C E R C A

Eternal Inflation

Confronting Gravity
Ritz-Carlton Hotel
St. Thomas, USVI
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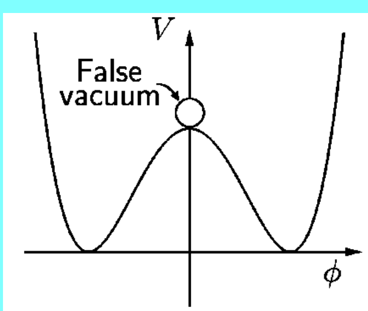
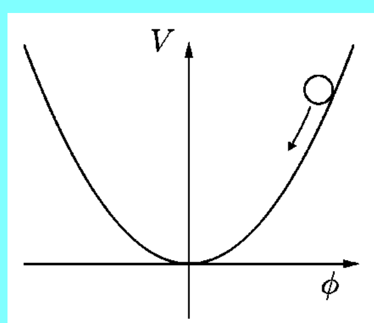
Alan Guth
Massachusetts Institute of Technology

Inflationary Scenarios

- **Negative Pressure** $\Longrightarrow$ **Repulsive Gravity.**
- State dominated by scalar field potential energy $\Longrightarrow$ Negative Pressure.



New (Small Field) Inflation
Linde; Albrecht & Steinhardt (1982)



Chaotic (Large Field) Inflation
Linde (1983)

- 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 it could have expanded 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.

Successes of Inflation

1) The universe is big— about 10^{90} particles!

2) Hubble expansion— what was the repulsive driving force?

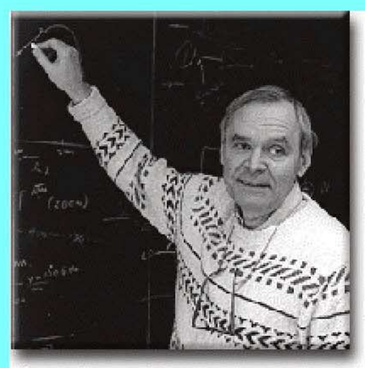
3) Homogeneity and isotropy— in the conventional big bang (without inflation), cosmic microwave background uniformity requires communication ~ 100 times speed of light.

4) Flatness Problem — why was the mass density at $t = 1$ sec equal to the critical density to 15 decimal places?

5) Why no magnetic monopoles?

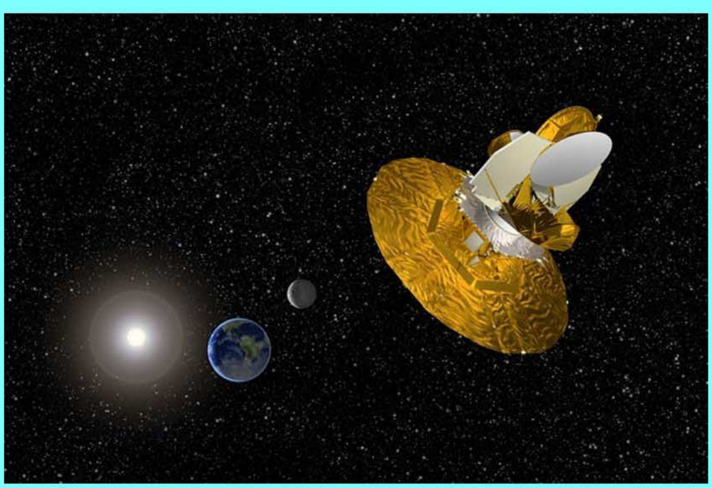
6) Nearly scale invariant, adiabatic, Gaussian density perturbations.

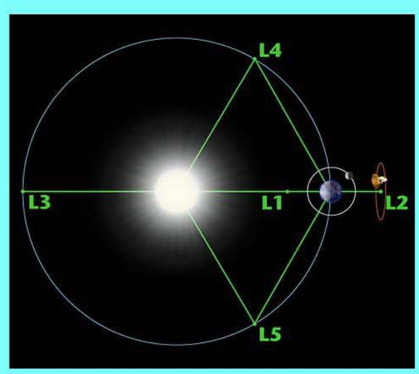
WMAP: Wilkinson Microwave Anisotropy Probe

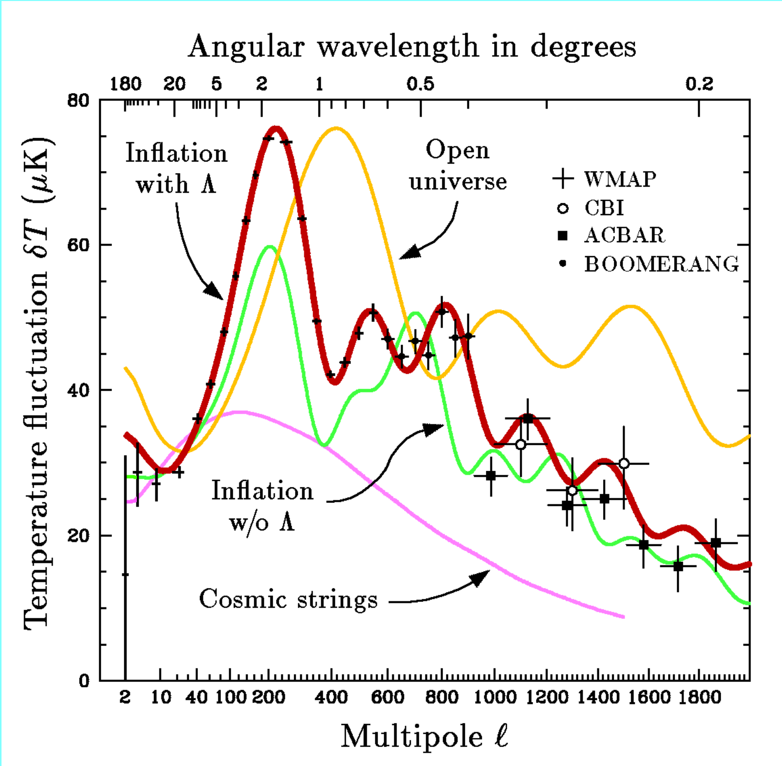


David T. Wilkinson

Images courtesy of NASA/WMAP Science Team

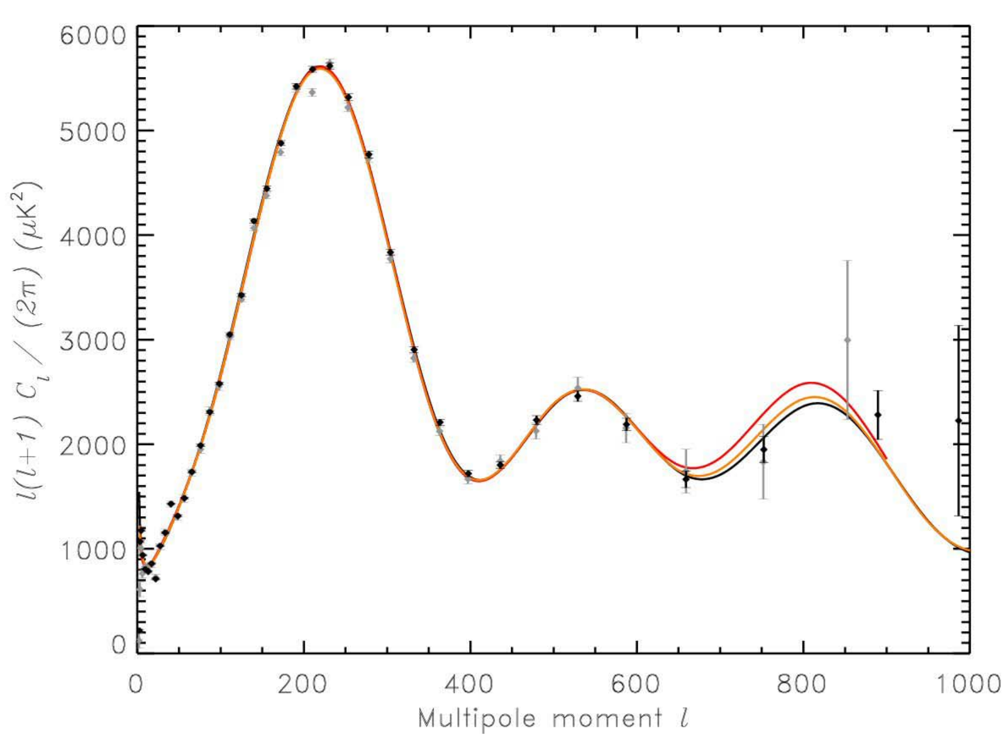


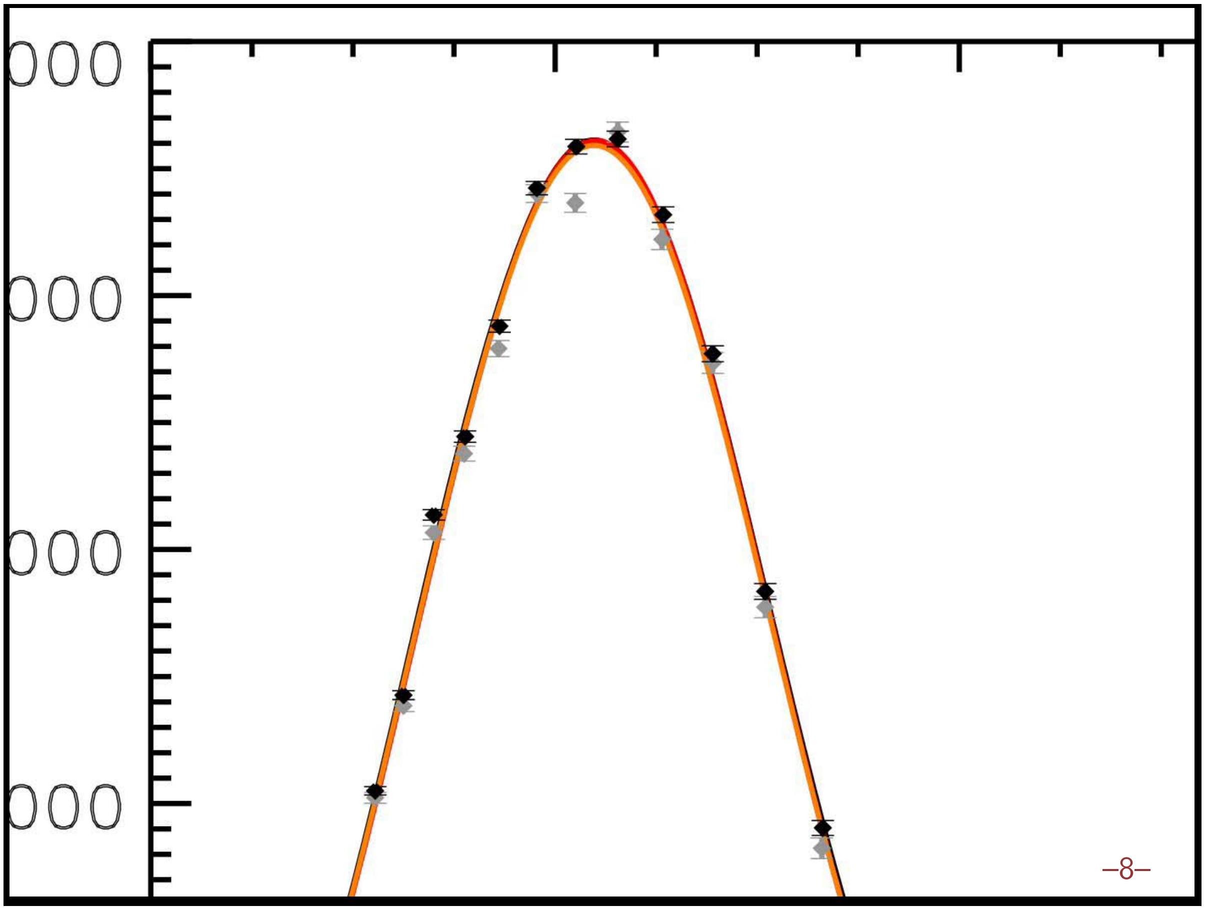




CMB: Comparison of Theory and Experiment

Graph by Max Tegmark
for A. Guth & D. Kaiser,
Science **307, 884**
(Feb 11, 2005)





Mechanisms of Eternal Inflation: Eternity of Small Field (New) Inflation

Essentially all known inflationary models are eternal — once inflation starts it ***never*** stops.

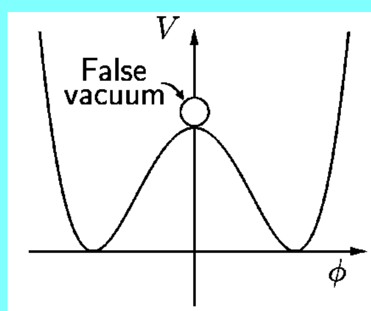
1) False vacuum is metastable, and decays exponentially.

2) Volume of false vacuum inflates exponentially.

3) Rate of inflation $\gg$ rate of decay.

∴ Volume of false vacuum increases with time! (Steinhardt, 1983; Vilenkin, 1983)

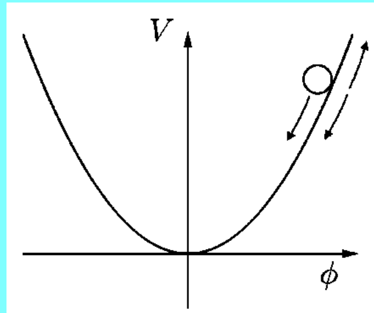
4) Inflationary universe has a fractal structure — on scales much too large to observe.



5) If inflation happens once, an ***infinite*** number of universes are produced.

Mechanisms of Eternal Inflation: Eternal Chaotic Inflation

Andrei Linde showed in 1986 that even chaotic inflation can be eternal. One needs to consider quantum fluctuations of ϕ:



- For inflating spaces, quantum fluctuations play an important role, as they are constantly stretched to classical sizes.
- Simple random walk picture: In each time interval $\Delta t = H^{-1}$, the average field ϕ in each region of size H^{-1} receives a random increment with root mean square $\Delta\phi_{\rm qu} = H/2\pi$. This random increment, either up or down, is superimposed on the downward classical motion.
- Suppose $\phi = \phi_0$ at the start of some time interval $\Delta t = H^{-1}$. During Δt, the volume expands by $e^3 \approx 20$. If the fraction of space in which ϕ increases is $> 1/e^3$, then volume of region with $\phi > \phi_0$ INCREASES. If so, inflation never ends.

Implications for the Landscape

- Many string theorists believe that string theory has perhaps 10^{1000} vacuum-like states.

Eternal inflation can allow the ***multiverse*** to completely explore the ***landscape*** of string theory vacua.

Anthropic Reasoning: To many physicists, the landscape picture is a welcome opportunity to invoke anthropic reasoning: in the multiverse, life will evolve only in very rare regions where the local laws of physics just happen to have the properties needed for life, giving the illusion of intelligent design.

Anthropic Abhorrence: To many other physicists, anthropic reasoning means the end of the hope that precise and unique predictions can be made on the basis of pure logic. Since this hope should not be given up lightly, many physicists still hope to find some mechanism to pick out a unique vacuum from string theory. So far there is no discernable progress.

Inflationary Selection? One possibility is that inflation might help to at least significantly reduce the number of vacua that are populated, since inflation might make it overwhelmingly more likely to populate some states than others. In particular, those states that lead to the fastest exponential expansion rates seem to be favored. These fastest expanding states — and their decay products — could dominate the multiverse. But so far this is only wishful thinking.

Ambiguities in Calculating Probabilities

Anything that can happen will happen; so the implications of eternal inflation must be described in terms of probabilities. But in the infinite spacetime, the fraction with any particular property is infinity/infinity. If one regularizes by cutting out a finite spacetime volume, the answer depends on how one chooses the cutoff.

The Youngness Paradox: Suppose one cuts of the distribution by stopping at some fixed time, say in a synchronous coordinate system. Then one finds peculiar effects. The rate of production of new pocket universes is growing exponentially with a time constant of perhaps 10^{-37} second. For every pocket universe of age t, there are $\exp\left\{10^{37}\right\}$ that are 1 sec younger! The result is an incredibly ***youth-dominated*** “society”.

All historical inferences are distorted, because the probability of any scenario that can “get us here” 1 sec faster is enhanced by $\exp\left\{10^{37}\right\}$.

Do we live in the center of the world?, by Linde, Linde, & Mezhlumian, 1994: used such an argument to show that we most likely live near the center of a spherical hole in the cosmic density distribution. Vilenkin and collaborators (Garriga, Schwartz-Perlov, Tanaka, Vanchurin, Winitzki) have shown that these conclusions can be avoided with an alternative method of calculation, but to me it is still unclear how one decides on the right method of calculation.

SUMMARY

The inflationary paradigm is in great shape!

- Inflation can explain the large size, the Hubble expansion, the homogeneity, isotropy, and flatness of the universe. Can also explain the absence of monopoles, and the nearly scale-invariant adiabatic Gaussian density perturbations.
- Both small field and large field inflationary models are generically eternal into the future.
- Eternal inflation populates the landscape of string theory, and offers the possibility that inflation MIGHT choose a preferred class of vacuum states.
- Although eternal inflation seems inevitable and has attractive features, the problem of calculating probabilities in an eternally inflating universe remains unclear.