Dark radiation constraints on portal interactions with hidden sectors

arxiv:2206.13530

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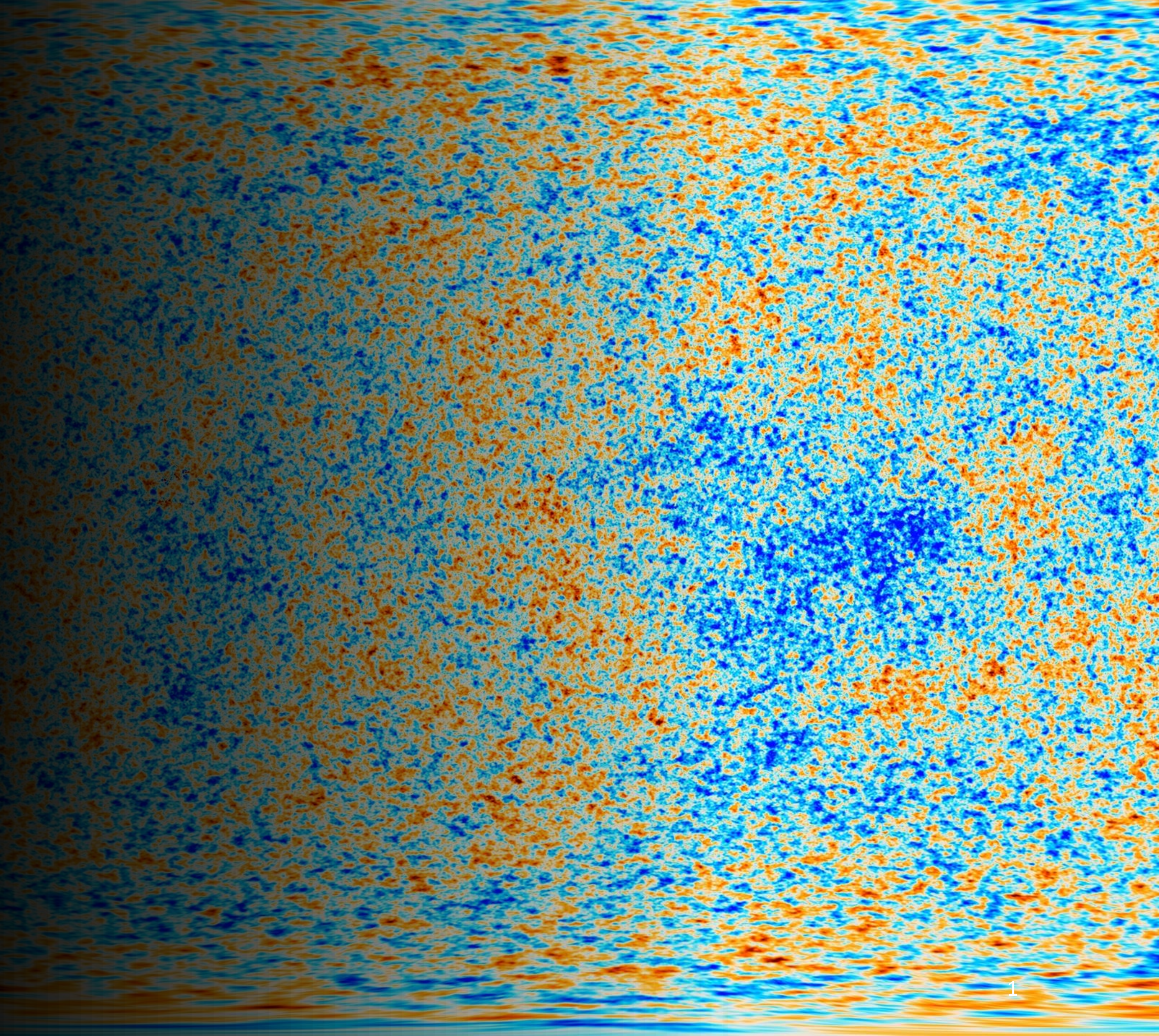
Collaborators: Peter Adshead and Jessie Shelton



N_{eff} 101

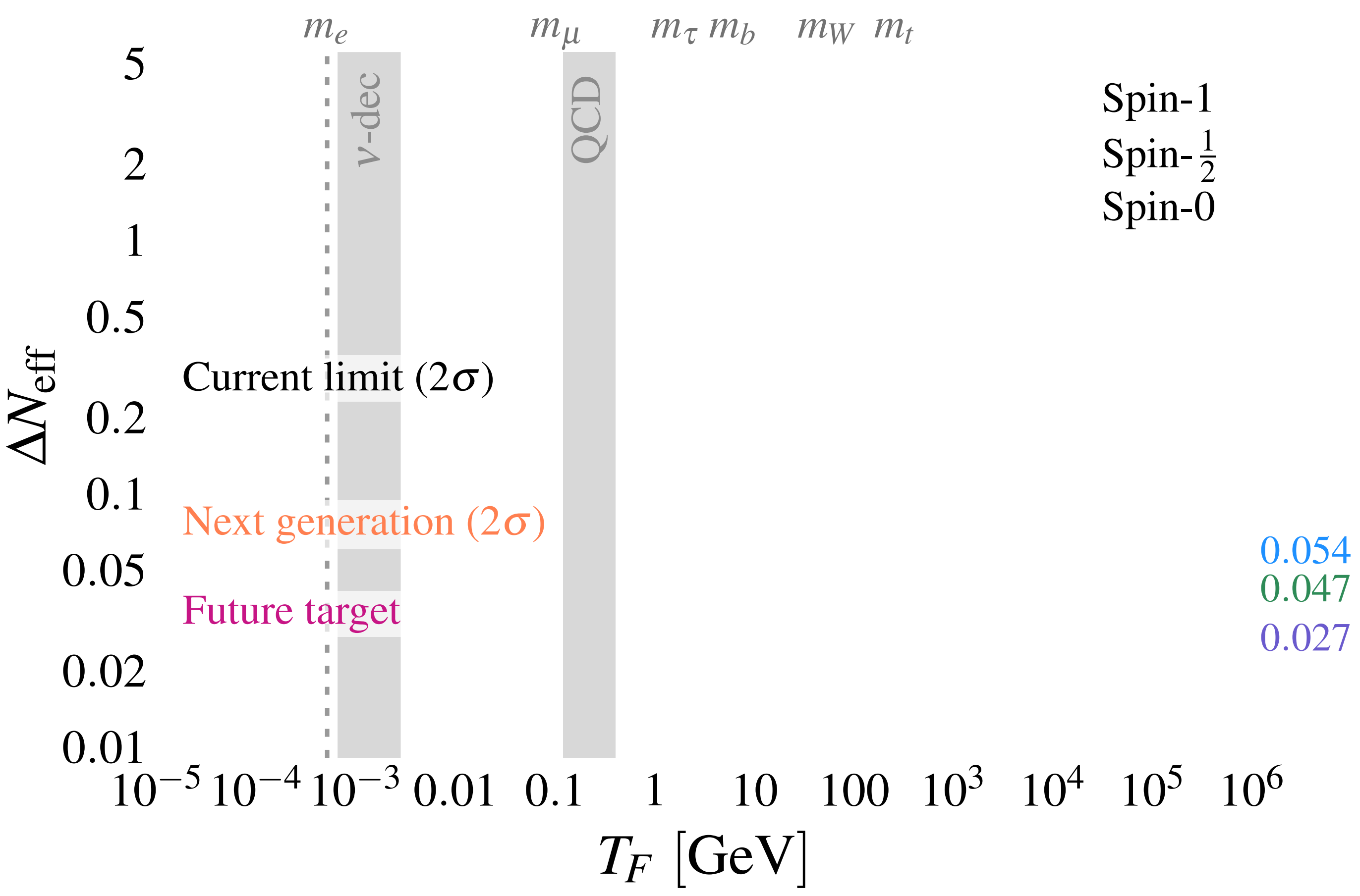
- N_{eff} : effective number of neutrino species

- CMB sensitive to ρ_ν: $N_{\text{eff}}^{\text{SM}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_\nu}{\rho_\gamma} = 3.044$

- CMB also sensitive to ρ_{dr}: $\Delta N_{\text{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_{\text{dr}}}{\rho_\gamma}$

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

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

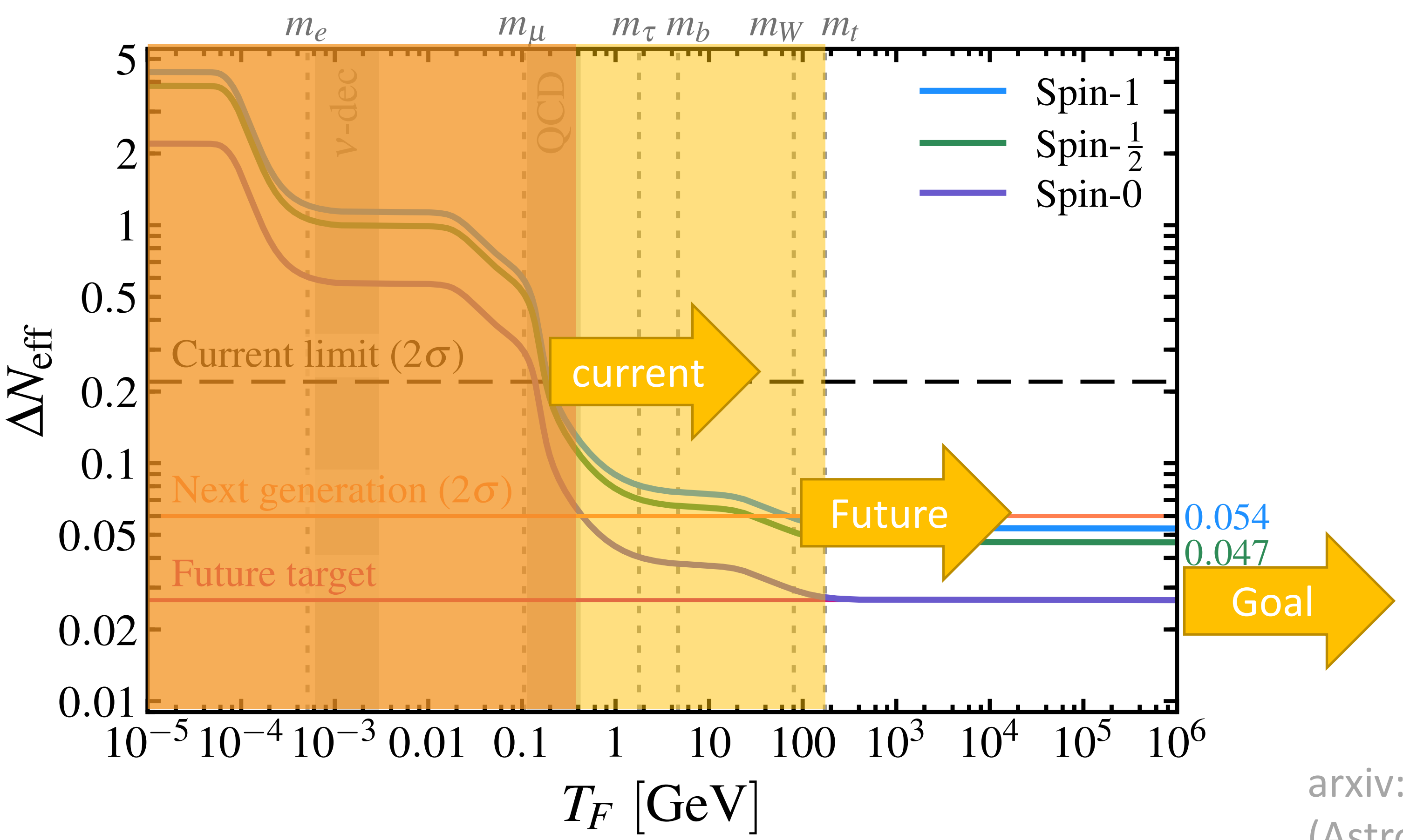


Decoupling temperature of new light particle

arxiv:1903:04763
(Astro 2020 white paper)

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

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



Decoupling temperature of new light particle

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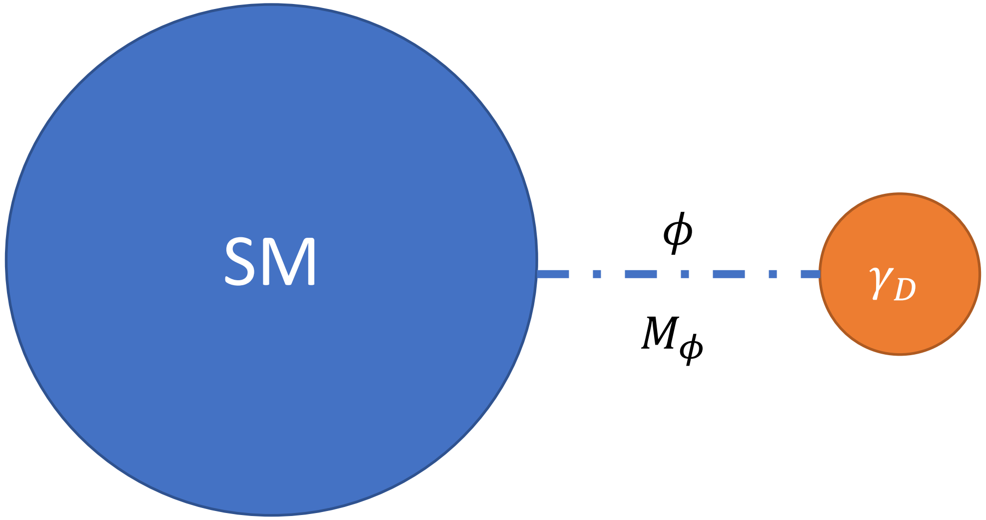
Unified treatment for calculating $N_{\mathbf{eff}}$ constraints on beyond SM interactions

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

Strong Implications for model building with HS with dark radiation

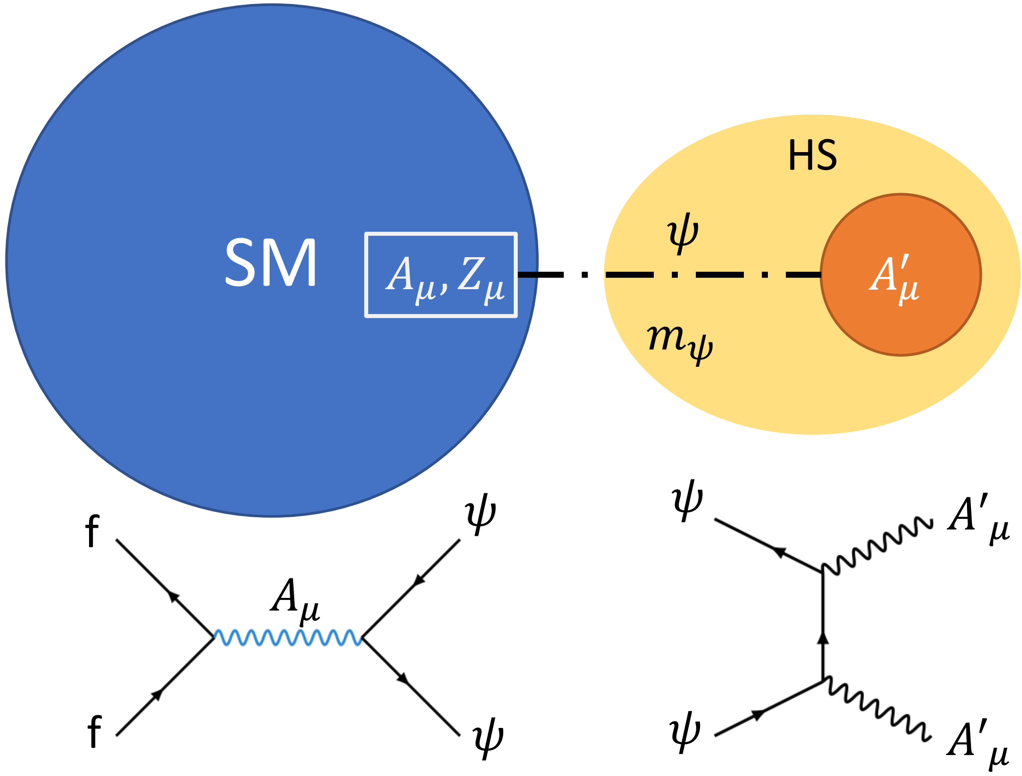
Application of N_{eff} constraint : Relevant types of interaction



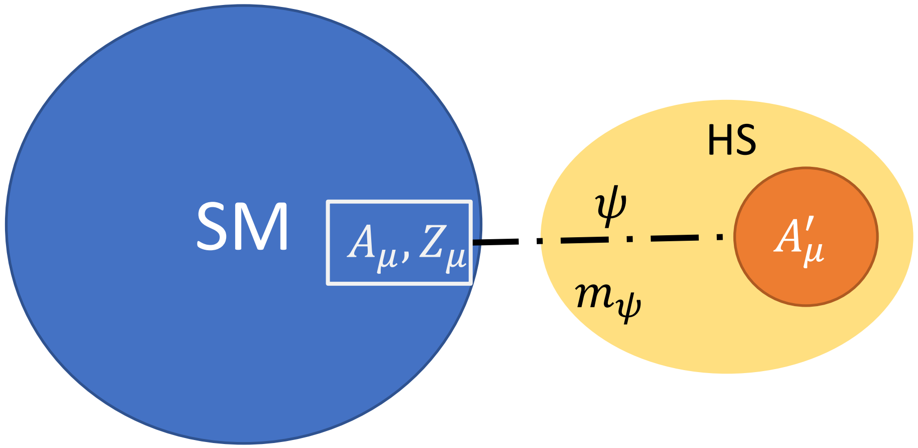
Application of N_{eff} constraint: Millicharged particle example

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

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



Physics behind dark radiation production: Boltzmann equations



Boltzmann equations:

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

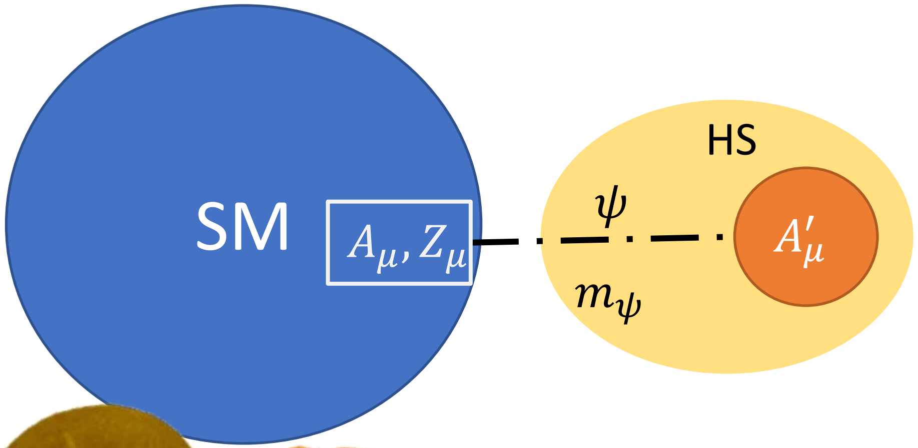
$$\frac{d\rho_{HS}}{dt} + 3H(1 + w_{HS})\rho_{HS} = C$$

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

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

Energy transfer collision term

Physics behind dark radiation production: Boltzmann equations



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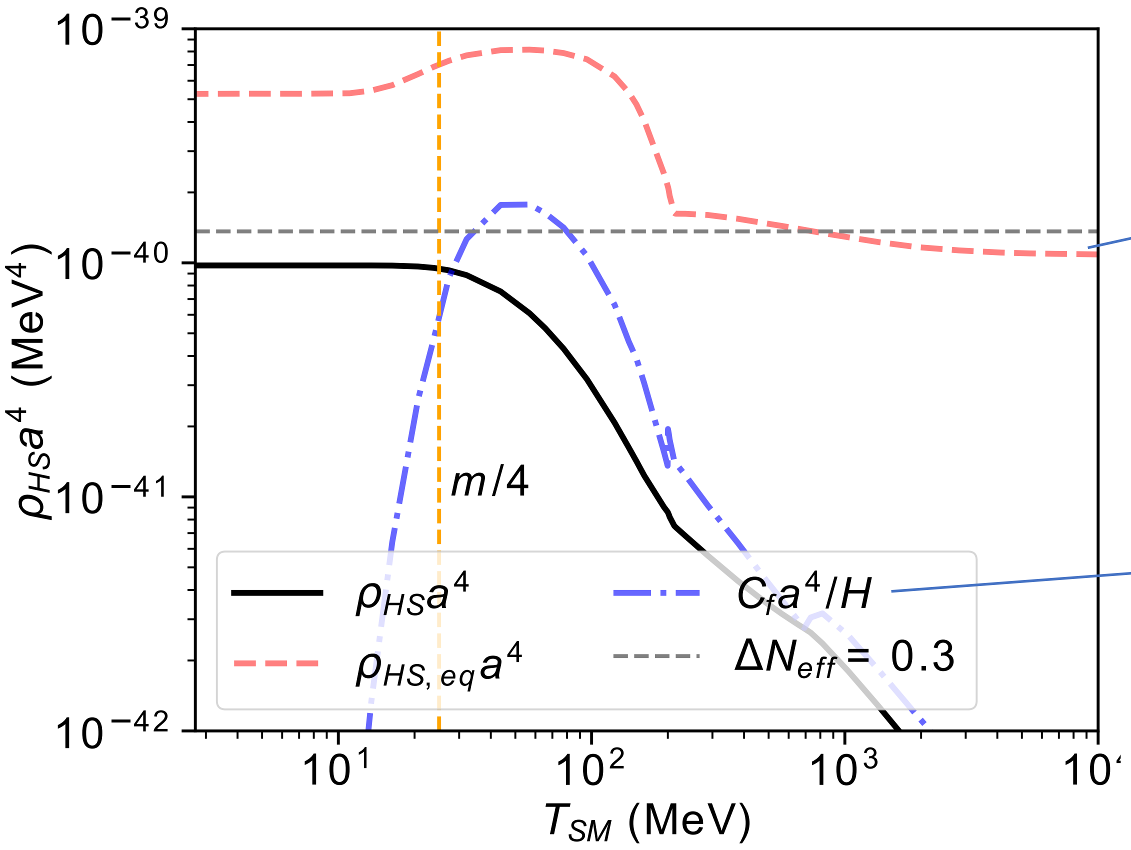
Energy transfer collision term

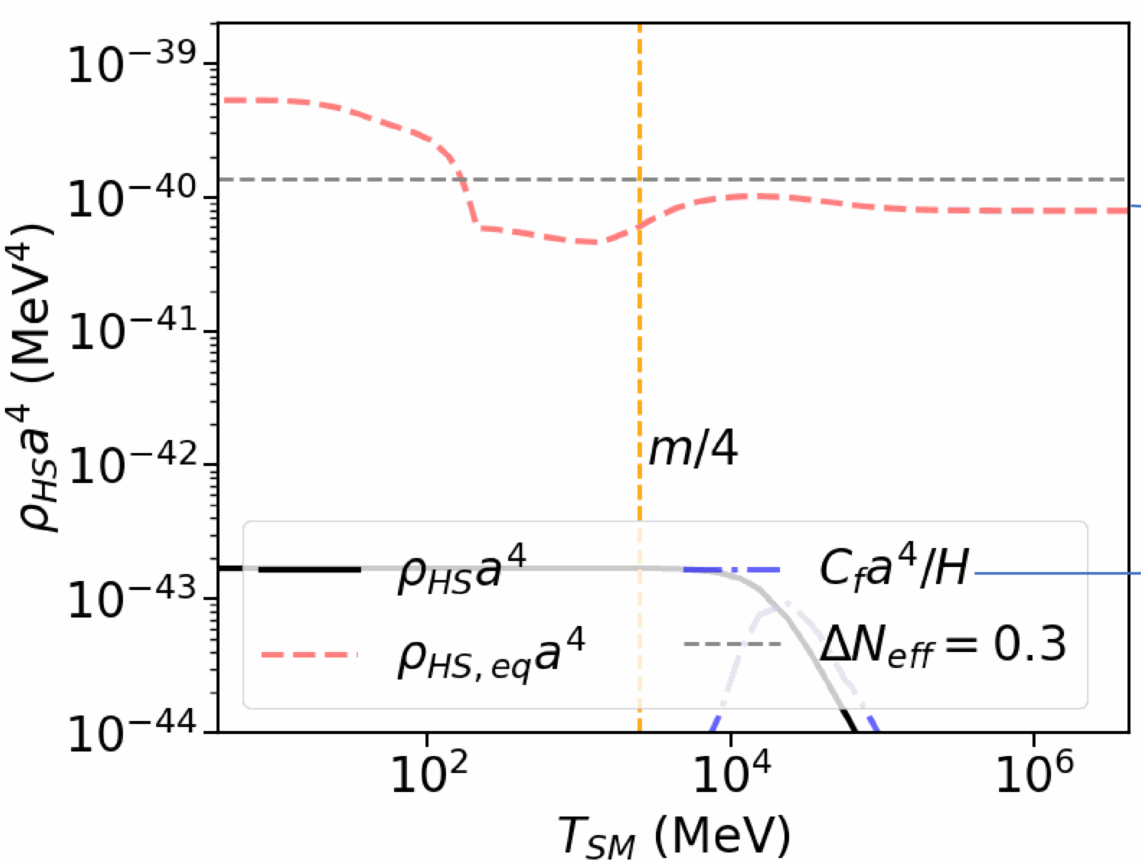
Physics behind dark radiation production: Plots!



If HS is always in equilibrium with the Standard Model plasma

Only the forward part of the collision term

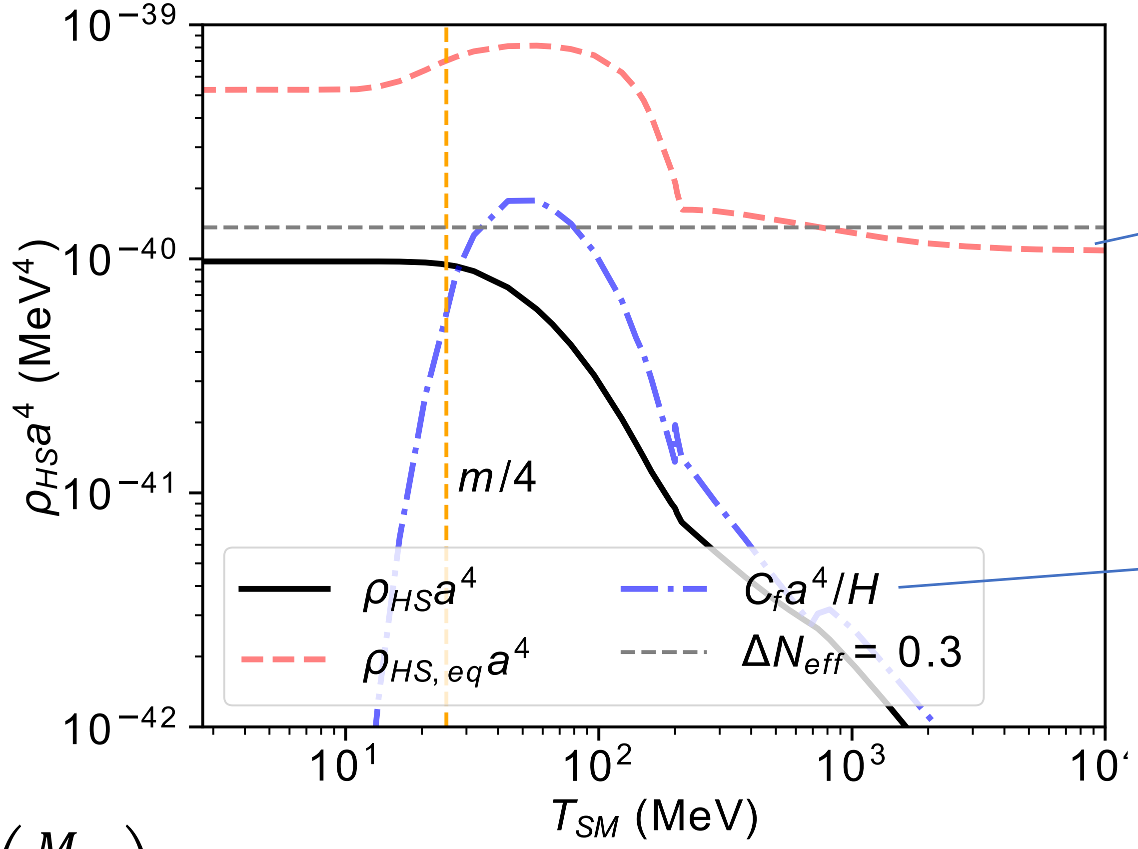
Physics behind dark radiation production: GIF!



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 ρ_{DR} proportional to portal coupling



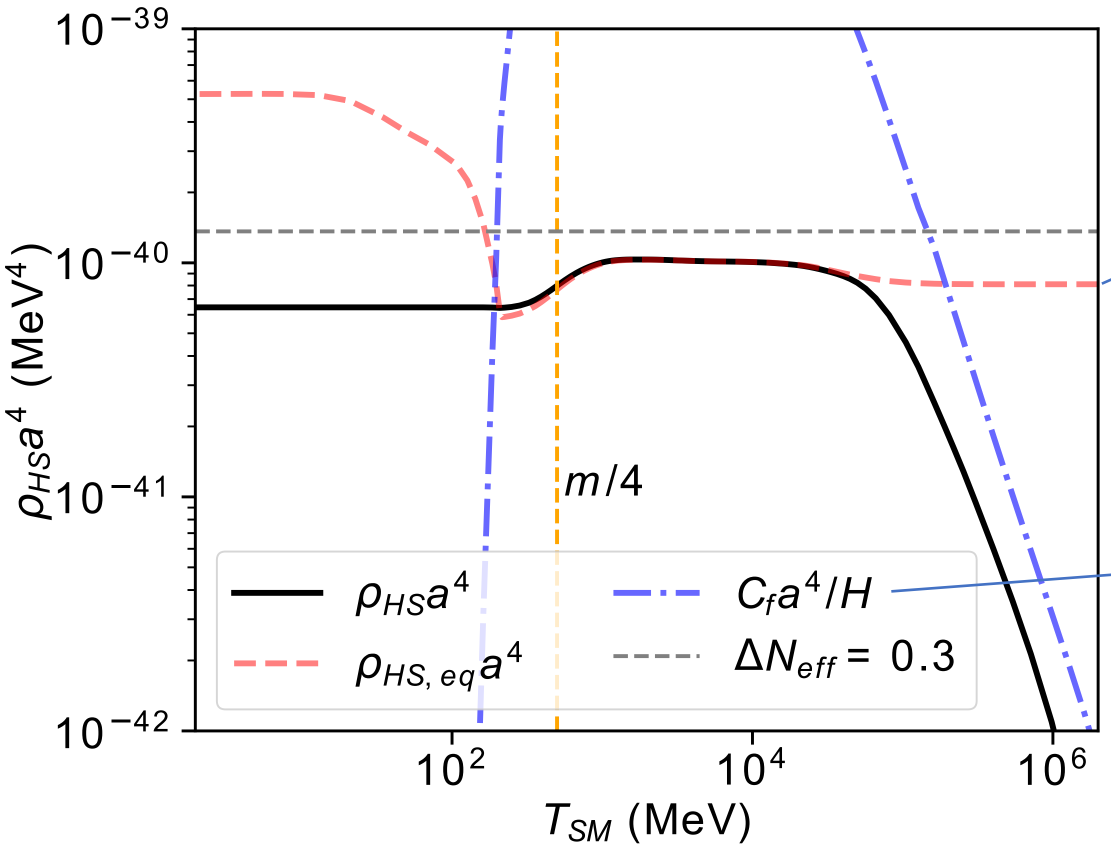
If HS is always in equilibrium with the Standard Model plasma

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



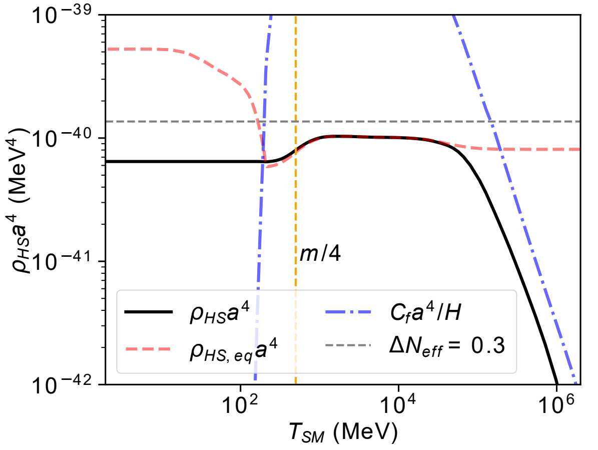
If HS is always in equilibrium with the Standard Model plasma

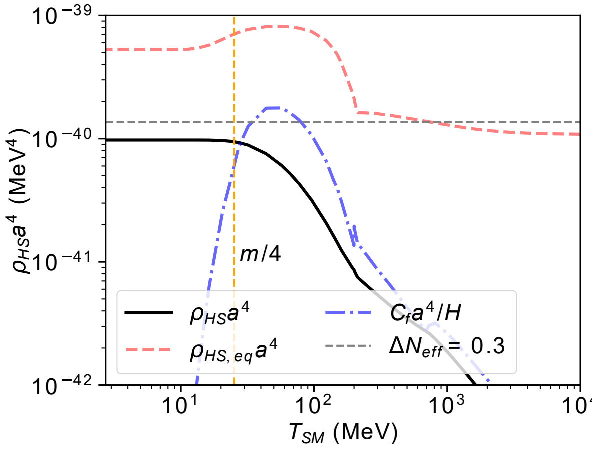
Only the forward part of the collision term

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

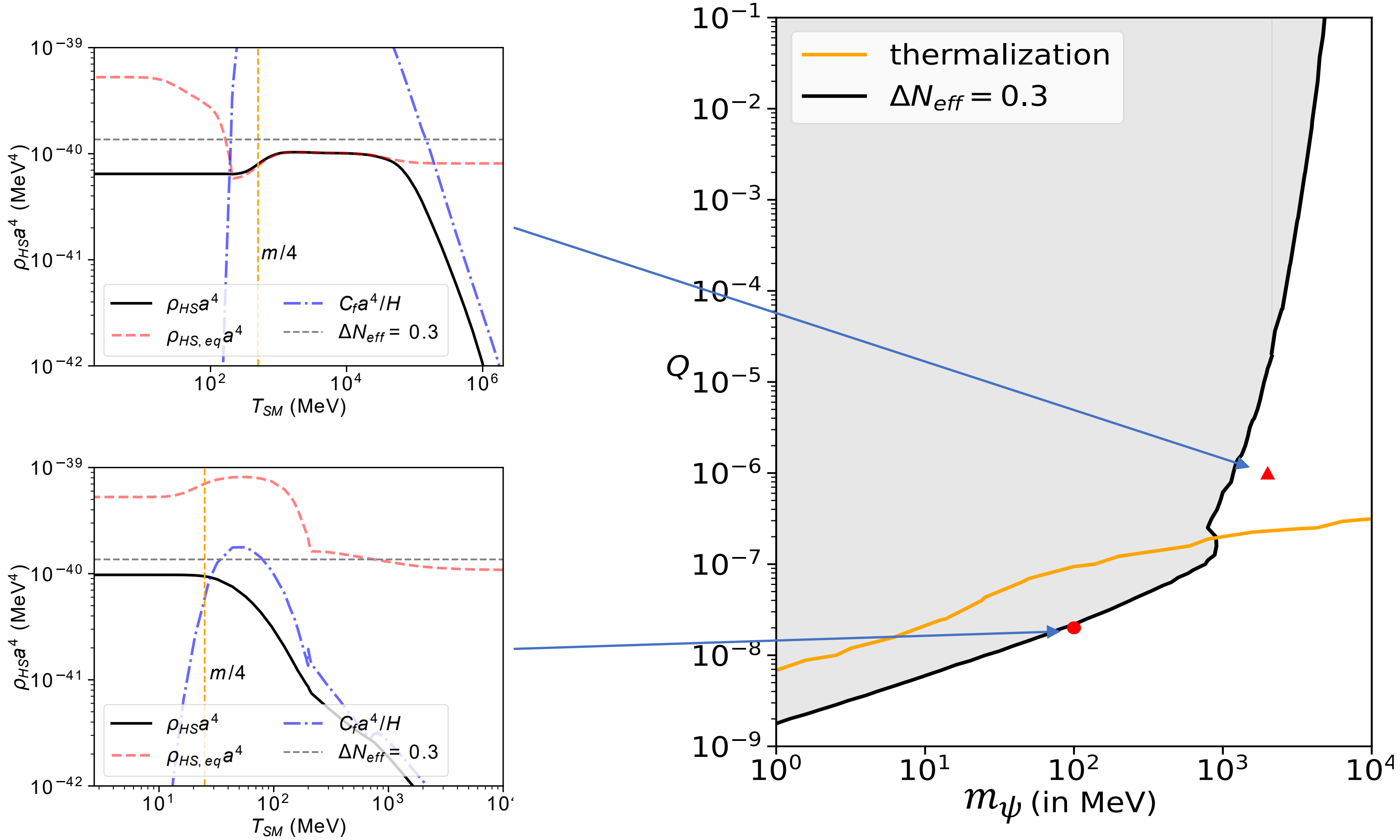
Degrees of freedom

Physics behind dark radiation production: Translating to constraints

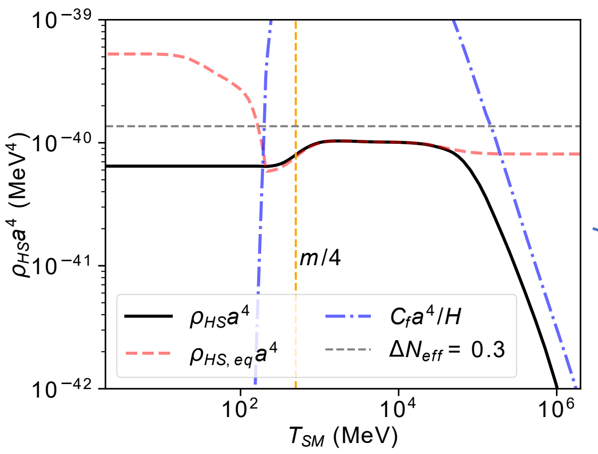


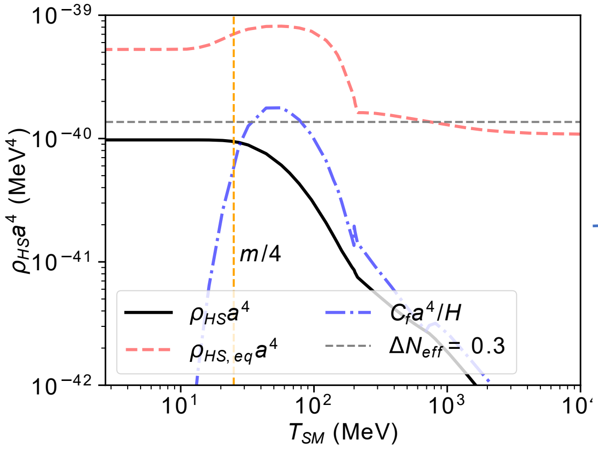


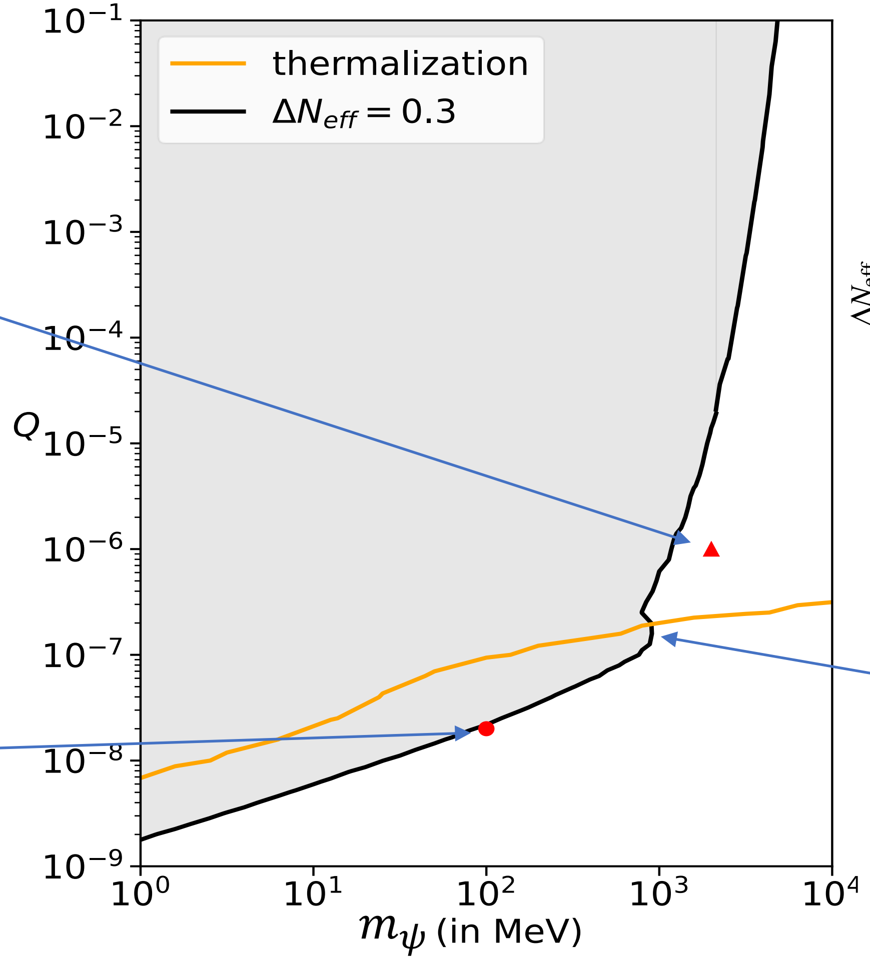
Physics behind dark radiation production : Translating to constraints

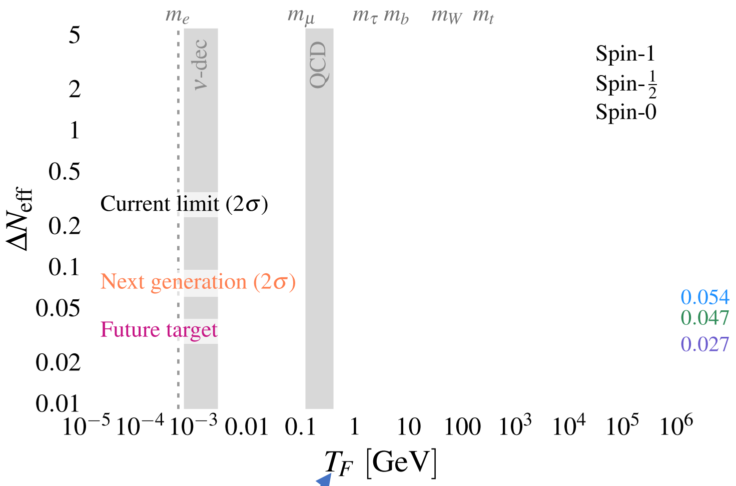


Physics behind dark radiation production : Most relevant when thermally decoupled



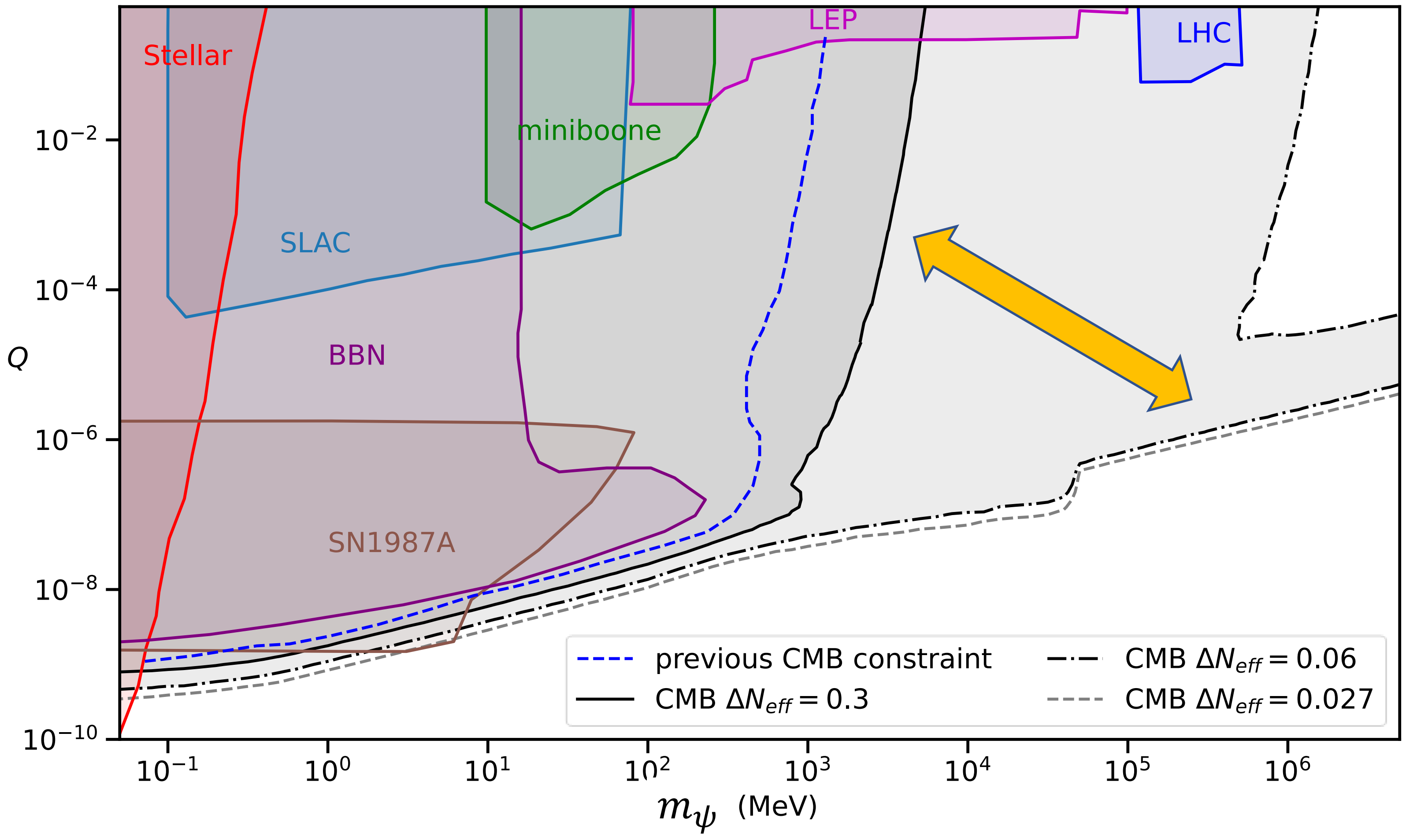




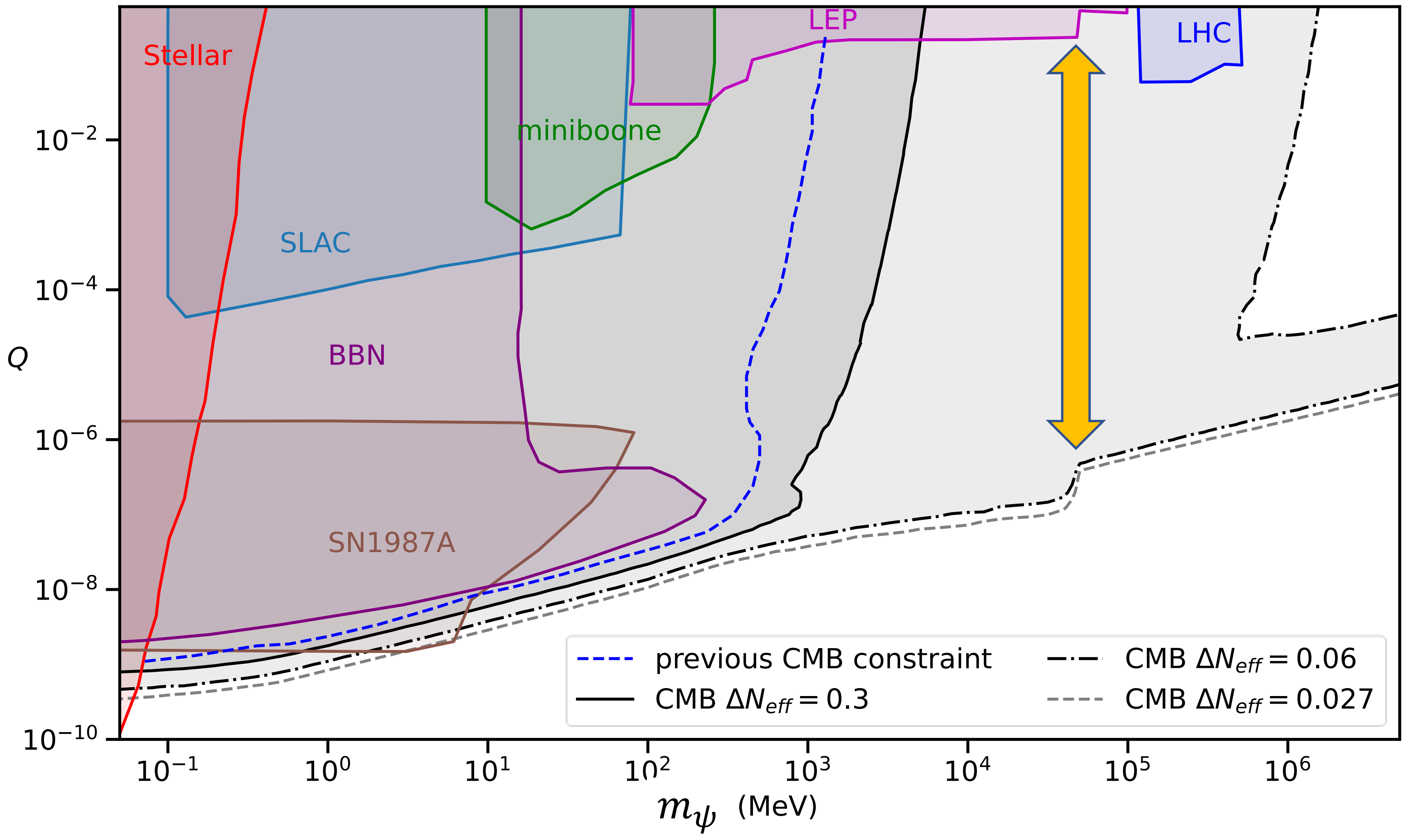


$$m_{th} = 4T_{d,s}$$

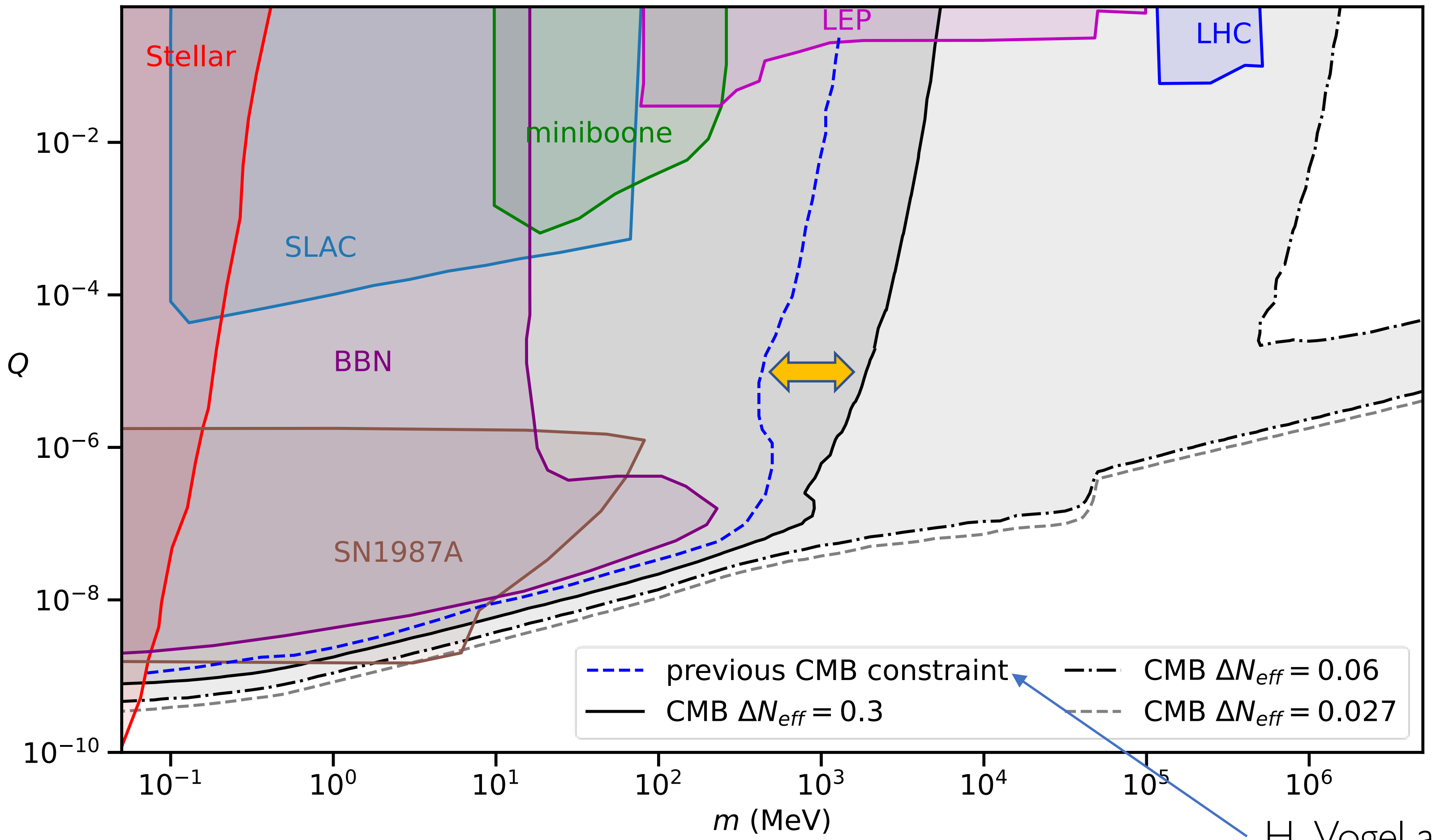
Comparing Neff constraints: Future constraint will extend to much larger parameter space



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

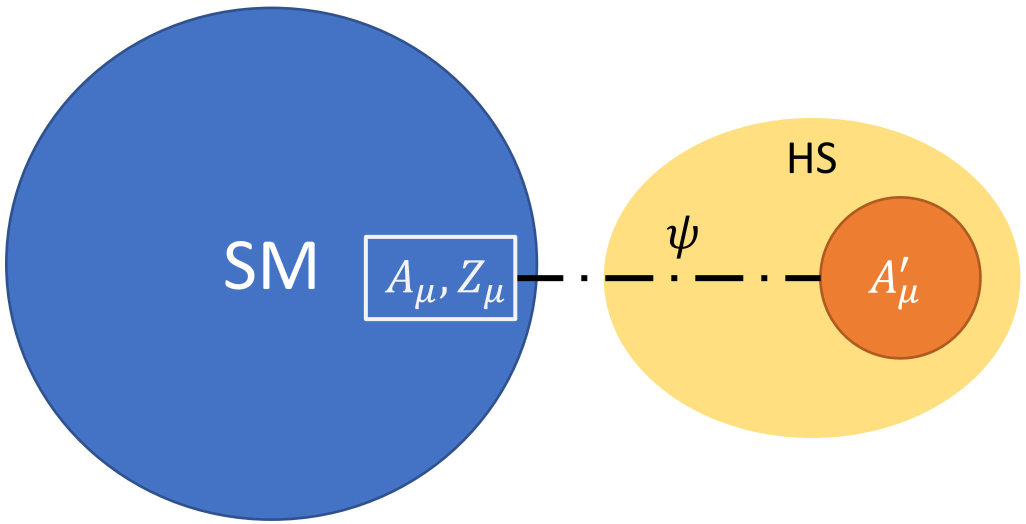


Comparing Neff constraints: Updating previous constraint



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

Extending to general hidden sector



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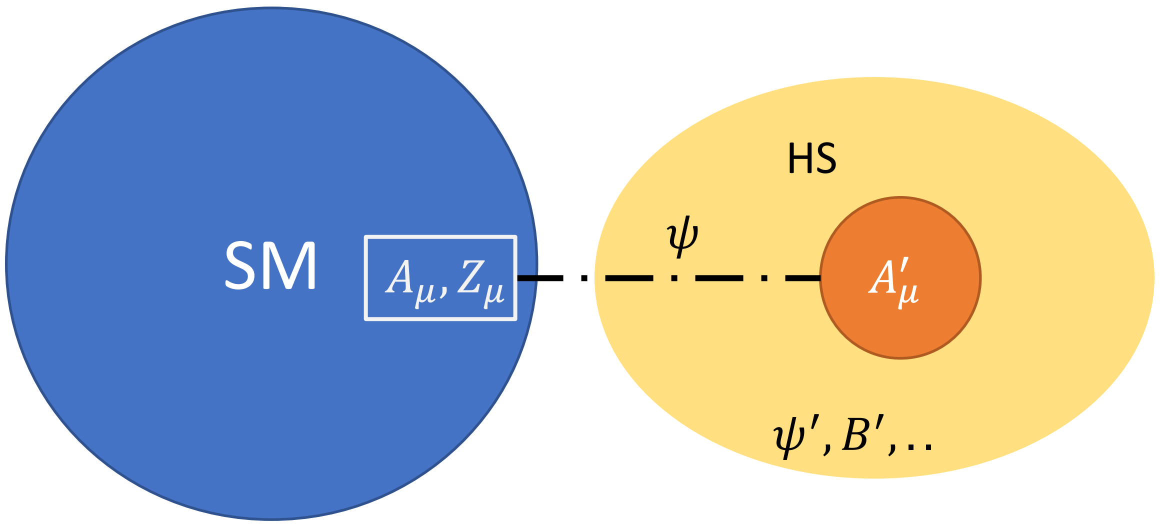

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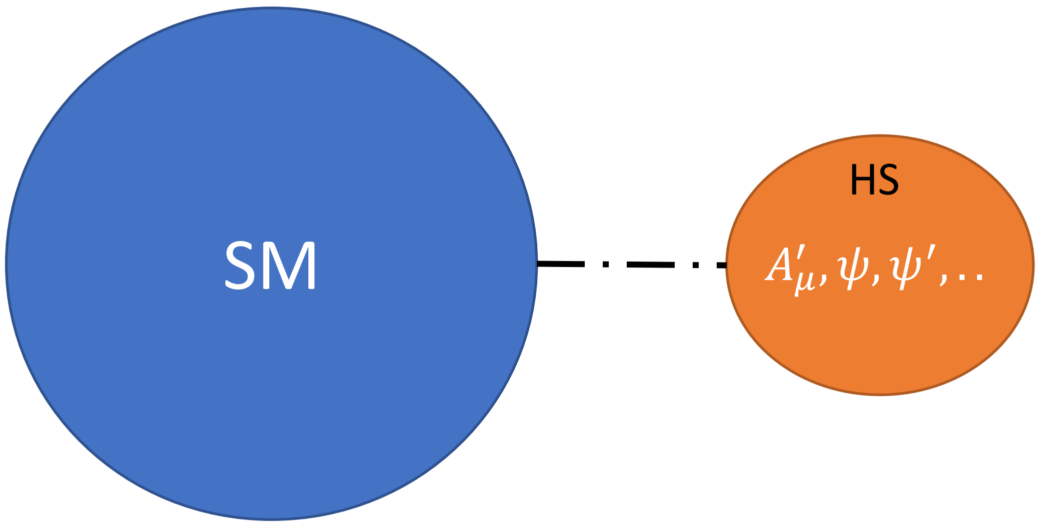
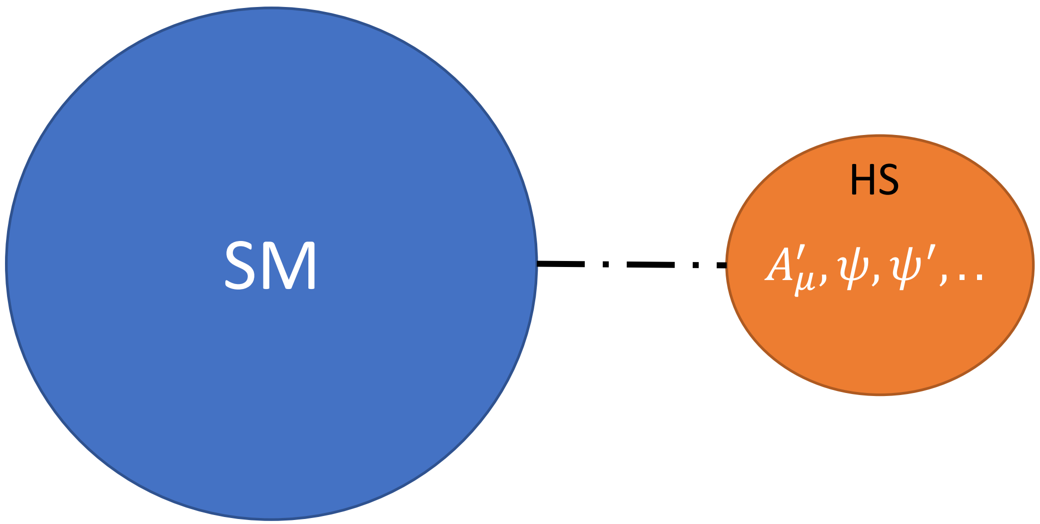
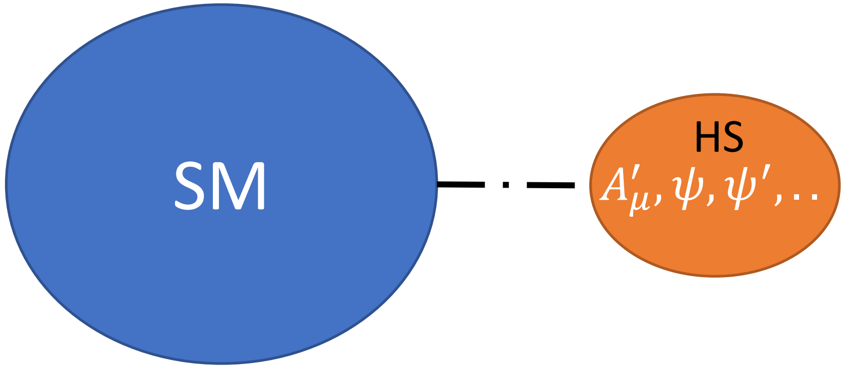


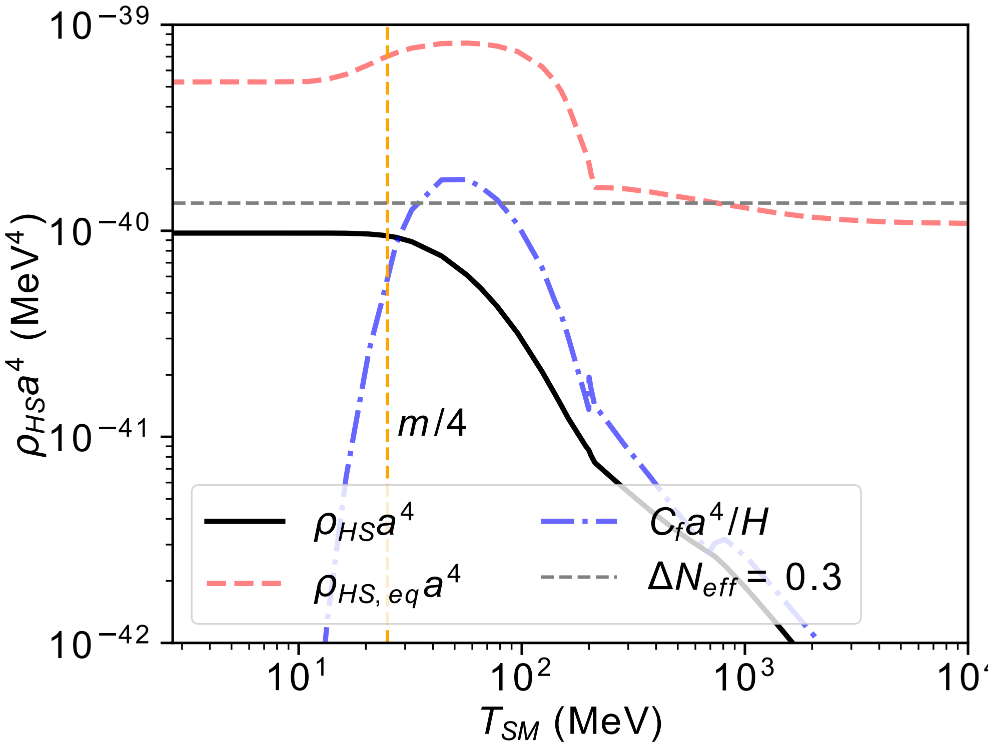
Extending to general hidden sector



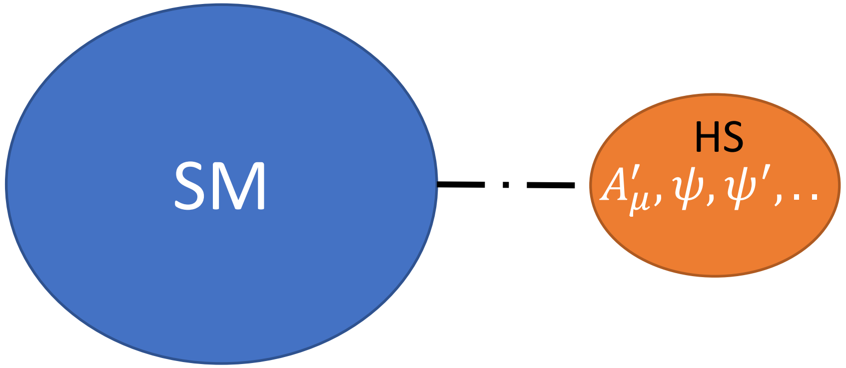
One can calculate a conservative Neff constraint on the millicharge interaction that is independent of details of hidden sector.

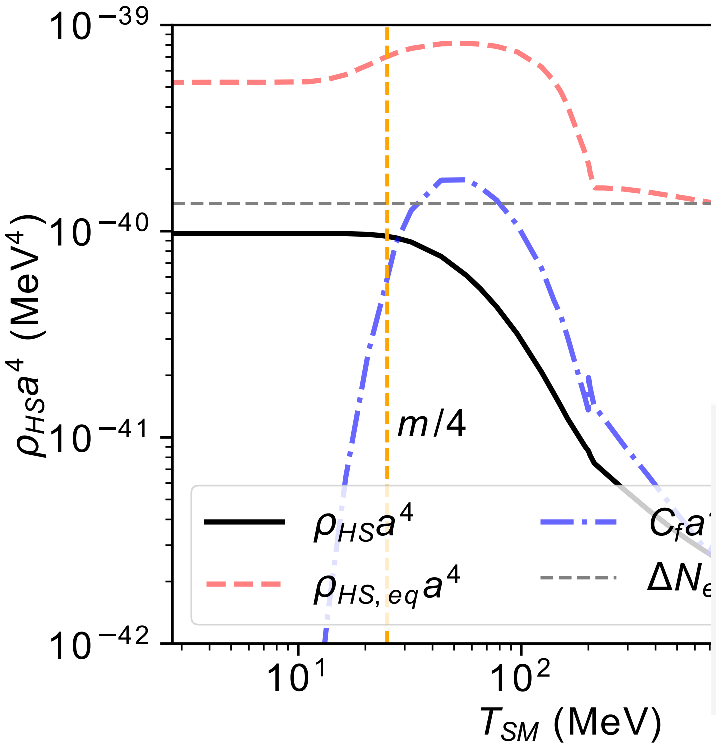
Minimum leaked energy independent of details within HS





Minimum leaked energy independent of details within HS





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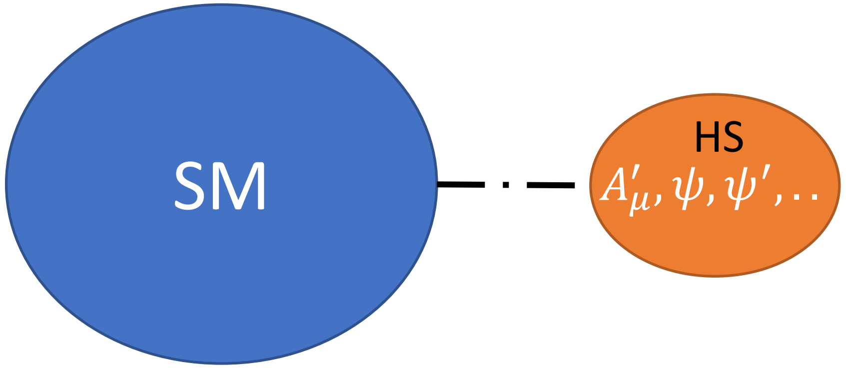

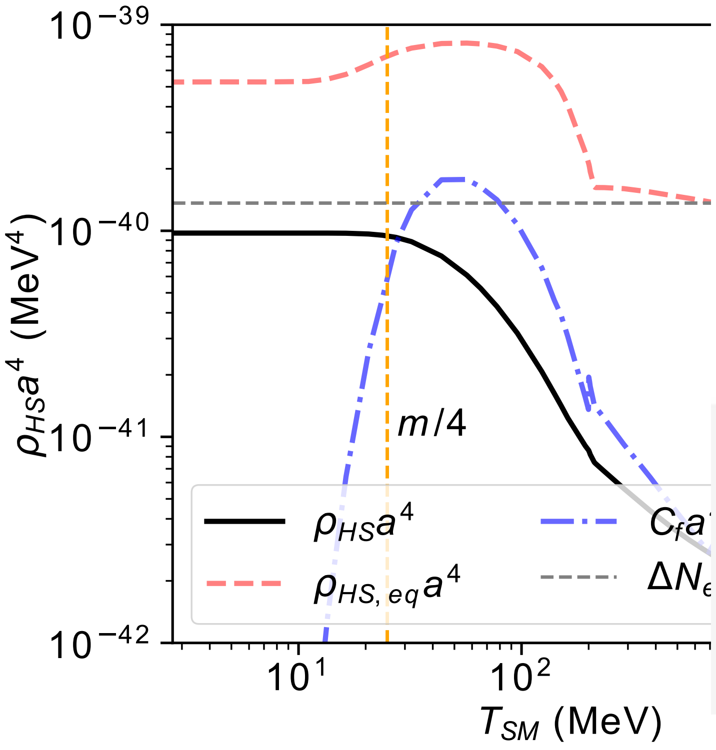

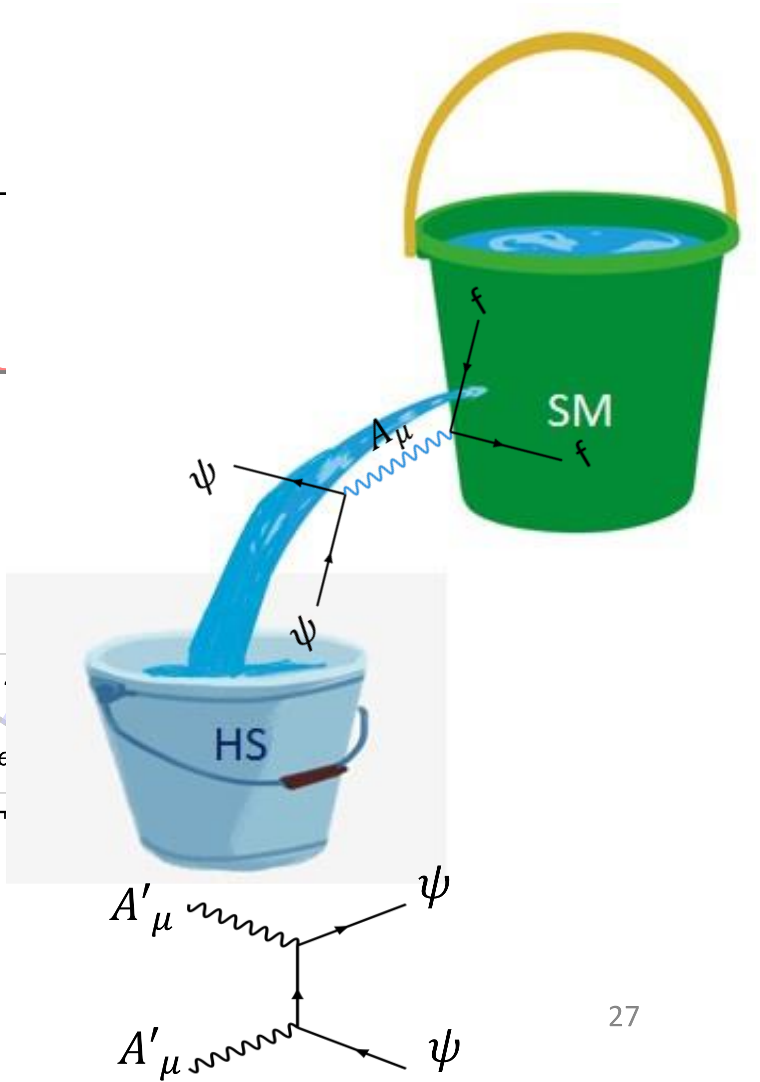

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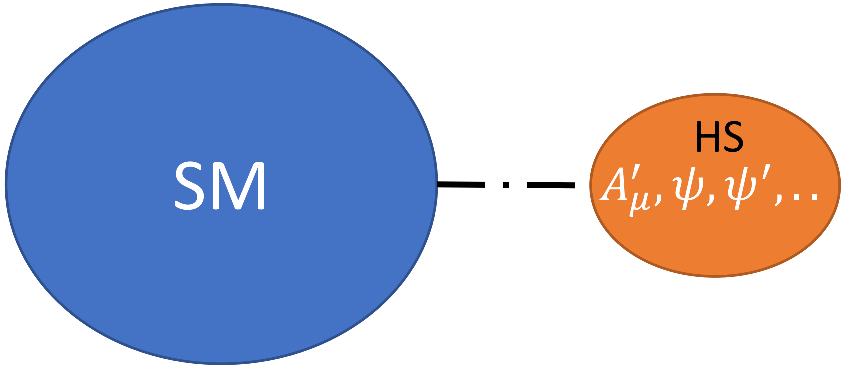
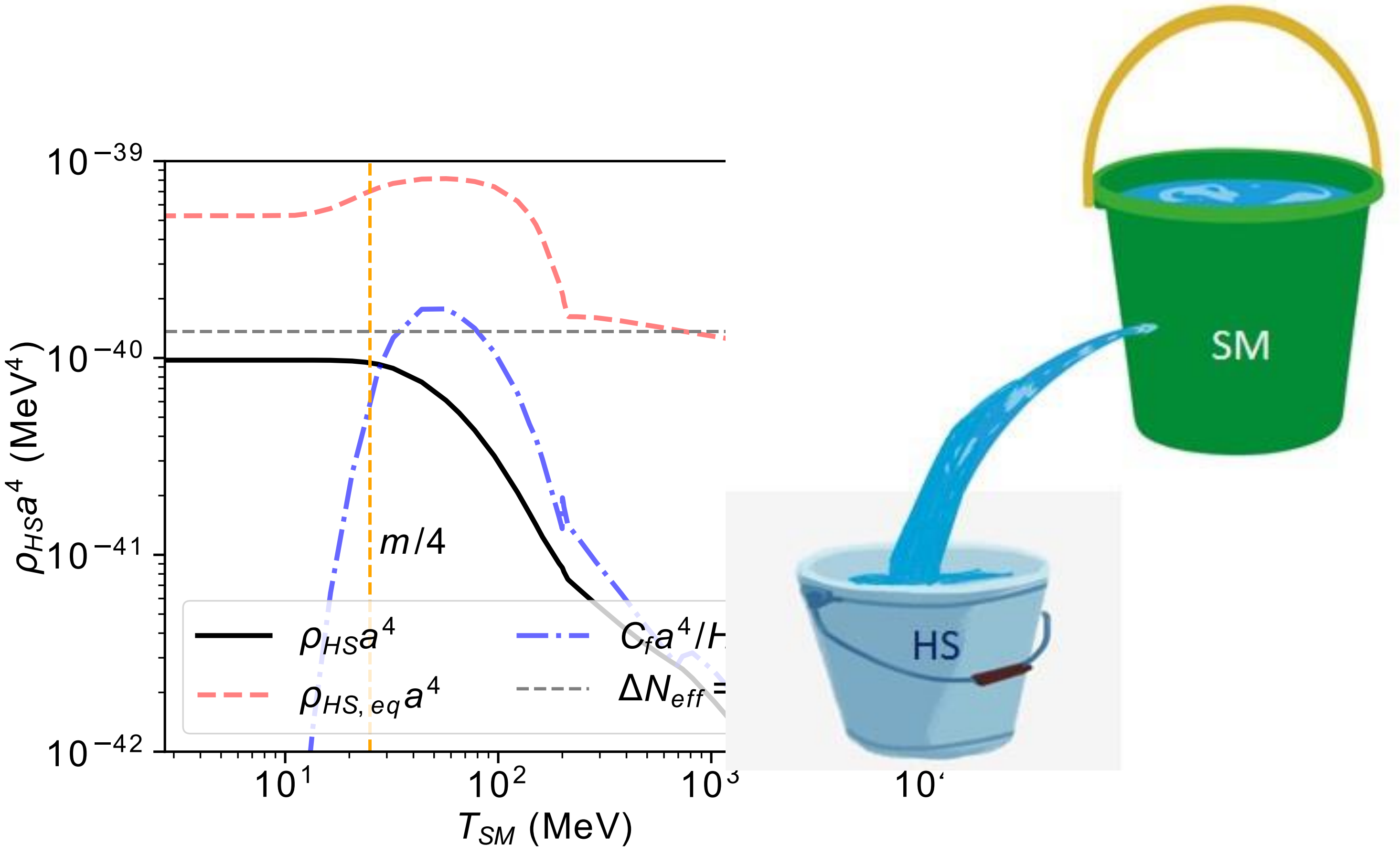


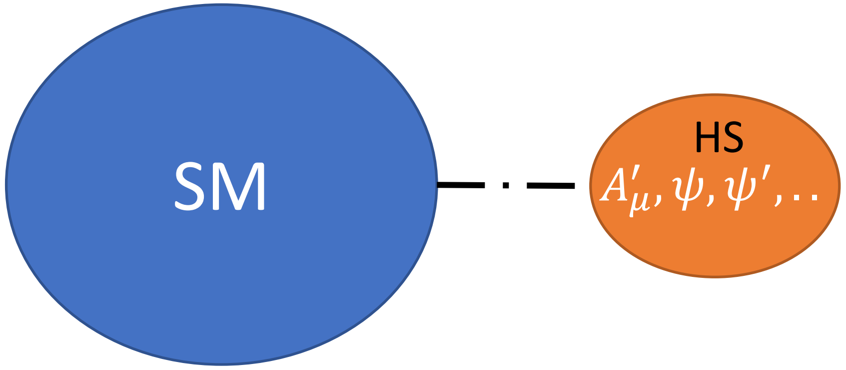
$$\left(\frac{\rho_{HS}}{\rho_{SM}}\right)_{\min} \propto \frac{M_{\rm Pl}}{m_\psi} L$$

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

Leak factor



Minimum leaked energy independent of details within HS



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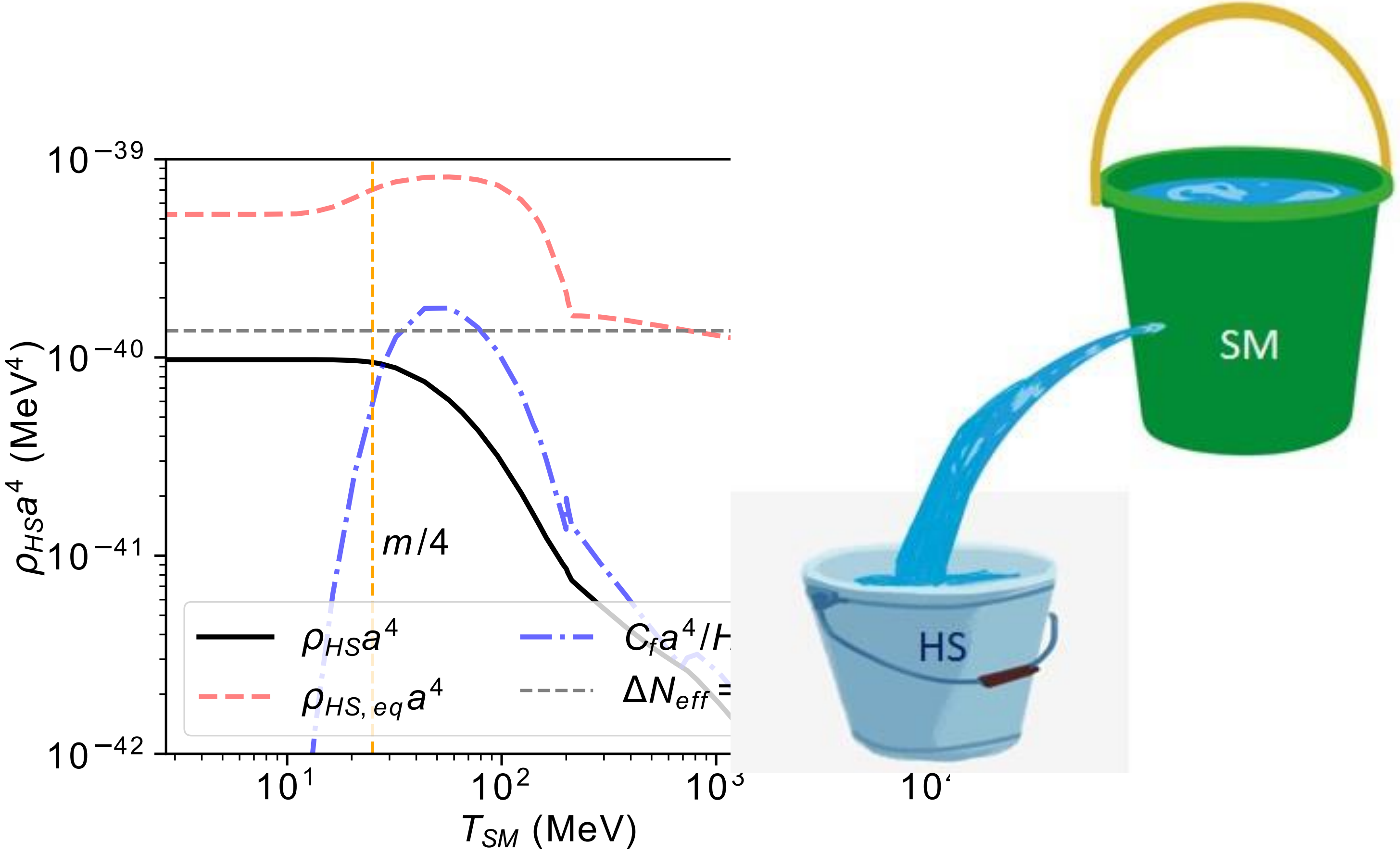
$$L = m_\psi \int ds \, \frac{s - 4m_f^2}{s\sqrt{s}} \sigma_{ff\to\psi\psi} \propto Q^2$$

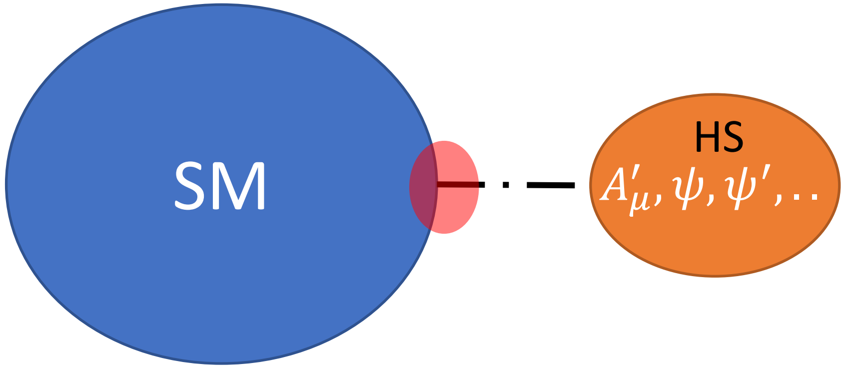
Leak factor

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

Beyond Standard Model

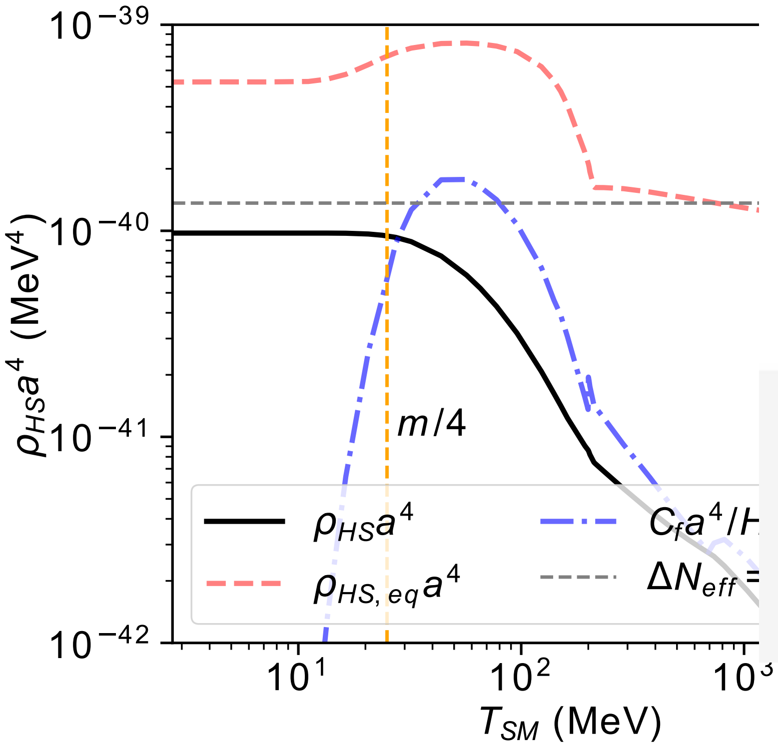


$$\left(\frac{\rho_{HS}}{\rho_{SM}}\right)_{\min} \propto \frac{M_{\rm Pl}}{m_\psi} L$$

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

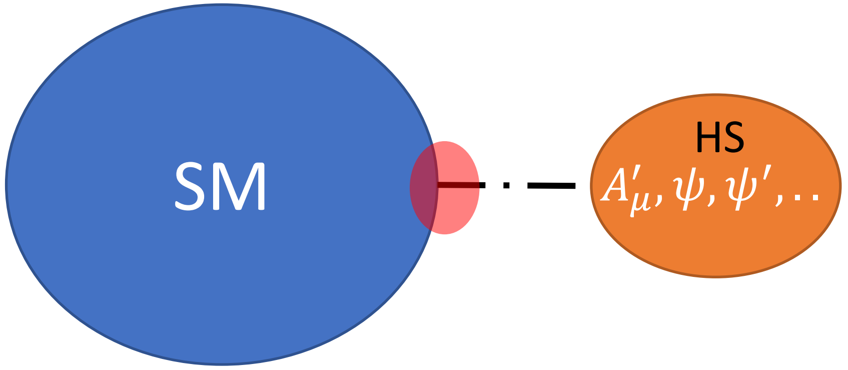
Leak factor

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



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

Beyond Standard Model

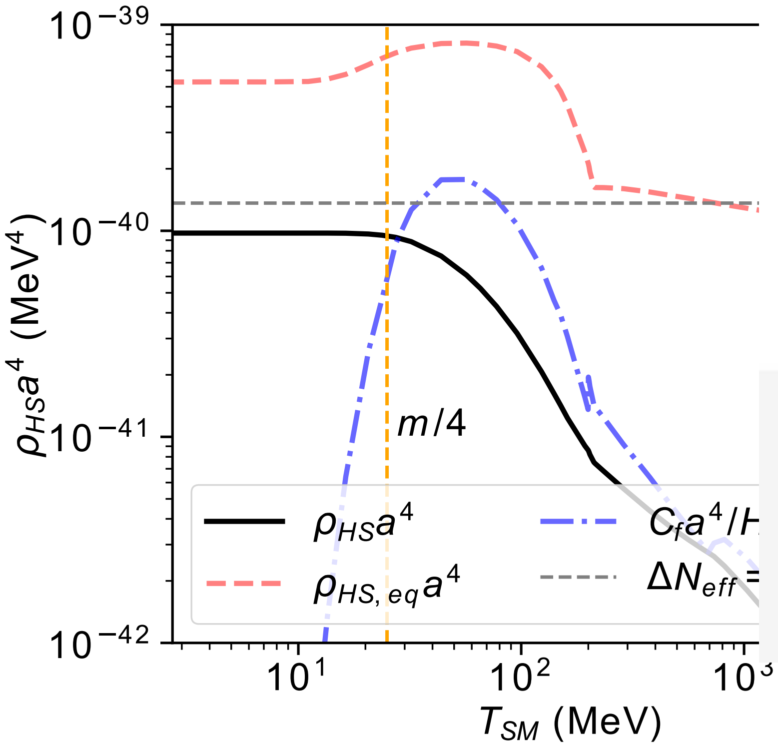


$$\left(\frac{\rho_{HS}}{\rho_{SM}}\right)_{\min} \propto \frac{M_{\rm Pl}}{m_\psi} L$$

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

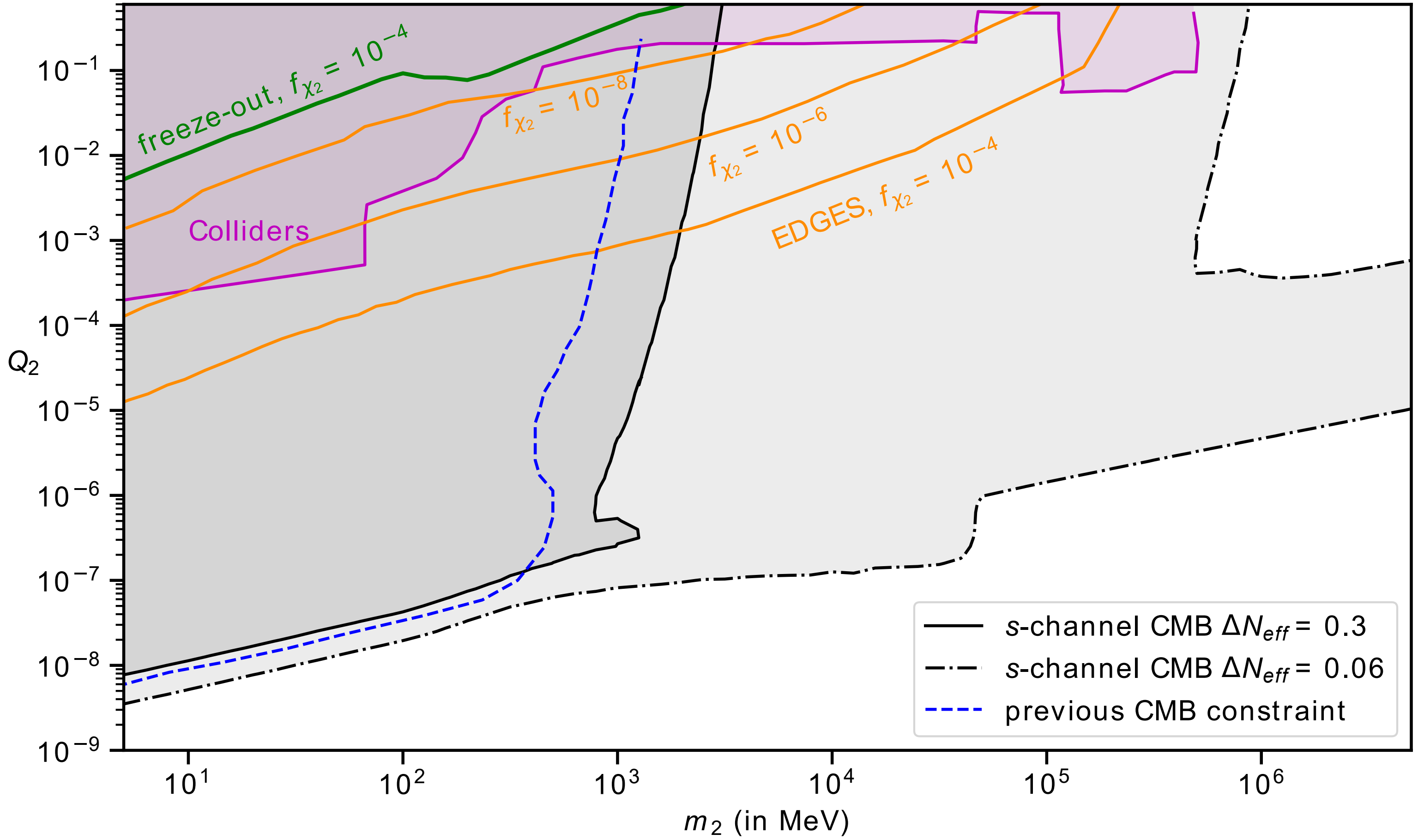
Leak factor

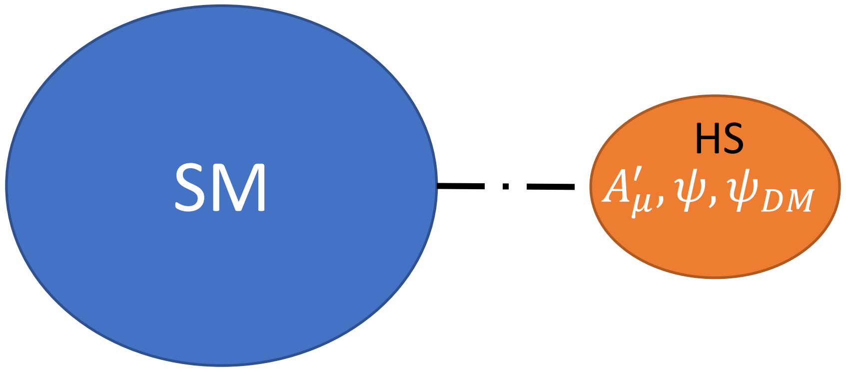
Independent of g_{HS} or T_{HS} or value of dark charge.



$$L < g_*^{3/4}(m)\, g_*^{1/3}\left(\frac{m}{4}\right) \frac{m/4}{M_{\rm Pl}} (\Delta N_{\rm eff})_{\max}$$

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

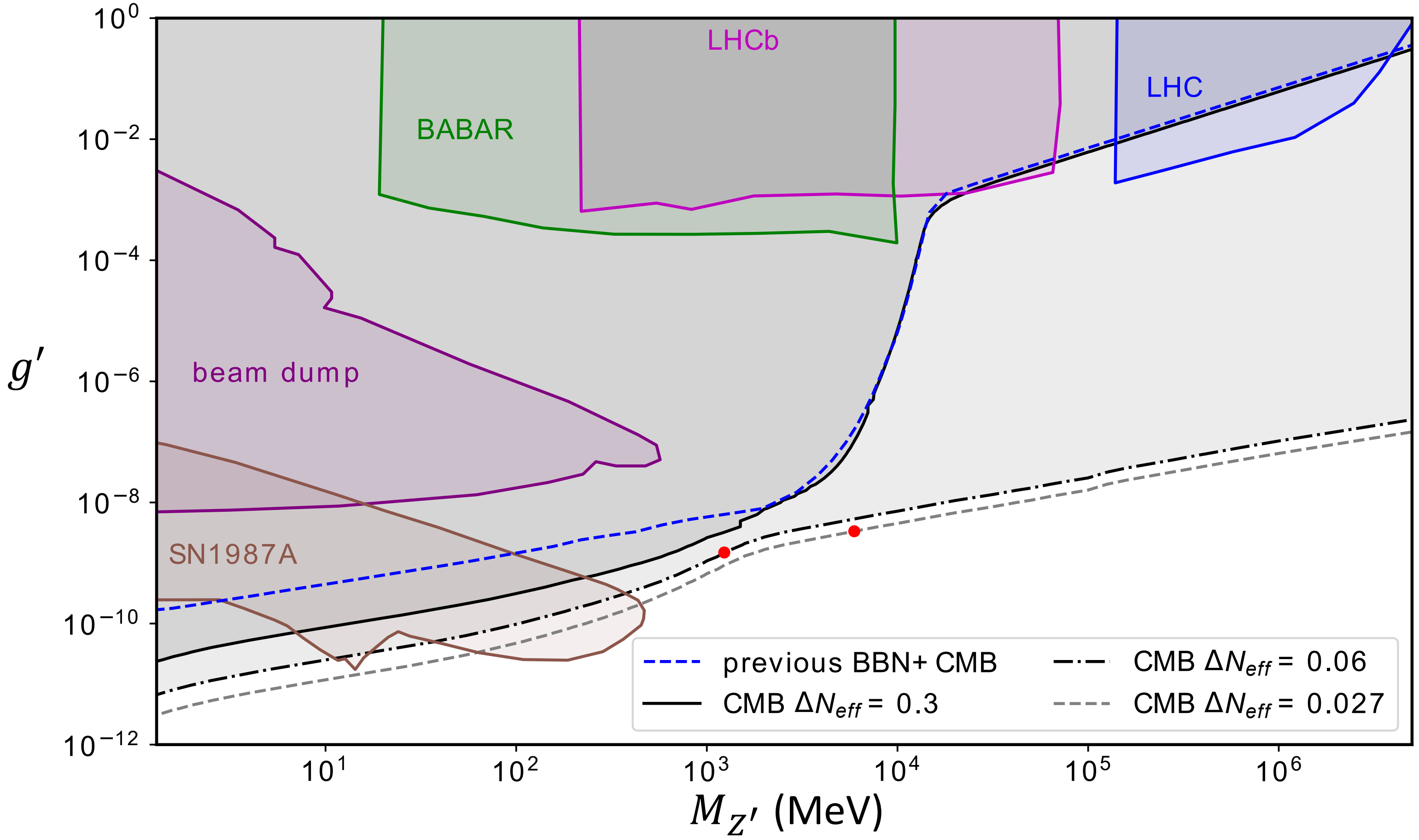


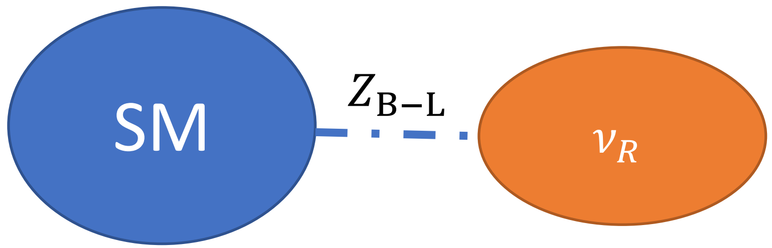


H. Liu, N. J. Outmezguine, D. Redigolo, and T. Volansky, Phys. Rev. D 100 no. 12, (2019) 123011.

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

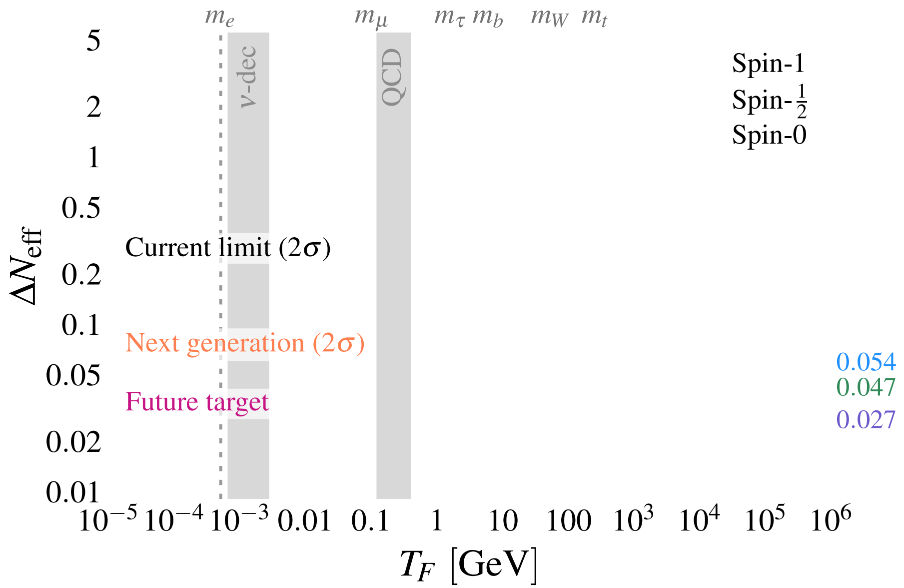
$$L_{int} \supset -\frac{1}{4}F'_{\mu\nu}F^{\mu\nu'} + g'Z'_\mu J^\mu_{B-L,SM} - g'Z'_\mu \sum_i \bar{\nu}_{R,i}\gamma^\mu \nu_{R,i} + \frac{1}{2}M^2_{Z'}Z'^\mu Z'_\mu$$

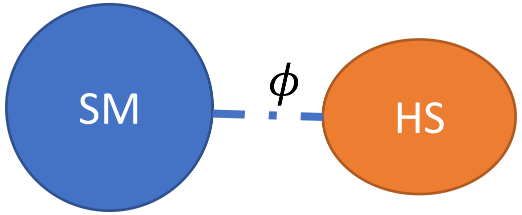


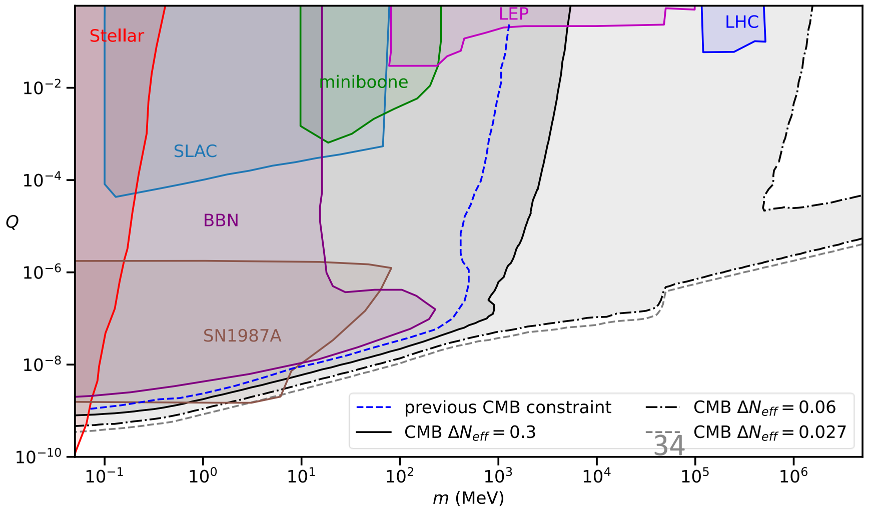


Summary

- With improving Neff measurements, we should interpret them as constraints on portal interactions with out-of-equilibrium sectors
- $N_{\rm eff}$ 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: $L < g_*^{3/4}(4\Lambda)\, g_*^{1/3}(\Lambda)\, \frac{\Lambda}{M_{\rm Pl}}\, (\Delta N_{\rm eff})_{\max}$

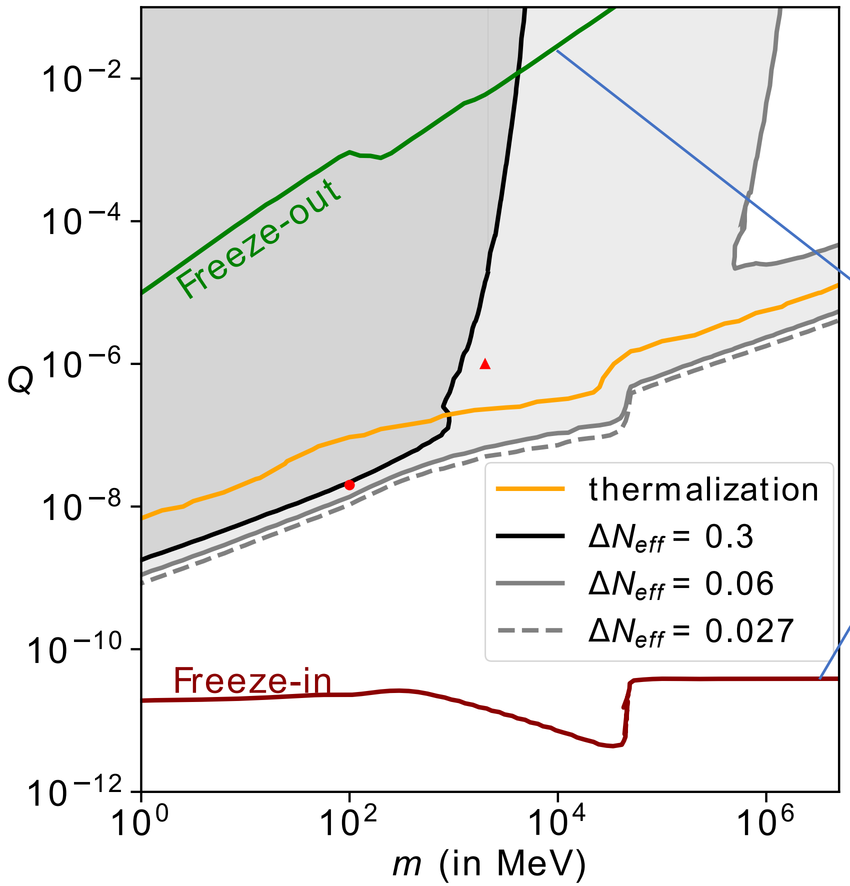






Backup slides

Millicharged particles must dominantly annihilate into dark photons



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