Is the Dark Matter real?

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1 Historical Introduction

The idea of the dark matter was introduced 72 years ago, when the astronomer Fritz Zwicky studied the orbital motion of the Coma cluster. Zwicky provided evidence that the luminous mass of the cluster was much smaller than the orbital motion generated by the gravitational mass (1933).This idea was considered seriously after of seventies. Before, the astronomers only studied the rotation curves in the central part of the galaxies and it was normal to extrapolate the Keplerian behavior to large distances of the galaxies. Therefore it was natural to consider that the rotation motion of all the components in galaxies were caused by the luminous masses. The first measurements of the Hydrogen clouds far away of the center of the galaxies disproved this idea.

The hypothesis of the existence of matter to explain anomalous motions is historically. In 1846, for example, Galle discovered the planet Neptuno due to the irregular motion on the trajectory of Uranus. Therefore, the first hypothesis to explain the anomalous rotation curves, is to consider the existence of another type of matter.

To compute the rotation motion of the stars or hydrogen clouds located far away of the galactic center, we only need (extrapolated to galactic distances) the gravitation Newton equation (1), and, taking into account that a rotation motion has associated a centrifugal force, given by (2), we can use the Newton's law and obtain the equation [3],

$$F_g = \frac{GM(r)}{r^2}, \tag{1}$$

$$F_c = \frac{v(r)^2}{r}, \tag{2}$$

$$v(r) = \sqrt{\frac{GM(r)}{r}}. \tag{3}$$

Where v(r) is the average orbital velocity of the galaxy, G[1] is the Newton's Constant and M(r) is the mass between the galactic centre and the distance r. Following these equations, we can obtain that the orbital velocity decreases with the distance, as for example, the orbital velocity of the planets around the sun.If we calculate the orbital velocity of the Earth around the Sun, using (3), (considering solar mass M= 1.989×10^{30} kg, distance Sun-Earth r= $150 \times 10^6 km$) the rotation velocity is v= 30 kms^{-1}. For Neptune, which is 30 times more far away than the Earth, the orbital velocity is smaller, v= 5.4 kms^{-1}, as we expected.

[1] $G_N = 6.673 \times 10^{-11}\ m^3\ Kg^{-1}\ s^{-2}$

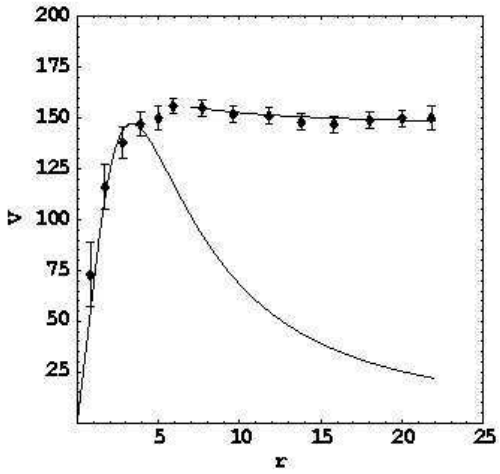

Figure 1: *Rotation-velocity curve plot for the spiral galaxy NGC3198, with v is in km/s, and r in kpc. The solid curve is the rotation curve expected from Newtonian theory of the gravitation for an exponential disk, and the dots are the measurements fitted with a model.(Ref [1])*

The figure 1 represents the rotation curve of the NGC3198 spiral galaxy obtained by the Doppler shifts of the line 21 cm. If we consider a spherical distribution of the galaxy mass, we can expect, following equation (3), that the velocity as a function of the distance r, decreases for large values of r as $v(r) \approx \sqrt{1/r}$. But measurements give us a constant velocity for large distances. Further measurements for different clusters of galaxies give the same flat section (constant velocity) to large distances. This is the first step of indirect evidence for the existence of dark matter.

Using the equation [3], and the results of the measurements, we can estimate the ratio between luminous mass and non-luminous mass (dark matter), that is $M_{DM} = 9M_{luminous}$. Several measurements for different galaxies give the same ratio at large scales.

If we consider the total density in a galaxy, including the dark matter, we obtain the following equation for the density as a function of the radius to the center of galaxy:

$$\rho = \frac{\rho_o}{1 + \frac{r^2}{r_c^2}}. \tag{4}$$

We can suggest that the dark matter is distributed in extended halos around the galaxies, where the central density ρ_o and the core radius r_c are

fitting parameters. Taking this into account, the dark masses should extend until a r_{max}, otherwise, the galaxy mass would be infinite. This parameter is determined by the further point measured.(Ref [4]). It could be that halos of one galaxy was extended until another galaxy.

Following own current understanding of the composition of the universe, we can estimate that (picture [2]) only a 27% is composed of matter. The baryonic matter contributes with only $\sim 4\%$ to the total mass density of the universe, and only $\sim 1\%$ of this is visible matter (as stars); The rest could be a new type of matter that we don't know. (Ref. [3])

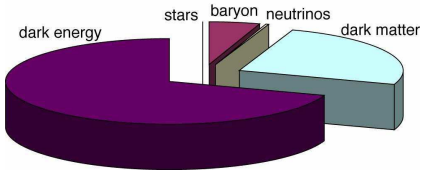

Figure 2: *The total distribution of the matter-energy in the Universe.(Ref [8])*

The cosmologists speak in terms of critical density, ρ_c, given by (from Ref [4]):

$$\rho_c = \frac{3H_o^2}{8\pi G_N}, \tag{5}$$

and then we define a Ω as the ratio between the density of the universe and the critical density, $\Omega = \rho/\rho_c$. If the density of the universe is bigger than the critical one, the universe will expand until its maximum and then it will contract itself (Big Crunch), that is refered to as closed Universe ($\Omega > 1$). In the case of that $\Omega < 1$, the universe will expand forever (open universe), and when $\Omega = 1$, the universe is flat (picture 3).

The latest measurements give $\Omega \sim 1$, it means that we are living in a flat Universe. Ω is a sum of all the density contributions, $\Omega = \Omega_M + \Omega_K + \Omega_\Lambda$, where Ω_M is the density of matter, which in this case is the sum of the barionic and non-barionic matter ($\Omega_M = \Omega_{DM} + \Omega_{BM}$), Ω_Λ is the density of the dark energy of the universe and Ω_K is the space-time metric contribution. Actually, the measured of the rotation velocity data for cluster galaxies and anothers methods predicts a density of Dark Matter of $\Omega_{DM} \approx 0.2 - 0.3$ (from Ref [4]).

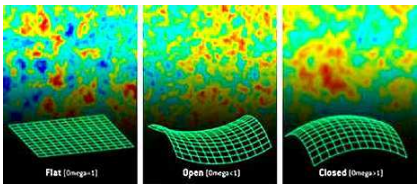

Figure 3: *The different geometries for the space-time of the Universe attending to the value of* Ω.

2 Could it be New Physics?

Are there others explanations? is it possible a new physics? In this paper we will introduce the most favourite theory that explain the DM, but in this section, we would like to remind that others alternatives were also proposed. As an example, in the following subsection we will explain the MOND-theory briefly.

2.1 The MOND-theory

The MOdified Newton Dynamics is an alternative to dark matter particles,it was proposed by Milgrom (1983) and the basic idea is to suppose that for small accelerations (large scales), the gravity strength decreases slowly. The modification consists of introduction of a constant with dimension of an acceleration, a_o. The Newtonian dynamics is a good approximation only for accelerations bigger than a_o, i.e. small scales. The modification implies:

$$\frac{a^2}{a_o} \approx \frac{MG_N}{R^2}. \tag{6}$$

This is the fundamental relation in this theory. If we consider large scales, $a << a_o$, the rotation velocity only depends of the total mass, $v^4 \approx G_N M a_o$. There is a coincidence, because the value of a_o is of the order of the product of the speed of light, c, and Hubble constant, H_o. This might be a hint for hidden physics. The big problem of this theory is the inconsistencies with the relativistic theory. Currently studies are still ongoing, e.g. by Bekenstein, to solve this problem.(Ref. [9])

3 Dark Matter Candidates

3.1 Baryonic Dark Matter

An obvious candidate for the dark matter is the invisible baryonic matter,e.g. in form of brown and white dwarfs, dust, objects like Jupiter, neutron stars and primordial black holes (all this astrophysical bodies are collectively known as MACHOs[2]). But Different observations, as the measurements of the distortions of trajectories in binary stars or studies of gravitational lensing effects on the light emitted from far galaxies, exclude this baryonic matter as dark matter (DM). The baryonic density is also limited by a good nucleosystesis model, which describes the distributions of the elements after the big bang. This model constrains the baryonic density to $\Omega_{DM} < 0.04$ (Ref.[6])

Another candidate ,which we know, could be the neutrino. It is a weakly interacting particle (but in Standard Model is defined as massless). Recent experiments, e.g. the Superkamiokande experiment and K2K[3], have proved the neutrino oscillation, as a consequence the neutrino has mass. In Several extensions of SM, as SUSY[4] or GUTs[5], the neutrino mass appears in a natural way.

There are three types (or flavours) of neutrinos, electronic neutrino,ν_e, muonic neutrino ν_μ, and tauonic neutrino ν_τ. The experimental upper limits to the total neutrino mass is given by $\Sigma m_\nu < 0.7eV$, sum for all types of neutrinos (Ref. [5]). This limit gives a contribution to the density between $0.0005 < \Omega_\nu h^2 < 0.0076$[6] which is very small contribution to Ω_{DM}. Since the neutrinos have relativistic velocities, they only could form the so called 'hot' dark matter. Therefore, new particles have to exist and they have to be non-baryonic matter.

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[2]Massive Compact Halo Objects.

[3]From KEK to Kamiokande experiment (Ref. [15]).

[4]The SuperSymmetry theory is an extension of the Standard Model. The theory propose the existence of a super-particle, associated to each particle, but with a half spin less than the particles. These super-partners are more heavy masses than particles known.

[5]Great Unification Theories. This theory is based in the unfication of the electroweak interactions with the strong interaction. The symmetry group associated is the SU(5). In this theory , the leptons can transform in quarks and vice versa. The main prediction of this theory is the decay of the proton ($p \longrightarrow e^+ \pi^o$). The lifetime of the proton is 2-3 $\times 10^{34}$ years. Several experiments was done to detect this decay but they had negative results.

[6]h is the normalized Hubble expansion rate, $h \sim 0.7$.

3.2 Non-Barionic Dark Matter

3.2.1 Conditions for Dark Matter

If the dark matter exists, it has to satisfy several conditions: It has to be non-baryonic matter, stable, cold, a weakly interaction, and has to explain the relic density of dark matter actually measured.
It must be stable on cosmological time scales, therefore the lifetime must be bigger than the age of the universe. The second one, cold, means that they have to be non-relativistic particles. If all the dark matter is hot one, that means relativistic particles (e.g. the neutrinos), it could not explain the formation of structures.
In the early universe, the matter was strongly coupled with radiation and any metric fluctuation that made a concentration of matter was eliminated. Since the first decopled interaction force was the weak interaction, the neutrinos and the dark matter did not interact with the radiation, it means that they were free. Therefore the dark matter could form gravitationally clusters and generate the distribution of the galaxies that we actually can observe.

The physicists have many ideas of what particle the dark matter could be: axions, neutralinos, Q-balls, wimpzillas, axinos,self-interacting dark matter, Kaluza-klein dark matter, branons and many other strange names.But in the following sections, we will speak of the particles which are the most probable as candidates, the axions and WIMPs (e.g. the neutralinos).

3.2.2 The Axion Candidate

QCD may include in its Lagrangian the following invariant term:

$$\frac{\Theta}{16\pi^2} tr(F^{`}{}_{\nu\mu} F^{\nu\mu}), \tag{7}$$

where, $F_{\nu\mu}$ is the strength field and $\frac{\Theta}{16\pi^2}$ describes the intensity of the interaction. This term is required for non-perturbative effects in QCD. An important prediction for this theory is the electric dipole moment of the neutron. But this term violates CP and it is refered to as 'strong CP problem'. Experimental bounds give a value of $\Theta \approx 10^{-19}$. Why is this a small value, when the strong interaction is of the order of 1? Reccei-Quinn proposed a new global symmetry U(1) (the Peccie-Quinn symmetry) which is spontaneously broken by a Goldstone boson, the so called Axion (similar to the Higgs mechanism) which explain the strong CP problem. Axions are coupled with ordinary matter with an intensity of $g_a \approx m_f/f_a$, where f_a is the dimensionful axion decay constant, related with the broken symmetry. Its value is between 10^9 GeV $< f_a < 10^{12}$ GeV. Its mass is given by:

$$m \approx 10^{-5} eV \times \frac{10^{12} GeV}{f_a}. \tag{8}$$

The limits of f_a implies a small coupling with the ordinary matter, therefore a very large lifetime and a lager mass. These are good qualities to be candidate for the dark matter.

3.2.3 The WIMP Candidate

The Weakly Interactive Massive Particles, WIMPs, are a further interesting candidate for dark matter. WIMP is coupled with the matter weakly and its mass is between 10 GeV and a few TeV (from Ref.[4]).

The first candidate for the WIMP is the neutralino[7]. It is a particle which appears in a natural way in the supersymmetry theory (SUSY). The neutralino, χ, is a superposition of the fermionic partners of the neutral electroweak gauge bosons, bino and wino[8], and the fermionic partners of the two neutral Higgs bosons, the higgsinos (χ_i i=1,2,3,4 where i represents the different particles). However, in the next sections we will speak in terms of WIMPs, and of this way, we will not exclude others possible candidates.

The WIMPs were in thermal equilibrium with the standard model particles and decoupled when they were non-realtivistic particles. When the temperature of the universe was of the same order of the WIMP mass, the number of WIMPs and photons were approximately the same. Therefore, the density of the WIMPs were $n_{WIMP} \approx T^3$ and the WIMP was annihilating with its antiparticle into lighter particles and vice versa. When the temperature was less than WIMP mass, the WIMP density dropped exponentially $n_{WIMP} \propto \exp^{-m/T}$, because the particles had not enough kinetic energy to generate the WIMPs or vice versa. Then this density of the WIMP is called relic density and it should be the same that the density observed actually. The picture 4 describes the before explanation but in terms of the expansion time ($t \propto 1/T$).

The theoretical density obtained is (Ref. [4]):

$$\Omega \simeq const. \frac{T_o^3}{M_{Plank}^3 < \sigma_{ann} v >}. \tag{9}$$

Where, $\sigma_{ann} \approx \alpha^2 / m_{WIMP}^2$ is the cross section of the annihilation of a WIMP pair (WIMP particle with WIMP antiparticle), α the coupling constant, v the relative velocity between the pair of WIMPs, $<>$ denotes the

[7]The neutralino should be the super-partner of the neutrino.

[8]Super-partners of gauge field B and W.

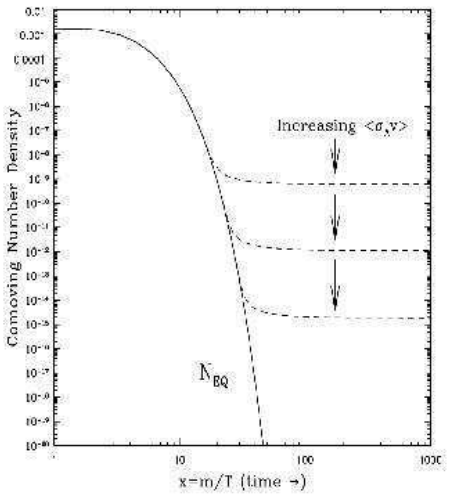

Figure 4: *Model of the WIMP relic density. The decoupling depends on the cross section. When the cross section is increasing, the relic density is decoupled later and then smaller.(Ref. [8])*

thermal average, M_{Plack} the Planck mass[9], and T_o is the temperature of the cosmic microwave background. This density can reproduce the observed relic density for the dark matter if we consider a WIMP mass of around 100 GeV and a cross section of the order of 10^{-9} GeV^{-2}.

4 How to detect the Dark Matter

4.1 Detection of WIMPs

The direct detection of the WIMP can be achieved by the effect of the elastic dispersion of the WIMP with a nucleus of the detector. For these cases we consider a cross section between WIMP and nucleus of the detector with a spin-independ [10] factor, this means the cross section scales of the order of

[9] $M_{Plank} = \sqrt{\hbar c/G_N} = 1.2210 \times 10^{19}$ GeV/c^2.

[10] The cross section of the WIMP with the matter depends of the nature of its coupling. We can distinguish between two, the spin-independent and the spin-dependent factor. In the last case, we have scalar and vectorial WIMP currents with the current of the nucleous, and in the other case, we only have axial WIMP current. For the case of the spin-independent the cross section scales are of the order of the square of the nucleus mass of the detector, and in the other case also, the cross section depends of the spin factor.

the square of the mass of the nucleus. The physical quantity measured in the detectors is the nuclear recoil energy. We have three different techniques to measure this quantity, based in: the charge, light or heat (picture 5). These effects are produced when WIMP interact with a nucleus.

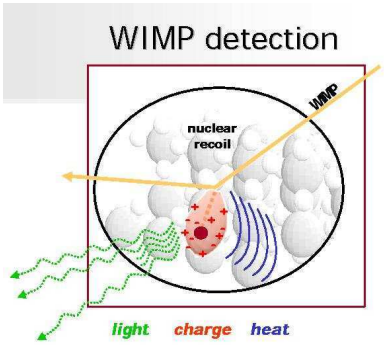

Figure 5: *Different techniques of WIMP detection.(Ref. [8])*

The density of dark matter have been measured more precisely in clusters of galaxies than in our galaxy, due to the position of the Earth in the galaxy. But some measurements give a spherical distribution of dark matter in our galaxy. Considering the radius from the Earth to the center of our galaxy, the density of dark matter should be $\rho \approx 0.3 GeV cm^{-3}$ (Ref [4]). If we consider that dark matter moves itself in the same gravitational potential, as the Sun, it should have a velocity of $v_o \approx 220 kms^{-1}$ (around the center of the galaxy). Supposing the WIMP mass of approximately 100 GeV, the density number is $n_o = 3 \times 10^{-3}$. Therefore the incident flux in the Earth is $J_o = n_o v_0 \approx 10^4 cm^{-2} s^{-1}$. This is a large number, however, the WIMP interact only weakly and make their detection very difficult.

Another important problem related to the detection of WIMPs, is the measured nuclear recoil energy, since the motion of the dark matter is low ($\approx 200 Kms^{-1}$) and is a heavy particle ($\approx 100 GeV$).The kinetic energy is only around 100 keV. The largest recoil energy transfered to the nucleus in the detector is obtained when its mass is of the order of the WIMP mass, that is few KeV. Same energies can be obtained through the cosmic rays that bombard the Earth constantly. Then , it implies to consider background experiments with very good discrimination signals. This protection is not enough because these signals can be produced by natural radioactivity of the surroundings (as rocks) and for the material of the detector itself.

There are many different experiments to detect WIMPs, but here we will concentrate on some of them. The technique to determine the energy recoil measuring the ionization charge is adopted by IGEX (Gran Sasso, Italy) and Canfranc (Huesca, Spain) with detectors based on Ge[76]. They have established an upper limit on the WIMP cross section (due to negative results) of $\sigma < 10^{-6} GeV$, considering a WIMP mass of 100 GeV. The problem with the germanium crystals is that only masses less or equal to 10Kg can be assembled.

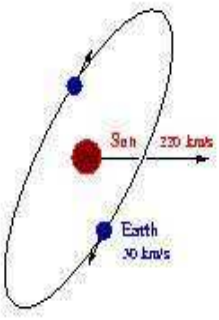

Figure 6: *Earth's motion around the Sun.(Ref. [6])*

The UKDMC (UK Dark Matter Collaboration) has the technique for the energy recoil measuring the light using scintillator detectors (composed by NaI).It is located at 1100 meters below ground at the Boulby salt mine (Yorkshire, UK). The detector mass ranging are between 1 and 10 kg. They started to take data in 1997.

4.1.1 The signal of DAMA

The DAMA detector (Gran Sasso, Italy) uses a different method to measure the signal, the so-called annual modulation signature. It measures the variation of the signal due to the different fluxes measured in June and December. To explain this, we only have taking to account the Earth's motion around the Sun (picture 6) where the velocity of the Sun around the galaxy center is $\sim 220 kms^{-1}$, the orbit velocity of the Earth is $\sim 30 ms^{-1}$ and its orbital plane is inclined at an angle of 60 degrees with respect to the galactic plane. As a consequence the flux of WIMPs should be larger in June (when the velocity of the Earth adds to the velocity of the Sun) than December.

The DAMA detector is located at 1400 meters below ground, it is composed by 100 kg of NaI. They started to take data in November 1996 and

run seven years. They found the presence of a yearly modulation (picture 7). It means, a positive signal of the WIMPs.

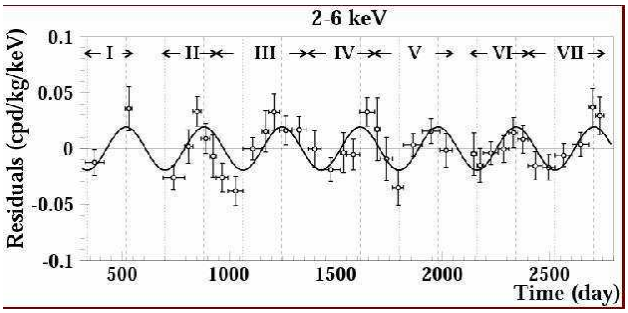

Figure 7: *Modulation detected along 7 years.(Ref. [8])*

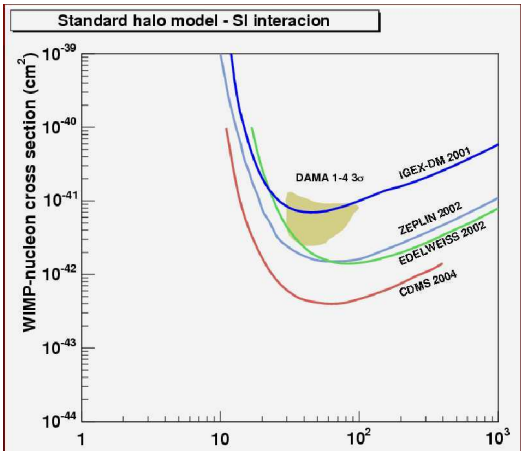

Figure 8: *The space parameter (σ and E[GeV]) for different experiments. The space parameter region of DAMA is in yellow. The CDMS and EDELWESSS do not agree with the Dama results.(Ref. [8])*

This possible signal is consistent with a WIMP of mass $\sim 30 - 200 GeV$ and a WIMP-nucleus cross section $\sigma \sim 10^{-6} - 10^{-7} GeV^{-2}$ corresponding to a rate of about 1 event per kg per day. These results are in agreement with the weak-interaction value of the supersymmetric model. But there are another experiments with different techniques (picture 8) which can not confirm the DAMA results. For example the Cryogenic Dark Matter Search (CDMS) experiment in the US uses two of the three techniques described

before to measure the signal. These are the temperature (heat) and the ionization (charge). This group obtained a similar rate than DAMA (13 nuclear recoils observed per 10.6 kg per day) but they said that these are neutrons of background particles which survives to the different barriers to stop them. The detector masses involved in CDM is not comparable with the DAMA-experiment (CDM used 165g of Ge for the first measurement and 100g of Si for the second one). This is an important difference which does not clear to confirm or to refuse the results of DAMA. DAMA will increase the detector mass from 100 kg to 250 kg to confirm their results, and new experiments are proposed to search the WIMP, as CUORE[11] and PICASSO[12].

4.2 Detection of Axion

The axions can come for different sources. The first one is the relic density of axionic dark matter, the second source is the Sun. Finally, it is possible to generate axions in the laboratory. The next sections describe briefly three techniques to detect axions depending of their production source. First, we will explain the Primakoff effect on which all detections techniques is based.

As we told in section 2.3, the axion is a neutral pseudo-escalar Goldstone boson which couples to photon as the following way:

$$L = g_{a\gamma\gamma}(E \times B)a, \tag{10}$$

where, $g_{a\gamma\gamma} = \frac{\alpha_s}{2\pi f_a}(E/N - 1.92)$ is the coupling constant. The transformation of the axion into photons in an electric or magnetic field is called the Primakoff Effect (diagram 9).

4.2.1 Axion Haloscope

The axion haloscope is used to detect the axionic relic density (it is based on the Primakoff effect). The axion is converted into photon inside of a resonant cavity. This cavity has a magnetic field and when the axion enters in the cavity, it interacts with a virtual photon of the magnetic field and generates a real photon which gives a resonance peak. This peak contains information about the axion model. The picture 10 is an scheme of this explanation. ADMX (in Livermore) is an experiment that use this technique.

[11] Cryogenic Underground Observatory for Rare Events. Ref [14]
[12] Project In CAnada to Search for SyperSymmetric Objects. Ref [13]

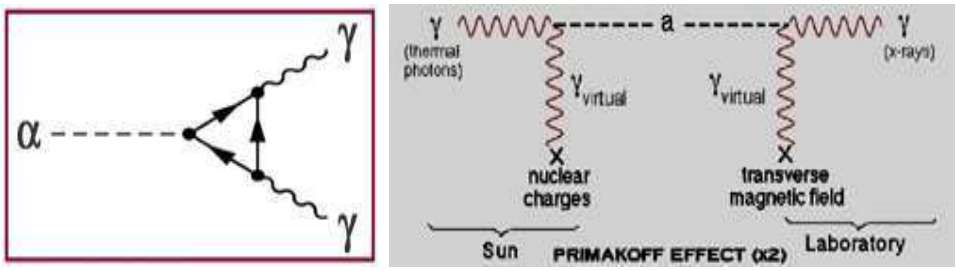

Figure 9: *The left picutre is the diagram of the axion coupling with two photons, the so-called Effect Primakoff. The right one showes the scheme of application of the Primakoff effect in the laboratory.(Ref. [8])*

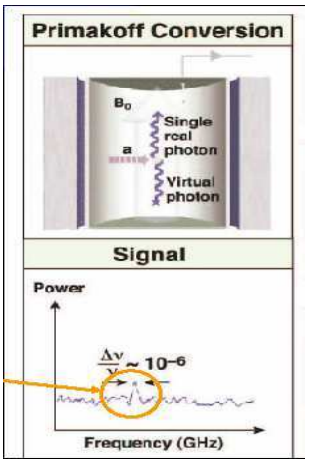

Figure 10: *Axion Haloscope technique to detect axion.(Ref.[8])*

4.2.2 Axion Helioscope

The axion helioscope is designed to detect axions coming from the Sun. The method is based in th conversion of the axion in a photon using a strong magnetic field (it does in the helioscope cavity) .The conversion generates X-rays which are detected by the telescope.

The CAST-experiment (Cern Axion Solar Telescope) is an example of an axion helioscope. It has a magnetic field of 9 Teslas, a telescope of length $L \sim 9.26$ m and a cross-sectional area of A $= 2 \times 14.5\ cm^2$. The results of CAST gave an upper limit of the coupling constant $g_{a\gamma\gamma} < 1.16 \times 10^{-10} GeV$ and the axion mass of $m < 0.02 eV/c^2$. The space parameter constrains by CAST in comparation with other experiments are shown in figure 11.

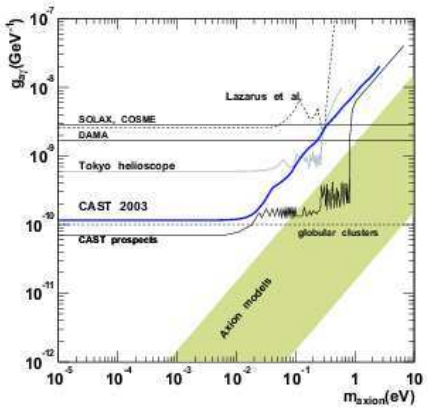

Figure 11: *The CAST 2003 data exclusions limits compared with others. The paramenters are not included in the axion models, but the next prospects will be inside.[7]*

4.2.3 Laboratoy Axion

Finally, we have the laboratories of axions. The study of the vacuum quantum field properties can give information of axion too.

In the PVLAS experiment in the Laboratori di Legnaro(Ref. [11]), a linear polarized photon is created. This photon passes through an external magnetic field ,which disturbs the vacuum quantum field. After, the properties of the photon are measured again. Since the quantum field theory predicts that the vacuum is not 'vacuum', but it is filled with pairs of virtual particles which are created and anihilated. The photon coming of the detector should be elliptical polarized. The polarization of the photon is different if the vacuum is filled of these 'vacuum particles'.This is so called Birefringence effect.

Taking into account the Primakoff effect, we can use the same experiment but supposing a coupling with virtual axions (in the 'vacuum') (diagram 12) and then studying the properties of the final state photon . From this measurements, information about the axion can be extracted.

5 Conclusions

It is clear that $\sim 95\%$ of the mass density of the universe is unknown. The latest experiments predicts the existence of this matter. There are many experiments which search the dark matter, but until now, no one has been able

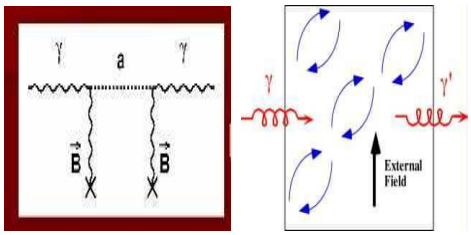

Figure 12: *The right represents the photon coupling with virtual axion in a magnetic field. The left one, a schematic figure of the birefringence effect in vacuum.The blue arrows represent pairs of particles which are creating and annihilating.(Ref. [8])*

to find a clear signal. The resolution of the detectors are still quite limited, so that a possible signal can not be distinguished from the background (e.g. the controversial signal of DAMA, section 4.1.1), a lot of effort is spent to improve the detectors. The next 5 or 7 years, many other experiments will obtain new results. I think that this is the most relevant time to find a direct signal of the existence of the dark matter. If the results are negavite, this might be a hint that the theoretical model has to be reconsidered.

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