Small-scale challenges to the cold dark matter model

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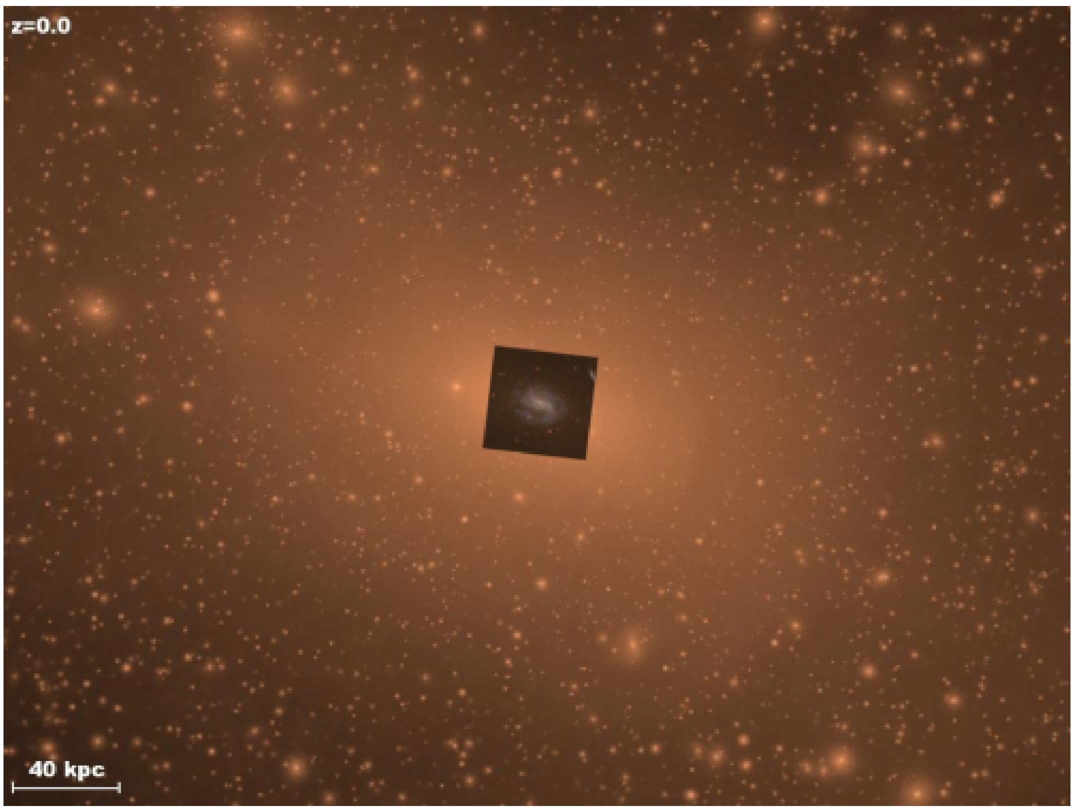

The cusp-core problem. An optical image of the galaxy F568-3 (small inset, from the Sloan Digital Sky Survey) is superposed on the the dark matter distribution from the "Via Lactea" cosmological simulation of a Milky Way-mass cold dark matter halo (Diemand et al. 2007). In the simulation image, intensity encodes the square of the dark matter density, which is proportional to annihilation rate and highlights low mass substructure. Credit: arXiv:1306.0913.

(Phys.org)—A collaborative of researchers from several U.S. universities has published a new paper that explains the major contradictions presented by the prevailing cold dark matter (CDM) cosmological model, and proposes approaches for reconciling cosmological observations with the CDM model's predictions. The paper, titled "Cold dark matter: Controversies on small scales," was published in the *Proceedings of the National Academy of Sciences* in December.

In the last decade, investigations of the CDM cosmological model have explained cosmic structure over large spans of redshift. The prevailing theory holds that 80 percent of the matter comprising the universe consists of CDM, with a smaller percentage of baryonic matter composing the visible and more easily observed structures such as stars and planets.

The CDM model successfully demonstrates how the smooth early state of the universe evolved into the lumpy distribution of matter observed in galaxies and galactic clusters today. By contrast with the older "hot dark matter" model, CDM theory holds that universal structure grows hierarchically, with small-scale gravitational structures forming successively larger structures over time.

Despite its success as a model of universal evolution over long periods, the predictions made by the CDM cosmological model diverge from observational data in several problematic ways.

The "cusp-core" problem

Cosmologists believe that galaxies are suspended within vast, essentially spherical halos of dark matter. Cosmological simulations suggest that that CDM halos should have a "cuspy" distribution, with density spikes of dark matter at the centers of galaxies. However, the observed rotational speeds of galaxies fail to indicate the predicted density of dark matter in galactic cores.

The authors note that the the biggest discrepancies between the CDM model's predictions and the observational data arise for fairly small galaxies, and that a majority of galaxy rotation curves have so-called "cored" dark matter profiles, rather than the "cuspy" profiles of the predictions.

They describe possible solutions to this contradiction derived from the physics of baryonic matter. Simulations incorporating episodic models of star formation and supernovae feedback into the overall CDM model yield results more closely aligned with the flat CDM distributions actually observed in galaxies. The authors note that in a hydrodynamic simulation with star formation and feedback, "over time, the central dark matter density drops and the cuspy profile is transformed to one with a nearly constant density core."

The "missing satellite" problem

Large galaxies are orbited by systems of smaller satellite galaxies, each with its own dark matter halo. The authors explain, "Because CDM preserves primordial fluctuation down to very small scales, halos today are filled with enormous numbers of subhalos that collapse in the early times and preserve their identities after falling into larger systems."

The problem is that CDM simulations predict a higher number of these satellites around galaxies like the Milky Way than observations reveal. Prior to 2000, only nine dwarf galaxies were known at the 250 kiloparsec virial radius of the Milky Way halo; researchers had predicted on the order of five to 20 more dwarf galaxies above a certain velocity threshold at that radius. Where are these missing satellite galaxies?

The authors believe that the "missing satellite" problem can be easily resolved by incorporating baryonic physics. The velocity threshold at which at which the subhalo observations diverge from the predictions is close to the value at which heating of intergalactic gases by the UV photoionizing background should suppress gas accretion onto halos. This dynamic could explain why proposed subhalos remain dark.

The observation of these subhalos is difficult for many reasons, including the relative dimness of many dwarf galaxies, and consequently, there remain gaps in the understanding of dwarf galaxy populations.

The "too big to fail" problem

Galactic simulations predict subhalos with central masses which cosmologists expect to host classical dwarf galaxies like the Milky Way's. However, the mass at the centers of these simulated subhalos actually exceeds the observed masses in the most luminous galactic satellites. The authors concede that it is possible in principle that the observed dwarf galaxies reside within less massive host subhalos, but it is physically very unlikely to be the case. Thus, researchers have described this conflict as the "too big to fail" problem.

Here, the authors write, "The degree of discrepancy varies with the particular realization of halo substructure and with the mass of the main halo, but even for a halo mass at the low end of estimates for the Milky Way, the discrepancy appears too large to be a statistical fluke, and a similar conflict is found in the satellite system of the Andromeda galaxy."

Additionally, they note that satellites in low-mass subhalos may also be explained by baryonic effects for which simulations have not yet accounted, but the "too big to fail" problem arises within more massive systems with gravitational potential that is dominated by dark matter. As in the "cusp-core" problem, the simulations predict too much mass in the central regions of subhalos.

Exploring dark-matter solutions

If future researchers want to upend the current CDM model in favor of an alternative, the authors suggest that a potential solution may lie in assuming a "warm dark matter" model in which free-streaming velocities in the early universe are substantial enough "to erase primordial fluctuations on subgalactic scales." The good news: Collisionless collapse of warm dark matter (WDM) still leads to a cuspy halo profile in simulations, but the central concentration is actually lower than that of CDM models, more closely aligning with the observations of galaxy rotation curves. As a result, the mass function of halos and subhalos drops at low masses in the absence of small-scale perturbations that produce collapsed objects, and the subhalo mass function corresponds with observational dwarf satellite counts.

The bad news: WDM eliminates power on small scales, resulting in too few subhalos in the Milky Way to support the number of dwarf galaxies observed. The authors conclude that despite some remaining uncertainties in the numerical simulations and observational data, it appears that WDM cannot solve the cusp-core and missing satellite problems with regard to cosmological observations.

Future developments

Hope for the refinement of CDM to align it with observations may come from one or more future research directions:

• Improved simulations of models interacting with dark matter may solve the small-scale problems, or find that parameters chosen to match one set of observations fail when applied to another set.

• Researchers could make a direct test of the CDM prediction that vast numbers of low-mass subhalos are orbiting within the virial radius of large galaxies.

• Improved measurements of stellar velocities in satellite galaxies may better delineate the satellite problem.

• Underground detection experiments, next-generation observatories, or collider experiments could identify the dark matter particle within the next decade.

More information: David H. Weinberg, James S. Bullock, Fabio Governato, Rachel Kuzio de Naray, Annika H. G. Peter. "Cold dark matter: controversies on small scales." *PNAS* (2015) www.pnas.org/content/early/201 … /1308716112.abstract . On *Arxiv*: arXiv:1306.0913. arxiv.org/abs/1306.0913

Abstract
The cold dark matter (CDM) cosmological model has been remarkably successful in explaining cosmic structure over an enormous span of redshift, but it has faced persistent challenges from observations that probe the innermost regions of dark matter halos and the properties of the Milky Way's dwarf galaxy satellites. We review the current observational and theoretical status of these "small-scale controversies." Cosmological simulations that incorporate only gravity and collisionless CDM predict halos with abundant substructure and central densities that are too high to match constraints from galaxy dynamics. The solution could lie in baryonic physics: Recent numerical simulations and analytical models suggest that gravitational potential fluctuations tied to efficient supernova feedback can flatten the central cusps of halos in massive galaxies, and a combination of feedback and low star formation

efficiency could explain why most of the dark matter subhalos orbiting the Milky Way do not host visible galaxies. However, it is not clear that this solution can work in the lowest mass galaxies, where discrepancies are observed. Alternatively, the small-scale conflicts could be evidence of more complex physics in the dark sector itself. For example, elastic scattering from strong dark matter self-interactions can alter predicted halo mass profiles, leading to good agreement with observations across a wide range of galaxy mass. Gravitational lensing and dynamical perturbations of tidal streams in the stellar halo provide evidence for an abundant population of low-mass subhalos in accord with CDM predictions. These observational approaches will get more powerful over the next few years.