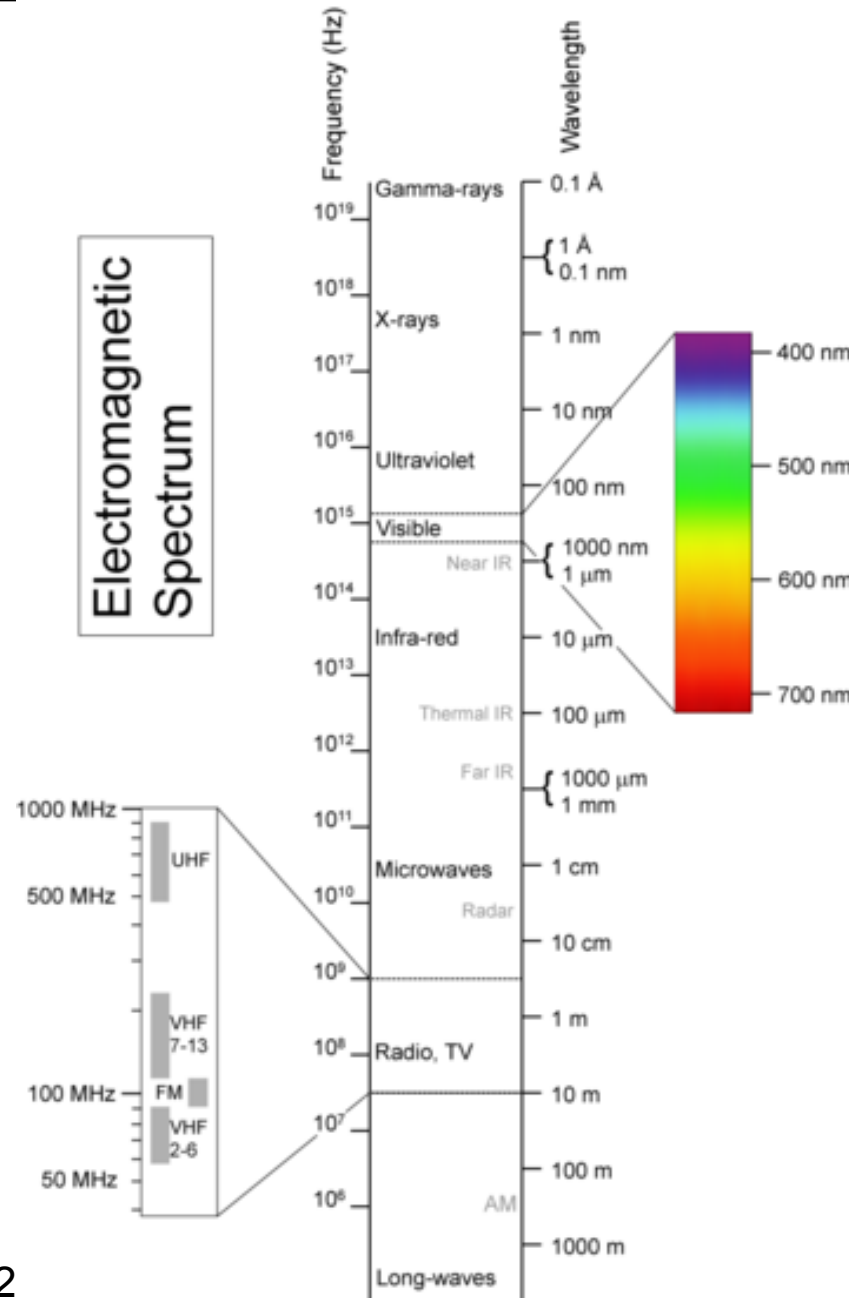


# Investigating electromagnetic radiation

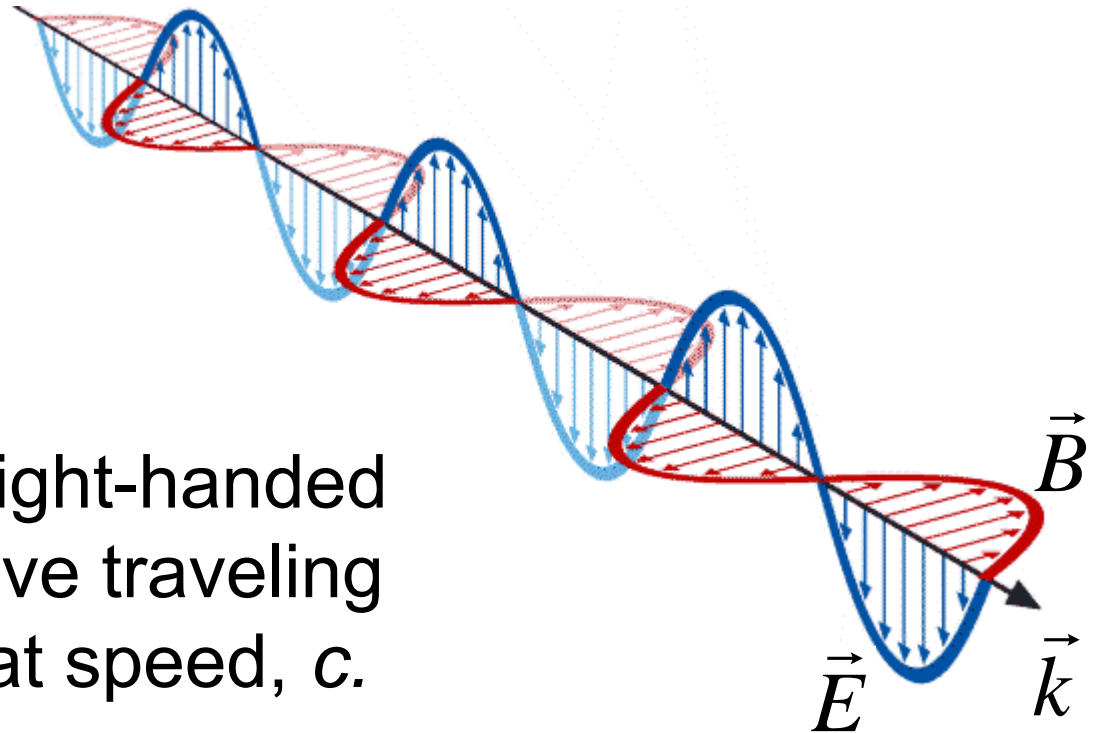
## Announcements:

- First midterm is 7:30pm on 2/17/09
- Problem solving sessions M3-5 and T3-4,5-6.
- Homework due at 12:50pm on Wednesday.
- We are covering Chapter 4 this week. You should also read over the parts of Chapter 3 we covered Friday (3.1–3.6, 3.10–3.12)



# Maxwell's Equations describe EM radiation in vacuum:

$E$ ,  $B$ , and  $k$  form a 'right-handed system', with the wave traveling in the direction of  $k$  at speed,  $c$ .



# Wave or Particle?

Question arises often throughout course:

- Is something a wave, a particle, or both?
- How do we know?
- When best to think of as a wave? as a particle?

In classical view of light, EM radiation is viewed as a wave (after lots of debate in 1600-1800's).

How would one decide it is a wave experimentally?

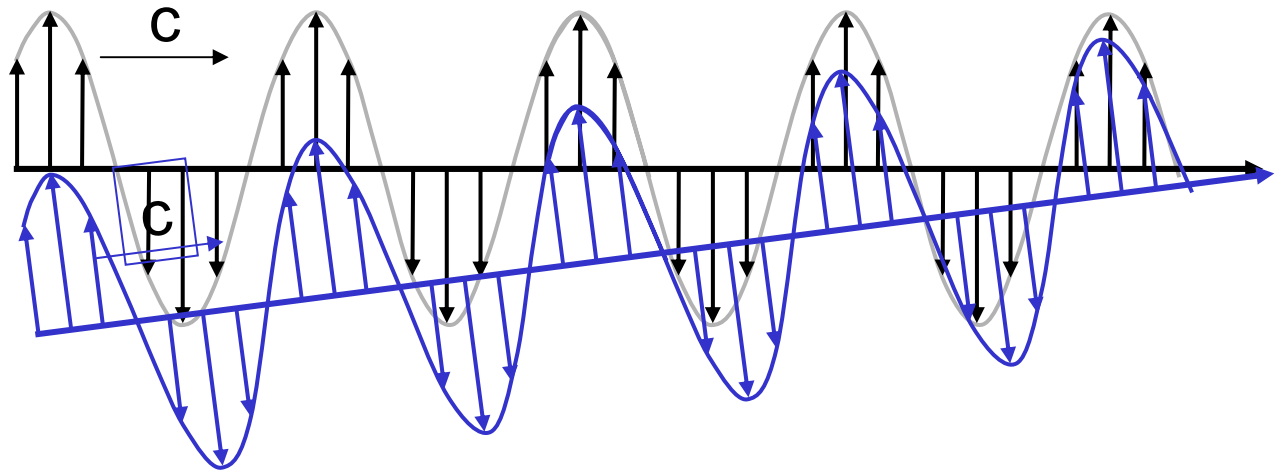
# EM radiation is a wave

What is the most definitive observation we can make that tells us something is a wave?

Observe interference.

Constructive interference:

(peaks are lined up and valleys are lined up)

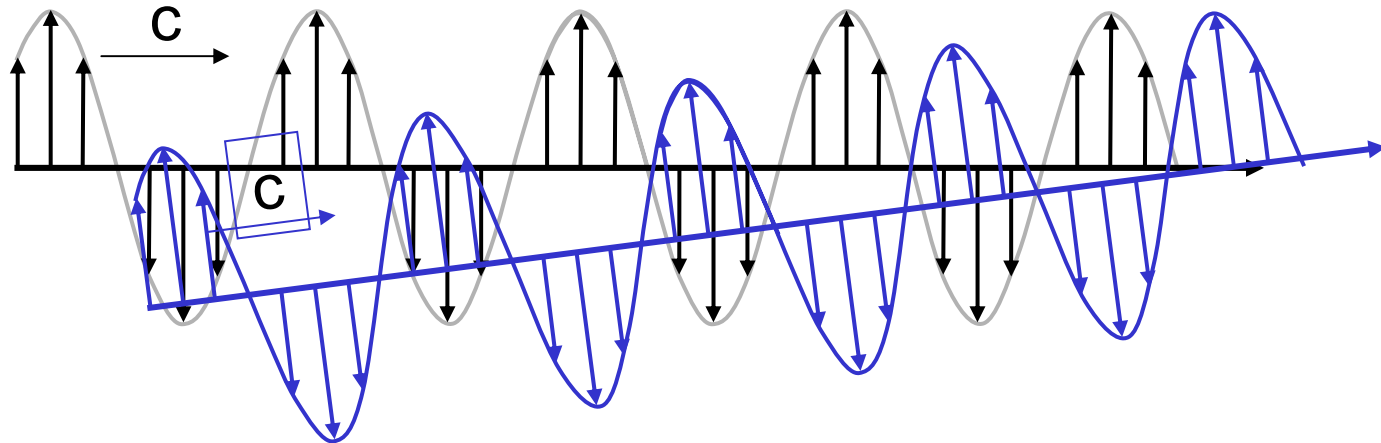


# EM radiation is a wave

What is most definitive observation we can make that tells us something is a wave?

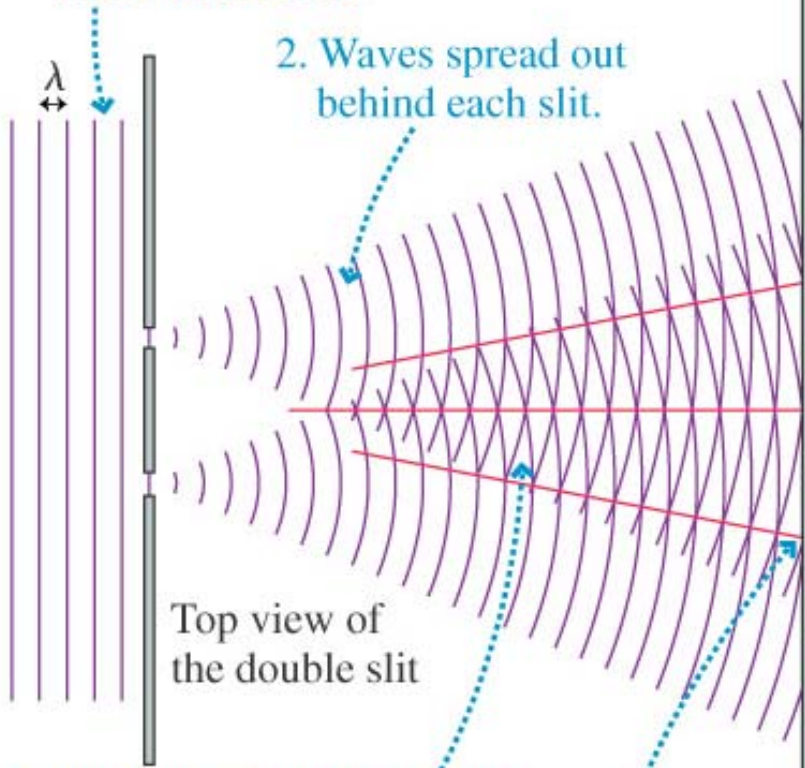
**Observe interference.**

Destructive interference: (peaks align with valleys – cancel)



# Two slit interference

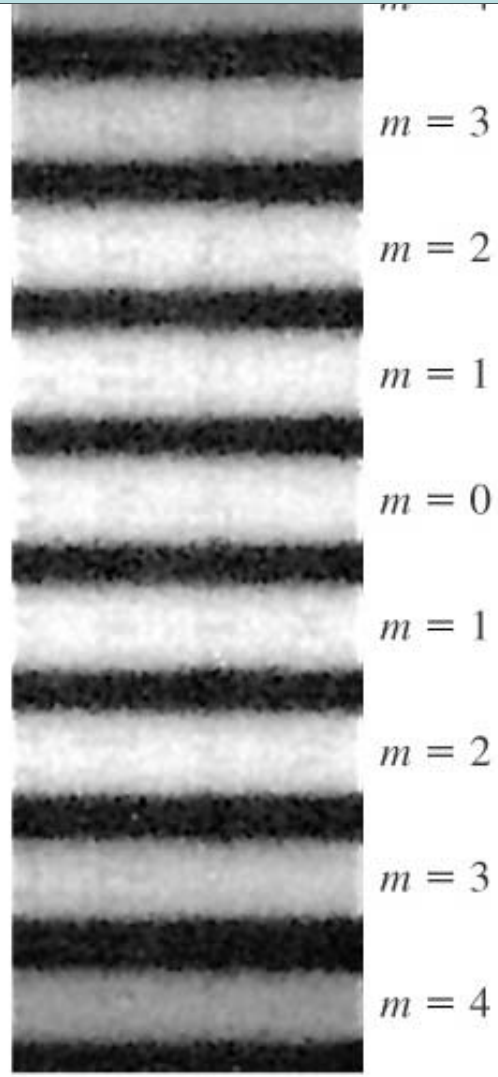
1. A plane wave is incident on the double slit.



2. Waves spread out behind each slit.

3. The waves interfere in the region where they overlap.

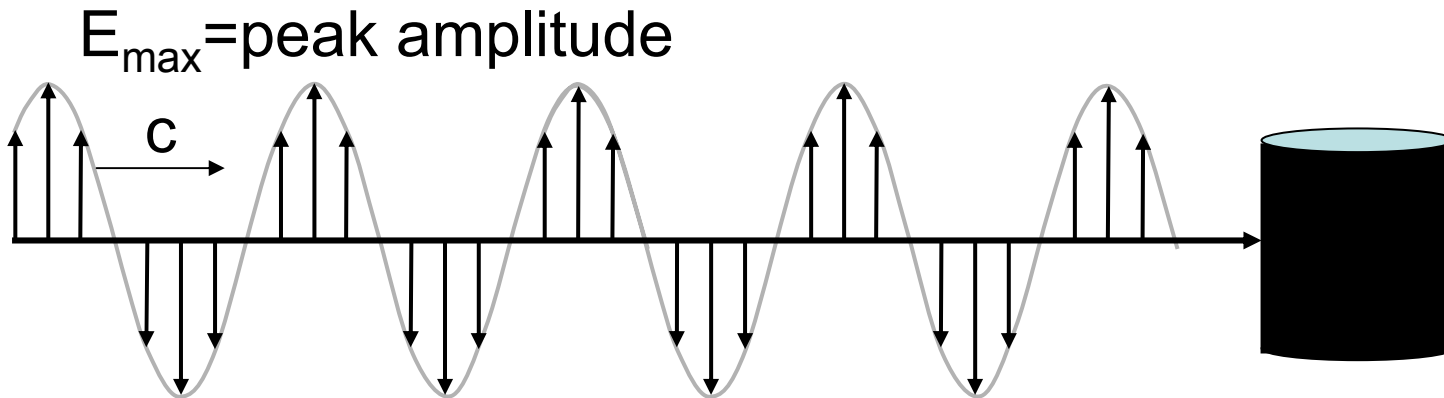
4. Bright fringes occur where the antinodal lines intersect the viewing screen.



The observation of diffraction & interference convinced everyone that light was a wave.

# Electromagnetic waves carry energy

Light shines on a black tank full of water.  
How much energy is absorbed?



$$E(x, t) = E_{\max} \sin(ax - bt) \quad \text{standard wave equation}$$

$$\text{Intensity} = \frac{\text{Power}}{\text{area}} = \frac{\text{energy/time}}{\text{area}} \propto E_{\text{avg}}^2 \propto E_{\text{max}}^2$$

EM waves carry energy proportional to the amplitude squared.

Which barrel will heat up the fastest?

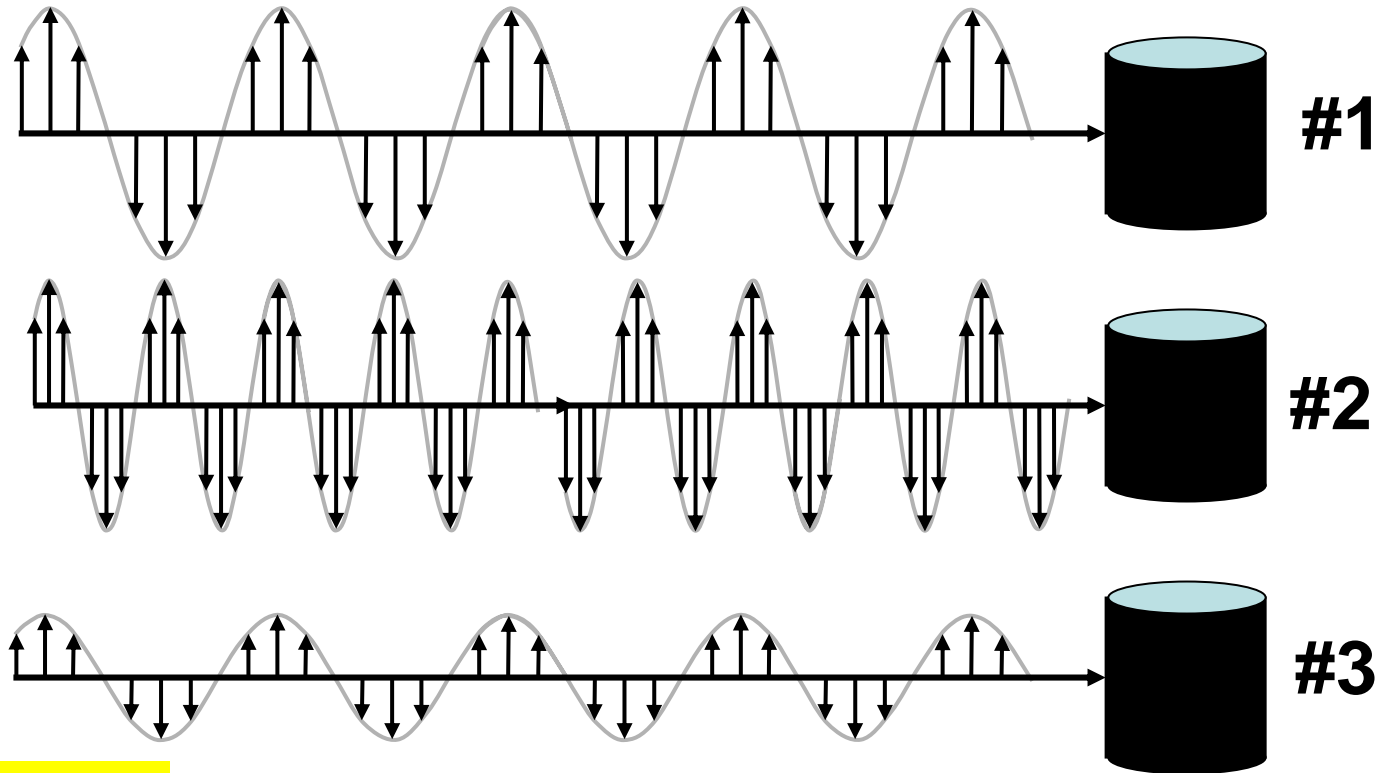
A.  $2 > 1 > 3$

B.  $1 > 2 > 3$

C.  $1 = 2 > 3$

D.  $1 = 3 > 2$

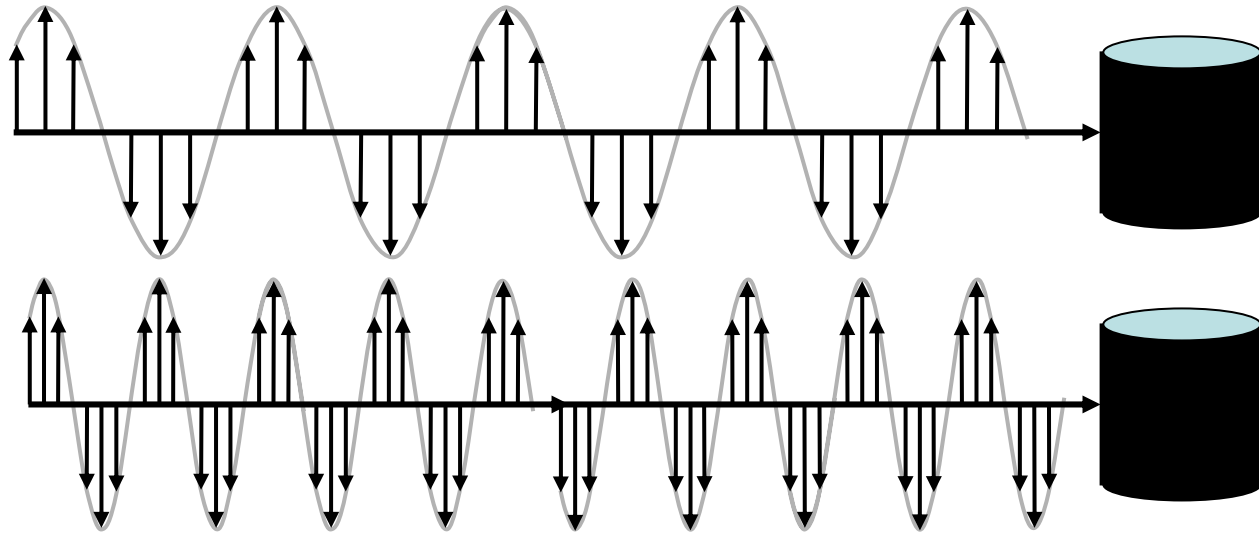
E.  $2 > 1 = 3$



$$E_{1\max} = E_{2\max} > E_{3\max}$$

$$\text{Intensity} = \frac{\text{Power}}{\text{area}} = \frac{\text{energy/time}}{\text{area}} \propto E_{\text{avg}}^2 \propto E_{\text{max}}^2$$

**Recap:** Intensity  $\propto E_{\max}^2$  ... what about frequency?



**Interference was definitive test that light is a wave.**

Questions you may have:

*Why do higher frequency gamma rays carry more energy than lower frequency radio waves when frequency has nothing to do with intensity?  
I was told that energy of light depends on frequency?*

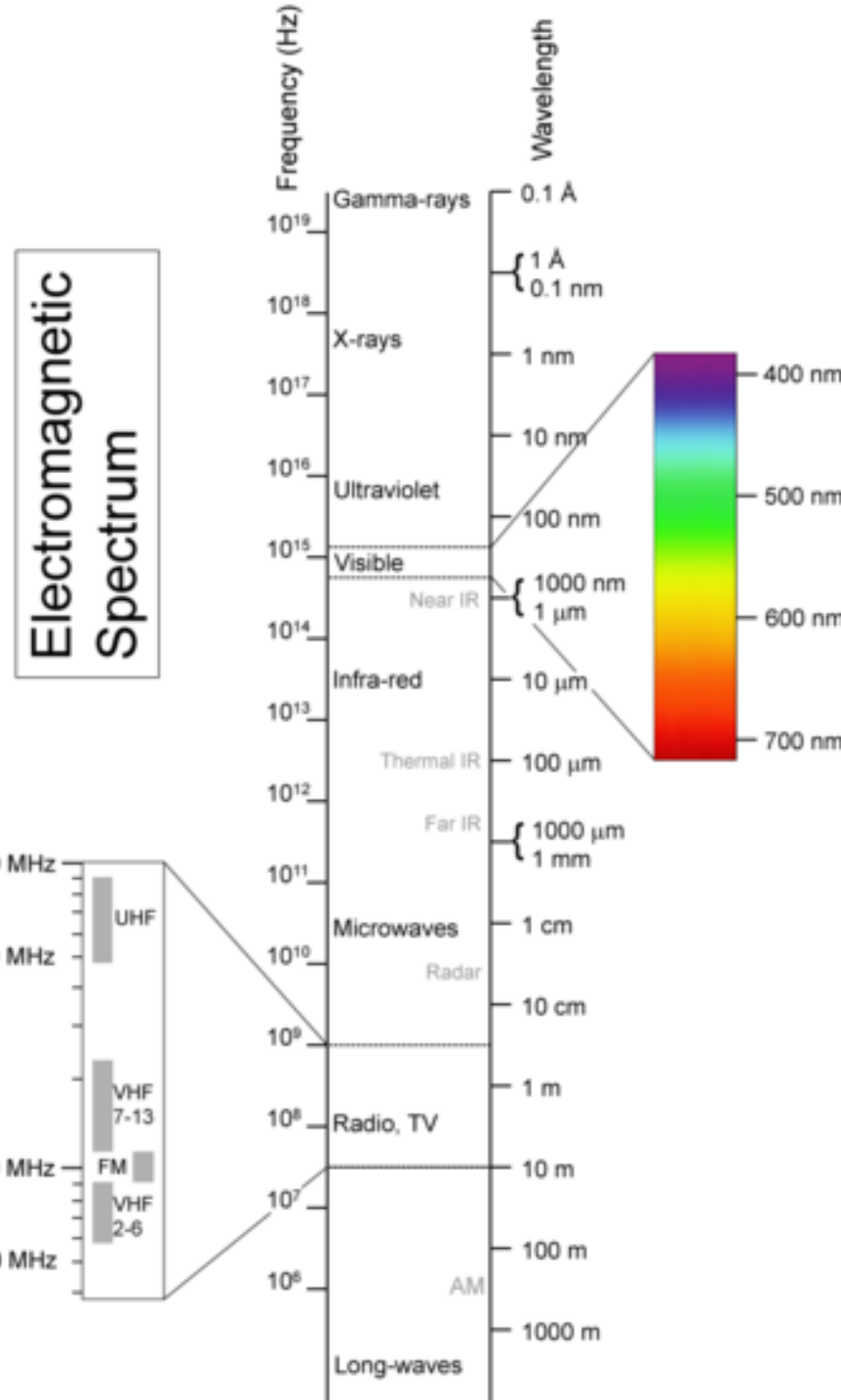
Confusion is between energy carried by a beam of light  
vs. energy in a single quantum particle of light

# Features of light as a wave

Light has well defined frequency and wavelength extending from low frequency radio waves to microwaves to infrared to visible light to ultraviolet to X-rays to gamma rays.

Light exhibits interference and diffraction proving it is a wave.

The intensity of the light measures the power and is proportional to the square of the amplitude (with no dependence on frequency).



# Blackbody radiation

A perfect blackbody absorbs all incoming radiation and emits radiation just due to the thermal energy.

When a perfect blackbody is cold it emits almost zero radiation but absorbs everything so it appears black.

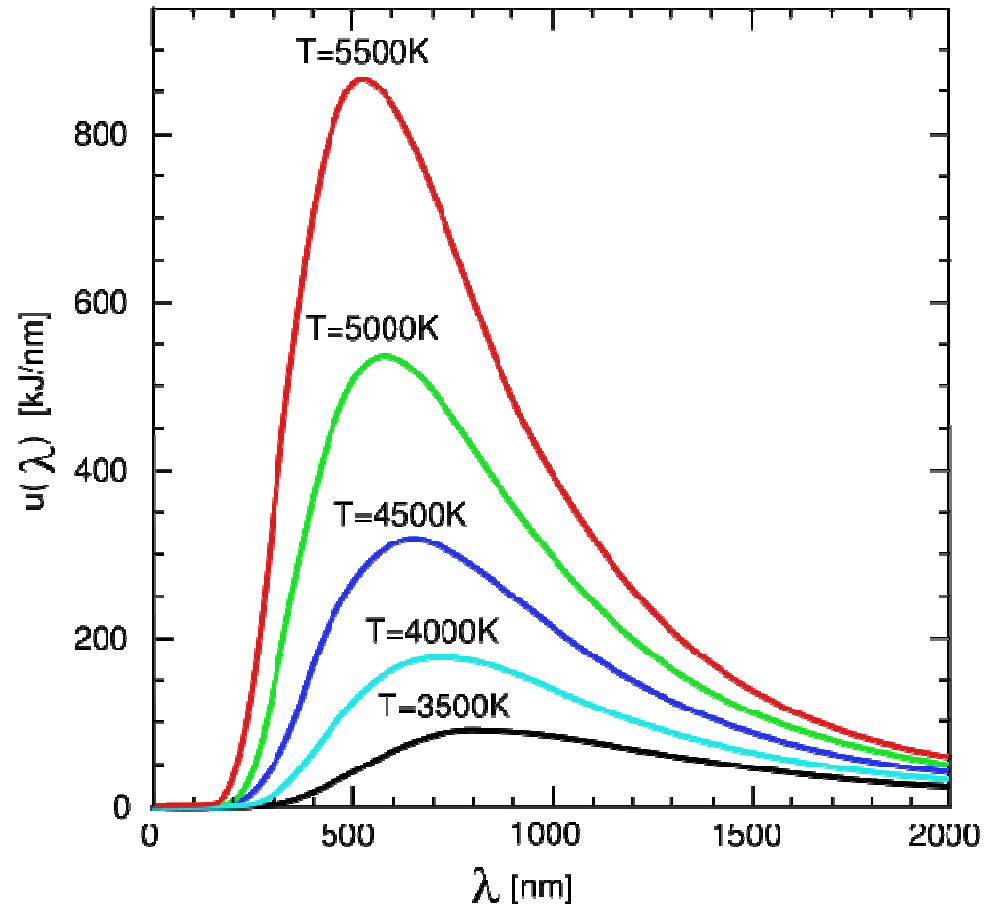
When hot, a blackbody emits a particular continuous spectrum of light which depends only on the temperature (not on the properties of the material).

Can measure blackbody temperature by looking at spectrum (color)



# Blackbody spectrum

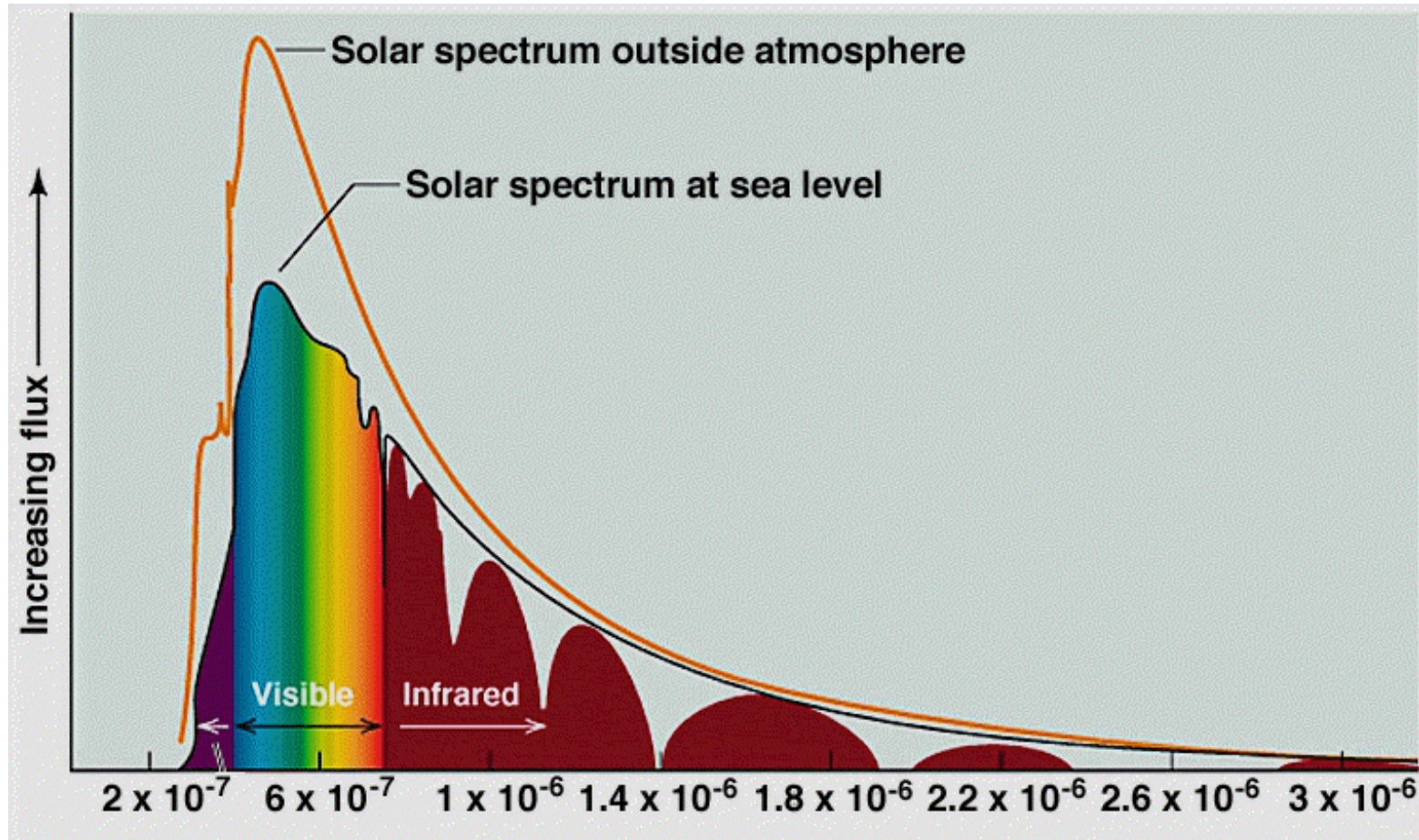
For relatively cool objects, most blackbody radiation is in the infrared; observable by thermal imaging devices.



# Sun is approximately a blackbody

The temperature of the surface of the sun is about 5800 K.

It is close to a black body although there are absorption lines from the hydrogen gas

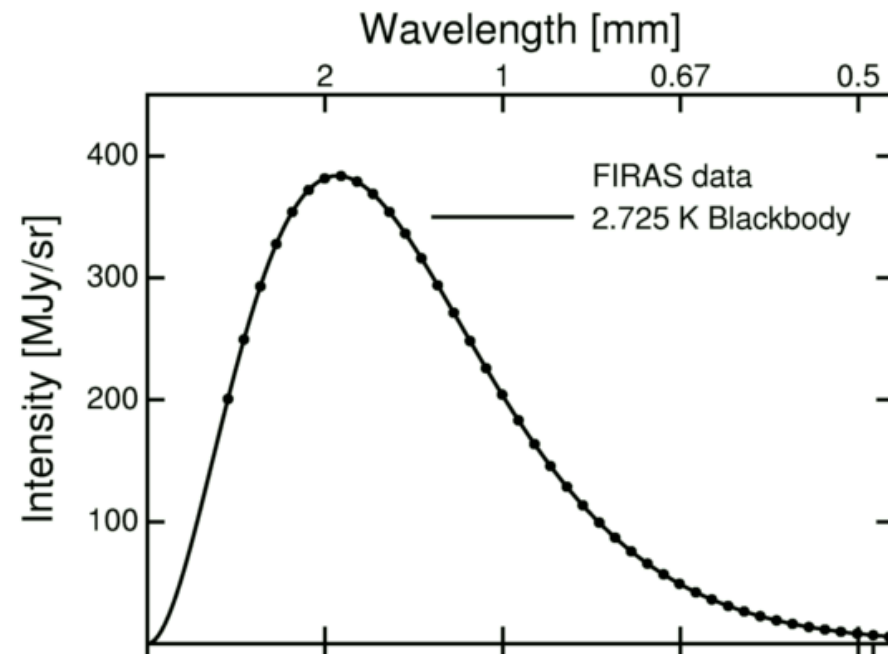
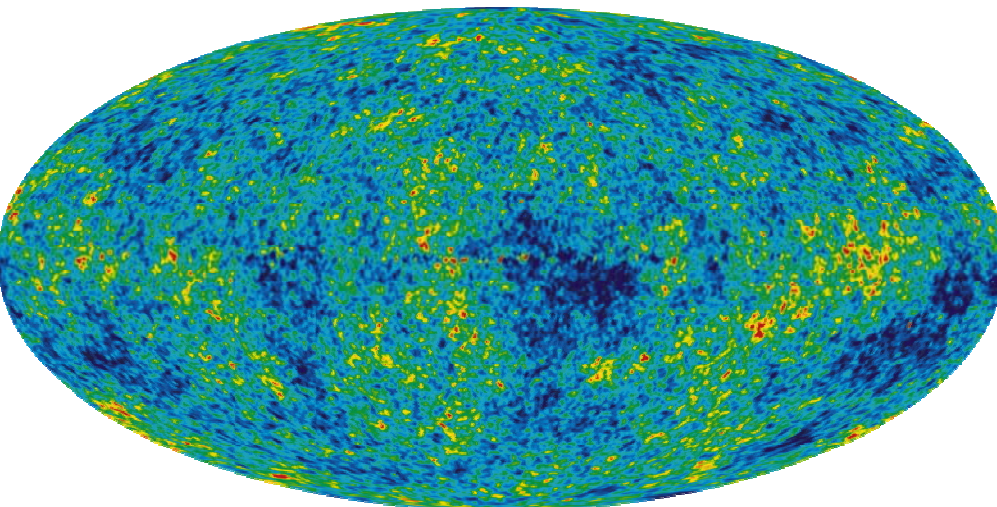


# Cosmic Microwave Background (CMB)

The cosmic microwave background radiation comes from radiation that was emitted 13.3 billion years ago (400,000 years after the Big Bang).

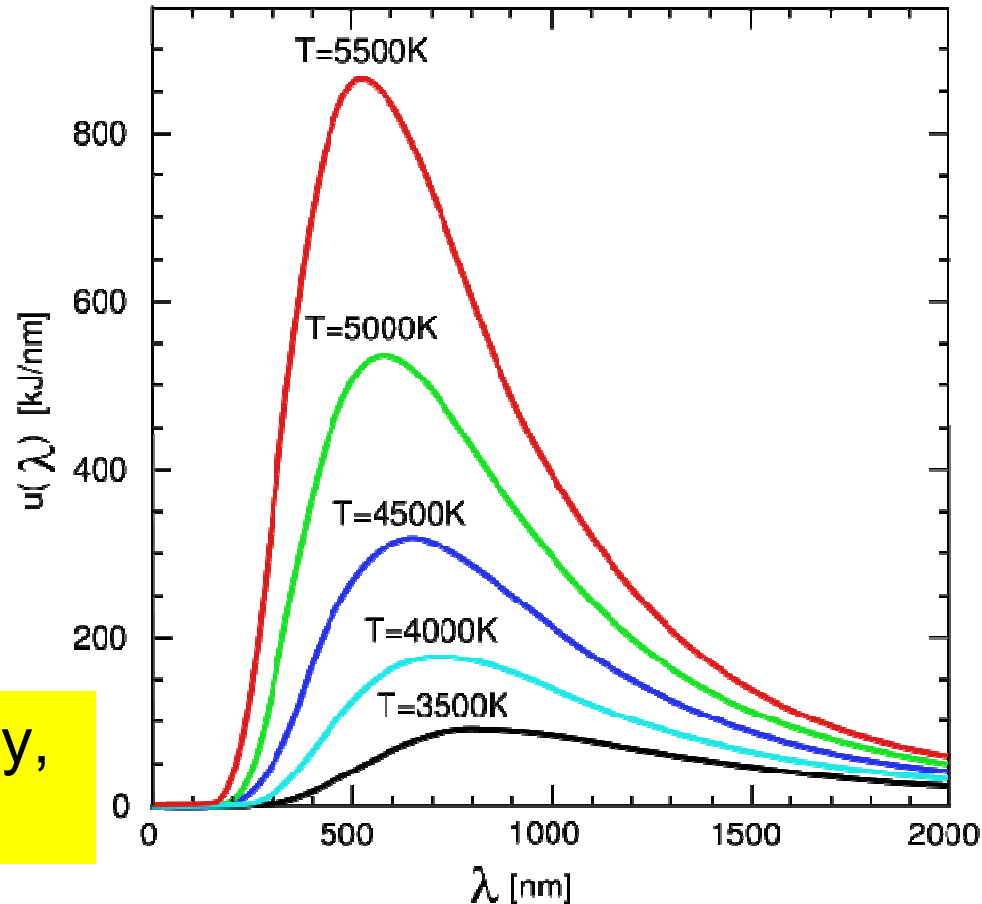
At the time, the universe was about 3000 K but as the universe expanded, the wavelengths of the light increased so now it shows a blackbody at 2.725 K and is the most precise blackbody known.

Only 1 part in 100,000 anisotropy



Assuming stars are perfect blackbodies, what can you say about the relative surface temperatures of a blue giant, red giant, and our sun?

- A.  $T_{\text{blue giant}} = T_{\text{red giant}} > T_{\text{Sun}}$
- B.  $T_{\text{blue giant}} > T_{\text{red giant}} > T_{\text{Sun}}$
- C.  $T_{\text{blue giant}} > T_{\text{Sun}} > T_{\text{red giant}}$
- D.  $T_{\text{red giant}} > T_{\text{Sun}} > T_{\text{blue giant}}$
- E. Depends on other factors



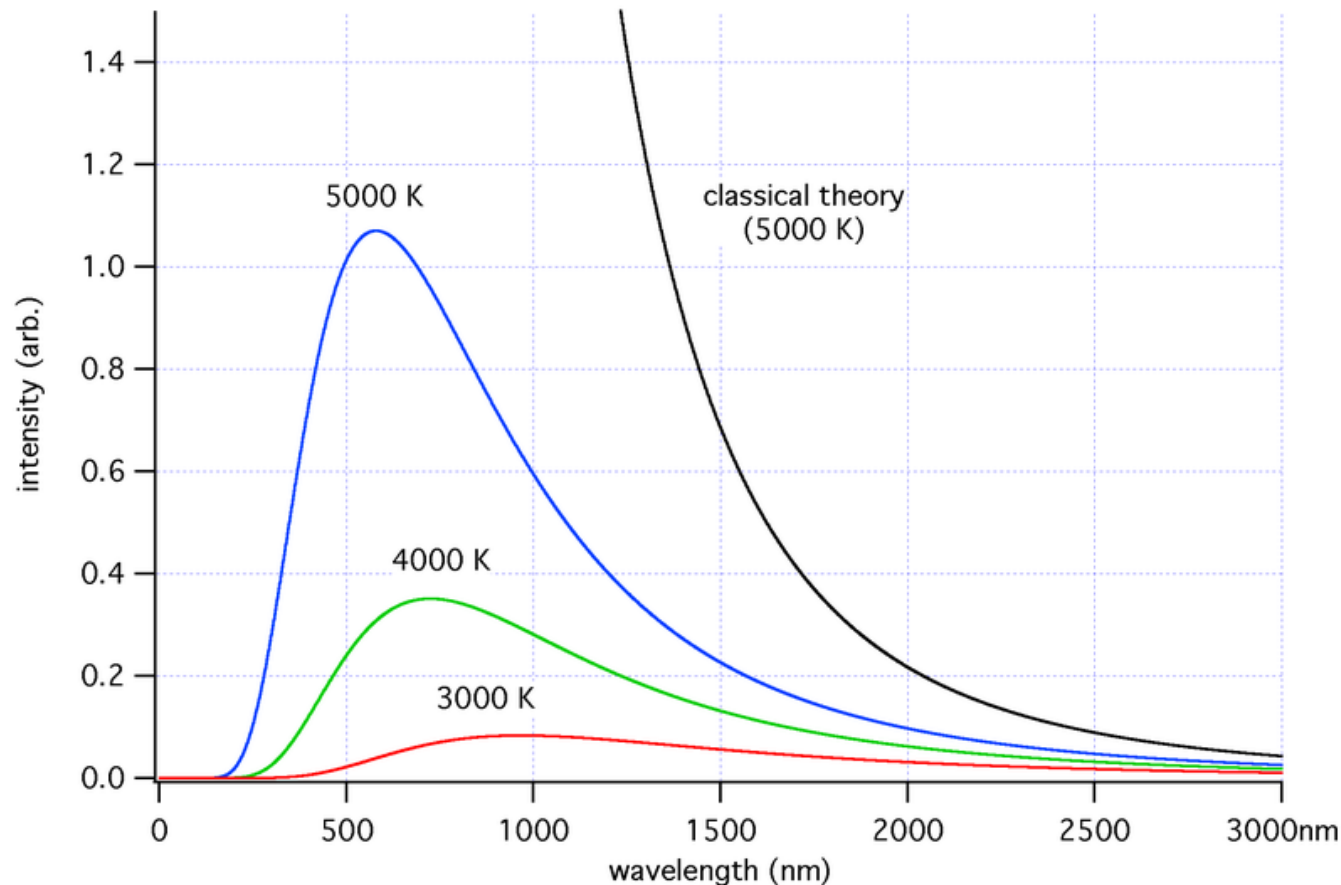
Our Sun is yellow (not cowardly, that's just its color)

Shorter wavelengths correspond to hotter blackbodies.

# Classical understanding of the blackbody spectrum

Using the wave nature of light, the classical theory for the blackbody spectrum was the Rayleigh-Jeans theory.

This theory predicted an infinite amount of energy at short wavelengths which was called the ultraviolet catastrophe.



# Understanding the blackbody spectrum

In 1900, Max Planck proposed a new theory which matched the blackbody observations perfectly.

The new theory required a minimum energy in the emitted light which was proportional to the frequency of light.

The energy coming out of the blackbody is *quantized* as a multiple of  $hf$ .

This is the first example of a quantum effect.

The proportionality constant is now called Planck's constant  $h$ .

Planck did not think that light itself was quantized. He just found that when he required the atoms in the blackbody to emit quantum amounts of energy in the form of light that everything worked.

Energy emitted is  $E = nhf$  where  $n$  is an integer.