The Universe in my pocket

TUIMP No. 41 THE UNIVERSE IN MY POCKET

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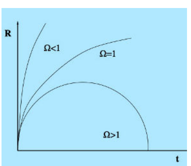
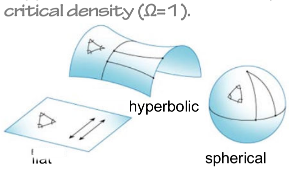


The evolution of the radius of the Universe as a function of time for different values of the density of matter Ω

https://media4.obspm.fr/public/ressources_lu

The velocity of galaxies due to expansion is known from observations, but we do not know the strength of the gravitation of matter which is controlled by its density. If the density is high enough (Ω>1), the expansion will stop and the Universe will contract. If the density is too low (Ω<1) the gravitational force is not strong enough and expansion will go on forever. The limiting case between these two possibilities happens when the density is equal to the critical density (Ω=1).



Different geometries of the Universe correspond to different values of Ω. (credit: Tom Dunne)

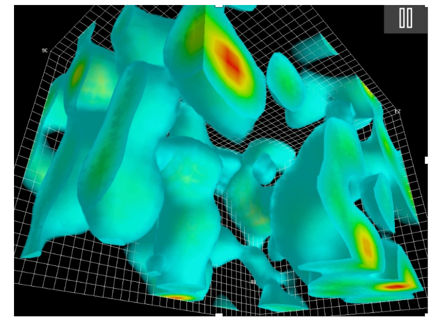
The destiny of the Universe

Albert Einstein

Expansion is best described by the theory of general relativity, published by Albert Einstein in 1915. This theory tells us that the geometry of space is linked to the density of the Universe.

Einstein was not satisfied by the first version of his theory, because it was inconsistent with a static (i.e. non-expanding) Universe. He therefore introduced in 1917 a new term, the cosmological constant Λ.

It was to be the start of a saga that, more than a century later, is now perhaps at its height...



https://physicscommunication.ie/nothing-matters-how-the-study-of-vacuum-energy-is-proving-catastrophic

Go to this site to see the animation

According to quantum mechanics, a vacuum is not the absence of everything, but rather a permanent swarming of particles and antiparticles, continuously appearing and disappearing.

The vacuum must therefore have a non-zero density.

The quantum vacuum

Wolfgang Pauli Yakov Zeldovich Steven Weinberg

Three of the greatest physicists of the 20th century examined the question of the quantum vacuum, noting the incredibly large value predicted for the density of the quantum vacuum compared to that deduced from the observations. The quantum value is about 10^{120} times * greater; this is often described as the most erroneous order of magnitude calculation in all of physics.

Again, a question that might have remained in the wardrobe of useless curiosities in physics.

* 10^{120} = (10x10x10... 10) 120 times

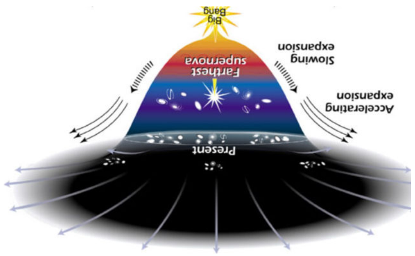


Diagram depicting the accelerated expansion of the Universe.

Credit: Design Alex Mittelmann, Coldcreation

Explaining the accelerating expansion of the Universe has lead to a great diversity of theories. Needless to say, describing these theories in some detail is mathematically tricky.

Another possible solution consists in modifying Einstein's gravity theory. There are many ways of achieving this, but it is difficult to do so without violating one or more of the many successful predictions of general relativity. Finally, both approaches can be combined in different ways...

Dark Energy

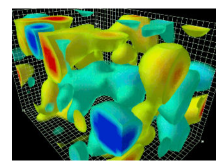
The cosmological constant introduced by Einstein is very artificial from a theoretical point of view. The value of the quantum vacuum predicted by quantum field theory exceeds the value deduced from observations by 120 orders of magnitude at least.

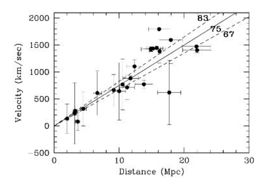
Therefore, many alternative explanations for the origin of the accelerated expansion have been proposed, an origin dubbed 'dark energy'.

Quintessence is the simplest form of dark energy: it is a hypothetical component that interacts with the rest of the Universe only through gravity. Its density can vary over time, but can also behave very much like a cosmological constant, depending on the potential that governs its evolution.

In 2024, the DESI collaboration claims to have found some hints of such evolving dark energy.

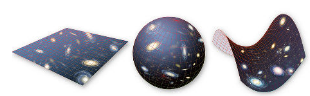
Quiz



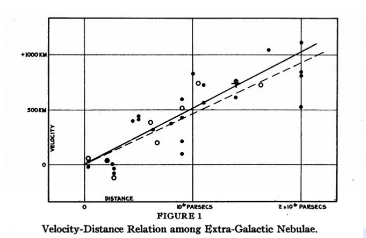


Which of these images shows:

- Different geometries of space
- A representation of the quantum vacuum
- The Hubble diagram



Answers on overleaf



The original Hubble diagram (Hubble 1929).

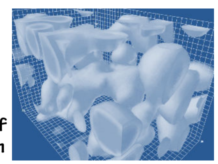
It shows the measured speed V of galaxies as a function of their distance D, the latter being deduced using the period-luminosity relation for Cepheid stars established a few years earlier by Henrietta Leavitt (see TUIMP 15).

The relation $V = H_0 \times D$, called the Hubble-Lemaître law, changed dramatically our vision of the Universe.

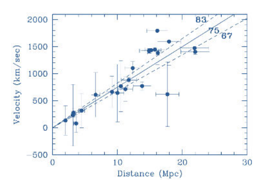
The value of H_0, the Hubble constant, was first estimated at about 500 km/s per Mpc, then at about 100 km/s per Mpc in the early 1960s. Present estimates are about 73 km/s per Mpc.

1 Mpc is equal to 3 millions light years

Answers

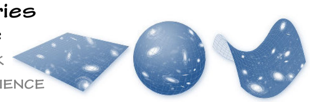


A representation of the quantum vacuum



The Hubble diagram from Hubble Space Telescope observations of Cepheids in distant galaxies.

(Freedman et al 2001)



Different geometries of space

Credit: MARK GARLICK/SCIENCE PHOTO

The Universe in my pocket No. XX

This booklet was written in 2024 by Alain Blanchard from Université Paul Sabatier and revised by Stan Kurtz from IRyA (Mexico).

Cover image:

Darth Vader of the Star Wars series is the character who has "gone over to the dark side of The Force". The Universe itself is subject to an unknown force whose mysterious origin has been called `Dark Energy'.

To learn more about this series and about the topics presented in this booklet, please visit http://www.tuimp.org

Translation: Stan Kurtz

The Hubble-Lemaître law

Just after the Great Debate in 1925, which concluded that there are galaxies outside our own, Edwin Hubble observed that the recession velocities of these galaxies were proportional to their distances. Georges Lemaître interpreted this as an effect of the expansion of the Universe.

The expansion of the Universe is a non-trivial concept to understand: putting aside the individual movements that accompany the Cosmic Web structure (see TUIMP 13), galaxies move away from each other with a speed proportional to their respective distances.

What governs this speed is gravitation, like throwing a stone upwards: if the initial speed is low, the stone rises and then falls again. If the initial speed is high enough (forgetting the Earth's atmosphere) the stone rises indefinitely.

Albert Einstein and Georges Lemaître

In 1948, Georges Lemaître built the first cosmological model dealing with the early phase of the Universe, named the `primeval atom', the ancestor of the Big Bang. He noticed that given the expansion speed measured by Hubble, the Universe would be younger than the age of the Earth unless one advocates a cosmological constant (C.C.), an argument that did not persuade Einstein, who abandoned the C.C. after the discovery of the expansion.

With the value of the Hubble constant known today the discrepancy between the age of the Universe and that of the Earth disappears anyway.

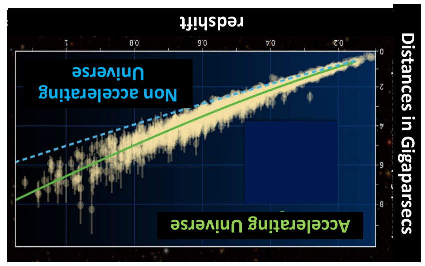
The accelerated expansion

In 1998, two teams studying the Hubble diagram of distant supernovae made a discovery that revolutionized cosmology and fundamental physics.

These supernovae are so distant that the light detected from them was produced when the Universe was much younger. This makes it possible to compare the expansion speed of the Universe at that time with its current speed.

In a Universe dominated by matter, the expansion speed would decrease. The Hubble diagram of supernovae revealed that the expansion speed of the Universe is increasing.

The Supernova Hubble diagram



Adapted from NOIRlab DES collaboration

The supernovae selected for this study were of type Ia. Supernovae of this type have a very regular luminosity, which means they can be reliably used to determine distances.

The modern version of the Hubble diagram from Type Ia supernovae showed that the expansion is accelerating. This discovery won the 2011 Nobel Prize in Physics for Saul Perlmutter, Brian P. Schmidt and Adam G. Riess. This result is quite amazing: it means that, on the scale of the Universe, gravitation acts as a repulsive force.

The nature of Λαμβδα

Λ

The discovery of the expansion of the Universe led to the cosmological constant being consigned to the wardrobe of useless curiosities in physics, with Einstein's assent…

But in 1931 Lemaître made a crucial remark that went unnoticed at the time: the cosmological constant previously seen as an additional term in the geometric part of Einstein's equations can just as easily be attributed to the pressure and density of a fluid, the fluid being the vacuum of space!