What is dark matter?

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1 Introduction: What is dark matter?

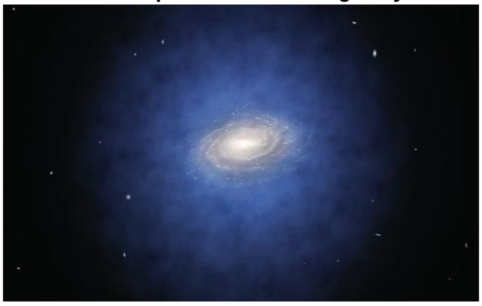
Dark matter is a mystery. It occupies a big percentage of all matter in space, but does not emit electromagnetic waves, so we cannot observe it.
Then, why do researchers think that dark matter exists? How can they try to discover it? What actually is dark matter? I will explain the answers to these questions.

2 Why researchers consider dark matter to exist?

2.1 The galaxies move too fast.

In the 1930s, Fritz Zwicky, a Swiss astronomer, studied the speed and mass of all galaxies in the Coma Cluster, and found that each of the galaxies moved faster than his prediction. If the speed of the galaxies was accurate, they would have been squeezed out of the cluster. In order for them not to be squeezed out, gravity is needed with a mass 400 times as heavy as all of the galaxies in the cluster. So he said that there is something we could not see, which has mass around the cluster. However, nobody agreed with him.

2.2 The speed of stars of a galaxy does not change.



When a star (mass is m, distance from the galactic center is r) revolves around the galactic center at speed v(v>0), the motion of this star is determined by balancing gravity by mass of all matter out of radius r with centrifugal force by rotation of the galactic disk.

$$\frac{GMm}{r^2} = \frac{mv^2}{r} \quad \text{(G: gravitational constant)}$$

(Gravity) (Centrifugal force)

$$\Leftrightarrow \quad v=\sqrt{\frac{GM}{r}}$$

According to this equation, the rotation speed of a star becomes slow in the distance between the galactic center and the star to minus half power. However, the facts are very different.
From the 1950s, Vera Rubin, an American astronomer, studied the rotation speed of stars of the Andromeda Galaxy. Through observation, she found that the rotation speed of the outer side of the galaxy is as fast as the interior. To solve this contradiction, she reached the same conclusion as Zwicky.

2.3 There is dark matter.

When two clusters crash, the gas which composes each cluster slows down, but dark matter goes through, keeping the same speed, because dark matter hardly interacts with any other matter. In 2006, the Bullet Cluster was observed. Now, almost all researchers think there is dark matter.

3 What does dark matter do in the space?

Before we think what dark matter is, we have to know what dark matter does in the universe. This is because the properties of dark matter are limited by how it works.

3.1 Properties of dark matter.

The properties of dark matter are

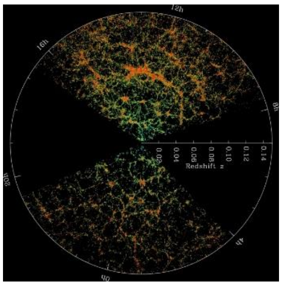
1. It hardly interacts with other materials.
   -If it interacted with them, we could discover it.
2. It has mass.
   -A galaxy abounds with dark matter, as above.

2’. It has mass more than 1 TeV.
   -Please see 5.3.1.

3. It does not emit electromagnetic waves.
4. It has existed since the young space.
5. It occupies about 23% of all matter and energy, and about 85% of all matter.
   -I wrote “matter and energy”. This is because matter and energy are essentially the same. ($E = mc^2$, E: energy, m: mass, c: speed of light)

3.2 Dark matter made the large-scale structure of the cosmos. (The reason for 4)

In 1999, Sloan Digital Sky Survey (SDSS) was started. Two hundred million astronomical objects are studied with a CCD camera, and a universe map within about two billion light years was made.



As a result, it was found that the universe has the structure of foam, and there are parts with little matter in the universe called "void". Dark matter has a relation to this structure. Soon after the universe's birth, dark matter was born. At that time, the universe is roughly though not completely, uniform, it is a little uneven. This condition is called "temperature fluctuations (=density fluctuations)".

In 1989, COBE (Cosmic Background Explorer) was launched. The mission was to research temperature fluctuations. COBE made a universe map which expresses them using the cosmic microwave background (CMB).

After that, the WMAP (Wilkinson Microwave Anisotropy Probe) was launched in 2001, and the Planck probed in 2009. From these sources, researchers got detailed data about density fluctuations.

According to the data, density fluctuations in the early universe (1×10^{-5}) are much less than that needed to make the universe now (more than 1×10^{-2}). The researchers thought that dark matter was gathered in those density fluctuations and baryon was gathered accordingly (Baryon has two meanings, one is a member of the proton family, the other is observable matter. In this article, baryon means the latter). This theory fits the observation results; dark matter needed to have existed for a long time.

Supplement 1: cosmic microwave background (CMB)

The CMB is microwave which is observed from all directions on the celestial sphere.

Supplement 2: calculation of density fluctuations

Assumption: Temperature fluctuations of CMB are δT.

The average temperature is $<T>$.

$$\frac{\delta T}{<T>} \sim 10^{-5}$$

Temperature fluctuations are the same as density fluctuations (P).

$$\frac{\delta P}{<P>} \sim 10^{-5} \cdots A$$

(In the early universe)

Bryon mass of a galaxy $(M_{gal}) = 1\times10^{11}\cdot M_{(\odot)}$
$= 2.0\times10^{44} g$

Volume of a mass $(V_{gal}) = \frac{4\pi}{3}R^3$
$= 4.4\times10^{68} cm^3$

The average density of mass of a galaxy $< p_{gal} > = \frac{M_{gal}}{V_{gal}}$
$= 4.5\times10^{-25} g/cm^3$

The critical density (pcr) $= 9.4\times10^{-30} g/cm^3$

The density of the average baryon mass in the universe

$(p_{baryon} > = 0.046\times(pcr)$
$= 4.3\times10^{-31} g/cm^3$

$$\frac{<p_{gal}>}{(p_{baryon}>} \sim 10^6 \cdots B$$

Comparing A with B, matter which makes up for 11vdigits.

4 What actually is dark matter?

Nobody knows for certain dark matter is. I will explain the different hypothesis of dark matter in this paragraph.

4.1 modified Newtonian dynamics (MOND)

In 1983, Moldehai Milgrom, an Israeli physicist, advocated modified Newtonian dynamics (MOND). According to this hypothesis, there is not unknown matter, but another force that we cannot explain with Newtonian mechanics. To put it concretely, MOND works as a force which is inversely proportioned to distance in a large sphere; Newtonian mechanics works in a small sphere. MOND is much bigger than Newtonian mechanics. So we do not need to postulate dark matter.

However, if this hypothesis is true, researchers have to change the conventional physical laws. They do not think it is natural. Therefore it is not most likely.

4.2 Baryon

4.2.1 Massive Compact Halo Object (MACHO)

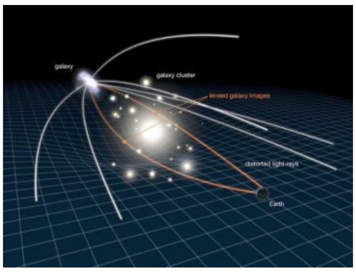
The halo is a part of the outside of a galaxy. The Massive Compact Halo Object (MACHO) is a baryon which is in a halo, for example, a brown dwarf, white dwarf or primordial black hole. A brown dwarf is an astronomical object which has mass less than 0.08 the mass of the sun ($1M_{(\odot)}$ =1.99× 10^{30}kg). A white dwarf is an astronomical object which is made from a star which has mass as heavy as $1M_{(\odot)}$. A primordial black hole has a mass up to m_{BH} ~ $10^5 M_{(\odot)}$. It is as heavy as the mass of 30 billion Earths.

In 1986, Bohdan Paczynski, a Polish astronomer, tried to observe MACHO using 10 million stars in the Large Magellanic Cloud. Of course we cannot see them. So he tried to use a "gravitational lens".

In the 1990s, two research teams, the MACHO and the EROS, observed the Large and Small Magellanic Cloud.

As a result, it is evident that there is MACHO, equivalent to 9% of the cloud halo dark matter. However, this result has doubts. Consequently, researchers reassessed their theories on dark matter.

Supplement 3: gravitational lens



According to the general theory of relativity, light curves at gravitationalfields. A gravitational lens is when the gravitational field of an astronomical object bends light from a star behind it, like a lens. In fact, because stars move randomly, when a star goes behind the lens object, the possibility of gathering light changes with time. This is called a "gravitational micro lens".

4.3 Elementary particle

4.3.1 Neutrino

A neutrino is a neutral particle which hardly interacts with other materials and does not emit electromagnetic waves. They have existed since the young universe as the cosmic neutrino background (CNB). In 1998, it was discovered that neutrino has mass, but it is too light to be dark matter. If dark matter is a neutrino, it moves at the speed of light and cannot make the large-scale structure of the cosmos.

4.3.2 Axion

An axion is a virtual particle which was introduced by Steven Weinberg, an American physicist, to explain the reason why CP Violation is not observed experimentally. PC symmetry regards particles and antiparticles as equivalent. The mass of an axion is one trillionth of that of an electron (10^{-6}~$10^{-3}eV$, 1eV:the power which is come into existence when an electron moves potential difference of 1V). Axions hardly interact with other matter, but change to photons in a strong magnetic field. Using this feature, axions can be detected.

4.3.3Weakly Interacting Massive Particle (WIMP)

This is an unknown elementary particle that is like a neutrino but heavier with a speed much slower than the speed of light. (N.B. WIMP does not mean any specific particle.)
There are some mysteries that The Standard Model of particle physics, which explains almost all experiment results, cannot explain.
To solve these problems, "supersymmetry theory" was advocated. It can explain them using supersymmetry partner particles, which are similar to all elementary particles. Among these, the ones which do not have an electrical charge are called "neutralino", for example, photino, gravitino, and so forth.
This neutralino is a good candidate for dark matter.

5 How to discover dark matter (WIMP)

I researched the reasons why it is said that there is dark matter in the universe and candidates of dark matter. Then, how do researchers try to discover it?

5.1 direct searching experiments

Direct searching experiment works for dark matter by using nucleuses. In rare cases, a WIMP hits a nucleus and flicks it. Then, dark matter has dozens of keV of kinetic energy because it moves at 1/1000 the speed of light. The recoil nucleus (the flicked nucleus) has energy as big as dark matter. We can detect dark matter by detecting this recoil nucleus.

5.1.1 Cryogenic Dark Matter Search (CDMS)

CDMS is an experiment that a research group led by Stanford University and the University of California at Berkeley is doing in Soudan, U.S.A. They use silicon and germanium and discovered two candidates for dark matter, but it is unknown whether they truly are dark matter.

5.1.2 XMASS

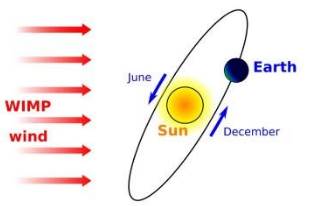
XMASS is a dark matter search experiment that Institute for Cosmic Ray Research University of Tokyo is doing in Kamioka, Gifu. The detector is 1,000 meters underground to protect the observations from electromagnetic waves which can prevent them being taken.
For this experiment, about 1 ton of liquid xenon and 1,000 tons of water are used. Water is used to block electromagnetic waves, and recognize muon (an elementary particle).
When dark matter flies into the detector and hits a nucleus of xenon, the nucleus ionizes another nucleus around it. Then, some energy is radiated as light. The light becomes stronger through photo multipliers, and it is detected as ultra violet by scintillator detectors.

There are three advantages to using xenon.

1. It is easy to establish more detectors.
2. There is a large amount of luminescence.
3. It does not have much background interference.
   -γ-ray and β-ray fly around us. When detectors detect them in error, we misunderstand that there is dark matter. If detectors use xenon, the reaction to dark matter and that of other rays is different. So, xenon does not have much background interference.

5.1.3 DAMA

Dark matter moves at 270km/s randomly. Our galaxy moves at 230km/s. So dark matter moves at 230km/s relatively. It is called "wind of WIMP". Furthermore, the Earth moves around the sun at 30km/s. Therefore, dark matter moves faster in spring and summer, and slower in autumn and winter. In short, the speed of dark matter fluctuates with the seasons. Observing this fluctuation becomes an important piece of evidence in discovering dark matter.



DAMA reported that they had discovered this fluctuation in 1998. This experiment has used NaI scintillator detectors. Since 2003, it has used bigger detectors, and this experiment is called DAMA/LIBRA. According to their report, the data fluctuates over a one-year period, but there is a doubt whether it is truly about dark matter. It may be a fluctuation of background.
Now, the project which they use to detect the fluctuation is in Antarctica called "DM-Ice". This is because the Antarctic does not have much background interference

5.1.4 Nagoya University's research

A research group in Nagoya University is trying to detect dark matter using an original detector. They use a Nano Imaging Tracker (NIT), a polymer made from carbon, nitrogen and oxygen which includes crystals of silver and bromine. When dark matter goes through this tracker, it hits electrons and silver ions and makes silver. They observe amplified silver. The advantage of this detector is that they can see the way dark matter went. It is easy to judge whether traces are about dark matter even if we can see the direction as above, 5.1.3.
Also, it can record dark matter if it has only small energy.

5.1.5 The others There are a lot of projects to discover dark matter as I have showed.

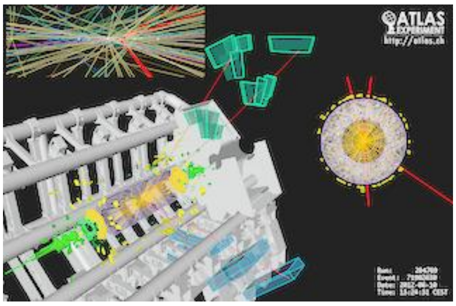
5.2 indirect searching experiments

Research teams in universities such as University of Tokyo, Carnegie Mellon University, and Stanford University try to observe γ-ray from center of a galaxy. There is strong gravity at the center of a galaxy, so dark matter gathers and seldom annihilates. Then they emit γ-ray.

5.3 Accelerator

An accelerator is a device to see the smaller structure of particles which produces various particles, including unknown ones, by crashing two high-energy particles together.

5.3.1 LHC (The Large Hadron Collider)



The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator in a suburb of the City of Geneva, Switzerland. It consists of a 27-kilometre ring of 1,232 superconducting magnets which are 15m long with a number of accelerating structures to boost the energy of the protons.
It first started in 2008 to discover the Higgs boson. It is known that the LHC succeeded in making one. Now the LHC is trying to discover the reaction that gives birth to dark matter. LHC can create a maximum energy of 14TeV. LHC is so far showing no signs of dark matter at 1TeV.

5.3.2 ILC (International Linear Collider)

ILC is an accelerator whose plan is discussed now as the next generation accelerator. The advantage of this is using electrons, the LHC uses protons. However, a proton is made from some elementary particles. So, extra crashes happen. The crash of protons is often compared to that of "manju". This is because a crashed proton is no less a mess than a crushed manju.
Meanwhile, electrons are elementary particles, therefore, two electrons can crash directly with small background interference. It may start in 2035, when the LHC will be retired.

6. Conclusion

The ways to discover dark matter are to detect, to make, and to observe. Though it is not certain which way will succeed in its detector, discovering dark matter is invaluable because it is one of the key that we can understand the origin of the universe.

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