



The Case Against Dark Matter

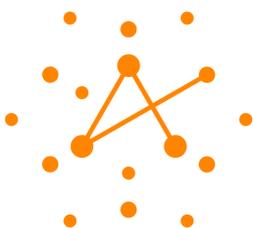
A proposed theory of gravity does away with dark matter, even as new astrophysical findings challenge the need for galaxies full of the invisible mystery particles.

By Natalie Wolchover

For 80 years, scientists have puzzled over the way galaxies and other cosmic structures appear to gravitate toward something they cannot see. This hypothetical “dark matter” seems to outweigh all visible matter by a startling ratio of five to one, suggesting that we barely know our own universe. Thousands of physicists are doggedly searching for these invisible particles.

But the dark matter hypothesis assumes scientists know how matter in the sky ought to move in the first place. This month, a series of developments has revived a long-disfavored argument that dark matter doesn’t exist after all. In this view, no missing matter is needed to explain the errant motions of the heavenly bodies; rather, on cosmic scales, gravity itself works in a different way than either Isaac Newton or Albert Einstein predicted.

The latest attempt to explain away dark matter is a much-discussed proposal by [Erik Verlinde](#), a theoretical physicist at the University of Amsterdam who is known for bold and prescient, if sometimes imperfect, ideas. In [a dense 51-page paper](#) posted online on Nov. 7, Verlinde casts gravity as a byproduct of quantum interactions and suggests that the extra gravity attributed to dark matter is an effect of “dark energy” — the background energy woven into the space-time fabric of the universe.



Abstractions

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Instead of hordes of invisible particles, “dark matter is an interplay between ordinary matter and dark energy,” Verlinde said.

To make his case, Verlinde has adopted a radical perspective on the origin of gravity that is currently in vogue among leading theoretical physicists. Einstein defined gravity as the effect of curves in space-time created by the presence of matter. According to the new approach, gravity is an

emergent phenomenon. Space-time and the matter within it are treated as a hologram that arises from an underlying network of quantum bits (called “qubits”), much as the three-dimensional environment of a computer game is encoded in classical bits on a silicon chip. Working within this framework, Verlinde traces dark energy to a property of these underlying qubits that supposedly encode the universe. On large scales in the hologram, he argues, dark energy interacts with matter in just the right way to create the illusion of dark matter.

In his calculations, Verlinde rediscovered the equations of “modified Newtonian dynamics,” or MOND. This 30-year-old theory makes an ad hoc tweak to the famous “inverse-square” law of gravity in Newton’s and Einstein’s theories in order to explain some of the phenomena attributed to dark matter. That this ugly fix works at all has long puzzled physicists. “I have a way of understanding the MOND success from a more fundamental perspective,” Verlinde said.

Many experts have called Verlinde’s paper compelling but hard to follow. While it remains to be seen whether his arguments will hold up to scrutiny, the timing is fortuitous. In a [new analysis of galaxies](#) published on Nov. 9 in *Physical Review Letters*, three astrophysicists led by Stacy McGaugh of Case Western Reserve University in Cleveland, Ohio, have strengthened MOND’s case against dark matter.

The researchers analyzed a diverse set of 153 galaxies, and for each one they compared the rotation speed of visible matter at any given distance from the galaxy’s center with the amount of visible matter contained within that galactic radius. Remarkably, these two variables were tightly linked in all the galaxies by a universal law, dubbed the “radial acceleration relation.” This makes perfect sense in the MOND paradigm, since visible matter is the exclusive source of the gravity driving the galaxy’s rotation (even if that gravity does not take the form prescribed by Newton or Einstein). With such a tight relationship between gravity felt by visible matter and gravity given by visible matter, there would seem to be no room, or need, for dark matter.

Even as dark matter proponents rise to its defense, a third challenge has materialized. In new research that has been presented at seminars and is under review by the *Monthly Notices of the Royal Astronomical Society*, a team of Dutch astronomers have conducted what they call the first test of Verlinde’s theory: In comparing his formulas to data from more than 30,000 galaxies, [Margot Brouwer](#) of Leiden University in the Netherlands and her colleagues found that Verlinde correctly predicts the gravitational distortion or “lensing” of light from the galaxies — another phenomenon that is normally attributed to dark matter. This is somewhat to be expected, as MOND’s original developer, the Israeli astrophysicist Mordehai Milgrom, showed years ago that MOND accounts for gravitational lensing data. Verlinde’s theory will need to succeed at reproducing dark matter phenomena in cases where the old MOND failed.

[Kathryn Zurek](#), a dark matter theorist at Lawrence Berkeley National Laboratory, said Verlinde’s proposal at least demonstrates how something like MOND might be right after all. “One of the challenges with modified gravity is that there was no sensible theory that gives rise to this behavior,” she said. “If [Verlinde’s] paper ends up giving that framework, then that by itself could be enough to breathe more life into looking at [MOND] more seriously.”

The New MOND

In Newton’s and Einstein’s theories, the gravitational attraction of a massive object drops in proportion to the square of the distance away from it. This means stars orbiting around a galaxy should feel less gravitational pull — and orbit more slowly — the farther they are from the galactic center. Stars’ velocities do drop as predicted by the inverse-square law in the inner galaxy, but instead of continuing to drop as they get farther away, their velocities level off beyond a certain

point. The “flattening” of galaxy rotation speeds, discovered by the astronomer Vera Rubin in the 1970s, is widely considered to be Exhibit A in the case for dark matter — explained, in that paradigm, by dark matter clouds or “halos” that surround galaxies and give an extra gravitational acceleration to their outlying stars.

Searches for dark matter particles have proliferated — with hypothetical “[weakly interacting massive particles](#)” (WIMPs) and [lighter-weight “axions”](#) serving as prime candidates — but so far, experiments have found nothing.

Meanwhile, in the 1970s and 1980s, some researchers, including Milgrom, took a different tack. Many early attempts at tweaking gravity were easy to rule out, but Milgrom found a winning formula: When the gravitational acceleration felt by a star drops below a certain level — precisely 0.0000000012 meters per second per second, or 100 billion times weaker than we feel on the surface of the Earth — he postulated that gravity somehow switches from an inverse-square law to something close to an inverse-distance law. “There’s this magic scale,” McGaugh said. “Above this scale, everything is normal and Newtonian. Below this scale is where things get strange. But the theory does not really specify how you get from one regime to the other.”

Physicists do not like magic; when other cosmological observations seemed far easier to explain with dark matter than with MOND, they left the approach for dead. Verlinde’s theory revitalizes MOND by attempting to reveal the method behind the magic.

Verlinde, ruddy and fluffy-haired at 54 and lauded for highly technical string theory calculations, first jotted down a back-of-the-envelope version of his idea in 2010. It built on [a famous paper](#) he had written months earlier, in which he boldly declared that gravity does not really exist. By weaving together numerous concepts and conjectures at the vanguard of physics, he had concluded that gravity is an emergent thermodynamic effect, related to increasing entropy (or disorder). Then, as now, experts were uncertain what to make of the paper, though it inspired fruitful discussions.

The particular brand of emergent gravity in Verlinde’s paper turned out not to be quite right, but he was tapping into the same intuition that led other theorists to develop the modern holographic description of emergent gravity and space-time — an approach that Verlinde has now absorbed into his new work.

In this framework, bendy, curvy space-time and everything in it is a geometric representation of pure quantum information — that is, data stored in qubits. Unlike classical bits, qubits can exist simultaneously in two states (0 and 1) with varying degrees of probability, and they become “entangled” with each other, such that the state of one qubit determines the state of the other, and vice versa, no matter how far apart they are. Physicists have begun to work out the rules by which the entanglement structure of qubits mathematically translates into an associated space-time geometry. An array of qubits entangled with their nearest neighbors might encode flat space, for instance, while more complicated patterns of entanglement give rise to matter particles such as quarks and electrons, whose mass causes the space-time to be curved, producing gravity. “The best way we understand quantum gravity currently is this holographic approach,” said [Mark Van Raamsdonk](#), a physicist at the University of British Columbia in Vancouver who has done influential work on the subject.

The mathematical translations are rapidly being worked out for holographic universes with an Escher-esque space-time geometry known as anti-de Sitter (AdS) space, but universes like ours, which have de Sitter geometries, have proved far more difficult. In his new paper, Verlinde speculates that it’s exactly the de Sitter property of our native space-time that leads to the dark matter illusion.

De Sitter space-times like ours stretch as you look far into the distance. For this to happen, space-time must be infused with a tiny amount of background energy — often called dark energy — which drives space-time apart from itself. Verlinde models dark energy as a thermal energy, as if our universe has been heated to an excited state. (AdS space, by contrast, is like a system in its ground state.) Verlinde associates this thermal energy with long-range entanglement between the underlying qubits, as if they have been shaken up, driving entangled pairs far apart. He argues that this long-range entanglement is disrupted by the presence of matter, which essentially removes dark energy from the region of space-time that it occupied. The dark energy then tries to move back into this space, exerting a kind of elastic response on the matter that is equivalent to a gravitational attraction.

Because of the long-range nature of the entanglement, the elastic response becomes increasingly important in larger volumes of space-time. Verlinde calculates that it will cause galaxy rotation curves to start deviating from Newton's inverse-square law at exactly the magic acceleration scale pinpointed by Milgrom in his original MOND theory.

Van Raamsdonk calls Verlinde's idea "definitely an important direction." But he says it's too soon to tell whether everything in the paper — which draws from quantum information theory, thermodynamics, condensed matter physics, holography and astrophysics — hangs together. Either way, Van Raamsdonk said, "I do find the premise interesting, and feel like the effort to understand whether something like that could be right could be enlightening."

One problem, said Brian Swingle of Harvard and Brandeis universities, who also works in holography, is that Verlinde lacks a concrete model universe like the ones researchers can construct in AdS space, giving him more wiggle room for making unproven speculations. "To be fair, we've gotten further by working in a more limited context, one which is less relevant for our own gravitational universe," Swingle said, referring to work in AdS space. "We do need to address universes more like our own, so I hold out some hope that his new paper will provide some additional clues or ideas going forward."

The Case for Dark Matter

Verlinde could be capturing the zeitgeist the way his 2010 entropic-gravity paper did. Or he could be flat-out wrong. The question is whether his new and improved MOND can reproduce phenomena that foiled the old MOND and bolstered belief in dark matter.

One such phenomenon is the Bullet cluster, a galaxy cluster in the process of colliding with another. The visible matter in the two clusters crashes together, but gravitational lensing suggests that a large amount of dark matter, which does not interact with visible matter, has passed right through the crash site. Some physicists consider this indisputable proof of dark matter. However, Verlinde thinks his theory will be able to handle the Bullet cluster observations just fine. He says dark energy's gravitational effect is embedded in space-time and is less deformable than matter itself, which would have allowed the two to separate during the cluster collision.

But the crowning achievement for Verlinde's theory would be to account for the suspected imprints of dark matter in the cosmic microwave background (CMB), ancient light that offers a snapshot of the infant universe. The snapshot reveals the way matter at the time repeatedly contracted due to its gravitational attraction and then expanded due to self-collisions, producing a series of peaks and troughs in the CMB data. Because dark matter does not interact, it would only have contracted without ever expanding, and this would modulate the amplitudes of the CMB peaks in exactly the way that scientists observe. One of the biggest strikes against the old MOND was its failure to predict this modulation and match the peaks' amplitudes. Verlinde expects that his version will work

— once again, because matter and the gravitational effect of dark energy can separate from each other and exhibit different behaviors. “Having said this,” he said, “I have not calculated this all through.”

While Verlinde confronts these and a handful of other challenges, proponents of the dark matter hypothesis have some explaining of their own to do when it comes to McGaugh and his colleagues’ recent findings about the universal relationship between galaxy rotation speeds and their visible matter content.

In October, responding to a preprint of the paper by McGaugh and his colleagues, two teams of astrophysicists [independently argued](#) that the dark matter hypothesis can account for the observations. They say the amount of dark matter in a galaxy’s halo would have precisely determined the amount of visible matter the galaxy ended up with when it formed. In that case, galaxies’ rotation speeds, even though they’re set by dark matter and visible matter combined, will exactly correlate with either their dark matter content or their visible matter content (since the two are not independent). However, computer simulations of galaxy formation do not currently indicate that galaxies’ dark and visible matter contents will always track each other. Experts are busy tweaking the simulations, but [Arthur Kosowsky](#) of the University of Pittsburgh, one of the researchers working on them, says it’s too early to tell if the simulations will be able to match all 153 examples of the universal law in McGaugh and his colleagues’ galaxy data set. If not, then the standard dark matter paradigm is in big trouble. “Obviously this is something that the community needs to look at more carefully,” Zurek said.

Even if the simulations can be made to match the data, McGaugh, for one, considers it an implausible coincidence that dark matter and visible matter would conspire to exactly mimic the predictions of MOND at every location in every galaxy. “If somebody were to come to you and say, ‘The solar system doesn’t work on an inverse-square law, really it’s an inverse-cube law, but there’s dark matter that’s arranged just so that it always looks inverse-square,’ you would say that person is insane,” he said. “But that’s basically what we’re asking to be the case with dark matter here.”

Given the considerable indirect evidence and near consensus among physicists that dark matter exists, it still probably does, Zurek said. “That said, you should always check that you’re not on a bandwagon,” she added. “Even though this paradigm explains everything, you should always check that there isn’t something else going on.”

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