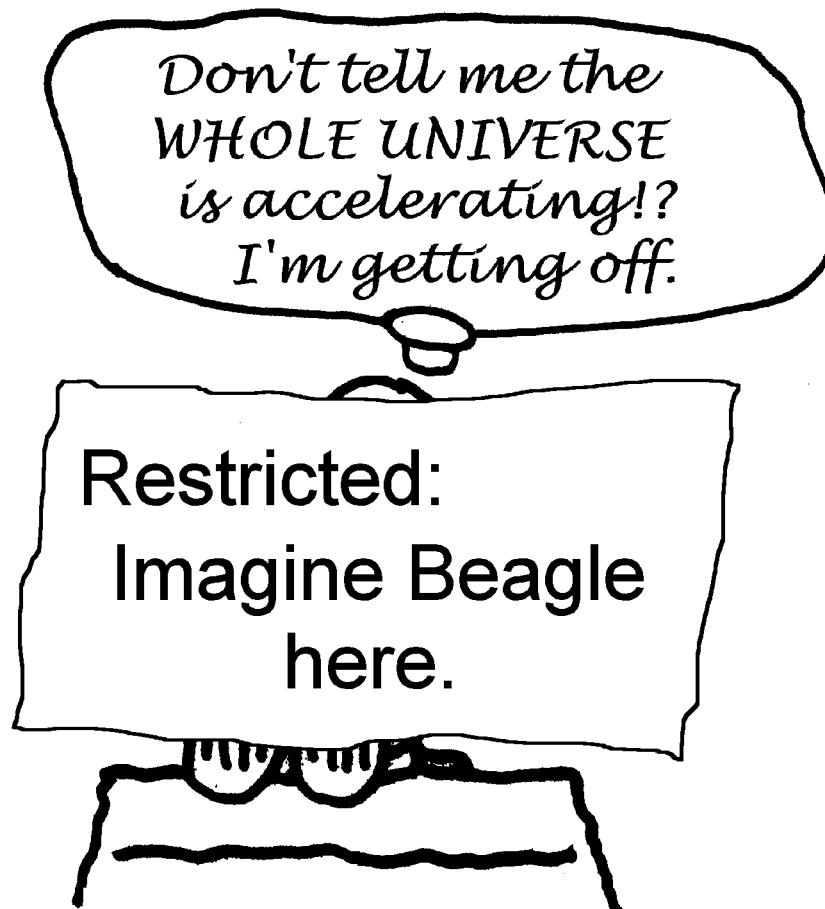


INFLATIONARY COSMOLOGY and the ACCELERATING UNIVERSE

— Alan Guth, MIT —



An Open World of Physics

Talks and Discussion by Friends of Fred Goldhaber
Harriman Hall, SUNY Stony Brook, October 7, 2001

OUTLINE

- The “standard” (without inflation) big bang
 - Basics of inflation
 - Evidence for inflation
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- Evidence for acceleration
 - What is a cosmological constant?
 - Impact of cosmological constant on inflation
 - Impact of cosmological constant on particle physics

THE STANDARD BIG BANG

What it is:

- Theory that the universe as we know it began 10-15 billion years ago.
- 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

- Modern particle theories predict that, at very high energies, there exists a form of matter that creates a

gravitational repulsion!

- Inflation proposes that a patch of this form of matter existed in the early universe — it was probably more than a billion times smaller than a single proton!
- The gravitational repulsion created by this material was the driving force behind the big bang. The repulsion drove it into exponential expansion, doubling in size every 10^{-37} second or so!
- The density of the repulsive gravity material was not lowered as it expanded!

- Although more and more mass/energy appeared as the repulsive-gravity material expanded, total energy was conserved!

The energy of a gravitational field is negative!

The positive energy of the material was compensated by the negative energy of gravity.

- The repulsive-gravity material is unstable, so it decayed like a radioactive substance, ending inflation. The decay released energy which produced ordinary particles, forming a hot, dense “primordial soup.”
- Inflation lasted maybe 10^{-35} second. At the end, the region destined to become the presently observed universe was about the size of a marble.
- The “primordial soup” matches the assumed starting point of the standard big bang—the standard big bang description takes over. The region continues to expand and cool to the present day.

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 300,000 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?

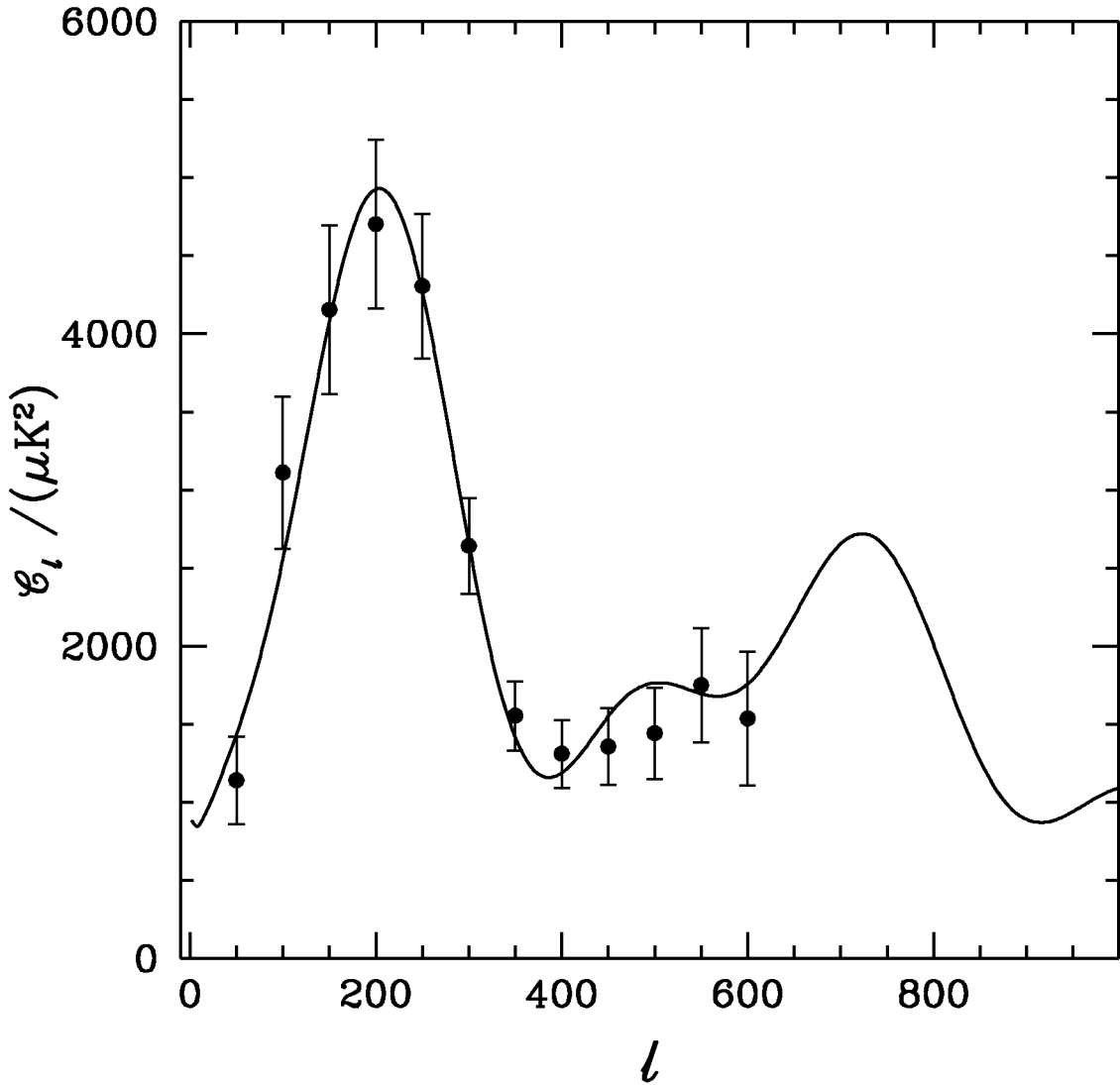
$$\Omega = \frac{\text{actual mass density}}{\text{critical mass density}},$$

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.

3) Small scale nonuniformity of the cosmic background radiation. Although 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.

BOOMERANG 2000 ANISOTROPY RESULTS

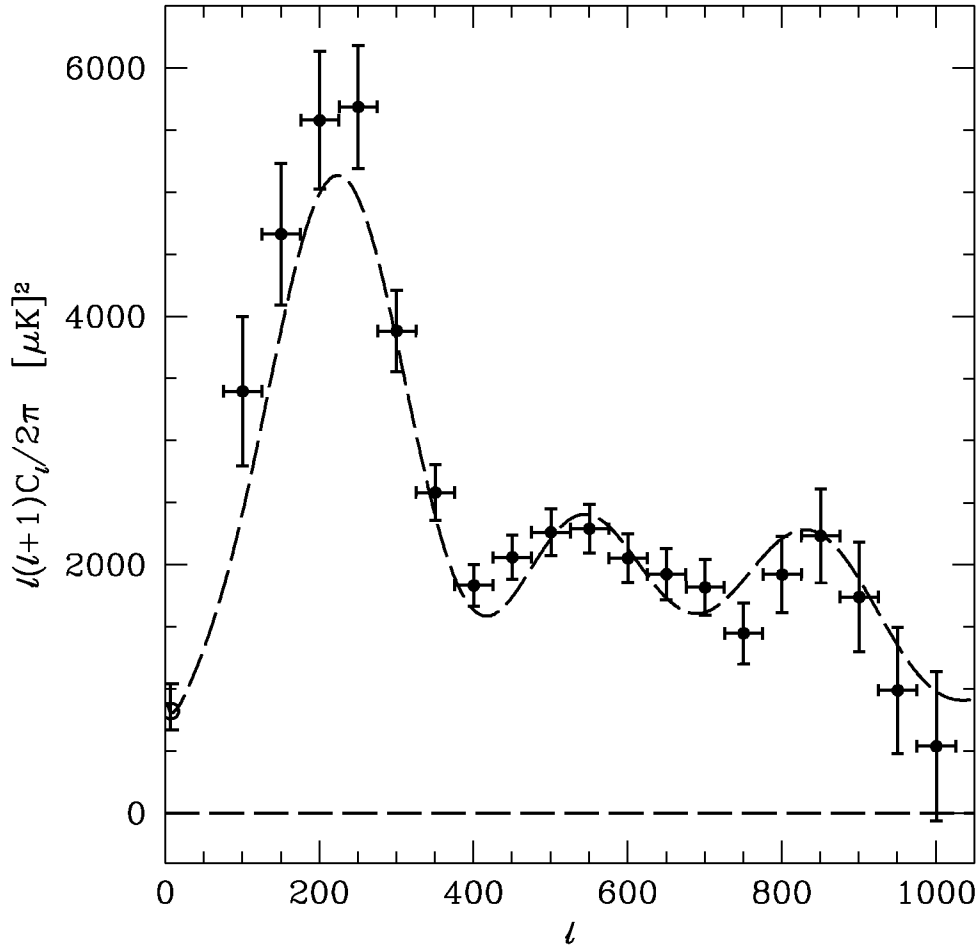


Boomerang Data, *Nature* 404, 955 (2000).

Fit from Lange et al., astro-ph/0005004.

Fit parameters: $\Omega_{\text{tot}} = 1$, $\Omega_b h^2 = 0.03$, $\Omega_c h^2 = 0.27$, $\Omega_\Lambda = 0.60$, $n_s = 0.975$, $\tau_C = 0$.

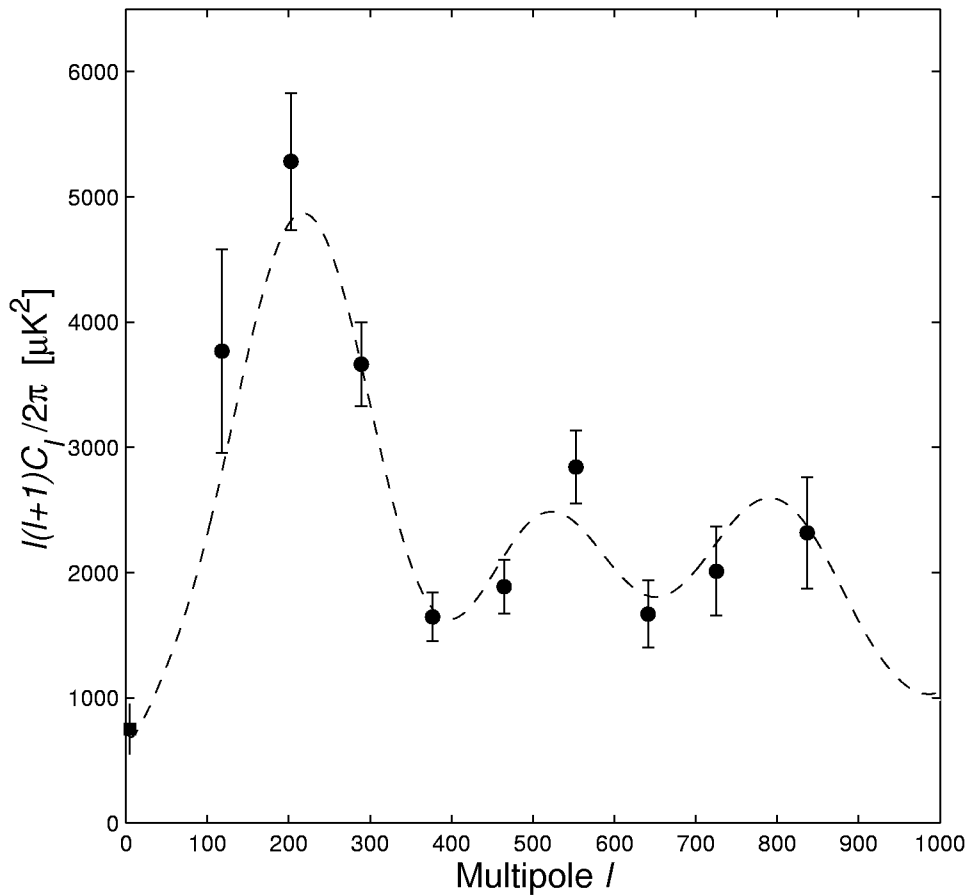
BOOMERANG 2001 ANISOTROPY RESULTS



Boomerang Data, Netterfield *et al.*, astro-ph/0104460

Fit parameters: $\Omega_{\text{tot}} = 1$, $\Omega_b h^2 = 0.021$, $\Omega_c h^2 = 0.13$, $\Omega_\Lambda = 0.62$, $n_s = 0.96$, $\tau_C = 0.1$, $h = 0.62$.

DASI 2001 ANISOTROPY RESULTS



DASI Data, Pryke *et al.*, astro-ph/0104490

Fit parameters: $\Omega_{\text{tot}} = 1$, $\Omega_b h^2 = 0.021$, $\Omega_b = 0.05$, $\Omega_c = 0.35$, $\Omega_\Lambda = 0.60$, $n_s = 1.0$, $\tau_C = 0$, $h = 0.65$.

COSMIC ACCELERATION?

How are distances measured?

Astronomers look for *standard candles* — objects for which they think they know the actual brightness. The distance is then inferred from the apparent brightness.

For the past three years, supernovae of type IA have been explored heavily by two groups of astronomers: the Supernova Cosmology Project and the High Z Supernova Search Team.

The brightness has been found to correlate well with the duration of the light curve.

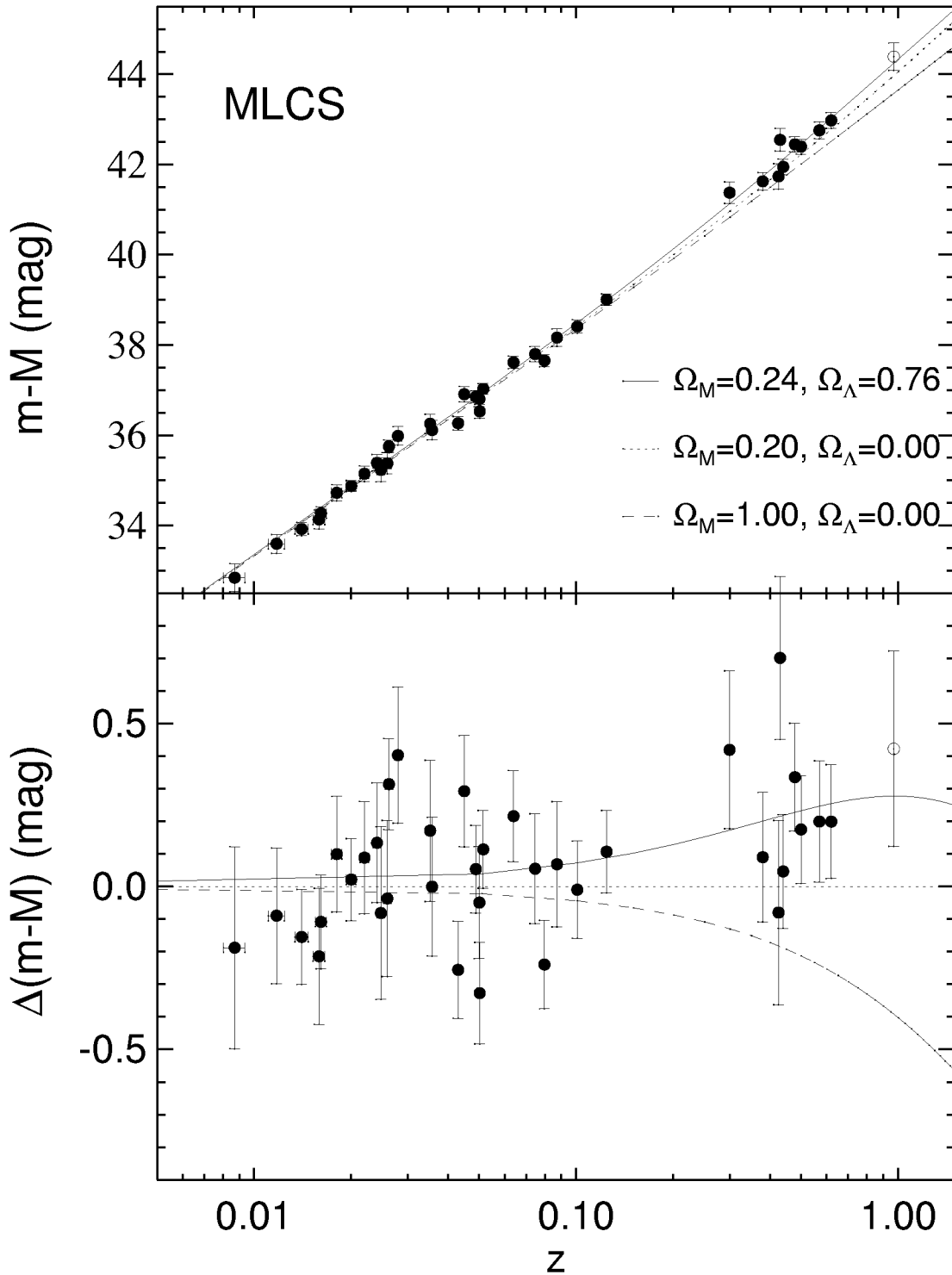
How are speeds measured?

Speeds can be inferred reliably by measuring the redshift of the light.

What has been found?

For “nearby” galaxies, Hubble discovered in 1929 that the velocity of recession is proportional to the distance. Corresponds to uniform expansion.

Starting in 1998, supernova observations have indicated that the expansion rate has *accelerated* over the last 5 billion years. More precisely, H has not gone up, but the velocity between any two galaxies has increased.



Data from High Z Supernova Search Team
 Riess et al., astro-ph/9805201
 Multi-Color Light Curve Shape Analysis

THE ACCELERATION DEBATE

Supernovae evidence might be wrong:

- Ancient supernovae might have been dimmer.
- Dust might cause distant supernovae to look dimmer.

BUT:

- Distant supernovae are very similar to nearby ones in (almost) all measurable properties.
- Dust usually affects the spectrum of transmitted light, but no such effect is seen here.

Besides, there are two other indications of acceleration:

- The cosmic background radiation shows a critical density, but only ~ 0.3 of critical density has been found.
- Without acceleration, the age of the universe estimated from the expansion rate is a little younger than the oldest stars.

WHAT IS THE COSMOLOGICAL CONSTANT?

- Introduced by Einstein in 1917 to allow for a static universe
- Provides a universal repulsion, pushing all matter apart
- From the point of view of particle physics, it corresponds to an energy density of the vacuum

Why does a positive energy vacuum create a repulsion?

Ans: it creates a large NEGATIVE pressure.

IMPACT ON INFLATION

- Simple models of inflation predict that the universe should be geometrically flat.

Reason: Gargantuan expansion causes anything to look flat.

- According to general relativity, a flat universe requires a critical mass density,

$$\text{critical density} = \frac{3H^2}{8\pi G} ,$$

where H is the Hubble “constant”, and G is Newton’s constant. So far, astronomers have found only enough dark matter to make up 0.2–0.3 of the critical density.

- If the present observations are right, the energy density of the vacuum could be the missing mass needed for inflation.

PARTICLE THEORY AND THE COSMOLOGICAL CONSTANT

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 it is cut off at the Planck energy, $E_p = \sqrt{\hbar c^5 / G} = 10^{19}$ GeV, by quantum gravity. An estimate of the resulting energy density would be $E_p^4 / (\hbar c)^3$, but this is too large — 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!

- Expressed in units recognizable to particle physicists, the energy density of the alleged cosmological constant is only about $(10^{-3} \text{ eV})^4/(\hbar c)^3$. How can this energy scale be explained in terms of fundamental physics?

CONCLUSIONS

- 1) The inflationary paradigm is in great shape:
 - Size, expansion, homogeneity, isotropy, flatness, spectrum of nonuniformities
- 2) There is significant evidence that the universe today is accelerating:
 - Direct evidence from supernovae type 1A.
 - Evidence of flatness from the cosmic background radiation, and the absence of sufficient matter for flatness.
 - Evidence from reconciling the age of the universe as estimated from the expansion rate with the age as estimated by the oldest stars.
- 3) If the acceleration is real, it is good news for inflation enthusiasts: a cosmological constant can account for the energy density needed to raise the total to the critical value.
- 4) For particle physics, a cosmological constant is a mystery: where could such a small number come from?