Earth 101
Introduction to Astronomy

Cosmology & Dark Matter

Instructor:
Erin O'Connor

OpenStax Ch 29
Cosmology
Dark Matter & Dark Energy
More Advanced Material

Photo/Material Credit:
- Fred Marschak
- Dr. Jatila van der Veen
- Erin O'Connor + others

NGC 2359 Thor's Helmet © 2022 Hector Jimenez

1) Discovery that the Universe is Expanding

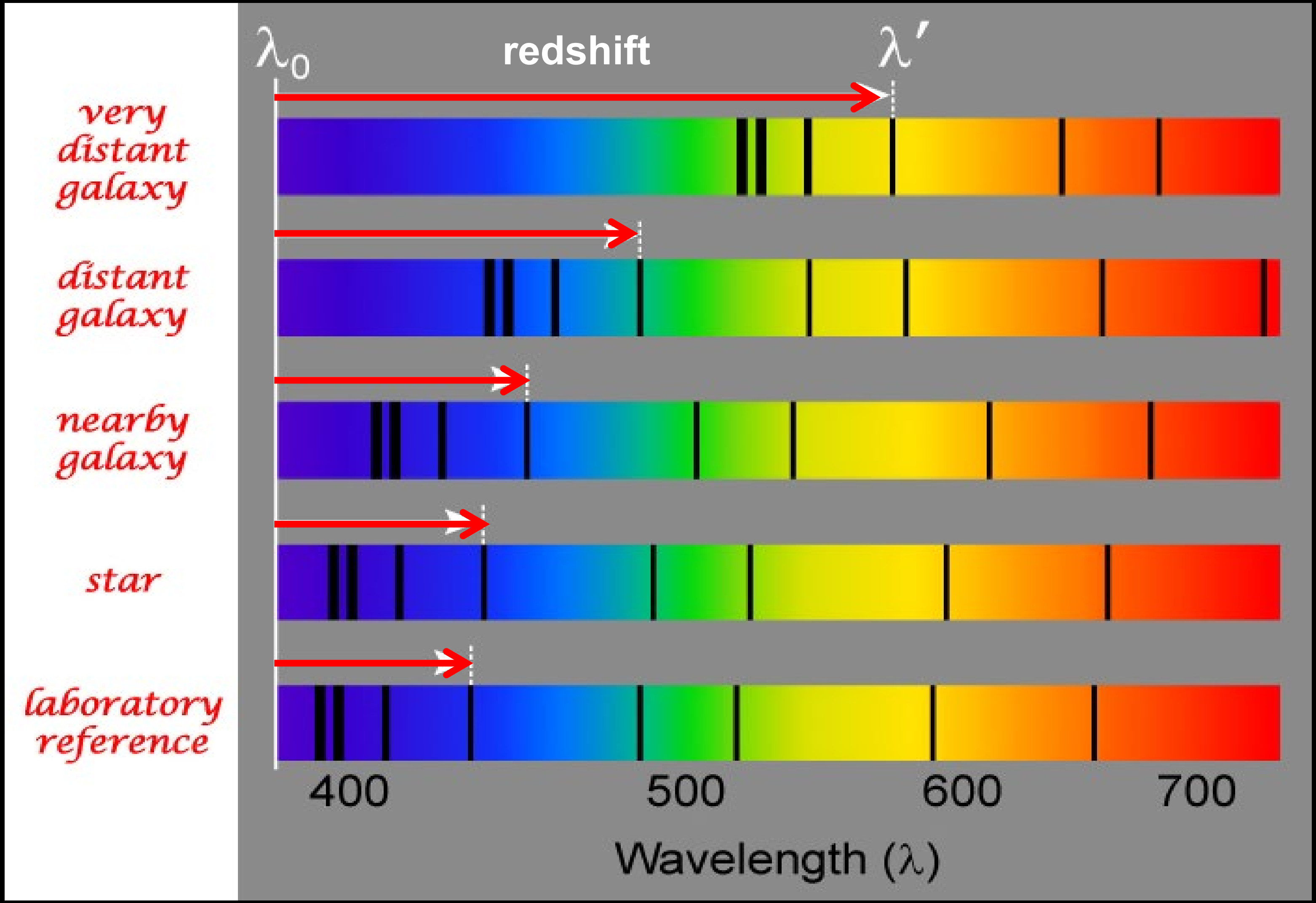
The first clues that the Universe is Expanding were contained in the measurements by Edwin Hubble of the redshifts of galaxies.

Edwin Hubble in 1929 using the 100-inch Hale Telescope on Mt. Wilson, in California

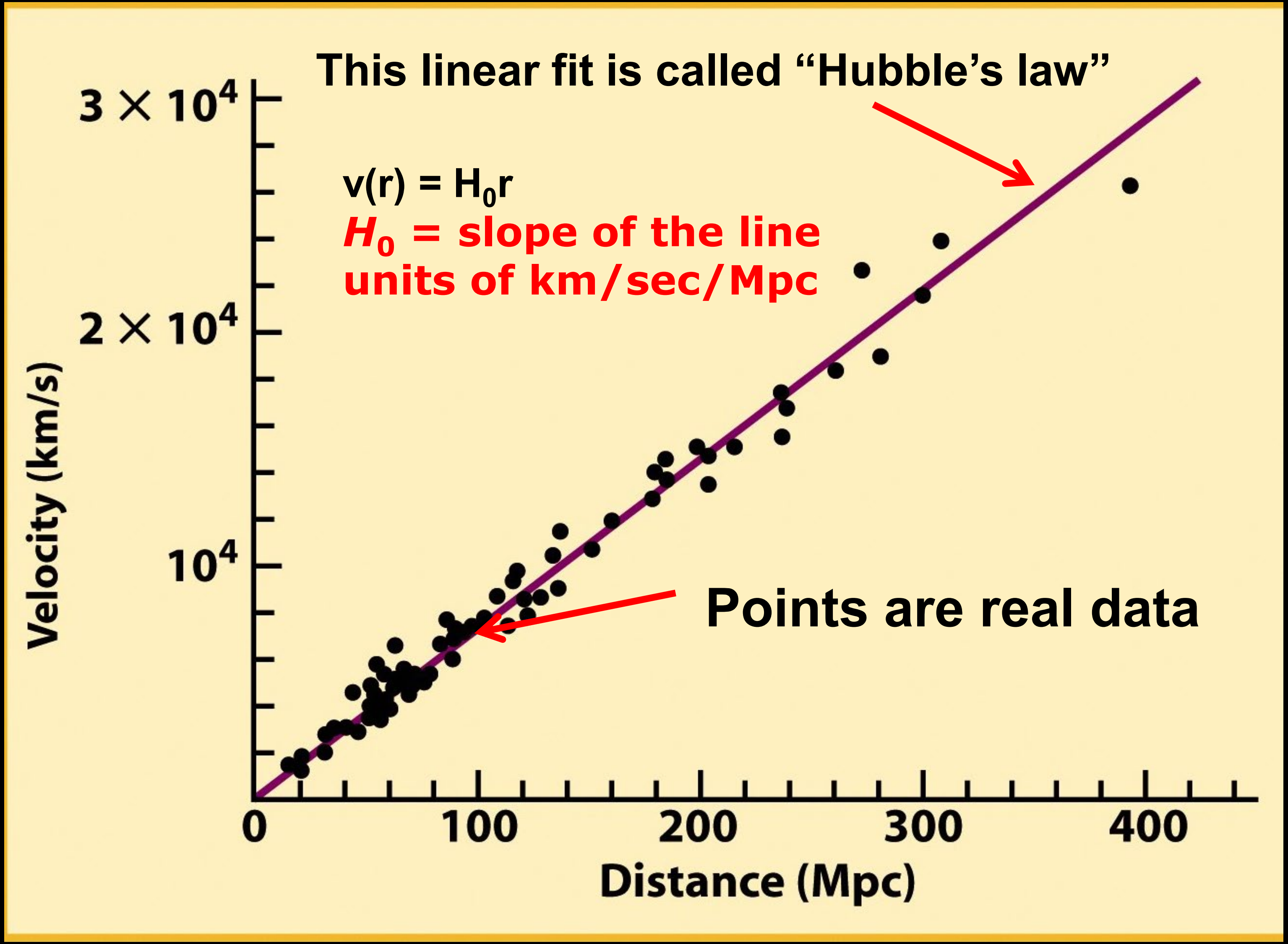
$$\frac{\lambda' - \lambda_0}{\lambda_0} = \frac{v}{c}$$

Red shift gives a measurement of speed. The greater the redshift, the faster a galaxy is receding from us.

v = recession velocity
c = speed of light
λ' = stretched wavelength
λ_0 = wavelength as measured in the lab



When Hubble graphed the velocity of galaxies as a function of their distance from us, he got a graph like this:



Hubble's Law

The farther away the galaxy, the greater its velocity of recession.

$$v(r) = H_0 r$$

recessional speed between two galaxies

We call this motion the "Hubble flow"

Hubble flow is an expansion of the Universe!!

The “Hubble Constant”

$$H_0 = \frac{68(km/s)}{Mpc}$$

recessional speed between two galaxies…

latest results from the Planck Mission

…for each 1 Mpc that they are apart

Cosmic Flow

Example:

How fast are two galaxies receding that are 5 Mpc away from each other?

use: $$v(r) = H_0 r$$

$$v(r) = H_0 r = \frac{68 km/s}{Mpc} \times 5Mpc = 340 km/s$$

Expansion of the Universe – a few basics:

1. Only pertains to objects (such as galaxies) that are in the “cosmic flow” (or “Hubble flow”).

Expansion of the Universe – a few basics:

1. Only pertains to objects (such as galaxies) that are in the “cosmic flow” (or “Hubble flow”).

2. Solar systems and galaxies that are gravitationally bound DON’T expand.

Hubble Expansion:

1. Everything is moving AWAY from us (on larger scales where the nearby gravitational tugs and pulls are negligible).

2. SPACE IS EXPANDING – galaxies don't move into existing space, the expansion between galaxies CREATES space!

“Cosmological Redshift”

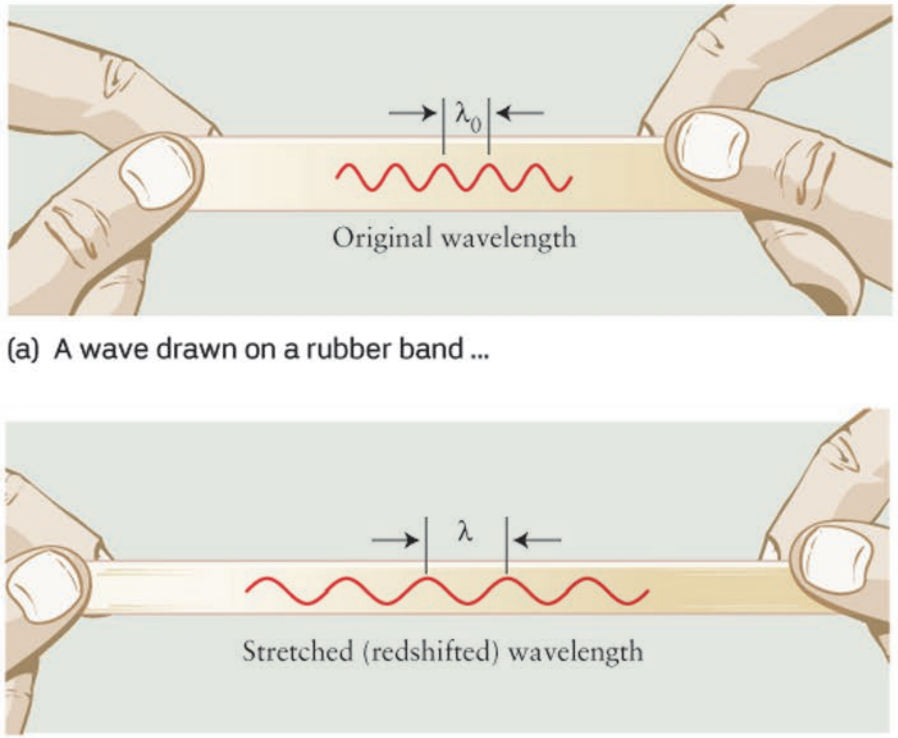
With the resulting picture that the Universe is expanding, we now think of the redshifted light as resulting from the expansion of space, and not merely Doppler shifts of moving objects.

...the red shift really tells us about the stretching of the wavelengths of light due to the expansion of the Universe:

$$\boxed{\frac{\Delta\lambda}{\lambda} = z = \frac{R_0}{R} - 1}$$

z = red shift
R_0 = present radius of the universe
R = radius of the universe at the time the observed light originated
The ratio R_0/R tells how many times larger the universe is now than it was at that time

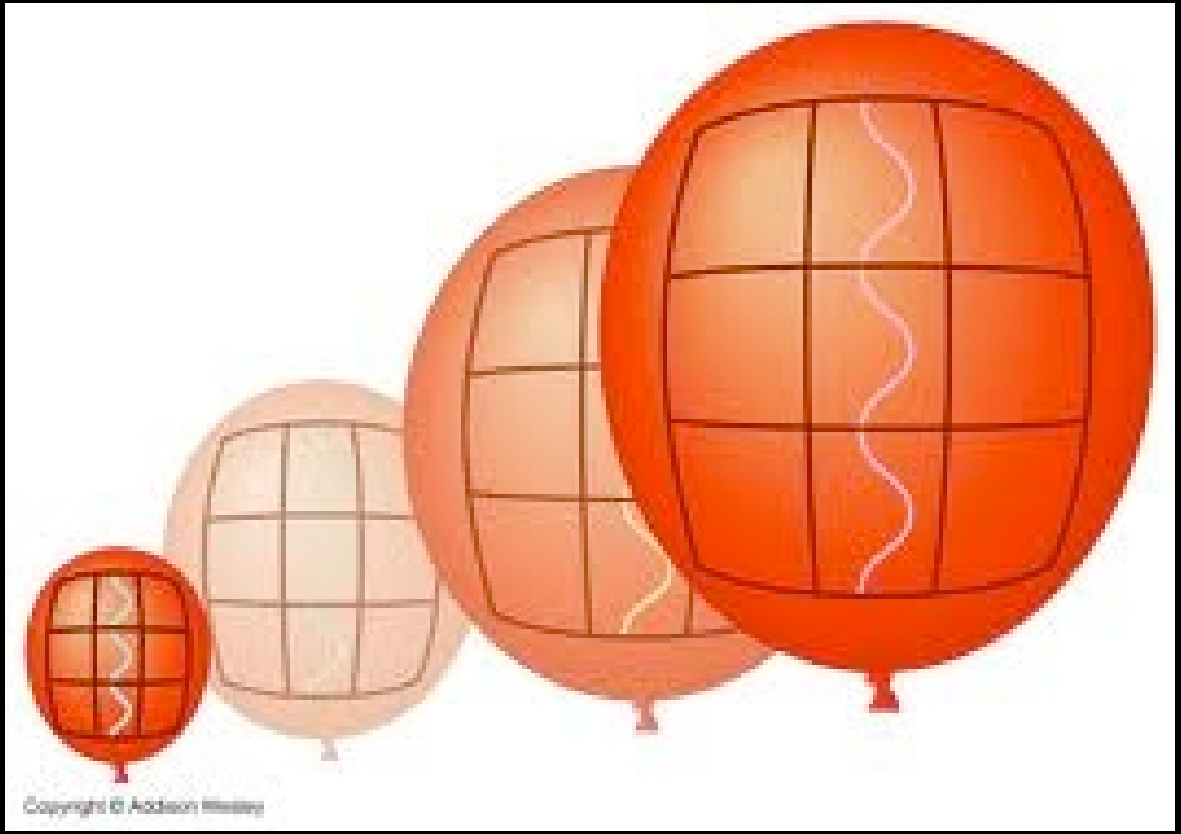
Examples:
For z = 1.7, R_0/R = 2.7
For z = 3, R_0/R = 4
For z = 10, R_0/R = 11



(a) A wave drawn on a rubber band ...

(b) ... increases in wavelength as the rubber band is stretched.

Expanding space stretches out light as it travels from distant galaxies…



Hubble Expansion causes “REDSHIFT” of all distant galaxies

Pause to reflect...

What does it mean to say the universe is expanding?

A. Galaxies are moving through space away from each other.
B. Space is expanding, carrying galaxies along with it.
C. All galaxies are moving away from a point at the center of the universe.
D. Space is expanding but the galaxies are not carried along with it, so the separation of galaxies does not change.
E. The galaxies are all getting larger.

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Galaxies farther away from us have larger cosmological redshifts than those closer to us.

What is the cosmological redshift?

A. **A Doppler shift in which the wavelength of photons is increased due to the motion of the galaxies away from us**
B. **A Doppler shift in which the wavelength of photons is decreased due to the motion of the galaxies away from us**
C. **Photons traveling through space have their wavelength increased because the space through which they are traveling is expanding**
D. **Photons traveling through space have their wavelength decreased because the space through which they are traveling is expanding**

Galaxies further away from us have larger cosmological redshifts than those closer to us. What is the cosmological redshift?

A. A Doppler shift in which the wavelength of photons is increased due to the motion of the galaxies away from us
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C. Photons traveling through space have their wavelength increased because the space through which they are traveling is expanding
D. Photons traveling through space have their wavelength decreased because the space through which they are traveling is expanding

We can calculate the approximate age of the universe from the Hubble constant:

$$v(r) = H_0 r$$

velocity = rate x distance

$$\frac{v}{r} = H_0$$

velocity/distance = rate

$$\frac{r}{v} = \frac{1}{H_0}$$

distance/velocity = 1/rate = time

So if we can measure H_0 – the expansion rate of the universe – then we can calculate its age!

How Old is the Universe?

See p. 447 in your text.

$$age = \frac{1}{H_0}$$

$$= \frac{1}{68km/s/Mpc}$$

1 Mpc = 3.08 x 10^{19} km

$$= \frac{1}{68km/s/3.08\times10^{19}km} = \frac{1}{2.20\times10^{-18}/\sec}$$

$$= 4.54\times10^{17}\ \sec$$

= approx. 14 billion years

Our “observable universe”

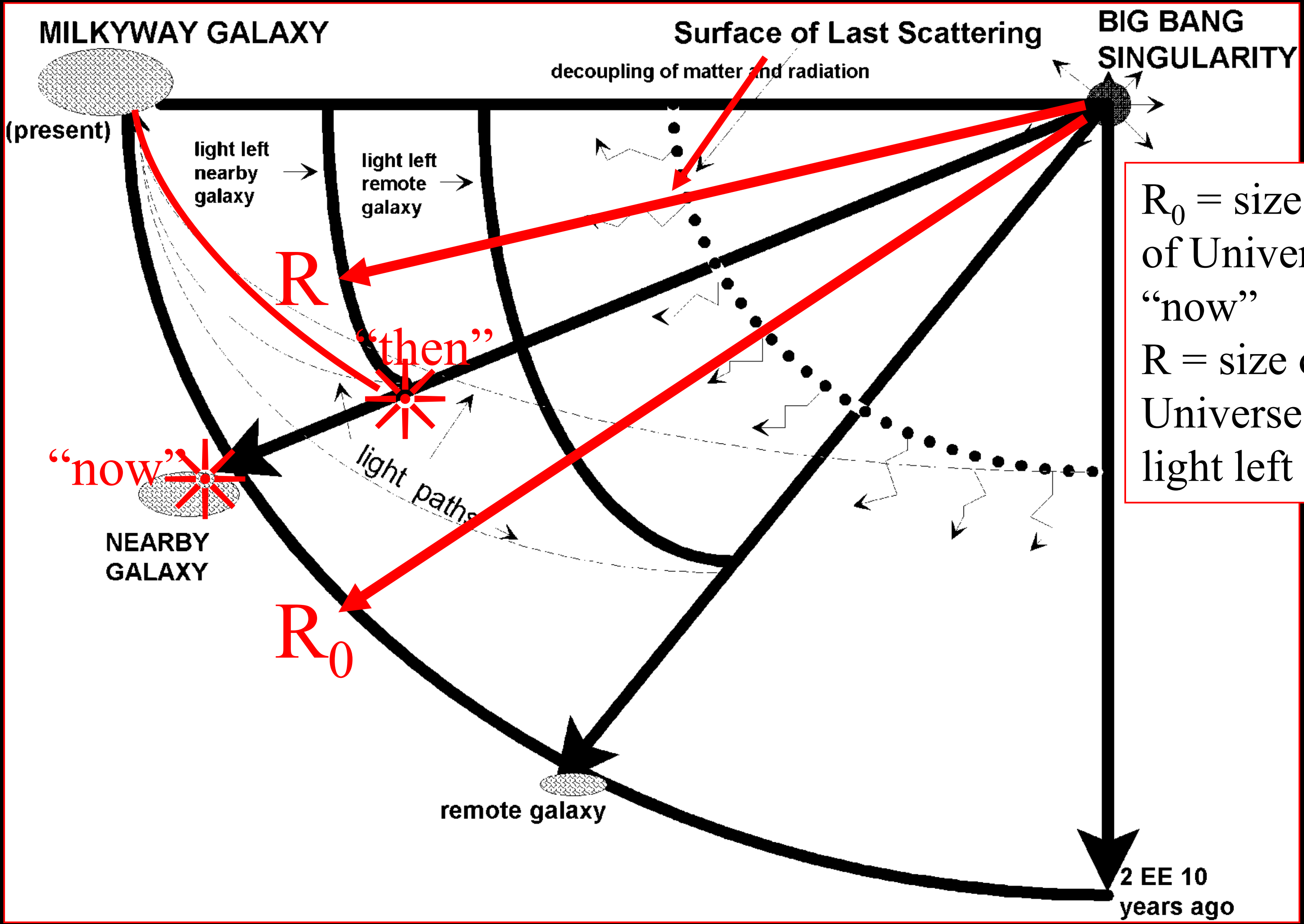
This is our Known Universe – what we can see to compare observations with predictions.

It is limited only by the speed of light, and increases as the universe gets older.

Example: If the universe was “static” (not expanding), we could only look a distance of 13.8 billion light years.

Because of the expansion of space the observable universe is about 46 billion light years in radius, although we see it as it was at the time that the last light left it – the Cosmic Microwave Background.

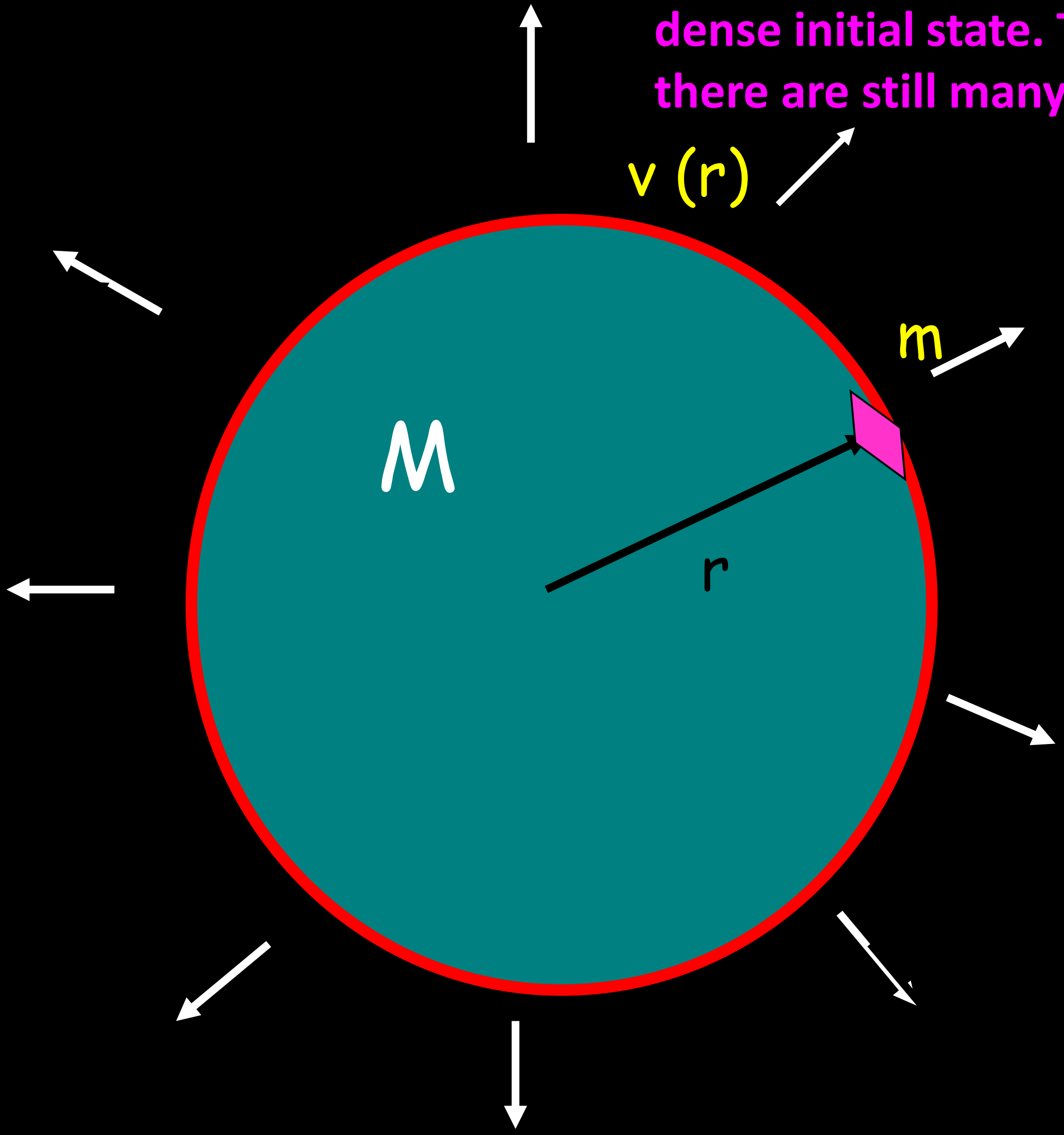
The dashed curves in this diagram represent the paths of light from a source to us, when the universe was smaller than it is now. We see light from a distant source as it was when the light left it. Meanwhile, the universe has expanded, so the object is farther away than it appears. We cannot see anything as it is *now,* not simply due to the finite speed of light, but also due to the expansion of the universe.



R_0 = size of Universe "now"

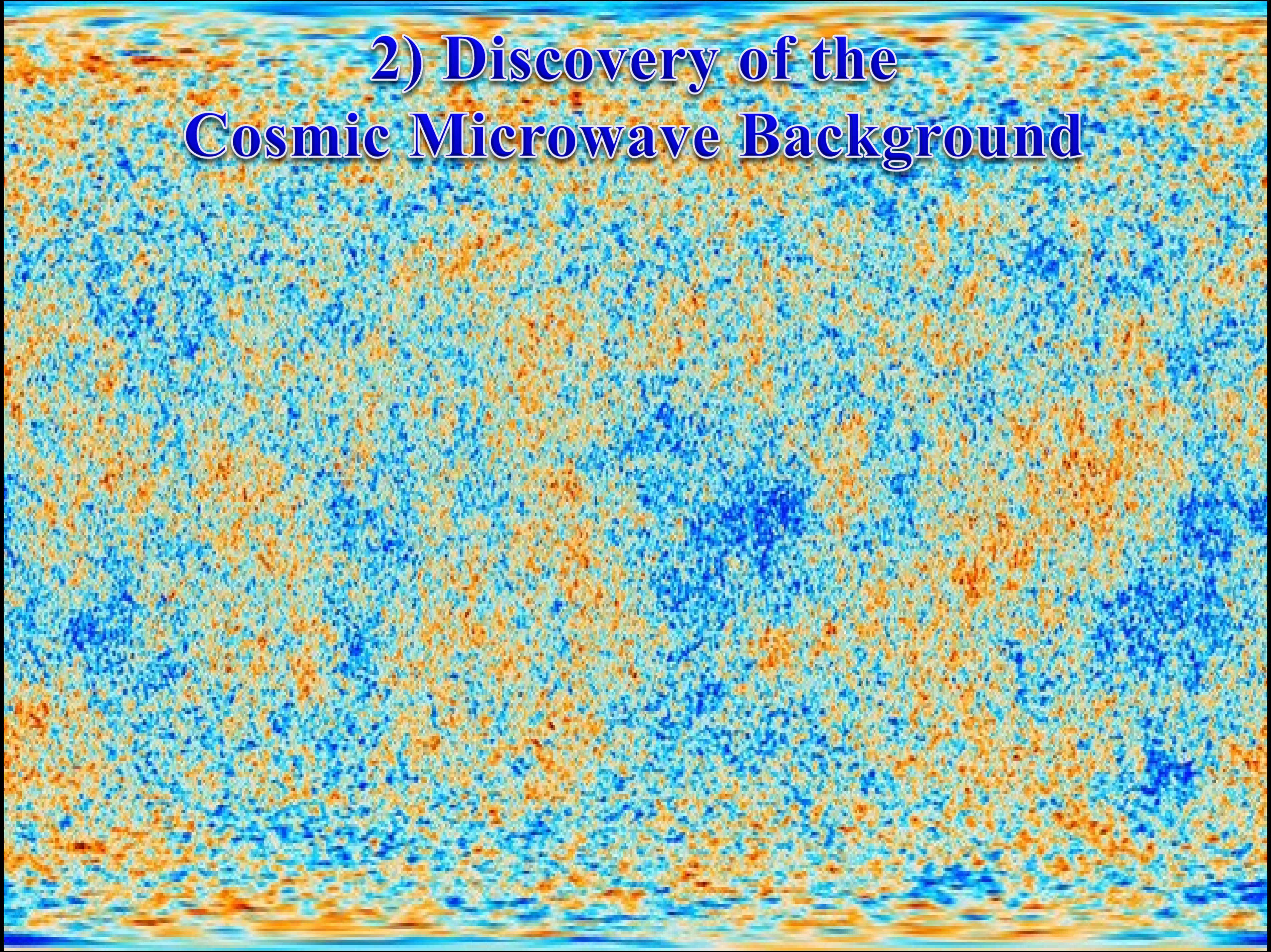
R = size of Universe when light left source

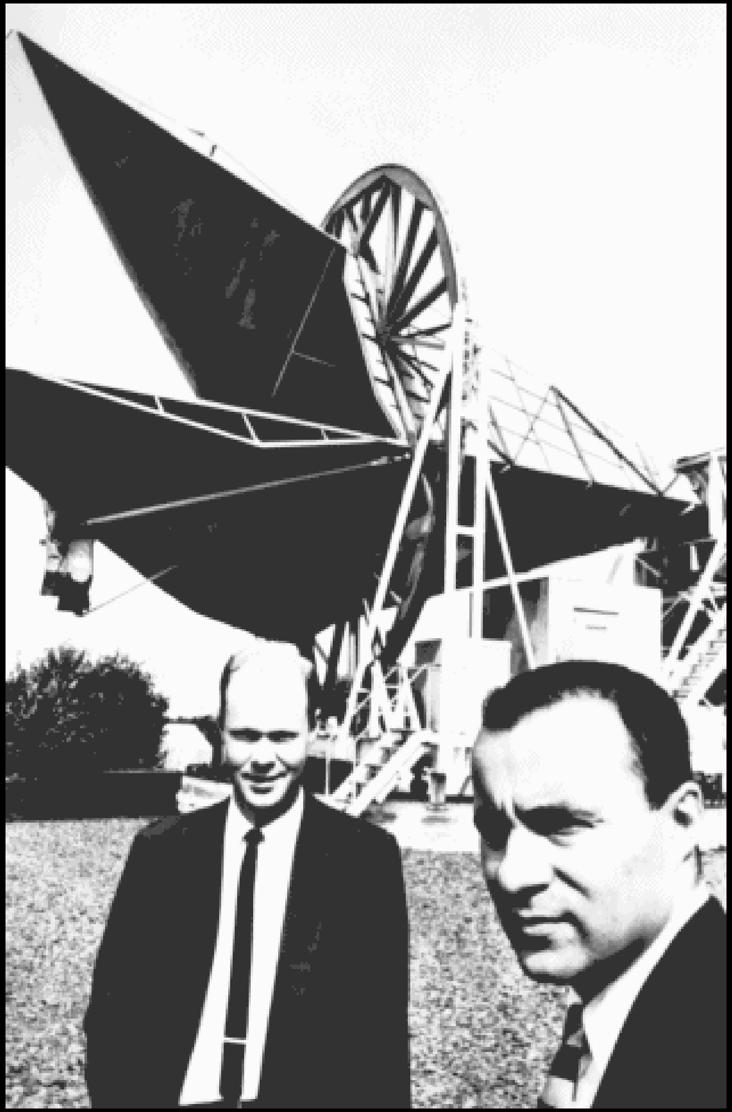
We now understand that the universe is expanding, presumably from some extremely hot, dense initial state. That much is accepted. But – there are still many details that are unknown.



Hubble flow:
$v(r) = H_0 r$

2) Discovery of the Cosmic Microwave Background





In the early 1960's Arno Penzias and Robert Wilson, then at Bell Labs in Holmdel, New Jersey, noticed a small discrepancy in their microwave instruments that indicated an excess of radiation coming in from space.

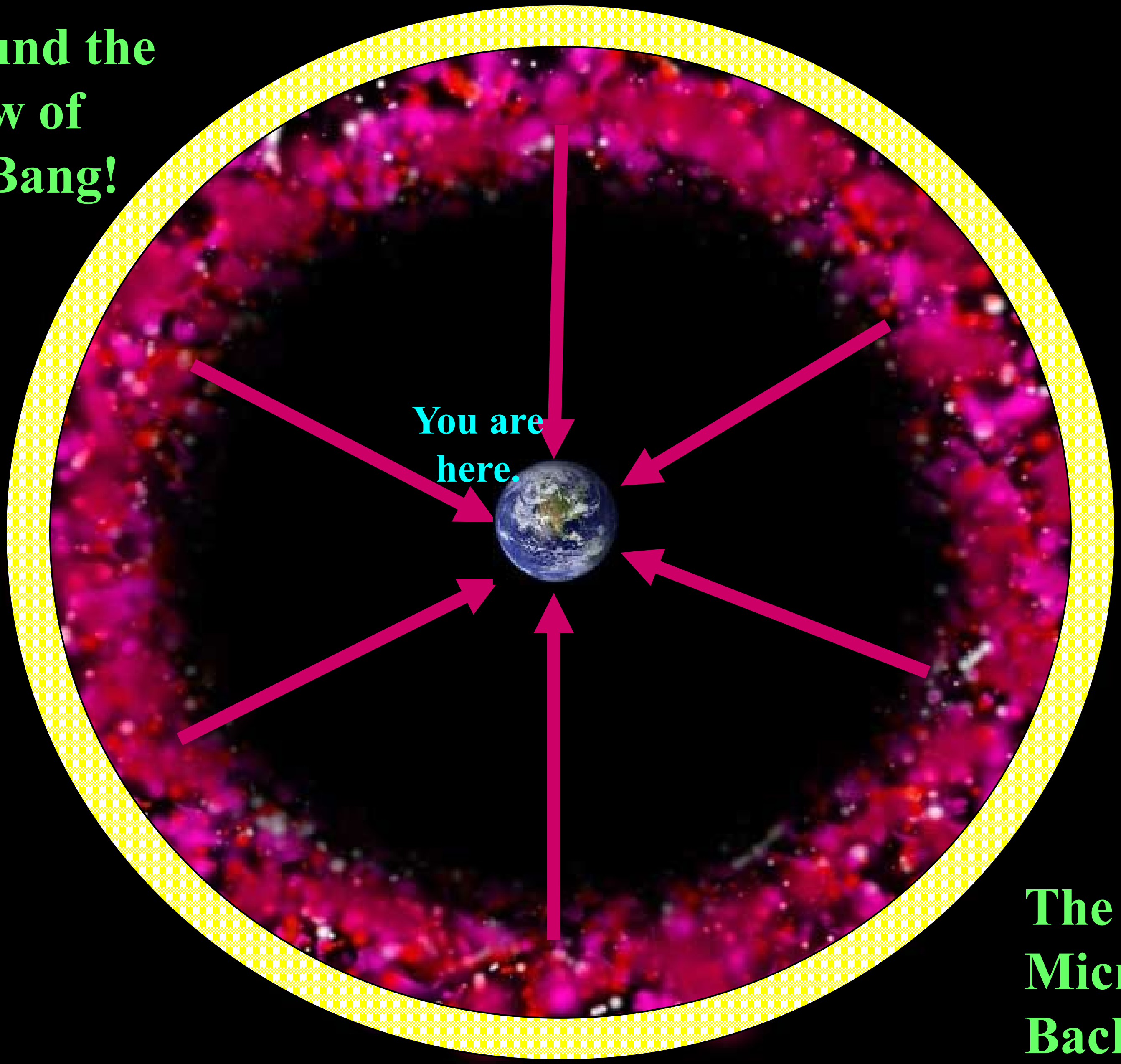
At first, they thought it was due to droppings of pigeons roosting in their microwave horn but, even after thoroughly cleaning their detector, the background noise remained.

Day, night, summer, winter – there was a constant hiss they could not get rid of.

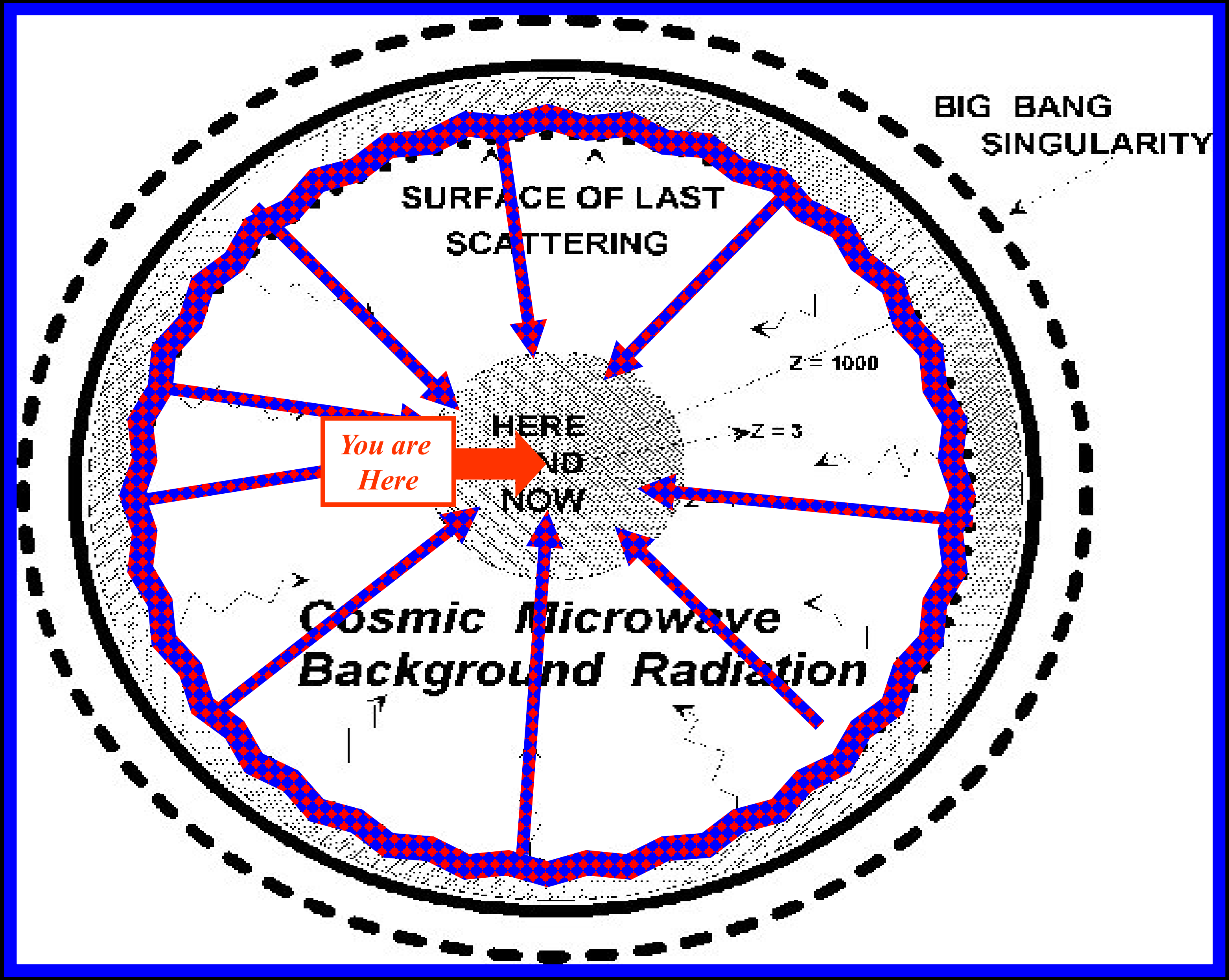
Not content to ignore it, they soon made one of the profound discoveries of the 20th century:

they had found the heat left over from the early universe!

They found the afterglow of the Big Bang!



The Cosmic Microwave Background (CMB)


BIG BANG
SINGULARITY
SURFACE OF LAST
SCATTERING
Z = 1000
Z = 3
HERE
NOW
You are
Here
Cosmic Microwave
Background Radiation

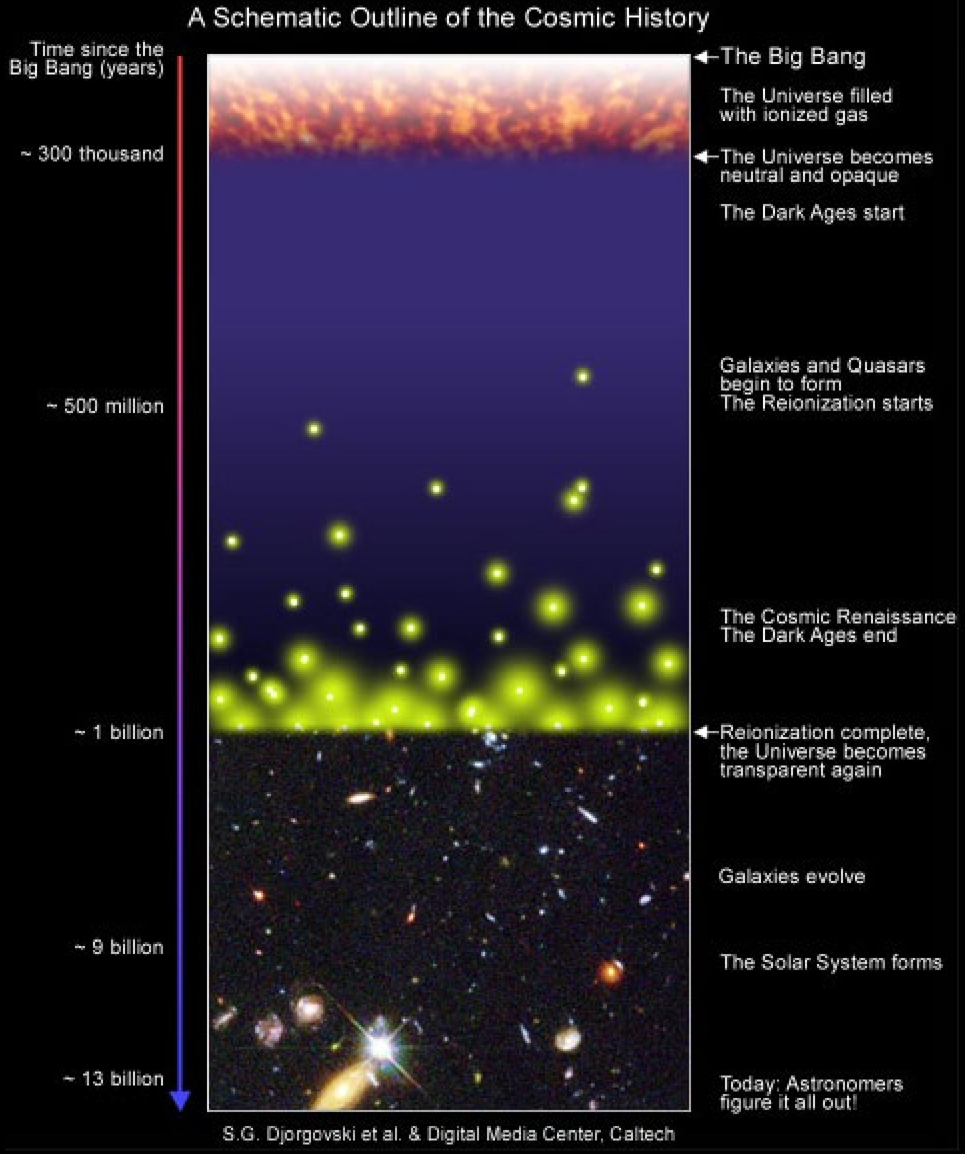
What is the Cosmic Microwave Background, or CMB?

The CMB is the thermal radiation left over from the hot Big Bang, 13.8 billion years ago, now observed at a temperature of 2.726 Kelvin.

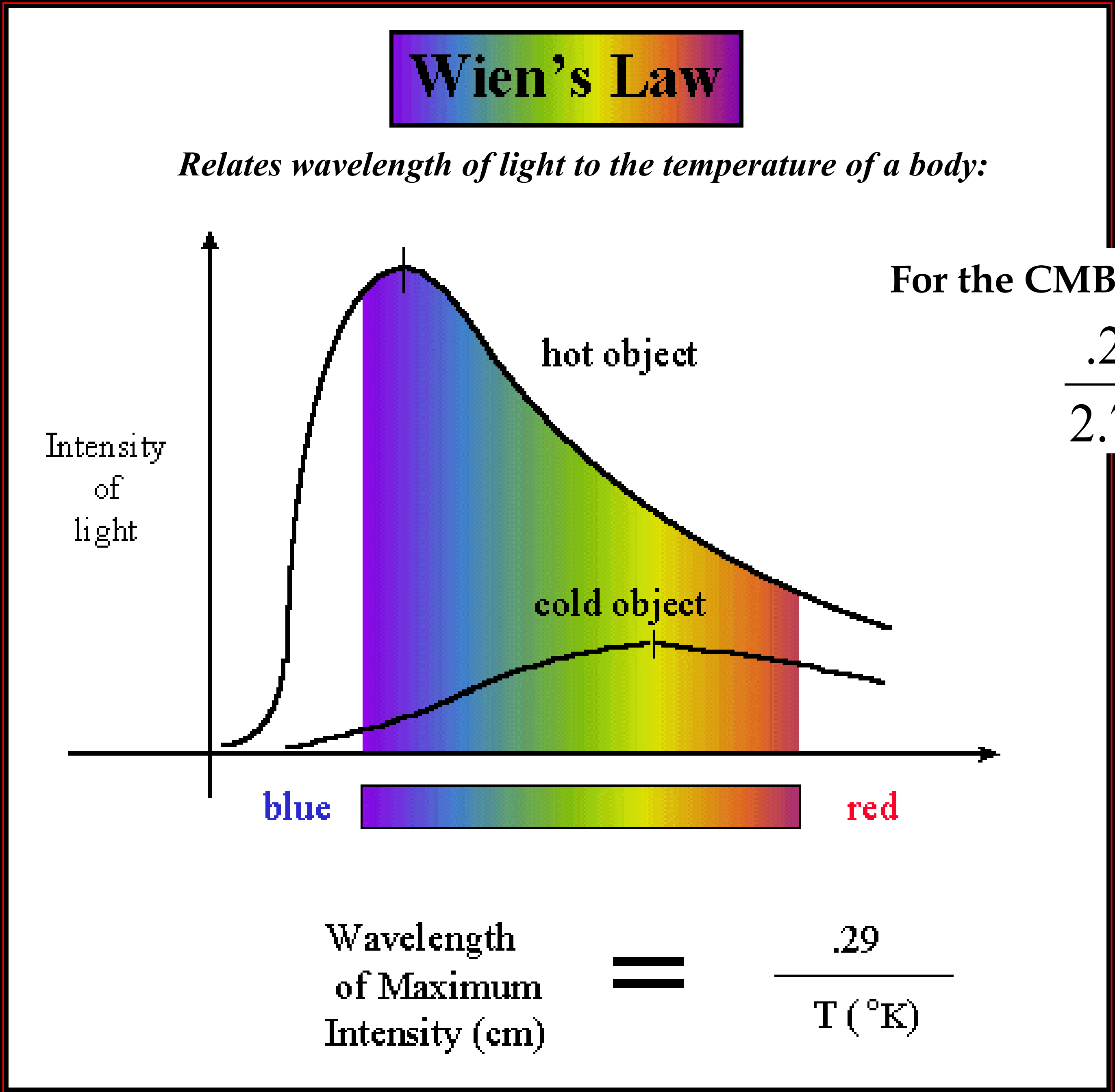
The CMB is the oldest light we can observe, coming to us from the time when the universe first became cool enough so as to be transparent to electromagnetic radiation, approximately 380,000 years after the Big Bang.

Before this time the universe was too hot and bright to see through, and photons could not travel very far before being scattered by charged particles.

A geologic column of the universe, looking back in time from the present to the past



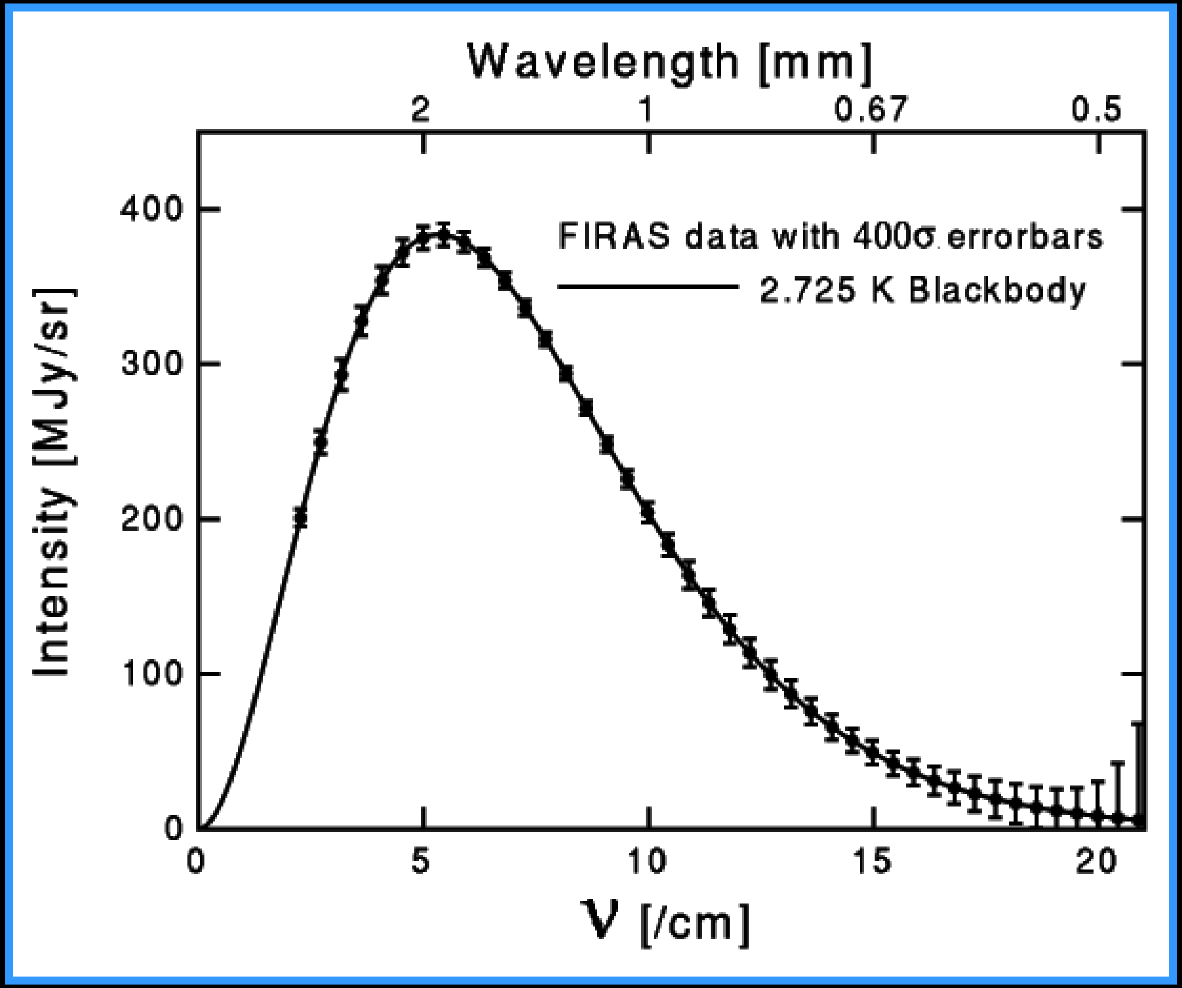
Remember this!



For the CMB, Wein's Law predicts:

$$\frac{.29cm}{2.725K} \cong 1mm$$

The black body spectrum of space peaks at a wavelength of approximately 1 millimeter, in the microwave region of the electromagnetic spectrum. Thus it was shown that the temperature of space is NOT ZERO!

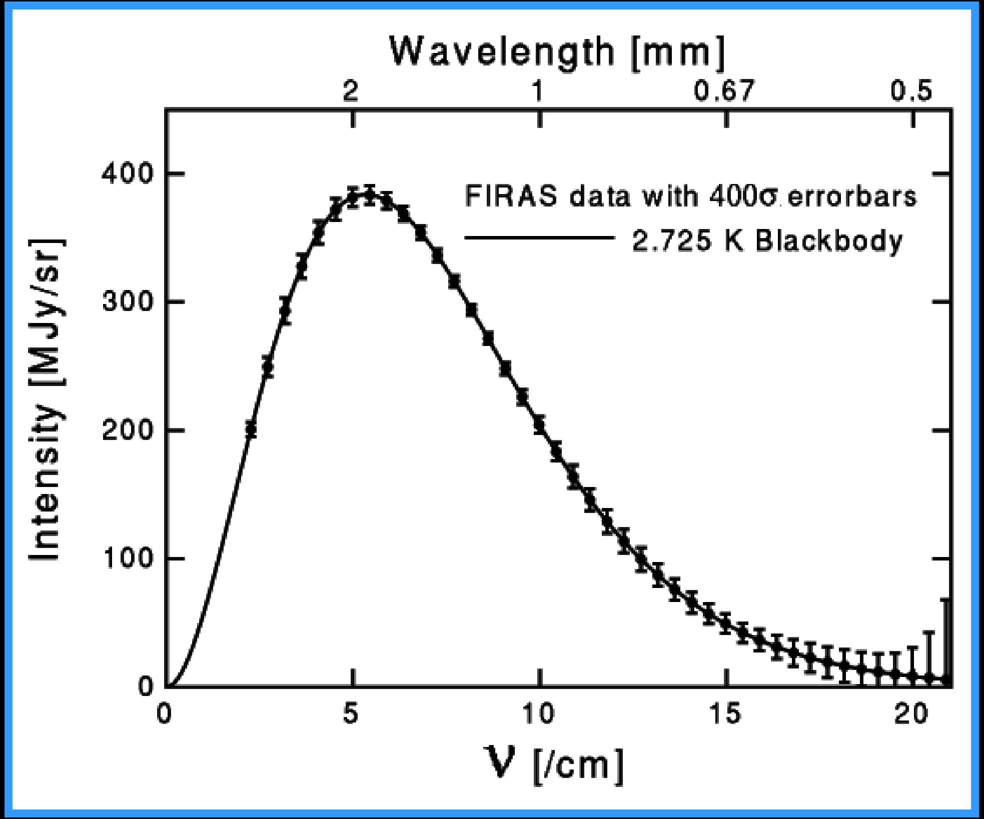


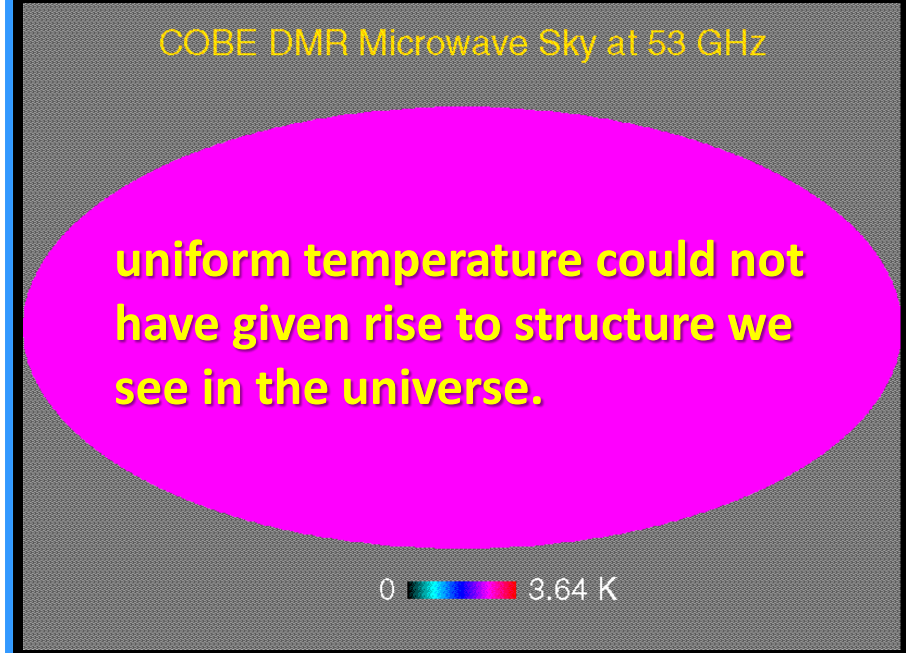
This is consistent with the prediction that the universe began in a hot, dense state, and the wavelengths of light from the early universe have been stretched by a factor of 1100 due to the expansion of the universe.

Remember when you calculated the temperatures of stars from the peak wavelength in their spectra? You can do this for the universe, too, because it is also a black body radiator!

The peak in the CMB black body curve indicates a temperature of 2.726 Kelvin.

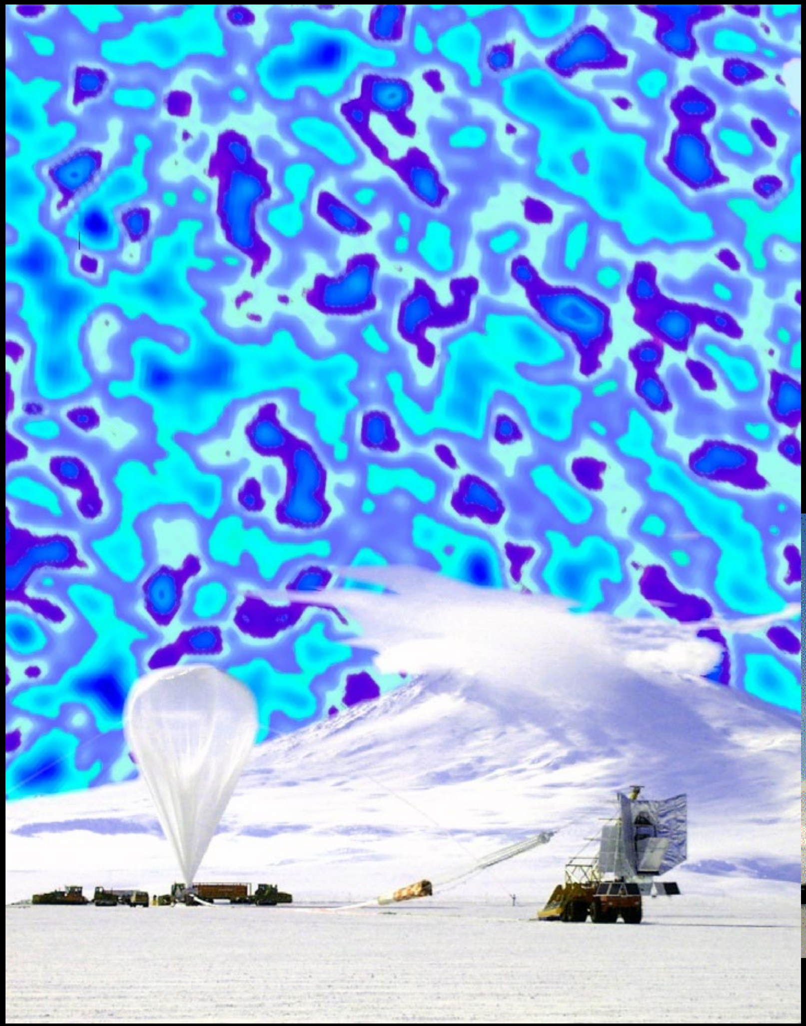
To a first order, the CMB follows a perfect black body thermal radiation curve which peaks at 2.726 Kelvin, however…





If the CMB were totally uniform, galaxies, stars, and life would not have evolved!! Thus, as soon as it was discovered, people began looking for variations in the CMB, which would indicate some inhomogeneities in the earliest moments of the universe, and which eventually led to the growth of structure in the universe.

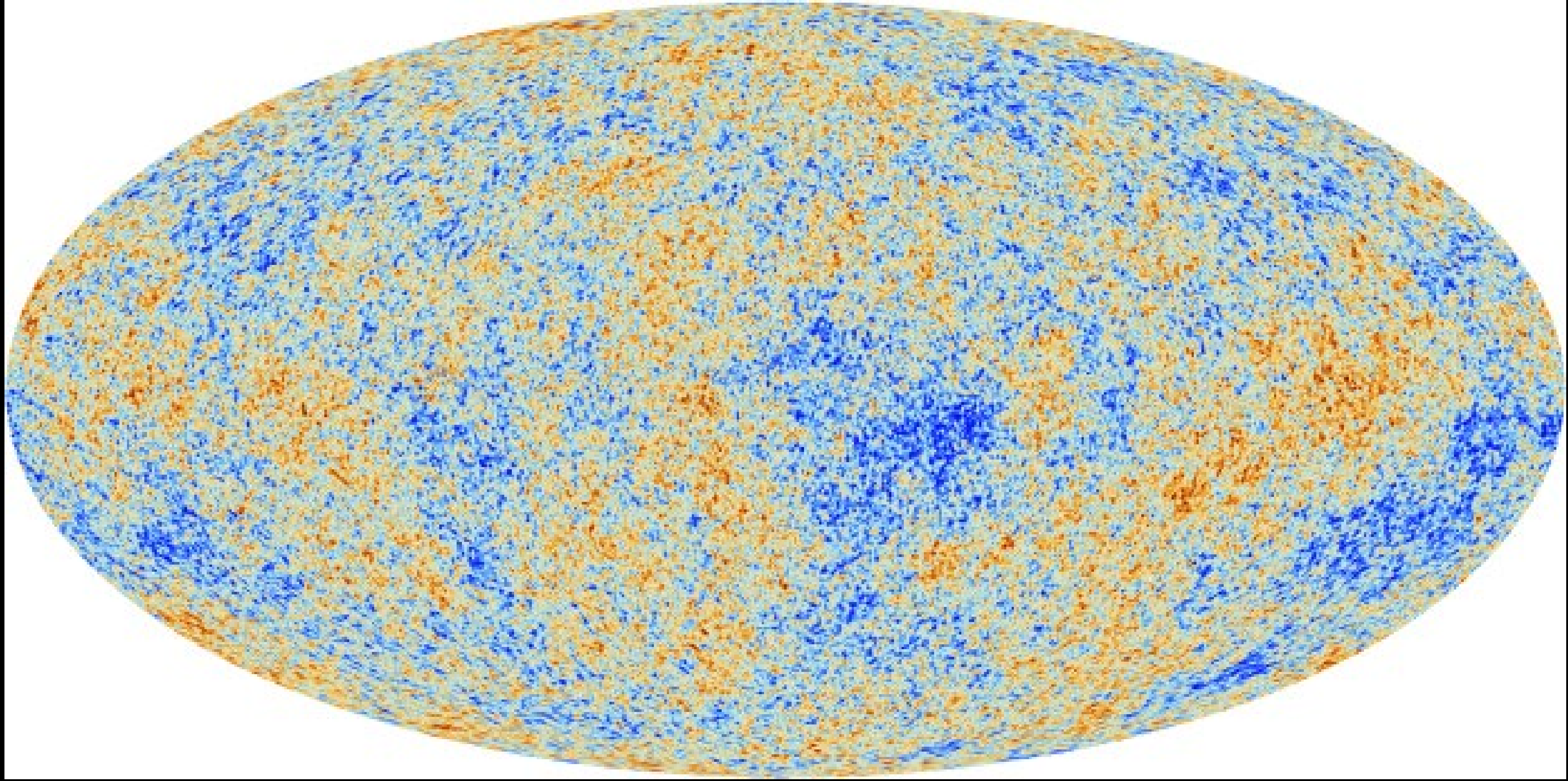
Since the discovery of the CMB by Penzias and Wilson in 1964, people have been mapping, with increasing precision, the small variations in the black body temperature of the universe, which would be the seeds of structure formation – how the universe developed galaxies and all the stuff we now see.



The BOOMERANG Mission: In 1999-2000 Boomerang mapped a portion of the CMB over Antarctica. The South Pole is a good place from which to observe the CMB because you are looking away from the plane of the galaxy, so there is much less interference.

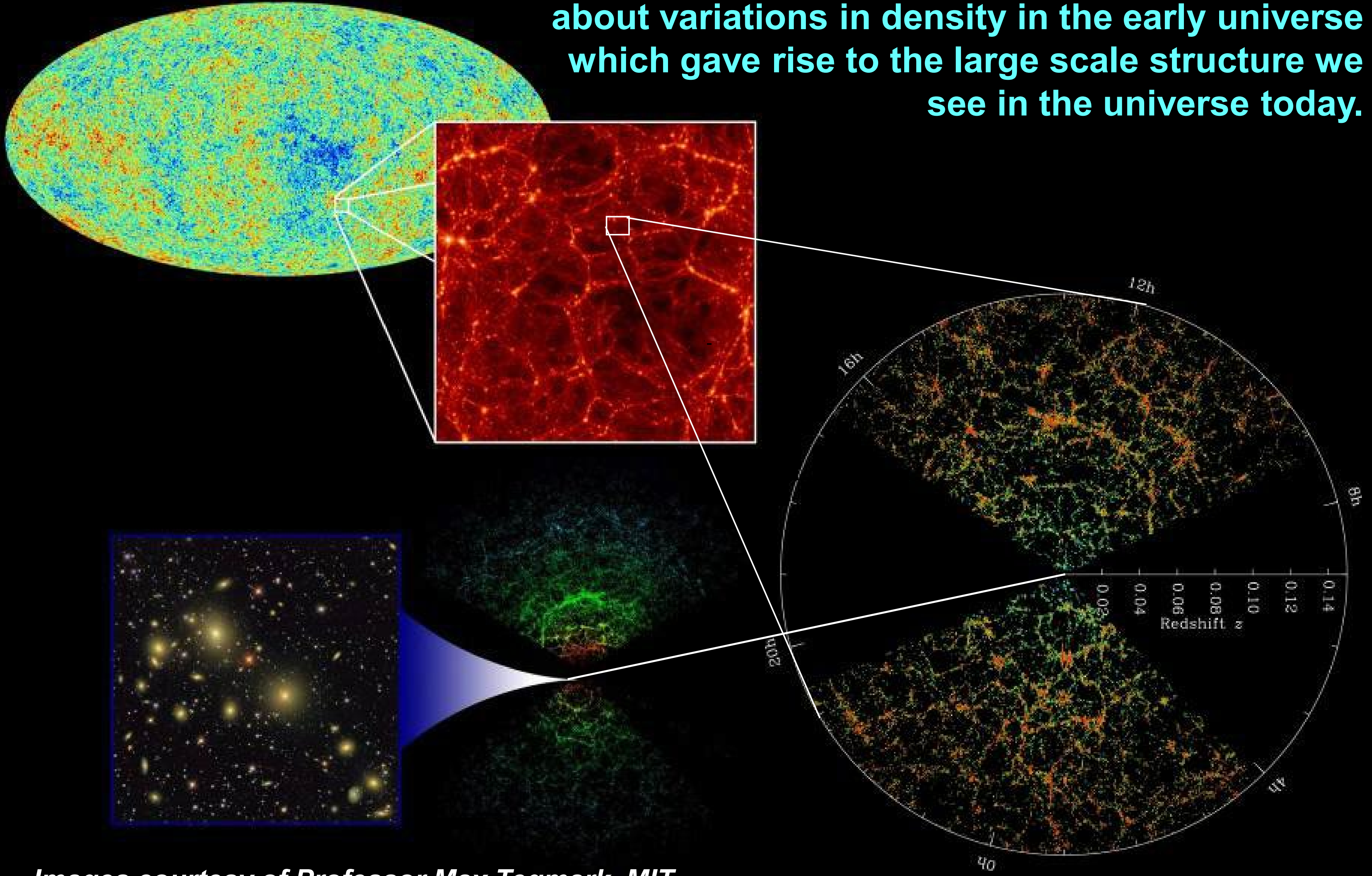
Left: The sky at a wavelength of 2 mm
Below: The sky at visible wavelengths

The most recent map (2016, Planck Mission) reveals the fine details in the temperature variations of the CMB, a few 100,000ths of a degree above (red) and below (blue) in the black body temperature of 2.726 Kelvin.



Distance to the measurable CMB:
13.8 billion ly
Distance to the actual CMB today:
around 46 billion ly

Understanding the minute temperature fluctuations in the CMB tells us about variations in density in the early universe which gave rise to the large scale structure we see in the universe today.

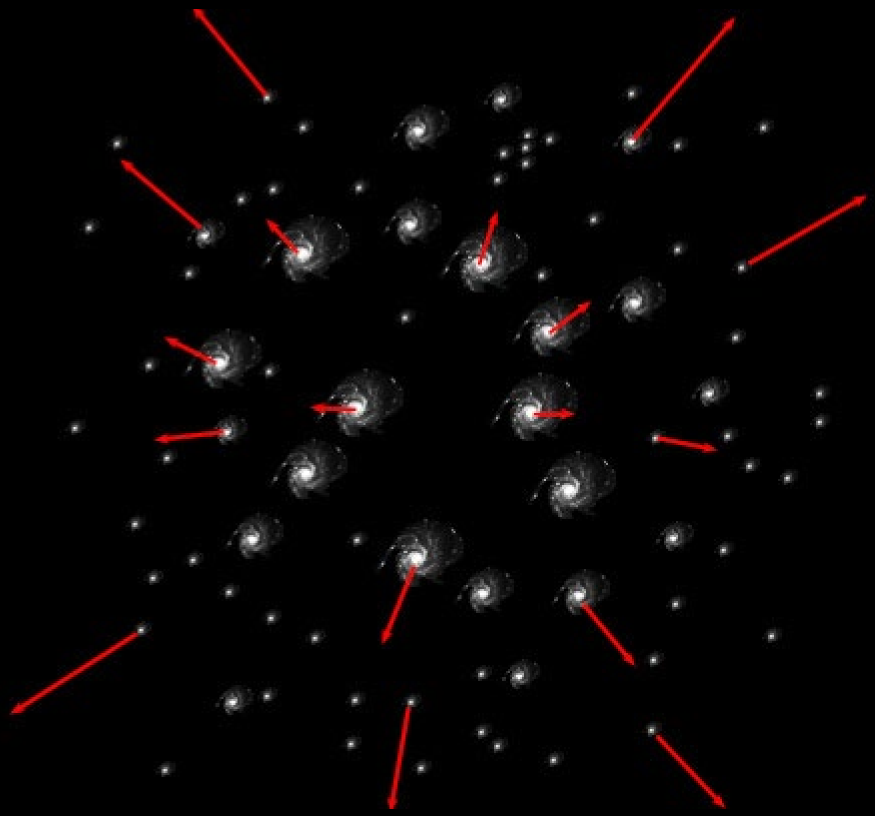


Images courtesy of Professor Max Tegmark, MIT

SUMMARY OF

Evidence for a Big Bang

1. **OBSERVED EXPANSION**



Evidence for Big Bang

2. The Cosmic Microwave Background. Diffuse light, now cold, left over from the early universe, when it was an expanding ball of plasma, now seen at a red shift of 1100.

This light provides evidence from a time when the universe was about 380,000 years old, and 3000 K (appearing red, actually).

The universe was about 1100 times smaller than it is today.

Today, this CMB radiation is at a temperature of 2.726 K, and has been observed in great detail.

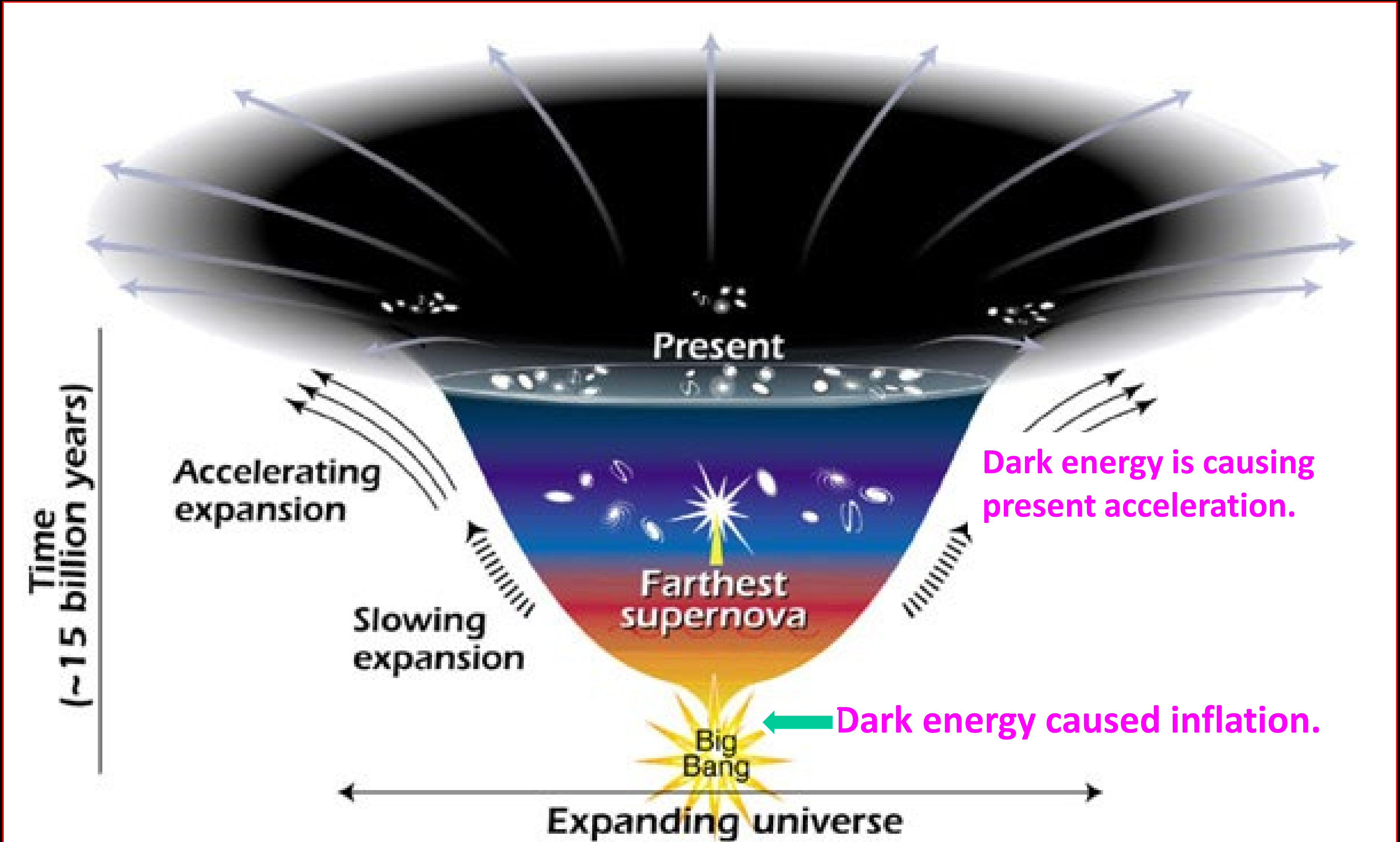
Evidence for Big Bang

3. Early Nuclear Byproducts. In the early hot dense state, the entire known universe was one big thermonuclear reactor! Predictions match observed atomic byproducts exceptionally well.

Amazingly, matching predictions to observations allows us to test the Big Bang back to a time when the universe was about one second old!

This is as far back as we have direct verification of the Big Bang. Predictions for earlier phenomena await further testing.

To make a long story short, we now understand that the universe is accelerating in its expansion rate, and that this acceleration began approximately 5 billion years ago.

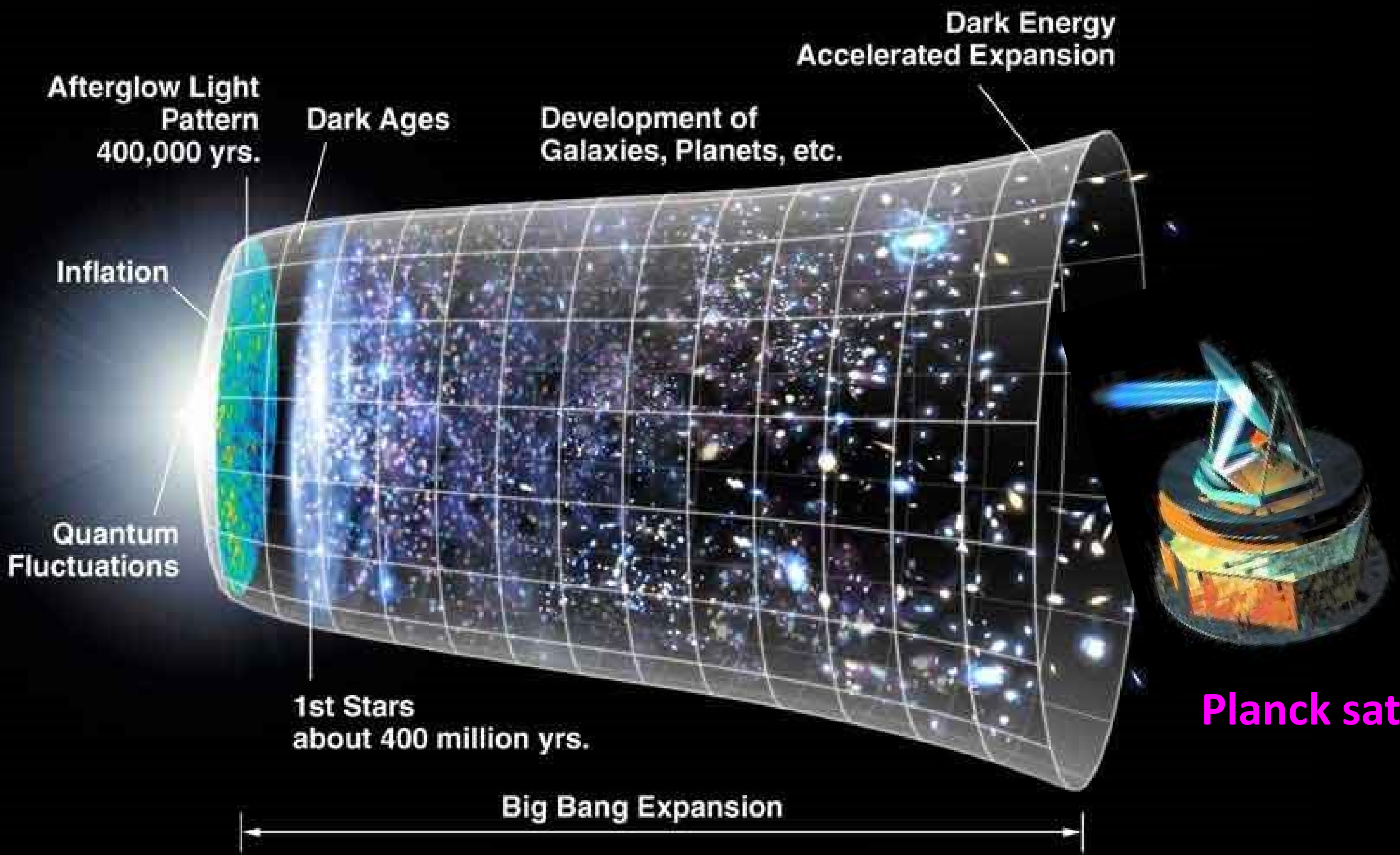


Dark energy is causing present acceleration.

Dark energy caused inflation.

And the evidence from high red shift supernovae is the most compelling evidence for the existence of dark energy, which is confirmed by evidence from the CMB.

5) Putting all the pieces of evidence together



Planck satellite

13.8 billion years

Brief History of the Universe – Reader's Digest Version!

10^{-44} second: Planck time – we don't know anything before this time

10^{-35} second – 10^{-30} second (???) : INFLATION ERA

10^{-30} second – 10^{-7} second: QUARK SOUP ERA

10^{-7} second: particle and antiparticle pair production stops

Somewhere in here neutrinos decouple

~ .75 second: electron/positron pair production stops when the temperature falls to 1 Mev/particle

~ 1 second: Nucleosynthesis begins – hydrogen & helium form, and a touch of lithium

~ 3 minutes: Nucleosynthesis ends!

Universe is filled with positively-charged light nuclei, electrons, and photons

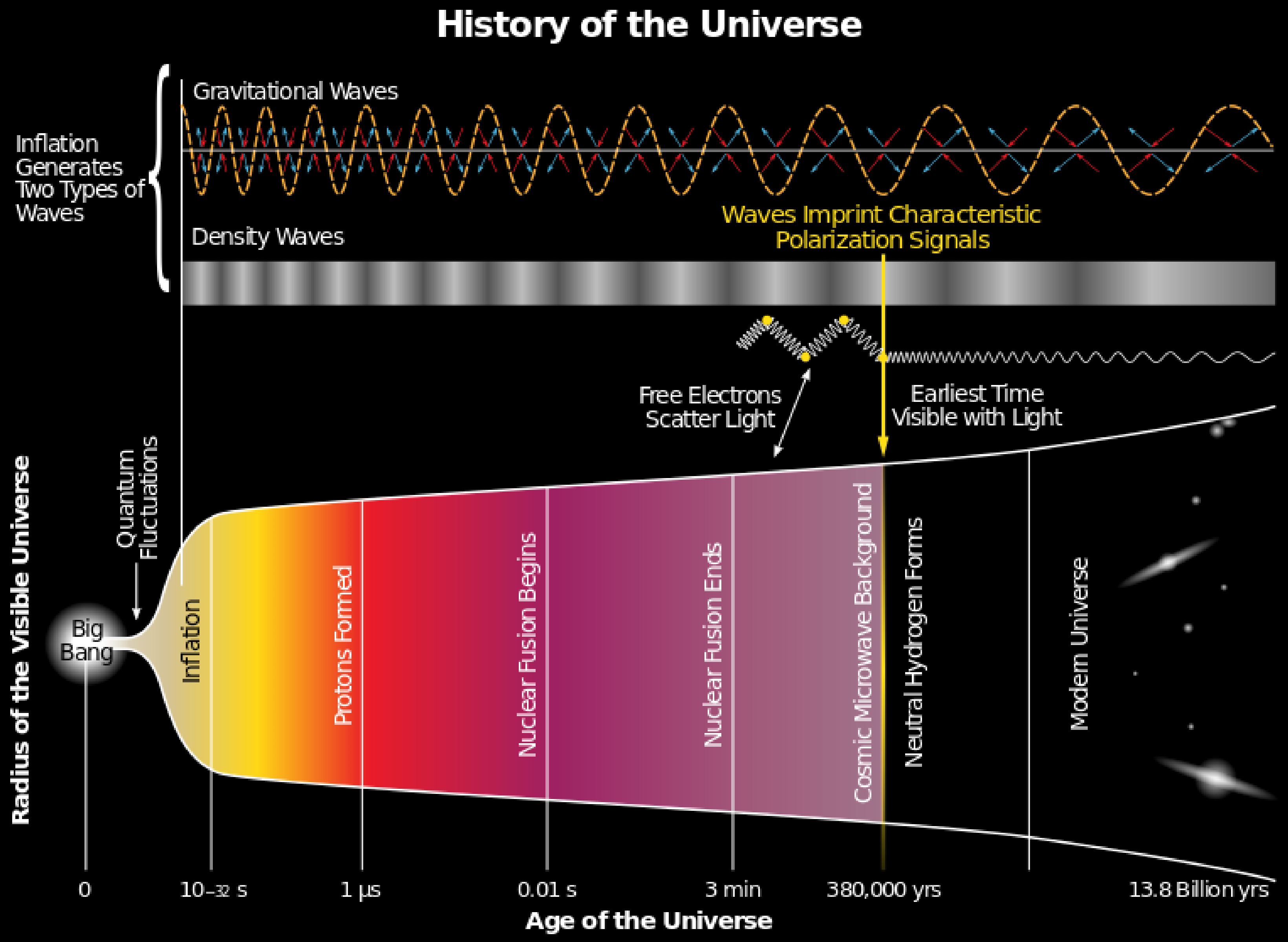
~380,000 years: Matter and radiation first decouple; first neutral atoms form; origin of the CMB

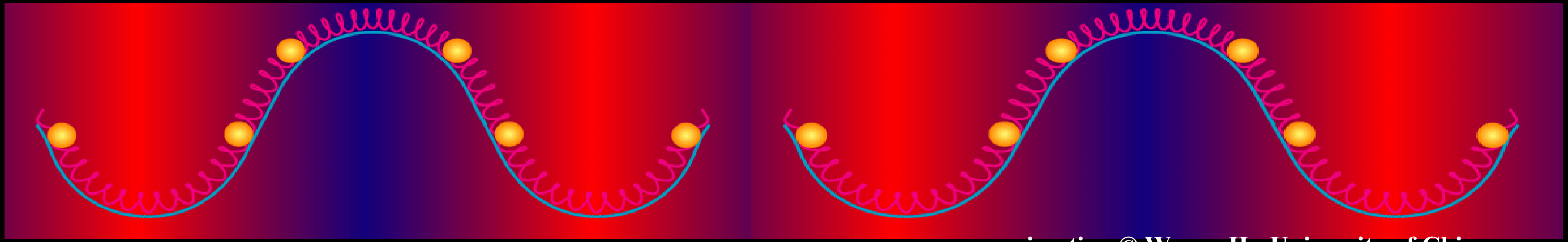
~ 200,000,000 years: First stars form

~ 690,000,000 years: First galaxies form – evidence from oldest known quasars

~13,800,000,000 years: TODAY

Pressure fluctuations in the early universe before 380,000 years gave rise to the structures we see today.




animation © Wayne Hu University of Chicago

Pressure Waves in the early Universe:

The small scale variations in temperature that we observe today in the CMB which are at a scale of one degree or less, were caused by oscillations in the plasma which filled the early Universe, causing local variations in the pressure and density of radiation and matter.

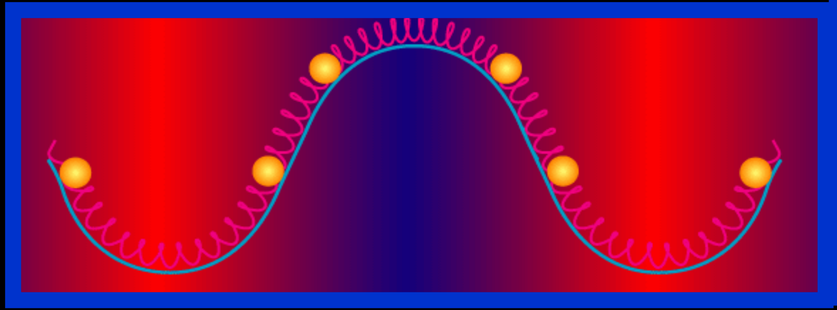
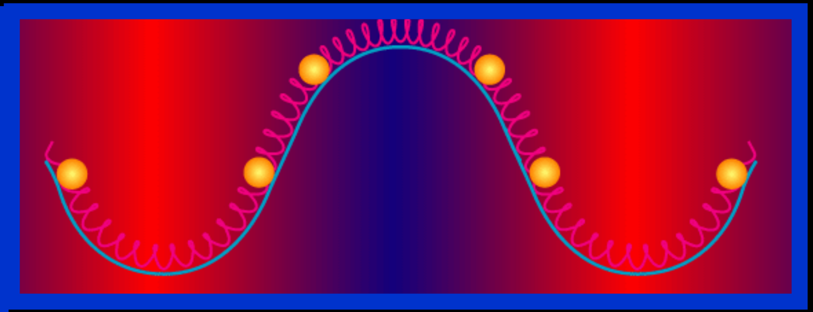
The variations in temperature that we observe in the CMB ...

$$\left\{ \boxed{\frac{\Delta T}{T} = \frac{\phi}{3c^2} \Rightarrow \frac{\Delta\rho}{\rho}} \right\}$$

...tell us about variations in density in the early universe...

Variations in density in the early universe led to

ACOUSTIC OSCILLATIONS
in the photon-baryon fluid which were induced by primordial inhomogeneities in the Big Bang

animation by Wayne Hu, University of Chicago

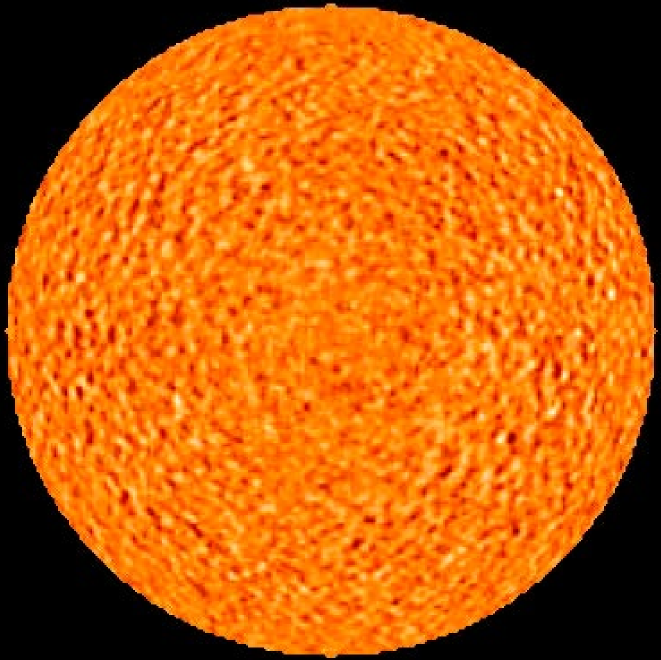
Recall sound waves in the Sun!

Pressure waves sloshing around inside a big ball of gas, such as the Sun, also generate sound waves!

We listened to these back in the chapter about the Sun, compressed by a factor of around 1,000, to the range of human hearing.

This same phenomenon was going on in the early universe, so we can model it as overlapping sound waves.

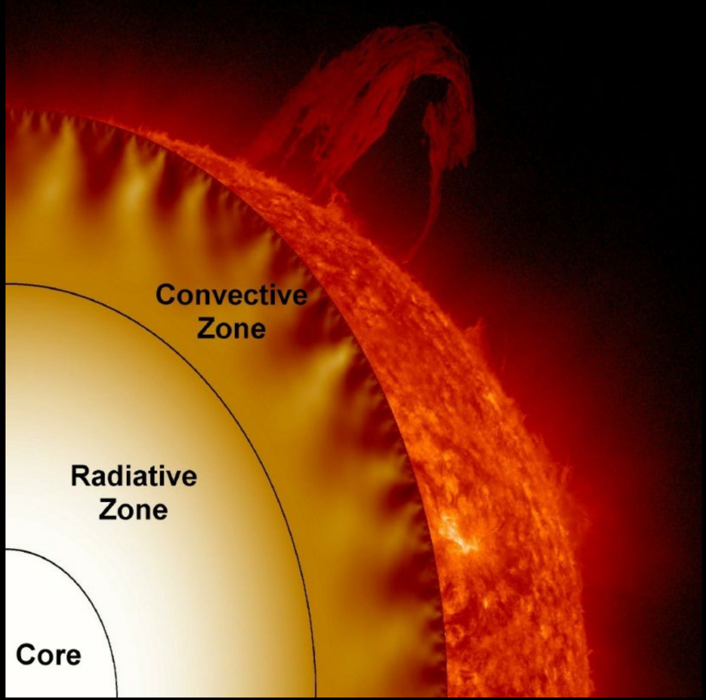
Review Lecture 10b: Our Sun, interior!



Recall from our study of the Sun:

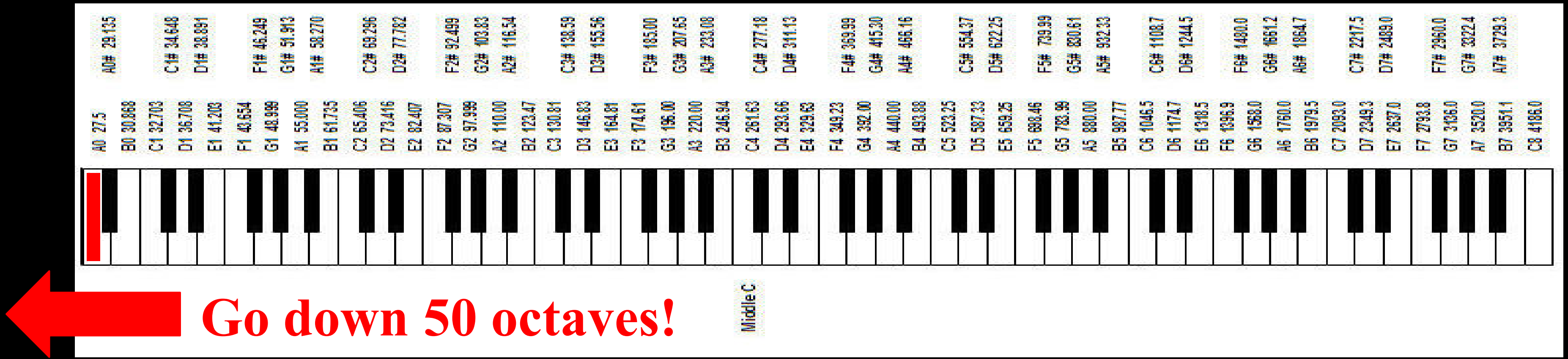
If you could go inside the convective zone of the Sun, here is what it might sound like. Frequencies have been compressed by a factor of 42,000 so that we can hear them.

Source: http://bison.ph.bham.ac.uk/ .



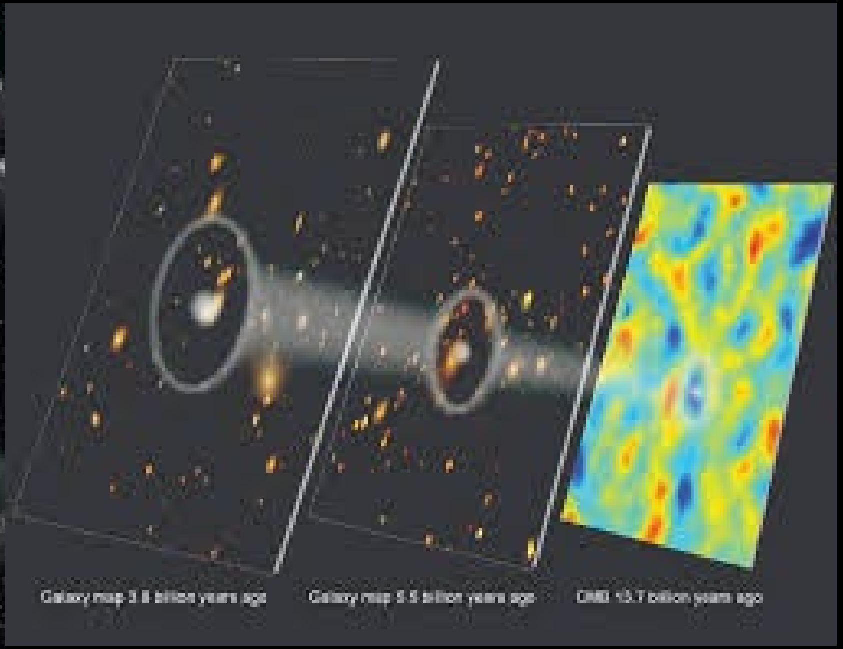
Power spectrum of the sounds of the Sun (above) that I derived using a sound editing program called CoolEdit Pro. The peak in the spectrum tells you the frequency at which the majority of sounds are – just like a light spectrum!

The fundamental "tone" of the early universe (longest pressure wave) was around *500,000 light years across*. This tone would have been on the order of 10^{-14} Hz, or around 50 octaves below the lowest note on the piano



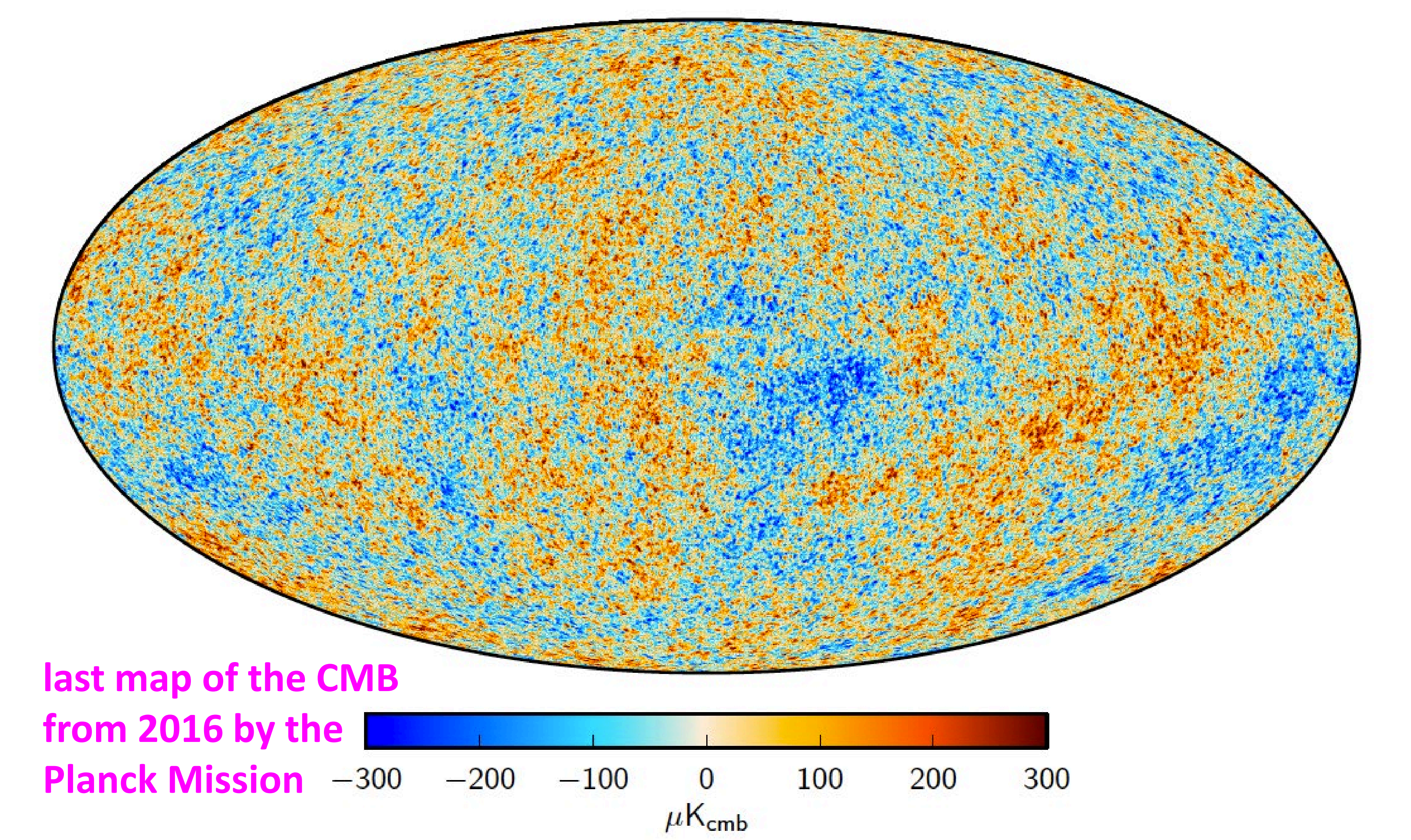
Here is the raw sound of the early universe during the era of photon-baryon acoustic oscillations, compressed by 52 octaves, to the range of human hearing. This sound file was created by Prof. Mark Whittle of the University of Virginia.

These sound waves in the primordial universe created regions of excess density, which can be seen today in the large scale clustering of galaxies.



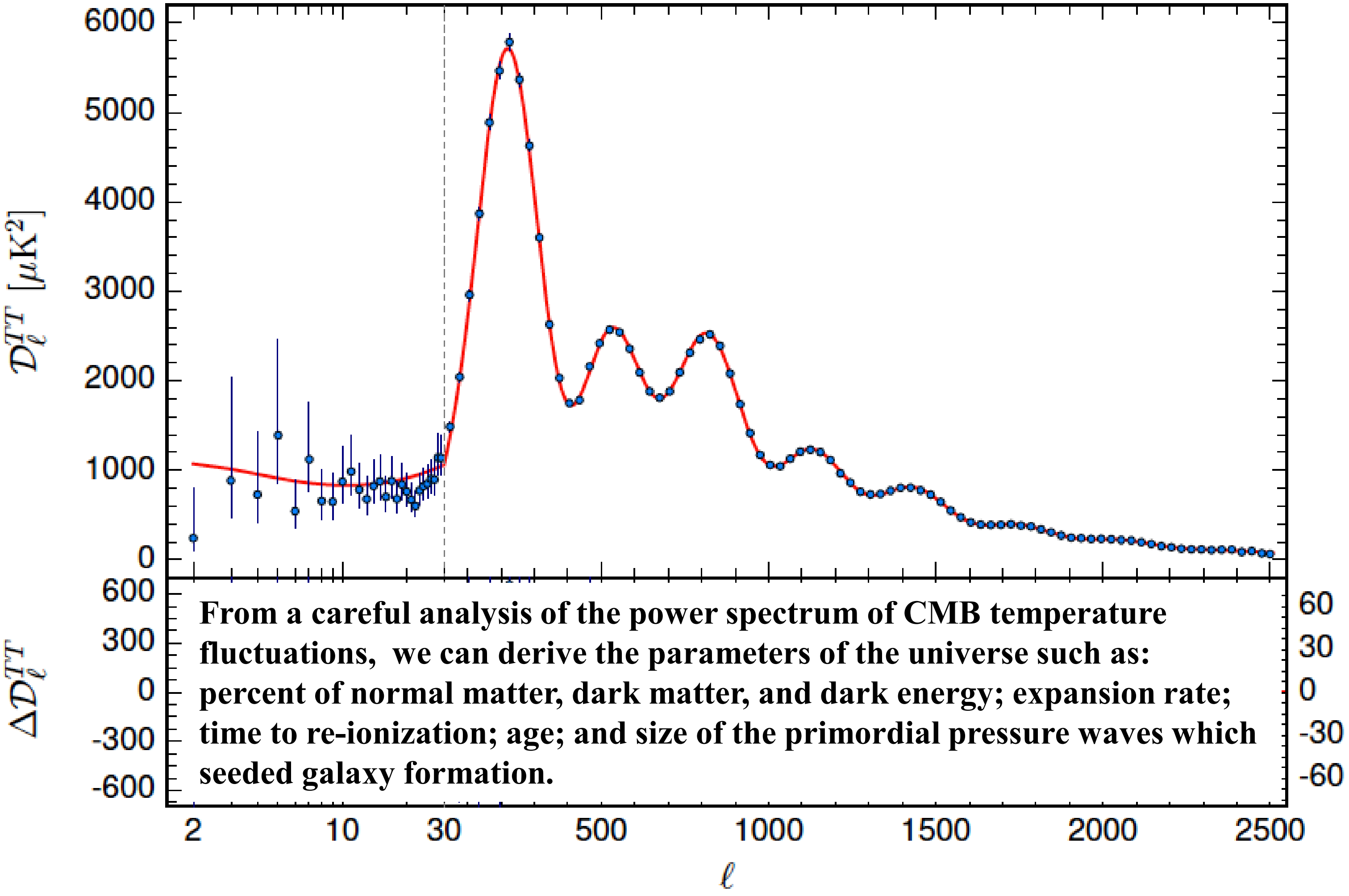
See video assigned in this week’s Canvas module on Acoustic Fluctuations in the Early Universe.

From the most recent detailed map of temperature variations in the CMB by the Planck Mission, we derive the Power Spectrum of the CMB



last map of the CMB from 2016 by the Planck Mission

Power Spectrum of Temperature Fluctuations in the CMB



From a careful analysis of the power spectrum of CMB temperature fluctuations, we can derive the parameters of the universe such as: percent of normal matter, dark matter, and dark energy; expansion rate; time to re-ionization; age; and size of the primordial pressure waves which seeded galaxy formation.

l **is the angular wave number – the spatial analogy of frequency in a time-dependent series of waves, such as a sound spectrum**

Each "omega" represents the ratio of the density of each component to the critical density for a spatially flat universe:

$$\Omega_{baryon} + \Omega_{darkmatter} + \Omega_{radiation} + \Omega_{\Lambda} = 1$$

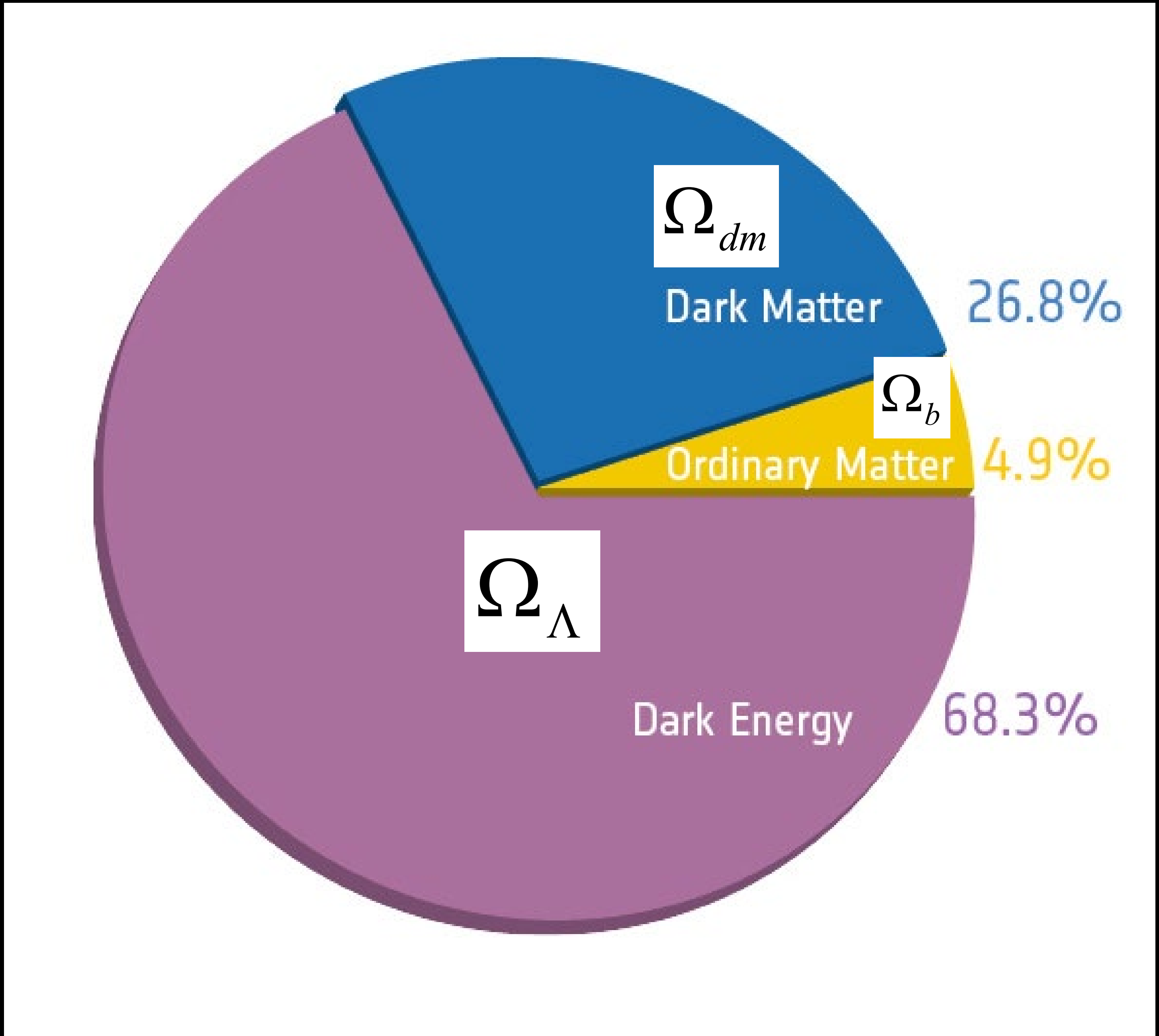
consider these together as "Omega matter"

neglect, 'cause it's so teensy weensy

Mysterious dark energy that appears to make up most of the Universe

These represent ratios of the density of each component relative to the CRITICAL DENSITY of the universe that matches the CMB power spectrum.

Best estimates for ordinary matter, dark matter, and dark energy derived from the power spectrum of the CMB.



http://planck.cf.ac.uk/results/cosmic-microwave-background

Our present best understanding of our universe:
"Lambda-CDM" – namely, that our universe started as a singularity with cold dark matter (CDM) and a cosmological constant (Λ, "Lambda").

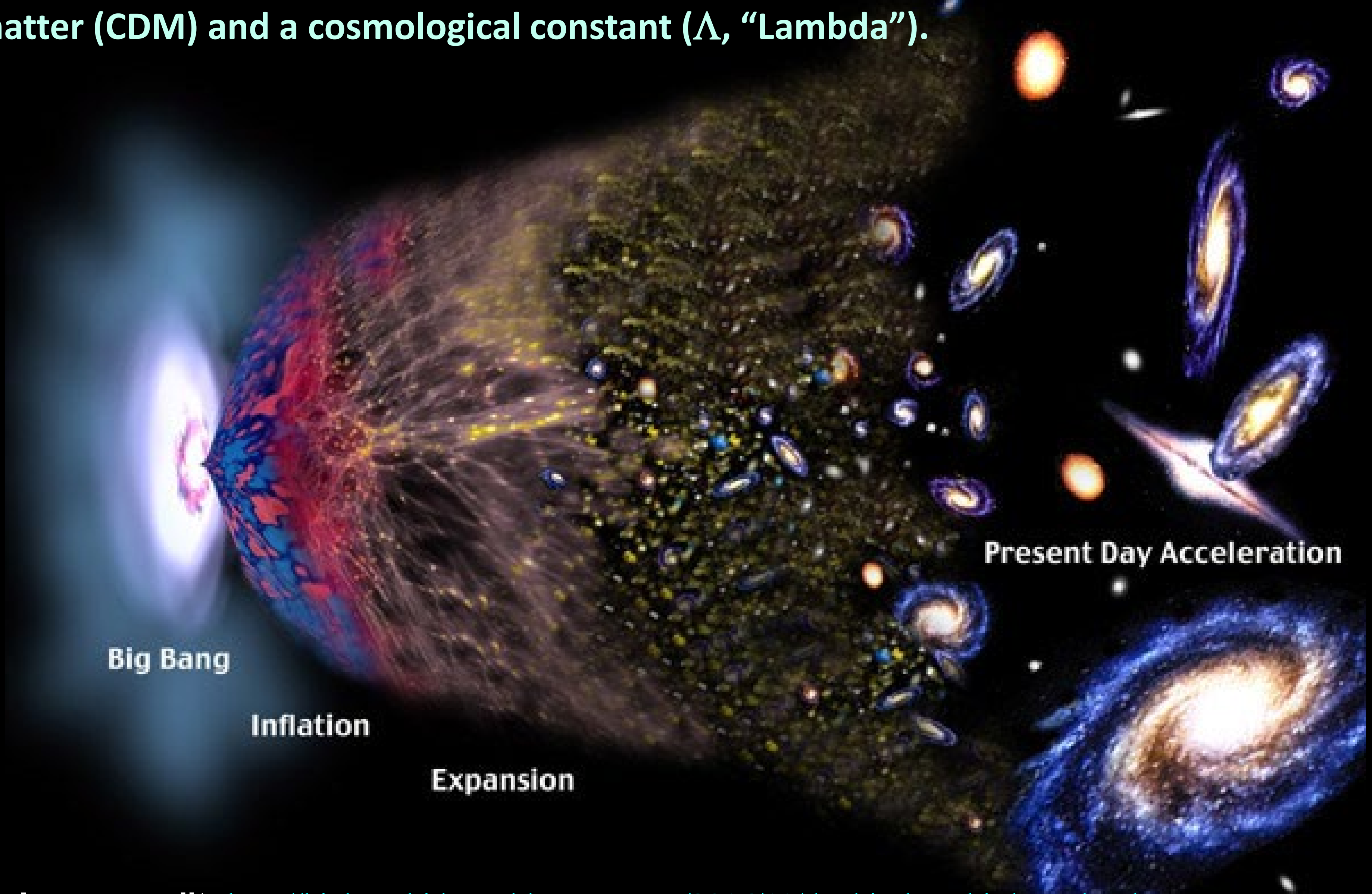


Image credit: http://bigbangbitbang.blogspot.com/2016/11/the-big-bangbit-bang.html

Contents of the universe:

< 5% Atoms – regular matter

> 95% unknown!!!!

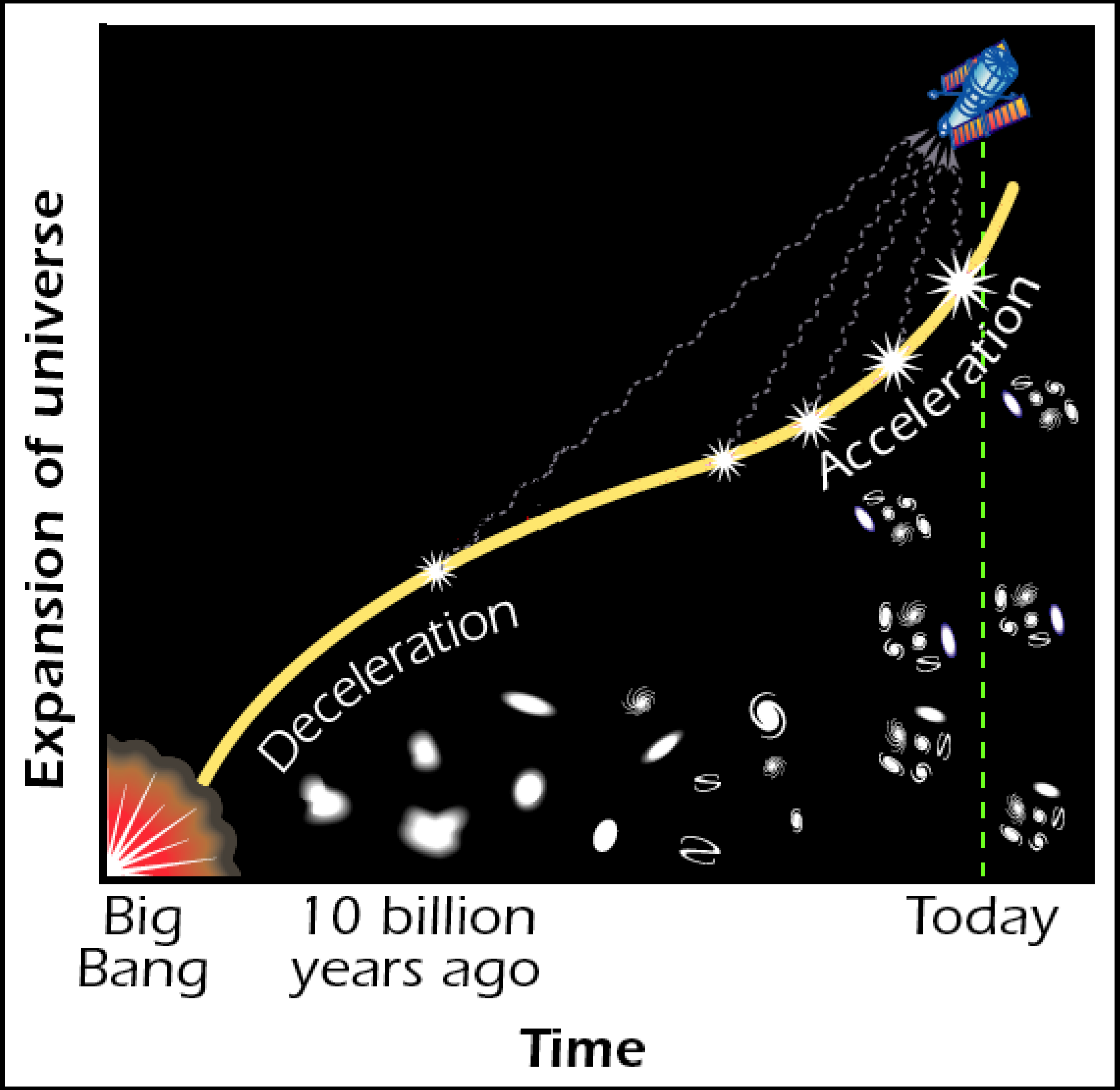
We need new physics to figure out the 95%

See short videos by Brian Greene and Neil deGrasse Tyson in this week's Canvas module.

Conclusions:

- **Until about 5 billion years ago, the expansion of the universe was *slowing down*.**

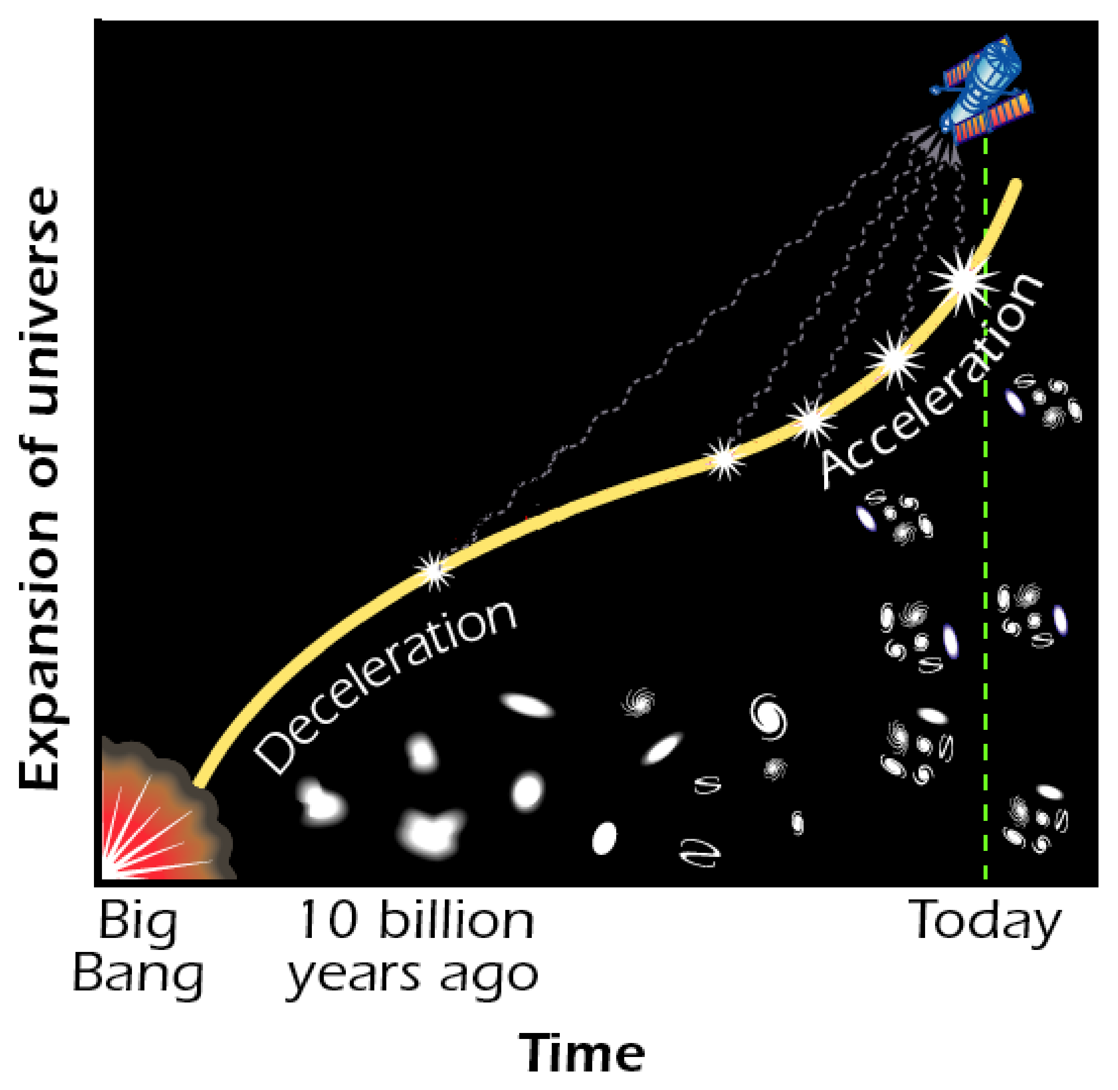
- **Since then, the expansion has been *speeding up.***



Our best explanation:

- **The universe is suffused with a kind of "antigravity" called DARK ENERGY.**

- **For the past 5 billion years, *dark energy has been the dominant form of energy in the universe.***



What is the Source of Dark Energy?

(weird particles, mysterious fields, properties of space itself, modifying Einstein’s equations, the existence of hidden extra dimensions that we can’t see???)

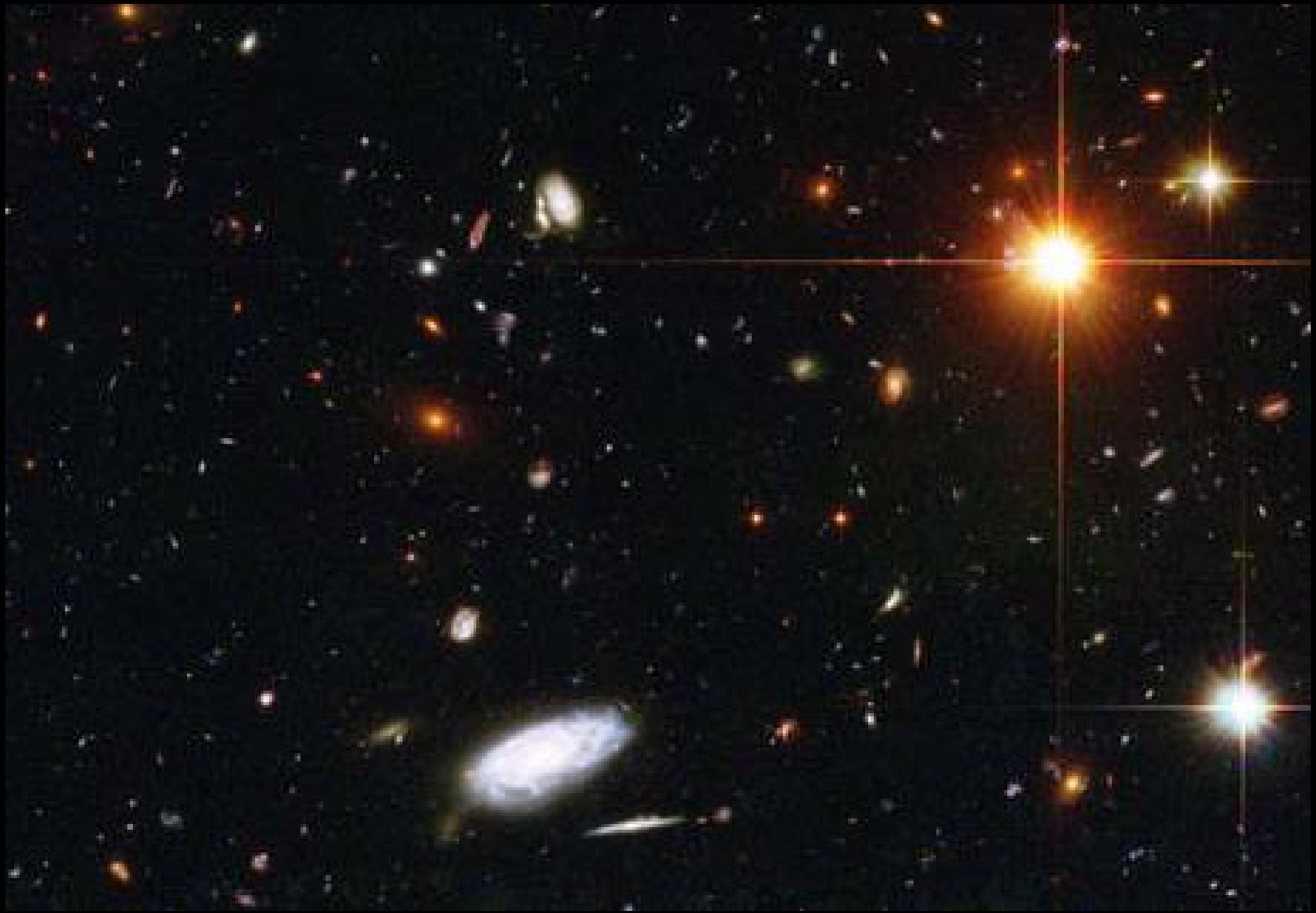
We don’t know…

There are ideas, but none have worked out so far.

Other ideas require more observations to test.

Because dark energy is dominant, at the present time, the expansion of the universe will continue forever at an ever-increasing rate.

…eventually receding away faster than the speed of light!



Tens of billions of years from now, other galaxies will be so far away as to be invisible…

...and a future observer in our Milky Way galaxy will think they are the only galaxy in a vast universe of darkness.