Supercooled phase transitions: Could they explain gravitational wave signals?

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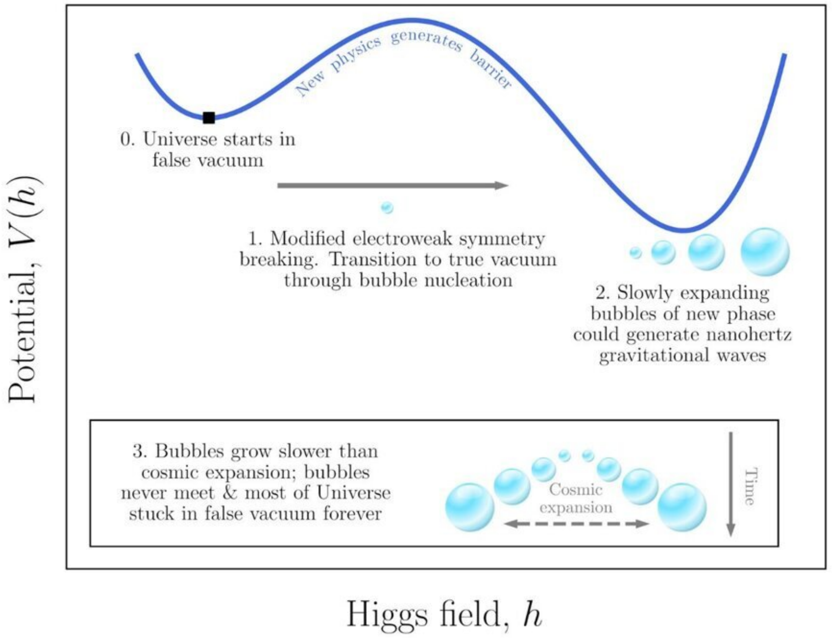

To create nHz frequency signals, the vacuum transitions must be supercooled. These slow transitions struggle to complete due to the cosmic expansion of the universe. Even if the transition is complete, the wave frequencies may shift away from nHz. Therefore, while nanohertz gravitational waves are cool, their origin is likely not supercooled. Credit: Andrew Fowlie

A new study published in *Physical Review Letters* explores the possibility that a strongly supercooled, first-order phase transition in the early universe could explain gravitational wave signals observed by pulsar timing arrays (PTAs).

Gravitational waves, first proposed by Albert Einstein in his general theory of relativity, are ripples in the fabric of spacetime caused by violent processes like the merging of black holes.

They were first detected by LIGO in 2016, confirming Einstein's predictions nearly a century later. The most common sources of gravitational black holes are merging black holes, spinning neutron stars, and supernovae.

Recently, the NANOGrav, or the North American Nanohertz Observatory for Gravitational Waves, detected the presence of stochastic gravitational wave background (SGWB) from pulsar timing arrays (PTAs).

SGWB are different because they are isotropic, meaning they spread equally in all directions, indicating that the source of these are distributed uniformly throughout the universe.

This finding prompted the scientists in the *PRL* study to explore the origin of these waves, which could be from first-order phase transitions (FOPT) in the early universe.

Phys.org spoke to co-authors of the study, Prof. Yongcheng Wu, Prof. Chih-Ting Lu, Prof. Peter Athron, and Prof. Lei W from Nanjing Normal University, to learn more about their work.

"Our probe into the early universe is limited to the period after the formation of CMB [cosmic microwave background]. Although we have some indirect hints about what happened before CMB, gravitational waves are currently the only method to probe the very early universe," said Yongcheng.

Prof. Lei added, "In the past few years, the supercooled FOPT has been widely considered a possible source of the SGWB."

"A new signal seen by PTAs may be evidence of this happening—a very exciting possibility," said Prof. Athron.

Prof. Chih-Ting said that he wanted to understand the connection between the Higgs field and the Higgs boson and its connection to the mechanism of electroweak symmetry breaking. "Linking gravitational wave signals of different frequencies with cosmic phase transitions has opened another window for me to study this," he said.

First-order phase transitions

FOPT are phase transitions in which a system transitions between different phases abruptly or discontinuously. One such example we see in our daily life is the freezing of water.

"The water can stay in a liquid state even if the temperature is below the frozen point. Then, with a small perturbation [change], it suddenly turns into ice. The key signature is that the system stays in the phase for a long time below the transition temperature," explained Prof. Yongcheng.

The electroweak force is a unified description of two of the four fundamental forces of nature: the electromagnetic force and the weak nuclear force.

"We know that in our universe, one drastic change—the breaking of the electroweak symmetry that predicts all weak nuclear interactions—generates the masses of all fundamental particles we have observed today," said Prof. Athron.

This led to the electroweak force splitting into the electromagnetic and weak forces via the Higgs field (which gives all particles their mass). The process by which this happens is the strong first-order electroweak phase transition.

A supercooled FOPT is one where the temperature drop during the phase transition is sudden. The researchers wanted to understand if such a FOPT could be the source of the SGWB observed by the NANOGrav collaboration.

Potential mechanism for generation of SGWB

The idea behind the theory is that the early universe was in a high-temperature state known as a false vacuum state, meaning that its energy is not the lowest possible energy.

As the universe expands and cools, the potential energy decreases. Below a critical temperature, the false vacuum state becomes unstable.

At this temperature, quantum fluctuations (random motions) can initiate the formation of true vacuum states, which are the lowest energy states. This happens through the process of nucleation (formation) of bubbles.

Bubbles represent regions where the FOPT of false vacuum to true vacuum has happened.

Once nucleated, these bubbles of true vacuum grow and expand. They can collide and merge, eventually percolating through space. Percolation refers to the formation of a connected network of true vacuum regions.

The phase transition is completed when a sufficient fraction of the universe is in the true vacuum state. This completion typically requires that bubbles percolate across a significant portion of the universe.

During this process, the collisions and dynamics of expanding bubbles generate SGWB, which the NANOGrav collaboration has observed.

Modifying the Higgs potential

The researchers' work started by building a theoretical model to study the supercooled FOPTs and the possibility of SGWB generation.

Prof. Lei explained, "In the case of supercooled FOPTs, models can predict the conditions under which such transitions might occur, including the temperature at which the phase transition happens and the characteristics of the transition process."

The researchers began by modifying the Higgs potential, which explains how the Higgs field interacts with itself and with other fundamental particles.

They added a cubic term to facilitate the dynamics of the supercooled FOPT in the early universe.

Here, they define four key parameters to study the challenges of fitting the nano Hz (nHz) signal (detected by the NANOGrav collaboration) with this cubic potential:

1. Percolation temperature is the temperature at which bubbles of the true vacuum state nucleate and grow sufficiently to form a connected network throughout the universe.

2. Completion temperature is the temperature by which the phase transition has fully completed, with the entire universe transitioning to the true vacuum state.
3. Benchmark point 1 represents a scenario with a significant degree of supercooling while satisfying both percolation and completion criteria.
4. Benchmark point 2 represents a scenario where stronger supercooling has been achieved with a nominal percolation temperature of around 100 MeV but fails to meet realistic percolation criteria and does not complete the transition.

The two temperature measures are essential for understanding the dynamics and timing of the phase transition. They ensure that the transition is comprehensive and complete, which is necessary for generating a gravitational wave signal.

The benchmark points, on the other hand, bring to light the challenges for a supercooled FOPT to generate SGWB.

Limitations of the model

The researchers identified two main challenges that rule out the supercooled FOPT model as an explanation for the nHz signal detected by the NANOGrav collaboration.

The first challenge is the percolation and completion of the supercooled FOPT. When the temperature of the universe drops below a critical value, the phase transition will not happen.

This is because the energy needed for bubbles of the new phase (true vacuum) to nucleate and grow is low.

"Only a few bubbles form and don't grow quickly enough to fill the universe," explained Prof. Athron.

Therefore, the completion of the phase transition, where the entire universe transitions to the new phase, becomes less likely.

The second challenge is that of reheating. Even if a scenario is considered where somehow completion is achieved, the energy released during the phase transition releases heat in the universe. This process increases the temperature of the universe, a process known as reheating.

"This makes it difficult to maintain the conditions necessary for the SGWB to be produced," added Prof. Lei.

The gravitational waves produced in this scenario will not have the same frequency as the ones observed by PTAs, typically in the nHz range.

Conclusion and future work

Supercooled FOPT as explanations for SGWB can help evade constraints on modifications to the standard model and connect the nHz signal to higher-scale new physics, such as those involved in the electroweak phase transition or beyond.

However, as the researchers have shown, challenges suggest that supercooled FOPT may not be the source of the observed SGWB.

The researchers have plans to explore other FOPTs that could explain the observed signal.

"If the unknown dark sector is capable of generating chiral phase transitions similar to those in quantum chromodynamics, thereby further producing nHz gravitational wave signals, it could naturally account for such low-frequency gravitational wave signals," explained Prof. Chih-

Ting.

Prof. Yongcheng added, "The supercooled phase transition can trigger the formation of primordial black holes, which can be part of the dark matter component of our universe. The violent process of supercooled FOPT and much higher energy released during the procedure can also provide an environment for particle production, which is much more important if we are considering dark matter production."

Prof. Lei also mentioned exploring broader cosmological implications like supermassive black hole binaries.

The researchers also plan on releasing the software and calculations they have developed in this work.

"We are planning to release public software with a full calculation from the particle physics model to the gravitational wave spectra that is fully state of the art and as precise as can be achieved today so that other teams can easily apply the same level of rigor as we have," concluded Prof. Athron.

More information: Peter Athron et al, Can Supercooled Phase Transitions Explain the Gravitational Wave Background Observed by Pulsar Timing Arrays? *Physical Review Letters* (2024). DOI: 10.1103/PhysRevLett.132.221001

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