Dark Matter

What is the universe made of?

What fraction of the density is made of stars, and other familiar types of baryonic matter?

What fraction of the density is made of dark matter?

What constitutes the dark matter – cold stellar remnants, black holes, exotic elementary particles, or some other substance too dim for us to see?

These questions, and others, have driven astronomers to take a census of the universe, to find out what types of matter it contains, and in what quantities.

Critical energy density:

$$\varepsilon_{c,0} = \frac{3c^2}{8\pi G} H_0^2 = (7.8 \pm 0.5) \times 10^{-10}\,\mathrm{J\,m^{-3}} = 4870 \pm 290\,\mathrm{MeV\,m^{-3}}.$$

$$\rho_{c,0} \equiv \frac{\varepsilon_{c,0}}{c^2} = (8.7 \pm 0.5) \times 10^{-27}\,\mathrm{kg\,m^{-3}}$$
$$= (1.28 \pm 0.08) \times 10^{11}\,\mathrm{M_\odot\,Mpc^{-3}}.$$

From the crude estimates that a typical galaxy weighs about 10^11 M⊙ and that galaxies are typically about a megaparsec apart, we know that the Universe cannot be a long way from the critical density.

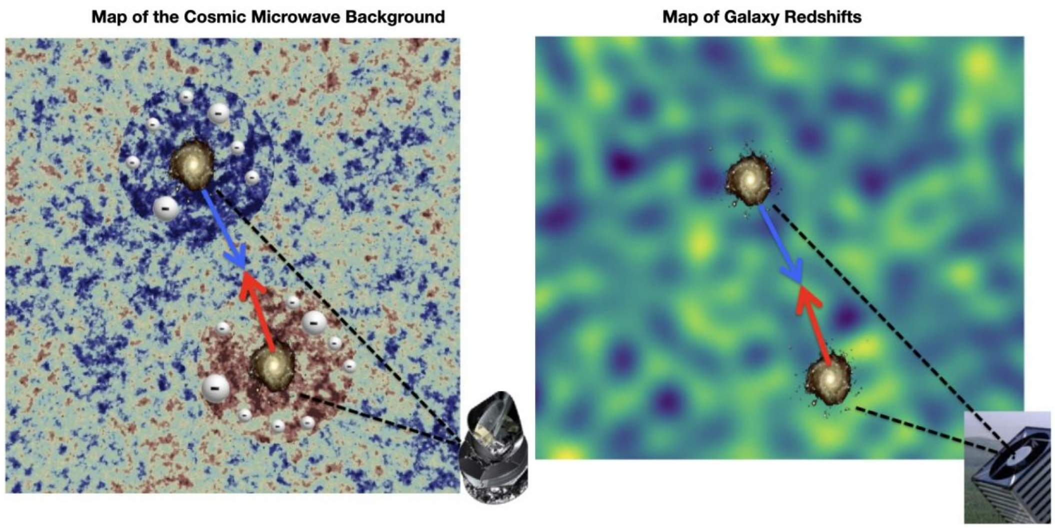
But how good an estimate can be made?

Missing baryon problem

The missing baryon problem is an observed discrepancy between the amount of baryonic matter detected from shortly after the Big Bang and from more recent epochs.

Observations of the CMB and BBN studies have set constraints on the abundance of baryons in the early universe, finding that baryonic matter accounts for approximately 4.8% of the energy contents of the Universe.

At the same time, a census of baryons in the recent observable universe has found that observed baryonic matter accounts for less than half of that amount.

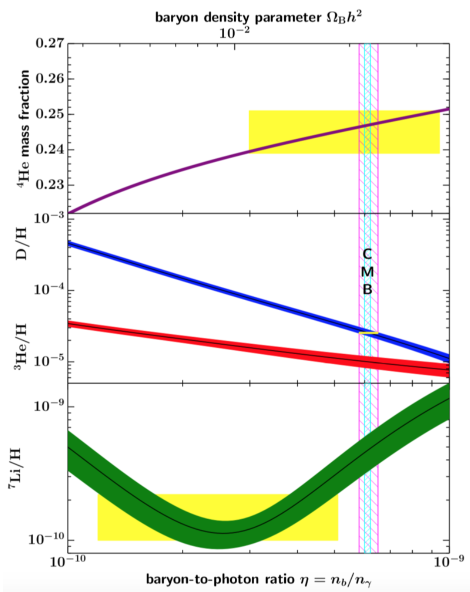


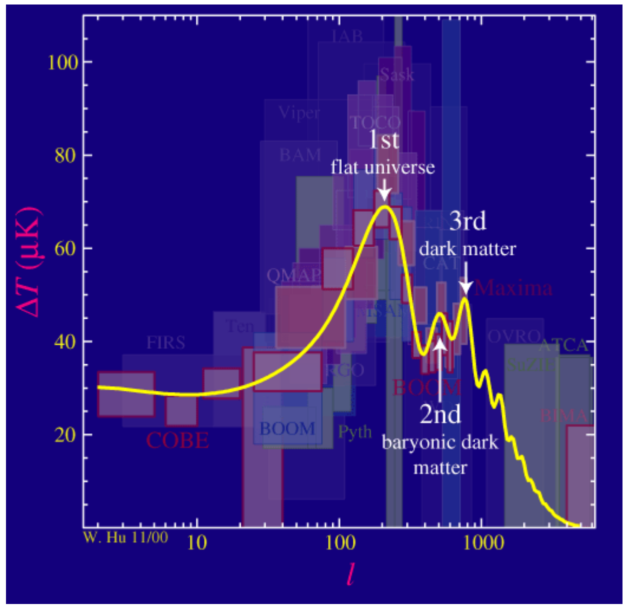
Early universe measurements

The abundance of baryonic matter in the early universe can be obtained indirectly from two independent methods:

The theory of Big Bang nucleosynthesis, which predicts the observed relative abundance of the chemical elements in observations of the recent universe. Higher numbers of baryons in the early universe should produce higher ratios for helium, lithium, and heavier elements relative to hydrogen.
Agreement with observed abundances requires that baryonic matter makes up between 4–5% of the universe's critical density.

Detailed analysis of the small fluctuations (anisotropies) in the CMB, especially the second peak of the CMB power spectrum. Baryonic matter interacts with photons and therefore leaves a visible imprint on the CMB. CMB analysis also yields a baryon fraction on the order of 5%.





The CMB constraint is much more precise than the BBN constraint, but the two are in agreement.

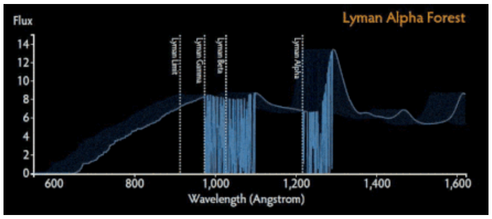
$$\Omega_{\mathrm{bary},0} = 0.048 \pm 0.003,$$

10 to 20 times the density parameter for stars!!

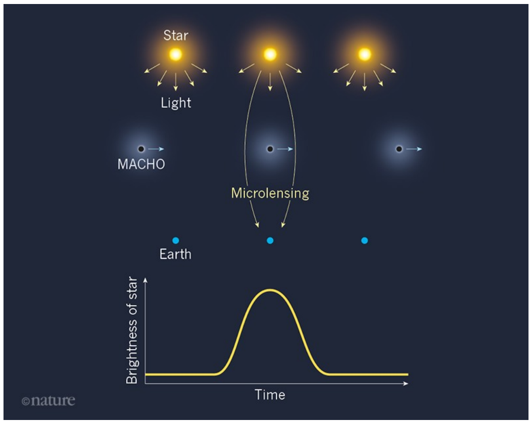
Late universe measurements

The density of baryonic matter can be obtained directly by summing up all the known baryonic matter. This is highly nontrivial, since although luminous matter such as stars and galaxies are easily summed, baryonic matter can also exist in highly non-luminous form, such as black holes, planets, and highly diffuse interstellar gas. Nonetheless, it can still be done, using a range of techniques:

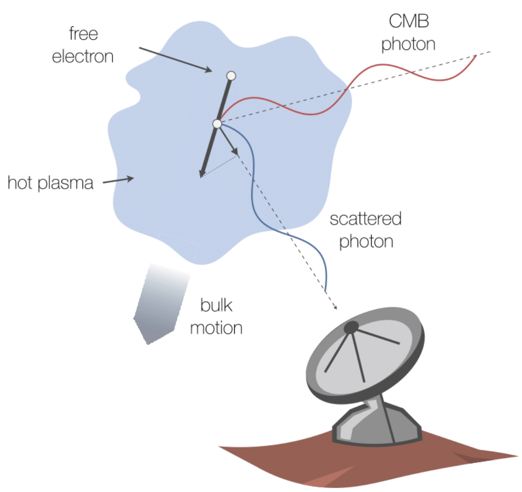
Making use of the Lyman-alpha forest.
Clouds of diffuse, baryonic gas or dust are sometimes visible when backlit by stars. The resulting spectra can be used to infer the mass between the star and the observer.

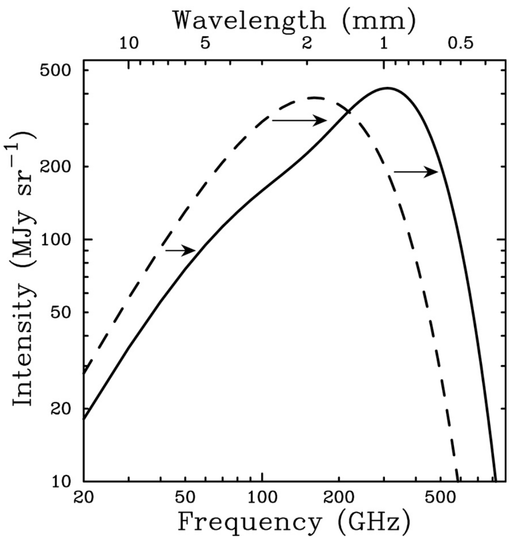


Gravitational microlensing.
If a planet or other dark object moves between the observer and a faraway source, the image of the source is distorted. The mass of the dark object can be inferred based on the amount of distortion.



Sunyaev–Zel'dovich effect.
The interaction between CMB photons and free electrons leaves an imprint in the CMB. This effect is sensitive to all free electrons independently of their temperature or the density of the surrounding medium, and thus it can be used to study baryonic matter otherwise not hot enough to be detected.





Based on the current experimental data, the contents of the universe, interpreted using the consensus cosmological model (or ΛCDM), are dark energy (72.8%), dark matter (22.7%) and ordinary (baryonic) matter (4.5%) 2.

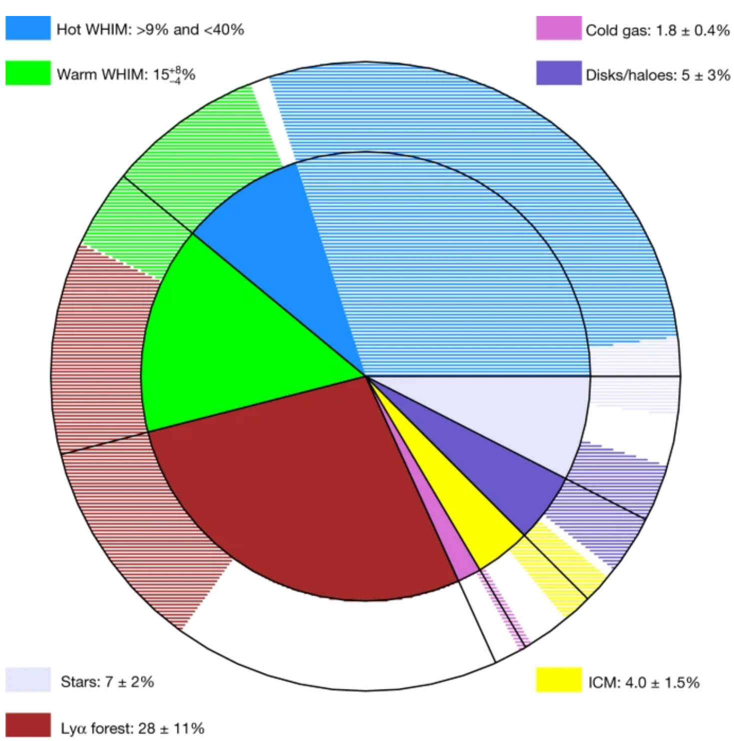
The baryon content can be classified in four classes based on the results of cosmological hydrodynamic galaxy formation simulations:

(1) about the 12% is the cold gas condensed in galaxies, including stars and interstellar gas;

(2) about the 26% is the warm gas, with temperature $T < 10^5$ K, in the clouds of neutral hydrogen in the intergalactic medium, between distant quasars and the Earth, that absorb ultraviolet light at the wavelength of the Lyman alpha line of hydrogen at a wavelength of 122 nm (the so-called Lyman-alpha forest);

(3) about the 52% is the warm-hot gas, with $10^5 \text{ K} < T < 10^7$ K, mainly in unvirialized intercluster regions, i.e., filaments and oblate non-spherical regions where the equilibrium between the total kinetic and potential energies has not been reached, hence the so-called virial theorem does not apply; and

(4) the last 12% is the hot X-ray emitting gas, with $T > 10^7$ K, in collapsed and virialized clusters of galaxies (regions having a nearly spherical shape as expected from the virial theorem). Before Planck satellite mission, there was no experimental evidence of the warm/hot gas, i.e., about half of the baryons of the universe had not been observed.



Pie diagram of the baryonic components of the local universe. Hatched regions in the external corona indicate the 90% uncertainties on the individual components; they are plotted across one of the two sides of each slice to show to what extent of each slice could be smaller or bigger. The exception is our measurement of the 105.7 K ≤ T ≤ 106.2 K WHIM component, where the solid-shaded area shows the 3σ lower limit on the amount of baryons in these physical conditions, whereas the hatched area indicates and represents our 3σ upper limit, namely, the maximum amount of baryons that is allowed by our study to be contained in this phase at 99.97% confidence

Visible matter in form of stars

The "V" in V-band stands for "visual"; although your eyes can detect the broader wavelength range 400 nm < λ < 700 nm, a V-band filter lets through the green and yellow wavelengths of light to which your retina is most sensitive. About 12 percent of the Sun's luminosity can pass through a V-band filter; thus, the Sun's luminosity in the V band is $L_{\odot,V} \approx 0.12 L_{\odot} \approx 4.6 \times 10^{25}$ watts.[1]

Surveys of galaxies reveal that in the local universe (out to $d \sim 0.1c/H_0$), the luminosity density in the V band is

$$\boxed{\Psi_V = 1.1 \times 10^8 L_{\odot,V}\,\mathrm{Mpc}^{-3}.} \qquad (7.1)$$

The mass-to-light ratio of quiescent galaxies can rise to as large as $M/L_V \approx 8\ \mathrm{M}_{\odot}/\mathrm{L}_{\odot,V}$. In the local universe, there is a mix of star-forming and quiescent galaxies, so we can't go too badly wrong if we take an averaged mass-to-light ratio of $\langle M/L_V \rangle \approx 4\ \mathrm{M}_{\odot}/\mathrm{L}_{\odot,V}$. With this value, we find that the mass density of stars in the universe today is

$$\boxed{\rho_{\star,0} = \langle M/L_V \rangle \Psi_V \approx 4 \times 10^8\,\mathrm{M}_{\odot}\,\mathrm{Mpc}^{-3}.} \qquad (7.4)$$

Since the current critical density of the universe, expressed as a mass density, is $\rho_{c,0} = 1.28 \times 10^{11}\ \mathrm{M}_{\odot}\ \mathrm{Mpc}^{-3}$, the current density parameter of stars is

$$\boxed{\Omega_{\star,0} = \frac{\rho_{\star,0}}{\rho_{c,0}} \approx \frac{4 \times 10^8\,\mathrm{M}_{\odot}\,\mathrm{Mpc}^{-3}}{1.28 \times 10^{11}\,\mathrm{M}_{\odot}\,\mathrm{Mpc}^{-3}} \approx 0.003.}$$

By this accounting, stars make up just 0.3% of the density needed to flatten the universe. The density parameter in stars is boosted slightly if you broaden the category of stars to include stellar remnants such as white dwarfs, neutron stars, and black holes, as well as substellar objects such as brown dwarfs. However, even when you add ex-stars and not-quite-stars to the total, you still find a density parameter $\Omega_{\star,0} < 0.005$.

Galaxies also contain baryonic matter that is not in the form of stars, stellar remnants, or brown dwarfs. In our galaxy and in M31, for instance, the mass of interstellar gas is about 20 percent of the mass in stars. In irregular galaxies such as the Magellanic Clouds, the ratio of gas to stars is even higher.

Consider a rich cluster of galaxies such as the Coma cluster, located about 100 Mpc from our galaxy.

$$L_{\mathrm{Coma},V} \approx 5 \times 10^{12}\ \mathrm{L}_{\odot,V}.$$

$$\langle M/L_V \rangle \approx 4\ \mathrm{M}_{\odot}/\ \mathrm{L}_{\odot,V}, \longrightarrow \quad M_{\mathrm{Coma},\star} \approx 2 \times 10^{13}\ \mathrm{M}_{\odot}.$$

X-rays emission with a typical energy of E ~ kTgas ~ 9 keV.
The total amount of X-ray emitting gas in the Coma cluster is estimated to be

$$\boxed{M_{\mathrm{Coma,gas}} \approx 2 \times 10^{14}\ \mathrm{M}_{\odot}, \text{ roughly ten times the mass in stars.}}$$

This image shows the bright, nearby, and massive Coma galaxy cluster in X-ray and optical light, as seen by XMM-Newton's European Photon Imaging Camera (EPIC) and the Sloan Digital Sky Survey (SDSS).

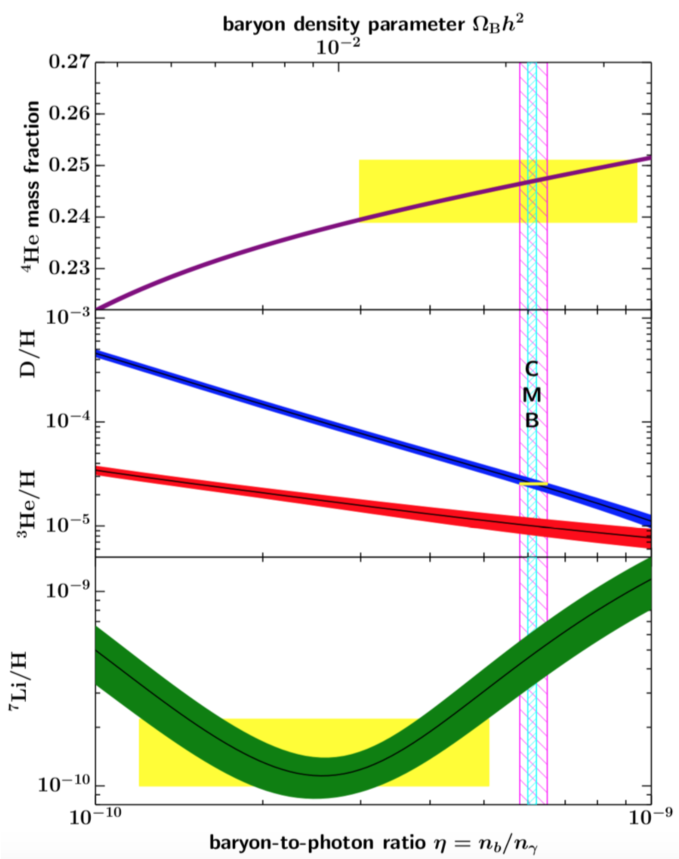
Not all the baryonic matter in the universe is easy to detect. About 85% of the baryons in the universe are in the extremely tenuous gas of intergalactic space, outside galaxies and clusters of galaxies. Much of this intergalactic gas is too low in density to be readily detected with current technology.

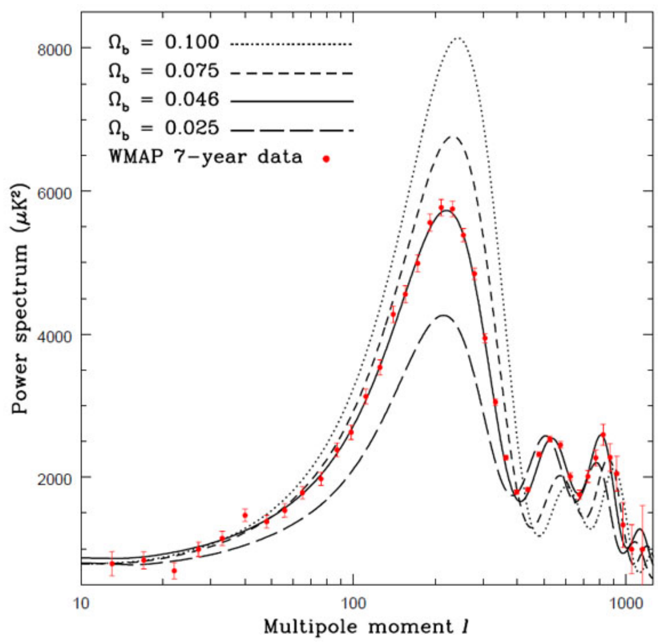
The best limits on the baryon density of the universe actually come from observations of the:
1. Cosmic microwave background.
2 Predictions of primordial nucleosynthesis in the early universe.

Both these sources of information about the early universe indicate that the density parameter of baryonic matter today must be

$$\Omega_{\rm bary,0} = 0.048 \pm 0.003,$$

ten to twenty times the density parameter for stars.





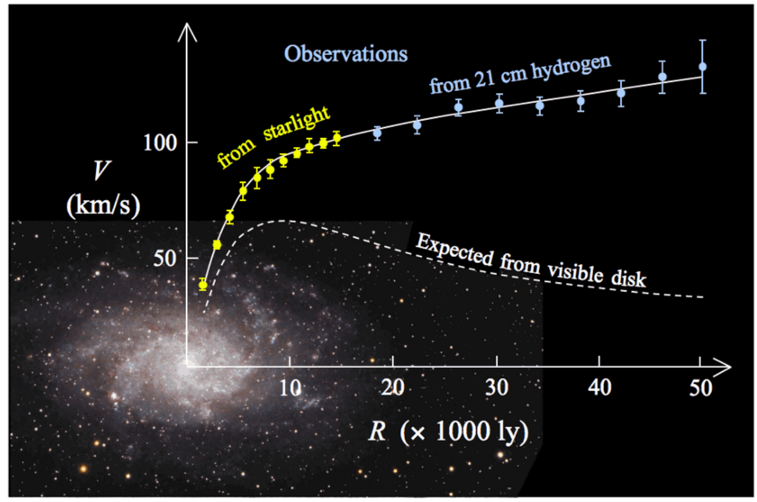
Dark Matter in Galaxies

Not only is most of the baryonic matter undetectable by our eyes, but most of the matter is not even baryonic. The majority of the matter in the universe is nonbaryonic dark matter, which doesn't absorb, emit, or scatter light of any wavelength.

Suppose that a star is on a circular orbit around the center of its galaxy. If the radius of the orbit is R and the orbital speed is v, then the star experiences an acceleration

$$a = \frac{v^2}{R},$$

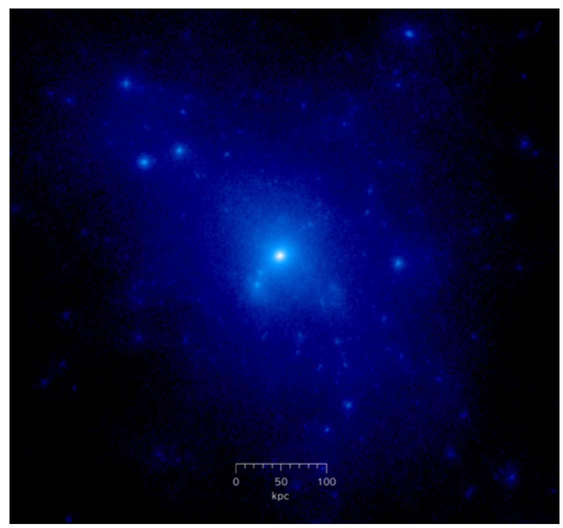
$$\frac{v^2}{R} = \frac{GM(R)}{R^2}, \qquad v = \sqrt{\frac{GM(R)}{R}}.$$



Thus, if stars contributed all, or most, of the mass in a galaxy, the velocity would fall as $v \propto 1/\sqrt{R}$ at large radii. This relation between orbital speed and orbital radius, $v \propto 1/\sqrt{R}$, is referred to as "Keplerian rotation," since it's what Kepler found for orbits in the solar system, where 99.8 percent of the mass is contained within the Sun.

If we approximate the orbital speed v as being constant with radius, the mass of a spiral galaxy, including both the luminous disk and the dark halo, can be found that:

Simulated dark matter halo from a cosmological N-body simulation



$$M(R) = \frac{v^2 R}{G} = 1.05 \times 10^{11}\,\mathrm{M}_\odot \left(\frac{v}{235\,\mathrm{km\,s^{-1}}}\right)^2 \left(\frac{R}{8.2\,\mathrm{kpc}}\right).$$

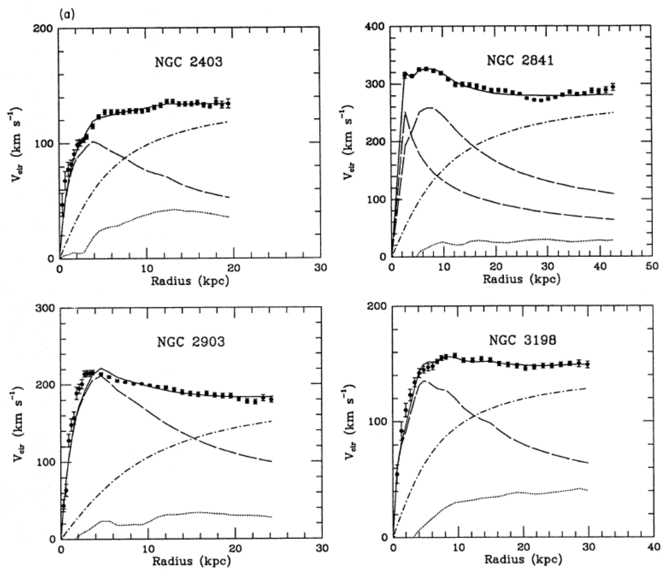
$$L_{\mathrm{gal},V} = 2.0 \times 10^{10}\,\mathrm{L}_{\odot,V},$$

$$\langle M/L_V \rangle_{\mathrm{gal}} \approx 64\,\mathrm{M}_\odot/\,\mathrm{L}_{\odot,V} \left(\frac{R_{\mathrm{halo}}}{100\,\mathrm{kpc}}\right),$$

$R_{\mathrm{halo}} \approx 75$ kpc, implying a total mass for our galaxy of $M_{\mathrm{gal}} \approx 9.6 \times 10^{11}\,\mathrm{M}_\odot$,

$$\langle M/L_V \rangle_{\mathrm{gal}} \approx 48\mathrm{M}_\odot/\,\mathrm{L}_{\odot,V}.$$

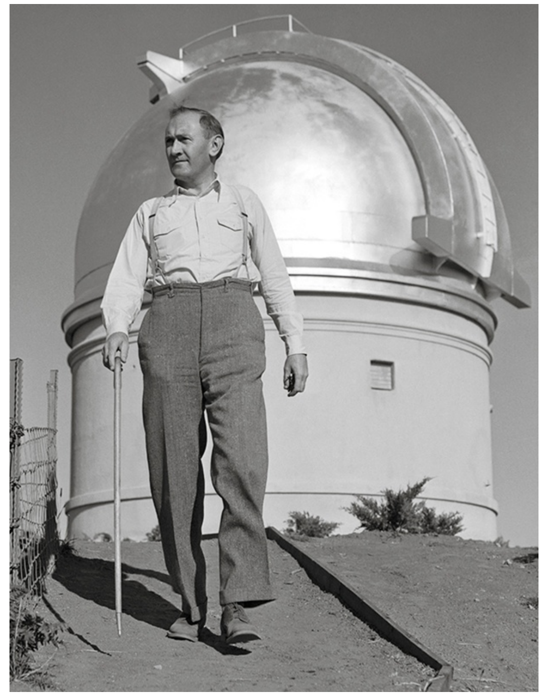
This mass-to-light ratio is an order of magnitude greater than that of the stars in our galaxy, implying a dark halo much more massive than the stellar disk.



Therefore, if the rotational velocities remain constant with increasing radius, the mass interior to this radius must be increasing. Since the density of luminous mass falls past the central bulge of the galaxy, the "missing" mass must be non-luminous. Rubin summarized, "The conclusion is inescapable: mass, unlike luminosity, is not concentrated near the center of spiral galaxies. Thus the light distribution in a galaxy is not at all a guide to mass distribution."[4]

Dark Matter in Clusters

The first astronomer to make a compelling case for the existence of large quantities of dark matter was Fritz Zwicky, in the 1930s. In studying the Coma cluster of galaxies, he noted that the dispersion in the radial velocity of the cluster's galaxies was very large – around 1000 km/s. The stars and gas visible within the galaxies simply did not provide enough gravitational attraction to hold the cluster together.
In order to keep the galaxies in the Coma cluster from flying off into the surrounding voids, Zwicky concluded, the cluster must contain a large amount of "dunkle Materie," or (translated into English) "dark matter."



Difficult and enigmatic: Fritz Zwicky feuded with many leading scientists of his day.
He is shown here at the California Institute of Technology in 1931. Front row (from left): Robert Oppenheimer, Harry Bateman, Richard Tolman, William Houston, Robert Millikan, Albert Einstein, Paul Sophus Epstein, Zwicky, Ernest Charles Watson.
(Courtesy: AIP Emilio Segrè Visual Archives)

steady-state virial theorem $K = -\frac{W}{2}$.

$$\frac{1}{2}M\langle v^2\rangle = \frac{\alpha}{2}\frac{GM^2}{r_h}.$$

This means we can use the virial theorem to estimate the mass of a cluster of galaxies, or any other self-gravitating steady-state system:

$$M = \frac{\langle v^2\rangle r_h}{\alpha G}.$$

For the Coma cluster: $\langle z\rangle = 0.0232,$

$$d_{\text{Coma}} = (c/H_0)\langle z\rangle = 102\,\text{Mpc}.$$

$$\langle v^2\rangle = 3(880\,\text{km}\,\text{s}^{-1})^2 = 2.32\times10^{12}\,\text{m}^2\,\text{s}^{-2}.$$

$$r_h \approx 1.5\,\text{Mpc} \approx 4.6\times10^{22}\,\text{m}.$$

$$M_{\text{Coma}} = \frac{\langle v^2\rangle r_h}{\alpha G} \approx \frac{(2.32\times10^{12}\,\text{m}^2\,\text{s}^{-2})(4.6\times10^{22}\,\text{m})}{(0.45)(6.67\times10^{-11}\,\text{m}^3\,\text{s}^{-2}\,\text{kg}^{-1})}$$
$$\approx 4\times10^{45}\,\text{kg} \approx 2\times10^{15}\,\text{M}_\odot.$$

Thus, about one percent of the mass of the Coma cluster consists of stars ($M_{\text{Coma},\star} \approx 2\times10^{13}\,\text{M}_\odot$), and about ten percent consists of hot intracluster gas ($M_{\text{Coma,gas}} \approx 2\times10^{14}\,\text{M}_\odot$). Combined with the luminosity of the Coma cluster, $L_{\text{Coma},V} \approx 5\times10^{12}\,\text{L}_{\odot,V}$, the total mass of the Coma cluster implies a mass-to-light ratio

$$\langle M/L_V\rangle_{\text{Coma}} \sim 400\,\text{M}_\odot/\text{L}_{\odot,V},$$

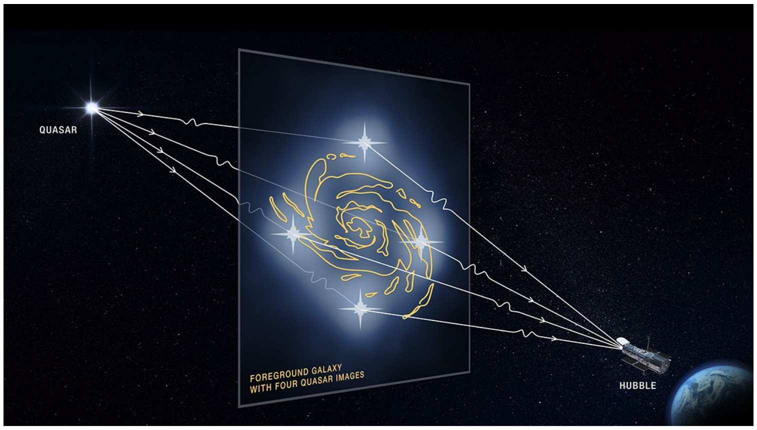
greater than the mass-to-light ratio of our galaxy.

Other clusters of galaxies besides the Coma cluster have had their masses estimated, using the virial theorem applied to their galaxies.
Typical mass-to-light ratios for rich clusters are similar to those of the Coma cluster.
If the masses of all the clusters of galaxies are added together, it is found that their density parameter is

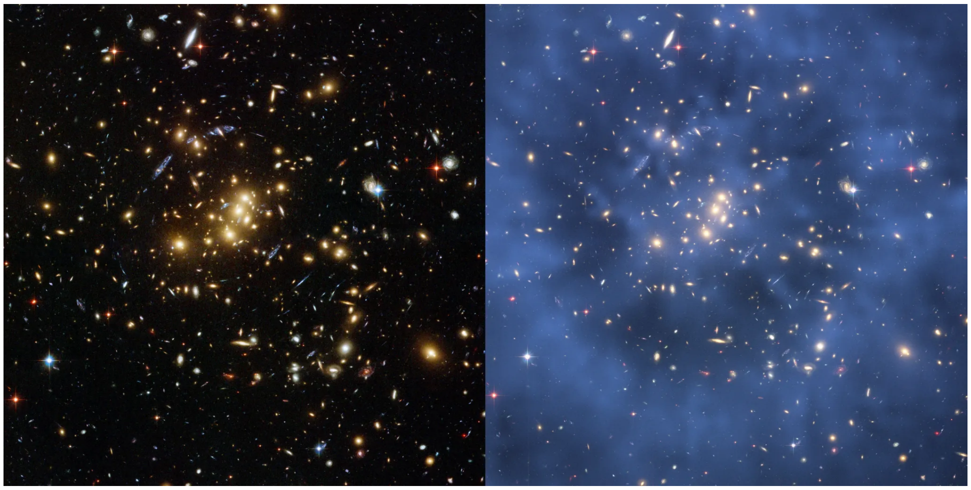
$$\Omega_{\text{clus},0} \approx 0.2.$$

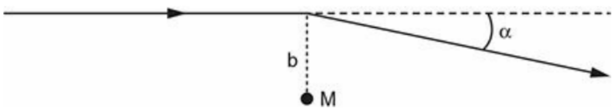
This provides a lower limit to the matter density of the universe, since any smoothly distributed matter in the intercluster voids will not be included in this number.

Gravitational Lensing



This view of the massive galaxy cluster Cl 0024+17 (ZwCl 0024+1652) reveals the bent and amplified light of distant galaxies. The left view is in visible light with odd-looking blue arcs appearing among the yellowish galaxies. These are the magnified and distorted images of galaxies located far behind the cluster. The right image holds added blue shading that indicates the location of invisible dark matter. The shape and position of the gravitationally lensed galaxies we see in the left-hand image, mathematically requires the presence of this dark matter.
NASA, ESA, M.J. Jee, and H. Ford (Johns Hopkins University)





Deflection of light by a massive compact object.

$$\alpha = \frac{4GM}{c^2 b},$$

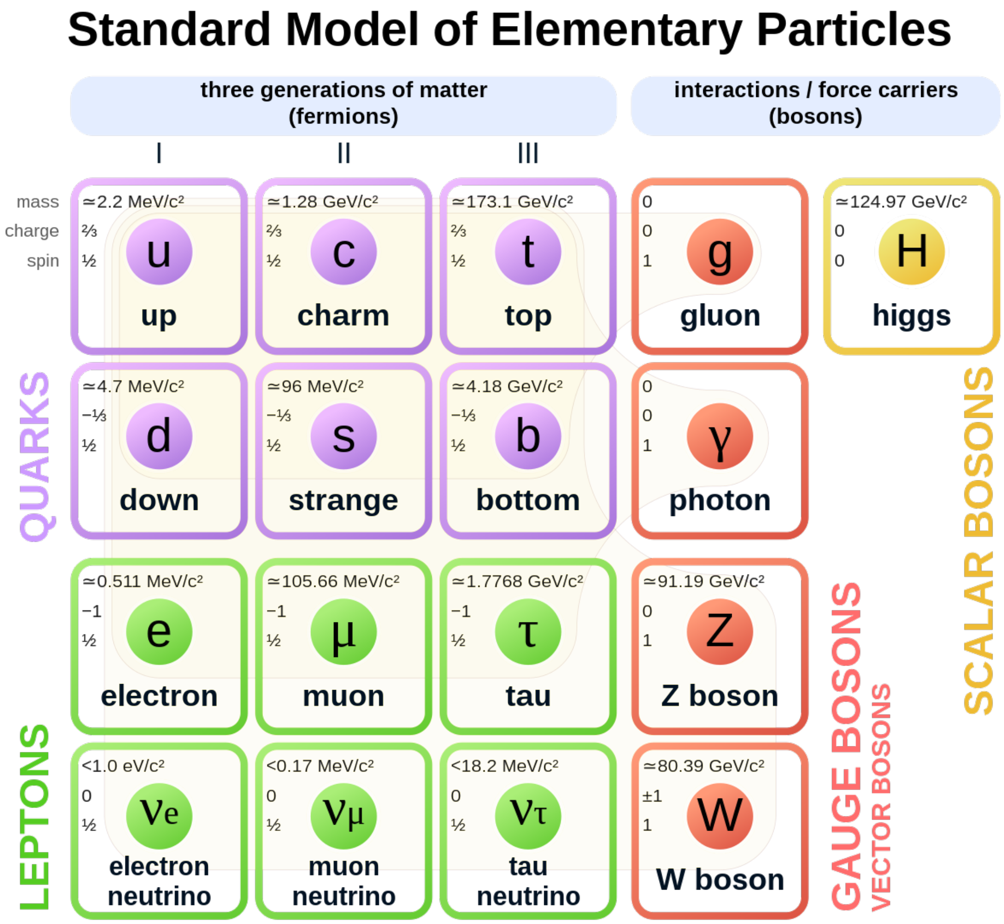
$$\alpha = \frac{4G\,\mathrm{M}_\odot}{c^2\,\mathrm{R}_\odot} = 1.7\,\text{arcsec}.$$

$$\theta_E = \left(\frac{4GM}{c^2 d}\frac{1-x}{x}\right)^{1/2},$$

If $x \approx 0.5$ (that is, if the MACHO is roughly halfway between the observer and the lensed star), then

For instance, Figure 7.6 shows a *Hubble Space Telescope* image of the cluster Abell 2218, which has a redshift $z = 0.176$, and hence is at a proper distance $d = 740$ Mpc. The elongated, slightly curved arcs seen in Figure 7.6 are not oddly shaped galaxies within the cluster; instead, they are background galaxies, at redshifts $z > 0.176$, which

What might the dark matter be?



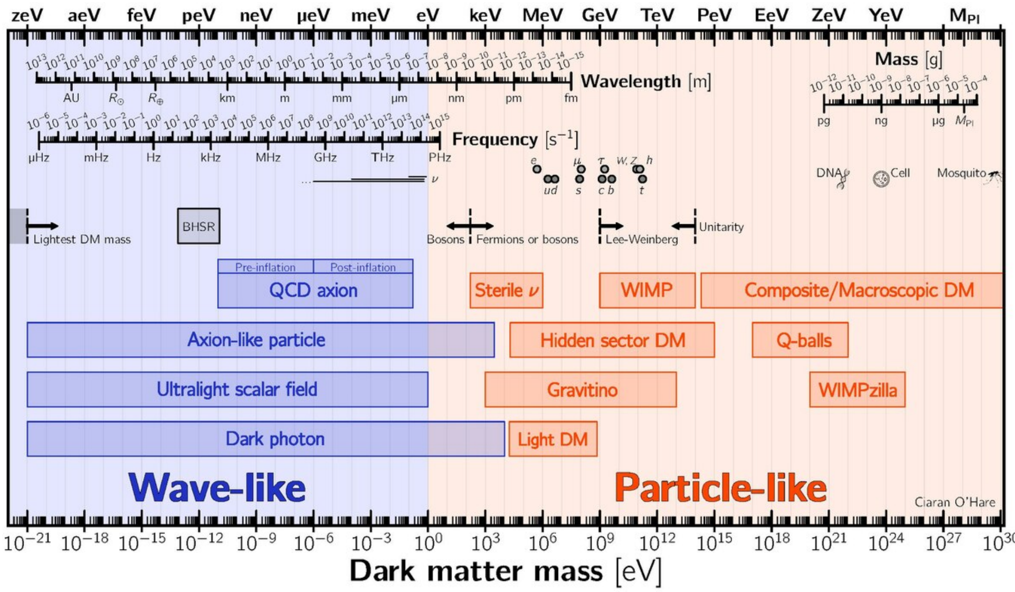
Fermions

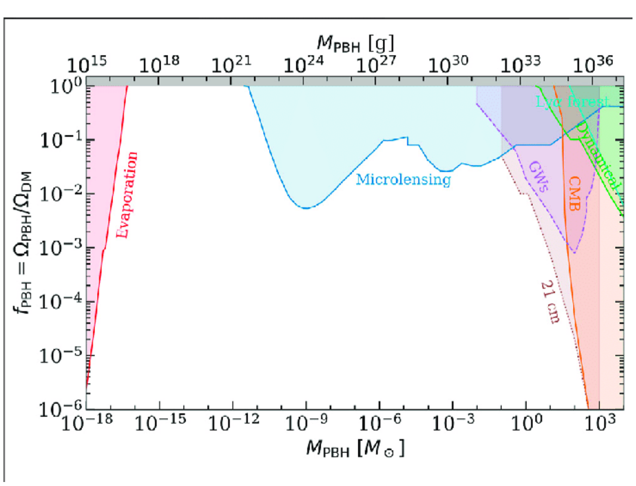
Generation 1			Generation 2			Generation 3		
Particle	Mass (MeV)	Charge	Particle	Mass (MeV)	Charge	Particle	Mass (MeV)	Charge
up quark (u)	2.55	$+\frac{2}{3}$	charm quark (c)	1270	$+\frac{2}{3}$	top quark (t)	171200	$+\frac{2}{3}$
down quark (d)	5.04	$-\frac{1}{3}$	strange quark (s)	104	$-\frac{1}{3}$	bottom quark (b)	4200	$-\frac{1}{3}$
electron (e^-)	0.511	-1	muon (μ^-)	105.7	-1	tau (τ^-)	1776.8	-1
e neutrino (ν_e)	$< 2.0 \times 10^{-6}$	0	μ neutrino (ν_μ)	< 0.19	0	τ neutrino (ν_τ)	< 18.2	0

Gauge Bosons

Particle	Force	Acts through	Acts on	Mass (MeV)	Charge
Photon (γ)	Electromagnetic	Electric charge	Electrically charged particles	$< 1\times10^{-24} \approx 0$	0
Z boson (Z)	Weak nuclear	Weak interaction	Quarks and leptons	91188	0
$W^\pm$ bosons ($W^\pm$)	Weak nuclear	Weak interaction	Quarks and leptons	80398	±1
Gluon (g)	Strong nuclear	Color charge	Quarks and gluons	-	0
Higgs boson (H^0)	Higgs force	Higgs field	Massive particles	125 GeV	0

DM candidates





DM detection