Dark Energy: Constraints from Astronomy, Answers from Physics?

Jim Condon

Constraining Dark Energy

Dark energy accounts for 70% of the mass of the Universe but is invisible (no electromagnetic interaction), smoothly distributed in space (no clustering), and (at most) slowly varying with time. It is detectable only because its repulsive gravity (negative pressure) accelerates the expansion of the Universe. However, this acceleration has a wide variety of observable consequences.

Friedmann Equations for Expansion

$$\left(\frac{\dot{a}}{a}\right)^2 = \left(\frac{8\pi G}{3c^2}\rho - k\frac{c^2}{a^2}\right)$$
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho + 3p).$$

a = distance between comoving objects (galaxies, wave crests,…)

(a_0 / a) is proportional to (1+z) = wavelength_{obs} / wavelength_{em}

k = 0 for our flat Universe (k = -1 is open, k = +1 is closed)

rho = *energy* (mc^2 for matter) density, p = pressure (can be < 0)

Both pressure and energy density are gravitationally active in GR

Good reference: Trodden & Carroll 2005, astro-ph/0401547

Beware c = 1 is dropped in most references

Current Expansion Rate

$$H \equiv \frac{\dot{a}}{a}$$

$$h \equiv \frac{H_0}{100 \text{ km s}^{-1} \text{ Mpc}^{-1}} \approx 0.72$$

$H_0 = 72 \pm 7$ km s^{-1} Mpc^{-1} observed for “nearby” galaxies (Freedman et al. 2001, ApJ, 553, 47)

1 Mpc = $3.086 \cdot 10^{19}$ km

$H_0 = 2.33 \cdot 10^{-18}$ s^{-1} $1/H_0$ = Hubble time = 13.6 Gyr
= age of empty ($\ddot{a} = 0$) universe

There is an “age problem” if objects older than the Universe exist (Carroll et al. 1992, ARA&A, 30, 499).

Critical Density

"Flat" universe ($k = 0$, $\Omega = 1$) implies a critical total density, which is an upper limit to the DE density much smaller than expected for a quantum vacuum (Weinberg 1989, Rev Mod Phys, 61, 1)

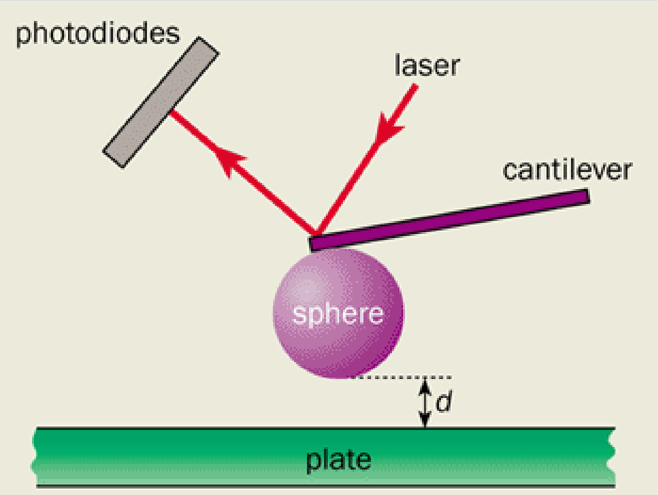
$$\left(\frac{\dot{a}}{a}\right)^2 = \left(\frac{8\pi G}{3c^2}\rho - k\frac{c^2}{a^2}\right)$$

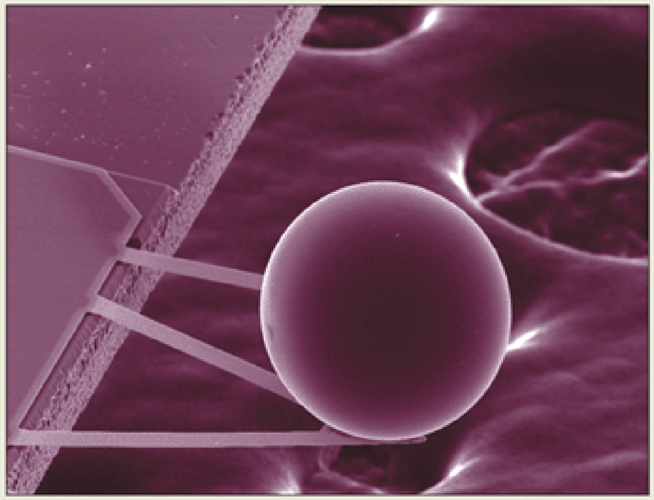
$$\rho_{\rm c} = \frac{3H_0^2c^2}{8\pi G} \approx 10^{-8}\ {\rm erg\ cm}^{-3}$$

$$\rho_{\rm c}/c^2 = \frac{3H_0^2}{8\pi G} \approx 1.0 \times 10^{-29}\ {\rm g\ cm}^{-3}$$

$$\Omega \equiv \frac{\rho}{\rho_{\rm c}}$$

Quantum Vacuum Energy Density





$$\rho_{\rm v} = \hbar \frac{k_{\rm max}^4}{16\pi^2} \approx 10^{92}\ {\rm g\ cm^{-3} c^2\ if\ E_{max}} \approx 10^{19}\ {\rm GeV}$$

$$p_{\rm c} = \frac{\hbar c \pi^2}{240 d^4}$$

Casimir pressure observed to d ~ 10^{-4} cm

(http://physicsweb.org/articles/world/15/9/6)

Conflict with observed Hubble constant?

Age Problem in an $\Omega_m = 1$ Universe

First hint of dark energy (Carroll & Turner, ARA&A, 30, 449

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

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho + 3p).$$

"Matter" defined by $p = 0$ yields "deceleration" only. If $\Omega = 1$, then $k = 0$ and $t_0 <$ age of oldest stars

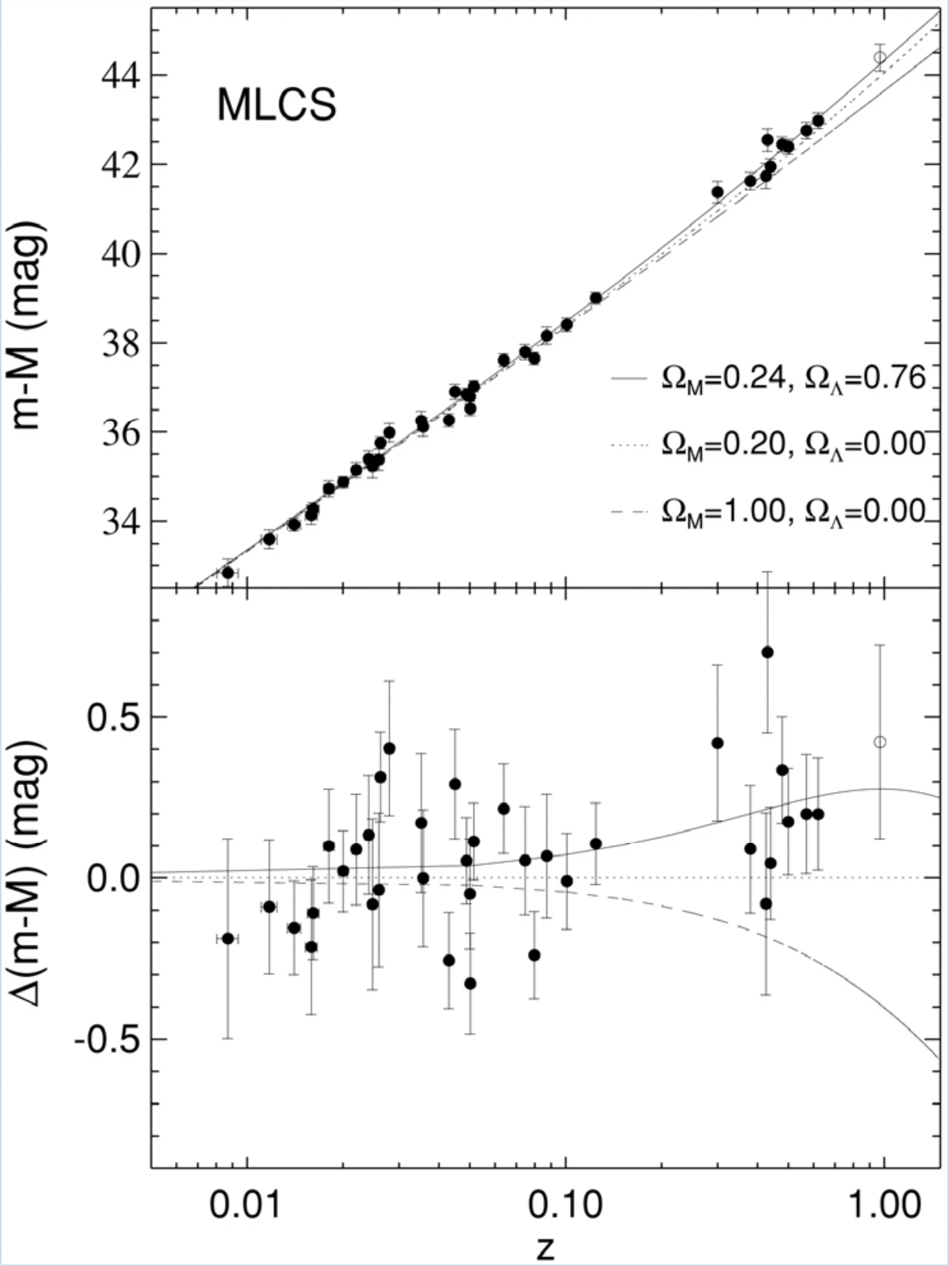
$$\frac{\ddot{a}}{a} = \frac{-\dot{a}^2}{2a^2}$$

$$a \propto t^{2/3} \qquad \dot{a} \propto t^{-1/3}$$

$$\frac{\dot{a}}{a} = H = \frac{2}{3t}$$

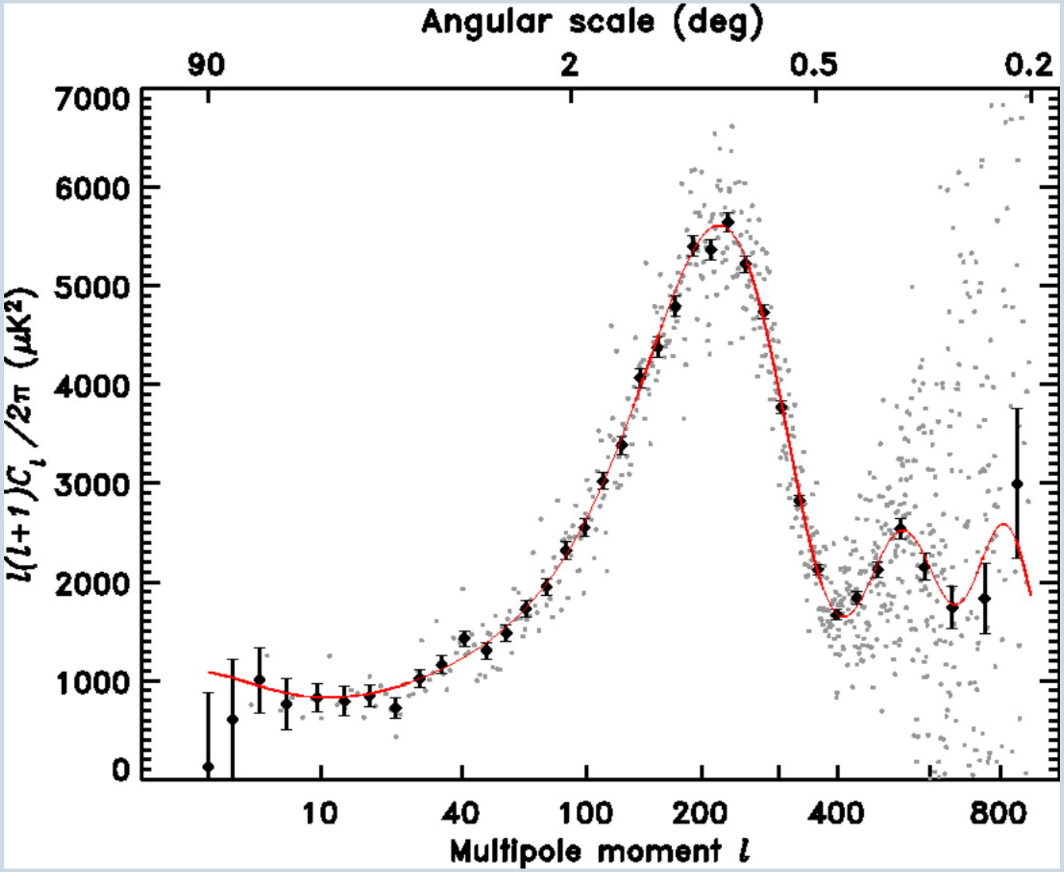
$$t_0 = \frac{2}{3H_0} \approx 9 \text{ Gyr}$$

SNe Ia as "relative" (depending on H_0) "standard candles" also suggest "acceleration" at moderate redshifts $z \sim 1$



The Riess et al. 1998, AJ, 116, 1009 'discovery paper' is probably correct, but the absolute luminosity depends on chemical composition of the collapsing white dwarf. The duration of the SN light curve is used to correct luminosity, reducing the scatter from 40% to 15% (see Trodden & Carroll 2005, astro-ph/0401547).

Baryonic Acoustic Oscillations



The first peak in the CMB TT power spectrum (Spergel et al. 2003, ApJS, 148, 175) is expected at $l = 220$ if the Universe is flat (see Trodden & Carroll 2005, astro-ph/0401547; Hu 2004, astro-ph/0407158). $\Omega_m \sim 0.3$ so $\Omega_{DE} \sim 0.7$.

Baryonic Acoustic Oscillations

The sound horizon provides an absolute (independent of H_0) standard ruler of length today

144 Mpc

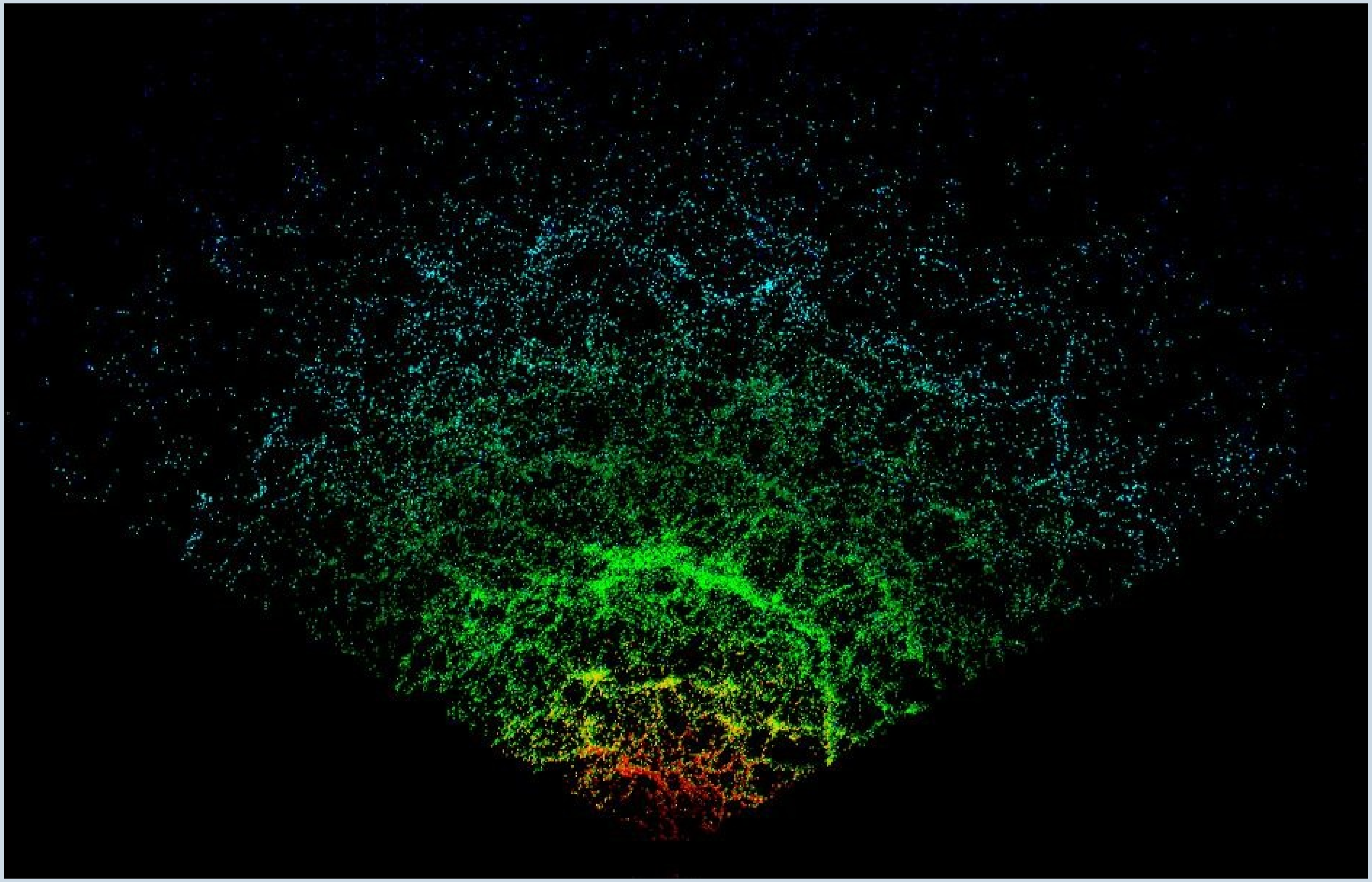
* (□lph$\tilde{a}$□lpha$_0$)$^{-1.36}$

* $(\Omega_m h^2)^{-0.252}$

* $(\Omega_b h^2)^{-0.083}$

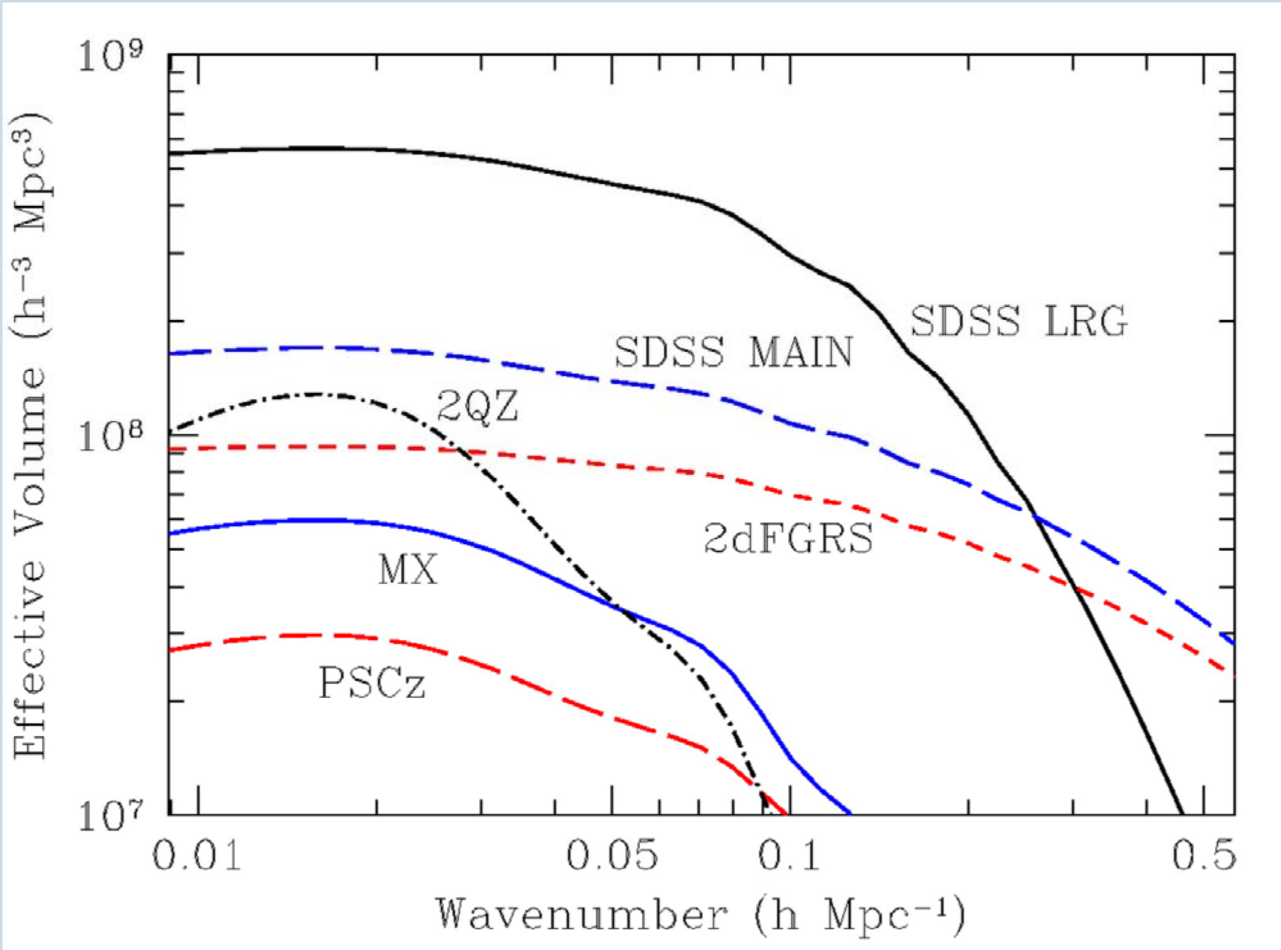
(Hu 2004, astro-ph/0407158)

Baryonic Acoustic Oscillations



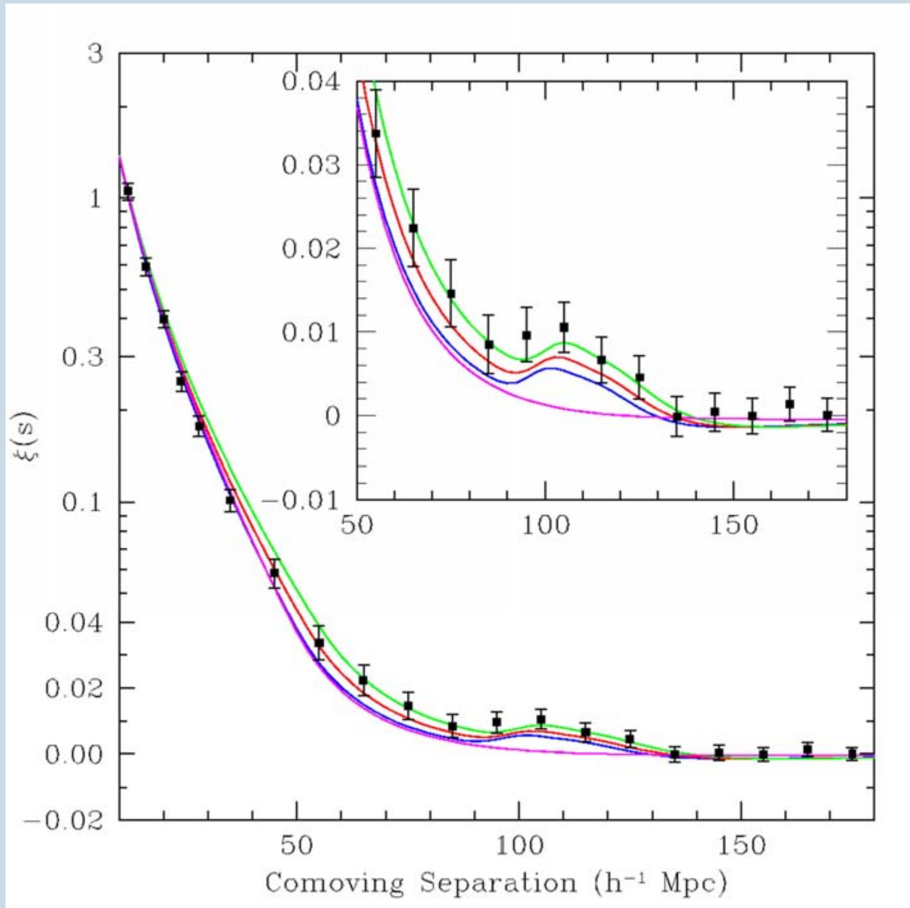
SDSS slice of the universe to $z = 0.47$
Eisenstein et al. 2005, ApJ, 633, 560

Baryonic Acoustic Oscillations



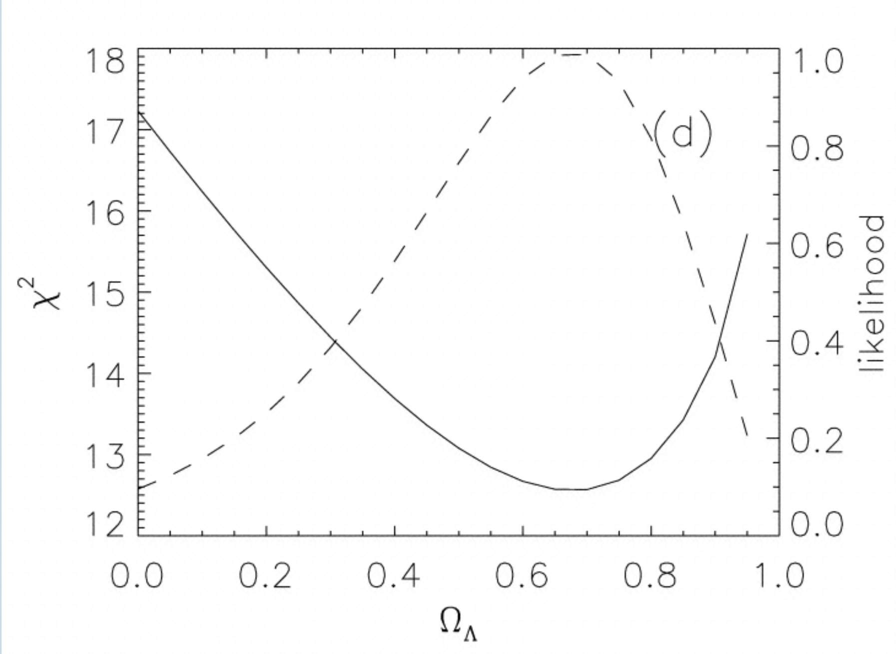
~ 700 volumes of $(100/h\ \mathrm{Mpc})^3$ give statistical rms ~ $(700)^{-0.5}$ ~ 4%

Baryonic Acoustic Oscillations



Measures *h* = 105 Mpc / 144 Mpc = 0.73 and the ratio of distances to *z* = 0.35 and *z* = 1089 to get $\square_m$ = 0.27.

Integrated Sachs-Wolfe effect



WMAP/NVSS position cross-correlation implies

$\Omega_{DE} = 0.68 \pm 0.22$ (Nolta et al. 2004, ApJ, 608, 10)

Structure Growth

Acceleration impedes the formation of massive structures (clusters of galaxies). Massive clusters can be detected and weighed because their gravity distorts (shears) the images of background galaxies. Extensive lensing surveys have been proposed to trace the evolution of dark energy (see Linder 2005, astro-ph/0501057). Also, surveys to detect clusters via the Sunyaev-Zeldovich effect.

Abell 2218

How to Get Acceleration?

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho + 3p).$$

Only the density and pressure are relevant. For each constituent of the Universe, define *w* = *p* / *rho*. For nonrelativistic matter, *w* = 0; for radiation, *w* = 1/3. To get acceleration, neither will do; we need something with sufficiently negative pressure: *w* < -1/3.

Conservation of stress-energy

$$\dot{\rho} + 3\left(\frac{\dot{a}}{a}\right)(\rho + p) = 0$$

$$\frac{\dot{\rho}}{\rho} + \frac{3\dot{a}}{a}(1 + w) = 0$$

$$\text{matter } w = 0 \to \rho \propto a^{-3}$$

$$\text{radiation } w = 1/3 \to \rho \propto a^{-4}$$

$$\text{constant vacuum energy} \, \dot{\rho} = 0 \to w = -1$$

Radiation dominates at early times (small *a*), then matter, and finally vacuum energy. See Trodden and Carroll 2005, astro-ph/0401547

Detectability at high redshifts

If the DE is vacuum energy, before $a/a_0 = (0.3/0.7)^{1/3}$ (z = 0.33) the matter density exceeded the vacuum density. At high redshifts (e.g., $z > 5$) the vacuum density was negligible (< 1%), but the ages of high-redshift sources still depend on the present Ω_{DE} and H_0. Thus the age of the z = 6.4 quasar is 800 Myr with DE and only 450 Myr without. (See Friaca et al. 2005, MNRAS, 362, 1295 for an example of the age problem with a quasar at z = 3.91)

Expansion History (flat universe)

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\rho$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2 a^3} \quad \rightarrow a \propto t^{2/3} \quad \text{(matter)}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2 a^4} \quad \rightarrow a \propto t^{1/2} \quad \text{(radiation)}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \text{constant} \quad \rightarrow a \propto \exp(Ht) \quad \text{(vacuum)}$$

$$\rho_{\text{vac}} = \frac{3H^2c^2}{8\pi G}, \quad H = H_0$$

What is the Dark Energy?

What is the value of *w* in the equation of state?

Does *w* vary with time ("dynamical" dark energy)?