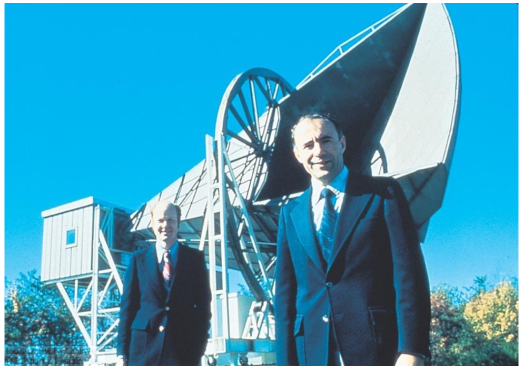
The Cosmic Microwave Background Radiation

Mark Birkinshaw

1. History: the discovery and interpretation of the radiation
2. COBE: large-scale structure, spectrum
3. WMAP: small-scale structures, interpretation
4. Planck: more structure, interpretation

1

Bell Laboratories Crawford Hill, NJ; 1964



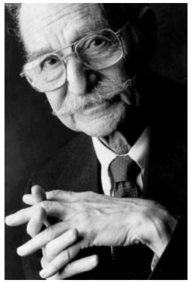
Bob Wilson, Arno Penzias, and the horn antenna at Crawford Hill. Excess radio noise of about 3 K at 7.35 cm. Uniform brightness over sky.

2

George Washington University, 1948

George Gamow

Ralph Alpher



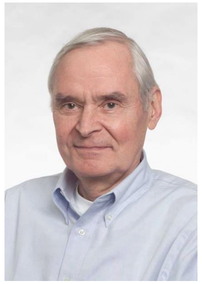
Robert Herman

Gamow and Alpher paper on Big Bang nucleosynthesis (αβγ paper). Alpher moved to Johns Hopkins University, and with Herman showed that this implied cosmic background radiation, refining earlier calculation by Gamow.

3

Princeton University, 1965

Robert Dicke

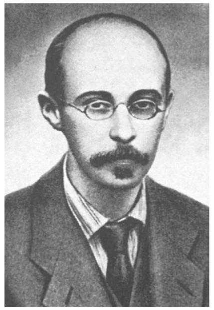


David Wilkinson

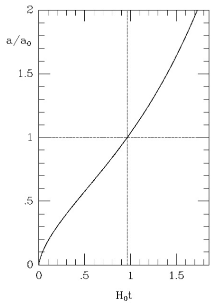
Bob Dicke and students (including David Wilkinson) were trying to measure the predicted background radiation. Scooped by Penzias and Wilson, but wrote important 1965 paper on interpretation of radiation.

4

Пермский государственный университет, 1922



Алекса́ндр Фри́дман



Modern solution of equations

Equations for expansion of Universe derived by Alexander Friedmann, solved by him, Georges Lemaitre, Howard Robertson, Arthur Walker, …

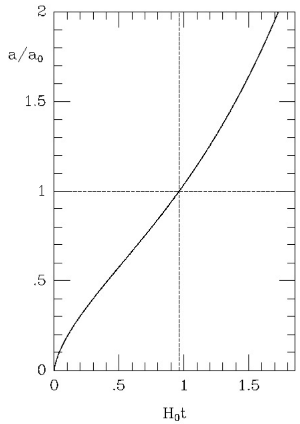
5

Matter and radiation in cosmology

Since Universe was smaller in past, it was hotter in the past – its contents were squeezed into less space.

Before 13.6×10^9 years ago it was hot enough that all the matter in it was ionized to electrons and nuclei at about 3000 K, and emitted optical and infrared light characteristic of its temperature.

This is “black body radiation”.



6

Matter and radiation in cosmology

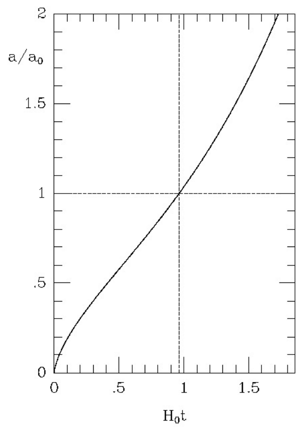
After 13.6×10^9 years ago the matter cooled off and became neutral.

Light interacts weakly with neutral matter.

So the thermal radiation travels to us affected only* by the expansion of the Universe.

This causes the temperature of the radiation to drop and the light to redshift to peak at much longer wavelengths.

It is now the CMB. *well, nearly.



7

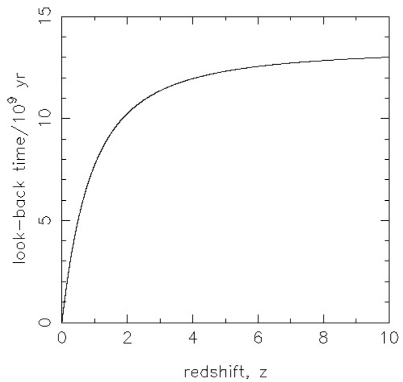
Time, scale factor, redshift

Redshift measures scale of Universe

$$1+z = a_0/a$$

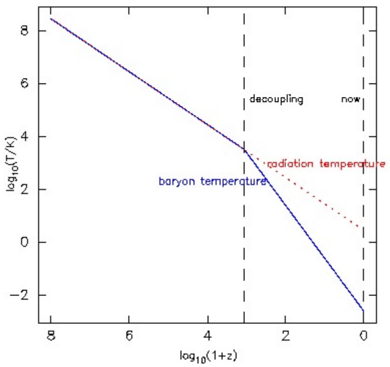
$z = 0$: present
$z > 0$: past (∞ at Big Bang)
$z < 0$: future (-1 at End of Time)

z implicitly also measures distances (light travel times).



8

Matter and radiation in cosmology



Simple Friedman cosmology predicts cold gas today – but it's heated by stars.

9

Details, details

Is the background radiation really cosmological?

Check whether foreground objects cast shadows

Is the radiation field entirely thermal?

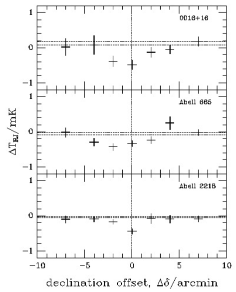
Measure spectrum

Is the background radiation entirely uniform?

Measure angular structure

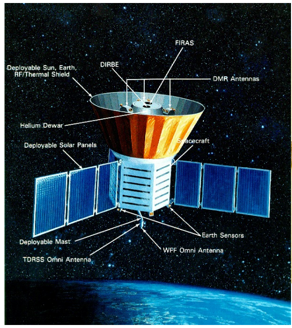
10

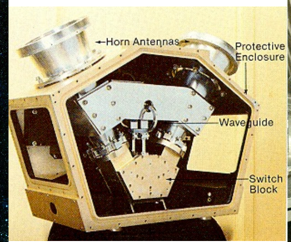
Shadows: SZ effect

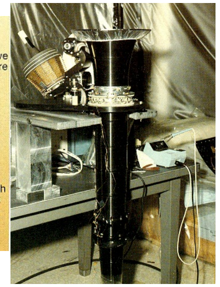


Clusters of galaxies contain hot gas that alters the brightness of the background radiation: 0.01% shadows (Birkinshaw *et al*. 1984). More about this later today.

COBE

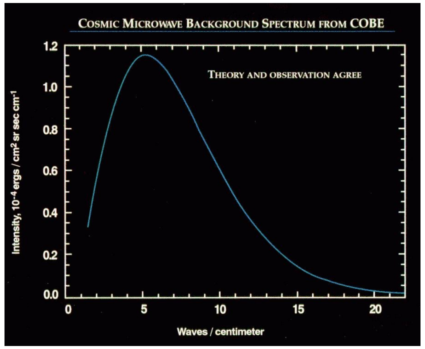






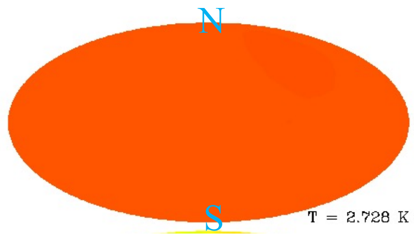
COBE, the COBE DMR, the FIRAS horn and calibrator.

Thermal spectrum



Error bars too small to see. Thermal spectrum at 2.73 K: COBE FIRAS (Mather *et al*. 1994).

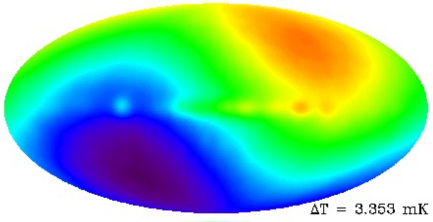
Uniform background?



COBE satellite (Smoot *et al*. 1994)

Fake – DMR measured only differences

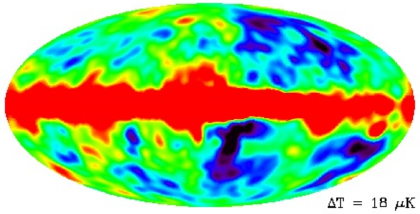
Uniform background?



Not quite uniform.
Small-scale lumpiness on Galactic plane (foreground contamination).
Large-scale 陰陽 pattern: Doppler dipole, 400 km s^{-1} motion of Earth relative to distant matter (600 km s^{-1} for Galaxy).

15

Uniform background?



Not quite uniform.
After dipole removed radio emission from the Galaxy dominates.
Remaining lumps are mostly, but not all, measurement noise.

16

Sound and gravity

Lumpiness of CMB is indicator of cosmological parameters and test of theory of formation of structure.

Precision of measurement has improved

- COBE satellite (1989-1993)
- WMAP satellite (2001-2009)
- Planck satellite (2009-2016)
- Ground projects (1965-present)

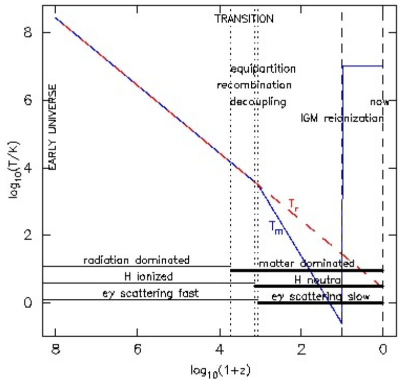
17

The thermal history of the Universe

Temperatures of radiation and matter from 10 sec to today.

Cartoon of phase changes as function of redshift, *z*.

Radiation field today is visible as the cosmic microwave background, CMB.

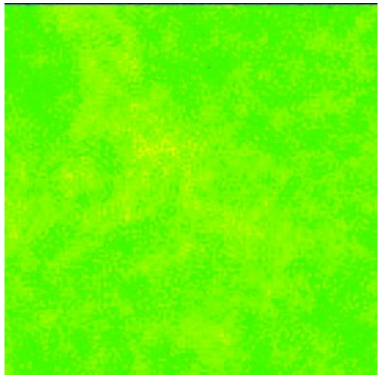


18

Early lumps

Structures grow slowly from early inhomogeneities.

To form structure by today, need sufficiently over-dense and large structures at $z \sim 1000$



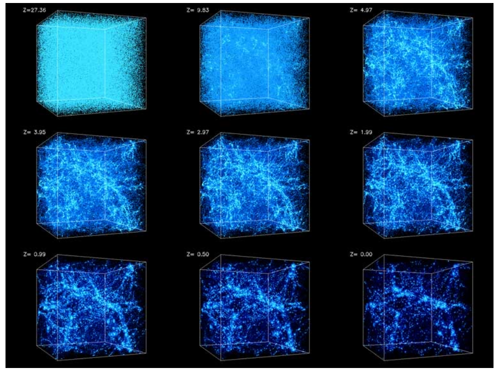
19

Early sound

Pattern and amplitudes of lumps must be right to match today's structure.

Density lumps compress the gas, causing temperature peaks, and move the gas, causing Doppler effects.

These give CMB structures we see today.



20

Sound and gravity

Jeans mass, M_J, grows roughly as $t^{3/2}$ early.

M_J drops dramatically at 3×10^{12} s (t_{rec} here).

Lumps grow, then convert to oscillations, then become unstable again.

At t_{rec} different masses have different phase and amplitude.

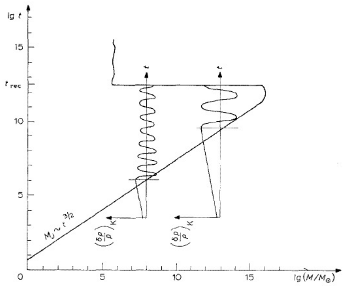


Рис. 1а. Диаграмма гравитационной неустойчивости в горячей модели. Правее линии $M_J(t)$ – область неустойчивости, левее – область устойчивости. Два дополнительных графика демонстрируют эволюцию возмущений плотности вещества со временем: рост до того момента, пока рассматриваемая масса меньше джинсовской и колебания после. Видно, что к моменту рекомбинации возмущения, соответствующие разным массам, приходят с разными фазами.

Zel'dovich & Sunyaev (1970)

21

Sound and gravity

- Mass oscillations appear as CMB brightness changes with direction on the sky. These are the lumps under COBE's noise.

- Calculation of brightness and scale complicated by
  - non-instantaneous transition from strong to zero coupling
  - ionization structure of matter in Universe
  - presence of dark matter and neutrinos
  - Doppler signal from motions

- Expect pattern to be dominated by scale of sound waves that can exist at z = 1000 ("sound horizon" scale, s_h = 150 Mpc)

22

Sound horizon

Given by

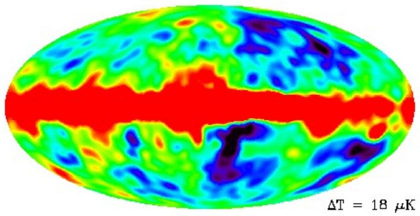
$$s_h = \int_0^{t_{rec}} c_{s(z)}(1+z)\,dt = \int_{z_{rec}}^{\infty} \frac{c_s(z)}{H(z)}\,dz$$

Sound speed a weak function of baryon/radiation density ratio

$$\frac{c_s(z)}{c} = \left[3\left(1+\frac{3\rho_b}{4\rho_\gamma}\right)\right]^{-\frac{1}{2}}$$

23

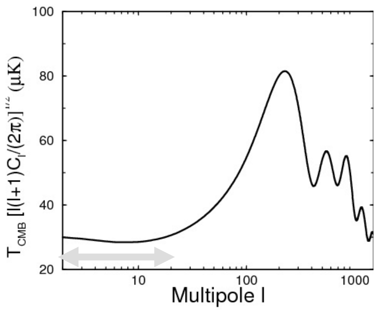
COBE



COBE was a small satellite, so only measured the biggest lumps. This showed that the general picture is reasonably accurate, but couldn't see the complicated expected pattern.

24

COBE



COBE was a small satellite, so only measured the biggest lumps. Most of the interesting information is on smaller angular scale ("at higher multipole", *l*). $l \approx 180°/\theta$ (peak at about 2°)

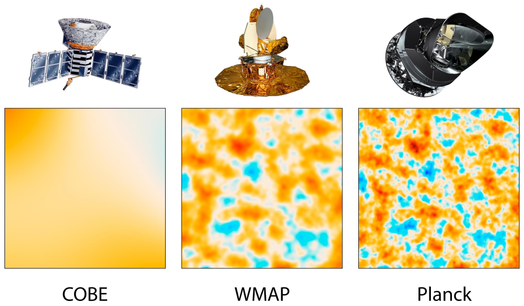
25

Sound and gravity

- Measurements of noise peaks measure key cosmological parameters. The peaks are from self-gravitating sound waves, and probe
  – flatness of Universe (position of first peak)
  – constituents of Universe (heights of peaks)
  – theory of gravity (shapes of peaks)
- COBE measured the amount of noise but was too small to measure the shape of the power spectrum.

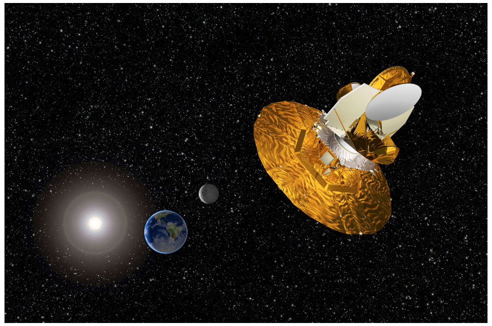
26

COBE, WMAP, Planck



Increased size of telescopes, from a few cm (COBE) to a few m (Planck). Higher resolution only from ground.

WMAP



WMAP had a radio telescope and flew near L2. The detectors were more sensitive than COBE and operated for 9 years, so produced more precise results than COBE.

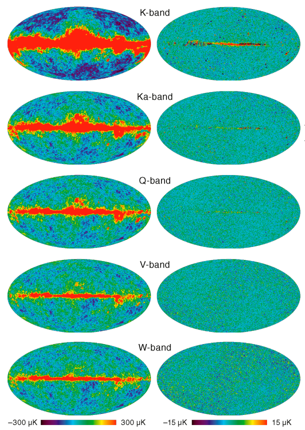
WMAP

All-sky maps of the CMB (7-year dataset).

Five observing bands from 20 to 90 GHz.

With dipole removed (left). With dipole and estimate of Galaxy removed (right).

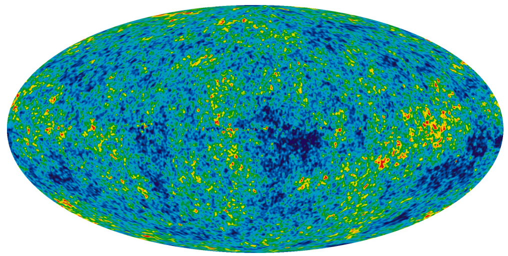
Jarosik *et al*. (2011).



K
Ka
Q
V
W

29

WMAP



9-year dipole- and Galaxy-subtracted image, ± 200 μK range.
ILC map – far more detail than COBE – much smaller beam.
Galaxy removed using multiple observing frequencies.
Lumpiness is not random – see distinct scales by eye.

30

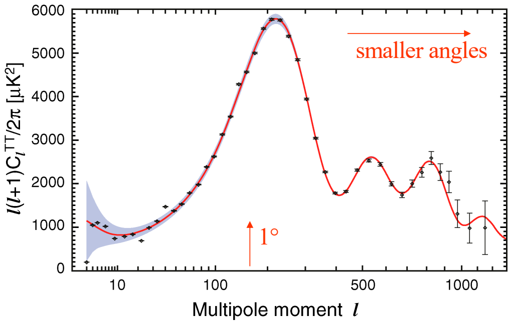
Sound and gravity

Measured power spectrum

First peak: compression, $kc_s t_{ls} = \pi$

First trough: velocity maximum, no density change.

Second peak: rarefaction, $kc_s t_{ls} = 2\pi$



WMAP, 7-years, TT. Larson *et al*., 2011.

Sound and gravity

WMAP fits: to power spectrum

$\Omega_b h^2$ = 0.0227(5)

$\Omega_c h^2$ = 0.111(4)

Ω_Λ = 0.74(2)

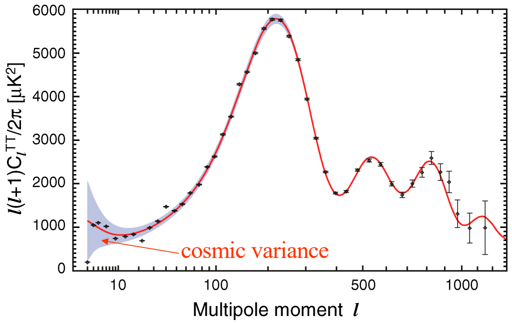
τ = 0.09(1)

n_s = 0.97(1)

Δ^2_R = 2.38 × 10^{-9}

A_{SZ} = 0.52

[assumes $k = 0$]



WMAP, 7-years, TT. Larson *et al*., 2011.

Later structure

CMB/matter interactions didn't end at decoupling: WMAP found $\tau = 0.09$

The densest parts of the Universe, clusters of galaxies, contain atmospheres that also interact with the CMB via inverse-Compton scattering (SZ effect)

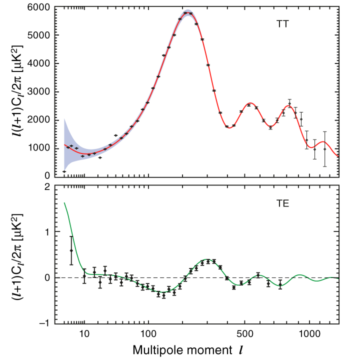
Also measured interaction of CMB with growing clusters of galaxies (ISW effect).

33

Sound and gravity

Polarization of CMB adds extra information, but precision is quite low at present.

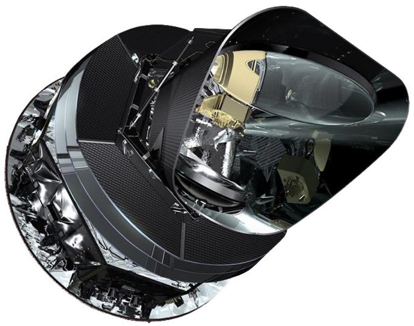
Two modes "E" and "B". WMAP only measured E, and then only in correlation with the unpolarized signal.



WMAP, 7-years, TT, TE. Jarosik *et al*., 2011.

34

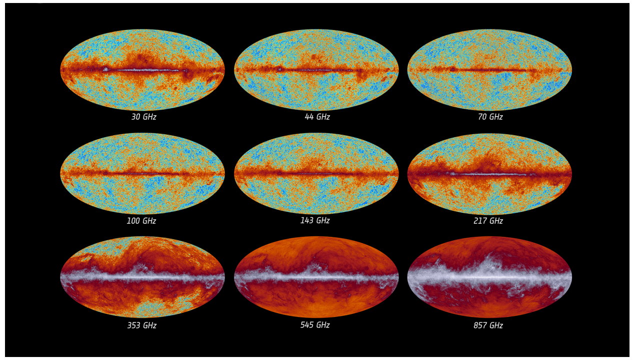
Planck



Bigger than WMAP, more and better detectors, more frequencies (better protection against foreground signals), plus polarization

35

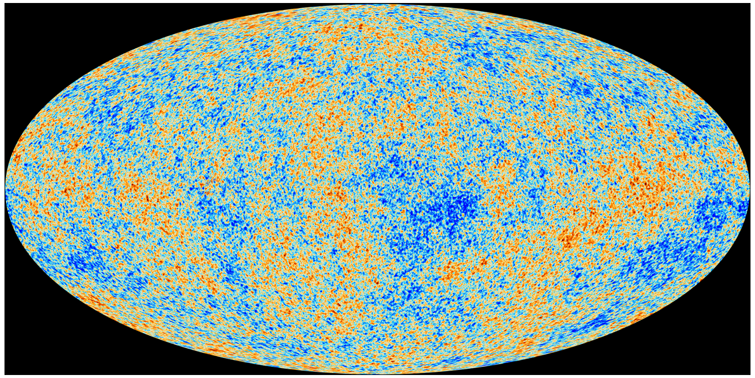
Planck



Nine frequencies, with the Galaxy bright in all of them.

36

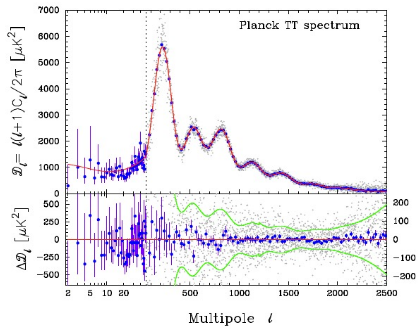
Planck



Use spectrum to remove Galaxy, leaving background radiation.

37

Planck



Spectrum extends further than WMAP and fits theory well.

38

Planck

Comparison of *Planck*-only and *WMAP*-only Six-Parameter ΛCDM Fits[a]

Parameter	*Planck* ("CMB+Lens")	*WMAP* (9-year)	Difference value	Difference *WMAP* σ
$\Omega_b h^2$	0.02217 ± 0.00033	0.02264 ± 0.00050	-0.00047	0.9
$\Omega_c h^2$	0.1186 ± 0.0031	0.1138 ± 0.0045	0.0048	1.1
Ω_Λ	0.693 ± 0.019	0.721 ± 0.025	-0.028	1.1
τ	0.089 ± 0.032	0.089 ± 0.014	0	0
t_0 (Gyr)	13.796 ± 0.058	13.74 ± 0.11	56 Myr	0.5
H_0 (km $s^{-1}Mpc^{-1}$)	67.9 ± 1.5	70.0 ± 2.2	-2.1	1.0
σ_8	0.823 ± 0.018	0.821 ± 0.023	0.002	0.1
Ω_b	0.0481[b]	0.0463 ± 0.0024	0.0018	0.7
Ω_c	0.257[b]	0.233 ± 0.023	0.024	1.0

[a]The new *Planck* results strongly favor the standard six-parameter ΛCDM model with parameter values that are consistent with *WMAP* parameters, as shown in this table which compares results derived entirely from *Planck* data with those derived entirely from *WMAP* data.

[b]Parameters derived from quoted values. No error estimate is given for this data/model combination.

Pretty good agreement with WMAP – but Planck measured more.

39

Key results - 1

Hot Big Bang Universe supported (thermal spectrum and gross uniformity).

Structure forms by growth of seed structures (fluctuation spectrum).

Only 6 cosmological parameters are needed to describe structure ($\Omega_b h^2$, $\Omega_c h^2$, τ, n_s, A_s, θ_{MC}).

Spacetime is flat to 0.1% accuracy.

There are only three types of neutrino.

40

Key results - 2

Dark energy = cosmological constant – no dynamics.

Rate of collapse of clusters from ISW effect as expected.

Inflation supported via spectral index n_s.

Numbers of clusters seen via SZ effect don't match expectations.

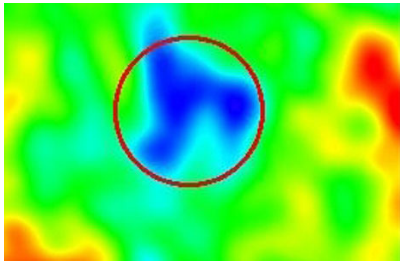
No anisotropy at $l > 50$, but issues at low l.

Cold spot.

41

Cold spot

- WMAP and Planck both find a "cold spot" on the sky
- Amplitude unexpectedly high, given statistics of data
- Corresponds to deficit of radio sources, but not galaxies in normal mix
- Still unexplained.



WMAP cold spot in Eridanus

42

The future

Parameters describing the Universe will be more precisely measured by CMB structure data using oscillations …

… or perhaps we will find the ΛCDM "concordance" model fails. Hints in Hubble constant incompatibilities and cluster numbers?

Post-Planck satellites should be able to measure more CMB parameters (polarization; gravity waves?) – multiple projects under construction and being planned.

Processes occurring in clusters will be seen in tSZ maps to $z > 2$ ($t < 3.5 \times 10^9$ years), and other cluster signals (kSZ and BG effects) will tell us whether structure forms the way we think it does.