Extra-galactic Astronomy - I
Cosmology

Tirthankar Roy Choudhury
National Centre for Radio Astrophysics, Pune

Lecture 06
IUCAA-NCRA Graduate School
NCRA
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Standard model of cosmology

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- Radiation

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- Radiation
- Baryons

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- (Cold) Dark Matter

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- Spatial curvature $\Omega_k \approx 0$
- Hubble parameter

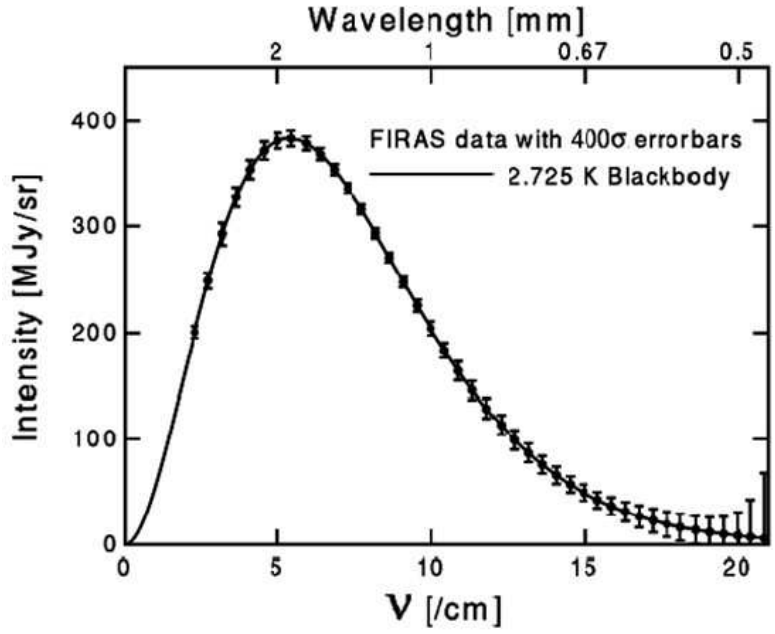
$$\frac{H^2(z)}{H_0^2} = \Omega_{r,0}(1+z)^4 + \Omega_{b,0}(1+z)^3 + \Omega_{\mathrm{DM},0}(1+z)^3 + \Omega_\Lambda + \Omega_{k,0}(1+z)^2$$

where $\Omega_{k,0} = 1 - \Omega_{r,0} - \Omega_{b,0} - \Omega_{\mathrm{DM},0} - \Omega_\Lambda$.
Convenient to use $\Omega_{m,0} = \Omega_{b,0} + \Omega_{\mathrm{DM},0}$.

Radiation (CMB)

- We observe a blackbody radiation (CMBR) at a temperature of 2.73 K, hence the corresponding energy density is

$$\rho_r = a_B T^4 \approx 4.2 \times 10^{-13} \text{erg cm}^{-3}.$$



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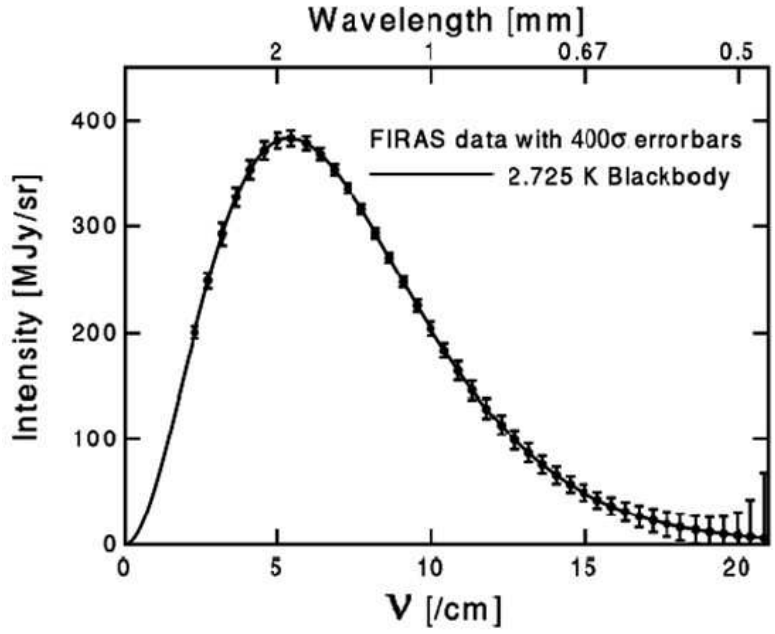

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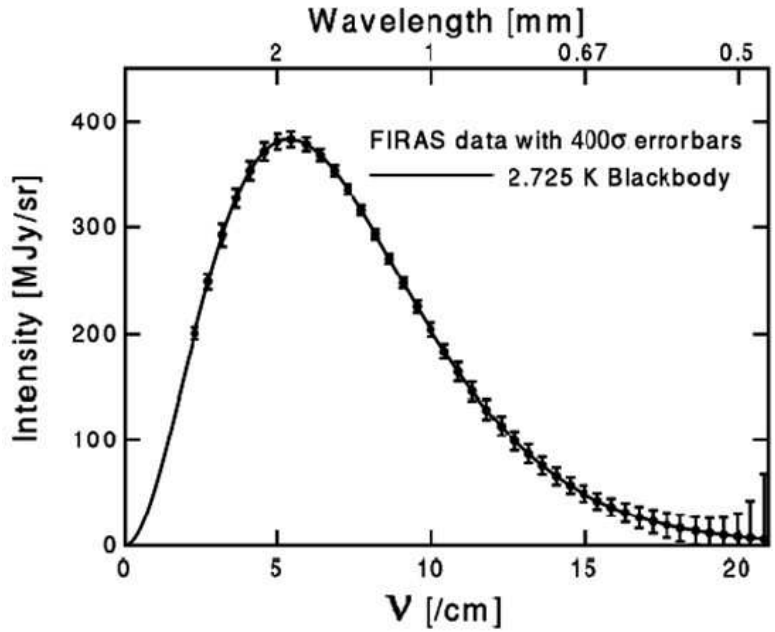

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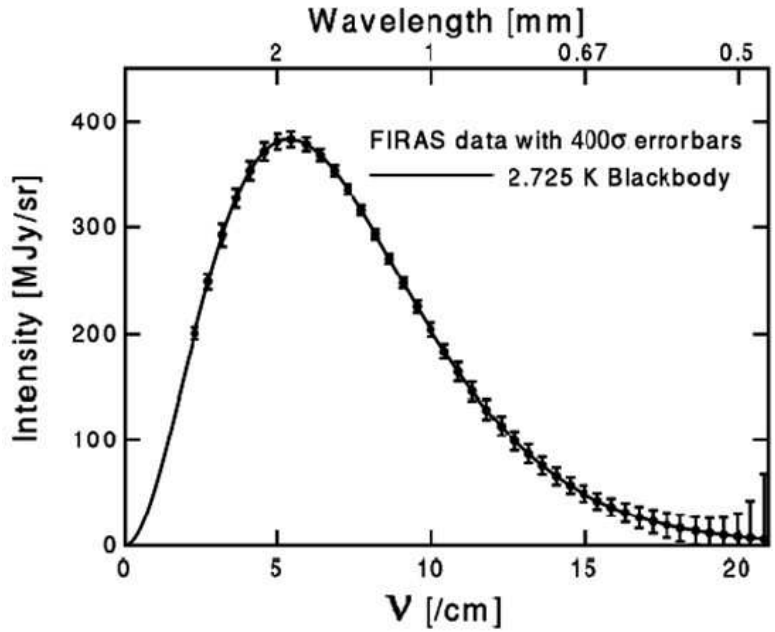
- If we include relativistic neutrinos too, then the value goes up to $\Omega_{r,0} \approx 4.3 \times 10^{-5} h^{-2}$.



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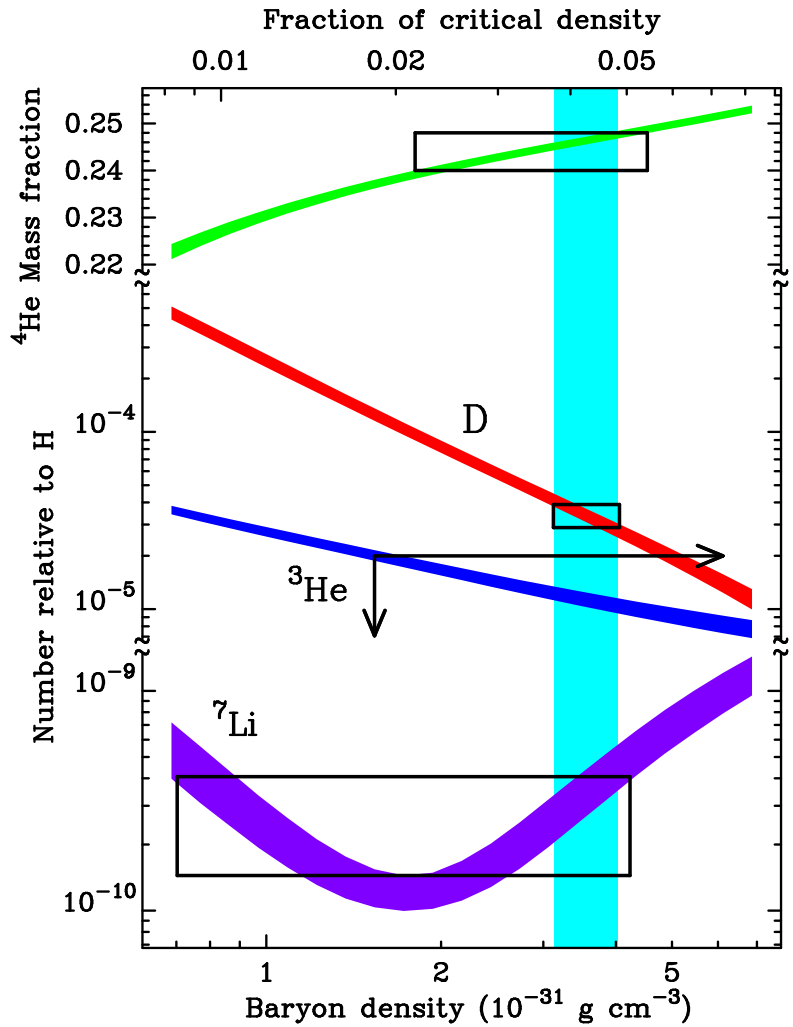
Baryons

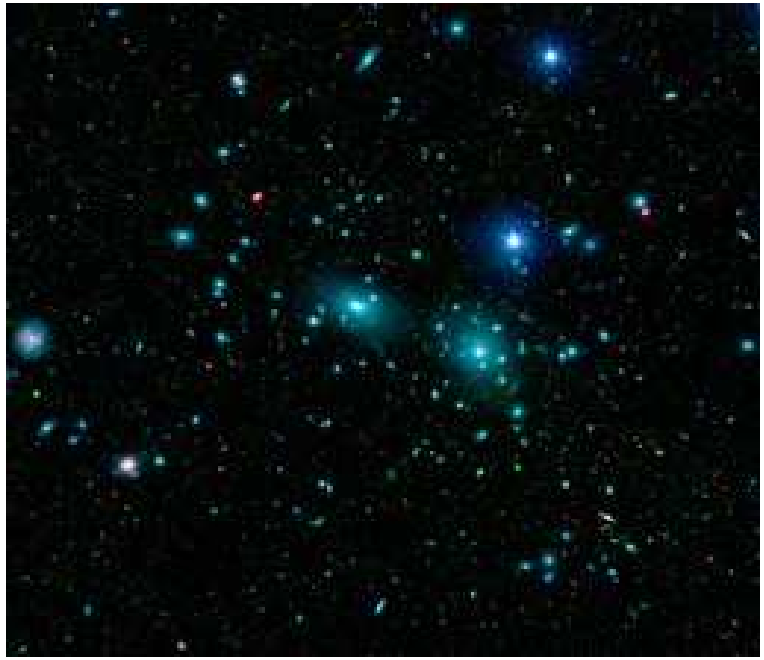
- Constraints from Big Bang nucleosynthesis: $\rho_{b,0} \approx 4 \times 10^{-31}$ gm cm^{-3} which implies $\Omega_{b,0} h^2 \approx 0.02$.
- Also constraints from CMB anisotropies: $\Omega_{b,0} h^2 \approx 0.02$.



Tytler et al (2000)

(Cold) Dark Matter

- Virial theorem applied to (Coma) cluster:
  $\langle v^2 \rangle = GM/R$.
  Measure $\langle v^2 \rangle$ from redshifts and also measure size
  $\Longrightarrow$ calculate M.
  Found $M \sim 10 M_{\rm gas}$.



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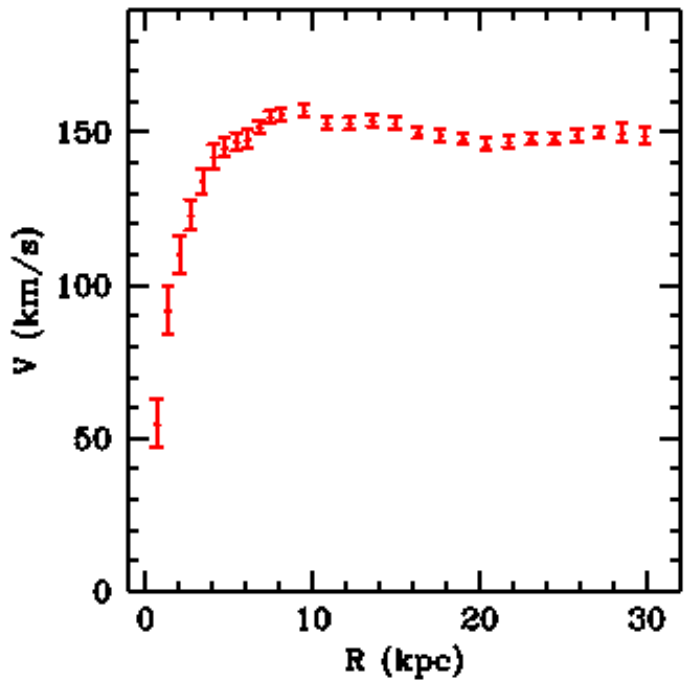

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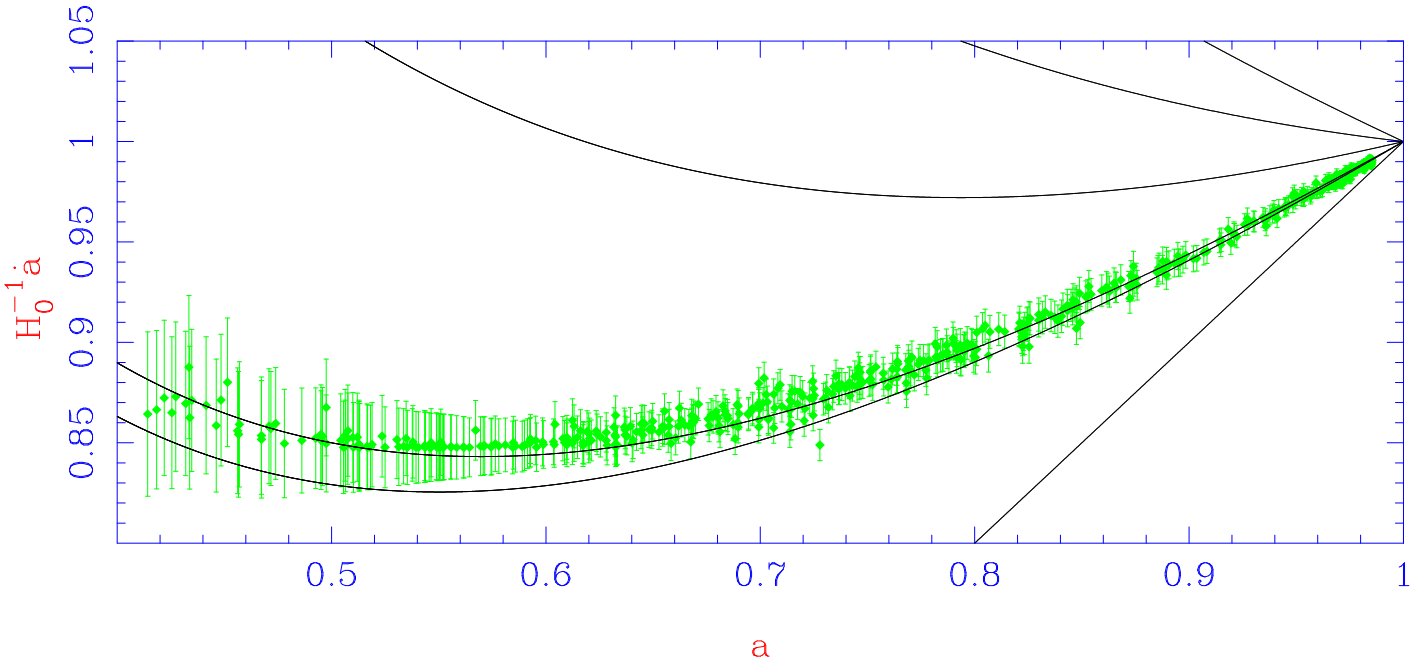
- Rotation curve of galaxies: expect $v \propto R^{-1/2}$ beyond the galaxy (visible) mass $\Longrightarrow$ require $\rho \propto R^{-2}$ to fit the flat curve.
- CMB observations (also large-scale structure) imply $\Omega_{m,0} \approx 0.3$.
- No viable candidates in the Standard Model of Particle Physics.

Cosmological constant

SN-Ia data from various experimental probes



Padmanabhan & **TRC** (2003); updated 2013

Data shows that the Universe is accelerating from $a \approx 0.6$ onwards.

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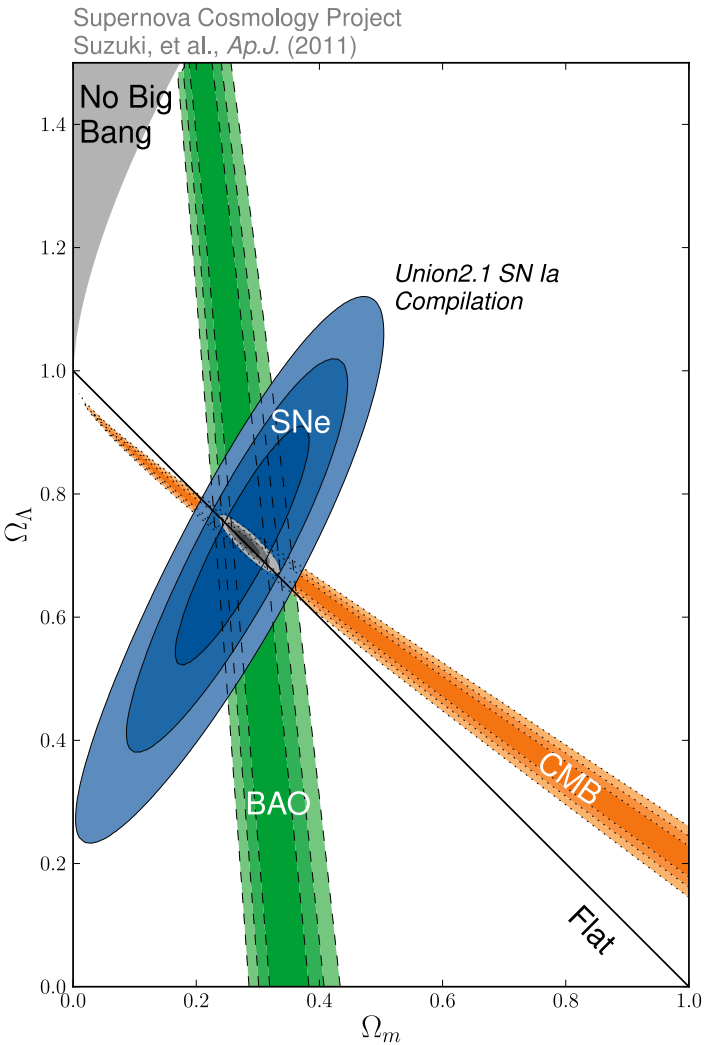
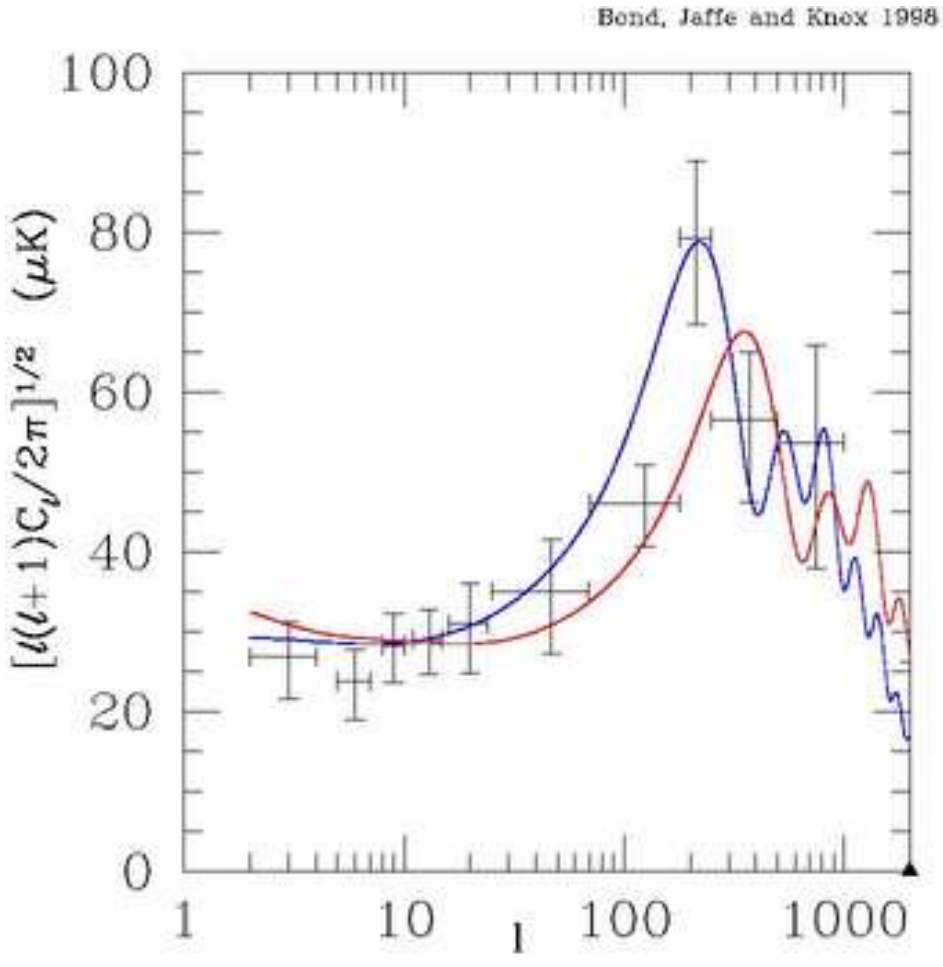


http://supernova.lbl.gov/union/

Require component with $w < -1/3$, data consistent with $w \approx -1$, and $\Omega_\Lambda \approx 0.7$.

Spatial curvature

Standard "ruler": the first peak of the CMB power spectrum.



Bond, Jaffe & Knox (1998)

Current constraints are consistent with $|\Omega_{k,0}| \lesssim 0.01$.

Cosmological parameters

Planck collaboration (2016)

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Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014	0.1422 ± 0.0013	0.14170 ± 0.00097
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086
$\sigma_8 \Omega_m^{0.5}$	0.466 ± 0.013	0.4521 ± 0.0088	0.4514 ± 0.0066	0.4668 ± 0.0098	0.4553 ± 0.0068	0.4535 ± 0.0059
$\sigma_8 \Omega_m^{0.25}$	0.621 ± 0.013	0.6069 ± 0.0076	0.6066 ± 0.0070	0.623 ± 0.011	0.6091 ± 0.0067	0.6083 ± 0.0066
z_{re}	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$
$10^9 A_s$	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063	2.143 ± 0.051	2.207 ± 0.074	2.130 ± 0.053	2.142 ± 0.049
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.874 ± 0.013	1.873 ± 0.011	1.882 ± 0.012	1.878 ± 0.011	1.876 ± 0.011
Age/Gyr	13.813 ± 0.038	13.799 ± 0.038	13.796 ± 0.029	13.813 ± 0.026	13.807 ± 0.026	13.799 ± 0.021
z_*	1090.09 ± 0.42	1089.94 ± 0.42	1089.90 ± 0.30	1090.06 ± 0.30	1090.00 ± 0.29	1089.90 ± 0.23
r_*	144.61 ± 0.49	144.89 ± 0.44	144.93 ± 0.30	144.57 ± 0.32	144.71 ± 0.31	144.81 ± 0.24
$100\theta_*$	1.04105 ± 0.00046	1.04122 ± 0.00045	1.04126 ± 0.00041	1.04096 ± 0.00032	1.04106 ± 0.00031	1.04112 ± 0.00029
z_{drag}	1059.57 ± 0.46	1059.57 ± 0.47	1059.60 ± 0.44	1059.65 ± 0.31	1059.62 ± 0.31	1059.68 ± 0.29
r_{drag}	147.33 ± 0.49	147.60 ± 0.43	147.63 ± 0.32	147.27 ± 0.31	147.41 ± 0.30	147.50 ± 0.24
k_D	0.14050 ± 0.00052	0.14024 ± 0.00047	0.14022 ± 0.00042	0.14059 ± 0.00032	0.14044 ± 0.00032	0.14038 ± 0.00029
z_{eq}	3393 ± 49	3365 ± 44	3361 ± 27	3395 ± 33	3382 ± 32	3371 ± 23
k_{eq}	0.01035 ± 0.00015	0.01027 ± 0.00014	0.010258 ± 0.000083	0.01036 ± 0.00010	0.010322 ± 0.000096	0.010288 ± 0.000071
$100\theta_{s,eq}$	0.4502 ± 0.0047	0.4529 ± 0.0044	0.4533 ± 0.0026	0.4499 ± 0.0032	0.4512 ± 0.0031	0.4523 ± 0.0023
f_{2000}^{143}	29.9 ± 2.9	30.4 ± 2.9	30.3 ± 2.8	29.5 ± 2.7	30.2 ± 2.7	30.0 ± 2.7
$f_{2000}^{143\times217}$	32.4 ± 2.1	32.8 ± 2.1	32.7 ± 2.0	32.2 ± 1.9	32.8 ± 1.9	32.6 ± 1.9
f_{2000}^{217}	106.0 ± 2.0	106.3 ± 2.0	106.2 ± 2.0	105.8 ± 1.9	106.2 ± 1.9	106.1 ± 1.8

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