Giant atoms could help unveil 'dark matter' and other cosmic secrets

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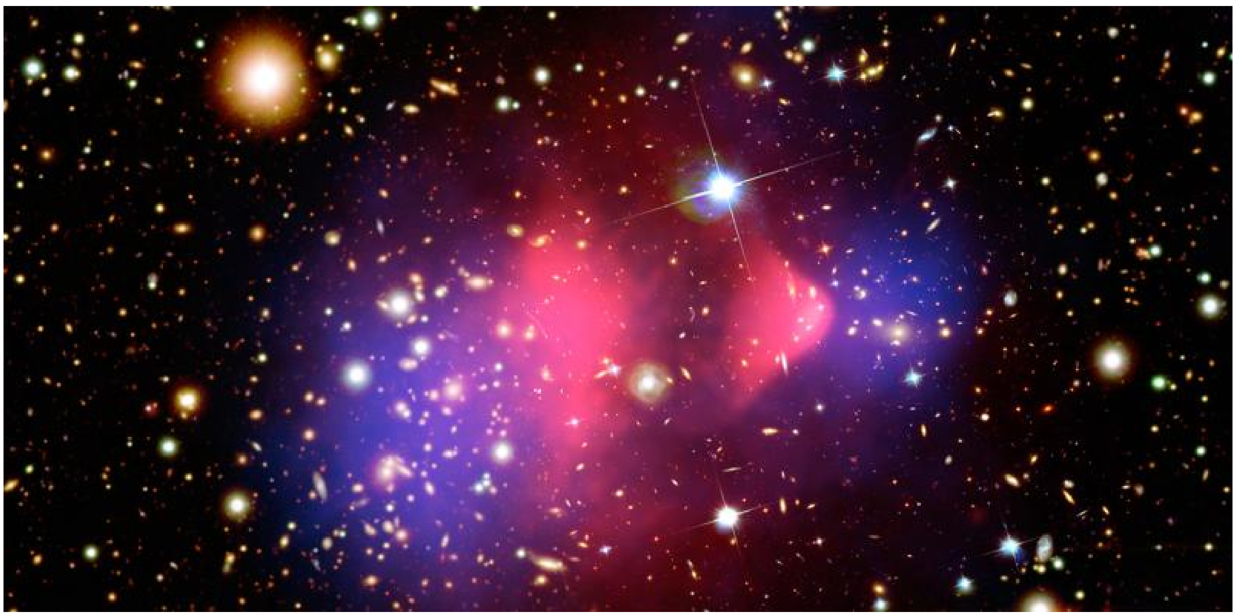

Composite image showing the galaxy cluster 1E 0657-56. Credit: Chandra X-Ray Observatory/NASA

The universe is an astonishingly secretive place. Mysterious substances known as dark matter and dark energy account for some 95% of it. Despite huge effort to find out what they are, we simply don't know.

We know dark matter exists because of the gravitational pull of galaxy clusters – the matter we can see in a cluster just isn't enough to hold it together by gravity. So there must be some extra material there, made up by unknown particles that simply aren't visible to us. Several candidate particles have already been proposed.

Scientists are trying to work out what these unknown particles are by looking at how they affect the ordinary matter we see around us. But so far it has proven difficult, so we know it interacts only weakly with normal matter at best. Now my colleague Benjamin Varcoe and I have come up with a new way to probe dark matter that may just prove successful: by using atoms that have been stretched to be 4,000 times larger than usual.

Advantageous atoms

We have come a long way from the Greeks' vision of atoms as the indivisible components of all matter. The first evidence-based argument for the existence of atoms was presented in the early 1800s by John Dalton. But it wasn't until the beginning of the 20th century that JJ Thomson and Ernest Rutherford discovered that atoms consist of electrons and a nucleus. Soon after, Erwin Schrödinger described the atom mathematically using what is today called quantum theory.

Modern experiments have been able to trap and manipulate individual atoms with outstanding precision. This knowledge has been used to create new technologies, like lasers and atomic clocks, and future computers may use single atoms as their primary components.

Individual atoms are hard to study and control because they are very sensitive to external perturbations. This sensitivity is usually an inconvenience, but our study suggests that it makes some atoms ideal as probes for the detection of particles that don't interact strongly with regular matter – such as dark matter.

Our model is based on the fact that weakly interacting particles must bounce from the nucleus of the atom it collides with and exchange a small amount of energy with it – similar to the collision between two pool balls. The energy exchange will produce a sudden displacement of the nucleus that will eventually be felt by the electron. This means the entire energy of the atom changes, which can be analysed to obtain information about the properties of the colliding particle.

However the amount of transferred energy is very small, so a special kind of atom is necessary to make the interaction relevant. We worked out that the so-called "Rydberg atom" would do the trick. These are atoms with long distances between the electron and the nucleus, meaning they possess high potential energy. Potential energy is a form of stored energy. For example, a ball on a high shelf has potential energy because this could be converted to kinetic energy if it falls off the shelf.

The Large Underground Xenon experiment installed 4,850 ft underground inside a 70,000-gallon water tank shield. Credit: Gigaparsec at English Wikipedia, CC BY-SA

In the lab, it is possible to trap atoms and prepare them in a Rydberg state – making them as big as 4,000 times their original size. This is done by illuminating the atoms with a laser with light at a very specific frequency.

This prepared atom is likely much heavier than the dark matter particles. So rather than a pool ball striking another, a more appropriate description will be a marble hitting a bowling ball. It seems strange that big atoms are more perturbed by collisions than small ones – one may expect the opposite (smaller things are usually more affected when a collision occurs).

The explanation is related to two features of Rydberg atoms: they are highly unstable because of their elevated energy, so minor perturbations would disturb them more. Also, due to their big area, the probability of the atoms interacting with particles is increased, so they will suffer more collisions.

Spotting the tiniest of particles

Current experiments typically look for dark matter particles by trying to detect their scattering off atomic nuclei or electrons on Earth. They do this by looking for light or free electrons in big tanks of liquid noble gases that are generated by energy transfer between the dark matter particle and the atoms of the liquid.

But, according to the laws of quantum mechanics, there needs to be a certain a minimum energy transfer for the light to be produced. An analogy would be a particle colliding with a guitar string: it will produce a note that we can hear, but if the particle is too small the string will not vibrate at all.

So the problem with these methods is that the dark matter particle has to be big enough if we are to detect it in this way. However, our calculations show that the Rydberg atoms will be disturbed in a significant way even by low-mass particles – meaning they can be applied to search for candidates of dark matter that other experiments miss. One of such particles is the Axion, a hypothetical particle which is a strong candidate for dark matter.

Experiments would require for the atoms to be treated with extreme care, but they will not require to be done in a deep underground facility like other experiments, as the Rydberg atoms are expected to be less susceptible to cosmic rays compared to dark matter.

We are working to further improve the sensitivity of the system, aiming to extend the range of particles that it may be able to perceive.

Beyond dark matter we are also aiming to one day apply it for the detection of gravitational waves, the ripples in the fabric of space predicted by Einstein long time ago. These perturbations of the space-time continuum have been recently discovered, but we believe that by using atoms we may be able to detect gravitational waves with a different frequency to the ones already observed.

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