The effect of the early kinetic decoupling in a fermionic dark matter model

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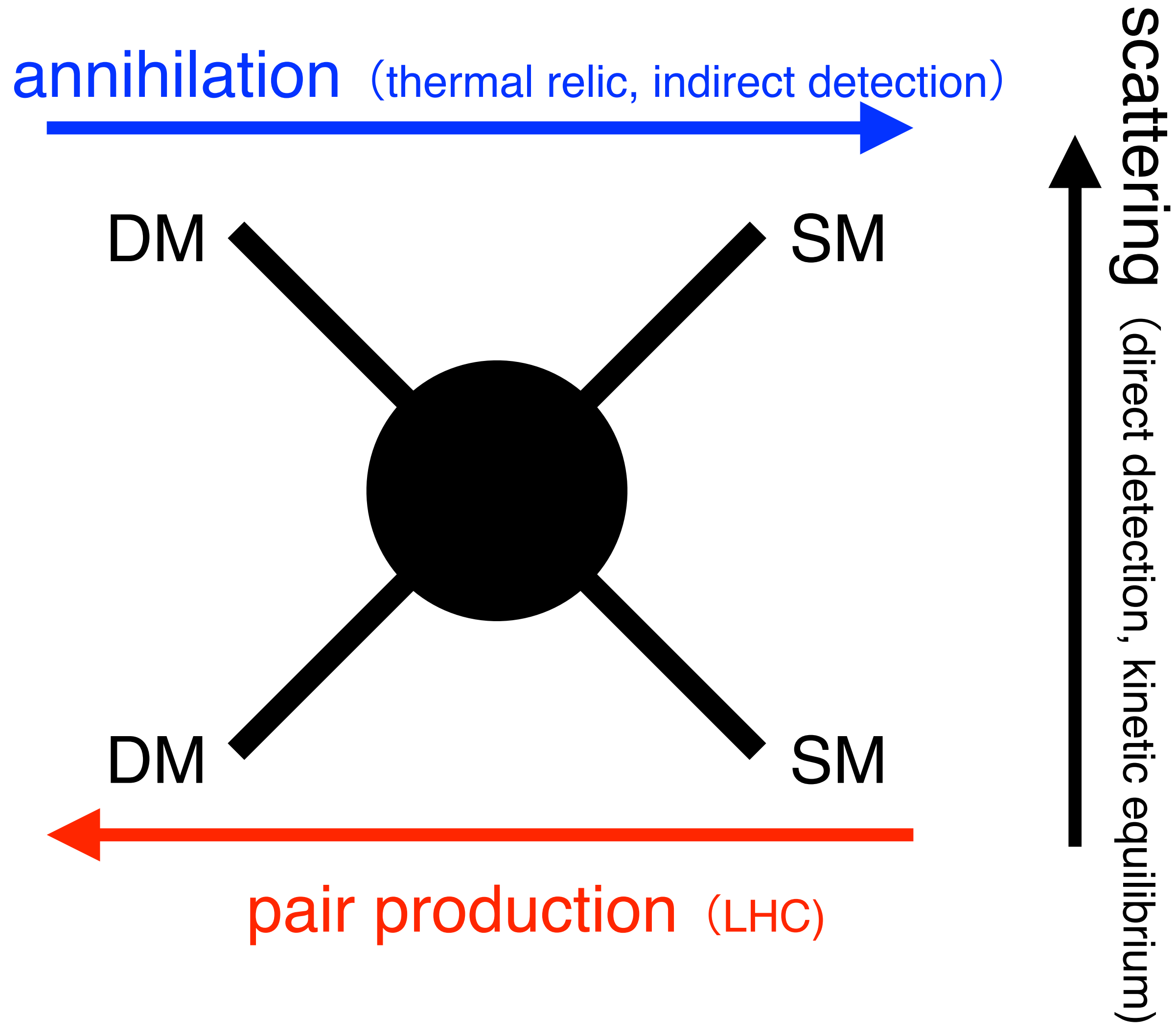
arXiv:2004.10041

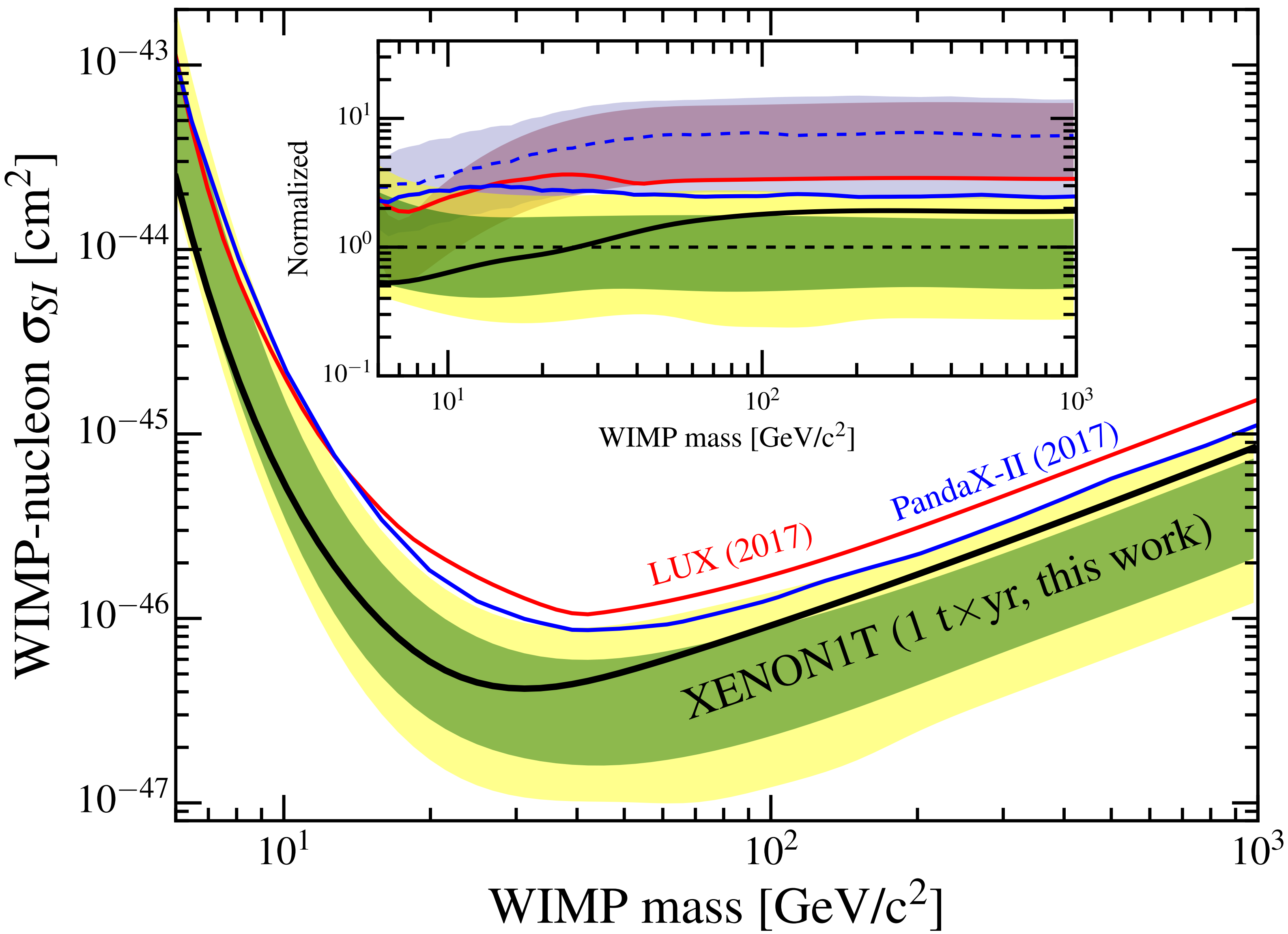
Weakly Interacting Massive Particle

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



Constraints from direct detection



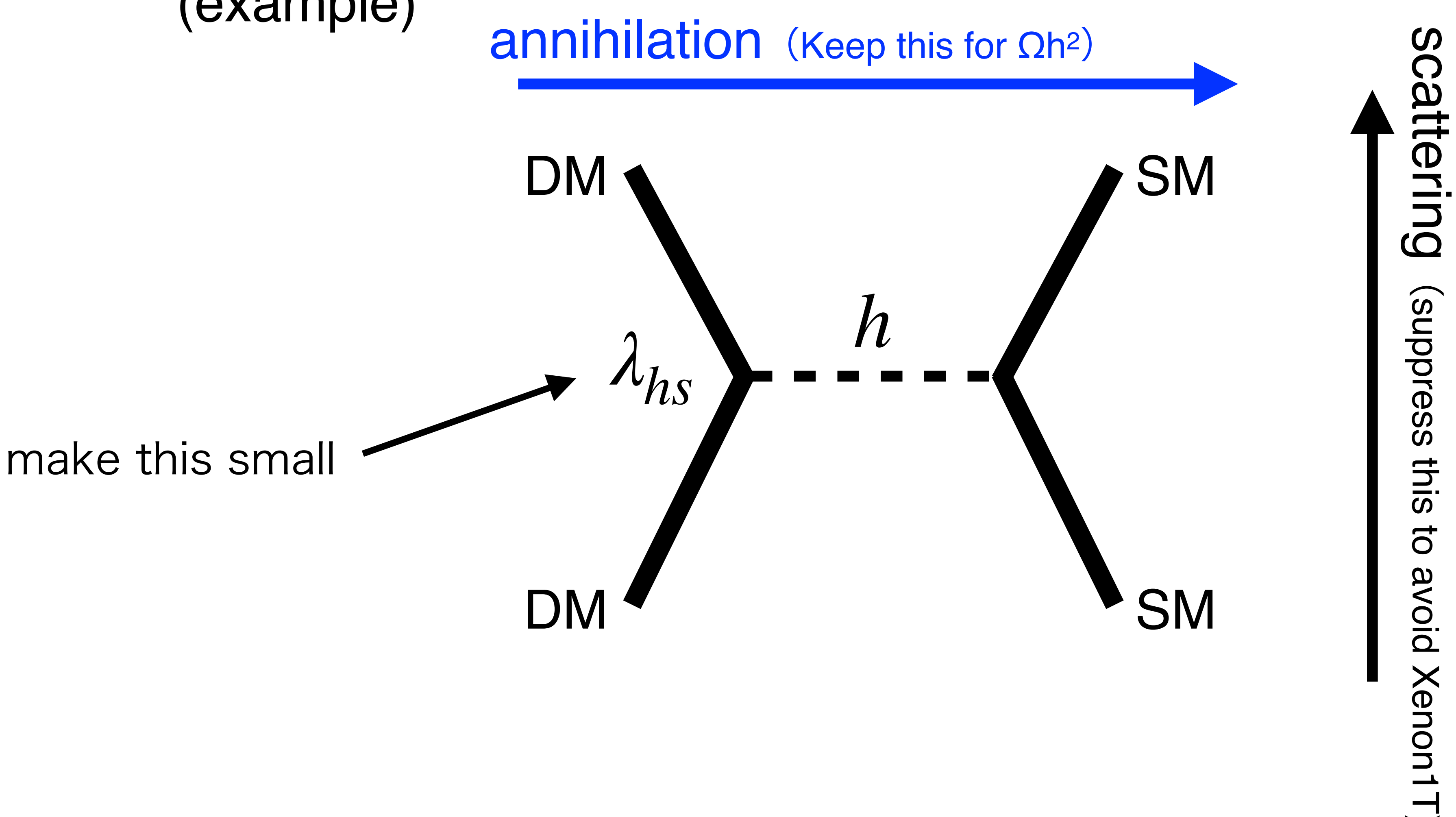
[XENON1T (2018)]

- WIMP models have been severely constrained today
- We need ideas to avoid this strong constraint

Small coupling

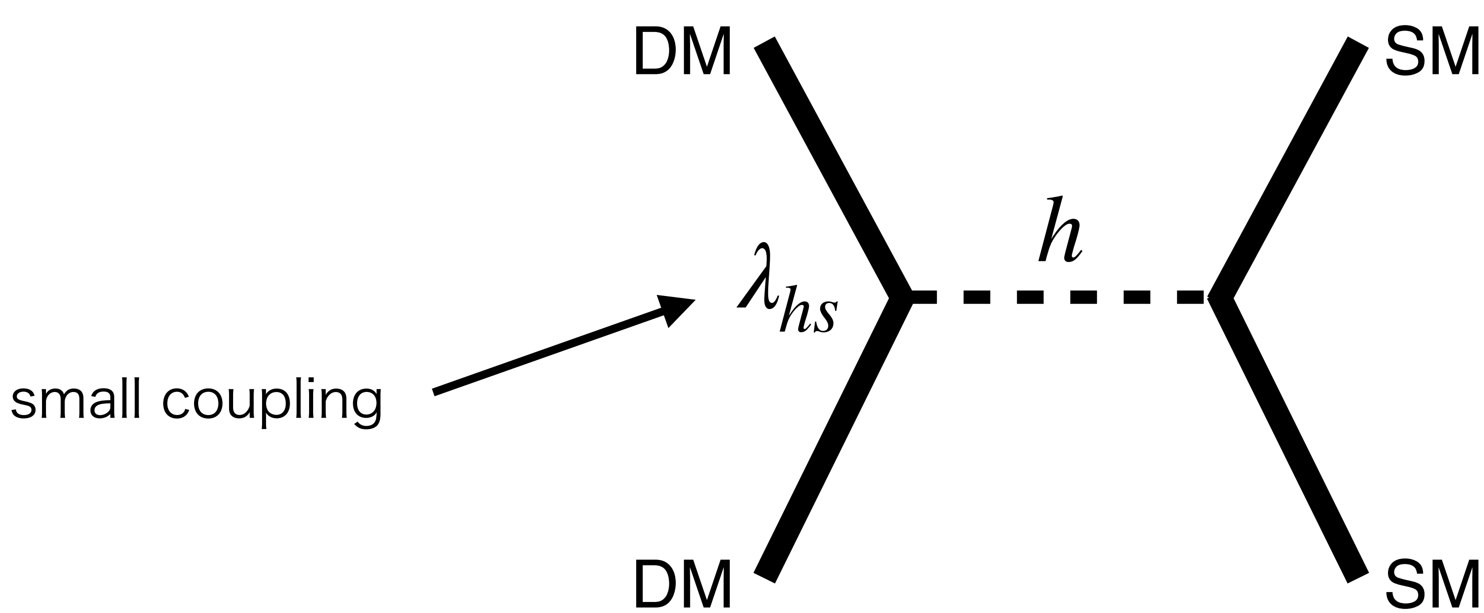
- suppress the scattering cross section ($\sigma_{SI} \ll O(10^{-46})$ cm^2)
- avoid the constraint from XENON1T experiment
- keep annihilation cross section ($\langle \sigma v \rangle = 10^{-26}$ cm^3/s) by resonance

(example)



DM temperature

- temperature of DM is assumed to be the same as the temperature of the thermal bath in WIMP models $(T_\chi = T)$
- This assumption is valid if the scattering processes are frequent
- Now the scattering is suppressed to avoid the XENON1T
- We cannot assume $T_\chi = T$
- We have to calculate T_χ by solving the Boltzmann equation



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

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

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

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

Fermion dark matter model

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

- χ : dark matter (Majorana fermion, gauge singlet)
- H : Higgs boson

Two types of interactions

- scalar-type : $\bar{\chi}\chi H^{\dagger}H$
- pseudo scalar-type : $\bar{\chi}i\gamma_5\chi H^{\dagger}H$

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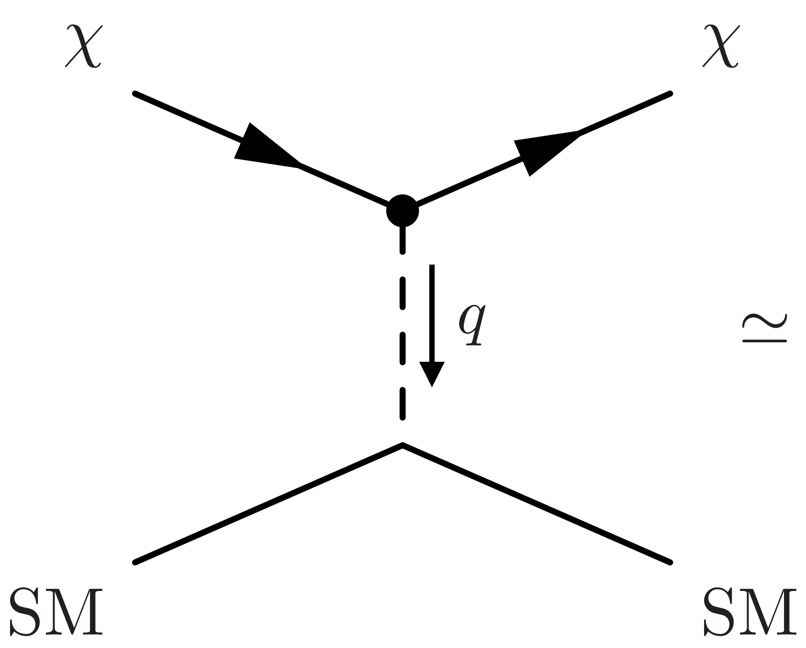
Scattering process

Two types of interactions

- scalar-type : $\bar{\chi}\chi H^\dagger H$
- pseudo scalar-type : $\bar{\chi} i\gamma_5 \chi H^\dagger H$

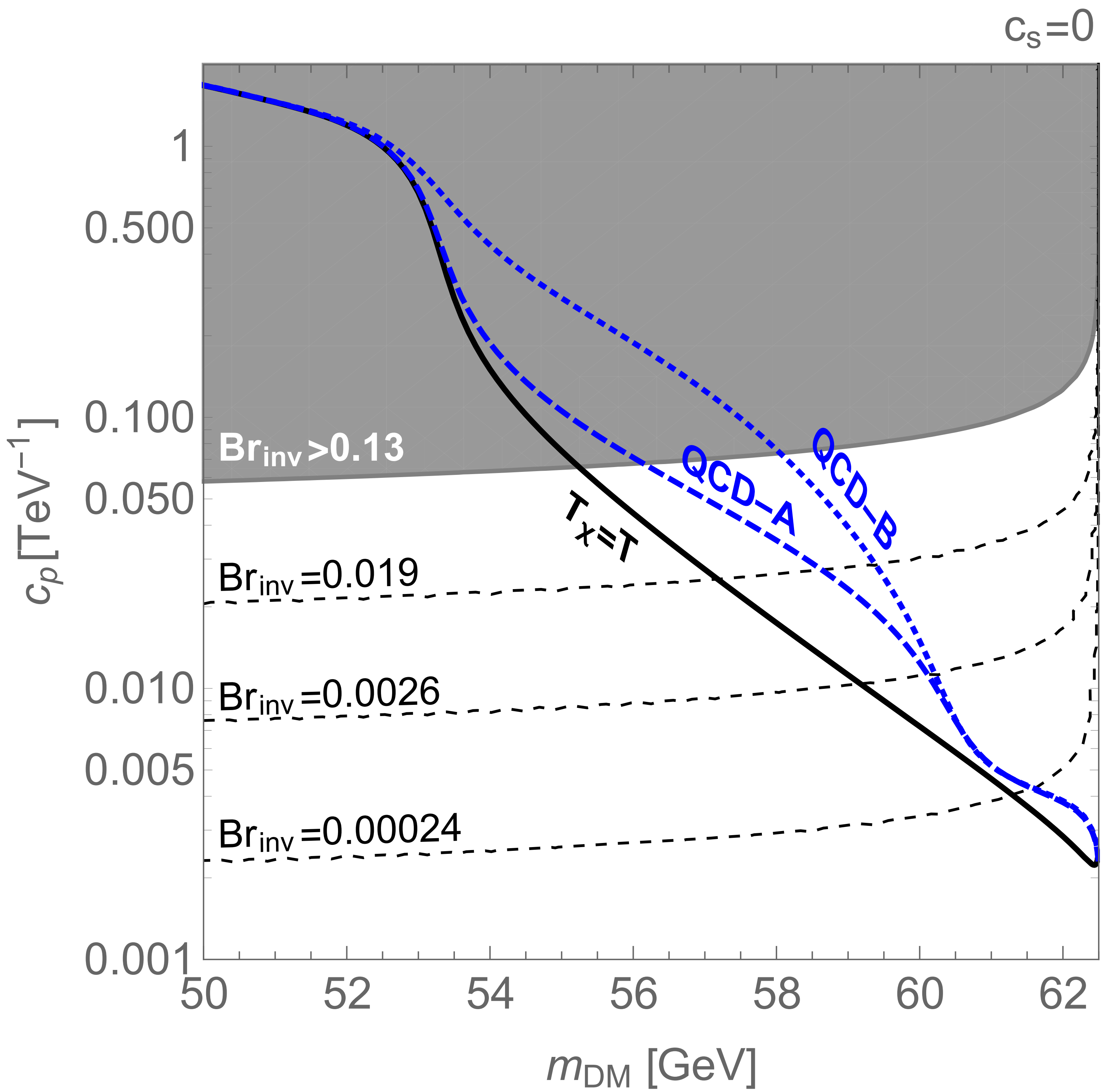


$$\frac{c_s}{2}\bar{\chi}\chi\left(H^\dagger H - \frac{v^2}{2}\right) + \frac{c_p}{2}\bar{\chi}i\gamma_5\chi\left(H^\dagger H - \frac{v^2}{2}\right)$$

$$\simeq \bar{u}(p)(c_s + i c_p \gamma^5)u(p) \sim c_s + c_p \frac{\vec{q}\cdot\vec{s}}{m_{\rm DM}}$$

- suppressed by q
- For non-relativistic DM, q is typically small
- elastic scattering is more suppressed by pseudo-scalar coupling

Result : only pseudo-scalar case



current bound

$$\mathrm{BR_{inv}} < \begin{cases} 0.13 & \text{(ATLAS)} \\ 0.19 & \text{(CMS)} \end{cases}$$

prospects

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

Summary

WIMP models are constrained by direct detection experiments

- small coupling with the Higgs resonance is a possible way to avoid the constraints

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

- though it is assumed in standard calculations
- T_χ should be calculated from the Boltzmann equation

Larger coupling is required

- to explain the energy density of DM by the freeze-out mechanism
- the coupling enhancement is really large in a fermionic DM model
- more chance to see DM signals at experiments

Backup

Freeze-out mechanism

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{\rm eq}^2\right)$$

thermal average of the annihilation cross section

scale factor a

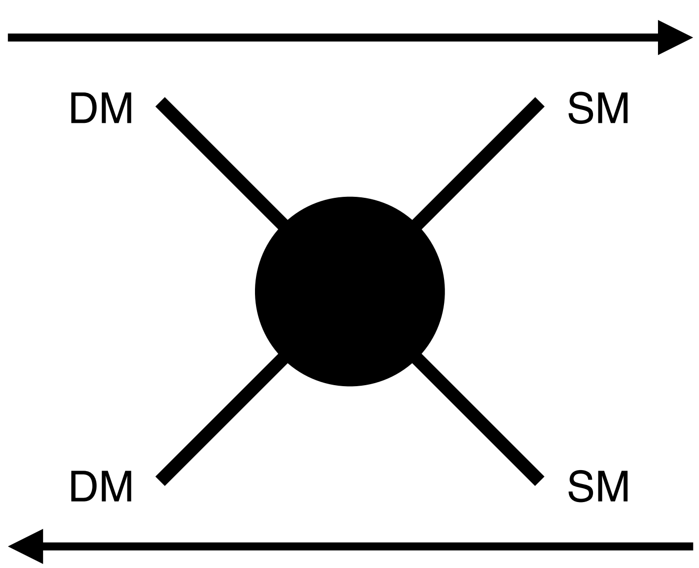
volume : a^3

particle number na^3

Hubble const. $H = \frac{1}{a}\frac{da}{dt}$

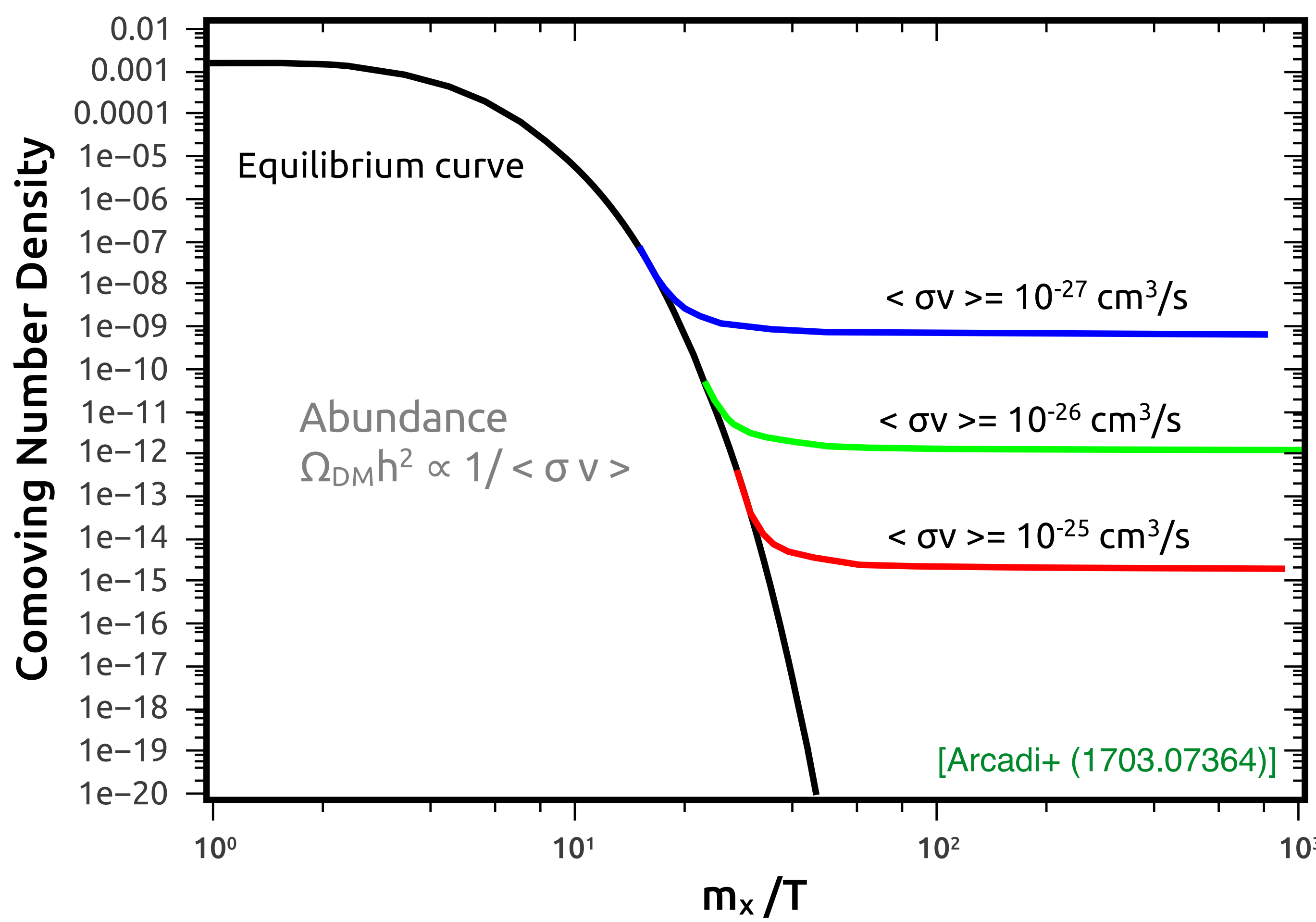
annihilation

stop if the expansion ratio is larger than the annihilation rate



creation

stop if temperature of the universe decrees and creation process is kinematically forbidden



This constraint is very strong

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

(e.g.) SM + singlet scalar

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

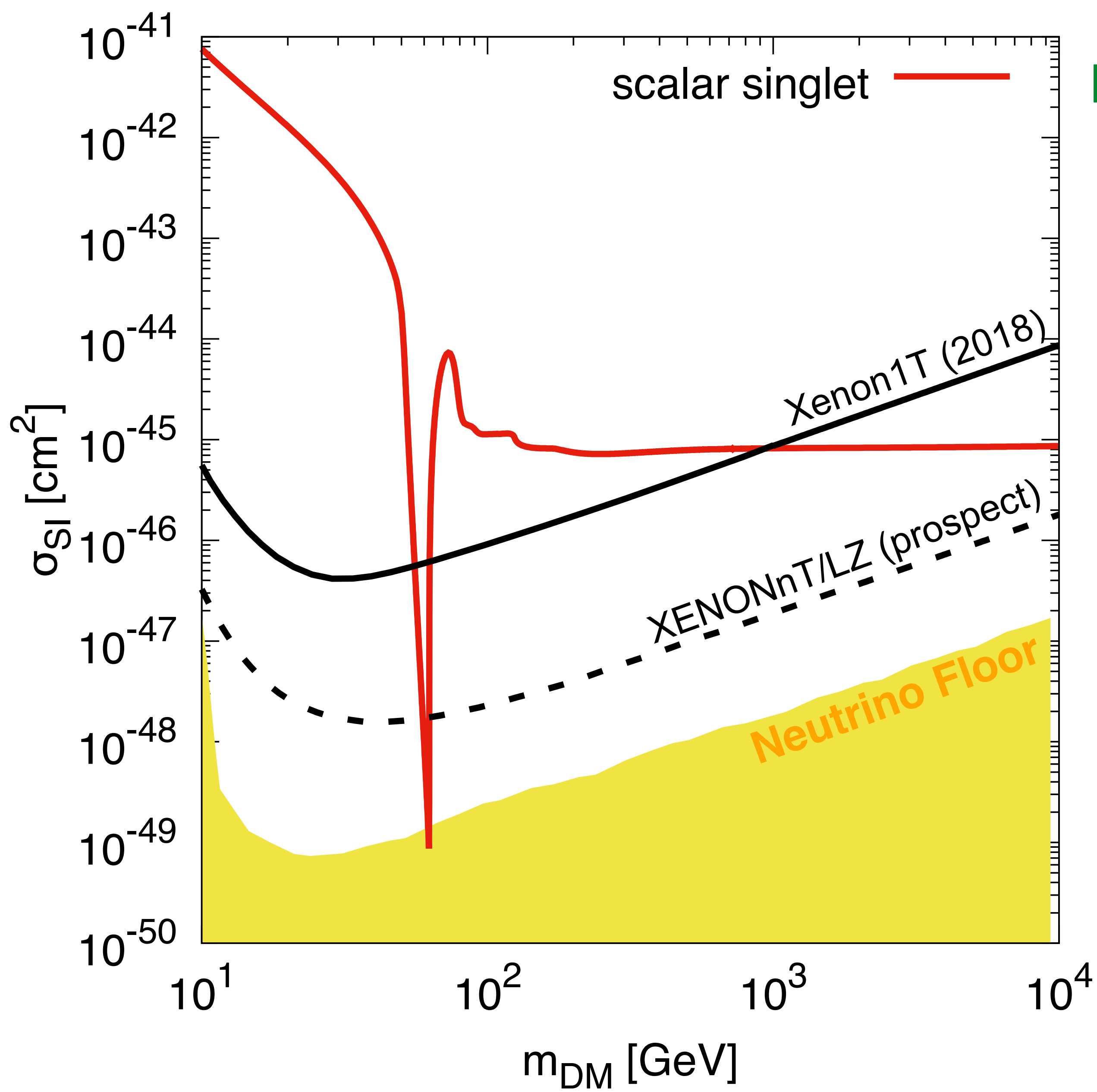
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{m^2}{2}S^2 - \frac{\lambda_{sH}}{2}S^2 H^\dagger H - \frac{\lambda_s}{4!}S^4$$

- two free parameters: DM mass and λ_{sH}
- determine λ_{sH} to obtain measured value of the DM energy density
- then we can predict σ_{SI} uniquely

How strong is the Xenon1T constraint?

singlet scalar DM vs direct detection

- $m_{DM} > 1\mathrm{TeV}$ is allowed
- $m_{DM} \sim m_h/2$ is also allowed (Higgs funnel/resonance)



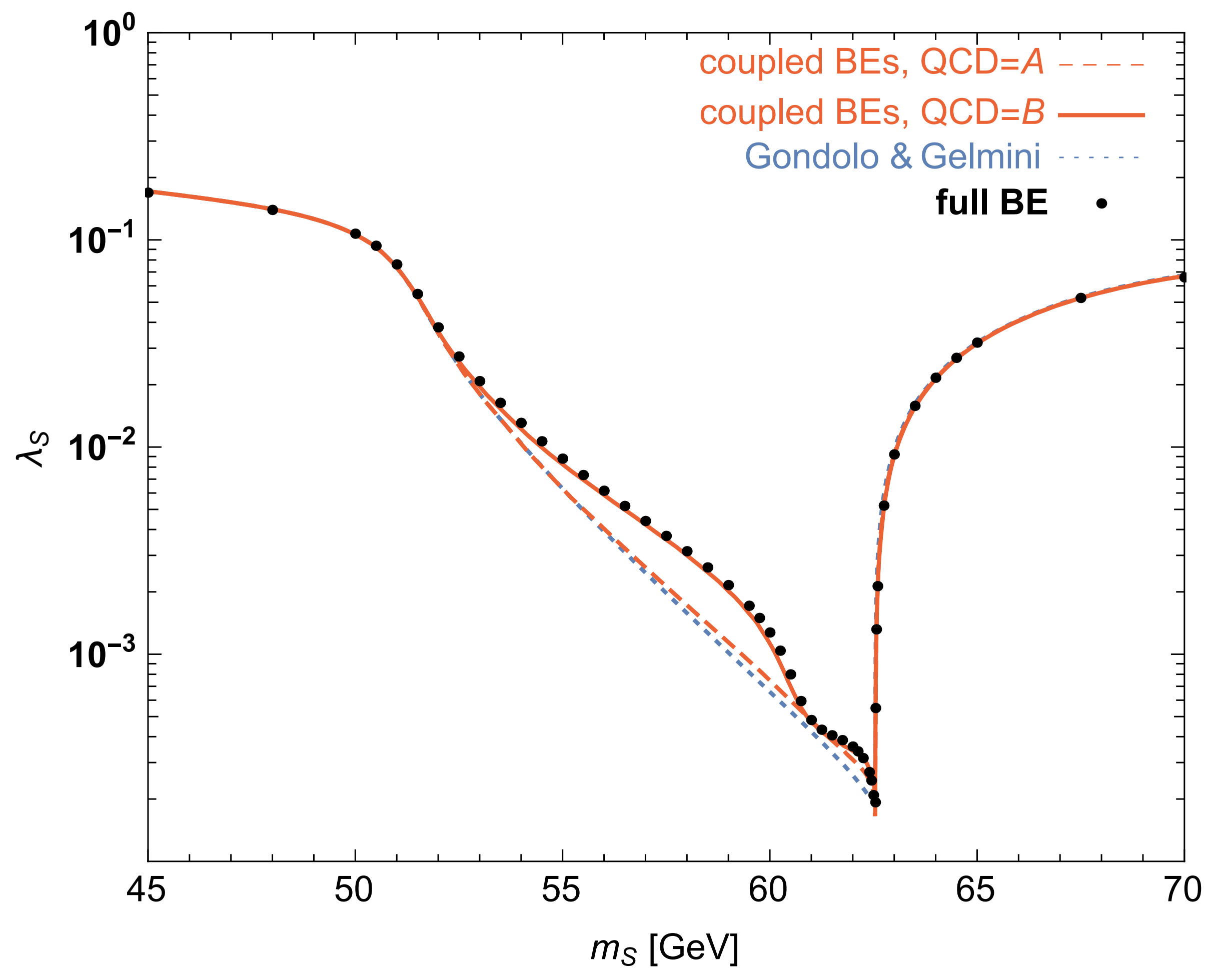
[TA Kitano Sato ('15) w/ update]

Early kinetic decoupling

[Duch, Grzadkowski ('17);
Binder, Bringmann, Gustafsson, Hryczuk ('17)]

Calculation in the Higgs funnel region required dedicated study

- coupling is very small
- kinetic decoupling happens before chemical decoupling
- $T_\chi \neq T$ ($T_\chi = T$ is assumed in standard treatment)
- coupling should be larger ==> stronger constraint from Xenon1T



withOUT assuming $T_\chi = T$ (cont'd)

$$\frac{dY}{dx} = \sqrt{\frac{8m_{pl}^2\pi^2}{45}}\frac{m_\chi}{x^2}\sqrt{g_*(T)}\left(-\left\langle\sigma v\right\rangle_{T_\chi}Y^2 + \left\langle\sigma v\right\rangle_T Y_{eq}^2\right),$$

$$\frac{1}{y}\frac{dy}{dx} = \sqrt{\frac{8m_{pl}^2\pi^2}{45}}\frac{m_\chi}{x^2}\sqrt{g_*(T)}\left\{Y\left(\left\langle\sigma v\right\rangle_{T_\chi} - \left\langle\sigma v\right\rangle_{2,T_\chi}\right) + \frac{Y_{eq}^2}{Y}\left(\frac{y_{eq}}{y}\left\langle\sigma v\right\rangle_{2,T} - \left\langle\sigma v\right\rangle_T\right)\right\}$$
$$+ \sqrt{g_*(T)}\frac{x^2}{g_s(T)}\tilde{\gamma}\left(\frac{y_{eq}}{y} - 1\right) + \left(1 + \frac{T}{3g_s(T)}\frac{dg_s(T)}{dT}\right)\frac{1}{3m_\chi}\frac{y_{eq}}{y}\left\langle\frac{p^4}{E^3}\right\rangle,$$

withOUT assuming $T_\chi = T$ (cont'd)

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$$\frac{1}{y}\frac{dy}{dx} = \sqrt{\frac{8m_{pl}^2\pi^2}{45}}\frac{m_\chi}{x^2}\sqrt{g_*(T)}\left\{Y\left(\langle\sigma v\rangle_{T_\chi} - \langle\sigma v\rangle_{2,T_\chi}\right) + \frac{Y_{eq}^2}{Y}\left(\frac{y_{eq}}{y}\langle\sigma v\rangle_{2,T} - \langle\sigma v\rangle_T\right)\right\}$$

$$+\sqrt{g_*(T)}\frac{x^2}{g_s(T)}\tilde{\gamma}\left(\frac{y_{eq}}{y} - 1\right) + \left(1 + \frac{T}{3g_s(T)}\frac{dg_s(T)}{dT}\right)\frac{1}{3m_\chi}\frac{y_{eq}}{y}\left\langle\frac{p^4}{E^3}\right\rangle,$$

$$\tilde{\gamma} = \sqrt{\frac{8m_{pl}^2\pi^2}{45}}\frac{15}{256\pi^5 m_\chi^6 g_\chi}\sum_{\mathcal{B}}\int_{m_{\mathcal{B}}}^{\infty} dE_k f_{\mathcal{B}}^{eq}(E_k)(1 \pm f_{\mathcal{B}}^{eq}(E_k))\int_{-4k_{cm}^2}^{0} dt(-t)\sum|\mathcal{M}_{\chi\mathcal{B}\to\chi\mathcal{B}}|^2$$

elastic scattering

$\mathcal{B}$: particles in the thermal bath

Result3: with scalar-couplings