# Imagination and Invention

## The Story of Dark Matter

Vera Rubin

One of the most pressing problems facing today's astronomers and cosmologists is that of 'dark matter.' While often called the 'missing mass' of the universe, that name isn't quite right. Astronomers know where the mass is located. The light is what is missing. This is how dark matter gets its name. For reasons yet undetermined, dark matter is either very dim or completely non-luminous. Scientists currently think as much as 90% of the universe's mass might fall into this murky category. Dark matter has become a darling for science magazines and daily newspapers. Many of their articles point out that the best scientists on Earth must admit that they cannot explain what makes up the majority of the universe. That's not from lack of trying, though. For decades scientists have put forth ideas that try to answer one of their most difficult questions: *What is dark matter?* Here, we are going to look at how astronomers and cosmologists concluded that dark matter exists.

The quest to understand dark matter is a relatively recent undertaking, but it illustrates how scientists will put forth ideas regarding unseen matter to account for observed celestial motion. Today we have telescopes sweeping the sky for dim objects and multi-billion dollar machines hidden miles underground waiting for trace signs of theoretical particles. Given the prominent role played by dark matter in modern astronomy and cosmology, it's important to understand the history of dark matter.

**1. The history of dark matter illustrates an important aspect of how science works. As you read this story, consider how astronomers interpret unexpected observations. If observations don't fit a well-established idea, do you think that scientists should trust their observations and rework the idea, or trust that the observations must somehow be in error?**

Modern scientists have considered the possibility of unseen matter affecting celestial motion, aether aside, for over a hundred years. As early as 1903, the astronomer Agnes Clerke wrote in her book *Problems of Astrophysics*: “Unseen bodies may, for aught we can tell, predominate in mass over the sum-total of those that shine; they possibly supply the chief part of the motive power of the universe.” Astronomers of Clerke's generation understood this concept of unseen matter quite well, having grown up experiencing two famous controversies involving the planets Mercury and Uranus.

In the mid-nineteenth century, astronomers noticed that the orbits of both Mercury and Uranus were not behaving as predicted by Newton's gravitational law. Let's start with Uranus. Astronomers realized the (then) outermost planet was veering off of its predicted orbit. Rather than abandon the highly successful Newtonian framework, scientists put forward the idea that a massive object further out in our solar system was responsible for the anomaly in Uranus' orbit. The culprit turned out to be the planet we now call Neptune. The case of Mercury was very similar – its observed orbit didn't match its predicted orbit. Astronomers proposed the existence of a small planet, which they named Vulcan, inside of Mercury's orbit that caused the apparent anomaly in Mercury's orbit. As we now know, this planet would only be found in the mythical tales of *Star Trek*. However, efforts to gather evidence in support of Vulcan were unsuccessful. Eventually, Einstein's Theory of Relativity explained Mercury's motion by introducing a stronger curvature of space near the sun. These two examples give us a good grounding for moving forward to the next stage in the history of dark matter, when one eccentric scientist realized that the universe seemed to be hiding something.

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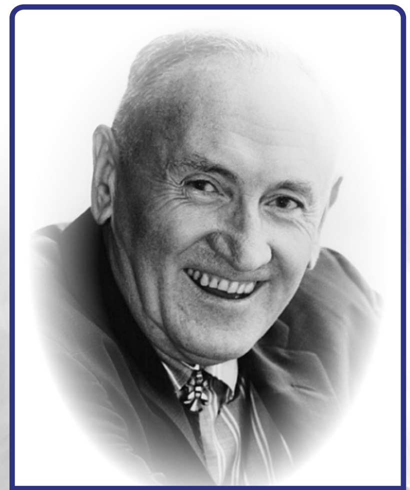
**The cases of Uranus and Mercury foreshadow many issues in the dark matter debate. Both Uranus and Vulcan were unseen masses put forward to account for anomalies in the orbits of known planets. With Uranus, the Newtonian framework was vindicated and an unseen mass (the planet Neptune) was responsible for the perturbations. With Mercury, the Newtonian framework was faulty and there was no unseen mass. Deciding whether prevailing conceptual frameworks can be preserved or must be abandoned are some of the most interesting aspects of doing science.**

If there's one myth worth debunking about science, it's that the field is filled with boring, lifeless characters. Fritz

Zwicky broke that mold in every sense. Born in Bulgaria, he retained his parents' Swiss citizenship, eventually going to Caltech in 1925 to study physics. On a campus noted for its bountiful sunshine, Mediterranean climate, and relaxed atmosphere, Zwicky stood out as a stubborn and opinionated fellow – the consummate European professor. A charitable man, he gave considerable amounts of money to orphanages throughout his life, but history remembers him as a near mad-scientist. Fearing a Japanese attack using chemical weapons on California during World War II, he developed a gas mask that could be fashioned from assorted household objects. He tested it on himself in an enclosed truck pumped full of gas, only to be rescued shortly thereafter by the Pasadena police department. The first chair of the astronomy department at the Palomar Observatory remembered one incident with him:


*Fritz Zwicky*

> I once went into Zwicky's office to reprove him for having raised the salary of the librarian without consulting me, causing an overrun in the budget. I was smoking a cigar, and as I started to yell and scream at him, which was the only way of commanding attention, he began coughing violently and clutching his chest and said at one point, 'I was gassed in the war, Jesse.' So I dashed out in the hall and got rid of the cigar and came back all apologies for having upset him. About a month or two later, it occurred to me that he was a Swiss national; he had never been in any army, not during World War I nor World War II.

Maybe he was referring to the gassing he gave himself.

This stand-out character of Zwicky is whom we owe the modern conception of dark matter, or as he first called it in German, *dunkel Materie*. He began by studying the Coma cluster of galaxies in the early 1930s, a time when observational astronomy boomed. Within the last decade, there had been considerable growth in our understanding that galaxies existed independently outside of the Milky Way, and that the universe expanded. A proposal had also been made that the universe began with a giant bang. Given all this excitement with galaxies, Zwicky obviously wanted a look. He began measuring redshifts in the Coma cluster, a collection of about 1,000 galaxies located 300 million light years distant. He determined that the galaxies had very different red shifts, meaning that they were gravitationally attracting each other. Curious, he decided to weigh the galaxies to see which one was doing the most attraction.

Weighing galaxies isn't like putting a scale underneath them and hoping they sit still. The only instrumental tool available to Zwicky, a telescope, measured light and not mass. The complexity of motions and distances in galactic clusters further complicated the situation, making analytic methods, like Newtonian or Einsteinian mechanics, too difficult. Instead, he reverted back to an equation used in thermodynamics, the *virial theorem*. Originally used for gravitationally bound particles, it can be applied to galaxy clusters if each galaxy is considered a particle. It requires that in a system, kinetic energy equals one-half of potential energy. Here's the virial theorem, expressed in algebraic form as an estimate,

$$M_{tot} \approx 2(R_{tot}V^2/G)$$

where M is total mass, R is total radius, V is an average velocity, and G is the gravitational constant.

Calculations can indicate the following things: 1) the radial extent of a system, 2) the mean square of the velocities of a system, 3) the total mass of the system. Here's an analogy provided by physicist Lawrence Krauss:

> Imagine that I drop a handful of marbles into a well whose sides and floor are very hard so that the marbles do not lose any energy when they bounce off them. As they fall, the marbles speed up. The deeper the well, the greater will be their final speed before they hit the floor. After they hit the floor they will rattle around the well, bouncing against each other and the walls. Since no energy is lost to the outside, their total energy of motion will remain the same. Thus, if we measure the average speed of the marbles after they have rattled around for a while, we can get a good estimate of the depth of the well. The same holds true for galaxies, or clusters of galaxies. Stars first form as diffuse gas particles 'fall' together under their own gravitational attraction. Galaxies form as stars 'fall' together, and clusters form as galaxies 'fall' together. It is reasonable that if no forces other than gravity are relevant and if the system has come into equilibrium, the relative velocities of the galaxies in a cluster should reflect on average the 'depth' of the gravitational 'potential well' into which they first fell.

Because the gravitational potential well is a direct function of mass in the area, measuring the motions of stars or galaxies in the system can tell us how much mass is nearby.

When Zwicky finished his measurements, he came to an astonishing conclusion: the visible mass could not account for the observed speed of the cluster. In his own words: “The average density of the Coma system must be at least 400 times greater than what is derived from observation of the luminating matter. Should this be confirmed, the surprising result thus follows that dark matter is present in a very much larger density than luminating matter." Zwicky had stumbled upon the very first observed evidence of dark matter.

More claims of dark matter appeared shortly after. The next year, 1934, Jan Oort, the namesake of the Oort Cloud, had been studying stars as they bobbed up and down across the galactic disc. He observed their speed to be far greater than permitted by gravitational attraction of the visible mass, leading him to also suggest a role in unseen matter. Then in 1936 Sinclair Smith at Mount Wilson Observatory announced that he had found the same occurrences in the Virgo cluster that Zwicky had found in the Coma cluster.

Faced with the possibility that the luminous universe might not accurately represent the real universe, astronomers had to decide on a path. They believed their model of gravity – the Theories of Relativity – explained observed phenomena with utmost accuracy. Astronomers also recognized their technological limitations. That is, their telescopes might not detect all the luminous matter. Uncertain about adding a new type of matter or revising relativity, astronomers put dark matter on the back burner for about thirty years while they focused on other problems. The discoveries in this period established the 'standard model' of astronomy and have often been called the "Golden Age of Cosmology." From 1945-1975, the Big Bang triumphed over the Steady-State; the origin of the atomic elements was understood; the discovery of quasars, pulsars, and radio galaxies stunned observers; and the Cosmic Background Radiation thrilled theorists. Zwicky continued to be on the fringes of astronomy, his work acknowledged but not enthusiastically pursued. The one who would pull dark matter from the – no pun intended – darkness, was a female astronomer, Vera Rubin.

**2. Astronomers decided to trust their theories and wait for further evidence in support of them. How does one's adherence to a theory affect his or her ability to accept a new idea?**

Rubin, born in 1928, faced great adversity for her gender throughout her career. Until the 1960s, women in astronomy (and in general, higher academia) were looked down upon. She was turned away from Swarthmore College for daring to be an astronomer, instead earning her undergraduate degree at Vassar College. Applying for her Master's, she got into Harvard and Cornell, eventually choosing Cornell because her husband was finishing his Ph.D. there. At Cornell the astronomy department (made up of two professors) practically told her to go away, but she persisted and made friends with notable professors in the physics department: Richard Feynman and Hans Bethe. She then got into Georgetown University for her Ph.D., again in an astronomy department that barely existed. Her husband, then working at George Washington University, would drive her to class at night and eat dinner in the car. During the day he shared an office with Ralph Alpher, George Gamow's former student. Through this association she managed to get Gamow on her dissertation committee despite their different universities, a decision that helped her career along greatly.

The boisterous Gamow sparked Rubin's career. She had practically dug her own grave after her Master's Thesis back in 1950. She examined one of Gamow's older ideas – that just as stars swirled around a galaxy, galaxies swirled around the universe – and checked if galaxies exhibited signs of this 'bouncing.' But as a female Master's student in a poor department, she had access to limited data. When she presented her information at an astronomy conference, she hardly received any other praise; many others told her to leave the field entirely. Her paper was turned down by every journal. Rubin became despondent and soon found herself dealing with a pregnancy. In her words,

> I actually cried every time the *Astrophysical Journal* came into the house. I knew that getting a degree didn't make me an astronomer, but nothing in my education had taught me that one year after Cornell my husband would be out doing his science and I would be home changing diapers.

After meeting Gamow – himself one of the most eccentric and respected scientists of his day – she saw a different way to succeed in astronomy than through brute data. As she remembered him,

> He was not technically competent at all. He couldn't spell; he couldn't do arithmetic – I may be exaggerating a little bit. But he could pose the questions that no one else thought of asking. He was incredible when it came to giving ideas. He did this throughout his whole lifetime. He wrote a postcard to Walter Baade, after a meeting that I had been to, saying, 'Tell me where the stars leave the main sequence, and I will tell you the age of the cluster.' He seemed to be the first person who understood what that meant. But I had been at that meeting with him, as a graduate student, and he embarrassed me no end because he would fall asleep and wake up and ask questions that I considered stupid questions. His behavior was unconventional. And then he would just understand things that no one else had understood. So it was fun, but I'm not smart enough to do science that way.

Encouraged to choose a dissertation topic that went against the 'party line,' she gathered evidence that galaxy clusters have a tendency to clump. This meant that vast empty spaces existed in the cosmos. Many astronomers assumed matter to be distributed somewhat evenly throughout the cosmos. Colleagues scoffed at Rubin's Ph.D. plan, but in time she would be vindicated.

**3. While there had been women astronomers before Rubin, few of them ever gained degrees and most of them gained their positions by starting out as assistants to established male astronomers. Beginning as an outcast among the males, Rubin found help from the eccentric Russian Gamow, himself a man against the grain. Rubin then flourished in studying non-traditional topics. While we like to think of science as presenting truth independent of the scientist, how does this example show how one's background and social affiliations affect their work?**

After graduation, in 1965 Rubin procured a job at the Department of Terrestrial Magnetism (DTM) in Washington, D.C. The DTM had been endowed by the generous donations of Andrew Carnegie, and followed a very different code than high-academia. Whereas the Ivy Leagues ran with a 'publish-or-perish' mentality, the DTM permitted its faculty the freedom to explore ideas with colleagues over time. Rubin did just this with Kent Ford, a keen instrumentalist. Ford had developed an image tube spectrograph, which looked like a series of glue cans stuck together. When photons entered, it set off a chain of electrons that hit a phosphorescent screen, amplifying the spectrum for investigation. This amplified the spectrum and made it much faster to collect data. In the 1920s, taking a spectrum of the Andromeda Galaxy could take up to 70 hours; with Ford's tool, it took 4.

Since Andromeda's disk is viewed nearly edge on from our solar system we can get a good measurement of its rotational speed from its spectrum. The stars in Andromeda, and other spiral galaxies, are concentrated towards the center and according to known gravitational theory, the rotation speed in the disk should be greatest near the center and less on the outskirts. Our solar system provides a good example of this; almost all the mass in the solar system is in the Sun and we find that Mercury whips around the sun at about 50 km/s while distant Neptune slogs along at only 5 km/s. Rubin and Ford expected motion like this, but they found the complete opposite. Measuring Andromeda and over a hundred other galaxies, they concluded that the matter at the outskirts moved just as fast as the matter near the central bulge. Speeds at the edge of the galaxies should have flung all the matter away, but obviously it hung in there. Again, the luminous mass didn't tell the whole story - there must have been something else holding the galaxies together. James Peebles and Jeremiah Ostriker corroborated this evidence. In 1973, they took all the data they had on the Milky Way and ran a computer simulation of the galaxy. It came flying apart. The only way to keep the galaxy together, they realized, was to add a 'dark halo' of matter. The diameter of this halo could be up to 10 times as large as Milky Way's visible disc.

In 1978, Rubin and Ford presented a thick book with rotational speeds of hundreds of galaxies, all of them 'flat' from the center to the edge. Her colleagues almost unanimously accepted her data, finally showing her due respect. The interpretation, however, left two gut-wrenching options: 1) Either the universe was filled with unseen mass, or 2) Our understanding of gravity was entirely wrong. Given that the Theory of Relativity had so far withstood every challenge, most scientists chose to accept that there really was unseen mass. This unseen mass, however, made up 90% of the universe, a fact that made many scientists queasy.

**4. Here's an example where scientists accepted their theory and proposed new entities to account for observation. Mendel did this in genetics (proposing “factors” without seeing genetic material). Chemists did this with atoms. How reasonable is it to make such propositions when the entity (in this case, dark matter) has never been directly observed?**

Contemporary astronomers use other methods outside of rotational speed and galaxy modeling to determine the existence of dark matter. They all agree that dark matter exists. The question that remains, then, is *what is dark matter?* Given this pressing question, it's worthwhile to see just how powerful the 'creative mind' can be in proposing new entities. While a very few scientists continue to posit that our understanding of gravity is wrong, the majority proposes two possibilities for dark matter: 1) MACHOs (MAssive Compact Halo Objects), and 2) WIMPs (Weakly Interacting Massive Particles). These objects are 'dark' because they are either incredibly dim or do not produce their own light, or do not interact with light and material objects.

MACHOs are generally non-luminous large objects, such as very faint brown dwarf stars, black holes, and Jupiter-sized planets. When dark matter became more widely accepted in the late 1970s, these objects had all been candidates for the 'missing mass' but none of them had yet been observationally detected. Currently, astronomers have ample observational evidence for the existence of all of them, including the existence of brown dwarfs harboring planets. The problem with giving credit to MACHOs, however, is that these objects simply aren't observed in sufficient quantities. If very small and dim brown dwarf stars were the culprit, they would need to be distributed throughout the galaxy such that there would be several within our own stellar neighborhood. This is not supported by the evidence. Black holes are by their very nature massive and invisible, but if they make up the bulk of dark matter, there should be so many of them that they would be easily seen by the illumination created as they devoured matter that crossed their path. Like the other two candidates, Jupiter-sized planets would have to be almost pervasive in the universe to account for the mass, something not supported by observation. While MACHOs probably account for some of the unseen mass, they certainly cannot account for all of it.

Then there are WIMPs. Most of the candidates for these types of particles have not been detected. So far, the only sure-fire candidate for a massive and weakly interacting particle is the neutrino ("neut" meaning neutrally charged and "ino" meaning "little one" in Italian). Neutrinos do pervade the universe – at this moment, trillions of them are passing through you. For decades they had been posited to be nothing more than a packet of energy and having no mass. But recent science has shown that neutrinos contain a very, very tiny bit of mass that has so far eluded exact measurement. By current estimates of neutrino densities and their upper weight limit, neutrinos would account for, at most, a few percent of the 'missing mass.' The very many other proposed particles go beyond the scope of this story.

The history of dark matter is rich, complex, and unfinished. Concepts of dark matter go back to the earliest history of scientific tradition. More modern estimations of dark matter have brought a new perspective to astronomy and cosmology. The story goes on in the depths of coal mines, where researchers oversee tanks filled with thousands of gallons of soapy liquid, awaiting the small tell-tale flicker of a crashing neutrino. It goes on in large telescope arrays, scanning the skies for planets and brown dwarfs. And scientists continue to devise new theories to explain dark matter. We are, however, confident that it is there.

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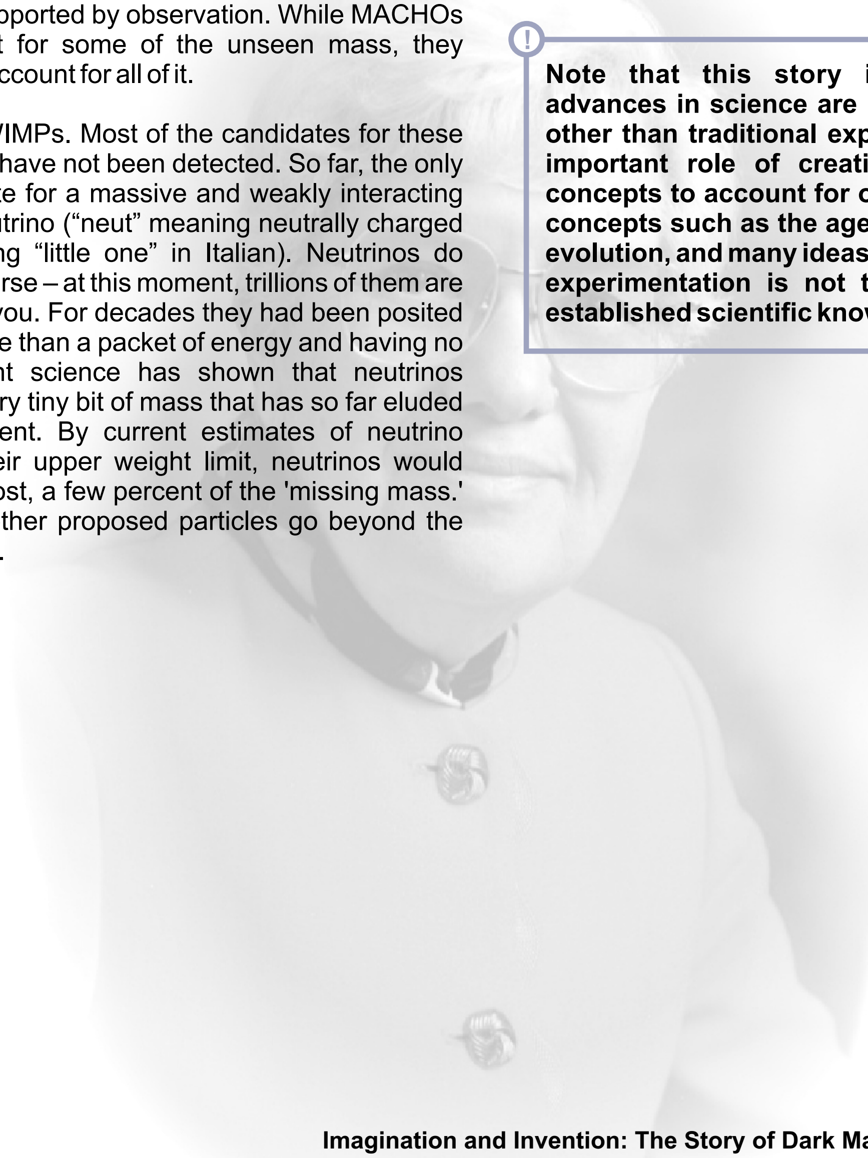
**Note that this story illustrates how many advances in science are made through methods other than traditional experiments. Consider the important role of creativity, and invention of concepts to account for observations. Like other concepts such as the age of the Earth, biological evolution, and many ideas in ecology and geology, experimentation is not the only route to well-established scientific knowledge.**



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