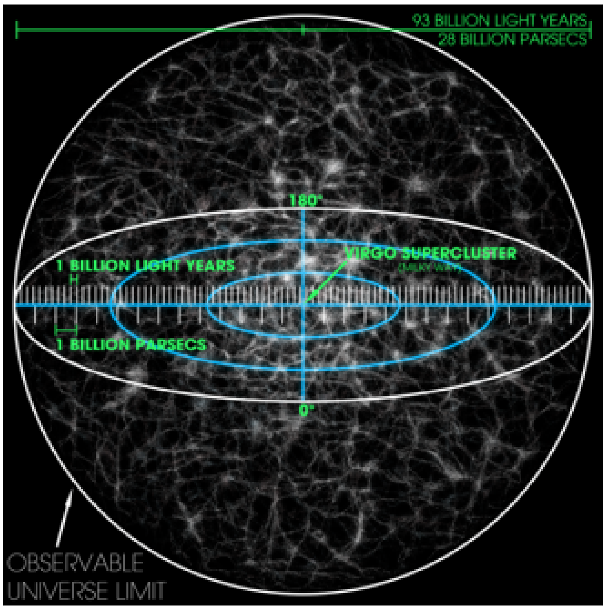
Observable universe

The **observable universe** is a spherical region of the universe consisting of all matter that can be observed from Earth; the electromagnetic radiation from these astronomical object has had time to reach the Solar System and Earth since the beginning of the cosmological expansion. Assuming the universe is isotropic, the distance to the edge of the observable universe is the same in every direction. That is, the observable universe is a spherical region centered on the observer. Every location in the universe has its own observable universe, which may or may not overlap with the one centered on Earth.

The word *observable* in this sense does not refer to the capability of modern technology to detect light or other information from an object, or whether there is anything to be detected. It refers to the physical limit created by the speed of light itself. No signal can travel faster than light, hence there is a maximum distance, called the particle horizon, beyond which nothing can be detected, as the signals could not have reached the observer yet.

According to calculations, the current comoving distance to particles from which the cosmic microwave background radiation (CMBR) was emitted, which represents the radius of the visible universe, is about 14.0 billion parsecs (about 45.7 billion light-years). The comoving distance to the edge of the observable universe is about 14.3 billion parsecs (about 46.6 billion light-years),[7] about 2% larger. The radius of the observable universe is therefore estimated to be about 46.5 billion light-years.[8][9] Using the critical density and the diameter of the observable universe, the total mass of ordinary matter in the universe can be calculated to be about 1.5×10^{53} kg.[10] In November 2018, astronomers reported that extragalactic background light (EBL) amounted to 4×10^{84} photons.[11][12]

Observable universe

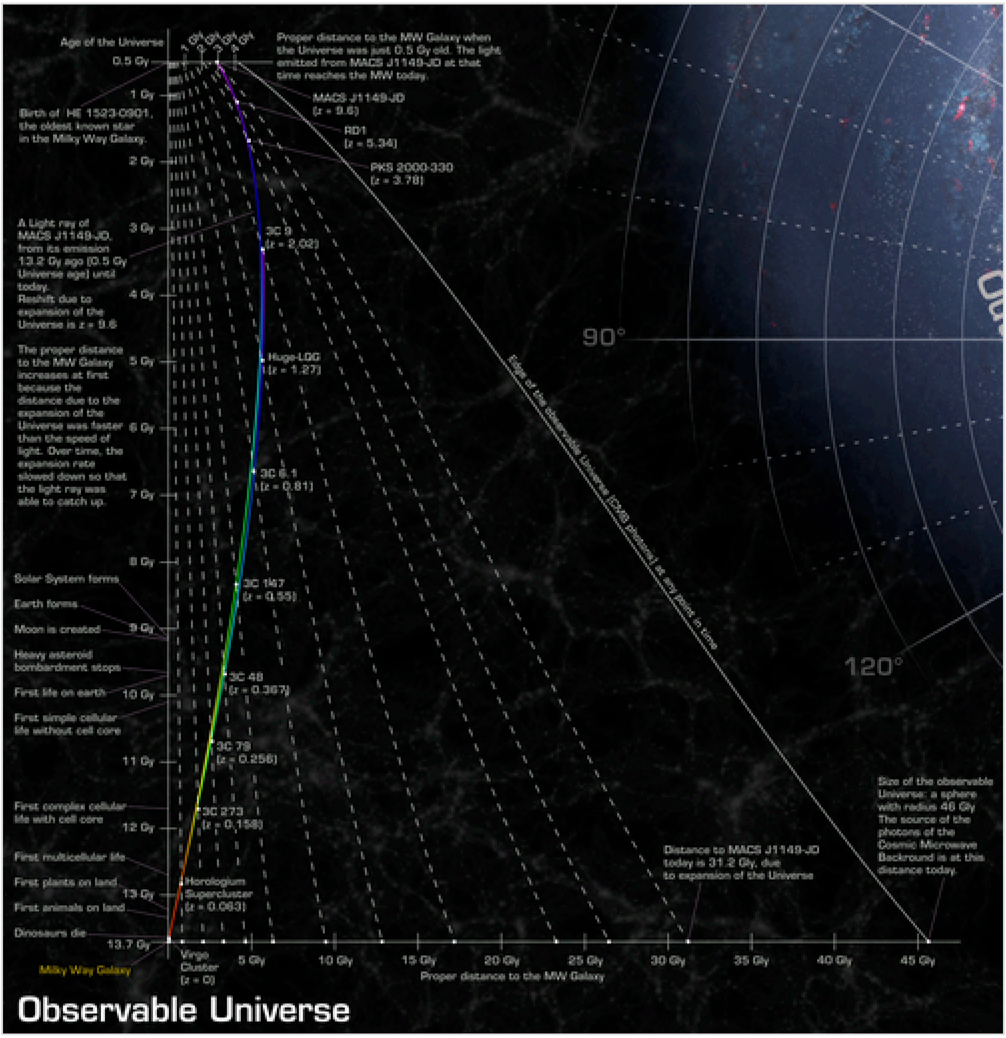


Visualization of the observable universe. The scale is such that the fine grains represent collections of large numbers of superclusters. The Virgo Supercluster—home of the Milky Way—is marked at the center, but is too small to be seen.

Diameter	8.8×10^{26} m or 880 Ym (28.5 Gpc or 93 Gly)[1]
Circumference	2.764×10^{27} m or 2.764 Rm (89.6 Gpc or 292.2 Gly)
Volume	3.566×10^{80} m^3[2]
Mass (ordinary matter)	1.5×10^{53} kg[3]
Density (of total energy)	8.5×10^{-27} kg/m^3 (equivalent to ~5 protons per cubic meter of space)[3]
Age	13.787 ± 0.020 billion years[4]
Average temperature	$2.725\,48 \pm 0.000\,57$ K[5]
Contents	Ordinary (baryonic) matter (4.9%) Dark matter (26.8%) Dark energy (68.3%)[6]

As the universe's expansion is accelerating, all currently observable objects, outside the local supercluster, will eventually appear to freeze in time, while emitting progressively redder and fainter light. For instance, objects with the current redshift *z* from 5 to 10 will only be observable up to an age of 4–6 billion years. In addition, light emitted by objects currently situated beyond a certain comoving distance (currently about 19 gigaparsecs (62 Gly)) will never reach Earth.[13]

Overview



Observable Universe as a function of time and distance, in context of the expanding Universe

The universe's size is unknown, and it may be infinite in extent.[14] Some parts of the universe are too far away for the light emitted since the Big Bang to have had enough time to reach Earth or space-based instruments, and therefore lie outside the observable universe. In the future, light from distant galaxies will have had more time to travel, so one might expect that additional regions will become observable. Regions distant from observers (such as us) are expanding away faster than the speed of light, at rates estimated by Hubble's law.[note 1] The expansion rate appears to be accelerating, which dark energy was proposed to explain.

Assuming dark energy remains constant (an unchanging cosmological constant) so that the expansion rate of the universe continues to accelerate, there is a "future visibility limit" beyond which objects will never enter the observable universe at any time in the future because light emitted by objects outside that limit could never reach the Earth. Note that, because the Hubble parameter is decreasing with time, there can be cases where a galaxy that is receding from Earth only slightly faster than light emits a signal that eventually reaches Earth.[9][15] This future visibility limit is calculated at a comoving distance of 19 billion parsecs (62 billion light-years), assuming the universe will keep expanding forever, which implies the number of galaxies that can ever be theoretically observed in the infinite future is only larger than the number currently observable by a factor of 2.36 (ignoring redshift effects).[note 2]

In principle, more galaxies will become observable in the future; in practice, an increasing number of galaxies will become extremely redshifted due to ongoing expansion, so much so that they will seem to disappear from view and become invisible.[16][17][18] A galaxy at a given comoving distance is defined to lie within the "observable universe" if we can receive signals emitted by the galaxy at any age in its history, say, a signal sent from the galaxy only 500 million years after the Big Bang. Because of the universe's expansion, there may be some later age at which a signal sent from the same galaxy can never reach the Earth at any point in the infinite future, so, for example, we might never see what the galaxy looked like 10 billion years after the Big Bang,[13] even though it remains at the same comoving distance less than that of the observable universe.

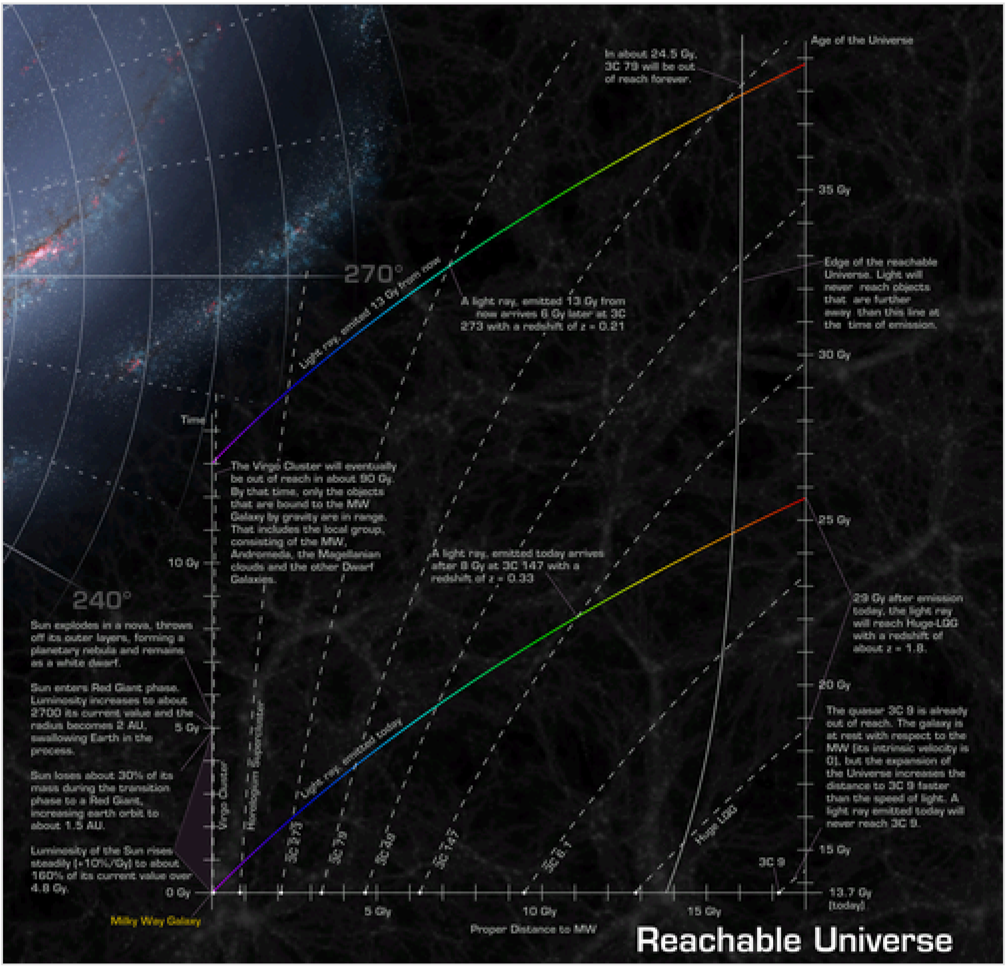
This can be used to define a type of cosmic event horizon whose distance from the Earth changes over time. For example, the current distance to this horizon is about 16 billion light-years, meaning that a signal from an event happening at present can eventually reach the Earth if the event is less than 16 billion light-years away, but the signal will never reach the Earth if the event is further away.[9]

The space before this cosmic event horizon can be called "reachable universe", that is all galaxies closer than that could be reached if we left for them today, at the speed of light; all galaxies beyond that are unreachable.[19][20] Simple observation will show the future visibility limit (62 billion light-years) is exactly equal to the reachable limit (16 billion light-years) added to the current visibility limit (46 billion light-years).[21][7]

"The universe" versus "the observable universe"

Both popular and professional research articles in cosmology often use the term "universe" to mean "observable universe". This can be justified on the grounds that we can never know anything by direct observation about any part of the universe that is causally disconnected from the Earth, although many credible theories require a total universe much larger than the observable universe. No evidence exists to suggest that the boundary of the observable universe constitutes a boundary on the universe as a whole, nor do any of the mainstream cosmological models propose that the universe has any physical boundary in the first place. However, some models propose it could be finite but unbounded,[note 3] like a higher-dimensional analogue of the 2D surface of a sphere that is finite in area but has no edge.

It is plausible that the galaxies within the observable universe represent only a minuscule fraction of the galaxies in the universe. According to the theory of cosmic inflation initially introduced by Alan Guth and D. Kazanas,[22] if it is assumed that inflation began about 10^{-37} seconds after the Big Bang and that the pre-inflation size of the universe was approximately equal to the speed of light times its age, that would suggest that at present the entire universe's size is at least 1.5×10^{34} light-years — this is at least 3×10^{23} times the radius of the observable universe.[23]



The reachable Universe as a function of time and distance, in context of the expanding Universe.

If the universe is finite but unbounded, it is also possible that the universe is *smaller* than the observable universe. In this case, what we take to be very distant galaxies may actually be duplicate images of nearby galaxies, formed by light that has circumnavigated the universe. It is difficult to test this hypothesis experimentally because different images of a galaxy would show different eras in its history, and consequently might appear quite different. Bielewicz et al.[24] claim to establish a lower bound of 27.9 gigaparsecs (91 billion light-years) on the diameter of the last scattering surface. This value is based on matching-circle analysis of the WMAP 7-year data. This approach has been disputed.[25]

Size

The comoving distance from Earth to the edge of the observable universe is about 14.26 gigaparsecs (46.5 billion light-years or 4.40×10^{26} m) in any direction. The observable universe is thus a sphere with a diameter of about 28.5 gigaparsecs[27] (93 billion light-years or 8.8×10^{26} m).[28] Assuming that space is roughly flat (in the sense of being a Euclidean space), this size corresponds to a comoving volume of about 1.22×10^4 Gpc^3 (4.22×10^5 Gly^3 or 3.57×10^{80} m^3).[29]

These are distances now (in cosmological time), not distances at the time the light was emitted. For example, the cosmic microwave background radiation that we see right now was emitted at the time of photon decoupling, estimated to have occurred about 380,000 years after the Big Bang,[30][31] which occurred around 13.8 billion years ago. This radiation was emitted by matter that has, in the intervening time, mostly condensed into galaxies, and those galaxies are now calculated to be about 46 billion light-years from Earth.[7][9] To estimate the distance to that matter at the time the light was emitted, we may first note that according to the Friedmann–Lemaître–Robertson–Walker metric, which is used to model the expanding universe, if we receive light with a redshift of z, then the scale factor at the time the light was originally emitted is given by[32][33]

$$a(t) = \frac{1}{1+z}.$$

Hubble Ultra-Deep Field image of a region of the observable universe (equivalent sky area size shown in bottom left corner), near the constellation Fornax. Each spot is a galaxy, consisting of billions of stars. The light from the smallest, most redshifted galaxies originated around 12.6 billion years ago,[26] close to the age of the universe.

WMAP nine-year results combined with other measurements give the redshift of photon decoupling as $z = 1\,091.64 \pm 0.47$,[34] which implies that the scale factor at the time of photon decoupling would be $^{1}\!/_{1092.64}$. So if the matter that originally emitted the oldest CMBR photons has a present distance of 46 billion light-years, then the distance would have been only about 42 million light-years at the time of decoupling.

The light-travel distance to the edge of the observable universe is the age of the universe times the speed of light, 13.8 billion light years. This is the distance that a photon emitted shortly after the Big Bang, such as one from the cosmic microwave background, has traveled to reach observers on Earth. Because spacetime is curved, corresponding to the expansion of space, this distance does not correspond to the true distance at any moment in time.[35]

Matter and mass

Number of galaxies and stars

The observable universe contains as many as an estimated 2 trillion galaxies[36][37][38] and, overall, as many as an estimated 10^{24} stars[39][40] – more stars (and, potentially, Earth-like planets) than all the grains of beach sand on planet Earth.[41][42][43] Other estimates are in the hundreds of billions rather than trillions.[44][45][46] If the model of cosmic inflation is correct and the universe expanded by >60 e-folds, then the universe could contain over 10^{100} stars.[47]

Matter content—number of atoms

Assuming the mass of ordinary matter is about 1.45×10^{53} kg as discussed above, and assuming all atoms are hydrogen atoms (which are about 74% of all atoms in the Milky Way by mass), the estimated total number of atoms in the observable universe is obtained by dividing the mass of ordinary matter by the mass of a hydrogen atom. The result is approximately 10^{80} hydrogen atoms, also known as the Eddington number.[48]

Mass of ordinary matter

The mass of the observable universe is often quoted as 10^{53} kg.[49] In this context, mass refers to ordinary (baryonic) matter and includes the interstellar medium (ISM) and the intergalactic medium (IGM). However, it excludes dark matter and dark energy. This quoted value for the mass of ordinary matter in the universe can be estimated based on critical density. The calculations are for the observable universe only as the volume of the whole is unknown and may be infinite.

Estimates based on critical density

Critical density is the energy density for which the universe is flat.[50] If there is no dark energy, it is also the density for which the expansion of the universe is poised between continued expansion and collapse.[51] From the Friedmann equations, the value for ρ_c critical density, is:[52]

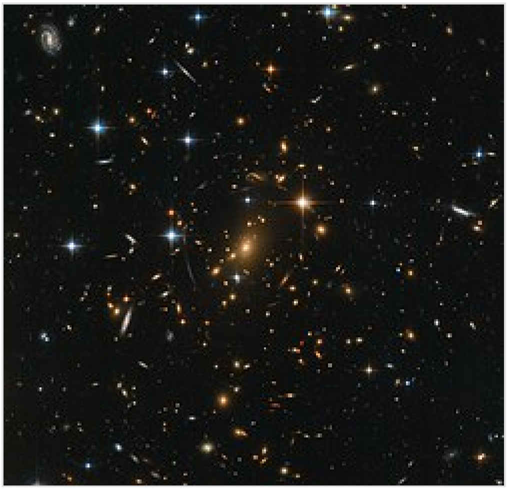
$$\rho_c = \frac{3H^2}{8\pi G},$$

where G is the gravitational constant and $H = H_0$ is the present value of the Hubble constant. The value for H_0, as given by the European Space Agency's Planck Telescope, is H_0 = 67.15 kilometres per second per megaparsec. This gives a critical density of 0.85×10^{-26} kg/m^3, or about 5 hydrogen atoms per cubic metre. This density includes four significant types of energy/mass: ordinary matter (4.8%), neutrinos (0.1%), cold dark matter (26.8%), and dark energy (68.3%).[53]

Although neutrinos are Standard Model particles, they are listed separately because they are ultra-relativistic and hence behave like radiation rather than like matter. The density of ordinary matter, as measured by Planck, is 4.8% of the total critical density or 4.08×10^{-28} kg/m^3. To convert this density to mass we must multiply by volume, a value based on the radius of the "observable universe". Since the universe has been expanding for 13.8 billion years, the comoving distance (radius) is now about 46.6 billion light-years. Thus, volume ($\frac{4}{3}\pi r^3$) equals 3.58×10^{80} m^3 and the mass of ordinary matter equals density (4.08×10^{-28} kg/m^3) times volume (3.58×10^{80} m^3) or 1.46×10^{53} kg.

Large-scale structure

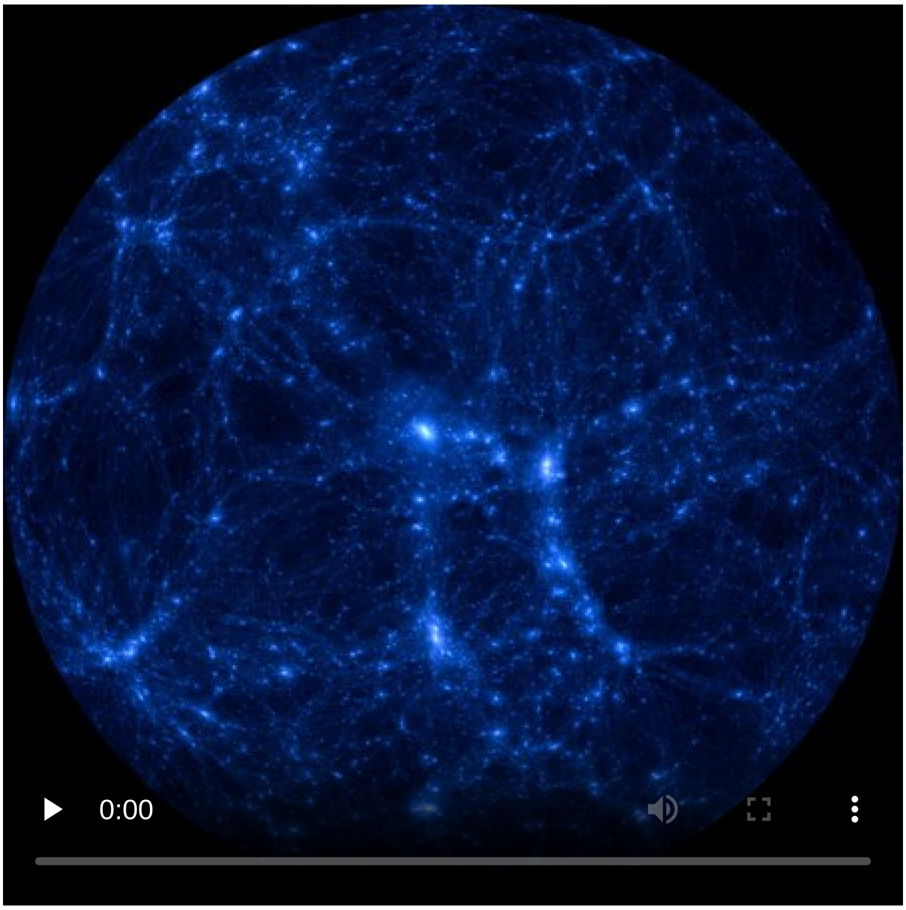
Sky surveys and mappings of the various wavelength bands of electromagnetic radiation (in particular 21-cm emission) have yielded much information on the content and character of the universe's structure. The organization of structure appears to follow a hierarchical model with organization up to the scale of superclusters and filaments. Larger than this (at scales between 30 and 200 megaparsecs),[56] there seems to be no continued structure, a phenomenon that has been referred to as the *End of Greatness*.[57] The shape of the large scale structure can be summarized by the matter power spectrum.



Galaxy clusters, like RXC J0142.9+4438, are the nodes of the cosmic web that permeates the entire Universe.[54]

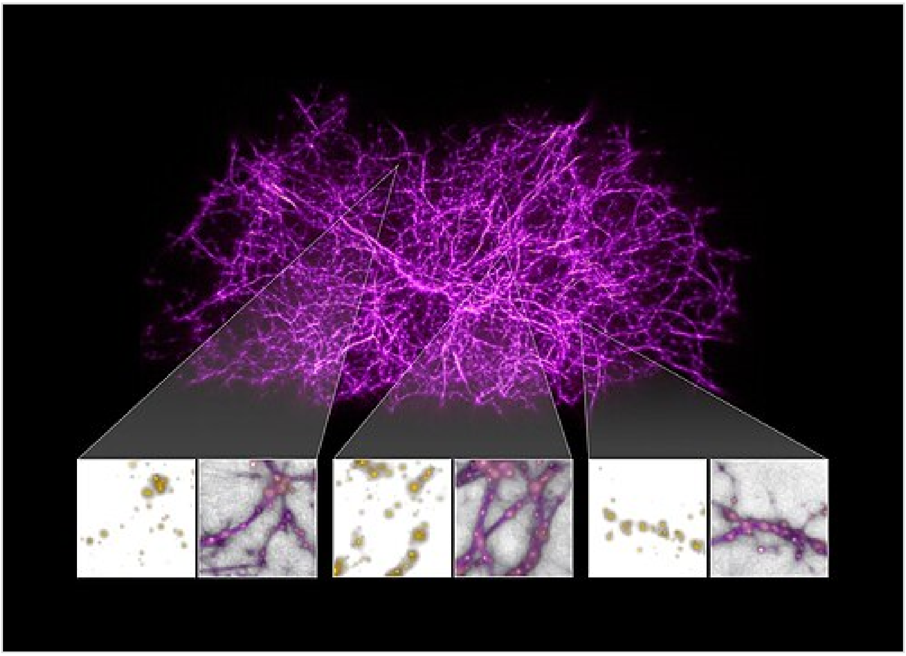
Cosmic Web: walls, filaments, nodes, and voids

The organization of structure arguably begins at the stellar level, though most cosmologists rarely address astrophysics on that scale. Stars are organized into galaxies, which in turn form galaxy groups, galaxy clusters, superclusters, sheets, walls and filaments, which are separated by immense voids, creating a vast foam-like structure[59] sometimes called the "cosmic web". Prior to 1989, it was commonly assumed that virialized galaxy clusters were the largest structures in existence, and that they were distributed more or less uniformly throughout the universe in every direction. However, since the early 1980s, more and more structures have been discovered. In 1983, Adrian Webster identified the Webster LQG, a large quasar group consisting of 5 quasars. The discovery was the first identification of a large-scale structure, and has expanded the information about the known grouping of matter in the universe.



Video of a cosmological simulation of the local universe, showing the large-scale structure of galaxy clusters and dark matter.[55]

In 1987, Robert Brent Tully identified the Pisces–Cetus Supercluster Complex, the galaxy filament in which the Milky Way resides. It is about 1 billion light-years across. That same year, an unusually large region with a much lower than average distribution of galaxies was discovered, the Giant Void, which measures 1.3 billion light-years across. Based on redshift survey data, in 1989 Margaret Geller and John Huchra discovered the "Great Wall",[60] a sheet of galaxies more than 500 million light-years long and 200 million light-years wide, but only 15 million light-years thick. The existence of this structure escaped notice for so long because it requires locating the position of galaxies in three dimensions, which involves combining location information about the galaxies with distance information from redshifts.



Map of the cosmic web generated from a slime mould-inspired algorithm[58]

Two years later, astronomers Roger G. Clowes and Luis E. Campusano discovered the Clowes–Campusano LQG, a large quasar group measuring two billion light-years at its widest point, which was the largest known structure in the universe at the time of its announcement. In April 2003, another large-scale structure was discovered, the Sloan Great Wall. In August 2007, a possible supervoid was detected in the constellation Eridanus.[61] It coincides with the 'CMB cold spot', a cold region in the microwave sky that is highly improbable under the currently favored cosmological model. This supervoid could cause the cold spot, but to do so it would have to be improbably big, possibly a billion light-years across, almost as big as the Giant Void mentioned above.

Unsolved problem in physics

? *The largest structures in the universe are larger than expected. Are these actual structures or random density fluctuations?*

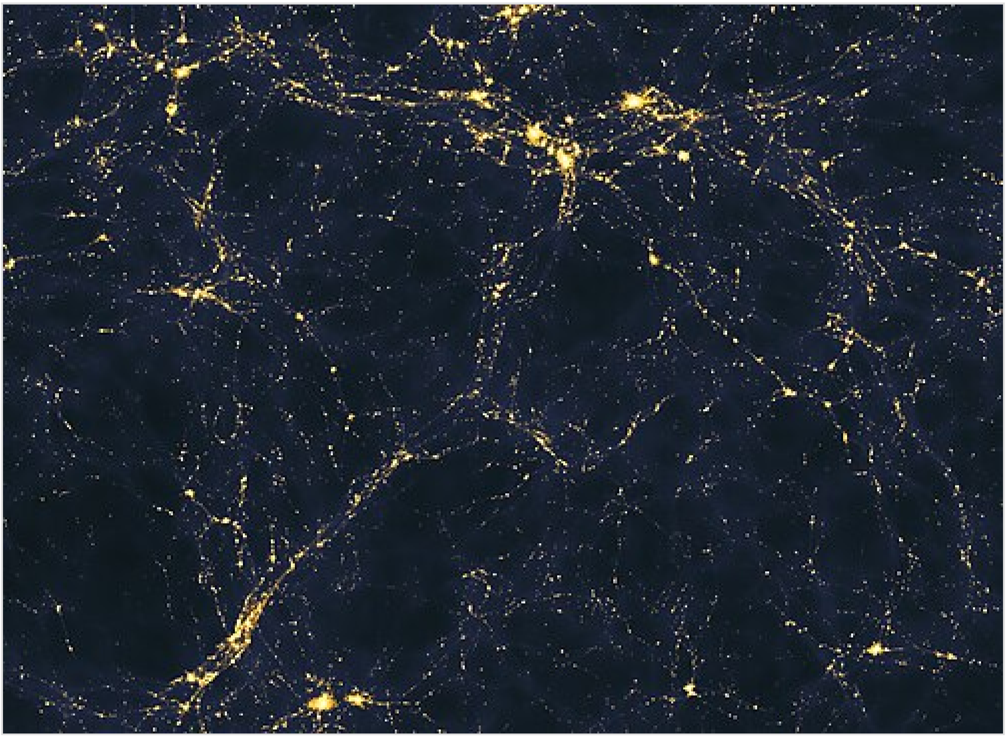
More unsolved problems in physics

Another large-scale structure is the SSA22 Protocluster, a collection of galaxies and enormous gas bubbles that measures about 200 million light-years across.

In 2011, a large quasar group was discovered, U1.11, measuring about 2.5 billion light-years across. On January 11, 2013, another large quasar group, the Huge-LQG, was discovered, which was measured to be four billion light-years across, the largest known structure in the universe at that time.[62] In November 2013, astronomers discovered the Hercules–Corona Borealis Great Wall,[63][64] an even bigger structure twice as large as the former. It was defined by the mapping of gamma-ray bursts.[63][65]

In 2021, the American Astronomical Society announced the detection of the Giant Arc; a crescent-shaped string of galaxies that span 3.3 billion light years in length, located 9.2 billion light years from Earth in the constellation Boötes from observations captured by the Sloan Digital Sky Survey.[66]

End of Greatness



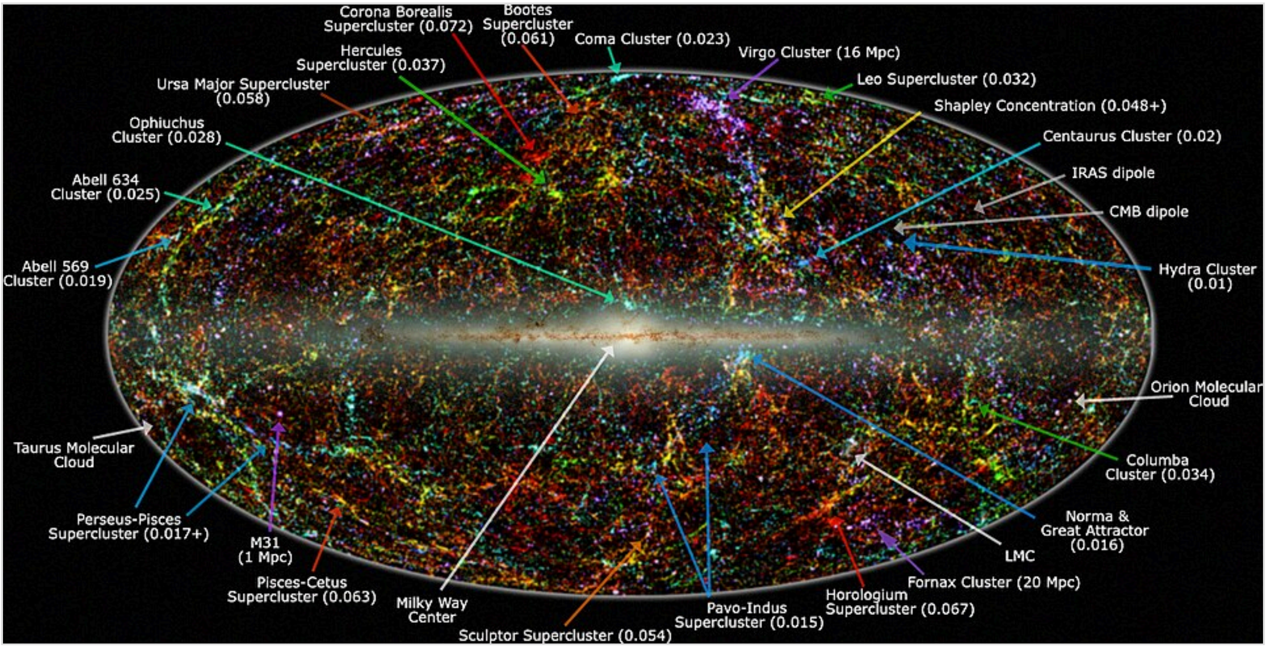
Computer simulated image of an area of space more than 50 million light-years across, presenting a possible large-scale distribution of light sources in the universe —precise relative contributions of galaxies and quasars are unclear.

The *End of Greatness* is the name occasionally given to an observational scale around 100 Mpc (roughly 300 million light-years) where the lumpiness seen in the large-scale structure of the universe is homogenized and isotropized in accordance with the cosmological principle.[67] The "lumpiness" is quantified by computing a fractal dimension from observations.[68][69] The superclusters and filaments seen in smaller surveys are randomized to the extent that the smooth distribution of the universe is visually apparent. It was not until the redshift surveys of the 1990s were completed that this scale could accurately be observed.[57]

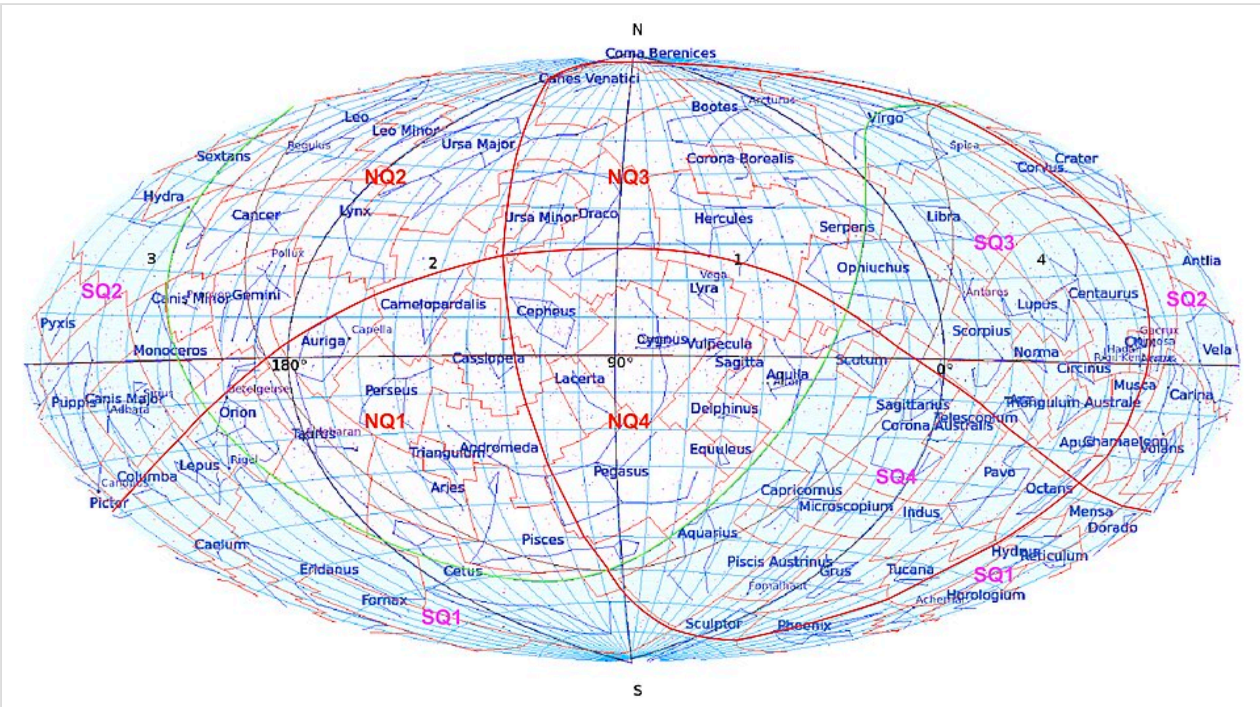
Observations

Another indicator of large-scale structure is the 'Lyman-alpha forest'. This is a collection of absorption lines that appear in the spectra of light from quasars, which are interpreted as indicating the existence of huge thin sheets of intergalactic (mostly hydrogen) gas. These sheets appear to collapse into filaments, which can feed galaxies as they grow where filaments either cross or are dense. An early direct evidence for this cosmic web of gas was the 2019 detection, by astronomers from the RIKEN Cluster for Pioneering Research in Japan and Durham University in the United Kingdom, of light from the brightest part of this web, surrounding and illuminated by a cluster of forming galaxies, acting as cosmic flashlights for intercluster medium hydrogen fluorescence via Lyman-alpha emissions.[71][72]

In 2021, an international team, headed by Roland Bacon from the Centre de Recherche Astrophysique de Lyon (France), reported the first observation of diffuse extended Lyman-alpha emission from redshift 3.1 to 4.5 that traced several cosmic web filaments on scales of 2.5−4 cMpc (comoving mega-parsecs), in filamentary environments outside massive structures typical of web nodes.[73]



"Panoramic view of the entire near-infrared sky reveals the distribution of galaxies beyond the Milky Way. The image is derived from the 2MASS Extended Source Catalog (XSC)—more than 1.5 million galaxies, and the Point Source Catalog (PSC)—nearly 0.5 billion Milky Way stars. The galaxies are color-coded by 'redshift' obtained from the UGC, CfA, Tully NBGC, LCRS, 2dF, 6dFGS, and SDSS surveys (and from various observations compiled by the NASA Extragalactic Database), or photo-metrically deduced from the K band (2.2 μm). Blue are the nearest sources (*z* < 0.01); green are at moderate distances (0.01 < *z* < 0.04) and red are the most distant sources that 2MASS resolves (0.04 < *z* < 0.1). The map is projected with an equal area Aitoff in the Galactic system (Milky Way at center)."[70]



Constellations grouped in galactic quadrants (N/S, 1–4) and their approximate divisions vis-a-vis celestial quadrants (NQ/SQ)

Some caution is required in describing structures on a cosmic scale because they are often different from how they appear. Gravitational lensing can make an image appear to originate in a different direction from its real source, when foreground objects curve surrounding spacetime (as predicted by general relativity) and deflect passing light rays. Rather usefully, strong gravitational lensing can sometimes magnify distant galaxies, making them easier to detect. Weak lensing by the intervening universe in general also subtly changes the observed large-scale structure.

The large-scale structure of the universe also looks different if only redshift is used to measure distances to galaxies. For example, galaxies behind a galaxy cluster are attracted to it and fall towards it, and so are blueshifted (compared to how they would be if there were no cluster). On the near side, objects are redshifted. Thus, the environment of the cluster looks somewhat pinched if using redshifts to measure distance. The opposite effect is observed on galaxies already within a cluster: the galaxies have some random motion around the cluster center, and when these random motions are converted to redshifts, the cluster appears elongated. This creates a "*finger of God*"—the illusion of a long chain of galaxies pointed at Earth.

Cosmography of Earth's cosmic neighborhood

At the centre of the Hydra–Centaurus Supercluster, a gravitational anomaly called the Great Attractor affects the motion of galaxies over a region hundreds of millions of light-years across. These galaxies are all redshifted, in accordance with Hubble's law. This indicates that they are receding from us and from each other, but the variations in their redshift are sufficient to reveal the existence of a concentration of mass equivalent to tens of thousands of galaxies.

The Great Attractor, discovered in 1986, lies at a distance of between 150 million and 250 million light-years in the direction of the Hydra and Centaurus constellations. In its vicinity there is a preponderance of large old galaxies, many of which are colliding with their neighbours, or radiating large amounts of radio waves.

In 1987, astronomer R. Brent Tully of the University of Hawaiʻi's Institute of Astronomy identified what he called the Pisces–Cetus Supercluster Complex, a structure one billion light-years long and 150 million light-years across in which, he claimed, the Local Supercluster is embedded.[74]

Most distant objects

The most distant astronomical object identified is a galaxy classified as MoM-z14,[75] at a redshift of 14.44. In 2009, a gamma ray burst, GRB 090423, was found to have a redshift of 8.2, which indicates that the collapsing star that caused it exploded when the universe was only 630 million years old.[76] The burst happened approximately 13 billion years ago,[77] so a distance of about 13 billion light-years was widely quoted in the media, or sometimes a more precise figure of 13.035 billion light-years.[76]

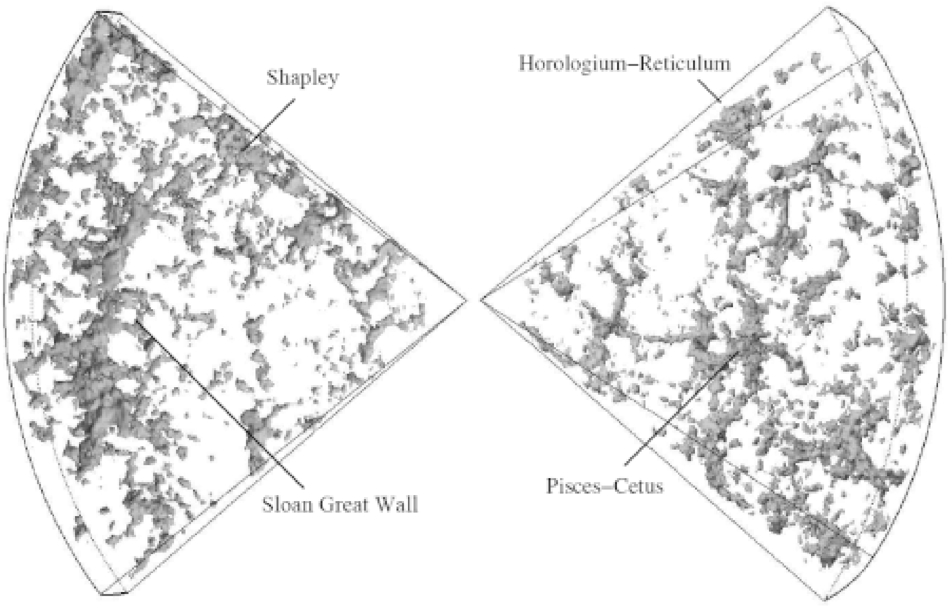
This would be the "light travel distance" (see Distance measures (cosmology)) rather than the "proper distance" used in both Hubble's law and in defining the size of the observable universe. Cosmologist Ned Wright argues against using this measure.[78] The proper distance for a redshift of 8.2 would be about 9.2 Gpc,[79] or about 30 billion light-years.

Horizons

The limit of observability in the universe is set by cosmological horizons which limit—based on various physical constraints—the extent to which information can be obtained about various events in the universe. The most famous horizon is the particle horizon which sets a limit on the precise distance that can be seen due to the finite age of the universe. Additional horizons are associated with the possible future extent of observations, larger than the particle horizon owing to the expansion of space, an "optical horizon" at the surface of last scattering, and associated horizons with the surface of last scattering for neutrinos and gravitational waves.

Gallery

Artist's logarithmic scale conception of the observable universe with the Solar System at the center, inner and outer planets, Kuiper belt, Oort cloud, Alpha Centauri, Perseus Arm, Milky Way galaxy, Andromeda Galaxy, nearby galaxies, Cosmic web, Cosmic microwave radiation and the Big Bang's invisible plasma on the edge. Celestial bodies appear enlarged to appreciate their shapes.



DTFE reconstruction of the inner parts of the 2dF Galaxy Redshift Survey

See also

- Bolshoi cosmological simulation – Computer simulation of the universe
- Causality (physics) – Physics of the cause–effect relation

- Chronology of the universe – History and future of the universe
- Dark flow – Controversial hypothesis in astrophysics
- Hubble volume – Region of the observable universe
- Illustris project – Computer-simulated universes
- Multiverse – Hypothetical group of multiple universes
- Orders of magnitude (length) – Comparison of a wide range of lengths
- UniverseMachine – Computer simulated universes

Notes

1. Special relativity prevents nearby objects in the same local region from moving faster than the speed of light with respect to each other, but there is no such constraint for distant objects when the space between them is expanding; see uses of the proper distance for a discussion.
2. The comoving distance of the future visibility limit is calculated on p. 8 of Gott et al.'s A Map of the Universe (http://www.astro.princeton.edu/universe/ms.pdf) to be 4.50 times the Hubble radius, given as 4.220 billion parsecs (13.76 billion light-years), whereas the current comoving radius of the observable universe is calculated on p. 7 to be 3.38 times the Hubble radius. The number of galaxies in a sphere of a given comoving radius is proportional to the cube of the radius, so as shown on p. 8 the ratio between the number of galaxies observable in the future visibility limit to the number of galaxies observable today would be $(4.50/3.38)^3 = 2.36$.
3. This does not mean "unbounded" in the mathematical sense; a finite universe would have an upper bound on the distance between two points. Rather, it means that there is no boundary past which there is nothing. See *Geodesic manifold*.

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External links

- "Millennium Simulation" of structure forming (http://www.mpa-garching.mpg.de/galform/millennium/) – Max Planck Institute of Astrophysics, Garching, Germany
- NASA Astronomy Picture of the Day: The Sloan Great Wall: Largest Known Structure? (7 November 2007) (https://apod.nasa.gov/apod/ap071107.html)
- Forming Galaxies Captured In The Young Universe By Hubble, VLT & Spitzer (https://www.sciencedaily.com/releases/2007/04/070419125240.htm)
- Animation of the cosmic light horizon (http://www.phys.ksu.edu/personal/gahs/phys191/horizon.html)
- Logarithmic Maps of the Universe (http://www.astro.princeton.edu/universe/)
- List of publications of the 2dF Galaxy Redshift Survey (http://www.mso.anu.edu.au/2dFGRS/)
- The Universe Within 14 Billion Light Years – NASA Atlas of the Universe (http://www.atlasoftheuniverse.com/universe.html) – Note, this map only gives a rough cosmographical estimate of the expected distribution of superclusters within the observable universe; very little actual mapping has been done beyond a distance of one billion light-years.
- Video: *The Known Universe*, from the American Museum of Natural History (https://www.youtube.com/watch?v=17jymDn0W6U)
- NASA/IPAC Extragalactic Database (http://ned.ipac.caltech.edu/)
- Cosmography of the Local Universe (http://irfu.cea.fr/cosmography) at irfu.cea.fr (17:35) (arXiv (https://arxiv.org/abs/1306.0091))
- Limits to knowledge about Universe (https://www.forbes.com/sites/startswithabang/2019/05/21/this-is-why-we-will-never-know-everything-about-our-universe/) – *Forbes*, May 2019