THE INFLATIONARY UNIVERSE —

Cosmic Acceleration and Dark Energy

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OUTLINE

What is inflation?

- ☆ What is the conventional big bang theory?
- ☆ What is the mechanism of inflation?
- ☆ What is the scenario of inflationary?
- ☆ What is the evidence for inflation?

Cosmic Acceleration and Dark Energy?

- ☆ Why do we think the universe is accelerating?
- ☆ Inflation and Dark Energy?
- ☆ What is the impact on particle physics?

The Standard Big Bang

What it is:

- Theory that the universe as we know it began 13-15 billion years ago. (Latest estimate: 13.7 ± 0.2 billion years!)
- Initial state was a hot, dense, uniform soup of particles that filled space uniformly, and was expanding rapidly.

What it describes:

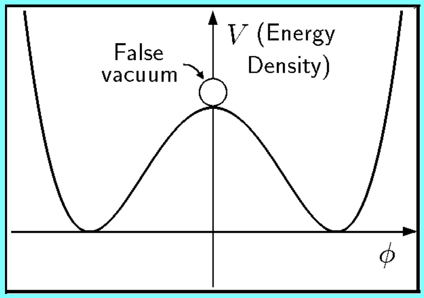
- How the early universe expanded and cooled
- How the light chemical elements formed
- How the matter congealed to form stars, galaxies, and clusters of galaxies

What it doesn't describe:

- What caused the expansion? (The big bang theory describes only the **aftermath** of the bang.)
- Where did the matter come from? (The theory assumes that **all matter** existed from the very beginning.)

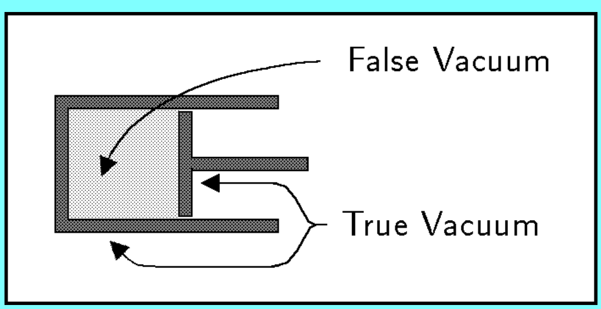
Inflation — the Mechanism

The False Vacuum:



When a scalar field is perched on top of a potential energy hill, the state is metastable. The energy density cannot be lowered quickly.

A fixed energy density implies NEGATIVE PRESSURE



- ☆ If the piston is pulled, the energy density inside remains constant!
- ☆ Therefore the energy increases.
- ☆ Therefore work must be done $(-p\,\Delta V)$.
- ☆ Therefore pressure must be negative!

Inflation — the Scenario

- ☆ Inflation proposes that a patch of negative pressure 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.)
- ☆ The gravitational repulsion created by the negative pressure was the driving force behind the big bang. The patch was driven into exponential expansion, with time constant $\sim 10^{-38}$ second.
- ☆ The patch expanded exponentially by a factor of at least 10^{28} (65 time constants), but may be by much more.

- ☆ The scalar field eventually rolled down the hill and oscillated about the energy minimum. The energy from the false vacuum produced a hot soup of "ordinary" particles, which quickly reached thermal equilibrium. Standard cosmology began.

Energy Conservation:

- ☆ Although more and more mass/energy appeared as the false vacuum expanded, the total energy was conserved. The energy of a gravitational field is negative! The positive energy of the false vacuum was compensated by the negative energy of gravity. The TOTAL ENERGY of the universe may very well be zero.

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.

2) **"Flatness problem:"** Why was the mass density of the early universe so close to the critical density?

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

where the "critical density" is that density which gives a geometrically flat universe. At one second after the big bang, Ω must have been equal to one **to 15 decimal places!** Inflation explains why.

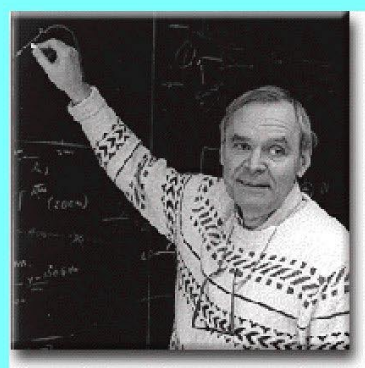
Since the mechanism by which inflation explains the flatness of the early universe almost always overshoots, it predicts that even today the universe should have a critical density.

Until 5 years ago, observation pointed to Omega$\approx$ 0.2–0.3. Latest observation by WMAP Satellite:

$$\text{Omega} = 1.02 \pm 0.02$$

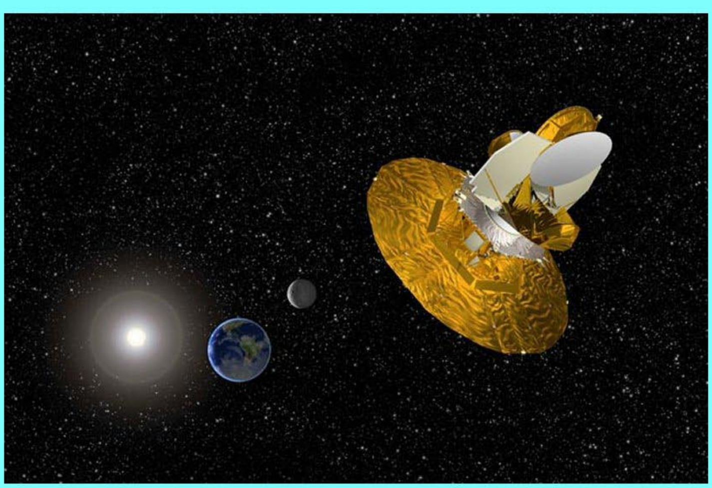
3) **Small scale nonuniformity:** Can be measured in the cosmic background radiation, although they are only at the level of 1 part in 100,000, these nonuniformities can now be measured! The properties measured so far agree beautifully with inflation.

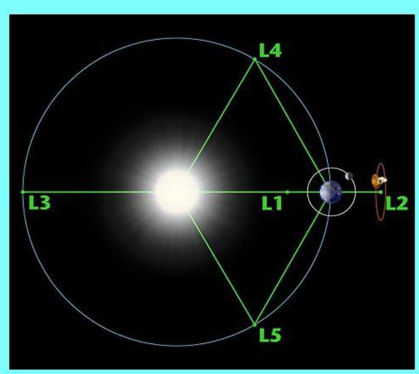
WMAP: Wilkinson Microwave Anisotropy Probe



David T. Wilkinson

Images courtesy of NASA/WMAP Science Team





WMAP Power Spectrum

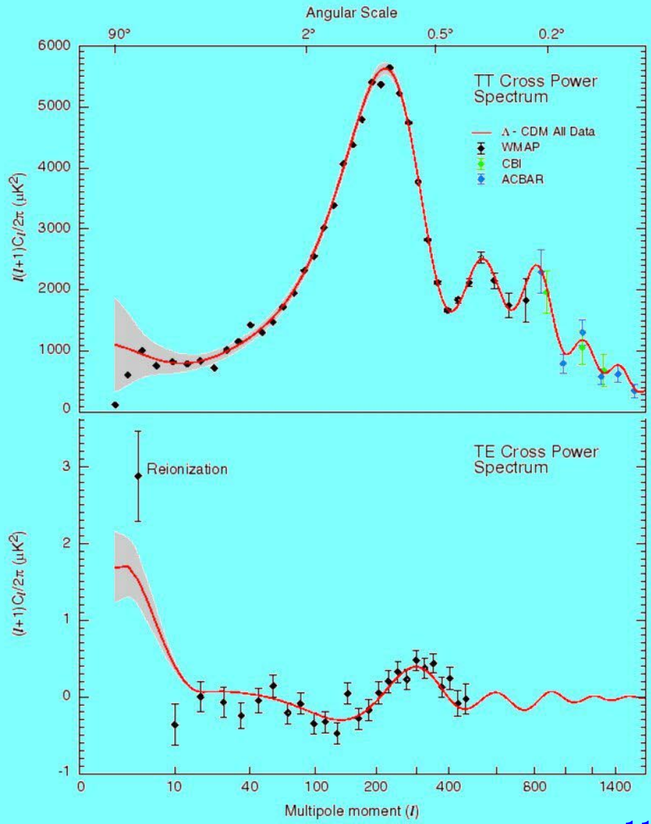


Image courtesy of NASA/WMAP Science Team

Why Do We Think the Universe is Accelerating?

Supernovae Type Ia:

Starting in 1998, astronomers have used supernovae as "standard candles," to measure the expansion rate of the universe over the past 5 billion years. Distance is measured by brightness, speed is measured by redshift.

Conclusion: Expansion of the universe is speeding up!

Age of Universe:

Given the current expansion rate, and the critical mass density as implied by the cosmic background radiation, without expansion the universe would be only about 9-10 billion years old. But the oldest stars appear to be 13 billion years old. Accounting for acceleration, the age estimate goes up to 13.7 billion years.

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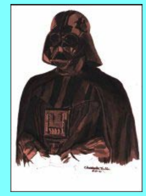
Inflation and Dark Energy



1) Prediction: $\Omega_{\rm tot} = 1$.
(i.e., the density of matter must be critical)

WMAP: $\mathbf{\Omega_{\rm tot} = 1.02 \pm 0.02}$ **.**

It is all consistent, but

WMAP: $\mathbf{\Omega_{\rm dark} = 0.73 \pm 0.04}$ **.**

2) Present acceleration of the universe (dark energy) is very similar to inflation:

- "Certainly" driven by a negative pressure.
- Possibly driven by a scalar field.
- The other known possibility is a "cosmological consant," AKA vacuum energy density.

Particle Theory and Vacuum Energy

Particle theorists know of many contributions to the energy density of the vacuum:

☆ Quantum fluctuations of electric, magnetic, and similar fields (positive, divergent).

☆ Correction for energies of electrons and positrons, and similar particles (negative, divergent).

But, particle theorists do ***NOT*** understand the magnitude of the cosmological constant.

☆ Since contributions are divergent, one sensible hope is that the sum is cut off by quantum gravity at the Planck energy, $E_p = \sqrt{\hbar c^5/G} = 10^{19}$ GeV. But this estimate $(E_p^4/(\hbar c)^3)$ is too high by 120 orders of magnitude!

☆ If present observations are right, then the positive and negative contributions to the vacuum energy apparently cancel for the first 120 significant figures, but then miss at the 121st!

Conclusions

1) The inflationary paradigm is in great shape:
   - ☆ Large scale uniformity
   - ☆ Flatness
   - ☆ Spectrum of nonuniformities (WMAP)
2) There is significant evidence that the universe today is accelerating.
3) If the acceleration is real, it is good news for inflation enthusiasts: a cosmological constant or scalar field energy can account for the energy density needed to raise the total to the critical value.
4) For particle physics, however, a cosmological constant is a mystery: where could such a small number come from?

Bottom Line:

We have never had a model of the universe that works so well, or that is so mysterious.