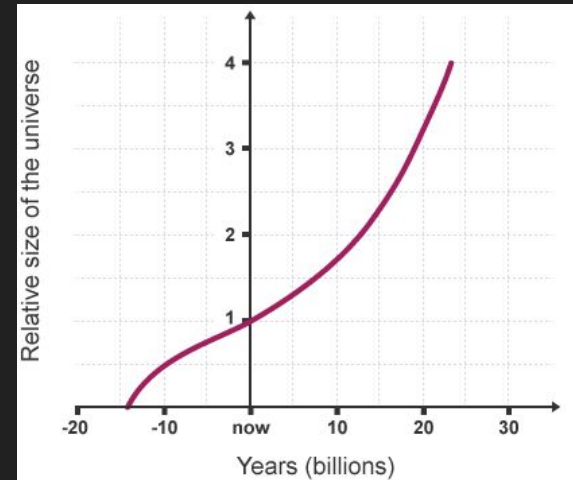
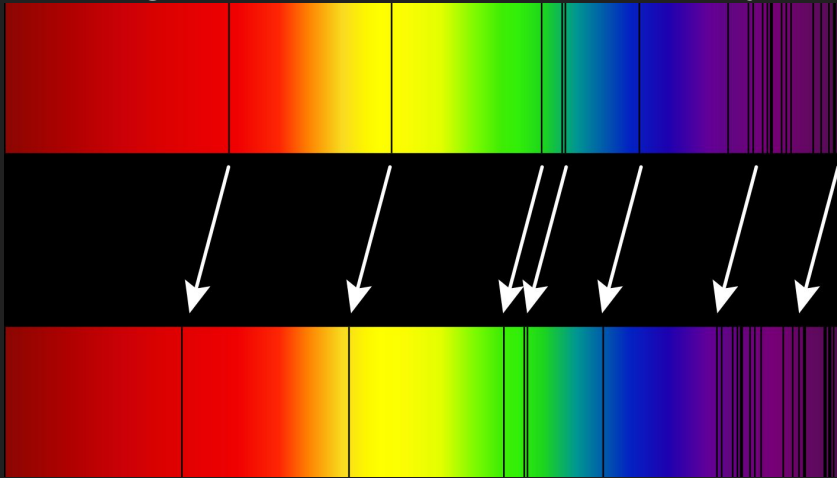
A circular cross-section of the universe, showing a complex web of galaxies and dark matter filaments. The central region is filled with numerous galaxies, including a prominent spiral galaxy. The outer regions are dominated by a dense network of filaments and clusters, with a reddish-brown glow. The background is a deep blue space filled with stars.

Is the expansion of the universe caused by dark energy?

# How do we know the universe is expanding?

Redshift - light traveling from far away galaxies is stretched by the expansion of the universe. This makes its wavelength longer, causing it to look more red.

Wavelength = wave speed / frequency



# What is dark energy?

Energy that acts in opposition to gravity and we can't detect other than from its effects.

Dark energy is a property of space, and due to its opposition to gravity it induces a “negative pressure” which stretches the fabric of spacetime.

Dark energy looks like this:

(aka: it's invisible)

# Energy Density

The 1st Friedmann equation describes how the rate of expansion of the universe is related to the mass and energy density.

$$H^2 = (kc^2 / S^2) + (8\pi G\rho / 3)$$

H - rate of expansion, G - gravitational constant, c - speed of light,  $\rho$  - average density of matter and energy, S - scale factor, k - curvature of the universe

expansion = curvature + energy density

expansion  $\propto$  energy density

# Redshift

Redshift causes light to lose energy.

$$E = hc / \lambda$$

$$E \propto 1 / \lambda$$

This seems to VIOLATE the 1st law of thermodynamics.

$$\Delta E_{\text{int}} = Q - W$$

The internal energy of a system only changes if it does work (loses energy) or gains energy.

One explanation for redshift is that energy is lost from the universe during this however:

# Blueshift

Blueshift can be thought of as the opposite of redshift; if an object that emits waves of energy moves towards the observer, the wavelengths become shortened, and the light appears to become blue.

As it is the opposite of redshift, blueshift causes light to gain energy.

This shows that energy from redshift cannot be permanently lost from the universe.

## Redshift (again)

Redshift could do work on the universe causing it to expand. This could allow it to not violate the 1st law of thermodynamics.

Blueshift would then get energy from the universe as it contracts.

# $\Lambda$ CDM

This is a model for the universe. It has 2 notable parts, Cold Dark Matter and  $\Lambda$ .

$\Lambda$  represents inherent energy in space.

When more space is created as the universe expands, more energy is created with it.

This causes the universe to expand even faster.



# Quintessence

Quintessence is a similar theory to  $\Lambda$ CDM however in this model the dark energy is not a part of space and can flow around and have different densities.

Equation of state:

$$w = p / q , \quad 0 \geq w > -1$$

$p$  is pressure and  $q$  is energy density

The closer  $w$  is to  $-1$  the greater the accelerating effect. This could allow for different rates of expansion in different places in space.

# What else could cause the expansion?

One notable alternative is modified gravity.

These theories change the equation for gravity.

One of these theories called  $f(Q)$  seems to be able to predict the expansion of the universe better than the  $\Lambda$ CDM model

