Probing freeze-in scalar dark matter through decay

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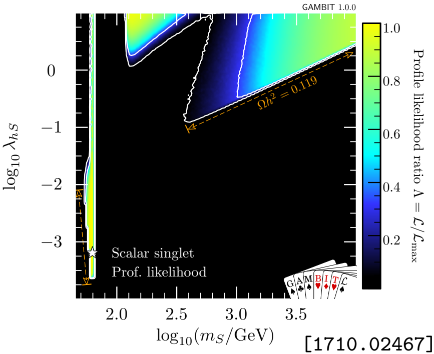
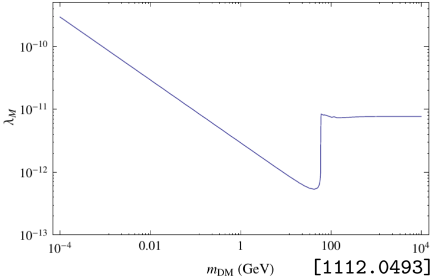
$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 - \frac{1}{4!}\lambda_\phi \phi^4 - \frac{1}{2}\lambda_{\phi h}\left(H^\dagger H\right)\phi\phi$$

WIMP DM



[1710.02467]

FIMP DM

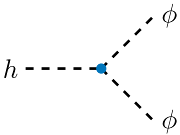


[1112.0493]

Freeze-in production

Relic density from

$$\dot{n}_\phi + 3Hn_\phi = g_h \int \frac{d^3 p_h}{(2\pi)^3} \frac{f_h \Gamma_{h\to\phi X}}{\gamma_h} + 2 \to 2 \text{ processes}$$



$$\Rightarrow \quad \Gamma_{h\to\phi\phi} = \frac{\lambda_{\phi h}^2 v^2}{16\pi m_h}\sqrt{1-\frac{4m^2}{m_h^2}},$$

correct relic density for

$$\lambda_{\phi h} = 9\cdot 10^{-12}\left(\frac{m}{\mathrm{GeV}}\sqrt{1-\frac{4m^2}{m_h^2}}\right)^{-1/2}$$

(assuming initial abundance negligible)

$\Rightarrow$ *how can we probe this coupling?*

keV decaying FIMP

- Feeble coupling g to heavy bath particle Σ
- Production requires

$$\Gamma_{\text{production}} \sim \frac{g^2}{16\pi} m_\Sigma \sim 10^{-25} m \left(\frac{m_\Sigma}{m}\right)^2$$

- Decay constraints typically

$$\Gamma_{\text{decay}} \sim \frac{g^2}{16\pi}\frac{m^5}{m_\Sigma^4} < 10^{-25} s^{-1} \sim 10^{-50}\,\text{GeV}$$

$$\Rightarrow m \lesssim 10^{-6}(m_\Sigma^3\,\text{GeV})^{1/4}$$

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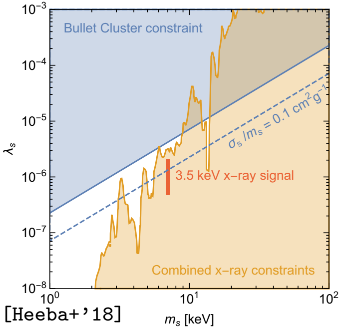
→ *Felix Kahlhoefer's talk Thursday*



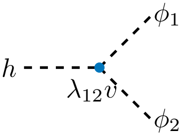
[Heeba+'18]

$\Rightarrow$ *For γ ray signals at higher energies from FIMP dark matter, need additional suppression of DM-decay.*

Multicomponent FIMP dark matter decay

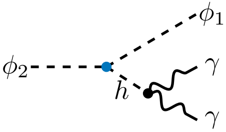
Two scalar singlets $\phi_{1,2}$, odd under a stabilising $\mathbb{Z}_2$ symmetry:

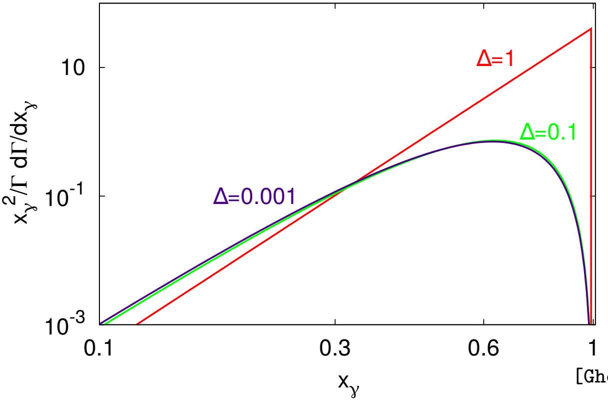
$$\mathcal{L}_{\text{scalar}} = \frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i - \frac{1}{2}m_{ij}\phi_i\phi_j - \frac{1}{4}\lambda_{ijkl}\phi_i\phi_j\phi_k\phi_l - \frac{1}{2}\lambda'_{ij}\left(H^\dagger H\right)\phi_i\phi_j$$



$$\lambda_{12\,\text{DM}} \simeq 1.2\cdot 10^{-11}\left(\frac{m_1+m_2}{\text{GeV}}\right)^{-1/2}\sqrt{\frac{\Omega_{\lambda_{12}}}{\Omega_{\text{DM}}}}$$

Decay induced by λ_{12}:



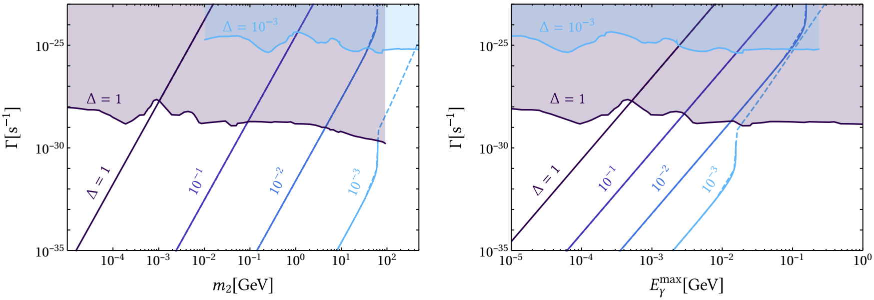


[Ghosh+'in prep.]

$$\Gamma_{\phi_2\to\phi_1\gamma\gamma} = \frac{1}{26880\pi^3}\left(\frac{\lambda_{12}c_{\gamma\gamma}}{m_h^2}\right)^2 m_2^5\Delta^7\,{}_2F_1\left(3,4,8;\Delta\right),$$

with $c_{\gamma\gamma} = -2.03\cdot 10^{-3}$ and ${}_2F_1$ a hypergeometric function and mass splitting $\Delta = 1 - m_1^2/m_2^2$. [Ghosh,Ibarra,Mondal,Mukhopadhyaya'in prep.]

Maximal attainable (ie. $\lambda_{11,22} = 0$) effective decay rate $\Gamma_{\text{eff}} = \Gamma_{\phi_2 \to \phi_1 \gamma\gamma} \cdot \Omega_2/\Omega_{\text{DM}}$:



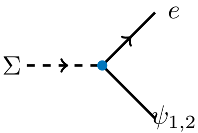
$\Rightarrow$ *multicomponent real scalar FIMP can be probed by MeV γ-rays*

Leptophilic fermion model

$$\mathcal{L} \supset (\mathcal{D}_\mu \Sigma)^\dagger (\mathcal{D}^\mu \Sigma) + m_\Sigma \Sigma^\dagger \Sigma + \frac{1}{2}\overline{\psi_i} i \partial\!\!\!/ \psi_i - \frac{1}{2} m_i \overline{\psi_i^c} \psi_i + g_{ei} \bar{l}_e P_L \psi_i \Sigma + \text{h.c.}$$

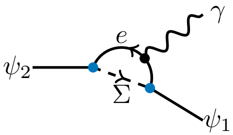
single-ψ $\rightarrow$ Laura Lopez Honorez' talk

- Freeze-in production, dominantly through Σ-decays *



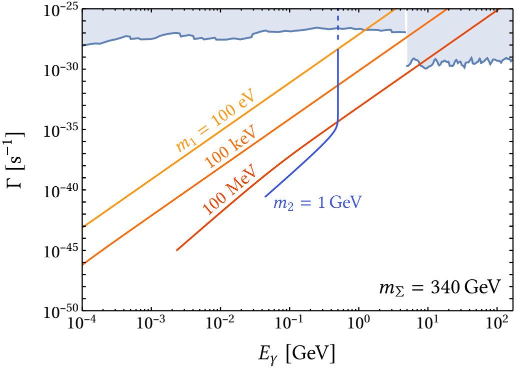
$$g_{ei} \sim 4 \cdot 10^{-12} \sqrt{\frac{m_\Sigma}{m_2} \frac{\Omega_{\text{FIMP}i}}{\Omega_{\text{DM}}}}$$

- Gamma ray lines from dark matter decay

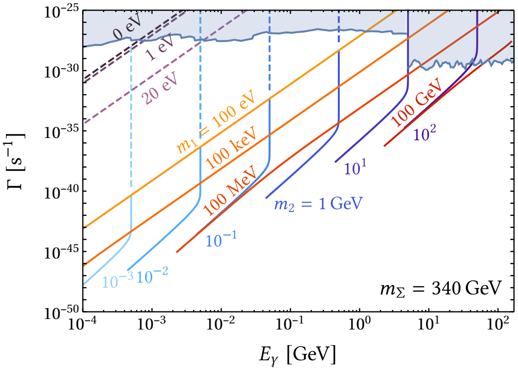


$$\Gamma_{\psi_2 \to \psi_1 \gamma} = \frac{e^2 (g_{e1} g_{e2})^2}{2^9 \pi^5} \frac{m_2^5}{m_\Sigma^4} \left(1 - \frac{m_1^2}{m_2^2}\right)^5$$

*$2 \rightarrow 2$ production relevant, dominates for $m_2 \sim m_\Sigma$. [Garny,Heisig'18],[Junius+'19]



- Gamma ray line limits [Essig+'13],[Fermi-LAT'13]
- $m_\Sigma > 339\,\mathrm{GeV}$ charged track search [CMS'13]
- Fraction of non-cold dark matter and dark radiation [Diamanti+'17] [Kamada+'19]



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Conclusions

- Multicomponent freeze-in dark matter can be probed by DM-decay
- Portal coupling responsible for abundance controls gamma ray signals
- Real scalar singlet
  - (softened) sawtooth-like γ-ray spectral feature in the MeV range from decay via off-shell Higgs
- Leptophilic fermion
  - γ-ray lines in MeV to TeV range