

INFLATIONARY COSMOLOGY: IS OUR UNIVERSE PART OF A MULTIVERSE?

PART 2

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8.286 Lecture 2
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SUMMARY OF LAST LECTURE

The Standard Big Bang: Really describes only the aftermath of a bang, beginning with a hot dense uniform soup of particles filling an expanding space.

Cosmic Inflation: The prequel, describes how repulsive gravity — a consequence of negative pressure — could have driven a tiny patch of the early universe into exponential expansion. The total energy would be very small or maybe zero, with the negative energy of the cosmic gravitational field canceling the energy of matter.

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Summary p. 2: Evidence for Inflation

1) Inflation can explain the large-scale uniformity of the universe. (Cosmic microwave background (CMB) uniform to 1 part in 100,000.)

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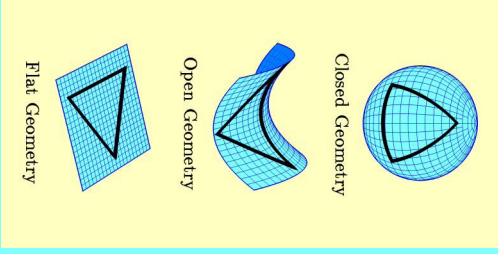
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2) "Flatness problem:"

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.

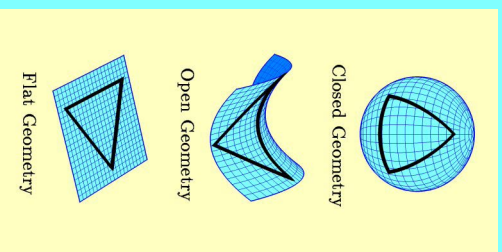


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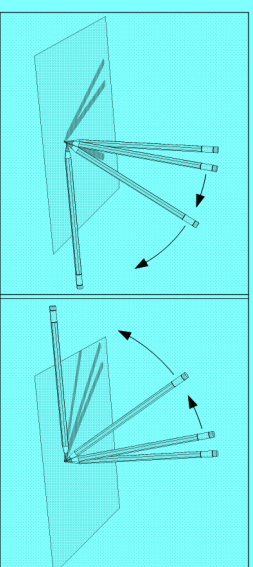
- ★ According to general relativity, the flatness of the universe is related to its mass density:

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

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 astronomical observations):

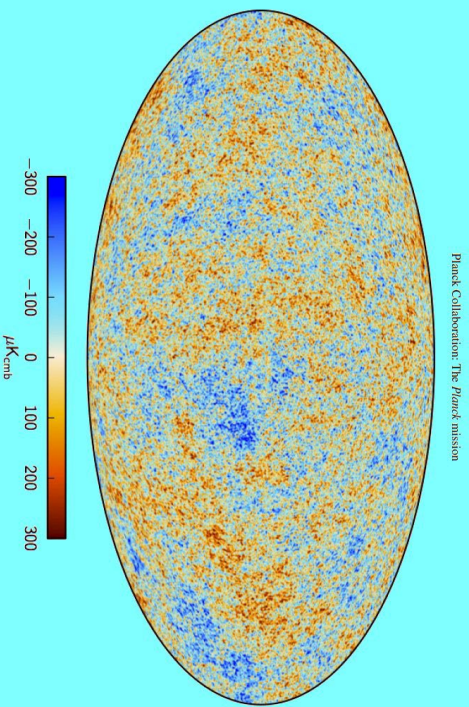
$$\Omega = 0.999 \pm 0.004 \text{ (95\% confidence)}$$

- ★ 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.

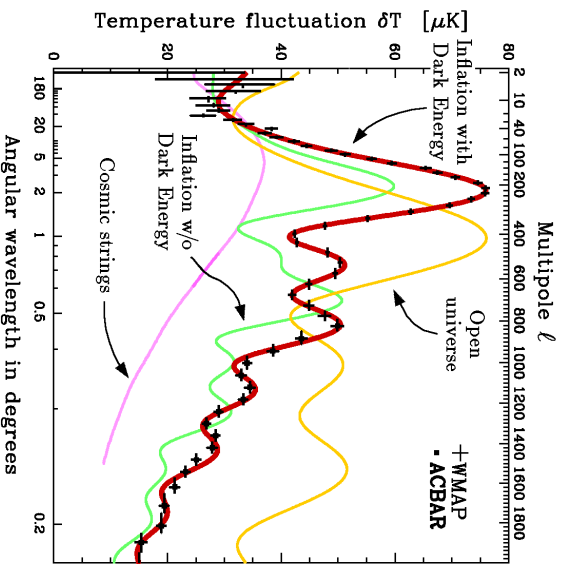
- 3) **Small scale nonuniformity:** Can be measured in the cosmic background radiation. The intensity is almost uniform across the sky, but there are small ripples. Although these ripples are only at the level of 1 part in 100,000, these nonuniformities are now detectable! Where do they come from?

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



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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.

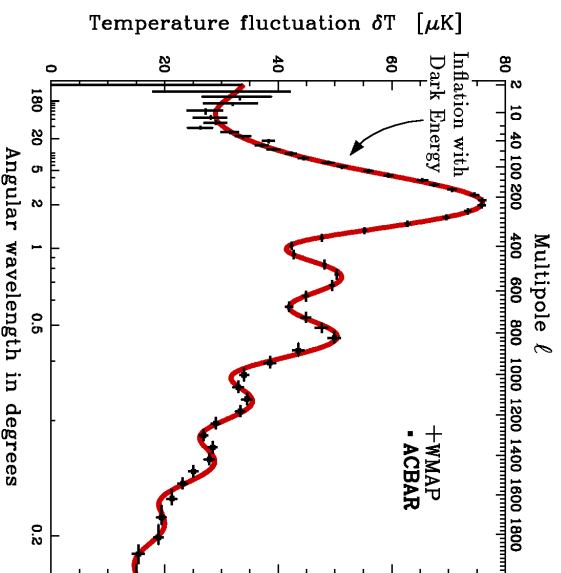
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CMB: Comparison of Theory and Experiment

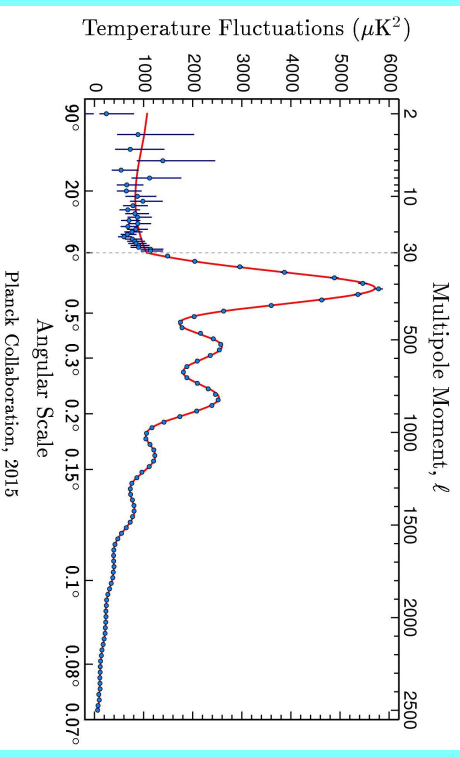


Graph by Max Tegmark, for A. Guth & D. Kaiser, *Science* 307, 884 (Feb 11, 2005), updated to include WMAP 7-year data.

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Spectrum of CMB Ripples



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Gravitational Waves: Came and Went

March 17, 2014: The BICEP2 press conference announced the detection of swirly patterns (B-modes) in the polarization of the CMB, indicating gravitational waves from the early universe, in agreement with inflation.

Result: After accounting for their best estimate of contamination due to dust, they found a tensor/scalar ratio $r = 0.16^{+0.06}_{-0.05}$, with $r = 0$ disfavored at 5.9σ .

Translation: the probability that there are no primordial gravitational waves is only about one in a billion.

April 14, 2015: *A Joint Analysis of BICEP2/Keck Array and Planck Data*: “We find strong evidence for dust and no statistically significant evidence for tensor modes.”

Inflation Suggests a Multiverse

Almost all detailed models of inflation lead to “eternal inflation,” and hence to a multiverse.

Roughly speaking, inflation is driven by a metastable state, which decays with some half-life.

After one half-life, half of the inflating material has become normal, noninflating matter, but the half that remains has continued to expand exponentially. It is vastly larger than it was at the beginning.

Once started, the inflation goes on FOREVER, with pieces of the inflating region breaking off and producing “pocket universes.”

We would be living in one of the infinity of pocket universes.

The search for B-modes is still on, and if they are found they will provide additional strong evidence for inflation, and a tool for probing the details of inflation.

Current limit: $r < 0.07$. Future sensitivity: if $r > 0.001$, it can be found by about 2024 (CMB Stage 4).

If B-modes are not found, that is not evidence against inflation: many inflationary models predict a B-mode intensity much smaller than 0.001.

The Cosmological Constant Problem

- ★ In 1998, two groups of astronomers discovered that for the past 5–6 billion years, the expansion of the universe has been accelerating.
- ★ According to GR, this requires a repulsive gravity material, which is dubbed “Dark Energy”.

★ Simplest explanation: dark energy is vacuum energy — the energy density of empty space. The physicist’s vacuum is far from empty, so a nonzero energy density is expected.

★ **Value of Vacuum Energy Density Makes No Sense:** We cannot calculate the vacuum energy density, but the natural particle physics estimate is called the Planck scale — the energy scale at which the effects of quantum gravity are expected to become important. But it is MUCH larger than the observed value:

It is larger by 120 orders of magnitude!

The Multiverse and the Cosmological Constant Problem

- ★ One of the thorniest problems in particle theory is to understand why the energy density of the vacuum (equivalent to the cosmological constant) is 120 orders of magnitude smaller than the (expected) Planck scale.
- ★ The multiverse offers a possible (although controversial) solution.
- ★ If there are 10^{500} different types of vacuum (as in string theory), there will be many with energy densities in the range we observe.
- ★ The vacuum energy affects cosmic evolution: if it is too large and positive, the universe flies apart too fast for galaxies to form. If too large and negative, the universe implodes.
- ★ It is therefore plausible that life only forms in those pocket universes with incredibly small vacuum energies, so all living beings would observe a small vacuum energy. (Anthropic principle, or observational selection effect.)

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Three Winds Blowing Us Towards the Multiverse

- 1) Almost all inflationary models are eternal into the future. Once inflation starts, it never stops, but goes on forever producing pocket universes.
- 2) Astronomers have discovered that the universe is accelerating, which probably indicates a vacuum energy that is nonzero, but incredibly much smaller than we can understand. What is happening?
- 3) String theorists mostly agree that string theory has no unique vacuum, but instead a landscape of perhaps 10^{500} long-lived metastable states, any of which could be our vacuum. With the multiverse, this allows the small vacuum energy density to be explained as a selection effect: perhaps we see a small vacuum energy density because conscious beings only form in those parts of the multiverse where the vacuum energy density is small.

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SUMMARY

The Inflationary Paradigm is in Great Shape!

- ★ Explains large scale uniformity.
- ★ Predicts the mass density of the universe to better than 1% accuracy.
- ★ Explains the ripples we see in the cosmic background radiation as the result of quantum fluctuations.

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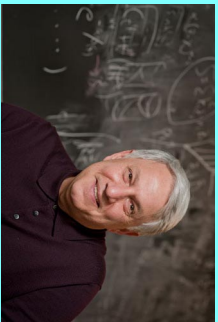
Do Physicists Take the Multiverse Seriously?



Martin Rees (Astronomer Royal of Great Britain and (former) President of the Royal Society) has said that he is sufficiently confident about the multiverse to bet his dog's life on it.

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Do Physicists Take the Multiverse Seriously?



Andrei Linde (Stanford University, major role in developing inflationary cosmology, shared in the 2002 Dirac Prize, the 2004 Gruber Prize, the 2012 Fundamental Physics Prize, and the 2014 Kavli Prize) has said that he is so confident that he would bet his own life.

Do Physicists Take the Multiverse Seriously?



Steven Weinberg (1979 Nobel Prize in Physics): “I have just enough confidence about the multiverse to bet the lives of both Andrei Linde *and* Martin Rees’s dog.”