

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

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2021.4.1

[arXiv:2004.10041](https://arxiv.org/abs/2004.10041)

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Br(h → DMs)

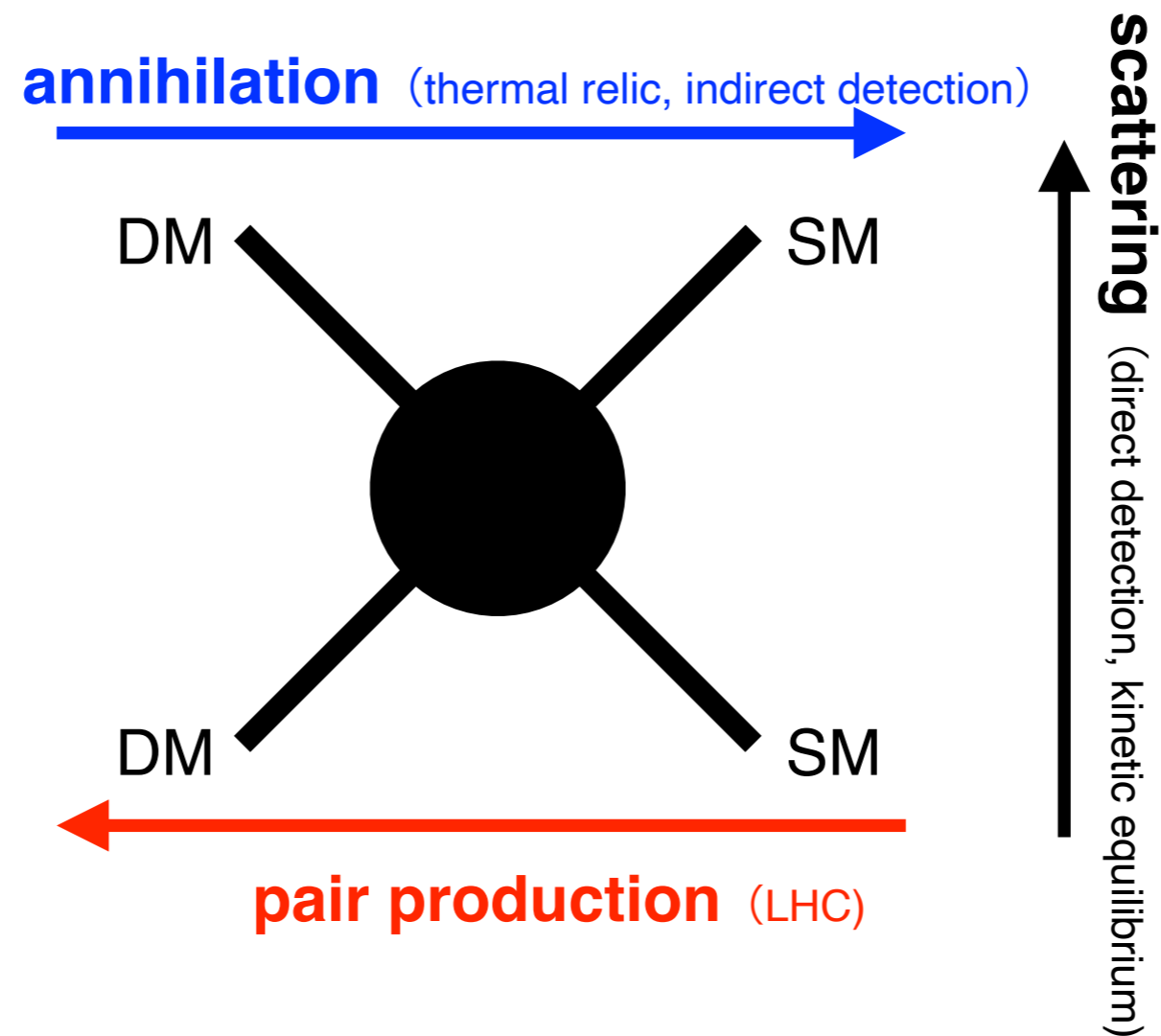
was

***underestimated
in WIMP models***

Weakly Interacting Massive Particle

WIMP (Weakly Interacting Massive Particle)

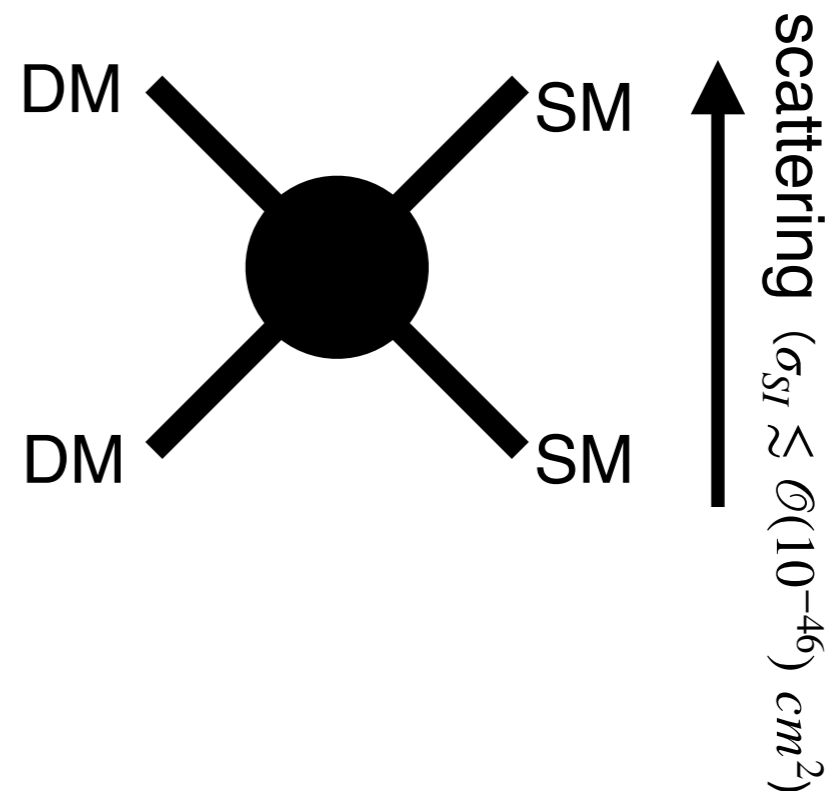
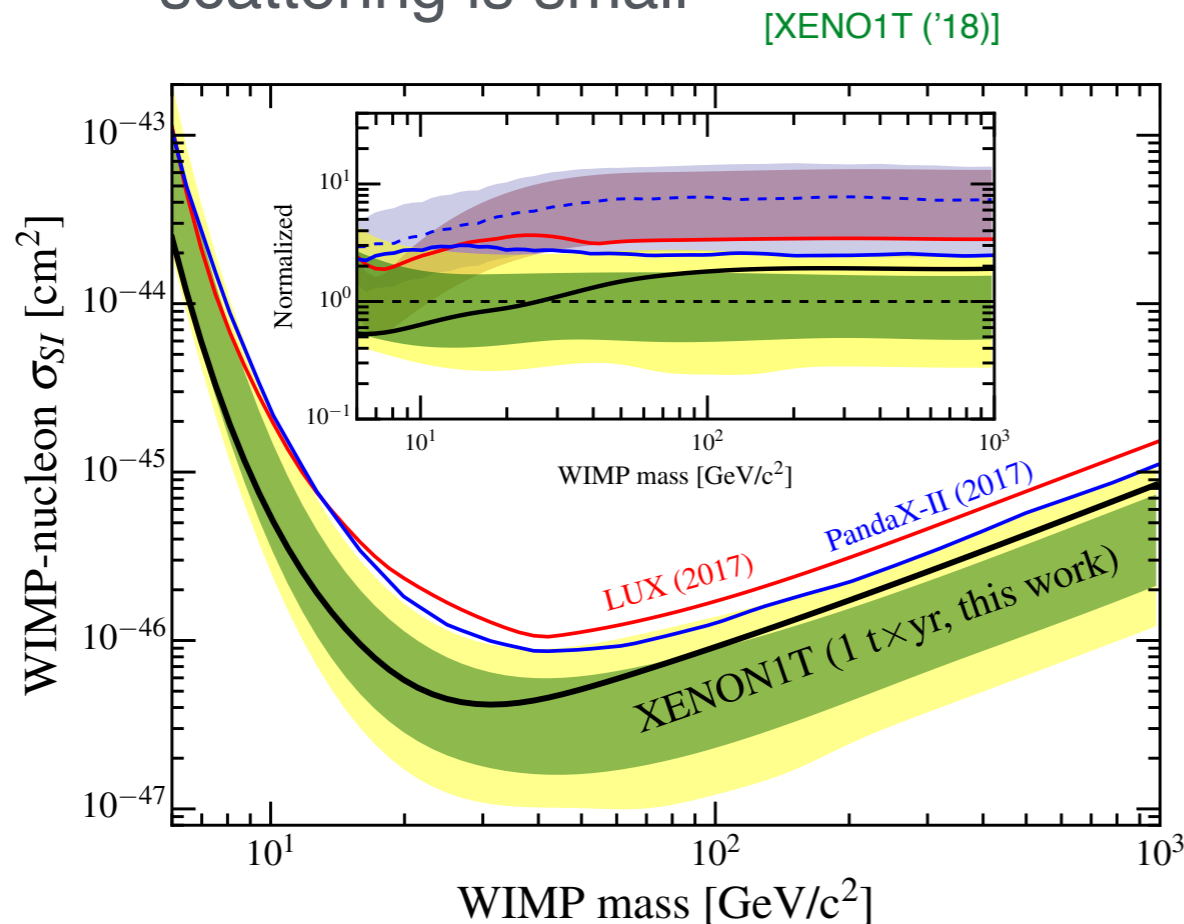
- has short range interactions with the standard model particles
- energy density is explained by the freeze-out mechanism
- correlation btw. various processes



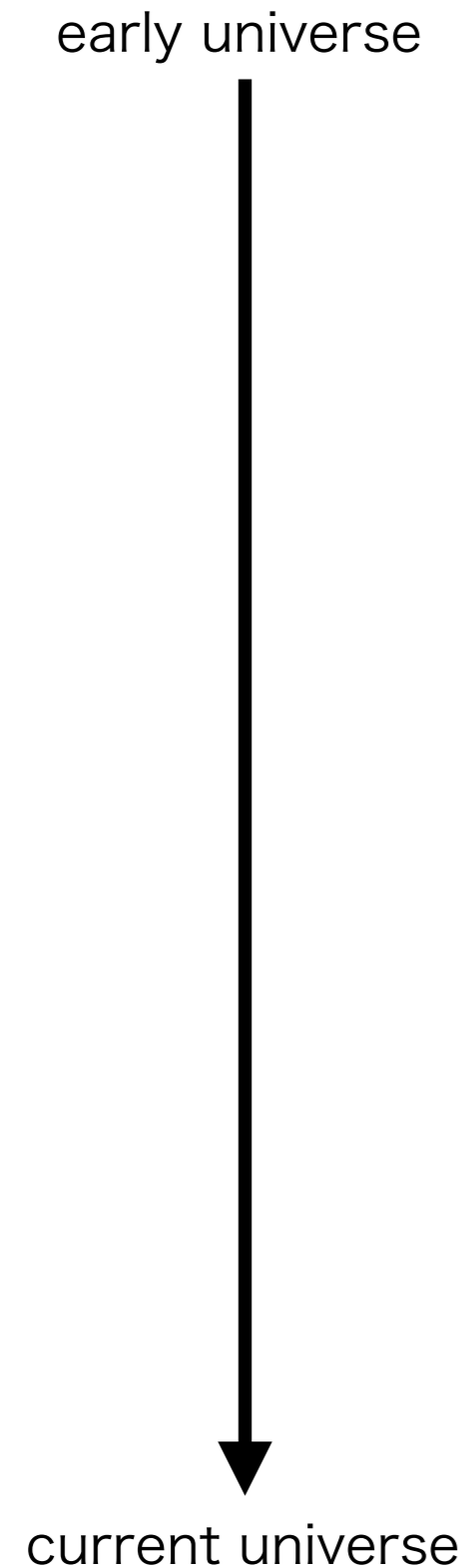
WIMP vs direct detection experiments

small σ_{SI} is required

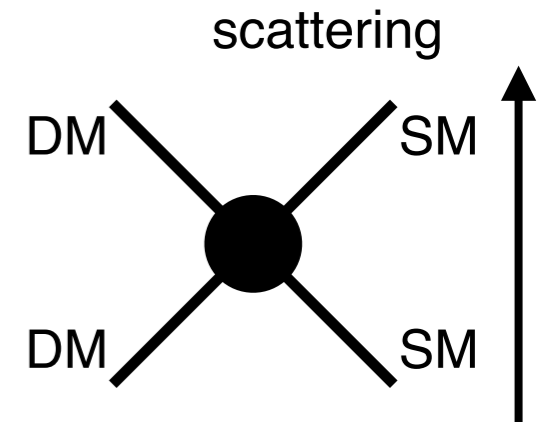
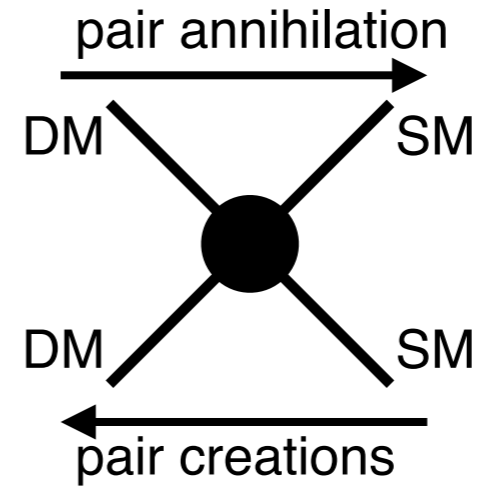
- $\sigma_{SI} \lesssim \mathcal{O}(10^{-46}) \text{ cm}^2$
- many models can satisfy this constraint (s-channel resonance, pseudo-scalar interaction, CP-odd mediator, pseudo Nambu-Goldstone model, ...)
- calculation of the thermal relic should be revisited when DM-SM scattering is small



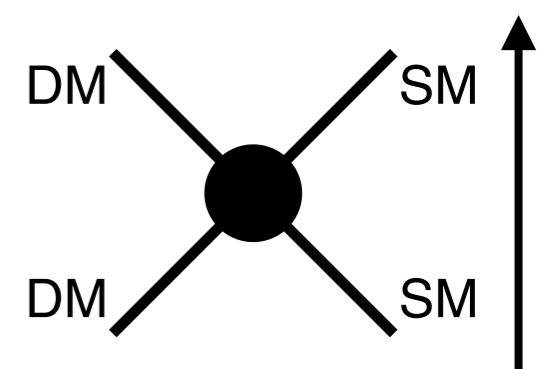
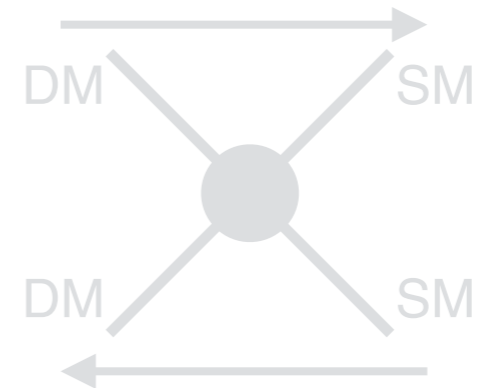
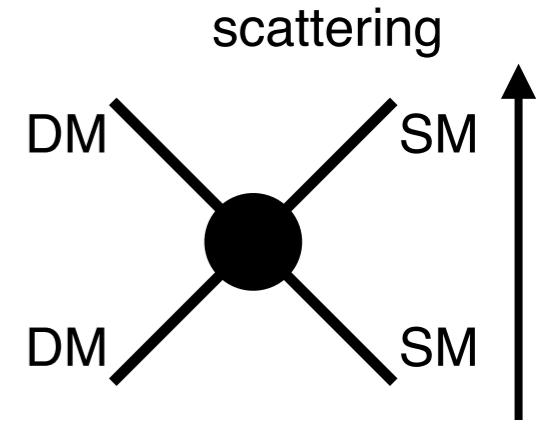
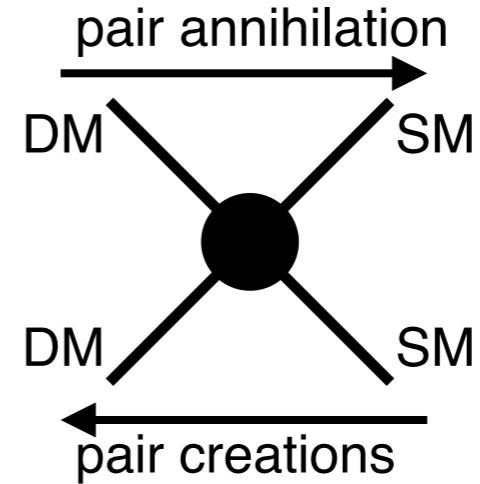
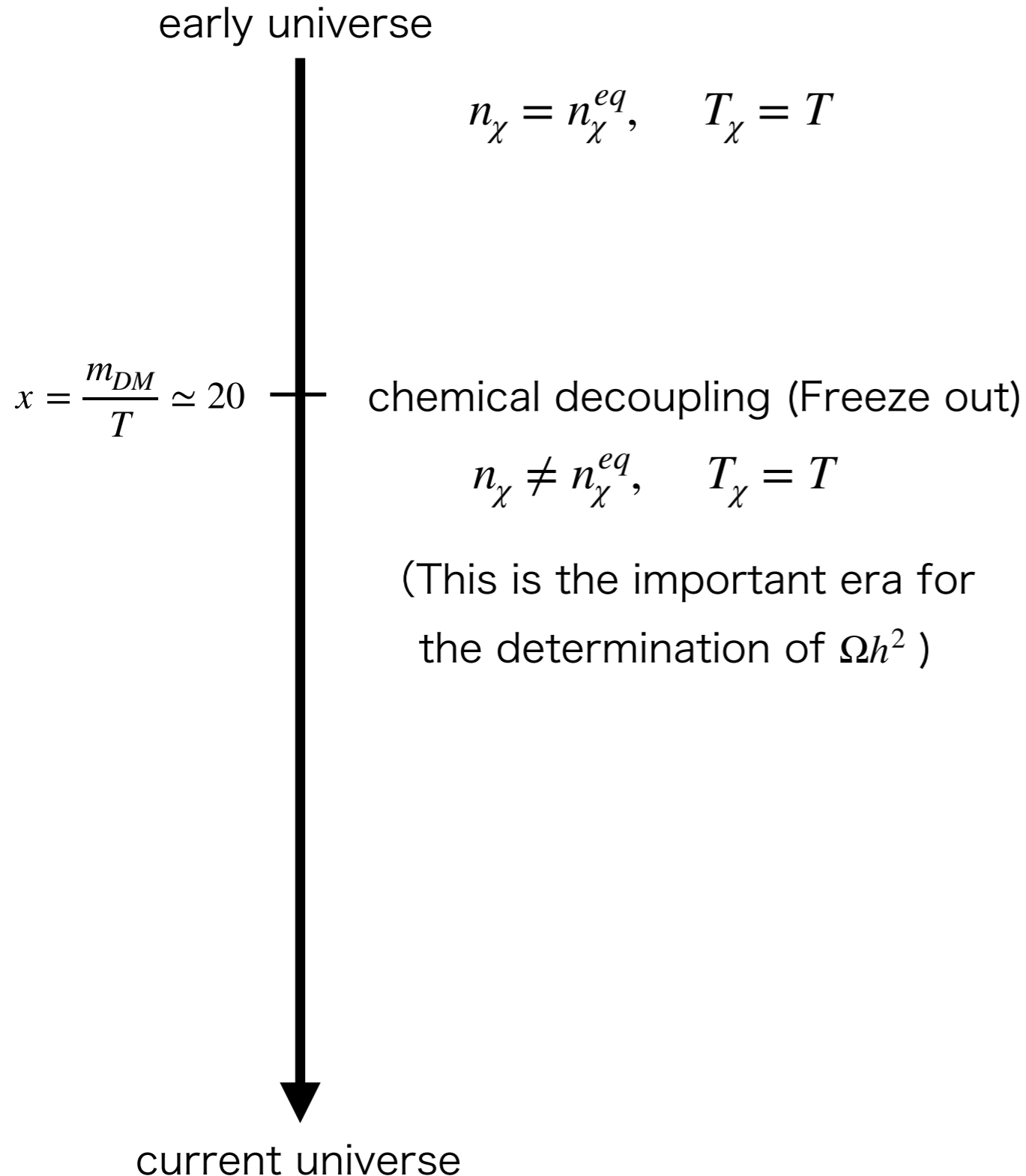
standard way to calculate Ωh^2



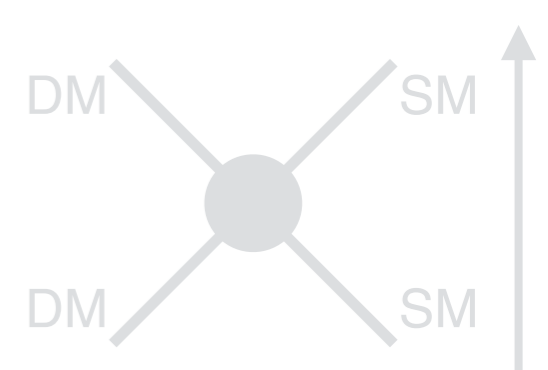
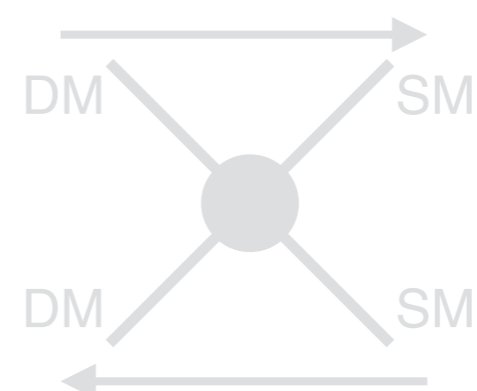
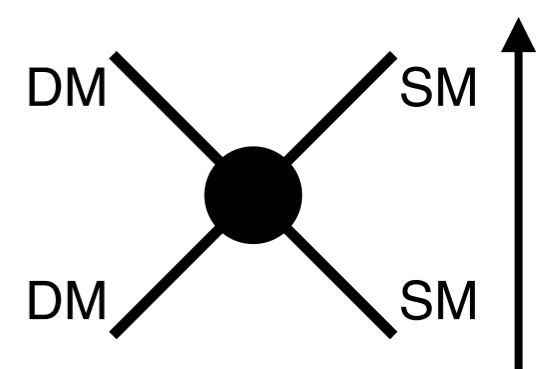
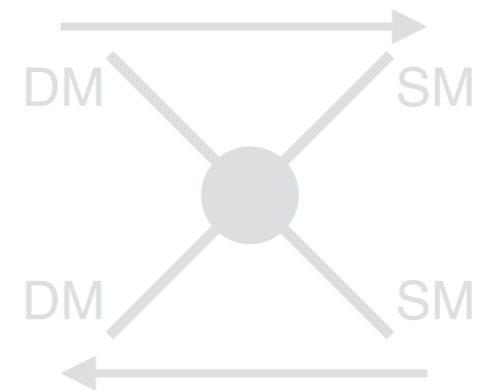
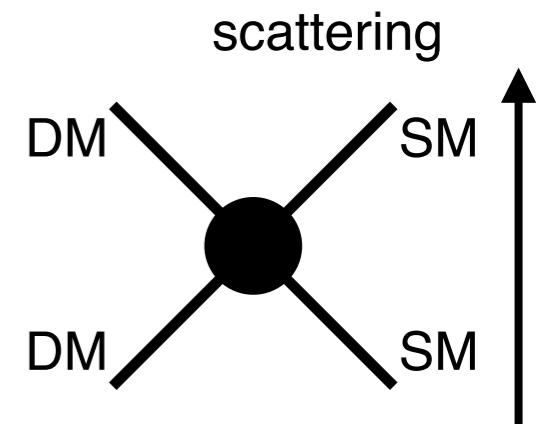
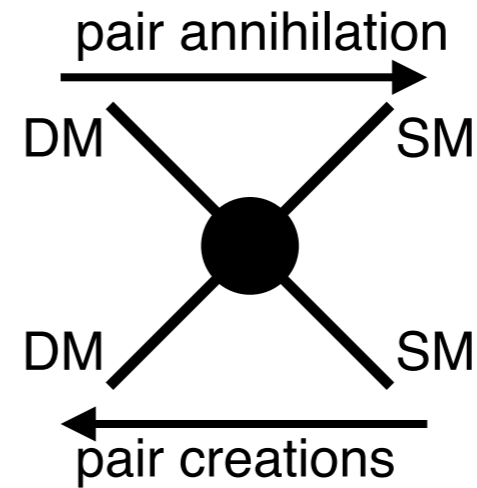
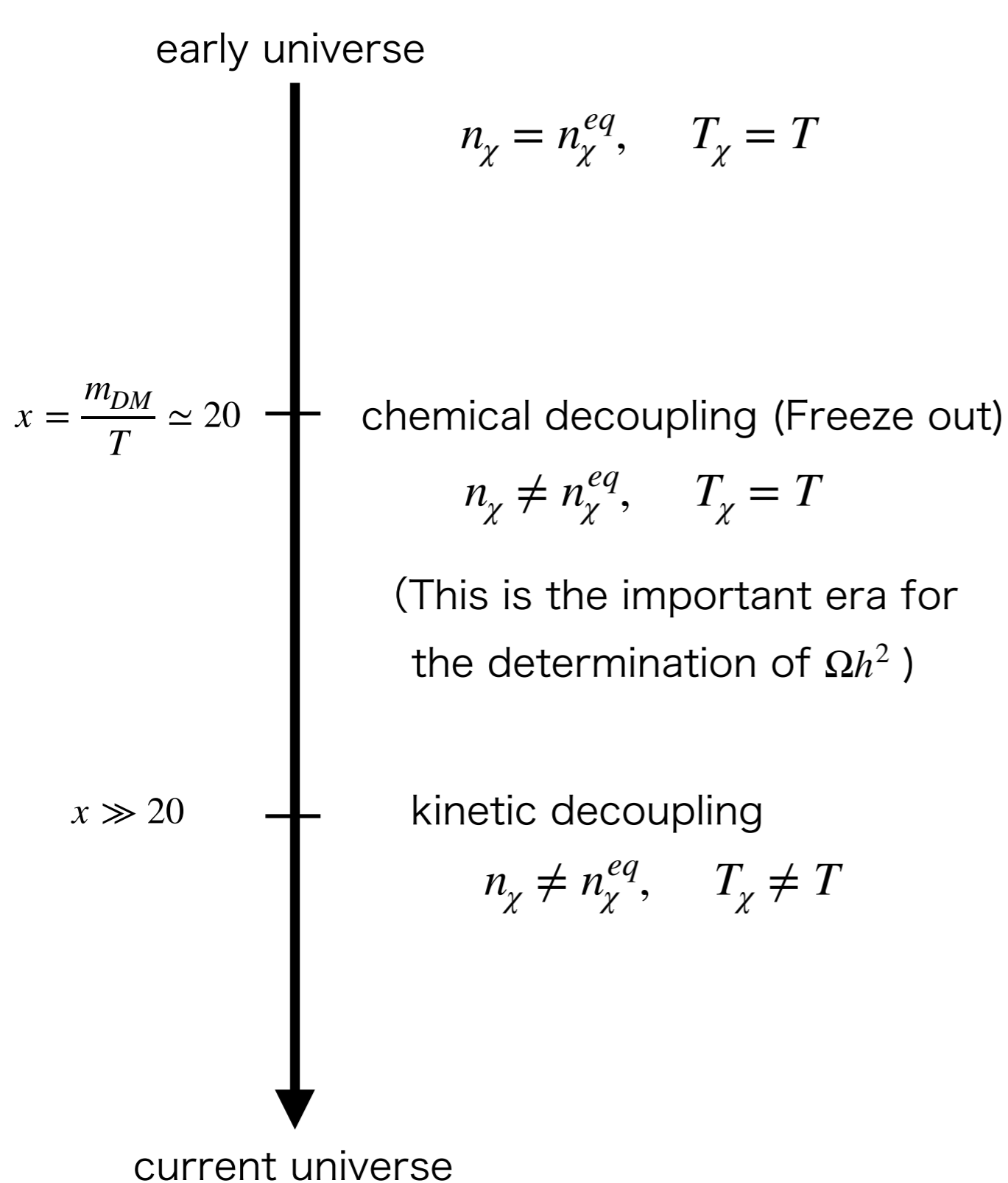
$$n_\chi = n_\chi^{eq}, \quad T_\chi = T$$



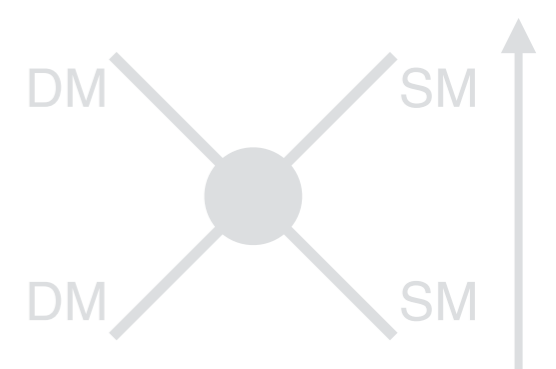
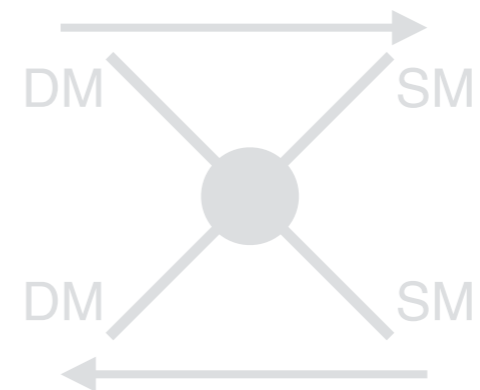
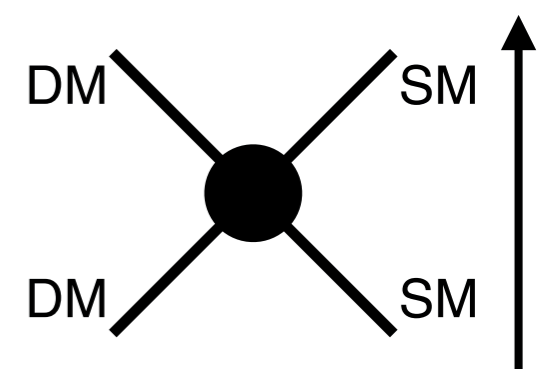
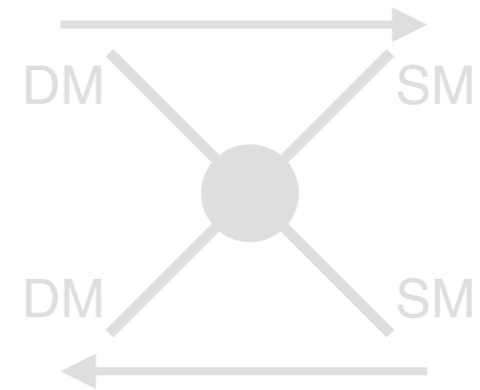
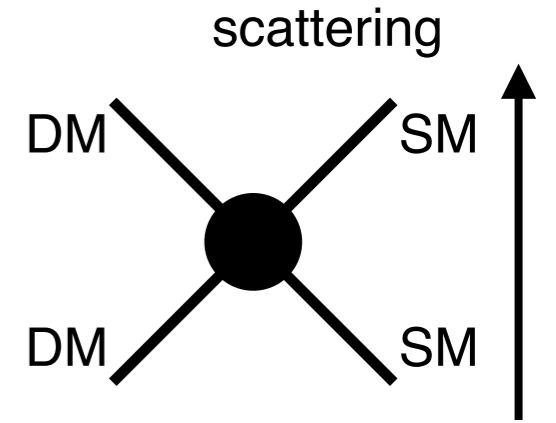
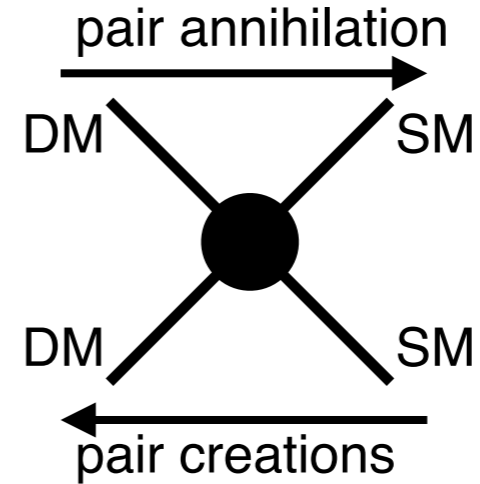
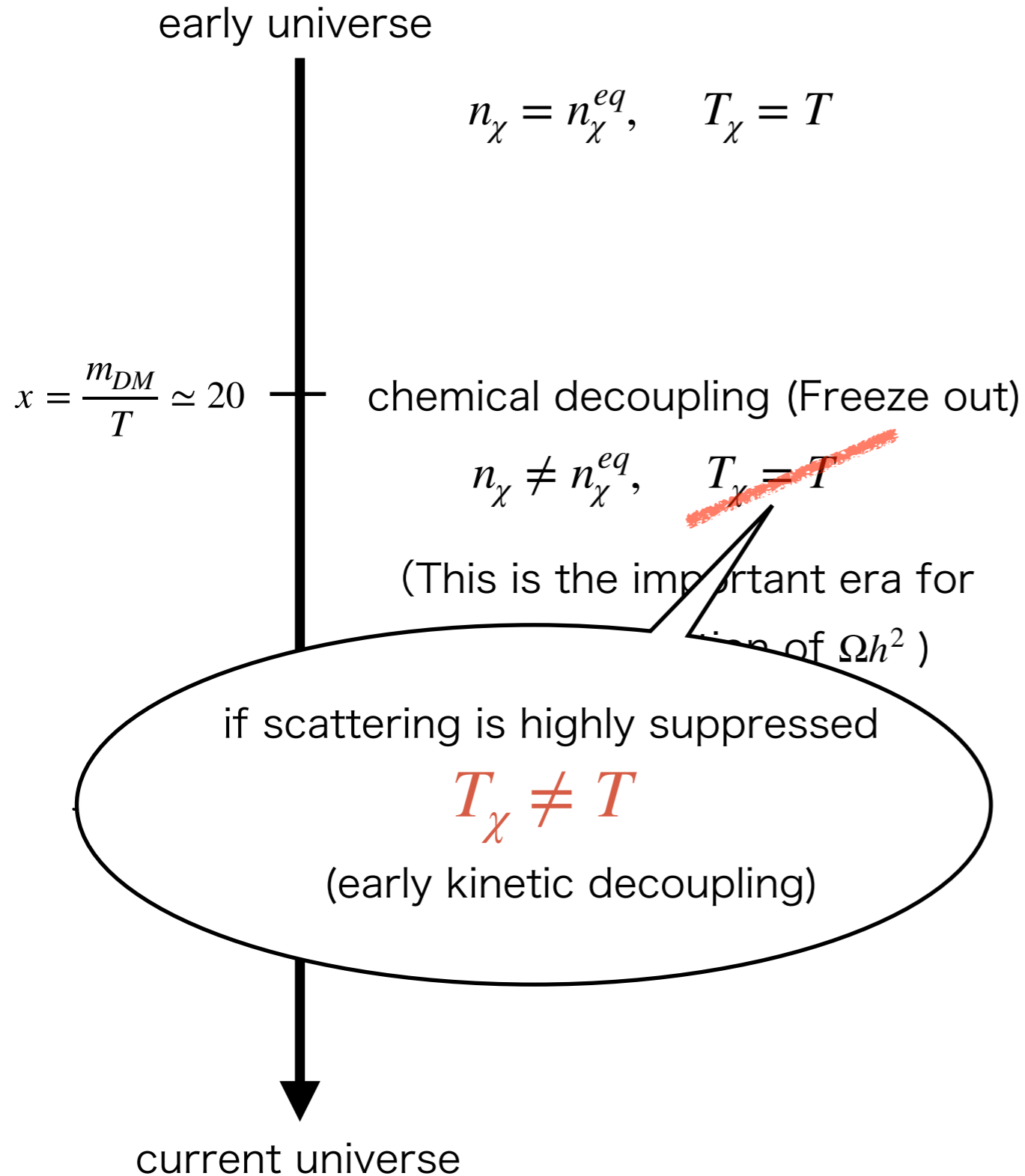
standard way to calculate Ωh^2



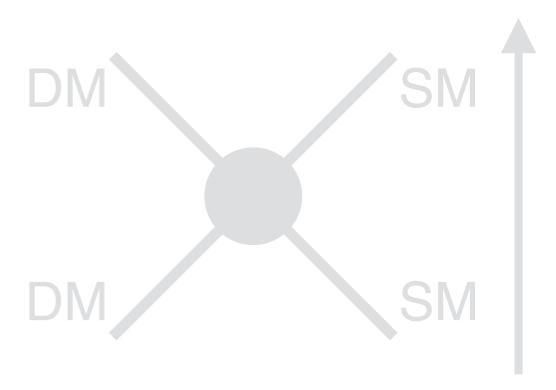
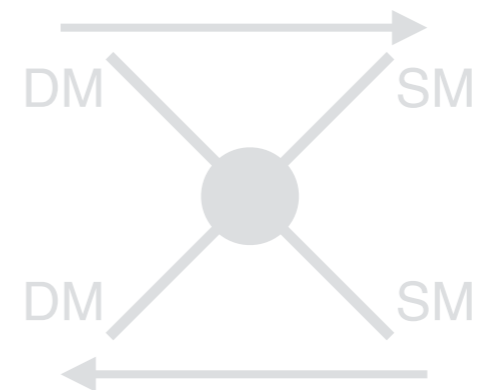
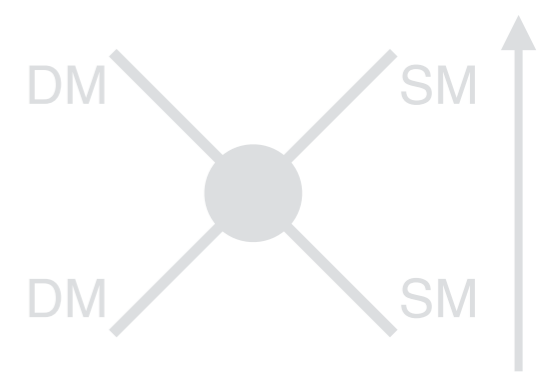
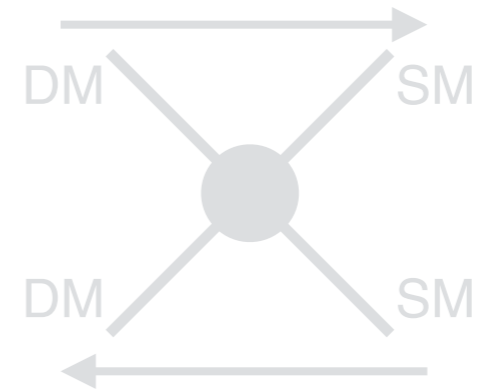
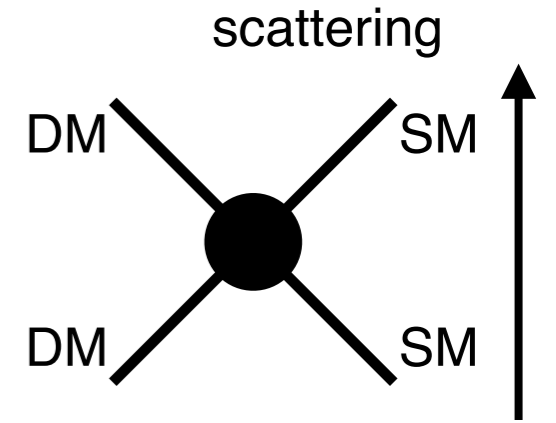
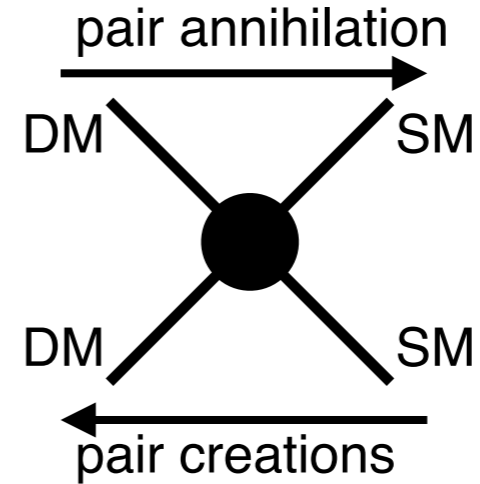
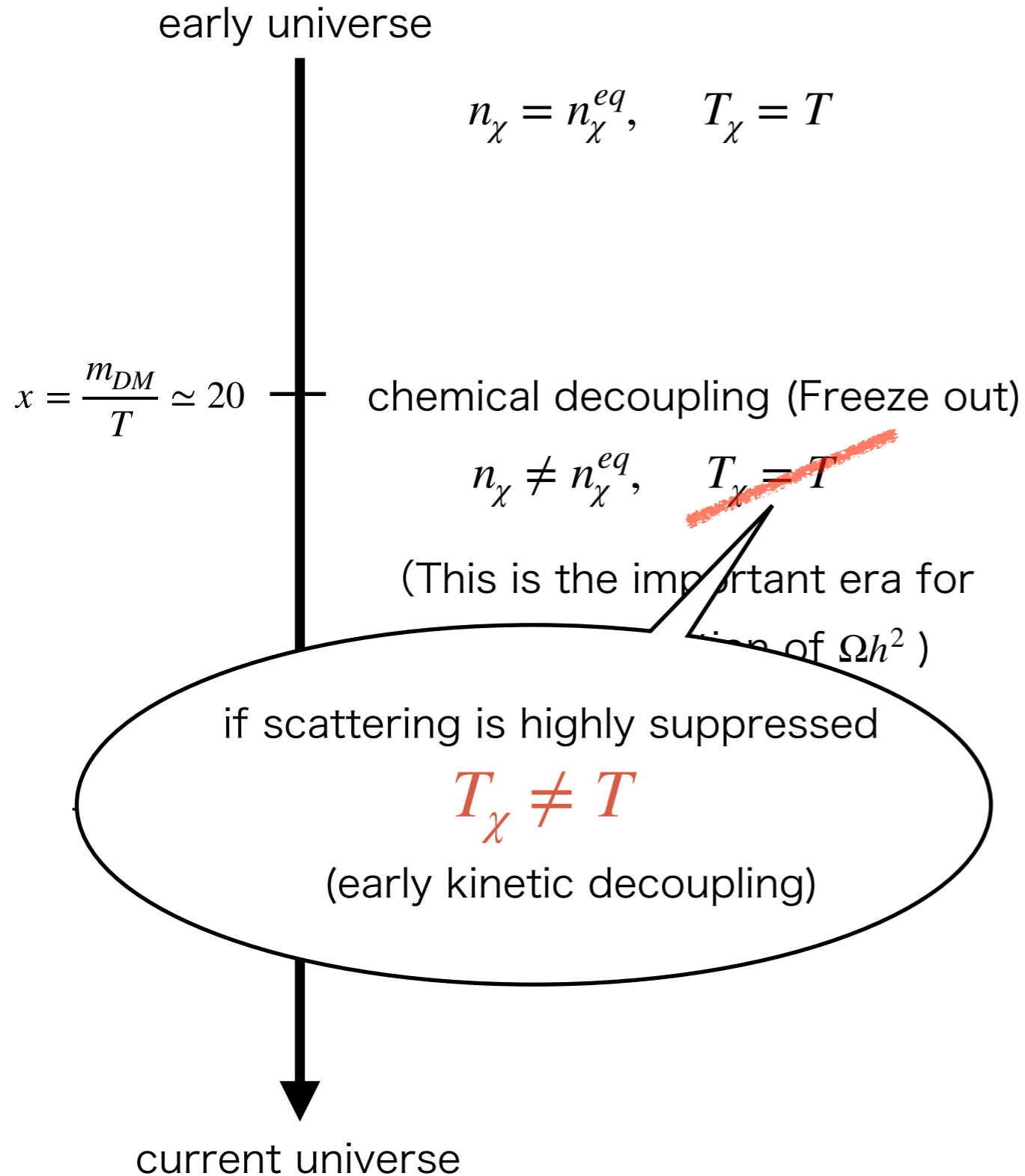
standard way to calculate Ωh^2



standard way to calculate Ωh^2



standard way to calculate Ωh^2



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 $T_\chi \neq T$

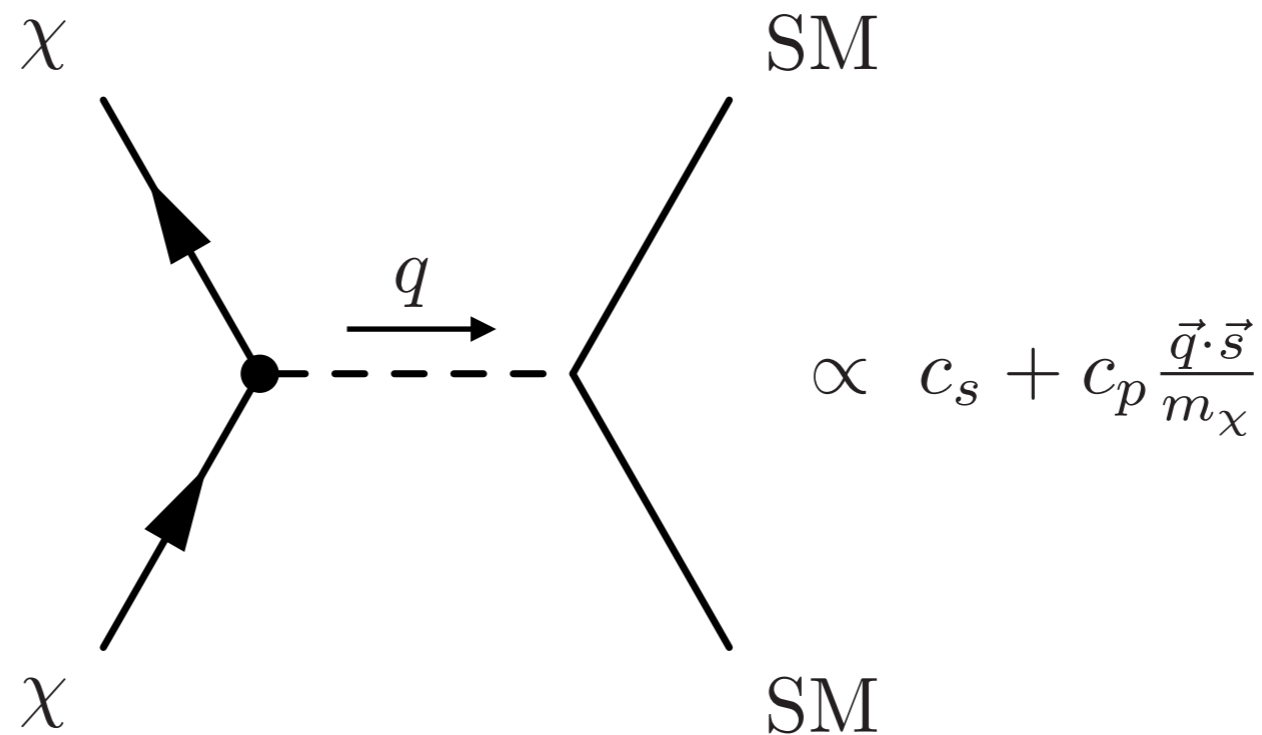
$$\left\{ \begin{array}{l} \frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle_{T_\chi} n_\chi^2 + \langle \sigma v \rangle_T n_{\chi,eq}^2 \\ \frac{dT_\chi}{dt} = (\text{complicated equations depending on } \langle \sigma v \rangle, \langle \sigma v \rangle_2, \text{ and } |\mathcal{M}_{\text{scattering}}|^2).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

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), ...]

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

- two types of 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

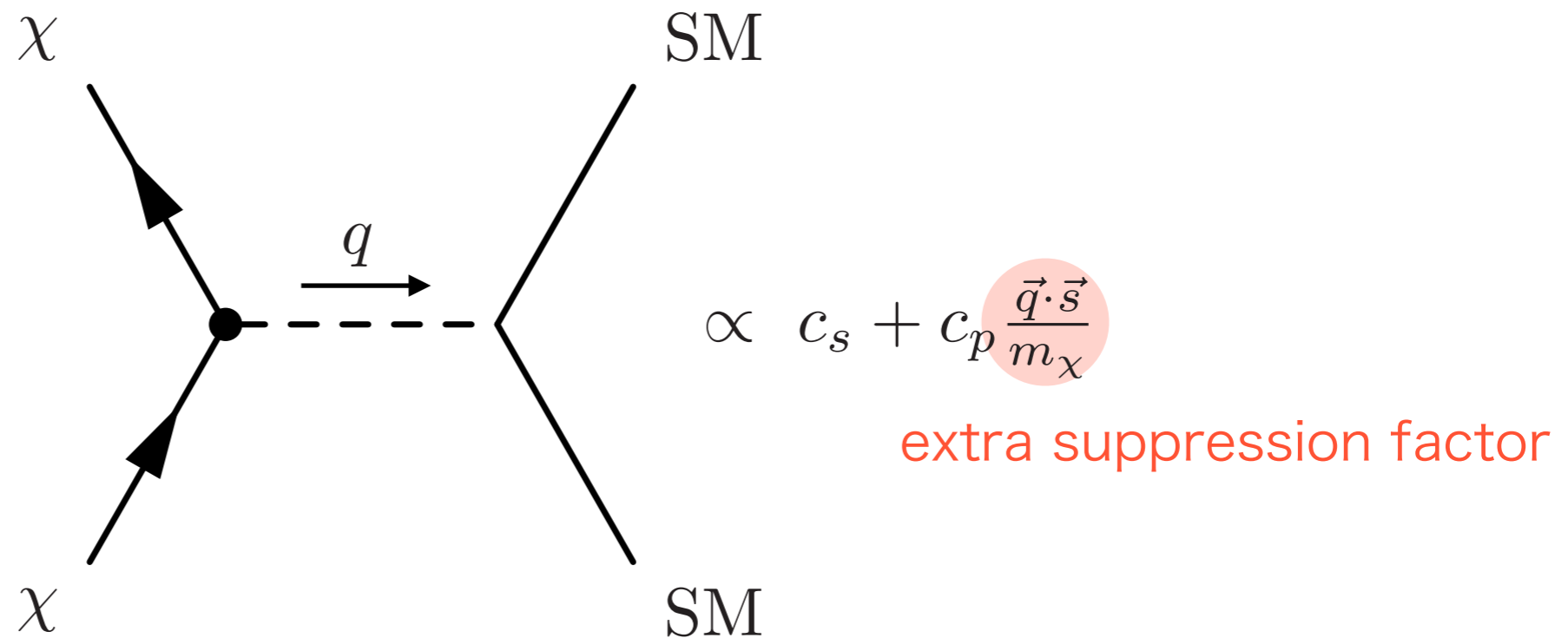


A Fermion DM model

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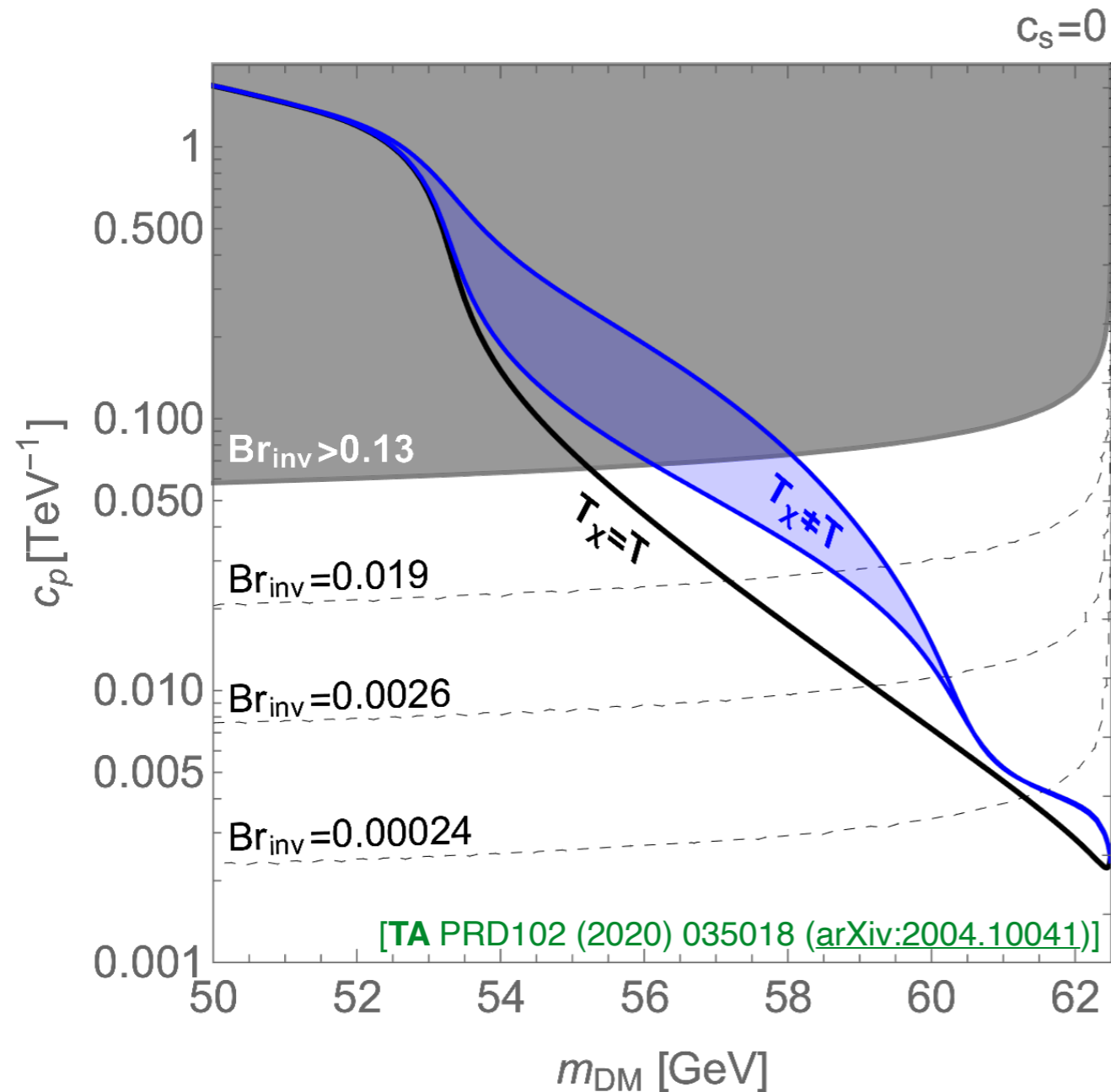
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \bar{\chi} (i\gamma^\mu \partial_\mu - m_\chi) \chi + \frac{c_s}{2} \bar{\chi} \chi \left(H^\dagger H - \frac{v^2}{2} \right) + \frac{c_p}{2} \bar{\chi} i\gamma_5 \chi \left(H^\dagger H - \frac{v^2}{2} \right)$$

- two types of 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



Result

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



- $T_\chi = T$: 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

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

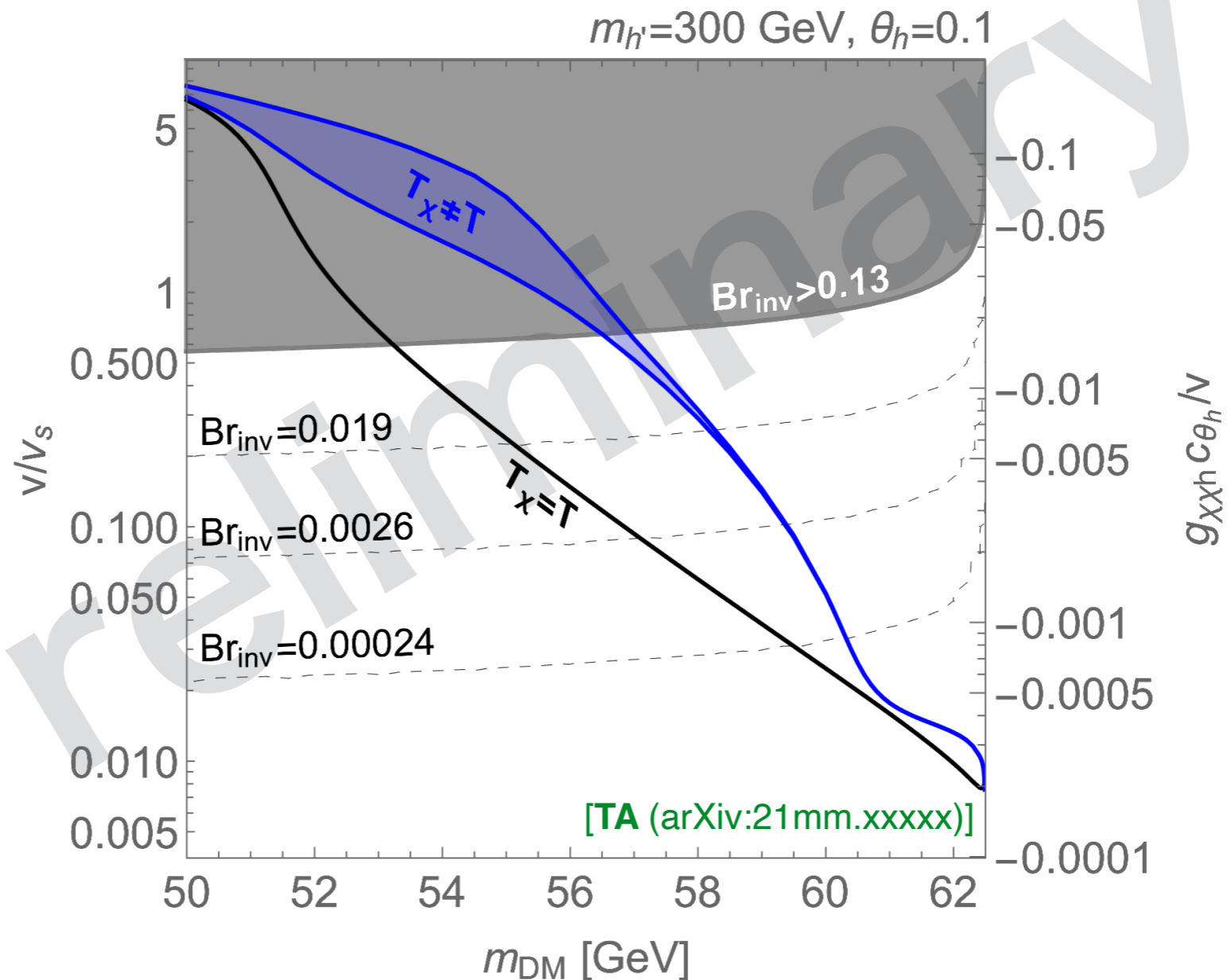
prospect [1905.03764]

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

Another example

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

- DM-SM scattering is much suppressed
- prediction of $\text{Br}(h \rightarrow \text{DMs})$ 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
- $\text{Br}(H \rightarrow \text{inv.})$ can be much larger than in the previous studies

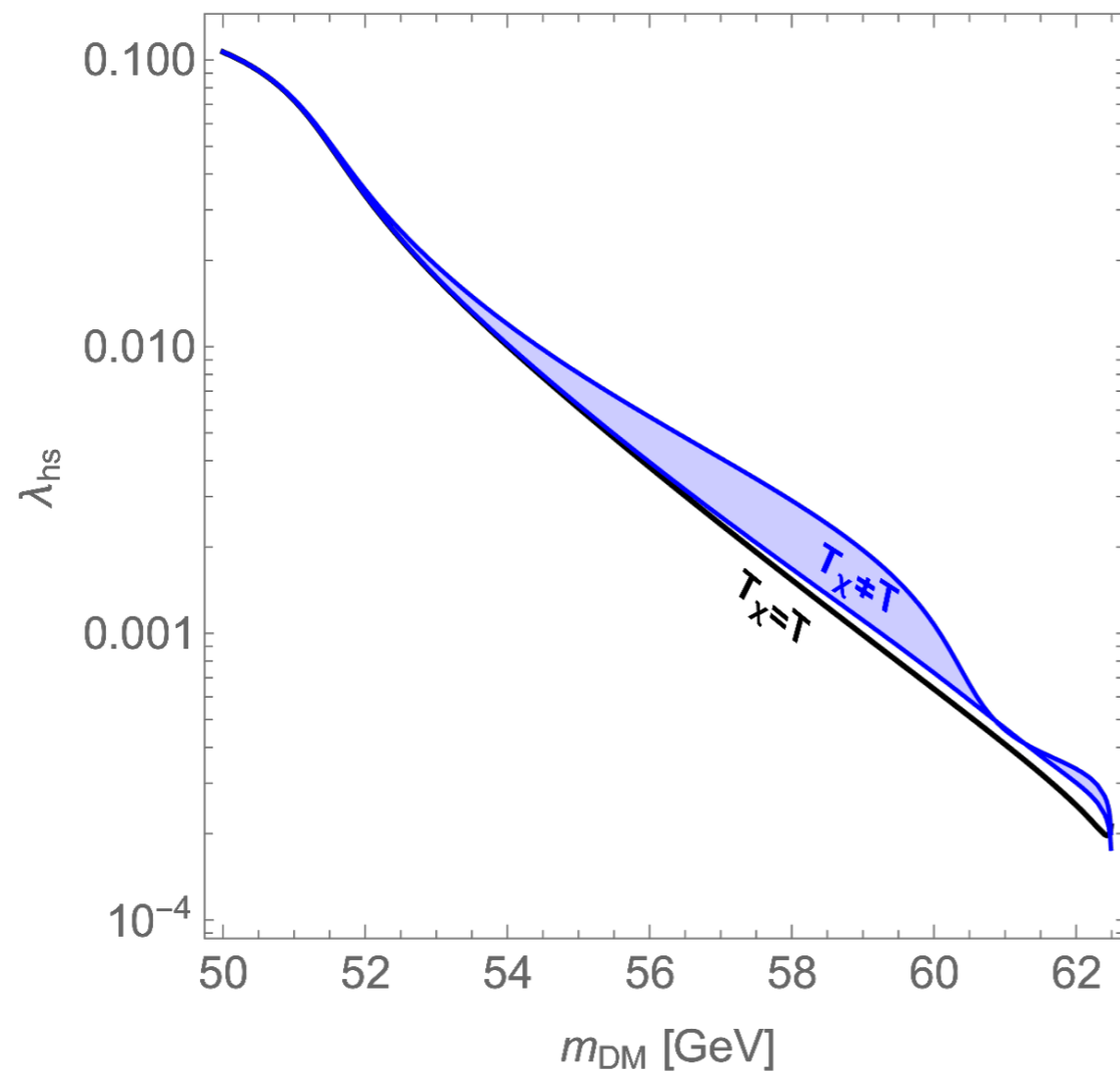
Backup

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)]

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

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

[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 $|\mathcal{M}|^2$ then we obtain result

Dark matter Relic Abundance beyond Kinetic Equilibrium

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