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Thermal Loophole in the Higgs Portal

Kristjan Kannike

NICPB, Estonia

Andi Hektor, K.K., Ville Vaskonen

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2 Motivation

- Direct detection puts strong bounds on usual WIMP dark matter
- Recent interest in thermal effects on dark matter:
  ‘forbidden’ channels, D’Agnolo & Ruderman 1505.07107
  cannibal DM, Pappadopulo, Ruderman & Trevirsan 1602.04219
  VEV flip-flop Baker & Kopp 1608.07578

3 Motivation

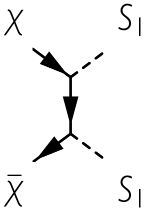
- VEV flip-flop: freeze-in with a dark matter decay channel open in a $\mathbb{Z}_2$-breaking phase

  Baker & Kopp 1608.07578

- Construct a minimal model with dark matter *freeze-out* before phase transition to the electroweak minimum

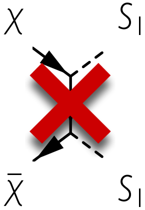
4 Considerations

- Dark matter itself cannot be thermal due to its freeze-out: $m_{\mathrm{DM}} \gg T$
- Fermion dark matter with a thermal scalar
- Only one scalar does not work: t-channel annihilation works in any phase



5 Considerations

- Dark matter itself cannot be thermal: it has to freeze out: $m_{\text{DM}} \gg T$
- Fermion dark matter with a thermalised scalar singlet
- Only one scalar does not work: *t*-channel annihilation works in any phase
- Must have two scalars: light S_1 with $y_1 = 0$ and heavy S_2 ($m_2 > m_\chi$)



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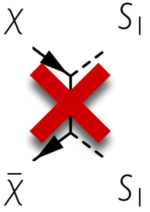
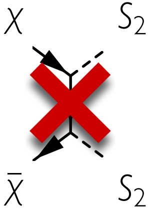




6 Considerations

- The light singlet S_1 and the heavy singlet S_2 do not mix with each other
- Only Higgs and S_1 obtain thermal masses
- For simplicity impose $\mathbb{Z}_2$ given by $S_i \to -S_i$ broken only by Yukawas

7 Minimal Model

$$\mathcal{L} \supset \bar{\chi}\partial\!\!\!/\chi + |D_\mu H|^2 + \frac{1}{2}(\partial_\mu S_1)^2 + \frac{1}{2}(\partial_\mu S_2)^2 - m_\chi\bar{\chi}\chi - y_1 S_1\bar{\chi}\chi - y_2 S_2\bar{\chi}\chi - V,$$

where

$$V = \mu_H^2|H|^2 + \frac{1}{2}\mu_{20}^2 S_1^2 + \frac{1}{2}\mu_{11}^2 S_1 S_2 + \frac{1}{2}\mu_{02}^2 S_2^2 + \lambda_H|H|^4 + \lambda_{H20}|H|^2 S_1^2 + \lambda_{H11}|H|^2 S_1 S_2 + \lambda_{H02}|H|^2 S_2^2 + \lambda_{40}S_1^4 + \lambda_{31}S_1^3 S_2 + \lambda_{22}S_1^2 S_2^2 + \lambda_{13}S_1 S_2^3 + \lambda_{04}S_2^4$$

7 Minimal Model

$$
\begin{aligned}
\mathcal{L} \supset\ & \bar{\chi} \partial\!\!\!/ \chi + |D_\mu H|^2 + \frac{1}{2}(\partial_\mu S_1)^2 + \frac{1}{2}(\partial_\mu S_2)^2 \\
& - m_\chi \bar{\chi}\chi - y_1 S_1 \bar{\chi}\chi - y_2 S_2 \bar{\chi}\chi - V,
\end{aligned}
$$

where

$$
\begin{aligned}
V =\ & \mu_H^2 |H|^2 + \frac{1}{2}\mu_{20}^2 S_1^2 + \frac{1}{2}\mu_{11}^2 S_1 S_2 + \frac{1}{2}\mu_{02}^2 S_2^2 \\
& + \lambda_H |H|^4 + \lambda_{H20} |H|^2 S_1^2 + \lambda_{H11} |H|^2 S_1 S_2 \\
& + \lambda_{H02} |H|^2 S_2^2 + \lambda_{40} S_1^4 + \lambda_{31} S_1^3 S_2^1 + \lambda_{22} S_1^2 S_2^2 \\
& + \lambda_{13} S_1 S_2^3 + \lambda_{04} S_2^4
\end{aligned}
$$

8 Thermal Corrections

Thermal corrections to mass terms are given by

$$\delta m_{ij}^2 \approx \sum_k \frac{g_k}{24} \frac{\partial m_k^2}{\partial \phi_i \partial \phi_j} T^2,$$

where $g_k = n_k$ for bosonic degrees of freedom

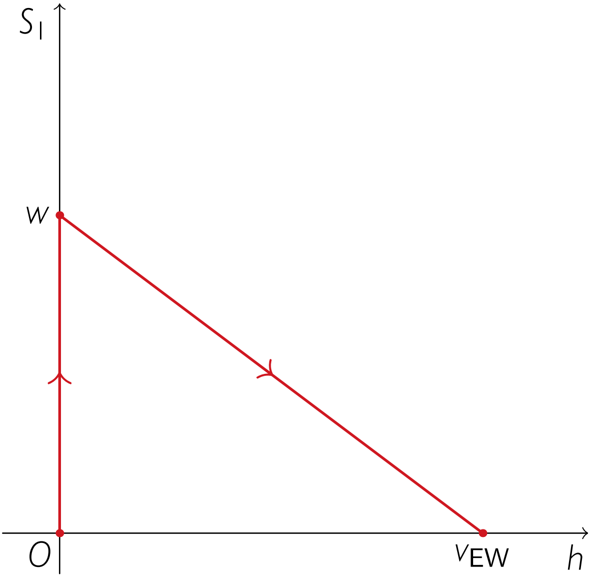
9 Thermal Corrections to Masses

$$\mu_H^2 \to \mu_H^2 + c_H T^2,$$
$$\mu_{20}^2 \to \mu_{20}^2 + c_{20} T^2,$$

where

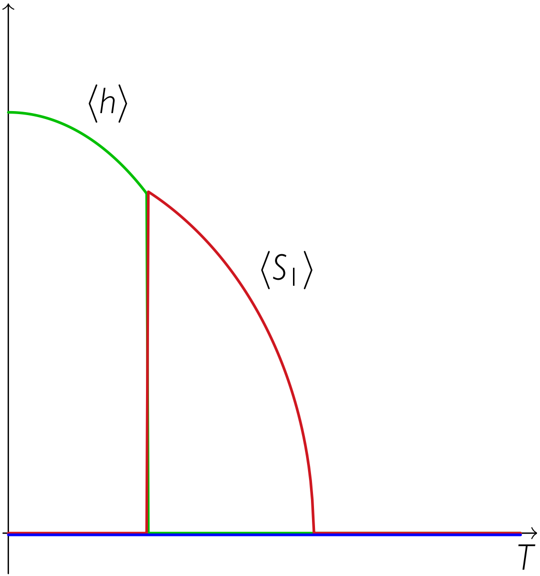
$$c_H = \frac{1}{48}(24\lambda_H + 3g'^2 + 9g^2 + 12y_t^2 + 4\lambda_{H20}),$$
$$c_{20} = \lambda_{40} + \frac{1}{3}\lambda_{H20}$$

- The contributions to the terms $\mu_{11}^2 S_1 S_2$ and $\frac{1}{2}\mu_{02}^2 S_2^2$ are approximately zero due to the high mass of S_2

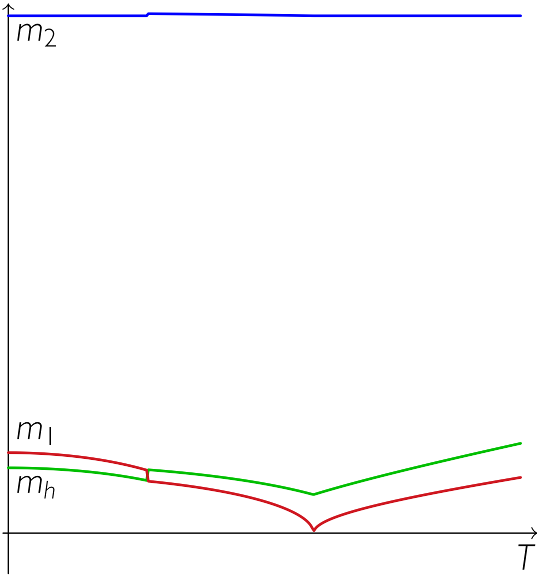


S_1
w
O
v_{EW}
h

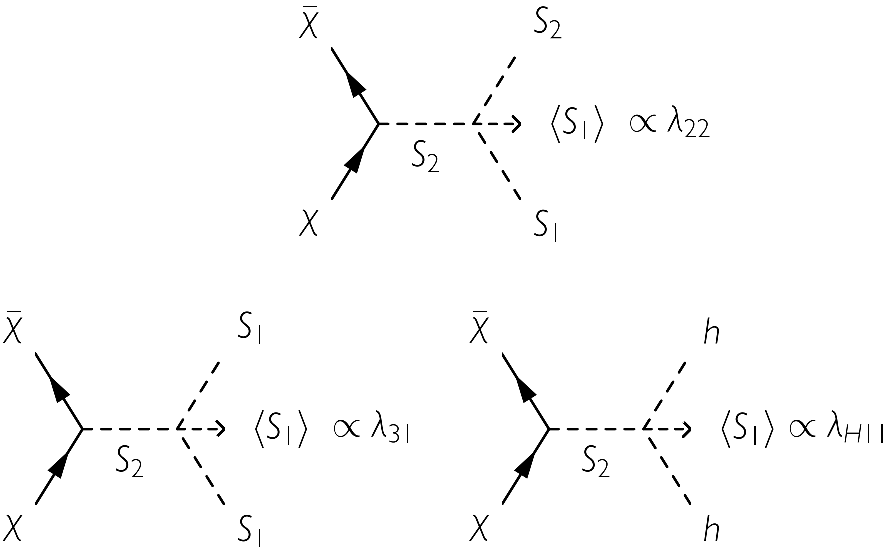
11 Phase Transitions



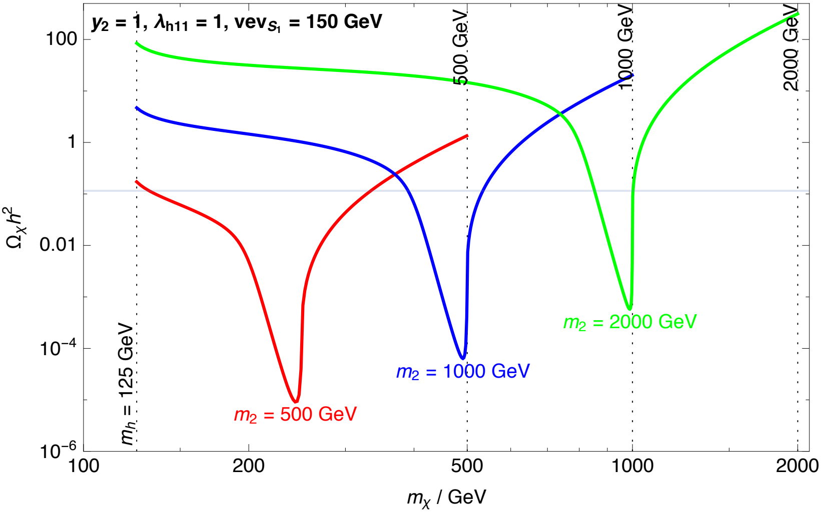
12 Phase Transitions



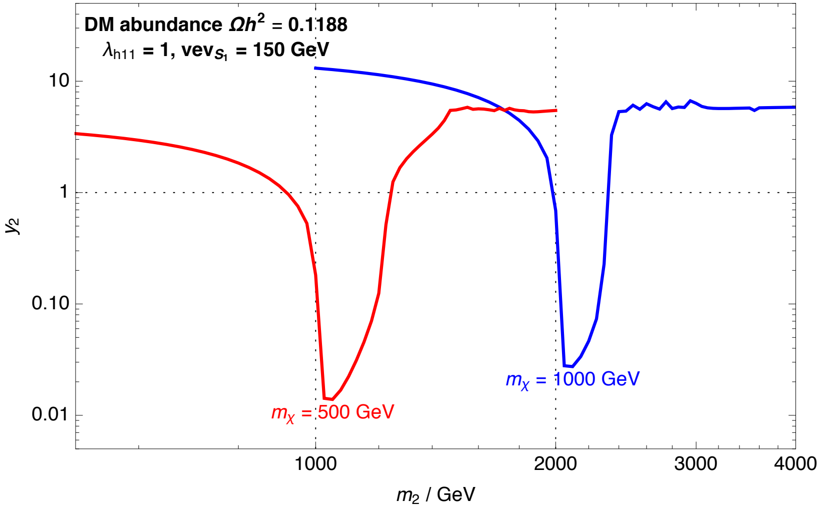
13 Annihilation Channels



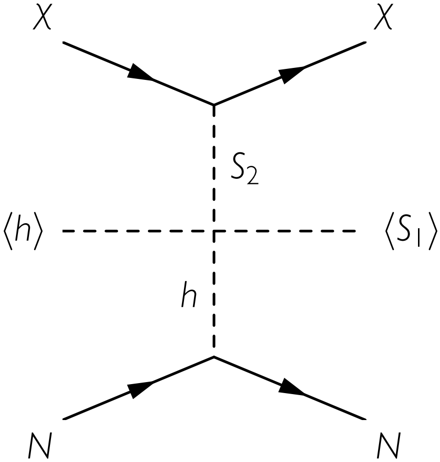
14 Relic Density



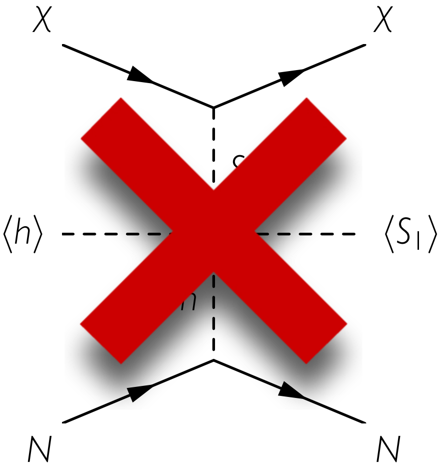
15 Relic Density



16 Direct Detection



17 Direct Detection



18 Gravitational Waves

- Gravitational wave production similar to the model of the SM with an EW singlet

  Vaskonen 1611.02073

  — work in progress

Conclusions

- Non-zero temperature can have effect on dark matter freeze-out
- We have constructed a minimal model with freeze-out before phase transition
- While direct detection cross-section is negligible, there can be a gravitational wave signal