INFLATIONARY COSMOLOGY:
IS OUR UNIVERSE PART OF A MULTIVERSE?

PART 1

— Alan Guth —

8.286 Opening Lecture
September 7, 2016
The Standard Big Bang

What it is:

★ Theory that the universe as we know it began 13-14 billion years ago. (Latest estimate: $13.82 \pm 0.05$ billion years!)

★ Initial state was a hot, dense, uniform soup of particles that filled space uniformly, and was expanding rapidly.
The Standard Big Bang

What it is:

★ Theory that the universe as we know it began 13-14 billion years ago. (Latest estimate: 13.82 ± 0.05 billion years!)
★ Initial state was a hot, dense, uniform soup of particles that filled space uniformly, and was expanding rapidly.

What it describes:

★ How the early universe expanded and cooled
★ How the light chemical elements formed
★ How the matter congealed to form stars, galaxies, and clusters of galaxies
What it doesn't describe:

★ What caused the expansion? (The big bang theory describes only the aftermath of the bang.)

★ Where did the matter come from? (The theory assumes that all matter existed from the very beginning.)
What it doesn't describe:

★ What caused the expansion? (The big bang theory describes only the *aftermath* of the bang.)
★ Where did the matter come from? (The theory assumes that all *matter* existed from the very beginning.)

In other words, it says nothing about what banged,
What it doesn't describe:

★ What caused the expansion? (The big bang theory describes only the *aftermath* of the bang.)

★ Where did the matter come from? (The theory assumes that *all* matter existed from the very beginning.)

In other words, it says nothing about what banged, why it banged,
What it doesn't describe:

★ What caused the expansion? (The big bang theory describes only the **aftermath** of the bang.)

★ Where did the matter come from? (The theory assumes that all **matter** existed from the very beginning.)

In other words, it says nothing about what banged, why it banged, or what happened before it banged!
What is Inflation?

★ Inflation is a “prequel” to the conventional big bang picture.
What is Inflation?

★ Inflation is a “prequel” to the conventional big bang picture.
★ In particular, inflation is a theory about the bang of the big bang. That is, inflation is a possible answer to the question of what propelled the gigantic expansion of the big bang.
What is Inflation?

★ Inflation is a “prequel” to the conventional big bang picture.
★ In particular, inflation is a theory about the bang of the big bang. That is, inflation is a possible answer to the question of what propelled the gigantic expansion of the big bang.
★ Inflation is also a possible answer to the question of where almost all of the matter came from.
What is Inflation?

★ Inflation is a “prequel” to the conventional big bang picture.

★ In particular, inflation is a theory about the bang of the big bang. That is, inflation is a possible answer to the question of what propelled the gigantic expansion of the big bang.

★ Inflation is also a possible answer to the question of where almost all of the matter came from.

★ Inflation is **NOT** a theory of the origin of the universe, but it can explain how the entire observed universe emerged from a patch only $10^{-28}$ cm across, with a mass of only a few grams.
What is Inflation?

★ Inflation is a “prequel” to the conventional big bang picture.

★ In particular, inflation is a theory about the bang of the big bang. That is, inflation is a possible answer to the question of what propelled the gigantic expansion of the big bang.

★ Inflation is also a possible answer to the question of where almost all of the matter came from.

★ Inflation is **NOT** a theory of the origin of the universe, but it can explain how the entire observed universe emerged from a patch only $10^{-28}$ cm across, with a mass of only a few grams.

★ Inflation explains the expansion by means of
What is Inflation?

★ Inflation is a “prequel” to the conventional big bang picture.

★ In particular, inflation is a theory about the bang of the big bang. That is, inflation is a possible answer to the question of what propelled the gigantic expansion of the big bang.

★ Inflation is also a possible answer to the question of where almost all of the matter came from.

★ Inflation is NOT a theory of the origin of the universe, but it can explain how the entire observed universe emerged from a patch only $10^{-28}$ cm across, with a mass of only a few grams.

★ Inflation explains the expansion by means of

Gravitational Repulsion.
Two Miracles of Physics
Two Miracles of Physics

Definition:
Two Miracles of Physics

Definition: A “miracle of physics” is a feature of the laws of physics which
Two Miracles of Physics

Definition: A “miracle of physics” is a feature of the laws of physics which

(a) was never taught to me when I was a student;
Two Miracles of Physics

Definition: A “miracle of physics” is a feature of the laws of physics which

(a) was never taught to me when I was a student; and

(b) is so far-reaching in its consequences that it can change our picture of the universe.
Miracle of Physics #1: Gravitational Repulsion

★ Since the advent of general relativity, physicists have known that gravity can act repulsively.

★ In GR, pressures can create gravitational fields, and negative pressures create repulsive gravitational fields.

★ Einstein used this possibility, in the form of the “cosmological constant,” to build a static mathematical model of the universe, with repulsive gravity preventing its collapse.

★ Modern particle physics suggests that at superhigh energies there should be many states with negative pressures, creating repulsive gravity.
Inflation proposes that a patch of repulsive gravity material existed in the early universe — for inflation at the grand unified theory scale ($\sim 10^{16}$ GeV), the patch needs to be only as large as $10^{-28}$ cm. (Since any such patch is enlarged fantastically by inflation, the initial density or probability of such patches can be very low.)
Inflation proposes that a patch of repulsive gravity material existed in the early universe — for inflation at the grand unified theory scale ($\sim 10^{16}$ GeV), the patch needs to be only as large as $10^{-28}$ cm. (Since any such patch is enlarged fantastically by inflation, the initial density or probability of such patches can be very low.)

$1 \text{ GeV} \approx \text{mass energy of a proton.}$
Inflation proposes that a patch of repulsive gravity material existed in the early universe — for inflation at the grand unified theory scale ($\sim 10^{16}$ GeV), the patch needs to be only as large as $10^{-28}$ cm. (Since any such patch is enlarged fantastically by inflation, the initial density or probability of such patches can be very low.)

$1$ GeV $\approx$ mass energy of a proton.

The gravitational repulsion created by this material was the driving force behind the big bang. The repulsion drove it into exponential expansion, doubling in size every $10^{-37}$ second or so!
The patch expanded exponentially by a factor of at least $10^{28}$ ($\sim 100$ doublings), but it could have expanded much more. Inflation lasted maybe $10^{-35}$ second, and at the end, the region destined to become the presently observed universe was about the size of a marble.

The repulsive-gravity material is unstable, so it decayed like a radioactive substance, ending inflation. The decay released energy which produced ordinary particles, forming a hot, dense “primordial soup.” Standard cosmology began.
The patch expanded exponentially by a factor of at least $10^{28}$ ($\sim 100$ doublings), but it could have expanded much more. Inflation lasted maybe $10^{-35}$ second, and at the end, the region destined to become the presently observed universe was about the size of a marble.

The repulsive-gravity material is unstable, so it decayed like a radioactive substance, ending inflation. The decay released energy which produced ordinary particles, forming a hot, dense “primordial soup.” Standard cosmology began.

Caveat: The decay happens almost everywhere, but not everywhere — we will come back to this subtlety, which is the origin of eternal inflation.
After the repulsive-gravity material decayed, the universe continued to coast and cool from then onward.
After the repulsive-gravity material decayed, the universe continued to coast and cool from then onward.

Key feature: During the exponential expansion, the density of matter and energy did NOT thin out. The density of the repulsive gravity material was not lowered as it expanded!
After the repulsive-gravity material decayed, the universe continued to coast and cool from then onward.

Key feature: During the exponential expansion, the density of matter and energy did NOT thin out. The density of the repulsive gravity material was **not lowered** as it expanded!

Although more and more mass/energy appeared as the repulsive-gravity material expanded, total energy was conserved!
After the repulsive-gravity material decayed, the universe continued to coast and cool from then onward.

Key feature: During the exponential expansion, the density of matter and energy did NOT thin out. The density of the repulsive gravity material was not lowered as it expanded!

Although more and more mass/energy appeared as the repulsive-gravity material expanded, total energy was conserved! HOW????
Miracle of Physics #2:
Energy is Conserved, But Not Always Positive
Miracle of Physics #2: Energy is Conserved, But Not Always Positive

★ The energy of a gravitational field is negative (both in Newtonian gravity and in general relativity).

★ The negative energy of gravity cancelled the positive energy of matter, so the total energy was constant and possibly zero.
Miracle of Physics #2:
Energy is Conserved, But Not Always Positive

★ The energy of a gravitational field is negative (both in Newtonian gravity and in general relativity).

★ The negative energy of gravity cancelled the positive energy of matter, so the total energy was constant and possibly zero.

★ The total energy of the universe today is consistent with zero. Schematically,
1) Large scale uniformity. The cosmic background radiation is uniform in temperature to one part in 100,000. It was released when the universe was about 400,000 years old. In standard cosmology without inflation, a mechanism to establish this uniformity would need to transmit energy and information at about 100 times the speed of light.
Evidence for Inflation

1) **Large scale uniformity.** The cosmic background radiation is uniform in temperature to one part in 100,000. It was released when the universe was about 400,000 years old. In standard cosmology without inflation, a mechanism to establish this uniformity would need to transmit energy and information at about 100 times the speed of light.

**Inflationary Solution:** In inflationary models, the universe begins so small that uniformity is easily established — just like the air in the lecture hall spreading to fill it uniformly. Then inflation stretches the region to be large enough to include the visible universe.
2) “Flatness problem:”

Why was the early universe so FLAT?
2) “Flatness problem:”

Why was the early universe so FLAT?

What is meant by “flat”?
2) **“Flatness problem:”**

Why was the early universe so **FLAT**?

What is meant by “flat”?

★ Flat does not mean 2-dimensional.

★ Flat means Euclidean, as opposed to the non-Euclidean curved spaces that are also allowed by Einstein’s general relativity.
2) “Flatness problem:”

Why was the early universe so **FLAT**?

What is meant by “flat”?

★ Flat does not mean 2-dimensional.

★ Flat means Euclidean, as opposed to the non-Euclidean curved spaces that are also allowed by Einstein’s general relativity.

★ 3-dimensional curved spaces are hard to visualize, but they are analogous to the 2-dimensional curved surfaces shown on the right.
According to general relativity, the flatness of the universe is related to its mass density:

\[
\Omega(\text{Omega}) = \frac{\text{actual mass density}}{\text{critical mass density}},
\]

where the “critical density” depends on the expansion rate. \( \Omega = 1 \) is flat, \( \Omega \) greater than 1 is closed, \( \Omega \) less than 1 is open.
A universe at the critical density is like a pencil balancing on its tip:

If $\Omega$ in the early universe was slightly below 1, it would rapidly fall to zero — and no galaxies would form.

If $\Omega$ was slightly greater than 1, it would rapidly rise to infinity, the universe would recollapse, and no galaxies would form.
A universe at the critical density is like a pencil balancing on its tip:

If $\Omega$ in the early universe was slightly below 1, it would rapidly fall to zero — and no galaxies would form.

If $\Omega$ was slightly greater than 1, it would rapidly rise to infinity, the universe would recollapse, and no galaxies would form.

To be as close to critical density as we measure today, at one second after the big bang, $\Omega$ must have been equal to one to 15 decimal places!
**Inflationary Solution:** Since inflation makes gravity become repulsive, the evolution of $\Omega$ changes, too. $\Omega$ is driven towards one, extremely rapidly. It could begin at almost any value.
**Inflationary Solution:** Since inflation makes gravity become repulsive, the evolution of $\Omega$ changes, too. $\Omega$ is driven towards one, extremely rapidly. It could begin at almost any value.

Since the mechanism by which inflation explains the flatness of the early universe almost always overshoots, it predicts that even today the universe should have a critical density.
Inflationary Solution: Since inflation makes gravity become repulsive, the evolution of $\Omega$ changes, too. $\Omega$ is driven towards one, extremely rapidly. It could begin at almost any value.

Since the mechanism by which inflation explains the flatness of the early universe almost always overshoots, it predicts that even today the universe should have a critical density.

Until 1998, observation pointed to $\Omega \approx 0.2–0.3$. 

★
**Inflationary Solution:** Since inflation makes gravity become repulsive, the evolution of $\Omega$ changes, too. $\Omega$ is driven towards one, extremely rapidly. It could begin at almost any value.

Since the mechanism by which inflation explains the flatness of the early universe almost always overshoots, it predicts that even today the universe should have a critical density.

Until 1998, observation pointed to $\Omega \approx 0.2$–$0.3$.

Latest observation by Planck satellite (combined with other astronomical observations):

$$\Omega = 1.0008 \pm 0.0040 \text{ (95\% confidence)}$$
**Inflationary Solution:** Since inflation makes gravity become repulsive, the evolution of $\Omega$ changes, too. $\Omega$ is driven towards one, extremely rapidly. It could begin at almost any value.

Since the mechanism by which inflation explains the flatness of the early universe almost always overshoots, it predicts that even today the universe should have a critical density.

Until 1998, observation pointed to $\Omega \approx 0.2–0.3$.

Latest observation by Planck satellite (combined with other astronomical observations):

$$\Omega = 1.0008 \pm 0.0040 \text{ (95\% confidence)}$$

New ingredient: Dark Energy. In 1998 it was discovered that the expansion of the universe has been accelerating for about the last 5 billion years. The “Dark Energy” is the energy causing this to happen.
3) **Small scale nonuniformity:** Can be measured in the cosmic background radiation. The intensity is almost uniform across the sky, but there are small ripples. Although these ripples are only at the level of 1 part in 100,000, these nonuniformities are now detectable! Where do they come from?
3) **Small scale nonuniformity:** Can be measured in the cosmic background radiation. The intensity is almost uniform across the sky, but there are small ripples. Although these ripples are only at the level of 1 part in 100,000, these nonuniformities are now detectable! Where do they come from?

**Inflationary Solution:** Inflation attributes these ripples to *quantum fluctuations*. Inflation makes generic predictions for the spectrum of these ripples (i.e., how the intensity varies with wavelength). The data measured so far agree beautifully with inflation.
Ripples in the Cosmic Microwave Background

Planck Collaboration: The Planck mission

\( \mu K_{\text{cmb}} \)
CMB: Comparison of Theory and Experiment

Graph by Max Tegmark, for A. Guth & D. Kaiser, Science 307, 884 (Feb 11, 2005), updated to include WMAP 7-year data.
Inflation with Dark Energy

Multipole $\ell$

Temperature fluctuation $\delta T$ [\(\mu K\)]

Angular wavelength in degrees

Graph by Max Tegmark, for A. Guth & D. Kaiser, Science 307, 884 (Feb 11, 2005), updated to include WMAP 7-year data.
CMB: Comparison of Theory and Experiment

Graph by Max Tegmark, for A. Guth & D. Kaiser, Science 307, 884 (Feb 11, 2005), updated to include WMAP 7-year data.
Spectrum of CMB Ripples

Planck Collaboration, 2013