Cosmic Microwave Background Anisotropies
= structure in the CMB

Blue = 0°K
Red = 4°K

Blue = 2.724°K
Red = 2.732°K
Dipole Anisotropy ~ 1 part in 300

After removing dipole
Red–blue = 0.0002°K
~ 1 part in 10^5

Cosmic Microwave Background Anisotropies
= structure in the CMB

Structure = snapshot of oscillations

\[ M < M_c \]
\[ \delta \rho / \rho = \exp(-ir - i\omega t) \rightarrow \text{Oscillations} \]
Structure in the CMB

Boomerang balloon flight.
Mapped Cosmic Background Radiation with far higher angular resolution than previously available.

Launch near Mt. Erebus in Antarctica

What is measured?

Basically,
Power spectrum of $\Delta T/T$
vs. $l = \pi/\theta$

(think of Fourier transforming the sky in angular coordinates)
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Power spectrum of $\Delta T/T$

vs. $l = \pi/\theta$

(think of Fourier transforming the sky in angular coordinates)

Print-through of spectrum of primordial fluctuations (Sachs-Wolfe effect)

Photon diffusion (Silk damping)
Position of 1st peak:

- Density fluctuations print through CMB fluctuations.
  \[ \frac{\delta \rho}{\rho} = 3 \delta T/T \]  
  [CO 30.30]
- Measures angular size of pulsations which permeated universe just before decoupling of CMB.
- Linear size of largest structure
  \[ = \text{speed of sound} \times \text{age of universe at that time}. \]
- (Linear size) / (Angular size) = angular size distance.
- Ang. Size Distance depends on geometry = \( \Omega_{\text{tot}} \)
  
  \[ d = \frac{2c}{H_0 \Omega_{\text{tot}}} \]  
  for large \( z \).

Position of 1st peak measures curvature

First peak:

Size of “acoustic horizon”

\[ r = v_s (t_{\text{Decoupling}} - t_{\text{Horizon}}) \]
\[ \theta = r/\chi(d) \]
\[ \chi = \sin(d), \sinh(d) \]
\[ l_{\text{peak}} = 220/\Omega_{\text{tot}}^{1/2} \]

Measured \( l_{\text{peak}} \) \( \Rightarrow \) \( \Omega_{\text{tot}} = 1.02 \pm 0.02 \)

Sonic Horizon Distance

\[ d(t) = ct/3 \]

= linear size of perturbation

All models:

\( \Omega_b = 0.04, \Omega_{\text{m}} = 0.23 \)
The “Concordance” Cosmology (or $\Lambda$CDM)

- Type Ia Supernovae as “standard candles”
  - Accelerating expansion
    - $q_0 = \Omega_m/2 - \Omega_\Lambda$
- CBR anisotropy $\Omega_{\text{total}} = \Omega_m + \Omega_\Lambda$
- Can solve for $\Omega_m$, $\Omega_\Lambda$

The “Concordance” Cosmology (or $\Lambda$CDM)

$\Omega_m = \text{matter density/critical density}$

Another independent measure:
Rate of galaxy cluster evolution

The “Concordance” Cosmology (or $\Lambda$CDM)

Position & height of first peak also depend on $\Omega_m$, $\Omega_b$, $h$

- Larger $\Omega_m \Rightarrow$ all peaks have smaller amplitudes.
  - Through change in matter/radiation density ratio during radiation-dominated phase.
  - Through effect on when universe becomes matter dominated.

$\theta \propto \Omega_m h^{3/4}$

$\Omega_{\text{tot}} = 1$
So use constraints from other measurements:

Position & height of first peak also depend on $\Omega_m$, $\Omega_b$, $h$

- Calculated for $\Omega_{\text{tot}} = 1$

Galaxy cluster evolution

- BBN results
- $f_b = \text{baryon fraction in clusters}$
  - $t_e = \text{minimum age of universe}$
- HST

- Position of Peak $\theta \propto \Omega_m h^{3/4}$

Hubble parameter, $h$

- $0.1$ to $0.8$

- $0.0$ to $1.0$

- $\Omega_m$
  - $0.1$ to $0.8$

WMAP also measured second peak

- Due to rarefaction of an acoustic wave.
- Larger $\Omega_b \Rightarrow$ smaller amplitude of second peak.
  - greater inertial mass in oscillating plasma.
Results:

• Total density: \( \Omega_0 = \Omega_{\text{tot}} = 1.02 \pm 0.02 \)

• Age of Universe: \( t_0 = 13.7 \pm 0.2 \text{ Gyr} \)

• Matter density: \( \Omega_m h^2 = 0.135 \pm 0.008 < 0.009 \Rightarrow \Omega_m = 0.27 \)

• Baryon density: \( \Omega_b h^2 = 0.0224 \pm 0.009 \Rightarrow \Omega_b = 0.044 \)

73% Dark Energy, 22% Dark Matter, 4.4% Baryonic Matter

Flat Universe with density fluctuations \( P(k) \sim k^n, n \sim 1 \)

\( \Rightarrow \) INFLATION

Power spectrum measures many things

• But still needs to be combined with other measurements.