Dark matter decays from non-minimal coupling to gravity

(to appear soon)

O. Catà[1] A. Ibarra[2] S. Ingenhütt[2]

[1]Ludwig-Maximilians-Universität München

[2]Technische Universität München

IMPRS EPP Workshop, October 26, 2015

Outline

1. Motivation
2. Scenarios
3. Results
4. Summary

Outline

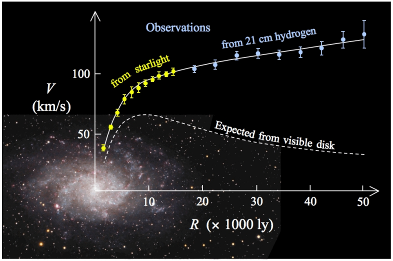
1 Motivation

2 Scenarios

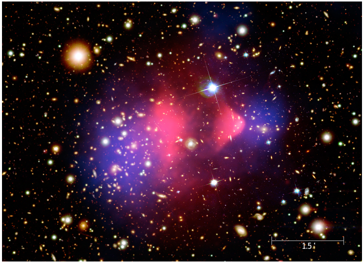
3 Results

4 Summary

Evidence for dark matter



(a) M33 rotation curve



(b) Bullet cluster

- Cosmology: ample evidence for a non-luminous matter component in the universe
- ΛCDM model: dark matter particle required to be absolutely stable or have a very long lifetime $> \tau_{\text{universe}}$

Dark matter stability

- Light dark matter: phase space suppression

- In principle: DM mass $\lesssim \Lambda_{\mathrm{GUT}} \approx 10^{16}$ GeV
- Heavy dark matter: symmetry (global/local) to ensure stability
- Global symmetries might not be exact in curved spacetime
- Clearly, DM couples gravitationally

$\Rightarrow$ **DM decays from non-minimal coupling to gravity?**

Matter + gravity I: minimal coupling

- Framework: Standard Model + general relativity

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(-\frac{\overline{M}_P^2}{2}R + \mathcal{L}_{\text{SM}}\right), \quad \overline{M}_P = \kappa^{-1} = \sqrt{\frac{\hbar c}{8\pi G}}$$

- Equations of motion: SM + Einstein field equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \kappa^2 T_{\mu\nu}$$

- Vacuum: $\kappa^4 T_{\mu\nu} \ll 1$

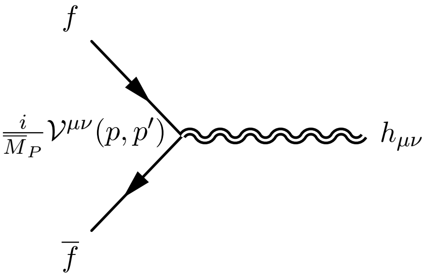
$\Rightarrow$ Expand metric around Minkowski background

Matter + gravity I: minimal coupling

- "Minkowski background + graviton field"

$$g_{\mu\nu} = \eta_{\mu\nu} + 2\kappa h_{\mu\nu}, \qquad \kappa h_{\mu\nu} \ll 1$$

- Minimal coupling ⇒ SM Feynman rules + graviton exchange (Planck mass suppressed)



Matter + gravity II: non-minimal coupling

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

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

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

- Reduces to stable DM in the flat-space limit $(R \to 0)$
- (Decay into gravitons?)

Outline

1 Motivation

2 Scenarios

3 Results

4 Summary

Non-minimally coupled DM: Lagrangian

- Jordan frame action:

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

$$\Omega^2(\phi) = 1 + 2\kappa^2\xi M\phi \qquad (\phi)$$

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

(Einstein-Hilbert + non-minimal coupling)

Non-minimally coupled DM: metric tensor

- Find background metric in Jordan frame:
  solve Einstein equations

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

  $\Rightarrow$ Vacuum limit?

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

Weyl transformation

- Easier: perform transformation into Einstein frame to decouple DM field

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

- Einstein frame action:

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

$\Rightarrow$ Gravitational part canonical

- Expand metric as usual, derive Feynman rules, compute decay rates

Einstein frame: matter action

- Tradeoff: non-trivial coupling to SM field content

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

- Schematically:

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

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

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

Inert doublet model: Lagrangian

- Add second scalar $SU(2)$ doublet η to the SM

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

- $\mathbb{Z}_2$ ensures lightest component of η is absolutely stable in flat spacetime
- Particularly η^0 and A^0 viable DM candidates

$$\mathcal{L}_\xi = -\xi R\left(H^\dagger\eta + \text{h.c.}\right)$$
$$\Omega^2(\eta, h) = 1 + 2\kappa^2\xi(v+h)\eta^0$$

Outline

1 Motivation

2 Scenarios

3 Results

4 Summary

Scalar singlet DM ϕ

- Two-body final states: only contribute for $300\text{ GeV} \lesssim m_\phi \lesssim 1\text{ TeV}$

$$\phi \to hh,\ W^+W^-,\ ZZ \qquad \sim m_\phi^3$$
$$\phi \to f\bar{f} \qquad \sim m_f^2 m_\phi$$

- Three-body decays: dominate for $m_\phi \lesssim 50$ TeV

$$\phi \to W^+W^-h,\ ZZh,\ f\bar{f}W^\pm,\ f\bar{f}Z \qquad \sim \frac{m_\phi^5}{v^2}$$
$$\phi \to f\bar{f}h \qquad \sim \frac{m_f^2 m_\phi^3}{v^2}$$
$$\phi \to f\bar{f}\gamma,\ q\bar{q}g \qquad \sim m_\phi^3$$
$$\phi \to hhh \qquad \sim m_h^2 m_\phi$$

Scalar singlet DM ϕ

- Four-body final states: dominate above $m_\phi \gtrsim 50$ TeV

$$\phi \to W^+W^-hh,\ ZZhh \qquad \sim \frac{m_\phi^7}{v^4}$$

$$\phi \to hhhh \qquad \sim \frac{m_h^4 m_\phi^3}{v^4}$$

- Coupling function: $1 + 2\kappa^2 \xi M \phi$

  $\Rightarrow$ Generically: SM vertex + DM scalar

- All rates $\sim \frac{\xi^2 M^2}{\overline{M}_P^4}$

Scalar (inert) doublet DM η^0

- Similar to scalar singlet, $\xi M \to \xi(v+h)$
- Two-body decays:
  $\eta^0 \to hh,\ W^+W^-,\ ZZ,\ f\overline{f}$
- Three-body:
  $\eta^0 \to hhh,\ W^+W^-h,\ ZZh,\ f\overline{f}h,\ f\overline{f}V$
- Four-body:
  $\eta^0 \to hhhh,\ W^+W^-hh,\ ZZhh,\ f\overline{f}hh,\ f\overline{f}Vh$
- Five-body:
  $\eta^0 \to hhhhh,\ W^+W^-hhh,\ ZZhhh$

Fermionic singlet DM χ

- Coupling function: $1 + \sqrt{2}\kappa^2(v+h)(\overline{\nu}\chi + \overline{\chi}\nu)/M^2$

  $\Rightarrow$ Schematically: SM vertices + $\big((v+h)\nu\chi\big)$

- $\chi \to hh\nu,\ W^+W^-\nu,\ ZZ\nu,\ f\overline{f}\nu, ...$
- "Scalar doublet + neutrino"

Stability considerations

- BRs fully calculable, given by SM Lagrangian
- Multi-body final states dominate once kinematically accessible

- Constraints on τ_{DM}:
  - $\tau_{\mathrm{DM}} \gtrsim \tau_{\mathrm{universe}} \sim 4 \times 10^{17}$ s
  - $\tau_{\mathrm{DM}} \gtrsim 10^{27}$ s for 200 MeV $< m_{\mathrm{DM}} <$ 30 TeV from γ-ray flux (Fermi-LAT, H.E.S.S.)
  - $\tau_{\mathrm{DM}} \gtrsim 10^{25}$ s for 1 TeV $< m_{\mathrm{DM}} < 10^{15}$ GeV from ν flux (AMANDA, IceCube, ANITA)

Outline

1 Motivation

2 Scenarios

3 Results

4 Summary

Summary

- We consider scenarios where DM stabilized by a global symmetry in flat space becomes unstable in curved spacetime
- Non-minimal coupling to curvature linear in DM field allowed by SM symmetries
- Vertices involving all Standard Model particles arise after Weyl transformation
- **BRs fixed** by SM structure, only two parameters
- Limits on couplings obtainable from CR fluxes