Galaxy clustering and Baryon Acoustic Oscillations: status and prospects

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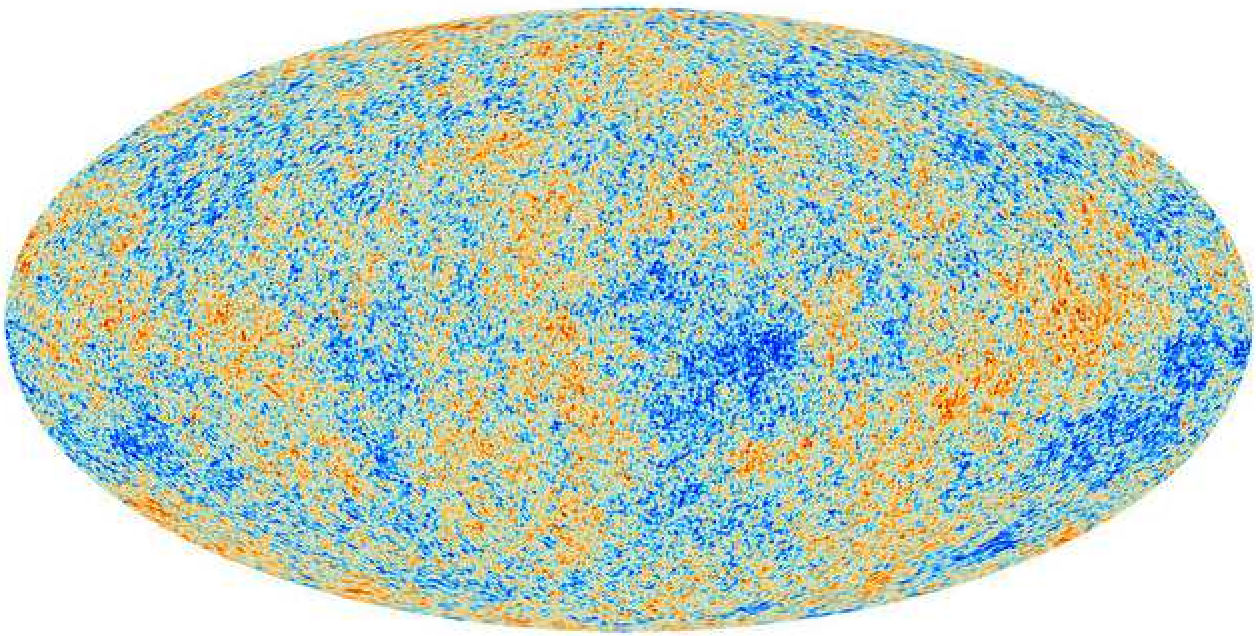
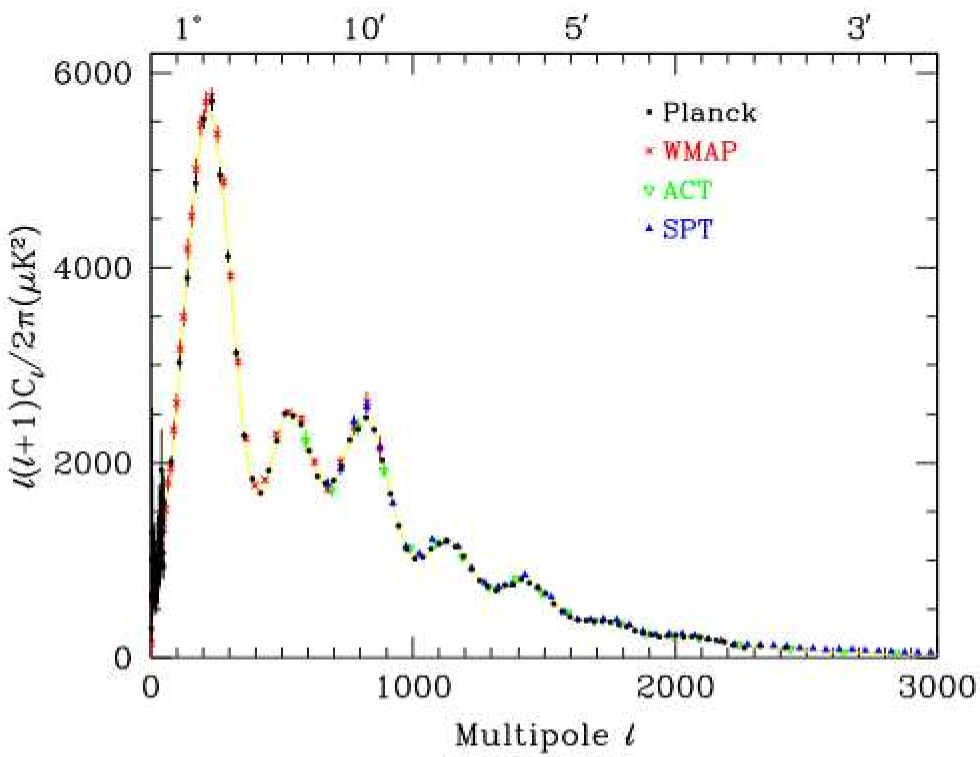
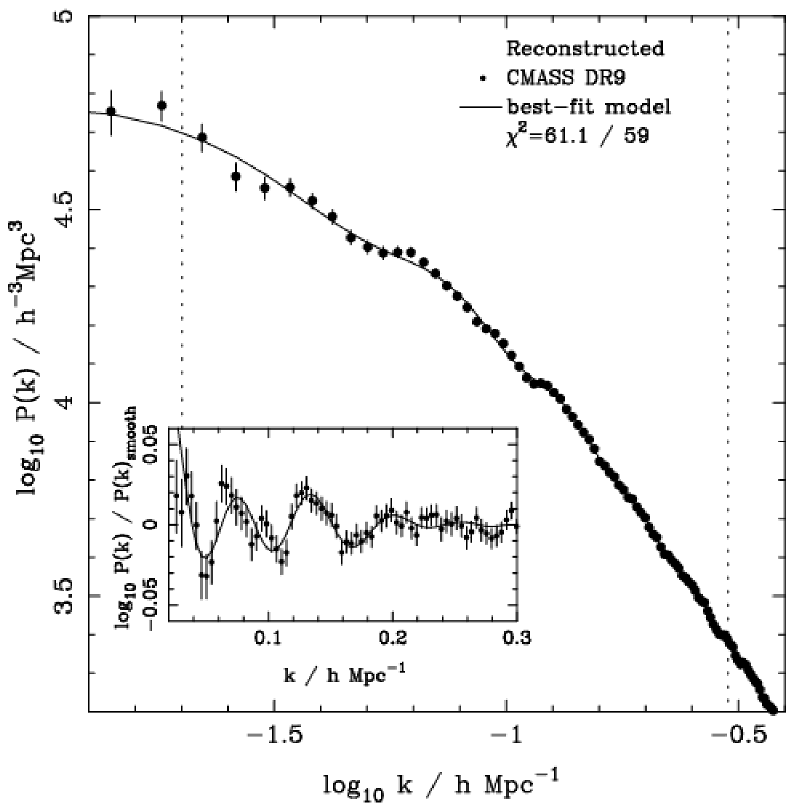
BAO as an uncalibrated standard ruler: Ω_k, $\Omega_{\text{DE}}(a)$, d_{BAO}, Ω_m



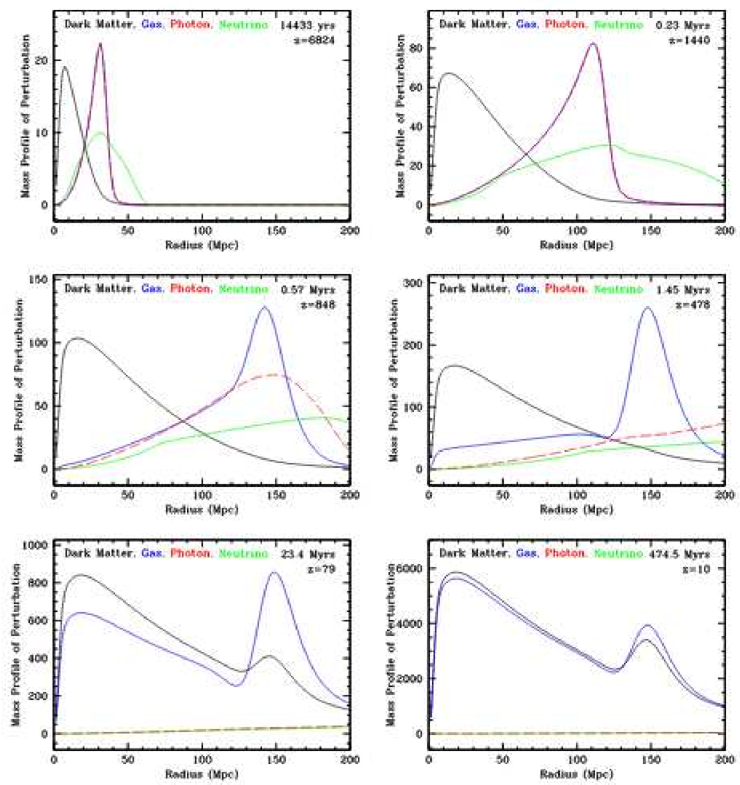
Fluctuations in the Cosmic Microwave Background (CMB) have a correlation angle $\theta_{\text{MC}} = 0.010410 \pm 0.000005$ ("Planck TT + low P + lensing", PDG 2016).



θ_{MC} is due to Baryon Acoustic Oscillations (BAO).



θ_{MC} corresponds to the galaxy-galaxy correlation distance $d' \equiv \frac{c}{H_0} d \approx 150$ Mpc, or $d \approx 0.034$, that can be used as a standard ruler. SDSS-III BOSS data.



An initial point density excess results in density excesses on spherical shells of radii ≈ 150 Mpc and ≈ 11 Mpc. Histograms of galaxy-galaxy distances have an excess in range $\approx 150 - 11$ Mpc to $\approx 150 + 11$ Mpc (from Eisenstein et al.).

The Friedmann equation:

$$\frac{1}{H_0}\frac{da}{adt} = E(a) \equiv \sqrt{\frac{\Omega_{\rm m}}{a^3} + \frac{\Omega_{\rm r}}{a^4} + \frac{\Omega_k}{a^2} + \Omega_{\rm DE}(a)}.$$

$$a(t_0) \equiv 1; \qquad E(1) \equiv 1; \qquad \Omega_{\rm m} + \Omega_{\rm r} + \Omega_k + \Omega_{\rm DE}(1) \equiv 1.$$

$$\Omega_{\rm m} = \Omega_{\rm d} + \Omega_{\rm b} \approx 0.25 + 0.05, \qquad \Omega_{\rm DE}(1) \approx 0.7, \qquad \Omega_k \approx 0.$$

$$a = \frac{1}{1+z}.$$

- Distance, in units of c/H_0, between two galaxies with z_1 and z_2 with $\alpha \approx 0$:

$$d_z = \chi(z_1) - \chi(z_2) \approx \frac{z_1 - z_2}{E(z)}.$$

- Distance, in units of c/H_0, between two galaxies with same z and angle α:

$$\begin{aligned} d_\alpha &= 2 d_A(z) \sin\left(\frac{\alpha}{2}\right), \\ d_A(z) &= \chi(z)\left(1 + \frac{1}{6}\Omega_k \chi^2(z)\right), \\ \chi(z) &\equiv \int_0^z \frac{dz'}{E(z')}. \end{aligned}$$

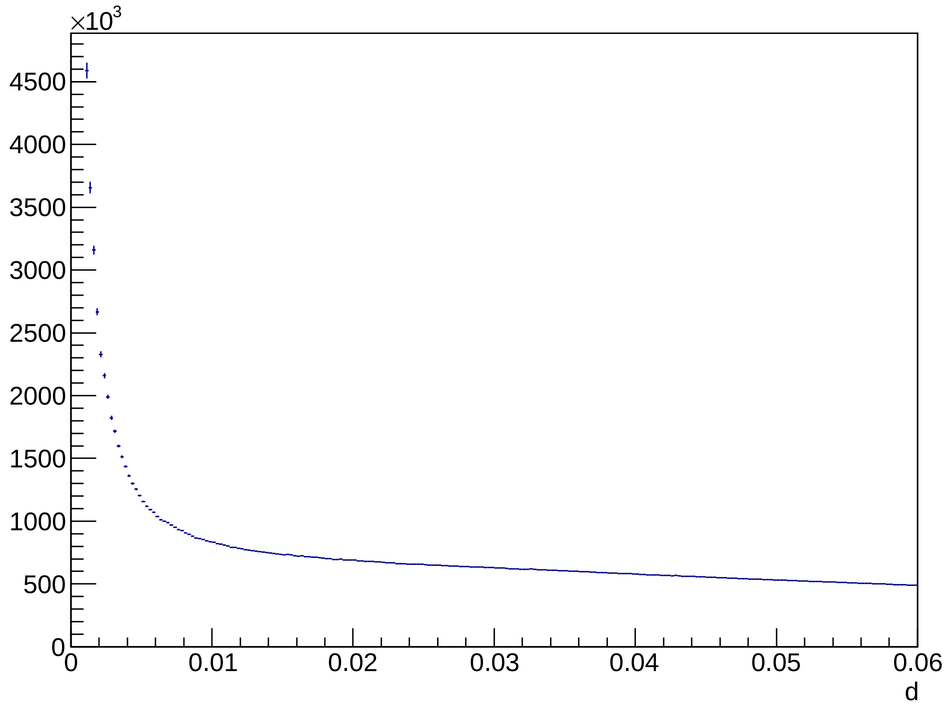
- Approximations that define a reference cosmology (these approximations are later undone for any set of cosmological parameters):

$$\chi(z) \approx z\,\mathrm{exp}\left(-\frac{z}{z_C}\right), \qquad \frac{1}{E(z)} \approx \left(1-\frac{z}{z_C}\right)\mathrm{exp}\left(-\frac{z}{z_C}\right), \qquad \text{for } 0 \le z < 1.$$

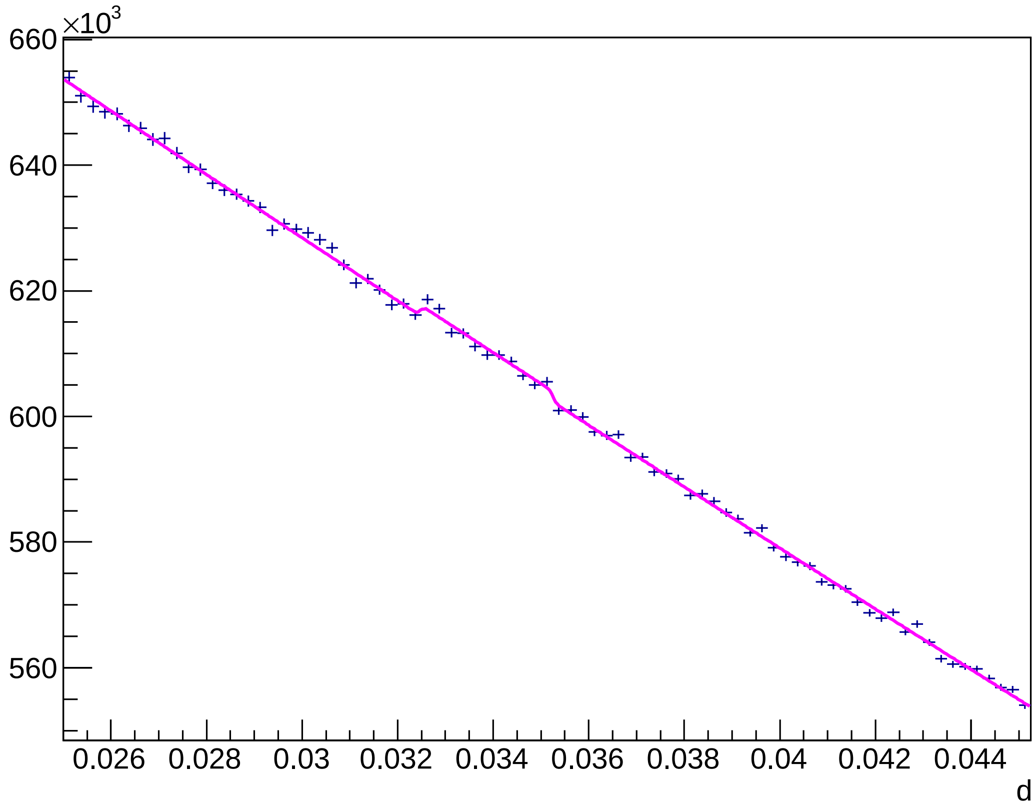
- If $d_z(z, z_C)/d_\alpha(z, z_C) < 1/3$ fill a histogram of $d(z, z_C)$ that obtains a BAO signal centered at $\widehat{d}_\alpha(z, z_C)$.

- If $d_\alpha(z, z_C)/d_z(z, z_C) < 1/3$ fill a second histogram of $d(z, z_C)$ that obtains a BAO signal centered at $\widehat{d}_z(z, z_C)$.

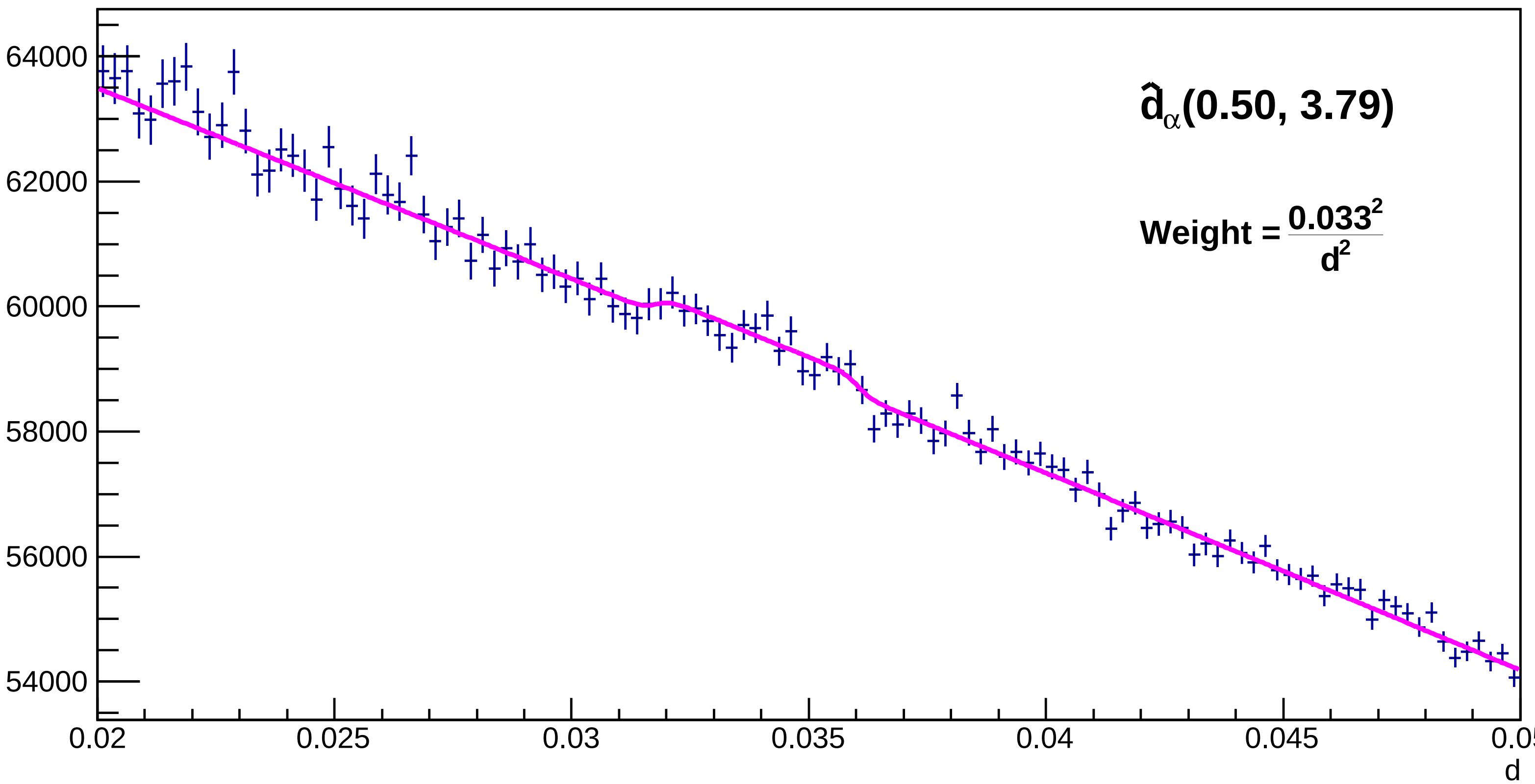
- Else, fill a third histogram of $d(z, z_C)$ that obtains a BAO signal centered at $\widehat{d}_/(z, z_C)$.



Distribution of galaxy-galaxy distances $d(z, z_c)$, with weight $0.033^2/d^2$, of pairs with $d_z(z, z_c) < d_\alpha(z, z_c)/3$ and $0.5 < z < 0.6$ from the Sloan Digital Sky Survey (SDSS) DR13.



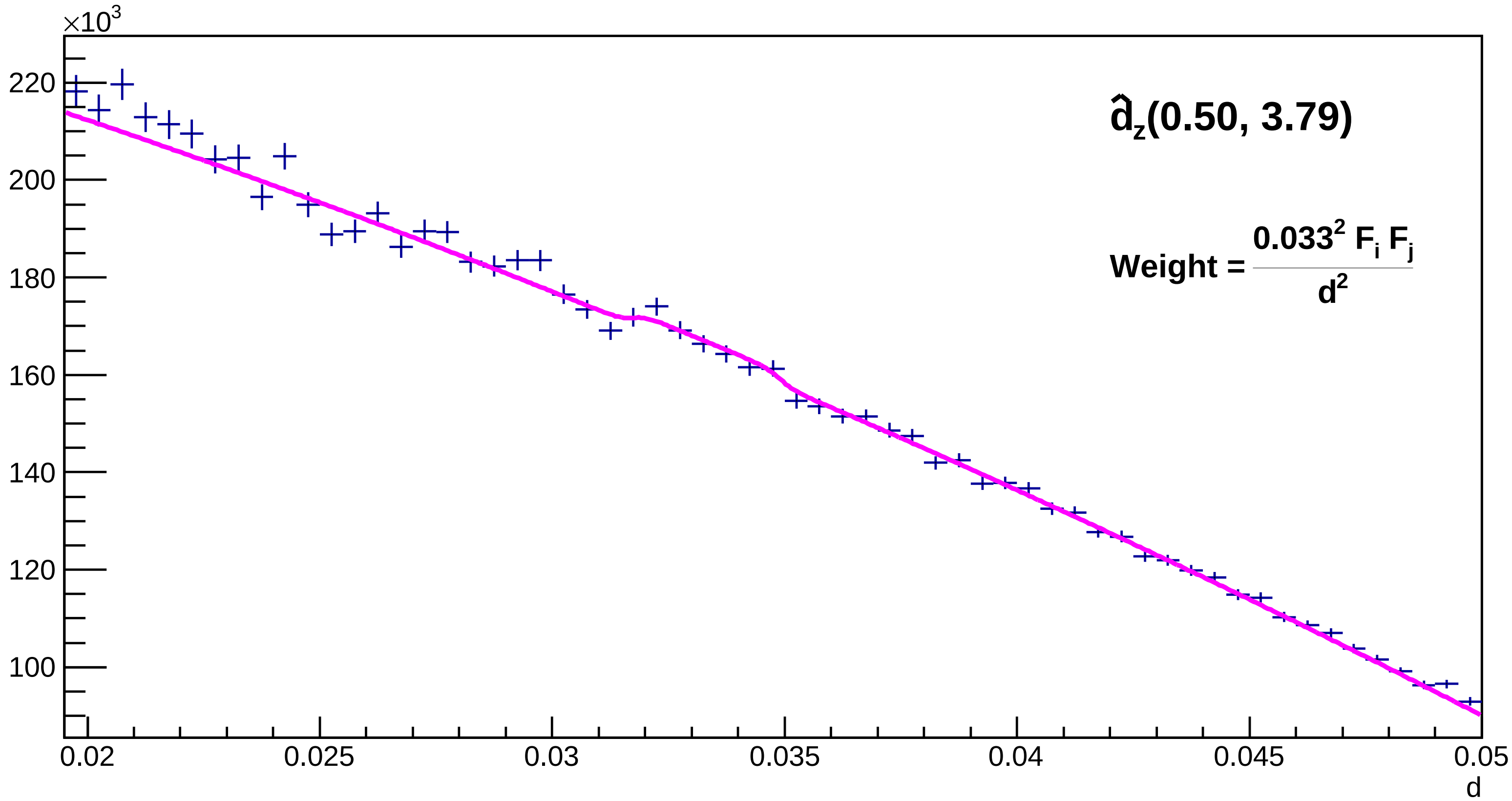
Detail of previous figure. The fit determines $\hat{d}_\alpha(0.54, 3.79)$.



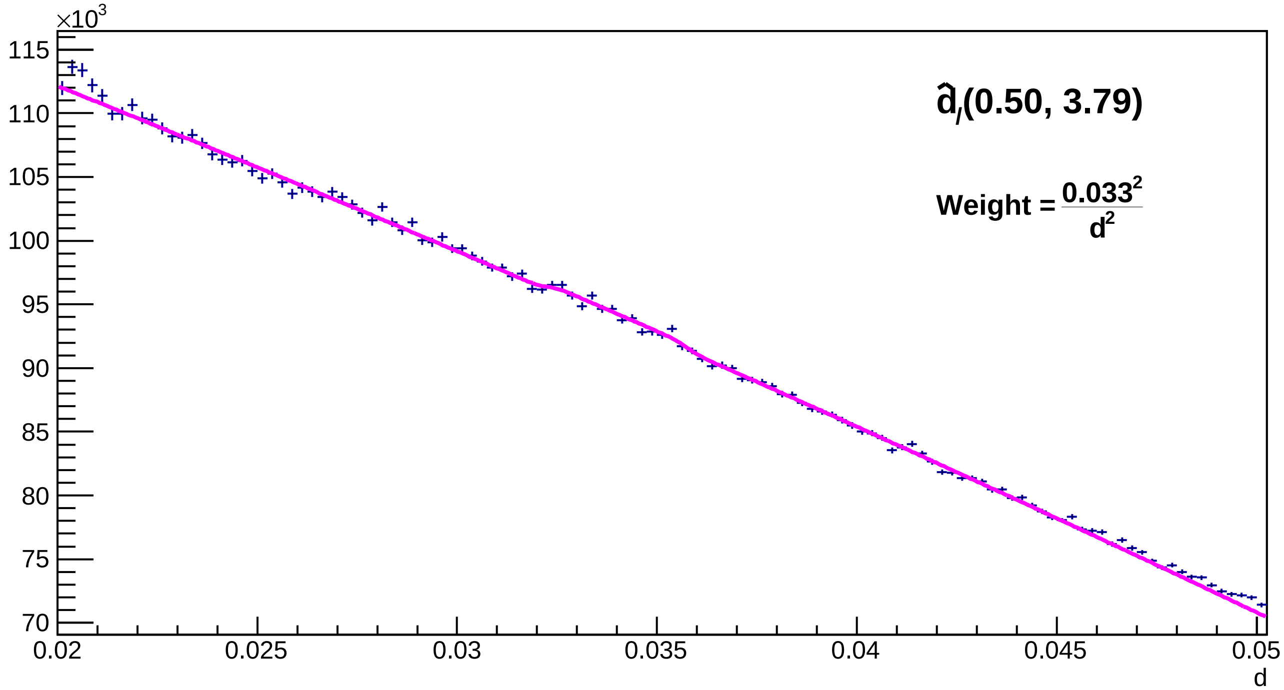
Another example of d_α. Note characteristic steps at ≈ 0.031 and ≈ 0.036.

Dark matter follows the BAO wave. The result, well after decoupling, for an initial point-like peak in the density, are two concentric shells of overdensity of radius ≈ 150 Mpc and ≈ 11 Mpc (from simulations by Eisenstein et al.). So the BAO signal in galaxy-galaxy distance histograms extends from $d' \approx 150 - 11$ to $\approx 150 + 11$ Mpc, or

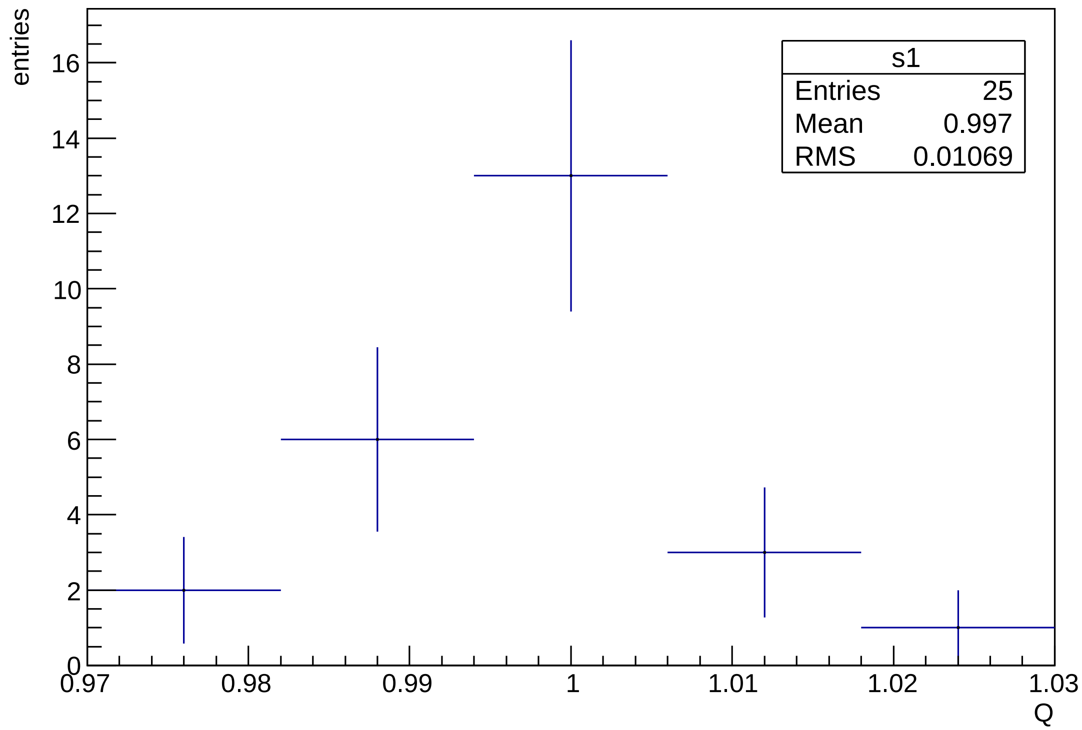
$$d \equiv d' H_0 / c \approx 0.0314 \text{ to } 0.0364!!!$$



An example of d_z.



An example of $d_/$. All individual measurements are marginal (significance of amplitude of fit $> 1\sigma$) so redundancy is needed: consistent d_α, d_z and $d_/$ triplets ($0.97 < Q < 1.03$), $G - G$, $G - LG$ and $G - C$ measurements, separate N and S galactic cap measurements, in each bin of z.



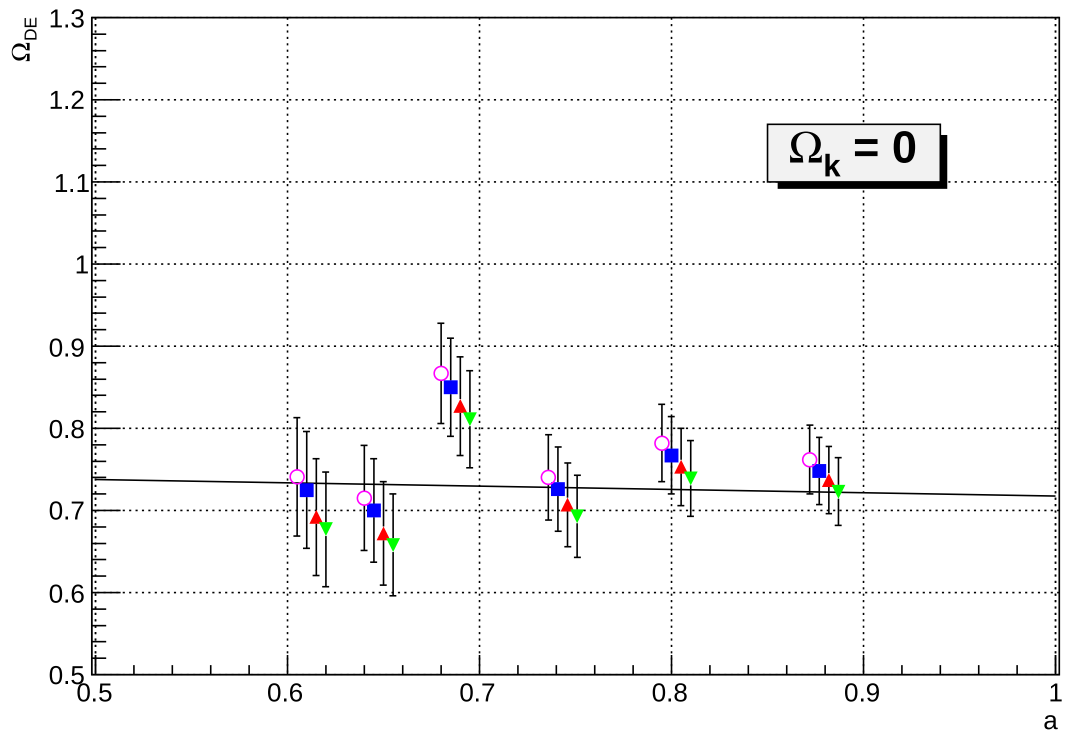
The independent measurements of d_α, d_z and $d_/$ satisfy the consistency relation $Q \equiv \frac{d_/}{d_\alpha^{0.567} d_z^{0.433}} = 1$, shown for 25 triplets.

Examples of measurements of $\hat{d}_\alpha(z, z_c)$, $\hat{d}_z(z, z_c)$ and $\hat{d}_/(z, z_c)$, in units of c/H_0, with $0.60 < z < 0.70$, in the northern/southern galactic caps. The systematic uncertainty is ± 0.00055 for $\hat{d}_\alpha(z, z_c)$ and $\hat{d}_/(z, z_c)$, and ± 0.00093 for $\hat{d}_z(z, z_c)$. SDSS DR13 data.

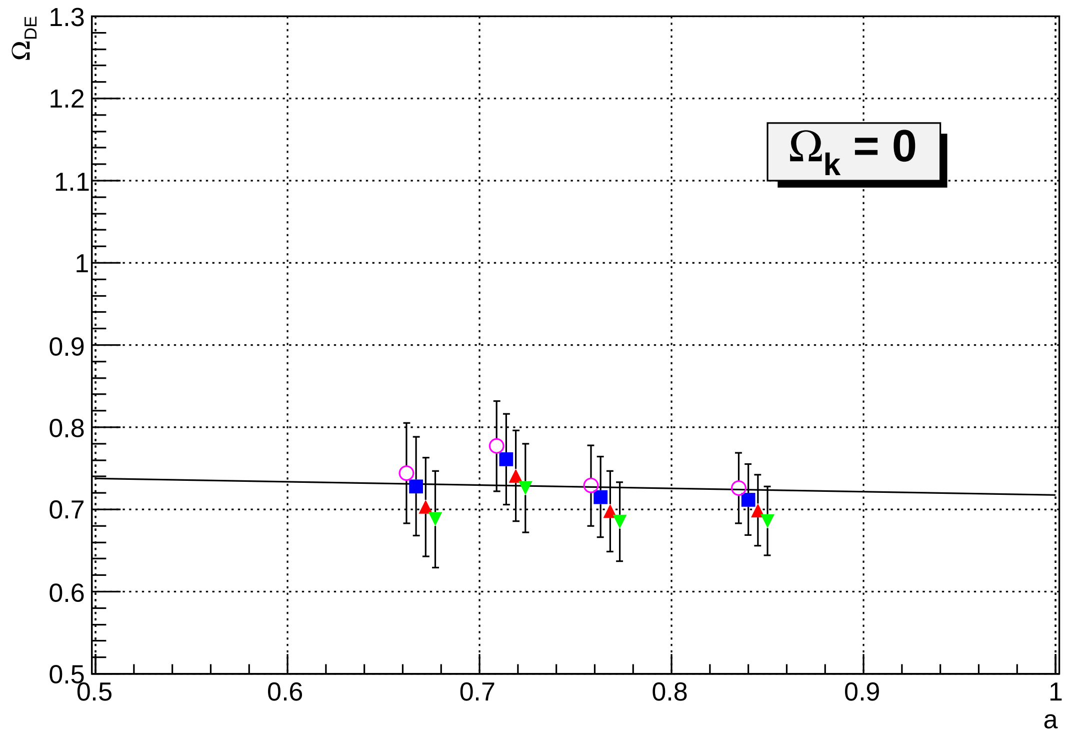
z	z_{min}	z_{max}	galaxies	centers	type	$\hat{d}_\alpha(z, z_c) \times 100$	$\hat{d}_z(z, z_c) \times 100$	$\hat{d}_/(z, z_c) \times 100$
0.64	0.6	0.7	81624	81624	G-G	3.368 ± 0.014	3.572 ± 0.021	3.439 ± 0.012
0.64	0.6	0.7	81624	33982	G-LG	3.378 ± 0.009	3.586 ± 0.016	3.481 ± 0.009
0.64	0.6	0.7	53518	53518	G-G	3.424 ± 0.015	3.327 ± 0.019	3.373 ± 0.016
0.64	0.6	0.7	53518	23384	G-LG	3.393 ± 0.017	3.427 ± 0.028	3.373 ± 0.019
0.64	0.6	0.7	53518	941	G-C	3.349 ± 0.014	3.316 ± 0.046	3.346 ± 0.020
0.64	0.6	0.7	23384	23384	LG-LG	3.446 ± 0.016	3.371 ± 0.026	3.381 ± 0.015
0.64	0.6	0.7	53518	689	G-C	3.416 ± 0.020	3.317 ± 0.021	3.316 ± 0.036

Summary of measurements of distances $\hat{d}_\alpha(z, z_c)$, $\hat{d}_z(z, z_c)$ and $\hat{d}_/(z, z_c)$, in units of c/H_0. Chosen triplets are those with least $|Q - 1|$. The total uncertainties are ± 0.00030 for $\hat{d}_\alpha(z, z_c)$ and $\hat{d}_/(z, z_c)$, and ± 0.00060 for $\hat{d}_z(z, z_c)$. $z_c = 3.79$. SDSS DR13 data.

z	$z_{\rm min}$	$z_{\rm max}$	$100\hat{d}_\alpha(z, z_c)$	$100\hat{d}_z(z, z_c)$	$100\hat{d}_/(z, z_c)$
0.14	0.1	0.2	3.376	3.375	3.363
0.25	0.2	0.3	3.311	3.381	3.360
0.35	0.3	0.4	3.354	3.320	3.350
0.46	0.4	0.5	3.323	3.445	3.369
0.55	0.5	0.6	3.338	3.293	3.300
0.64	0.6	0.7	3.349	3.316	3.346



Measurements of $\Omega_{\mathrm{DE}}(a)$ obtained from $\hat{d}_z(z, z_c)$, for $\pm 1\sigma$ choices of $(d_{\mathrm{BAO}}, \Omega_{\mathrm{DE}})$.



Measurements of $\Omega_{\text{DE}}(a)$ in offset bins of a.

Results from 18 BAO measurements in $0.1 < z < 0.7$ with SDSS DR13 data, 2 BAO measurements in the Lyman-alpha forest (cross-correlation at $z = 2.36$, and auto-correlation at $z = 2.34$), and θ_{MC} of the CMB. Scenarios shown are:
1 has Ω_{DE} constant.
4 has $\Omega_{DE}(a) = \Omega_{DE}[1 + w_1(1 - a)]$.

	1	1	4	4
Ω_k	0 fixed	0.002 ± 0.007	0 fixed	-0.015 ± 0.030
$\Omega_{DE} + 2.2\Omega_k$	0.719 ± 0.003	0.718 ± 0.004	0.718 ± 0.004	0.717 ± 0.004
w_1	n.a.	n.a.	0.06 ± 0.15	0.37 ± 0.61
$d_{BAO} \times 100$	3.40 ± 0.02	3.39 ± 0.02	3.39 ± 0.03	3.37 ± 0.05
χ^2/d.f.	11.2/17	11.2/16	11.1/16	10.8/15

For comparison, for $\Omega_k = 0$, and Ω_{DE} constant, $\Omega_{DE} = 0.692 \pm 0.012$ ["Planck TT + low P + lensing", PDG 2016]. These results are independent.

BAO as a calibrated standard ruler: h, $\Omega_b h^2$, $N_{\rm eff}$

The sound horizon is calculated from first principles as follows:

$$r'_S \equiv \frac{c}{H_0} r_S = \int_0^{t_{\rm dec}} \frac{c_s dt}{a} = \int_0^{a_{\rm dec}} \frac{c_s da}{H_0 a^2 E(a)},$$

where the speed of sound is

$$c_s = \frac{c}{\sqrt{3(1 + 3\rho_{b0} a/(4\rho_{\gamma 0}))}}.$$

We can write the result for our purposes as

$$r_S = 0.03389 \times A \times \left(\frac{0.30}{\Omega_{\rm m}}\right)^{0.255},$$

where, assuming $m_\nu = 0$,

$$A = \left(\frac{h}{0.72}\right)^{0.489} \left(\frac{0.023}{\Omega_{\rm b} h^2}\right)^{0.098} \left(\frac{3.36}{N_{\rm eq}}\right)^{0.245}.$$

Setting $d = r_s$ (calibrated BAO), we obtain:

$$\Omega_k = -0.013 \pm 0.009, \qquad \Omega_{\mathsf{DE}} + 2.2\Omega_{\mathsf{k}} = 0.717 \pm 0.004,$$
$$w_1 = 0.34 \pm 0.24, \qquad A = 0.965 \pm 0.014,$$

For $\Omega_{\mathsf{b}} h^2 = 0.0225 \pm 0.0008$, and $h = 0.720 \pm 0.030$ we obtain $N_{\mathsf{eff}} = 4.2 \pm 0.9$ active neutrino flavors ($N_{\mathsf{eq}} = 2 + 0.454 N_{\mathsf{eff}}$).

For $\Omega_k = 0$ and Ω_{DE} constant, we obtain:

$$A = 0.9855 \pm 0.0012. \tag{1}$$

For $\Omega_{\mathsf{b}} h^2 = 0.02226 \pm 0.00023$, and $h = 0.678 \pm 0.009$ we obtain $N_{\mathsf{eff}} = 2.64 \pm 0.20$ active neutrino flavors.

BAO as a calibrated standard ruler: m_ν

We now assume 3 active Dirac or Majorana neutrino eigenstates with degenerate mass m_ν: $\sum m_\nu = 3m_\nu$. We assume $\Omega_k = 0$ and Ω_{DE} constant. We obtain $d \approx 0.0340 \pm 0.0002$, and

$$r_s \approx 0.0339 \times A \times \left(\frac{0.28}{\Omega_m}\right)^{0.24}$$

with

$$A \approx 0.990 + 0.007 \cdot \delta h - 0.001 \cdot \delta b + 0.020 \cdot \frac{\sum m_\nu}{1\text{eV}},$$

where

$$\begin{aligned} \delta h &\equiv (h - 0.678)/0.009, \\ \delta b &\equiv (\Omega_b h^2 - 0.02226)/0.00023. \end{aligned}$$

Setting $r_s = d$ (calibrated standard ruler) we obtain

$$\sum m_\nu \approx 0.73 - 0.35 \cdot \delta h + 0.05 \cdot \delta b \pm 0.15 \text{ eV}.$$

Due to correlations and non-linearities, a more precise result is obtained with a global fit by minimizing the χ^2 with 21 terms (18 BAO, θ_{MC}, 2 Lyα) varying Ω_{DE} and $\sum m_\nu$ directly. We obtain $\Omega_{DE} = 0.7175 \pm 0.0023$ and

$$\sum m_\nu = 0.711 - 0.335 \cdot \delta h + 0.050 \cdot \delta b \pm 0.063 \text{ eV},$$

with $\chi^2/\text{d.f.} = 19.9/19$.

This result, obtained from BAO measurements alone, may be combined with independent constraints on the cosmological parameters $\sum m_\nu$, h and $\Omega_b h^2$, such as measurements of the power spectrum of density fluctuations $P(k)$, the CMB, and direct measurements of the Hubble parameter.

... to be continued on Wednesday 27 June

References

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	This BAO analysis	PDG 2018
Ω_Λ	0.719 ± 0.003	0.692 ± 0.012
Ω_k	0.002 ± 0.007	$-0.005^{+0.008}_{-0.009}$
d'_{BAO}	$(150.3 \pm 0.9) \times \frac{0.678}{h}$ Mpc	144.9 ± 0.4 Mpc
N_{eff} $(m_\nu = 0)$	2.64 ± 0.20 $(h = 0.678)$	3.13 ± 0.32
	4.2 ± 0.9 $(h = 0.720)$	
$\sum m_\nu$	$0.711 - 0.335 \cdot \delta h$ $+ 0.050 \cdot \delta b \pm 0.063$ eV	< 0.68 eV, 95% conf.

Comparison of this BAO analysis with PDG 2018 (mostly CMB, Planck collab. (2015)). 68% confidence. $\delta h \equiv (h - 0.678)/0.009$. $\delta b \equiv (\Omega_b h^2 - 0.02226)/0.00023$. (See references for details.)