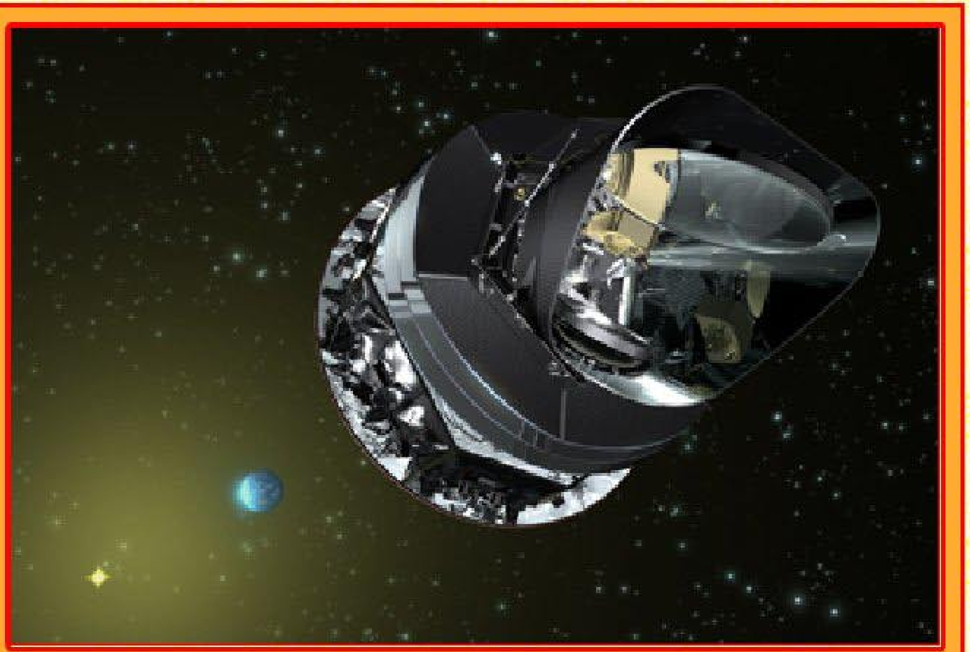
INFLATIONARY COSMOLOGY:

IS OUR UNIVERSE PART OF A MULTIVERSE?

PART 2



— Alan Guth —

Massachusetts Institute of Technology

8.286 Lecture 3
September 14, 2020

SUMMARY OF LAST LECTURE

The Conventional Big Bang Theory (i.e., without inflation): Really describes only the aftermath of a bang: It says nothing about what banged, why it banged, or what happened before it banged. The description begins 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.

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.

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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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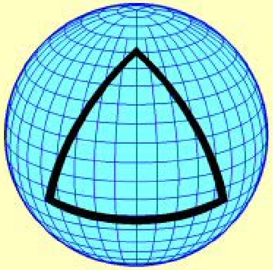
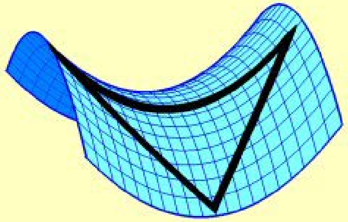
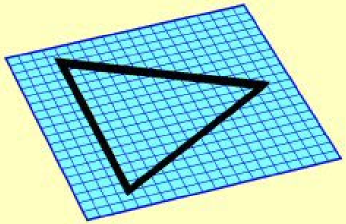


Closed Geometry



Open Geometry



Flat Geometry

2) **"Flatness problem:"**

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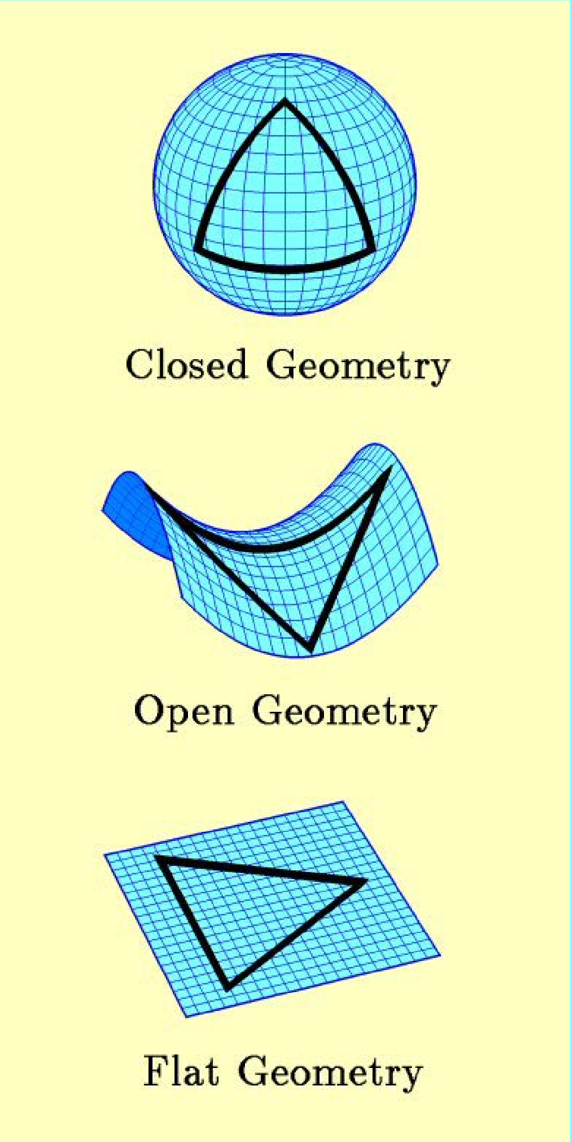
- ☆ If we assume that the universe is homogeneous (same in all places) and isotropic (same in all directions), then there are only three possible geometries: closed, open, or flat.

- ☆ 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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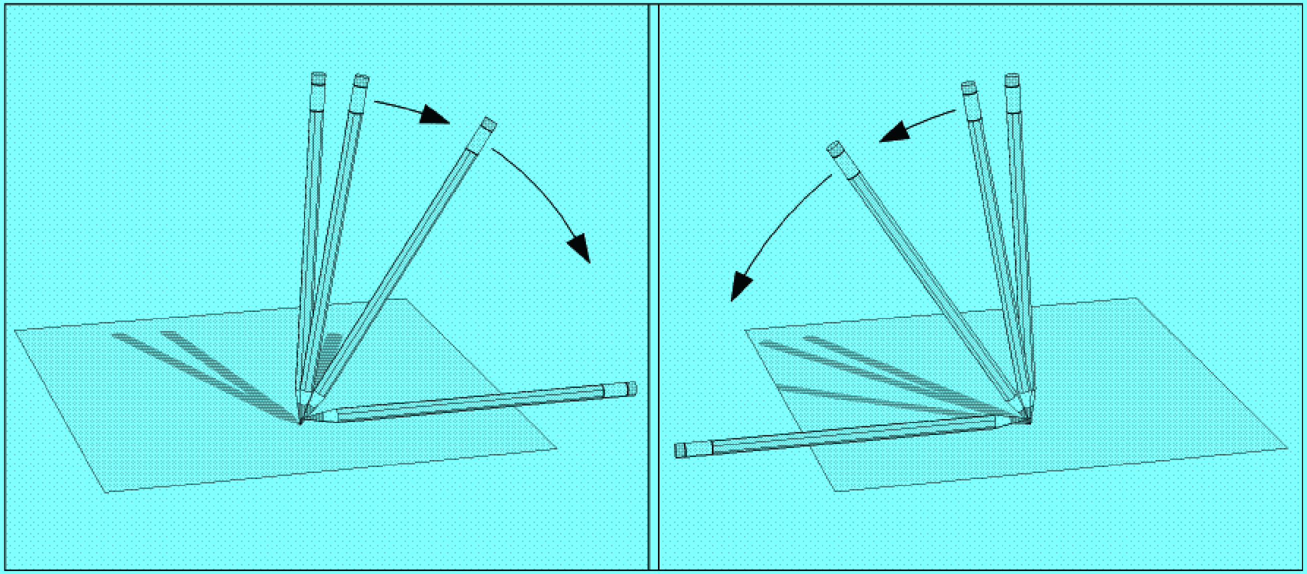

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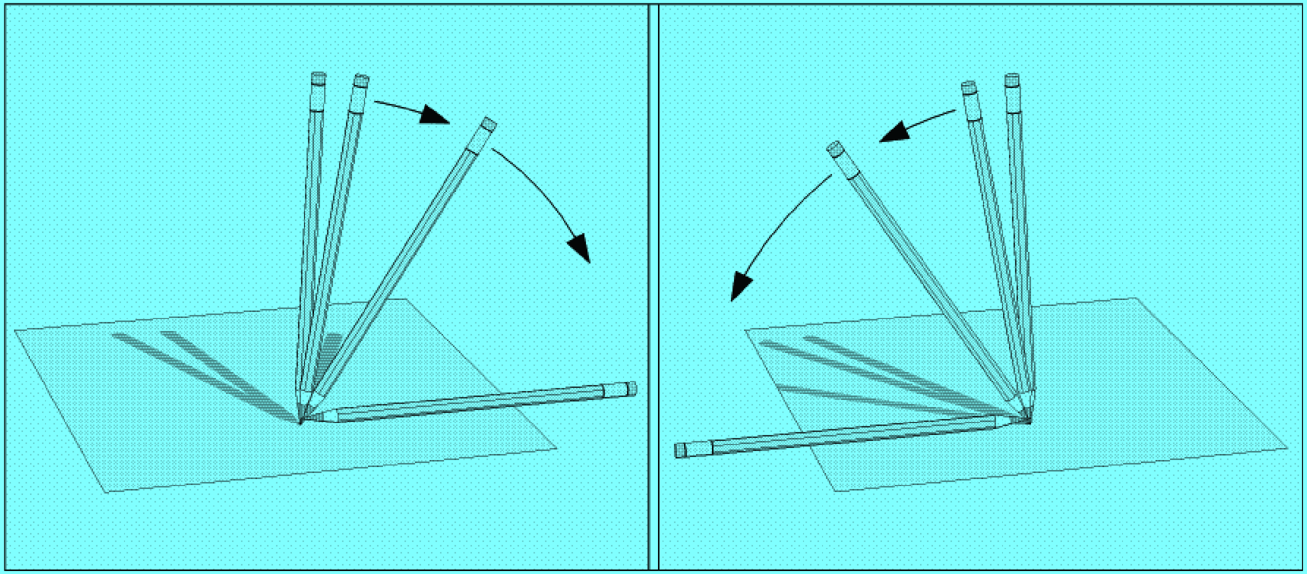

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- ☆ To be even within a factor of 10 of the critical density today (which is what we knew in 1980), at one second after the big bang, Ω must have been equal to one **to 15 decimal places!**

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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 1 part in 100,000, these nonuniformities are now detectable! Where do they come from?

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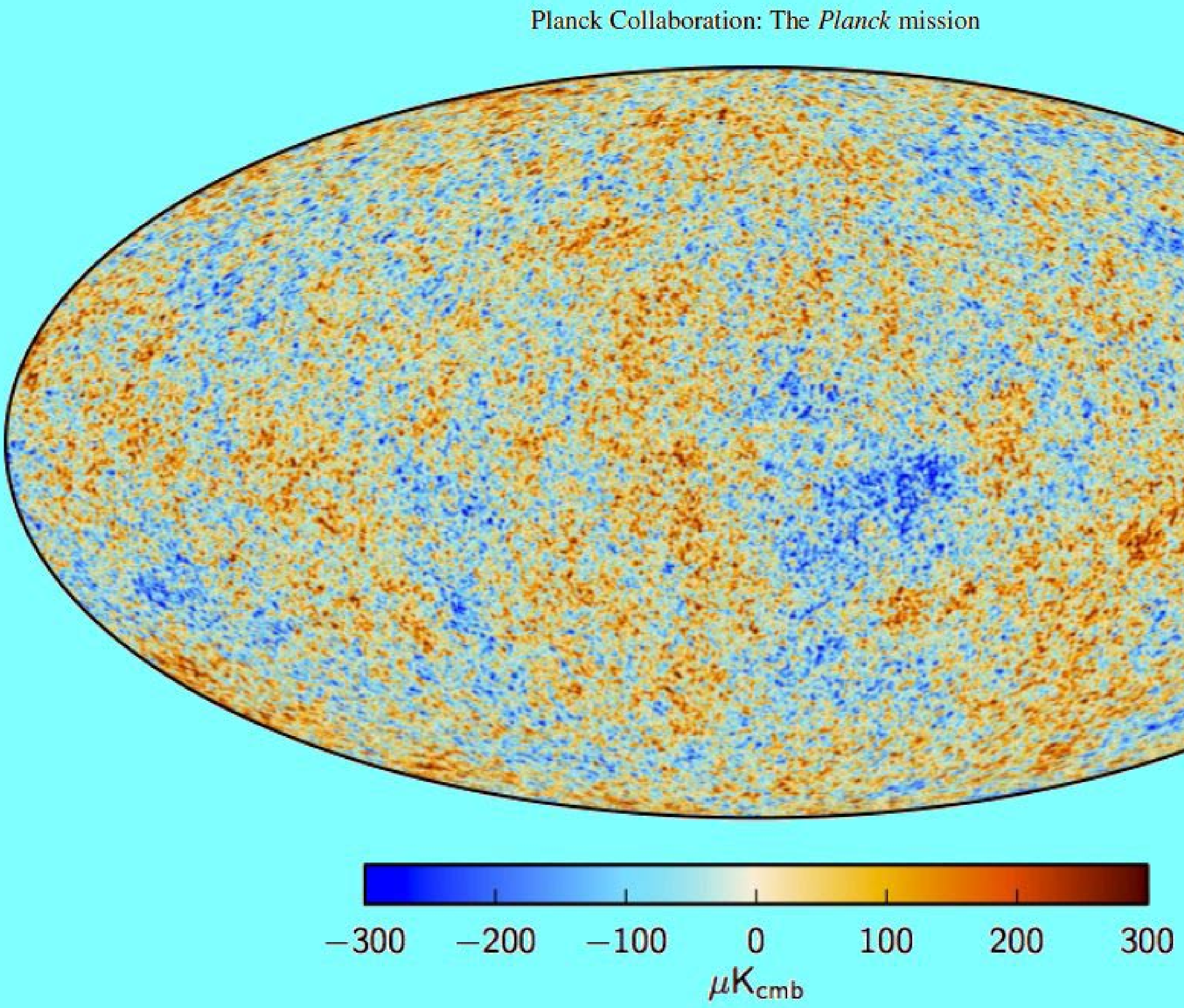
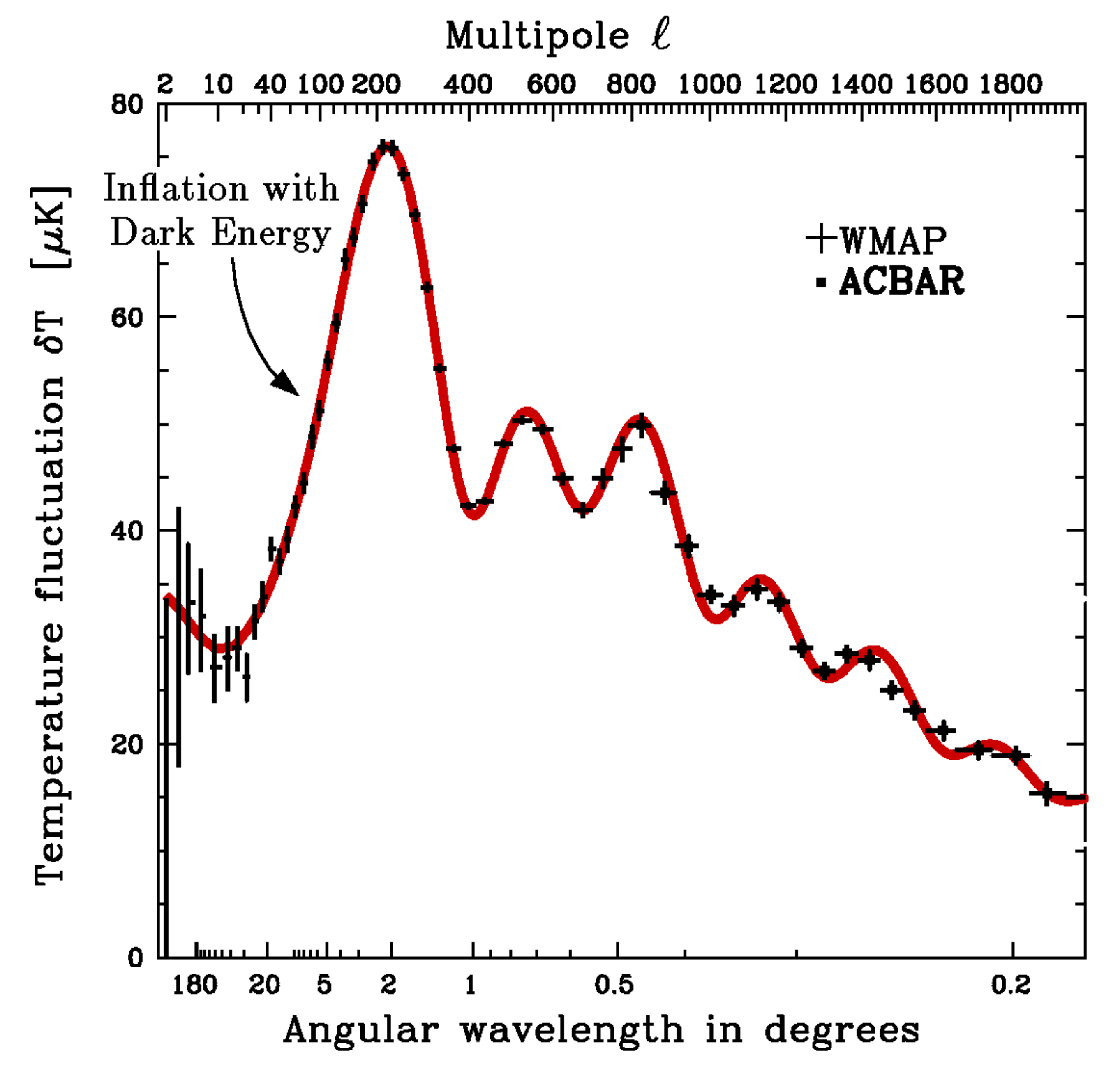
Inflationary Solution: Inflation attributes these ripples to *quantum fluctuations.* Inflation makes generic predictions for the spectrum of these ripples (i.e., how the intensity varies with wavelength). The data measured so far agree beautifully with inflation.

Ripples in the Cosmic Microwave Background





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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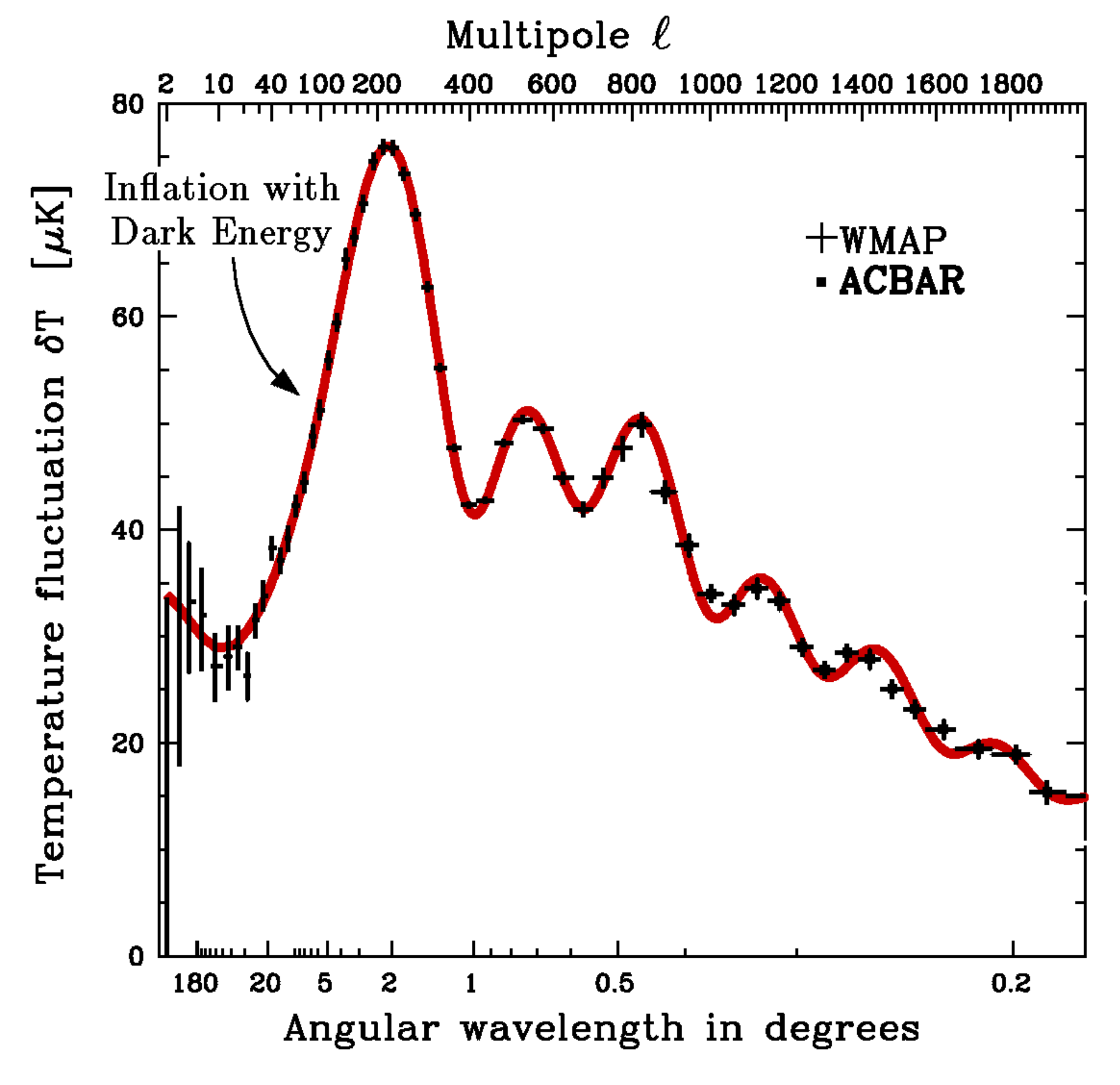

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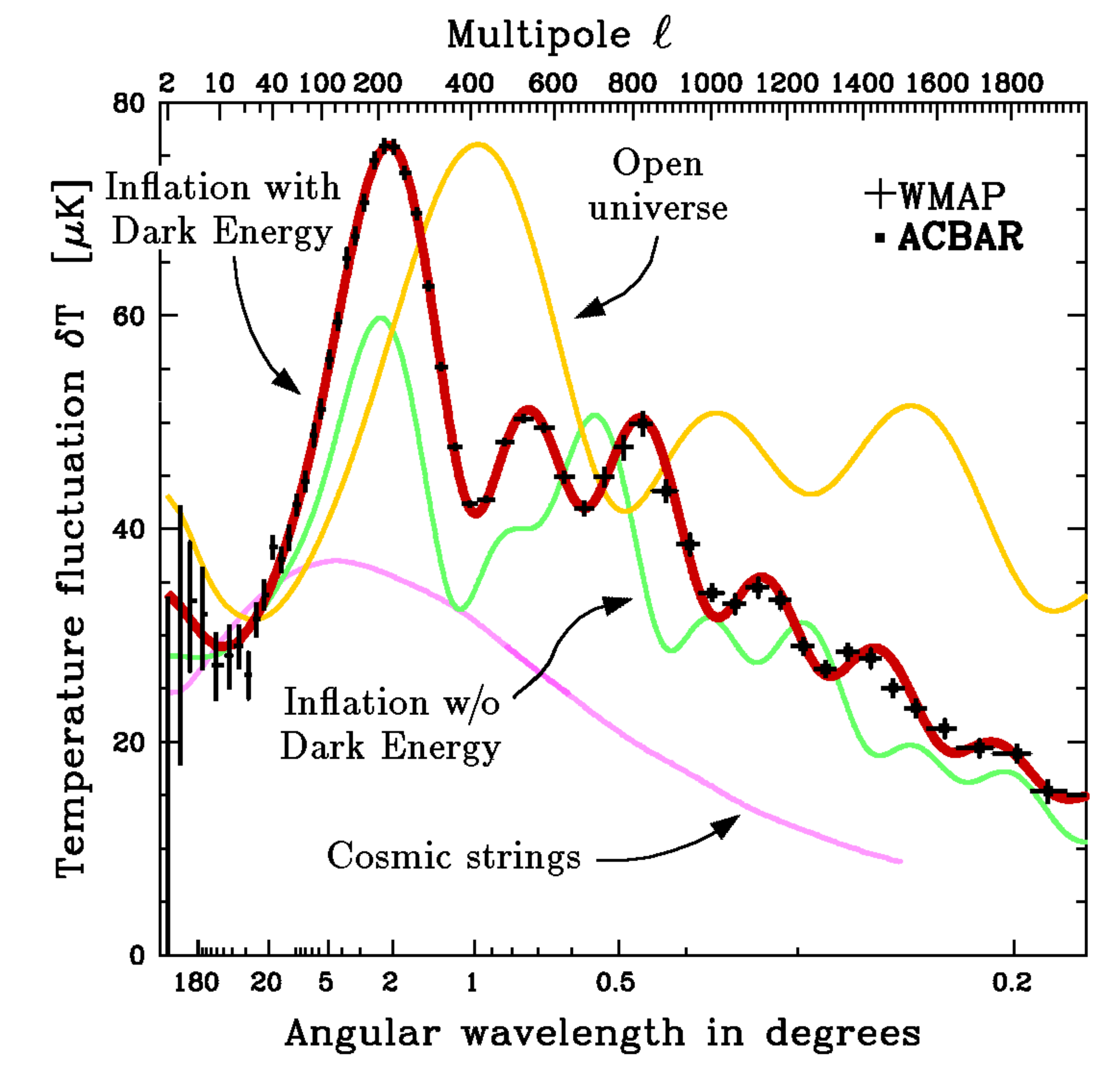

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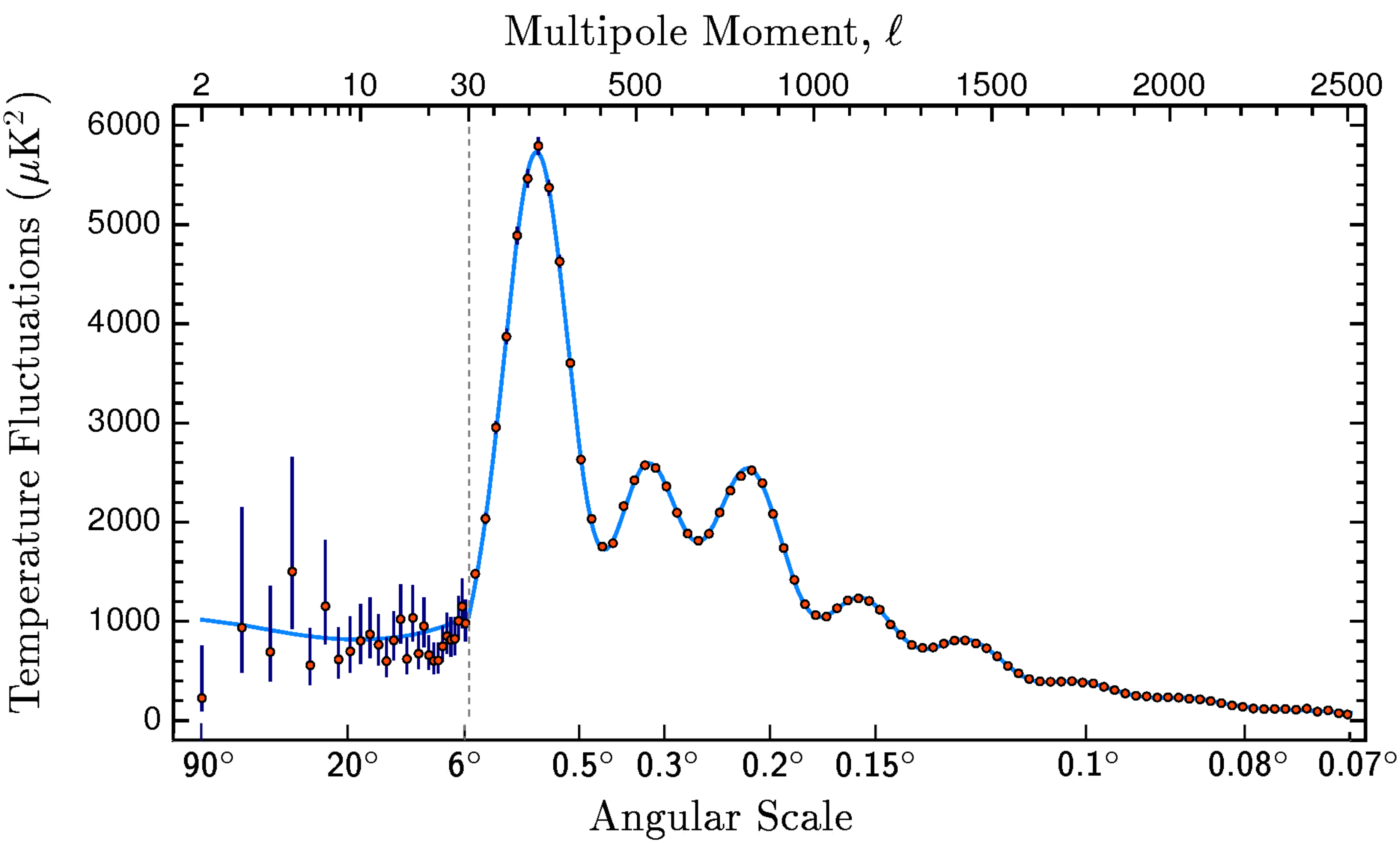
Spectrum of CMB Ripples



Planck Collaboration, 2018

Gravitational Waves:

Gravitational Waves: Came

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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."

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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. In 2018 I was involved in a paper about an inflationary model that gave $r \sim 10^{-29}$!

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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.
- According to GR, this requires a repulsive gravity material (i.e., a negative pressure 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.

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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.)

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.

Three Strong Winds Blowing Us Towards the Multiverse — a diverse multiverse where selection effects play an important role

1) Theoretical Cosmology: Almost all inflationary models are eternal into the future. Once inflation starts, it never stops, but goes on forever producing pocket universes.

2) Observational Astronomy: 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. Why should this happen?

3) String Theory: String theorists mostly agree that string theory has no unique vacuum, but instead a landscape of perhaps 10^{500} or more long-lived metastable states, any of which could serve as the substrate for a pocket universe, including our own. This situation allows an "anthropic" argument: perhaps we see an incredibly small vacuum energy density because conscious beings only form in those parts of the multiverse where the vacuum energy density is incredibly small.