Computing Our Universe

Special Topic VII – Cosmic Microwave Background

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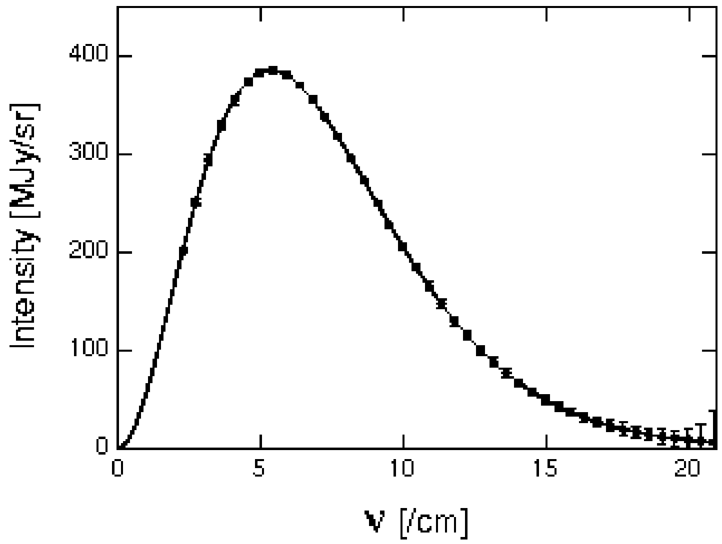
0 IMPLICATIONS OF THE CMB

The four basic properties of the CMB probe four very different and important epochs in the history of the universe:

- **Blackbody Spectrum:** thermal equilibrium, $z > 10^6$
- **Spectral Distortions:** nonequilibrium energetics, $z < 10^6$
- **Isotropy:** inflation at $z \approx 10^{28}$, or superhorizon scales
- **Anisotropy:** large scale structure at/after recombination $z \leq 10^3$

1 SPECTRUM AND HISTORY OF CMB

The CMB spectrum is measured to be a blackbody, Planck spectrum to a fantastic accuracy for an astrophysical measurement.



Its physical characteristics are

$$\rho = 4.7\times 10^{-34}\,(T/2.73\,K)^4\,\mathrm{g\,cm^{-3}} \quad \Rightarrow \quad \Omega_\gamma h^2 = 2.5\times 10^{-5}$$

$$\nu_{peak} = 160\,(T/2.73\,K)\,\mathrm{GHz} \quad ; \quad \lambda_{peak} = 1.9\,(T/2.73\,K)^{-1}\,\mathrm{mm}$$

With expansion $\lambda \sim a$, $T \sim a^{-1}$ so spectrum remains blackbody.
Peaks today in the microwave region.

The lack of spectral distortion shows no significant energy releases occured since thermalization $z \approx 10^6$. Exception is if optical depth was small, so only small fraction of photons affected.

Optical depth from electron scattering is

$$\begin{aligned}
\tau(z) &= \sigma_T \int_{t(z)}^{t_0} dt\, n_e = \sigma_T \int_0^z dz\,(dt/dz) n_\gamma (n_e/n_\gamma) \\
&= \sigma_T H_0^{-1} \eta\, n_{\gamma,0} \int dz (1+z)(1+\Omega z)^{-1/2} \\
&\to \left(\frac{1+z}{121}\right)^{3/2} h^{-1}, \quad (\Omega = 1)
\end{aligned}$$

if all electrons available (full **reionization** back to redshift z).

Reionization from energy input (e.g. galaxy/star formation) could also cause Compton distortion

$$\begin{aligned}
y = \langle \tau \frac{\Delta E}{E} \rangle &= \sigma_T \int dt\, n_e (T_e/m_e) \\
&= 2.3\times 10^{-5} \left(\frac{T_e}{5000\,K}\right) \left(\frac{z_{heat}}{1000}\right)^{3/2},
\end{aligned}$$

just about current limits. Not known if reionization occurred.

Local version of reionization – electron "heating" – occurs in cluster cores, called **Sunyaev-Zel'dovich effect**. Useful probe of cluster properties and cosmological distances.

2 ANISOTROPIES AND LARGE SCALE STRUCTURE

2.1 Primordial Perturbations

Matter affects CMB through perturbations in density $\delta\rho/\rho$, velocity v, and gravitational potential ϕ. Resulting temperature perturbations in Fourier space are

$$\mathcal{T}^2(k) = \left[(f_{\delta\rho} + f_\phi)^2(k) + f_v^2(k)\,\mu^2\right]\,\Delta_k^2(z_{ls})$$

where direction cosine $\mu = \hat{k}\cdot\hat{n}$, band power $\Delta_k^2(z_{ls}) = k^3 P_k$, and

$$f_{\delta\rho} = \frac{1}{3}$$
$$f_v = \frac{2}{kD_{ls}}$$
$$f_\phi = -\frac{2}{(kD_{ls})^2}$$

It is clear that on

- Large scales (small k): Sachs-Wolfe potential effect dominates
- Medium $\approx$cluster scales: Doppler effect of velocity flows is important
- Small $\approx$galaxy scales (large k): density perturbations dominate

2.2 Sachs-Wolfe Effect

Equivalence Principle gives $\delta T/T$ from ϕ

$$\frac{\delta T}{T} = -\int_e^o dt\,\frac{\partial\phi(\vec{x},t)}{\partial t}.$$

In linear perturbation theory, Einstein-deSitter universe has $\delta_k \propto a$ so Poisson's equation

$$\phi_k \propto -4\pi k^{-2}\rho a^2\delta_k \propto a^0.$$

Therefore only surface terms of integral survive – **endpoint Sachs-Wolfe** effect. Expected order of magnitude $\delta T/T \approx \phi \approx 10^{-5}$.

Other Sachs-Wolfe contributions are hallmarks of breakdown of linearity or of Einstein-deSitter. These **integrated Sachs-Wolfe** (ISW) effects could be from early times (near z_{ls}) when radiation energy density still affects expansion somewhat, so $\delta \propto a$ not exact; or at late times, near the present, an open universe causes deviations from $\delta \propto a$.

For scale invariant ($n = 1$) perturbations, $\delta T/T$ is flat in Fourier space for endpoint SW (not ISW though). Deviation $n - 1$ alters this, as does contribution of gravitational waves (e.g. from inflation) to ϕ; this is called **tilt**.

2.3 Angles, Multipoles, and Power Spectra

Analyze temperature perturbations on celestial sphere in spherical harmonics of multipole

$$l = kr_c(z_{ls}) \approx \frac{1}{\theta} \approx 57 \left(\frac{\theta}{1^\circ}\right)^{-1} \to 5800 \left(\frac{\lambda}{h^{-1}\mathrm{Mpc}}\right)^{-1}$$

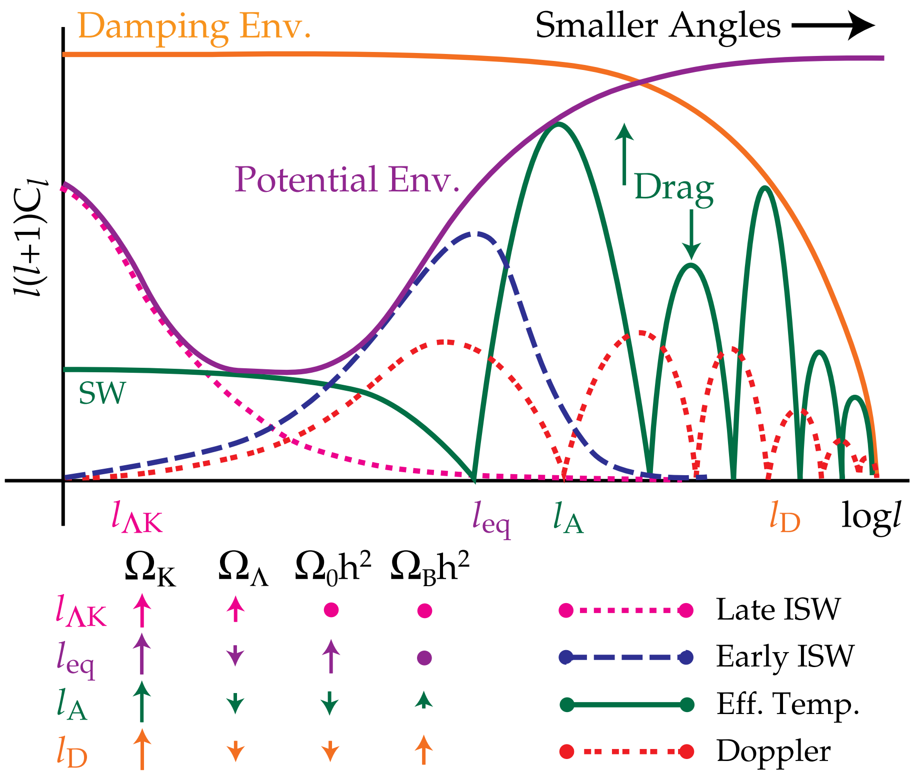
and measure power spectrum (correlation function) C_l, or broad band power

$$T_l^2 = (1/2\pi)\, l(l+1)C_l.$$

3 PROBE OF COSMOLOGY AND STRUCTURE

CMB acts as test of entire paradigm for structure formation.

- Is inflation origin of primordial perturbations?



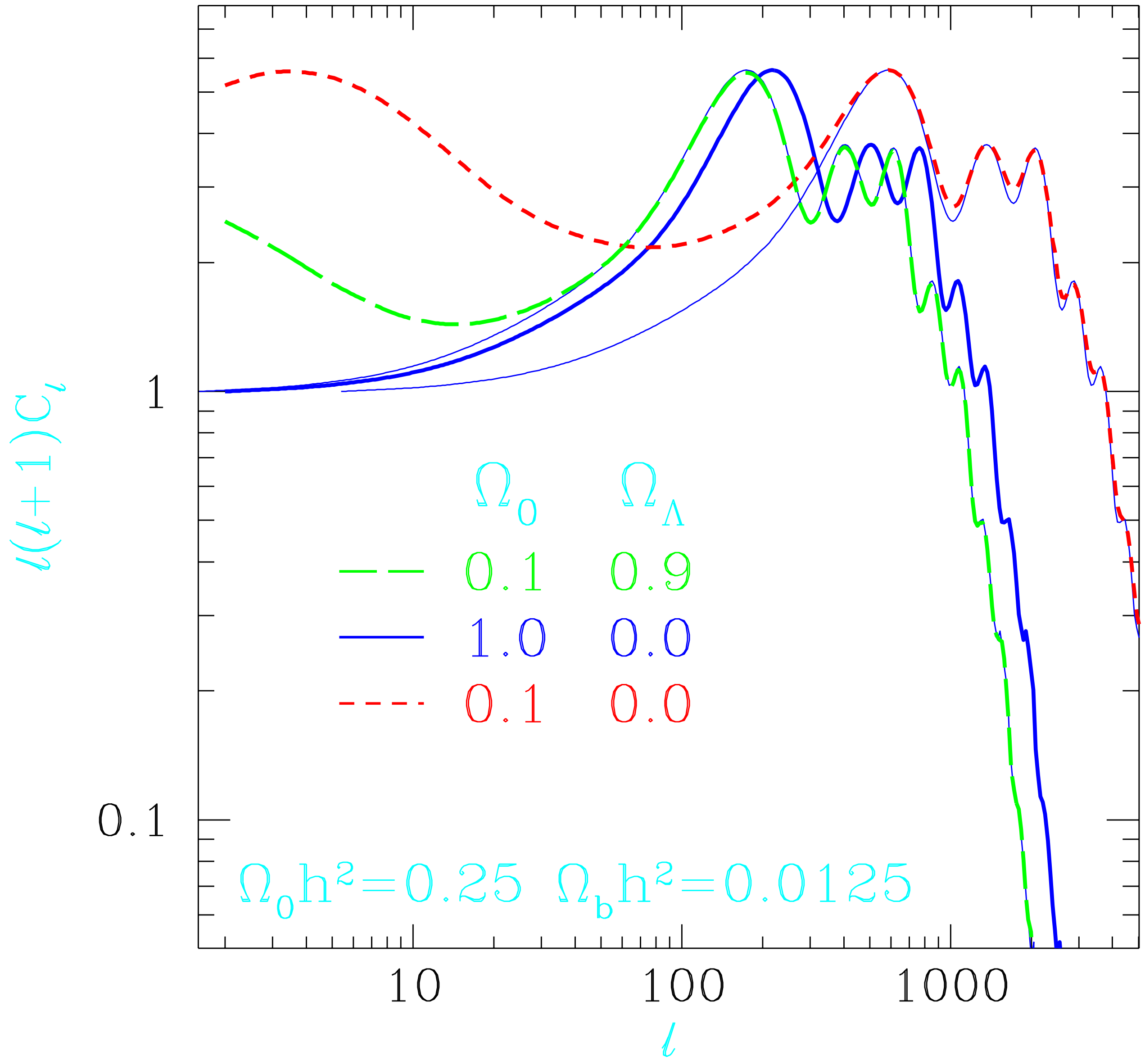
- Are perturbations adiabatic?
- Are perturbations Gaussian?
- What is form of the potential, i.e. GUT/Planck energy physics?

- Is gravitational instability driving mechanism for structure formation?
  - What is the dark matter?
  - What are the values of the cosmological parameters?

Greatest leverage in probing universe thru combination of CMB results with galaxy power spectrum, supernovae distance-redshift tests.

`Phil Mauskopf will tell us about the latest in CMB experiments and results.`

FIRAS figure from Smoot, astro-ph/9705101; other two figures from Hu, http://www.sns.ias.edu/˜whu/physics/physics.html


$\ell(\ell+1)C_\ell$
1
0.1
10
100
1000
ℓ
Ω_0 Ω_Λ
0.1 0.9
1.0 0.0
0.1 0.0
$\Omega_0 h^2=0.25$ $\Omega_b h^2=0.0125$