Early kinetic decoupling and Higgs invisible decay in simple dark matter models

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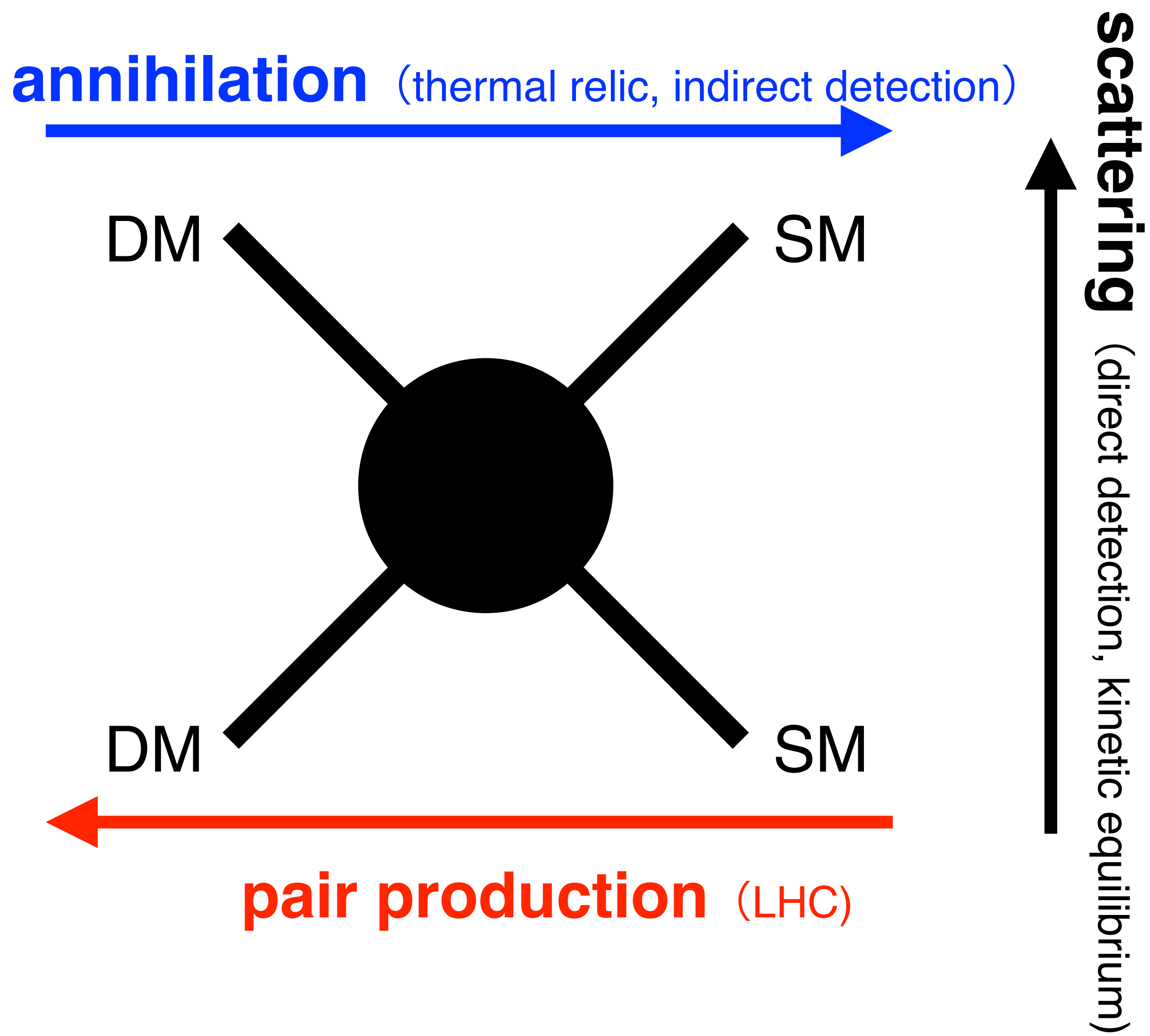
$Br(h \to DMs)$ was underestimated in WIMP models

Weakly Interacting Massive Particle

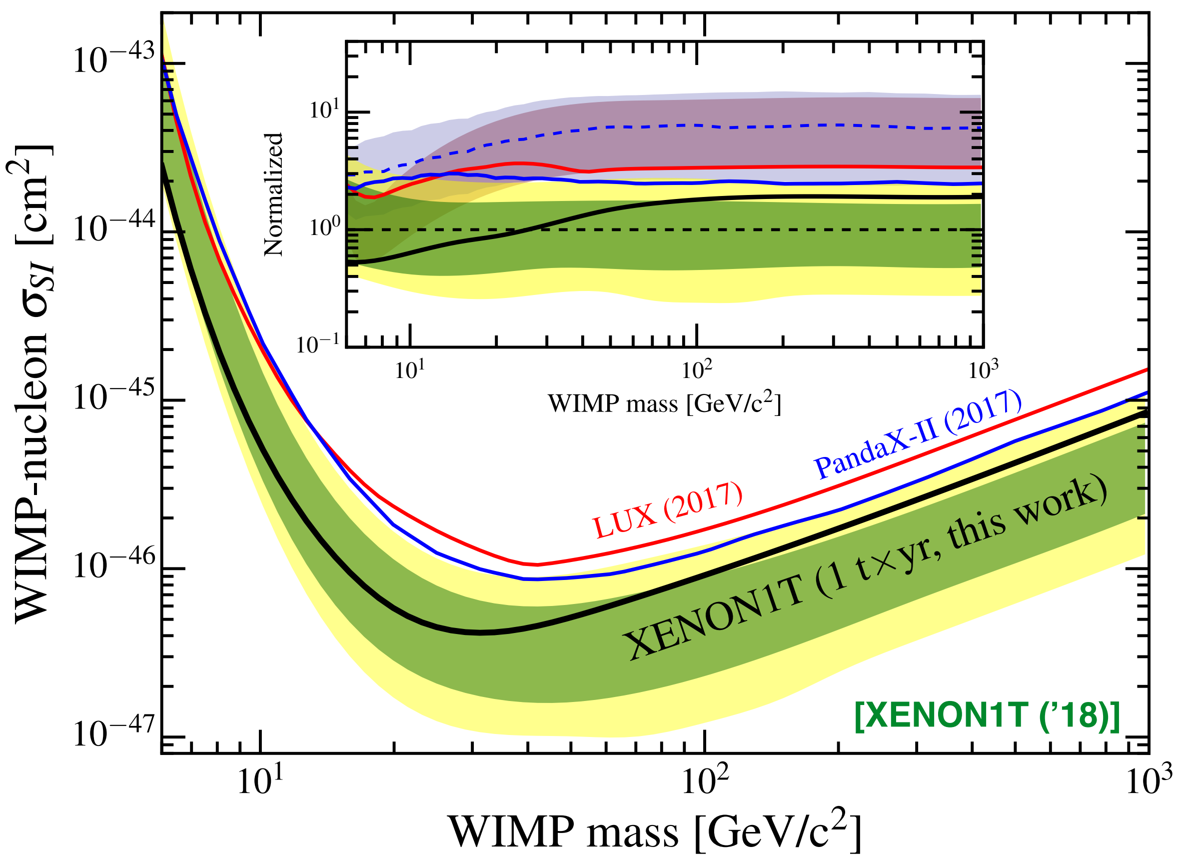
WIMP (Weakly Interacting Massive Particle)

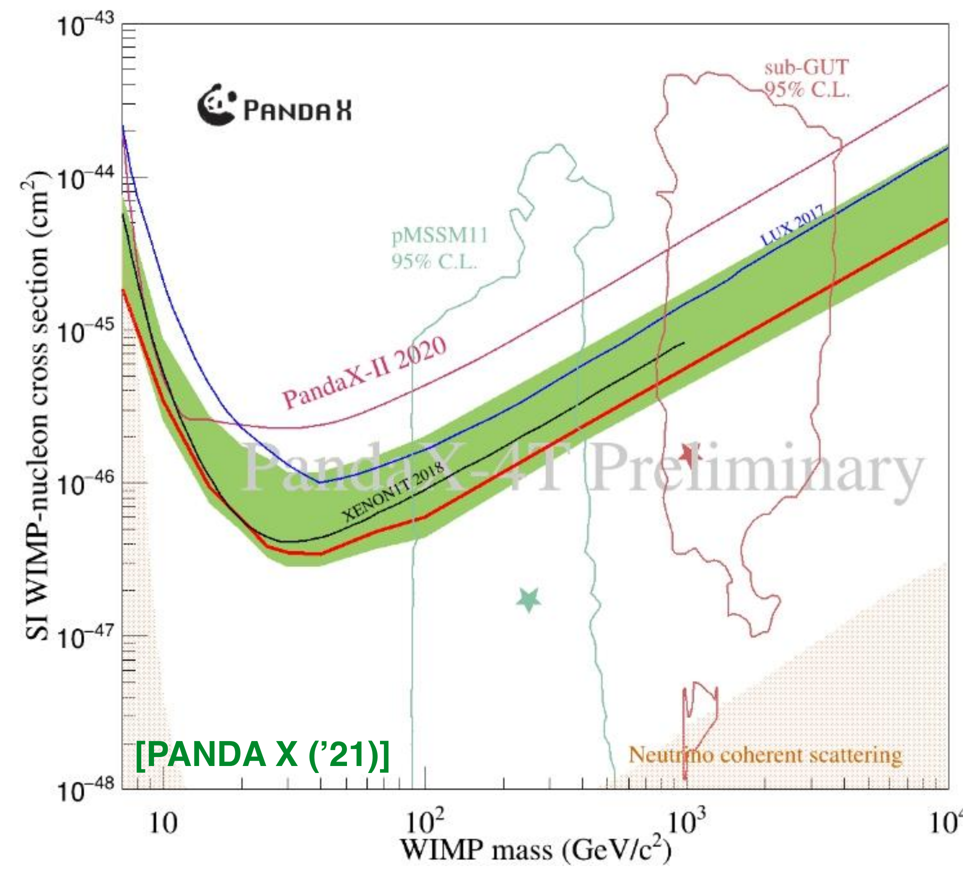
- has short range interactions with the standard model particles
- energy density is explained by the freeze-out mechanism
- correlation btw. various processes



scattering has to be suppressed

No significant signals at the direct detection experiments





- we still have many models that can explain these null results （s-channel resonance, pseudo-scalar interaction, CP-odd mediator, pseudo Nambu-Goldstone model, ...)
- ***However,*** we have to revisit the thermal relic calculation because the small σ_{scat} can cause the kinetic decoupling earlier than usual

standard way to calculate Ωh^2

early universe

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

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

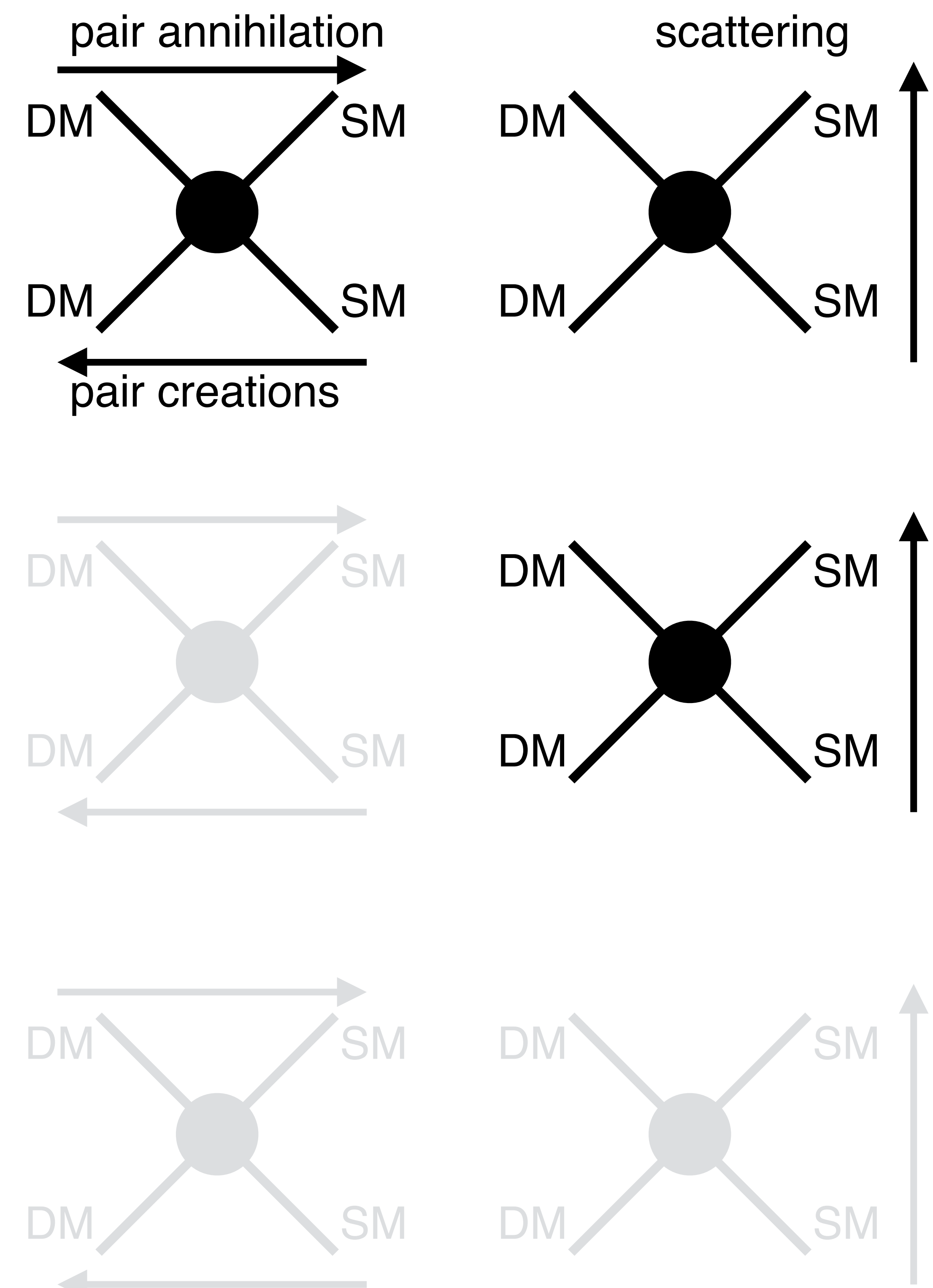
$$n_\chi \neq n_\chi^{eq}, \quad T_\chi = T$$

(This is the important era for the determination of Ωh^2)

$x \gg 20$ — kinetic decoupling

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

current universe



standard way to calculate Ωh^2

early universe

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

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

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

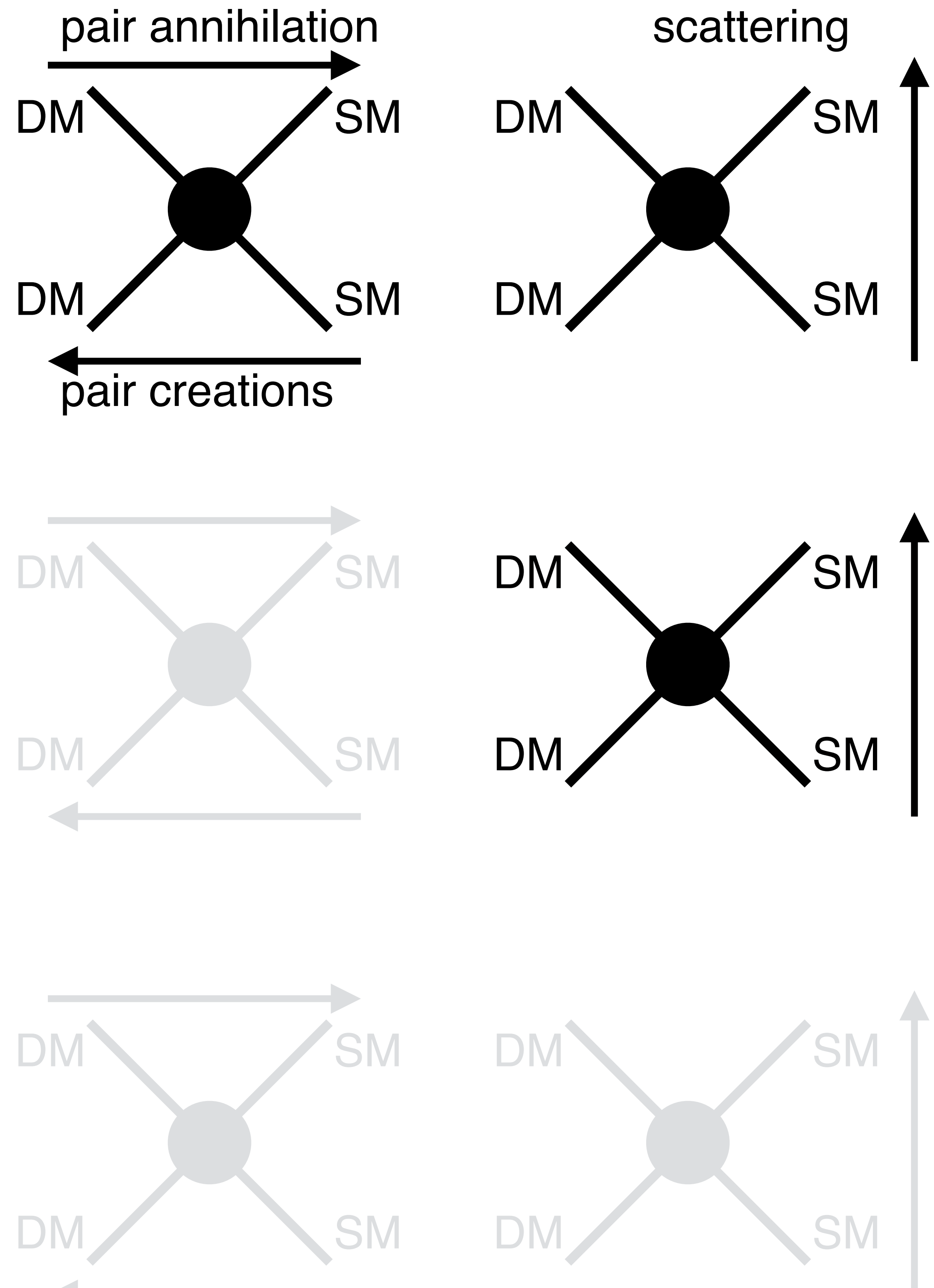
(This is the imp rtant era for
ion of Ωh^2)

if scattering is highly suppressed

$$T_\chi \neq T$$

(early kinetic decoupling)

current universe



How to calculate Ωh^2 without assuming $T_\chi = T$

Boltzmann equation

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

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

If $T_\chi = T$

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

If $T_\chi \neq T$

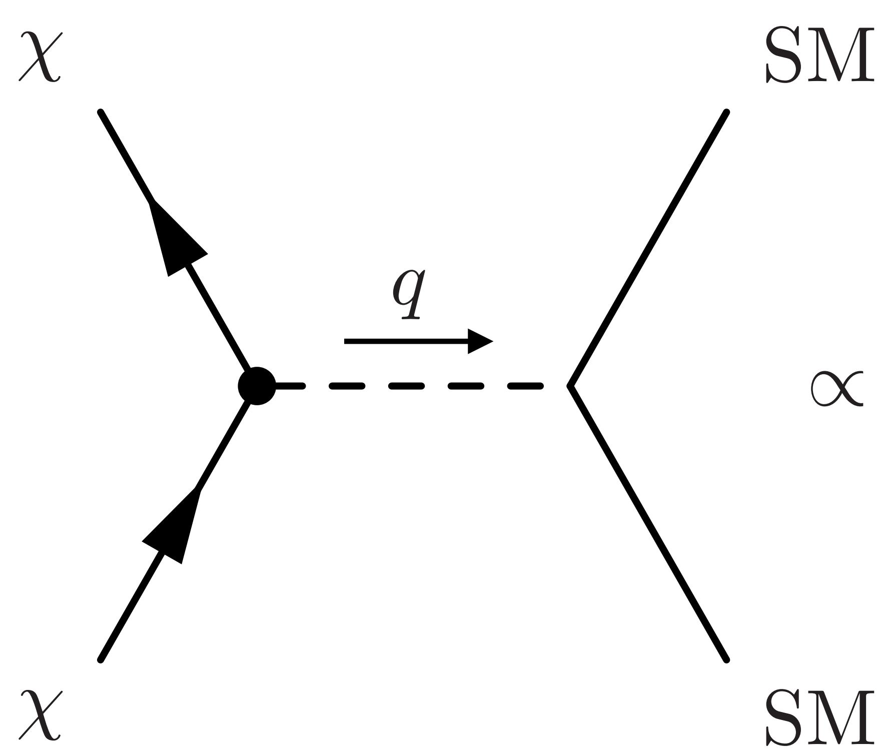
$$\begin{cases} \dfrac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_{T_\chi} n_\chi^2 + \langle\sigma v\rangle_T n_{\chi,eq}^2 \\ \dfrac{dT_\chi}{dt} = \text{(complicated equations depending on } \langle\sigma v\rangle, \langle\sigma v\rangle_2, \text{and } |\mathcal{M}_{\text{scattering}}|^2). \end{cases}$$

A Fermion DM model

[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 DM-Higgs interactions ($\bar{\chi}\chi H^\dagger H$ and $\bar{\chi}i\gamma_5\chi H^\dagger H$)
- scattering can be suppressed by the momentum transfer

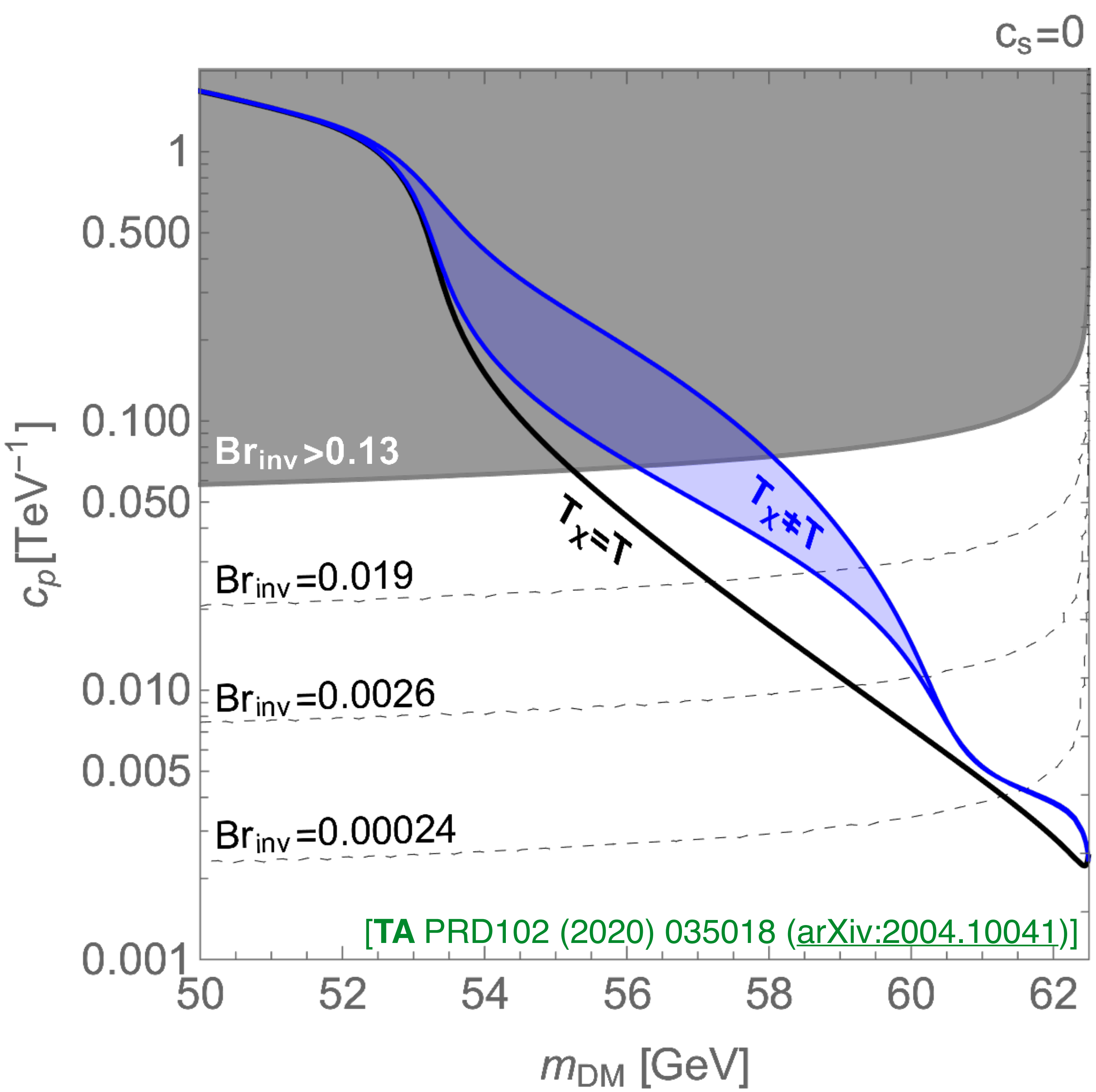


$$\propto \; c_s + c_p\frac{\vec{q}\cdot\vec{s}}{m_\chi}$$

extra suppression factor

Result

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



The coupling (c_p) is determined to obtain the right amount of the DM energy density

- $T_\chi = T$: result in the literatures
- $T_\chi \neq T$: with early kinetic decoupling effect
  (blue band is due to the QCD uncertainty)

current bound on the Higgs invisible decay

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

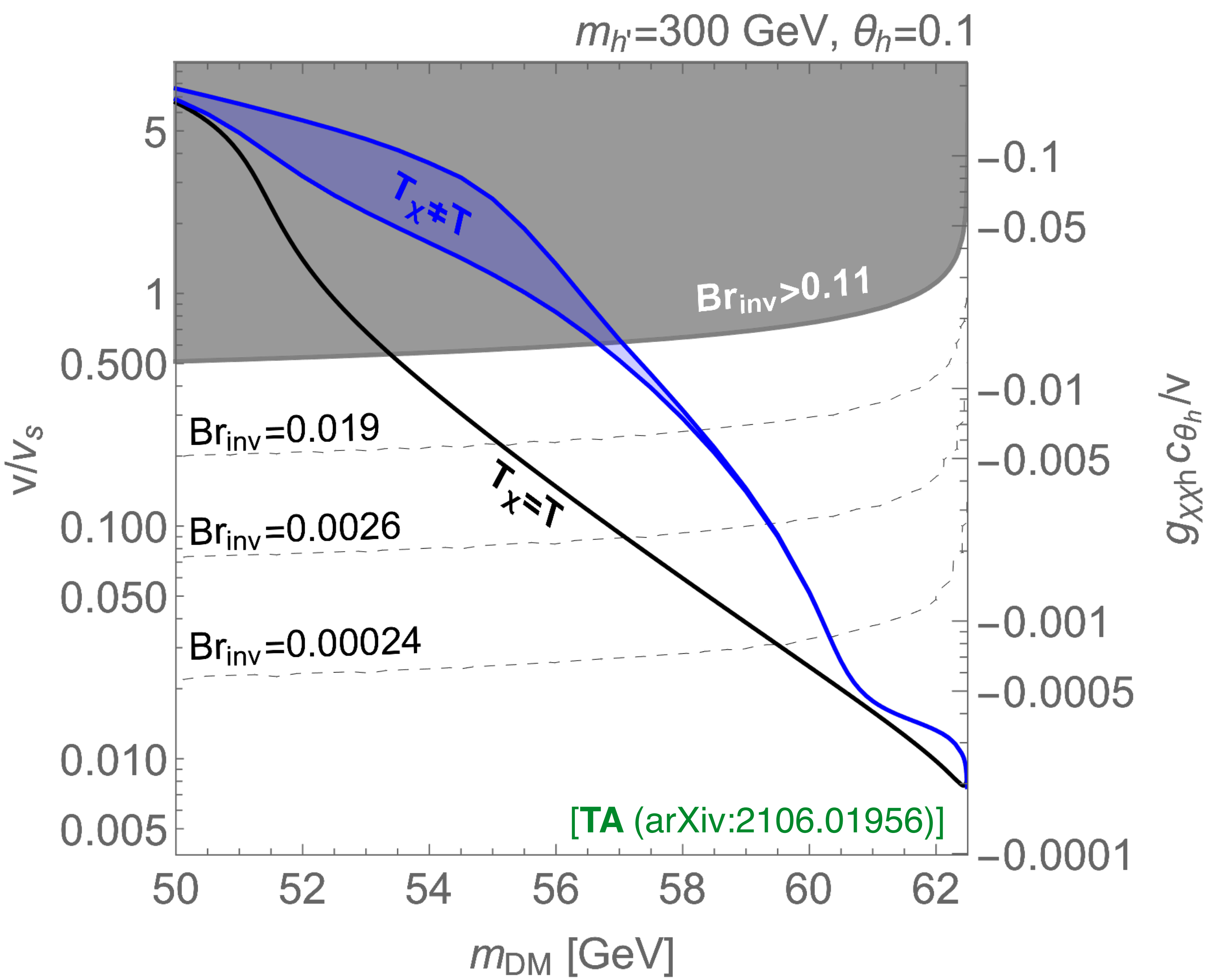
prospect [1905.03764]

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

Another example

pseudo-Nambu-Goldstone DM model [Gross Lebedev Toma ('17)]

- DM-SM scattering is much suppressed
- prediction of Br(h→DMs) was really underestimated



Summary

$T_\chi = T$ is not a good assumptions in some WIMP models

- if DM-SM scattering is highly suppressed, then we need to calculate the evolution of DM temperature as well

example of phenomenological consequence

- DM-Higgs coupling was underestimated in Higgs resonant regime
- Br(H → inv.) can be much larger than in the previous studies

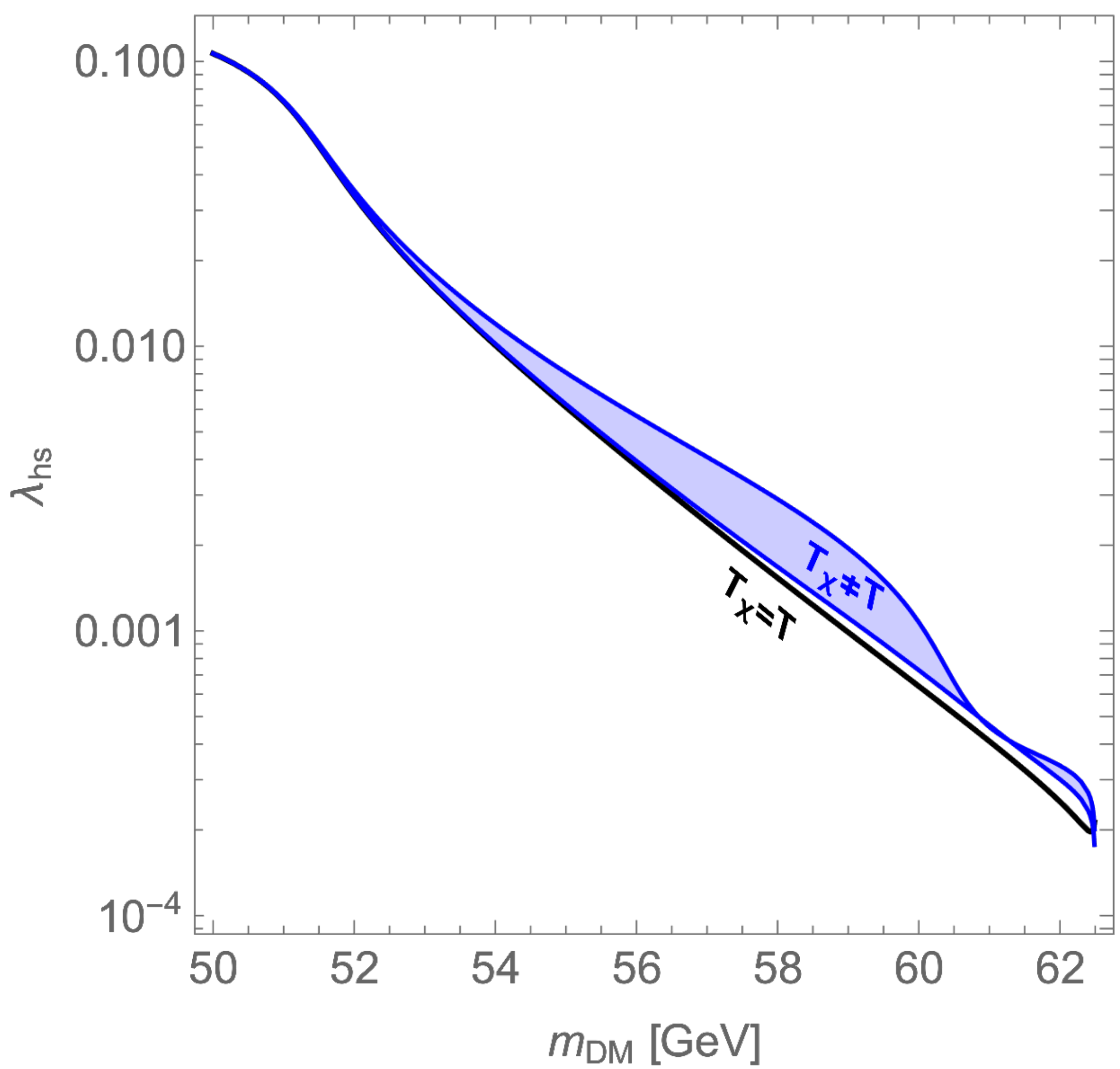
Backup

real scalar DM model case

[Silveria et.al. ('85), McDonald ('94), Burgess ('01), …, Cline et.al. ('13), TA Kitano Sato ('15), … GAMBIT collaboration ('17, '19)]

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

- λ_{sH} is determined to obtain the measured value of Ωh^2
- λ_{sH} should be larger than one in the literature, but enhancement is mild



- $T_\chi = T$: result in the literatures
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[Binder, Bringmann, Gustafsson, Hryczuk ('17)]

Public code is available

DRAKE [Binder, Bringmann, Gustafsson, Hryczuk (2103.01944)]

- calculate Ωh^2 with the evolution of DM temperature
- Mathematica / Wolfram Engine
- give the code σv and $|\mathscr{M}|^2$ then we obtain result

Dark matter Relic Abundance beyond Kinetic Equilibrium

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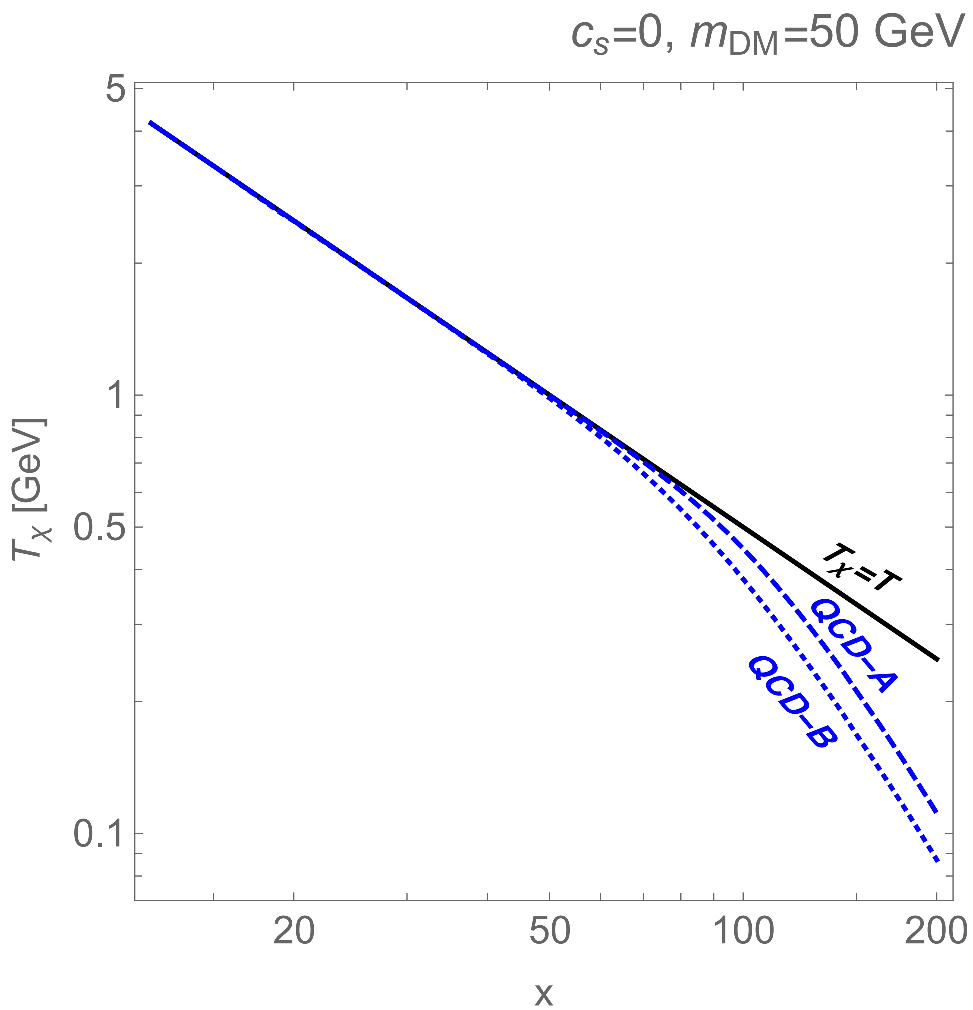
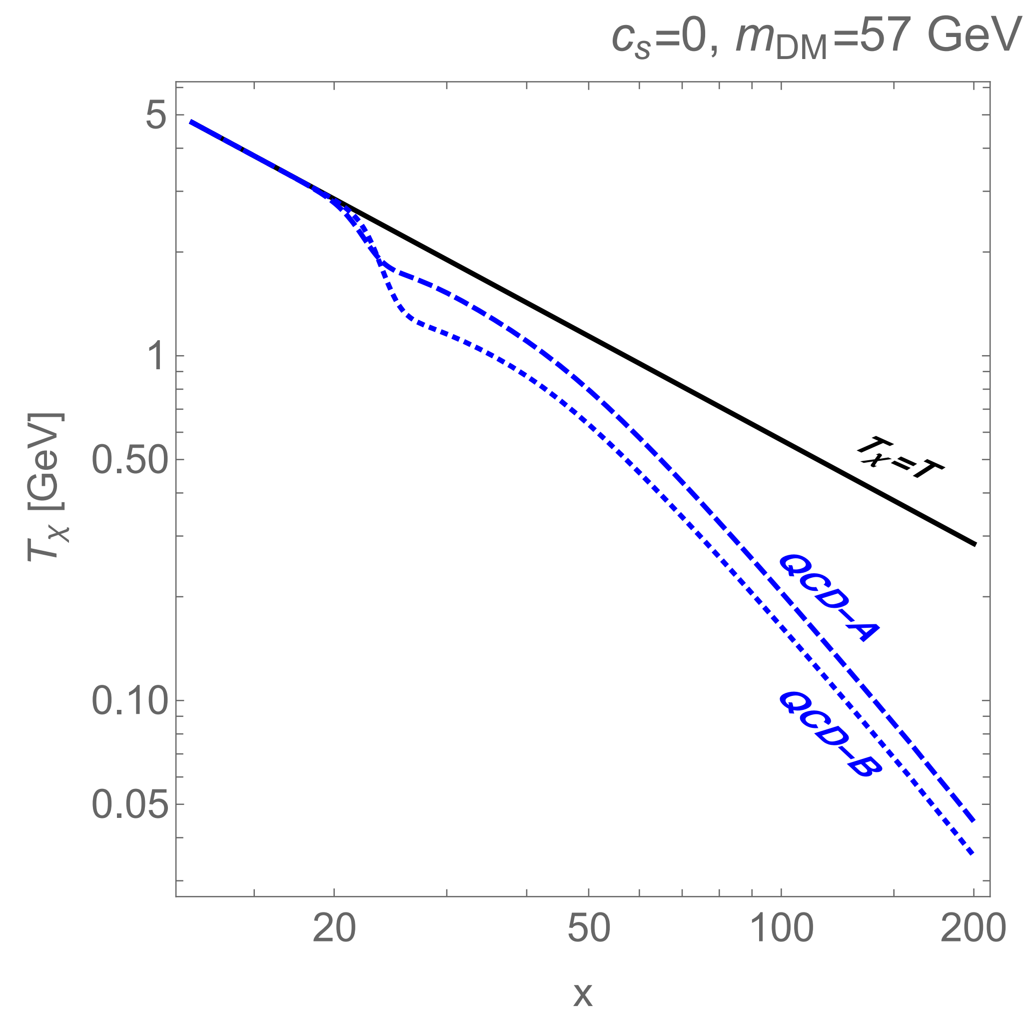
Evolution of T_χ in the fermionic DM model

- In the small coupling region, $T_\chi \neq T$ happens around x = 20 (x = m_χ/T)





t dependence in the scattering amplitude

model	$\sum_{spin} \lvert\mathcal{M}_{\chi b\to\chi b}\rvert^2$ (for low momentum transfer region)
real scalar singlet (spin = 0)	$24\lambda_{hS}^2 \frac{m_b^4}{m_h^4}$
fermion DM (w/ CPV int.) (spin = 1/2)	$48(c_p m_h)^2 \frac{m_b^4}{m_h^4} \times \left(\frac{-t}{m_h^2}\right)$
pNG model (spin = 0)	$24 s_h^2 c_h^2 \frac{m_h^4}{m_{h'}^4} \frac{(m_h^2 - m_{h'}^2)^2}{v^2 v_s^2} \frac{m_b^4}{m_h^4} \times \left(\frac{-t}{m_h^2}\right)^2$

power of the t dependence is a key to suppress the scattering amp..
($-t \simeq$ (momentum transfer)^2 is quite small)