March 31, 2021

Earth & Space

A missing ingredient in dark matter theories?

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doi.org/10.25250/thescbr.brk504

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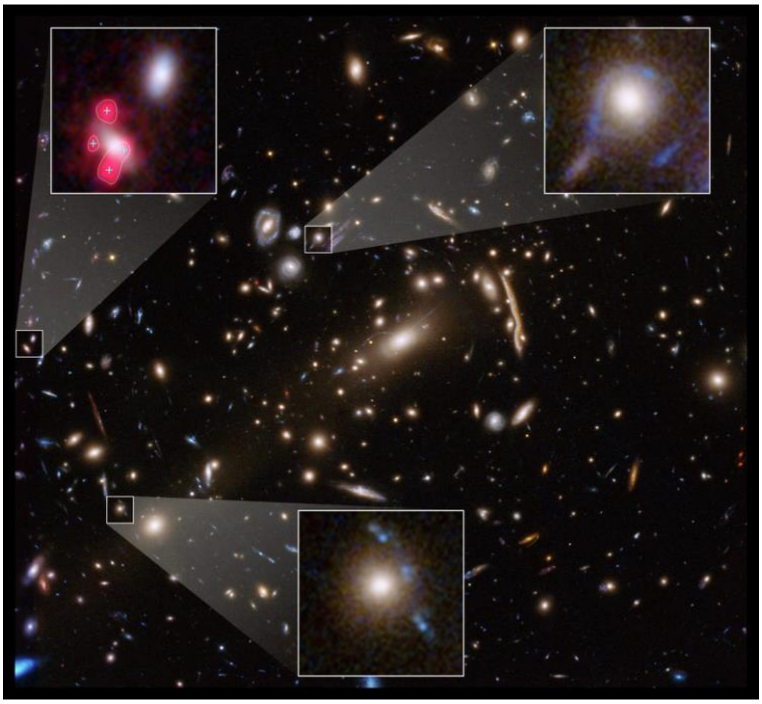
This Break was edited by Max Caine, Editor-in-chief - TheScienceBreaker

Recent observations of 11 galaxy clusters reveal that cluster galaxies produce ten times more gravitational lensing effects than expected from cosmological simulations. This suggests that they have dark matter halos more compact and massive than predicted in the standard cosmological model.



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In 1933, Fritz Zwicky, observing the Coma galaxy cluster, noted that single galaxies were moving too fast for the cluster to remain bound, according to the measure of visible mass. Only a far more significant amount of invisible matter could explain the strong gravitational force keeping the galaxies together. Later, scientists called this matter "dark" because it does not emit or absorb light. Only its gravitational interaction with ordinary matter can reveal its presence.

Several observations allowed us to estimate that dark matter accounts for approximately 85% of the universe's matter. In the standard cosmological model, this matter is called Cold Dark Matter (CDM). It is assumed to be made of massive, weakly interacting particles whose physical nature remains unknown. In the context of CDM, gravitationally bound dark matter halos form hierarchically, with the most massive systems forming through mergers of smaller ones. As structure assembles in this fashion, large dark-matter halos contain smaller-scale substructure in the form of embedded subhalos. Galaxy clusters are not different: they have large dark matter halos. They contain thousands of galaxies hosted in subhalos. The formation and evolution of galaxies and clusters and the interplay between dark and luminous matter are studied theoretically using cosmological simulations. Comparing them with observations allows us to test the standard cosmological model.

Galaxy clusters are the most significant bound structures in the universe. Their total mass can exceed a quadrillion of solar masses. As explained by Einstein's Theory of General Relativity, their colossal mass deflects the light of distant galaxies, distorting their shapes and occasionally splitting them into multiple images. Observations of this phenomenon, known as strong gravitational lensing, allow us to map the spatial distribution of dark and ordinary matter in the cluster cores, where the mass density is very high.

The principle is simple: we reverse engineer the observed image distortions to infer the lenses' mass distributions. We used this technique with tens of multiply imaged galaxies lensed by 11 massive galaxy clusters recently observed with the Hubble Space Telescope in the framework of two programs, called “Cluster Lensing and Supernova Survey with Hubble” (CLASH) and “Hubble Frontier Fields” (HFF).

To improve our ability to constrain the mass distribution on the smallest scales, we used the Multi-Unit Spectroscopic Explorer mounted at the Very Large Telescope in Chile. We measured the stars' velocity dispersion in several galaxies in three clusters, MACSJ1206+0847, MACSJ0416.1-2403, and AbellS1063. Stars move under the effects of gravity, thus their velocities are a proxy of the subhalo masses.

We obtained high-resolution mass maps of each galaxy cluster by combining gravitational lensing with the galaxy kinematics measurements from MUSE. These maps revealed that cluster galaxies are hosted by very compact and massive dark matter subhalos.

The multiple images of distant sources lensed by foreground galaxy clusters have angular separations of several tens of arcseconds. Subhalos within each cluster act as smaller-scale gravitational lenses embedded within the larger lens. Suppose these subhalos are massive enough and compact enough. In that case, they can also produce additional local strong lensing events on much smaller scales with separations of less than a few arcseconds. As expected from our lensing mass reconstructions, we found several of these events, called “Galaxy-Galaxy Strong Lensing” (GGSL) events, in each of the clusters we observed.

We next compared the observed cluster mass distributions with those of 25 simulated galaxy clusters evolved in the standard cosmological model. We found that cosmological simulations do not show the same dark-matter concentration level on the smallest scales – the scales associated with individual cluster galaxies as seen in the universe. As a result, they produce more than ten times fewer GGSL events than we observe.

Thus, the observed number of GGSL events are inconsistent with theoretical predictions within the standard cosmological model. These results suggest that there are some features of the real universe that we still fail to understand. There might be systematic issues with the prevailing simulation methods, or we might be making incorrect assumptions about dark matter properties.

Future observations with instruments such as the ESA’s and NASA’s planned Euclid and Nancy Grace Roman Space Telescopes will help clarify these issues by enlarging the sample of clusters that we can analyze to further stress-test dark matter models.