Traces of Sound

Reflections of Sounds Unheard

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Listening to the Universe

Leif Lönnblad

My topic is listening to the universe.[1]

Listening to the smallest things and the biggest things in the universe. Keep in mind that I am a theoretical physicist, so when I hear the word 'sound' I think of wave motions in a medium as particles. The small wave motions I work with lead to phenomena such as quantum mechanics. I will also discuss things that sound in space (there are still some waves, though actually you cannot really hear anything in space). I will concentrate on two fairly new discoveries. One is the discovery of the Higgs particle, which gave Peter Higgs and Francois Englert the Nobel Prize in 2013. The other is the discovery of gravitational waves, which gave the Nobel Prize to Kip Thorne, Rainer Weiss and Barry Barish in 2017.

First, I will explain how I understand sound and waves in a medium. Sound is vibrations or pressure waves in the air—other waves I can mention are light, which is electromagnetic waves in electromagnetic fields, and gravitational waves, which are disturbances in the curvature of space-time. What is interesting is that there are different kinds of waves. Sound is a pressure wave. This means that we can describe sound by giving each point in space and time a number, which is the air pressure at that point. And this pressure can spread. Light is different as it has direction. It has a strength at every point, but also a

1 This essay is based on a lecture given at the Trances of Sound symposium at Lund University's Sound Environment Centre on 27 September 2021. I would like to thank Sanne Krogh Groth for transcribing the lecture.

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direction, and we sometimes talk about polarized light. When it comes to gravitational waves, things are even more complicated.

As a particle physicist, I study the smallest elements of the universe. I focus on quarks and gluons, which build up protons and neutrons, atomic nuclei (together with electrons), atoms, molecules, cells, and ultimately us. There are large orders of magnitude between these elements: I am about one metre in size; cells are about one-hundredth of a millimetre; molecules are down to nanometres; atoms are ten times smaller than that; atomic nuclei are even smaller. The particles I study are smaller than a billionth of a billionth of a metre.

When it comes to such small things, things get a little tricky. A particle does not have a definite position. It is associated with uncertainty. So, what it really has is a probability distribution. There is a probability that it exists in one place *or* another. We call that distribution a wave function—it behaves like a normal wave in any medium. When you do not look at a particle, it behaves like a wave motion—it interferes with other particles, and it can be refracted like light is refracted in a prism—but when we observe it, then it acts as a particle. The fact that all particles can be described as waves also means that all waves can be described in terms of particles. We can describe the electromagnetic waves, or light, in terms of the flow of photons. It is the same for sound. Sound waves can be described as particles, which we call phonons. Normally, it is not practical to use the particle properties of sound, but when looking at vibrations in crystals it makes sense to use phonons.

The electrons and quarks I study are also wave motions in their respective fields. Electrons are waves in an electron field, and quarks are waves in a quark field. I work with the standard model for particle physics. What we know about the smallest constituents of the universe is that everything is made up of quarks and leptons. *All* matter is quarks and leptons. We talk of 'down-quarks' and 'up-quarks'. The usual leptons are the electrons, but there are also some called 'neutrinos'. We have several different varieties: we have heavier varieties of quark. They are not normally found in nature, but can be formed in violent collisions. There is another family of lepton, and there are also antiquarks and antileptons, all of them with their own fields, in which they can be described as wave motions. That is what everything consists of.

Then there are forces, such as the electromagnetic force. These forces are also described by wave motions in a field and can therefore also be described in terms of particles. There are photons for the electromagnetic field, and other particles and fields that I will not go into here.

Every force and every particle is described by quantum field theory. Take the Lagrange density function for the standard model of particle physics. It describes how different quantum fields, such as quark fields, interact with different force fields, such as the gluon fields. Or how leptons interact with the electric field. It has proved to be an extremely successful formula: almost all observations we have ever made in the microcosm are consistent with it; all matter and all forces are described by it. In theory, it is almost all we need to know. [See fig. 1]

The key word being almost. It describes everything we can see in the universe, but there are things in the universe we cannot see. In addition, the formula was initially inconsistent, because the fields in quantum field theory require that all particles are massless. They are not. Electrons and quarks do have mass, which was a significant problem

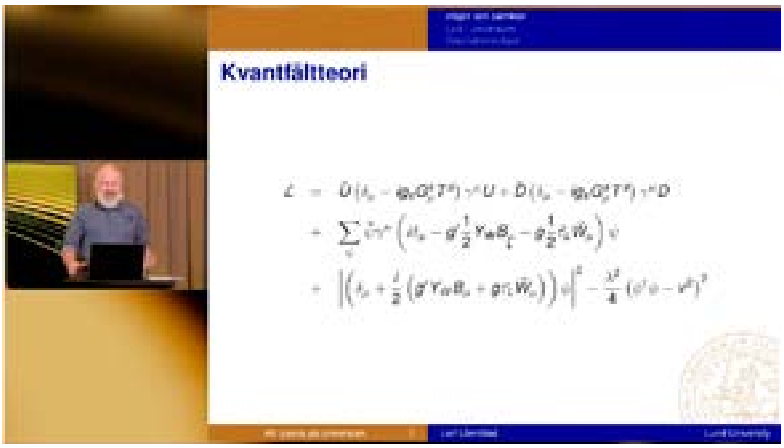

FIGURE 1 Lagrange density function.

for the theory. It was not until the 1960s that the last term was added. What was added is the Higgs field, and it is rather special because it solves the problem with masses in the following way. The Higgs field is assumed to be found all over the universe, and everywhere it has a value that is not zero. Different particles interact with the Higgs field in different ways. Heavy particles interact with the Higgs field more, and for them the field becomes quite difficult to get through. This means that a particle does not really have a mass, but it looks like that when it moves forward due to its interaction with the Higgs field. This worked exceptionally well, except for one detail: if there is a field, where there can be wave motions, there must also be a particle, the Higgs particle. And no one had seen it, and in the end it took 40 years to find. It has a mass and interacts with its own field. It acts as a resonance in the field. The field is special, as it is scalar: just like sound, it does not have any direction; it is just a change in density in the field.

How to find the Higgs particle? Use the Large Hadron Collider at CERN in Geneva. It consists of a 27-kilometre circular tunnel, where we accelerate protons and collide them with one another. The tunnel has superconducting magnets to get the protons up to extremely high energies. The protons travel both clockwise and anticlockwise in two separate tubes, and in some places the beams have been aligned so that they can collide. At these collision points are gigantic detectors to see what comes out. What we get when we collide two protons is enormous: in just one collision the energy is so high that hundreds of particles are formed and are spread out in all directions. The question is, how to find a Higgs in such a collision? [See fig. 2]

From the theory we can calculate that the probability of a Higgs particle being formed in a collision like this is small. So, there will be a great many collisions that we do not care about—that are just noise. In the noise we try to find the tiny signal of a Higgs particle by using the way it decays. We do a kind of frequency analysis. By looking at light particles coming out of the collisions, we search for the frequency corresponding to the resonance frequency of the Higgs field. [See fig. 3]

We have a background that is a green line that is equivalent to noise. Just as in a regular frequency spectrum of sound, noise gives you a

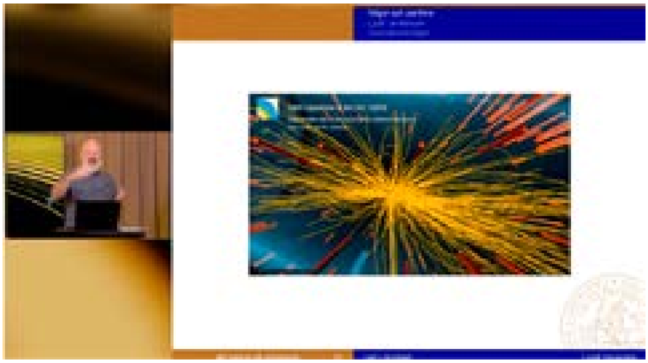

FIGURE 2 Higgs particle.

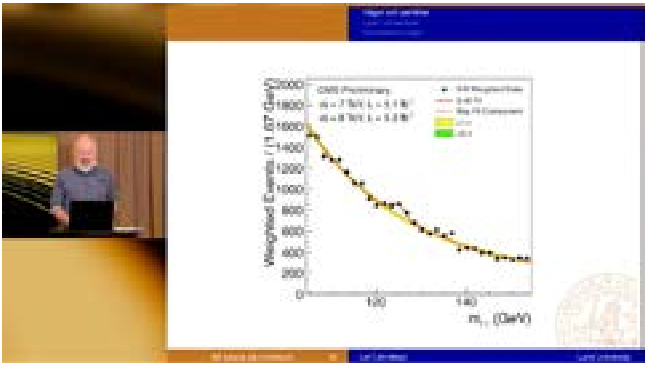

FIGURE 3 Hearing the Higgs particle.

smooth curve. The little bump is a resonance that we can 'hear'. It is the Higgs particle. A little simplified, but in principle this is how we look for particles in the microcosm. We listen.

If we now turn to large, even cosmic, scales, we can still listen to the universe. It is said that in space no one can hear you scream, because sound must have a medium—air. And in space there is a vacuum. Although that is not completely true, because there is a good deal of gas in space, and this can in principle transmit sound. Not the kind of sound we can hear, because the wavelengths are too long to hear. In the beginning the universe consisted of dense gas, following the Big Bang, about 15 billion years ago, when everything was hot—so hot that

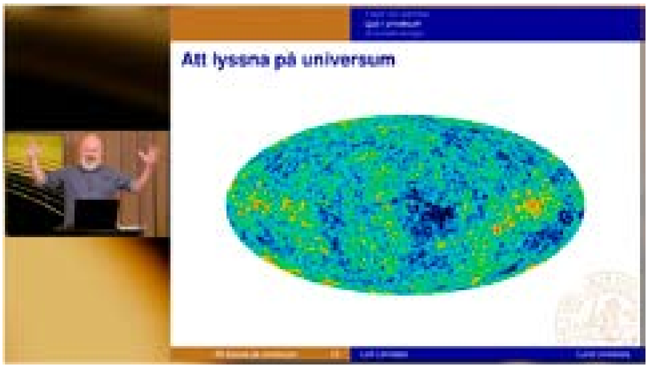

FIGURE 4 The universe 13 billion years ago.

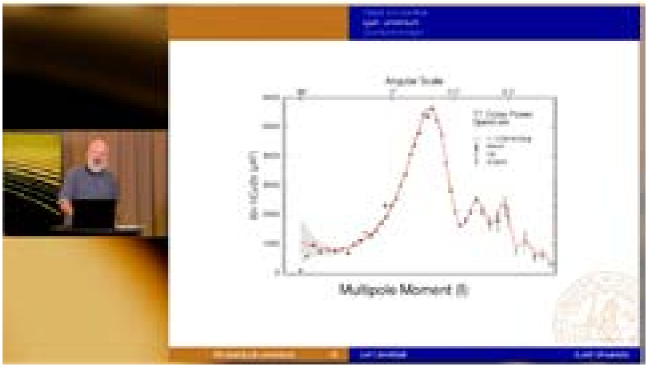

FIGURE 5 A frequency analysis of the universe.

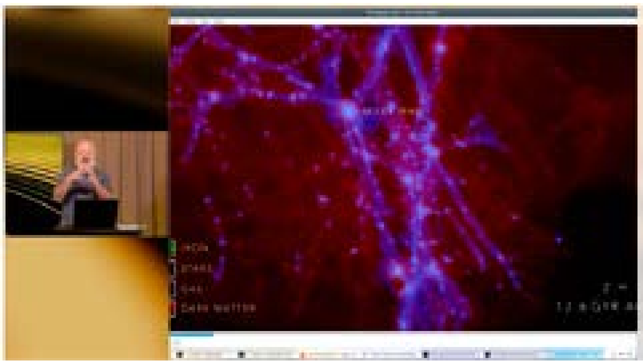

FIGURE 6 A simulation of the universe.

it was plasma. After 300,000 years, the plasma cooled so much that atoms were formed everywhere. The whole universe was filled with a dense, hot gas. [See fig. 4]

That is what the universe was like more than 13 billion years ago. Everything was a gas and it had almost the same temperature, 3000 degrees. Cosmic background radiation tells us there were small differences and the gas was in places one-tenth of a degree warmer and in some places one-tenth of a degree colder. So, a gas that was hot, under high pressure, and expanding, but with differences—and pressure differences. And those differences created sound. [See fig. 5]

Look at a frequency analysis of the universe and we see clear resonances from which we can tell what the universe looked like in the beginning, and from that, what exists in the universe. It turns out that only 5 per cent of the energy is matter we know about. There is also a great deal of energy that comes from dark matter and dark energy that we know little about. Put it altogether and we can find the initial state of the universe. We can do simulations of the universe over billions of years, as in an example by my colleagues in Lund, Oscar Agertz and Florent Renaud. [See fig. 6]

There were different temperatures, and different pressures in different parts, that made gravity put things together in a specific way. We see how stars were drawn together into galaxies and how they travelled around. We see what would soon be the Milky Way—our galaxy. We see how everything interacted as galaxies collided and gas dispersed in all directions. The gas expanded and there were whirlwinds in the gas, which meant there was also sound there. Thus there are sounds in the universe. We cannot hear them, but we can simulate them.

Turning to gravitational waves, it helps to know something of the general theory of relativity. Most people know of Einstein's theory of relativity and will have seen the formula $E = mc^2$. This is the special theory of relativity; the general one is more complicated. [See fig. 7]

One place to begin is the Pythagorean theorem for a right-angled triangle: the square of the hypotenuse is the sum of the squares of the other two sides. But this is not true for all triangles. If you make a triangle from, say, the North Pole that goes down to the equator and

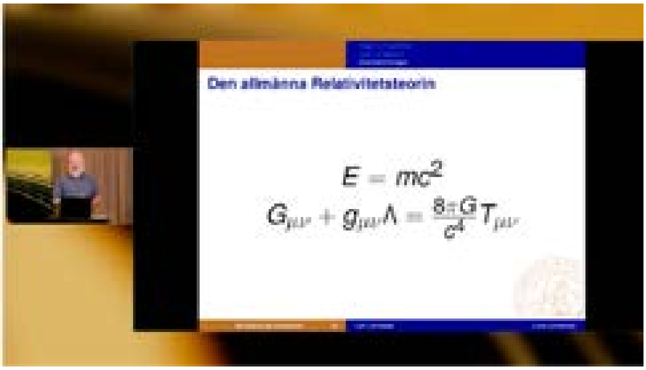

FIGURE 7 The general theory of relativity.

FIGURE 8 Two neutron stars.

measure the lengths of the sides and the base, the Pythagorean theorem no longer applies. That is because the earth's surface is curved; because the earth is a globe the Pythagorean theorem does not apply to large triangles on the surface of a sphere—sorry, Flat Earth Society. However, we can take the curvature of the earth into account by using modified Pythagorean theorem in three dimensions rather than two. In the theory of relativity we can even add the time dimension. That is exactly what is in the form of the general theory of relativity. It tells us, if we are looking at a coordinate system in space and time, how the Pythagorean theorem works there.

Yet even the four-dimensional continuum (three dimensions of space and one in time) is curved. It is curved by heavy things. If we have a coordinate system and a heavy star, the space-time will curve in some way. If something is curved and something moves, the curvature will spread. This is a state of two neutron stars. [See fig. 8]

They are terribly heavy and roll around each other in a closed system. They send out waves in the fabric of space-time. These waves had never been seen when Einstein claimed that they existed in 1915, but now we have finally been able to see them. The way we saw them—because they are difficult to see—is that we imagine an even heavier system. Take two black holes that are gravitationally bound to each other, that spin around each other: when they emit gravitational radiation, they lose kinetic energy and get closer to each other and spin faster and faster. Eventually, the two black holes will collapse into one. In the collapse, an immense quantity of energy is emitted, and that energy could perhaps be seen as waves that spread from the collapse.

These gravitational waves are special. When the wave hits the earth, the space will stretch out in some directions and shrink in other, in a wobbling kind if motion. The waves are not one-dimensional like neither sound, nor two-dimensional like electric waves. At the same time as the space expands in one direction, it contracts in another, so the waves are almost three-dimensional. What we saw was an exaggerated effect on the earth. What really happens is that the waves expand and contract the space by tiny amounts, smaller than the size of an atomic nucleus. They are weak waves: even though a lot of energy goes out, the waves become weak because the gravity is weak.

An experiment has been done using laser interferometers, where researchers accurately measure distance differences in two directions. They send in a laser beam that is divided into two in a semi-transparent mirror. They send the beams four kilometres in different direction to mirrors, sending them back in the opposite direction, and combining the beams again so that they interfere destructively with each other. If the mirrors at each end are perfectly still you will not measure any light coming back; move a mirror even the tiniest bit, however, and the interference is broken and you get a signal.

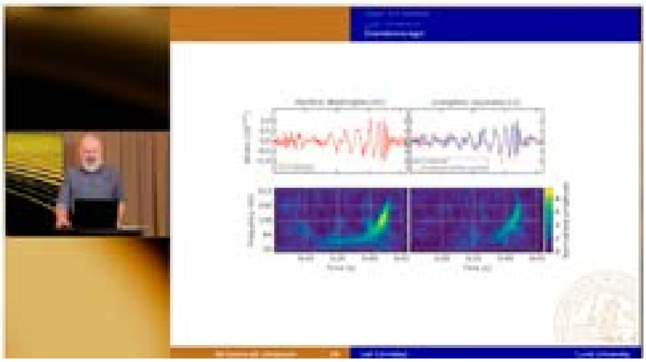

FIGURE 9 Measurements taken during the 2015 tests.

It is complicated. There is a lot of noise, things vibrate all the time, there are thermal movements, a lorry driving by, small earthquakes. To accommodate that we have two almost identical laboratories—one in Washington State and one in Louisiana—and we look at things in exactly the same way in both places. In 2015, when they were testing the equipment before starting proper measurements, they found a signal that appeared to be noise, but looking at one place, they could see it looked the same as in the other place. [See fig. 9]

This is exactly what we would expect to find if there was a gravitational wave, which first hits one place and a fraction of a second later hits the other. That is how the first proof was found that it is possible to detect gravitational waves. Calculations were made and they came to the conclusion it was a collision between two black holes, one weighing 30 times more than our sun, the other 35 times more, which had collapsed into a single black hole that weighed 62 times more than our sun. The rest of the three solar masses had been sent out as gravitational waves. The energy emitted was greater than the total radiation from all the stars in the entire universe. Thankfully it was far away—1.2 billion light years—so there is no cause for concern.

The striking thing about it is that the wave motions are in the audible spectrum. So we can listen to what it sounds like when two black holes collapse. A weak, squirp-like sound. That is what the biggest explosion ever recorded sounds like.