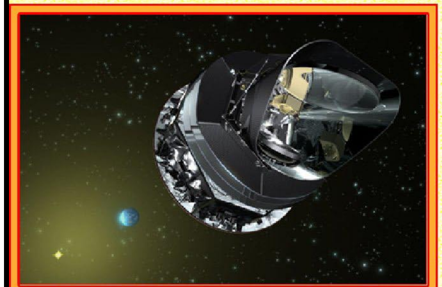
INFLATIONARY COSMOLOGY:

IS OUR UNIVERSE PART OF A MULTIVERSE?



— Alan Guth —

Massachusetts Institute of Technology

8.286 Opening Lecture
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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.)

In other words, it says nothing about what banged, why it banged, or what happened before it banged!

Cosmic Inflation

- ☆ Inflation is a modification of the standard big bang theory, providing a very brief "prequel".
- ☆ Inflation can explain the bang of the big bang (i.e, the outward propulsion), in terms of

☆ Miracle of Physics #1:

Gravitational Repulsion!

- ☆ The combination of general relativity and modern particle theories predicts that, at very high energies, there exists forms of matter that create a gravitational repulsion! (In general relativity, gravitational repulsion is created by negative pressures.)

☆ 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.

Caveat: The decay happens almost everywhere, but not everywhere — we will come back to this subtlety, which is the origin of eternal inflation.

☆ The density of the repulsive gravity material was **not lowered** as it expanded!

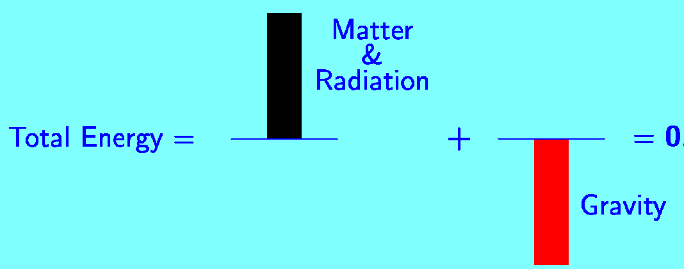
☆ Although more and more mass/energy appeared as the repulsive-gravity material expanded, total energy was conserved!

☆ Miracle of Physics #2:

The energy of a gravitational field is negative!

☆ The positive energy of the repulsive gravity material was compensated by the negative energy of gravity. The TOTAL ENERGY of the universe may very well be zero.

Schematically,



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.

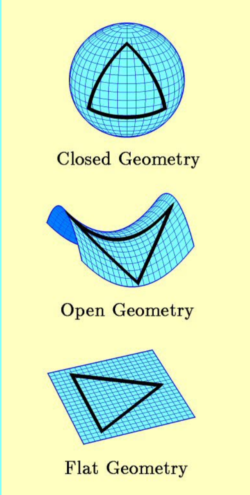
Inflationary Solution: In inflationary models, the universe begins so small that uniformity is easily established — just like the air in the lecture hall spreading to fill it uniformly. Then inflation stretches the region to be large enough to include the visible universe.

2) **"Flatness problem:"**

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

What is meant by "flat"?

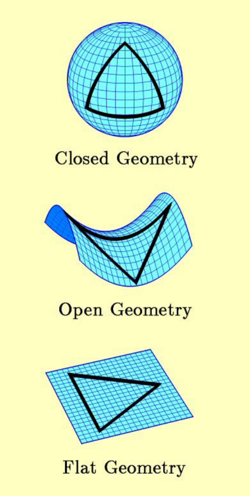
- ☆ Flat does not mean 2-dimensional.
- ☆ Flat means Euclidean, as opposed to the non-Euclidean curved spaces that are also allowed by Einstein's general relativity.
- ☆ 3-dimensional curved spaces are hard to visualize, but they are analogous to the 2-dimensional curved surfaces shown on the right.



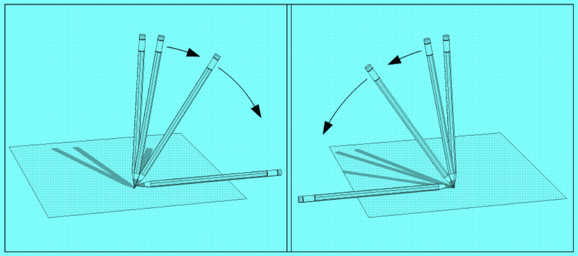
- ☆ According to general relativity, the flatness of the universe is related to its mass density:

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

where the "critical density" depends on the expansion rate. $\Omega = 1$ is flat, Ω greater than 1 is closed, Ω less than 1 is open.



- ☆ A universe at the critical density is like a pencil balancing on its tip:



- ☆ If Ω in the early universe was slightly below 1, it would rapidly fall to zero — and no galaxies would form.
- ☆ If Ω 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, Ω must have been equal to one **to 15 decimal places!**

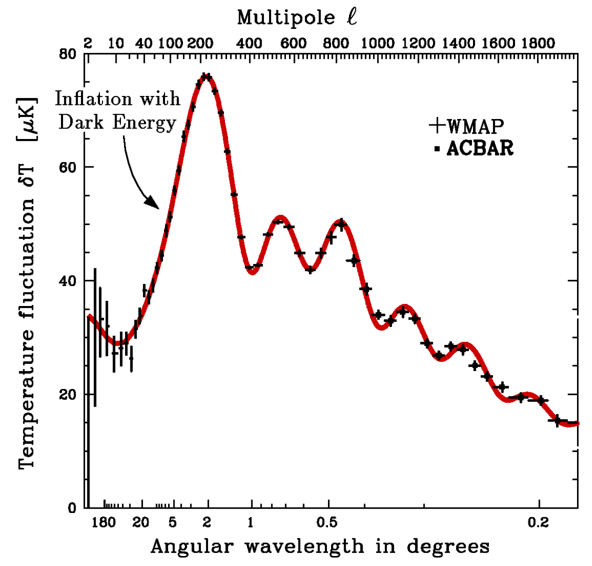
- **Inflationary Solution:** Since inflation makes gravity become repulsive, the evolution of Ω changes, too. Ω is driven towards one, extremely rapidly. It could begin at almost any value.
- Since the mechanism by which inflation explains the flatness of the early universe almost always overshoots, 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 astonomical observations):

$$\Omega = 1.0010 \pm 0.0065$$

- 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.

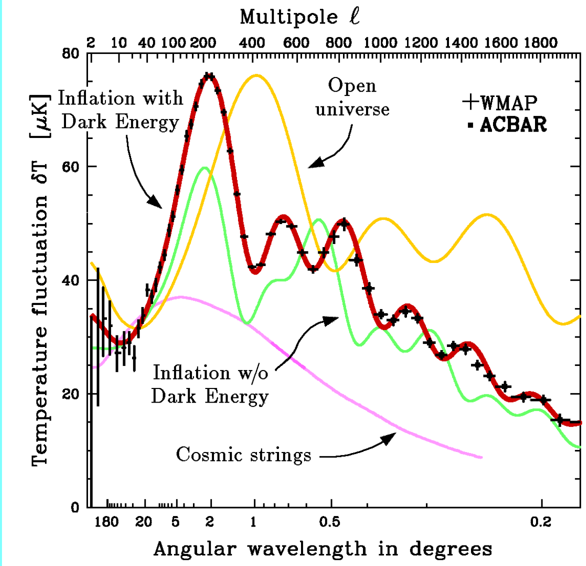
3) **Small scale nonuniformity:** Can be measured in the cosmic background radiation. The intensity is almost uniform across the sky, but there are small ripples. Although these ripples are only at the level of 1 part in 100,000, these nonuniformities are now detectable! Where do they come from?

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.



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.



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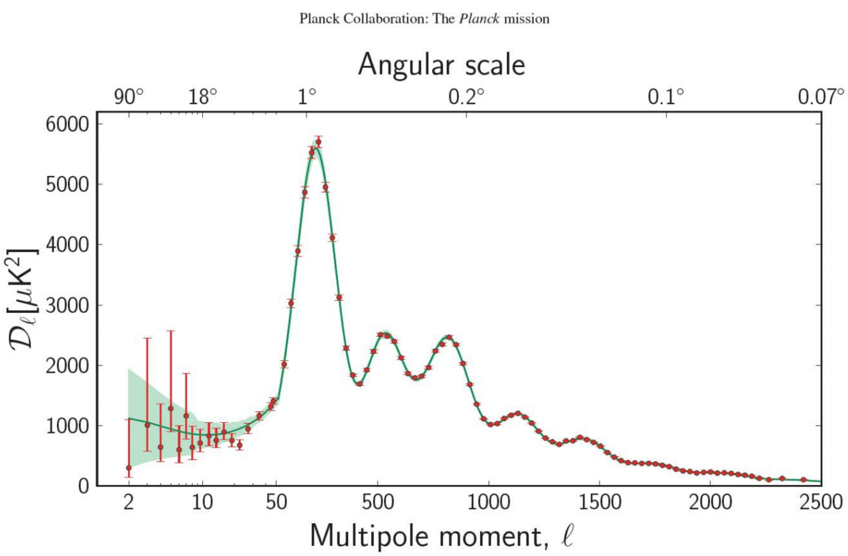

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Universe to Multiverse

- The repulsive gravity material that drives the inflation is metastable. In any one location, the probability of remaining in an inflating state decreases with time — usually exponentially.
- BUT, the universe in the meantime is expanding exponentially. In any successful version of inflation, the exponential expansion is faster than the exponential decay! Therefore,

  The volume that is inflating increases with time, even though the inflating material is decaying!
- The inflation becomes eternal — once it starts, it never stops. The inflating region never disappears, but pieces of it undergo decay and produce **"pocket universes,"** ad infinitum.
- Instead of one universe, inflation produces an infinite number —

  A Multiverse

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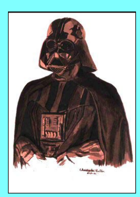
DARK ENERGY
Key Mystery of the Universe

In 1998, astronomers discovered that the universe has been accelerating for about the last 5 billion years (out of its 14 billion year history).

IMPLICATION: Inflation is happening today, so the universe today is filled with a repulsive gravity material. (Within general relativity, this requires negative pressure.) The repulsive gravity material, which apparently fills space, is called the ***"Dark Energy."***



WHAT IS THE DARK ENERGY? Who knows?

SIMPLEST EXPLANATION: Dark energy = vacuum energy, also known as a cosmological constant.

The NIGHTMARE of DARK ENERGY

- The quantum vacuum is far from empty, so a nonzero energy density is no problem.
- In quantum field theory, the energy density of quantum fluctuations diverges. All wavelengths contribute, and there is no shortest wavelength.
- A plausible cutoff for the fluctuations is the Planck length, $\sim 10^{-33}$ cm, the scale of quantum gravity.
- Using this cutoff, the estimated vacuum energy density is too large

It is too large by 120 orders of magnitude! **WHOOPS!**

THE LANDSCAPE OF STRING THEORY

- Since the inception of string theory, theorists have sought to find the vacuum of string theory — with no success.
- Within the past 10 years or so, most string theorists have come to the belief that there is no unique vacuum.
- Instead, there are maybe 10^{500} long-lived metastable states, any of which could serve as a substrate for a pocket universe. This is the landscape!
- Eternal inflation can presumably produce an infinite number of pocket universes of every type, populating the landscape.
- Although string theory would govern everywhere, each type of vacuum would have its own low-energy physics — its own "standard model," its own "constants" of nature, and its own vacuum energy density.

To Be Continued . . .