Modern cosmology 4: The cosmic microwave background

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

**Expectations**

- Reasonable characteristic size would be Hubble length \( c/H \approx 0.2 \) Mpc at \( z \approx 1100 \)
- Angular diameter distance of surface of last scattering = \( d_p/1100 \approx 3ct_0/1100 \approx 12 \) Mpc
- So characteristic angular size \( \approx 17 \) mrad = 1° (more precisely \( l = 220/\sqrt{\Omega} \))
  - depends on geometry
  - in closed universe given linear size corresponds to larger angle
  - vice versa for open universe

All pictures from Wayne Hu, http://background.uchicago.edu/~whu/intermediate/intermediate.html
**Expectations**

- Gravity and pressure create oscillations in photon-baryon fluid
  - these give higher “harmonics” in power spectrum
  - baryons add to density but not pressure $\rightarrow$ enhance compression peaks (odd numbers) over rarefaction

*red is hot – blue is cold!*

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**Effect on power spectrum**

Animations by Wayne Hu:
- curvature/$\Lambda$
- baryons
- matter

Animation by Daniel Eisenstein
- Formation of acoustic peak in galaxy surveys

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*PHY306*
Experiments

- Basic aim
  - obtain measurements of $\delta T/T$
    - over as much of the sky as possible
    - with as high an angular resolution as possible

- Problems
  - foreground emission from Galaxy and solar system
    - can be distinguished by different spectrum
  - instrumental noise
    - must minimise
Experiments

- COBE
  - low Earth orbit
  - poor angular resolution so only sensitive to $l < 20$

Next generation after COBE: ground and balloon-based experiments
  - much better angular resolution
  - limited sky coverage
  - limited exposure time

Next generation space-based experiments
  - WMAP and Planck
    - whole-sky coverage with good angular resolution

New ground-based experiments
  - polarisation and high angular resolution
Experiments

BOOMERanG
Balloon Observations Of Millimetric Extragalactic Radiation AND Geophysics

Experiments

DASI
Degree Angular Scale Interferometer
Experiments

VSA Very Small Array

CBI: Cosmic Background Imager
ACBAR: Arcminute Cosmic Background Array Receiver
Experiments

WMAP
Wilkinson Microwave Anisotropy Probe

Planck
launched 14 May 2009
CMB results came out April 2013
Experiments

South Pole Telescope
10 m telescope for mm and sub-mm wavelengths
Measured B-mode polarisation at high ℓ due to gravitational lensing, July 2013

BICEP2
26 cm refractor in cryostat for very low-noise polarisation measurements
Measured B-mode polarisation at low ℓ, March 2014
Unfortunately this seems to have been largely due to dust, not primordial gravitational waves as initially thought
Results

- WMAP measured first three peaks
- Planck measures out to 7th peak
- Planck also measures E-mode polarisation
  - first seen by DASI
  - good cross-check of model

Health Warning...

- CMB data are not the answer to Life, the Universe, and Everything
  - need to combine with other data
  - but together with those other data, do provide unprecedented precision