Sommerfeld Enhancement in Scotogenic Model with Large Electroweak Scalar Multiplets

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Motivation

- The scotogenic model is a minimal model of the dark matter (DM) and neutrino mass. Deshpande and Ma, PRD, 18, 2574 (1978),Ma, PRD, 73, 077301 (2006)
- It contains

$$D = \begin{pmatrix} C^+ \\ \frac{1}{\sqrt{2}}(S + iA) \end{pmatrix}_{J=\frac{1}{2}, Y=\frac{1}{2}}, \quad N_{R_{J=0, Y=0}}$$

  charged under Z_2 symmetry (stabilizing DM). Here either S or N can be considered as DM (depending on parameter space). We choose, S to be the DM.
- There is no symmetry to forbid the replacement:

$$D \to \mathbf{\Delta}_{J=\frac{n}{2}, Y=\frac{1}{2}}, \quad \text{and} \quad N_R \to F_{J=\frac{n-1}{2}, Y=0}$$

- So, considering DM phenomenology, which scalar multiplet with **high mass DM (in the TeV range)** is more viable: doublet or larger multiplet?

- At present, in our galaxy, TeV mass-ranged non-relativistic DM annihilation will be greatly modified by **Sommerfeld Enhancement**.

  hep-ph/0212022, hep-ph/0307216, hep-ph/0412403, arXiv:0706.4071, arXiv:0810.0713

- Because of that, DM indirect detection signals, specially gamma ray, achieve better prospects of being detected in the currently operating or future Imaging Atmospheric Cherenkov Telescopes.
- To compare Sommerfeld enhanced DM annihilation cross sections, we choose the usual scalar doublet and its immediate generalization, the quartet;

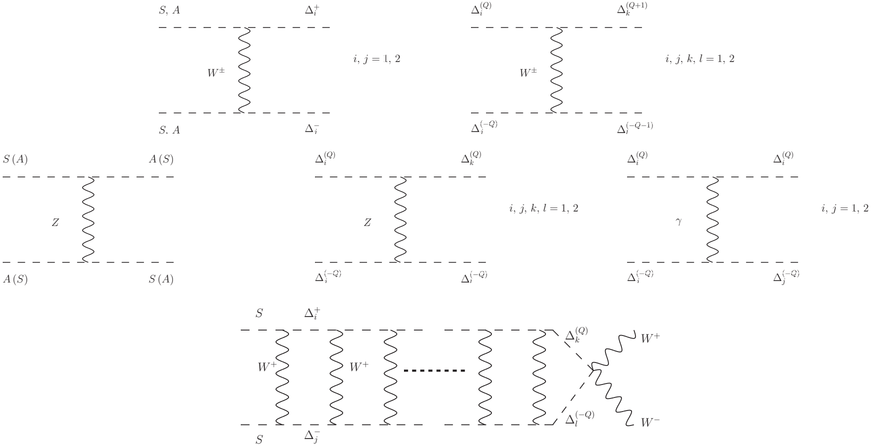
$$D = \begin{pmatrix} \Delta^{+} \\ \frac{1}{\sqrt{2}}(S+iA) \end{pmatrix}, \; \Delta = \begin{pmatrix} \Delta^{++} \\ \Delta_1^{+}\cos\theta - \Delta_2^{+}\sin\theta \\ \frac{1}{\sqrt{2}}(S+iA) \\ \Delta_1^{-}\sin\theta + \Delta_2^{-}\cos\theta \end{pmatrix}$$

- The mass spectrum will be,

$$\text{doublet: } m_S < m_{\Delta^+} < m_A$$
$$\text{quartet: } m_S < m_{\Delta_1^+} < m_{\Delta^{++}} < m_{\Delta_2^+} < m_A$$

Sommerfeld Enhancement

- When DM is heavy and non-relativistic or more precisely, $\epsilon_\phi = (m_W/m_{DM})/\alpha_W \ll 1$ & $\epsilon_v = (v_{DM}/c)/\alpha_W \ll 1$, Sommerfeld enhancement in cross section arises due to the long-range interaction mediated by W, Z and γ bosons.



Potential and Annihilation Matrices

The potential matrix is

$$V_{ii',jj'} = \begin{pmatrix} 0 & V_{SS,AA} & V_{SS,\Delta^{++}\Delta^{--}} & V_{SS,\Delta_1^+\Delta_1^-} & \cdots \\ V_{SS,AA} & V_{AA,AA} & V_{AA,\Delta^{++}\Delta^{--}} & \cdots & \cdots \\ \cdots & \cdots & V_{\Delta^{++}\Delta^{--},\Delta^{++}\Delta^{--}} & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{pmatrix}$$

The annihilation matrix for the final state $f = WW,\ ZZ,\ \gamma\gamma,\ \gamma Z$ is

$$\Gamma^{(f)}_{ii',jj'} = \begin{pmatrix} \Gamma_{SS,SS} & \Gamma_{SS,AA} & \Gamma_{SS,\Delta^{++}\Delta^{--}} & \Gamma_{SS,\Delta_1^+\Delta_1^-} & \cdots \\ \Gamma_{SS,AA} & \Gamma_{AA,AA} & \Gamma_{AA,\Delta^{++}\Delta^{--}} & \cdots & \cdots \\ \cdots & \cdots & \Gamma_{\Delta^{++}\Delta^{--},\Delta^{++}\Delta^{--}} & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{pmatrix}$$

The Sommerfeld enhanced cross section is

$$\sigma v_{SS\to f} = 2(T.\Gamma^{(f)}.T^{\dagger})_{SS,SS}$$

Benchmarks for SE in Scotogenic Model

- Mass splittings among charged states and DM can suppress Sommerfeld enhancement even if $\epsilon_\phi \ll 1 \,\&\, \epsilon_v \ll 1$.
- Two cases in the mass splittings. (Almost) degenerate: radiatively induced mass splitting between DM and charged state, O(100 MeV). And maximum allowed mass splittings of the doublet and quartet as follows; arXiv:1608.07648, arXiv:1512.07501, arXiv:1502.01589

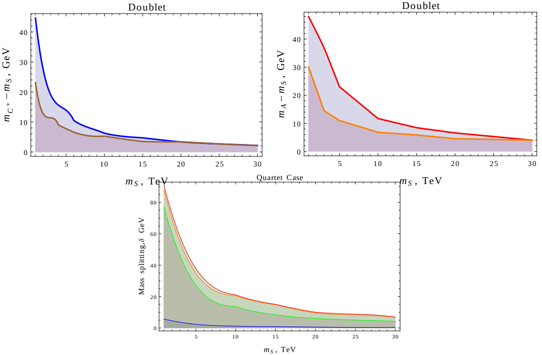


Figure : Upper left: blue (LUX2016) and brown (XENON1T), Upper right: red (LUX2016) and orange (XENON1T), lower: $m_{\Delta_1^+} - m_S$ (blue), $m_{\Delta^{++}} - m_S$ (green), $m_{\Delta_2^+} - m_S$ (orange) and $m_A - m_S$ (red).

SE Enhanced DM annihilation cross sections

$SS \to WW$:

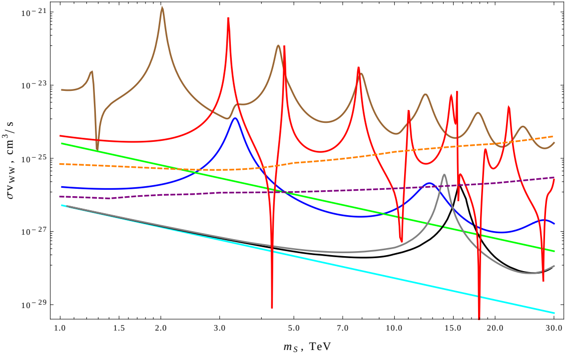


Figure : (almost) degenerate limit: blue (doublet) and brown (quartet) lines. Maximum allowed splitting: black (doublet, LUX2016), grey (doublet, XENON1T) and red (quartet) lines. Tree-level σv_{WW}: light blue (doublet) and green (quartet) lines. The orange dashed line (H.E.S.S. limit) and purple dashed line (future CTA limit). arXiv:1607.08142, arXiv:1508.06128

SE Enhanced DM annihilation cross sections

$SS \to ZZ$:

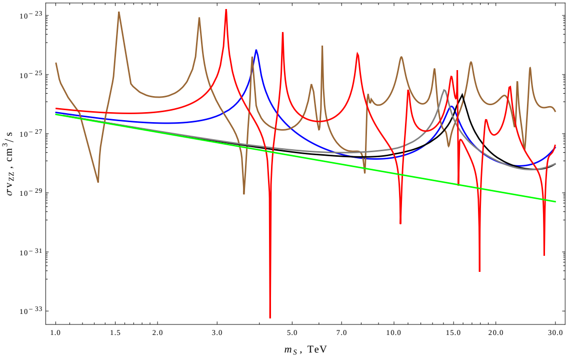


Figure : (almost) degenerate limit: blue (doublet) and brown (quartet) lines and for maximum limits of mass splittings: black (doublet, LUX2016), grey (doublet, XENON1T) and red (quartet) lines. The green line is the tree-level σv_{ZZ} for both doublet and quartet.

SE Enhanced DM annihilation cross sections

$SS \to \gamma\gamma$ and $SS \to \gamma Z$:

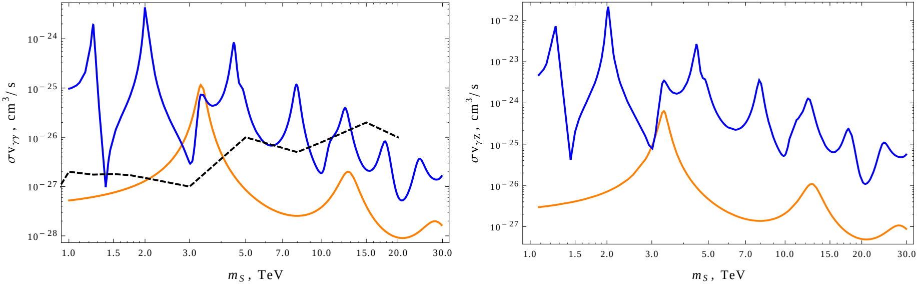


Figure : left fig: $\sigma v_{\gamma\gamma}$ and right fig: $\sigma v_{\gamma Z}$, for the doublet (orange line) and quartet (blue line) cases at the almost degenerate limits. Also black dashed line: H.E.S.S. limits on $\gamma\gamma$ annihilation. arXiv:1609.08091

In maximum allowed splitting, both $\sigma v_{\gamma\gamma}$ and $\sigma v_{\gamma Z}$ are highly suppressed and given by 1-loop processes: for the mass range of $1 - 30$ TeV,$\sigma v_{\gamma\gamma} \sim 10^{-28} - 10^{-31}\,\mathrm{cm}^3\mathrm{s}^{-1}$ (both doublet and quartet) and $\sigma v_{\gamma Z} \sim 10^{-29} - 10^{-32}\,\mathrm{cm}^3\mathrm{s}^{-1}$ (doublet) and $10^{-27} - 10^{-30}\,\mathrm{cm}^3\mathrm{s}^{-1}$ (quartet).

Conclusion

- Sommerfeld enhanced cross sections increase with the size of the multiplet.
- For $SS \to WW$, H.E.S.S. has already achieved the sensitivity to probe almost the entire 1-30 TeV mass range, except for the dips, of the quartet for (almost) degenerate and maximum mass splitting cases.
- Future CTA improves the above exclusion limit by $O(10)$.
- For $SS \to \gamma\gamma$, again H.E.S.S. can probe 1-14 TeV mass range of the quartet in (almost) degenerate limit whereas for doublet, its 2-4 TeV, out of the considered 1-20 TeV mass range.
- Such large indirect signal implies that scalar DM of larger electroweak multiplet can't be the dominant DM component of the universe.
- Sommerfeld enhanced DM annihilation cross sections enable us to check the viability of DM models with large electroweak multiplets by probing high energy gamma rays with Cherenkov telescopes.

Thank you very much for your attention.

Backup Slides: The Potential

- The Lagrangian is

$$\mathcal{L} \supset -\frac{M_{F_i}}{2}\overline{F_i^c}P_R F_i + y_{i\alpha}\overline{F}_i.l_\alpha.\Delta + \text{h.c}$$

- The scalar potential is

$$V_0(H,\Delta) = -\mu^2 H^\dagger H + M_0^2\Delta^\dagger\Delta + \lambda_1(H^\dagger H)^2 + \lambda_2(\Delta^\dagger\Delta)^2 + \lambda_3|\Delta^\dagger T^a\Delta|^2$$
$$+ \alpha H^\dagger H\Delta^\dagger\Delta + \beta H^\dagger\tau^a H\Delta^\dagger T^a\Delta + \gamma\left[(H^T\epsilon\tau^a H)(\Delta^T C T^a\Delta)^\dagger + h.c\right]$$

-

$$m_S^2 = M_0^2 + \frac{1}{2}\left(\alpha + \frac{1}{4}\beta - \frac{2n+1}{2}\gamma\right)v_0^2$$
$$m_A^2 = M_0^2 + \frac{1}{2}\left(\alpha + \frac{1}{4}\beta + \frac{2n+1}{2}\gamma\right)v_0^2$$

Backup Slides: Mass eigenstates

The mixing matrix between components with charge $|Q|$ is,

$$M_Q^2 = \begin{pmatrix} m^2_{(m)} & \frac{\gamma v^2}{4}\sqrt{\left(\frac{n}{2}-m\right)\left(\frac{n}{2}+m+1\right)} \\ \frac{\gamma v^2}{4}\sqrt{\left(\frac{n}{2}-m\right)\left(\frac{n}{2}+m+1\right)} & m^2_{(-m-1)} \end{pmatrix}$$

where

$$m^2_{(m)} = M_0^2 + \frac{1}{2}\left(\alpha - \frac{1}{2}\beta\, m\right) v_0^2 .$$

And the mass eigenstates are,

$$\begin{aligned} \Delta_1^Q &= \cos\theta_Q\, \Delta'^{Q}_{(m)} + \sin\theta_Q\, \Delta'^{*Q}_{(-m-1)} \\ \Delta_2^Q &= -\sin\theta_Q\, \Delta'^{Q}_{(m)} + \cos\theta_Q\, \Delta'^{*Q}_{(-m-1)} \end{aligned}$$

where we have

$$\tan 2\theta_Q = \frac{2(M_Q^2)_{12}}{(M_Q^2)_{11} - (M_Q^2)_{22}}$$

Coupled Channel Schroedinger equation

- The coupled-channel Schroedinger equation is

$$\frac{d^2\Psi_{jj',ii'}}{dr^2} + \left[\left((m_S v)^2 - \frac{l(l+1)}{r^2}\right)\delta_{jj',kk'} - m_S V_{jj',kk'}(r)\right]\Psi_{kk',ii'} = 0$$

- For s-wave annihilation ($l = 0$),

$$\frac{d^2\Psi_{jj',ii'}}{dr^2} + \left[k^2_{jj'}\delta_{jj',kk'} + m_S\left(\frac{f_{jj',kk'}\alpha_a e^{-n_a m_W r}}{r} + \frac{Q^2_{kk'}\alpha_{\rm em}}{r}\delta_{jj',kk'}\right)\right]\Psi_{kk',ii'} = 0$$

Here, $k^2_{jj'} = m_S(m_S v^2 - d_{jj'})$, $d_{jj'} = m_j + m_{j'} - 2m_S$. $Q_{kk'}$ is the electric charge. Also, $\alpha_W = \alpha$ and $n_W = 1$ for W boson exchange and $\alpha_Z = \alpha/\cos^2\theta_W$ and $n_Z = 1/\cos\theta_W$ for Z boson exchange.

- By using dimensionless variables defined as $x = \alpha m_S r$, $\epsilon_\phi = (m_W/m_S)/\alpha$, $\epsilon_v = (v/c)/\alpha$ and $\epsilon_{d_{ii'}} = \sqrt{d_{ii'}/m_S}/\alpha$, the coupled radial Schrodinger equations is

$$\frac{d^2\Psi_{jj',ii'}}{dx^2} + \left[\hat{k}^2_{jj'}\delta_{jj',kk'} + \frac{f_{jj',kk'}n_a^2 e^{-n_a\epsilon_\phi x}}{x} + \frac{Q^2_{kk'}\sin^2\theta_W}{x}\delta_{jj',kk'}\right]\Psi_{kk',ii'} = 0$$

where the dimensionless momentum, $\hat{k}^2_{jj'} = \epsilon_v^2 - \epsilon^2_{d_{jj'}}$.

- $\Psi_{jj',ii'} \sim T_{jj',ii'}e^{i\hat{k}_{jj'}x}$ when $x \to \infty$

Backup Slides: DM Parameter Space

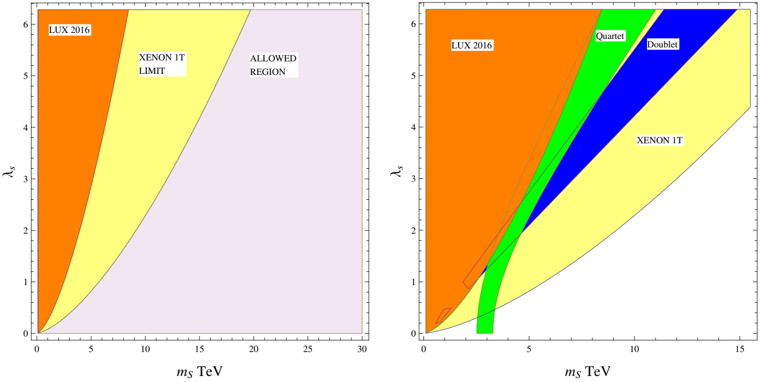


Figure : LUX(2016) exclusion limits and XENON 1T projected limits on $m_S - \lambda_S$ plane

$$\lambda_S = \alpha + \frac{1}{4}\beta - \frac{2n+1}{2}\gamma$$

Backup Slides: Non-thermal DM production

$$N_1 \to S\,\nu, \text{ and } F_1^0 \to S\nu,\ F_1^+ \to Sl^+$$

m_{F_1}	$T_{\rm dec}$	$\Gamma_{F_1}^{(\rm max)}$	Γ_{F_1}	T_D
1 TeV	31.25 GeV	10^{-12} GeV	10^{-16} GeV	17 GeV
40 TeV	1380 GeV	10^{-9} GeV	5×10^{-13} GeV	990 GeV

Table : Decoupling temperature for gauge interaction $T_{\rm dec}$, maximum decay width $\Gamma_{F_1}^{(\rm max)}$, decay width Γ_{F_1} and temperature T_D at decay for the respective masses m_{F_1} of fermion triplet