Lecture 3

# The Universe's first million years: Primordial light and sound

## Introduction

The first million years is equivalent to the first day of a human's life

For humans: no structures, just DNA
For the Universe: no structures, almost perfectly smooth hot thin glowing gas, and sound waves

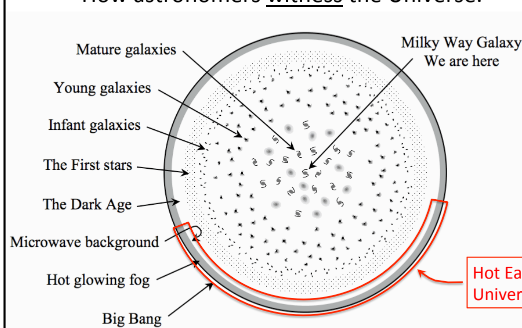
How do we know this? From studying the microwave background!

Topics:
- The microwave background
- Conditions: density, temperature, brightness, fogginess
- Sound waves

Transition to the first stars, near 200 million years.

## 1. The Cosmic Microwave Background (CMB)

## How astronomers <u>witness</u> the Universe.




Strangely, the Big Bang appears all around us !!

## What do we see?

The young Universe was <u>hot</u> and very <u>bright</u>

Why isn't the night sky very bright??

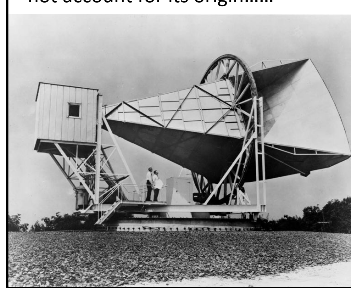
The light has traveled for almost 14 billion years. During that time, the Universe has expanded greatly – by a factor of 1000!

The light waves are also stretched by ×1000. They leave as light, but arrive as microwaves.

→ The Cosmic Microwave Background.

## The Microwave Background

In 1964 Penzias and Wilson found an excess of microwave emission coming from the sky. They could not account for its origin……

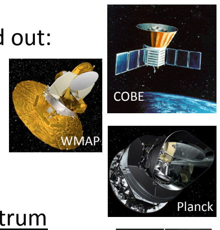


Wilson Penzias

## Observations of the CMB

One of the most intensely studied things in science

Many experiments, three stand out:
- 1990 COBE (NASA)
- 2003 WMAP (NASA)
- 2013 Planck (ESA)

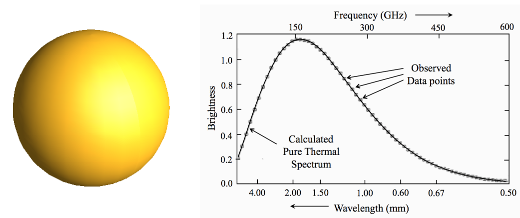


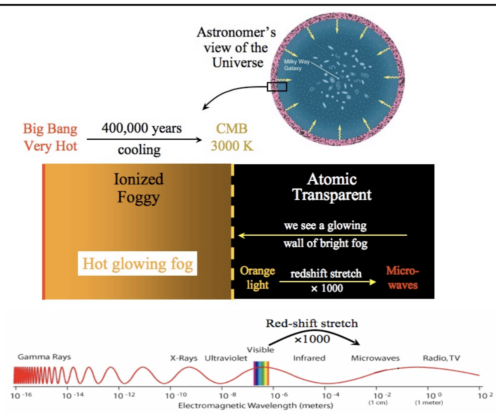

Two Primary observations:
- Measuring an accurate spectrum
- Measuring an accurate all-sky image

Nobel Prize (2006) for COBE results on both these →

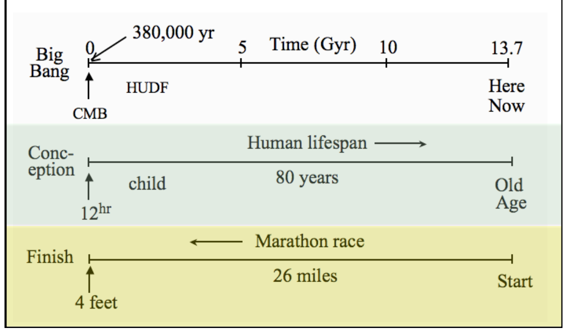

## The CMB Reveals a Smooth Hot Glowing Gas

In 1990 NASA's COBE satellite measured extremely uniform emission with an accurate thermal spectrum.



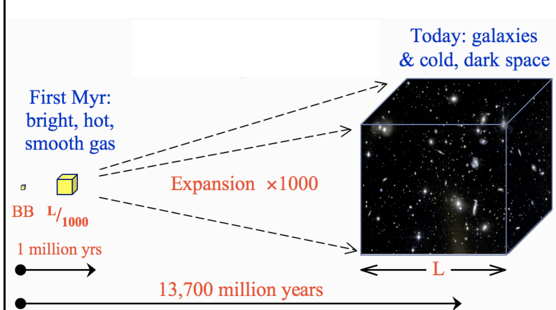




## The microwave background is very "close" to the Big Bang




## 2. Conditions in the first million years

## The early universe was radically different

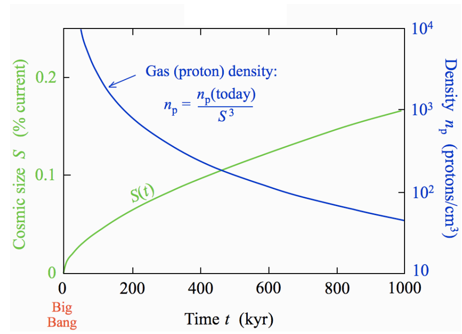


## Conditions in the infant Universe

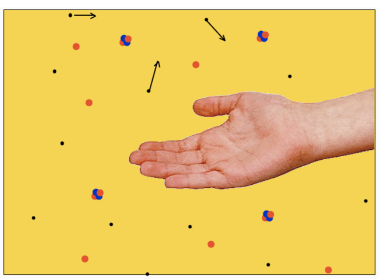
A very uniform:
- hot
- dilute
- foggy
- glowing
- gas

As expansion proceeds, conditions change.

## Gas density across the first million years



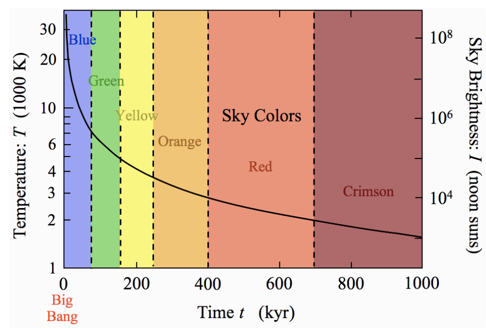

## The gas is too thin to burn you!



Heat from gas: 0.0003 Watts

Heat from light: 1,000,000 Watts!

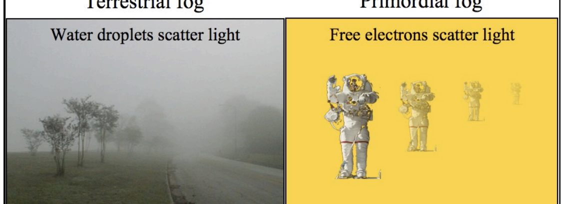
## Temperature, sky color, and sky intensity




## The gas was foggy

Terrestrial fog

Primordial fog




The fog clears at 380,000 years.
From then on, the Universe is transparent (luckily!)

## 3. Slightly Lumpy

## The young Universe was not completely smooth

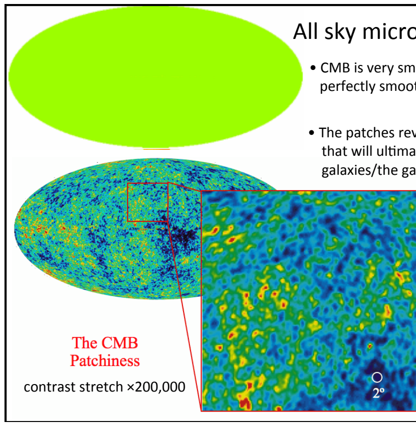
Today's Universe is extremely lumpy – galaxies here and there with gaps between them.

This lumpness must have been present in the young Universe to some degree.

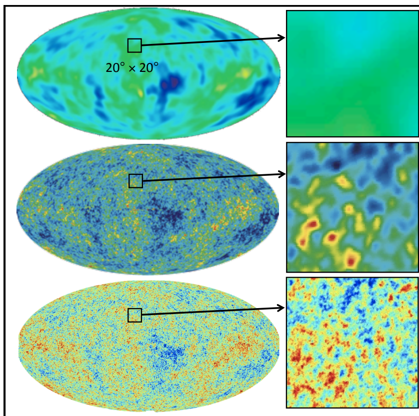
It should show up as patchiness in the microwave background.

After many years it was finally found in 1990 by the COBE satellite, and then mapped in detail in 2003 by the WMAP satellite and in 2013 by the Planck Satellite.

## All sky microwave images




- CMB is very smooth, but not perfectly smooth.
- The patches reveal slight roughness that will ultimately turn into stars/galaxies/the galaxy web.
- The patches are also the peaks and troughs of sound waves.



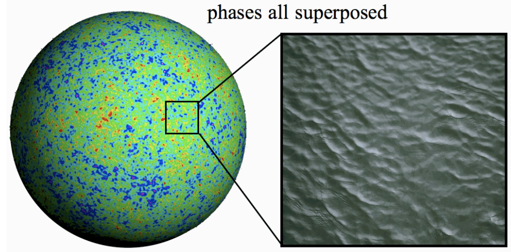

COBE: 1990
Resolution: 7°
Sensitivity: ×1
Cost: 600 M$

WMAP: 2003
Resolution: 0.13°
Sensitivity: ×5
Cost: 800 M$

Planck: 2013
Resolution: 0.08°
Sensitivity: ×15
Cost: 1000 M$

## CMB patches are peaks and troughs of sound waves

Many waves of different sizes, directions & phases all superposed



Sound waves
high/low gas pressure

Water waves
high/low surface height

## 4. Making Primordial Sound Waves

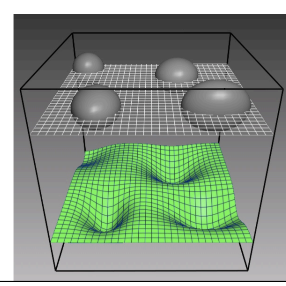
## Dark matter's gravity & gas pressure make the primordial sound

Dark matter is spread about slightly unevenly. There are places with slightly higher than average density.

Four (idealized!) dark matter clumps

Their gravitational field seems like four valleys

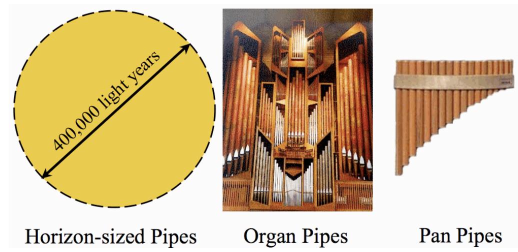
Gas falls in & bounces out: a sound wave. Pitch of sound depends on size of region.

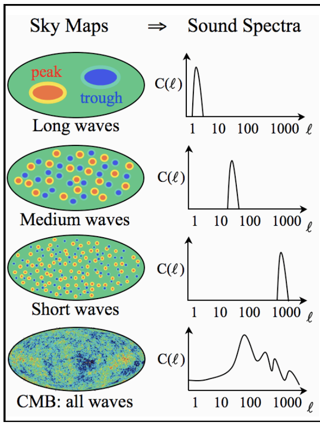


## 5. Primordial Sound Pitch and Quality

The deepest sounds come from the largest dark matter regions, which are roughly the horizon size.

Hence primordial sound is very DEEP
(~ 50 octaves below human range!)

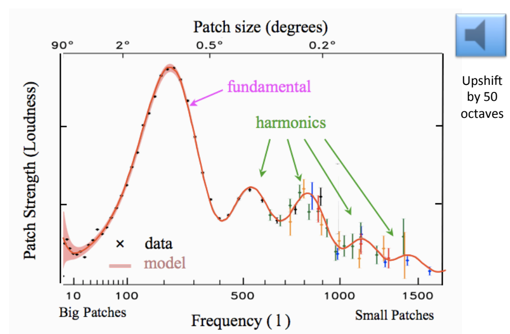


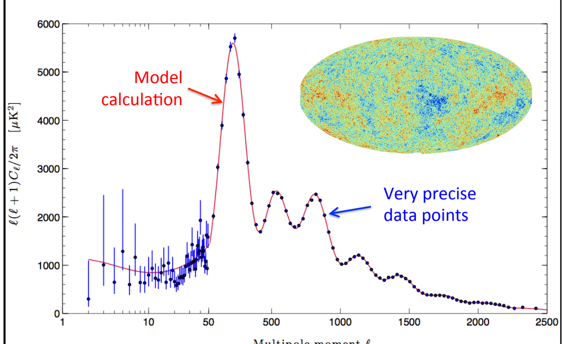

A sound spectrum quantifies how much sound there is (loudness) at each wavelength (actually, frequency, or pitch)

A computer program can extract the sound spectrum from the all-sky image of patches.

## The Measured CMB Sound Spectrum




## Update: New Planck Data (3/21/13)




## 6. Using sound to measure the Universe's Properties

## The sound spectrum is a goldmine!

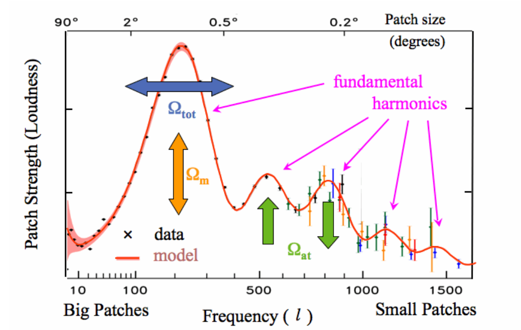
Hit a wine glass & teacup: they sound different!

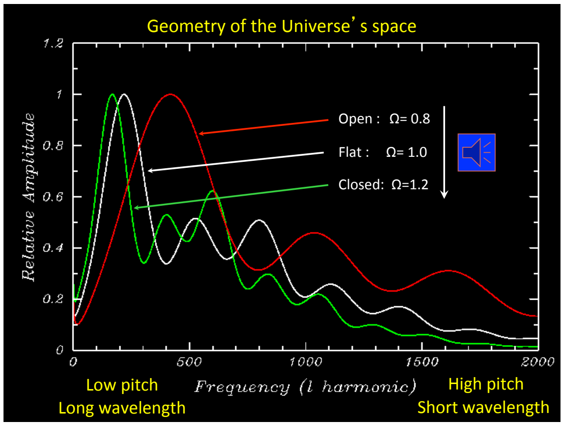
The sound an object makes depends on its properties.

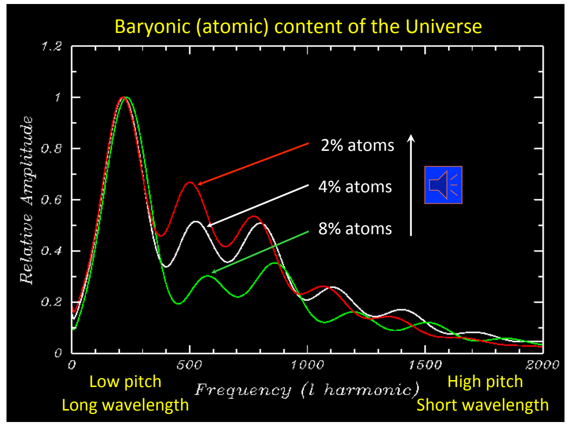
The same is true for the Universe!
Use the cosmic sound spectrum to figure out the properties of the Unviverse.

Some examples:

## Properties of the Universe affect the primordial sound.

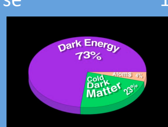


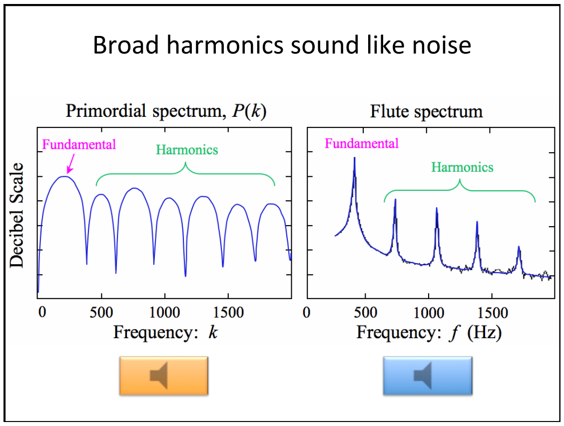

## The Concordance Model

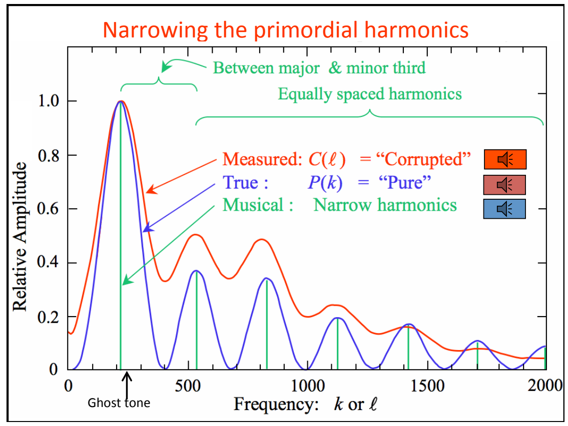
| | | |
|---|---|---|
| •Age of Universe | 13.8 Gyr | (1%) |
| •Flatness | 1.01 | (1%) |
| •Atoms | 4.4% | (2%) |
| •Dark matter | 22% | (3%) |
| •Dark energy | 73% | (2%) |
| •Hubble constant (km/s/Mpc) | 72 | (3%) |
| •Photon/proton ratio | $1.6\times10^9$ | (2%) |
| •Time of first stars | 400 Myr | (30%) |
| •Time of CMB | 380,000yr | (1%) |



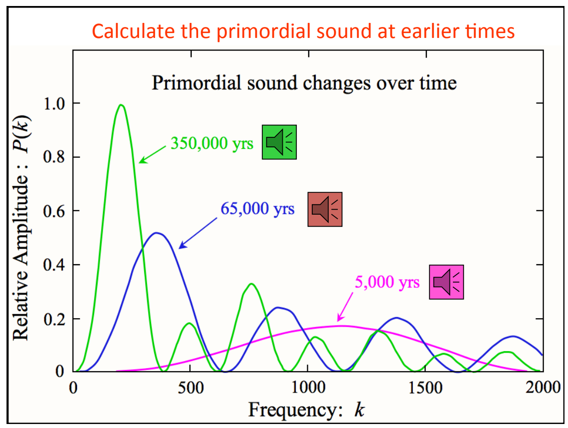

## 7. Having fun with primordial sound:

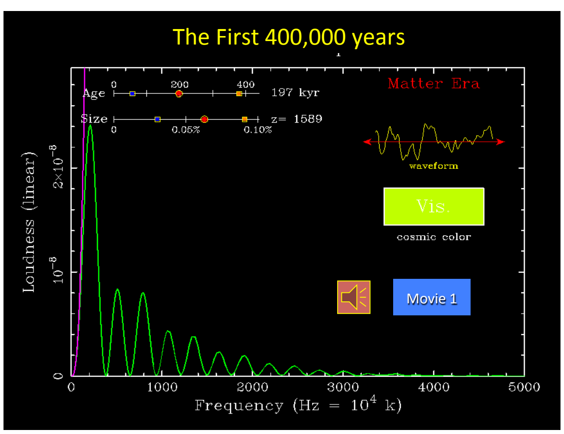
## Narrowing the harmonics

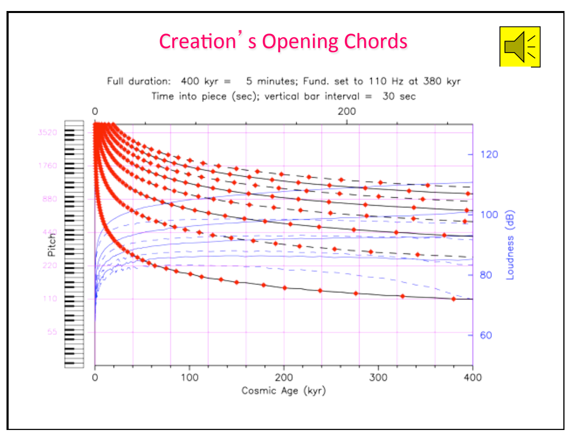



# 8. Time evolving sound



## Choral work (8 parts)

Commissioned: Ander Mikalson
Composer: Elliott Shelton
Performance: VCU Choir

## Summary

The Microwave Background gives us direct access to the million-year-old Universe (equal to one day in a human lifetime).

Everywhere was a hot thin glowing gas of free electrons, protons and helium nuclei – with a sea of dark matter, and brilliant light.

The light is incredibly bright, and before 60,000 years even weighs more than the matter.

Near 380,000 years, atoms form and the fog clears

There is slight uneveness in the dark matter, and the glowing gas bounces in and out of these pockets, making sound waves.

It is possible to measure the sound spectrum from the CMB patchiness, and this reveals a number of the Universe's properties.