INFLATIONARY COSMOLOGY:

IS OUR UNIVERSE PART OF A MULTIVERSE?

PART 1

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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.

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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:

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Gravitational Repulsion.

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(a) was never taught to me when I was a student; and

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

Miracle of Physics # 1: Gravitational Repulsion

- ☆ Since the advent of general relativity, physicists have known that gravity can act repulsively.
- ☆ In GR, pressures can create gravitational fields, and negative pressures create repulsive gravitational fields.
- ☆ 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.

- 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.)

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- ⭐ 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.

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

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

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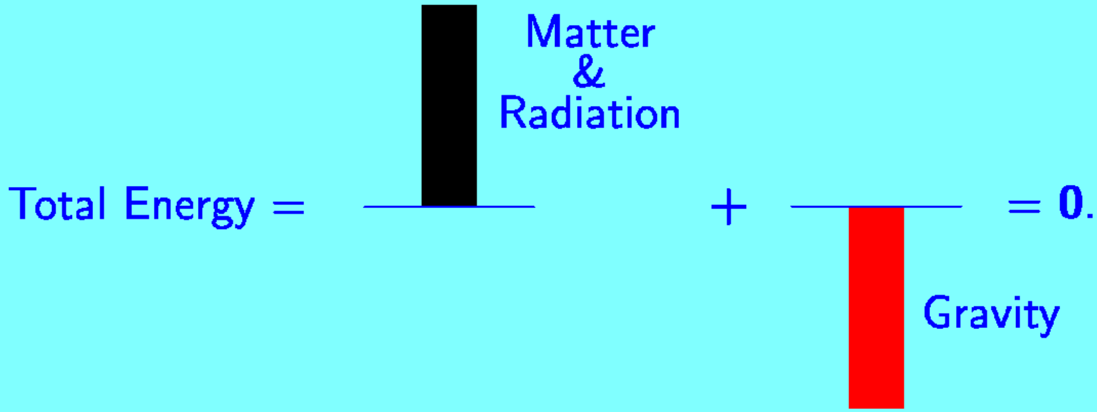
- ☆ The total energy of the universe today is consistent with zero. Schematically,



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.

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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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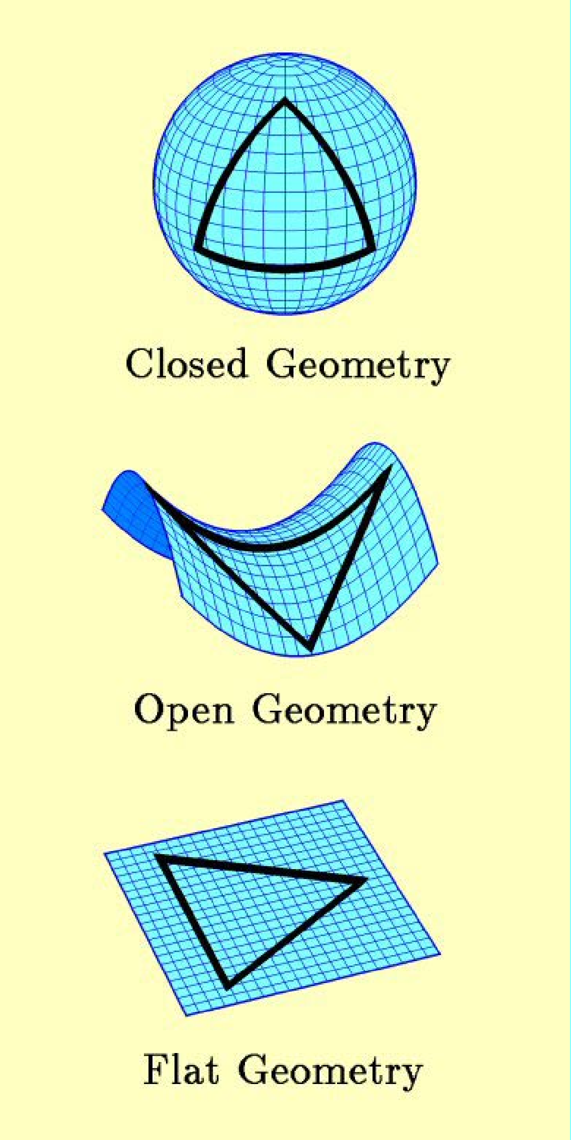
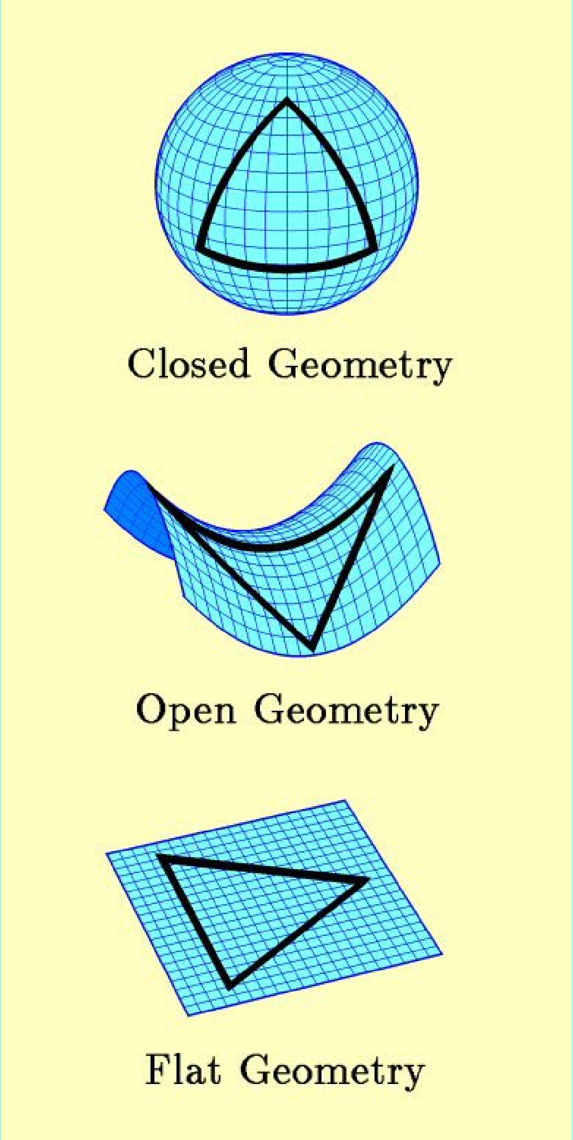
- ☆ Flat means Euclidean, as opposed to the non-Euclidean curved spaces that are also allowed by Einstein's general relativity.
- ☆ 3-dimensional curved spaces are hard to visualize, but they are analogous to the 2-dimensional curved surfaces shown on the right.



☆ 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.



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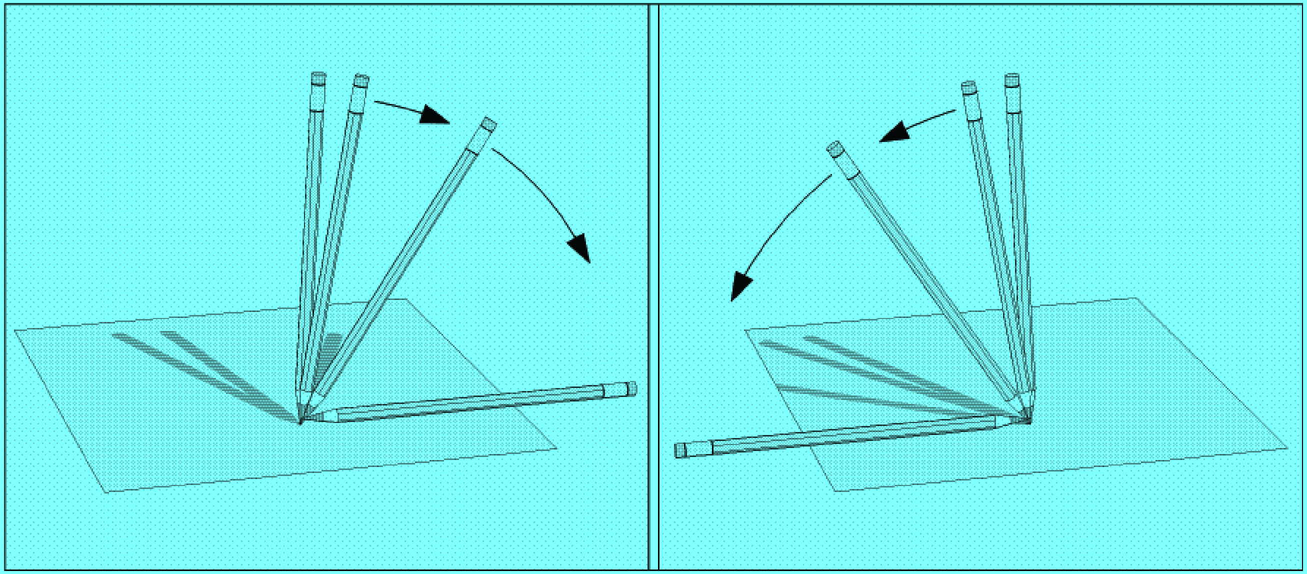

- If Ω in the early universe was slightly below 1, it would rapidly fall to zero — and no galaxies would form.
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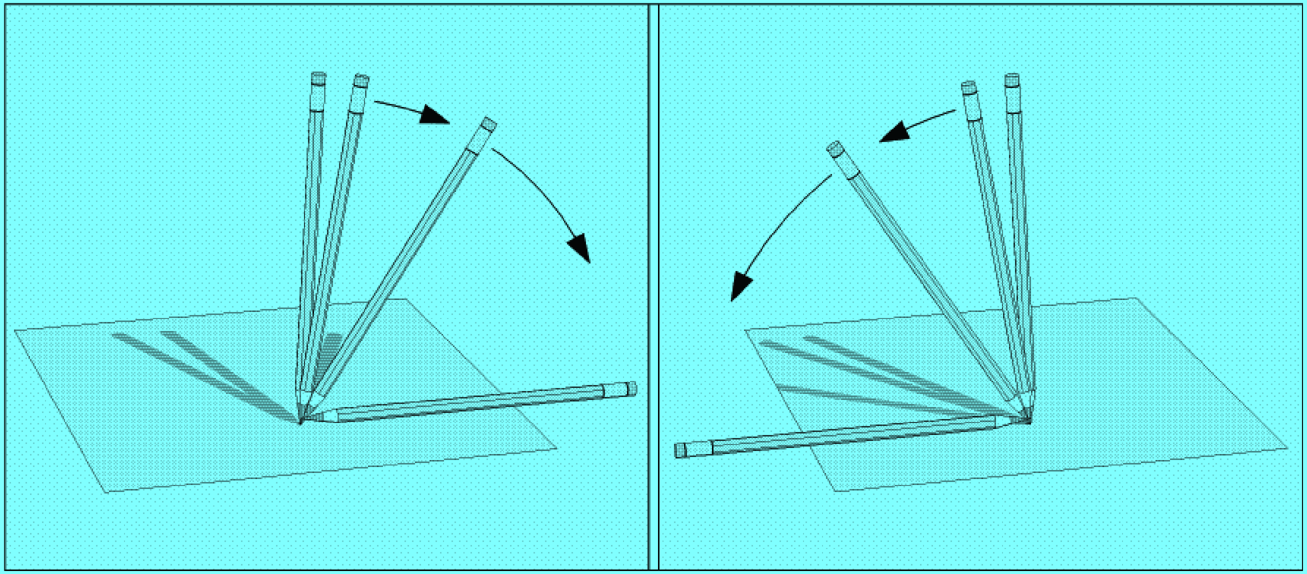

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- To be as close to critical density as we measure today, at one second after the big bang, Ω must have been equal to one **to 15 decimal places!**

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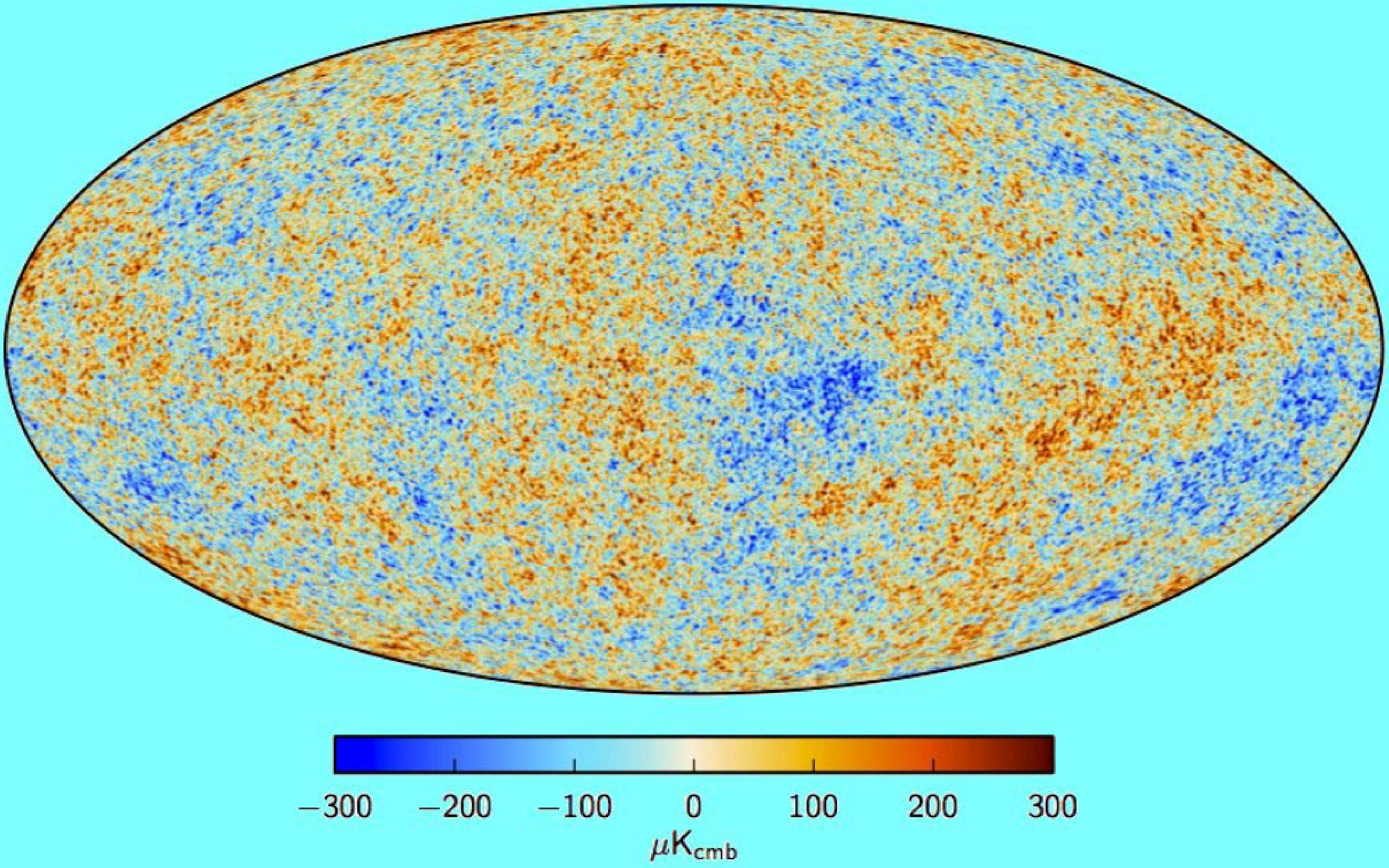
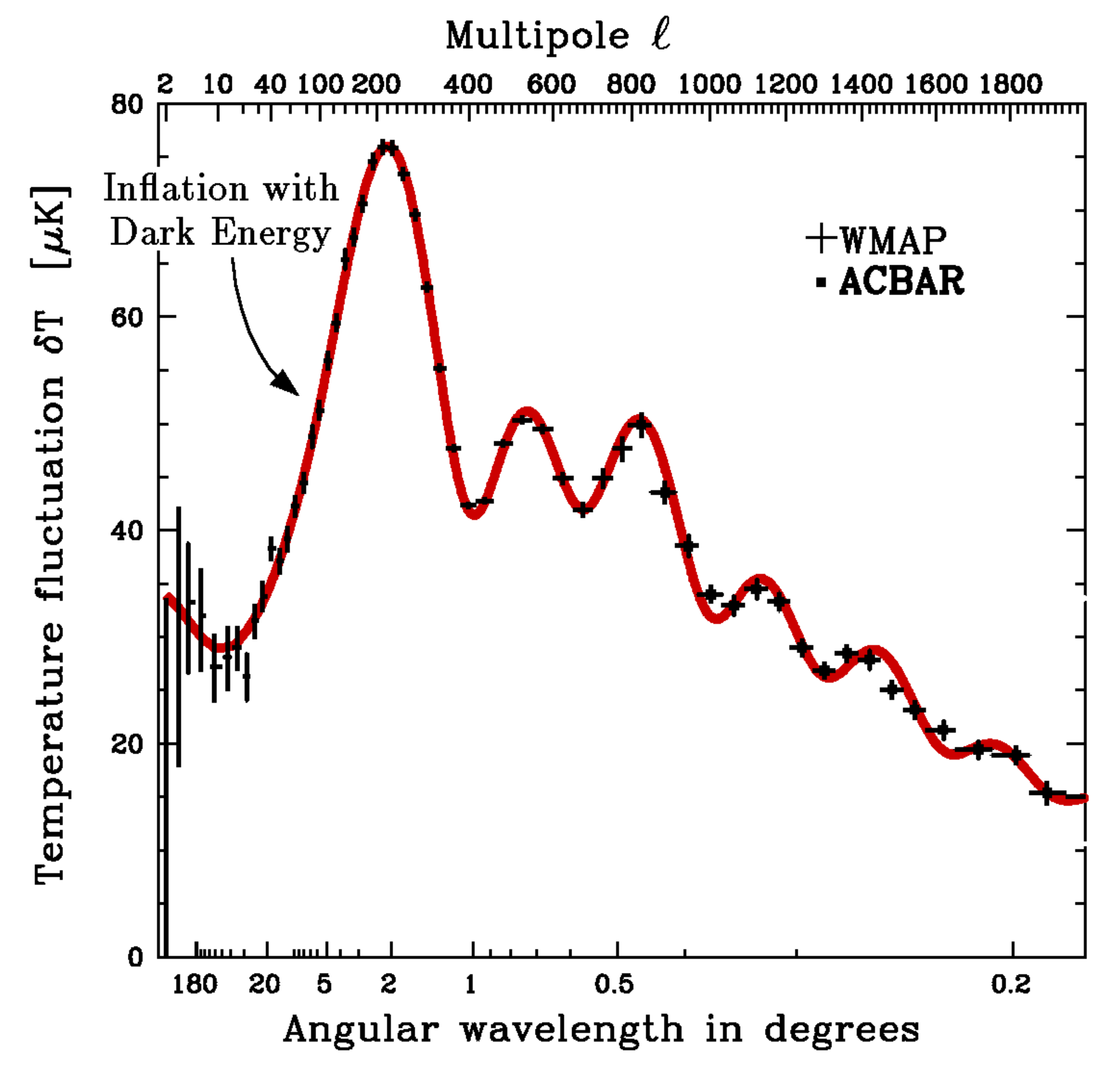
Inflationary Solution: Inflation attributes these ripples to *quantum fluctuations.* Inflation makes generic predictions for the spectrum of these ripples (i.e., how the intensity varies with wavelength). The data measured so far agree beautifully with inflation.

Ripples in the Cosmic Microwave Background

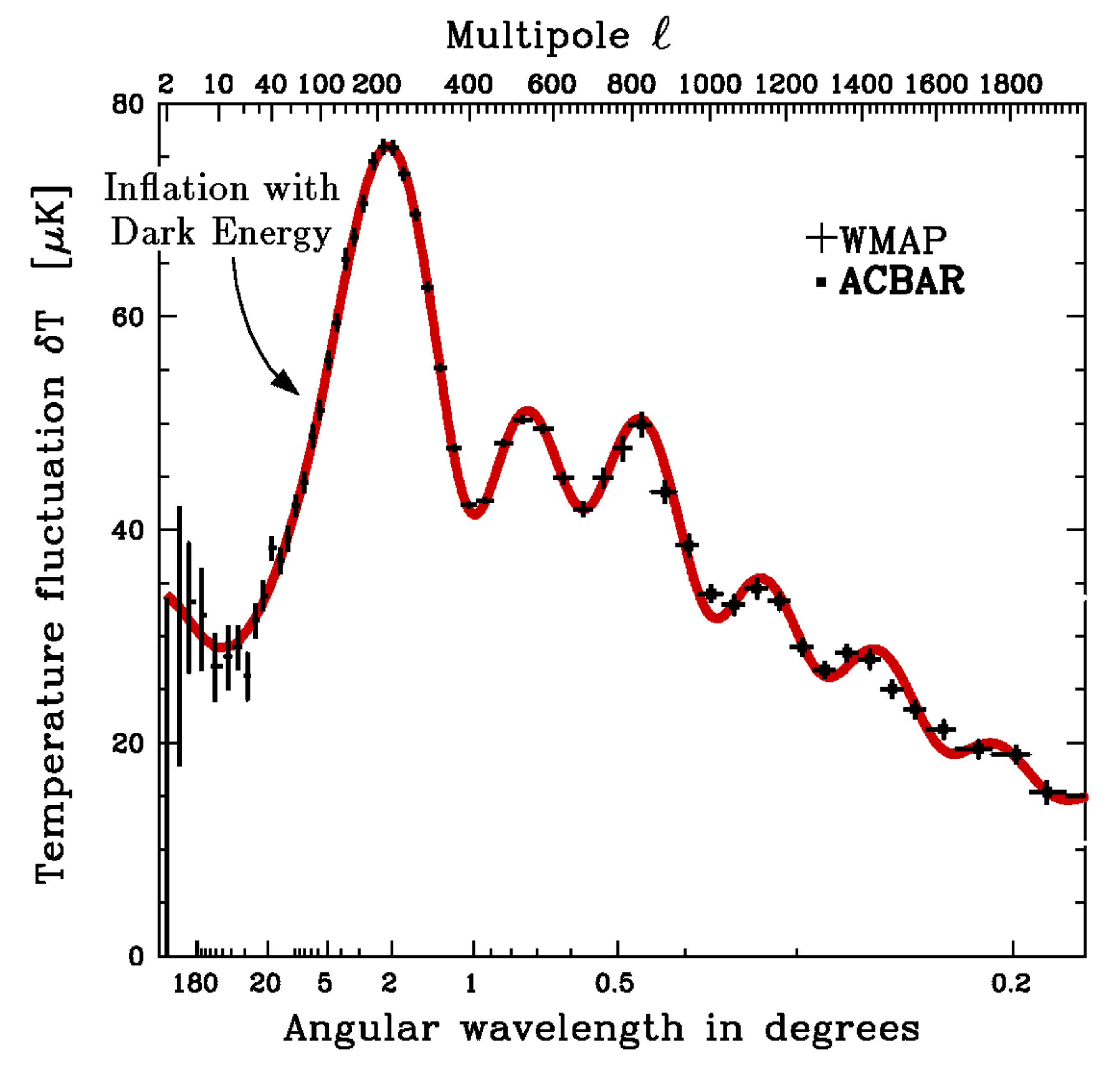
Planck Collaboration: The *Planck* mission



CMB: Comparison of Theory and Experiment



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



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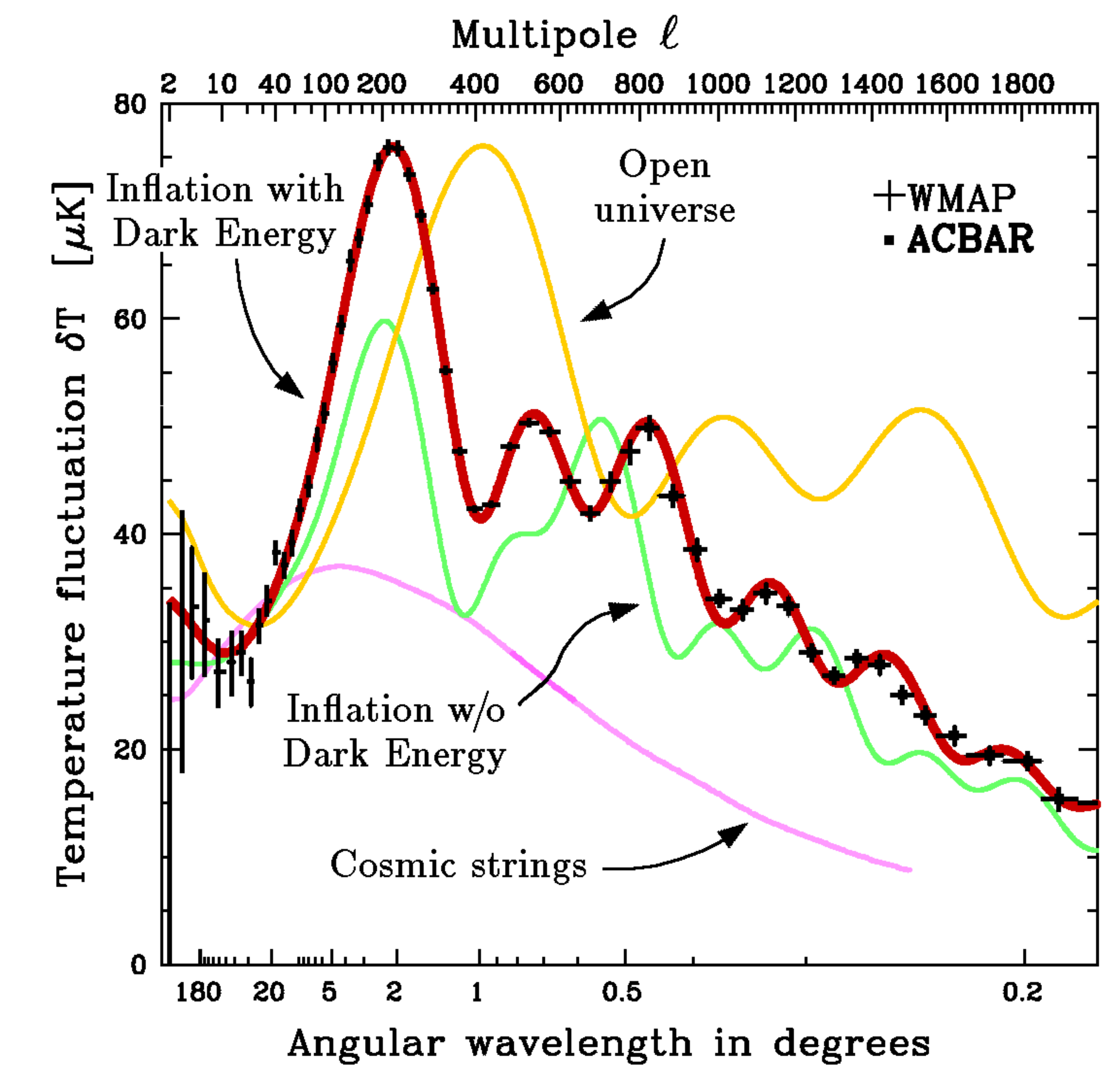

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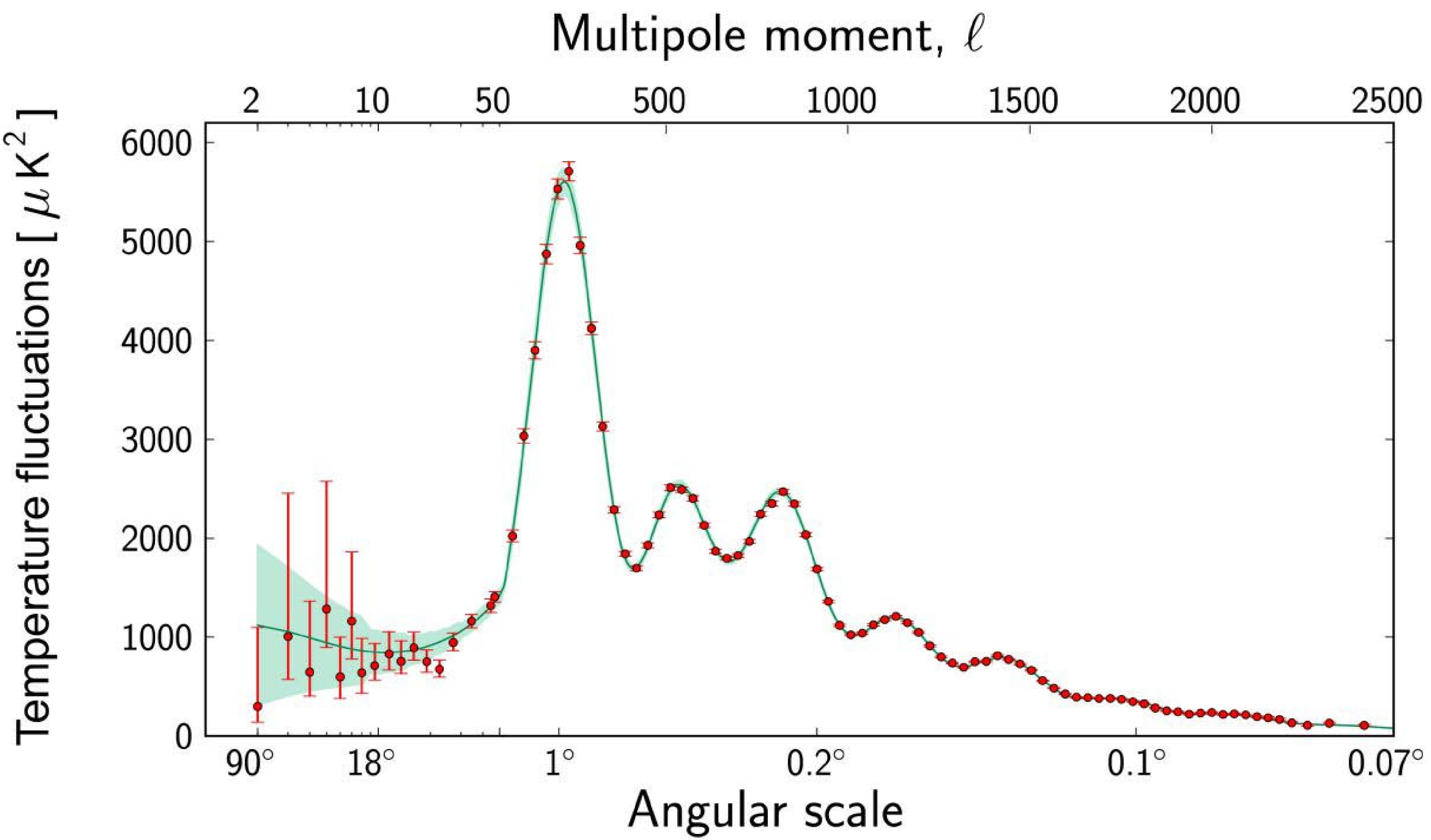
Spectrum of CMB Ripples



Planck Collaboration, 2013