Heavy long-lived coannihilation partner from inelastic Dark Matter model and its signatures at the LHC

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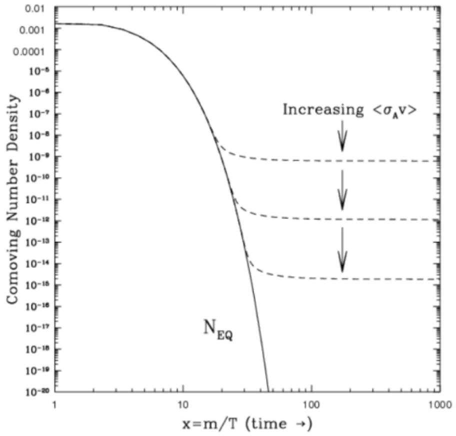
Coannihilation Dark Matter and LLPs

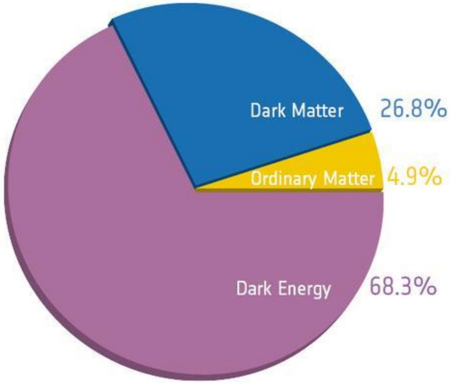
- Introduction
- Coannihilation inelastic DM Models
- Existing constraints from Cosmology and LHC
- LLPs phenomenology in collider
- Conclusion

Introduction

- The dark matter (DM) is a fundamental and unresolved problem in particle physics.
- The Weakly Interacting Massive Particles （WIMPs） can explain the dark matter relic density $\Omega h^2 = 0.1198 \pm 0.0026$ through its **thermal freeze-out** with a weak scale annihilation cross-section

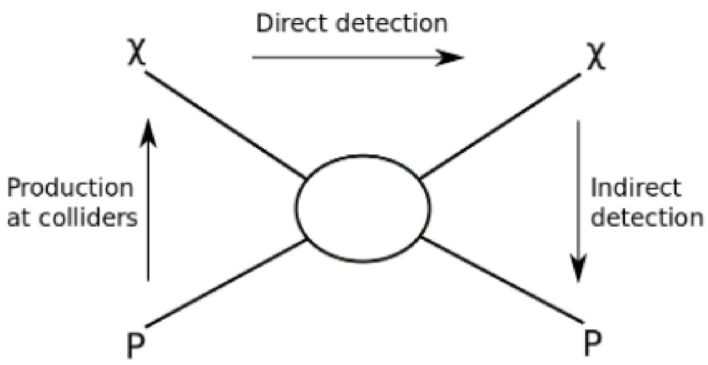
.Planck 2020 Astron.Astro.641(2020)

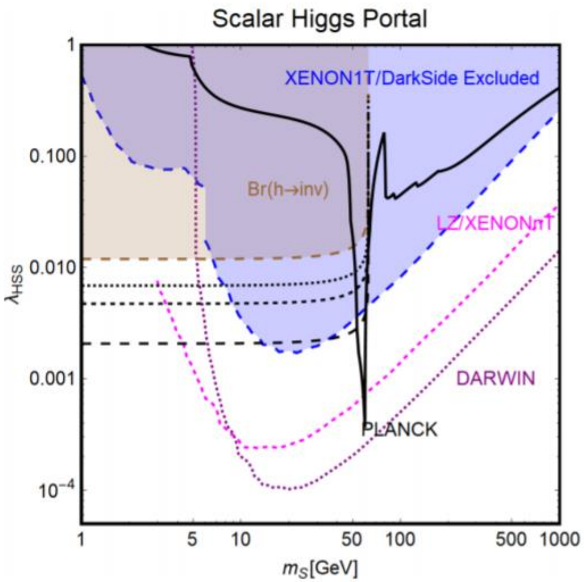




Introduction

- Dark matter **(in)direct detection** constrains many of WIMP models





G. Arcadi, et. al. Phys.Rept. 842 (2020) 1-180

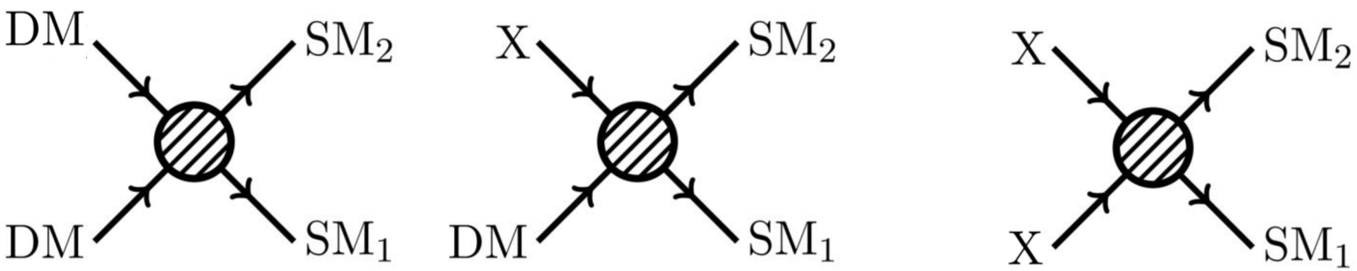
Introduction

- **Coannihilation** mechanism provides an alternative way to explain DM relic abundance through the annihilation with **slightly heavier particles**, denoted as coannihilation partner.
- The contribution from coannihilation are encoded in effective cross section:

$$\sigma_{eff} = \frac{g_{s_1}^2}{g_{eff}^2}(\sigma_{11} + 2\sigma_{12}\frac{g_{s_2}}{g_{s_1}}(1+\Delta)^{3/2}e^{-x_f\Delta} + \sigma_{22}\frac{g_{s_2}^2}{g_{s_1}^2}(1+\Delta)^3 e^{-2x_f\Delta})$$

Where $\Delta \equiv \frac{m_2 - m_1}{m_1}$

K. Griest and D. Seckel PRD 43 (1991)3191-3203



Introduction

- Elastic scatterings between DM and SM particles are negligible and **inelastic scatterings** are kinematic suppressed. Models are free from direct detection constraints.
- The decay widths of heavier states are suppressed by small mass splittings. They can be probed in collider as **LLPs**.
- **Previous studies:** coannihilation dominated by σ_{12}

  LLP search for light DM.

  E. Izaguirre et.al. PRD93.6(2016)063523
  A. Berlin F. Kling PRD99.1(2019)015021
- **This study :** σ_{22} is dominant

$$\sigma_{11} \approx 0, \quad \sigma_{12} \ll \sigma_{22}$$

DM mass >100GeV

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Coannihilation inelastic DM Models

- Consider Lagrangian with **complex scalar** $\hat{S} = (\hat{s}_1 + i\hat{s}_2)/\sqrt{2}$

$$\mathcal{L} \supset \left(\partial_\mu \hat{S}\right)^* \left(\partial^\mu \hat{S}\right) - m_S^2 \hat{S}^* \hat{S} - \delta\hat{m}_{ij}^2 \hat{s}_i \hat{s}_j - \hat{\lambda}_{ij} \hat{s}_i \hat{s}_j \left(H^\dagger H - \frac{v^2}{2}\right)$$

Where **U(1) violation** terms $\delta\hat{m}_{ij}^2$ and $\hat{\lambda}_{ij}$ are 2×2 **rank 1** matrices

and $\hat{\lambda}_{ij}$ is proportional to $\delta\hat{m}_{ij}^2$. After diagonalizing the mass terms:

$$\mathcal{L} \supset (\partial_\mu S)^\dagger (\partial^\mu S) - \frac{m_1^2}{2} s_1^2 - \frac{m_2^2}{2} s_2^2 - \lambda_{22} s_2^2 \left(H^\dagger H - \frac{v^2}{2}\right)$$

We have $\sigma_{11} = 0, \quad \sigma_{12} = 0$

Only s_2 couple with SM particles, s_1 can not be DM candidate

Coannihilation inelastic DM Models

- Scalar-vector model

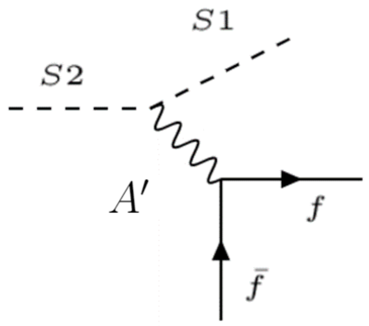
Gauging the U(1) Symmetry, introducing dark photon A', which have kinetic mixing with SM B field:

$$\mathcal{L} \supset (D_\mu S)^\dagger (D^\mu S) - \frac{m_1^2}{2} s_1^2 - \frac{m_2^2}{2} s_2^2 - \lambda_{22} s_2^2 \left(H^\dagger H - \frac{v^2}{2} \right) - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{\epsilon}{2 \cos\theta_W} F'^{\mu\nu} B_{\mu\nu} + \frac{m_{A'}^2}{2} A'^\mu A'_\mu.$$

Where $D_\mu S = \partial_\mu S + i g_D A'_\mu S$ introducing coupling between 2 scalars. Diagonalizing mass terms we have:

$$\mathcal{L}_{\rm int} = \tilde{Z}_\mu (g J_Z^\mu - g_D \frac{m_Z^2 \tan\theta_W}{m_Z^2 - m_{A'}^2} \epsilon J_D^\mu) + \tilde{A}'_\mu (g_D J_D^\mu + g \frac{m_{A'}^2 \tan\theta_W}{m_Z^2 - m_{A'}^2} \epsilon J_Z^\mu + e\epsilon J_{\rm em}^\mu) + \tilde{A}_\mu e J_{\rm em}^\mu.$$

s_2 decay mainly mediated by dark photon, its width is suppressed by dark photon mass small coupling and mass splitting.



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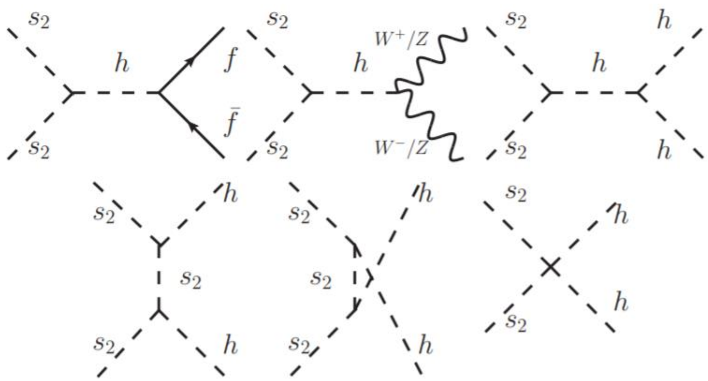
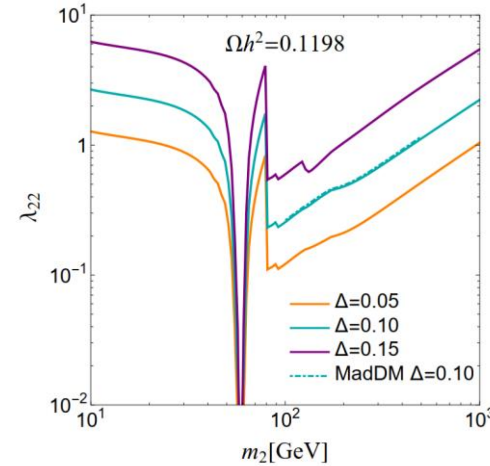
Existing constraints from Cosmology and LHC

- Dark Matter relic abundance



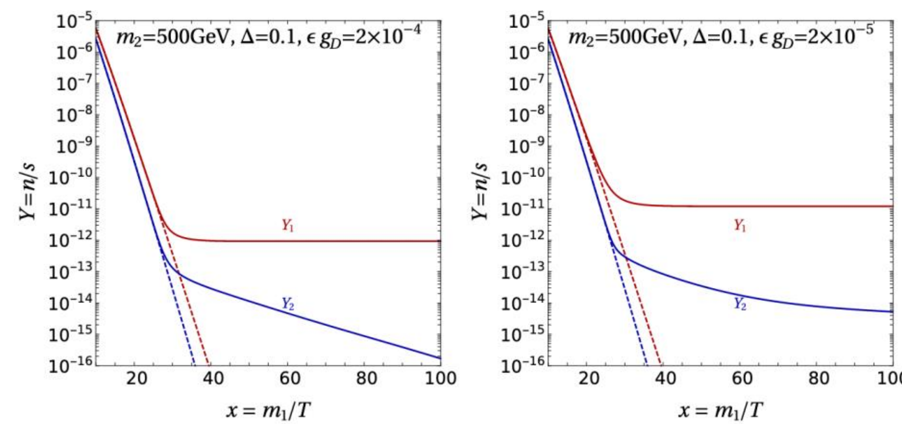


- Thermalization requirement

$$s_1 + f \leftrightarrow s_2 + f$$

$$\begin{cases} \frac{dY_1}{dx} = -\frac{\lambda_f}{x^2} Y_f (Y_1 - \frac{Y_1^{eq}}{Y_2^{eq}} Y_2) + \gamma x (Y_2 - \frac{Y_2^{eq}}{Y_1^{eq}} Y_1), \\ \frac{dY_2}{dx} = -\frac{\lambda_{22}}{x^2} (Y_2^2 - Y_2^{eq2}) + \frac{\lambda_f}{x^2} Y_f (Y_1 - \frac{Y_1^{eq}}{Y_2^{eq}} Y_2) - \gamma x (Y_2 - \frac{Y_2^{eq}}{Y_1^{eq}} Y_1) \end{cases}$$

$$\Gamma(T) = \sum_f n_f^{eq} \langle \sigma_f v \rangle \gtrsim H \quad \lambda = \frac{s(m_1)}{H(m_1)} \langle \sigma v \rangle, \; \gamma = \frac{\langle \Gamma_2 \rangle}{H(m_1)}$$



Existing constraints from Cosmology and LHC

- Direct detection:
  elastic scatterings : very small
  inelastic scatterings : suppressed by **non-relativistic** velocity.
  E. Izaguirre et.al. PRD93.6(2016)063523
  A. Berlin F. Kling PRD99.1(2019)015021
- Indirect detection:
  s_1 : tiny pair annihilation cross-section.
  s_2 : already decayed in early universe.
- E. Izaguirre et.al. PRD93.6(2016)063523
  LHC search: **MET+mono jet, dilepton resonance** search in LHC constrains some of parameter space.
- Electroweak precision measurement (EWPM) is not sensitive to parameter region in our model since A' is very heavy.

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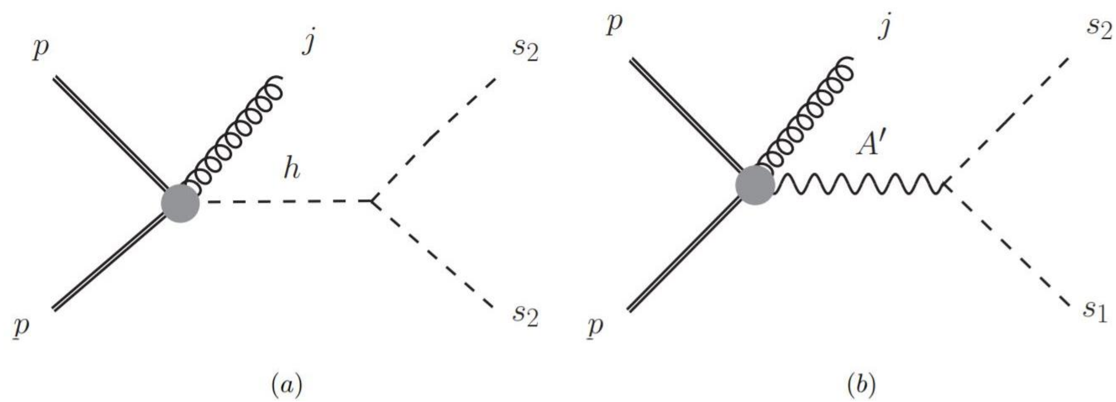
LLPs phenomenology at collider

- Producing and decaying of s_2 at LHC



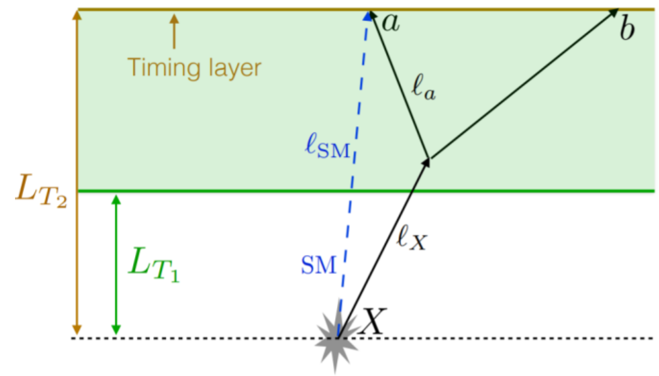
- The initial radiation jet can trigger the event or become time stamp in delay time strategy in LLP search.
- As long lived particle, s_2 will have displaced or delayed signatures in detector.

LLPs phenomenology at collider

- Time delayed signature at LHC

$$\Delta t = L_{s_2}/\beta_{s_2} + L_f/\beta_f - L_{\rm SM}/\beta_{\rm SM}$$

J.Liu Z. Liu L.T.Wang PRL 122.13(2019)



can identify LLP event at LHC and suppress background

- Scalar-vector search at HL-LHC ($\mathcal{L} = 3\ \rm ab^{-1}$)

$$pp \to j s_2 s_2\ (j s_2 s_1), \quad s_2 \to s_1 \ell^+ \ell^-$$

DMJ cut: $p_{T,j} > 120\rm GeV,\ p_{T,\mu} > 5GeV,\quad r_{s_2} < 30\ cm,\quad d_0^\mu > 1\ mm$

E. Izaguirre et.al. PRD93.6(2016)063523

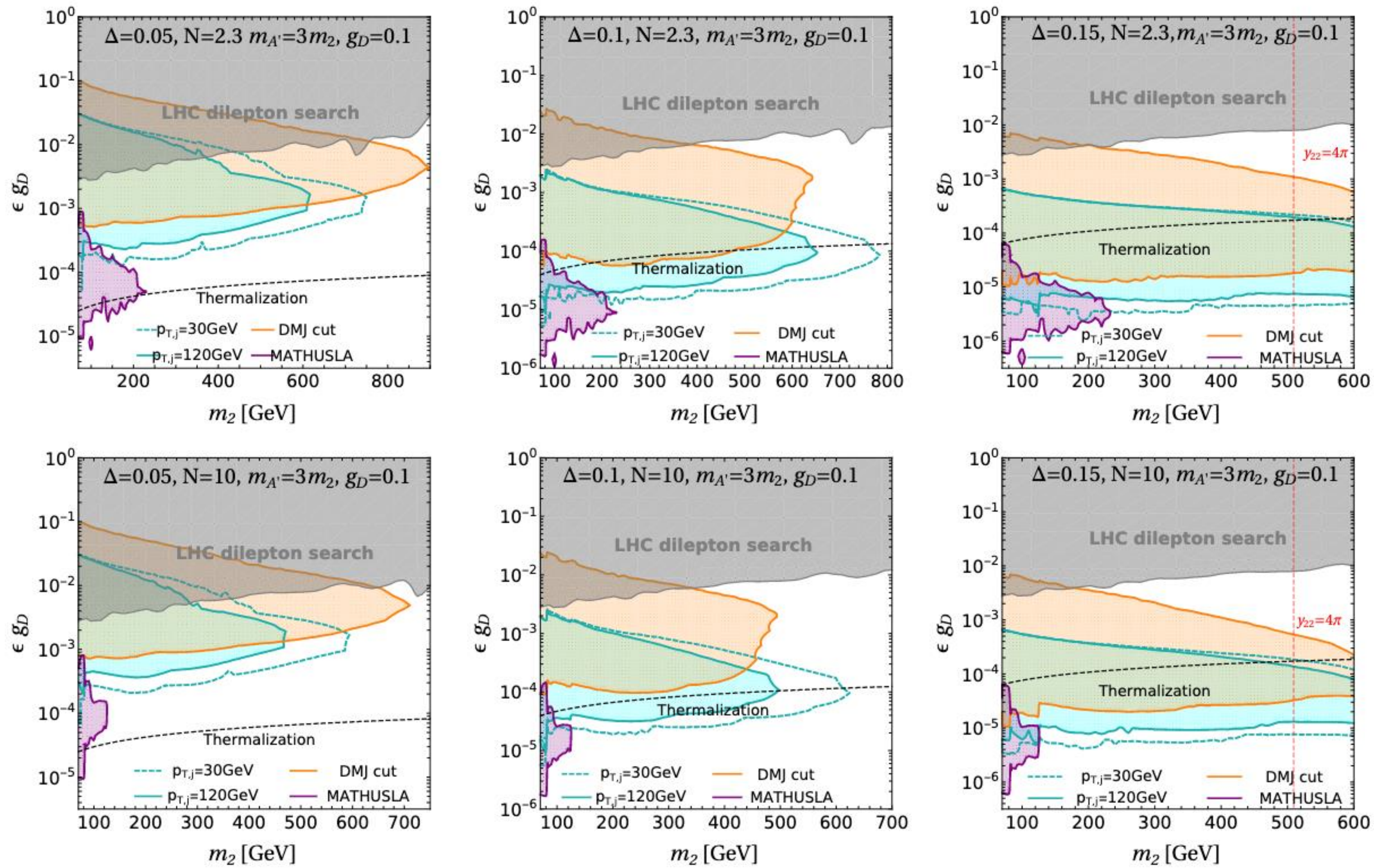
Delay time cut: $p_T^j > 120\ \rm GeV\ (30\ GeV),\quad p_T^\ell > 3\ GeV,\quad |\eta| < 2.4,$

$$\Delta t_\ell > 0.3\ \rm ns,\quad 5\ cm < r_{s_2} < 1.17\ m,\quad z_{s_2} < 3.04\ m,$$

J.Liu Z. Liu L.T.Wang PRL 122.13 (2019)
A. Berlin F. Kling PRD99.1(2019)015021

ATLAS PLB 796 (2019) 68-87

LLPs phenomenology at collider



The expected sensitivity at HL-LHC to the scalar-vector model in the ϵg_D, m_2 plane for $L = 3\ \mathrm{ab}^{-1}$ and $\sqrt{s} = 13\ \mathrm{TeV}$

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Conclusion

- We explore a coannihilation scenario that annihilation between coannihilation partner is the dominant contribution.
- We illustrate this mechanism with simplified scalar DM model.
- The heavier scalar can be LLP, and can be probed in HL-LHC.

Thanks

Backup

- Derivation of co-annihilation effective cross section

$$\frac{dn_i}{dt} = -3Hn_i - \sum_{j,X} [\langle \sigma_{ij} v \rangle (n_i n_j - n_i^{eq} n_j^{eq}) - (\langle \sigma'_{ij} v \rangle n_i n_X - \langle \sigma'_{ji} v \rangle n_j n_{X'}) - \Gamma_{ij}(n_i - n_i^{eq})] ,$$

$$\frac{dn}{dt} = -3Hn - \sum_{i,j=1}^{N} \langle \sigma_{ij} v \rangle (n_i n_j - n_i^{eq} n_j^{eq})$$

$$n_i n_j \sigma_{ij} \sim T^3 m_i^{3/2} m_j^{3/2} \sigma_{ij} \exp[-(m_i + m_j)/T] ,$$

while the rate for a reaction of type (6b) is

$$n_i n_X \sigma'_{ij} \sim T^{9/2} m_i^{3/2} \sigma'_{ij} \exp(-m_i/T) .$$

So the latter rates are larger by a factor of roughly

$$n_X/n_j \sim (T/m_j)^{3/2} \exp(m_j/T) \sim 10^9 ,$$

K. Griest and D. Seckel PRD 43 (1991)3191-3203

$$r_i \equiv n_i^{eq}/n^{eq} = \frac{g_i(1+\Delta_i)^{3/2}\exp(-x\Delta_i)}{g_{\rm eff}}$$

$$g_{\rm eff} = \sum_{i=1}^{N} g_i (1+\Delta_i)^{3/2} \exp(-x\Delta_i)$$

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2) ,$$

where

$$\sigma_{\rm eff} = \sum_{ij}^{N} \sigma_{ij} r_i r_j = \sum_{ij}^{N} \sigma_{ij} \frac{g_i g_j}{g_{\rm eff}^2} (1+\Delta_i)^{3/2} (1+\Delta_j)^{3/2} \times \exp[-x(\Delta_i + \Delta_j)] .$$

Backup

- Scalar-vector model details

realized in UV models with dark Higgs. For instance we consider dark Higgs Φ carrying a opposite charge comparing to S. Terms like $y\mathrm{Im}(S\Phi^*)^2$ can be added to the Lagrangian and generating mass splitting yv_Φ^2. The kinetic mixing between SM Higgs and dark Higgs generates appropriate terms like $\frac{\lambda_{22}S_2S_2}{2}(|H|^2-\frac{v^2}{2})$ after integrating out Φ field.

$$\begin{pmatrix} Z_\mu \\ A_\mu \\ A'_\mu \end{pmatrix} = \begin{pmatrix} 1 & 0 & \frac{m_{A'}^2 \tan\theta_W}{m_Z^2 - m_{A'}^2}\epsilon \\ 0 & 1 & \epsilon \\ \frac{m_Z^2 \tan\theta_W}{m_{A'}^2 - m_Z^2}\epsilon & 0 & 1 \end{pmatrix} \begin{pmatrix} \tilde{Z}_\mu \\ \tilde{A}_\mu \\ \tilde{A}'_\mu \end{pmatrix}$$

$$\frac{g_D^2}{2}(S_1^2+S_2^2)\left(\tilde{A}'_\mu + \epsilon\frac{m_Z^2 \tan\theta_W}{m_Z^2 - m_{A'}^2}\tilde{Z}_\mu\right)^2$$

Backup

- Co-annihilation calculation

$$\langle \sigma v \rangle_s = \langle \sigma v \rangle_{f\bar{f}} + \langle \sigma v \rangle_{WW} + \langle \sigma v \rangle_{ZZ} + \langle \sigma v \rangle_{hh},$$

$$\langle \sigma v \rangle_{f\bar{f}} = \frac{\lambda_{22}^2 m_f^2 (m_2^2 - m_f^2)^{3/2}}{4\pi m_2^3 (4m_2^2 - m_h^2)^2},$$

$$\langle \sigma v \rangle_{WW} = \frac{\lambda_{22}^2 (4m_2^2 - 4m_W^2 m_2^2 + 3m_W^4)\sqrt{m_2^2 - m_W^2}}{8\pi m_2^3 (4m_2^2 - m_h^2)^2},$$

$$\langle \sigma v \rangle_{ZZ} = \frac{\lambda_{22}^2 (4m_2^2 - 4m_Z^2 m_2^2 + 3m_Z^4)\sqrt{m_2^2 - m_Z^2}}{16\pi m_2^3 (4m_2^2 - m_h^2)^2},$$

$$\langle \sigma v \rangle_{hh} = \frac{\lambda_{22}^2 (\lambda_{22} v_h^2 (4m_2^2 - m_h^2) - 4m_2^4 + m_h^4)^2 \sqrt{m_2^2 - m_h^2}}{16\pi m_2^3 \left(8m_2^4 - 6m_2^2 m_h^2 + m_h^4\right)^2}.$$

Backup

- Decay width