Observational Constraints on Decoupled Hidden Sectors

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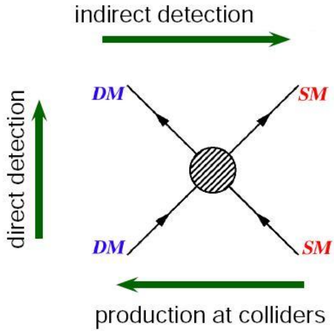
What is Dark Matter?

- Does the dark matter particle exist? Or are there many dark matter particles?
- Are they WIMP's, FIMP's, SIMP's, GIMP's, PIDM's, WISP's, ALP's, Wimpzillas, or sterile neutrinos? Or should gravity be modified?

Image: Chandra X-ray Observatory

Search for Dark Matter

- Many on-going experiments exist to find the correct explanation



- But... what if dark matter interacts only very feebly with the known particles, or not at all?

Original image: Max-Planck-Institut Für Kernphysik

Model for a Decoupled Hidden Sector

- The scalar sector of the model is specified by the potential

$$V(\Phi, s) = \mu_{\rm h}^2\Phi^\dagger\Phi + \lambda_{\rm h}(\Phi^\dagger\Phi)^2 + \frac{1}{2}\mu_{\rm s}^2 s^2 + \frac{\lambda_{\rm s}}{4}s^4 + \frac{\lambda_{\rm sh}}{2}\Phi^\dagger\Phi s^2$$

- Here Φ and s are, respectively, the usual Standard Model Higgs doublet and a real singlet scalar.

- The coupling between Φ and s acts as a portal between the Standard Model and an unknown Dark Sector (the so-called Higgs portal).

The Hidden Sector

- We also introduce a sterile neutrino ψ with

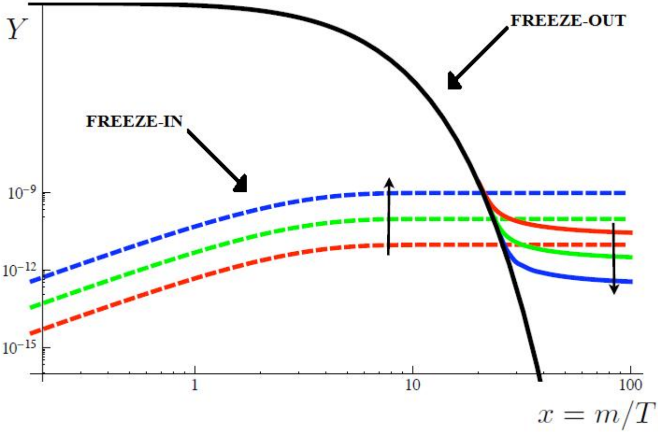
$$\mathcal{L}_{\rm Hidden} = \bar{\psi}(i\partial\!\!\!/ - m_\psi)\psi + igs\bar{\psi}\gamma_5\psi$$

- Either the fermion ψ or the scalar s, or both, can play the role of dark matter

- How was the observed DM abundance produced?

Dark Matter production mechanisms

- Two basic mechanisms for dark matter production: freeze-out and freeze-in



The original image is from Hall et al. (arXiv:0911.1120)

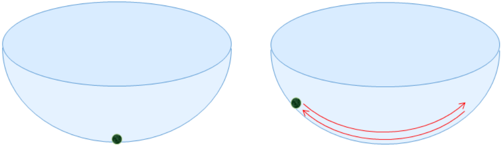
Frozen-in Dark Matter

- Requires $\lambda_{\rm sh} \lesssim 10^{-7}$, or otherwise the singlet sector thermalizes with the SM (this is sometimes called a FIMP scenario)
- Is produced from many different sources including thermal bath of Standard Model particles and primordial scalar condensates[1]
- Leaves observable imprints on CMB[2]
- Cannot be tested in colliders but can be tested by cosmological and astrophysical observations[3]

[1] S. Nurmi, TT, K. Tuominen (arXiv: 1506.04048)
[2] K. Kainulainen, S. Nurmi, TT, K. Tuominen, V. Vaskonen (arXiv: 1601.07733)
[3] M. Heikinheimo, TT, K. Tuominen, V. Vaskonen (arXiv:1604.02401)

Dark Matter from a primordial field

- During cosmic inflation, scalar fields typically acquire fluctuations proportional to the inflationary scale[4], $h, s \simeq H_* \lesssim 10^{14}$ GeV



Scalar fields fluctuate during cosmic inflation.

- After inflation, these scalar condensates will decay to particles
- The end products can constitute Dark Matter

[4] Starobinsky & Yokoyama (arXiv:astro-ph/9407016)

Imprints on CMB

- The observational bounds are significantly different depending on whether the DM perturbations are isocurvature or adiabatic
- The dark matter component sourced by a primordial scalar field is isocurvature and therefore strictly constrained by CMB observations[5]:

$$\frac{\Omega_{\rm DM}h^2}{0.12} \lesssim 10^{-5}\lambda_s^{-1/4}$$

[5] See K. Kainulainen, S. Nurmi, TT, K. Tuominen, V. Vaskonen (arXiv: 1601.07733) for details

The isocurvature bound

- To constrain the dark sector parameters, we compute $\Omega_{\rm DM} = \Omega_{\rm DM}(\lambda_{\rm s}, m_{\rm DM}, H_*)$ from theory

$$\frac{\Omega_{\rm DM}h^2}{0.12} \simeq 10^{-4}\lambda_{\rm s}^{-5/8}\left(\frac{m_{\rm DM}}{\rm GeV}\right)\left(\frac{H_*}{10^{11}{\rm GeV}}\right)^{3/2},$$

  and combine it with the isocurvature bound, $\Omega_{\rm DM}h^2/0.12 \lesssim 10^{-5}\lambda_{\rm s}^{-1/4}$.

- For fixed $m_{\rm DM}, H_*$, this gives a lower bound on $\lambda_{\rm s}$

- Note: $\Omega_{\rm DM}$ depends on $H_* \Rightarrow$ a novel connection between the dark matter abundance and the inflationary scale

Dark Matter self-interactions

- Astrophysical observations provide an upper bound on DM self-interactions[6]

$$\frac{\sigma_{\rm DM}}{m_{\rm DM}} = \frac{9\lambda_{\rm s}^2}{32\pi m_{\rm s}^3} \lesssim 1\,\frac{\rm cm^2}{\rm g}$$

- What kind of constraints do these limits place together?

[6] See e.g. D. Harvey et al. (arXiv: 1503.07675)

Thermal history of the Hidden Sector

- An initial population of DM is produced through Higgs decays $h \to ss$ at $T \sim m_{\mathrm{h}}$. In the standard freeze-in scenario, this is also the final abundance.
- However, if the number changing interactions $2 \to 4$ in the dark sector are fast, they will lead to thermalization of the dark sector
- This reduces the average momentum of DM particles and increases their number density until thermal equilibrium is reached

Dark Freeze-out

- The $2 \leftrightarrow 4$ interactions maintain thermal equilibrium until the $4 \to 2$ interaction rate drops below the Hubble rate and the number density freezes out

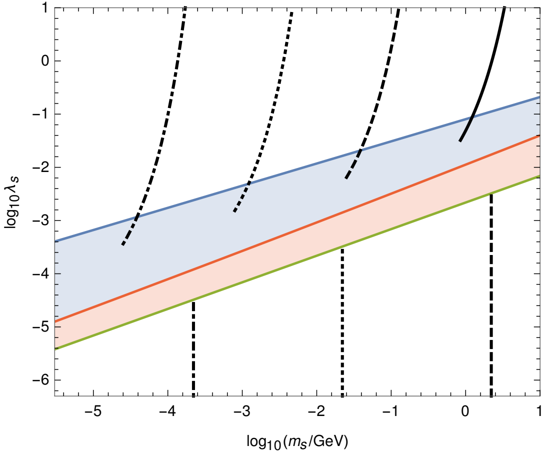
- This mechanism is referred to as dark freeze-out[7]

- By knowing the initial DM abundance sourced by Higgs decays, the resulting DM relic density can be computed from the conservation of entropy

[7] See e.g. Y. Hochberg et al. (arXiv: 1402.5143), N. Bernal and X. Chu (arXiv: 1510.08527), and D. Pappadopulo et al. (arXiv: 1602.04219) for other recent studies on the scenario.

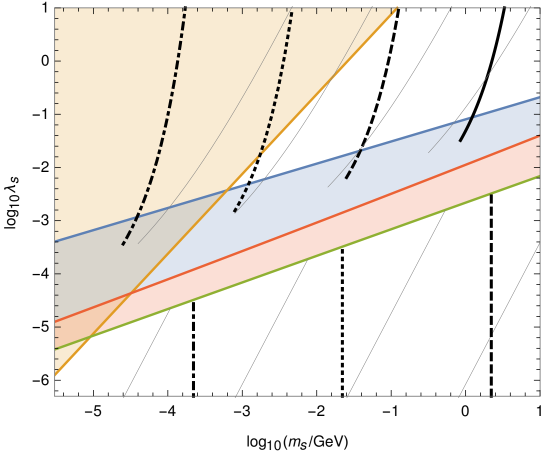
The results (scalar case)

- Three regimes: The dark freeze-out (above red line), the standard freeze-in (below green line), no solution at all (red)

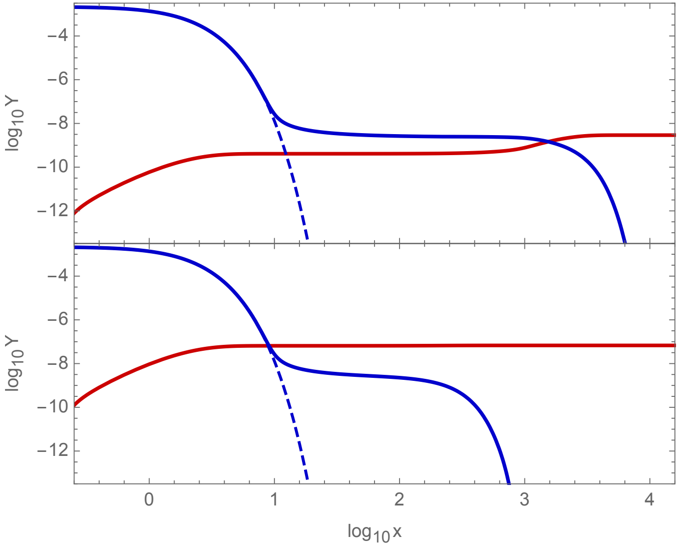


The constraints (scalar case)

- Three regimes: The dark freeze-out (above red line), the standard freeze-in (below green line), no solution at all (red)
- Two constraints: DM self-interactions (yellow), isocurvature perturbations (gray contours for different H_*'s)



Sterile neutrino dark matter



Conclusions

- Thermal history of dark sector contains many interesting features, which have been studied only vaguely
- Cosmological and astrophysical observations provide a valuable resource on testing different dark matter models
- We have derived stringent constraints on Higgs portal dark matter model and found a novel connection between dark matter abundance and inflationary energy scale