Could quantum fluctuations in the early universe enhance the creation of massive galaxy clusters?

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Pandora's Cluster (NIRCam Image). Credit: SCIENCE: NASA, ESA, CSA, Ivo Labbe (Swinburne), Rachel Bezanson (University of Pittsburgh). Image processing: Alyssa Pagan (STScI)

Astrophysicists have been trying to understand the formation of cosmological objects and phenomena in the universe for decades. Past theoretical studies suggest that quantum fluctuations in the early universe, known as primordial quantum diffusion, could have given rise to so-called primordial black holes.

In a paper published in *Physical Review Letters*, researchers at Niels Bohr Institute, Universidad Autónoma de Madrid and CNRS Université de Paris recently explored the possibility that these fluctuations could also affect the creation of even larger cosmological structures, such as heavy galaxy clusters like "El Gordo." El Gordo is the largest distant galaxy cluster ever observed using existing telescopes, which was first captured more than 10 years ago.

"The question of how structure formed in the universe might be one of the most ancient ones, but since the early 1980s it has gained a new dimension," Jose María Ezquiaga, one of the researchers who carried out the study, told Phys.org. "At the time, scientists realized the incredible connection between the smallest and the largest scales, in which quantum fluctuations in the very early universe are stretched by a cosmic inflation to seed the formation of galaxies and large-scale structures in the universe."

After physicists first started learning more about the connections between the early and late universe, the idea that black holes could be formed in the early universe started emerging. In 2015, the first observations of black hole mergers via gravitational waves renewed interest in this area, sparking new theoretical studies focusing on the primordial origin of black holes.

"Juan, Vincent and I had been investigating the formation of primordial black holes in the early universe," Ezquiaga said. "Our key contribution was realizing that when quantum fluctuations are dominating the dynamics of cosmic inflation, this leads to a spectrum of density fluctuations that is non-Gaussian, with heavy exponential tails. In other words, quantum diffusion makes it easier to generate large fluctuations that would collapse into a primordial black hole."

After studying primordial black holes in the early universe, Ezquiaga and his colleagues Vincent Vennin and Juan Garcia-Bellido started wondering whether the same mechanism underpinning their formation, namely an enhanced non-Gaussian tail in the distribution of primordial perturbations, could also lead to the formation of other very large cosmological structures. In their recent work, they specifically explored the possibility that this mechanism affects the collapse of larger objects such as dark matter halos, which will later host galaxies and groups of galaxies.

"The formation of larger objects early on in the history of the universe could help alleviate some tensions between observations and our standard cosmological model," Ezquiaga explained. "For example, under standard assumptions, massive clusters like El Gordo may look like outlier, while quantum diffusion make them natural."

As part of their recent study, Ezquiaga and his colleagues computed the halo mass function and cluster abundance as a function of redshift in the presence of heavy exponential tails. This allowed them to determine whether quantum diffusion could increase the number of large galaxy clusters, depleting dark matter halos.

"Because gravity is always attractive, inhomogeneities will only grow as overdensities will attract mass for their surroundings and under densities will become emptier," Ezquiaga said. "The question is whether inhomogeneities in the early universe are large and frequent enough to lead to the gravitational collapse necessary to explain the observed structures in the cosmos. Given an initial distribution of perturbations one only needs to press 'play' and let the system evolve gravitationally, In our case, we had a previous understanding of the distribution of initial perturbations when including quantum diffusion, so our job in this work was to parametrize in a suitable way this spectrum and analyze the results for the number of massive clusters as a function of redshift."

The researchers' paper suggests that quantum fluctuations in the early universe might not only underly the formation of average-sized galaxies and primordial black holes, but also that of massive galaxy clusters, like the fascinating "El Gordo" and Pandora clusters. This would mean that current observations of galaxy clusters could be explained using existing theories, without the need to incorporate new physics in the standard model.

"The other very exciting outcome of our work is that it predicts unique signatures that could be tested in the near future," Ezquiaga said. "In particular, we demonstrate that quantum diffusion not only makes heavy clusters easier to form early on, but also that the amount of substructure should be lower than expected."

The simultaneous enhancement of massive cosmological structures and the depletion of substructures (i.e., halos) is not predicted by other theoretical models. Nonetheless, this potential theoretical explanation for the formation of large galaxy clusters appears to be aligned with recent cosmological observations and could also potentially solve other shortcomings of the standard model.

In their next studies, Ezquiaga and his colleagues would like to paint a more complete picture of the structures in the universe and their formation. This could ultimately also help to fully probe the predictions of quantum diffusion.

"Next for us is fully testing the predictions of this model against observations," Ezquiaga added. "Luckily, there are many new observations that we can use. In particular, the very recent observations of James Webb Space Telescope seem to indicate that there are many more massive galaxies at high redshift, somethings naturally aligning with our predictions, but we are waiting for astronomers to fully understand their systematics and confirm this 'unexpected' population. The other observations that might be interesting for us are number counts of dwarf galaxies with galaxy surveys like the Dark Energy Survey and constraints on subhalos from strong lensing."

More information: Jose María Ezquiaga et al, Massive Galaxy Clusters Like El Gordo Hint at Primordial Quantum Diffusion, *Physical Review Letters* (2023). DOI: 10.1103/PhysRevLett.130.121003

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