The CMB since 1990 - WMAP

D T Wilkinson 1935- 2002

Dave Wilkinson

Cyrus Fogg Brackett Professor of Physics, Princeton

1965 with Peebles, Dicke, and Roll – interpretation of the 3K radiation found by Penzias and Wilson

Many subsequent experiments (ground-based) to measure 3K spectrum

1989 – COBE

2001 – MAP, renamed WMAP for DTW

Experimenter, project leader, teacher, mentor, publicist

Last time ....

Where statistics took us with the great galaxy surveys, 2dF GRS and SDSS LRGs:

- 2dF GRS - AAT and 2° fibre-fed field; SDSS and purpose-built telescope, five-colour sky survey, spectra via plug-plates

- **2-point (3D) correlation function** and the **(3D) Power Spectrum**

- 2dF $w(\theta)$; 'Kaiser effect', ellipticity (2σ previous surveys) can only be explained by **coherent infall** – hierarchical galaxy building by gravitational attraction

- 2dF PS = > **key cosmo parameters Ω_m, Ω_b**

- SDSS PS refined these parameters and showed **Baryon Acoustic Oscillations**

- SDSS 2-pt (3D) correlation function : BAO effect, **precise acoustic scale at z=0.35** for comparison with scale already defined by the CMB at z=1089

- unparalleled measure of curvature: **the flat universe prevails: ΛCDM, Ωtot = 1.000000000, inflation….**

Our Universe at 1990, again

(0) **Hot Big Bang** origin, creating CMB, H, He and some of the lighter elements

(1) Yet **Cold Dark Matter** prevails. Why?

- We need to grow galaxies in a Hubble time
- CDM perturbations live through recombination (z~1000)
- Only after recombination (z~1000) can the baryons fall into the waiting traps set up by CDM

(2) Inflation (Guth 1982) => Ω_{total} = 1.00000...

- solved (a) why the Universe is flat, isotropic and homogeneous (the \`horizon problem')
- and (b) why we don't see monopoles, as exotic particles are highly diluted in the vacuum phase

(3) Ω_{total} = 1.00000... = Ω_{matter}

Finding the CMB in 1965

3K isotropic emission discovered while Bob Wilson and Arno Penzias were calibrating a horn antenna.

Bob Dicke's group predicted ~5K radiation as the relic of a Hot Big Bang universe.

Bernie Burke, radio astronomer, was in discussion with both groups, and alerted each to the status of the other.

Back-to-back 1965 ApJ: Penzias and Wilson announce discovery of 3° isotropic radiation; Dicke, Peebles. Roll and Wilkinson interpret this as the relic radiation from the Hot Big Bang. Nobel prizes for Penzias and Wilson.

See **Finding the Big Bang**, Peebles, Page and Partridge 2009

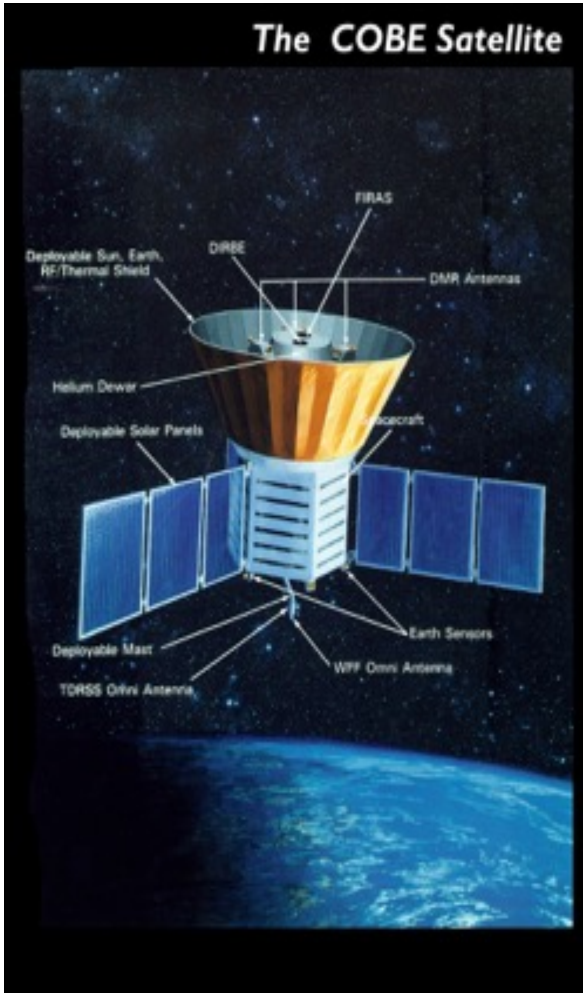
What is/was COBE?

1990-1993

Far Infrared Absolute Spectrophotometer (FIRAS): precise measurement of the spectrum of the CMB radiation

Differential Microwave Radiometers (DMR): detected (statistical) fluctuations in the CMB corresponding to density structure in the early Universe

Diffuse Infrared Background Experiment (DIRBE): obtained data to seek the cosmic infrared background and study the structure of the Milky Way Galaxy and the interstellar and interplanetary dust.

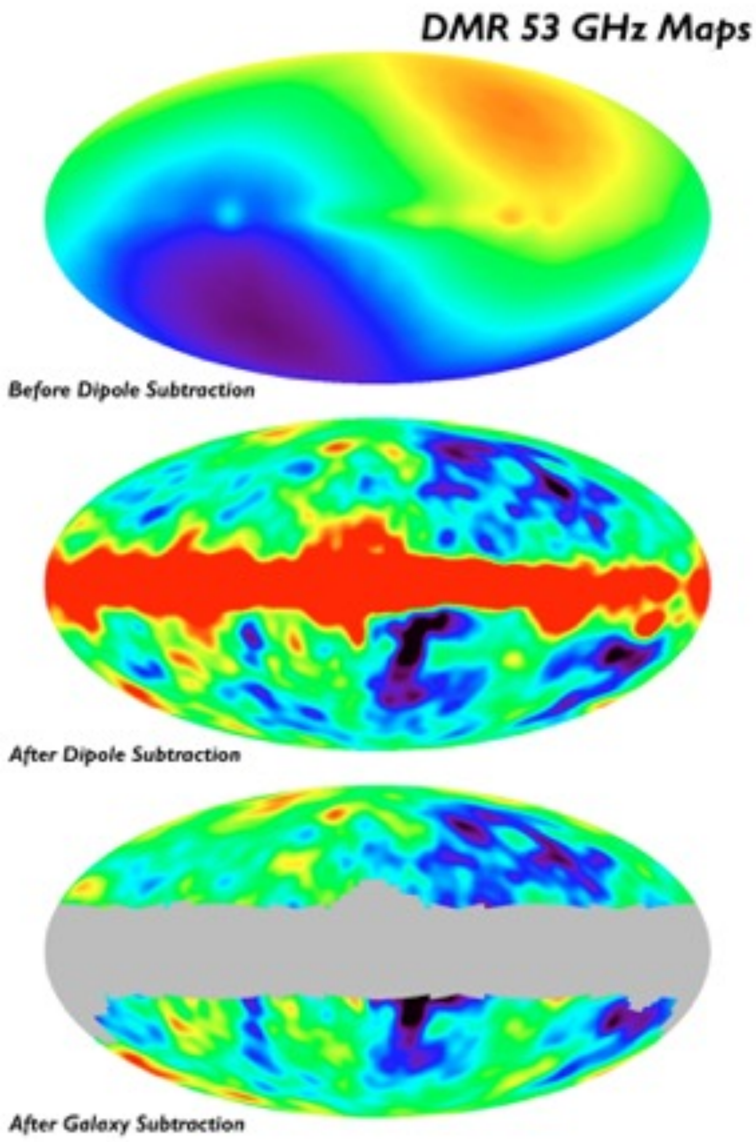


How COBE Changed Our Universe

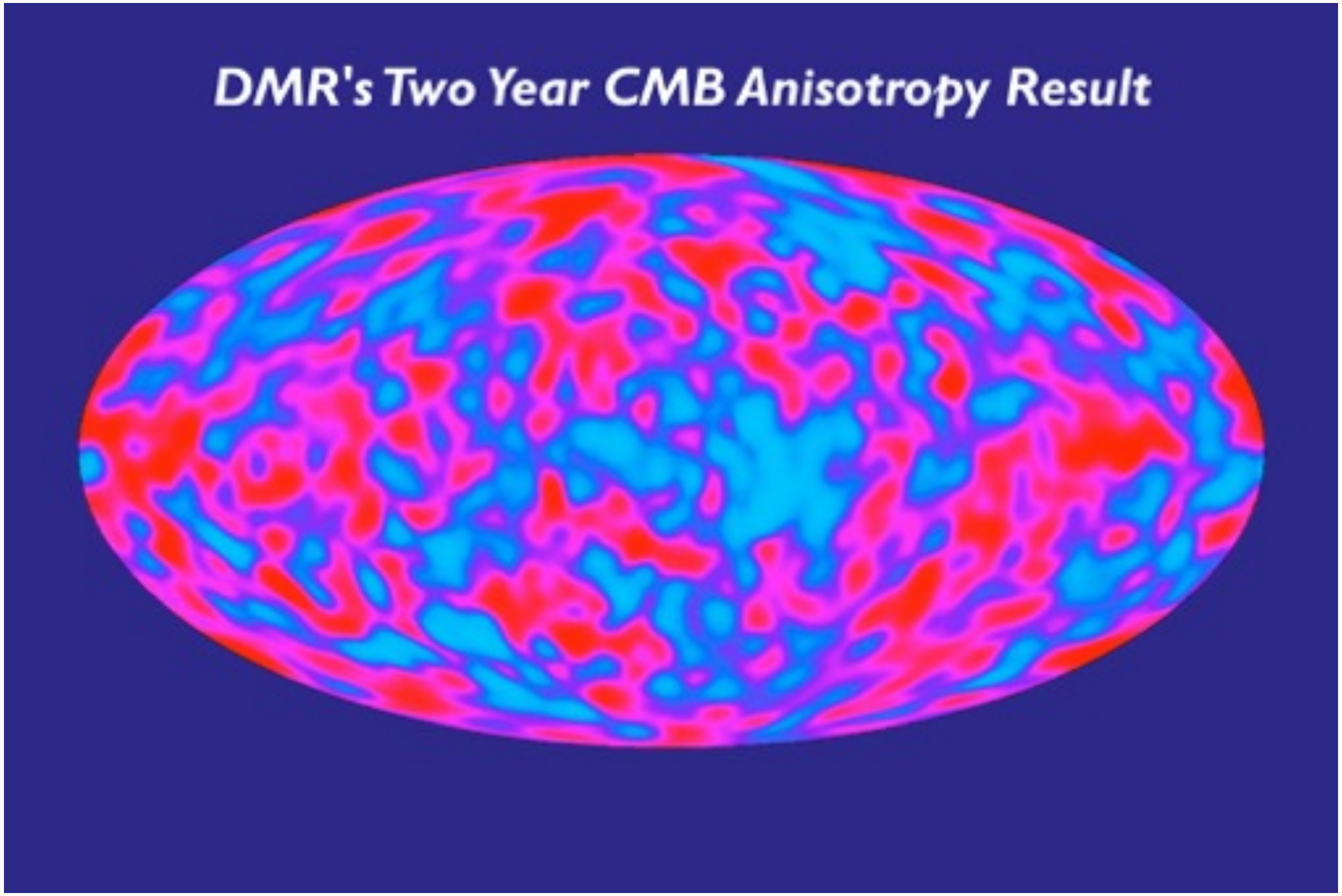
1. Dipole analysis: we are flying at 600 km s^{-1} towards the Virgo cluster.

2. Dipole subtracted: blobs plus our Galaxy revealed.

3. Multiple DMR frequencies: Galaxy emission identified and removed - leaving the famous blobby maps:



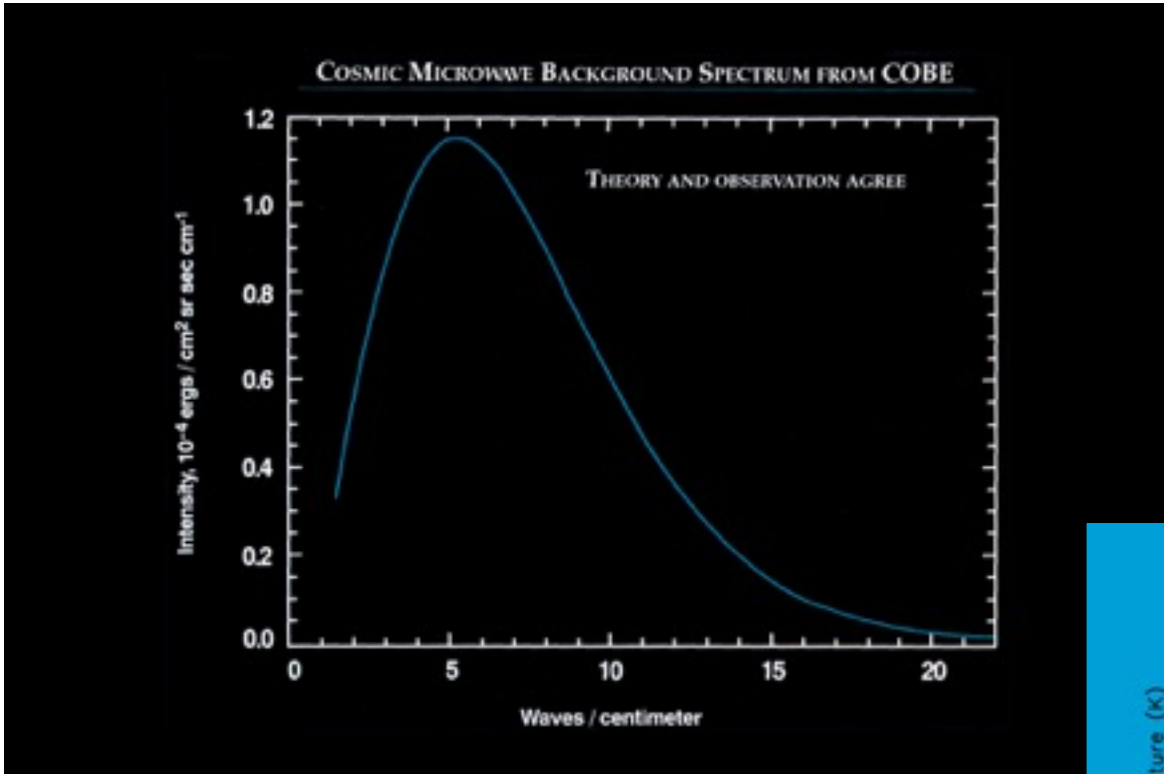
How Cobe Changed our Universe (2)

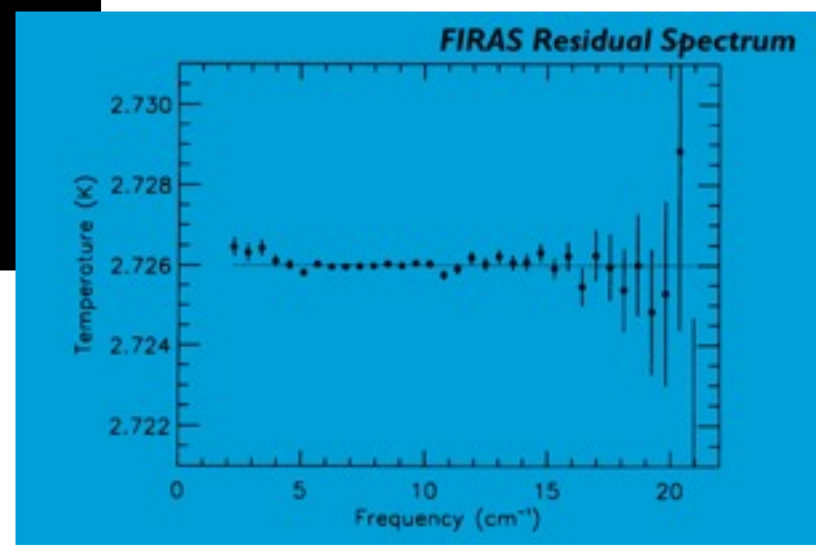


Smoot et al. 1992 – The fluctuations at $\Delta T/T \sim 10^{-5}$.

'Cosmology can start now'

How COBE Changed our Universe (3)

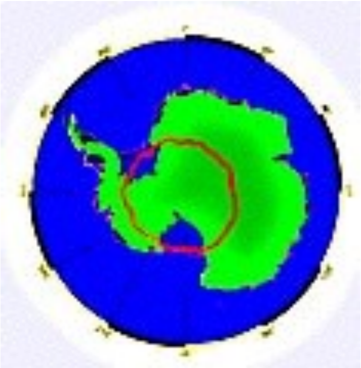


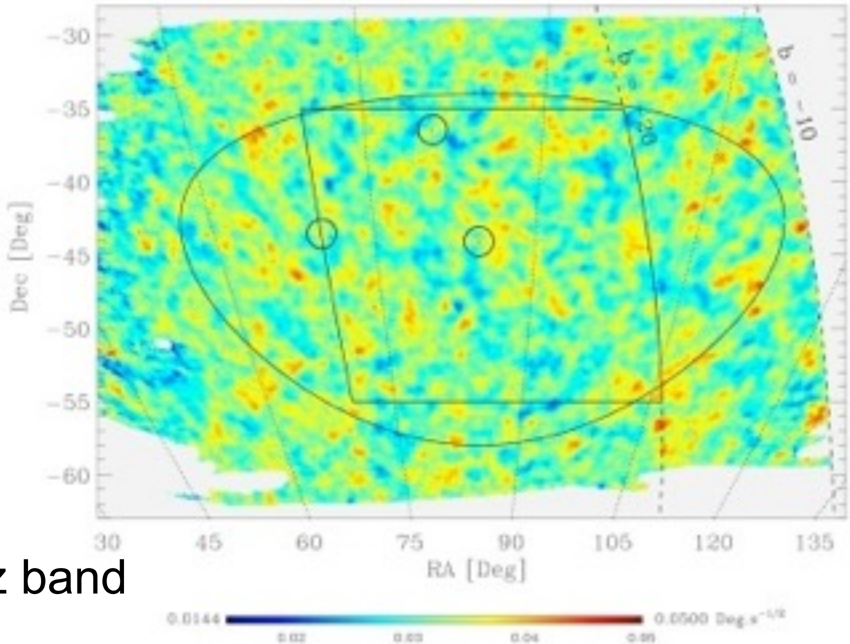


Mather et al. 1990:

A perfect black-body spectrum, 2.728 ±0.004 K

BOOMERanG and MAXIMA





BOOMERanG: 1800 deg sq, 100-350 GHz band

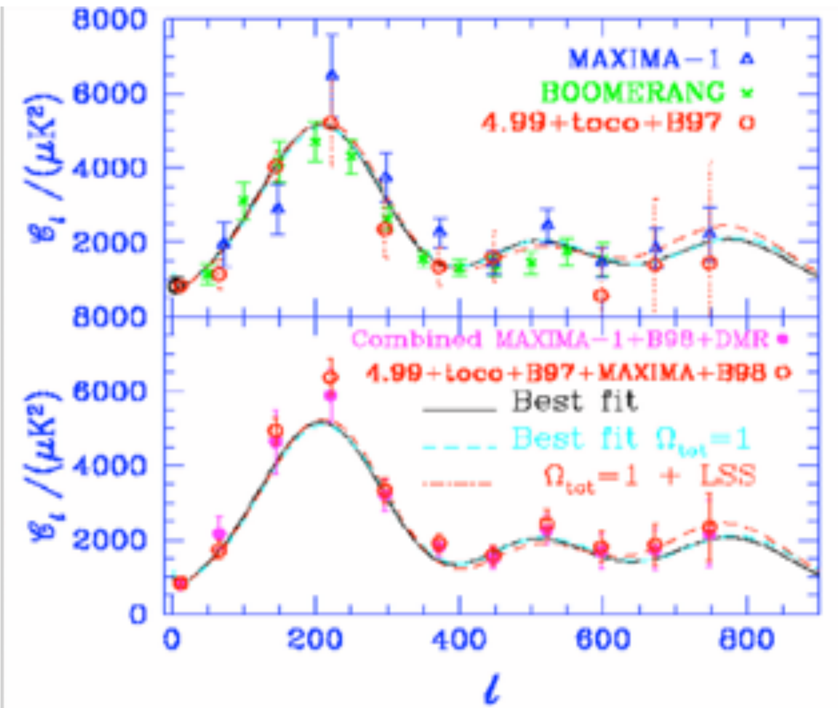
MAXIMA: 124 deg sq, much deeper

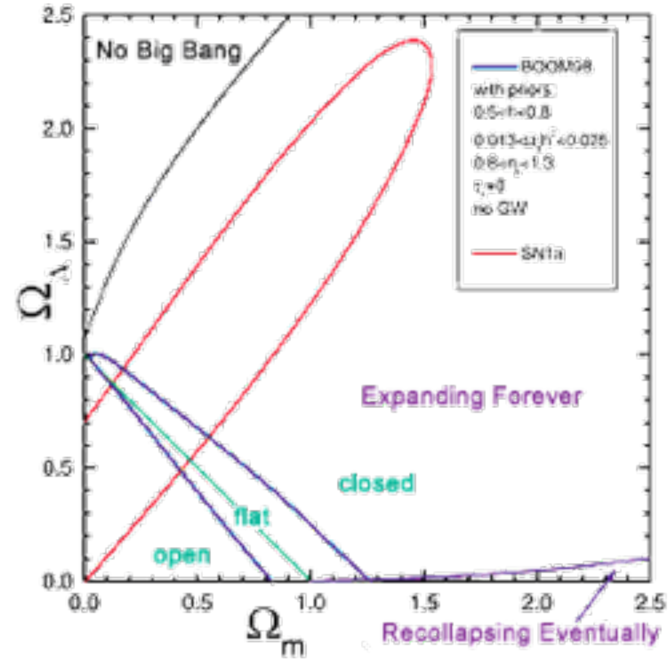
=> Angular scales from 10 arcmin to 5 deg; PS definition of 1st acoustic peak

(de Bernardis et al. 2000, Hanany et al. 2000)

BOOMERanG and MAXIMA

Angular Power Spectrum at last!

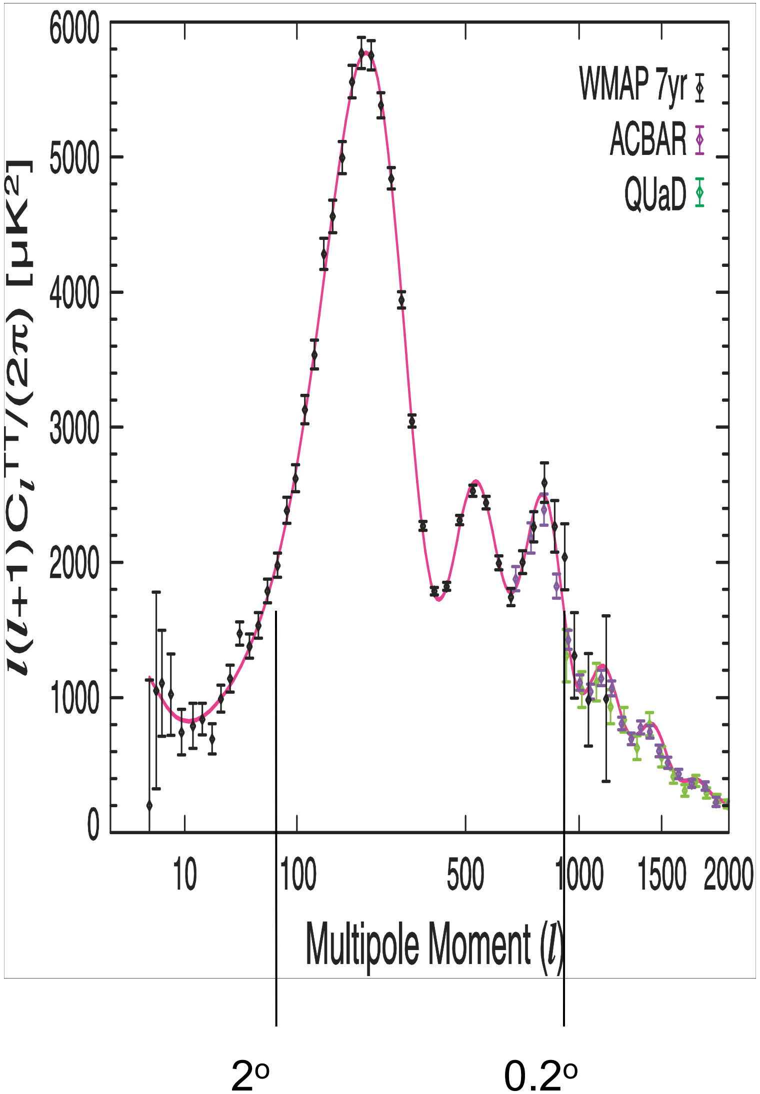




Bond and Efstathiou 1987: 'We hope that the parameters for CDM models presented…will serve as a challenge for prospective experimenters…'

Position of 1st acoustic peak - dominated by Ω_{tot}; for flat universe l ≈ 200

CMB Angular Power Spectrum



l < 90: scales > horizon size at decoupling (as observed today); **Sachs-Wolfe plateau**; unprocessed primordial fluctuation spectrum. '**Cosmic variance**'.

90 < l < 900: acoustic peak region; physics of 3000K plasma of n_e = 300 cm^{-3} responding to DM grav potential fluctuations. 1^{st} – compression; 2^{nd} – rarefaction, 3^{rd} – compression at 2^{nd} harmonic of 1^{st} peak…

l > 900: Silk damping tail, diffusion of photons from the fluctuations and washing out of observed fluctuations by hot and cold regions along line of sight.

Wilkinson Microwave Anisotropy Probe

Launched 2001 to L2 for 2 years; ran for 9.

Two back-to-back optical systems for differential measurements (140°)

5 frequencies, 23, 33, 41, 61 and 94 GHz, beam sizes from 53 to 13 arcmin.

10 horn pairs feeding 10 differencing receivers

Stokes parameters I, Q, U

WMAP - from Scans to Maps (1)

1. **Removal of infamous 1/f noise** – 'prewhitening' with a high-pass Wiener filter.

2. **Disentangling** the very complex and interlaced scan pattern.

3. **Measuring the beam patterns**: raw CMB PS requires division by the beam transfer function, the beam profile in harmonic space.

First approx with physical optics; then observations of planet Jupiter; finally parallel processing with additional Fourier-mode construction optimized by modified conjugate gradient method to find main min X^2 valley, augmenting primary-mirror modes with Gram-Schmidt orthogonal polys. Many simulations.

4. **Primary flux calibration**: Mars and Saturn, with fluxes calculated for changing distances and albedos.

5. **Removal of radio AGN** 'foreground sources' by fitting Gaussians to 5σ deviations above a smoothed background.

WMAP - from Scans to Maps (2)

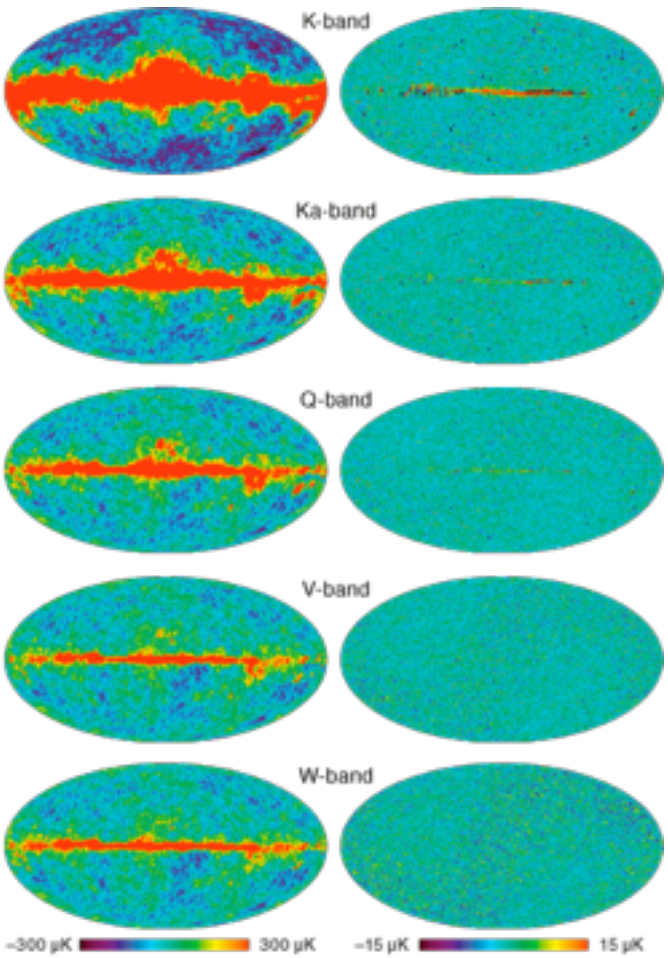
6. Galaxy 'removal' - 7 papers discuss this!

- Gal emission exceeds CMB by 10^3 at K band (lowest freq)

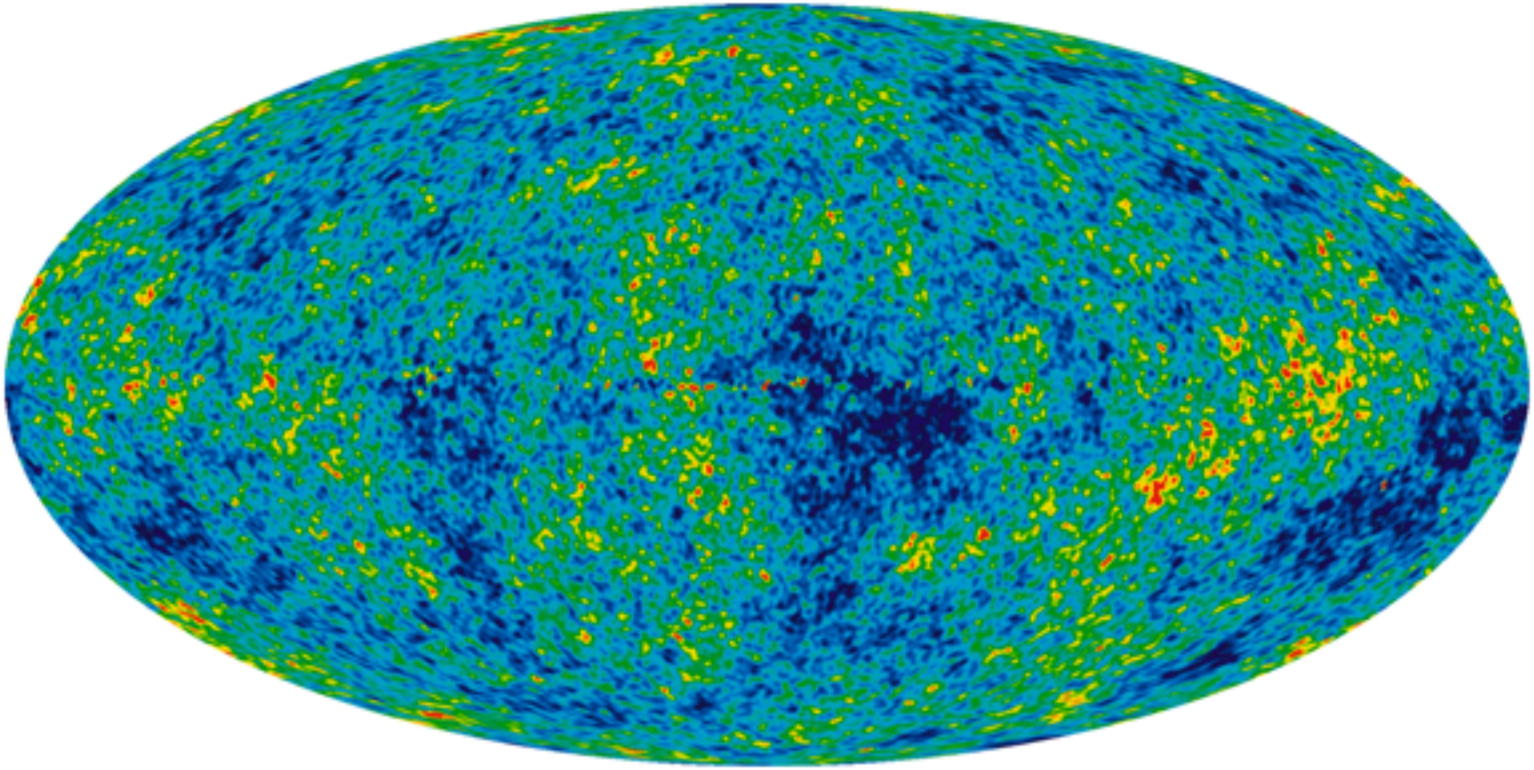
- modelled from 3 components: free-free emission (electron-ion scattering), synchrotron emission (primarily SN Ib and SNII supernova remnants), and thermal dust emission

- >4 techniques used, involving masking, MEM, Bayesian modelling, and an MCMC technique in which each pixel was modelled independently by 4 components with marginalization over the other pixels.

- final variance 100 μK^2 is far below CMB power

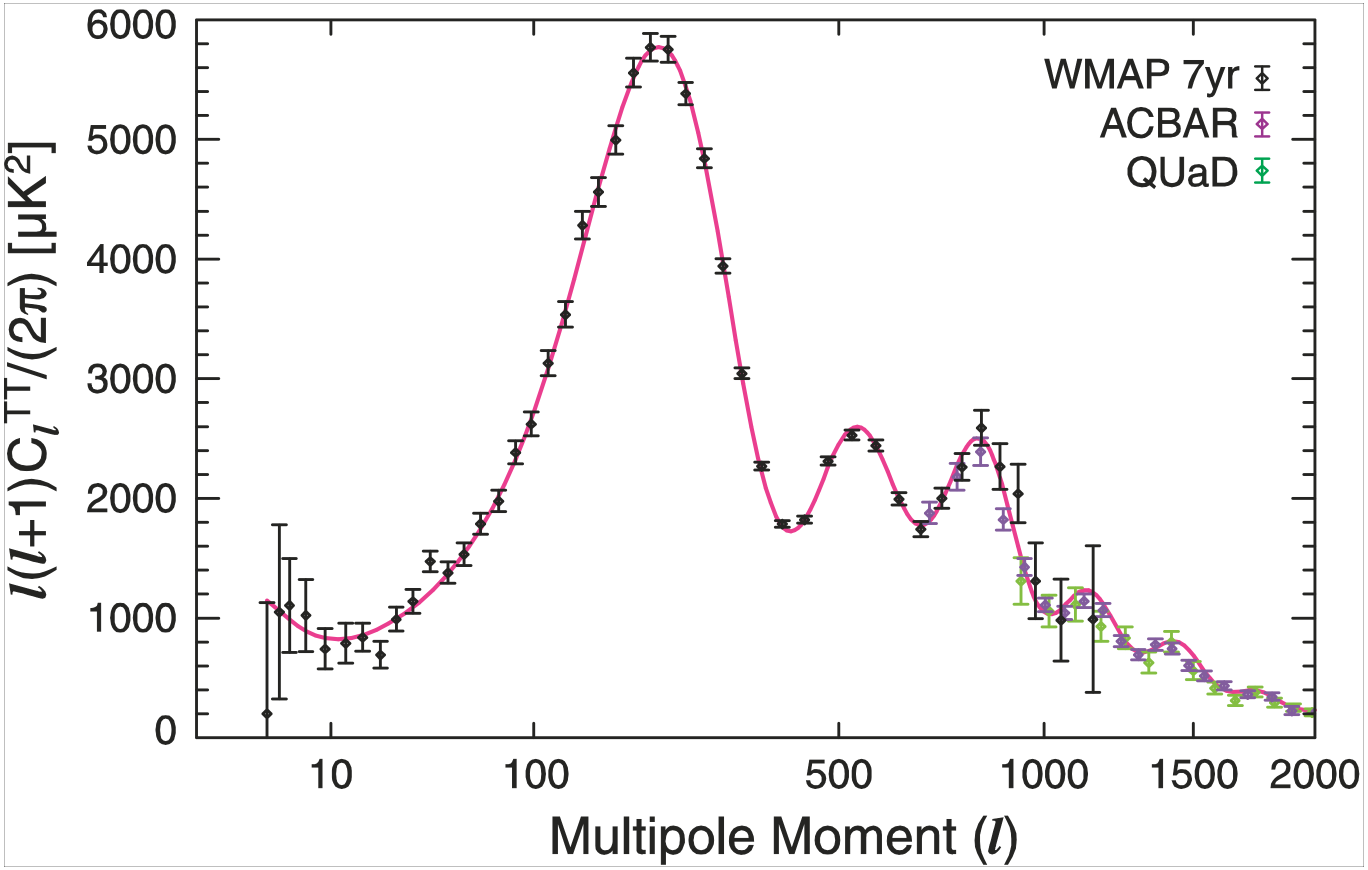


The WMAP



7-year all-sky map

WMAP Power Spectrum



Power-spectrum status in 2010. Data limited by cosmic variance for all ***l*** < 548. High-***l*** values are from ACBAR and QUaD ground-based telescopes, where WMAP is dominated by noise errors.

WMAP Power Spectrum (2)

The 7 WMAP-team papers by 2011 interpreting the power spectrum (100s since), plus the analysis leading up to them have used the following:

✓ - 1/f noise and its analysis

✓ - analysis of gappy data

✓ - Bayesian analysis

✓ - X^2 or LS as the goodness-of-fit parameter

✓ - Fisher matrix

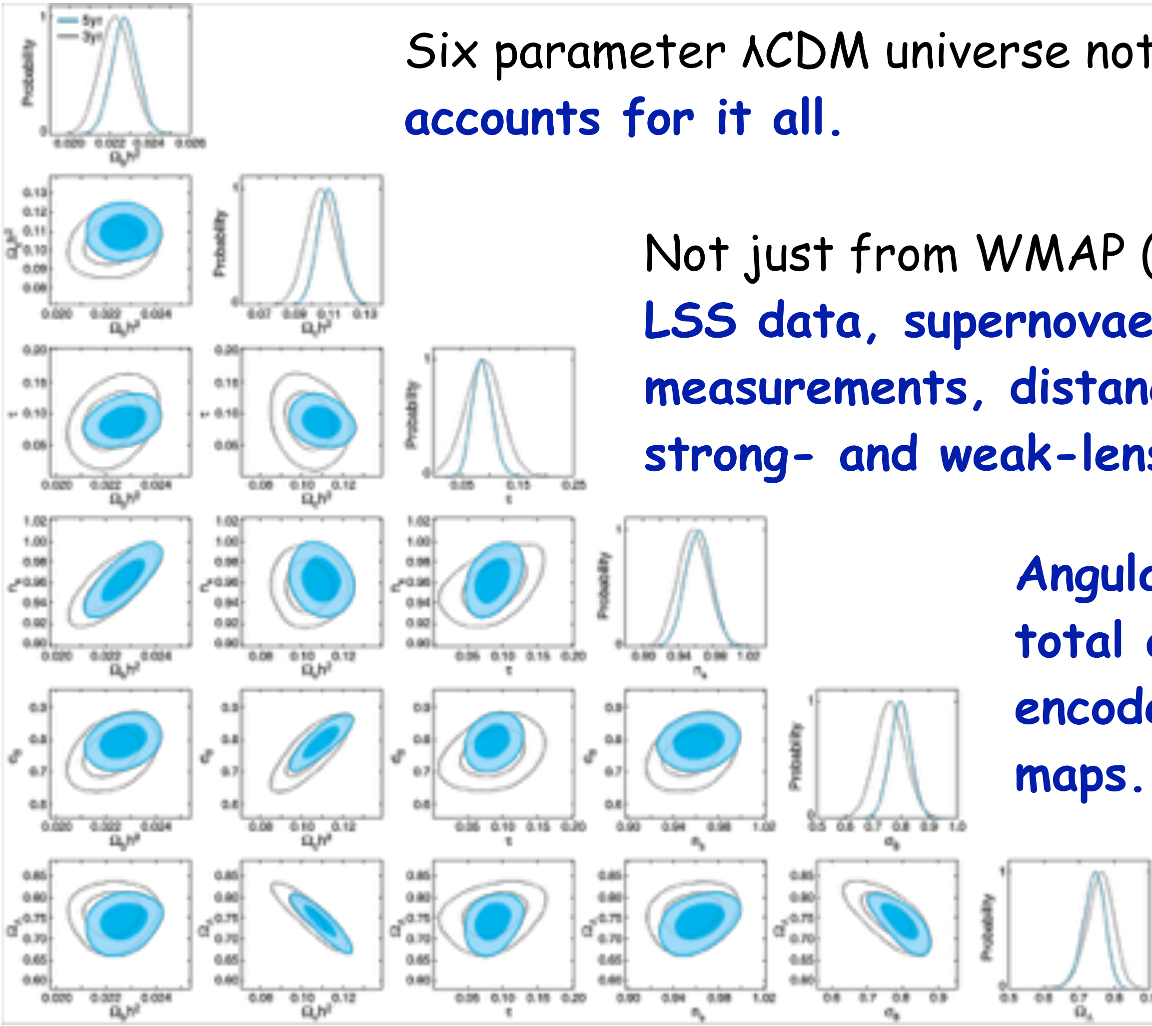
✓ - MCMC to sample the likelihood function

✓ - simulations to test and calibrate the likelihood code so that X^2 values may be used for goodness-of-fit tests as well as for model comparison;

✓ - simulations again to test for bias in the observed parameter set.

The Spergel et al. (2007) paper has received over 4500 citations. Since 2000 the 3 most cited papers in all of astrophysics and physics have been WMAP science papers.

WMAP Power Spectrum (3)



Six parameter ΛCDM universe not only fits the data – **it accounts for it all.**

Not just from WMAP (Komatsu et al. 2010), but from **LSS data, supernovae Type Ia data, cluster measurements, distance measurements, and strong- and weak-lensing data.**

Angular power spectra of both total and polarized emission fully encode all information in the CMB maps.

Dunkley et al. 2009

WMAP Power Spectrum (4)

The 6 parameters:

h (Hubble constant in units of 100 Km s^{-1} Mpc^{-1})

σ_8 (linear-theory amplitude of matter fluctuations on $8h^{-1}$ Mpc scales)

2 out of 3 of the mass fractions Ω_b (baryon density), Ω_c (cold dark matter density) Ω_λ (Dark Energy density) : sum of three $\equiv$ 1.0

τ (reionization optical depth)

n_s (power-law index of the primordial fluctuation spectrum)

Consistent with previous estimates with one exception: n_s = 0.968 +/- 0.012. Harrison-Zeldovich-Peebles spectrum ruled out at 99.5%.

Peaks detected in the E-mode power spectrum imply reionization redshift of $\sim$20 ± 10, larger than suggested by absorption in z>6 quasars.

=> complex, lengthy ionization history for Universe.

WMAP - is there anything else?

New limits on curvature

Details on the epoch of reionization

Confirmation of pre-stellar Helium, hinted at by WMAP, and an estimate of its mass fraction

Estimates of the total mass of neutrinos and the number of species

Constraints on the DE equation of state

Limits on parity violation

Limits on gravitational waves

Details of the Sunyaev-Zeldovich effect and confirmation of differences between cooling-flow and non-cooling-flow clusters

Quantitative tests on inflationary models

Opening of fundamentally new areas of physics and cosmology?

Over to Planck ...

WMAP - NASA's View

1. First fine-resolution (0.2^0) full-sky map of the microwave sky

2. Age of the universe 13.73×10^9 y ±1%

3. Curvature of space within 1% of "flat" Euclidean

4. Baryon fraction 4.6 ± 0.1%

5. Dark Matter fraction 23.3 ± 1.3%

6. Dark Energy fraction 72.1 ±1.5%

7. Linear polarization map: universe reionized earlier than previously believed

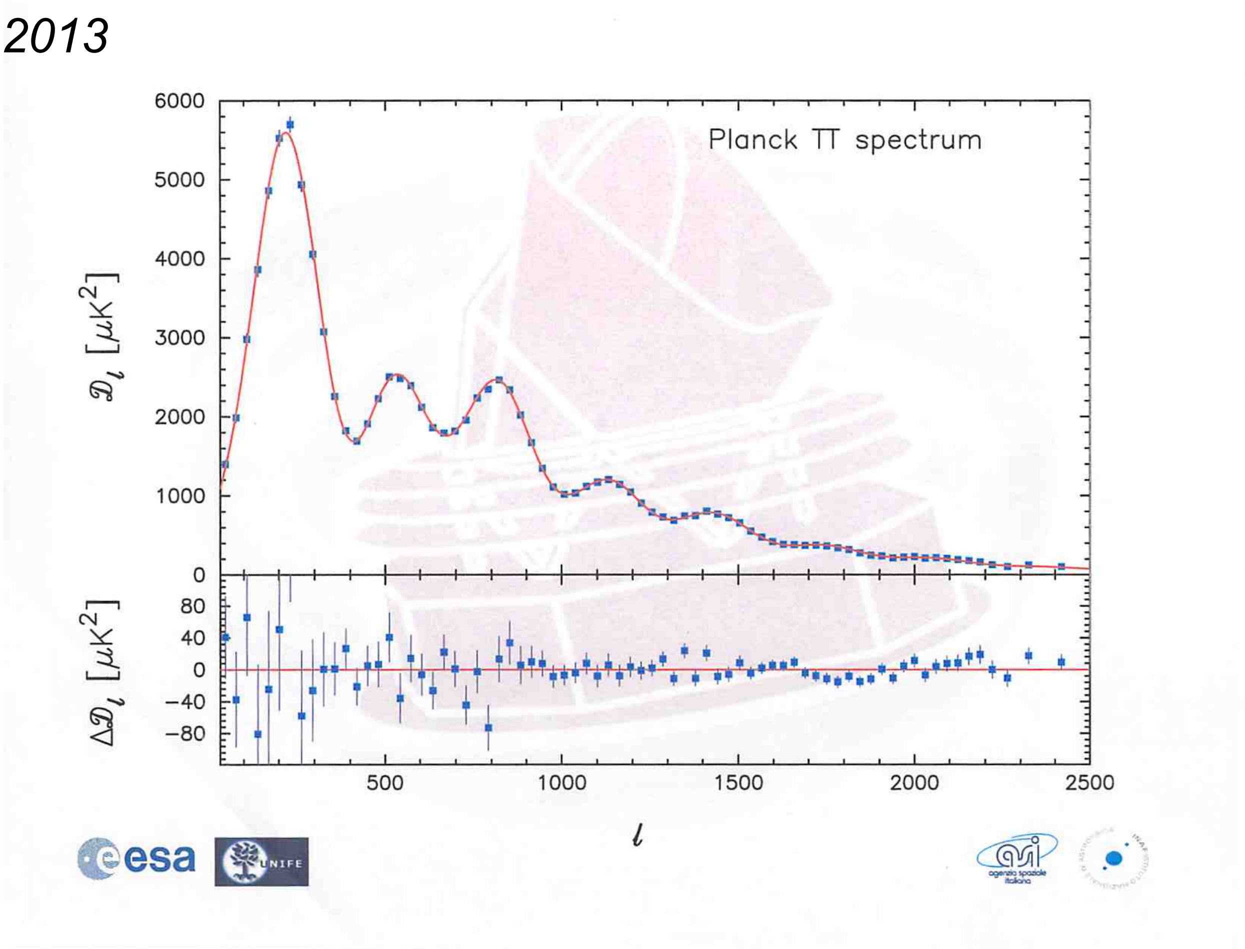
8. $n_s \neq 1.0$

9. Hints of deviations from simple randomness that are still being assessed

Since 2000, the three most highly cited papers in all of physics and astronomy are WMAP science papers.

Planck Power Spectrum

Natoli Oct 2013



The red line is a PREDICTION from the WMAP parameters

Planck Disagreement with H_0 Measurements

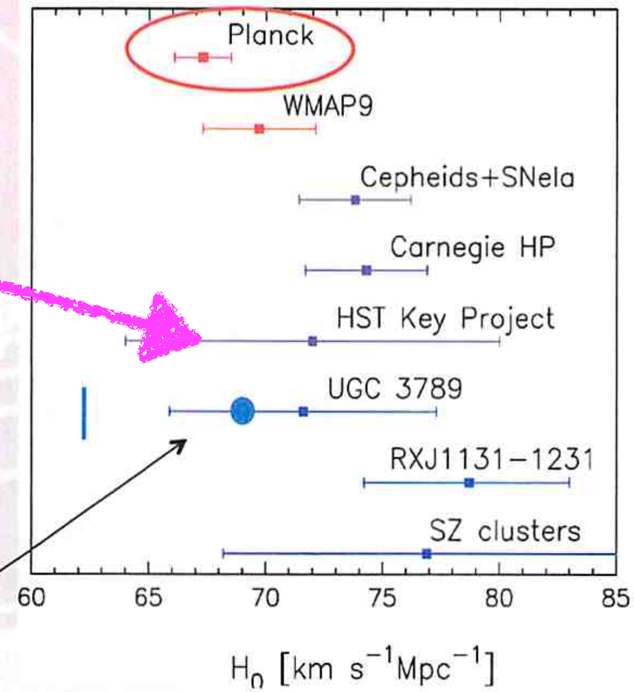
Tension with Hubble Constant astrophysical measurements

Disagreement?

Planck value for the Hubble constant is in at tension with several other measurements (most notably the HST determination).

Systematics in luminosity distance measurements can be clearly there, however this tension could be also hinting towards new physics.

The determination of H_0 from Planck is indeed **model dependent**.



UGC 3789 distance recalibrated, now H_0 = 68.9 ± 7.1 Km/s/Mpc

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Take-Home Stuff

A rant about "Tension" - used in the literature to describe a 1σ to 3σ difference / disagreement /result …

Sigmas	Corresponding probabilities (p-values)	
1σ	0.32	)
2σ	0.045	) there's a rather large difference…..
3σ	0.0027	)
4σ	0.0000063	

In fact -

Statistical inference allows us to formulate the logic of what we are doing and why. It allows us to make precise statements.

(Unh - so why should we invent a term as slovenly as "TENSION"?)

A statistic is a quantity that summarizes data; it is the ultimate data-reduction.

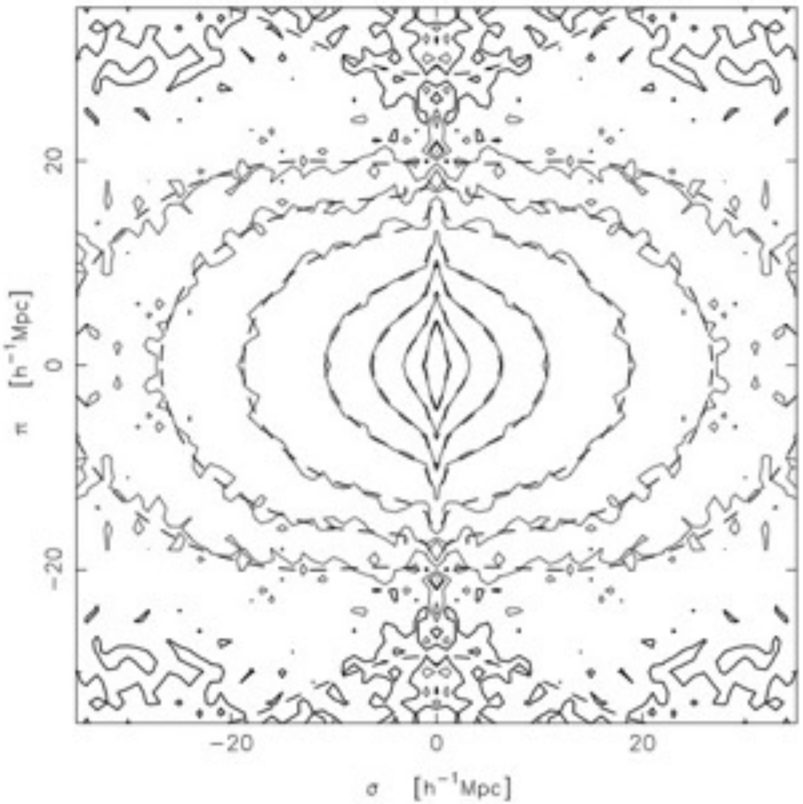
It is a property of the data and nothing else. It may be a number, a mean for example, but it doesn't have to be. It is a basis for using the data or experimental result to make a decision.

IN SCIENCE, ONLY DECISION COUNTS

You now have the tools - what are you waiting for?

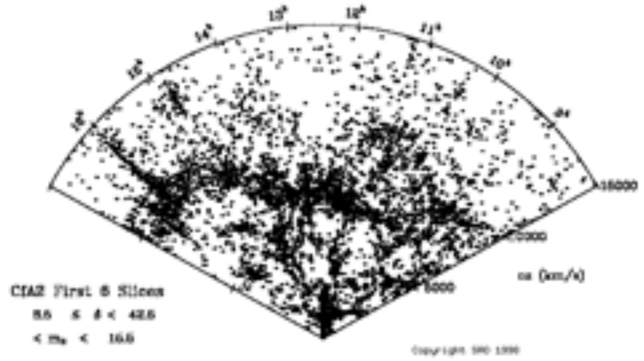
END

3D 2-Point Correlation Function



$\xi(\sigma_t,\pi)$ – 2-pt correl fn with σ_t the transverse distance and π the 'redshift' distance (Hawkins et al 2003)

Effect 1: 'Fingers of God', due to the peculiar velocities of galaxies in clusters



Effect 2: the 'Kaiser effect' – the ellipticity describes the peculiar velocities of galaxies bound to a central mass as they undergo infall. The peculiar velocities are coherent, not random, towards the central mass

Redshift-Space Distortions