THE EARLY UNIVERSE

— Alan Guth, MIT —

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INFLATION: The Propulsion Mechanism of the Big Bang

Miracle of Physics #1: Gravity can be repulsive.

Negative pressure $\Longrightarrow$ repulsive gravity.

Scalar field potential energy $\Longrightarrow$ negative pressure.

If the early universe contained a tiny patch of negative pressure material, it would grow exponentially and produce a universe.

Miracle of Physics #2: Gravitational fields have negative energy.

During inflation, positive energy appears as particles, negative energy as gravity, with total energy = 0 and is conserved.

KEY SUCCESSES OF INFLATION

1) Horizon/Homogeneity Problem: Can explain the observed uniformity of the universe.

- ☆ Cosmic background radiation is uniform to 1 pt in 100,000.
- ☆ To achieve this uniformity without inflation, information and energy must travel ~100 times the speed of light.
- ☆ *SOLUTION:* Uniformity is established in a tiny region before inflation, and then inflation magnifies this region to encompass the entire observed universe and more.

2) Flatness Problem: Can explain why the mass density of the early universe was *SO* close to the critical value.

- ☆ At $t = 1$ sec, density was critical to 1 part in 10^{15}.
- ☆ At $t = t_{\rm GUT} \approx 10^{-37}$ sec, 1 part in 10^{52}.
- ☆ *SOLUTION:* During inflation, the enormous stretching causes the universe to appear flat, even if it is really curved — like the Earth looks flat.
- ☆ *SUCCESSFUL PREDICTION:*
  - ☆ Until 8 years ago, observation pointed to $\Omega \approx 0.2$–0.3.
  - ☆ Latest observation by WMAP Satellite:

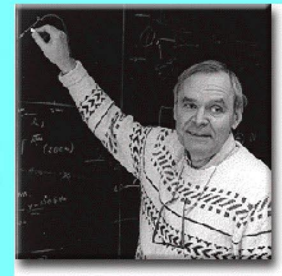
$$\Omega = 1.02 \pm 0.02$$

  - ☆ 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) Density Fluctuation Problem: Can explain how the early universe acquired very weak ripples in its mass density — which later grew in intensity to form large scale structure (galaxies, clusters of galaxies, etc.)

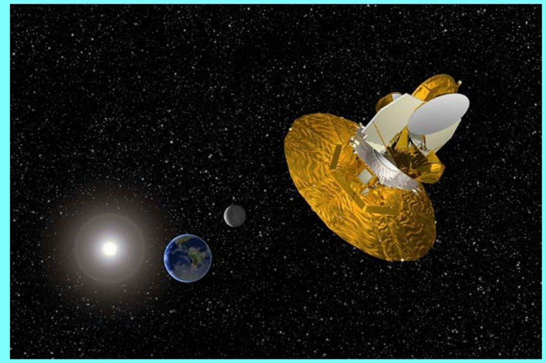
- ☆ In inflationary models, these ripples arise from quantum fluctuations at the end of inflation.
- ☆ The quantum fluctuation model makes a generic prediction for the shape of the spectrum of the fluctuations. These predictions compare beautifully with the measurements of the cosmic background radiation.

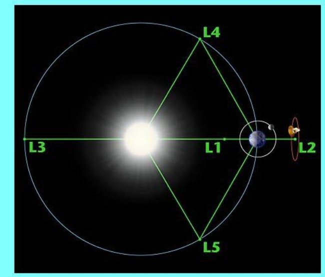
WMAP: Wilkinson Microwave Anisotropy Probe



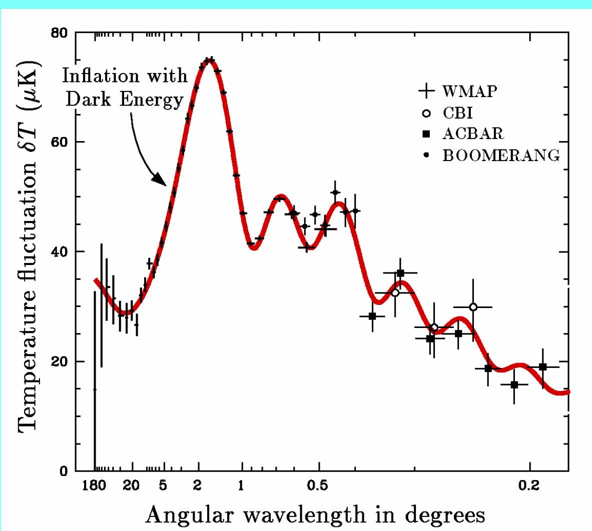
David T. Wilkinson

Images courtesy of NASA/WMAP Science Team





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 3-year data.

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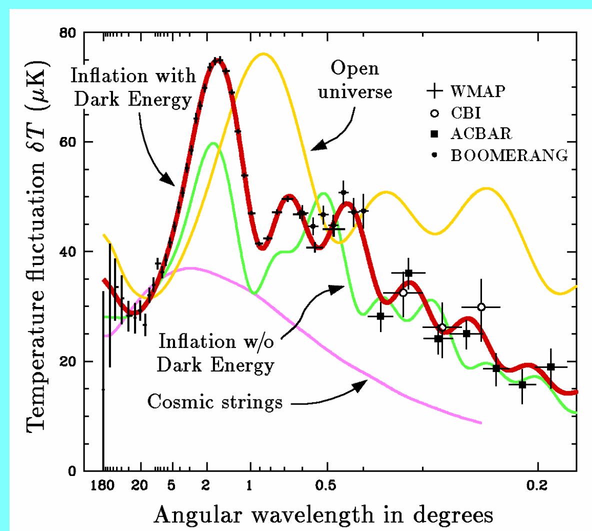

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DARK ENERGY
Key Mystery of the Universe

In 1998, astronomers discovered that the universe has been accelerating for about the last 5 billion years (out of its 14 billion year history).

IMPLICATION: Inflation is happening today. Within general relativity, this requires negative pressure. The negative pressure material, which apparently fills space, is called the ***"Dark Energy."***

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

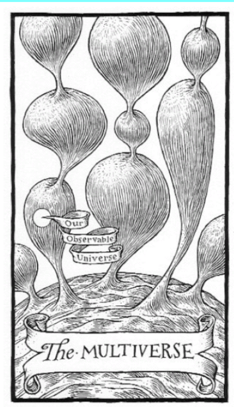
The NIGHTMARE of DARK ENERGY

- ☆ The quantum vacuum is far from empty, so a nonzero energy density is no problem.
- ☆ In quantum field theory, the energy density of quantum fluctuations diverges.
- ☆ A plausible cutoff for the fluctuations is the Planck scale, $E_P \approx 10^{19}$ GeV, the scale of quantum gravity.
- ☆ Using this cutoff, the estimated vacuum energy density is too large

It is too large by 120 orders of magnitude!

ETERNAL INFLATION

- ☆ Almost all models of inflation are future-eternal: once inflation starts, it never completely stops!
- ☆ *EXPLANATION:* The negative pressure material driving the inflation is unstable and decays exponentially, but the space grows exponentially much faster.
- ☆ *CONCLUSION:* Inflation generically produces not just one universe, but a multiverse containing an infinite number of pocket universes.



OUR UNIVERSE The Multiverse
Diagram by Fred Adams

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 5 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, etc.
- ☆ *ANTHROPIC EXPLANATION OF SMALL VACUUM ENERGY:* A tiny fraction of the vacua will have an energy density as small as what we see. Life as we know it can form only when the energy density is so small.

KEY OUTSTANDING PROBLEM: HOW TO DEFINE PROBABILITIES IN ETERNAL INFLATION

See excellent reviews by Alex Vilenkin (hep-th/0609193) and by Serge Winitzki (gr-qc/0612164).

THE PROBLEM: Everything that is possible will happen an infinite number of times, so we need to compare infinities to distinguish between the probable and the highly improbable.

FORMULATION: Most of the literature discusses the counting of observers living in different types of vacua. I prefer a more mathematical formulation (suggested by Larry Guth): Given an arbitrary function defined on the eternally inflating spacetime, can we define the average value of the function?

WHY IS THERE A PROBLEM: If one selects a finite sample volume and allows it to approach infinite volume, the results depend on the method of selection. The root of the problem is the exponential expansion: volumes will not dominate over surfaces.

PITFALLS IN PROBABILITY DEFINITIONS

1) Youngness paradox: If the sample spacetime volume is cut off at some arbitrarily defined final time, then the exponential growth will mean that the sample is dominated by pocket universes that form just before that final time. The sample can be overwhelmingly dominated by very young pocket universes.

2) Freak observer paradox: Our observed universe is beginning to exponentially expand, and that exponential expansion might extend to infinite times in the future. Isolated "freak observers," or "Boltzmann brains," can form as quantum flucuations in this infinite spacetime. If the future region has infinite weight compared to the current era, then even if the freak observer formation rate is incredibly small, they would outnumber us by an infinite amount.

Bottom Line:

We have never had a model of the universe that works so well (homogeneity, flatness, spectrum of density fluctuations), or that is so mysterious.

Dark Energy