What drives the Universe?

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- the standard Big Bang cosmology
- CMBR and galaxy spectrum
- Precision measurements of CMB temeperature
- "Blast from the past"
- The new cosmography
- Challenges to theory
- M Theory, Quintessence and all that

orthodox Big Bang

General Relativity the theory of the space-time metric

$$ds^2 = \sum_{\mu\nu} g_{\mu\nu} dx^\mu dx^\nu = dx^T g_{matrix} dx$$

$$= dt^2 - R(t)^2 \{ \frac{dr^2}{1+kr^2} + r^2 d\theta^2 + r^2 \sin^2 d\phi^2 \}$$

$R(t)$ the Scale factor ... A. A. Friedmann

$k = 0, \pm 1$ curvature constant : flat, spherical or hyperbolic geometries

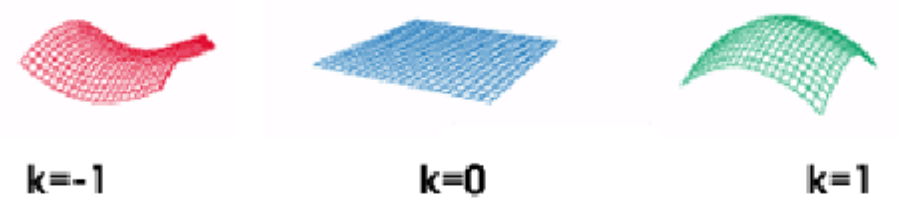
$$\left(\frac{1}{R} \frac{dR}{dt} \right)^2 + \frac{k}{R^2} = \frac{8\pi}{3} G\rho$$

Radiation dominated Universe :

$p = \frac{1}{3}\rho \Rightarrow R(t) \propto t^{1/2}$

Matter dominated Universe :

$p = 0 \Rightarrow R(t) \propto t^{2/3}$



Observable parameters

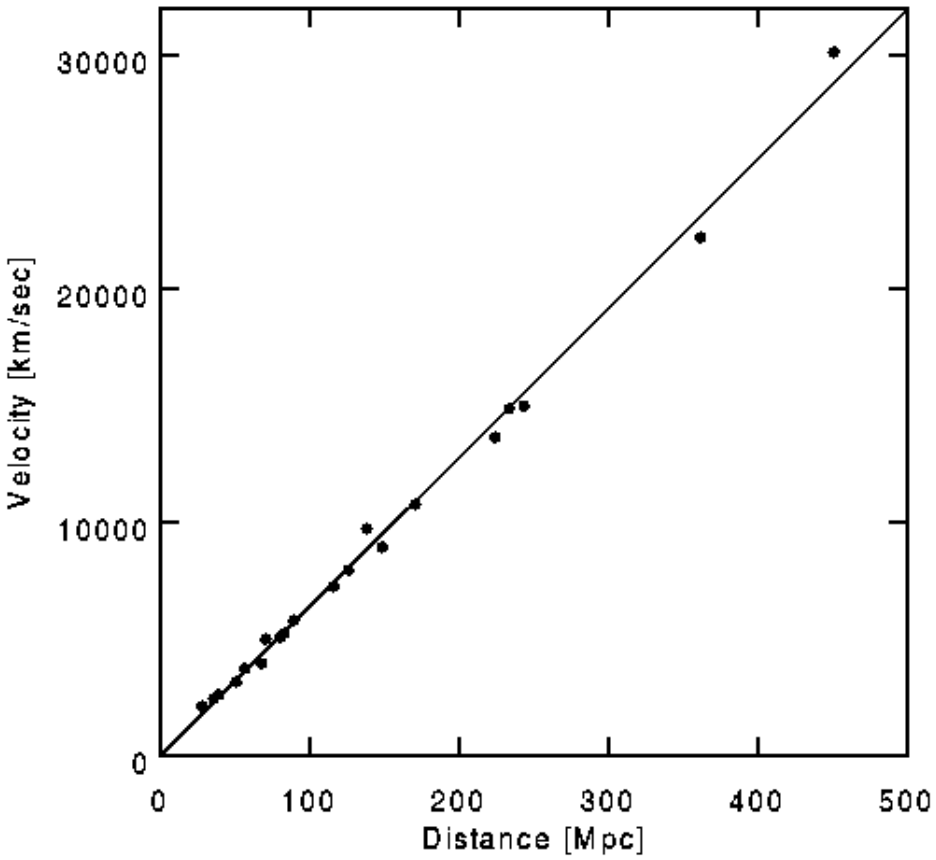
Hubble $'$Constant$'$ $\qquad H = \dot{R}/R$

Deceleration parameter $\quad q = -\dfrac{\ddot{R}/\dot{R}}{\dot{R}/R} = -\dfrac{\dot{R}R}{\dot{R}^2}$

with $cz \approx v_{recession} = H D_L$.

$4\pi D_L^2 \times$(local flux) = Total absolute flux

Operationally, $D_L = R(t_0) \int^{t_0} \frac{dt'}{R(t')}$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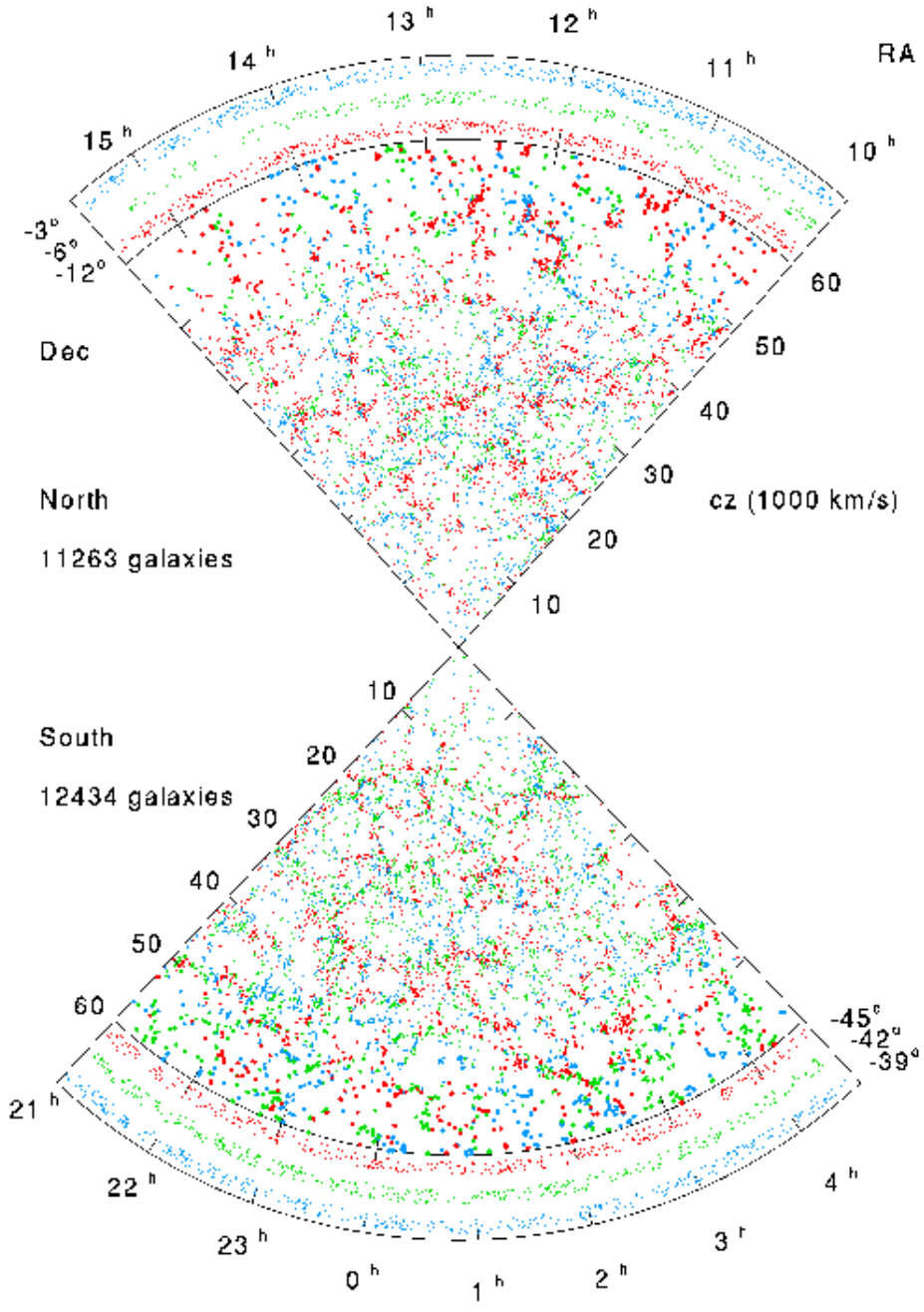
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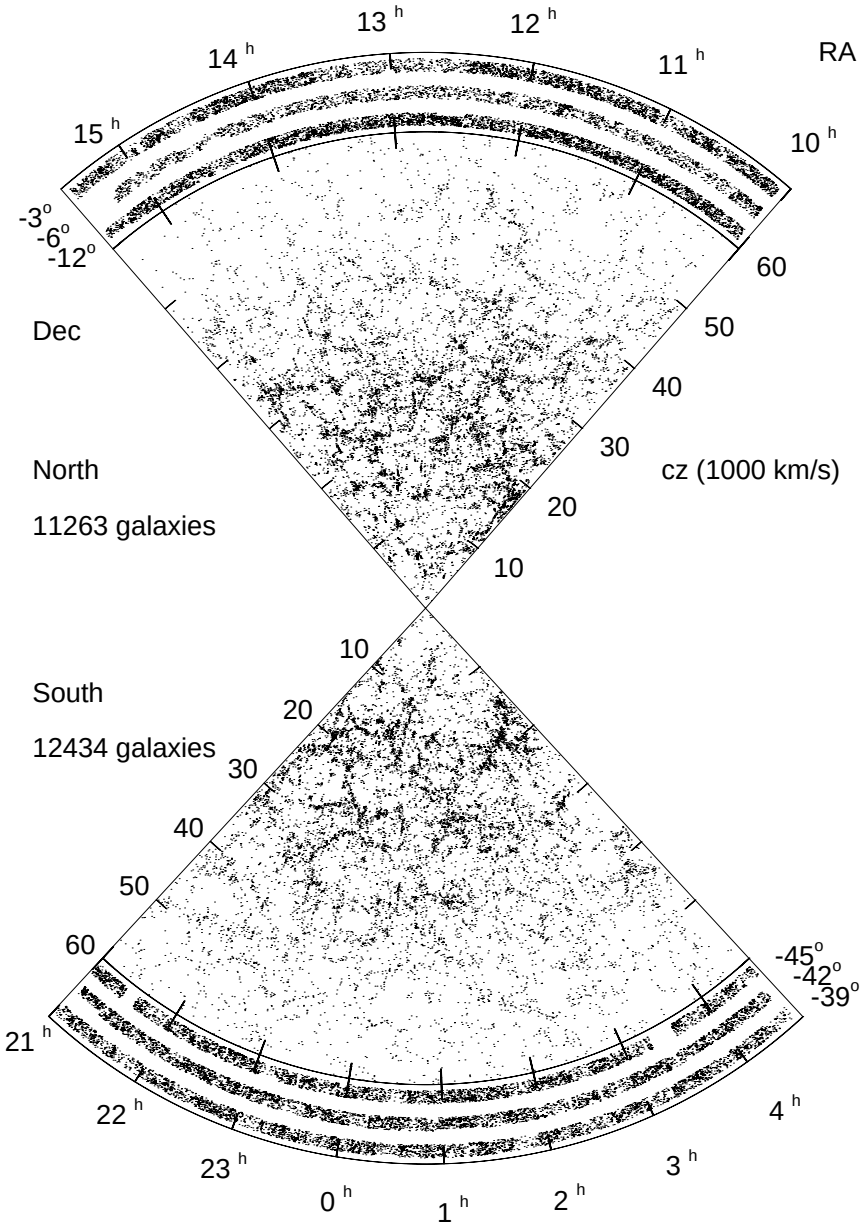
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The cosmological constant

Einstein's field equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$\left(\frac{1}{R}\frac{dR}{dt}\right)^2 + \frac{k}{R^2} - \Lambda = \frac{8\pi}{3} G\rho$$

$[\Lambda] = [G]^{-2} \Rightarrow \rho_{eff} = \rho + (3/8\pi G)\Lambda$

Vacuum energy ; *negative pressure!*

$T_{\mu\nu} = \mathrm{Diag}(\rho, p, p, p) = \Lambda \eta_{\mu\nu}$

$p = -\rho \Rightarrow R(t) = R(t_0) e^{\Lambda(t-t_0)} \quad H = \Lambda$

Einstein saw this as a way of avoiding an "unstable" Universe. But unstable it indeed was! So he withdrew it and called its introduction his "biggest blunder".

More observables and more puzzles

Present energy density of the Universe

Ω_0 : (Total ρ_0 today)/$(3H^2_{today}/8\pi G)$

Ω_B : fraction in the form of baryons

Ω_{DM} : All the remaining part of ρ_0 .... until recently

Ω_Λ : Cosmological constant contribution

But first the Ω_{DM}

- "Rotation curves" of galaxies
- Virial velocities within clusters of galaxies

Conclusion : 90 to 99% of the energy driving the Universe is non-baryonic. (Latest figure 97%)

What could the Dark Matter be?

probable Elementary Particle Physics candidates :

Neutrino, axion, gravitino and friends, ...

From the point of view of galaxy formation, two broad possibilities

- Cold DM : Heavy and non-relativistic at 10^5 yr. Result in down-up scenario; stars form first and come together to form galaxies

- Hot DM : Light and relativistic. top-down scenario; mega gas clouds with stars nucleating in the interior, later clumping into samller galactic units.

The simulations have to be verified against the kind of distribution of galaxies into mass values that may result $N(M)$.

Cosmic Microwave Background Radiation

Events in the history of the Universe

- Quarks and glouns form hadrons $t \approx 10^{-6}$ sec
- Nucleons fuse into light nuclei
  - Anti-catalytic photons $n_B/n_\gamma \approx 10^{-11}$
  - $t \approx 100$ sec.; the "First three minutes"
- Protons and electrons combine to form neutral Hydrogen $t \approx 10^{12}$sec $= 10^5$yr.
- Photons begin free streaming in neutral matter

Estimated temperature of this Planckian spectrum was 10 to 40 K. Observed now to be 2.7 K.

CMBR, baryon number and galaxy formation

Primordial abundances : He/H$\approx$ 7% by mass; all other nuclei $\leq 10^{-3}$.

The overwhelming amount of photons do not allow formation of heavier nuclei.

Borne out by direct observations. The required $n_B/n_\gamma \approx 10^{-11}$ then tallies exactly with the fact that $\sim$ 95% of the matter is non-luminous.

Origin of galaxies :

"Before there was anything there was nothing, so where did everything come from?" ... *B.C. cartoon*

If everything was homogeneous how did the galaxies form?

Galaxies seem to have $\Delta M/M$ constant on all large scales. The seed perturbations must be consistent with that. This requires $\delta\rho/\rho \approx 10^{-6}$.

Since CMB originates from the time these perturbations have existed, it should also carry the same extent of anisotropy.

These have now been accurately measured.

Angular spectrum of anisotropy gives detailed information regarding nature of matter content.

Conclusion : Cold Dark Matter no more than 30%.

Hot Dark Matter not permitted.

The Inflationary Universe (Guth, 1980)

Unreasonably isotropic and homogeneous Universe.

Horizon Problem

Flatness Problem

Exponential expansion of the scale factor ought to explain perfect homogeneity over a staggering 10^{27} horizon volumes.

Particle Physics explanation :

Spontaneous Symmetry Breaking. The quantum groundstate is like that of a ferromagnet. It is the preferred state but carries special ordering information. If the system begins away from this in a chaotic state, it carries excess energy.

Grand Unification scale energy densities $(10^{15} GeV)^4$ will adequately explain the tremendous expansion factor.

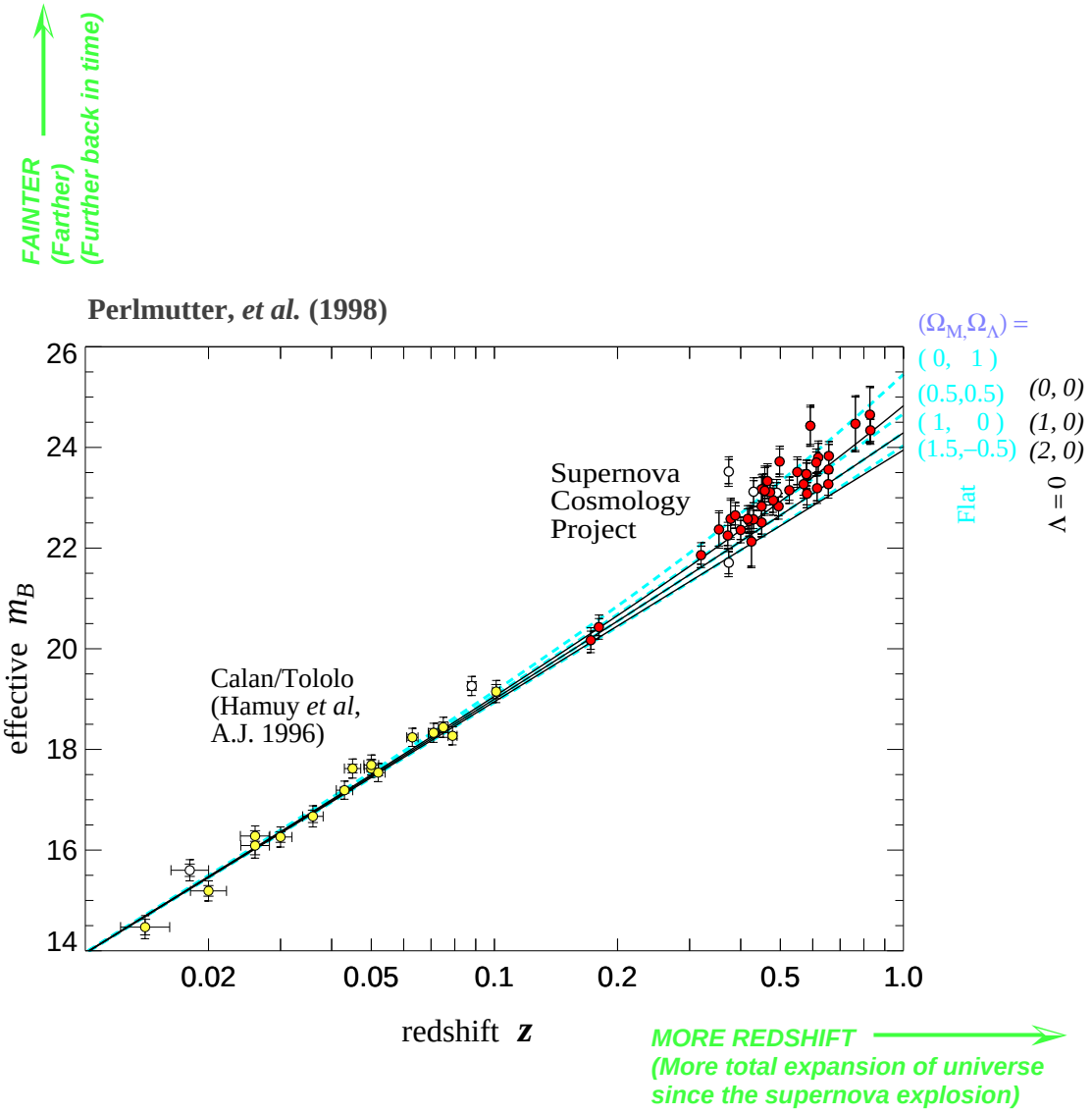
It also explains scale invariant remnant perturbations from *quantum fluctuations*

Why isn't (or wasn't) the Weinberg-Salam vacuum energy causing an exponenetial expansion?

This is the High Energy problem of Cosmological Constant.

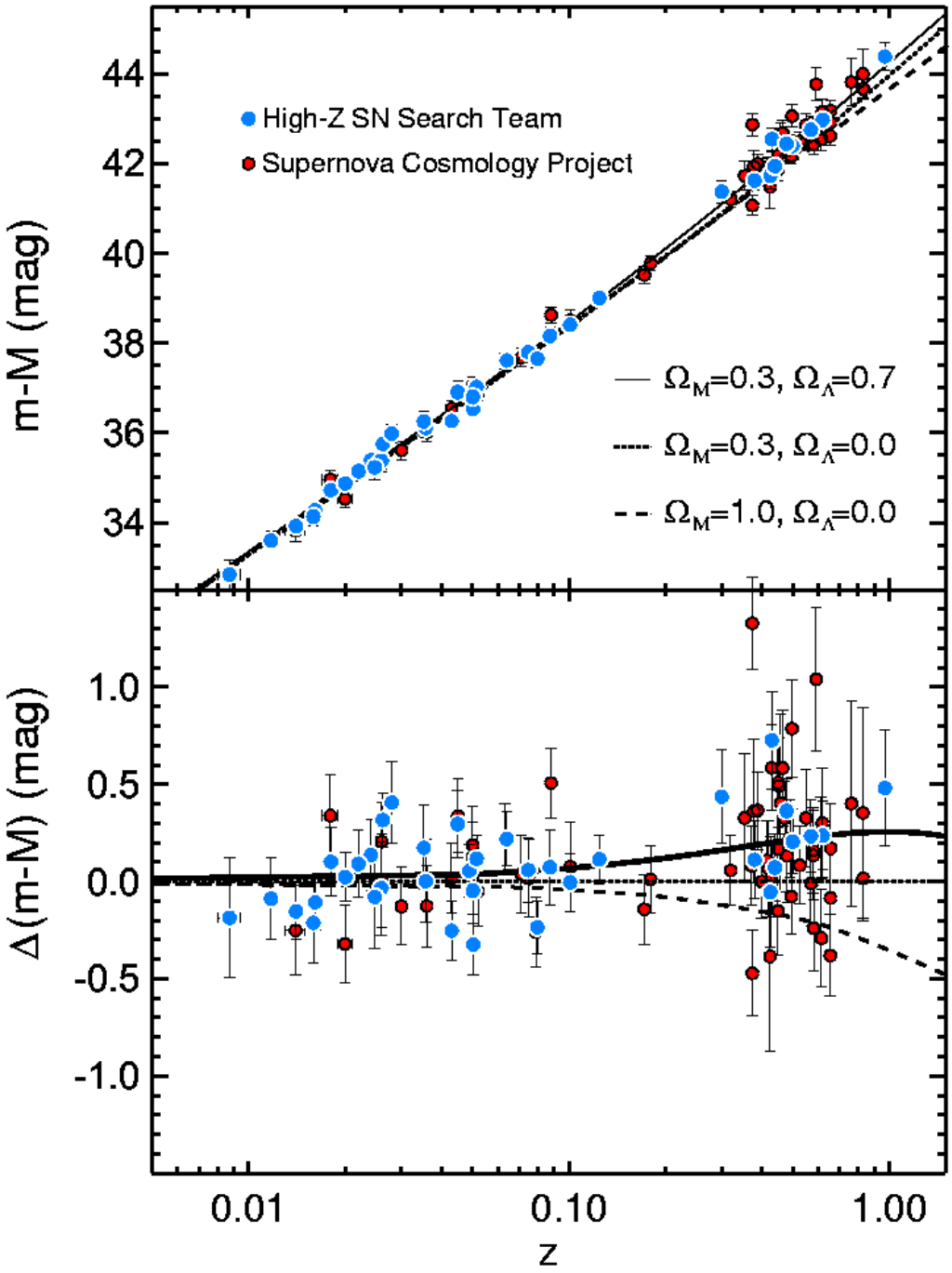
“Blasts from the past” and the minuscule Cosmological Constant.

Emergence of "dark energy"; an accelerating Universe

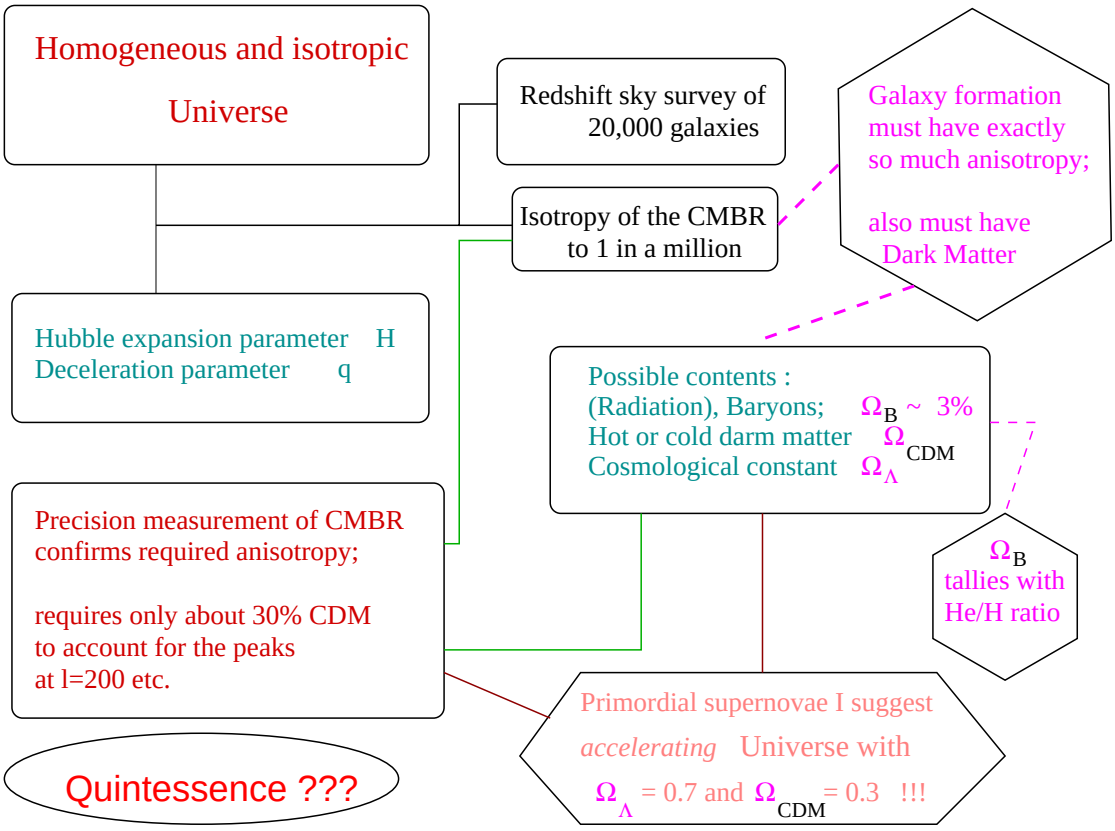


In flat universe: $\Omega_M = 0.28$ [± 0.085 statistical] [± 0.05 systematic]

Prob. of fit to $\Lambda = 0$ universe: 1%



From Cosmology Supernova Project, LANL


Homogeneous and isotropic Universe
Redshift sky survey of 20,000 galaxies
Galaxy formation must have exactly so much anisotropy;
also must have Dark Matter
Isotropy of the CMBR to 1 in a million
Hubble expansion parameter H
Deceleration parameter q
Possible contents :
(Radiation), Baryons; Ω_B ~ 3%
Hot or cold darm matter Ω_{CDM}
Cosmological constant Ω_Λ
Ω_B tallies with He/H ratio
Precision measurement of CMBR confirms required anisotropy;
requires only about 30% CDM to account for the peaks at l=200 etc.
Primordial supernovae I suggest *accelerating* Universe with Ω_Λ = 0.7 and Ω_{CDM} = 0.3 !!!
Quintessence ???

What light can theory shed?

(Hawking at M-Theory Cosmo '01)

The structure of the peaks - location and width

are considered a confirmation of inflation.

A viable "inflaton" from fundamental physics is awaited.

Amplitude of fluctuations 10^{-6} not explained in QFT.

Two separate inflationary phses, one with $\sqrt{\Lambda} = 10^{-5} M_{Planck} \approx 10^{23}$ eV,
another at $\sqrt{\Lambda} = 10^{-60} M_{Planck} \approx 10^{-32}$ eV!

Available tricks :

- Supersymmetry
- Extra dimensions
- Exotic matter-energy

Constraints :

- Global Supersymmetry $\Rightarrow$ stable space-time
- Inflationary phase not possible in String Theory
  - Perhaps just as well!
- Extra dimensions not justified so far; little control over them

Quintessence

In string physics there are degrees of freedom which in 4 dimensions will be scalars whose equlibrium value can be $\phi_0 = \infty$.

Also their dynamics may be governed by artificially small couplings, resulting in artificially large time scales.

If there is a field with potential energy

$$V[\phi] = V_0 e^{-\alpha\phi}$$

and if this is slowly rolling towards its minimum, we may have this residual "cosmological constant", but which will eventually (100 b.yr.?) disappear.

Existence of genuine continua may be the one novel implication that may be here to stay.

या सृष्टिः स्रष्टुराद्या वहतिविधिहुतं

या हविर्या च होत्री ।

ये द्वे कालं विधत्तः श्रुतिविषयगुणा

या स्थिता व्याप्य विष्वम् ॥

यामाहुः सर्वबीजप्रकृतिरितियया

प्राणिनः प्राणवन्तः ।

प्रत्यक्षाभिः प्रपन्नस्तनुभिरवतुवस्

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