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THE INFLATIONARY PARADIGM

(DIRAC LECTURE)

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— Alan Guth, MIT —

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Dirac Quotations

☆ I think that there is a moral to this story, namely that it is more important to have beauty in one's equations than to have them fit experiment. If Schroedinger had been more confident of his work, he could have published it some months earlier, and he could have published a more accurate equation.

— *Scientific American*, May 1963

☆ In science one tries to tell people, in such a way as to be understood by everyone, something that no one ever knew before. But in poetry, it's the exact opposite.

— Quoted in *Mathematical Circles Adieu*, by H. Eves

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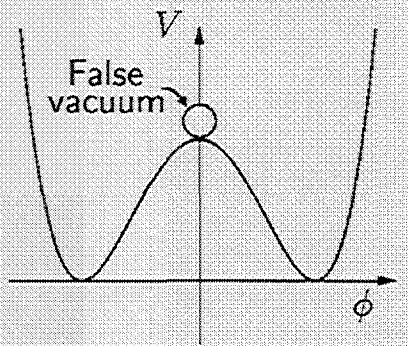
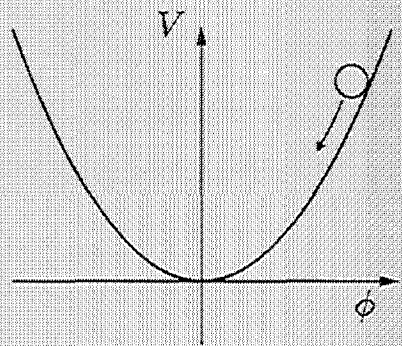
Inflationary Scenarios

☆ **Negative Pressure ⟹ Repulsive Gravity.**

☆ State dominated by scalar field potential energy ⟹ Negative Pressure.



New Inflation
Linde; Albrecht & Steinhardt (1982)



Chaotic Inflation
Linde (1983)

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☆ 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^{-24} 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 $\sim 10^{-37}$ second.

☆ The patch expanded exponentially by a factor of at least 10^{25} (60 time constants), but maybe 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.

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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.

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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 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.

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

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

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!** Extrapolating back to the Planck time, 10^{-43} seconds, Ω must have been one to **58 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:

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

The difference is the DARK ENERGY.

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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 simple inflationary models.

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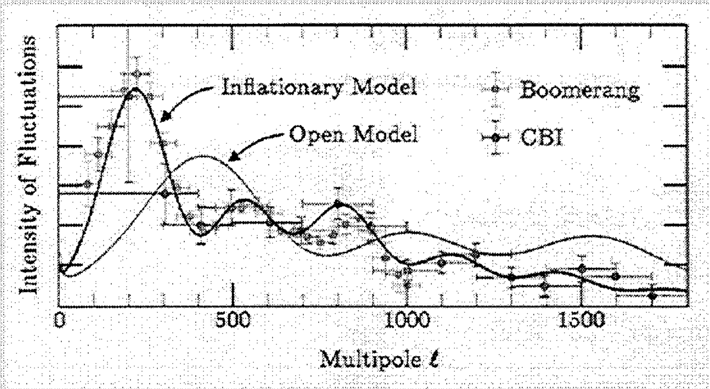
CMB: Cosmic Microwave Background



Parameters of theoretical curve (best fit to all CMB data, CBI group, astro-ph/0205388):

$\Omega_{tot} = 1$ (naturally)

$\Omega_\Lambda = 0.7$ (large dark energy component)

$\Omega_{CDM} = 0.257$ (cold dark matter, consistent with astronomical estimates)

$h = H/(100\ \text{km-sec}^{-1}\text{-Mpc}^{-1}) = 0.68$ (Hubble Key Project: $h = 0.72 \pm 0.08$)

$\Omega_b h^2 = 0.020$ (Big bang nucleosynthesis: $0.020 \pm .001$)

$n_s = 0.95$ (nearly scale-invariant)

$\tau_c = 0$ (no absorption)

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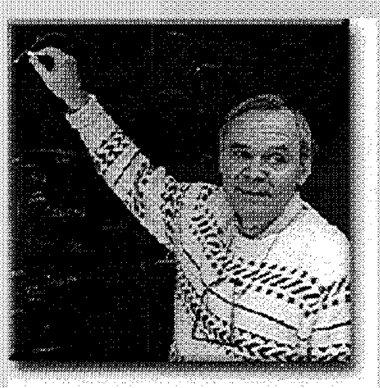
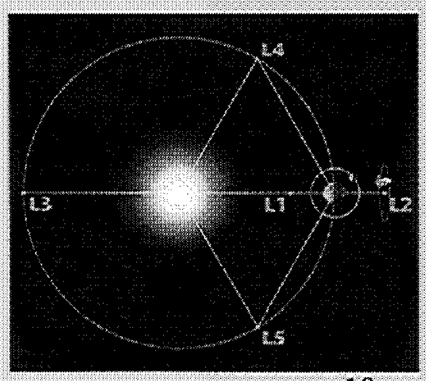
WMAP: Wilkinson Microwave Anisotropy Probe



David T. Wilkinson

Images courtesy of NASA/WMAP Science Team



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WMAP vs. COBE

COBE: Cosmic Background Explorer

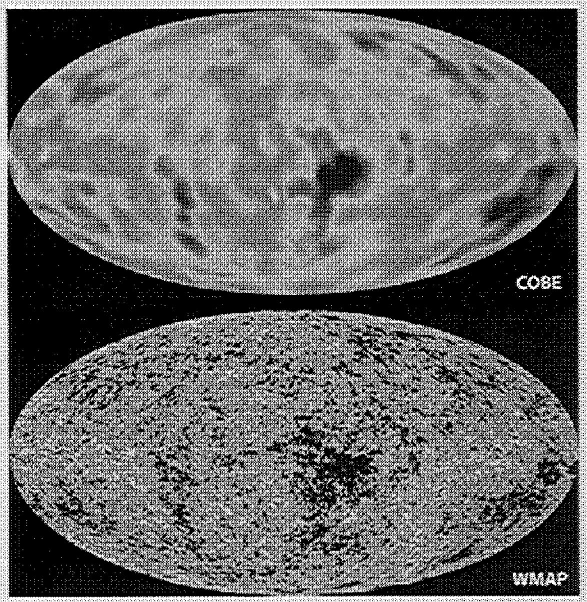
Launched 1989

Data released April 23, 1992

Wilkinson Microwave Anisotropy Probe

Launched June 30, 2001

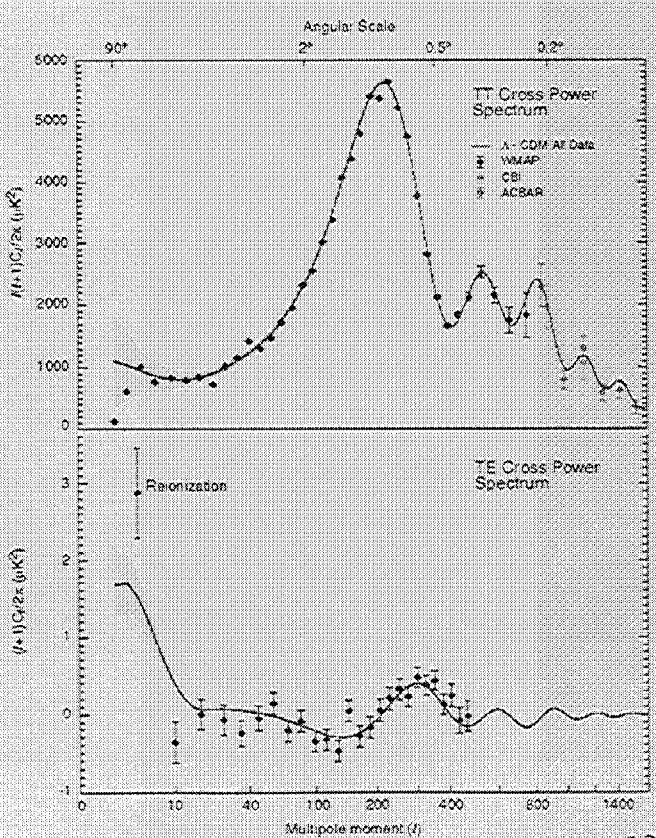
Data released February 11, 2003



Images courtesy of NASA/WMAP Science Team

WMAP Power Spectrum

Image courtesy of NASA/WMAP Science Team



Conclusions

The inflationary paradigm is in great shape!

1) The inflationary mechanism can supply the outward thrust of the big bang, and can explain the origin of essentially all the matter in the universe.

2) Inflation can explain:

   ☆ why the universe is so homogeneous and isotropic on large scales.

   ☆ why the early universe was so extraordinarily close to flat, and why the current universe is at least approximately flat.

   ☆ how the observed spectrum of inhomogeneities was generated.

3) The inflationary prediction of $\Omega = 1$ is now strongly supported by observation, with "dark energy" contributing about 73% to the total. Dark energy has a negative pressure, and is causing the universe to accelerate. The nature of this dark energy is even more obscure than the nature of the dark matter.

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