Self-interacting dark matter and cosmology of a light scalar mediator

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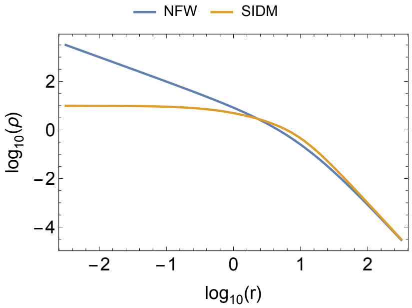
Introduction

- Motivation: Small-scale structure problems (core-cusp etc.).



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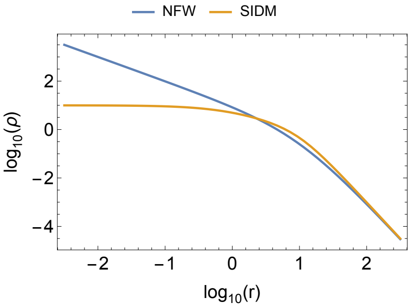

- Self-interacting dark matter with $\sigma/m \sim 0.1 - 1\mathrm{cm}^2/\mathrm{g}$ can solve these problems.
- Model: Fermionic dark matter ψ, self-interactions mediated by a light scalar S.

Model

- Extend the SM scalar sector with a real singlet s,

$$\mathcal{L} \ni \mu_1 s\phi^2 + \lambda_p s^2\phi^2.$$

- The mass eigenstates are

$$H = h\cos\beta + s\sin\beta, \quad S = -h\sin\beta + s\cos\beta,$$

- $m_H = 126\,\mathrm{GeV}$.

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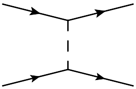
- $m_H = 126\,\mathrm{GeV}$.
- The dark matter candidate is a SM singlet fermion ψ:

$$\mathcal{L}_{\mathrm{DM}} = \bar{\psi}(\mathrm{i}\partial\!\!\!/ - m_\psi)\psi + s\bar{\psi}\,(g_s + i\gamma_5 g_p)\,\psi.$$

Self-interaction

Scattering from a Yukawa potential

$$V(r) = -\frac{\cos^2\beta\, g_s^2}{4\pi r} e^{-m_S r}.$$



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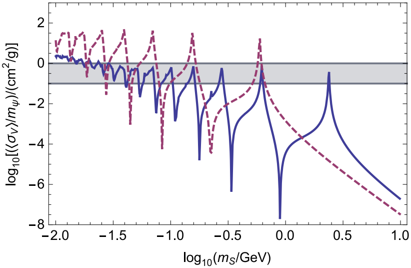

Figure : Solid line: $m_\psi = 400\,\mathrm{GeV}$, dashed line: $m_\psi = 100\,\mathrm{GeV}$.

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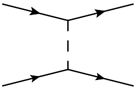

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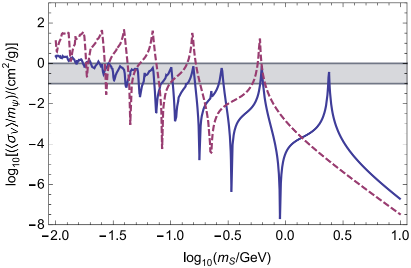
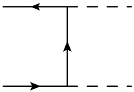


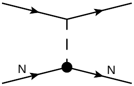
Figure : Solid line: $m_\psi = 400\,\mathrm{GeV}$, dashed line: $m_\psi = 100\,\mathrm{GeV}$.

$\Longrightarrow$ S has to be light, $m_S \lesssim 1\,\mathrm{GeV}$.

DM freeze-out and constraints



freeze-out



direct detection

$$\sigma_{\rm SI} \sim \frac{g_s^2 \sin^2\beta \cos^2\beta}{m_S^4}.$$

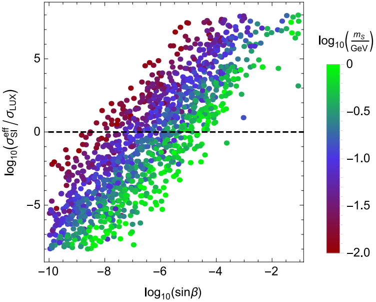


Figure : $\Omega h^2/0.12 > 0.8.$

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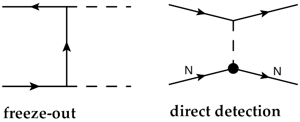

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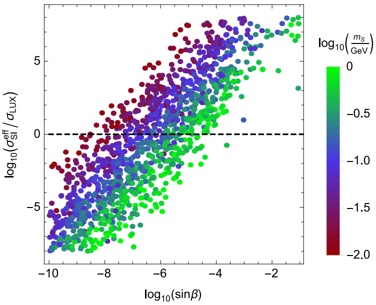
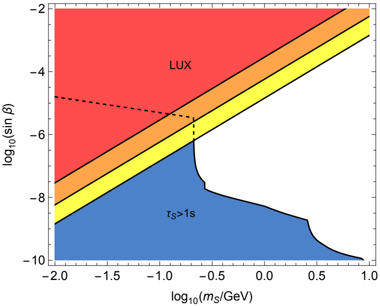


Figure : $\Omega h^2/0.12 > 0.8$.

$\implies$ $\sin\beta$ has to be small, $\sin\beta \lesssim 10^{-5}$.

BBN

$m_S \lesssim 1\,\mathrm{GeV}$ and $\sin\beta \lesssim 10^{-5} \implies$ lifetime of S is long. Succesful BBN requires $\tau_S < 1\mathrm{s}$.



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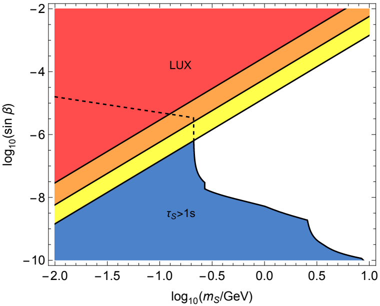
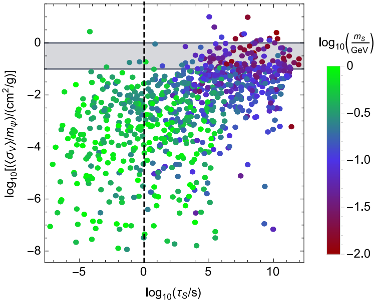




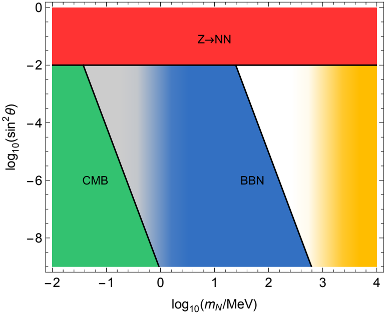
Conclusions

- The model can saturate the observed DM relic density.
- For the self-interactions to be sufficiently strong, the scalar mediator has to be light.
- Light long-lived particle causes problems in the early universe.
- These problems can be alleviated with a sterile neutrino N, but the BBN gives stringent constraints on the mass and the mixing of N.

Extension

Introduce a light sterile neutrino N which couples to S, $\mathcal{L}_{SNN} = y_N S N \bar{N}$, and mixes with the SM neutrinos mixing angle $\sin\theta$.

- lifetime of S is less than 0.1sec if $y_N \gtrsim 2 \times 10^{-11}(\text{GeV}/m_N)^{1/2}$
- also τ_N less than 0.1sec $\implies$ $m_N(\sin\theta)^{2/5} > 10\text{MeV}$



- If N is light and decouples before QCD phase transition, it's effect on BBN may be insignificant.