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

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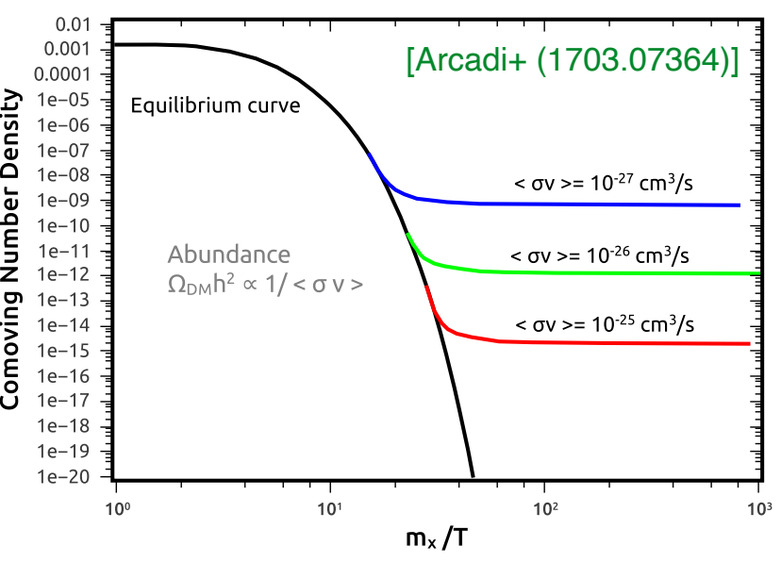
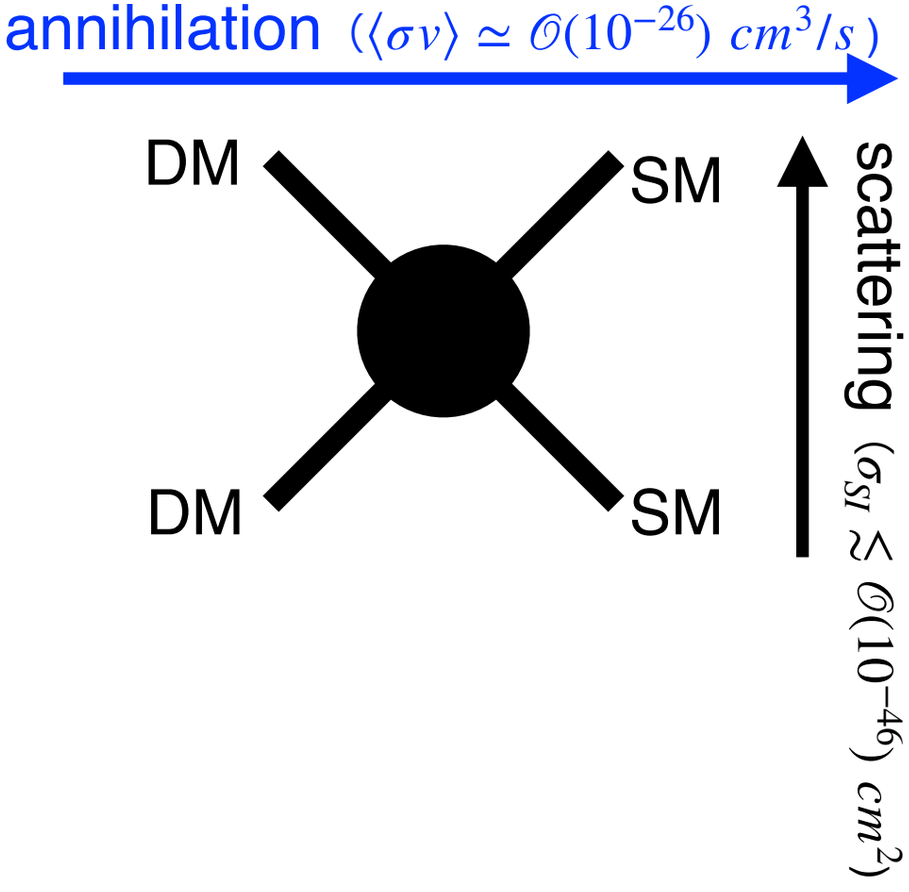
(references) 1706.07433, 2004.10041

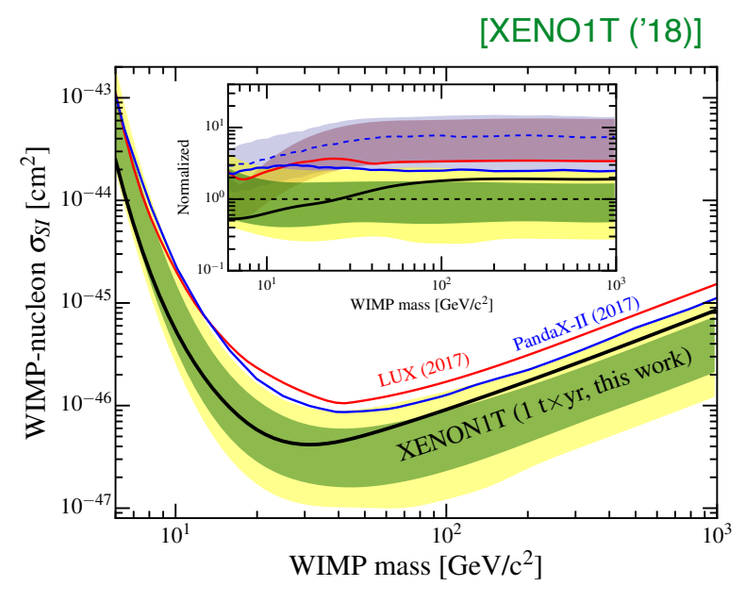
Weakly Interacting Massive Particle

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

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

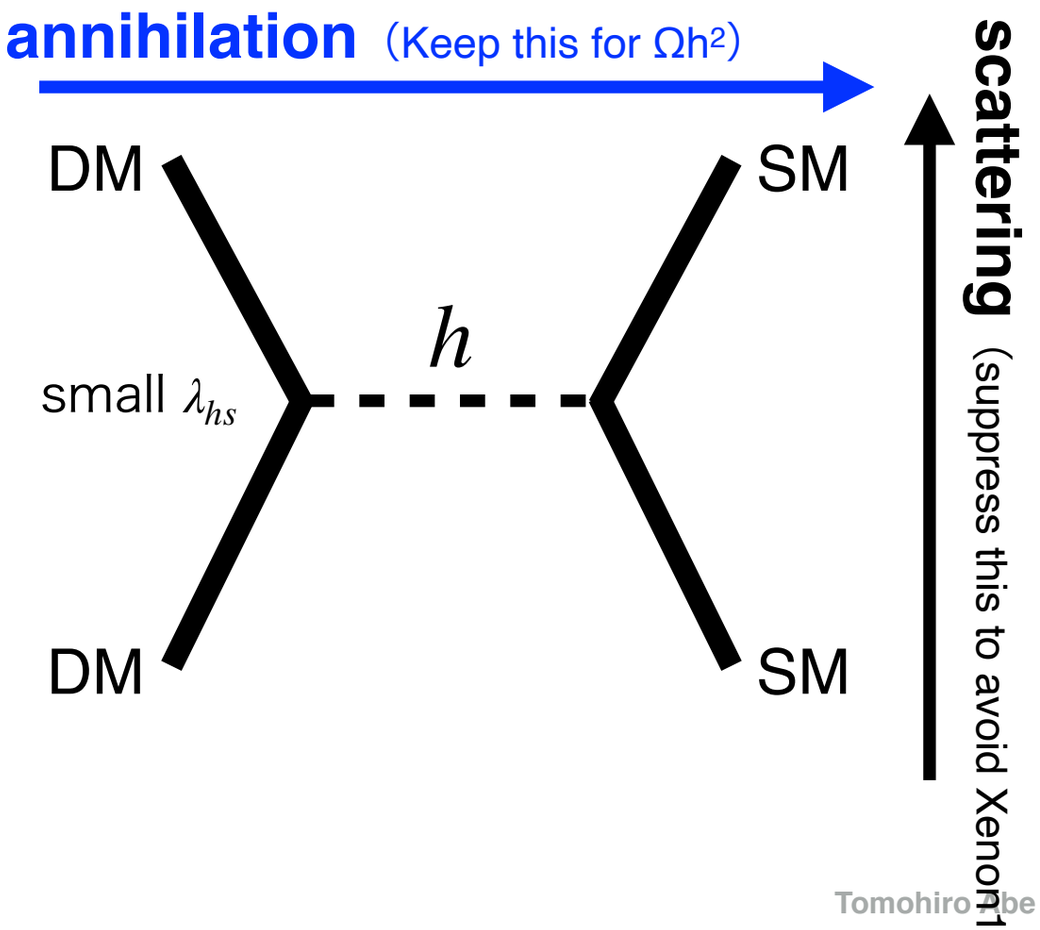




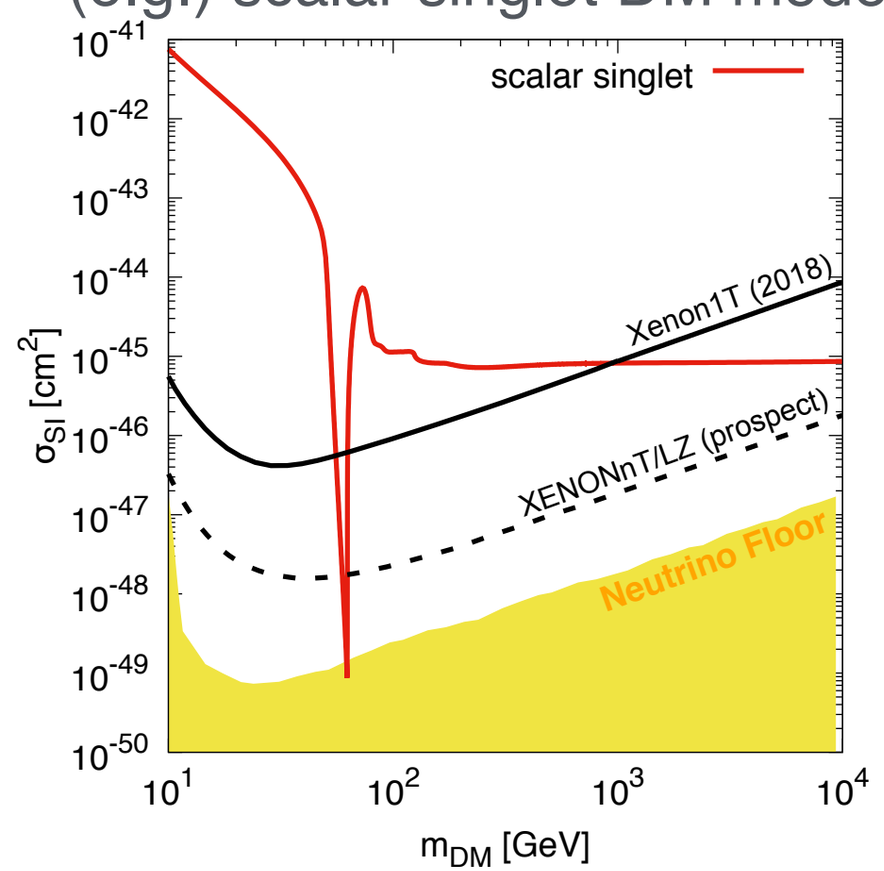


Higgs Resonance

- DM pair annihilation enjoys the Higgs resonance for $m_{DM} \sim m_h/2$
- the DM-Higgs coupling (λ_{hs}) should be small for $\langle \sigma v \rangle = 10^{-26}$ cm^3/s
- small λ_{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

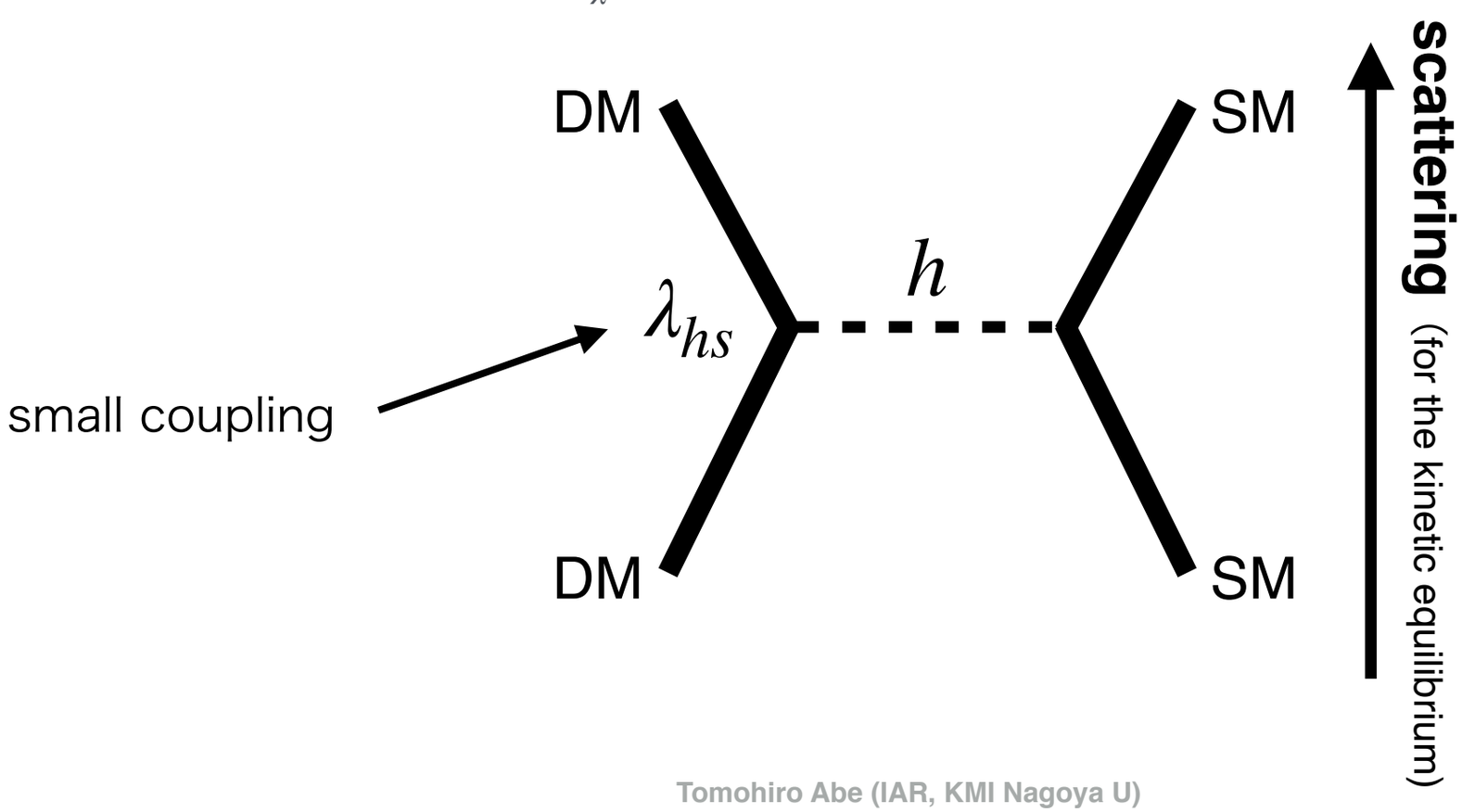


(e.g.) scalar singlet DM model



Kinetic decoupling may happen earlier

- 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 $T_\chi = T$

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

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

DM temperature

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

$$\frac{dn_\chi}{dt} = (\text{complicated equations}),$$

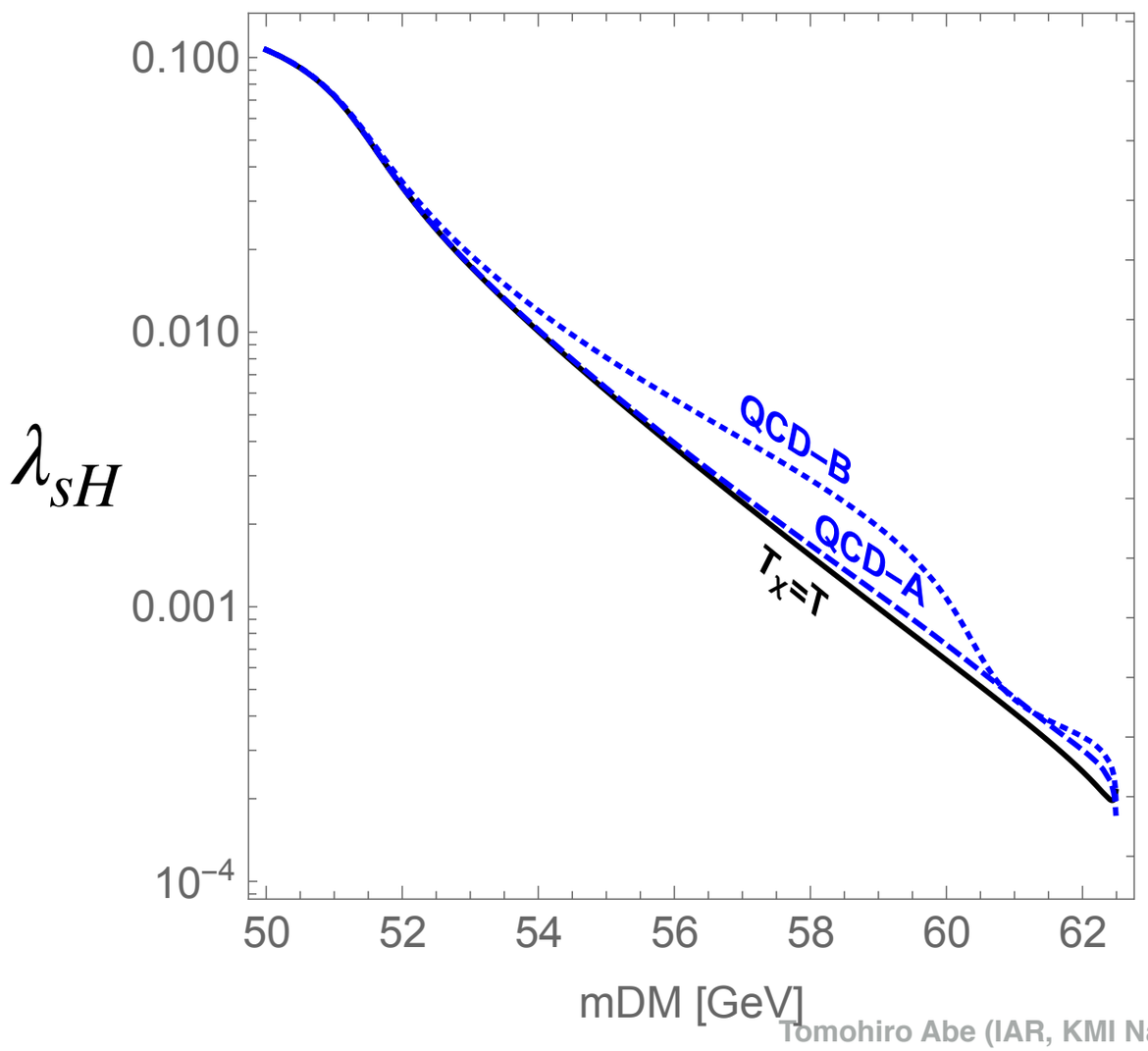
$$\frac{dT_\chi}{dt} = (\text{complicated equations}).$$

scalar singlet DM case

- 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)]

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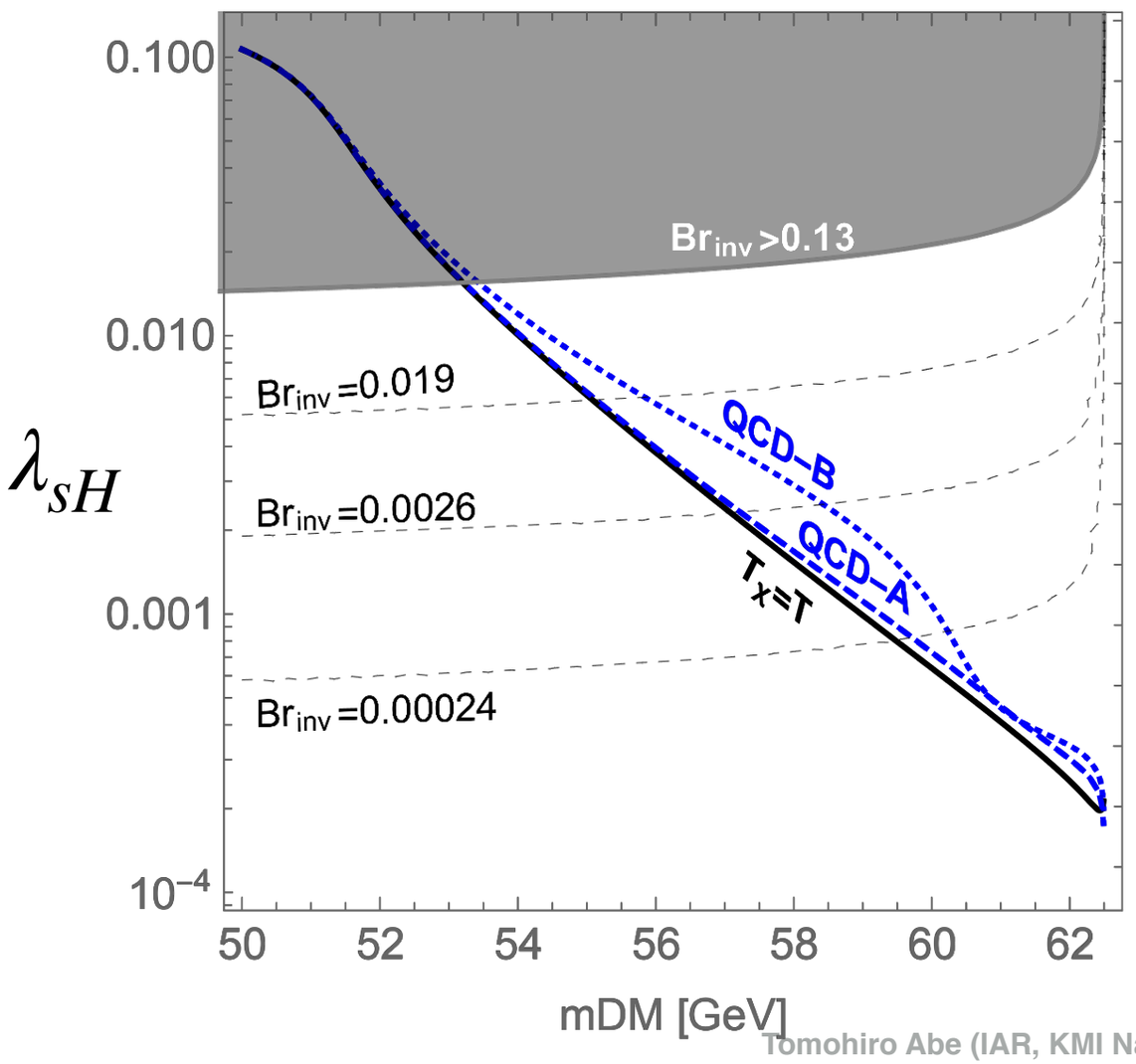


current bound on the Higgs invisible decay

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

prospect [1905.03764]

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

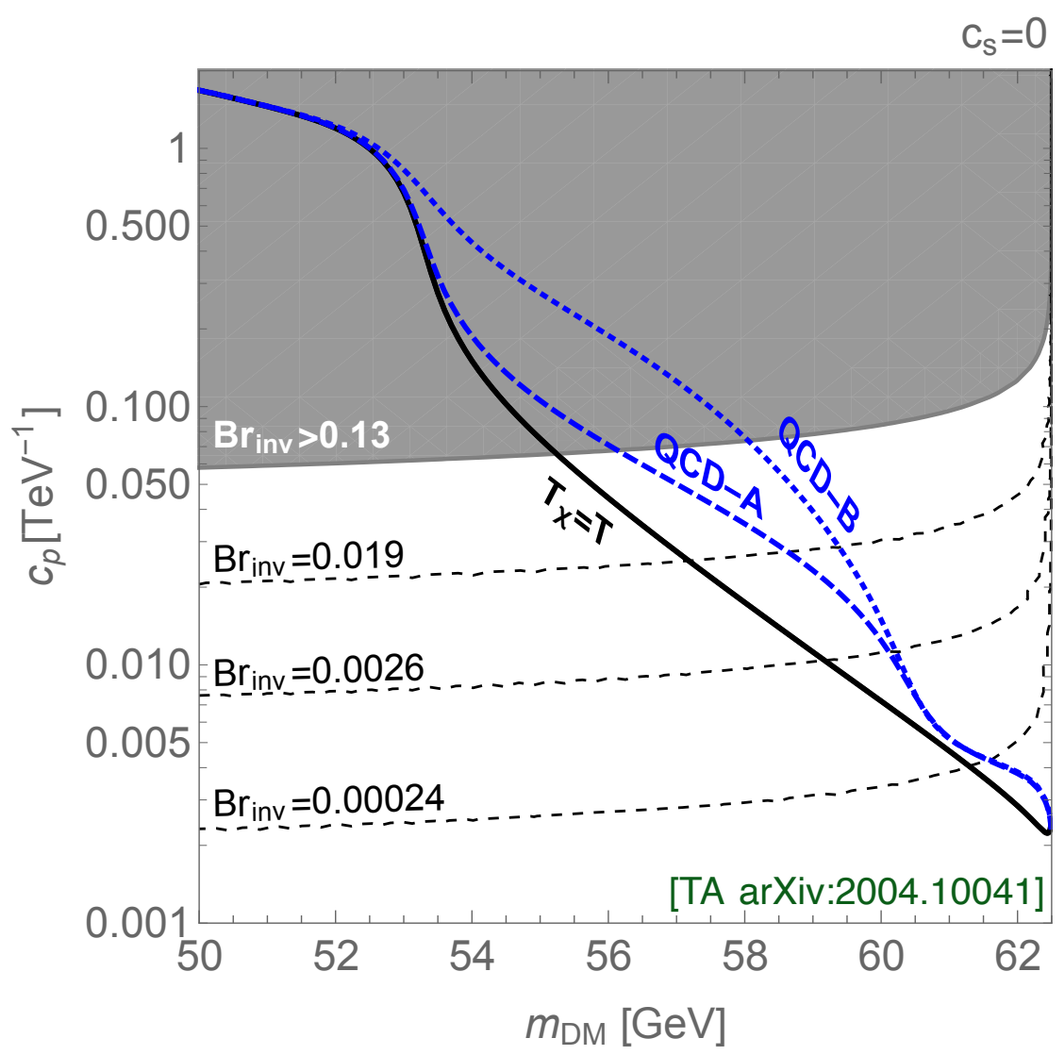
results from [Binder, Bringmann, Gustafsson, Hryczuk ('17)]
Br_{inv} is overlaid by TA

Fermion DM case

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

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

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



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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 σ_{SI}
- Higgs invisible decay can be used to study DM at collider experiments

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

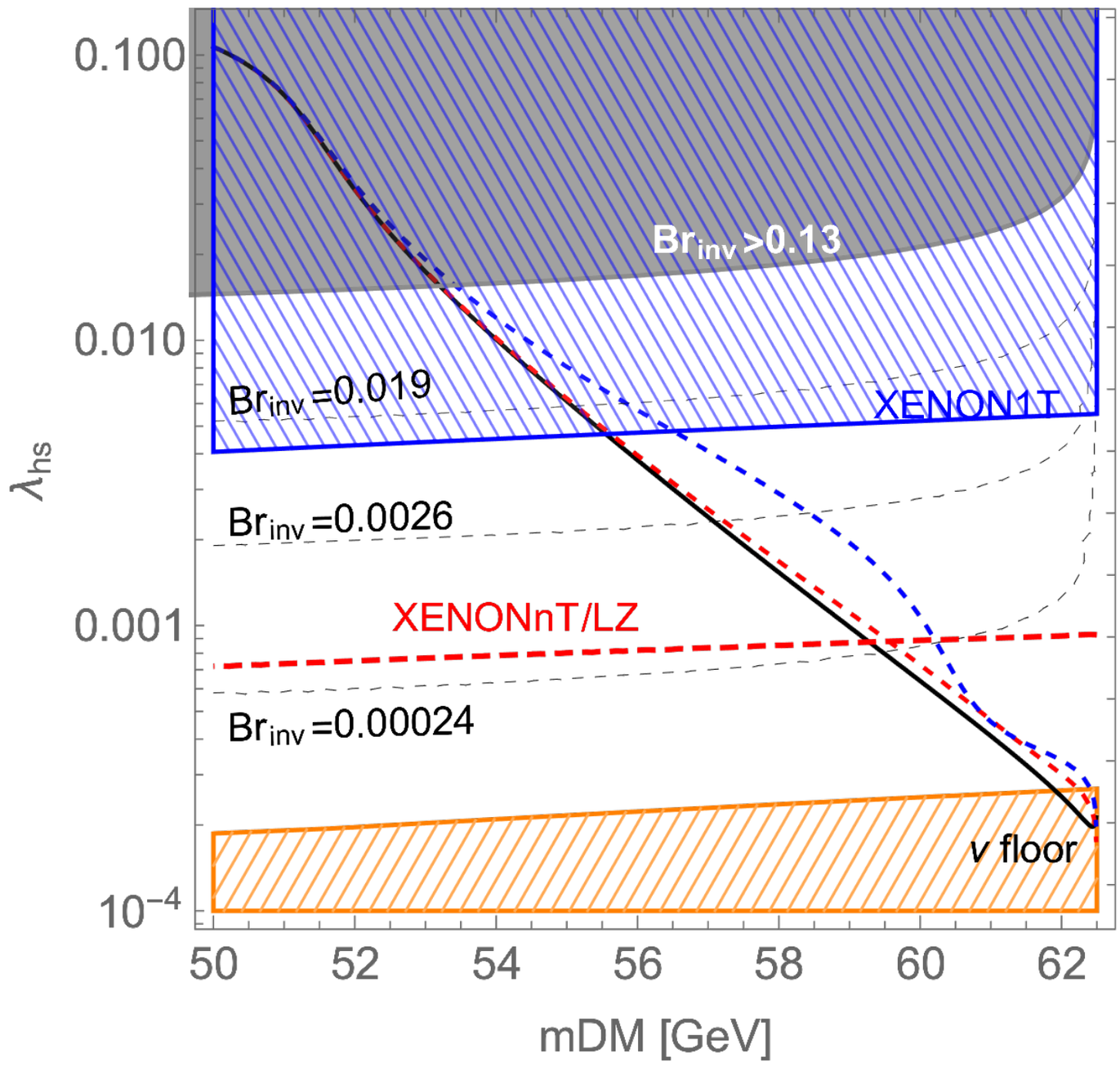
- kinetic decoupling may happen earlier
- need to calculate both n_χ and T_χ

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