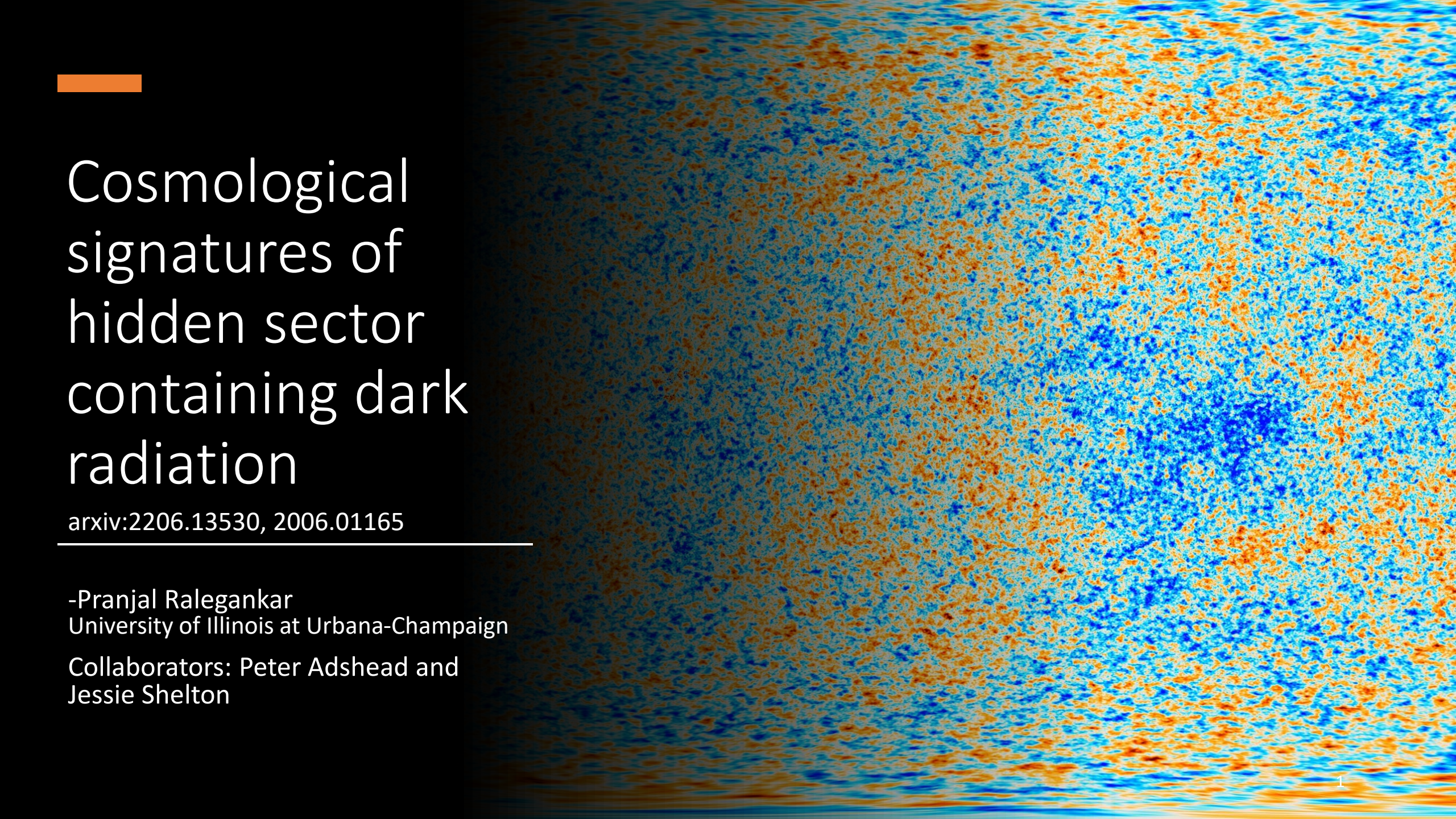
Cosmological signatures of hidden sector containing dark radiation

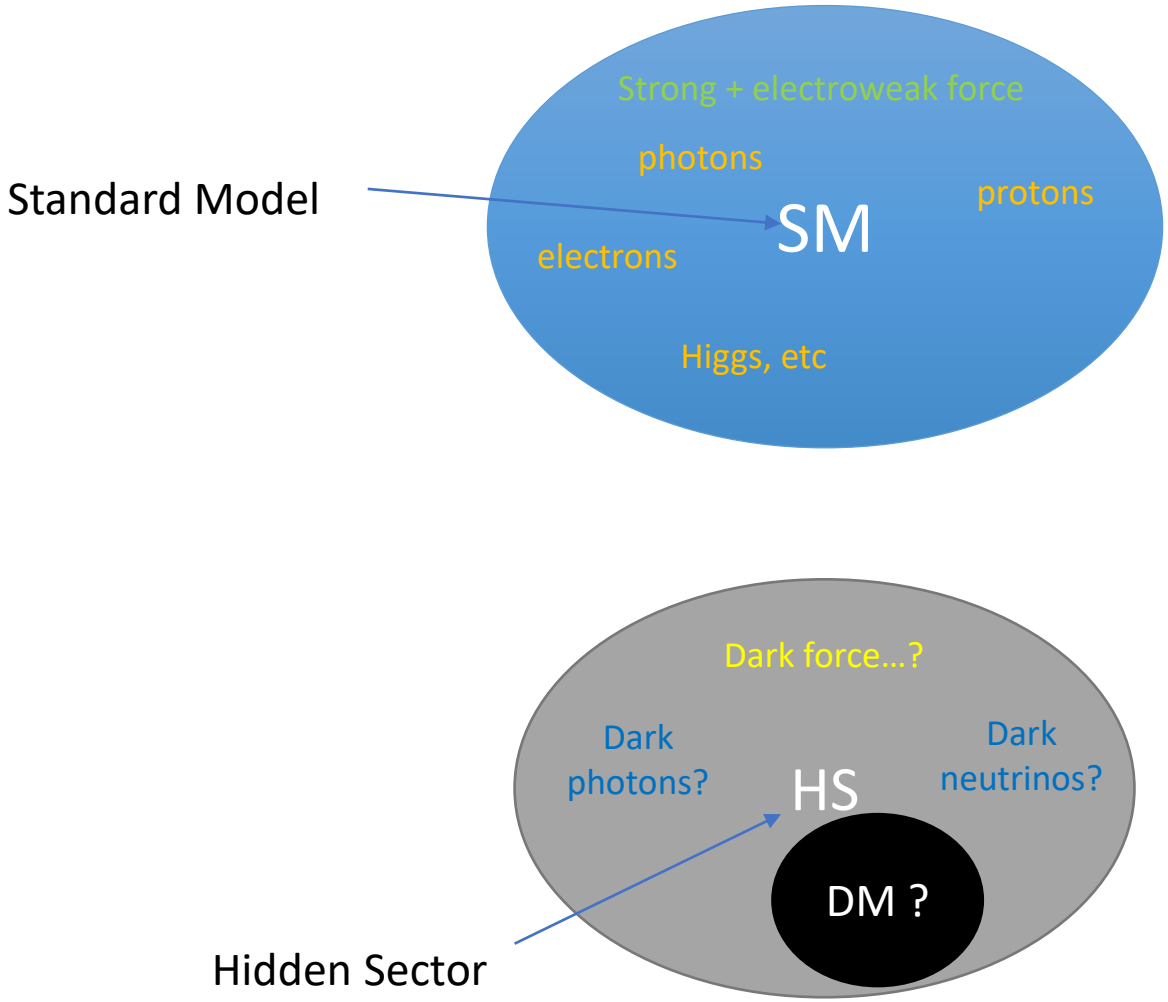
arxiv:2206.13530, 2006.01165

-Pranjal Ralegankar
University of Illinois at Urbana-Champaign

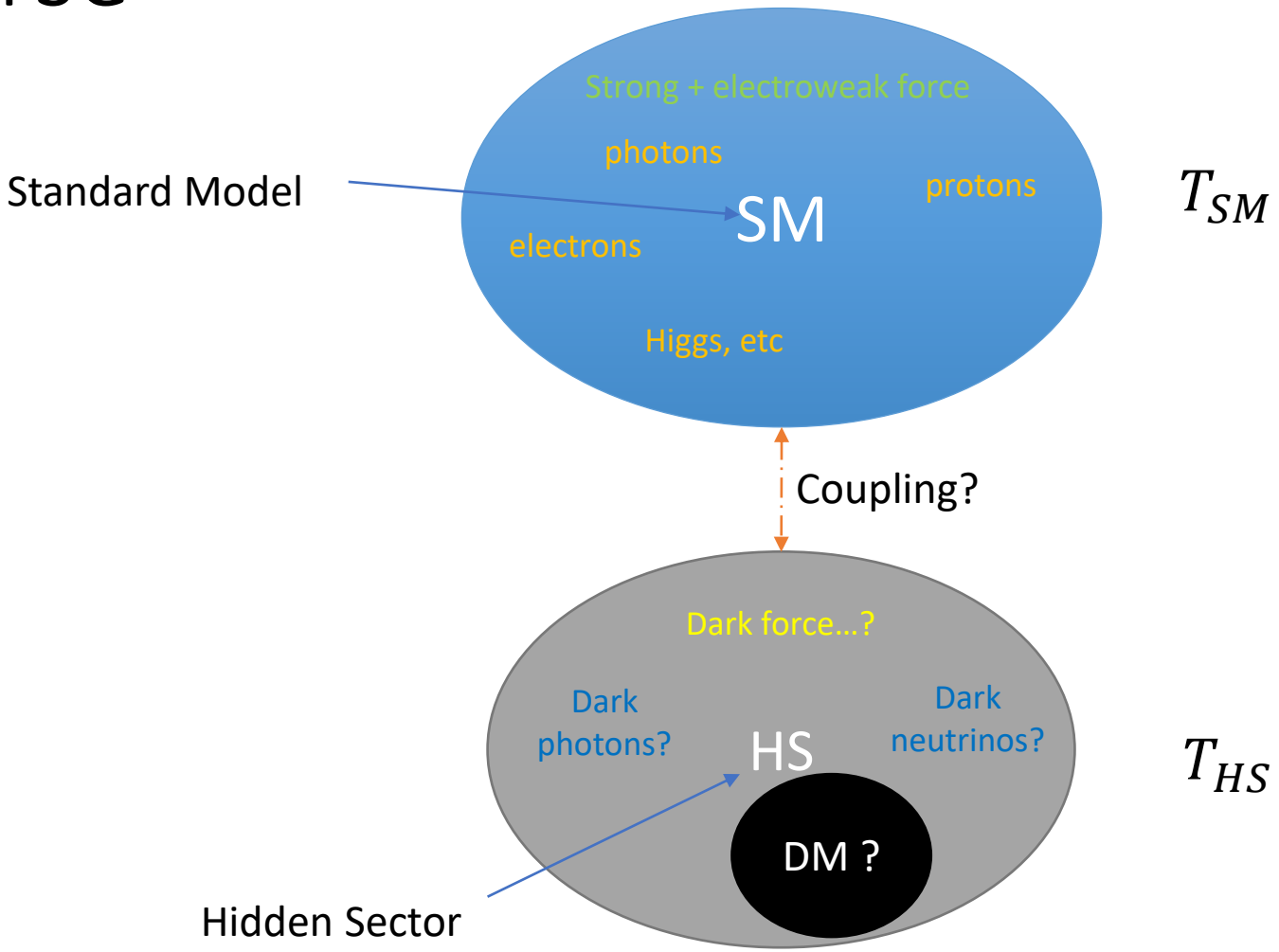
Collaborators: Peter Adshead and Jessie Shelton



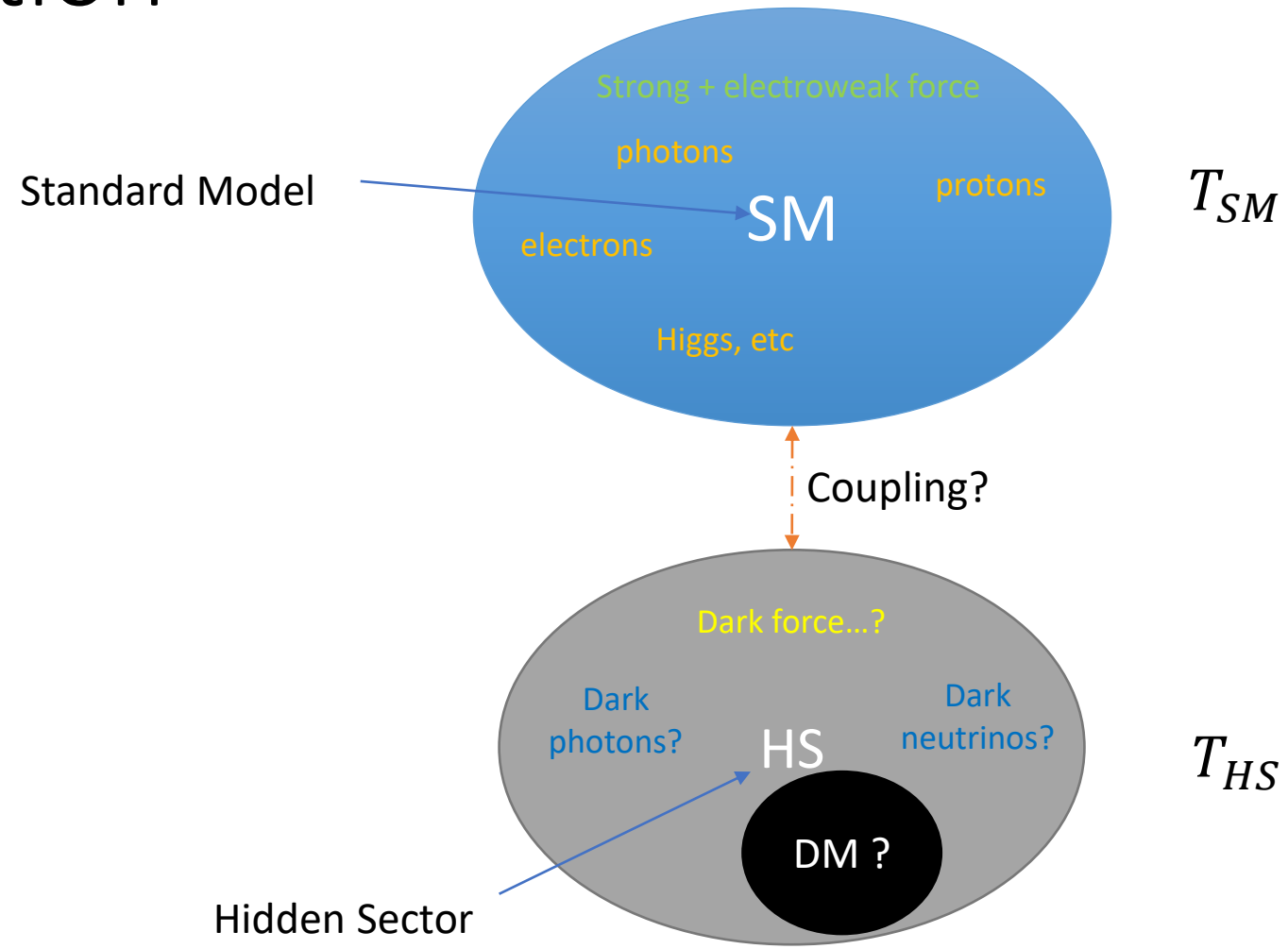
Hidden sector 101



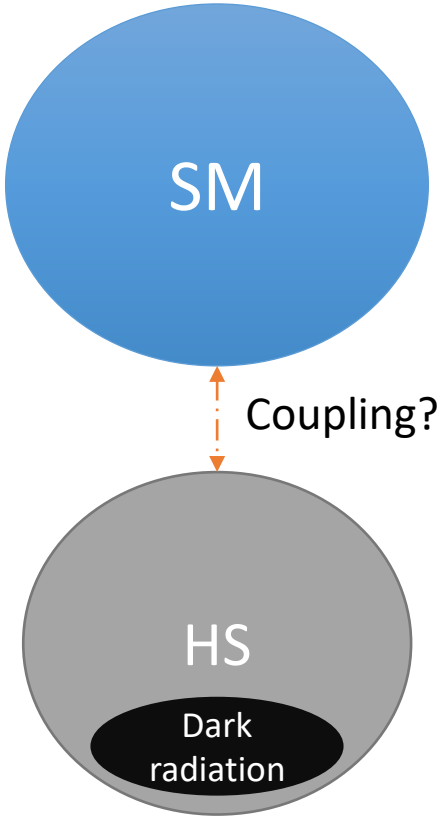
Hidden sector 101: Two baths in the early universe



Hidden sector 101: generically have dark radiation



Goal: Probe models containing dark radiation using cosmological observations



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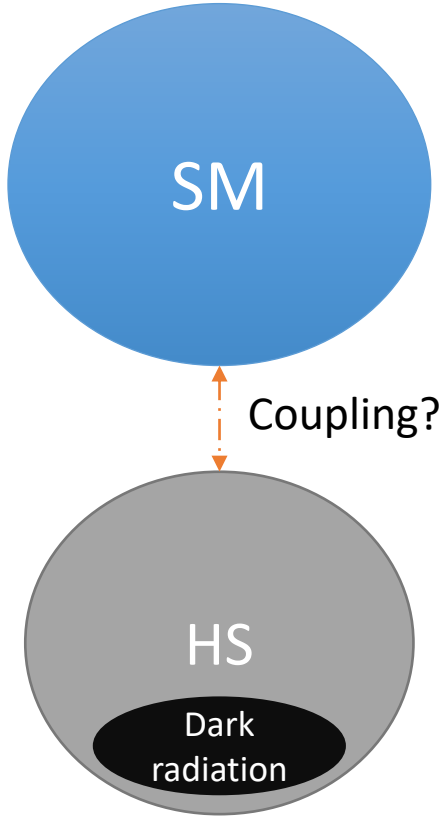

- If no dark radiation detected in future: Constrain portal interactions with hidden sectors
  (Adshead, Ralegankar, Shelton 2022)

- If dark radiation detected: Search for interaction by checking adiabaticity of perturbations during BBN
  (Adshead, Holder, Ralegankar 2020)

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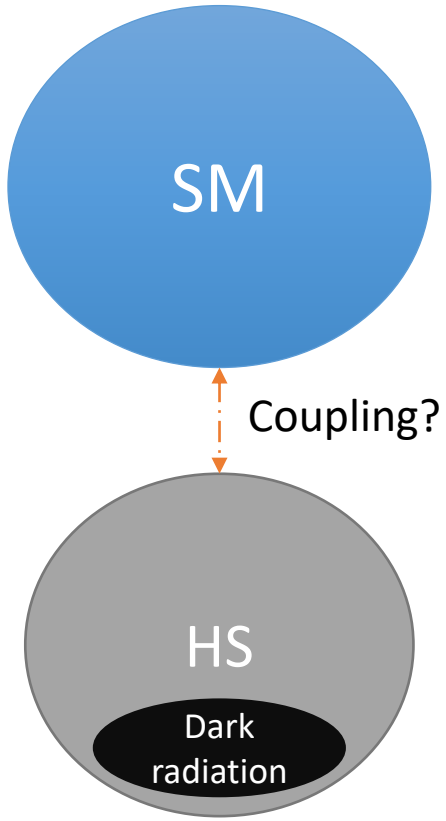

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N_{eff}: A parametrization for dark radiation abundance

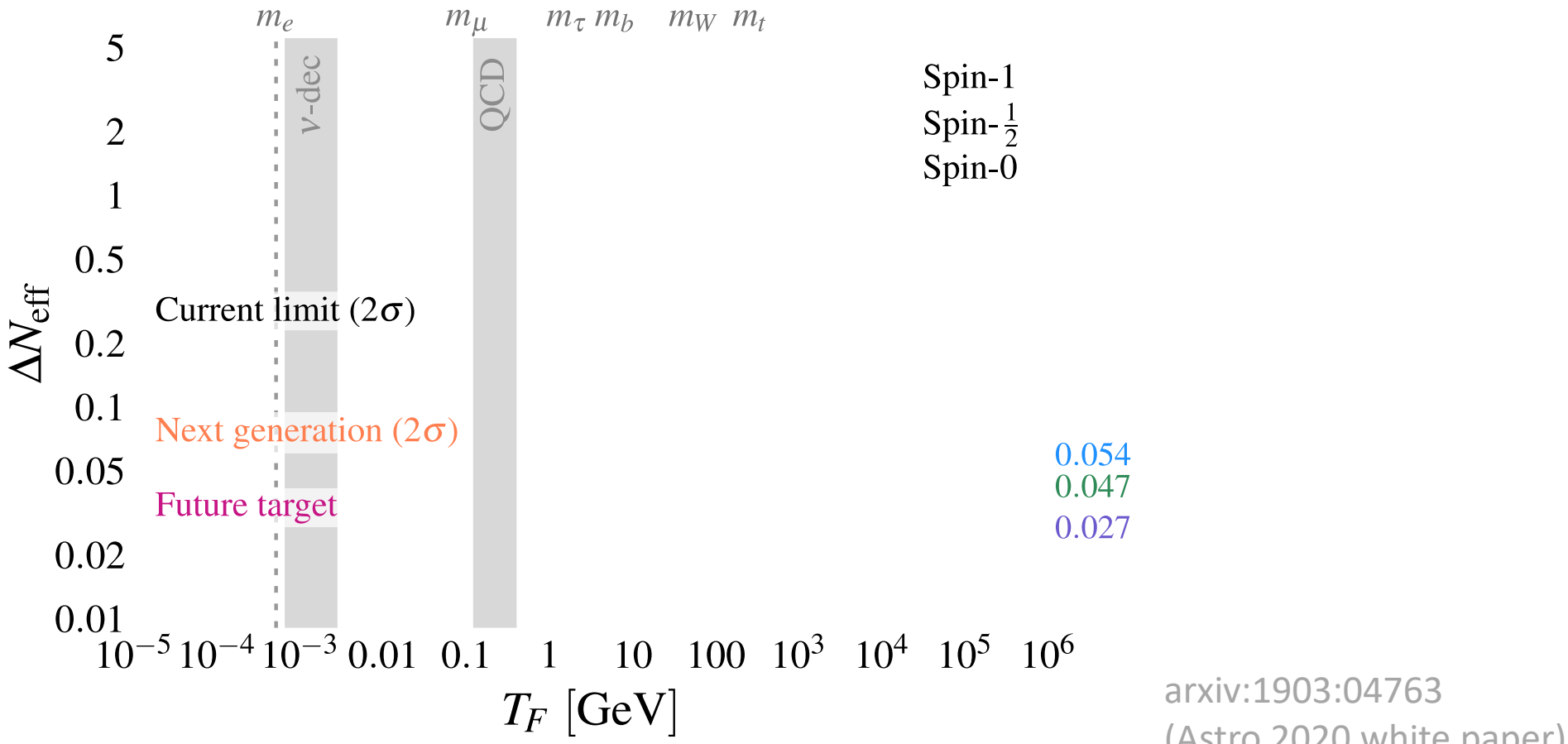
- N_{eff} : effective number of neutrino species

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

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

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

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

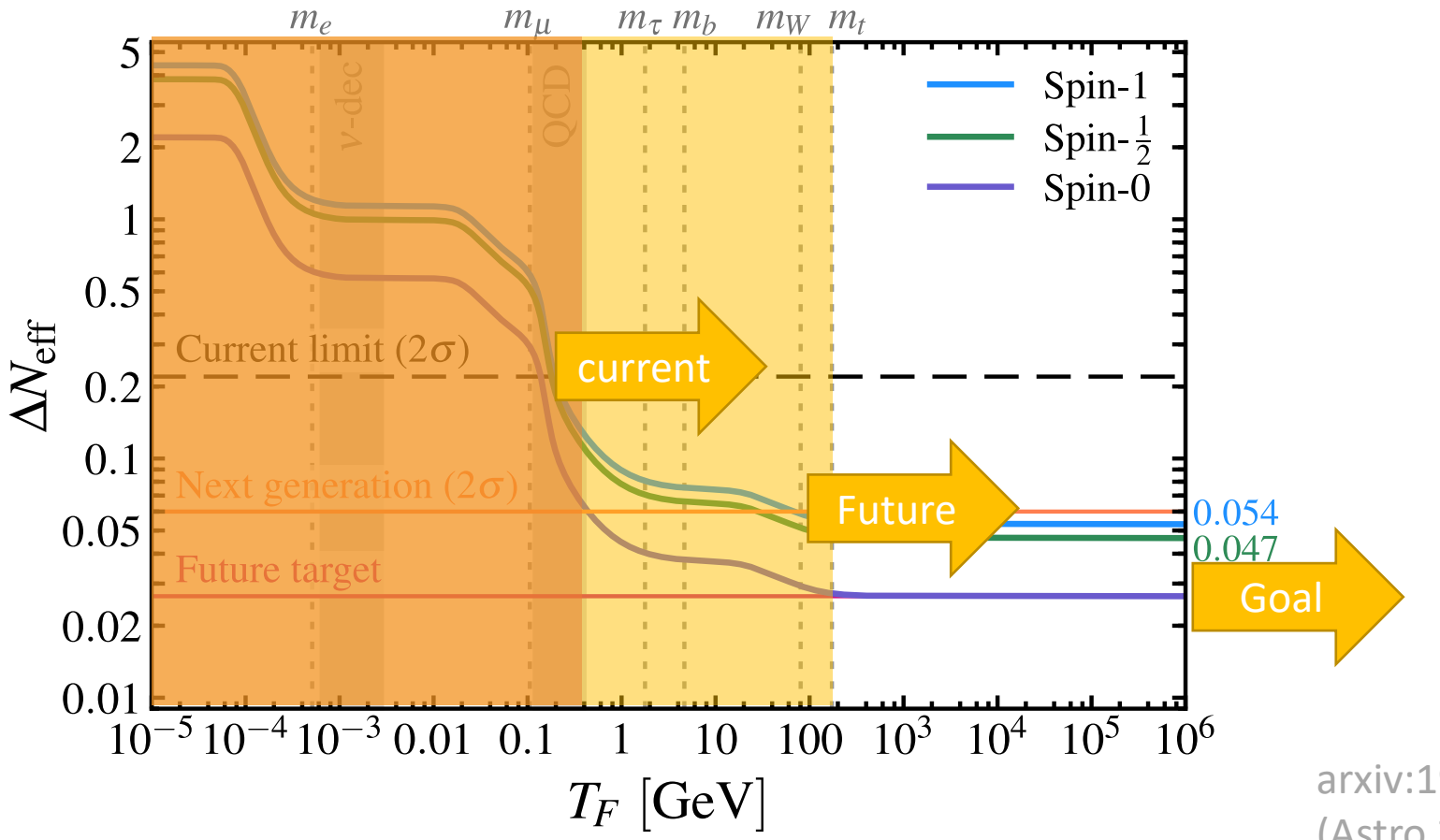


Decoupling temperature of new light particle

arxiv:1903:04763
(Astro 2020 white paper)

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

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



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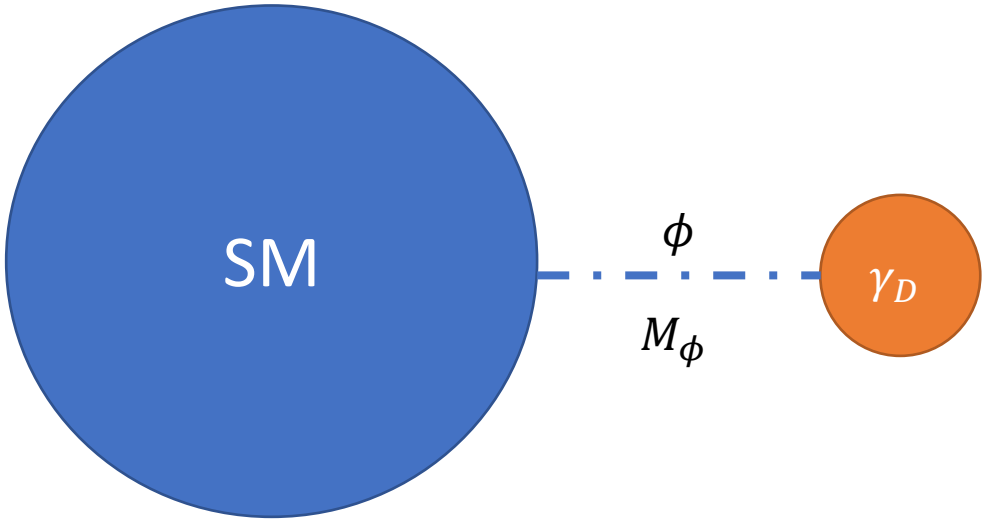
Unified treatment for calculating $N_{\mathbf{eff}}$ constraints on beyond SM interactions

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

Strong Implications for model building with HS containing dark radiation

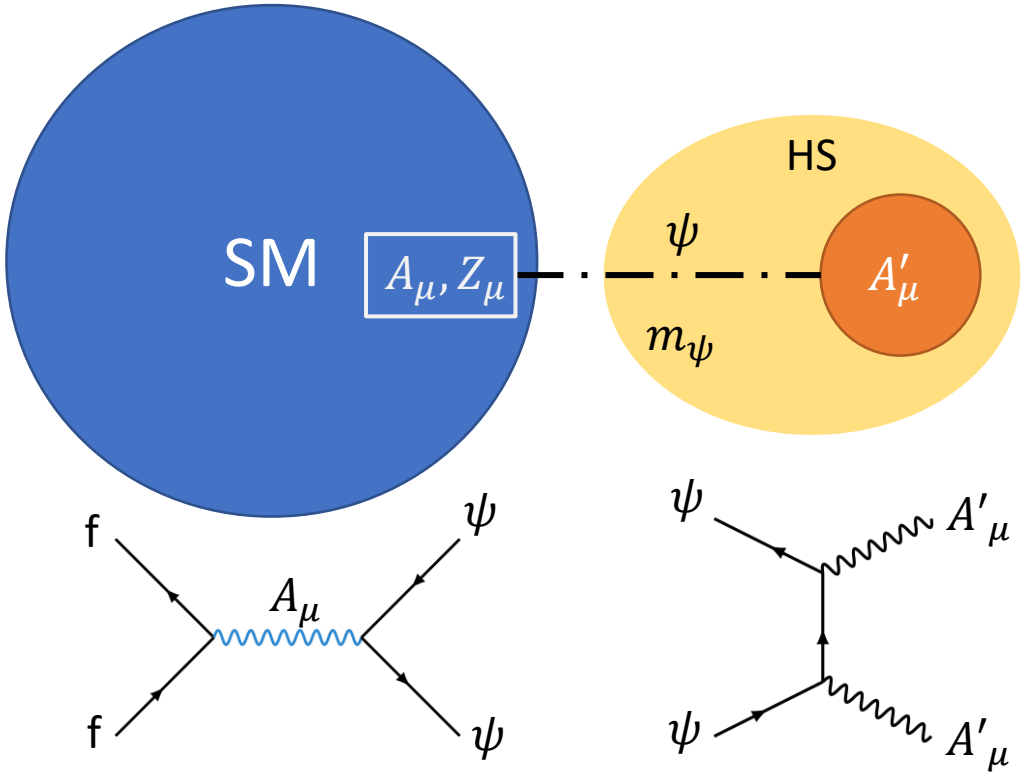
Application of $N_{\mathbf{eff}}$ constraint : Relevant types of interaction



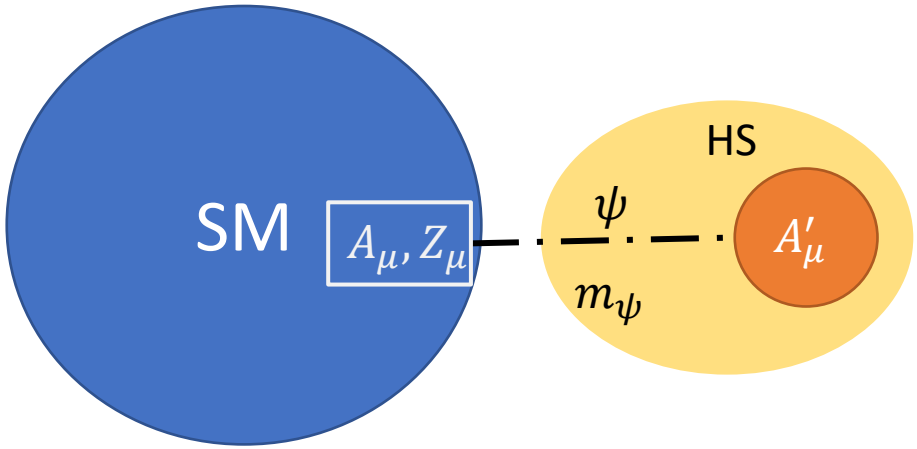
Application of N_{eff} constraint: Millicharged particle example

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

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



Physics behind dark radiation production: Boltzmann equations



Boltzmann equations:

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

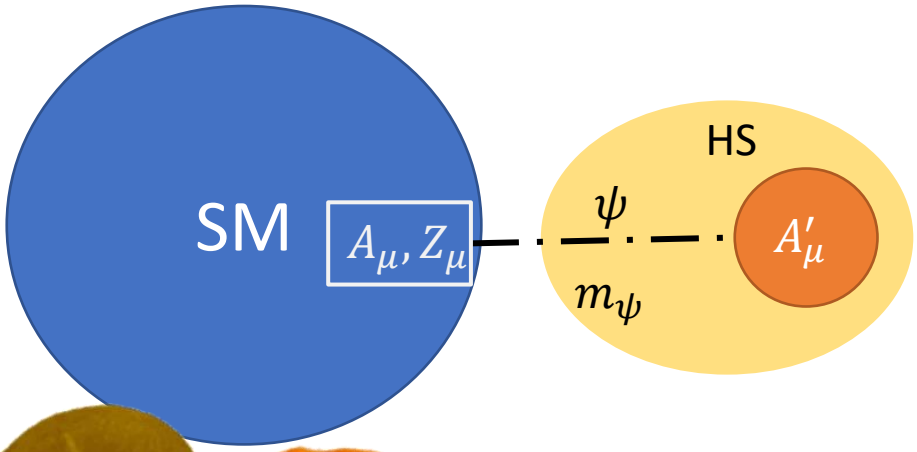
$$\frac{d\rho_{HS}}{dt} + 3H(1 + w_{HS})\rho_{HS} = C$$

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

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

Energy transfer collision term

Physics behind dark radiation production: Boltzmann equations



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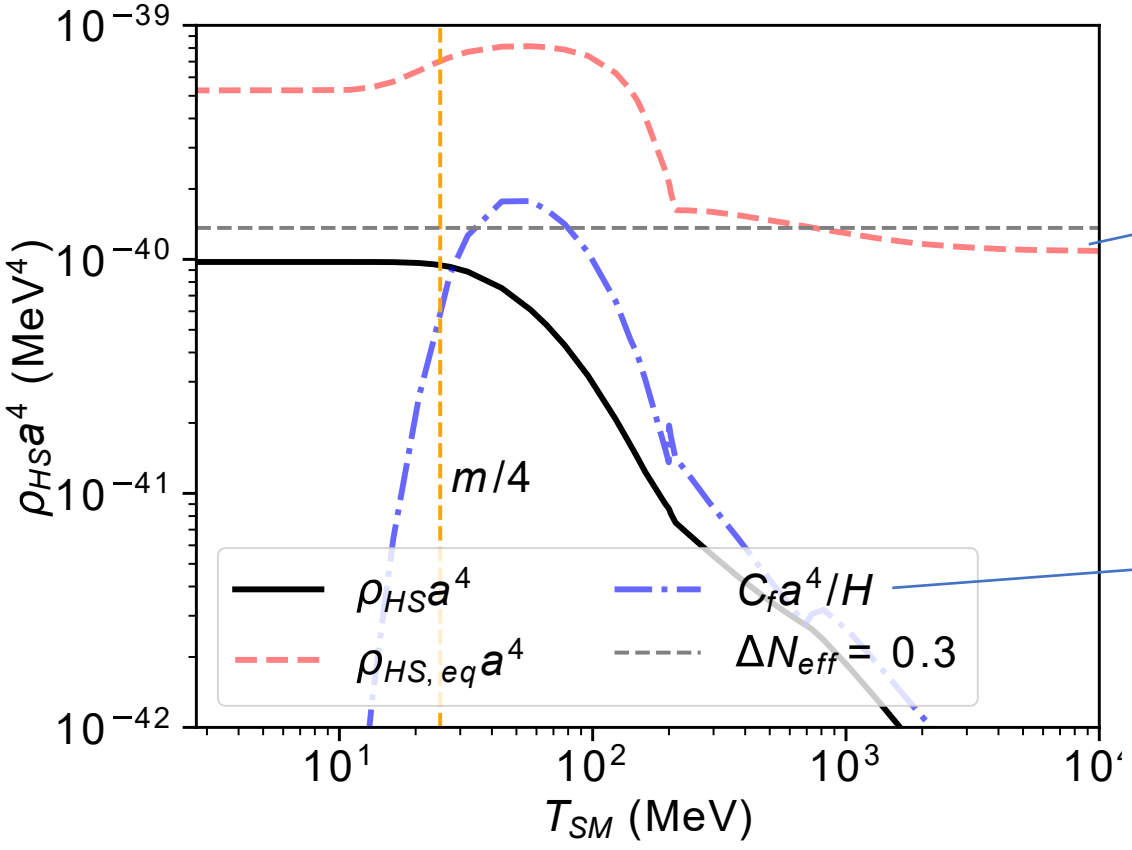
Energy transfer collision term

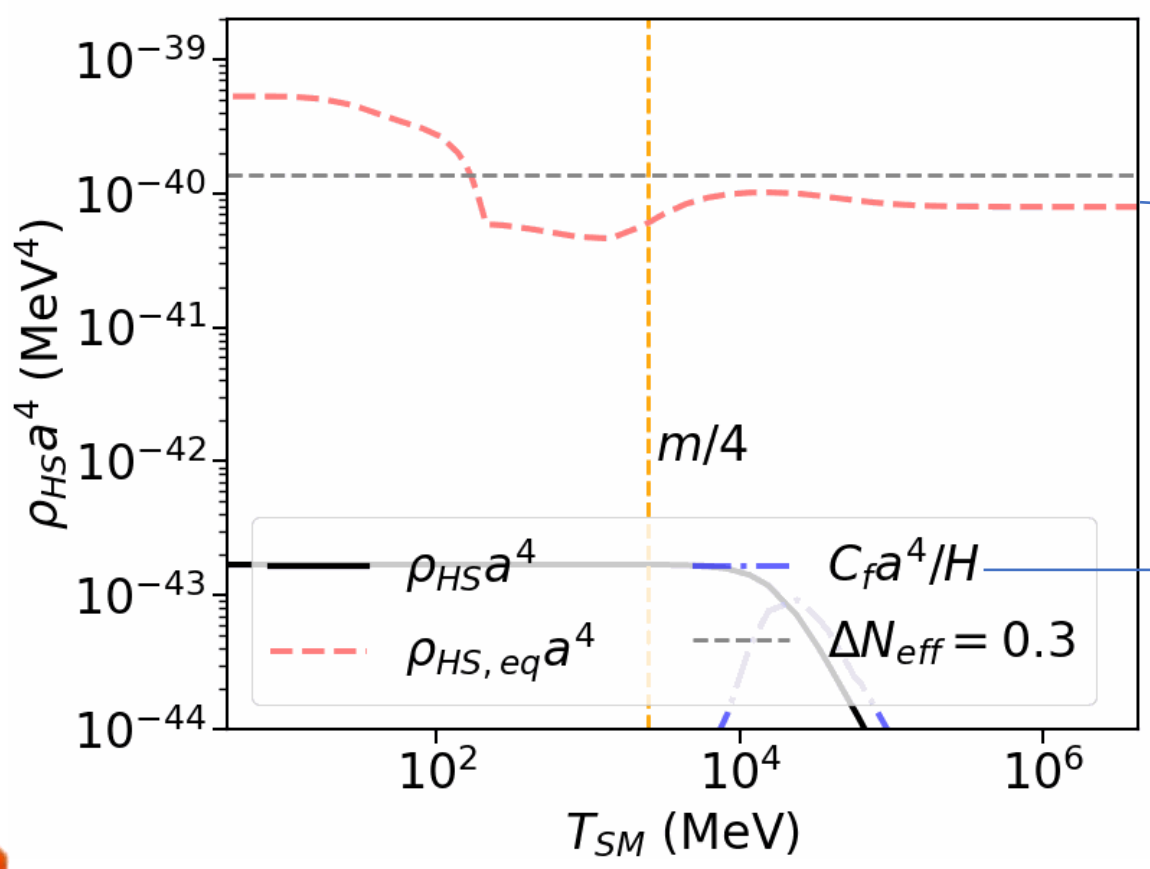
Physics behind dark radiation production: Plots!



If HS is always in equilibrium with the Standard Model plasma

Only the forward part of the collision term

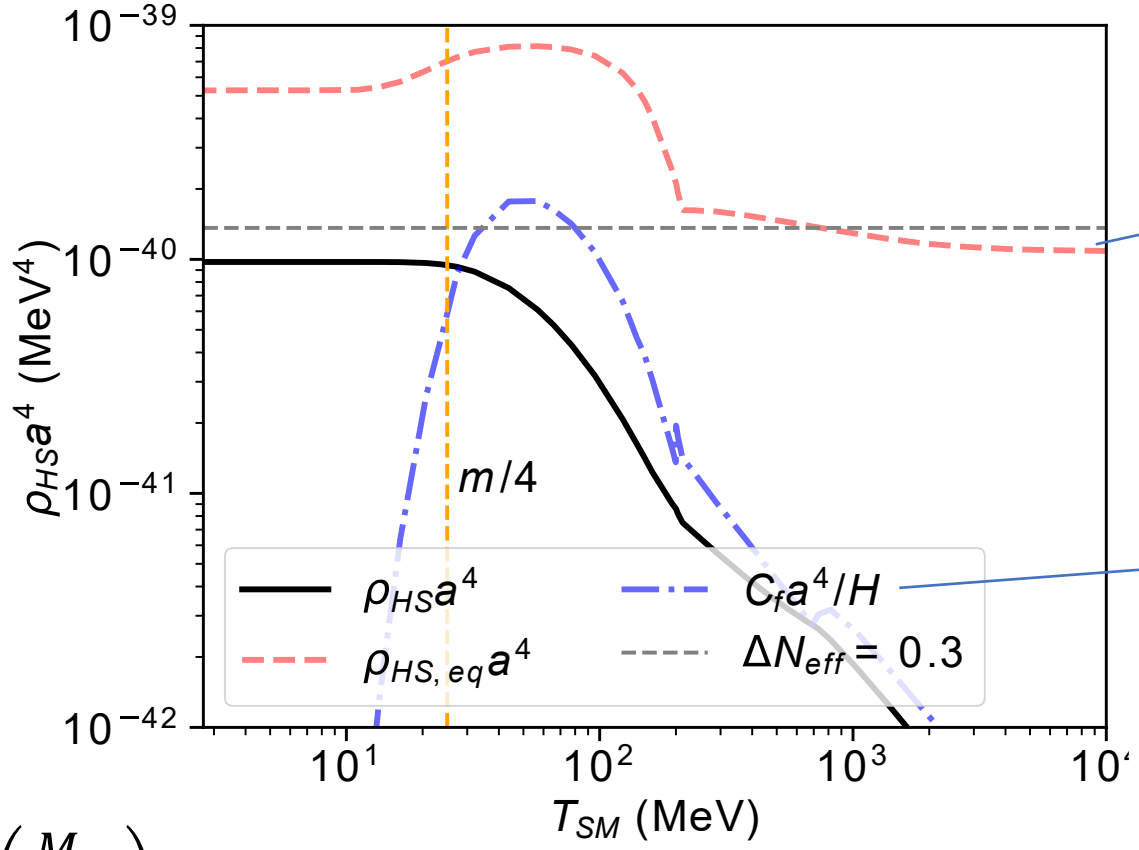
Physics behind dark radiation production: GIF!



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



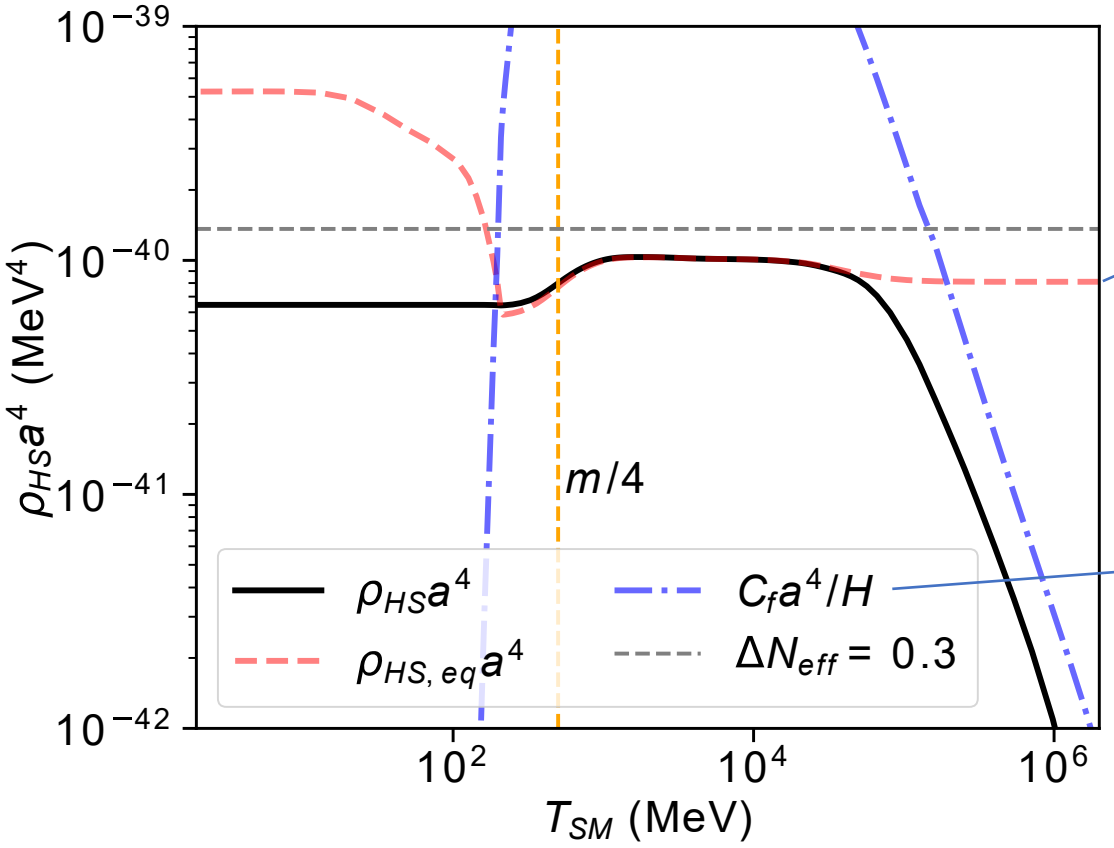
If HS is always in equilibrium with the Standard Model plasma

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



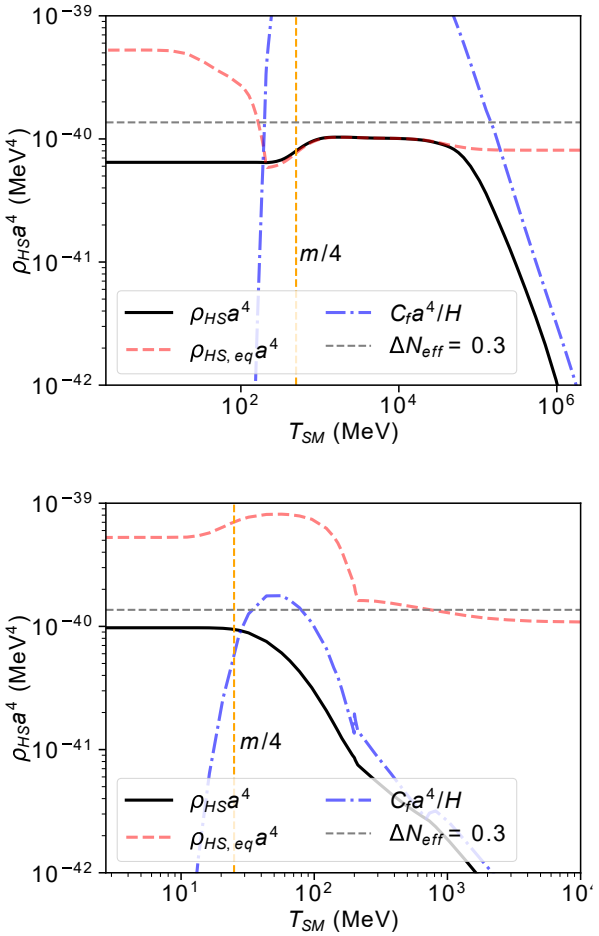
If HS is always in equilibrium with the Standard Model plasma

Only the forward part of the collision term

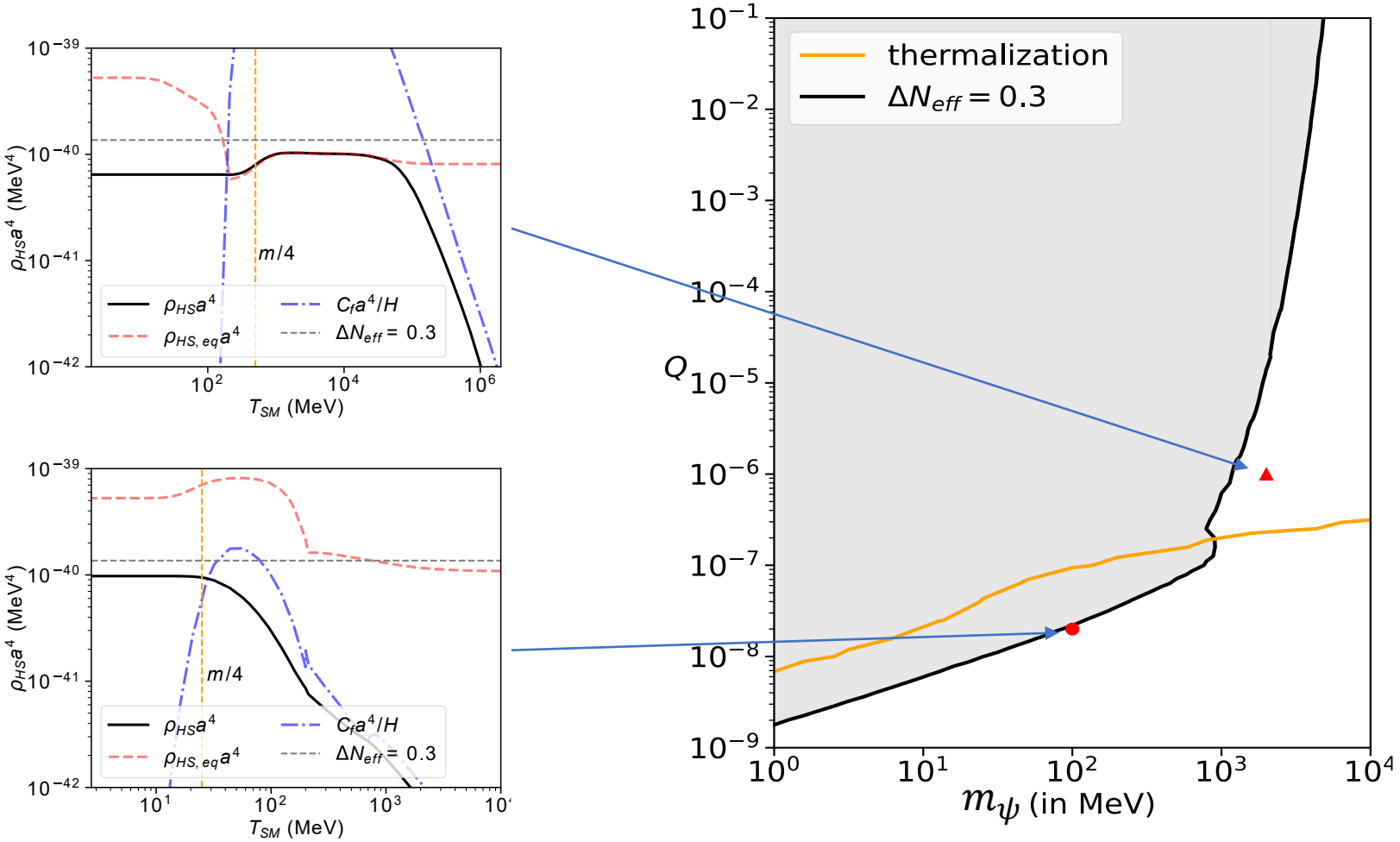
$$\frac{\rho_{HS}}{\rho_{SM}} \propto \frac{g_{HS}}{g_{*SM}(T_d)}$$

Degrees of freedom

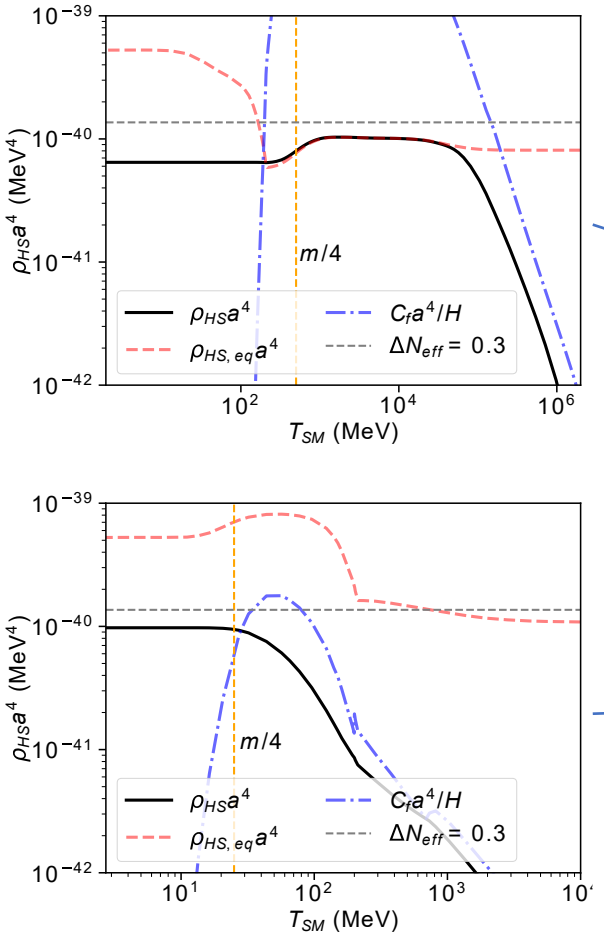
Physics behind dark radiation production: Translating to constraints

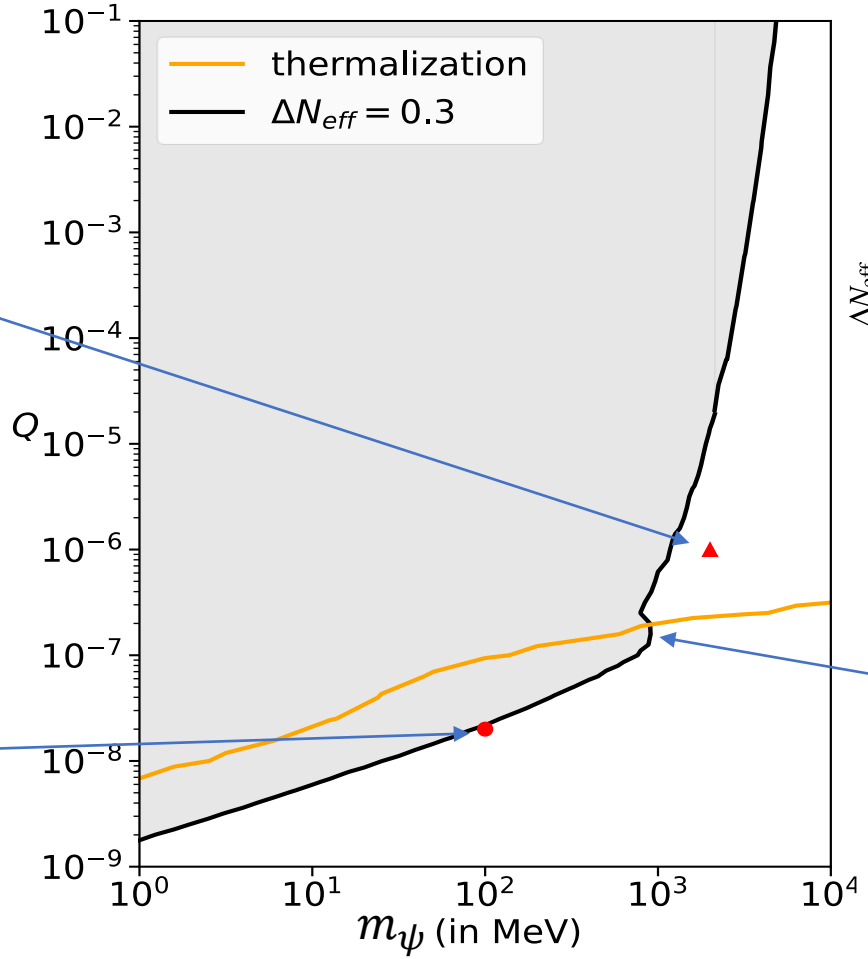


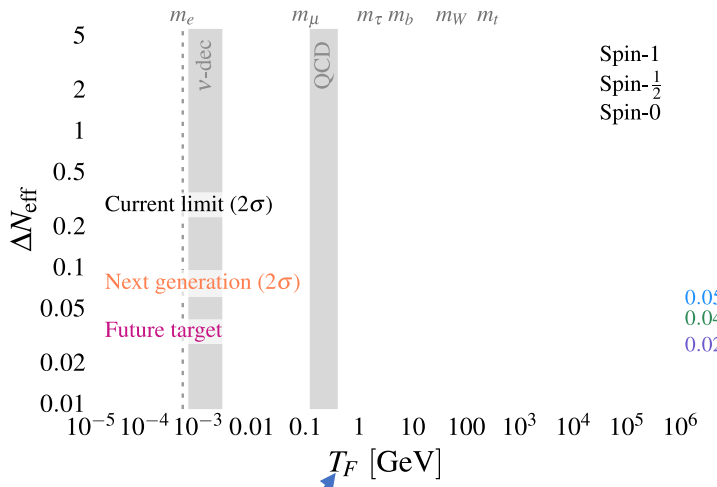
Physics behind dark radiation production : Translating to constraints



Physics behind dark radiation production : Most relevant when thermally decoupled

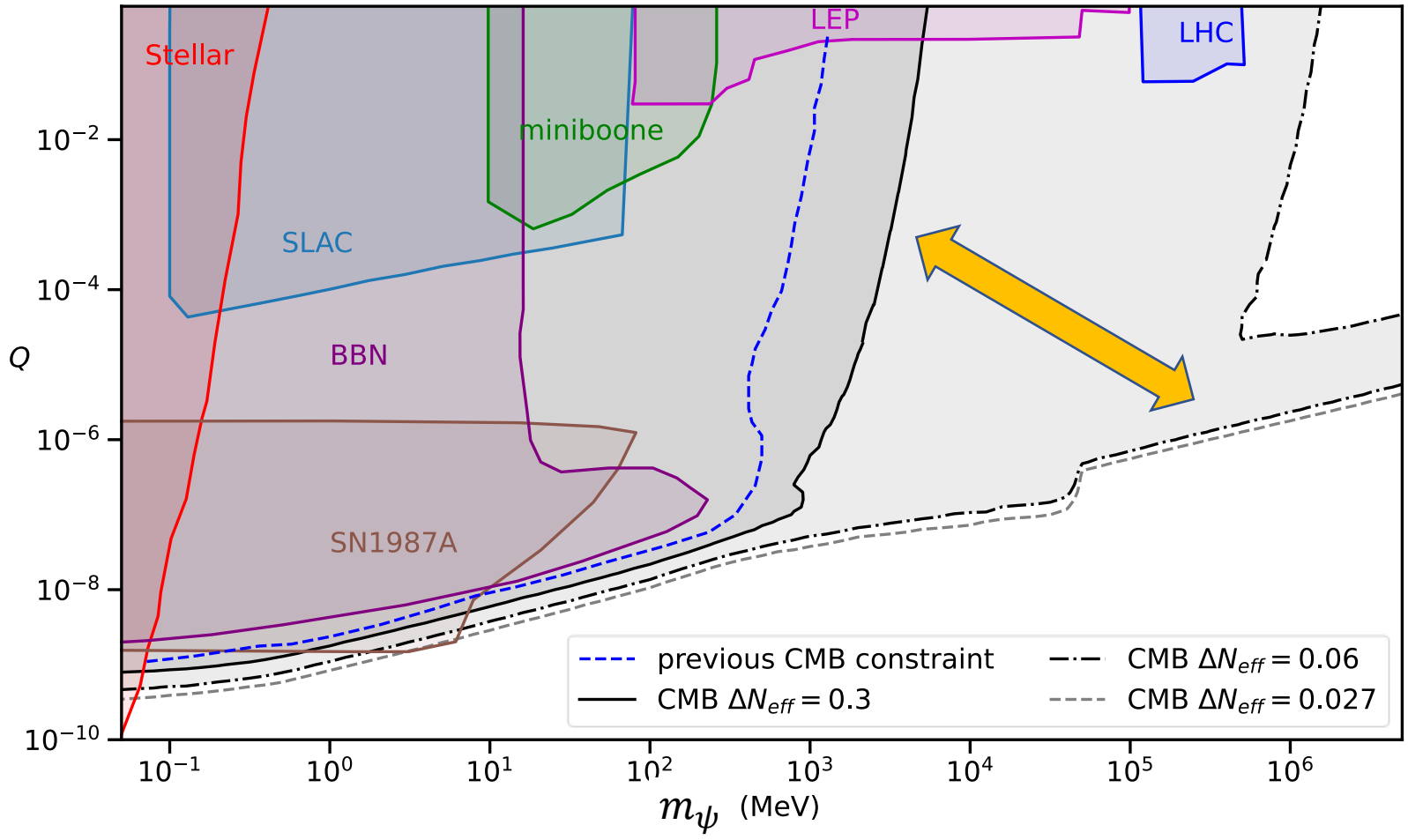




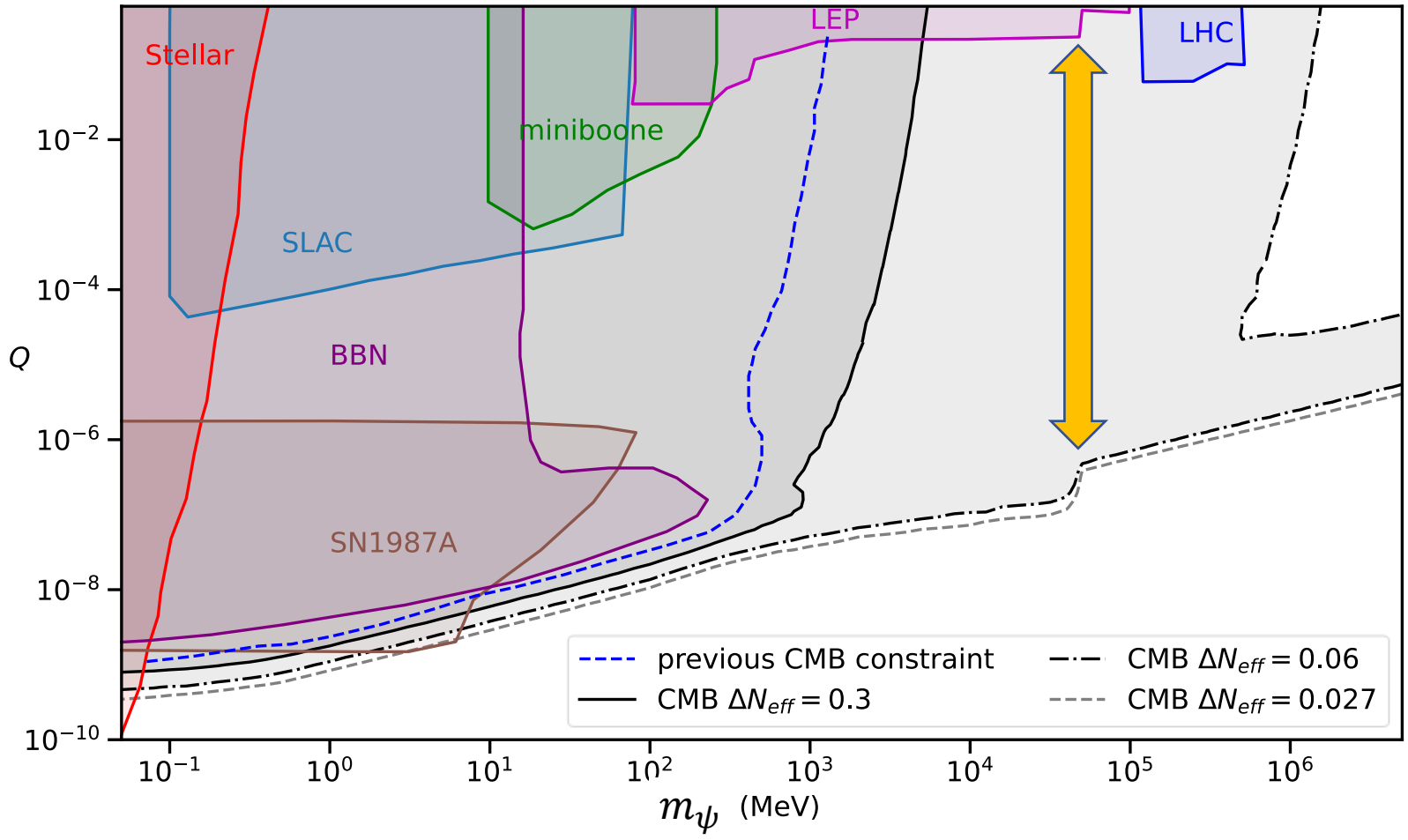


$m_{th} = 4T_{d,s}$

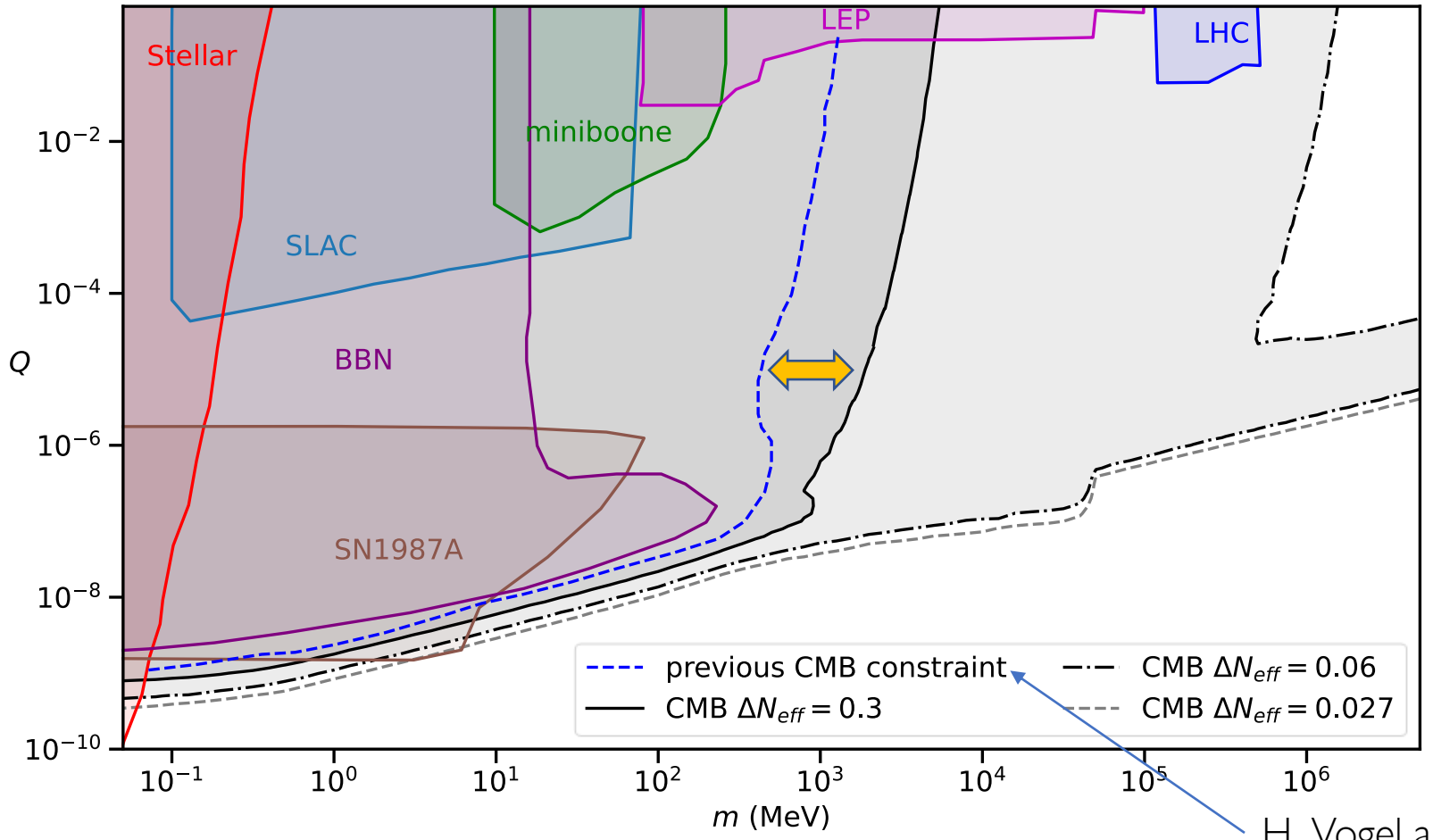
Comparing Neff constraints: Future constraint will extend to much larger parameter space



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

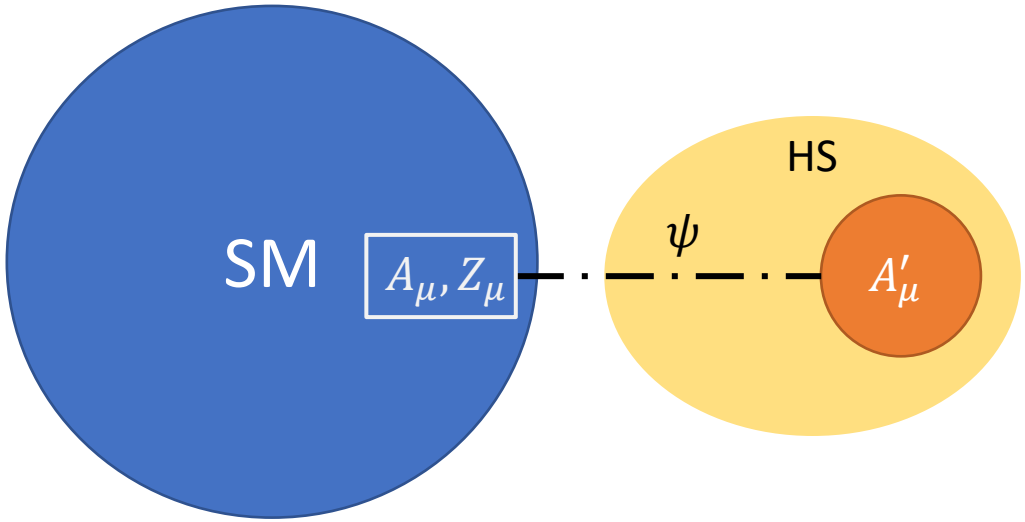


Comparing Neff constraints: Updating previous constraint



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

Extending to general hidden sector



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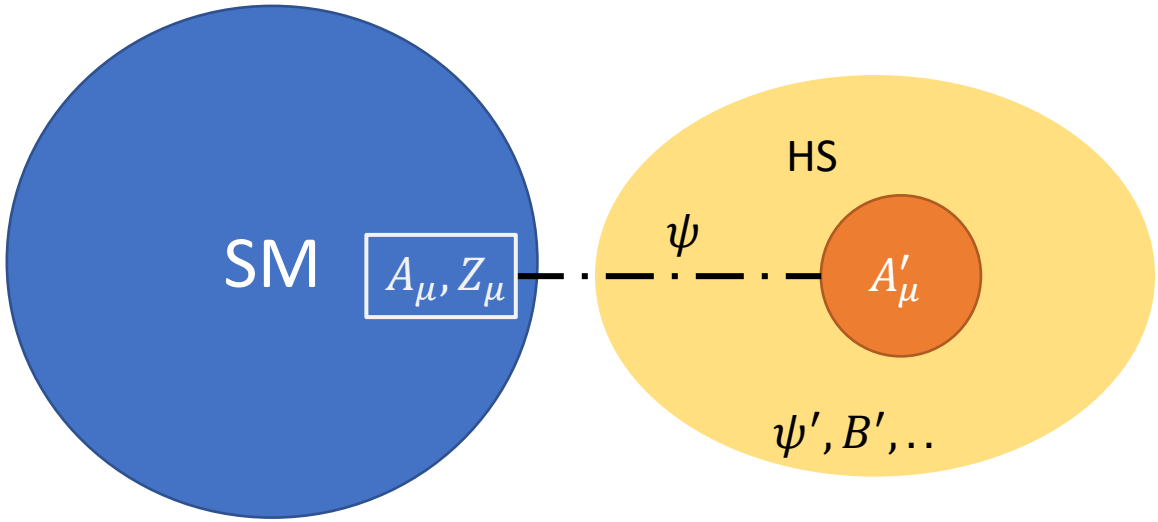

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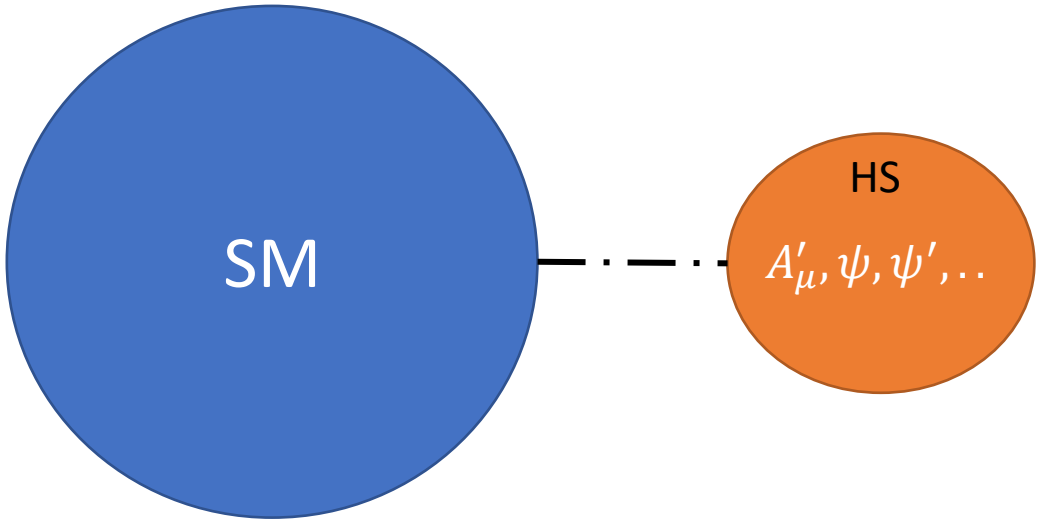

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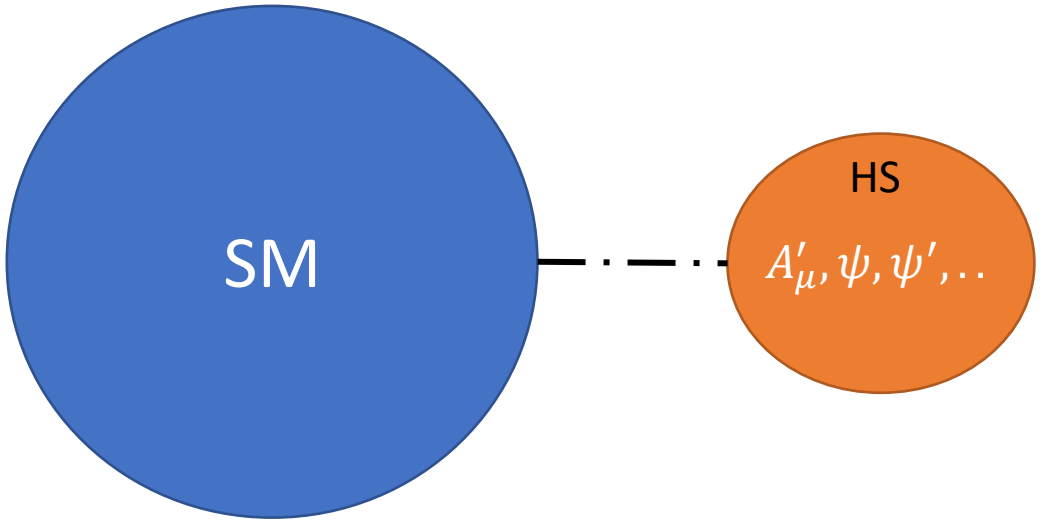
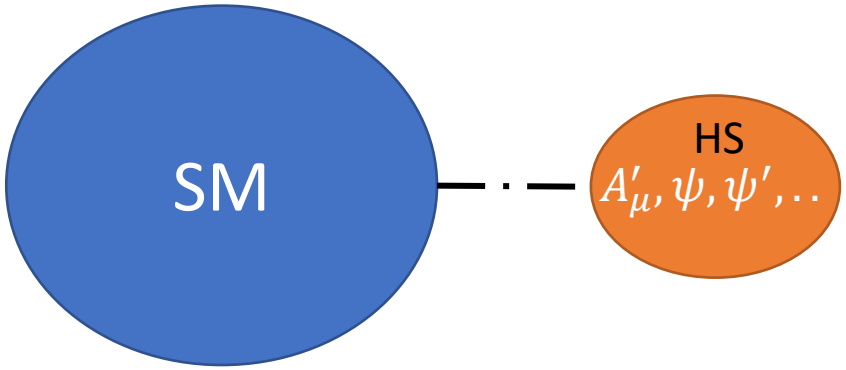
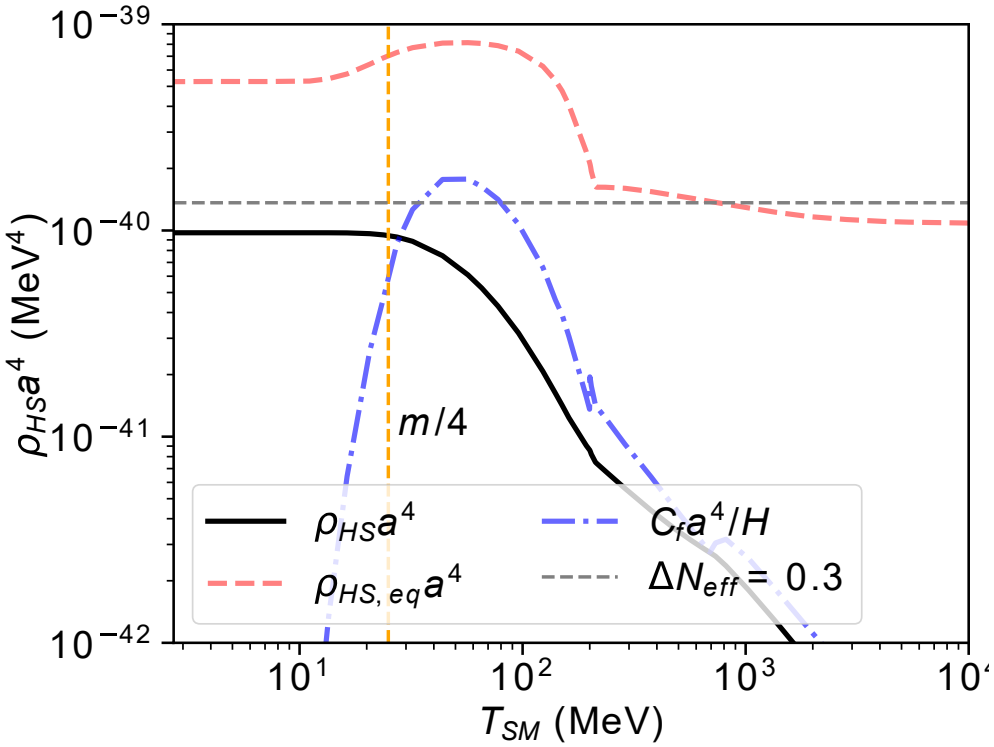


One can calculate a conservative Neff constraint on the millicharge interaction that is independent of details of hidden sector.

Minimum leaked energy independent of details within HS





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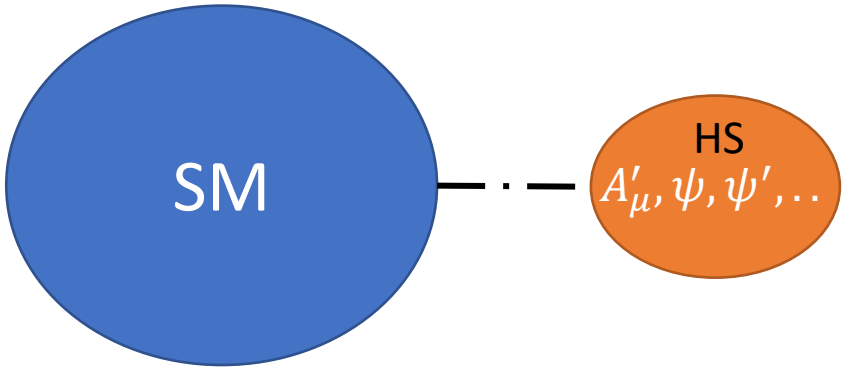

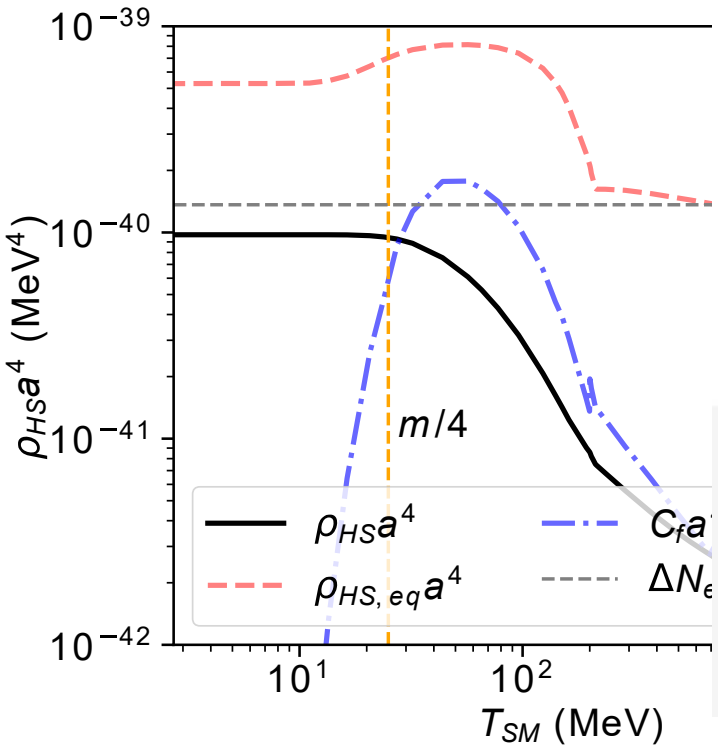

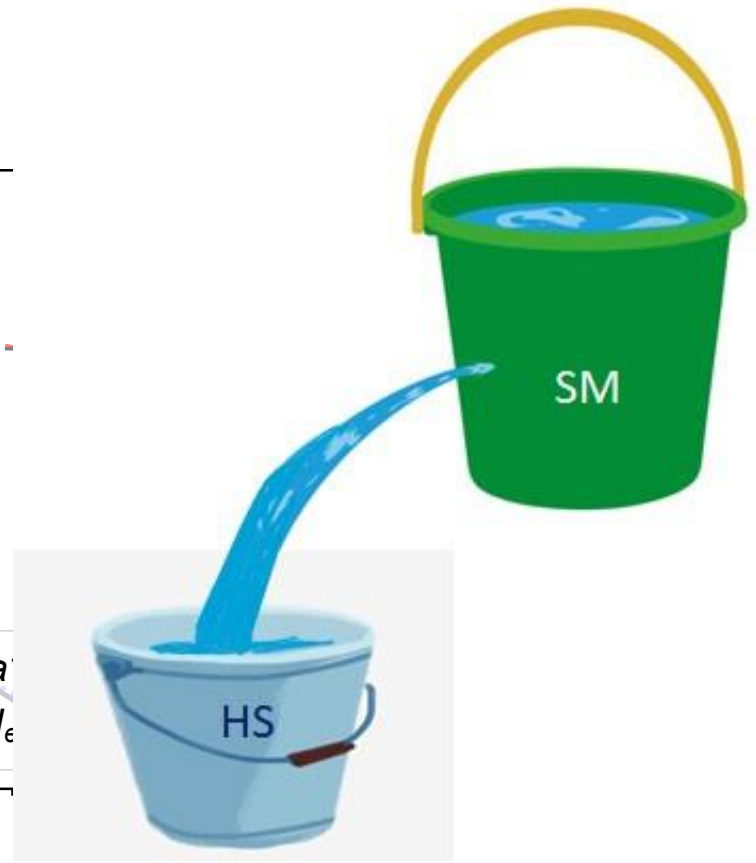

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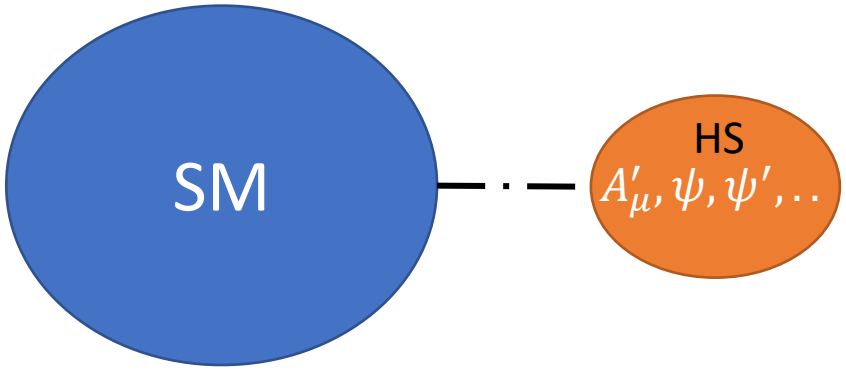

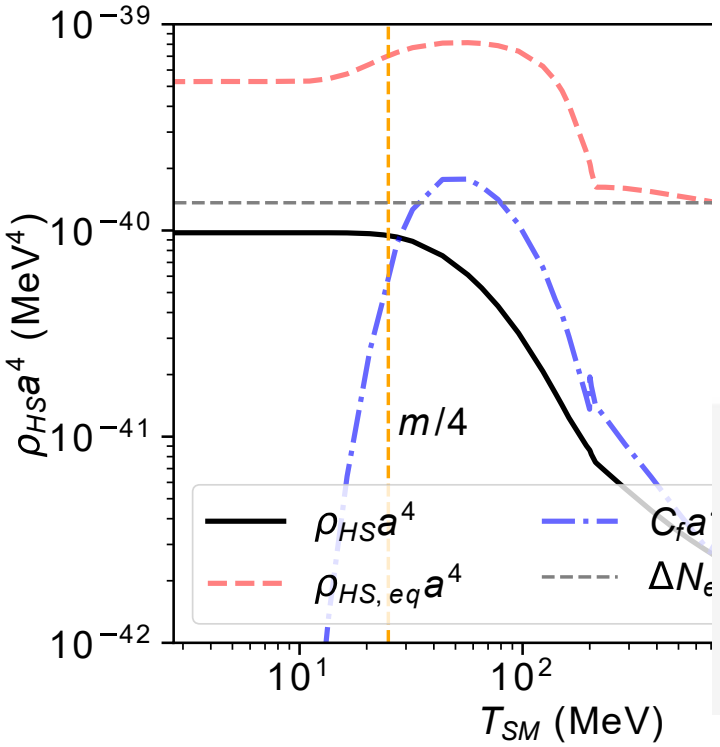

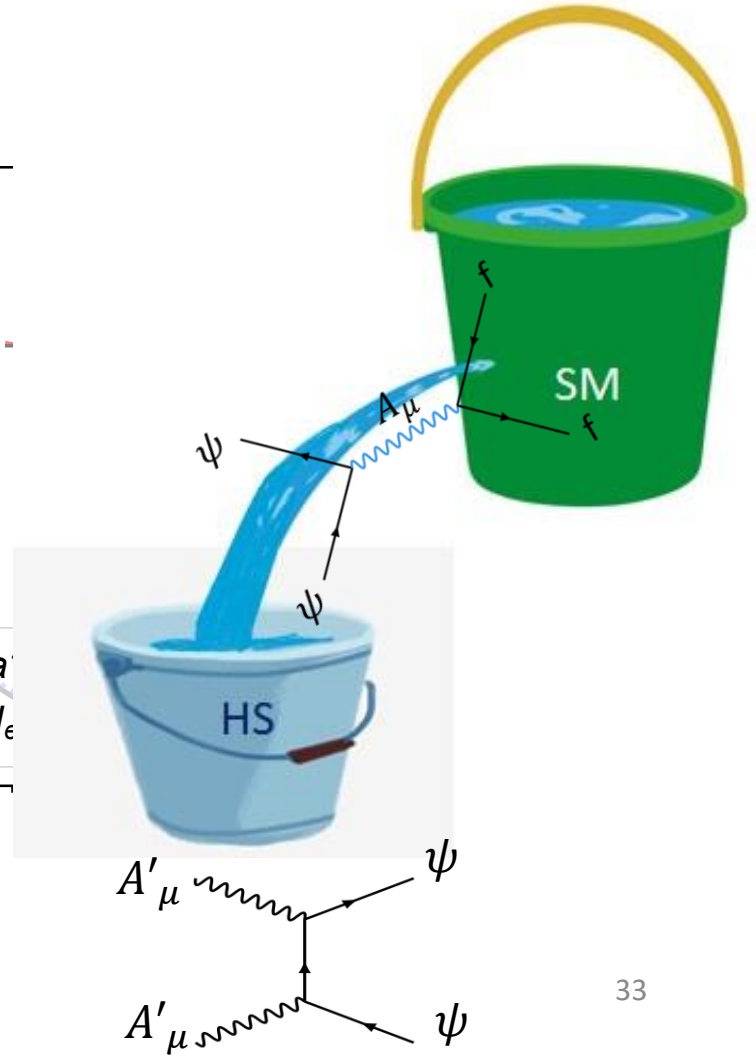

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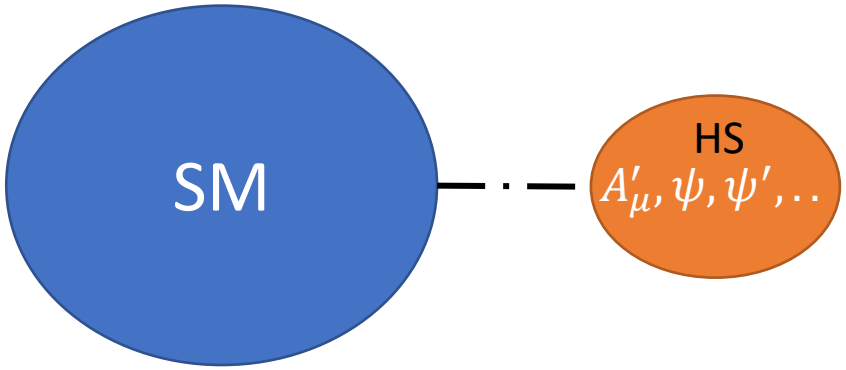
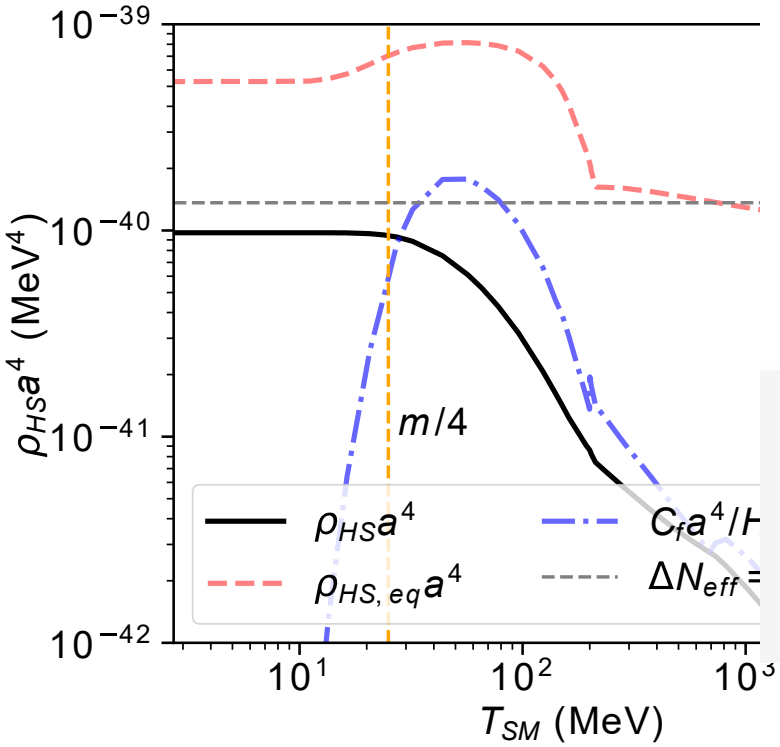


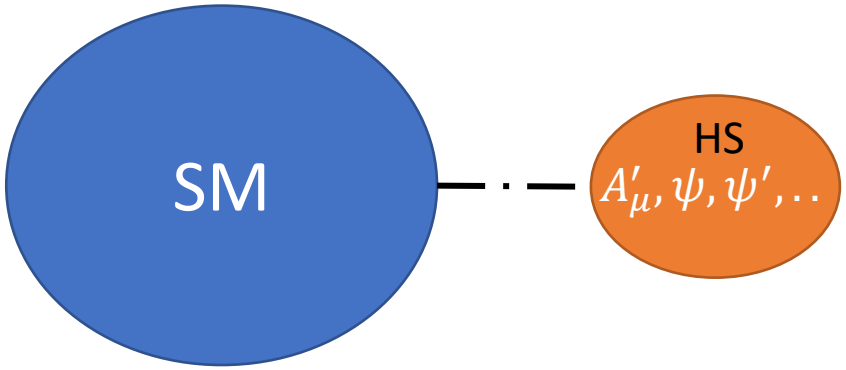
$$\left(\frac{\rho_{HS}}{\rho_{SM}}\right)_{\min} \propto \frac{M_{\rm Pl}}{m_\psi} L$$

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

Leak factor



Minimum leaked energy independent of details within HS



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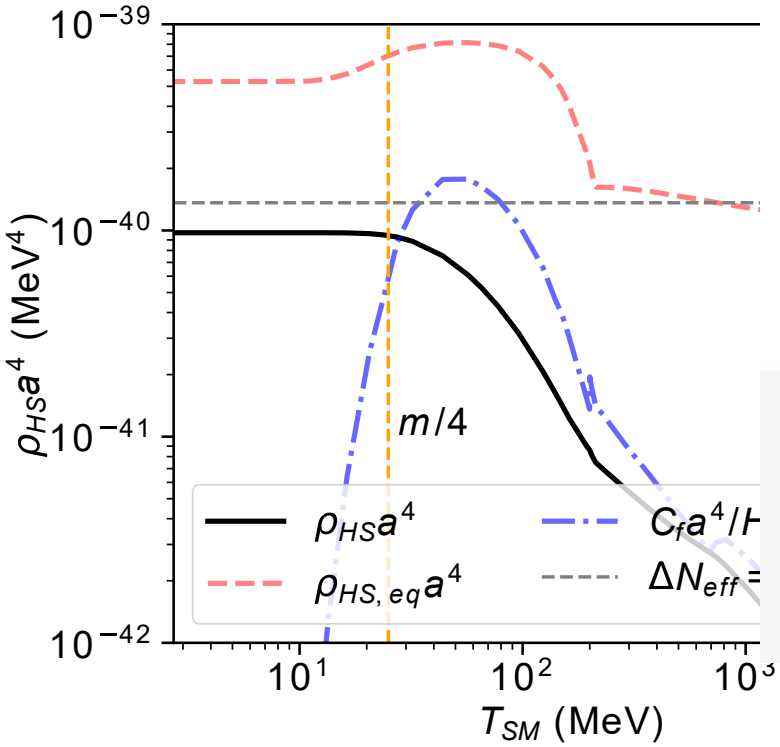
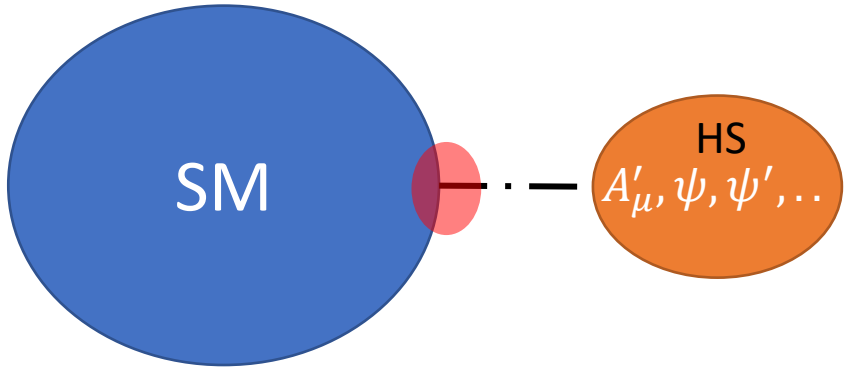
Leak factor

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



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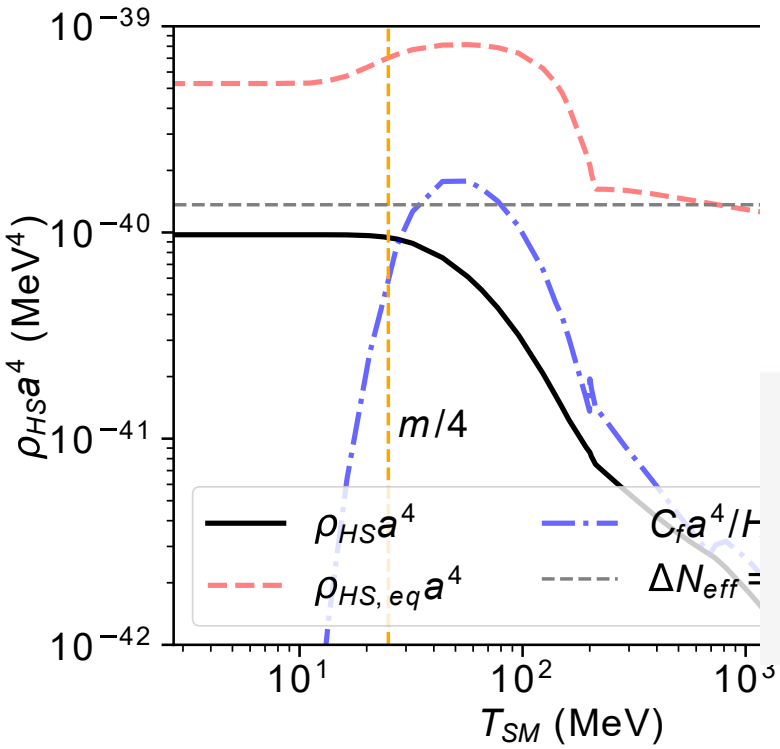
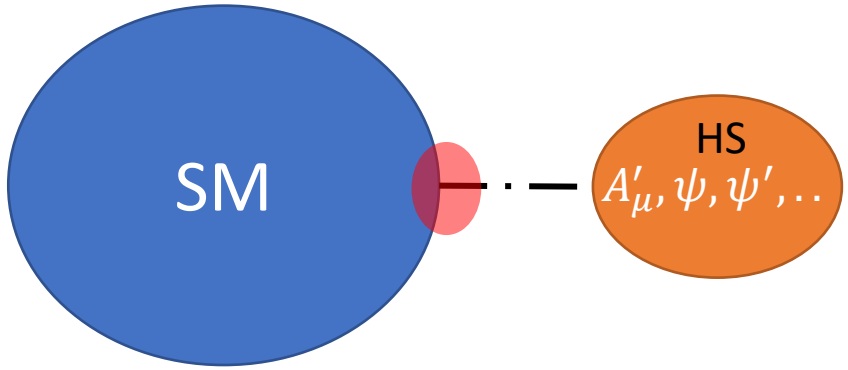
Leak factor

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



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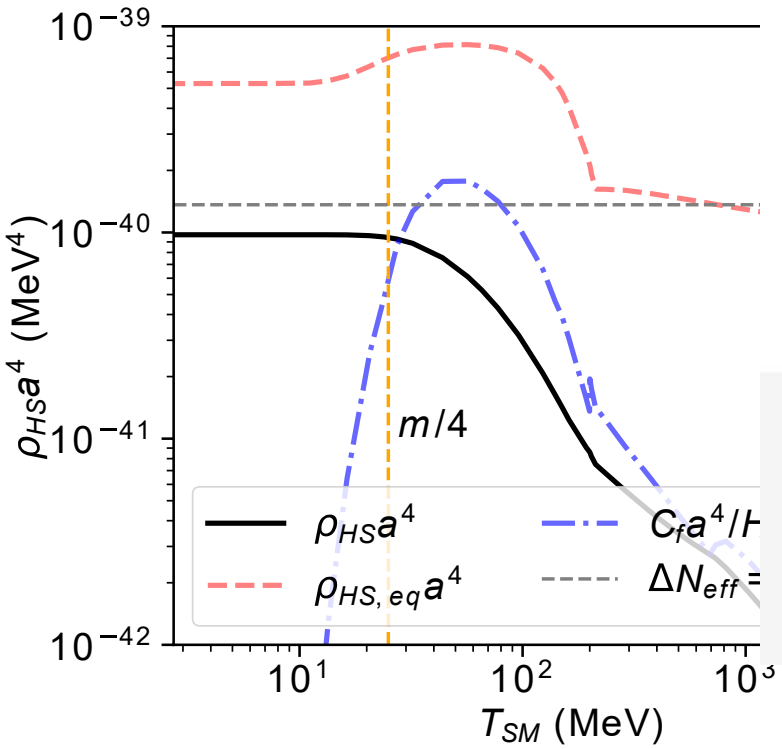
Leak factor

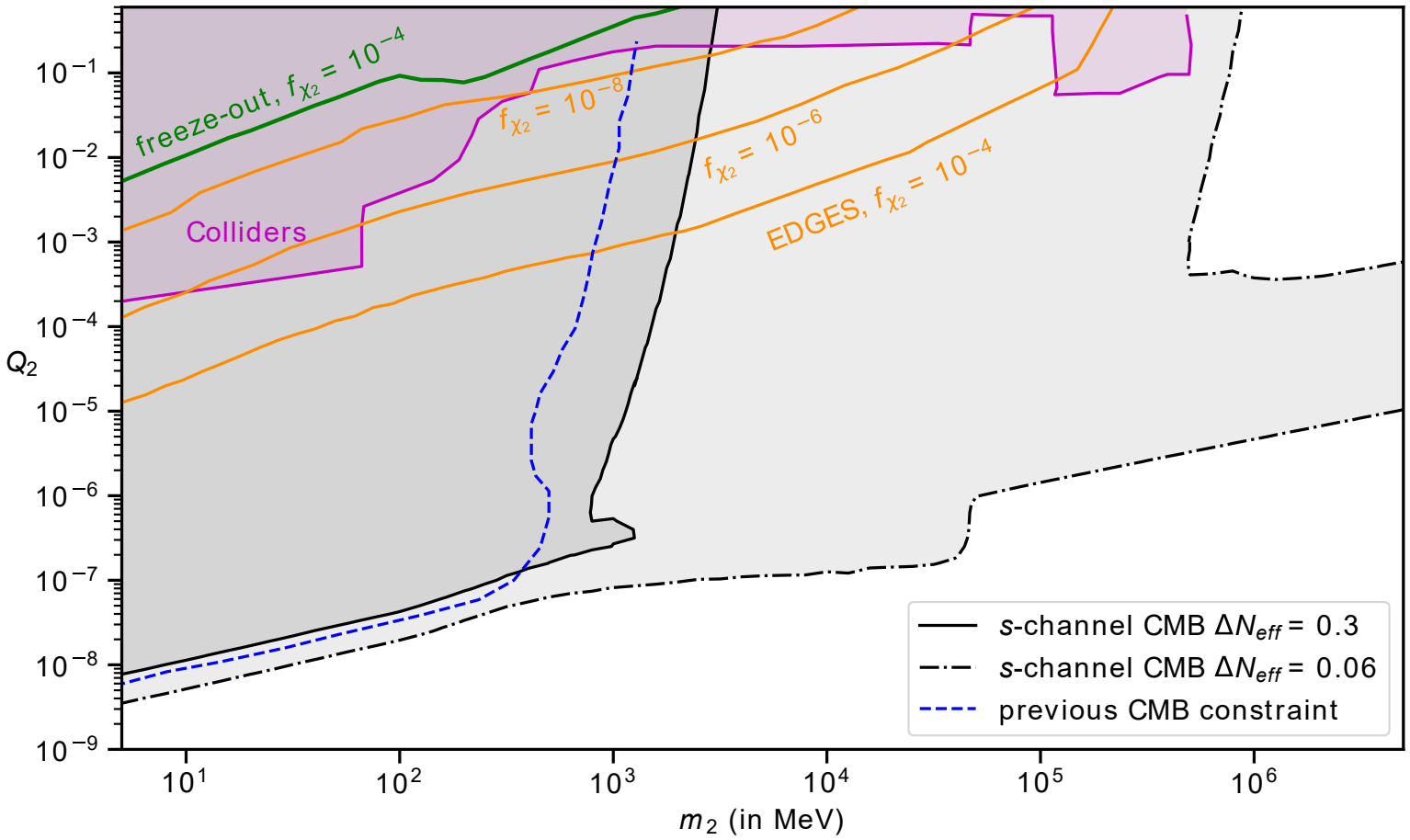
Independent of g_{HS} or T_{HS} or value of dark charge.

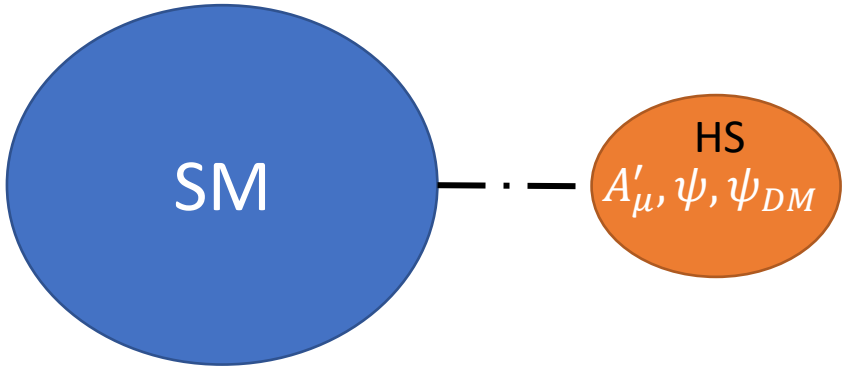
Beyond Standard Model



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

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

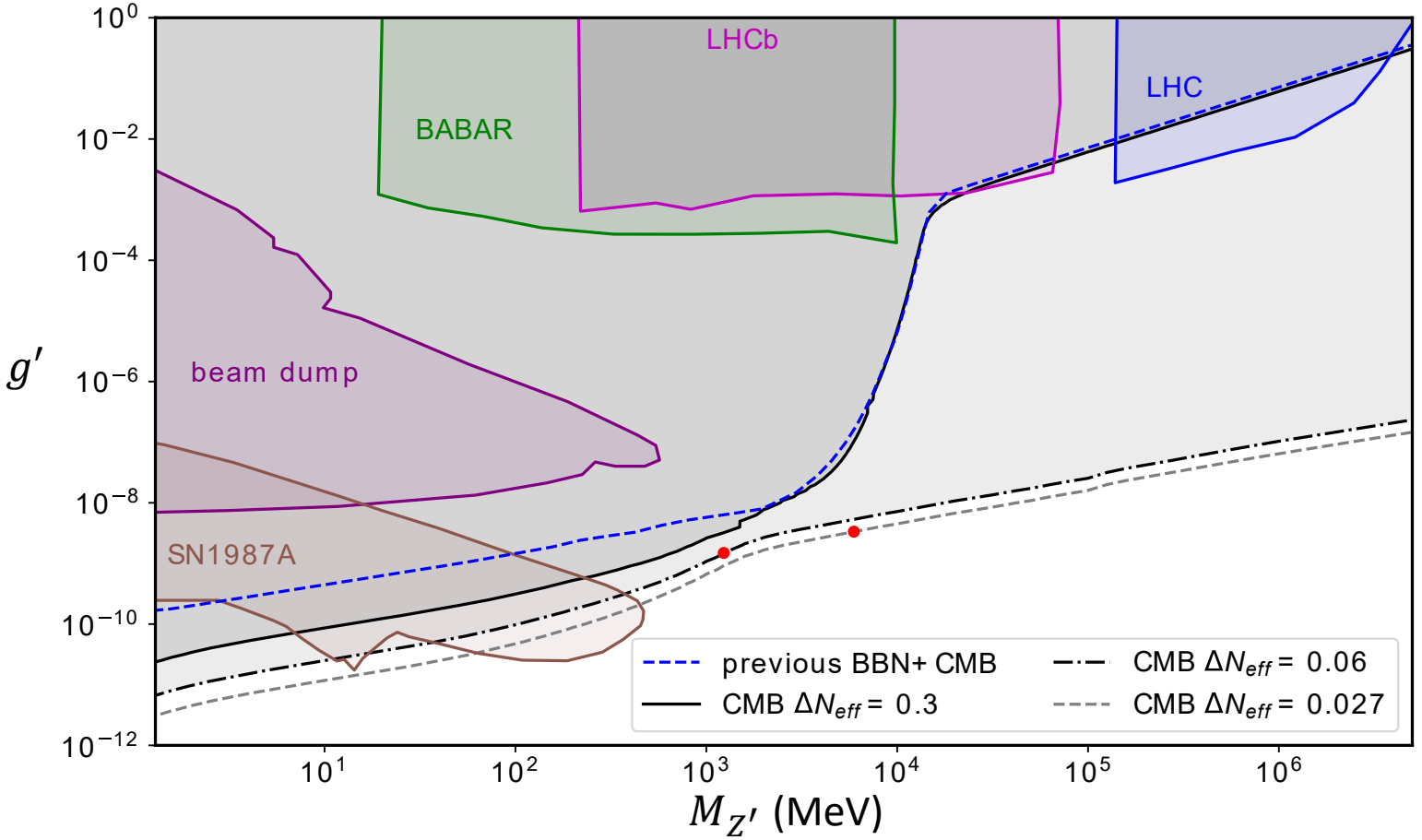


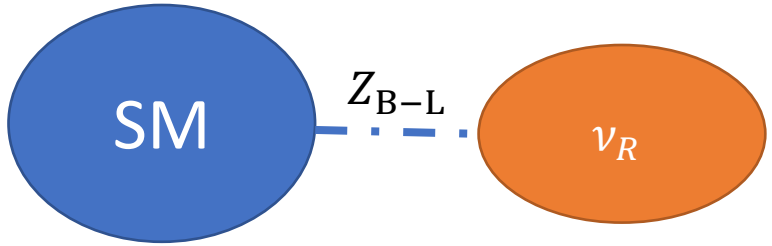


H. Liu, N. J. Outmezguine, D. Redigolo, and T. Volansky, Phys. Rev. D 100 no. 12, (2019) 123011.

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

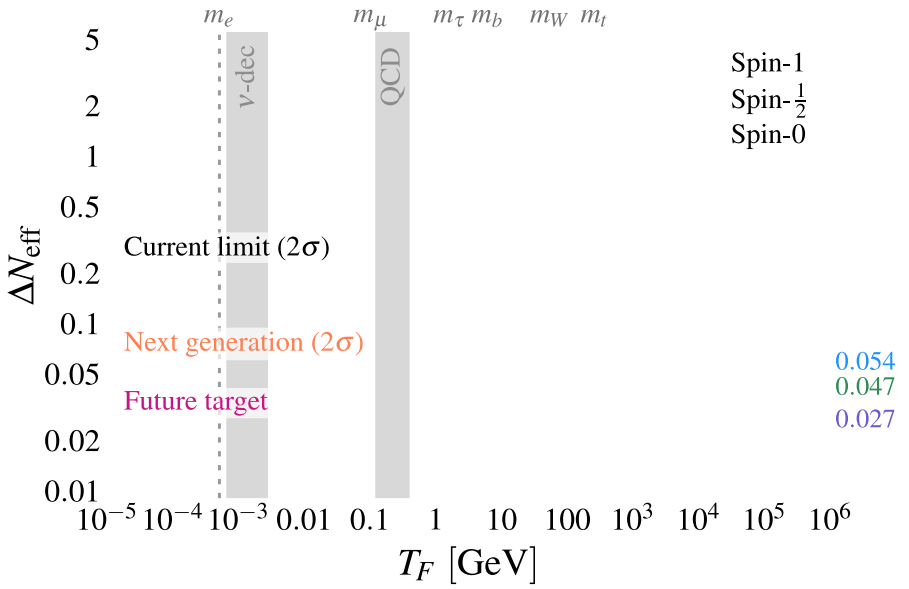
$$L_{int} \supset -\frac{1}{4}F'_{\mu\nu}F^{\mu\nu'} + g'Z'_{\mu}J^{\mu}_{B-L,SM} - g'Z'_{\mu}\sum_i \bar{\nu}_{R,i}\gamma^{\mu}\nu_{R,i} + \frac{1}{2}M^2_{Z'}Z'^{\mu}Z'_{\mu}$$

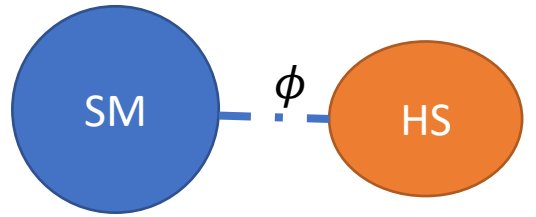


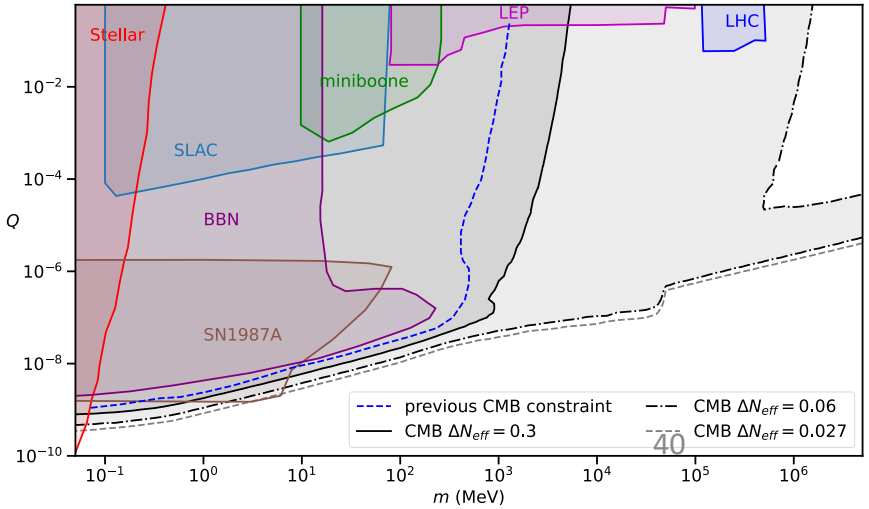


Summary

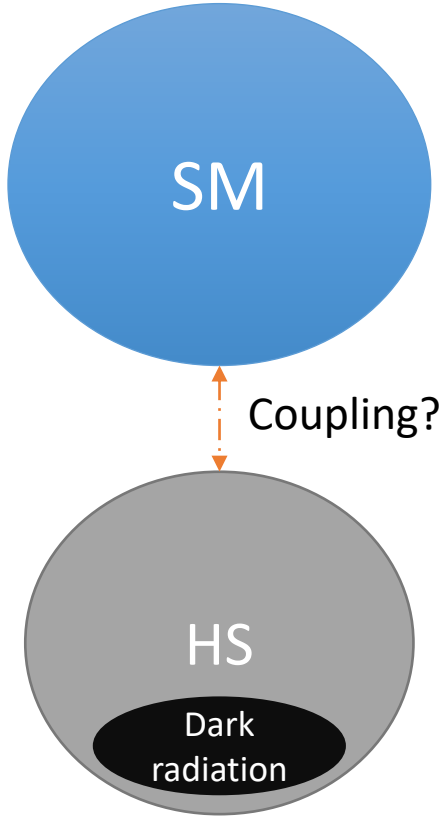
- With improving Neff measurements, we should interpret them as constraints on portal interactions with out-of-equilibrium sectors
- $N_{\rm eff}$ constraints on out-of-equilibrium particles are:
  - Most relevant for portal interactions mediated by a particle heavier than 0.1 MeV
  - Orders of magnitude stronger than collider experiments
  - Constraints largely independent of internal hidden sector model
- Simple way to calculate: $L < g_*^{3/4}(4\Lambda)\, g_*^{1/3}(\Lambda)\, \frac{\Lambda}{M_{\rm Pl}} (\Delta N_{\rm eff})_{\rm max}$







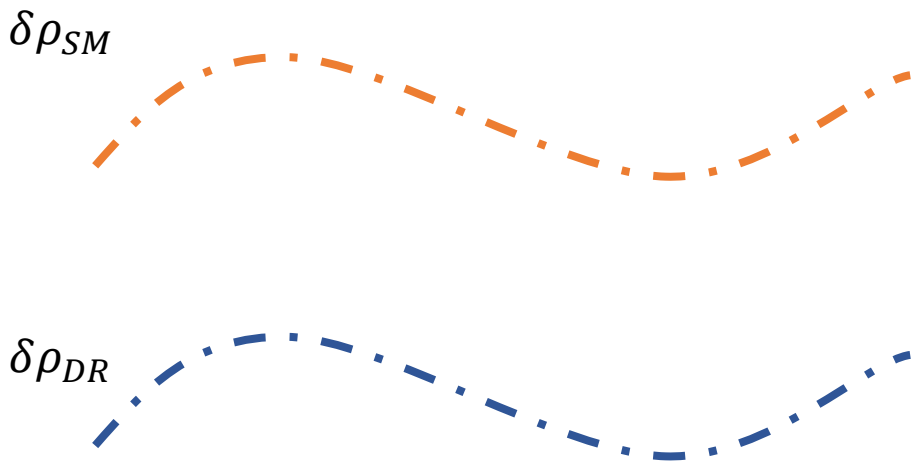
Goal: Probe models containing dark radiation using cosmological observations



- If no dark radiation detected in future: Constrain portal interactions with hidden sectors
  (Adshead, Ralegankar, Shelton 2022)

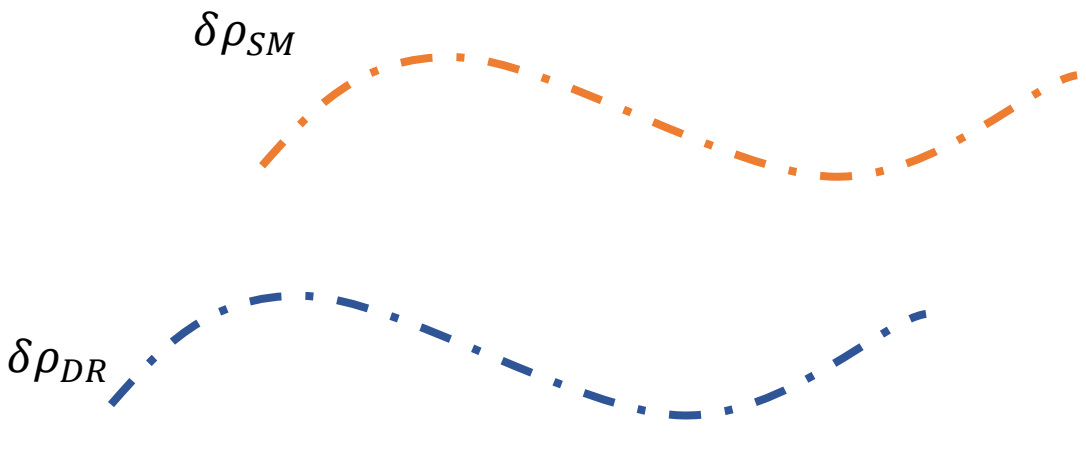
- If dark radiation detected: Search for interaction by checking adiabaticity of perturbations during BBN
  (Adshead, Holder, Ralegankar 2020)

Adiabaticity: ‘sync’ between perturbations



Adiabatic perturbations

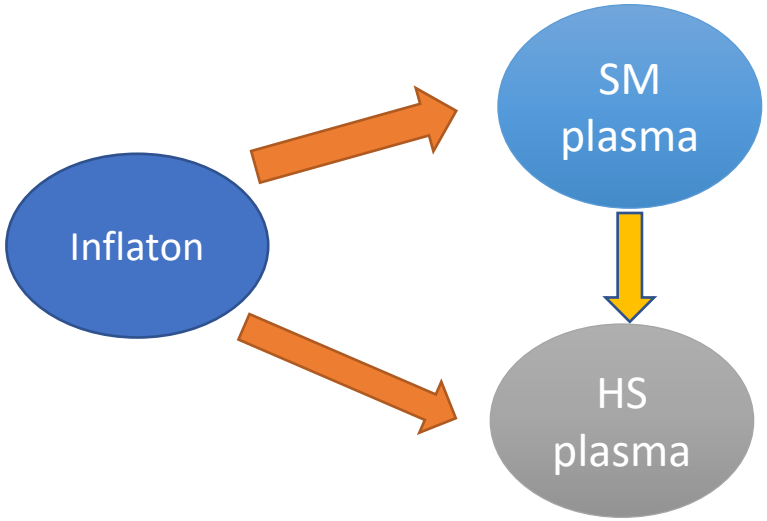
$$\frac{\delta\rho_{SM}}{\rho_{SM}} = \frac{\delta\rho_{DR}}{\rho_{DR}}$$



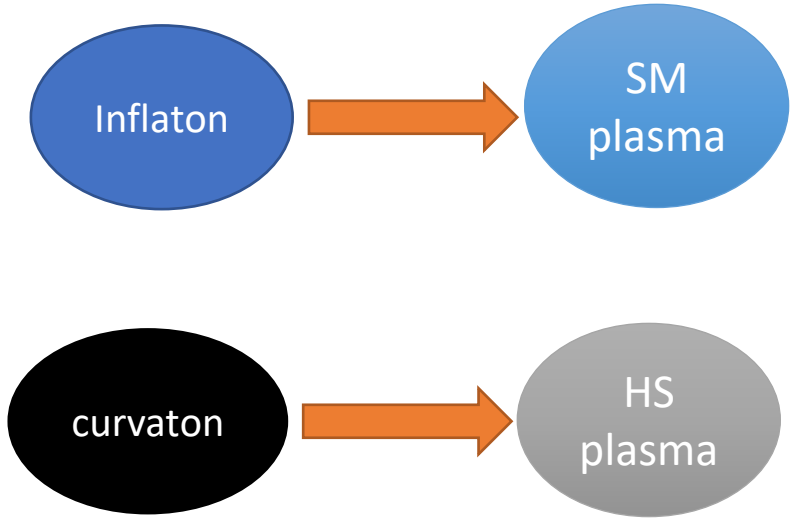
Isocurvature component in perturbations

$$S_{DR} = \frac{4}{3}\left(\frac{\delta\rho_{DR}}{\rho_{DR}} - \frac{\delta\rho_{SM}}{\rho_{SM}}\right)$$

Adiabaticity: Related to early universe production



Adiabatic perturbations



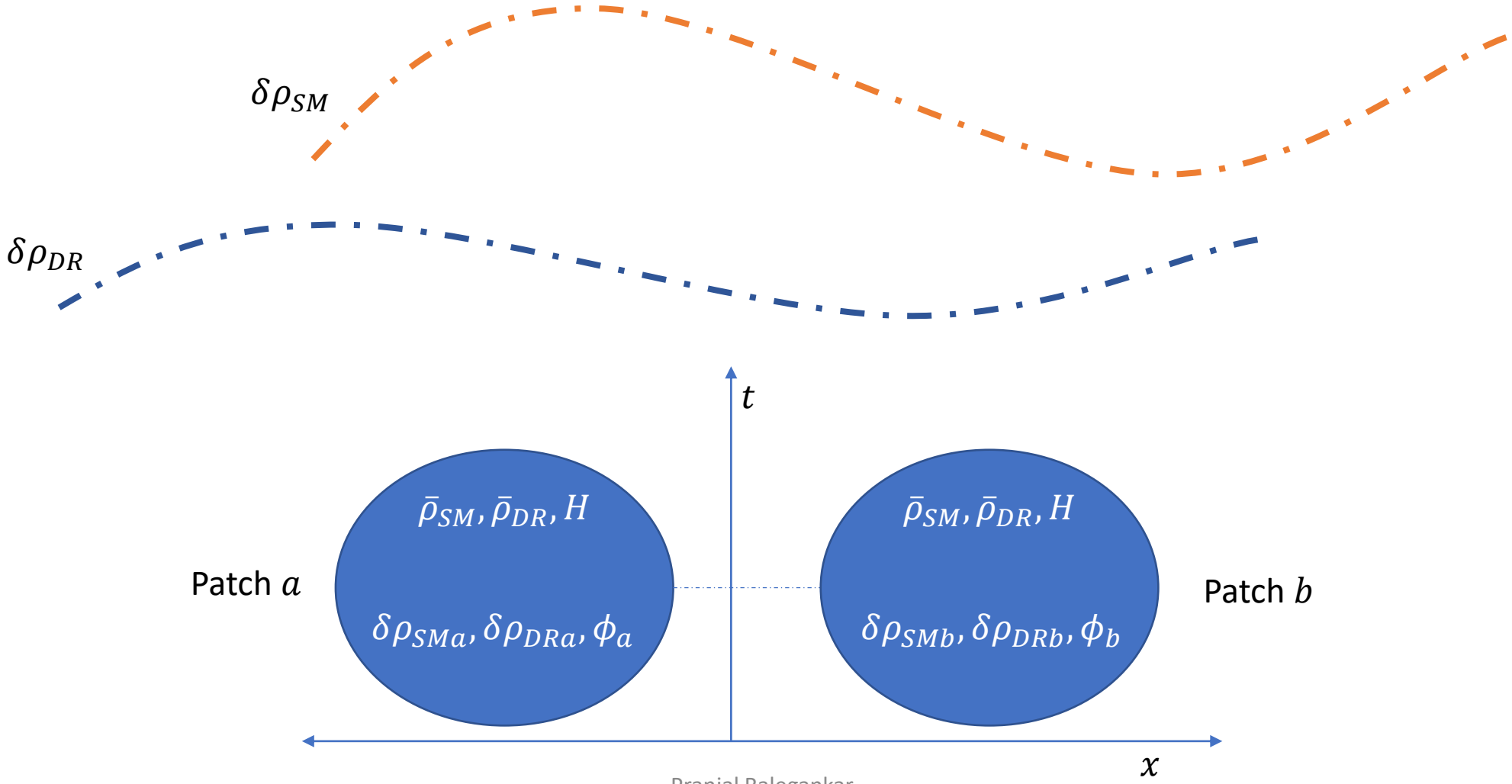
Isocurvature component in perturbations

$$\frac{\delta\rho_{SM}}{\rho_{SM}} = \frac{\delta\rho_{DR}}{\rho_{DR}}$$

$$S_{DR} = \frac{4}{3}\left(\frac{\delta\rho_{DR}}{\rho_{DR}} - \frac{\delta\rho_{SM}}{\rho_{SM}}\right)$$

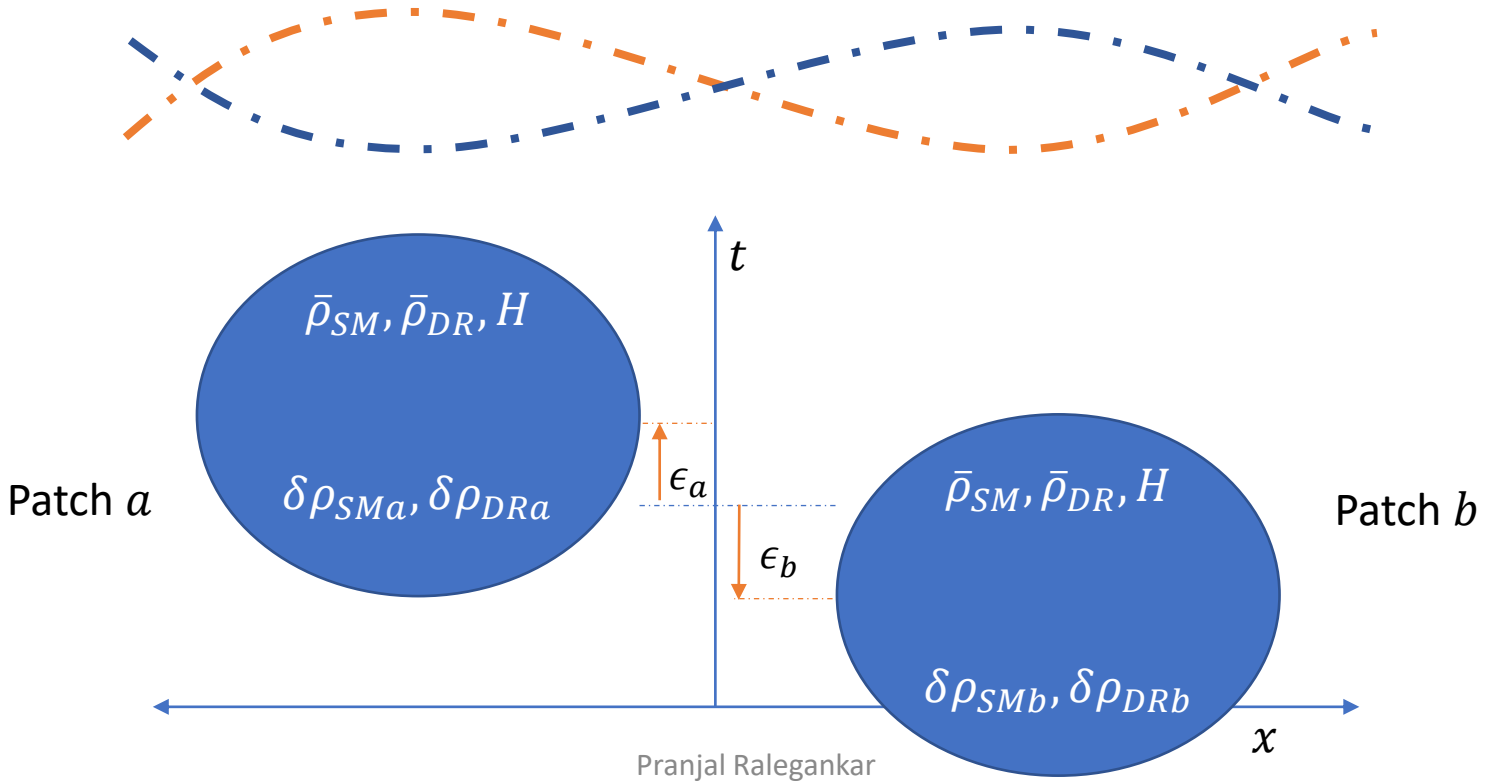
Goal: Use BBN observations to find dark radiation isocurvature

Dark radiation isocurvature => Variation in N_{eff}



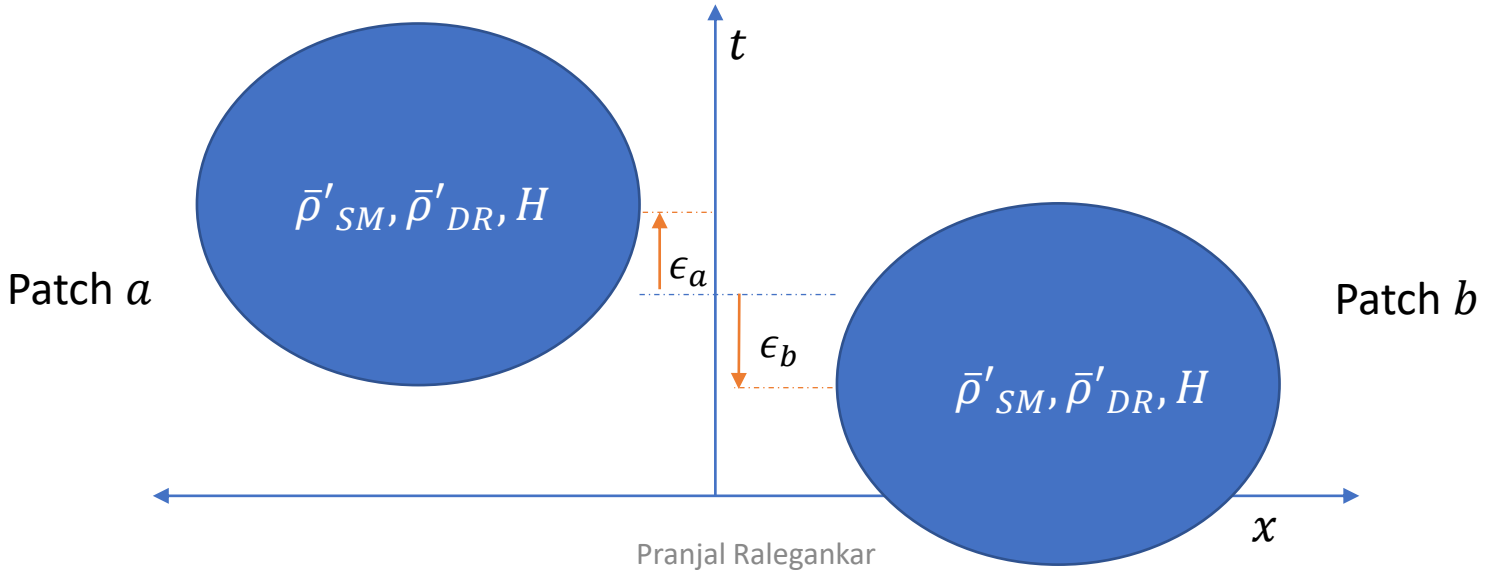
Dark radiation isocurvature => Variation in N_{eff}

$$\delta\rho_{SM} + \delta\rho_{DR} = 0$$



Dark radiation isocurvature => Variation in N_{eff}

$$\bar{\rho}' = \bar{\rho} + \delta\rho$$

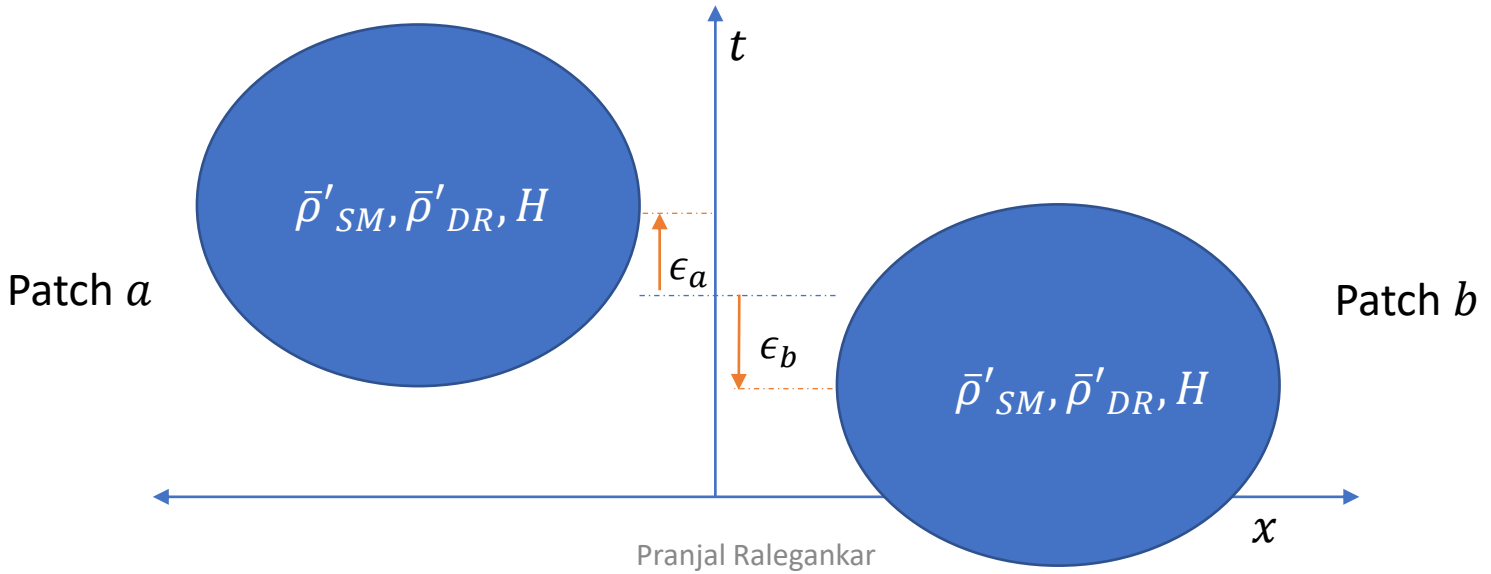


Dark radiation isocurvature => Variation in N_{eff}

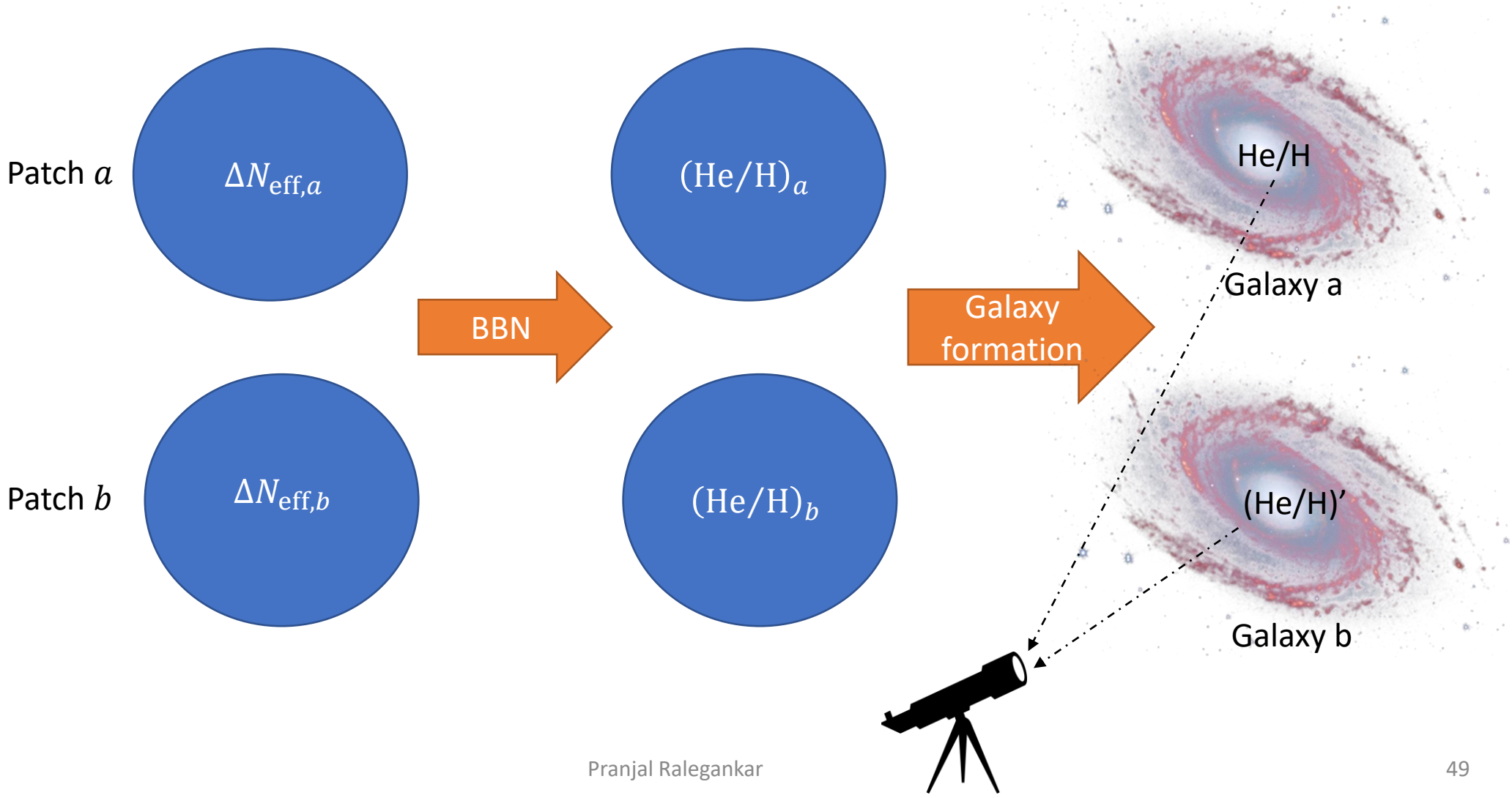
$$\bar{\rho}' = \bar{\rho} + \delta\rho$$

$$N_{\mathrm{eff}} \propto \frac{\bar{\rho}'_{SM}}{\bar{\rho}'_{DR}} \quad \Rightarrow \quad \Delta N_{\mathrm{eff}}(\vec{x}) = \Delta \bar{N}_{\mathrm{eff}} \left(1 + \frac{4}{3} S_{DR}(\vec{x})\right)$$

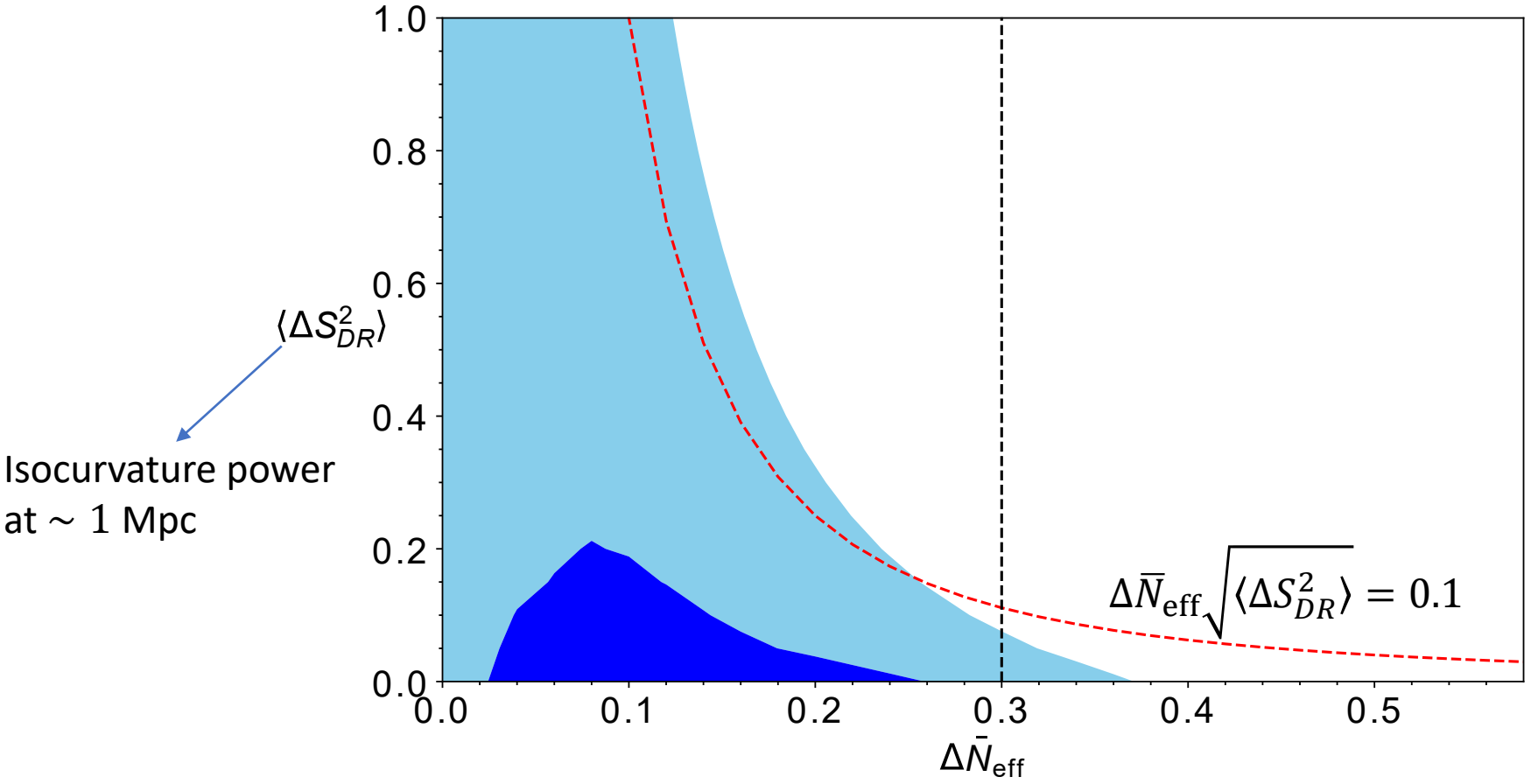
$$S_{DR} = \frac{4}{3}\left(\frac{\delta\rho_{DR}}{\rho_{DR}} - \frac{\delta\rho_{SM}}{\rho_{SM}}\right)$$



Dark radiation isocurvature => Variation in He/H

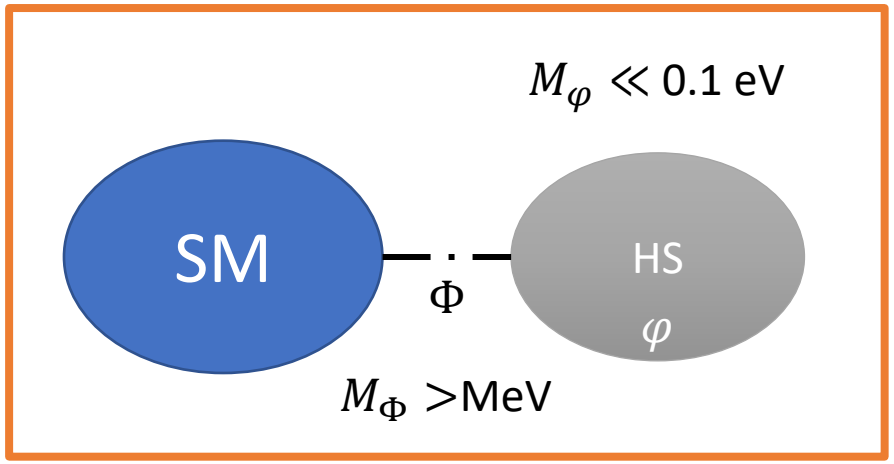


Constraint on dark radiation isocurvature

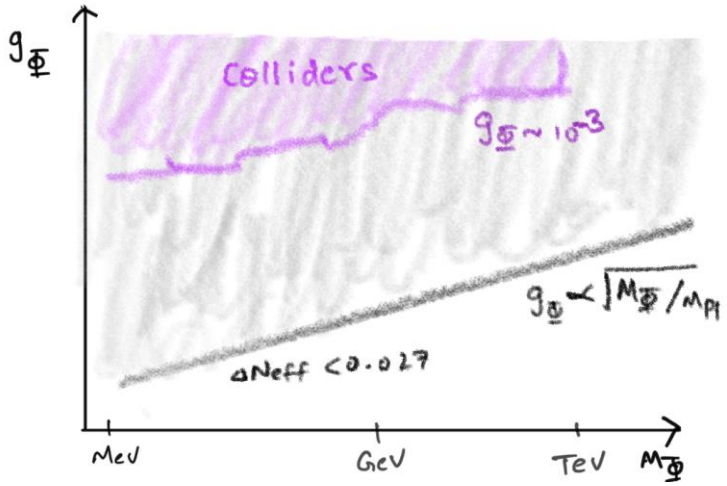


Combined implication of projects

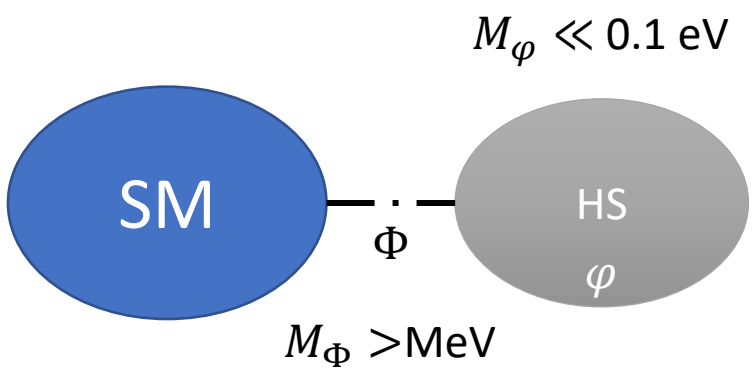
Massless lightest particle + portal interaction => Impact CMB N_{eff}



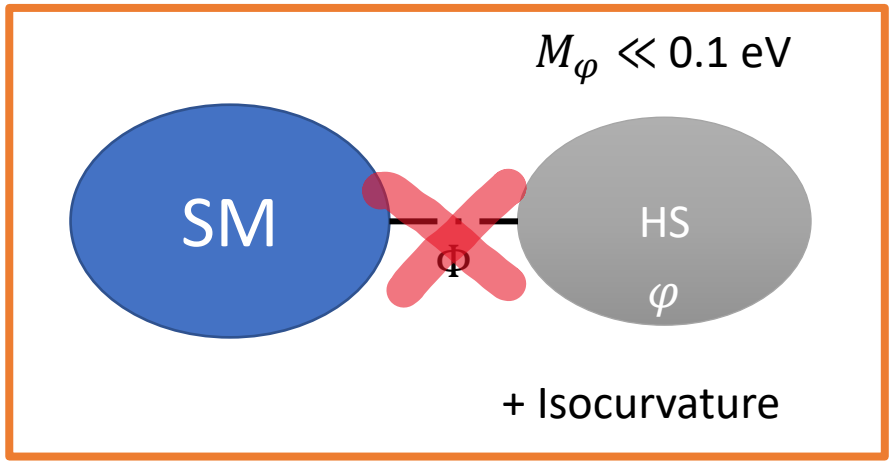
$\varphi =$ dark radiation

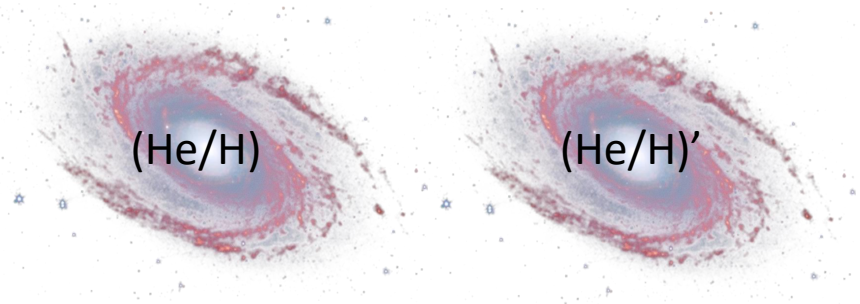


Massless lightest particle + no interaction => inhomogeneous BBN



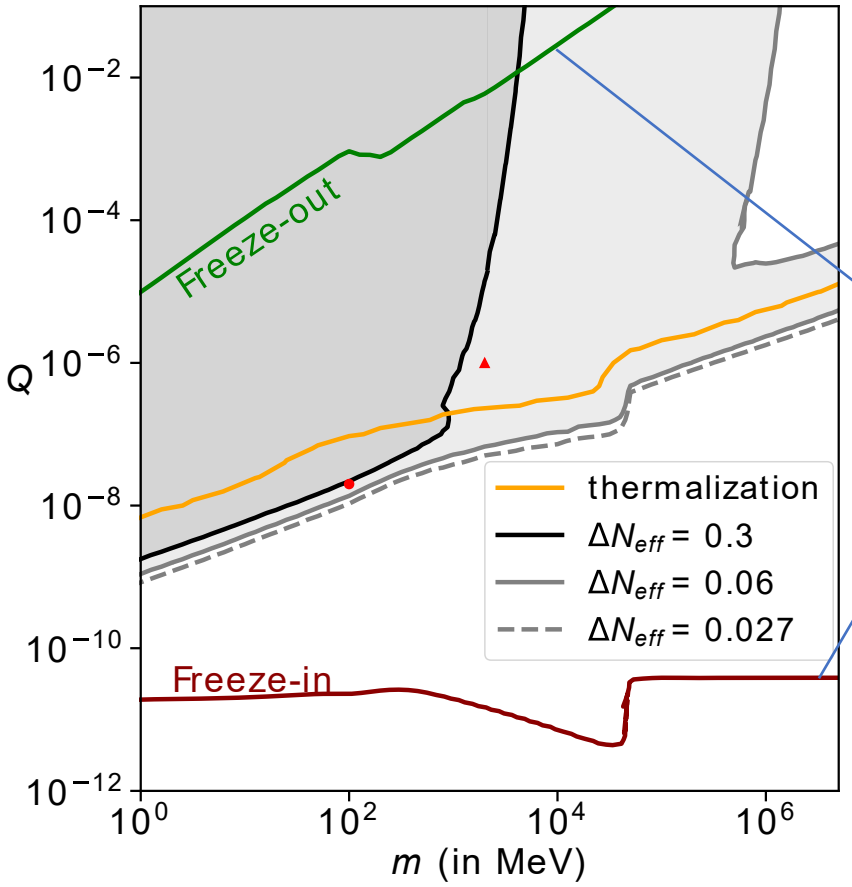
$\varphi =$ dark radiation





Backup slides

Millicharged particles must dominantly annihilate into dark photons



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

BBN constraints on dark radiation isocurvature

Likelihood analysis: Deuterium

D/H value from i^{th} gas cloud

$$P(D_i|\{\bar{D},\sigma_d\}) = \frac{1}{\sqrt{2\pi(\sigma_{n,i}^2+\sigma_d^2)}}\exp\left(-\frac{(D_i-\bar{D})^2}{2(\sigma_{n,i}^2+\sigma_d^2)}\right)$$

Theory prediction for average and variance of D/H

Noise in measurement

$$\mathcal{L}_0(\Delta N_{\rm eff},\sigma_{\Delta N_{\rm eff}}) = \int_0^\infty \left[\prod_i P(D_i|\{\bar{D},\sigma_d\})\right]_{\Delta N_{\rm eff},\Omega_b h^2,\sigma_{N_{\rm eff}}} \frac{\exp\left(-\frac{(\Omega_b h^2-\Omega_b h^2)^2}{2\sigma_{\Omega_b}^2}\right)}{\sqrt{2\pi\sigma_{\Omega_b}^2}} d(\Omega_b h^2).$$

Variance in $\Delta N_{\rm eff}$ due to isocurvature

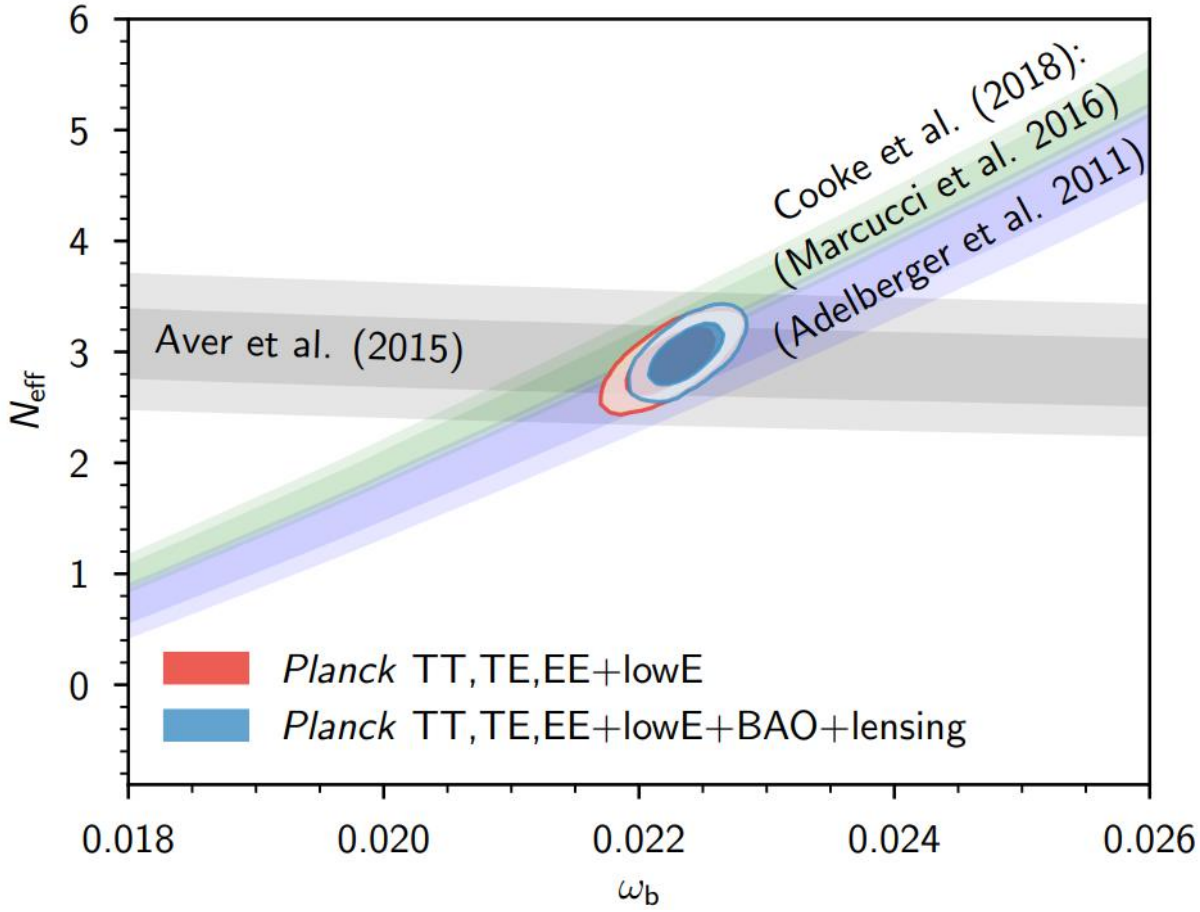
Marginalizing over baryon-to-photon ratio using Planck data

Error in Deuterium nuclear rates

- Still uncertainty in nuclear reaction of $\mathrm{d(p,\gamma)^3He}$:

$$d + p \rightarrow \gamma + {}^3\mathrm{He}$$

- In my BBN code I used ab-initio calculated rate of above reaction (from Marcucci eta al. 2016) in Parthenope.



Planck 2018