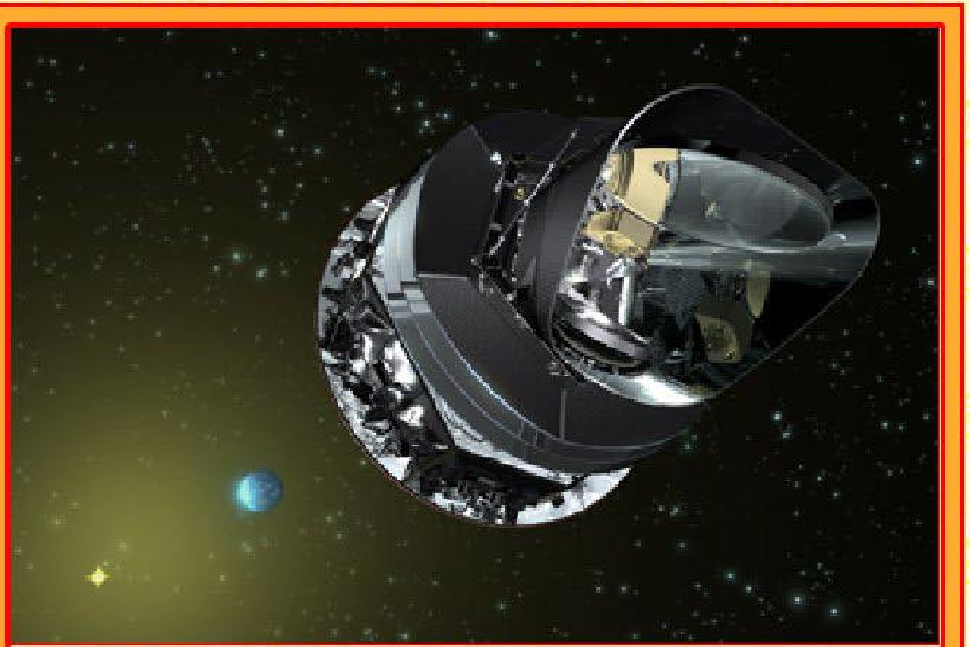
INFLATIONARY COSMOLOGY:

IS OUR UNIVERSE PART OF A MULTIVERSE?

PART 2



— Alan Guth —

Massachusetts Institute of Technology

8.286 Lecture 2
September 10, 2018

SUMMARY OF LAST LECTURE

The Standard Big Bang: Really describes only the aftermath of a bang, beginning 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.

Summary p. 2: Evidence for Inflation

1) Inflation can explain the large-scale uniformity of the universe. (Cosmic microwave background (CMB) uniform to 1 part in 100,000.)

2) "Flatness problem:"

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- ☆ Flat means Euclidean, as opposed to the non-Euclidean curved spaces that are also allowed by Einstein's general relativity.

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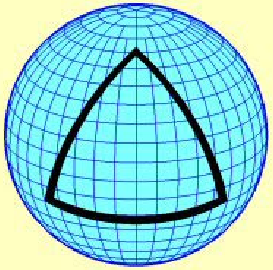
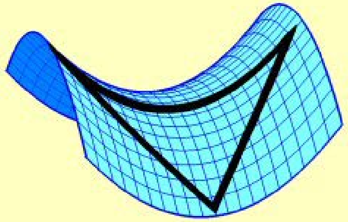
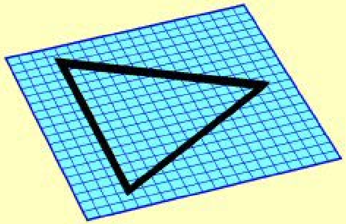
- ☆ Flat means Euclidean, as opposed to the non-Euclidean curved spaces that are also allowed by Einstein’s general relativity.
- ☆ 3-dimensional curved spaces are hard to visualize, but they are analogous to the 2-dimensional curved surfaces shown on the right.



Closed Geometry



Open Geometry

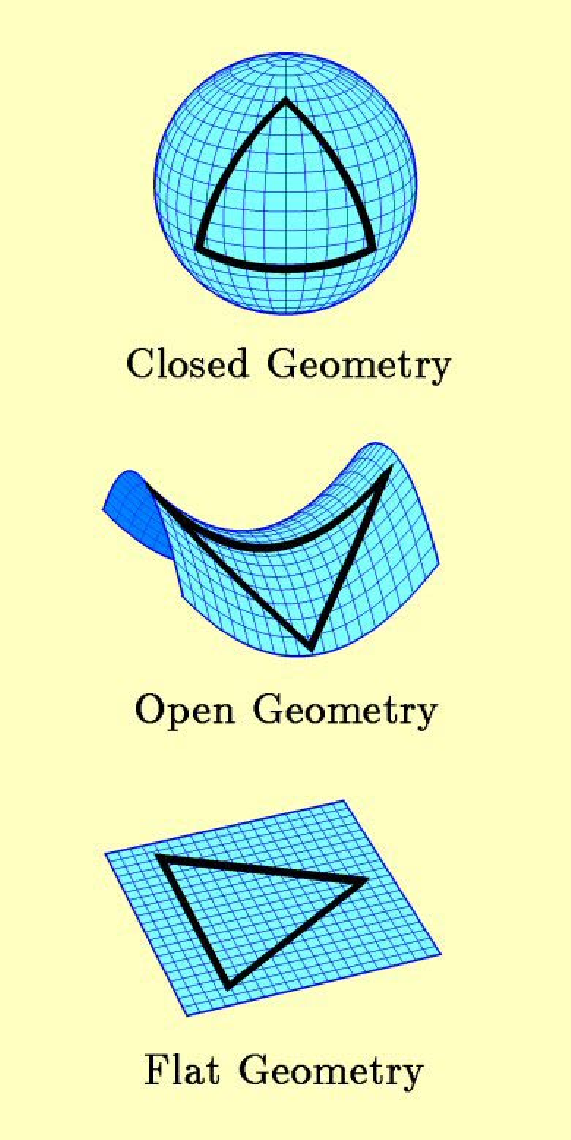


Flat Geometry

☆ 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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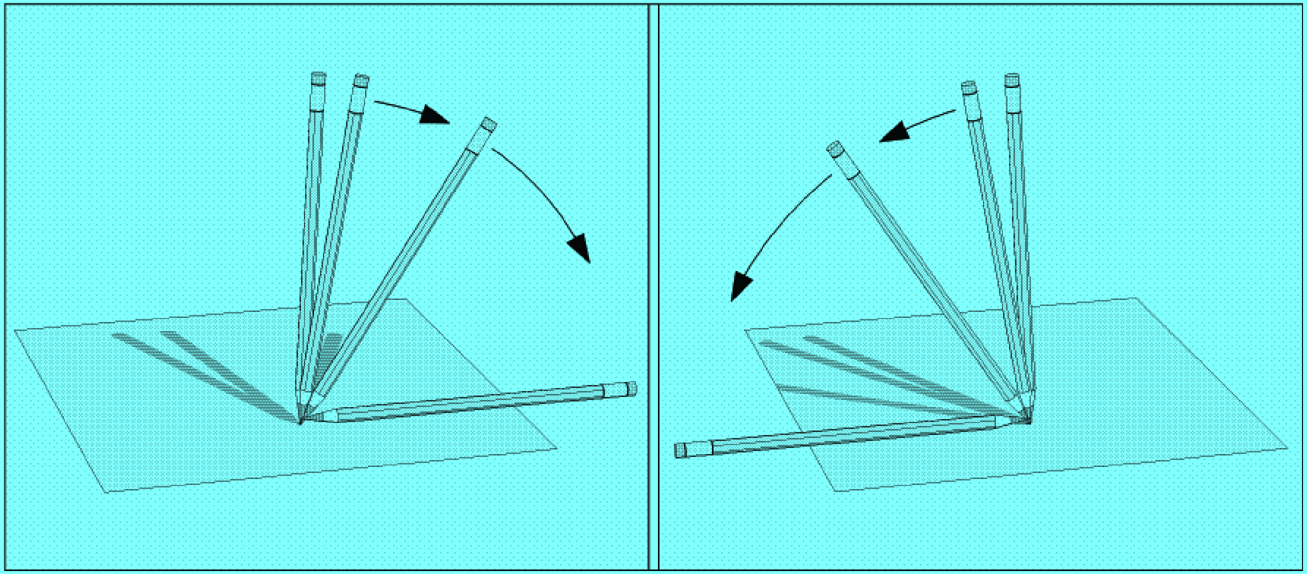

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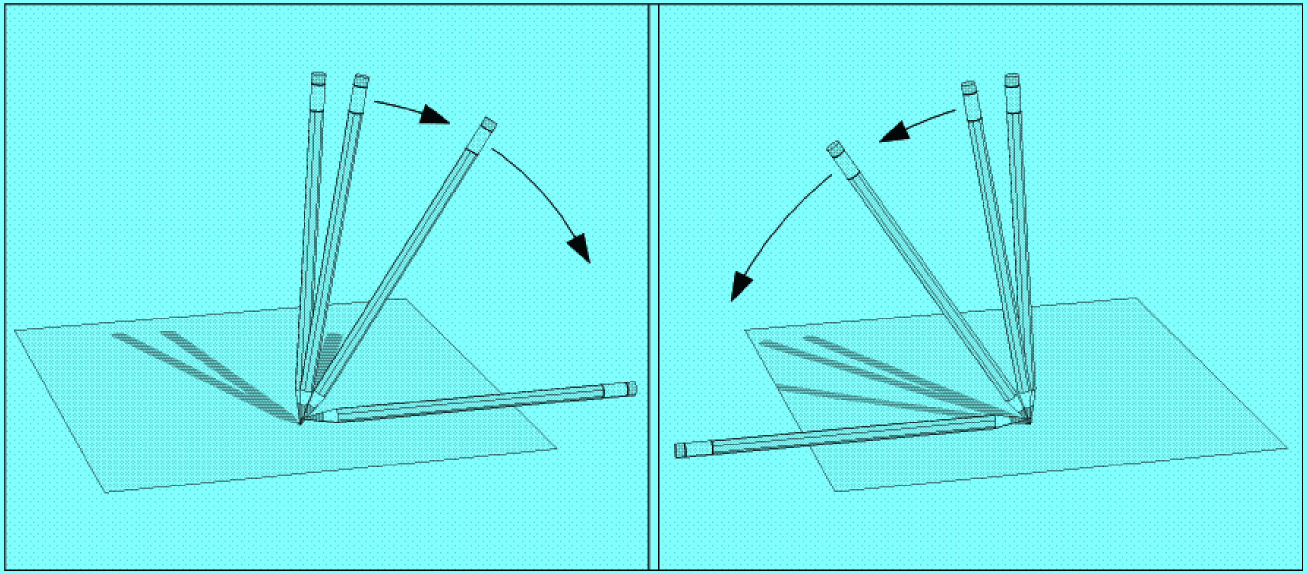

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- To be as close to critical density as we measure today, at one second after the big bang, Ω must have been equal to one **to 15 decimal places!**

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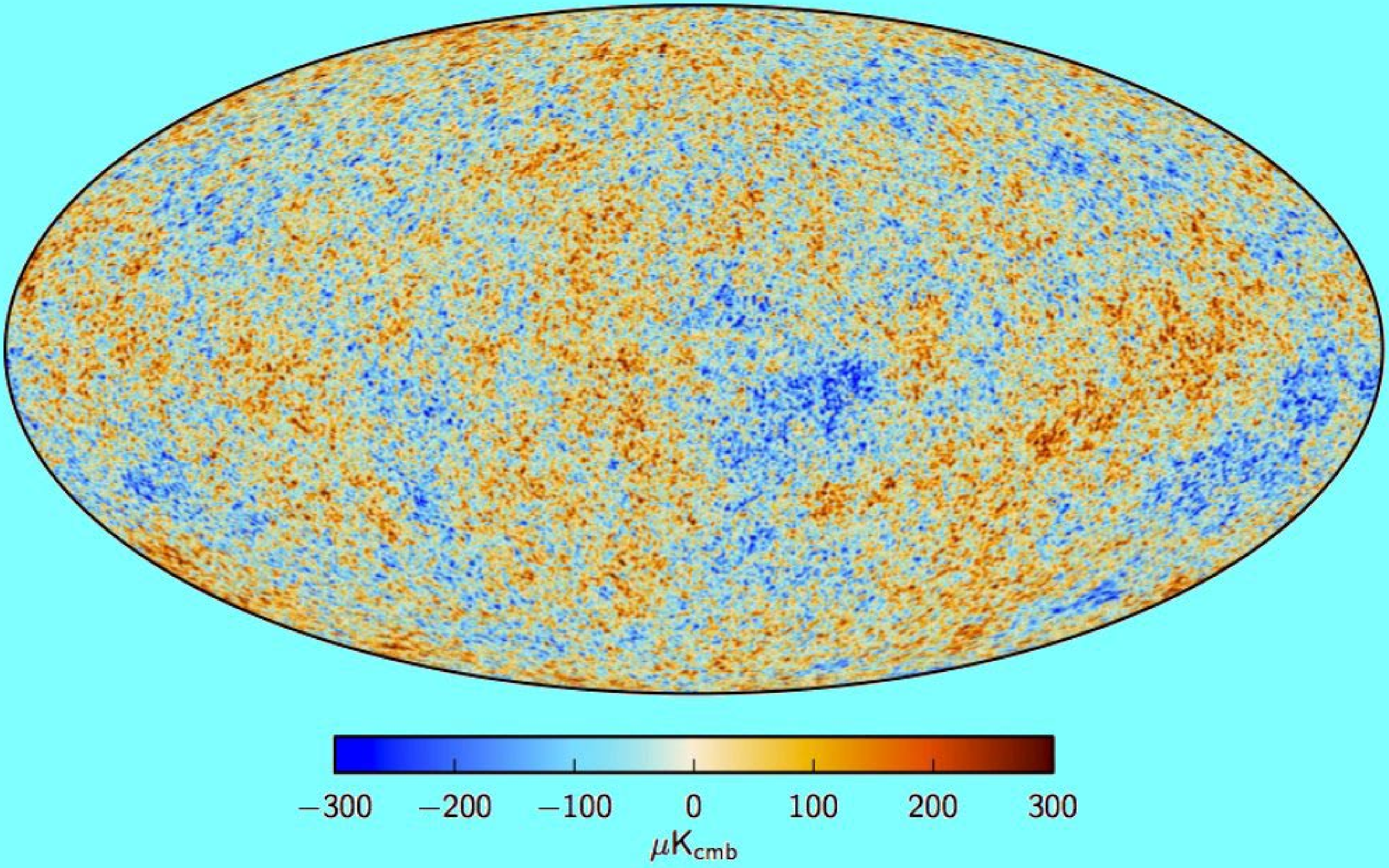
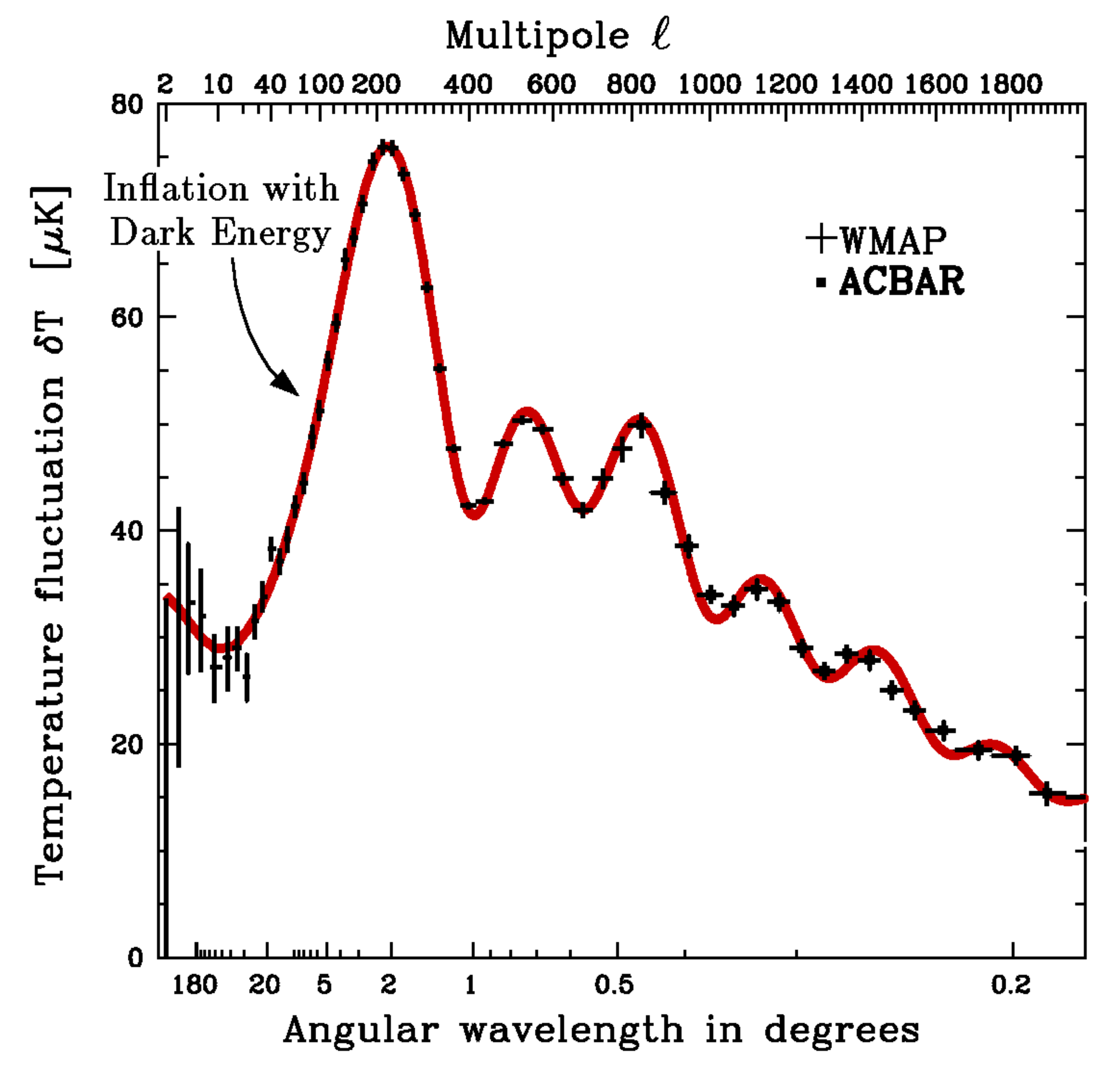
Inflationary Solution: Inflation attributes these ripples to *quantum fluctuations.* Inflation makes generic predictions for the spectrum of these ripples (i.e., how the intensity varies with wavelength). The data measured so far agree beautifully with inflation.

Ripples in the Cosmic Microwave Background

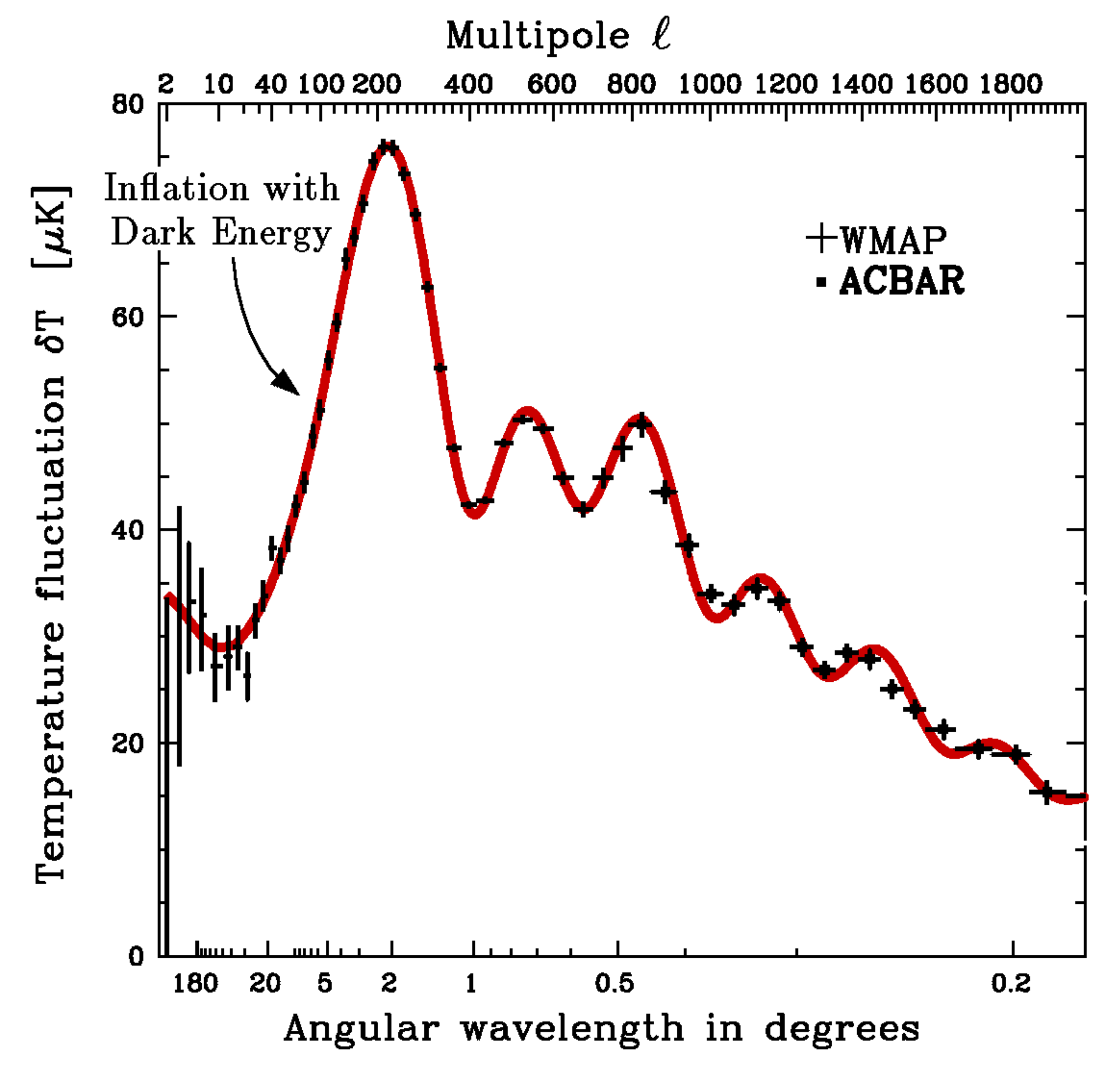
Planck Collaboration: The *Planck* mission





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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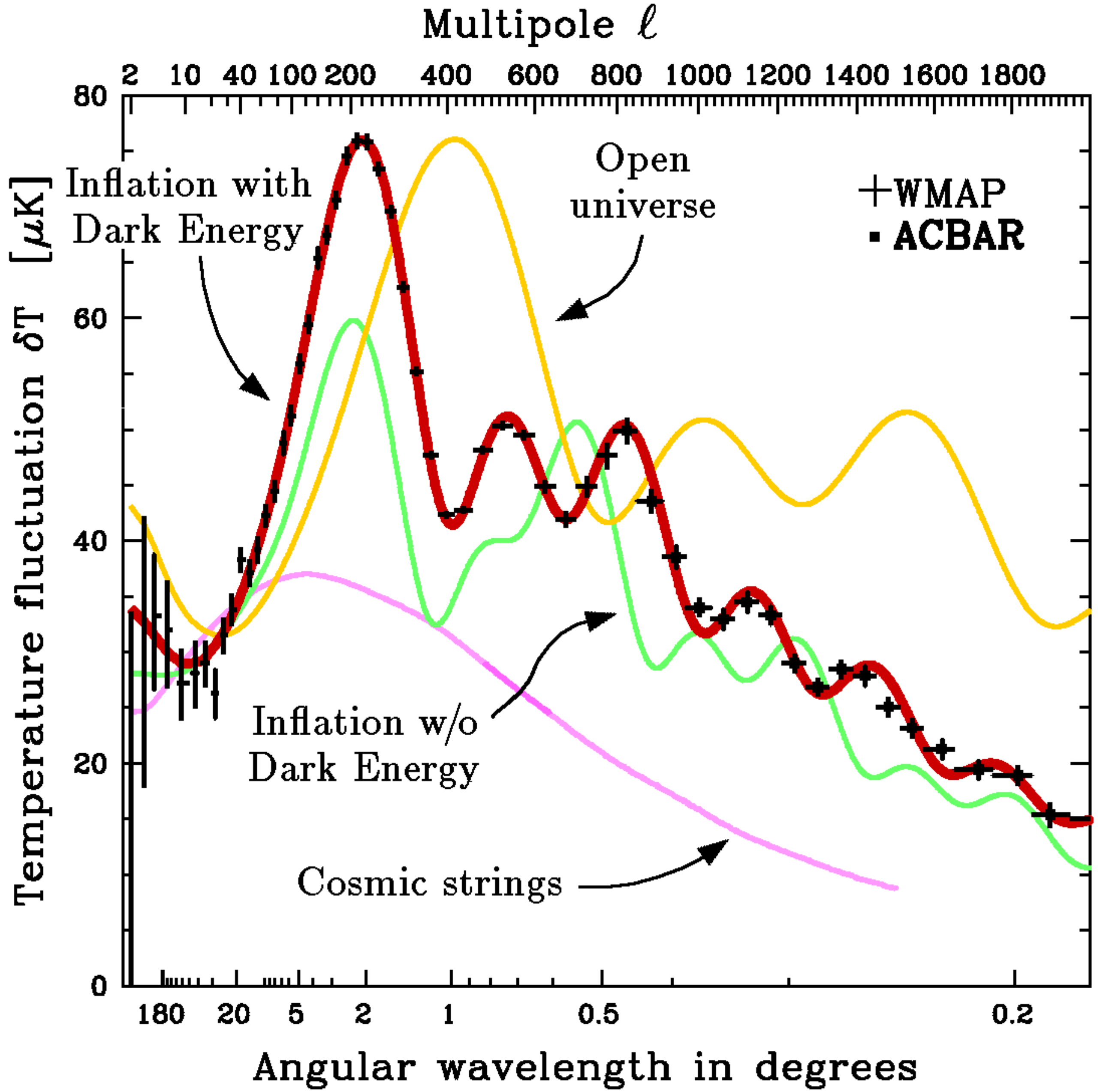

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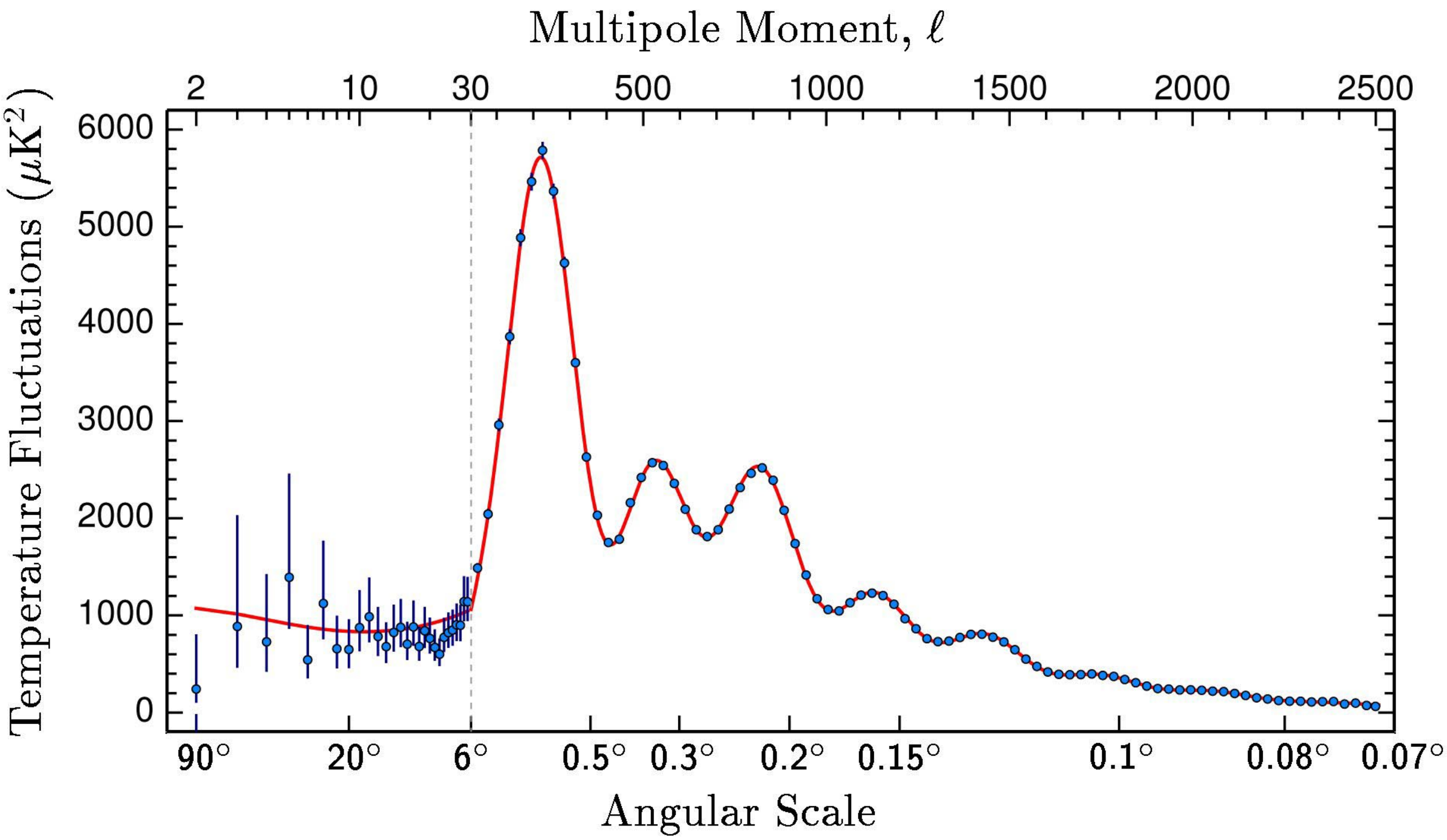
Spectrum of CMB Ripples



Planck Collaboration, 2015

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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Current limit: $r < 0.07$. Future sensitivity: if $r > 0.001$, it can be found by about 2024 (CMB Stage 4).

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.

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Roughly speaking, inflation is driven by a metastable state, which decays with some half-life.

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.
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It is larger by 120 orders of magnitude!

The Multiverse and the Cosmological Constant Problem

- One of the thorniest problems in particle theory is to understand why the energy density of the vacuum (equivalent to the cosmological constant) is 120 orders of magnitude smaller than the (expected) Planck scale.
- The multiverse offers a possible (although controversial) solution.
- If there are 10^{500} different types of vacuum (as in string theory), there will be many with energy densities in the range we observe.
- The vacuum energy affects cosmic evolution: if it is too large and positive, the universe flies apart too fast for galaxies to form. If too large and negative, the universe implodes.
- 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 Winds Blowing Us Towards the Multiverse

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

2) 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. What is happening?

3) String theorists mostly agree that string theory has no unique vacuum, but instead a landscape of perhaps 10^{500} long-lived metastable states, any of which could be our vacuum. With the multiverse, this allows the small vacuum energy density to be explained as a selection effect: perhaps we see a small vacuum energy density because conscious beings only form in those parts of the multiverse where the vacuum energy density is small.

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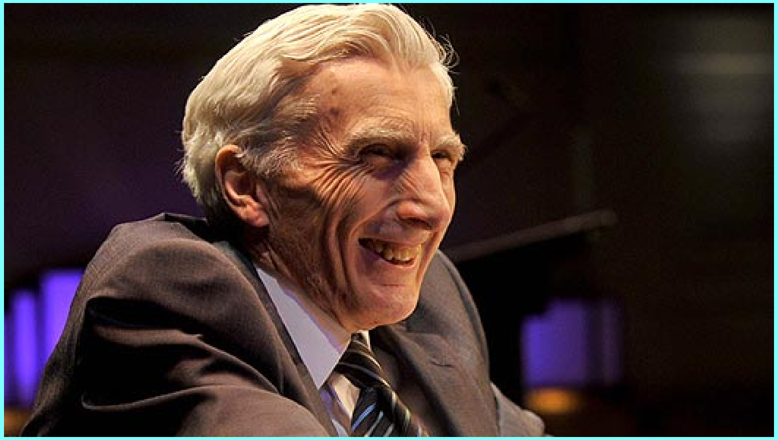

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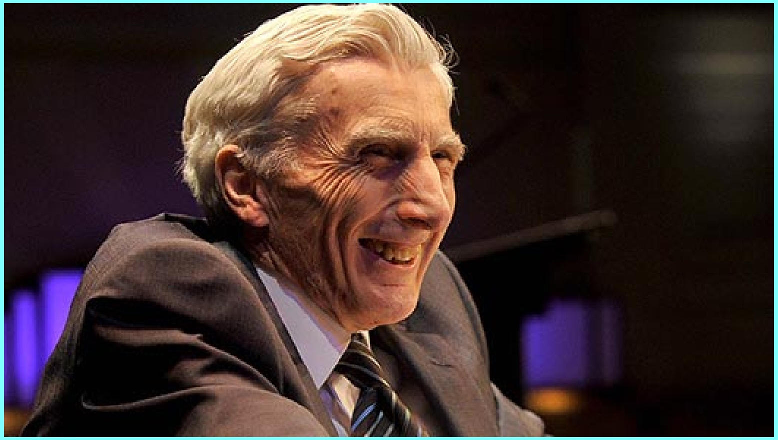

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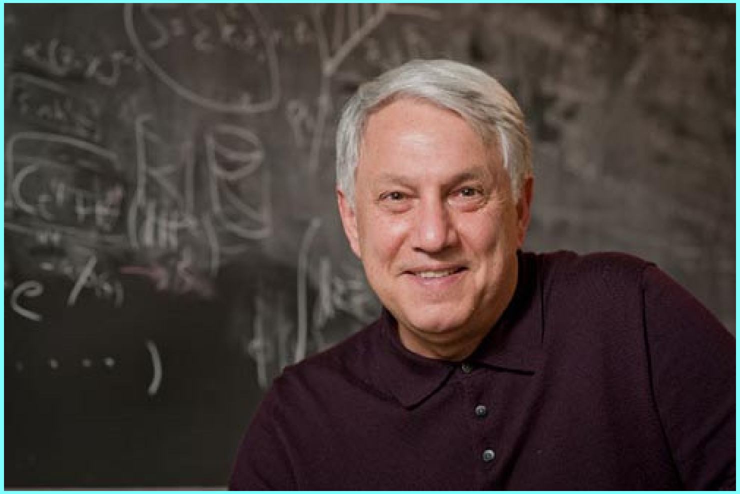

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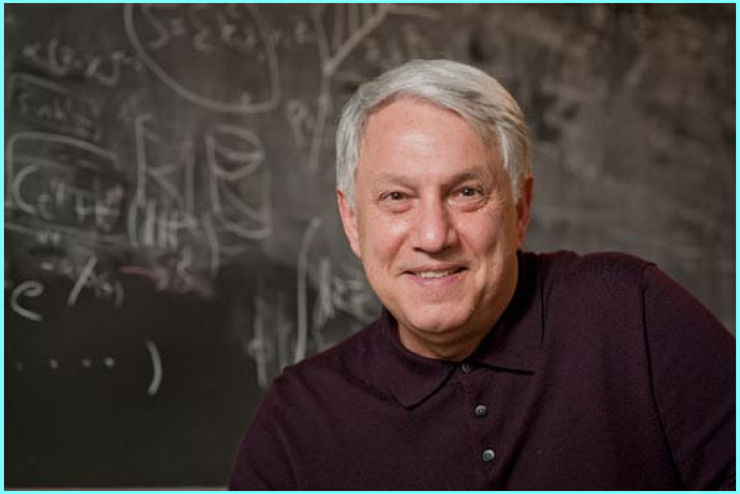

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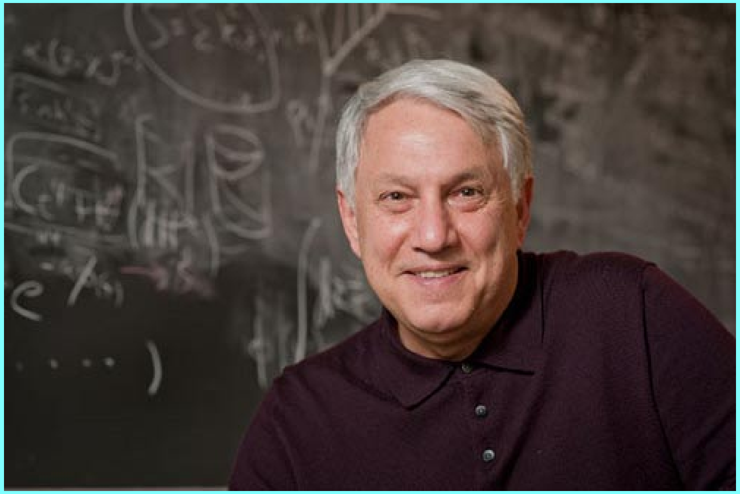

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