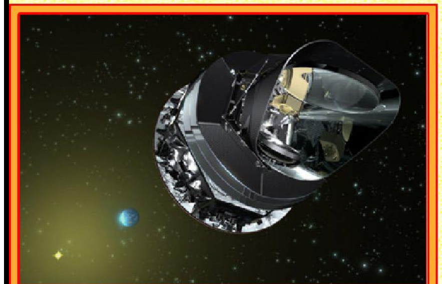
INFLATIONARY COSMOLOGY:

IS OUR UNIVERSE PART OF A MULTIVERSE?



— Alan Guth —
Massachusetts Institute of Technology

8.286 Lecture 2
September 10, 2013

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.

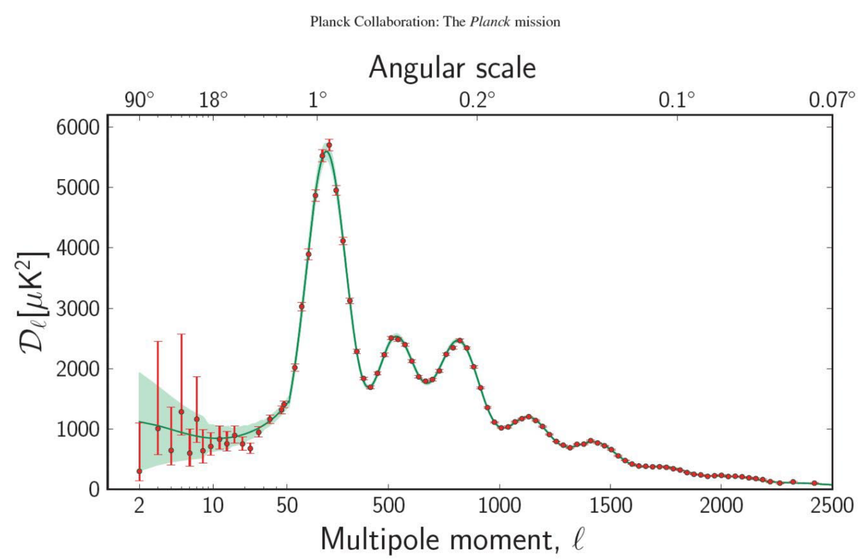
Cosmic Inflation: The prequel, describes how repulsive gravity — a consequence of negative pressure — could have driven a tiny patch of the early universe into exponential expansion. The total energy would be very small or maybe zero, with the negative energy of the cosmic gravitational field canceling 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) Inflation can explain why $\Omega \equiv \rho/\rho_{\rm crit} = 1$ was accurate to >15 decimal places at $t = 1$ second. Predicts $\Omega = 1$. Data: $\Omega = 1.0010 \pm 0.0065$.

3) Predicts small quantum fluctuations in the mass density, which can be seen today as ripples in the CMB. Predictions agree very well with data.



Summary p. 4: Inflation and the Multiverse

Most inflationary models become eternal — the expansion overpowers the decay of the repulsive gravity material, so inflation never ends. An exponentially growing and never-ending number of pocket universes are formed where decays occur.

Summary p. 5: The Nightmare of Dark Energy

- ☆ The expansion of the universe is accelerating, indicating that space is filled with "dark energy," most simply described as vacuum energy.
- ☆ Vacuum energy in a quantum field theory is not surprising — field fluctuations, nonzero Higgs field — there are positive and negative contributions. But typical magnitudes are $\sim 10^{120}$ times too large.
- ☆ *The Landscape of String Theory*: String theory predicts $\sim 10^{500}$ long-lived, metastable "vacua," any one of which can act as the vacuum for a pocket universe. Each would have its own value for the vacuum energy density, with values ranging from roughly -10^{120} to $+10^{120}$ times the observed value.

The Landscape and Environmental Selection AKA: The Anthropic Principle

- ☆ If the landscape has 10^{500} vacua, and a fraction 10^{-120} have small vacuum energy densities like our universe, then we expect about

$$10^{-120} \times 10^{500} = 10^{380}$$

vacua with low energy densities like ours.

- ☆ But how could we explain why we are living in such a fantastically unusual type of vacuum?
- ☆ Consider, as an example, the local density of matter in which we find ourselves — it is about 10^{30} times larger than the mean density of the visible universe.
- ☆ Why is this so? Chance? Luck? Divine Providence?
- ☆ Most of us would presumably accept this as a selection effect: life can evolve only in those rare regions of the universe where the density of matter is unusually high.

- ☆ As early as 1987, Steve Weinberg pointed out that the vacuum energy density might be explained in the same way.
- ☆ Maybe the vacuum energy density ***IS*** huge in most pocket universes. Nonetheless, we need to remember that vacuum energy causes the expansion of the universe to accelerate. If large and negative, the universe quickly collapses. If large and positive, the universe flies apart before galaxies can form. It is plausible, therefore, that life can arise only if the vacuum energy density is very near zero.
- ☆ In 1998 Martel, Shapiro, and Weinberg made a serious calculation of the effect of the vacuum energy density on galaxy formation. They found that to within a factor of order 5, they could "explain" why the vacuum energy density is as small as what we measure.

The Controversy

- A number of physicists regard these anthropic arguments as ridiculous.
- My recommendation is that the anthropic explanation (for anything) should be considered the explanation of last resort.
  - Until we actually understand the landscape, and the initiation of life, we can only give plausibility arguments for anthropic explanations.
  - Hence, the anthropic arguments only become attactive when the search for more deterministic explanations has failed, as so far is the case for the vacuum energy density. (Anthropic explanations are also discussed for many other quantities, including the Higgs mass, the top quark mass, the magnitude of density perturbations.)

Is It Time to Accept The Explanation of Last Resort?

Your guess is as good as mine!

- For the vacuum energy density, because it seems so hard to explain any other way, it seems like it is time to strongly consider the selection-effect explanation.
- It is even hard to deny that, as of now, the selection-effect explanation is by far the most plausible that is known.

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.

Do Physicists Take This Seriously?

Martin Rees (Astronomer Royal of Great Britain and (former) President of the Royal Society) has said that he is sufficiently confident about the multiverse to bet his dog's life on it.

Andrei Linde (Stanford University) has said that he is so confident that he would bet his own life.

Steven Weinberg (1979 Nobel Prize in Physics): "I have just enough confidence about the multiverse to betthe lives of both Andrei Linde *and* Martin Rees's dog."