Higher Multiplet Dark Matter

Takashi Toma

Laboratoire de Physique Théorique d'Orsay

Exploring the Dark Sector@KIAS

In collaboration with
Avelino Vicente (Université de Liège)
Mayumi Aoki (Kanazawa University)

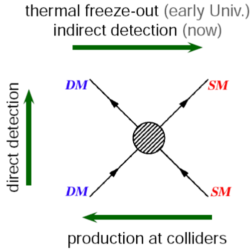
Work in Progress

Dark Matter Candidates

- MACHO (Massive Astrophysical Compact Halo Object)
- Axion
- WIMP (Weakly Interacting Massive Particle)
- Asymmetric Dark Matter
- Q-ball etc

WIMP: Most promising DM candidate.
Many experiments focus on exploring WIMP.

- Direct detection
- Indirect detection
- Collider search



DM Stability

Where does Dark Matter stability come from?

- Impose discrete symmetry by hand $\mathbb{Z}_2$, $\mathbb{Z}_3$ etc.
- Remnant symmetry after spontaneous symmetry breaking
  ex. $U(1) \to \mathbb{Z}_2$, $SU(2) \to SO(3)$. Hambye: arXiv:0811.0172.
- Minimal DM scenario Cirelli et al: hep-ph/0512090
  Accidental $\mathbb{Z}_2$ symmetry is obtained when we consider $SU(2)_L$ higher multiplet.
  higher than 5-plet for fermion and 7-plet for scalar can be DM candidate.
- Anti-symmetric tensor $B_{\mu\nu}$ (gauge singlet in the SM)
  Cata, Ibarra: arXiv:1404.0432

Minimal DM Scenario

- DM has only gauge interaction.
  (No scalar coupling $|\phi|^2\chi^2$ for scalar DM is assumed)
- All the components are degenerate at tree level. But mass splitting is derived at one-loop level.

$$\Delta m \approx \frac{\alpha_W}{4\pi} m_\chi F_{\rm loop} \lesssim \text{ a few GeV}$$

  The neutral component can be lightest.
- Sommerfeld correction affetcs to DM relic density.
  $\rightarrow$ Too large annihilation cross section due to large $SU(2)_L$ gauge coupling.
  $\rightarrow$ DM mass must be more than 10 TeV.

- We want to consider lighter DM mass in such a scenario and also mind generation of neutrino masses.

The Model

- New particles
  Real septet scalar χ (χ^{+++}, χ^{++}, χ^{+}, χ^{0})
  Three right-handed neutrinos N_i.
  We do not impose any extra symmetry to the SM.
- Interactions

$$\mathcal{L}_Y = y^{\nu}_{i\alpha}\phi\overline{N_i}P_L L_\alpha + \mathrm{h.c.}$$

$$\mathcal{V} = \mu_\phi^2|\phi|^2 + \frac{\mu_\chi^2}{2}\chi^2 + \frac{\lambda_\phi}{4}|\phi|^4 + \sum_{i=1}^{2}\frac{\lambda_{\chi i}}{4!}\chi^4 + \frac{\lambda_{\phi\chi}}{2}|\phi|^2\chi^2$$

  where ϕ is the SM Higgs doublet.
- Mass of septet scalar at tree level: $m_\chi^2 = \mu_\chi^2 + \lambda_{\phi\chi}\langle\phi\rangle^2$
  All components are degenerate at tree level.

Neutrino Masses

- Induced by Type I Seesaw

$$\begin{pmatrix} \overline{\nu_L^c} & \overline{N_R} \end{pmatrix} \begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix} \quad \rightarrow \quad m_\nu \approx -m_D^T M^{-1} m_D$$

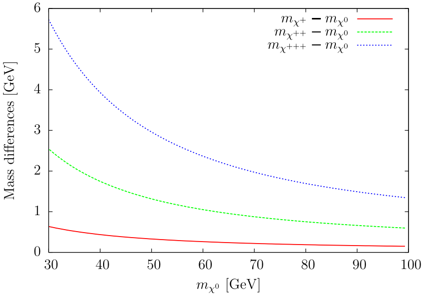
- $m_\nu \sim y^{\nu 2} \langle \phi \rangle^2 / M$ (experimental value $m_\nu \sim 0.1$ eV)
- Heavy neutrino masses $\sim M$.
- Required Yukawa coupling is $y^\nu \sim 10^{-7}$ for $M \sim 1 - 10$ TeV
- We consider $M \gtrsim 2m_{\chi^0}$ to get decay channel into two DM: $N_1 \rightarrow \nu_L \chi^0 \chi^0$ etc.
  $\rightarrow$ DM is generated by decay of N after freeze-out.

Mass Difference of Septet χ

- Mass differences are induced at one-loop level.

$$m_Q - m_{Q'} = (Q^2 - Q'^2)\frac{m_\chi}{4\pi}\left[\alpha_W\left\{f\left(\frac{m_W}{m_\chi}\right) - f\left(\frac{m_Z}{m_\chi}\right)\right\} + \alpha_{\mathrm{em}}\left\{f\left(\frac{m_Z}{m_\chi}\right) - f(0)\right\}\right]$$

where $f(z) = -\frac{1}{2}\int_0^1 \left[6(1-x)z^2 + 9x^2 - 4x - 4\right]\log\left((1-x)z^2 + x^2\right)dx$



- For $m_\chi \gg m_W, m_Z$
  $m_Q - m_{Q'} = (Q^2 - Q'^2)\,\alpha_W m_W \sin^2\left(\frac{\theta_W}{2}\right) \approx (Q^2 - Q'^2) \times 0.166$ GeV
- Neutral component is the lightest.

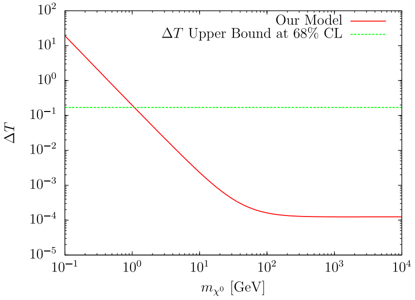
Constraint of Oblique Parameters

T-parameter

$$\alpha_{\rm em} T = \frac{1}{m_W^2}\Pi_{WW}(0) - \frac{1}{m_Z^2}\Pi_{ZZ}(0)$$

where $\Pi_{WW}(0) = \frac{\alpha_W}{4\pi}\left[3F\left(m^2_{\chi^{+++}}, m^2_{\chi^{++}}\right) + 5F\left(m^2_{\chi^{++}}, m^2_{\chi^{+}}\right) + 6F\left(m^2_{\chi^{+}}, m^2_{\chi^{0}}\right)\right]$

No correction to Z mass: $\Pi_{ZZ}(0) = 0$

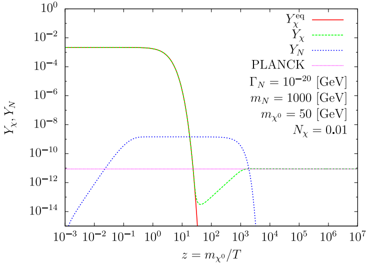


- DM mass should be $m_{\chi^0} \gtrsim 1$ GeV from T-parameter.
- The constraints of S- and U-parameters are much weaker than T-parameter.

Non-thermal Production of DM

Boltzmann equations

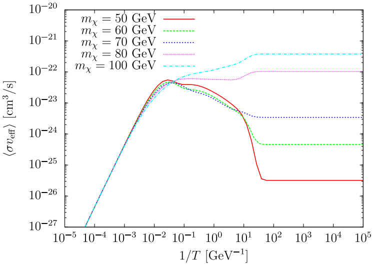
$$\frac{dn_N}{dt} + 3Hn_N = \frac{g_N m_N^2 \Gamma_N}{2\pi^2 T} K_1\left(\frac{m_N}{T}\right) - \Gamma_N n_N,$$
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\rm eff} v\rangle\left(n_\chi^2 - n_\chi^{\rm eq\,2}\right) + N_{\chi^0}\Gamma_N n_N$$

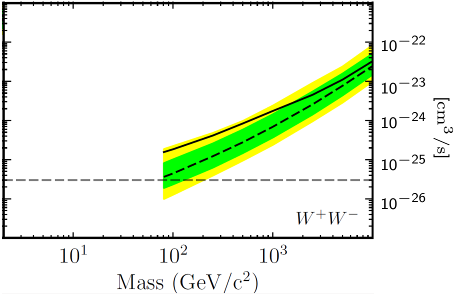


- N_1 is produced by freeze-in mechanism.
- DM χ^0 is produced by the decay of N_1 after freeze-out.
- Branching ratio of decay into DM is subdominant ($N_{\chi^0} \ll 1$).

Non-thermal Production of DM

- Co-annihilation among the septet is effective when $\Delta m/T \lesssim 1$. $\chi^0\chi^+ \to W^+ \to W^+\gamma$, $\chi^+\chi^- \to Z \to f\bar{f}$ etc.

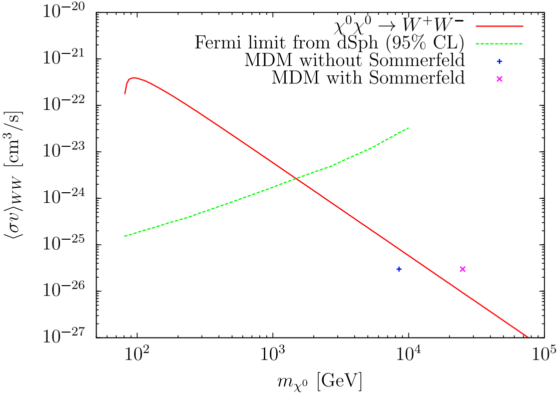




arXiv:1310.0828

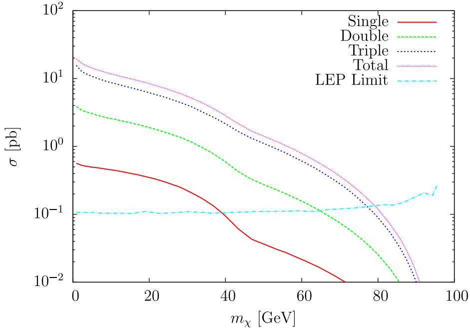
- Dominant annihilation channel is $\chi^0\chi^0 \to WW^*$ even if DM mass is slightly below the threshold.
- $60\ \mathrm{GeV} \lesssim m_{\chi^0} \lesssim 1.5\ \mathrm{TeV}$ is excluded.

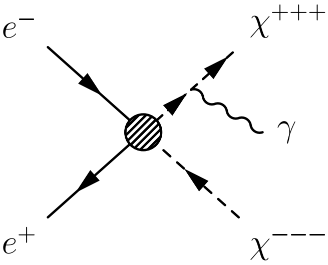
Constraint on DM cross section from dwarf spheroidal galaxies



- Dominant annihilation channel is $\chi^0\chi^0 \to WW^*$ even if DM mass is slightly below the threshold.
- $60\ \mathrm{GeV} \lesssim m_{\chi^0} \lesssim 1.5\ \mathrm{TeV}$ is excluded.

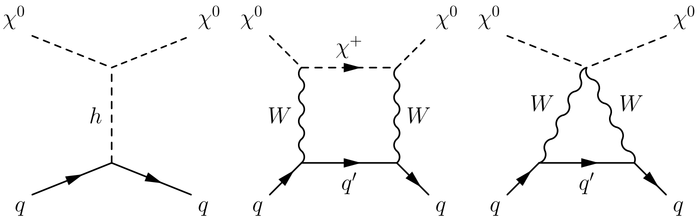
LEP Limit





- $e^+e^- \to \gamma +$ Missing. Background $e^+e^- \to \gamma\nu\overline{\nu}$.
- Our processes are $e^+e^- \to \gamma, Z \to \gamma\chi^{+++}\chi^{---}$, $\gamma\chi^{++}\chi^{--}$, $\gamma\chi^{+}\chi^{-}$. Assumed that $\pi^\pm$ produced by $W^\pm$ decay is not detectable.
- $m_{\chi^0} \lesssim 80$ GeV is excluded.

Direct detection

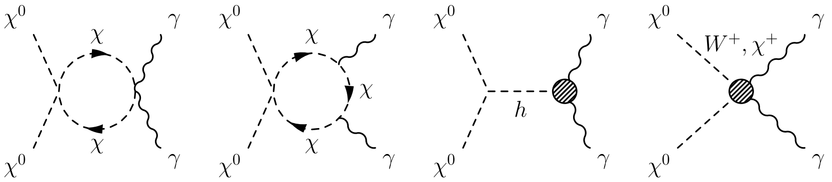


- There are tree level contribution via Higgs and one-loop contribution via gauge bosons.
- Large contribution is obtained from gauge boson loop, but it can be controlled by the Higgs coupling $\lambda_{\phi\chi}$.

$$\sigma_{SI} = 4.6 \times 10^{-44}\ \mathrm{cm}^2 \text{ in MDM}, \quad i\mathcal{M}_{SI} \sim (\text{scalar}) + (W \text{ boson})$$

- $\mathcal{O}(1)$ coupling of $\lambda_{\phi\chi}$ is needed to cancel the gauge contribution.
- This occurs only for scalar DM, but not for fermion DM.

Indirect detection of DM



- $\chi^0\chi^0 \to \gamma\gamma$ is enhanced by multi-charged scalars $\chi^{\pm\pm\pm}$
- Gauge boson contribution $\sigma v_{\gamma\gamma} = \dfrac{288\pi\alpha_{\rm em}^2\alpha_W^2}{m_W^2} \approx 4 \times 10^{-26}\ {\rm cm}^3/{\rm s}$ by perturbative way.
  $\to \sigma v_{\gamma\gamma} \propto 1/m_{\chi^0}^2$ is expected for non-perturbative way.
- Scalar contribution

$$\sigma v_{\gamma\gamma} = \frac{\alpha_{\rm em}^2}{128\pi^3 m_\chi^2}\left(1-\frac{\pi^2}{4}\right)^2\left(\sum_\chi Q_\chi^2 \lambda_{\chi^0\chi^0\chi\chi}\right)^2 \approx 10^{-27}\ {\rm cm}^3/{\rm s}$$

at $\lambda_{\phi\chi} \sim 1$, $m_\chi^0 \sim 2$ TeV

Summary

- We have considered $SU(2)_L$ septet DM which can be stabilized by accidental $\mathbb{Z}_2$ symmetry and Neutrino masses.
- Although DM mass should be more than 10 TeV in minimal scenario, 1 TeV scale DM is possible in our case.
- DM relic density is non-thermally produced by decay of right-handed neutrinos.
- Strong monochromatic gamma-rays are generated by multi-charged scalars and Sommerfeld effect.