Baryonic Dark Matter: Theory and Experiment. Overview. †

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ABSTRACT

The general arguments for baryonic and galactic dark matter are presented. Limits coming from a variety of theoretical considerations and observations are discussed. The surviving candidates for galactic baryonic dark matter seem most likely to be in the form of compact objects and could be in one of two mass windows: either in the brown dwarf regime or in the mass range corresponding to supermassive black holes. Microlensing towards LMC is probing the first window. It is important to keep in mind that these experiments may detect compact heavy objects, independent of their constituency.

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1 INTRODUCTION

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

As we will see, there are strong indications that there is baryonic DM. A priori, this does not preclude the existence or even dominance of non-baryonic (mainly elementary particle) DM.

Of course in both cases the existence of dark matter is inferred from the comparison of the corresponding halo or baryonic density with the visible matter density.

In this workshop non-baryonic DM was reviewed by Berezinsky [1]. In my talk I will concentrate on baryonic and galactic dark matter, which are sometimes thought as the ones for which we have the strongest evidence. Other reviews on baryonic DM are cited in [2].

2 LIGHT AND MASS

We start quoting a recent estimation by Persic and Salucci [3] of the density of visible matter in the Universe

\[ \rho_v = \sum \int dL \phi(L) L \Upsilon_v . \]  

(1)

The integration is over the luminosity \( L \) and the sum extends to different galaxy types and hot gas in clusters and groups of galaxies. For each case, Persic and Salucci take the corresponding luminosity function \( \phi(L) \) and mass-to-light ratio \( \Upsilon_v = M_v/L \). Their careful scrutiny leads to

\[ \Omega_v = \frac{\rho_v}{\rho_{\text{crit}}} \approx 0.003 . \]  

(2)

As usual we normalize to the critical density \( \rho_{\text{crit}} = 0.69 \times 10^{11} h_{50}^2 \ M_\odot/Mpc^3; \ H_0 = 50 \ h_{50} \ km/s/Mpc \).

The key question is: Can we extrapolate this low density to other regions of the Universe? In order to discuss whether in general light is a good tracer of mass in the Universe, one considers the mass-to-light ratio

\[ \Upsilon = \frac{M}{L} , \]  

(3)

conventionally normalized to the value \( \Upsilon_\odot = M_\odot/L_\odot \). In the cores of galaxies, the visible contribution to \( \Upsilon \) is a few times the value of \( \Upsilon_\odot \). If light were a good tracer of mass, the value of \( \Upsilon \) would be about the same when going to different astronomical systems. However, the
values found in the cores of galaxies cannot be extrapolated to regions of lower luminosity. One indeed observes much larger values of $\Upsilon$ in a variety of systems with scales larger than galaxies. This shows that there is non-visible matter in the Universe; the DM manifesting itself through gravitational effects. One of the main goals of modern physics is to discover the nature of this DM.

From two points of view, the DM problem should be regarded as not too surprising. First, mass and light are already not well correlated even in main-sequence stars in our solar neighbourhood: the quantity $\Upsilon_{\text{star}} = M_{\text{star}}/L_{\text{star}}$ is strongly varying with $M_{\text{star}}$. It is the low-luminosity stars that contribute the most to mass: stars with $L < L_\odot$ contribute at least 75% of the total mass [3]. Second, there are many forms of stable matter that we may conceive of, some visible and some dark. From this point of view, it would be naive to think that all matter in the Universe should only be in visible form. Here we are thinking of very conventional forms of matter like brown dwarves but also of neutral stable particles arising in extensions of the Standard Model of particle physics, like axions or neutralinos.

3 BARYONIC DARK MATTER

We will discuss three important issues in connection with baryonic DM:

(a) The flatness of galactic rotation curves, which is the strongest observational evidence of DM. Galactic dark halos are the most natural place for dark baryons.

(b) Big bang nucleosynthesis, since it is sensitive to the baryonic density, which includes visible and dark baryons.

(c) The detected (LMC) microlensing events, that probably show that there is some baryonic DM in our Galaxy. However, it is not clear whether it is halo DM.

In this Section we shall discuss items (a) and (b). The microlensing events (c) will be discussed along with other limits on astrophysical DM in Sect.4.

Apart from all that, we would like to mention the recent ROSAT X-ray observations that seem to indicate that clusters and groups of galaxies could contain a relatively large density of gas [5], leading to a contribution $\Omega_B \sim 0.01$.

3.1 Galactic rotation curves

The rotation curves $v(r)$ of spiral galaxies are well measured for distances $r$ to the galactic center larger than the disk radius, $r_{\text{vis}}$. Stars, gas and dust are inside $r_{\text{vis}}$, and contribute a mass $M_{\text{vis}}$. If all the mass of the galaxy were in such a visible form we would have that, for $r$ much larger than $r_{\text{vis}},$

$$\frac{v^2(r)}{r} \simeq \frac{GM_{\text{vis}}}{r^2} \, .$$

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

$$v(r) \simeq \left( \frac{GM_{\text{vis}}}{r} \right)^{1/2} \sim \frac{1}{r^{1/2}} \, .$$

Instead of this behavior, it is measured that
for large $r$. Flat rotation curves are the common trend of all spiral galaxies that have been studied [6].

It is accepted that the flat rotation curves of galaxies are the gravitational effect of galactic dark halos. It is easy to see which is the required behavior of the dark mass density at large $r$. 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 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

$$v(r) \sim \text{constant} \quad (6)$$

$$v(r) \simeq \left( \frac{GM(r)}{r} \right)^{1/2} \sim \text{constant} \quad (7)$$

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

$$\rho(r) \sim \frac{M(r)}{r^3} \sim \frac{1}{r^2} \quad (8)$$

More precise determinations of the mass distribution of the dark halo of our Galaxy use also the assumption of spherical symmetry. (This assumption is supported by numerical calculations, but it should be kept in mind that it is not observationally proved.) The dark halo density is then taken as a (non-singular) generalization of eq.(8)

$$\rho(r) = \rho(r_0) \frac{a^2 + r_0^2}{a^2 + r^2} \quad (9)$$

with $r_0 \simeq 8.5 \text{kpc}$ the distance of our solar system to the center of the Galaxy. This halo form is sometimes referred as the standard halo. The parameters $a$ and $\rho(r_0)$ have been determined by several authors [7, 8]. One finds a local density

$$\rho(r_0) \simeq 0.01 \frac{M_{\odot}}{pc^3} \quad (10)$$

and a core radius

$$a \approx 6 \text{kpc} \quad (11)$$

The local density is obviously crucial for experiments that aim at detecting the galactic DM, but unfortunately the number quoted in eq.(10) is subject to an uncertainty of about a factor 2 [7, 8]. Also, the core radius $a$ has a large incertitude; one finds values from $a = 2 \text{kpc}$ to $a = 8 \text{kpc}$ in the literature. 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 [3].

The estimation of the galactic halo density depends on this total extent, and on the objects we choose to study the velocity dispersion. All the estimations lead to values higher than 2 \%.
\[ \Omega_{\text{halo}} > 0.02 \] ,

and a fortiori higher than the visible density \( \Omega_v \).

### 3.2 Big bang nucleosynthesis

Big bang nucleosynthesis (BBN) allows us to understand the formation of light elements in the early Universe (see the talk of G. Steigman at this workshop \[10\]). Their relative amounts can be calculated as a function of the number density of baryons. The theoretical calculations have then to be compared to the primordial abundances, obtained from the observed yields and taking into account the chemical evolution of elements. The analysis leads to a bound on the present density of baryons \( \rho_B \). Walker et al. \[11\] have obtained

\[ 0.04 \leq \Omega_B h_{50}^2 \leq 0.06 \] . \hspace{1cm} (13)

In updated analyses, Olive and Scully \[12\] have confirmed the range in eq.(13) while Kernan and Krauss \[13\] find the same lower bound than in eq.(13) but a lower upper bound \( (\Omega_B h_{50}^2 \leq 0.044) \).

Let us now compare the lower bound on the baryon density in eq.(13) with the visible density, eq.(2),

\[ \frac{\Omega_B}{\Omega_v} \geq \frac{13}{h_{50}^2} \geq 3. \] , \hspace{1cm} (14)

where the last inequality follows from \( h_{50} \leq 2 \). The meaning of eq.(14) is that at least 75\% of the baryons in the Universe are dark. More firm conclusions on this baryonic DM would be obtained sharpening the value of the Hubble constant \( H_0 \); for example, a value \( H_0 = 50 \text{ km/s/Mpc} \) would imply that dark baryons constitute more than 90\% of the total baryonic matter.

BBN shows that the bulk of baryons in the Universe is dark, and this is based on the lower bound in eq.(13). In turn, the precise value for this lower bound depends quite strongly on the deuterium D and \(^3\)He abundances. Recently, there has been some debate on these abundances.

First, there has been a claim of BBN crisis \[14, 10\] when using specific models of chemical evolution for D. However, a very recent reanalysis \[15\] of BBN conclude that predicted and measured abundances of light elements are consistent with 95\% credibility if \( \Omega_B h_{50}^2 \geq 0.028 \). We need more work along these lines to see whether the standard scenario is in trouble or not.

Second, some reports \[16\] on detection of D in low-metallicity, high redshift quasar absorption systems could indicate high primordial D densities which could affect the bounds on the baryonic density of the Universe. Based on these measurements (and on the X-ray observations we quoted in Sect.2), Dar \[17\] claims most of the baryons in the Universe are visible. However, there are other observations in absorption systems which lead to results that do not coincide with Ref.\[13\], perhaps showing that there are large systematic corrections to this type of measurements. Again, more observations and theoretical work would be welcome, since this important point should be elucidated.
A very interesting study has been performed by Fields and Olive [18]. Their idea is that, since using D and $^3$He abundances is controversial, one may use solely the more solid $^4$He and $^7$Li yields in the nucleosynthesis analysis. They obtain (95% CL)

$$0.02 \leq \Omega_B h_{50}^2 .$$  \hspace{1cm} (15)

As expected, the fact of not using D and $^3$He abundances as input weakens the bound (15). Still, since $h_{50} \leq 2$, there are more dark than visible baryons.

Finally, we would like to comment that it seems difficult to evade the bounds on the baryonic density. One can relax them a bit by invoking non-standard scenarios like inhomogeneous nucleosynthesis [19], or late decaying particles [20].

### 4 BARYONIC DARK MATTER CANDIDATES

In the last Section we saw that rotation curves are compelling evidence for galactic DM, and we also saw that comparing the baryonic density deduced from BBN we find evidence for dark baryons. It turns out that:

(A) the ranges for $\Omega_{\text{halo}}$ and $\Omega_B$ overlap.

(B) the most natural place for dark baryons is in the Galaxy.

The natural questions are: Are there dark baryons in the galactic halo? What is the contribution of dark baryons to the halo density? We will analyze in turn the plausibility of the different candidates for baryonic DM, starting with diffuse matter.

Dust forming the galactic DM would lead to too much starlight extinction, and is therefore excluded. Another conservative assumption on diffuse baryonic DM is that it is in the form of gas. However, gas with the required mass density and at the virial temperature of the Galaxy,

$$T_{\text{virial}} \sim m_p < v^2 > \sim 2 \times 10^6 K ,$$  \hspace{1cm} (16)

would emit soft X-rays that we should have detected.

Although this may exclude gas as DM, a word of caution is needed here. There are galactic scenarios in which cold molecular H$_2$ clouds exist at galactocentric distances larger than about 10 kpc [21]. These clouds could contribute substantially to the galactic halo density. In Ref.[21], the authors propose ways to observe such clouds. Another scenario has been recently developed in Ref.[22]. Here, substantial quantities of cold gas are stabilized by macho clusters.

Next, we turn our attention to galactic compact objects. We will review in the rest of the Section the constraints we have on their presence in the galactic halo. We first discuss limits on small solid objects, $M << O(M_\odot)$. Planet-like objects with $M < O(M_\odot)$ and the issue of microlensing and brown dwarves are discussed in Subsection 4.2. The last Subsection is devoted to very heavy galactic objects, $M > O(M_\odot)$. 
4.1 Snowballs

Could snowballs (formed by cold condensed hydrogen) be the baryonic DM in our halo? There are strong constraints on such objects.

For very small masses, a galactic population of snowballs has a high density (if they have to form the whole of the dark halo), and collisions among them would lead to destruction of such objects. This establishes a lower bound

\[ M \geq 1 \, g . \]  

(17)

Another effect is that such solid objects would continuously hit the Earth. The observed frequency of interstellar meteors and comets exclude the range

\[ 10^{-3} \, g \leq M \leq 10^{22} \, g . \]  

(18)

4.2 Brown Dwarves, Machos and Microlensing

The nuclear-ignition threshold for a hydrogenous compact object is

\[ M_{\text{nuc}} = 0.08 \, M_\odot . \]  

(19)

Below this mass, the objects are called brown dwarves.

Thermal evaporation of brown dwarves might be an important effect. If we require that a brown dwarf with mass \( M \) has not evaporated in a galactic time-scale we can set an absolute lower bound

\[ M \geq M_{\text{evap}} \simeq 10^{-7} \, M_\odot . \]  

(20)

Failed stars that have not yet evaporated are a galactic baryonic DM candidate. Their masses can be in the brown dwarf window:

\[ 10^{-7} \, M_\odot \simeq M_{\text{evap}} \leq M \leq M_{\text{nuc}} \simeq 10^{-1} \, M_\odot \]  

(21)

We will now examine constraints on such objects.

Although brown dwarves do not start nuclear reactions in their interior, they still generate some infrared luminosity. This has been investigated by Kerins and Carr [26]. If brown dwarves with a common mass \( M \) form the galactic halo, the expected distance \( < d > \) to the nearest one is given by

\[ < d > \simeq 1.2 \, M_{0.1}^{1/3} \, \text{pc} . \]  

(22)

\( (M_{0.1} \) is the mass of the compact object in units of \( 0.1 \, M_\odot \)). For a normal star, a distance \( O(\text{pc}) \) is small. However, a brown dwarf is very cold and then the expected flux [26] is too low to have been detected by IRAS. The European satellite ISO will be sensitive to brown dwarves with \( M > .01 \, M_\odot \). In any case, the microlensing effect is a much more efficient way to detect brown dwarves if they form a substantial part of the galactic halo, so that we deserve the rest of the Subsection to that effect.
In 1986, Paczyński [27] showed how to detect massive halo objects in our galactic halo by means of the 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 halo object leads to a time-dependent magnification of the original brightness of the source. The effect depends on the gravitational field of the object, and not on the composition. Microlensing events could thus be a signature of the presence of dark galactic objects, independently of whether or not they are hydrogenous (brown dwarves). We will refer to the deflector as macho, for massive compact halo object.

The scale of microlensing is set by the Einstein radius

$$R_E = 2 \sqrt{GMDx(1-x)}$$

$$= 6.7AU \frac{M^{1/2}}{M_{0.1}} \left( \frac{x(1-x)D}{55 \text{kpc}} \right)^{1/2}$$ (23)

Here $D = 55 \text{kpc}$ is the distance to the LMC and $xD$ is the distance between us and the deflector of mass $M$. In eq.(23) we also show the value of $R_E$ as a function of $x$ and $M_{0.1}$. We see that the value of $R_E$ is large compared to the expected typical radius of the galactic object (for reference $R_\odot = 0.0046AU$).

Paczyński, in a seminal paper [27], evaluated that one needs to monitor on the order of millions of stars (in the LMC) to be sensitive to a dark halo in form of machos. The microlensing signature (when both the source and the lens are single and point-like) is clear: achromaticity and non-repetitiveness of the signal, and light-curve magnified by the time-dependent factor

$$A(t) = \frac{u^2 + 2}{u \sqrt{u^2 + 4}} ,$$ (24)

leading to a magnification with a shape symmetric in time. (The shift in magnitude is given by $\Delta m = -2.5 \log A$.)

In (24) the time-dependent parameter $u$ is the distance $d$ of the macho to the line of sight in units of the Einstein radius

$$u^2 = \frac{d^2}{R_E^2} = \frac{b^2 + (v_T t)^2}{R_E^2} .$$ (25)

The distance is of course changing with time since the macho has a relative transverse velocity $v_T$. The minimum value of the distance, $b$, is called the impact parameter. It is at the moment that $d = b$ (closest approach) that the amplification is maximal (it happens at $t = 0$ by definition).

How large is the maximal magnification depends on the value of $b/R_E$. When $b$ is less than $R_E$ the change in the star magnitude at the peak of the effect is more than 0.3 (a measurable shift).

As it follows from what we say, $u$ (and $A$) are functions of time; microlensing is a transient effect that lasts a time on the order of $T = R_E/v_T$ (see Refs. [27, 23, 28] for details). The most probable lensing time $T$ depends on the mass of the deflector and, for a standard halo and velocity distribution, is given by
\[ T \simeq 20 \text{ days} \sqrt{M_{0.1}}. \] (26)

Given a microlensing event (and always assuming that the source and the deflector are point-like), one deduces two parameters: the maximal amplification and the lensing time \( T \). The physical effect, however, depends on four parameters: \( M, v_T, d \) and the distance where the lensing took place, \( xD \). It follows that in an event-by-event basis we are not able to identify the precise values of these four variables.

In 1990, several groups announced their decision to start experimental searches. The French collaboration EROS [29] and the American-Australian collaboration MACHO [30, 31] have reported the detection of microlensing events, discovered by long-term photometric monitoring of stars in the LMC.

When monitoring towards the galactic bulge, a high number of events have been found, as has been reported by the Polish-American collaboration OGLE [32] and by the MACHO group [33]. These observations can help to further understand the (conventional) galactic structure, and so may indirectly help to clarify the dark halo properties. Other collaborations are currently searching for microlensing: the DUO [34] and the VATT-Columbia groups.

The group AGAPE [35] has started a microlensing search in the Andromeda galaxy (M31) direction. They monitor pixels rather than individual M31 stars. The experiment is complementary to other microlensing searches since the M31 line of sight is very different from the LMC and bulge directions. As we will see, probing the halo in various directions will probably be of crucial importance for the whole issue of brown dwarves in the galactic halo.

The MACHO group has recently presented [31] an analysis of the first year data of LMC results, that correspond to a total exposure of about \( 10^7 \) star-yr. They find three events consistent with microlensing. When comparing their results with the expectations from a dark halo having the form in eq.(9) -they call this form the standard halo- they are able to assess that the macho mass fraction \( f \) of the dark halo is less than 0.5 in the macho mass range

\[ 3 \times 10^{-4} \leq \frac{M}{M_\odot} \leq 0.06. \] (27)

Thus for the standard spherical halo \( \mathcal{H} \) machos in the range (27) cannot constitute more than half the dark matter density. However, this limit depends on the halo model, as emphasized in the MACHO analysis. A very massive halo (with rising rotation curve) would imply stronger limits, but an extreme maximal disk model with a very light halo would not give useful limits [31]. A change in the halo shape would also alter the conclusions.

A related analysis [36] takes into account the different Galactic components: luminous and dark disk, bulge and Galactic halo with machos and cold DM. They vary parameters as to generate millions of Galactic models. These models are of course restricted to agree within the errors with the observational data, including the microlensing data towards LMC and also towards the bulge. They conclude that most viable models have \( f < 0.3 \). They find that Galactic models with a high proportion of machos have a light halo (this is in agreement with the MACHO group analysis [33]) and also distinctive features that could help to test more definitively whether a (relatively) high proportion of machos in the halo is excluded or not.

Apart from the three events found by MACHO, there are two more events consistent with microlensing that have been detected by EROS [29]. Their second event, if it is indeed
microlensing, does not show the simple form of (24); it may correspond to a binary source star [37]. These two microlensing candidates have been detected in 3 years of Schmidt plates data. The total EROS exposure and efficiency are not drastically different from the ones from MACHO, and the microlensing times are of the same order. Thus EROS has similar (but independent) conclusions to the MACHO ones, in particular the one referring to the range (21).

In addition, however, EROS has been also performing a CCD search of short term microlensing events [38], with no candidates found. The data is sensitive to low-mass brown dwarves -see eq.(26)- and the null result has the consequence of lowering the tested macho mass range below $10^{-4} M_{\odot}$. Testing lower masses is important since below $10^{-4} M_{\odot}$ there could very well exist compact baryonic DM, since one is still above the evaporation limit [25] -compare eqs. (27) and (21).

In fact, at the time of writing the present review, EROS has presented a combined analysis of their CCD and photometric data [39]. One of their conclusions is that machos in the range

$$10^{-7} \leq \frac{M}{M_{\odot}} \leq 10^{-1}$$

(28)
cannot contribute more than 50% to the mass of the standard galactic halo. Again, the limit (28) can be weakened if the halo is not standard.

We notice that the lower limit in (28) is near the expected cut-off on brown dwarves due to the expected thermal evaporation, i.e. near $M_{\text{evap}}$ in (20). In fact the expected range of DM in (21) and the range constrained by the EROS result (28) coincide. Thus, if the microlensing bounds are confirmed in the future (we would like to have a confirmation independent of not-well tested assumptions on the halo form), the window of brown dwarves in the halo would be excluded. In this respect, we would like to stress the importance of testing other directions in the galactic halo, since it would help to probe its shape and form.

Let us now address the important question about whether the detected events are from lensing by objects in our Galactic halo or in conventional populations like the Galactic or LMC disk, etc. It turns out that the expected number of events from the known stellar populations for the first year MACHO data is $N \sim 0.5$ [10, 31]. Thus one may conclude that a new (dark) Galactic component has been detected.

Unfortunately, as we have already mentioned, given a microlensing event one cannot deduce from the data at which distance in between the light source and the observer the event took place. Thus, we do not know whether this new component is part of the dark Galactic halo. Still, it is interesting to assume that the microlensing events are due to objects in the halo, in order to see which are the consequences. (To obtain the limits in eqs. (27) and (28) we do not need to make such an assumption!)

Let us then assume that:

(A) this new component is the galactic dark halo, i.e., the detected microlensing events are due to massive objects in the Milky Way halo.

(B) the Galactic halo is spherical, and given by eq.(1).

(C) the velocity distribution is maxwellian with a dispersion of $\sigma \approx 270$ km/s.

With these hypotheses, we can go further and estimate that the lens masses are most probably in the range [31, 11]
\[ \frac{M}{M_\odot} \simeq 0.04 - 0.06 \]  

although these figures have very large error bars, and that the fraction \( f \) of machos in the halo is

\[ f = 0.19^{+0.16}_{-0.10} \]  

To obtain the macho mass function will be a long-term project since it would require much more data than we have now. The method of mass moments [42] could help to reconstruct the mass function.

### 4.3 Heavy objects

White dwarves and neutron stars are dark remnants of stars, and thus they are candidates for baryonic DM. The problem is that the precursors of the first class have synthesised and ejected a lot of helium [2], and the precursors of the second class have ejected large quantities of heavy elements [43]. We do not detect these features in the Galactic halo, and so this makes the two candidates unlikely.

Above a critical mass \( M_{\text{crit}} \), supermassive stars undergo complete collapse to a supermassive black hole and constitute a viable DM candidate. It is estimated that

\[ M_{\text{crit}} \simeq 200 M_\odot \]  

There are upper limits on the mass of supermassive compact objects in galactic halos. Very heavy objects would disrupt halo globular clusters [44] and also would disrupt nearby dwarf galaxies [45], unless

\[ M \leq M_{\text{dis}} \simeq 10^4 M_\odot \]  

The allowed range of masses for supermassive black holes is between the bounds (31) and (32). This a second mass window on compact baryonic DM:

\[ 10^2 M_\odot \simeq M_{\text{crit}} \leq M \leq M_{\text{dis}} \simeq 10^4 M_\odot \]

### 5 CONCLUSIONS

We have compelling evidence for galactic and baryonic DM. It is important to stress that the need for galactic DM is based on

1. the observed galactic rotation curves
2. newtonian mechanics.

The experimental search for galactic DM is thus independent of theoretical conjectures as inflation, etc.

The need for baryonic DM is based on
(a) the theory of BB nucleosynthesis

(b) the observation of the yields of light elements and the deconvolution of the chemical evolution to deduce the primordial abundances.

The natural place for dark baryons is in galaxies, and thus most probably they constitute at least a fraction of the dark galactic halos. These galactic dark baryons are probably not in diffuse form (although such a possibility is not completely excluded). The possibility that they are non-shining light objects is restricted by a variety of arguments, as self-destruction by collisions, Earth hitting and thermal evaporation. Star remnants (white dwarfs and neutron stars) have contaminated the Galaxy beyond the observed yields of elements and thus are unlikely candidates.

Compact baryonic objects could be very heavy since then there is no ejection of matter in the star history. However, too heavy objects would disrupt astronomical systems and they are also excluded.

Two windows for \( M \) remain, the one that corresponds to brown dwarves \([21]\), and the one that corresponds to supermassive black holes \([33]\).

It is remarkable that the first window can be tested with microlensing experiments. One has to keep in mind however that this effect is independent of the constituency of the compact object. The second window, although there is no compelling scenario where such supermassive black holes are produced, has to be considered as candidate for a dark halo of baryonic constituency.

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