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

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Introduction

- Motivation: Small-scale structure problems (missing satellite, core-cusp, too big to fail) and observations of galaxy clusters (Abell 3827, Abell 520).
- If interpreted as evidences of DM self-interactions these imply DM self-interaction strength $\sigma/m \sim 0.1 - 1\mathrm{cm}^2/\mathrm{g}$.
- Model: Fermionic dark matter ψ, self-interactions mediated by a scalar S.

Model

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

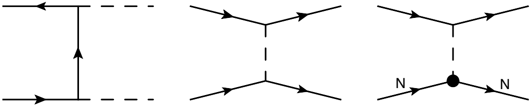
$$\mathcal{L} \ni \mu_1 s\phi^2 + \lambda_p s^2\phi^2.$$

- The mass eigenstates are

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

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

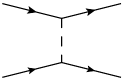
$$\mathcal{L}_{\rm DM} = \bar{\psi}(\mathrm{i}\partial\!\!\!/ - m_\psi)\psi + s\bar{\psi}\left(g_s + i\gamma_5 g_p\right)\psi.$$



freeze-out **self-interaction** **direct detection**

Self-interaction

Scattering from a Yukawa potential



self-interaction

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

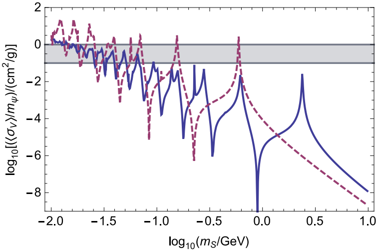
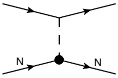


Figure : Solid line: $m_\psi = 400\,\mathrm{GeV}$, dashed line: $m_\psi = 100\,\mathrm{GeV}$.

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

DM freeze-out and constraints



direct detection

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

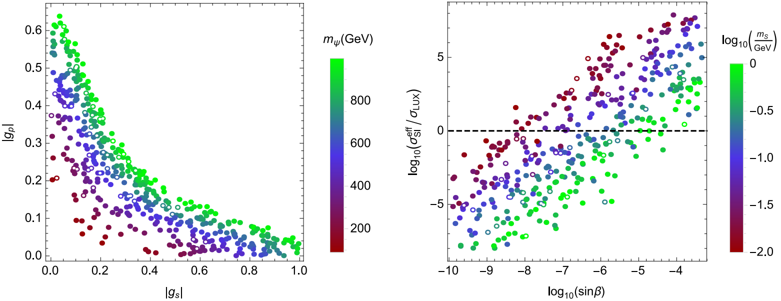
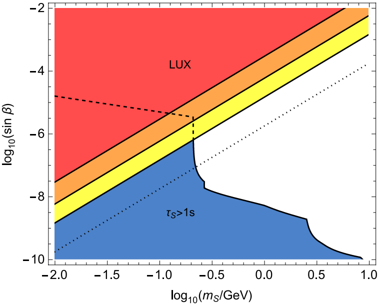


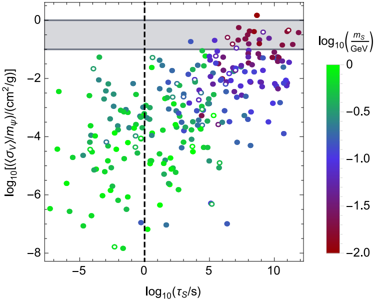
Figure : $\Omega_\psi h^2/0.12 > 0.8$

$\Longrightarrow$ $\sin\beta$ 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 $\tau_S < 1\mathrm{s}$.

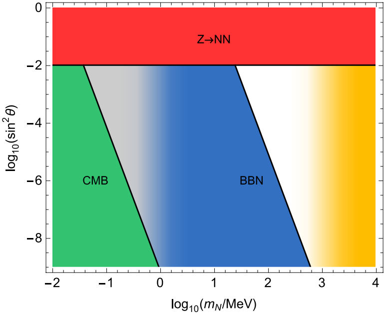




Extension

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 is insignificant.

Conclusions

- For the self-interactions to be sufficiently strong, the mediator S has to be light.
- Since S mediates also dark matter-nucleon scattering, its coupling to SM fermions has to be very small.
- Hence S is long-lived, but the BBN sets an upper limit on lifetime of S and excludes the region where $\sigma/m \sim 0.1 - 1\mathrm{cm}^2/\mathrm{g}$.
- The problems with the BBN can be alleviated with a sterile neutrino N, but the BBN gives stringent constraints on the mass and the mixing of N.