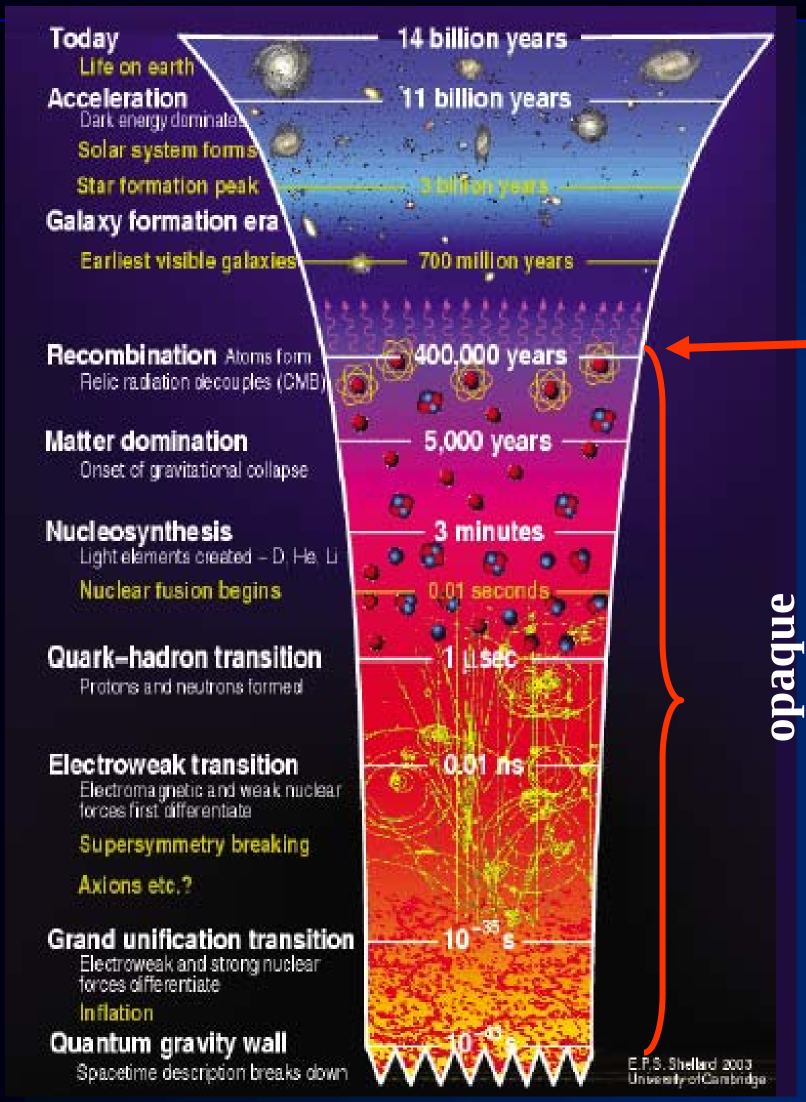
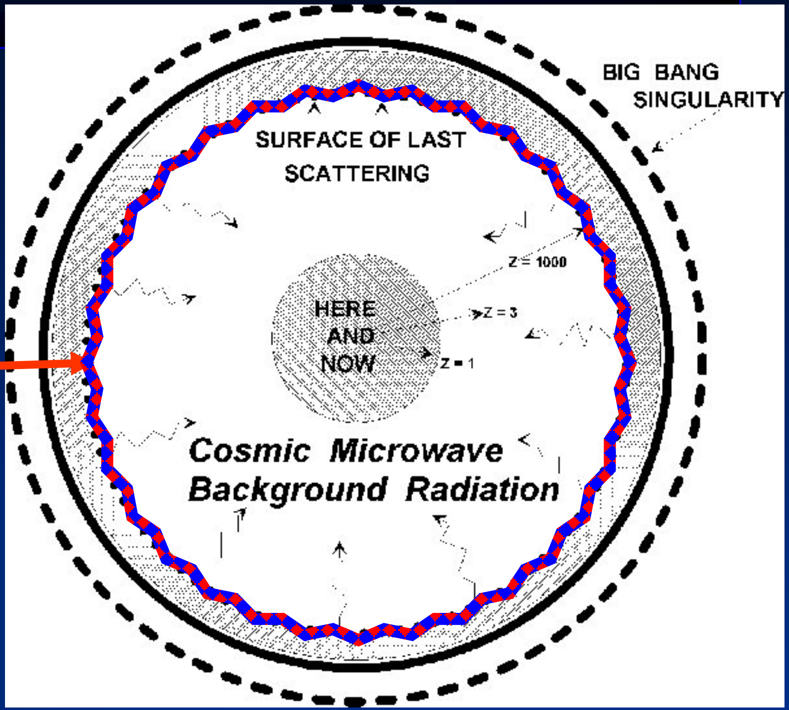
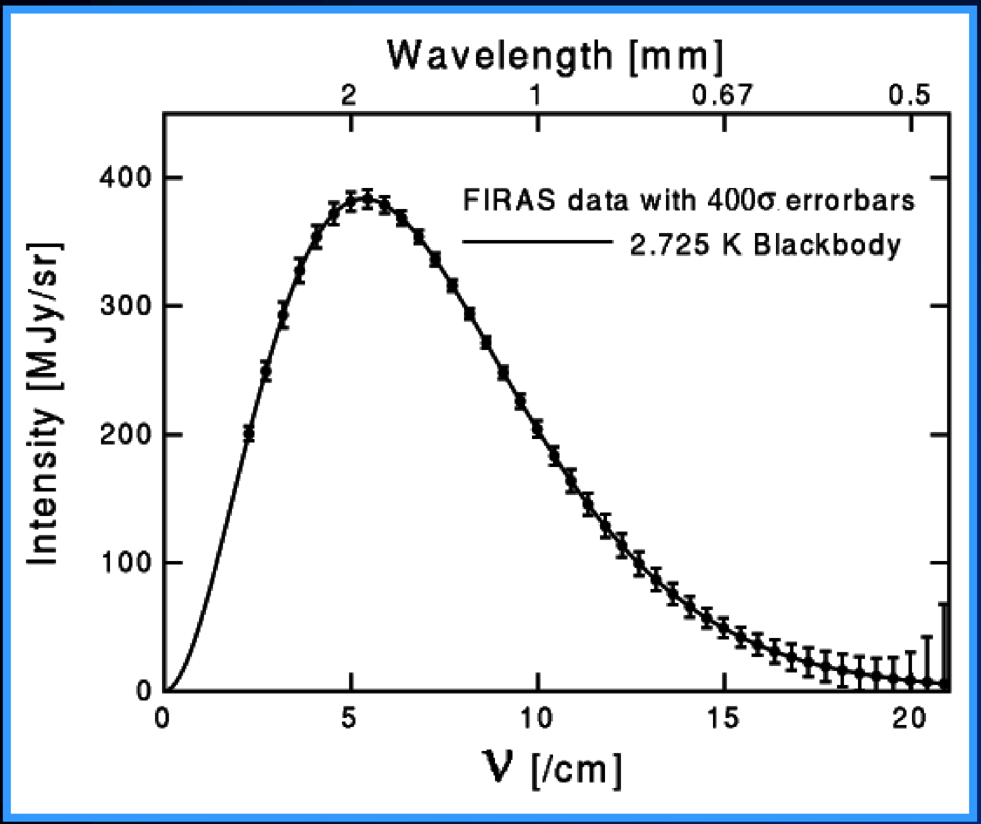
3. Overview of the CMB – the oldest light we can detect:

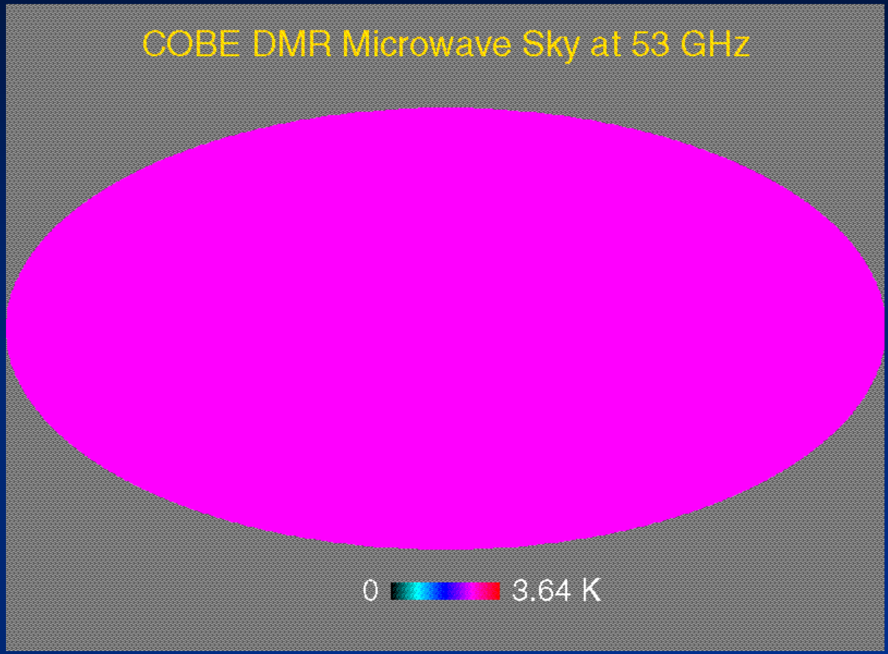




Prior to a red shift of ~1000, the universe was opaque to electromagnetic radiation. Thus, the CMB is the oldest light that we can observe. It comes to us from a time when the Universe cooled sufficiently for matter and radiation to separate for the first time.

To a first order, the CMB follows a perfect black body, thermal radiation curve which peaks at 2.7 Kelvin.

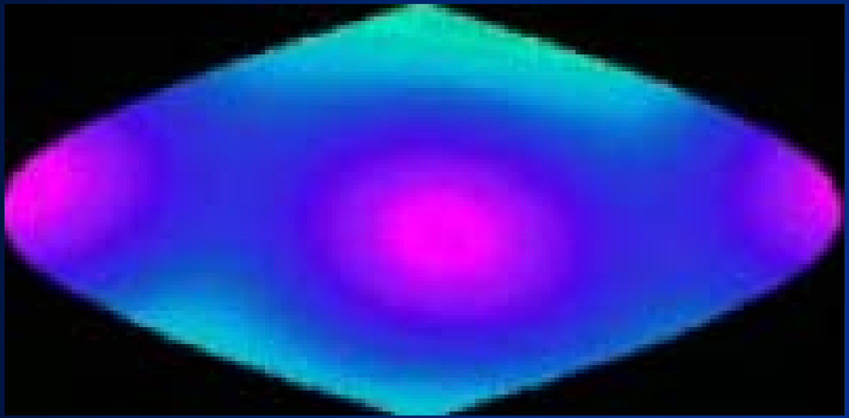


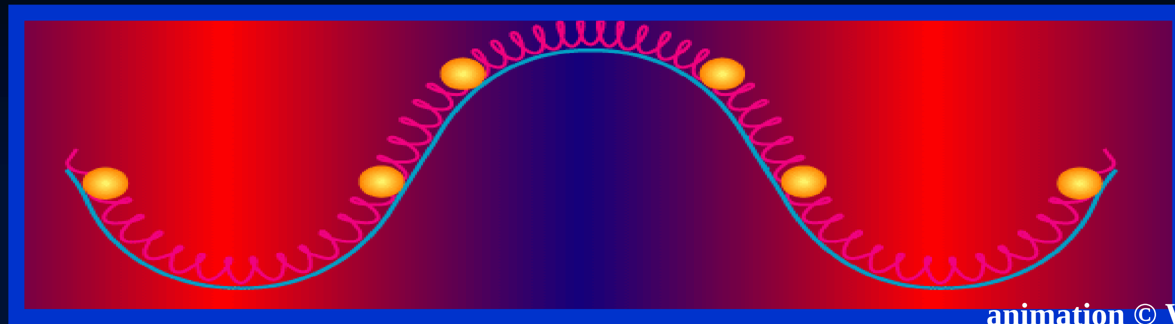


Anisotropies – small-amplitude variations from thermal black body temperature come primarily from two sources:

1) *Potential Fluctuations in the Early Universe*:

On angular scales $\theta > 1^\circ$, CMB anisotropies probe fluctuations in the gravitational potential along different lines of sight, $\Delta T/T_0 \sim \Delta\varphi/3c^2$ where φ is the gravitational potential.





animation © Wayne Hu

2) Sound Waves Prior to Recombination:

Small scale fluctuations in the matter-radiation fluid at the recombination epoch were causally connected and oscillated like sound waves. The small scale variations in temperature we observe today in the CMB are believed to be a consequence of these oscillations in pressure, hence density, in the early universe. The characteristic scale of structures that arose from these fluctuations is observed at $\Delta\theta \sim 1^0$ on the sky today.

The little balls in the animation represent photons being compressed and rarified, using the analogy of little masses on springs. Note that in the animation, red indicates a region of cooler (red shifted) temperature that we see today, and blue indicates a region of sky today that appears hotter (blue shifted).

These temperature variations appear to have been “frozen in” at the time of recombination. They can be measured as angular variations of the temperature of the universe today.

The fluctuations are thought to have been generated within 10^{-35} seconds of the Big Bang, so by studying CMB anisotropies we probe fundamental physics at energy scales many orders of magnitude higher than those accessible to particle accelerators.

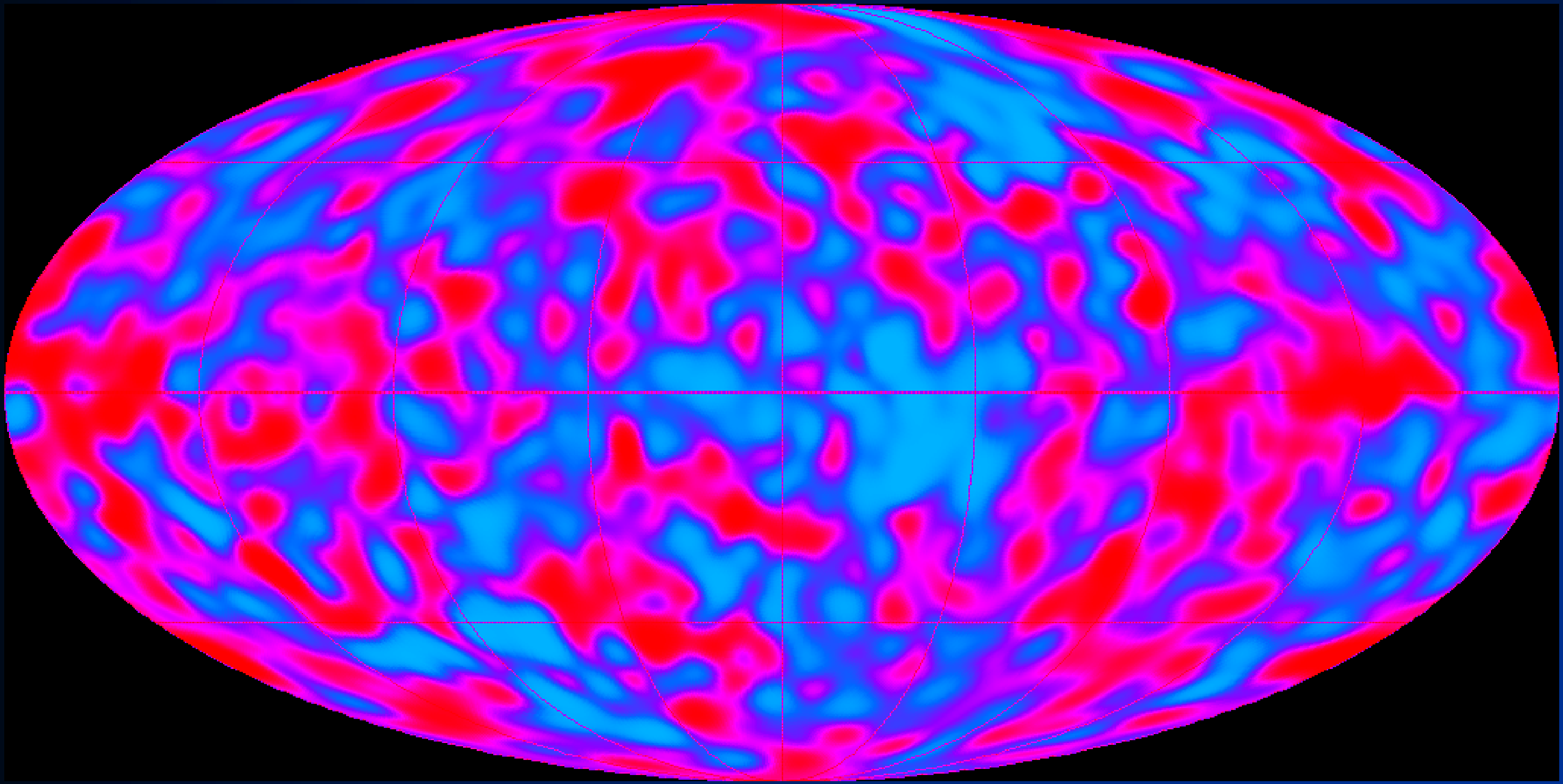
Variations in temperature observed “now”

$$\frac{\Delta T}{T} \propto \frac{\Delta \rho}{\rho}$$

Variations in density inferred “then”

are proportional to

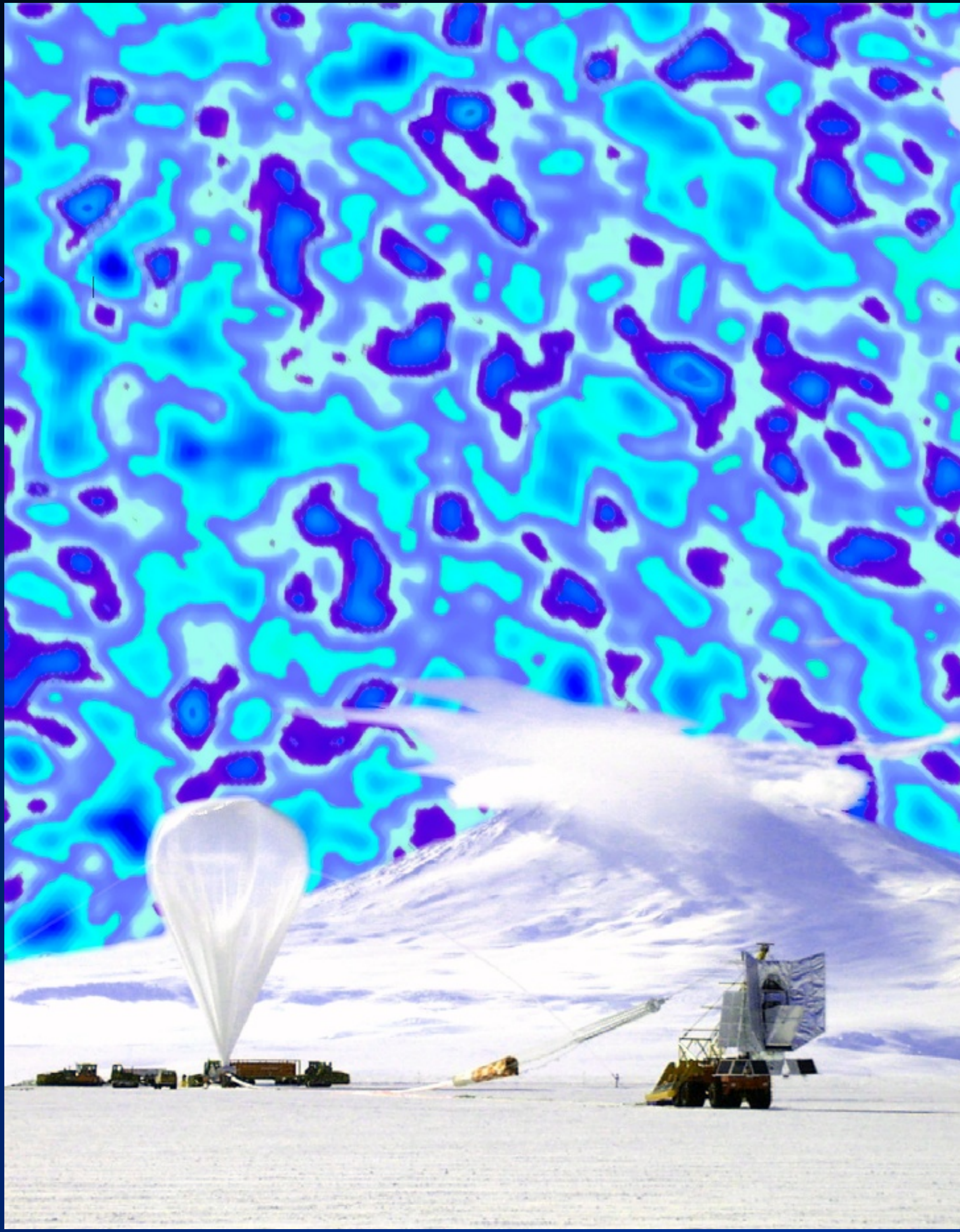
In 1992, data from the Cosmic Background Explorer satellite, launched by NASA in 1989, showed evidence for minute temperature variations (anisotropy) in the CMB at a level of just one part in 10^5, at angular scales around 10^o or so.



The COBE sky at 53 GHz

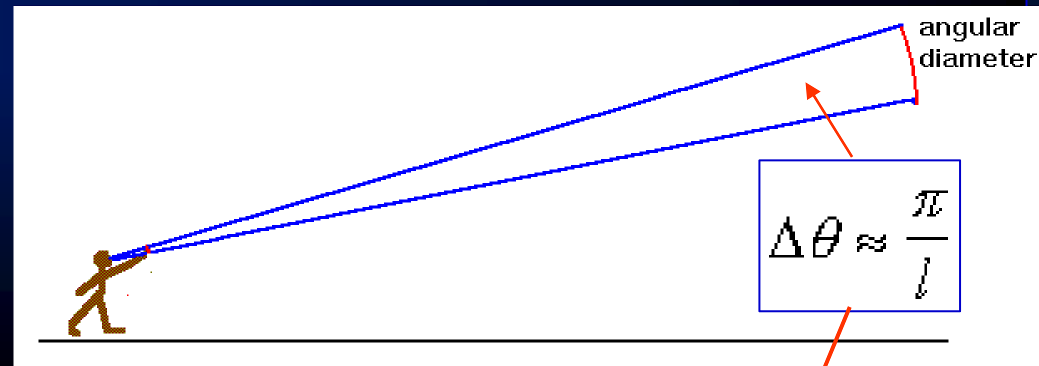
An interesting comparison:

Here's what the sky might look like to your eyes, if you could "see" at 150 GigaHz (~2 mm)

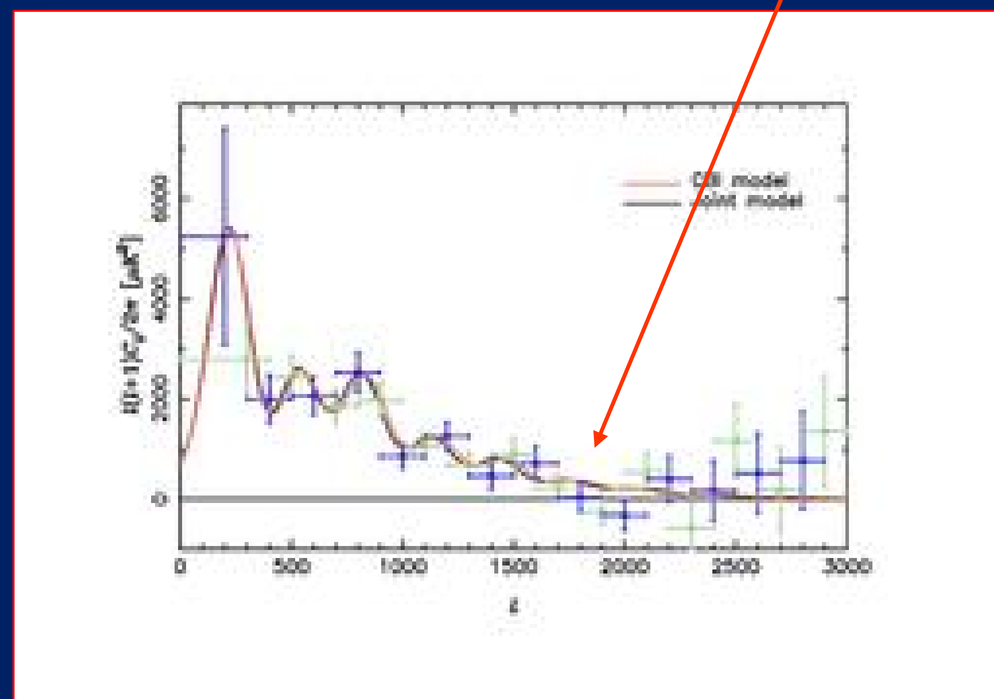


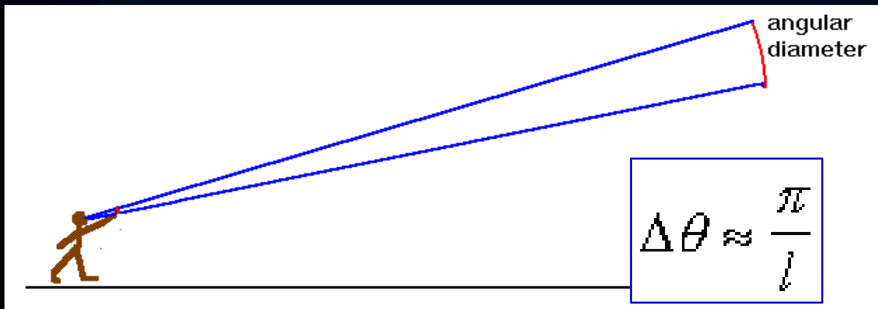
And, for comparison, here's what the sky does look like to our eyes, which have a peak response at ~ 545 TeraHz (~550 nm)

Next: How do we go from observing temperature variations on the sky to understanding the physics of the early universe?



We measure the ***power spectrum*** *of these temperature variations. The peaks in the spectrum are controlled by the density of matter and the expansion rate of the universe, among other things.*

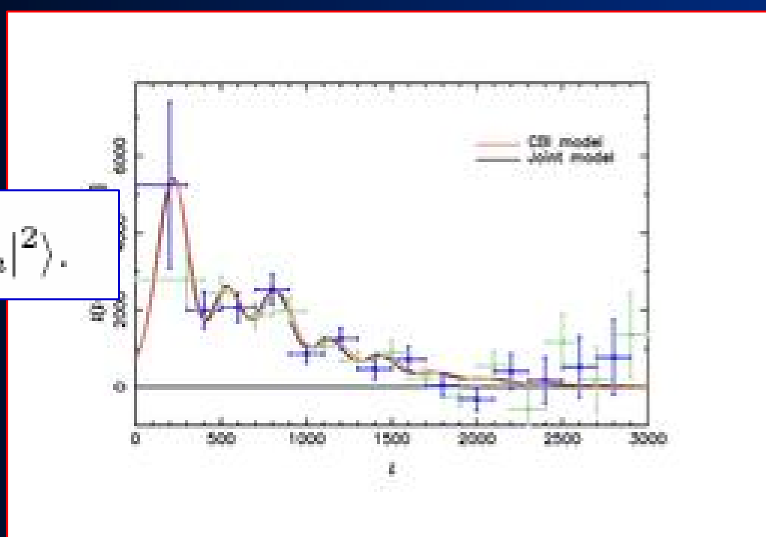




$$\Delta\theta \approx \frac{\pi}{l}$$

$$\Delta T = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi).$$

$$Y_{l,m} = \sqrt{\frac{2l+1(l-m)!}{4\pi(l+m)!}} P_l^m(\cos\theta) e^{im\phi}$$



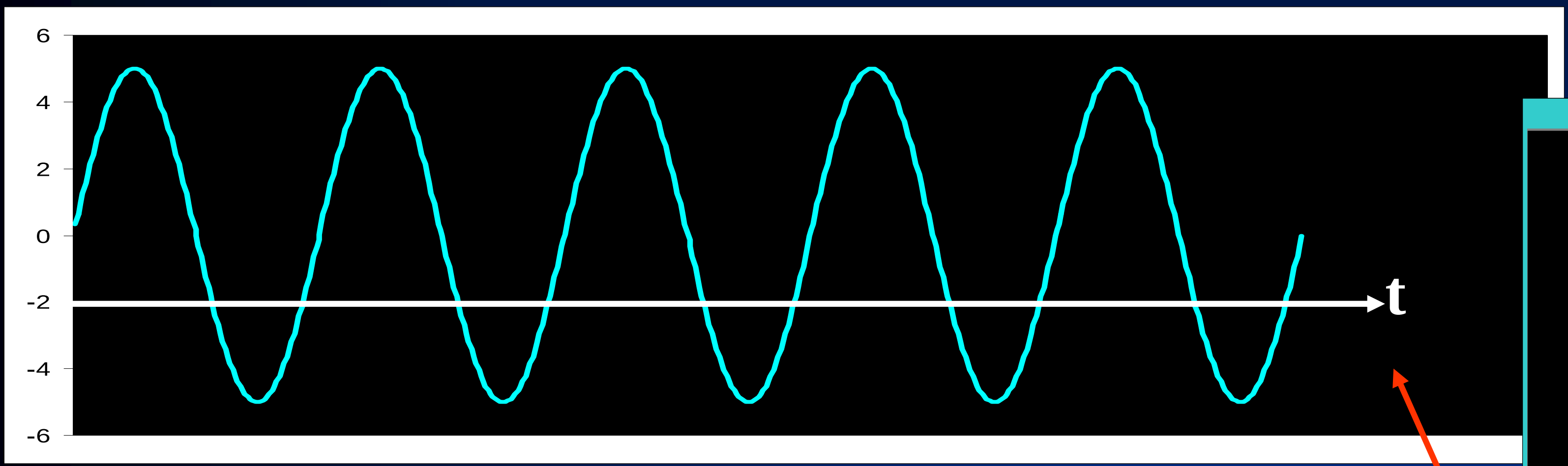
$$C_\ell^T = \langle |a_{\ell m}|^2 \rangle.$$

Using **spherical harmonic analysis**, the **power spectrum** of these temperature variations can be analyzed.

To get an idea of what this means, we will first investigate the wave forms and power spectra of simple waves, then samples of music, and finally the sounds of some actual astrophysical phenomena.

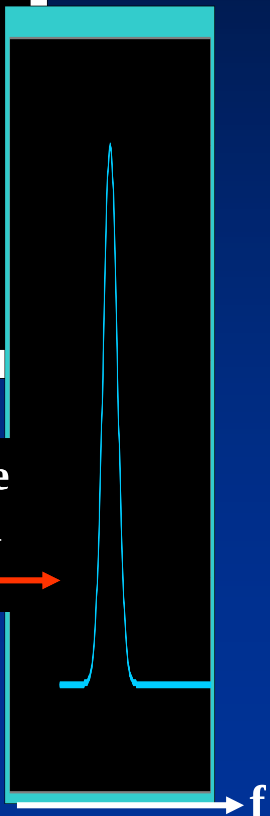
Finally, we will see how this technique applies to the study of the CMB.

The simplest mathematical representation of a wave $F(t) = A \sin(\omega t)$ **represents a periodic displacement of some medium, in one location, with amplitude "A" and angular frequency** ω. The simplest wave form **looks something like this:**



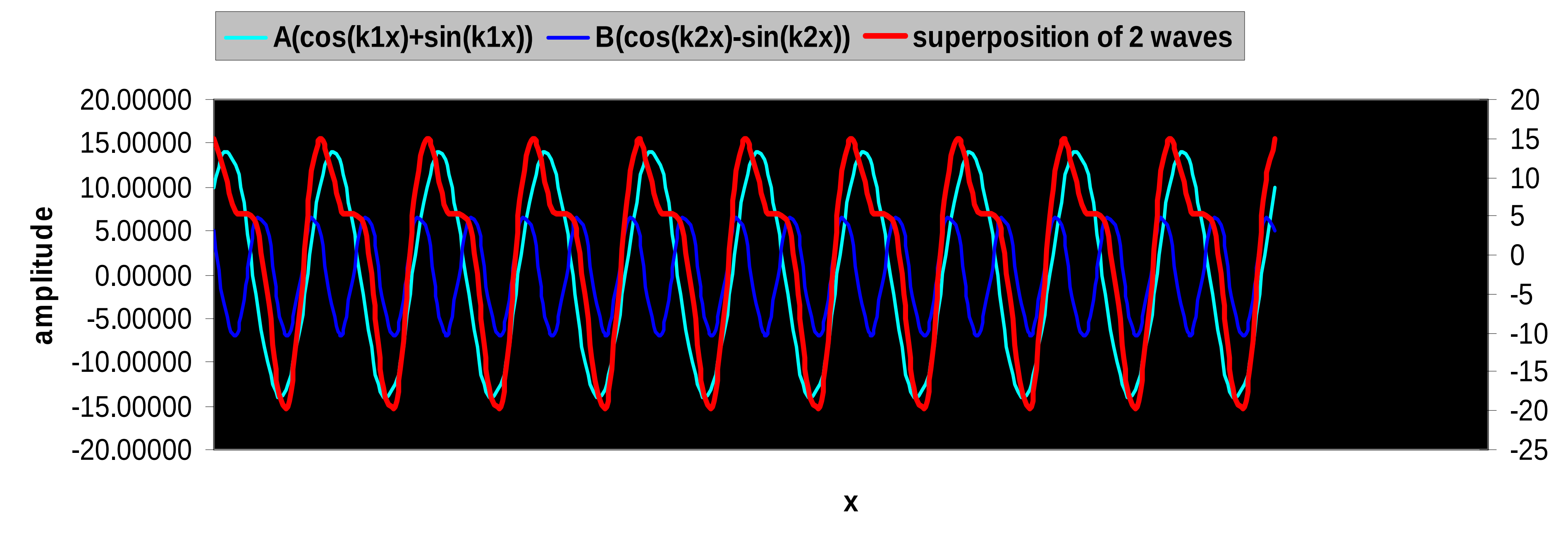
A single frequency of 440 Hz sounds like this:

The power spectrum of this wave would look something like this, a single spike:

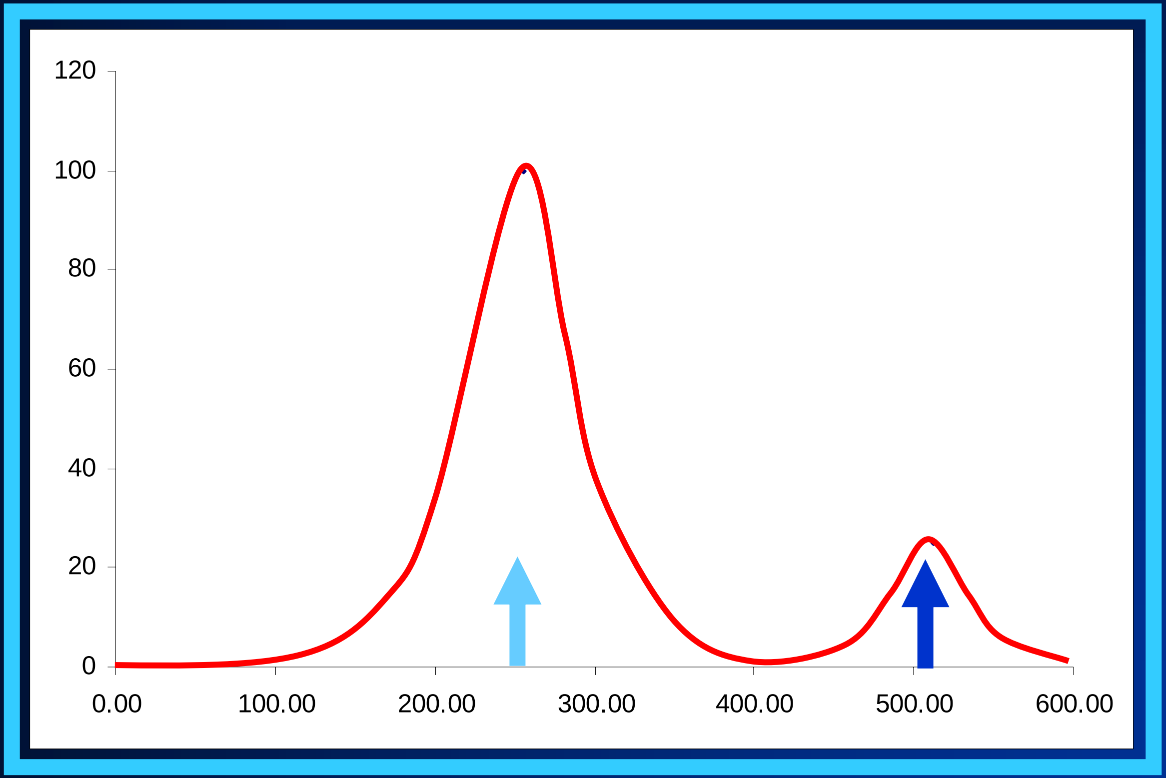


pure A, 440 Hz.
Source: http://www.ugcs.caltech.edu/~tasha/

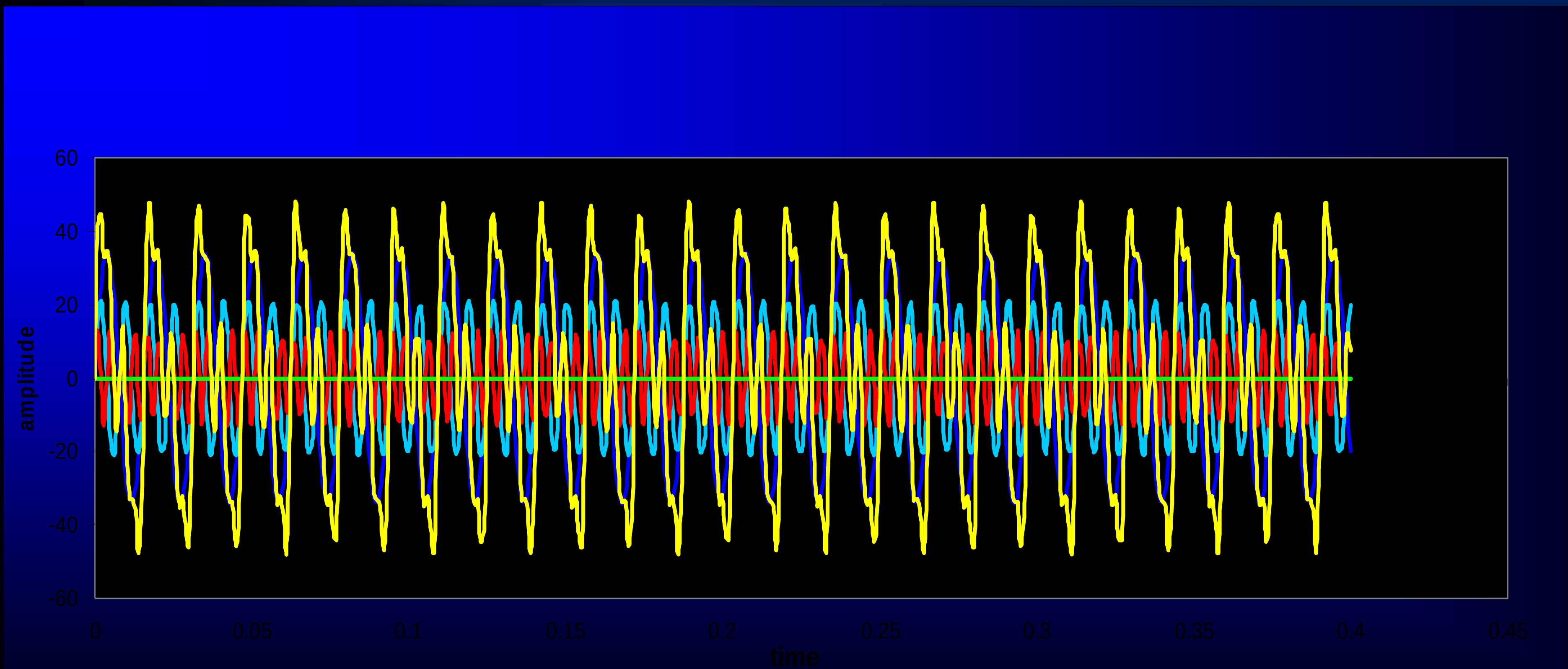
If we add two waves of different frequencies, we get a more complicated wave form, like this example. Here the frequency of the light blue wave is half that of the darker blue wave, while the amplitude of the light blue wave is twice that of the darker blue wave. The red wave is the superposition of the two blue waves.



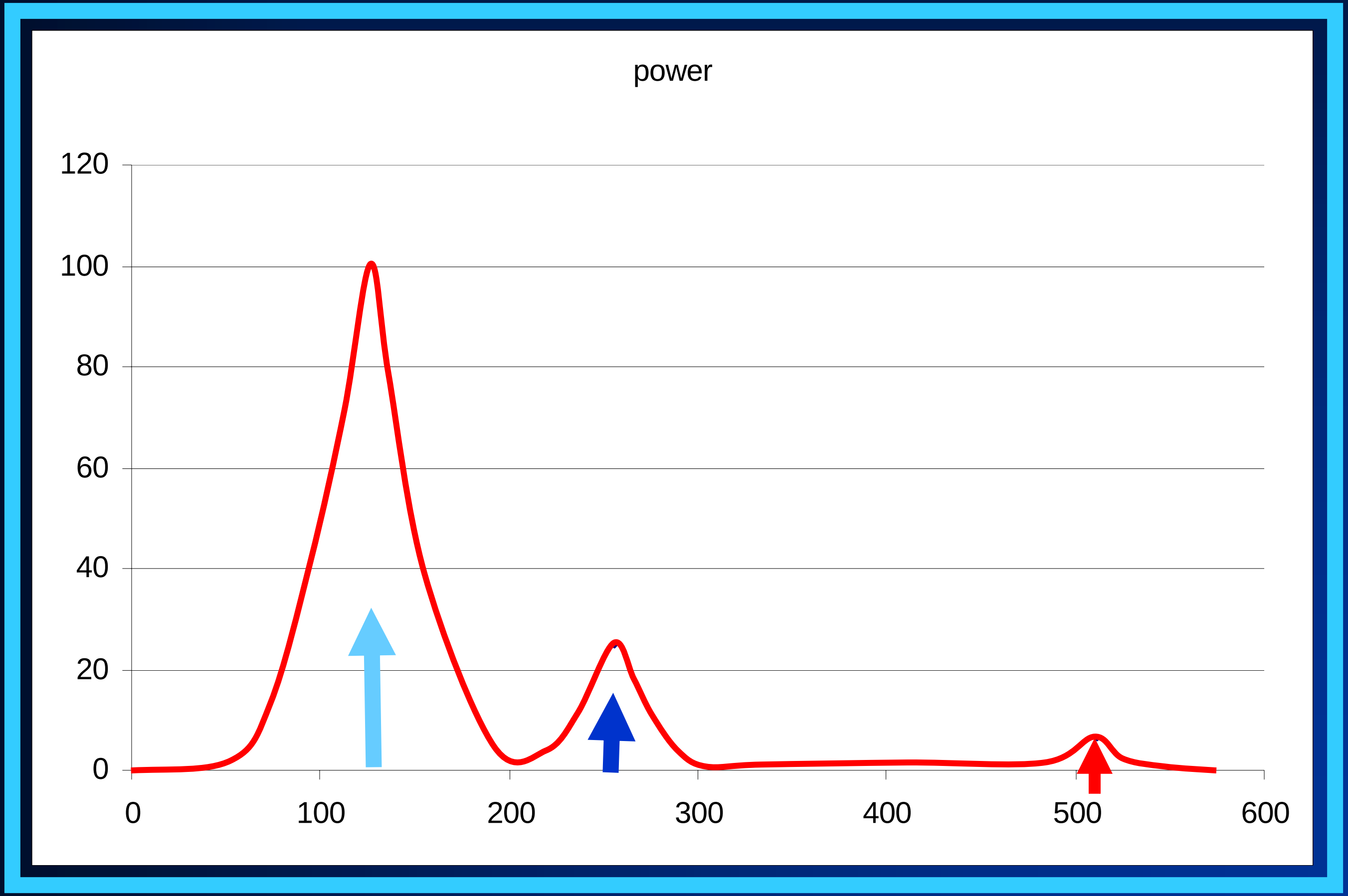
The power spectrum of the red wave, which is the sum of the two blue waves, looks something like this, with two peaks. Since power is proportional to the square of the amplitude, the first peak, corresponding to the light blue wave, is four times as high as the second peak, which corresponds to the darker blue wave.



Here is a graph of three pure sine waves, at 128 Hz, 256 Hz, and 512 Hz, which have been superimposed. Suppose that we let their amplitudes be in 'Golden Ratio' proportions, say 34:21:13, respectively. When we add these three waves, we get an even more complicated-looking wave than the previous example. The yellow wave is the superposition of all three.



The power spectrum would look something like this, for this superposition of three idealized sound waves. Real sounds made by real instruments have additional harmonics, or overtones, and their power spectra are considerably more complex – as we shall see.

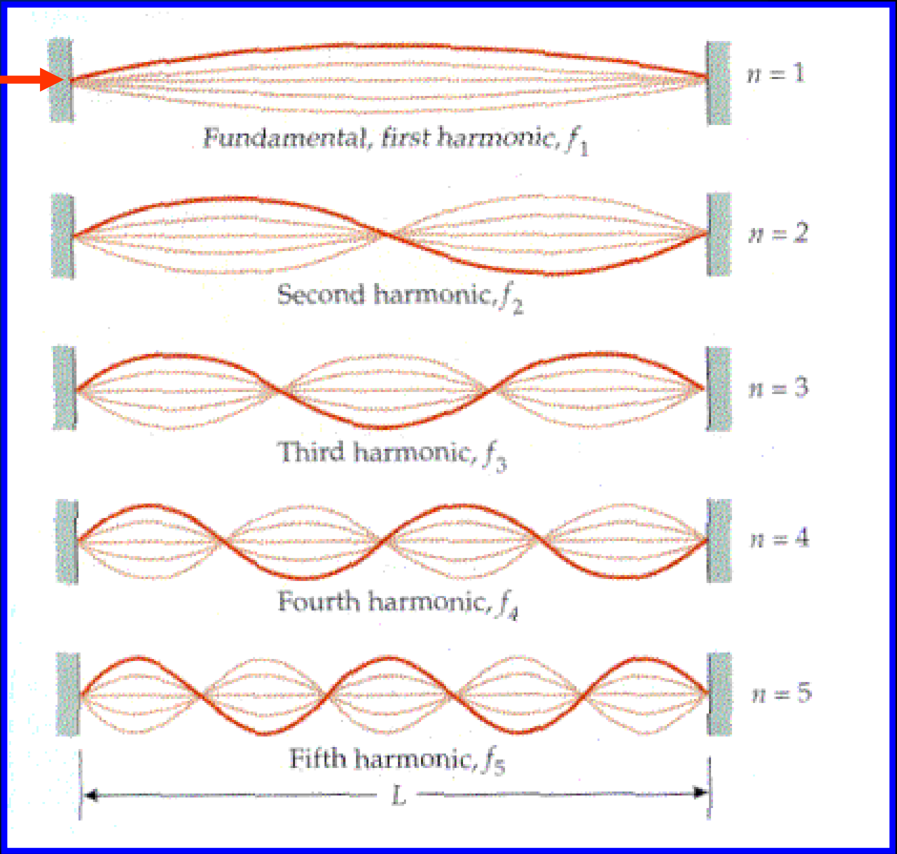


When we pluck a string, we generate a standing wave which is the superposition of waves that travel to the right and left, bounce off the fixed ends, and set up an interference pattern like those shown here.

The fundamental frequency gives us the lowest tone we can hear for a particular length of string.

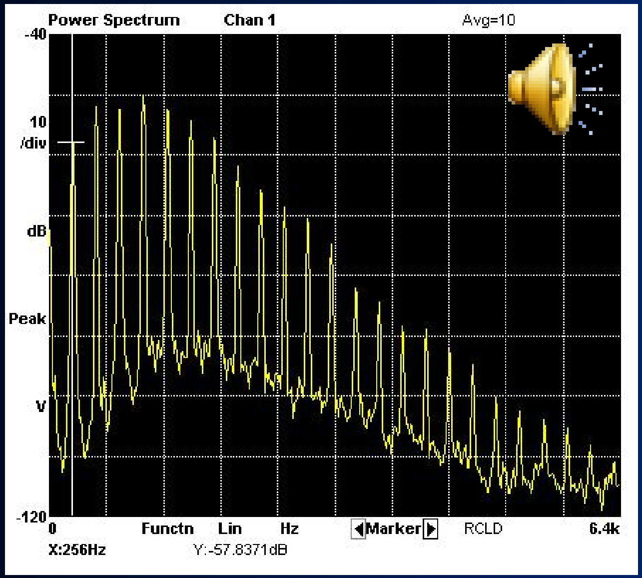
Since frequency = number of vibrations per second, the fundamental is the lowest frequency, hence longest wavelength, for a given length of string. According to our western system of music, when we double the frequency, the tone is higher by one octave.

Higher multiples of the fundamental frequency produce higher tones.

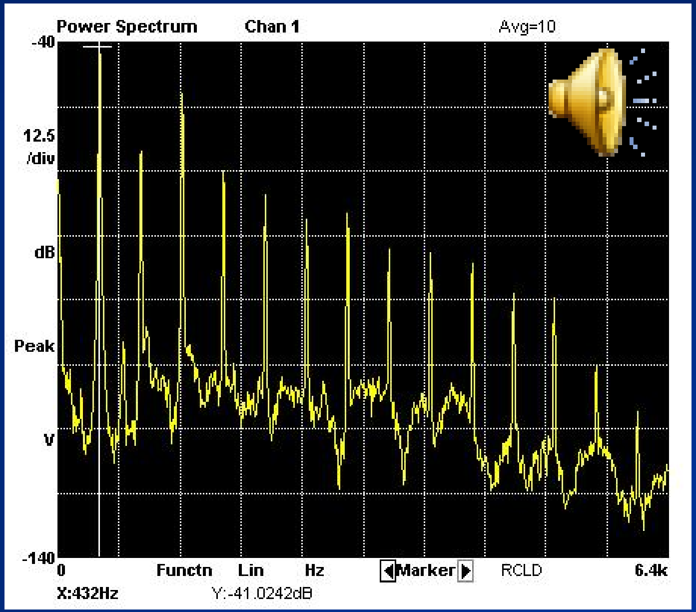


http://kottan-labs.bgsu.edu/teaching/workshop2001/chapter7_files/image023.gif

Every musical note made by a real instrument contains harmonics of the fundamental tone. The combination of these harmonics gives the quality we call timbre, and allows us to distinguish one instrument from another, just by hearing the tone. By analyzing the power spectrum for each type of instrument, we can tell what instrument is being played. A power spectrum for an instrument is like a finger print for a human being, in that it is a unique identifier. Here, for example, are the spectra of a trumpet and a clarinet playing one note. The greatest power comes from the fundamental, and the higher harmonics have progressively less power. Click on the speakers to hear the tones.



Trumpet playing a C (261Hz)



Clarinet playing an A (440 Hz)

Source: http://www.ugcs.caltech.edu/~tasha/

Next we will look at the wave forms and spectra of a few actual samples of music.

The first example is of a piano playing a middle C (256 Hz), with the octave above (512 Hz) and below (128 Hz). Unlike the last example of three superimposed waves, the real one contains overtones, and is considerably more complex.

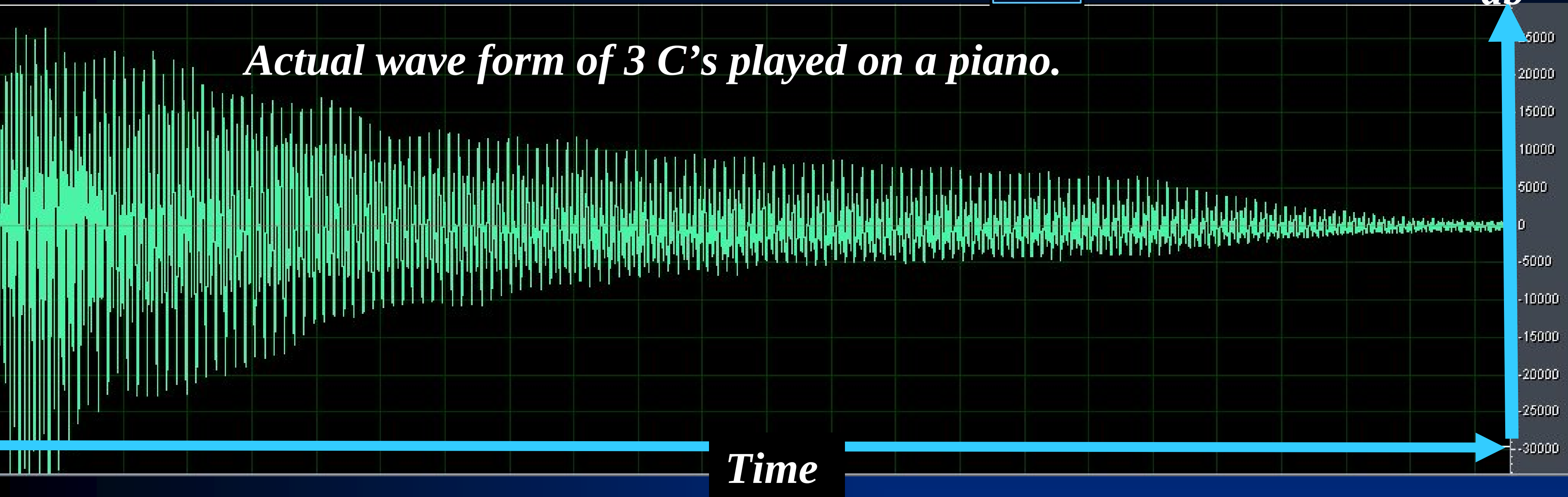
The second piece of music we shall investigate is a synthesizer playing Bach's 2-part invention # 13 in A minor.

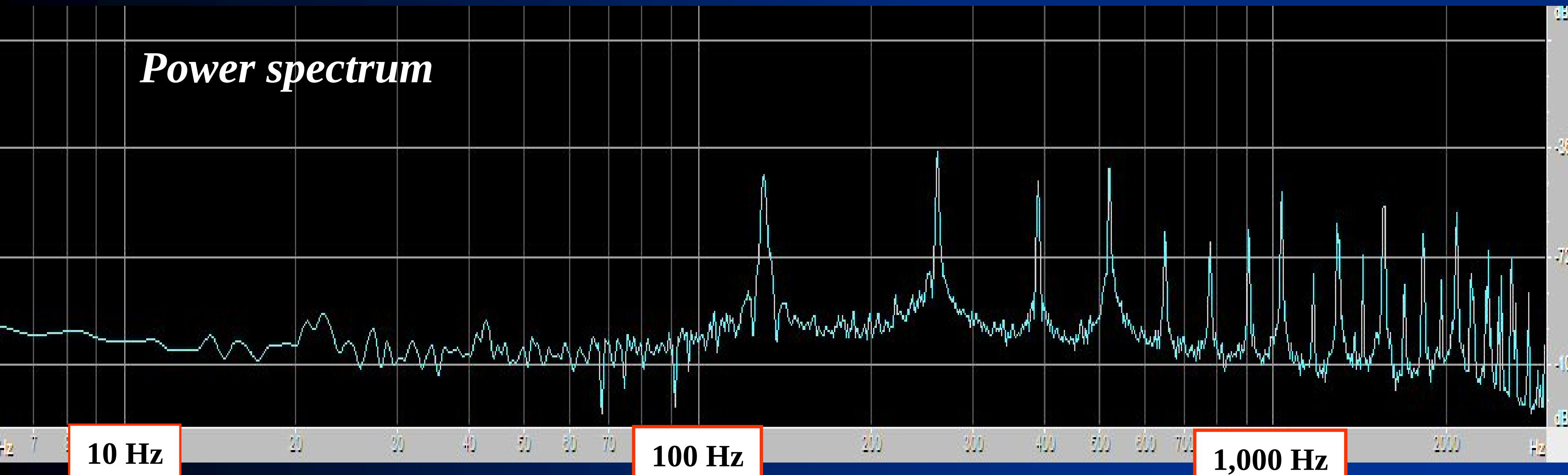
The third is a recording of an actual symphony orchestra playing an excerpt from the "Coffee Variation" from Tchaikovsky's Nutcracker Ballet.

In each example, we show the actual wave form as a sampled time series, and the power spectrum, which shows the total power contained in each frequency, integrated over the whole wave form.

3 C's, approx. 128, 256, and 512 Hz

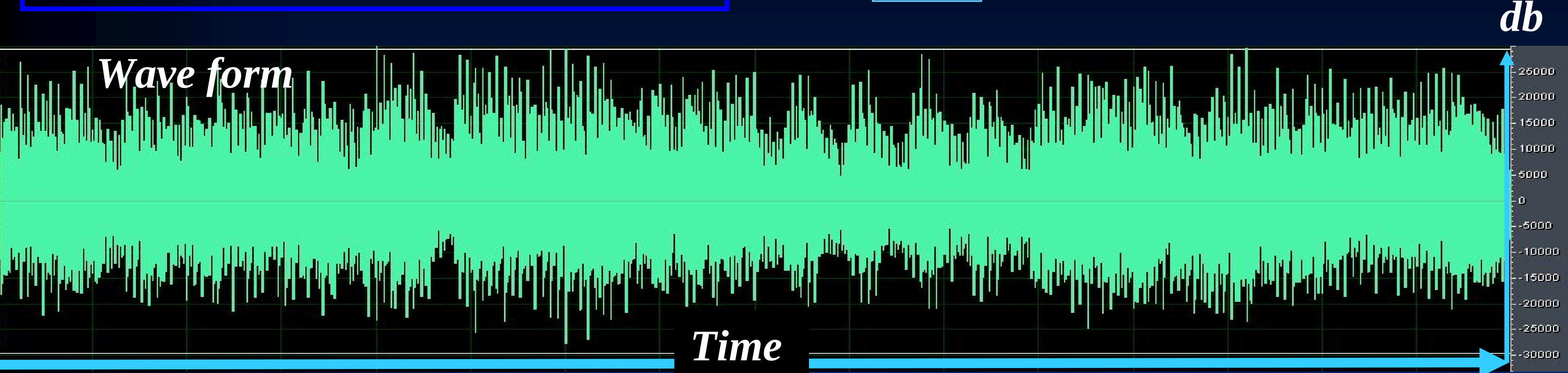
Click on the speaker icon to hear the music

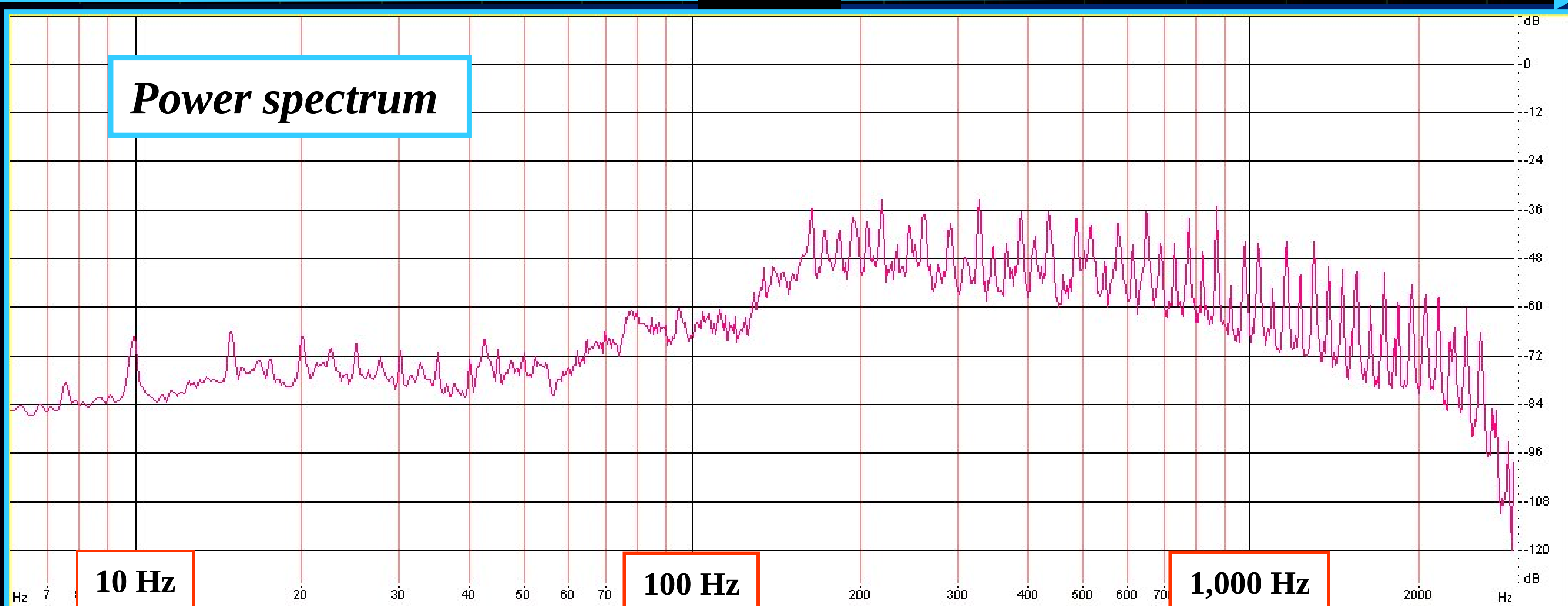




Bach's 2-part invention No. 13, in A minor, played on a keyboard.

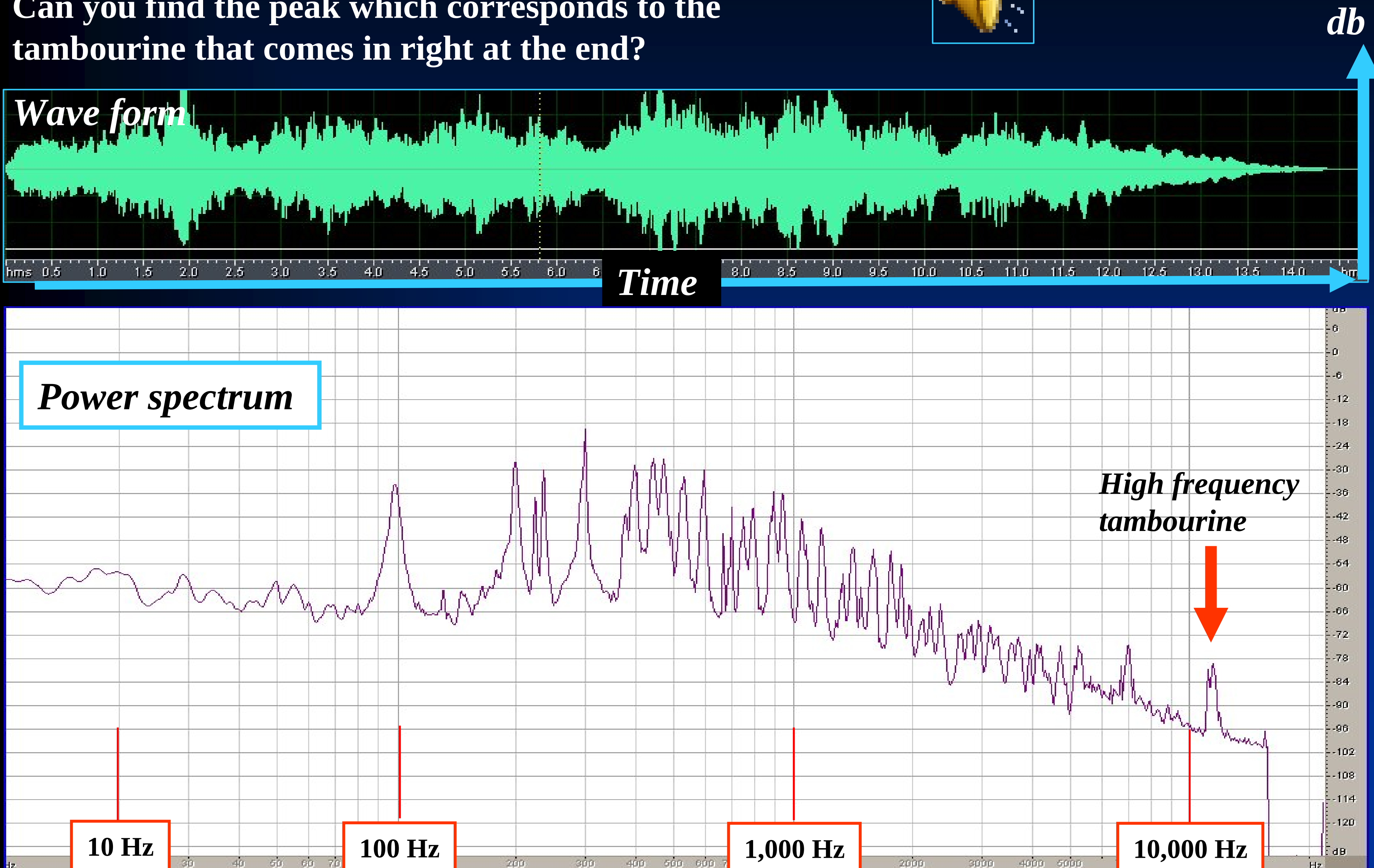
Click on the speaker icon to hear the music





Here is a selection from Nutcracker Ballet by Tchaikovsky. Can you find the peak which corresponds to the tambourine that comes in right at the end?

Click on the speaker icon to play music



There are many astrophysical phenomena which can be heard, either directly or through amplification, electronic recording, or shifting the frequency.

At the European Space Agency you can download many such sounds: http://www.esa.int/esaSC/index.html . Here we show two examples.

1) The Wailing of the Leonids

When meteors streak through the Earth's atmosphere they leave trails of ionized gas, which reflect high frequency radio signals from around the world. These radio signals can be recorded and played back, and they sound like a high-pitched whistle.

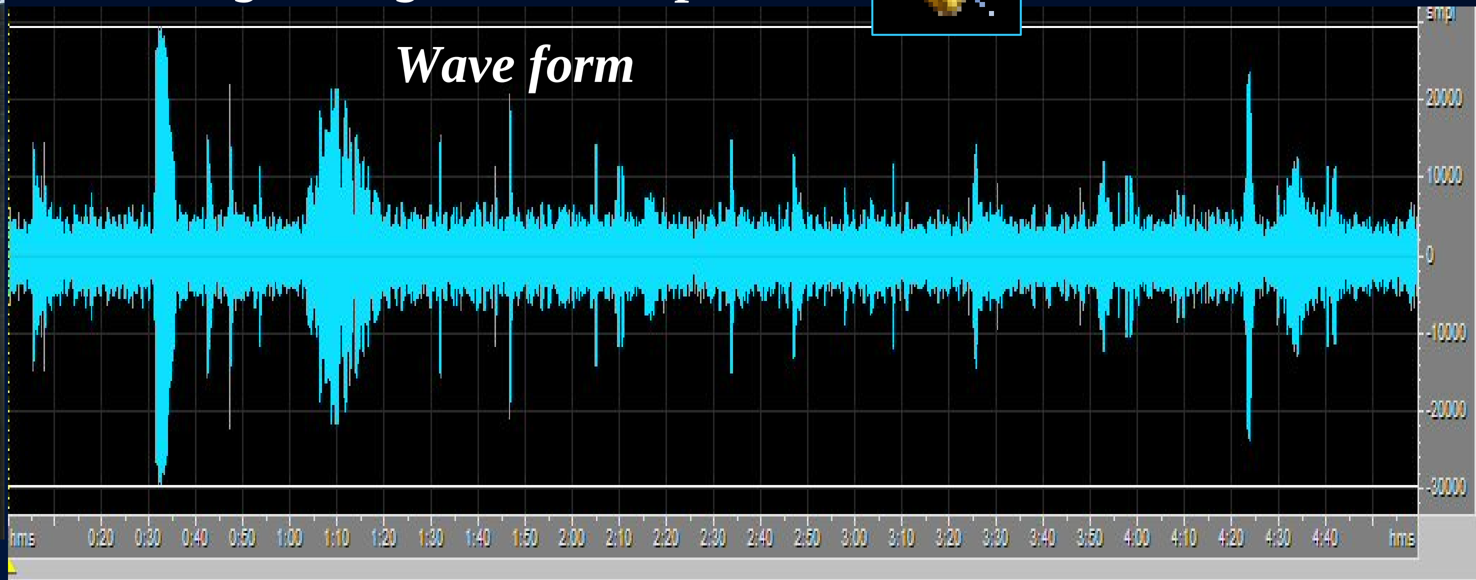
2) The Sound of the Sun

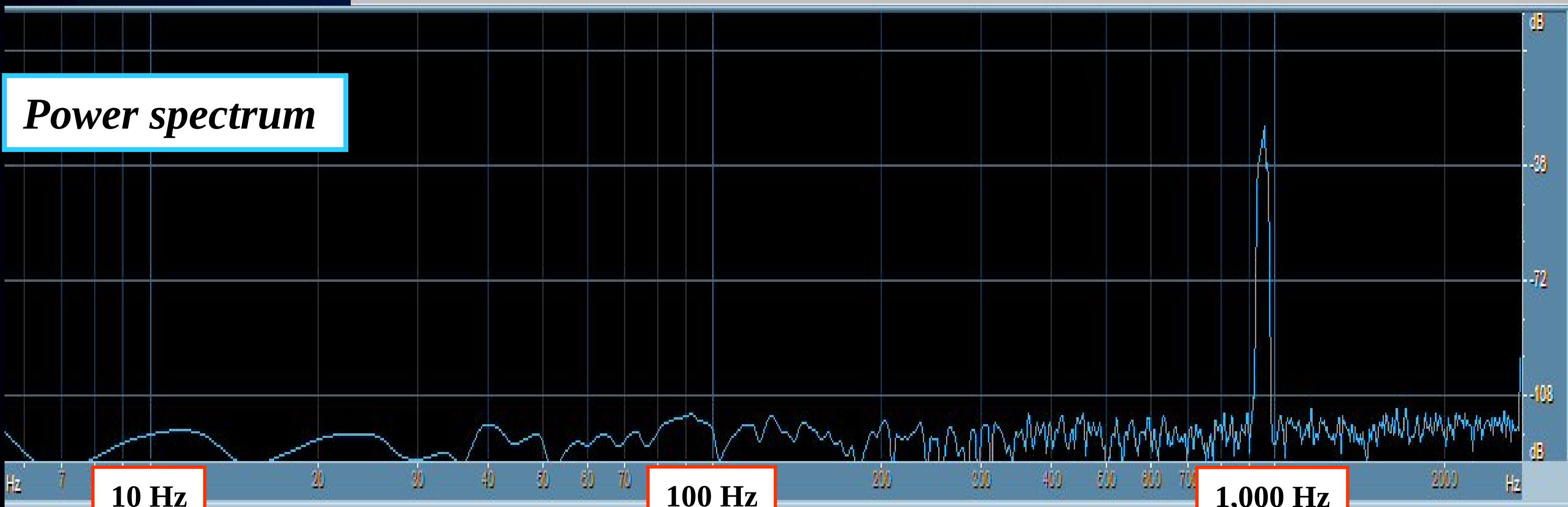
The gases inside the Sun are in constant motion, and produce pressure waves which in turn compress the gases at the surface, which rise and fall in response. These pressure waves produce variations across the entire surface of the Sun. Although too low to actually be heard by human ears, they can be scaled to audible frequencies, which sound like a low-pitched rumble.

The images of the Sun on the following pages were taken from http://gong.nso.edu/ and http://sohowww.nascom.nasa.gov/gallery/Helioseismology/mdi025.html .

The wailing of the Leonids, streaming through the atmosphere:

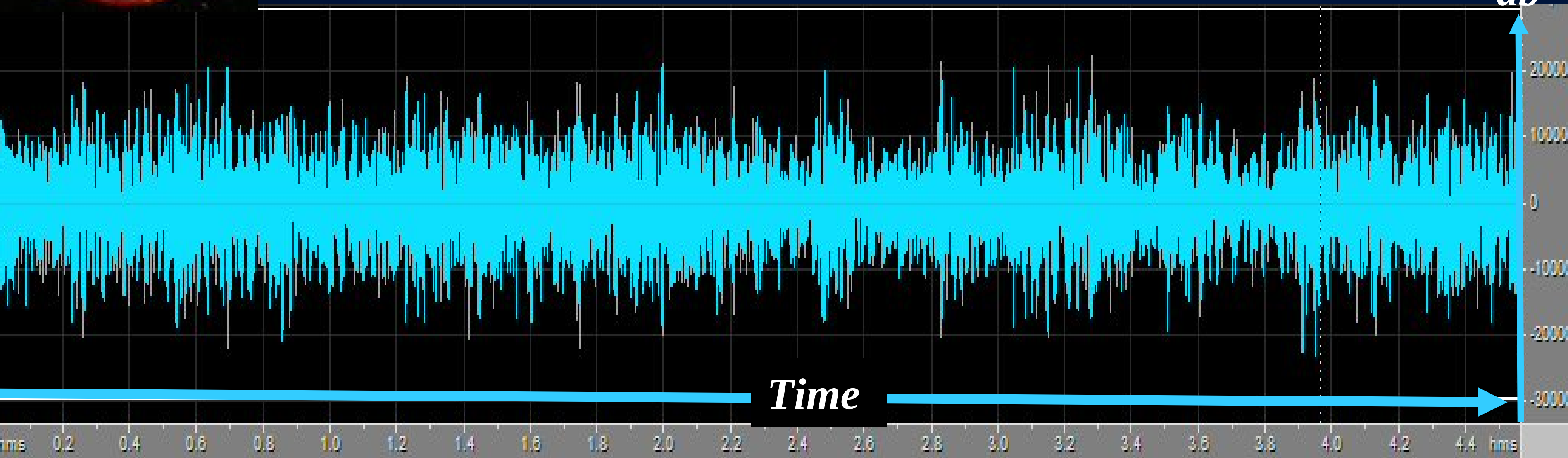
Click on the speaker icon to hear the sounds



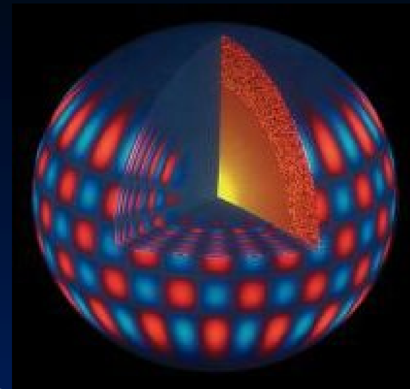


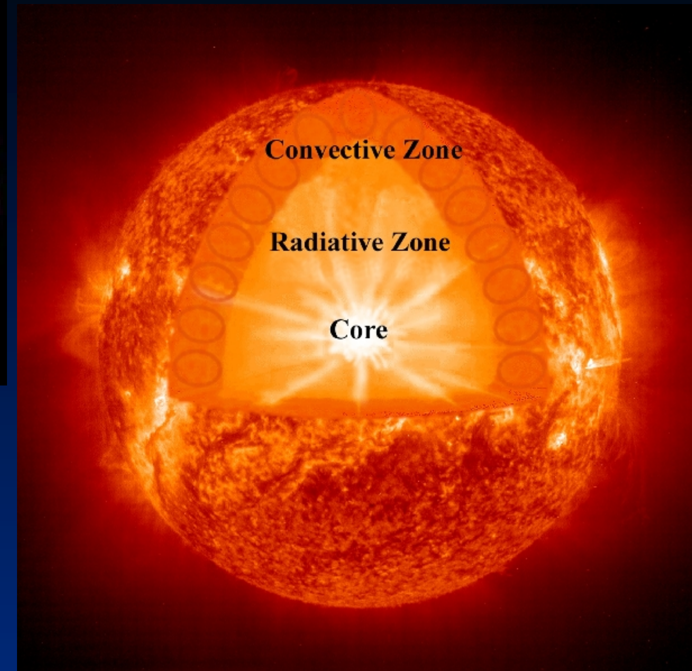
Here is the sound of pressure waves sloshing around inside the Sun, recorded by the BiSON group in Birmingham, UK, http://bison.ph.bham.ac.uk/ .

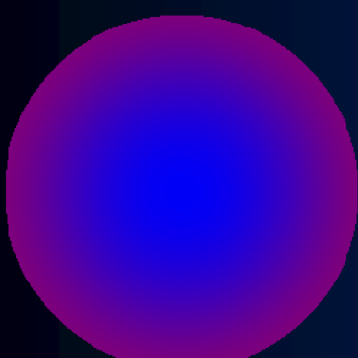
Click on the speaker icon to hear the sounds



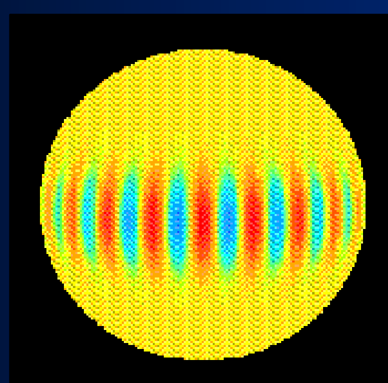
The variations of the surface of the Sun can be analyzed using the technique of Spherical Harmonic Analysis, which we mentioned earlier. Instead of waves on a string which are described by a wavelength, the surface waves are two dimensional, and characterized by two numbers, l and m. l gives the total number of surface node circles that run parallel to the equator, and m indicates the number of surface node circles intersecting at the north and south poles. l can take any integer value, and m can take values from 0 to l.



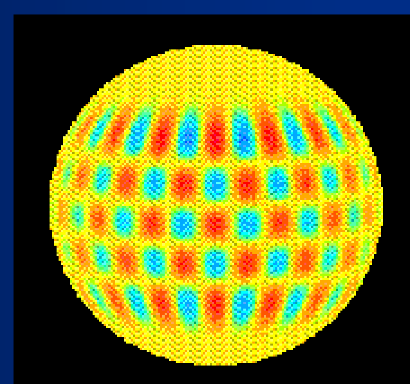




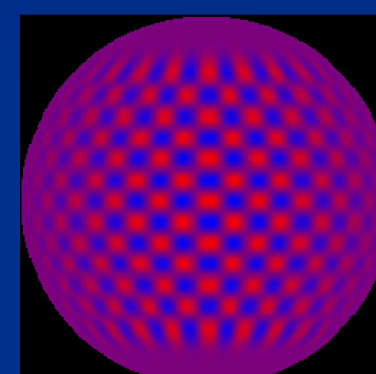
l = 1, m = 1



l = 19, m = 19



l = 19, m = 15

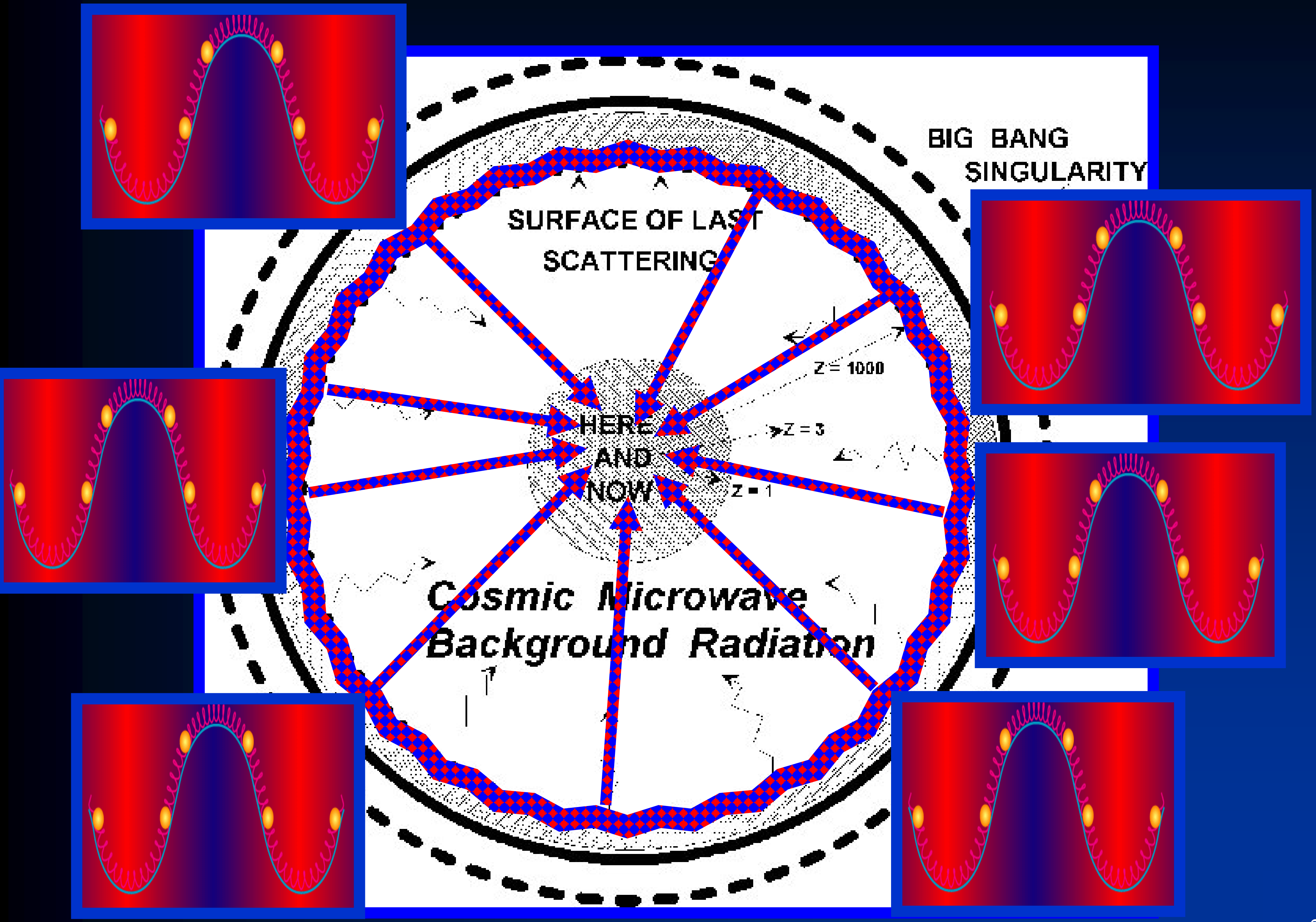


l = 36, m = 24

Now, back to the CMB:

IF we could have been present in the very early universe, it might have sounded something like the sound of the Sun.

So, just as the power spectrum of the pressure waves in the Sun gives us a way to probe inside the otherwise opaque plasma of the Sun, similarly, by analyzing the power spectrum of the temperature variations in the CMB that we observe today, we can get some idea of the processes and composition of the very early universe from whence this radiation, which we now see red shifted into the microwave region of the electromagnetic spectrum, came.



BIG BANG
SINGULARITY
SURFACE OF LAST
SCATTERING
Z = 1000
Z = 3
Z = 1
HERE
AND
NOW
Cosmic Microwave
Background Radiation

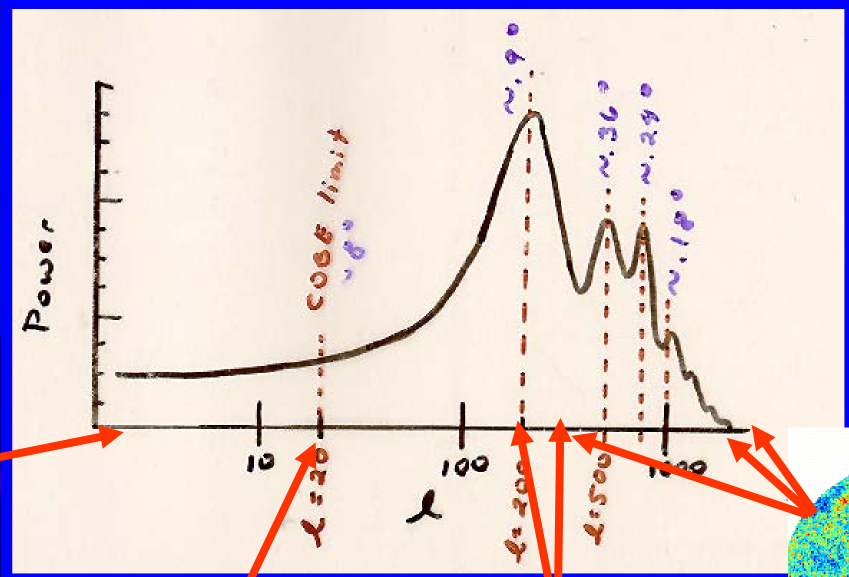
Imagine the sound (pressure) waves sloshing around in the dense plasma of the early universe.

Then - during a relatively short period of time, approximately 400,000 years after the initial "big bang" singularity, the universe cooled so that neutral hydrogen, plus some helium and deuterium, condensed out of this fluid.

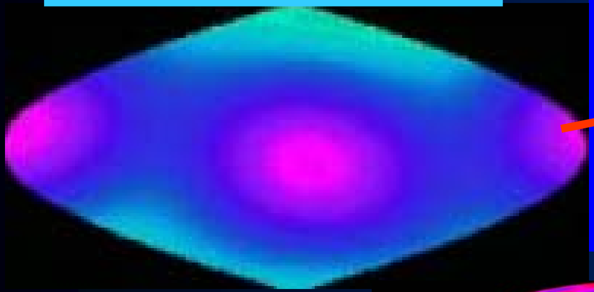
Denser dark matter would have condensed out first, creating gravity 'wells' in regions where the fluid had been compressed. Thus there would have been variations in the density and temperature in the early plasma-filled universe.

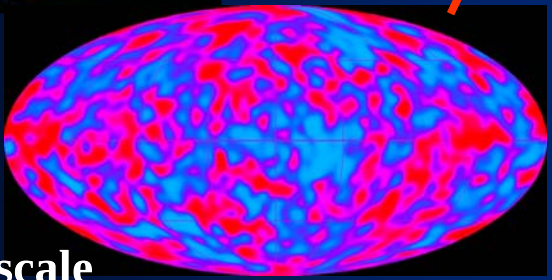
Today, we see these as slightly warmer and cooler patches in the temperature of the universe that lies far beyond the farthest stars and galaxies. By mapping these small variations in temperature, and then calculating the power spectrum of this map – that is, how much power is found at each spatial frequency – we can work backwards to analyze the processes in the early Universe that operated on the various length scales.

The size on the sky that we see corresponds to the spatial frequency or angular wave number, which is the 2-dimensional analogy in space, of the frequency of the music we observed in time. The lowest order on the power spectrum corresponds to variations in the gravitational potential of the early universe, while fluctuations of a degree and smaller correspond to the temperature and density fluctuations due to the sloshing of the matter and radiation in the time from the first minute or so after the "Big Bang," until ~ 400,000 years.

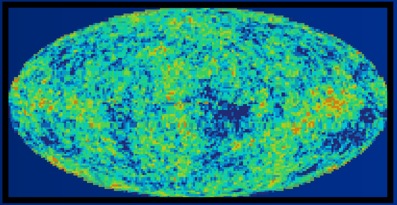


$$\Delta T/T \sim \Delta\varphi/3c^2$$



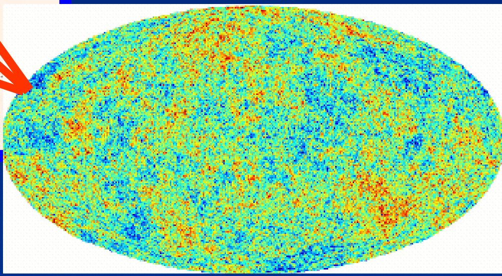


COBE scale



WMAP and balloon-borne experiments mapped at these scales

Planck will map at these scales



$$\frac{\Delta T}{T} \propto \frac{\Delta\rho}{\rho}$$

The very high resolution of the map expected by Planck, at angular scales on the sky of around a tenth of a degree, will be able to constrain the CMB power spectrum out to very high spatial frequencies which correspond to very small scales, so that we can extract more details from the power spectrum with greater confidence than ever before.