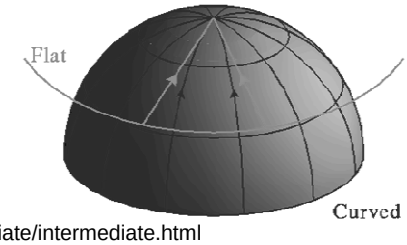
# *Modern cosmology 4: The cosmic microwave background*

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



# *Expectations*

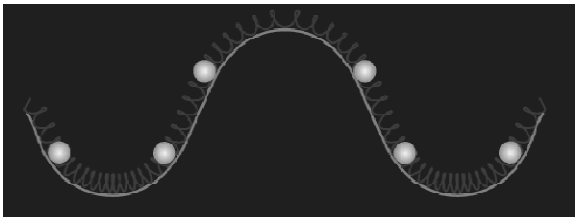
- **Reasonable characteristic size would be Hubble length $c/H \approx 0.2$ Mpc at $z \approx 1100$**
- **Angular diameter distance of surface of last scattering = $d_P/1100 \approx 3ct_0/1100 \approx 12$ Mpc**
- **So characteristic angular size ≈ 17 mrad = 1° (more precisely $l = 220/\sqrt{\Omega}$)**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

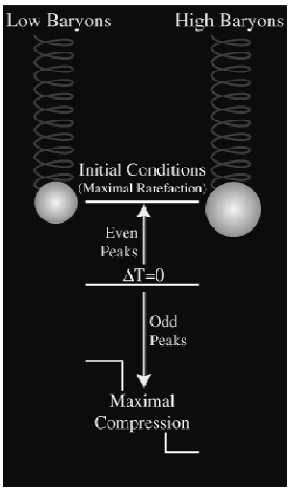



All pictures from Wayne Hu, http://background.uchicago.edu/~whu/intermediate/intermediate.html

# *Expectations*

- **Gravity and pressure create oscillations in photon-baryon fluid**
  - **these give higher "harmonics" in power spectrum**
  - **baryons add to density but not pressure → enhance compression peaks (odd numbers) over rarefaction**

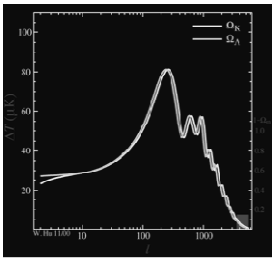







red is hot – blue is cold!

# *Effect on power spectrum*

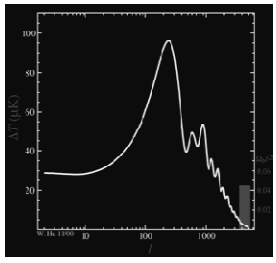


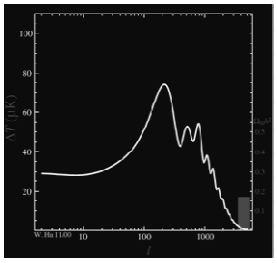
Animations by Wayne Hu:

curvature/Λ

baryons

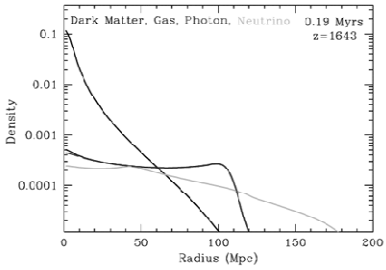
matter

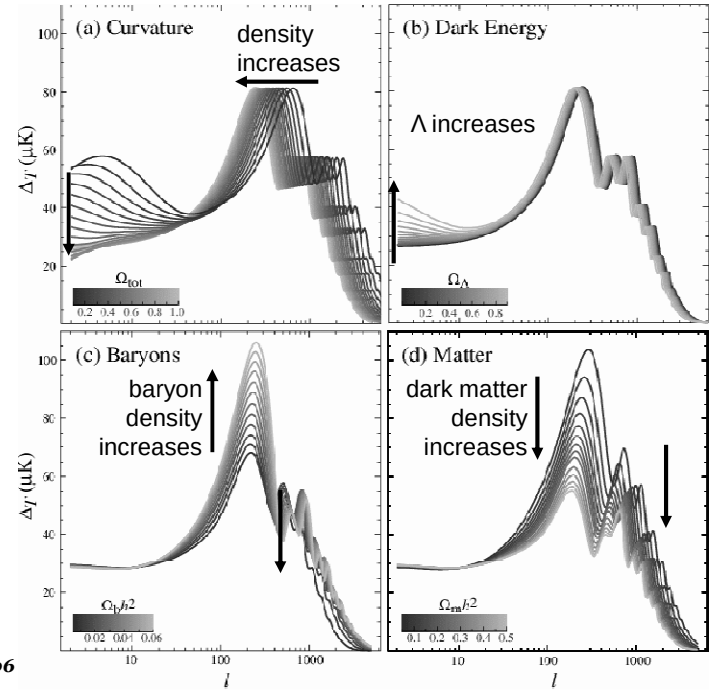




Animation by Daniel Eisenstein

Formation of acoustic peak in galaxy surveys





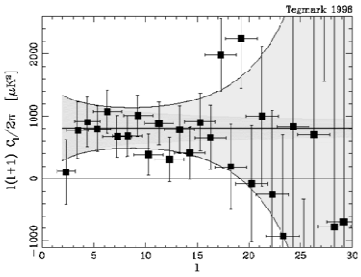


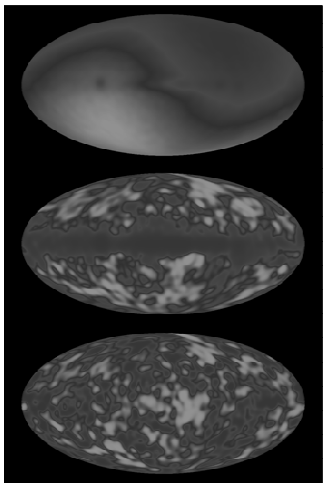

# *Experiments*

- **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 $l < 20$**



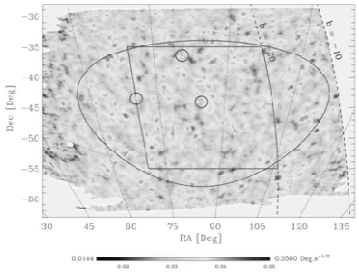





# *Experiments*

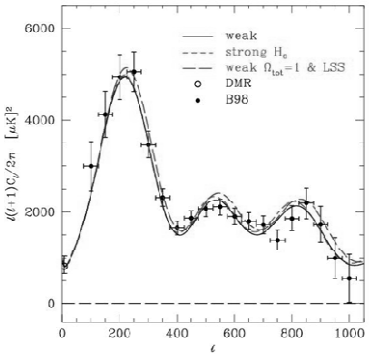
- **Next generation after COBE: ground and balloon-based experiments**
  - **much better angular resolution**
  - **limited sky coverage**
  - **limited exposure time**
- **Next generation space-based experiments**
  - **WMAP and Planck**
    - whole-sky coverage with good angular resolution
- **New ground-based experiments**
  - **polarisation and high angular resolution**

# *Experiments*



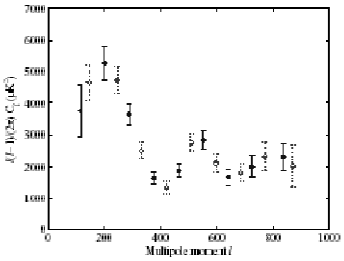

## BOOMERanG

Balloon Observations Of Millimetric Extragalactic Radiation ANd Geophysics



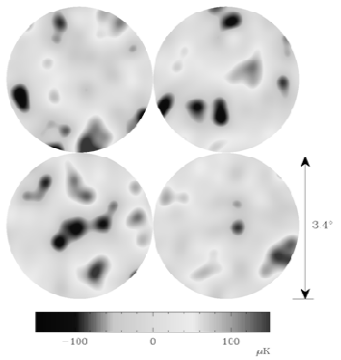



# *Experiments*



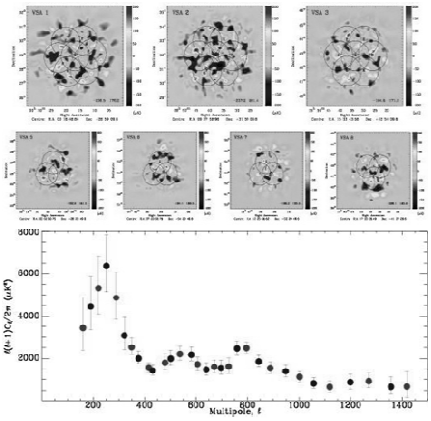

## DASI

Degree Angular Scale Interferometer



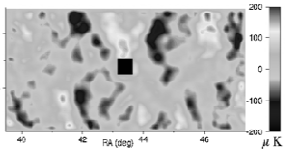
# *Experiments*

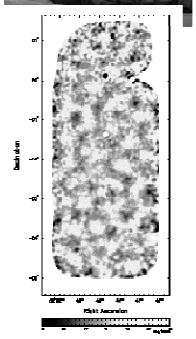
VSA Very Small Array

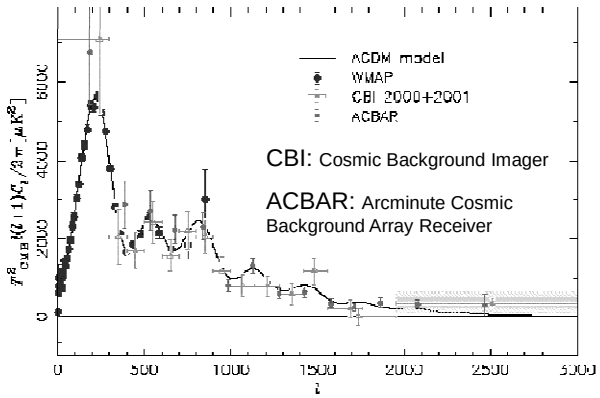




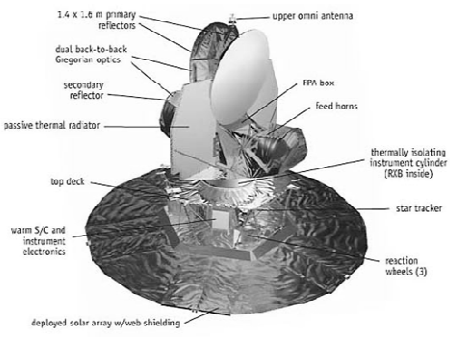

# *Experiments*

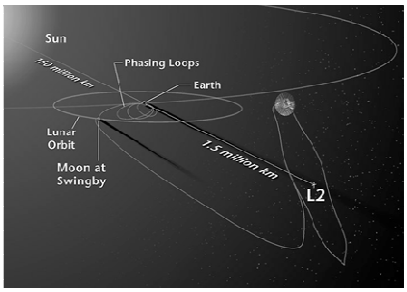


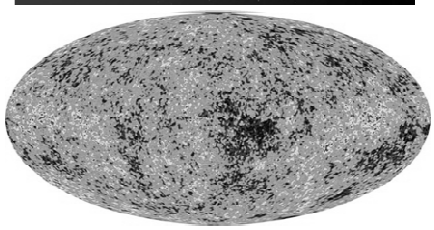





# Experiments



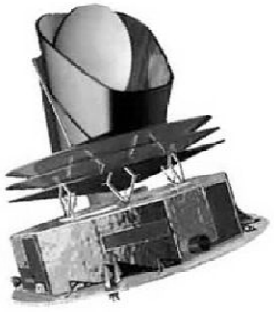



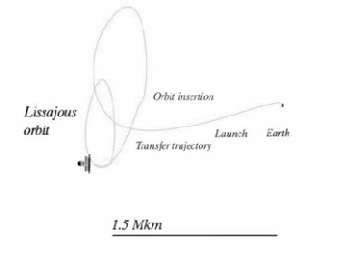
WMAP

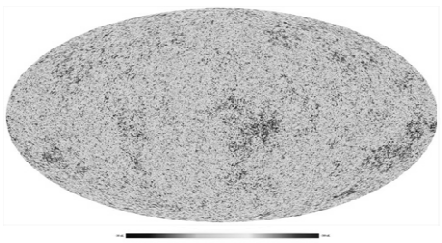
Wilkinson Microwave Anisotropy Probe



# Experiments





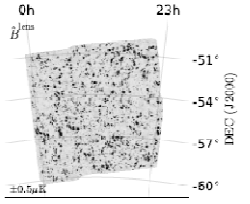



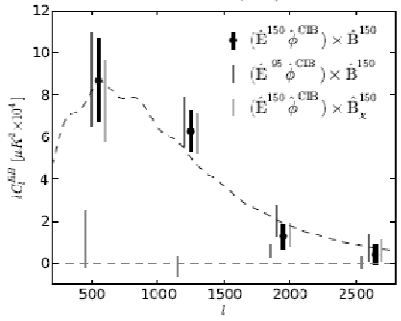
Planck

launched 14 May 2009

CMB results came out April 2013

# Experiments



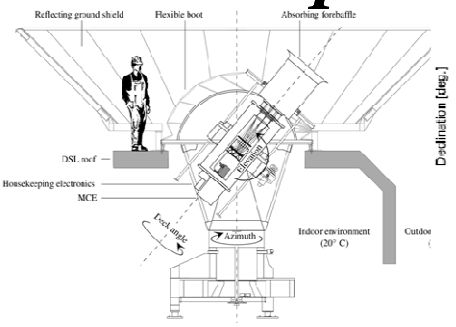

## South Pole Telescope

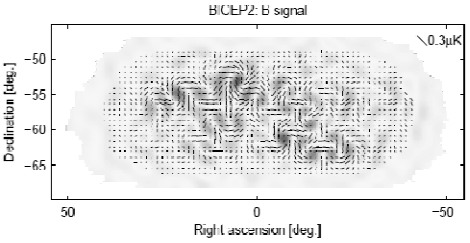
10 m telescope for mm and sub-mm wavelengths

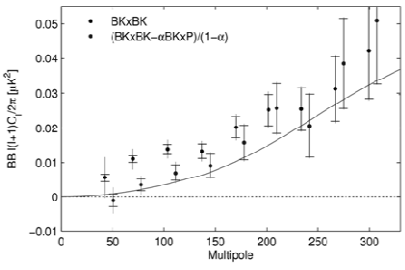
Measured B-mode polarisation at high $\ell$ due to gravitational lensing, July 2013



# Experiments




## BICEP2

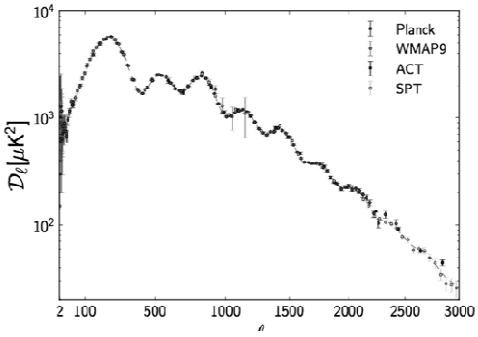
26 cm refractor in cryostat for very low-noise polarisation measurements

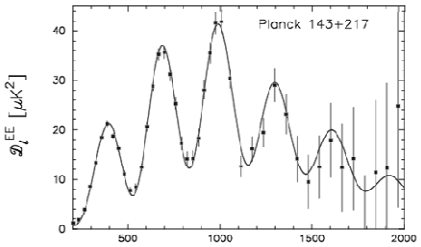
Measured B-mode polarisation at low $\ell$ , March 2014

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**