WIKIPEDIA

Inflation (cosmology)

In physical cosmology, **cosmic inflation**, **cosmological inflation**, or just **inflation**, is a theory of exponential expansion of space in the early universe. The inflationary epoch lasted from 10^{-36} seconds after the conjectured Big Bang singularity to some time between 10^{-33} and 10^{-32} seconds after the singularity. Following the inflationary period, the universe continued to expand, but at a slower rate. The acceleration of this expansion due to dark energy began after the universe was already over 9 billion years old (~4 billion years ago).[1]

Inflation theory was developed in the late 1970s and early 80s, with notable contributions by several theoretical physicists, including Alexei Starobinsky at Landau Institute for Theoretical Physics, Alan Guth at Cornell University, and Andrei Linde at Lebedev Physical Institute. Alexei Starobinsky, Alan Guth, and Andrei Linde won the 2014 Kavli Prize "for pioneering the theory of cosmic inflation."[2] It was developed further in the early 1980s. It explains the origin of the large-scale structure of the cosmos. Quantum fluctuations in the microscopic inflationary region, magnified to cosmic size, become the seeds for the growth of structure in the Universe (see galaxy formation and evolution and structure formation).[3] Many physicists also believe that inflation explains why the universe appears to be the same in all directions (isotropic), why the cosmic microwave background radiation is distributed evenly, why the universe is flat, and why no magnetic monopoles have been observed.

The detailed particle physics mechanism responsible for inflation is unknown. The basic inflationary paradigm is accepted by most physicists, as a number of inflation model predictions have been confirmed by observation;[4] however, a substantial minority of scientists dissent from this position.[5][6][7] The hypothetical field thought to be responsible for inflation is called the inflaton.[8]

In 2002 three of the original architects of the theory were recognized for their major contributions; physicists Alan Guth of M.I.T., Andrei Linde of Stanford, and Paul Steinhardt of Princeton shared the prestigious Dirac Prize "for development of the concept of inflation in cosmology".[9] In 2012 Alan Guth and Andrei Linde were awarded the Breakthrough Prize in Fundamental Physics for their invention and development of inflationary cosmology.[10]

Contents

Overview

Around 1930, Edwin Hubble discovered that light from remote galaxies was redshifted; the more remote, the more shifted. This was quickly interpreted as meaning galaxies were receding from Earth. If Earth is not in some special, privileged, central position in the universe, then it would mean all galaxies are moving apart, and the further away, the faster they are moving away. It is now understood that the universe is expanding, carrying the galaxies with it, and causing this observation. Many other observations agree, and also lead to the same conclusion. However, for many years it was not clear why or how the universe might be expanding, or what it might signify.

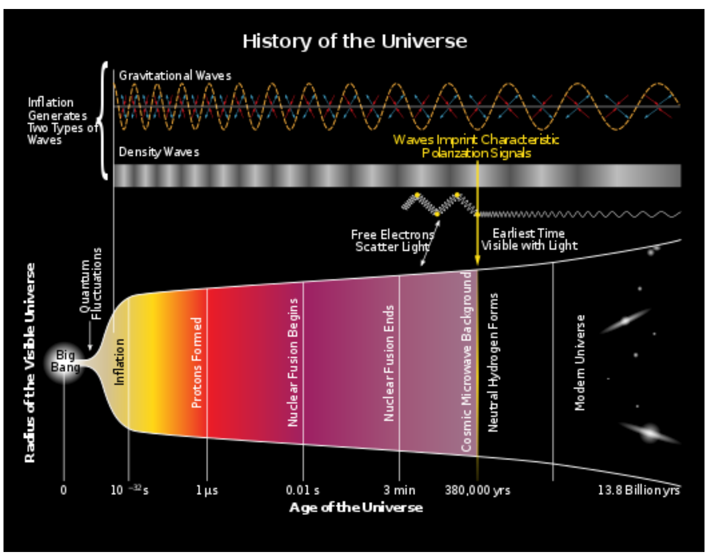
Based on a huge amount of experimental observation and theoretical work, it is now believed that the reason for the observation is that *space itself is expanding*, and that it expanded very rapidly within the first fraction of a second after the Big Bang. This kind of expansion is known as a *"metric"* expansion. In the terminology of mathematics and physics, a "metric" is a measure of distance that satisfies a specific list of properties, and the term implies that *the sense of distance within the universe is itself changing*, although at this time it is far too small an effect to see on less than an intergalactic scale.

The modern explanation for the metric expansion of space was proposed by physicist Alan Guth in 1979, while investigating the problem of why no magnetic monopoles are seen today. He found that if the universe contained a field in a positive-energy false vacuum state, then according to general relativity it would generate an exponential expansion of space. It was very quickly realized that such an expansion would resolve many other long-standing problems. These problems arise from the observation that to look like it does *today*, the Universe would have to have started from very finely tuned, or "special" initial conditions at the Big Bang. Inflation theory largely resolves these problems as well, thus making a universe like ours much more likely in the context of Big Bang theory.

No physical field has yet been discovered that is responsible for this inflation. However such a field would be scalar and the first relativistic scalar field proven to exist, the Higgs field, was only discovered in 2012–2013 and is still being researched. So it is not seen as problematic that a field responsible for cosmic inflation and the metric expansion of space has not yet been discovered. The proposed field and its quanta (the subatomic particles related to it) have been named the inflaton. If this field did not exist, scientists would have to propose a different explanation for all the observations that strongly suggest a metric expansion of space has occurred, and is still occurring (much more slowly) today.

Theory

An expanding universe generally has a cosmological horizon, which, by analogy with the more familiar horizon caused by the curvature of Earth's surface, marks the boundary of the part of the Universe that an observer can see. Light (or other radiation) emitted by objects beyond the cosmological horizon in an accelerating universe never reaches the observer, because the space in between the observer and the object is expanding too rapidly.



History of the Universe – gravitational waves are hypothesized to arise from cosmic inflation, a faster-than-light expansion just after the Big Bang (17 March 2014).[11][12][13]

The observable universe is one *causal patch* of a much larger unobservable universe; other parts of the Universe cannot communicate with Earth yet. These parts of the Universe are outside our current cosmological horizon. In the standard hot big bang model, without inflation, the cosmological horizon moves out, bringing new regions into view.[14] Yet as a local observer sees such a region for the first time, it looks no different from any other region of space the local observer has already seen: its background radiation is at nearly the same temperature as the background radiation of other regions, and its space-time curvature is evolving lock-step with the others. This presents a mystery: how did these new regions know what temperature and curvature they were supposed to have? They couldn't have learned it by getting signals, because they were not previously in communication with our past light cone.[15][16]

Inflation answers this question by postulating that all the regions come from an earlier era with a big vacuum energy, or cosmological constant. A space with a cosmological constant is qualitatively different: instead of moving outward, the cosmological horizon stays put. For any one observer, the distance to the cosmological horizon is constant. With exponentially expanding space, two nearby observers are separated very quickly; so much so, that the distance between them quickly exceeds the limits of communications. The spatial slices are expanding very fast to cover huge volumes. Things are constantly moving beyond the cosmological horizon, which is a fixed distance away, and everything becomes homogeneous.

As the inflationary field slowly relaxes to the vacuum, the cosmological constant goes to zero and space begins to expand normally. The new regions that come into view during the normal expansion phase are exactly the same regions that were pushed out of the horizon during inflation, and so they are at nearly the same temperature and curvature, because they come from the same originally small patch of space.

The theory of inflation thus explains why the temperatures and curvatures of different regions are so nearly equal. It also predicts that the total curvature of a space-slice at constant global time is zero. This prediction implies that the total ordinary matter, dark matter and residual vacuum energy in the Universe have to add up to the critical density, and the evidence supports this. More strikingly, inflation allows physicists to calculate the minute differences in temperature of different regions from quantum fluctuations during the inflationary era, and many of these quantitative predictions have been confirmed.[17][18]

Space expands

In a space that expands exponentially (or nearly exponentially) with time, any pair of free-floating objects that are initially at rest will move apart from each other at an accelerating rate, at least as long as they are not bound together by any force. From the point of view of one such object, the spacetime is something like an inside-out Schwarzschild black hole—each object is surrounded by a spherical event horizon. Once the other object has fallen through this horizon it can never return, and even light signals it sends will never reach the first object (at least so long as the space continues to expand exponentially).

In the approximation that the expansion is exactly exponential, the horizon is static and remains a fixed physical distance away. This patch of an inflating universe can be described by the following metric:[19][20]

$$ds^2 = -(1 - \Lambda r^2)\, dt^2 + \frac{1}{1 - \Lambda r^2}\, dr^2 + r^2\, d\Omega^2.$$

This exponentially expanding spacetime is called a de Sitter space, and to sustain it there must be a cosmological constant, a vacuum energy density that is constant in space and time and proportional to Λ in the above metric. For the case of exactly exponential expansion, the vacuum energy has a negative pressure p equal in magnitude to its energy density ρ; the equation of state is $p=-\rho$.

Inflation is typically not an exactly exponential expansion, but rather quasi- or near-exponential. In such a universe the horizon will slowly grow with time as the vacuum energy density gradually decreases.

Few inhomogeneities remain

Because the accelerating expansion of space stretches out any initial variations in density or temperature to very large length scales, an essential feature of inflation is that it smooths out inhomogeneities and anisotropies, and reduces the curvature of space. This pushes the Universe into a very simple state in which it is completely dominated by the inflaton field and the only significant inhomogeneities are tiny quantum fluctuations. Inflation also dilutes exotic heavy particles, such as the magnetic monopoles predicted by many extensions to the Standard Model of particle physics. If the Universe was only hot enough to form such particles *before* a period of inflation, they would not be observed in nature, as they would be so rare that it is quite likely that there are none in the observable universe. Together, these effects are called the inflationary "no-hair theorem"[21] by analogy with the no hair theorem for black holes.

The "no-hair" theorem works essentially because the cosmological horizon is no different from a black-hole horizon, except for philosophical disagreements about what is on the other side. The interpretation of the no-hair theorem is that the Universe (observable and unobservable) expands by an enormous factor during inflation. In an expanding universe, energy densities generally fall, or get diluted, as the volume of the Universe increases. For example, the density of ordinary "cold" matter (dust) goes down as the inverse of the volume: when linear dimensions double, the energy density goes down by a factor of eight; the radiation energy density goes down even more rapidly as the Universe expands since the wavelength of each photon is stretched (redshifted), in addition to the photons being dispersed by the expansion. When linear dimensions are doubled, the energy density in radiation falls by a factor of sixteen (see the solution of the energy density continuity equation for an ultra-relativistic fluid). During inflation, the energy density in the inflaton field is roughly constant. However, the energy density in everything else, including inhomogeneities, curvature, anisotropies, exotic particles, and standard-model particles is falling, and through sufficient inflation these all become negligible. This leaves the Universe flat and symmetric, and (apart from the homogeneous inflaton field) mostly empty, at the moment inflation ends and reheating begins.[22]

Duration

A key requirement is that inflation must continue long enough to produce the present observable universe from a single, small inflationary Hubble volume. This is necessary to ensure that the Universe appears flat, homogeneous and isotropic at the largest observable scales. This requirement is generally thought to be satisfied if the Universe expanded by a factor of at least 10^{26} during inflation.[23]

Reheating

Inflation is a period of supercooled expansion, when the temperature drops by a factor of 100,000 or so. (The exact drop is model-dependent, but in the first models it was typically from 10^{27} K down to 10^{22} K.[24]) This relatively low temperature is maintained during the inflationary phase. When inflation ends the temperature returns to the pre-inflationary temperature; this is called *reheating* or thermalization because the large potential energy of the inflaton field decays into particles and fills the Universe with Standard Model particles, including electromagnetic radiation, starting the radiation dominated phase of the Universe. Because the nature of the inflation is not known, this process is still poorly understood, although it is believed to take place through a parametric resonance.[25][26]

Motivations

Inflation resolves several problems in Big Bang cosmology that were discovered in the 1970s.[27] Inflation was first proposed by Alan Guth in 1979 while investigating the problem of why no magnetic monopoles are seen today; he found that a positive-energy false vacuum would, according to general relativity, generate an exponential expansion of space. It was very quickly realised that such an expansion would resolve many other long-standing problems. These problems arise from the observation that to look like it does *today*, the Universe would have to have started from very finely tuned, or "special" initial conditions at the Big Bang. Inflation attempts to resolve these problems by providing a dynamical mechanism that drives the Universe to this special state, thus making a universe like ours much more likely in the context of the Big Bang theory.

Horizon problem

The horizon problem is the problem of determining why the Universe appears statistically homogeneous and isotropic in accordance with the cosmological principle.[28][29][30] For example, molecules in a canister of gas are distributed homogeneously and isotropically because they are in thermal equilibrium: gas throughout the canister has had enough time to interact to dissipate inhomogeneities and anisotropies. The situation is quite different in the big bang model without inflation, because gravitational expansion does not give the early universe enough time to equilibrate. In a big bang with only the matter and radiation known in the Standard Model, two widely separated regions of the observable universe cannot have equilibrated because they move apart from each other faster than the speed of light and thus have never come into causal contact. In the early Universe, it was not possible to send a light signal between the two regions. Because they have had no interaction, it is difficult to explain why they have the same temperature (are thermally equilibrated). Historically, proposed solutions included the *Phoenix universe* of Georges Lemaître,[31] the related oscillatory universe of Richard Chase Tolman,[32] and the Mixmaster universe of Charles Misner. Lemaître and Tolman proposed that a universe undergoing a number of cycles of contraction and expansion could come into thermal equilibrium. Their models failed, however, because of the buildup of entropy over several cycles. Misner made the (ultimately incorrect) conjecture that the Mixmaster mechanism, which made the Universe *more* chaotic, could lead to statistical homogeneity and isotropy.[29][33]

Flatness problem

The flatness problem is sometimes called one of the Dicke coincidences (along with the cosmological constant problem).[34][35] It became known in the 1960s that the density of matter in the Universe was comparable to the critical density necessary for a flat universe (that is, a universe whose large scale geometry is the usual Euclidean geometry, rather than a non-Euclidean hyperbolic or spherical geometry).[36]:61

Therefore, regardless of the shape of the universe the contribution of spatial curvature to the expansion of the Universe could not be much greater than the contribution of matter. But as the Universe expands, the curvature redshifts away more slowly than matter and radiation. Extrapolated into the past, this presents a fine-tuning problem because the contribution of curvature to the Universe must be exponentially small (sixteen orders of magnitude less than the density of radiation at Big Bang nucleosynthesis, for example). This problem is exacerbated by recent observations of the cosmic microwave background that have demonstrated that the Universe is flat to within a few percent.[37]

Magnetic-monopole problem

The magnetic monopole problem, sometimes called the exotic-relics problem, says that if the early universe were very hot, a large number of very heavy, stable magnetic monopoles would have been produced. This is a problem with Grand Unified Theories, which propose that at high temperatures (such as in the early universe) the electromagnetic force, strong, and weak nuclear forces are not actually fundamental forces but arise due to spontaneous symmetry breaking from a single gauge theory.[38] These theories predict a number of heavy, stable particles that have not been observed in nature. The most notorious is the magnetic monopole, a kind of stable, heavy "charge" of magnetic field.[39][40] Monopoles are predicted to be copiously produced following Grand Unified Theories at high temperature,[41][42] and they should have persisted to the present day, to such an extent that they would become the primary constituent of the Universe.[43][44] Not only is that not the case, but all searches for them have failed, placing stringent limits on the density of relic magnetic monopoles in the Universe.[45] A period of inflation that occurs below the temperature where magnetic monopoles can be produced would offer a possible resolution of this problem: monopoles would be separated from each other as the Universe around them expands, potentially lowering their observed density by many orders of magnitude. Though, as cosmologist Martin Rees has written, "Skeptics about exotic physics might not be hugely impressed by a theoretical argument to explain the absence of particles that are themselves only hypothetical. Preventive medicine can readily seem 100 percent effective against a disease that doesn't exist!"[46]

History

Precursors

In the early days of General Relativity, Albert Einstein introduced the cosmological constant to allow a static solution, which was a three-dimensional sphere with a uniform density of matter. Later, Willem de Sitter found a highly symmetric inflating universe, which described a universe with a cosmological constant that is otherwise empty.[47] It was discovered that Einstein's universe is unstable, and that small fluctuations cause it to collapse or turn into a de Sitter universe.

In the early 1970s Zeldovich noticed the flatness and horizon problems of Big Bang cosmology; before his work, cosmology was presumed to be symmetrical on purely philosophical grounds. In the Soviet Union, this and other considerations led Belinski and Khalatnikov to analyze the chaotic BKL singularity in General Relativity. Misner's Mixmaster universe attempted to use this chaotic behavior to solve the cosmological problems, with limited success.

False vacuum

In the late 1970s, Sidney Coleman applied the instanton techniques developed by Alexander Polyakov and collaborators to study the fate of the false vacuum in quantum field theory. Like a metastable phase in statistical mechanics—water below the freezing temperature or above the boiling point—a quantum field would need to nucleate a large enough bubble of the new vacuum, the new phase, in order to make a transition. Coleman found the most likely decay pathway for vacuum decay and calculated the inverse lifetime per unit volume. He eventually noted that gravitational effects would be significant, but he did not calculate these effects and did not apply the results to cosmology.

Starobinsky inflation

In the Soviet Union, Alexei Starobinsky noted that quantum corrections to general relativity should be important for the early universe. These generically lead to curvature-squared corrections to the Einstein–Hilbert action and a form of $f(R)$ modified gravity. The solution to Einstein's equations in the presence of curvature squared terms, when the curvatures are large, leads to an effective cosmological constant. Therefore, he proposed that the early universe went through an inflationary de Sitter era.[48]

This resolved the cosmology problems and led to specific predictions for the corrections to the microwave background radiation, corrections that were then calculated in detail. Starobinsky used the action

$$S = \frac{1}{2} \int d^4x \left(R + \frac{R^2}{6M^2} \right)$$

which corresponds to the potential

$$V(\phi) = \Lambda^4 \left(1 - e^{-\sqrt{2/3}\phi/M_p^2} \right)^2$$

in the Einstein frame. This results in the observables: $n_s = 1 - \frac{2}{N}, \qquad r = \frac{12}{N^2}$.[49]

Monopole problem

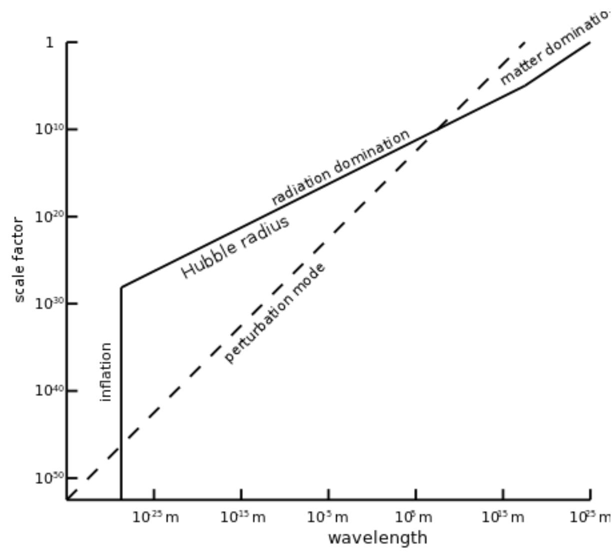
In 1978, Zeldovich noted the monopole problem, which was an unambiguous quantitative version of the horizon problem, this time in a subfield of particle physics, which led to several speculative attempts to resolve it. In 1980 Alan Guth realized that false vacuum decay in the early universe would solve the problem, leading him to propose a scalar-driven inflation. Starobinsky's and Guth's scenarios both predicted an initial de Sitter phase, differing only in mechanistic details.

Early inflationary models

Guth proposed inflation in January 1981 to explain the nonexistence of magnetic monopoles;[50][51] it was Guth who coined the term "inflation".[52] At the same time, Starobinsky argued that quantum corrections to gravity would replace the initial singularity of the Universe with an exponentially expanding de Sitter phase.[53] In October 1980, Demosthenes Kazanas suggested that exponential expansion could eliminate the particle horizon and perhaps solve the horizon problem,[54][55] while Sato suggested that an exponential expansion could eliminate domain walls (another kind of exotic relic).[56] In 1981 Einhorn and Sato[57] published a model similar to Guth's and showed that it would resolve the puzzle of the magnetic monopole abundance in Grand Unified Theories. Like Guth, they concluded that such a model not only required fine tuning of the cosmological constant, but also would likely lead to a much too granular universe, i.e., to large density variations resulting from bubble wall collisions.

Guth proposed that as the early universe cooled, it was trapped in a false vacuum with a high energy density, which is much like a cosmological constant. As the very early universe cooled it was trapped in a metastable state (it was supercooled), which it could only decay out of through the process of bubble nucleation via quantum tunneling. Bubbles of true vacuum spontaneously form in the sea of false vacuum and rapidly begin expanding at the speed of light. Guth recognized that this model was problematic because the model did not reheat properly: when the bubbles nucleated, they did not generate any radiation. Radiation could only be generated in collisions between bubble walls. But if inflation lasted long enough to solve the initial conditions problems, collisions between bubbles became exceedingly rare. In any one causal patch it is likely that only one bubble would nucleate.

> ... Kazanas (1980) called this phase of the early Universe "de Sitter's phase." The name "inflation" was given by Guth (1981). ... Guth himself did not refer to work of Kazanas until he published a book on the subject under the title "The inflationary universe: the quest for a new theory of cosmic origin" (1997), where he apologizes for not having referenced the work of Kazanas and of others, related to inflation.[58]



The physical size of the Hubble radius (solid line) as a function of the linear expansion (scale factor) of the universe. During cosmological inflation, the Hubble radius is constant. The physical wavelength of a perturbation mode (dashed line) is also shown. The plot illustrates how the perturbation mode grows larger than the horizon during cosmological inflation before coming back inside the horizon, which grows rapidly during radiation domination. If cosmological inflation had never happened, and radiation domination continued back until a gravitational singularity, then the mode would never have been inside the horizon in the very early universe, and no causal mechanism could have ensured that the universe was homogeneous on the scale of the perturbation mode.

Slow-roll inflation

The bubble collision problem was solved by Linde[59] and independently by Andreas Albrecht and Paul Steinhardt[60] in a model named *new inflation* or *slow-roll inflation* (Guth's model then became known as *old inflation*). In this model, instead of tunneling out of a false vacuum state, inflation occurred by a scalar field rolling down a potential energy hill. When the field rolls very slowly compared to the expansion of the Universe, inflation occurs. However, when the hill becomes steeper, inflation ends and reheating can occur.

Effects of asymmetries

Eventually, it was shown that new inflation does not produce a perfectly symmetric universe, but that quantum fluctuations in the inflaton are created. These fluctuations form the primordial seeds for all structure created in the later universe.[61] These fluctuations were first calculated by Viatcheslav Mukhanov and G. V. Chibisov in analyzing Starobinsky's similar model.[62][63][64] In the context of inflation, they were worked out independently of the work of Mukhanov and Chibisov at the three-week 1982 Nuffield Workshop on the Very Early Universe at Cambridge University.[65] The fluctuations were calculated by four groups working separately over the course of the workshop: Stephen Hawking;[66] Starobinsky;[67] Guth and So-Young Pi;[68] and Bardeen, Steinhardt and Turner.[69]

Observational status

Inflation is a mechanism for realizing the cosmological principle, which is the basis of the standard model of physical cosmology: it accounts for the homogeneity and isotropy of the observable universe. In addition, it accounts for the observed flatness and absence of magnetic monopoles. Since Guth's early work, each of these observations has received further confirmation, most impressively by the detailed observations of the cosmic microwave background made by the Planck spacecraft.[70] This analysis shows that the Universe is flat to within 0.5 percent, and that it is homogeneous and isotropic to one part in 100,000.

Inflation predicts that the structures visible in the Universe today formed through the gravitational collapse of perturbations that were formed as quantum mechanical fluctuations in the inflationary epoch. The detailed form of the spectrum of perturbations, called a nearly-scale-invariant Gaussian random field is very specific and has only two free parameters. One is the amplitude of the spectrum and the *spectral index*, which measures the slight deviation from scale invariance predicted by inflation (perfect scale invariance corresponds to the idealized de Sitter universe).[71] The other free parameter is the tensor to scalar ratio. The simplest inflation models, those without fine-tuning, predict a tensor to scalar ratio near 0.1.[72]

Inflation predicts that the observed perturbations should be in thermal equilibrium with each other (these are called *adiabatic* or *isentropic* perturbations). This structure for the perturbations has been confirmed by the Planck spacecraft, WMAP spacecraft and other cosmic microwave background (CMB) experiments, and galaxy surveys, especially the ongoing Sloan Digital Sky Survey.[73] These experiments have shown that the one part in 100,000 inhomogeneities observed have exactly the form predicted by theory. There is evidence for a slight deviation from scale invariance. The *spectral index*, n_s is one for a scale-invariant Harrison–Zel'dovich spectrum. The simplest inflation models predict that n_s is between 0.92 and 0.98.[74][72][75][76] This is the range that is possible without fine-tuning of the parameters related to energy.[75] From Planck data it can be inferred that n_s=0.968 ± 0.006,[70][77] and a tensor to scalar ratio that is less than 0.11. These are considered an important confirmation of the theory of inflation.[17]

Various inflation theories have been proposed that make radically different predictions, but they generally have much more fine tuning than should be necessary.[74][72] As a physical model, however, inflation is most valuable in that it robustly predicts the initial conditions of the Universe based on only two adjustable parameters: the spectral index (that can only change in a small range) and the amplitude of the perturbations. Except in contrived models, this is true regardless of how inflation is realized in particle physics.

Occasionally, effects are observed that appear to contradict the simplest models of inflation. The first-year WMAP data suggested that the spectrum might not be nearly scale-invariant, but might instead have a slight curvature.[78] However, the third-year data revealed that the effect was a statistical anomaly.[17] Another effect remarked upon since the first cosmic microwave background satellite, the Cosmic Background Explorer is that the amplitude of the quadrupole moment of the CMB is unexpectedly low and the other low multipoles appear to be preferentially aligned with the ecliptic plane. Some have claimed that this is a signature of non-Gaussianity and thus contradicts the simplest models of inflation. Others have suggested that the effect may be due to other new physics, foreground contamination, or even publication bias.[79]

An experimental program is underway to further test inflation with more precise CMB measurements. In particular, high precision measurements of the so-called "B-modes" of the polarization of the background radiation could provide evidence of the gravitational radiation produced by inflation, and could also show whether the energy scale of inflation predicted by the simplest models (10^{15}–10^{16} GeV) is correct.[72][75] In March 2014, the BICEP2 team announced B-mode CMB polarization confirming inflation had been demonstrated. The team announced the tensor-to-scalar power ratio r was between 0.15 and 0.27 (rejecting the null hypothesis; r is expected to be 0 in the absence of inflation).[80] However, on 19 June 2014, lowered confidence in confirming the findings was reported;[81][82][83] on 19 September 2014, a further reduction in confidence was reported[84][85] and, on 30 January 2015, even less confidence yet was reported.[86][87] By 2018, additional data suggested, with 95% confidence, that r is 0.06 or lower: consistent with the null hypothesis, but still also consistent with many remaining models of inflation.[80]

Other potentially corroborating measurements are expected from the Planck spacecraft, although it is unclear if the signal will be visible, or if contamination from foreground sources will interfere.[88] Other forthcoming measurements, such as those of 21 centimeter radiation (radiation emitted and absorbed from neutral hydrogen before the first stars formed), may measure the power spectrum with even greater resolution than the CMB and galaxy surveys, although it is not known if these measurements will be possible or if interference with radio sources on Earth and in the galaxy will be too great.[89]

Theoretical status

Unsolved problem in physics:

? *Is the theory of cosmological inflation correct, and if so, what are the details of this epoch? What is the hypothetical inflaton field giving rise to inflation?*

(more unsolved problems in physics)

In Guth's early proposal, it was thought that the inflaton was the Higgs field, the field that explains the mass of the elementary particles.[51] It is now believed by some that the inflaton cannot be the Higgs field[90] although the recent discovery of the Higgs boson has increased the number of works considering the Higgs field as inflaton.[91] One problem of this identification is the current tension with experimental data at the electroweak scale,[92] which is currently under study at the Large Hadron Collider (LHC). Other models of inflation relied on the properties of Grand Unified Theories.[60] Since the simplest models of grand unification have failed, it is now thought by many physicists that inflation will be included in a supersymmetric theory such as string theory or a supersymmetric grand unified theory. At present, while inflation is understood principally by its detailed predictions of the initial conditions for the hot early universe, the particle physics is largely *ad hoc* modelling. As such, although predictions of inflation have been consistent with the results of observational tests, many open questions remain.

Fine-tuning problem

One of the most severe challenges for inflation arises from the need for fine tuning. In new inflation, the *slow-roll conditions* must be satisfied for inflation to occur. The slow-roll conditions say that the inflaton potential must be flat (compared to the large vacuum energy) and that the inflaton particles must have a small mass.[93] New inflation requires the Universe to have a scalar field with an especially flat potential and special initial conditions. However, explanations for these fine-tunings have been proposed. For example, classically scale invariant field theories, where scale invariance is broken by quantum effects, provide an explanation of the flatness of inflationary potentials, as long as the theory can be studied through perturbation theory.[94]

Linde proposed a theory known as *chaotic inflation* in which he suggested that the conditions for inflation were actually satisfied quite generically. Inflation will occur in virtually any universe that begins in a chaotic, high energy state that has a scalar field with unbounded potential energy.[95] However, in his model the inflaton field necessarily takes values larger than one Planck unit: for this reason, these are often called *large field* models and the competing new inflation models are called *small field* models. In this situation, the predictions of effective field theory are thought to be invalid, as renormalization should cause large corrections that could prevent inflation.[96] This problem has not yet been resolved and some cosmologists argue that the small field models, in which inflation can occur at a much lower energy scale, are better models.[97] While inflation depends on quantum field theory (and the semiclassical approximation to quantum gravity) in an important way, it has not been completely reconciled with these theories.

Brandenberger commented on fine-tuning in another situation.[98] The amplitude of the primordial inhomogeneities produced in inflation is directly tied to the energy scale of inflation. This scale is suggested to be around 10^{16} GeV or 10^{-3} times the Planck energy. The natural scale is naïvely the Planck scale so this small value could be seen as another form of fine-tuning (called a hierarchy problem): the energy density given by the scalar potential is down by 10^{-12} compared to the Planck density. This is not usually considered to be a critical problem, however, because the scale of inflation corresponds naturally to the scale of gauge unification.

Eternal inflation

In many models, the inflationary phase of the Universe's expansion lasts forever in at least some regions of the Universe. This occurs because inflating regions expand very rapidly, reproducing themselves. Unless the rate of decay to the non-inflating phase is sufficiently fast, new inflating regions are produced more rapidly than non-inflating regions. In such models, most of the volume of the Universe is continuously inflating at any given time.

All models of eternal inflation produce an infinite, hypothetical multiverse, typically a fractal. The multiverse theory has created significant dissension in the scientific community about the viability of the inflationary model.

Paul Steinhardt, one of the original architects of the inflationary model, introduced the first example of eternal inflation in 1983.[99] He showed that the inflation could proceed forever by producing bubbles of non-inflating space filled with hot matter and radiation surrounded by empty space that continues to inflate. The bubbles could not grow fast enough to keep up with the inflation. Later that same year, Alexander Vilenkin showed that eternal inflation is generic.[100]

Although new inflation is classically rolling down the potential, quantum fluctuations can sometimes lift it to previous levels. These regions in which the inflaton fluctuates upwards expand much faster than regions in which the inflaton has a lower potential energy, and tend to dominate in terms of physical volume. It has been shown that any inflationary theory with an unbounded potential is eternal. There are well-known theorems that this steady state cannot continue forever into the past. Inflationary spacetime, which is similar to de Sitter space, is incomplete without a contracting region. However, unlike de Sitter space, fluctuations in a contracting inflationary space collapse to form a gravitational singularity, a point where densities become infinite. Therefore, it is necessary to have a theory for the Universe's initial conditions.

In eternal inflation, regions with inflation have an exponentially growing volume, while regions that are not inflating don't. This suggests that the volume of the inflating part of the Universe in the global picture is always unimaginably larger than the part that has stopped inflating, even though inflation eventually ends as seen by any single pre-inflationary observer. Scientists disagree about how to assign a probability distribution to this hypothetical anthropic landscape. If the probability of different regions is counted by volume, one should expect that inflation will never end or applying boundary conditions that a local observer exists to observe it, that inflation will end as late as possible.

Some physicists believe this paradox can be resolved by weighting observers by their pre-inflationary volume. Others believe that there is no resolution to the paradox and that the multiverse is a critical flaw in the inflationary paradigm. Paul Steinhardt, who first introduced the eternal inflationary model,[99] later became one of its most vocal critics for this reason.[101][102][103]

Initial conditions

Some physicists have tried to avoid the initial conditions problem by proposing models for an eternally inflating universe with no origin.[104][105][106][107] These models propose that while the Universe, on the largest scales, expands exponentially it was, is and always will be, spatially infinite and has existed, and will exist, forever.

Other proposals attempt to describe the ex nihilo creation of the Universe based on quantum cosmology and the following inflation. Vilenkin put forth one such scenario.[100] Hartle and Hawking offered the no-boundary proposal for the initial creation of the Universe in which inflation comes about naturally.[108][109][110][111]

Guth described the inflationary universe as the "ultimate free lunch":[112][113] new universes, similar to our own, are continually produced in a vast inflating background. Gravitational interactions, in this case, circumvent (but do not violate) the first law of thermodynamics (energy conservation) and the second law of thermodynamics (entropy and the arrow of time problem). However, while there is consensus that this solves the initial conditions problem, some have disputed this, as it is much more likely that the Universe came about by a quantum fluctuation. Don Page was an outspoken critic of inflation because of this anomaly.[114] He stressed that the thermodynamic arrow of time necessitates low entropy initial conditions, which would be highly unlikely. According to them, rather than solving this problem, the inflation theory aggravates it – the reheating at the end of the inflation era increases entropy, making it necessary for the initial state of the Universe to be even more orderly than in other Big Bang theories with no inflation phase.

Hawking and Page later found ambiguous results when they attempted to compute the probability of inflation in the Hartle-Hawking initial state.[115] Other authors have argued that, since inflation is eternal, the probability doesn't matter as long as it is not precisely zero: once it starts, inflation perpetuates itself and quickly dominates the Universe.[5][116]:223–225 However, Albrecht and Lorenzo Sorbo argued that the probability of an inflationary cosmos, consistent with today's observations, emerging by a random fluctuation from some pre-existent state is much higher than that of a non-inflationary cosmos. This is because the "seed" amount of non-gravitational energy required for the inflationary cosmos is so much less than that for a non-inflationary alternative, which outweighs any entropic considerations.[117]

Another problem that has occasionally been mentioned is the trans-Planckian problem or trans-Planckian effects.[118] Since the energy scale of inflation and the Planck scale are relatively close, some of the quantum fluctuations that have made up the structure in our universe were smaller than the Planck length before inflation. Therefore, there ought to be corrections from Planck-scale physics, in particular the unknown quantum theory of gravity. Some disagreement remains about the magnitude of this effect: about whether it is just on the threshold of detectability or completely undetectable.[119]

Hybrid inflation

Another kind of inflation, called *hybrid inflation*, is an extension of new inflation. It introduces additional scalar fields, so that while one of the scalar fields is responsible for normal slow roll inflation, another triggers the end of inflation: when inflation has continued for sufficiently long, it becomes favorable to the second field to decay into a much lower energy state.[120]

In hybrid inflation, one scalar field is responsible for most of the energy density (thus determining the rate of expansion), while another is responsible for the slow roll (thus determining the period of inflation and its termination). Thus fluctuations in the former inflaton would not affect inflation termination, while fluctuations in the latter would not affect the rate of expansion. Therefore, hybrid inflation is not eternal.[121][122] When the second (slow-rolling) inflaton reaches the bottom of its potential, it changes the location of the minimum of the first inflaton's potential, which leads to a fast roll of the inflaton down its potential, leading to termination of inflation.

Relation to dark energy

Dark energy is broadly similar to inflation and is thought to be causing the expansion of the present-day universe to accelerate. However, the energy scale of dark energy is much lower, 10^{-12} GeV, roughly 27 orders of magnitude less than the scale of inflation.

Inflation and string cosmology

The discovery of flux compactifications opened the way for reconciling inflation and string theory.[123] *Brane inflation* suggests that inflation arises from the motion of D-branes[124] in the compactified geometry, usually towards a stack of anti-D-branes. This theory, governed by the *Dirac-Born-Infeld action*, is different from ordinary inflation. The dynamics are not completely understood. It appears that special conditions are necessary since inflation occurs in tunneling between two vacua in the string landscape. The process of tunneling between two vacua is a form of old inflation, but new inflation must then occur by some other mechanism.

Inflation and loop quantum gravity

When investigating the effects the theory of loop quantum gravity would have on cosmology, a loop quantum cosmology model has evolved that provides a possible mechanism for cosmological inflation. Loop quantum gravity assumes a quantized spacetime. If the energy density is larger than can be held by the quantized spacetime, it is thought to bounce back.[125]

Alternatives/adjuncts

Other models explain some of the observations explained by inflation. However none of these "alternatives" has the same breadth of explanation and still require inflation for a more complete fit with observation. They should therefore be regarded as adjuncts to inflation, rather than as alternatives.

Big bounce

The big bounce hypothesis attempts to replace the cosmic singularity with a cosmic contraction and bounce, thereby explaining the initial conditions that led to the big bang.[126] The flatness and horizon problems are naturally solved in the Einstein-Cartan-Sciama-Kibble theory of gravity, without needing an exotic form of matter or free parameters.[127][128] This theory extends general relativity by removing a constraint of the symmetry of the affine connection and regarding its antisymmetric part, the torsion tensor, as a dynamical variable. The minimal coupling between torsion and Dirac spinors generates a spin-spin interaction that is significant in fermionic matter at extremely high densities. Such an interaction averts the unphysical Big Bang singularity, replacing it with a cusp-like bounce at a finite minimum scale factor, before which the Universe was contracting. The rapid expansion immediately after the Big Bounce explains why the present Universe at largest scales appears spatially flat, homogeneous and isotropic. As the density of the Universe decreases, the effects of torsion weaken and the Universe smoothly enters the radiation-dominated era.

Ekpyrotic and cyclic models

The ekpyrotic and cyclic models are also considered adjuncts to inflation. These models solve the horizon problem through an expanding epoch well *before* the Big Bang, and then generate the required spectrum of primordial density perturbations during a contracting phase leading to a Big Crunch. The Universe passes through the Big Crunch and emerges in a hot Big Bang phase. In this sense they are reminiscent of Richard Chace Tolman's oscillatory universe; in Tolman's model, however, the total age of the Universe is necessarily finite, while in these models this is not necessarily so. Whether the correct spectrum of density fluctuations can be produced, and whether the Universe can successfully navigate the Big Bang/Big Crunch transition, remains a topic of controversy and current research. Ekpyrotic models avoid the magnetic monopole problem as long as the temperature at the Big Crunch/Big Bang transition remains below the Grand Unified Scale, as this is the temperature required to produce magnetic monopoles in the first place. As things stand, there is no evidence of any 'slowing down' of the expansion, but this is not surprising as each cycle is expected to last on the order of a trillion years.

Varying *c*

Another adjunct, the varying speed of light model was offered by Jean-Pierre Petit in 1988,[129][130][131][132] John Moffat in 1992,[133] and the two-man team of Andreas Albrecht and João Magueijo in 1998.[134][135][136][137][138][139] Instead of superluminal expansion the speed of light was 60 orders of magnitude faster than its current value solving the horizon and homogeneity problems in the early universe.

String gas cosmology

String theory requires that, in addition to the three observable spatial dimensions, additional dimensions exist that are curled up or compactified (see also Kaluza–Klein theory). Extra dimensions appear as a frequent component of supergravity models and other approaches to quantum gravity. This raised the contingent question of why four space-time dimensions became large and the rest became unobservably small. An attempt to address this question, called *string gas cosmology*, was proposed by Robert Brandenberger and Cumrun Vafa.[140] This model focuses on the dynamics of the early universe considered as a hot gas of strings. Brandenberger and Vafa show that a dimension of spacetime can only expand if the strings that wind around it can efficiently annihilate each other. Each string is a one-dimensional object, and the largest number of dimensions in which two strings will generically intersect (and, presumably, annihilate) is three. Therefore, the most likely number of non-compact (large) spatial dimensions is three. Current work on this model centers on whether it can succeed in stabilizing the size of the compactified dimensions and produce the correct spectrum of primordial density perturbations.[141] Supporters admit that their model "does not solve the entropy and flatness problems of standard cosmology ..... and we can provide no explanation for why the current universe is so close to being spatially flat".[142]

Criticisms

Since its introduction by Alan Guth in 1980, the inflationary paradigm has become widely accepted. Nevertheless, many physicists, mathematicians, and philosophers of science have voiced criticisms, claiming untestable predictions and a lack of serious empirical support.[5] In 1999, John Earman and Jesús Mosterín published a thorough critical review of inflationary cosmology, concluding, "we do not think that there are, as yet, good grounds for admitting any of the models of inflation into the standard core of cosmology."[6]

In order to work, and as pointed out by Roger Penrose from 1986 on, inflation requires extremely specific initial conditions of its own, so that the problem (or pseudo-problem) of initial conditions is not solved: "There is something fundamentally misconceived about trying to explain the uniformity of the early universe as resulting from a thermalization process. [...] For, if the thermalization is actually doing anything [...] then it represents a definite increasing of the entropy. Thus, the universe would have been even more special before the thermalization than after."[143] The problem of specific or "fine-tuned" initial conditions would not have been solved; it would have gotten worse. At a conference in 2015, Penrose said that "inflation isn't falsifiable, it's falsified. [...] BICEP did a wonderful service by bringing all the Inflation-ists out of their shell, and giving them a black eye."[7]

A recurrent criticism of inflation is that the invoked inflaton field does not correspond to any known physical field, and that its potential energy curve seems to be an ad hoc contrivance to accommodate almost any data obtainable. Paul Steinhardt, one of the founding fathers of inflationary cosmology, has recently become one of its sharpest critics. He calls 'bad inflation' a period of accelerated expansion whose outcome conflicts with observations, and 'good inflation' one compatible with them: "Not only is bad inflation more likely than good inflation, but no inflation is more likely than either [...] Roger Penrose considered all the possible configurations of the inflaton and gravitational fields. Some of these configurations lead to inflation [...] Other configurations lead to a uniform, flat universe directly – without inflation. Obtaining a flat universe is unlikely overall. Penrose's shocking conclusion, though, was that obtaining a flat universe without inflation is much more likely than with inflation – by a factor of 10 to the googol (10 to the 100) power!"[5][116] Together with Anna Ijjas and Abraham Loeb, he wrote articles claiming that the inflationary paradigm is in trouble in view of the data from the Planck satellite.[144][145] Counter-arguments were presented by Alan Guth, David Kaiser, and Yasunori Nomura[146] and by Andrei Linde,[147] saying that "cosmic inflation is on a stronger footing than ever before".[146]

See also

- Brane cosmology
- Conservation of angular momentum
- Cosmology
- Dark flow
- Doughnut theory of the universe
- Hubble's law
- Non-minimally coupled inflation
- Nonlinear optics
- Varying speed of light
- Warm inflation

Notes

1. "First Second of the Big Bang". *How The Universe Works 3*. 2014. Discovery Science.

2. "2014 Astrophysics Citation" (http://www.kavlifoundation.org/2014-astrophysics-citation). *The Kavli Foundation*. The Kavli Foundation. Retrieved 27 July 2014.
3. Tyson, Neil deGrasse and Donald Goldsmith (2004), *Origins: Fourteen Billion Years of Cosmic Evolution*, W. W. Norton & Co., pp. 84–5.
4. Tsujikawa, Shinji (28 April 2003). "Introductory review of cosmic inflation". arXiv:hep-ph/0304257 (https://arxiv.org/abs/hep-ph/0304257). "In fact temperature anisotropies observed by the COBE satellite in 1992 exhibit nearly scale-invariant spectra as predicted by the inflationary paradigm. Recent observations of WMAP also show strong evidence for inflation."
5. Steinhardt, Paul J. (2011). "The inflation debate: Is the theory at the heart of modern cosmology deeply flawed?". *Scientific American*. **304** (4): 18–25. Bibcode:2011SciAm.304d..36S (https://ui.adsabs.harvard.edu/abs/2011SciAm.304d..36S). doi:10.1038/scientificamerican0411-36 (https://doi.org/10.1038%2Fscientificamerican0411-36). PMID 21495480 (https://pubmed.ncbi.nlm.nih.gov/21495480).
6. Earman, John; Mosterín, Jesús (March 1999). "A Critical Look at Inflationary Cosmology". *Philosophy of Science*. **66** (1): 1–49. doi:10.1086/392675 (https://doi.org/10.1086%2F392675). JSTOR 188736 (https://www.jstor.org/stable/188736).
7. Hložek, Renée (12 June 2015). "CMB@50 day three" (https://storify.com/reneehlozek/cmb-50-day-three). Retrieved 15 July 2015.
   This is a collation of remarks from the third day of the "Cosmic Microwave Background @50" (http://physics.princeton.edu/cmb50/home.shtml) Archived (https://web.archive.org/web/20171219102718/http://physics.princeton.edu/cmb50/home.shtml) 19 December 2017 at the Wayback Machine conference held at Princeton, 10–12 June 2015.
8. Guth, Alan H. (1997). *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins* (https://archive.org/details/inflationaryuniv0000guth). Basic Books. pp. 233 (https://archive.org/details/inflationaryuniv0000guth/page/233)–234. ISBN 978-0201328400.
9. "The Medallists: A list of past Dirac Medallists" (https://www.ictp.it/about-ictp/prizes-awards/the-dirac-medal/the-medallists.aspx). *ictp.it*.
10. "Laureates of the Breakthrough Prize in Fundamental Physics in 2012" (https://breakthroughprize.org/Laureates/1/P1/Y2012).
11. Staff (17 March 2014). "BICEP2 2014 Results Release" (http://bicepkeck.org). *National Science Foundation*. Retrieved 18 March 2014.
12. Clavin, Whitney (17 March 2014). "NASA Technology Views Birth of the Universe" (http://www.jpl.nasa.gov/news/news.php?release=2014-082). *NASA*. Retrieved 17 March 2014.
13. Overbye, Dennis (17 March 2014). "Space Ripples Reveal Big Bang's Smoking Gun" (https://www.nytimes.com/2014/03/18/science/space/detection-of-waves-in-space-buttresses-landmark-theory-of-big-bang.html). *The New York Times*. Retrieved 17 March 2014.
14. Saul, Ernest (2013). *The Coded Universe: The Path to Eternity* (https://books.google.com/books?id=E22mj8ImiKwC&pg=PA65). Dorrance Publishing Co. p. 65. ISBN 978-1434969057. Retrieved 14 July 2019.
15. Using Tiny Particles To Answer Giant Questions (https://www.npr.org/templates/story/story.php?storyId=102715275). Science Friday, 3 April 2009.
16. See also Faster than light#Universal expansion.
17. Spergel, D.N. (2007). "Three-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Implications for cosmology" (http://lambda.gsfc.nasa.gov/product/map/current/map_bibliography.cfm). *The Astrophysical Journal Supplement Series*. **170** (2): 377–408. arXiv:astro-ph/0603449 (https://arxiv.org/abs/astro-ph/0603449). Bibcode:2007ApJS..170..377S (https://ui.adsabs.harvard.edu/abs/2007ApJS..170..377S). CiteSeerX 10.1.1.472.2550 (https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.472.2550). doi:10.1086/513700 (https://doi.org/10.1086%2F513700). "WMAP... confirms the basic tenets of the inflationary paradigm..."

18. "Our Baby Universe Likely Expanded Rapidly, Study Suggests" (http://www.space.com/14699-universe-inflation-cosmic-expansion-theory.html). *Space.com*.
19. Melia, Fulvio (2008). "The Cosmic Horizon". *Monthly Notices of the Royal Astronomical Society*. **382** (4): 1917–1921. arXiv:0711.4181 (https://arxiv.org/abs/0711.4181). Bibcode:2007MNRAS.382.1917M (https://ui.adsabs.harvard.edu/abs/2007MNRAS.382.1917M). doi:10.1111/j.1365-2966.2007.12499.x (https://doi.org/10.1111%2Fj.1365-2966.2007.12499.x).
20. Melia, Fulvio; et al. (2009). "The Cosmological Spacetime". *International Journal of Modern Physics D*. **18** (12): 1889–1901. arXiv:0907.5394 (https://arxiv.org/abs/0907.5394). Bibcode:2009IJMPD..18.1889M (https://ui.adsabs.harvard.edu/abs/2009IJMPD..18.1889M). doi:10.1142/s0218271809015746 (https://doi.org/10.1142%2Fs0218271809015746).
21. Kolb and Turner (1988).
22. Barbara Sue Ryden (2003). *Introduction to cosmology*. Addison-Wesley. ISBN 978-0-8053-8912-8. "Not only is inflation very effective at driving down the number density of magnetic monopoles, it is also effective at driving down the number density of every other type of particle, including photons.":202–207
23. This is usually quoted as 60 *e*-folds of expansion, where $e^{60} \approx 10^{26}$. It is equal to the amount of expansion since reheating, which is roughly $E_{\text{inflation}}/T_0$, where T_0=2.7 K is the temperature of the cosmic microwave background today. See, *e.g.* Kolb and Turner (1998) or Liddle and Lyth (2000).
24. Guth, *Phase transitions in the very early universe*, in *The Very Early Universe*, ISBN 0-521-31677-4 eds Hawking, Gibbon & Siklos
25. See Kolb and Turner (1988) or Mukhanov (2005).
26. Kofman, Lev; Linde, Andrei; Starobinsky, Alexei (1994). "Reheating after inflation". *Physical Review Letters*. **73** (5): 3195–3198. arXiv:hep-th/9405187 (https://arxiv.org/abs/hep-th/9405187). Bibcode:1986CQGra...3..811K (https://ui.adsabs.harvard.edu/abs/1986CQGra...3..811K). doi:10.1088/0264-9381/3/5/011 (https://doi.org/10.1088%2F0264-9381%2F3%2F5%2F011).
27. Much of the historical context is explained in chapters 15–17 of Peebles (1993).
28. Misner, Charles W.; Coley, A A; Ellis, G F R; Hancock, M (1968). "The isotropy of the universe". *Astrophysical Journal*. **151** (2): 431. Bibcode:1998CQGra..15..331W (https://ui.adsabs.harvard.edu/abs/1998CQGra..15..331W). doi:10.1088/0264-9381/15/2/008 (https://doi.org/10.1088%2F0264-9381%2F15%2F2%2F008).
29. Misner, Charles; Thorne, Kip S. & Wheeler, John Archibald (1973). *Gravitation* (https://archive.org/details/gravitation00whee). San Francisco: W. H. Freeman. pp. 489 (https://archive.org/details/gravitation00whee/page/n521)–490, 525–526. ISBN 978-0-7167-0344-0.
30. Weinberg, Steven (1971). *Gravitation and Cosmology* (https://archive.org/details/gravitationcosmo00stev_0/page/740). John Wiley. pp. 740, 815 (https://archive.org/details/gravitationcosmo00stev_0/page/740). ISBN 978-0-471-92567-5.
31. Lemaître, Georges (1933). "The expanding universe". *Annales de la Société Scientifique de Bruxelles*. **47A**: 49., English in *Gen. Rel. Grav.* **29**:641–680, 1997.
32. R. C. Tolman (1934). *Relativity, Thermodynamics, and Cosmology*. Oxford: Clarendon Press. ISBN 978-0-486-65383-9. LCCN 34032023 (https://lccn.loc.gov/34032023). Reissued (1987) New York: Dover ISBN 0-486-65383-8.
33. Misner, Charles W.; Leach, P G L (1969). "Mixmaster universe". *Physical Review Letters*. **22** (15): 1071–74. Bibcode:2008JPhA...41o5201A (https://ui.adsabs.harvard.edu/abs/2008JPhA...41o5201A). doi:10.1088/1751-8113/41/15/155201 (https://doi.org/10.1088%2F1751-8113%2F41%2F15%2F155201).
34. Dicke, Robert H. (1970). *Gravitation and the Universe*. Philadelphia: American Philosophical Society.
35. Dicke, Robert H.; P. J. E. Peebles (1979). "The big bang cosmology – enigmas and nostrums". In S. W. Hawking; W. Israel (eds.). *General Relativity: an Einstein Centenary Survey*. Cambridge University Press.

36. Alan P. Lightman (1 January 1993). *Ancient Light: Our Changing View of the Universe*. Harvard University Press. ISBN 978-0-674-03363-4.
37. "WMAP- Content of the Universe" (http://map.gsfc.nasa.gov/universe/uni_matter.html). *nasa.gov*.
38. Since supersymmetric Grand Unified Theory is built into string theory, it is still a triumph for inflation that it is able to deal with these magnetic relics. See, *e.g.* Kolb and Turner (1988) and Raby, Stuart (2006). Bruce Hoeneisen (ed.). *Grand Unified Theories* (https://archive.org/details/arxiv-hep-ph0608183). arXiv:hep-ph/0608183 (https://arxiv.org/abs/hep-ph/0608183). Bibcode:2006hep.ph....8183R (https://ui.adsabs.harvard.edu/abs/2006hep.ph....8183R).
39. 't Hooft, Gerard (1974). "Magnetic monopoles in Unified Gauge Theories" (http://dspace.library.uu.nl:8080/handle/1874/4686). *Nuclear Physics B*. **79** (2): 276–84. Bibcode:1974NuPhB..79..276T (https://ui.adsabs.harvard.edu/abs/1974NuPhB..79..276T). doi:10.1016/0550-3213(74)90486-6 (https://doi.org/10.1016%2F0550-3213%2874%2990486-6). hdl:1874/4686 (https://hdl.handle.net/1874%2F4686).
40. Polyakov, Alexander M. (1974). "Particle spectrum in quantum field theory". *JETP Letters*. **20**: 194–5. Bibcode:1974JETPL..20..194P (https://ui.adsabs.harvard.edu/abs/1974JETPL..20..194P).
41. Guth, Alan; Tye, S. (1980). "Phase Transitions and Magnetic Monopole Production in the Very Early Universe" (http://repository.ust.hk/ir/bitstream/1783.1-49322/1/PhysRevLett.44.631.pdf) (PDF). *Physical Review Letters*. **44** (10): 631–635, Erratum *ibid.*, **44**:963, 1980. Bibcode:1980PhRvL..44..631G (https://ui.adsabs.harvard.edu/abs/1980PhRvL..44..631G). doi:10.1103/PhysRevLett.44.631 (https://doi.org/10.1103%2FPhysRevLett.44.631).
42. Einhorn, Martin B; Stein, D. L.; Toussaint, Doug (1980). "Are Grand Unified Theories Compatible with Standard Cosmology?". *Physical Review D*. **21** (12): 3295–3298. Bibcode:1980PhRvD..21.3295E (https://ui.adsabs.harvard.edu/abs/1980PhRvD..21.3295E). doi:10.1103/PhysRevD.21.3295 (https://doi.org/10.1103%2FPhysRevD.21.3295).
43. Zel'dovich, Ya.; Khlopov, M. Yu. (1978). "On the concentration of relic monopoles in the universe". *Physics Letters B*. **79** (3): 239–41. Bibcode:1978PhLB...79..239Z (https://ui.adsabs.harvard.edu/abs/1978PhLB...79..239Z). doi:10.1016/0370-2693(78)90232-0 (https://doi.org/10.1016%2F0370-2693%2878%2990232-0).
44. Preskill, John (1979). "Cosmological production of superheavy magnetic monopoles" (https://authors.library.caltech.edu/6133/1/PREprl79.pdf) (PDF). *Physical Review Letters*. **43** (19): 1365–1368. Bibcode:1979PhRvL..43.1365P (https://ui.adsabs.harvard.edu/abs/1979PhRvL..43.1365P). doi:10.1103/PhysRevLett.43.1365 (https://doi.org/10.1103%2FPhysRevLett.43.1365).
45. See, *e.g.* Yao, W.-M.; et al. (2006). "Review of Particle Physics" (http://pdg.lbl.gov/). *Journal of Physics G*. **33** (1): 1–1232. arXiv:astro-ph/0601168 (https://arxiv.org/abs/astro-ph/0601168). Bibcode:2006JPhG...33....1Y (https://ui.adsabs.harvard.edu/abs/2006JPhG...33....1Y). doi:10.1088/0954-3899/33/1/001 (https://doi.org/10.1088%2F0954-3899%2F33%2F1%2F001).
46. Rees, Martin. (1998). *Before the Beginning* (New York: Basic Books) p. 185 ISBN 0-201-15142-1
47. de Sitter, Willem (1917). "Einstein's theory of gravitation and its astronomical consequences. Third paper" (https://doi.org/10.1093/mnras/78.1.3). *Monthly Notices of the Royal Astronomical Society*. **78**: 3–28. Bibcode:1917MNRAS..78....3D (https://ui.adsabs.harvard.edu/abs/1917MNRAS..78....3D). doi:10.1093/mnras/78.1.3 (https://doi.org/10.1093%2Fmnras%2F78.1.3).
48. Starobinsky, A. A. (December 1979). "Spectrum Of Relict Gravitational Radiation And The Early State Of The Universe". *Journal of Experimental and Theoretical Physics Letters*. **30**: 682. Bibcode:1979JETPL..30..682S (https://ui.adsabs.harvard.edu/abs/1979JETPL..30..682S).; Starobinskii, A. A. (December 1979). "Spectrum of relict gravitational radiation and the early state of the universe". *Pisma Zh. Eksp. Teor. Fiz*. **30**: 719. Bibcode:1979ZhPmR..30..719S (https://ui.adsabs.harvard.edu/abs/1979ZhPmR..30..719S).

49. Ade, P. A. R.; et al. (2016). "Planck 2015 results. XX. Constraints on inflation". *Astronomy & Astrophysics*. **594**: 17. arXiv:1502.02114 (https://arxiv.org/abs/1502.02114). Bibcode:2016A&A...594A..20P (https://ui.adsabs.harvard.edu/abs/2016A&A...594A..20P). doi:10.1051/0004-6361/201525898 (https://doi.org/10.1051%2F0004-6361%2F201525898).
50. SLAC seminar, "10^{-35} seconds after the Big Bang", 23 January 1980. see Guth (1997), pg 186
51. Guth, Alan H. (1981). "Inflationary universe: A possible solution to the horizon and flatness problems" (http://www.astro.rug.nl/~weygaert/tim1publication/cosmo2007/literature/inflationary.universe.guth.physrevd-1981.pdf) (PDF). *Physical Review D*. **23** (2): 347–356. Bibcode:1981PhRvD..23..347G (https://ui.adsabs.harvard.edu/abs/1981PhRvD..23..347G). doi:10.1103/PhysRevD.23.347 (https://doi.org/10.1103%2FPhysRevD.23.347).
52. Chapter 17 of Peebles (1993).
53. Starobinsky, Alexei A. (1980). "A new type of isotropic cosmological models without singularity". *Physics Letters B*. **91** (1): 99–102. Bibcode:1980PhLB...91...99S (https://ui.adsabs.harvard.edu/abs/1980PhLB...91...99S). doi:10.1016/0370-2693(80)90670-X (https://doi.org/10.1016%2F0370-2693%2880%2990670-X).
54. Kazanas, D. (1980). "Dynamics of the universe and spontaneous symmetry breaking". *Astrophysical Journal*. **241**: L59–63. Bibcode:1980ApJ...241L..59K (https://ui.adsabs.harvard.edu/abs/1980ApJ...241L..59K). doi:10.1086/183361 (https://doi.org/10.1086%2F183361).
55. Kazanas, D. (2009). "Cosmological Inflation: A Personal Perspective" (https://books.google.com/books?id=QfipHB0XK58C&pg=PA485). In Contopoulos, G.; Patsis, P. A. (eds.). *Chaos in Astronomy: Conference 2007*. *Astrophysics and Space Science Proceedings*. **8**. Springer Science & Business Media. pp. 485–496. arXiv:0803.2080 (https://arxiv.org/abs/0803.2080). Bibcode:2009ASSP....8..485K (https://ui.adsabs.harvard.edu/abs/2009ASSP....8..485K). doi:10.1007/978-3-540-75826-6_49 (https://doi.org/10.1007%2F978-3-540-75826-6_49). ISBN 978-3-540-75825-9.
56. Sato, K. (1981). "Cosmological baryon number domain structure and the first order phase transition of a vacuum". *Physics Letters B*. **33** (1): 66–70. Bibcode:1981PhLB...99...66S (https://ui.adsabs.harvard.edu/abs/1981PhLB...99...66S). doi:10.1016/0370-2693(81)90805-4 (https://doi.org/10.1016%2F0370-2693%2881%2990805-4).
57. Einhorn, Martin B; Sato, Katsuhiko (1981). "Monopole Production In The Very Early Universe In A First Order Phase Transition". *Nuclear Physics B*. **180** (3): 385–404. Bibcode:1981NuPhB.180..385E (https://ui.adsabs.harvard.edu/abs/1981NuPhB.180..385E). doi:10.1016/0550-3213(81)90057-2 (https://doi.org/10.1016%2F0550-3213%2881%2990057-2).
58. Contopoulos, George (2004). *Adventures in order and chaos: a scientific autobiography* (https://books.google.com/books?id=3UXak_7yR3MC&pg=PA88). **313**. Springer Science & Business Media. pp. 88–89. ISBN 9781402030406.
59. Linde, A (1982). "A new inflationary universe scenario: A possible solution of the horizon, flatness, homogeneity, isotropy and primordial monopole problems". *Physics Letters B*. **108** (6): 389–393. Bibcode:1982PhLB..108..389L (https://ui.adsabs.harvard.edu/abs/1982PhLB..108..389L). doi:10.1016/0370-2693(82)91219-9 (https://doi.org/10.1016%2F0370-2693%2882%2991219-9).
60. Albrecht, Andreas; Steinhardt, Paul (1982). "Cosmology for Grand Unified Theories with Radiatively Induced Symmetry Breaking" (https://web.archive.org/web/20120130063002/http://astrophysics.fic.uni.lodz.pl/100yrs/pdf/07/060.pdf) (PDF). *Physical Review Letters*. **48** (17): 1220–1223. Bibcode:1982PhRvL..48.1220A (https://ui.adsabs.harvard.edu/abs/1982PhRvL..48.1220A). doi:10.1103/PhysRevLett.48.1220 (https://doi.org/10.1103%2FPhysRevLett.48.1220). Archived from the original (http://astrophysics.fic.uni.lodz.pl/100yrs/pdf/07/060.pdf) (PDF) on 30 January 2012.
61. J.B. Hartle (2003). *Gravity: An Introduction to Einstein's General Relativity* (https://archive.org/details/gravityintroduct00hart_100) (1st ed.). Addison Wesley. p. 411 (https://archive.org/details/gravityintroduct00hart_100/page/n423). ISBN 978-0-8053-8662-2.
62. See Linde (1990) and Mukhanov (2005).

63. Chibisov, Viatcheslav F.; Chibisov, G. V. (1981). "Quantum fluctuation and "nonsingular" universe". *JETP Letters*. **33**: 532–5. Bibcode:1981JETPL..33..532M (https://ui.adsabs.harvard.edu/abs/1981JETPL..33..532M).
64. Mukhanov, Viatcheslav F. (1982). "The vacuum energy and large scale structure of the universe". *Soviet Physics JETP*. **56**: 258–65.
65. See Guth (1997) for a popular description of the workshop, or *The Very Early Universe*, ISBN 0-521-31677-4 eds Hawking, Gibbon & Siklos for a more detailed report
66. Hawking, S.W. (1982). "The development of irregularities in a single bubble inflationary universe". *Physics Letters B*. **115** (4): 295–297. Bibcode:1982PhLB..115..295H (https://ui.adsabs.harvard.edu/abs/1982PhLB..115..295H). doi:10.1016/0370-2693(82)90373-2 (https://doi.org/10.1016%2F0370-2693%2882%2990373-2).
67. Starobinsky, Alexei A. (1982). "Dynamics of phase transition in the new inflationary universe scenario and generation of perturbations". *Physics Letters B*. **117** (3–4): 175–8. Bibcode:1982PhLB..117..175S (https://ui.adsabs.harvard.edu/abs/1982PhLB..117..175S). doi:10.1016/0370-2693(82)90541-X (https://doi.org/10.1016%2F0370-2693%2882%2990541-X).
68. Guth, A.H. (1982). "Fluctuations in the new inflationary universe". *Physical Review Letters*. **49** (15): 1110–3. Bibcode:1982PhRvL..49.1110G (https://ui.adsabs.harvard.edu/abs/1982PhRvL..49.1110G). doi:10.1103/PhysRevLett.49.1110 (https://doi.org/10.1103%2FPhysRevLett.49.1110).
69. Bardeen, James M.; Steinhardt, Paul J.; Turner, Michael S. (1983). "Spontaneous creation Of almost scale-free density perturbations in an inflationary universe". *Physical Review D*. **28** (4): 679–693. Bibcode:1983PhRvD..28..679B (https://ui.adsabs.harvard.edu/abs/1983PhRvD..28..679B). doi:10.1103/PhysRevD.28.679 (https://doi.org/10.1103%2FPhysRevD.28.679).
70. Ade, P. A. R.; et al. (Planck Collaboration) (1 October 2016). "Planck 2015 results. XIII. Cosmological parameters". *Astronomy & Astrophysics*. **594**: A13. arXiv:1502.01589 (https://arxiv.org/abs/1502.01589). Bibcode:2016A&A...594A..13P (https://ui.adsabs.harvard.edu/abs/2016A&A...594A..13P). doi:10.1051/0004-6361/201525830 (https://doi.org/10.1051%2F0004-6361%2F201525830). ISSN 0004-6361 (https://www.worldcat.org/issn/0004-6361).
71. Perturbations can be represented by Fourier modes of a wavelength. Each Fourier mode is normally distributed (usually called Gaussian) with mean zero. Different Fourier components are uncorrelated. The variance of a mode depends only on its wavelength in such a way that within any given volume each wavelength contributes an equal amount of power to the spectrum of perturbations. Since the Fourier transform is in three dimensions, this means that the variance of a mode goes as k^{-3} to compensate for the fact that within any volume, the number of modes with a given wavenumber k goes as k^3.
72. Boyle, Latham A.; Steinhardt, Paul J.; Turok, Neil (24 March 2006). "Inflationary Predictions for Scalar and Tensor Fluctuations Reconsidered". *Physical Review Letters*. **96** (11): 111301. arXiv:astro-ph/0507455 (https://arxiv.org/abs/astro-ph/0507455). Bibcode:2006PhRvL..96k1301B (https://ui.adsabs.harvard.edu/abs/2006PhRvL..96k1301B). doi:10.1103/PhysRevLett.96.111301 (https://doi.org/10.1103%2FPhysRevLett.96.111301). PMID 16605810 (https://pubmed.ncbi.nlm.nih.gov/16605810).
73. Tegmark, M.; et al. (August 2006). "Cosmological constraints from the SDSS luminous red galaxies". *Physical Review D*. **74** (12): 123507. arXiv:astro-ph/0608632 (https://arxiv.org/abs/astro-ph/0608632). Bibcode:2006PhRvD..74l3507T (https://ui.adsabs.harvard.edu/abs/2006PhRvD..74l3507T). doi:10.1103/PhysRevD.74.123507 (https://doi.org/10.1103%2FPhysRevD.74.123507). hdl:1811/48518 (https://hdl.handle.net/1811%2F48518).
74. Steinhardt, Paul J. (2004). "Cosmological perturbations: Myths and facts" (https://semanticscholar.org/paper/eba085f5040f88a59722600e40a35e19b7113f93). *Modern Physics Letters A*. **19** (13 & 16): 967–82. Bibcode:2004MPLA...19..967S (https://ui.adsabs.harvard.edu/abs/2004MPLA...19..967S). doi:10.1142/S0217732304014252 (https://doi.org/10.1142%2FS0217732304014252).

75. Tegmark, Max (2005). "What does inflation really predict?". *Journal of Cosmology and Astroparticle Physics*. **2005** (4): 001. arXiv:astro-ph/0410281 (https://arxiv.org/abs/astro-ph/0410281). Bibcode:2005JCAP...04..001T (https://ui.adsabs.harvard.edu/abs/2005JCAP...04..001T). doi:10.1088/1475-7516/2005/04/001 (https://doi.org/10.1088%2F1475-7516%2F2005%2F04%2F001).
76. This is known as a "red" spectrum, in analogy to redshift, because the spectrum has more power at longer wavelengths.
77. Ade, P. A. R.; et al. (Planck Collaboration) (1 October 2016). "Planck 2015 results. XX. Constraints on inflation". *Astronomy & Astrophysics*. **594**: A20. arXiv:1502.02114 (https://arxiv.org/abs/1502.02114). Bibcode:2016A&A...594A..20P (https://ui.adsabs.harvard.edu/abs/2016A&A...594A..20P). doi:10.1051/0004-6361/201525898 (https://doi.org/10.1051%2F0004-6361%2F201525898). ISSN 0004-6361 (https://www.worldcat.org/issn/0004-6361).
78. Spergel, D. N.; et al. (2003). "First year Wilkinson Microwave Anisotropy Probe (WMAP) observations: determination of cosmological parameters". *Astrophysical Journal Supplement Series*. **148** (1): 175–194. arXiv:astro-ph/0302209 (https://arxiv.org/abs/astro-ph/0302209). Bibcode:2003ApJS..148..175S (https://ui.adsabs.harvard.edu/abs/2003ApJS..148..175S). doi:10.1086/377226 (https://doi.org/10.1086%2F377226).
79. See cosmic microwave background#Low multipoles for details and references.
80. Grant, Andrew (2019). "Five years after BICEP2". *Physics Today*. doi:10.1063/PT.6.3.20190326a (https://doi.org/10.1063%2FPT.6.3.20190326a).
81. Ade, P.A.R.; et al. (BICEP2 Collaboration) (19 June 2014). "Detection of B-Mode Polarization at Degree Angular Scales by BICEP2". *Physical Review Letters*. **112** (24): 241101. arXiv:1403.3985 (https://arxiv.org/abs/1403.3985). Bibcode:2014PhRvL.112x1101B (https://ui.adsabs.harvard.edu/abs/2014PhRvL.112x1101B). doi:10.1103/PhysRevLett.112.241101 (https://doi.org/10.1103%2FPhysRevLett.112.241101). PMID 24996078 (https://pubmed.ncbi.nlm.nih.gov/24996078).
82. Overbye, Dennis (19 June 2014). "Astronomers Hedge on Big Bang Detection Claim" (https://www.nytimes.com/2014/06/20/science/space/scientists-debate-gravity-wave-detection-claim.html). *The New York Times*. Retrieved 20 June 2014.
83. Amos, Jonathan (19 June 2014). "Cosmic inflation: Confidence lowered for Big Bang signal" (https://www.bbc.com/news/science-environment-27935479). *BBC News*. Retrieved 20 June 2014.
84. Planck Collaboration Team (2016). "Planck intermediate results. XXX. The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes". *Astronomy & Astrophysics*. **586** (133): A133. arXiv:1409.5738 (https://arxiv.org/abs/1409.5738). Bibcode:2016A&A...586A.133P (https://ui.adsabs.harvard.edu/abs/2016A&A...586A.133P). doi:10.1051/0004-6361/201425034 (https://doi.org/10.1051%2F0004-6361%2F201425034).
85. Overbye, Dennis (22 September 2014). "Study Confirms Criticism of Big Bang Finding" (https://www.nytimes.com/2014/09/23/science/space/study-confirms-criticism-of-big-bang-finding.html). *The New York Times*. Retrieved 22 September 2014.
86. Clavin, Whitney (30 January 2015). "Gravitational Waves from Early Universe Remain Elusive" (http://www.jpl.nasa.gov/news/news.php?release=2015-46). *NASA*. Retrieved 30 January 2015.
87. Overbye, Dennis (30 January 2015). "Speck of Interstellar Dust Obscures Glimpse of Big Bang" (https://www.nytimes.com/2015/01/31/us/a-speck-of-interstellar-dust-rebuts-a-big-bang-theory.html). *The New York Times*. Retrieved 31 January 2015.
88. Rosset, C.; PLANCK-HFI collaboration (2005). "Systematic effects in CMB polarization measurements". *Exploring the universe: Contents and structures of the universe (XXXIXth Rencontres de Moriond)*. arXiv:astro-ph/0502188 (https://arxiv.org/abs/astro-ph/0502188).

89. Loeb, A.; Zaldarriaga, M (2004). "Measuring the small-scale power spectrum of cosmic density fluctuations through 21 cm tomography prior to the epoch of structure formation" (http://cds.cern.ch/record/690135). *Physical Review Letters* (Submitted manuscript). **92** (21): 211301. arXiv:astro-ph/0312134 (https://arxiv.org/abs/astro-ph/0312134). Bibcode:2004PhRvL..92u1301L (https://ui.adsabs.harvard.edu/abs/2004PhRvL..92u1301L). doi:10.1103/PhysRevLett.92.211301 (https://doi.org/10.1103%2FPhysRevLett.92.211301). PMID 15245272 (https://pubmed.ncbi.nlm.nih.gov/15245272).
90. Guth, Alan (1997). *The Inflationary Universe* (https://archive.org/details/inflationaryuniv0000guth). Addison–Wesley. ISBN 978-0-201-14942-5.
91. Choi, Charles (29 June 2012). "Could the Large Hadron Collider Discover the Particle Underlying Both Mass and Cosmic Inflation?" (http://www.scientificamerican.com/article/could-lhc-discover-higgs-boson/). *Scientific American*. Retrieved 25 June 2014. "The virtue of so-called Higgs inflation models is that they might explain inflation within the current Standard Model of particle physics, which successfully describes how most known particles and forces behave. Interest in the Higgs is running hot this summer because CERN, the lab in Geneva, Switzerland, that runs the LHC, has said it will announce highly anticipated findings regarding the particle in early July."
92. Salvio, Alberto (2013). "Higgs Inflation at NNLO after the Boson Discovery". *Physics Letters B*. **727** (1–3): 234–239. arXiv:1308.2244 (https://arxiv.org/abs/1308.2244). Bibcode:2013PhLB..727..234S (https://ui.adsabs.harvard.edu/abs/2013PhLB..727..234S). doi:10.1016/j.physletb.2013.10.042 (https://doi.org/10.1016%2Fj.physletb.2013.10.042).
93. Technically, these conditions are that the logarithmic derivative of the potential, $\epsilon = (1/2)(V'/V)^2$ and second derivative $\eta = V''/V$ are small, where V is the potential and the equations are written in reduced Planck units. See, *e.g.* Liddle and Lyth (2000), pg 42–43.
94. Salvio, Strumia (17 March 2014). "Agravity". *Journal of High Energy Physics*. **2014** (6): 80. arXiv:1403.4226 (https://arxiv.org/abs/1403.4226). Bibcode:2014JHEP...06..080S (https://ui.adsabs.harvard.edu/abs/2014JHEP...06..080S). doi:10.1007/JHEP06(2014)080 (https://doi.org/10.1007%2FJHEP06%282014%29080).
95. Linde, Andrei D. (1983). "Chaotic inflation". *Physics Letters B*. **129** (3): 171–81. Bibcode:1983PhLB..129..177L (https://ui.adsabs.harvard.edu/abs/1983PhLB..129..177L). doi:10.1016/0370-2693(83)90837-7 (https://doi.org/10.1016%2F0370-2693%2883%2990837-7).
96. Technically, this is because the inflaton potential is expressed as a Taylor series in φ/m_{Pl}, where φ is the inflaton and m_{Pl} is the Planck mass. While for a single term, such as the mass term $m_\varphi^4(\varphi/m_{Pl})^2$, the slow roll conditions can be satisfied for φ much greater than m_{Pl}, this is precisely the situation in effective field theory in which higher order terms would be expected to contribute and destroy the conditions for inflation. The absence of these higher order corrections can be seen as another sort of fine tuning. See *e.g.* Alabidi, Laila; Lyth, David H (2006). "Inflation models and observation". *Journal of Cosmology and Astroparticle Physics*. **2006** (5): 016. arXiv:astro-ph/0510441 (https://arxiv.org/abs/astro-ph/0510441). Bibcode:2006JCAP...05..016A (https://ui.adsabs.harvard.edu/abs/2006JCAP...05..016A). doi:10.1088/1475-7516/2006/05/016 (https://doi.org/10.1088%2F1475-7516%2F2006%2F05%2F016).
97. See, *e.g.* Lyth, David H. (1997). "What would we learn by detecting a gravitational wave signal in the cosmic microwave background anisotropy?" (https://archive.today/20120629010941/http://www.slac.stanford.edu/spires/find/hep/www?rawcmd=FIND+EPRINT+HEP-PH/9606387). *Physical Review Letters*. **78** (10): 1861–3. arXiv:hep-ph/9606387 (https://arxiv.org/abs/hep-ph/9606387). Bibcode:1997PhRvL..78.1861L (https://ui.adsabs.harvard.edu/abs/1997PhRvL..78.1861L). doi:10.1103/PhysRevLett.78.1861 (https://doi.org/10.1103%2FPhysRevLett.78.1861). Archived from the original (http://www.slac.stanford.edu/spires/find/hep/www?rawcmd=FIND+EPRINT+HEP-PH/9606387) on 29 June 2012.
98. Brandenberger, Robert H. (November 2004). "Challenges for inflationary cosmology (10th International Symposium on Particles, Strings and Cosmology)". arXiv:astro-ph/0411671 (https://arxiv.org/abs/astro-ph/0411671).

99. Gibbons, Gary W.; Hawking, Stephen W.; Siklos, S.T.C., eds. (1983). *"Natural Inflation," in The Very Early Universe*. Cambridge University Press. pp. 251–66. ISBN 978-0-521-31677-4.
100. Vilenkin, Alexander (1983). "Birth of Inflationary Universes". *Physical Review D*. **27** (12): 2848–2855. Bibcode:1983PhRvD..27.2848V (https://ui.adsabs.harvard.edu/abs/1983PhRvD..27.2848V). doi:10.1103/PhysRevD.27.2848 (https://doi.org/10.1103%2FPhysRevD.27.2848).
101. Steinhardt, Paul J. (April 2011). "Inflation Debate: Is the theory at the heart of modern cosmology deeply flawed?" (http://www.physics.princeton.edu/~steinh/0411036.pdf) (PDF). *Scientific American*. **304** (4): 36–43. Bibcode:2011SciAm.304d..36S (https://ui.adsabs.harvard.edu/abs/2011SciAm.304d..36S). doi:10.1038/scientificamerican0411-36 (https://doi.org/10.1038%2Fscientificamerican0411-36). PMID 21495480 (https://pubmed.ncbi.nlm.nih.gov/21495480).
102. http://www.physics.princeton.edu/~steinh/vaasrev.pdf
103. https://www.cfa.harvard.edu/~loeb/sciam3.pdf
104. Carroll, Sean M.; Chen, Jennifer (2005). "Does inflation provide natural initial conditions for the universe?". *General Relativity and Gravitation*. **37** (10): 1671–4. arXiv:gr-qc/0505037 (https://arxiv.org/abs/gr-qc/0505037). Bibcode:2005GReGr..37.1671C (https://ui.adsabs.harvard.edu/abs/2005GReGr..37.1671C). doi:10.1007/s10714-005-0148-2 (https://doi.org/10.1007%2Fs10714-005-0148-2).
105. Carroll, Sean M.; Jennifer Chen (2004). "Spontaneous inflation and the origin of the arrow of time". arXiv:hep-th/0410270 (https://arxiv.org/abs/hep-th/0410270).
106. Aguirre, Anthony; Gratton, Steven (2003). "Inflation without a beginning: A null boundary proposal". *Physical Review D*. **67** (8): 083515. arXiv:gr-qc/0301042 (https://arxiv.org/abs/gr-qc/0301042). Bibcode:2003PhRvD..67h3515A (https://ui.adsabs.harvard.edu/abs/2003PhRvD..67h3515A). doi:10.1103/PhysRevD.67.083515 (https://doi.org/10.1103%2FPhysRevD.67.083515).
107. Aguirre, Anthony; Gratton, Steven (2002). "Steady-State Eternal Inflation" (http://cds.cern.ch/record/526126). *Physical Review D* (Submitted manuscript). **65** (8): 083507. arXiv:astro-ph/0111191 (https://arxiv.org/abs/astro-ph/0111191). Bibcode:2002PhRvD..65h3507A (https://ui.adsabs.harvard.edu/abs/2002PhRvD..65h3507A). doi:10.1103/PhysRevD.65.083507 (https://doi.org/10.1103%2FPhysRevD.65.083507).
108. Hartle, J.; Hawking, S. (1983). "Wave function of the universe". *Physical Review D*. **28** (12): 2960–2975. Bibcode:1983PhRvD..28.2960H (https://ui.adsabs.harvard.edu/abs/1983PhRvD..28.2960H). doi:10.1103/PhysRevD.28.2960 (https://doi.org/10.1103%2FPhysRevD.28.2960).; See also Hawking (1998).
109. Staff (University of Cambridge) (2 May 2018). "Taming the multiverse—Stephen Hawking's final theory about the big bang" (https://phys.org/news/2018-05-multiversestephen-hawking-theory-big.html). *Phys.org*. Retrieved 2 May 2018.
110. Hawking, Stephen; Hertog, Thomas (20 April 2018). "A smooth exit from eternal inflation?". *Journal of High Energy Physics*. **2018** (4): 147. arXiv:1707.07702 (https://arxiv.org/abs/1707.07702). Bibcode:2018JHEP...04..147H (https://ui.adsabs.harvard.edu/abs/2018JHEP...04..147H). doi:10.1007/JHEP04(2018)147 (https://doi.org/10.1007%2FJHEP04%282018%29147).
111. Hawking, Stephen; Hertog, Thomas (20 April 2018). "A smooth exit from eternal inflation". *Journal of High Energy Physics*. **2018** (4). arXiv:1707.07702 (https://arxiv.org/abs/1707.07702). Bibcode:2018JHEP...04..147H (https://ui.adsabs.harvard.edu/abs/2018JHEP...04..147H). doi:10.1007/JHEP04(2018)147 (https://doi.org/10.1007%2FJHEP04%282018%29147).
112. Hawking (1998), p. 129.
113. Wikiquote
114. Page, Don N. (1983). "Inflation does not explain time asymmetry". *Nature*. **304** (5921): 39–41. Bibcode:1983Natur.304...39P (https://ui.adsabs.harvard.edu/abs/1983Natur.304...39P). doi:10.1038/304039a0 (https://doi.org/10.1038%2F304039a0).; see also Roger Penrose's book The Road to Reality: A Complete Guide to the Laws of the Universe.

115. Hawking, S. W.; Page, Don N. (1988). "How probable is inflation?". *Nuclear Physics B*. **298** (4): 789–809. Bibcode:1988NuPhB.298..789H (https://ui.adsabs.harvard.edu/abs/1988NuPhB.298..789H). doi:10.1016/0550-3213(88)90008-9 (https://doi.org/10.1016%2F0550-3213%2888%2990008-9).
116. Paul J. Steinhardt; Neil Turok (2007). *Endless Universe: Beyond the Big Bang*. Broadway Books. ISBN 978-0-7679-1501-4.
117. Albrecht, Andreas; Sorbo, Lorenzo (2004). "Can the universe afford inflation?". *Physical Review D*. **70** (6): 063528. arXiv:hep-th/0405270 (https://arxiv.org/abs/hep-th/0405270). Bibcode:2004PhRvD..70f3528A (https://ui.adsabs.harvard.edu/abs/2004PhRvD..70f3528A). doi:10.1103/PhysRevD.70.063528 (https://doi.org/10.1103%2FPhysRevD.70.063528).
118. Martin, Jerome; Brandenberger, Robert (2001). "The trans-Planckian problem of inflationary cosmology". *Physical Review D*. **63** (12): 123501. arXiv:hep-th/0005209 (https://arxiv.org/abs/hep-th/0005209). Bibcode:2001PhRvD..63l3501M (https://ui.adsabs.harvard.edu/abs/2001PhRvD..63l3501M). doi:10.1103/PhysRevD.63.123501 (https://doi.org/10.1103%2FPhysRevD.63.123501).
119. Martin, Jerome; Ringeval, Christophe (2004). "Superimposed Oscillations in the WMAP Data?". *Physical Review D*. **69** (8): 083515. arXiv:astro-ph/0310382 (https://arxiv.org/abs/astro-ph/0310382). Bibcode:2004PhRvD..69h3515M (https://ui.adsabs.harvard.edu/abs/2004PhRvD..69h3515M). doi:10.1103/PhysRevD.69.083515 (https://doi.org/10.1103%2FPhysRevD.69.083515).
120. Brandenberger, Robert H. (2001). *A Status Review of Inflationary Cosmology*. arXiv:hep-ph/0101119 (https://arxiv.org/abs/hep-ph/0101119). Bibcode:2001hep.ph....1119B (https://ui.adsabs.harvard.edu/abs/2001hep.ph....1119B).
121. Linde, Andrei; Fischler, W. (2005). "Prospects of Inflation". *Physica Scripta*. **117** (T117): 40–48. arXiv:hep-th/0402051 (https://arxiv.org/abs/hep-th/0402051). Bibcode:2005PhST..116...56B (https://ui.adsabs.harvard.edu/abs/2005PhST..116...56B). doi:10.1238/Physica.Topical.117a00056 (https://doi.org/10.1238%2FPhysica.Topical.117a00056).
122. Blanco-Pillado, J. J.; Burgess, C. P.; Cline, J. M.; Escoda, C.; Gomez-Reino, M.; Kallosh, R.; Linde, A.; Quevedo, F. (2004). "Racetrack Inflation". *Journal of High Energy Physics*. **2004** (11): 063. arXiv:hep-th/0406230 (https://arxiv.org/abs/hep-th/0406230). Bibcode:2004JHEP...11..063B (https://ui.adsabs.harvard.edu/abs/2004JHEP...11..063B). doi:10.1088/1126-6708/2004/11/063 (https://doi.org/10.1088%2F1126-6708%2F2004%2F11%2F063).
123. Kachru, Shamit; et al. (2003). "Towards inflation in string theory". *Journal of Cosmology and Astroparticle Physics*. **2003** (10): 013. arXiv:hep-th/0308055 (https://arxiv.org/abs/hep-th/0308055). Bibcode:2003JCAP...10..013K (https://ui.adsabs.harvard.edu/abs/2003JCAP...10..013K). CiteSeerX 10.1.1.264.3396 (https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.264.3396). doi:10.1088/1475-7516/2003/10/013 (https://doi.org/10.1088%2F1475-7516%2F2003%2F10%2F013).
124. Dvali, Gia; Henry Tye, S. -H. (1998). "Brane Inflation". *Physics Letters B*. **450** (1999): 72–82. arXiv:hep-ph/9812483 (https://arxiv.org/abs/hep-ph/9812483). Bibcode:1999PhLB..450...72D (https://ui.adsabs.harvard.edu/abs/1999PhLB..450...72D). doi:10.1016/S0370-2693(99)00132-X (https://doi.org/10.1016%2FS0370-2693%2899%2900132-X).
125. Bojowald, Martin (October 2008). "Big Bang or Big Bounce?: New Theory on the Universe's Birth" (http://www.scientificamerican.com/article/big-bang-or-big-bounce/). Retrieved 31 August 2015.

126. Itzhak Bars; Paul Steinhardt; Neil Turok (2014). "Sailing through the big crunch-big bang transition". *Physical Review D*. **89** (6): 061302. arXiv:1312.0739 (https://arxiv.org/abs/1312.0739). Bibcode:2014PhRvD..89f1302B (https://ui.adsabs.harvard.edu/abs/2014PhRvD..89f1302B). doi:10.1103/PhysRevD.89.061302 (https://doi.org/10.1103%2FPhysRevD.89.061302). "In the standard big bang inflationary model, the cosmic singularity problem is left unresolved and the cosmology is geodesically incomplete. Consequently, the origin of space and time and the peculiar, exponentially fine-tuned initial conditions required to begin inflation are not explained. In a recent series of papers, we have shown how to construct the complete set of homogeneous classical cosmological solutions of the standard model coupled to gravity, in which the cosmic singularity is replaced by a bounce: the smooth transition from contraction and big crunch to big bang and expansion."
127. Poplawski, N. J. (2010). "Cosmology with torsion: An alternative to cosmic inflation". *Physics Letters B*. **694** (3): 181–185. arXiv:1007.0587 (https://arxiv.org/abs/1007.0587). Bibcode:2010PhLB..694..181P (https://ui.adsabs.harvard.edu/abs/2010PhLB..694..181P). doi:10.1016/j.physletb.2010.09.056 (https://doi.org/10.1016%2Fj.physletb.2010.09.056).
128. Poplawski, N. (2012). "Nonsingular, big-bounce cosmology from spinor-torsion coupling". *Physical Review D*. **85** (10): 107502. arXiv:1111.4595 (https://arxiv.org/abs/1111.4595). Bibcode:2012PhRvD..85j7502P (https://ui.adsabs.harvard.edu/abs/2012PhRvD..85j7502P). doi:10.1103/PhysRevD.85.107502 (https://doi.org/10.1103%2FPhysRevD.85.107502).
129. J.P. Petit (1988). "An interpretation of cosmological model with variable light velocity" (https://web.archive.org/web/20150203223151/http://bigravitytheory.com/pdf/modern_physics_letters_a1.pdf) (PDF). *Modern Physics Letters A*. **3** (16): 1527–1532. Bibcode:1988MPLA....3.1527P (https://ui.adsabs.harvard.edu/abs/1988MPLA....3.1527P). CiteSeerX 10.1.1.692.9603 (https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.692.9603). doi:10.1142/S0217732388001823 (https://doi.org/10.1142%2FS0217732388001823). Archived from the original (http://www.bigravitytheory.com/pdf/modern_physics_letters_a1.pdf) (PDF) on 3 February 2015. Retrieved 24 December 2014.
130. J.P. Petit (1988). "Cosmological model with variable light velocity: the interpretation of red shifts" (https://web.archive.org/web/20140718123926/http://bigravitytheory.com/pdf/modern_physics_letters_a2.pdf) (PDF). *Modern Physics Letters A*. **3** (18): 1733–1744. Bibcode:1988MPLA....3.1733P (https://ui.adsabs.harvard.edu/abs/1988MPLA....3.1733P). CiteSeerX 10.1.1.692.9067 (https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.692.9067). doi:10.1142/S0217732388002099 (https://doi.org/10.1142%2FS0217732388002099). Archived from the original (http://www.bigravitytheory.com/pdf/modern_physics_letters_a2.pdf) (PDF) on 18 July 2014. Retrieved 24 December 2014.
131. J.P. Petit; M. Viton (1989). "Gauge cosmological model with variable light velocity. Comparizon with QSO observational data" (https://web.archive.org/web/20150204010624/http://bigravitytheory.com/pdf/modern_physics_letters_a3.pdf) (PDF). *Modern Physics Letters A*. **4** (23): 2201–2210. Bibcode:1989MPLA....4.2201P (https://ui.adsabs.harvard.edu/abs/1989MPLA....4.2201P). doi:10.1142/S0217732389002471 (https://doi.org/10.1142%2FS0217732389002471). Archived from the original (http://www.bigravitytheory.com/pdf/modern_physics_letters_a3.pdf) (PDF) on 4 February 2015. Retrieved 24 December 2014.
132. P. Midy; J.P. Petit (1989). "Scale invariant cosmology" (https://web.archive.org/web/20140717164810/http://bigravitytheory.com/pdf/scale_inv.pdf) (PDF) (8): 271–280. Archived from the original (http://www.bigravitytheory.com/pdf/scale_inv.pdf) (PDF) on 17 July 2014. Retrieved 24 December 2014.
133. J. Moffat (1993). "Superluminary Universe: A Possible Solution to the Initial Value Problem in Cosmology". *International Journal of Modern Physics D*. **2** (3): 351–366. arXiv:gr-qc/9211020 (https://arxiv.org/abs/gr-qc/9211020). Bibcode:1993IJMPD...2..351M (https://ui.adsabs.harvard.edu/abs/1993IJMPD...2..351M). CiteSeerX 10.1.1.339.6182 (https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.339.6182). doi:10.1142/S0218271893000246 (https://doi.org/10.1142%2FS0218271893000246).

134. J.D. Barrow (1998). "Cosmologies with varying light-speed". *Physical Review D*. **59** (4): 043515. arXiv:astro-ph/9811022 (https://arxiv.org/abs/astro-ph/9811022). Bibcode:1999PhRvD..59d3515B (https://ui.adsabs.harvard.edu/abs/1999PhRvD..59d3515B). CiteSeerX 10.1.1.256.8442 (https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.256.8442). doi:10.1103/PhysRevD.59.043515 (https://doi.org/10.1103%2FPhysRevD.59.043515).
135. A. Albrecht; J. Magueijo (1999). "A time varying speed of light as a solution to cosmological puzzles". *Physical Review D*. **59** (4): 043516. arXiv:astro-ph/9811018 (https://arxiv.org/abs/astro-ph/9811018). Bibcode:1999PhRvD..59d3516A (https://ui.adsabs.harvard.edu/abs/1999PhRvD..59d3516A). doi:10.1103/PhysRevD.59.043516 (https://doi.org/10.1103%2FPhysRevD.59.043516).
136. J. Magueijo (2000). "Covariant and locally Lorentz-invariant varying speed of light theories". *Physical Review D*. **62** (10): 103521. arXiv:gr-qc/0007036 (https://arxiv.org/abs/gr-qc/0007036). Bibcode:2000PhRvD..62j3521M (https://ui.adsabs.harvard.edu/abs/2000PhRvD..62j3521M). doi:10.1103/PhysRevD.62.103521 (https://doi.org/10.1103%2FPhysRevD.62.103521).
137. J. Magueijo (2001). "Stars and black holes in varying speed of light theories" (http://cds.cern.ch/record/473573). *Physical Review D* (Submitted manuscript). **63** (4): 043502. arXiv:astro-ph/0010591 (https://arxiv.org/abs/astro-ph/0010591). Bibcode:2001PhRvD..63d3502M (https://ui.adsabs.harvard.edu/abs/2001PhRvD..63d3502M). doi:10.1103/PhysRevD.63.043502 (https://doi.org/10.1103%2FPhysRevD.63.043502).
138. J. Magueijo (2003). "New varying speed of light theories". *Reports on Progress in Physics*. **66** (11): 2025–2068. arXiv:astro-ph/0305457 (https://arxiv.org/abs/astro-ph/0305457). Bibcode:2003RPPh...66.2025M (https://ui.adsabs.harvard.edu/abs/2003RPPh...66.2025M). doi:10.1088/0034-4885/66/11/R04 (https://doi.org/10.1088%2F0034-4885%2F66%2F11%2FR04).
139. J. Magueijo (2003). *Faster Than the Speed of Light: The Story of a Scientific Speculation* (https://archive.org/details/fasterthanspeedo00magu). Massachusetts: Perseus Books Group. ISBN 978-0-7382-0525-0.
140. Brandenberger, R; Vafa, C. (1989). "Superstrings in the early universe" (http://www.to.infn.it/~gasperin/ps/brown673.ps). *Nuclear Physics B*. **316** (2): 391–410. Bibcode:1989NuPhB.316..391B (https://ui.adsabs.harvard.edu/abs/1989NuPhB.316..391B). CiteSeerX 10.1.1.56.2356 (https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.56.2356). doi:10.1016/0550-3213(89)90037-0 (https://doi.org/10.1016%2F0550-3213%2889%2990037-0).
141. Battefeld, Thorsten; Watson, Scott (2006). "String Gas Cosmology". *Reviews of Modern Physics*. **78** (2): 435–454. arXiv:hep-th/0510022 (https://arxiv.org/abs/hep-th/0510022). Bibcode:2006RvMP...78..435B (https://ui.adsabs.harvard.edu/abs/2006RvMP...78..435B). doi:10.1103/RevModPhys.78.435 (https://doi.org/10.1103%2FRevModPhys.78.435).
142. Brandenberger, Robert H.; Nayeri, ALI; Patil, Subodh P.; Vafa, Cumrun (2007). "String Gas Cosmology and Structure Formation" (http://cds.cern.ch/record/978863). *International Journal of Modern Physics A* (Submitted manuscript). **22** (21): 3621–3642. arXiv:hep-th/0608121 (https://arxiv.org/abs/hep-th/0608121). Bibcode:2007IJMPA..22.3621B (https://ui.adsabs.harvard.edu/abs/2007IJMPA..22.3621B). doi:10.1142/S0217751X07037159 (https://doi.org/10.1142%2FS0217751X07037159).
143. Penrose, Roger (2004). *The Road to Reality: A Complete Guide to the Laws of the Universe*. London: Vintage Books, p. 755. See also Penrose, Roger (1989). "Difficulties with Inflationary Cosmology". *Annals of the New York Academy of Sciences*. **271**: 249–264. Bibcode:1989NYASA.571..249P (https://ui.adsabs.harvard.edu/abs/1989NYASA.571..249P). doi:10.1111/j.1749-6632.1989.tb50513.x (https://doi.org/10.1111%2Fj.1749-6632.1989.tb50513.x).
144. Ijjas, Anna; Steinhardt, Paul J.; Loeb, Abraham (2013). "Inflationary paradigm in trouble after Planck2013". *Physics Letters B*. **723** (4–5): 261–266. arXiv:1304.2785 (https://arxiv.org/abs/1304.2785). Bibcode:2013PhLB..723..261I (https://ui.adsabs.harvard.edu/abs/2013PhLB..723..261I). doi:10.1016/j.physletb.2013.05.023 (https://doi.org/10.1016%2Fj.physletb.2013.05.023).

145. Ijjas, Anna; Steinhardt, Paul J.; Loeb, Abraham (2014). "Inflationary schism after Planck2013". *Physics Letters B*. **736**: 142–146. arXiv:1402.6980 (https://arxiv.org/abs/1402.6980). Bibcode:2014PhLB..736..142I (https://ui.adsabs.harvard.edu/abs/2014PhLB..736..142I). doi:10.1016/j.physletb.2014.07.012 (https://doi.org/10.1016%2Fj.physletb.2014.07.012).
146. Guth, Alan H.; Kaiser, David I.; Nomura, Yasunori (2014). "Inflationary paradigm after Planck 2013". *Physics Letters B*. **733**: 112–119. arXiv:1312.7619 (https://arxiv.org/abs/1312.7619). Bibcode:2014PhLB..733..112G (https://ui.adsabs.harvard.edu/abs/2014PhLB..733..112G). doi:10.1016/j.physletb.2014.03.020 (https://doi.org/10.1016%2Fj.physletb.2014.03.020).
147. Linde, Andrei (2014). "Inflationary cosmology after Planck 2013". arXiv:1402.0526 (https://arxiv.org/abs/1402.0526) [hep-th (https://arxiv.org/archive/hep-th)].

References

- Guth, Alan (1997). *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins*. Perseus. ISBN 978-0-201-32840-0.
- Hawking, Stephen (1998). *A Brief History of Time*. Bantam. ISBN 978-0-553-38016-3.
- Hawking, Stephen; Gary Gibbons (1983). *The Very Early Universe*. Cambridge University Press. ISBN 978-0-521-31677-4.
- Kolb, Edward; Michael Turner (1988). *The Early Universe*. Addison-Wesley. ISBN 978-0-201-11604-5.
- Linde, Andrei (2005). *Particle Physics and Inflationary Cosmology*. Contemporary Concepts in Physics. **5**. pp. 1–362. arXiv:hep-th/0503203 (https://arxiv.org/abs/hep-th/0503203). Bibcode:2005hep.th....3203L (https://ui.adsabs.harvard.edu/abs/2005hep.th....3203L). ISBN 978-3-7186-0490-6.
- Linde, Andrei (2006). "Inflation and String Cosmology". *Progress of Theoretical Physics Supplement*. **163**: 295–322. arXiv:hep-th/0503195 (https://arxiv.org/abs/hep-th/0503195). Bibcode:2006PThPS.163..295L (https://ui.adsabs.harvard.edu/abs/2006PThPS.163..295L). doi:10.1143/PTPS.163.295 (https://doi.org/10.1143%2FPTPS.163.295).
- Liddle, Andrew; David Lyth (2000). *Cosmological Inflation and Large-Scale Structure*. Cambridge. ISBN 978-0-521-57598-0.
- Lyth, David H.; Riotto, Antonio (1999). "Particle physics models of inflation and the cosmological density perturbation". *Physics Reports*. **314** (1–2): 1–146. arXiv:hep-ph/9807278 (https://arxiv.org/abs/hep-ph/9807278). Bibcode:1999PhR...314....1L (https://ui.adsabs.harvard.edu/abs/1999PhR...314....1L). doi:10.1016/S0370-1573(98)00128-8 (https://doi.org/10.1016%2FS0370-1573%2898%2900128-8).
- Mukhanov, Viatcheslav (2005). *Physical Foundations of Cosmology*. Cambridge University Press. ISBN 978-0-521-56398-7.
- Vilenkin, Alex (2006). *Many Worlds in One: The Search for Other Universes* (https://archive.org/details/manyworldsinoneo00vile). Hill and Wang. ISBN 978-0-8090-9523-0.
- Peebles, P. J. E. (1993). *Principles of Physical Cosmology* (https://archive.org/details/principlesofphys00pjep). Princeton University Press. ISBN 978-0-691-01933-8.

External links

- Was Cosmic Inflation The 'Bang' Of The Big Bang? (http://nedwww.ipac.caltech.edu/level5/Guth/Guth_contents.html), by Alan Guth, 1997
- Andrew R Liddle (1999). "An introduction to cosmological inflation". *High Energy Physics and Cosmology*: 260. arXiv:astro-ph/9901124 (https://arxiv.org/abs/astro-ph/9901124). Bibcode:1999hepc.conf..260L (https://ui.adsabs.harvard.edu/abs/1999hepc.conf..260L).

- update 2004 (https://web.archive.org/web/20041120175509/http://www2.iap.fr/Conferences/Colloque/col2004/Docs/20040628_liddle.pdf) by Andrew Liddle
- Covi, Laura (2003). "Status of observational cosmology and inflation". *Physics in Collision*: 67. arXiv:hep-ph/0309238 (https://arxiv.org/abs/hep-ph/0309238). Bibcode:2003phco.conf...67C (https://ui.adsabs.harvard.edu/abs/2003phco.conf...67C).
- Lyth, David H. (2003). "Which is the best inflation model?". *String Phenomenology 2003*: 260. arXiv:hep-th/0311040 (https://arxiv.org/abs/hep-th/0311040). Bibcode:2003stph.conf..260L (https://ui.adsabs.harvard.edu/abs/2003stph.conf..260L).
- The Growth of Inflation (https://web.archive.org/web/20061002183844/http://www.symmetrymag.org/cms/?pid=1000045) *Symmetry*, December 2004
- Guth's logbook showing the original idea (https://web.archive.org/web/20061002193415/http://www.symmetrymag.org/cms/?pid=1000037)
- WMAP Bolsters Case for Cosmic Inflation, March 2006 (https://archive.today/20121216135256/http://skyandtelescope.com/news/article_1697_1.asp)
- NASA March 2006 WMAP press release (http://www.nasa.gov/home/hqnews/2006/mar/HQ_06097_first_trillionth_WMAP.html)
- Max Tegmark's *Our Mathematical Universe* (2014), "Chapter 5: Inflation" (http://space.mit.edu/home/tegmark/pdf/inflation_excerpt.pdf)
