On the fraction of dark matter in charged massive particles (CHAMPs)

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ABSTRACT: From various cosmological, astrophysical and terrestrial requirements, we derive conservative upper bounds on the present-day fraction of the mass of the Galactic dark matter (DM) halo in charged massive particles (CHAMPs). If dark matter particles are neutral but decay lately into CHAMPs, the lack of detection of heavy hydrogen in sea water and the vertical pressure equilibrium in the Galactic disc turn out to put the most stringent bounds. Adopting very conservative assumptions about the recoiling velocity of CHAMPs in the decay and on the decay energy deposited in baryonic gas, we find that the lifetime for decaying neutral DM must be \( \gtrsim (0.9 - 3.4) \times 10^3 \) Gyr. Even assuming the gyroradii of CHAMPs in the Galactic magnetic field are too small for halo CHAMPs to reach Earth, the present-day fraction of the mass of the Galactic halo in CHAMPs should be \( \lesssim (0.4 - 1.4) \times 10^{-2} \). We show that redistributing the DM through the coupling between CHAMPs and the ubiquitous magnetic fields cannot be a solution to the cuspy halo problem in dwarf galaxies.

KEYWORDS: dark matter – galaxies: haloes – galaxies: kinematics and dynamics – galaxies: magnetic fields.
1. Introduction

So far, other than its gravitational interaction, the detailed properties of the dark matter (DM) are still largely unknown. The lack of direct detection suggests that DM particles are stable, neutral and weakly interacting. However, it is important to know how well these properties are constrained from an observational point of view. In recent years, mainly motivated by the cuspy problem of dark haloes in low-surface brightness galaxies and dwarf galaxies, and the excessive abundance of satellite galaxies inferred in cosmological simulations, much work has been done to study the cosmological and astrophysical implications of other variants, such as decaying, collisional or annihilating DM. New interesting phenomena at galactic scales, ignored under the assumptions of collisionless and neutral DM, arise if a fraction of DM is made up by massive particles with electric charge (CHAMPs). Several theoretical physics models beyond the Standard Model (SM) have shown the possibility of CHAMPs (e.g., [1, 2]). The existence of CHAMPs is well-motivated in the model of super Weakly Interacting Massive Particle (super-WIMP) dark matter [3]. In supersymmetric theories, some popular examples of CHAMPs include a slepton, such as the supersymmetric staus (e.g., [1, 2]).
The hypothesis that the DM is made up by a mixture of bare CHAMPs and neutra-
CHAMPs (a neutral bound atom formed by a CHAMP of electric charge $-1$ and a proton) 
was considered in the late eighties [5]. Dimopoulos et al. [6] noticed that the astrophysical 
and terrestrial limits are hardly compatible with such a scenario (see [7] and [8] for updated 
reviews). Nevertheless, all these constraints were derived for the standard flux of particles 
at Earth from the Galactic halo, assuming it was constant over time. If DM particles are 
originally neutral and decay lately into charged particles, many constraints can be avoided 
and one must reevaluate earlier bounds.

This paper is organized as follows. In section 2, we describe our assumptions, which 
were especially designed to minimize the potentially disastrous effects of charged DM. 
The constraints from big bang nucleosynthesis (BBN) and cosmic microwave background 
(CMB) anisotropy on the lifetime of decaying neutral DM particles are discussed in section 
3. In sections 4 and 5, we examine the distribution of CHAMPs in the disc and in the halo 
of the Galaxy. We will discuss the implications of the lack of detection of anomalously 
heavy hydrogen in sea water and the vertical (magneto-)hydrostatic configuration of the 
Galactic disc on the fraction of halo CHAMPs. Other physical implications of CHAMPs 
embedded in galaxy clusters are briefly discussed in section 6. Concluding remarks are 
given in section 7.

2. Assumptions

In order to remedy purported problems with the collisionless CDM family of cosmological 
models on galactic and galaxy cluster scales, Chuzhoy & Kolb [9] have revived the possibil-
ity that a significant fraction of the DM in haloes is made up by unneutralized CHAMPs. 
These authors claim that the distribution of CHAMPs in galaxies may be altered by the 
coupling between CHAMPs and ubiquitous magnetic fields. For instance, CHAMPs may 
be depleted from the central parts of galaxies, erasing the DM cusp, if they are accelerated 
through the Fermi mechanism in supernova shocks.

Here we explore a generic scenario in which neutral dark matter, denoted by $\chi$, decay 
with lifetime $\tau_{\text{dec}}$ into non-relativistic and exotic massive particles with electric charge. 
The model of Chuzhoy & Kolb [9] corresponds to a scenario where the decay lifetime is shorter 
than the age of the Universe. The decay of DM into another dark or SM species could have 
a bearing upon possible problems with the $\Lambda$CDM scenario, e.g., the reionization of the 
Universe, the structure formation at small-scales and the low abundance of satellite galax-
ies, the formation of galactic cores, the synthesis of light elements in the early Universe, 
the origin of ultra-high energy cosmic rays, the positron excess observed by PAMELA, the 
Tully-Fisher relation with $z$ or the gas fraction of galaxy clusters. However, we will focus 
on the exclusion range of parameters.

Stringent limits on DM decay into photons or SM particles have been derived from 
diffuse $\gamma$-ray observations [10], the effects on BBN [11] and from the reionization history of 
the Universe (e.g., [12, 13]). In order to set an upper limit on the fraction of CHAMPs as 
generous as possible, we will consider the most favourable and simplest scenario to permit
the maximum amount of charged particles in galactic haloes. Our model starts from the following, rather artificial, assumptions:

1. The coupling strength of the decay of a neutral DM particle into two (electrically) charged particles, $X_1^+$ and $X_2^-$, plus a very light (or massless) weak interacting particle $\bar{X}_\nu$, is large. Therefore, $\chi$ dominantly decays without the emission of photons or $Z$ bosons. The $\chi$-decay mode is thought to be analogous to the neutron $\beta$-decay but in the dark sector. Note that $X_2^-$ is not the anti-particle of $X_1^+$ and thus they may have different masses. To keep the discussion manageable, however, we will assume that both particles have the same mass.

2. $X_1^+$ and $X_2^-$ are stable and cannot decay. This can be accomplished if they are the lightest particles carrying conserved ‘dark baryon’ number $B'$ and ‘dark lepton’ number $L'$, respectively. Conservation of these quantum numbers in the decay is met if $\chi$ and $X_1^+$ are dark baryons and $X_2^-$ is a dark lepton and $\bar{X}_\nu$ a dark anti-lepton.

3. The decay $\chi \rightarrow X_1^+ + X_2^- + \bar{X}_\nu$ is the dominant way through which CHAMPs can be produced. This non-thermal production of particles is present in some schemes such as SUSY (e.g., [14]). In practice, it is assumed that DM is neutral before freeze-out and afterwards it decays into CHAMPs.

4. The charged $X$ particles from the decay are non-relativistic so that they are cold DM by the time of structure formation and its contribution to the reionization of the intergalactic medium does not contradict CMB data. This is fulfilled in models where $\Delta m/m_\chi \lesssim 2 \times 10^{-4}$, where $\Delta m$ is the mass difference between the initial and final states. Although this fine-tuning is unlikely, it is not so rare in nature. For instance, the corresponding ratio in the classical neutron $\beta$-decay is comparable ($\sim 8 \times 10^{-4}$).

We will see that, even under these somewhat artificial assumptions, the fraction of dark matter that can be made by CHAMPs is vanishingly small for astrophysical phenomena to be affected and the standard Cold DM cosmology is recovered. The proposed scenario is in some ways reminiscent of models already discussed in the literature but introduce important conceptual differences. In previous works, decaying DM was introduced to dissolve the central cusp in DM haloes and the overabundance of satellite galaxies by the depletion [15, 16] or energy release in the decays [17, 18]. As suggested by Chuzhoy & Kolb [9], in the CHAMP model, even if the recoiling velocities of CHAMPs were very small, they may be ejected from the central parts of the galaxies by Fermi acceleration in shock waves, or from the Galactic disc, making them very evasive for direct terrestrial detection (see [9] for a discussion). In the next section, we discuss the limits on $\tau_{\text{dec}}$ imposed by BBN and CMB.

3. Pregalactic constraints

The standard BBN theory has been well established to predict precisely the primordial light element abundances and constrain the number density of long-lived CHAMPs at $t < 10^5$ s. Since the recombination of CHAMPs with protons, $\alpha$-particles, electrons, or other CHAMPs to form neutral atoms, occurs well after BBN, CHAMPs remain bare at BBN. If $X_2^-$ particles, with masses below the weak scale, are present at the BBN and they
do not decay into other particles, excessive production of $^6\text{Li}$ and $^7\text{Li}$ may occur only if the fractional contribution of negative CHAMPs to the present critical density, $\Omega_X$, is larger than a certain maximum value $\Omega_X^{\text{max}} = 3 \times 10^{-6}$ (e.g., [14, 20], and references therein). For masses above the weak scale, this bound can be weakened. In our case, the abundance of CHAMPs increases in time due to $\chi$ decays and this constraint only applies at $t < 10^{53}$ s. By imposing that, at most, a particle number fraction of $\Omega_X^{\text{max}}/\Omega_c$ of $\chi$'s, with $\Omega_c$ the present density of cold DM ($\Omega_c = 0.23$), has decayed by the end of BBN, $t \simeq 10^{55}$ s, we obtain $\tau_{\text{dec}} > 200$ yr.

A much more stringent constraint can be placed by studying the effect on the CMB anisotropy of a scattering interaction between charged CHAMPs and the photon-baryon fluid. Throughout the paper, we will refer to “charged CHAMPs” to indicate both the free CHAMPs and the bound states of CHAMPs having a net electric charge. Kohri & Takahashi [21] have shown that most of the negative CHAMPs are captured by $\alpha$ particles, forming charged CHAMPs. Hence, all the CHAMPs are expected to be in a charged state at the epoch of recombination. Since charged particles have low velocities, they can thermalize very quickly by their interaction with the baryons [5]. The effect on the CMB of coupling baryons with charged CHAMPs is equivalent to a standard model with a larger value of $\Omega_b$. Given that the WMAP uncertainty in $\Omega_b$ is < 3%, the fraction of DM particles that are allowed to decay before recombination epoch, $t_R$, is $\lesssim 0.03(\Omega_b/\Omega_c) \simeq 6 \times 10^{-3}$, where $\Omega_b/\Omega_c$ is the fraction of baryonic energy density $\Omega_b h^2$, relative to that of the (cold) DM, $\Omega_c h^2$. Consequently, CMB power spectra is obtained if $\tau_{\text{dec}} > t_R \times 10^3/6 \simeq 7 \times 10^7$ yr, where we have used $t_R \simeq 376,000$ yr (see [24] for the case of millicharged CHAMPs).

For invisible decay to weakly interacting particles such as neutrinos or $X_\nu$, Gong & Chen [23] constrain the decay lifetime to $\tau_{\text{dec}} > 0.7 \times 10^5 \xi$ Gyr, where $\xi$ is the fraction of the rest mass which gets converted to neutrinos or $X_\nu$. Our assumption (4) implies that $\xi \simeq 2 \times 10^{-4}$ and, consequently, we should constrain ourselves to models with $\tau_{\text{dec}} > 1.5 \times 10^8$ yr.

In contrast to the model of De Rújula et al. [3], the contribution of the pressureless $\chi$ component, and not neutrachAMPs, is dominant in driving galaxy formation. In this sense, our model is closer to the standard collisionless CDM.

4. The density of CHAMPs in the Galaxy

After recombination, when photons and baryons become noninteracting, baryons and charged CHAMPs fall into the gravitational wells formed by pressureless $\chi$-particles and neutrachAMPs. In the halo of a galaxy like ours, the temperature becomes high enough to ionize hydrogen and superheavy hydrogen ($X_+^2e^-$) –see the Appendix [A]. In contrast, although the equilibrium fraction of ($X_+^2e^-$) in the halo is small, neutrachAMPs formed at pregalactic stages (we will refer to them as ’primordial neutrachAMPs) can survive a long time compared to the Hubble time, without being dissociated (see the Appendix [A]). Nevertheless, the initial density of primordial neutrachAMPs is expected to be small [21].

\footnote{The CHAMP-to-entropy ratio $Y_X$ was converted to $\Omega_X$ using $\Omega_X h^2 = 2.73 \times 10^{11} Y_X (m_X/1 \text{TeV})$.}
and they might be converted to \((X^2 \alpha)\) ions by charge-exchange scattering and then they behave as charged CHAMPs in the lifetime of the Galaxy [6].

In order to constrain the abundance of CHAMPs in the Galactic disc and in the halo we must consider the following processes: (1) magnetic fields can prevent the charged CHAMPs in the halo to penetrate the Galactic disc, (2) charged CHAMPs may be ejected from the disc and blown either back to the halo, or right out of the galaxy if charged CHAMPs are shock accelerated by supernovae (e.g., [6, 9]), (3) Neutral \(\chi\) particles have no difficulties to penetrate the disc and may have a decay when they are crossing the disc, replenishing the disc with fresh CHAMPs. In the following, we study conditions for which the abundance of CHAMPs is small in the disc, making its detection unlikely, but large in the halo.

4.1 Shielding the disc with magnetic fields

In principle, a charged CHAMP may lose all its kinetic energy by interacting with the interstellar gas as it intersects the Galactic disc [24]. However, the penetration of unneutralized coronal CHAMPs along the Galactic disc is impeded by the presence of Galactic magnetic fields. Chuzhoy & Kolb [9] claim that charged CHAMPs cannot cross the disc if they have masses \(m_X < 10^8\) TeV. A more precise calculation taking into account that the Galactic magnetic field is not plane-parallel is given below.

It is well-known that when charged particles interact with a magnetized body, a boundary layer that divides two regions with different conditions is created [25]. Thus, charged particles will penetrate this boundary by some distance before they are turned around by the \(\vec{v} \times \vec{B}\) force (Figure 1).

![Figure 1](image.png)

**Figure 1:** Sketch of the structure of the magnetic boundary layer formed by the partial penetration of the charged particles before they are deflected back. We also illustrate the corresponding orbits of particles in the neighborhood of such boundary for both types of charge, that is, negative and positive. The degree of shielding depends on the topology of the magnetic field. In galactic discs, the magnetic field lines are not plane-parallel.

The boundary layer is formed because of the partial penetration of the charged particles before they are deflected back. A schematic representation of the orbits described by negative and positive charged particles in the neighborhood of the magnetic boundary are drawn in Fig. 1.

The degree of shielding by magnetic fields depends on the configuration of the magnetic field. In the case of the magnetized Galactic disc, the magnetic field is not plane-parallel.
and the propagation of charged particles is more complex because the magnetic field has a turbulent component, i.e. $\vec{B} = \vec{B}_0 + \vec{b}$, where $\vec{B}_0$ is the regular (homogeneous) magnetic field and $\vec{b}$ denotes the turbulent field. The particle motion is determined not only by the average magnetic field but also by scattering at field fluctuations, a stochastic process which requires the solution of transport equations with particle ensembles. Particle propagation in turbulent fields can be understood as a diffusive process, reason why we consider the spatial diffusion of halo CHAMPs into the galactic disc.

As occurs when one considers the escape timescale of cosmic rays from the Galactic disc (e.g., [26]), the timescale for the penetration of halo CHAMPs is governed by the diffusion timescale across the galaxy disc thickness, $\tau_{\text{diff}}$. The ordered magnetic lines follow the spiral pattern, come out of the Galaxy disc and unfold in the halo. However, due to the presence of the tangled (turbulent) component of the magnetic field, the penetration timescale of halo particles through the magnetic spiral arms is much longer than $\tau_{\text{diff}}$ because they must diffuse a distance much longer than the galaxy disc thickness $H$. The diffusion timescale $\tau_{\text{diff}}$ across $H$ for a halo CHAMP, is bracketted in the range:

$$\frac{H^2}{2D_{||}} < \tau_{\text{diff}} \lesssim \frac{H^2}{2D_{\perp}},$$

where $D_{||}$ and $D_{\perp}$ are the diffusion coefficients parallel and transverse to the mean component of the magnetic field, which is observed to be parallel to the disc.

The magnetic field that feels a charged CHAMP moving within the disc can be considered static because Alfvén waves propagate with velocities of the order of the Alfvén speed $v_A \sim 6$ km s$^{-1}$, which is smaller than the typical velocities of CHAMPs $\gtrsim \sqrt{3}\sigma_v$, where $\sigma_v \simeq 150$ km s$^{-1}$ is the one-dimensional velocity dispersion for halo particles. The diffusion coefficients depend on the turbulence level $\eta \equiv (1 + \langle B_0^2 \rangle / \langle b^2 \rangle)^{-1}$, and on the rigidity $\chi \equiv 2\pi r_L/\lambda_{\text{max}}$, with $r_L$ the Larmor radius defined with respect to the total magnetic field and $\lambda_{\text{max}}$ the maximum scale of the turbulence $\sim H/2$ [26, 27]. Observations of the Galactic polarized synchrotron background yield $1 < \langle b^2 \rangle / \langle B_0^2 \rangle < 9$ ([28], and references therein), implying that $0.5 < \eta < 0.9$. Since $\tau_{\text{diff}}$ scales as the inverse of the diffusion coefficients and those are essentially a monotonic function of $\eta$, we use $\eta \simeq 0.5$ in our estimate of $D_{\perp}$ in order to give an upper limit on the diffusion timescale. From the numerical result by [28], we know that $D_{\perp}/(r_L v) \sim 0.3$ for Kolmogorov turbulence with $\eta = 0.5$ and $\chi$ between 0.05 and 0.4, we find that the diffusion timescale average over the velocity distribution is

$$\tau_{\text{diff}} \lesssim \left\langle \frac{5H^2}{3r_L v_X} \right\rangle = 10 \text{ Gyr} \left( \frac{H}{300 \text{pc}} \right)^2 \left( \frac{m_X}{10^6 \text{TeV}} \right)^{-1} \left( \frac{\sigma_v}{150 \text{ km s}^{-1}} \right)^{-2} \left( \frac{B}{5 \mu\text{G}} \right).$$

The values of the turbulence level and rigidity depend on the galactocentric distance but also on the azimuthal angle in the disc, because both the regular and the turbulent fields are commonly more intense within the spiral arms ([29], and references therein). The efficiency of the magnetic shielding can be reduced along Galactic magnetic chimneys. Moreover, it
is likely that CHAMPs are accelerated to much higher velocities by supernova shocks as soon as they penetrate inside the disc, decreasing $\tau_{\text{diff}}$ further. In the most optimistic scenario where all these effects can be ignored, the present configuration and strength of the Galactic magnetic field can prevent diffusion of (unaccelerated) charged CHAMPs across the Galactic disc in the lifetime of the disc for mass particles $m_X < 10^6$ TeV. Note that the corresponding gyroradius for a mass of $10^6$ TeV moving at $300$ km s$^{-1}$ in a field of $5\mu$G is $0.2$ pc. The equation that governs the number of CHAMPs in the disc will be discussed in section 4.3.

### 4.2 Energy gain and loss of CHAMPs in the disc

In the foregoing section we have seen that halo CHAMPs with masses $m_X < 10^6$ TeV may have difficulty in penetrating the magnetized Galactic disc, whereas those inside it would stay confined to the disc unless they are accelerated. Charged CHAMPs in the disc gain energy through electrostatic fields, Fermi acceleration in shock waves, and its descendants (e.g., [30]), and lose kinetic energy due to Coulomb scatterings with electrons and protons of the diffuse interstellar gas.

Consider masses of $m_X$ larger than the electron mass$^2$. The dissipation timescale due to collisions with the electrons is $\tau_{\text{dis}} = E/|\dot{E}|$, with $E = m_X v_X^2/2$ and

$$|\dot{E}| = 4\pi n_e \frac{e^4}{m_e v_X} \ln \Lambda,$$

(4.3)

where $v_X$ is the velocity of the CHAMP in the interstellar medium, $e$ is the electron charge, and $n_e$ is the electron density ($\approx 0.025$ cm$^{-3}$ in the solar vicinity) and the Coulomb logarithm has a value of about 20. CHAMPs moving in the Galactic disc may avoid strong cooling if the dissipation timescale $\tau_{\text{dis}}$ is greater than the shock acceleration timescale $\tau_{\text{acc}}$, which is $\gtrsim 0.01$ Gyr (e.g., [32, 33]). The condition $2\tau_{\text{dis}} > \tau_{\text{acc}} \gtrsim 0.01$ Gyr implies that particles with initial velocities

$$v_X > v_{\text{crit}} \equiv 150\sqrt{3} \text{ km s}^{-1} \left( \frac{m_X}{2 \times 10^3 \text{TeV}} \right)^{-1/3},$$

(4.4)

can be accelerated and escape from the disc, whereas those particles with velocities $< v_{\text{crit}}$ are expected to lose kinetic energy until they become neutral by recombining with a proton to form a neutraCHAMP ($X^{-}_\chi \ p$), or an electron to form superheavy hydrogen ($X^+_\chi \ e^{-}$). Basdevant et al. [24] suggested that neutraCHAMPs and superheavy hydrogen in the disc will reach thermal equilibrium with the environment and will present turbulent velocities as those of interstellar neutral hydrogen, $\sim 10$ km s$^{-1}$. Charge-exchange equilibrium with hydrogen dictates that $20\% - 40\%$ of superheavy hydrogen in the disc should be ionized.

Assuming that the velocity distribution of CHAMPs just after the decay of $\chi$ particles is Maxwellian, the fraction $F$ of CHAMPs created in the Galactic disc that will be trapped in the disc forming neutraCHAMPs or superheavy hydrogen is

$$F = \text{erf} \left( \frac{v_{\text{crit}}}{\sqrt{2} \sigma_v} \right) - \sqrt{\frac{2}{\pi}} \frac{v_{\text{crit}}}{\sigma_v} \exp \left( -\frac{v_{\text{crit}}^2}{2\sigma_v^2} \right).$$

(4.5)

$^2$We will not consider the regime $m_X < m_e$ because they are excluded for $10^{-15} \lesssim \epsilon < 1$, where $\epsilon$ is the electric charge units of $e_e$, the elementary electron charge [31].
After one Hubble time, $t_H$, the relative abundance of superheavy hydrogen in the solar neighbourhood is

$$\frac{[X^+_1 e^-]}{[\text{HI}]} = (F \times 10^{-7})(1 - \exp[-t_H/\tau_{\text{dec}}]) \left(\frac{m_X}{2 \times 10^3 \text{TeV}}\right)^{-1}, \quad (4.6)$$

where we have assumed a total density of dark matter of $0.01 M_\odot$ pc$^{-3}$.

Searches for interstellar superheavy hydrogen performed by looking at the Lyman $\beta$ absorption in the direction of some nearby stars constrain the relative abundance of superheavy hydrogen over ordinary hydrogen to $< 2 \times 10^{-8}$ (e.g., [24, 34]). Combining Eqs (4.5) and (4.6) using $\sigma_v = 150 \text{ km s}^{-1}$, we find that for $\tau_{\text{dec}} \ll t_H$, the relative abundance is smaller than $\sim 10^{-8}$ provided that $m_X > 6 \times 10^3 \text{ TeV}$. For $\tau_{\text{dec}} \simeq t_H$, the condition is fulfilled for $m_X > 4.5 \times 10^3 \text{ TeV}$.

### 4.3 Constraints from sea water searches

If CHAMPs are singly charged, the most stringent bound on the abundance of CHAMPs in the disc comes from searches of anomalously heavy sea water\(^3\). The gyroradius for a charged CHAMP of mass $2.5 \times 10^3 \text{ TeV}$ at 300 km s$^{-1}$ is 10 AU in the magnetic field of the solar wind ($50 \mu G$ in the Earth vicinity). Therefore, the arrival of charged CHAMPs at Earth cannot be impeded by the magnetic field of the solar wind for $m_X$ values in the range of interest ($m_X \gtrsim 10^3 \text{ TeV}$). The null results of searches of CHAMPs, between $10^3 \text{ TeV}$ and $10^5 \text{ TeV}$, in ocean water by Verkerk et al. [36] may be used to constrain the admissible value for $\tau_{\text{dec}}$.

Denote by $n_h^+(R)$ the number density of positively charged DM particles at galactocentric distance $R$ in the halo. Ignoring the expansion of the dark halo by the recoiling velocities in the decay, $n_h^+$ increases in time by:

$$\frac{dn_h^+}{dt} = -\frac{dn_\chi}{dt} = \frac{n_\chi}{\tau_{\text{dec}}}, \quad (4.7)$$

where $n_\chi(R, t)$ is the number density of neutral DM particles in the halo. In the equation above, we have neglected the flux of CHAMPs from the disc to the halo since the mass of DM in the disc is small as compared to that in the quasi-spherical dark halo. Solving this equation, we have $n_h^+(R, t) = n_0(R)[1 - \exp(-t/\tau_{\text{dec}})]$. Here, $n_0(R)$ is the number of $\chi$ particles at the galactocentric distance $R$ if they would have not decayed.

As discussed in §4.2, for CHAMPs in the disc, we need to differentiate between initially slow CHAMPs ($v < v_{\text{crit}}$) and initially fast CHAMPs ($v > v_{\text{crit}}$). Slow CHAMPs lose energy until they reach thermal equilibrium with the interstellar medium gas, whereas fast CHAMPs will be accelerated by supernova shock waves and eventually be ejected from the disc. Denote by $n^+_{\text{cd}}$ the density of neutral and ionized superheavy hydrogen in the ‘cold’ phase (one-dimensional rms velocities of $\sim 10 \text{ km s}^{-1}$) and by $n^+_{\text{hd}}$ the density of $X^+_1$ in the

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\(^3\)The heating of the interstellar H i gas by the impacts of CHAMPs crossing the gaseous disc imposes a constraint of a factor $\sim 5$ less stringent [35].
‘hot’ phase (one-dimensional rms velocities of $\gtrsim 150$ km s$^{-1}$). According to our discussion in section 4.2, $n_{cd}^+\cd$ increases in time according to

$$n_{cd}^+(t) = F n_0(R) \left[ 1 - \exp\left( -\frac{t}{\tau_{\text{dec}}} \right) \right]. \quad (4.8)$$

The escape of cold CHAMPs through diffusion is very small and can be neglected.

For the hot CHAMPs in the disc, we need to consider the evacuation from the disc by Fermi acceleration processes, the replenishment of CHAMPs by the decay of neutral particles and the flux from the halo to the disc through diffusion. Let $\tau_{\text{esc}}$ the timescale for CHAMPs to escape from the disc. The equation for $n_{hd}^+$ at times $t > t_d$, where $t_d$ is the epoch of the formation of the magnetized Galactic disc, is

$$\frac{dn_{hd}^+}{dt} = F' \frac{n_x}{\tau_{\text{dec}}} - \frac{n_{hd}^+}{\tau_{\text{esc}}} + \frac{n_h - n_{hd}^+}{\tau_{\text{diff}}}, \quad (4.9)$$

with $F' \equiv 1 - F$. We have made the approximation that the diffusion of CHAMPs from the halo to the disc is $D_\perp \nabla^2 n^+ \simeq (n_h^n - n_{hd}^+)/\tau_{\text{diff}}$. Using the value of $n_x$ previously calculated, Equation (4.9) can be immediately solved. For instance, if we define $\tau_{\text{eff}}$ as

$$\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_{\text{esc}}} + \frac{1}{\tau_{\text{diff}}}, \quad (4.10)$$

the density of CHAMPs in the disc at $t > t_d$ is

$$n_{hd}^+(t) = n_0 \frac{\tau_{\text{eff}}}{\tau_{\text{diff}}} \left[ 1 + \left( \frac{F' \tau_{\text{diff}} - \tau_{\text{dec}}}{\tau_{\text{dec}} - \tau_{\text{eff}}} \right) \exp\left( -\frac{t}{\tau_{\text{dec}}} \right) \right]$$

$$+ C \exp\left( -\frac{t}{\tau_{\text{eff}}} \right), \quad (4.11)$$

provided that $\tau_{\text{dec}} \neq \tau_{\text{eff}}$ (see Appendix B for details). The constant $C$ is fixed by imposing the initial condition that $n_{hd}^+(t_d) = n_0 F'[1 - \exp(-t_d/\tau_{\text{dec}})]$. Since the Galactic disc is about 12 Gyr old, we take $t_d \simeq 1.6$ Gyr.

The number density of positive CHAMPs in the sea water is predicted to be:

$$n_{\text{sea}}^+ \simeq \frac{1}{4d} \int_{\text{last 3 Gyr}} (n_{cd}^+(t)v_{cd} + n_{hd}^+(t)v_{hd})dt, \quad (4.12)$$

where $d$ is the average ocean depth ($d \simeq 2.6$ km), $v_{cd}$ and $v_{hd}$ are the characteristic velocities of particles in the frame corotating with the Sun for the cold and hot population (i.e. $v_{cd} \simeq 17$ km s$^{-1}$, $v_{hd} \gtrsim 300$ km s$^{-1}$). The integration is carried out over the accumulation time of the CHAMPs inside the sea water, about the age of oceans, $\sim 3$ Gyr (e.g., [36, 37]).

By requiring that the relative abundance of superheavy isotopes of hydrogen, compared to ordinary hydrogen is less than about $6 \times 10^{-15}$ in the range $10$ TeV $< m_X < 6 \times 10^4$ TeV [36], the exclusion diagram was derived for three different values of $m_X$ (see Figure 3) for $v_{hd} = 300$ km s$^{-1}$. Note that $n_{hd}^+ \propto v_{hd}^{-1}$. For $\tau_{\text{diff}}$ we have adopted the maximum value permitted by the inequality (1.2). Those neutraCHAMPs that are converted to $X_2^2 \alpha$ by charge-exchange scattering when they cross the disc will also contribute as a source of
heavy hydrogen in Eq. (4.12). The inclusion of this additional source of superheavy sea water shifts the curves in the top panel of Figure 2 downwards, making the allowed region of parameters more restrictive.

The curves in the $\tau_{\text{esc}}$ versus $\tau_{\text{dec}}$ plane at the top panel of Figure 2 define the maximum value of $\tau_{\text{esc}}$ compatible with the heavy-water searches, as a function of $\tau_{\text{dec}}$, i.e. $\tau_{\text{esc}}^{\text{max}} = \mathcal{G}(\tau_{\text{dec}}, m_X)$. Along these curves, we have derived the maximum present-day values of $n_h^+$, $n_{hd}^+$ and $n_{vd}^+$ allowed by sea water searches (Figure 2b). We see that in order for CHAMPs to be abundant in the halo (say, $n_h^+ / n_0 > 0.2$), $m_X > 10^4$ TeV is required. It is interesting to note that the permitted region of parameters $(\tau_{\text{dec}}, \tau_{\text{esc}})$ is very restricted for a particle mass of $2 \times 10^3$ TeV.

We see from Figure 2 that for $m_X = 2 \times 10^4$ TeV, $\tau_{\text{esc}} < 0.6$ Gyr is a guarantee that the sea-water constraint is fulfilled. However, according to Eq. (4.12), the population of hot CHAMPs should be accelerated to a velocity dispersion of $\gtrsim 3,400$ km s$^{-1}$ in order to escape in less than $\sim 1$ Gyr. This value is, of course, much larger than our reference value $v_{hd} = 300$ km s$^{-1}$ used to derive $n_{\text{sea}}^+$ in Eq. (4.12). A set of self-consistent calculations, which include the fact that $v_{hd}$ and $\tau_{\text{esc}}$ are not independent, shows that solutions compatible with the lack of detection of sea water and $300 < v_{hd} < 10,000$ km s$^{-1}$, require $\tau_{\text{dec}} > 500$ Gyr for a particle mass of $2 \times 10^4$ TeV and $\tau_{\text{dec}} > 2.5 \times 10^3$ Gyr for a mass of $2 \times 10^3$ TeV.

It is now clear that the allowed values for $\tau_{\text{dec}}$ depend on $m_X$ but also on the adopted value for $v_{hd}$. The parameters $\tau_{\text{esc}}$ and $\tau_{\text{dec}}$ are unconstrained for $m_X > 6 \times 10^4$ TeV, because the concentration of anomalously heavy hydrogen in sea water is very uncertain. In the next section we will consider the vertical pressure equilibrium in the Galactic disc and will find out a more robust lower limit on the lifetime of $\chi$ particles.

5. The global magnetic support of halo CHAMPs

In the idealised situation that the magnetic field in the disc, at $|z| < Z_{\text{min}}$, is horizontal and the halo is unmagnetized, when charged particles with small gyroradii try to penetrate the disc, they execute approximately half a gyro-orbit before finding themselves back in the unmagnetized region and with velocities directed away from the magnetized region (Fig. 1). In the boundary layer, a current layer develops as a result of a thermal, unmagnetized plasma interacting with a magnetized region. It is a classical result that the (kinetic) motions of individual particles in collisionless plasmas can be reconciled with the role inferred for the pressure in MHD (e.g., [28, 39]). Since charged CHAMPs in the halo are essentially collisionless, the CHAMP momentum flux $m_X (n_h^+ + n_h^-) \sigma_v^2$ at the caps of the disc should be balanced by the pressure $P_B$ of the magnetic field in the disc. As we discussed in the previous section, the galactic disc may contain hot CHAMPs that may participate in the pressure balance, whereas particles trapped in the cold phase do not contribute to support the halo CHAMPs because its density is very low at $|z| \sim Z_{\text{min}}$. Ignoring the weight of coronal gas and taking $n_h^+ = n_h^-$ and $n_{hd}^+ = n_{hd}^-$, it holds

$$P_B(Z_{\text{min}}) \gtrsim 2m_X n_h^+ \sigma_v^2 - 2m_X n_{hd}^+ \sigma_{hd}^2.$$  \hspace{1cm} (5.1)
Figure 2: The allowed regions of $\tau_{\text{esc}}$ versus $\tau_{\text{dec}}$ parameter space from searches for superheavy hydrogen in deep sea water, for different $m_X$ (top panel). At each mass $m_X$, the region of parameters below the corresponding curve is allowed. The maximum present-day abundance of neutral and ionized superheavy hydrogen, normalized to $n_0$, in the halo, cold disc and hot disc, allowed by the searches of heavy water in the sea, is shown as a function of $\tau_{\text{dec}}$ (bottom panel).

Here $n_{h}^+$ is the density at the top of the disc.

Let us now consider the term $n_{h\Delta}^+\sigma_{h\Delta}^2$ in Eq. (5.1) Both CHAMPs and cosmic rays in the Galactic disc may be subject to Fermi acceleration mechanisms in shock waves. It is known that cosmic rays are in approximate energy equipartition with the magnetic field in the diffuse interstellar medium [40]. Equipartition arguments are usually adopted to find the magnetic field in other external galaxies (e.g., [41]). The concept of equipartition between the magnetic field and energetic cosmic rays in our Galaxy (or other galaxies) is consistent with the widely held belief that the cosmic rays diffuse through the field but do not dominate it. In analogy to cosmic rays, we expect equipartition between magnetic fields and CHAMPs in the hot disc. If we assume that the pressure exerted by the CHAMPs in the hot disc is a fraction $\beta_{h\Delta}$ of the magnetic pressure, Eq. (5.1) is simplified to $P_B \gtrsim 2(1 + \beta_{h\Delta})^{-1}n_{h}^+\sigma_{v}^2$, with $\beta_{h\Delta}$ of order of unity. It is convenient to express this equation in
terms of the mass fraction of dark matter in charged CHAMPs in the halo $f_h$ as

$$P_B(Z_{\text{min}}) \gtrsim \left( \frac{1}{1 + \beta_{hd}} \right) f_h \rho_0 \sigma_v^2, \quad (5.2)$$

where $\rho_0$ is the density of dark matter at the top of the disc if it would have not decayed. We see that by requiring that the confinement of the magnetic pressure is entirely due to the halo charged CHAMPs, an upper value on the abundance of CHAMPs can be derived.

In a real galaxy, the topology of the magnetic field is more complex. The halo is also magnetized and the magnetic field may rise above the disc. In the following, we derive a constraint analogous to Eq. (5.2) but for this more general case. Suppose that charged halo CHAMPs cannot penetrate down to $z = Z_{\text{min}}$ (with $Z_{\text{min}} > H$) in the lifetime of the Galaxy because of the Galactic magnetic barrier (see §4.1). Integrating the equation of vertical equilibrium from $z = Z_{\text{min}}$ to $z = \infty$, assuming that the magnetic field is horizontal at $Z_{\text{min}}$ and zero pressure at $z = \infty$, we find

$$P_B(Z_{\text{min}}) \gtrsim \frac{1}{1 + \beta_{hd}} \int_{Z_{\text{min}}}^{\infty} f_h \rho_0(R, z) K_z dz, \quad (5.3)$$

where $\rho_0(R, z)$ is the density of dark matter if it would have not decayed and $K_z$ the vertical positive gravitational acceleration. Again, Eq. (5.3) is written as an inequality because the weight of coronal gas has been neglected. If the magnetic field is not horizontal at $Z_{\text{min}}$ because the topology of the magnetic field is such that only in certain areas the magnetic field rises above the disc, the effective vertical magnetic pressure can be represented by $(B^2 - 2B_z^2)/8\pi$ with $B^2$ and $B_z^2$ interpreted as averages in the $(x, y)$ plane [42]. Therefore, the magnetic tension reduces the effective vertical magnetic pressure and the inequality in Eq. (5.3) still applies.

For a spherical dark halo, the weight term of charged halo CHAMPs at the solar vicinity is

$$\int_{Z_{\text{min}}}^{\infty} f_h \rho_0 K_z dz = 1.7f_h \times 10^{-10} \text{dyn cm}^{-2}$$

$$\times \left( \frac{\rho_0}{0.01 \text{M}_\odot \text{pc}^{-3}} \right) \left( \frac{\sigma_v}{150 \text{ km s}^{-1}} \right)^2. \quad (5.4)$$

Interestingly, the observed synchrotron emission above the plane in the solar neighbourhood implies that the scale height of the magnetic field is greater than what would be inferred from the weight distribution of the interstellar matter (e.g., [13]). The observed synchrotron emission above the plane in the solar neighbourhood indicates that the total magnetic field strength is $2 - 5 \mu G$ at a height of $z = 1$ kpc [13, 41, 42]. If we identify $Z_{\text{min}}$ as the half width at half maximum (HWHM) of the magnetoionic disc $\sim 1$ kpc (e.g., [46]) and by evaluating the magnetic pressure at $z = Z_{\text{min}} \approx 1$ kpc, we obtain the desired constraint on $f_h$, once adopting the highest magnetic value of $5 \mu G$ allowed by observations:

$$f_h \leq 7 \times 10^{-3}(1 + \beta_{hd}) \left( \frac{\rho_0}{0.01 \text{M}_\odot \text{pc}^{-3}} \right)^{-1} \left( \frac{\sigma_v}{150 \text{ km s}^{-1}} \right)^{-2}. \quad (5.5)$$
This estimate is very robust to the precise value adopted for $Z_{\text{min}}$ because the magnetic field decays very slowly with $z$.

In our derivation, we have assumed that the halo is spherical. Consider now an oblate isothermal dark halo with axis ratio $q$:

$$\rho_0(R,z) = \frac{v_c^2}{4\pi G \nu q} \left( R^2 + \frac{z^2}{q^2} \right)^{-1},$$  \hspace{1cm} (5.6)$$

where $v_c$ is the asymptotic circular velocity at the equatorial plane and $\nu = \gamma^{-1} \arcsin \gamma$, with $\gamma = \sqrt{1 - q^2}$. In this model, the velocity dispersion is given, within less than 10%, by $\sigma_v \simeq 1.16 \sqrt{\pi} (v_c/\sqrt{2})$, for flattening $0.05 < q < 0.5$ (e.g. [47]). Even though the velocity dispersion for $q < 1$ is smaller than in the spherical case, the weight term changes only by $\sim 10\%$ as compared to the spherical case, even for rather flattened haloes ($q \approx 0.5$).

Consider now a portion of the disc at larger galactocentric distances, say $R = 2R_\odot$. Following the same procedure as in the solar neighbourhood, we need to estimate the total magnetic pressure at $(2R_\odot, Z_{\text{min}})$, which should be responsible to give support to the charged halo CHAMPs. The large-scale magnetic field may have a scaleheight 5–10 times the scaleheight of the neutral gas disc, so that we may assume that $B_0(Z_{\text{min}}) \simeq B_0(z = 0)$. The random magnetic field is expected to be roughly in equipartition with the kinetic energy in the turbulence. Therefore, its vertical scaleheight should be similar to that of the gas. If magnetic fields are still a barrier for halo CHAMPs, then we may assume that $Z_{\text{min}} > H$ and, consequently, the magnetic pressure by the random component at $Z_{\text{min}}$ is less than 10% the pressure by the random field at $z = 0$. Collecting both contributions, we derive an upper limit for the total magnetic pressure at $Z_{\text{min}}$:

$$P_B < B_0^2 + 0.1b^2$$

where $\alpha \equiv b^2/B_0^2$, with $b^2$ and $B_0^2$ evaluated at $z = 0$. The ordered magnetic field is difficult to measure in the outer Galaxy, but there is evidence that it decays with radius $R$ as a power-law between $R^{-1}$ and $R^{-2}$, probably as $\exp(-R/R_B)$ with $R_B = 8.5$ kpc [48, 49]. The uniform magnetic field in the solar neighbourhood is 2–4 $\mu$G, depending on the authors [48, 50]. If we generously take a value in the solar circle of 4 $\mu$G, we infer a strength of $B_0 \sim 1.5$ $\mu$G at $2R_\odot$. Assuming a spherical dark halo with a mass density at $2R_\odot$ of $\sim \rho_{0,\odot}/4$, then $\int f_h \rho_0 K_z dz = f_h \rho_0 \sigma_v^2/4$. At $2R_\odot$, our assumption that the halo is spherical is a very good approximation (e.g., [51, 52]). By imposing pressure balance at $z = Z_{\text{min}}$ (Eq. 5.3), the following constraint for $f_h$ is inferred

$$f_h \leq 2 \times 10^{-3} (1 + 0.1\alpha)(1 + \beta_{\text{hd}}) \times \left( \frac{\rho_{0,\odot}/4}{0.0025M_\odot\text{pc}^{-3}} \right)^{-1} \left( \frac{\sigma_v}{150 \text{ km s}^{-1}} \right)^{-2}.$$  \hspace{1cm} (5.8)$$

Other observational estimates assure our generously-taken magnetic intensity. In fact, data from rotation measurements of pulsars suggest uniform magnetic fields of $\sim 0.7$ $\mu$G at $R = 2R_\odot$ [53], which coincides with the extrapolation of the fit of radial variation of the regular field by Han et al. [48].
Beyond $2R_\odot$ it is uncertain if supernovae shocks are able to clean the disc from CHAMPs. It might be also possible that beyond the optical radius, the magnetic field is too weak to prevent CHAMPs from crossing the disc, but any more complicated analysis is useless in the face of such ignorance.

Combining Eqs (5.5) and (5.8) and taking $\beta_{hd} \approx 1$, the present-day fraction of charged CHAMPs in the halo must be smaller than $(4 - 14) \times 10^{-3}$, which implies $\tau_{\text{dec}} \gtrsim (0.95 - 3.4) \times 10^3$ Gyr. This lower limit on $\tau_{\text{dec}}$, which is valid for $m_X$ as large as $10^6$ TeV, is comparable to the constraint inferred from the lack of anomalously heavy water in the sea for $m_X \approx 2 \times 10^3$ TeV (see section 4.3). We conclude that although charged particles can be suspended in the halo, so that they would be impossible to detect as they never reach the Earth, the mass fraction of charged CHAMPs in the halo must be rather small.

We must note that, whereas constraints from BBN and heavy-water searches are only relevant if CHAMPs are singly charged, because for other charges, a CHAMP no longer behaves as a proton, the constraint $f_h \lesssim (0.4 - 1.4) \times 10^{-2}$ derived in this section, is independent of charge $\epsilon$, as long as charged CHAMPs and magnetic fields are in pressure equipartition in the Galactic disc.

6. Ram pressure stripping and collisions of galaxy clusters

Magnetic fields couple charged CHAMPs with themselves and with ordinary matter. This coupling might cause ram pressure stripping of both baryonic and DM of subhaloes and satellite systems. Consider, for instance, the collision of two galaxy clusters. Estimates for the magnetic field strength in clusters range from roughly $1 - 10 \mu G$ at the center and $0.1 - 1 \mu G$ at a radius of 1 Mpc. With these values, the ratio between thermal pressure $P_{th}$ and magnetic pressure for the CHAMPs is $\beta \equiv 8\pi P_{th}/B^2 \approx 2f \times 10^{-4}$, that is, a hot plasma. Even in this dynamically weak magnetic field, the mean gyroradius for a CHAMP with $m_X = 10^6 \epsilon$ TeV, is $\lesssim 5$ pc at the center and $\lesssim 50$ pc at 1 Mpc. The governing equations of collisionless hot plasmas were developed by Chew et al. [54], whose theory is known as the Chew-Goldberger-Low approximation. This approximation, which leads to MHD equations with anisotropic pressure, is satisfactory when the Larmor frequency is large compared to other characteristic frequencies of the problem and the mean particle gyroradius is short compared to the distance over which all the macroscopic quantities change appreciably (e.g., [55, 56]). Therefore, charged massive particles in the halo of galaxy clusters can be described in the fluid-like anisotropic MHD approximation; in the merger process, they would behave as a clump of fluid, experiencing ram pressure stripping and drag deceleration similar to the gas component. Since CHAMPs should be attached to the gas component, the observed offset between the centroid of DM and the collisional gas of the subcluster in the Bullet Cluster implies $f \ll 1$ (e.g., [57, 58]). Although the current lensing data accuracy is not sufficient to derive the mass distribution of the subcluster in the Bullet Cluster, the derived mass estimates of the subcluster leave little room for DM in the gas bullet.

Galactic halo CHAMPs may also exert ram pressure on the gas component of the LMC and its stream due to their continuous scattering by the intrinsic magnetic field of the LMC.
and the Magellanic stream. For a Milky Way-type halo of $\sim 10^{12} \, \text{M}_\odot$, a fraction $f_h$ of $4 \times 10^{-3}$ implies that the mass in charged CHAMPs could be up to $\sim 4 \times 10^9 \, \text{M}_\odot$ and the density at 50 kpc of $1.2 \times 10^{-6} \, \text{M}_\odot \, \text{pc}^{-3}$. Since these values are smaller than those required to explain the mass and extension of the Magellanic Stream and the size and morphology of the gaseous disc of LMC \cite{59}, we cannot reduce any further our upper limit on $f_h$ with the current observations of the LMC disc and the Magellanic Stream.

7. Conclusions

Whilst the common wisdom holds that DM is neutral and collisionless, it is important to explore the possibility of it having nonzero, not necessarily integer, charge. If a fraction of the mass of haloes is made up by charged CHAMPs, it may have a strong impact on the observable Universe because of the coupling between magnetic fields and CHAMPs. For instance, ejection of charged CHAMPs from the regions with intense magnetic fields, i.e., from the central parts of galaxies, would help alleviate the cuspy halo problem. In this work, we have constrained the present abundance of CHAMPs in galactic haloes.

We have explored a model where neutral dark matter decays into non-relativistic charged products. From BBN and CMB, we find that the decay lifetime should be $\gtrsim 0.1$ Gyr. The non-detection of heavy sea-water puts a limit on the timescale for charged CHAMPs to escape from the Galactic disc. We have considered the pressure support of CHAMPs in our Galaxy to derive a simple, upper limit on the fraction of CHAMPs and milliCHAMPs in galactic haloes. Assuming that the accelerated CHAMPs in the disc are in pressure equilibrium with the magnetic field, we find that $f_h \lesssim (0.4 - 1.4) \times 10^{-2}$. This constraint rules out CHAMPs as the origin of the cores in LSB and dwarf galaxies. The reduction of the central density after they have driven the formation of galactic haloes would be insignificant. Even if all the CHAMPs were depleted from the central parts of the galaxies, the rotation velocity in a certain galaxy would suffer a negligible change of $(0.2 - 0.7)\%$ for $f_h \sim (0.4 - 1.4) \times 10^{-2}$. In the range of astrophysical interest, CHAMPs behave like strongly interacting (fluid-like) dark matter (SIDM). Thus, they face many of the problems attributed to SIDM. As some examples, we have discussed the survival of the Magellanic Stream and the mass distribution of the Bullet Cluster. Our constraint that the mass in CHAMPs in the Galaxy is not larger than the mass of coronal gas in the halo seems to apply also to galaxy clusters.

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A. Recombination and ionization of CHAMPs in the Galactic corona

Positive CHAMPs can recombine with free electrons in the Galactic corona to form neutral bound atoms \((X_1^+e^-)\). As \(X_1^+\)'s behave exactly like protons with thermal velocity dispersion\(^4\) of 150 km s\(^{-1}\), the fraction of \(X_1^+\) nuclei that are neutral is comparable, or even smaller, than the neutral fraction of hydrogen in the coronal gas, which is extremely small (\(\sim 10^{-6}\), e.g., \([59]\)), and therefore it can be ignored.

The recombination rate of negative CHAMPs with protons in the Galactic halo including the ground \(n = 1\) level is given by 
\[
\alpha_R^{(1)} = \langle \sigma_{\text{rec}} v \rangle = \frac{2^{10} \exp(-4) \pi \sqrt{\pi} \alpha^3 h^2}{3 m_p^2 v_{\text{eff}}^3} \sum_{n=1}^{4n^2},  
\]  

(A.1)

where \(v_{\text{eff}} = v_X^2 + v_p^2\) (e.g., \([5, 51]\)). At the Galactic halo, we have \(v_{\text{eff}} \simeq 180\) km s\(^{-1}\) and thus \(\alpha_R^{(1)} = 4 \times 10^{-18}\) cm\(^3\) s\(^{-1}\).

Ionization of \((X_2^-p)\) by collisions with \(X_2^-\) and \(X_1^+\) are also important for the determination of the abundance of neutral CHAMPs in galactic haloes. The coefficient for collisional ionization is:

\[
\gamma_{\text{ion}} = 1.3 \times 10^{-8} T_X^{1/2} F E_{\text{bin}}^{-2} (\text{eV}) \exp \left( - \frac{E_{\text{bin}}}{k_B T_X} \right) \left[ \text{cm}^3/\text{s} \right],  
\]

(A.2)

where \(E_{\text{bin}} \simeq 25\) keV is the binding energy of the atom \((X_2^-p)\), \(T_X\) the temperature of bare CHAMPs and \(F \simeq 0.83\) for hydrogenic atoms (e.g., \([62]\)). For massive CHAMPs in the Galactic halo, we have

\[
\gamma_{\text{ion}} = 1.0 \times 10^{-10} \left( \frac{m_X}{2 \times 10^4\text{TeV}} \right)^{1/2} \left( \frac{\sigma v}{150\text{km/s}} \right) \left[ \text{cm}^3/\text{s} \right].  
\]

(A.3)

Putting together,

\[
\frac{dn_h^-}{dt} = \frac{n_X}{\tau_{\text{dec}}} + \gamma_{\text{ion}} (n_h^- + n_h^+) n_{nC} - \alpha_R^{(1)} n_p n_h^-,  
\]

(A.4)

where \(n_{nC} = n_h^+ - n_h^-\) is the density of neutral CHAMPs in the halo. The abundance of neutral CHAMPs as compared to CHAMPs at ionization equilibrium is \(\sim 1.0 \times 10^{-3}\). This estimate should be considered as an upper limit because \((X_2^-p)\) may be converted to a charged state, \((X_2^- \alpha)\), by a charge exchange reaction. Unfortunately, the exchange cross section is very uncertain \([5]\).

Coronal neutral CHAMPs can penetrate the Galactic disc, reach Earth and stop in the atmosphere or ocean \([5]\). Searches for coronal neutral CHAMPs in cosmic rays rule out particles with masses between 100 and a few \(10^4\) TeV if all the \(X_2^-\) are bound to a proton and the charge exchange cross section with C and O nuclei is in the interval from 30 mb to 30 b \([24, 63, 64]\).

\(^4\)CHAMPs and protons have different temperatures. The thermal (one-dimensional) velocity dispersion of protons of the hot gas (\(\sim 10^6\) K) at the Galactic corona is \(v_p = \sqrt{k_B T/m_p} \approx 100\) km s\(^{-1}\), which is a bit smaller than the adopted value for the velocity dispersion of dark matter particles in the halo (\(\sim 150\) km s\(^{-1}\)).
B. Solving the differential equation for $n_{hd}^+$

In section 4.3, we derived the differential equation for the number density of hot $X^+$ in the disc as:

$$\frac{dn_{hd}^+}{dt} = F' \frac{n_X}{\tau_{dec}} - \frac{n_{hd}^+}{\tau_{esc}} + \frac{n_h - n_{hd}^+}{\tau_{diff}}, \quad \text{(B.1)}$$

with

$$n_X(t) = n_0 \exp\left(-\frac{t}{\tau_{dec}}\right), \quad \text{(B.2)}$$

and

$$n_{h}^+(t) = n_0 \left[1 - \exp\left(-\frac{t}{\tau_{dec}}\right)\right]. \quad \text{(B.3)}$$

Inserting them into Eq. (B.1), we find

$$\frac{dn_{hd}^+}{dt} + \frac{n_{hd}^+}{\tau_{eff}} = \frac{n_0}{\tau_{diff}} g(t), \quad \text{(B.4)}$$

where the definition of $\tau_{eff}$ was given in Eq. (4.10) and

$$g(t) \equiv 1 + \left(F'\frac{\tau_{diff}}{\tau_{dec}} - 1\right) \exp\left(-\frac{t}{\tau_{dec}}\right). \quad \text{(B.5)}$$

The general solution of Eq. (B.4) when $\tau_{dec} \neq \tau_{eff}$ is

$$n_{hd}^+(t) = \exp\left(-\frac{t}{\tau_{eff}}\right) \left[\int \frac{n_0}{\tau_{diff}} g(t) \exp\left(\frac{t}{\tau_{eff}}\right) dt + C\right], \quad \text{(B.6)}$$

where $C$ is a constant. The integral can be performed analytically:

$$\exp\left(-\frac{t}{\tau_{eff}}\right) \int g(t) \exp\left(\frac{t}{\tau_{eff}}\right) dt = \tau_{eff} \left[1 + \left(F'\frac{\tau_{diff}}{\tau_{dec} - \tau_{eff}} - \frac{\tau_{dec}}{\tau_{dec} - \tau_{eff}}\right) \exp\left(-\frac{t}{\tau_{dec}}\right)\right]. \quad \text{(B.7)}$$

The resulting form for $n_{hd}^+(t)$ is given in Eq. (4.11).

References

[1] M. Fairbairn, A.C. Kraan, D.A. Milstead, T. Sjöstrand, P. Skands, & T. Sloan, Stable massive particles at colliders, Physics Reports 438 (2007) 1

[2] M. Pospelov & A. Ritz Resonant scattering and recombination of pseudodegenerate WIMPs, Phys. Rev. D 78 (2008) 055003

[3] J.L. Feng, A. Rajaraman, F. Takayama Superweakly interacting massive particles, Phys. Rev. Lett. 91 (2003) 011302

[4] Y. Huang, M.H. Reno, I. Sarcevic & J. Uscinski Weak interactions of supersymmetric staus at high energies, Phys. Rev. D 74 (2006) 115009

[5] A. De Rújula, S.L. Glashow & U. Sarid Charged dark matter, Nucl. Phys. B 333 (1990) 173

[6] S. Dimopoulos, D. Eichler, R. Esmailzadeh, & G. D. Starkman Getting a charge out of dark matter, Phys. Rev. D 41 (1990) 2388
[7] M.L. Perl, et al. *The search for stable, massive, elementary particles*, Int. J. Mod. Phys. A 16 (2001) 2137

[8] M. Taoso, G. Bertone & A. Masiero *Dark matter candidates: A ten-point test*, JCAP 03 (2008) 022

[9] L. Chuzhoy & E.W. Kolb *Reopening the window on charged dark matter*, JCAP 07 (2009) 014

[10] G.D. Kribs & I.Z. Rothstein *Bounds on long-lived relics from diffuse gamma ray observations*, Phys. Rev. D 55 (1997) 4435

[11] E. Holttmann, M. Kawasaki, M., K. Kohri & T. Moroi *Radiative decay of a long-lived particle and big-bang nucleosynthesis*, Phys. Rev. D 60 (1999) 023506

[12] L. Zhang, X. Chen, M. Kamionkowski, Z.-G. Si & Z. Zheng *Constraints on radiative dark-matter decay from the cosmic microwave background*, Phys. Rev. D 76 (2007) 061301

[13] S. De Lope Amigo, W.M.-Y. Cheung, Z. Huang, Z., & S.-P. Ng *Cosmological constraints on decaying dark matter*, JCAP 06 (2009) 005

[14] D.G. Cerdeño, K.-Y. Choi, K. Jedamzik, L. Roszkowski, L., & R. Ruiz de Austri *Gravitino dark matter in the constrained minimal supersymmetric standard model with improved constraints from big bang nucleosynthesis*, JCAP 06 (2009) 005

[15] R. Cen *Decaying cold dark matter model and small-scale power*, Astroph. J. 546 (2001) L77

[16] F. Ferrer, C. Nipoti & S. Ettori *Secular evolution of galaxies and galaxy clusters in decaying dark matter cosmology*, Phys. Rev. D 80 (2009) 061303

[17] F.J. Sánchez-Salcedo *Unstable cold dark matter and the cuspy halo problem in dwarf galaxies*, Astrophys. J. 591 (2003) L107

[18] M. Abdelqader & F. Melia *Decaying dark matter and the deficit of dwarf haloes*, Mon. Not. Roy. Astron. Soc. 388 (2008) 1869

[19] K. Hamaguchi, T. Hatsuda, M. Kamimura, Y. Kino, & T.T. Yanagida *Stau-catalyzed $^6$Li production in big-bang nucleosynthesis*, Phys. Lett. B 650 (2007) 268

[20] K. Jedamzik *The cosmic $^6$Li and $^7$Li problems and BBN with long-lived charged massive particles*, Phys. Rev. D 77 (2008) 063524

[21] K. Kohri & T. Takahashi *Cosmology with long-lived charged massive particles*, Phys. Lett. B 682 (2009) 337

[22] S.L. Dubovsky, D.S. Gorbunov & G.I. Rubtsov *Narrowing the window for millicharged particles by CMB anisotropy*, JETPL 79 (2004) 1

[23] Y. Gong, & X. Chen *Cosmological constraints on invisible decay of dark matter*, Phys. Rev. D 77 (2008) 103511

[24] J.L. Basdevant, R. Mochkovitch, J. Rich, M. Spiro, M., & A. Vidal-Madjar *Is there room for charged dark matter?*, Phys. Lett. B 234 (1990) 395

[25] G.K. Parks 1991, *Physics of Space Plasmas. An Introduction*, 1st Edition (Addison-Wesley Publ.)

[26] F. Casse, M. Lemoine, & G. Pelletier *Transport of cosmic rays in chaotic magnetic fields*, Phys. Rev. D 65 (2002) 3002
[27] J. Giacalone & J.R. Jokipii *The transport of cosmic rays across a turbulent magnetic field*, Astrophys. J. 520 (1999) 204

[28] A. Fletcher & A. Shukurov *Hydrostatic equilibrium in a magnetized, warped Galactic disc*, Mon. Not. Roy. Astron. Soc. 325 (2001) 312

[29] R. Beck *Magnetism in the spiral galaxy NGC 6946: magnetic arms, depolarization rings, dynamo modes, and helical fields*, Astron. and Astrophys. 470 (2007) 539

[30] R.D. Blandford *Particle acceleration mechanisms*, Astrophys. J. Suppl. 90 (1994) 515

[31] S. Davidson, S. Hannestad, S., & G. Raffelt *Updated bounds on milli-charged particles*, Journal of High Energy Physics 05 (2000) 003

[32] A.R. Bell *The acceleration of cosmic rays in shock fronts. I*, Mon. Not. Roy. Astron. Soc. 182 (1978) 147

[33] A. Wandel, D. Eichler, J.R. Letaw, R. Silberberg & C.H. Tsao *Distributed reacceleration of cosmic rays*, Astrophys. J. 316 (1987) 676

[34] M. Jura & D.G. York *Search for interstellar superheavy hydrogen*, Science 216 (1982) 54

[35] S.R. Chivukula, A.G. Cohen, S. Dimopoulos & T.P. Walker *Bounds on halo-particle interactions from interstellar calorimetry*, Phys. Rev. Lett. 65 (1990) 957

[36] P. Verkerk, et al. *Search for superheavy hydrogen in sea water*, Phys. Rev. Lett. 68 (1992) 1116

[37] A. Kudo & M. Yamaguchi *Inflation with low reheat temperature and cosmological constraint on stable charged massive particles*, Phys. Lett. B 516 (2001) 151

[38] J.W. King & W.S. Newman 1967, Solar-terrestrial physics (Academic Press, London)

[39] T.E. Cravens 1997, Physics of Solar System Plasmas (Cambridge University Press)

[40] W.R. Webber *A new estimate of the local interstellar energy density and ionization rate of Galactic cosmic rays*, Astrophys. J. 506 (1998) 329

[41] R. Beck, A. Brandenburg, D. Moss, A. Shukurov & D. Sokoloff *Galactic magnetism: Recent developments and perspectives*, ARA&A 34 (1996) 155

[42] A. Boulares & D. Cox *Galactic hydrostatic equilibrium with magnetic tension and cosmic-ray diffusion*, Astro. J. 365 (1990) 544

[43] D.P. Cox *The three-phase interstellar medium revisited*, ARA&A 43 (2005) 337

[44] K.M. Ferrière *The interstellar environment of our galaxy*, Rev. Mod. Phys. 73 (2001) 1031

[45] B.M. Gaensler, G.J. Madsen, S. Chatterjee & S.A. Mao *The vertical structure of warm ionised gas in the Milky Way*, PASA 25 (2008) 184

[46] P.M.W. Kalberla *Dark matter in the Milky Way. I. The isothermal disk approximation*, Astrophys. J. 588 (2003) 805

[47] O. Gerhard & J. Silk *Baryonic dark halos: a cold gas component?*, Astrophys. J. 472 (1996) 34

[48] C. Heiles 1996, in ASP Conf. Ser. 97, Polarimetry of the Interstellar Medium, ed. W. Roberge & D. Whittet (San Francisco: ASP), 457
[49] J.L. Han, R.N. Manchester, A.G. Lyne, G.J. Qiao & W. van Straten Pulsar rotation measures and the large-scale structure of the Galactic magnetic field, Astrophys. J. 642 (2006) 868

[50] R. Beck 2002, in The Astrophysics of Galactic Cosmic Rays, eds. R. Diel et al. (Kluwer, Dordrecht, The Netherlands)

[51] V. Belokurov, et al. The field of streams: Sagittarius and its siblings, Astrophys. J. 642 (2006) L137

[52] M. Fellhauer, et al. The origin of the bifurcation in the Sagittarius Stream, Astrophys. J. 651 (2006) 167

[53] R.J. Rand, & A.G. Lyne New rotation measures of distant pulsars in the inner Galaxy and magnetic field reversals, Mon. Not. Roy. Astron. Soc. 268 (1994) 497

[54] G.F. Chew, M.L. Goldberger & F.E. Low The Boltzmann equation and the one-fluid hydromagnetic equations in the absence of particle collisions, Proc. Roy. Soc. A236 (1956) 112

[55] L.Jr. Spitzer 1962, Physics of Fully Ionized Gases, 2nd Edition, Interscience Publ. (New York: Willey)

[56] G. Schmidt 1966, Physics of High Temperature Plasmas (Academic Press, New York and London)

[57] P. Natarajan, A. Loeb, J.-P. Kneib & I. Smail Constraints on the collisional nature of the dark matter from gravitational lensing in the cluster A2218, Astrophys. J. 580 (2002) L17

[58] M. Markevitch, et al. Direct constraints on the dark matter self-interaction cross section from the merging galaxy cluster 1E 0657-56, Astrophys. J. 606 (2004) 819

[59] C. Mastropietro, B. Moore, L. Mayer, J. Wadsley & J. Stadel The gravitational and hydrodynamical interaction between the Large Magellanic Cloud and the Galaxy, Mon. Not. Roy. Astron. Soc. 363 (2005) 509

[60] L.Jr. Spitzer 1978, Physical Processes of the Interstellar Medium, Wiley-Interscience Publication (John Wiley & Sons, New York)

[61] J.L. Feng, M. Kaplinghat, H. Tu, H.-B. Yu Hidden charged dark matter, JCAP 07 (2009) 004

[62] D.P. Cox & W.H. Tucker Ionization equilibrium and radiative cooling of a low-density plasma, Astrophys. J. 157 (1969) 1157

[63] S.W. Barwick, P.B. Price, & D.P. Snowden-Ifft Search for charged massive particles in cosmic rays, Phys. Rev. Lett. 64 (1990) 2859

[64] T.K. Hemmick, et al. Search for low-Z nuclei containing massive stable particles, Phys. Rev. D 41 (1990) 2074