CMB SIGNATURE OF NON-THERMAL DARK MATTER FROM SELF INTERACTING DARK SECTOR

SK JEESUN

IACS, KOLKATA

10.09.24

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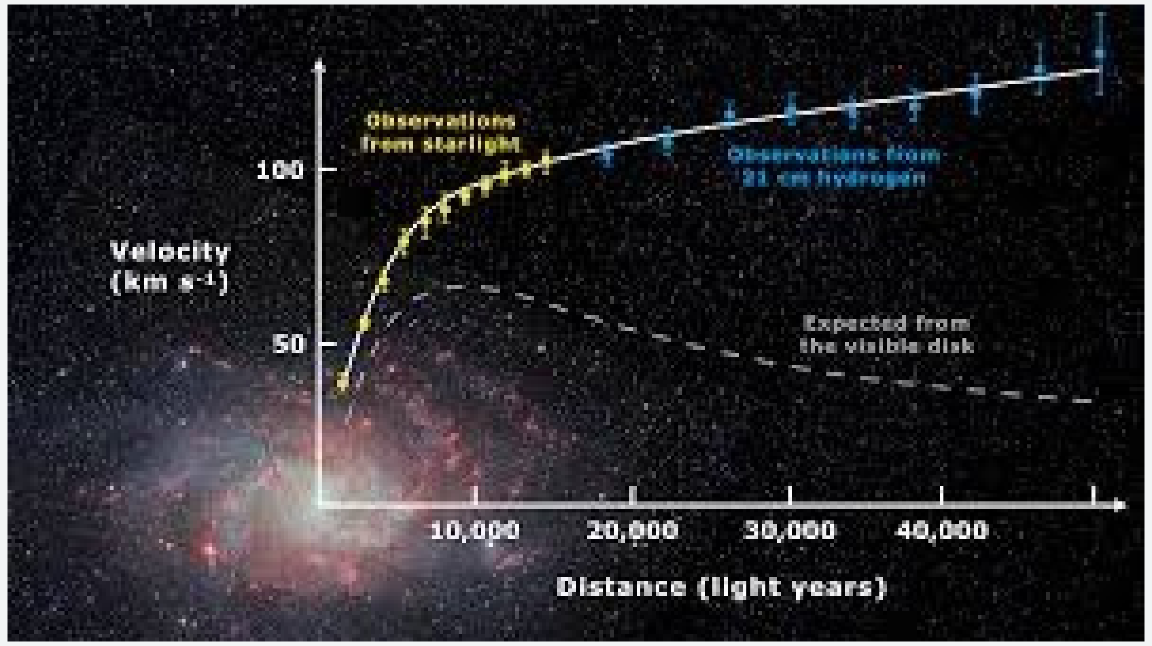
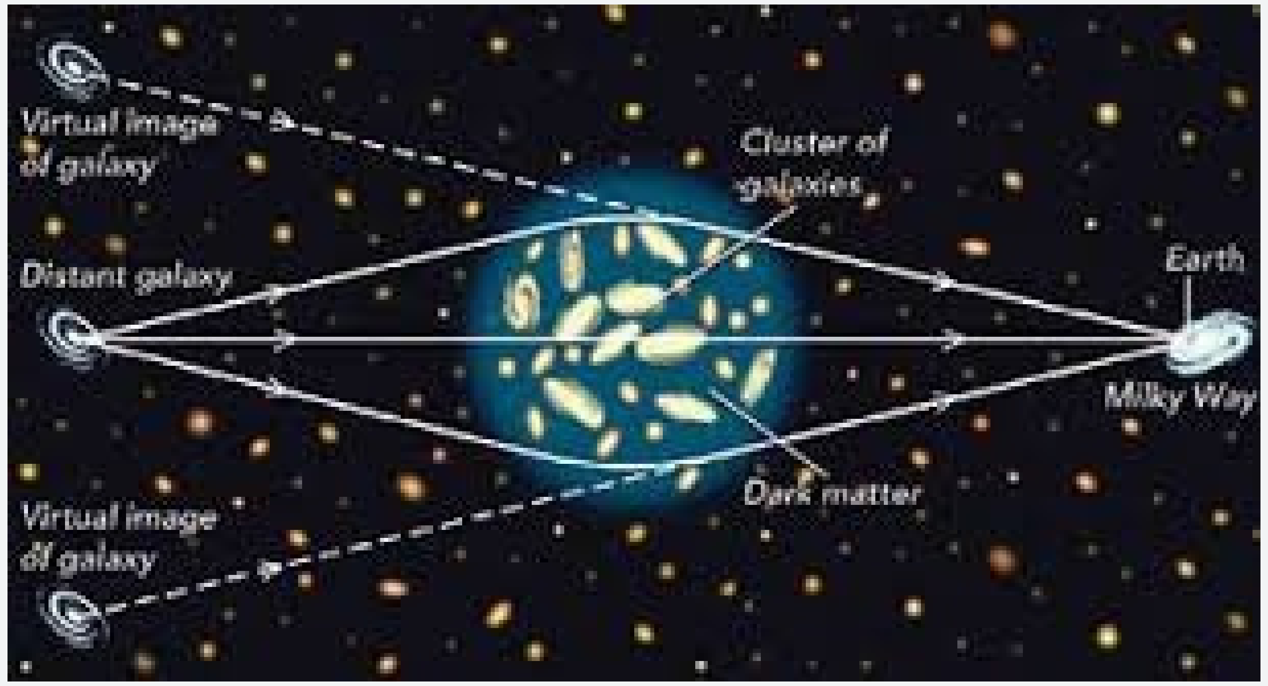
PARTICLE PRODUCTION IN THE EARLY UNIVERSE

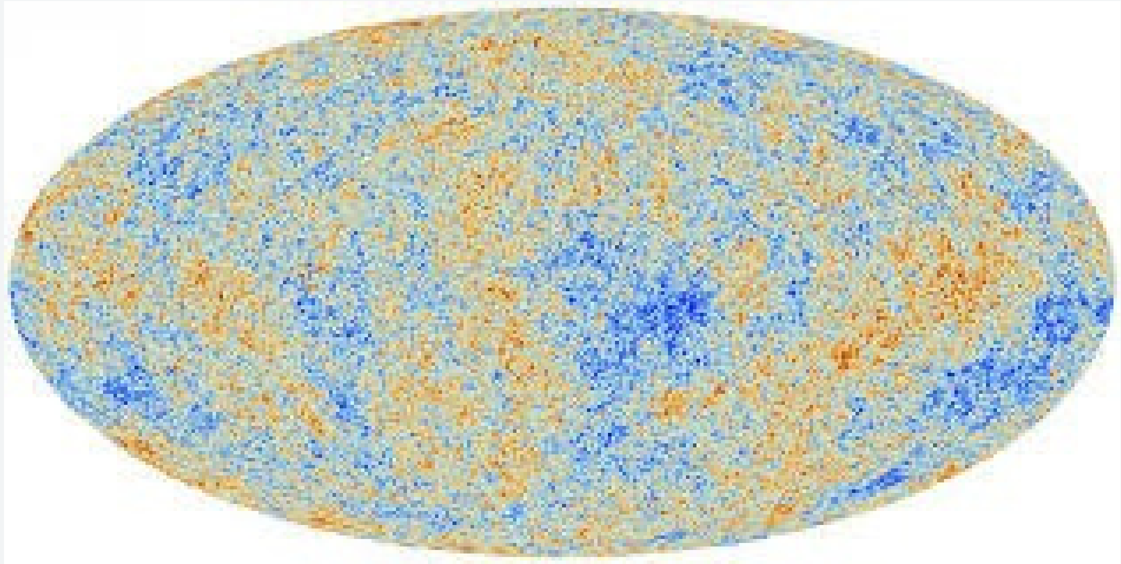
Outline

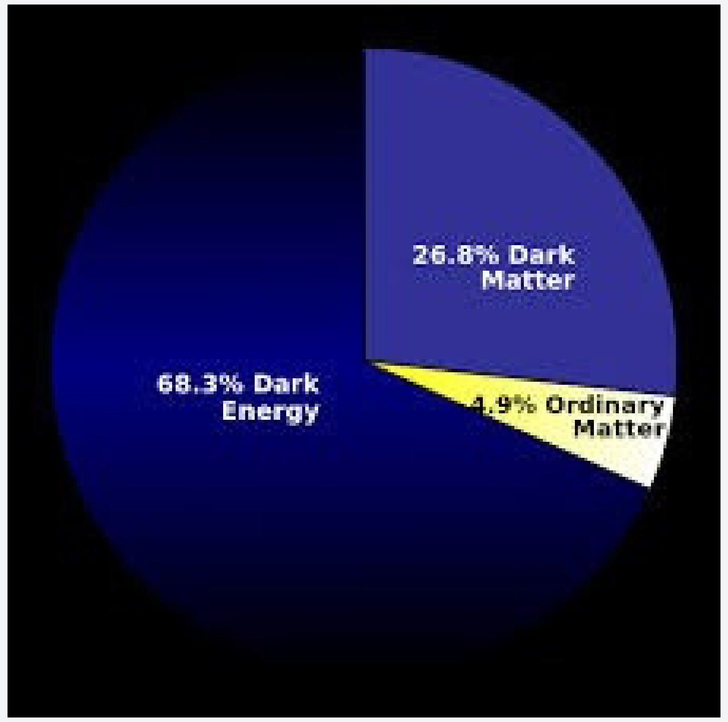
- Introduction
  1. Evidence of dark matter
  2. Particle dark matter
  3. DM Production
- Non thermal DM
- CMB signature as DM probe
  1. Model
  2. Dynamics of dark sector
  3. Results
- Conclusion

Evidence of Dark matter









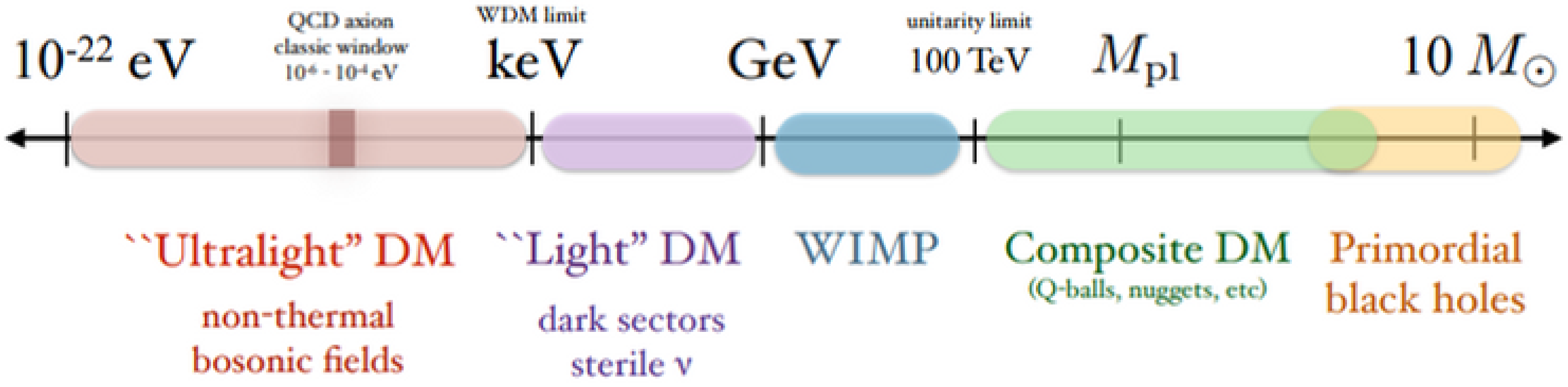
- Strongly suggest ~25% non-luminous, non baryonic DM
- SM fails to explain : begs for an extension

V.Rubin, WMAP, Planck 2018, M.Lisanti 2016

The puzzle of particle Dark matter

What we know:

- Interacts gravitationally
- Non luminous, electric charge very small
- Cold with mass<< momentum
- Collisionless at large scale



- Mass spanning from 1e-22 ev to the mass of least massive DM galaxy

M.Lisanti 2016, T. Lin 2019, Cirelli et al 2024

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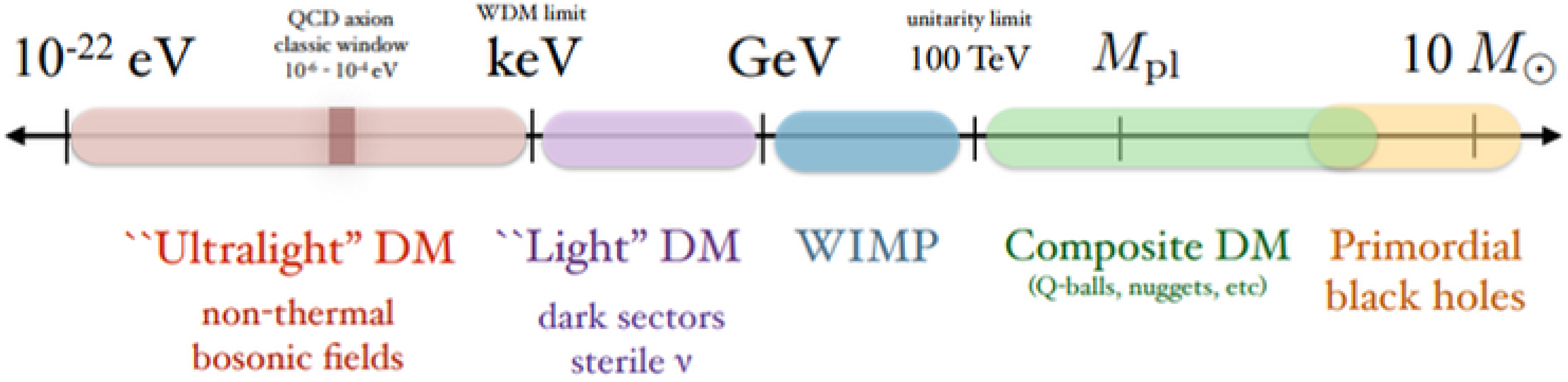

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- Mass, Spin?
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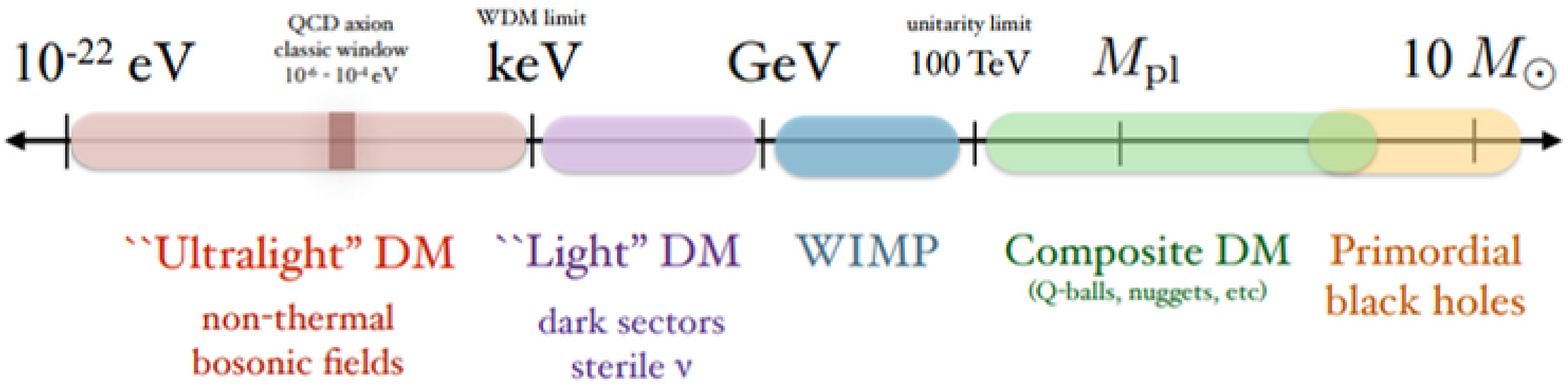

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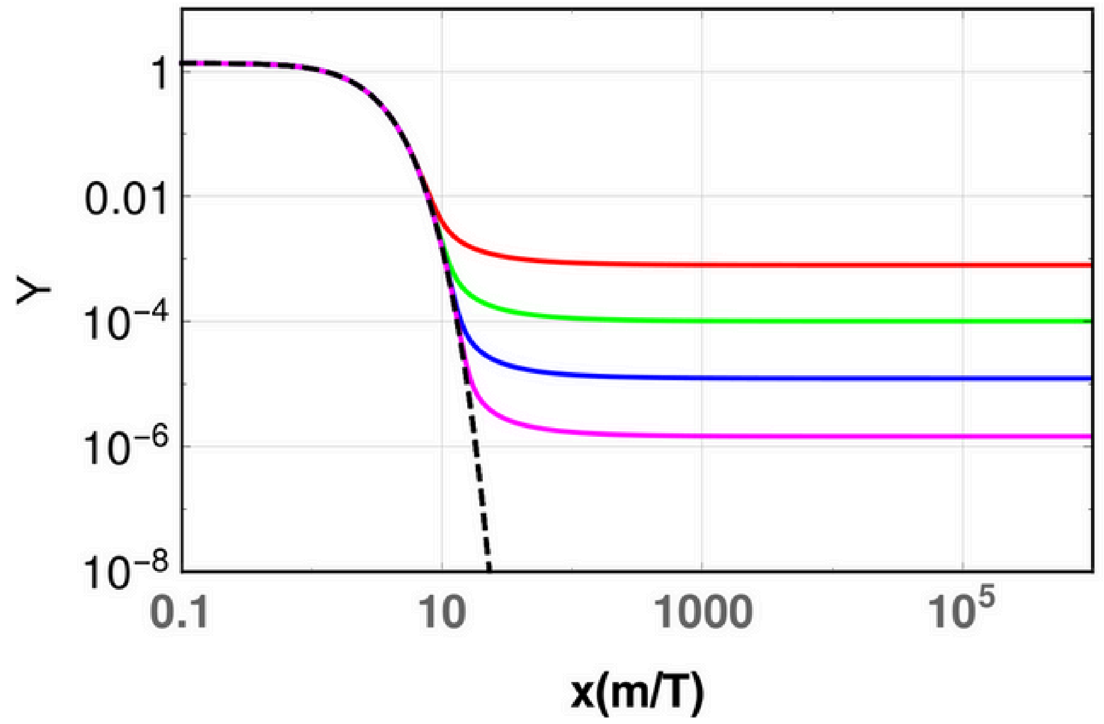
DM imprints can be related to production

M.Lisanti 2016, T. Lin 2019, Cirelli et al 2024

Dark matter production mechanisms

1.Thermal dark matter

- DM was in thermal equlibrium with SM bath at early time
- Kinetic eq. $\chi + SM \to \chi + SM \longrightarrow T_\chi = T_{SM}$
- Chemical eq. $\chi + \chi \to SM + SM \longrightarrow n_\chi = n_\chi^{eq.}$
- WIMP,SIMP and so on...



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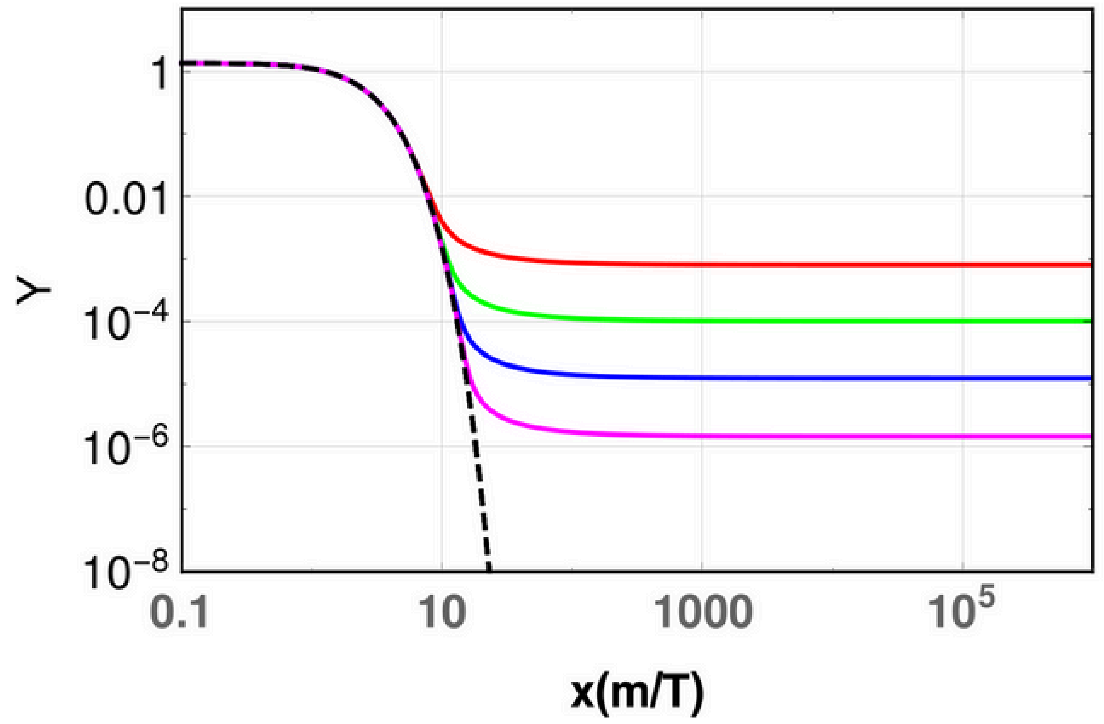
Can have imprints in Direct searches



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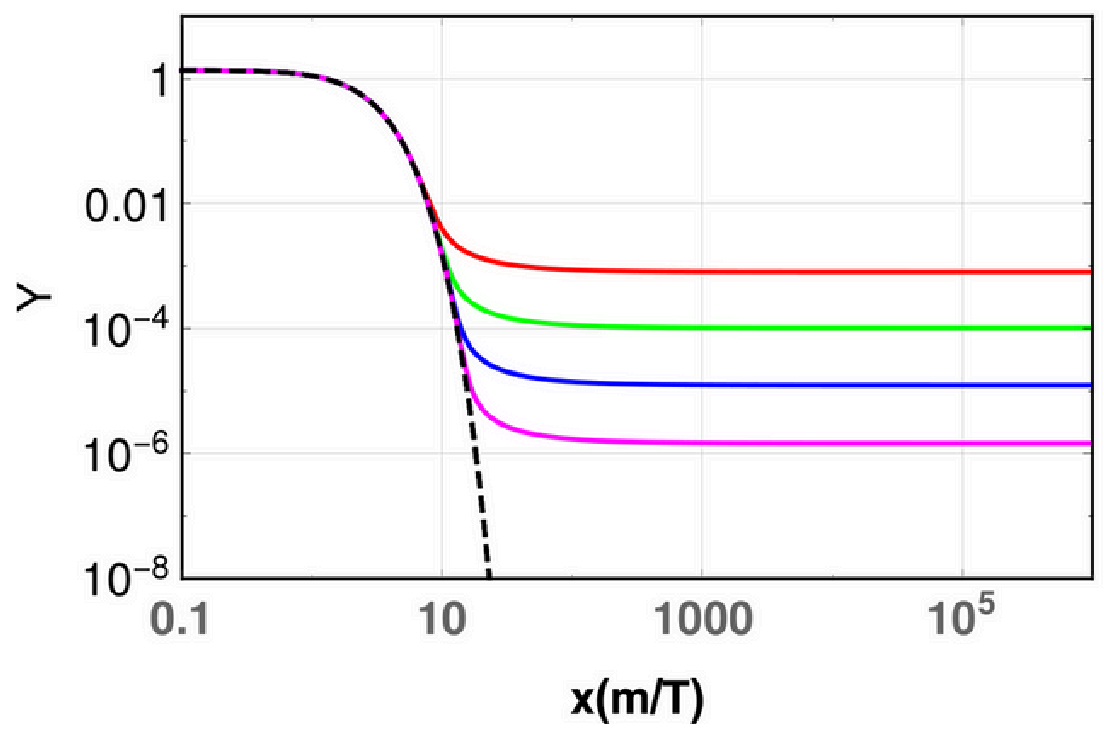

2.Non-thermal dark matter

- DM never attains equlibrium due to feeble interaction
- Initial abundance negligible
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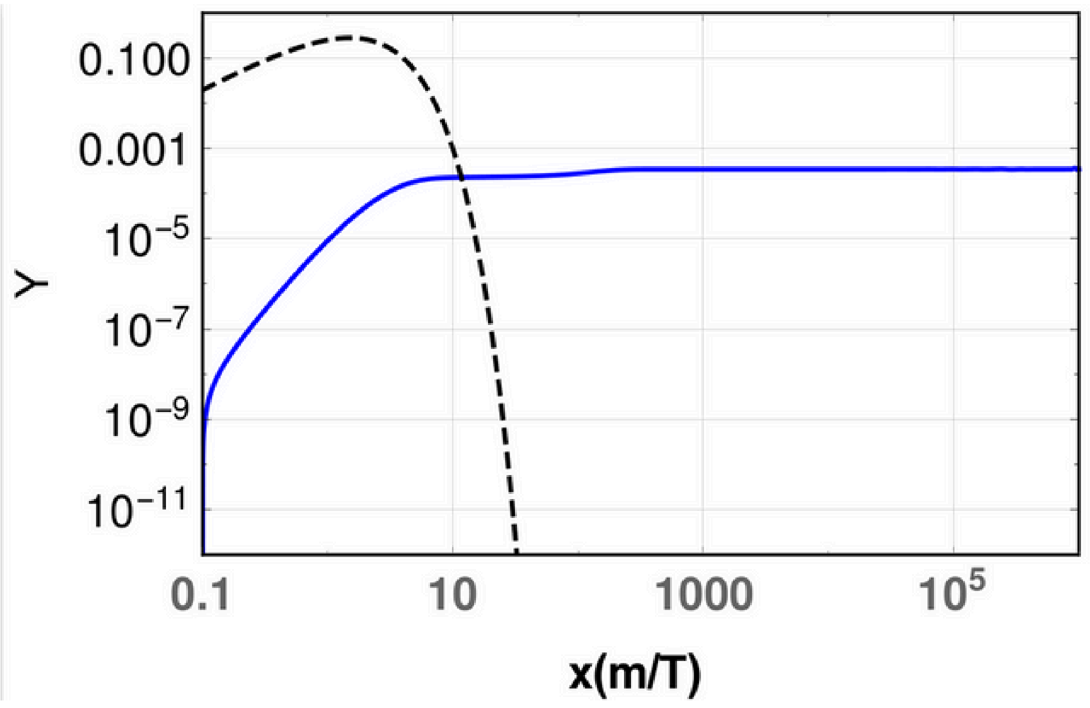

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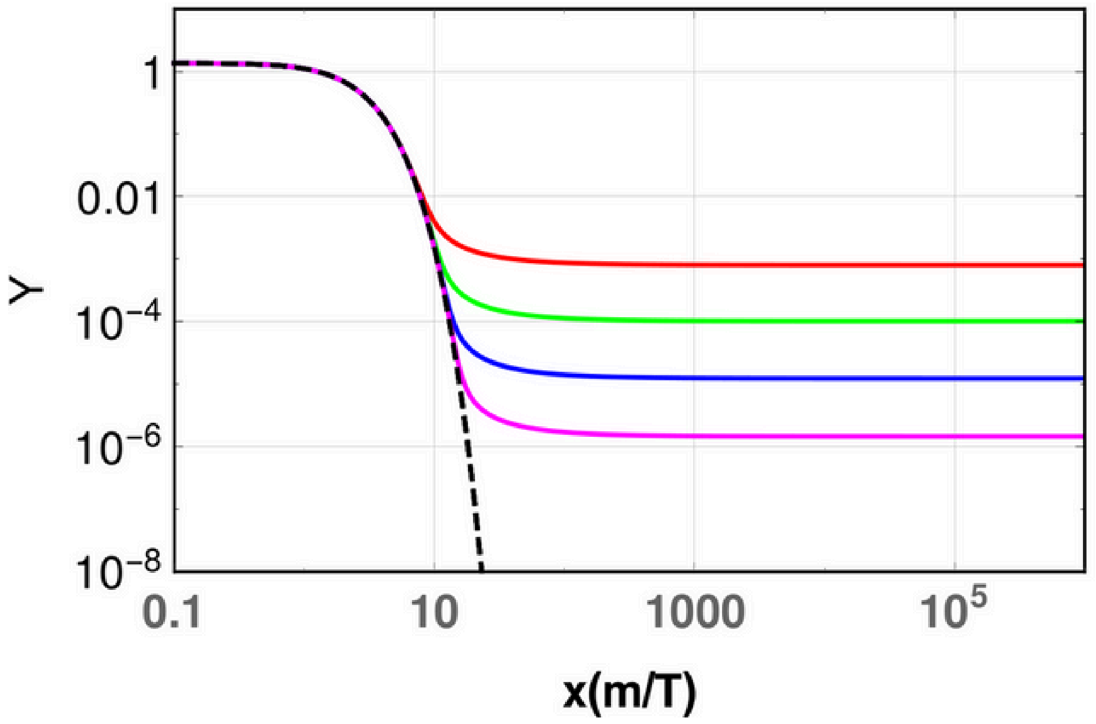

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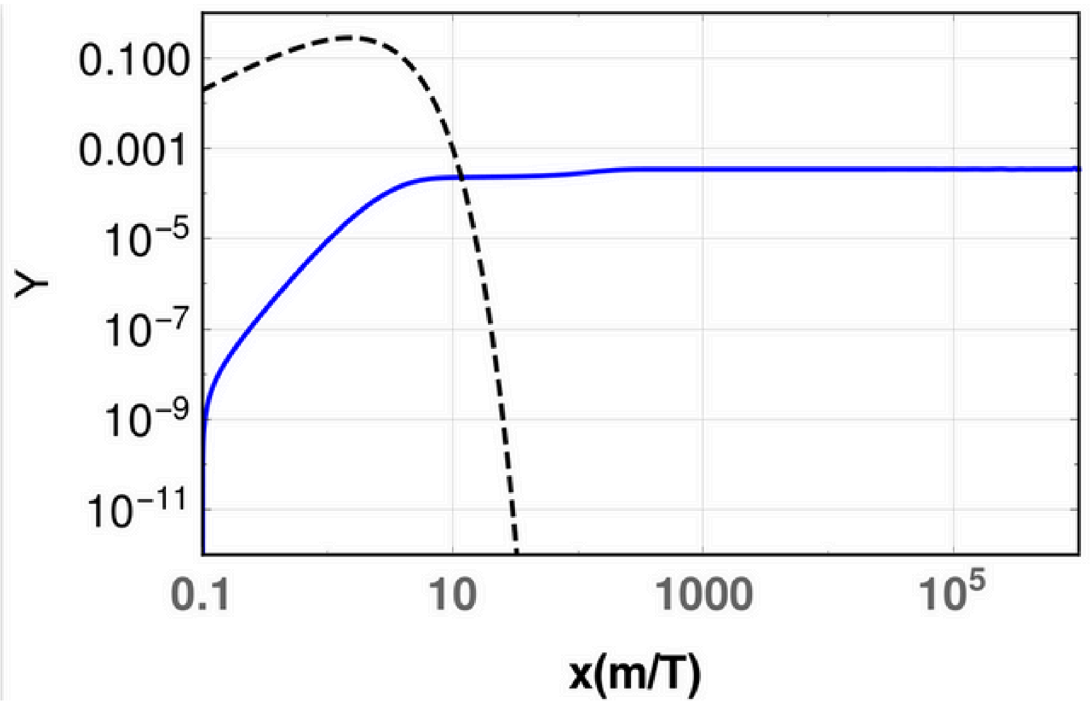

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Directly from SM bath

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Long lived particle searches

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  Production $\phi \to \chi + \ldots$

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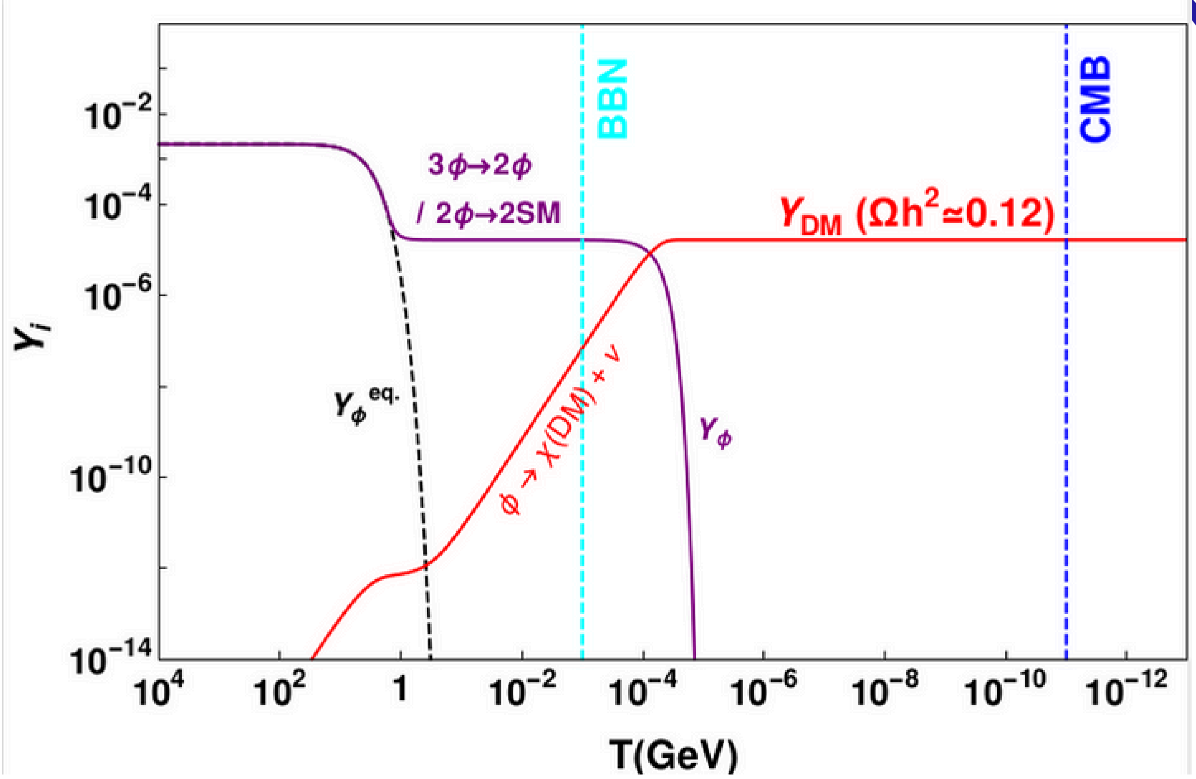

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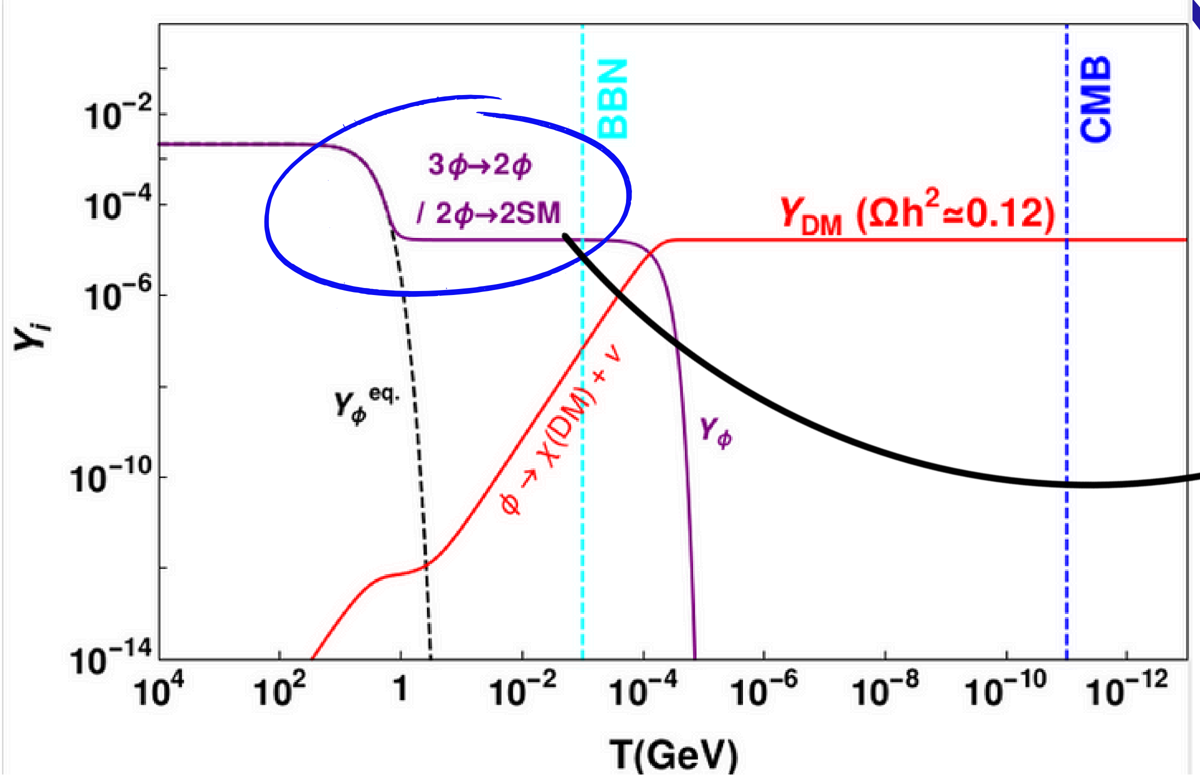

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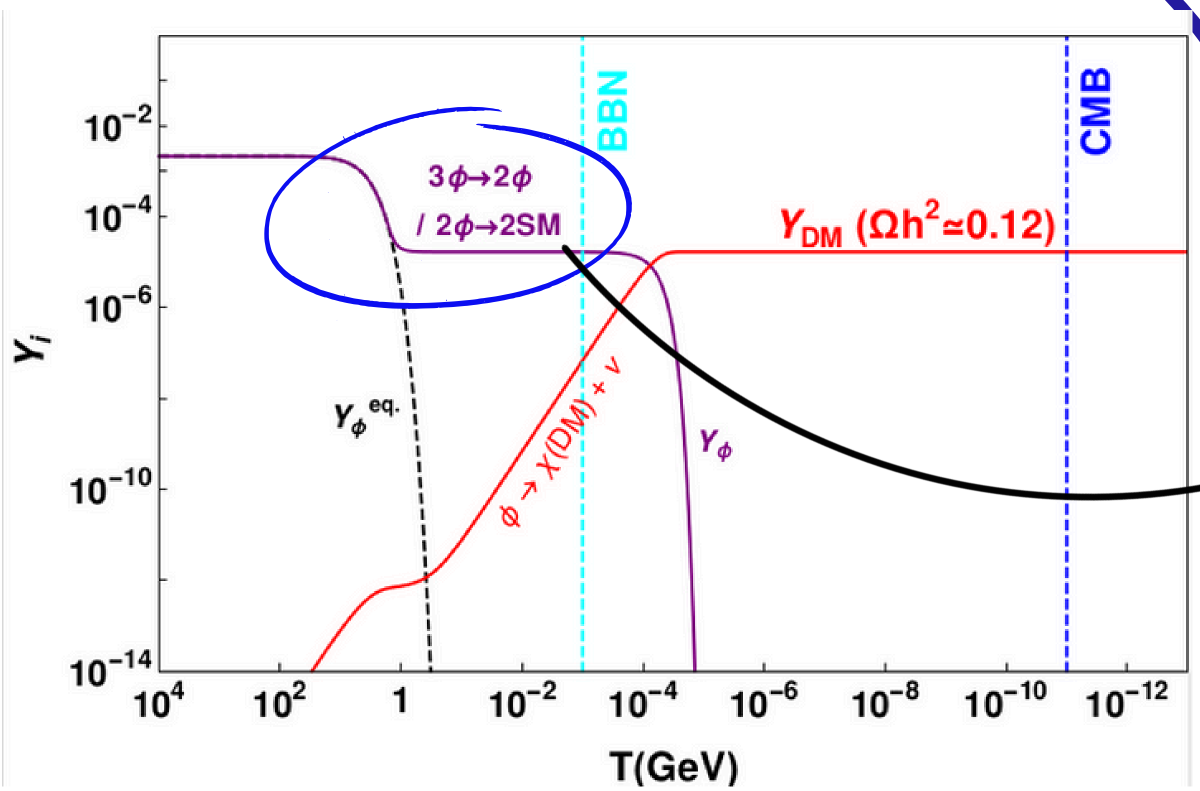

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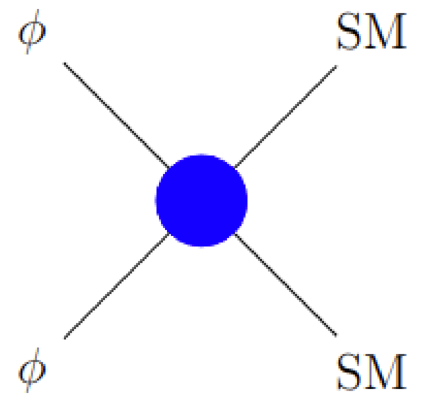

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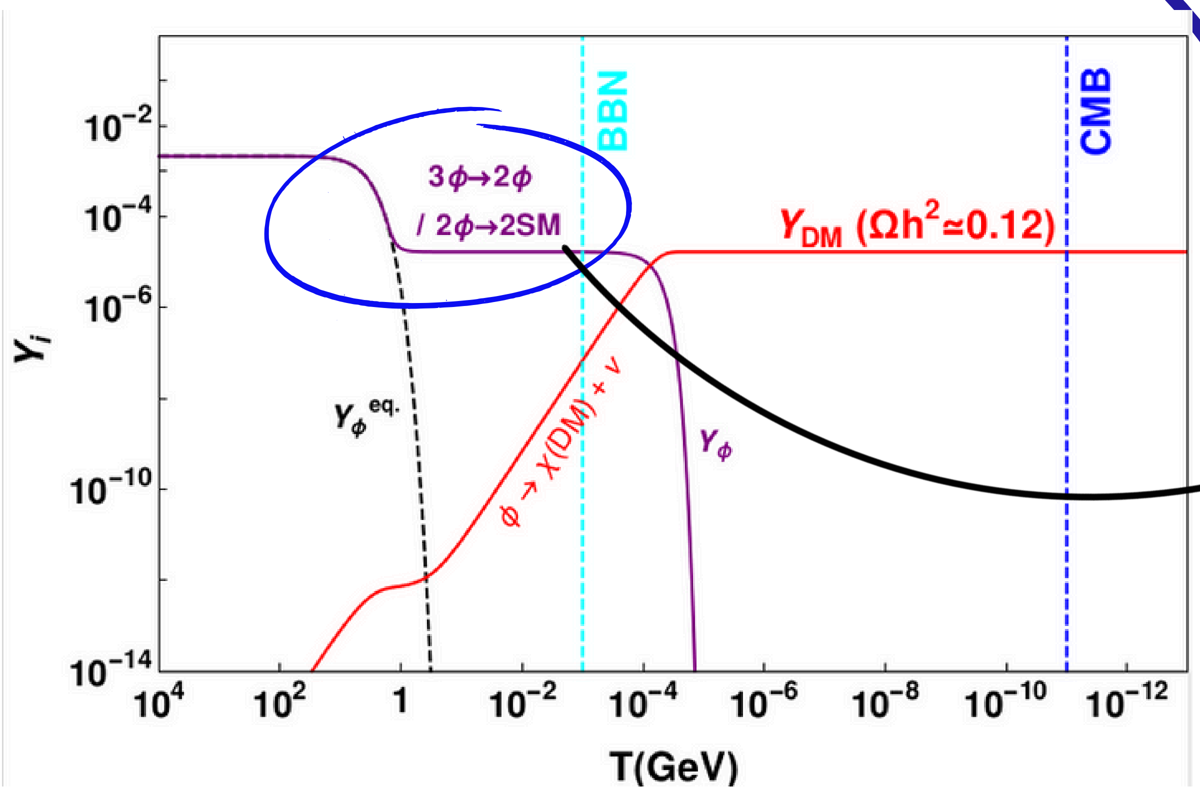

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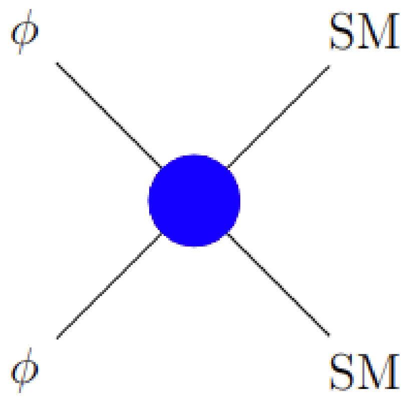
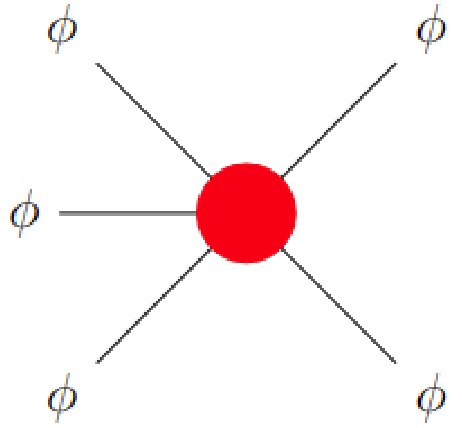


2.Self interaction



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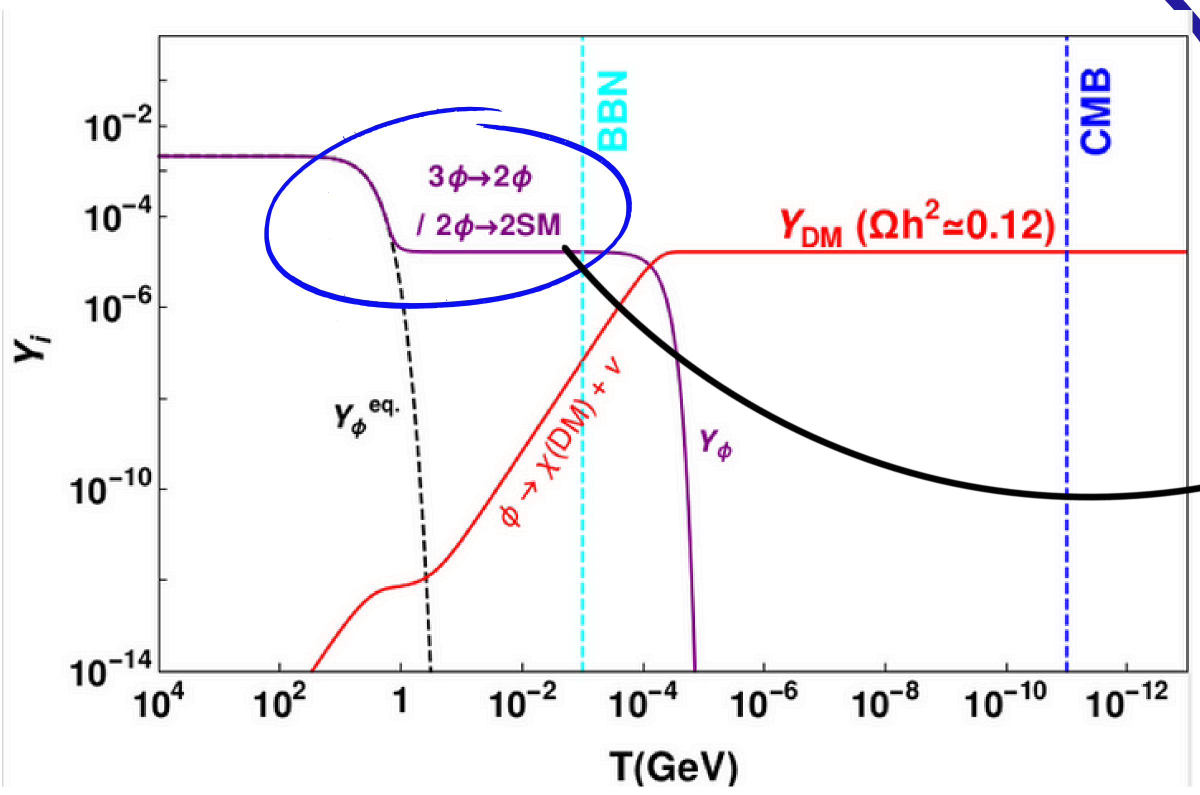

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Q.Is it possible to probe such scenarios?---> Possible via CMB

If DM production affects N_{eff}

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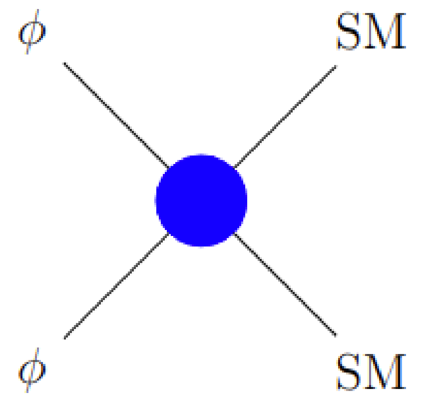

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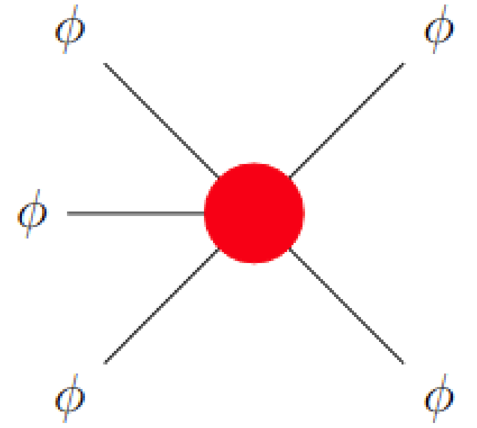
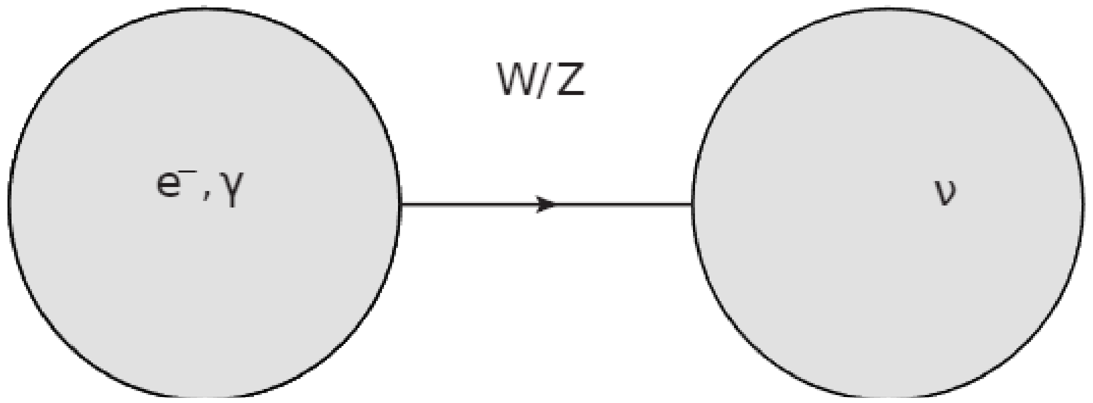


Contribution to N_{eff}

- $N_{eff}^{CMB} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}}\left(\frac{\rho_\upsilon}{\rho_\gamma}\right)_{CMB}$ where, $\rho_i \sim T_i^4$
- SM predicted value $N_{eff}^{CMB} = 3.046$



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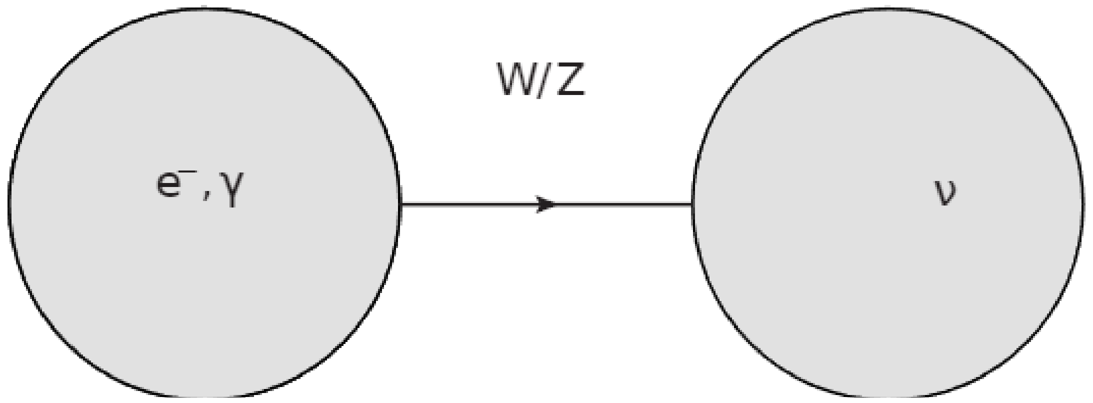

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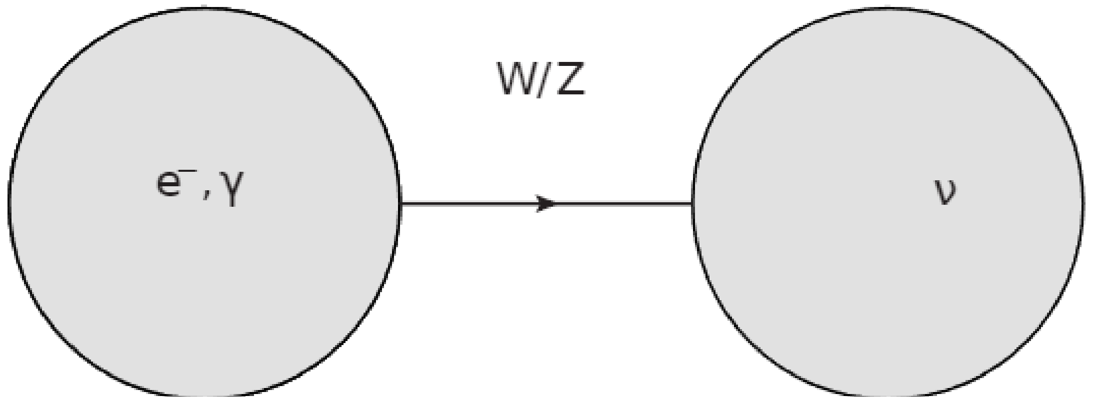

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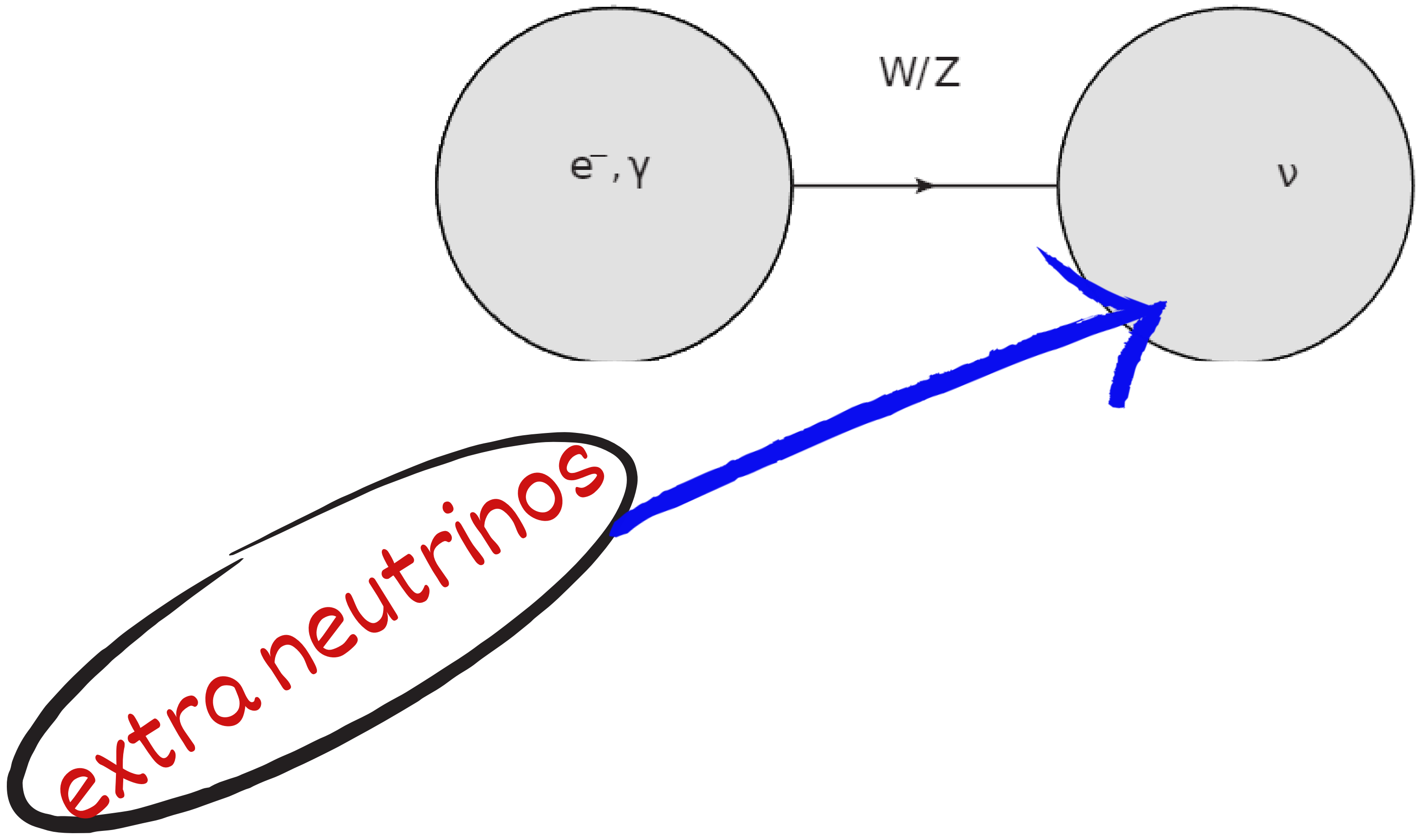

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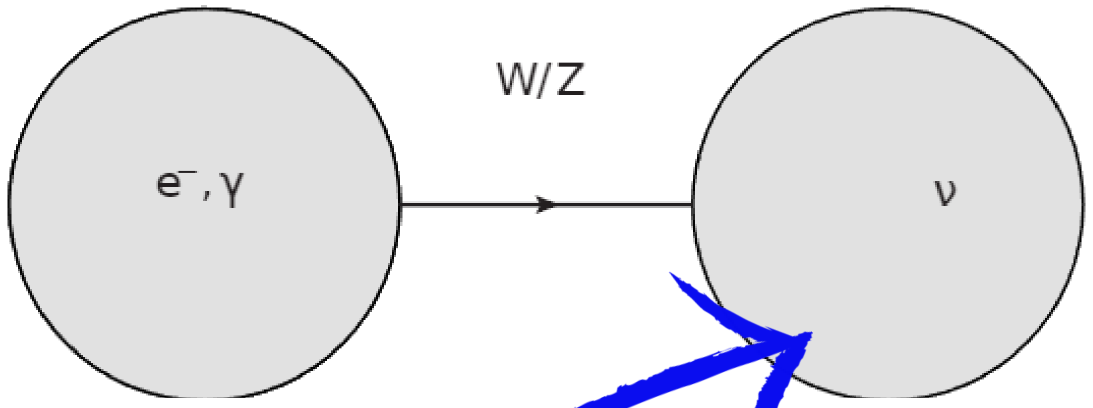

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extra neutrinos

- $\frac{N'_{eff}}{N_{eff}^{SM}} = \left(\frac{\rho'_\nu}{\rho_\nu^{SM}}\right)_{CMB}$ $\Delta N_{eff} = \left(\frac{\rho'_\nu}{\rho_\nu^{SM}} - 1\right) N_{eff}^{SM}\Big|_{T=T_{CMB}}$

- Boltzmann equations to track the energy densities

Q.How will we relate χ and N_{eff}?

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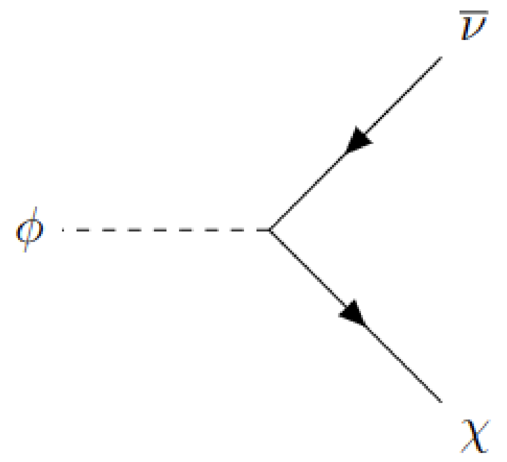
- Possible if ➡ $\mathcal{L} \supset y\phi\bar{\chi}\nu$ with $M_\phi > M_\chi$



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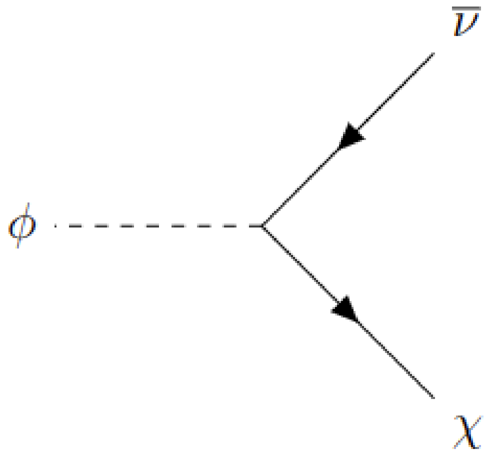
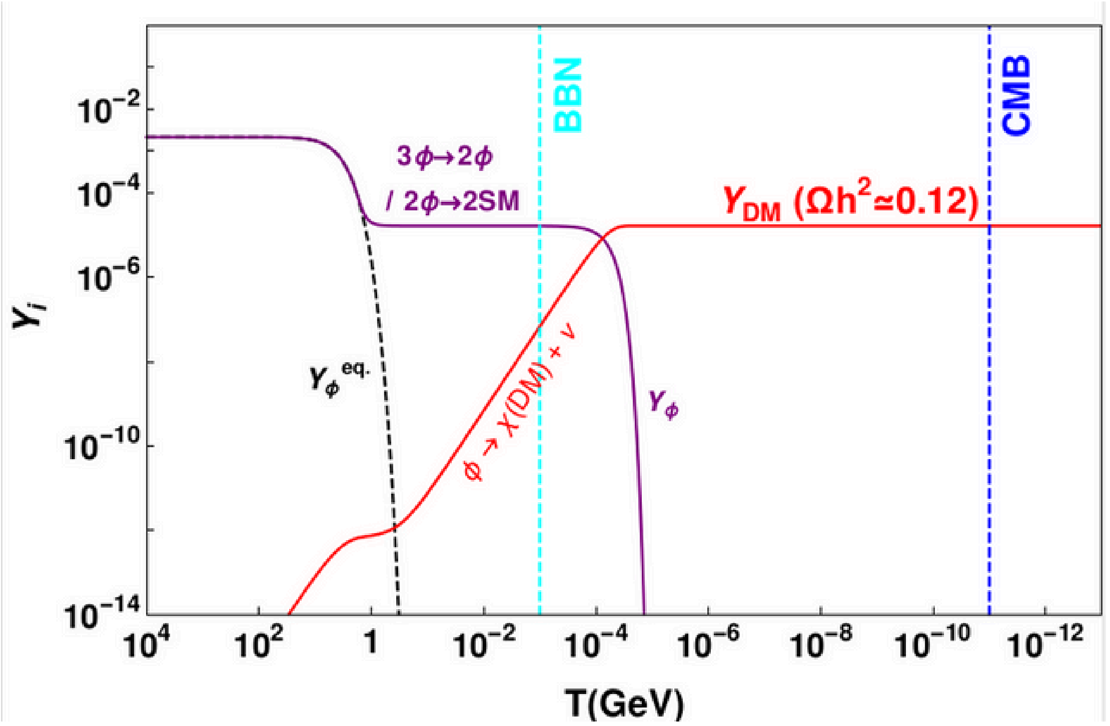


Recap of previous slide



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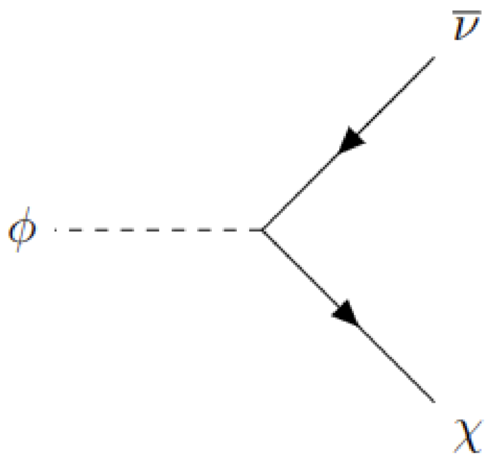

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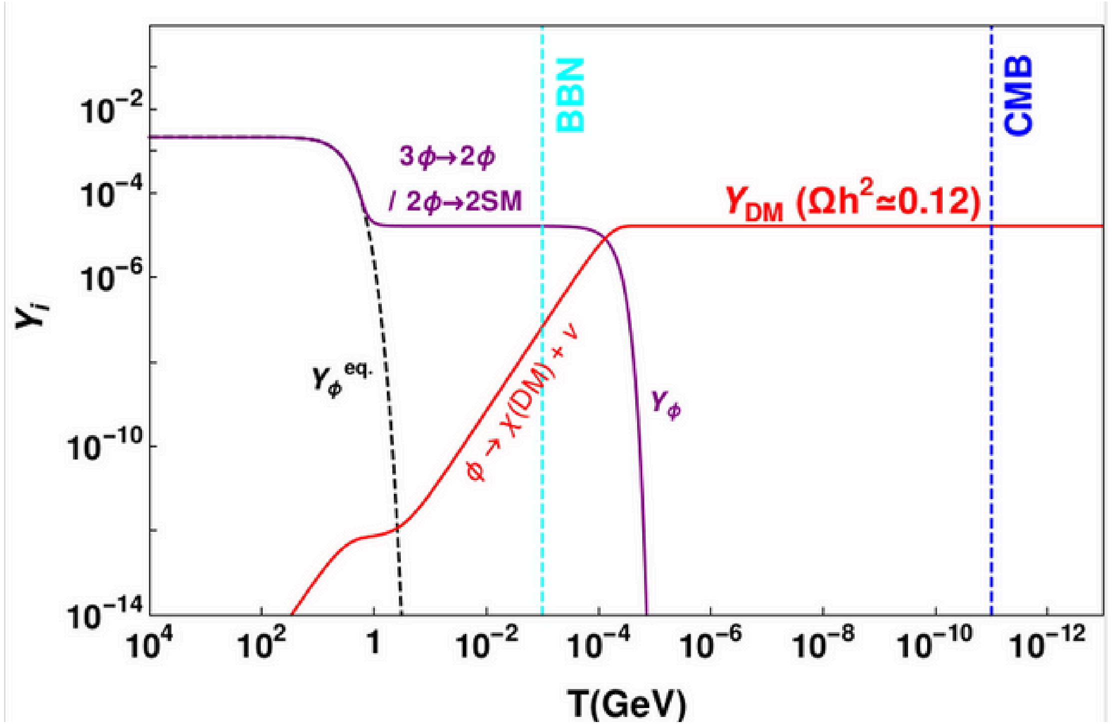

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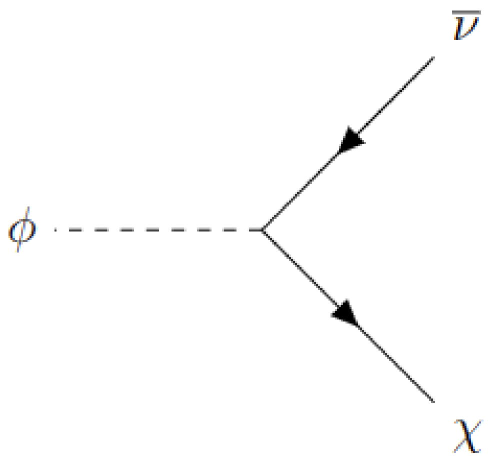

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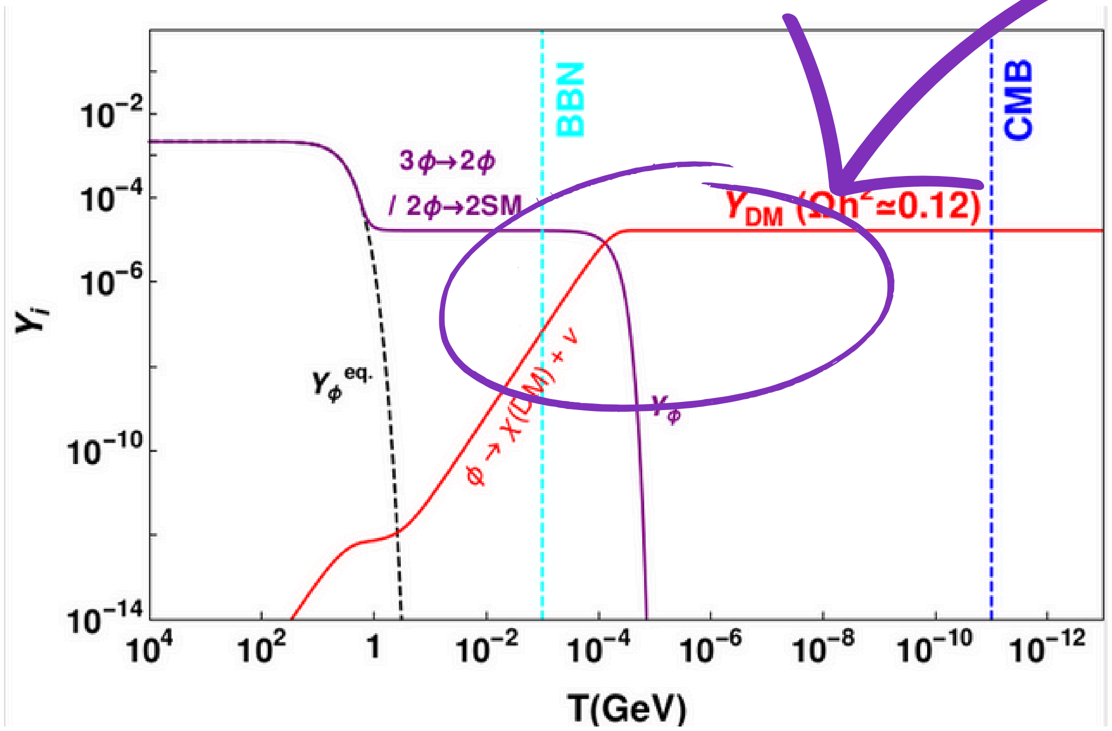

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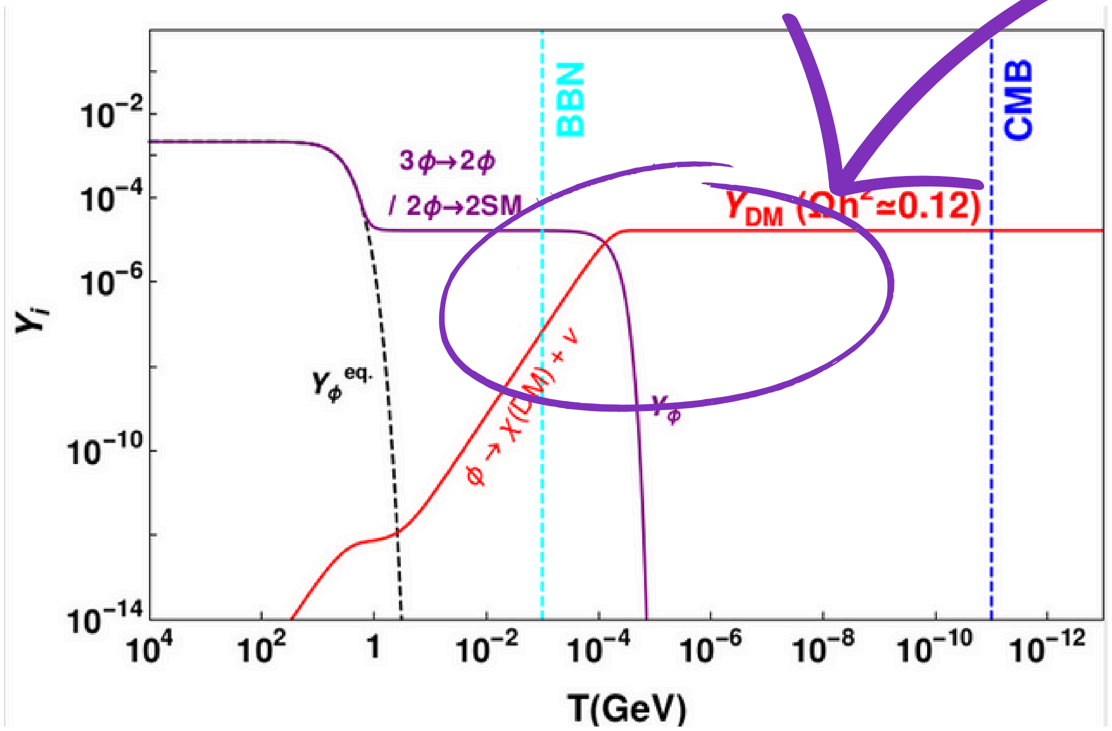

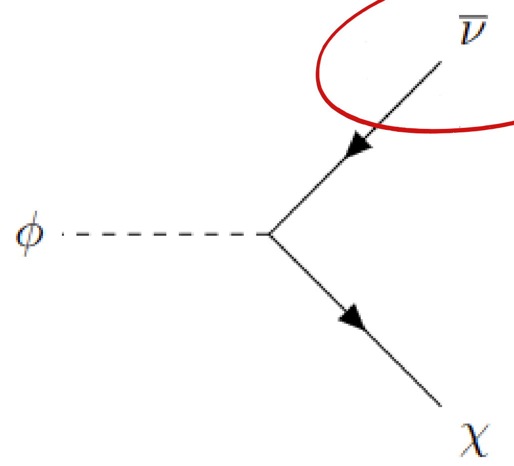

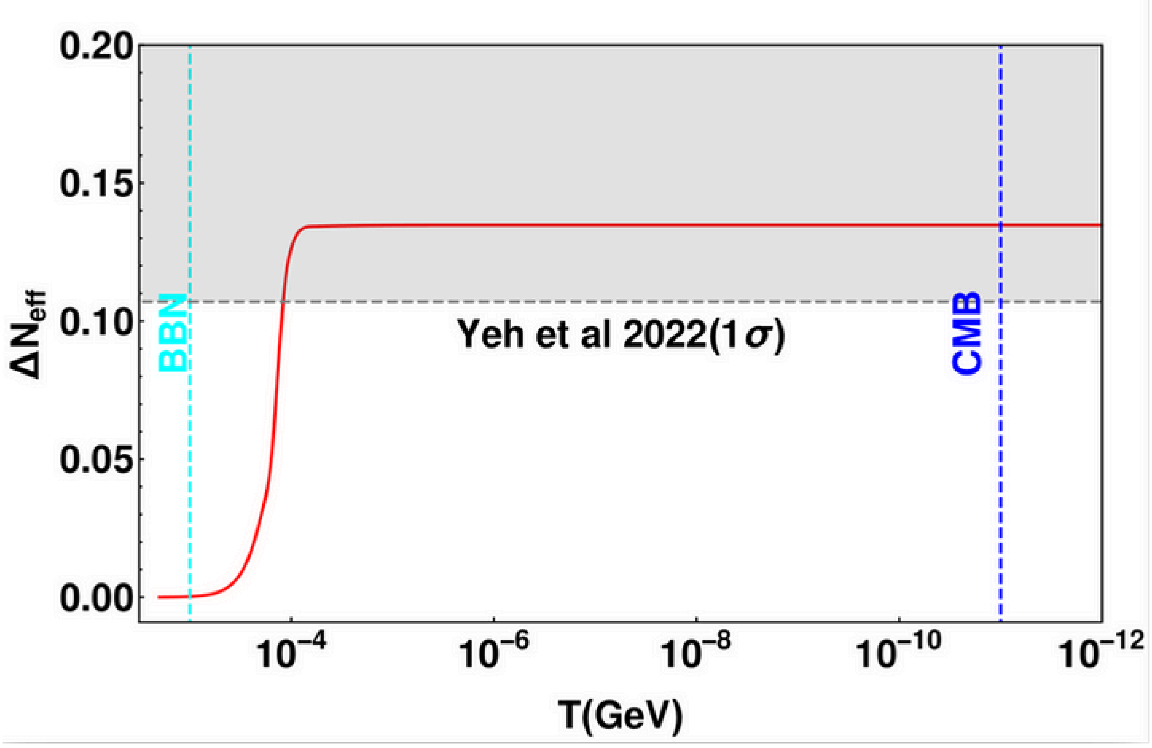

Boltzmann eqn: $d\rho'_\nu/dt + 4H\rho_\nu = \Gamma_{\phi\to\chi\,\nu}\,\rho_\phi$

The model

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$$\mathcal{L}_{\rm N} = \sum_i i\bar{N}_i\gamma^\mu\partial_\mu N_i - \sum_{i,j}\frac{1}{2}M_{N_{ij}}\bar{N}_i^c N_j - \sum_{\ell,j} Y_{\ell j}\bar{L}_\ell\tilde{H}N_j + h.c.$$

$$\begin{aligned}\mathcal{L}_{\rm BSM} &\supset \mathcal{L}_{\rm DS} + \mathcal{L}_{\rm DS-H} + \mathcal{L}_{\rm DS-\nu}\\ &= \Big(|\partial_\mu\phi|^2 - \mu^2|\phi|^2 + i\bar{\chi}\gamma^\mu\partial_\mu\chi - M_{\rm DM}\bar{\chi}\chi - \lambda_\phi|\phi|^4 - \frac{\mu_\phi}{3!}(\phi^3+\phi^{*3})\\ &\quad -y_{\phi\chi}\overline{\chi^c}\chi\phi\Big) + \Big(-\lambda_{\phi H}|H|^2|\phi|^2\Big) + \Big(-\sum_i y_{\phi N_i}\bar{\chi}\phi N_i + h.c.\Big)\ ,\end{aligned}$$

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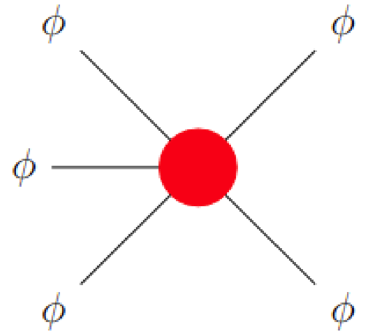
Self scattering



$$\phi + \phi + \phi \Leftrightarrow \phi + \phi$$

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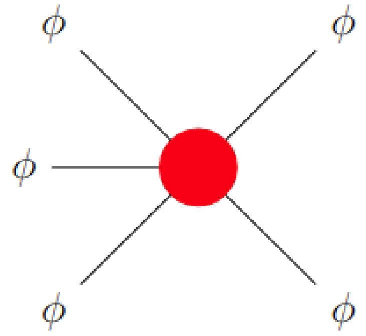
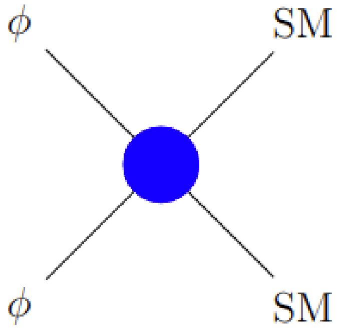
Self scattering



$$\begin{aligned}\mathcal{L}_{\mathrm{BSM}} &\supset \mathcal{L}_{\mathrm{DS}} + \mathcal{L}_{\mathrm{DS-H}} + \mathcal{L}_{\mathrm{DS-}\nu} \\ &= \Big(|\partial_\mu\phi|^2 - \mu^2|\phi|^2 + i\bar{\chi}\gamma^\mu\partial_\mu\chi - M_{\mathrm{DM}}\bar{\chi}\chi - \lambda_\phi|\phi|^4 - \frac{\mu_\phi}{3!}(\phi^3 + \phi^{*3}) \\ &\quad - y_{\phi\chi}\overline{\chi^c}\chi\phi\Big) + \Big(-\lambda_{\phi H}|H|^2|\phi|^2\Big) + \Big(-\sum_i y_{\phi N_i}\bar{\chi}\phi N_i + h.c.\Big) ,\end{aligned}$$

$$\phi + \phi + \phi \Leftrightarrow \phi + \phi$$

Annihilations



$$\phi + \phi \Leftrightarrow f + f\,(W^+W^-, ZZ)$$

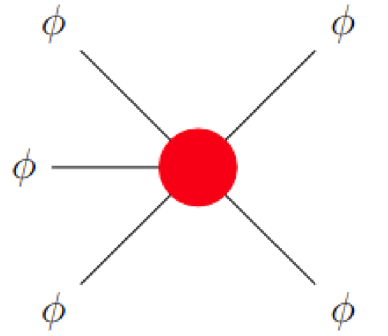
The model

- Type-I Seesaw Model + Z_3 odd complex scalar ϕ and fermion χ

$$\mathcal{L}_{\rm N} = \sum_i i\bar{N}_i\gamma^\mu\partial_\mu N_i - \sum_{i,j}\frac{1}{2}M_{N_{ij}}\bar{N}_i^c N_j - \sum_{\ell,j} Y_{\ell j}\bar{L}_\ell\tilde{H}N_j + h.c.$$

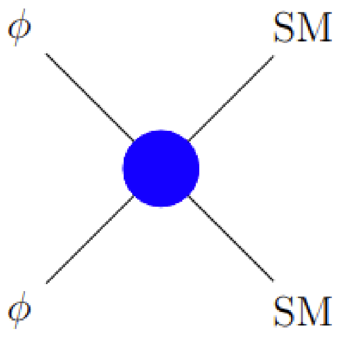
$$\begin{aligned}\mathcal{L}_{\rm BSM} &\supset \mathcal{L}_{\rm DS} + \mathcal{L}_{\rm DS-H} + \mathcal{L}_{\rm DS-\nu} \\ &= \Big(|\partial_\mu\phi|^2 - \mu^2|\phi|^2 + i\bar{\chi}\gamma^\mu\partial_\mu\chi - M_{\rm DM}\bar{\chi}\chi - \lambda_\phi|\phi|^4 - \frac{\mu_\phi}{3!}(\phi^3 + \phi^{*3}) \\ &\quad - y_{\phi\chi}\overline{\chi^c}\chi\phi\Big) + \Big(-\lambda_{\phi H}|H|^2|\phi|^2\Big) + \Big(-\sum_i y_{\phi N_i}\bar{\chi}\phi N_i + h.c.\Big) \ ,\end{aligned}$$

Self scattering



$$\phi + \phi + \phi \Leftrightarrow \phi + \phi$$

Annihilations



$$3 \to 2 \ : \quad \mu_\phi, \lambda_\phi$$
$$2 \to 2 \ : \quad \lambda_{\phi H}$$

$$\phi + \phi \Leftrightarrow f + f\,(W^+W^-, ZZ)$$

The model

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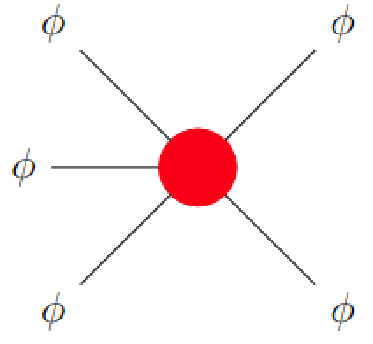
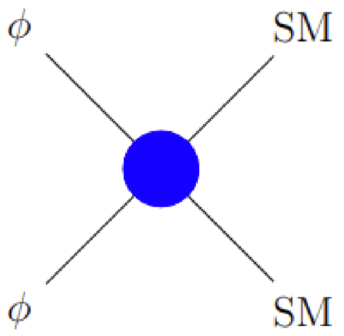
Self scattering



$$\phi+\phi+\phi \Leftrightarrow \phi+\phi$$

Annihilations



$$\phi+\phi \Leftrightarrow f+f\,(W^+W^-, ZZ)$$

Elastic scattering

$$\phi+f \Leftrightarrow \phi+f$$

$3\to 2$: μ_ϕ, λ_ϕ

$2\to 2$: $\lambda_{\phi H}$

The model

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$$\mathcal{L}_{\rm N} = \sum_i i\bar{N}_i\gamma^\mu\partial_\mu N_i - \sum_{i,j}\frac{1}{2}M_{N_{ij}}\bar{N}_i^c N_j - \sum_{\ell,j} Y_{\ell j}\bar{L}_\ell \tilde{H} N_j + h.c.$$

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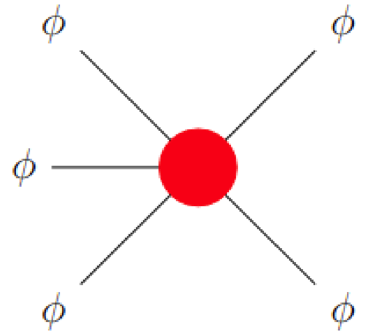
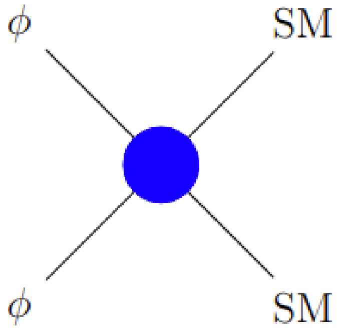
Self scattering



$$\phi+\phi+\phi \Leftrightarrow \phi+\phi$$

Annihilations



$$\phi+\phi \Leftrightarrow f+f\,(W^+W^-, ZZ)$$

Elastic scattering

$$\phi+f \Leftrightarrow \phi+f$$

$$T_\phi = T_{SM}$$

$3 \to 2$: μ_ϕ, λ_ϕ

$2 \to 2$: $\lambda_{\phi H}$

The model

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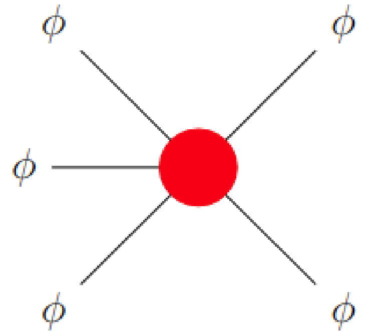
$$\mathcal{L}_{\rm N} = \sum_i i\bar{N}_i\gamma^\mu\partial_\mu N_i - \sum_{i,j}\frac{1}{2}M_{N_{ij}}\bar{N}_i^c N_j - \sum_{\ell,j} Y_{\ell j}\bar{L}_\ell\tilde{H}N_j + h.c.$$

Self scattering



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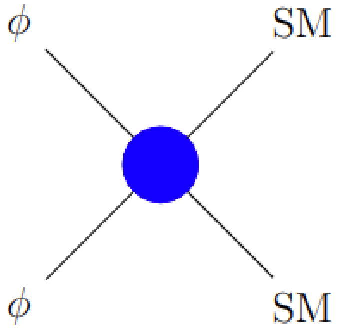
$$\phi + \phi + \phi \Leftrightarrow \phi + \phi$$

Annihilations



$$\phi + \phi \Leftrightarrow f + f\ (W^+W^-, ZZ)$$

Elastic scattering

$$\phi + f \Leftrightarrow \phi + f$$

$$T_\phi = T_{SM}$$

?

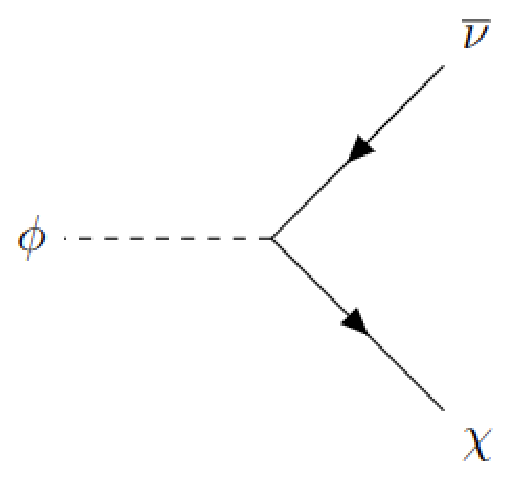
$3 \to 2$: μ_ϕ, λ_ϕ

$2 \to 2$: $\lambda_{\phi H}$

Dark matter production with CMB signature

- $\mathcal{L}^{\text{int}}_{\text{DS}-\nu} = y_1 \overline{\chi} \nu \phi + h.c.$

  where, $y_1 = \sum_i y_{\phi N_i} \theta^i_{\text{mix}}$ with $M_\phi > M_\chi$



- Imprint in, $N_{eff} \Longrightarrow \tau_{BBN} < \tau_\phi < \tau_{CMB}$

  $\Longrightarrow y_1 \sim 10^{-12} - 10^{-14}$

Dark matter production with CMB signature

- $\mathcal{L}^{\rm int}_{\rm DS-\nu} = y_1 \overline{\chi} \nu \phi + h.c.$

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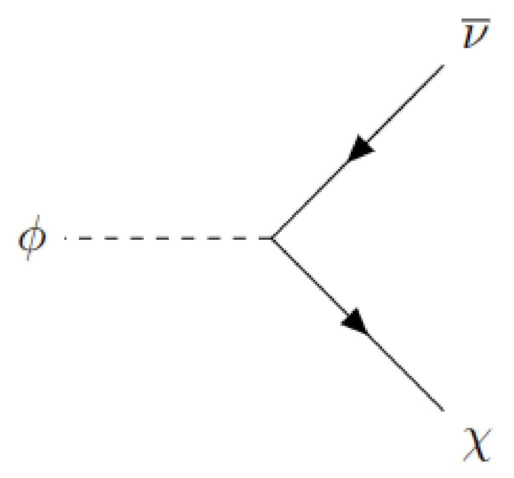


- Imprint in, $N_{eff} \Longrightarrow \tau_{BBN} < \tau_\phi < \tau_{CMB}$

  $\Longrightarrow y_1 \sim 10^{-12} - 10^{-14}$

- Boltzmann eq.

$$\frac{dY_\phi}{dx} = -0.116 \frac{g_s^2}{\sqrt{g_\rho}} \frac{M_\phi^4}{x^5} M_{pl} \langle \sigma v^2 \rangle_{3\phi \to 2\phi} \left(Y_\phi^3 - Y_\phi^2 Y_\phi^{eq} \right)$$

$$-0.264 \frac{g_s}{\sqrt{g_\rho}} \frac{M_\phi}{x^2} M_{pl} \langle \sigma v \rangle_{2\phi \to 2\rm SM} \left(Y_\phi^2 - Y_\phi^{eq\,2} \right) - \sqrt{\frac{45}{4\pi^3}} \langle \Gamma_{\phi \to \chi\nu} \rangle \frac{x}{M_\phi^2} \frac{M_{pl}}{\sqrt{g_\rho}} Y_\phi$$

$$\frac{dY_\chi}{dx} = \sqrt{\frac{45}{4\pi^3}} \langle \Gamma \rangle_{\phi \to \chi\nu} \frac{x}{M_{sc}^2} \frac{M_{pl}}{\sqrt{g_\rho}} Y_\phi$$

Dynamics of dark sector

$$
\begin{aligned}
\frac{dY_\phi}{dx} &= -0.116\frac{g_s^2}{\sqrt{g_\rho}}\frac{M_\phi^4}{x^5}M_{pl}\left\langle\sigma v^2\right\rangle_{3\phi\to2\phi}\left(Y_\phi^3 - Y_\phi^2 Y_\phi^{eq}\right) \\
&\quad -0.264\frac{g_s}{\sqrt{g_\rho}}\frac{M_\phi}{x^2}M_{pl}\left\langle\sigma v\right\rangle_{2\phi\to2\mathrm{SM}}\left(Y_\phi^2 - Y_\phi^{eq2}\right) - \sqrt{\frac{45}{4\pi^3}}\left\langle\Gamma_{\phi\to\chi\nu}\right\rangle\frac{x}{M_\phi^2}\frac{M_{pl}}{\sqrt{g_\rho}}Y_\phi \\
\frac{dY_\chi}{dx} &= \sqrt{\frac{45}{4\pi^3}}\left\langle\Gamma\right\rangle_{\phi\to\chi\nu}\frac{x}{M_{sc}^2}\frac{M_{pl}}{\sqrt{g_\rho}}Y_\phi
\end{aligned}
$$

Dynamics of dark sector

- Scenario-I

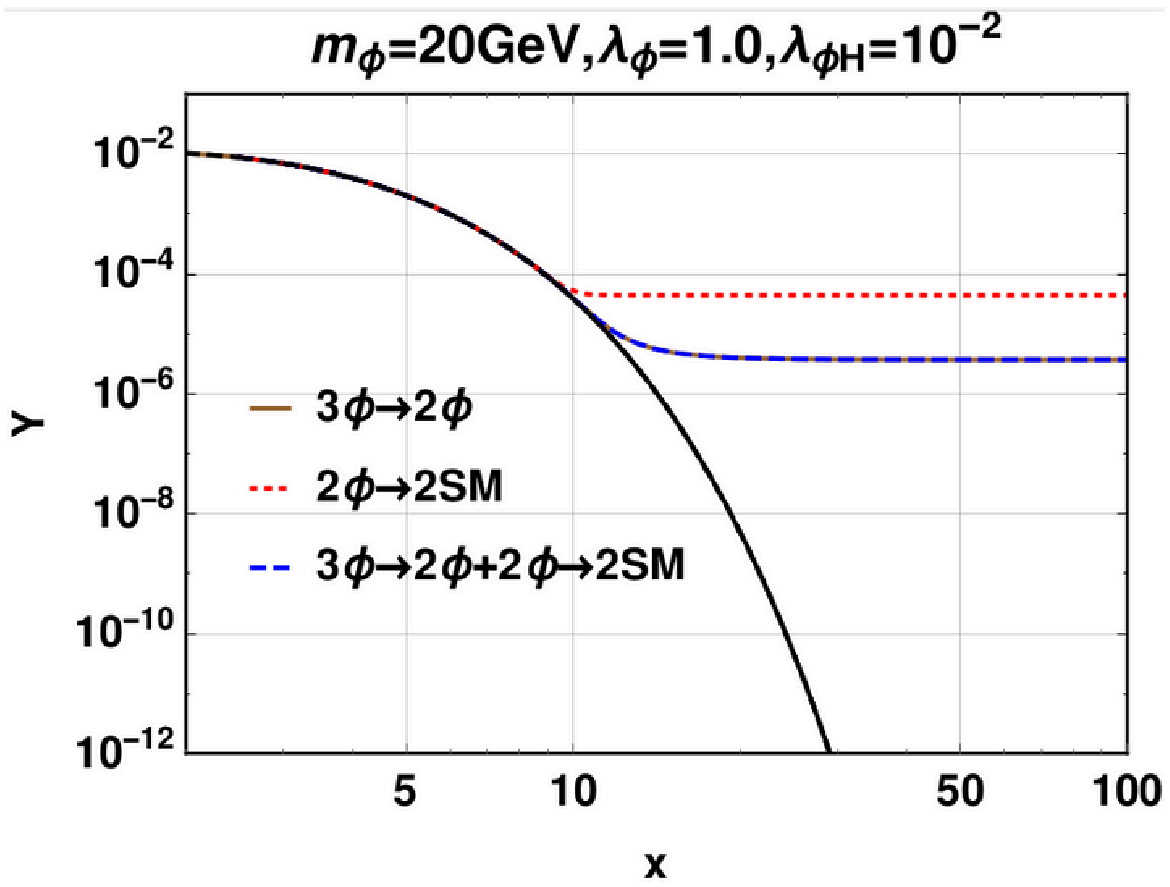
$$\Gamma_{[\phi\, SM \to \phi\, SM]} > \underline{\Gamma_{3\phi\to 2\phi} \gg \Gamma_{2\phi\to 2SM}}$$

$$\begin{aligned}
\frac{dY_\phi}{dx} &= -0.116\frac{g_s^2}{\sqrt{g_\rho}}\frac{M_\phi^4}{x^5}M_{pl}\left\langle\sigma v^2\right\rangle_{3\phi\to 2\phi}\left(Y_\phi^3 - Y_\phi^2 Y_\phi^{eq}\right) \\
&\quad -0.264\frac{g_s}{\sqrt{g_\rho}}\frac{M_\phi}{x^2}M_{pl}\left\langle\sigma v\right\rangle_{2\phi\to 2\mathrm{SM}}\left(Y_\phi^2 - Y_\phi^{eq\,2}\right) - \sqrt{\frac{45}{4\pi^3}}\left\langle\Gamma_{\phi\to\chi\nu}\right\rangle\frac{x}{M_\phi^2}\frac{M_{pl}}{\sqrt{g_\rho}}Y_\phi \\
\frac{dY_\chi}{dx} &= \sqrt{\frac{45}{4\pi^3}}\left\langle\Gamma\right\rangle_{\phi\to\chi\nu}\frac{x}{M_{sc}^2}\frac{M_{pl}}{\sqrt{g_\rho}}Y_\phi
\end{aligned}$$

Dynamics of dark sector

- **Scenario-I**

$$\Gamma_{[\phi\, SM \to \phi\, SM]} > \underline{\Gamma_{3\phi\to 2\phi} \gg \Gamma_{2\phi \to 2SM}}$$



$$\frac{dY_\phi}{dx} = -0.116 \frac{g_s^2}{\sqrt{g_\rho}} \frac{M_\phi^4}{x^5} M_{pl} \left\langle \sigma v^2 \right\rangle_{3\phi\to 2\phi} \left(Y_\phi^3 - Y_\phi^2 Y_\phi^{eq}\right)$$

$$-0.264 \frac{g_s}{\sqrt{g_\rho}} \frac{M_\phi}{x^2} M_{pl} \left\langle \sigma v \right\rangle_{2\phi\to 2\mathrm{SM}} \left(Y_\phi^2 - Y_\phi^{eq\,2}\right) - \sqrt{\frac{45}{4\pi^3}} \left\langle \Gamma_{\phi\to\chi\nu} \right\rangle \frac{x}{M_\phi^2} \frac{M_{pl}}{\sqrt{g_\rho}} Y_\phi$$

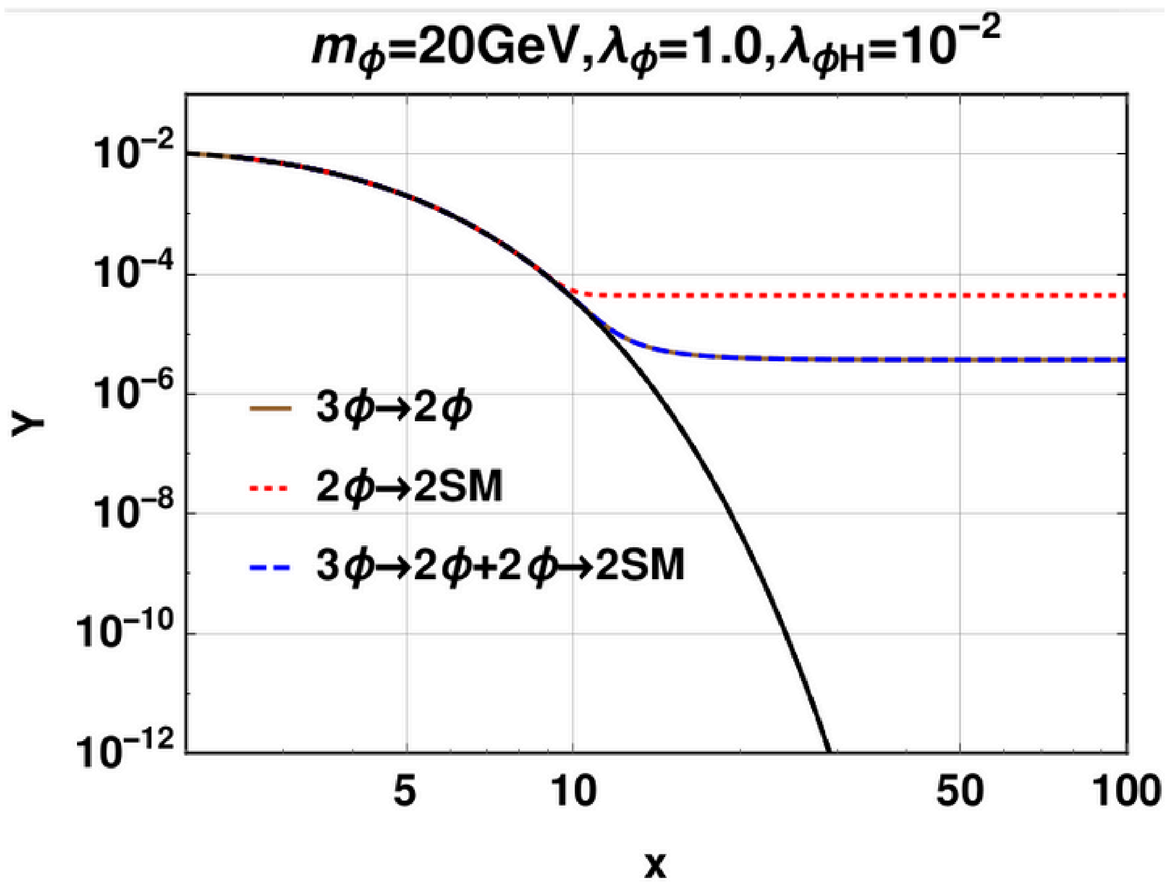
$$\frac{dY_\chi}{dx} = \sqrt{\frac{45}{4\pi^3}} \left\langle \Gamma \right\rangle_{\phi\to\chi\nu} \frac{x}{M_{sc}^2} \frac{M_{pl}}{\sqrt{g_\rho}} Y_\phi$$

Dynamics of dark sector

- **Scenario-I**

$$\Gamma_{[\phi\, SM \to \phi\, SM]} > \underline{\Gamma_{3\phi\to 2\phi} \gg \Gamma_{2\phi\to 2SM}}$$

F.O.. $\quad x_F^{tot} \approx x_F^{3\phi\to 2\phi}$



$$\frac{dY_\phi}{dx} = -0.116\frac{g_s^2}{\sqrt{g_\rho}}\frac{M_\phi^4}{x^5}M_{pl}\left<\sigma v^2\right>_{3\phi\to 2\phi}(Y_\phi^3 - Y_\phi^2 Y_\phi^{eq}) -0.264\frac{g_s}{\sqrt{g_\rho}}\frac{M_\phi}{x^2}M_{pl}\left<\sigma v\right>_{2\phi\to 2\mathrm{SM}}(Y_\phi^2 - Y_\phi^{eq\,2}) - \sqrt{\frac{45}{4\pi^3}}\left<\Gamma_{\phi\to\chi\nu}\right>\frac{x}{M_\phi^2}\frac{M_{pl}}{\sqrt{g_\rho}}Y_\phi$$

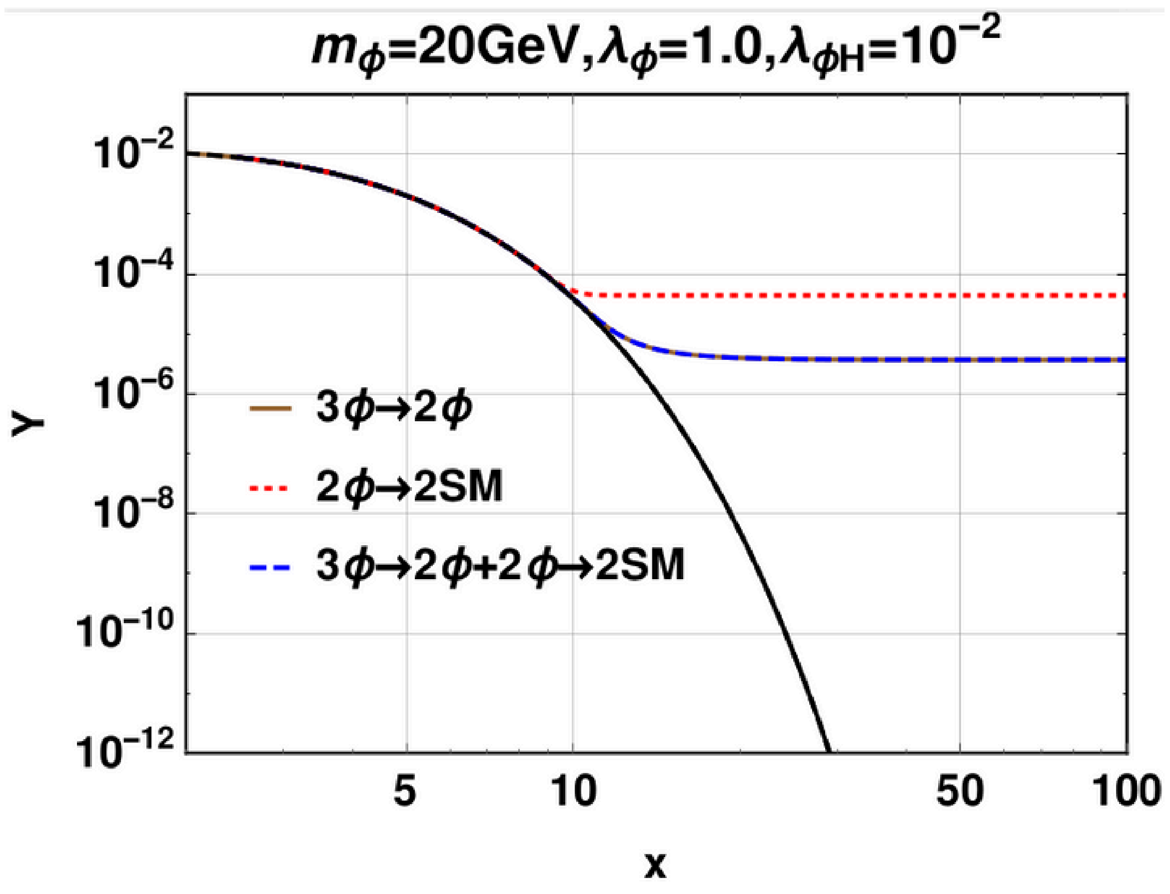
$$\frac{dY_\chi}{dx} = \sqrt{\frac{45}{4\pi^3}}\left<\Gamma\right>_{\phi\to\chi\nu}\frac{x}{M_{sc}^2}\frac{M_{pl}}{\sqrt{g_\rho}}Y_\phi$$

Dynamics of dark sector

- Scenario-I

$$\Gamma_{[\phi\, SM \to \phi\, SM]} > \underline{\Gamma_{3\phi\to 2\phi} \gg \Gamma_{2\phi \to 2SM}}$$

F.O.. $x_F^{tot} \approx x_F^{3\phi\to 2\phi}$ $\quad Y_\phi(x_F) \Rightarrow 3\phi \to 2\phi$



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$$-\cancel{0.264\frac{g_s}{\sqrt{g_\rho}}\frac{M_\phi}{x^2}M_{pl}\left\langle\sigma v\right\rangle_{2\phi\to 2\mathrm{SM}}\left(Y_\phi^2 - Y_\phi^{eq\,2}\right)} - \sqrt{\frac{45}{4\pi^3}}\left\langle\Gamma_{\phi\to\chi\nu}\right\rangle\frac{x}{M_\phi^2}\frac{M_{pl}}{\sqrt{g_\rho}}Y_\phi$$

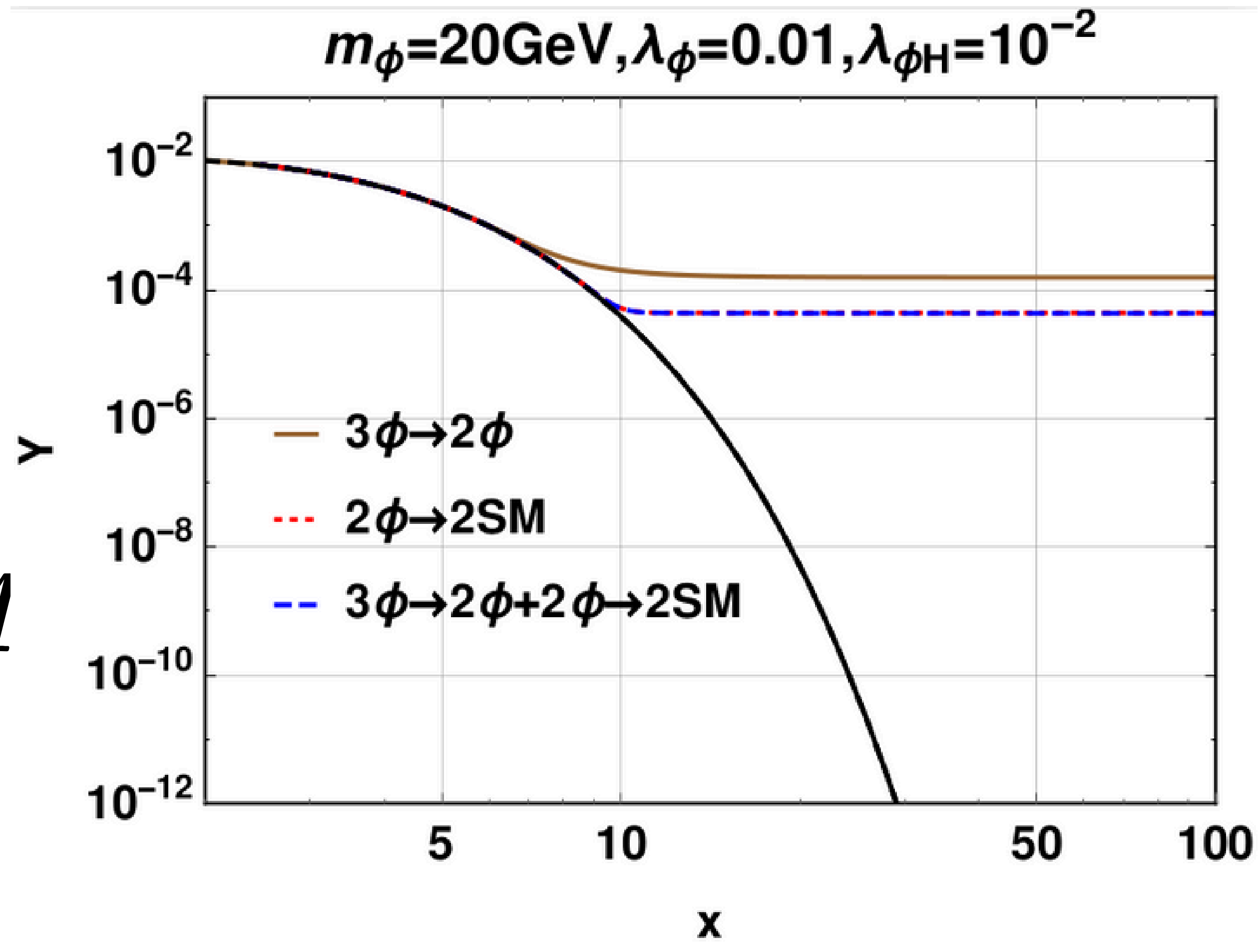
$$\frac{dY_\chi}{dx} = \sqrt{\frac{45}{4\pi^3}}\left\langle\Gamma\right\rangle_{\phi\to\chi\nu}\frac{x}{M_{sc}^2}\frac{M_{pl}}{\sqrt{g_\rho}}Y_\phi$$

Dynamics of dark sector

- Scenario-II

$$\Gamma_{[\phi\, SM \to \phi\, SM]} > \underline{\Gamma_{2\phi \to 2\mathrm{SM}} \gg \Gamma_{3\phi \to 2\phi}}$$

F.O.. $x_F^{tot} \approx x_F^{2\phi \to 2SM}$ $Y_\phi(x_F) \Rightarrow 2\phi \to 2SM$



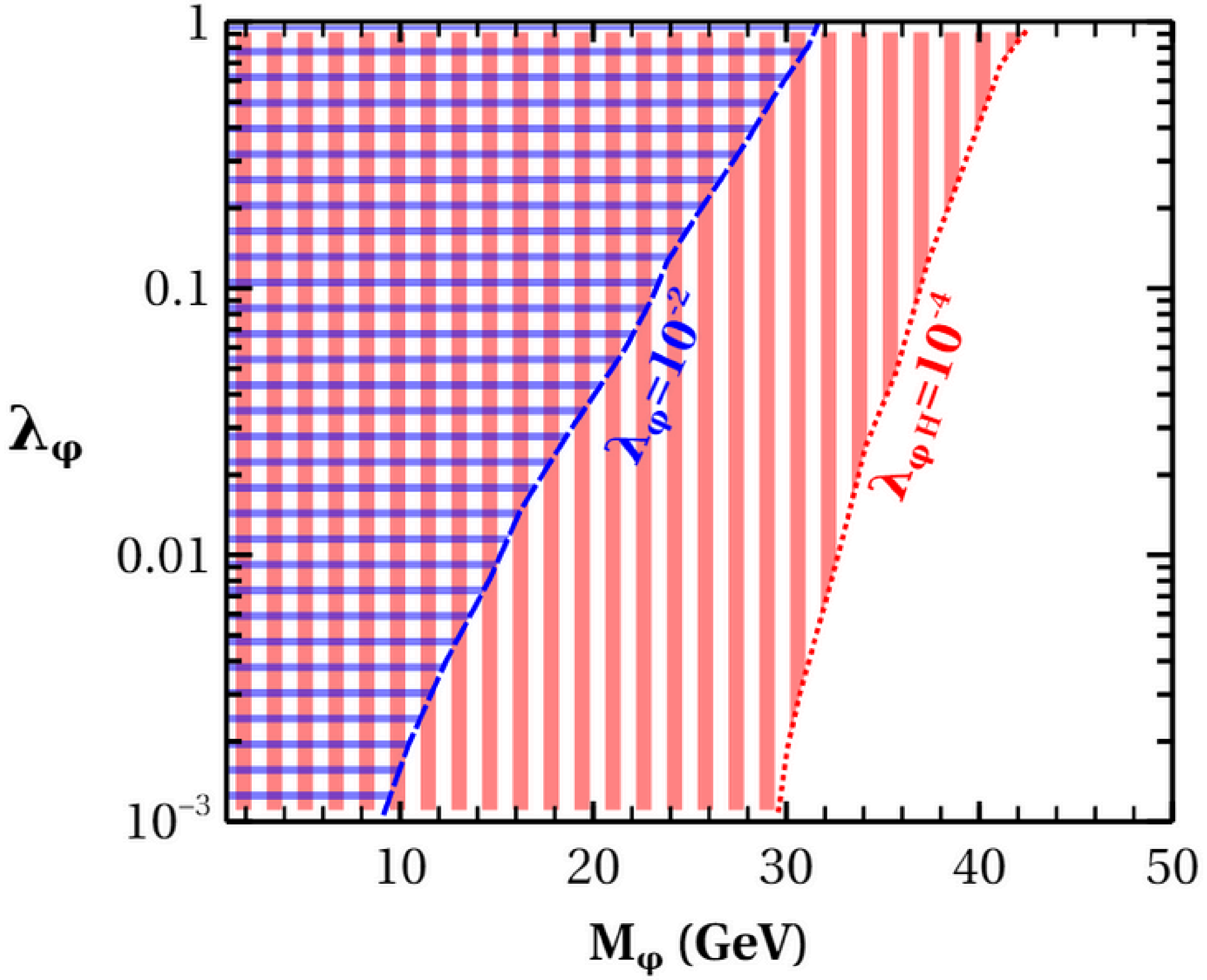
$$\frac{dY_\phi}{dx} = -\cancel{0.116\frac{g_s^2}{\sqrt{g_\rho}}\frac{M_\phi^4}{x^5}M_{pl}\langle\sigma v^2\rangle_{3\phi\to 2\phi}\left(Y_\phi^3 - Y_\phi^2 Y_\phi^{eq}\right)}$$

$$-0.264\frac{g_s}{\sqrt{g_\rho}}\frac{M_\phi}{x^2}M_{pl}\langle\sigma v\rangle_{2\phi\to 2\mathrm{SM}}\left(Y_\phi^2 - Y_\phi^{eq2}\right) - \sqrt{\frac{45}{4\pi^3}}\langle\Gamma_{\phi\to\chi\nu}\rangle\frac{x}{M_\phi^2}\frac{M_{pl}}{\sqrt{g_\rho}}Y_\phi$$

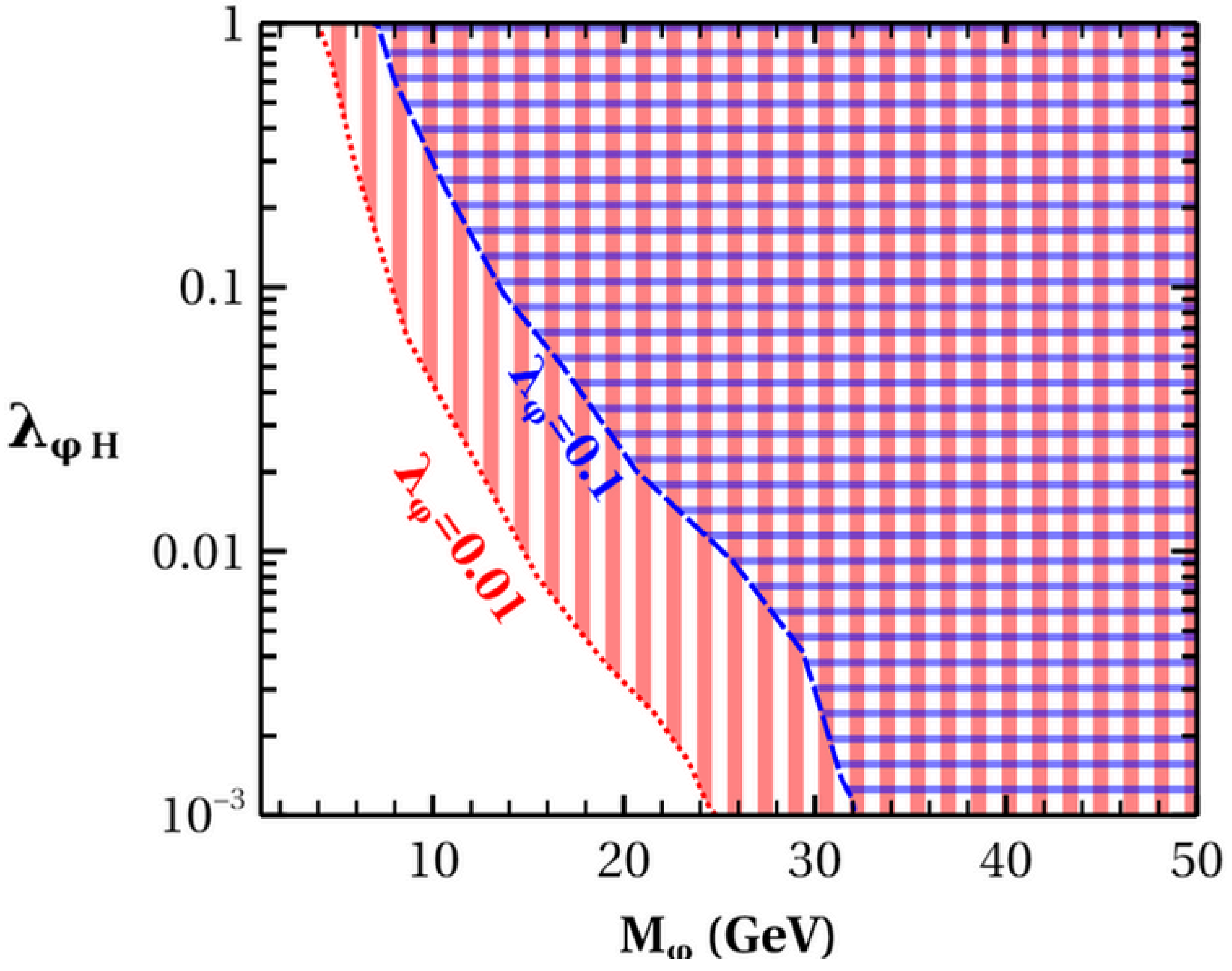
$$\frac{dY_\chi}{dx} = \sqrt{\frac{45}{4\pi^3}}\langle\Gamma\rangle_{\phi\to\chi\nu}\frac{x}{M_{sc}^2}\frac{M_{pl}}{\sqrt{g_\rho}}Y_\phi$$

Parameter space of two scenarios

- Scenario-I



- Scenario-II



Numerical results

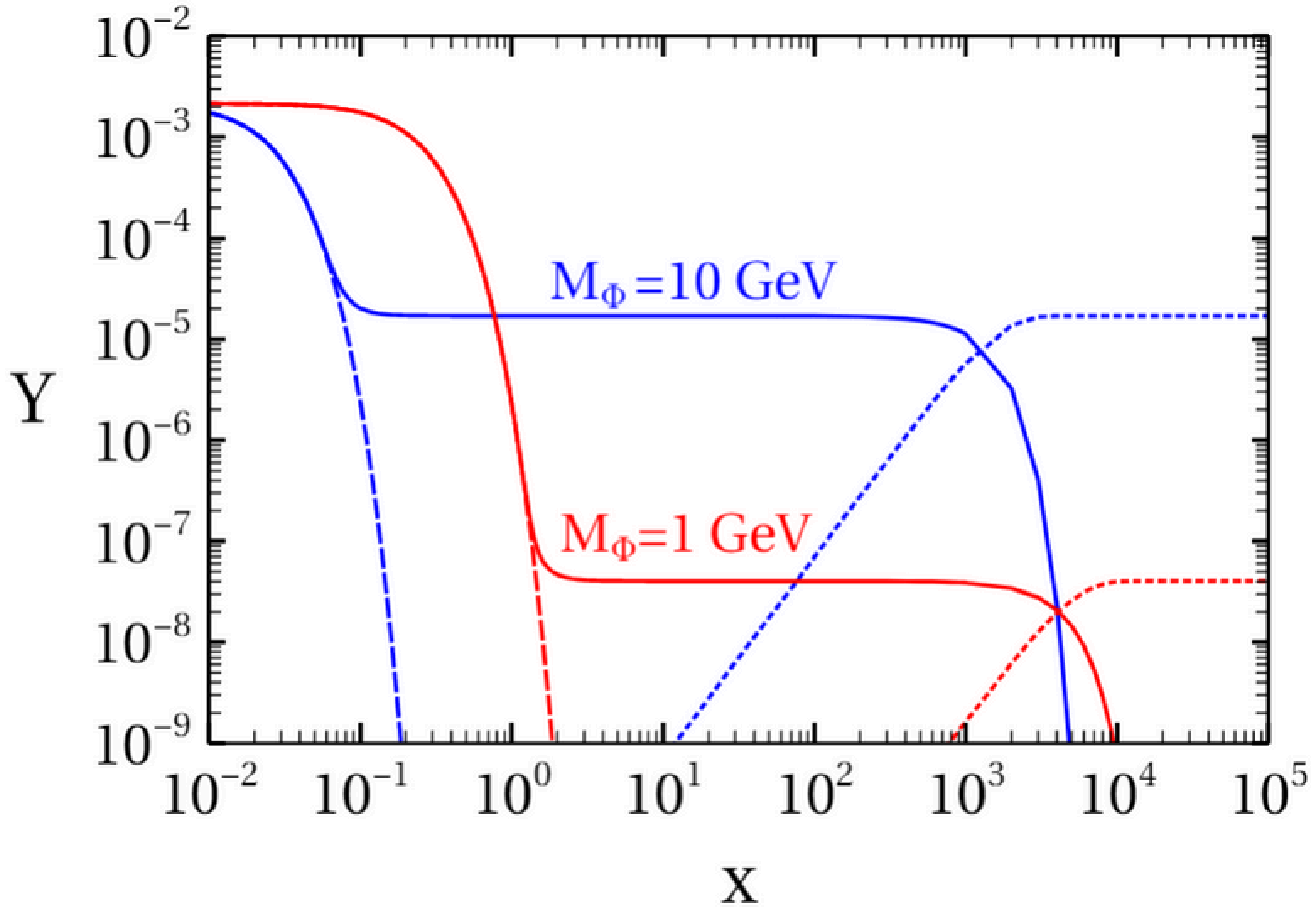
Self interacting HDS
Scenario-I

- Variation of mass

Numerical results

Self interacting HDS
Scenario-I

- Variation of mass

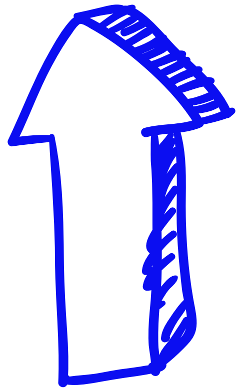


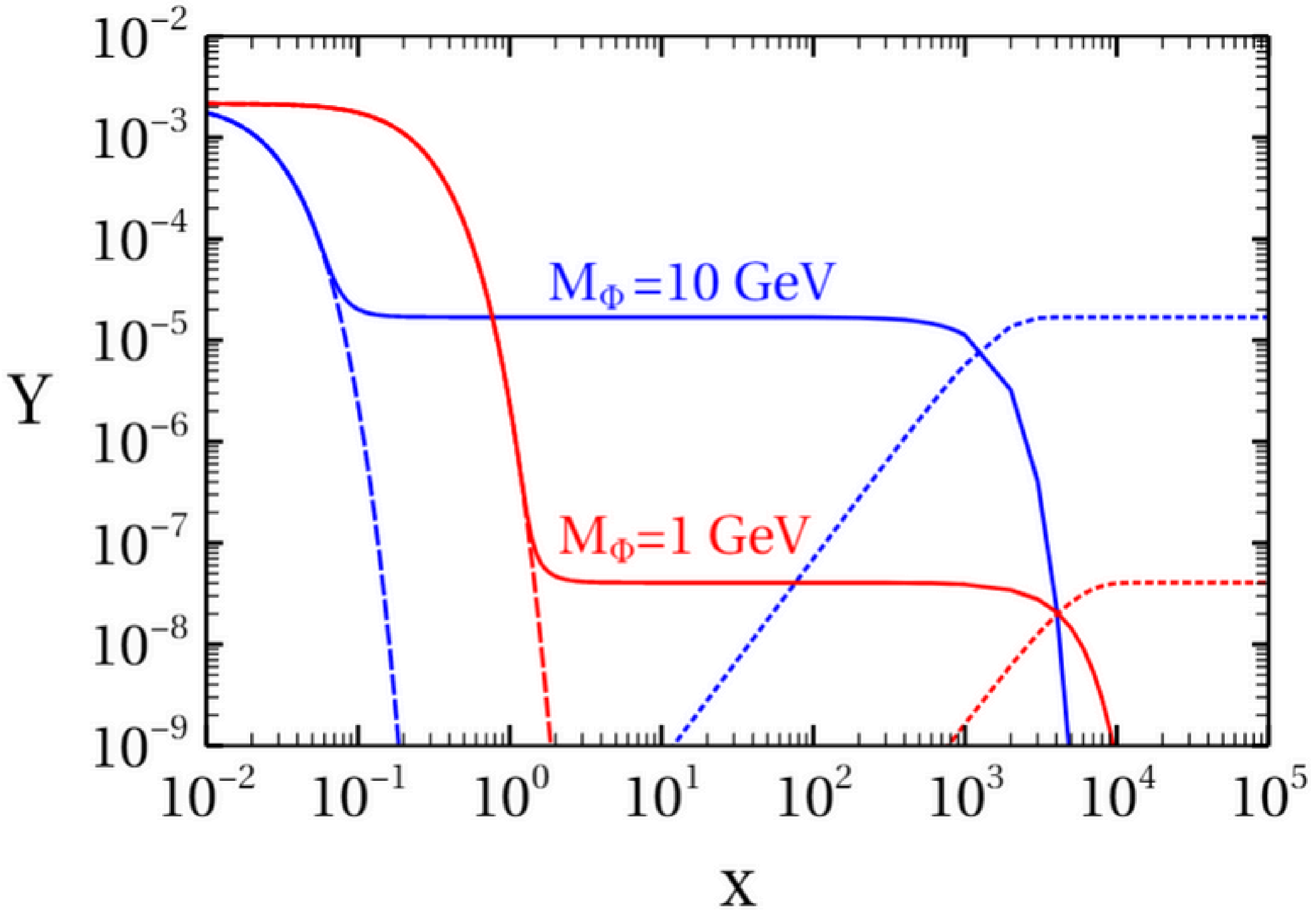
DM abundance

Numerical results

Self interacting HDs
Scenario-I

- Variation of mass

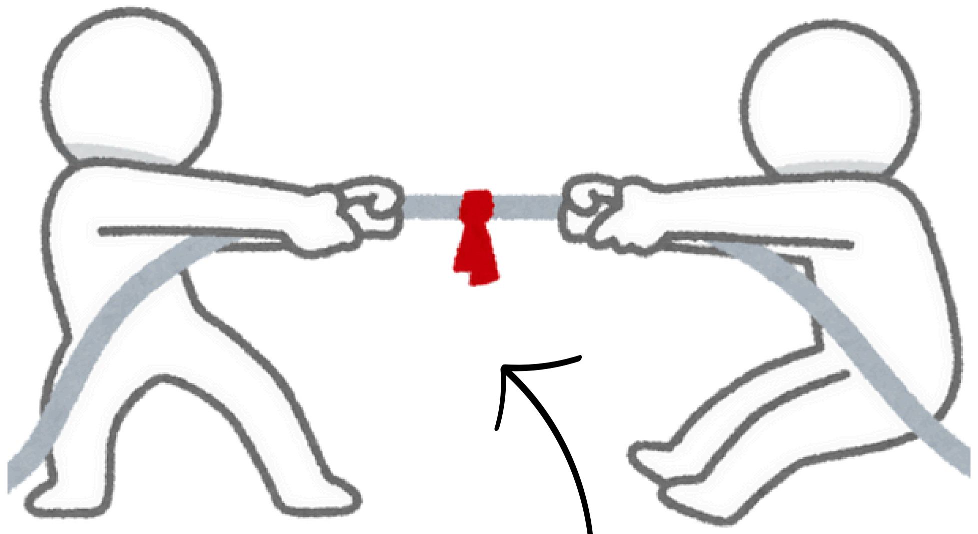




DM abundance

Interaction

Hubble



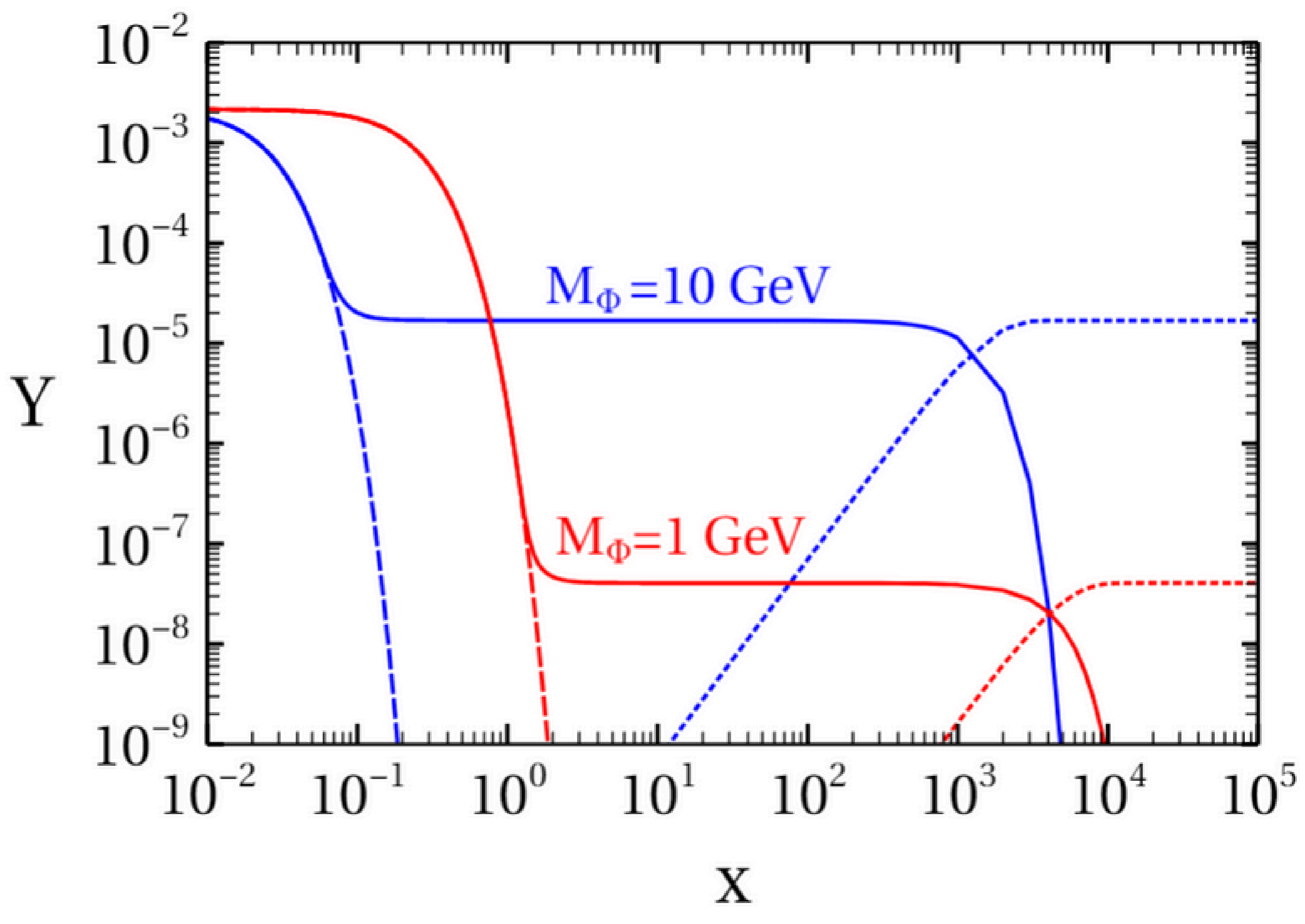
Freeze-out

Numerical results

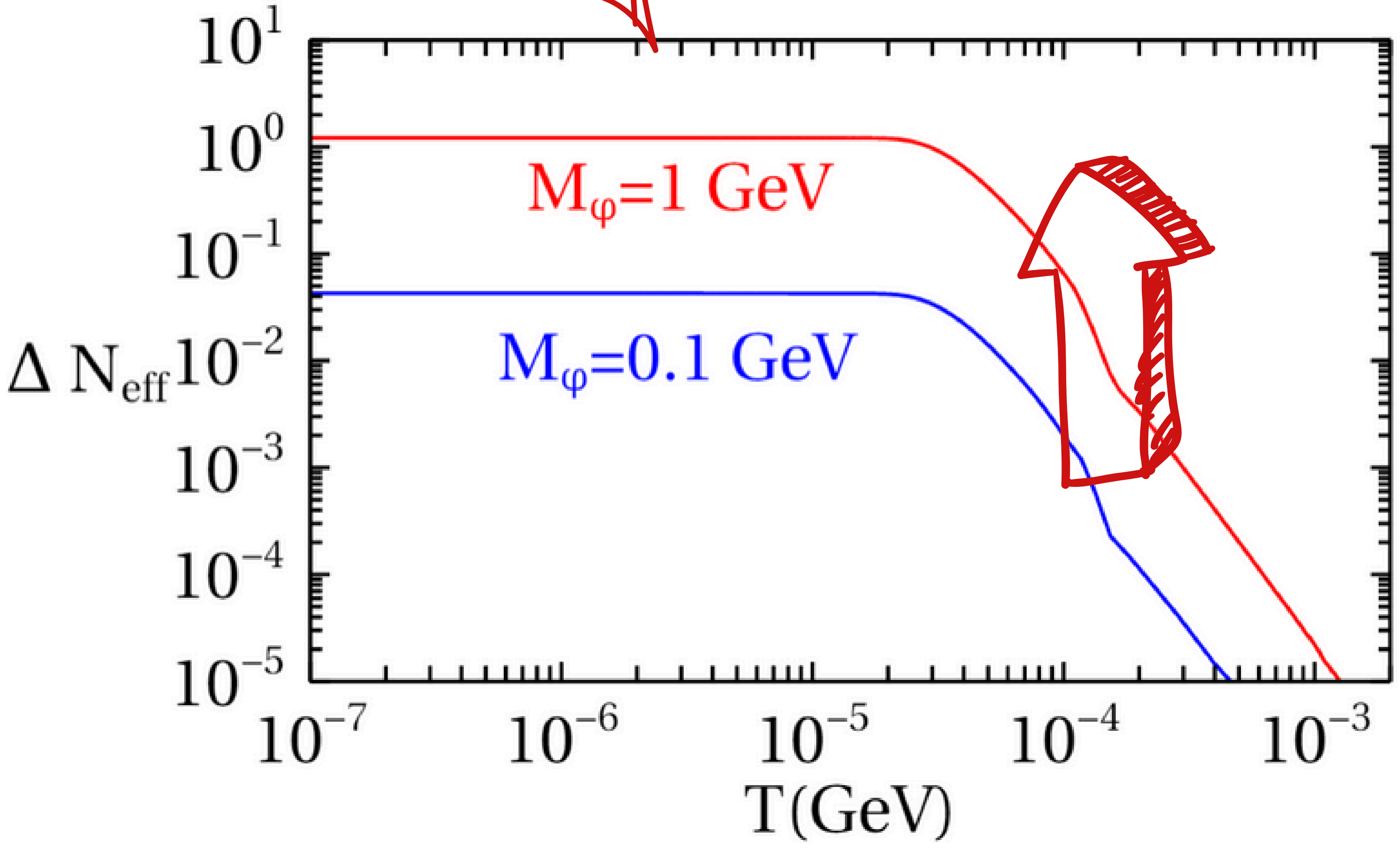
Self interacting HDS
Scenario-I

- Variation of mass

$\rho_\nu^{'} \sim Y_\phi$



DM abundance



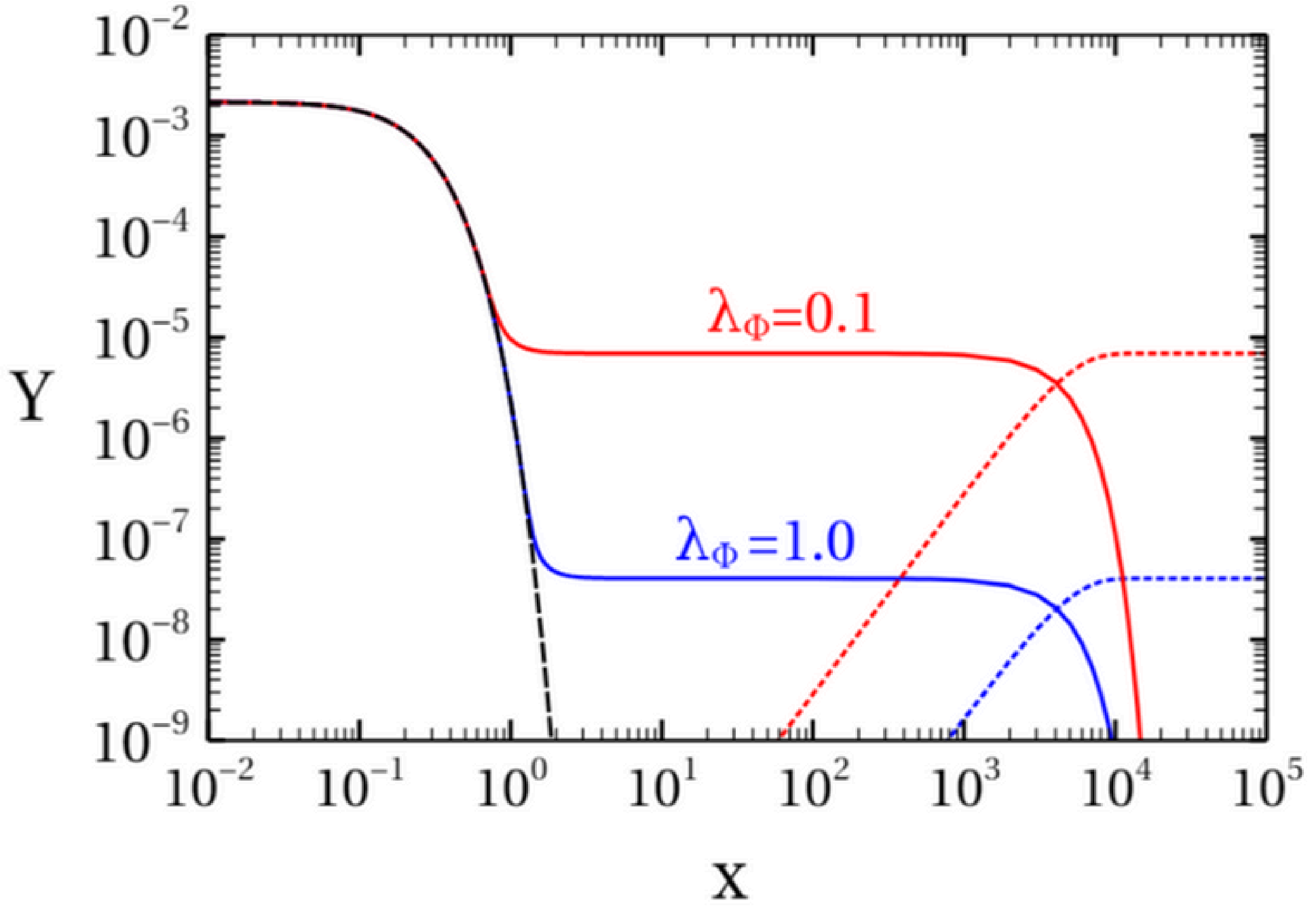
Contribution to $\rho_\nu^{'}$

Numerical results

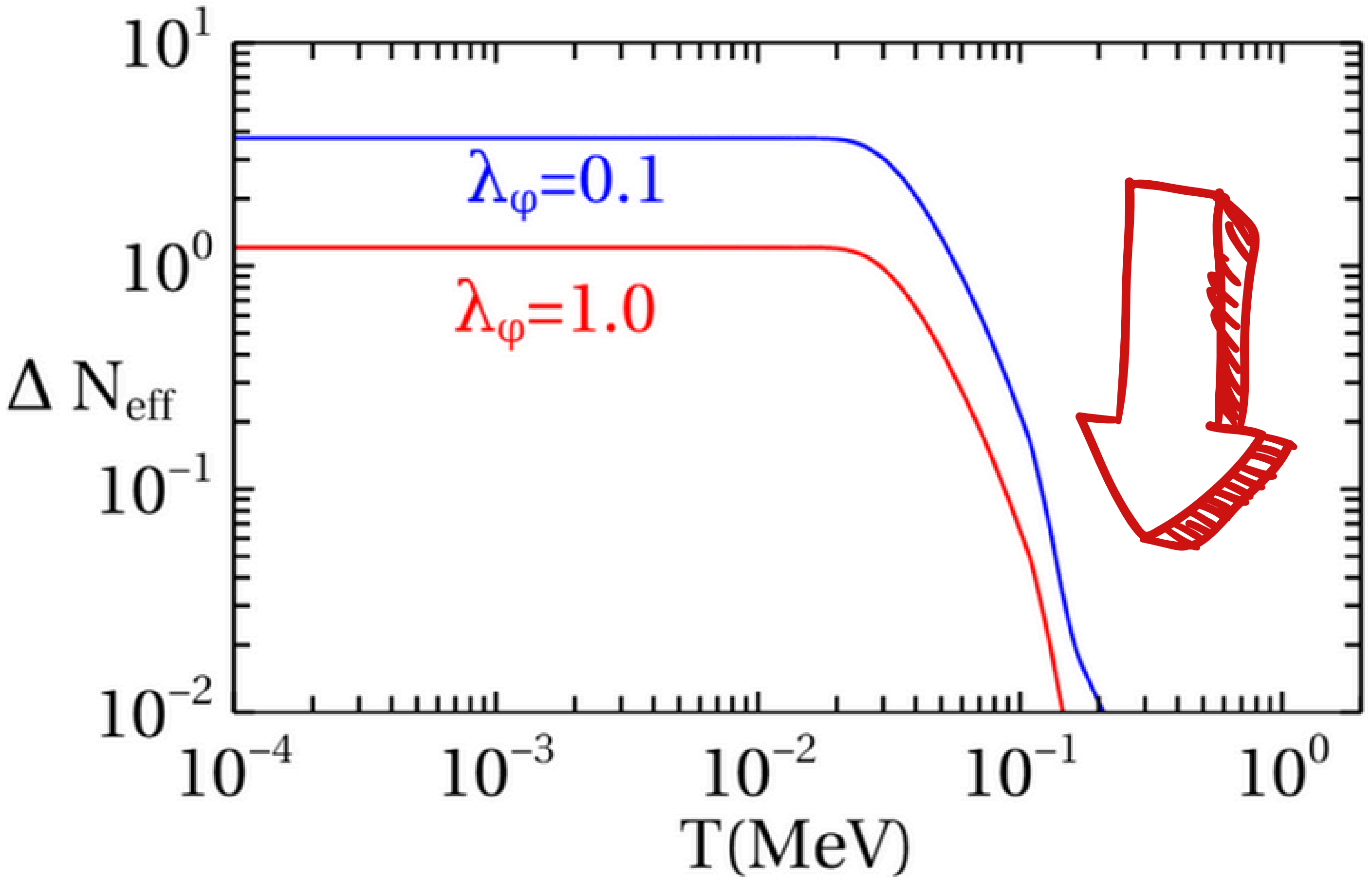
Self interacting HDS
Scenario-I

- Variation of coupling

$\rho_\nu^{'} \sim Y_\phi$



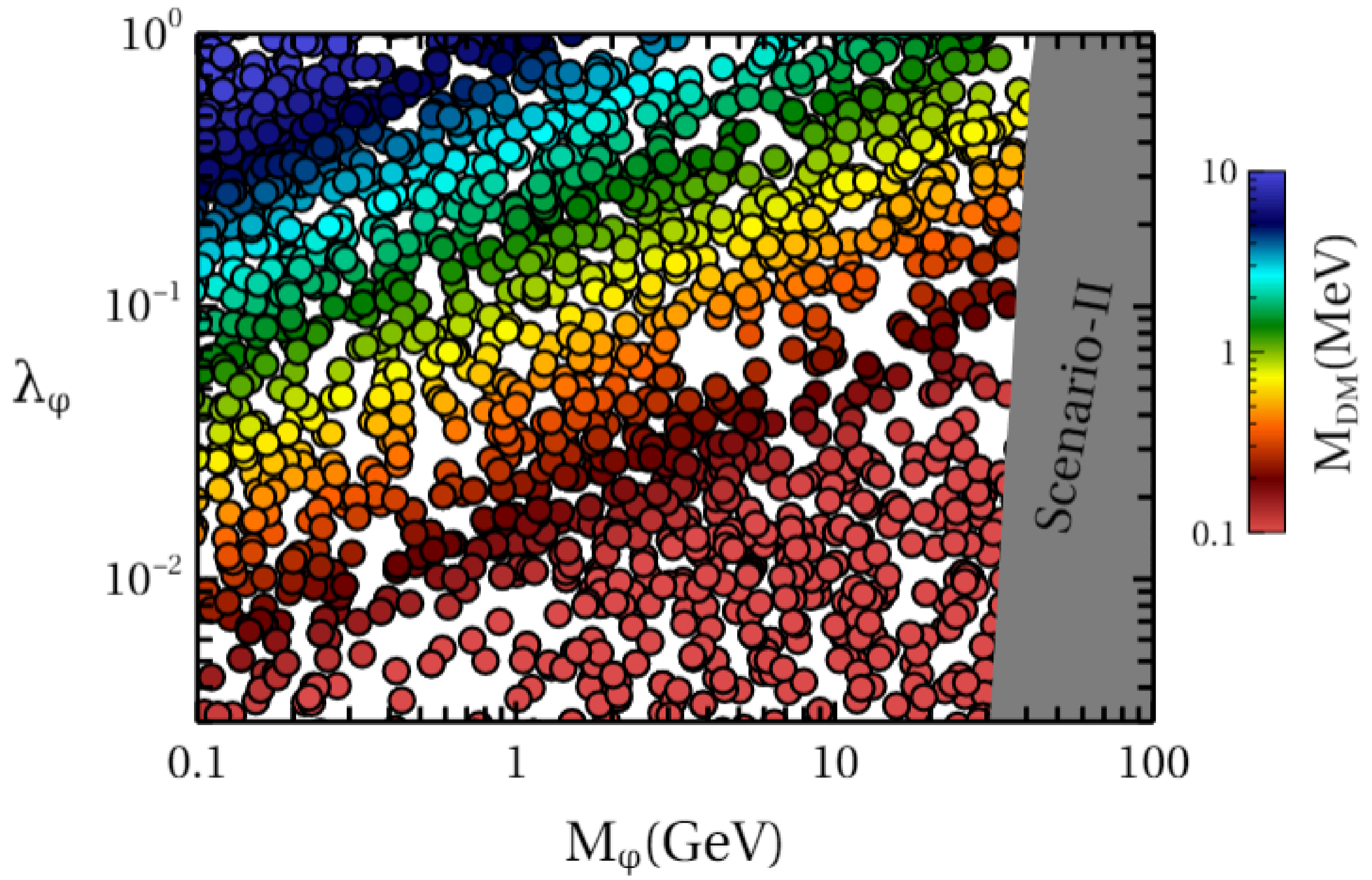
DM abundance



Contribution to $\rho_\nu^{'}$

Numerical results

Self interacting HDS

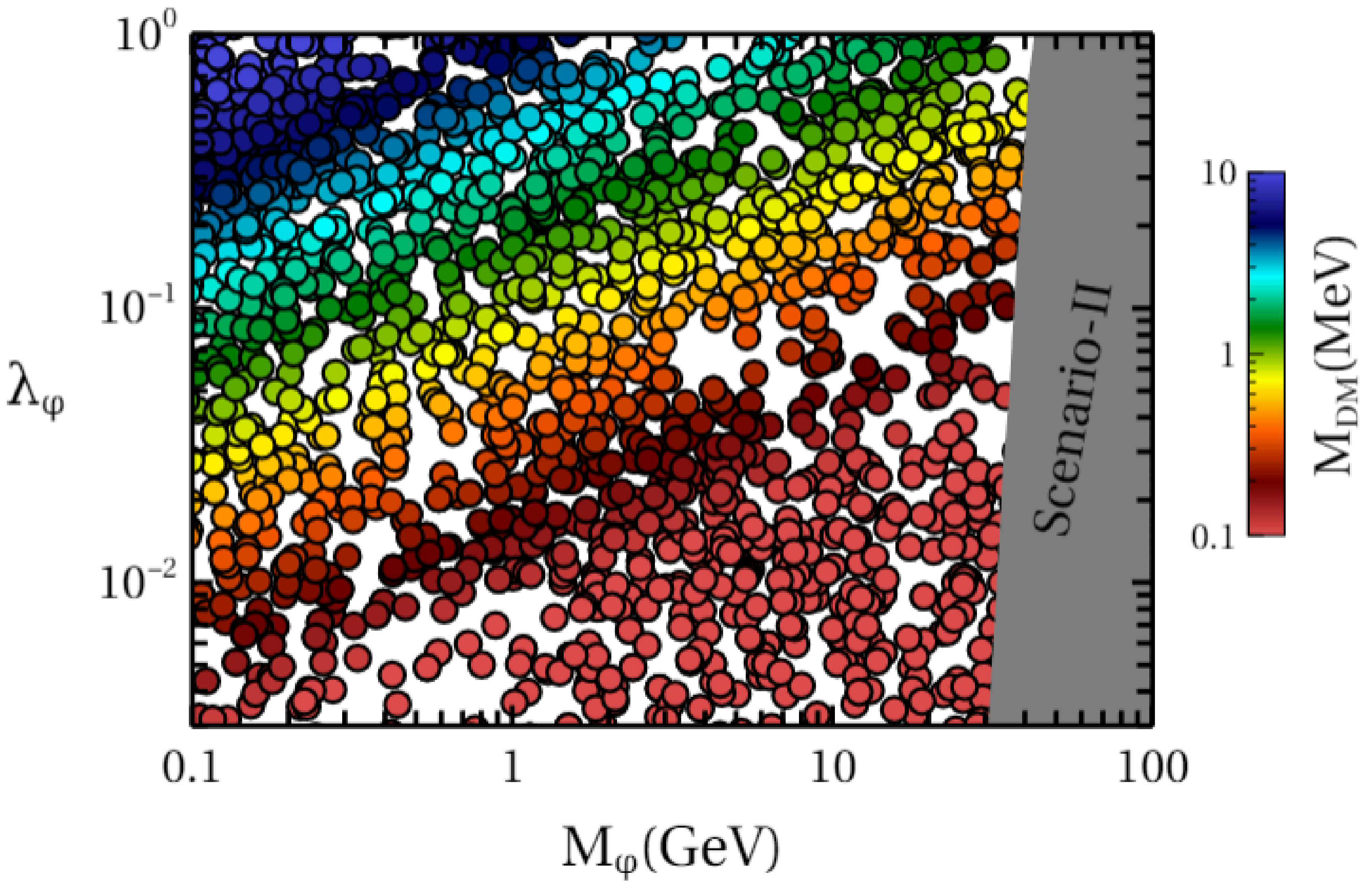


DM abundance

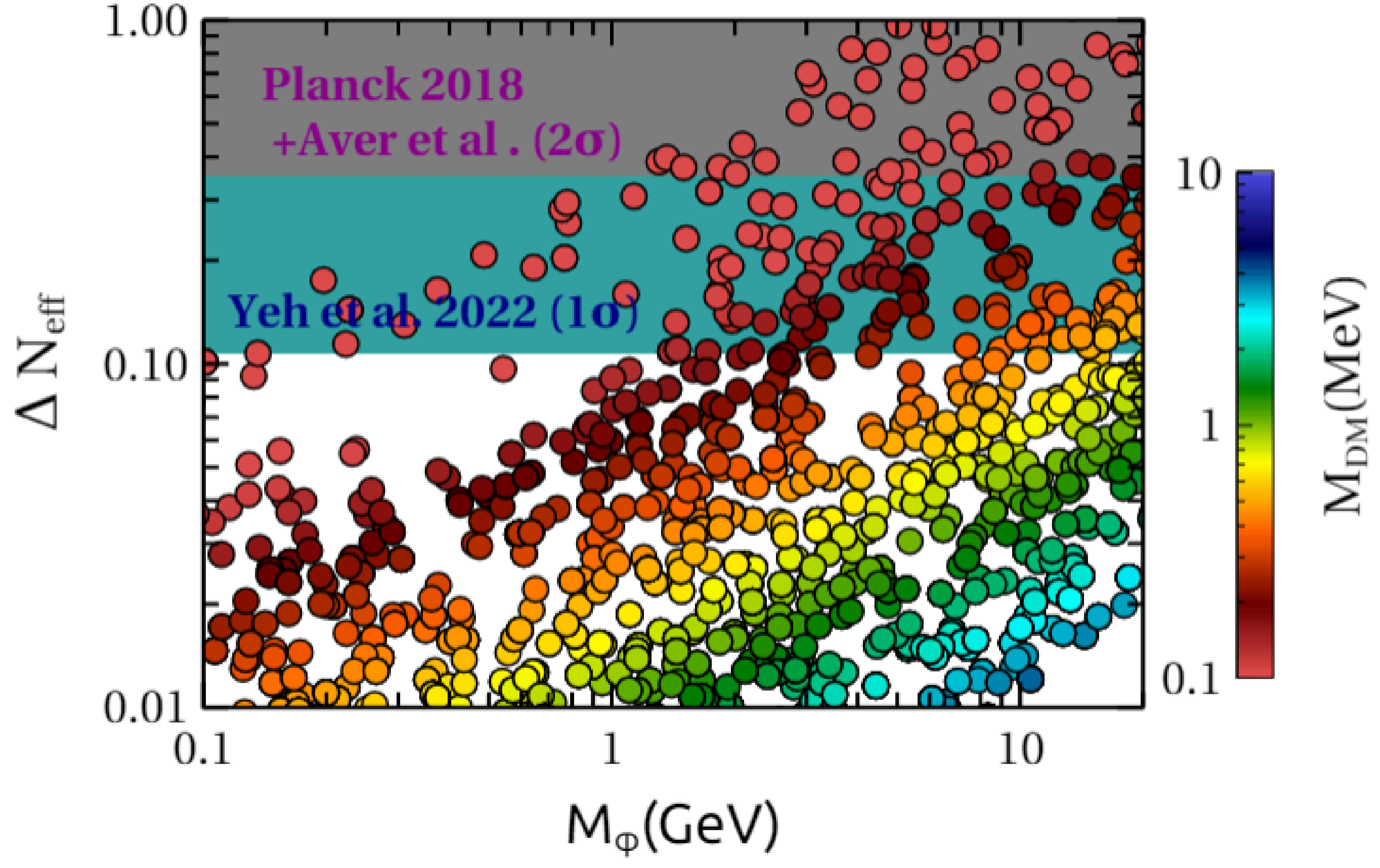
Numerical results

D.k.Ghosh, P. Ghosh, SJ, JCAP2023

Self interacting HDS



DM abundance



Contribution to N_{eff}

Conclusion

- CMB bound can probe significant parameter space of nonthermal DM if its production contains extra radiation
- The model successfully explains the observed relic of a non-thermal DM and its connection with CMB via additional light relativistic degrees of freedom.
- Same exercise can be performed for DM production associated with other light particles!

Thank you

Numerical results for scenario-II

Weakly interacting HDS