Shining Light on the Dark Side of the Universe

Tim Linden

Arthur Compton Lecture Series - Fall 2014

Thanks for Attending!

Shining Light on the Dark Side of the Universe

Tim Linden

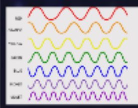
Arthur Compton Lecture Series - Fall 2014


How Do We Observe our Universe?
For most of human history, our only way of understanding the universe was by looking at the light which reached Earth
How do we use light to understand our universe?
Things that emit light
Things that absorb light
What Else Can Light Tell Us?
Remember, light travels at a constant speed (186,000 miles per second)
So when we are looking at a source that is far away, we are also looking back in time
Sun
8 minutes
Alpha Centauri
4.4 years
Andromeda
2.5 million years
Looking At the Early Universe
Redshift
The First Photons
The Dark Side of the Universe
The "Light" Side of the Universe

How Do We Observe our Universe?

For most of human history, our only way of understanding the universe was by looking at the light which reached Earth

What is Light?



Light is a wave that carries energy

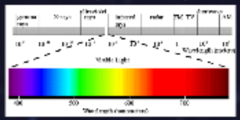
The amount of energy carried by a wave is determined by the wavelength of the light

For the "visible light" that our eyes can detect, different wavelengths are interpreted in our brain as different colors

What is Light?

Not all light is visible!

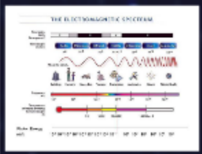
Light can also have wavelengths that cannot be seen by the human eye



What is Light?

Measuring the energy of light:

$$\lambda \nu = c$$



$$E = h\nu$$

What is Light?

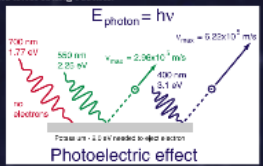
"Light" is composed of particles called photons.

This sets specific quantities in the amount of light an object can emit.

For instance a sodium lamp could emit 1 photon with a 590 nm wavelength (which we regard as "yellow"), or 2 photons with this wavelength -- but not 1.5

What is Light?

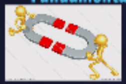
The fact that light is both a wave and a particle leads to some interesting results:



What Else is Light?

Light is also related to the phenomenon that explains many of the interactions between the world around us. In physics, we call it the "force carrier" of the electromagnetic force

Fundamentally, What is Light?

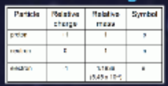


Light is an excitation of the electromagnetic field.

It corresponds to a natural mode of vibration

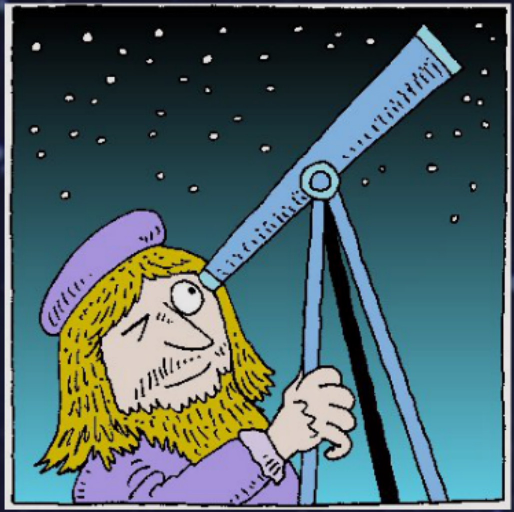
Unnatural vibrations of the electromagnetic field are sometimes called "virtual particles" and control the interactions between the particles we see in nature

Particles That Interact With Light

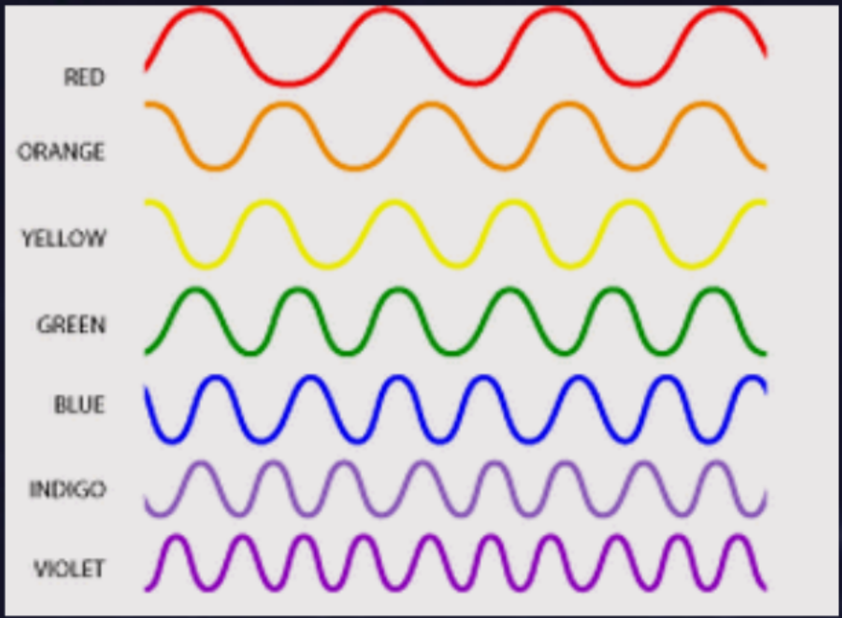


Nearly all known particles interact with the electromagnetic field. Even neutrons, for instance, which are not charged particles, can interact with photons

One counter-example is neutrinos, we will come back to this later



What is Light?



Light is a wave that carries energy

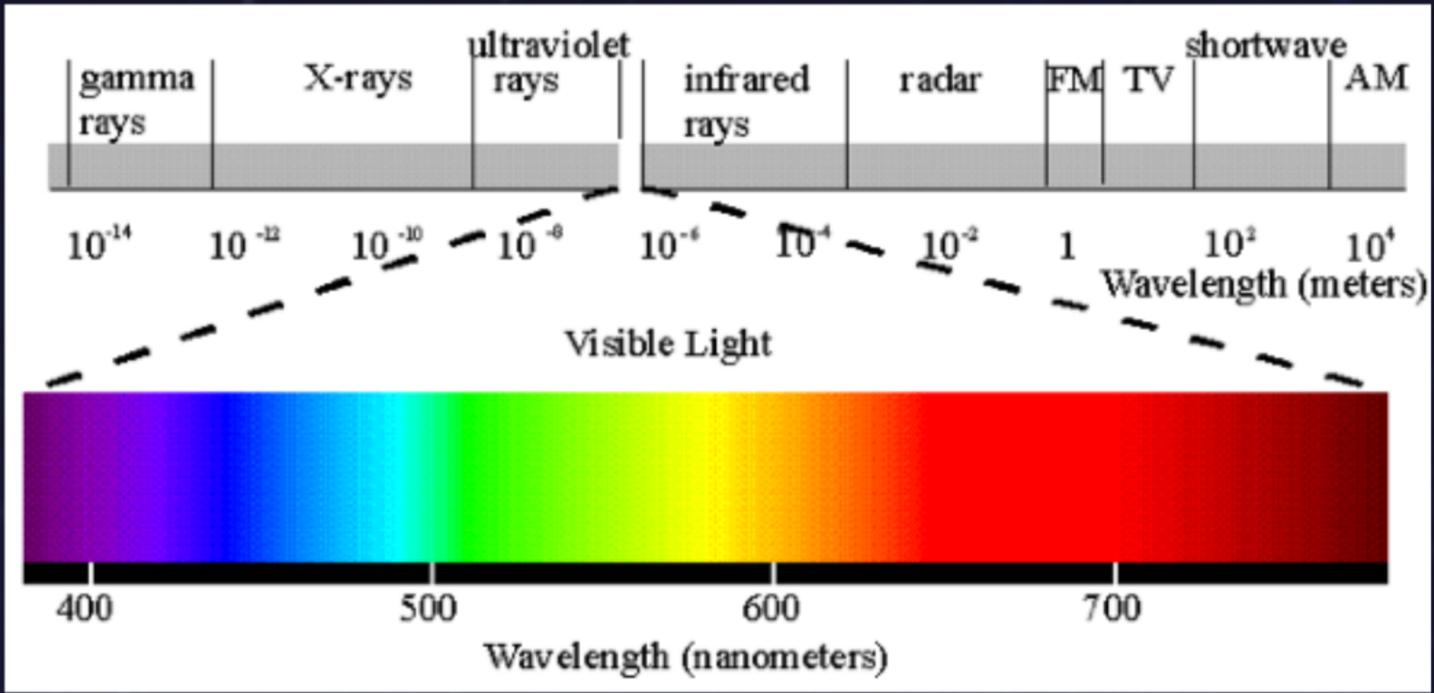
The amount of energy carried by a wave is determined by the wavelength of the light

For the "visible light" that our eyes can detect, different wavelengths are interpreted in our brain as different colors

What is Light?

Not all light is visible!

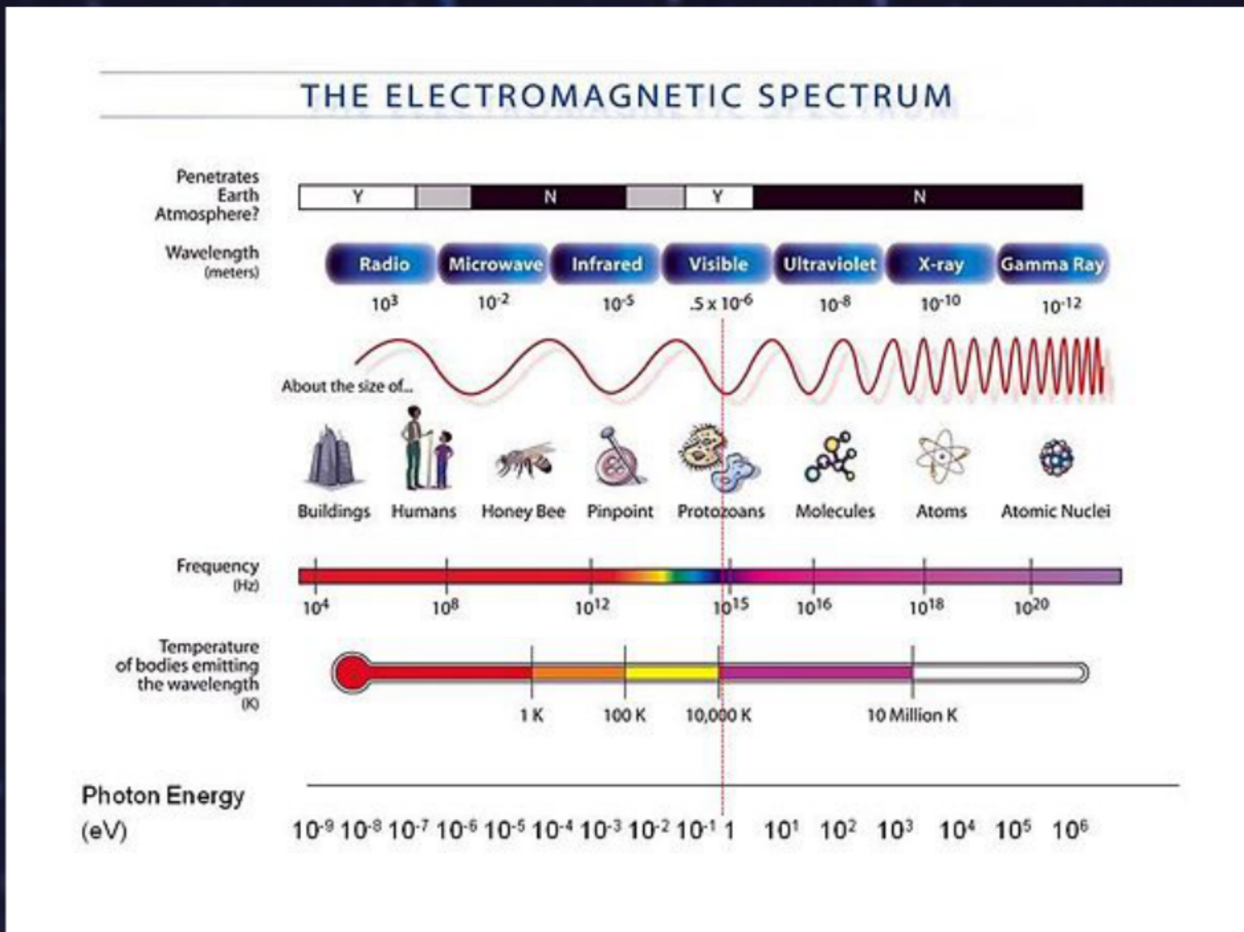
Light can also have wavelengths that cannot be seen by the human eye



What is Light?

Measuring the energy of light:

$$\lambda \nu = c$$



$$E = h\nu$$

What is Light?

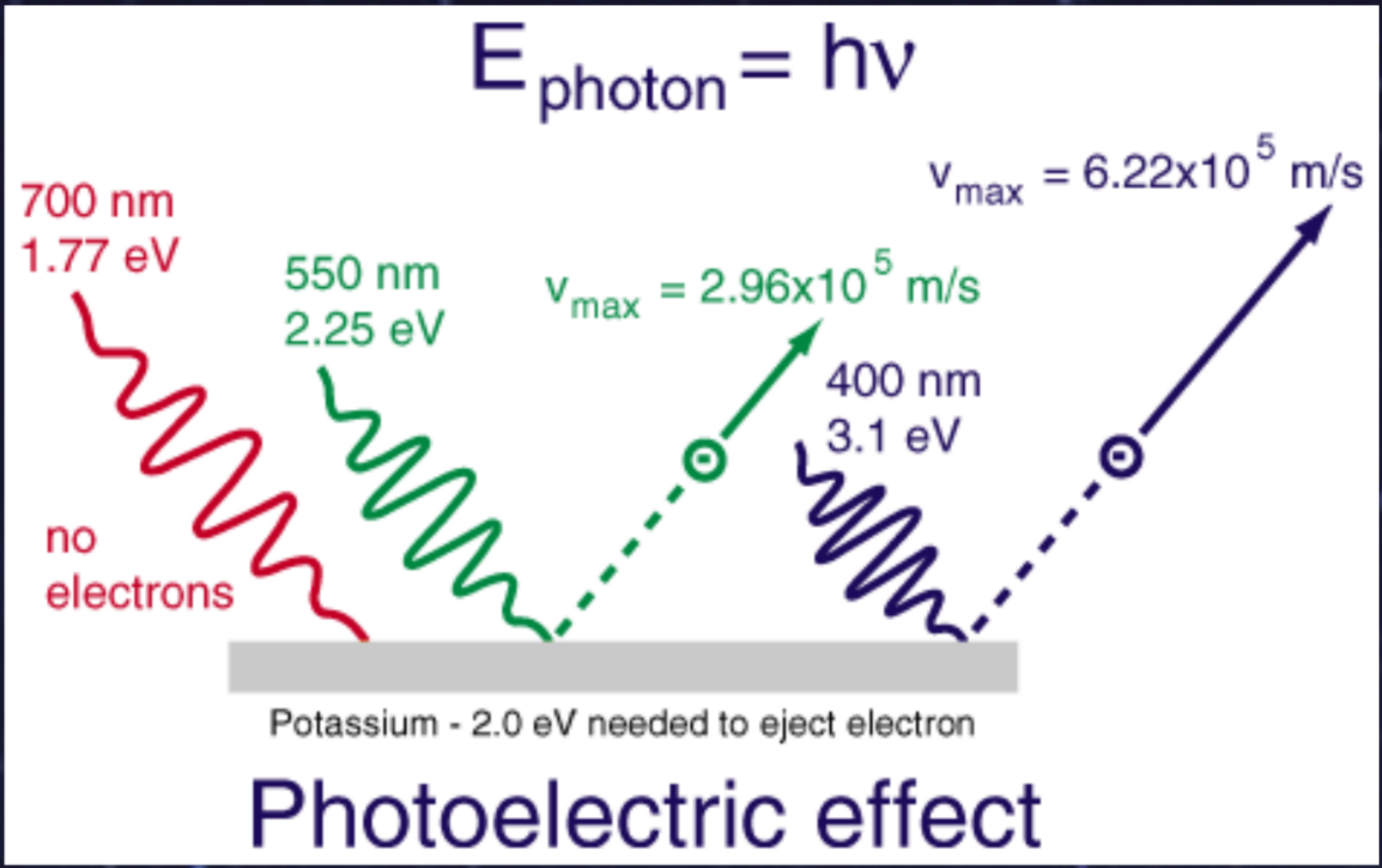
"Light" is composed of particles called photons.

This sets specific quantities in the amount of light an object can emit.

For instance a sodium lamp could emit 1 photon with a 590 nm wavelength (which we regard as "yellow"), or 2 photons with this wavelength -- but not 1.5

What is Light?

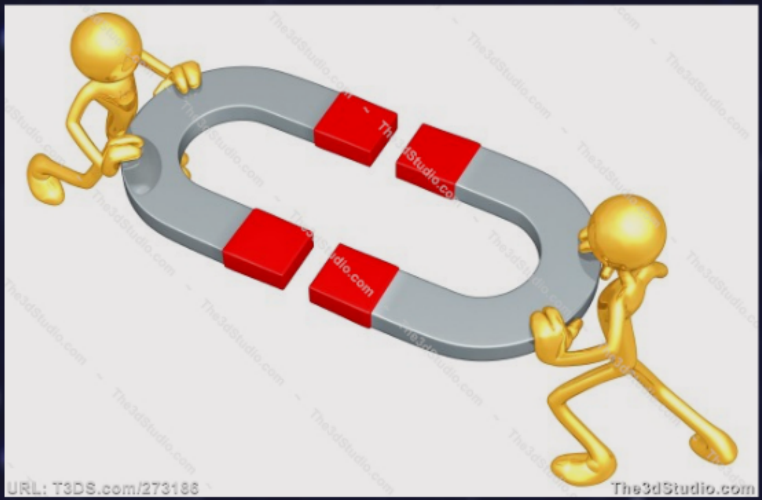
The fact that light is both a wave and a particle leads to some interesting results:

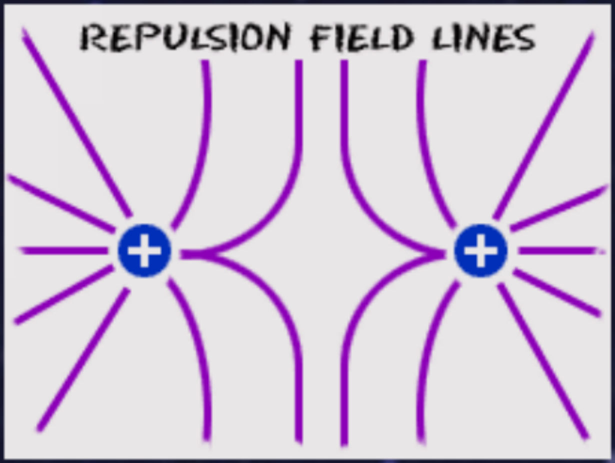


What Else is Light?

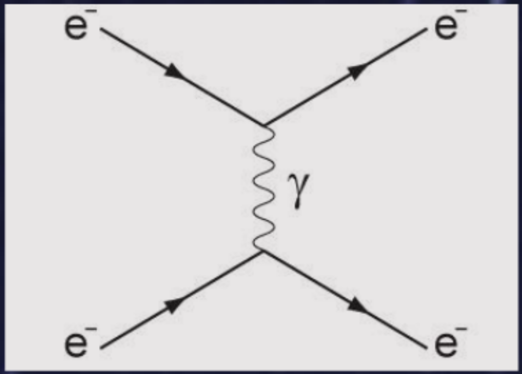
Light is also related to the phenomenon that explains many of the interactions between the world around us. In physics, we call it the "force carrier" of the electromagnetic force

Fundamentally, What is Light?





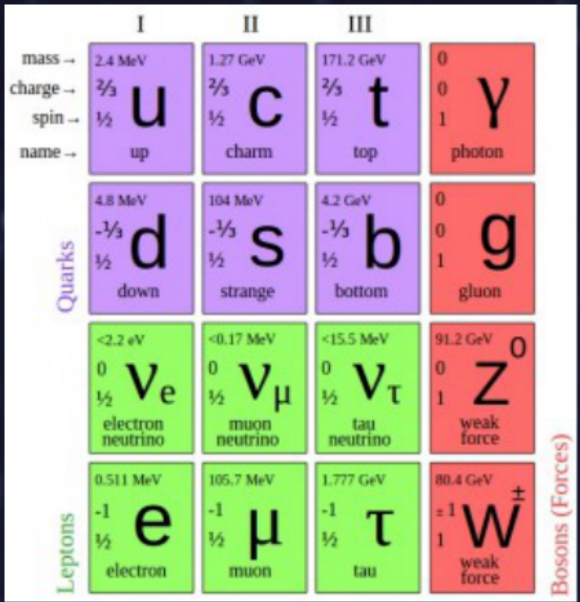
Light is an excitation of the electromagnetic field.



It corresponds to a natural mode of vibration

Unnatural vibrations of the electromagnetic field are sometimes called "virtual particles" and control the interactions between the particles we see in nature

Particles That Interact With Light



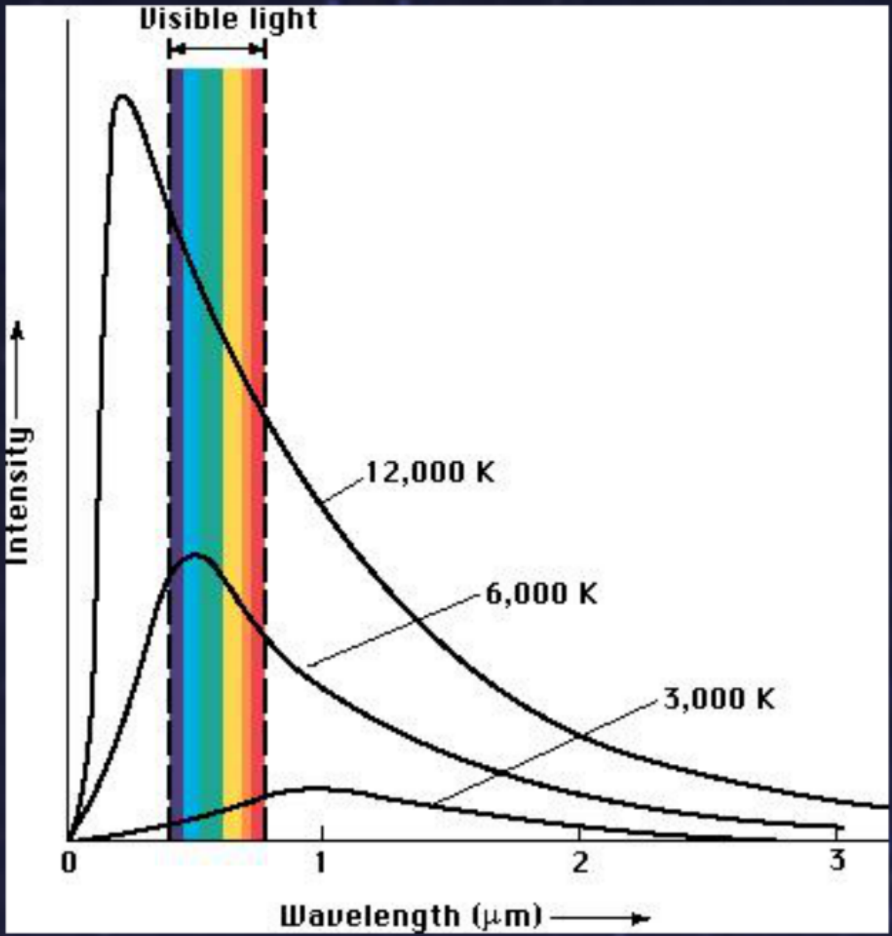
Particle	Relative charge	Relative mass	Symbol
proton	+1	1	p
neutron	0	1	n
electron	-1	1/1836 (5.45×10^{-4})	e^-

Nearly all known particles interact with the electromagnetic field. Even neutrons, for instance, which are not charged particles, can interact with photons

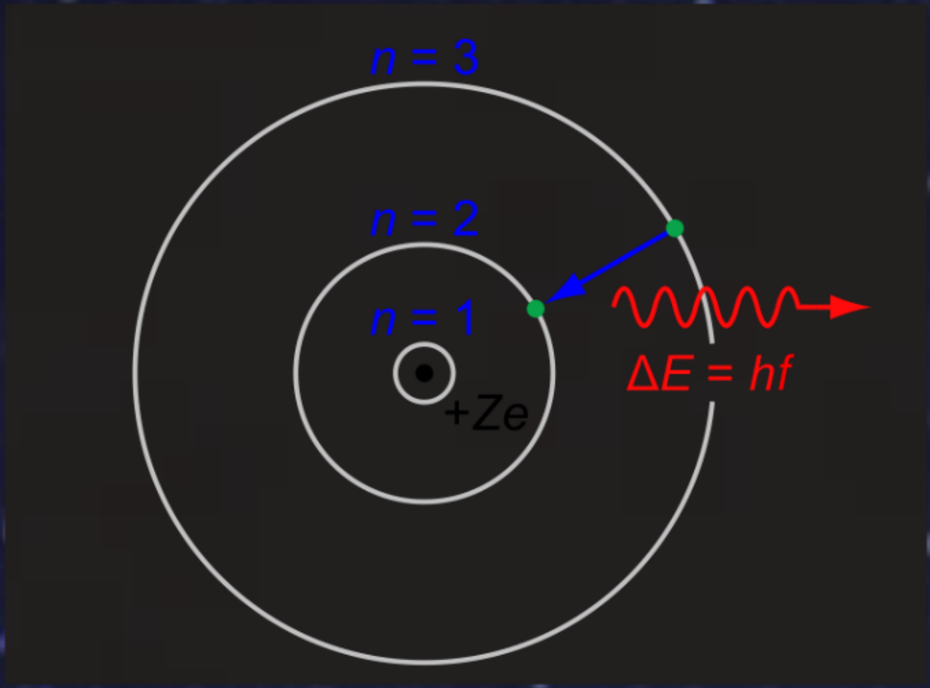
One counter-example is neutrinos, we will come back to this later

How do we use light to understand our universe?
Things that emit light
Things that absorb light
What Can You Learn By Looking at a Source?
Non-Thermal Light
There are other ways to emit light, in addition to blackbody emission.
How do you Detect Absorption?
Look for a source with a known spectrum, see how much light is missing at different wavelengths
Absorption At Different Energies
Galactic Center
To get a full picture of the universe, we need telescopes that can look at lots of different wavelengths

What Can You Learn By Looking at a Source?

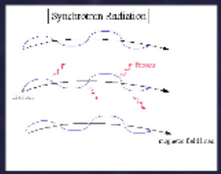


Non-Thermal Light

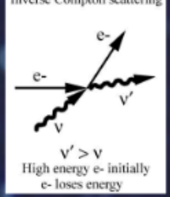


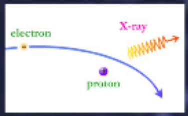
There are other ways to emit light, in addition to blackbody emission.

In Astrophysics



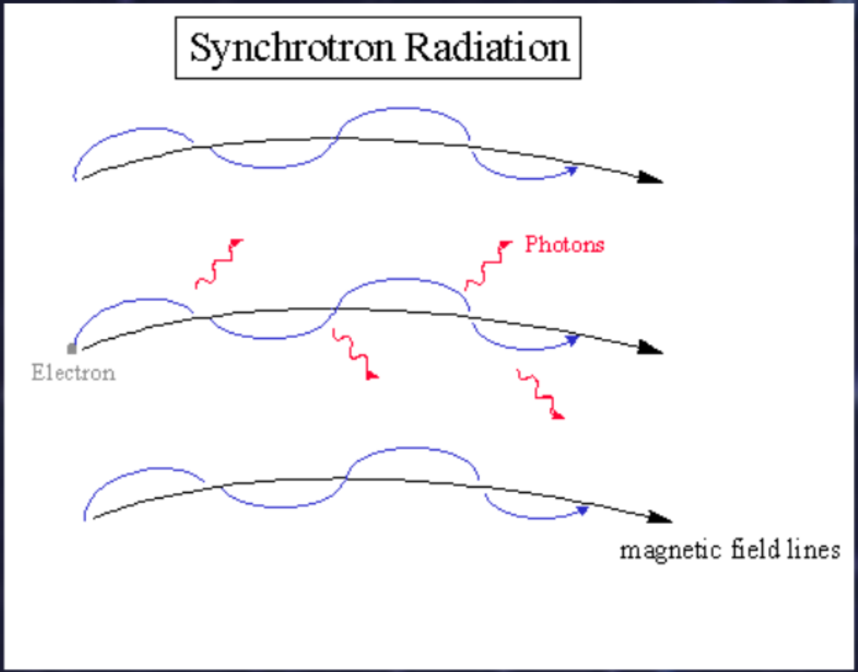
Inverse Compton scattering

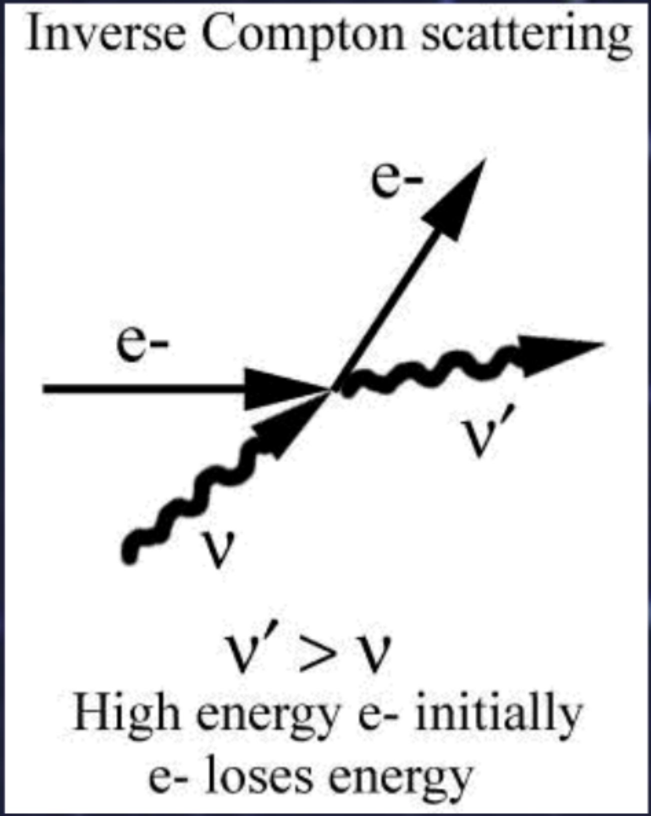


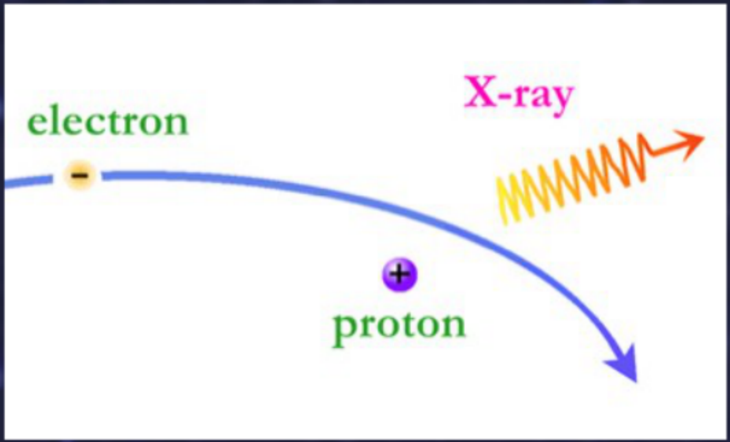


Bremsstrahlung

In Astrophysics

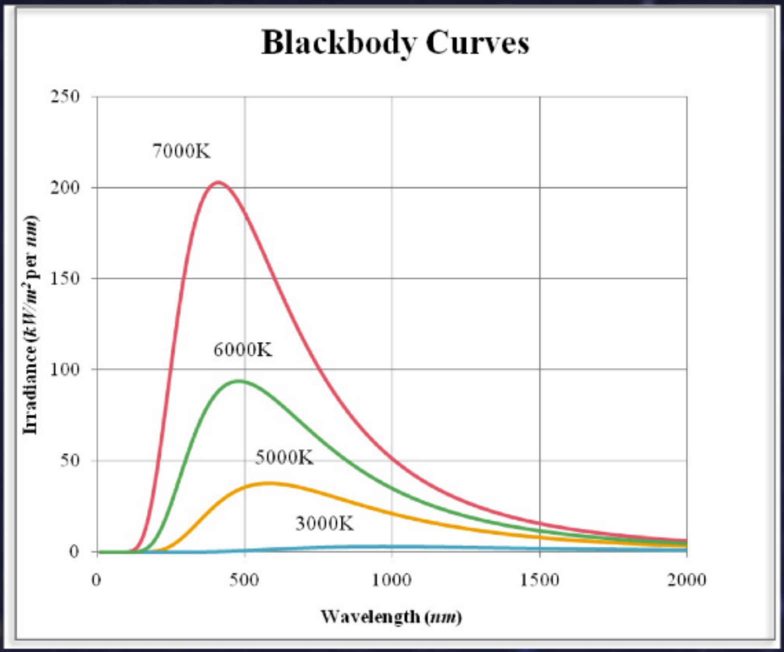




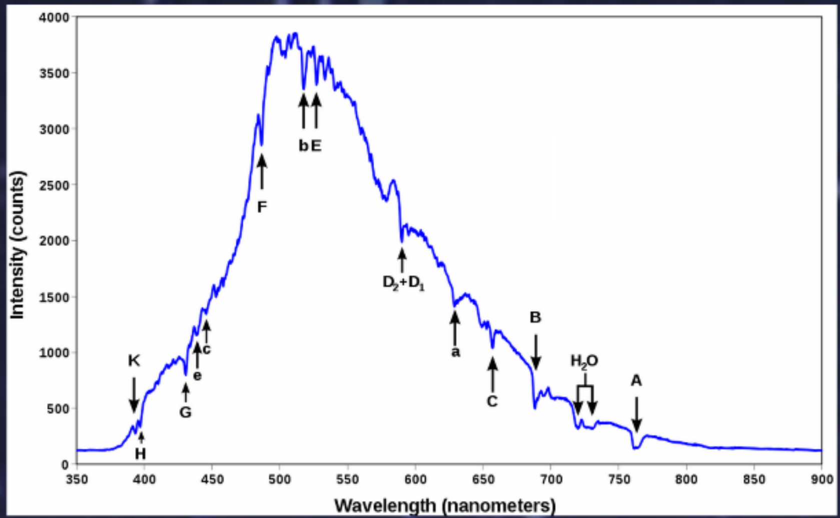


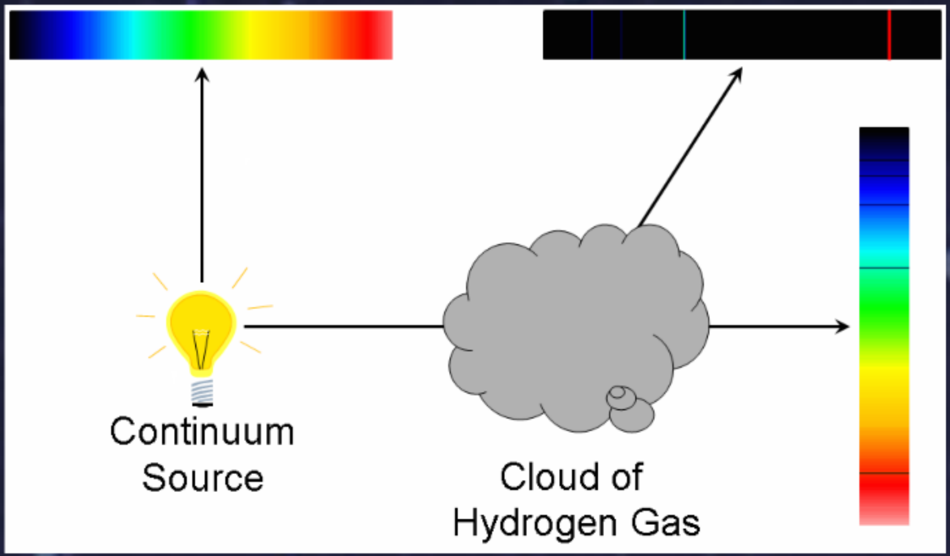
Bremsstrahlung

How do you Detect Absorption?



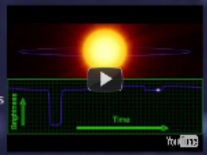
Look for a source with a known spectrum, see how much light is missing at different wavelengths





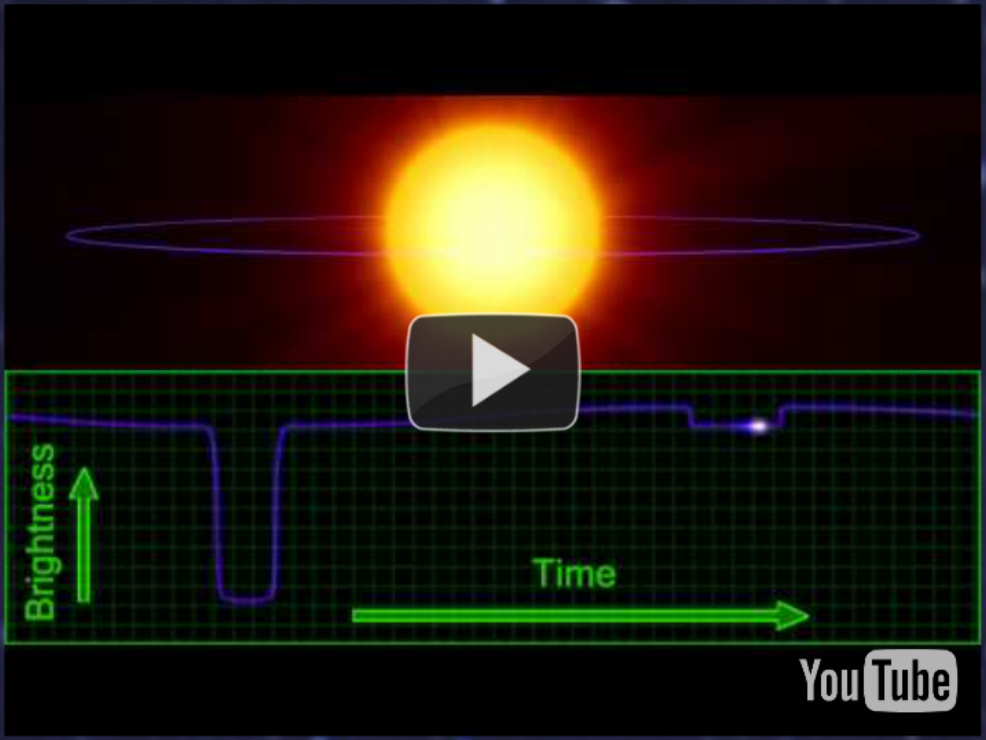
Finding Planets

Kepler Satellite
March 7, 2009 - Present
977 confirmed planets
3,277 unconfirmed candidates

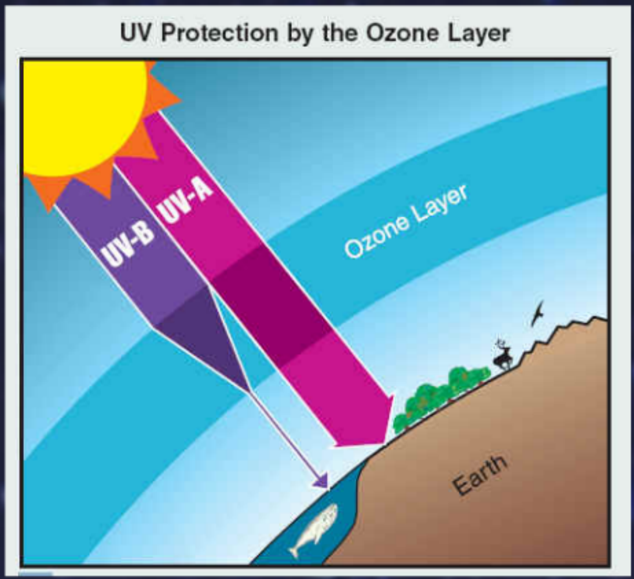


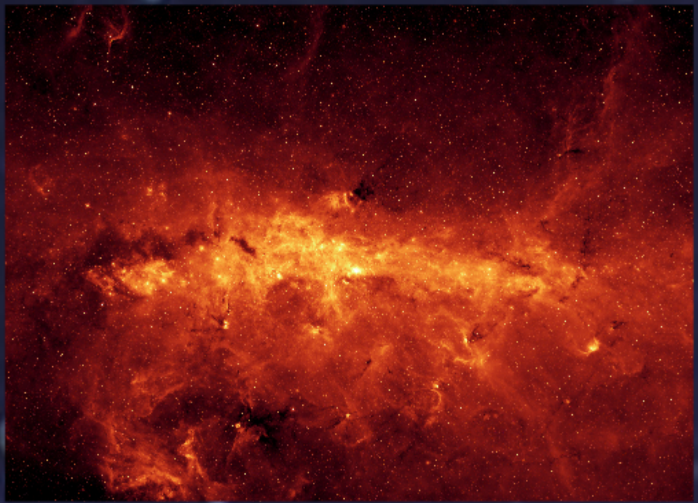
Finding Planets

Kepler Satellite
March 7, 2009 - Present
977 confirmed planets
3,277 unconfirmed candidates



Absorption At Different Energies





Galactic Center

To get a full picture of the universe, we need telescopes that can look at lots of different wavelengths

What Else Can Light Tell Us?

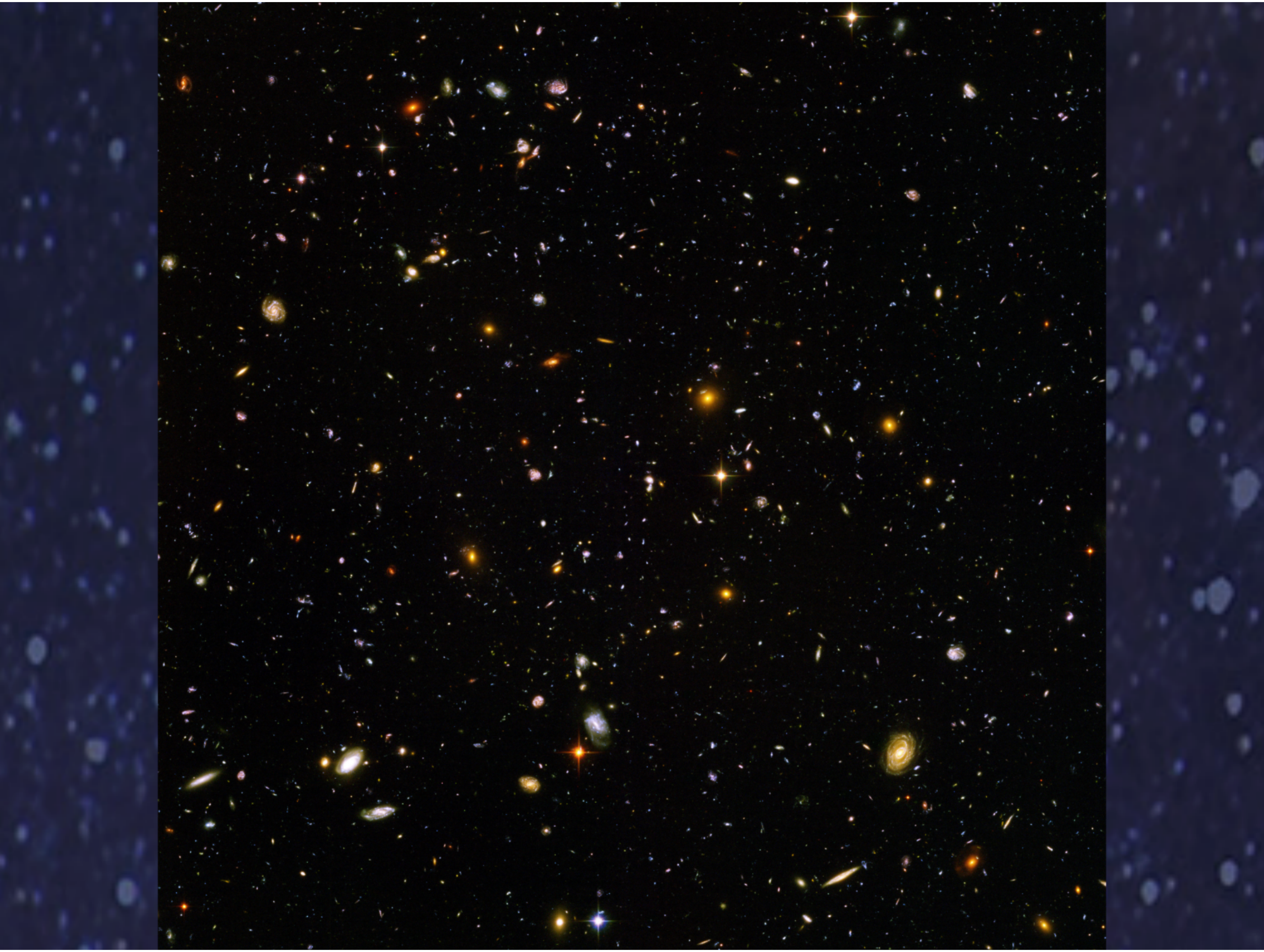
Remember, light travels at a constant speed (186,000 miles per second)

So when we are looking at a source that is far away, we are also looking **back in time**

Sun
8 minutes

Alpha Centauri
4.4 years

Andromeda
2.5 million years



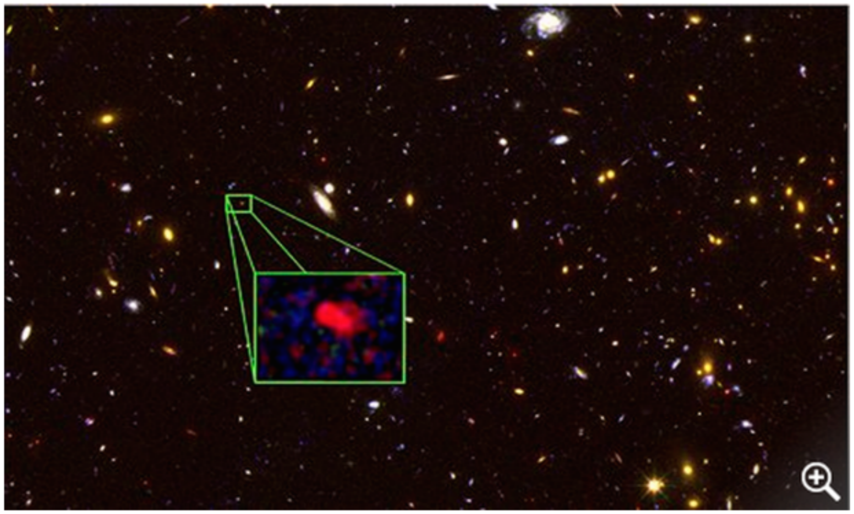
Looking At the Early Universe

Oldest and most distant galaxy ever discovered was a prolific star factory

Exceptionally high rate of star formation in the galaxy, formed a mere 700m years after the big bang, has baffled astronomers

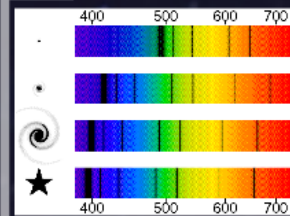
Ian Sample, science correspondent
Follow @iansample Follow @guardian
The Guardian, Wednesday 23 October 2013

Jump to comments (490)



The galaxy z8_GND_5296 is 40m years older than the previous record holder. Photograph: HST/Nasa

Redshift

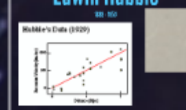


Simple Notation:

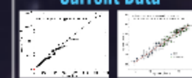
$$z = \frac{\text{observed wavelength}}{\text{emitted wavelength}} - 1$$

Can describe a galaxy as being at z = 4, just like we could say it is 12 billion light years away

Edwin Hubble

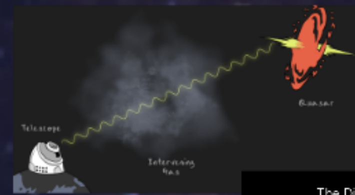


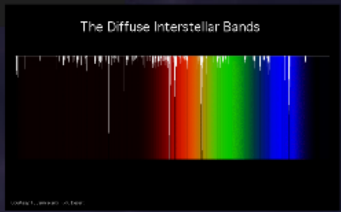
Current Data



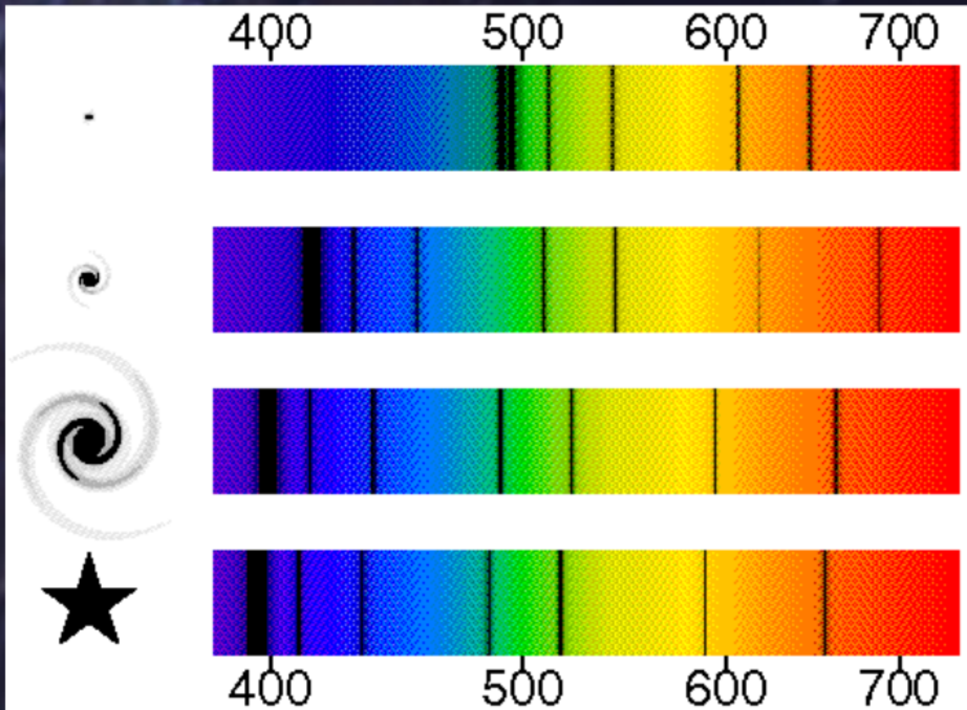
Hubble's Constant ~ 70 km s⁻¹ Mpc⁻¹

What Else Could This Tell Us?



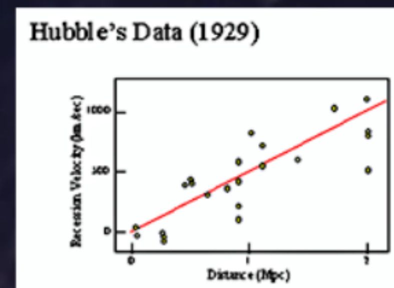


Redshift



Edwin Hubble

1889 - 1953

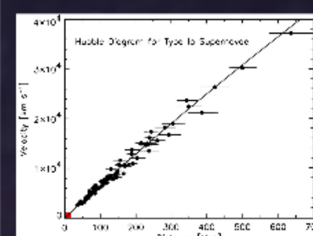


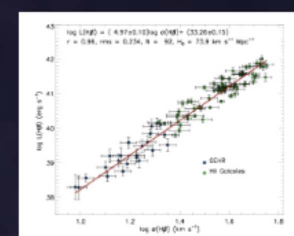
Simple Notation:

$$z = \frac{\text{observed wavelength}}{\text{emitted wavelength}} - 1$$

Can describe a galaxy as being at z = 4, just like we could say it is 12 billion light years away

Current Data





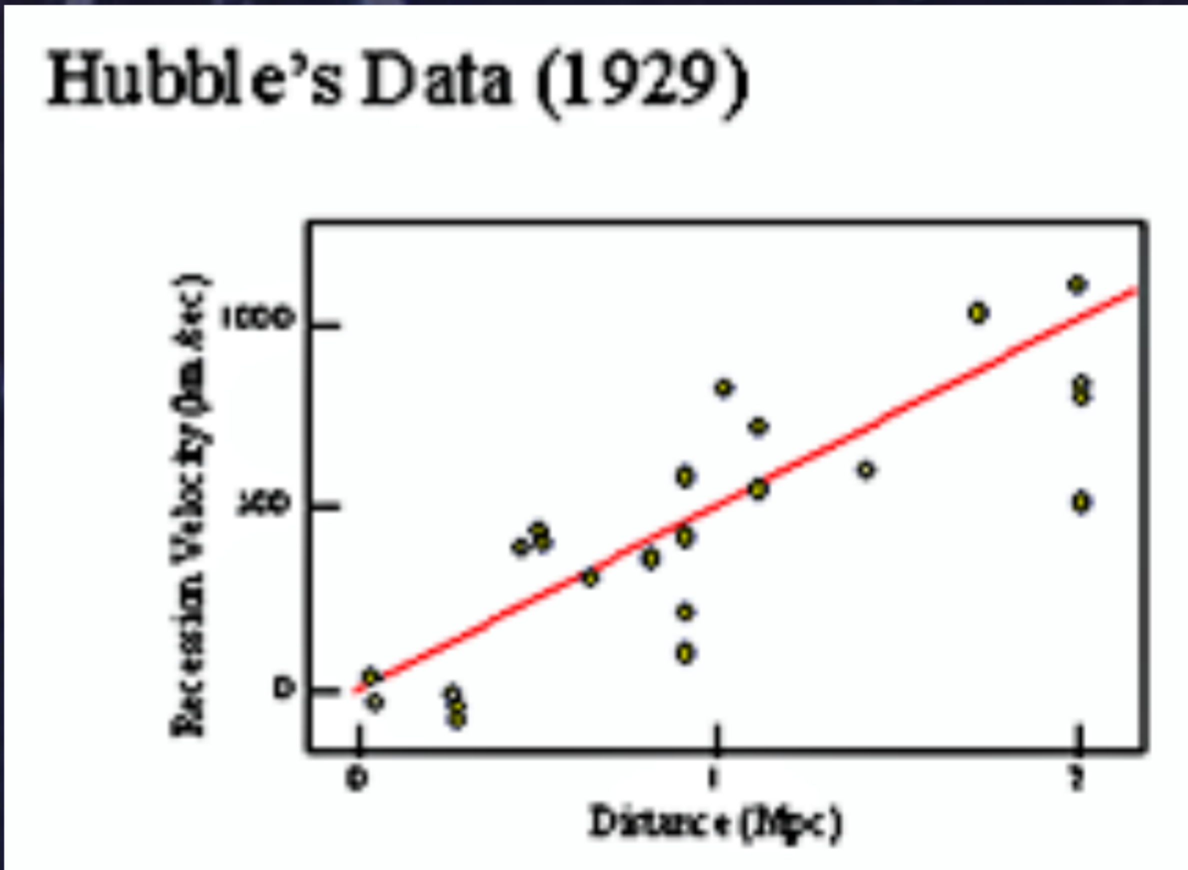
Hubble's Constant ~ 70 km s^{-1} Mpc^{-1}

1 pc = 3.26 light years

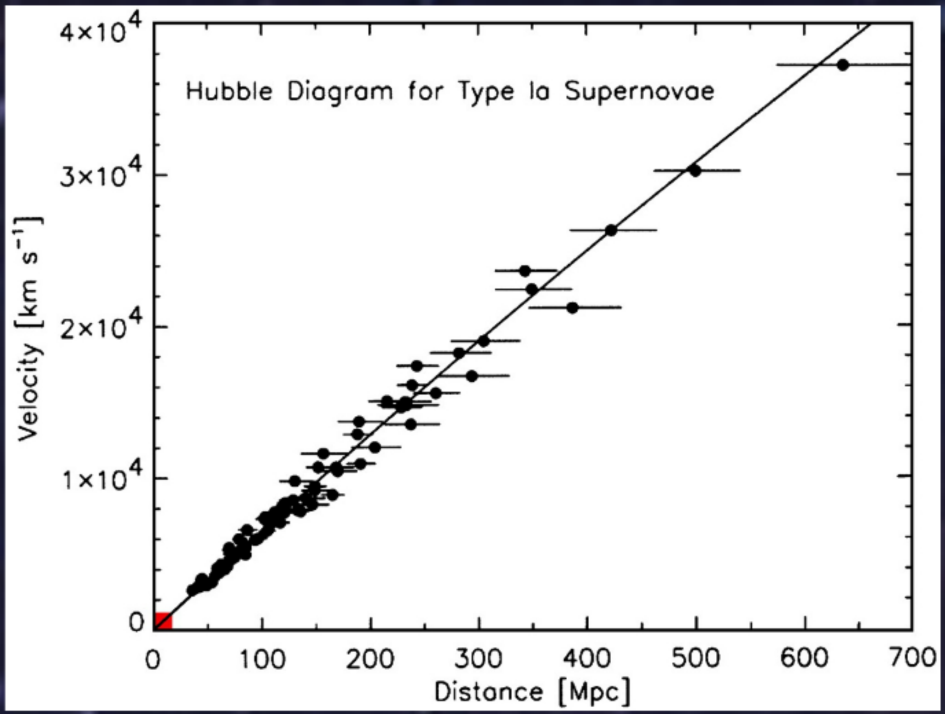
1 Mpc = 3,260,000 light years

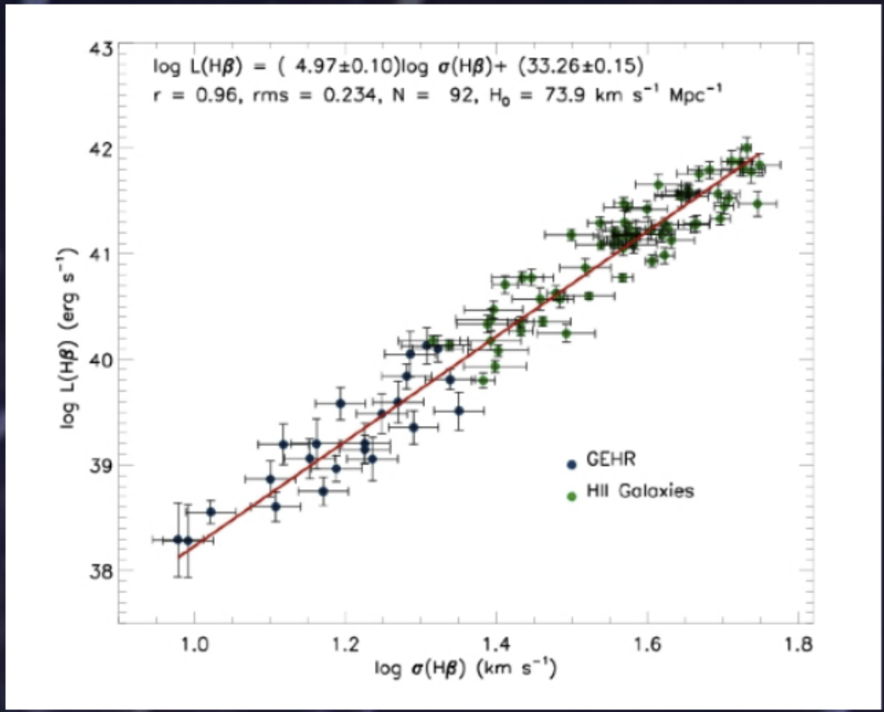
Edwin Hubble

1889 - 1953



Current Data



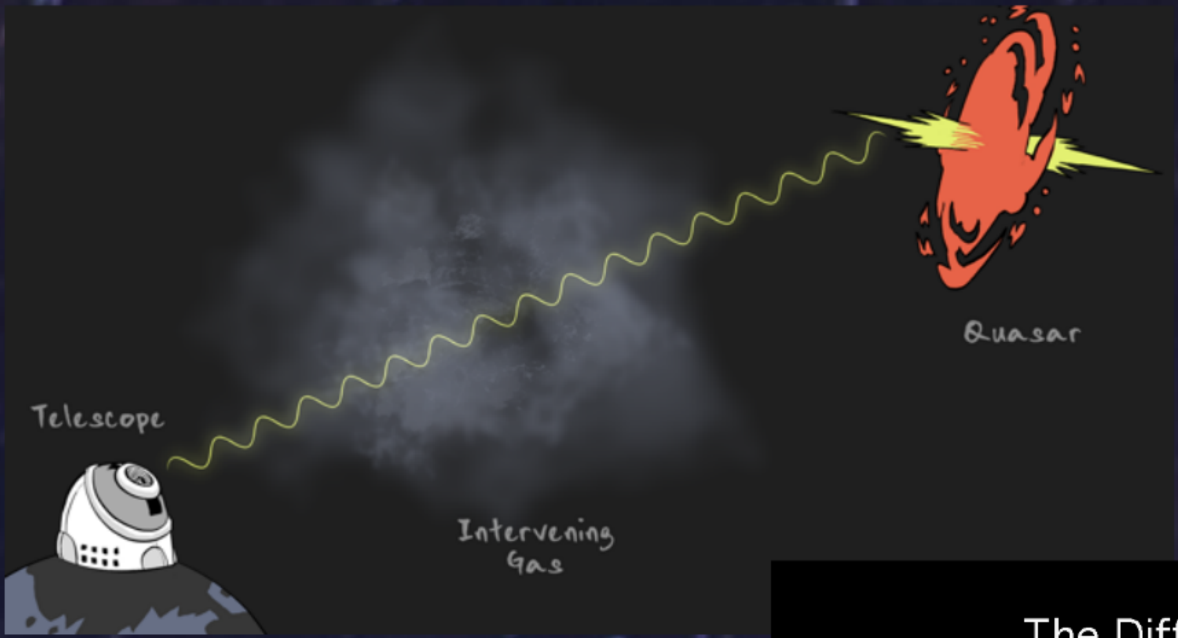


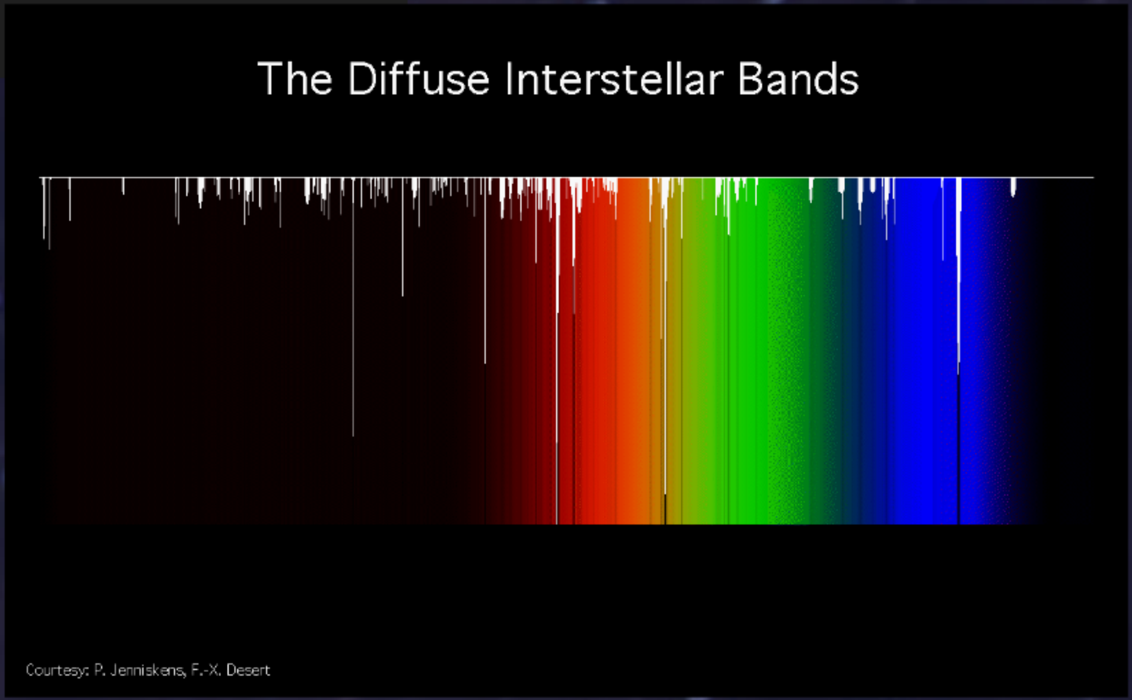
Hubble's Constant ~ 70 km s^{-1} Mpc^{-1}

1 pc = 3.26 light years

1 Mpc = 3,260,000 light years

What Else Could This Tell Us?

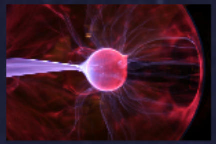




The First Photons

The Ionized Universe

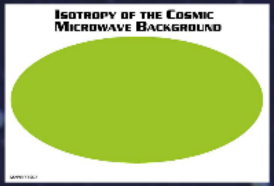
The early universe was very hot, too hot for electrons and protons to combine to form atoms



Plasmas emit and absorb light efficiently, so any photon produced in the early universe would be immediately absorbed again

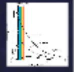
The Gas Cools

Cool Molecular Gas does not absorb light efficiently. Photons emitted once the gas cools are never absorbed again



It's a Blackbody!

$T_{CMB} = 3K$



$Z_{CMB} \sim 1000$

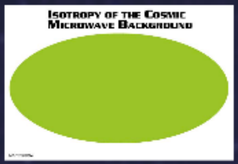
The Detection of the CMB

(1964, Bell Labs, Princeton)

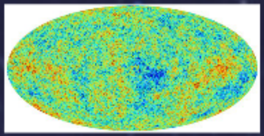
Arno Penzias and Robert Wilson

Robert Dicke

Anisotropies in the CMB

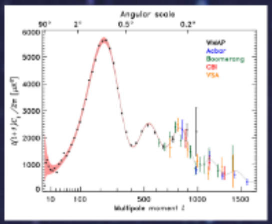


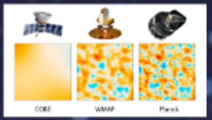
Cosmic Microwave Background is very isotropic, but not 100%

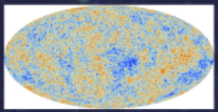


Anisotropies correspond to changes in the transition time between the plasma and molecular gas phases

Anisotropies in the CMB

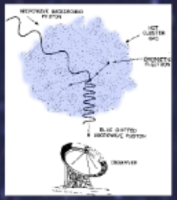


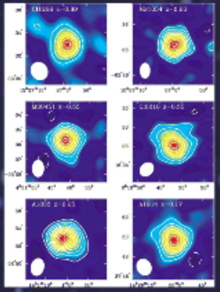




Lots of information is encoded in the position and height of each peak

Sunyaev-Zel'dovich Effect

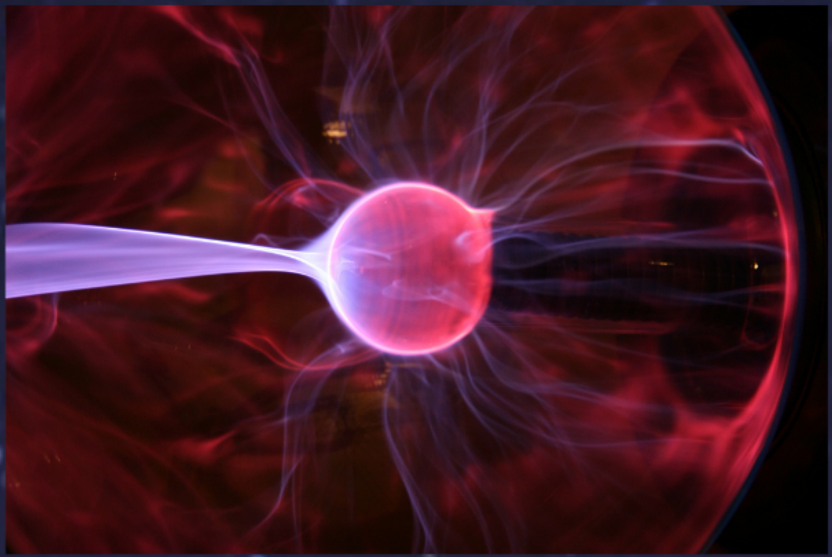




One way you can use the CMB is as a backlight, to see large clusters of galaxies

The Ionized Universe

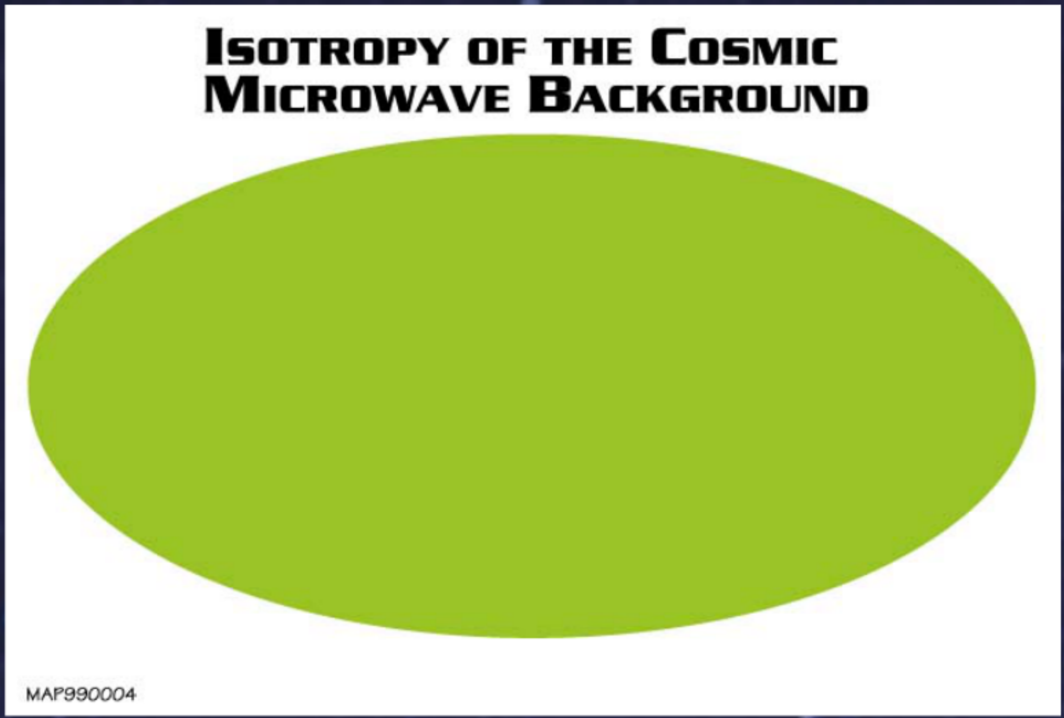
The early universe was very hot, too hot for electrons and protons to combine to form atoms



Plasmas emit and absorb light efficiently, so any photon produced in the early universe would be immediately absorbed again

The Gas Cools

Cool Molecular Gas does not absorb light efficiently. Photons emitted once the gas cools are never absorbed again



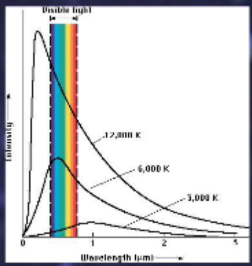
It's a Blackbody!

That means it can be described by only it's temperature:

$$T_{CMB} = 3K$$

The plasma of the universe condenses at a temperature of around 3000K, so the CMB has been significantly redshifted on its way to earth

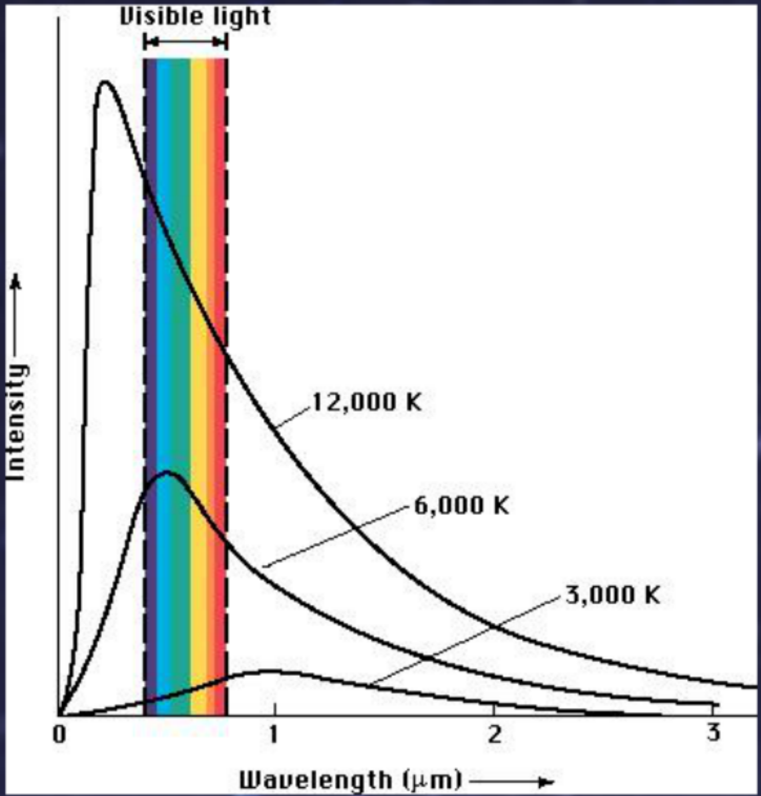
$$Z_{CMB} \sim 1000$$



It's a Blackbody!

That means it can be described by only it's temperature:

$$T_{CMB} = 3K$$



The plasma of the universe condenses at a temperature of around 3000K, so the CMB has been significantly redshifted on its way to earth

$$Z_{CMB} \sim 1000$$

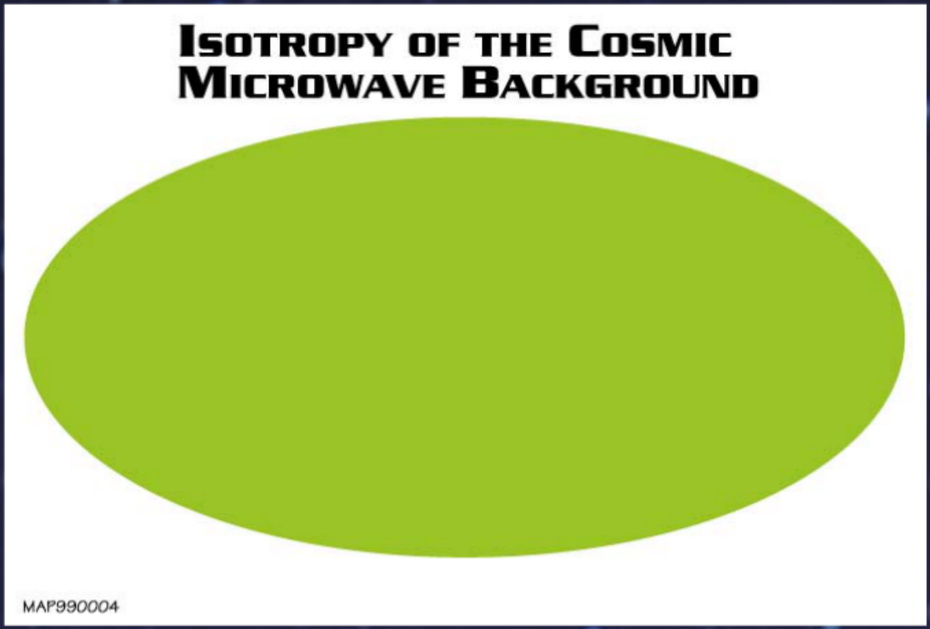
The Detection of the CMB

(1964, Bell Labs, Princeton)

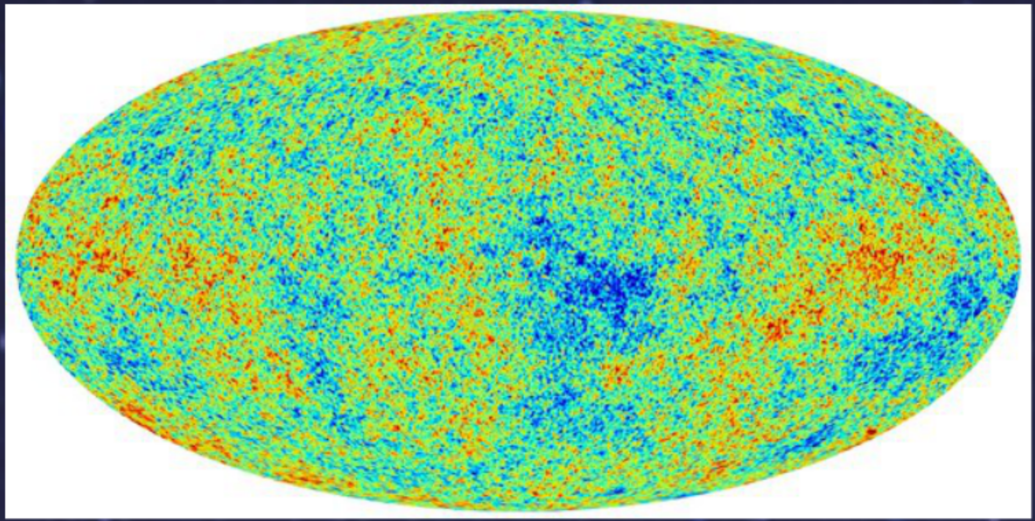
Arno Penzias and Robert Wilson

Robert Dicke

Anisotropies in the CMB

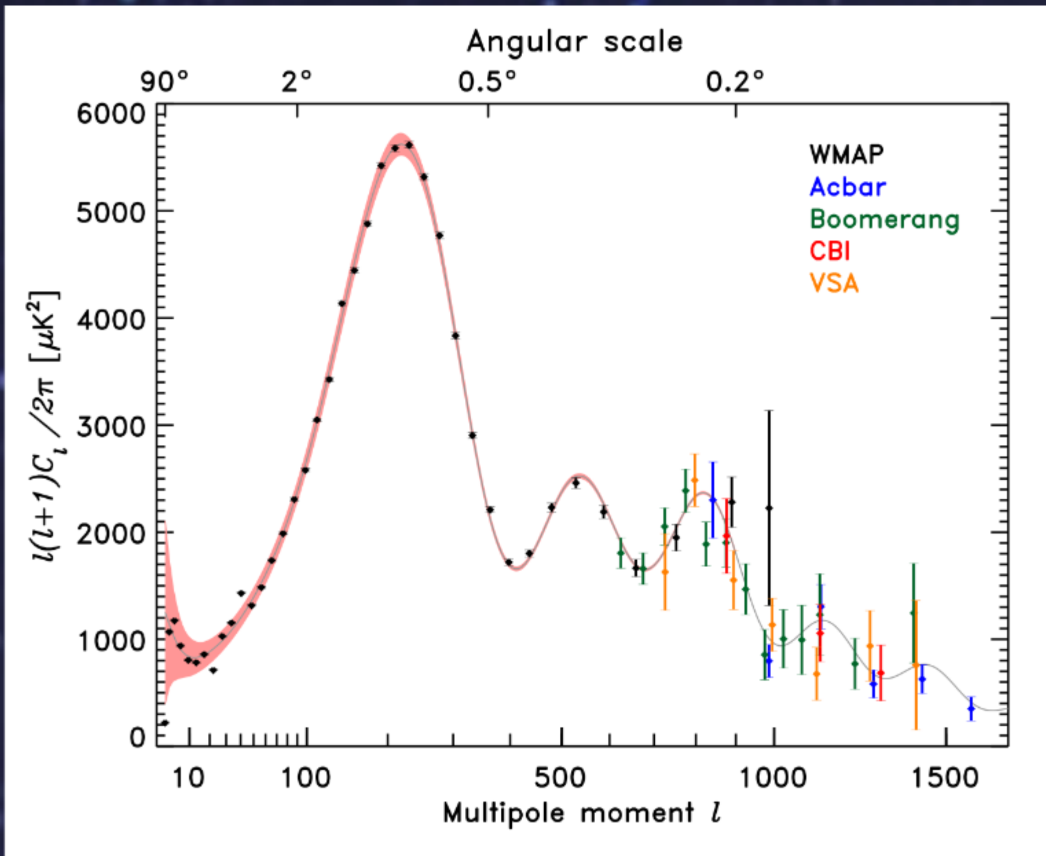


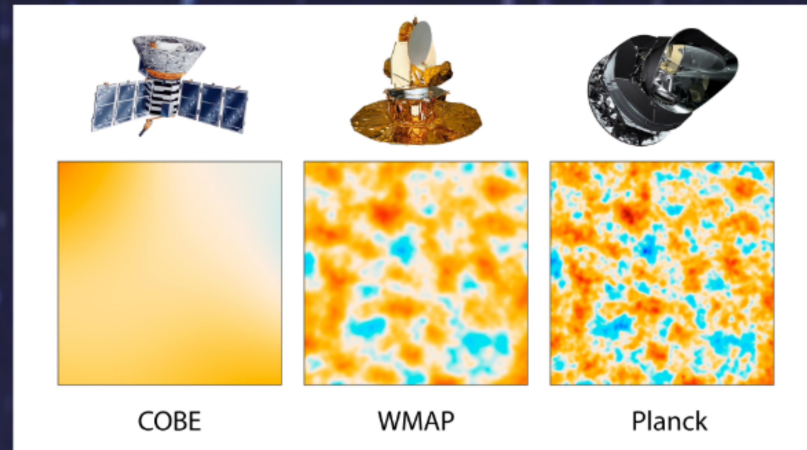
Cosmic Microwave Background is very isotropic, but not 100%

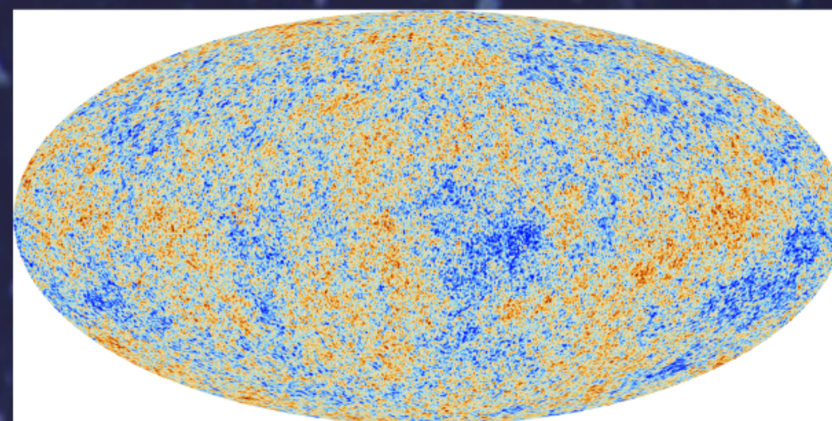


Anisotropies correspond to changes in the transition time between the plasma and molecular gas phases

Anisotropies in the CMB

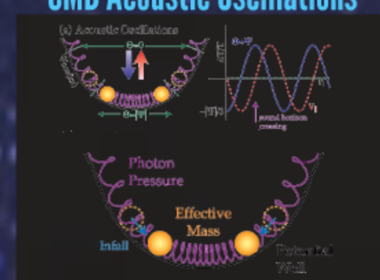


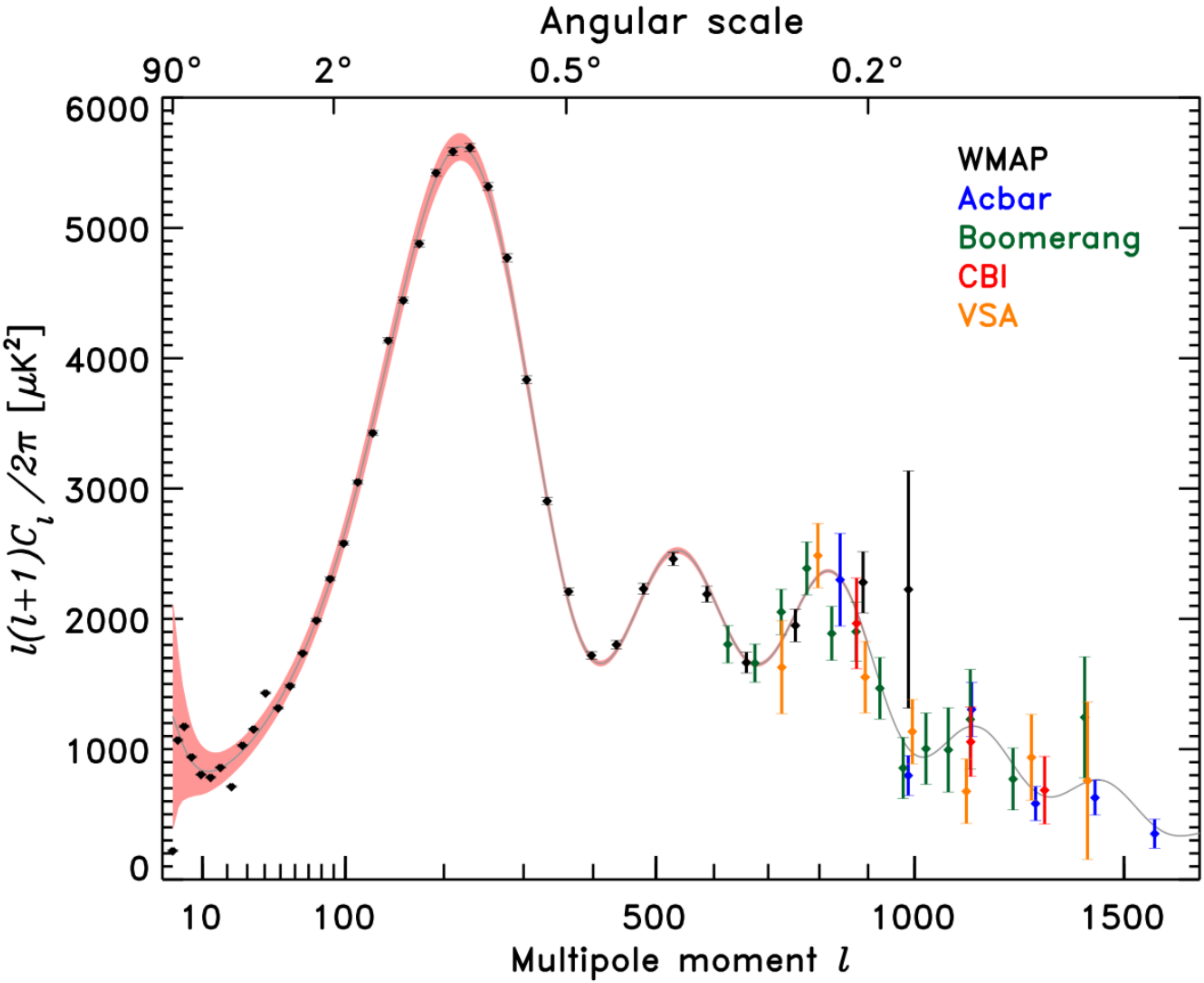




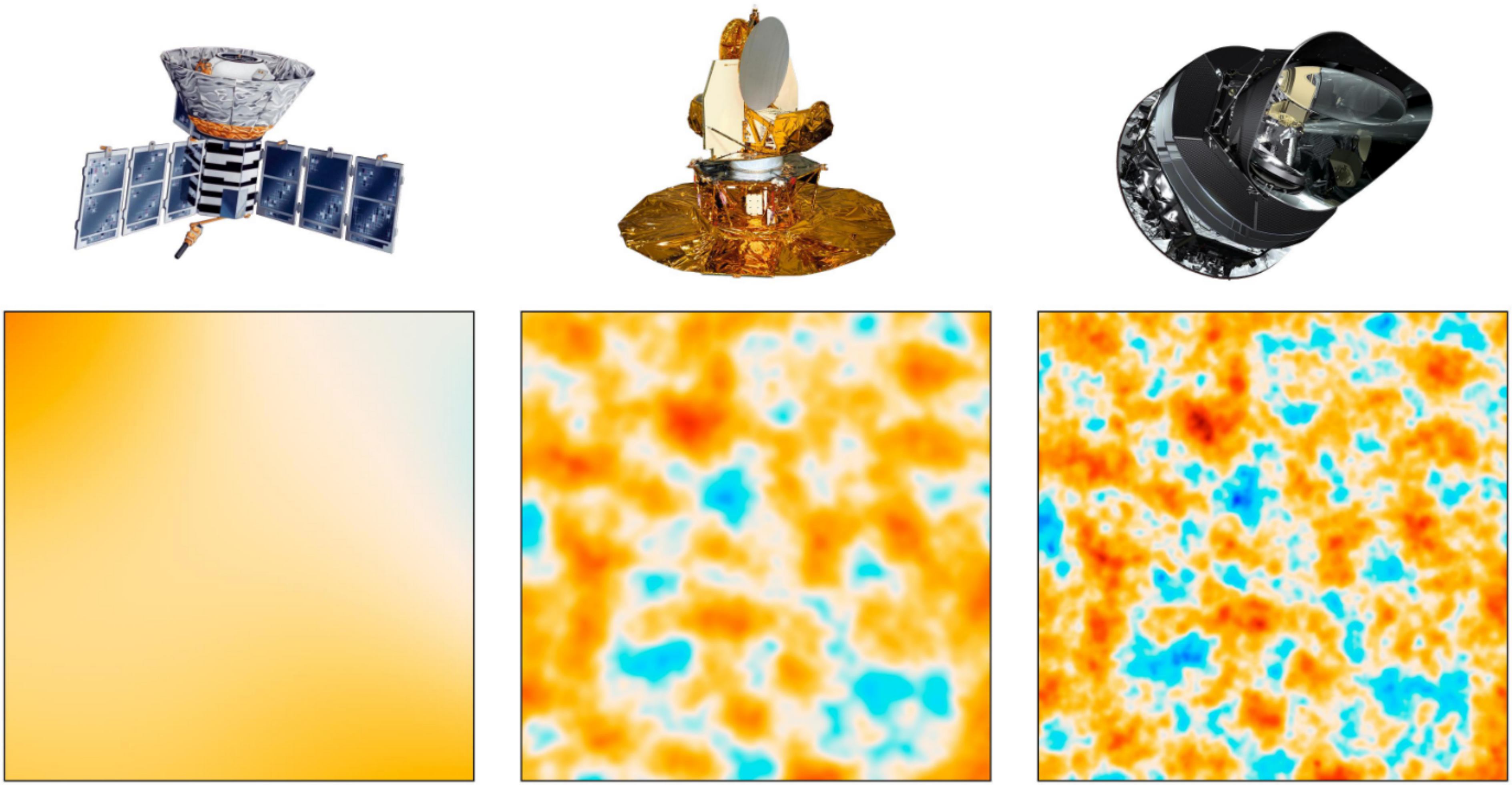
Lots of information is encoded in the position and height of each peak

CMB Acoustic Oscillations

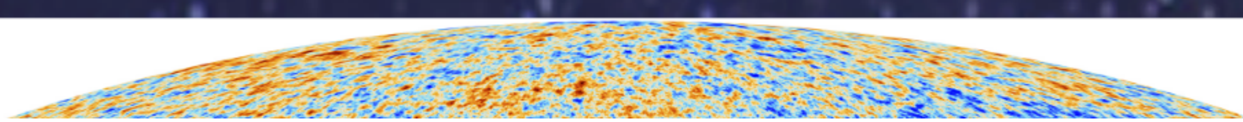




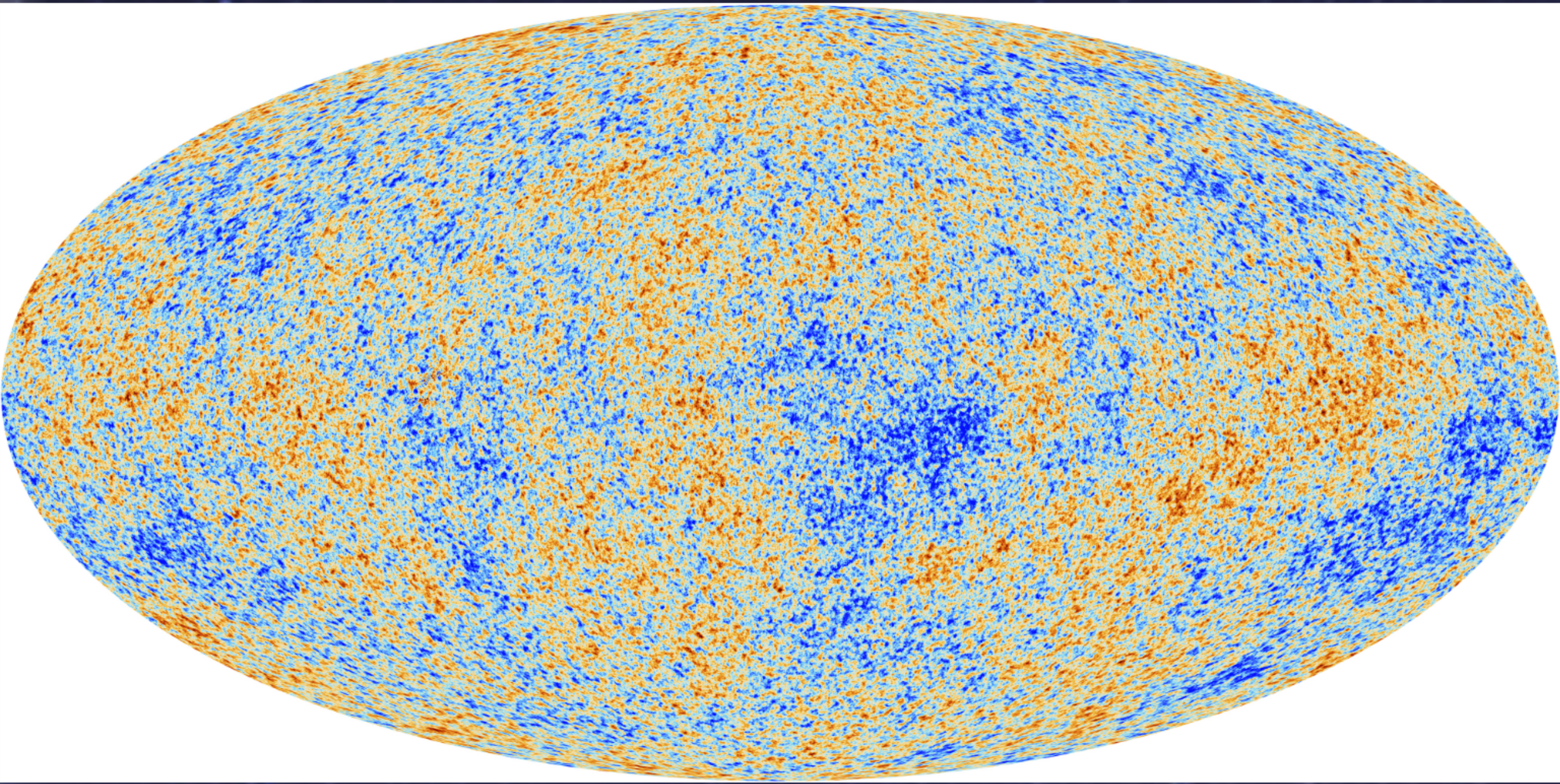
Angular scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ [μK^2]
WMAP
Acbar
Boomerang
CBI
VSA
10
100
500
1000
1500
Multipole moment l



COBE WMAP Planck



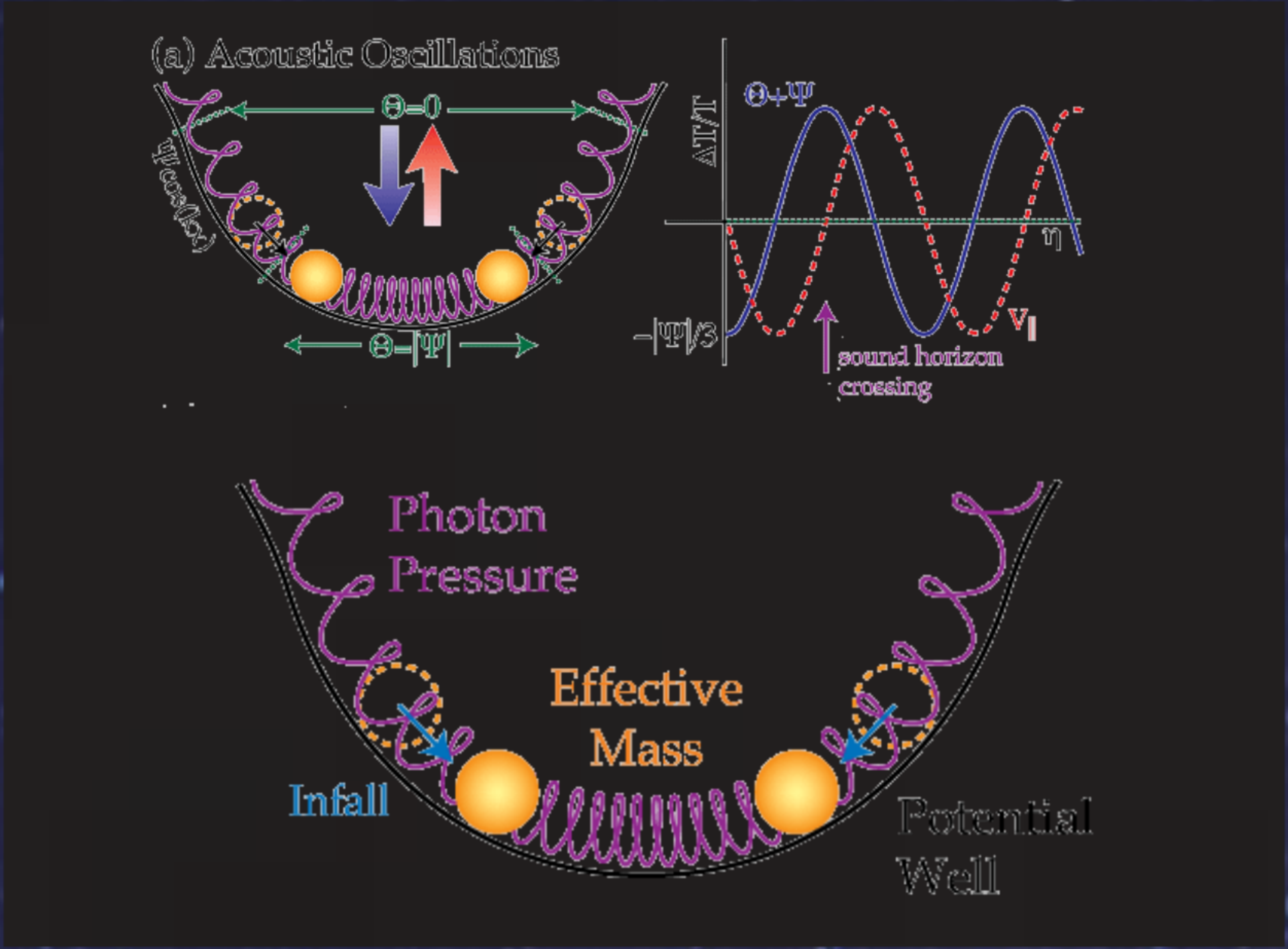
COBE WMAP Planck



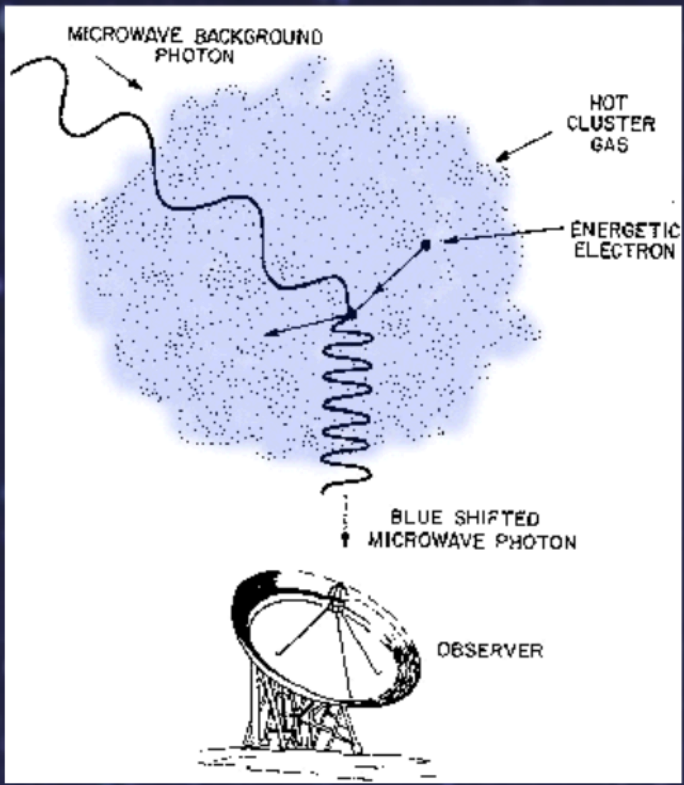
CMB Acoustic Oscillations

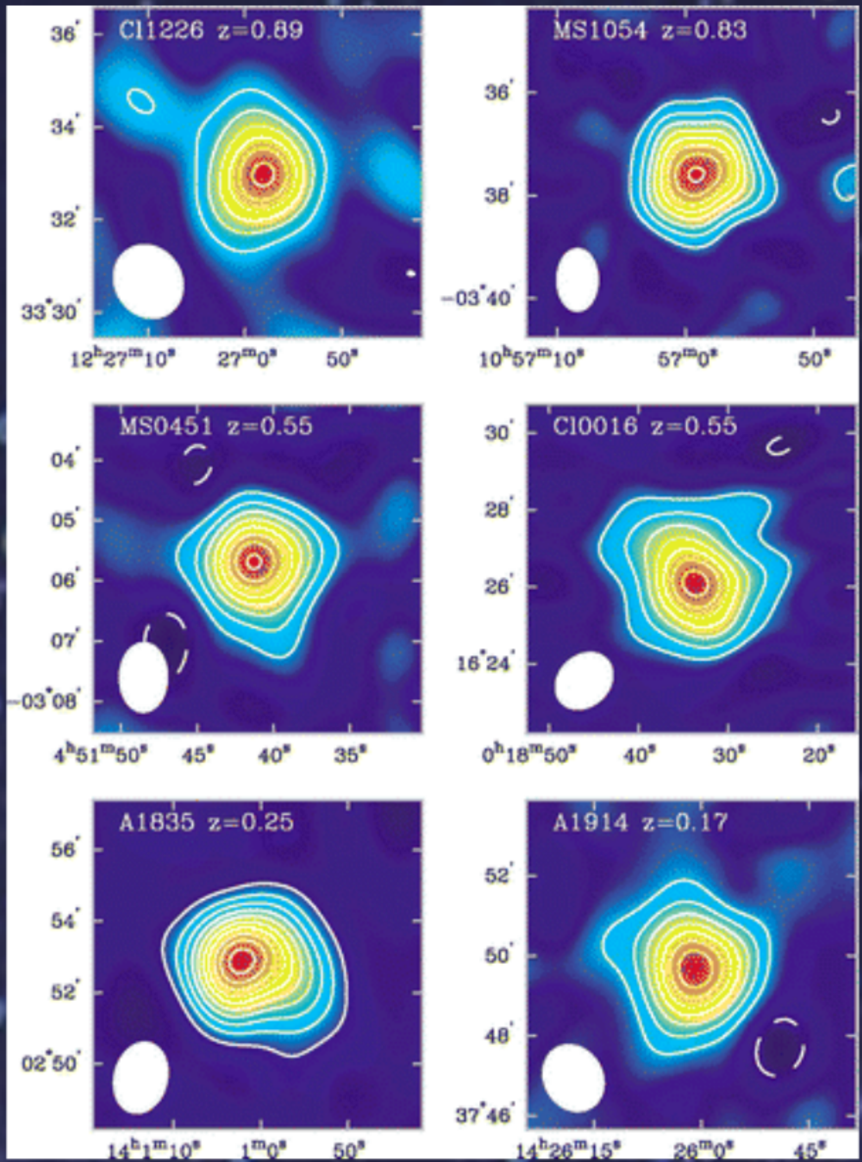
(a) Acoustic Oscillations

CMB Acoustic Oscillations



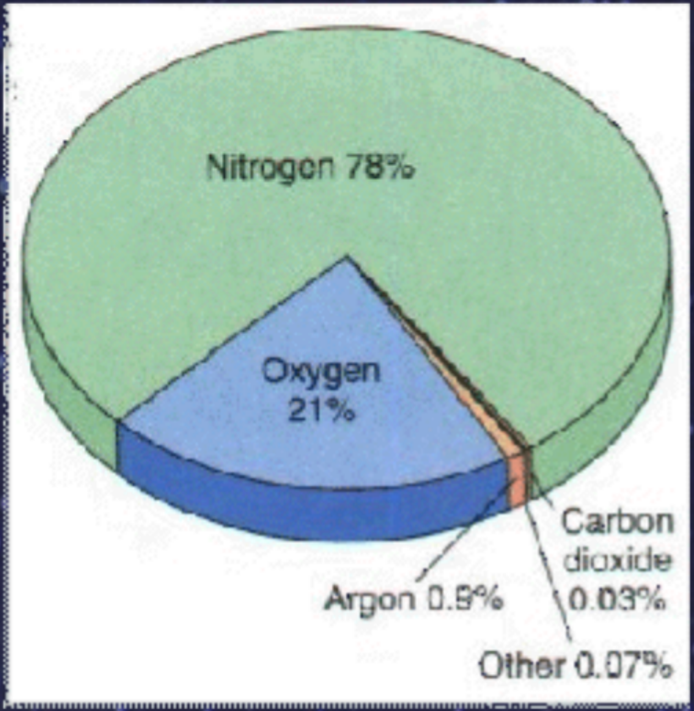
Sunyaev-Zel'dovich Effect

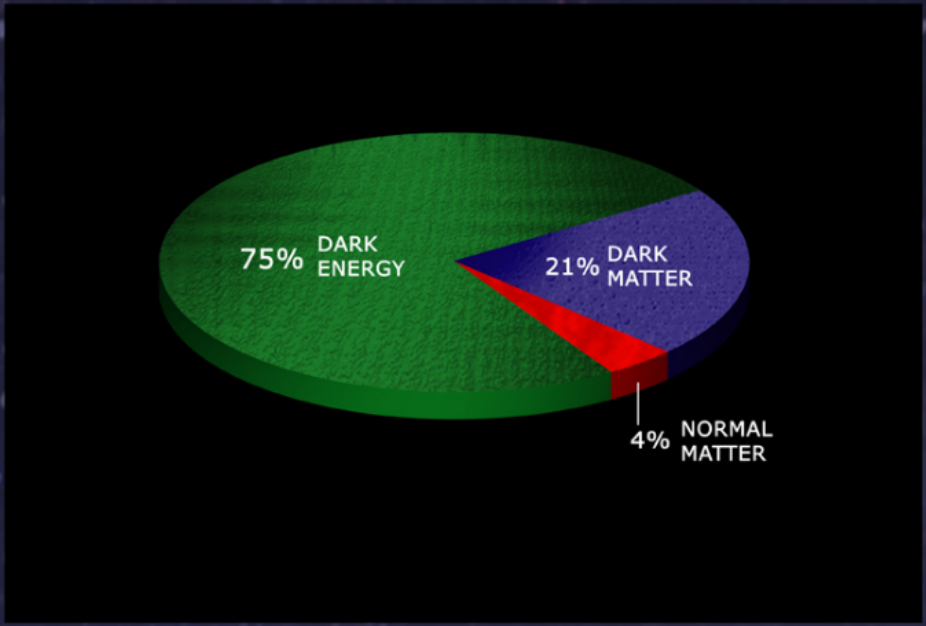




One way you can use the CMB is as a backlight, to see large clusters of galaxies

The Dark Side of the Universe





Seeing the Dark Side of the Universe with Light

Dark Matter and Dark Energy don't interact with light - so how will we use light to detect them?

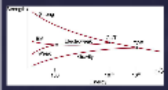
Discovery of Neutrinos

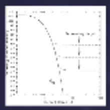
Neutrinos don't interact with light, but they do interact with other particles via the weak interaction

The positron then interacts with an electron to produce gamma-rays, which we can see

Today, we build large detectors to search for these very rare interactions, and to learn about neutrinos

Early Universe Hints





Seeing the Dark Side of the Universe with Light

Dark Matter and Dark Energy don't interact with light - so how will we use light to detect them?

Discovery of Neutrinos

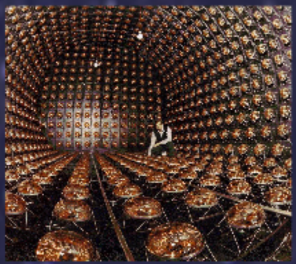
Neutrinos don't interact with light, but they do interact with other particles via the weak interaction

Cowan-Reines Experiment 1956 (Nobel Prize 1995)

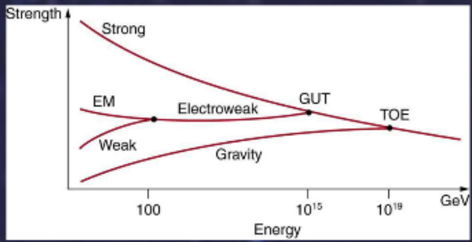
$$\bar{\nu}_e + p^+ \rightarrow n^0 + e^+$$

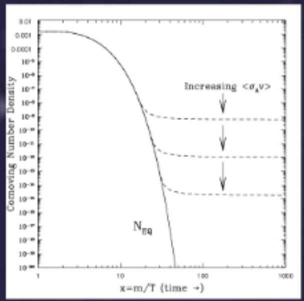
The positron then interacts with an electron to produce gamma-rays, which we can see

Today, we build large detectors to search for these very rare interactions, and to learn about neutrinos



Early Universe Hints





Discovery of Neutrinos

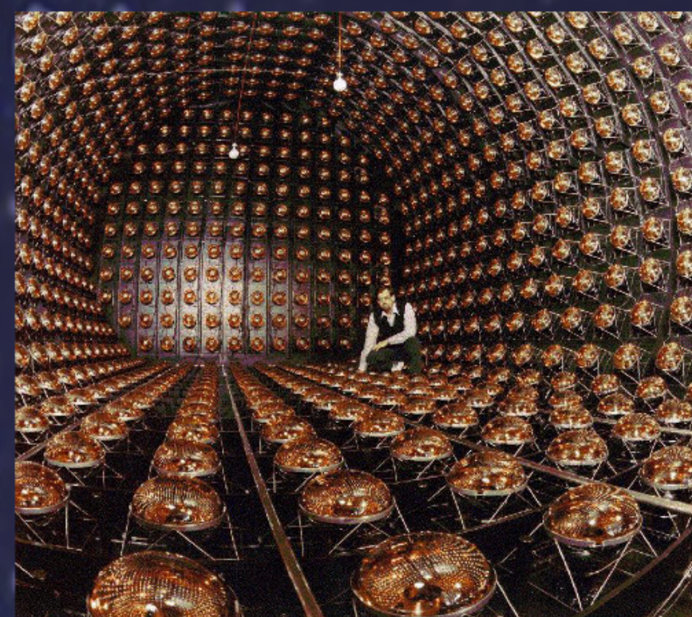
Neutrinos don't interact with light, but they do interact with other particles via the weak interaction

Cowan-Reines Experiment
1956 (Nobel Prize 1995)

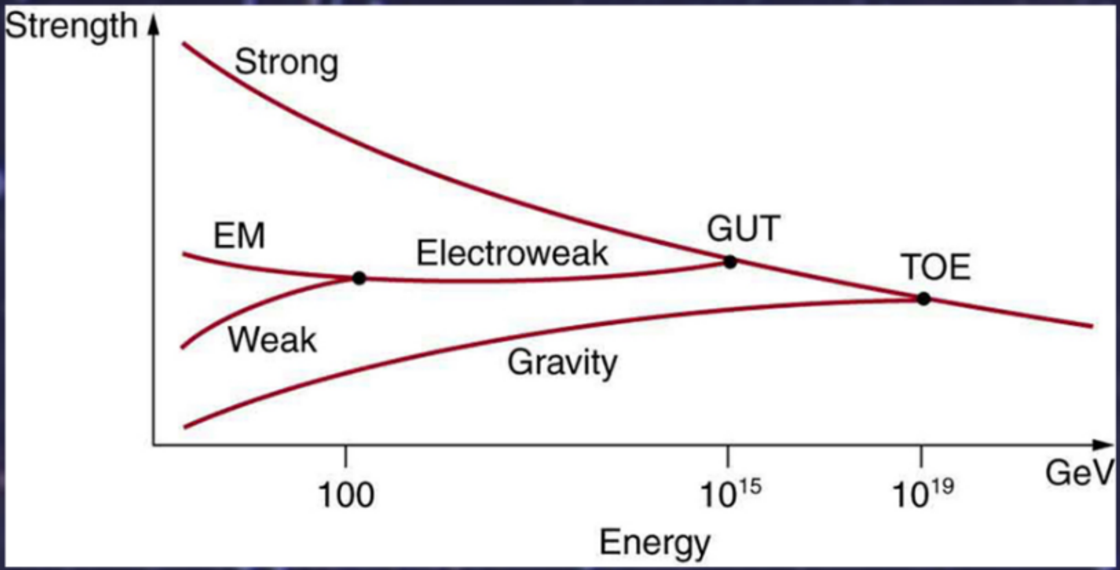
$$\bar{\nu}_e + p^+ \rightarrow n^0 + e^+$$

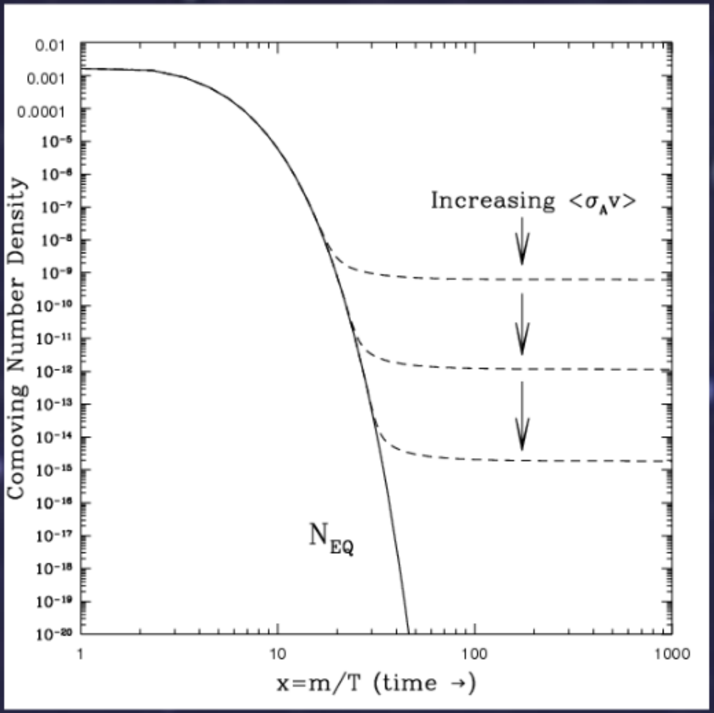
The positron then interacts with an electron to produce gamma-rays, which we can see

Today, we build large detectors to search for these very rare interactions, and to learn about neutrinos



Early Universe Hints






How Do We Observe our Universe?
For most of human history, our only way of understanding the universe was by looking at the light which reached Earth
How do we use light to understand our universe?
Things that emit light
Things that absorb light
What Else Can Light Tell Us?
Remember, light travels at a constant speed (186,000 miles per second)
So when we are looking at a source that is far away, we are also looking back in time
Sun
8 minutes
Alpha Centauri
4.4 years
Andromeda
2.5 million years
Looking At the Early Universe
Redshift
The First Photons
The Dark Side of the Universe
Nitrogen 78%
Oxygen 21%
Argon 0.9%
Carbon dioxide 0.03%
Other 0.07%
The "Light" Side of the Universe

Upcoming Lectures

October 11 - What is Dark Energy?
October 18 - How Could We Detect Dark Energy?
October 25 - Dark Matter as Missing Mass
November 1 - Dark Matter Particle Physics Models
November 8 - Direct Detection of Dark Matter
November 15 - Dark Matter at the LHC
November 22 - Indirect Detection of Dark Matter I
December 13 - Indirect Detection of Dark Matter II

Elise Jennings

Keith Bechtol

Shining Light on the Dark Side of the Universe

Tim Linden

Arthur Compton Lecture Series - Fall 2014

Thanks for Attending!