Cosmological Implications of 3rd Year WMAP Data

Cosmology — Cosmological implications of 3rd year WMAP data

Consistency — Small and large scale, Supernovas, Lensing,…

Fits — ΛCDM parameter fit using just WMAP

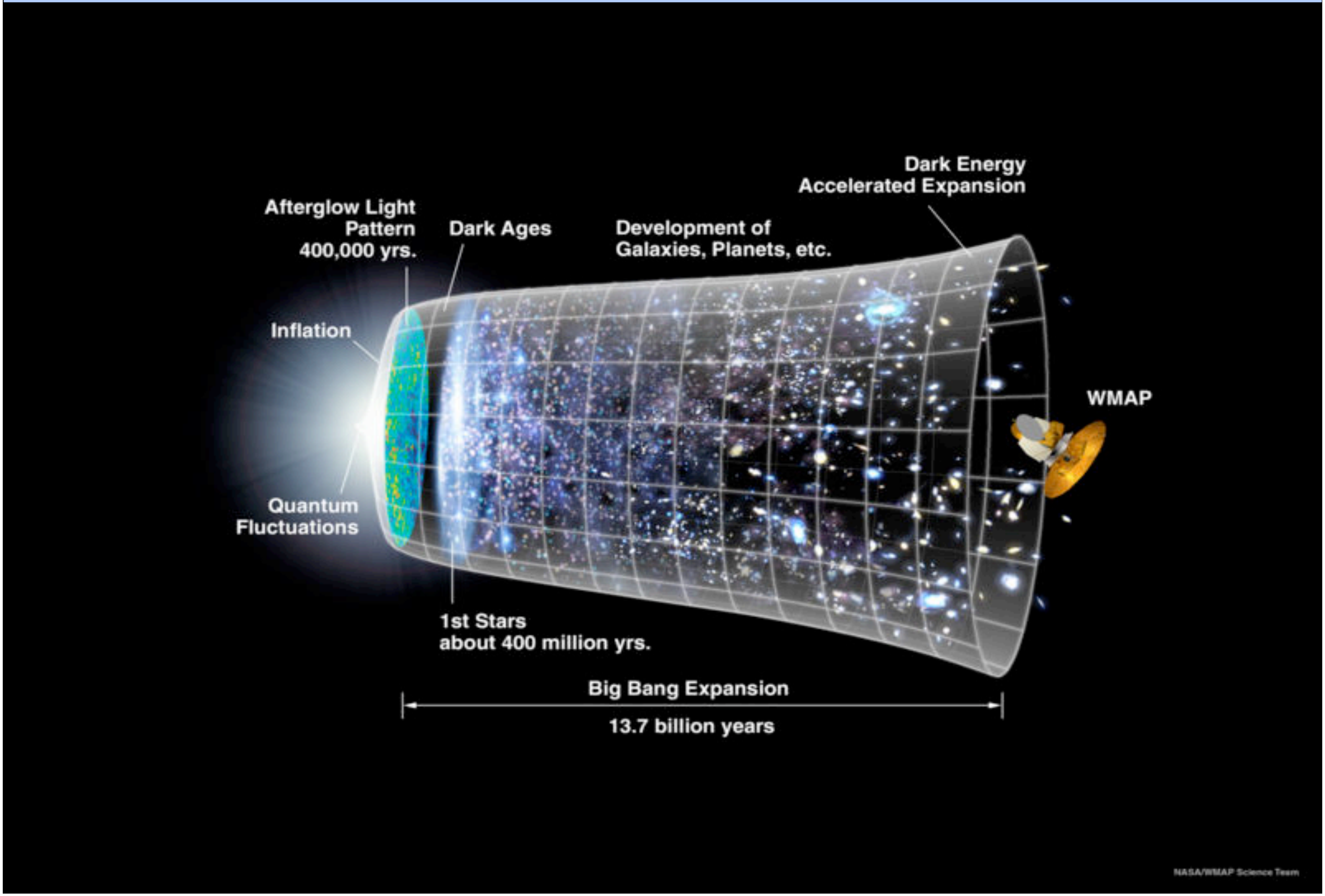
Parameters — How to describe the data usefully

WMAP Data — What have WMAP collected and how to show it

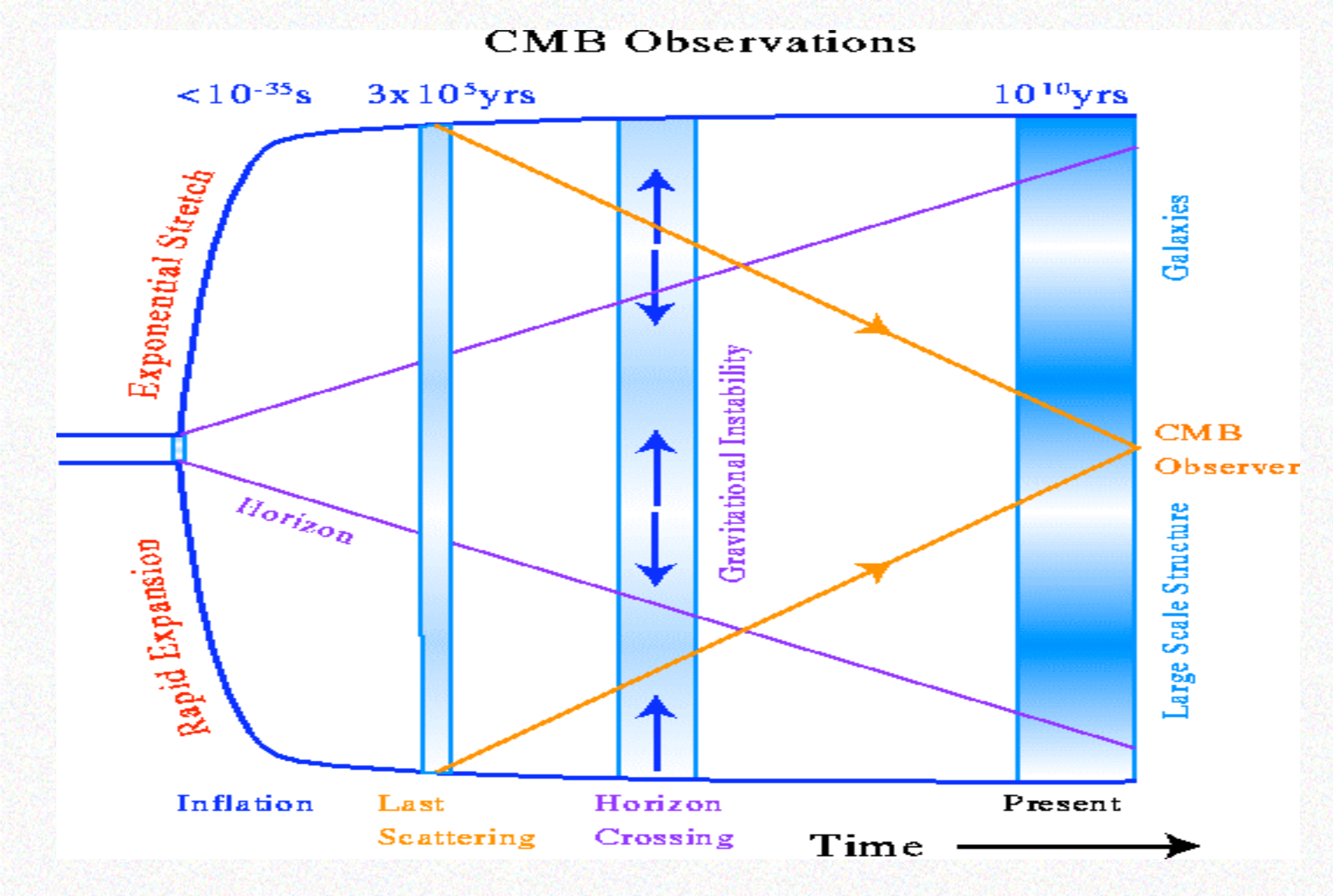
CMB Basics — Big Bang, Inflation, Last Scattering, Reionization, CMB structure,…

Review of Spergel et al. 2007 “Three Year WMAP Observations: Implications for Cosmology” ApJS 170, 377 – by Dusan Maletic

CMB Basics

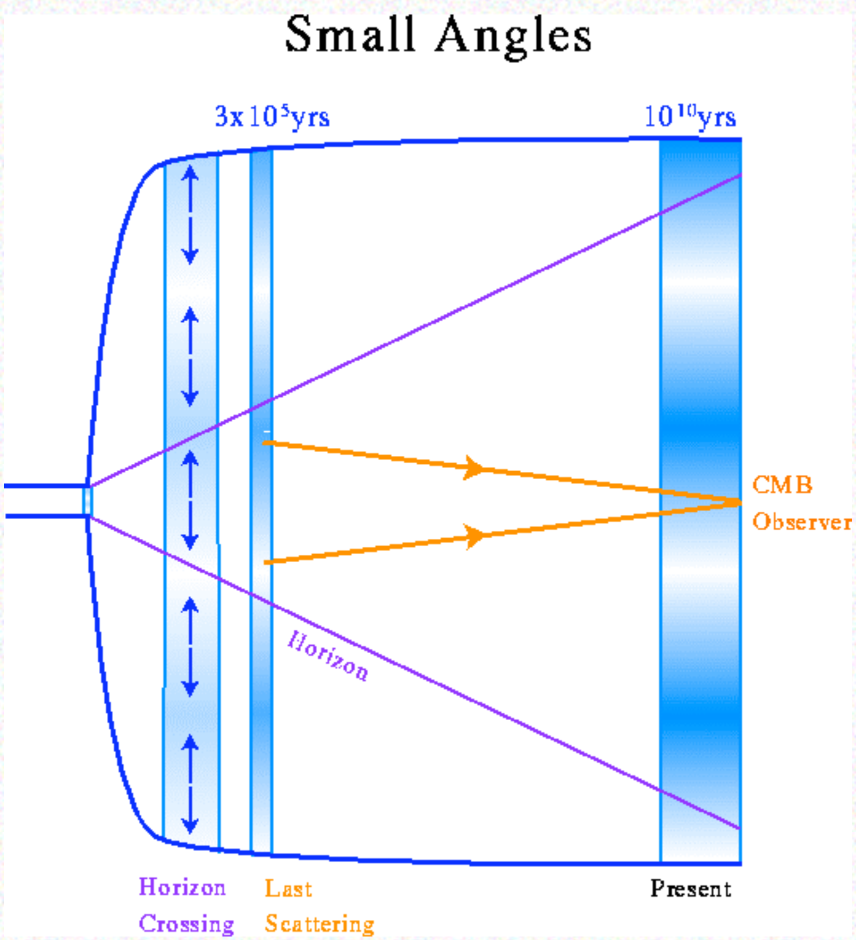

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

CMB Basics

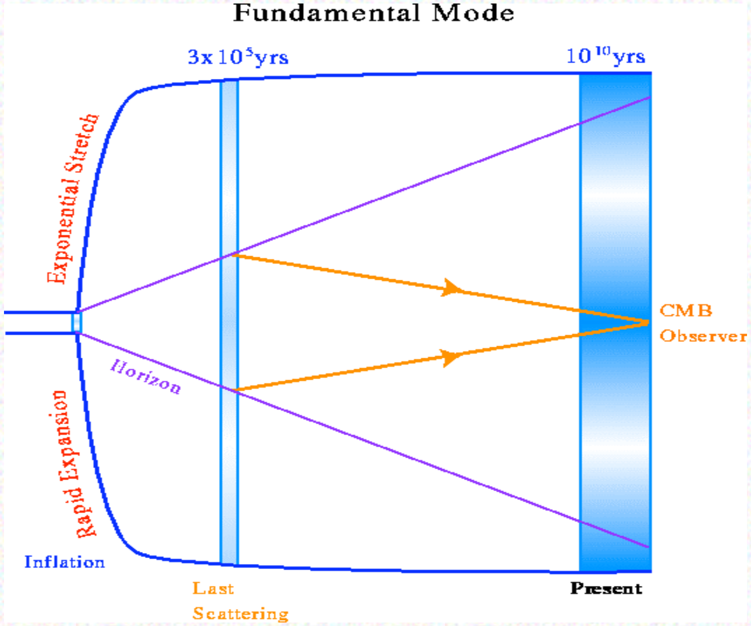


CMB Observations
<10^{-35}s
3x10^{5}yrs
10^{10}yrs
Exponential Stretch
Rapid Expansion
Horizon
Gravitational Instability
Galaxies
CMB
Observer
Large Scale Structure
Inflation
Last
Scattering
Horizon
Crossing
Present
Time

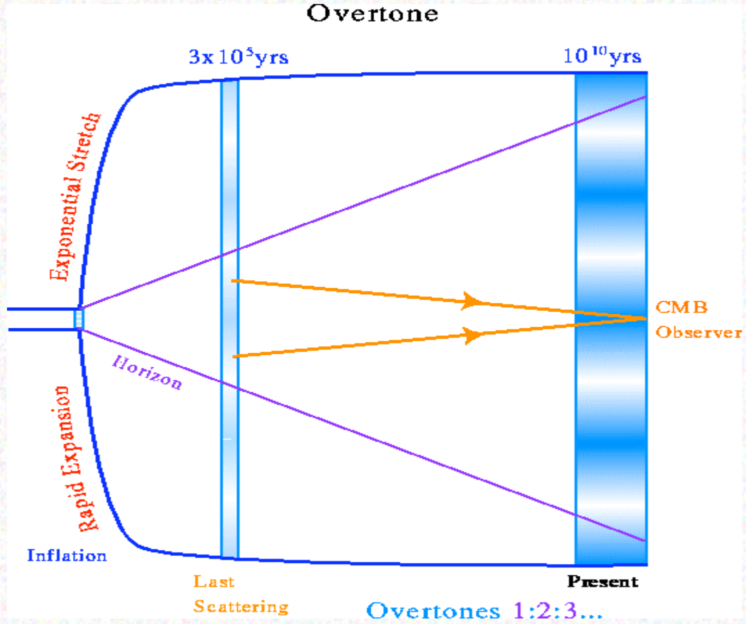
CMB Basics



Small Angles
3x10^5yrs
10^10yrs
CMB
Observer
Horizon
Horizon
Crossing
Last
Scattering
Present

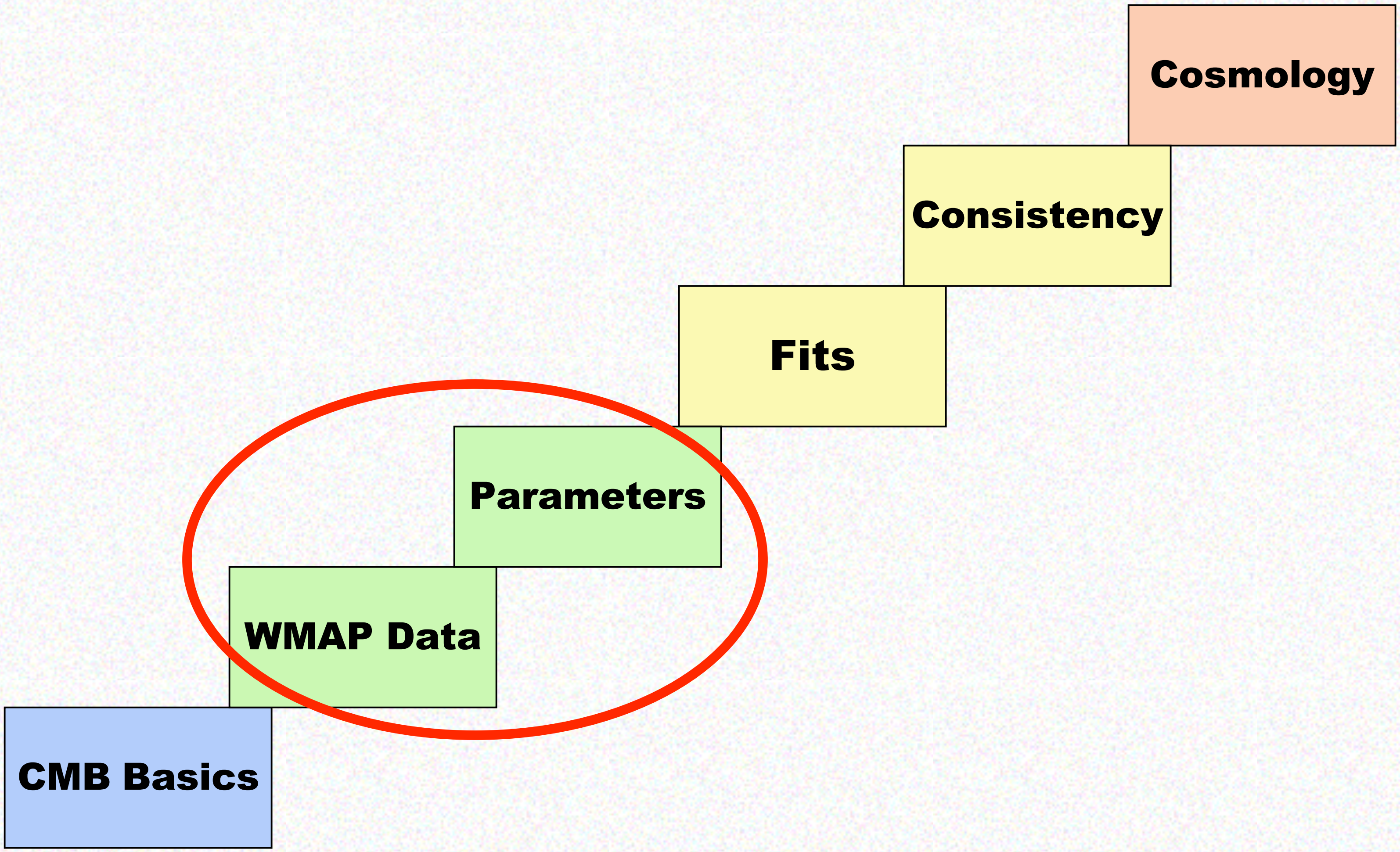


Fundamental Mode
3x10^5yrs
10^10yrs
Exponential Stretch
Rapid Expansion
Horizon
CMB
Observer
Inflation
Last
Scattering
Present

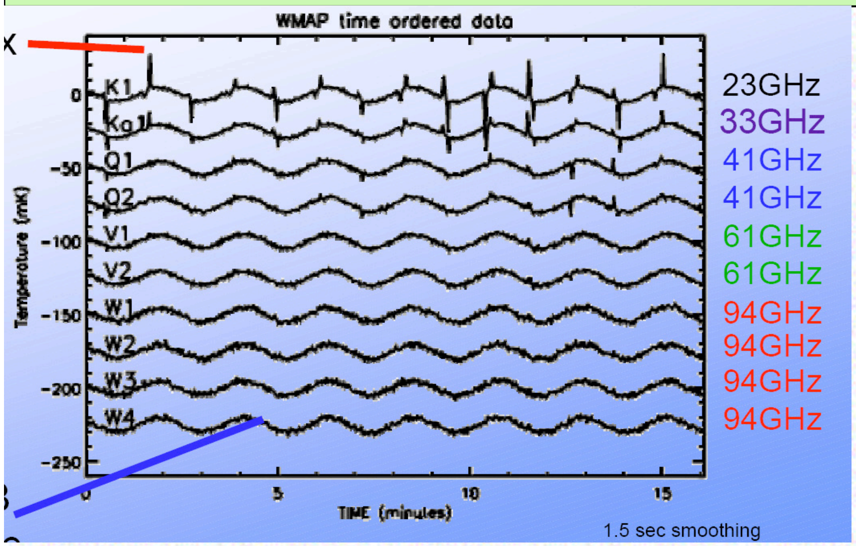


Overtone
3x10^5yrs
10^10yrs
Exponential Stretch
Rapid Expansion
Horizon
CMB
Observer
Inflation
Last
Scattering
Present
Overtones 1:2:3…

Data and Parameters

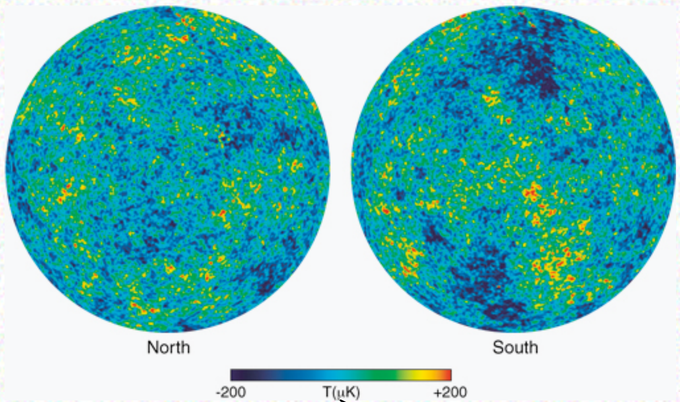


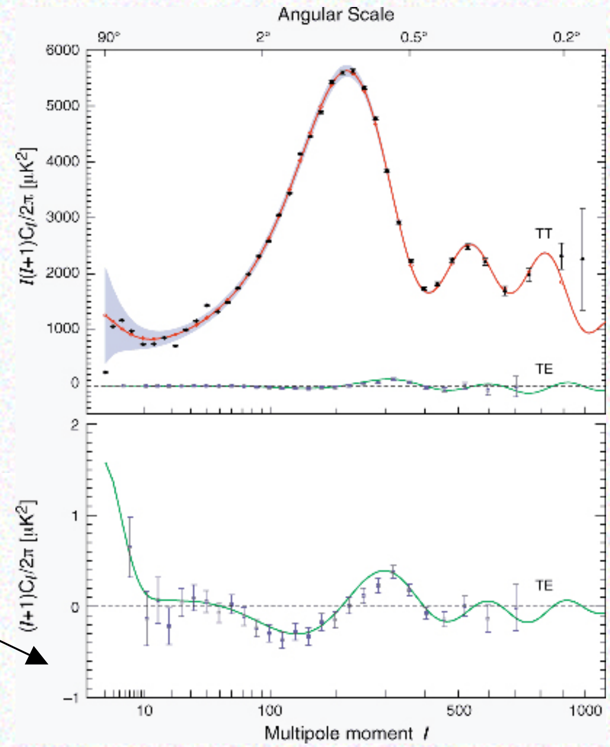
WMAP Data



Time Ordered Data,
Instrument corrections,
Local foregrounds: Earth, Sun,…
Order of **10^{10} data points**.

Temperature maps,
Galactic foregrounds,
ILC of various bands,
Order of **10^6 data points**.





TT, TE **Power spectrum** (there is EE also)
Binning, averaging, smoothing…
Order of **10^3 data points**.

Parameters

Power spectrum can be described by **10-20 Physically meaningful parameters**.

Parameter	Value	Description
	Basic parameters	
H_0	$73.2^{+3.1}_{-3.2}$ km s^{-1} Mpc^{-1}	Hubble parameter
Ω_b	$0.0444^{+0.0042}_{-0.0035}$	Baryon density
Ω_m	$0.266^{+0.025}_{-0.040}$	Total matter density (baryons + dark matter)
τ	$0.079^{+0.029}_{-0.032}$	Optical depth to reionization
A_s	$0.813^{+0.042}_{-0.052}$	Scalar fluctuation amplitude
n_s	$0.948^{+0.015}_{-0.018}$	Scalar spectral index
	Derived parameters	
ρ_0	$0.94^{+0.06}_{-0.09} \times 10^{-26}$ kg/m^3	Critical density
Ω_Λ	$0.732^{+0.040}_{-0.025}$	Dark energy density
z_{ion}	$10.5^{+2.6}_{-2.9}$	Reionization red-shift
σ_8	$0.772^{+0.036}_{-0.048}$	Galaxy fluctuation amplitude
t_0	$13.73^{+0.13}_{-0.17} \times 10^9$ years	Age of the universe

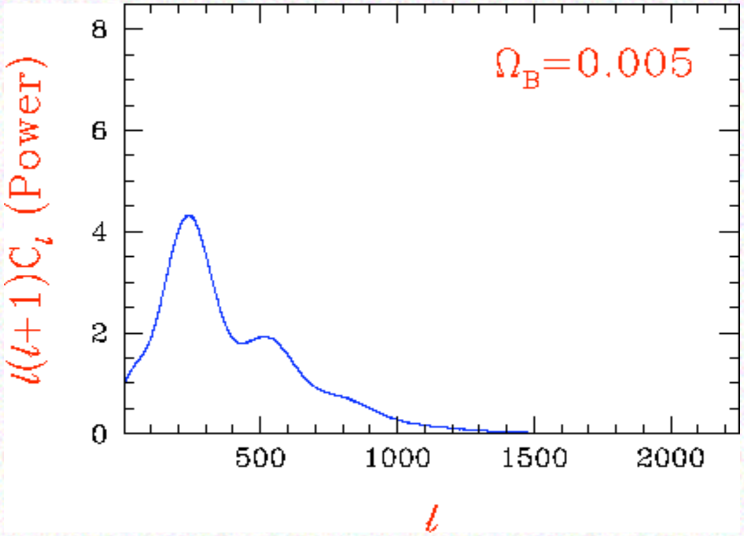
Extended parameters

Parameter	Value	Description
w	$-0.926^{+0.051}_{-0.075}$	. . . . . . Equation of state
r	< 0.55 (2σ)	. . . . . . Tensor-to-scalar ratio
Ω_k	$-0.010^{+0.014}_{-0.012}$	. . . . . . Spatial curvature
α	$-0.102^{+0.050}_{-0.043}$	. . . . . . Running of the spectral index
Σm_ν	< 0.87 eV (2σ)	. . . . . . Summed neutrino masses

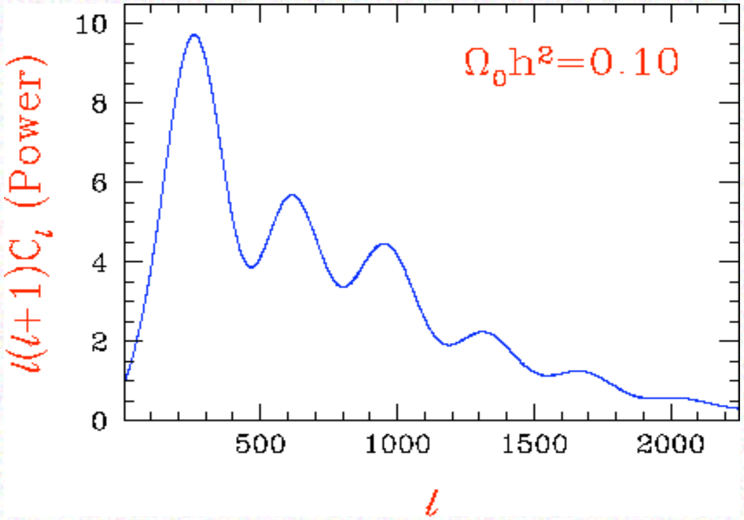
Parameters are not independent but constrained depending on a model used.

Parameters

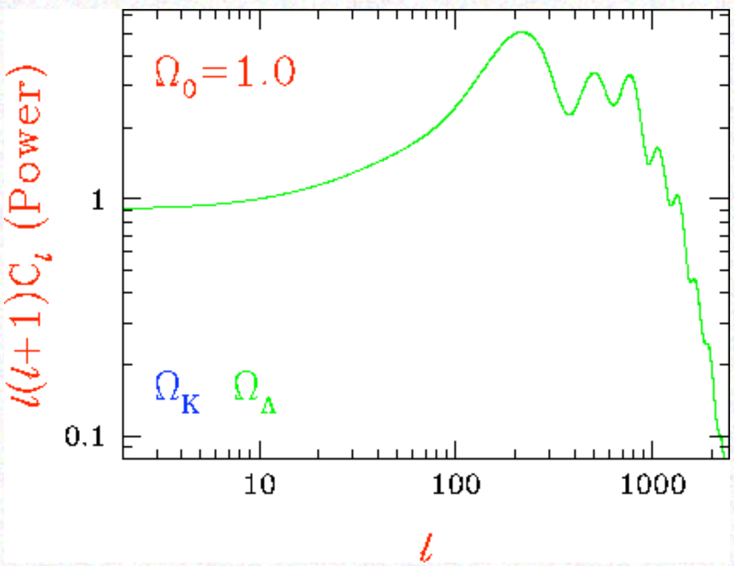
Baryon Content



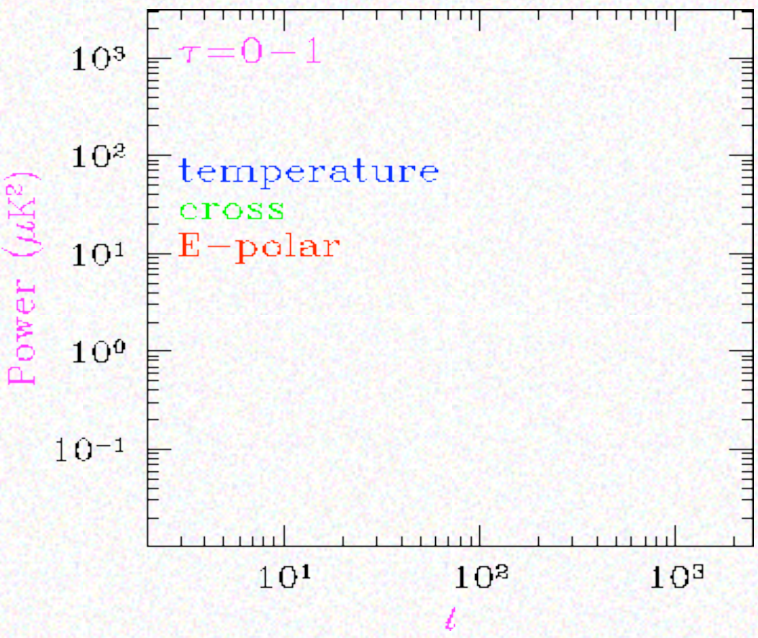
Matter Density



Curvature and Cosmological Constant

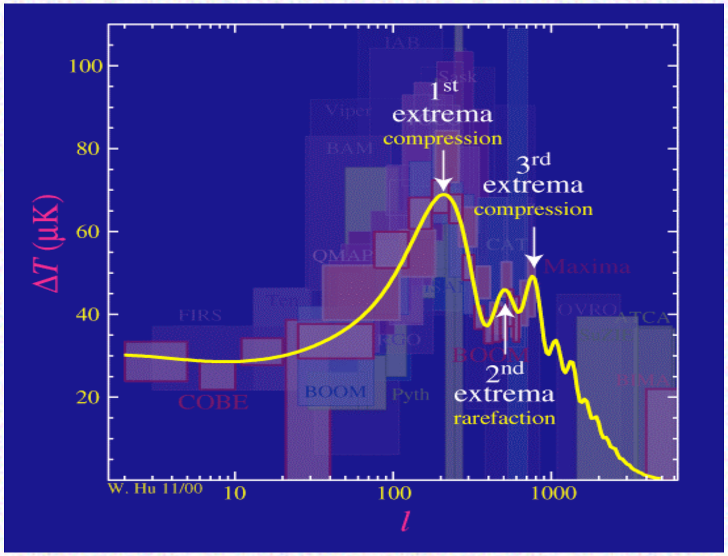


Reionization Optical Depth

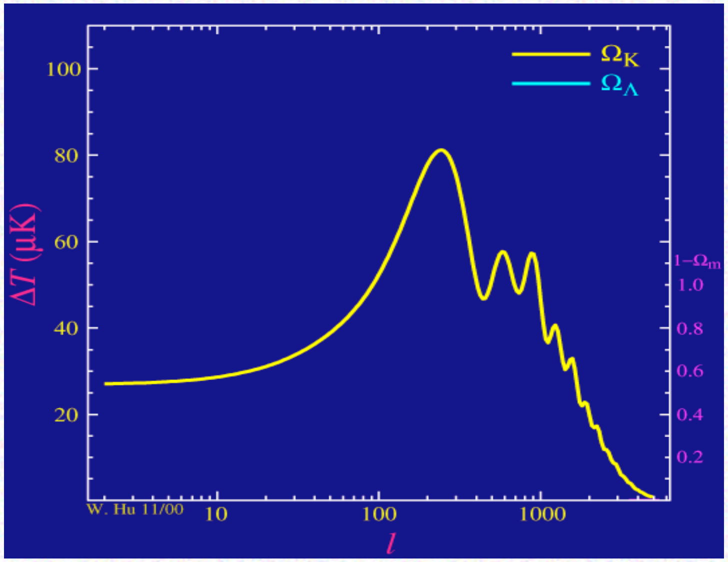


Parameters

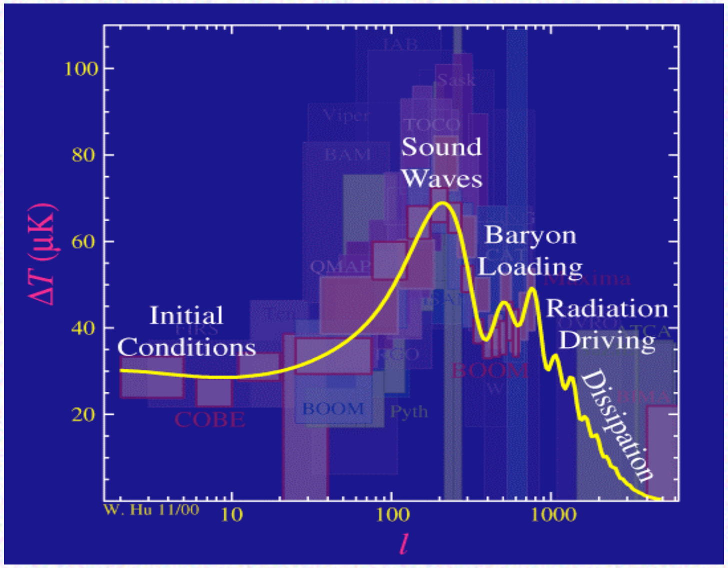
Sounds

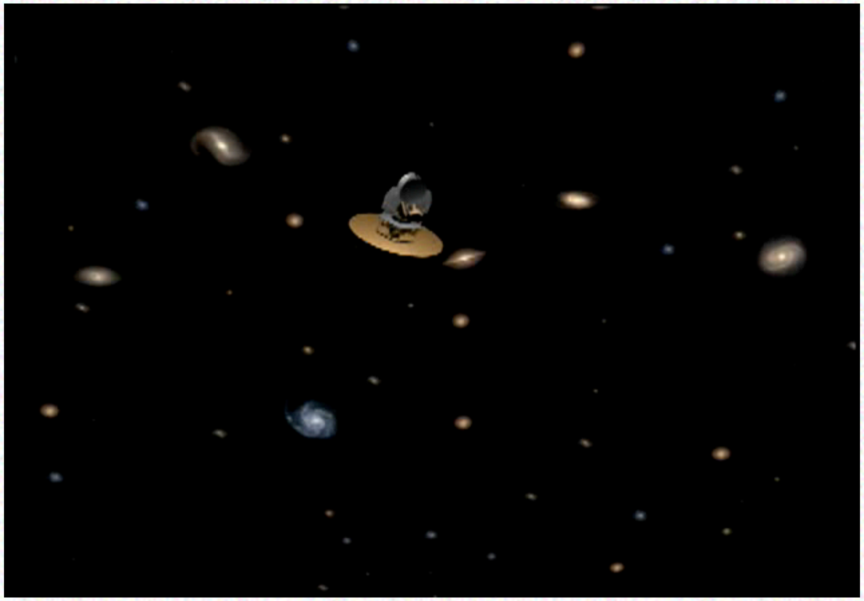


Curvature

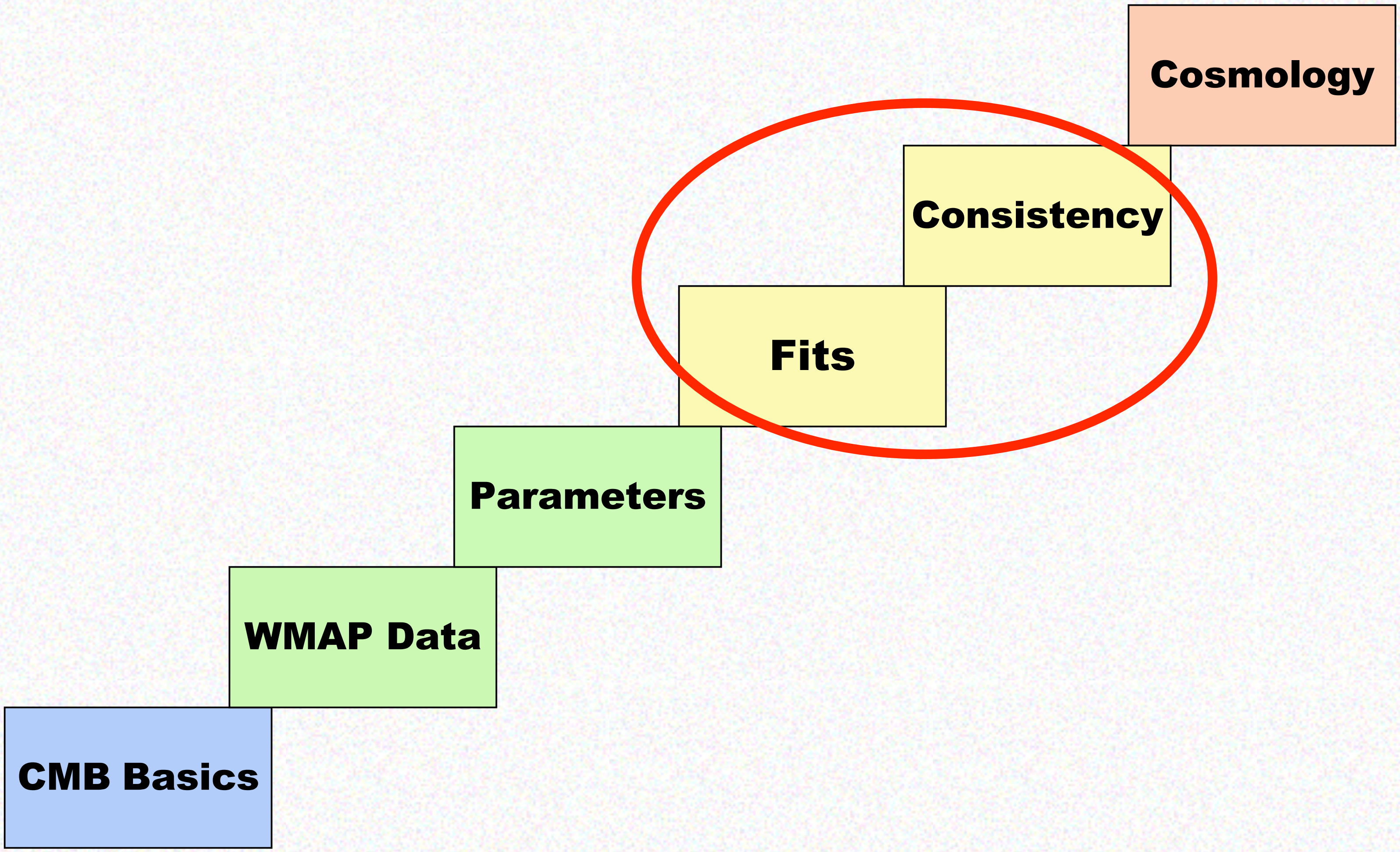


Physical Landscape





Fits and Consistency



Fits

Parameter set is chosen:

$$\boldsymbol{p} = \{\omega_b, \omega_c, \tau, \Omega_\Lambda, w, \Omega_k, f_\nu, N_\nu, \\ \Delta^2_{\mathcal{R}}, n_s, r, dn_s/d\ln k, A_{\rm SZ}, b_{\rm SDSS}, z_s\},$$

Bayesian fits are done using uniform priors for these parameters.

Physical model is chosen, Cold Dark Matter with Cosmological Constant.

Other models are compared.

Other experimental results are used to enhance and test WMAP.

Fits

ΛCDM model parameter fit using just WMAP: Power Spectrum

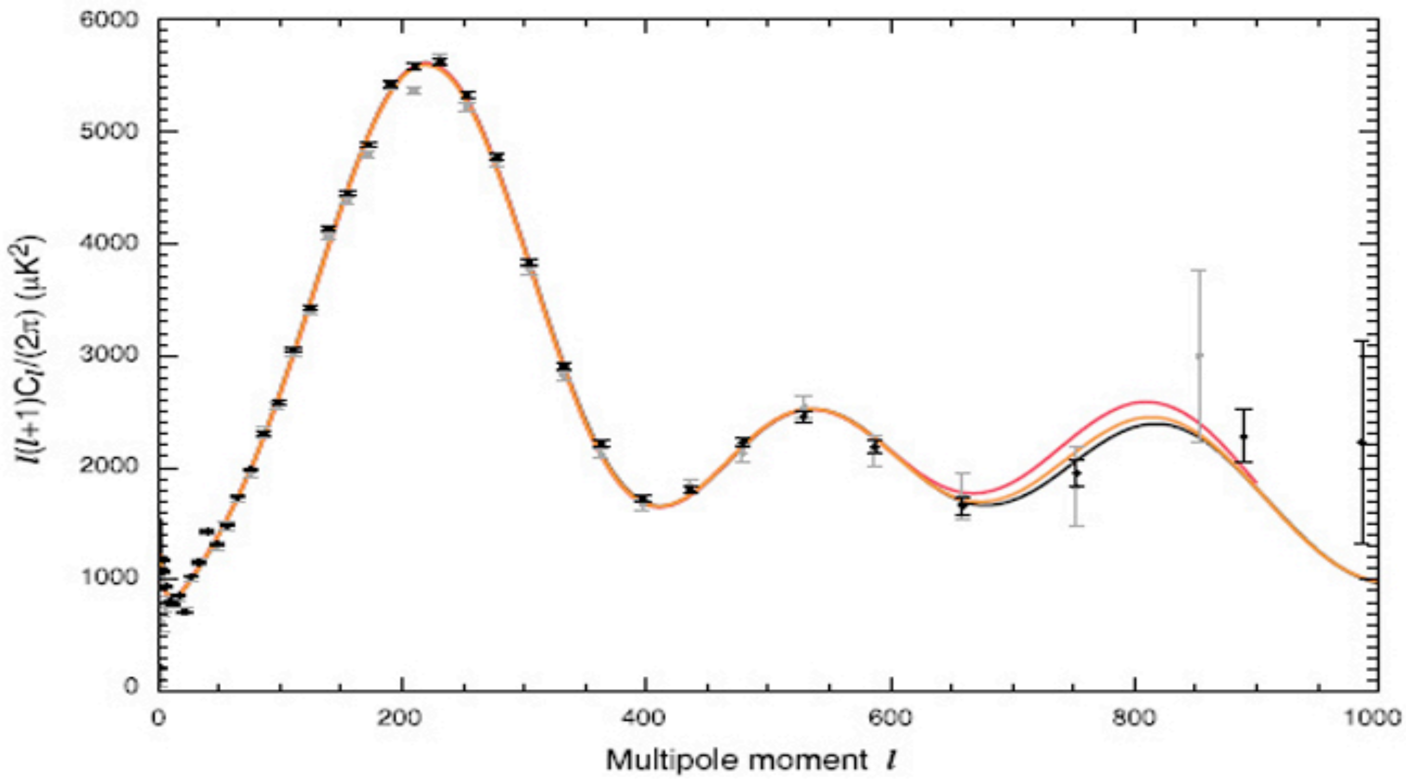


FIG. 2.—Comparison of the predictions of the different best-fit models to the data. The black line is the angular power spectrum predicted for the best-fit 3 year *WMAP* only ΛCDM model. The red line is the best fit to the 1 year *WMAP* data. The orange line is the best fit to the combination of the 1 year *WMAP* data, CBI and ACBAR (WMAPext in Spergel et al. 2003). The solid data points represent the 3 year data and the light gray data points the first-year data.

Fits

ΛCDM model parameter fit using just WMAP: Improvement

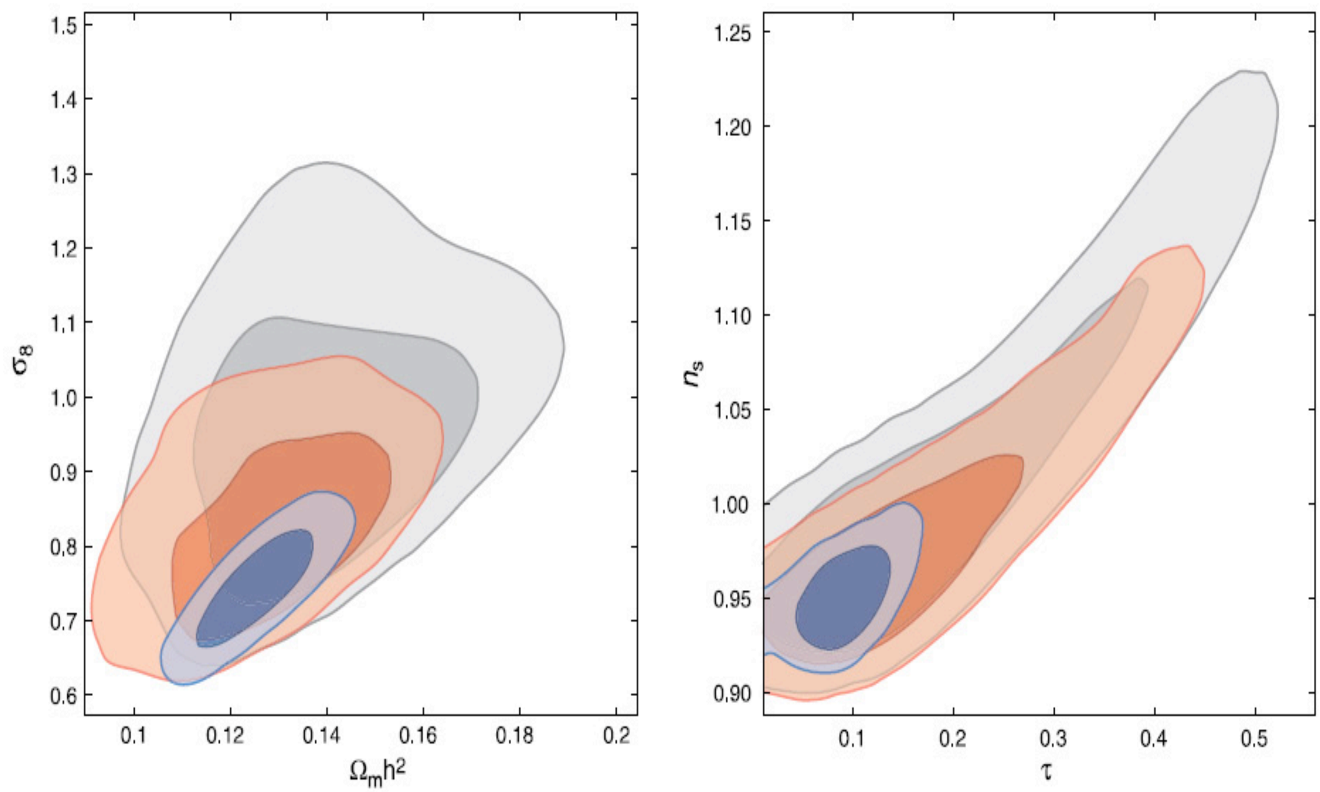


FIG. 1.—Improvement in parameter constraints for the power-law ΛCDM model (model M5 in Table 3). The contours show the 68% and 95% joint 2D marginalized contours for the ($\Omega_m h^2$, σ_8) plane (*left*) and the (n_s, τ) plane (*right*). The black contours represent the first-year *WMAP* data (with no prior on τ). The red contours show the first-year *WMAP* data combined with CBI and ACBAR (WMAPext in Spergel et al. 2003). The blue contours represent the three year *WMAP* data only with the SZ contribution set to 0 to maintain consistency with the first-year analysis. The *WMAP* measurements of EE power spectrum provide a strong constraint on the value of τ. The models with no reionization ($\tau = 0$) or a scale-invariant spectrum ($n_s = 1$) are both disfavored at $\Delta\chi^2_{\rm eff} > 6$ for five parameters (see Table 3). Improvements in the measurement of the amplitude of the third peak yield better constraints on $\Omega_m h^2$.

Fits

Is the chosen ΛCDM model the best?

Goodness of Fit, $\Delta\chi^2_{\rm eff} = -2\ln\mathcal{L}$, for *WMAP* Data only Relative to a Power-Law ΛCDM Model

Model Number	Model	$-\Delta(2\ln\mathcal{L})$	$N_{\rm par}$
M1	Scale-invariant fluctuations ($n_s = 1$)	6	5
M2	No reionization ($\tau = 0$)	7.4	5
M3	No dark matter ($\Omega_c = 0$, $\Omega_\Lambda \neq 0$)	248	6
M4	No cosmological constant ($\Omega_c \neq 0$, $\Omega_\Lambda = 0$)	0	6
M5	Power law ΛCDM	0	6
M6	Quintessence ($w \neq -1$)	0	7
M7	Massive neutrino ($m_\nu > 0$)	−1	7
M8	Tensor modes ($r > 0$)	0	7
M9	Running spectral index ($dn_s/d\ln k \neq 0$)	−4	7
M10	Nonflat universe ($\Omega_k \neq 0$)	−2	7
M11	Running spectral index and tensor modes	−4	8
M12	Sharp cutoff	−1	7
M13	Binned $\Delta^2_{\mathcal{R}}(k)$	−22	20

Note.—A worse fit to the data is $\Delta\chi^2_{\rm eff} > 0$.

This is the simplest test, Bayesian testing is needed.

Consistency

Small number of parameters and models lead to degeneracy.

Observations of other physical events and on other scales helps break these.

Observations focused on other scales and events test WMAP results.

Three main groups of external data:

1) Large scale: SDSS

2) Small scale: CBI,VSA, BOOMERANG, ACBAR

3) Other physics: Supernovas, Lensing,…

Consistency

Large Scale

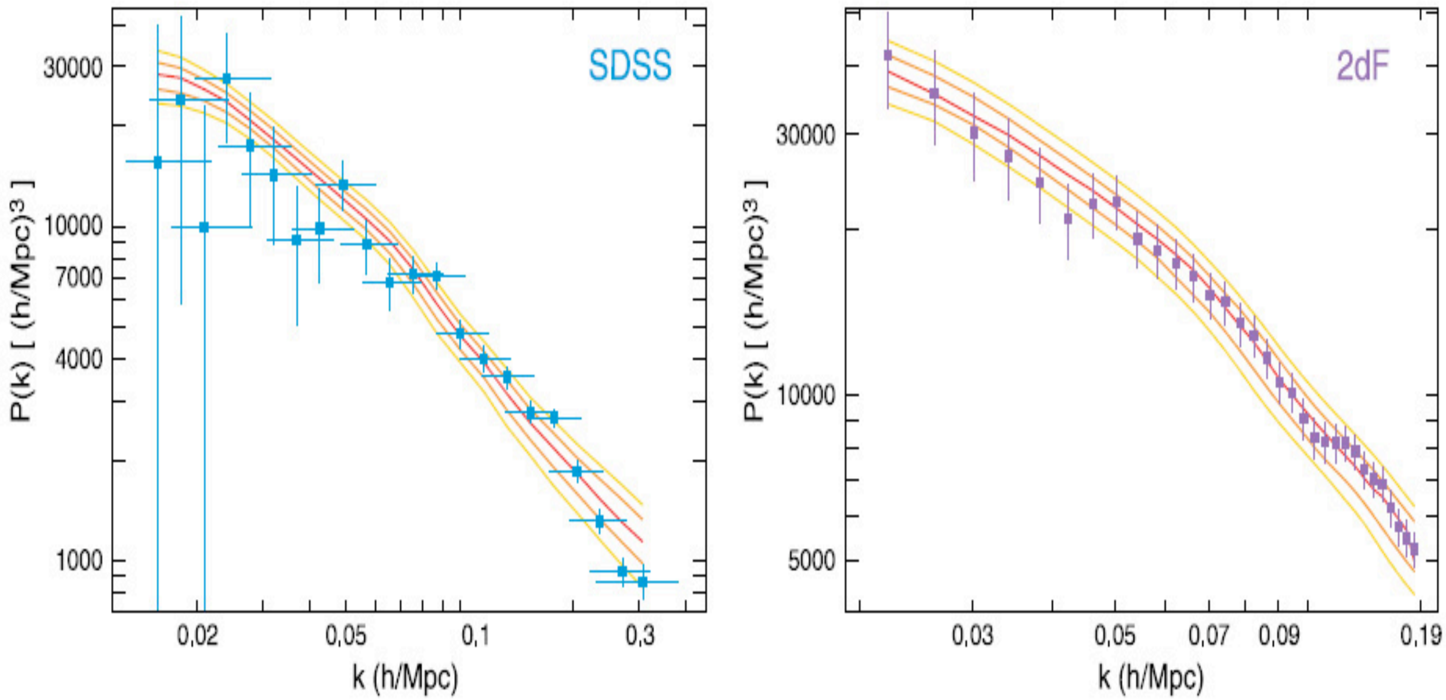


FIG. 6.—*Left*: Predicted power spectrum (based on the range of parameters consistent with the *WMAP*-only parameters) is compared to the mass power spectrum inferred from the SDSS galaxy power spectrum (Tegmark et al. 2004b) as normalized by weak lensing measurements (Seljak et al. 2005b). *Right*: Predicted power spectrum is compared to the mass power spectrum inferred from the 2dFGRS galaxy power spectrum (Cole et al. 2005) with the best-fit value for b_{2dFGRS} based on the fit to the *WMAP* model. Note that the 2dFGRS data points shown are correlated.

Consistency

Small Scale:

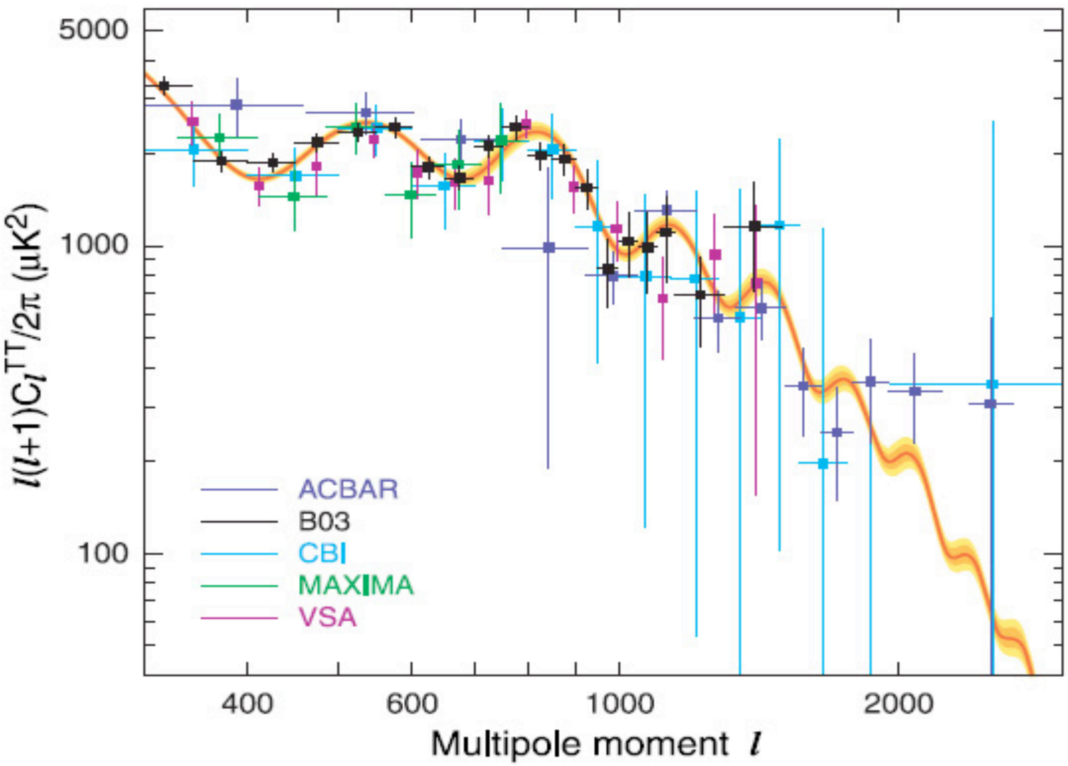


FIG. 5.—Prediction for the small-scale angular power spectrum seen by ground-based and balloon CMB experiments from the ΛCDM model fit to the *WMAP* data only. The colored lines show the best-fit (*red*) and the 68% (*dark orange*) and 95% confidence levels (*light orange*) based on fits of the ΛCDM models to the *WMAP* data. The points in the figure show small-scale CMB measurements (Ruhl et al. 2003; Abroe et al. 2004; Kuo et al. 2004; Readhead et al. 2004a; Dickinson et al. 2004). The plot shows that the ΛCDM model (fit to the *WMAP* data alone) can accurately predict the amplitude of fluctuations on the small scales measured by ground and balloon-based experiments.

Consistency

Lensing:

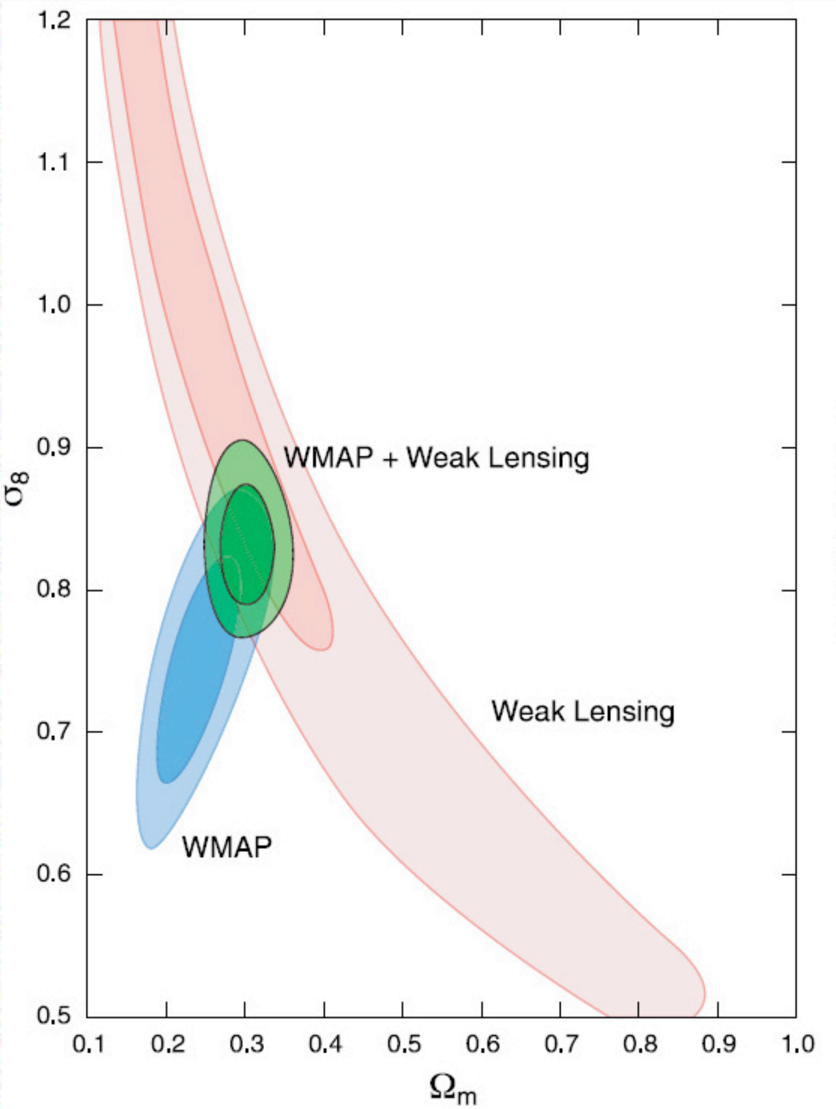


FIG. 7.—Prediction for the mass fluctuations measured by the CFTHLS weak-lensing survey from the ΛCDM model fit to the *WMAP* data only. The blue, red, and green contours show the joint 2D marginalized 68% and 95% confidence limits in the (σ_8, Ω_m) plane for *WMAP* only, CFHTLS only and *WMAP* + CFHTLS, respectively, for the power-law ΛCDM models. All constraints come from assuming the same priors on input parameters, with the additional marginalization over z_s in the weak lensing analysis, using a top-hat prior of $0.613 < z_s < 0.721$. While lensing data favors higher values of $\sigma_8 \simeq 0.8-1.0$ (see § 4.1.7), X-ray cluster studies favor lower values of $\sigma_8 \simeq 0.7-0.8$ (see § 4.1.9).

Consistency

Issues

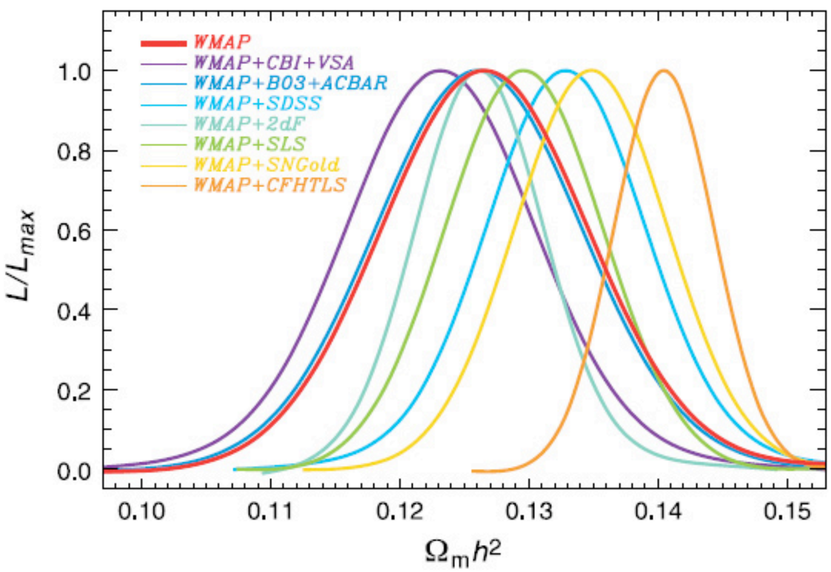


FIG. 9.—One-dimensional marginalized distribution of $\Omega_m h^2$ for *WMAP*, *WMAP* + CBI + VSA, *WMAP* + BOOM + ACBAR, *WMAP* + SDSS, *WMAP* + SN(SNLS), *WMAP* + SN(*HST*/GOODS), *WMAP* + 2dFGRS, and *WMAP* + CFHTLS for the power-law ΛCDM model.

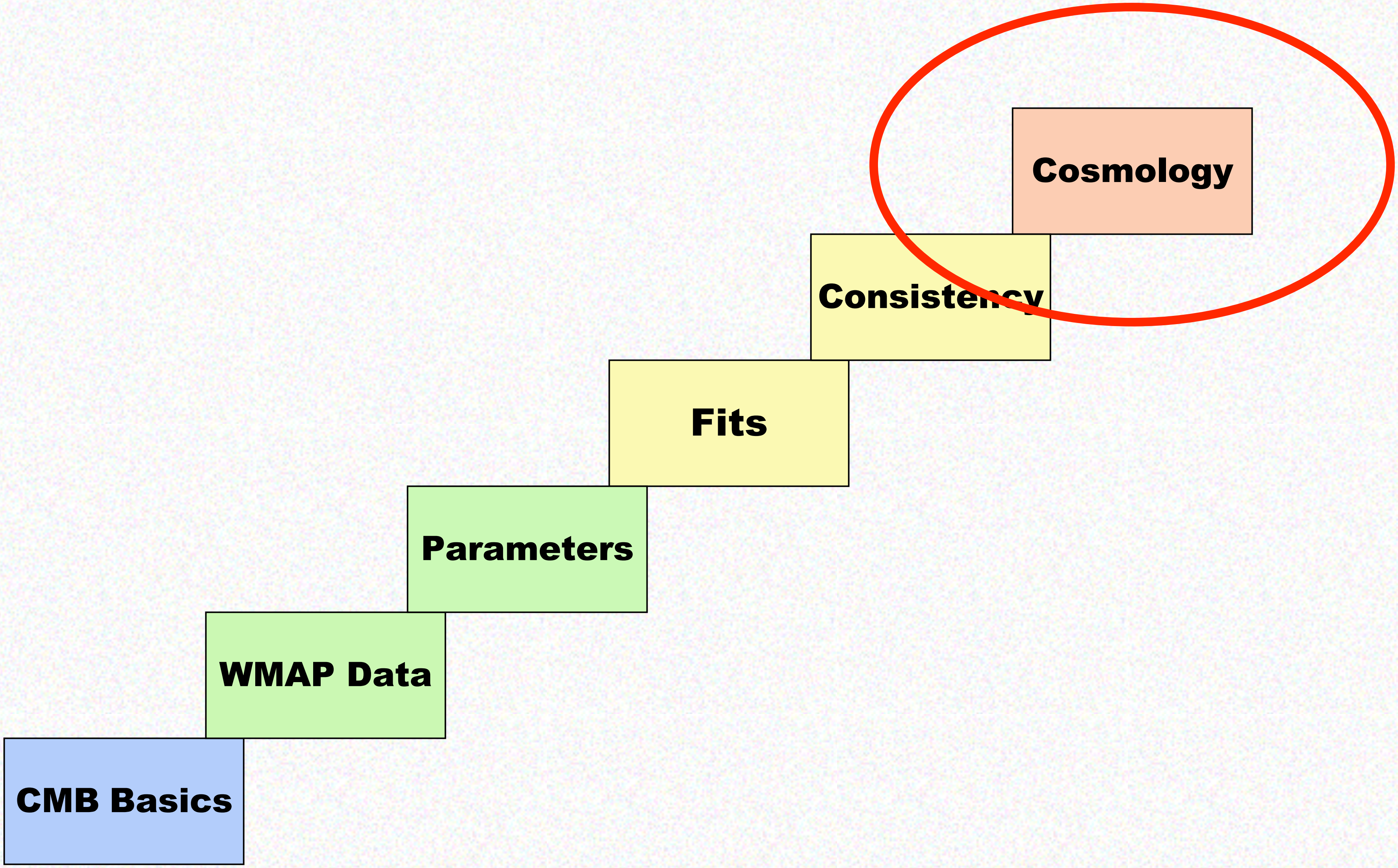
Li abundance:

Theory: 2.64 +/- 0.03

WMAP: 2.3+/- 0.1

H_o

Cosmology


Cosmology
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Cosmology

Inflation?

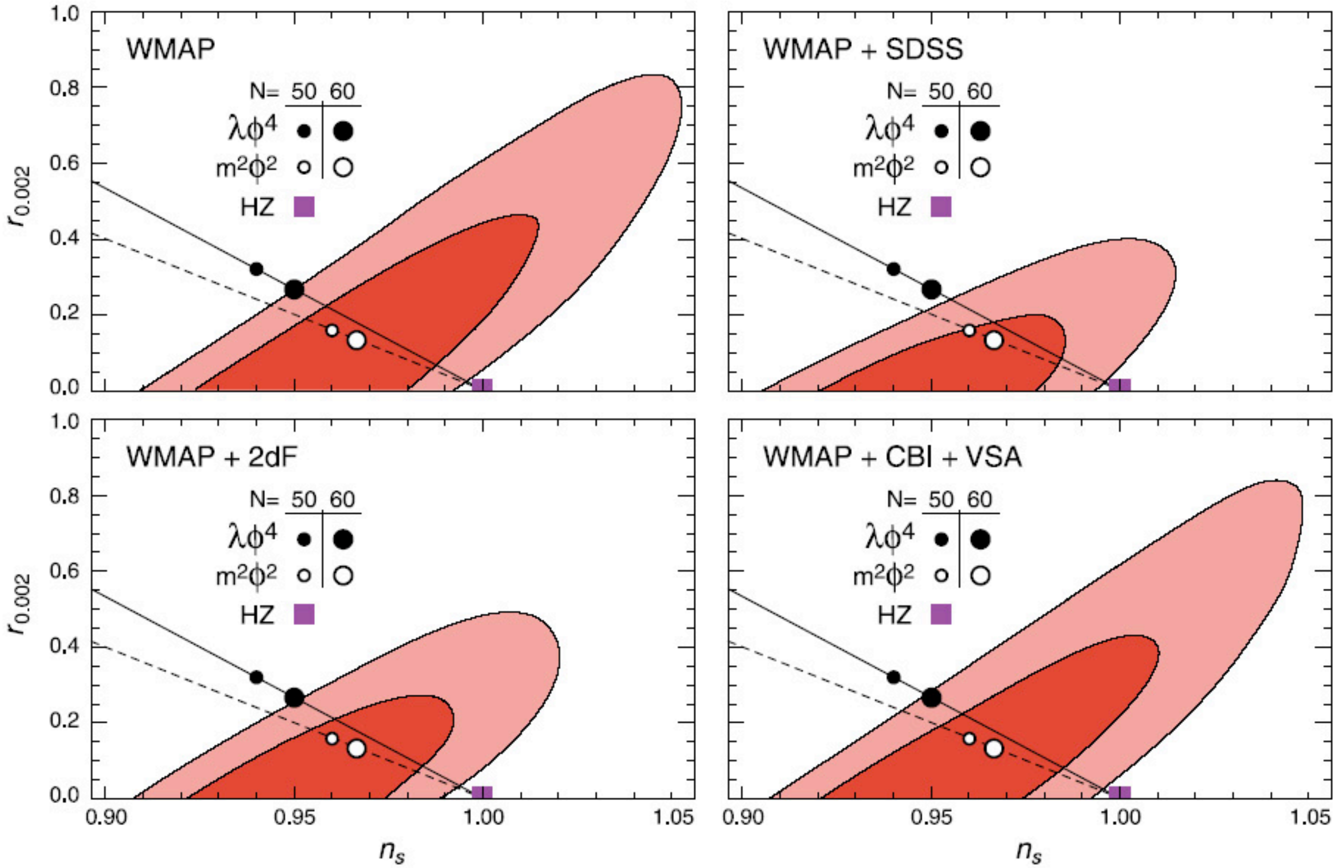

FIG. 14.—Joint two-dimensional marginalized contours (68% and 95% confidence levels) for inflationary parameters ($r_{0.002}$, n_s). We assume a power-law primordial power spectrum, $dn_s/d\ln k = 0$, as these models predict a negligible amount of running index, $dn_s/d\ln k \approx -10^{-3}$. *Upper left*: *WMAP* only. *Upper right*: *WMAP* + SDSS. *Lower left*: *WMAP* + 2dFGRS. *Lower right*: *WMAP* + CBI + VSA. The dashed and solid lines show the range of values predicted for monomial inflaton models with 50 and 60 *e*-folds of inflation (eq. [13]), respectively. The open and filled circles show the predictions of $m^2\phi^2$ and $\lambda\phi^4$ models for 50 and 60 *e*-folds of inflation. The rectangle denotes the scale-invariant Harrison-Zel'dovich-Peebles (HZ) spectrum ($n_s = 1$, $r = 0$). Note that the current data prefer the $m^2\phi^2$ model over both the HZ spectrum and the $\lambda\phi^4$ model by likelihood ratios greater than 12. ($\delta\chi^2 > 5$).

Cosmology

Composition?

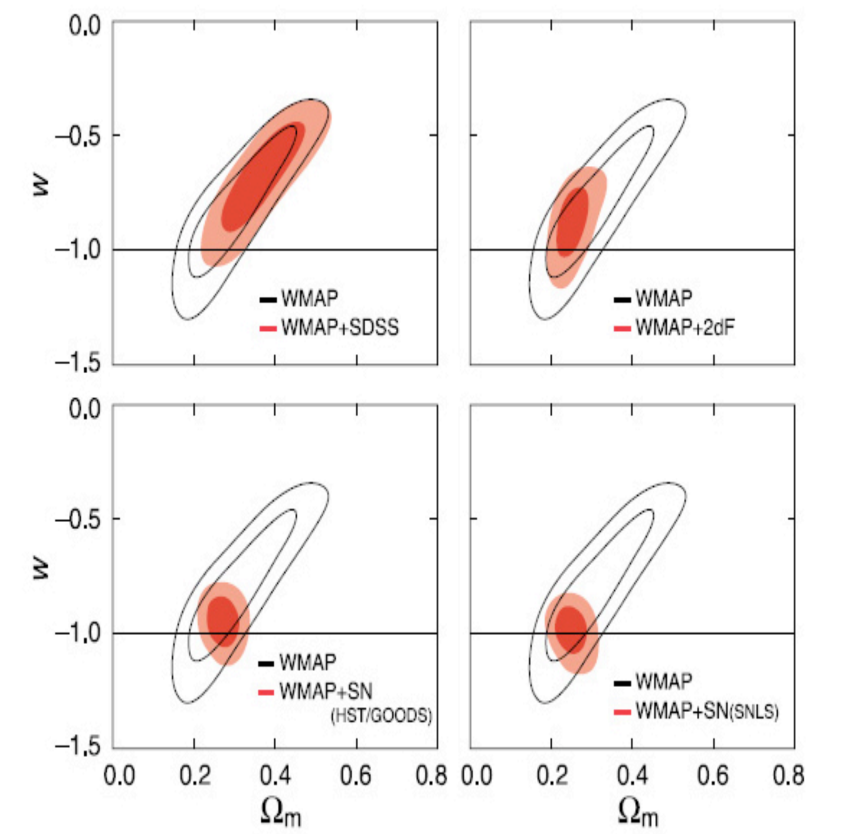

FIG. 15.—Constraints on w, the equation of state of dark energy, in a flat universe model based on the combination of *WMAP* data and other astronomical data. We assume that w is independent of time and ignore density or pressure fluctuations in dark energy. In all of the figures, *WMAP* only constraints are shown in blue and *WMAP* + astronomical data set in red. The contours show the joint 2D marginalized contours (68% and 95% confidence levels) for Ω_m and w. *Upper left*: *WMAP* only and *WMAP* + SDSS. *Upper right*: *WMAP* only and *WMAP* + 2dFGRS. *Lower left*: *WMAP* only and *WMAP* + SN(*HST*/GOODS). *Lower right*: *WMAP* only and *WMAP* + SN(SNLS). In the absence of dark energy fluctuations, the excessive amount of ISW effect at $l < 10$ places significant constraints on models with $w < -1$.

Cosmology

Geometry?

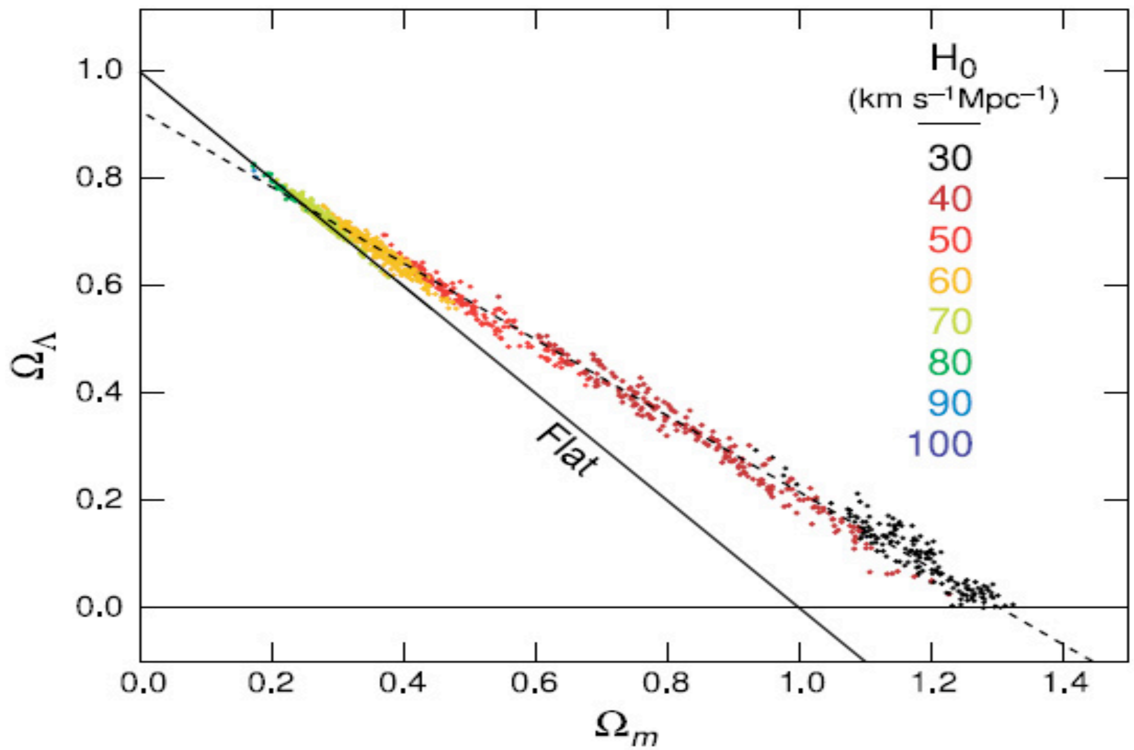

FIG. 21.—Range of nonflat cosmological models consistent with the *WMAP* data only. The models in the figure are all power-law CDM models with dark energy and dark matter, but without the constraint that $\Omega_m + \Omega_\Lambda = 1$ (model M10 in Table 3). The different colors correspond to values of the Hubble constant as indicated in the figure. While models with $\Omega_\Lambda = 0$ are not disfavored by the *WMAP* data only ($\Delta\chi^2_{\rm eff} = 0$; model M4 in Table 3), the combination of *WMAP* data plus measurements of the Hubble constant strongly constrain the geometry and composition of the universe within the framework of these models. The dashed line shows an approximation to the degeneracy track: $\Omega_K = -0.3040 + 0.4067\Omega_\Lambda$. Note that for these open universe models, we assume a flat prior on Ω_Λ.

Cosmology

Conclusions:

3rd year WMAP data in concert with other observations and ΛCDM theory.

Significantly improved parameter precision.

Significant limits on composition and geometry of the Universe.

Issues:

H_o value and Li abundance.

ΛCDM model is now very constrained: double edged sword?

Other models are very undeveloped: fair comparison?