Freeze-in as a Complementary Process to Freeze-Out [arXiv: 2407.04809]

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Outline

- Motivation
- Next-to Two Higgs Doublet Model
- Numerical Analysis
- Results
- Conclusions

Motivation

Evidences for Dark Matter

- Observed discrepancies in stellar rotational curves

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- Temperature fluctuations in the Cosmic Microwave Background (CMB)
  [Aghanim et al., 2020]

Dark Matter Relic Density [Aghanim et al., 2020]

From the experimental data of the PLANCK experiment we obtain the DM relic density

$$\Omega_{\text{exp}} h^2 = 0.1200 \pm 0.0012$$

with $h^2 = \frac{H^2}{(100 \frac{km}{sMpc})^2}$.

Two Real Singlet Model

- Simplest extension of the SM with freeze-out and freeze-in: extension of the SM with two real singlets ϕ_{FO} and ϕ_{FI} acting as DM candidates
- Two discrete symmetries:

$$\mathbb{Z}_2^{\text{FO}} : \phi_{\text{FO}} \to -\phi_{\text{FO}} \qquad \mathbb{Z}_2^{\text{FI}} : \phi_{\text{FI}} \to -\phi_{\text{FI}}$$

- The most general renormalisable scalar potential is

$$\begin{aligned} V_{\text{Scalar}} = {} & \mu_h^2|H|^2 + \lambda_h|H|^4 + \frac{1}{2}\mu_{\text{FO}}^2\phi_{\text{FO}}^2 + \frac{\lambda_1}{4!}\phi_{\text{FO}}^4 + \frac{1}{2}\mu_{\text{FI}}^2\phi_{\text{FI}}^2 + \frac{\lambda_2}{4!}\phi_{\text{FI}}^4 \\ & + \frac{\lambda_{\text{FO}}}{2}\phi_{\text{FO}}^2|H|^2 + \frac{\lambda_{\text{FI}}}{2}\phi_{\text{FI}}^2|H|^2 + \frac{\lambda_{\text{IO}}}{4}\phi_{\text{FI}}^2\phi_{\text{FO}}^2 \end{aligned}$$

- The two $\mathbb{Z}_2$ symmetries remain unbroken $\Rightarrow$ two stable DM candidates with masses m_{FO}, m_{FI}

Freeze-Out vs Freeze-In [Gondolo and Gelmini, 1991], [Hall et al., 2010]

- Consider the limits $\lambda_{\text{FI}} = 0$ and $\lambda_{\text{FO}} = 0$, with $\lambda_{\text{IO}} = 0$ in both cases:
  - $\lambda_{\text{FI}} = 0$: DM produced via **freeze-out**
  - $\lambda_{\text{FO}} = 0$: DM produced via **freeze-in**

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  - Correct relic density with small λ_{FI}
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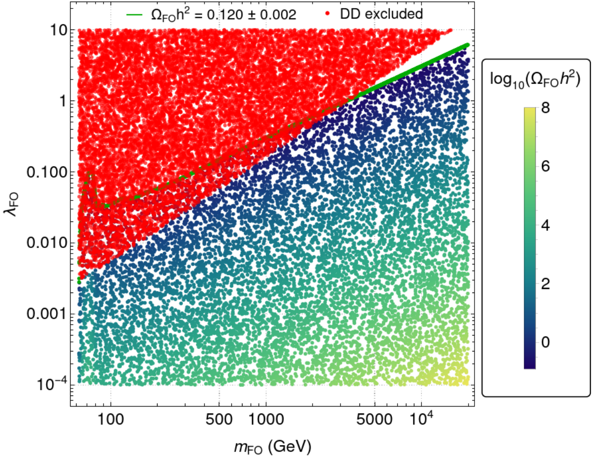
  - Vast regions of parameter space are already **excluded**

Freeze-Out Scenario



The plot was obtained using `micrOMEGAs` 6.0 [Bélanger et al., 2002],[Bélanger et al., 2018],[Alguero et al., 2024] .

Limiting Cases: Freeze-Out vs Freeze-In

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- **Conclusion:** Each scenario has limitations — motivating the study of their **complementarity**.

Next-To-2 Higgs Doublet Model (N2HDM)

Next-to-2 Higgs Doublet Model [Mühlleitner et al., 2017]

- Scalar sector with two $SU(2)_L$ doublets Φ_1, Φ_2 and one real singlet Φ_S .
- Scalar potential invariant under two discrete $\mathbb{Z}_2$ symmetries:

$$\mathbb{Z}_2^{(1)} : \quad \Phi_1 \to \Phi_1,\, \Phi_2 \to -\Phi_2,\, \Phi_S \to \Phi_S$$
$$\mathbb{Z}_2^{(2)} : \quad \Phi_1 \to \Phi_1,\, \Phi_2 \to \Phi_2,\, \Phi_S \to -\Phi_S$$

- Most general renormalisable scalar potential:

$$\begin{aligned} V_{\text{Scalar}} = \;& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}\right] + \frac{1}{2} m_s^2 \Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 \\ & + \frac{\lambda_7}{2}(\Phi_1^\dagger \Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger \Phi_2)\Phi_S^2 \end{aligned}$$

- λ_7 and λ_8 are the relevant couplings for Freeze-In

Scalar fields of the N2HDM

After electroweak symmetry breaking the fields can be parameterized as

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \qquad \Phi_S = v_S + \rho_S$$

Hereby η_i ($i \in \{1, 2\}$) denotes the neutral CP-odd, ρ_i ($i \in \{1, 2, s\}$) the neutral CP-even and ϕ_i^+ ($i \in \{1, 2\}$) the complex charged fields.

Full Dark Phase [Engeln et al., 2020]

- Due to two unbroken $\mathbb{Z}_2$ symmetries, this phase predicts the existence of two DM candidates. The mass eigenstates are obtained via

$$\begin{pmatrix} H_{\text{SM}} \\ H_{\text{DD}} \\ H_{\text{DS}} \end{pmatrix} = I_3 \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}, \quad A_D = \eta_2, \quad H_D^{\pm} = \phi_2^{\pm}$$

- The couplings of H_{SM} to the SM particles remain the same as in the SM.
- However, additional couplings of H_{SM} are obtained due to the scalar potential of the N2HDM.

The input parameter set to parameterize the scalar potential is given by

$$v, \quad m_{H_{SM}}, \quad m_{H_{DD}}, \quad m_{A_D}, \quad m_{H_{DS}}, \quad m_{H_D^{\pm}}, \quad m_{22}^2, \quad \lambda_2, \quad \lambda_6, \quad \lambda_7, \quad \lambda_8$$

Numerical analysis

Numerical analysis

- Parameter scan performed using `ScannerS` [Azevedo et al., 2018], applying all relevant theoretical and experimental constraints.
- Relic density and direct detection cross section calculated with `micrOMEGAs`.
- Relic density is given by

$$\Omega_c h^2 = \Omega_{\mathrm{FO}} h^2 + \Omega_{\mathrm{FI}} h^2$$

- The scanned parameter ranges are given by

Parameter	Scan Range
$m_{H_{\mathrm{DD}}},\ m_{A_{\mathrm{D}}},\ m_{H_{\mathrm{D}}^{\pm}}$	$[60\ \mathrm{GeV},\ 1\ \mathrm{TeV}]$
$m_{H_{\mathrm{DS}}}$	$[1\ \mathrm{GeV},\ 1\ \mathrm{TeV}]$
$\lambda_7,\ \lambda_8$	$[10^{-14},\ 10^{-9}]$
$\lambda_2,\ \lambda_6$	$[0,\ 20]$
m_{22}^2	$[0,\ 10^6\ \mathrm{GeV}^2]$

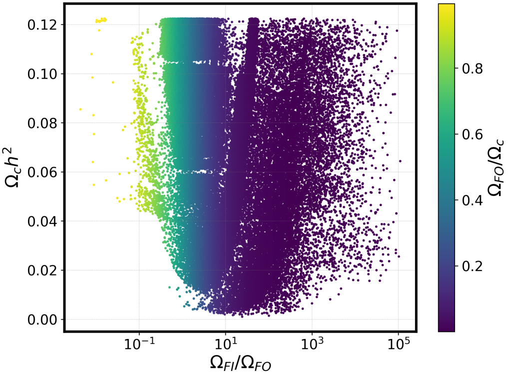
Applied Constraints

- Boundedness from below [R. Coimbra et al., 2013]
- Unitarity [B.W.Lee et al., 1977]
- Electroweak precision observables via S, T, U [M. E. Peskin and T. Takeuchi, 1992]
- Vacuum stability
- DM constraints [J. Aalbers et al., 2023], [Aghanim et al., 2020]
- Vacuum stability:
  - Checked with `Evade` [Jonas Wittbrodt et al, 2022]
- Collider Higgs data:
  - Checked with HiggsTools [H. Bahl et al., 2023]

Results

Impact of Complementarity on the Relic Density

- All points obtained with `ScannerS`, which fulfill all relevant theoretical and experimental constraints



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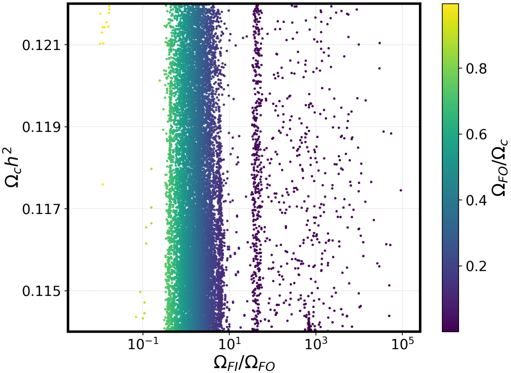
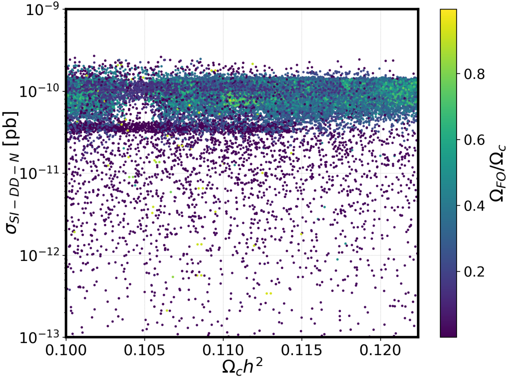


Impact of Complementarity on the Direct Detection

- Spin-independent direct detection cross section of the Freeze-Out particle ϕ_{FO} as a function of the relic density $\Omega_c h^2$



Conclusions

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- Two DM components: freeze-out + freeze-in
- Realised in minimal and extended models (e.g., N2HDM, CP in the Dark)
- While **freeze-in** is generally difficult to probe directly, **freeze-out** remains accessible at colliders, even for subdominant relic density fractions.
- Complementarity:
  - Relaxes relic density constraint on freeze-out
  - Allows larger portal couplings
  - Enlarges viable parameter space
- Future data: stronger constraints, better model discrimination

Thank You!

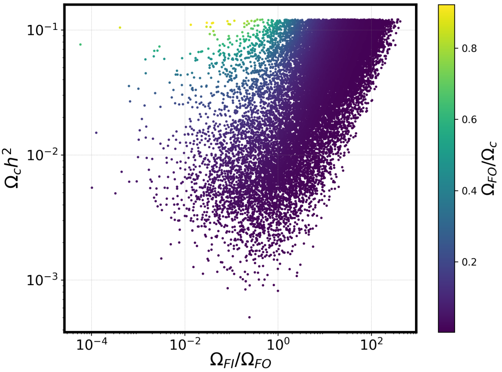
Backup

Boltzmann equations for Freeze-In and Freeze-Out

$$\frac{dY_{\mathrm{FI}}}{dx} = \sqrt{\frac{\pi}{45G}}\,\frac{g_*^{1/2} m_{\mathrm{FI}}}{x^2}\left[\langle \sigma v\rangle_{\phi_{\mathrm{FI}}\phi_{\mathrm{FI}}\mathrm{SMSM}} + \langle \sigma v\rangle_{\phi_{\mathrm{FI}}\phi_{\mathrm{FI}}\phi_{\mathrm{FO}}\phi_{\mathrm{FO}}}\right]\; Y^2_{\mathrm{FI,eq}}$$

$$\frac{dY_{\mathrm{FO}}}{dx} = -\sqrt{\frac{\pi}{45G}}\,\frac{g_*^{1/2} m_{\mathrm{FI}}}{x^2}\langle \sigma v\rangle_{\phi_{\mathrm{FO}}\phi_{\mathrm{FO}}\mathrm{SMSM}}\left(Y_{\mathrm{FO}} - Y^2_{\mathrm{FO,eq}}\right)$$

Impact of Complementarity on the Relic Density CPVDM



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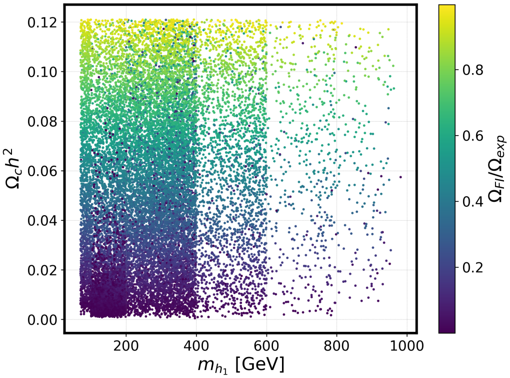

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