

# 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



The "Light" Side of the Universe

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### 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: 25 million years

### Looking At the Early Universe

What does the early universe look like? The early universe was a hot, dense, and opaque plasma. As it expanded and cooled, it became transparent, allowing light to travel freely. This light is what we see today as the Cosmic Microwave Background (CMB).

What does this tell us? The CMB provides a snapshot of the universe at the time of recombination, about 380,000 years after the Big Bang. It shows a nearly uniform temperature with small fluctuations that correspond to the formation of the first structures in the universe.

### The First Photons

The earliest photons were released during the recombination era, about 380,000 years after the Big Bang. These photons have been traveling through the universe ever since, and their study provides valuable information about the early universe.

The CMB is the most direct evidence of the first photons. It is a nearly uniform background of microwave radiation that fills the entire universe. The small fluctuations in its temperature are a result of the density variations in the early universe, which eventually led to the formation of galaxies and other structures.

### The Dark Side of the Universe

Dark Energy: 68%  
Dark Matter: 27%  
Ordinary Matter: 5%

Understanding the dark side of the universe is one of the greatest challenges in cosmology. While we know that dark energy and dark matter exist, we do not yet know what they are or how they interact with each other and with ordinary matter.

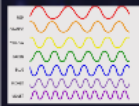
# The "Light" Side of the Universe



# 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

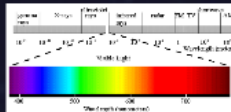
For the "visible light" that our eyes can detect, different wavelengths are interpreted in our brain as different colors

## What is Light?



Not all light is visible!

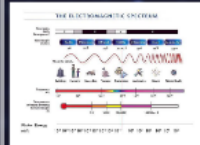
Light can also have wavelengths that cannot be seen by the human eye



## What is Light?

Measuring the energy of light:

$$\lambda \nu = c$$



$$E = h\nu$$

## What is Light?

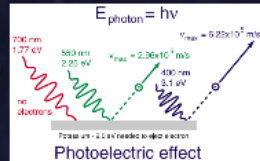
"Light" is composed of particles called photons.

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:



Photoelectric effect

## 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



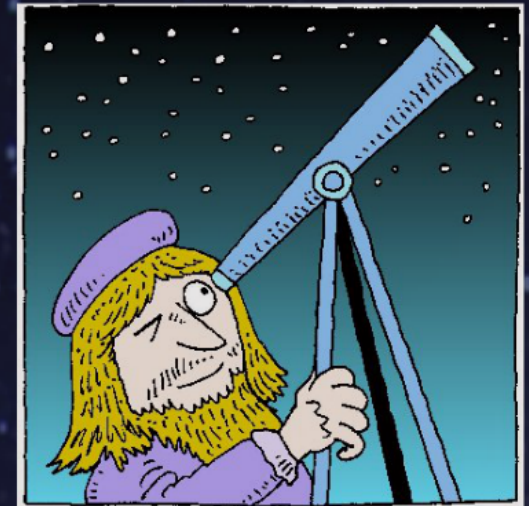
## Particles That Interact With Light

u	c	y
d	s	b
e	f	v

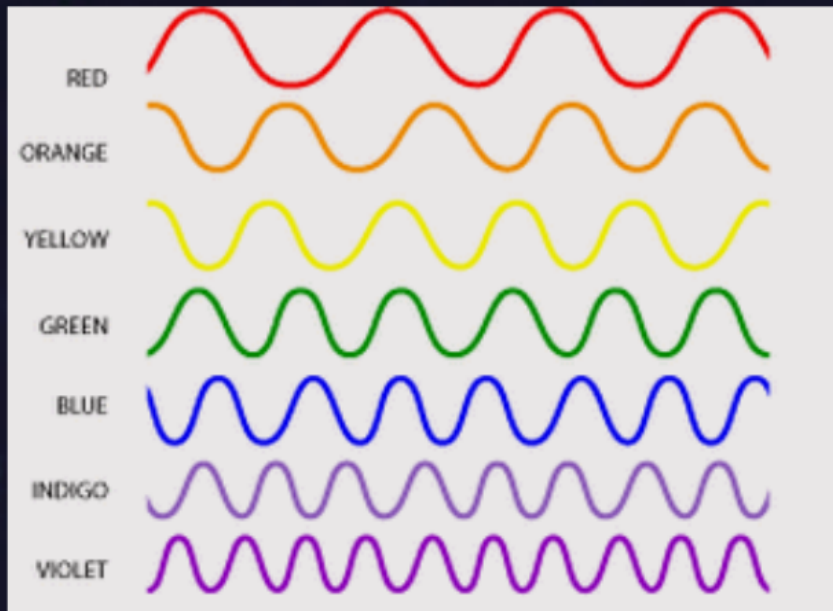
Particle	Relative charge	Relative mass	Symbol
electron	-1	1	e
proton	+1	1	p
neutron	0	1	n

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



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Light is a wave that carries energy

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

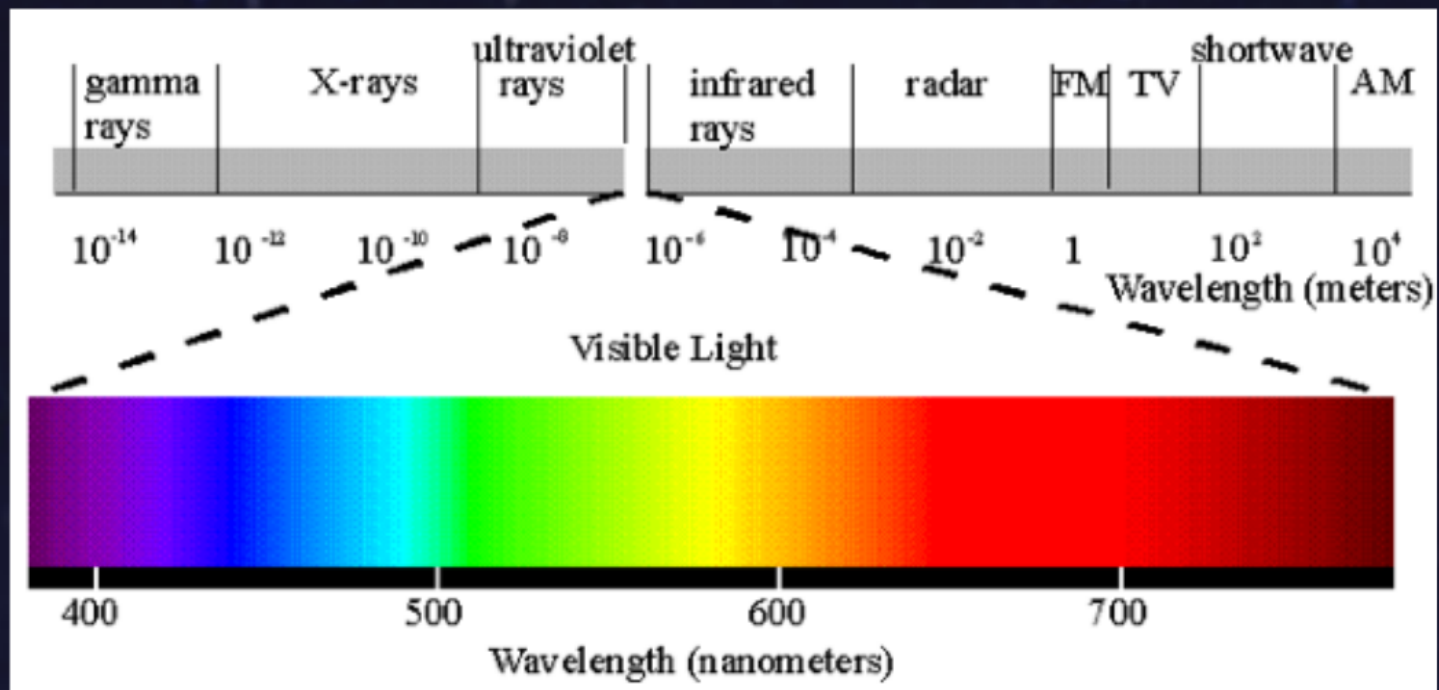
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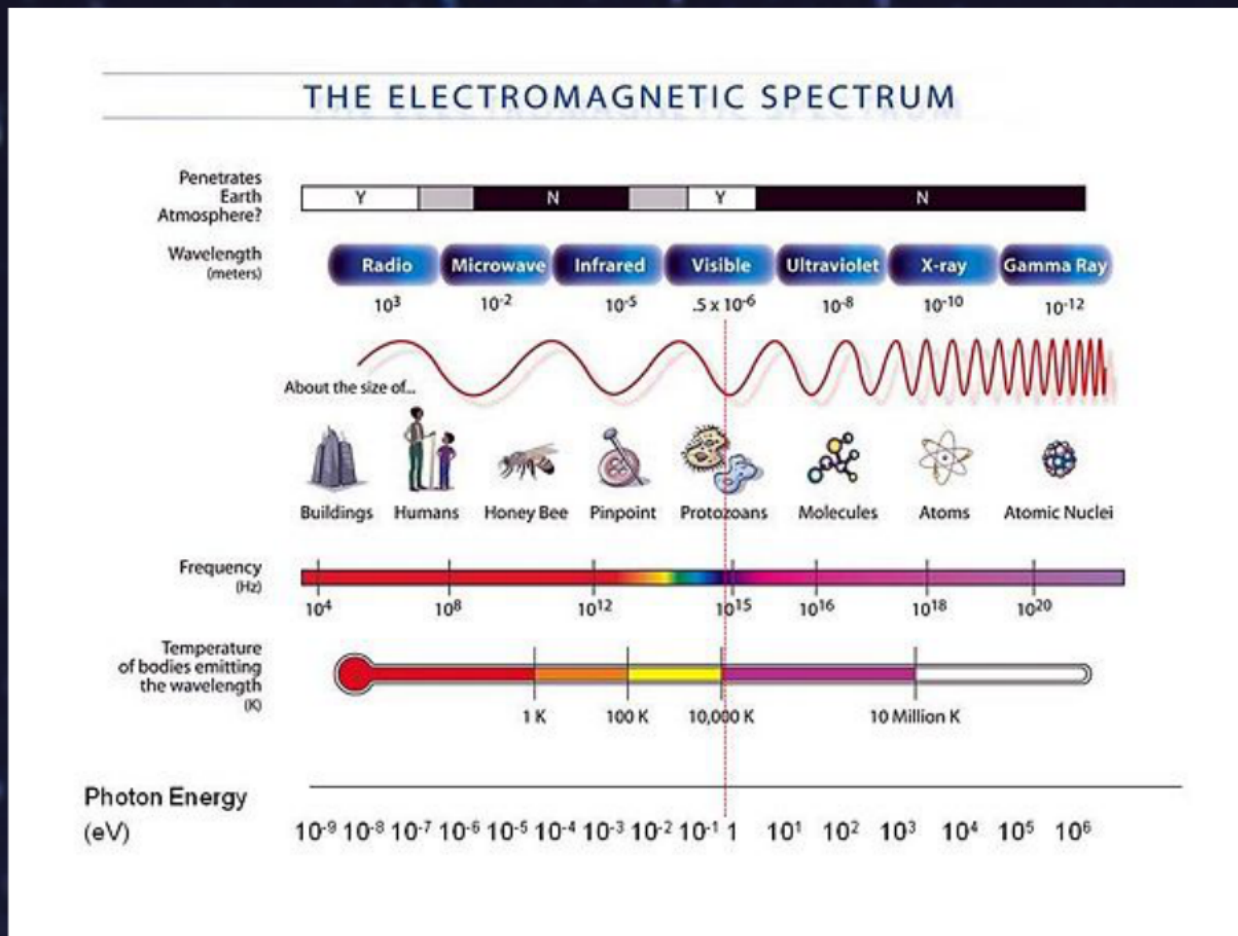


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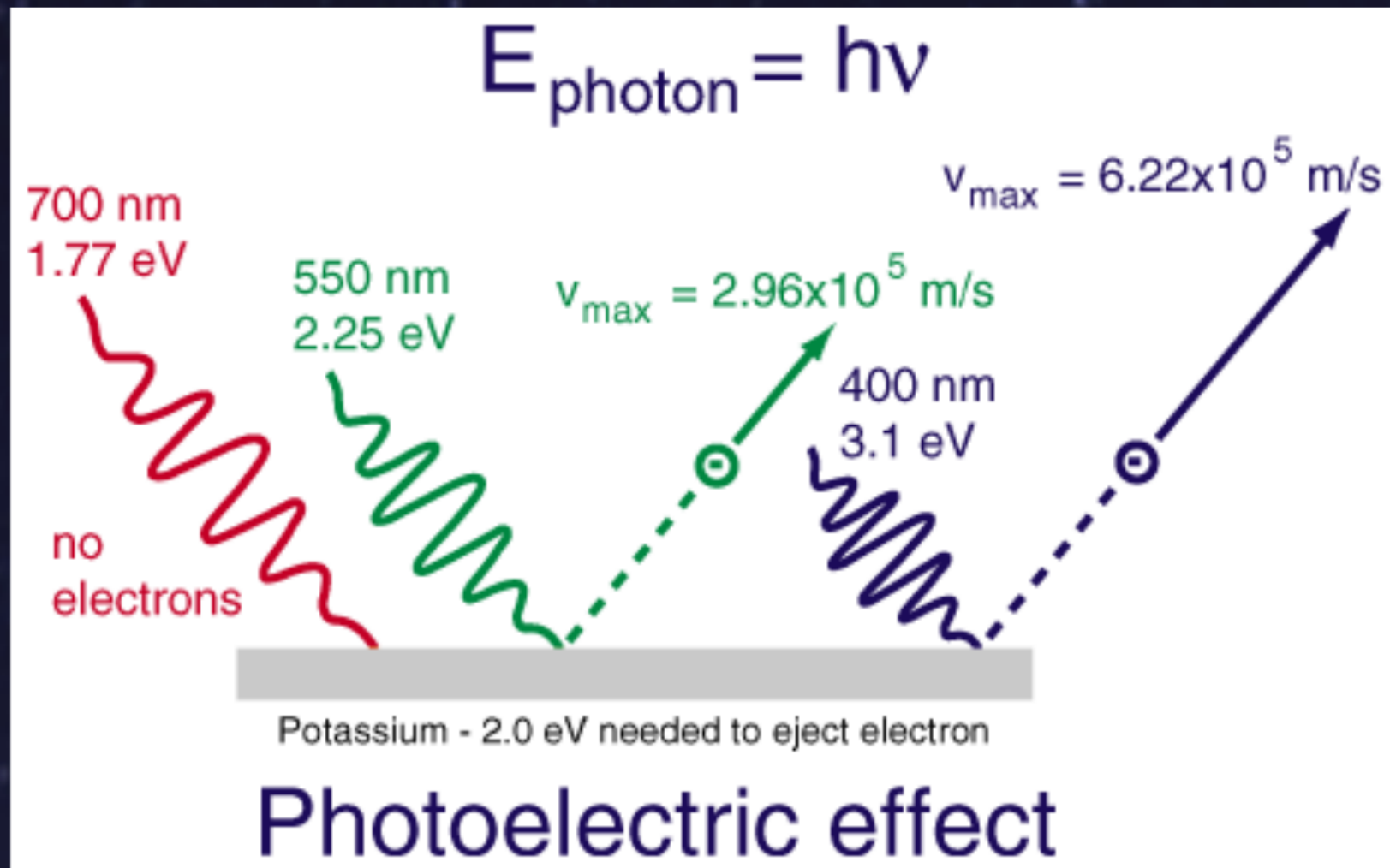
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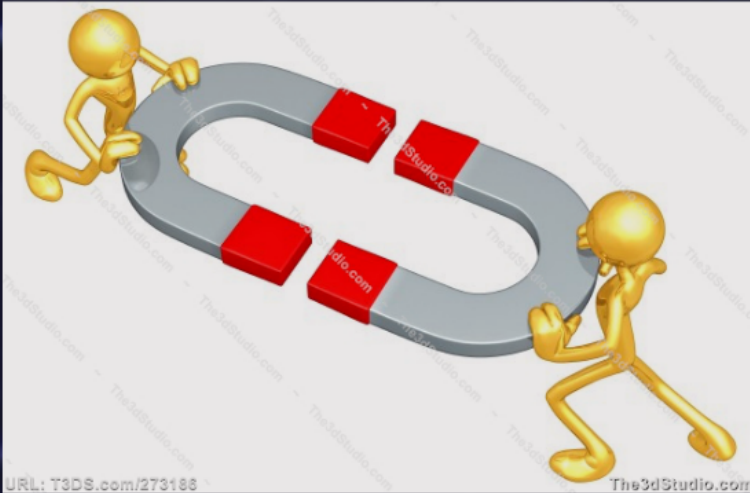
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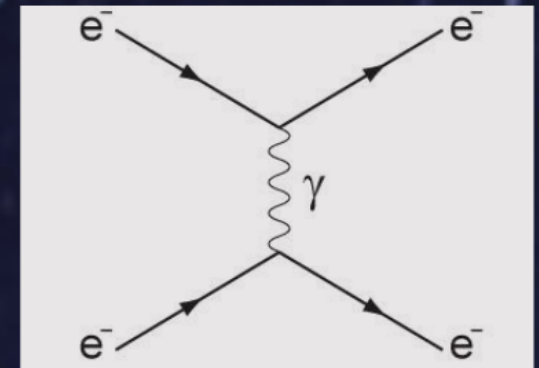
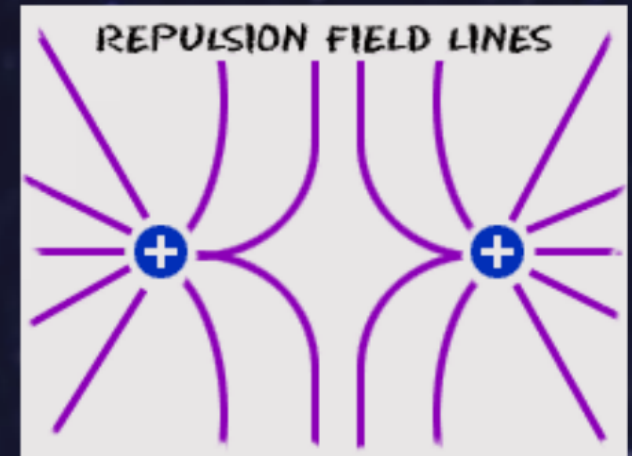
# Fundamentally, What is Light?



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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

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	u up	c charm	t top	$\gamma$ photon
Quarks	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	d down	s strange	b bottom	g gluon
Leptons	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino	Z <sup>0</sup> weak force
Bosons (Forces)	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	$\pm 1$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	e <sup>-</sup> electron	$\mu$ muon	$\tau$ tau	W <sup>±</sup> weak force

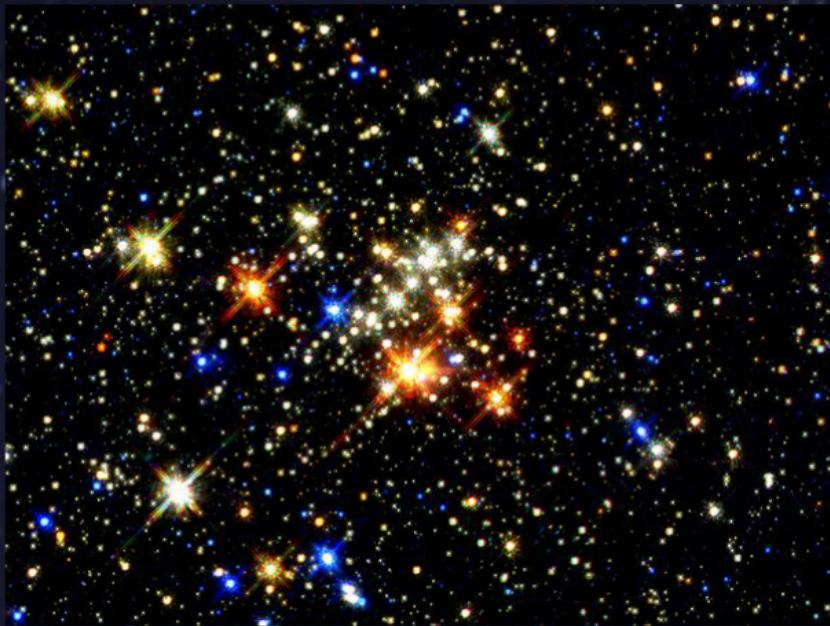
Particle	Relative charge	Relative mass	Symbol
proton	+1	1	p
neutron	0	1	n
electron	-1	1/1836 (5.45 x 10 <sup>-4</sup> )	e <sup>-</sup>

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?

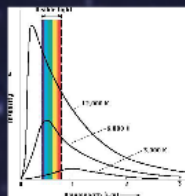


Things that emit light



Things that absorb light

## What Can You Learn By Looking at a Source?

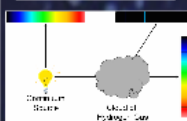
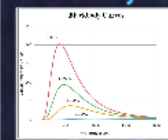


## Non-Thermal Light

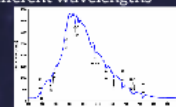
There are other ways to emit light, in addition to blackbody emission.



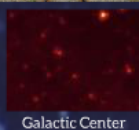
## How do you Detect Absorption?



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



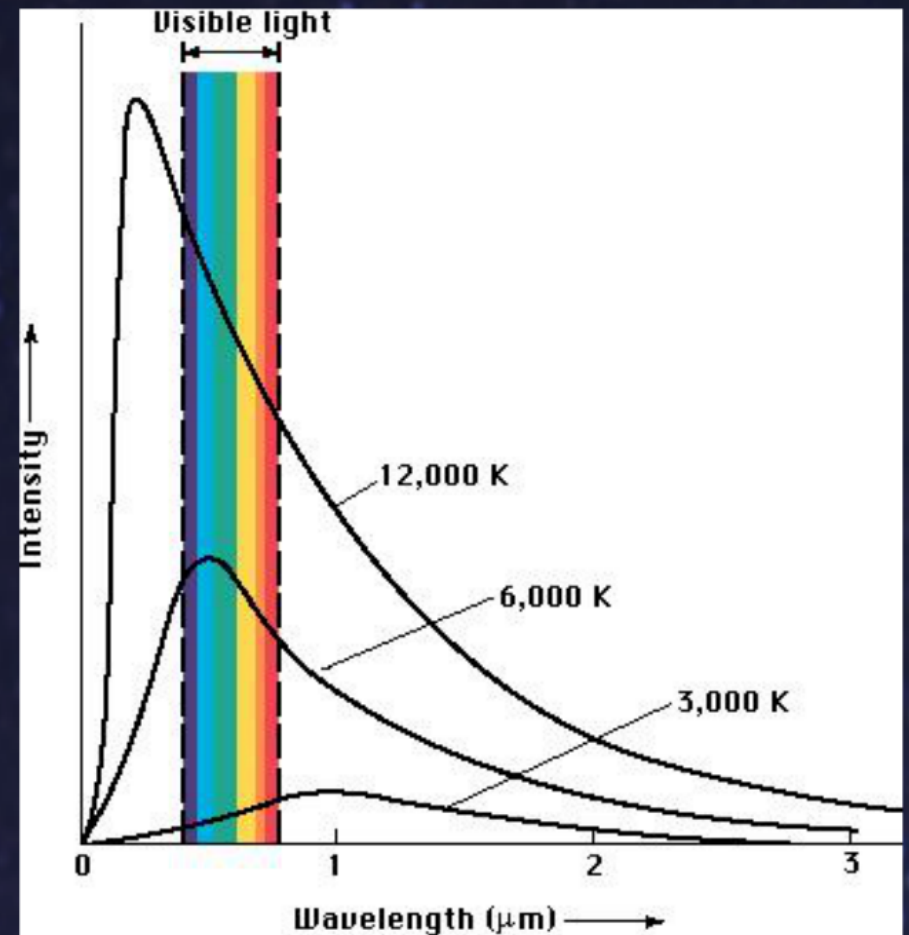
## Absorption At Different Energies



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

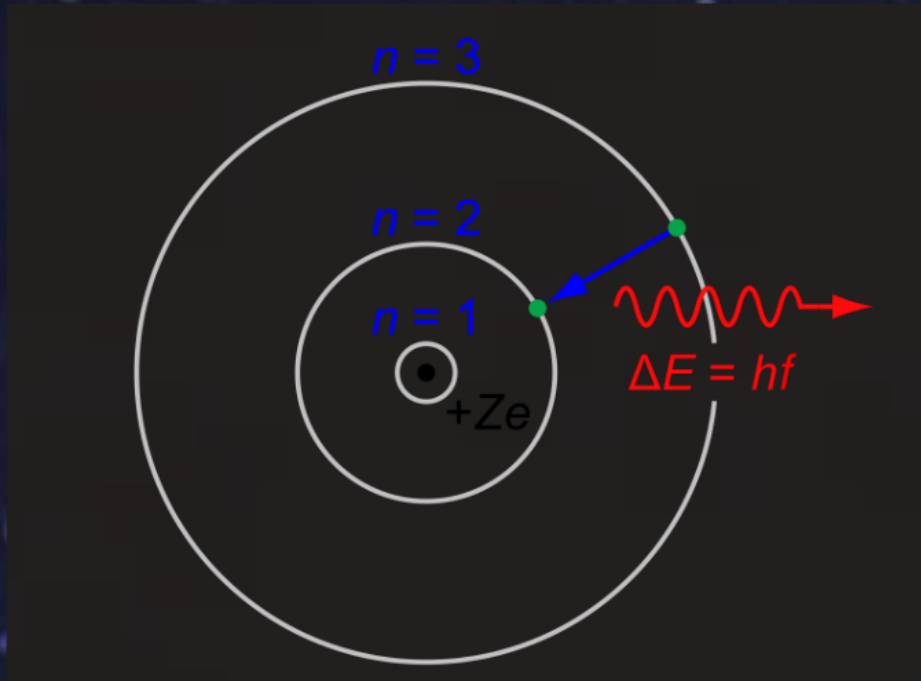


# What Can You Learn By Looking at a Source?

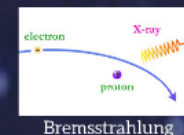
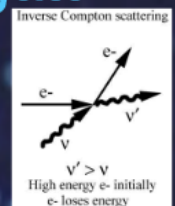


# Non-Thermal Light

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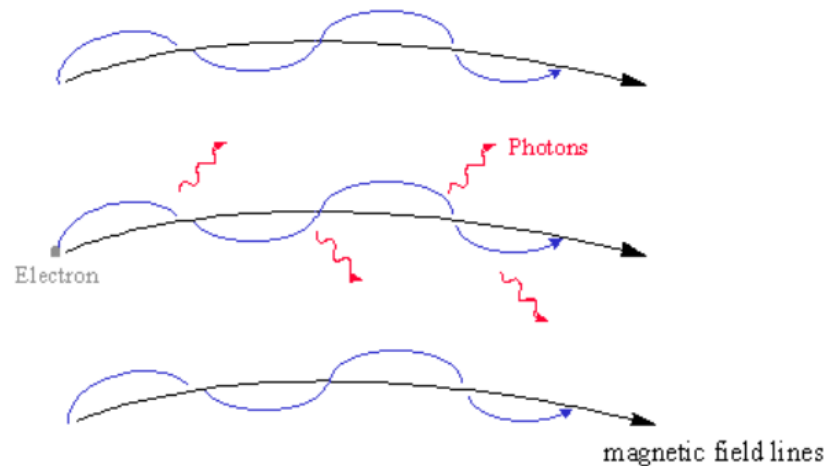


## In Astrophysics

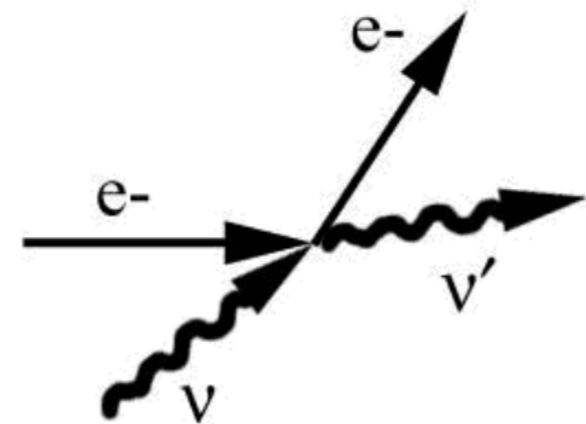


# In Astrophysics

Synchrotron Radiation

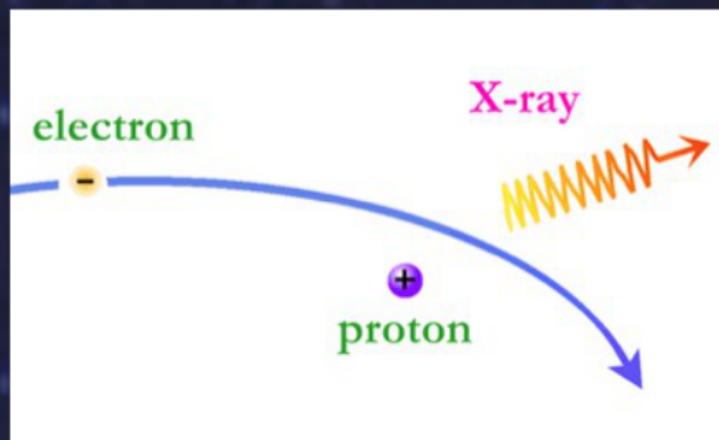


Inverse Compton scattering



$$\nu' > \nu$$

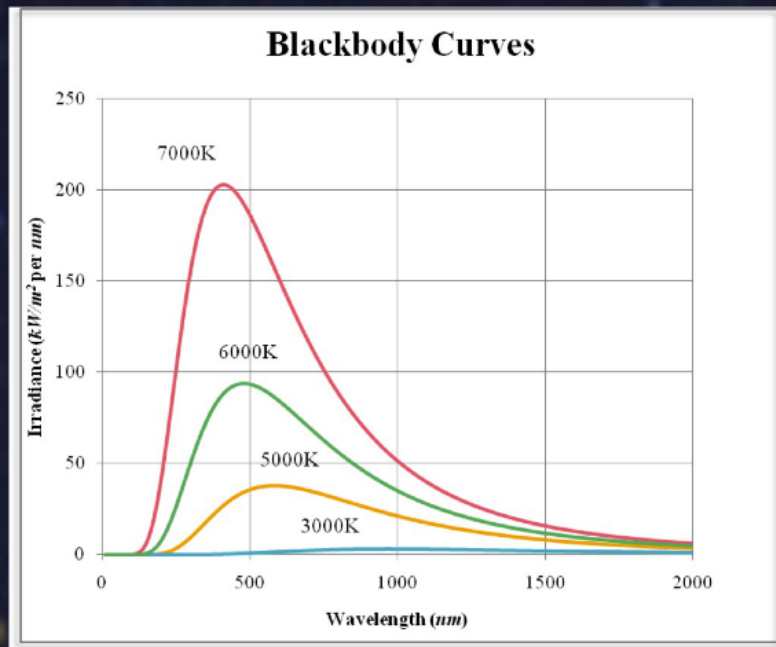
High energy  $e^-$  initially  
 $e^-$  loses energy



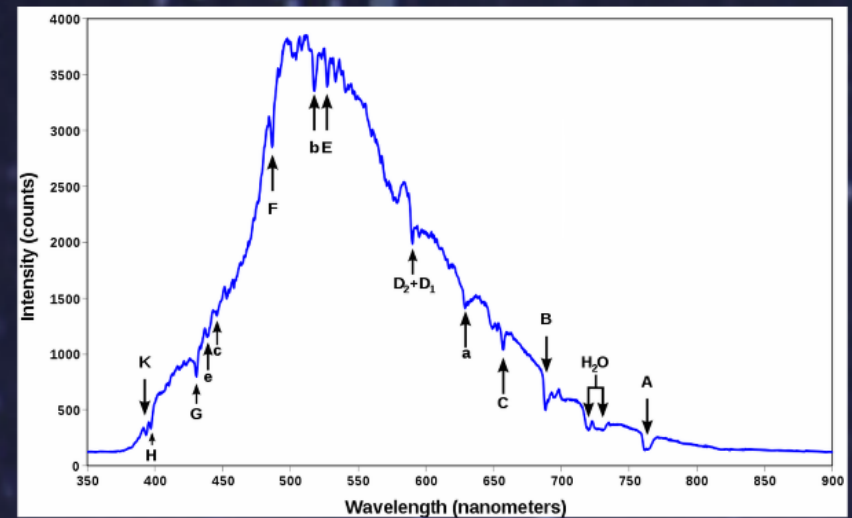
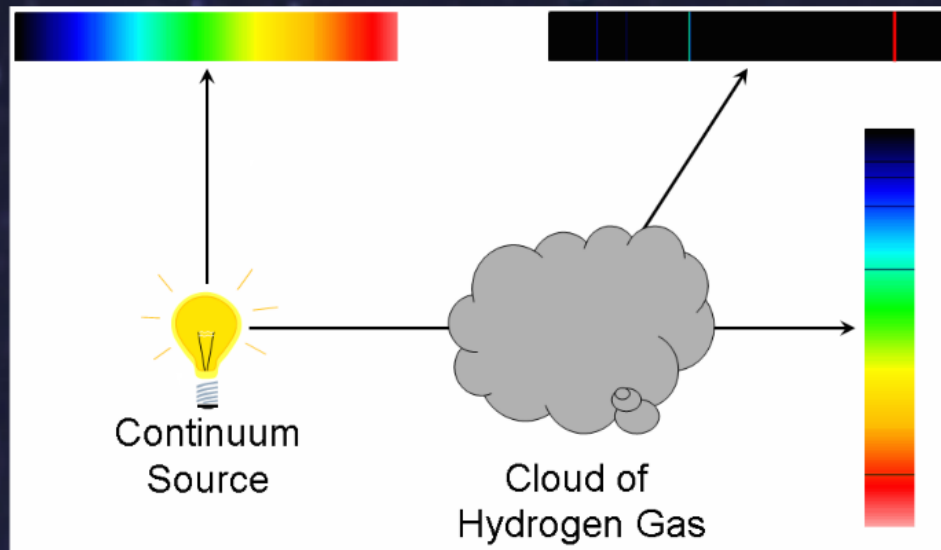
Bremsstrahlung



# How do you Detect Absorption?



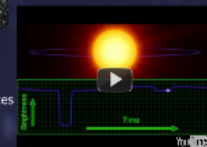
Look for a source with a known spectrum, see how much light is missing at different wavelengths



## Finding Planets



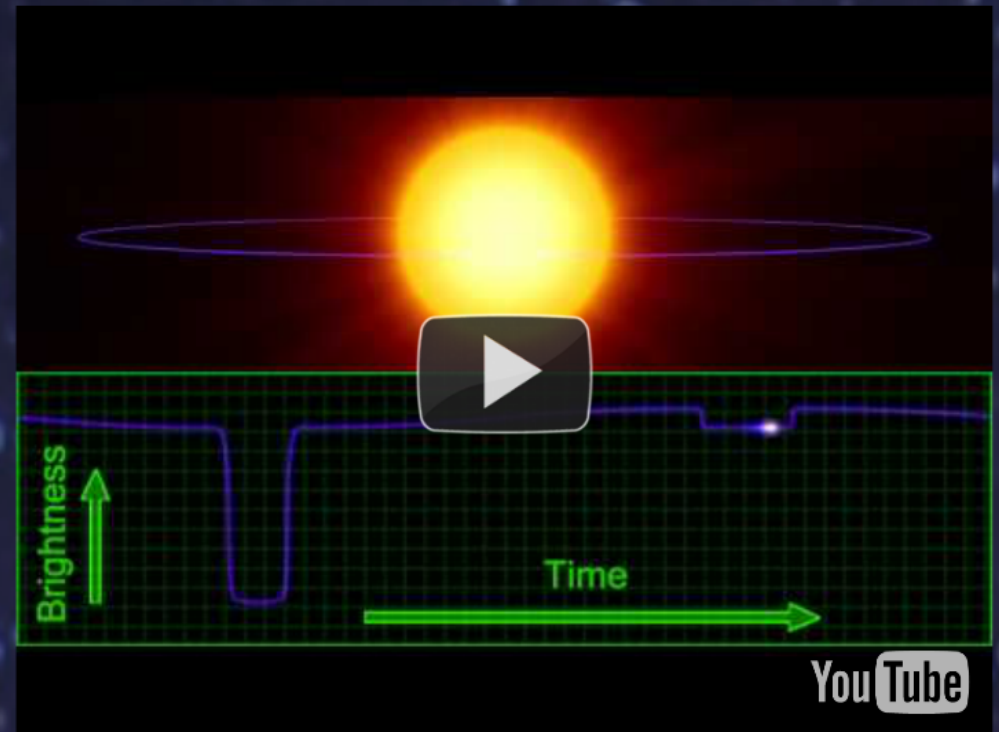
Kepler Satellite  
March 7, 2009 - Present  
977 confirmed planets  
3,277 unconfirmed candidates



# Finding Planets

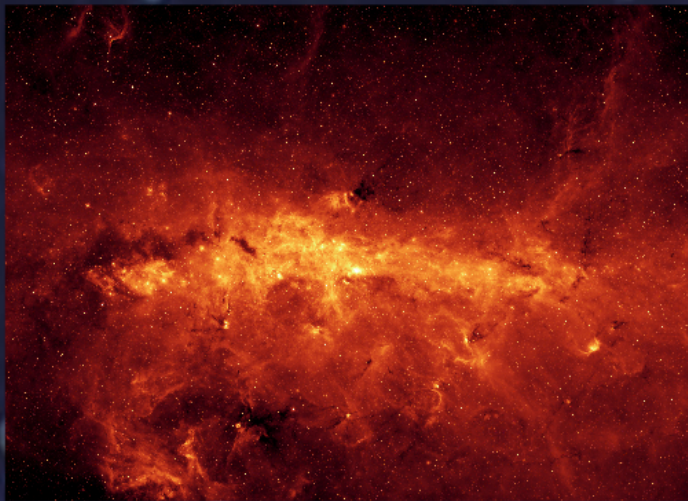
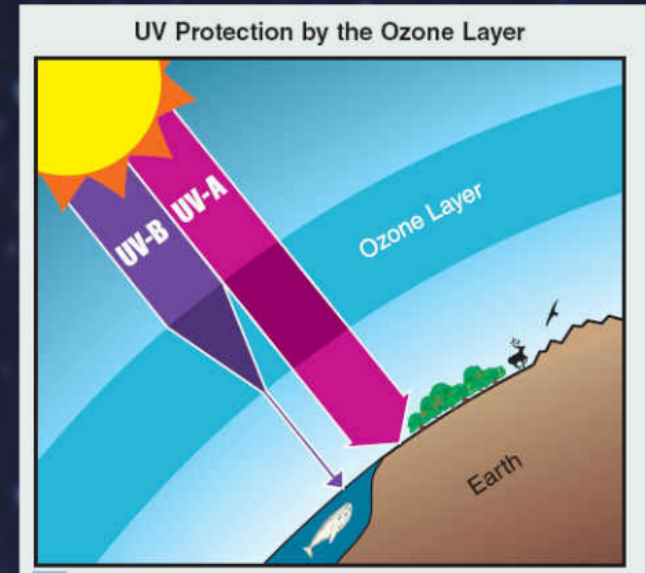


Kepler Satellite  
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# Absorption At Different Energies



Galactic Center

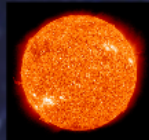
To get a full picture of the universe, we need telescopes that can look at lots of different wavelengths



# 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







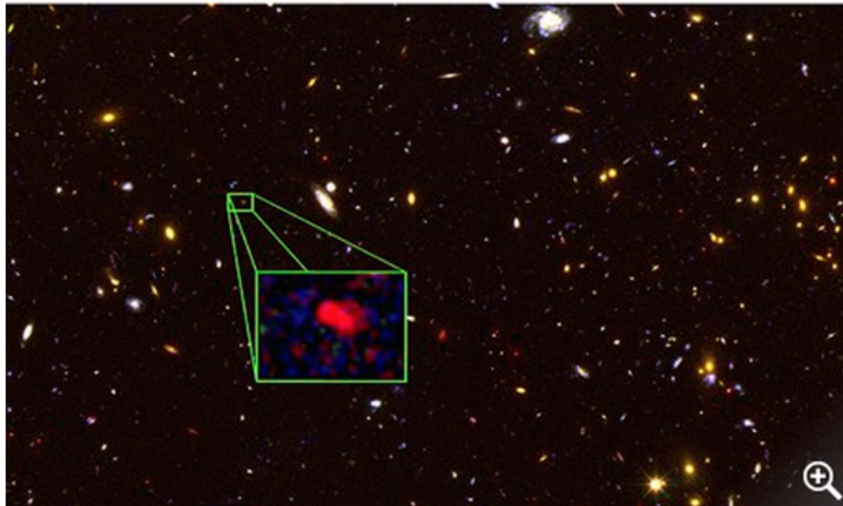
# Looking At the Early Universe

## 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

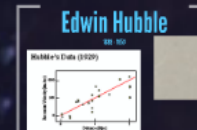
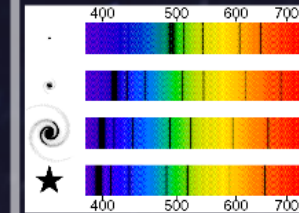
Ian Sample, science correspondent  
Follow @iansample Follow @guardian  
The Guardian, Wednesday 23 October 2013

[Jump to comments \(490\)](#)



The galaxy z8\_GND\_5296 is 40m years older than the previous record holder.  
Photograph: HST/Nasa

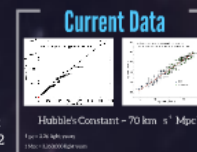
## Redshift



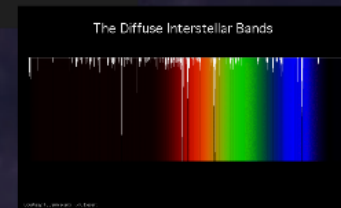
Simple Notation:

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

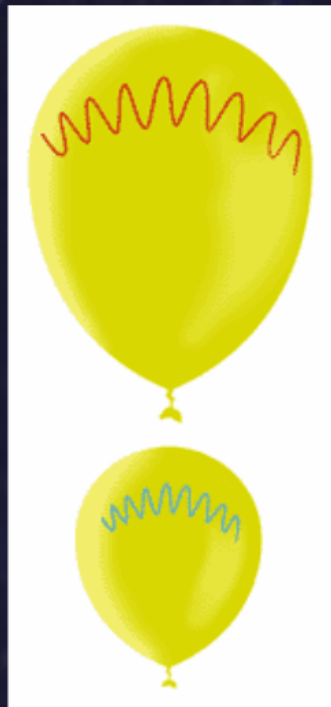
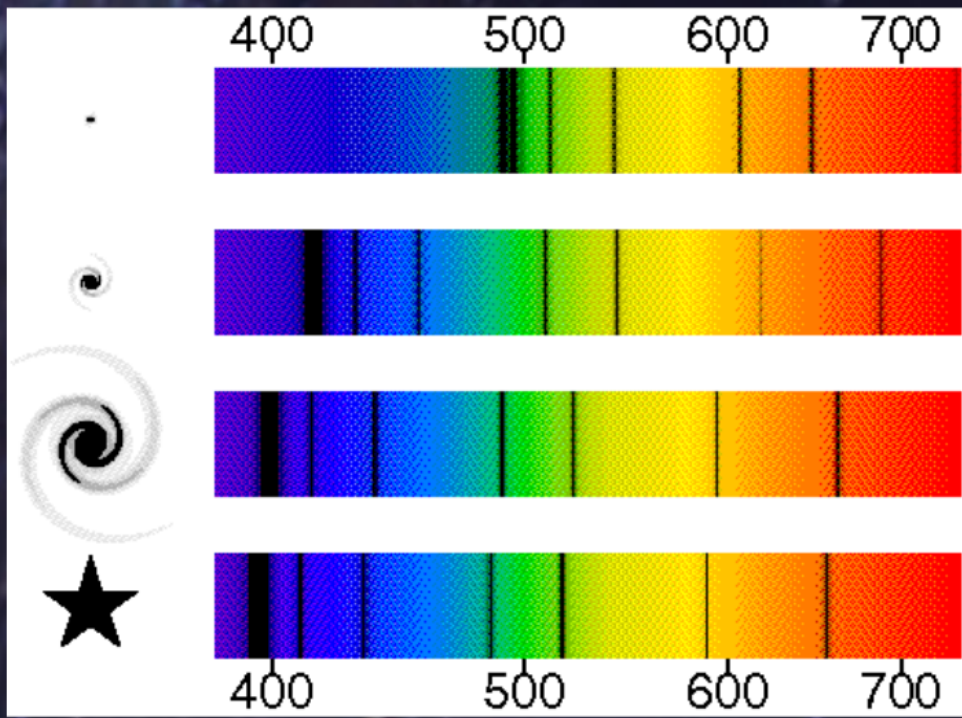
Can describe a galaxy as being at  $z = 4$ , just like we could say it is 12 billion light years away



## What Else Could This Tell Us?



# Redshift



## Simple Notation:

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

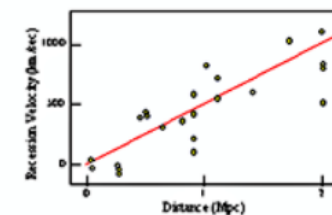
Can describe a galaxy as being at  $z = 4$ , just like we could say it is 12 billion light years away

## Edwin Hubble

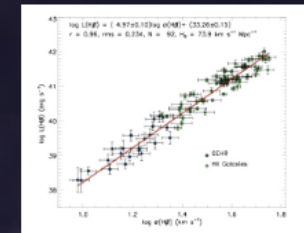
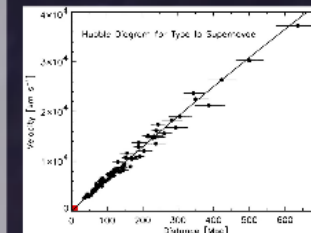
1889 - 1953



Hubble's Data (1929)



## Current Data



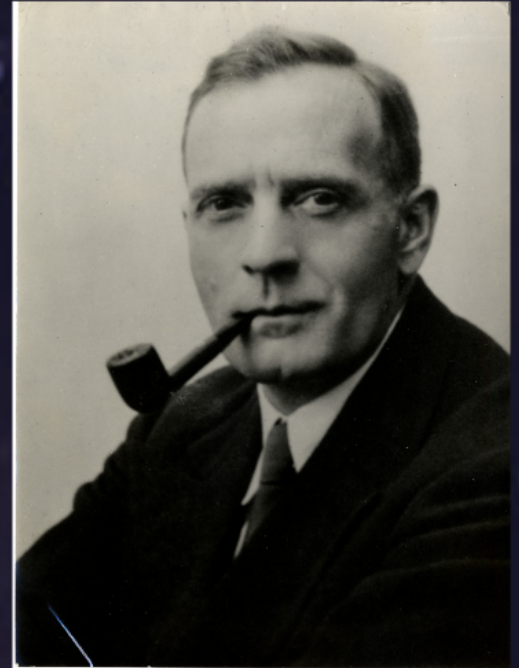
Hubble's Constant  $\sim 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$

1 pc = 3.26 light years

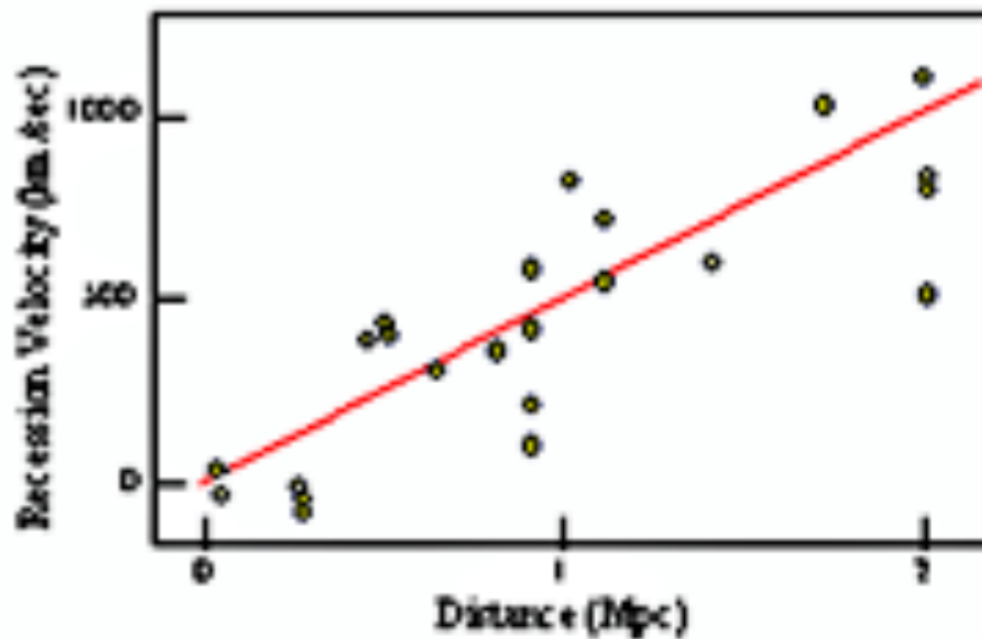
1 Mpc = 3,260,000 light years

# Edwin Hubble

1889 - 1953

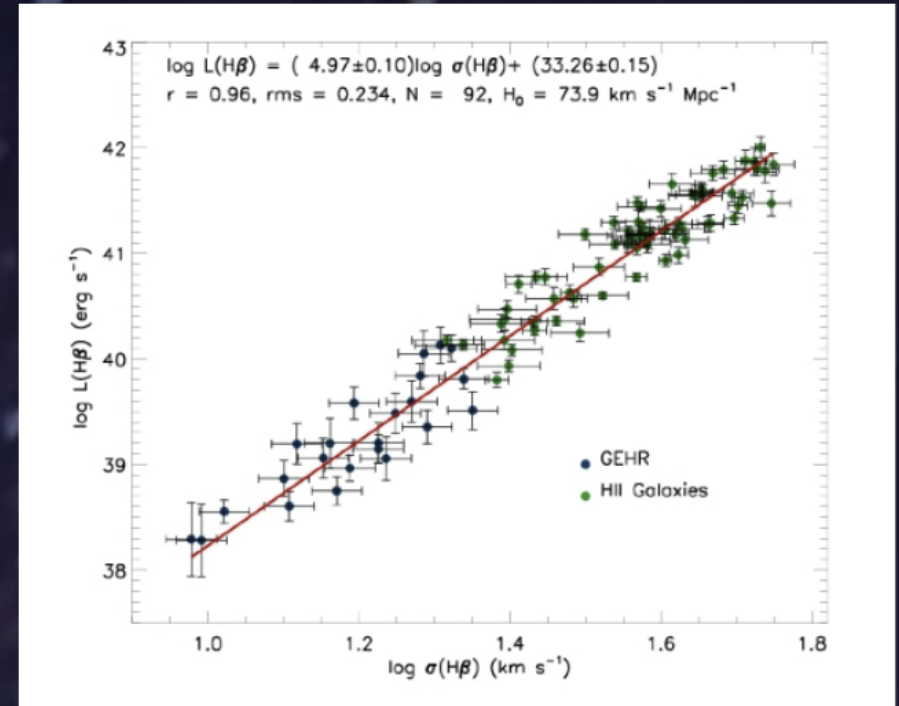
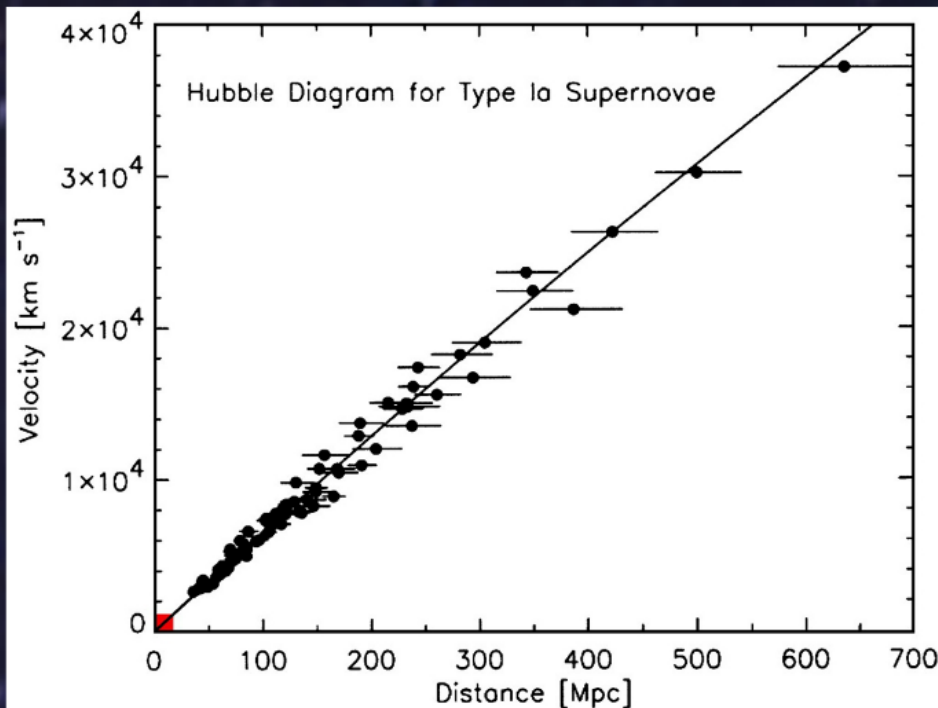


Hubble's Data (1929)





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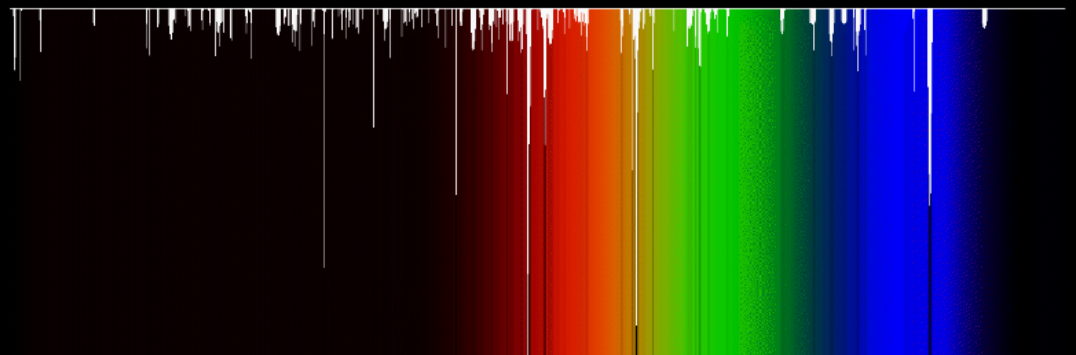
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1 Mpc = 3,260,000 light years

# What Else Could This Tell Us?



## The Diffuse Interstellar Bands



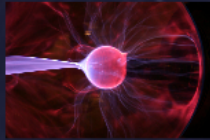
Courtesy: P. Jenniskens, F.-X. Desert



# The First Photons

## The Ionized Universe

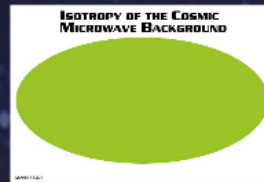
The early universe was very hot, too hot for electrons and protons to combine to form atoms



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!  
 $T_{\text{CMB}} = 2.7\text{K}$   
 The absence of scattering centers in the intergalactic medium after CMB has been emitted for recombination is very unlikely  
 $Z_{\text{CMB}} = 1000$

## The Detection of the CMB

(1964, Bell Labs, Princeton)

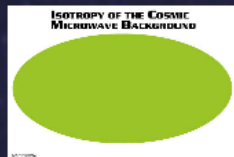


Arno Penzias and Robert Wilson

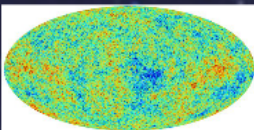


Robert Dicke

## Anisotropies in the CMB

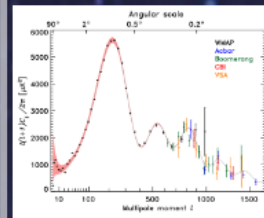


Cosmic Microwave Background is very isotropic, but not 100%

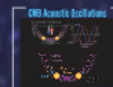
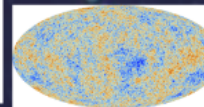


Anisotropies correspond to changes in the transition time between the plasma and molecular gas phases

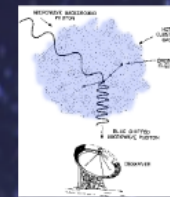
## Anisotropies in the CMB



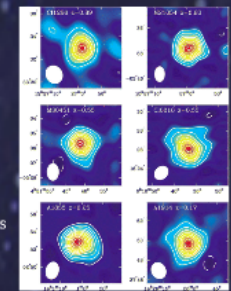
Lots of information is encoded in the position and height of each peak



## Sunyaev-Zel'dovich Effect



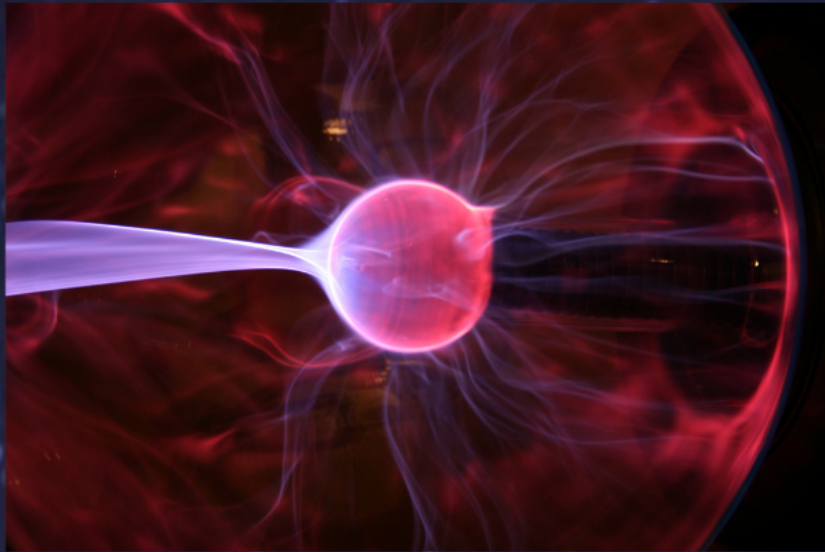
One way you can use the CMB is as a backlight, to see large clusters of galaxies





# The Ionized Universe

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## ISOTROPY OF THE COSMIC MICROWAVE BACKGROUND



MAP990004

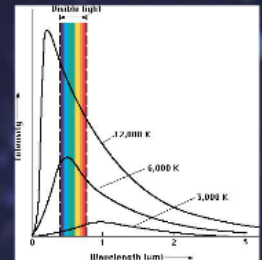
## It's a Blackbody!

That means it can be described by only its temperature:

$$T_{\text{CMB}} = 3\text{K}$$

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

$$z_{\text{CMB}} \sim 1000$$





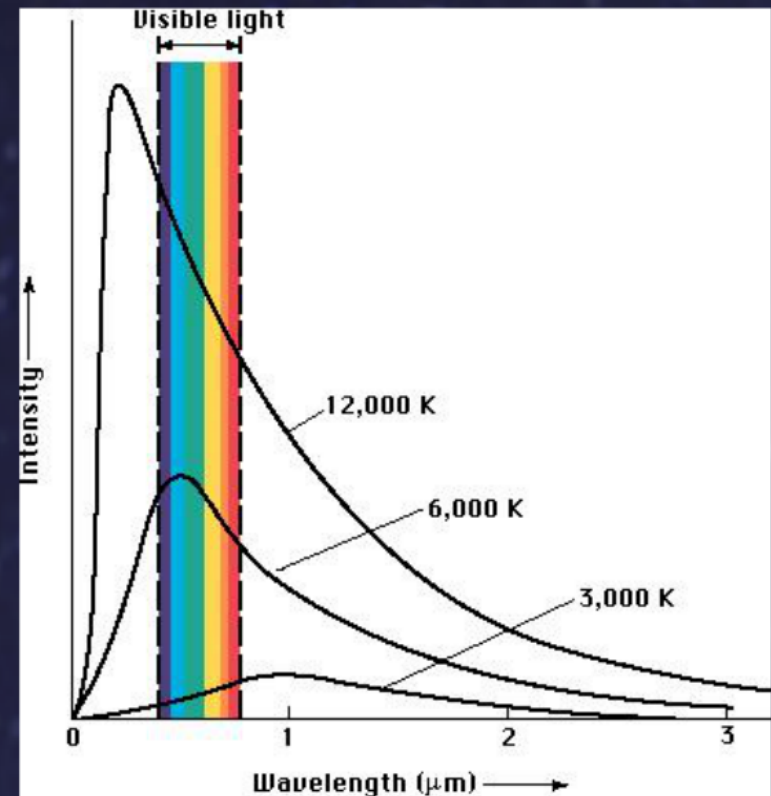
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The plasma of the universe condenses at a temperature of around 3000K, so the CMB has been significantly redshifted on its way to earth

$$z_{\text{CMB}} \sim 1000$$



# The Detection of the CMB

(1964, Bell Labs, Princeton)



Robert Dicke



Arno Penzias and Robert Wilson





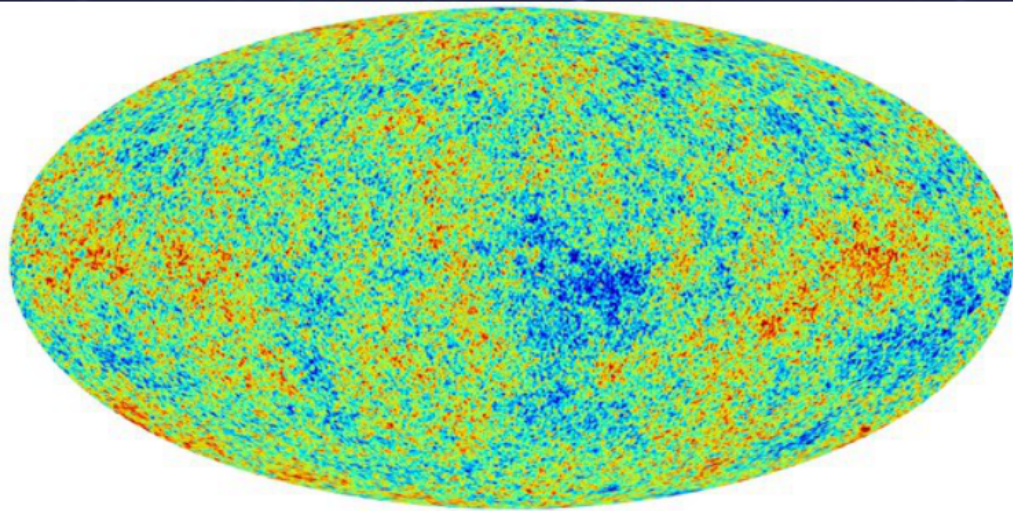
# Anisotropies in the CMB

## ISOTROPY OF THE COSMIC MICROWAVE BACKGROUND



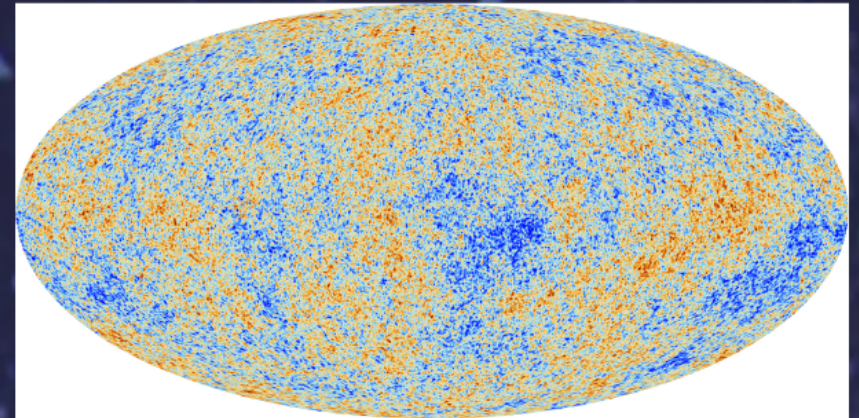
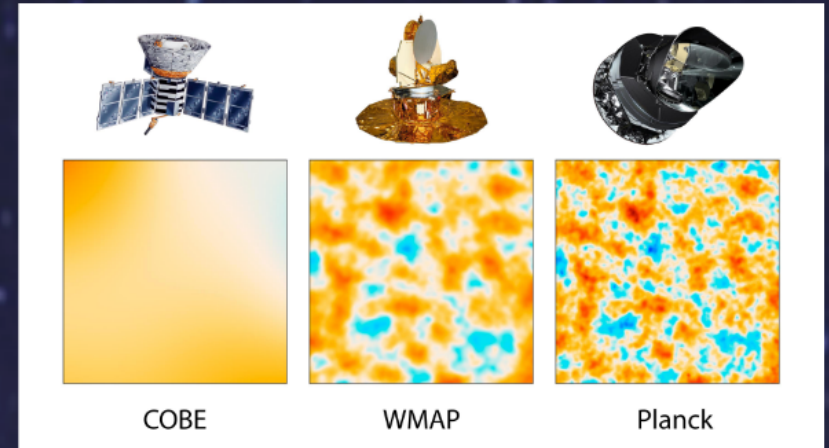
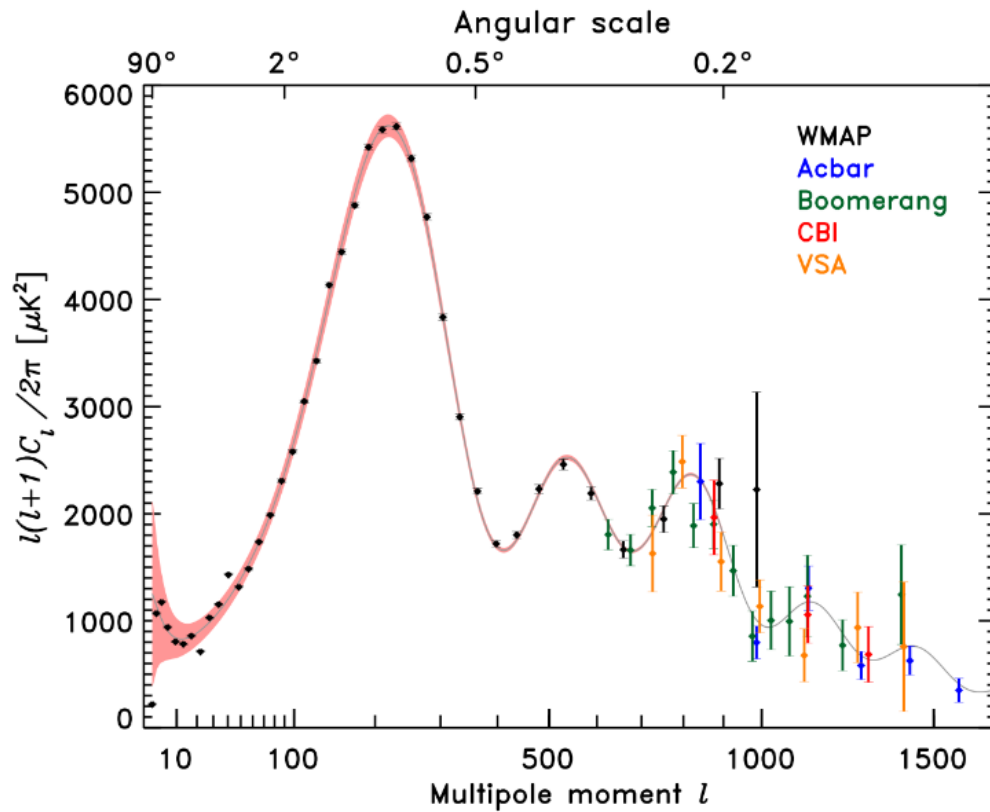
MAP990004

Cosmic Microwave Background is very isotropic, but not 100%

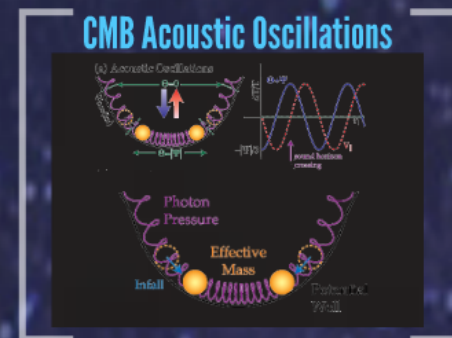


Anisotropies correspond to changes in the transition time between the plasma and molecular gas phases

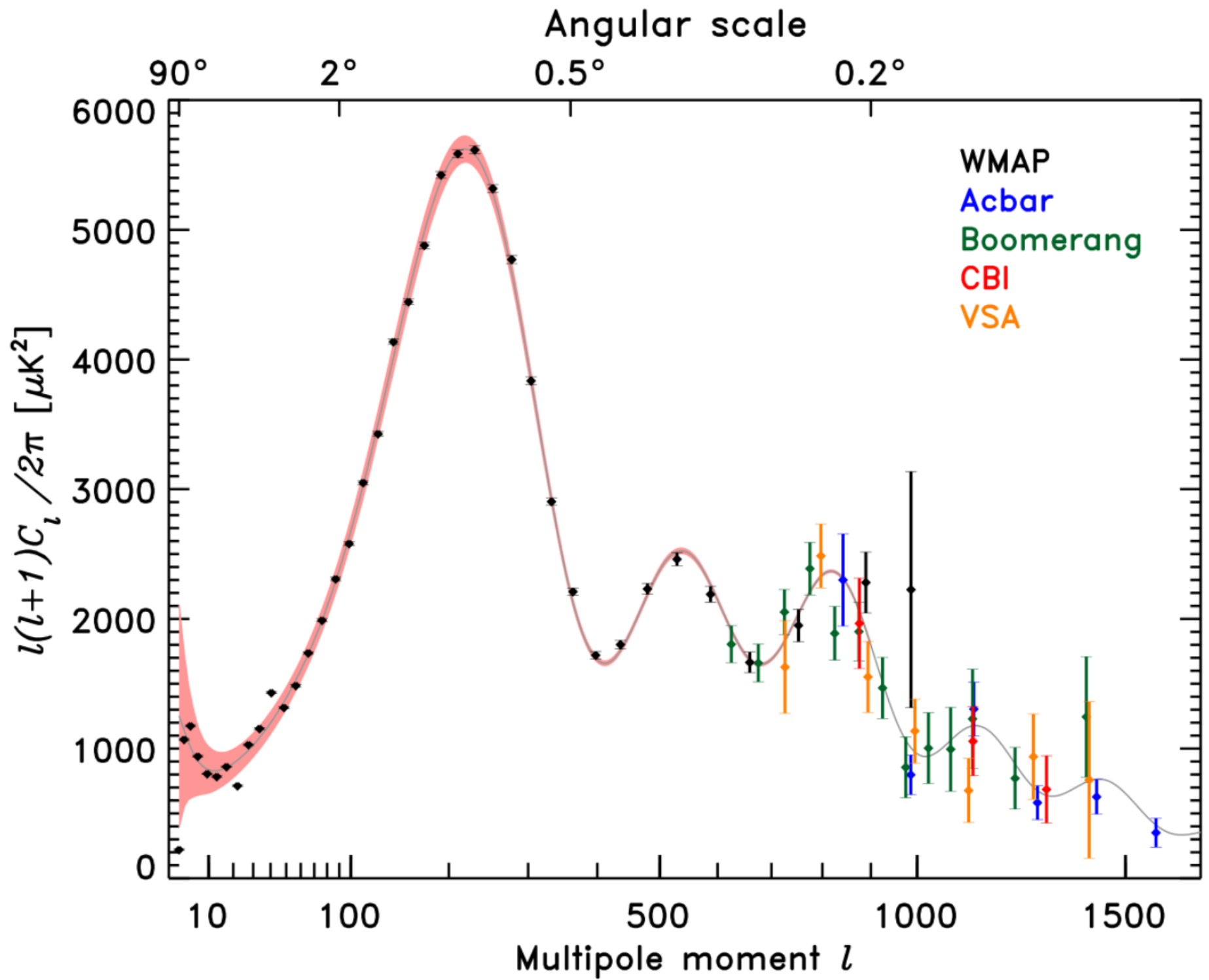
# Anisotropies in the CMB



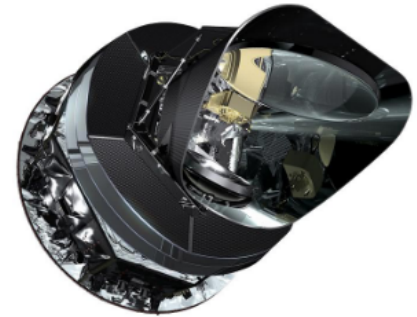
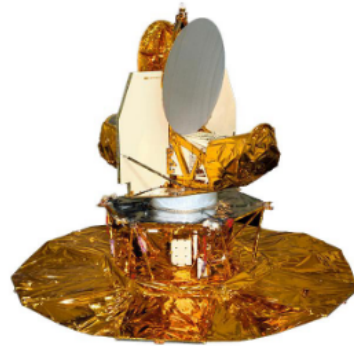
Lots of information is encoded in the position and height of each peak



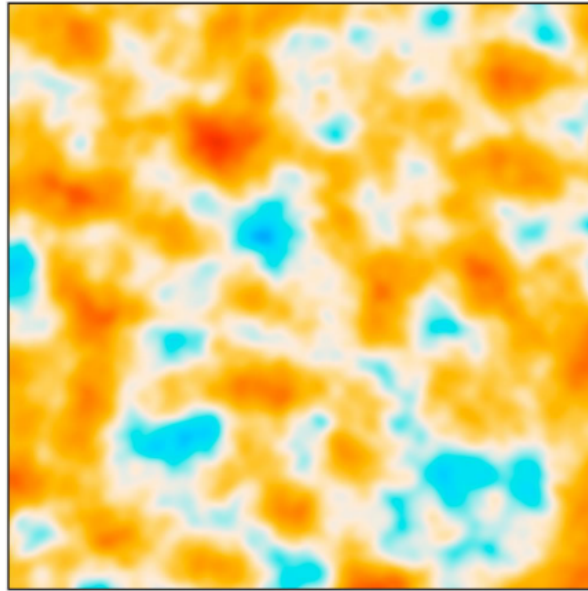




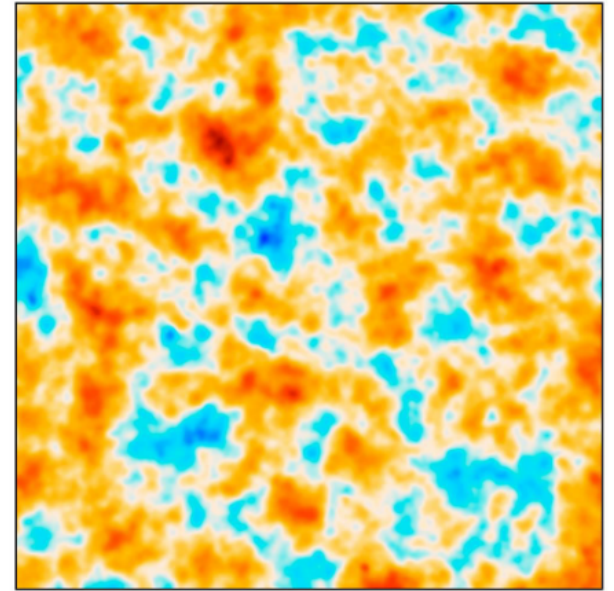




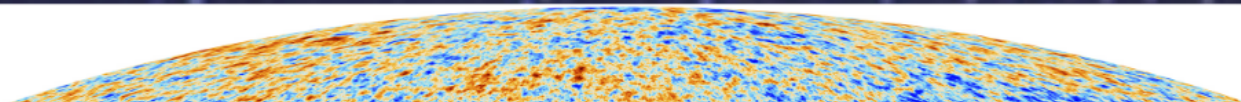
COBE



WMAP



Planck

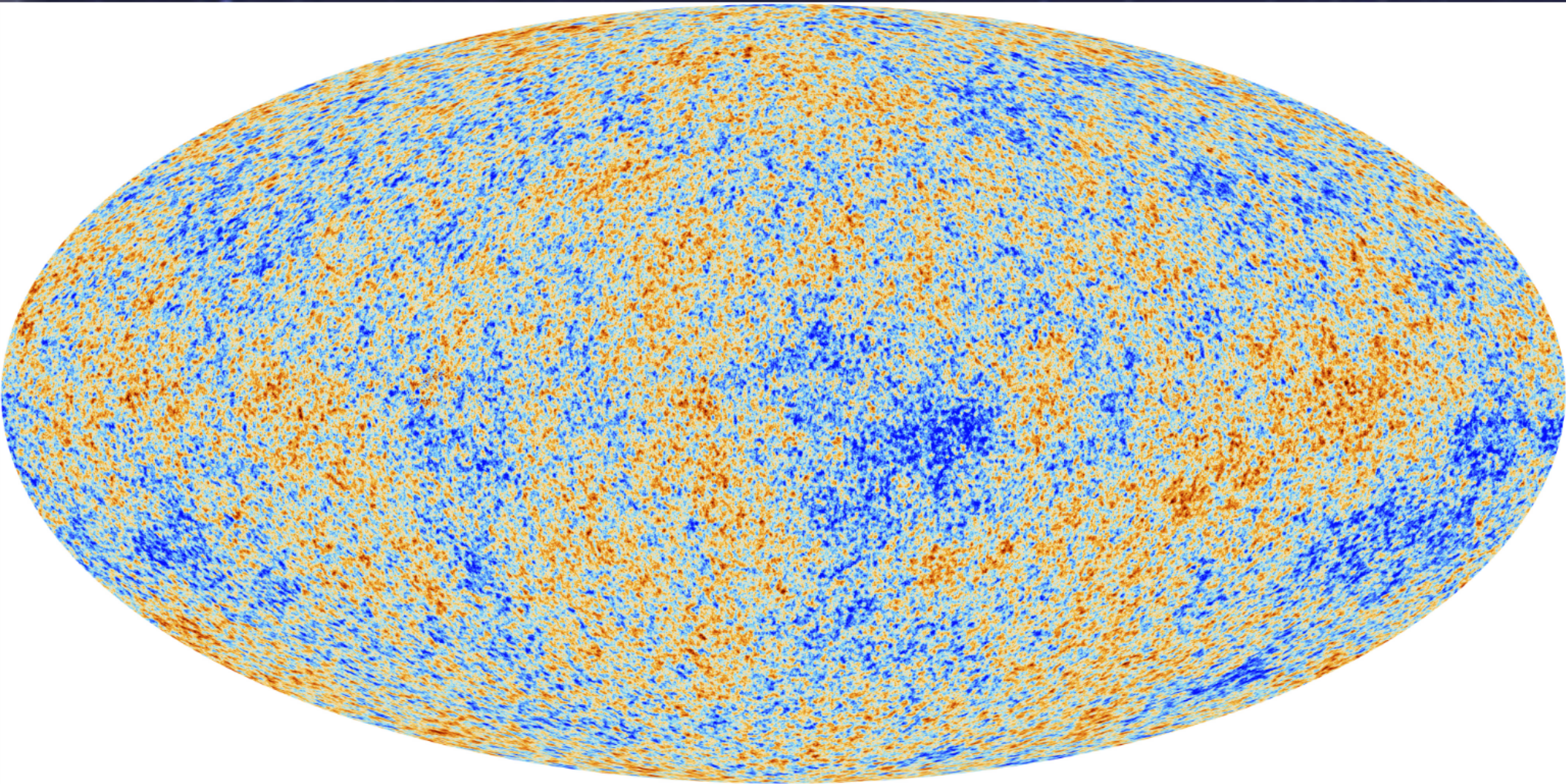




COBE

WMAP

Planck



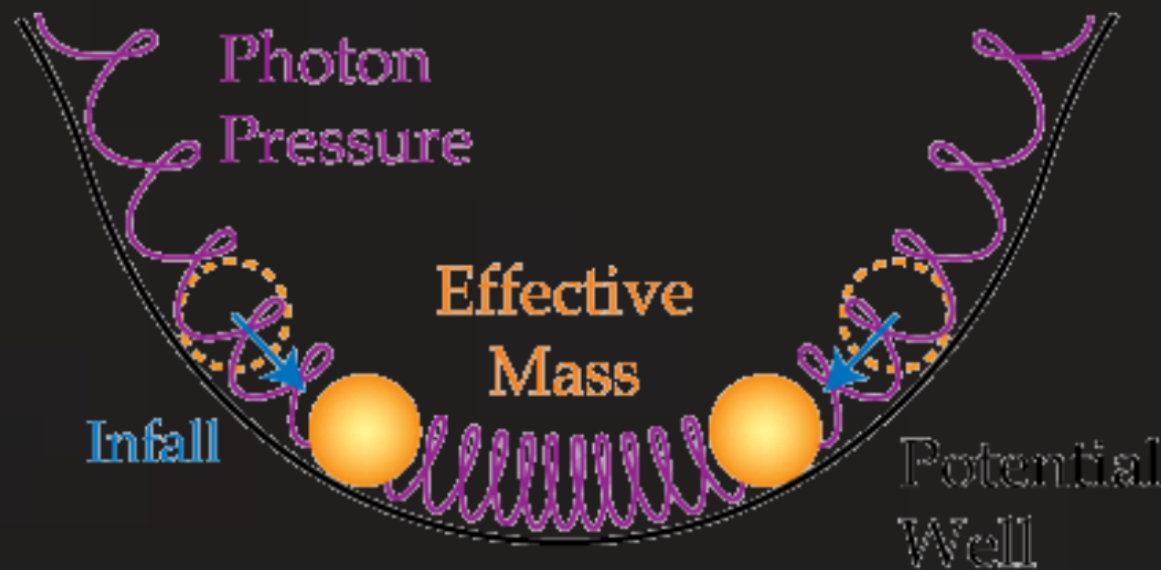
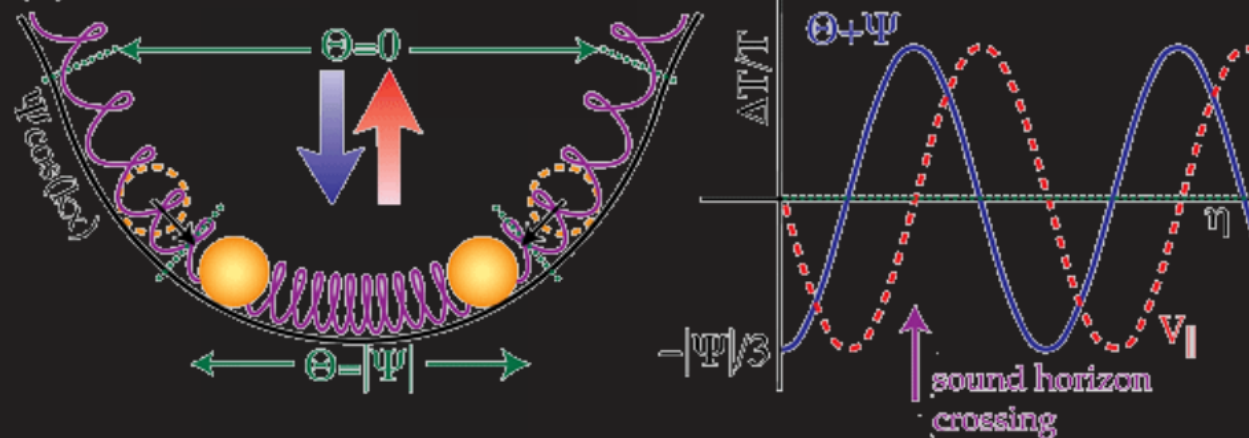
**CMB Acoustic Oscillations**

(a) Acoustic Oscillations

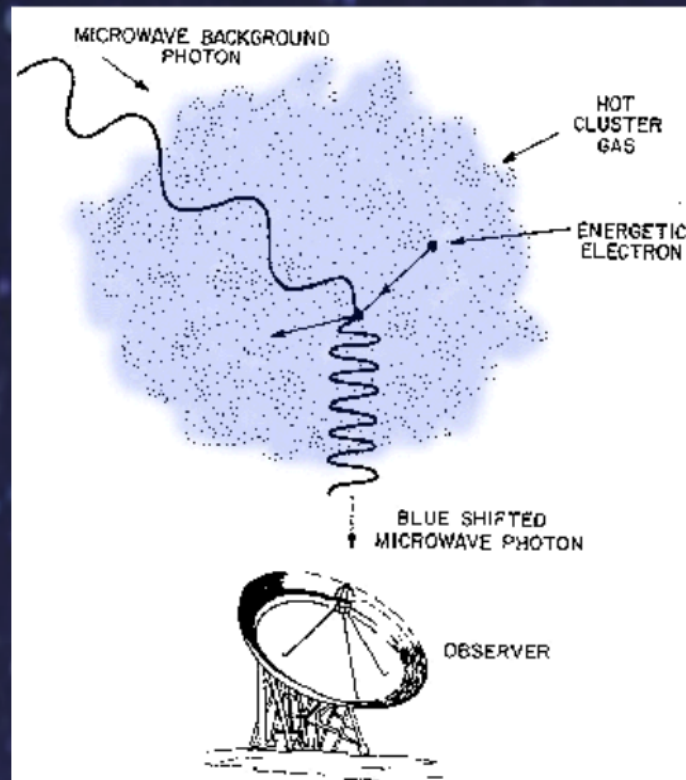


# CMB Acoustic Oscillations

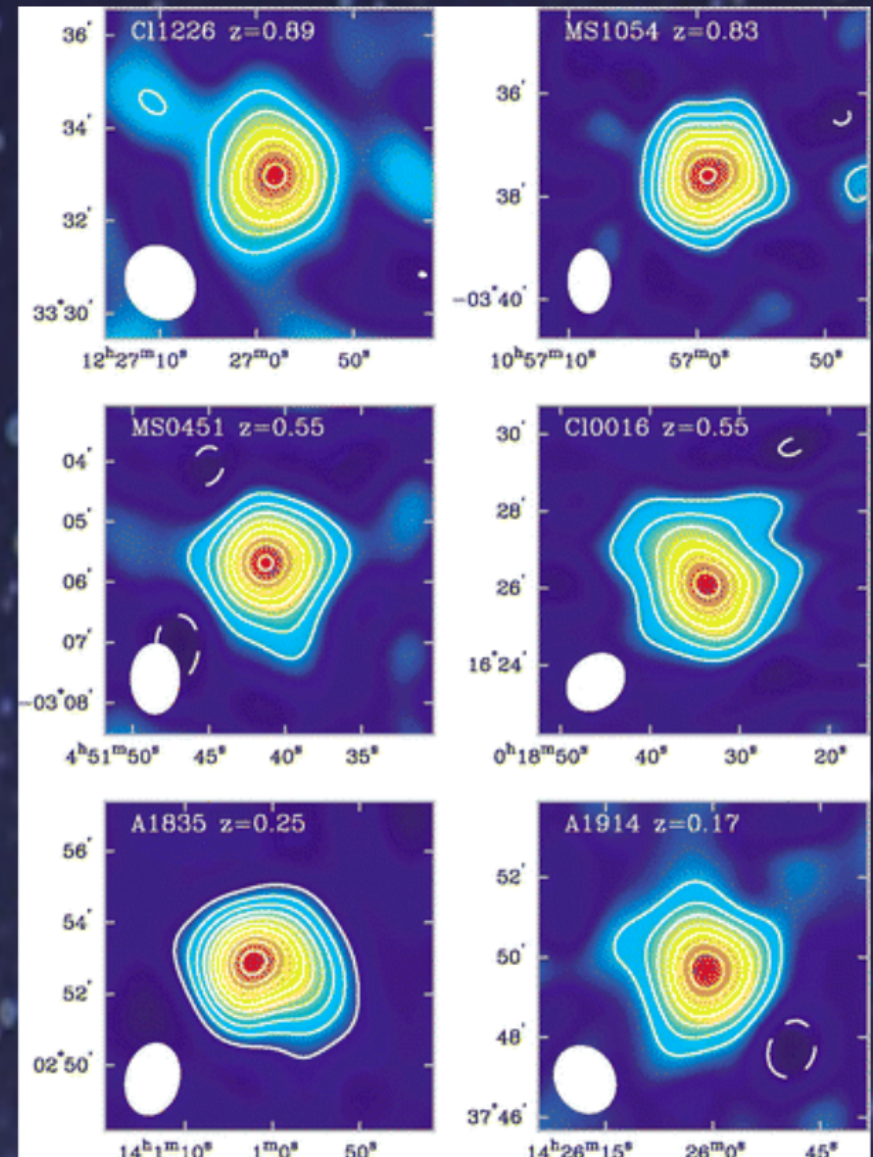
(a) Acoustic Oscillations



# Sunyaev-Zel'dovich Effect

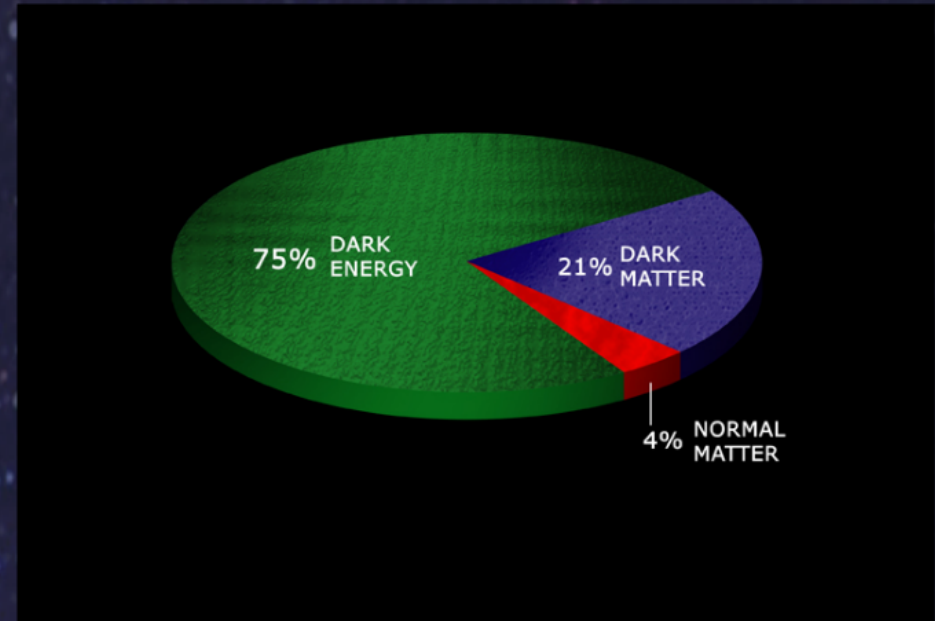
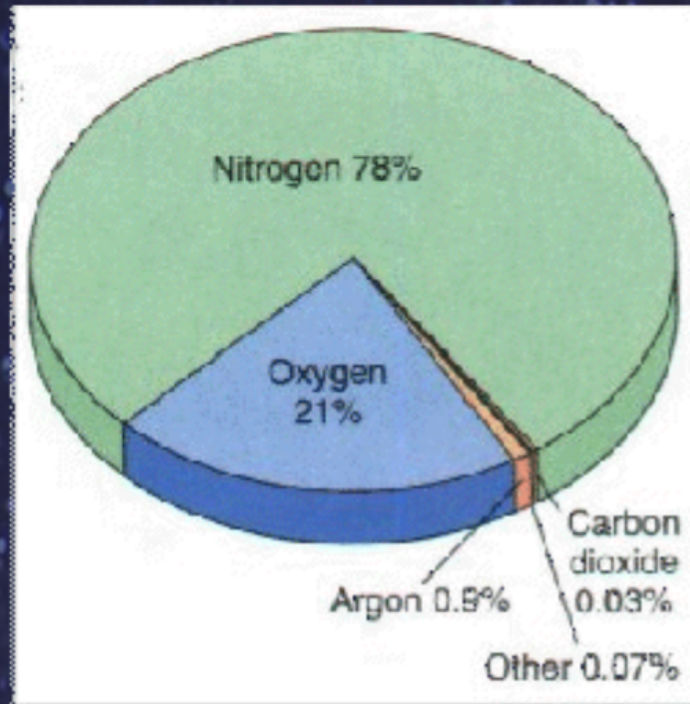


One way you can use the CMB is as a backlight, to see large clusters of galaxies





# 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.

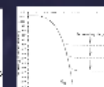
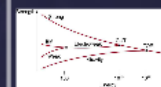


The positron then interacts with an electron to produce a gamma-ray, which we can see.



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

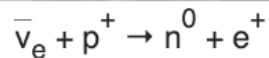
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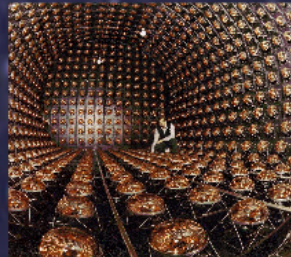
Neutrinos don't interact with light, but they do interact with other particles via the weak interaction



Cowan-Reines Experiment  
1956 (Nobel Prize 1995)

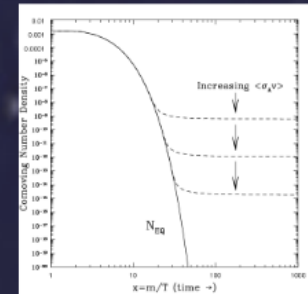
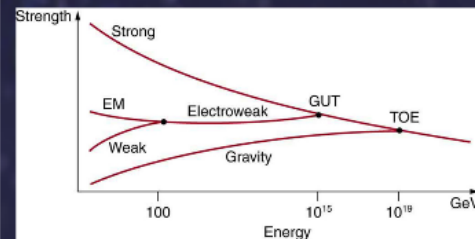


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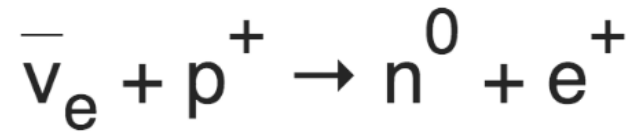


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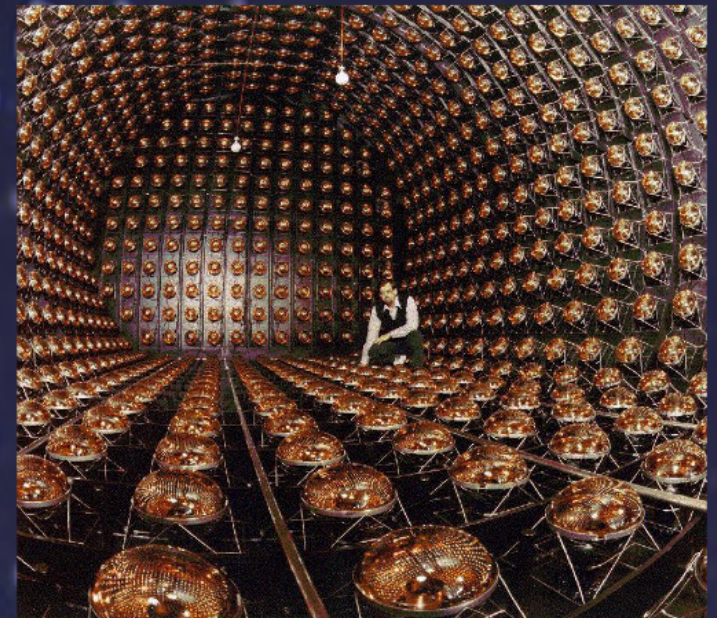


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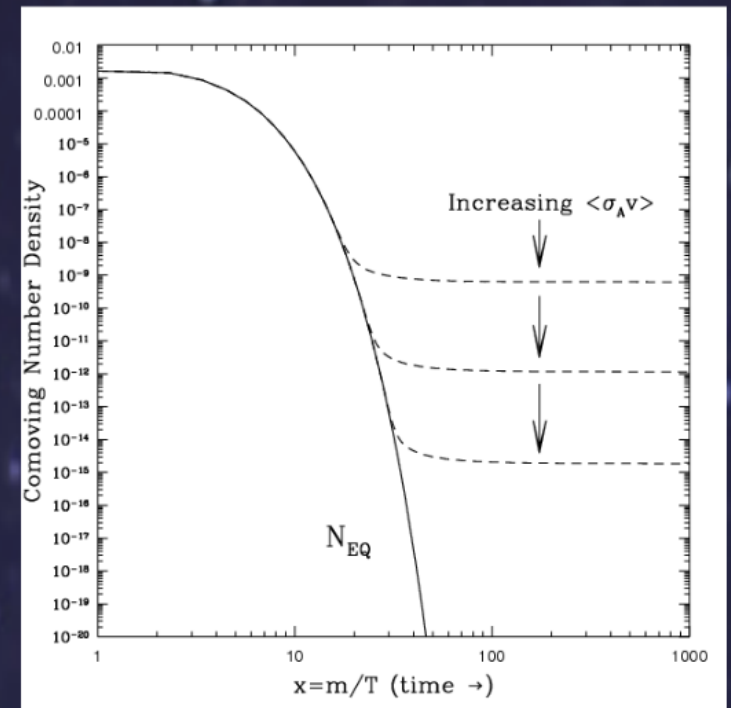
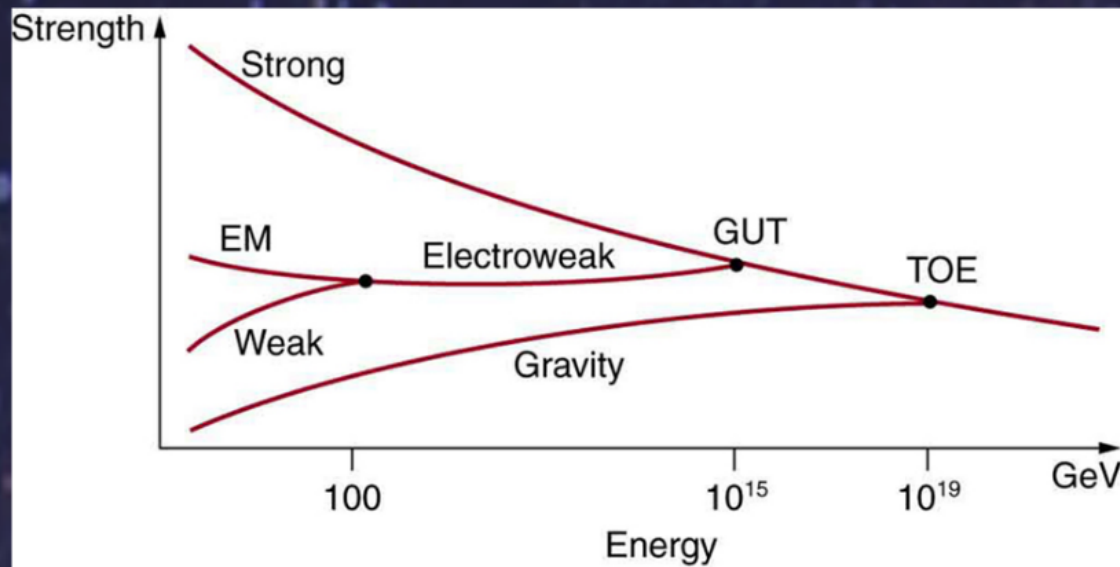


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# Early Universe Hints





### 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: 25 million years

### Looking At the Early Universe

What does the early universe look like? The early universe was a hot, dense, and opaque plasma. As it cooled, it became transparent, and the first light was emitted. This light is now the Cosmic Microwave Background (CMB).

What does this tell us? The CMB provides a snapshot of the universe at the time of recombination, about 380,000 years after the Big Bang. It shows the universe was very uniform, but with small fluctuations that led to the formation of galaxies and other structures.

### The First Photons

The earliest photons were emitted at the time of recombination, about 380,000 years after the Big Bang. These photons have been traveling through the universe ever since, and are now the Cosmic Microwave Background (CMB).

The CMB is a uniform background of radiation that fills the universe. It is the oldest light we can see, and it provides a snapshot of the universe at the time of recombination.

Anisotropies in the CMB are small variations in the temperature of the CMB. These variations are caused by the distribution of matter and energy in the early universe, and they provide a window into the structure of the universe at that time.

The Sunyaev-Zeldovich Effect is a phenomenon that occurs when CMB photons interact with the hot gas in galaxy clusters. This interaction causes the photons to gain energy, and it results in a characteristic distortion of the CMB spectrum.

### The Dark Side of the Universe

Dark Energy: 68%  
Dark Matter: 27%  
Ordinary Matter: 5%

Dark matter is a form of matter that does not interact with light, but it has a gravitational effect on the universe. It is thought to be made up of particles that are heavier than ordinary matter, and it is distributed throughout the universe in a way that forms a halo around galaxies and galaxy clusters.

Dark energy is a form of energy that is thought to be responsible for the accelerated expansion of the universe. It is a mysterious force that acts in opposition to gravity, and it is distributed uniformly throughout the universe.

# 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!