Alternative theory of gravity explains large structure formation -- without dark matter

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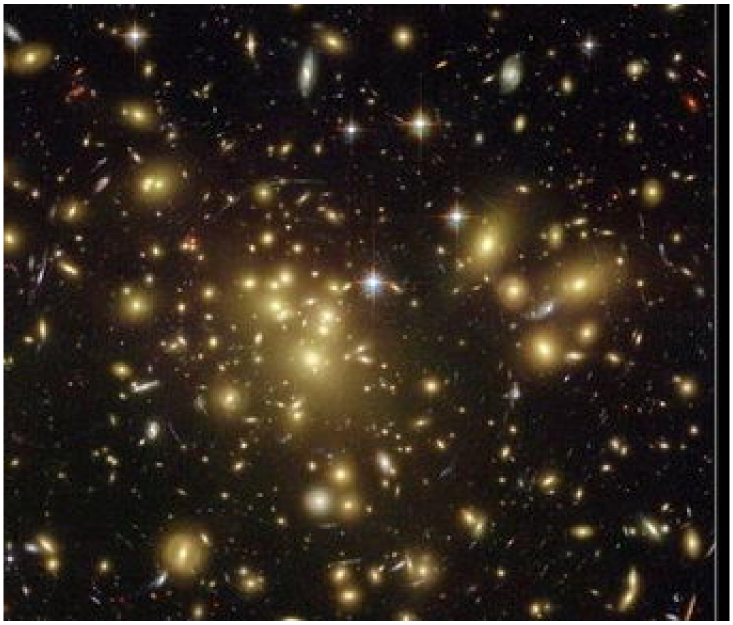

The light from galaxies in the background has been warped and “arced” by the galaxy cluster Abell 1689 in the foreground, and perhaps with some help by either dark matter or a stronger type of gravity on this large scale. Image Source: NASA, N. Benitez (JHU), T. Broadhurst (Racah Institute of Physics/The Hebrew University), H. Ford (JHU), M. Clampin (STScI),G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA.

In the standard theory of gravity—general relativity—dark matter plays a vital role, explaining many observations that the standard theory cannot explain by itself. But for 70 years, cosmologists have never observed dark matter, and the lack of direct observation has created skepticism about what is really out there.

Lately, some scientists have turned the question around, from “is dark matter correct?” to “is our standard theory of gravity correct?” Most recently, Fermilab scientists Scott Dodelson and former Brinson Fellow Michele Liguori demonstrated one of the first pieces of theoretical evidence that an alternative theory of gravity can explain the large scale structure of the universe.

“To definitively claim that dark matter is the answer, we need to find it,” Dodelson explained to *PhysOrg.com*. “We can do this in one of three ways: produce it in the lab (which might happen at Fermilab, the soon-to-start LHC, or ultimately the International Linear Collider), see a pair of dark matter particles annihilate and produce high energy photons (there are about a half dozen experiments designed to look for this), or see a dark matter particle bump a nucleus in a large underground detector (again, about 10 experiments are looking for this). Until one or more of these things happen, skeptics are still allowed. … After they happen, skeptics will become crackpots.”

Although cosmologists have never directly observed dark matter, they have many good reasons for not giving up hope. The ways that galaxies rotate and starlight bends (gravitational lensing) stray from predictions based on visible matter. Further, the formation of large cosmic structures (such as galaxies and galaxy clusters) would have required significantly large matter perturbations when the Universe was less than a million years old that simply don’t exist in a theory of general relativity before “tacking on” dark matter.

“It is extremely important to see how well a no-dark-matter cosmology does,” said Dodelson. “[In the standard theory,] we are asking the community to believe in the existence of a particle that has never been seen. We have to be damned sure that you can't explain the universe without this huge leap. Our Figure 1 [see citation below] illustrates that, in standard gravity, a no-dark-matter model does not do well at all.”

While altering the theory of gravity may seem like pulling the rug out from under a century of observations and pain-staking calculations, an alternative theory may simply be “more correct” than today’s standard theory. Just as Einstein’s theory was “more correct” than Newton’s because it improved upon the older one by noticing more specific details (e.g. extraordinary masses and speeds), a new alternative theory may only drastically change gravity at certain scales.

“Perhaps a fundamental theory of gravity which differs from general relativity on large scales can explain the observations without recourse to new, unobserved particles,” wrote Dodelson and Liguori in their study published in *Physical Review Letters*. “Now more than ever before, there are very good reasons to explore this idea of modifying gravity. For, the case of dark energy also hinges on the assumption that general relativity describes gravity on larges scales. Dark energy is even more difficult to explain than dark matter, so it seems almost natural to look at gravity as the culprit in both cases.”

The new theory (or groundwork for it) under investigation would be Jacob Bekenstein’s relativistic covariant theory of gravity (TeVeS), published in 2004. Bekenstein based his theory on a modified version of Newtonian theory from the early ‘80s, dependent on gravitational acceleration and called modified Newtonian dynamics (MOND) by its founder, Mordecai Milgrom.

“MOND, the original theory on which TeVeS is based, was already quite successful at explaining galactic dynamics (even better, in some cases, than the dark matter paradigm), but it failed completely at explaining other observations—gravitational lensing in particular,” explained Liguori. “For this reason, it couldn't be considered a real alternative to dark matter. Bekenstein’s theory, by generalizing MOND, retains its good features while overcoming its main problems at the same time. This makes TeVeS a much more interesting theory than MOND. It is then worthwhile (and necessary) to test TeVeS’ predictions in detail and compare them to the standard dark matter paradigm to see if TeVeS can be a viable alternative.”

Dodelson and Liguori find Bekenstein’s theory intriguing in this context because, for one, the gravitational acceleration scale in the theory is very close to that required for the observed acceleration of the Universe. The scale is also very similar to that proposed in “post hoc” theories such as dark energy. Even more interesting is the fact that the origins of Bekenstein’s theory had nothing to do with cosmic acceleration.

But the feature of Bekenstein’s theory that Dodelson and Liguori focus on most is that the theory—unlike standard general relativity—allows for fast growth of density perturbations arising from small inhomogeneities during recombination. Building on this finding from scientists Skordis et al. earlier this year, Dodelson and Liguori have found which aspect of the theory actually causes the enhanced growth—the part that may solve the cosmological structure problem.

The pair has discovered that, while Bekenstein’s theory has three functions which characterize space-time—a tensor, vector and scalar (TeVeS)—it’s the perturbations in the vector field that are key to the enhanced growth. General relativity describes space-time with only a tensor (the metric), so it does not include these vector perturbations.

“The vector field solves only the enhanced growth problem,” said Dodelson. “It does so by exploiting a little-known fact about gravity. In our solar system or galaxy, when we attack the problem of gravity, we solve the equation for the Newtonian potential. Actually, there are two potentials that characterize gravity: the one usually called the Newtonian potential and the perturbation to the curvature of space. These two potentials are almost always very nearly equal to one another, so it is not usually necessary to distinguish them.

“In the case of TeVeS, the vector field sources the difference between the two,” he continued. “As it begins to grow, the difference between the two potentials grows as well. This is ultimately what drives the overdense regions to accrete more matter than in standard general relativity. The quite remarkable thing about this growth is that Bekenstein introduced the vector field for his own completely independent reasons. As he remarked to me, ‘Sometimes theories are smarter than their creators.’"

Dodelson and Liguori see this solution to large structure formation as an important step for a gravity theory based on baryon-only matter. Other problems that their theory (or any alternative theory) will have to confront include accounting for the mismatch in galaxy clusters between mass and light. Also, the theory must conform to at least two observations: the galaxy power spectrum on large scales, and the cosmic microwave background fluctuations, which correspond to baby galaxies and galaxy clusters.

“As Scott says, until dark matter will be observed, skeptics will be allowed,” said Liguori. “Despite the many and impressive successes of the dark matter paradigm, which make it very likely to be correct, we still don't have any final and definitive answer. In light of this, it is important to keep an eye open for possible alternative explanations. Even when, after the analysis, alternative theories turn out to be wrong, the result is still important, as it strengthen the evidence for dark matter as the only possible explanation of observations.”

Citation: Dodelson, Scott and Liguori, Michele. “Can Cosmic Structure Form without Dark Matter?” *Physical Review Letters* 97, 231301 (2006).

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