Dark matter

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Dark matter is a hypothetical form of matter. It has to be postulated to describe phenomenons, which could not be explained by known forms of matter. It has to be assumed that the largest part of dark matter is made out of heavy, slow moving, electric and color uncharged, weakly interacting particles. Such a particle does not exist within the standard model of particle physics. Dark matter makes up 25 % of the energy density of the universe. The true nature of dark matter is still unknown.

1 Introduction

Due to the cosmic background radiation the matter budget of the universe can be divided into a pie chart. Only 5% of the energy density of the universe is made of baryonic matter, which means stars and planets. Visible matter makes up only 0,5 %. The influence of dark matter of 26,8 % is much larger. The largest part of about 70% is made of dark energy.

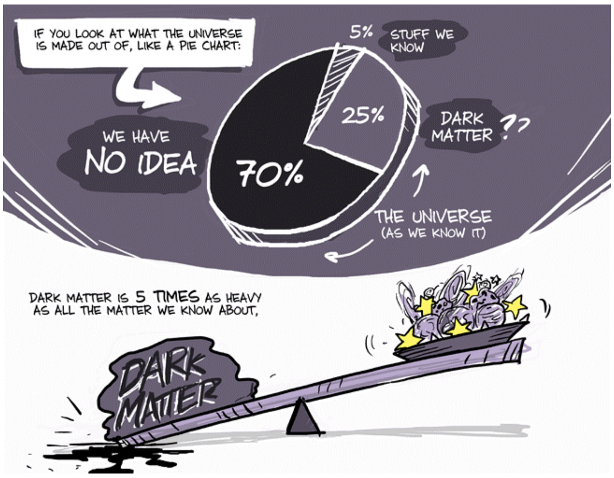

Figure 1: The universe in a pie chart [1]

But this knowledge was obtained not too long ago. At the beginning of the 20th century the distribution of luminous matter in the universe was assumed to correspond precisely to the universal mass distribution. In the 1920s the Caltech professor Fritz Zwicky observed something different by looking at the neighbouring Coma Cluster of galaxies. When he measured what the motions were within the cluster, he got an estimate for how much mass there was. Then he compared it to how much mass he could actually see by looking at the galaxies. It didn't add up. The galaxies were moving too fast within the cluster for the amount of illuminated stuff. By his calculation there should have been a 100 times more luminous mass to account for the random speed of the galaxies. [2]

2 Evidence of dark matter

2.1 Virial theorem

The time a galaxy needs to travel trough the cluster is much smaller than the age of the world, therefore it can be assumed that clusters of galaxies are relatively bound systems. The cluster is in viral balance

$$T = -\frac{1}{2}U. \tag{1}$$

The single mass, as well as the single velocity can not be measured directly. It has to be assumed that the system is spherically symmetric and in equilibrium, so that the velocity is uniformly distributed over all directions. $\langle v^2 \rangle$ is the deviation of the radial velocity from the cluster mean. The kinetic energy equals to

$$T = \frac{1}{2} M \cdot 3 \langle v \rangle^2. \tag{2}$$

The elevation energy equals to

$$U \sim -G \frac{M^2}{R}. \tag{3}$$

Putting the equations (1),(2) and (3) together yields for the mass

$$M \sim \frac{3R\langle v \rangle^2}{G}. \tag{4}$$

Inserting data of the Coma Cluster into (4) yields $M \sim 10^{15} \cdot M_\odot$. With $L_{tot} \sim 10^{13} L_\odot$ the mass-luminosity-relation can be determined to be

$$(\frac{M}{L_{tot}})_{Cluster} \sim 100 \frac{M_\odot}{L_\odot}. \tag{5}$$

Analysing the motions of all kinds of clusters shows that they cannot be stable unless there is a lager amount of mass than visible. But Zwicky's discovery was largely ignored. In 1932 he was one of the first to really grasp the significant presence of dark matter. He called it missing matter. What he didn't know then was, whether dark matter was just dark objects and galaxies that he couldn't see or whether it was something truly different. [3]

2.2 Rotation curves of galaxies

It took 50 more years for dark matter to attract interest. The american astronomer Vera Rubin provided a major contribution to this. She observed the rotation curves of galaxies similar to the Milky Way. Equating gravitational and centripetal force

$$m \frac{v^2}{R} = \frac{GM(R)m}{R^2} \tag{6}$$

and putting it in order to the velocity

$$v^2 = \frac{GM(R)}{R} \tag{7}$$

proves that the more stuff an object has, the more gravitational pull it should have. And the further an object is from the centre, the slower it should travel in orbit, because the gravitational pull declines, It should be likewise for a galaxy. Within the bulge the density is almost constant and the mass increases with the cube of the radius. In the bulge the rotational velocity increases linear to the radius, while in the disc the mass is constant. A decline of the curve is to be expected. The theoretical curve should therefore look like the disk in figure 2.

But Vera Rubin measured that with an increasing distance to the galactic centre the velocity of the orbiting gas and dust remained constant until the visible edge of the galaxy. She concluded that there had to be more mass. Otherwise the galaxy would have fallen apart. The only way to resolve that paradox was to assume that there is a halo of invisible matter surrounding the galaxy. [4]

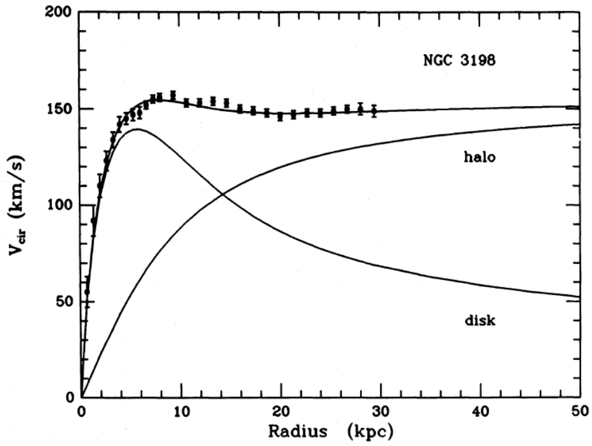

Figure 2: Rotation curve of NGC 3198 [5]

2.3 Bullet Cluster

Another important discovery was made in 2006. A clash of two galaxies called Bullet Cluster was observed. Analysing the spectral regions shows that the clash caused a strong separation of the individual components of the galaxy clusters. The stars and galaxies passed each other without interaction. The homogeneously distributed gas clouds interacted significantly and created the bullet like image (cp. figure 3). The maxima of the gravitational potential is not on the maxima of the visible matter density. Therefore there has to be an additional contribution of dark matter. The lager amount of matter is at the position of the galaxies and not, as expected, with the more massive gas clouds. Before the clash, the dark matter was homogeneously distributed in the galaxies as well as in the gas clouds. But while the gas interacted due to the crash the dark matter didn't, neither with itself nor with others. It travelled trough the gas clouds, which were slowed down. [2]

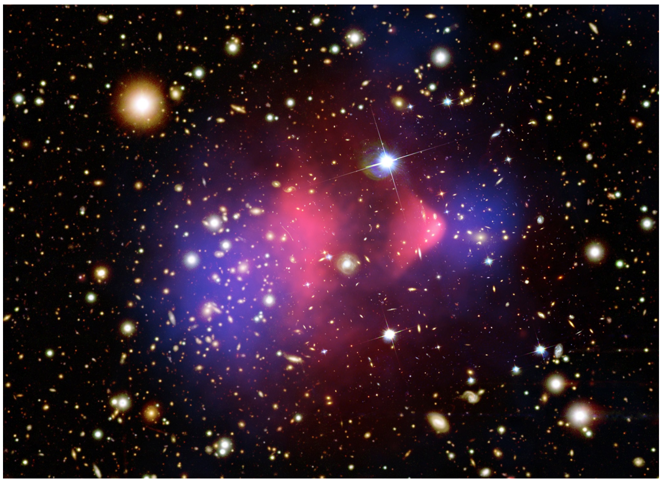

Figure 3: Bullet Cluster, blue: gravitational potential, red: x-ray emitting gas [6]

3 Searching for dark matter

3.1 Candidates

The existence of dark matter was postulated because the gravity of the existing visible matter in the universe could not nearly be enough to explain the clumping of matter in the early stage

of the cosmos. Scientists wondered if it was a new undetected particle or just invisible ordinary matter.
Black holes could be a possible explanation. They don't emit light, they attract matter and they are detected by gravitational lensing. All kind of Machos (massiv compact halo objects) like brown dwarfs were considered. They hide out in the halo of a galaxy, they have a large mass and do not emit much light. But there weren't enough to account for the amount of dark matter needed.
Neutrinos were suitable. Like dark matter neutrinos are passing through objects without interacting with them. But they are to light to account for dark matters effect on gravity. They are also too fast. Their speed would have prevented the clumping of the universe and thus the density fluctuation would have collapsed on large scales. Galaxy clusters would have formed first, followed by galaxies and stars (Top-Down-Scenario).
After excluding all the particles of the standardmodel as candidates, scientist believe that dark matter is an exotic new particle with the following physical properties:

1. Strong gravitational force
2. Weak interaction with other particles
3. Uncharged
4. Colour Force does not appear
5. Massive
6. Stable (13,7 billion years)

Today the most popular idea of what dark matter could be made of is something called a WIMP (weakly interaction massive particle). They weigh between 10 GeV and some TeV.
But there are a lot of competing theories to the dark matter particle like the Modified Newtonian Dynamics (MoND). It is a theory that proposes a modification of Newton's law of gravity to explain the galaxy rotation problem. [7]

3.2 Attempts to find dark matter

There are three ways to find a particle that corresponds to these properties of a WIMP:

1. Sit and wait, well shielded in a laboratory under a high mountain with a large, extremely sensitive detector, which allows to see one of the very rare clashes of a dark matter particle with a nucleus of the detector medium. It has to be isolated from background processes. Concrete realizations are the CRESST, Edelweiss, CDMS. They use cryogenic detectors made of pure germanium and cool it down to near zero temperatures. If the dark matter particle hits the nucleus it will change the temperature.

2. Hunting down dark matter in the space. Space telescopes such as AMS are studying centers of gravity to find high energy photons and neutrinos. Although dark matter is stable, they can annihilate in pairs in places where dark matter is highly concentrated. Scientists suspect that photons and neutrinos could be messenger particles for dark matter.

3. Creating artificial dark matter. When the high energy density in the early states of the universe could produce dark matter, then scientist should also succeed creating these particles with larger particle colliders at CERN.

No such particle has been detected so far. [2]

4 Conclusion

There is strong experimental and theoretical evidence that dark matter exists. The properties of a potential particle are very precisely determined. The standard model can not explain dark matter and is therefore at least uncompleted. Dark energy is even less explored. There is no need to be afraid about a future lack of tasks and challenges in physics.

References

[1] Jorge Cham: *Dark Matters - A Tales from the Road Comic* http://www.phdcomics.com/darkmatter/index.php?page=2 (2011)

[2] Sanders R.H. *The Dark Matter Problem A Historical Perspectiv* Cambridge University Press (2010) Spektrum der Wissenschaft (1983)(3)

[3] Klapdor-Kleingrothaus H.V., Arnowitt R.: *Dark Matter in Astro- and Particle Physics* Springer (2004)

[4] Rubin V. *Dunkle Materie in Spiralgalaxien* Spektrum der Wissenschaft (1983)(3)

[5] Albada, T. S., Bahcall, J. N., Begeman et al.: *Distribution of dark matter in the spiral galaxy NGC 3198* Astrophysical Journal (295)(1985) 305-313

[6] Composite Credit: X-ray: NASA/CXC/CfA/ M.Markevitch et al., Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al., Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.: *Astronomy Picture of the Day* http://apod.nasa.gov/apod/ap060824.html (2006)

[7] Klapdor-Kleingrothaus H.V.,Zuber K.: *Teilchenastrophysik* Teubner Studienbücher (1997)