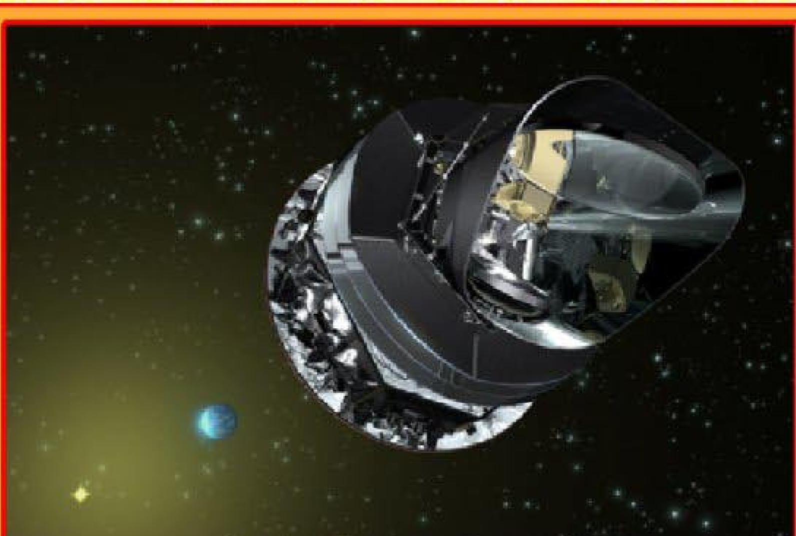
INFLATIONARY COSMOLOGY:
IS OUR UNIVERSE PART OF A MULTIVERSE?

— Alan Guth —
Massachusetts Institute of Technology



Abdus Salam Lectures 2018: Lecture 1
Budinich Lecture Hall
Leonardo Da Vinci Building
International Centre for Theoretical Physics
Trieste, Italy
January 29, 2018

The Conventional Big Bang Theory

What it is: The theory that the universe as we know it began 13-15 billion years ago. (Latest estimate: 13.82 ± 0.05 billion years!) The initial state was a hot, dense, uniform soup of particles that filled space uniformly, and was expanding rapidly.

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- ☆ What caused the expansion? (The conventional theory describes only the **aftermath** of the bang. It says nothing about what banged, why it banged, or what happened before it banged.)
- ☆ Where did the matter come from? (The theory assumes that **all matter** existed from the very beginning.)

What is Inflation?

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(b) is so far-reaching in its consequences that it can change our picture of the universe.

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- ☆ 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. (These are states whose energy is dominated by the potential energy of a scalar field.)

Sequence of Events

- Inflation proposes that a patch of repulsive gravity material existed in the early universe — for inflation at the grand unified theory scale, 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.)
- The gravitational repulsion was the driving force behind the big bang. The patch was driven into exponential expansion, with a doubling time of maybe $\sim 10^{-38}$ second.
- The patch expanded exponentially by a factor of at least 10^{28} (100 doubling times), but it could have expanded much more. 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." 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.
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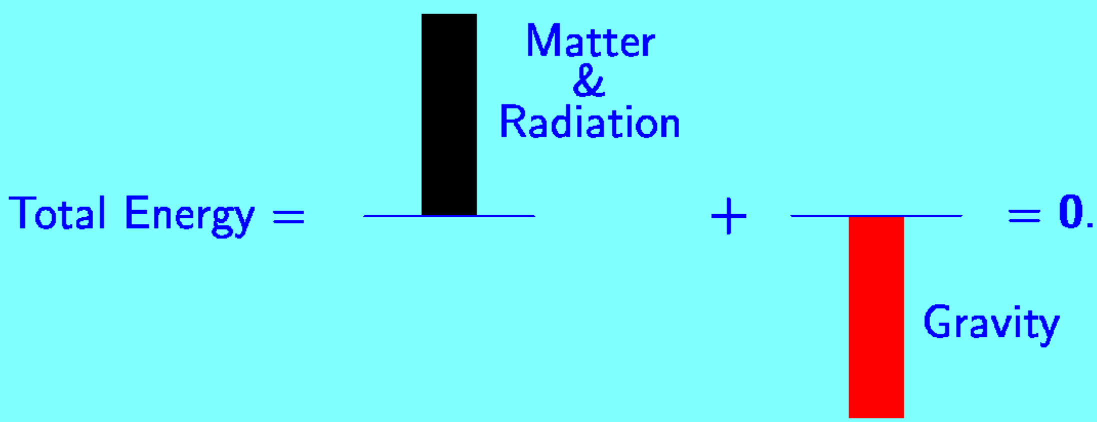
- ☆ The total energy of the universe today is consistent with zero. Schematically,



Alan Guth
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Abdus Salam Lecture I, ICTP, Trieste, January 29, 2018

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 380,000 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.

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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.

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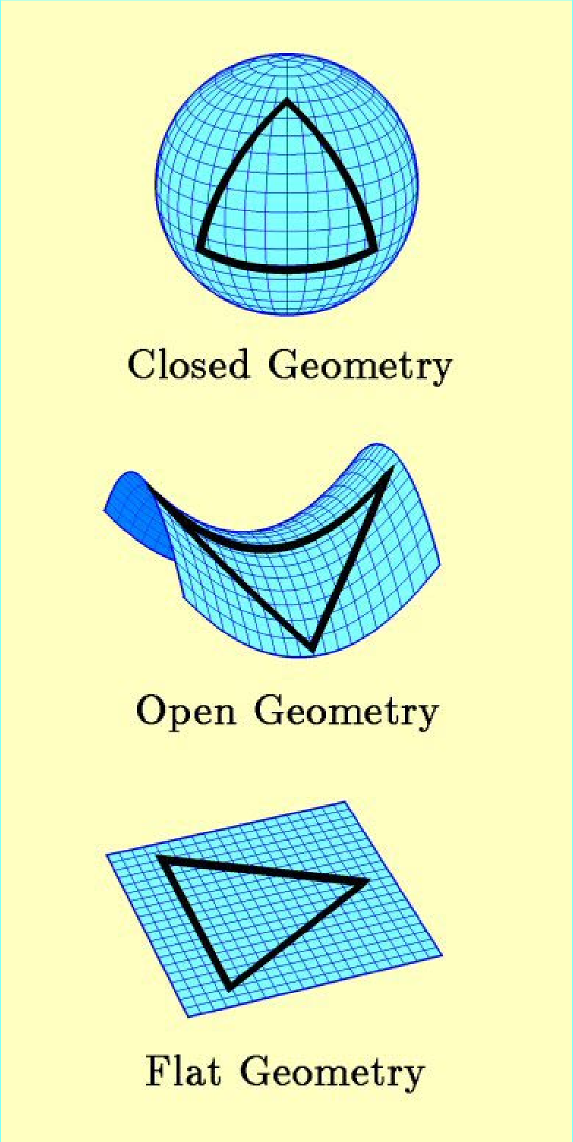

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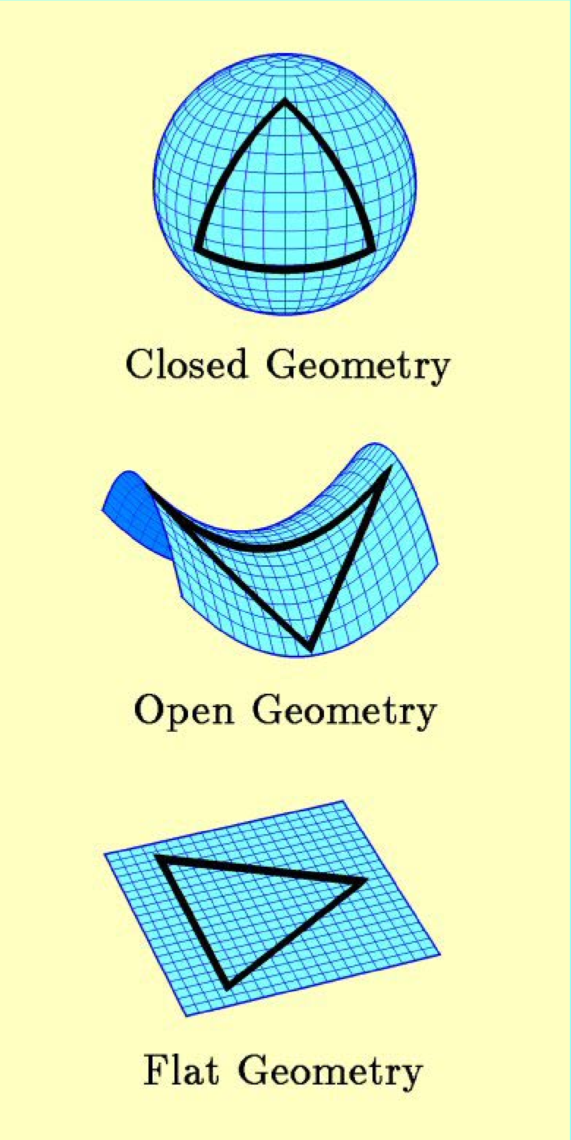
- ☆ If we assume that the universe is homogeneous (same in all places) and isotropic (same in all directions), then there are only three possible geometries: closed, open, or flat.
- ☆ According to general relativity, the flatness of the universe is related to its mass density:

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

where the "critical density" depends on the expansion rate. $\Omega = 1$ is flat, $\Omega > 1$ is closed, $\Omega < 1$ is open.



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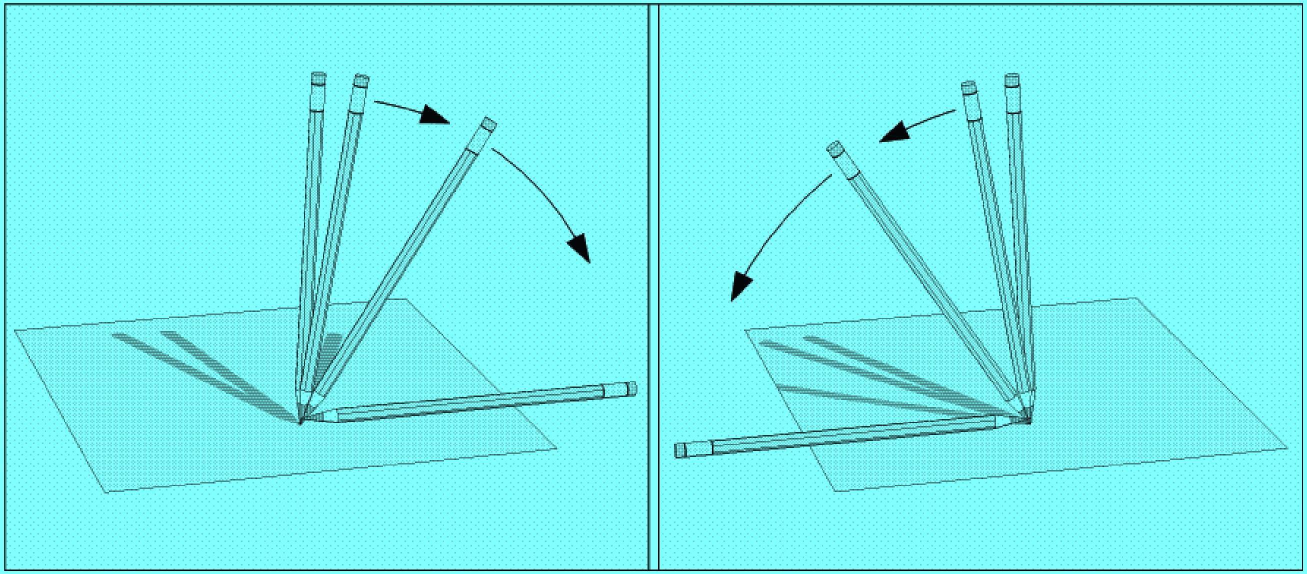

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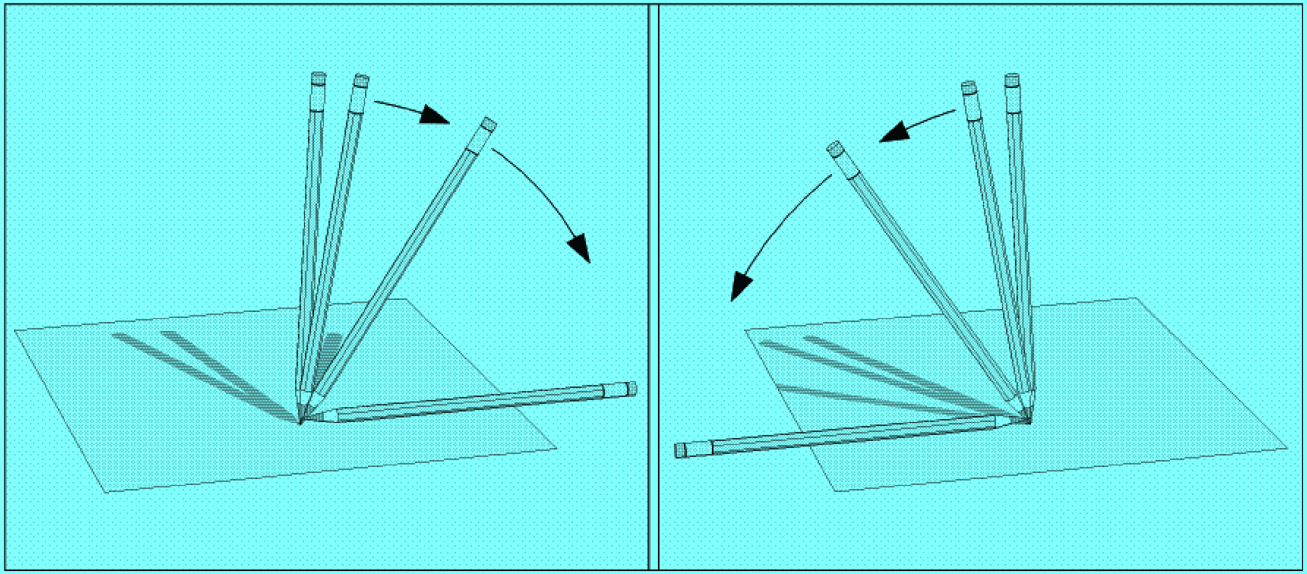

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- To be even within a factor of 10 of the critical density today (which is what we knew in 1980), at one second after the big bang, Ω must have been equal to one **to 15 decimal places!**

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☆ 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 a few parts in 100,000, these nonuniformities are now detectable! Where do they come from?

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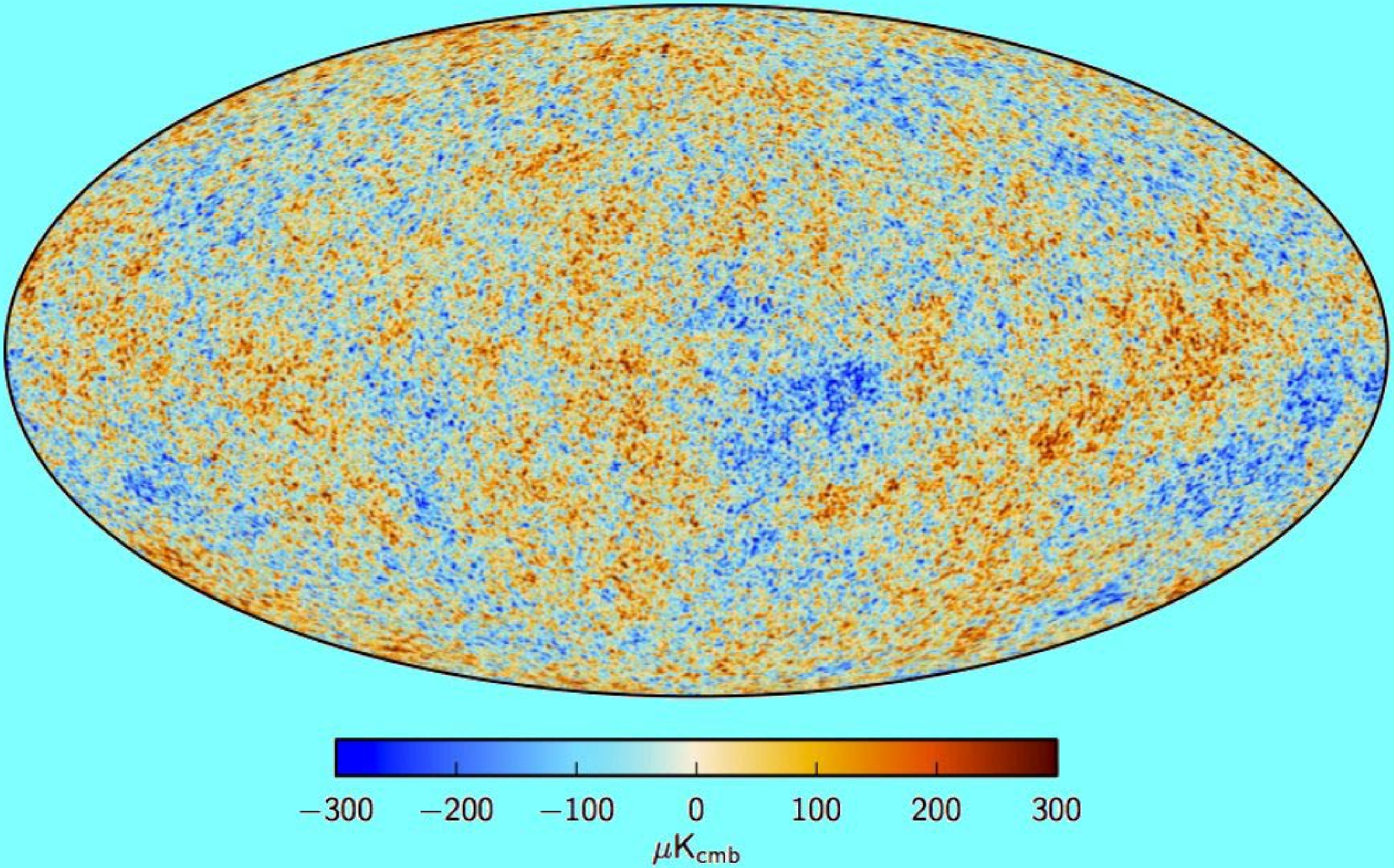
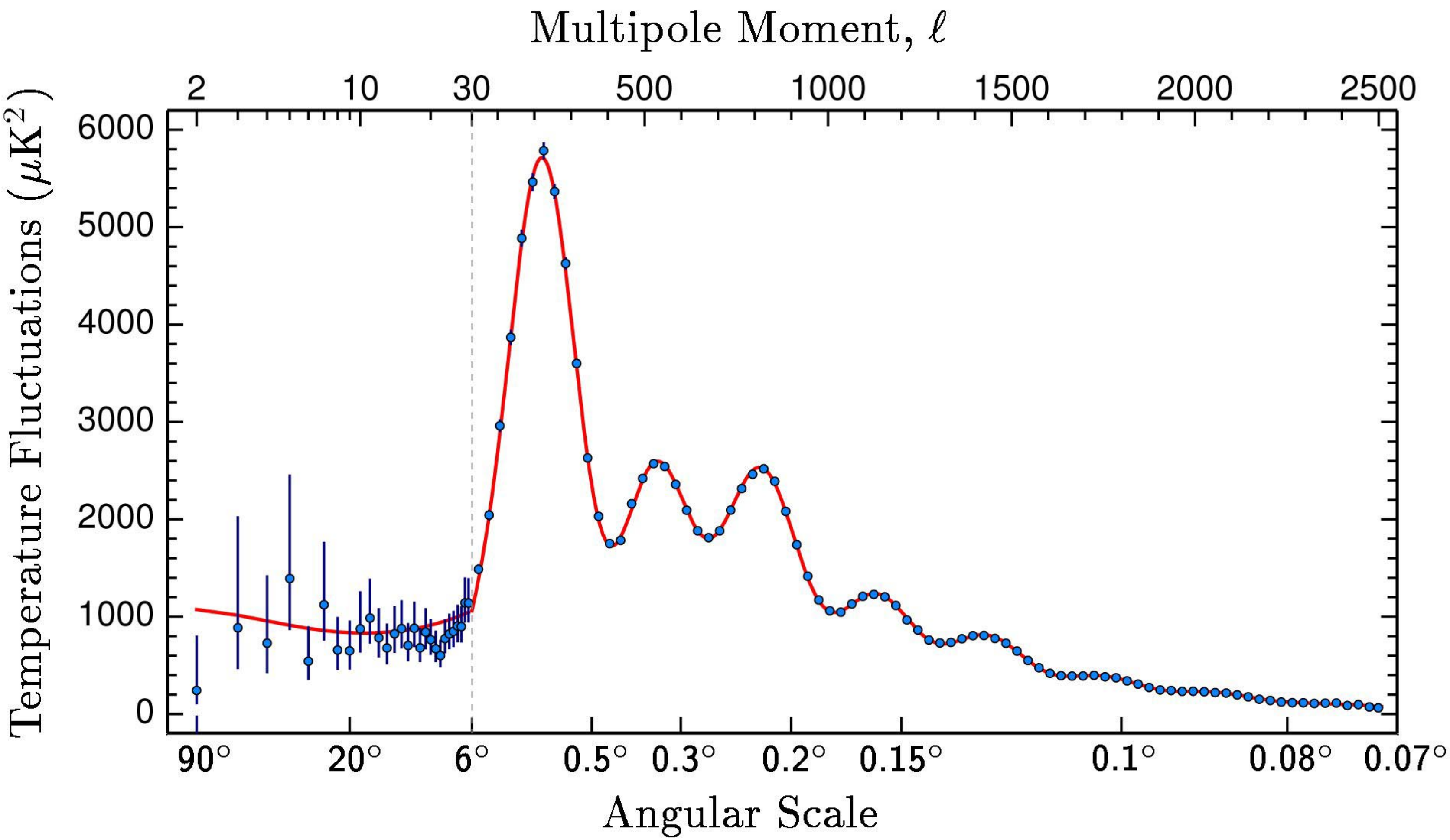
Inflationary Solution: Inflation attributes these ripples to *quantum fluctuations.* Inflation makes generic predictions for the spectrum of these ripples (i.e., how the intensity varies with wavelength). The data measured so far agree beautifully with inflation.

Ripples in the Cosmic Microwave Background

Planck Collaboration: The *Planck* mission



Spectrum of CMB Ripples



Planck Collaboration, 2015

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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.

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

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 (2011 Nobel Prize: Perlmutter, Riess, & Schmidt).
- According to GR, this requires a repulsive gravity (i.e., negative pressure) material, which is dubbed "Dark Energy".
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It is larger by 120 orders of magnitude!

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- 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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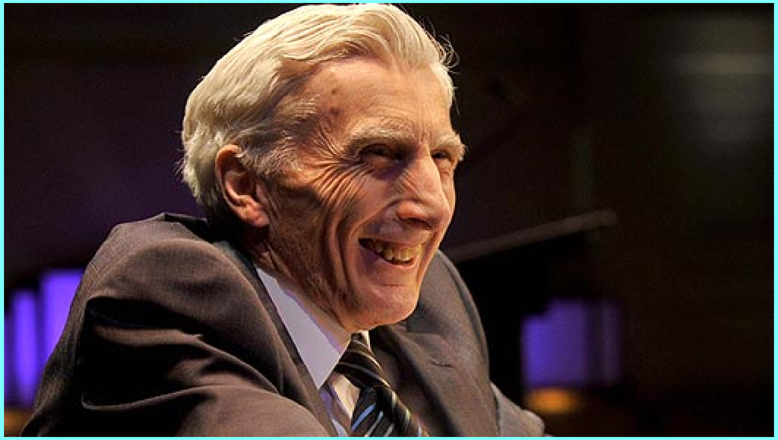

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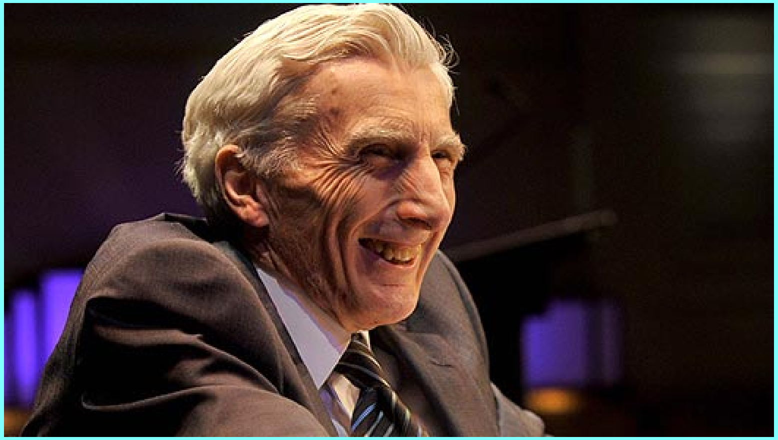

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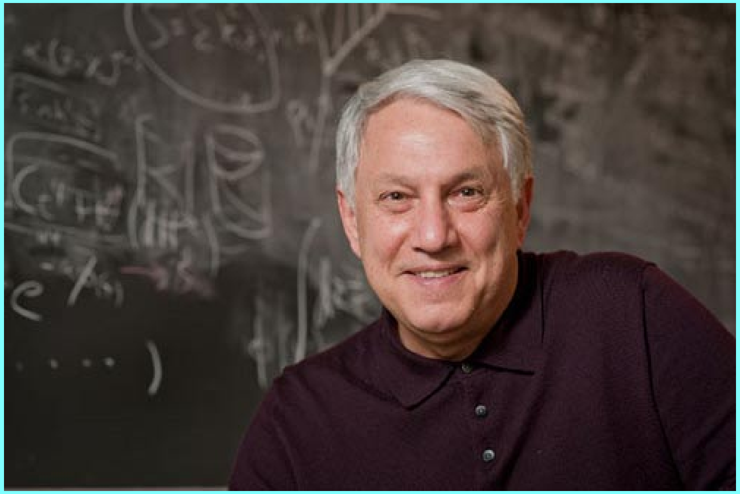

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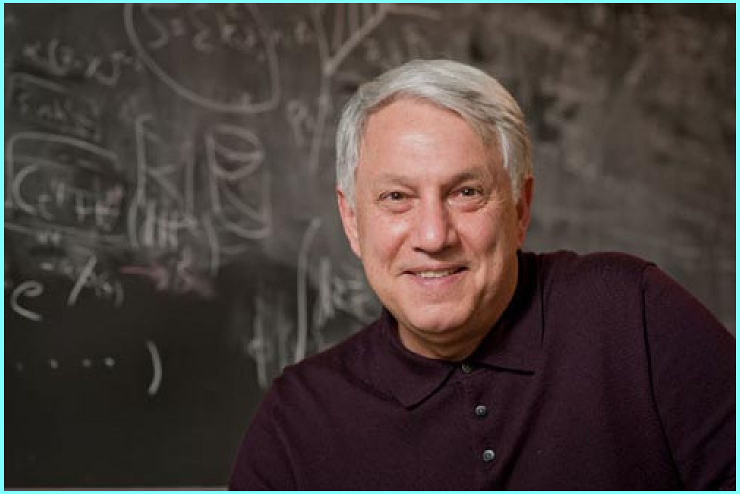

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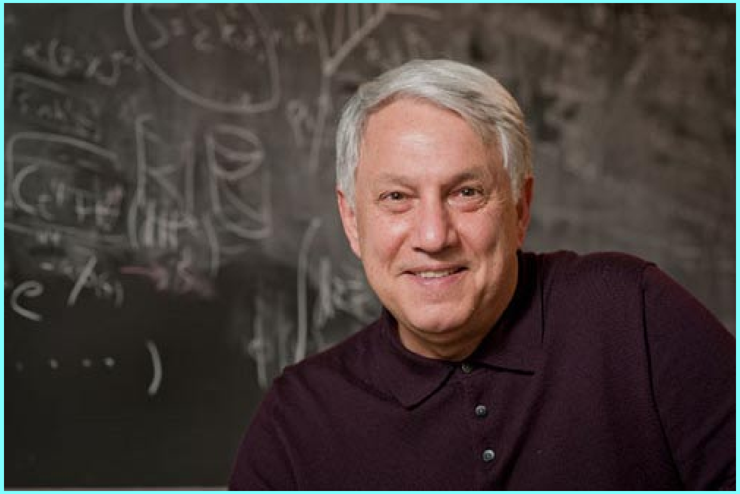

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