Observational Constraints on a Decoupled Hidden Sector

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Dark Side of the Universe: July 28th 2016

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Introduction

- Direct detection and collider experiments have seen no conclusive signals of DM.
- This implies that the interactions between DM and SM are very weak.
- Freeze-in mechanism allows for producing the observed DM abundance with tiny couplings.
- ☺ Freeze-in models easily avoid any existing bounds from DM searches.
- ☹ Freeze-in models are very difficult to experimentally test.

The freeze-in mechanism

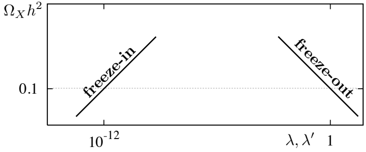
Freeze-out

Dark matter is *in equilibrium* with the SM plasma, until the DM DM → SM SM annihilation rate drops below the Hubble rate and the number density freezes.

Freeze-in

Dark matter is produced *out of equilibrium* from the SM plasma, via SM SM → DM DM scattering or SM → DM DM decays.

- In the freeze-out scenario, *stronger* SM-DM interactions imply more efficient DM annihilations, resulting in *smaller* relic abundance.
- In the freeze-in scenario, *stronger* SM-DM interactions imply more efficient DM production, resulting in *larger* relic abundance.



Self interacting dark matter

Apart from DM-SM scattering, which is suppressed in the freeze-in scenario, DM self scattering can have observable effects:

- Small scale structure: cusp-vs-core, missing satellites...
- Galaxy cluster mergers: effective drag force on DM halo, separation between the visible stars and the center of mass.
  (See e.g. R. Massey *et al.* arXiv:1504.03388 [astro-ph.CO], F. Kahlhoefer, K. Schmidt-Hoberg, J. Kummer and S. Sarkar arXiv:1504.06576 [astro-ph.CO])
- Upper bounds on self scattering cross section from e.g. observations of the Bullet cluster imply $\sigma/m \lesssim 1\ \mathrm{cm}^2/\mathrm{g}$.
- Observable effects in small scale structure and cluster mergers for self scattering cross section in the range $0.1\ \mathrm{cm}^2/\mathrm{g} \lesssim \sigma/m \lesssim$ a few cm^2/g.

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Isocurvature fluctuations

- Single field inflation and the following reheating from the decay of the scalar field sources adiabatic perturbations.
- Adiabatic perturbations: Overall density perturbations for all forms of matter and radiation (DM, baryons, photons, neutrinos...).
- Additional subdominant fields present during inflation can source isocurvature perturbations, i.e. independent density fluctuations between the various species of matter and radiation.
- In freeze-in models, DM never thermalizes with the SM plasma. $\rightarrow$ Isocurvature modes between DM and photons are not washed out.
- No isocurvature modes are observed in the CMB, and the amplitude of these fluctuations is constrained to be less than $\mathcal{O}(1\%)$ of the adiabatic fluctuations.

Light scalars in the early universe

- In the inflationary universe, a light scalar field undergoes random walk and typically obtains a non-zero field value over the observable universe:

$$\sqrt{\langle s^2 \rangle} \approx 0.36 H_* \lambda_s^{-\frac{1}{4}}, \quad V(s) = \frac{1}{4}\lambda_s s^4.$$

- The energy density contained in the resulting condensate constitutes an isocurvature component, uncorrelated with the density perturbations of the SM plasma.
- If the scalar is feebly coupled to the SM and does not enter thermal equilibrium with the SM plasma, the isocurvature fluctuation persists.
- This setup generically occurs in *e.g.* scalar portal models for freeze-in DM.

Isocurvature from the primordial condensate

- If the scalar condensate decays into DM, it will constitute an isocurvature component for a fraction of the total DM abundance:

$$\frac{\Omega_{\rm DM}^{s_0} h^2}{0.12} \approx 3.4 \times 10^{-4} \lambda_s^{-\frac{1}{4}} \left(\frac{m_{\rm DM}}{\rm GeV}\right) \left(\frac{s_0}{10^{11}\ {\rm GeV}}\right)^{\frac{3}{2}} .$$

- The non-observation of isocurvature fluctuations in the CMB imposes an upper bound on the isocurvature component of DM:

$$\frac{\Omega_{\rm DM}^{s_0} h^2}{0.12} \lesssim 4.5 \times 10^{-5} \frac{s_0}{H_*} .$$

- This implies a lower bound on the scalar self coupling

$$\frac{m_{\rm DM}}{\rm GeV} \lesssim 6 \lambda_{\rm s}^{3/8} \left(\frac{H_*}{10^{11} {\rm GeV}}\right)^{-3/2} .$$

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Higgs portal model

Let's study the effects of the isocurvature bound on a simple Higgs portal DM model, consisting of a $\mathbf{Z}_2$-symmetric singlet scalar s.

$$V(\Phi, s) = \mu_{\rm h}^2 \Phi^\dagger \Phi + \lambda_{\rm h}(\Phi^\dagger \Phi)^2 + \frac{\mu_{\rm s}^2}{2} s^2 + \frac{\lambda_{\rm s}}{4} s^4 + \frac{\lambda_{\rm hs}}{2} \Phi^\dagger \Phi s^2 .$$

- For $\lambda_{\rm hs} \lesssim 10^{-7}$ the singlet sector will not thermalize with the SM, and any isocurvature component generated from the scalar condensate during inflation will persist.
- The DM abundance for $m_s < \frac{1}{2} m_h$, produced by the freeze-in mechanism from the Higgs decays is

$$n_{\rm D} \simeq 3 \frac{n_{\rm h}^{\rm eq} \Gamma_{h \to ss}}{H} \bigg|_{T = m_{\rm h}} .$$

- The observed DM abundance is produced for $\lambda_{\rm hs} \approx 2 \times 10^{-11} \sqrt{{\rm GeV}/m_s}$.

Self interactions in the hidden sector

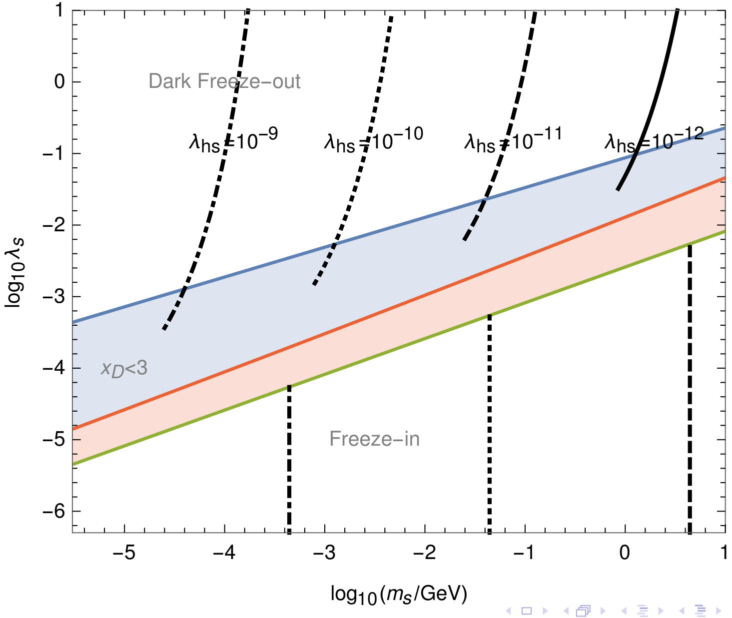
- Due to the isocurvature bound on the scalar self coupling, some amount of self-interaction is necessarily present in the hidden sector.
- Furthermore, self-interacting dark matter is motivated by the astrophysical observations.
- Number changing self scattering can thermalize the hidden sector, if the scattering rate exceeds the Hubble rate: $n_D \langle \sigma_{2\to 4} v \rangle \gtrsim H$.
- Critical coupling for thermalization:

$$\lambda_{\rm s}^{\rm FI} \simeq \sqrt{\frac{52.7 (g_*(m_{\rm h}) g_*(m_{\rm s}))^{\frac{1}{4}} \sqrt{m_{\rm h} m_{\rm s}}}{\lambda_{\rm hs} M_{\rm P}}}.$$

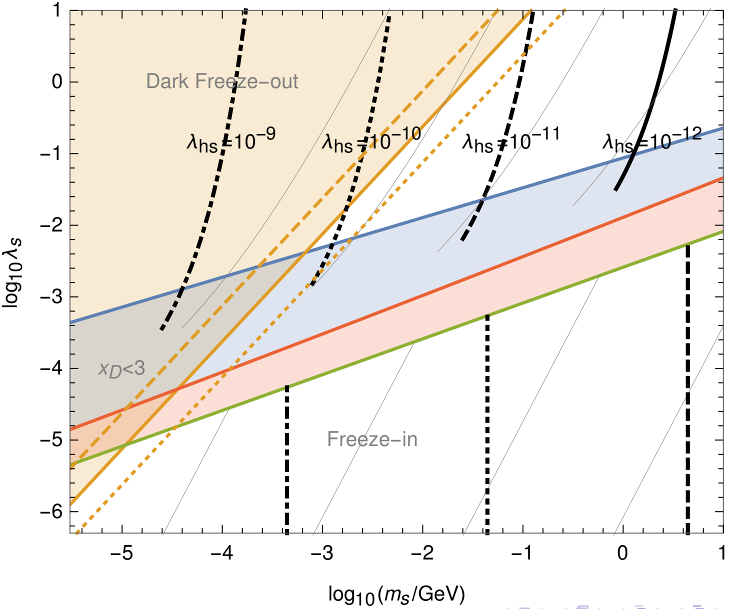
- In this case, the final DM relic abundance is determined by the freeze-out of the number changing self scattering, in a *dark freeze-out* process:

$$\Omega_{\rm DM} h^2 = \frac{m_{\rm s}}{3.6 \text{ eV } x_{\rm D}^{\rm FO} \chi}, \quad \chi = \frac{s}{s_{\rm D}}.$$

Phase diagram for DM production



Phase diagram for DM production



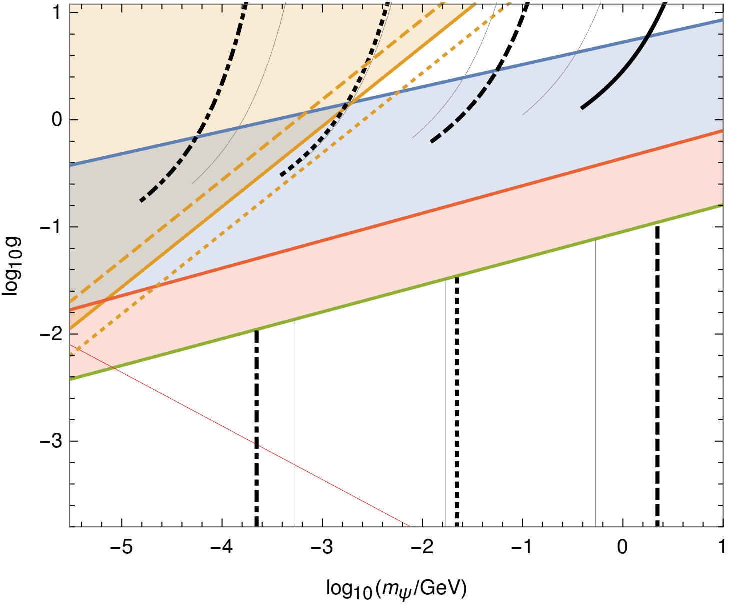
Fermion DM

- A fermionic DM particle can be included in the scalar portal model:

$$\mathcal{L}_\psi = \bar{\psi}(i\partial\!\!\!/ - m_\psi)\psi + igs\bar{\psi}\gamma_5\psi.$$

- Assuming $m_\psi < \frac{1}{2}m_s$, the scalar is produced as above and then decays into fermions.
- Fermion self-scattering is mediated by the scalar.
- The fermion can be interpreted as a sterile neutrino, possibly explaining the tentative 3.5 keV X-ray line.

Phase diagram for DM production: fermions



conclusions

- Light scalar fields obtain large field values during inflation.
- In freeze-in DM models, the resulting primordial condensate constitutes an isocurvature component to DM.
- The non-observation of isocurvature fluctuations then imposes a lower bound on scalar self coupling.
- Self interacting DM, initially produced via freeze-in, may enter chemical equilibrium within the hidden sector, resulting in *dark freeze-out*.
- If the scale of inflation is High ($\gtrsim \mathcal{O}(10^{10})$ GeV), light DM with non-negligible self interactions is preferred.

Thank you!

Backup: formulas

Self scattering cross sections, scalars:

$$\langle \sigma_{2\to 4} v \rangle \simeq \frac{\lambda_{\rm s}^4}{m_{\rm s}^2}, \quad \langle \sigma_{4\to 2} v^3 \rangle \simeq \frac{\lambda_{\rm s}^4}{m_{\rm s}^8}, \quad \frac{\sigma_{\rm s}}{m_{\rm s}} = \frac{9\lambda_{\rm s}^2}{32\pi m_{\rm s}^3}.$$

Fermions:

$$\langle \sigma_{2\to 4} v \rangle \simeq \frac{g^8}{m_{\rm s}^2}, \quad \langle \sigma_{4\to 2} v^3 \rangle \simeq \frac{g^8}{m_{\rm s}^8}\frac{m_\psi^2}{m_{\rm s}^2}, \quad \frac{\sigma_\psi}{m_\psi} = \frac{g^4 m_\psi}{4\pi m_{\rm s}^4}.$$

Freeze-out temperature, scalars:

$$x_{\rm D}^{\rm FO} = \frac{1}{3}\xi \log\left(\left(\frac{\xi}{2\pi}\right)^{\frac{9}{2}} \frac{\lambda_{\rm s}^4 M_{\rm P}}{1.66\sqrt{g_*}\, m_{\rm s} (x_{\rm D}^{\rm FO})^{\frac{5}{2}}}\right), \quad \xi = \frac{T_{\rm D}}{T} = \left(\frac{\rho_{\rm D}}{g_{*\rm D}}\frac{g_*}{\rho}\right)^{\frac{1}{4}},$$

Fermions:

$$x_{\rm D}^{\rm FO} = \frac{1}{3}\xi \log\left(\left(\frac{\xi}{2\pi}\right)^{\frac{9}{2}} \frac{g^8 M_{\rm P} m_\psi^9}{1.66\sqrt{g_*}\, m_{\rm s}^{10} (x_{\rm D}^{\rm FO})^{\frac{5}{2}}}\right).$$

Backup: freeze-in vs dark freeze-out