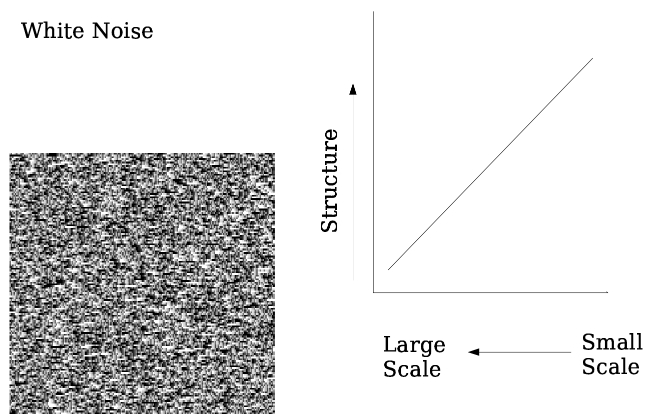
Structure in the Universe

In the beginning, the universe was about as random as you can get. Quite literally, it was nothing more complicated than a sea of energy. Now, you might think that a newly exploding universe is likely to be uniform. In other words, you might expect that there will be as much radiation in one part as in another. You'd be wrong, however. Why? Well, for one thing, when the universe was very, very young (about 10^{-43} seconds old) it was also staggeringly small. And, if there's one thing that I hope you got out of our discussion of quantum mechanics, it's that on small scales, randomness is created in the universe from quantum mechanics.

So, around that time, if we were to make a "map" of the universe, with hot spots represented by white, and cool spots represented by black, it might look something like this:



Does this look familiar? It should. Basically, it's just the white noise that you might see on an olde tyme TV with an antenna which isn't receiving a coherent signal. We might call it "white noise" or "static." But to a mathematician (or a physicist, for that matter) noise is simply another word for randomness.

What happens to this noise as the universe evolves and grows?

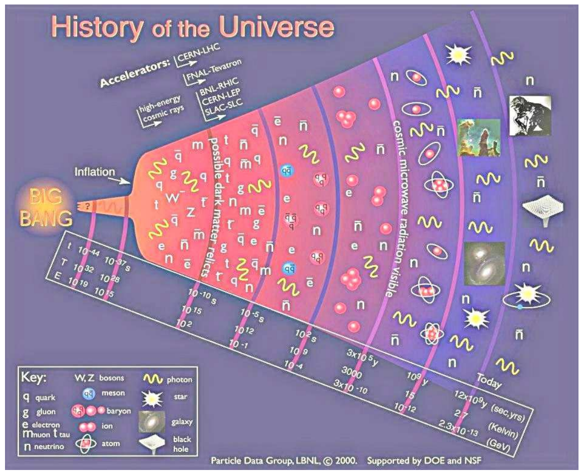
1. As the universe gets larger and larger, the radiation gets more and more diffuse, and thus, it gets cooler.

2. If a "hot spot" was near a "cool spot" the two of them might mix and form a lukewarm spot. As a similar experiment, put an ice cube in a hot drink and see what happens.

However, only nearby spots can mix with one another. It takes time to mix (and light can only travel at the speed of light). Meanwhile the universe is expanding very quickly. Some spots are far enough from one another that they might never mix. Thus, physicists were left with a question: If two parts of the universe never mix, then why are they (very nearly) the same?

This is known as the **horizon problem**, and it can be restated another way. Why does one of part of the night sky look more or less the same (at least on average) as any other? There are about as many galaxies to the east as to the west, for example. Why is this, especially since, as we'll see, the hot and cool spots in the early universe were what gave rise to galaxies in the first place?

Well, around when the universe was about 10^{-35} seconds old, we hypothesize that there was a period of incredibly rapid expansion known as **inflation**, during which the universe increased in size by a factor of about 10^{100}.



However, early in the universe, the most important game in town was pressure. Believe it or not, radiation – light – can exert enormous forces. At early times in the universe, the hot and cool spots sloshed back and forth like water waves. The biggest waves took the longest to slosh. The shortest waves sloshed back and forth very quickly. But here's the thing, as the universe continued to expand, something interested started happening – Stuff was being created.

Photons were colliding with one another creating particles and the particles were colliding to make photons. However, as the universe cooled, the energy of the photons became lower and lower and lower. Thus, by Einstein's famous equation:

$$E = mc^2 \tag{1}$$

Eventually, there wasn't enough energy to make any new particles, and the process stopped.

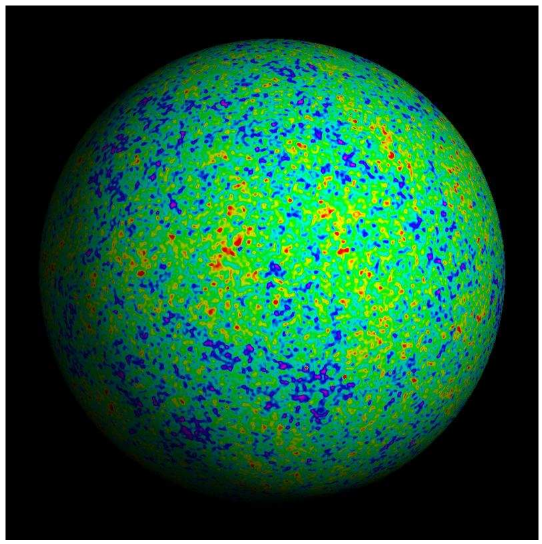
Note that now the "hot spots" become the regions of the universe with the most particles in them. The "cool spots" are relatively devoid of particles. Moreover, as more and more the radiation in the universe becomes matter, the waves slow down ("stuff" typically moves much slower than light), and eventually, the peaks and valleys become frozen.

At this point, just to give you an update, the universe is about 10,000 years old. There's still a lot of radiation in the universe at this point. So much, in fact, that Hydrogen (the most common element in the universe) immediately becomes ionized. As a result, light can't travel very far before running into electrons. Thus, the universe at that time was very much opaque.

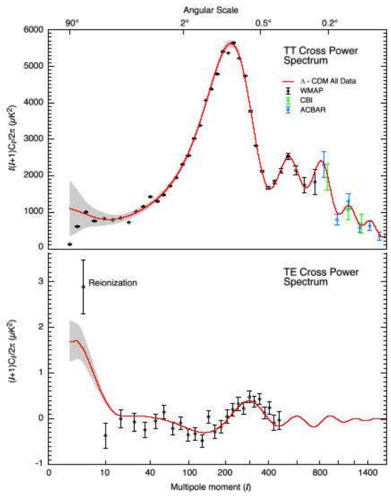
Eventually, around when the universe was 100,000 years old, it was cool enough to form neutral hydrogen, and the light in the universe could freely stream, reaching us today, although much, much cooler. In fact, this soup of photons should only be about 3K (3 degrees above absolute zero) today, and form a "background" in the universe. You can actually detect this with your TV set. About 1% of the static on your TV is primordial, from the creation of the universe. In 1964, Penzias & Wilson discovered the Cosmic Microwave Background or CMB.

The CMB remains one of the most important measurements of cosmology because the structure we see today arose from the bumps and wiggles within the early universe. There are also tiny little bumps and wiggles (about 1 part in 100,000) within the CMB.

In 2001, the WMAP satellite was launched to measure the CMB incredibly accurately. Here's an image of the creation of the universe:



And what of those "waves" in the early universe? We can still see them! The scales which underwent a full oscillation are still seen as peaks, and those which were suppressed are seen as valleys.



What happened next? Say, for the next 14 Billion years during which the universe evolved? Well, at that point, the "hot spots" have become high concentrations of particles, which, as I've said, attract still more particles. One of the things that cosmologists need to do at this point is model the evolution of the universe using gravity. Running "typical" regions using billions of particles, we can observe how these initially "random" fluctuations evolve.

On the course webpage, you can see a couple of movies which show, first, what simulations tells us about how the universe evolved, and secondly, what we actually see when we look out into the universe.