Dark Matter

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Citation: Phys. Teach. **51**, 134 (2013); doi: 10.1119/1.4792003
View online: http://dx.doi.org/10.1119/1.4792003
View Table of Contents: http://tpt.aapt.org/resource/1/PHTEAH/v51/i3
Published by the American Association of Physics Teachers

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It's a dark, dark universe out there, and I don't mean because the night sky is black. After all, once you leave the shadow of the Earth and get out into space, you're surrounded by countless lights glittering everywhere you look. But for all of Sagan's billions and billions of stars and galaxies, it's a jaw-dropping fact that the ordinary kind of matter like that which makes up you and me is but 5% of the energy budget of the universe. The glittering spectacle of the heavens is a rather thin icing on a very large and dark cake.

According to the most current estimates, ordinary matter makes up merely 4.6% of the universe, with a form of matter called "dark matter" being 22.7%. An even more esoteric component of the cosmos is called "dark energy" and it comprises a whopping 72.8% of the energy and matter budget of the universe. This article describes our current understanding of dark matter and why so many astronomers are confident that it exists. One of the various strands of evidence for the existence of dark matter is also of pedagogical interest, as it is perhaps unique in being a conundrum on the cosmic frontier that is easily understood using only algebra-based introductory physics.

The first inkling astronomers had that perhaps their telescopes were not telling the entire story came not long after a publication in 1925 by Edwin Hubble. Combining the observations of others along with his own, Hubble made the scientific community aware of the existence of other galaxies, with the implicit consequence that we lived in a galaxy of our own—the Milky Way galaxy. The realization that the Milky Way was a compact, gravitationally bound conglomeration of stars led theorist Bertil Lindblad and observer Jan Oort (of Oort cloud fame) to compare Newtonian predictions of the rotation of the Milky Way with observations. The implications were clear. The Milky Way was rotating faster than predicted using Newtonian principles and the observed amount of matter. Linblad and Oort's work led Oort to state in 1932 that there seemed to be two to three times more mass in the Milky Way than could be observed. Of course, this was the 1920s and 1930s, and a data/theory agreement within a factor of two was actually pretty good. It was quite possible that the simplest explanation (observational error) was the correct one.

In 1933, astronomer Fritz Zwicky studied the Coma cluster of galaxies and ascertained that the galaxies in the outskirts of the cluster were moving far too fast to remain gravitationally bound to the cluster core. This discrepancy was much larger than Oort's, with the luminous mass able to account for only 10% of the gravity necessary to describe the motion of these galaxies. The plot thickened. Subsequent attempts to measure the mass of galaxies using gravitational lensing added to the tension. Zwicky invented the term "dark matter" to describe this invisible component of the cosmos.

In the intervening decades, there have been many observations[1] supporting the contention that dark matter is everywhere, from the mentioned motion of clusters of galaxies and gravitational lensing, to objects like NGC 4555, an elliptical galaxy surrounded by hydrogen gas heated to 10,000,000 K. The temperature of this gas is so high that it should have dispersed, were it not for something holding it in. However, the evidence for dark matter that is simplest for an introductory physics student to understand is the rotation curves of galaxies. Rotation curves are simply plots of the orbital velocity of stars as a function of their distance from the galactic center.

Astronomers can exploit the Doppler shift to measure the velocity of stars in galaxies. Further, they can use known relationships between the brightness and color of stars to the star's mass to work out the distribution of the light-emitting (i.e., visible) mass in the galaxy. By combining simple Newtonian principles, it is easy to work out the dominant features expected to be present in the rotation curve. The calculation begins by identifying gravity as the centripetal force. We then insert the standard formulae for these terms:

$$\frac{m_{\text{star}} v^2_{\text{star}}}{r} = G\frac{m_{\text{star}} M_{\text{attractive}}}{r^2}, \tag{1}$$

and with some manipulation, we get

$$v_{\text{star}} = \sqrt{\frac{GM_{\text{attractive}}}{r}}. \tag{2}$$

$M_{\text{attractive}}$ is the amount of the galaxy's mass that attracts the star to move in its orbit. Outside the galaxy, this is trivial; $M_{\text{attractive}} = M_{\text{galaxy}}$. However, inside the galaxy, not all of the galaxy's mass plays a role in determining the motion of the stars. The distribution of mass within a typical galaxy is complex, necessitating that we turn to numerical techniques. However, as an illustration we can treat the galaxy as a sphere of uniform density. By employing Newton's shell theorem, which is the same logic familiar to introductory students in their exploration of Gauss' law, one sees that the mass that attracts a star is the mass inside a sphere of radius equal to the distance between the center of the galaxy and the star. Thus, inside the galaxy, $M_{\text{attractive}} = M_{\text{galaxy}} \times (r/R_{\text{galaxy}})^3$. By inserting this term into Eq. (2), we are able to predict the rotation curve of stars inside this simplified galaxy.

$$v_{\text{star}} = \begin{cases} r\sqrt{\dfrac{GM_{\text{galaxy}}}{R^3_{\text{galaxy}}}} & r < R_{\text{galaxy}} \\ \sqrt{\dfrac{GM_{\text{galaxy}}}{r}} & r \geq R_{\text{galaxy}} \end{cases}. \tag{3}$$

Thus we see that the orbital velocity of a star rises linearly as a function of radius within the body of the galaxy and then falls as the inverse of the square root of the radius outside of the mass distribution of the galaxy. While physical galaxies have a more complex mass distribution than the one used here, the actual rotation curves have similar features, as shown in Fig. 1. Near the center of the galaxy, the veloc-

 DOI: 10.1119/1.4792003

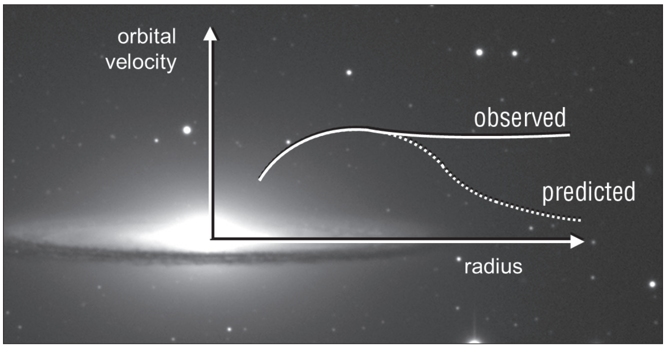

Fig. 1. Rotation curves of thousands of galaxies tell the same tale. Inside the galaxy, data and theory are in agreement. However, in the outskirts of the galaxy, stars are observed to orbit with nearly constant velocity. This is in striking contrast with predictions. (Figure adapted from Ref. 2.)

ity is roughly proportional to the orbital radius, and outside the galaxy the velocity decreases, since the increased radius incorporates no new mass but does decrease the force due to gravity. In the outskirts of the galaxy, the rotation curve is predicted to smoothly bridge these two behaviors, reflecting the fact that real galaxies aren't uniform spheres but instead have a gradient in the distribution of mass.

Figure 1 shows a prediction and observation for a typical galaxy. Over the decades, thousands of galaxies have been investigated. Time and time again, astronomers found that at large radii, stars all tend to orbit with the same velocity, in clear disagreement with the predictions.

The pedagogical beauty of the dark matter conundrum is exemplified in the simplicity of Eq. (1) and in the cover image. The very crux of Eq. (1) says that the origin of the centripetal force is the gravitational force. In order to account for the disparity seen in Fig. 1, we are forced to conclude that one or more of a few simple assumptions are incorrect. These are:

1. Newton's second law ($F = ma$) is wrong;
2. Newton's theory of gravity ($F = Gm_1m_2/r^2$) is wrong;
3. There are unconsidered forces (i.e. $F_{\text{centripetal}} \neq F_{\text{gravity}}$); or
4. The universe contains a type of mass that is not visible.

MOND: Modifications of Newtonian dynamics

In 1981, physicist Mordehai Milgrom proposed[3] that for very low values of acceleration, Newton's second law is invalid. Rather than the familiar $F = ma$, he proposed that $F = ma\,\mu(a/a_0)$, where the function $\mu(a/a_0)$ is not specified in detail, but is unity for accelerations large compared to a_0 and is equal to a/a_0 for $a < a_0$. The variable a_0 is an acceleration of order 10^{-10} m/s^2. While the form of $\mu(a/a_0)$ is unknown, we can investigate its effect on Newton's second law by taking the simplifying assumption that it can take on just two values, which are those seen at large distances from a_0. This changes the relationship between force and acceleration to

$$F = \begin{cases} ma & a > a_0 \\ ma^2/a_0 & a \leq a_0 \end{cases} . \tag{4}$$

By invoking the standard relationship between centripetal acceleration and velocity, $a = v^2/r$, and making the appropriate substitutions into Eq. (1), we find that MOND predicts that at large orbital radii, $v_{\text{star}} = \sqrt[4]{GMa_0}$, which is independent of the radius. At smaller radii, MOND makes the same predictions as traditional Newtonian theory. This behavior is consistent with observations. Of course, this agreement is by construction.

There are many valid criticisms of the MOND theory. First, the form of the function $\mu(a/a_0)$ is known only in its limiting cases. Another criticism of the simplified version given in Eq. (4) is that it conserves neither energy nor momentum. This serious deficiency was overcome in a 1984 paper by Milgrom and Jakob Bekenstein, in which a Lagrangian formulation was employed. Another criticism of the early versions of MOND is that it is not a relativistic theory. Subsequent work, including some by Bekenstein, has found various ways to marry MOND with relativity.

The proof of a theory is in how well it works. So how well does MOND work? For the question of galaxy rotation curves, it works extremely well. It also has some successes for the myriad other bits of evidence that has led to the dark matter conundrum. We will return to the strengths of the various proposed solutions to this problem after other solutions have been discussed.

Dark matter: Baryonic

The general idea of dark matter is that there exists matter in the universe that does not emit or absorb light. While modern ideas of dark matter are more exotic, the initial thinking was far more prosaic. Following the maxim "Hear hoof beats, look for horses and not zebras," astronomers considered candidates for dark matter that were made of ordinary matter. Since the mass of ordinary matter resides in the baryons (protons and neutrons) at the center of atoms, we refer to this form of ordinary dark matter as "baryonic dark matter." Examples of baryonic dark matter include: cold clouds of gas, black holes, brown dwarfs, burned out white dwarfs, rogue planets, etc.

Searches using radio telescopes have observed significant hydrogen gas in the universe, but this is not considered to be "dark" as it emits electromagnetic radiation and can therefore be included in the visible matter budget. The prime candidate for baryonic dark matter is generically called a MAssive Compact Halo Object, or MACHO. As the name suggests, these objects would be massive and compact and exist in the halo of the galaxy, consisting of brown dwarfs, rogue planets, and similar objects.

Searches for these kinds of objects were performed in the 1990s[4] by collaborations with names such as MACHO, OGLE, and others. These experiments exploited the principle of gravitational lensing, first predicted by Orest Khvolson in 1924, but made widely known a dozen years later by a paper by Einstein.[5] When a massive body passes through the line of sight between a distant star and an observer, the star will appear to brighten as the massive body will act effectively as

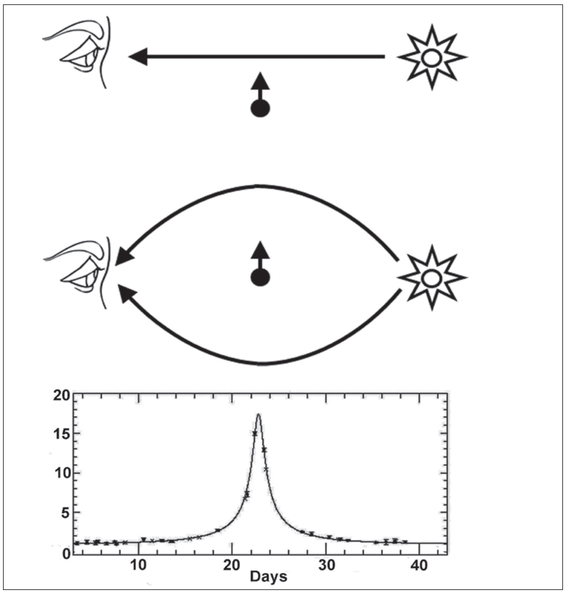

Fig. 2. When a massive body passes between a distant star and your eye (top), it will gravitationally lens the light from the star so that more light hits your instrument (middle). A representative brightening curve is shown in the bottom figure. The vertical axis is relative brightness, with the light output before the microlensing event normalized to unity. In order to guard against stars with naturally varying light output, several different colors are sampled to ensure that all colors brighten equally. If they do, this is a candidate microlensing event. (Figure adapted from Ref. 2.)

a lens and bend more light into an observer's instruments. Telescopes were turned toward the Greater and Lesser Magellanic Clouds and toward the galactic center. These targets provided a large sample of distant stars. If there are invisible compact massive objects in the galactic halo, they should occasionally pass in front of one of those distant stars. A characteristic brightening and dimming will be observed and the phenomenon is called "microlensing." The important principles can be seen in Fig. 2.

Each of about half a dozen experiments have observed a handful of microlensing events from stars in the Magellanic Clouds and typically an order of magnitude more from stars in the center of the Milky Way. After initial reports of a large MACHO component of dark matter, modern experiments conclude that the compact component of dark matter is no more than 20% of missing mass that is needed to explain the rotation curve of the Milky Way, with some experiments concluding that the fraction is much less and some measuring none at all.

Dark matter: Non-baryonic

If we can rule out compact dark matter as the explanation for the plethora of unanswered cosmic questions like the rotation curves of galaxies, what is left? It remains possible that there could be kinds of matter that are not baryonic. One possibility is relic neutrinos left over from the Big Bang. In 1998, neutrinos were shown to have a small but non-zero mass,[6,7] and there are a tremendous number left over from the creation of the universe. However, as we shall see, this is no longer considered a viable candidate.

Non-baryonic dark matter could be like a gas of particles that envelops the galaxy and suffuses the cosmos. We know these hypothetical particles must be electrically neutral and contain no quarks and gluons. Were they charged, they would be heated up by light from stars and galaxies and thus be observed. If they contained quarks and gluons, then cosmic rays would interact with them as they cross the universe, again to be observed. Thus these postulated particles must have mass (in order to have the desired gravitational footprint) and possibly interact via the weak nuclear force. If these particles are light, then they would have a high velocity and could penetrate great distances before undergoing a weak force interaction. Matter of this form is called "hot" dark matter. In contrast, if this kind of matter is heavy and slow, it would have a mean free path that is relatively small. This form of matter is called "cold" dark matter. Matter of intermediate mass is called "warm" dark matter. Note that the distance scale that is relevant is of order of tens or hundreds of thousands of light-years, roughly the size of a cloud of gas that will eventually collapse into a galaxy.

Simulations of how the universe would have evolved under the influence of the various possible temperatures of non-baryonic dark matter result in very different universes. If dark matter is hot, then the first structures will be large pancake-like structures of gas that eventually fragment into the observed superclusters of galaxies. This is called the "top down" scenario. In contrast, cold dark matter, due to the shorter distance it can travel before interacting, first forms proto-galaxies, which in turn eventually coalesce first into individual galaxies and then clusters of galaxies. Studies of the spatial distribution of galaxies out to distances of billions of light-years strongly favor the cold dark model scenario.[8]

This is not to say that the cold dark model is without problems. For instance, this model predicts that there should be more small satellite galaxies of the Milky Way than have been observed.[9] There is no answer to the question of dark matter that is without issues.

Still, the dark matter hypothesis that is considered to be the strongest is the cold dark matter one. This matter is a massive, slowly moving electrically neutral particle that interacts gravitationally and maybe via the weak force. Because we don't know the nature of this particle, it has been given the generic name of Weakly Interacting Massive Particle, or WIMP, in contrast with the earlier MACHO candidate for dark matter.

If WIMPs exist, then they should be everywhere. Depending on the mass of the WIMP, some few to tens to hundreds or so of them could be passing through you at any particular moment. If that is true, then perhaps this dark matter can be observed.

There are three major ways to potentially observe WIMPs: direct, indirect, and by creating them. Direct searches place detectors here on Earth, typically deep in underground mines. The basic idea is that WIMPs traveling through the Earth will interact with the detector and make their presence

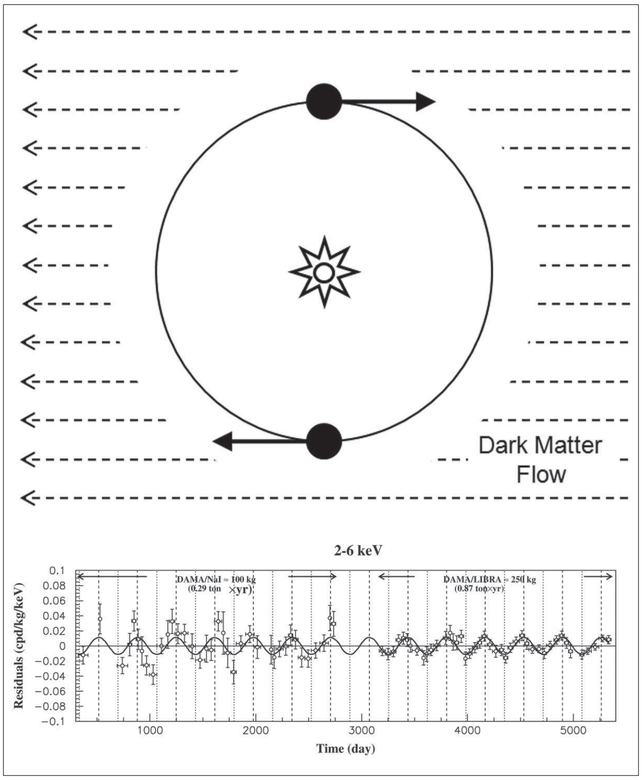

Fig. 3. Motion of the Earth through the WIMPs passing through the solar system results in a varying velocity between the WIMPs and the detectors. This variation could lead to an annual modulation in the experiment's observation rate of WIMP candidates.

known. There are dozens of dark matter experiments under way all over the world. The technologies include solid state detectors, liquid argon and xenon, bubble chambers, scintillator-based technology, and other approaches. Many technologies require that the detectors be cooled, some to millikelvin levels, although others not. Care is made to select materials that have minimal radioactive contamination. The detectors' location deep underground shields them from the ubiquitous rain of cosmic rays.

Most detectors have failed to find any evidence for WIMPs. Some have. The DAMA experiment has seen[10] an annual modulation in their observed signal, as illustrated in Fig. 3. This is to be expected if they are seeing dark matter. The way to envision this is to imagine dark matter as a wind passing through the solar system. At one point during the year, the orbit of the Earth carries it into the dark matter wind. This increases the relative velocity between the Earth-based detector and the dark matter particles. Six months later, the Earth will be moving in the same direction as the wind, reducing the dark matter/detector closing velocity. This variation in closing velocity should be reflected in an annual variation in signal, which is exactly what the DAMA detector has reported for over a decade. Many other detectors, some expected to have much greater sensitivity, do not confirm the DAMA result. On the other hand, in 2011, the CoGent experiment announced that they had observed the characteristic annual modulation. The experimental situation in the direct detection of dark matter is currently very murky, and new and improved detectors are coming online, hopefully to shed light on the situation.

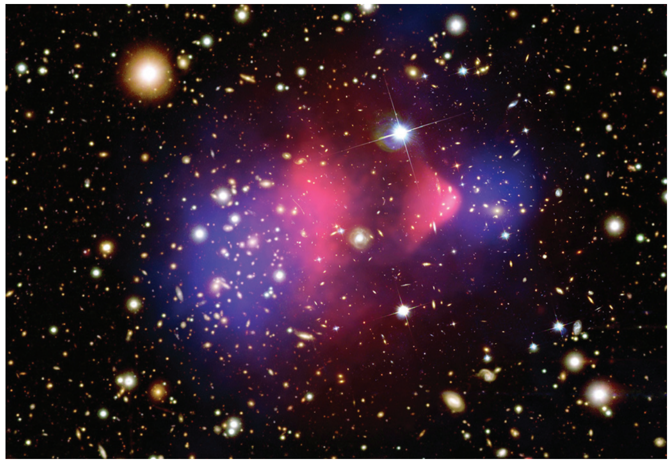

Fig. 4. This NASA image shows the collision of two clusters of galaxies. The red regions are hot hydrogen gas left between the two clusters as a consequence of the collision. The blue regions show where the bulk of the mass is to be found. This mass is co-located with the visible galaxies and is far larger than contained in the galaxies themselves. This observation is considered to be strong evidence that the cold dark matter hypothesis is correct. (Figure courtesy NASA.)

Indirect measurements are different. If dark matter particles exist and follow certain models, there should also be dark matter antiparticles. These matter/antimatter pairs should occasionally meet up in outer space and annihilate. These interactions may result in pairs of gamma rays or electron/positron pairs, which can be observed by satellite experiments. Like the direct measurement case, there are disagreements between various experiments.[11]

While it is puzzles from the cosmos that have led scientists to speculate about the existence of dark matter, if dark matter is some sort of as yet undiscovered subatomic particle, it is likely that this matter can be created in large particle accelerators such as the Large Hadron Collider at CERN. Just as the top quark was discovered in 1995 and like the July 2012 observation of a new particle that might be the Higgs boson, these particle accelerators convert energy into new forms of matter. Without knowing the nature of dark matter, it is difficult to know exactly how this will be accomplished. Theories containing supersymmetry have been proposed[12,13] to solve myriad particle physics conundrums. These mysteries are seemingly unrelated to the questions of dark matter, but one prediction of many supersymmetric theories is that there will be a stable electrically neutral and massive particle. Since these are the same properties expected to be carried by dark matter, it is natural that these experiments have drawn the attention of astrophysicists. Perhaps the first time dark matter is observed won't be from the cosmos, but created in the same detectors that may have discovered the Higgs boson.

MOND versus cold dark matter

If we return our attention to the message of the image on the cover, we recall that there are several unexplained observations that could be solved by one of several hypotheses. As described in this article, the baryonic dark matter solution is no longer viable, nor is the non-baryonic hot dark matter hypothesis. While the cold dark matter hypothesis is considered by most astrophysicists to be the most likely, there remains a small community of very passionate MOND enthusiasts. Given that dark matter has not yet been observed, it seems prudent to remain open to the MOND hypothesis. However, there is one observation that many have considered to provide definitive evidence that cold dark matter is the answer. This evidence is to be found in the aftermath of one of the grandest collisions in the universe, when two large clusters of galaxies passed through each other. This cosmic pileup is called the Bullet Cluster (see Fig. 4).

Prior to the collision, the center of mass of ordinary luminous matter (stars and galaxies), ordinary dark matter (hydrogen clouds), and "real" dark matter (cold dark matter) should have been more or less identical in each of the two clusters. When the two clusters collide, the stars and galaxies are expected to pass through one another, gravitationally slowed but essentially unchanged. The hydrogen gas clouds, being dispersed, should collide, heat up, and remain between the clusters as they pull away from one another. Both of these predictions have been observed. However, MOND and cold dark matter theories do make one different prediction. Since cold dark matter is at best weakly interacting, it is expected that the dark matter will be found in the same location as the luminous matter. In MOND, on the other hand, deviations from Newtonian physics should look like an excess of mass, where the bulk of the baryonic mass lies. This bulk is found in the hydrogen gas. Observations of the Bullet Cluster favor the cold dark matter hypothesis.

"Not so fast," claim the MOND proponents. While the cold dark matter hypothesis requires 10 times as much dark matter as ordinary matter, the MOND hypothesis reduces the need for unseen matter to be only twice the observed matter. This much smaller discrepancy could just be ordinary matter that has not yet been observed. Further, they note, the solution to the gravitational discrepancies seen in clusters of galaxies may be unrelated to the problem of the galaxy rotation curves. In riposte, the cold dark matter proponents note that MOND requires both the modification of Newtonian dynamics and some residual dark matter to explain the dynamics of clusters of galaxies, and that it is simply more parsimonious to assume only extra dark matter.

Summary

That there are many cosmic mysteries is undisputed. Galaxies rotate too fast to be explained by Newton's laws and the luminous mass. Individual galaxies in the outskirts of clusters of galaxies move so quickly that the clusters should have dispersed over time. Gravitational lensing that is qualitatively similar to the microlensing described here but on a vastly larger scale shows tremendous quantities of unobserved matter, dispersed throughout the universe. Something is definitely afoot.

The cover image gives an intuitive representation of the ongoing scientific debate. While the bulk of the scientific community favors the cold dark matter hypothesis, the debate is by no means settled. Until dark matter is observed by many experiments that tell a common tale and until dark matter is made at particle physics laboratories, the identity and even the existence of dark matter must remain an open question—one of the most tantalizing and important scientific questions in contemporary physics.

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