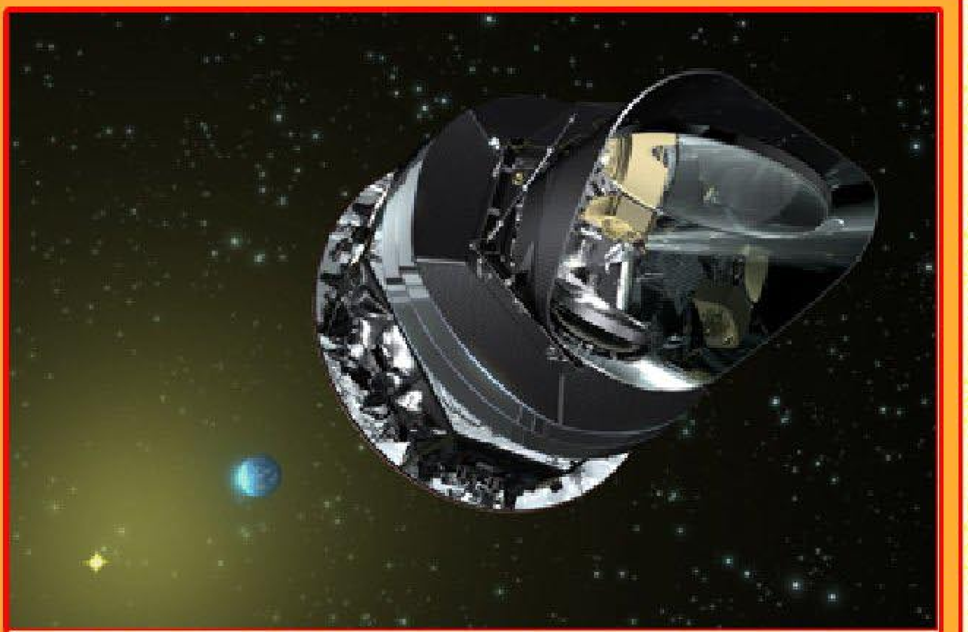
UNIVERSITY of VIRGINIA

# INFLATIONARY COSMOLOGY:

## IS OUR UNIVERSE PART OF A MULTIVERSE?

— Alan Guth —

Massachusetts Institute of Technology



*The 43rd Annual Llewellyn G. Hoxton Lecture*
*Chemistry Building*
*University of Virginia*
*Charlottesville, Virginia*
*April 15, 2015*

# The Conventional Big Bang Theory

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- ☆ What caused the expansion? (The conventional theory describes only the **aftermath** of the bang. It says nothing about what banged, why it banged, or what happened before it banged.)
- ☆ Where did the matter come from? (The theory assumes that **all matter** existed from the very beginning.)

# What is Inflation?

- Inflation is a theory about the bang of the big bang. That is, inflation is a possible answer to the question of what propelled the gigantic expansion of the big bang.
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**Gravitational Repulsion.**

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## 1) Gravitational Repulsion!

Since the advent of general relativity, physicists have known that gravity can act repulsively. Einstein used this option, 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 exist materials that create gravitational repulsion.

# Sequence of Events

- Inflation proposes that a patch of repulsive gravity material existed in the early universe — for inflation at the grand unified theory scale, 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.)
- The gravitational repulsion was the driving force behind the big bang. The patch was driven into exponential expansion, with a doubling time of maybe $\sim 10^{-38}$ second.
- The patch expanded exponentially by a factor of at least $10^{28}$ (100 doubling times), but it could have expanded much more. 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." The universe continued to coast and cool from then onward.
- Key feature: During the exponential expansion, the density of matter and energy did NOT thin out.
- Although more and more mass/energy appeared as the repulsive-gravity material expanded, total energy was conserved!

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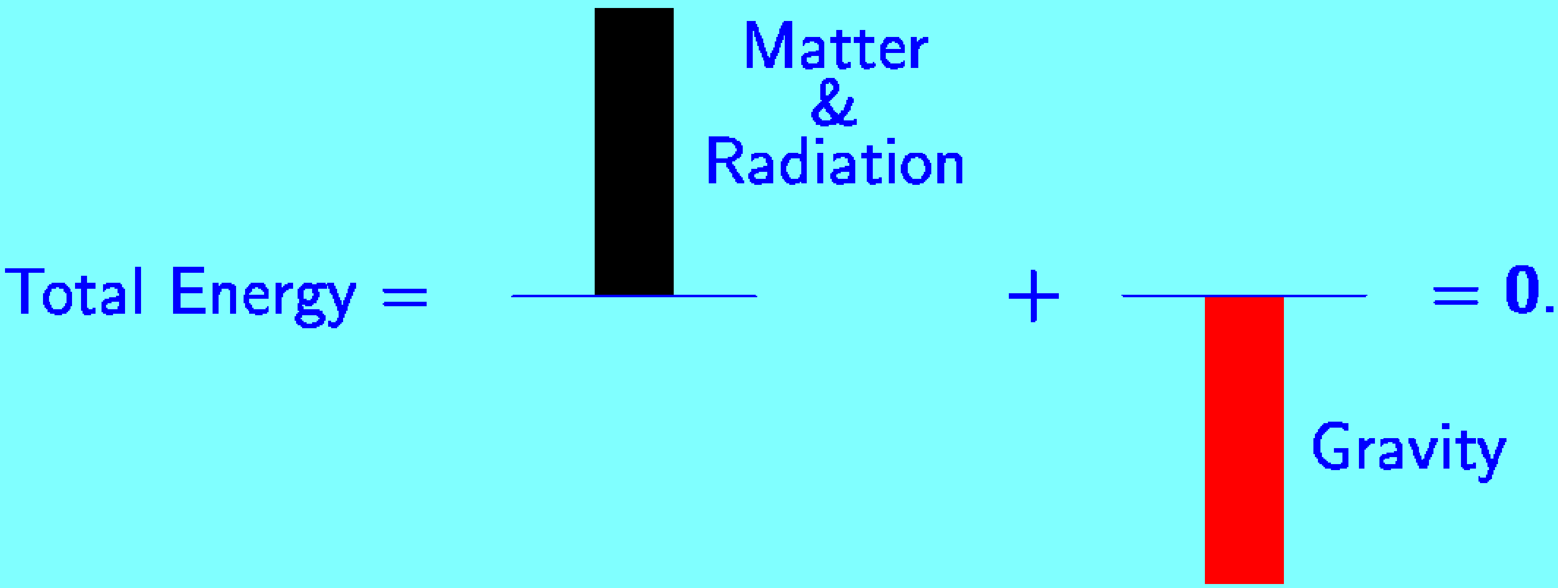
- **Miracle of Physics #2:**

  **The energy of a gravitational field is negative!!**
- The negative energy of gravity cancelled the positive energy of matter, so the total energy was constant and possibly zero.

Schematically,

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# 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 380,000 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) **Mass Density:** Cosmologists measure mass density by the ratio

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

where the "critical density" is that density for which the universe is flat (obeys Euclidean geometry).

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- ☆ New ingredient: Dark Energy.

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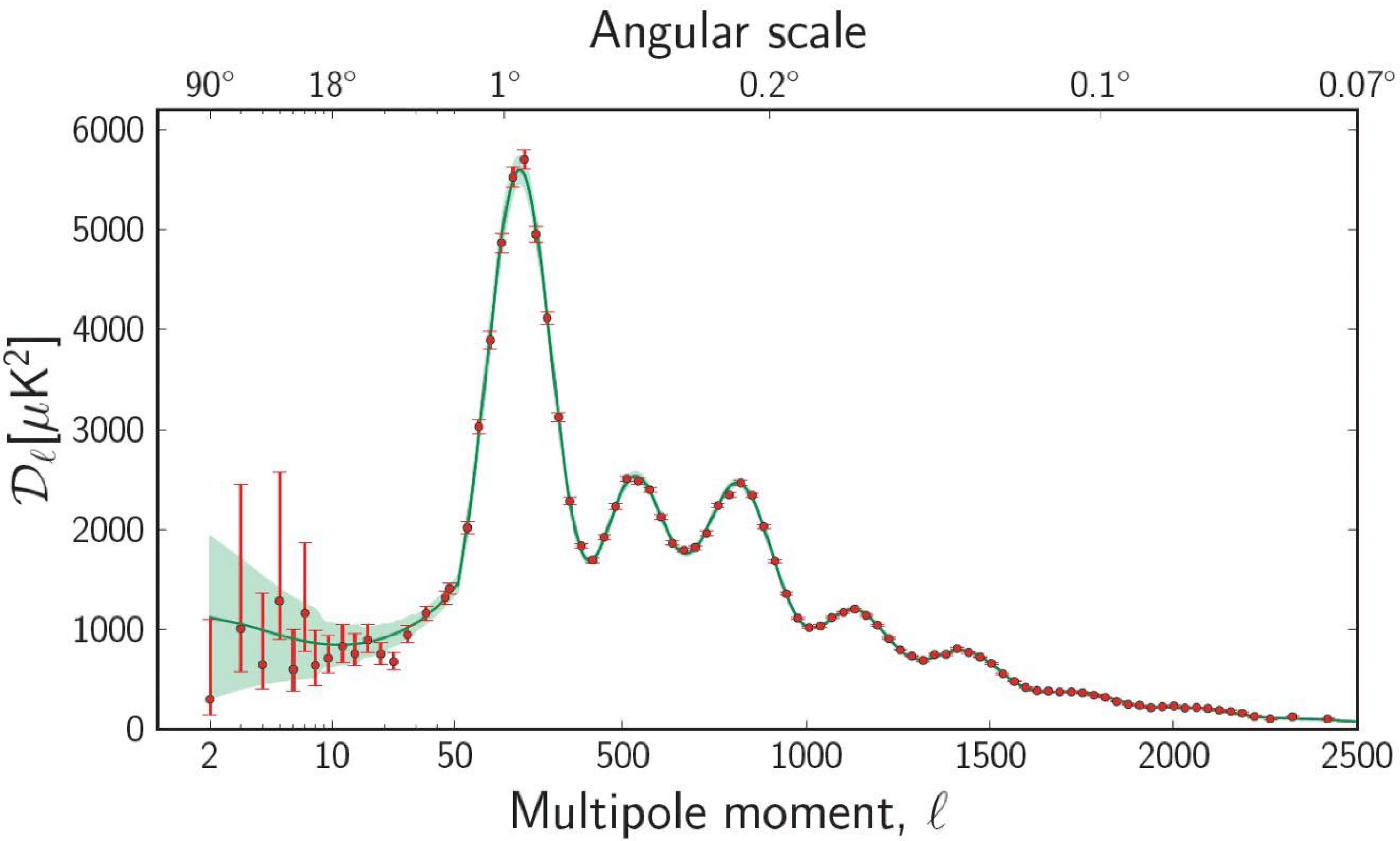
**Inflationary Solution:** Inflation attributes these ripples to *quantum fluctuations.* Inflation makes generic predictions for the spectrum of these ripples (i.e., how the intensity varies with wavelength). The data measured so far agree beautifully with inflation.


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, $\ell$

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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 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.)

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