Astroparticle Physics 80 (2016) 1–7

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

Sommerfeld enhancement of invisible dark matter annihilation in galaxies and galaxy clusters

Man Ho Chan*

Department of Science and Environmental Studies, The Hong Kong Institute of Education, Hong Kong

ARTICLE INFO

Article history:
Received 28 October 2015
Revised 14 March 2016
Accepted 15 March 2016
Available online 21 March 2016

Keywords:
Dark matter
Sterile neutrino

ABSTRACT

Recent observations indicate that core-like dark matter structures exist in many galaxies, while numerical simulations reveal a singular dark matter density profile at the center. In this article, I show that if the annihilation of dark matter particles gives invisible sterile neutrinos, the Sommerfeld enhancement of the annihilation cross-section can give a sufficiently large annihilation rate to solve the core-cusp problem. The resultant core density, core radius, and their scaling relation generally agree with recent empirical fits from observations. Also, this model predicts that the resultant core-like structures in dwarf galaxies can be easily observed, but not for large normal galaxies and galaxy clusters.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

It is commonly believed that the existence of dark matter can account for the missing mass in galaxies, galaxy clusters and our universe. However, the nature of dark matter remains a fundamental problem in astrophysics. If the dark matter particles are cold and collision less, *N*-body simulations show that the density profile should be singular at the center (a cusp profile, $\rho \sim r^{-1}$) [1]. This model generally gives good agreements with observations on large-scale structures such as Lyα spectrum [2,3] and some galaxy clusters [4]. However, observations reveal that cores exist in many galaxies ($\rho \sim r^{-\gamma}$ with $\gamma < 0.5$), especially in dwarf galaxies [5–7]. Some dwarf galaxies can even have $\gamma < 0.2$ [8]. This discrepancy is commonly known as the core-cusp problem [8]. Moreover, recent studies show that this problem might also be associated with another problem, called the too-big-to-fail (TBTF) problem. This problem illustrates the fact that the densities of dark matter subhaloes which surround nearby dwarf spheroidal galaxies are significantly lower than those of the most massive subhaloes expected around a normal sized galaxies in cosmological simulations [9,10]. In other words, solving the core-cusp problem might also provide a solution to the TBTF problem [11].

Some proposals have been suggested to solve the core-cusp problem. For example, the existence of keV dark matter particles, as a candidate of warm dark matter (WDM), has been proposed to solve the problem [12,13]. However, recent observations indicate that the simplest model oWDM (e.g. the non-resonant sterile neutrino model) cannot account for the major component of dark matter [14–17]. Some extra properties of WDM or free parameters are needed in order to satisfy the observational constraints. Some recent analyses even suggest that WDM model cannot solve the core-cusp problem [18]. Another proposal suggests that core-like structures would be produced if dark matter particles are self-interacting [19]. Simulations show that dark matter particles with a constant cross-section per unit mass $\sigma/m \sim 1$ cm^2 g^{-1} can produce core-like structures in galaxies [20,21]. Unfortunately, recent observations put a tight constraint on the cross-section: $\sigma/m \leq 1$ cm^2 g^{-1} [22,23]. Therefore, it leaves only a small window open for this velocity-independent self-interacting dark matter model to work [23]. Nevertheless, this model might still endure if the cross-section is velocity-dependent, though some more parameters have to be involved [24,25].

Besides the above two proposals, some suggest that the energy exchange between baryons and dark matter particles might also be possible to produce core-like structures. These mechanisms include the steller and supernova feedback [26,27], and dynamical friction [28,29]. It is now a controversial issue because these baryonic processes involve some uncertainties, such as the total energy released by the supernovae and the fraction of energy that can be transferred to the dark matter haloes [11]. For example, for a total mass of $10^9 M_\odot$, recent studies show that at least 1/20 of supernova energy is required to transfer to the dark matter halo to give $\gamma < 0.6$ [11,30]. However, we are not sure whether this fraction of transferred energy is physically possible or not. Also, it is challenging to invoke baryonic processes as the main mechanisms to solve the core-cusp problem for some dark-matter-dominated galaxies because the baryonic content is too small to affect the dark matter distribution [8,25].

* Tel.: +852 29488241.
E-mail address: chanmh@ied.edu.hk

http://dx.doi.org/10.1016/j.astropartphys.2016.03.005
0927-6505/© 2016 Elsevier B.V. All rights reserved.

In this article, I suggest another proposal that the core-cusp problem can be solved by Sommerfeld-enhanced dark matter annihilation. The possibility of the dark matter annihilation to solve the core-cusp problem is first suggested in [31]. The required annihilation cross-section is $<\sigma v>\sim 10^{-19}(m/\mathrm{GeV})$ cm^3 s^{-1} [31]. They suggest two possible mechanisms so that the required cross-section would not violate the relic dark matter annihilation cross-section $<\sigma v>=3\times 10^{-26}$ cm^3 s^{-1} [31]. However, if the annihilation products are visible particles such as neutrinos, electrons or photons, this required cross-section is ruled out by observations [32,33]. Moreover, this model predicts that halo core density is universal ($\sim 0.02 M_\odot$ pc^{-3}) [31] while observations indicate that the core density of dwarf galaxies varies from 0.01–0.1 $M_\odot$ pc^{-3} [34]. In the following, I use the idea from [31] but assume that the dark matter annihilation is enhanced by the Sommerfeld's mechanism ($<\sigma v>\propto v^{-\alpha}$) [35,36], and the annihilation products are invisible sterile neutrinos only. It can be shown that a significant amount of dark matter particles would be annihilated, which is enough to produce the observed core-like structures in galaxies.

2. The annihilation model

It has been suggested that dark matter would self-annihilate to give smaller particles with high energy. The possible stable products formed are photons, electron–positron pairs, and neutrinos. In particular, the fact that active neutrino have non-zero rest mass probably suggests that right-handed neutrinos should exist, which may indeed be sterile neutrinos [37]. Some recent models suggest that dark matter particles can annihilate dominantly into light dark neutrinos (sterile neutrinos) via exchange of a Higgs field ($\chi\chi\to\Phi\Phi\to\nu_s\nu_s$) [38]. This model can agree with the results obtained from DAMA [39] and CoGeNT [40] experiments, which point toward light dark matter ($m\sim$ 1–10 GeV) with isospin-violating and possibly inelastic couplings [38]. However, the light dark matter model is largely constrained by observations, such as cosmic microwave background and SuperK limits. Cline and Frey [38] propose a model of quasi-Dirac dark matter, interacting via two gauge bosons, one of which couples to baryon number and the other which kinetically mixes with the photon. The annihilation product is dark neutrinos that do not mix with the Standard Model. They also show that the dark neutrinos produced in the universe would not violate the current observational bounds [38].

In the following, we are going to discuss the consequences of the sterile neutrinos being the only dark matter annihilation product (the model proposed in [38] may be one of the possible scenarios). If the annihilation cross-section is large enough due to the Sommerfeld enhancement, a significant amount of dark matter would be changed to high energy sterile neutrinos. These high energy sterile neutrinos would finally leave the structure and make the central density lower. The Sommerfeld enhancement arises when a scattering object is coupled to a light mediator particle [41]. This enhancement can increase the cross-section for annihilation process in a velocity-dependent fashion due to the generic attractive force between the incident dark matter particles [36].

If dark matter particles were produced at the very beginning, the annihilation cross-section should be close to 3×10^{-26} cm^3 s^{-1} [42]. However, the Sommerfeld enhancement might significantly change the relic annihilation cross-section to a lower value [23,43,45]. The actual value of the annihilation cross-section at the thermal freeze out is model-dependent. Nevertheless, [23] show that the Sommerfeld enhancement near resonance would suppress the dark matter abundance by a factor of a few. As a result, the annihilation cross section needs to be suppressed by this same factor in order to be consistent with the observed relic density.

Therefore, we write the annihilation cross section at the thermal freeze out as $<\sigma v_0>=1\times 10^{-26} f$ cm^3 s^{-1}, where $f\sim 1$ is a model-dependent parameter. Here, $v_0\approx 0.2c$ is the velocity of the dark matter particles at decoupling [46].

If the velocity of dark matter particles v is lower, the Sommerfeld enhancement might increase the cross-section to $<\sigma v>=<\sigma v_0>(v_0^\alpha/v^\alpha)$ [35,36]. The value of α is close to 1 for non-resonance case while $\alpha\approx 2$ for resonance [44]. Therefore, the low velocity of dark matter particles in a galaxy or galaxy cluster would increase the rate of annihilation to form core-like structures.

Also, this cross-section satisfies the unitarity bound. Harling and Petraki [47] obtain the unitarity bound (upper bound) of the Sommerfeld-enhanced cross-section, which is just a factor of 3 greater than the unitarity bound without Sommerfeld enhancement. For $m\sim 1$ GeV and $v\sim$ 10–1000 km/s, the unitarity bound is $<\sigma v>_{ub}\sim 10^{-13}$–$10^{-11}$ cm^3 s^{-1} [47–49], which is much greater than the cross-section considered in our model.

On the other hand, the presence of sterile neutrinos as a by-product of dark matter annihilation would change the effective number of neutrinos (N_{eff}) in cosmology. This number is strongly constrained by cosmic microwave background anisotropies recently, which gives $N_{eff}=2.88\pm 0.20$ [50]. However, N_{eff} depends on the kinetic decoupling temperature of dark matter T_{de}, which is a model-dependent parameter in cosmology. Assuming a reliable range $T_{de}\sim$ 10–1000 MeV (at 10^{-7}–10^{-3} s after Big Bang) [51], the number density of active neutrinos is $n_\nu\sim 10^{34}$–10^{40} cm^{-3}. The number density of sterile neutrinos produced from dark matter annihilation is given by $n_s\sim\rho_{DM}^2<\sigma v_0>t_{de}/m^2\sim 10^{23}$–$10^{32}$ cm^{-3}, where ρ_{DM} and t_{de} are the mass density of dark matter and the age of universe at the kinetic decoupling respectively. Therefore, the sterile neutrinos produced at the kinetic decoupling are negligible compared with the relic active neutrinos. Since the scale factor dependence are the same for n_s and n_ν, the sterile neutrinos produced would not significantly affect N_{eff}.

Since the mass of the mediator particle m_ϕ must be smaller than the dark matter mass [41,52], this requires $m_\phi\sim$ 1 MeV–1 GeV. This new scalar field is likely to mix with the Higgs boson and possibly be in tension with current collider constraints. In view of this, a study in [53] examines this mixing effect seriously by assuming $m_\phi\sim 1$ GeV for the Sommerfeld enhancement. Since the mixing between the scalar field and the Higgs field involves some unknown free parameters, including m_ϕ and the mixing angle $\theta_{\phi h}$, a large area of parameter space is still possible to satisfy the constraints obtained in the Large Hadron Collider (LHC) experiments [53]. For the CMS measurements, there is an experimental upper limit for the Higgs total width of cross coupling. Based on the calculations in [53], the upper limit of the Higgs-ϕ cross coupling λ_1 converges to about 0.05 for $m_\phi<1$ GeV, which is not a prohibited value.

Besides the Higgs constraints, the mediator particle would probably emit photons or charged bosons which would possibly conflict with the constraints from indirect detection experiments. However, the emission of photons by the mediator is model-dependent. For example, a study in [54] estimates a corresponding annihilation cross section by considering two dark matter particles annihilating via an intermediate pseudoscalar A^0 and a charged fermion f in the loop (see the Feymann diagram in [54]). For a small coupling ($g\approx 1$), the model gives $<\sigma_{\gamma\gamma}v>\sim 10^{-40}$ cm^3 s^{-1} $(m/1\ \mathrm{GeV})^4(500\ \mathrm{GeV}/m_A)^4(500\ \mathrm{GeV}/m_f)^2$, where m_A and m_f are the mass of the pseudoscalar particle and the fermion respectively [54]. For $m<1$ GeV, this cross-section is well-below any current constraint.

Download English Version:

https://daneshyari.com/en/article/1770430

Download Persian Version:

https://daneshyari.com/article/1770430

Daneshyari.com