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Modern Cosmology – nearly perfect but incomplete

Editorial

”Cosmologists are often in error, but never in doubt”. This aphorism by Lev Davidovich Landau (1908–1968) may have been applied to cosmology before the discovery of the cosmic microwave background (CMB), predicted in 1933 by Erich Regener, vaguely indicated by Andrew McKellar in 1940/41, postulated in the 1940s by George Gamow, Ralph Alpher and Robert Herman, and definitely detected in 1964 by Arno Penzias and Robert Woodrow Wilson. Cosmology was a rather theoretical and perhaps highly speculative branch of astrophysics at the time. Several cosmological models were discussed based on and resulting from Albert Einstein’s General Theory of Relativity. However, observations and, particularly, accurate distance measurements on large scales were missing or too uncertain to confirm either the one or the other model. These models concerned the steady-state theory, the pulsating Universe, and the Big Bang theory implying an ever expanding Universe. It was even impossible to make any reliable statements on the size, age, evolution, structure, and topology of the Universe.

Since then, however, cosmology has undergone two dramatic shifts in paradigm, namely from a mathematical to a physical science and from a physical to an observational science, thus turning it into an exact science that follows the method of prediction (modelling) and falsification (comparing with observations). The main reasons for this development were the beginning of the space age enabling the launch of dedicated satellite missions, and of the computer age allowing the simulation of more and more complex cosmological as well as astrophysical models. This is why discriminating the “traditional” from the “modern” cosmology is justified. Moreover, modern cosmology is built on physical, astrophysical, and cosmological concepts and parameters which are confirmed by experiments and measurements to a high degree of precision.

The content of this issue resulted from the talk “Cosmology Today” by Prof. Dr. Bruno Leibundgut held on October 14, 2020, in the Pro ISSI seminar series. In his presentation Prof. Leibundgut briefly reviewed the major steps made in cosmology from earlier times to today. He addressed the methods and results of modern cosmology and pointed out still unresolved problems. Although becoming an established exact science has made modern cosmology “nearly perfect”, these open issues are the reason why it is still “incomplete”. It may well be that new space-borne and ground-based instruments providing refined observational data will allow us to answer many of the open questions in near future. However, a central issue will remain perhaps forever, as the cosmologist Dennis William Sciama (1926-1999) stated in 1978 without any doubt: “None of us can understand why there is a Universe at all, why anything should exist; that’s the ultimate question.” Was he in error, too?

Andreas Verdun
Zimmerwald, May 2021

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Title Caption

Hubble Space Telescope-Image of the Type Ia Supernova 1994D (SN1994D) in galaxy NGC 4526 (SN1994D is the bright spot on the lower left). The supernova was discovered with a small (70cm) telescope and observed by chance by HST.
(Credits: Peter Challis (CfA) and the High-z Supernova Search Team)

Modern Cosmology – nearly perfect but incomplete

Bruno Leibundgut, European Southern Observatory (ESO) and Technical University Munich (TUM)
Johannes Geiss Fellow 2019

Cosmologists map the past evolution of the Universe through diverse observations probing the state of the Universe at a given epoch. A theoretical model is then used to tie these vantage points into a coherent evolution. There are four important epochs which astrophysics can probe: (1) the current Universe, presumably at an age of about 13.8 billion years, (2) the evolution of structure over the past 12 billion years, (3) a snapshot of the plasma state of the Universe at an age of about 350,000 years, and (4) nuclear reactions taking place within the first three minutes of the Big Bang. The theory connecting these observations is based on the assumption that the known laws of physics hold throughout the observable Universe, and that we can describe the Universe essentially as homogeneous and isotropic. This assumption is called the "cosmological principle". The cosmological principle leads to a simplification which allows us to describe the evolution of the Universe with its (energy) contents.

Our view of the cosmos has changed dramatically in the past three decades. Many basic ideas had already been in place for most of the 20th century, starting with General Relativity as a theory that describes a dynamic universe at large scales, the realisation of large distances between galaxies, and the observation of expansion between them. During the first half of the 20th century the evolution of elemental abundances was proposed and the existence of dark matter postulated. The discovery of the cosmic microwave background in the 1960s implied a hot past of the Universe and strengthened the idea of nucleosynthesis in the very early Universe. Simulations of the growth of large-scale structure and the formation of clusters of galaxies tried to reproduce the distribution of galaxies in the Universe. Some important additions and extensions to the emerging picture of the Universe were made at the start of the new millennium. The status of cosmology some 20 years ago can be found in the excellent exposés by Johannes Geiss (*Spatium* 1, April 1998) and Gustav Andreas Tammann (*Spatium* 3, May 1999). Since then, new observations have improved our knowledge concerning the geometry of space and added the discovery of a current acceleration of the expansion of the Universe. Theorists have made significant progress in simulating the formation and growth of structures on almost all scales. The particle physics standard model has been completed with the detection of the Higgs particle and helps in firming up our views of the Universe.

> ***"The enormous progress in the construction of modern telescopes in space and on the ground is therefore driven not only by the aim to use them as 'space ships', bringing distant objects closer to the observer, but also as 'time ships', bringing past events into the present."***
>
> *Gustav Andreas Tammann, Spatium-No. 3, May 1999*

Over recent years, many cosmological parameters have been measured with high precision. A prime example is the value of the current expansion rate, the Hubble constant. Thirty years ago, it was still uncertain by almost a factor of two, but it has now been determined to a few percent. New parameters have been added to describe various effects that have become observable. Among them is the strength of the growth of structure or the equation of state parameter of an additional ingredient to the universal contents. The current model, for the first time, yields a dynamical age that is larger than the oldest stars and provides a nearly complete description of many observables. This "concordance" model goes under the name of ΛCDM. Λ stands for the cosmological constant, a late addition by Albert Einstein into his field equations, and the remaining letters for Cold Dark Matter. The ingredients of this model are the validity of General Relativity as the description of gravity, three (energy) constituents, and the simplifying assumptions of isotropy and homogeneity. The latter assumptions are to ensure that we are "neutral" observers and can observe a "typical" part of the Universe. The Universe contains matter in two forms: baryonic matter, which encompasses the observable Universe (all known elementary particles and the matter built up from it: dust, flora and fauna, planets, stars, galaxies), and dark matter, which only acts gravitationally. So far, dark matter has been inferred only indirectly (Klaus Pretzl, 2001, *Spatium* 7) and has been deduced by high velocity dispersions in galaxy clusters (first by Fritz Zwicky almost 90 years ago), the mass distribution in galaxy clusters as observed through their gravitational effects by lensing the light of background galaxies (see Georges Meylan 2013, *Spatium* 32), and extended rotation curves observed in nearby galaxies. The inclusion of a cold dark matter particle in the simulations of the evolution of the growth of structure can reproduce the observed distribution of galaxies on large scales. Further ingredients of the cosmological model are radiation, observed today mostly in the form of microwave photons distributed throughout the Universe, and dark energy, an enigmatic component that accelerates cosmic expansion.

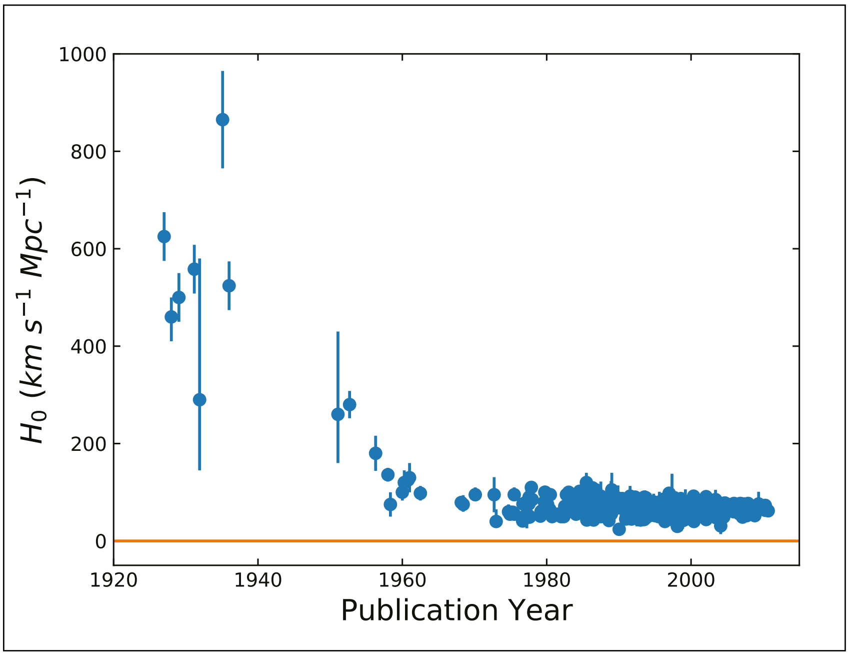
This article presents the main cosmological observables which led to the current cosmological model. Main measurements are (a) the expansion rate today (Hubble's constant), (b) the growth of structure from tiny fluctuations in the early Universe to today's distribution of galaxies and galaxy clusters, (c) a remnant glow from a hot phase in the early Universe, and (d) the abundances of various elements and their evolution over the age of the Universe.

The Universe today

At an age of 13.8 billion years, we observe a universe that is fairly quiet and settled. Many galaxies are in groups or clusters. Most of them have had one or two intensive phases of star formation and galaxy encounters, and mergers are fairly rare today. Galaxies vigorously forming stars or disturbed by massive mergers are observed at large distances and large lookback times, when the galaxies were considerably younger than the ones we observe nearby.

The Hubble-Lemaître law relates the observed recession velocities of galaxies to their distances. This describes the cosmic expansion as a function of distance and yields the Hubble constant, commonly denominated H_0. Due to the cosmic expansion, the observed velocity vectors of the galaxies point away from us and the photons are shifted to larger wavelengths. The expansion rate (velocity per distance) is a critical parameter for all cosmological models as it sets the absolute scale and age of the Universe. The cosmological redshift is a relativistic effect coming from General Relativity related to the expansion of space and is not a Doppler shift as it is sometimes portrayed. While the redshift measurement is rather simple – one observes the shifted wavelength of a known atomic transition in an electromagnetic spectrum – deter-

Figure 1: Evolution of the measured value of the Hubble constant (H_0) over the past century. Based on data collected by John Huchra *(2010: https://www.cfa.harvard.edu/~dfabricant/huchra/hubble/)*

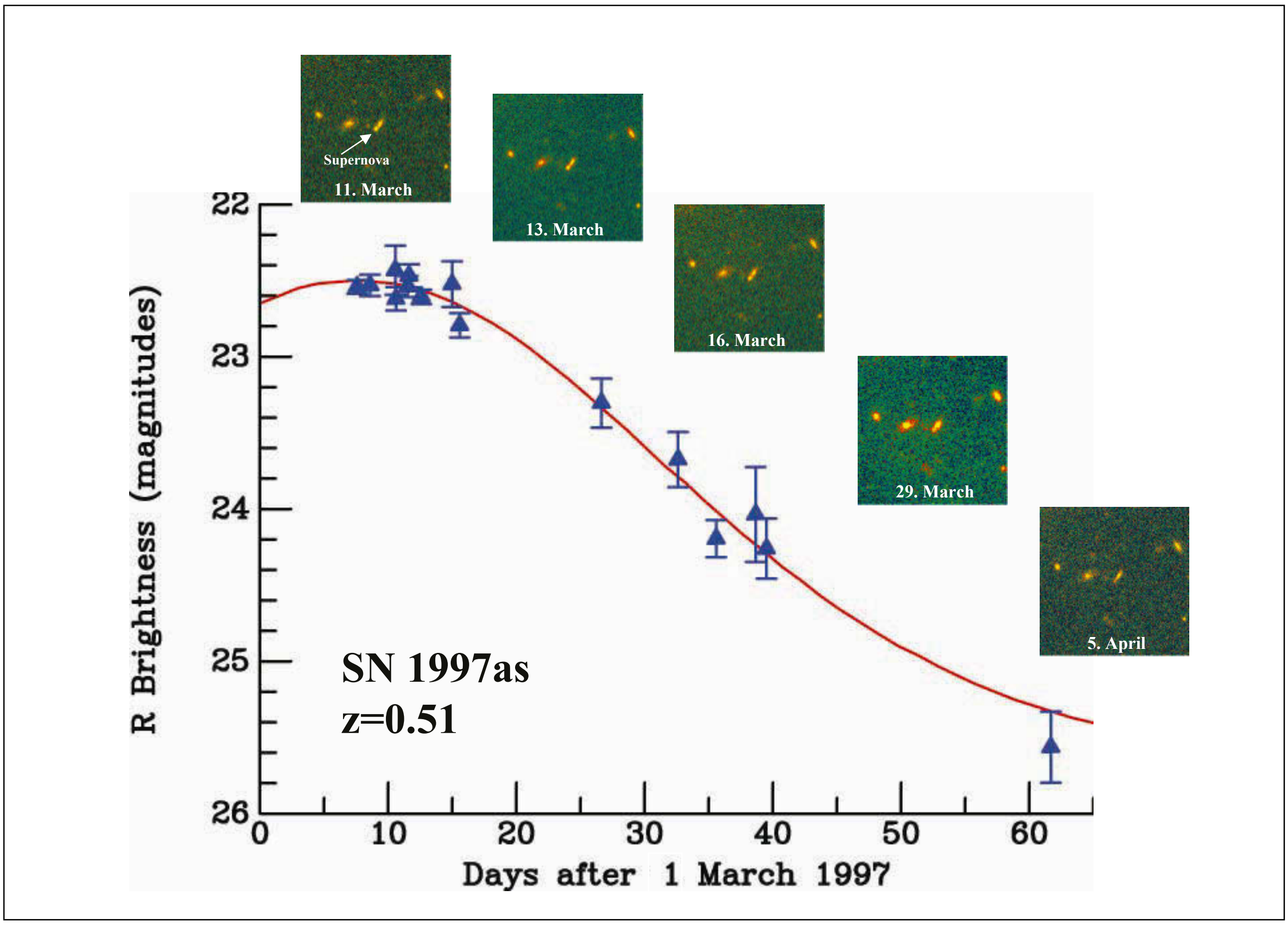


mining an accurate cosmological distance is very difficult. The problem lies in the absolute calibration of distance indicators and has occupied astronomers for decades.

View 25 years ago (Spatium 1 and 3)

The cosmic expansion was established observationally just over 90 years ago by Vesto Slipher, Knud Lundmark, Carl Wilhelm Wirtz, Georges Lemaître and Edwin Hubble. It is Hubble's famous diagram showing the increased recession velocity for objects at larger distances that demonstrated this expansion. The value of the expansion rate derived by Lemaître and Hubble was of a size that the expansion age of the Universe would have been about a quarter of the known age of the Earth – clearly a contradiction that was not tenable. It took several decades for new measurements during which a significant decrease in the value of the Hubble constant can be observed **(figure 1)** just before 1960. Some 60 years ago, the measurements settled to values somewhere between 50 and 100 km s^{-1} Mpc^{-1}. Alan Sandage and Gustav Andreas Tammann set out to measure the Hubble constant through a series of increasing distance determinations. This was done by calibrating new distance indicators based on previously determined distances and establishing a "distance ladder" to step further out into the Universe. Thus, they took "Steps

Figure 2: Light curve of a Type Ia supernova at high redshift.
The fading of the supernova can be appreciated in the images after 16 March.



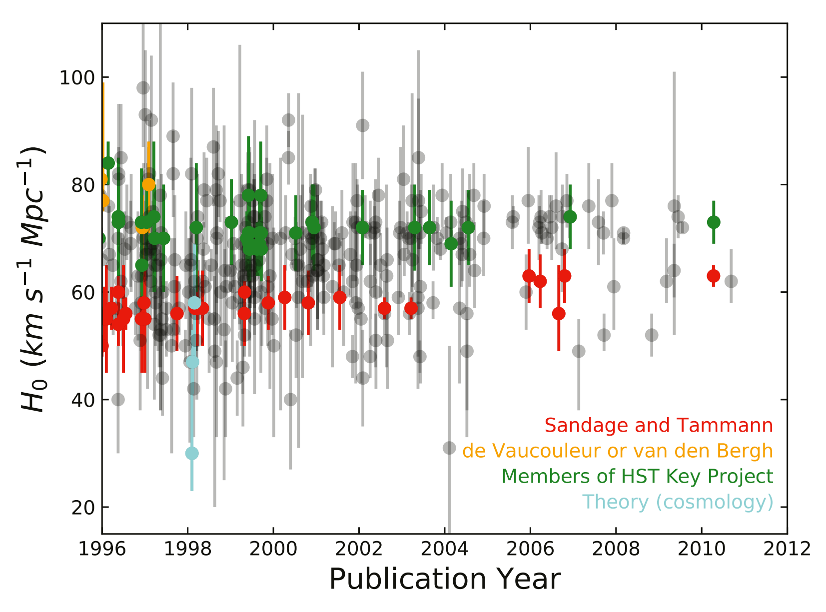
towards the Hubble Constant", which was the title of a series of publications over nearly two decades. Of course, it is advantageous to keep the number of steps as small as possible in order to minimise the accumulating uncertainties. Today, two important classes of variable stars play a crucial role: Cepheids and Type Ia supernovae (SN Ia). Cepheid stars display a periodic variation in their luminosity and colour. Henrietta Swan Leavitt found in 1917 that Cepheids in the Small Magellanic Cloud display a tight correlation between their luminosities and their periods. Cepheids with longer periods are more luminous. Once this period-luminosity relation is calibrated the distance can be inferred by simply measuring their period. Hubble observed a Cepheid star in the Andromeda Nebula in 1924 and could show that this galaxy lies outside the Milky Way. Type Ia supernovae – the supernova types were originally defined by Zwicky, who dedicated most of his observational activities to the study of galaxies and supernovae – show a rather small scatter in observed luminosities, and their peak brightness can be used to derive cosmic distances for individual objects. Most critical is the coverage of the maximum in the light curves **(figure 2)**, which occurs two to three weeks after explosion, but often was not observed. Tammann had recognised the potential of supernovae early on and was instrumental in calibrating them as reliable distance indicators.

For several decades the measured value of the Hubble constant remained fairly stable although with a significant scatter. The dynamical age of the Universe still remained lower than its oldest stars for the favourite cosmological model. This model had a flat space geometry and was dominated by matter. The theoretical bias was so strong that the discrepancy to the observed mean matter density was mostly ignored at the time.

For many years at the beginning of this century the value of the Hubble constant hovered between 50 and 80 km s^{-1} Mpc^{-1} (see **figure 3**). There was a major improvement in the measurement through the observation of Cepheid stars in nearby galaxies with the Hubble Space Telescope (HST) reducing the number of rungs in the distance ladder dramatically.

It was a key project for HST to determine the cosmic expansion rate with an accuracy of about 10%, which was achieved by two separate teams. One (identified as "Members of HST Key Project" in **figure 3**) originally favoured several different secondary distance indicators. The second team led by Sandage and Tammann used mainly Type Ia supernovae as the secondary distance indicator and derived somewhat smaller values for the Hubble constant. While supernovae had been used earlier for distance measurements, their accuracy was mostly established in small samples, and only dedicated searches yielded sizeable samples of well-observed supernovae.

Figure 3: Recent evolution of the Hubble constant (H_0) according to research group *(based on data from John Huchra)*



Changes in the past 25 years

The Calán-Tololo supernova search was the first survey to overcome the problem of incomplete light curve coverage and provided a suitable sample of Type Ia supernovae. Cepheids were observed with HST in galaxies where Type Ia supernovae had exploded before and hence the supernova peak luminosity could be calibrated.

The measurement uncertainties for the local Hubble constant have now been reduced to only a few percent. This has mostly come about through the reduction to three rungs in the distance ladder.

> ***“Then, as precision increases, the array of possible interpretations permitted by uncertainties in the observation will be correspondingly reduced. Ultimately, when a definite formulation has been achieved, free from systematic errors and with reasonably small probable errors, the number of competing interpretations will be reduced to a minimum.”***
>
> *Edwin Hubble, The Law of Red-Shifts, 1953, MNRAS 113, 658*

The luminosity of Cepheid stars is calibrated in the Milky Way by geometric methods, mostly trigonometric parallaxes, or in the Magellanic Clouds. With calibrated Cepheid luminosities such stars are observed in local galaxies in which a Type Ia supernova has been observed. The maximum luminosity of the supernovae can then be calibrated through the Cepheid distances. Alternatively, the supernovae can be calibrated by the tip of the red giant branch, where stars reach a unique luminosity, when helium burning starts in their centre, or by some other methods. Large samples of distant supernovae can be used to measure distances where the cosmic expansion dominates the movement of the galaxies, the so-called “Hubble flow”, and where the Hubble constant is derived. Today, many transient searches are active (Zwicky Transient Factory, Pan-STARRS, ATLAS) and several thousand supernovae are discovered every year. Supernovae are now the preferred secondary distance indicators to reach the Hubble flow.

In recent years, new methods independent of the distance ladder have been proposed and employed. They include the time delay observed in quasars gravitationally lensed by a foreground galaxy cluster or a galaxy. Since the path lengths for the individual lensed images are different, the time lag determines the distances between us, the source and the lens, and the ratios of these distances provides a measurement of the Hubble constant. This method has led to very competitive determinations of the Hubble constant. A further geometric method is the measurement of water (mega-)masers orbiting a galactic centre. The radial velocity and the angular separation define the disk rotation and yield a distance.

All methods converge to values for the Hubble constant of about 73 km s^{-1} Mpc^{-1} with uncertainties of about 2 to 3 percent.

The observation of cosmic acceleration in the expansion of the late Universe by Type Ia supernovae introduced an important paradigm shift. The addition of an acceleration in the form of a cosmological constant increases the dynamical age of the Universe dramatically, and in one fell swoop the age problem with the oldest stars disappeared. This can be observed in **figure 3** where the few theoretical predictions were pushing the values of the Hubble constant to very low values to accommodate a matter-dominated, flat universe (the so-called Einstein-de Sitter model).

The Universe over the past 12 billion years

The evolving Universe is revealed in many observations. The appearance of galaxies changes dramatically when we look back to earlier times, i.e. when we look into the deep Universe. A marked change in the rate of star formation within galaxies is observed, and the abundance of various elements changes over time. Clusters of galaxies formed only late in the Universe. The changes indicate an evolution towards more structure. Stars in our Milky Way which map its history and tell us about the formation and evolution of galaxies and stars in general provide a further tracer.

Views 25 years ago

Quasi-stellar objects (quasars) are extremely luminous cores of massive galaxies. They were discovered in the 1960s and were the most distant objects known at the time. There are two major steps visible in the diagrams shown in **figure 4:** one around 1930, when the extragalactic nature of the “nebulae” as galaxies was recognised, and the second one in 1963 with the discovery of the high redshifts in quasar spectra. It can be seen how the known universe increased by a factor of 1,000 in the 1930s and again by a factor of 10 with the large distances of the quasars. By 1995 quasars were observed out to redshifts of 5, which corresponds to a lookback time of about 12.3 billion years or 91% of the observable Universe, while galaxies were not observed that far away and were mostly restricted to smaller redshifts around 3.

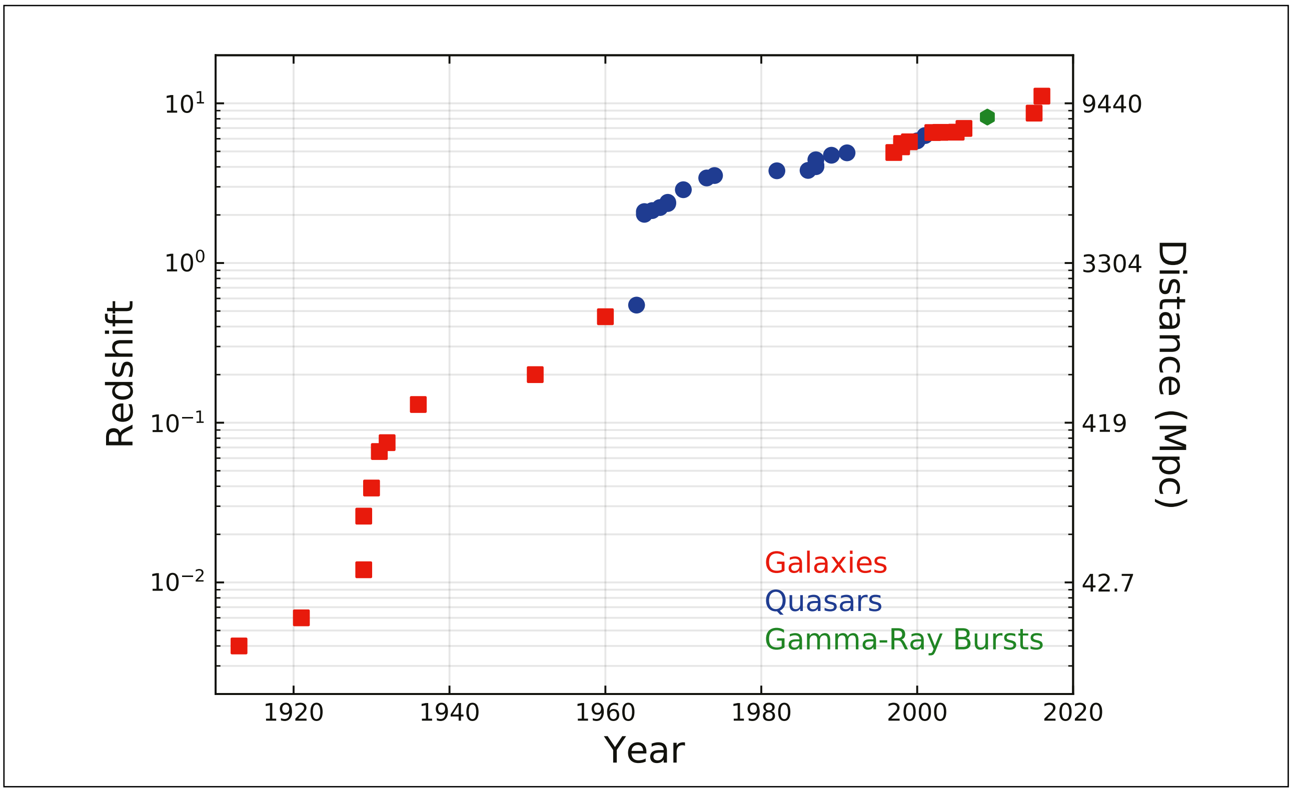


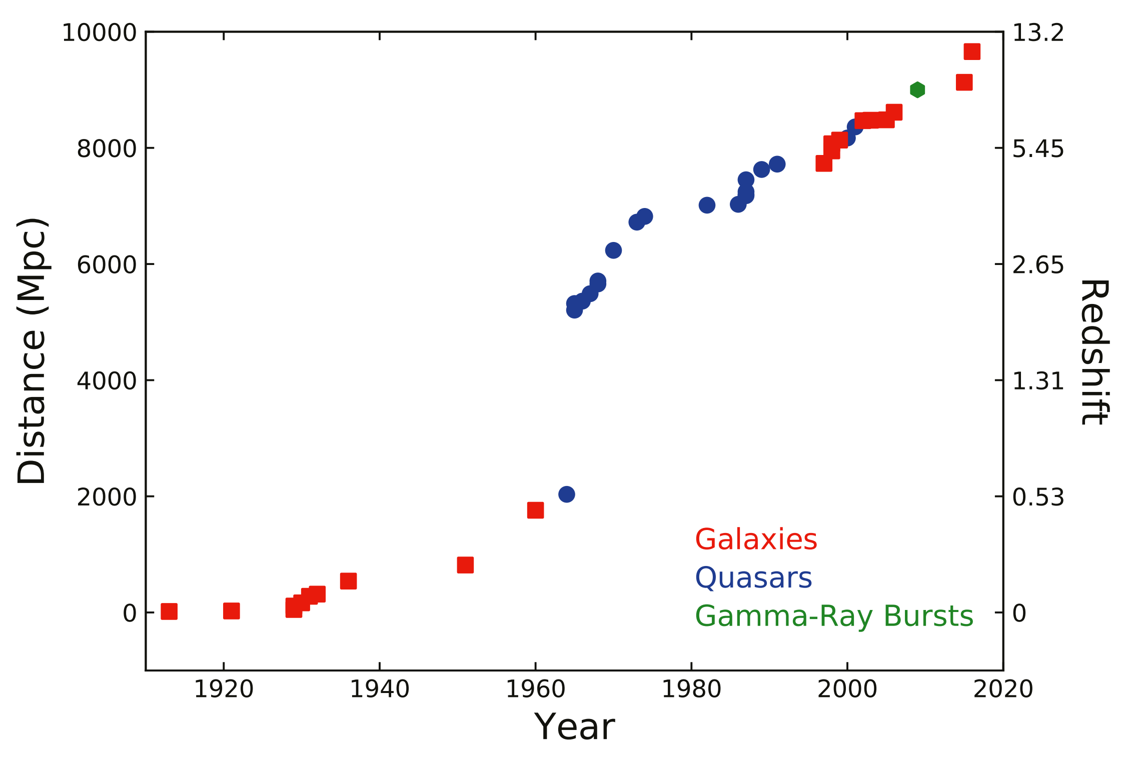
Figure 4: Evolution of the most distant known objects.
(Left panel) Graph with redshifts and the distances provided on the right axis.
(Right panel) Linear distances to highlight the jump with the discovery of quasars.

Extensive spectroscopic observations of distant galaxies showed that the rate at which stars form within a galaxy is not constant and in fact has been decreasing for the past 10 billion years. HST provided the first detailed images of galaxies at ultraviolet wavelengths and images of very distant galaxies.

The distribution of galaxies is not uniform. Most galaxies are found either in clusters or aligned along filaments delineating huge empty volumes ("voids"), where there appear to be no galaxies. The recognition of the inhomogeneous distribution of galaxies was only slowly realised as due to the growth of structure from the early Universe (see below). Simulations of the emergence of this large-scale structure were based on a model involving dark matter particles increasing the gravitational potential wells, which allowed the structures to grow fast enough within the available time. Dark matter had been implied by the observation of rotation curves of galaxies, which remain constant beyond the (optically) observable edges, and hence require additional, unseen mass to explain the high rotation velocities.

At the end of the last millennium the matter content of the universe still remained unclear. The measurements from galaxy clusters indicated about one third of the critical density, whereas an inflationary period at the Big Bang predicted a flat universe with a critical density – a factor-of-3 difference. The matter-filled, flat Einstein-de Sitter model was favoured by theory, but still had an age problem with some stars older than the dynamical expansion age. As a consequence, the Hubble constant had to be very low (see cyan points in **figure 3**).

Both panels display the same data and the relation between linear (proper motion) distance and redshift changes the appearance. The relation between redshifts and distances is calculated for a flat universe with a Hubble constant of 70 km s^{-1} Mpc^{-1}, 30% of matter and 70% of dark energy (ΛCDM model). *(Data from Wikipedia; 4 February 2021)*



Changes in the past 25 years

Over the past couple of decades the record holder for the most distant objects observed changed from quasars to galaxies to gamma-ray bursts and back to galaxies. The effective increase in "explored volume" at this point is relatively modest (about 70% over the past 25 years, see **figure 4**), simply because objects over most of the observable Universe can now be seen. By observing "deep fields", with extremely long exposure times, of a single "empty" region in the sky, extremely faint and distant galaxies could be detected. New sensitivity limits could be reached and revealed objects significantly older than the Sun or even our Milky Way. HST and the Chandra X-ray telescope were detecting many distant galaxies or active galactic nuclei (AGN). Since the activity of a galaxy nucleus is typically limited in time, quasars are only a subset of galaxies and are observed much less frequently. Due to the high redshifts and additional blocking of light in the ultraviolet by absorbing hydrogen atoms, galaxy spectra appear redder and redder with distance and display no or only negligible flux at observed blue wavelengths – they "drop out" in the blue. This signature can be used to discover ever more distant and fainter galaxies. The same method was employed for a gamma-ray burst found at a redshift of 8.2. From measurements of the cosmic microwave background, it is now clear that it will be impossible to "see" galaxies, i.e. to observe them at optical wavelengths, with redshifts larger than about 12. Only radio observation will be able to detect galaxies at higher redshifts as hydrogen gas clouds when the required sensitivity will be achieved.

The simulations of large-scale structure formation have made tremendous progress. With the inclusion of dark energy, the simulations can reproduce the statistical matter distribution on large scales rather well. The simulations are working on much finer grids (mass, time and space) and the latest incarnations involve baryonic physics, which makes for some truly realistic looking modelling of galaxies.

Huge redshift surveys have found statistical homogeneity on large scales again, i.e. the local inhomogeneities are smoothed out over large enough volumes. They also confirmed a prediction of the cold dark matter model, namely that there should be an increased clustering at specific scales, which were originally set by the sound horizon at the time of reionisation. These Baryonic Acoustic Oscillations (BAO) have indeed been found and provide a new (statistical) distance indicator out to very large distances and have independently confirmed the cosmic acceleration found by supernovae. A new discrepancy has surfaced from the comparison of the strength of the clustering at scales of about 8 Mpc. This parameter can be reliably measured through distance samples, which are now assembled with large imaging surveys, like the Kilo Degree Survey (KiDS) at the VLT Survey Telescope or the Dark Energy Survey (DES) at the Victor Blanco Telescope at the Cerro Tololo Observatory. These will be superseded in the coming years by the ESA satellite, Euclid, and the Legacy Survey of Space and Time (LSST) at the Vera C. Rubin Observatory.

> ***"I don't know if we have dark matter or need a change in gravity or need something else; we know so little about our universe. It is a strange and mysterious universe. But that's fun."***
>
> *Vera Cooper Rubin, quoted by Neta Bahcall in Physics Today, March 2017, p. 74*

The Universe at 350,000 years

One of the main sources of our understanding of the Universe comes from a faint glow from the early universe. Today, this is observed as the Cosmic Microwave Background (CMB) with a black body temperature of about 2.73 Kelvin. It reaches us from all directions and provides an imprint of the status of radiation and matter some 350,000 years after the Big Bang. This radiation is currently the oldest image we can make of the Universe. It is the signature of the hot Big Bang and has cooled down continuously throughout the history of the Universe.

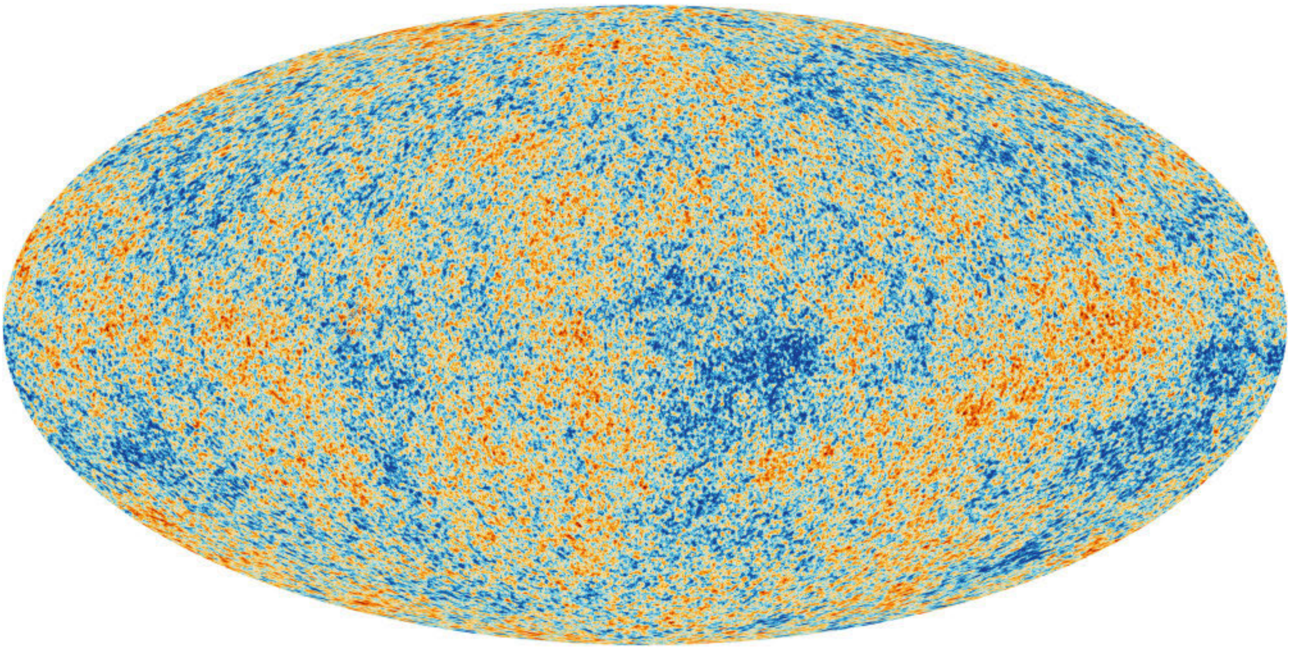
Views 25 years ago

The cosmic background was predicted by George Gamow in the 1940s to solve the problem of the creation of the elements. The predictions were mostly forgotten until Jim Peebles re-derived them. The background radiation was found accidentally by Arno Penzias and Robert Wilson while testing a sensitive radio telescope. The discovery of the CMB was taken as a clear sign of a hot past of the Universe, and is generally used as the strongest indication of a Big Bang. The CMB is highly isotropic, i.e. it is the same in all directions to better than 1 per mill. The Cosmic Background Explorer (COBE) satellite measured a perfect black body spectrum and found fluctuations in temperature at a contrast of 0.00001. What was missing was a measurement of the typical angular separation between the fluctuations to determine the geometry of the Universe.

Changes in the past 25 years

Since the microwave radiation is mostly blocked by Earth's atmosphere, its observations require balloons and satellites. Balloons have the advantage that they are much cheaper and can be deployed faster than satellites, but due to the limited flight times they can observe only small patches of sky. Two balloon experiments in the 1990s (MAXIMA: Millimeter wave Anisotropy eXperiment IMaging Array and BOOMERanG: Balloon

Figure 5: Temperature map of the Cosmic Microwave Background (CMB) as measured by the ESA Planck satellite. *(© ESA and the Planck Consortium)*



Observations Of Millimetric Extragalactic Radiation ANd Geophysics) found that the angular spacings of the fluctuations in the CMB indicated a flat space geometry. This was important information as it showed that the Universe was likely to be at the critical energy density and is also seen as proof of an inflationary period in the very early Universe. However, it was in contradiction to the measured matter density. Dark energy driving an accelerated expansion makes up for exactly this missing energy.

> ***"The effort to understand the universe is one of the few things that lifts human life a little above the level of farce, and gives it some of the grace of tragedy."***
>
> *Steven Weinberg in The First Three Minutes:*
> *A Modern View of the Origin of the Universe (1977), p. 155*

The CMB has been measured with increasing angular resolution and exquisite accuracy by the Wilkinson Microwave Anisotropy Probe (WMAP) and then by the ESA satellite Planck (**figure 5**). The temperature fluctuations shown in **figure 5** display a typical scale between cold and warm regions. This physical scale is set by primordial fluctuations, and their observed size gives us an indication of the path traveled by photons from the recombination until now. The observed scale tells us the geometry of space. The flatness of space has been determined to a very high precision. Other cosmological parameters that could be derived from the fluctuations are the baryonic density and the density of dark matter. These are imprinted in the fluctuations during the first 350,000 years, and with the richness of the CMB and in combination with the observed structure at later times provide accurate values. All measurements are consistent with the ΛCDM model and successfully connect the state of the early Universe to what is observed today. In particular, the growth of structure is confirmed successfully when applied to the simulations within ΛCDM.

The microwave background still holds some secrets. Polarisation provides information on the formation of the fluctuations themselves and would give an indication of gravitational waves interacting during the Big Bang. Ground-based measurements are already trying to observe the small-scale polarisation, and future all-sky satellite missions are proposed.

The first minutes – Big Bang nucleosynthesis

A universe dominated by matter consists of stars, gas and dust. These are typically combined in the term "baryons" defined in particle physics as all particles containing quarks. The most common baryons are protons and neutrons, which form the atomic nuclei. Stars are mostly made of hydrogen and helium, and contain very small contributions of elements beyond helium. This was realised less than 100 years ago by Cecilia Payne-Gaposchkin in her PhD thesis. The stellar composition contrasts the composition of Earth, where the inner core is mostly composed of iron and nickel, and the crust is dominated by oxygen and silicon. The human body on the other hand consists mostly of oxygen (by weight). Where did the elements come from and how were they formed? The simplest assumption is that they always have been there and do not change. That would immediately beg the question, why the abundances would be as disparate as they are? The evolution of abundances and the structure of the atoms indicate the build-up of larger and heavier atoms (Rudolf von Steiger, 2004, *Spatium* 13). In a first attempt by Gamow and his collaborators, all elements would have been built in the early, hot Universe. But atomic structure prevented the formation of stable elements with atomic numbers 5 or 8, and no elements heavier than lithium and boron could be formed. The early Universe produced, essentially, helium from hydrogen with very small additions of deuterium and lithium. Free neutrons decayed after the equilibrium between protons and neutrons was lifted, and the remaining neutrons were bound in helium nuclei. The ratio of helium to hydrogen is set by the balance of the neutron decay time, and when the helium nuclei can form. This all happened during the first three minutes of the Big Bang, and the helium to hydrogen ratio set then can still be observed today. The helium-3 nuclei from the Sun were first measured directly by the solar wind sail developed by Geiss and put up by the Apollo missions on the moon, confirming this picture beautifully.

Only refinements have been made to this general picture in the past decades. An accurate determination of the baryonic matter density in the early Universe through the CMB has significantly decreased the range of the allowable helium abundance. At the same time measurements of the deuterium abundance in distant gas clouds with the 8m and 10m telescopes on the ground have set severe constraints on the baryonic density. Overall, a consistent picture of Big Bang nucleosynthesis has emerged and strengthened considerably. However, the predicted and measured abundance of lithium, as measured in stars today, is significantly different from the CMB predictions. This "Lithium Problem" has been addressed in theoretical studies. A potential solution could be if there were more than three families of elementary particles, or a particle that changes the radiation field in the early Universe but does not interact with the rest of matter at later times. Potentially, we are missing a piece of physics here.

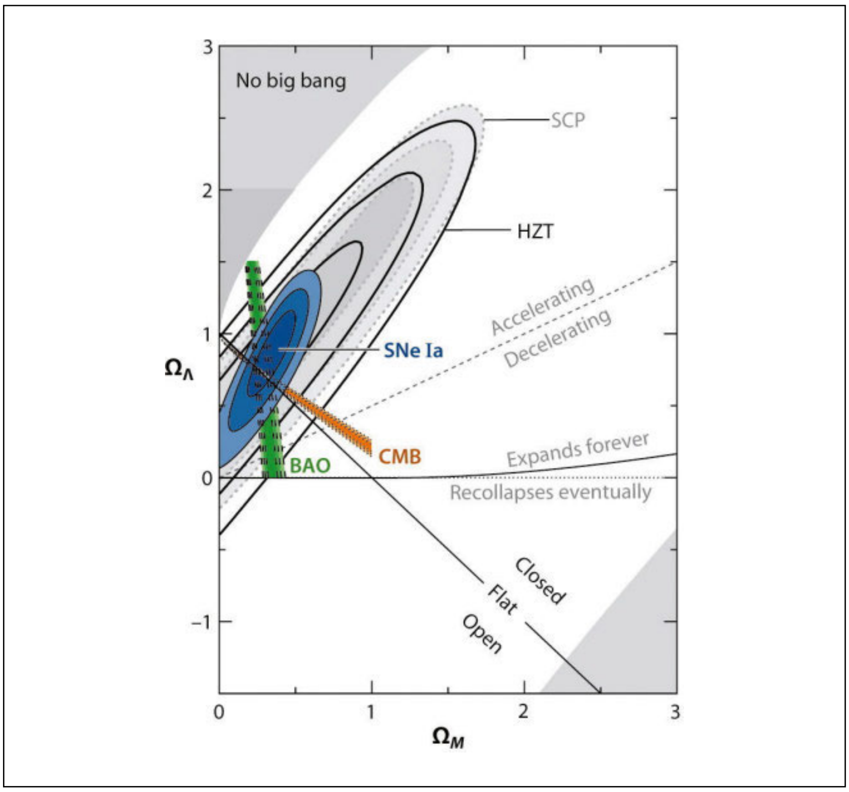


Figure 6: Combination of different observations pointing towards the "concordance" model (from Goobar and Leibundgut 2011). The contribution of the cosmological constant (Ω_Λ, ordinate) is plotted against the matter density (Ω_M, abscissa) for different measurement methods. The original likelihood regions from distant supernovae showing the accelerated expansion of the Universe are the grey contours (Supernova Cosmology Project) and dark ellipses (High-z Supernova Search Team). The modern supernova measurements are the blue contours. The possible solutions provided by the fluctuations in the cosmic microwave background are displayed as the orange region closely following solutions of flat models. A method to measure density fluctuations of the galaxy distribution (baryonic acoustic oscillations – BAO) is shown in green. The three measurements single out a unique region near ($\Omega_\Lambda \approx 0.7$ and $\Omega_M \approx 0.3$), which is consistent with ΛCDM.

A nearly perfect cosmological model

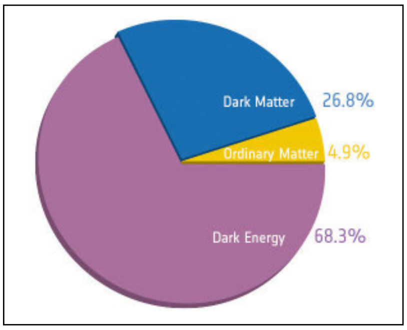
We have arrived at a rather complete view of the Universe today. The ΛCDM model connects the physics at our observing windows (first minutes, 350,000 years, and after one billion years until today) with only a few free parameters. It has been called a "concordance" model, because many disparate measurements converge to a small region of parameter space that fits (almost) all observations. The combination of the measurements of acceleration by supernovae (SNe Ia), curvature by the CMB and matter density through the observation of baryonic acoustic oscillations (BAO) leads to a unique set of allowed parameters **(figure 6)**. These measurements are completely independent of each other and use widely different tracers and methods (supernovae, microwave background, clusters of galaxies). This "concordance" model has become the currently most favoured description of the Universe and is encapsulated in the ΛCDM model.

The successes in cosmology have been celebrated in different forms. The Nobel Prizes in Physics have been awarded for cosmological topics over the years (1978 for the discovery of the CMB; 2006 for the COBE measurement of the black body and the fluctuations of the CMB; 2011 for the discovery of the accelerated cosmic expansion and 2019 for "theoretical discoveries of physical cosmology").

The concordance model has several appealing characteristics. The Universe has a flat geometry and a critical density, which seems to follow from an inflationary period in the Big Bang that also explains the fluctuations in the CMB. The various measurements independently single out a unique set of parameters, which now makes the Universe old enough to form the oldest known stars. The predictions for the cosmic abundance of deuterium and helium are a natural consequence of this model, and the growth of large-scale structure is easily explained with the composition of the density ingredients.

Yet it is clear that we have not reached the end of cosmological studies. There are important limitations of this model, which require future observations and refinements. A glaring problem is the lack of physical characterisation of most of the contents in this model.

Figure 7: Composition of the Universe. Not shown is the contribution of radiation, which is less than 0.00001. *(© ESA and the Planck Consortium)*



Dark matter and dark energy make up 95% of the energy content today **(figure 7)**, yet we do not have an explanation of what they are.

A new problem appeared in recent years with an apparent disagreement between the Hubble constant as derived from the CMB in the early Universe and the direct measurements today. Many different distance indicators have been employed to measure and check the local Hubble constant, and all point towards a value that is significantly larger than predicted by the ΛCDM model when calibrated by the CMB. It is at the moment unclear whether systematic uncertainties in the measurements or an incomplete (or wrong) model is the culprit. The "Hubble tension" has become the focus of most cosmological discussions today and a resolution may point towards "new" physics, if the differences between the early and the late Universe cannot be reconciled.

There are other discrepancies that may indicate deficiencies of the model. The measured normalisation of the matter density in the local Universe deviates from the predictions made by the CMB. The abundance of lithium from the Big Bang nucleosynthesis does not correspond to the model predictions and the growth of structure may still hold surprises when the new imaging and spectroscopic surveys have been analysed in the coming years.

Are these discrepancies due to limited accuracy of the measurements or do they point to deficiencies of the model? Are basic assumptions in the model inadequate or even wrong? It is currently not possible to give a definite answer to these questions.

How will cosmology look like 25 years from now? If the progress of the past 25 years is any indication, much improved observations of a large fraction of the accessible Universe will have challenged some of the current views. After all, nobody had predicted an accelerated expansion of the universe. In fact, it was against the accepted theory, although indications of a paradigm change were present as all measurements indicated a matter density too low for the favoured Einstein-de Sitter model. The tension between the dynamical age, the matter density and the expansion rate were used to predict a Hubble constant that was too small compared to all measurements (see **figure 3**). It was resolved by an observation that originally wanted to confirm the existing model and ultimately changed the paradigm that allowed only a decelerated expansion.

Cosmology is the attempt to construct a worldview based on the known laws of physics and the available observations. Clearly, progress is driven by the available data, and we are expecting an explosion of new measurements of the critical cosmological parameters in the coming decade. Several large survey facilities dedicated to cosmology have been in development for the past decade (Euclid satellite, Vera Cooper Rubin Observatory, Nancy Grace Roman Space Telescope) and will certainly change our view of the Universe. Another avenue is extensions to the physical laws, in particular our understanding of gravity. Other questions include whether we are actually observing a "typical" region of the Universe or whether we are confined to a special place. This questions the validity of the cosmological principle, which has some support through the smoothness of the CMB but requires further testing.

The answers will lie in the resolution of the current "tension" and new and improved observations. The field is vibrant and has attracted wide-spread interest. Many new missions and projects are under way to answer some of the outstanding questions.

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Prof. Dr. Bruno Leibundgut studied physics, astronomy, and mathematics from 1979 to 1983 at the University of Basel, where he obtained his PhD (supervised by G. A. Tammann) at the Astronomical Institute in 1989. After a brief post-doctoral stint there, he became a post-doctoral research associate, first at the Harvard-Smithsonian Center for Astrophysics, Cambridge Massachusetts, from 1989 to 1992, and later at the University of California, Berkeley, from 1992 to 1993. Since December 1993, he has been staff astronomer of the European Southern Observatory (ESO). He has held several positions within the ESO, starting with supporting the VLT Programme Scientist from 1995 to 1997 and as the head of the VLT Data Flow Groups from 1998 to 2001. During this period he contributed significantly to the development of the VLT operations. From 2001 to 2009, he led the Office for Science in Garching and Santiago de Chile and was the ESO Director for Science from 2008 to 2014. Since August 2014, he has been the VLT Programme Scientist. Prof. Leibundgut has researched extensively on supernova physics and cosmology and has been allocated observing time at the world's leading optical and infrared telescopes (VLT, HST, Keck, Gemini and 4m telescopes in the USA and Chile). He has published, as first author and co-author, about 140 refereed papers and is the co-editor of three books. As a member of the High-z Supernova Search Team he has received the Science Magazine Breakthrough of the Year (1998), the Gruber Cosmology Prize (2007), and the Breakthrough Prize in Fundamental Physics (2015). Since 2019, he has held an honorary professorship at the Physics Department of the Technical University Munich.