

Exploring the Dark Universe with the Cosmic Microwave Background

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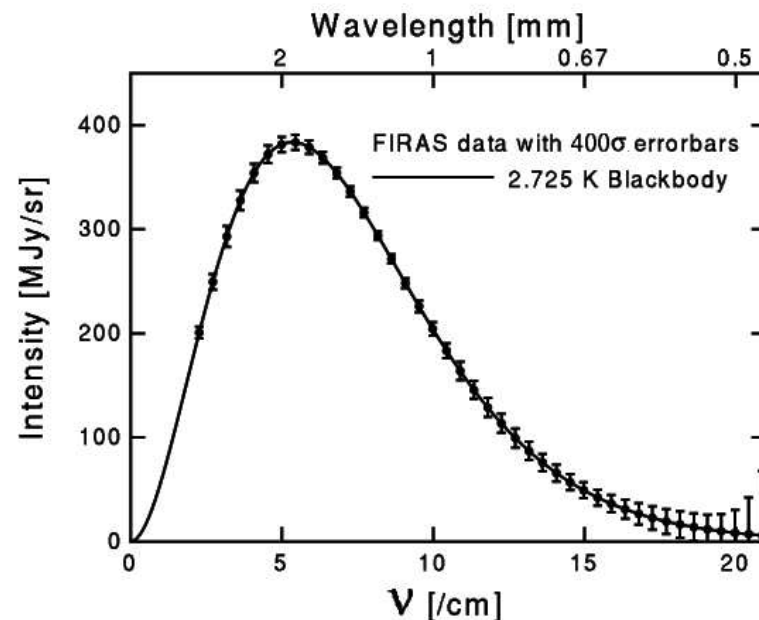
What was after the universe? Nothing. But
was there anything round the universe to show
where it stopped before the nothing place be-
gan? It could not be a wall; but there could be
a thin thin line there all round everything.

History of the CMB

- Cosmic Microwave Background with $T \approx 5$ K predicted by George Gamov in 1946.
- First observational evidence (though not yet interpreted as such): excitation of rotation bands in interstellar CN gas (1941).
- Direct detection by Penzias and Wilson in 1965 as isotropic background noise.
- Subsequent ground/balloon/satellite-based experiments studying the anisotropy of the CMB included COBE (1992), BOOMERANG, WMAP (2003); the PLANCK mission is in preparation.

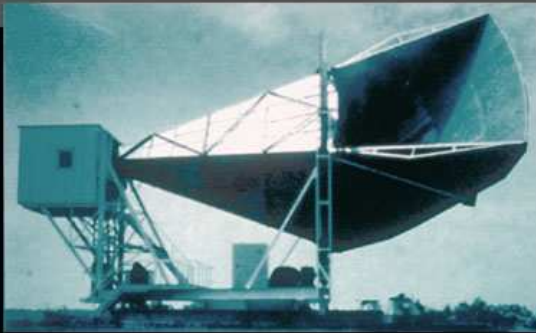
Right: Spectrum of the CMB compared to black-body spectrum.

Οὐ γὰρ ἀπὸ νώτοιο δύο κλάδοι αἴσσονται, οὐ πόδες, οὐ θοὰ γοῦνα, οὐ μήδεα γεννήεντα, ἀλλὰ Σφαῖρος ἔην καὶ πάντοθεν ἴσος ἑαυτῷ. (Empedocles)

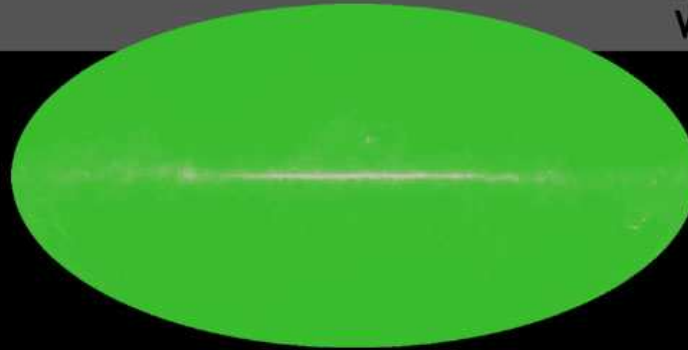


Past and Future CMB Experiments

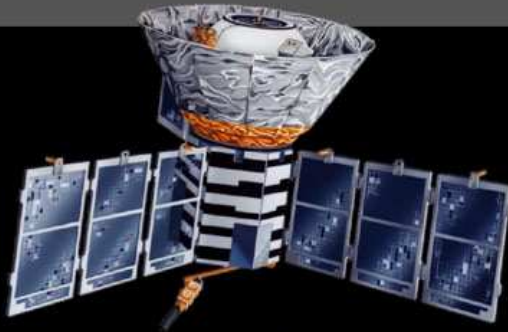
1965



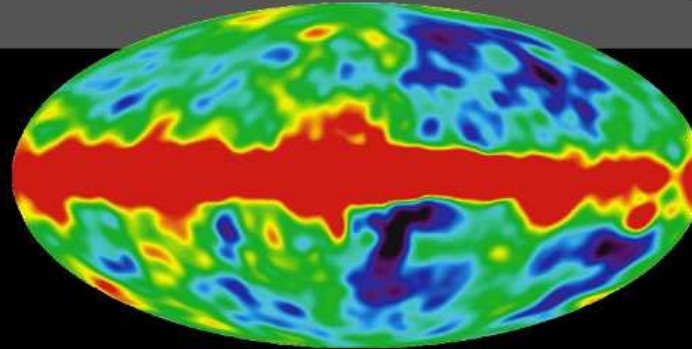
Penzias and Wilson



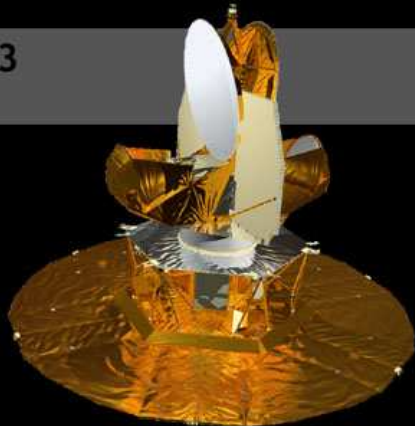
1992



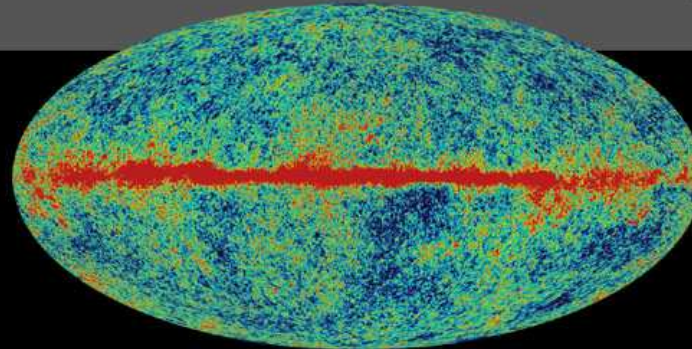
COBE



2003



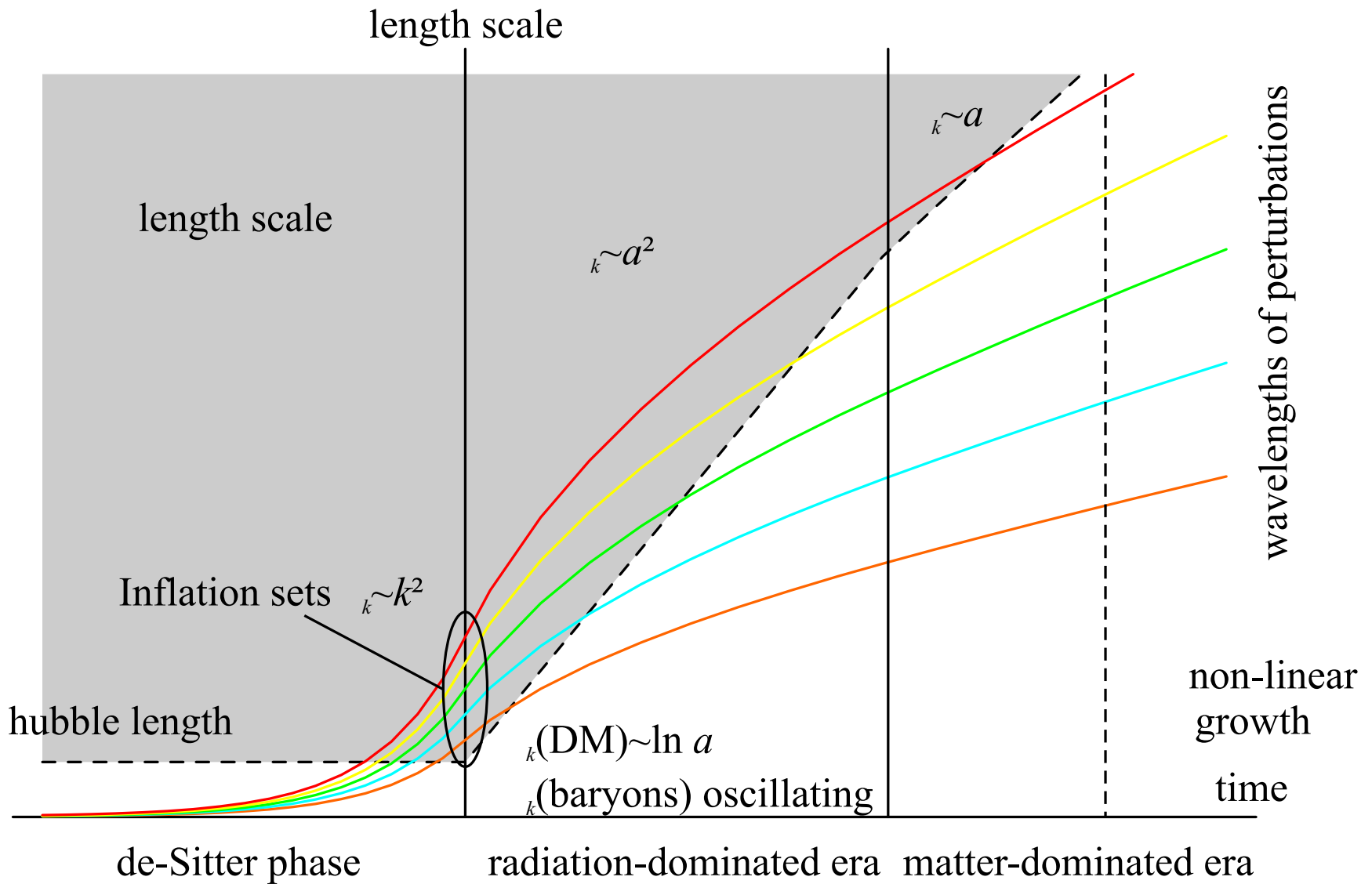
WMAP



From Inflation to the CMB

- Quantum fluctuations during inflation
- Growth/damping of perturbations until decoupling
- Perturbations imprinted on CMB at last scattering
- Modification of CMB by foreground effects

Growth of Perturbations



Relic Fluctuations from Inflation

Fluctuations of the inflaton field ϕ from quantum field theory (frozen in at horizon crossing):

$$\delta_{\phi}^2(k) = \left(\frac{\hbar H}{2\pi} \right)^2$$

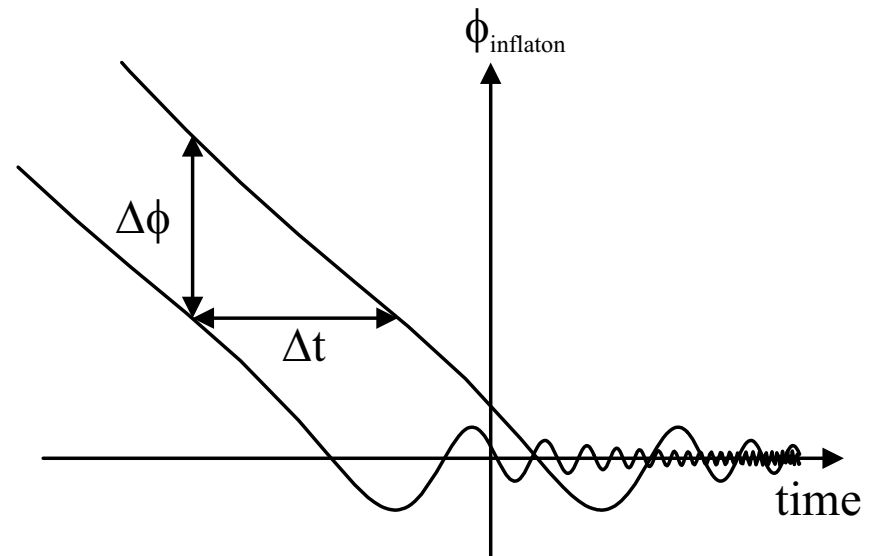
Hence: Almost scale-invariant fluctuations of the “local scale factor” and of the gravitational potential Φ at the end of inflation:

$$\delta_{\Phi}(k) = \frac{\delta_a(k)}{a} = \frac{H^2}{2\pi \dot{\phi}}$$

Perturbations of the density:

$$\delta_{\rho}(k) \sim k^2$$

Most inflation models predict a slight deviation from scale-invariance (*tilt*) \rightarrow Spectrum contains information about the physics of the early universe.



Growth of Density Perturbations

$\lambda >$ Hubble length:

$$\delta_k \sim a^2(\text{radiation dominated}); \quad \delta_k \sim a(\text{matter dominated})$$

$\lambda <$ Hubble length:

Dark Matter:

$$\ddot{\delta}_{\mathbf{k}} + 2\frac{\dot{a}}{a}\dot{\delta}_{\mathbf{k}} = 4\pi G(\bar{\rho}_{\text{B}} + \bar{\rho}_{\text{DM}})\delta_{\mathbf{k}}$$

$$\delta_k \sim \ln a(\text{radiation dominated}); \quad \delta_k \sim a(\text{matter dominated});$$

Baryons (and photons before decoupling):

$$\ddot{\delta}_k + 2\frac{\dot{a}}{a}\dot{\delta}_k + \frac{k^2 c_s^2}{a^2}\delta_k = 4\pi G(\bar{\rho}_{\text{B}} + \bar{\rho}_{\text{DM}})\delta_k$$

→ No growth of perturbations for high k ($\lambda < \lambda_{\text{Jeans}}$), oscillations instead.

Damping Processes

- As long as the dark matter particles are relativistic, density perturbations can be erased by free streaming over $\lambda_{\text{FS}} \approx \lambda_H$. For particles of mass m_X the maximum scale is $\lambda_{\text{FS};\text{max}} \sim m_X$. \rightarrow Distinction hot/cold DM possible.
- In the process of decoupling from the baryons, the photons undergo a diffusion phase, which leads to damping on a length scale of $\lambda_{\text{Silk}} \approx \sqrt{\lambda_H \lambda_{\text{scat}}}$, where λ_{scat} is the photon mean free path.

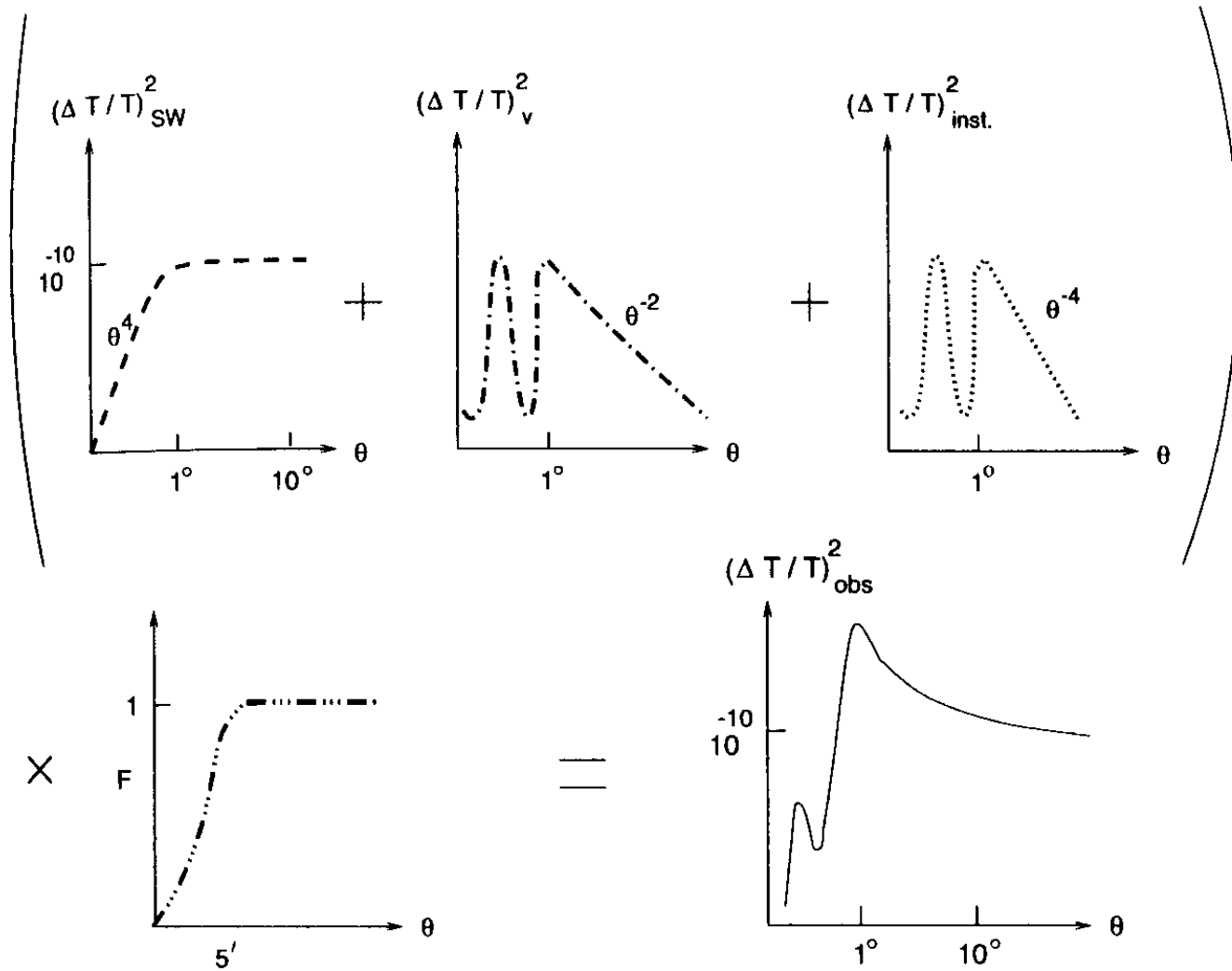
The Photon-Baryon Fluid

- At $z \approx 1500$: Transition to the matter-dominated phase ($\Omega_b \approx \Omega_\gamma$).
- The redshift of the recombination phase depends weakly on Ω_b : $1 + z_{\text{rec}} \approx 1380(\Omega_b h^2)^{0.023} \approx 1240 \dots 1380$. As the number of free electrons drops, the opacity of the baryon fluid decreases significantly.
- When the mean free path for Thomson scattering becomes comparable to the Hubble length (at $1 + z \approx 1100(\Omega_0/\Omega_b)^{0.018}$, the photons decouple from the baryons. The last scattering events are distributed over a finite redshift region of $\Delta z \approx 80$. \rightarrow Fluctuations in the photon temperature on scales $\lesssim 5'$ are smeared out.

Anisotropy at Decoupling

- Photons from overdense regions are redshifted (*Sachs-Wolfe effect*)
$$\frac{\delta T}{T} \sim \delta\Phi \sim \frac{\delta_k}{k^2}$$
- Adiabatically compressed regions are hotter: $\frac{\delta T}{T} \sim \delta_k$. Hence, acoustic oscillations will lead to peaks in the power spectrum for those modes which happen to be in the phase of maximum or minimum compression at decoupling.
- The velocity perturbation associated with the density perturbation causes a Doppler shift: $\frac{\delta T}{T} \sim \delta\mathbf{v} \cdot \mathbf{r} \sim \frac{\mathbf{k} \cdot \mathbf{r}}{r} \dot{\delta}_k$.
- Because of the phase-shift of 90° , the Doppler effect tends to cancel the peaks due to the adiabatic temperature variation, depending on the speed of sound c_s . Cancellation is exact for $c_s = c/\sqrt{3}$.

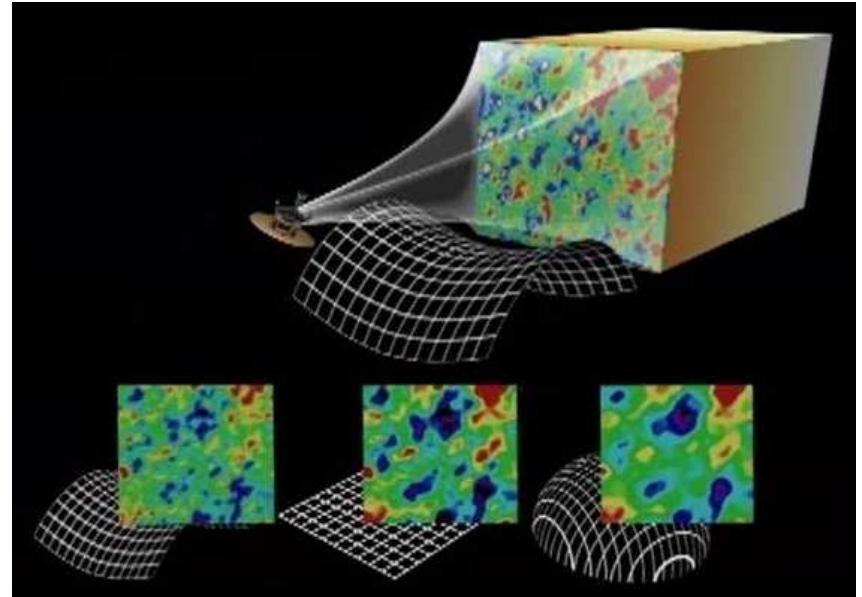
Anisotropy Spectrum of the CMB



6.1. Schematic diagram showing the expected anisotropies in the CMBR temperature at different angular scales.

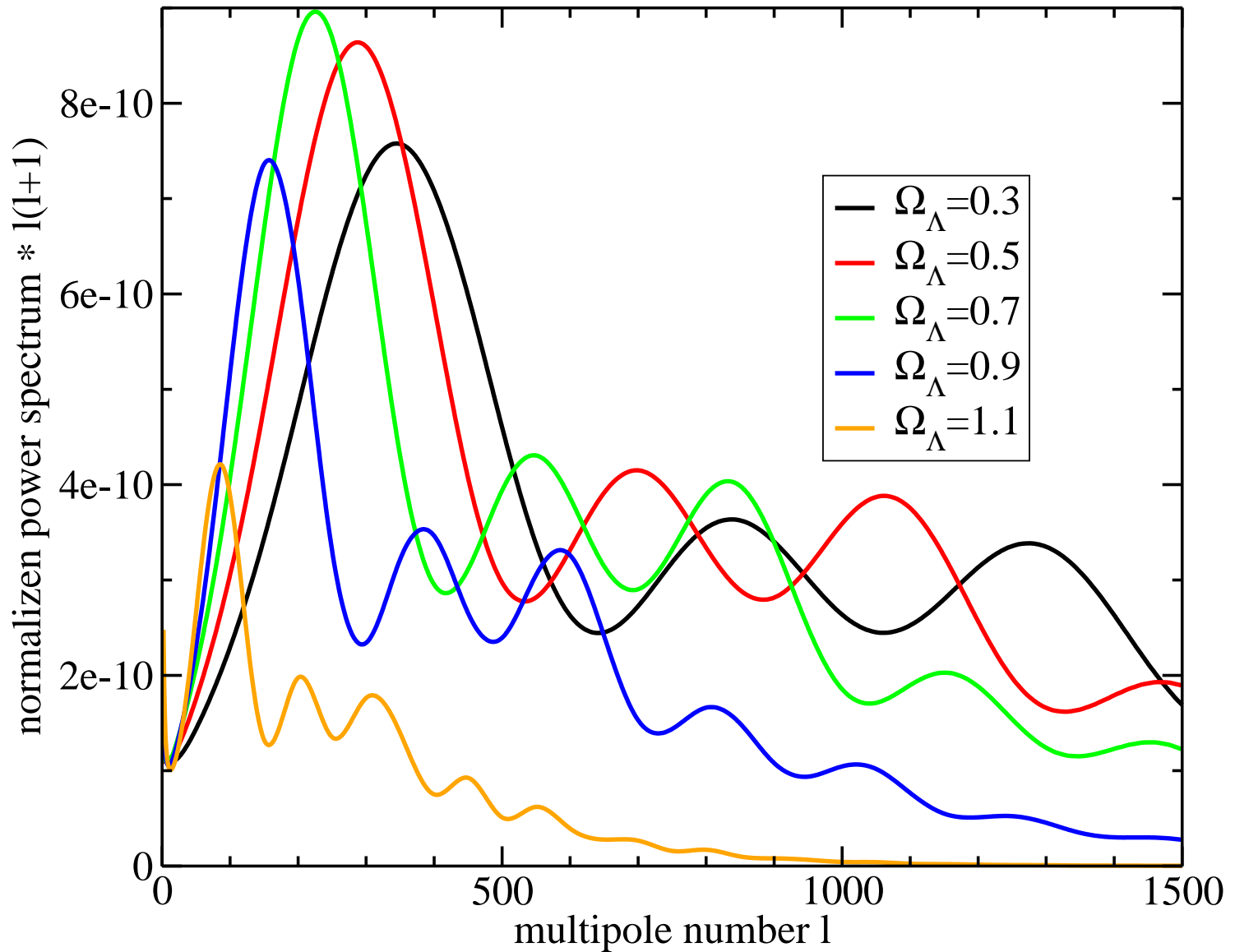
The Cosmological Parameters

- The spectrum of temperature fluctuations (in 3D) needs to be converted into the power spectrum of CMB anisotropies on the last scattering surface (LSS) view from earth (2D).
- The geometry of the universe has to be taken into account as well: For positive/negative spatial curvature, a fixed length scale on the LSS appears larger/smaller than in a flat universe.
- Since first acoustic peak appears at a more or less fixed wavenumber corresponding to $\lambda_1 \approx \lambda_H(\text{decoupling})$, its location in the power spectrum determines Ω_{tot}

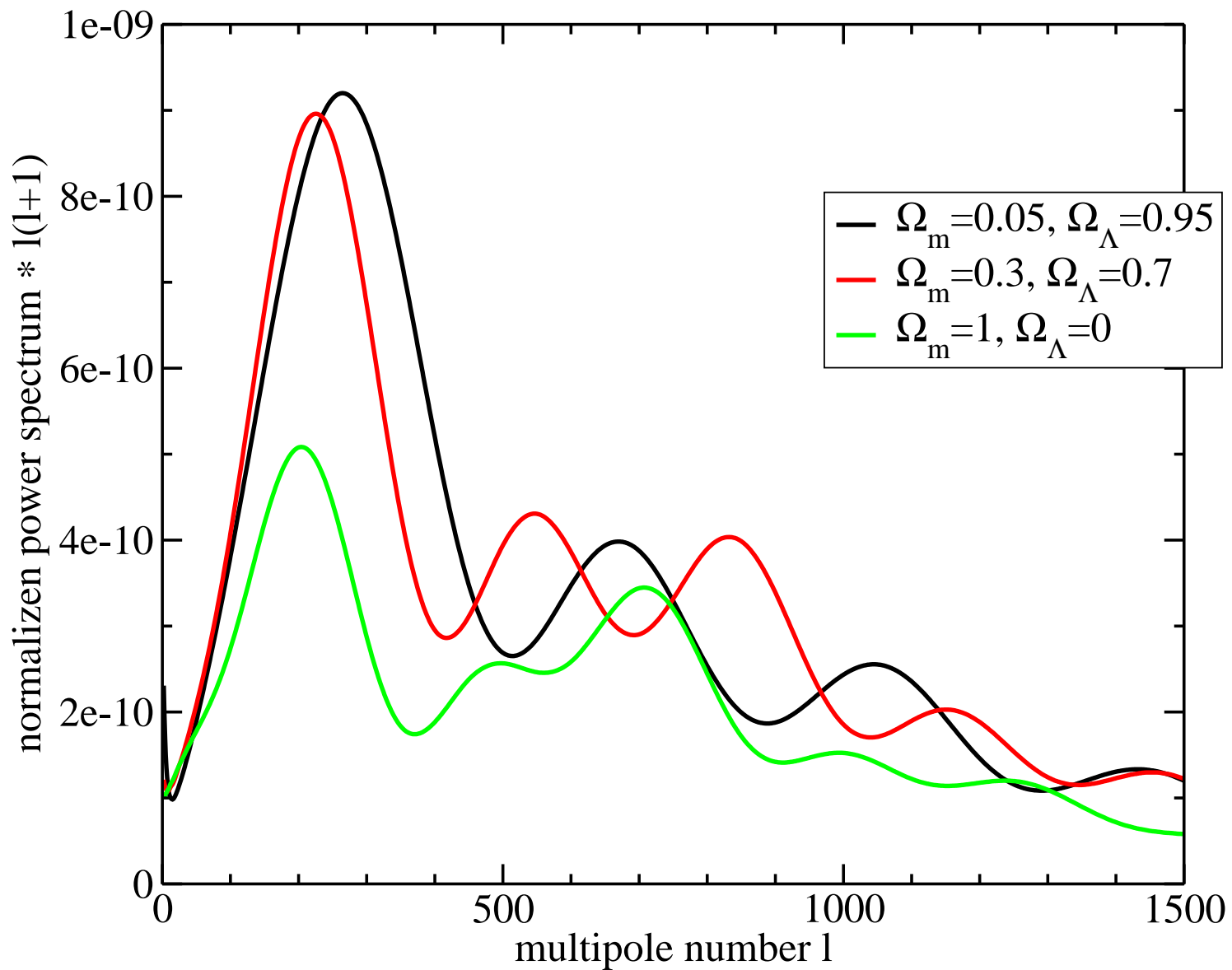


- The relative strengths of the acoustic peaks is sensitive to the baryon density Ω_b (complex interplay between Doppler effect and adiabatic temperature variations).

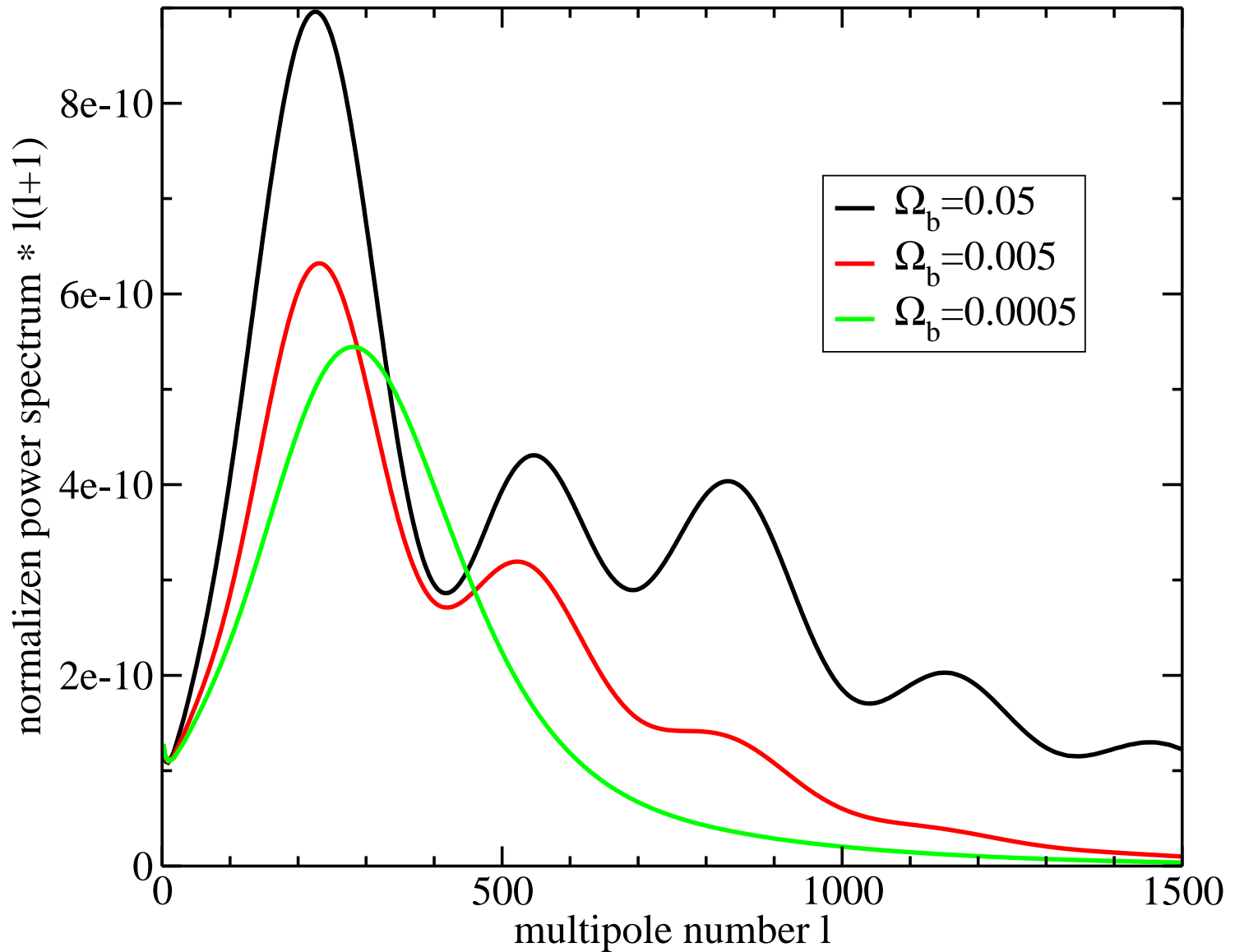
Varying Ω_{tot}



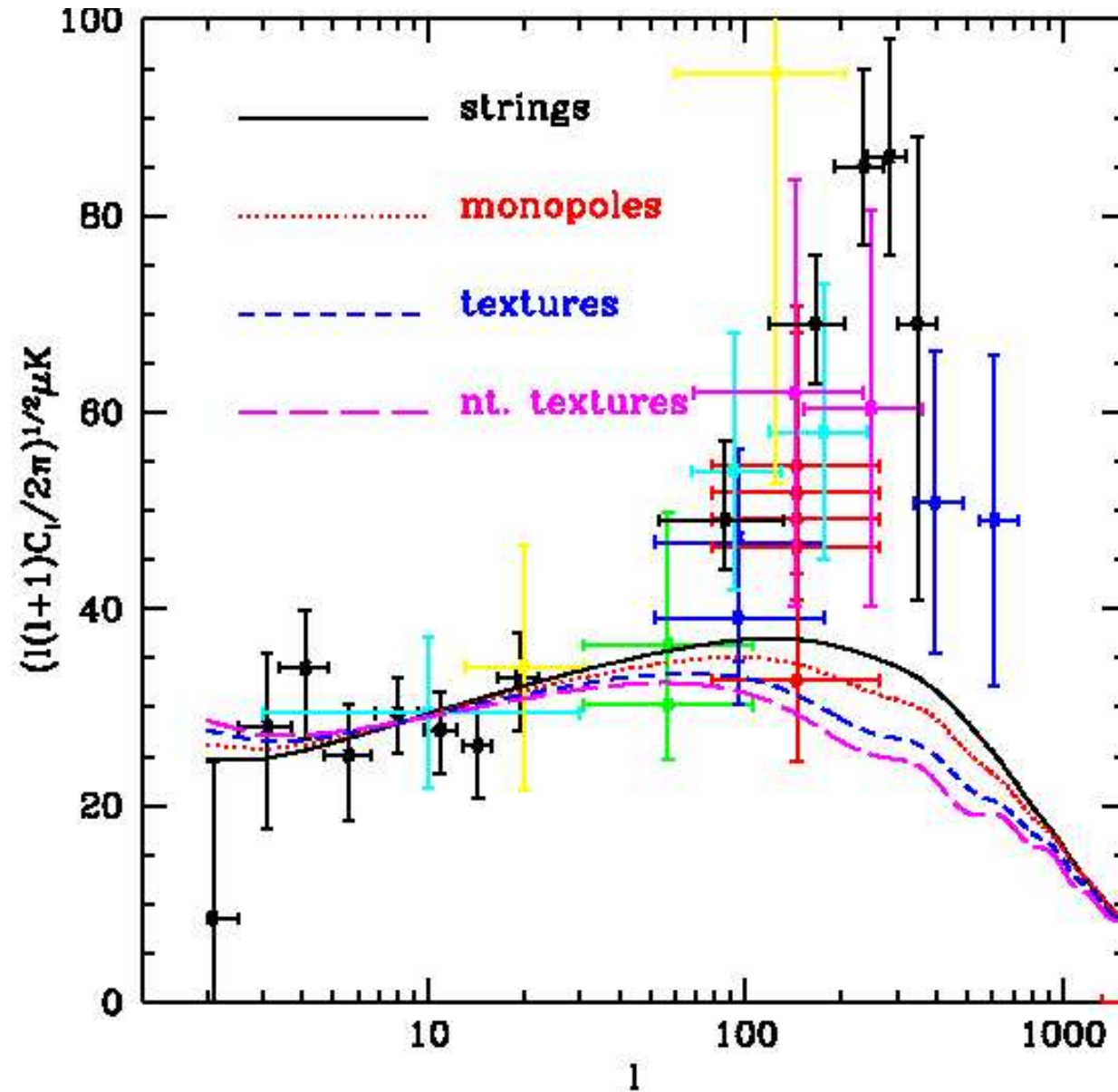
Varying $\Omega_m - \Omega_\Lambda$



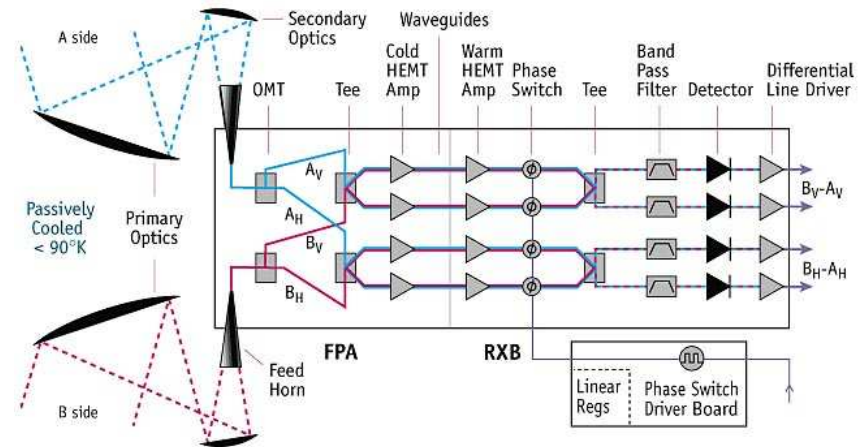
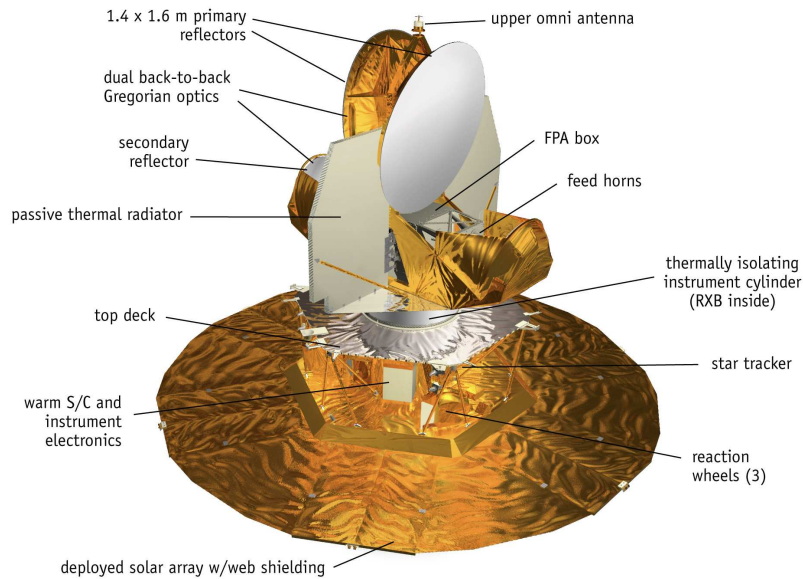
Varying Ω_b



Ruling out Some Dark Matter Scenarios



Measuring the CMB – WMAP



Microwave Band	K	Ka	Q	V	W
Frequency/GHz	22	30	40	60	90
Wavelength/mm	13.6	10.0	7.5	5	3.3
Angular Resolution (FWHM)/degrees	0.93	0.68	0.53	0.35	< 0.35

Analysis of Experimental Data

Principle:

Decompose into spherical harmonics:

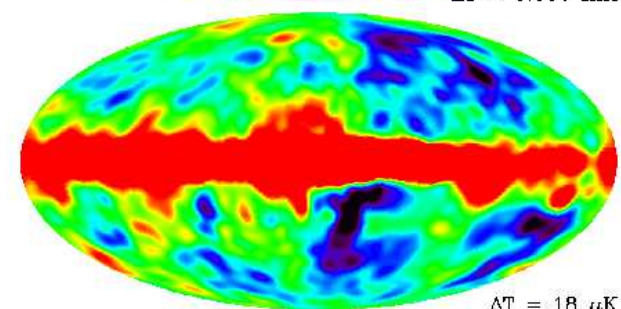
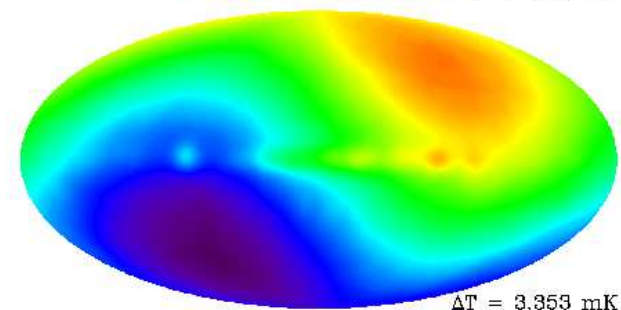
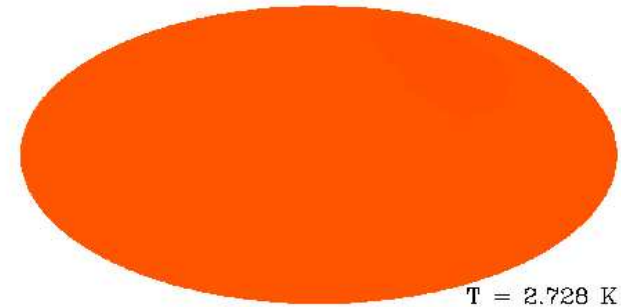
$$\Delta T/T(\theta, \phi) = \frac{1}{4\pi} \sum_{m, \ell} a_{\ell}^m Y_{\ell m}(\theta, \phi).$$

Compare the power spectrum

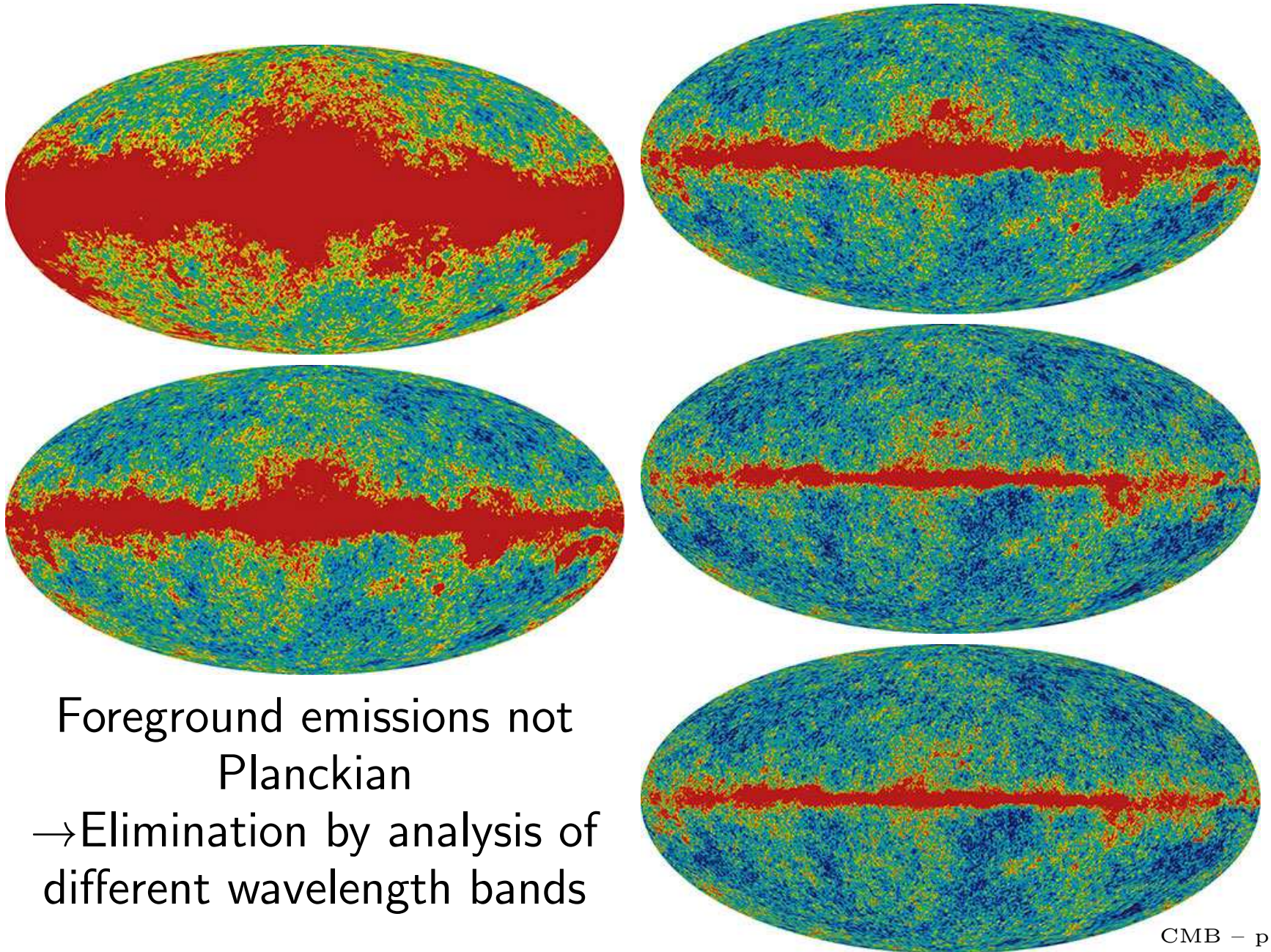
$$c_{\ell} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{\ell}^m$$
 and compare to numerical predictions.

Issues:

- Peculiar motion of the earth (→CMB dipole)
- Modification of the CMB by re-ionization
- Foreground emissions from our galaxy

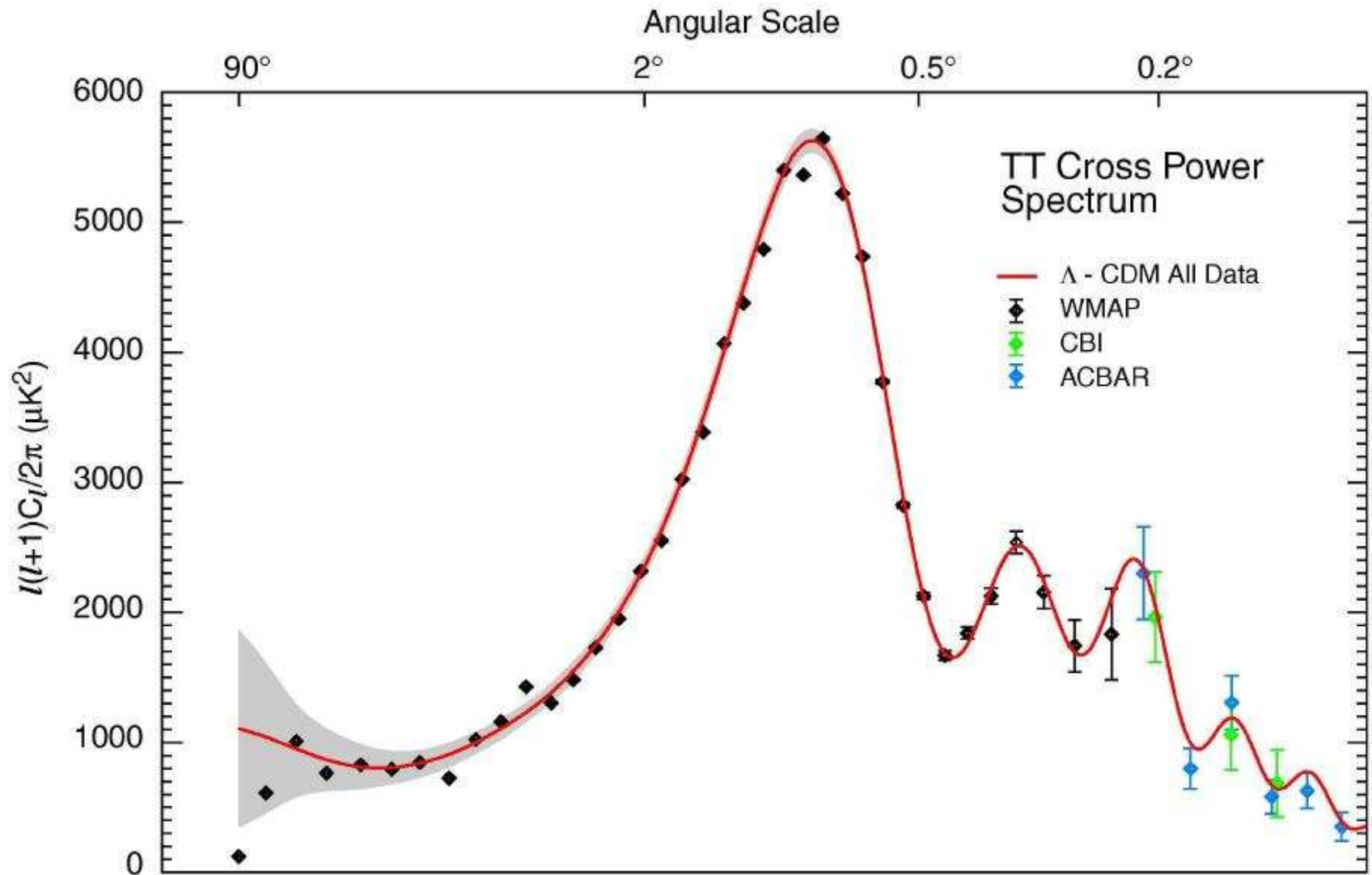


The Galactic Foreground



Foreground emissions not
Planckian
→ Elimination by analysis of
different wavelength bands

The Observed Power Spectrum



Summary of Basic WMAP Results

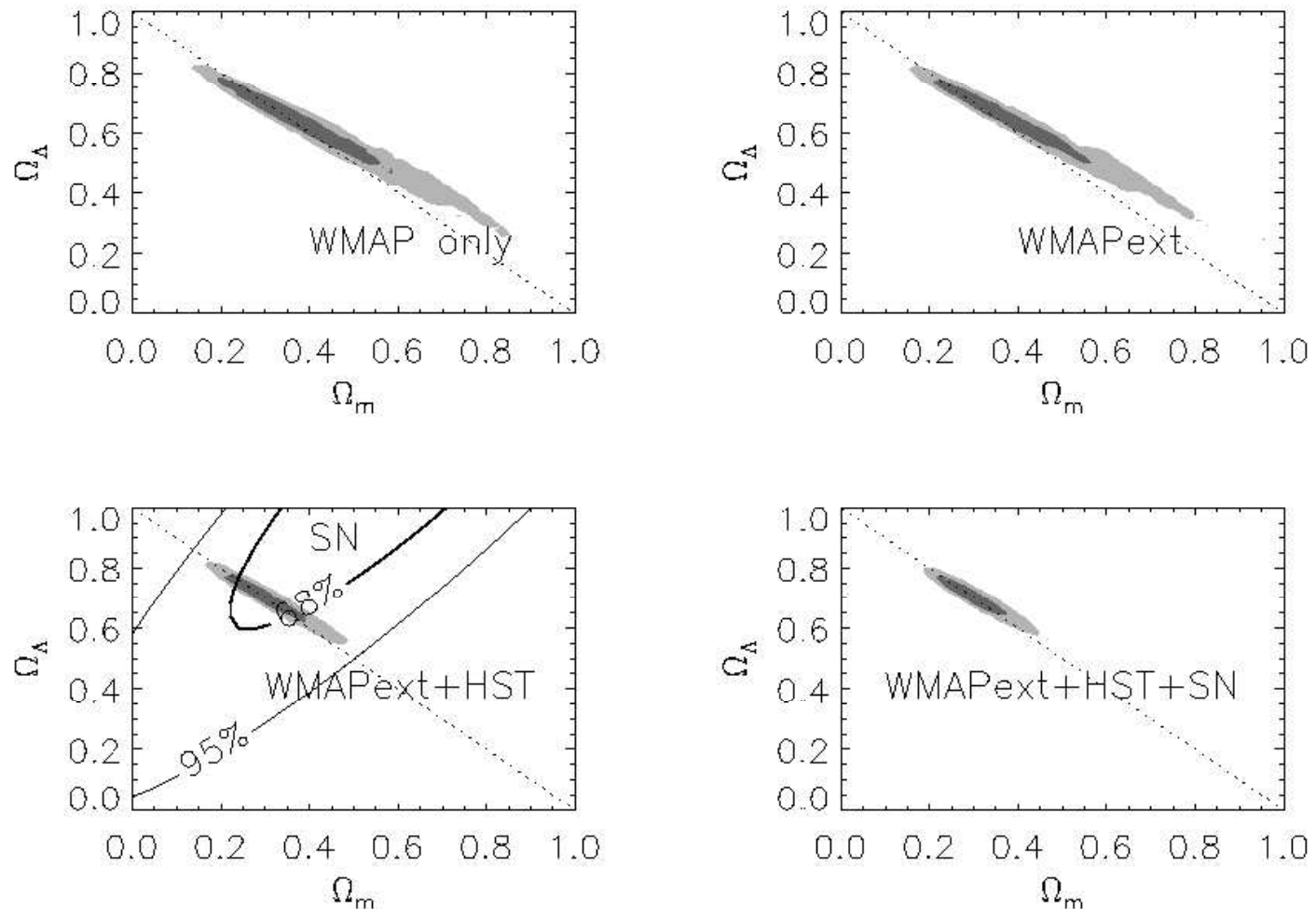
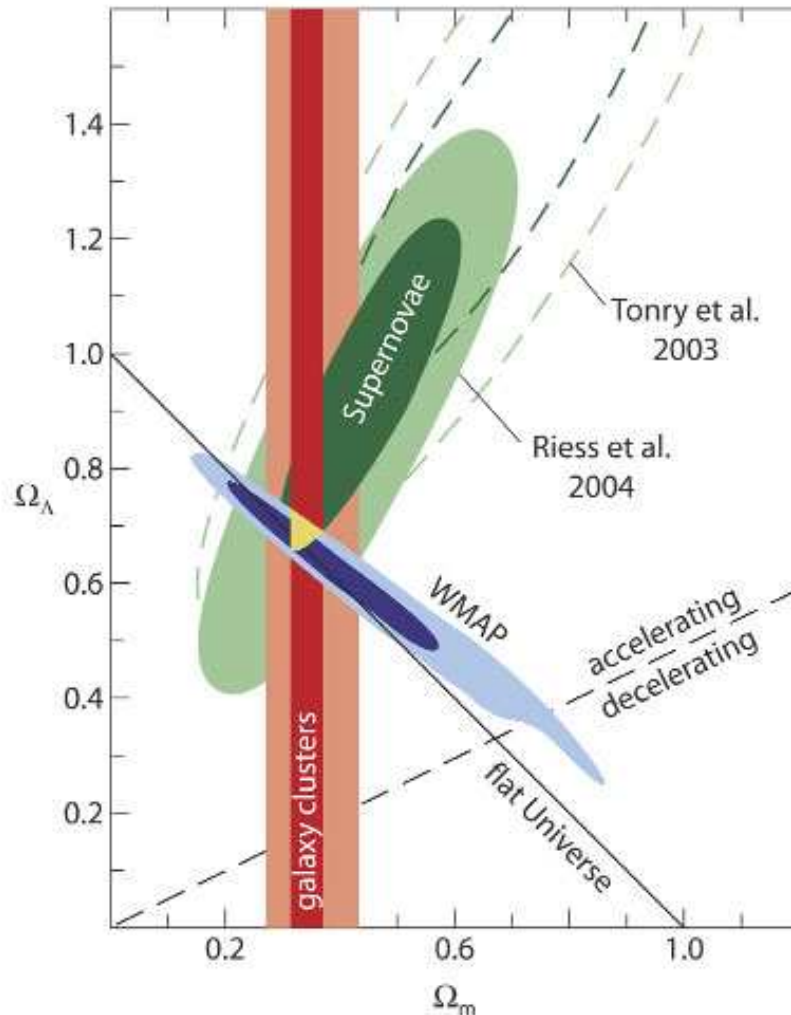


Fig. 13.— Constraints on the geometry of the universe: $\Omega_m - \Omega_\Lambda$ plane. This figure shows the two dimensional likelihood surface for various combinations of data: (upper left) WMAP (upper right) WMAPext (lower left) WMAPext+ HST Key Project (supernova data (Riess et al. 1998, 2001) is shown but not used in the likelihood in this part of the panel; (lower right) WMAPext+ HST Key Project + supernova

Summary of Basic WMAP Results

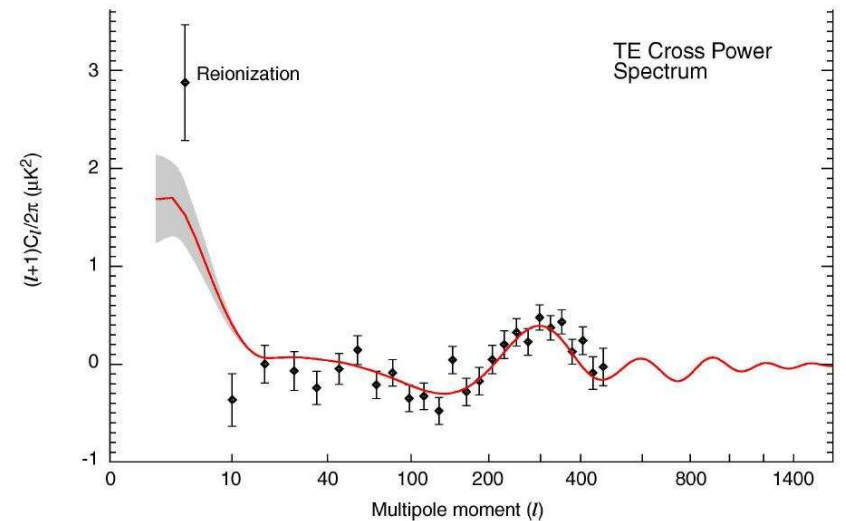
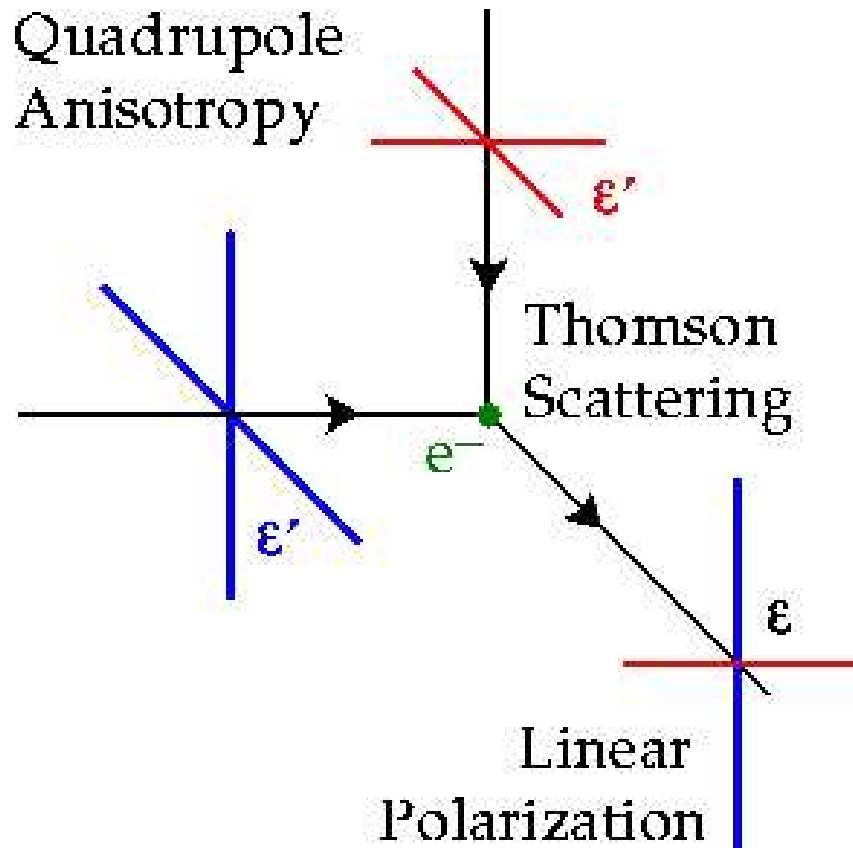


Some cosmological parameters from WMAP (+additional data from other experiments):

Ω_{tot}	1.02 ± 0.02
Ω_b	0.044 ± 0.004
Ω_Λ	0.73 ± 0.04
Ω_m	0.27 ± 0.04
Ω_ν (light neutrinos)	$\lesssim 0.015$
Age of universe	$(13.7 \pm 0.2) \cdot 10^9 \text{a}$

Constraining the Cosmological Parameters

Polarization of the CMB



(Temperature-polarization cross-power spectrum from APJS 148(2003)161-173)

- Scattering of an anisotropic radiation field leads to polarization.
- During re-ionization, large angular scales ($> 1^\circ$) affected \rightarrow separable from "primary" anisotropies (result: $z_{\text{reionization}} \approx 17$)
- Polarization also sensitive to the physics of the early universe.

The Sunyaev-Zeldovich Effect

Mechanism:

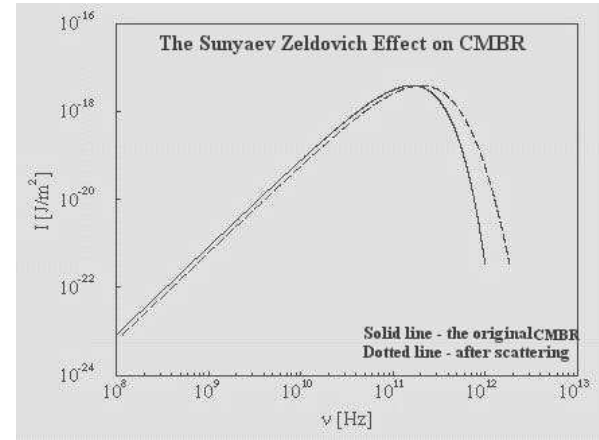
- Thomson scattering of CMB photons by highly energetic can lead to a distortion of the Planck spectrum.
- Rayleigh-Jeans part: decrease of the brightness temperature
- Wien part: increase of the brightness temperature

Cosmological application to galaxy clusters containing hot ionized gas of temperature T_e :

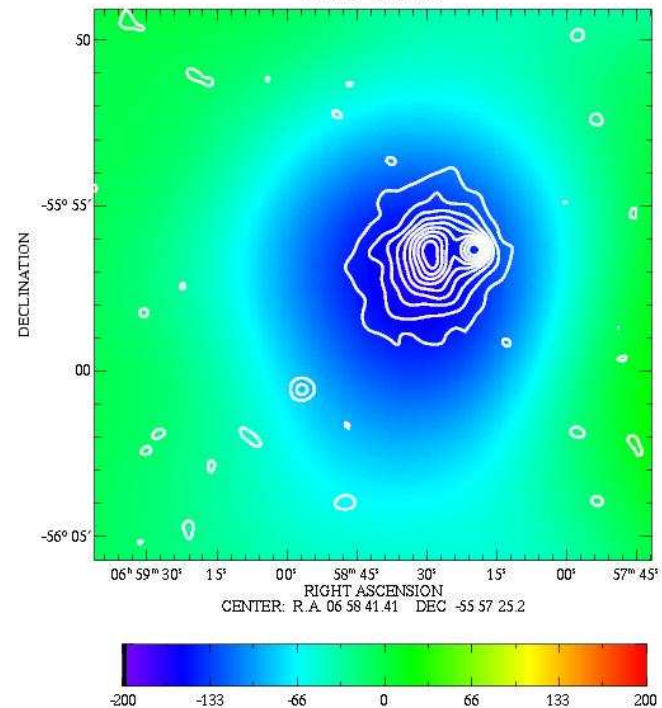
$$\Delta_T/T = \frac{4kT_e}{m_e c^2} \sigma_{\text{Thompson}} n_e R$$

If number density n_e of electrons and T_e known (from X-ray spectra) \rightarrow SZ effect gives the cluster radius R and allows a precise determination of the distance.

Bottom right: Deviation of the brightness temperature from the background value due to the SZ effect for an X-ray cluster.



150 GHz



The Sunyaev-Zeldovich Effect

Mechanism:

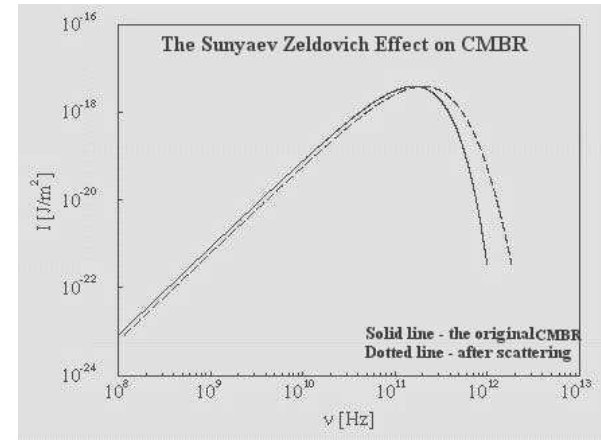
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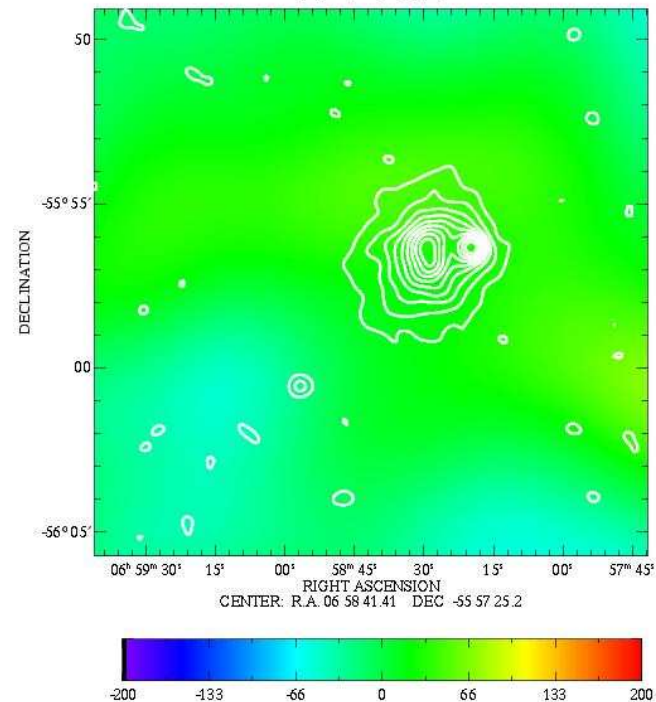
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Bottom right: Deviation of the brightness temperature from the background value due to the SZ effect for an X-ray cluster.



220 GHz



The Sunyaev-Zeldovich Effect

Mechanism:

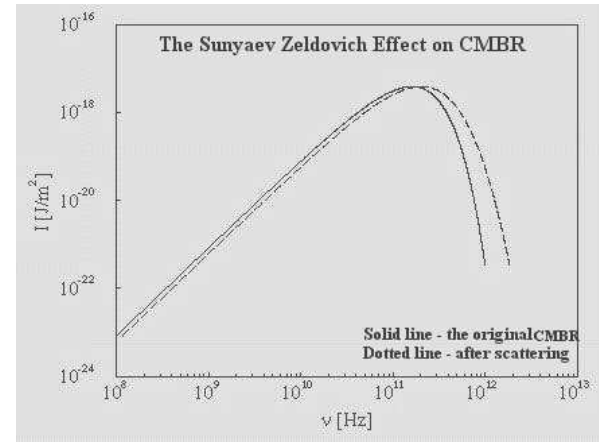
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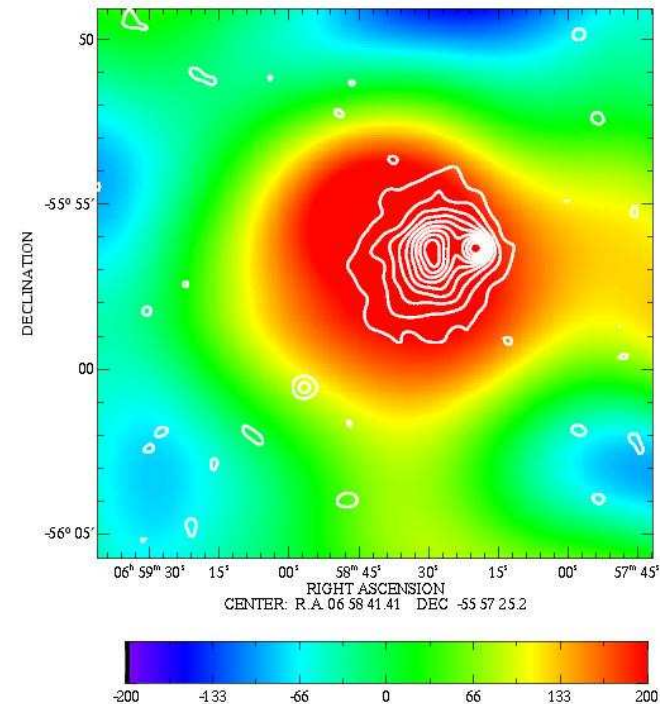
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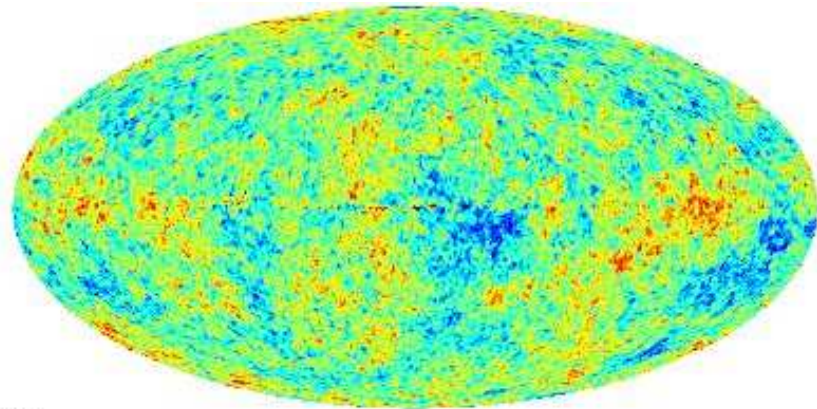
275 GHz



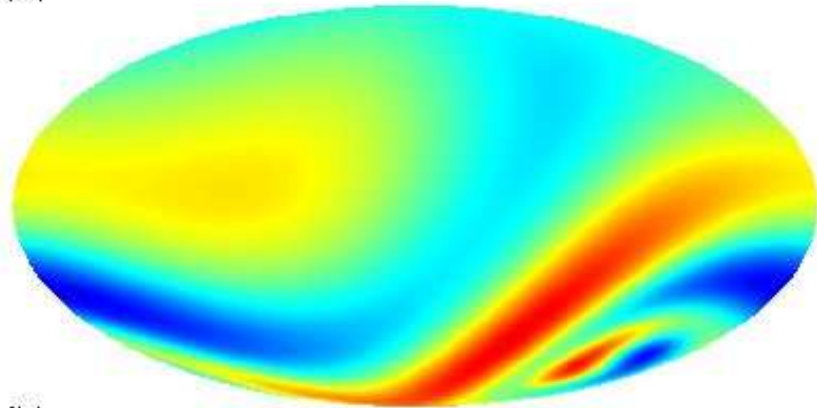
Some Advanced Topics

- Deviation of the primordial power spectrum from scale-invariance → testing inflationary predictions (WMAP result: running spectral index $d \ln P_k / d \ln k$ preferred to simple power law, Φ^4 -potential not preferred, etc.)
- Non-scalar perturbations and traces of gravitational waves from inflation
- Origin and interpretation of large-scale anisotropies in the CMB
- Gaussianity or non-Gaussianity of the fluctuations

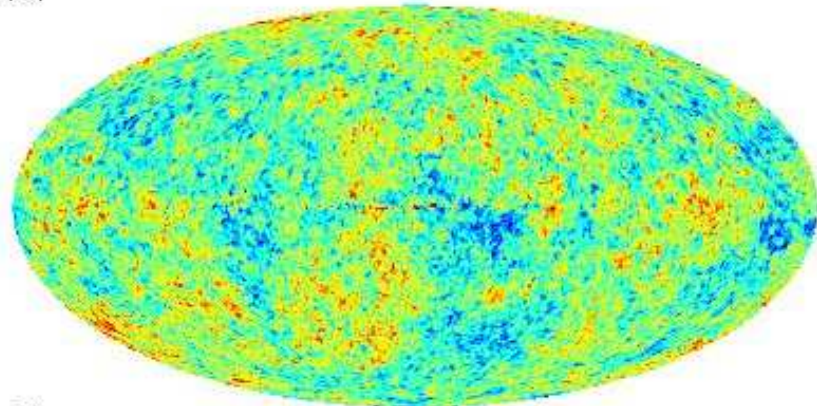
Global Anisotropies



(a)



(b)

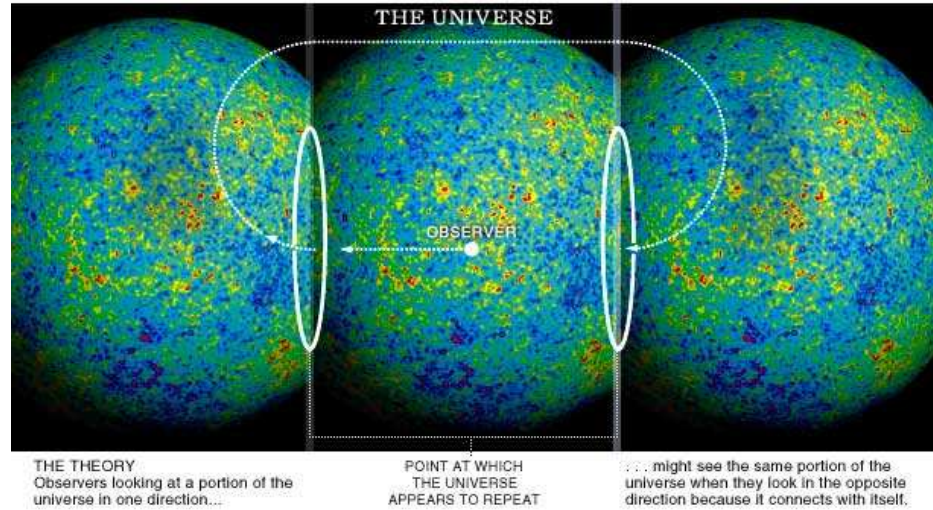
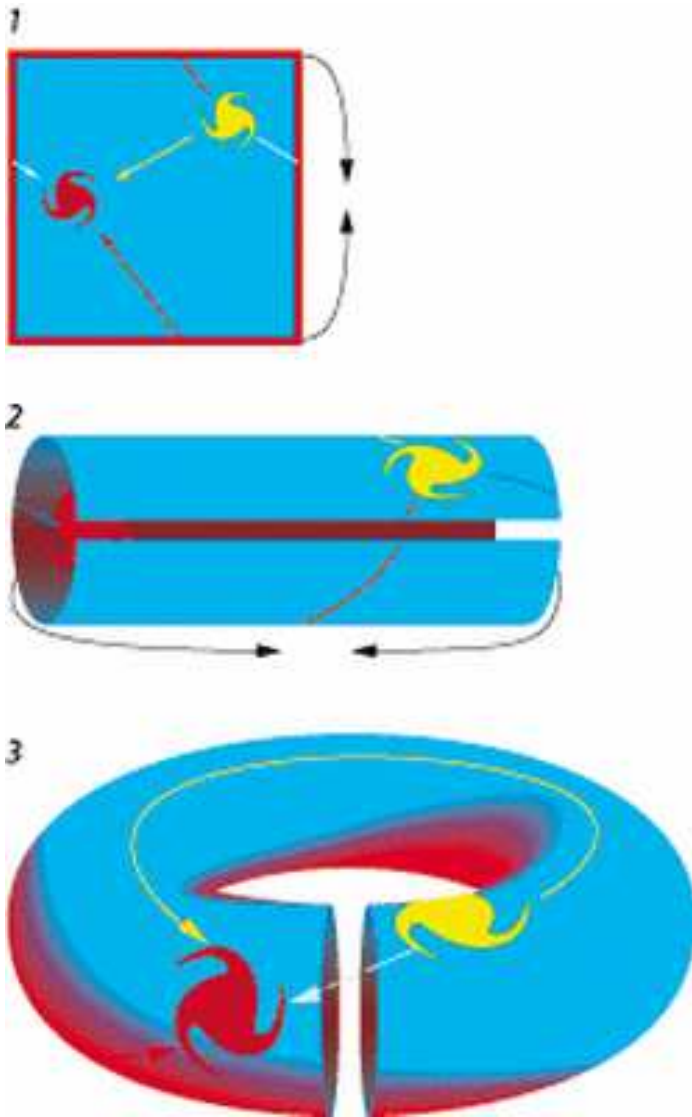


(c)

Certain large-scale features in the CMB (different fluctuation amplitudes in different hemispheres) suggest (cf. Jaffe et al., ApJL, 629(2005)L1) that the correct model for the background metric might be non-isotropic (Bianchi solution). However, statistics is a tough business!

Left: a) observed CMB pattern, b) anisotropy contribution from best-fit Bianchi model (anisotropic homogeneous GR solution), c) CMB with correction for global anisotropy

The Topology of the Universe



Even if the hypothesis of constant curvature and (with an isotropic Riemann tensor in the sense that $R_{\lambda\mu\nu\xi} = k(g_{\lambda\nu}g_{\mu\xi} - g_{\lambda\xi}g_{\mu\nu})$) is correct, the topology of the universe is still not fixed. Non-trivial correlations in the CMB might provide a clue to its topological structure.

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Figures

Slide 2: <http://www.astro.ucla.edu/wright/spectrum.gif> Slides 3, 12, 17-19: NASA: <http://map.gsfc.nasa.gov>

Slide 11: T. Padmanabhan, Theoretical Astrophysics, vol. 3

Slide 16: <http://www.livingreviews.org/lrr-1998-11>

Slide 18: <http://www.astronet.ru/db/xware/msg/1166084>

Slide 21: <http://www.eso.org/outreach/press-rel/pr-2004/pr-15-04.html>

Slide 24 (top): <http://universe-review.ca/I02-07-SZE.jpg>

Slide 24 (bottom): Plasmas in the Laboratory and in the Universe: New Insights and New Challenges. AIP Conference Proceedings, Volume 703, pp. 361-366 (2004)

Slide 26: http://www.mpa-garching.mpg.de/mpa/research/current_research/hl2005-9

Slide 27: <http://astro.uchicago.edu/home/web/olinto/courses/A18200/nbower.htm>

The CMB power spectra on slides 13-15 have been computed with the code CMBFAST

(available from <http://www.cmbfast.org/>)