Early kinetic decoupling of dark matter and the Higgs invisible decay in collider experiments

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tension between $\langle \sigma v \rangle$ and $\sigma_{SI}$

- $\langle \sigma v \rangle \simeq \mathcal{O}(10^{-26}) \text{ cm}^3/\text{s}$ is required for $\Omega h^2$
- $\sigma_{SI} \lesssim \mathcal{O}(10^{-46}) \text{ cm}^2$ from XENON1T
- how to suppress the DM-WIMP scattering while keeping the annihilation process?

annihilation ($\langle \sigma v \rangle \simeq \mathcal{O}(10^{-26}) \text{ cm}^3/\text{s}$)

scattering ($\sigma v \lesssim \mathcal{O}(10^{-46}) \text{ cm}^2$)
Higgs Resonance

- DM pair annihilation enjoys the Higgs resonance for $m_{DM} \sim m_h/2$
- the DM-Higgs coupling ($\lambda_{hs}$) should be small for $\langle \sigma v \rangle = 10^{-26}$ cm$^3$/s
- small $\lambda_{hs}$ suppresses the scattering cross section ($\sigma_{SI} \ll O(10^{-46})$ cm$^2$)
- avoid the constraint from XENON1T experiment
- bonus: Higgs invisible decay can be studied at collider experiments

(e.g.) scalar singlet DM model

[Graph showing scattering and annihilation processes with a focus on the Higgs resonance and constraints from XENON1T experiment]
Kinetic decoupling may happen earlier

- temperature of DM ($T_{\chi}$) is usually assumed to be the same as the temperature of the thermal bath ($T$) in WIMP models ($T_{\chi} = T$)
- This assumption is valid if the scattering processes are frequent
- the scattering is highly suppressed at the Higgs resonance
- We CANNOT assume $T_{\chi} = T$
- We have to calculate $T_{\chi}$ by solving the Boltzmann equation (and we found actually, $T_{\chi} < T$)
withOUT assuming $T_{\chi} = T$

**Boltzmann equation**

$$E \left( \frac{\partial}{\partial t} - H\vec{p} \cdot \frac{\partial}{\partial \vec{p}} \right) f_{\chi}(t, \vec{p}) = C_{\text{ann.}}[f_{\chi}] + C_{\text{el.}}[f_{\chi}]$$

**DM number density**

$$n_{\chi}(T_{\chi}) = g_{\chi} \int \frac{d^3p}{(2\pi)^3} f_{\chi}(\vec{p}, T_{\chi}) = sY$$

**DM temperature**

$$T_{\chi} = \frac{g_{\chi}}{3n_{\chi}} \int \frac{d^3p}{(2\pi)^3} \frac{\vec{p}^2}{E} f_{\chi}(\vec{p}) = \frac{s^{2/3}}{m_{\chi}} y$$

$$(\text{complicated equations})$$

$$\frac{dn_{\chi}}{dt} =$$

$$\frac{dT_{\chi}}{dt} =$$
scalar singlet DM case

- introduce a gauge singlet scalar “S” that is $Z_2$ odd
  \[ \mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} \partial^\mu S \partial_\mu S - \frac{m^2}{2} S^2 - \frac{\lambda_{sH}}{2} S^2 H^\dagger H - \frac{\lambda_s}{4!} S^4 \]

- $\lambda_{sH}$ is determined to obtain measured value of the DM energy density
- we can see the enhancement in the determined coupling

\[ T_\chi = T: \text{ standard calculation} \]
\[ \text{QCD-A}: \text{all quarks are treated as free particles} \]
\[ \text{QCD-B}: \text{only the light quarks (u,d,s) are treated as free particles} \]
\[ \text{(in both scenario, quarks are assumed to decouple below } T < 600 \text{ MeV due to the hadronization)} \]

results from [Binder, Bringmann, Gustafsson, Hryczuk ('17)]
scalar singlet DM case

- introduce a gauge singlet scalar “S” that is $Z_2$ odd
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- $\lambda_{sH}$ is determined to obtain measured value of the DM energy density
- we can see the enhancement in the determined coupling

\[ 10^{-4} \]

\[ m_{\text{DM}} \text{[GeV]} \]

\[ \lambda_{sH} \]

\[ \text{Br}_{\text{inv}}>0.13 \]

\[ \text{Br}_{\text{inv}}=0.019 \]

\[ \text{Br}_{\text{inv}}=0.0026 \]

\[ \text{Br}_{\text{inv}}=0.00024 \]

\[ \text{current bound on the Higgs invisible decay} \]

\[ \text{BR}_{\text{inv}} < \begin{cases} 0.13 & \text{[ATLAS-CONF-2020-008]} \\ 0.19 & \text{[CMS 1809.05937]} \end{cases} \]

\[ \text{prospect} \ [1905.03764] \]

\[ \text{BR}_{\text{inv}} < \begin{cases} 0.019 & \text{(HL-LHC)} \\ 0.0026 & \text{(ILC(250))} \\ 0.0023 & \text{ILC}_{500} \\ 0.0022 & \text{ILC}_{1000} \\ 0.0027 & \text{(CEPC)} \\ 0.00024 & \text{(FCC)} \end{cases} \]

results from [Binder, Bringmann, Gustafsson, Hryczuk ('17)]
\[ \text{Br}_{\text{inv}} \text{ is overlaid by TA} \]
Fermion DM case

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \bar{\chi} (i \gamma^\mu \partial_\mu - m_\chi) \chi + \frac{c_s}{2} \bar{\chi} \chi \left( H^\dagger H - \frac{v^2}{2} \right) + \frac{c_p}{2} \bar{\chi} i \gamma_5 \chi \left( H^\dagger H - \frac{v^2}{2} \right) \]

- two types of interactions (\( \bar{\chi} \chi H^\dagger H \) and \( \bar{\chi} i \gamma_5 \chi H^\dagger H \))
- for \( c_s = 0 \), scattering amplitude is suppressed by the small momentum transfer

\[ i\mathcal{M} \propto c_s + c_p \frac{\vec{q} \cdot \vec{s}}{m_\chi} \]

prospect [1905.03764]

\[ \text{BR}_{\text{inv}} < \begin{cases} 
0.019 & \text{(HL-LHC)} \\
0.0026 & \text{(ILC(250))} \\
0.0023 & \text{ILC}_{500} \\
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0.00024 & \text{(FCC)} 
\end{cases} \]
Summary

Higgs resonance perfectly fits the current status of WIMP

- small coupling is required to obtain the correct DM relic abundance
- small coupling predicts suppressed $\sigma_{SI}$
- Higgs invisible decay can be used to study DM at collider experiments

$T_\chi = T$ is not a good assumption

- kinetic decoupling may happen earlier
- need to calculate both $n_\chi$ and $T_\chi$

Larger coupling is required

- $T_\chi < T$
- DM-Higgs coupling is enhanced
- Higgs invisible decay rate is also enhanced
- enlarged chance to the DM signal from the Higgs decay!
Backup
scalar DM with direct detection experiments
fermionDM with scalar-couplings

Figure 3: The values of the couplings that explain the measured value of the DM energy density. The blue-hatched region (\(\square\)) is excluded by the XENON1T experiment [4]. The red-dashed line shows the prospect of the XENONnT and LZ experiments [32, 33]. The orange-hatched region (///) is below the neutrino floor and cannot be accessed by the direct detection experiments. The other color notation is the same as in Fig. 1.