Using velocity-induced acoustic oscillations as a standard ruler at cosmic dawn

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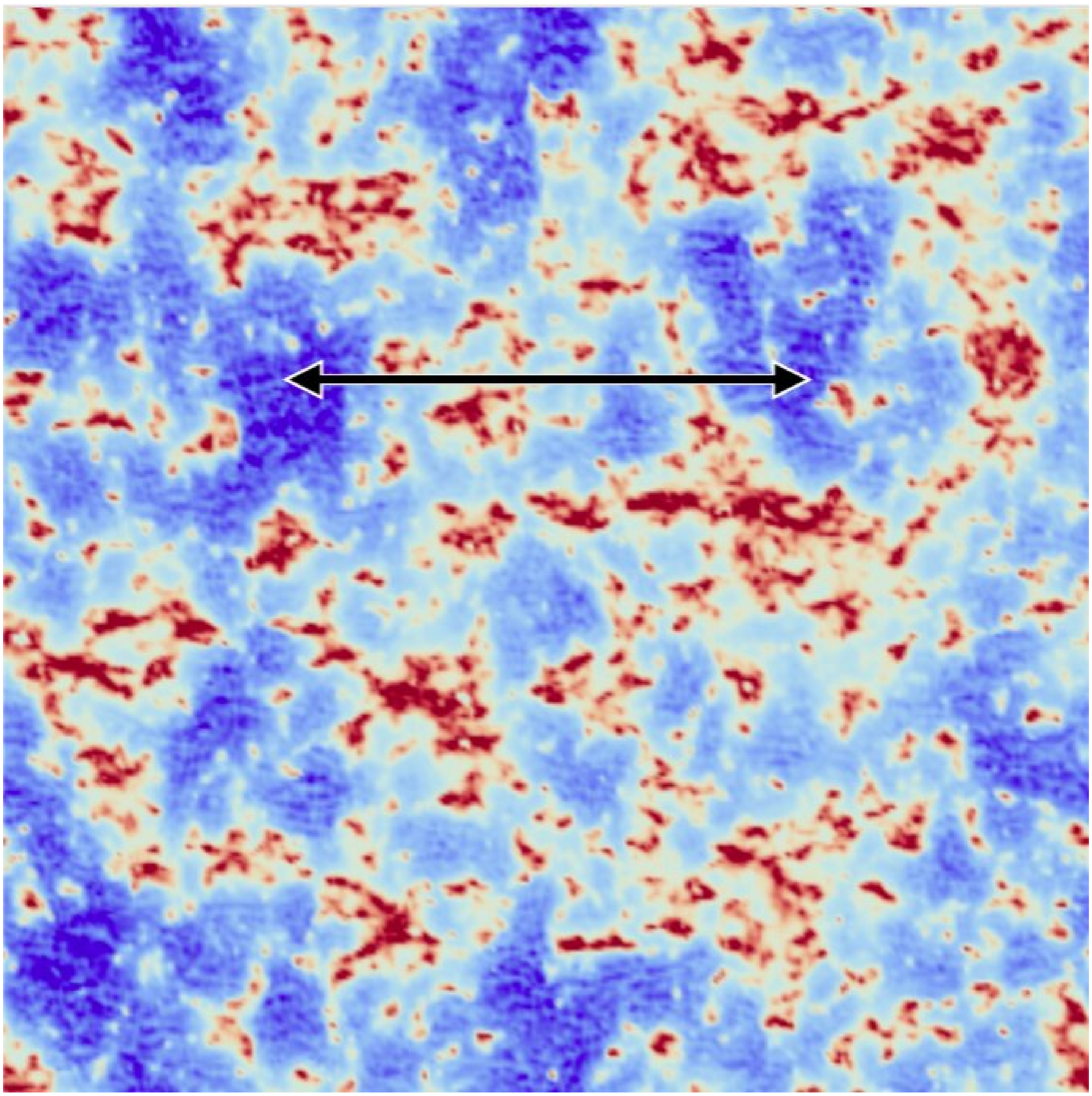

Image showing a slice of the simulated 21-cm map during cosmic dawn, where the blue and red patches (which denote 21-cm absorption and emission) are preferentially separated by 150 Mpc, the length of our standard ruler. Credit: Julian B. Muñoz.

Our current understanding of physics suggests that there are two main types of matter in the universe known as dark and baryonic matter. Dark matter is made up of material that scientists cannot directly observe, as it does not emit light or energy. On the other hand, baryonic matter is made up of normal atomic matter, including protons, neutrons and electrons.

In contrast with dark matter, baryonic matter can interact with photons, giving rise to what is known as baryon acoustic oscillations (BAOs), which are essentially fluctuations in density caused by acoustic waves. While producing BAOs, the same interactions also generate supersonic relative velocities between dark matter and baryons.

These generated velocities are known to impede the formation of the first stars at cosmic dawn, the era after the Big Bang when the first stars and galaxies burst into existence, modulating the expected signal from this specific era. In a fascinating two-part study, a researcher at Harvard University has recently showed that this signal modulation takes the form of robust velocity-induced acoustic oscillations (VAOs), which could in turn provide valuable insight about the cosmic dawn era.

"The idea that dark matter and baryons have a large relative velocity has been around since 2010," Julian B. Muñoz, the researcher who carried out the study, told Phys.org. "In fact, that same year, other researchers realized that this relative velocity would have a large impact on the formation of the first stars. While we cannot directly see these stars, as they are very far away and dim, they can be indirectly detected using the 21-cm line of hydrogen."

When Muñoz started working on his project, he initially wanted to implement the effects of relative velocity using a public simulation code known as 21cmFAST, which is the standard tool used by cosmologists to understand the cosmic 21-cm signal. He then presented the results of these simulations in a paper published in *Physical Review D*.

"While conducting my simulations, I realized that adding the velocities produces robust velocity-induced acoustic oscillations (VAOs) in the 21-cm signal, which have the same origin as the baryon acoustic oscillations (BAOs) that we are used to, but are produced by relative velocities, and not over/under-densities," Muñoz said. "These VAOs imprint the baryon acoustic scale of 150 Mpc onto the 21-cm maps, which can then be used as a standard ruler."

In a new paper published in *Physical Review Letters*, Muñoz then introduced the idea that the VAOs ultimately arising from the coupling of baryonic matter and photons result in the 21-cm signal (typically used to detect stars) spatially oscillating, with a known period of 150 Mpc (about 450 million lightyears). He then suggests that as the shape and characteristics of these oscillations is known, they can be used as a standard ruler to measure the size of the universe during cosmic dawn (i.e., a quarter-billion years after the Big Bang).

The idea introduced by Muñoz is fascinating to say the least, as astrophysicists currently have no other way of accessing this specific cosmic era. In other words, this measurement or 'standard ruler' would be the first of its kind, opening up new exciting possibilities for studies related to the 21-cm signal, such as the hydrogen epoch of reionization array (HERA) project.

The HERA project is a collaboration between astrophysicists and researchers at U.S., South African and British institutions aimed at building a telescope that can robustly detect the epoch of reionization (EOR) red-shifted hydrogen power spectrum signature. A further goal of this project will be the collection of data that could broaden the current understanding of the cosmic dawn era.

"One of the goals of my project was to include the relative velocities onto the public 21-cm code 21cmFAST, since they change all the predictions during cosmic dawn," Muñoz said. "This is necessary to understand the 21-cm signal that will hopefully be detected in the next few years, for instance, by the HERA collaboration."

As Muñoz goes on to explain, the modulation induced by the VAOs is an interesting phenomenon in itself, as the acoustic physics of the baryons become imprinted onto the distribution of the first stars and thus onto 21-cm maps. Precisely because the acoustic physics of the baryons is known, these velocities could provide a robust standard ruler during cosmic dawn.

"Measuring the size of the universe during cosmic dawn would be exciting, since this era is halfway between the cosmic microwave background (CMB) and the local universe, which are in disagreement on measurements of the size of the universe (the famous H0 tension between supernovae and CMB data)," Muñoz said.

The HERA collaboration will soon start collecting data related to the 21-cm power signal emitted at cosmic dawn. Once this data becomes available, it could be used to measure the expansion rate of the universe during cosmic dawn, an era that has so far remained a mystery due to a lack of tools to investigate it. When this happens, the ideas introduced by Muñoz could prove to be extremely valuable, as they highlight the possible use of VAOs as a standard ruler during this previously unprobed epoch.

While the theory introduced in this project could be of great value, some aspects of VAOs are still poorly understood. In his future work, Muñoz plans to continue investigating VAOs, for instance trying to better understand how they modulate the feedback on the first stellar formation, which is currently unclear.

"I also intend to refine the forecasts including more complex foreground and noise models, which mimic those of the HERA instrument, as HERA is very likely to observe these VAOs in the next decade," Muñoz said.

More information: Julian B. Muñoz. Standard Ruler at Cosmic Dawn, *Physical Review Letters* (2019). DOI: 10.1103/PhysRevLett.123.131301

Relative velocity of dark matter and baryonic fluids and the formation of the first structures. arXiv:1005.2416 [astro-ph.CO]. arxiv.org/abs/1005.2416

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Julian B. Muñoz. Robust velocity-induced acoustic oscillations at cosmic dawn, *Physical Review D* (2019). DOI: 10.1103/PhysRevD.100.063538

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