N_{eff} constraints on portal interactions with hidden sectors
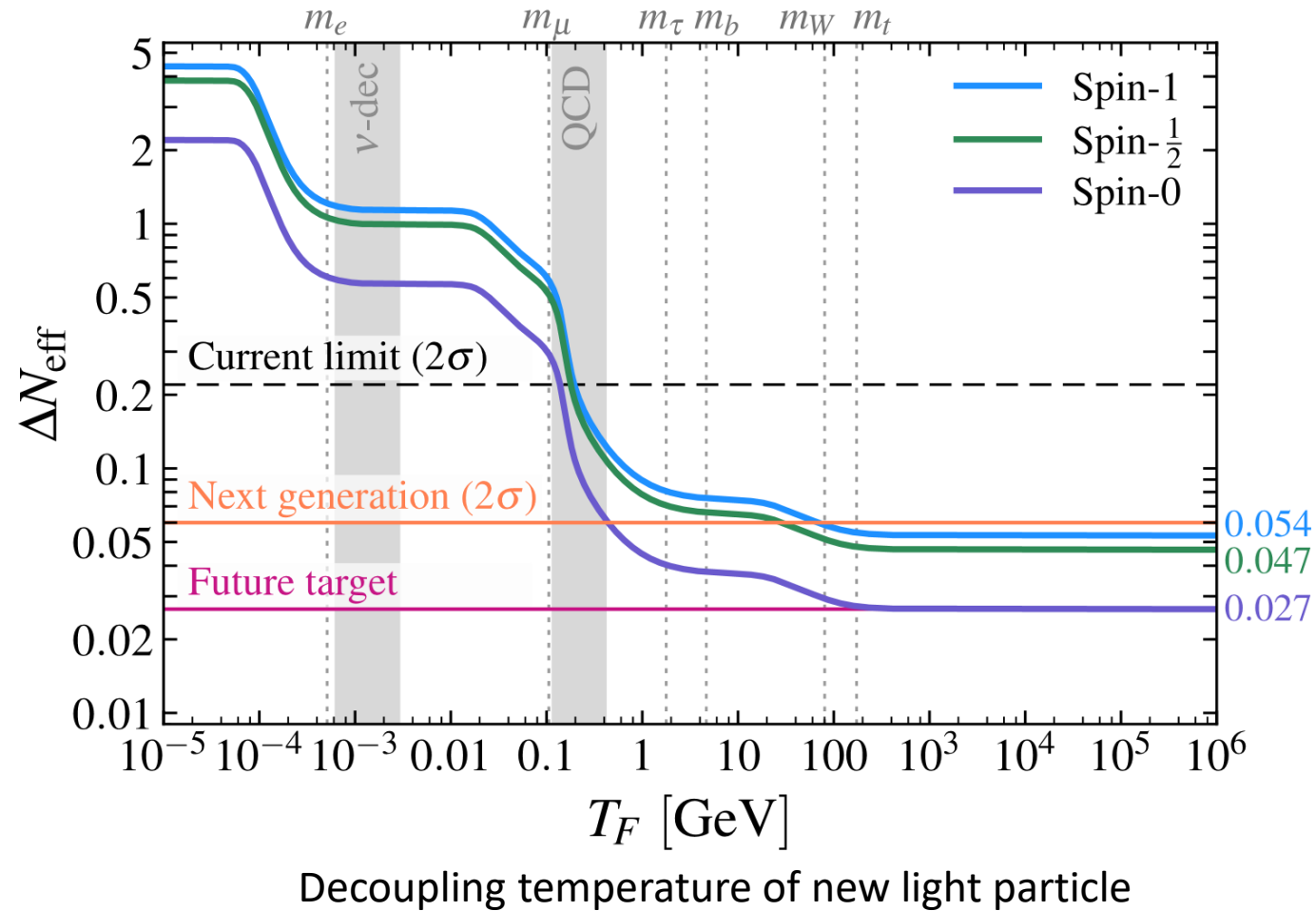
arxiv:2206.xxxxx

-Pranjal Ralegankar
University of Illinois at Urbana-Champaign

Collaborators: Peter Adshead and Jessie Shelton

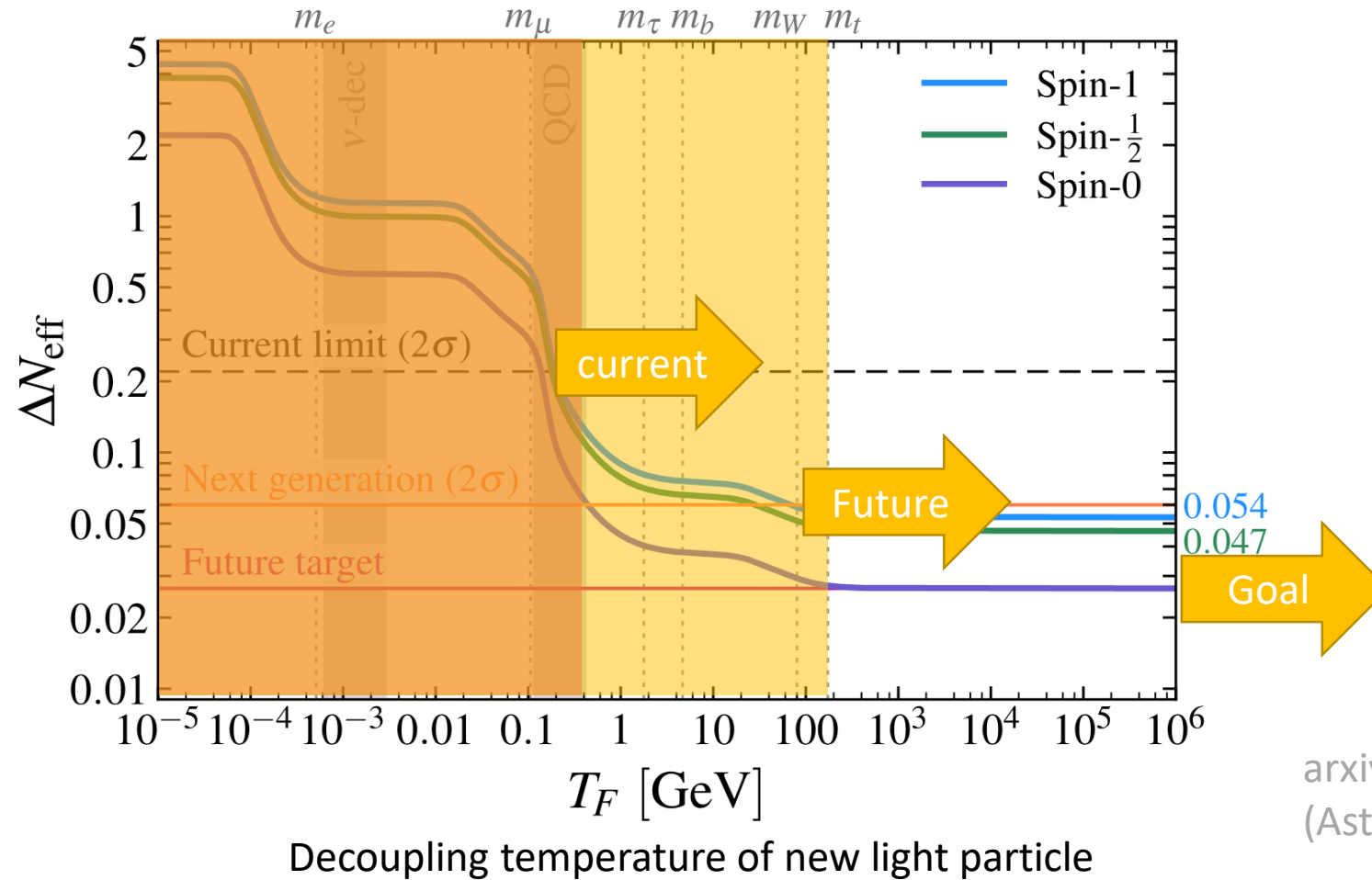# ΔN_{eff} : Typically discussed as constraint on decoupling temperature

$$\Delta N_{\text{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_{\text{dr}}}{\rho_\gamma}$$

Decoupling temperature of new light particle

Reinterpreting ΔN_{eff} : Constraint on interactions with out-of-equilibrium sectors

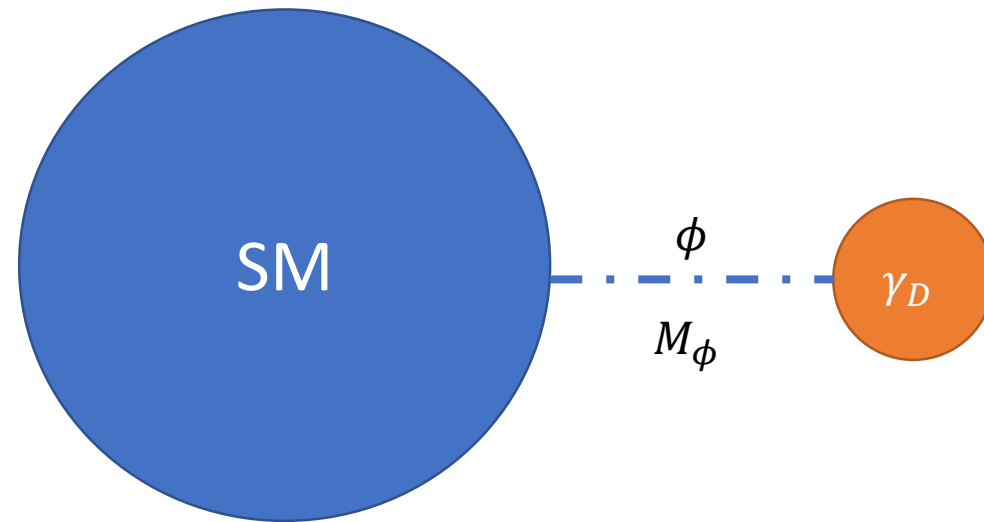$$\Delta N_{\text{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_{\text{dr}}}{\rho_{\gamma}}$$

Decoupling temperature of new light particle

arxiv:1903:04763
(Astro 2020 white paper)

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Unified treatment for calculating N_{eff} constraints on beyond SM interactions

Unified treatment for calculating N_{eff} constraints on beyond SM interactions

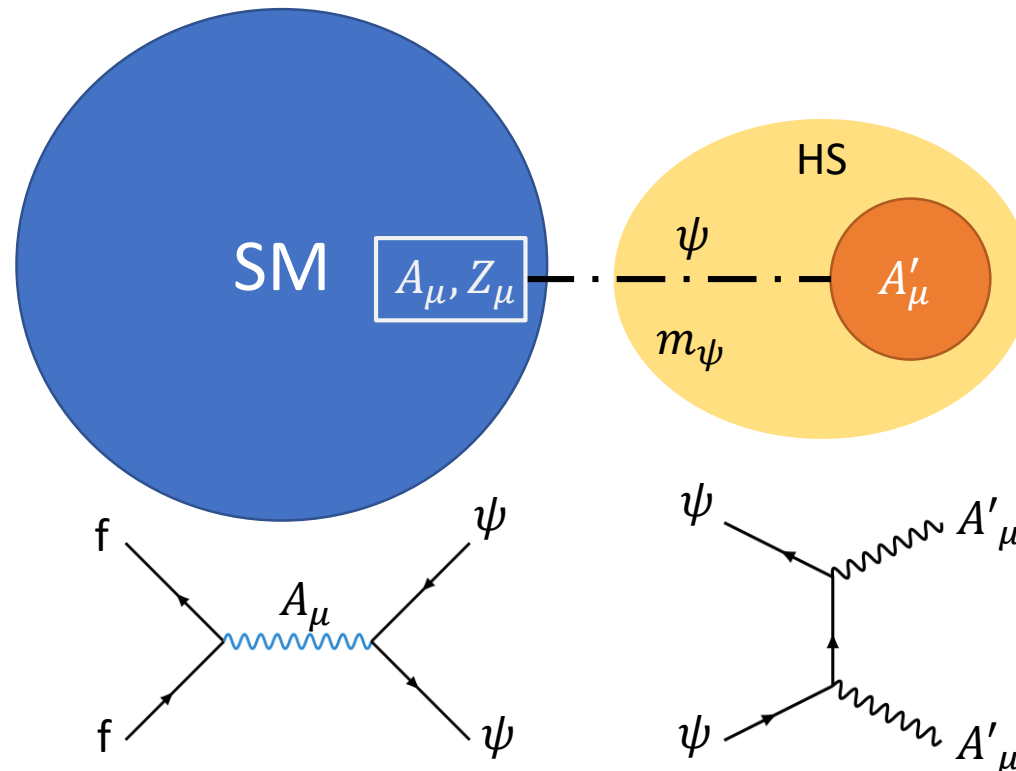# Strong Implications for model building with HS with dark radiation

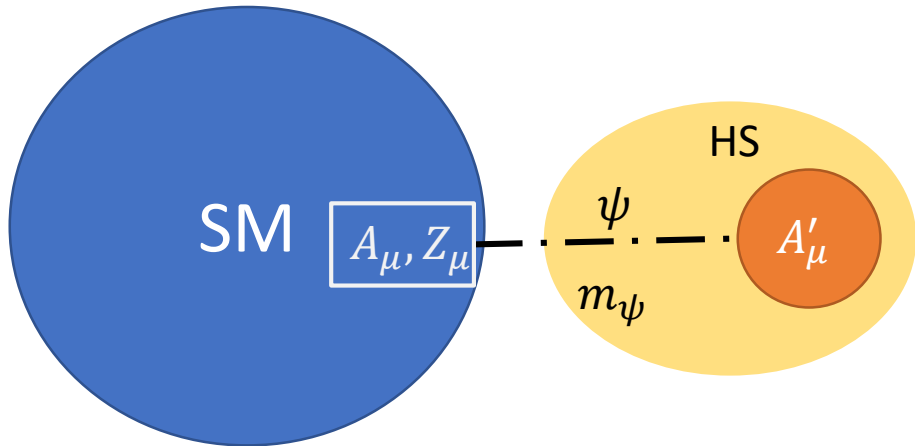# Application of N_{eff} constraint : Relevant types of interaction

Application of N_{eff} constraint: Millicharged particle example

$$L_{int} \supset -\frac{\epsilon}{2} B_{\mu\nu} F^{\mu\nu'} + e' A'_\mu \bar{\psi} \gamma^\mu \psi - m_\psi \bar{\psi}\psi$$

$$L_{int} \supset -eQ A_\mu \bar{\psi}\gamma^\mu\psi + e' A'_\mu \bar{\psi}\gamma^\mu\psi + eQZ_\mu \tan\theta_W \bar{\psi}\gamma^\mu\psi - m_\psi\bar{\psi}\psi$$

Physics behind dark radiation production: Boltzmann equations

Boltzmann equations:

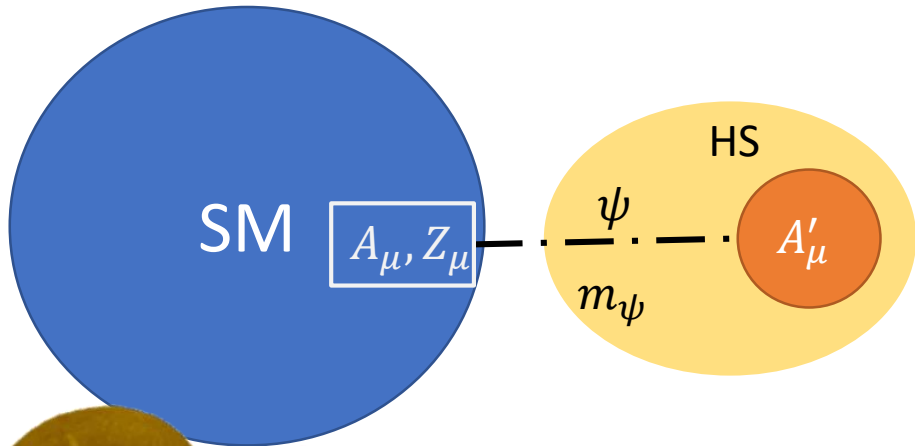$$\frac{d\rho_{SM}}{dt} + 3H(1 + w_{SM})\rho_{SM} = -C$$

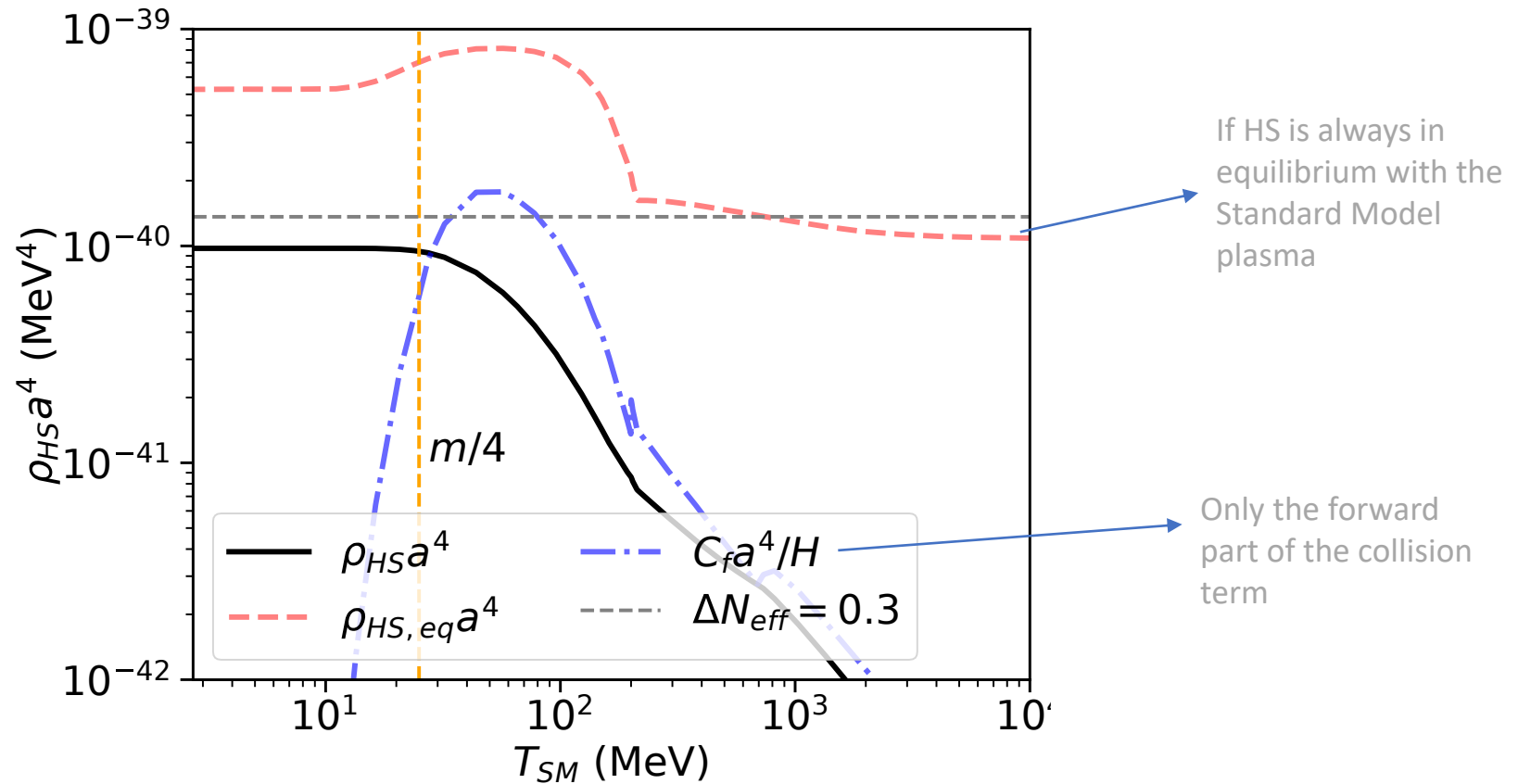$$\frac{d\rho_{HS}}{dt} + 3H(1 + w_{HS})\rho_{HS} = C$$

$$H = \frac{\sqrt{\rho_{SM} + \rho_{HS}}}{\sqrt{3}M_{\text{Pl}}}$$

$$C = \frac{1}{32\pi^4}\sum_f \int ds\,(s - 4m_f^2)s\sigma_{ff\to\psi\psi}[T_{SM}G(\sqrt{s}/T_{SM}) - T_{HS}G(\sqrt{s}/T_{HS})] + ..$$
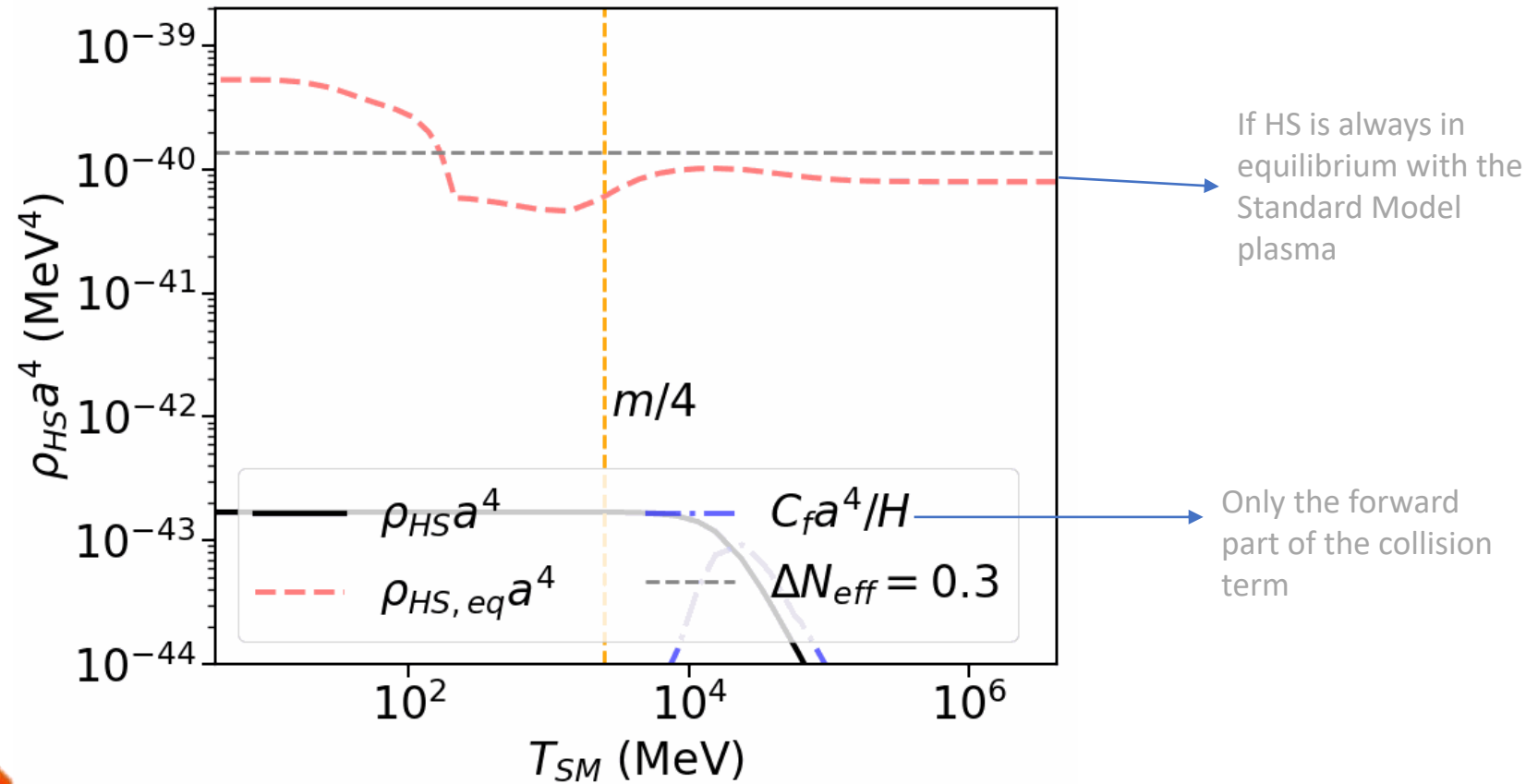
Energy transfer collision term

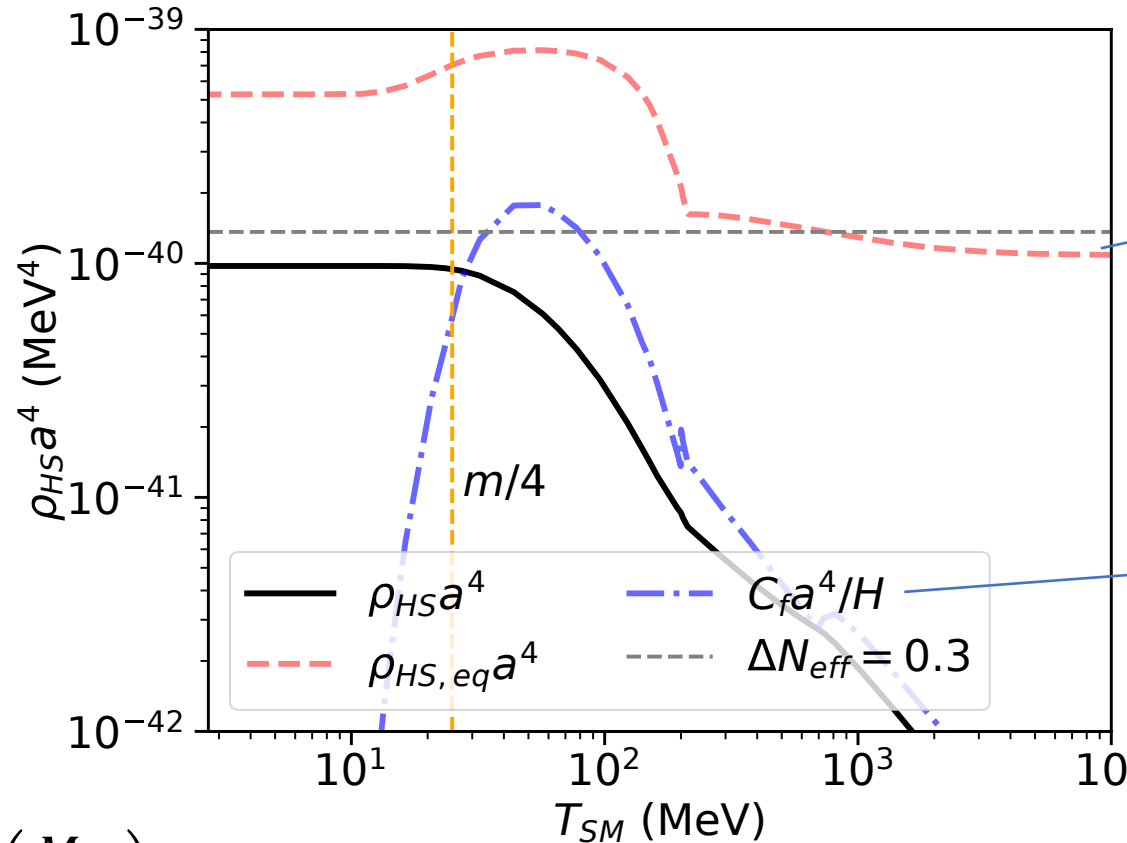# Physics behind dark radiation production: Boltzmann equations

SM

A_μ, Z_μ

HS

$\dfrac{\psi}{m_\psi}$

A'_μ

Boltzmann equations:

$$\frac{d\rho_{SM}}{dt} + 3H(1 + w_{SM})\rho_{SM} = -C$$

$$\frac{d\rho_{HS}}{dt} + 3H(1 + w_{HS})\rho_{HS} = C$$

$$H = \frac{\sqrt{\rho_{SM} + \rho_{HS}}}{\sqrt{3}M_{\text{Pl}}}$$

$$C = \frac{1}{32\pi^4}\sum_f \int ds\,(s - 4m_f^2)s\,\sigma_{ff\to\psi\psi}[T_{SM}G(\sqrt{s}/T_{SM}) - T_{HS}G(\sqrt{s}/T_{HS})] + ..$$

Energy transfer collision term

Physics behind dark radiation production: Plots!

If HS is always in equilibrium with the Standard Model plasma

Only the forward part of the collision term

Physics behind dark radiation production: GIF!

If HS is always in equilibrium with the Standard Model plasma

Only the forward part of the collision term

Physics behind dark radiation production: Out-of-equilibrium $\rho_{\mathbf{DR}}$ proportional to portal coupling

If HS is always in equilibrium with the Standard Model plasma

Only the forward part of the collision term

$$\Gamma_E = \frac{C_f}{\rho_{HS,eq}}$$

$$\frac{\rho_{HS}}{\rho_{SM}} \sim \left(\frac{\Gamma_E}{H}\right)_{T_{SM} \sim \frac{m}{4}} \propto Q^2 \left(\frac{M_{\mathrm{Pl}}}{m/4}\right)$$

Physics behind dark radiation production: Thermalized ρ_{DR} insensitive to portal coupling

$$\frac{\rho_{HS}}{\rho_{SM}} \propto \frac{g_{HS}}{g_{*SM}(T_d)}$$
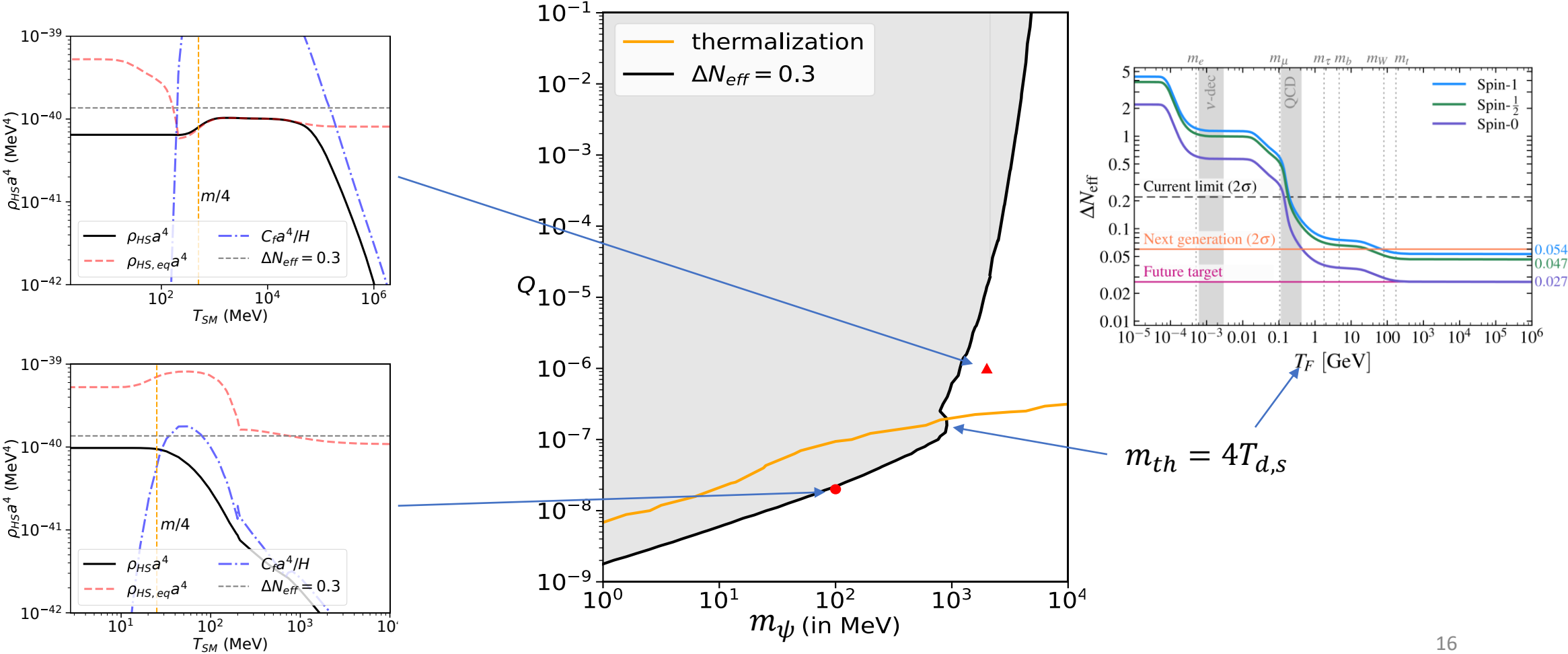
Degrees of freedom

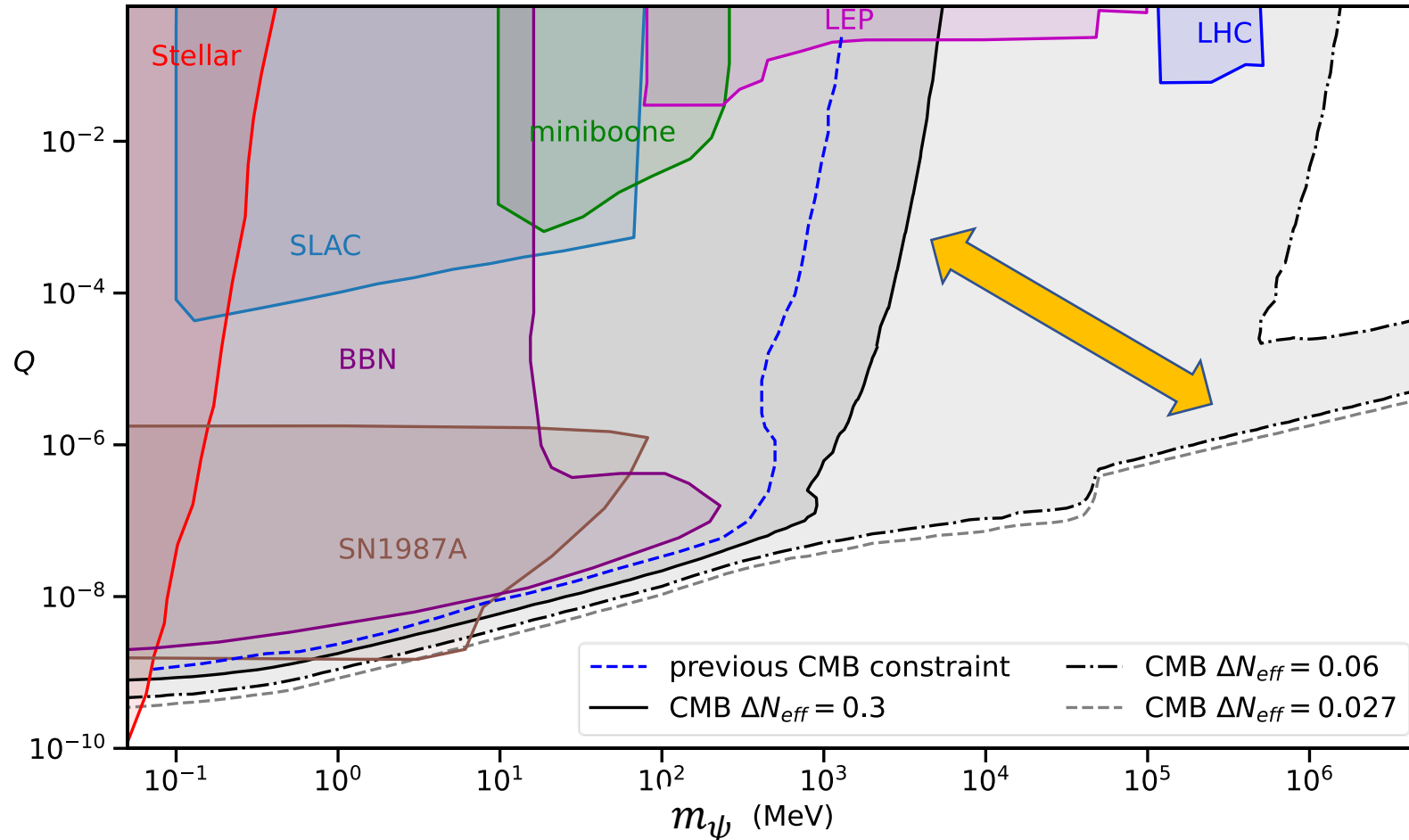# Physics behind dark radiation production: Translating to constraints

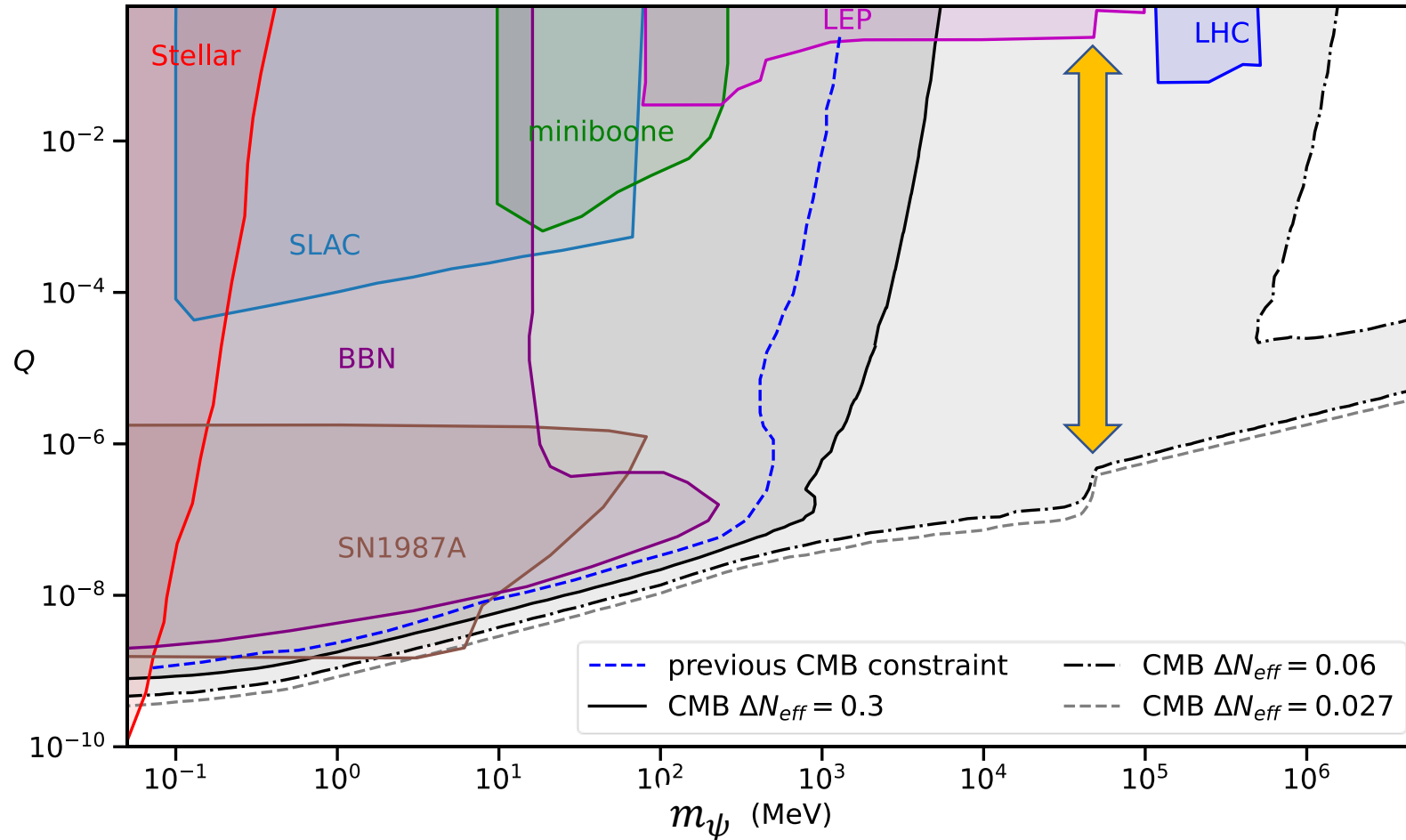# Physics behind dark radiation production : Translating to constraints

Physics behind dark radiation production : Most relevant when thermally decoupled
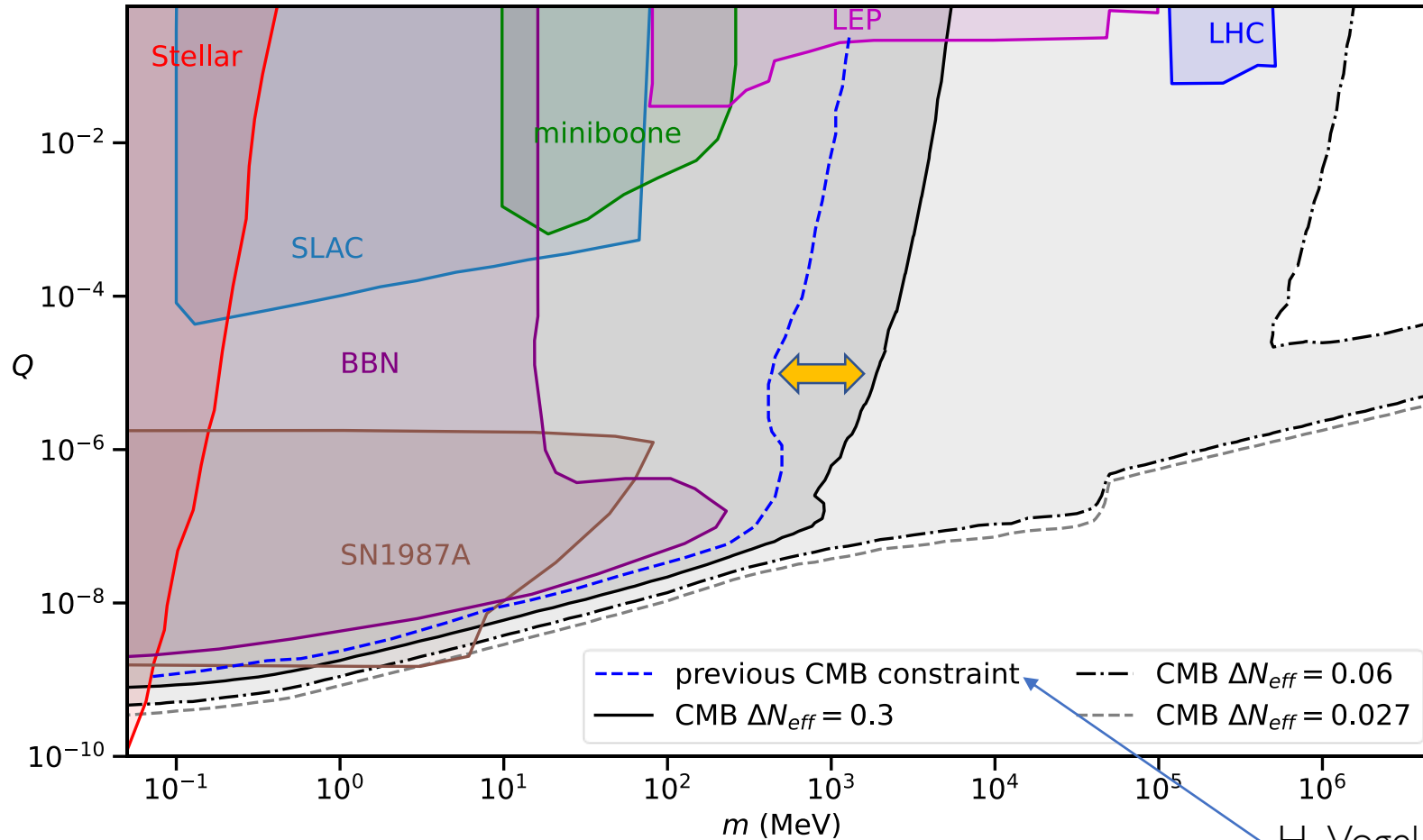

$m_{th} = 4T_{d,s}$

Comparing Neff constraints: Future constraint will extend to much larger parameter space

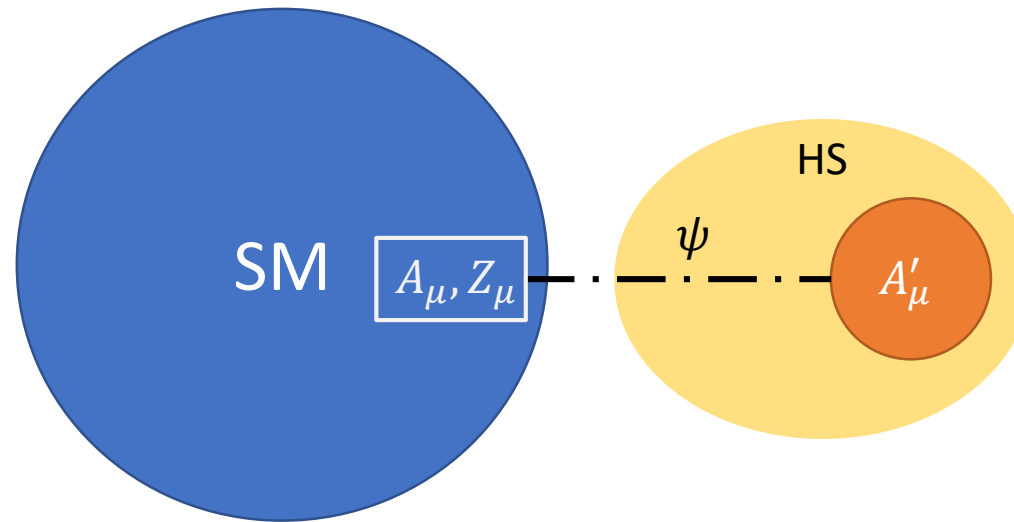# Comparing Neff constraints: Dominant for $M_\psi > 0.1$ MeV

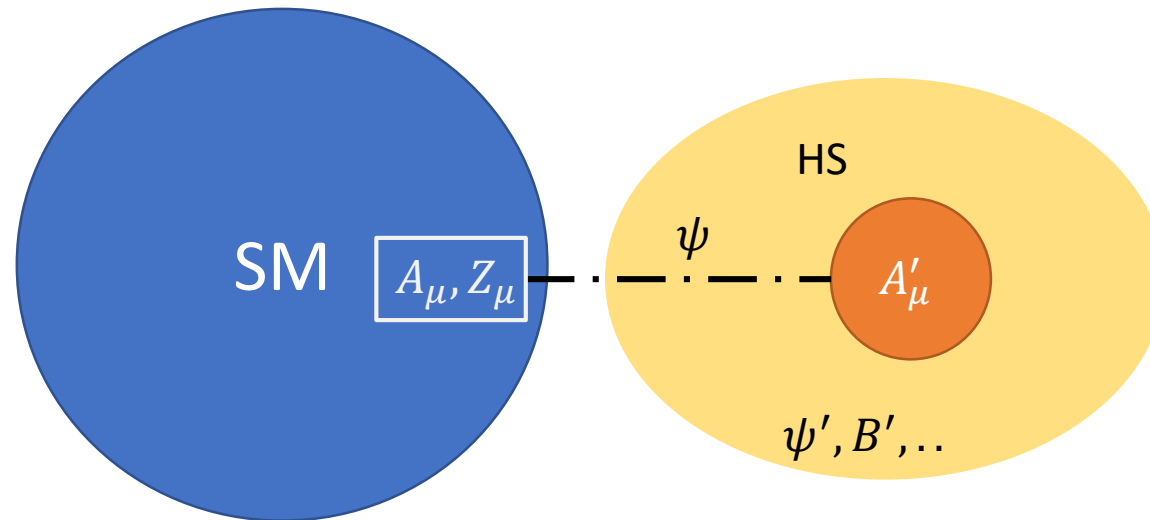# Comparing Neff constraints: Updating previous constraint

previous CMB constraint — ⋅ — CMB $\Delta N_{eff} = 0.06$

CMB $\Delta N_{eff} = 0.3$ — — — CMB $\Delta N_{eff} = 0.027$

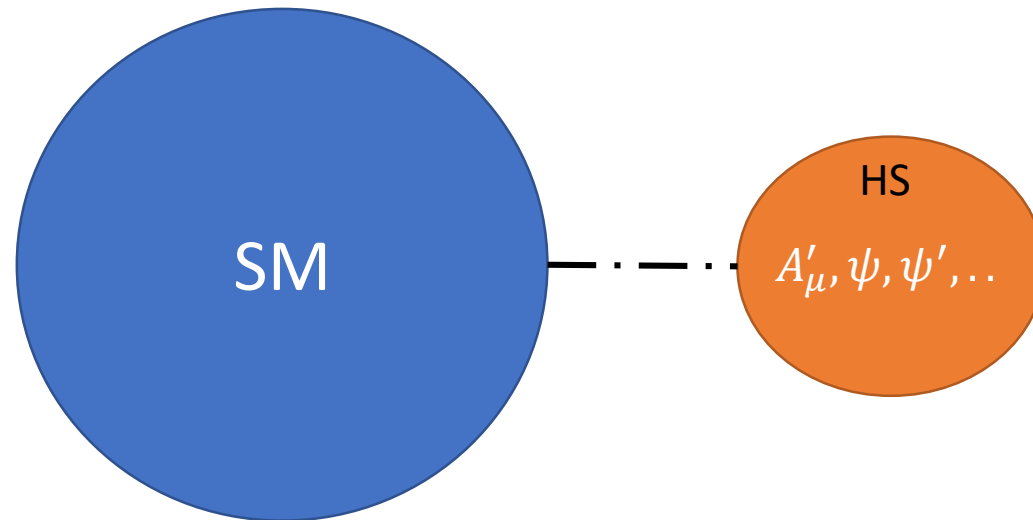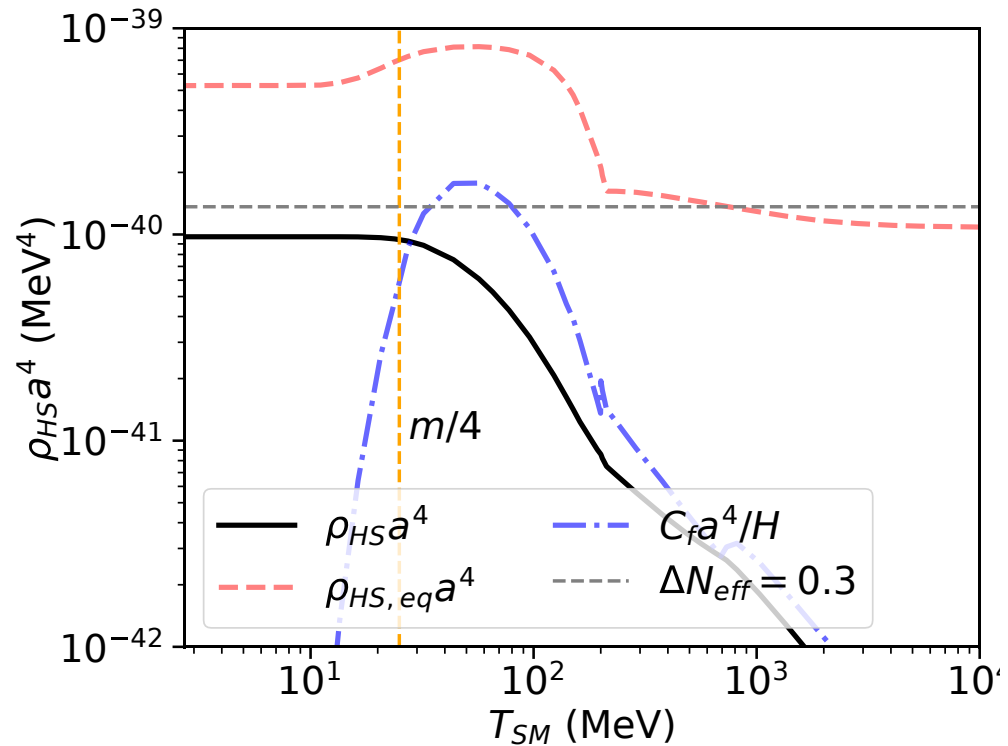H. Vogel and J. Redondo, JCAP 02 (2014) 029.

Extending to general hidden sector

Extending to general hidden sector
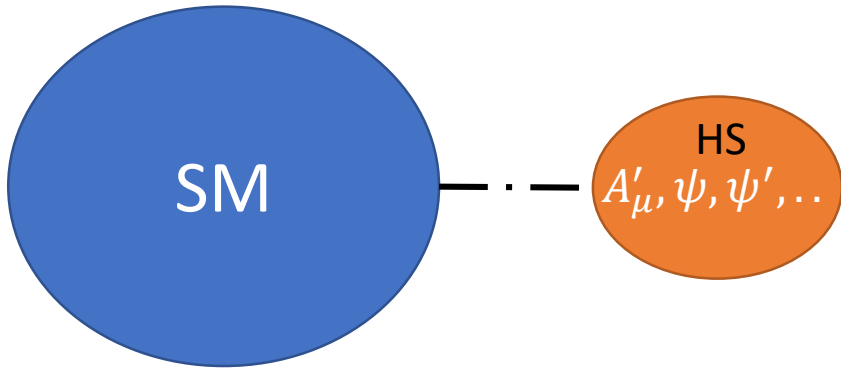
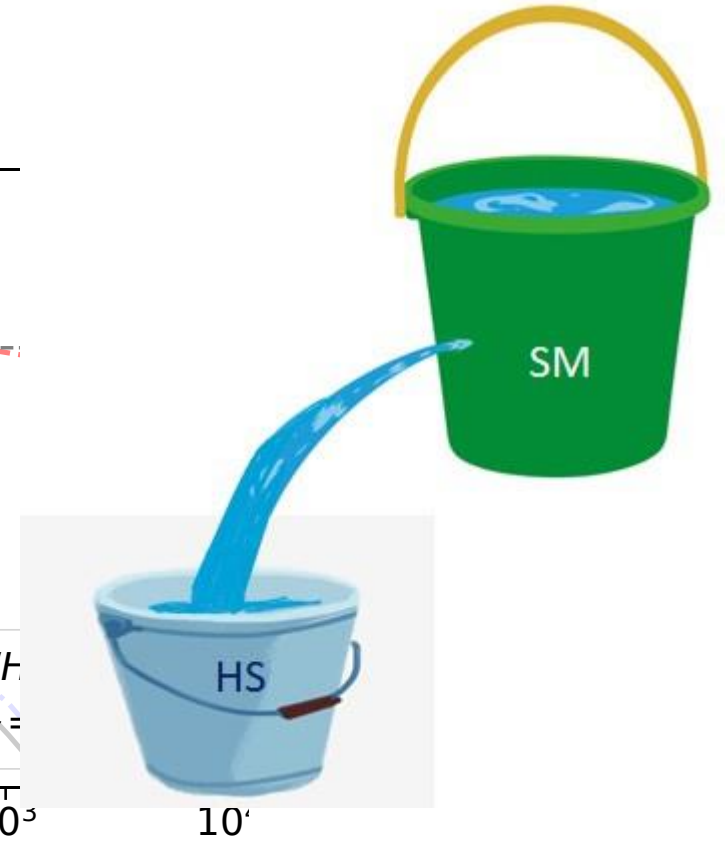# Extending to general hidden sector
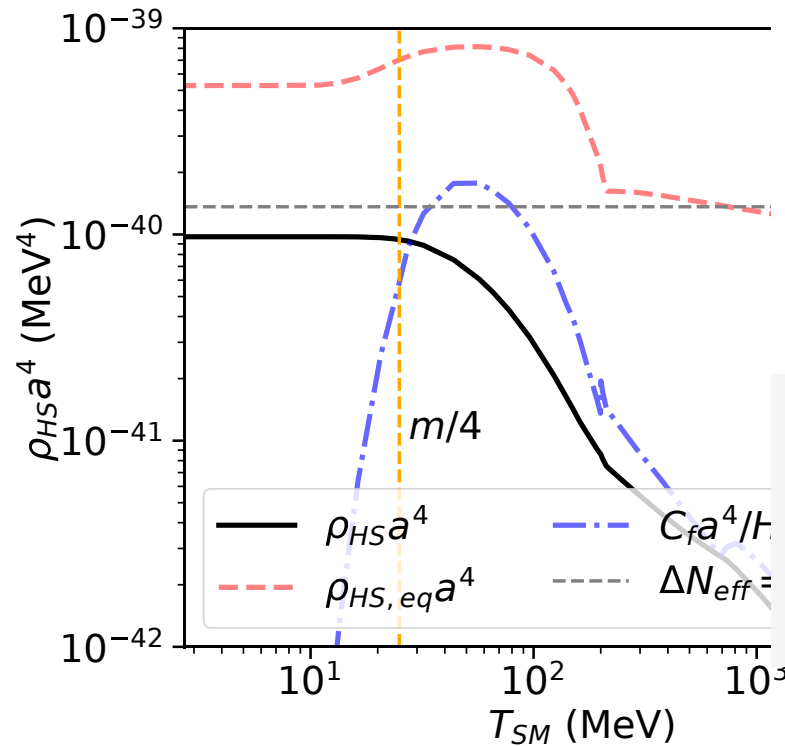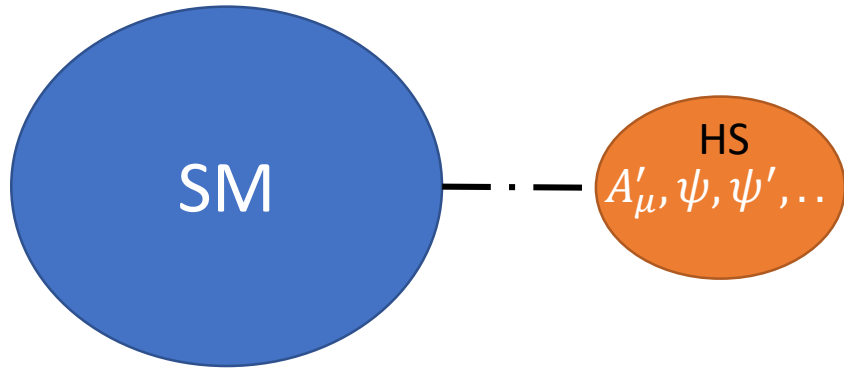
Extending to general hidden sector

One can calculate a conservative Neff constraint on the millicharge interaction that is independent of details of hidden sector.
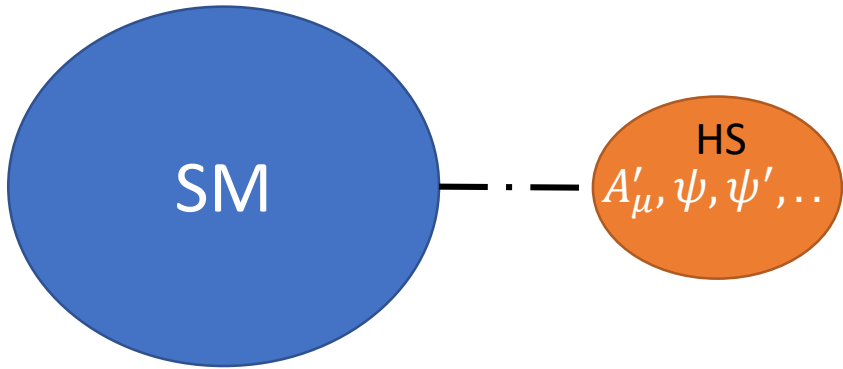
Minimum leaked energy independent of details within HS

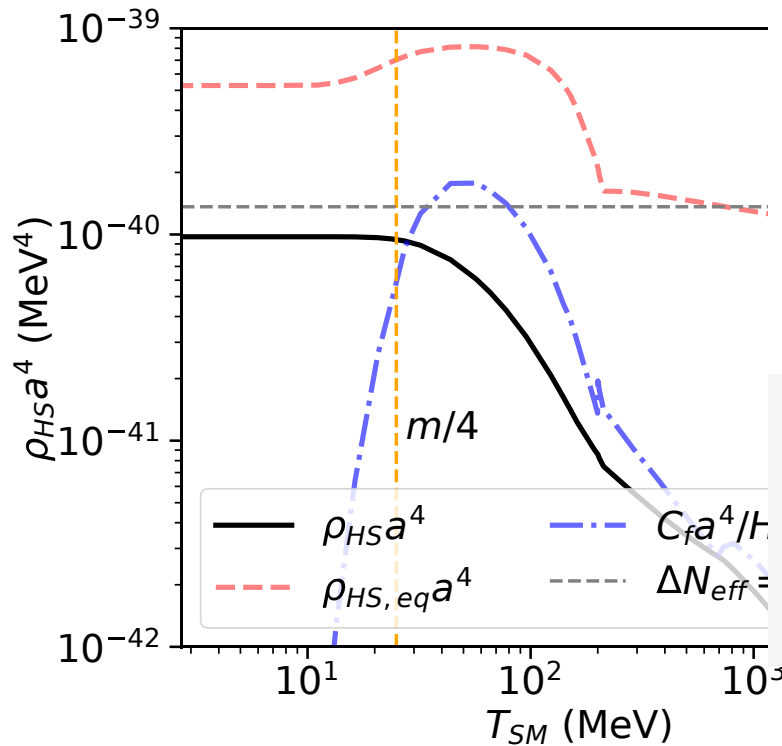# Minimum leaked energy independent of details within HS

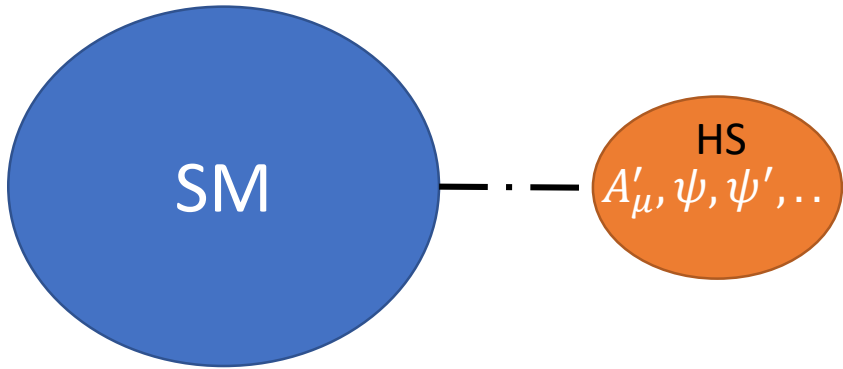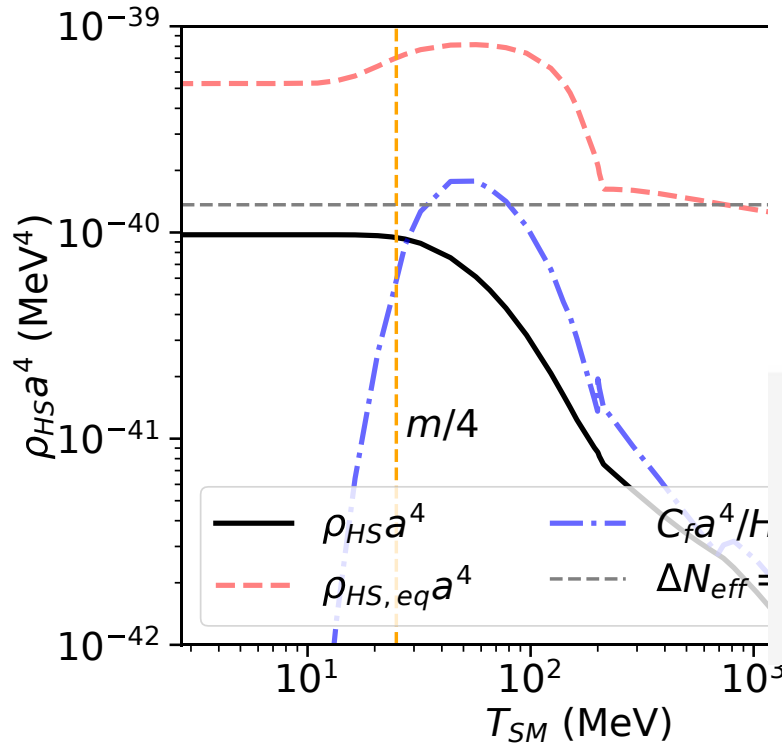# Minimum leaked energy independent of details within HS

$$\left(\frac{\rho_{HS}}{\rho_{SM}}\right)_{\min} \propto \frac{M_{\text{Pl}}}{m_\psi} L$$

$$L = m_\psi \int ds \, \frac{s - 4m_f^2}{s\sqrt{s}} \, \sigma_{ff\to\psi\psi} \propto Q^2$$

Leak factor

$\rho_{HS} a^4 \ (\text{MeV}^4)$

$T_{SM} \ (\text{MeV})$

m/4

— $\rho_{HS} a^4$ — · — $C_f a^4/H$
- - - $\rho_{HS,eq} a^4$ - - - $\Delta N_{eff} =$

SM

HS

Minimum leaked energy independent of details within HS

SM — · — · — HS
$A'_\mu, \psi, \psi', ..$

$$\left(\frac{\rho_{HS}}{\rho_{SM}}\right)_{\min} \propto \frac{M_{\rm Pl}}{m_\psi} L$$

$$L = m_\psi \int ds \, \frac{s - 4m_f^2}{s\sqrt{s}} \, \sigma_{ff \to \psi\psi} \propto Q^2$$

Leak factor

Independent of g_{HS} or T_{HS} or value of dark charge.

Minimum leaked energy independent of details within HS: Depends only on one BSM coupling
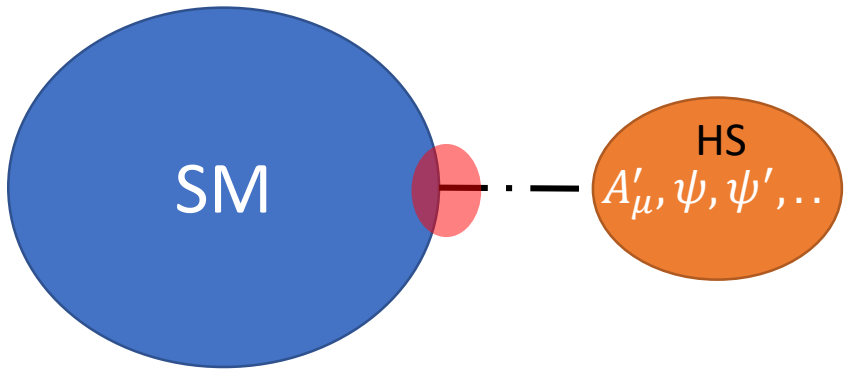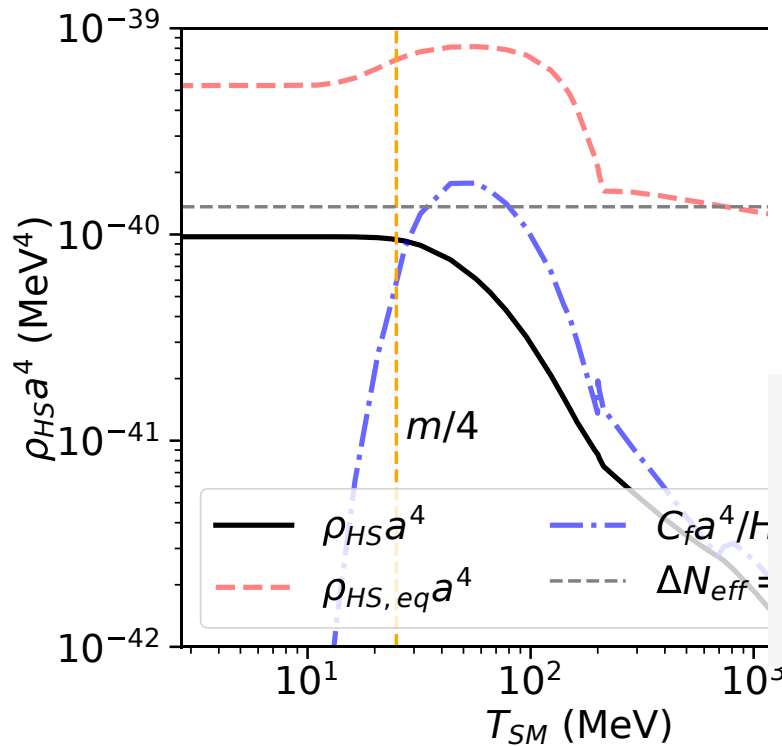
SM

HS
$A'_\mu, \psi, \psi', ..$

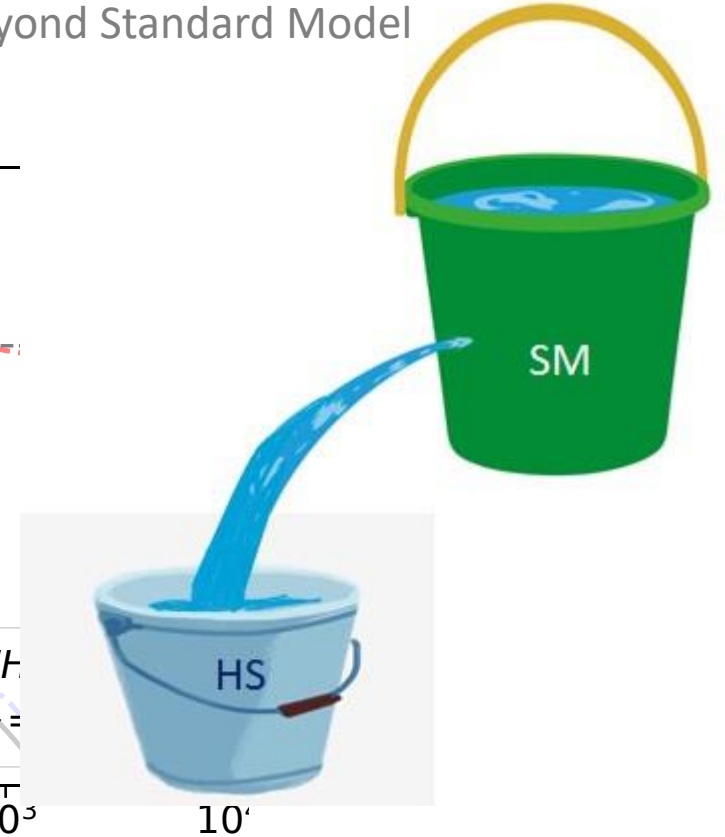$$\left(\frac{\rho_{HS}}{\rho_{SM}}\right)_{\min} \propto \frac{M_{\mathrm{Pl}}}{m_\psi} L$$

$$L = m_\psi \int ds \, \frac{s - 4m_f^2}{s\sqrt{s}} \sigma_{ff \to \psi\psi} \propto Q^2$$

Leak factor

Independent of g_{HS} or T_{HS} or value of dark charge.

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Minimum leaked energy independent of details within HS: Conservative constraint on BSM coupling

Beyond Standard Model

SM

HS
$A'_\mu, \psi, \psi', ..$

$$\left(\frac{\rho_{HS}}{\rho_{SM}}\right)_{\min} \propto \frac{M_{\mathrm{Pl}}}{m_\psi} L$$

$$L = m_\psi \int ds \, \frac{s - 4m_f^2}{s\sqrt{s}} \sigma_{ff \to \psi\psi} \propto Q^2$$

Leak factor

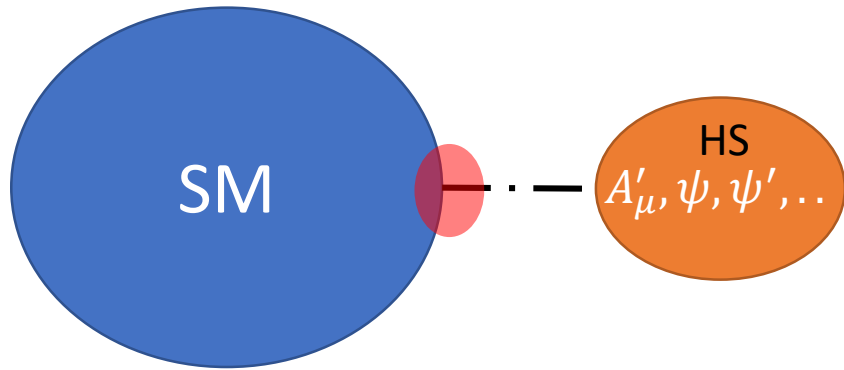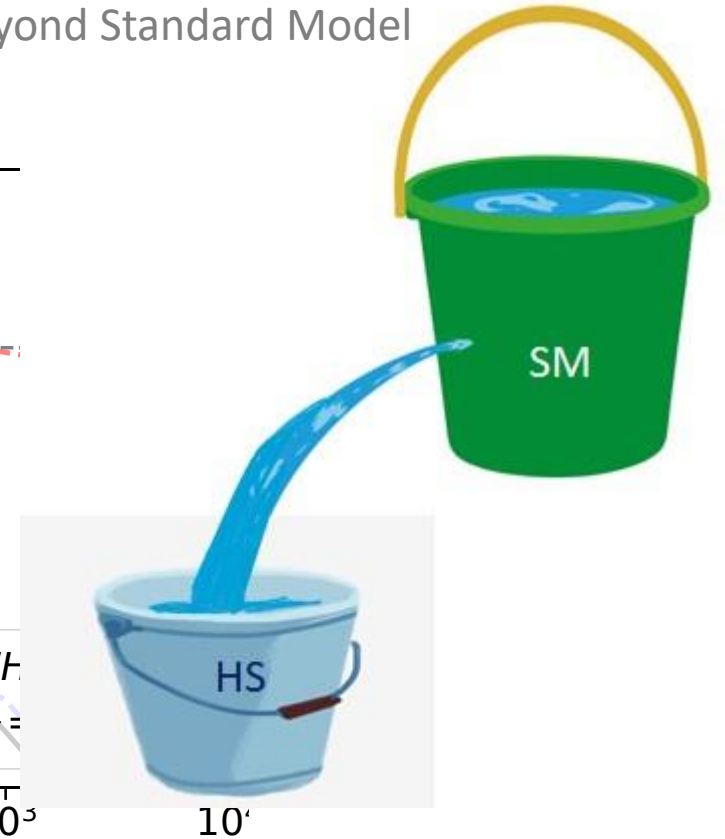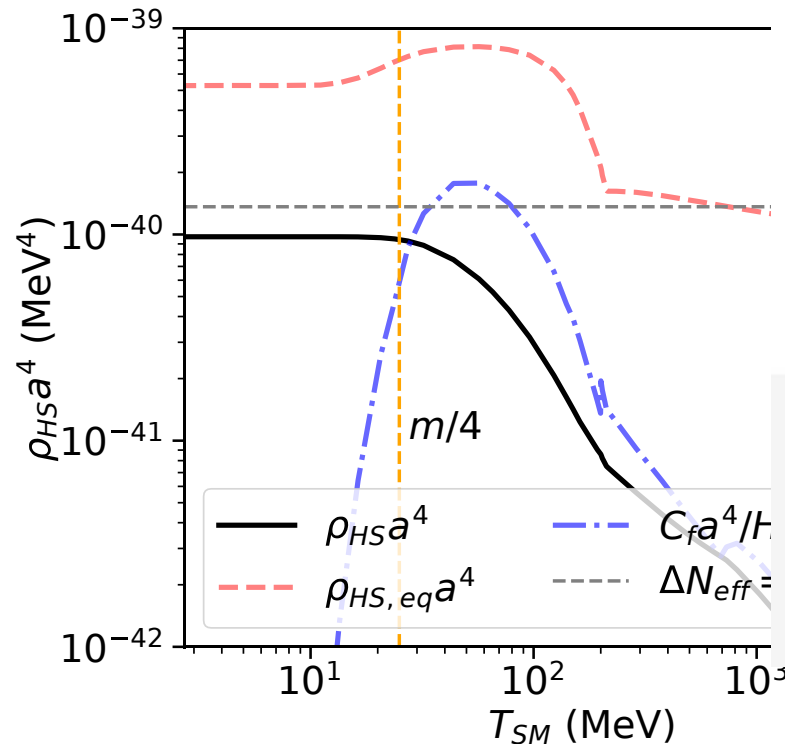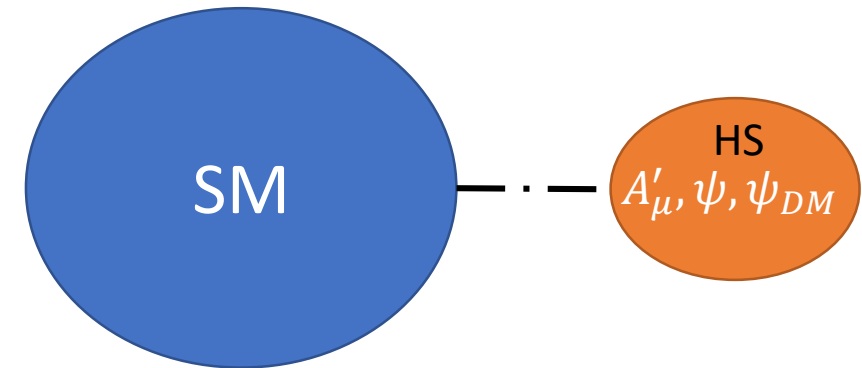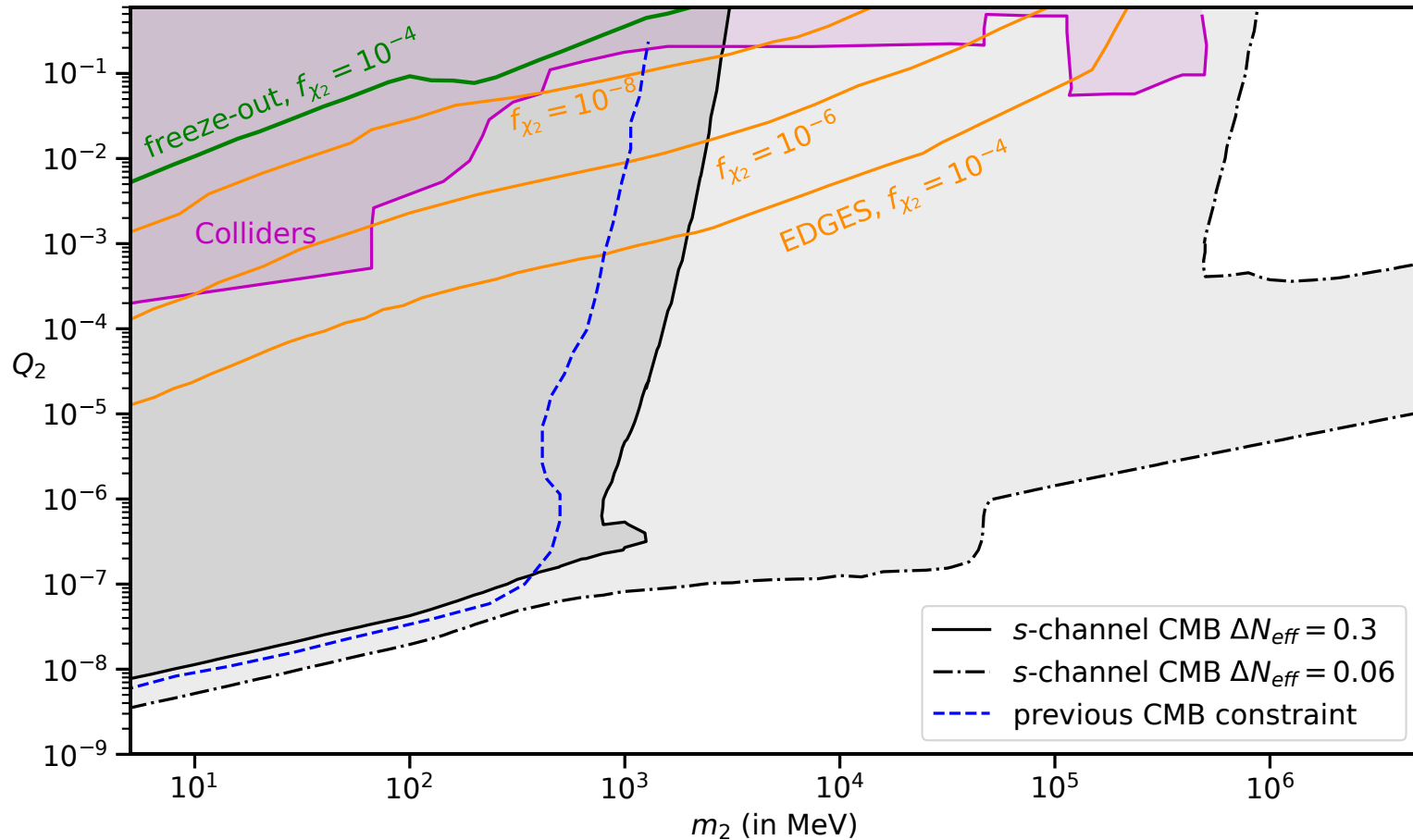Independent of g_{HS} or T_{HS} or value of dark charge.

$$L < g_*^{3/4}(m) \, g_*^{1/3} \left(\frac{m}{4}\right) \frac{m/4}{M_{\mathrm{Pl}}} (\Delta N_{\mathrm{eff}})_{\max}$$
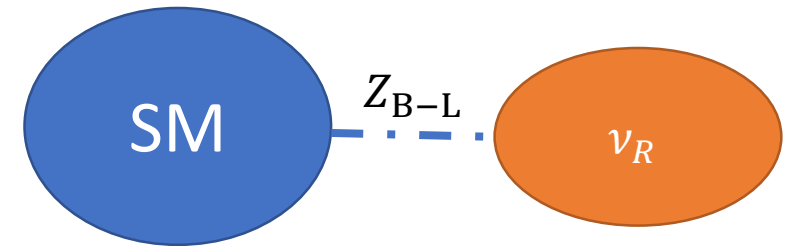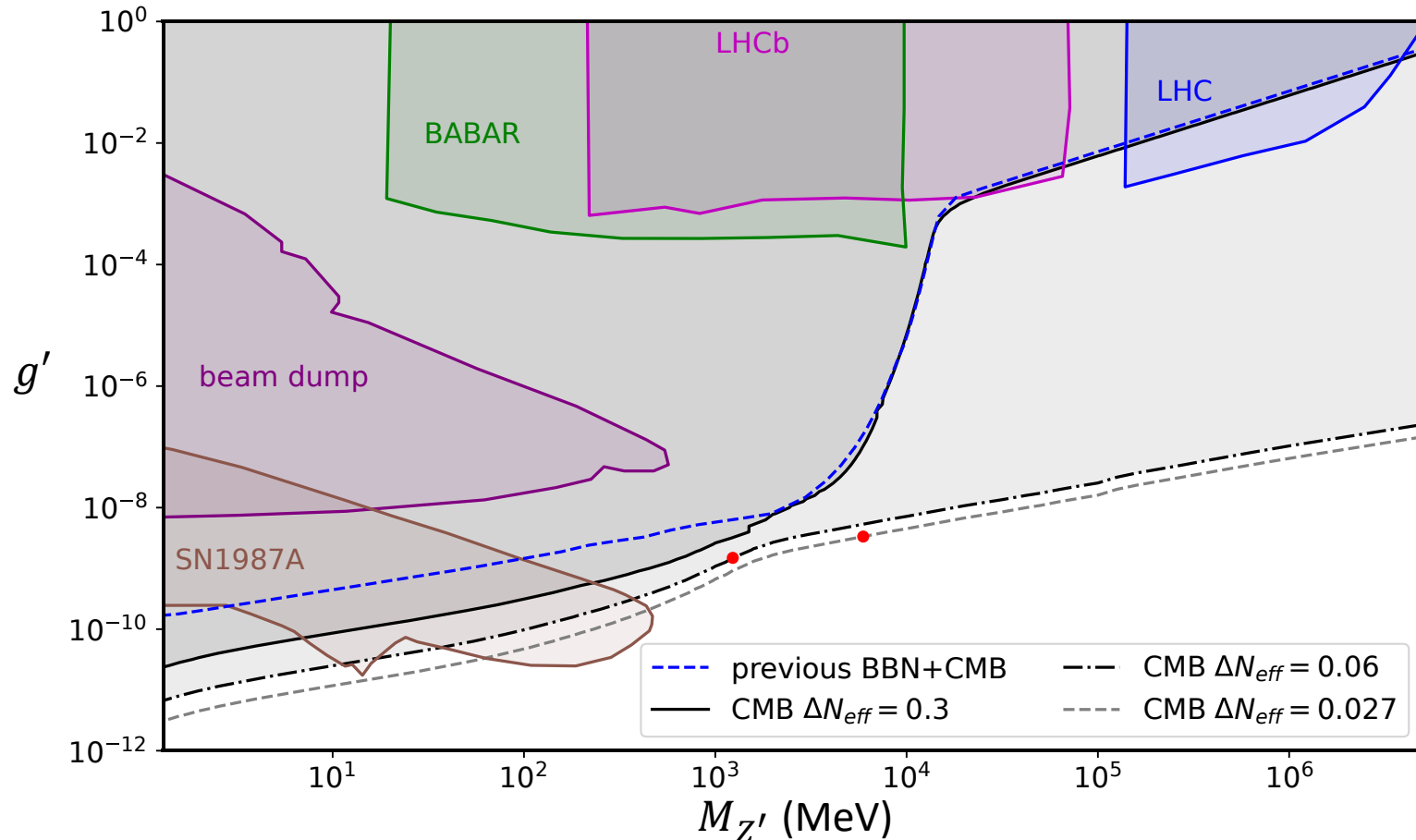
Neff constraints applicable for wide class of hidden sectors: Application to EDGES

H. Liu, N. J. Outmezguine, D. Redigolo, and T. Volansky, Phys. Rev. D 100 no. 12, (2019) 123011.

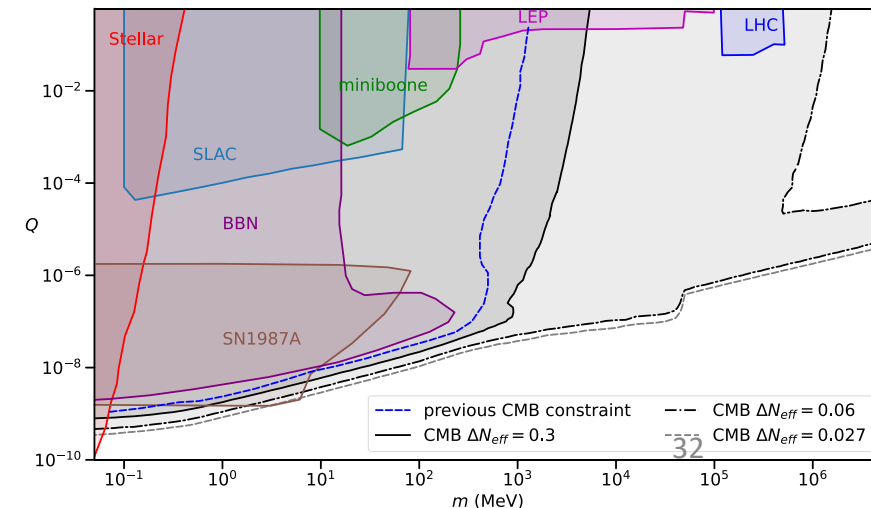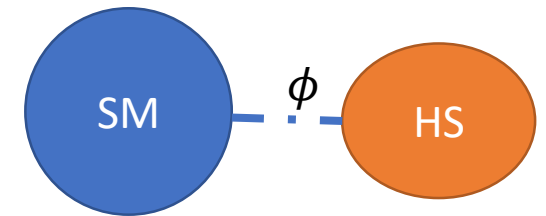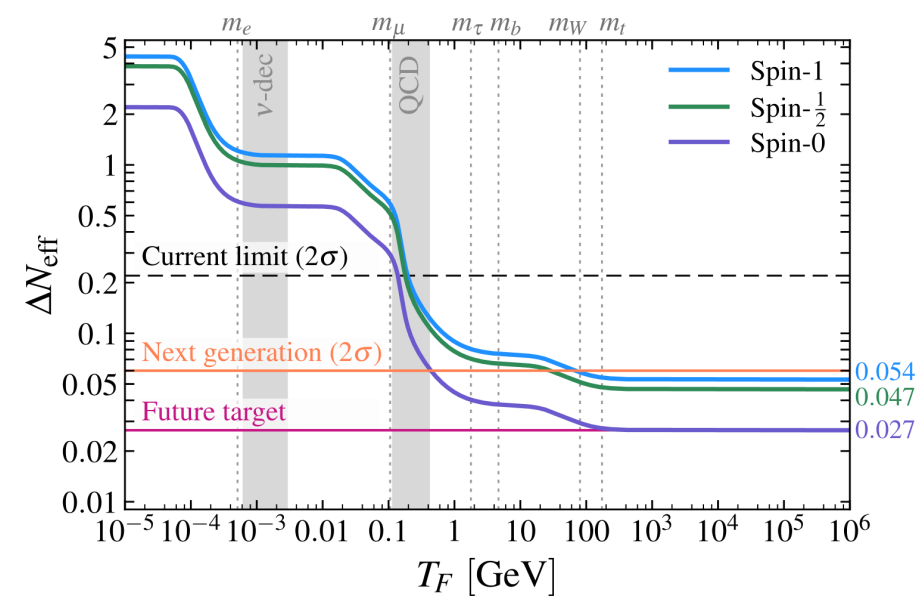# Neff constraints applicable for wide class of hidden sectors: B-L model

$$L_{int} \supset -\frac{1}{4}F'_{\mu\nu}F^{\mu\nu\prime} + g'Z'_\mu J^\mu_{B-L,SM} - g'Z'_\mu \sum_i \bar{\nu}_{R,i}\gamma^\mu \nu_{R,i} + \frac{1}{2}M^2_{Z'}Z'^\mu Z'_\mu$$
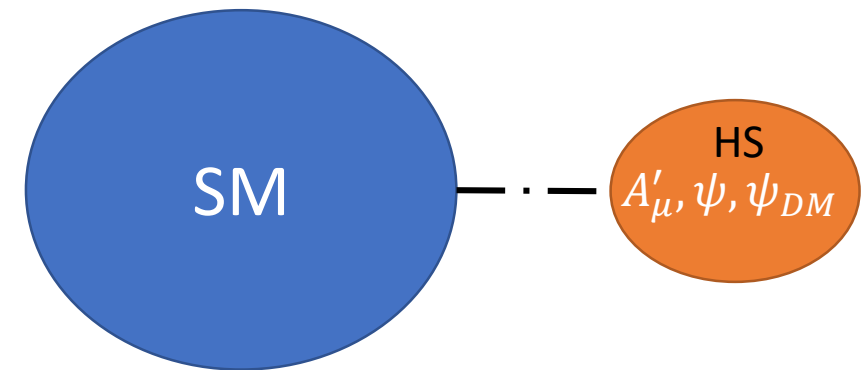
Summary

- With improving Neff measurements, we should interpret them as constraints on portal interactions with out-of-equilibrium sectors

- N_{eff} constraints on out-of-equilibrium particles are:

  - Most relevant for portal interactions mediated by a particle heavier than 0.1 MeV

  - Orders of magnitude stronger than collider experiments

  - Constraints largely independent of internal hidden sector model

- Simple way to calculate: $L < g_*^{3/4}(4\Lambda)\, g_*^{1/3}(\Lambda)\, \dfrac{\Lambda}{M_{\text{Pl}}}\,(\Delta N_{\text{eff}})_{\text{max}}$
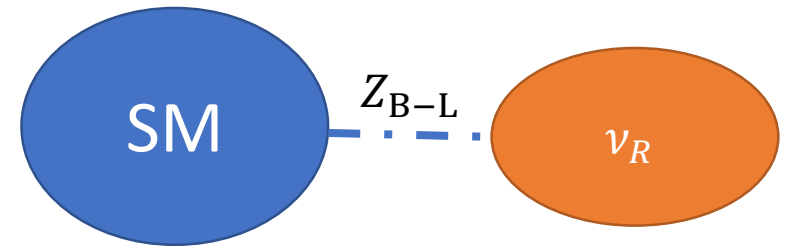
Backup slides

Neff constraints applicable for wide class of hidden sectors: Application to EDGES

SM

HS
A'_μ, ψ, ψ_{DM}

H. Liu, N. J. Outmezguine, D. Redigolo, and T. Volansky, Phys. Rev. D 100 no. 12, (2019) 123011.

Neff constraints applicable for wide class of hidden sectors: B-L model

$$L_{int} \supset -\frac{1}{4}F'_{\mu\nu}F^{\mu\nu'} + g'Z'_\mu J^\mu_{B-L,SM} - g'Z'_\mu \sum_i \bar{\nu}_{R,i}\gamma^\mu \nu_{R,i} + \frac{1}{2}M^2_{Z'}Z'^\mu Z'_\mu$$

Millicharged particles must dominantly annihilate into dark photons

Millicharged particle abundance= dark matter abundance
Assuming negligible interaction with dark phton