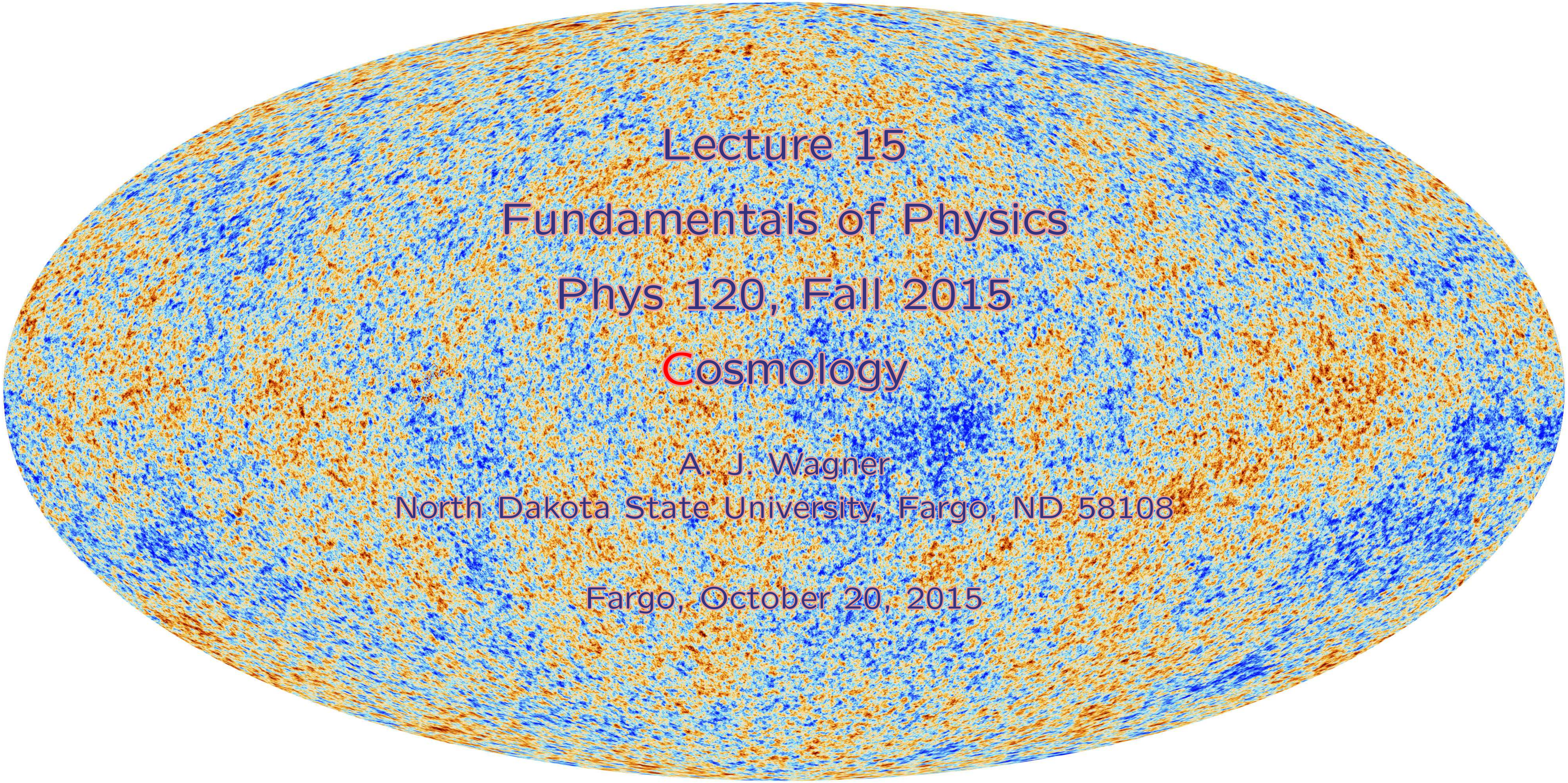

Lecture 15

Fundamentals of Physics

Phys 120, Fall 2015

Cosmology

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Overview

- A history of our view of the universe
- The Big Bang
- The possible geometries of the universe
- Dark Matter
- The accelerating universe and dark energy
- Cosmic inflation and a brief history of the universe

Early cosmology

In the helenistic world the Ptolomeic worldview reigned.

Copernicus brought the idea of a Heliocentric world, and Kepler showed that planets move on ellipses around the sun.

Newton showed that this is exactly what you should expect to find if the planets follow Newton's second law and there is Netwon's force of gravity acting between them.

People start to speculate that the firmament is made up of lots of independent stars with their own planets.

Einstein's general theory of relativity made intersting predictions about the nature of gravity, and lead to corrections to Newton's law of gravity. It predicted the precession of Mercury, that had been previously predicted.

It did something more: according to Einstein's general theory of relativity the universe was not stationary! This was too much, even for Einstein, who altered his equations and added a "fudge factor", so that he could recover the stationary universe.

Looking ahead

There are some parts of later lectures that we need to “borrow” right now:

- Atomic nuclei are made up of parts, called protons (carrying a charge of +e) and neutrons (no charge). The number of protons determines the chemical element, but the same chemical atom can have a varying number of neutrons. (These different atoms are called isotopes).

- Light interacts strongly with free electrons and protons, but very little with neutral atoms (i.e. once electrons and protons have combined to atoms).

- Atoms emit light of very specific wavelength. This allows us to determine what kinds of atoms the light came from. (This is known as spectroscopy).

- If radiation comes from a source moving away (or if the space it is moving through expands) the wavelength increases. This change in wavelength is called “Doppler shift” and it allows us to determine the speed of an object through spectroscopy.

The expanding universe and the big bang

Edwin Hubble (1889-1952) was an astronomer. He discovered that some smudgy looking objects, which they called nebulae, were located outside the milky way*. Thus began the discovery of many distant galaxies.

In 1929 Hubble discovered that all galaxies in the universe are moving away from each other†. This looked like they were driven apart by an explosion. Currently the Universe expands by 1% in the next 10^8 years. Extrapolating backwards in time from the speeds and distances we see today, the galaxies should have all been together 14×10^9 years ago.

Einstein was amazed and angry with himself for disbelieving the predictions of his own theory.

*In order to do that he needed a measure for distance that only depended on the light that reaches us here on earth! He used the brightness of some special stars that come in one size, then brightness $\propto (distance)^2$.

†How did they do that? He also needed a measure for speed, which came in the form of shifts in spectral lines. More about those later.

Concept Check

What does the general theory of relativity predict about the universe?

1. The universe is static

2. The universe needs to be expanding

3. The universe is collapsing under its own gravity

4. The universe is either expanding or contracting, but not stationary.

Cosmology and the Big Bang

We are living in a golden age of **cosmology**: the study of the origin, structures, and evolution of the large-scale universe. It started in 1992 when satellites charted the first detailed map of the early universe.

With the help of exciting new observational tools (such as the Hubble space telescope) and armed with the theoretical understanding of general relativity we can predict the possible ways our three-dimensional universe could evolve throughout past and future time.

This allowed us to conclude that the universe is 13.73 billion years ($\pm 1\%$) old. The universe began in a single event called the **big bang**. This event created the different forms of matter and energy, and it caused it to expand from a much smaller initial size.

How do we know there was a big bang? II

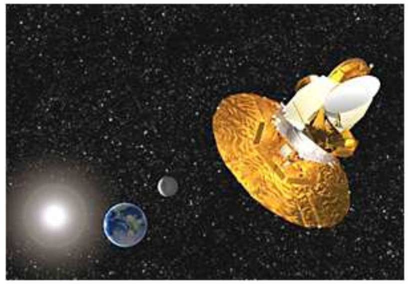
In 1964 astronomers first detected the **cosmic microwave background**, the faint afterglow that still fills the universe from the hot initial explosion. This is the light that remains from the time when the universe became transparent to light, after the electrons and protons combined into neutral atoms that only weakly interact with light.

This radiation has now cooled down to $-270°$C ($3°$ above absolute zero) because the expansion of space increases its wavelength*. This cold radiation has too little energy to be visible and is observable today only as a faint radio static in the microwave and radio regions of the spectrum. The observed details agree with the big bang theory predictions.

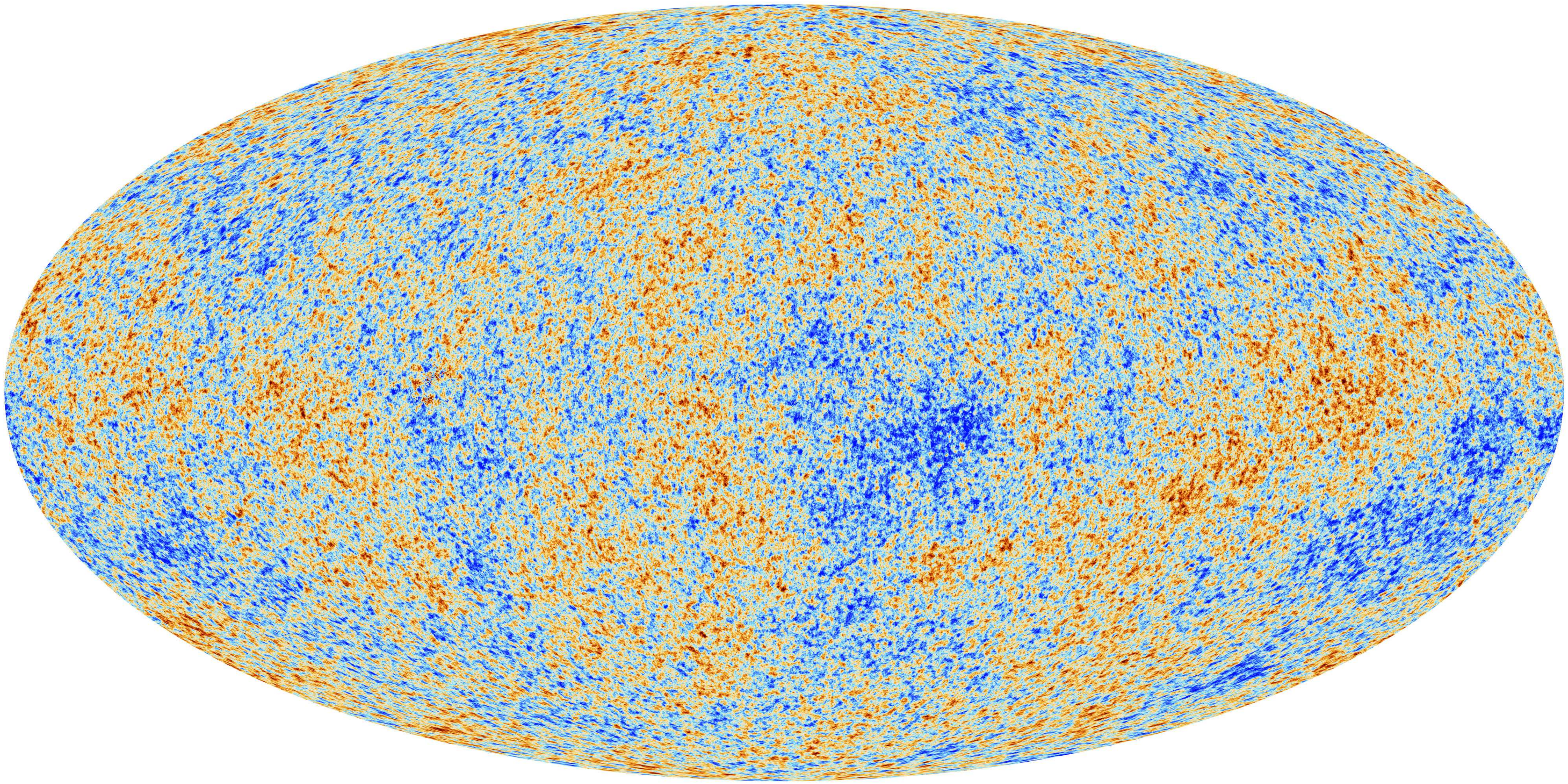
*Remember that light with larger wavelength has less energy.

How do we know there was a big bang? III

In 1992 and again in 2003, observing satellites mapped the cosmic microwave background arriving at Earth (or rather in space just outside of Earth) from all directions. The result shows complex “ripples” that can be correlated to the predictions from the big bang theory. It is used to predict how the initial matter will congeal into galaxies, and the size observed fits well with the predicted size. This is seen as strong evidence for the big bang theory.



Microwave Background radiation 2012



Concept check

Why is the background radiation left-over from the big bang in the microwave range? Should the radiation not be highly energetic since the big bang is supposed to have been a very energetic environment?

How do we know there was a big bang? IV

The first kind of ordinary matter formed were electrons, protons, and neutrons. During the next 3 minutes they started to "fuse" together into more complex nuclei. After that time the universe was too cool for further "fusing" of matter and more complex nuclei were not yet formed.

Well developed and highly reliable nuclear physics calculations predict the composition of elements (in the form of ions) after these first three minutes. (see table on right).

Astronomers have made light (or "spectral") measurements of the earliest known stars, who presumably had the same composition as the early universe. These measurements agree well with the theoretical predictions.

Nuclear type	Relative concentration by mass
${}^{1}_{1}H$	75%
${}^{2}_{1}H$	5–10 parts in 100,000
${}^{3}_{2}He$	2–5 parts in 100,000
${}^{4}_{2}He$	25 %
${}^{7}_{3}Li$	2–5 parts in 10 billion

Concept Check

The gold nuclei in the universe were

a) all created in the big bang;
b) all created some time after the big bang;
c) partly created during the big band, and partly after.

The beginning and the big bang

You may well wonder: what happened **before** the big bang?

The answer is that there is no before. Time and space were created during the big bang. Also there is no space outside the universe.

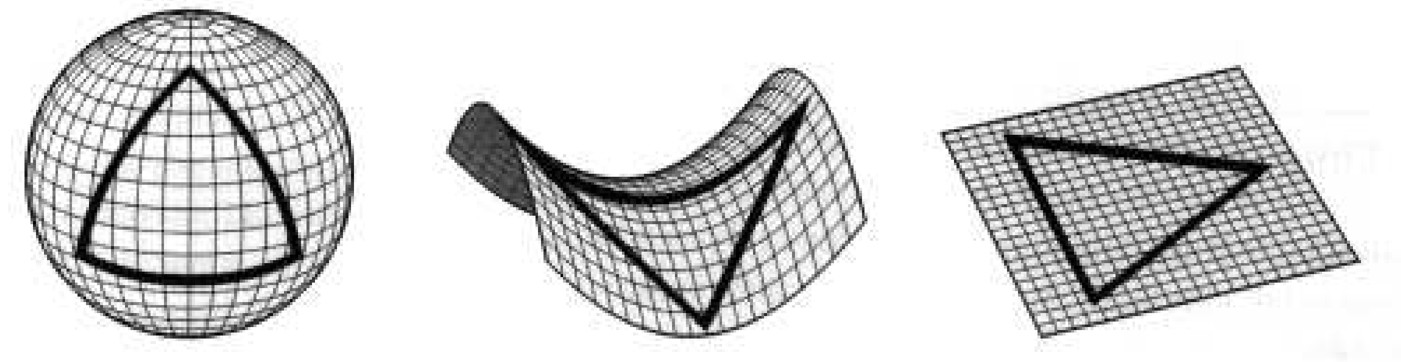
One of the predictions of general relativity is that space always either expands or contracts. Astronomical observations show that the galaxies are moving away from us and that galaxies further away are moving away faster. But this is not a special feature of our galaxy, you would observe the same from any other galaxy.

While the universe is expanding, ordinary matter like atoms retains its original size. So our planet retains its size and galaxies are kept together by gravity while the distance between the galaxies increases.

We can't visualize the expansion of the three-dimensional universe. However, we can do that for our two-dimensional universe.

The possible Geometries of the universe

We saw that space is curved in the presence of matter. But what is the geometry of the universe as a whole? General relativity gives three options: a closed geometry, a flat geometry and an open geometry:



Positive Curvature Negative Curvature Flat Curvature

Can this be detected?
In a flat universe the sum of all angles in a triangle is 180°, in a closed geometry it is larger than 180°, and an open geometry it is smaller than 180°.

A closed universe would be finite in extend whereas it would be infinite for the other geometries.

Concept check

The universe is expanding. Is everything in the universe expanding?

a) Yes.

b) No, the distance between the galaxies are not expanding.

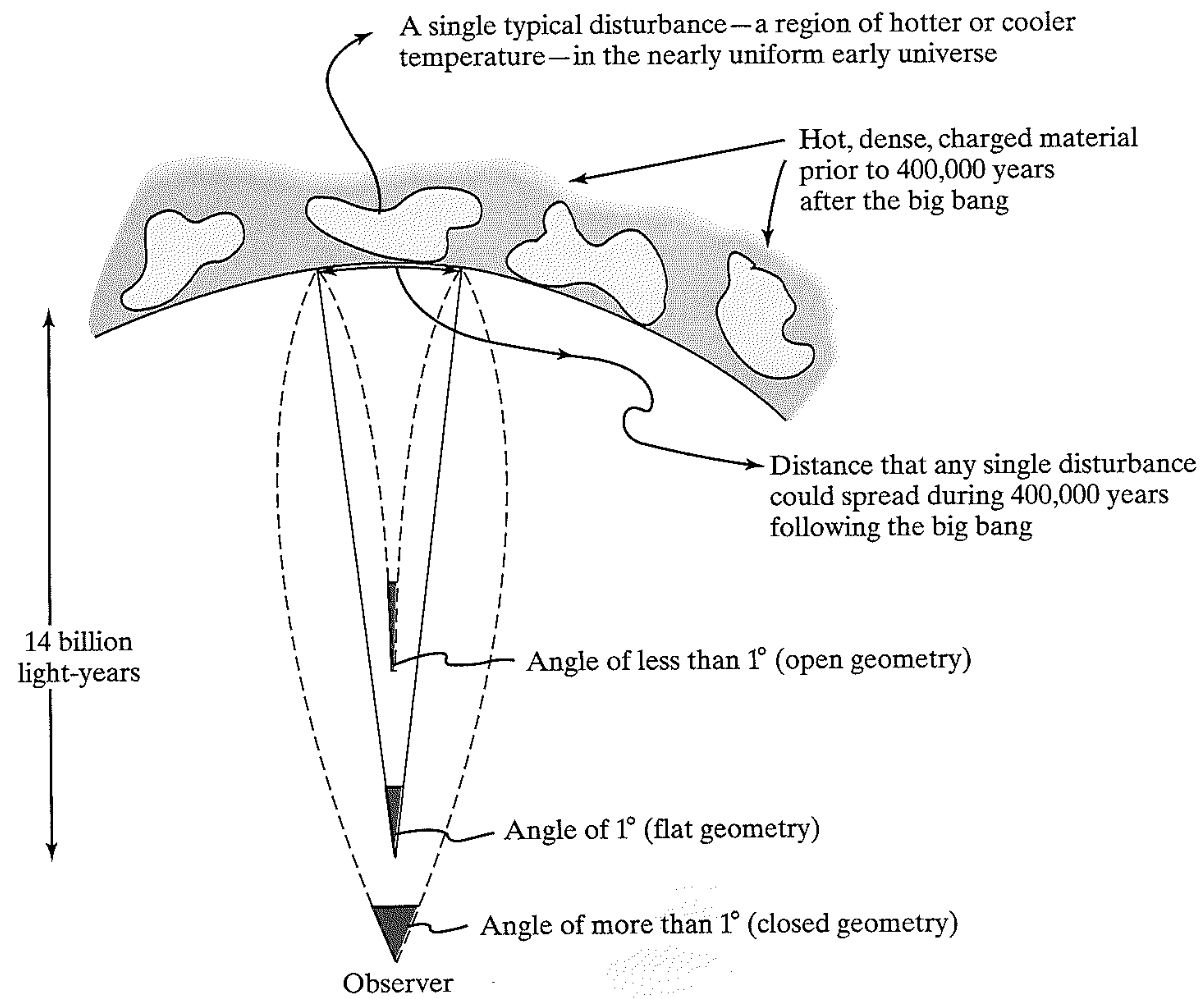
c) No, the Milky Way galaxy is not expanding.

d) No, our solar system is not expanding.

e) No, Earth is not expanding.

The Shape of the Universe

Until recently there was no good way of predicting what the shape of the universe is. However, the measurement of the microwave background radiation changed that: from the big bang theory we can predict the size of the initial fluctuations shown in the microwave background image. However, the appearance of these ripples depends on the geometry of the universe!



These measurements suggest that the universe is flat on large scales (even though it is locally curved where there are concentrations of masses).

Dark matter

We can see **stars**. We know there are **planets**. There is also **hydrogen gas** as remnants of the big bag in the intergalactic space. We know about it because it absorbs (small amounts) of light from other galaxies. The gas has 10 times the mass of all known suns and planets.

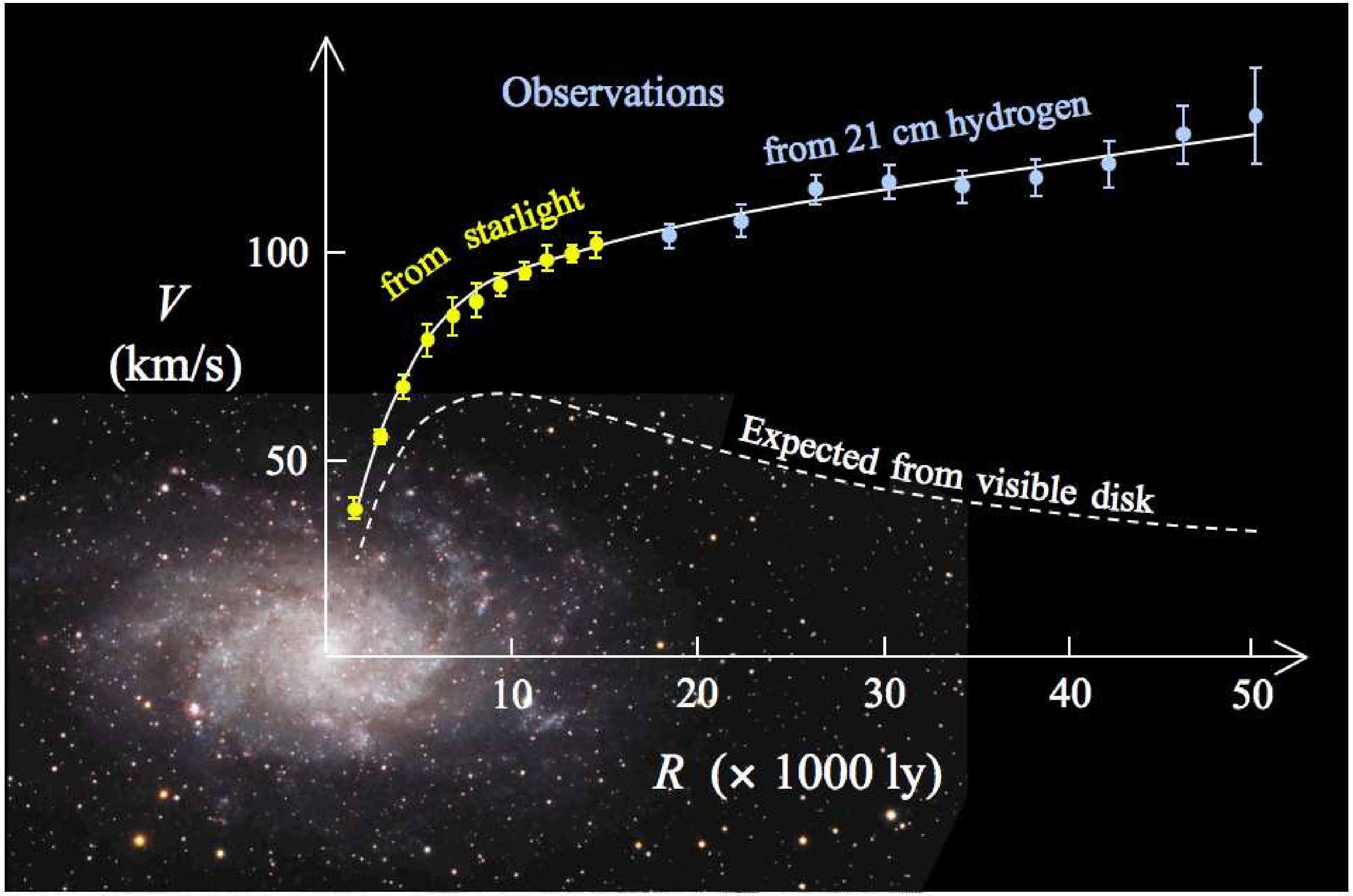
Then there are neutrinos which are estimated to have about 25% of the mass of known suns and planets.

Black holes are estimated to have a mass of about 10% of stars and planets.

But from observing the motion of galaxies we know that there must be much more mass. We have know idea what that mass consists off. But it is 60 times more than the matter we know about!

Additional evidence comes from gravitational lensing of galaxies, that show much more matter is required that would be estimated from the luminous matter that we can observe.

Galaxy rotation curve



Expected galaxy rotation rate from observed matter and the observed rotation rate do not agree. Fudging the theory by assuming a distribution of dark matter "fixes" the problem, but it is unknown what the physical reality of this dark matter is. (from wikipedia)

The accelerating Universe and Dark Energy

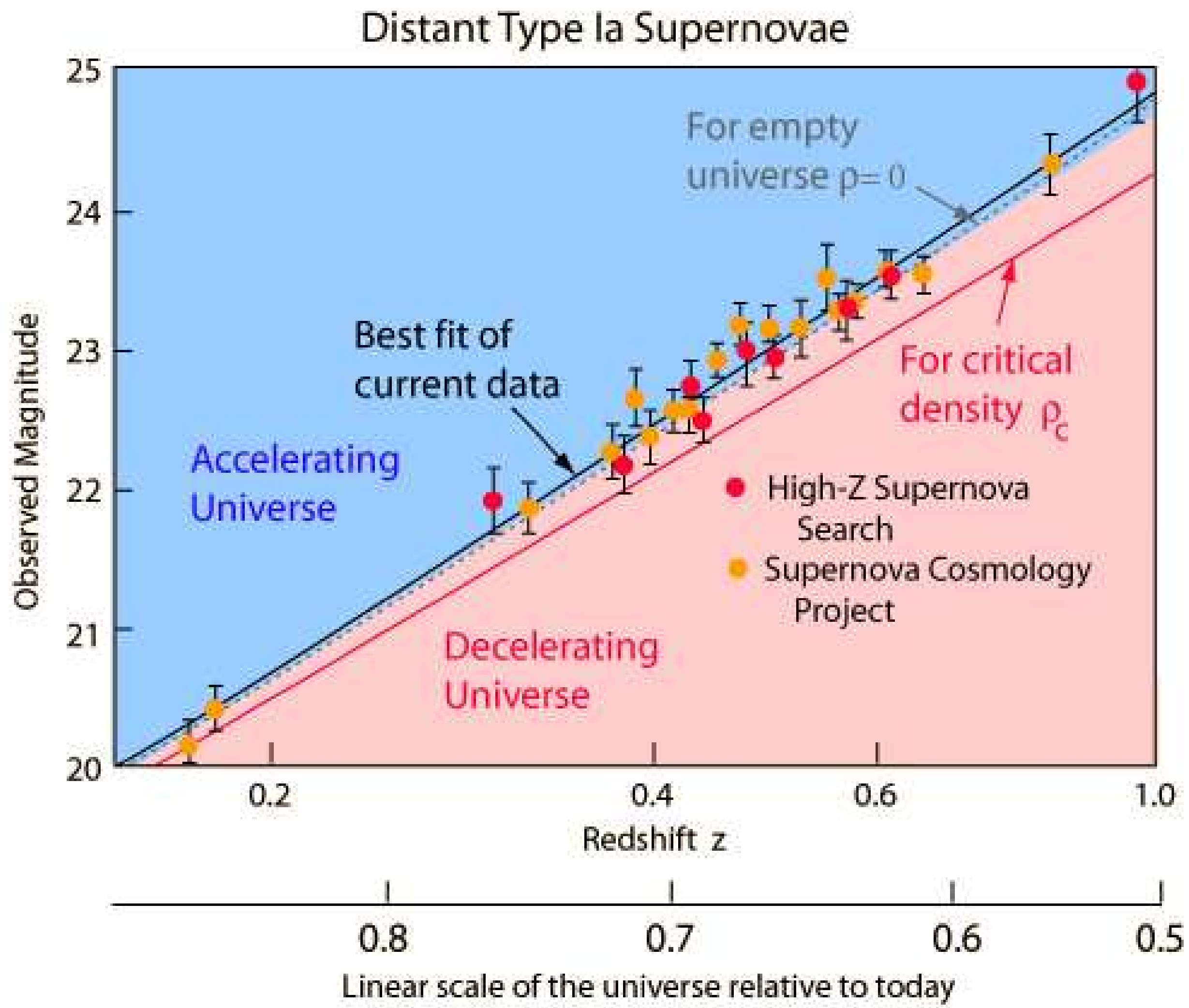
When you throw up a stone it will slow down and eventually fall down. But if you throw it fast enough (escape velocity) it will leave the earth never to return.

Similarly the expansion of the universe should slow down. If it slows down fast enough then it will eventually collapse in a *big crunch*, otherwise it will go on expanding for ever. So it is important to measure the rate of expansion.

In the 1990s cosmologists managed to measure the deceleration of the universe. The totally unexpected result: the universe does not decelerate, it accelerates!

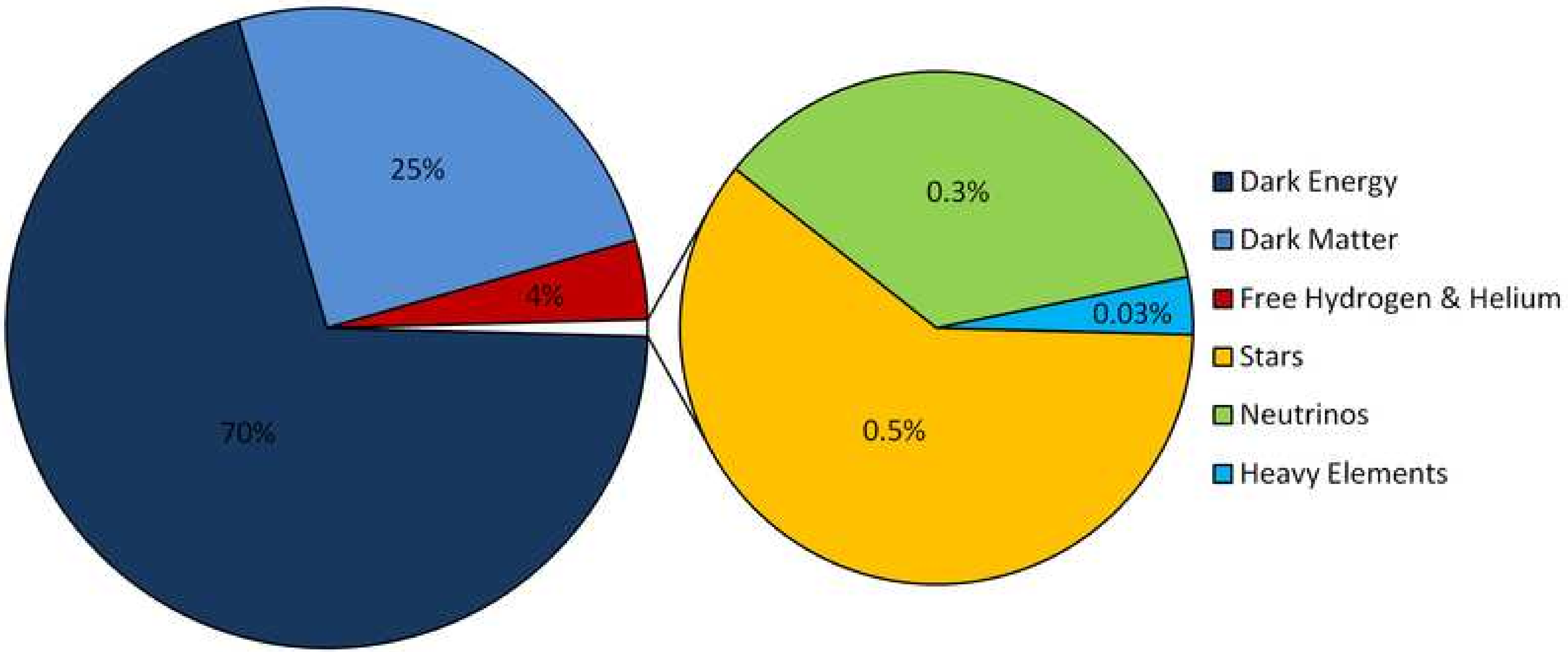
So something must "push" on the fabric of our space, and this energy was called **dark energy**, and no one knows what form of energy this is.

Evidence for acceleration of expansion

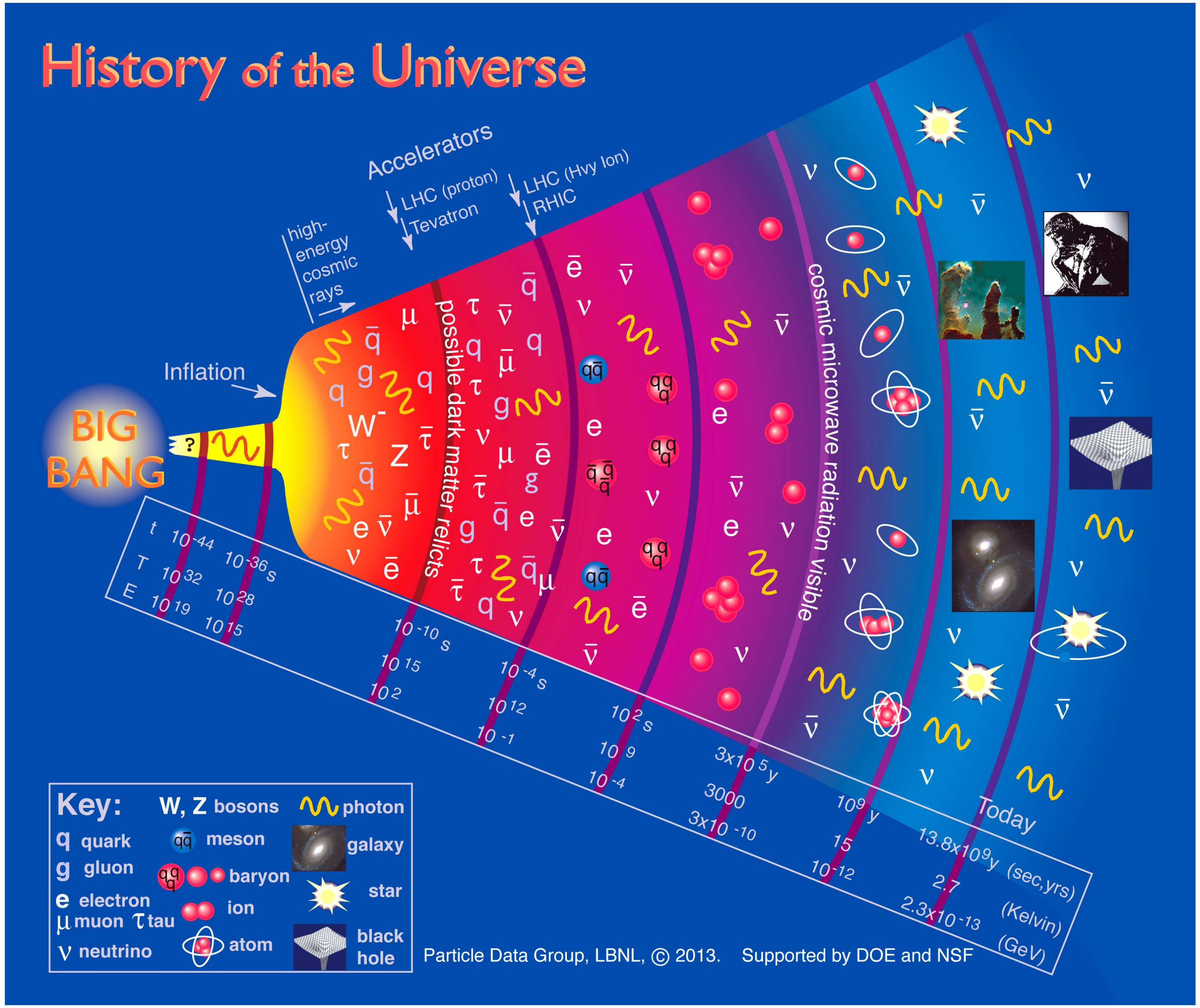


Evidence for the acceleration of the universe comes from observation of supernovae, explosions of stars that are quite uniform in their energy distribution. Such exploding stars (supernovae) can be as bright as a whole galaxy, so we can observe these supernovae in distant galaxies (more about them later).

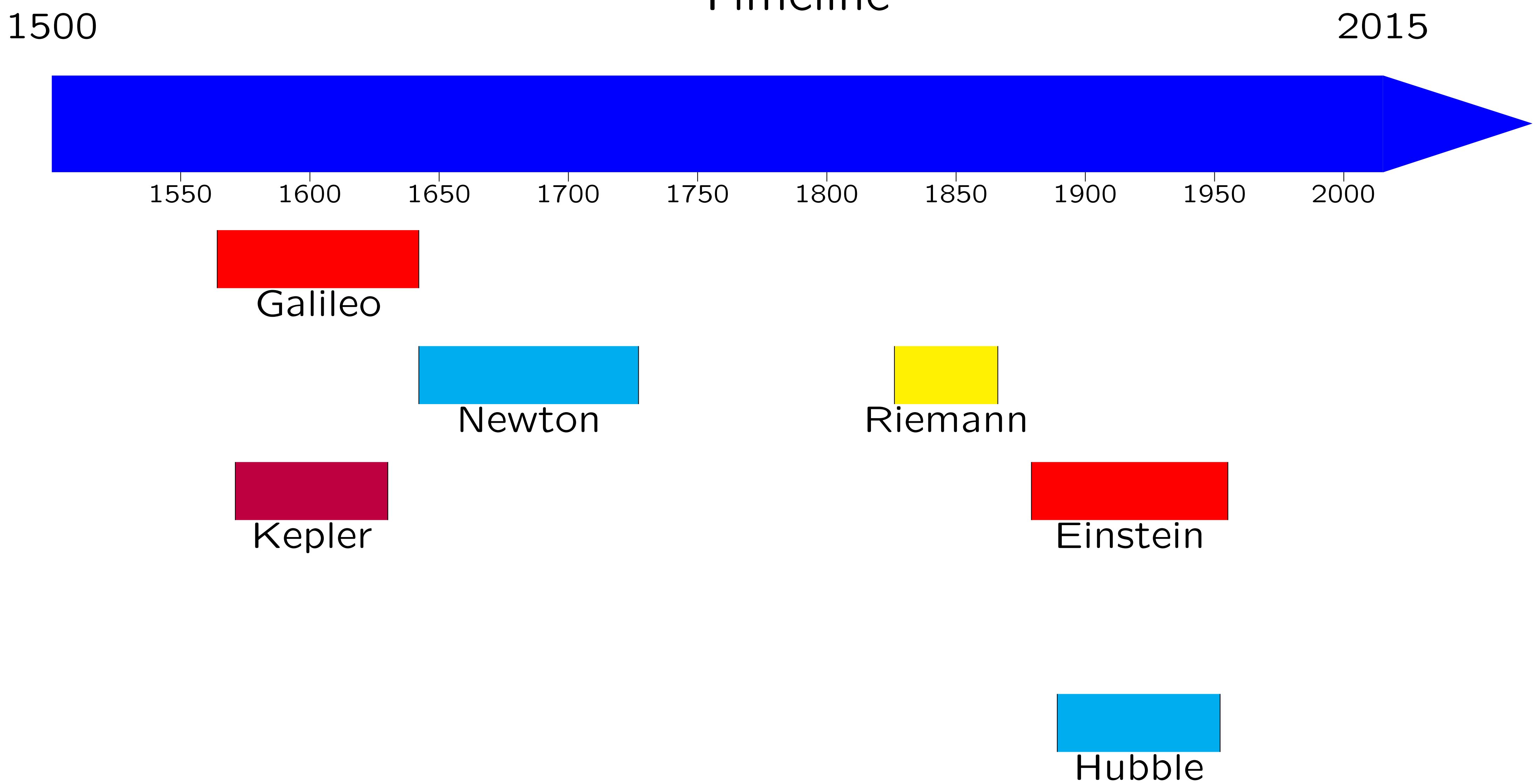
Composition of the universe



Cosmic inflation and a brief history of the Universe



Timeline



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1900
1950
2000
Galileo
Newton
Riemann
Kepler
Einstein
Hubble

Summary

- Ptolomeic cosmology
- Copernican/Newtonian cosmology
- Einstein's general relativity and the non-stationary universe
- Observations of expansion
- A history of the universe
- Dark matter and dark energy.