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NEW CONSTRAINTS ON GALACTIC DARK MATTER*

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ABSTRACT

I discuss two aspects of the galactic halo problem. First, I review the experimental search for baryonic dark matter in our galactic halo. In one year, the data should either discover dark astronomical objects or put strong constraints on the baryonic constituency of the halo. Second, I present recent work that constrains non-gravitational interactions involving galactic dark matter.

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INTRODUCTION

In 1844, after accurate measurements of the position of Sirius, F.W. Bessel was able to infer the existence of a non-luminous (dark) object from its gravitational effects on the star. The object, a white dwarf that was named SiriusB, was observed 18 years later. In 1846, Le Verrier and Adams were able to explain the anomalous motion of Uranus by invoking an extra planet (Neptune) which was also observed later.

These two early examples of dark matter existence and detection should be contrasted with a historical counterexample. There was an attempt to explain the anomalous precession of Mercury by the gravitational effects of an inner planet, Vulcan, which turned out not to exist. The explanation of the effect came from what we might call "new physics": general relativity.

A century and a half after Bessel's remarkable prediction, we have evidence that a large fraction of the matter in the Universe is non-luminous. Discovering, in a way or another, the nature of this dark matter is one of the most pressing issues in physics. In addition, we have reasons, based on inflationary models, to believe that much of the dark matter is non-baryonic. In this case the dark matter should have a nature that is beyond the standard model of particle physics. In fact, we have some particle candidates for exotic forms of matter coming from well motivated extensions of the standard model.

Thus, the optimistic point of view is that we may inherit the best of the historical examples I was mentioning, namely, that we discover dark matter and new physics.

Dark matter has been proposed in different contexts and scales. There are very strong observational indications of the existence of dark matter in galactic halos and in clusters. Dark matter associated to our galactic disk has been proposed but its existence is dubious. In inflationary models one has a cosmological background of dark matter.

In this talk I will concentrate on galactic dark matter, which is sometimes thought as the one for which we have strongest evidence. For a recent review on dark matter, see Ref.[1].

Ongoing microlensing experiments will give very soon a definite and quantitative answer to the possibility that massive astronomical objects are the dark constituents of our halo. I present a short review of the motivations for such a search, and present the status of the experiments. I will also discuss recent work related to the possibility of non-gravitational interactions of dark matter.

GALACTIC DARK MASS

The Doppler shift of spectral lines allows to measure the circular speed v of matter at a distance r of the galactic center. The rotation curves $v(r)$ of spiral galaxies are well measured for distances r larger than the disk radius, r_{vis}, where stars, gas and dust are. In the case that all the mass of the galaxy is in visible form, M_{vis}, we have that, for $r \gg r_{vis}$

$$\frac{v^2(r)}{r} = \frac{GM_{vis}}{r^2} \quad . \tag{1}$$

Thus, we would expect a keplerian fall-off of the rotation curves for large r

$$v(r) = \left(\frac{GM_{vis}}{r}\right)^{1/2} \sim \frac{1}{r^{1/2}} \quad . \tag{2}$$

Instead of this behavior, it is measured that

$$v(r) \sim constant \quad , \tag{3}$$

for large r. Flat rotation curves are the common trend of all spiral galaxies that have been studied [2].

It is commonly accepted that the flat rotation curves of galaxies are the gravitational effect of galactic dark halos. Assume spherical symmetry and consider a sphere of radius r and with center the galactic center. In a first approximation it is clear that the dark mass contained in such sphere, $M(r)$, should increase linearly with the radius, i.e. $M(r) \sim r$, since then we will have the observed behavior

$$v(r) = \frac{GM(r)}{r} \sim constant \quad . \tag{4}$$

This simple analysis tells us already that for large r the dark mass density should behave as

$$\rho(r) \sim \frac{M(r)}{r^3} \sim \frac{1}{r^2} \quad . \tag{5}$$

To determine more precisely the mass distribution of the dark halo of our Galaxy, it is also assumed that it has spherical symmetry. This assumption is supported by numerical calculations, but it should be kept in mind that it is not experimentally proved. The dark halo density is then taken as a (non-singular) generalization of eq.(5)

$$\rho(r) = \rho(r_0)\,\frac{a^2 + r_0^2}{a^2 + r^2} \quad , \tag{6}$$

with r_0 the distance of our solar system to the center of the Galaxy,

$$r_0 \simeq 8.5\ kpc \quad . \tag{7}$$

The parameters a and $\rho(r_0)$ have been determined by several authors [3, 4]. One finds a local density

$$\rho(r_0) \simeq 0.01\,\frac{M_\odot}{pc^3} \quad , \tag{8}$$

and a core radius

$$a \simeq 6\ kpc \quad . \tag{9}$$

The local density is obviously crucial for experiments that aim at detecting the galactic dark matter, but unfortunately the number quoted in eq.(8) is subject to an incertitude of about a factor 2 [3, 4]. Also, the core radius a has a large incertitude, and may range from $a = 2\ kpc$ to $a = 8\ kpc$ [3]. A related issue concerns the total extent and mass of the Milky Way halo. Our galactic halo is probably more than a factor 10 larger that the galaxy itself in both mass and size [5].

We will just mention two lines of work which challenge the dark matter solution to the galactic rotation curves. One is the the Modified Nonrelativistic Dynamics proposed by Milgrom [6], which leads to flat rotation curves without a galactic halo (see Ref.[7] for a recent discussion of this approach). The other one refers to the possibility that spiral galaxies are opaque rather than transparent. The orthodox view is that spiral galaxies are transparent, except their central regions. An opposite conclusion was however reached by Valentijn [8], who analyzed a much larger set of galaxies. Dust is the source of opacity, and the observed rotation curves can be explained without a dark galactic halo. A very recent analysis analysis of the two spiral galaxies NGC3314 a and b has given support to the heterodox view, namely, that there is a high degree of dust obscuration in those galaxies [9].

BARYONIC DARK MATTER AND ITS SEARCH

Primordial nucleosynthesis allows us to understand the formation of the light elements. Their relative amounts can be calculated as a function of the number density of baryons, and then compared to the observed abundances. The analysis leads to a bound on the present density of baryons (as usual, we express densities in units of the critical density, i.e. $\Omega = \rho_{obs}/\rho_{crit}$),

$$0.01 \leq \Omega_B \leq 0.1 \quad . \tag{10}$$

This bound can be compared to the visible contribution to the matter density of the Universe,

$$\Omega_{vis} < 0.01 \quad , \tag{11}$$

to conclude that most probably there exist baryons that are dark.

A suggestion of where in the Universe are these dark baryons might be comes from the data on galactic dark matter that we were discussing in the preceding section. The data lead to the following contribution to the matter density of the galactic dark halos

$$0.03 \leq \Omega_{gal} \leq 0.1 \quad . \tag{12}$$

Comparing eq.(10) with eq.(12) the possibility arises than the bulk of the galactic dark matter is baryonic. This possibility may be considered as the most conservative assumption on the nature of the halo.

Baryonic dark matter could be in the form of brown dwarfs, that are compact hydrogenous objects with masses in the range

$$10^{-7} M_\odot \leq M \leq 0.08 M_\odot \quad , \tag{13}$$

where the lower bound must hold if the object has not evaporated in a galactic time scale [10], and the upper bound is the nuclear ignition threshold. It is encouraging that there exist simple examples of how the mass distribution of these non-luminous objects could be a smooth continuation of the corresponding quantity for optically visible stars, with the two distributions properly and independently normalized in an absolute sense [10].

Interesting enough, the domain in eq.(13) is where the efficiency of the searches for massive objects is high. In 1986, Paczyński [11] showed how to detect massive halo objects (MHO) in our galactic halo by means of their gravitational lensing effect on the images of stars in the Large Magellanic Cloud (LMC). The gravitational deflection of the light of the LMC star by the MHO leads to a time-dependent magnification of the original brightness of the source. Microlensing events (achromatic, they happen only once for a given star, well-defined and symmetric shape) would be a clear signature of the presence of massive objects in our galactic halo.

The scale of microlensing is set by the Einstein radius

$$R_E = 2\sqrt{GMDx(1-x)} \quad . \tag{14}$$

Here $D = 55\ kpc$ is the distance to the LMC and xD is the distance between us and the deflector of mass M. When the impact parameter (minimum distance between the undeflected line-of-sight and the MHO) is less than R_E the magnification of the star magnitude is more than 0.3 (a measurable shift). Since the MHO is moving with a velocity on the order of 220 km/s the microlensing event will last a time on the order of R_E/v_T where v_T is the relative transverse velocity (see Refs.[11, 10, 12] for details). The most probable lensing time T is

$$T \simeq 2\ days \sqrt{\frac{M}{10^{-3}M_\odot}} \quad . \tag{15}$$

Paczyński, in his paper [11], already evaluated that one needs to monitor on the order of millions of stars to be sensitive to a dark halo in form of MHOs. In 1990, several groups announced their decision to start experimental searches.

There are two main collaborations that have started to analyze data from microlensing searches. One is the MACHO Collaboration (Livermore + Berkeley CfA + Mount Stromlo + San Diego + Santa Barbara) [13]. Another one is the EROS Collaboration (DAPNIA Saclay + LAL Orsay + Institut d'Astrophysique de Paris + Observatoire de Paris + Observatoire de Marseille + Laboratoire d'Astronomie Spatiale de Marseille) [14].

The MACHO (Massive Astronomical Compact Halo Object) Collaboration has already done a preliminary analysis on about 1 million stars with no clear microlensing events. A review, where details on the status of the MACHO Collaboration experiment are found, has been recently written by Griest [15]. Here I will rather give details of the status of the French group [14, 16].

The EROS (Expérience de Recherche d'Objects Sombres) group consists of two programs [14] of observation of the LMC from the ESO observatory at La Silla (Chile). One of them, sensitive to masses [14]

$$10^{-4}M_\odot \leq M \leq 10^{-1}M_\odot \quad , \tag{16}$$

and corresponding to lensing times 1 day $\leq T \leq$ 1 month -see eq.(15)-, uses Schmidt plates of the LMC. They have taken 308 plates, and they need one year to treat the whole set of data. They expect 20 events if the halo dark mass is indeed formed by MHOs in the domain of masses of eq.(16).

The second program is the CCD program. It is designed to be sensitive to masses in the regime

$$10^{-7}M_\odot \leq M \leq 10^{-3}M_\odot \quad , \tag{17}$$

since this range leads to lensing times 1 hour $\leq T \leq$ 3 days. In March 1993 they had 8100 exposures [14]. Only a fraction of the total data has been analyzed, and for this fraction they expect 0.5 candidates. They again need one year to treat entirely the present data. This will result in about 10 candidates if MHOs form the halo dark matter and are in the range of eq.(17).

Thus the experimental efforts on microlensing searches currently made should in the next year or so give a definite quantitative answer to the possibility that MHO constitute an important fraction of our galactic dark mass. If the answer is positive, the next quantitative question will be to extract the mass function of this objects. Some work on a method (mass moments) to do that can be found in Ref.[17].

In the case of a negative result, the case for an exotic non-baryonic nature for the halo will be of course much reinforced.

NON-GRAVITATIONAL INTERACTIONS OF DARK MATTER

The arguments that lead to the need for galactic dark matter use the assumption that dark matter only gravitates (i.e. it does not couple to other feeble long range interactions). Since we still do not know the nature of dark matter it would be desirable to test this hypothesis as much as possible. From the phenomenological point of view we would like to bound the strength of an hypothetical new force that couples to what we may call darkness [18] (darkness might be lepton number, or baryon number, or an entirely new quantum number, or an arbitrary combination of all of them).

Several recent papers address in fact this question. The authors of Ref.[19] have reported results on the differential acceleration of *Be*, *Cu* and *Al* test bodies toward the galactic center. If one supposes then than an extra force coupling dark matter to ordinary matter is composition dependent, one gets interesting limits on the strength of the force. The study of Ref.[19], concludes that extra forces, in the case they exist, should be smaller than gravity itself.

Other work has been done by Frieman and Gradwohl [20]. These authors postulate a new interaction that couples dark matter to dark matter. A series of phenomenological inputs allow them to conclude also that the new interaction should not be greater than the gravitational interaction.

We have also recently addressed this question [18]. We use the neutrino data from SN1987A as probes of new interactions between neutrinos and dark matter. In the presence of a new interaction described by a potential $V(r)$ with "fine structure constant" α_d, and normalized such that $V(r_0) = 0$, the arrival times of two neutrinos differ by $\delta t = t_2 - t_1$ given by[18]

$$\delta t = \frac{r_0}{2}\,\delta\left(\frac{1}{T^2}\right)\int_0^{\theta_{SN}} d\phi\,\frac{1}{\sin^2\phi}V^2(r_0/\cos\phi) + O(\alpha_d^3)\ , \tag{18}$$

which depend on the the kinetic energies T of the neutrinos when they reach the detector at the Earth:

$$\delta\left(\frac{1}{T^2}\right) = \frac{1}{T_2^2} - \frac{1}{T_1^2}\ . \tag{19}$$

We have defined θ_{SN} in such a way that $\cos\theta_{SN} = r_0/r_{SN}$, with r_{SN} the distance of the supernova to the center of the Galaxy. Since neutrinos did arrive at the Earth within seconds, with different measured energies, it is possible to use the result of eq.(19) to bound new interactions.

The potential energy generated by the dark mass distribution in eq.(6), assuming a massless scalar or vector exchange with strength α_d, is easily found to be

$$V(r) = \pm 4\pi\rho_0\,\frac{a^2+r_0^2}{m_d}\,\alpha_d\left[\frac{1}{2}\log\frac{a^2+r^2}{a^2+r_0^2} + \frac{a}{r}\tan^{-1}\frac{r}{a} - \frac{a}{r_0}\tan^{-1}\frac{r_0}{a}\right]\ . \tag{20}$$

Here we have assumed that the mass of the dark matter constituent is m_d, and we assume each particle has one unit of darkness. It is easy to scale our results for other cases.

Using now the Kamioka results, we get [18]

$$\alpha_d \leq 9\times 10^{-40}\left[\frac{m_d}{1\ GeV}\right]^2\ . \tag{21}$$

This limit indicates that the non-gravitational interaction of two test bodies at rest endowed with a unit of darkness quantum number each is less than one order magnitude smaller than their gravitational interaction.

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