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Dark Matter and its Effect on the Gravitational Wave Signal

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In this work, we present two gauge models for light-dark matter: one with an exotic positive charged lepton and the other one is a variant with right-handed neutrinos. The scalar self-interacting dark matters are stable without imposing new symmetry and should be weak-interacting. We study the impact of the self-interacting light dark matter on the formation of the dark halo, the observation properties of neutron stars, and its effect on the gravitational wave signal. We also summarize searches by the LIGO-Virgo-KAGRA collaborations for ultralight dark matter using cross-correlation and excess power methods for O3 observing run.

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1. Introduction

Understanding the nature of most of the matter in the universe remains a challenge in modern cosmology. ΛCDM models with a mixture of roughly 25% collisionless cold dark matter, such as WIMPs, axions, massive neutrinos, etc., that interact through the weak and gravitational forces, plus about 70% cosmological constant (or vacuum dark energy density) match current observations of the cosmic microwave background and large scale structure with remarkable accuracy [1, 2]. Indeed, it is now believed that only a fraction of the present total matter can be made of ordinary baryons, while most of the mass-energy content of the universe has an unknown, nonbaryonic origin [3]. Evidence for the existence of cold dark matter is derived from observations of the cosmic microwave background, galaxy clusters, gravitational lensing, and the Lyman-α forest [4]. For the most part these observation agree with the predictions of the ΛCDM model. However, it is now widely appreciated [5] that conventional models of collisionless cold dark matter can lead to problems with regard to galactic structure. The possible way to avoid these problems is to hypothesize self-interacting dark matter and ultralight dark matter models as a well motivated alternative to the standard ΛCDM model. It is a well-accepted fact that plausible candidates for dark matter are elementary particles. The key property of these particles is that they must have a weak scattering cross-section and presently be non-relativistic. In response to the original work [6] many follow-up studies have been made [7–10]. In this work, we focus on the direct detection of ultralight dark matter and indirect detection of self interacting dark matter.

2. Self Interacting Dark Matter in Beyond Standard Model physics

We consider a dark matter model wherein the scalar boson only couples to Higgs boson in the standard model [11]. The main properties that a good dark matter candidate must satisfy are stability and neutrality. Therefore, we go to the scalar sector of the model, more specifically to the neutral scalars, and we examine whether any of them can be stable and in addition whether they can satisfy the self-interacting dark matter criterions [12]. In addition, one should notice that such dark matter particles must not overpopulate the Universe. To get the interaction of dark matter to the SM Higgs boson, we consider the following relevant parts

$$L(\sigma,\zeta_\eta)_{int} = \frac{1}{4}\lambda_1[v^2+2v\xi_\eta+\xi_\eta^2+\zeta_\eta^2+\xi_\eta'^2+\zeta_\eta'^2+2\eta^+\eta^-]^2+\frac{1}{4}\lambda_4[v^2+2v\xi_\eta+\xi_\eta^2+\zeta_\eta^2+\xi_\eta'^2+\zeta_\eta'^2+2\eta^+\eta^-] \tag{1}$$

which σ is Higgs Boson, ζ,η,ξ are scalar fields.

The couplings of self interacting dark matter (SIDM) with the SM Higgs boson:

$$L = \left(\frac{\sigma(x)}{\sqrt{\lambda_5^2v^2+\lambda_6^2u^2}}\left(\lambda_1\lambda_5v^2+\frac{\lambda_4\lambda_6}{2}u^2\right)+\frac{H_1(x)\sigma(x)}{(\lambda_5^2v^2+\lambda_6^2u^2)}\left(\lambda_1-\frac{\lambda_4}{2}\right)\lambda_5\lambda_6uv+\frac{\sigma^2(x)}{2\lambda_5^2v^2+\frac{\lambda_6^2u^2}{2}}\right)(\xi_\eta'^2+\zeta_\eta'^2). \tag{2}$$

which ξ'_η, ζ'_η are singlet of SU(2), λ is coupling.
The decay of the h^0 scalar is automatically forbidden in all orders of perturbative expansion. This is because of the following features:

- this scalar comes from the triplet χ, the one that induces the spontaneous symmetry breaking of the 3-3-1 model to the standard model. Therefore, the SM fermions and the standard gauge bosons cannot couple with h^0 .
- the h^0 scalar comes from the imaginary part of the Higgs triplet χ. As we mentioned above, the imaginary parts of η and ρ are pure massless Goldstone bosons.

The thermal average of the decay rate is given by

$$\Gamma = \frac{\alpha(\Theta T)^2}{8\pi^3 n_H} e^{m_1/T} \tag{3}$$

where α is an integration parameter. We define $\beta = \frac{n_h}{T^3}$ and in the radiation dominated era we write the evolution Boltzmann Equation as

$$\frac{d\beta}{dT} = -\frac{\Gamma\beta}{KT^3} = -\frac{\alpha}{8\pi^3 K e^{m_1/T}} \left(\frac{\Theta}{T^2}\right)^2 \tag{4}$$

where $K^2 = \frac{4\pi^3 g(T)}{45 m_{Pl}^2}$ $\beta = \frac{n_h}{T^3}$ is the parameter in the thermal equilibrium, $m_{Pl} = 1.2 \times 10^{19}$ GeV is the Planck mass and $g(T) = g_B + 7\frac{g_F}{8} = 136.25$ (Kob and Turner, 1990)

Cosmic density of the scalar particles h is:

$$\Omega_h = 2g(T_\Gamma) T_\gamma^3 \frac{m_h \beta}{\rho_c g(T)} \tag{5}$$

A self interacting dark matter candidate has mean free path $\frac{1}{n_\sigma}$ in the range of Kpc, this range less than Mpc. We know that the number density of the scalar particles h_0 is $n = \frac{\rho}{m_h}$, where ρ is the density at the solar radius. Since that we obtain the mass for the scalar particles is from 4.7 MeV to 29 MeV and density of the scalar particles is from 0.14 to 0.3 and cross section is

$$3.7\text{cm}^2\text{g}^{-1} \leqslant \frac{\sigma}{m_{dm}} \leqslant 5.2\ \text{cm}^2\text{g}^{-1} \tag{6}$$

Tensor energy is

$$T_{\mu\nu} = (\rho + p) u_\mu u_\nu - p g_{\mu\nu} \tag{7}$$

fluid with shear viscosity and bulk viscosity [13]

$$T_{\mu\nu} = (\rho + p) u_\mu u_\nu - p g_{\mu\nu} - 2\eta\sigma_{\mu\nu} - \xi\theta(u_\mu u_\nu + g_{\mu\nu}) \tag{8}$$

FRW metric with tensor perturbations

$$ds^2 = a(\tau)^2 [d\tau^2 - (\delta_{ij} + 2hij) dx^i dx^j] \tag{9}$$

From Einstein's equation we get

$$h''_{ij} - \nabla^2 h_{ij} + 2H h_{ij} = -16\pi a^2 \eta \sigma_{ij} \tag{10}$$

The shear perturbations in velocity are caused by gravitational waves

$$\sigma_{ij} = h'_{ij} + H h_{ij} \tag{11}$$

Predicted gravitational wave amplitude

$$A_0 = 2(4\pi)^{\frac{1}{3}} \frac{G^{\frac{5}{3}}}{c^4} f^{\frac{2}{3}} M_{\rm ch}^{\frac{5}{3}} \tag{12}$$

Chirp mass

$$M_{\rm ch} = \frac{(m_1 m_2)^{\frac{3}{5}}}{(m_1 + m_2)^{\frac{1}{5}}} = \frac{c^3}{G} \left[\frac{5}{96} \pi^{-\frac{8}{6}} f^{\frac{11}{3}} \frac{df}{dt} \right]^{\frac{3}{5}} \tag{13}$$

Measured GW strain

$$h(t, r) = \frac{A_0}{r} e^{-16\pi G \eta r} \tag{14}$$

from the GW150914 If the amplitude can be predicted with a 1% accuracy

$$\eta \times 16\pi G \times 410 \text{ Mpc} < 0.01 => \eta < 5 \times 10^{-7} \text{ GeV}^3 = 6 \times 10^6 \text{ Pc} \tag{15}$$

Self interaction cross section from Abell 3827 cluster [14]

$$\frac{\sigma}{m} = (1.5 - 3) \text{ cm}^2 / \text{ g} \tag{16}$$

Mean free path of the self-interacting dark matter is $l = \frac{1}{n\sigma}$ $\eta = \frac{1}{3} mnvl = \frac{1}{3n\sigma} mnv$, Dark matter with the self interaction cross section predicted in models can be detected with gravitational waves.

3. Direct Detection of Ultra Light Dark Matter

Ultralight dark matter could directly interact with standard-model particles in gravitational-wave interferometers and cause observable, correlated imprints in various data channels. Dilaton dark matter could couple to electrons in the beam splitter [15–18] or in the reference cavity [19], causing oscillatory changes in the size and index of refraction. Axions [20] would alter the phase velocities of left- and right- hand circularly polarized light, which would be visible in auxiliary channels that monitor polarizations of the laser light [21–23]. Dark photons could couple to baryon or baryon-lepton number in the mirrors, resulting in a "dark" electric force that causes the mirrors to oscillate in the presence of the dark-matter field [24]. Tensor bosons would, similarly to gravitational waves, perturb the space-time metric around the mirrors [25].

Gravitational-wave interferometers such LIGO, Virgo, KAGRA and GEO600 [26–28] essentially measure the positions of test masses extremely precisely, thus making them ideal "fith-force" detectors, similarly to the Eötvös [29] torision balance or MICROSCOPE satellite [30] sensitive instruments, and thus have comparable sensitivity [24]. In fact, over the last few years, numerous searches have been performed looking for various dark-matter couplings to standard-model particles with masses of $O(10^{-14} - 10^{-11})$ eV. The first, using data from LIGO's first observing run [26] and a cross-correlation method [24], surpassed existing constraints on ultralight dark photon dark matter for a wide range of masses [31]; the second [32] significantly improved upon these constraints using data from the third observing run of LIGO and Virgo, which included to a new method [33] designed to be optimally sensitive to each masses and an enhancement of the dark-matter strain due to a finite-light travel time effect [34]. Finally, dilaton dark-matter was searched for in data from GEO600 [35], since the signal strength from this kind of dark matter does not depend on arm length but on specific aspects of the instrument itself that, at the time, made GEO600 more sensitive to dilatons than LIGO/Virgo [36]. Additionally, other searches in auxiliary channels of the detector, particularly in KAGRA [37] for scalar [19, 23] and vector [38, 39] dark matter have been performed [40], but have not yet reached their maximal sensitivity, although they could be even more sensitive to dark-matter interactions than those observable in the standard strain channel in the future.

The methods that search for ultralight dark matter do not assume a particular dark-matter model; rather, they look for a monochromatic signal with some stochastic frequency fluctuations of $\Delta f/f \sim v_0^2/c^2 \sim 10^{-6}$, where $v_0 \sim 220$ km/s is the virial velocity of dark matter [41]. Thus, these methods could not distinguish between different dark matter that they may have seen. Recently, however, two ways of differentiating dark-matter types using cross power spectra [42] and the spin [43] have been proposed, showing promising results in the event that any of our methods detect a signal of unknown origin.

Ultralight dark matter could also couple to space-based instruments currently and in the future, but would have different masses than those that can be probed by ground-based detectors, i.e. in the range $O(10^{-19} - 10^{-15})$ eV. Using LISA Pathfinder data [44–46], upper limits on dark photon dark matter coupling to baryons were set for the first time by analyzing data of the relative acceleration of the two test masses [47]. Though the bounds from this search did not surpass existing dark-matter experiments, they motivated the study of other ways to detect ultralight dark matter with space-based instruments, which resulted in projected constraints on $\mathrm{U}(1)_{\mathrm{B-L}}$ dark matter using an amplitude spectral density arising from the relative acceleration of a test mass and the spacecraft [48]. If a search were performed with data from this channel, constraints from existing experiments could be surpasses around $O(10^{-16})$ eV.

The field of searching for dark-matter interactions with gravitational-wave interferometers is just beginning, and as detectors become more sensitive, and as third-generation detectors [49, 50] come online, both the range of masses and coupling strengths to which we are sensitive will greatly improve. Thus, gravitational-wave detectors provide a meaningful and interesting probe of fundamental dark-matter physics, a purpose for which they were not even designed.

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