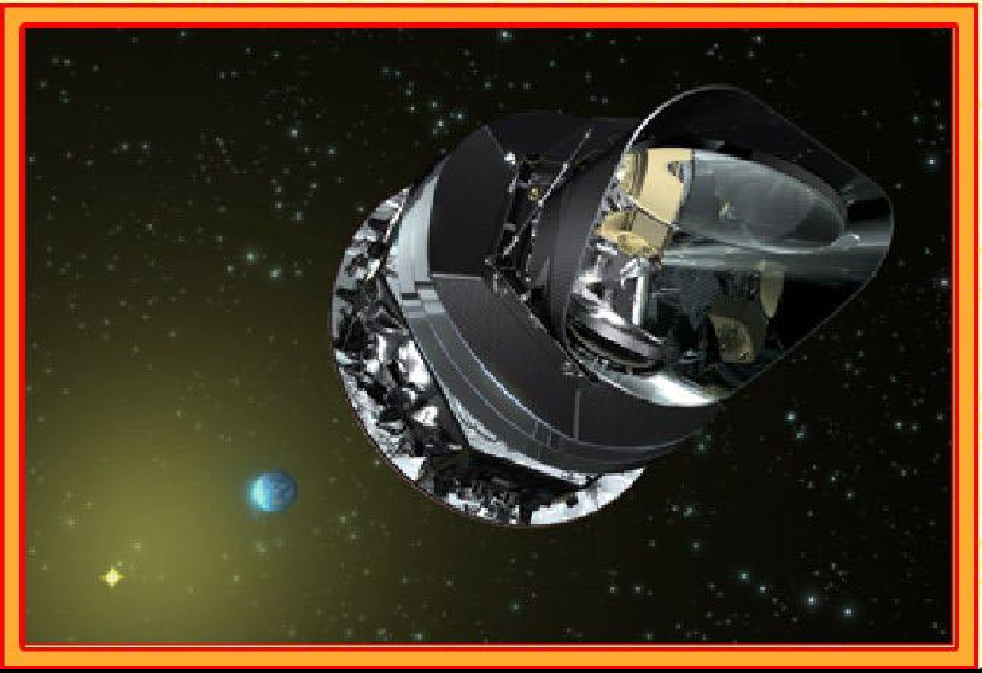
INFLATIONARY COSMOLOGY:

IS OUR UNIVERSE
PART OF
A MULTIVERSE?



— Alan Guth —

Massachusetts Institute of Technology

8.286 Opening Lecture
September 5, 2013

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!)
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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:

- ☆ What caused the expansion? (The big bang theory describes only the **aftermath** of the bang.)
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Gravitational Repulsion!

- ☆ The combination of general relativity and modern particle theories predicts that, at very high energies, there exists forms of matter that create a gravitational repulsion! (In general relativity, gravitational repulsion is created by negative pressures.)

- 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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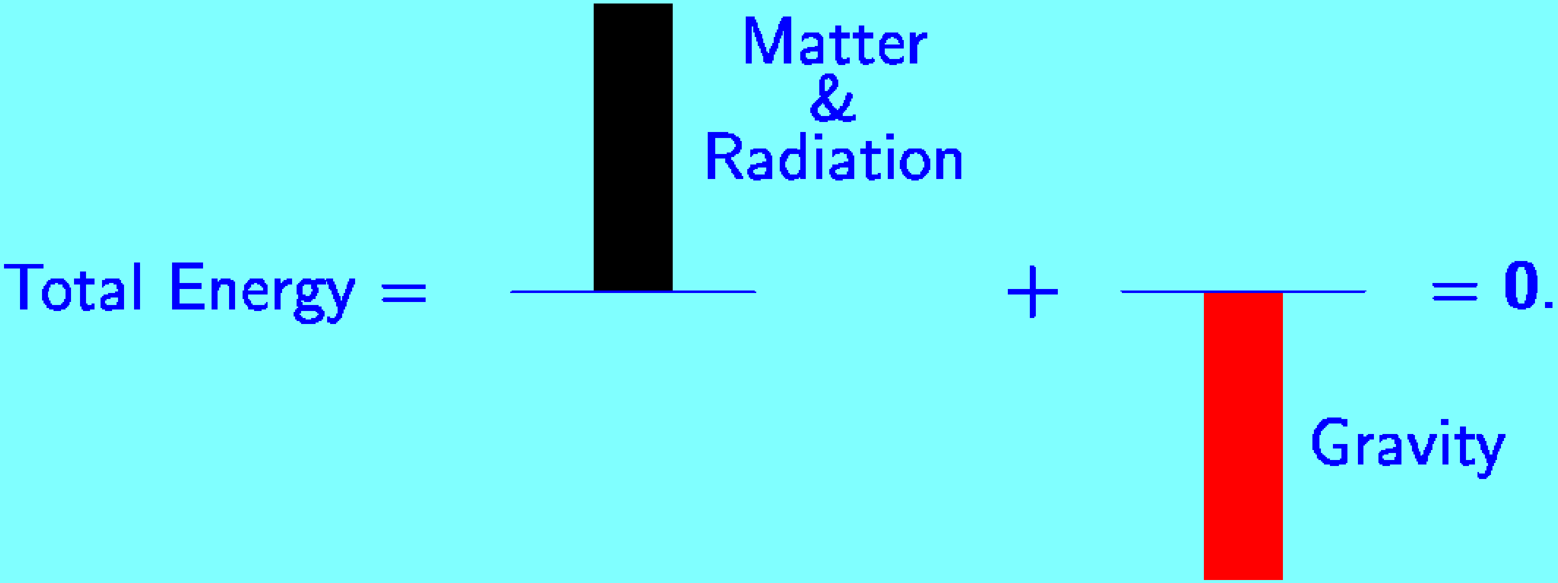
The energy of a gravitational field is negative!

- ☆ The positive energy of the repulsive gravity material was compensated by the negative energy of gravity. The TOTAL ENERGY of the universe may very well be zero.

Schematically,



Total Energy = Matter & Radiation + Gravity = **0**.

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 does not mean 2-dimensional.
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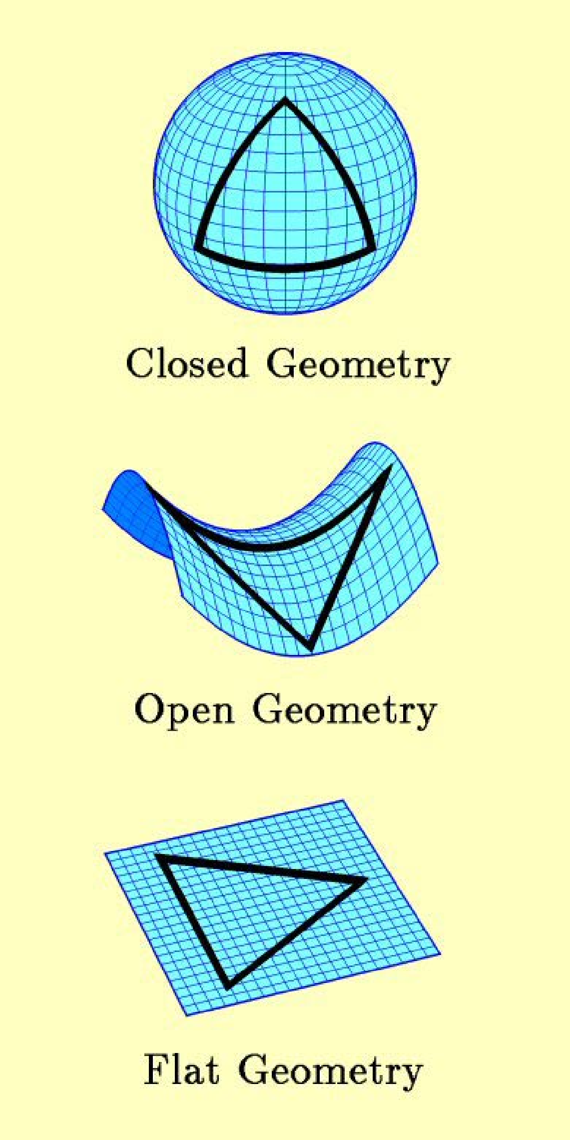
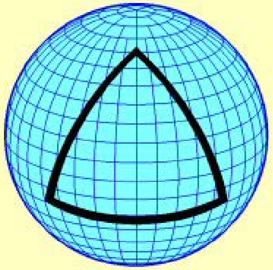
- ☆ Flat does not mean 2-dimensional.
- ☆ Flat means Euclidean, as opposed to the non-Euclidean curved spaces that are also allowed by Einstein’s general relativity.
- ☆ 3-dimensional curved spaces are hard to visualize, but they are analogous to the 2-dimensional curved surfaces shown on the right.



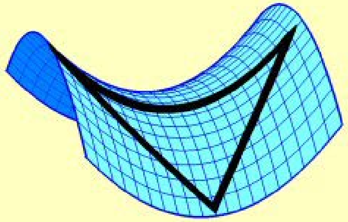
- According to general relativity, the flatness of the universe is related to its mass density:

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

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.



Closed Geometry



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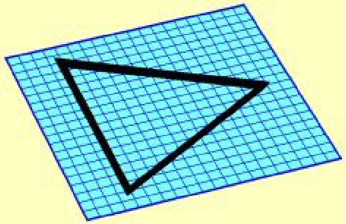

Flat Geometry

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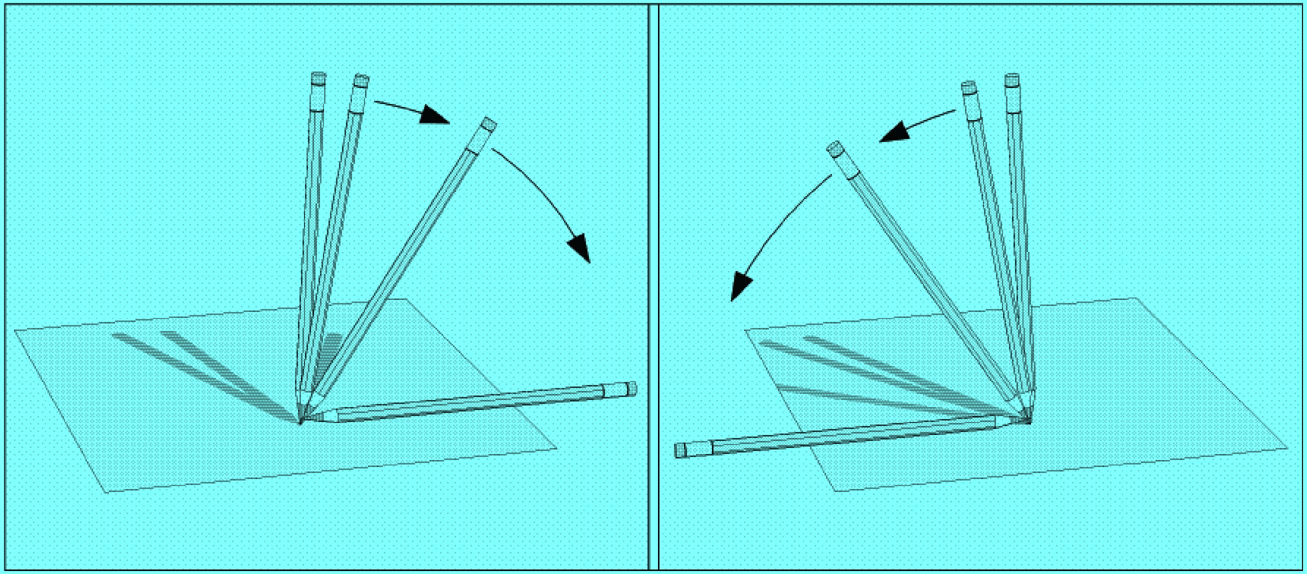

- If Ω in the early universe was slightly below 1, it would rapidly fall to zero — and no galaxies would form.
- If Ω was slightly greater than 1, it would rapidly rise to infinity, the universe would recollapse, and no galaxies would form.

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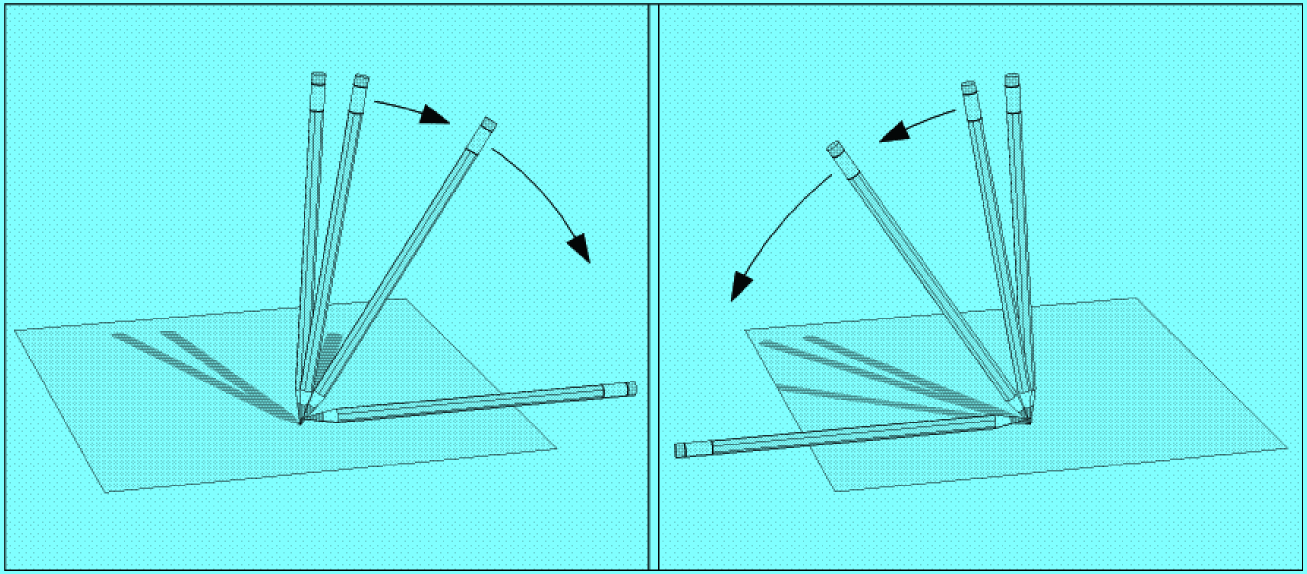

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- ☆ To be as close to critical density as we measure today, at one second after the big bang, Ω must have been equal to one **to 15 decimal places!**

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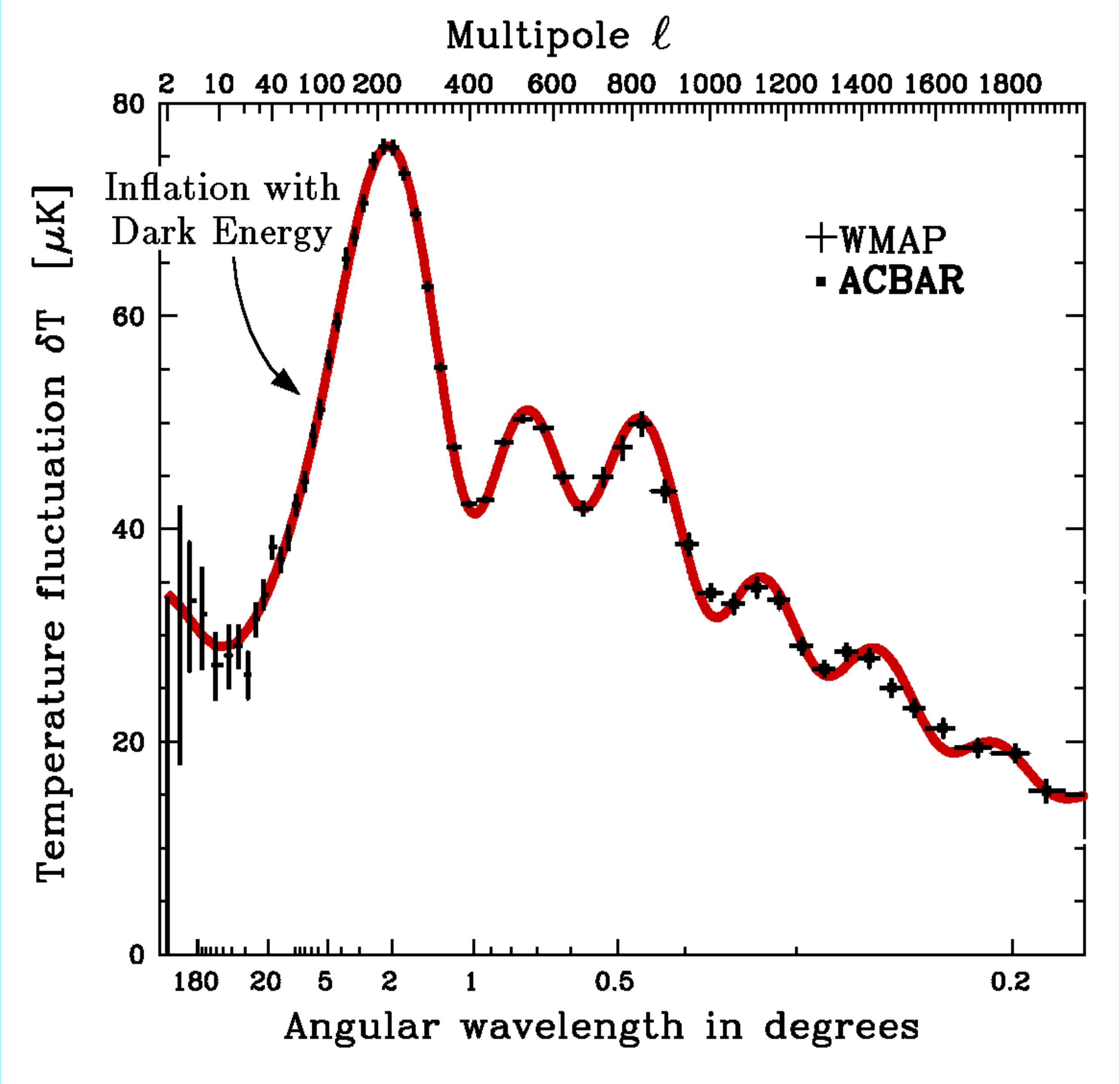
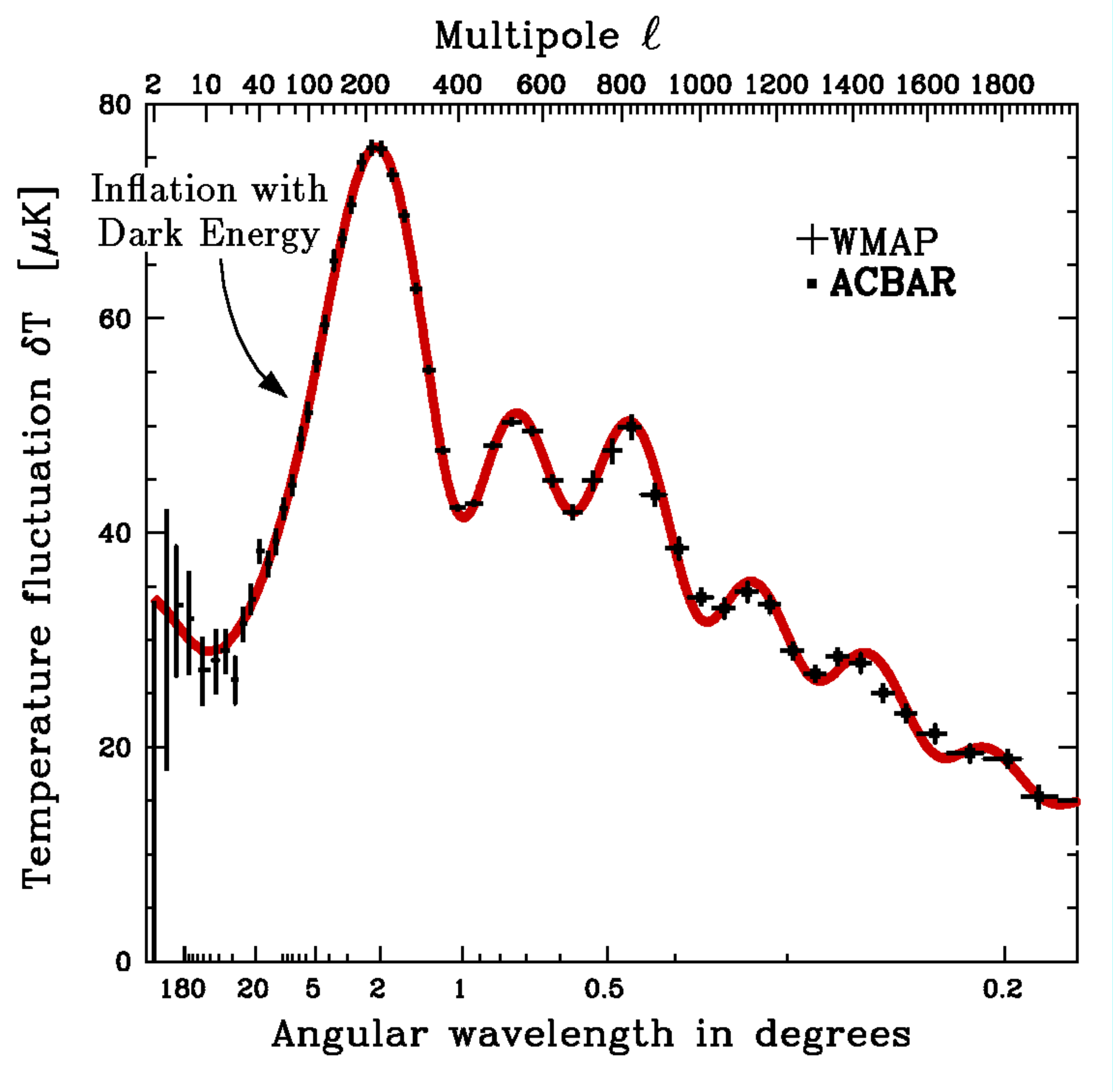
Inflationary Solution: Inflation attributes these ripples to *quantum fluctuations.* Inflation makes generic predictions for the spectrum of these ripples (i.e., how the intensity varies with wavelength). The data measured so far agree beautifully with inflation.

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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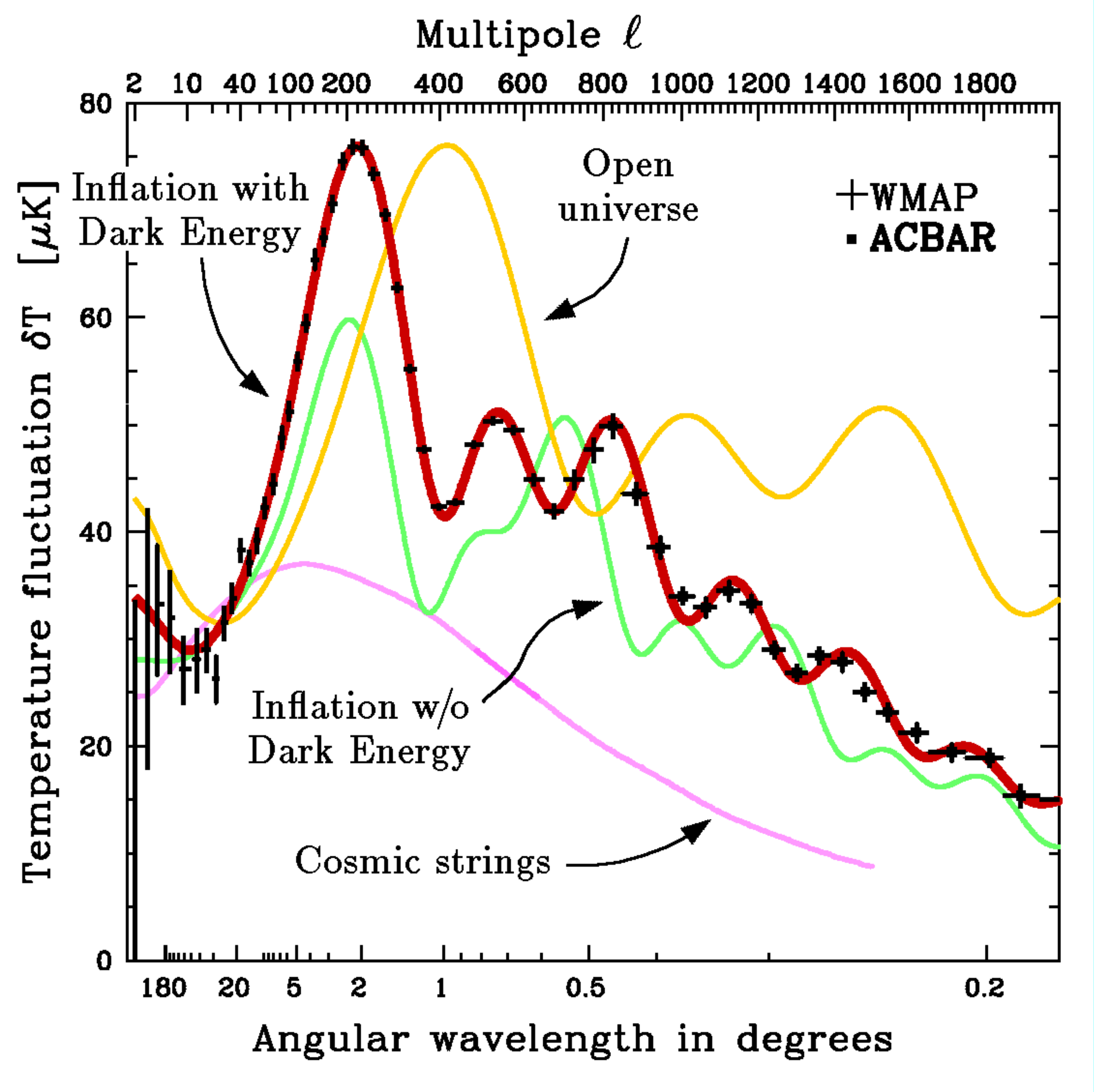

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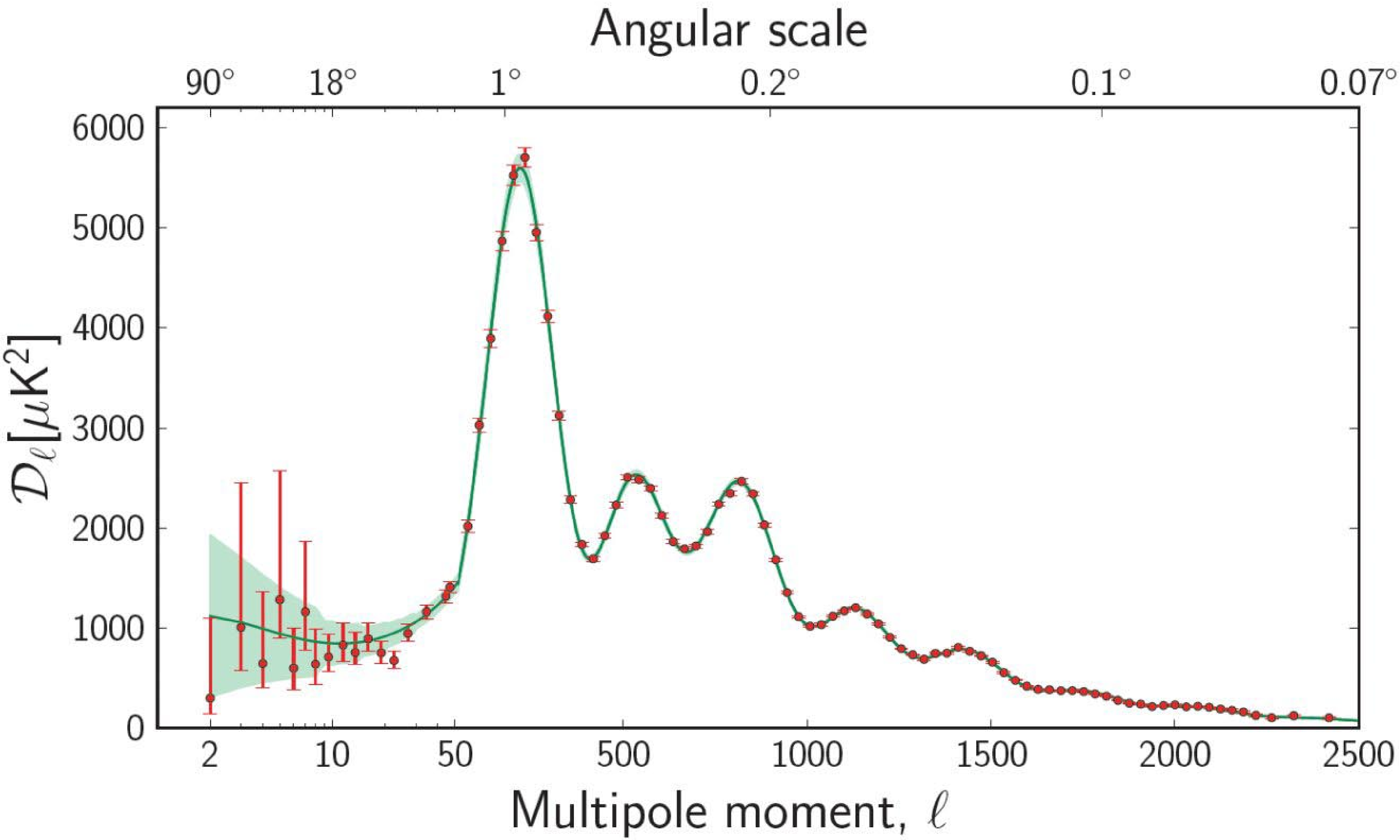
Planck Collaboration: The *Planck* mission



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Key Mystery of the Universe

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SIMPLEST EXPLANATION: Dark energy = vacuum energy, also known as a cosmological constant.

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- ☆ In quantum field theory, the energy density of quantum fluctuations diverges. All wavelengths contribute, and there is no shortest wavelength.
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WHOOPS!

THE LANDSCAPE OF STRING THEORY

- ☆ Since the inception of string theory, theorists have sought to find the vacuum of string theory — with no success.
- ☆ Within the past 10 years or so, most string theorists have come to the belief that there is no unique vacuum.
- ☆ Instead, there are maybe 10^{500} long-lived metastable states, any of which could serve as a substrate for a pocket universe. This is the landscape!
- ☆ Eternal inflation can presumably produce an infinite number of pocket universes of every type, populating the landscape.
- ☆ Although string theory would govern everywhere, each type of vacuum would have its own low-energy physics — its own “standard model,” its own “constants” of nature, and its own vacuum energy density.

To Be Continued . . .