Observational Properties of Feebly Coupled DM

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Introduction

Evidence for Dark Matter

- Great deal of evidence for the existence of dark matter: rotational velocity curves of galaxies, Bullet Cluster[1], acoustic peaks in the Cosmic Microwave Background (CMB) radiation spectrum...

- Still the nature of dark matter is unknown

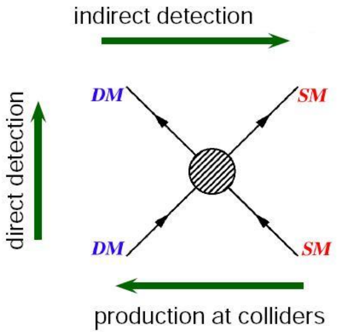
[1] Image: Chandra X-ray Observatory

What is Dark Matter?

- What is the correct explanation for the invisible matter content observed in the universe? Does the dark matter particle exist? Or are there many dark matter particles?
- Are they WIMP's, FIMP's, SIMP's, GIMP's, PIMP's, WISP's, ALP's, Wimpzillas, or sterile neutrinos? Or should gravity be modified?
- How can we tell which model is the correct one (if any)?

Search for Dark Matter

- Many on-going experiments exist[2]



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

[2] Original image: Max-Planck-Institut Für Kernphysik

The Model

The Model

- 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 model may explain the observed DM abundance or the origin of baryon asymmetry[3].

[3] J. Cline & K. Kainulainen (arXiv: 1210.4196), see also K. Enqvist, S. Nurmi, TT, K. Tuominen (arXiv: 1407.0659)

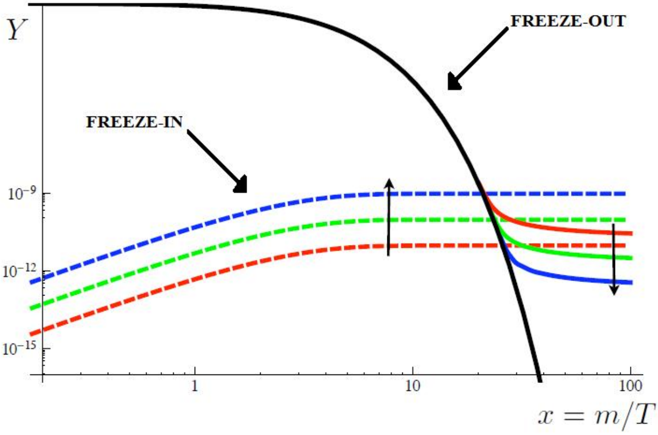
- We also introduce a sterile neutrino ψ

$$\mathcal{L}_{\rm Dark} = \bar{\psi}(i\partial\!\!\!/ - m_\psi)\psi + igs\bar{\psi}\gamma_5\psi \tag{1}$$

- 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

- There are basically two mechanisms for dark matter production: freeze-out and freeze-in[4]



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

The Freeze-Out

- Dark matter is initially in thermal equilibrium with the SM particles. This requires a rather strong coupling, $\lambda_{\rm sh} \simeq 0.1$.
- May lead to a WIMP miracle: thermal relic with weak cross-section and a mass $m_{\rm s} \sim$ EW scale gives the right relic abundance.
- Starts to be very constrained by experiments[5]

[5] For a recent review, see e.g. M. Klasen, M. Pohl, G. Sigl (arXiv: 1507.03800)

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[6]
- Leaves observable imprints on CMB[7]
- Cannot be tested in colliders but can be tested by cosmological and astrophysical observations[8]

[6] S. Nurmi, TT, K. Tuominen (arXiv: 1506.04048)

[7] K. Kainulainen, S. Nurmi, TT, K. Tuominen, V. Vaskonen (arXiv: 1601.07733)

[8] M. Heikinheimo, TT, K. Tuominen, V. Vaskonen (arXiv:1604.XXXXX)

Thermal History of the Dark Sector

Thermal history of the Dark Sector

- An initial population of DM is produced through Higgs decays $h \to ss$ at $T \sim m_{\rm h}$. 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

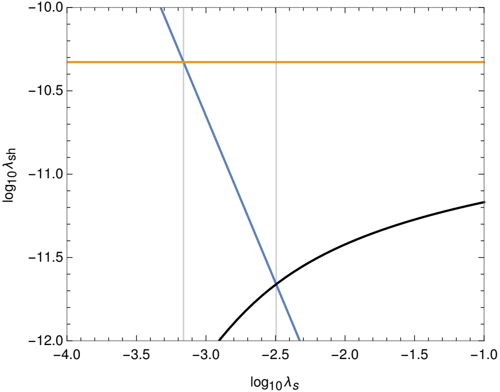
Dark Freeze-out

- The $2 \leftrightarrow 4$ interactions maintain thermal equilibrium until the $4 \rightarrow 2$ interaction rate drops below the Hubble rate and the number density freezes out
- This mechanism is referred to as dark freeze-out
- By knowing the initial DM abundance sourced by Higgs decays, the resulting DM relic density can be computed from the conservation of entropy[9]. This can be cast as an equation for the dark freeze-out temperature
- On the other hand, the dark freeze-out temperature can be estimated as the temperature at which the $4 \rightarrow 2$ interaction rate drops below the Hubble rate

[9] E.D. Carlson, M.E. Machacek, L.J. Hall, Astrophys. J. 398, 43 (1992)

Standard Freeze-in or Dark Freeze-out?

- By equating these, we find that sometimes there are no solutions at all[10]

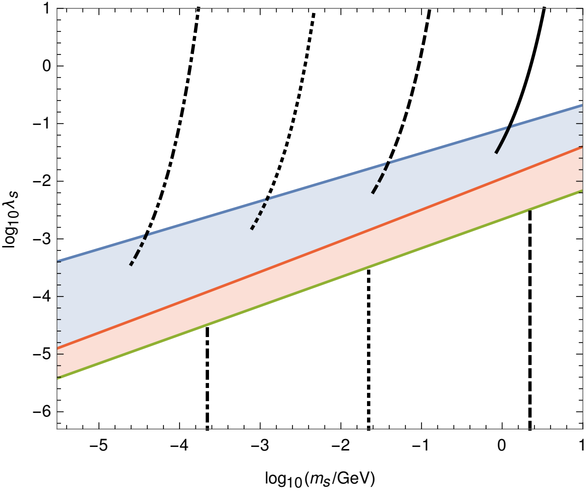


The portal coupling $\lambda_{\rm hs}$ that yields the correct DM abundance as a function of the DM self-coupling $\lambda_{\rm s}$ for $m_{\rm s} = 0.1$ GeV.

[10] M. Heikinheimo, TT, K. Tuominen, V. Vaskonen (arXiv:1604.XXXXX)

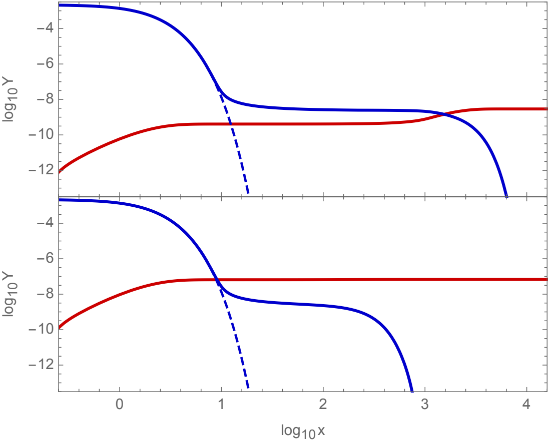
Dark Freeze-out

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



Fermionic Dynamics

- Similar results can be derived for other fields in the dark sector, including sterile neutrinos



- The complete results will be out soon

Observational Constraints

Dark Matter self-interactions

- Astrophysical observations provide an upper bound on DM self-interactions[11]

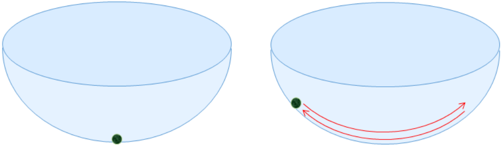
$$\frac{\sigma_{\mathrm{DM}}}{m_{\mathrm{DM}}} = \frac{9\lambda_{\mathrm{s}}^2}{32\pi m_{\mathrm{s}}^3} \lesssim 1\,\frac{\mathrm{cm}^2}{\mathrm{g}} \qquad (2)$$

- Do we expect DM to have large self-interactions?

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

Dark Matter from a primordial field

- During cosmic inflation, scalar fields typically acquire fluctuations proportional to the inflationary scale[12], $h, s \simeq H_* \lesssim 10^{14}$ GeV



Scalar fields fluctuate during cosmic inflation.

- After inflation, these scalar condensates will decay to particles

- The end products can constitute Dark Matter

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

Imprints on CMB

- The observational bounds are significantly different depending on whether the singlet constitutes isocurvature or adiabatic dark matter[13]
- The dark matter component sourced by a primordial scalar field clearly is isocurvature and therefore strictly constrained by CMB observations[14]:

$$\frac{\Omega_{\rm DM}h^2}{0.12} \lesssim 10^{-5}\lambda_s^{-1/4} \tag{3}$$

[13] Planck collaboration (arXiv:1502.02114)

[14] 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 can compute $\Omega_{\rm DM} = \Omega_{\rm DM}(\lambda_{\rm s}, m_{\rm DM}, H_*)$ from the theory[15]

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

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

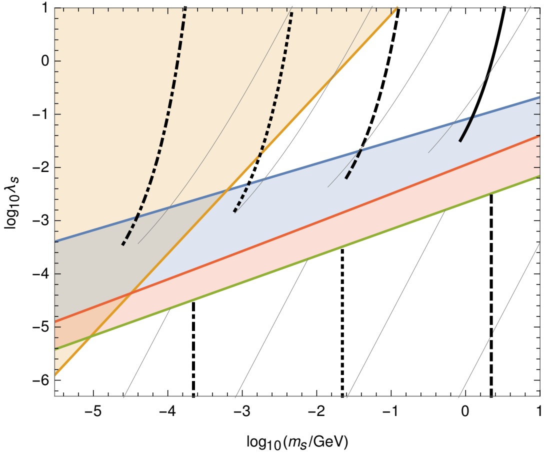
- For fixed $m_{\rm DM}, H_*$, this gives a lower bound on $\lambda_{\rm s}$

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

[15] See S. Nurmi, TT, K. Tuominen (arXiv: 1506.04048) and K. Kainulainen, S. Nurmi, TT, K. Tuominen, V. Vaskonen (arXiv: 1601.07733) for details

The results

- 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)



Conclusions and Outlook

Conclusions

- The nature of dark matter is still unknown
- 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

Outlook

- Solve the dark freeze-out dynamics numerically in regimes where the analytic approximation breaks down[16]
- Choose a general scalar potential
  $\Rightarrow$ is it possible to realize both inflation and EWPT in the same model, and maybe obtain the correct DM relic abundance as well?
  $\Rightarrow$ provides new ways to test the Higgs portal model[17]
- Can we say something about the inflationary dynamics by studying DM properties in today's universe?[18]

[16] M. Heikinheimo, TT, K. Tuominen, V. Vaskonen (arXiv: 16XX.XXXXX)
[17] TT, K. Tuominen, V. Vaskonen (arXiv: 1605.XXXXX)
[18] K. Enqvist, TT (arXiv: 16XX.XXXXX)