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Observational properties of feebly interacting dark matter

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Talk based on arXiv: 1506.04048, 1601.07733, 1604.02401, 1704.05359

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28/4/2017

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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

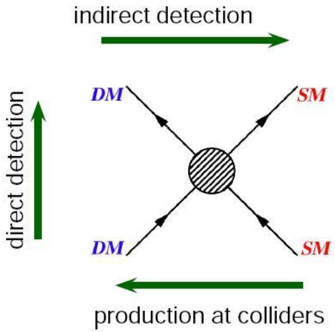
[1] Image: Chandra X-ray Observatory

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, PIDM'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 feebly with the known particles, or not at all?

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

The Model

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 Hidden Sector (the so-called Higgs portal).

The Hidden Sector I

- We can also introduce a sterile neutrino ψ

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

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

The Hidden Sector II

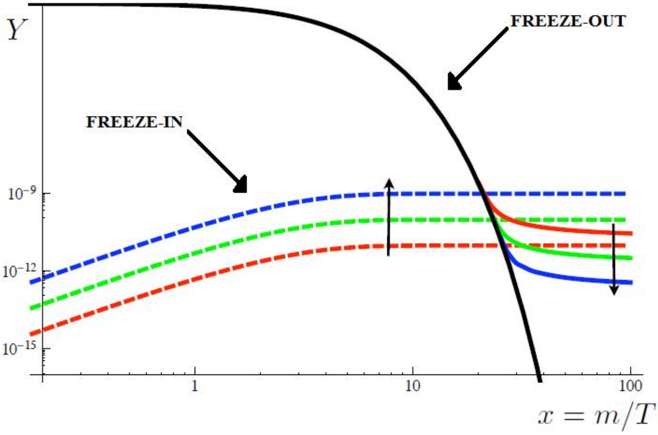
- Or, we can promote s to be a complex doublet of a hidden $SU(2)$ symmetry

$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}F_i^{\mu\nu}F_{\mu\nu}^i + (D^\mu s)^\dagger(D_\mu s) - \mu_{\rm s}^2 s^\dagger s - \lambda_{\rm s}(s^\dagger s)^2, \qquad (1)$$

- Here $F_{\mu\nu}^i = \partial_\mu A_\nu^i - \partial_\nu A_\mu^i + g\epsilon^{ijk}A_\mu^j A_\nu^k$ and $D^\mu = \partial^\mu - ig\tau A^\mu/2$
- Either the scalar s or the vector A_μ 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[3]



[3] 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[4]

[4] 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[5]
- Leaves observable imprints on CMB[6]
- Cannot (usually) be tested by collider experiments but can be tested by cosmological and astrophysical observations[7]

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

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

[7] M. Heikinheimo, TT, K. Tuominen, V. Vaskonen (arXiv:1604.02401)

Thermal History of the Hidden Sector

Thermal history of the Hidden Sector

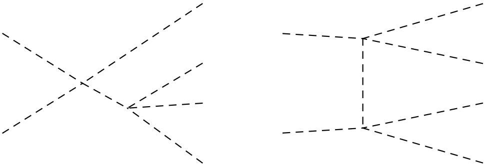
- An initial population of DM is produced through Higgs decays $h \to ss$ at $T \sim m_{\rm h}$. In the standard freeze-in scenario, this is also the final abundance.

- However, if the number changing interactions $2 \to 4$ in the hidden sector are fast, they will lead to thermalization of the hidden sector

- This reduces the average momentum (temperature) 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

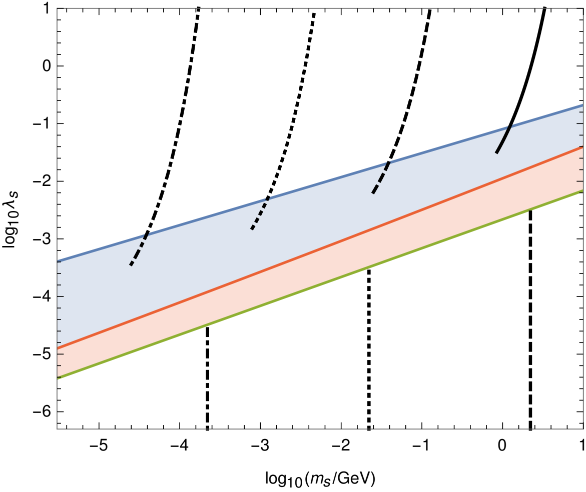


Examples of number-changing interactions.

- This mechanism is referred to as dark freeze-out

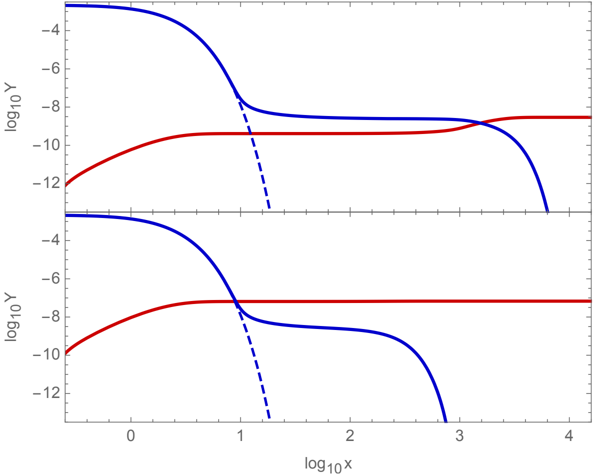
Dark Freeze-out

- 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)



Hidden Sector dynamics

- Similar results can be derived for other fields in the hidden sector, including sterile neutrino or vector DM



- See more: Heikinheimo et al., arXiv:1604.02401 (sterile neutrinos), 1704.05359 (sterile neutrinos and vectors)

Observational Constraints

Dark Matter self-interactions

- Astrophysical observations provide an upper bound on DM self-interactions[8]

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

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

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

Cosmic inflation

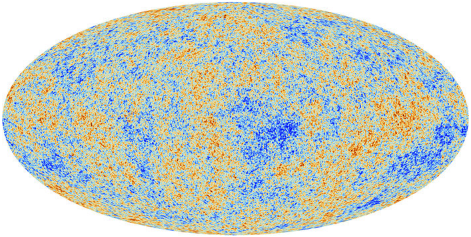
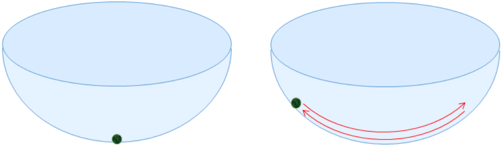


Image: Planck/ESA

- Must explain the observed curvature perturbations in the Cosmic Microwave Background (+ several fine-tuning problems) $\Rightarrow$ Cosmic inflation
- Inflaton: SM Higgs? $f(R)$? Flat direction in MSSM? Axion? ...

Dark Matter from a primordial field

- During a de Sitter type cosmic inflation, scalar fields typically acquire fluctuations proportional to the inflationary scale[9], $h, s \simeq H_* \lesssim 10^{14}$ GeV



Scalar fields fluctuate during cosmic inflation.

- After inflation, these scalar condensates will decay to particles

- The end products can constitute Dark Matter

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

Isocurvature perturbations

- The observational bounds are significantly different depending on whether the singlet constitutes isocurvature or adiabatic dark matter
- Adiabatic perturbations are perturbations in the total energy density (in the geometry of the Universe) such that $\delta(n_X/n_Y) = 0$
- Isocurvature perturbations are variations in the particle number ratios (no effect on geometry), $\delta(n_X/n_Y) \neq 0$

DM Imprints on CMB

- In principle, we could see a large fraction of isocurvature perturbations in the CMB. But we do not[10].

- The dark matter component sourced by a primordial scalar field clearly is isocurvature and therefore strictly constrained by CMB observations[11]:

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

[10] Planck collaboration (arXiv:1502.02114)

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

The isocurvature bound

- To constrain the hidden sector parameters, we compute the DM abundance[12]

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

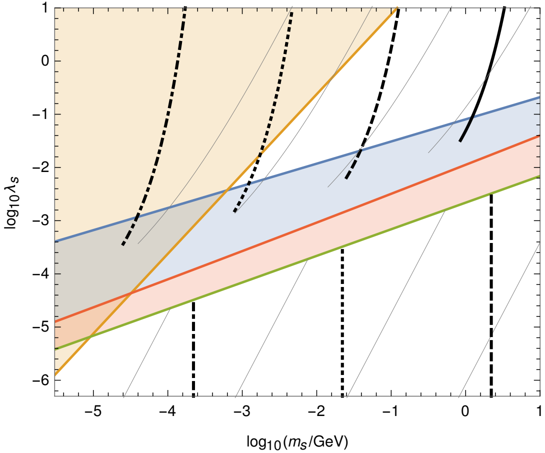
and combine it with the isocurvature bound, $\Omega_{\rm DM}h^2/0.12 \lesssim 10^{-5}\lambda_{\rm s}^{-1/4}$.

- 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

[12] 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 hidden 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 the energy scale of inflation