DARK BARYONS IN GALACTIC HALOS

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Abstract
Primordial nucleosynthesis as well as anisotropies in the cosmic microwave background radiation imply that the total amount of baryons in the Universe largely exceeds the visible contribution, thereby making a strong case for *baryonic dark matter*. Moreover, certain recent developments lead to a consistent picture of the dark baryon budget in the present-day Universe. Accordingly, *dark baryons are mostly locked up in galactic halos* – which are anyway dominated by non-baryonic dark matter – and *a sizable fraction of them consists of gas clouds*. While *a priori* various forms of baryonic dark matter in galaxies can be conceived, observational constraints rule out most of the possibilities, leaving *brown dwarfs* and *cold gas clouds mostly made of* $H_2$ *as the only viable candidates* (besides supermassive black holes). So, it looks natural to suppose that baryonic dark matter in galaxies is accounted for by *dark clusters* made of brown dwarfs and cold $H_2$ clouds. A few years ago, it was shown that indeed these dark clusters are predicted to populate the outer halos of normal spiral galaxies by the Fall-Rees theory for the formation of globular clusters, which was based on the standard cold dark matter paradigm described in Blumenthal et al. 1984 *Nature* 311, 517. We review the dark cluster formation mechanism, and argue that its *qualitative features* are expected to remain true even in the contemporary picture of galaxy formation. We also discuss various ramifications of the dark cluster scenario in question, paying particular attention to its observational implications. One of them – the diffuse gamma-ray emission from the Milky Way halo – appears to have been confirmed by the discovery of Dixon et al. 1998 *New Astronomy* 3, 539. Whether this is actually fact or fiction only the future satellite missions *AGILE* and *GLAST* will tell.
1 Introduction and motivation

All available observational evidence – including flat rotation curves of spiral galaxies, X-ray emission from elliptical galaxies and clusters of galaxies, gravitational lensing by galaxy clusters, velocity fields in deep galaxy surveys, light curves of high-redshift Type-Ia supernovae and cosmic microwave background radiation (CMBR) anisotropies – invariably lead to the conclusion that the Universe is dominated by dark matter. Denoting (as usual) by $\Omega$ the actual density of the present-day Universe in units of the critical density, the situation can be summarized as follows.

Measurements of anisotropies in the CMBR yield both the total value $\Omega \simeq 1$ from the location of the first acoustic peak \(^1\) (De Bernardis et al. 2002; Balbi et al. 2000; Pryke et al. 2002) and the baryonic contribution from the height of the second peak $\Omega_b \simeq 0.04$ (Sievers et al. 2002; Stompor et al. 2001). Quite remarkably, the latter value is in good agreement with two independent estimates. One arises by combining measurements of the primeval abundance of light elements (especially deuterium) with theoretical predictions from primordial nucleosynthesis (Burles et al. 2001; O’Meara et al. 2001). The other follows from the observed features of high-redshift Lyman-\(\alpha\) forest absorption lines of neutral hydrogen (Rauch et al. 1998) observed in the spectra of background quasars \(^3\). However, this is not the end of the story, since estimates of the total matter distribution – based on the spectral features of the CMBR, on deep galaxy surveys and on various studies of clusters of galaxies – yield $\Omega_m \simeq 0.3$ (Turner 2002). Evidently, matter alone – as clustered on various cosmic scales – fails to account for the total energy budget of the Universe, leaving a gap of $\Omega - \Omega_m \simeq 0.7$. Actually, the situation is even more puzzling, since observations of high-redshift Type-Ia supernovae entail that the present cosmic expansion is accelerated. Nevertheless, this behaviour is explained by a nontrivial vacuum (unclustered energy) with negative pressure and $\Omega_\Lambda \simeq 0.7$ \(^4\) (Riess et al. 1998; Perlmutter

\(^1\)Observe that this result agrees with the natural implication of cosmic inflationary scenarios (Liddle & Lyth 2000).

\(^2\)Behind this second conclusion there is the assumption that primordial fluctuations are adiabatic, which is just what cosmic inflation entails. The value $H_0 \simeq 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for the Hubble constant is adopted throughout.

\(^3\)Lyman-\(\alpha\) forest lines will be addressed in more detail in Sect. 3.

\(^4\)This vacuum is described by a cosmological constant $\Lambda$. 
et al. 1999). Notice that such a vacuum provides just the missing contribution \( \Omega - \Omega_m \simeq 0.7 \) mentioned above, and so the overall picture is indeed remarkably consistent.

The foregoing discussion implies \( \Omega_b/\Omega_m \simeq 0.13 \), thereby showing that most of the dark matter is nonbaryonic. This is in agreement with contemporary theories of galaxy formation, which demand that the observed dark galactic halos should be dominated by nonbaryonic matter.

Still – as we will see below – half of the total amount of baryons in the present-day Universe remains observationally unaccounted. Hence, there is also a baryonic dark matter problem, which is the main topic addressed in this paper.

An inventory of the baryonic content of the various cosmic structures has been attempted by Persic and Salucci (1992), Gnedin and Ostriker (1992), Bristow and Phillipps (1994), and Fukugita, Hogan and Peebles (1998) by combining available observational data with the whole body of theoretical knowledge. According to the latter authors, the baryon budget in the present-day Universe yields \( \Omega_b' \simeq 0.02 \) and is dominated by hot gas in groups and clusters of galaxies, while the equivalent cosmological contribution from luminous baryons \(^5\) in galaxies is as small as \( \Omega_{bg}' \simeq 0.004 \).

Yet, we know that the observed CMBR anisotropies, primordial nucleosynthesis and high-redshift Lyman-\(\alpha\) forest absorption require \( \Omega_b \simeq 0.04 \). Where are the dark baryons?

An answer to this question is provided by hydrodynamic simulations of currently favoured structure formation models (Cen & Ostriker 1999; Davè et al. 1999). They indicate that – in the present-day Universe – baryons are divided almost equally among three phases: (i) warm gas \( (T = 10^5 - 10^7 \text{ K}) \), forming transient filamentary structures in intergalactic space; (ii) cool gas \( (T < 10^5 \text{ K}) \), smoothly diffuse in intergalactic space; and (iii) cold gas and stars associated with galaxies (Davè et al. 2001). Although the uncertainties in the simulations prevent a precise estimate of the fractional abundance of baryons in the three phases, the equivalent cosmological density in each one is roughly 0.013. This means that the equivalent cosmological contribution from galactic baryons should be \( \Omega_{bg}'' \simeq 0.013 \). Because we have seen that luminous baryons in galaxies only give \( \Omega_{bg}' \simeq 0.004 \), we are led to

\(^5\)Luminous baryons include stars, atomic and molecular hydrogen whose existence is inferred from detection of the emitted electromagnetic radiation at any wavelength.
the conclusion that in the low-redshift Universe most of the galactic baryons are dark.

Actually, a strong case for a somewhat larger amount of baryonic dark matter in galaxies has recently been made by Kochanek (2001). He has investigated the mass function of the dark matter halos – as predicted by the current cold dark matter paradigm – by using certain dynamical probes (Kochanek & White 2001). More specifically, Kochanek has shown that the distribution of gravitational lens separations and the circular velocity function predicted by semi-analytic models of hierarchical clustering are both in agreement with observations only provided that $\Omega_{bg} \simeq 0.02^6$. Basically the same conclusion has been reached by Klypin, Zhao and Somerville (2001) via N-body simulation modelling of the Milky Way and Andromeda galaxy. These authors found that the observed properties are reproduced only if 50% – 75% of the galactic baryons are nonluminous. Consequently, galactic halos are the main repository of dark baryons at low redshift $^7$ $^8$.

As a matter of fact, this circumstance is in remarkable agreement with the claim of Lanzetta and collaborators (Chen et al. 1998, 2001) that low-redshift Lyman-α forest absorption lines of neutral hydrogen are produced by baryonic gas clouds located inside the dark galactic halos. Notice that these gaseous baryons are missing in the above-mentioned inventories.

Apparently, a consistent picture of the dark baryon budget in the low-redshift Universe emerges from the previous considerations. Dark baryons are mostly locked up in galactic halos, and a sizable fraction of them consists

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$^6$We remark that no serious conflict exists between this conclusion and the outcome of hydrodynamic simulations, owing to their intrinsic uncertainties.

$^7$Of course, this does not undermine the fact that galactic halos are dominated by nonbaryonic dark matter.

$^8$Strictly speaking, there is a logical gap here, which should be discussed. Contrary to hydrodynamical simulations, N-body simulations and semi-analytical models of galaxy formation neglect feedback processes, which give rise to galactic outflows. Therefore, the above results of Kochanek and Klypin, Zhao and Somerville do not prevent ejection of a large amount of baryons during the galaxy evolution. Nevertheless, there are good reasons to believe that most of the baryons should still lie inside galactic halos today. For, galactic winds powered by supernova explosions appear unable to drive a huge amount of gas out of galactic halos (Mac Low & Ferrara 1999). In addition, a large amount of ejected baryons from spiral galaxies would produce an equivalent cosmological density of the intergalactic medium larger than the one predicted by the above-mentioned hydrodynamical simulations.
of gas clouds.

Several kinds of astronomical objects – like brown dwarfs, red dwarfs, white dwarfs, neutron stars, black holes and gas clouds – may account for baryonic dark matter in galaxies (Carr 1994), but observational constrains rule out most of them. Before a star becomes a white dwarf, a neutron star or a black hole, it goes through phases in which heavy elements are produced and ejected into interstellar space and its luminosity is greatly enhanced. Existing upper limits on the metallicity of the environment and on the background light then rule out these objects as candidates for baryonic dark matter 10 (Carr 2000; Madau et al. 2000). A similar conclusion holds for red dwarfs as well, because they would give rise to infrared fluxes stronger than are detected (more about this, in Sect. 3). As far as gas clouds are concerned, only cold gas mostly made of $\text{H}_2$ is a viable possibility, for otherwise an unseen excess of photons at some wavelength (21 cm for neutral hydrogen) would be produced 11. So – with the exception of supermassive black holes – only brown dwarfs and cold $\text{H}_2$ clouds turn out to be realistic forms of

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9 We recall that brown dwarfs are stellar-like objects in which ordinary nuclear reactions do not occur in the core, because their central temperature never exceeds the hydrogen-burning threshold (for a review, see Kulkarni 1997; Basri 2000; Chabrier & Baraffe 2000). In the case of solar metallicity, the brown dwarf mass range is $0.01 - 0.08 M_\odot$, but for primordial metallicity the upper limit becomes $M < 0.11 M_\odot$ (D’Antona 1987). For a long time, brown dwarfs were regarded merely as a theoretical possibility, until they were first discovered in 1995 (Rebolo et al. 1995; Nakajima et al. 1995). Further observations have shown that brown dwarfs form like ordinary stars. Similarly to what happens in very low-mass stars (Drake et al. 1996), it has been argued that also in brown dwarfs a turbulent dynamo process should heat the corona, which consequently emits soft X-rays (Kashyap et al. 1994; Neuhäußer et al. 1999). This point will be important in some later considerations.

10 The metallicity constraint is evaded by black holes with mass > $200 M_\odot$, because they would ingurgitate their whole parent stars. However, only supermassive black holes – with mass > $10^5 M_\odot$ – turn out to be viable dark matter candidates, for otherwise the parent stars would violate background light constraints.

11 As $\text{H}_2$ does not possess a permanent electric dipole moment, the first transition line to be detected in emission occurs by quadrupole radiation at 512 K above the ground state. Thus, cold $\text{H}_2$ clouds do not emit any radiation (Combes & Pfenniger 1997). Notice that astronomers tend to infer the existence of $\text{H}_2$ by using CO as a tracer. Needless to say, this practice makes sense only when the $\text{H}_2$/CO conversion ratio is under control (like in the Milky Way disk), but this is not the case in galactic halos. The possibility that a large amount of $\text{H}_2$ may be present in the Universe was first suggested by Zwicky (1959).
baryonic dark matter in galaxies. Our aim is to discuss the possibility that the dark galactic baryons indeed consist of dark clusters – made of brown dwarfs and cold H$_2$ clouds – lurking in the halos of normal spiral galaxies.

More specifically, we will focus our attention on a model of this kind, which was developed from first principles by De Paolis, Ingrosso, Jetzer and Roncadelli (1995a,b, 1996, 1998a) within the standard cold dark matter picture of galaxy formation. We stress that an almost identical scenario has been independently proposed and investigated by Gerhard and Silk (1996). Somewhat similar ideas have been put forward by Ashman and Carr (1988), Ashman (1990), and Fabian and Nulsen (1994, 1997). Slightly different baryonic pictures have been suggested by Pfenniger, Combes and Martinet (1994), Wassermann and Salpeter (1994), Gibson and Schild (1999a,b), Sciama (2000), and Lawrence (2001).

Here, we offer an updated review of the above-mentioned dark matter model.

The paper is organized as follows. In Sect. 2, we discuss the formation mechanism (Subsect. 2.1) and the main properties (Subsect. 2.2) of the dark clusters. Next, we address some of their observational implications in Sect. 3. Finally, we summarize our conclusions in Sect. 4. Suggestions for further work will be scattered throughout the paper.

$^{12}$Of course, a small fraction of red dwarfs, white dwarfs, neutron stars and black holes can be present in the galactic halos, but they cannot account for the bulk of baryonic dark matter.

$^{13}$A strong constraint on the brown dwarf fraction in galactic halos – which would prevent them from playing any rôle for dark matter – was derived by Graff and Freese (1996a) under the assumption that the initial mass function is spatially homogeneous. However, within the dark matter model to be discussed below the initial mass function depends on the galactocentric distance, and brown dwarfs can copiously form only at galactocentric distances larger than $10 - 20$ kpc. Hence, the conclusion of Graff and Freese (1996a) is not valid in the present context.

$^{14}$We anticipate (from Sect. 3) that old brown dwarfs are not ruled out by current infrared searches (especially if they are clustered).
2 Dark clusters in galactic halos

In the past, brown dwarfs have been repeatedly recognized as an important contributor to baryonic dark matter in galaxies (Carr 1994). Much like ordinary stars, brown dwarfs are expected to form in clusters, thereby giving rise to dark clusters (Carr & Lacey 1987; Silk 1991; Rix & Lake 1993; Kerins & Carr 1994; Moore & Silk 1995). However, insufficient attention was paid to the fact that even in this case – the star-formation mechanism is highly inefficient, in that most of the original gas fails to get transformed into stars, thereby remaining trapped inside the dark clusters. As we shall see, this gas plays a crucial rôle, since it can both change the properties of the brown dwarfs and make the dark clusters directly visible in the gamma-ray band and indirectly observable along the line of sight to a distant quasar.

2.1 Formation of the dark clusters

Starting point of the considered dark matter model was the Fall-Rees (1985) theory for the formation of globular clusters in galactic halos. Indeed, it was shown (De Paolis et al. 1995a,b, 1996, 1998a) that the Fall-Rees theory automatically predicts – without any further physical assumption – that dark clusters made of brown dwarfs and cold H$_2$ clouds should form in the outer halos of normal spiral galaxies, namely at galactocentric distances larger than 10 – 20 kpc.

The Fall-Rees theory was formulated within the standard cold dark matter picture of galaxy formation described in Blumenthal et al. (1984). However, in the last few years numerical simulations of structure formation have led to a considerable improvement in the understanding of hierarchical clustering, with mergers playing an increasing rôle. As a result, some features of the above-mentioned cold dark matter paradigm turned out to be incorrect and had to be revised. Therefore, it is not clear whether the present dark matter model remains true. Although this is at the moment an open question, we will argue – on the basis of the following discussion – that the qualitative features of the dark matter scenario under consideration are likely to remain unchanged even in contemporary models of galaxy formation.

Consider a protogalactic cloud with mass $M \sim 10^{12} M_\odot$, made of both
nonbaryonic and baryonic matter. We imagine that its inner part eventually produces – upon gravitational collapse – the luminous component of a normal spiral galaxy, whereas its outer region gives rise to the corresponding dark halo.

The Fall-Rees theory rests on the assumption that the outer part of the protogalactic cloud is modelled by a singular isothermal sphere (SIS), so that the observed flat rotation curve is recovered. Accordingly, the overall density profile is

\[ \rho_o(r) = \frac{V_{\text{max}}^2}{4\pi G r^2}, \]

where \( V_{\text{max}} \) is the value at which the rotation velocity becomes constant at a large galactocentric distance \( r \). Typically one finds \( V_{\text{max}} \sim 200 \text{ km s}^{-1} \), and we will choose \( V_{\text{max}} = 220 \text{ km s}^{-1} \), which is the value appropriate to the Milky Way. Hence, we get

\[ \rho_o(r) \simeq 0.9 \left( \frac{\text{kpc}}{r} \right)^2 M_\odot \text{pc}^{-3}. \]  

(1)

Correspondingly, the free-fall time \( t_{\text{ff}} \simeq 0.5 \alpha^{-1/2}(G\rho_o)^{-1/2} \) becomes

\[ t_{\text{ff}} \simeq 7.4 \cdot 10^6 \alpha^{-1/2} \left( \frac{r}{\text{kpc}} \right) \text{yr}, \]  

(2)

where \( \alpha \) is a constant of order unity which reflects the actual mass distribution (a pure SIS yields \( \alpha = 1 \)). Moreover, the mean square velocity of any baryon in the considered region is \( \bar{v}^2 = \frac{3V_{\text{max}}^2}{2} \simeq 7.3 \cdot 10^4 \text{ km}^2 \text{s}^{-2} \). Therefore the temperature of the diffuse baryonic gas is \( T_d \simeq 1.7 \cdot 10^6 \text{ K} \). One can easily see that this temperature is quite close to the virial temperature, and so the diffuse gas is initially in virial equilibrium.

Since the diffuse gas tends to cool, in order to understand its further behaviour one has to compare the cooling time \( t_{\text{cool}} \) with the free-fall time \( t_{\text{ff}} \) as given by eq. (2). One can show that at the above temperature both Bremsstrahlung and ion-recombination processes contribute to the cooling rate of the diffuse gas, and the resulting cooling time is

\[ t_{\text{cool}} \simeq 5.5 \cdot 10^{-18} \left( \frac{g \text{cm}^{-3}}{\rho_d} \right) \text{yr}, \]  

(3)

\footnote{We suppose that the baryonic matter has primordial composition.}

\footnote{As we will be explicitly concerned with the baryonic gas component only, the attribute baryonic will be implicitly understood. Also, the meaning of the attribute diffuse will become clear later on.}

\footnote{We recall that a cloud collapses in free-fall and fragments when \( t_{\text{cool}} < t_{\text{ff}} \), whereas the collapse proceeds quasi-statically for \( t_{\text{cool}} > t_{\text{ff}} \).}
where $\rho_d$ denotes the density of the diffuse gas. The comparison between eqs. (2) and (3) entails

$$\frac{t_{\text{cool}}}{t_{ff}} \simeq \frac{\rho_*}{\rho_d},$$

where we have set

$$\rho_* \equiv 1.1 \cdot 10^{-2} \alpha^{1/2} \left(\frac{kpc}{r}\right) M_\odot pc^{-3}. \quad (5)$$

On account of eq. (4), we would conclude that the diffuse gas undergoes quasi-static collapse as long as its density is sufficiently small – namely for $\rho_d < \rho_*$ – since then $t_{\text{cool}} > t_{ff}$. Still, as soon as $\rho_d > \rho_*$ the collapse enters the free-fall regime. Actually, in the latter case we would expect a monotonic increase of $\rho_d$, and – thanks to eq. (4) – a steady decrease of the $t_{\text{cool}}/t_{ff}$ ratio, which would signal efficient fragmentation and star formation within the whole protogalactic cloud.

But in reality the situation is more complex, since the above picture would be correct only within a perfectly homogeneous medium. In fact, Fall and Rees have shown that the unavoidable presence of density fluctuations during the collapse can totally upset such an expectation. Basically, this is due to the fact that density fluctuations produce a thermal instability within the diffuse gas. To see this, consider eq. (3): an overdense region cools more rapidly than average, but then compression from the surrounding hotter gas leads to a further increase of the density. Thus, density fluctuations give rise to a substructure within the protogalaxy, made of denser and cooler gas bubbles embedded in the diffuse gas. Besides, Fall and Rees have shown that the bubble condensation implies the condition

$$\frac{t_{\text{cool}}}{t_{ff}} \simeq 1$$

(6)

to hold true for the diffuse gas. This fact is extremely important, for three different reasons. First, the diffuse gas actually stays in virial equilibrium at $T_d \simeq 1.7 \cdot 10^6 K$. Second, there is no star formation within the diffuse gas. Third, eqs. (4), (5) and (6) imply that the density profile of the diffuse gas is

$$\rho_d(r) \simeq 1.1 \cdot 10^{-2} \alpha^{1/2} \left(\frac{kpc}{r}\right) M_\odot pc^{-3}. \quad (7)$$
The bubbles – which are pressure-confined by the diffuse gas – are originally made of ionized hydrogen and helium (plus their respective electrons). Assuming that this plasma is in *thermal equilibrium*, the cooling brought about Bremsstrahlung and ion-recombination processes is operative only at temperatures larger than \( \sim 10^4 \text{ K} \), since at lower temperatures the gas becomes neutral and the corresponding cooling rate suddenly drops to zero. Hence, we expect that inside the bubbles *hydrostatic equilibrium* sets in when the temperature reaches \( \sim 10^4 \text{ K} \). In such a situation, the baryonic component of the protogalaxy is made of bubbles with \( T_b \sim 10^4 \text{ K} \) embedded in the diffuse gas at \( T_d \sim 10^6 \text{ K} \).

Let us denote by \( \rho_b(r) \) the (constant) density inside a bubble located at galactocentric distance \( r \). At hydrostatic equilibrium, the pressure \( p_b \) just inside the considered bubble coincides with the pressure \( p_d \) just outside it (within the diffuse gas). This condition entails

\[
\rho_b(r) = \left( \frac{m_b}{m_d} \right) \left( \frac{T_d}{T_b} \right) \rho_d(r),
\]

where \( m_d \simeq 10^{-24} \text{ g} \) and \( m_b \simeq 2 \cdot 10^{-24} \text{ g} \) are the mean particle mass of a ionized and neutral gas having primordial composition, respectively. Combining eqs. (7) and (8) together, we find

\[
\rho_b(r) \simeq 3.6 \alpha^{1/2} \left( \frac{kpc}{r} \right) M_\odot \text{ pc}^{-3}.
\]

Therefore the Jeans mass and the Jeans radius for the bubble in question are

\[
M_J(r) = \left( \frac{3k_BT_b}{\alpha G m_b} \right)^{3/2} \left( \frac{3}{4\pi \rho_b(r)} \right)^{1/2} \simeq 2.3 \cdot 10^6 \alpha^{-7/4} \left( \frac{r}{kpc} \right)^{1/2} M_\odot
\]

and

\[
r_J(r) = \left( \frac{3k_BT_b}{\alpha G m_b} \right)^{1/2} \left( \frac{3}{4\pi \rho_b(r)} \right)^{1/2} \simeq 54 \alpha^{-3/4} \left( \frac{r}{kpc} \right)^{1/2} \text{ pc},
\]

respectively, where \( k_B \) denotes the Boltzmann constant.

However, the above assumption – namely thermal equilibrium of the plasma inside the bubbles – turns out to be *violated*, since cooling occurs
very rapidly (Kang et al. 1990). The resulting out-of-equilibrium ion
recombination entails a substantial ionization fraction at $T_b < 10^4 K$ (which
would otherwise vanish at thermal equilibrium). This circumstance is in
fact irrelevant for $T_b > 10^4 K$, but alters dramatically the above conclusions
for $T_b < 10^4 K$. Indeed, the presence of a nonnegligible amount of ions at
$T_b < 10^4 K$ gives rise to the formation of molecular hydrogen via the reactions
$^{18} H + p \rightarrow H_2^+ + \gamma$, $H + e \rightarrow H^- + \gamma$ and $H_2^+ + H \rightarrow H_2 + p$,
$H + H^- \rightarrow H_2 + e$ (notice that ions only act as catalysts).

The presence of $H_2$ in the bubbles brings about a further cooling, owing
to photon emission in roto-vibrational molecular transitions. We stress that
this process is very efficient and can cause a temperature drop down to
$T_b \sim 10 K$. Evidently in such a situation $t_{cool} \ll t_{ff}$, and so the bubbles
collapse in free-fall and fragment. When the number density in the bubbles
exceeds $\sim 10^8 \text{ cm}^{-3}$ – which corresponds to $\rho_b \simeq 2.8 \cdot 10^6 \text{ M}_\odot \text{ pc}^{-3}$ – a further
$H_2$ production takes place via the three-body reactions $H + H + H \rightarrow H_2 + H$
and $H + H + H_2 \rightarrow H_2 + H_2$, as realized by Palla, Salpeter and Stahler (1983).
At variance with the former reactions, the latter ones do not involve ions as
catalysts. As a consequence, the bubbles get transformed almost entirely into
$H_2$. Besides modifying their internal composition, this circumstance makes
cooling even more efficient.

Still, a priori nothing ensures that $H_2$ – once produced – will survive:
because of its fragility, its actual existence crucially depends on the environ-
mental conditions.

In fact, in the central region of the protogalaxy an AGN (Active Galactic
Nucleus) along with a first population of massive stars (population III)
are expected to form. They act as strong sources of ultraviolet radiation,
which dissociates the $H_2$ molecules up to a critical galactocentric distance $r_*$
(because the radiative flux decreases as the galactocentric distance increases).
It is not difficult to estimates that the $H_2$ destruction should occur for $r < r_*$,
with $r_* = 10 - 20 \text{ kpc}$. Consequently, the further evolution of the inner
region of the protogalaxy ($r < 10 - 20 \text{ kpc}$) will be totally different from that
of the outer part ($r > 10 - 20 \text{ kpc}$). Actually, since the spheroid of radius

\[18\] As already pointed out, $H_2$ has no permanent electric dipole moment, and so the
standard reaction $H + H \rightarrow H_2 + \gamma$ can only occur on dust grains. But since the composition
of the protogalaxy is supposed to be primordial, no grains exist. Hence, the considered
reaction is not operative. We stress that this fact implies that CO is not a tracer of $H_2$ in
the present context.
10−20 kpc gives rise to the inner halo of a normal spiral galaxy, we will distinguish between inner and outer halo.

Owing to the above considerations, we are now in position to summarize the dynamics of the halo as follows.

- **Inner halo** (Fall & Rees 1985) – The lack of $H_2$ prevents the bubbles from cooling down to temperatures smaller than $\sim 10^4 K$, and so they stay for a long time in hydrostatic equilibrium, which coincides with virial equilibrium (since $t_{\text{cool}} \gg t_{\text{ff}}$ for $T_b < 10^4 K$). As a result, their mass and radius are given (respectively) by the corresponding Jeans values (10) and (11). Indeed, the main result of the Fall-Rees theory is that these values are in agreement with those observed for globular clusters provided that mass loss during formation and evolution is taken into account. Subsequently the ultraviolet flux decreases, thereby allowing for the formation and survival of $H_2$. Accordingly, the bubbles can further cool, collapse in free-fall and fragment, ultimately producing ordinary stars. Thus, the Fall-Rees theory provides a natural explanation for the formation of globular clusters in the halos of normal spiral galaxies.

- **Outer halo** (De Paolis et al. 1995a,b) – The presence of $H_2$ allows the bubbles to cool down to temperatures much lower than $10^4 K$, thereby collapsing in free-fall and fragmenting. As is well known, the collapse becomes adiabatic – and eventually stops – when a fragment becomes optically thick. Palla, Salpeter and Stahler (1983) have shown that this occurs when the fragment Jeans mass is as low as $10^{-2} - 10^{-1} M_\odot$. So, clusters of brown dwarfs in the mass range $10^{-2} - 10^{-1} M_\odot$ should form in the outer halos of normal spiral galaxies.

Notice that the present dark matter model gives rise to an initial mass function in the halo that depends on the galactocentric distance.\textsuperscript{19} 20

\textsuperscript{19}Evidence for a spatially varying initial mass function in the Milky Way disk has been reported by Taylor (1998).

\textsuperscript{20}Because of this fact, no extrapolation from the initial mass function in the disk can yield informations about the initial mass function in the halo. Consequently, the bound on the fraction of halo brown dwarfs derived by Graff and Freese (1996a) is not valid in the present context.
As a matter of fact, recent N-body simulations of hierarchical clustering produce dark matter halos with a universal Navarro-Frenk-White (1997) (NFW) density profile. However, this profile gets modified by the baryonic infall (associated with the disk formation) (Blumenthal et al. 1986; Mo, Mao & White 1998). In the case of Milky-Way-type galaxies, over galactocentric distances ranging from a few $kpc$ up to nearly $50kpc$ the NFW density profile is turned into a SIS profile, which gives rise to the observed flat rotation curves. Manifestly, this result contradicts the Fall-Rees assumption of a SIS profile before baryonic infall, and so invalidates the above discussion. For instance, eqs. (1) and (7) imply that the fractional abundance of baryonic matter *increases linearly* with the galactocentric distance and should eventually dominate the mass density, but numerical experiments disprove this behaviour. In addition, self-consistency of the model ($\rho_d < \rho_o$) demands that the radius of the dark halos should obey the constraint $r < 83 \alpha^{-1/2} kpc$, but again there is good observational evidence that dark halos are considerably more extended (Zaritsky et al. 1997) 21.

Yet, the main point of the present dark matter scenario – namely the *survival of $H_2$ at large galactocentric distances*, which gives rise to the dark cluster formation via efficient cooling and fragmentation – is *independent* of the specific halo density profile. So, the *qualitative features* of the model in question are expected to remain true even within the contemporary picture of galaxy formation. Unfortunately, before this issue is settled no prediction about the actual distribution of the dark clusters in galactic halos can be made.

### 2.2 Properties of the dark clusters

Let us summarize the main properties of the dark clusters, as suggested by the above considerations.

Dark clusters resemble both morphologically and dynamically globular clusters, apart from the obvious difference of being made of brown dwarfs rather than ordinary stars. This fact entails in turn further, crucial differences, which we are now going to discuss.

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21 Besides, it has become clear that the formation of globular clusters does not proceed in accordance with the Fall-Rees theory (see e.g. Fall & Zhang 2001; Van den Bergh 2001; Beasley et al. 2002).
A difference between globular and dark clusters concerns their mass spectrum. In fact, globular cluster masses exhibit a small scatter around a preferred value $\sim 10^5 M_\odot$. Within the Fall-Rees model, this circumstance is naturally traced to the formation mechanism. Indeed, the permanence of the corresponding bubbles for a long time in virial equilibrium results in the imprinting of the associated Jeans mass, which is just $\sim 10^5 M_\odot$ when eq. (10) is corrected for the mass loss. On the other hand, the bubbles that generate the dark clusters cool monotonically, and so no preferred mass scale gets singled out. Accordingly, we expect the dark cluster mass spectrum to be much wider. However, disruptive effects – like evaporation, encounters (both among themselves and with globular clusters), tidal disruption and spiralling motion towards the galactic centre (brought about dynamical friction) – strongly constraint their mass range. Specifically, only dark clusters in the mass range $3 \cdot 10^2 - 10^6 M_\odot$ are expected to survive all these effects, and therefore to still populate the outer galactic halos today (De Paolis et al. 1996, 1998a). We stress that this is possible only because the dark matter model in question predicts that dark clusters do not populate the inner halo.

Typical values of the dark cluster radius lie in the range $1 - 10$ pc. Moreover, all dark clusters more massive than $\sim 10^5 M_\odot$ have presumably entered the phase of core collapse.

Another difference between globular and dark clusters concerns their gas content. Because the process of star formation is highly inefficient, at least 60% of the original amount of gas does not get transformed into stars (Scalo 1985). Within globular clusters, such a leftover gas is expelled by stellar winds and shock waves driven by supernova explosions. The case of dark clusters is different. Since practically no nuclear process and no evolution occur in the brown dwarfs, the leftover gas – which is mainly $H_2$ – remains trapped inside the dark clusters in the form of self-gravitating clouds. Indeed, we expect these gas clouds to provide the leading mass contribution to the dark clusters.

Although these clouds are primarily made of $H_2$, they are expected to be surrounded by a layer of neutral hydrogen HI and a ionized “skin”, owing to the interaction with the diffuse photon background (De Paolis et al. 1996, 22

\footnote{A general analysis of these constraints has been carried out by Carr and Lacey (1987), Moore and Silk (1995), and Carr and Sakellariadou (1998). As they assumed that the dark cluster distribution extends all the way down to the galactic centre, their results do not apply to the present model.}

14
As we shall see, the presence of HI and ions in the outer region of the clouds plays an important rôle in some subsequent considerations.

An analysis of the cloud thermal balance shows that they are very cold, with a central temperature $\sim 10 \, K$. Moreover, Gerhard and Silk (1996) have demonstrated that for realistic values of their parameters the clouds should survive evaporation and collisional disruption. Typical values of the cloud mass and radius are $\sim 10^{-3} \, M_\odot$ and $\sim 10^{-5} \, pc$, respectively.

Mainly in view of the observational implications, an important question concerns the present dust-to-gas ratio of the clouds. Unfortunately, a clear-cut answer cannot be given. It looks natural to suppose that the clouds formed from almost primordial gas. But even if they were essentially dust free at the beginning, their interaction with the interstellar matter – when they periodically pass through the galactic disk – should have produced a sizable dust-to-gas ratio today, as pointed out by Kerins, Binney and Silk (2002). Accordingly, it has been suggested that the clouds should be opaque to visible light (Gerhard & Silk 1996; Kerins, Binney & Silk 2002). However, this conclusion may not be true. For instance, Draine (1998) has argued that dust grains could have sedimented in a small core, so that a cloud would be essentially transparent at optical wavelengths. In the following, both possibilities will be considered.

Cloud stability is a critical issue. Although a completely satisfactory treatment is still lacking, various mechanisms have been envisaged that can stabilize the clouds against gravitational collapse. A possibility investigated by Gerhard and Silk (1996) is that the clouds get stabilized by the gravitational field produced by the brown dwarfs clumped into the dark clusters. Alternatively, it has been suggested that cosmic-ray heating can balance either molecular cooling in dust-free clouds (Sciama 2000) or cooling by dust emission in dusty clouds (Lawrence 2001). Finally, Wardle and Walker (1999) have argued that stability can be achieved via sublimation of liquid or solid hydrogen, which is expected to be present in clouds with mass $< 0.02 \, M_\odot$.

In turn, it looks remarkable that the presence of gas clouds in the dark clusters can affect the properties of the brown dwarfs. Indeed – as shown by Hansen (1999) – the cloud-brown dwarf interaction can give rise to a

\footnote{As we will see later, the clouds are likely to be magnetized. However, it is not clear whether this fact helps to stabilize them, since the energy balance depends critically on the configuration of the magnetic field.}
low-entropy accretion process \(^{24}\) (Lenzuni, Chernoff & Salpeter 1992). Accordingly, the brown dwarf mass gets substantially increased – up to \(0.3\ M_\odot\) – while the central temperature stays below the hydrogen-burning threshold. Although it would then be more appropriate to talk about beige dwarfs – as indeed suggested by Hansen – we will continue to use the name brown dwarfs for simplicity, but it should be kept in mind that their mass can be as large as \(0.3\ M_\odot\).

Finally, we point out that also binary brown dwarfs should be clumped into the dark clusters. In fact – much in the same way as it occurs for ordinary stars – also in this case the fragmentation process is expected to produce a large fraction (up to 50\% in mass) of binary objects \(^{25}\). Because of dynamical friction on the gas clouds, the overwhelming majority of binary brown dwarfs become so close (hard) today that they cannot be resolved in current gravitational microlensing experiments towards the Magellanic Clouds (more about this, later) \(^{26}\) (De Paolis et al. 1998b).

3 Observational implications

The formation mechanism discussed in Subsect. 2.1 obviously provides a rationale for the existence of dark clusters with the properties stated in Subsect. 2.2. Yet, a more pragmatic attitude can also be taken (Gerhard & Silk 1996). Indeed – regardless of the specific formation process – one can simply suppose that dark clusters of brown dwarfs \(^{27}\) and cold \(H_2\) clouds account for baryonic dark matter and populate the halos of normal spiral galaxies at galactocentric distances \(> 10 – 20\ kpc\).

What are then the observational signatures of this scenario? Below, we discuss a few most important effects.

\(\gamma\)-ray emission – At the qualitative level, the situation looks quite simple. Very high-energy \((E > 1\ GeV)\) cosmic-ray protons travelling in the halo of a normal spiral galaxy produce (in particular) neutral pions upon scattering

\(^{24}\)We stress that this process is likely to occur in the quiet environment inside the dark clusters.

\(^{25}\)Binary brown dwarfs tend to concentrate in the dark cluster cores owing to the mass-stratification instability (Spitzer 1987).

\(^{26}\)We remark that the energy released during the hardening process of binary brown dwarfs is efficiently radiated away by the clouds.

\(^{27}\)Recall that by brown dwarfs we actually mean beige dwarfs throughout the paper.
on the gas clouds. And of course the pions rapidly decay into photons. So, a \( \gamma \)-ray emission is expected, whose flux is proportional to the column density of the clouds.

Unfortunately, a quantitative analysis is difficult, since nobody knows how the cosmic-ray protons propagate inside the dark halos\(^\text{28}\). Hence, some further assumptions are definitely needed at this point.

A strategy to proceed can be sketched as follows, focusing the attention on the Milky Way (De Paolis et al. 1999, 2000). First of all, recall that in the Milky Way disk cosmic rays are produced by stellar winds and supernova explosions, and tend to escape into intergalactic space. However – owing to the inhomogeneities of the disk magnetic field over scales \( 10^{-6} - 10^2 \text{ pc} \) – they undergo a diffusion process, which gives rise to a temporary confinement controlled by the escape time from the disk. Next, observe that – within the present dark matter model – a similar situation is expected to occur in the Milky Way halo as well. For, we have seen that the gas clouds – with a photo-ionized “skin” – have typical size \( \sim 10^{-5} \text{ pc} \), and they are clumped into dark clusters having typical size \( \sim 10 \text{ pc} \). Thus, we expect inhomogeneities of the halo magnetic field of the same kind as the ones occurring in the disk\(^\text{29}\).

This circumstance allows for an estimate of the cosmic-ray escape time from the halo. It turns out that cosmic-ray protons with energy \( E < 10^3 \text{ GeV} \) have an escape time larger than the Hubble time. Still, their spectrum goes like \( E^{-\alpha} \) (\( 2 < \alpha < 3 \)), and so just these protons give the leading contribution to the cosmic-ray proton flux in the halo. Therefore, most of the cosmic-ray protons produced in the Milky Way disk should still be trapped inside the Galactic halo today. As a result, we can estimate the average density of cosmic-ray protons in the halo, which turns out to be \( \sim 0.1 \text{ eV} \text{ cm}^{-3} \),

\(^{28}\)We stress that – contrary to the practice used in the cosmic-ray community – by halo we mean the almost spherical galactic component which extends well beyond \( \sim 10 \text{ kpc} \), and not the thick disk.

\(^{29}\)This picture is supported by Kronberg’s (1994) suggested existence of a cosmic background magnetic field with strength \( \sim 1 \mu G \), which is motivated by the fact that magnetic fields with this strength are found nearly everywhere, regardless of the actual density and composition of the corresponding region. Moreover, the inhomogeneities of the magnetic field inside a dark cluster are expected to be produced both by the ionized envelop of the clouds and by the turbulent dynamo process likely present in the brown dwarf coronae (Drake et al. 1996).

\(^{30}\)This value is consistent with the upper bound derived from EGRET observations (Sreekumar et al. 1993).
namely roughly one-tenth of the disk value. Such a high cosmic-ray proton flux gives rise to a potentially detectable $\gamma$-ray flux from the Milky Way halo through the above-mentioned mechanism. Owing to the very poor angular resolution of present-day $\gamma$-ray detectors, this flux is indistinguishable from a truly diffuse emission from the Galactic halo. Although its intensity depends on various somewhat uncertain parameters, an order-of-magnitude estimate yields for the integrated flux above 1 GeV (De Paolis et al. 1995a,b)

$$\Phi_\gamma(> 1 GeV) = 10^{-7} - 10^{-6} \, \gamma \text{cm}^{-2} s^{-1} sr^{-1}.$$  (12)

We stress that an independent calculation (Kalberla, Shchekinov & Dettmar 1999) – based on different assumptions – leads to the same conclusion.

In spite of the fact that the flux in eq. (12) is slightly less than the observed diffuse extragalactic flux (Sreekumar et al. 1998), a wavelet-based statistical analysis can discriminate between a Milky Way halo emission and an extragalactic flux. In 1998 such an analysis has been carried out for EGRET data and has led to the discovery of a diffuse $\gamma$-ray emission from the Galactic halo (Dixon et al. 1998). Remarkably enough, the observed flux is in agreement with both the intensity and the spatial distribution of the emission predicted by the considered dark matter model, provided that a moderate halo flattening is allowed \(^{31}\) (De Paolis et al. 1999, 2000).

It goes without saying that the future planned satellite missions AGILE and GLAST will play a crucial rôle in settling this issue.

As is well known, the Milky Way is a typical normal spiral galaxy, and so we expect such a $\gamma$-ray halo emission from nearly all normal spiral galaxies. In particular, observing the $\gamma$-ray flux from the halo of Andromeda galaxy will be a challenge for the next generation $\gamma$-ray detectors (De Paolis et al. 2000).

A final comment is in order. When high-energy cosmic-ray protons scatter on the gas clouds, also charged pions are produced, which ultimately give rise

\(^{31}\text{As already pointed out, the dark matter model in question does not predict (in its present form) how dark clusters are distributed in the Galactic halo. While it looks natural to suppose that their distribution follows that of the nonbaryonic dark matter – namely a SIS density profile – some flattening can be expected (Samurovic, Cirkovic & Milosevic-Zdjelar 1999). In the present calculation, the baryonic halo is modelled as a flattened spheroid – which becomes a SIS in the limit of spherical symmetry – with the flattening parameter left free. Because nonbaryonic dark matter dominates over the baryons, a moderately flattened baryonic dark halo is consistent with the recent evidence of a nearly spherical Galactic halo (Ibata et al. 2001).}
to a flux of high-energy electrons \(^{32\,33}\). Were these electrons to escape from a cloud, two further effects would come about and should be addressed. One is emission of synchrotron radiation in the halo magnetic field. The other is inverse Compton scattering against CMBR photons, leading to a soft X-ray flux. Although in either case the intensity is expected to be \(\text{subdominant}^{34}\), the latter effect might be disentangled from the background by its characteristic angular distribution. However, the relativistic electrons hardly escape from a cloud – owing to its ionized outer envelope – and so these effects fail to provide a signature of the dark matter scenario under consideration.

**X-ray emission** – As already emphasized, brown dwarfs are expected to possess a coronal soft X-ray emission. More explicitly, Kayshap et al. (1994) have quantified this flux in \(\sim 10^{27} \text{erg s}^{-1}\) in the \(0.1 - 10 \text{keV}\) energy range. Consequently, the possibility arises to discover the dark clusters in X-ray searches.

A thorough analysis has shown that this should in fact be the case for dark clusters with mass as large as \(10^5 \, M_\odot\), provided that the fractional abundance of brown dwarfs in the dark clusters is sizable (De Paolis et al. 1998c). Unfortunately, it is impossible to tell \emph{a priori} whether this circumstance is indeed realized, and so an intrinsic uncertainty affects the present discussion. More specifically, dark clusters with mass \(\sim 10^5 \, M_\odot\) can contribute to the new population of faint X-ray sources advocated by Hasinger et al. (1993) and by McHardy et al. (1997), whereas dark clusters with mass \(\sim 10^6 \, M_\odot\) can be observed as resolved sources with the future planned satellite missions.

We stress that these results were obtained in 1998, when only \emph{ROSAT} data were available. The impact of the \emph{Chandra} and \emph{XMM-Newton} missions on this issue has still to be investigated.

**Infrared emission** – A different kind of dark matter search addresses the...
infrared emission from very low-mass stars in the dark halos of various galaxies, including the Milky Way. Although strong constrains have been set on the abundance of red dwarfs, dark halos dominated by old brown dwarfs are still a viable possibility (Boughn & Uson 1995; Graff & Freese 1996b; Gilmore & Unavane 1998). In this respect, it should be stressed that all the analyses performed so far rest upon the strong assumption of a smooth distribution of low-mass stars within a canonical SIS halo model\textsuperscript{35}. Yet, we have seen that within the present dark matter scenario things are different. Brown dwarfs are clumped into the dark clusters, and this very fact reduces the expected infrared flux (Kerins 1997a,b). In addition, we expect gas clouds – rather than brown dwarfs – to give the leading mass contribution to the dark clusters, and so the resulting infrared flux gets further reduced\textsuperscript{36}. Therefore only future observations might detect the infrared emission in question.

Infrared emission from both dust-less (Sciama 2000) and dusty (Lawrence 2001) clouds has been considered in a different context, with the conclusion that only for clouds close to the Milky Way disk can the resulting flux lie above the threshold of the infrared detector \textit{SCUBA}.

\textit{Occultation effects} – As discussed in Subsect. 2.2, there are good reasons to expect that the gas clouds clumped into the dark clusters are opaque at optical wavelengths. Consequently, they can be detected by looking for occultations of background stars (Gerhard & Silk 1996). Quite recently, Kerins, Binney and Silk (2002) have suggested that the data sets of gravitational microlensing experiments towards the Magellanic Clouds (see below), the Galactic bulge and the Andromeda galaxy can also be used to search for occultation signatures by gas clouds. Actually, they have demonstrated that – for cloud parameters typical of the considered dark matter model – thousands of transit events should already exist within microlensing survey data sets.

\textit{Optical lensing} – It might nevertheless happen that the gas clouds are effectively transparent at optical light. In this case, the light of a background star can be magnified – in a symmetric fashion – when a cloud crosses its line of sight. The resulting light curves resemble those of gravitational microlensing (see below), apart from the fact that red light suffers a stronger magnifi-

\textsuperscript{35}Hence, low-mass stars are spread out all the way down to the galactic centre with a $r^{-2}$ density profile.

\textsuperscript{36}In the case of the Milky Way, yet another reduction of the infrared flux is due to the fact that dark clusters populate only the outer halo.
cation than blu light (because of Rayleigh scattering). The phenomenology of the corresponding chromatic events has been studied by Draine (1998) and by Rafikov and Draine (2001), who have computed the event rates in the case of background stars in the Large Magellanic Cloud (LMC). They also suggested that searches for gravitational microlensing could be used to detect optical lensing events, provided that the achromaticity constraint imposed so far is relaxed (a study of the absorption features caused by the gas clouds would help to identify the desired events).

Gravitational microlensing – This effect towards the Magellanic Clouds was proposed by Paczynski (1986) as a tool to discover compact dark matter objects – named MACHOs (Massive Astrophysical Compact Halo Objects) – presumably lurking in the halo of the Milky Way. Basically, a background star gets magnified – in a symmetric and achromatic fashion – when a MACHO crosses its line of sight. Since 1993, the MACHO collaboration has detected 13 – 17 events towards the LMC, the observed optical depth being \( \tau_{\text{obs}} \approx 1.2 \cdot 10^{-7} \) (Alcock et al. 2000). Only 4 events have been found by the EROS2 collaboration (Milsztajn & Lasserre 2001). In the following, we shall focus our attention on the MACHO data.

Because a 100% MACHO canonical SIS halo model predicts \( \tau_{\text{pred}} \approx 5 \cdot 10^{-7} \), one would conclude that roughly 20% of the halo dark matter should be in the form of MACHOs. As the theory of galaxy formation requires most of the galactic dark matter to be nonbaryonic, this result looks reasonable, but we emphasize that it relies upon two strong assumptions: all microlensing events are due to MACHOs, and a canonical SIS MACHO distribution. As a matter of fact, the former assumption is grossly violated. Besides faint stars in the various components of the Milky Way (thin disk, thick disk, spheroid and halo), also faint stars inside the LMC itself can produce microlensing events (the latter phenomenon being referred to as self-lensing), but – as

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37 A thorough account of microlensing can be found in Mollerach and Roulet (2002).

38 A comparison of the results of the MACHO and EROS2 collaborations is not straightforward, since they look at different fields on the LMC, monitoring a different number of stars with different observation times.

39 Accordingly, MACHOs are smoothly spread out all the way down to the Galactic centre with a \( r^{-2} \) density profile. However, it should be stressed that this model is purely academic, since it also assumes a 100% efficiency in the MACHO formation process and neglects nonbaryonic dark matter.

40 An updated discussion of the various contributions is given by Jetzer, Mancini and Scarpetta (2002).
a rule – observations provide no information about the location of the lenses (unless they happen to be binary objects). Although various attempts at estimating the optical depth for self-lensing $\tau_{self}$ have been made, discordant results emerged (due to the poor knowledge of the mass distribution in the LMC), ranging from $\tau_{self} = (0.7 - 7.8) \cdot 10^{-8}$ (Gyuk, Dalal & Griest 2000) up to $\tau_{self} = (0.7 - 1.8) \cdot 10^{-7}$ (Evans & Kerins 2000) \footnote{In spite of the fact that the large value $\tau_{self} \simeq 1.4 \cdot 10^{-7}$ estimated by Weinberg (2000) has been criticized by Gyuk, Dalal and Griest (2000), similar large values have been obtained on different grounds by Evans and Kerins (2000) and Zhao and Evans (2000). Hopefully, the new data of Van der Marel et al. (2002) on the LMC will clarify the situation.}. Evidently no sharp conclusion can be drawn about the fractional abundance of MACHOs in the Milky Way halo, but it seems fair to state that a MACHO contribution to the optical depth $\tau_{MACHO} \sim 10^{-8}$ is quite consistent with present microlensing data.

A set of microlensing events is also characterized by the average lens mass $\overline{M}$, which is related to the event duration and depends strongly on the assumed galactic model. The MACHO collaboration finds $\overline{M} \simeq 0.7 \, M_\odot$ for a canonical SIS halo model, whereas the extreme cases of a maximal and minimal halo yield $\overline{M} \simeq 0.9 \, M_\odot$ and $\overline{M} \simeq 0.5 \, M_\odot$, respectively (with large uncertainties). Unfortunately, $\overline{M}$ does not possess any clear physical meaning, given that at least 5 different lens populations contribute to the optical depth (as already emphasized). Only by a detailed modelling of every population can the average mass corresponding to each population be estimated. According to Jetzer, Mancini and Scarpetta (2002), the MACHO average mass turns out to be $\overline{M}_{MACHO} \simeq 0.3 \, M_\odot$ for a canonical SIS halo model. Obviously – within such a model – ordinary brown dwarfs are ruled out as a candidate for MACHOs.

Let us now discuss how the observed microlensing events fit within the considered dark matter scenario. It goes without saying that – while not logically compelling – here MACHOs are naturally identified with brown dwarfs, and this fact raises two questions which will be addressed separately.

- A question arises because then MACHOs make up a nonnegligible fraction of the halo dark matter, and so the predicted MACHO contribution to the optical depth $\tau'_{MACHO}$ might well come out too large (i.e. larger than $\sim 10^{-8}$).
In order to clarify this issue, we compare the dark matter model in question with a realistic canonical SIS halo model. Because leftover gas as well as nonbaryonic dark matter have to be taken into account, the MACHO fractional abundance in a realistic canonical SIS halo model cannot exceed, say, 20%. Then the above considerations entail that the MACHO contribution to the optical depth predicted by a realistic canonical SIS halo model is \( \tau''_{\text{MACHO}} \simeq 1.2 \cdot 10^{-7} \). So, the critical point is whether the morphological difference between the two models indeed entails that \( \tau'_{\text{MACHO}} \) is lower than \( \tau''_{\text{MACHO}} \) by roughly one order of magnitude. We believe that the answer is yes, as we are going to show.

A natural expectation is that also the baryonic dark halo under consideration has a SIS density profile – but a noncanonical one – since only the outer halo is populated by dark clusters, hence by MACHOs. Thus, we can formally regard the present dark matter model as a realistic canonical SIS model with no MACHOs in the inner part. Consequently, \( \tau'_{\text{MACHO}} \) is reduced with respect to \( \tau''_{\text{MACHO}} \) and we actually get \( \tau'_{\text{MACHO}} \simeq (0.4 - 0.8) \cdot 10^{-7} \) (Jetzer 2001). Notice that a moderate flattening of the baryonic dark halo – as suggested by the observed \( \gamma \)-ray emission – would further lower \( \tau'_{\text{MACHO}} \). As a matter of fact, we expect the MACHO fraction to be less than 20%, because the dark clusters should mainly consist of \( H_2 \) clouds – instead of brown dwarfs – and this circumstance causes an additional reduction of \( \tau'_{\text{MACHO}} \). Gas clouds are not compact enough to produce microlensing events (Henriksen & Widrow 1995), but – depending on their dust-to-gas ratio – can either obscure or magnify a background star. As pointed out above, in the latter case the effect is chromatic. Therefore – owing to the achromaticity constraint imposed in current microlensing searches – the resulting events would simply be discarded. Now, within this context MACHOs are associated with the gas clouds, and so some would-be genuine microlensing events – produced by MACHOs – can either become chromatic or disappear altogether owing to an intervening gas cloud. Because the resulting events would not be observed

\[ \text{r} = 10 - 20 \, \text{kpc}. \]

\[ \text{A quantitative analysis of these chromatic microlensing events has been performed by Bozza et al. (2002)}. \]
in present-day experiments, yet another reduction of $\tau'_{MACHO}$ comes about. On the whole, there should be little doubt that the desired reduction can indeed be achieved, even if a precise estimate would be impossible.

An alternative possibility has been suggested by Kerins and Evans (1998), who suppose that the initial mass function in the halo varies smoothly with the galactocentric distance. Observe that here the baryonic halo model necessarily differs from the SIS. They have shown that in such a situation brown dwarfs fail to dominate the optical depth while still dominating the (baryonic) mass density. As a result, the risk of too large values of $\tau'_{MACHO}$ disappears 44.

- Another question concerns the predicted value of $\overline{M}_{MACHO}$, because it can turn out to largely exceed the brown dwarf mass, thereby preventing MACHOs from being brown dwarfs.

Again, let us consider first a (noncanonical) SIS halo model. An explicit calculation shows that the lack of brown dwarfs in the inner halo produces a reduction of $\overline{M}_{MACHO}$, and we get $\overline{M}_{MACHO} \simeq 0.2 M_\odot$ (Jetzer 2001). As before, a moderate flattening of the baryonic dark halo further lowers $\overline{M}_{MACHO}$. Yet, we have seen that within the considered dark matter model brown dwarfs are to be replaced by beige dwarfs, with masses up to $0.3 M_\odot$. Moreover, a substantial fraction of these beige dwarfs should be binary systems, which are presently so close (hard) that cannot be resolved in current microlensing searches (De Paolis et al. 1998b). As a result, the effective brown dwarf mass can well be as large as $0.3 M_\odot$. So, no problem arises.

Within the Kerins-Evans scenario the situation is different and depends on the quantitative details of the model. However, $\overline{M}_{MACHO}$ tends to come out close to the value predicted by the canonical SIS model. Therefore MACHOs are not brown dwarfs in this setting, and their nature is an open question. A possibility could be that MACHOs are white dwarfs (Oppenheimer et al. 2001). Because of their low fractional abundance, the constraints discussed in Sect. 1 might be circumvented.

44Because it is not clear at this stage whether MACHOs are really brown dwarfs in this context (see below), here $\tau'_{MACHO}$ actually denotes the brown dwarf contribution to the optical depth.
In conclusion, the considered dark matter model is fully consistent with present-day microlensing data \footnote{Because so few microlensing events are produced by MACHOs, it is impossible to decide observationally whether or not MACHOs are clustered (Maoz 1994; Metcalf & Silk 1996).}

It goes without saying that detection of chromatic microlensing events in future experiments would provide evidence that MACHOs are indeed surrounded by gas clouds.

**CMBR anisotropies** – Dark clusters can also be discovered by performing high-precision measurements of the CMBR anisotropy. This strategy involves a sort of kinematic Sunyaev-Zeldovich effect (Sunyaev & Zeldovich 1980) in the gas clouds clumped into the dark clusters and can be illustrated as follows \footnote{We are neglecting here the kinematic Sunyaev-Zeldovich effect arising from the Compton scattering of CMBR photons on the ionized “skin” of the clouds.} (De Paolis et al. 1995c). Assuming for simplicity that dust effects can be neglected, absorption and emission processes merely involve molecular roto-vibrational transition lines, because of the very low cloud temperature. So, photons of the CMBR can be absorbed and re-emitted by the clouds. Since the latter photons are evidently Doppler-shifted – owing both to the cloud velocity dispersion inside the cluster and to the cluster peculiar velocity – an anisotropy in the CMBR shows up when looking towards a dark cluster.

Of course, in order for the effect to be sizable a sufficiently large number of photons must be involved, and the transition line in question has to be optically thick. Hence, the real question is whether any such molecular line falls close enough to the pick of the CMBR. Although the answer obviously depends on the poorly-known cloud composition, even in the limiting case of a primordial metallicity the first rotational transition line of LiH lies very close to the CMBR pick and is optically thick \footnote{This is basically due to the fact that the very low column density is compensated by the huge resonance cross-section.}.

Observe that for dark clusters in the Milky Way halo the resulting CMBR anisotropies show up on the angular scale of $\sim 1$ arcminute. This happens to be just the typical angular scale associated with CMBR anisotropies produced – via the Sunyaev-Zeldovich effect – by clusters of galaxies (Rephaeli 1995; Birkenshow 1999). Consequently, the same observing strategies employed in the latter case (for a review, see Rephaeli 2001) can be used to detect the dark clusters in the Milky Way halo. Obviously, only the occur-
rence of a microlensing event can tell us the actual position of a dark cluster on the sky— in real time, if microlensing data are analyzed on-line—and so a coordinated effort is required.

A nonconventional procedure to detect dark clusters in the Andromeda halo—which operates on the angular scale of $\sim 1$ degree—has been proposed by De Paolis et al. (1995c).

**Extreme Scattering Events (ESEs)**—They are dramatic flux changes occurring—over several weeks to months—during radio flux monitoring of some quasars (Fiedler et al. 1987). It is generally agreed that ESEs are *not* intrinsic variations, but rather apparent flux changes caused by radio wave *refraction* when a cloud crosses the line of sight to a quasar. Evidently, in order to produce an ESE the cloud has to be *ionized*, and the radio signal features demand that the cloud radius and electron density should be $\sim 10^{-5}$ pc and $\sim 10^3$ cm$^{-3}$, respectively. Assuming *full ionization* may look natural at first sight, but then the resulting electron pressure turns out to exceed that of the interstellar medium by a factor $\sim 10^3$, thereby leading to complete evaporation of the cloud within $\sim 1$ yr.

In 1998, Walker and Wardle (1998) claimed that the first consistent explanation of the ESEs involves an unclustered population of cold ($T \sim 10 K$) $H_2$ clouds with radius $\sim 10^{-5}$ pc and mass $\sim 10^{-3} M_\odot$, distributed in a canonical SIS halo and comprising most of its mass. Basically, radio wave refraction is caused by the photo-ionized “skin”, whereas the inner neutral region keeps the electron pressure sufficiently small.

It looks intriguing that these clouds are practically identical to those clumped into the dark clusters, and so it would tempting to imagine that the present dark matter scenario could explain the ESEs. However, the cloud spatial distribution is very different in the two models and the effect of clustering on the ESEs has to be investigated before any conclusion can be drawn.

**Lyman-α clouds**—A typical line of sight to a distant quasar contains a huge number of absorption features, brought about by intervening gas clouds with column density in the range $3 \cdot 10^{12} - 2 \cdot 10^{20}$ cm$^{-2}$. In particular, a *forest* of Lyman-α absorption lines of $HI$ is associated with clouds having column density in the range $3 \cdot 10^{12} - 3 \cdot 10^{15}$ cm$^{-2}$. Because it is difficult to establish whether the Lyman-α lines are produced by transient filamentary intergalactic gas structures or by gas clouds clustered around galaxies, the physical nature of Lyman-α absorption systems is still controversial. While
both options are likely to be – at least partially – correct, Lanzetta and collaborators claim that low-redshift Lyman-α lines are mostly produced by gas clouds inside dark galactic halos (Chen et al. 1998, 2001). Moreover, Chen, Prochaska and Lanzetta (2001) have estimated the cosmological equivalent amount of HI in these Lyman-α clouds to be $\Omega_{HI,g} = (2 - 8) \cdot 10^{-3}$.

Naturally, the question arises as to whether the clouds clumped into the dark clusters can be identified with the low-redshift Lyman-α clouds. Superficially, the answer seems to lie in the negative. For, we have seen that typical cloud parameters are $M \sim 10^{-3} M_\odot$ and $R \sim 10^{-5} \text{pc}$, resulting in an average column density of $\sim 10^{25} \text{cm}^{-2}$, namely ten orders of magnitude larger than allowed. However, such a column density actually pertains to $H_2$, not to HI. In fact, two points should be emphasized.

- Given that HI is present only in the outer region of the clouds, its volume density is presumably much smaller than the average cloud density.

- The reported typical values of the Lyman-α cloud column density are inferred under the implicit assumption of full HI cloud composition. However, this is presently not the case, and what matters here is the thickness of the external HI layer (rather than the cloud radius), which is expected to be several orders of magnitude smaller than the cloud size.

Altogether, the actual HI column density can well lie in the allowed range. Furthermore, the fractional abundance of HI appears to fit within the above estimate if the clouds in questions indeed provide the main contribution to the dark baryon budget at low-redshift. Needless to say, only a detailed analysis of the cloud distribution predicted by the considered dark matter model can show whether the observed properties of low-redshift Lyman-α forest lines are correctly reproduced.

$H_2$ absorption lines – No doubt, in principle the most straightforward way to discover the clouds clumped into the dark clusters is based upon detection of ultraviolet Lyman and Werner absorption lines of $H_2$ in the quasar spectra. This strategy is conceptually identical to the one discussed above for the

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48Because of this fact, the effect of dust should be irrelevant here, since dust is expected to dominate the inner part of a cloud.
Lyman-\(\alpha\) lines of \(HI\). However, in practice things are different. For, while positive detection would provide unambiguous evidence, sizable dust effects in the clouds would totally upset this method, and so no conclusion can be drawn from lack of detection.

As a matter of fact, \(H_2\) has already been detected in this way (Folz et al. 1988; Ge & Bechtold 1997), but these observations suffer from a severe confusion problem. Nevertheless, the \textit{FUSE} satellite (Sembach et al. 2002) should collect high-quality data on the \(H_2\) absorption lines, and so a clarification of this issue is to be expected.

\textit{Clusters of galaxies} – As is well known, clusters of galaxies contain a large amount of hot X-ray emitting gas. Besides thermal Bremsstrahlung, the intracluster gas also produces heavy-element recombination lines. This fact implies that at least part of the gas must have been processed inside the galaxies and subsequently ejected. Actually, specific models of galactic chemical evolution correctly account for the observed metallicity of the intracluster gas, but its predicted total amount invariably turns out to be about one order of magnitude lower than observed (Matteucci & Vettotani 1988; Ciotti et al. 1991; Metzler & Evrard 1994). So, it appears that roughly 90\% of the intracluster gas cannot be galactic in origin.

To the extent to which the present dark matter scenario describes the cluster galaxies, such a conclusion is not necessarily true. In fact, what the above galactic evolution models implicitly assume is that only luminous baryons are present. However, a nontrivial amount of dark gaseous baryons lurking in galactic halos provides an additional supply, which can be progressively transferred to the intracluster medium via ram-pressure stripping and galaxy-galaxy interaction \(^{49}\). Moreover, an order-of-magnitude estimate shows that a large fraction of the intracluster gas can be accounted for in this way. Accordingly – following a previous analysis \(^{50}\) by David (1997) – one can conclude that the fractional baryonic content of individual galaxies, groups and rich clusters is nearly a constant (independent of scale).

\(^{49}\) The relevance of galactic outflows for clusters of galaxies has been emphasized by Binney, Gerhard and Silk (2001).

\(^{50}\) This analysis was based on the preliminary evidence – then turned out to be wrong – that MACHOs make up \(\sim 50\%\) of the Milky Way halo.
4 Conclusions

After some introductory remarks about the observational evidence for dark matter, we have shown that the need for baryonic dark matter is today even more solid than it was in the past. What is still missing, however, is some clear-cut observational evidence about the specific form taken by the dark baryons.

Nevertheless, recent developments in computer simulations of galaxy formation as well as in the understanding of low-redshift Lyman-α clouds have provided valuable hints. When they are combined with metallicity and background light constraints, the list of baryonic dark matter candidates in galaxies gets dramatically shortened.

Dark clusters of brown dwarfs and cold $H_2$ clouds in galactic halos certainly look as a natural possibility. We have discussed how they are expected to form, the properties they presumably should have and the observations in which they are likely to show up.

A good deal of theoretical and observational work has still to be done before claiming that the present dark matter scenario is correct. But – we believe – the stakes are worth the effort.

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