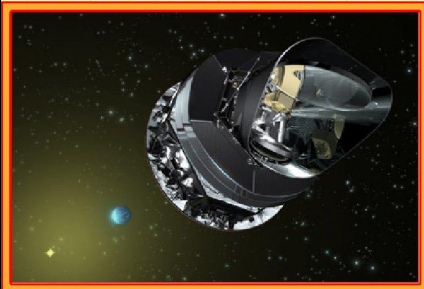


INFLATIONARY COSMOLOGY:

IS OUR UNIVERSE
PART OF
A MULTIVERSE?

PART 1



— Alan Guth —



Massachusetts Institute of Technology

8.286 Opening Lecture
September 5, 2018

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



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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!



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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.



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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.)

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!

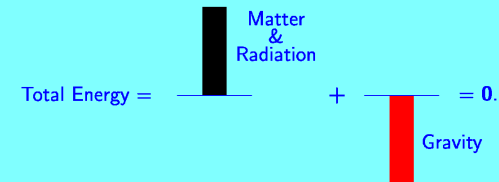
- ★ The patch expanded exponentially by a factor of at least 10^{28} (~ 100 doublings), but it could have expanded much more. Inflation lasted maybe 10^{-35} second, and at the end, the region destined to become the presently observed universe was about the size of a marble.
- ★ The repulsive-gravity 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.
- ★ 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

- ★ 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,

$$\text{Total Energy} = \begin{array}{c} \text{Matter} \\ \& \\ \text{Radiation} \end{array} + \begin{array}{c} \text{Gravity} \end{array} = 0.$$


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.