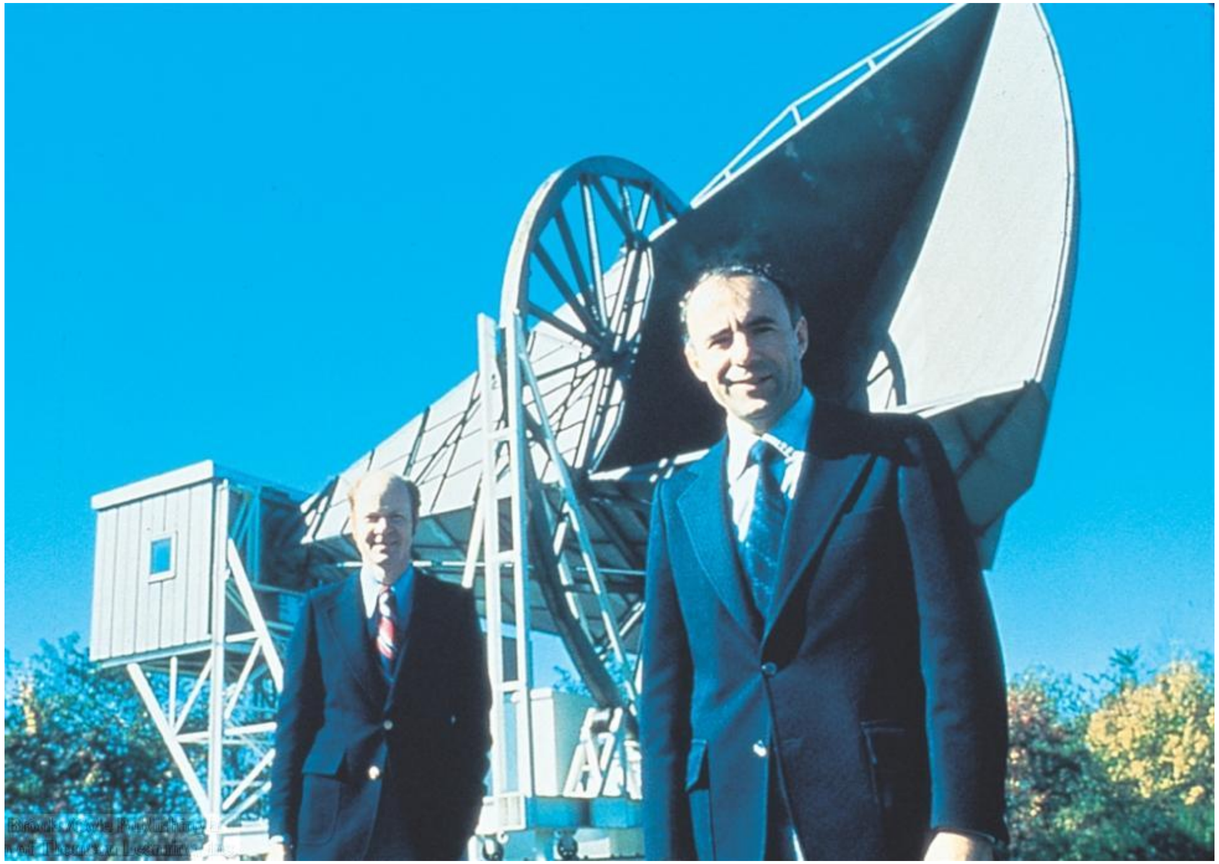
Cosmology and the CMB

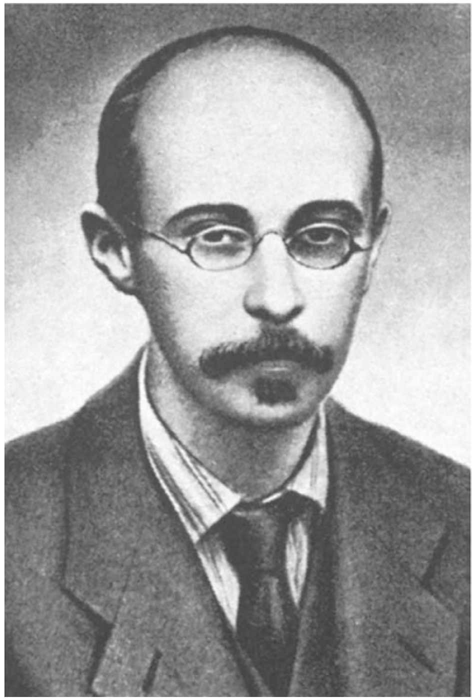
- Cosmic microwave background
- Data on the cosmic microwave background from three satellites
- Fluctuations and galaxy formation
- Sunyaev-Zel’dovich and other effects

Bell Laboratories Crawford Hill, NJ; 1964

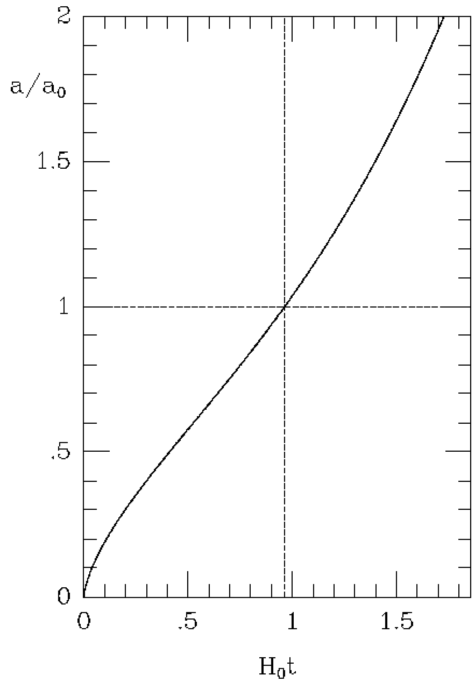


Bob Wilson, Arno Penzias, and the horn antenna at Crawford Hill.
Excess radio noise of about 3 K at 7.35 cm. Uniform brightness over sky.

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, …

Matter and radiation

Since Universe was smaller in past, it was hotter in the past.

About 13.6×10^9 years ago it was hot enough for matter to be ionized.

The matter radiated light, mostly optical and IR at that time, with peak in the infra-red.

Expansion of the Universe causes the temperature of the radiation to drop and the wavelength of the radiation to increase.

Today the light is at radio and mm wavelengths. Temperature about 4 K (Alpher and Herman), down from temperatures for nucleosynthesis (αβγ). Predicted to be in radio band (Dicke and students), and discovered at Crawford Hill (Penzias and Wilson).

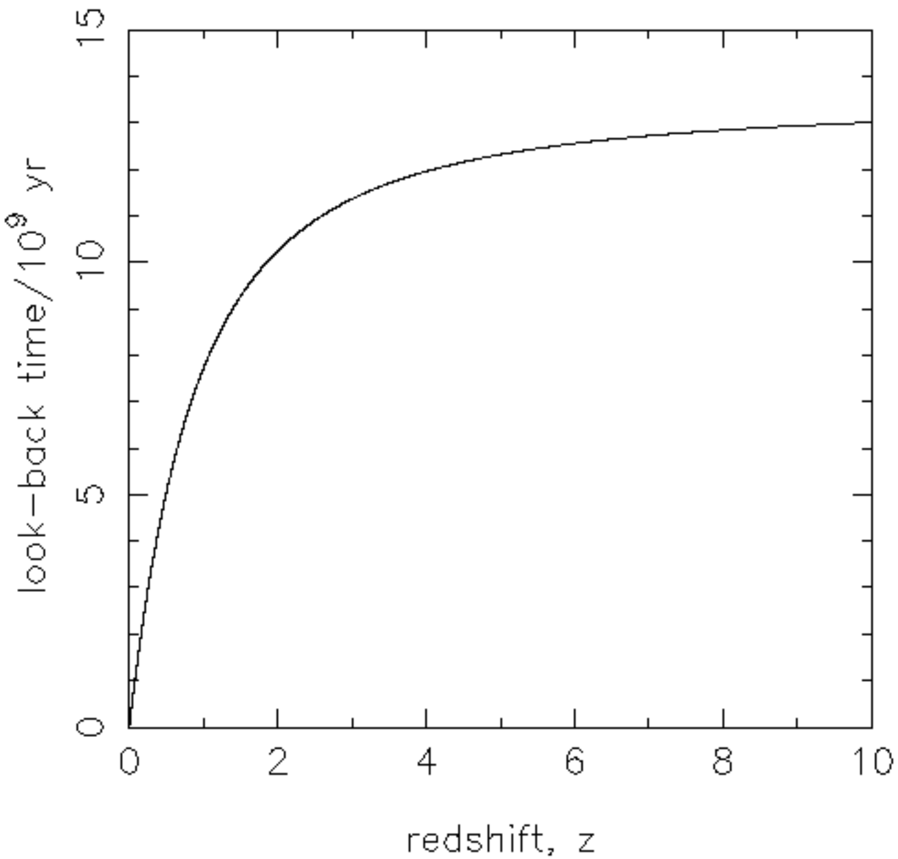
Time, scale factor, redshift

Redshift measures scale of Universe

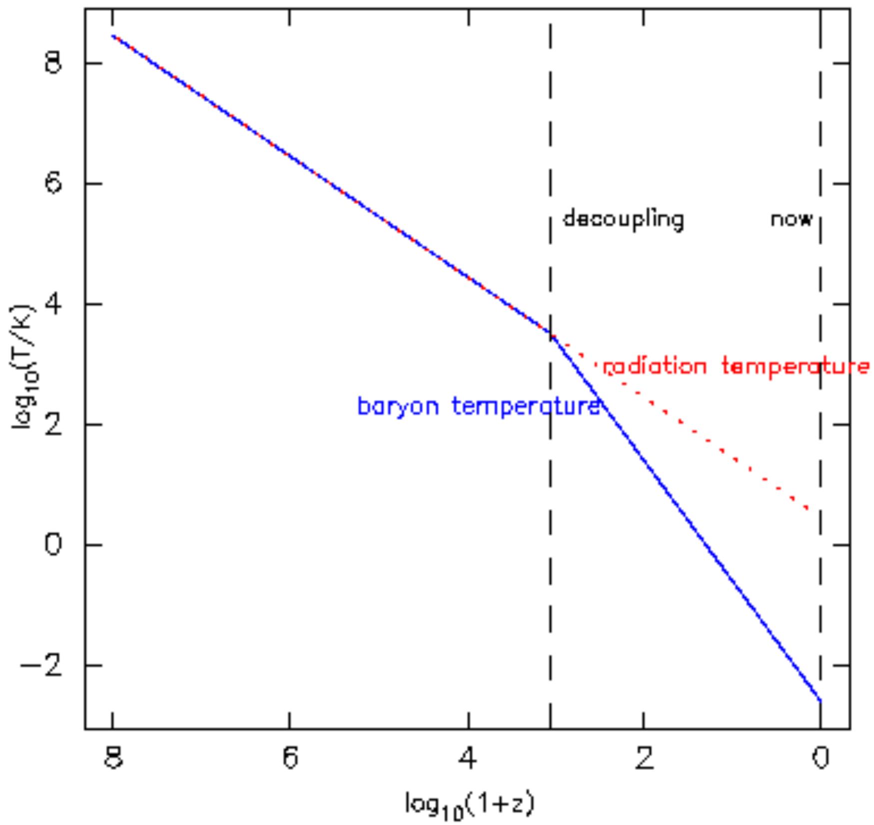
$$1+z = a_0/a$$

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).



Matter and radiation



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

Details, details

Is the background radiation really cosmological?

Check whether foreground objects cast shadows

Is the radiation field entirely thermal?

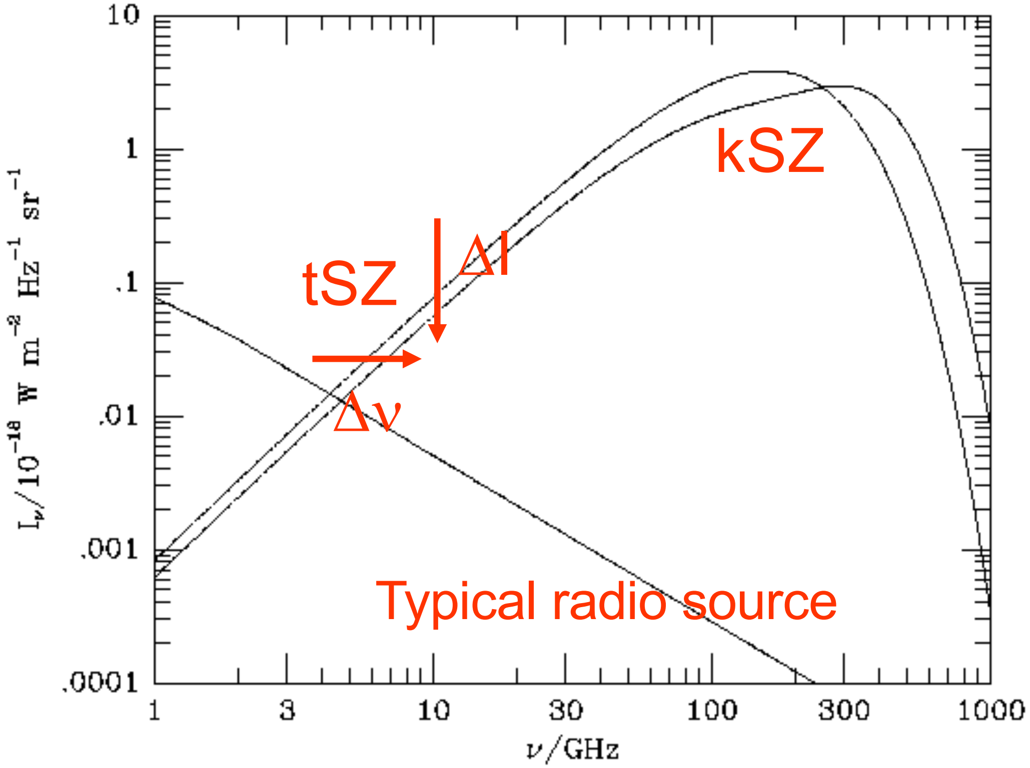
Measure spectrum

Is the background radiation entirely uniform?

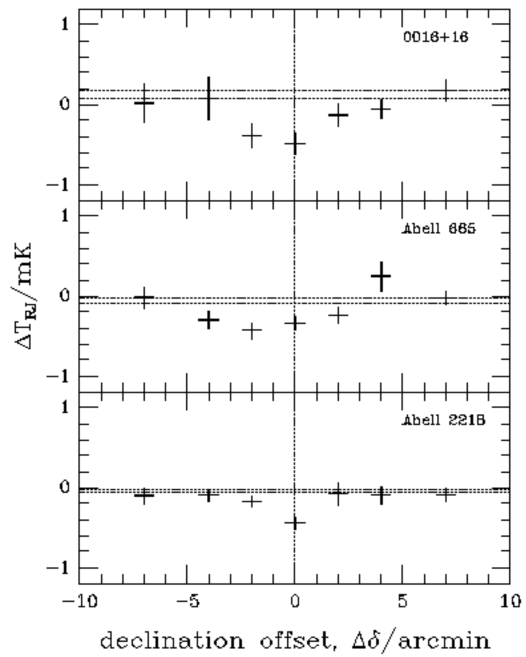
Measure angular structure

Shadows: SZ effect

Photons gain energy from hot gas, spectrum depressed at low frequencies.



Shadows: SZ effect



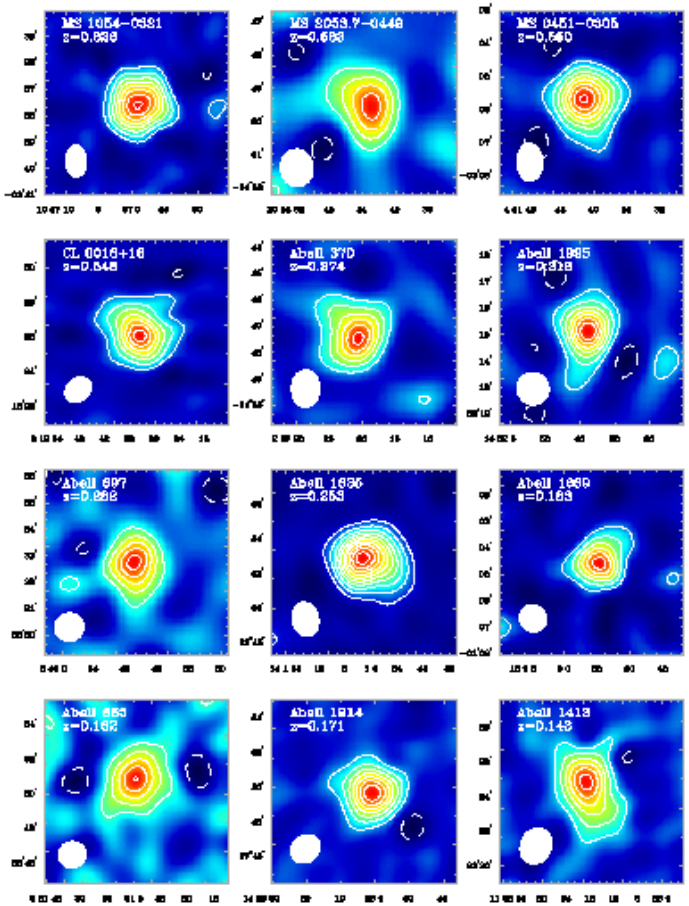
Clusters of galaxies contain hot gas that alters the brightness of the background radiation: 0.01% shadows (Birkinshaw *et al*. 1984).

Shadows: SZ effect

Maps in the 1990s and 2000s showed little structure: few independent detectors doing the mapping.

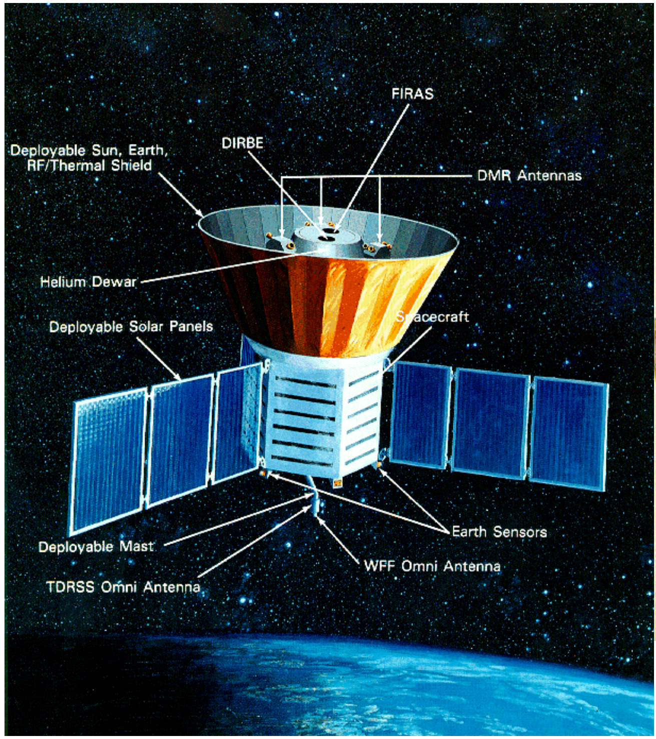
Proof of concept for larger-scale projects with dedicated ground-based telescopes.

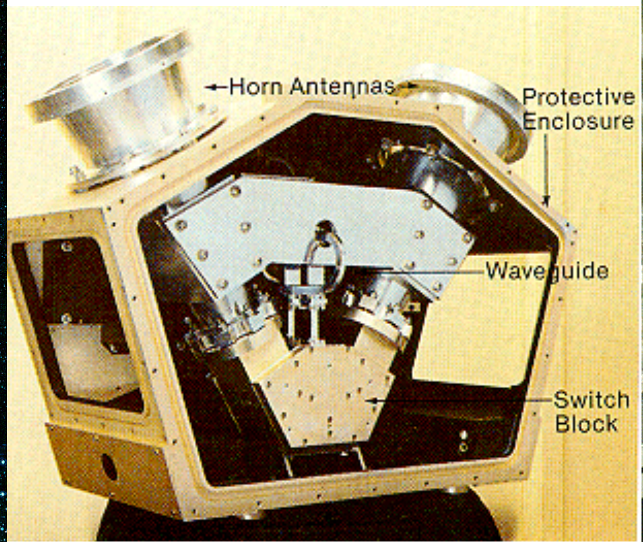
SZ "shadows" seen at $z > 1$, less than 5 Gyr after Big Bang.

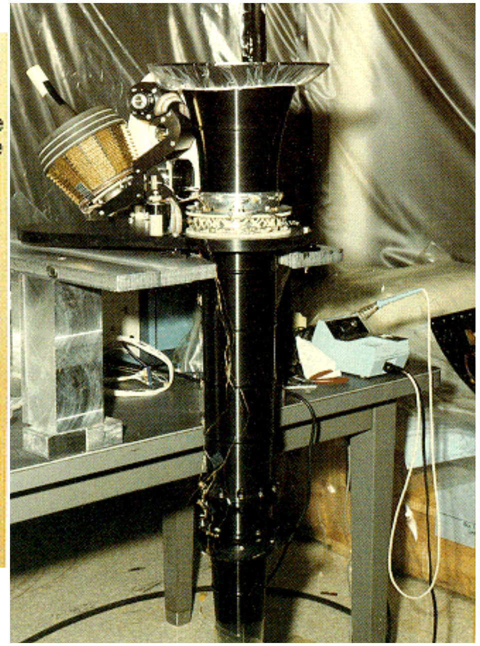


Carlstrom *et al.*, 2002.

COBE

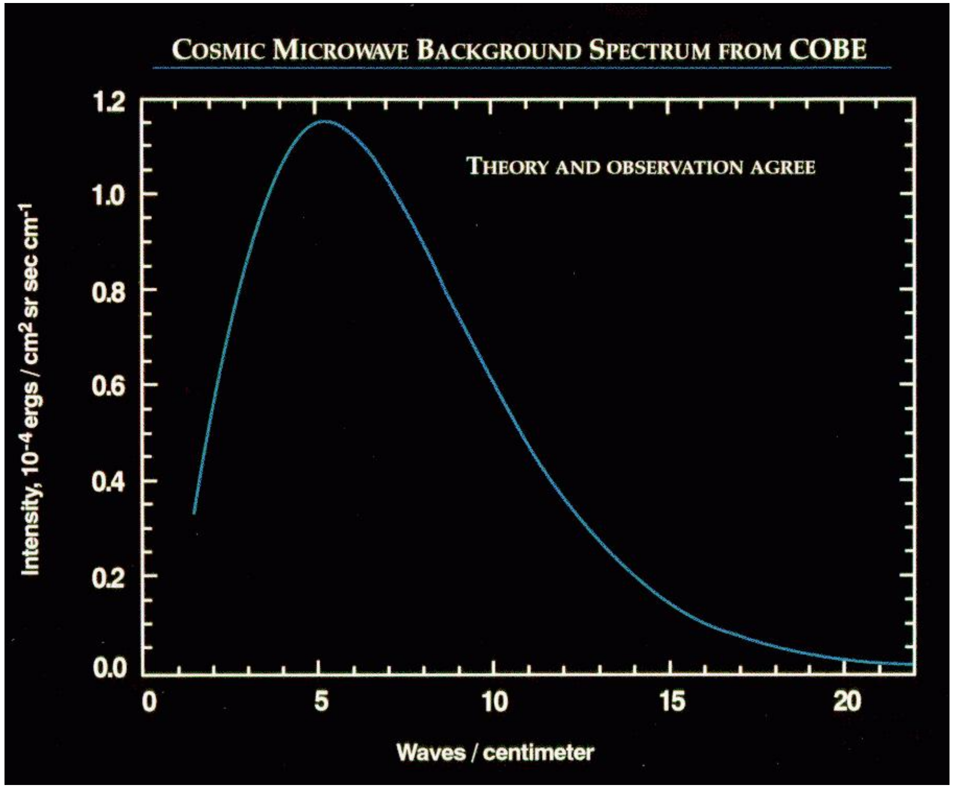






COBE, the COBE DMR, the FIRAS horn and calibrator.

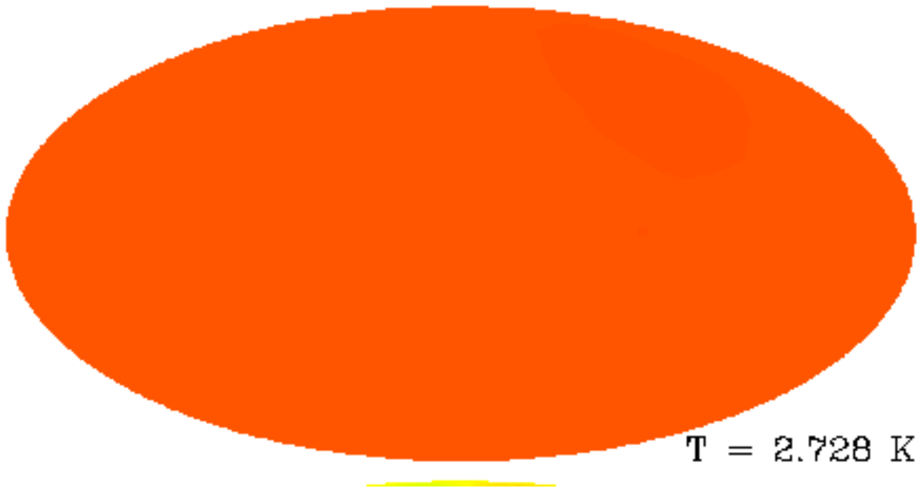
Thermal spectrum



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

Fake – satellite measured only differences

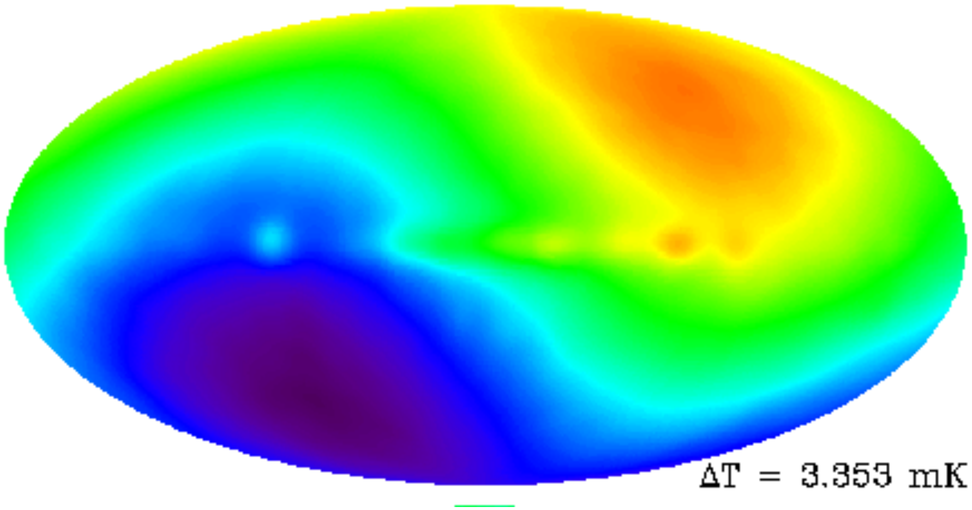
Uniform background?



COBE satellite (Smoot *et al*. 1994)

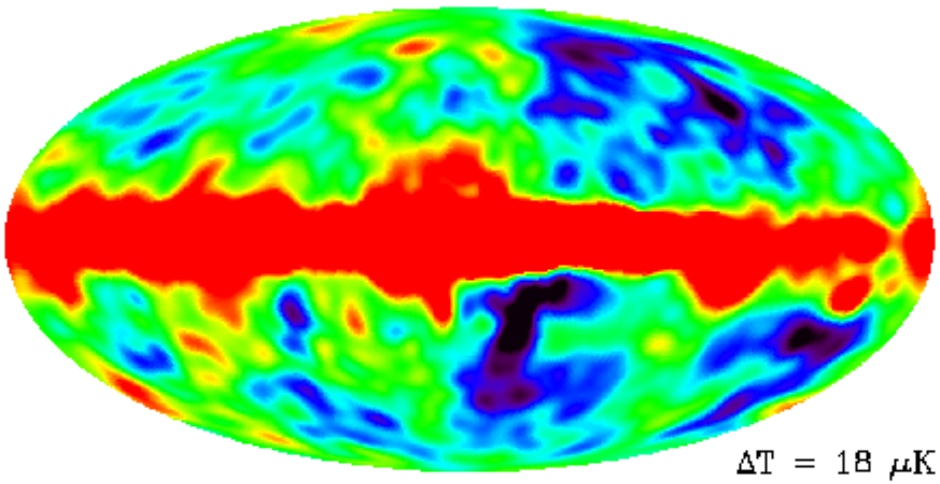
Fake – satellite measured only differences

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).

Uniform background?



Not quite uniform.
After subtract dipole, radio emission from the Galaxy is clearer.
Remaining lumps are mostly noise, but not quite.

Sound and gravity

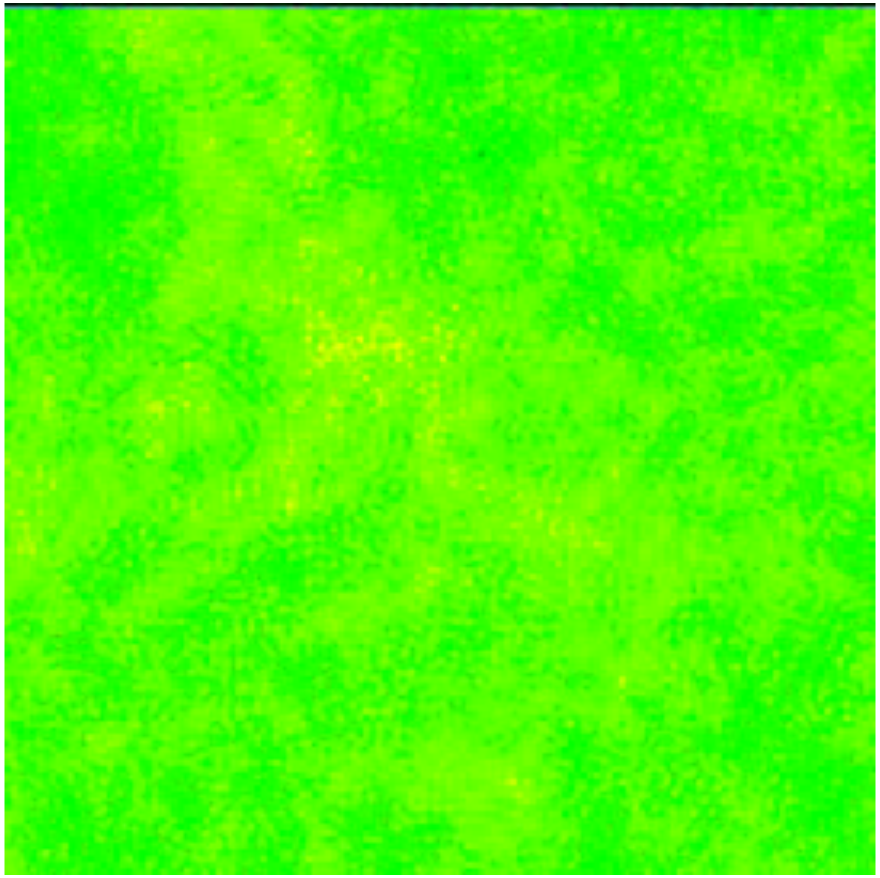
Lumpiness of CMB is indicator of cosmological parameters and test of theory of formation of structure.

Precision of measurement has improved

- COBE (1989-1993)
- WMAP (2001-present)
- Planck (2009-present)
- Ground projects (many)

Early sound

- Structure today is "non-linear": lumps have density contrast >> 1
- Most growth to galaxies and clusters since decoupling is at rate $\propto(1+z)$
- Need seeds with density contrasts > 10^{-3} at $z \sim 1000$



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 to $M = M_J$ then are sound waves to t_{rec}.

At t_{rec} some mass scales have high amplitude, others low.

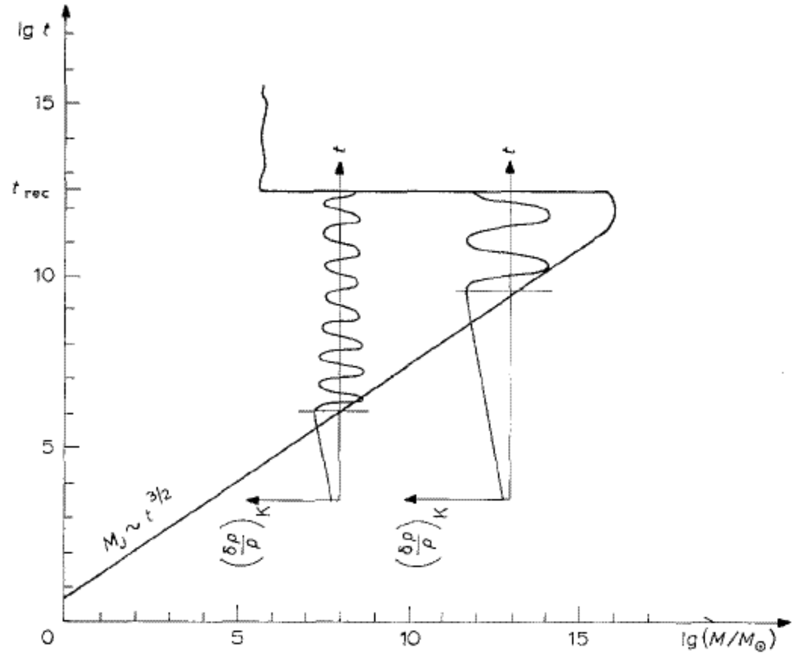


Рис. 1а. Диаграмма гравитационной неустойчивости в горячей модели. Правее линии $M_J(t)$ – область неустойчивости, левее – область устойчивости. Два дополнительных графика демонстрируют эволюцию возмущений плотности вещества со временем: рост до того момента, пока рассматриваемая масса меньше джинсовской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

Zel'dovich & Sunyaev (1970)

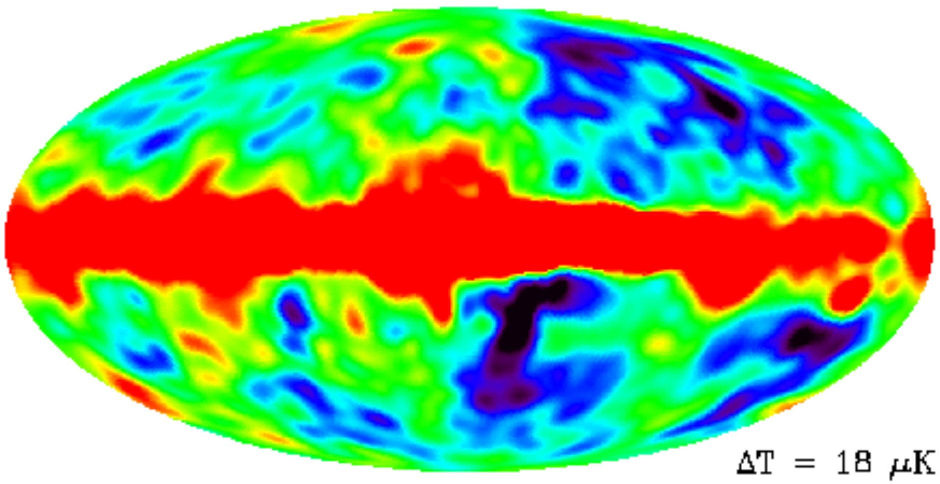
Sound and gravity

- Oscillations will appear as CMB different brightnesses in different directions. 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

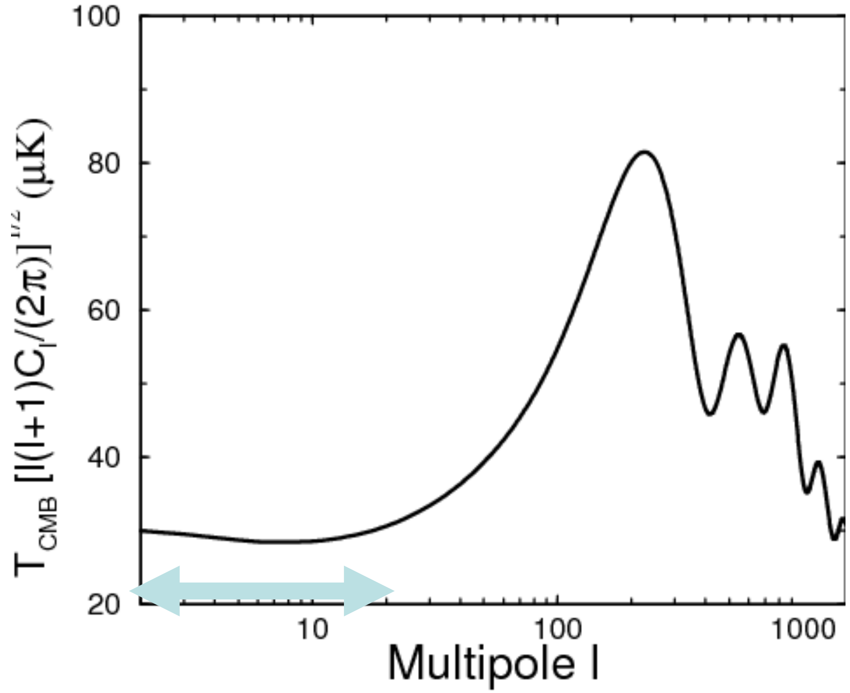
- Qualitatively still expect oscillations of mass fluctuations on scale of "sound horizon", s_h = 150 Mpc, and its harmonics

COBE



COBE was a small satellite, so only measured the biggest lumps.
This showed that the general picture is reasonably accurate.

COBE

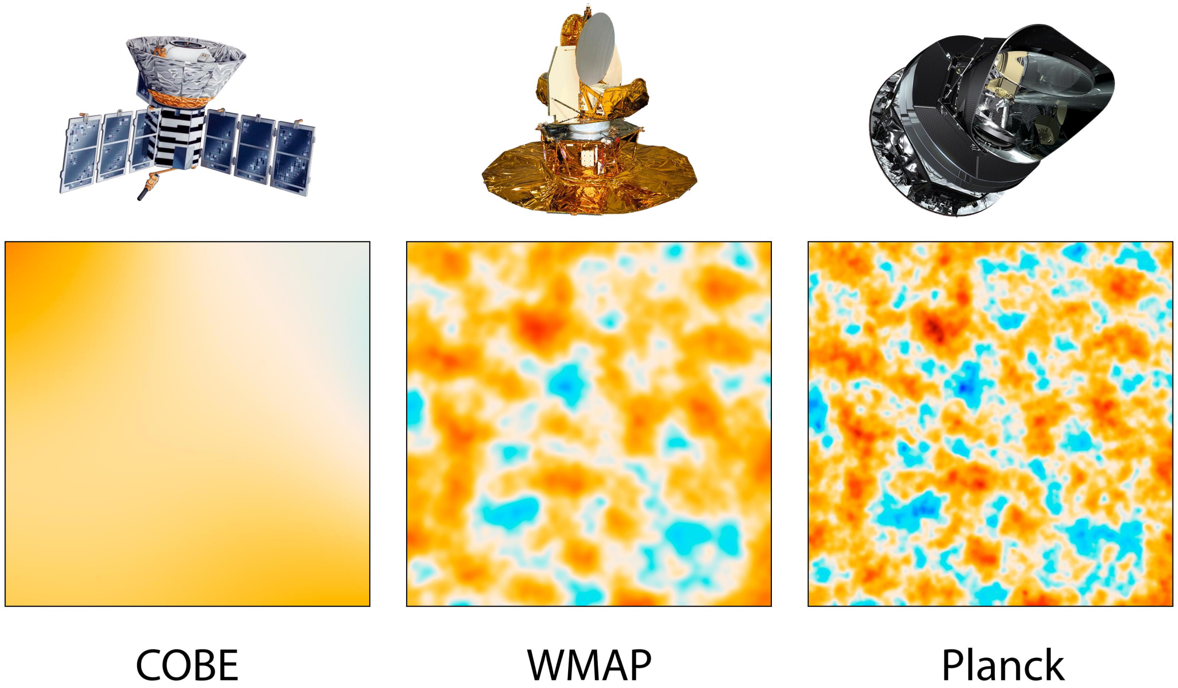


COBE was a small satellite, so only measured the biggest lumps. But most of the interesting information is on smaller angular scale ("at higher multipole", *l*). $l \approx 180°/\theta$ (peak at about 2°)

Sound and gravity

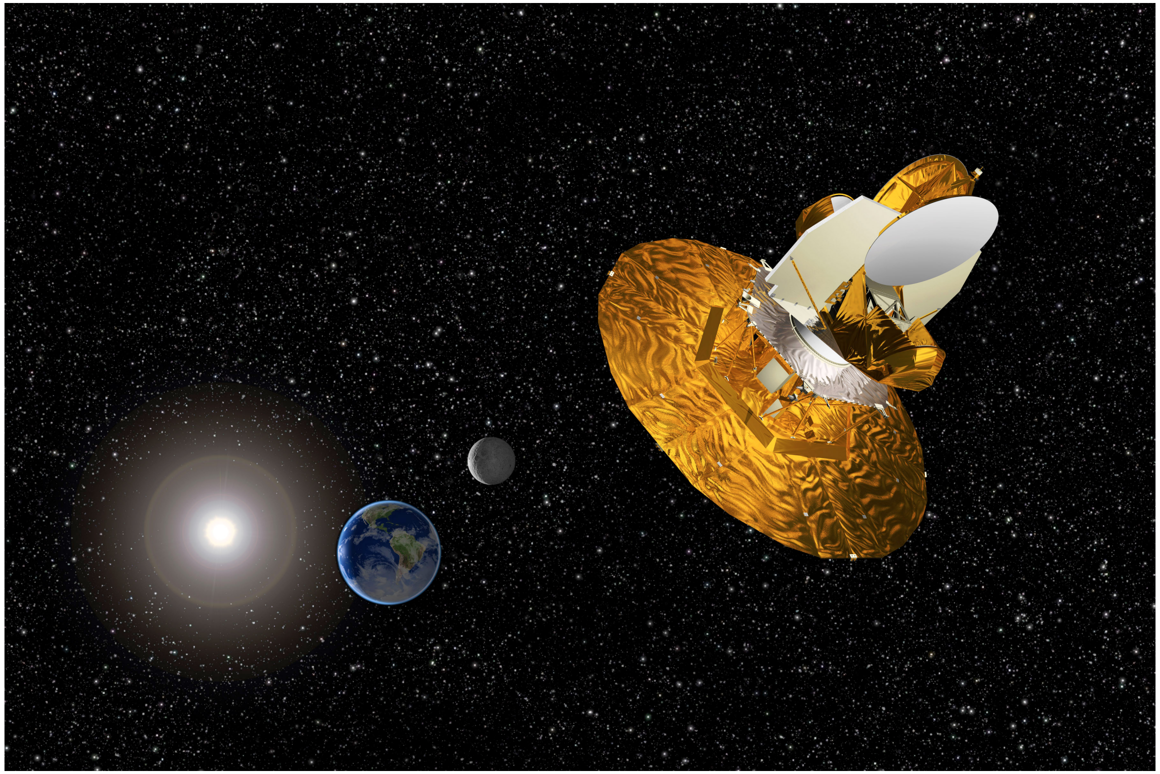
- Measurements of oscillations measure the key cosmological parameters from the properties of the noise
  - Flatness of Universe (position of first peak)
  - Constituents of Universe (heights of peaks)
  - Theory of gravity (shapes of peaks)
- COBE measured the amount of noise. But COBE was too small to measure the shape of the power spectrum.

COBE, WMAP, Planck



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

WMAP



WMAP has a telescope, not just small horns, and is near L2. The detectors are more sensitive than COBE, the system is designed for sensitivity, and has operated much longer than COBE.

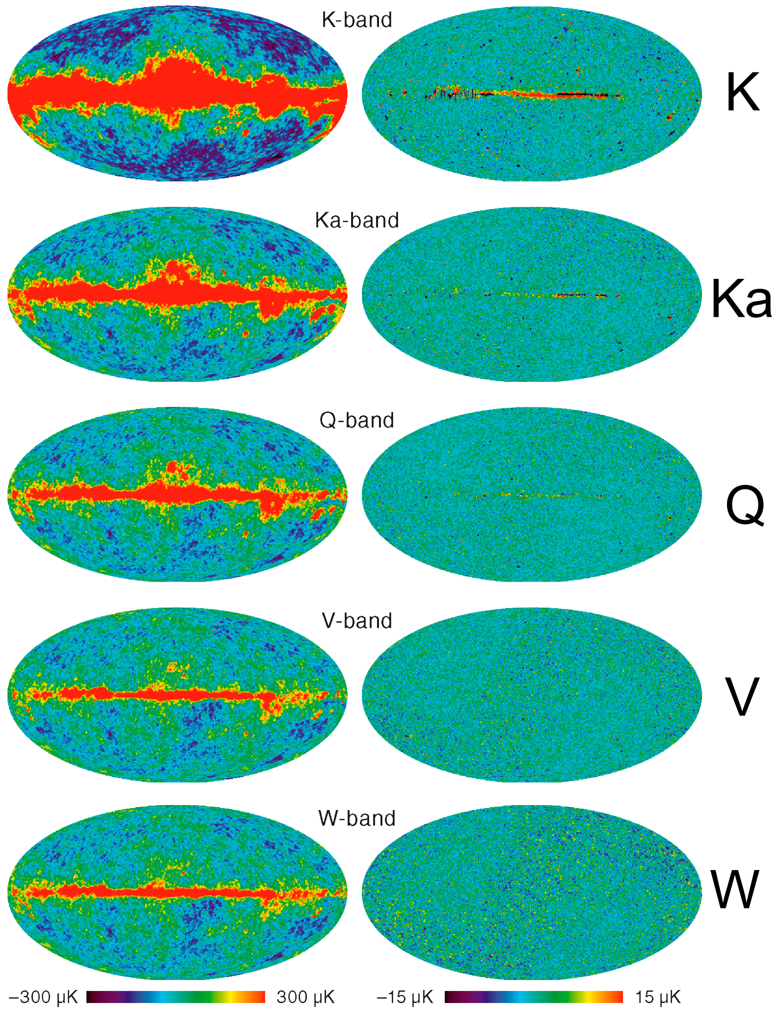
WMAP

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

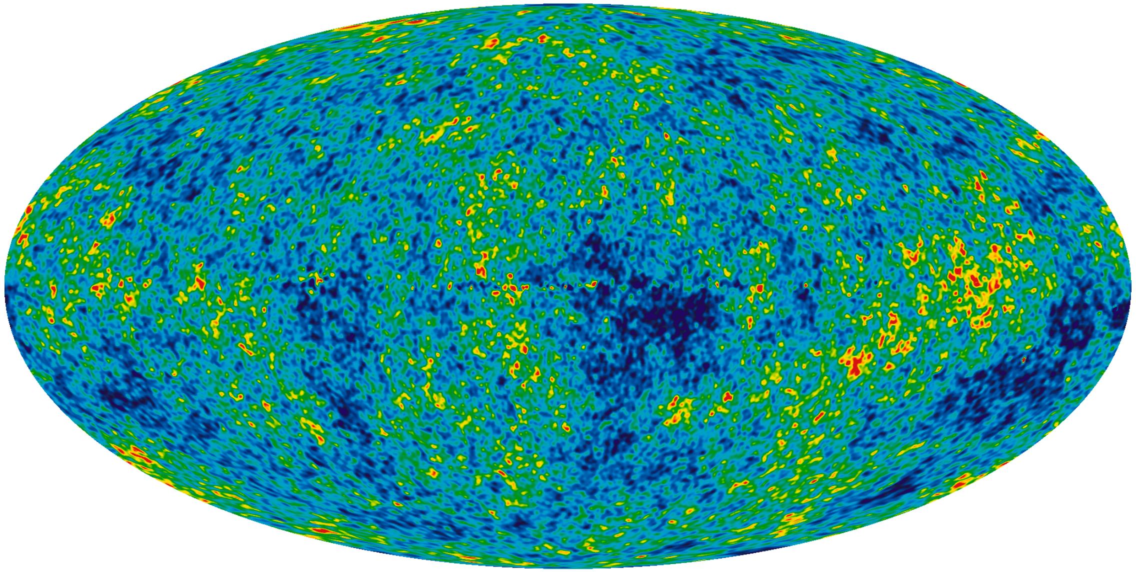
Five observing bands from 20 to 90 GHz.

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

Jarosik *et al*. (2011).



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.

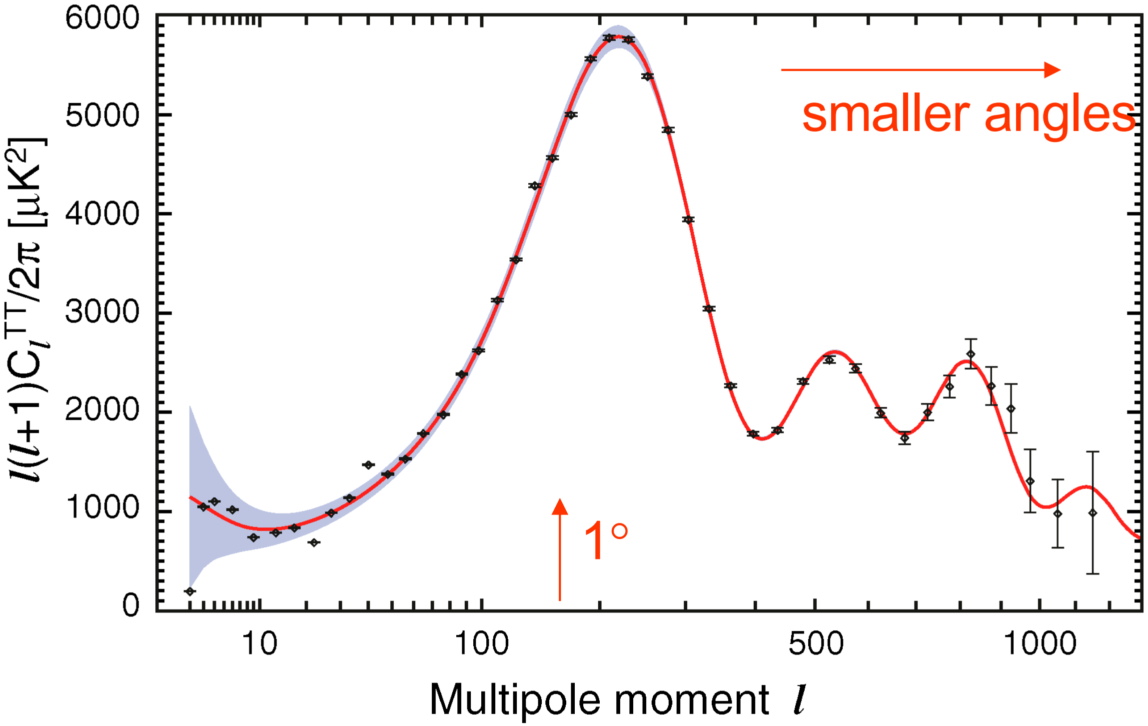
Sound and gravity

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:

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

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

$\Omega_\Lambda = 0.74(2)$

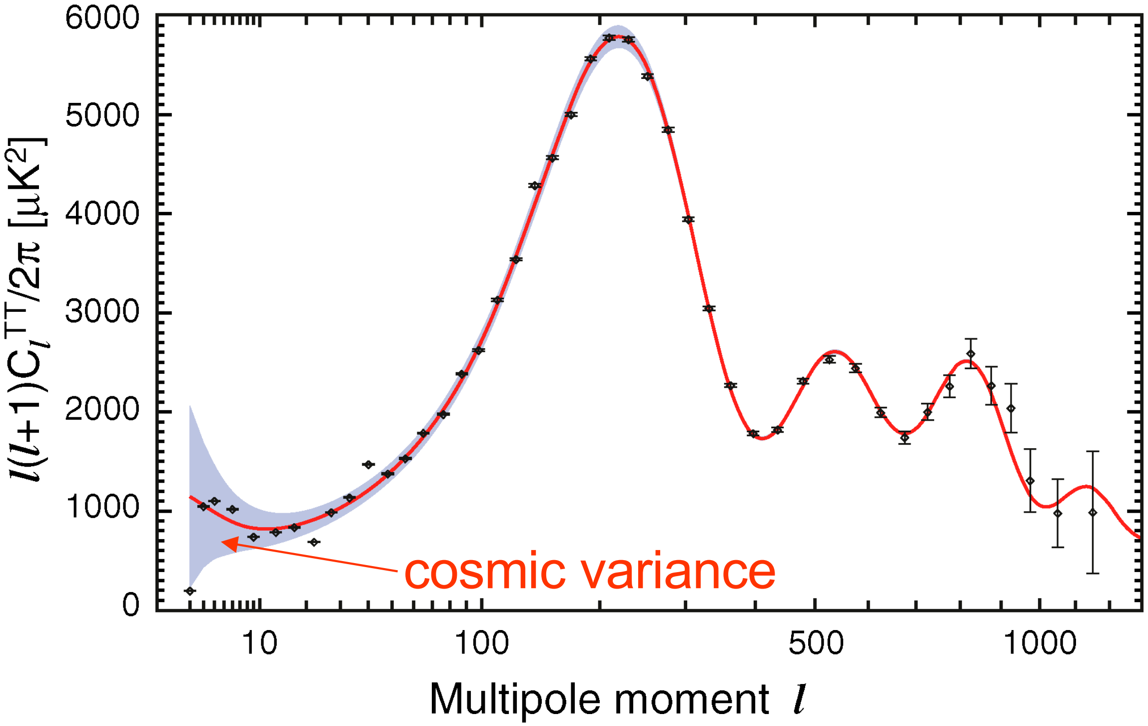
$\tau = 0.09(1)$

$n_s = 0.97(1)$

$\Delta^2_R = 2.38 \times 10^{-9}$

$A_{SZ} = 0.52$

[assumes k = 0]



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

Later structure

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

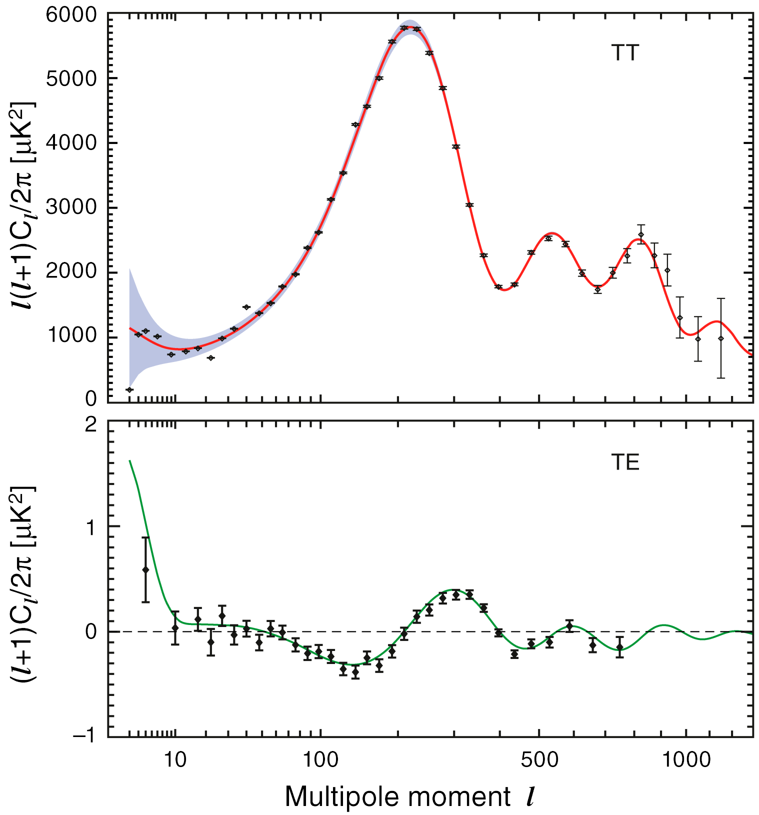
The densest parts of the Universe, clusters of galaxies, contain atmospheres that also interact with the CMB via inverse-Compton scattering (SZ effect)

Also get direct interaction with growing clusters of galaxies (ISW effect).

Sound and gravity

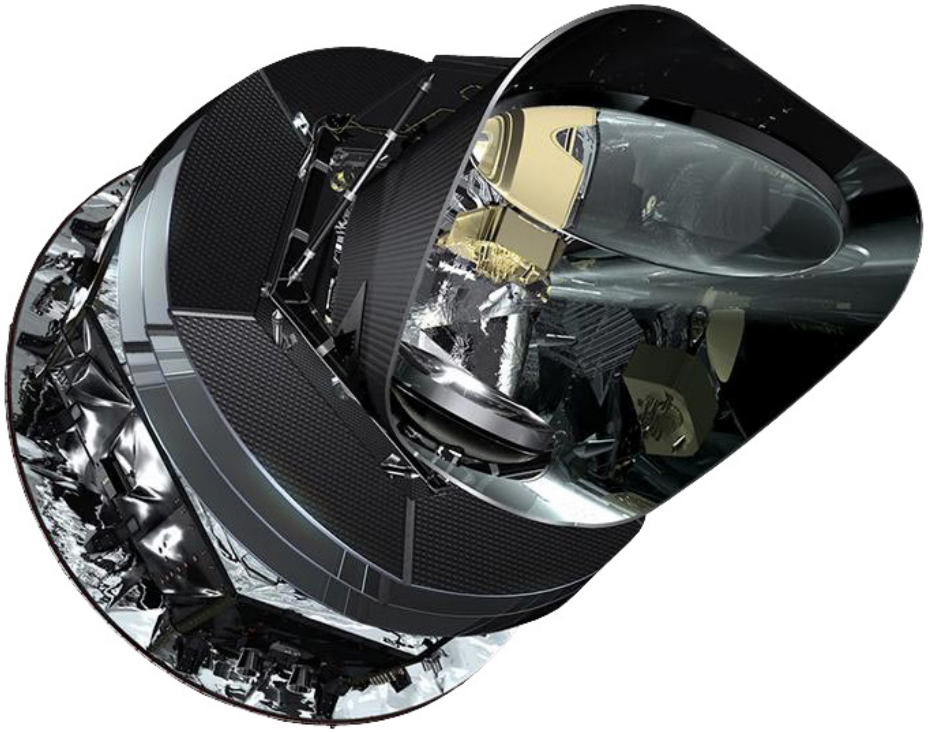
Polarization of CMB adds extra information, but precision is quite low at present.

Two modes “E” and “B”. WMAP can only measure E, and then only in correlation with the unpolarized signal.



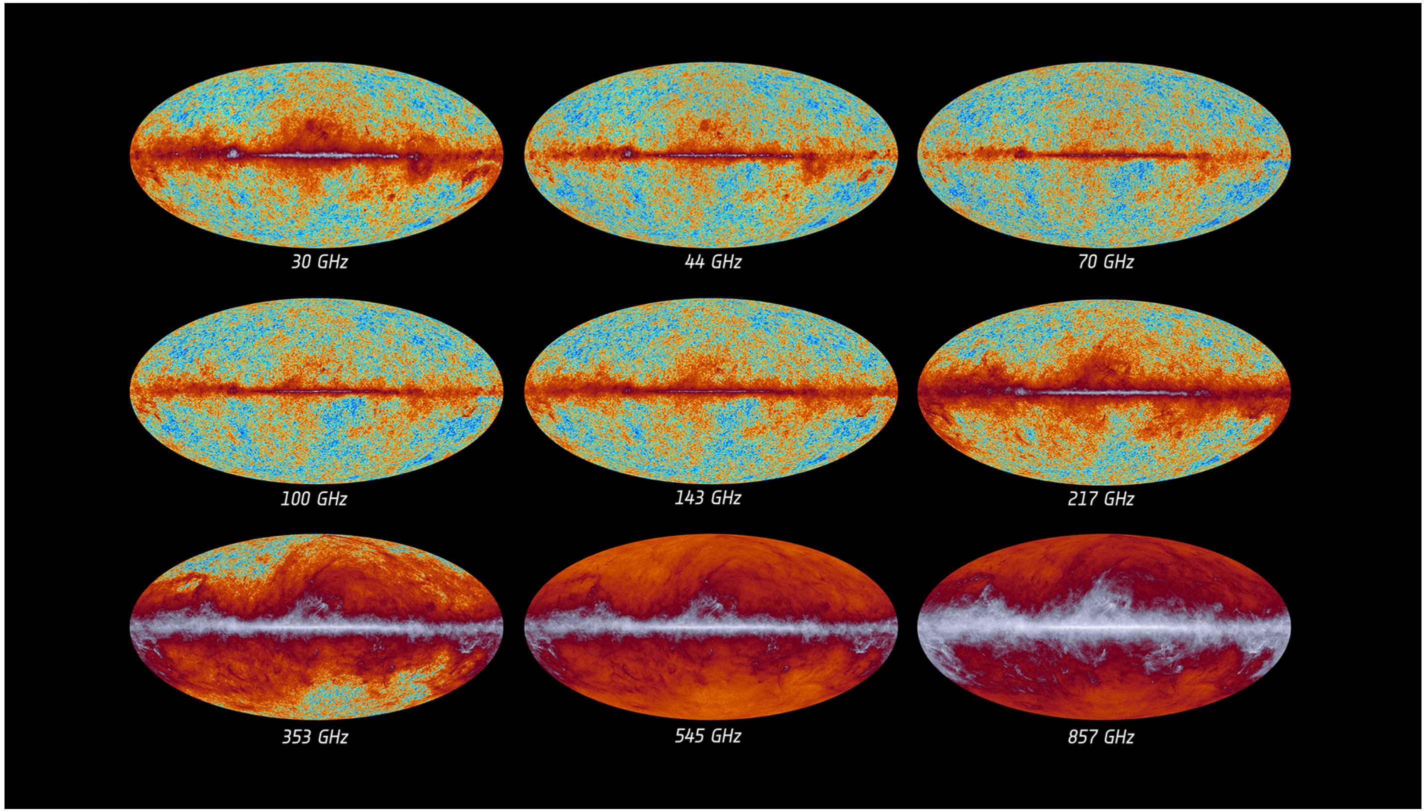
WMAP, 7-years, TT, TE. Jarosik *et al*., 2011.

Planck



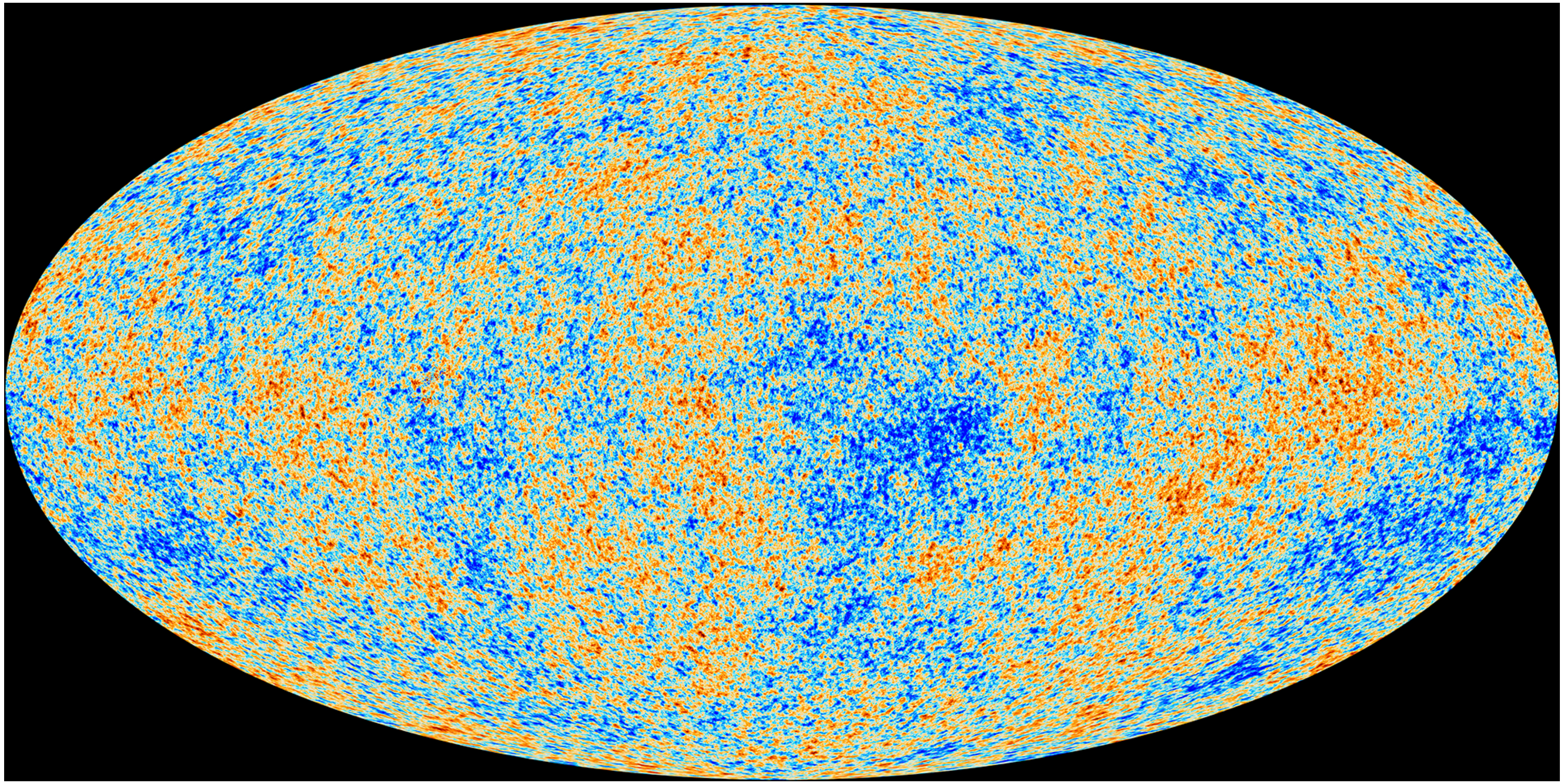
Bigger than WMAP, more and better detectors, more frequencies (better protection against foreground signals), plus polarization

Planck



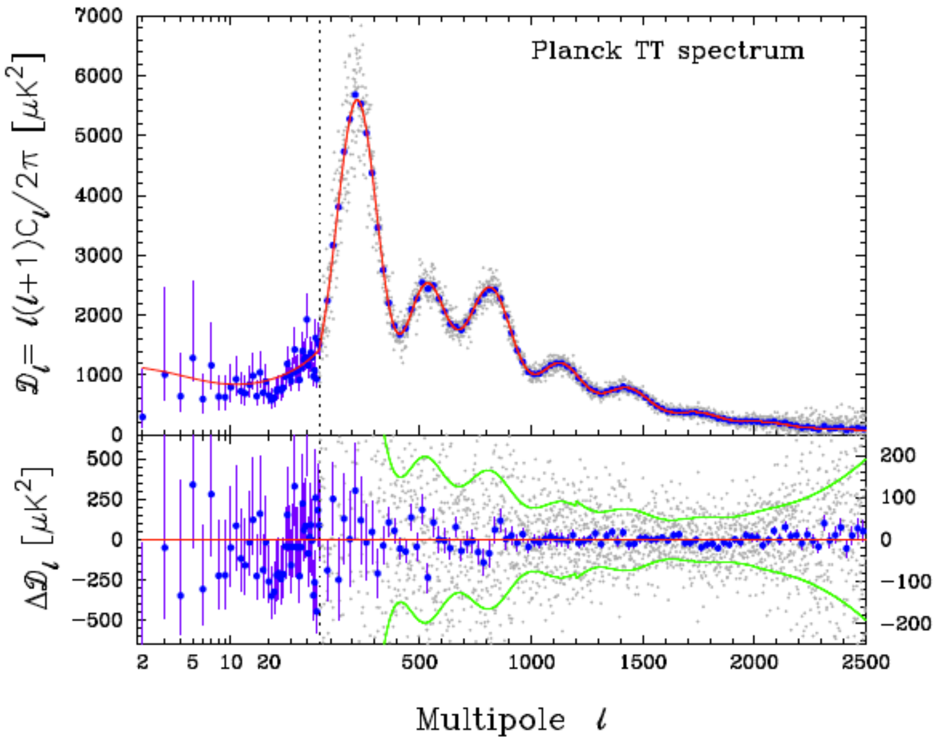
Nine frequencies, with the Galaxy bright in all of them.

Planck



Use spectrum to remove Galaxy, leaving background radiation.

Planck



Spectrum extends further than WMAP and fits theory well.

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 measures more.

Planck

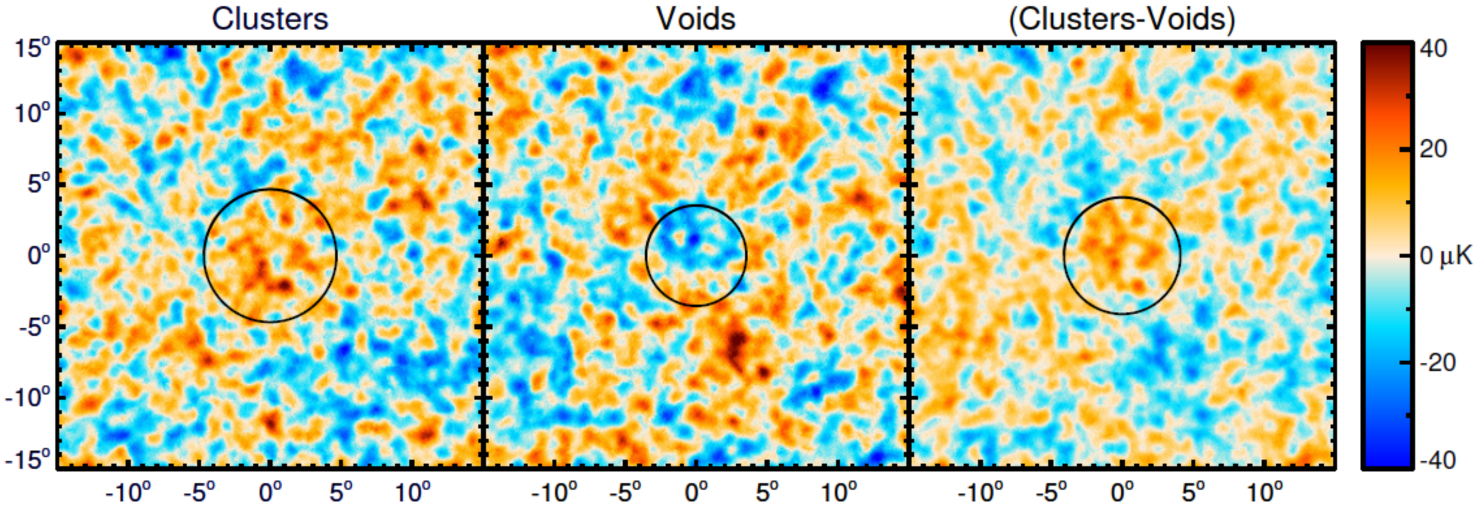
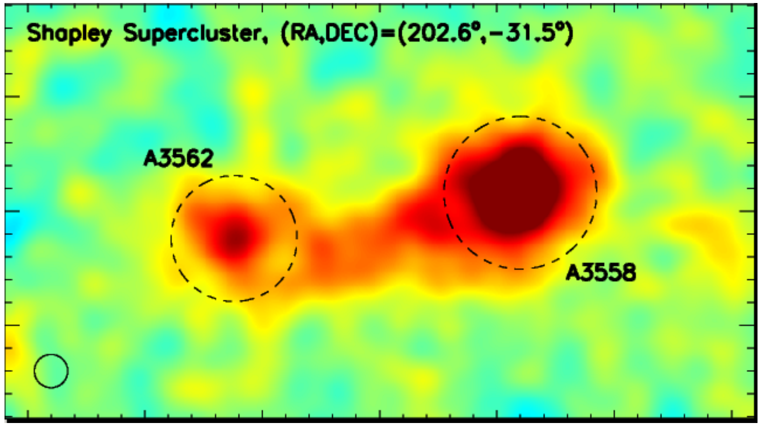
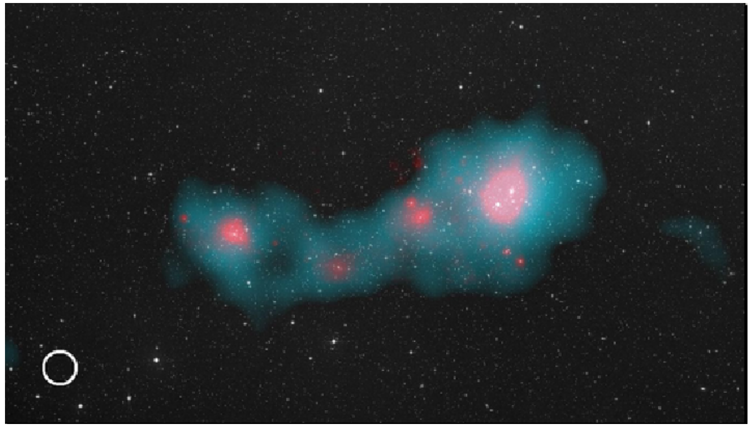


Fig. 6. Stacked regions of *Planck* maps corresponding to the locations of the superstructures identified by GR08. From left to right we show the images resulting from stacking of the 50 superclusters, the 50 supervoids, and the difference of both. The black circles superimposed indicate the angular radius at which the signal-to-noise ratio is maximal. See Fig. 7 for the corresponding temperature and photometry profiles, as well as their statistical significance.

Planck



Planck SZ



X-ray, SZ, optical

Planck measures SZ effect for nearby clusters (still small compared to ground-based telescopes, so can't see distant clusters).

Key results

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.

Key results

Dark energy = cosmological constant – no dynamics.

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

Inflation supported via spectral index n_s.

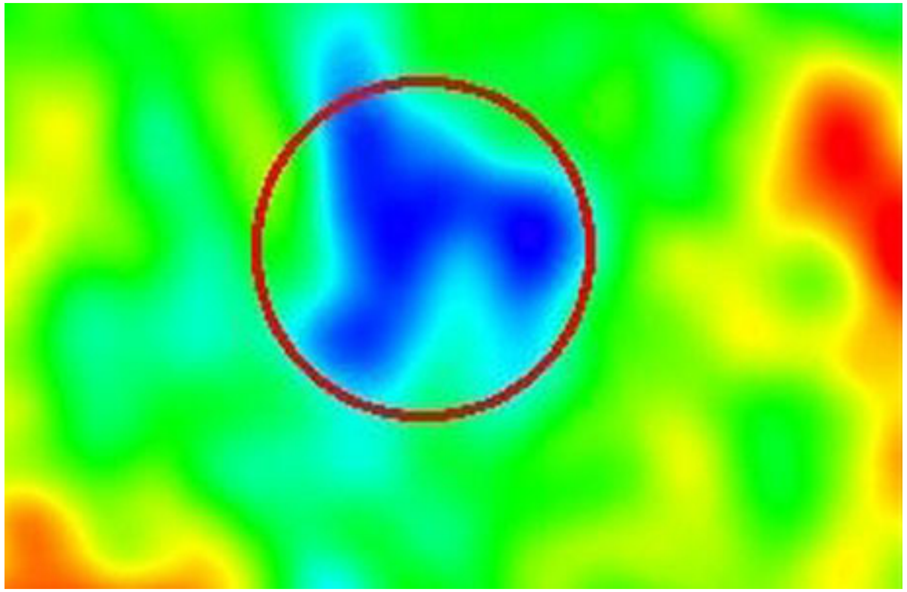
No anisotropy at l > 50, but issues at low l.

Rate of collapse of clusters from ISW effect

Cold spot.

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
- Still unexplained.



WMAP cold spot in Eridanus

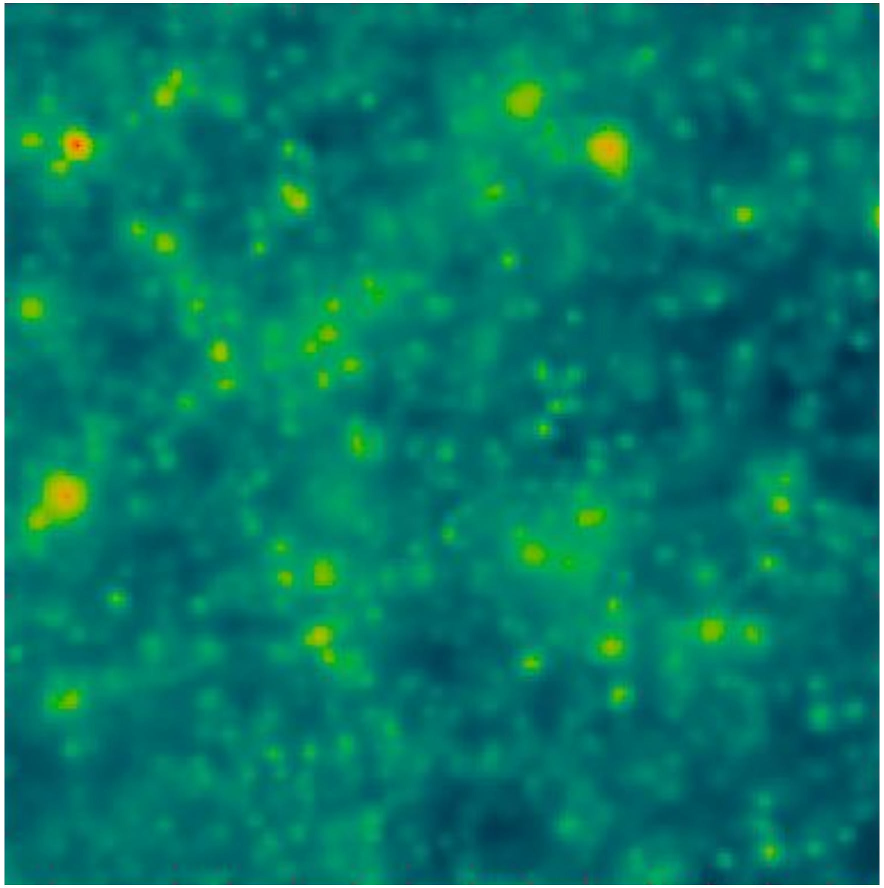
SZ effect confusion on CMB

SZ sky predicted using structure formation code (few deg^2, $y = 0 - 10^{-4}$)

Primordial fluctuations ignored

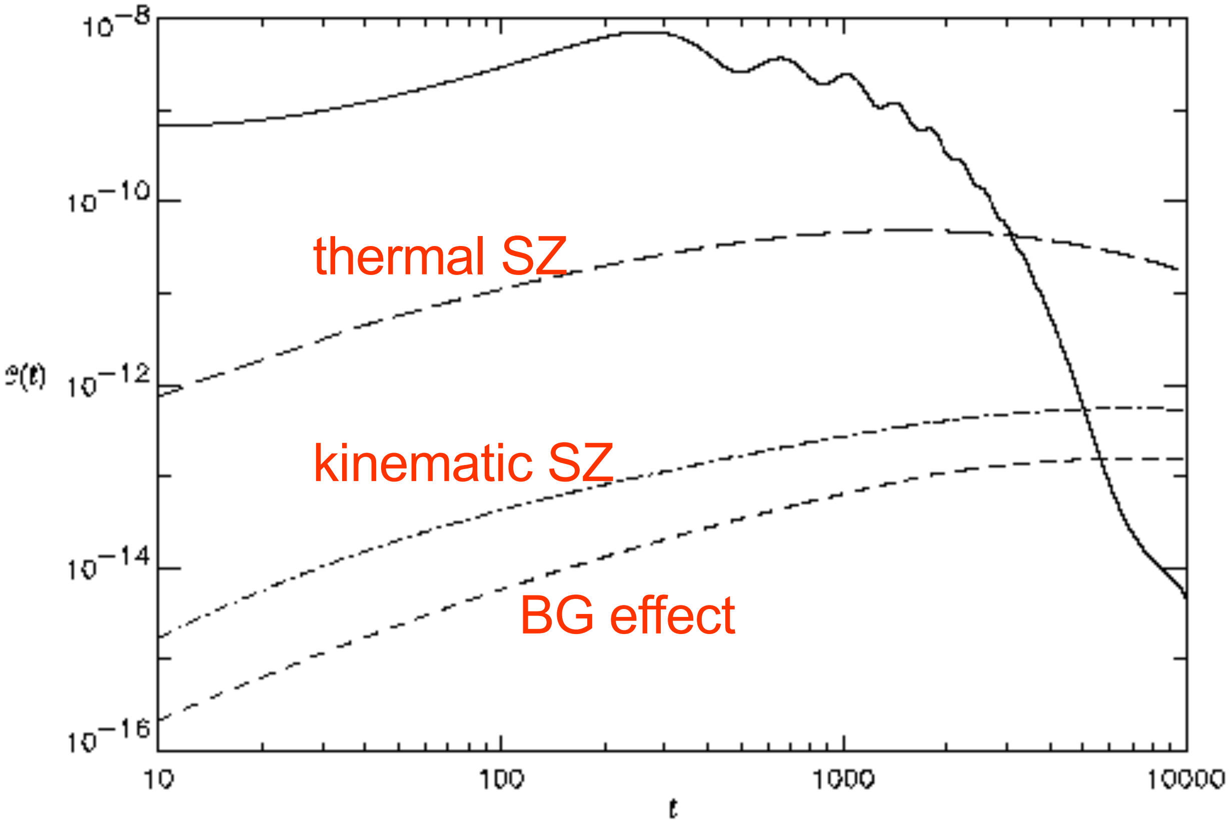
Cluster counts strong function of cosmological parameters and cluster formation physics.

Need new technology to perform surveys to low-mass, high-z clusters.



SZ effect confusion on CMB

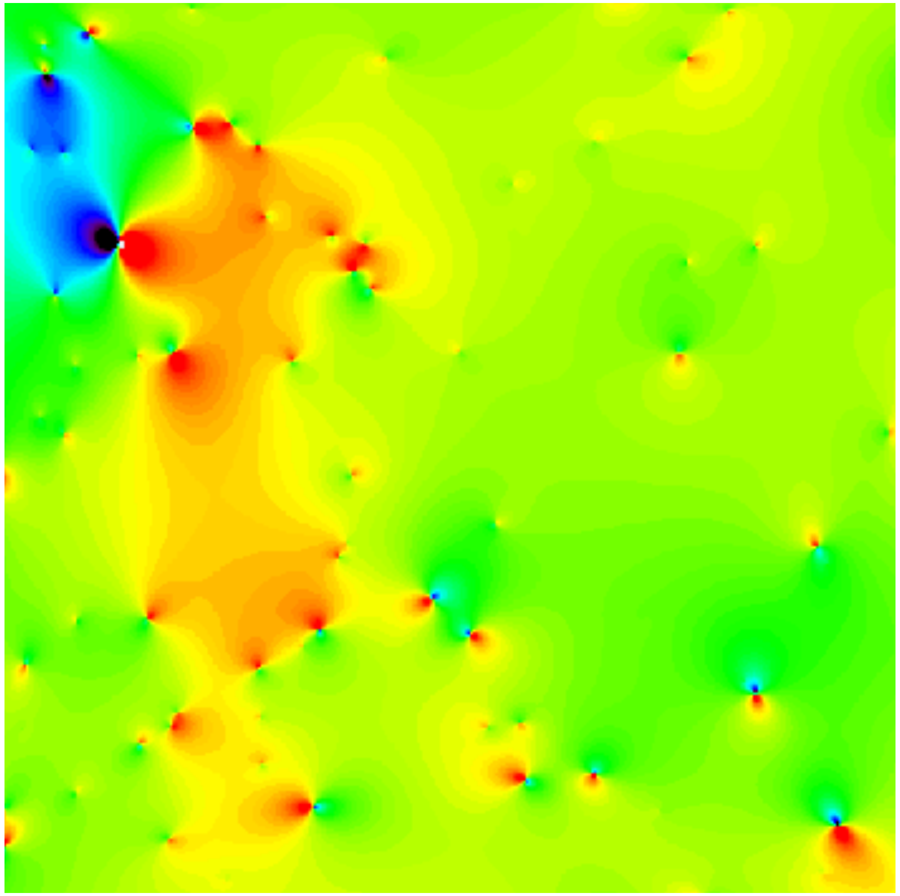
A_{SZ} = 0.52 (WMAP) shows signal already appearing as % contamination.



Molnar & Birkinshaw 2000. ApJ 537, 542

BG effect and velocity

- Sensitive to velocities across line of sight (Birkinshaw & Gull 1983)
- “Butterfly” shaped distortion
- Amplitude ~ 1 μK
- BG + kSZ effects give full velocity vectors of clusters: test dynamics of cluster formation.



The future

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

… or perhaps we will discover the ΛCDM "concordance" model is wrong

More Planck analyses and data are coming (polarization; gravity waves?)

Processes occurring as clusters form will be seen in tSZ mapping to $z > 2$

Further CMB signals: kSZ and BG effects for velocities, …