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DARK MATTER: EVIDENCE, DIRECT AND INDIRECT SEARCHES*

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Dark Matter (DM) is thought to comprise the majority of matter in the universe. In these proceedings, we will briefly describe the plethora of evidence for the existence of Dark Matter, discuss alternatives in the form of changing the laws of gravitation and present some experimental efforts to discover the particle nature of the Dark Matter.

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1. Introduction

Observations, ranging from galactic to cosmological scales, have led to the so-called Standard Model of Cosmology. The model assumes the validity of General Relativity and contains a matter content that does not interact with photons — Dark Matter (DM), and a constant vacuum energy density that permeates the universe — dark energy. According to this model, the energy density in our universe is comprised of the corresponding energy densities of the known standard model particles ($\sim 5\%$), Dark Matter ($\sim 27\%$) and dark energy ($\sim 68\%$) [1].

In these proceedings, we will briefly describe the different types of evidence leading to this world view, with a focus on DM. We will also describe some alternatives to the DM paradigm in the form of modified gravity. Eventually, we will present different efforts to detect potential DM particle candidates, both via direct and indirect approaches.

2. Evidence for DM

The evidence for DM ranges over many scales, here we divide them to three main scales: cosmological, galactic and galaxy cluster scales.

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2.1. Cosmology

The general cosmological framework we address is the ΛCDM model, which is the modern face of the "hot Big Bang". The model itself has three basic assumptions:

— the universe is homogeneous,

— the universe is isotropic,

— the laws of physics are universal and do not change with position or time.

These three assumptions, with current models (most notably General Relativity and the Standard Model) lead to a picture describing the universe as we know it [2–5].

When we look at the ΛCDM history of the universe, there are two points in time which are very interesting for the DM question: the first is Big Bang Nucleosynthesis (BBN) [6], a time at which the primordial elements composition was determined (up to ^{7}Li), and the second is the Cosmic Microwave Background (CMB) emission, which is measured today.

From BBN, we learn that the ratio of the baryon number to photons is constrained to a value of $\eta \sim 3\times 10^{-10}$. The CMB measurements give a very precise measurement of the photon number [1, 7], which eventually leads to the conclusion that the density of baryons is $\Omega_b h^2 \approx 0.022$. Analyzing the full spectrum of CMB acoustic peaks leads to the conclusion that there is a non-interacting, non-relativistic matter component with a density of $\Omega_\mathrm{c} h^2 \approx 0.12$ — which is the DM component. When examining also large scale structure and SN Ia surveys, a consistent picture emerges, which sets the ratio between DM baryonic densities at about 5.5. Today, there is no viable way of explaining these observations without "adding" the cold DM component.

2.2. Galaxies

Observations of DM on galactic scales were the breakthrough which brought DM into the mainstream astrophysics. First published by Rubin and Ford [8], the rotation velocity of stars was measured for edge-on spiral galaxy Andromeda and later many others, have shown that the velocity of stars and gas does not decrease when going to radii much larger than the light radius r_*. An expected decrease of $v \propto r^{-1/2}$ is not observed, which leads to the conclusion that for steady state stability of the galaxies, an additional mass of non-luminous matter should exist with a density profile similar to $\rho \propto r^{-2}$. The missing mass appears to be larger than that of the visible matter, by factors ranging from around 6 for very large galaxies to many tens in smaller galaxies.

The observations of galaxies dynamics have been improving constantly, and today we see that all galaxies, of any mass and geometry, require additional mass which is significantly larger than that of the visible matter. Elliptical galaxies which do not have an ordered velocity structure are assessed using velocity dispersion and alternatively with gravitational lensing, and show the same behavior as well.

2.3. Galaxy clusters

The observations of DM in galaxy clusters are where the idea started, with Zwickey [9] measuring the velocity dispersion of separate galaxies in the Coma cluster and using the virial theorem to infer the enclosed mass. At the time of these observations, the discrepancy between the gravitational mass and observed mass, which was stars in galaxies, was more than 100, and the German term "Dunkle Materie" was coined by Zwicky to describe the non-luminous matter. Later development in observation techniques have significantly reduced this ratio to about 5, showing that the vast majority of baryonic mass is in the form of warm, X-ray emitting gas, that can only be observed from above the atmosphere. A very famous example of DM observation in a cluster is the bullet cluster [10], which is in fact a collision between two galaxy clusters. In this case, combined observation of optical light (for the galaxies), X-rays (for the gas, the main contributor to baryonic mass) and background gravitational lensing, following the distribution of total mass, was used. It is shown very clearly that the baryonic mass in gas is stopped in the middle of the collision and the galaxies continue ahead collisionless — both are expected. The lensing map of the mass shows, in this case, that the mass has moved with the galaxies without colliding, and is geometrically separated from the majority of the baryons (gas) which are staying in the center.

2.4. Alternatives to DM

Since all of the evidence supporting DM come from the dynamics that follow gravitational influence, one may attack the problem from a different angle — a change in the manifestation of gravity, either in the classical Newtonian laws or better, with a change of General Relativity, which is covariant and allows to create a solution of a Big Bang equivalent.

The most famous and successful of modified gravity theories is MOND (MOdified Newtonian Dynamics), suggested by Milgrom [11] in 1983 and generalized by Milgrom and Bekenstein. It also has relativistic extensions, however, these are still to show specific benefits. The MOND concept is originally derived from the flat rotation curves of galaxies, and the Tully Fisher (TF) relation. The TF relation [12], published first in 1977, correlates the rotation velocity far from the center of disc galaxies v_∞ with the luminous mass M_*, and the relation seems to follow $v_\infty \propto M_*^4$. Simple dimensional analysis shows that such a relation has the dimensions of acceleration, and this was employed by Milgrom to set a modification of Newton's second law. At low accelerations, the famous $F = ma$ relation is replaced by $F = ma^2/a_0$, where F is the force, m the mass, a the acceleration and $a_0 \sim 10^{-10}\,\mathrm{m/s}^2$ is a new, universal acceleration constant. In such a case, the different apparent mass deficiency is explained by the different acceleration felt by the objects rather than by adding DM.

The success of MOND on galactic scales is impressive and covers the full range of galaxy sizes from Dwarfs to the largest galaxies. When applied to galaxy clusters, MOND reduces the needed "missing mass" to only a factor of 2–3, but cannot explain the whole effect. The major downside of MOND is that it is not applicable to cosmological scales, which makes it impossible to compare with the great development if cosmological measurements in the past two decades, most notably the CMB anisotropies. A covariant theory of MOND might address this question, but this has not been done so far.

3. MACHOs

One of the suggested solutions for the missing mass problem was that baryons in the form of MAssive Cold Halo Objects (MACHOs), undetectable by light emission or absorption, supply the DM mass. A way to detect such objects was suggested, using microlensing. Microlensing is an event where the small, cold object is passing close to the line of sight to a star, and through gravitational lensing there is an amplification of the light of the star which is transient and can be detected by continuously observing the star. In order to find these events, one needs millions of stars to follow, and this was done by observing the Large Magellanic Cloud [13]. After a survey of several years, it was concluded that the density of such objects is much lower than the required DM, which means that they cannot be the solution.

4. Direct searches

Direct searches for DM try to find a DM particle from our local galactic halo, interacting with a target mass on Earth. Our solar system is traveling around the galactic center at a speed of roughly $v_\odot$ ~230 km/s, and the DM particles should have a mean velocity close to zero with a dispersion $\sim v_\odot$, from the virial theorem. Therefore, we can expect a DM particle stream at non-relativistic velocities, which, if we assume a non-zero cross section with standard model particles, would give occasionally an interaction of a recoiling particle in a detector. In order to avoid backgrounds coming from cosmic radiation, this type of experiments is performed in underground laboratories with overburden of over a km (water equivalent), and additional shielding against local radioactivity is used as well. Due to the low velocities, a typical interaction with an electron will usually not result in a detectable signal, and therefore, most experiments search for interactions with the nuclei in the target. Ability to separate interaction with electrons and the nuclei can greatly suppress the backgrounds, as most background radiation types will interact with electrons.

Additional knowledge about the interactions is helpful, most notably two features: 1. Annual modulation — the rate of interactions is expected to be higher in June and lower in December, owing to the rotation of Earth around the Sun. 2. Directionality — in case the direction of the original particle can be estimated, the velocity is expected to be pointed mostly against the direction of the solar motion around the galaxy. The annual modulation can be tested in many cases, however, directionality measurements in real DM experiments is still in preliminary stage and does not provide competitive results.

4.1. Claimed detections

A few experiments have claimed a detection of DM particles. Most notably, the DAMA/LIBRA experiment [14] claims to observe annual modulation of the rate of events. The detector is based on a NaI scintillator with a single channel and limited ability to distinguish backgrounds. The observed modulation is of the order of 1% of the total rate, and has a phase not far from the expected one from DM. Even though this claim is over 15 years old, there has not been a confirmation by other experiments, and many efforts have concluded that they do not see such a signal with higher claimed sensitivities.

4.2. Current leading experiments

A short and not full list of experiments, currently or recently producing results:

— CRESST II [15] (scintillation and phonons in $CaOW_4$) and CoGeNT [16] (ionization in Ge) have claimed detection and later withdrew or were corrected. Currently not holding a claim, and seem to be in tension with DAMA/LIBRA.

— CDMS [17], using a combination of phonons and ionization in Ge and Si, have ruled out DAMA/LIBRA, but reanalysis of 2006 Si run revealed 3 events where the expected was 0.7. This is not a claimed result due to low significance, but is sometimes considered as an "anomaly".

— XENON [18] and LUX [19] use liquid xenon dual phase Time Projection Chambers detecting scintillation and ionization. Currently, the most sensitive technology in most mass range (above ~ 8 GeV), have supplied null results which are in tension with the previous claimed detections.

5. Indirect searches

Indirect searches are typically looking for signatures in cosmic sources that could not be explained by "standard" astrophysics and can point to interaction, annihilation or decay of DM. These searches have to overcome the given systematic uncertainties regarding the actual processes and nature of the sources, which in many cases are non-trivial. We discuss only a few of the many searches, which are currently raising interest:

— PAMELA/AMS2: In 2009, the PAMELA satellite [20] measured the relative number of positrons to electrons in cosmic rays above 1 GeV, and found that above ~ 30 GeV the ratio turns up, which seems to be against the previous predictions. Hundreds of attempts to explain the result as decay or annihilation of DM followed, as well as many attempts to explain in terms of various astrophysics sources, such as pulsars or transients. In parallel, there are also explanations of the results showing that within the astrophysical knowledge and uncertainties the result matches the expectation [21]. AMS2 [22] had confirmed the excess and increased the range of energies, but still is compatible with the claimed limits.

— FERMI: In 2014, an analysis of the γ-ray emission from near the galactic center revealed a "bump" in the energy around 3 GeV [23], which does not seem to match any astrophysical type of source. Such an emission would be expected from DM annihilation into photons, which sparked interest in the subject. Criticism of this analysis was raised, showing that the feature appears after subtraction of "known sources" which leaves about 10% of the total flux in the bump, and may be fine tuned with the assumptions about those sources. This debate is still not resolved.

— CMB with PLANCK [1]: An unprecedented accuracy of the measurements of the CMB is provided by PLANCK, including polarization measurements and cross correlation with temperature. An example of a new type of observation is the search for tiny contribution of energy to the plasma at the time of CMB (age of the universe of $\sim 360{,}000$ yr), which may come from annihilation of DM particles. Since the spectrum shows no deviation from the expected spectrum, one can set limits on the annihilation rate, which, in turn, ruled out a thermal relic DM of any mass below 30 GeV. It also ruled out some classes of DM proposed to solve the PAMELA anomaly mentioned above.

6. Summary

We have discussed the different evidence of DM and possible alternative. In the second part, we presented just the major results of many different experimental efforts to find the particle nature of DM. To date, there is no widely accepted claim of detection of such and the parameter space to explore is very large. Experiments of all fronts are being performed and developed, which increase our sensitivity by orders of magnitude every few years.

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