

INFLATIONARY COSMOLOGY:

IS OUR UNIVERSE
PART OF
A MULTIVERSE?

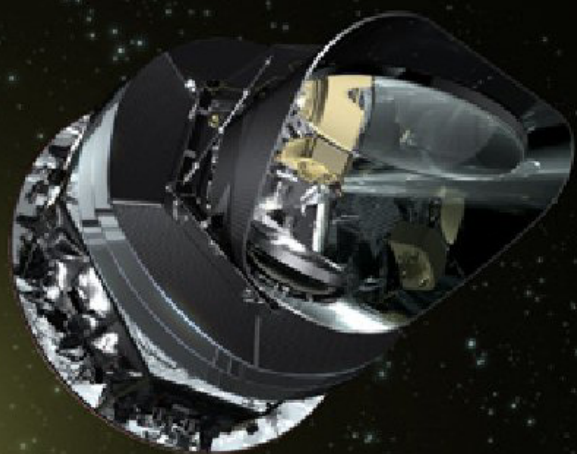
PART 2

— Alan Guth —



Massachusetts Institute of Technology

8.286 Lecture 2
September 12, 2022



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.

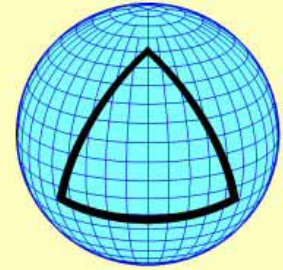
2) "Flatness problem:"

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

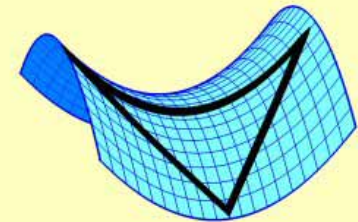
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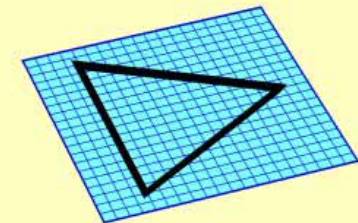
- ★ If we assume that the universe is homogeneous (same in all places) and isotropic (same in all directions), then there are only three possible geometries: closed, open, or flat.



Closed Geometry



Open Geometry



Flat Geometry

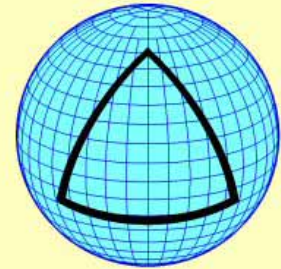
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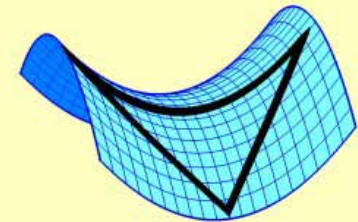
- ★ If we assume that the universe is homogeneous (same in all places) and isotropic (same in all directions), then there are only three possible geometries: closed, open, or flat.
- ★ According to general relativity, the flatness of the universe is related to its mass density:

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

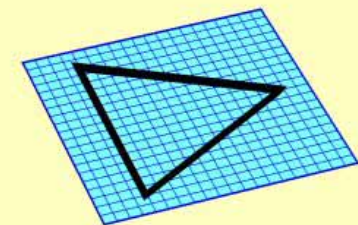
where the "critical density" depends on the expansion rate. $\Omega = 1$ is flat, $\Omega > 1$ is closed, $\Omega < 1$ is open.



Closed Geometry

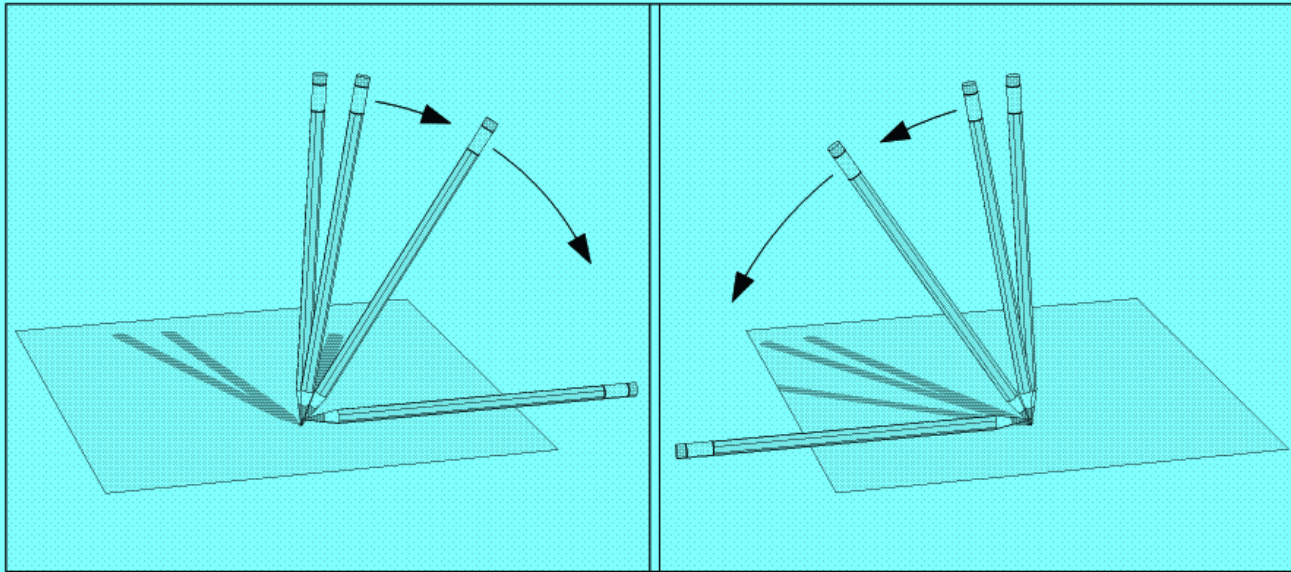


Open Geometry



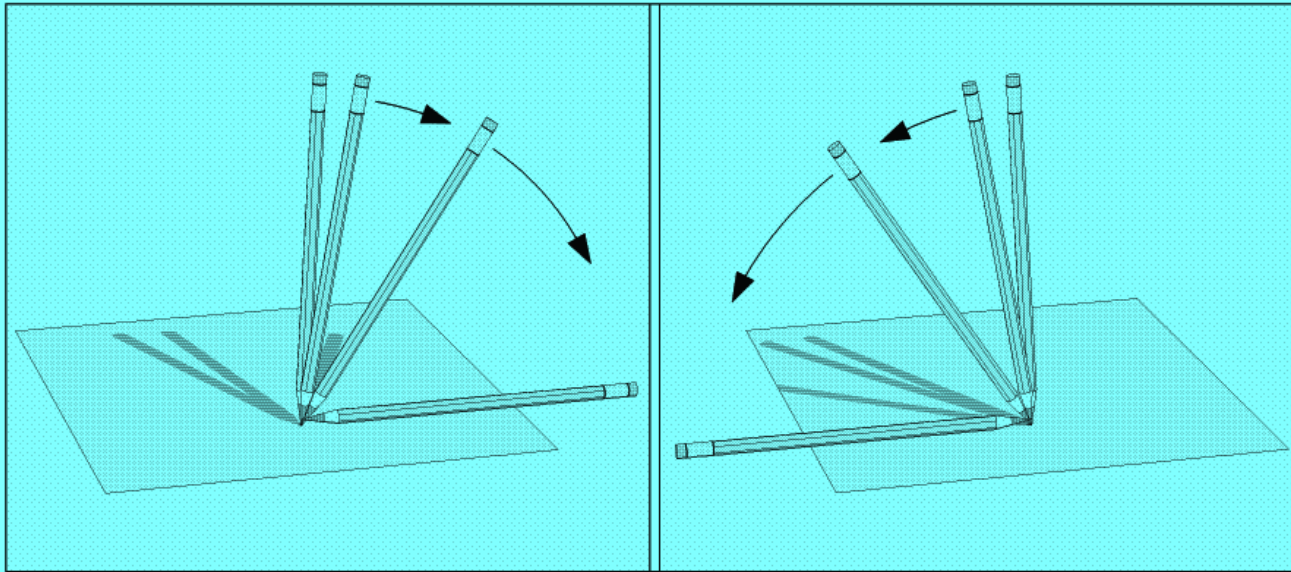
Flat Geometry

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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.

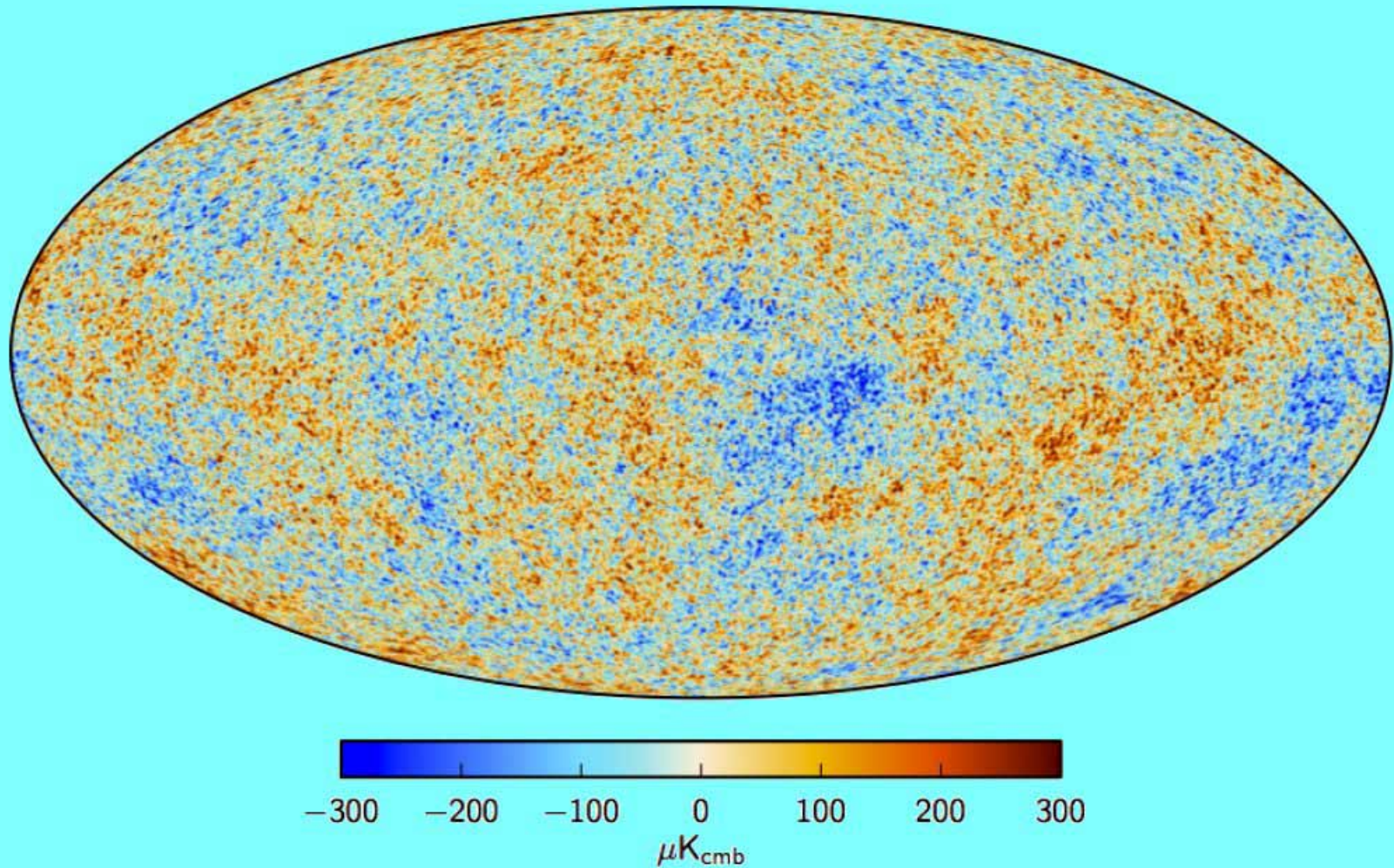
- 3) **Small scale nonuniformity:** Can be measured in the cosmic background radiation. The intensity is almost uniform across the sky, but there are small ripples. Although these ripples are only at the level of 1 part in 100,000, these nonuniformities are now detectable! Where do they come from?

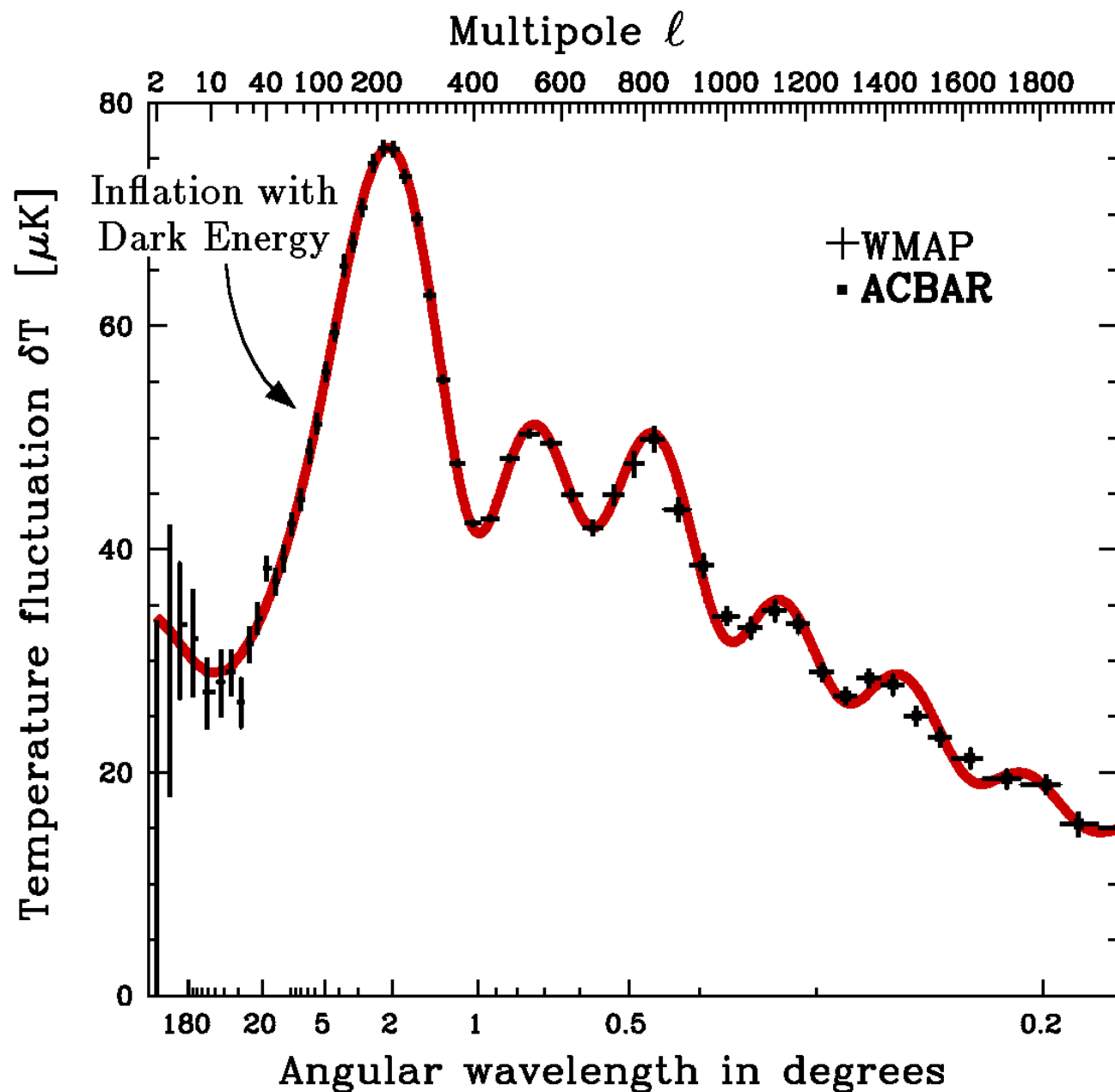
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Inflationary Solution: Inflation attributes these ripples to *quantum fluctuations*. Inflation makes generic predictions for the spectrum of these ripples (i.e., how the intensity varies with wavelength). The data measured so far agree beautifully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

Ripples in the Cosmic Microwave Background

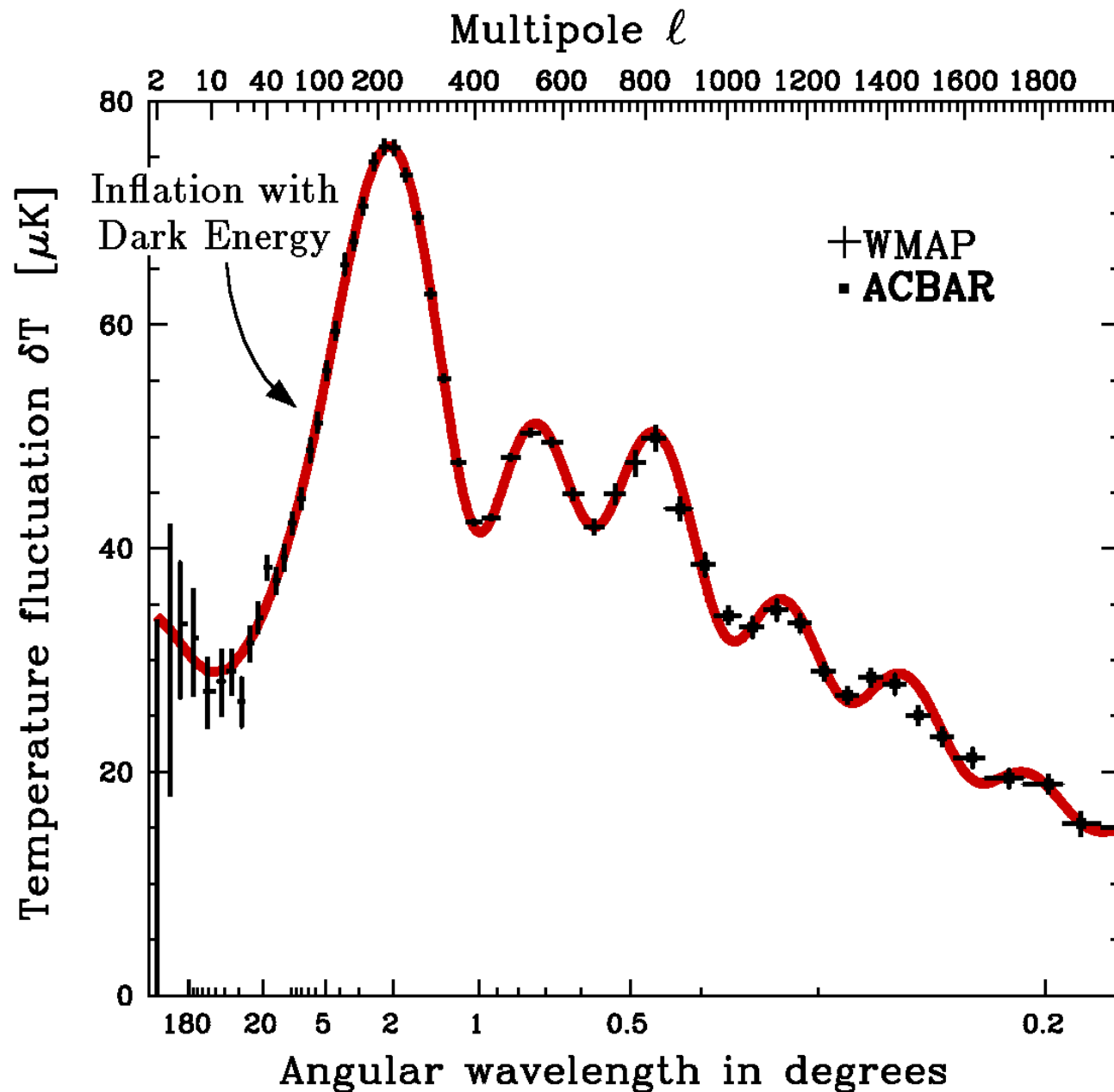
Planck Collaboration: The *Planck* mission





CMB: Comparison of Theory and Experiment

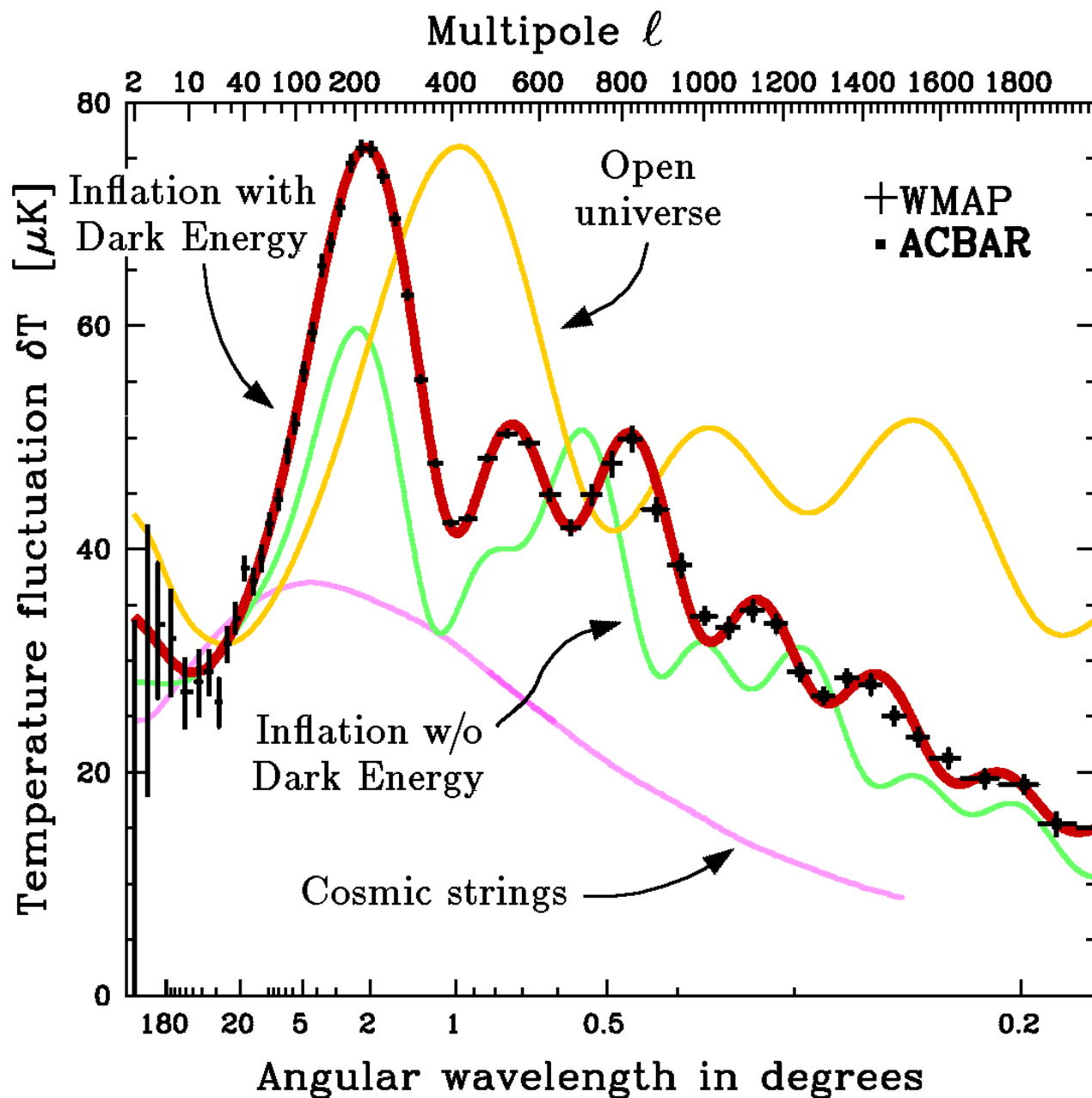
Graph by Max Tegmark,
for A. Guth & D. Kaiser,
Science 307, 884
(Feb 11, 2005), updated
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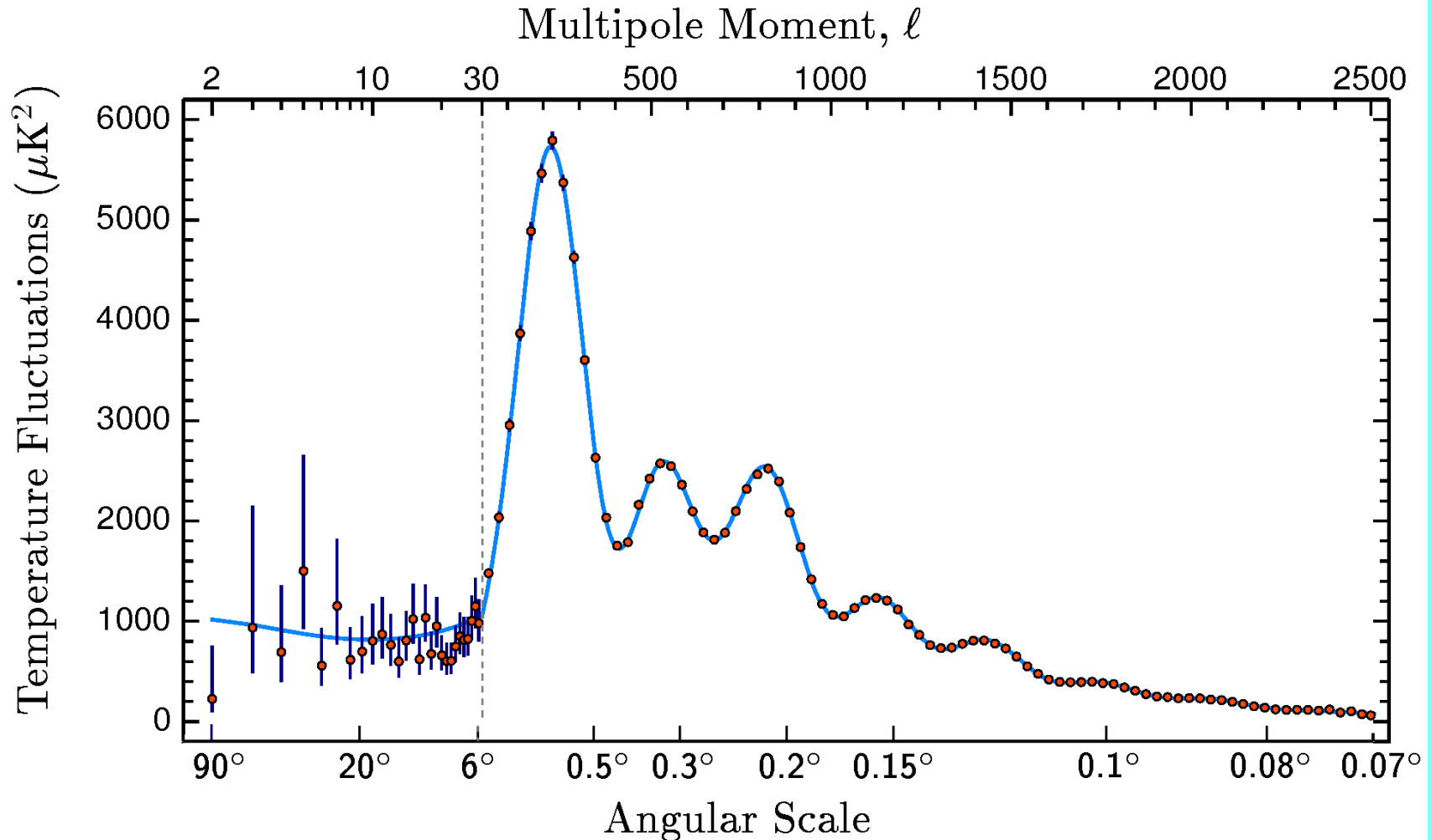


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Spectrum of CMB Ripples



Planck Collaboration, 2018

Gravitational Waves:



Gravitational Waves: Came



Gravitational Waves: *Came and Went*



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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”.
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It is larger by 120 orders of magnitude!