Early kinetic decoupling in Higgs portal dark matter models

Tomohiro Abe

Institute for Advanced Research,

KMI, Nagoya U.

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The DM-Higgs coupling was under estimated for $m_{DM} \simeq m_h/2$ *in WIMP models*

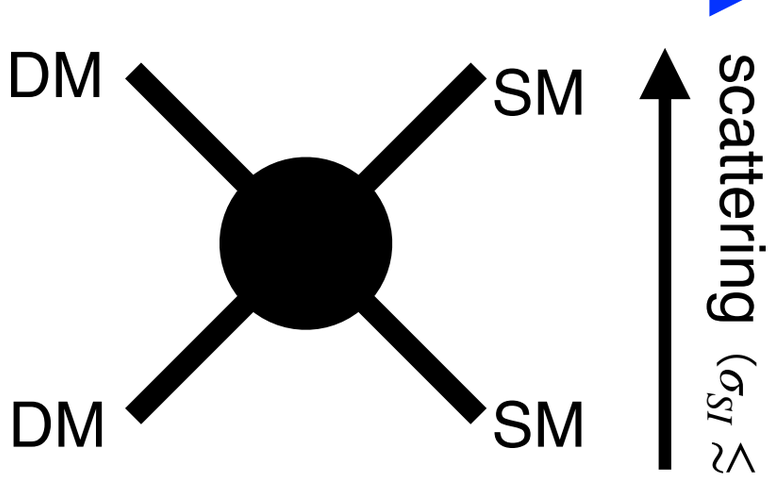
Higgs invisible decay is enhanced compared to the previous studies

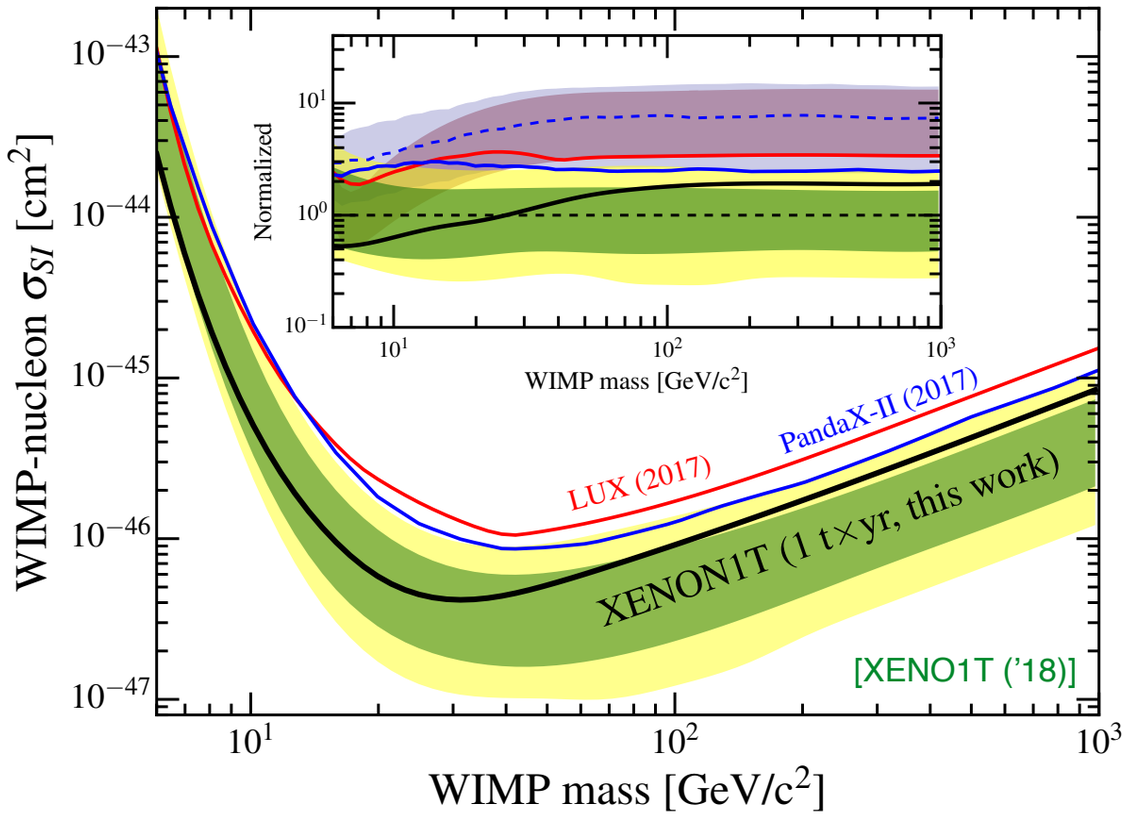
Weakly Interacting Massive Particle

SM-DM scattering should be suppressed

- $\sigma_{SI} \lesssim \mathcal{O}(10^{-46})\ cm^2$ from XENON1T

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

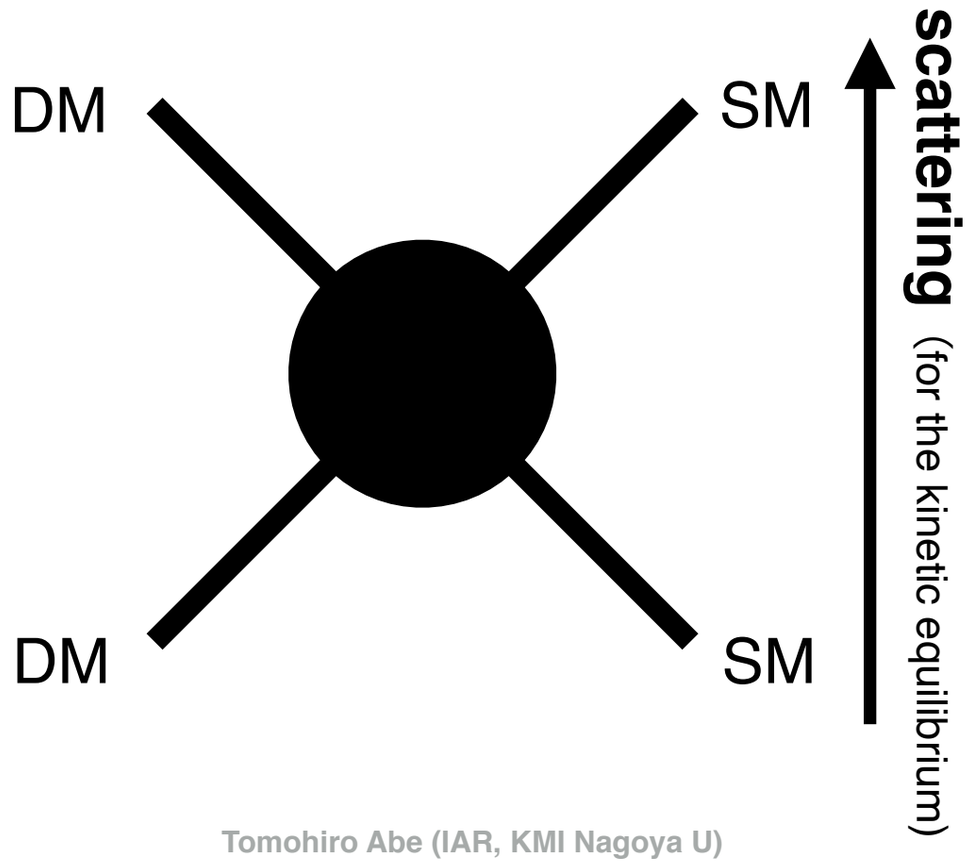




small scattering rate and DM temperature

- temperature of DM (T_χ) 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_χ by solving the Boltzmann equation

(and we found actually, $T_\chi < T$)



withOUT assuming $T_\chi = T$

[Binder, Bringmann, Gustafsson, Hryczuk ('17)]

Boltzmann equation

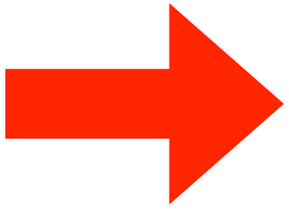
$$E\left(\frac{\partial}{\partial t} - H\vec{p}\cdot\frac{\partial}{\partial \vec{p}}\right) f_\chi(t,\vec{p}) = C_{ann.}[f_\chi] + C_{el.}[f_\chi]$$

DM number density

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

DM temperature

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



obtain and solve the following coupled equations

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_{T_\chi} n_\chi^2 + \langle\sigma v\rangle_T n_{\chi,eq}^2$$

$$\frac{dT_\chi}{dt} = (\text{complicated equations}).$$

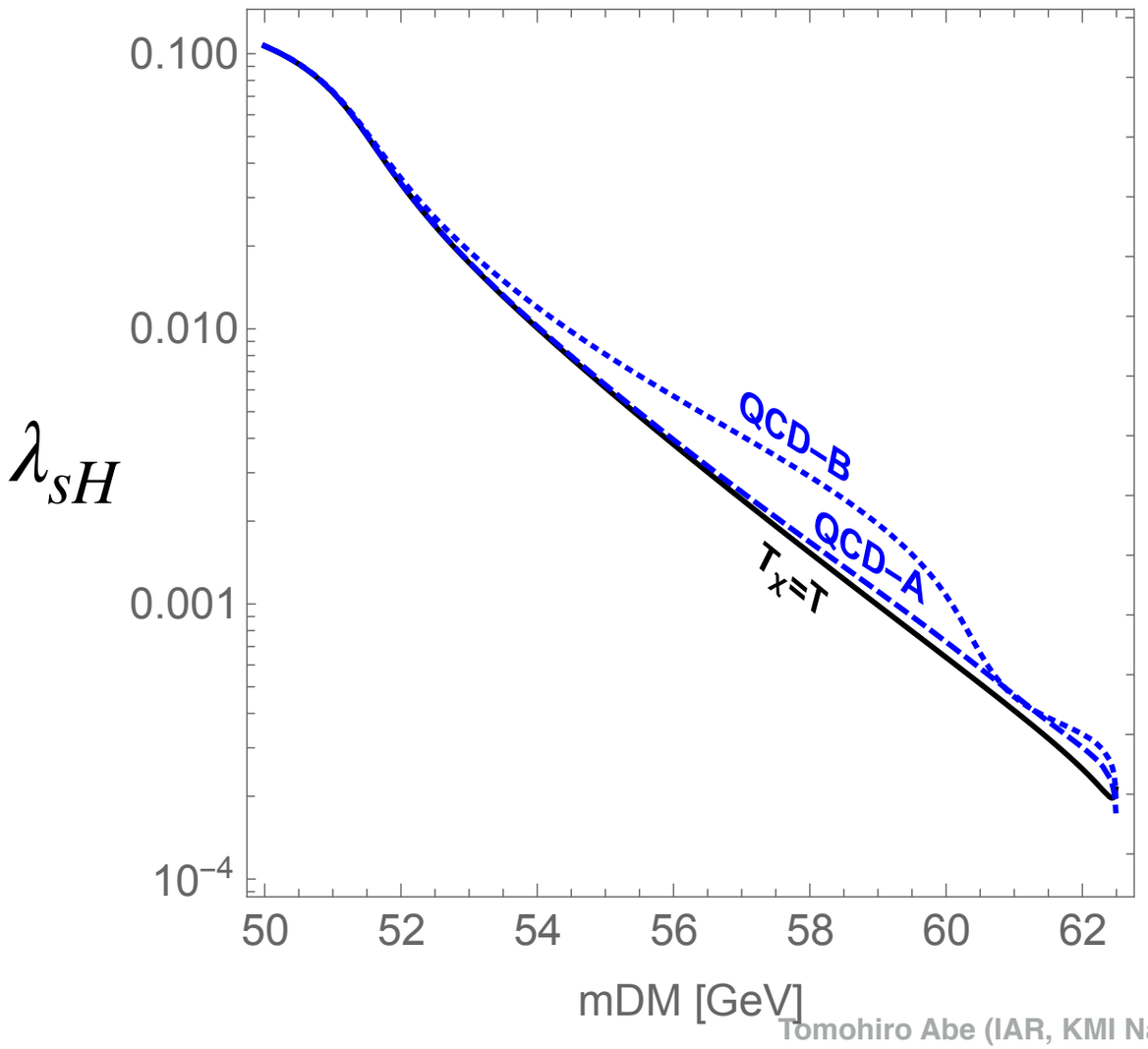
scalar singlet DM case (1/2)

[Silveira and Zee ('85), McDonald ('94), Burgess et.al ('01), Kanemura et. al ('10), … , TA Kitano Sato ('15), TA Sato ('19), …]

- introduce a gauge singlet scalar "S" that is Z_2 odd

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{m^2}{2} S^2 - \frac{\lambda_{sH}}{2} S^2 H^\dagger H - \frac{\lambda_s}{4!} S^4$$

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



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

results from
[Binder, Bringmann, Gustafsson, Hryczuk ('17)]

scalar singlet DM case (2/2)

[Silveira and Zee ('85), McDonald ('94), Burgess et.al ('01), Kanemura et. al ('10), … , TA Kitano Sato ('15), TA Sato ('19), …]

- introduce a gauge singlet scalar "S" that is Z_2 odd

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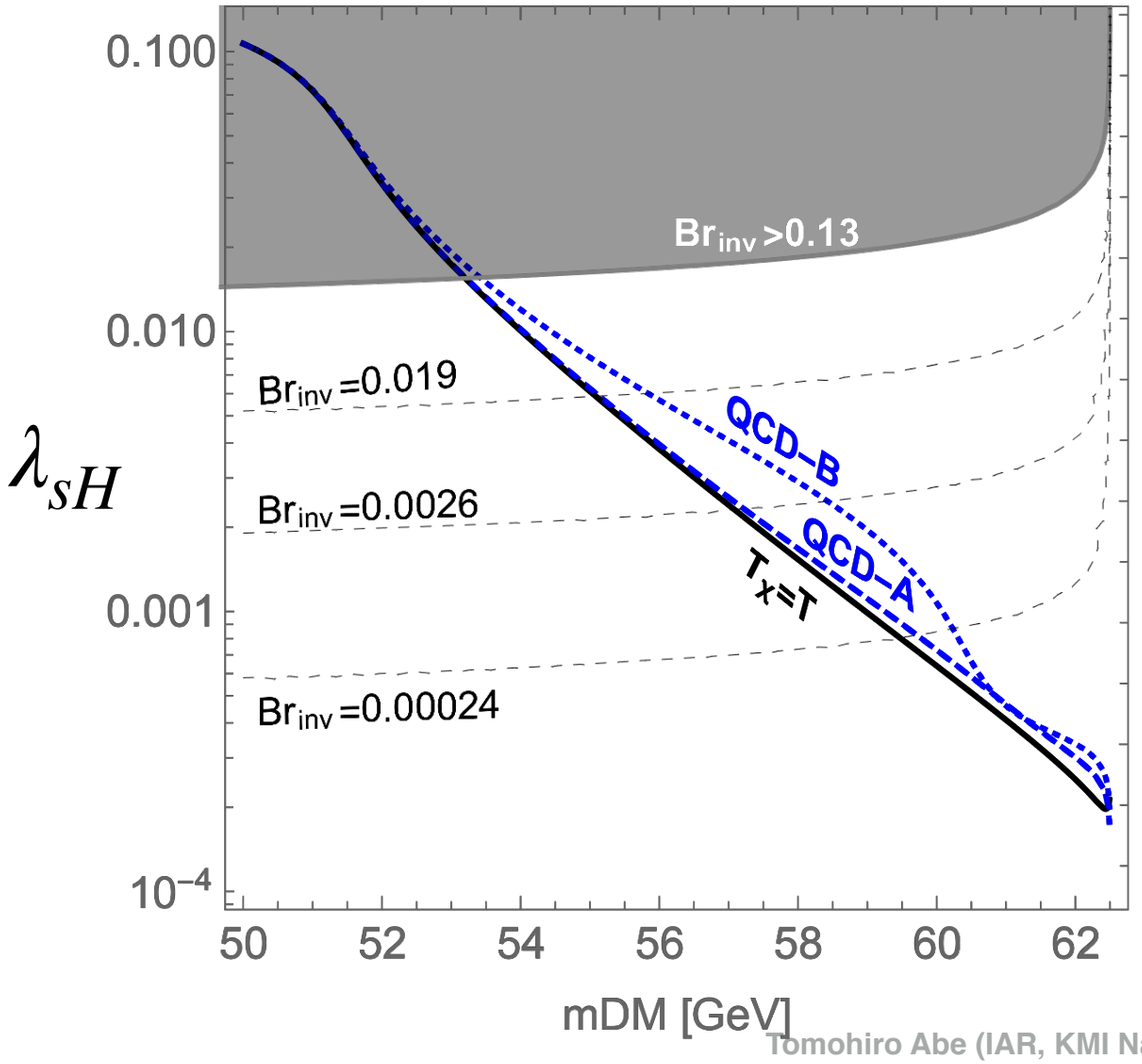


current bound on the Higgs invisible decay

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

prospect [1905.03764]

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

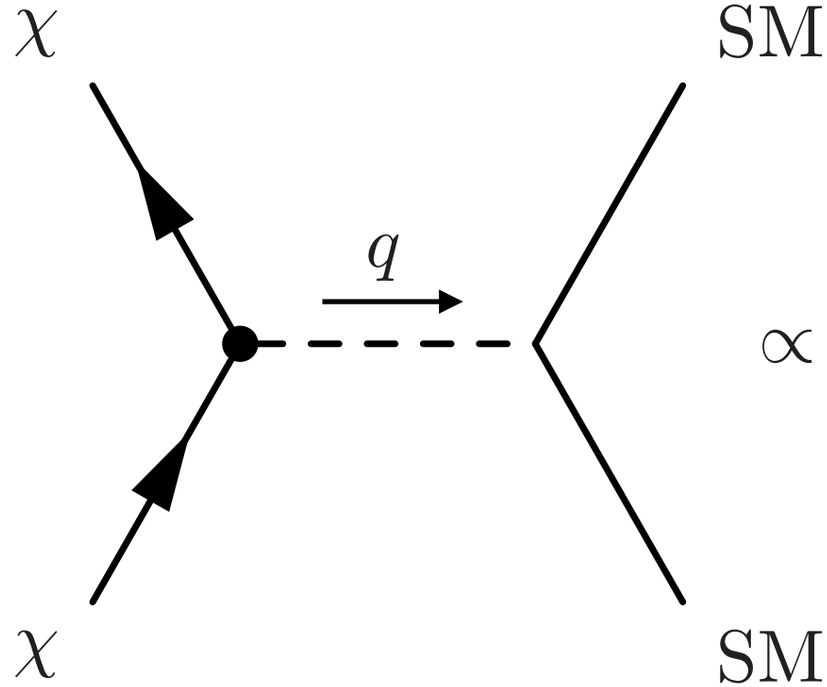
results from [Binder, Bringmann, Gustafsson, Hryczuk ('17)]
Br_{inv} is overlaid by TA

Fermion DM case (1/2)

[Kanemura et. al ('10), Lopez-Honorez et.al ('12), Djouadi et.al ('13), Greljo et.al ('13), Beniwal et.al ('16), GAMBITCollaboration ('18), TA Sato ('19), …]

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

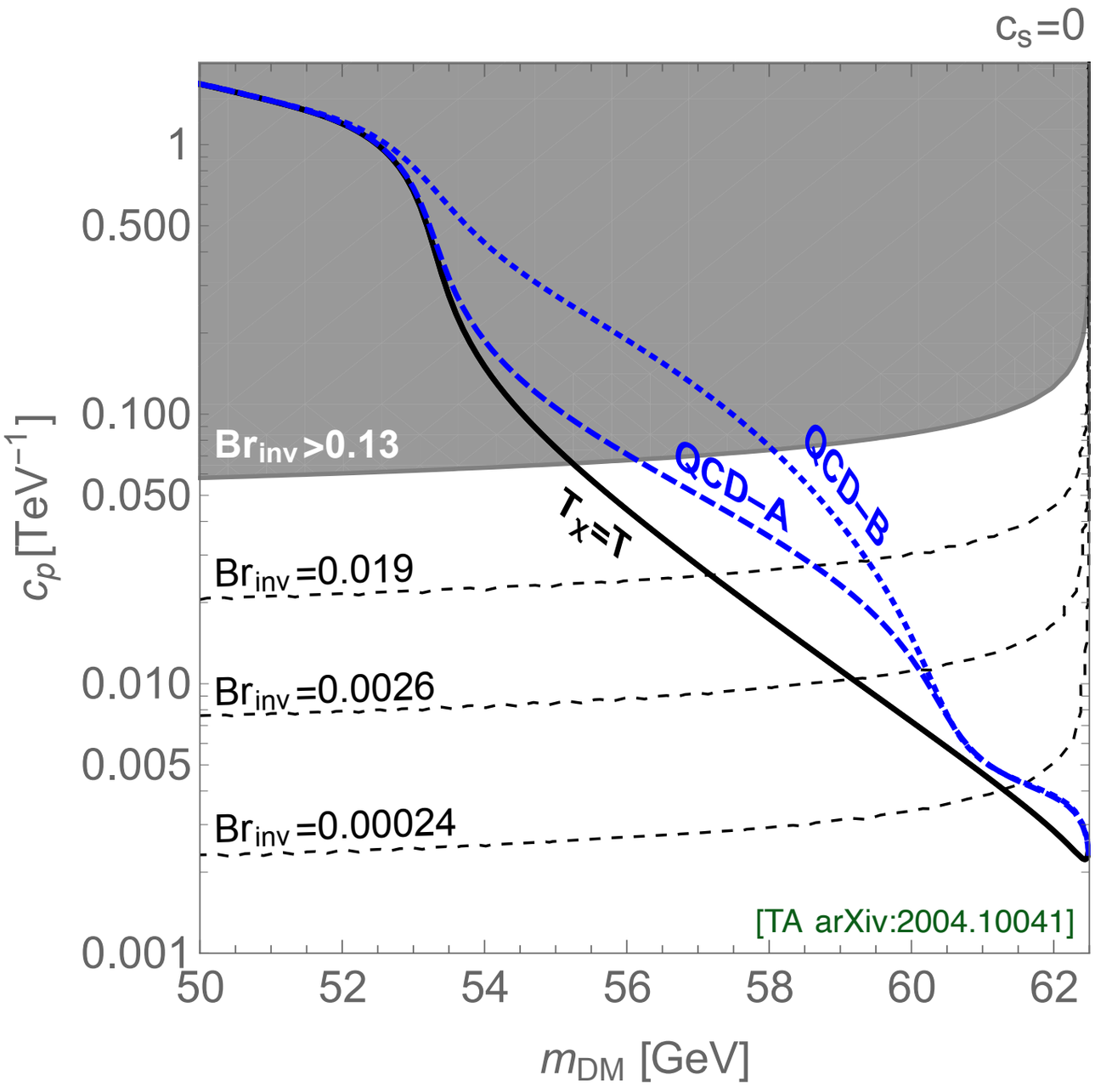
- two types of interactions ($\bar{\chi}\chi H^\dagger H$ and $\bar{\chi}i\gamma_5\chi H^\dagger H$)
- scattering amplitude is suppressed by the small momentum transfer if $c_s \ll c_p$



$$\propto \; c_s + c_p \frac{\vec{q}\cdot\vec{s}}{m_\chi}$$

extra suppression factor

Fermion DM case (2/2)



prospect [1905.03764]

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

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Summary

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

- kinetic decoupling may happen earlier
- need to calculate both n_χ and T_χ

DM-Higgs coupling was underestimated

- $T_\chi < T$
- DM-Higgs coupling is enhanced
- Higgs invisible decay rate is also enhanced

Chance to the DM signal from the Higgs decay is enlarged

Backup

Early kinetic decoupling

high temperature

$$n_\chi = n_\chi^{eq}, \quad T_\chi = T$$

$x = \frac{m_{DM}}{T} \simeq 20$ — chemical decoupling (freeze-out)

$$n_\chi \neq n_\chi^{eq}, \quad T_\chi = T$$

$x \gg 20$ — kinetic decoupling

$$n_\chi \neq n_\chi^{eq}, \quad T_\chi \neq T$$

low temperature

Early kinetic decoupling

high temperature

$$n_\chi = n_\chi^{eq}, \quad T_\chi = T$$

$x = \dfrac{m_{DM}}{T} \simeq 20$ — chemical decoupling (freeze-out)

$$n_\chi \neq n_\chi^{eq}, \quad T_\chi = T$$

If scattering is less efficient, then

$$T_\chi \neq T$$

(early kinetic decoupling)

$x \gg 20$ — kinetic decoupling

$$n_\chi \neq n_\chi^{eq}, \quad T_\chi \neq T$$

low temperature

two conditions to see the effect of $T_\chi \neq T$

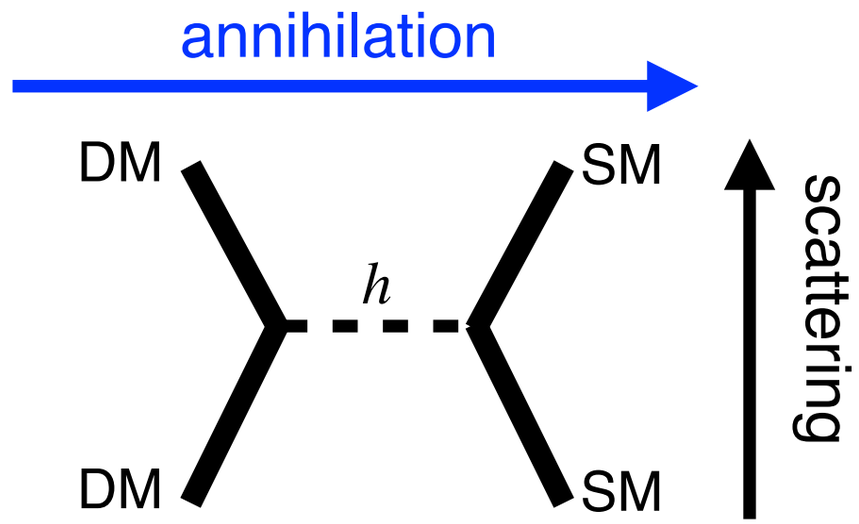
(1) small DM-SM scattering is required

- otherwise $T_\chi = T$
- (e.g.) DM pairs annihilation through Higgs resonance

(2) temperature dependence in $\langle \sigma v \rangle$

- otherwise the differential eq. is the same as the usual

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle_{T_\chi} n_\chi^2 + \langle \sigma v \rangle_T n_{\chi,eq}^2$$

- (e.g.) resonant annihilation, threshold, co-annihilation, co-scattering, …

Higgs portal models with the Higgs resonant DM annihilation is a nice play ground to see the effect