the cosmic microwave background (CMB)

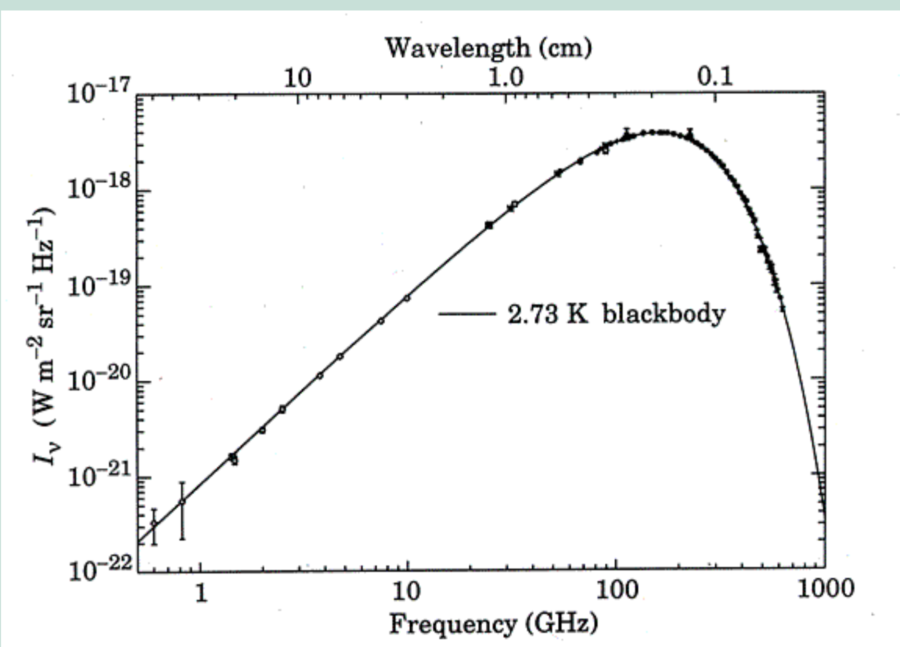
what it is

Discovered accidentally in 1964 by Penzias and Wilson (Nobel Prize, 1978), the CMB is a remnant of the hot, dense phase of the universe that followed the Big Bang. For several hundred thousand years after the Big Bang, the universe was hot enough for its matter (predominantly hydrogen) to remain ionized, and therefore opaque (like the bulk of the sun) to radiation. During this period, matter and light were in thermal equilibrium and the radiation is therefore expected to obey the classic blackbody laws (Planck, Wien, Stefan).

The existence of the CMB is regarded as one of three experimental pillars that point to a Big Bang start to the universe. (The other two pieces of evidence that indicate that our universe began with a Bang are the linearity of the Hubble expansion law and the universal cosmic abundances of the light element isotopes, such as helium, deuterium, and lithium.)

At some point about 400,000 years after the Bang, the universe had cooled to the point where the matter became neutral, at which point the universe's matter also became transparent to the radiation. (Completely ionized matter can absorb any wavelength radiation; neutral matter can only absorb the relatively few wavelengths that carry the exact energy that match energy differences between electron energy levels.) The temperature at which this transition from ionized to neutral (called the "moment of decoupling") occurred was roughly 3000 K.

The spectrum as measured by the COBE satellite looks like



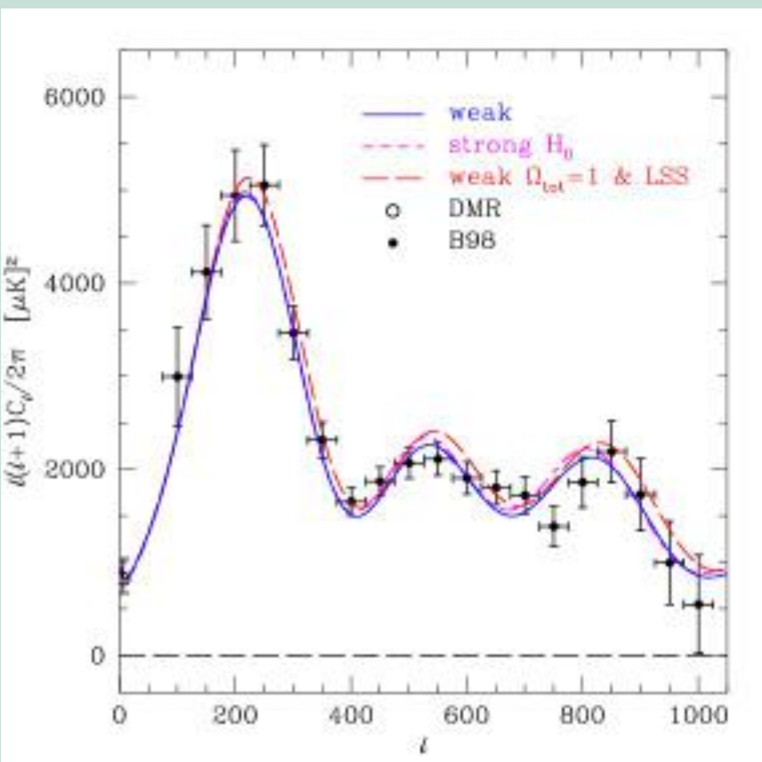
It indeed had the blackbody spectral shape predicted, but the peak in the microwave spectrum indicated a temperature of 2.726 K. Although this temperature is clearly insufficient to ionize hydrogen, the entire spectrum has been redshifted from that at the moment of decoupling (when the temperature *was* 3000

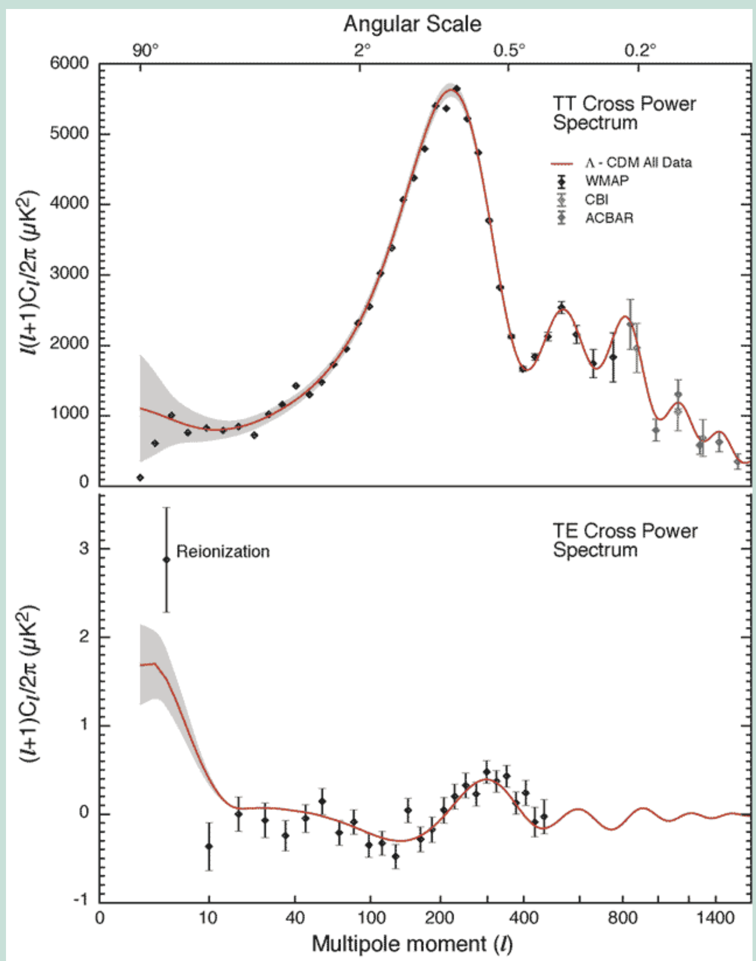
K) by the expansion of the universe. As space expands, the wavelengths of the CMB expand by the same factor. Wien's blackbody law says that the wavelength peak of the CMB spectrum is inversely proportional to the temperature of the CMB. Therefore, the drop in the CMB temperature by a factor of 1100 (= 3000 K/2.73 K) indicates an expansion of the universe by a factor of 1100 from the moment of decoupling until now.

what it can tell us

In addition to measuring the temperature of the overall CMB, anisotropies in the CMB are capable of telling us the Earth's motion with respect to the CMB, the geometry (or curvature) of the universe, the baryon content of the universe, the dark matter and dark energy content of the universe, the value of the Hubble constant, whether inflation incurred in the early universe, and more.

What various groups are measuring is usually presented in a format such as



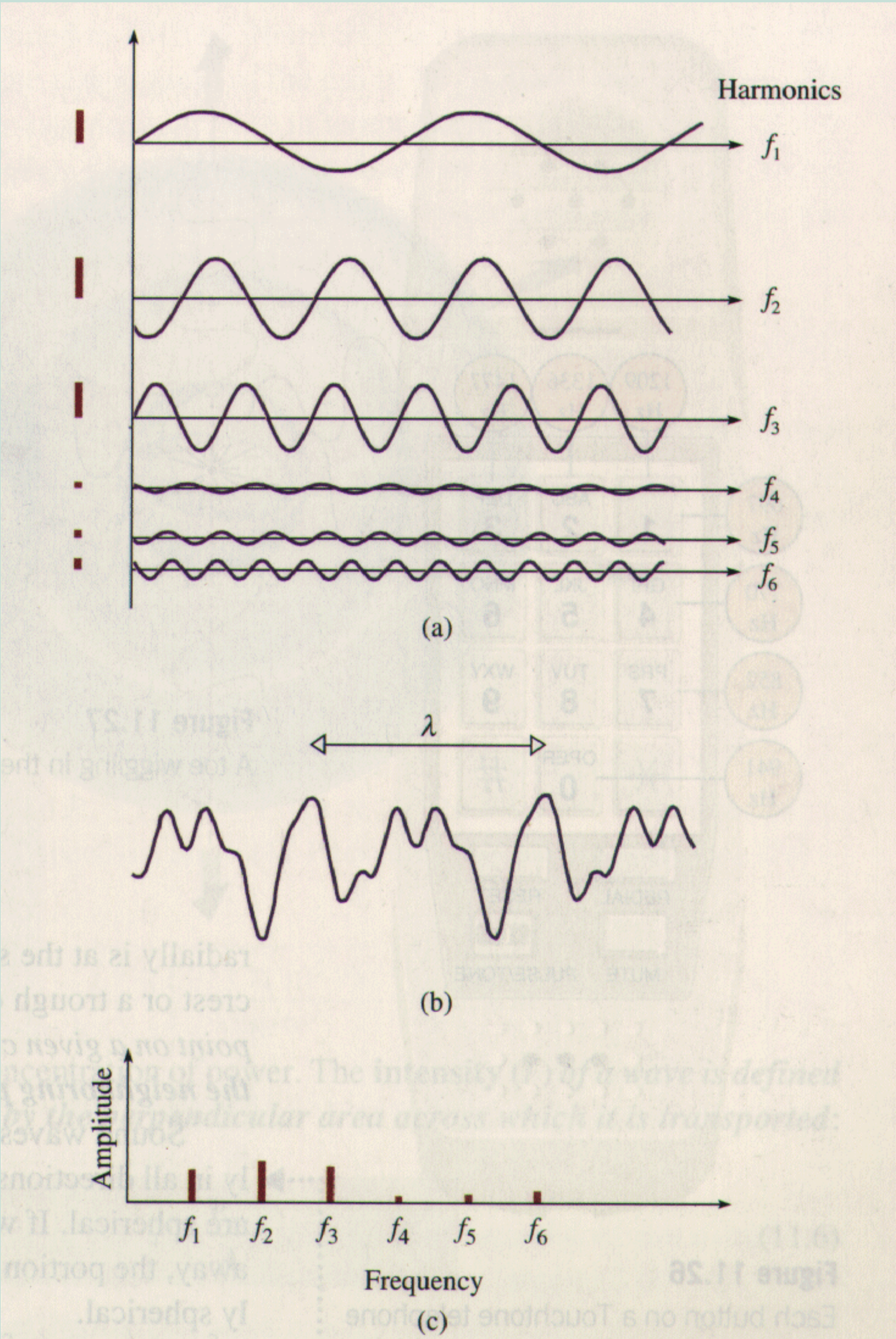


BOOMERandG in April 2001 WMAP February 2003

what it means

The above diagrams plot the CMB power as a function of harmonic number. These diagrams are very much like that for a complex musical instrument note, which is also the sum of the amplitudes (or "power") of various frequencies or harmonics.

For example, in the diagram below, 6 harmonics (top picture: each is a sinusoidal wave with an integral multiple of the fundamental frequency) are added together to produce the complex-shape wave shown in the middle picture. The bottom picture shows the relative amplitude contribution of each of the harmonics.



The CMB power spectra similarly plot the relative contribution of each spatial frequency (instead of temporal frequency).

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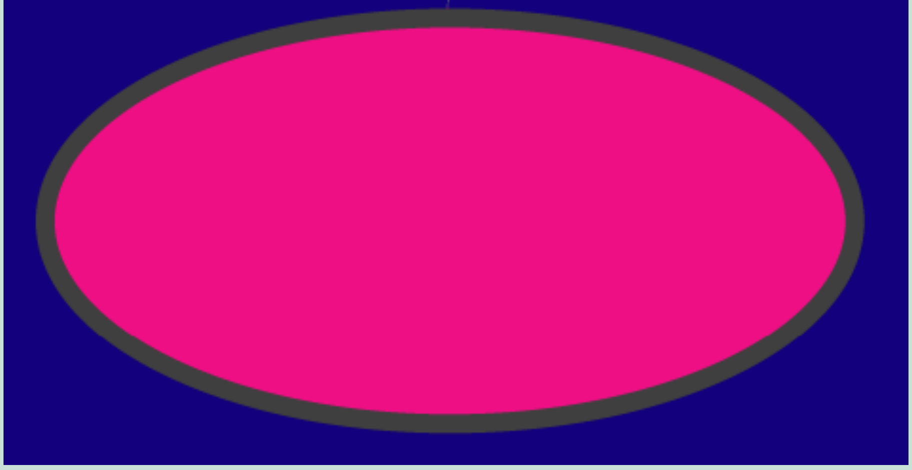
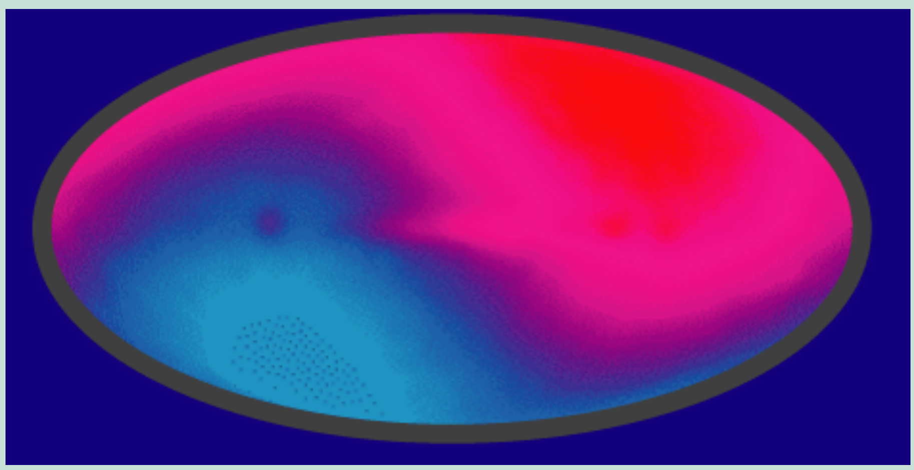
the math and physics of anisotropies



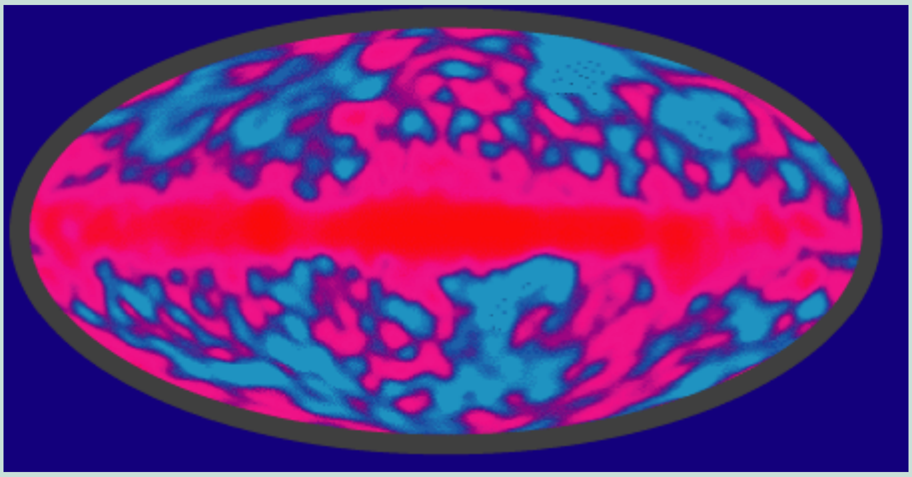
If the CMB had precisely the same temperature in every direction in the sky, the sky would have the same brightness in every direction. Astronomers often use a false coloring scheme to represent brightness (different brightnesses are represented by different colors) especially when the radiation is being emitted in a part of the spectrum that is not visible to the human eye. A uniformly bright CMB would therefore be represented by a single color. This power is called the "l = 1" contribution to the power spectrum. If we could see the CMB with our eyes, the sky would look uniformly the same, as in the figure at the left.

(In this and subsequent diagrams, the entire sky is represented by a Mercator projection, the same technique often employed to portray the entire earth. The equator (latitude 0 for earth) is a horizontal line in the middle of the oval, with northern latitudes above and southern latitudes below. The Greenwich meridian (longitude 0 on Earth) is a vertical line through the middle, with western longitudes to the left and eastern longitudes to the right. In a similar manner, the galactic equator or plane (latitude 0) is a line running through the middle of the sky pictures. The galactic center (galactic longitude 0) is at the center of the diagram.



In reality, however, not all directions in the sky appear to have the same CMB brightness. The earth is moving with respect to the matter that last emitted the CMB, and therefore the CMB spectrum looks bluest (and, by Wien's law, therefore hottest) in that direction and reddest (and coolest) opposite to that direction. This effect would contribute to the CMB power spectrum at a spatial frequency of l = 2. The "l = 2" contribution is often called a dipole contribution, because the brightness distribution over the sky has 2 poles (one hot, one cool) in it. If we were somehow able to see ONLY this dipole contribution [the brightness amplitude of which is far less than the that of the dominant "l=1" contribution] by removing the average brightness (or temperature) from the preceding diagram and amplify the contrast by approximately a thousand, the sky now looks like the figure at the right.

By measuring the amount of the dipole anisotropy (the bluest part of the sky is .0033 K hotter than average), we can determine the magnitude of the earth's motion with respect to the CMB: the earth is moving at a speed of 370 km/s in the direction of the constellation Virgo.



If the dipole contribution due to Earth's motion is now subtracted out, the sky looks like the figure at the left.

The temperature differences that remain are a composite of two things: a contribution from our galaxy and the true anisotropies in the CMB that were present at the moment of decoupling, hundreds of thousands of years after the Big Bang.

The galaxy is bright at microwave wavelengths due to emission by molecules (particularly CO), dust,

The anisotropies present at the moment of decoupling represent random noise present in the very early universe that was amplified by inflation to cosmic-sized scales. The anisotropies present at the moment of decoupling are of the appropriate magnitude to account for how the large-scale structures that we see today (from galaxies to superclusters of galaxies) formed under the influence of gravity.

It is possible to remove the contribution of the galaxy's emission by measuring

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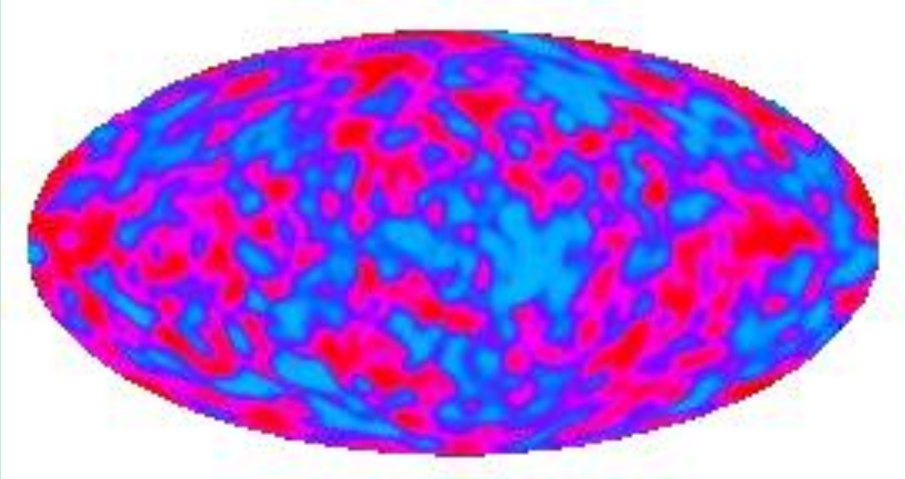
Once the galactic contribution is removed, COBE saw this:



This diagram is the sum of the amplitude (or power) contributions of all spatial frequency harmonics (but with those of l = 1 and l = 2 removed). It is the equivalent of the complex wave musical instrument wave shape above, which was formed by the sum of the amplitude (or audio power) contributions of several temporal (or harmonic) frequencies. The difference is that the CMB diagram shows the power as a function of position in the sky (i.e., as a function of galactic latitude and longitude), whereas the musical instrument wave shape shows the power as a function of the single dimension of time.

The goal for the CMB researchers is to decompose the CMB diagram into its harmonic components. And fortunately the relative amounts of the harmonic components are determined by intrinsic properties of the universe (such as the Hubble constant, the amount of dark matter, and the value of the cosmological constant, the age of the universe, and the amount of dark eenergy).

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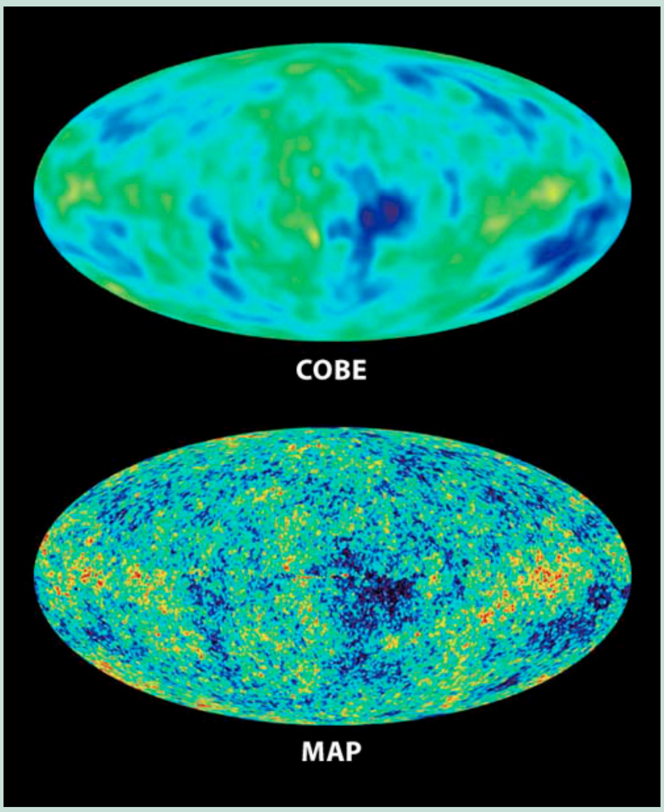
who is measuring this

COBE (Cosmic Background Explorer, launched in 1989) was the first satellite launched to measure the CMB properties outside Earth's atmosphere. COBE established the precise blackbody character of the radiation and measured the temperature as 2.726 K, measured the earth's velocity relative to the matter that last emiited the radiation, and eventually detected anisotropies in the background at the level of 1 part in 10^5.

BOOMERanG measures CMB properties by launching balloon-borne instruments at the South Pole. Here is their latest version of the anisotropy of a piece of the sky

MAXIMA does the same



NASA/WMAP Science Team

MAP (launched 6/30/01) will measure the individual properties of the universe (e.g., the Hubble constant, the baryon density, the cosmological constant value) to within 5%. The first MAP pictures (feb 2003) is on the left with the COBE result from 5 years earlier for comparison. Note that the MAP resolution is significantly better than the COBE resolution.

MAP found the following values (2003) for cosmological parameters:

present age: 13.7 ($\pm$ 0.1) Gyr

geometry of the universe: consistent with flat: omega total = 1.02 $\pm$ 0.02
omega (dark energy) = 0.73
omega (dark matter) = 0.23
omega (baryons) = 0.044 $\pm$ 0.004
omega (neutrinos) $\leq$ 0.0005
omega (radiation) = 0.0001

the content of the universe:

epoch of first star formation (end of the dark ages): 200 Myr after the Bang

moment of decoupling: 379,000 yr after the Bang

Hubble's constant = 71 ($\pm$ 3) km/s/Mpc

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how YOU can calculate the spectrum anisotropies

go to Max's cosmic cinema, where you plug in your own parameters for the universe and see the resulting anisotropy plot interactively... you can then see how well it fits the observations