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A testable scenario of WIMPZILLA with dark radiation

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ABSTRACT

As the electromagnetic gauge symmetry makes the electron stable, a new abelian gauge symmetry may be responsible for the stability of superheavy dark matter. The gauge boson associated with the new gauge symmetry naturally plays the role of dark radiation and contributes to the effective number of 'neutrino species', which has been recently measured by Planck. We estimate the contribution of dark radiation from the radiative decay of a scalar particle induced by the WIMPZILLA in the loop. The scalar particle may affect the invisible decay of the Higgs boson by the Higgs portal type coupling.

1. Introduction

Having no firmly established evidence for weakly interacting massive particle (WIMP) at the LHC and direct detection experiments below a TeV, we are motivated to consider dark matter (DM) in a heavier energy regime. If the DM particle is heavier than a TeV, however, some crucial difficulties arise as follows.

- *Overclosure of the universe*: The pair-annihilation cross section of dark matter, $\langle \sigma v \rangle \propto 1/m_{\mathrm{DM}}^2$, becomes small and leads to the overclosure of the universe with a large density, $\Omega_{\mathrm{DM}} = \rho_{\mathrm{DM}}/\rho_C > 1$, where ρ_C is the critical density.
- *Instability of dark matter*: A heavy particle, in general, tends to be unstable if no symmetry principle forbids its decay.
- *Lack of testability*: In currently on-going or future running experiments, heavier dark matter well above a TeV range is hard to get tested [1,2].

Rather surprisingly, the overclosure of the universe can be resolved in the case of superheavy dark matter, dubbed WIMPZILLA, in a mass window $m_{\mathrm{DM}} \approx 10^{12-14}$ GeV providing a nice fit to the observed DM abundance, $\Omega_{\mathrm{DM}} \simeq 0.2$–$0.3$, independently of the nongravitational interactions of the DM particles. The superheavy dark matter can be produced in various stages of cosmological history: during preheating, reheating and at the end of the inflationary era or in the bubble collision in a first-order phase transition as studied in detail in Refs. [3,4].

However, the stability problem is worse for WIMPZILLA with its extremely high mass. A global symmetry, such as R-parity in supersymmetry models, does not work since in the presence of gravity, especially in the vicinity of black hole, all the stable particles (strings and branes) should be associated with gauge symmetries [5,6]. An interesting observation is that the electron is stable due to the exact electromagnetic $\mathrm{U}(1)_{em}$ gauge symmetry in the standard model (SM). Here we consider the similar possibility that an abelian group $\mathrm{U}(1)_H$ is responsible for the stability of superheavy dark matter. The gauge symmetry may originate from a compact group such as E_6 or even larger group [7]. Just like the photon with $\mathrm{U}(1)_{em}$, a new massless gauge boson is associated with the new gauge symmetry and the presence of new gauge boson opens a new window of testability of WIMPZILLA![1]

The new gauge boson does not directly interact with the SM sector since it is associatively introduced for dark matter. We thus regard the new gauge boson as hidden photon or dark radiation. Dark radiation may have left the evidence of its presence in various circumstances in cosmological history of the universe. Indeed, recent observations show that there may exist non-standard model relativistic particles at the time of Big Bang nucleosynthesis (BBN) and also at the era of recombination shown in cosmic microwave background radiation (CMBR).

In the rest of this Letter, we examine possible experimental tests of this WIMPZILLA associated dark radiation in BBN and CMBR [9–12] and also collider physics [13] based on a model, which is shortly introduced.

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[1] The possibility that primordial superheavy particles with a new U(1) gauge charge is the source of Ultra High Energy Cosmic Rays is considered in [8].

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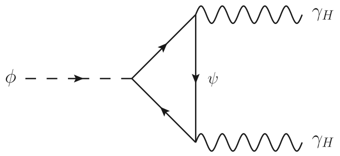

Fig. 1. A scalar particle (ϕ) decaying into two hidden photons through the WIMPZILLA (ψ) loop.

2. The model

The minimal model, which we propose, includes two new hidden sector particles: A Dirac fermion ψ and a scalar ϕ. The fermion is charged under the 'hidden' abelian gauge symmetry, $U(1)_H$, and identified with dark matter. The scalar particle is neutral under the gauge symmetry as well as the standard model interactions but is responsible for the late time decay to dark radiation. Obviously the model is free from anomaly. The generic gauge invariant Lagrangian[2] is given by

$$\begin{aligned}\mathcal{L} \supset \mathcal{L}_{\rm SM} + \mathcal{L}_\phi + \lambda_{\phi H}\phi^2\left(H^\dagger H\right) - \frac{1}{4}F_{H\mu\nu}F_H^{\mu\nu} \\ - y_\psi \phi\overline{\psi}\psi + i\overline{\psi}\gamma^\mu\left(\partial_\mu - i g_H A_\mu^H\right)\psi - m_\psi\overline{\psi}\psi,\end{aligned} \tag{1}$$

where the kinetic term for the scalar field is denoted as $\mathcal{L}_\phi = \frac{1}{2}[(\partial\phi)^2 - m_\phi^2\phi^2]$ and the 'Higgs portal' interaction with the coupling constant $\lambda_{\phi H}$ [16] is allowed. We comment on the mass scales in our model. Due to the vectorlike mass term the new fermion is naturally heavy and nice fit to the WIMPZILLA picture. However, to account the late time decay, the new scalar is required to be much lighter than the WIMPZILLA thus has a similar hierarchy problem for the SM Higgs boson, which is much lighter than a high scale, e.g. Planck scale. In our case, since the scalar particle is in the hidden sector, we are allowed to rely on a (super)symmetry in hidden sector due to which the scalar boson is protected from the radiative correction. Also unnecessary term, e.g., $\phi H^\dagger H$ is forbidden automatically. The details will be presented in other place [17].

Differently from the dark matter particle, which is protected by $U(1)_H$, the scalar particle is unstable and decays into two hidden photons at one-loop level through the triangle diagram with the virtual ψ in the loop as can be seen in Fig. 1. The decay width of ϕ is highly suppressed by the heavy mass of ψ:

$$\frac{1}{\tau_{\phi\to 2\gamma_H}} \approx \frac{(\alpha_H y_\psi)^2}{144\pi^3}\frac{m_\phi^3}{m_\psi^2}, \tag{2}$$

where the structure constant is $\alpha_H = g_H^2/4\pi$. With reasonable choice of parameters, the lifetime can lie in particularly interesting epochs:

- the BBN epoch, $t_{\rm BBN} \approx \mathcal{O}(0.1\text{–}1000)$ s,
- the CMB epoch, $t_{\rm CMB} \approx 3.8\times 10^5\ {\rm yr} \approx 1.2\times 10^{13}$ s,

thus, in principle, we can test the idea of WIMPZILLA by observing dark radiation in these epochs.

3. Observational bounds

Now we are ready to consider dark radiation components seeing in CMB and BBN data and the possible contribution to the Higgs invisible decay at the LHC.

Dark radiation: The effective number of relativistic degrees of freedom, $N_{\rm eff}$, is recently observed by Planck [18], WMAP 9 year [19] and also BBN [20]:

$$\begin{aligned} N_{\rm eff}^{\rm CMB} &= 3.30 \pm 0.27 \quad \text{(Planck 2013)},\\ N_{\rm eff}^{\rm CMB} &= 3.84 \pm 0.40 \quad \text{(WMAP9)},\\ N_{\rm eff}^{\rm BBN} &= 3.71^{+0.47}_{-0.45} \quad \text{(BBN)}.\end{aligned} \tag{3}$$

Compared to the SM expectation, $N_{\rm eff}^{\rm SM} = 3.046$ [21], there exists some deviation in particular in WMAP9 and BBN results, which may be explained by dark radiation. It is worth noticing that adding the H_0 measurement to the Planck CMB data gives $N_{\rm eff} = 3.62 \pm 0.25$, which is 2.3σ level away from the SM expectation [18]. Indeed new relativistic degree of freedom relieves the tension between the CMB data and H_0.

In our case, a sizable dark radiation component at CMB or BBN epoch is obtained if dark radiation is produced by a late time decay of a particle, the scalar particle ϕ in our case. The scalar ϕ is in contact with the SM through the Higgs portal. Provided that ϕ never has dominated the expansion of the universe, but produced extra relativistic degrees of freedom by its decay [9–12,22], the extra contribution to the effective number of relativistic degree of freedom, $\Delta N_{\rm eff}$, is calculated with $Y_\phi = n_\phi/s$, the number density over the entropy density of the universe describing the actual number of particles per comoving volume and the mass and the lifetime of ϕ by a simple formula [9,23]

$$\Delta N_{\phi\ {\rm decay}}^{\rm CMB} = 8.3(Y_\phi m_\phi/{\rm MeV})(\tau_\phi/{\rm s})^{1/2}. \tag{4}$$

In addition to the DR component originated from ϕ decay, the primordial hidden photon γ_H can contribute to $\Delta N_{\rm eff}$. The primordial γ_H is produced through the interactions with the SM thermal bath and we can calculate the contribution conveniently as a relative ratio compared to the energy density of one neutrino species: $\Delta N_{{\rm primo}\ \gamma_H} = \rho_{\gamma_H}/\rho_\nu$. The energy densities are given by $\rho_{\gamma_H} = g_{\gamma_H}T_{\gamma_H,0}^4$ and $\rho_\nu = (7/8)g_\nu T_{\nu,0}^4$ where $T_{i,0} = (\frac{g_{*S,0}}{g_{*S,i\ {\rm dec}}})^{1/3}T_{\gamma,0}$ and g_i and $T_{i,0}$ are the degrees of freedom and the present temperature of the species i. $g_{*S,0}$ and $g_{*S,i\ {\rm dec}}$ are respectively the total degrees of freedom associated with entropy at present and the decoupling time of the species i. We then found the primordial contribution is quite suppressed as

$$\begin{aligned}\Delta N_{{\rm primo}\ \gamma_H} &= \frac{2}{(7/8)\cdot 2}\left(\frac{11}{4}\right)^{4/3}\left(\frac{g_{*S,0}}{g_{*S,\gamma_H\ {\rm dec}}}\right)^{4/3}\\ &\approx 0.053,\end{aligned} \tag{5}$$

where we took $g_{*S,0} = 3.91$ and $g_{*S,\gamma_H\ {\rm dec}} = 107.75$ for γ_H and $g_{*S,0}/g_{*S,\nu\ {\rm dec}} = 4/11$ for neutrino. This small contribution is understandable since the interaction between the hidden photon γ_H and the SM thermal bath is loop suppressed with the WIMPZILLA in the loop thus the hidden photon is decoupled from the SM thermal bath at a high temperature well beyond the electroweak scale.

Finally, we get the total contribution of the WIMPZILLA as

$$\begin{aligned}\Delta N_{\rm eff}^{\rm WZ} &= N_{\rm eff} - N_{\rm eff}^{\rm SM}\\ &= \Delta N_{\phi\ {\rm decay}}^{\rm CMB} + \Delta N_{{\rm primo}\ \gamma_H},\end{aligned} \tag{6}$$

which we should compare with the observational results in Eq. (3), in particular, the Planck 2013 result.

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[2] The kinetic mixing term $\sim F_{\mu\nu}F_H^{\mu\nu}$ can be another source of communication between the hidden sector and the SM sector [14,15] if there exists a bi-charged particle of both sectors, which is absent in the current model. This is consistent with the fact that there is no charged particle under the hidden as well as the SM gauge symmetries.

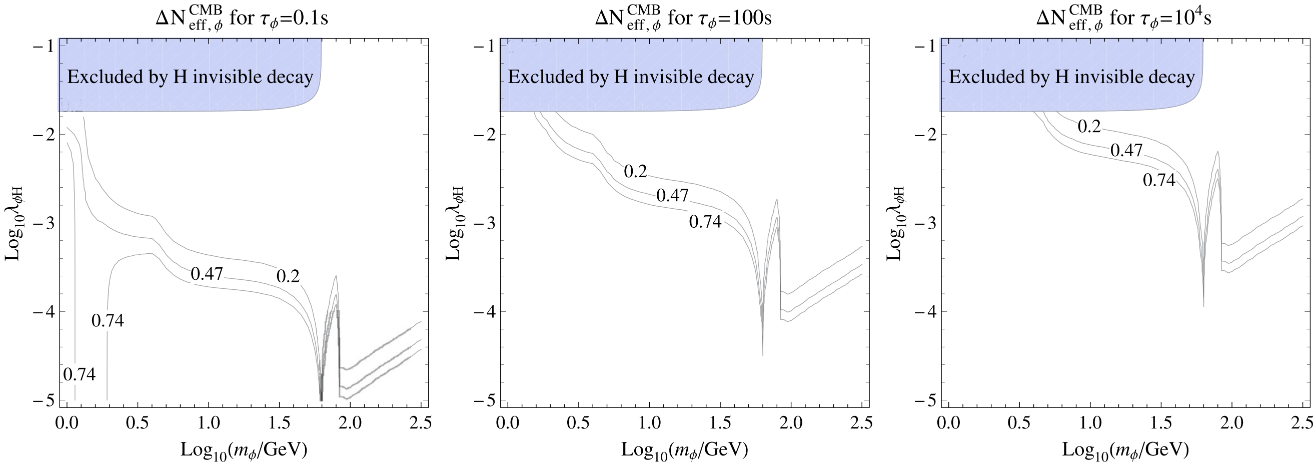

Fig. 2. Contour plots for $\Delta N^{\rm WZ}_{\rm eff}$ in the m_ϕ–$\lambda_{\phi H}$ plane when the decay lifetime of ϕ, τ_ϕ, is fixed as 0.1, 100 and 10^4 s from left to right panels. The shaded region is excluded by the conservative invisible Higgs decay width limit [26], $\mathrm{BR_{inv}} < 0.28$ at 95% C.L. allowing non-standard values for $h \to \gamma\gamma$ and $h \to gg$ modes. The left-lower regions below solid lines are constrained by the effective number of relativistic degrees of freedom limit from the Planck observation [18] at 1σ and 2σ level, respectively.

In Fig. 2, we plotted $\Delta N^{\rm WZ}_{\rm eff}$ at CMB epoch with the Higgs portal coupling $\lambda_{\phi H} \in (10^{-5}, 10^{-1})$ with respect to m_ϕ in (10^0, $10^{2.5}$) GeV with the interesting lifetime of ϕ given as 10^{-1} s (left), 10^2 s (middle) and 10^4 s (right), respectively. These particular time scales are chosen as they coincide with before, during or after BBN time, respectively. We show the best fit lines for the Planck observation taking 1σ and 2σ deviations into account [18]. The left-lower regions below solid lines provide too big contribution to DR component so are excluded. In each plot, a dip structure around $m_\phi = m_h/2$ appears due to the resonant s-channel annihilation of ϕ into SM particles mediated by the Higgs boson through the dependence on Y_ϕ which is controlled by the annihilation cross section of ϕ into SM particles.

To see the contribution at BBN epoch, we follow the discussion in Ref. [9]. When the scalar decays early, $\tau_{\phi\to 2\gamma_H} \lesssim 0.1$ s, the contribution to BBN is essentially same with the contribution to CMB because all of the energy density of ϕ should be converted into the dark photon γ_H before BBN. On the other hand, if the scalar decays after the BBN time, $\tau_{\phi\to 2\gamma_H} \gtrsim 1000$ s, the effect is entirely due to the energy density of ϕ, thus, $\Delta N^{\rm BBN}_\phi / \Delta N^{\rm CMB}_{\phi\to 2\gamma_H}$ decreases. Since the constraint from the BBN is weaker than that by CMB (Planck 2013) as in Eq. (3), and the contribution from ϕ decay is smaller with the longer lifetime, we do not find any useful bound beyond the bound from the CMB measurement in this regime.

Invisible decay of the Higgs: Our scenario includes a light scalar, ϕ, and it interacts with the SM Higgs boson, we can find another important channel to test our idea in collider experiments. Having non-vanishing ‘Higgs portal’ interaction, which induces communication between the hidden and visible sectors, the decay of the Higgs boson to the hidden sector scalar particles is available when kinematically allowed. Actually, the invisible branching fraction of the Higgs is recently measured by ATLAS and CMS [24,25]. A global fit analysis to all the Higgs search data sets a stringent limit on the branching fraction to the invisible Higgs decay width: $\mathrm{BR_{inv}} = \Gamma_{H\to \rm invisible}/\Gamma_{H\to \rm all} < 0.19$ at 95% C.L. assuming the SM decay rates for all the visible Higgs decay modes and $\mathrm{BR_{inv}} < 0.28$ at 95% C.L. allowing non-standard values for $h \to \gamma\gamma$ and $h \to gg$ modes, [26]. From these constraints, we obtained a bound on the Higgs portal coupling as is depicted in Fig. 2 where the shaded regions are excluded.

4. Conclusion

Superheavy dark matter with $m_{\rm DM} \approx 10^{12-14}$ GeV, dubbed WIMPZILLA, can satisfy the observed dark matter abundance but the stability of WIMPZILLA requires an explanation. In this Letter, a new gauge symmetry $\mathrm{U}(1)_H$ is introduced to stabilize WIMPZILLA just like the electromagnetic gauge symmetry to the electron. This simple cure provides interesting possibilities of probing WIMPZILLA by cosmological observations of dark radiation in CMBR and BBN data also by collider experiments of measuring invisible decay of the Higgs boson.

Acknowledgements

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References

[1] G. Bertone, D. Hooper, J. Silk, Phys. Rep. 405 (2005) 279, arXiv:hep-ph/0404175.
[2] J.L. Feng, Annu. Rev. Astron. Astrophys. 48 (2010) 495, arXiv:1003.0904 [astro-ph.CO].
[3] D.J.H. Chung, E.W. Kolb, A. Riotto, Phys. Rev. D 59 (1999) 023501, arXiv:hep-ph/9802238;
D.J.H. Chung, E.W. Kolb, A. Riotto, Phys. Rev. Lett. 81 (1998) 4048, arXiv:hep-ph/9805473;
D.J.H. Chung, E.W. Kolb, A. Riotto, Phys. Rev. D 60 (1999) 063504, arXiv:hep-ph/9809453.
[4] D.J.H. Chung, P. Crotty, E.W. Kolb, A. Riotto, Phys. Rev. D 64 (2001) 043503, arXiv:hep-ph/0104100.
[5] R. Kallosh, A.D. Linde, D.A. Linde, L. Susskind, Phys. Rev. D 52 (1995) 912, arXiv:hep-th/9502069.
[6] T. Banks, N. Seiberg, Phys. Rev. D 83 (2011) 084019, arXiv:1011.5120 [hep-th].
[7] J.L. Hewett, T.G. Rizzo, Phys. Rep. 183 (1989) 193.
[8] V.K. Dubrovich, M.Y. Khlopov, JETP Lett. 77 (2003) 335;
V.K. Dubrovich, M.Y. Khlopov, Pis’ma Zh. Eksp. Teor. Fiz. 77 (2003) 403, arXiv:astro-ph/0206138;
V.K. Dubrovich, D. Fargion, M.Y. Khlopov, Astropart. Phys. 22 (2004) 183, arXiv:hep-ph/0312105.
[9] J.L. Menestrina, R.J. Scherrer, Phys. Rev. D 85 (2012) 047301, arXiv:1111.0605 [astro-ph.CO].
[10] W. Fischler, J. Meyers, Phys. Rev. D 83 (2011) 063520, arXiv:1011.3501 [astro-ph.CO].
[11] M.C. Gonzalez-Garcia, V. Niro, J. Salvado, J. High Energy Phys. 1304 (2013) 052, arXiv:1212.1472 [hep-ph].
[12] J. Hasenkamp, J. Kersten, arXiv:1212.4160 [hep-ph].
[13] C.S. Kim, S.C. Park, K. Wang, G. Zhu, Phys. Rev. D 81 (2010) 054004, arXiv:0910.4291 [hep-ph].
[14] B. Holdom, Phys. Lett. B 166 (1986) 196;
L.B. Okun, Sov. Phys. JETP 56 (1982) 502, Zh. Eksp. Teor. Fiz. 83 (1982) 892.

[15] K.R. Dienes, C.F. Kolda, J. March-Russell, Nucl. Phys. B 492 (1997) 104, arXiv:hep-ph/9610479;
J.-H. Huh, J.E. Kim, J.-C. Park, S.C. Park, Phys. Rev. D 77 (2008) 123503, arXiv:0711.3528 [astro-ph];
E.J. Chun, J.-C. Park, J. Cosmol. Astropart. Phys. 0902 (2009) 026, arXiv:0812.0308 [hep-ph];
E.J. Chun, J.-C. Park, S. Scopel, J. High Energy Phys. 1102 (2011) 100, arXiv:1011.3300 [hep-ph];
J.-C. Park, S.C. Park, Phys. Lett. B 718 (2013) 1401, arXiv:1207.4981 [hep-ph].

[16] T. Binoth, J.J. van der Bij, Z. Phys. C 75 (1997) 17, arXiv:hep-ph/9608245;
R. Schabinger, J.D. Wells, Phys. Rev. D 72 (2005) 093007, arXiv:hep-ph/0509209.

[17] J.C. Park, S.C. Park, in preparation.

[18] P.A.R. Ade, et al., Planck Collaboration, arXiv:1303.5076 [astro-ph.CO].

[19] G. Hinshaw, D. Larson, E. Komatsu, D.N. Spergel, C.L. Bennett, J. Dunkley, M.R. Nolta, M. Halpern, et al., arXiv:1212.5226 [astro-ph.CO].

[20] G. Steigman, Adv. High Energy Phys. 2012 (2012) 268321, arXiv:1208.0032 [hep-ph].

[21] G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti, P.D. Serpico, Nucl. Phys. B 729 (2005) 221, arXiv:hep-ph/0506164.

[22] D. Hooper, F.S. Queiroz, N.Y. Gnedin, Phys. Rev. D 85 (2012) 063513, arXiv:1111.6599 [astro-ph.CO];
K. Choi, K.-Y. Choi, C.S. Shin, Phys. Rev. D 86 (2012) 083529, arXiv:1208.2496 [hep-ph];
P. Di Bari, S.F. King, A. Merle, Phys. Lett. B 724 (2013) 77, arXiv:1303.6267 [hep-ph];
C. Kelso, S. Profumo, F.S. Queiroz, Phys. Rev. D 88 (2013) 023511, arXiv:1304.5243 [hep-ph].

[23] R.J. Scherrer, M.S. Turner, Astrophys. J. 331 (1988) 33.

[24] G. Aad, et al., ATLAS Collaboration, Phys. Lett. B 716 (2012) 1, arXiv:1207.7214 [hep-ex].

[25] S. Chatrchyan, et al., CMS Collaboration, Phys. Lett. B 716 (2012) 30, arXiv:1207.7235 [hep-ex].

[26] P.P. Giardino, K. Kannike, I. Masina, M. Raidal, A. Strumia, arXiv:1303.3570 [hep-ph].