Non-particle dark matter from Hubble parameter

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Materia oscura sin partículas del parámetro de Hubble

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Abstract

The measurements of the Hubble parameter using the cosmic microwave background radiation appear to be inconsistent with the measurements of this parameter using Cepheid variable stars.

This inconsistency may be a result of using the ΛCDM cosmology, which assumes pressureless dark matter, in extrapolating the data from the recombination time to the present time.

We show that both measurements are consistent if dark matter satisfies an equation of state in which the pressure p and the energy density ε are related by $p = w\varepsilon$ with a negative value of w.
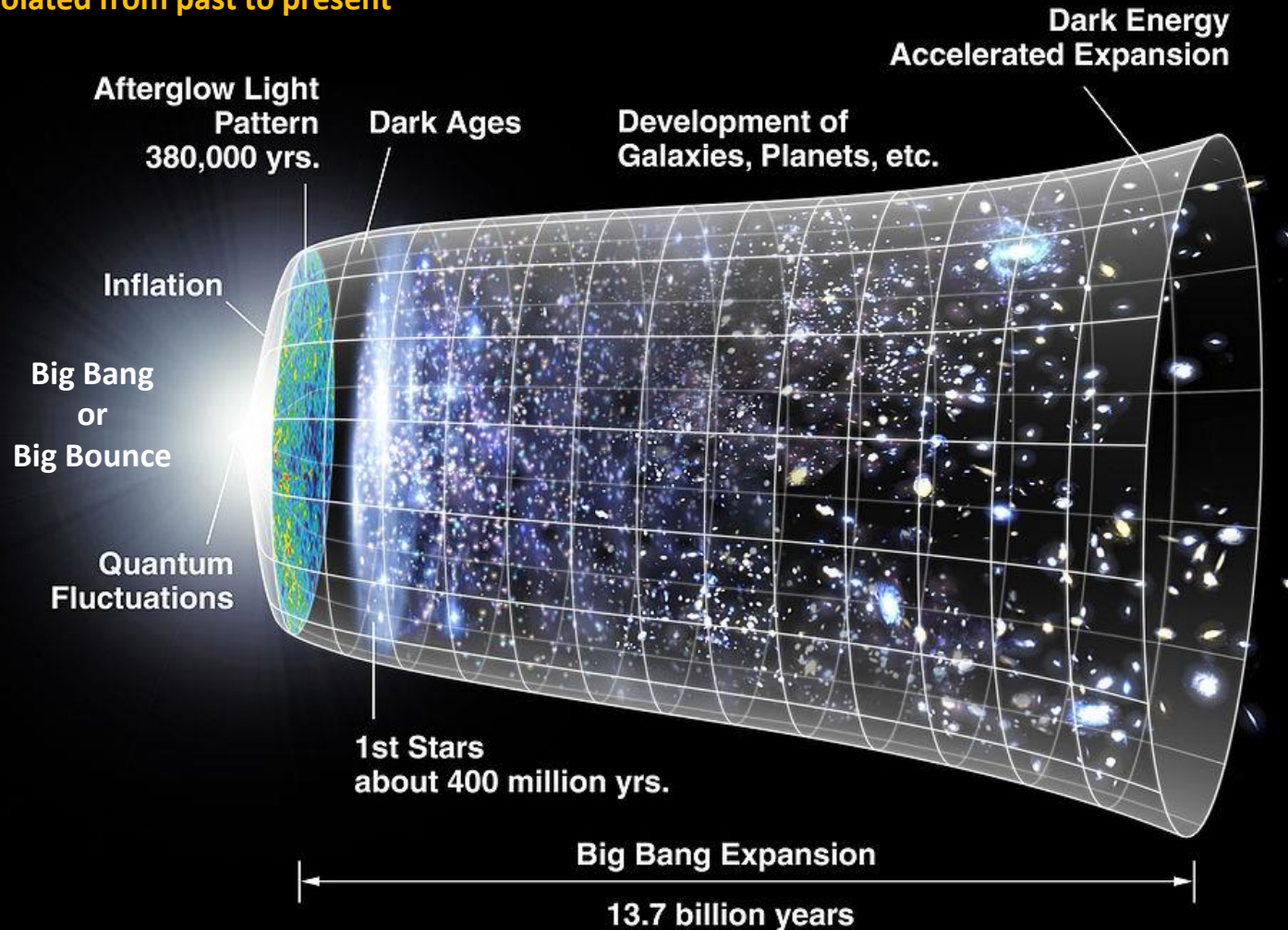
The data give $w \approx -0.01$.

The negative value of w indicates that dark matter would not be formed by particles, which is consistent with the lack of experimental evidence for them.

Measuring Hubble parameter

Data from Cosmic Microwave Background extrapolated from past to present

Data from local objects at present

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Measuring Hubble parameter from CMB

The observations of the temperature angular power spectrum of the cosmic microwave background (CMB) radiation provide the information about the composition of the universe.

The measurements of the position of the first acoustic peak show that the universe is nearly flat, with the density parameter $\Omega \approx 1$.

The measurements of the amplitudes of the peaks determine the values of $\Omega_{\mathrm{b}} h^2$ and $\Omega_{\mathrm{c}} h^2$, where Ω_{b} is the density parameter for baryonic matter, Ω_{c} is the density parameter for dark matter, and the present-day Hubble parameter $H_0 = 100 h$ km/s/Mpc.

Combining these values with the measured $h = 0.674 \pm 0.005$ gives (omitting errors) $\Omega_{\mathrm{b}} = 0.049$ and $\Omega_{\mathrm{c}} = 0.265$, as obtained by the Planck satellite.

Consequently, the density parameter for total matter is $\Omega_{\mathrm{m}} = 0.314$.

Measuring Hubble parameter from CMB

Before the Planck measurements, most measured values of h also clustered around 0.68, including the data from high-redshift type Ia supernovae (SN Ia), Wilkinson Microwave Anisotropy Probe CMB data, baryon acoustic oscillations (BAO), SN Ia and BAO data, measurements of the Hubble parameter at intermediate redshifts, and large-scale-structure data.

Assuming a flat universe, $\Omega_\Lambda = 1 - \Omega_m = 0.686$ for dark energy (cosmological constant).

The resulting age of the universe is

$$t_{\text{univ}} = \int da/(aH) = \int_0^\infty dz/[H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}],$$

where $H = \dot{a}/a$ is the Hubble parameter as a function of the scale factor a and its time derivative $\dot{a}$, and z is the redshift.

The numerical values give $t_{\text{univ}} = 13.8 \times 10^9$ years.

Measuring Hubble parameter locally

The observations of Cepheid variable stars in the Large Magellanic Cloud provide a different value of the present-day Hubble parameter, $\tilde{h} = 0.742 \pm 0.018$.

A tilde denotes a value measured locally.

Moreover, the observations of quasars gravitationally lensed by galaxies give even a larger value.

This apparent discrepancy between the CMB and Cepheid measurements cannot be attributable to an error and has caused the so-called "Hubble tension", suggesting physics beyond ΛCDM.

Other local measurements of the expansion rate have found a lower value with a larger uncertainty, including the data from SN Ia, low-redshift SN Ia, and the ionized gas in HII galaxies.

Many scenarios to resolve the Hubble tension have been proposed, including decaying dark matter particles, modified dark energy, and dark matter interacting with a cosmological constant.

What does CMB measure?

Hubble tension may be a result of extrapolating the CMB data from the time of recombination ($z = 1089$) to the present time ($z = 0$) using the ΛCDM cosmology, which assumes pressureless dark matter.

The CMB data do not measure directly Ω_{b} but rather $\Omega_{\mathrm{b}}h^2(1+z)^3$, where $z = 1089$.

Therefore, a different value of h yields a different value of Ω_{b}. The two interpretations of the same result require

$$\Omega_{\mathrm{b}}h^2(1+z)^3 = \tilde{\Omega}_{\mathrm{b}}\tilde{h}^2(1+z)^3,$$

from which we obtain the real value of the density parameter for baryonic matter, $\tilde{\Omega}_{\mathrm{b}} = 0.040$.

Similarly, the CMB data do not measure directly Ω_{c} but rather $\Omega_{\mathrm{c}}h^2(1+z)^3$.

Therefore, a different value of h yields a different value of Ω_{c}.

Proposal: dark matter has pressure < 0

We assume that dark matter may have a nonzero value of w and thus scale with z as $(1+z)^{3(1+w)}$.

For dark matter, we therefore require

$$\Omega_c h^2 (1+z)^3 = \tilde{\Omega}_c \tilde{h}^2 (1+z)^{3(1+w)}.$$

This equation means that the CMB data must be extrapolated to the present time, in order to determine the value $\tilde{\Omega}_c$, using the equation of state with w.

Combining this equation with $\tilde{\Omega}_b + \tilde{\Omega}_c = 1 - \Omega_\Lambda$ (for a flat universe), which gives the real value of the density parameter for dark matter, $\tilde{\Omega}_c = 0.274$, determines the value of w:

$$w = -0.0108.$$

The value of w is negative because $\tilde{\Omega}_c > \Omega_c$ and $\tilde{h} > h$.

N. J. Popławski, Eur. Phys. J. C 79, 734 (2019).

Proposal: dark matter has pressure < 0

The negative value of w indicates that dark matter may be not formed by particles, for which w must lie between 0 (nonrelativistic limit) and $1/3$ (ultra-relativistic limit).

This value agrees with the dark matter equation of state between $z = 10^5$ and $z = 0$ using the CMB and BAO data, showing that w is consistent with 0 but allows a small negative value.

This value also agrees with the dark matter equation of state obtained by measuring galaxy cluster mass profiles, showing $w = 0.00 \pm 0.15 \pm 0.08$.

The resulting age of the universe is

$$t_{\mathrm{univ}} = \int_0^\infty \frac{dz/(1+z)}{H_0 \sqrt{\tilde{\Omega}_{\mathrm{b}}(1+z)^3 + \tilde{\Omega}_{\mathrm{c}}(1+z)^{3(1+w)} + \Omega_\Lambda}}.$$

The numerical values give $t_{\mathrm{univ}} = 12.7 \times 10^9$ years.

Proposal: dark matter is not particles

If dark matter were a kind of fluid, it would have to satisfy the laws of fluid mechanics. For a barotropic equation of state $p = w\epsilon$, where w is constant, the adiabatic speed of sound in the fluid is equal to $c_s = \sqrt{\partial p/\partial \epsilon} c = \sqrt{w} c$.

For a negative w, the speed of sound is imaginary and the dark matter fluid would be unstable and rapidly become spatially inhomogeneous. To avoid this instability, one must then specify an additional condition $c_s = c$, as for scalar fields. In this case, however, dark matter would not cluster on galactic scales.

Also, the observed flat rotation curves of spiral galaxies constrain the speed of sound of dark matter to be $c_s < 10^{-4} c$.

Therefore, if dark matter has a generalized equation of state with a negative parameter w, such a parameter has no fluid-mechanical interpretation; it only represents how dark matter interacts gravitationally and influences the dynamics of the universe.

Accordingly, dark matter (without additional generalizations) could not be a dark fluid composed of particles. This conclusion may explain why various hypothetical candidates, such as WIMPs or axions, have not been observed.

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Reference:

NJP, Eur. Phys. J. C 79, 734 (2019)
& references therein.

¡Gracias!