



# **Cosmology's Mad Idea: Inflation & the Creation of Our Universe**

## **Lecture 1: Our Astronomical Future**

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### **23 September 2026**

#### *1. Introduction*

In my Gresham lectures to date, I've tried to stick to what we can understand about the Universe based on what we can observe. Our ability to test often quite baroque and grandiose theories, that describe exotic objects like black holes and conditions far from anything we can create on Earth, is astounding. As we'll see, a century of effort has led to an ability to speak with confidence about conditions in the Universe just a second or two after the Big Bang.

Yet my theoretical colleagues range much wider than our current technology allows us to test. From multiverses to considering a time before the Big Bang (or, indeed, the origins of time itself), much theoretical cosmology remains just that: theory. Tonight's topic, a crucial part of the cosmological framework, sits right between these worlds. For some scientists in the field, it is established beyond all reasonable doubt. Others fear it may remain forever untestable, in the realm of blackboard-driven speculation. (Almost) everyone agrees it solves a crucial problem in cosmology. Let's talk about inflation.

#### *2. Big Bang Basics*

The modern cosmological paradigm tells us that the Universe began in a hot dense state 13.8 billion years ago, and has been expanding ever since. This universal expansion can be measured<sup>1</sup>, but the most convincing evidence for this Big Bang model is the presence of the Cosmic Microwave Background (see previous Gresham lecture: <https://www.gresham.ac.uk/watch-now/first-light>), radiation emitted nearly 400,000 years after the start. The discovery of 'ripples' – regions of slightly varying temperature (and hence density) by the COBE satellite in 1992 – were interpreted as the seeds from which the large scale structure we see around us today grows under the influence of gravity. This basic picture is beautifully validated by modern supercomputer simulations, which, taking the initial conditions revealed by the CMB as a starting point do a great job of reproducing what we see.

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<sup>1</sup> And indeed, we can measure its rate of change too, leading to the mystifying discovery that it is currently speeding up under the influence of a force we call 'dark energy', whose nature remains puzzling.

What of the Universe before the time of the microwave background? We have surprisingly good evidence for what was happening in this sea of particles and high energy radiation, because the interaction between them produces the hydrogen and helium (and a little lithium and beryllium) that fills the cosmos. The ratio between the two is predicted by the theory, making an obviously falsifiable prediction for the detailed Big Bang. We can simply measure the hydrogen to helium ratio. Stars are machines for turning hydrogen into helium, so it's fine if we look around us and see an excess of helium – but we should never see a deficit. A result published in the last few weeks by Evan Skillman of Minnesota does exactly this test, looking at regions in distant galaxies where relatively little star formation has polluted the gas. Their results are consistent with the Big Bang predictions, as is more recent work by Miqaela Weller at Ohio State and colleagues, who have been studying stars themselves. As it has done for more than half a century now, the Big Bang model passes these stringent observational tests.

### *3. What sort of Universe are we in?*

As well as making detailed predictions, we want a well-founded theory to be able to explain the bulk properties of the cosmos. In a previous Gresham lecture, I reduced the Sun to being 'massive' and 'hot'. If you only know have two words to describe our Universe, then I'd go for 'isotropic' and 'flat'.

Let's take isotropy first. This just means that the Universe looks the same in all directions – on sufficiently large scales. This last bit is important, as on small scales the Universe definitely isn't isotropic (you can look down at the Earth or up at the sky, or through the disk of the Milky Way, or out of it). But take a big enough chunk and one can look in any direction without being able to discern any difference.

That feels like something we would want our theory of the Universe to explain, and yet the standard Big Bang picture struggles. If you imagine matter and energy randomly distributed in the early Universe, then a normal expansion would carry any differences forward into a decidedly non-isotropic present day. You can claim, if you like, that the Big Bang must necessarily produce an isotropic cosmos initially, but that seems like cheating. Instead, we want an explanation rooted in the theory of something that's happened since the Big Bang.

'Flat' requires some more unpicking. Einstein's insight taught us that gravity is essentially a distortion in space: as John Wheeler put it, 'Spacetime tells matter how to move; matter tells spacetime how to curve.' This way of thinking naturally leads us to considering the geometry of the Universe; on a large scale, is space flat, like a sheet of paper? Or does it curve, like the surface of a globe, or like a saddle<sup>2</sup>? Each of these geometries, shaped by both the initial conditions set by the Big Bang and the influence of matter since, would lead to a different past and future for the expanding cosmos.

If the physics that shaped the Big Bang picked a random geometry, we'd expect it to be either open (like a saddle) or closed (like a sphere). An equivalent statement is that, as the evolution of the Universe is dictated by its contents, if you pick randomly you almost certainly end up with a cosmos that collapses rapidly or expands too quickly to allow galaxies and other structure to form. In such Universes our existence would be unlikely, and yet, here we are. Furthermore, from measurements of the CMB and from studies of large scale structure

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<sup>2</sup> More specifically, like their four-dimensional equivalents.

(compared to those simulations I mentioned earlier), it seems resolutely flat. Once again, we need to believe the Big Bang can only produce flat Universes – or explain why we live in one regardless.

#### *4. A Spectacular Realisation*

The solution to both of these problems in modern cosmology is a deceptively simple idea called inflation. It emerged in the late 1970s and early 1980s through the work of an international group of physicists, sometimes competing and sometimes collaborating, but most clearly in the mind of a particle physicist called Alan Guth. One evening in December 1979, he had what he described in his notebook as a 'Spectacular Realisation' – that a period of inflation, rapid expansion slightly after the Big Bang (at something like  $10^{-37}$  seconds, in fact), could explain the flatness problem.

The required expansion is simultaneously modest – taking the volume of space that will form our observable Universe today from the size of a pinhead to that of a grapefruit – and spectacular, requiring this change to take place effectively instantaneously. This change allows the Universe pre-inflation to be much smaller, and thus to reach equilibrium, ironing out any initial inhomogeneity, before it blows up to form the isotropic cosmos we see today. The only remaining structures are initially tiny quantum fluctuations which are now blown up to the scale we see in the CMB. In this picture, the seeds of the largest structures we see are created by the physics of the very small.

Simultaneously, this rapid expansion explains the flatness – whatever the underlying geometry, we see only a tiny part of the whole Universe, and should be no more surprised that it appears flat than we should wonder that an ant is incapable of measuring the curvature of the Earth.

(A third significant problem is also solved by inflation, in that theories of the early Universe predict a large number of exotic particles known as magnetic monopoles should be created, and yet not a single one has ever shown up. If inflation happened, then they get spread throughout our now extremely large Universe, so we shouldn't be surprised we don't see any locally).

#### *5. Inflating Inflatons*

Inflation thus completes our standard picture of cosmology, explaining the large scale properties of the Universe produced by the Big Bang. However, this elegant explanation comes at a cost, which is that we need to invent a reason for it to have happened. Modern theories (of which there are many) tend to start from the idea of a field known as the 'inflaton', whose properties can be studied and explored. This field drives the rapid expansion, reducing the Universe to a supercooled state in doing so. As the expansion stops, the energy in the field reheats the Universe, producing the hot dense post-Big Bang state that our observations should exist.

There is a near infinite variety of theories along these general lines, with choices of the details constrained by ideas from string theory, guided by elegant mathematics, or just by personal choice. Many of them share a property known as eternal inflation which, on the basis that the rapid expansion produces more regions which are expanding than those where inflation has stopped, suggests that in most of the cosmos the rapid expansion never stops. What we might hitherto have thought of as 'our Universe' is just a bubble in this

expanding space, a small region – and almost certainly one of an infinite number – where a phase transition has occurred to slow the expansion. This model is thus a flavour of a multiverse theory, with each slowly expanding bubble evolving in isolation<sup>3</sup>.

## 6. *Testing inflation*

If you believe that the isotropy and flatness problems require solving (or are troubled by the lack of magnetic monopoles) then you might consider inflation a successful theory already: it predicts, after all, the exact sort of Universe we live in. However, some might argue that inflation was invented to solve precisely these problems, and while it's good it solves all of them that's not the same as being tested with new experiments.

Whichever side of this argument you find yourself, it's clear that it would be nice to know a bit more about how inflation operates, if only to distinguish between the hordes of theorists with their own favourite pet theories. Cosmologists, therefore, have spent a lot of effort and not a little angst chasing down the signs of inflation in the present-day Universe.

The target for much of this activity is the Cosmic Microwave Background. The dramatic events of the inflationary period would, we think, have caused gravitational waves – ripples in space produced whenever mass moves – to slosh around the early Universe. They would have left an imprint on the CMB, hundreds of thousands of years later, in the form of a particular style of polarization. (Polarization is an alignment of the electro-magnetic parts of light. It's most familiar from the use of sunglasses that cut out light scattered off the road surface; the scattering produces a particular polarization which the glasses can cut out, reducing glare).

Though it is possible to design viable forms of inflation that would not produce a detectable signal, seeing so-called 'B-mode' polarisation in the CMB would provide near-certainty that there was, indeed, a time when the Universe expanded rapidly. In 2015, the BICEP team, using telescopes which take advantage of the stable conditions and long night available at the South Pole, announced they'd seen just such a signal. Press releases were readied, Alan Guth featured in a promotional video, and the team did everything but buy their tickets to Stockholm for the Nobel Ceremony. The only problem was that it wasn't real.

The signal they had detected, it quickly became clear, was not cosmological but was due to the influence of dust in the Milky Way on the CMB radiation as it passed through the galaxy toward us. Working in secrecy as they thought a rival team were right behind them<sup>4</sup>, the team had misapplied the model they used for accounting for this effect, and been misled as a result. In a tale of frightening scientific hubris, the story fell apart in a matter of days after the immediate splash of publicity.

Yet experiments continue, and though so far all that has been achieved is limits on the strength of an inflationary polarization signal, hope springs eternal that something will someday be seen. Many theories of inflation also make predictions about the fluctuations we do see in the CMB; if these are quantum fluctuations blown up to macroscopic scales, then we should be able to predict their nature. In particular, cosmologists think that they can

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<sup>3</sup> Physicists would dearly love there to be enough bubbles for them to interact, perhaps imprinting on the sky or in the CMB the signature of the physics that creates them. Despite occasional controversial claims, no significant evidence has been found.

<sup>4</sup> They weren't: at the time BICEP was the leading experiment by quite some way, as it turns out.

predict the size distribution: how many large fluctuations should exist compared to smaller ones.

Simple models of inflation predict that this distribution should nearly – but not quite (!) – have a property which physicists call ‘scale invariance’. (This is a way of distributing energy between perturbations of different sizes). As best we can tell, from observations from ESA’s *Planck* satellite, this is indeed what we see – the CMB spectrum is slightly skewed towards more power in fluctuations on large scales. While this result depends slightly on which dataset you choose to use, it seems clear that this is a real property of the Universe.

### 7. An inflationary cosmos

The story of inflation is a remarkable one. Invented by theorists in an attempt to explain the most fundamental observations we have of the Universe, after decades of effort this theory is now sophisticated enough to predict observations we can make. In turn, as observational efforts become more sophisticated, with the launch of space-based observatories such as *Planck* as well as the development of new ground based facilities, real constraints of these seemingly obtuse theories are possible. This revolution demands of us a shift in perspective which is not easy for a non-theoretical physicist. The fundamental driving force (to use inappropriate language) is a field – the inflaton – whose development made our universe possible. The familiar language of particles and forces fades away to be replaced by this higher mathematics, which might hold within it a description of an eternally inflating Universe far greater than our little bubble. What started as a fudge to solve a problem is probably the greatest triumph of 21<sup>st</sup> century cosmology – and if we’re lucky, more discoveries are imminent.

## References and Further Reading

The literature on inflation gets very technical fast.

For a general background to the early Universe, I strongly recommend the classic ‘First Three Minutes’ by Stephen Weinberg, (updated 1993, Basic Books, ISBN 978-0465024377)

The new Big Bang Nucleosynthesis results I talk about are in two papers:

The LBT  $Y_p$  Project. I. An Improved Determination of the Primordial Helium Abundance-Project Description, Sample Selection, Observations, and Methodology by Silkman et al, *Astrophysical Journal*, 1008, 2, 237 available at <https://arxiv.org/abs/2601.22232>

And

‘Evidence for Enhanced Helium Enrichment from Asteroseismology’ by Weller et al available as a preprint at <https://arxiv.org/pdf/2609.05604>

Alan Guth himself provides a history and description of inflation in ‘The Inflationary Universe: The Quest for a New Theory of Cosmic Origins’, 1998, Vintage, ISBN 978-0099959502

A more recent (technical but readable) introduction is given by Andrew Liddle at <https://arxiv.org/abs/astro-ph/9901124>

An excellent readable guide is in the recent 'An Infinity of Worlds : Cosmic Inflation and the Beginning of the Universe', by Will Kinney, MIT Press, 2023, ISBN 9780262547222

A decent summary of the status of the Planck results is given by Bouchet in Comptes rendus - Physique, Volume 16, Issue 10, p. 891-913.

<https://ui.adsabs.harvard.edu/abs/2015CRPhy..16..891B/abstract> (For the 2015 results, but applicable to 2018)

An interesting insider story of the BICEP kaffuffle (told from a particular point of view) is given in 'Losing the Nobel Prize: A Story of Cosmology, Ambition, and the Perils of Science's Highest Honor', Brian Keating, 2018, Norton & Company, ISBN 978-1324000914

September 2026's Sky at Night included a feature on an attempt to test inflationary cosmology via a lab experiment. You can find this at [www.bbc.co.uk/skyatnight](http://www.bbc.co.uk/skyatnight) or on the iPlayer.