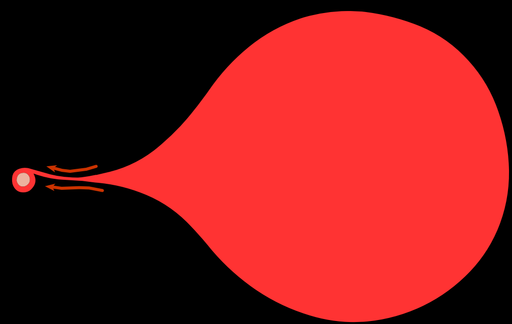
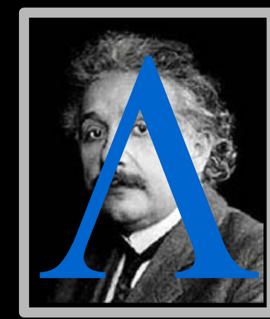
Cosmic Inflation in the New Cosmology

Evidence and Implications

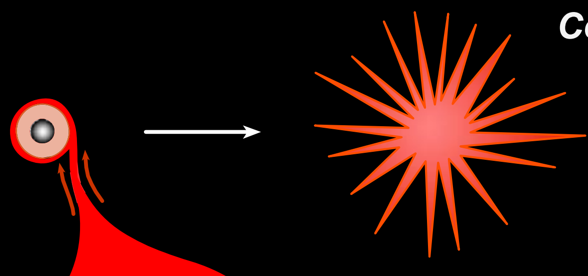


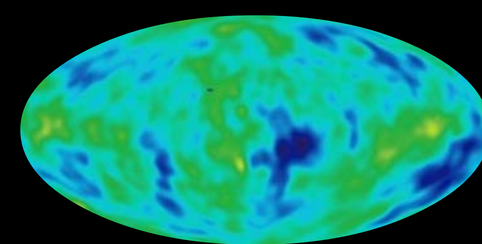


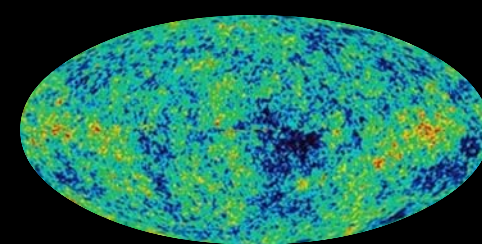
Mike Guidry

Department of Physics and Astronomy
University of Tennessee

Physics Division
and
Computer Science & Mathematics Division
Oak Ridge National Laboratory







http://eagle.phys.utk.edu/guidry/seminars/inflation/index.html

Cosmology

Cosmology asks the big questions:

- What is the overall structure of the Universe?
- What is its past and what will be its future?
- What mathematical principles govern space and time?

The Fundamental Theoretical Idea:

Evolution of the Universe is governed by the *General Theory of Relativity* and the *Cosmological Principle:*

> *Viewed on sufficiently large distance scales, there are no preferred directions (isotropy) or preferred places (homogeneity) in the Universe.*

The Fundamental Observation:

The Universe is expanding

The Einstein (Friedmann) Equations

$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$ (Einstein equations)

$R^{\sigma}_{\mu\nu\lambda}$ = *Riemann curvature tensor* (covariant measure of 4D curvature in locally Minkowski space; generalizes Gaussian curvature in 2D)

$R_{\mu\nu} = g^{\lambda\sigma} R_{\lambda\mu\sigma\nu}$ (Ricci tensor)

$R = g^{\mu\nu} R_{\mu\nu}$ (Ricci scalar)

Λ = scalar (Cosmological constant)

$T_{\mu\nu} = (\varepsilon + P) u_\mu u_\nu - P g_{\mu\nu}$ (Stress-Energy tensor: general form)

The Friedmann-Robertson-Walker Metric

Mathematical statement of homogeneity and isotropy:

$$ds^2 = -dt^2 + a(t)^2\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta \, d\phi^2\right) \quad \text{(Line element)}$$

$$k = \begin{cases} +1 & \text{(positive curvature)} \\ 0 & \text{(flat)} \\ -1 & \text{(negative curvature)} \end{cases}$$

$$ds^2 = g_{\mu\nu}\, dx^\mu dx^\nu$$

The *scale factor a(t)* contains *ALL* cosmological time dependence.

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \longrightarrow g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & \frac{a^2}{1-kr^2} & 0 & 0 \\ 0 & 0 & a^2r^2 & 0 \\ 0 & 0 & 0 & a^2r^2\sin^2\theta \end{pmatrix}$$

(Minkowski metric) (FRW metric)

$$T_{\mu\nu} = T_{\mu\mu} = (P + \rho)u_\mu u_\mu - Pg_{\mu\mu} \quad \text{(Stress-energy for FRW metric)}$$

The Equation of State for the Universe

Omitting the cosmological constant (its effect can be absorbed into $T_{\mu\nu}$), the Friedmann (Einstein) equations are

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} \qquad \text{(evolution of } a\text{)}$$

$$\frac{\dot{\rho}}{\rho} + 3\left(1 + \frac{P}{\rho}\right)\frac{\dot{a}}{a} = 0 \qquad \text{(conserve } p^{\mu}\text{)}$$

Two equations in three unknowns

$$P = P(\rho) = P(\varepsilon) \qquad \text{(Equation of state)}$$

Since the cosmic fluid is low density, assume equation of state

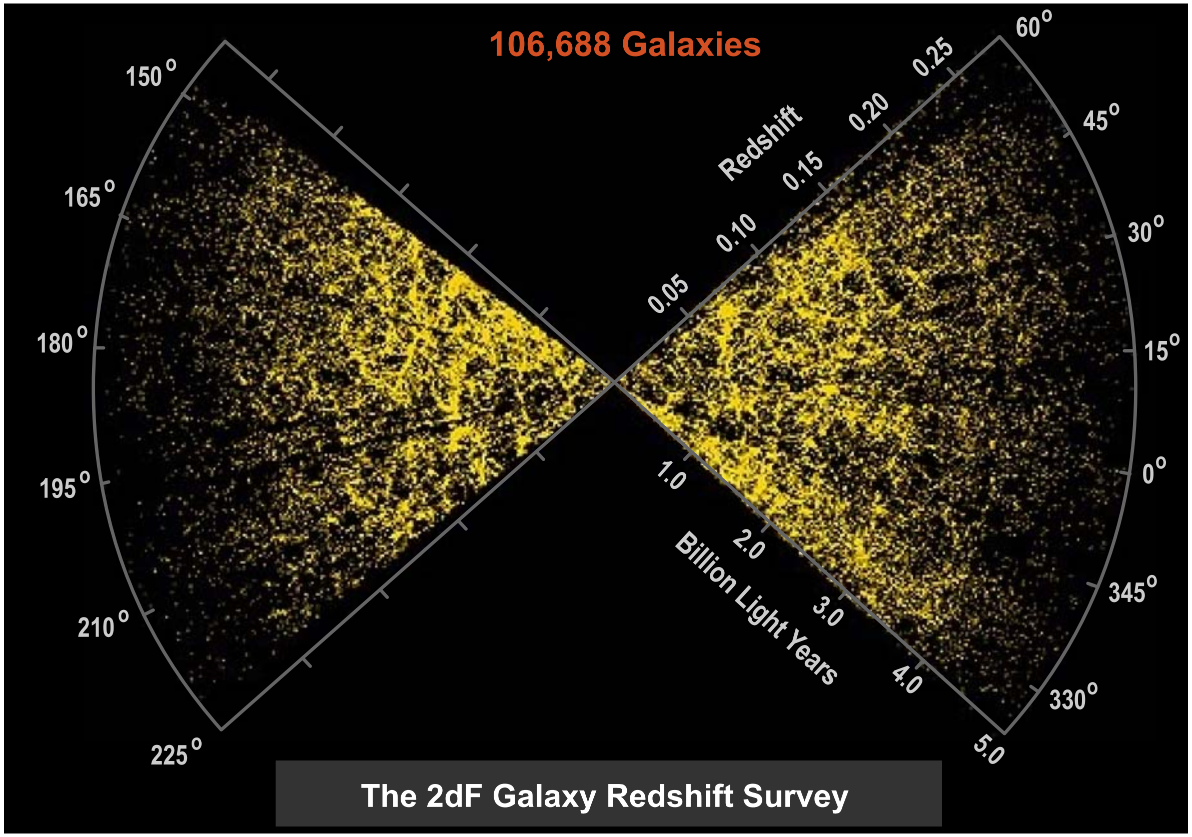
$$P = w\varepsilon$$

The adiabatic sound speed c_s is given by

$$c_s^2 = \frac{dP}{d\varepsilon}c^2$$

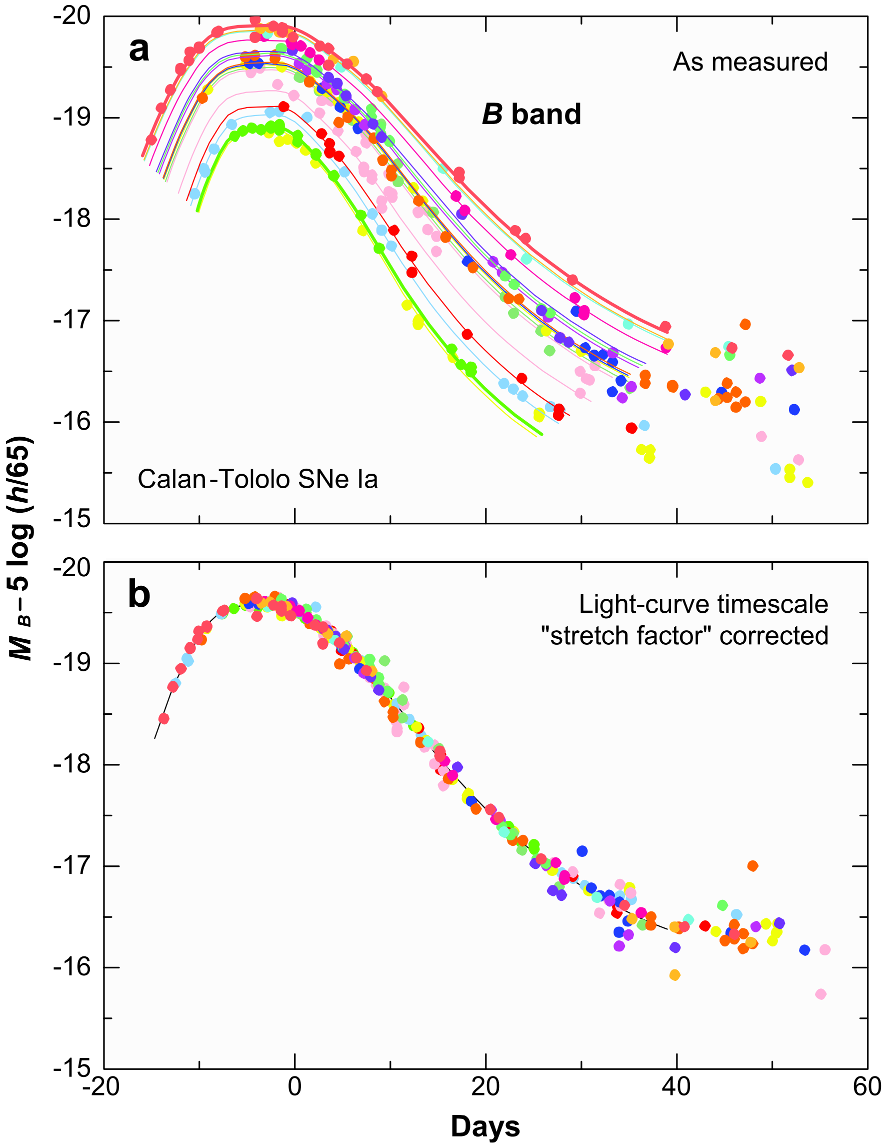
Thus, requiring that $c_s < c$ implies that $w < 1$

Data from Galaxy Surveys



2dF telescope ("two-degree field") determines redshifts of 400 galaxies at once. A robot arm puts 400 light fibers each at exactly the right position to gather light from one galaxy. About 200,000 galaxy spectra catalogued to depth of 4 billion LY (Sloan Digital Sky Survey will do about a million).

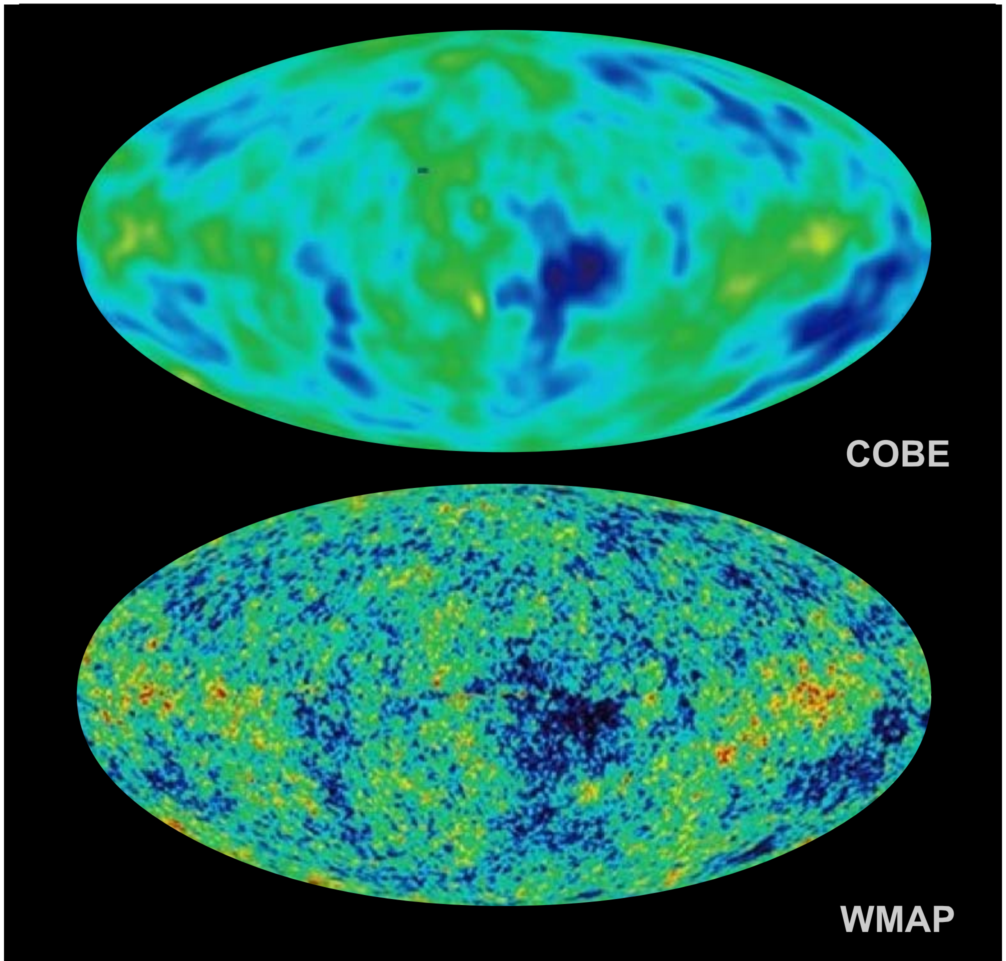
SNIa Standardizable Candles



B-band lightcurves for low-redshift Type Ia supernovae (Calan-Tololo survey; Hamuy, et al, 1996). As measured, the intrinsic scatter is 0.3 mag in peak luminosity. After 1-parameter correction the dispersion is 0.15 mag.

From *Ann. Rev. Astronomy and Astrophysics*, 46, 385 (2008)

Temperature Fluctuations in the CMB



COBE and WMAP Cosmic Microwave Maps

Remarkably uniform but fluctuations at the one part in 100,000 level

Definitions: Dark Matter and Dark Energy

- *Dark matter* is all matter/energy in the Universe that behaves "normally" in that it leads to attractive gravity, but is (so far) not observable by any probe except gravity.

  - Cold (massive) dark matter: $w = 0$

  - Hot (relativistic) dark matter: $w = +1/3$

  The equation of state for dark matter is like that for ordinary forms of matter, but no known elementary particles (or emergent condensates) have the observed properties of dark matter.

- *Dark energy* is any component of the cosmic fluid that has $w < -1/3$.

  - This implies an accelerated expansion.

  - Dark energy leads to a *repulsive gravitational force*.

  - Dark energy behaves as a gas with *negative pressure*.

  The equation of state for dark energy is totally unlike anything ever observed in the laboratory. Obviously no known elementary particle or condensate has the properties of dark energy.

Density Parameters

$$\rho_c = \frac{3H_0^2}{8\pi G}$$ (Critical density)

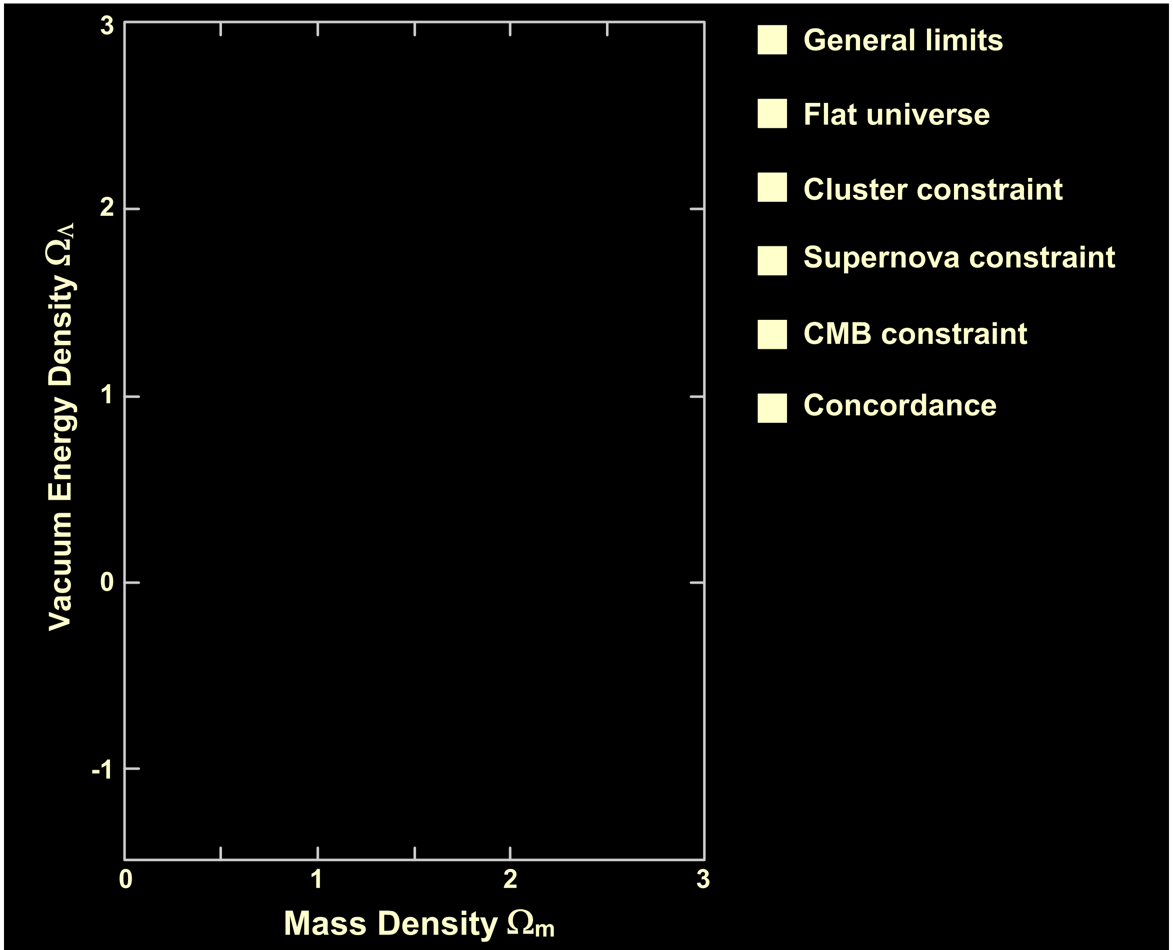
$$\Omega \equiv \frac{\rho}{\rho_c} = \frac{8\pi G}{3H_0^2}\rho$$ (Total density parameter)

Partial densities: $\Omega_i \equiv \frac{\rho_i}{\rho_c}$ $\sum_i \Omega_i = \Omega$

$$\Omega = \Omega_r + \Omega_m + \Omega_v = 1 - \Omega_c$$ (flat Universe)

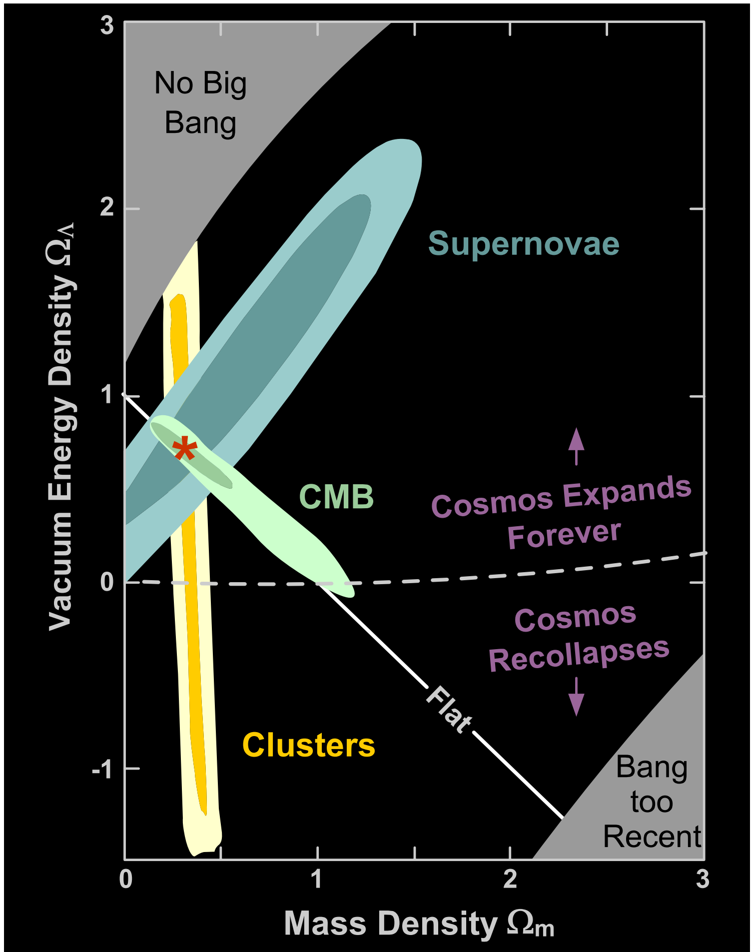
$$\Omega_c \equiv \frac{-k}{a_0^2 H_0^2}$$ (curvature density)

The Concordance Model



Vacuum Energy and Mass Density

The Concordance Model

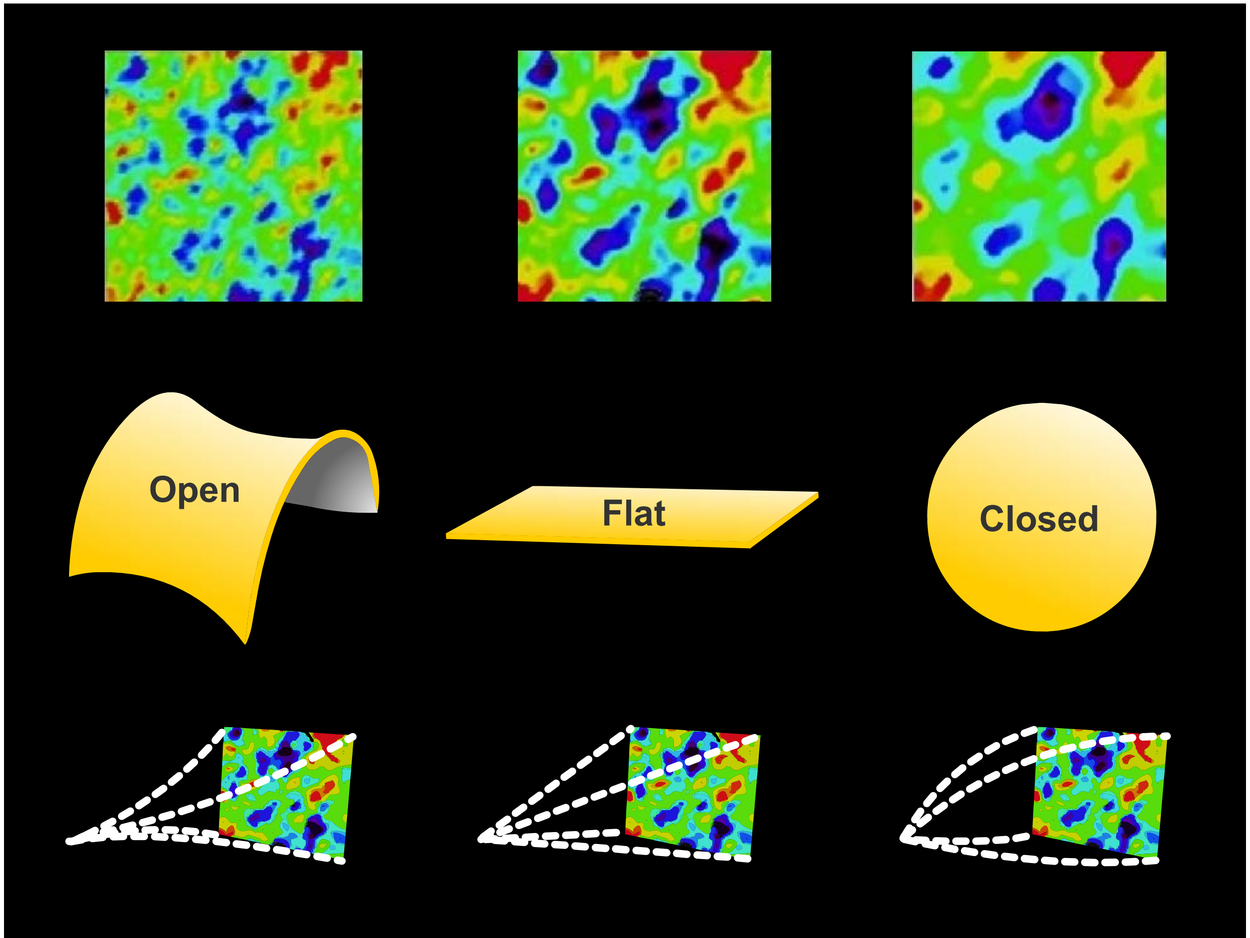


Vacuum Energy and Mass Density

- The Universe is flat (Euclidean), with $\Omega = \Omega_r + \Omega_m + \Omega_\Lambda = 1$. (Inflation)
- Hubble constant $H_0 \sim 72$ km/s/Mpc.
- The energy density of the Universe now in radiation is negligible ($\Omega_r \sim 0$). Earlier it was more important.
- The energy density of the Universe now in matter is about 30% of closure density ($\Omega_m \sim 0.3$). Only a few percent of that matter is normal (baryonic) matter. The rest is dark matter.
- The energy density of the Universe presently in dark energy is about 70% of closure density ($\Omega_\Lambda \sim 0.7$).
- The Universe is flat but will expand forever because of dark energy.

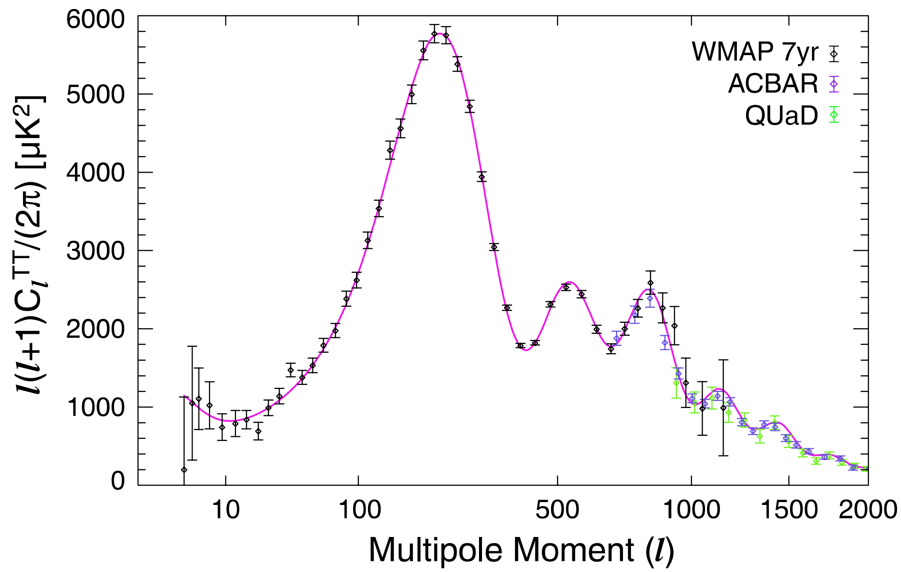
Friedmann Solver

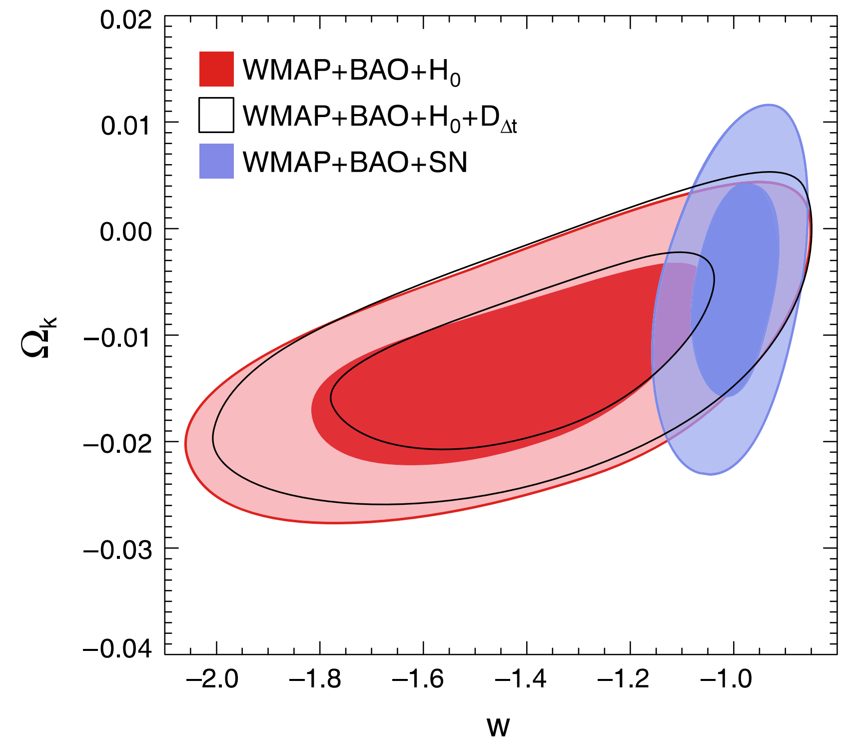
Spacetime Curvature and CMB Fluctuations



Spacetime Curvature and Microwave Fluctuations

WMAP 2010 Data Analysis





Ω_k measures the curvature density of the Universe. Inflation predicts $\Omega_k = 0$.

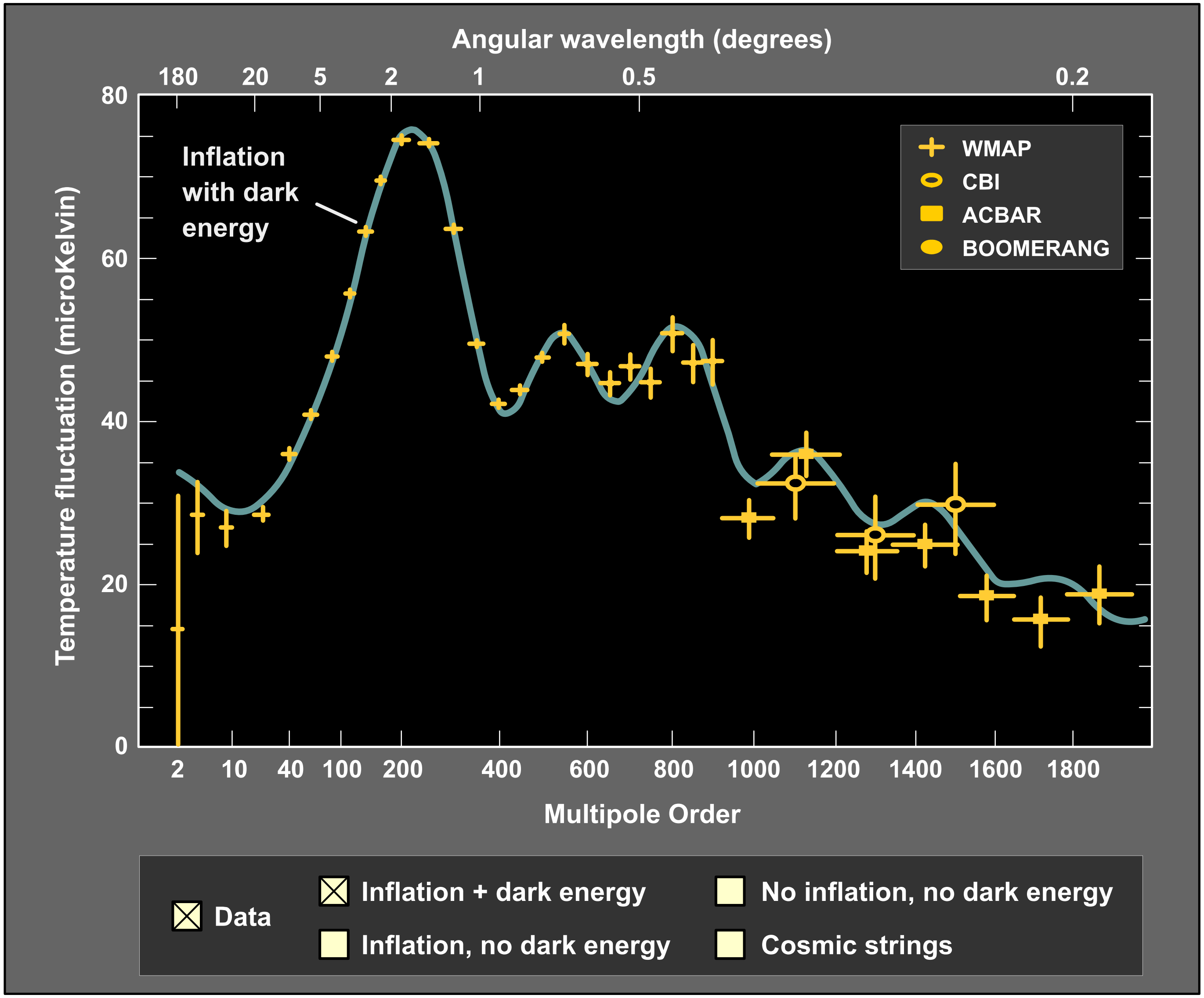
E. Komatsu et al, arXiv 1001.4538 (2010)Astro-ph. *Seven-Year Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation*

Cosmic Inflation

The big bang has some "problems" (actually, some *assumed but unexplained* initial conditions). These may be cured by a modification of the classical big bang in its first tiny fraction of a second called c*osmic inflation.*

Cosmic Inflation

WMAP Evidence for Dark Energy and Inflation

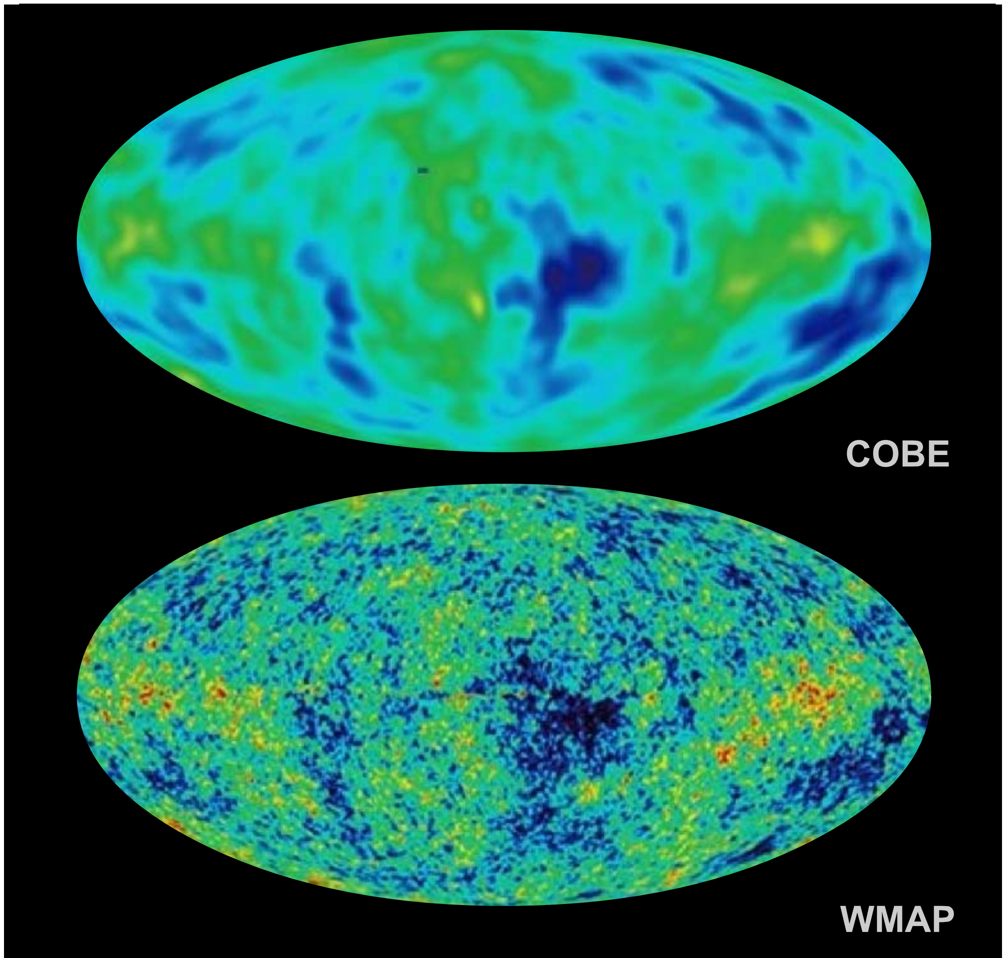


A. H. Guth and D. I. Kalser, Science, 307, 884 (2005)

Inflation and the Origin of Structure

There is a fundamental cosmological problem that only inflation provides a natural explanation for: The remarkable smoothness of the CMB (one part in 100,000) implies that the very early Universe was extremely smooth. *Where then did the density perturbations that lead to stars and galaxies and physicists come from?*

Temperature Fluctuations in the CMB



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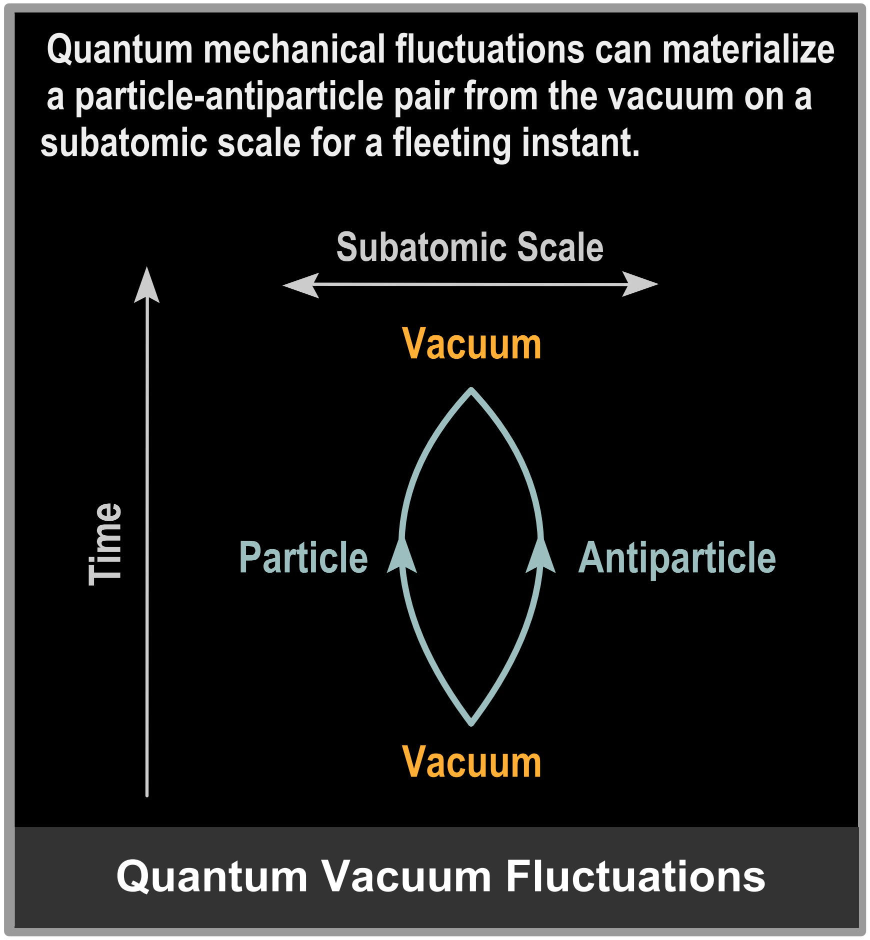
Inflation and the Origin of Structure

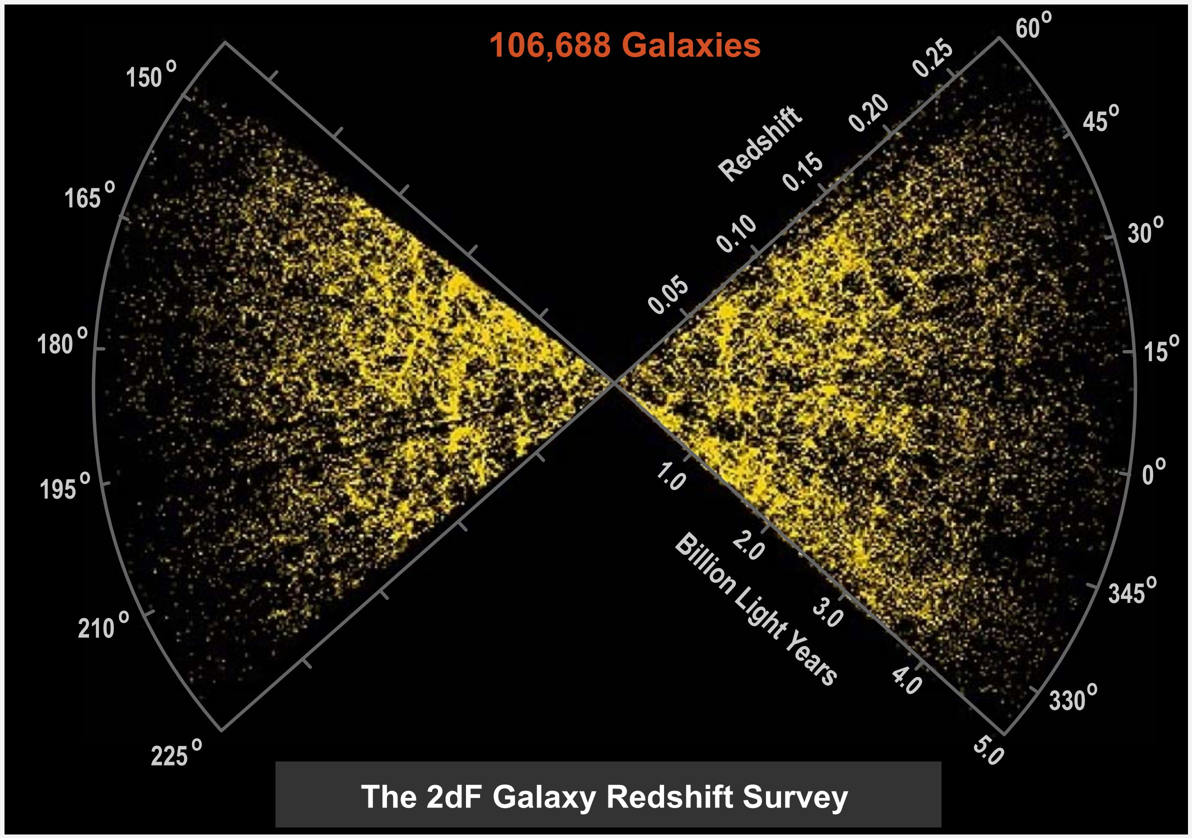
Inflation supplies a completely outrageous answer that plausibly gives the spectrum of density perturbations required by observations:



Microscopic quantum vacuum fluctuations were stretched to astronomical scales by the exponential expansion (!!). Those inhomogeneities eventually became the gravitational seeds for the formation of large-scale structure in the Universe.

Inflation and the Origin of Structure

That this:



is a quantum fluctuation is an astonishing claim! But it presently is our most consistent explanation of the origin of such structure.

Summary

- The Universe started with a big bang about 14 billion years ago. The Universe went through a period of cosmological inflation (exponential expansion) in the first tiny fraction of a second before settling into the standard big bang evolution.

- The evolution of the Universe is determined by the solution of the Friedmann equations (Einstein equations + Cosmological Principle).

- The Friedmann evolution is, in first approximation, determined by four quantities: (1) Hubble parameter, (2) matter energy density, (3) radiation energy density, and (4) the vacuum energy density, all evaluated at the present time.

- Galaxy surveys, the CMB, and Type Ia supernovae suggest that the Universe is flat and the energy density of the Universe is ~70% dark energy, ~30% massive particles (mostly dark matter), and much less than 1% radiation.

Summary

- "Ordinary" baryonic matter (the world that we see) is at most several percent of the mass density of the Universe. The present Universe is dominated by the flatness born of inflation, and dark energy and dark matter.
- The seeds for large-scale structure were quantum vacuum fluctuations stretched to astronomical scales by inflation.
- The geometry of the Universe is almost exactly flat (euclidean) because of inflation, and it appears that it will expand forever because of dark energy.