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An Unfolding Scientific Revolution in Cosmology

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> *There is a tendency, among both scientists and non-scientists, to assume that our current scientific theories are correct in some fundamental sense … but the history of science suggests otherwise. Almost all of the theories that were at one time viewed as correct have been abandoned.*
>
> — David Merritt, 2020

Whenever I get tired of the insanity of human politics (which is all the time these days), I read about astrophysics and cosmology. What I like about this field is that it's perhaps the most high minded of scientific pursuits; it's driven not by the search for wealth or technological gain, but by the innate desire to understand the cosmos. Of course, human sociology does enter the equation (as always), which is why astrophysics provides a fascinating window into both the universe at large, as well as the philosophy of scientific progress.

My reading of modern astrophysics and cosmology is that the field is in the midst of a (slow-burning) scientific revolution. Let me tell you about it.

The birth of science

Astronomy is arguably the field that sparked the scientific revolution. When Nicolaus Copernicus and Galileo Galilei placed the sun at the center of the solar system, it allowed Johannes Kepler to formulate (between 1608 and 1621) a set of empirical laws that described planetary motion.

Five decades later, Isaac Newton demonstrated that Kepler's equations were a consequence of a law of universal gravitation, in which the force of gravity falls with the inverse square of distance. Newton's theory was a stunning revelation that unified the study of motion. According to Newton, when a ball is tossed on Earth, its motion is determined by the same equations that describe the orbit of the planets. Looking at the known solar system, astronomers found that Newton's equations worked with exquisite precision. And so the foundations of science were put in place.

In hindsight, the stage was also set for a long-standing debate regarding the *philosophy* of science. When theories make predictions that are incorrect, what should be done? The problem, philosophers realized, is that predictions can fail for two reasons, which can be difficult to differentiate. First, the *theory* could itself be wrong. But second, the problem could lie with the *evidence*, which may be incomplete or flawed.

Of course, long before philosophers formalized this problem, scientists grappled with how to understand failed predictions. My impression is that scientists developed two rules of thumb. If a *new* theory makes bad predictions, it is (usually) discarded. But if an *established* theory makes bad predictions, the general response is to blame the data. Looking at the study of gravity, this blame-the-data attitude has had mixed success.

For example, by the mid 1800s, it had become clear that the planet Uranus (which was discovered in 1781) deviated from its predicted Newtonian orbit. (See Figure 1.) But rather than blame Newton's theory, scientists began searching for missing mass that would explain the error. Using Newton's equations, Urbain Le Verrier and John Couch Adams separately predicted (in 1845) the location of an unobserved planet. When astronomers aimed their telescopes at this point in the sky, they discovered the planet Neptune. It was a triumph of predictive science.

Fresh off this success, Le Verrier soon discovered that the planet Mercury had aberrations from a Newtonian orbit. And so again, astronomers searched for missing mass, this time in the form of the hypothetical planet 'Vulcan'. But after decades of looking, the missing planet was never found.

In hindsight, we know that the problem with Mercury's orbit was not the data, but the theory itself. In 1915, Albert Einstein revolutionized science with a new theory of gravity: general relativity. Crucially, Einstein's first test of the theory was to predict the precession of Mercury's orbit. (When Einstein initially calculated the correct solution, he was apparently so excited that for three days he could not work.)

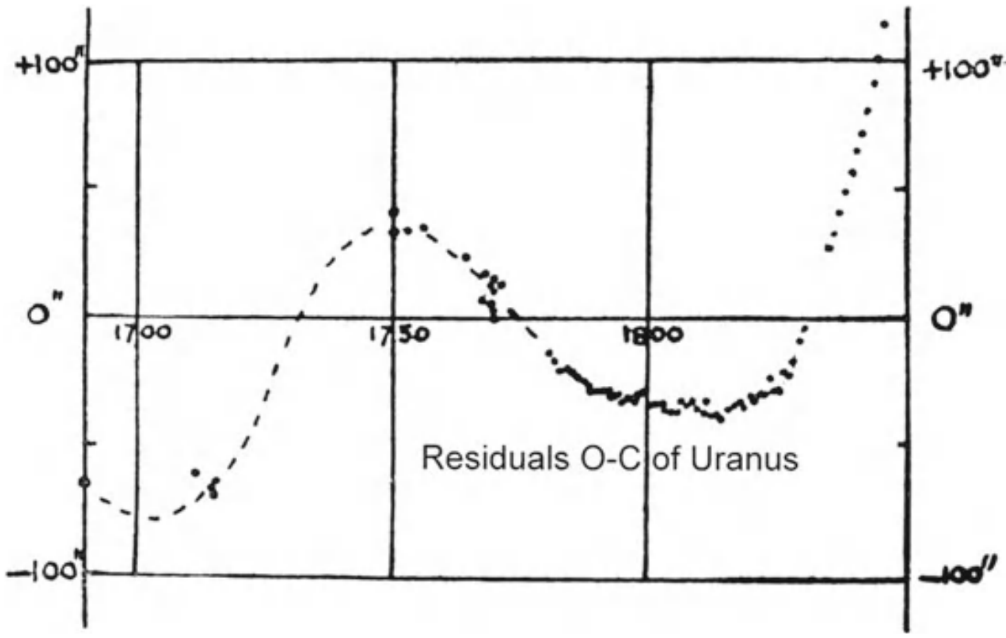

Figure 1: The orbital deviation of Uranus, calculated by Le Verrier

In 1849, Urbain Le Verrier published calculations documenting Uranus's deviation in the sky, relative to where Newton's equations predicted it ought to be (given the known planets). This plot of Le Verrier's calculations was made by André Danjon in 1946, and charts the orbital deviation as a function of time. Source: Le Verrier — Magnificent and Detestable Astronomer.

Of course, that was just the start of a series of extraordinary predictions, which have since been confirmed. For example, Einstein's theory predicts that sufficiently massive bodies should collapse to form black holes — bizarre objects out of which not even light can escape.

In 2019, a collaboration of radio astronomers was able to image the supermassive black hole at the center of a nearby giant elliptical galaxy, as shown in Figure 2. (More on giant elliptical galaxies later.) In this image, the black hole is the dark central circle. Around this black object, which is thought to weigh about 3 billion times more than the sun, sits an accretion disk of hot gas, which is orbiting (and gradually falling into) the black hole at close to the speed of light.

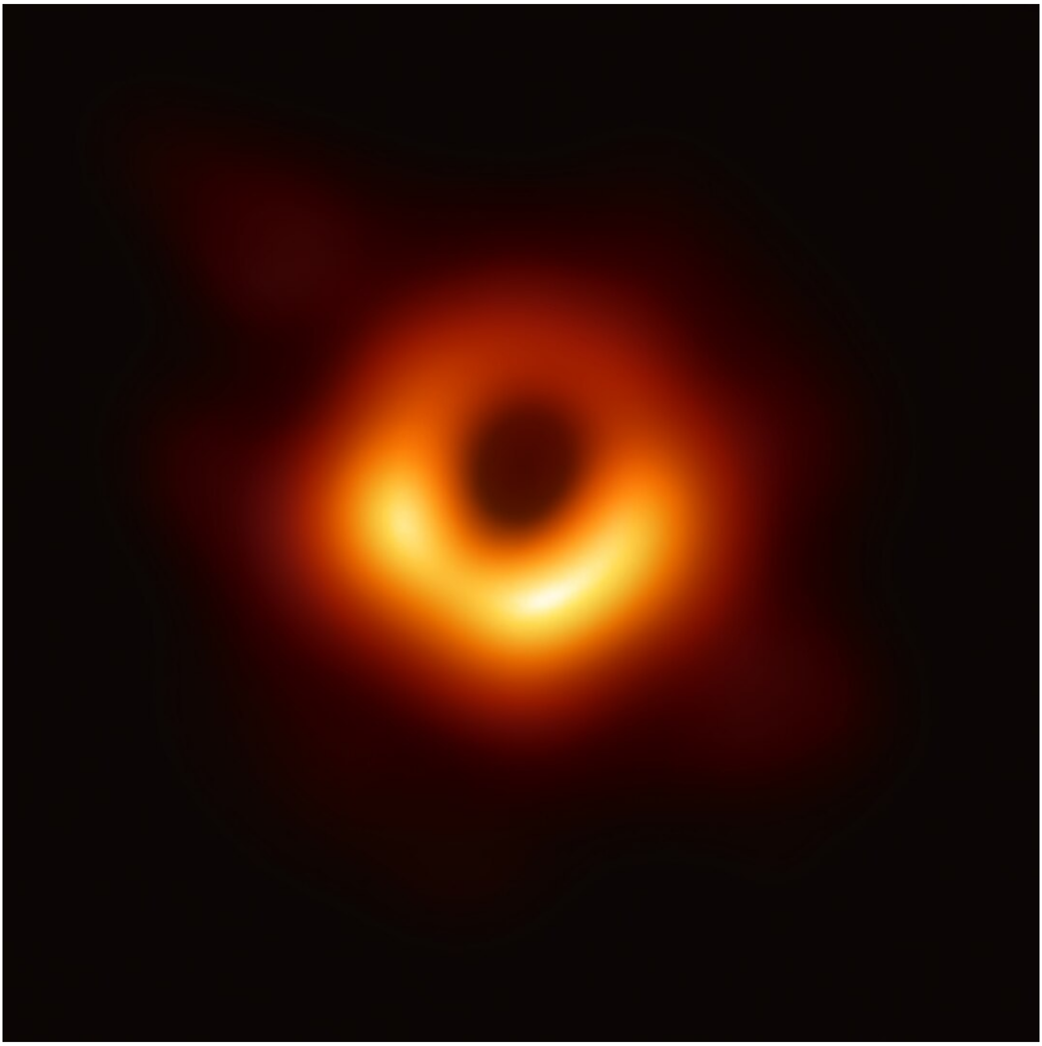

Figure 2: The first image of a black hole

In 2019, the Event Horizon Telescope captured this image of a supermassive black hole. The black hole is itself invisible; what we see here is the accretion disk surrounding the black hole. This particular supermassive black hole lives at the center of the nearby elliptical galaxy M87. Source: Wikipedia.

In the same vein, Einstein's theory predicts that when massive objects orbit at a close distance, they should radiate energy in the form of gravitational waves. Such radiation was discovered in 2015, and attributed to the orbit and merger of two black holes. Gravitational waves are now detected regularly.[1] In short, Einstein's theory of gravity has been a smashing success.

[1] In its timeless wisdom, the Trump regime recently proposed halving the funding for the National Science Foundation. This may cause one (of two) US gravitational wave observatories to close. Unfortunately, having only one detector is essentially useless, because the second detector is crucial for separating gravitational-wave signals from the background noise.

Failure in every direction

So far, I've told the standard story about our knowledge of gravity, which is that general relativity has been confirmed by every test ever conducted. The non-standard story is that general relativity fails almost everywhere.

Let me explain.

In the limit of weak gravity, Einstein's theory reduces to Newton's law of universal gravitation. (Yes, Einstein's framing is different than Newton's, but the predictions are the same.) This reduction is by design. Based on the evidence available in the early 20th century, Einstein surmised that Newton's equations were the correct description of weak gravity. Today, however, there is mounting evidence that this assumption is false.

Backing up a bit, until the mid 20th century, measurements of gravitational acceleration came exclusively from observations within the solar system. The reason for this paucity of non-local data was simple — most objects outside our solar system travel so slowly that their movement in space is difficult to observe.[2] However, in the early 20th century, astronomers developed a clever way around this slow-motion problem. Instead of measuring motion across the sky, astronomers realized that they could infer the motion of distant objects using the Doppler effect. If these objects travelled away from us, their light would be redshifted. (And if these objects travelled towards us, their light would be blue-shifted.)

This redshift analysis was perhaps the single most important technical development in modern astronomy. In 1929, it allowed Edwin Hubble to demonstrate that galaxies were travelling away from us with velocities proportional to their distance. The universe, it seemed, was expanding!

While this expansion was easily explained by Einstein's theory of gravity, other observations proved more problematic. For example, in 1933, the astrophysicist Fritz Zwicky showed that within clusters, galaxies moved faster than predicted by Newtonian mechanics. But given the messiness of this astronomical data, the problem was largely ignored. Then, in the 1970s, the astronomer Vera Rubin began to rigorously study the rotation of matter within galaxies. Almost without exception, she found that given the observable mass, galaxies rotated too quickly to be explained by Newton's equations. (See Figure 3 for a recent example.)

[2] It was only in 2013, with the launch of the Gaia spacecraft, that we began to collect accurate bulk measurement of star motion within the Milky Way.

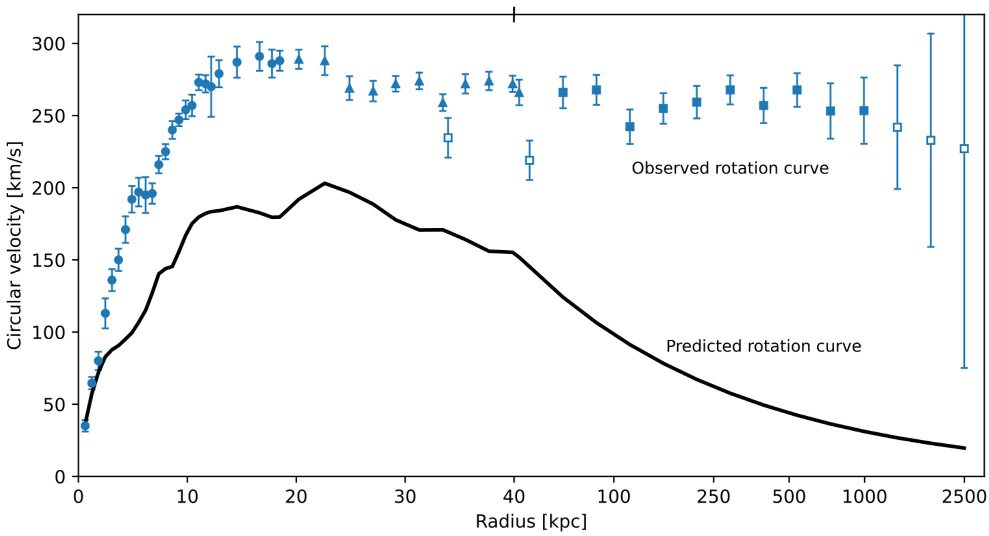

Figure 3: In galaxies, Newton gets it wrong

This chart shows a typical example of how galaxies rotate. The horizontal axis plots distance from the galactic center, measured in kiloparsecs. The vertical axis shows the circular velocity of matter within the galaxy. Blue points show the observed rotation curve, which is characteristically 'flat'. Outside of the galactic core, rotation velocity stays constant, even out to the far fringes of the galaxy. The observed pattern starkly contradicts the Keplerian decline predicted by Newton's equations, given the observable mass (black line). Source: remixed from Wikipedia.

Thus was born what is today the dominant paradigm in astrophysics and cosmology — the notion that the universe is permeated by ubiquitous 'dark matter', an unknown form of matter that is inferred to exist solely by way of its gravitational effect.[3] The presumption, then, is that 'dark matter' is like the planet Neptune ... a form of missing mass that is waiting to be discovered. (Unfortunately, experiments on Earth have detected no sign of this stuff.) But the lurking fear is that 'dark matter' may actually be a replay of the planet Vulcan — a form of missing mass which does *not* exist, but which is mistakenly inferred by the breakdown of Newtonian mechanics.

[3]By the late 1990s, much of the excitement about dark matter was coming from particle physicists, who were busy theorizing about the exotic matter that might lay beyond the standard model of particle physics. However, when the Large Hadron Collider came online in 2010, it began to poor cold water on these ideas. In the end, the LHC verified the standard model (it discovered the predicted Higgs boson), but found no evidence for new physics. This failure highlights a key problem in science, which is that when our imaginations are left unchecked by empirical evidence, they inevitably lead us down the wrong path.

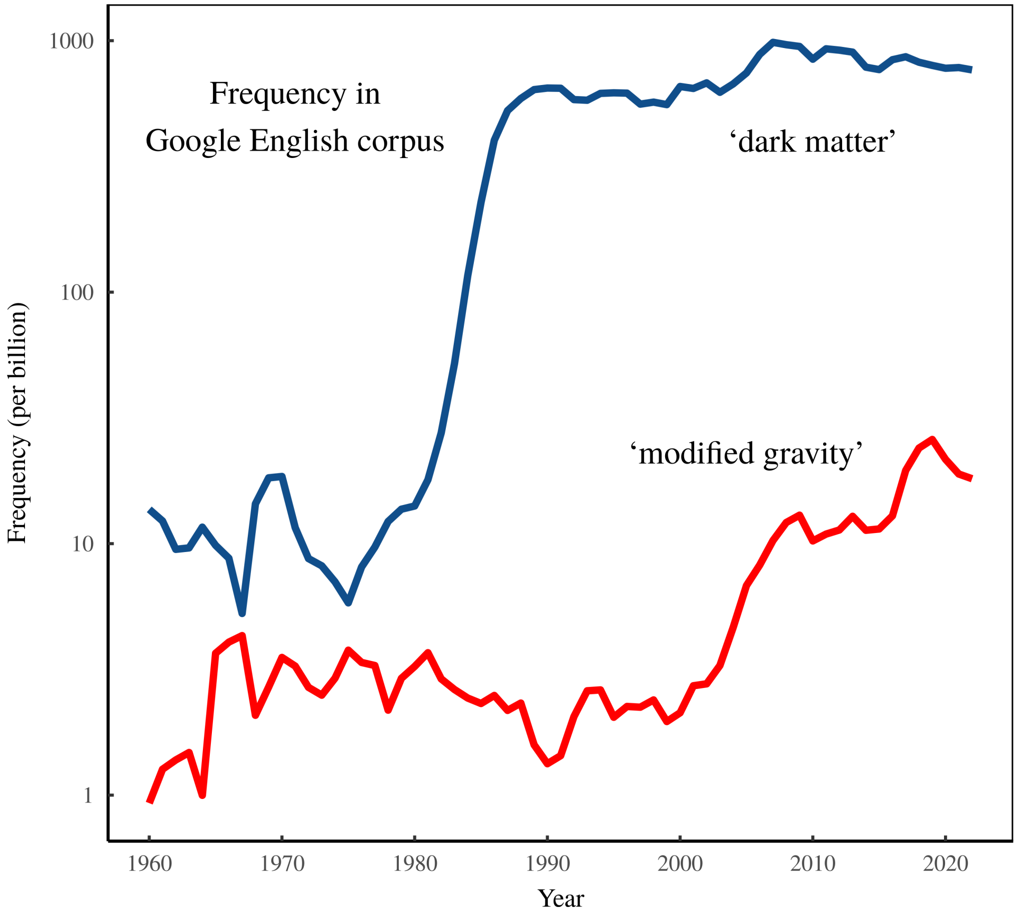

Figure 4: The dark-matter paradigm emerges

Judging by the frequency of the term 'dark matter' (measured here in the Google English corpus), the dark-matter paradigm rose to prominence in the 1980s. From then on, it became the standard orthodoxy in cosmology. In contrast, theories of 'modified gravity' have only recently become more popular, but are still vastly less discussed than dark-matter models.

On cosmology . . . and ideology

So is the dark-matter paradigm correct? Judging by its popularity, the answer is yes. The dark-matter hypothesis is the reigning orthodoxy in astrophysics and cosmology. (Figure 4 shows the rising popularity of the 'dark matter' hypothesis, as measured by word frequency in the Google English corpus.)

Of course, the popularity of these two competing theories says nothing about their scientific validity. Data source: Google Ngrams.

Of course, popularity has always been a horrible measure of scientific validity. Science is about the weight of evidence, not the weight of public opinion. To jump to the conclusion, the evidence that Newtonian physics is *wrong* (in the low acceleration regime) is now far more compelling than the evidence in favor of general relativity that was collected during Einstein's lifetime.

On this front, the history of 20th century physics is somewhat of an outlier in terms of the pace at which new theories were accepted. For example, when Einstein published his theory of general relativity in 1915, he lived to see it become the new orthodoxy. Of course, we now know that general relativity is supported by mountains of evidence (in the high acceleration regime). Yet when newspapers first heralded Einstein's 'revolution in science', the supporting evidence was fairly minimal.[4]

In short, while the correctness of a new theory hinges on the weight of evidence, the rate of *adoption* of a new theory is driven in large part by human sociology. For example, evidence in favor of the heliocentric model of the solar system mounted for centuries (if not millennia), and yet the geocentric view remained the standard orthodoxy. Why?

In part, it's because our senses mislead us. To the naked eye, it *looks* like the heavens travel around the Earth.[5] Only careful observation shows otherwise. But perhaps more importantly, geocentric cosmology became an entrenched ideology. In Europe, the Catholic church declared geocentrism as a god-given truth, hence any challenge to this dogma was an affront to clergical authority. As such, the acceptance of the heliocentric model required the gradual spread of secularism, and the declining influence of the church. This transformation took time.

Here, it's worth noting that while Newtonian physics may have kick-started science, it did not upend cosmology. What I mean is that following Newton, scientists mostly got busy studying practical problems. Questions about

[4]Other than the correct prediction of Mercury's orbit, the only early piece of evidence supporting Einstein's new theory came from observations of the 1919 solar eclipse. Led by Arthur Eddington, this expedition claimed to verify Einstein's prediction for how light would bend around the sun. But in hindsight, Eddington's evidence was rather poor. As Stephen Hawking observed in 1988, the Eddington experiment had measurement errors that were "as great as the effect they were trying to measure".

[5]In his book *Against Method*, Paul Feyerabend emphasizes the conceptual hurdles facing the heliocentric model. For example, throughout antiquity, the 'common sense' view was that there was a universal direction known as 'up'. But if the Earth was a sphere orbiting the sun, the notion of 'up' became relative, as did all motion. These conceptual issues were tackled by Galileo, but were not fully resolved until the work of Newton. Hence, in Feyerabend's opinion, skepticism of Galileo's theories was justified.

the origin of the universe were deemed essentially unanswerable. However, with Einstein's more expansive theory of general relativity, this situation changed dramatically. Using general relativity, scientists could (seemingly) describe the evolution of space, time, and everything within it (quantum effects notwithstanding).

In hindsight, the 'seemingly' part is key. When astronomers first gazed beyond the solar system, they noticed systematic deviations from the predictions of Newtonian gravity. Most scientists assumed that the problem was due to missing mass. But today, there is mounting evidence that this hypothesis is false, and that the observed discrepancy is caused by a breakdown of Newtonian physics. However, like the geocentric model of antiquity, the dark-matter paradigm lumbers on as the dominant belief, largely unfazed by the challenging evidence.

A new natural law

Speaking of difficult-to-explain evidence, let's dive into some empirical details in modern astrophysics.

To begin, note that once we assume that deviations from Newtonian gravity are caused by missing mass, we're forced to infer that dark matter constitutes about 84% of the gravitating mass in the universe. By extension, it follows that when it comes to gravitational acceleration, dark matter should be the driver, while the visible mass should be the passive passenger. Oddly, however, the inferred need for dark matter turns out to be a tight function of the visible matter itself, coupled with the rate of observed gravitational acceleration.

Figure 5 shows the astrophysicist Stacy McGaugh's presentation of the early evidence. Here, the horizontal axis plots the full range of gravitational acceleration observed across the known universe. Note the expansive log scale. From the wispy fringes of spiral galaxies (left) to the crushing surface of a neutron star (right), the range of observed gravitational acceleration spans more than 20 orders of magnitude. Looking at the vertical axis, it plots the inferred need for dark matter — the extra mass required to explain the observed gravitational acceleration using Newtonian mechanics (or general relativity).

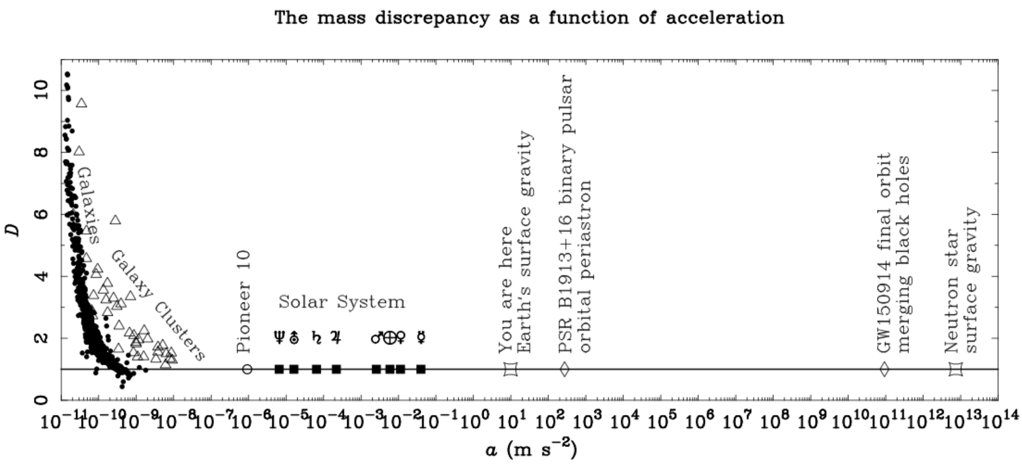

Figure 5: The inferred need for dark matter appears only at extremely low accelerations

This is Stacey McGaugh's presentation of the 'mass discrepancy' in the cosmos — the inferred need for dark matter required to explain observed gravitational dynamics. The horizontal axis plots observed gravitational acceleration (on a huge log scale). The vertical axis plots the inferred missing mass. It seems that dark matter is only needed when gravitational acceleration drops below 10^{-10} m/s^2. Source: Triton Station.

Human experience plays out at the center of this chart, where we see the gravitational acceleration on Earth's surface (which is a steady 10 m/s^2). Here on Earth, Newton's equations work exquisitely well, which means there is no need to infer dark matter.

As we move to the right side of the chart, we enter the domain of strong gravitational acceleration, described by general relativity. For example, on the surface of a neutron star, particles experience a gravitational acceleration that is a trillion times stronger than on the surface of the Earth. But despite this crushing difference, the available evidence suggests that our theory of gravity works just fine here. So again, there is no need for dark matter.

It is only when we move to the far left side of this chart that we infer the need for dark matter. As we pass outside our solar system, gravitational acceleration slows to a crawl. And when acceleration drops below roughly 10^{-10} m/s^2 (which is 100 billion times less acceleration than on the surface of the Earth), we find that Newton's equations stop working. To *make* them work (as acceleration continues to drop), we must infer a steadily growing mass of unobserved gravitating stuff.

Now, this mass-discrepancy presentation of the evidence is visually appealing, but is somewhat presumptive. It assumes that the discrepancy between theory and evidence is caused by missing mass. But this assumption is just that … an *assumption*. In more neutral terms, what we observe is an *acceleration* discrepancy — a discrepancy between the gravitational acceleration that we predict (using Newtonian physics and the observed mass), and the gravitational acceleration that we observe.

In the last few years, scientists have pinned down this acceleration discrepancy with remarkable accuracy. Figure 6 (from McGaugh and colleagues), shows the latest measurements. Here, the horizontal axis shows the gravitational acceleration predicted by Newtonian physics based on the visible mass. (Note the log scale.) The vertical axis shows the *observed* gravitational acceleration (also plotted on a log scale).

Each data point averages evidence compiled within many different galaxies. (Grey points show estimates derived from galaxy kinematics. Gold points show estimates derived from the lensing of light.) Now, if the observed acceleration followed Newtonian predictions, all of the data would sit on the diagonal grey line. But that's not how the universe behaves. Instead, as gravitational acceleration drops below 10^{-10} m/s^2, the observed acceleration takes a different path.

Now what is surprising here is that the deviation from Newtonian predictions is strikingly non-random. Indeed, the deviation is so orderly and so precise (both within and across galaxies) that Stacy McGaugh concludes that it is a 'law of nature'. By this, he means that the observed scatter in this relation is so minimal that it is consistent with having *zero intrinsic scatter*. In other words, what we are looking at here is a galactic equivalent to Kepler's laws of planetary motion. Regardless of the cause, it's a new natural law.

Milgromian dynamics

Had the evidence above been available during Newton's lifetime, one wonders how scientific history might have been different. After all, it would be odd to first propose a theory of 'universal' gravitation, but to then acknowledge that the theory horribly describes the available evidence. So in this sense, the whole foray into 'dark matter' may be a historical accident, created by the myopia of our limited (solar-system) observations.

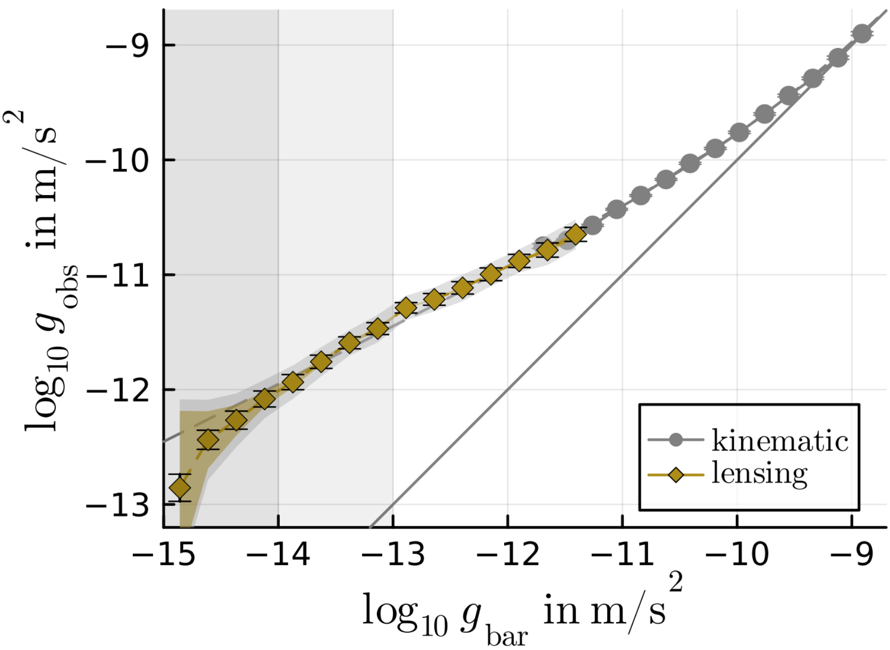

Figure 6: The latest measurements of the acceleration discrepancy

Looking at data from many galaxies, the horizontal axis plots the gravitational acceleration predicted by Newton's equations. The vertical axis shows the acceleration that is actually observed. (Each point is an average of many galaxies. Grey points come from kinematic data. Gold points come from measurements of the lensing of light.) If the data followed Newtonian predictions, it would sit on the horizontal grey line. It does not. But note that the acceleration discrepancy is surprisingly regular and predictable. Source: Mistele et al. (2024)

What is fascinating is that Newton's equations need only a minor tweak to accurately predict the observed gravitational behavior at extremely low accelerations. This serendipitous discovery was made by the physicist Mordehai Milgrom in 1983. Looking at the emerging discrepancy between how galaxies ought to rotate and how they *actually* rotate, Milgrom argued that the issue could be explained by a breakdown in Newtonian physics. Below a certain critical acceleration, Milgrom proposed that Newton's theory of gravity needed to be modified: the force of gravity would become non-linear, depending not just on mass and separation, but would also depend on the acceleration of the object itself. (As acceleration becomes minuscule, Milgrom's theory boosts the force of gravity.)[6]

[6] The non-linear nature of Milgrom's theory leads to fascinating differences from standard thinking. For example, Milgrom's theory violates one of the key tenets of general relativity — the strong equivalence principle. According to this principle, the internal dynamics of a gravitating body are unaffected by the presence (or lack thereof) of an external gravita-

In hindsight, Milgrom's theory is both a triumph and a tragedy. It is a triumph in the sense that it is a remarkable empirical success; it has made a series of predictions which have since been confirmed. (For example, the acceleration discrepancy, shown in Figure 6, is exactly what Milgromian dynamics predict. But this is just one of many successful predictions.)

That said, Milgromian dynamics are a tragedy in the sense that they are a frustrating theoretical step backward. You see, a key appeal of Einstein's theory of general relativity is that it stems from 'first principles'. If we assume that a gravitational field is indistinguishable from constant acceleration (the equivalence principle), Einstein's theory of gravity follows naturally. This is in marked contrast to Newton's theory of gravity, which was simply plucked from thin air to explain the solar-system evidence. Like Newton, but unlike Einstein, Milgrom's theory was plucked from thin air to explain aspects of how galaxies rotate. (Novel predictions then followed.) In other words, Milgromian dynamics 'work', but no one knows why. Of course, this ignorance is only a problem if we insist on being hubristic. If we are humble, the revelation of our ignorance is exhilarating.

Perhaps the most exciting possibility is that Milgromian dynamics are caused by quantum vacuum effects. You see, in quantum physics, it is theorized that the vacuum of space is teaming with unseen 'virtual' particles which are constantly popping in and out of existence. It has long been thought that this vacuum energy ought to have a gravitational effect. But attempts to incorporate it into general relativity have proved disastrous. So perhaps Milgromian dynamics — which are revealed only when acceleration is minuscule — tell us something about 'quantum gravity'. Nothing could be more exciting.

'Unanticipated' evidence from the early universe

Regardless of where our theory ends up, there is little doubt that we are now witnessing a revolution in our empirical understanding of the cosmos. Let me set the stage.

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tional field. In contrast, Milgromian dynamics violate this principle, leading to an 'external field effect', in which the gravitational acceleration within a massive body is affected by its surrounding environment. Remarkably, there is astronomical evidence that the strong equivalence principal does breakdown.

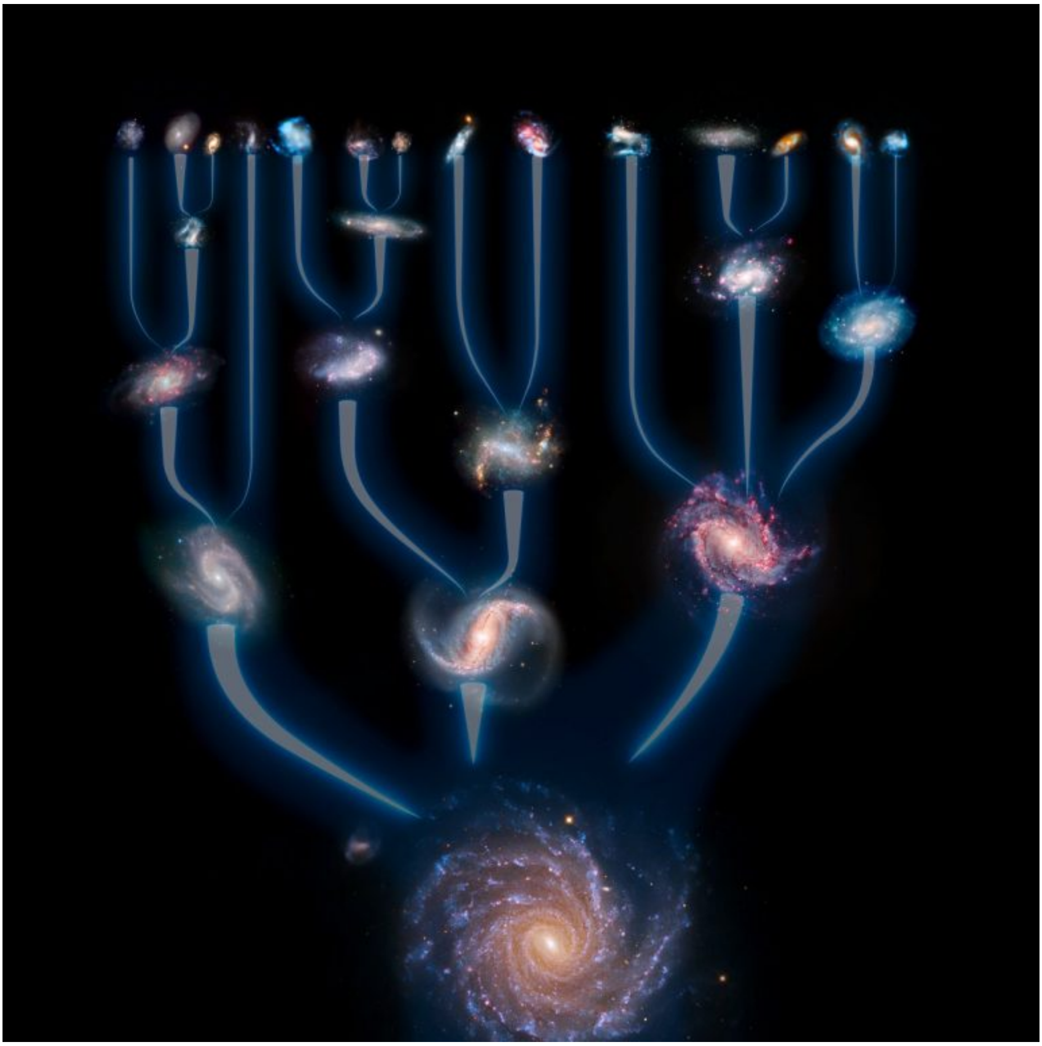

Figure 7: In dark-matter models, large galaxies form through mergers of smaller galaxies

This graphic, from the European Southern Observatory, illustrates how galaxies form in dark-matter models. On top are many proto-galaxies from the early universe. Over time, these galaxies collide and merge to form the large galaxies we see today (bottom).

When scientists settled on the 'need' for dark matter, they got busy simulating how a dark-matter-filled universe would behave. The key result of these simulations is that structure must form 'hierarchically'. (See Figure 7 for an illustration of this process.)

The idea is that the universe began as a nearly homogeneous mix of matter, marked by subtle variations in density. Over time, these density variations grew to form small-scale structure — small 'halos' of dark matter, with clumps of normal matter embedded inside. Larger structures were then built via waves of mergers. Small lumps combined to form bigger lumps, which combined to form still bigger lumps, and so on. As one might expect, the key feature of this hierarchical structure formation is that it is *slow*; it takes many billions of years to form the large galaxies we see around us.[7]

Looking (only) at the large-scale structure of today's universe, these dark-matter models do a plausible (if imperfect) job of explaining what we see.[8] But in the early universe, dark-matter models are turning out to be abject failures. We can thank the James Webb Space Telescope for showing that. Launched in 2021, the James Webb telescope was designed specifically to peer into the distant (ancient) universe. On this front, the project has succeeded admirably, and is now showering us in 'unforeseen' evidence. To the surprise of many scientists, the telescope has revealed that big galaxies formed far earlier than predicted by dark-matter models.

Not everyone was surprised. In early 2022, just before the James Webb observations began to roll in, Stacy McGaugh predicted that the telescope would immediately discover something 'unexpected': big galaxies at high redshift.

[7]Without dark matter, Newtonian physics simply fails to grow the structure that we observe today (given the estimated age of the universe). Aside from the acceleration discrepancy within galaxies, this structure-formation failure is one of the key motivations for inferring the existence of dark matter.

[8]Looking at galactic scales, there are many problems with dark-matter models of galaxy formation. For example, dark-matter models predict that large galaxies like the Milky Way should be surrounded by hundreds of satellite galaxies. And yet only a few such satellites are observed. Similarly, on small scales, dark-matter models have a missing baryons problem. ('Baryons' represent known forms of mass.) That is, the smaller the observed structure, the less visible mass it has relative to what dark-matter models predict.

There are still more problems. Pavel Kroupa points out that dark-matter halos have a characteristic friction effect, which causes satellite galaxies to rapidly merge with their larger neighbors. Yet calculations from the Milky Way and its close neighbors show no viable dark-matter solutions.

Yet another problem is that galaxies mergers are violent events, which means that they should perturb the disks of rotating galaxies, giving them a 'thick' appearance. But as Stacy McGaugh points out, most galaxies have very thin disks.

A further conceptual problem is that in dark-matter models, elliptical galaxies are thought to be the final stage of galactic evolution (the result of many waves of mergers). Yet, as Pavel Kroupa observes (1:02:00 mark), the relative portion of these galaxies seems to have remained unchanged for the last 6 billion years of the universe's history.

Also, in dark-matter models, merging galaxies must see their respective supermassive black holes merge into one monster. And yet models suggest that these black holes should not merge — they should essentially orbit each other indefinitely. (This is called the final parsec problem.) A simple solution to this problem is to suppose that galaxies do not form through mergers. See Kroupa et al. (2020) for a discussion.

Perhaps as a sign of how the universe behaves, if one adopts Milgromian dynamics, these problems largely disappear.

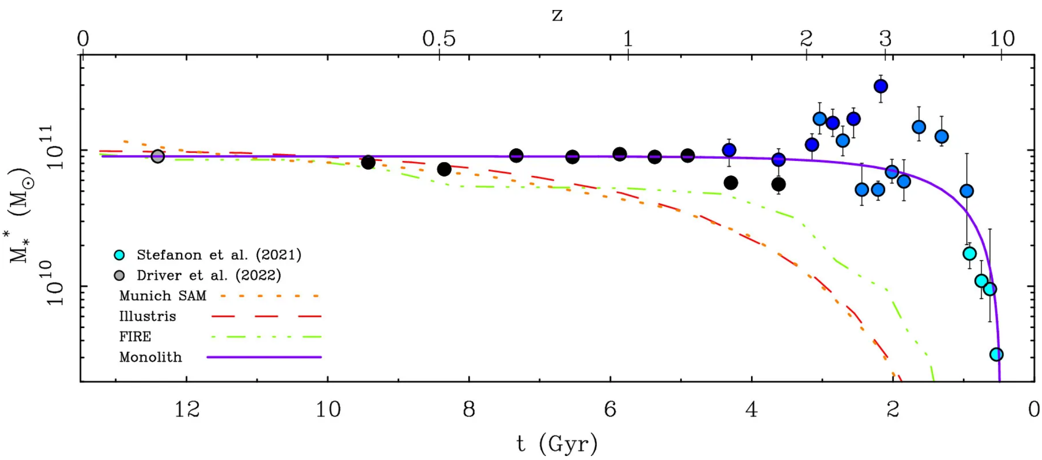

Figure 8: In the early universe, big galaxies formed quickly

Recent data from the James Webb Telescope shows that large galaxies formed far earlier than dark-matter models predict. In this chart, from McGaugh et al. (2024), the (inferred) age of the universe is shown on the horizontal axis, with a reverse scale. The vertical axis shows the mass of observed galaxies. The purple curve shows a model predicted by Milgromian dynamics, in which galaxies form from the 'monolithic' collapse of a cloud of gas. The dashed red and green curves show predictions from dark-matter models.

Crucially, this idea was not a hunch. It was a basic prediction that followed from Milgromian dynamics. You see, in Milgrom's theory, gravity gets a 'boost' at low accelerations. Back in 1998, the physicist Robert Sanders showed that this 'boost' would cause structure to form more rapidly than in dark-matter models. Also, the 'mode' of galaxy formation would be completely different. Instead of growing via waves of galactic mergers, Milgromian dynamics predicted that the first galaxies would form in a more dramatic fashion — vast clumps of nascent gas would collapse catastrophically all at once, birthing enormous galaxies in the blink of an eye.

Gazing at the picture emerging from the James Webb Telescope, it appears that the ancient universe did not get the dark-matter memo. Early galaxies, it seems, form as Milgromian dynamics predict. Figure 8 (from Stacy McGaugh in early 2025) shows the evidence so far.

On the top horizontal axis of this chart, we see how astronomers infer the passage of time (into the past). That is, when astronomers look into the distant universe, they see objects that are increasingly redshifted. From this redshift data, astronomers then infer the age of the object. On the bottom horizontal axis, this age is shown on a reverse scale. So if we want to 'watch' time pass, we move from right to left.

Looking at the vertical axis, it shows the estimated mass of galaxies (measured in units of solar mass). Each point represents the empirical observation of an individual galaxy. The curves show the behavior of different models. What's important is that the evidence is consistent with the 'monolith' model, in which early galaxies form all at once via a catastrophic collapse of a vast region of gas, driven by Milgromian dynamics. The dashed lines show the predictions from two dark-matter models, which are miles away from the empirical data.

Cosmology upended?

With these 'impossibly' big, 'impossibly' early galaxies in mind, let us look at the central tenets of modern cosmology, which were set in place by two monumental observations. In 1929, Edwin Hubble discovered that the universe was expanding. And in 1964, physicist Arno Allan Penzias and radio-astronomer Robert Woodrow Wilson discovered what is today called the 'cosmic microwave background' — a form of microwave radiation that emanates from all directions of the observable universe. Putting the two patterns together, physicists soon surmised that the microwave background might be 'relic' radiation, the remnant of a hot 'big bang'.

The idea is that the universe was born as a hot plasma which then cooled as the cosmos expanded. We can (in this theory) think of the early universe as a hot dense place similar to the interior of the sun — a place where photons of light could not travel far before they were absorbed by ionized matter. As the universe expanded and cooled, it eventually reached a critical temperature where the plasma condensed into atoms, suddenly allowing the sea of radiation to travel unimpeded (much as light does once it reaches the photosphere of the sun). From that point onward, this relic radiation sailed the cosmos, cooling as the universe expanded. What remains today is a frigid version of this ancient inferno, cooled to a chilly 2.7 Kelvin.

Or at least, that is the standard story of the cosmic microwave background. However, recent analysis by Eda Gjergo and Pavel Kroupa may upend this tidy theory.

The backstory is that there are two features of the cosmic microwave background which most interest scientists. The first feature is its striking uniformity; the microwave background appears nearly identical in every direction, and can be modelled as pure black-body radiation. The second interesting feature of the microwave background is that it ever-so-slightly *departs* from

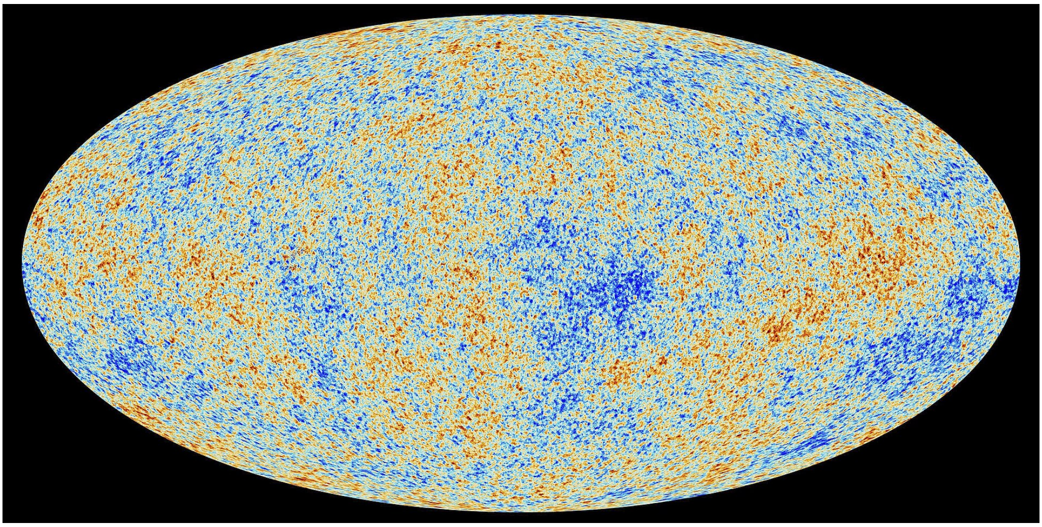

Figure 9: Variations in the cosmic microwave background

The cosmic microwave background emanates from all directions of the observable universe, with near perfect uniformity. However, the most precise measurements from the Planck mission, shown here, find tiny fluctuations across the sky at about 1 part per 100,000. These fluctuations are thought to be the seeds of structure within the early universe. Source: Wikipedia.

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uniformity. Looking across the sky, scientists have found tiny fluctuations in the microwave background which vary from place to place by about 1 part in 100,000. Figure 9 shows the most precise measurement of these fluctuations, as captured by the Planck observatory.[9]

The reason that these tiny fluctuations are interesting is that they are thought to represent regions of slight under-density and over-density in the early universe. These fluctuations, it is assumed, represents the seeds of structure in the primordial universe — the seeds from which everything else would grow.

On this front, fluctuations in the microwave background are taken to be the 'initial conditions' on which cosmologists tune their models of the universe. Here, the dark-matter paradigm works well, in the sense that it can be tuned to fit these initial conditions. (Note that 'tuning' is not the same as 'predicting'; dark-matter models can be made to fit the fluctuations in the microwave background ... but they do not predict these fluctuations.)

[9]It's worth noting that the measurement of these microwave fluctuations involves a fairly herculean exercise in data cleaning, much of it model dependent. Turning conventional wisdom on its head, Pavel Kroupa argues that the cosmic microwave fluctuations are the *weakest* evidence in cosmology. They are, he concludes, a theoretically wished-for construction based on massive data cleaning and reduction.

Back to the recent work of Gjergo and Kroupa. At issue is whether the observed fluctuations in the microwave background mean what cosmologists think they mean. The problem, Gjergo and Kroupa note, is that the cosmic microwave background could have been created (in part or in whole) by the formation of the first galaxies.

Now, in the dark-matter paradigm, this idea is a non-starter, because galaxies form too slowly to get in the way of radiation from the big bang. However, the evidence coming from the James Webb Telescope suggests that dark-matter models have it wrong; big galaxies formed remarkably early, most likely through the catastrophic collapse of proto-galactic clouds of gas.

The galaxies that would have emerged from this process are not the pristine spiral galaxies like our own Milky Way; rather, they would have been virtually featureless blobs of glowing dust and frenetically forming stars. Today, these 'elliptical' galaxies look like the picture in Figure 10, which is an image of the supergiant elliptical galaxy M87 — a neighboring behemoth that contains several trillion stars.

(Side note: The band of blue emanating from the galaxy's center is a jet of gas blown outward at close to the speed of light by the supermassive black hole at the galaxy's center. As it happens, this is the same black hole that was photographed by the Event Horizon Telescope. See Figure 2.)

Looking at the present-day chemical composition of these elliptical galaxies, Eda Gjergo and Pavel Kroupa ponder the nuclear processes required to create what we see. Backing up a bit, it's well established that the elements that astronomers call 'metals' (by which they mean anything heavier than helium) are forged inside stars through nuclear fusion. These elements are then spread throughout the galaxy when large stars explode at the end of their life (a process called a super nova). When new stars form from the remnant material, they contain the previously forged metals, which are then visible as spectral lines in the light they emit.

To create the chemical composition that we see in today's elliptical galaxies, Gjergo and Kroupa calculate that when these galaxies first formed, they must have rapidly birthed large populations of massive stars, stars which would vastly outshine our sun. Running the numbers, Gjergo and Kroupa conclude that these early blazing galaxies would have shone some *10,000 times* more brightly than the remnant ellipticals that we see today. In their words, today's massive elliptical galaxies are "merely embers in the ashes of ancient cosmic bonfires".

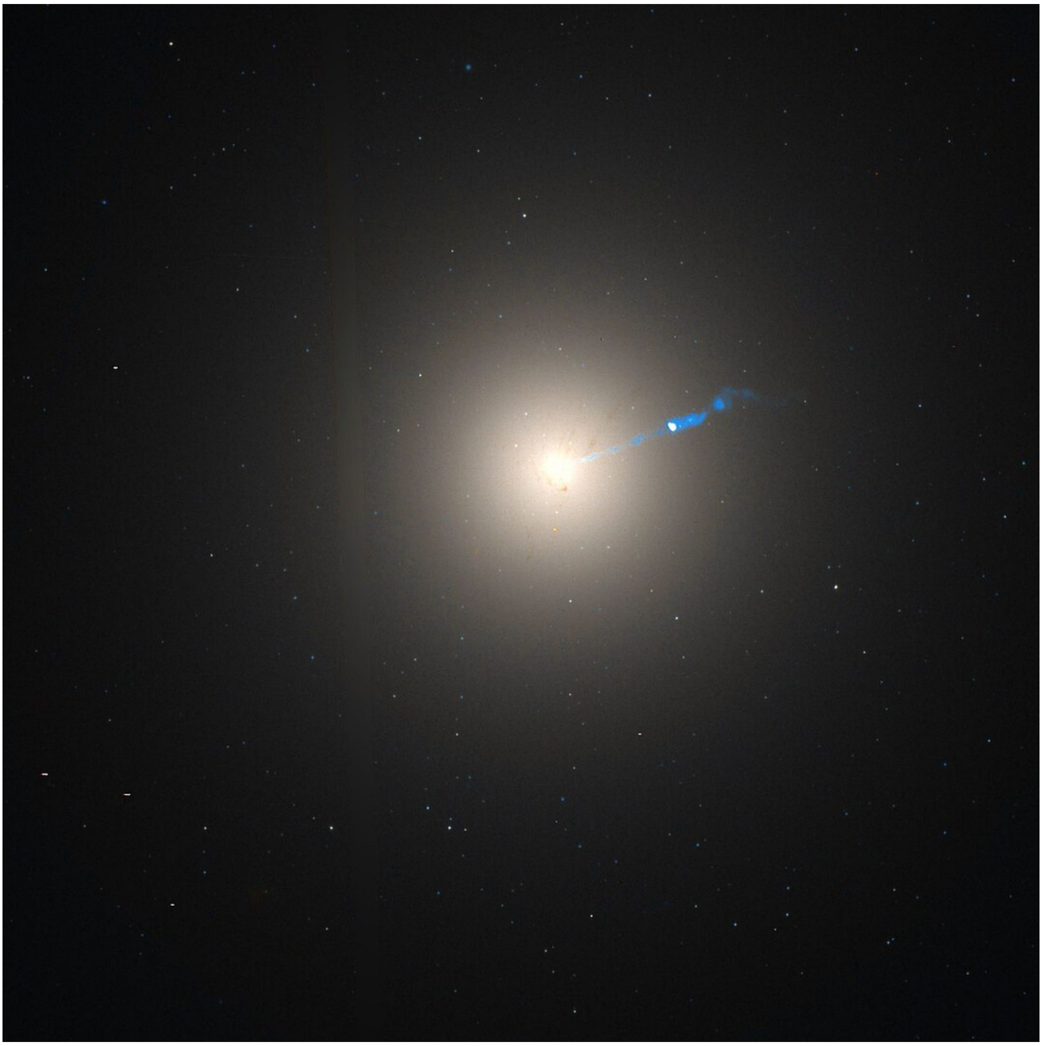

Figure 10: A supergiant elliptical galaxy

Unlike the more common spiral galaxies (like our own Milky Way), massive elliptical galaxies have almost no discernible structure — they consist of an undifferentiated blob of pressure-supported stars. Looking at the chemical composition of these objects, astronomers infer that they are among the oldest galaxies in the universe. Pictured here is the supergiant elliptical galaxy M87, which features a jet of blue gas emanating from the supermassive black hole at the galaxy's core. Source: Wikipedia.

Now here is the bombshell. Looking at how modern galaxies form stars, Gjergo and Kroupa note that the process is typically shrouded in dust. As this dust is warmed by the forming stars, it emits black-body radiation in the infrared spectrum. Let's say that again ... star-forming galaxies emit black-body radiation. If this radiation was emitted in the early universe, it would then get redshifted towards longer wavelengths as the universe expanded.

As it turns out, Gjergo and Kroupa's calculations indicate that this radiation would occur exactly in the spectrum of the *present-day cosmic microwave background*.

Figure 11 shows their jaw-dropping calculation. Looking at the horizontal axis, it plots the observed redshift of light (a proxy for object age). So as we move from left to right on this chart, we move backwards in time. Looking at the dashed red vertical line, it represents the moment (in standard cosmology) when the universe had cooled sufficiently for big-bang radiation to propagate throughout the cosmos. The red 'x' then marks the energy density of this radiation (at the time), measured on the vertical axis.

As the universe expanded, this relic radiation would cool, causing its energy density to slowly drop with time, as indicated by the solid red line. Following this line to the present day (the left side of the chart), we get the cosmic microwave background observed today. Or at least, that is the standard theory.

The problem with this interpretation, Gjergo and Kroupa observe, begins with the vertical grey band. This is the period in which they infer that elliptical galaxies first formed. Now, unlike the hot big bang, which cannot be observed directly, elliptical galaxies are real objects that are spread throughout the observable universe today. As Kroupa puts it, astronomers can essentially 'touch' these galaxies with modern telescopes, which means that much is know about them, including their average separation in space.

From this present-day separation, Gjergo and Kroupa calculate how closely packed these galaxies would have been when they first formed. The answer, it turns out, is *very densely packed*. Looking at the most detailed measurements of the cosmic microwave background, captured by the Planck mission, Gjergo and Kroupa calculate that each pixel of the Planck measurement would contain about 6 massive elliptical galaxies, imaged during their bonfire stage of formation.

During this bonfire era, elliptical galaxies would have emitted profuse blackbody radiation in the infrared spectrum. Then, as the universe expanded, this radiation would have cooled and would now live in the microwave spectrum, exactly where the cosmic microwave background is observed today. In Gjergo and Kroupa's chart, the dashed black lines show various scenarios for this radiation.

In the most extreme (but still highly plausible) scenario, radiation from forming elliptical galaxies accounts *completely* for the observed microwave background. But even in the most conservative scenario, this radiation accounts

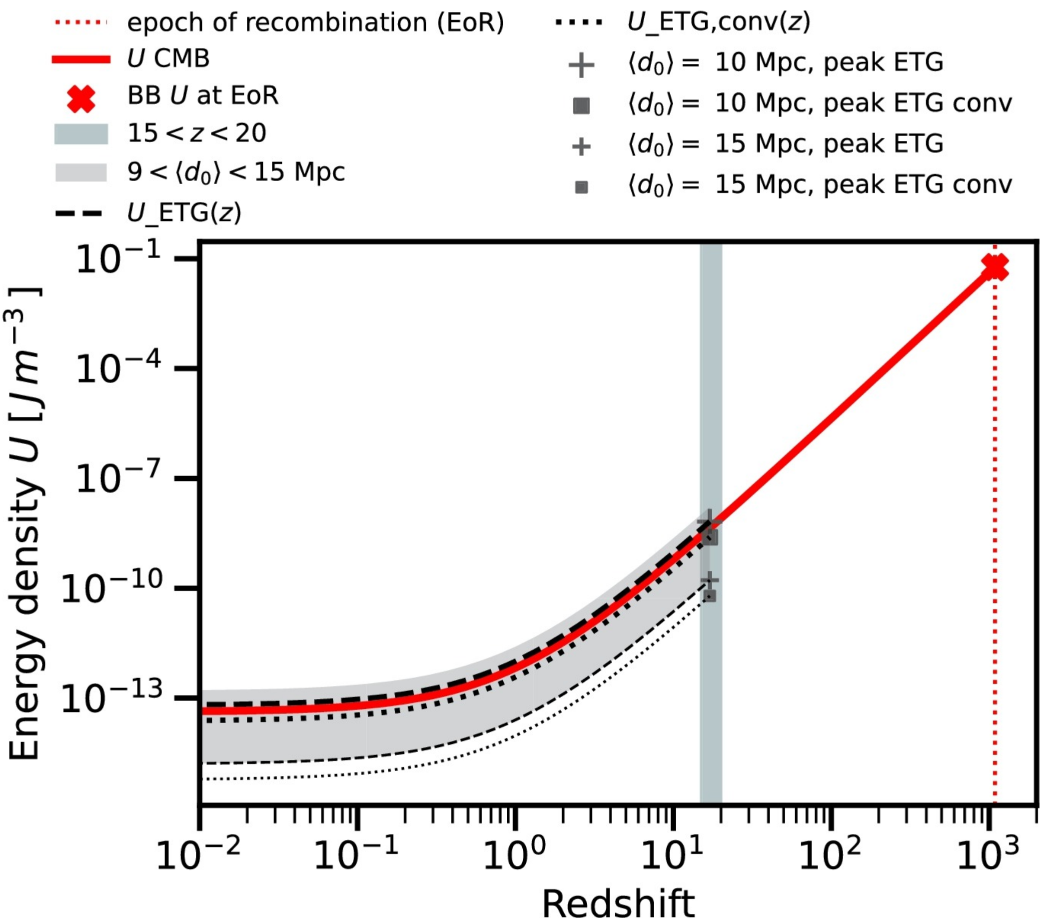

Figure 11: Emissions from early elliptical galaxies may explain the entirety of the observed cosmic microwave background

In this chart, Gjergo and Kroupa (2025) calculate the degree to which emissions from forming elliptical galaxies might contaminate (or completely account for) the cosmic microwave background as we see it today. Here, the horizontal axis shows redshift, which is how astronomers infer age in the universe. (Larger redshift indicates older age.) The vertical axis shows the energy density of radiation. If the cosmic microwave background stemmed from the big bang, it would evolve along the red line (from right to left). However, starting at a redshift of between 15 to 20, Gjergo and Kroupa calculate that elliptical galaxies would be born (vertical grey band). During their bonfire stage of evolution, these galaxies would emit infrared radiation in the same spectrum as the (then) big-bang radiation (dashed black lines and grey region). The result is that today, this elliptical radiation would exist exactly where the microwave background is observed. Even in the most conservative estimate, Gjergo and Kroupa conclude that radiation from forming elliptical galaxies would account for 1% of the microwave background — a value that dwarfs (by a factor of 1000) the observed variations in the microwave background which are assumed to be the seeds of structure in the early universe.

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for about 1% of the observed microwave background. Now, 1% contamina-

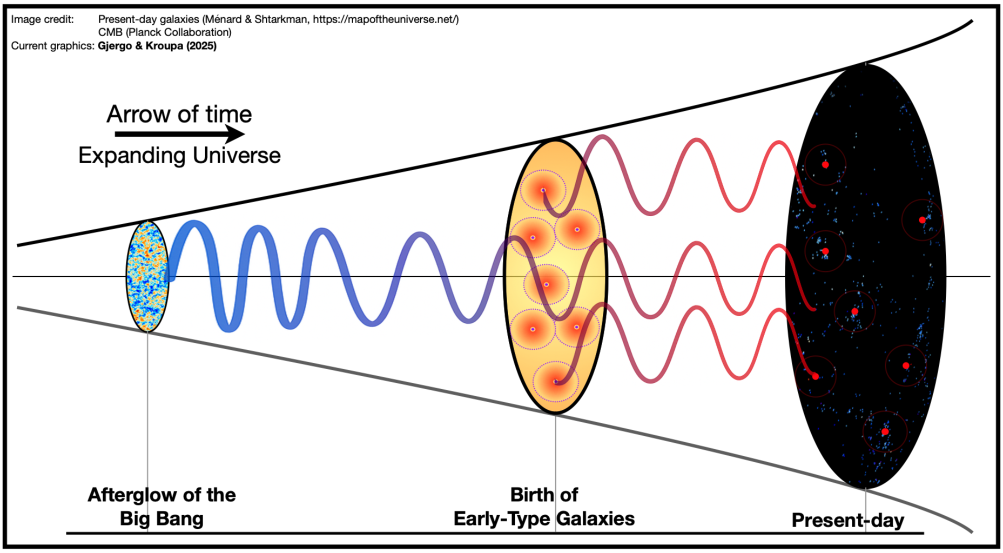

Figure 12: Is the cosmic microwave background a remnant of the big bang? Or a relic of bonfire galaxy formation?

According to standard theory, the cosmic microwave background is relic radiation from a hot big bang (left). But according to recent calculations by Gjergo and Kroupa (2025), the observed microwave background is hugely contaminated by emissions from forming elliptical galaxies (middle). In the most radical scenario, the microwave background may be caused completely by elliptical emissions, leaving no remaining evidence for a hot big bang. The problem for standard theory, as Kroupa observes, is that ellipticals are real objects with known empirical properties which cannot be ignored. In contrast, most of what is (thought to be) known about the hot big bang is inferred from indirect evidence.

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tion might sound trivial, but keep in mind that existing models of the universe are based on fluctuations in the microwave background that occur at a level of *1 part per 100,000*.

So even if the observed microwave background has a 1% contamination from forming elliptical galaxies (galaxies which are not distributed with perfect evenness across they sky), this contamination utterly dwarfs the minute fluctuations which standard cosmology interprets as the seeds of cosmic structure. In short, fluctuations in the microwave background (and perhaps the entire microwave background itself) may have nothing to do with the (hypothesized) big bang. Figure 12 illustrates this confounding effect.

Emerging cosmic consilience

As a social scientist, I am not qualified to assess the validity of Gjergo and Kroupa's calculations. But as someone who spends much of my time assessing empirical evidence (and reading about how other scientists assess evidence) I can tell you that the cosmic picture that is emerging is exciting. It has the ring of what the biologist E.O. Wilson calls 'consilience' — the interlocking compatibility of many different lines of evidence.

Consilience is a feature of all scientific revolutions. For example, the Newtonian revolution unified a host of observations about motion that previously seemed unconnected. Likewise, Darwin's theory of evolution unified diverse strands of biological evidence. Looking at patterns in modern astrophysics and cosmology, my impression is that Milgromian gravitational dynamics will prove to be similarly revolutionary, unifying seemingly divergent strands of evidence which are incomprehensible from within the dark-matter paradigm.

To be sure, the notion of dark matter was a good idea, at least initially. In other words, scientists were right to be conservative about amending the laws of gravity in the face of the initially conflicting evidence. But today, the evidence contradicting dark matter models is overwhelming, leading the field of cosmology to be frustratingly reactionary.

In the language of the philosopher Imre Lakatos, the dark-matter paradigm is increasingly degenerative. It repeatedly fails to predict what is observed, but then staves of 'falsification' by introducing numerous auxiliary hypotheses.[10] In contrast, Milgromian dynamics has consistently predicted new phenomenon in advance of their discovery (the gold standard for a scientific theory).

Of course, this successful prediction does not mean that Milgromian dynamics are the final say on gravity. (No one thinks they are.) But it does mean that we are likely in the midst of a scientific revolution in our understanding of the universe. In short, if you want to watch a paradigm shift in action, pay attention to cosmology, where the weight of (heretical) evidence slowly accumulates.

[10]Most of these auxiliary hypotheses involve fine-tuning dark-matter models with 'feedback' processes that make the models mimic what is observed. (Stacy McGaugh likens such feedback to 'dark epicycles'.) Or put another way, dark-matter models are tuned to explain behavior that Milgromian dynamics predict in advance.

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Blogs to watch

To follow the unfolding scientific revolution in cosmology and astrophysics, I recommend these sources:

- Triton Station, written by Stacy McGaugh. McGaugh writes with clarity and wit, and is a hard-nosed astrophysicist to boot. His commentary on sociological groupthink is particularly humorous.
- The Dark Matter Crisis, written by Pavel Kroupa and collaborators. This blog comes from Europe, so the English writing is sometimes less smooth than one might like. But the research being discussed is always extraordinary, and is described by the primary researchers themselves.
- Sabine Hossenfelder. Hossenfelder is a theoretical physicist who wrote the excellent book *Lost in Math: How Beauty Leads Physics Astray*. Her YouTube channel features general news in science, but is particularly good at covering research that challenges received wisdom in cosmology.

Further reading

Merritt, D. (2020). *A philosophical approach to MOND: Assessing the Milgromian research program in cosmology*. Cambridge University Press.