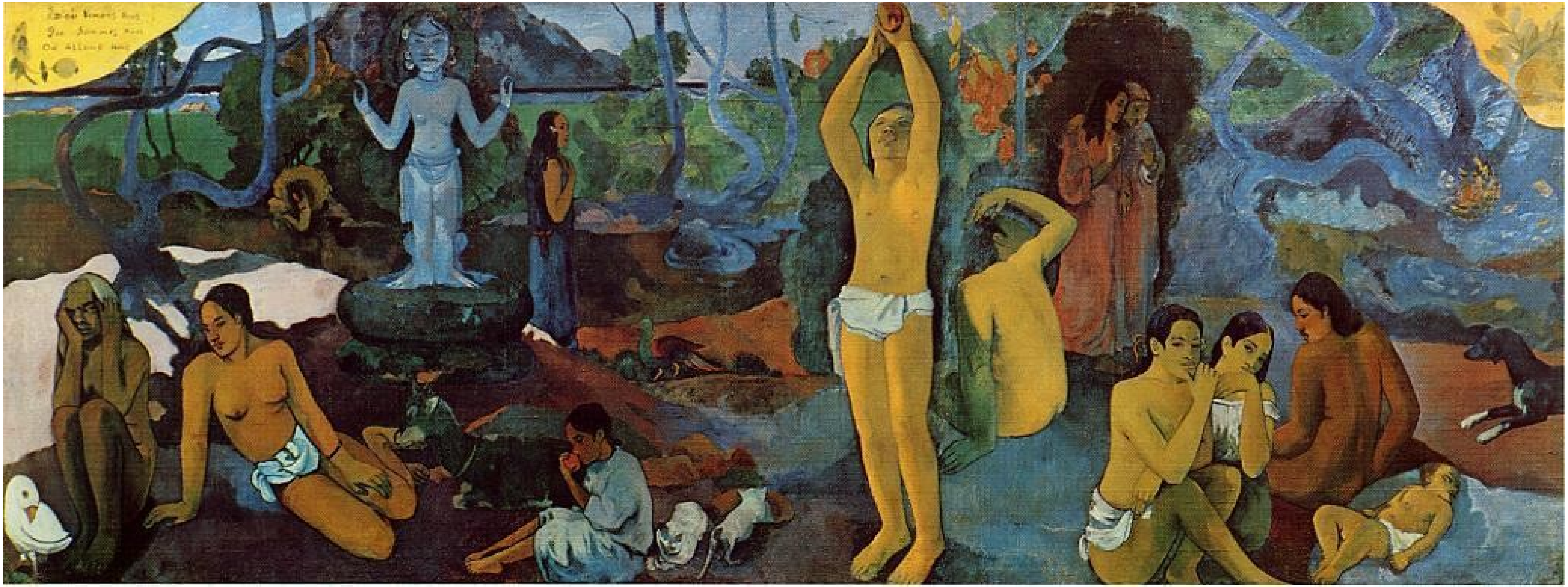
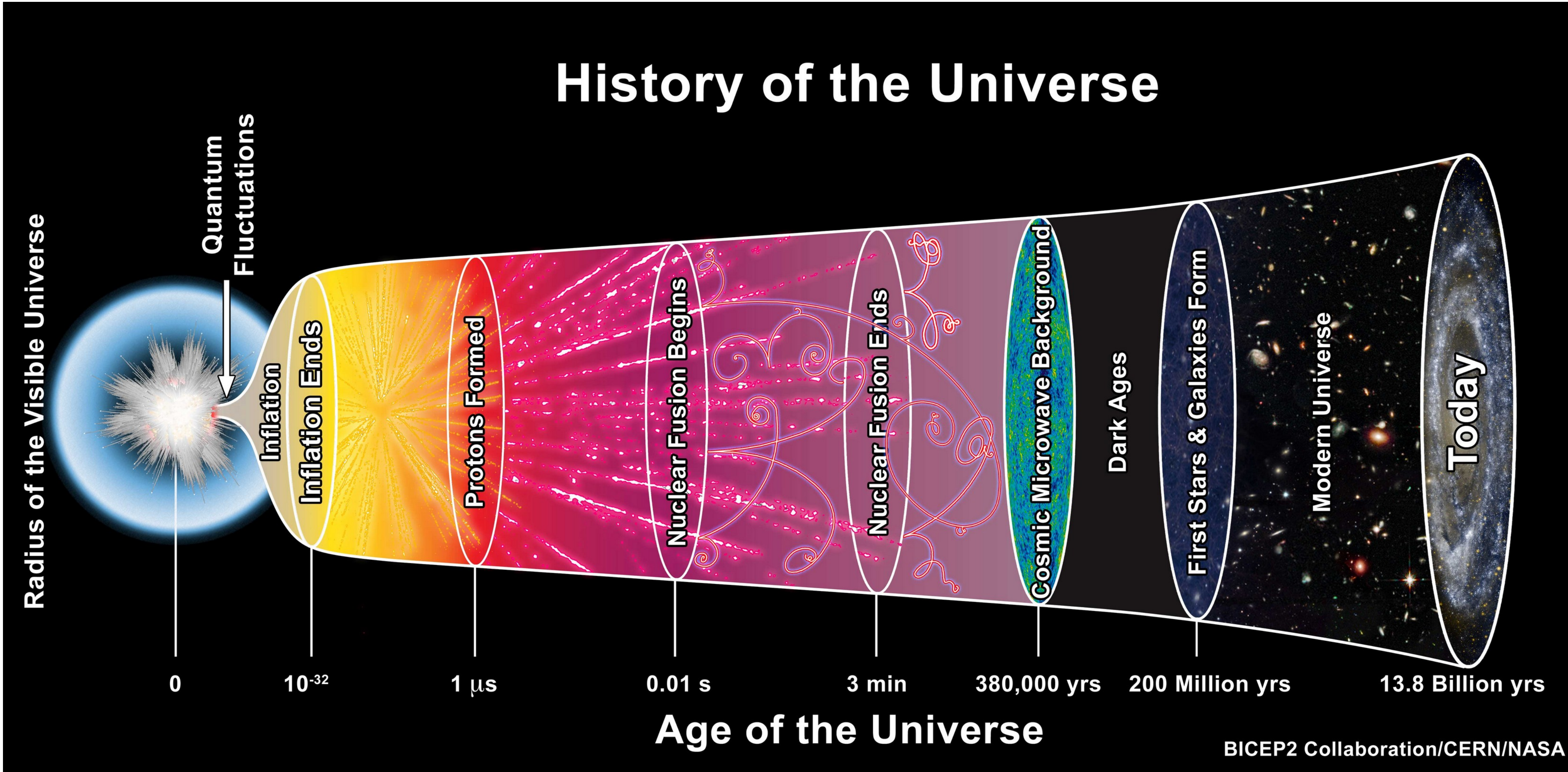
Early Universe



“Where do we come from? What are we? Where are we going?”

Early Universe



The Universe is Isotropic and Homogeneous

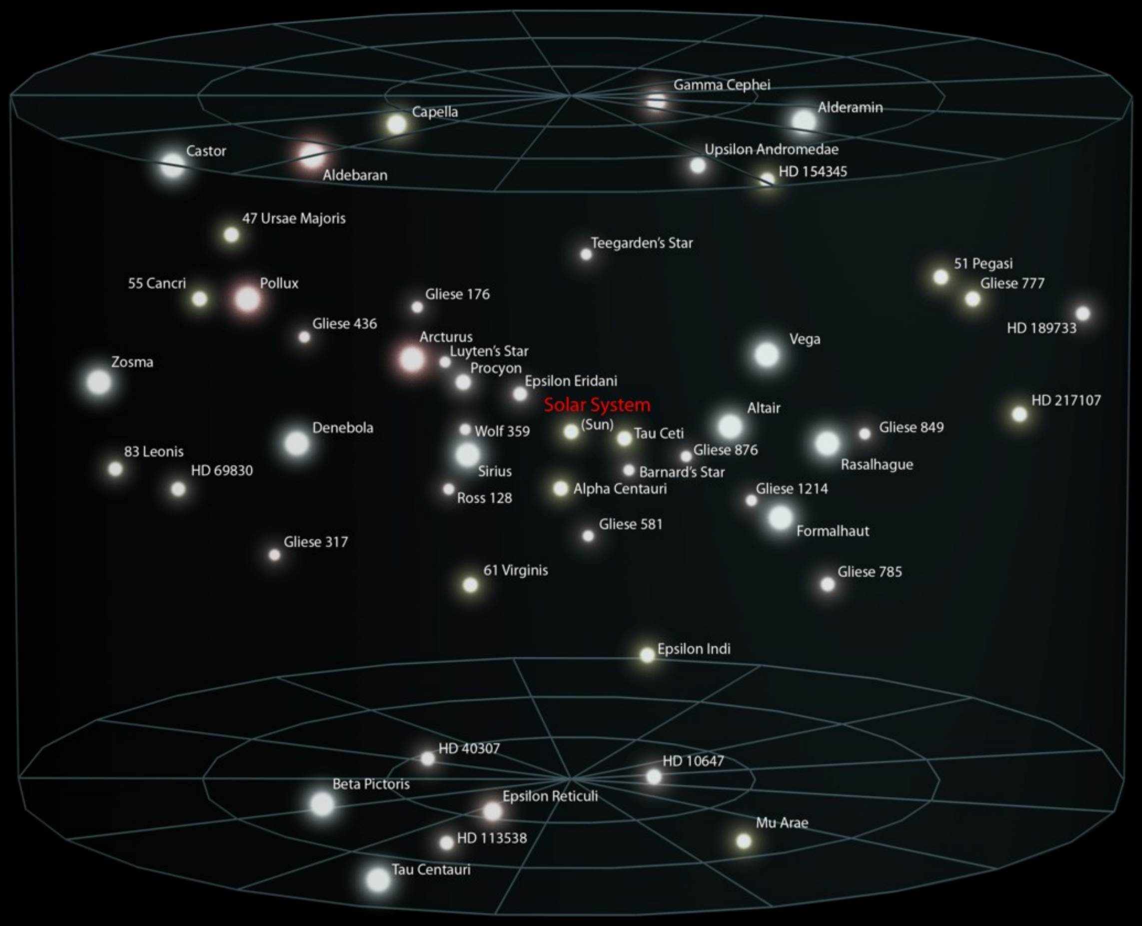
The evidence that the Universe becomes smooth on large scales supports the use of the cosmological principle. It is therefore believed that our large-scale Universe possesses two important properties, **homogeneity** and **isotropy**. Homogeneity is the statement that the Universe looks the same at each point, while isotropy states that the Universe looks the same in all directions.

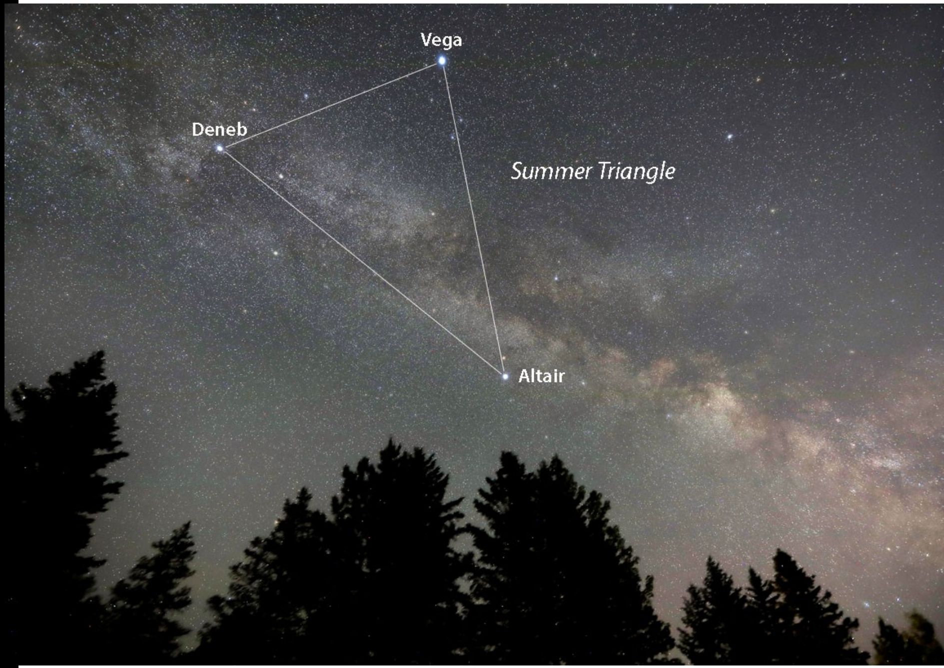
These do not automatically imply one another. For example, a universe with a uniform magnetic field is homogeneous, as all points are the same, but it fails to be isotropic because directions along the field lines can be distinguished from those perpendicular to them. Alternatively, a spherically-symmetric distribution, viewed from its central point, is isotropic but not necessarily homogeneous. However, if we require that a distribution is isotropic about *every* point, then that does enforce homogeneity as well.

Figure 2.3 Left: a pattern that is anisotropic, but is homogeneous on scales larger than the stripe width. Right: a pattern that is isotropic about the origin, but is inhomogeneous.

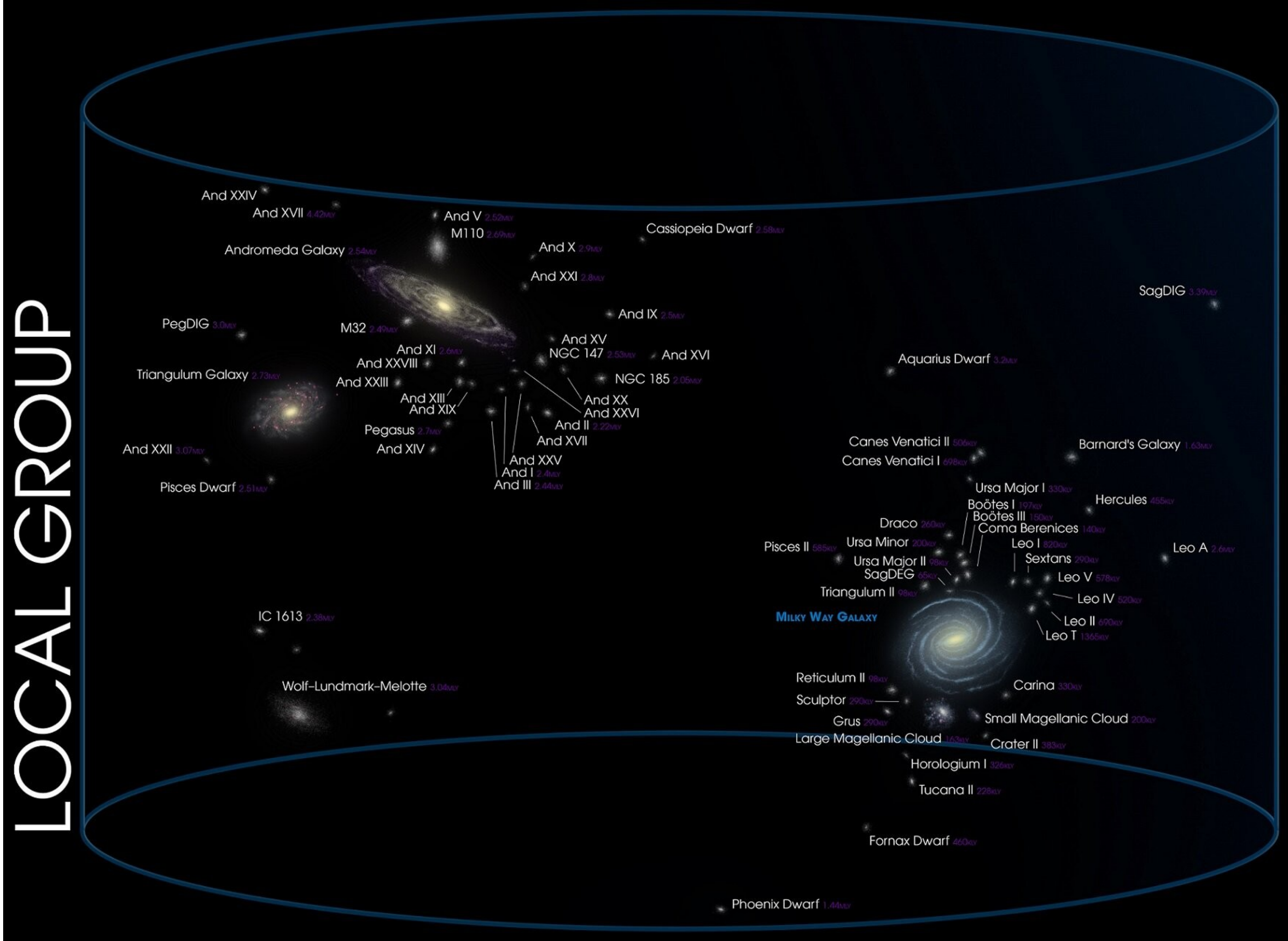
Stars: The main source of visible light in the Universe is nuclear fusion within stars. The Sun is a fairly typical star, with a mass of about 2×10^{30} kilograms. This is known as a solar mass, indicated $M_{\odot}$, and is a convenient unit for measuring masses. The nearest stars to us are a few light years away, a light year being the distance (about 10^{16} metres) that light can travel in a year. For historical reasons, an alternative unit, known as the **parsec** and denoted 'pc',[1] is more commonly used in cosmology.

INTERSTELLAR NEIGHBORHOOD

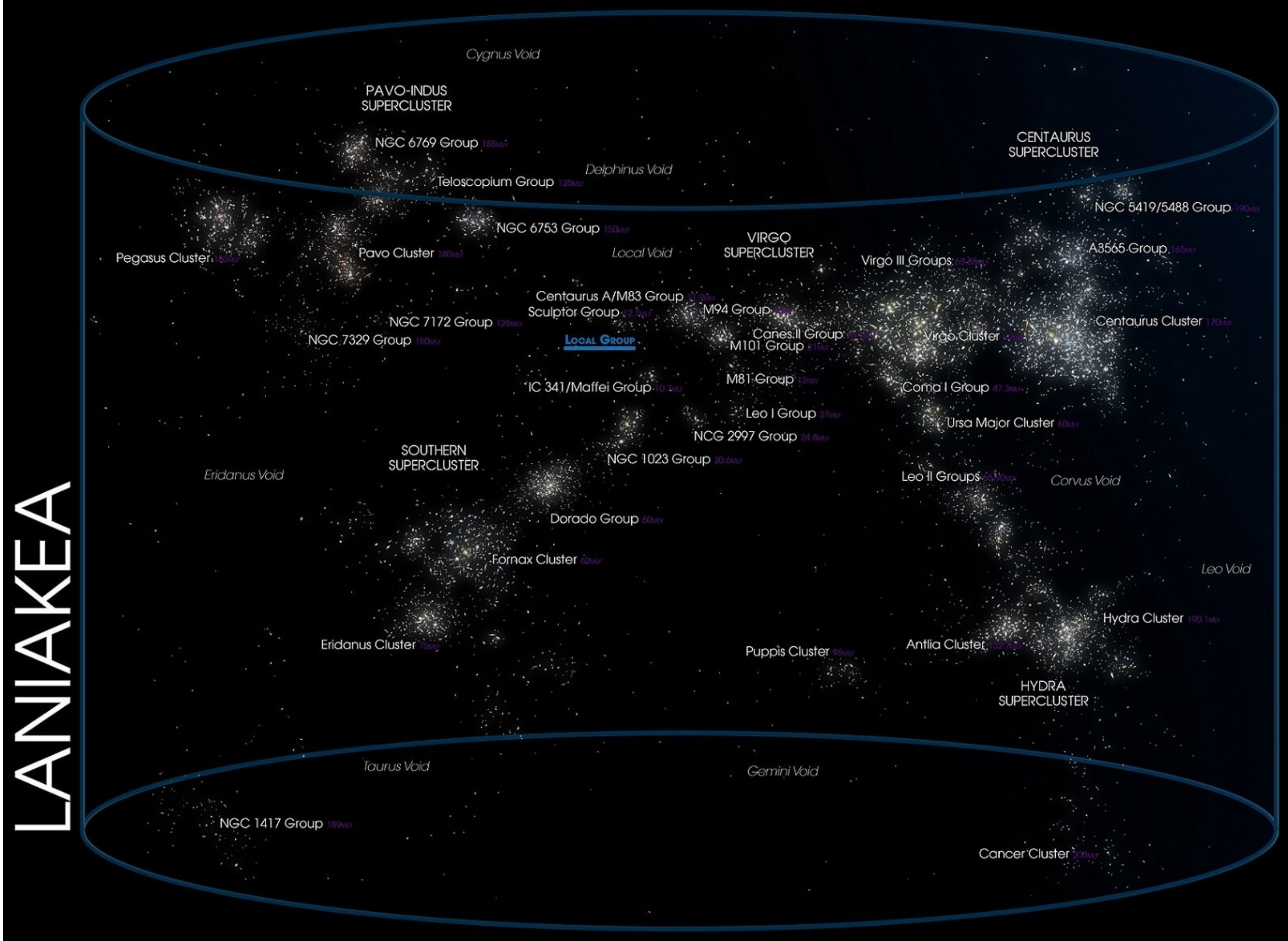




Our local group is part of the Virgo Supercluster, a galactic supercluster that is estimated to contain more than 47,000 galaxies! This is not where it ends though, in 2014, astronomers determined that the Virgo Supercluster is actually a component of an even larger supercluster called Laniakea.

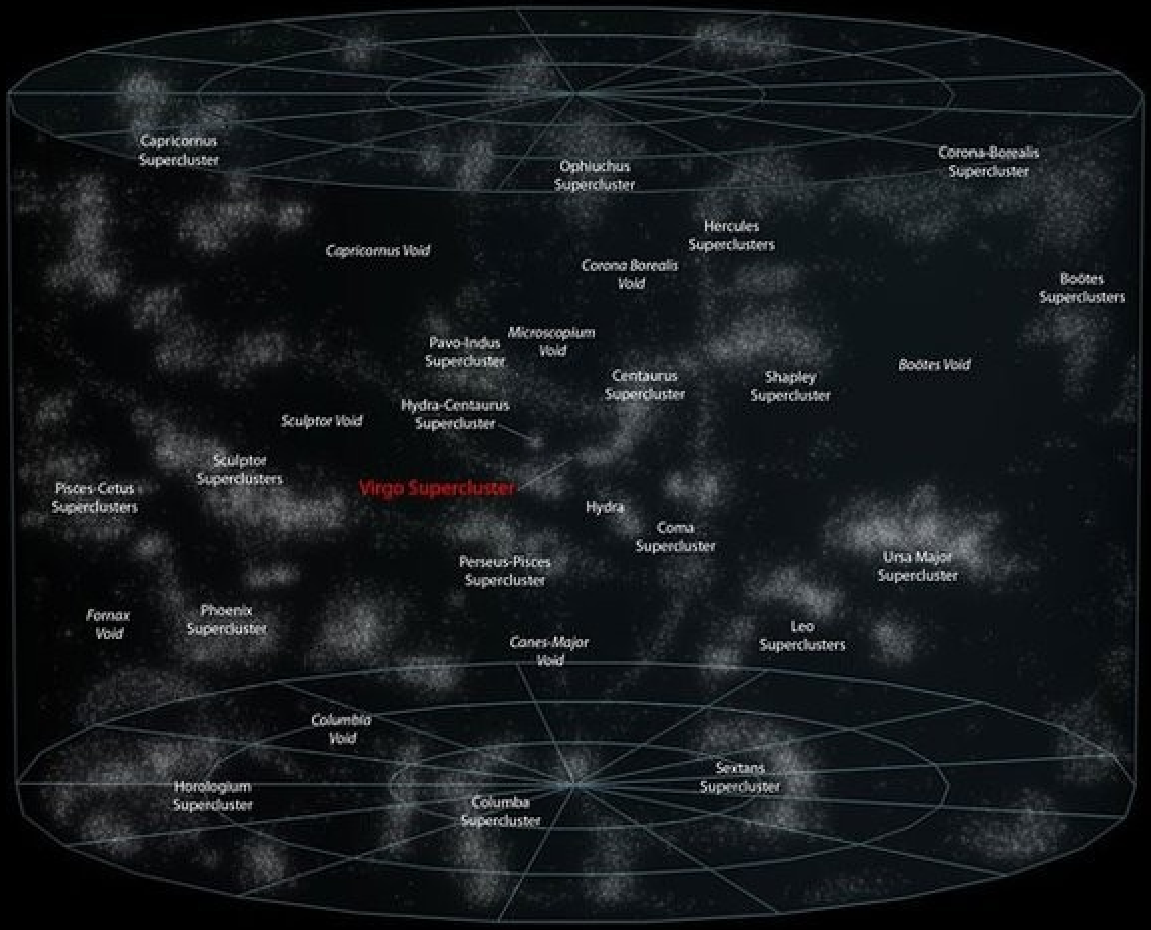


The Laniakea supercluster is estimated to contain 100,000 to 150,000 galaxies. Research indicates that the Laniakea Supercluster is not gravitationally connected; it will probably scatter rather than continue to sustain itself. Estimated diameter of 153 Mpc.

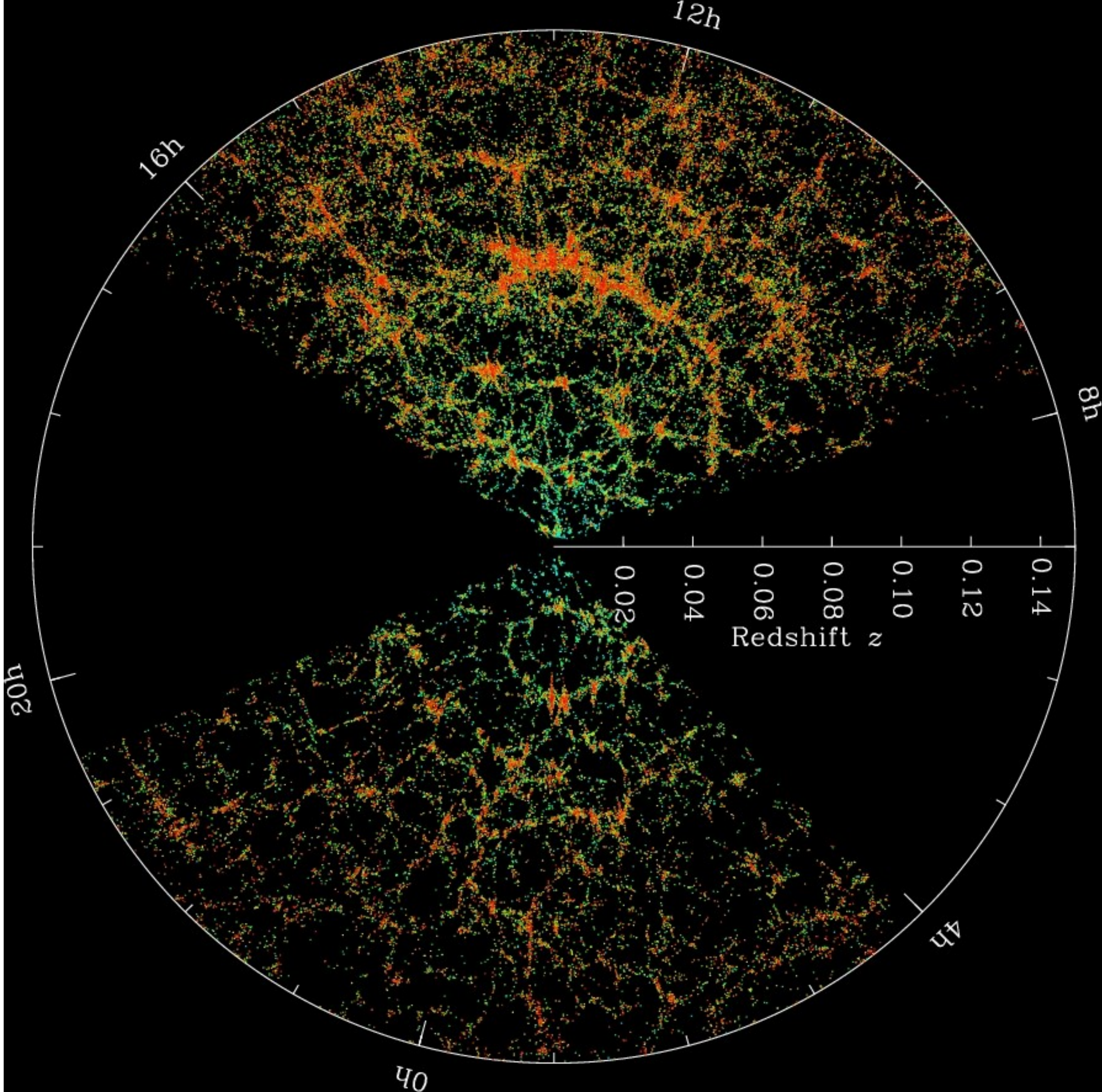


The Hercules–Corona Borealis Great Wall. Discovered in 2013, it is (currently) the largest known structure in the observable universe.
the wall's mean size is about 3 Gpc. The Hercules-Corona Borealis Great Wall is so vast that it covers one 5th of the distance to the horizon of the observable universe.

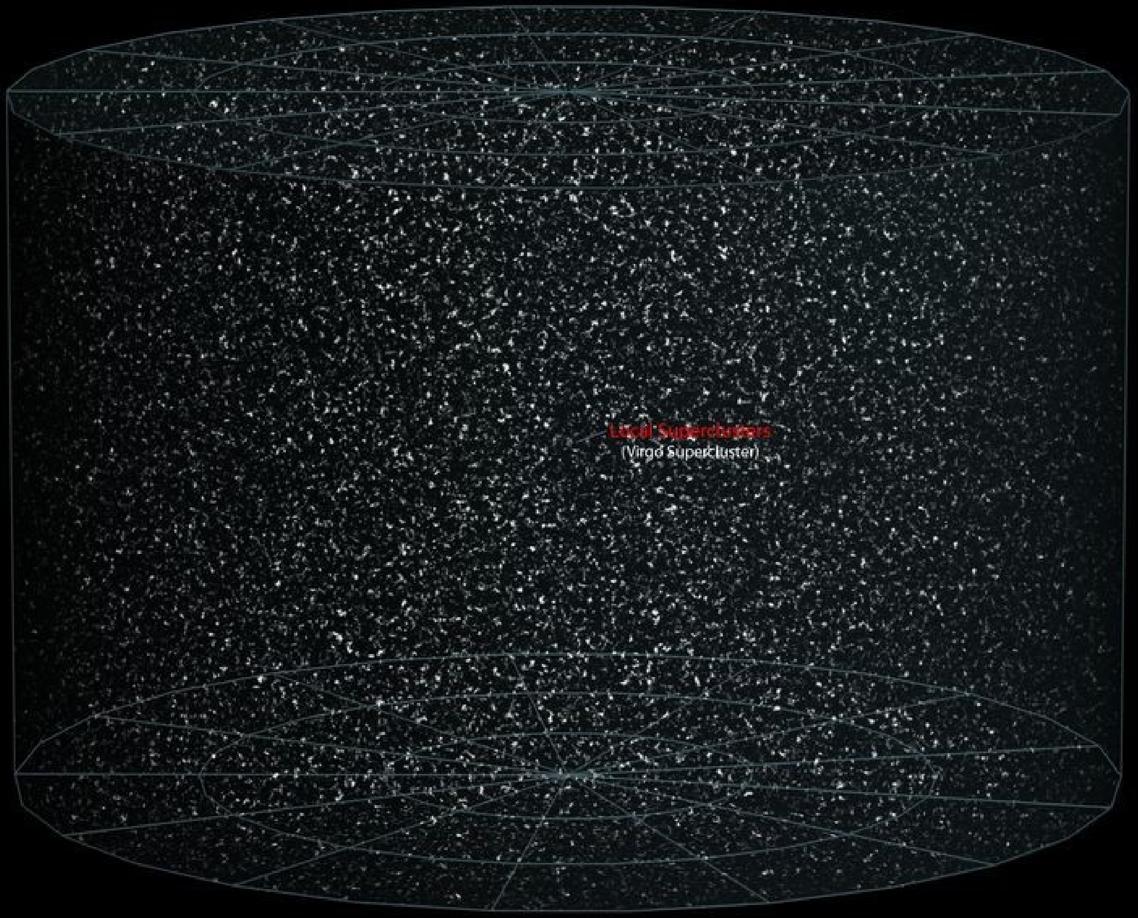
Local Superclusters



A map of galaxy positions in a narrow slice of the Universe, as measured by the Sloan Digital Sky Survey. Our galaxy is located at the centre, and the survey radius is around 600 Mpc. The galaxy positions were obtained by measurement of the shift of spectral lines.



Observable Universe

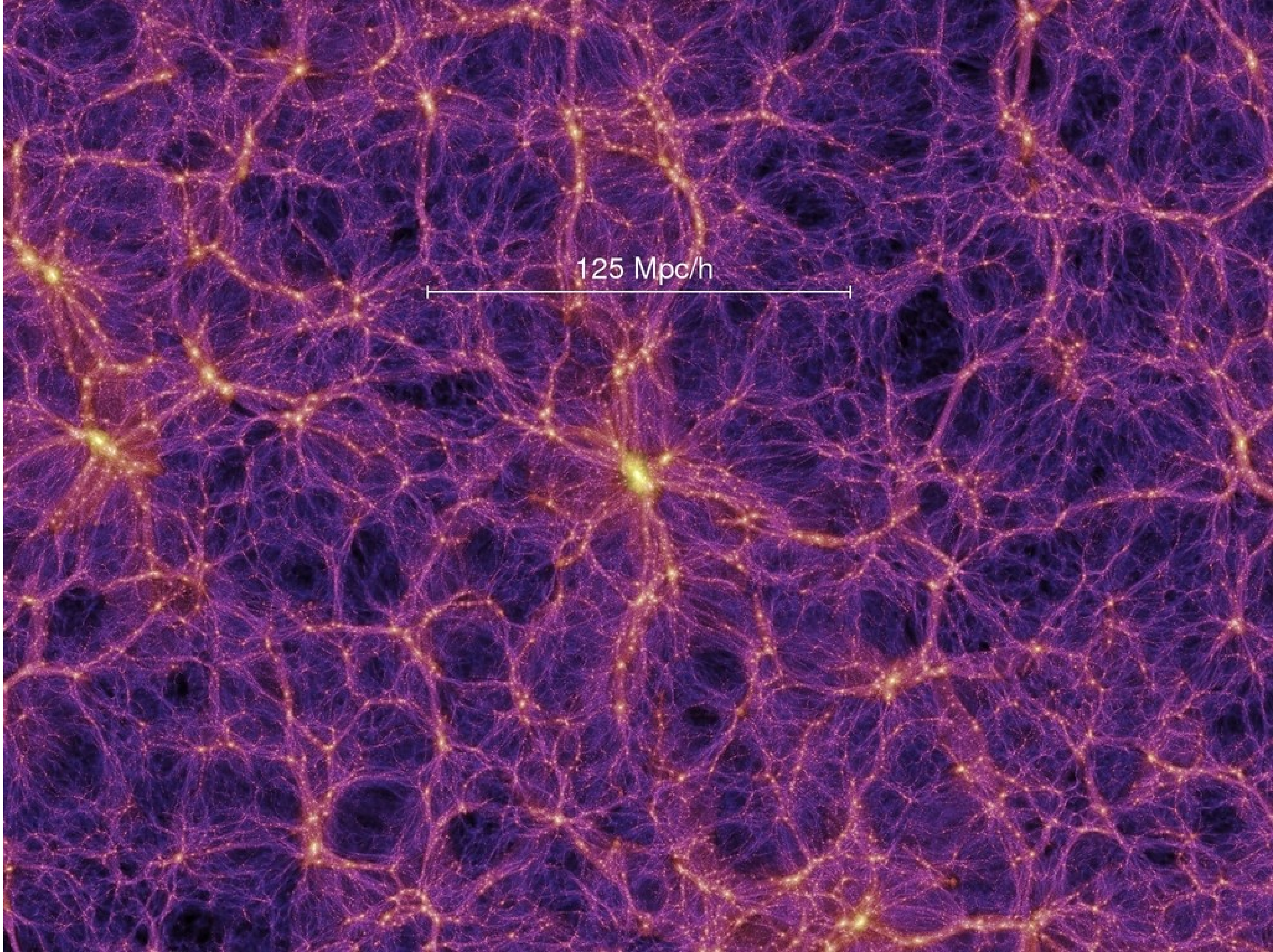


However, most galaxies, sometimes called field galaxies, are not part of a cluster.

Galaxy clusters are the largest gravitationally-collapsed objects in the Universe, and
they themselves are grouped into superclusters, joined by filaments and walls of galaxies.

In between this ‘foamlike’ structure lie large voids, some as large as 50 Mpc across.

Example of a computer simulation aiming to model the distribution of material within the Universe.



Observational support for the Big Bang Model

- The present expansion of the Universe.
- The existence of the cosmic microwave background radiation, CMBR.
- The relic radiation from the hot stage of the early Universe.
- The relative abundance of light elements in the Universe, which agrees accurately with what would be synthesized in an initially hot, expanding Universe.

Redshift is Proportional to Distance

$$z \equiv \frac{\lambda_{\rm ob} - \lambda_{\rm em}}{\lambda_{\rm em}}.$$

Strictly speaking, when $z < 0$, this quantity is called a blueshift, rather than a redshift. However, the vast majority of galaxies have $z > 0$.

Hubble's law: $$z = \frac{H_0}{c} r,$$

where H_0 is a constant (now called the Hubble constant). Interpreting the redshifts as Doppler shifts, Hubble's law takes the form

$$v = H_0 r.$$

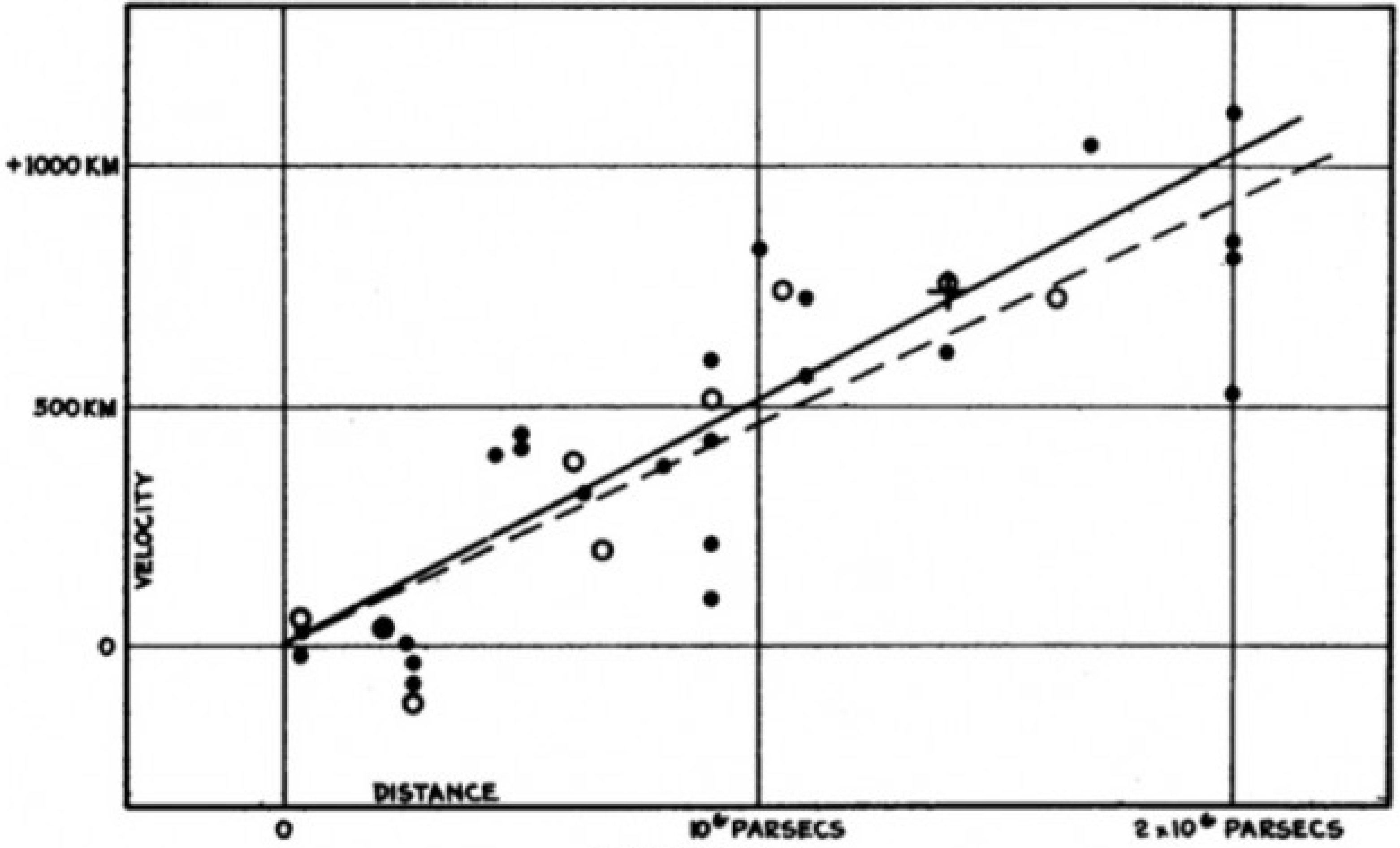
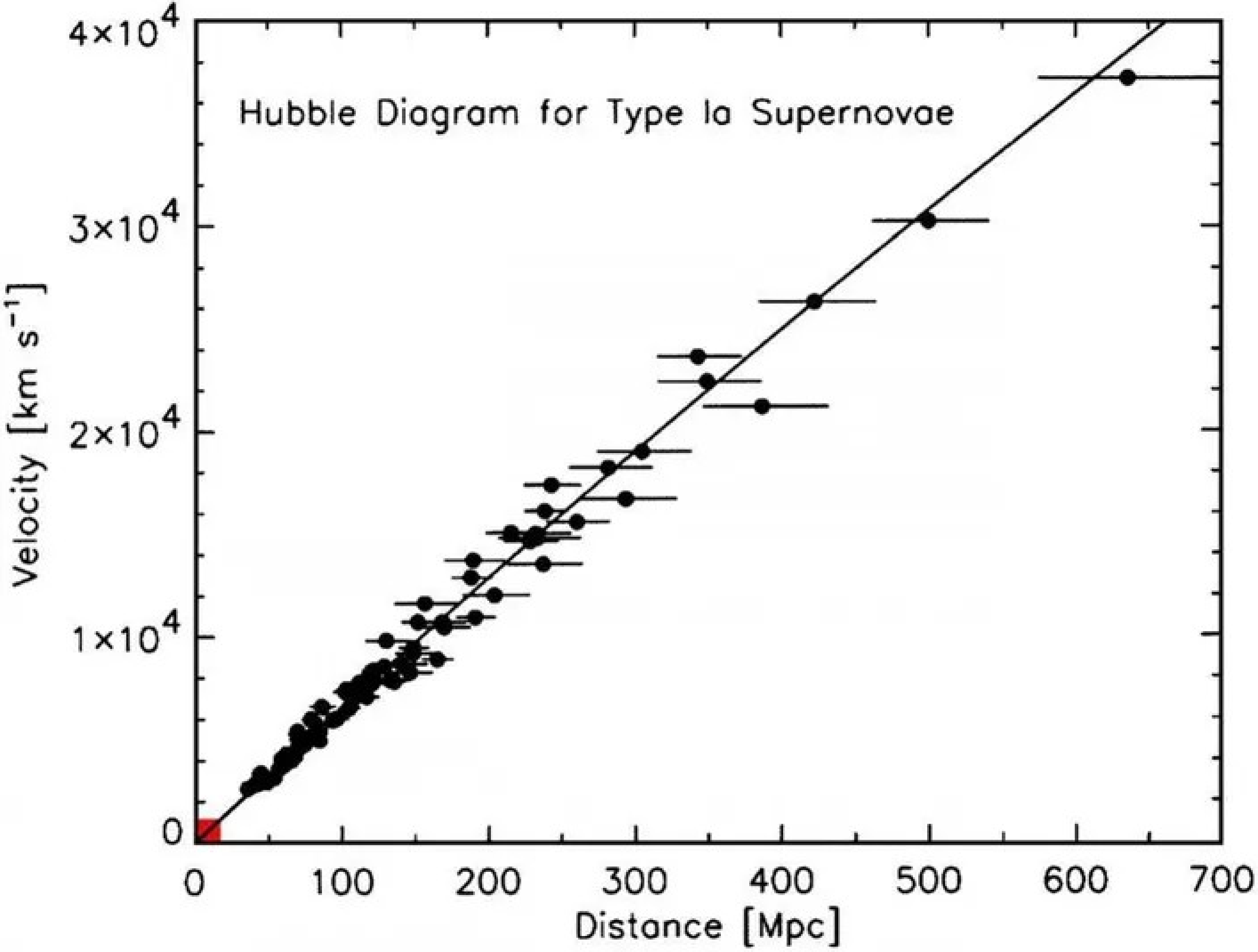
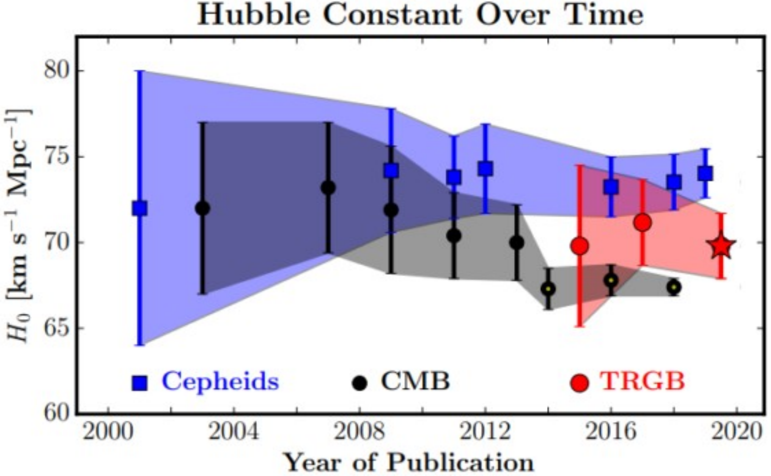


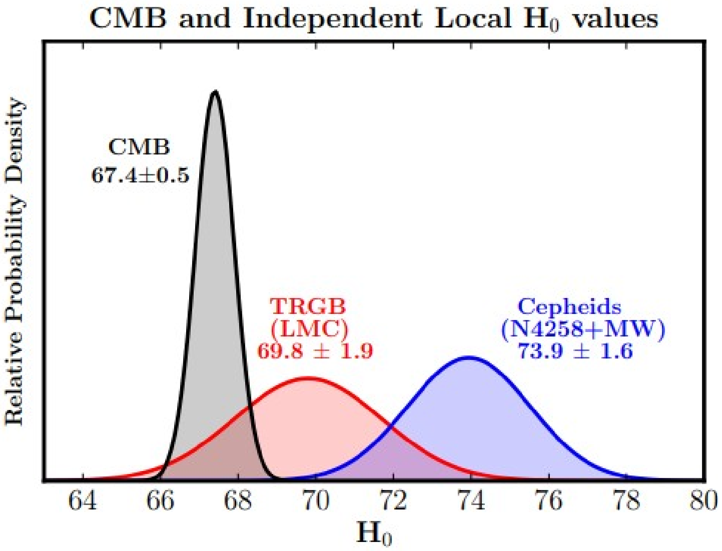
FIGURE 1

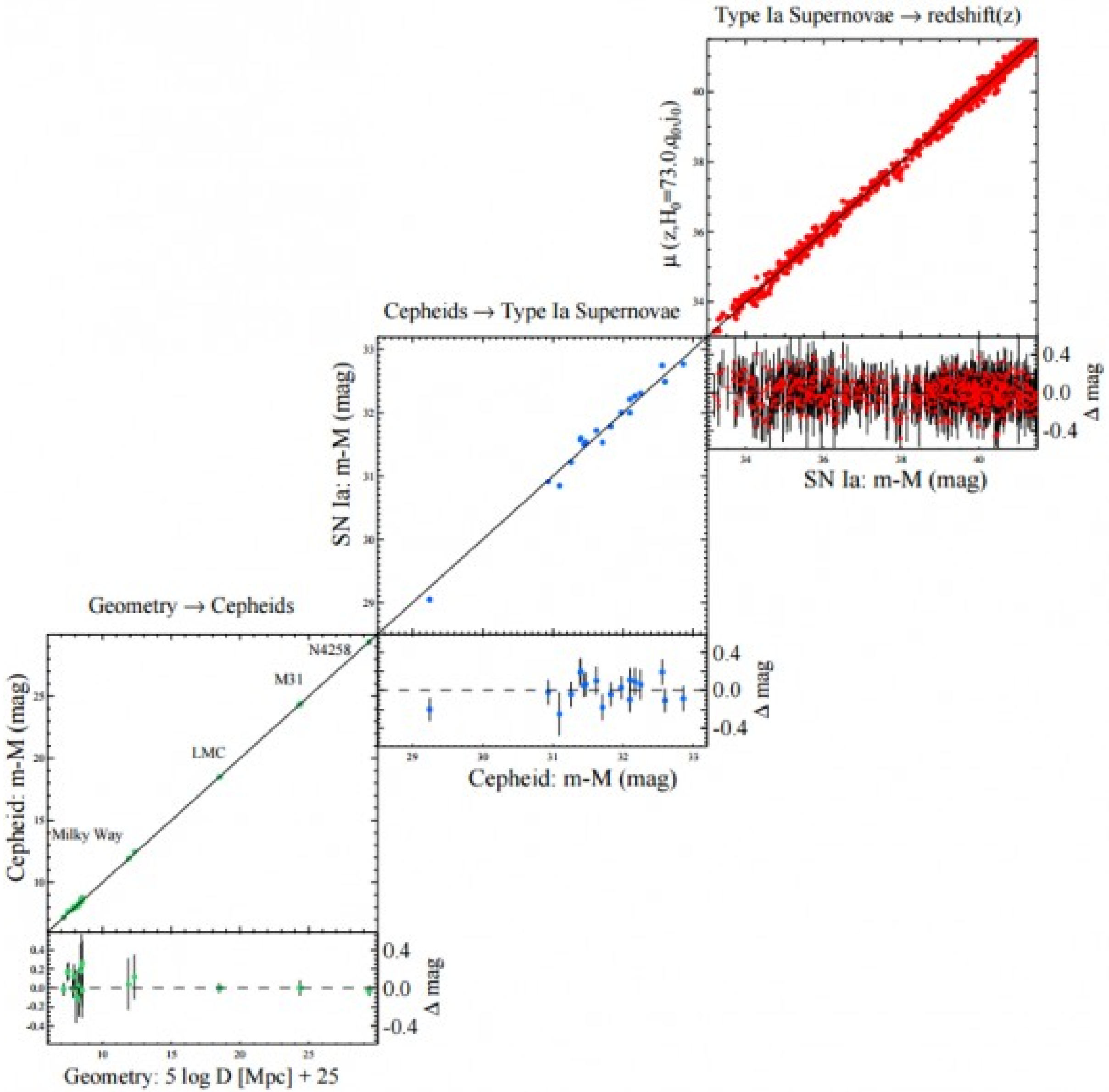
Velocity-Distance Relation among Extra-Galactic Nebulae.



Hubble Diagram for Type Ia Supernovae
Velocity [km s^{-1}]
Distance [Mpc]
4×10^4
3×10^4
2×10^4
1×10^4
0
0
100
200
300
400
500
600
700


Hubble Constant Over Time
H_0 [km s^{-1} Mpc^{-1}]
Year of Publication
Cepheids
CMB
TRGB
60
65
70
75
80
2000
2004
2008
2012
2016
2020


CMB and Independent Local H_0 values
Relative Probability Density
CMB
67.4±0.5
TRGB
(LMC)
69.8 ± 1.9
Cepheids
(N4258+MW)
73.9 ± 1.6
H_0
64
66
68
70
72
74
76
78
80


Type Ia Supernovae → redshift(z)
μ (z,H_0=73.0,q_0,j_0)
SN Ia: m-M (mag)
Δ mag
Cepheids → Type Ia Supernovae
SN Ia: m-M (mag)
Cepheid: m-M (mag)
Δ mag
Geometry → Cepheids
Cepheid: m-M (mag)
N4258
M31
LMC
Milky Way
Geometry: 5 log D [Mpc] + 25
Δ mag

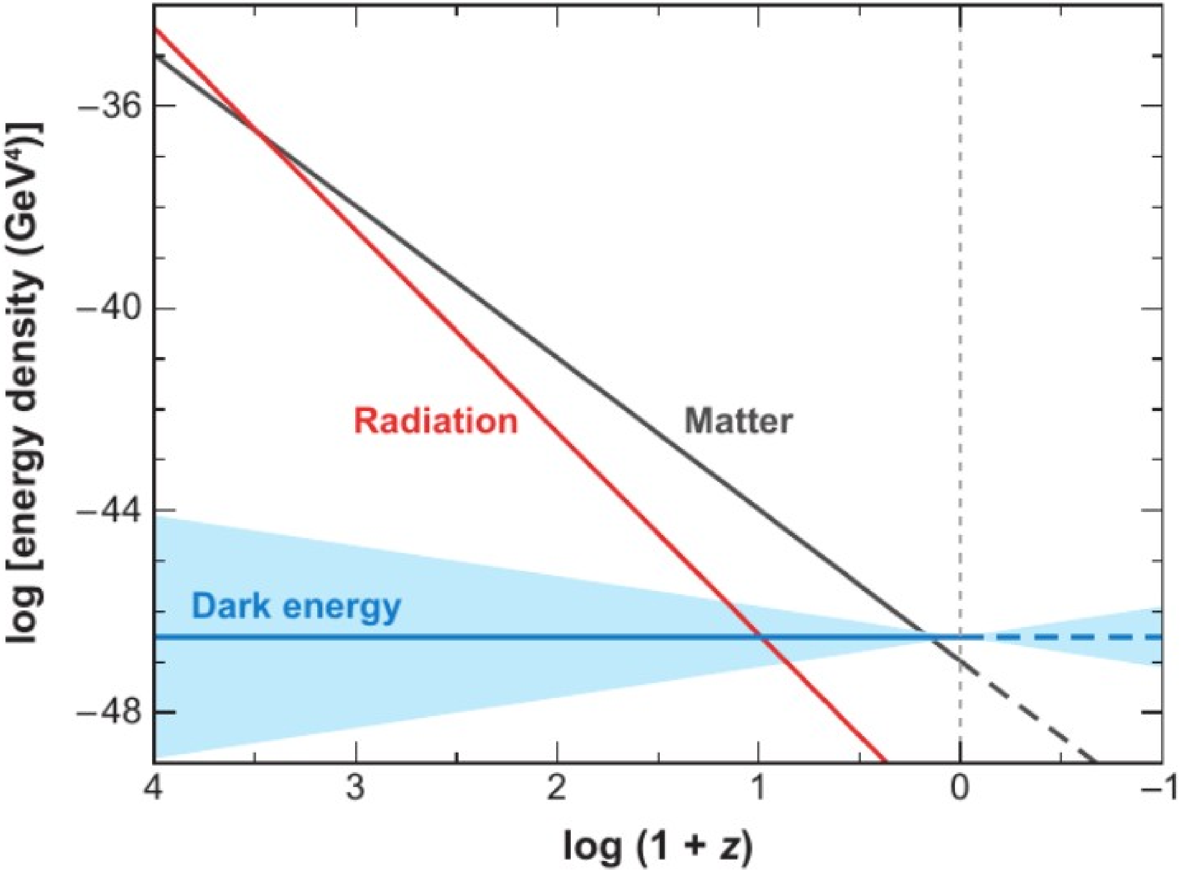
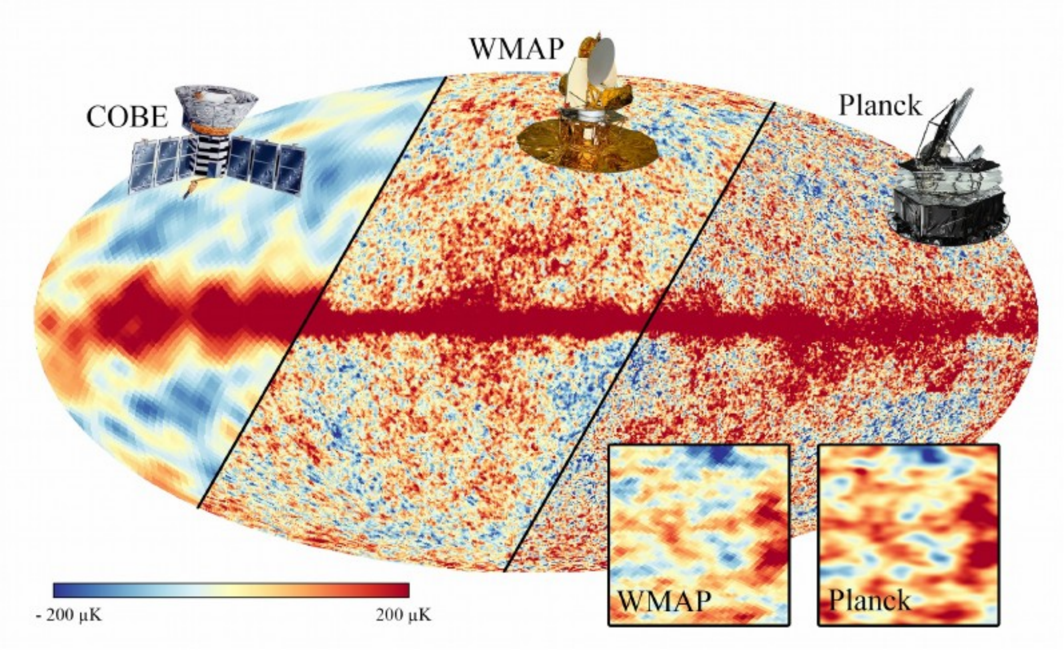


Figure 1 shows the evolution of the radiation, matter, and dark energy densities with redshift. The universe has gone through three distinct eras: radiation dominated, $z \geq 3000$; matter dominated, $3000 \geq z \geq 0.5$; and dark energy dominated, $z \leq 0.5$. The evolution of the scale

1.2.5 *"Warm" Universe*

The present Universe is filled with Cosmic Microwave Background (CMB), gas of non-interacting photons, which was predicted by the hot Big Bang theory and discovered in 1964. The number density of CMB photons is about 400 per cubic centimeter. The energy distribution of these photons has thermal, Planckian spectrum. This is shown in Fig. 1.3 [16]. According to the analysis of Ref. [17], the present CMB temperature is

$$T_0 = 2.726 \pm 0.001\,\mathrm{K}. \tag{1.11}$$



The present Universe is transparent to the CMB photons:[6] their mean free path well exceeds the horizon size H_0^{-1}. This was not the case in the early Universe, when photons actively interacted with matter.

Photons have two possible polarizations, and each has an occupation number per mode $\mathcal{N}$ given by the Planck function

$$\mathcal{N} = \frac{1}{\exp\left(hf/k_{\mathrm{B}}T\right) - 1}, \tag{2.7}$$

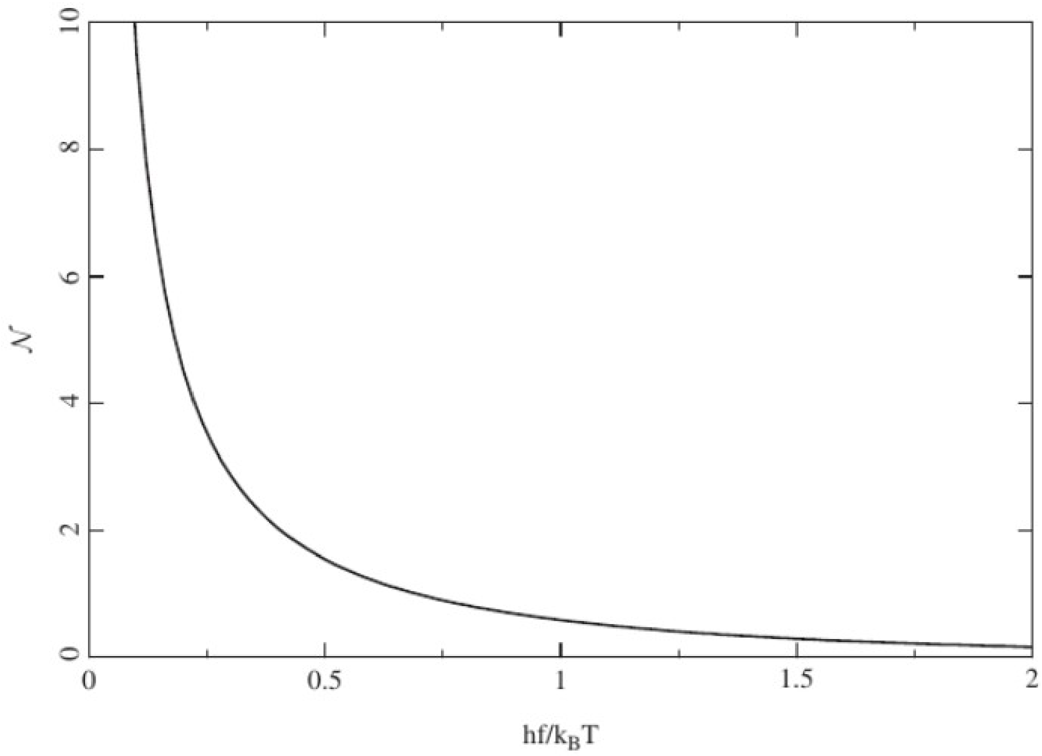


Figure 2.9 The Planck function of Equation (2.7). There are far more photons with very low energy than very high energy.

$$\epsilon(f)\,df = \frac{8\pi h}{c^3}\,\frac{f^3\,df}{\exp\left(hf/k_B T\right) - 1}\,,$$

$$E_{\text{peak}} = \hbar f_{\text{peak}} \simeq 2.8\,k_B T.$$

$$\epsilon_{\text{rad}} = \frac{8\pi k_B^4}{h^3 c^3}\,T^4 \times \int_0^\infty \frac{y^3\,dy}{e^y - 1}\,.$$

$$\epsilon_{\text{rad}} = \alpha T^4\,,$$
$$\alpha = \frac{\pi^2 k_B^4}{15\hbar^3 c^3} = 7.565 \times 10^{-16}\,\mathrm{J\,m^{-3}\,K^{-4}}\,.$$

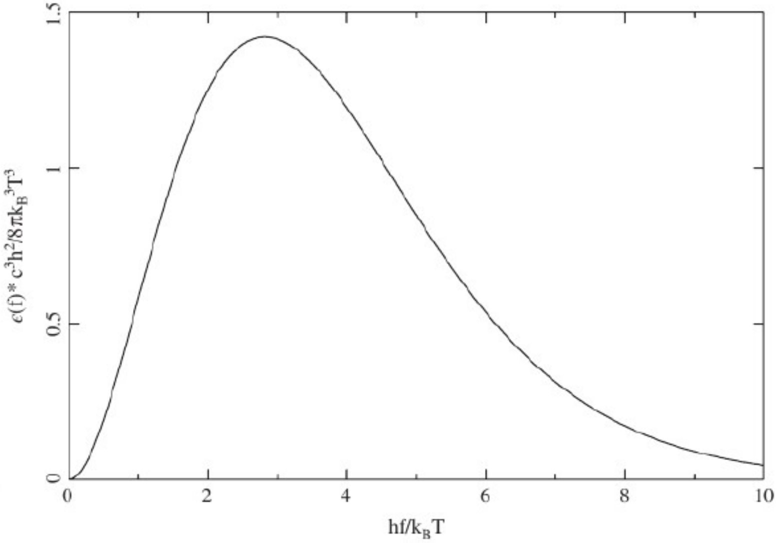


Figure 2.10 The energy density distribution of a black-body spectrum, given by Equation (2.8). Most of the energy is contributed by photons of energy $hf \sim k_B T$.

The temperature of photons coming from different directions on celestial sphere is the same at the level of better than 10^{-4} (modulo dipole component, see below); this is yet another evidence for homogeneity and isotropy of the Universe.

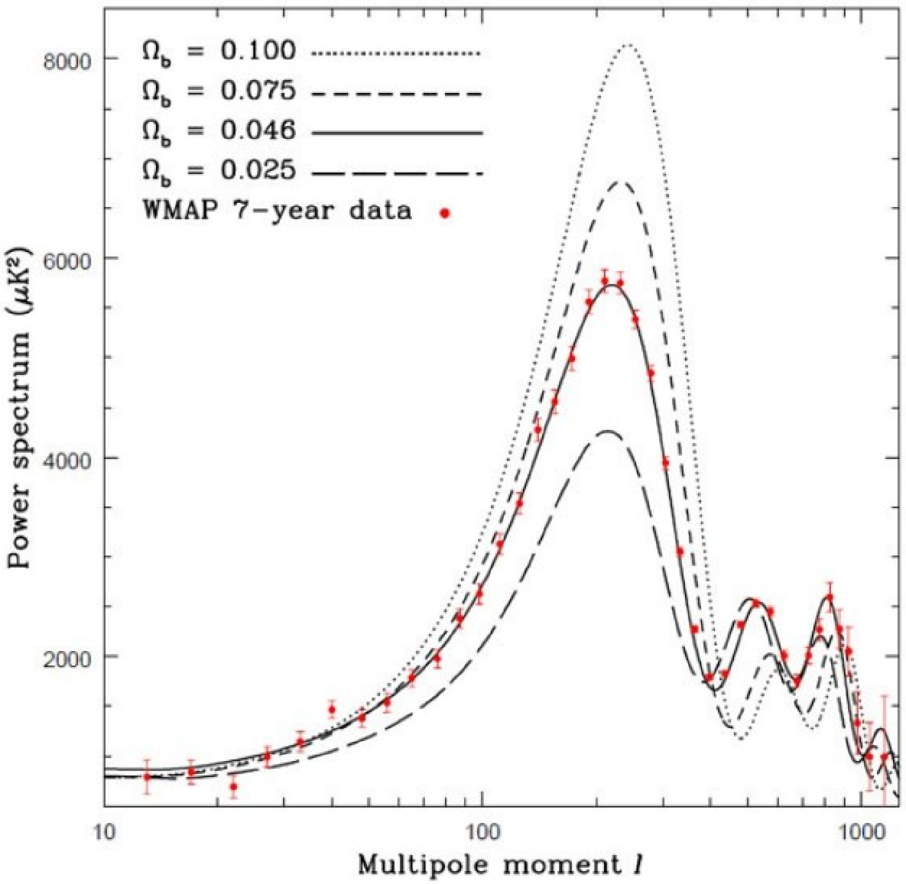
Still, the temperature does depend on the direction in the sky. The angular anisotropy of the CMB temperature has been measured, as shown in Fig. 1.4 [9] (see Fig. 13.2 on color pages). It is of order $\delta T/T_0 \sim 10^{-4} - 10^{-5}$.

We will repeatedly come back to CMB anisotropy and polarization, since, on the one hand, they encode a lot of information about the present and early Universe and, on the other hand, they can be measured with high precision.

Let us note that the existence of CMB means that there is special reference frame in our Universe: this is the frame in which the gas of photons is at rest. Solar system moves with respect to this frame towards Hydra constellation. The velocity of this motion determines the dipole component of the measured CMB anisotropy [18],

$$\delta T_{\text{dipole}} = 3.346\,\mathrm{mK}. \tag{1.12}$$

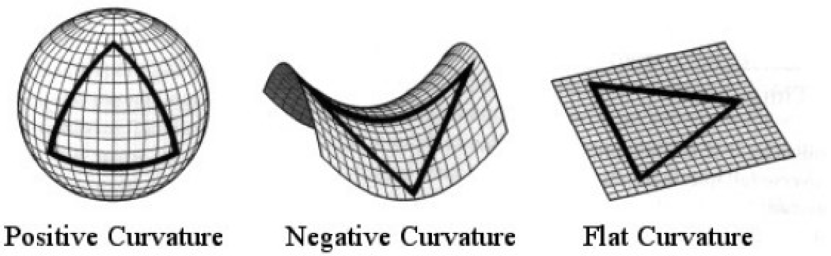
Microwaves: For cosmology, this is by far the most important waveband. Penzias & Wilson's accidental discovery in 1965 that the Earth is bathed in microwave radiation, with a black-body spectrum at a temperature of around 3 Kelvin, was and is one of



1.2.4 *Spatial flatness*

Homogeneity and isotropy of the Universe do not imply, generally speaking, that at each moment of time the 3-dimensional space is Euclidean, i.e., that the Universe has zero spatial curvature. Besides the 3-plane (3-dimensional Euclidean space), there are two homogeneous and isotropic spaces, 3-sphere (positive spatial curvature) and 3-hyperboloid (negative curvature). A fundamental observational result of recent years is the fact that the spatial curvature of our Universe is very small, if not exactly zero. Our 3-dimensional space is thus Euclidean to a very good approximation. We will repeatedly get back to this statement, both for quantifying it and for explaining which observational data set bounds on the spatial curvature. We only note here that the main source of these bounds is the study of the temperature anisotropy of the Cosmic Microwave Background (CMB), and that at the qualitative level, these bounds mean that the radius of spatial curvature is much greater than the size of the observable part of the Universe, i.e., much greater than H_0^{-1}.

We note here that CMB data are also consistent with the trivial spatial topology. If our Universe had compact topology (e.g., topology of 3-torus) and its size were of the order of the Hubble length, CMB temperature anisotropy would show a certain regular pattern. Such a pattern is absent in measured anisotropy, see Ref. [11].



Particles in the Universe

Table 2.1 Elementary particle properties.

Particle	*Symbol*	*Rest energy (MeV)*	*Charge*
Proton	p	938.27	+1
Neutron	n	939.57	0
Electron	e^-	0.5110	−1
Neutrino	ν_e, ν_μ, ν_τ	$< 3 \times 10^{-7}$	0
Photon	γ	0	0
Dark matter	?	?	0

$$E_{\text{total}}^2 = m^2c^4 + p^2c^2 \,, \qquad E_{\text{total}} = mc^2\left(1 + \frac{p^2}{m^2c^2}\right)^{1/2} \approx mc^2 + \frac{1}{2}\frac{p^2}{m} \,.$$

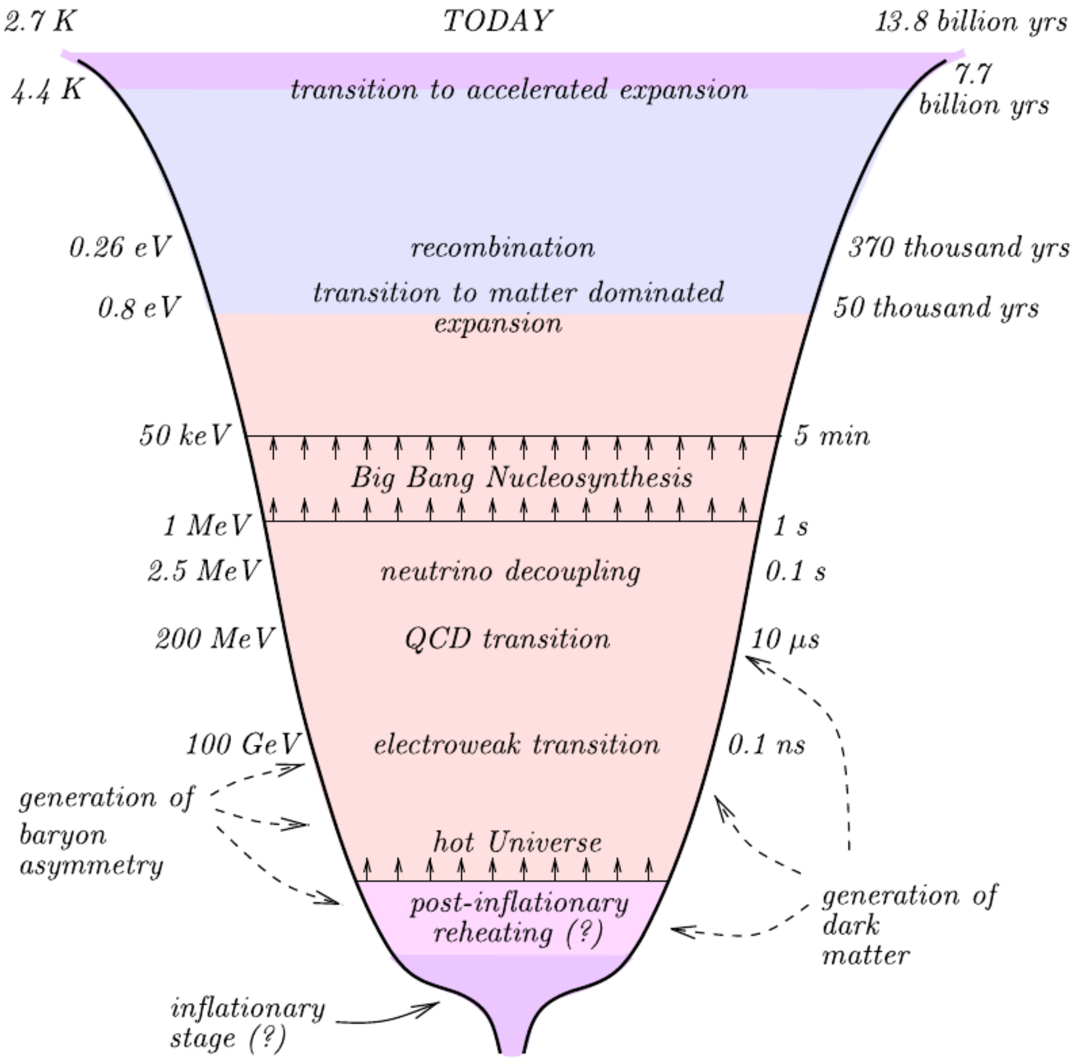


Fig. 1.10. Stages of the evolution of the Universe.