Beyond Popular Science

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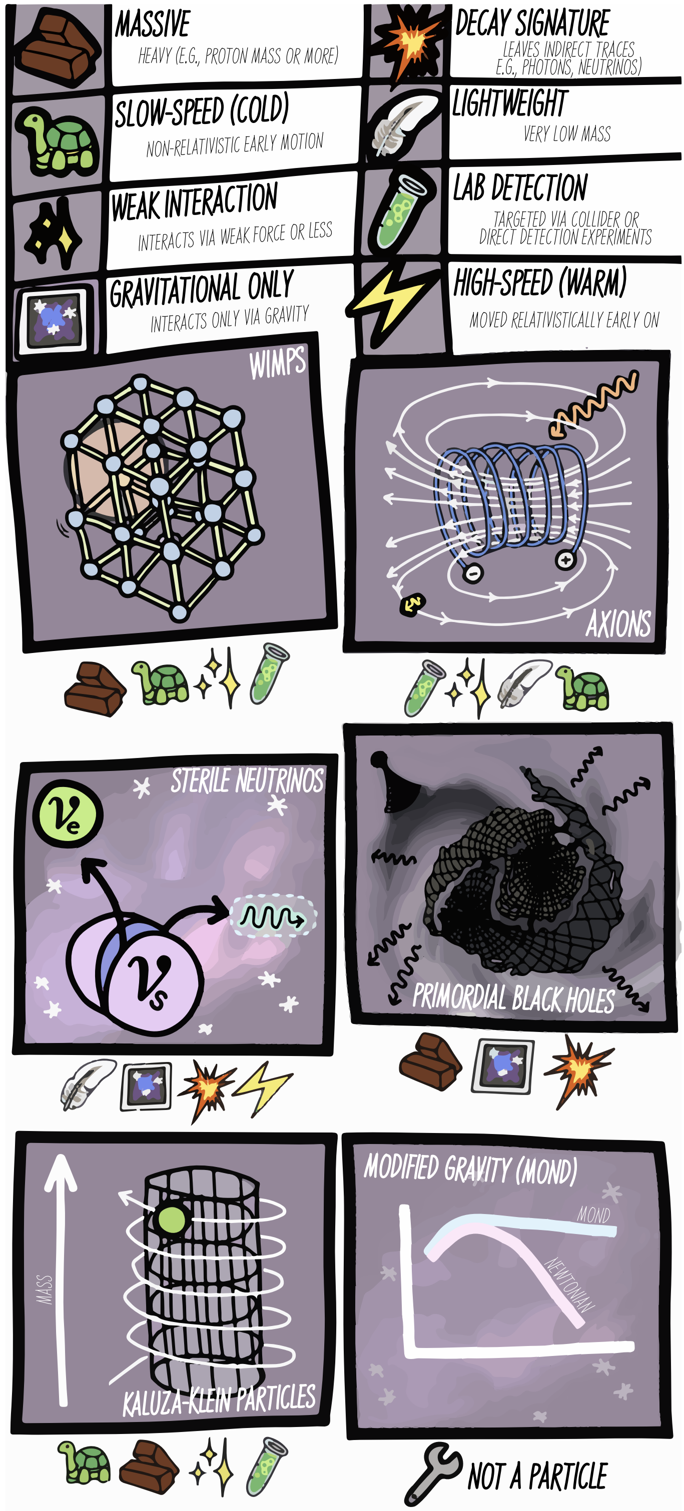
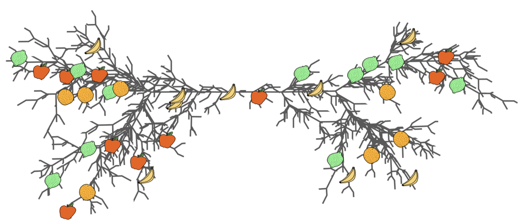
Darkness to Bind Them

Top (Candidate Properties): Dark matter candidates are evaluated by properties such as mass (from massless to heavy), speed (cold vs warm), interaction type (weak, gravitational only), and detectability (via lab or decay signatures). Each row indicates a possible property constraint.
Second Row (WIMPs and Axions): WIMPs (Weakly Interacting Massive Particles) are cold, massive, and weakly interacting, long favoured due to supersymmetric theories. Axions are extremely light, produced via field misalignment, and may convert to photons in magnetic fields.
Third Row (Sterile Neutrinos and Primordial Black Holes): Sterile neutrinos mix with active ones but don't interact via the weak force, allowing them to evade detection. Primordial black holes are relics from the early universe that behave as cold dark matter through pure gravitational influence.
Bottom Row (Kaluza-Klein theories and MOND): Kaluza-Klein particles arise from extra spatial dimensions; their quantised modes could serve as dark matter if stable. Modified Newtonian Dynamics (MOND) suggests gravity itself needs correction at low accelerations—removing the need for particle dark matter.



Darkness to Bind Them

Dark matter's existence is inferred through multiple independent lines of evidence spanning different cosmic scales. Galaxy rotation curves remain flat far beyond visible matter, indicating extended gravitational influence. Galaxy clusters contain hot gas whose temperature and confinement require gravitational potentials deeper than visible matter can provide. Gravitational lensing reveals mass distributions exceeding luminous components, particularly in systems such as the Bullet Cluster where dark and visible matter separate during collisions. The cosmic microwave background's fluctuation patterns indicate that ordinary matter comprises only 15% of the total matter content needed to match observations, with the remainder consisting of non-baryonic material already present before photon-matter decoupling.



Dark Matter Evidence ∘ Galaxy Rotation Curves ∘ Doppler Spectroscopy ∘ 21cm Hydrogen Mapping ∘ Gravitational Lensing ∘ Bullet Cluster Collision ∘ Cluster Dynamics ∘ CMB Acoustic Peaks ∘ Structure Formation Timeline ∘ Non-Luminous Mass ∘ MOND Limitations

"נְטֵ֤ה יָֽדְךָ֙ עַל־הַשָּׁמַ֔יִם וִ֥יהִי חֹ֖שֶׁךְ עַל־אֶ֣רֶץ מִצְרָ֑יִם וְיָמֵ֖שׁ חֹֽשֶׁךְ"
("...darkness spreads over Egypt — darkness that can be felt")
— Exodus 10:21

Darkness to Bind Them

> In 1933, Swiss astrophysicist Fritz Zwicky analysed the velocity dispersion of galaxies in the Coma Cluster and found their motions to be too fast to be gravitationally bound by the visible mass alone. He introduced the term *dunkle Materie* (dark matter) to describe the missing component. Though initially met with scepticism, his mass discrepancy hinted at a core problem in astrophysical mass accounting.
>
> The issue resurfaced in the 1970s when Vera Rubin and Kent Ford measured rotation curves of spiral galaxies using optical spectroscopy. Instead of decreasing with radius as expected from luminous matter distributions, the rotation speeds remained flat well beyond the visible edge. Independent radio observations by Albert Bosma confirmed this effect through 21 centimetre emission from neutral hydrogen, revealing a pervasive halo of unseen mass enveloping each galaxy.
>
> By the early 1980s, theorists such as Jeremiah Ostriker and Jim Peebles emphasised the necessity of dark matter to explain large-scale structure formation. Without a non-luminous component, galaxies and clusters could not form on observed timescales. Theoretical simulations incorporating dark matter successfully reproduced the filamentary distribution of galaxies seen in redshift surveys.
>
> Gravitational lensing provided additional, independent confirmation. Light from distant sources bent around foreground mass concentrations showed more deflection than visible matter alone could account for. In 2006, observations of the Bullet Cluster—a high-speed collision of galaxy clusters—visually separated dark matter from hot gas via X-ray and lensing data, offering direct evidence of a collisionless mass component.
>
> Dark matter's influence now spans cosmology, astrophysics, and particle physics. Measurements of cosmic microwave background anisotropies by missions such as WMAP and Planck established dark matter as essential for matching early-universe fluctuations to present-day structure.

To understand the structure and evolution of the universe, astrophysicists must measure not just light, but mass. Stars, galaxies, and gas clouds emit radiation that reveals their presence, but the dynamics of the cosmos are governed by gravity—by how much mass exists and how it is distributed. Knowing where matter is, and how much of it there is, is necessary for explaining motion, structure formation, and stability across cosmic scales. The question is: how can one measure mass across millions of light-years, when most of it emits no light at all?

The primary method is to observe motion. In Newtonian mechanics, any orbiting body experiences a centripetal acceleration that is directly related to the mass it orbits. This relationship allows astronomers to determine how much mass lies within a given radius, provided they can measure orbital speeds and distances. By measuring the velocities of stars at different radii from the centre of a galaxy, astrophysicists can infer how mass is distributed throughout the galaxy—not just in its luminous regions.

Spectroscopy plays a central role in this process. When light from a star or gas cloud is dispersed into its component wavelengths, the resulting spectrum reveals its motion via

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Doppler shifts. A redshift indicates motion away from the observer; a blueshift indicates motion toward. These shifts allow for measurements of velocity along the line of sight. Rotational velocities within galaxies, random velocities in galaxy clusters, and internal turbulence in gas clouds can all be extracted from spectral line profiles.

Radio astronomy extends these measurements beyond visible light. Neutral hydrogen, the most abundant element in the universe, emits radiation at a wavelength of 21 centimetres. This emission can be traced even in the outskirts of galaxies, where stars are sparse or absent. Observing the motion of this gas provides crucial data on gravitational effects well outside the luminous core.

In systems without a simple rotation pattern—such as elliptical galaxies or clusters—mass is inferred statistically. The velocities of constituent bodies follow distributions governed by the overall gravitational potential. In these cases, the virial theorem (as is explored also in the chapter on osmosis) connects the average kinetic energy of the system to the total mass required to confine it. This technique is especially important in estimating the masses of galaxy clusters, where galaxies orbit in all directions and the system behaves like a gravitationally bound swarm.

A complementary approach bypasses dynamics altogether: gravitational lensing. According to general relativity, mass curves spacetime, bending the path of light from background sources. When a massive object—such as a galaxy or cluster—lies along the line of sight to a more distant source, the background light is distorted. By analysing the shape and degree of this distortion, one can map the total mass distribution of the intervening object. This method is purely gravitational: it measures mass regardless of whether it emits, absorbs, or reflects light.

When mass in a galaxy is concentrated toward the centre, orbital velocities should decrease with distance, just as planets in the Solar System orbit more slowly the farther they are from the Sun. Observations do not match this expectation. In spiral galaxies, stars orbit the centre at nearly constant speed (Rubin & Ford, 1970) over vast radial distances. These flat rotation curves indicate that the enclosed mass does not level off where the stars end, but continues to increase. The luminous matter—stars, gas, and dust—cannot account for this excess gravity.

The persistence of high orbital speeds well beyond the visible edge of galaxies is confirmed by radio observations of neutral hydrogen. Radio telescopes can map the velocity of this gas across the outskirts of galaxies. These measurements show that rotational velocities remain flat or even rise at large radii, where the density of luminous matter has dropped to negligible levels. The simplest explanation is that galaxies are embedded in extended halos of non-luminous mass, whose gravitational influence dominates in the outer regions.

On larger scales, galaxy clusters present an analogous discrepancy. These systems contain hundreds or thousands of galaxies bound together by gravity, along with large amounts of hot gas that emits strongly in X-rays. The temperature and distribution of this gas reflect the depth of the gravitational potential well. If only the visible galaxies and gas contributed to the cluster's gravity, the hot gas would escape over cosmological timescales. That it remains bound implies a much larger total mass than what is seen. The internal motions of galaxies within clusters, measured by redshift dispersion, independently confirm this excess mass. Gravitational lensing applies also to these massive clusters, and in both contexts (individual galaxies and clusters), the lensing signal supports the presence of a dominant, unseen mass component.

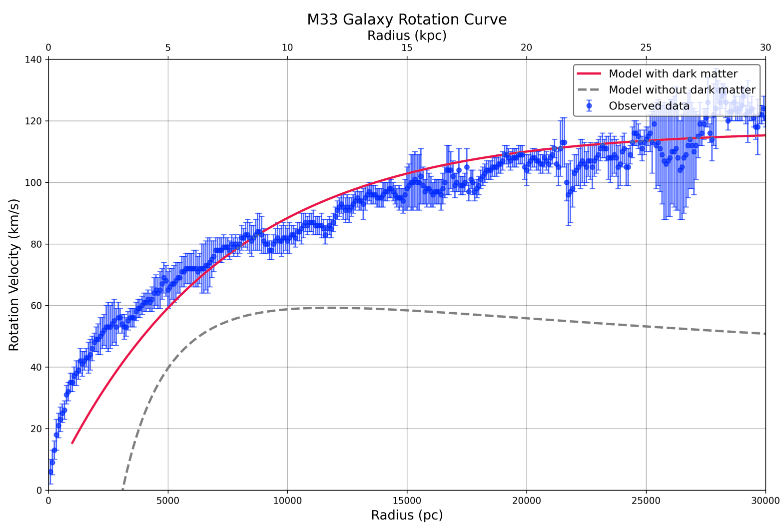
A unique astrophysical event—**the Bullet Cluster**—provides direct evidence for a non-luminous mass component that behaves differently from ordinary matter. This system consists of two galaxy clusters in the process of collision. As they pass through one another, the hot gas from each cluster interacts and slows down due to ram pressure (pressure due to bulk motion; compare to temperature, the internal kinetic component, in Chapter 28), becoming spatially displaced from the galaxies themselves. X-ray observations reveal this gas concentrated between the clusters. However, gravitational lensing maps of the same region show that most of the mass is still centred on the galaxies, not the gas. This separation implies that the dominant mass component did not experience significant drag during the collision. It must interact gravitationally, but not electromagnetically—suggesting it is both massive and effectively collisionless.

The early universe provides a separate window into the distribution of mass through the spectral composition of the cosmic microwave background (CMB). This radiation carries a record of acoustic oscillations in the primordial plasma—pressure waves driven by the interplay between gravity and radiation. The pattern of these oscillations, visible as peaks in the CMB power spectrum, (Spergel et al., 2003) depends sensitively on the matter content of the universe. Ordinary (baryonic) matter couples to photons and thus participates in pressure waves, while non-baryonic matter does not. Matching the observed amplitude and spacing of the peaks requires a dominant component of matter that does not interact with radiation, but contributes to gravitational attraction. Precision measurements by the WMAP (Wilkinson Microwave Anisotropy Probe) and Planck satellites confirm that ordinary matter accounts for only a small fraction of the total.

Numerical simulations of structure formation reinforce this conclusion. Starting from the nearly uniform density field observed in the CMB, simulations track the growth under gravity. The timing and scale of galaxy and cluster formation are highly sensitive to the amount and type of matter present. If only ordinary matter were included, structure would form too slowly to match what is observed in deep-field surveys. The emergence of galaxies, clusters, and the cosmic web within a few billion years requires a gravitational source that was present from the earliest epochs, unaffected by radiation pressure, and capable of seeding the collapse of matter on small scales. The observed universe forms on schedule only when this additional component is included.

Thus, the evidence for dark matter does not rest on a single anomalous measurement, but on the convergence of diverse and independent observational domains. Galaxy rotation curves, cluster dynamics, X-ray temperature profiles, gravitational lensing, and the cosmic microwave background all indicate that visible matter accounts for only a small fraction of the gravitational forces at work. The required additional mass must act through gravity, but not through electromagnetism; it must clump on galactic scales, but remain diffuse enough not to obstruct light; it must have existed before the era of recombination, but not interfered with photon-matter coupling. The simplest explanation consistent with all constraints is the existence of a non-luminous, cold, and effectively collisionless form of matter—distinct from atoms, but essential for the cosmic configuration. To convey the scale: the local dark matter density near the Sun is estimated at roughly 0.3 GeV/cm^3, equivalent to about one proton mass per every three cubic centimetres—an extraordinarily diffuse medium, yet one whose cumulative gravitational effect across galactic volumes is decisive.

Attempts to resolve these discrepancies by modifying the laws of gravity instead of introducing a new kind of matter have achieved only partial success. Modified Newtonian dynamics (MOND) can account (Milgrom, 1983) for some features of galactic rotation curves, but struggle with systems lacking clear symmetry or equilibrium. The Bullet Cluster, in particular, presents a direct conflict: the separation of gravitational and luminous mass cannot be explained by alterations to the gravitational field alone. Gravitational lensing imposes geometric constraints that any alternative theory must satisfy, and these constraints are difficult to reconcile with models that dispense entirely with unseen mass. The full range of phenomena—from early-universe fluctuations to present-day structure—aligns with the presence of a real, additional matter component, much better than by a reformulation of force laws.



The rotation curve of M33 (Triangulum Galaxy). Blue points show observed Hα velocities; the red curve includes dark matter contribution; the grey dashed line represents visible baryonic matter only. The persistent high velocities at large radii provide compelling evidence for an extended dark matter halo. Raw data from Kam et al. (2015), MNRAS 449, 4048. Fitted curve is not from the literature and is for illustrative purposes only.

Mass Scales in the universe

Object	**Mass (kg)**	**Object**	**Mass (kg)**
Electron neutrino	$< 2 \times 10^{-36}$	Human	~ 70
Electron	9.1×10^{-31}	Earth	6.0×10^{24}
Proton	1.7×10^{-27}	Jupiter	1.9×10^{27}
Gold atom	3.3×10^{-25}	Sun	2.0×10^{30}
Water molecule	3.0×10^{-26}	Milky Way	$\sim 10^{42}$
DNA base pair	$\sim 10^{-24}$	Local group	$\sim 4 \times 10^{42}$
E. coli bacterium	$\sim 10^{-15}$	Observable universe	$\sim 10^{53}$

Density Scales in Nature

Material / Region	**Density (g/cm³)**
Intergalactic vacuum	$\sim 10^{-30}$
Interstellar medium	$\sim 10^{-24}$
Best laboratory vacuum	$\sim 10^{-17}$
Air at sea level	1.2×10^{-3}
Water	1.0
Iron	7.9
Lead	11.3
Osmium (densest element)	22.6
White dwarf core	$\sim 10^{6}$
Atomic nucleus	$\sim 2 \times 10^{14}$
Neutron star core	$\sim 10^{15}$
Quark-gluon plasma	$\sim 10^{16}$

The universe spans roughly 90 orders of magnitude in mass and 46 orders of magnitude in density. The density range accessible to direct laboratory measurement occupies only a narrow band between 10^{-17} and 10^{2} g/cm³. Nuclear densities, neutron star cores, and the conditions of the early universe require inference from particle collisions, gravitational observations, and quantum chromodynamics.

Gravitational Inference and the Distribution of Dark Matter

Virial Mass in Galaxy Clusters (see also Chapter 31)

Clusters of galaxies are treated as self-gravitating systems in equilibrium. Let a system of N particles with masses m_i and velocities $\mathbf{v}_i$ have total kinetic and potential energy:

$$K = \sum_{i=1}^{N} \tfrac{1}{2} m_i v_i^2, \qquad U = -\sum_{i<j} \frac{G m_i m_j}{r_{ij}}.$$

By the virial theorem:

$$2\langle K \rangle + \langle U \rangle = 0.$$

Assuming an isotropic one-dimensional velocity dispersion so that $\langle v^2 \rangle = 3\sigma_v^2$ and, for a roughly uniform sphere, $U = -\frac{3}{5}\frac{GM^2}{R}$, we obtain:

$$M_{\text{vir}} \approx \frac{5\,\sigma_v^2 R}{G},$$

where R is the effective radius of the system. For rich clusters such as Coma, the mass inferred by this formula exceeds luminous mass (stars + gas) by over an order of magnitude.

Rotation Curves and Halo Profiles

In spiral galaxies, stars and gas orbit the galactic centre under gravitational attraction. For circular orbits:

$$\frac{v^2(r)}{r} = \frac{GM(r)}{r^2} \quad \Rightarrow \quad M(r) = \frac{v^2(r)\,r}{G}.$$

Observations show that $v(r)$ remains nearly constant beyond the optical radius, implying $M(r) \propto r$, inconsistent with the radial profile of visible mass.

This necessitates a dark matter halo extending beyond the visible disc. Simulations and fits to data often use the Navarro–Frenk–White (NFW) profile:

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2},$$

where ρ_0 is a characteristic density and r_s a scale radius. This profile produces approximately flat rotation curves at large r and matches the mass distributions required to stabilise galaxies against dispersal.

Weak Gravitational Lensing

Lensing measures projected surface mass. In the weak lensing regime, the convergence $\kappa(\theta)$ is given by:

$$\kappa(\theta) = \frac{\Sigma(\theta)}{\Sigma_{\text{crit}}}, \quad \Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \cdot \frac{D_s}{D_d D_{ds}},$$

with angular diameter distances D_s (observer to source), D_d (observer to lens), and D_{ds} (lens to source). The deflection angle is sensitive to the integrated surface mass density $\Sigma(\theta)$. Mapping κ via background galaxy distortions reconstructs the total projected mass distribution.

In systems such as the Bullet Cluster, lensing peaks and X-ray emission peaks are spatially offset. This implies that the dominant mass component is not collisional (as hot gas is), but rather behaves as a collisionless fluid, consistent with dark matter expectations.

Implications

The gravitational field inferred from cluster dynamics, orbital motion in galaxies, and lensing geometry all points to a dominant non-luminous mass component. Its spatial distribution is extended, centrally concentrated, and required across all scales. These observations define dark matter phenomenologically: a gravitationally interacting, non-emissive mass component that clumps and seeds structure.

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