Dark matter decays from a non-minimal coupling to gravity

(to appear soon)

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Outline

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Dark matter stability

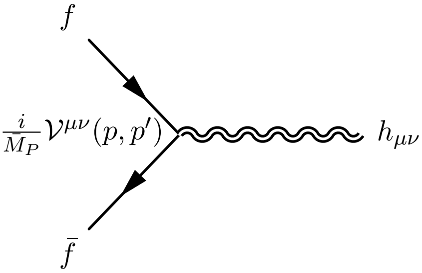
- Cosmology: dark matter particle required to be absolutely stable or have a very long lifetime
  $\Rightarrow$ Phase space suppression? Symmetry?
- Symmetry does not have to be exact
- Quantum gravity may break global symmetries
- Clearly, DM interacts gravitationally
  $\Rightarrow$ Decays from coupling to gravity?

Matter + gravity I: minimal coupling

- Framework: Standard Model + General Relativity

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(-\frac{\bar{M}_P^2}{2}R + \mathcal{L}_{SM}\right), \qquad \bar{M}_P = \sqrt{\frac{\hbar c}{8\pi G}}$$

- Equations of motion: SM + Einstein field equations
- SM Feynman rules + graviton exchange (Planck mass suppressed)



Matter + gravity II: non-minimal coupling

- Non-minimal coupling terms involving Ricci tensor/scalar allowed by SM symmetries, too
- Linear coupling of the DM field enables decay
- Lowest-dimensional operators coupling DM to curvature:

$$\mathcal{L}_\xi = -\xi M R \phi \qquad \text{(scalar DM)}$$

$$\mathcal{L}_\xi = -\frac{\xi}{M^2} R \left(\bar{L}_L \widetilde{H} \chi + \text{h.c.} \right) \qquad \text{(fermionic DM)}$$

- (Decay into gravitons?)

Outline

Non-minimally coupled DM: Lagrangian

- Jordan frame action:

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(-\frac{\bar{M}_P^2}{2}\Omega^2 R + \mathcal{L}_{SM} + \mathcal{L}_{DM}\right)$$

$$\Omega^2(\phi) = 1 + \frac{2\xi M}{\bar{M}_P^2}\phi$$

$$\Omega^2\left(\chi, \nu_L, h\right) = 1 + \frac{\sqrt{2}\xi}{M^2\bar{M}_P^2}(\bar{\nu}_L\chi + \bar{\chi}\nu_L)(v+h)$$

(Einstein-Hilbert + non-minimal coupling)

- DM field mixed into metric tensor
  $\Rightarrow$ Background metric? Graviton?

Weyl transformation

- Easier: perform transformation into Einstein frame

$$\widetilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}$$

  to ensure GR form of Einstein field equations

- Einstein frame action:

$$\mathcal{S} = \int d^4x \sqrt{-\widetilde{g}} \left(-\frac{\bar{M}_P^2}{2} \widetilde{R} + \widetilde{\mathcal{L}}_{matter} \right)$$

- Gravitational part minimal again
- Expand metric as "background + graviton" as usual, derive Feynman rules, compute decay rates

Einstein frame: matter action

- Einstein frame matter Lagrangian:

$$\widetilde{\mathcal{L}}_{matter} = \frac{1}{\Omega^4}\left(\mathcal{L}_{SM} + \mathcal{L}_{DM}\right) + \frac{3\bar{M}_P^2}{\Omega^2}(\widetilde{\nabla}_\mu \Omega)(\widetilde{\nabla}^\mu \Omega)$$

- Schematically:

$$\text{“}\left(\Omega^2 R + \mathcal{L}_{SM}\right) \xrightarrow{\text{Weyl trafo}} \left(\widetilde{R} + \mathcal{L}_{SM}/\Omega^4\right)\text{”}$$

- Direct DM decays into SM particles possible through $\mathcal{L}_{SM}/\Omega^4$ coupling introduced by Weyl transformation
- Example: $\phi \to ZZ$ from

$$\widetilde{\mathcal{L}}_{matter} \supset \left(-\frac{2\xi M}{\bar{M}_P^2}\phi\right)\frac{m_Z^2}{2}\eta^{\mu\nu} Z_\mu Z_\nu$$

DM decay channels

- Scalar singlet DM:
  - $\phi \to W^+W^-$
  - $\phi \to ZZ$
  - $\phi \to hh$
  - $(\phi \to t\bar{t})$
- Fermionic singlet DM:
  - $\chi \to W^+W^-\nu$
  - $\chi \to ZZ\nu$
  - $\chi \to hh\nu$
  - $(\chi \to t\bar{t}\nu)$
- No tree-level coupling to photons/gluons
- Decay into fermions (m_f^2/m_{DM}^2)-suppressed

Inert doublet model: Lagrangian

- Introduce second scalar $SU(2)$ doublet η

$$\mathcal{L}_\eta = g^{\mu\nu}(D_\mu\eta)^\dagger(D_\nu\eta) - V_{\mathbb{Z}_2}(\eta, H), \quad \eta = \left(\eta^+, \frac{1}{\sqrt{2}}(\eta^0 + iA^0)\right)$$

- Assume stability-ensuring $\mathbb{Z}_2$ to only hold in flat space
- Lowest-dimensional possible coupling:

$$\mathcal{L}_\xi = -\xi R \left(H^\dagger\eta + \text{h.c.}\right)$$

(Higher-dimensional operators suppressed by some mass scale M_*)

Inert doublet model: decay channels

- Two-body decays as for the scalar singlet, with $M = v$
- Three-body decays with additional Higgs, dominant for DM masses $\gtrsim 10$ TeV
  - $\eta^0 \to W^+ W^- h$
  - $\eta^0 \to ZZh$
  - $\eta^0 \to hhh$
  - $(\eta^0 \to t\bar{t}h)$

Outline

BRs: scalar singlet *(preliminary)*

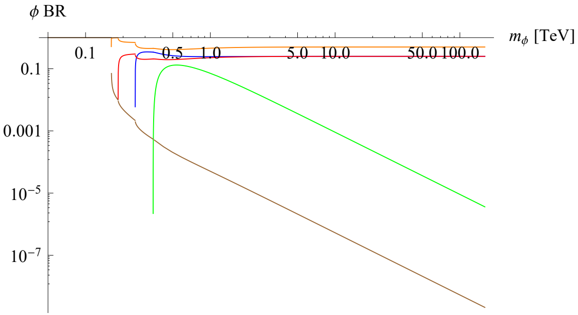


Figure: $\phi \to W^+W^-$ (orange), ZZ (red), hh (blue), $t\bar{t}$ (green), $b\bar{b}$ (brown)

- Total decay rate ($m_\phi \gtrsim 2.5$ TeV):

$$\Gamma_\phi \sim \frac{\xi^2}{8\pi}\left(\frac{M^2 m_\phi^3}{\bar{M}_P^4}\right)$$

BRs: fermionic singlet *(preliminary)*

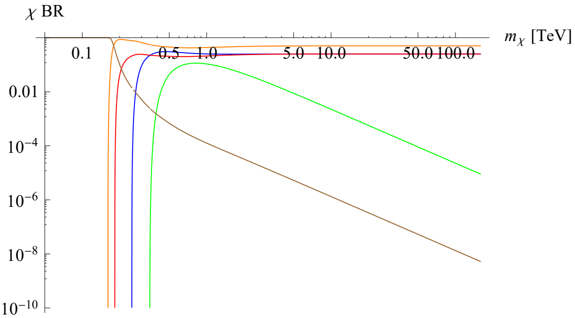


Figure: $\chi \to W^+W^-\nu$ (orange), $ZZ\nu$ (red), $hh\nu$ (blue), $t\bar{t}\nu$ (green), $b\bar{b}\nu$ (brown)

- Total decay rate ($m_\chi \gtrsim 0.5$ TeV):

$$\Gamma_\chi \sim \frac{\xi^2}{15360\pi^3}\left(\frac{v^2 m_\chi^7}{M^4 \bar{M}_P^4}\right)$$

Inert doublet model: decay rate

- Two regimes (2-/3-body decays dominant)
- Total decay rate:

$$\Gamma_{\eta^0} \sim \begin{cases} \dfrac{\xi^2}{8\pi}\left(\dfrac{v^2 m_{\eta^0}^3}{\bar{M}_P^4}\right) & \text{for } m_{\eta^0} \lesssim 5 \text{ TeV} \\ \dfrac{5\xi^2}{6144\pi^3}\left(\dfrac{m_{\eta^0}^5}{\bar{M}_P^4}\right) & \text{for } m_{\eta^0} \gtrsim 20 \text{ TeV} \end{cases}$$

Lifetimes *(preliminary)*

$$\tau_\phi \sim 10^5 \text{ s} \left(\frac{\xi M}{\bar{M}_P}\right)^{-2} \left(\frac{m_\phi}{1 \text{ TeV}}\right)^{-3} \qquad \text{(scalar singlet)}$$

$$\tau_\chi \sim 10^{19} \text{ s} \left(\frac{\xi \bar{M}_P^2}{M^2}\right)^{-2} \left(\frac{m_\chi}{10^{15} \text{ GeV}}\right)^{-7} \qquad \text{(fermionic singlet)}$$

$$\tau_{\eta^0} \sim \begin{cases} 10^{37} \text{ s } \xi^{-2} \left(\frac{m_{\eta^0}}{1 \text{ TeV}}\right)^{-3} & \text{for } m_{\eta^0} \lesssim 5 \text{ TeV} \\ 10^{29} \text{ s } \xi^{-2} \left(\frac{m_{\eta^0}}{100 \text{ TeV}}\right)^{-5} & \text{for } m_{\eta^0} \gtrsim 20 \text{ TeV} \end{cases}$$

(scalar doublet)

Stability considerations *(preliminary)*

- Compare lifetimes to $\tau_{\text{universe}} \sim 4 \times 10^{17}$ s

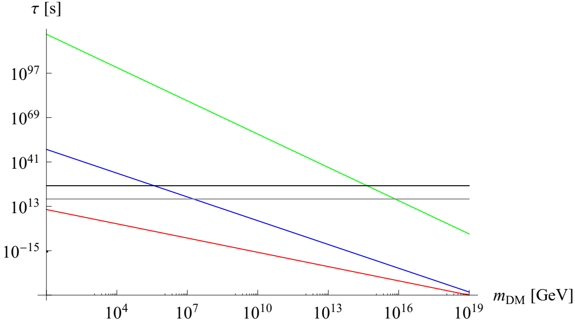


Figure: ϕ, χ, η^0 lifetimes for $\xi = 1$, $M = \bar{M}_P$; τ_{universe}, $\tau_{\text{DM}}^{(\nu)}$

- Limits on τ_{DM} from CR data?
  (unusual signatures: $\eta^0 \to hhh$, $\chi \to W^+W^-\nu$, ...)
- $\tau \sim 10^{26}$ s from neutrino fluxes (typically)

Outline

Summary

- Non-minimal coupling to curvature linear in DM field allowed by SM symmetries
- Vertices involving all massive Standard Model particles arise
- BRs calculable, decay into electroweak gauge bosons dominant
- Scalars less protected from decay than fermions
- In principle: limits on coupling obtainable from CR fluxes

Backup slides

- Einstein field equations (Jordan frame):

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \kappa^2 \left(\frac{1}{f} T_{\mu\nu} - \frac{1}{\kappa^2 f} \left(g_{\mu\nu} \nabla^2 f - \nabla_\mu \nabla_\nu f \right) \right)$$

- Energy-momentum tensor:

$$T_{\mu\nu} = \frac{2}{\sqrt{-g}} \frac{\partial(\sqrt{-g}\mathcal{L})}{\partial g^{\mu\nu}}$$