UV and IR freeze-in production of fermionic dark matter and its possible X-ray signature

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Motivation for FIMP

Experimental observation

- Direct detection experiments LUX, PANDA, XENON put a strong bound on DM-nucleon scattering cross-section.

Shortcoming

- Mostly studied WIMP scenario can not explain the results of direct detection experiments.
- Need to go beyond WIMP paradigm.

Proposal

- DM production via freeze-in is a well motivated scenario because
  - ✓ It can explain the null results of direct detection experiment due to its feeble coupling with visible sector.
  - ✓ Can be probed via indirect detection.

Classifications of Freeze-in

UV freeze-in

Arises due to the presence of higher dimensional operator $\left(\frac{\mathcal{O}^d}{\Lambda^{d-4}}\right)$ and relic density depends on the early state of the universe such as reheat temperature.

F.Elahi et. al. JHEP03(2015)048

IR freeze-in

Arises due to the presence of renormalizable operator and the contribution to the relic density coming from IR freeze-in is independent of early state of universe and it depends on the mass of bath particles.

L.J.Hall et. al. JHEP03(2010)080

The Model

Extension

- A Dirac fermion χ, singlet under SM-gauge group.
- A pseudo scalar $\tilde{\phi}$, singlet under SM-gauge group.

Stability of DM

- χ is odd under $\mathbb{Z}_2$.
  - ✓ $y\,\overline{L}\tilde{\Phi}\chi$ is forbidden $\Longrightarrow$ DM interacts with the visible sector via dimension five operators $\Longrightarrow$ Natural suppression in coupling.
- $\tilde{\phi}$ and all SM fields are even under $\mathbb{Z}_2$.
  - ✓ After electroweak symmetry breaking, $\langle\Phi\rangle \neq 0$ and $\mathbb{Z}_2$ symmetry remains unbroken and it ensures the stability of DM.

Important Interactions

Interactions for UV freeze-in

$$\mathcal{L}_{UV} \supset -\frac{\overline{\chi}\chi\Phi^\dagger\Phi}{\Lambda} - \frac{\epsilon^{\mu\nu\alpha\beta}\left(\partial_\mu B_\nu\right)\left(\partial_\alpha B_\beta\right)\tilde{\phi}}{\Lambda} - \frac{\epsilon^{\mu\nu\alpha\beta}\left(\partial_\mu W^a_\nu\right)\left(\partial_\alpha W^a_\beta\right)\tilde{\phi}}{\Lambda}$$
$$- \frac{\epsilon^{\mu\nu\alpha\beta}\left(\partial_\mu G^b_\nu\right)\left(\partial_\alpha G^b_\beta\right)\tilde{\phi}}{\Lambda} - g\,\bar{\chi}\gamma_5\chi\,\tilde{\phi} - \frac{i}{\Lambda}\left(y_t\,\bar{t}_L\,\gamma_5\,t_R\,\phi^{0*}\tilde{\phi} + h.c\right) .$$

Interactions for IR freeze-in

$$\mathcal{L}_{IR} \supset -\frac{\epsilon^{\mu\nu\alpha\beta}\left(\partial_\mu W^-_\nu\right)\left(\partial_\alpha W^+_\beta\right)\tilde{\phi}}{\Lambda} - \frac{\epsilon^{\mu\nu\alpha\beta}\left(\partial_\mu W^+_\nu\right)\left(\partial_\alpha W^-_\beta\right)\tilde{\phi}}{\Lambda}$$
$$- \frac{\epsilon^{\mu\nu\alpha\beta}(\partial_\mu A_\nu)(\partial_\alpha A_\beta)\tilde{\phi}}{\Lambda} - \frac{\epsilon^{\mu\nu\alpha\beta}\left(\partial_\mu G^b_\nu\right)\left(\partial_\alpha G^b_\beta\right)\tilde{\phi}}{\Lambda} - \frac{\epsilon^{\mu\nu\alpha\beta}\left(\partial_\mu Z_\nu\right)\left(\partial_\alpha Z_\beta\right)\tilde{\phi}}{\Lambda}$$
$$- \frac{i}{\Lambda}m_t\bar{t}\gamma_5 t\tilde{\phi} - \frac{v}{\Lambda}\overline{\chi}\chi h - \frac{1}{2\Lambda}\overline{\chi}\chi\,h^2 - g\,\overline{\chi}\gamma_5\chi\,\tilde{\phi}\,.$$

Production channels of DM

Production through pure freeze-in

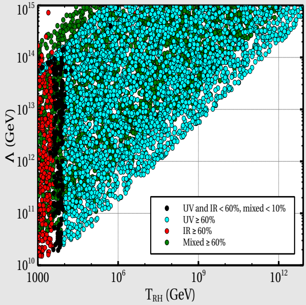
- In UV regime, $\phi_i^\dagger \phi_i \to \overline{\chi}\chi$ in the dominant production channel of DM production.
- After EWSB, DM can be produced dominantly from the annihilation of W^+W^-, ZZ, hh and also from the decay of h.

Production through mixed freeze-in

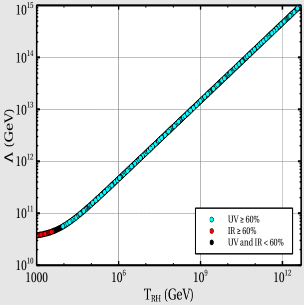
- $\tilde{\phi}$ can be dominantly produced from the top quark involving scattering in the UV regime due to presence of a dimension five operator $\frac{y_t}{\Lambda}\overline{t}_L\gamma_5\, t_R\phi^{0*}\tilde{\phi}$.
- $\tilde{\phi}$ produced from the UV processes can decay into $\overline{\chi}\chi$ through a renormlizable operator $g\overline{\chi}\gamma_5\chi\tilde{\phi}$.

Parameter space in $T_{RH} - \Lambda$ plane for correct relic density

$m_{\tilde{\phi}} = 100\,\mathrm{GeV}$ and $1\,\mathrm{keV} \leq m_\chi \leq 100\,\mathrm{GeV}$



$m_\chi \simeq m_{\tilde{\phi}} = 7.06\,\mathrm{keV}$



Indirect detection

Box shaped spectra

- We have considered the cascade annihilation process $\overline{\chi}\chi \to \tilde{\phi}\tilde{\phi} \to 4\gamma$.
- Since the decaying particle is a scalar so that the photon emission is isotropic and the photon spectrum looks like a box of width $\Delta E = E_\gamma^{max} - E_\gamma^{min} = \sqrt{m_\chi^2 - m_{\tilde{\phi}}^2}$.

A.Ibarra et.al JCAP07(2012)043

m_χ and $m_{\tilde{\phi}}$ must be degenerate for line spectrum.

Possible X-ray signature via $\sim$ 3.5 keV X-ray line observed by XMM Newton telescope from the galactic centre

- We have considered $m_\chi \simeq m_{\tilde{\phi}} = 7.06\,\mathrm{keV}$ to explain the origin of $\sim$3.5 keV X-ray line from DM annihilation.
- $\tilde{\phi}$ is long lived because of its two photon coupling and the coupling is strongly constrained from various astrophysical observations.
- Long lived $\tilde{\phi}$ modifies the DM density profile.

Photon flux and effective J factor

- Differential photon flux is given by

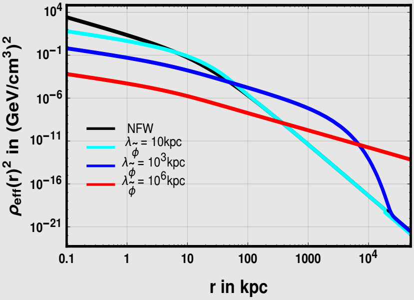
$$\frac{d\Phi_\gamma}{dE_\gamma} = 2 \times \frac{1}{4}\frac{r_\odot}{4\pi}\left(\frac{\rho_\odot}{m_\chi}\right)^2 \langle\sigma \mathrm{v}_{\rm rel}\rangle_{\bar{\chi}\chi\to\tilde{\phi}\tilde{\phi}} \frac{dN_\gamma}{dE_\gamma} J_{\rm eff}\Delta\Omega \ ,$$

where

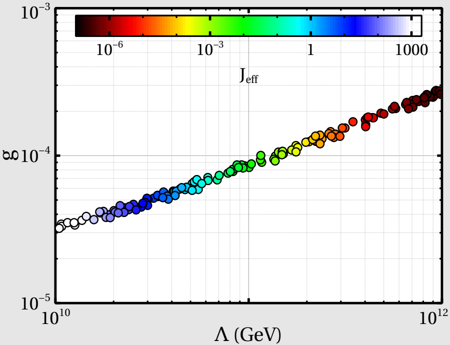
$$J_{\rm eff} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int \frac{dx}{r_\odot}\frac{\rho^2_{\rm eff}(x)}{\rho^2_\odot} \ .$$

Long lifetime of $\tilde{\phi}$ modifies the dark matter density profile effectively,

$$\rho^2_{\rm eff}(x) = \int dV_{\vec{x}_s} \frac{\rho^2_\chi(\vec{x}_s)}{4\pi\lambda_{\tilde{\phi}}} \frac{\exp\left(-\frac{|\vec{x}-\vec{x}_s|}{\lambda_{\tilde{\phi}}}\right)}{|\vec{x}-\vec{x}_s|^2}$$



$\Lambda - g$ plane for correct photon flux in 2σ range observed by XMM Newton telescope



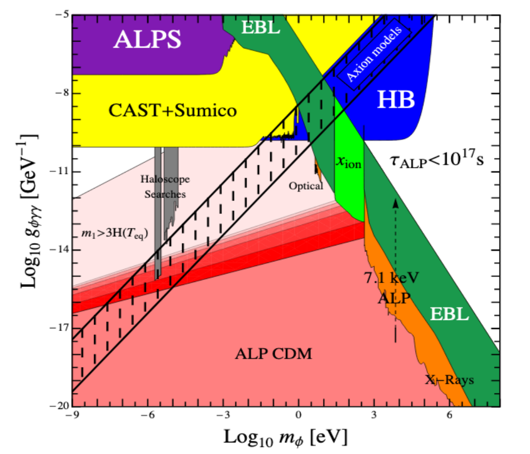
- $10^{12}\,\mathrm{GeV} \leq \Lambda \leq 10^{17}\,\mathrm{GeV}$ is disfavoured from various astrophysical observations.
  J.Jaeckel et. al. Phys. Rev. D 89,103511(2014)
- Mean free path of $\tilde{\phi}$ increases with the increase in Λ. Therefore $J_{\rm eff}$ will decrease and to get the correct photon flux observed by XMM Newton telescope, g must increase with the increase in Λ.

Conclusions

- DM production via freeze-in is well motivated scenario which can explain the null results of direct detection experiments.
- We have found in our model that for the lower end of $T_{RH} - \Lambda$ plane where $T_{RH} \lesssim 10^4$ GeV, DM is produced dominantly by IR and mixed freeze-in whereas for $T_{RH} > 10^4\ GeV$, DM is produced by UV and mixed freeze-in.
- Large lifetime of $\tilde{\phi}$ effectively modifies the DM density profile at galactic centre and that affects the calculation of photon flux.
- $\bar{\chi}\chi \to \tilde{\phi}\tilde{\phi} \to 4\gamma$ process can explain the $\sim$3.5 keV X-ray anomaly, which was observed from galactic centre and we have identified the allowed parameter space in Λ-g plane which reproduces the observed flux by XMM Newton telescope.

Thank You.

Backup slide: Allowed $m_{\tilde{\phi}} - \Lambda$ plane



J.Jaeckel et. al. Phys. Rev. D 89,103511(2014)