Physical Sciences 120
Winter 2005

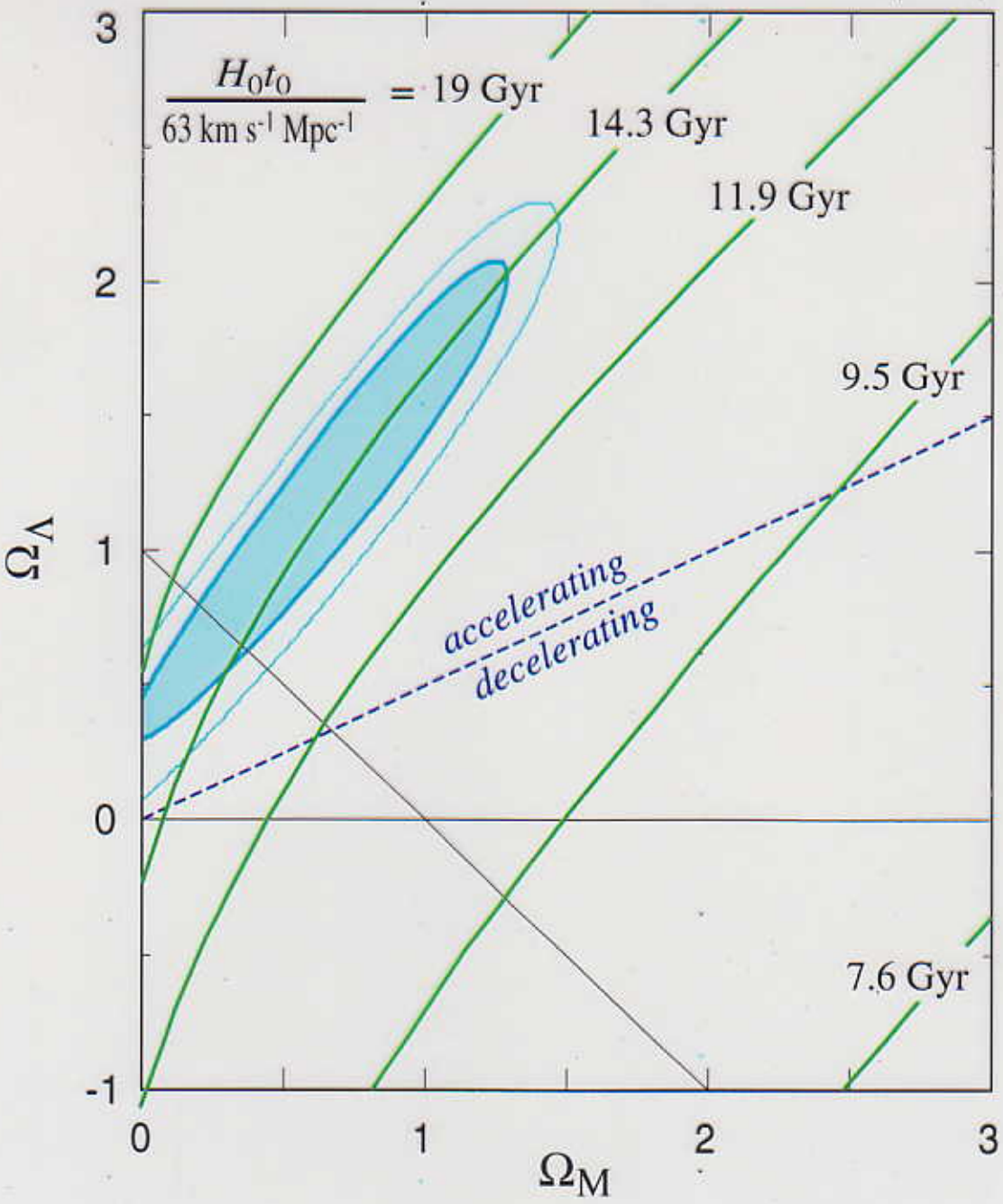
Origin of the Universe,
and How We Know

Don Q. Lamb

Lecture 24

DARK ENERGY

Supernova Cosmology Project
Perlmutter *et al.* (1998)



Best fit age of universe: $t_o = 14.5 \pm 1\ \ (0.63/h)$ Gyr

Best fit in flat universe: $t_o = 14.9 \pm 1\ \ (0.63/h)$ Gyr

www–supernova.LBL.gov

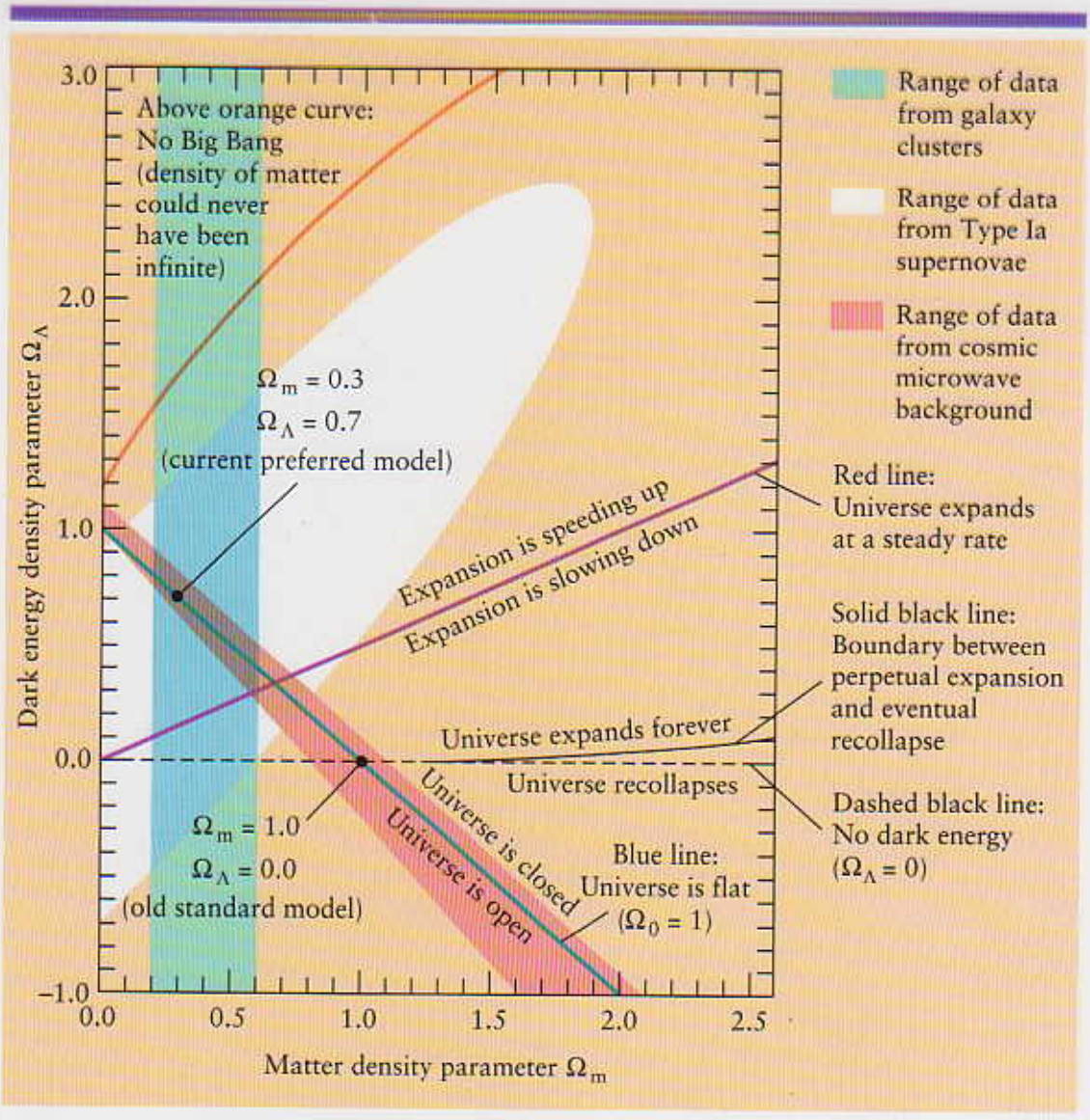
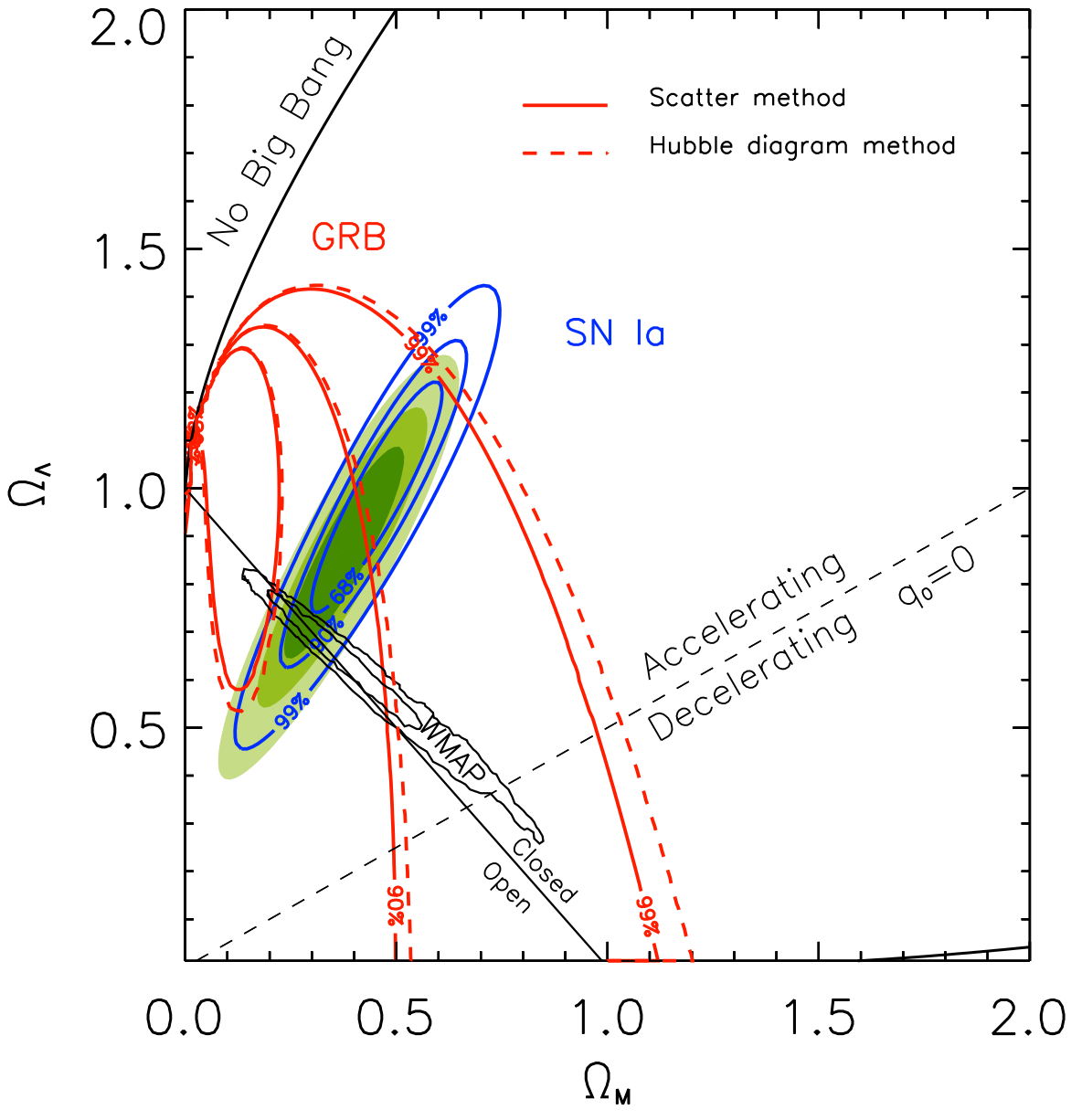


Figure 28-19


2.0
1.5
1.0
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0.5
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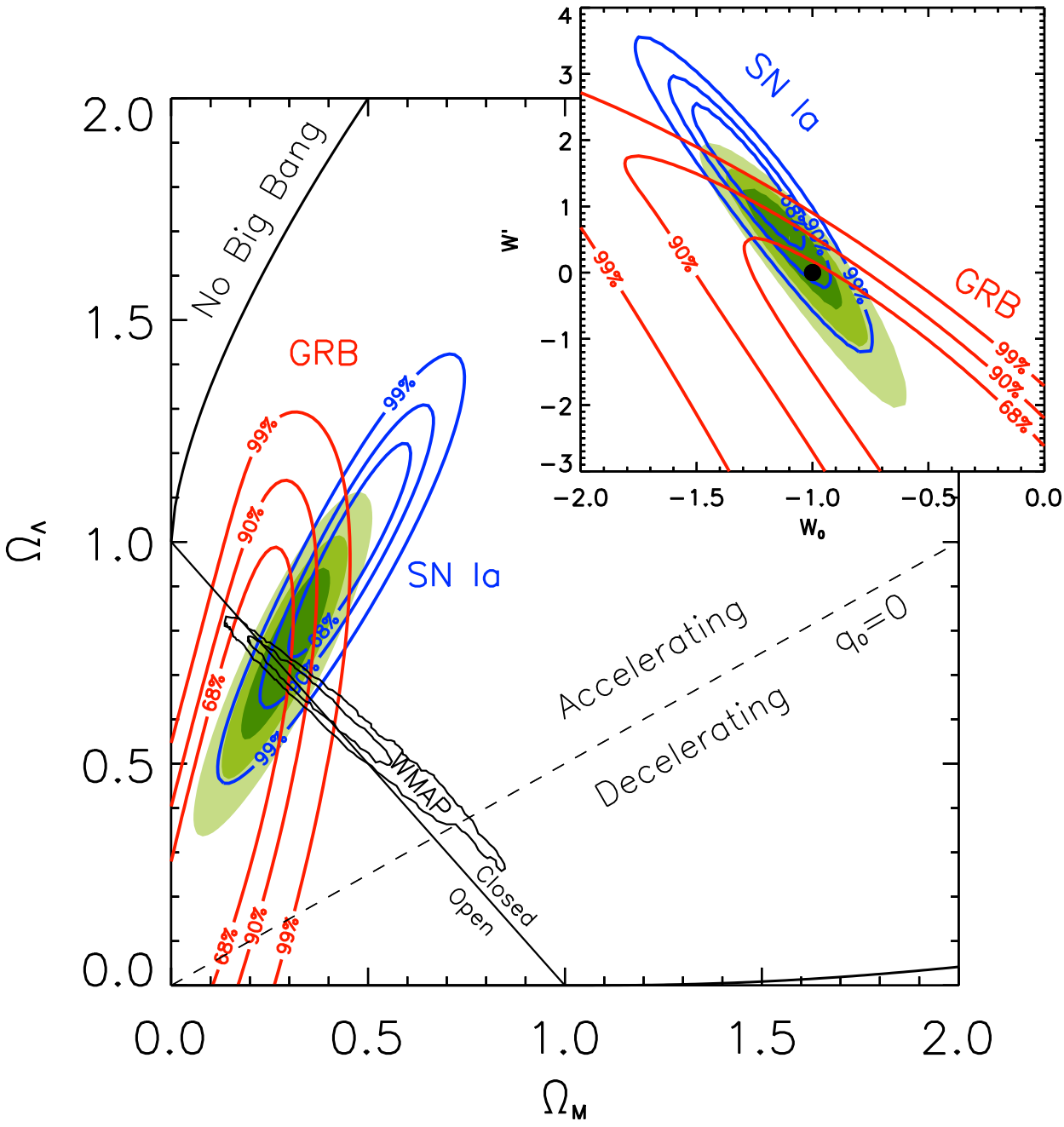
Ω_Λ
Ω_M
No Big Bang
Scatter method
Hubble diagram method
GRB
SN Ia
99%
68%
90%
99%
68%
99%
90%
99%
WMAP
Closed
Open
Accelerating
Decelerating
q_0=0


No Big Bang
GRB
SN Ia
WMAP
Closed
Open
Accelerating
Decelerating
q_0=0
99%
90%
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Ω_Λ
Ω_M
0.0
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SN Ia
GRB
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−2.0
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−1.0
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−1
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−3

Table 1. Power Law ΛCDM Model Parameters- *WMAP* Data Only

Parameter		Mean (68% confidence range)	Maximum Likelihood
Baryon Density	$\Omega_b h^2$	0.024 ± 0.001	0.023
Matter Density	$\Omega_m h^2$	0.14 ± 0.02	0.15
Hubble Constant	h	0.72 ± 0.05	0.68
Amplitude	A	0.9 ± 0.1	0.80
Optical Depth	τ	$0.166^{+0.076}_{-0.071}$	0.11
Spectral Index	n_s	0.99 ± 0.04	0.97
	χ^2_{eff}/ν		1431/1342

[a]Fit to *WMAP* data only

Table 2. Derived Cosmological Parameters

Parameter	Mean (68% confidence range)
Amplitude of Galaxy Fluctuations	$\sigma_8 = 0.9 \pm 0.1$
Characteristic Amplitude of Velocity Fluctuations	$\sigma_8 \Omega_m^{0.6} = 0.44 \pm 0.10$
Baryon Density/Critical Density	$\Omega_b = 0.047 \pm 0.006$
Matter Density/Critical Density	$\Omega_m = 0.29 \pm 0.07$
Age of the Universe	$t_0 = 13.4 \pm 0.3$ Gyr
Redshift of Reionization[b]	$z_r = 17 \pm 5$
Redshift at Decoupling	$z_{dec} = 1088^{+1}_{-2}$
Age of the Universe at Decoupling	$t_{dec} = 372 \pm 14$ kyr
Thickness of Surface of Last Scatter	$\Delta z_{dec} = 194 \pm 2$
Thickness of Surface of Last Scatter	$\Delta t_{dec} = 115 \pm 5$ kyr
Redshift at Matter/Radiation Equality	$z_{eq} = 3454^{+385}_{-392}$
Sound Horizon at Decoupling	$r_s = 144 \pm 4$ Mpc
Angular Diameter Distance to the Decoupling Surface	$d_A = 13.7 \pm 0.5$ Gpc
Acoustic Angular Scale[c]	$\ell_A = 299 \pm 2$
Current Density of Baryons	$n_b = (2.7 \pm 0.1) \times 10^{-7}$ cm^{-3}
Baryon/Photon Ratio	$\eta = (6.5^{+0.4}_{-0.3}) \times 10^{-10}$

[a]Fit to the *WMAP* data only

[b]Assumes ionization fraction, $x_e = 1$

[c] $l_A = \pi d_A / r_s$

Table 10. Basic and Derived Cosmological Parameters: Running Spectral Index Model[a]

	Mean and 68% Confidence Errors
Amplitude of fluctuations	$A = 0.83^{+0.09}_{-0.08}$
Spectral Index at $k = 0.05$ Mpc^{-1}	$n_s = 0.93 \pm 0.03$
Derivative of Spectral Index	$dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$
Hubble Constant	$h = 0.71^{+0.04}_{-0.03}$
Baryon Density	$\Omega_b h^2 = 0.0224 \pm 0.0009$
Matter Density	$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$
Optical Depth	$\tau = 0.17 \pm 0.06$
Matter Power Spectrum Normalization	$\sigma_8 = 0.84 \pm 0.04$
Characteristic Amplitude of Velocity Fluctuations	$\sigma_8 \Omega_m^{0.6} = 0.38^{+0.04}_{-0.05}$
Baryon Density/Critical Density	$\Omega_b = 0.044 \pm 0.004$
Matter Density/Critical Density	$\Omega_m = 0.27 \pm 0.04$
Age of the Universe	$t_0 = 13.7 \pm 0.2$ Gyr
Reionization Redshift[b]	$z_r = 17 \pm 4$
Decoupling Redshift	$z_{dec} = 1089 \pm 1$
Age of the Universe at Decoupling	$t_{dec} = 379^{+8}_{-7}$ kyr
Thickness of Surface of Last Scatter	$\Delta z_{dec} = 195 \pm 2$
Thickness of Surface of Last Scatter	$\Delta t_{dec} = 118^{+3}_{-2}$ kyr
Redshift of Matter/Radiation Equality	$z_{eq} = 3233^{+194}_{-210}$
Sound Horizon at Decoupling	$r_s = 147 \pm 2$ Mpc
Angular Diameter Distance to the Decoupling Surface	$d_A = 14.0^{+0.2}_{-0.3}$ Gpc
Acoustic Angular Scale[c]	$\ell_A = 301 \pm 1$
Current Density of Baryons	$n_b = (2.5 \pm 0.1) \times 10^{-7}$ cm^{-3}
Baryon/Photon Ratio	$\eta = (6.1^{+0.3}_{-0.2}) \times 10^{-10}$

[a]Fit to the *WMAP* , CBI, ACBAR, 2dFGRS and Lyman α forest data

[b]Assumes ionization fraction, $x_e = 1$

[c] $l_A = \pi d_A / r_s$