Introduction to Dark Energy.

I) Observation of an accelerating universe by two groups: High z supernova Team and Supernova Cosmology project. at $z \simeq 0.5$
SNIa

- What kind of observations: Supernovae at high redshifts are fainter than what can be predicted by a universe which is decelerating due to gravitational pull.

How is this so?

Light flux from distant supernova:

"absolute luminosity"

$$\boxed{F = \frac{\mathcal{L}}{4\pi d_L^2}}$$

d_L: "luminosity distance"

What's d_L?

In all of these discussions, it is common (for astronomers) to use a quantity called "redshift" z:

$$\boxed{\frac{\lambda_0}{\lambda_e} = \frac{a_0}{a_e} = 1+z}$$

λ_e: wavelength of emitted photon at time t_e

λ_0: wavelength of received photon at present time t_0

$a_e(t_e)$, $a_0(t_0)$ are scale factors

Assume a flat universe which is homogeneous & isotropic. The luminosity distance to a, e.g., supernova at redshift z is given by:

$$\boxed{d_L = (1+z)\int_0^z \frac{dz'}{H(z')}}$$

$$\boxed{H(z) = H_0\left[\Omega_m(1+z)^3 + \Omega_x(1+z)^{3(1+w)}\right]^{1/2}}$$

$$\Omega_m = \frac{\rho_{m0}}{\rho_c^0}, \quad \Omega_x = \frac{\rho_{x0}}{\rho_c^0}$$

$\rho_c^0 = \frac{3H_0^2}{8\pi G}$: critical density.

w comes from the equation of state: $p = w\rho$

More on that later.

For a cosmological constant: $p = -\rho$ or $w = -1$

(more later)

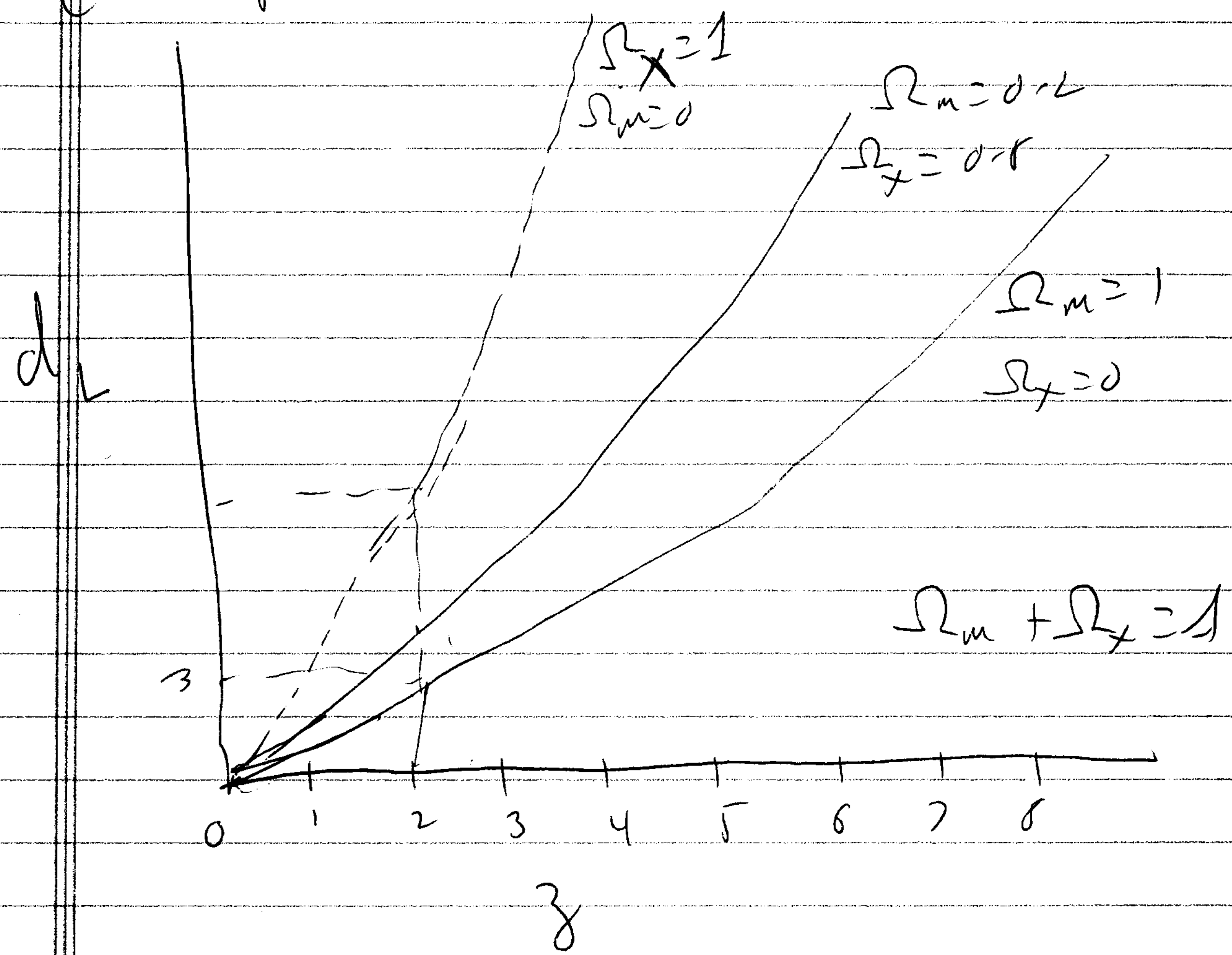
$$\Rightarrow H(z) = H_0\left[\Omega_m(1+z)^3 + \Omega_x\right]^{1/2}$$

Flat universe: $\boxed{\Omega_m + \Omega_x = 1}$

The "luminosity distance" d_L v.s. z is shown for various values of Ω_m and Ω_x

(Ω_m includes baryonic and non-baryonic matter)

(show picture here)



~~d_L~~ At a given redshift d_L is <u>smaller</u> for $\Omega_m = 1$, $\Omega_x = 0$ than that at $\Omega_x = 1, \Omega_m = 0$ or $\Omega_x = 0.8, \Omega_m = 0.2$

e.g. at $z=2$, it differs by a factor of 2

$\Rightarrow$ F is <u>smaller</u> at $\Omega_x = 0.8$, $\Omega_m = 0.2$ than the case $\Omega_m = 1$, $\Omega_x = 0$

Since the supernovae are dimmer than expected, it appears that one is dealing with a universe with a substantial vacuum energy or cosmological constant.

- Why is the universe thought to be accelerating?

1) Hand-waving argument:

decelerating universe: d_L smaller than constant speed expansion $\Rightarrow$ smaller than accelerating universe. Remember $F = \frac{\mathcal{L}}{4\pi d_L^2}$

Brighter	Bright	Dimmer.
decelerating universe	constant speed	accelerating

2) More rigorous:

From Einstein's eq. with an FRW metric, one can derive:

$$\boxed{\begin{aligned}\frac{\ddot{a}}{a} &= -\frac{4\pi G}{3}\sum_i (\rho_i + 3P_i) \\ &= -\frac{4\pi G}{3}\sum_i \rho_i (1 + 3w_i)\end{aligned}}$$

$$\boxed{P_i = w_i \rho_i}$$

Define a "deceleration" parameter q:

$$q = -\frac{\ddot{a}}{aH^2} = \sum_i \left(\frac{\rho_i}{\frac{3H^2}{4\pi G}}\right)(1+3w_i)$$

$$= \frac{1}{2}\sum_i \Omega_i (1+3w_i)$$

The present matter (baryonic + non-baryonic) is non-relativistic $\Rightarrow$ pressure $= 0$ $\Rightarrow$ $w_m = 0$

$$q = \left(\Omega_m + \Omega_x(1+3w_x)\right)/2$$

$$= \left(\underbrace{\Omega_m + \Omega_x}_{1} + 3w_x\Omega_x\right)/2$$

$$\boxed{q = \frac{1+3w_x\Omega_x}{2} = -\frac{\ddot{a}}{aH^2}}$$

For a cosmological constant $w_x = -1$ and take $\Omega_x = 0.7$ (more later) $q = -0.55 = -\frac{\ddot{a}}{aH^2}$

$\Rightarrow$ $\boxed{\ddot{a} > 0 \Rightarrow \text{Accelerating universe}}$

Type Ia supernovae appear to be good "standardized candles" because it is believed that ~~all types~~ they are all of similar intrinsic luminosity $\mathcal{L}$ which is nearly constant. However, skeptics may question that.

Supernovae: white dwarfs which cross the Chandrasekhar limit which is nearly-universal $\Rightarrow$ nearly-universal intrinsic $\mathcal{L}$. (Show pictures)

However there is still ~ 40% scatter in the peak luminosity $\Rightarrow$ <u>uncertainty</u> on <u>$\mathcal{L}$</u>.

However: Brighter supernovae take a <u>longer</u> <u>time</u> to <u>fade</u> than the <u>dimmer one</u>

$\Rightarrow$ Correlation between light curve and peak luminosity $\Rightarrow$ precision of $\sim 7\%$.

More measurements of supernovae with SNAP will help improve the estimation.

II) Cosmic Background Radiation

If it were for just supernovae results, the case for an accelerating universe which implies a substantial amount of D.E. might be a bit shaky..

Fortunately, CMB measurements have gotten very precise.

CMB is not perfectly isotropic in temperature

Deviations by 1 part in 10^5 have been observed.

Anisotropies analyzed by:

$$\frac{\Delta T}{T} = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi)$$

Power spectrum: $C_l = \langle |a_{lm}|^2 \rangle$

ensemble average

Show the plot $\ell(\ell+1)\,C_\ell$ v.s. ℓ.

For a flat universe $\Omega_{tot} = 1$, expect a peak at $\ell \sim 220$ $\Rightarrow$ seen!

$$\Rightarrow \boxed{\begin{aligned} \Omega_B &= 0.04 \\ \Omega_{DM} &= 0.26 \\ \Omega_\Lambda &= 0.7 \end{aligned}}$$

Actually:

$0.98 \lesssim \Omega_{tot} \lesssim 1.08$

Assuming $\Omega_{tot} = 1$

$$\Rightarrow \begin{cases} h = 0.72 \pm 0.05 \\ \Omega_M = 1 - \Omega_\Lambda = 0.29 \pm 0 \\ \Omega_B = 0.047 \pm 0.006 \end{cases}$$

Consistent with Supernova results.

Show picture of Ω_Λ v.s. Ω_M.

The fact that $\Omega_\Lambda = 0.7 \simeq O(\Omega_M = 0.3)$ <u>now</u>!

Is it just a "cosmic coincidence"?

2 questions:

1) What might be this "dark energy"?

2) When did the acceleration occur?

I) Suppose it is a cosmological constant.

From $\Omega_\Lambda = 0.7$

$\rho_{vac} \sim 10^{-8}\ \mathrm{erg/cm^3} \sim (10^{-3}\,\mathrm{eV})^4 = \text{constant!}$

The transition from deceleration to acceleration occurs around $\ddot{a} = 0$

i.e. $\Omega_M + \Omega_X (1 + 3w_X) = 0$

If Ω_X comes from a cosmological constant or vacuum energy, $w_X = -1$

$\Rightarrow \Omega_M(z_a) - 2\underbrace{\Omega_\Lambda(z_a)}_{\text{constant}} = 0$

From:

$$\frac{0.3}{0.7} = \frac{\Omega_M^0}{\Omega_\Lambda} = \frac{1}{(1+z)^3} \frac{\Omega_M(z)}{\Omega_\Lambda}$$

$$T_a^3 = T_0^3 \times 2 \times \frac{0.7}{0.3}$$

$$\Rightarrow \boxed{z_a \simeq 0.67}$$

$$\Rightarrow T_a \simeq 4.5\,{}^\circ K$$

What is the age of the universe at z_a
(for vacuum energy scenario)

$$t(z_a) = H_0^{-1} \int_{\underset{\sim 0.67}{z_a}}^{\infty} \frac{dz'}{(1+z')\left[\underbrace{\Omega_M^0}_{0.3}(1+z')^3 + \underbrace{\Omega_\Lambda}_{0.7}\right]^{1/2}}$$

$$\Rightarrow t(z_a) \sim 7.2 \pm 0.8 \text{ Gyr}$$

$$(t_0 = 13 \pm 1.5 \text{ Gy})$$

~6 billion years ago.

When did the vacuum energy begin to dominate the total energy density?

i.e. when $\rho_M(z_{eq}) \sim \rho_\Lambda$

Again from:

$$\frac{\rho_M^0}{\rho_\Lambda} = \frac{\Omega_M^0}{\Omega_\Lambda} = (1+z)^{-3} \underbrace{\frac{\Omega_M(z)}{\Omega_\Lambda}}_{=1} \text{ at } z = z_{eq}$$

$\Rightarrow z_{eq} \simeq 0.33$

$$t(z_{eq}) = H_0^{-1} \int_{z_{eq}}^{\infty} \frac{dz'}{(1+z')\left[0.3(1+z')^3 + 0.7\right]^{1/2}}$$

$\simeq 9.5 \pm 1.1$ Gyr

Roughly 3.5 Gyr ago!

Some pointers:

Friedmann Eq:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \left(T^{(m)}_{\mu\nu} + \rho_{vac}\, g_{\mu\nu} \right)$$

For homogeneous and isotropic universe:

$$T_\mu^{\ \nu} = \mathrm{diag}(\rho, -p, -p, -p)$$

For vacuum $T_\mu^{\ \nu\,(vac)} \propto g_\mu^{\ \nu}$

$$\Rightarrow T_\mu^{\ \nu\,(vac)} = \mathrm{diag}(\rho, \rho, \rho, \rho)$$

$$\Rightarrow p_{vac} = -\rho_{vac}.$$

Covariant energy conservation: $\nabla_\mu T^{\mu\nu} = 0$

$$\Rightarrow \dot{\rho} + 3H(\rho + p) = 0$$

$$\dot{\rho}_{vac} + 3H \underbrace{(\rho_{vac} + p_{vac})}_{=0} = 0$$

$$\Rightarrow \dot{\rho}_{vac} = 0$$

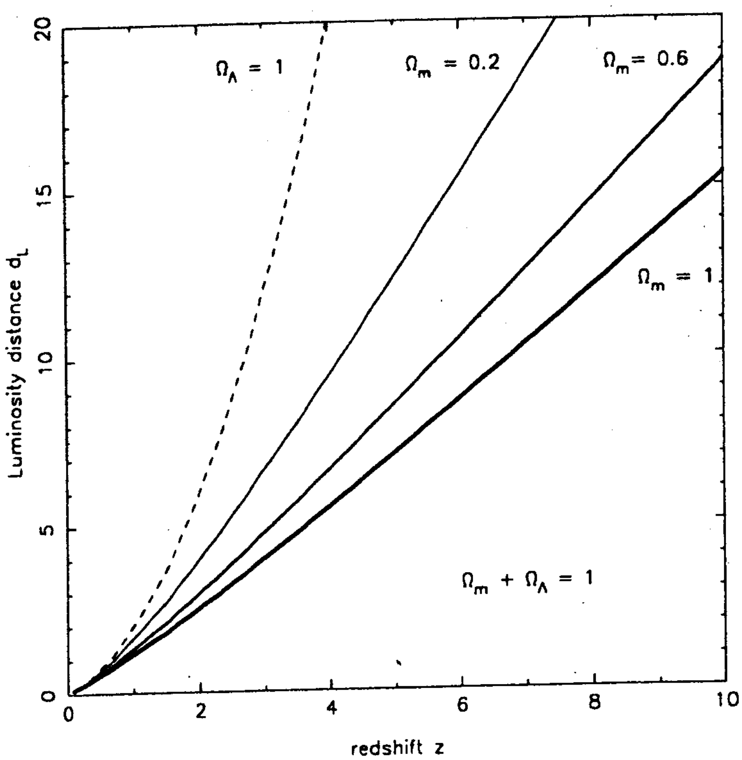
Dynamics of FRW universe completely specified by

$\boxed{p = w\rho}$ and $\boxed{H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3} \sum_i \rho_i - \frac{k}{a^2}}$

$k = 0$ flat
$k = 1$ clos
$k = -1$ open

$$d_L(z) = (1+z)\int_0^z \frac{dz'}{H(z')}. \quad (27)$$

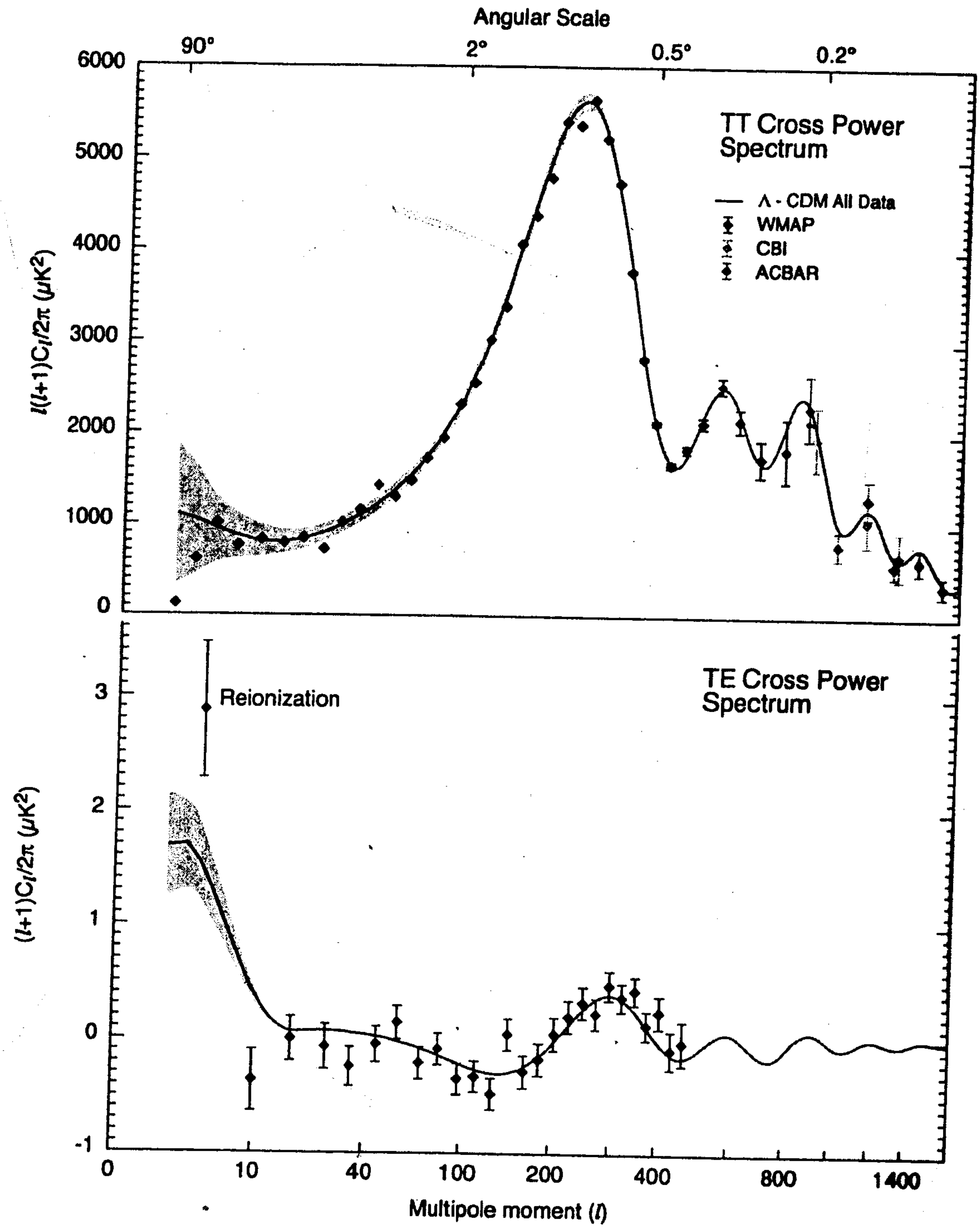
nosity distance is shown in Fig. 1 for a number of cosmological varying amounts of Ω_m & Ω_Λ. The limiting case $\Omega_m = 1$, $\Omega_\Lambda = 0$ to standard cold dark matter (SCDM) in which the universe is a weak power law $a(t) \propto t^{2/3}$. The other extreme example $= 0$ describes the de Sitter universe (also known as steady state which accelerates at the steady rate $a(t) \propto \exp\sqrt{\frac{\Lambda}{3}}t$. From figure t a supernova at redshift $z = 3$ will appear 9 times brighter in it will in de Sitter space !



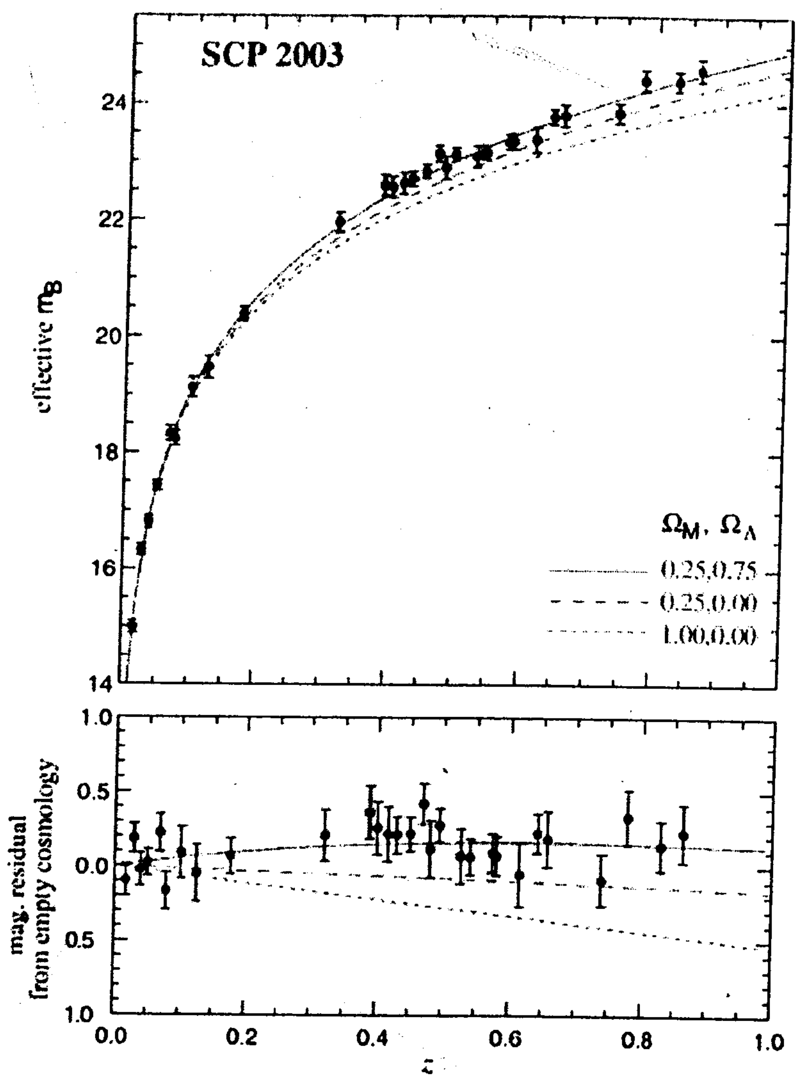
luminosity distance d_L (in units of H_0^{-1}) is shown as a function of redshift z for spatially flat cosmological models with $\Omega_m + \Omega_\Lambda = 1$. correspond to larger values of Ω_m. The dashed line shows the luminance in the spatially flat de Sitter universe ($\Omega_\Lambda = 1$). From Sahni and [172].

tic studies of type Ia supernovae have revealed that:

Sn are excellent stadardized candles. The dispersion in peak luminosity is small: $\Delta m \simeq 0.3$, and the corresponding change in y is about 25%. In addition the light curve of a type Ia supernova lated with its peak luminosity [149] to a precision of $\sim 7\%$, so supernovae take longer to fade. (Type Ia Sn take roughly



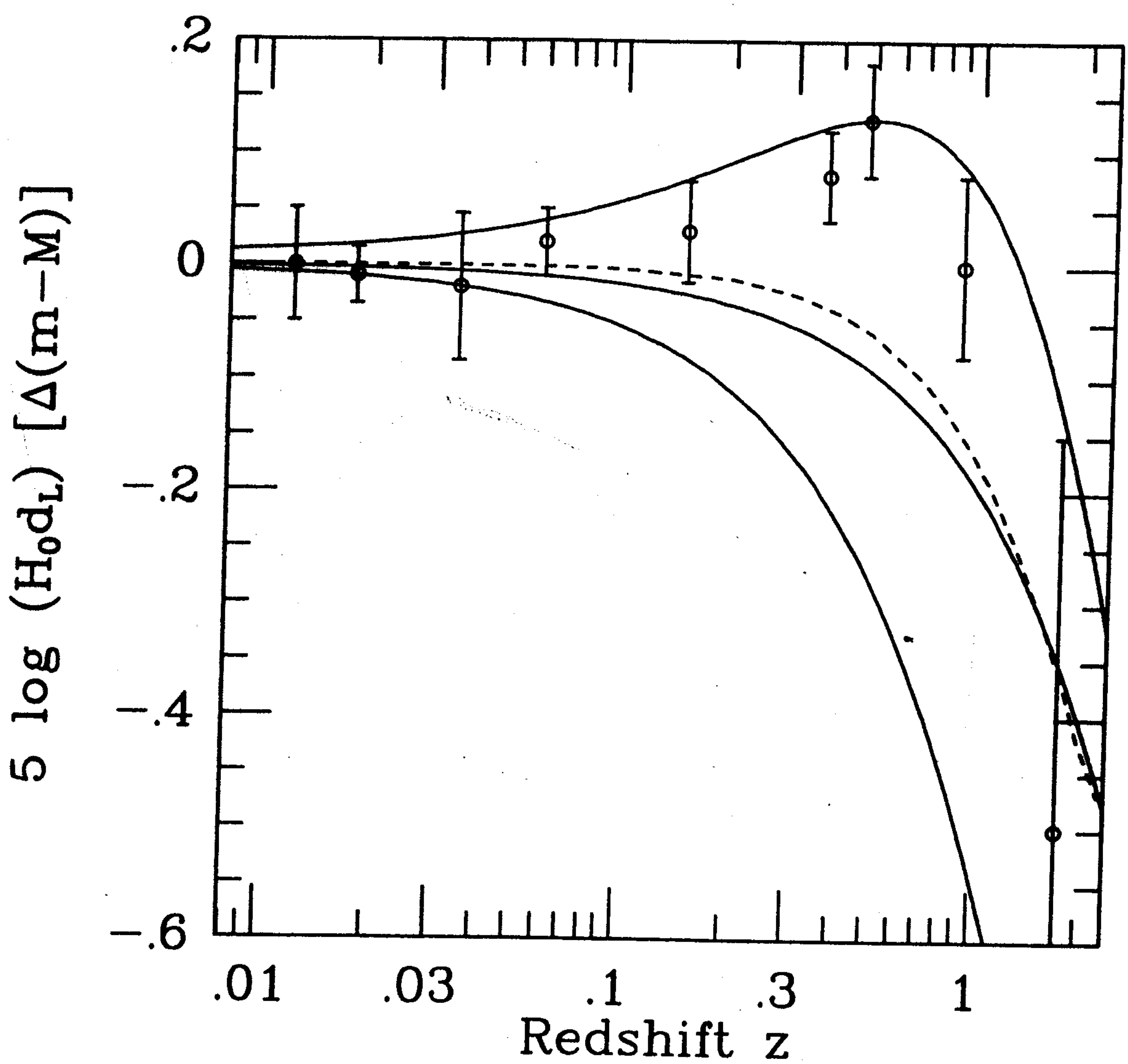
.6: The CMB power spectrum from the WMAP satellite [72]. The error bars on this 1-σ and the solid line represents the best-fit cosmological model [73]. Also shown is elation between the temperature anisotropies and the (E-mode) polarization.



ıble diagram from the Supernova Cosmology Project, as of 2003 [70].

ıount of ^{56}Ni produced in the supernova explosion; more nickel implies luminosity and a higher temperature and thus opacity, leading to a slower · an exaggeration, however, to claim that this behavior is well-understood

:ring work reported in [61], two independent groups undertook searches ⁄ae in order to measure cosmological parameters: the High-Z Supernova 5, 66], and the Supernova Cosmology Project [67, 68, 69, 70]. A plot of



Hubble diagram: High-redshift type Ia supernovae probe the expansion history and reveal ted expansion. In this differential Hubble diagram the distance modulus, which is 5 times rithm of the distance, relative to an empty Universe ($\Omega_0 = 0$) is plotted. Measurements ›re than 200 type Ia supernova are binned into 9 data points. The solid curves represent eoretical models: from the top, $\Omega_\Lambda = 0.7$ and $\Omega_M = 0.3$; $\Omega_\Lambda = 0$ and $\Omega_M = 0.3$; and and $\Omega_M = 1$. The broken curve represents a nonaccelerating, flat Universe (i.e., $q = 0$ for ›ints above this curve indicate acceleration (adapted from data in Tonry *et al.*, 2003).

What is the origin of this cosmological constant?
What are the various scenarios?

http://www.nrao.edu/darkenergy 11/30/05