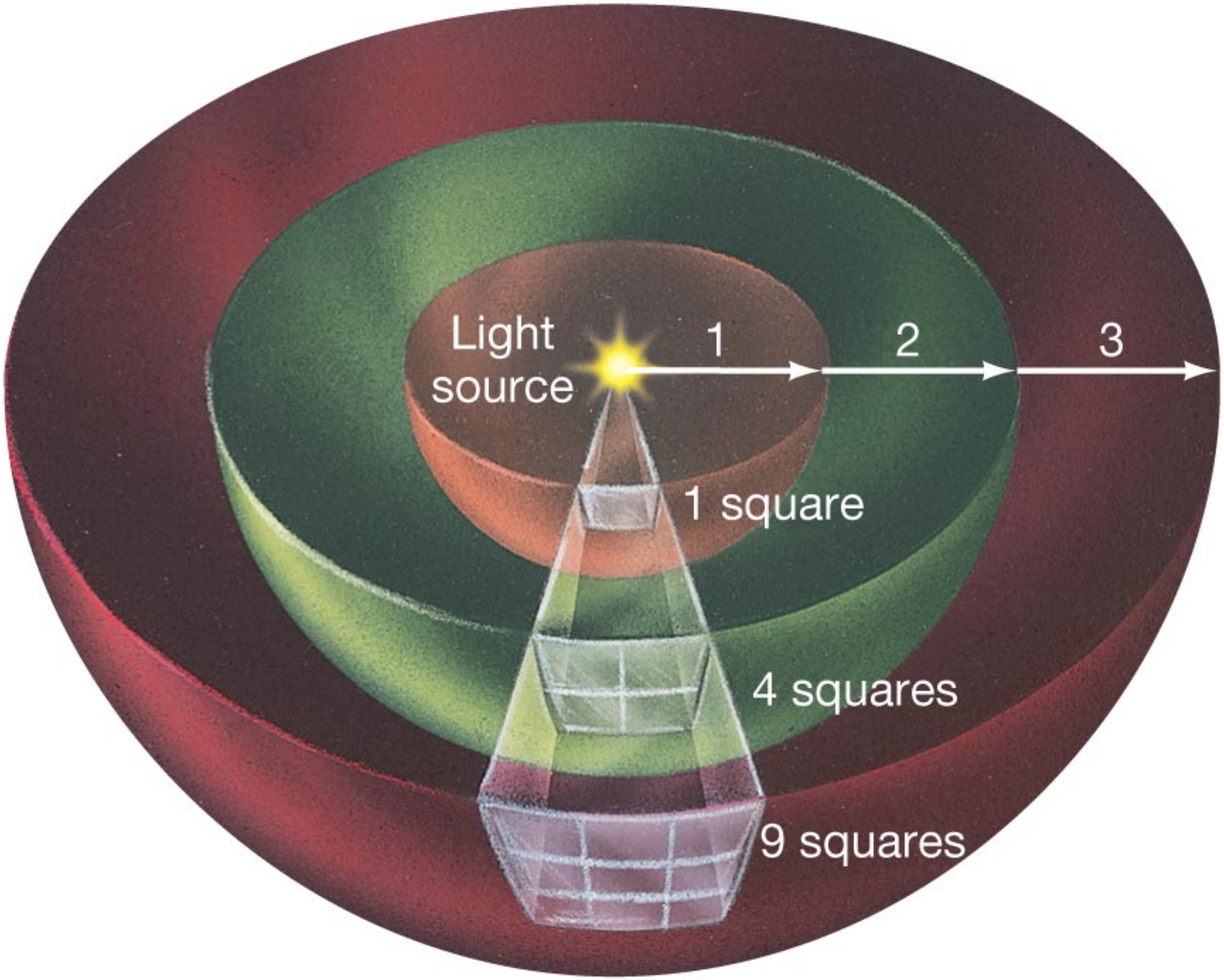
How bright it is

How far away it is

Some problems will be using the fact that apparent brightness is proportional to 1/(distance)^2

There is a very good reason for this!

As light moves away from a star (or light bulb) its energy is spread out over a larger area. That area is proportion to d^2



- Example: The brightness of sunlight at the Earth is 1400 watts/meter^2. What is the brightness of sunlight at Saturn, 10 AU from the Sun?

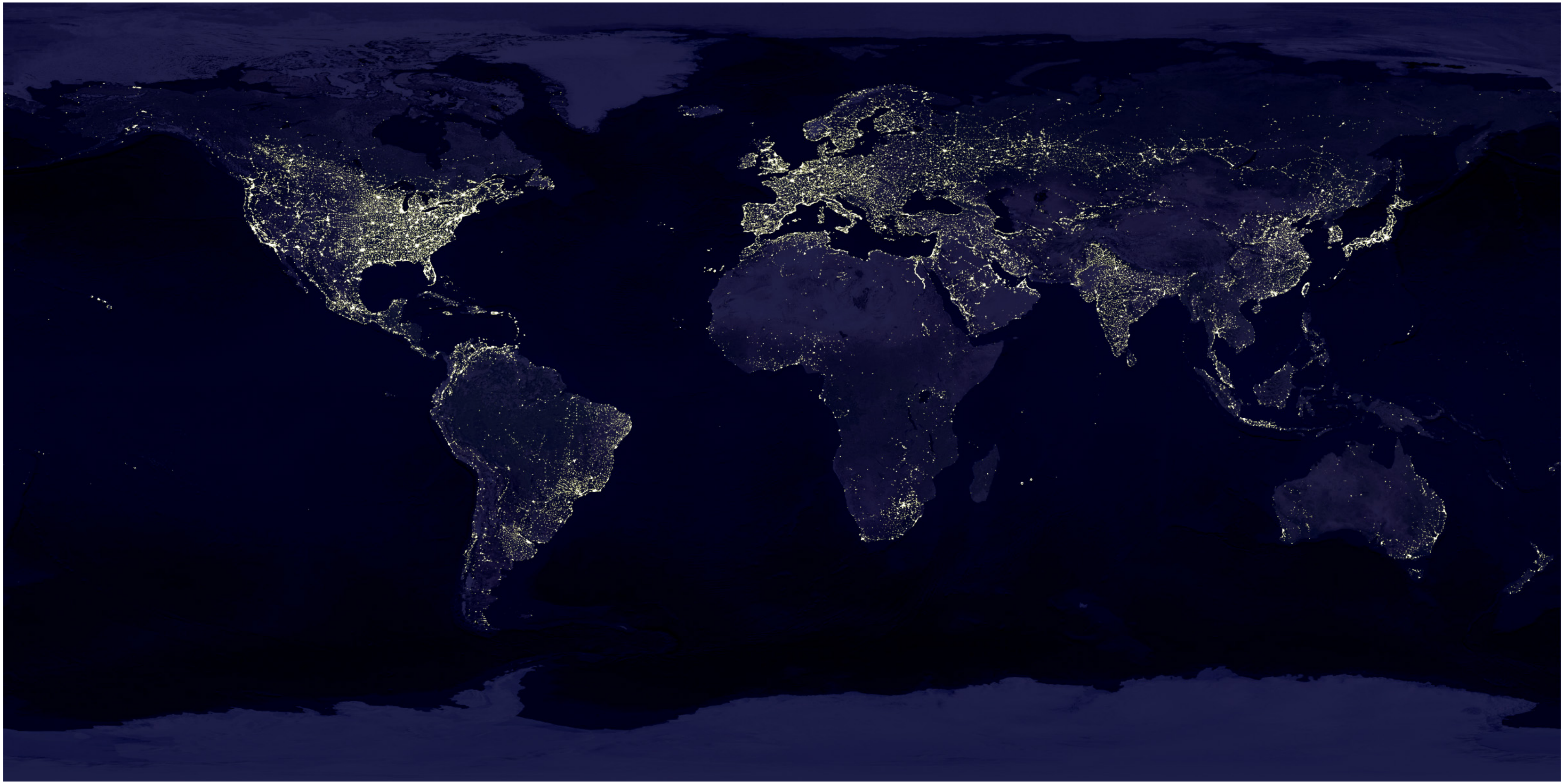
$$B \text{ proportional to } 1/\mathrm{d}^2$$

- Saturn is 10 times farther away from the Sun than the Earth, so sunlight is $1/10^2 = 1/100$ times brighter.
- The brightness of sunlight on Saturn is $1400/100 = 14$ watts/meter^2. This is why the outer planets are cold!

How bright are the stars?

How bright something is depends on:

1. How much light per unit area it is putting out
2. How big it is



Stellar Classification

The classification of a star is its **spectral type**.

- Ordered from hottest to coolest, the spectral types are:

O, B, A, F, G, K, M

(Use the mnemonic Oh, Be A Fine Guy/Girl Kiss Me).

- O stars are hottest with surface temperature > 25,000 K.

- G stars (like the Sun) have surface temperature of approximately 6000 K.

- M stars are coolest (Betelgeuse for example) with surface temperatures approximately 3000 K.

Stellar Sizes

So if you know the spectral type, you know the temperature. How do you know how luminous a star is?

The relation between temperature and luminosity is:

$$L = 4\pi\sigma T^4 R_*^2$$

Some constants we won't worry about ($4\pi\sigma$)

Temperature (T)

Radius (size) of star (R_*)

This relationship is for continuous, blackbody radiation.

So hot stars are (much!) brighter, and larger stars are also brighter.

$$L = 4\pi\sigma T^4 R_*^2$$

Some constants we won't worry about

Temperature

Radius (size) of star

The H-R Diagram

A plot of temperature vs luminosity for a collection of stars is called the **Hertzsprung-Russell diagram** or **H-R diagram**, and it's the most important tool for classifying and understanding stars.

Luminosity

If the stars are all at the same distance: $$L \propto B$$
This is what Hertzsprung did

Apparent brightness

Or if we know the distances to the stars

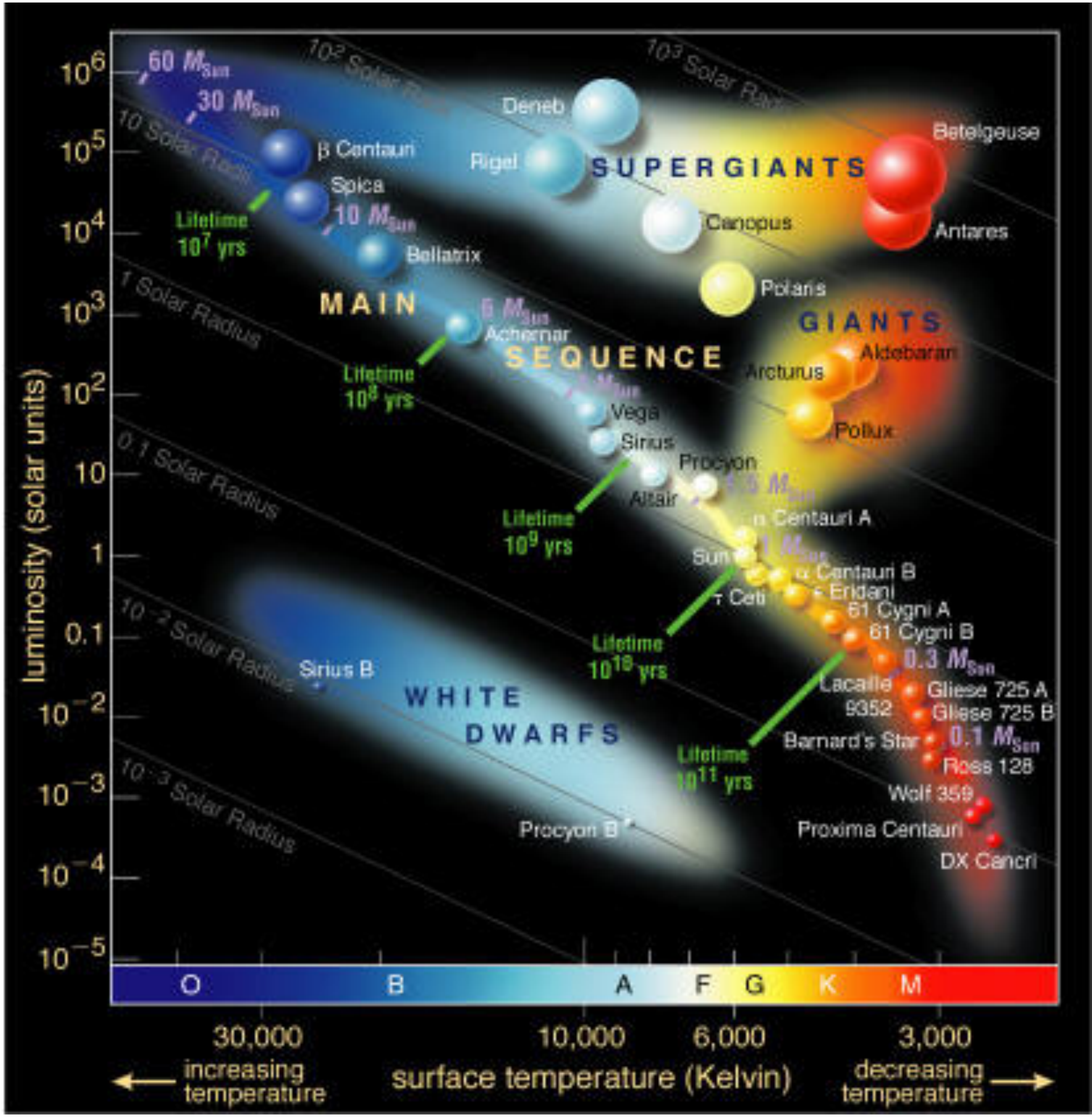
$$L = B \times 4\pi d^2$$

This is what Russell did

distance

The H-R Diagram

Every star that we know lives on the HR diagram – after all, stars all have a temperature and a luminosity.



On the Hertzsprung-Russell (H-R) diagram, almost all stars lie along a curve called the **main sequence**.

The hottest stars on the sequence are also the most luminous stars, and the coolest stars are the dimmest (least luminous).

- About 90% of all stars lie on the main sequence, almost all of them below the Sun (cooler and less luminous than the Sun).

The hottest stars on the **main sequence** are also the brightest stars, and the dimmest are also the coolest.

About half of all stars are in binary systems – so the Sun is unusual in that it does not have a companion.

- A visual binary is a binary system whose stars can be distinguished with a telescope.

In most binary systems, stars are too close to be able to tell them apart with a telescope --- even through a telescope, they look like a single star. Close stars, however, move more quickly, and the spectral lines of each star are first blue-shifted and then red-shifted.

- Spectroscopic binaries are observed by a periodic Doppler shift in the spectral lines of each star.

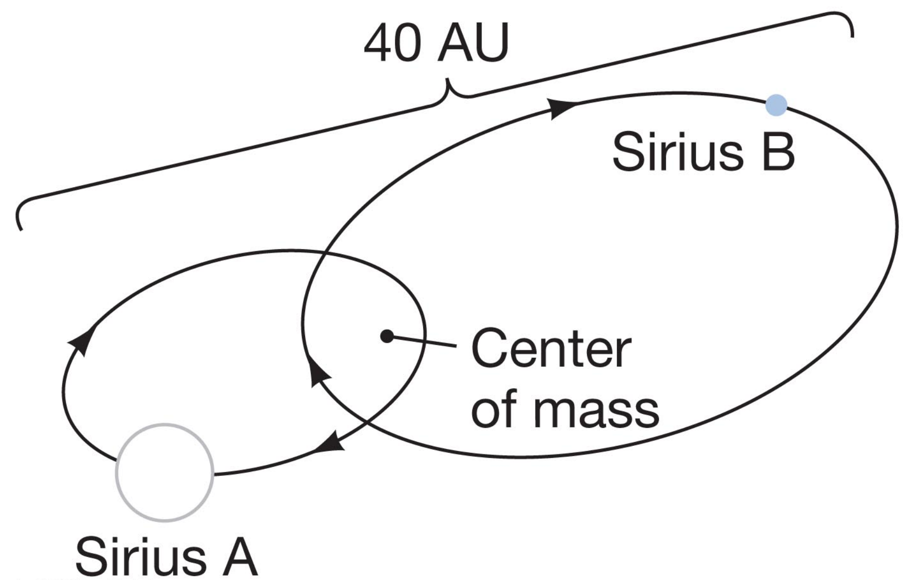
- Eclipsing binaries are observed by periodic changes in the "light curve"

<u>Stellar masses from binaries</u>

If one knows the period and the orbit of each star, one can find the mass of each star. By looking at the speed of each star in a binary system, one measures the mass of the two stars.

This is done with **Kepler's third law**; binary stars orbiting each other follow the same laws as a planet orbiting a star.

This is how we find the masses of stars.

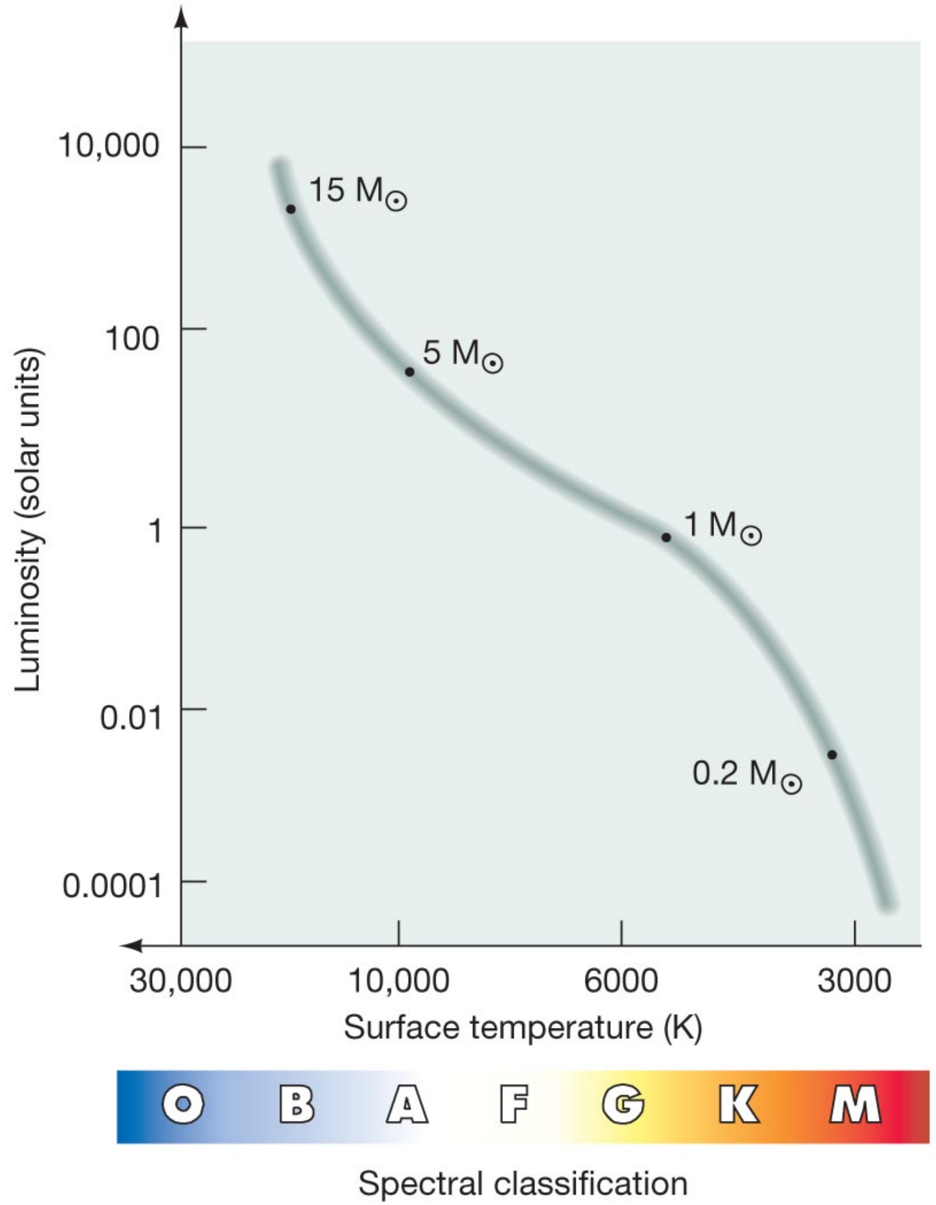


From the masses of stars, one can understand the main sequence.

What determines where on the main sequence a star will be when it forms?

Stars on the main sequence are only distinguished by their mass

Stars with small masses are the stars that are low on the main sequence. They burn much more slowly, so they are much dimmer and their surfaces are cooler. Stars with larger masses burn much more quickly and have hotter surfaces (and hotter interiors).



Summary:

- The difference between stars on the main sequence is due to the difference in their masses.

- Low mass stars are low on the main sequence, and are much dimmer --- a star of 1/10 of a solar mass is only 1/1000 as bright as the Sun.

- Similarly, high mass stars are high on the main sequence, and are much brighter --- a star of 10 solar masses is 10,000 times brighter than the Sun

Massive stars burn bright, die young

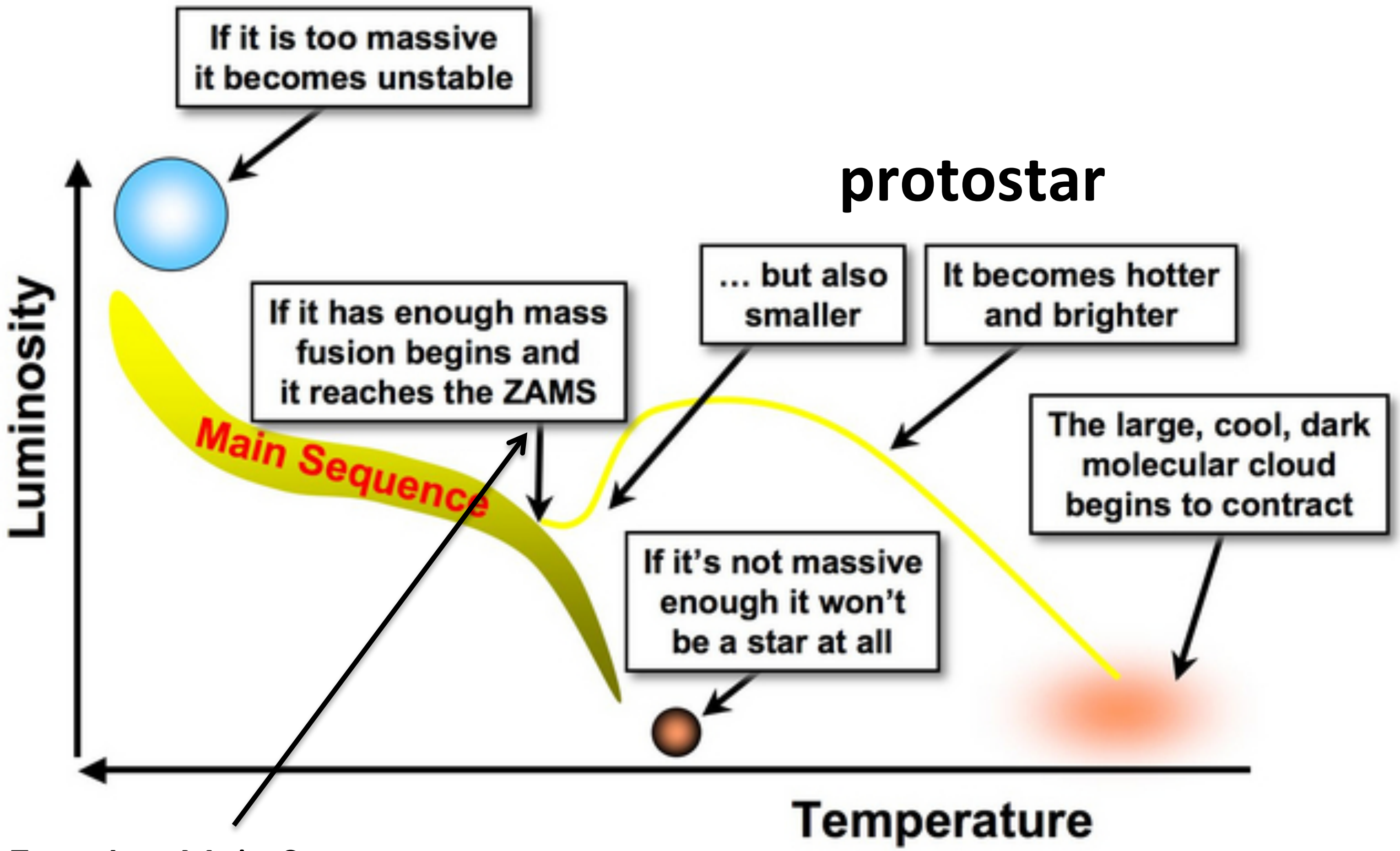
$$\text{lifetime of star} = 10^{10}\,\text{years}\,\frac{M}{L},$$

M/L gets very small for more massive stars!

- This tells us that **massive stars have very short lifetimes**
- They burn very brightly and use up their fuel very quickly

Star Formation

Collapse of a molecular cloud to form a star



Zero Age Main Sequence

Summary of evolution of stars like the Sun

I. Collapse of a gas cloud to form a star
II. Main Sequence: hydrogen fuses to helium in core
III. Red Giant: hydrogen shell fusion, helium core not fusing
IV. Helium Flash: core gets hot enough to ignite helium fusion
V. Second Red Giant (Asymptotic Giant Branch [AGB]): non-fusing carbon core, shells of helium fusion and hydrogen fusion
VI. Planetary Nebula and formation of White Dwarf: ejection of outer layers of star, cooling of dense core supported by degeneracy pressure

Novae: H-bombs at the surface of white dwarfs

Some white dwarfs are in binary systems with another star.

In a close binary, or when the other star becomes a red giant and is sufficiently large, hydrogen from the surface of the other star falls onto the white dwarf

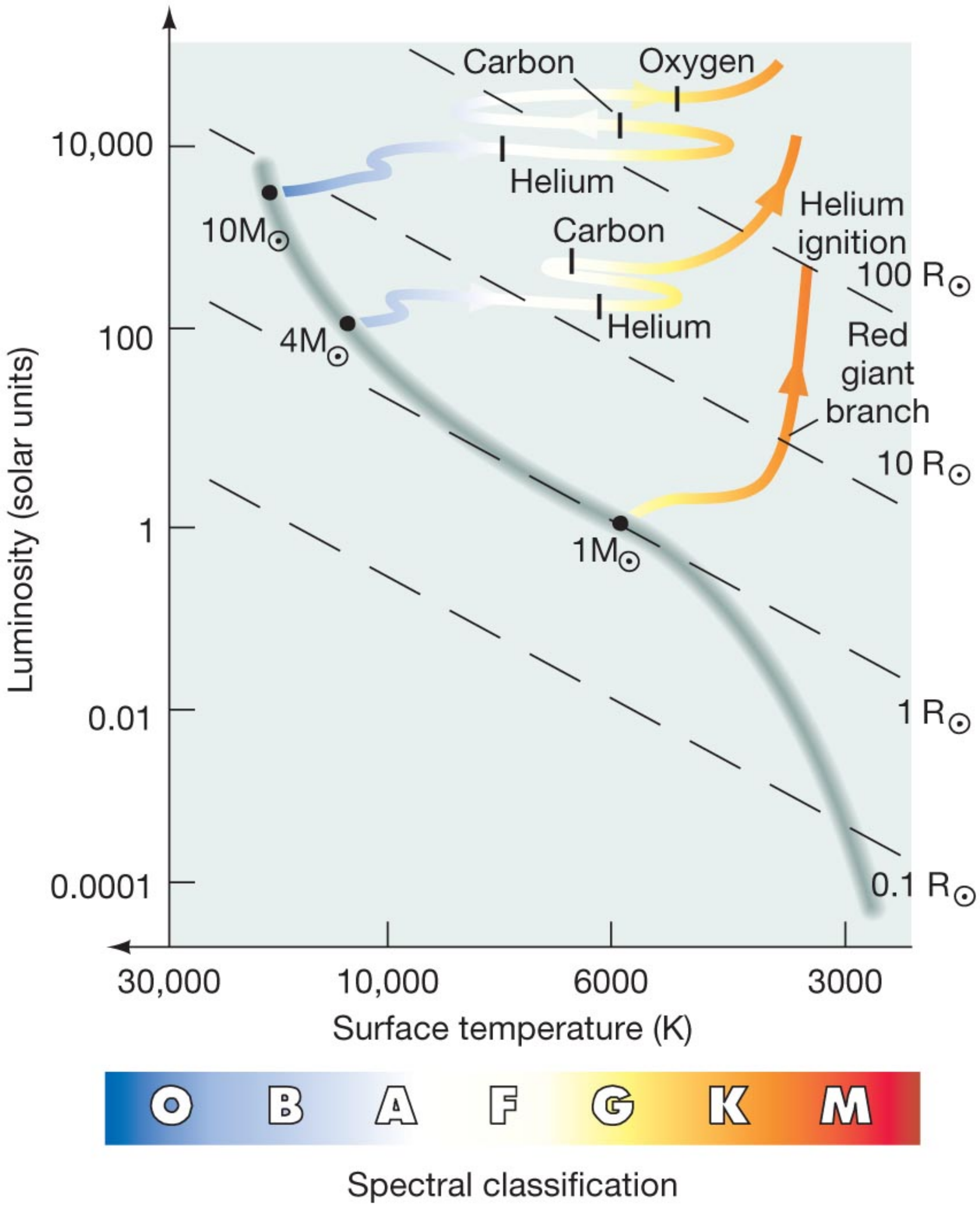
Once enough hydrogen builds up on a white dwarf, it will suddenly fuse to helium. This is a **nova**, the sudden fusion of hydrogen to helium on the surface of a dwarf.

Late evolution of stars more massive than the Sun and the formation of the elements

More massive stars will build heavier elements up from carbon:

$M < \frac{1}{12} M_\odot$	No fusion at all
$\frac{1}{12} M_\odot - 0.4 M_\odot$	H → He only
$0.4 M_\odot - 4 M_\odot$	H → He, He → C
$4 M_\odot - 8 M_\odot$	C → Ne, Na, Mg, O
$M > 8 M_\odot$	Ne and O fuse to form higher mass elements up to Fe

Evolution of Stars More Massive than the Sun



Evolution of Stars More Massive than the Sun

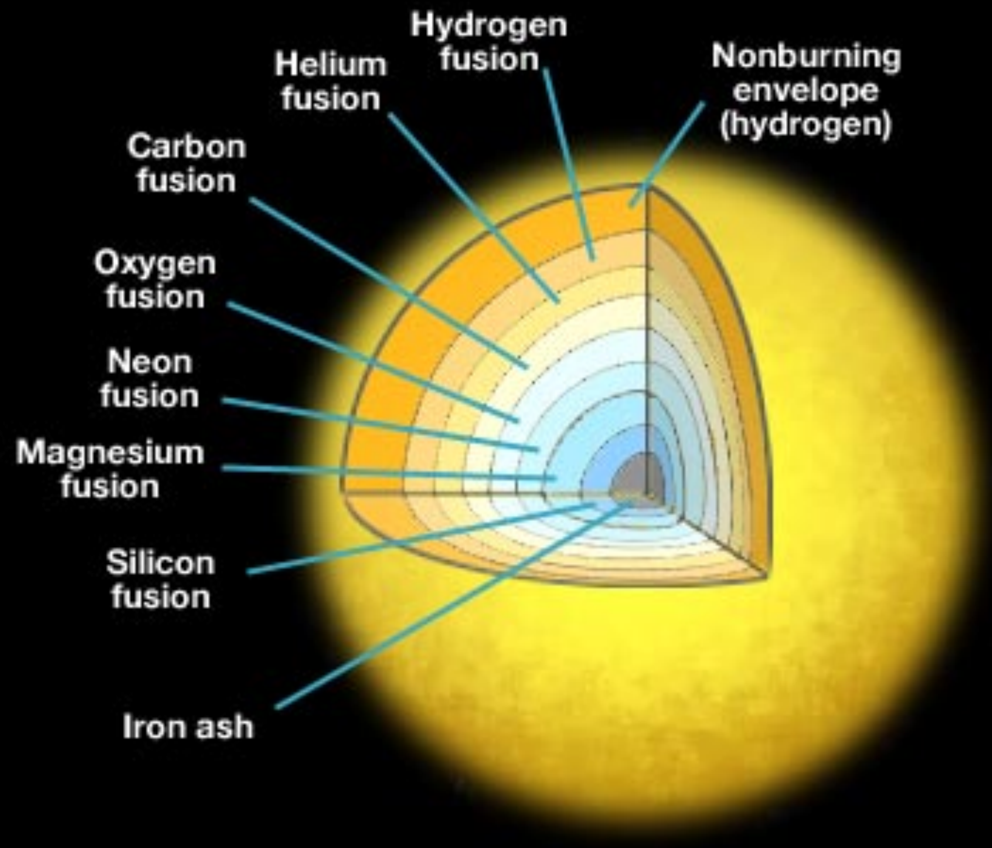
TABLE 12.3 End Points of Evolution for Stars of Different Masses

Initial Mass (Solar Masses)	Final State
Less than 0.08	(Hydrogen) brown dwarf
0.08–0.25	Helium white dwarf
0.25–8	Carbon–oxygen white dwarf
8–12 (approx.)*	Neon–oxygen white dwarf
Greater than 12*	Supernova

*Precise numbers depend on the (poorly known) amount of mass lost while the star is on, and after it leaves, the main sequence.

Evolution of the most massive stars

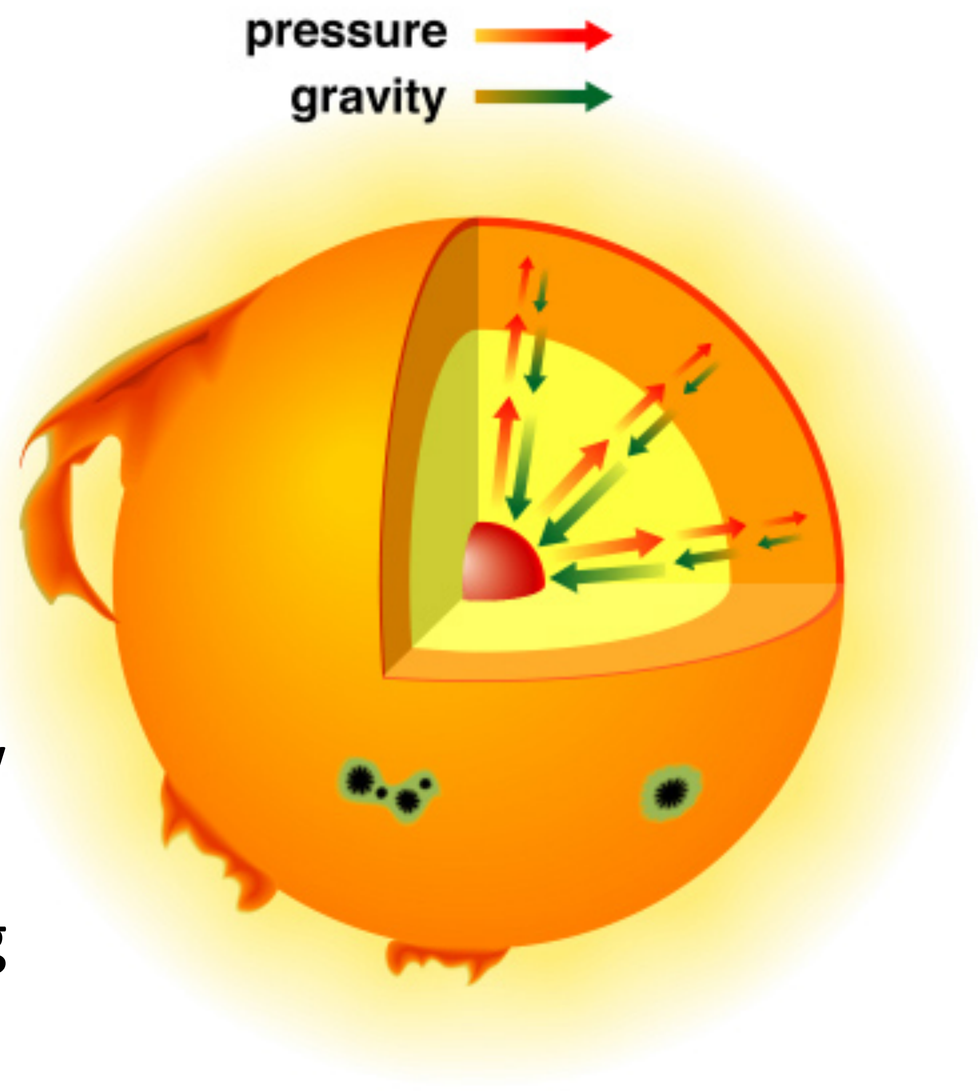
- The most massive stars are hot enough to fuse heavier and heavier elements in their cores
- Fusion of the heaviest element occurs in the center, surrounded by shells burning each of the lighter elements
- Star has an "onion" structure
- This happens until the core of the star has been fused into iron



Not to scale! The core containing the layers of fusion is only a small part of the star.

Evolution of the most massive stars

- Recall that stars are in **hydrostatic equilibrium**: nuclear fusion at the center produces enough **pressure** to balance the force of **gravity** and keep the star from collapsing
- Our very massive star now has a core made out of iron… and this is a very big problem!



Evolution of the most massive stars

- Iron is the most stable element – it has the most tightly bound nucleus
- For elements lighter than iron, fusing them into heavier elements produces energy
- This doesn't work for iron: fusing iron atoms together into heavier atoms does not create energy
- So our massive star suddenly no longer has fusion at its core, and it can't create the pressure needed to support itself against gravity
- This results in a sudden, catastrophic collapse of the star: a **supernova**

The Chandrasekhar limit

There is an upper limit c on the speed at which a particle can travel — and hence an upper limit on the pressure per unit mass that matter can exert.

But there is no upper limit on the gravitational force per unit mass.

When the mass of a dense object is too large, gravity overwhelms pressure and the object collapses.

This sets an upper limit on the mass of dead matter that can no longer provide energy via fusion:

A white dwarf or the dead iron core of a star cannot have more mass than 1.4 solar masses

Summary: Two types of supernovae

I. **Type I supernova**: The collapse of an accreting white dwarf when its mass reaches 1.4 solar masses.

II. **Type II supernova**: The collapse of the iron core of a massive star when its mass reaches 1.4 solar masses. The energy of matter falling during the gravitational collapse (and then rebounding) is the energy that explodes the rest of the star.