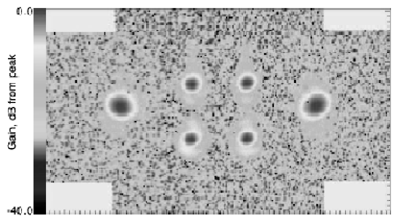
Modern cosmology 4: The cosmic microwave background

- **Expectations**
- **Experiments: from COBE to Planck**
  - **COBE**
  - **ground-based experiments**
  - **WMAP**
  - **Planck**
- **Analysis**
- **Results**

Analysis of WMAP data: the power spectrum

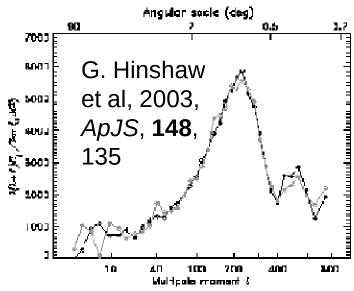
- **Resolution and sky coverage**
  - beam profiles mapped by looking at Jupiter (a microwave source of known size)
    - – sizes range from 49′ to 13′ depending on frequency
    - – this corresponds to ℓ_{max} ~ 800
  - orbit around L2 covers whole sky every 6 months

WMAP beam profiles from L. Page et al, 2003, *ApJS*, **148**, 39



Analysis of WMAP data: the power spectrum

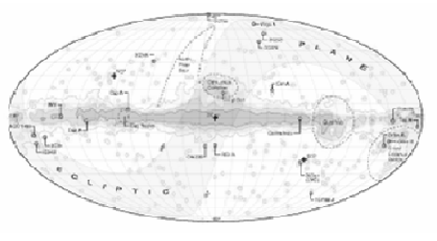
- **Instrumental noise**
  - **WMAP has 10 radiometer assemblies (each with 2 receivers of different polarisation) covering 5 frequencies**
    - derive angular power spectrum by cross-correlating measurements from maps by different radiometers
    - this cancels out noise properties of individual radiometers

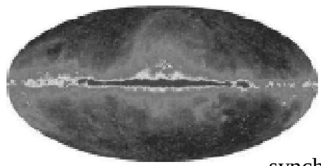


G. Hinshaw et al, 2003, *ApJS*, **148**, 135

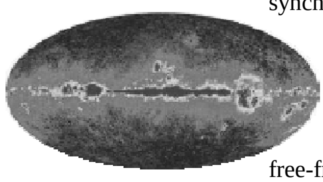
Analysis of WMAP data: the power spectrum

- **Foreground sources**
  - **have different spectra**
  - **Galactic plane region ignored in analysis**
  - **point sources subtracted**

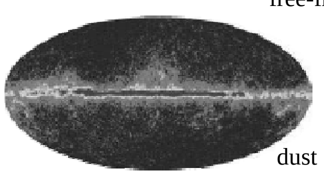




synchrotron



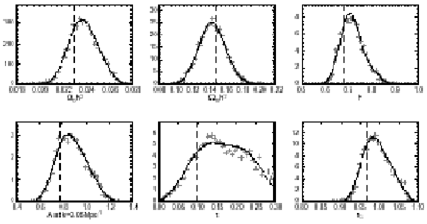
free-free



dust

Results

- WMAP team extract parameters including
  - baryon density $\Omega_b h^2$
  - matter density $\Omega_m h^2$
  - neutrino mass m_ν
  - Hubble constant h
  - optical depth to reionisation τ
  - spectral index of fluctuations n
  - overall normalisation A



- to WMAP alone or WMAP with various other data

Combined Analyses

- What other data samples can be used?
  - WMAP 9-year analysis uses baryon acoustic oscillations (i.e. galaxy redshift surveys) and an independent measurement of H_0
    - power spectrum of luminous red galaxies can be used instead of standard galaxy survey data
    - H_0 = 73.8±2.4 km s^{-1} Mpc^{-1}, Riess et al. (2011), from SNe Ia at z < 0.1
  - WMAP 5-year analysis used baryon acoustic oscillations and Type Ia supernovae
    - WMAP9 restricts use of SNe Ia because of significant systematic errors

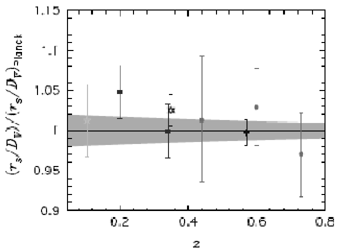
Results from different data

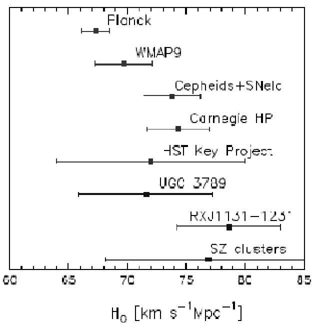
Parameter	Planck	WMAP9	W9+BAO+H_0
n	**0.962 ± 0.009**	**0.972 ± 0.013**	**0.971 ± 0.010**
τ	**0.097 ± 0.038**	**0.089 ± 0.014**	**0.088 ± 0.013**
h	**0.674 ± 0.014**	**0.700 ± 0.022**	**0.693 ± 0.009**
$\Omega_b h^2$ %	**2.207 ± 0.033**	**2.264 ± 0.050**	**2.266 ± 0.043**
$\Omega_{cdm} h^2$ %	**11.96 ± 0.31**	**11.38 ± 0.45**	**11.57 ± 0.23**
Σm_ν	**<0.23 eV**	**<1.3 eV**	**<0.58 eV***
Ω_k	**0.0000±0.0067**[1]	**−0.037 ± 0.043**	**–0.0027 ± 0.0039***
w	$-1.13^{+0.13}_{-0.10}$	**−1.1 ± 0.4***	**−1.07 ± 0.09***

• = includes ground-based CMB data (SPT, ACT)
¹ = includes WMAP polarisation

Consistency checks

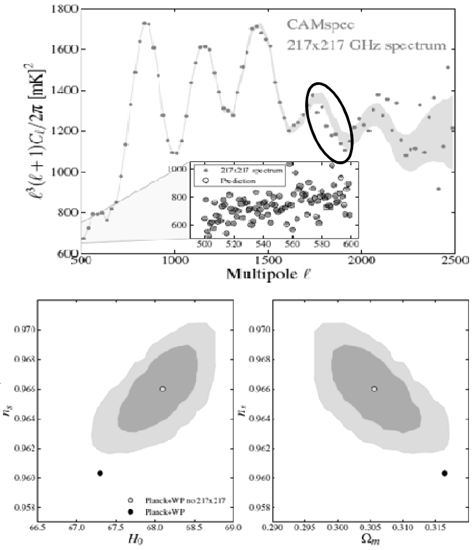
- **Compare CMB results with other data**
  - **good consistency with galaxy redshift surveys**
  - **not such good consistency with H_0**
    - Planck and, to lesser extent, WMAP9 prefer lower value
    - note that CMB estimates of H_0 are rather model dependent





Planck vs WMAP

- **Disagreement between Planck and WMAP9 is noticeable**
  - **WMAP9 agrees better with independent measures such as “conventional” H_0**
  - **could this point to systematic error in Planck data?**
- **Spergel, Flauger and Hložek (2013) suggest problem with Planck 217 GHz spectrum**
  - **but they are WMAP authors...**



arXiv 1312.3313 [astro-ph]

Conclusions

- **Agreed features of best fit cosmological model**
  - **the universe is flat to high precision**
    - as expected from inflation
  - **no evidence of significant neutrino contribution**
    - no hot dark matter
    - number of neutrinos consistent with 3
  - **dark energy is consistent with cosmological constant**
    - $w \simeq -1$
  - $\Omega_\Lambda \approx 0.7$, $\Omega_{m0} \approx 0.3$, $H_0 \approx 70$ **km/s/Mpc**
    - but some disagreement about exact values

Consequences

$$\dot{a}(t)^2 = H_0^2\left(\frac{\Omega_{\rm m0}}{a(t)} + (1-\Omega_{\rm m0})a(t)^2\right)$$

- **Universe is dominated by matter and Λ**
- **Universe is currently accelerating**
  - $\ddot{a}(t_0) = H_0^2(1 - {}^3/_2\,\Omega_{\rm m0}) > 0$
  - **acceleration started when $\Omega_{\rm m0}/a^2 = 2(1 - \Omega_{\rm m0})a$, i.e. $a = 0.613 \pm 0.016$ or $z = 0.632 \pm 0.043$ (Planck)**
    $a = 0.600 \pm 0.014$ or $z = 0.666 \pm 0.039$ (SFH13)
    - consistent with supernova results

Consequences

$$\dot{a}(t)^2 = H_0^2\left(\frac{\Omega_{\rm m0}}{a(t)} + (1-\Omega_{\rm m0})a(t)^2\right)$$

can be integrated (slightly messily) to give

$$H_0 t = \frac{2}{3\sqrt{1-\Omega_{\rm m0}}}\sinh^{-1}\left(\sqrt{\frac{1-\Omega_{\rm m0}}{\Omega_{\rm m0}}}\,a^{3/2}\right)$$

which enables us to calculate the age of the universe, proper distances, expansion as a function of time, etc.

Conclusions

- **Data from the HST, supernovae, galaxy surveys and the CMB have enabled us to determine cosmological parameters to within a few percent**
  - **different sources are basically consistent—need to wait and see if low Planck H_0 significant**
- **Data now provide strong constraints on theories**
  - **“benchmark” ΛCDM hard to beat**

Where are we?

- **We have a first class description of the Universe**
  - **its content, its age, its likely future**
- **We do not have good explanations for some aspects**
  - **the nature of dark matter (can LHC help?)**
  - **(especially) the nature of dark energy**
  - **the actual values of the parameters**
- **Immense progress in the last 15 years, but much still to do!**