How giant atoms may help catch gravitational waves from the Big Bang

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Some of the earliest known galaxies in the universe, seen by the Hubble Space Telescope. Credit: NASA/ESA

There was a lot of excitement last year when the LIGO collaboration detected gravitational waves, which are ripples in the fabric of space itself. And it's no wonder – it was one of the most important discoveries of the century. By measuring gravitational waves from intense astrophysical processes like merging black holes, the experiment opens up a completely new way of observing and understanding the universe.

But there are limits to what LIGO can do. While gravitational waves exist with a big variety of frequencies, LIGO can only detect those within a certain range. In particular, there's no way of measuring the type of high frequency gravitational waves that were generated in the Big Bang itself. Catching such waves would revolutionise cosmology, giving us crucial information about how the universe came to be. Our research presents a model that may one day enable this.

In the theory of general relativity developed by Einstein, the mass of an object curves space and time – the more mass, the more curvature. This is similar to how a person stretches the fabric of a trampoline when stepping on it. If the person starts moving up and down, this would generate undulations in the fabric that will move outwards from the position of the person. The speed at which the person is jumping will determine the frequency of the generated ripples in the fabric.

An important trace of the Big Bang is the cosmic microwave background. This is the radiation left over from the birth of the universe, created about 300,000 years after the Big Bang. But the birth of our universe also created gravitational waves – and these would have originated just a fraction of a second after the event. Because these gravitational waves contain invaluable information about the origin of the universe, there is a lot of interest in detecting them. The waves with the highest frequencies may have originated during phase transitions of the primitive universe or by vibrations and snapping of cosmic strings.

An instant flash of brightness

Our research team, from the universities of Aberdeen and Leeds, think that atoms may have an edge in detecting elusive, high-frequency gravitational waves. We have calculated that a group of "highly excited" atoms (called Rydberg atoms – in which the electrons have been pushed out far away from the atom's nucleus, making it huge – will emit a bright pulse of light when hit by a gravitational wave.

To make the atoms excited, we shine a light on them. Each of these enlarged atoms is usually very fragile and the slightest perturbation will make them collapse, releasing the absorbed light. However, the interaction with a gravitational wave may be too weak, and its effect will be masked by the many interactions such as collisions with other atoms or particles.

Trampolines: fun and educational. Credit: cotrim/pixabay

Rather than analysing the interaction with individual atoms, we model the collective behaviour of a big group of atoms packed together. If the group of atoms is exposed to a common field, like our oscillating gravitational field, this will induce the excited atoms to decay all at the same time. The atoms will then release a large number of photons (light particles), generating an intense pulse of light, dubbed "superradiance".

As Rydberg atoms subjected to a gravitational wave will superradiate as a result of the interaction, we can guess that a gravitational wave has passed through the atomic ensemble whenever we see a light pulse.

By changing the size of the atoms, we can make them radiate to different frequencies of the gravitational wave. This can be this useful for detection in different ranges. Using the proper kind of atoms, and under ideal conditions, it could be possible to use this technique to measure relic gravitational waves from the birth of the universe. By analysing the signal of the atoms it is possible to determine the properties, and therefore the origin, of the gravitational waves.

There may be some challenges for this experimental technique: the main one is getting the atoms in an highly excited state. Another one is to have enough atoms, as they are so big that they become very hard to contain.

A theory of everything?

Beyond the possibility of studying gravitational waves from the birth of the universe, the ultimate goal of the research is to detect gravitational fluctuations of empty space itself – the vacuum. These are extremely faint gravitational variations that occur spontaneously at the smallest scale, popping up out of

Discovering such waves could lead to the unification of general relativity and quantum mechanics, one of the greatest challenges in modern physics. General relativity is unparalleled when it comes to describing the world on a large scale, such as planets and galaxies, while quantum mechanics perfectly describes physics on the smallest scale, such as the atom or even parts of the atom. But working out the gravitational impact of the tiniest of particles will therefore help bridge this divide.

But discovering the waves associated with such quantum fluctuations would require a great number of atoms prepared with an enormous amount of energy, which may not be possible to do in the laboratory. Rather than doing this, it might be possible to use Rydberg atoms in outer space. Enormous clouds of these atoms exist around white dwarfs – stars which have run out of fuel – and inside nebulas with sizes more than four times larger than anything that can be created on Earth. Radiation coming from these sources could contain the signature of the vacuum gravitational fluctuations, waiting to be unveiled.

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