Neff constraints on the portal interactions with hidden sector

arxiv:2111.xxxxx

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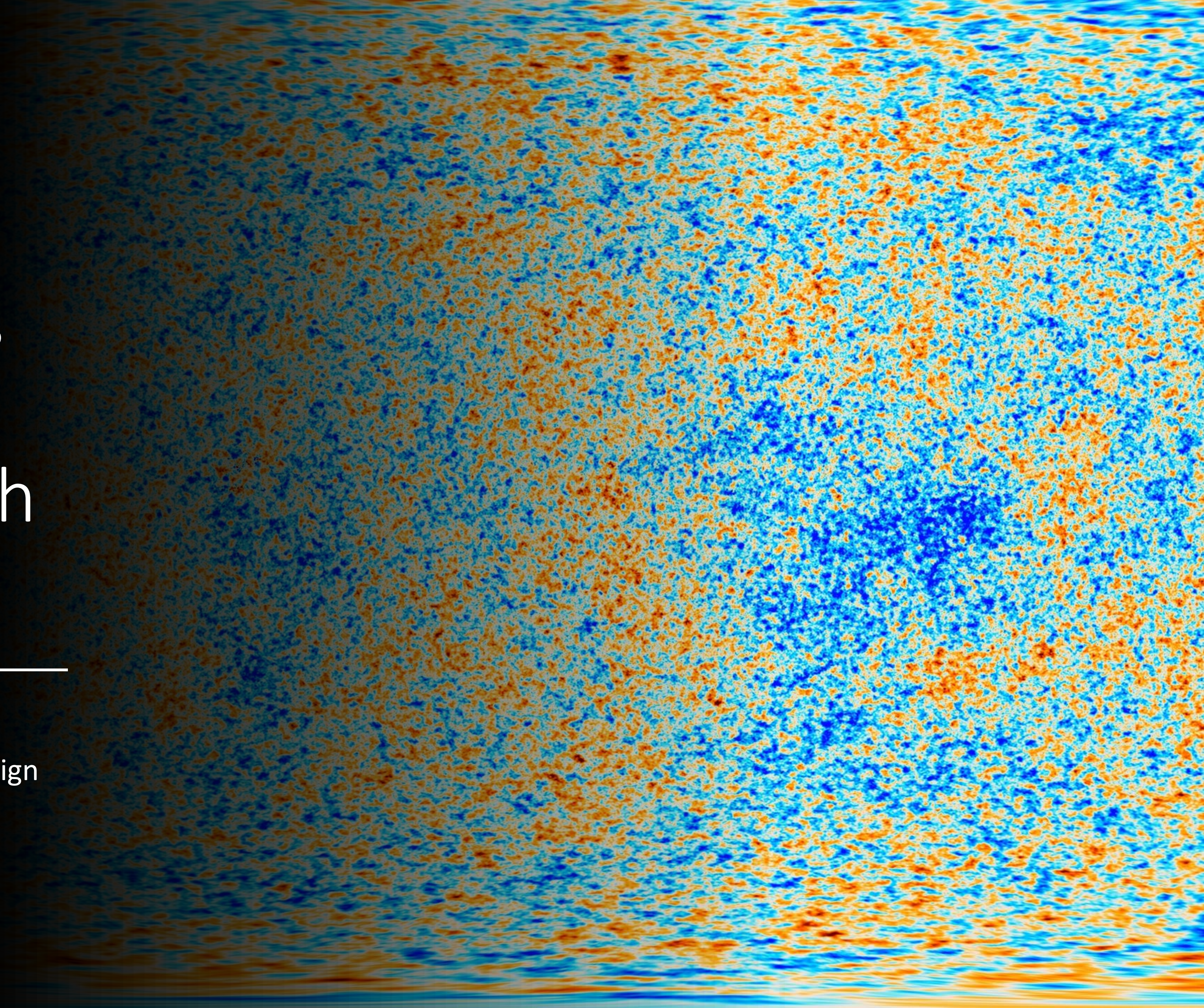
Collaborators: Peter Adshead and Jessie Shelton



Outline

- Background and motivation
- Physics behind Neff constraints
  - Gauged B-L with right handed neutrinos
- Extending to more general hidden sectors
- Summary

Background and Motivation

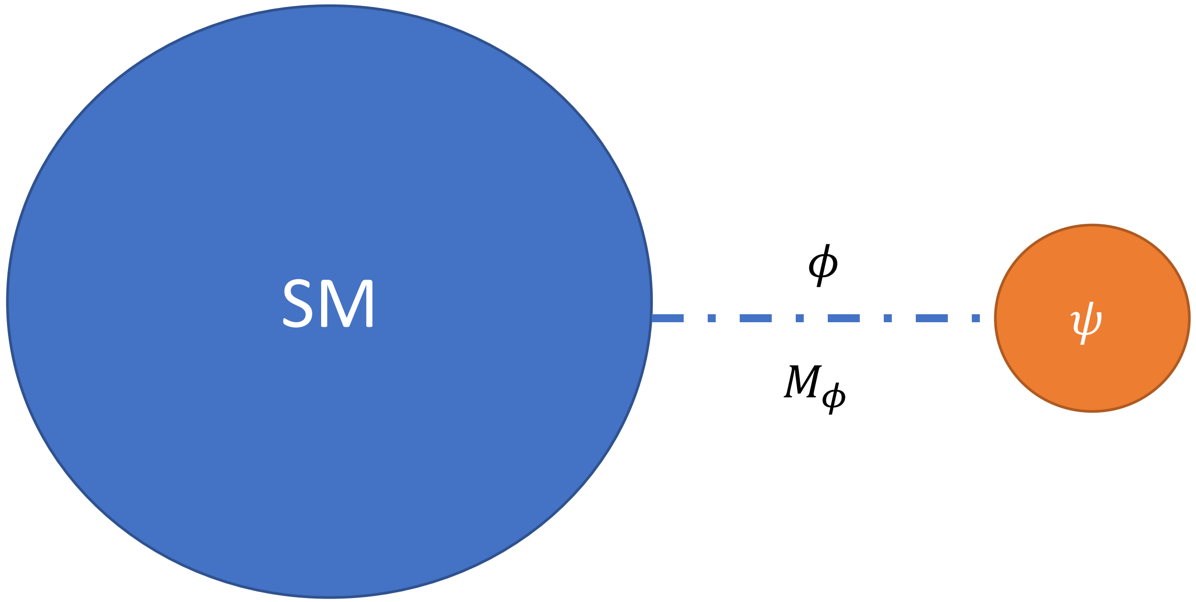
- All known particles are charged under Standard Model gauge symmetries, i.e. they interact with Strong and Electroweak forces.

Background and Motivation

- But there is no fundamental requirement for all particles in the universe to be charged under Standard Model symmetries.

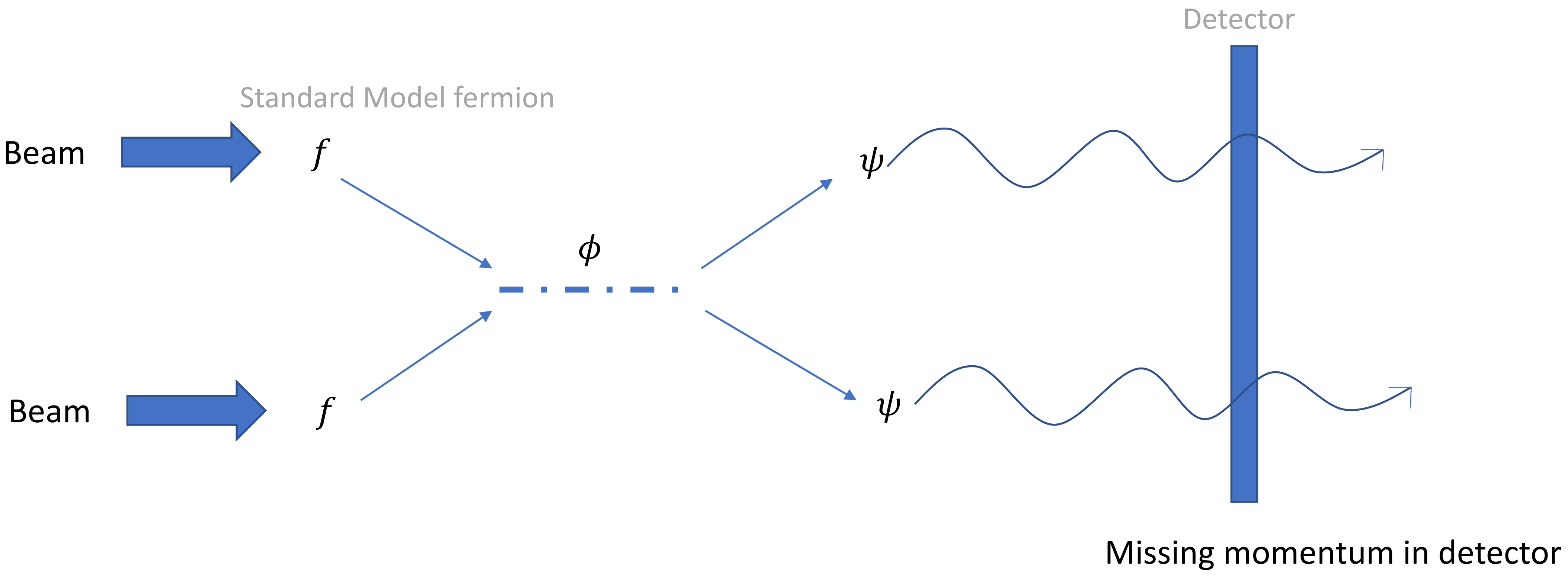
Background and Motivation

- Any such new particle can have renormalizeable portal couplings with the Standard Model particles that obey the Standard Model gauge symmetries.



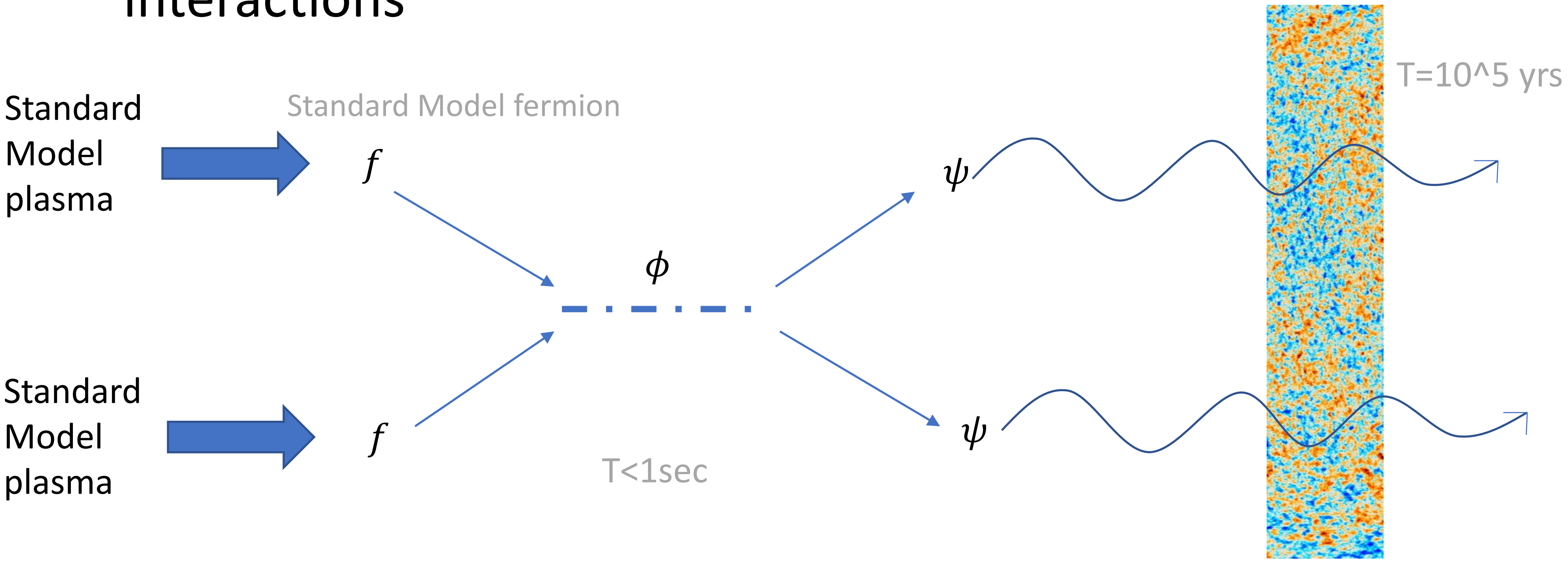
Background and Motivation

- Collider experiments can probe portal interactions



Background and Motivation

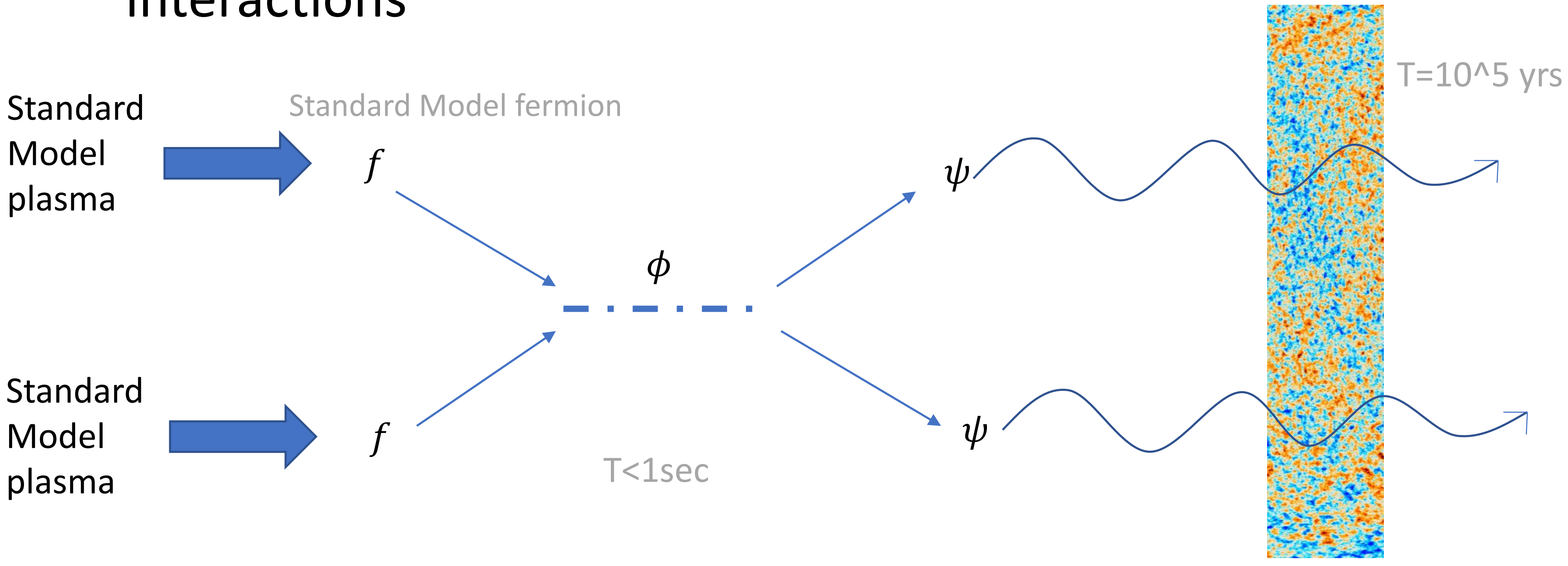
- So can Cosmic microwave background (CMB) spectrum probe portal interactions



Missing energy in CMB observation in the form of dark radiation (or dark matter).

Background and Motivation

- So can Cosmic microwave background (CMB) spectrum probe portal interactions



$$\Delta N_{eff} \propto \frac{\rho_{DR}}{\rho_{\gamma}}$$

Dark radiation during recombination behaves similar to neutrinos and hence its energy density is parametrized through effective number of neutrino species, N_{eff}.

Baryon minus Lepton

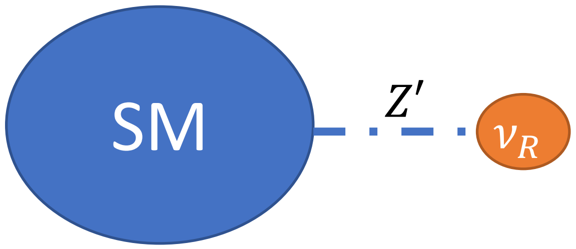
Physics behind Neff constraints: B-L example

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

Stueckelberg mass

Standard Model B-L current

Right handed neutrinos



Physics behind Neff constraints: Boltzmann equations

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

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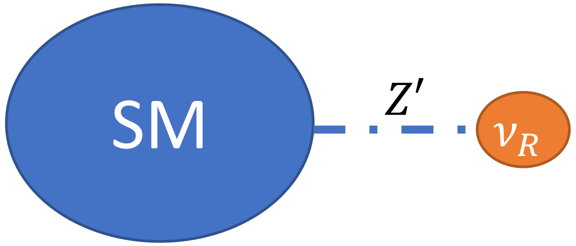

Boltzmann equations:

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

$$\frac{d\rho_{\nu_R}}{dt} + 4H\rho_{\nu_R} = C$$

$$H = \frac{\sqrt{\rho_{SM} + \rho_{\nu_R}}}{\sqrt{3}M_{pl}}$$

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

Energy transfer collision term

Physics behind Neff constraints: Energy density evolution without thermalization

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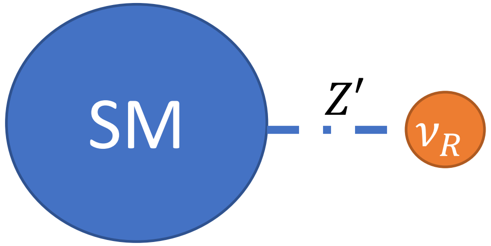

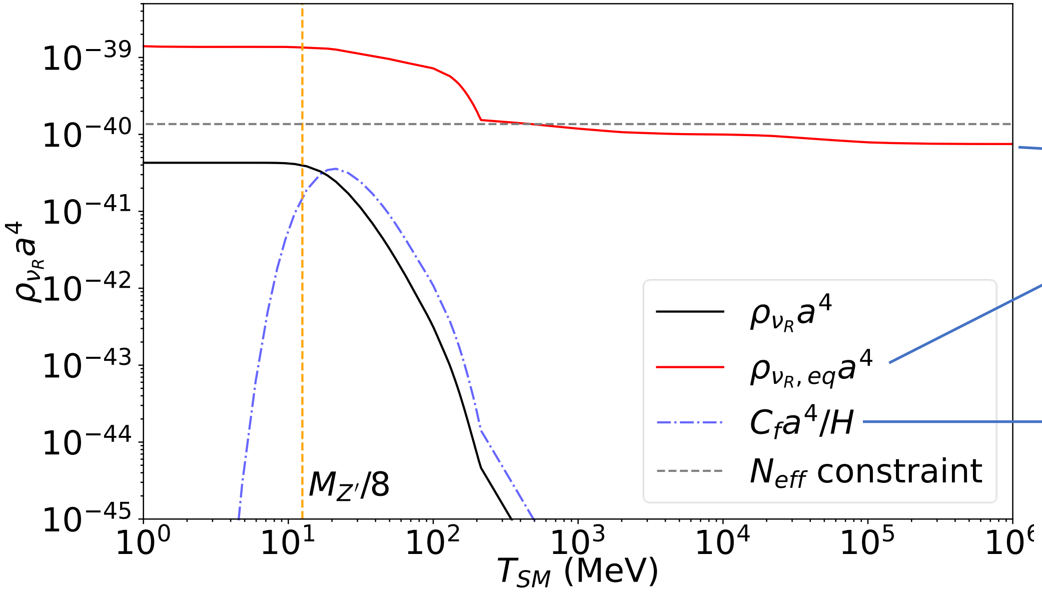

If ν_R is always in equilibrium with the Standard Model plasma

Only the forward part of the collision term

Physics behind Neff constraints: Energy density evolution without thermalization

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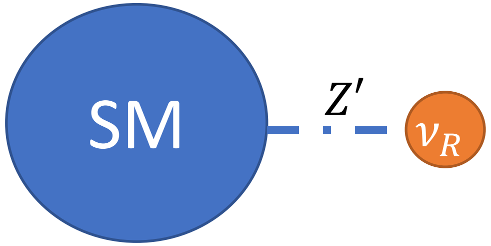
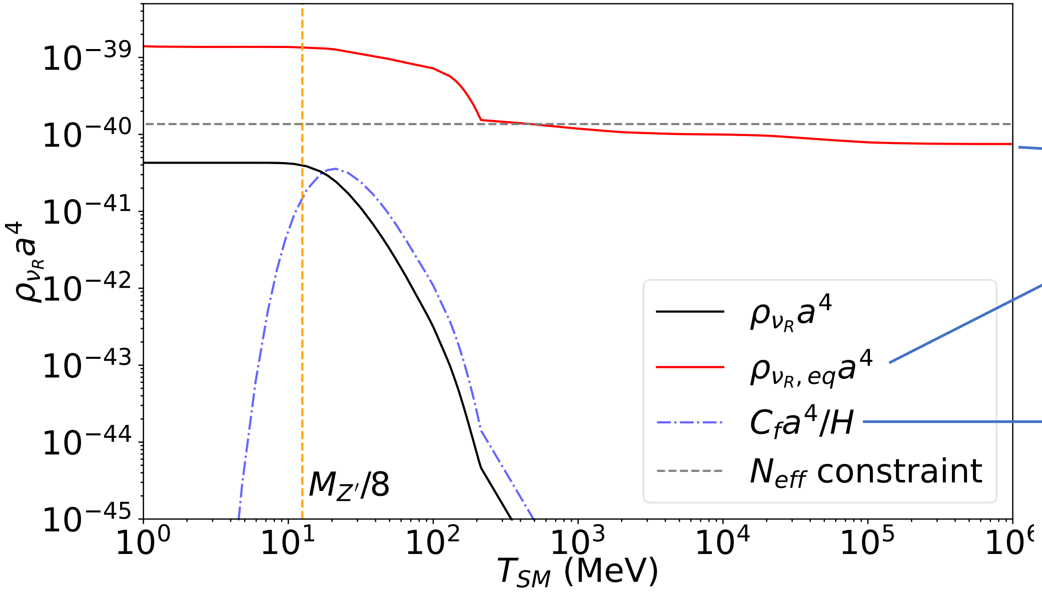


Final energy density proportional to the strength of the portal interaction



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Physics behind Neff constraints: Energy density evolution

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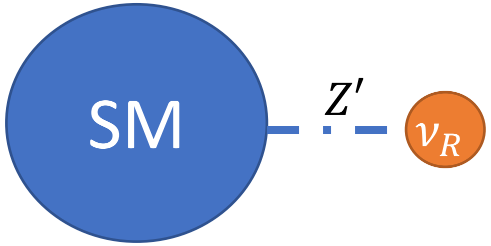

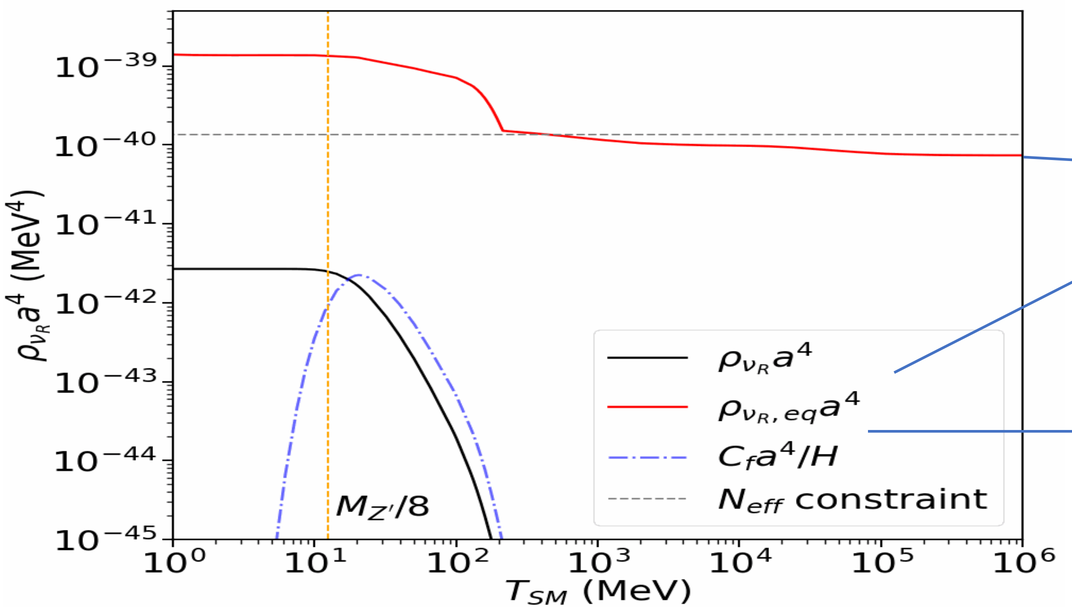

If ν_R is always in equilibrium with the Standard Model plasma

Only the forward part of the collision term

Physics behind Neff constraints: Energy density evolution with thermalization

Boltzmann equations:

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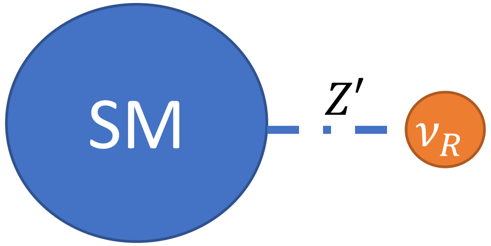
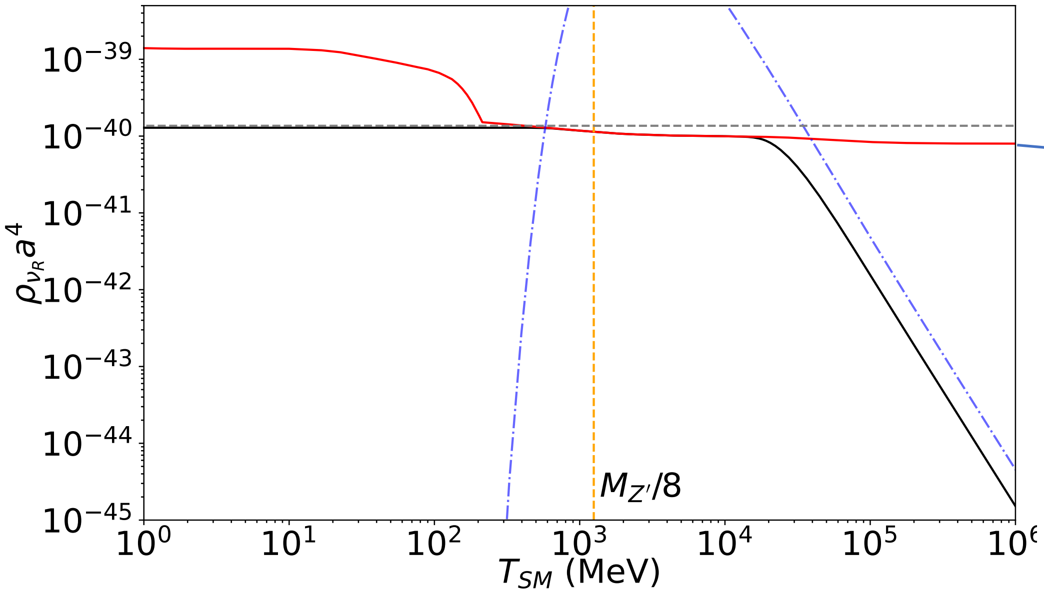


Final energy density largely insensitive to the strength of the portal interaction

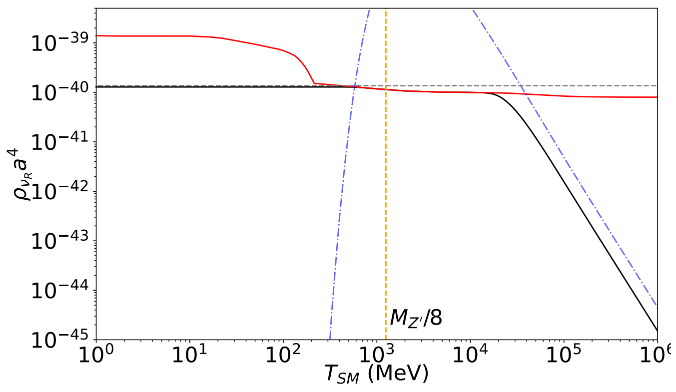
$$\frac{\rho_{\nu_R}}{\rho_{SM}} \propto \frac{g_{\nu_R}}{g_{*SM}}$$

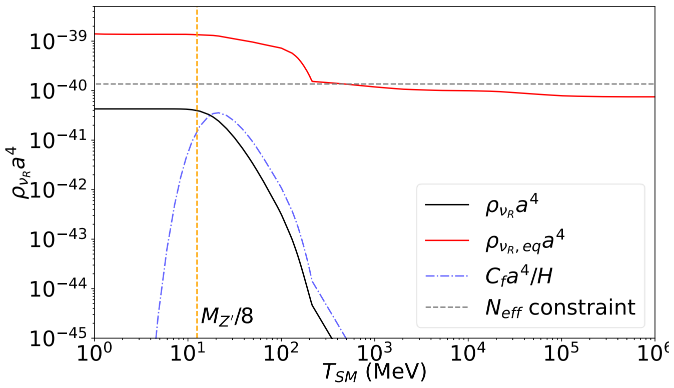
Degrees of freedom



If ν_R is always in equilibrium with the Standard Model plasma

Physics behind Neff constraints: Translating to constraints





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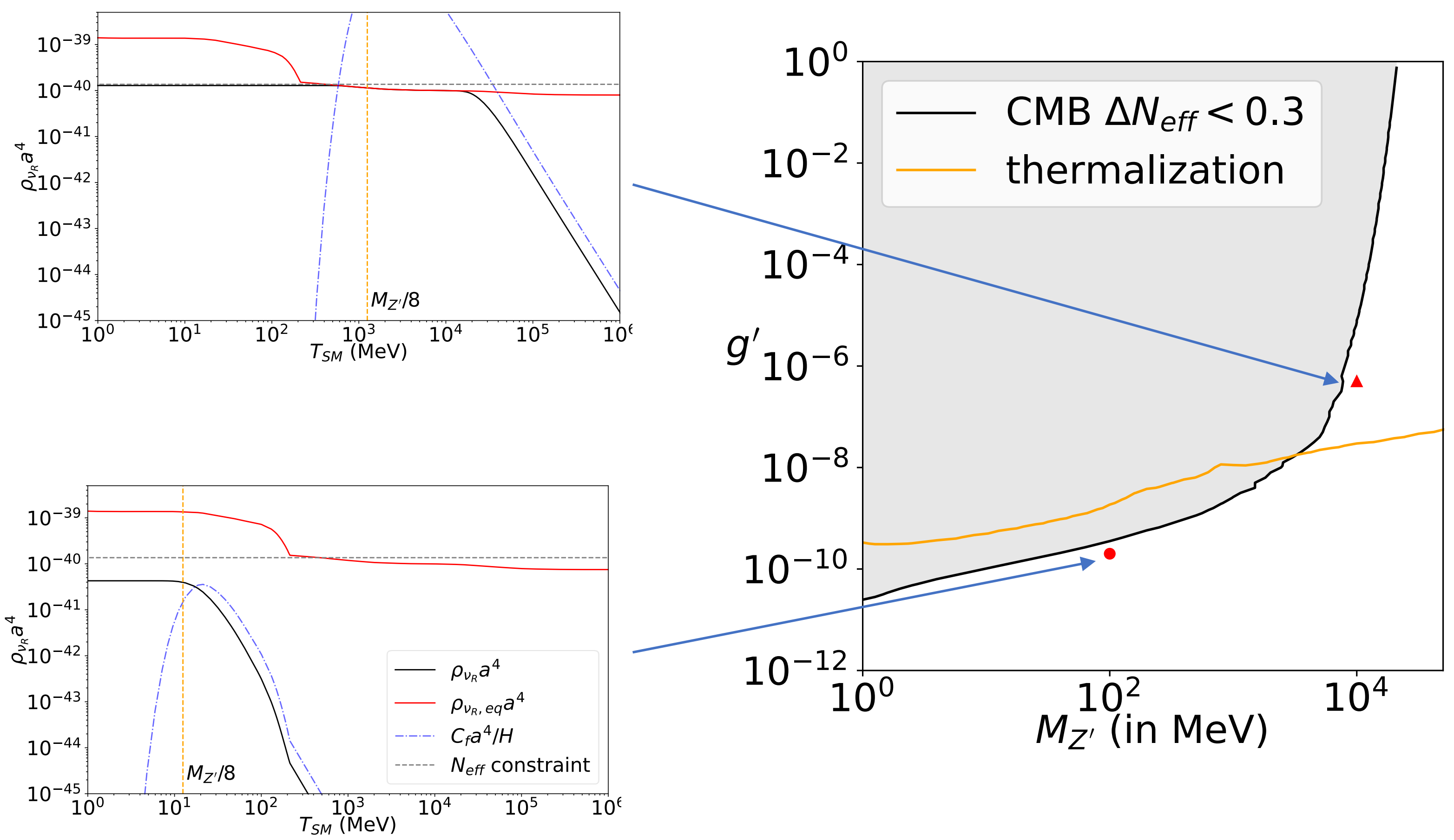
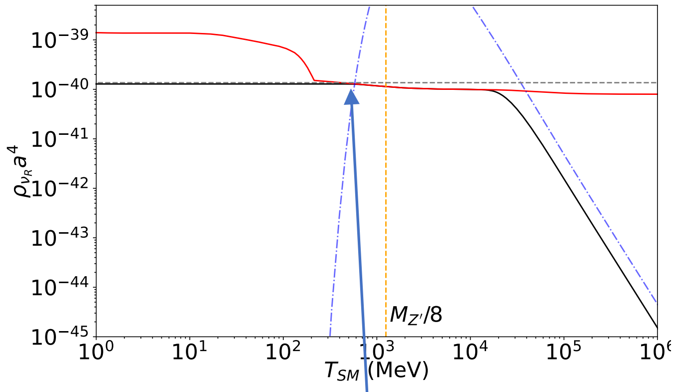
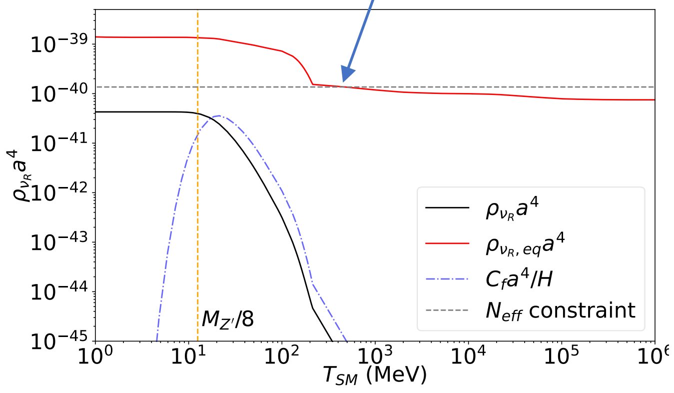


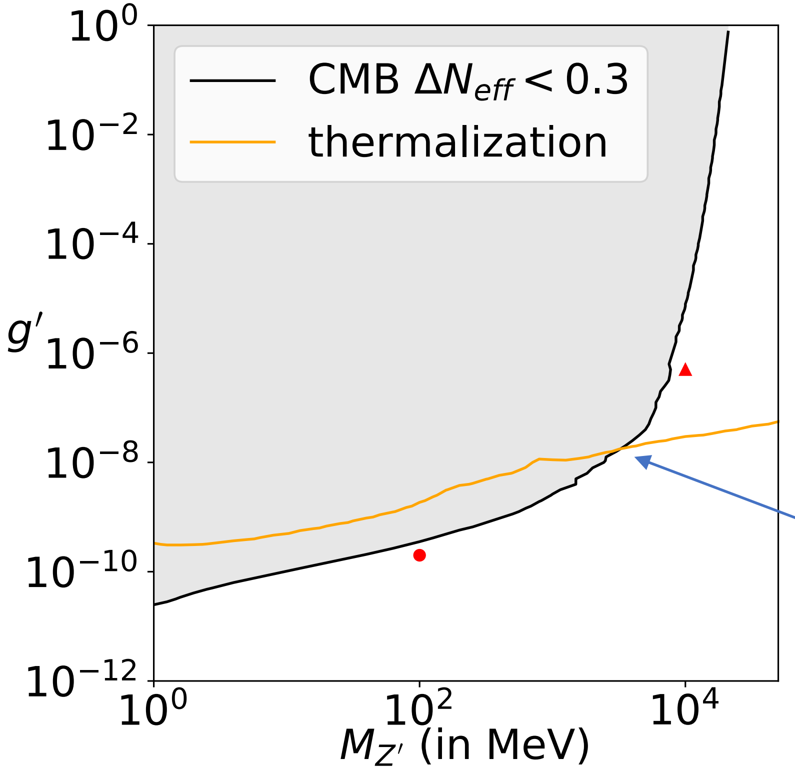
Physics behind Neff constraints: Most relevant when thermally decoupled



Smallest allowed decoupling temperature

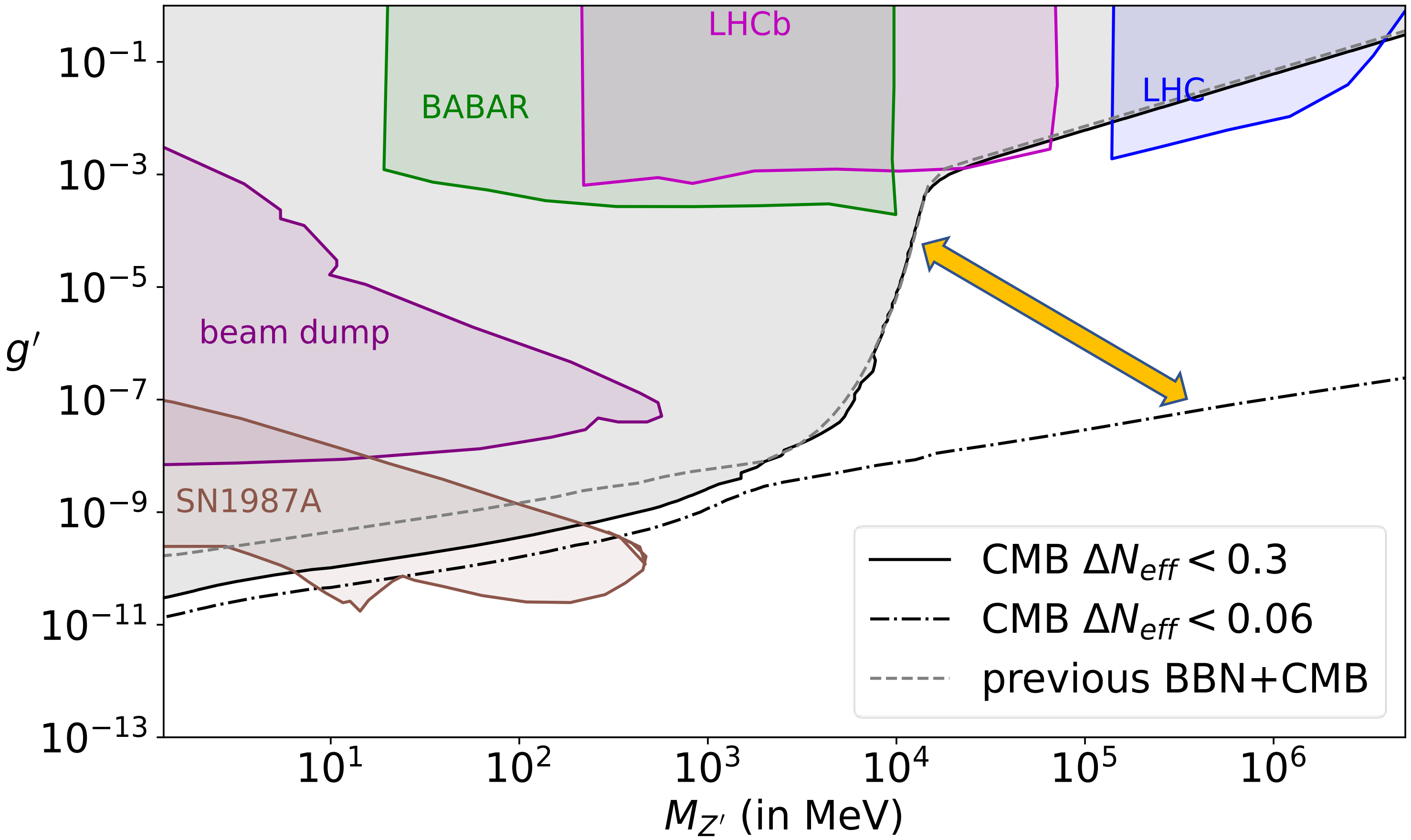
$T_{d,s}(g_{\nu_R}, \sigma_{N_{eff}})$



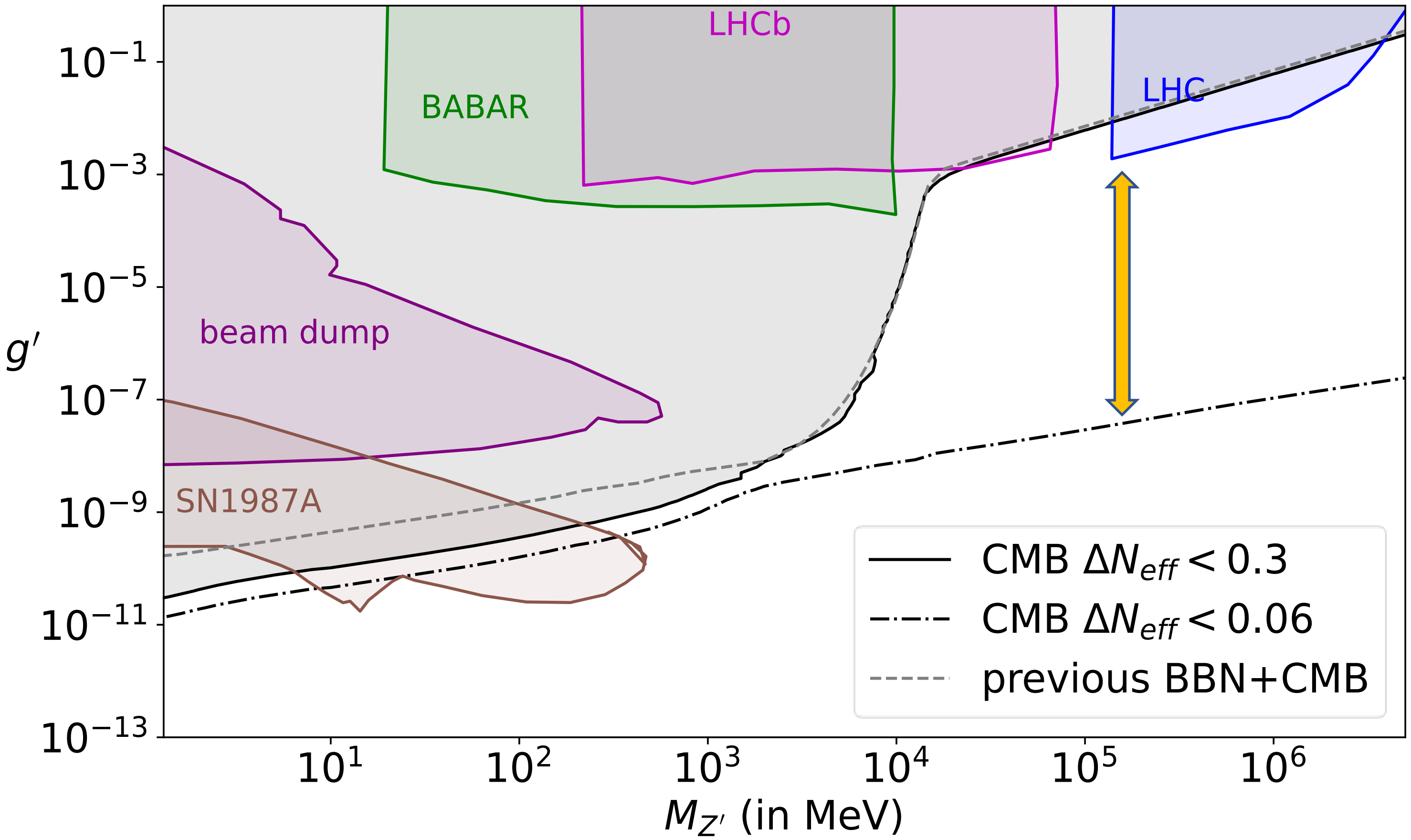


$M_{Z',th} = 8T_{d,s}$

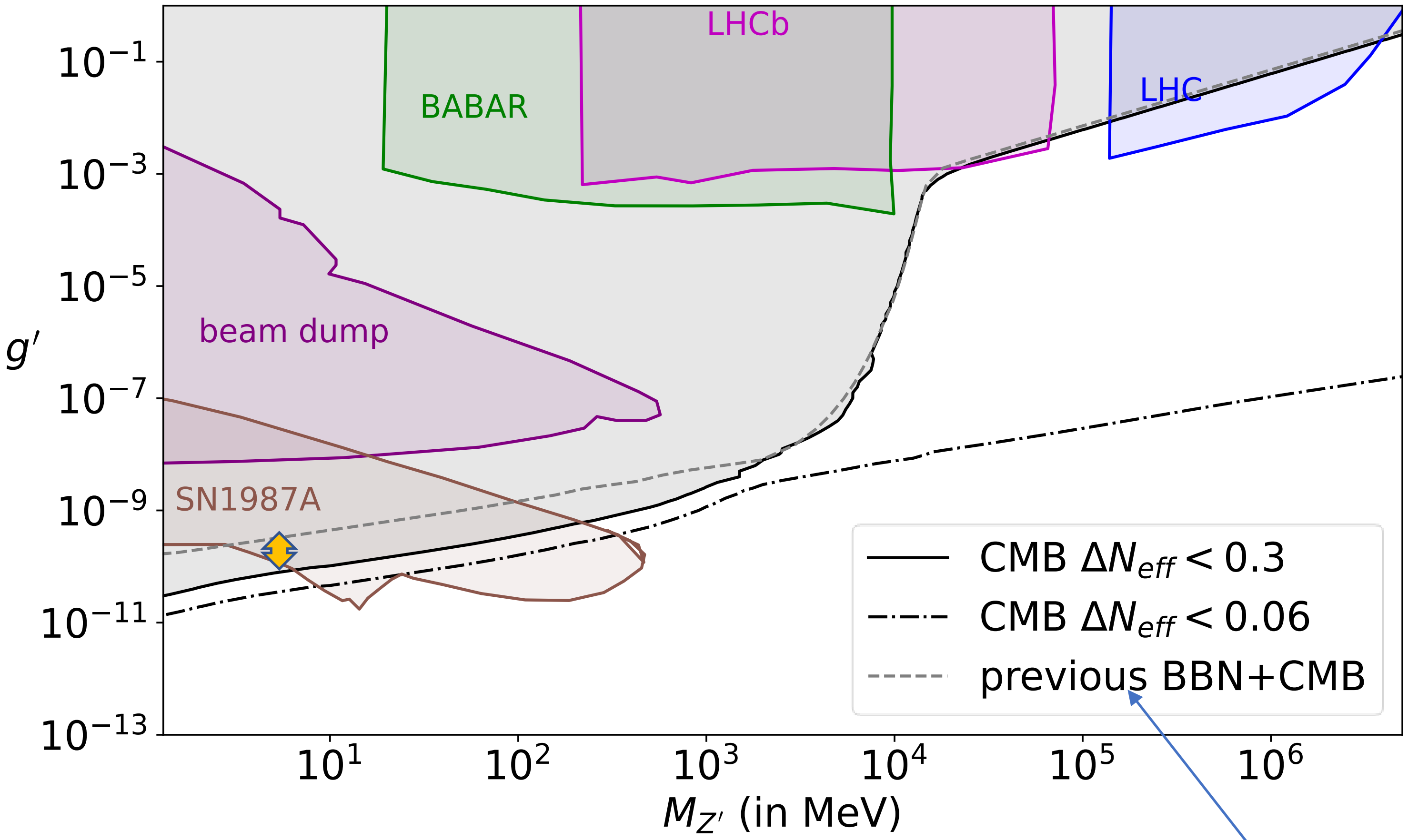
Comparing B-L constraints: Future constraint will extend to much larger parameter space



Comparing B-L constraints: Neff constraints dominant for $M_{Z'} > 0.1$ MeV

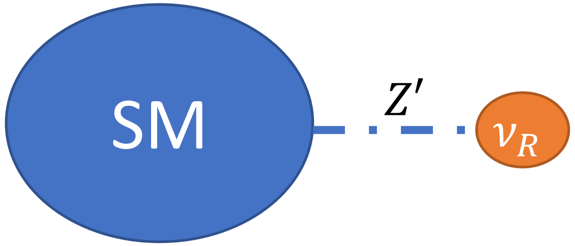


Comparing B-L constraints: Improving over previous analysis



1. K. N. Abazajian and J. Heeck, Phys. Rev. D 100 (2019) 075027.

Extending to general hidden sector



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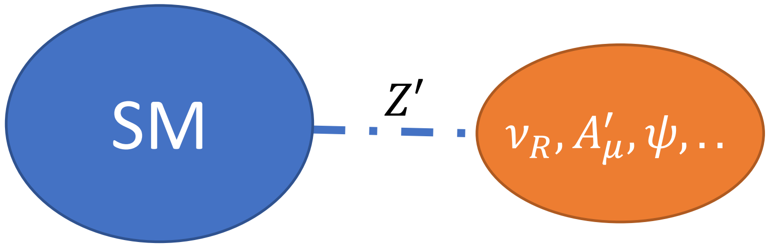

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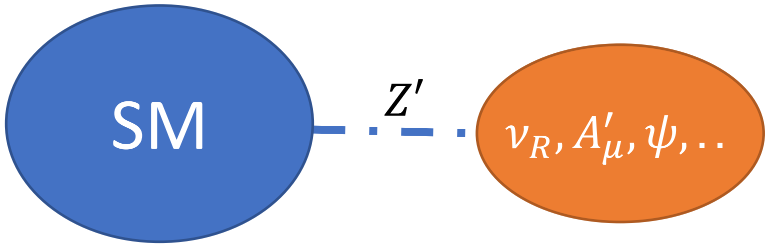
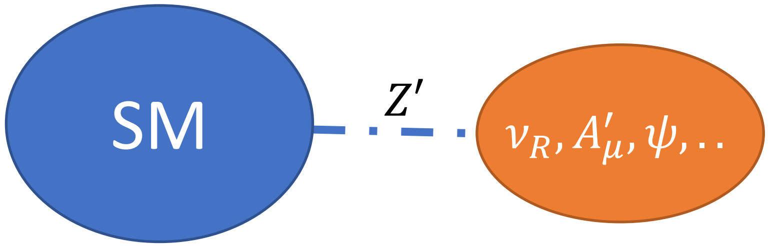


Neff constraints on the portal interactions with the minimal HS act as conservative constraints on extended HS.

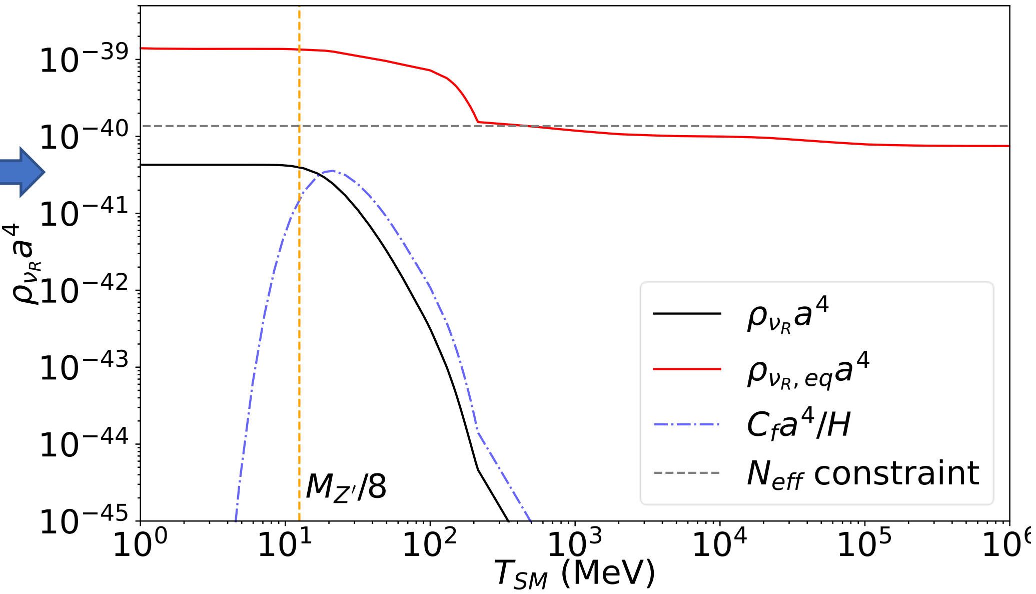
Leaked energy independent of details within HS



$$\frac{\rho_{HS}}{\rho_{SM}} \propto \frac{1}{g_{*SM}(M_{Z'}/8)} \frac{M_{pl}}{M_{Z'}} L$$

$$L = M_{Z'} \int ds \frac{s - 4m_f^2}{s\sqrt{s}} \sigma_{ff \to \nu_R \nu_R} \propto g'^2$$

Leak factor



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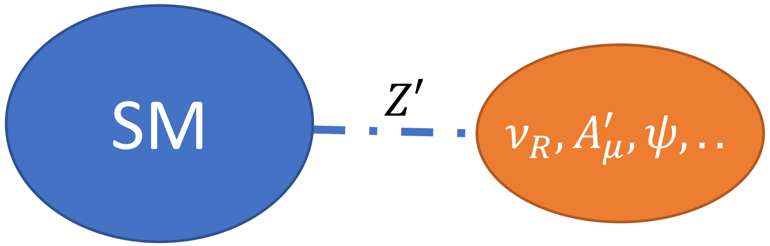

Independent of degrees of Freedom or the temperature In HS!

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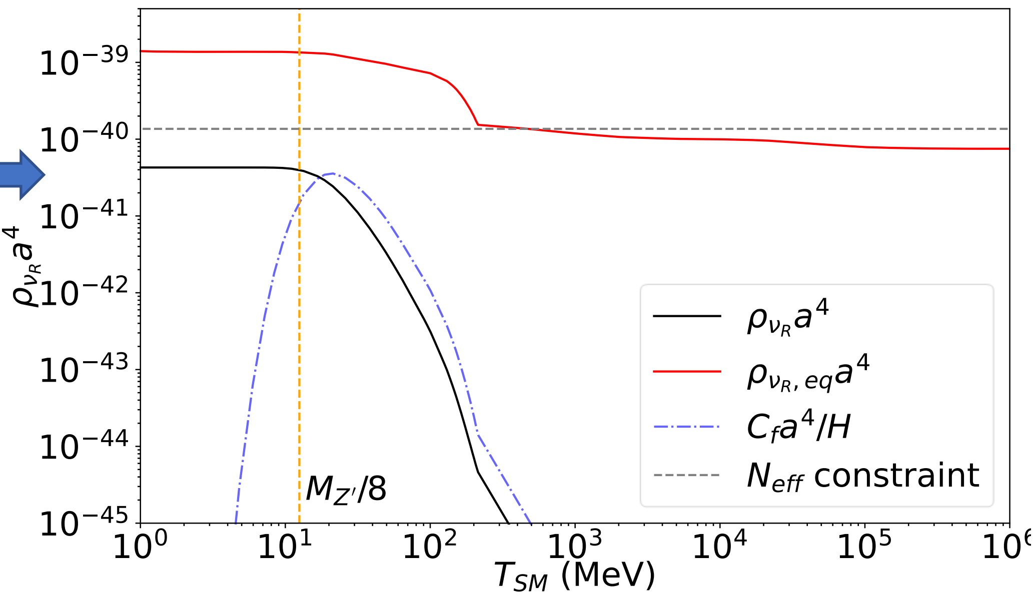
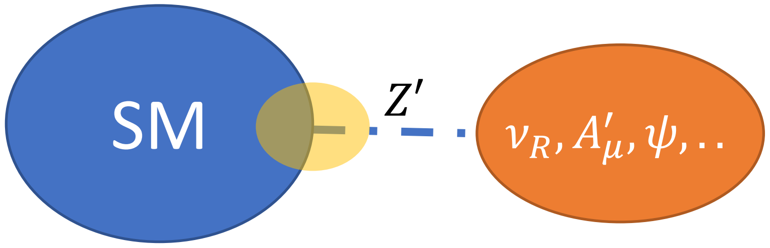


Leaked energy independent of details within HS: Depends only on one BSM coupling

Beyond Standard Model

Independent of degrees of Freedom or the temperature In HS!



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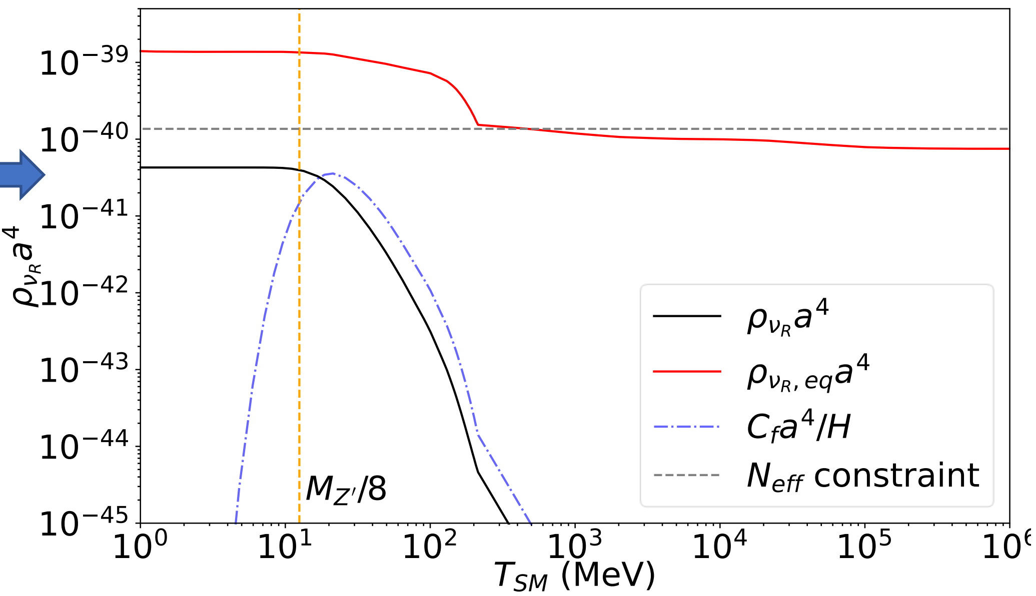
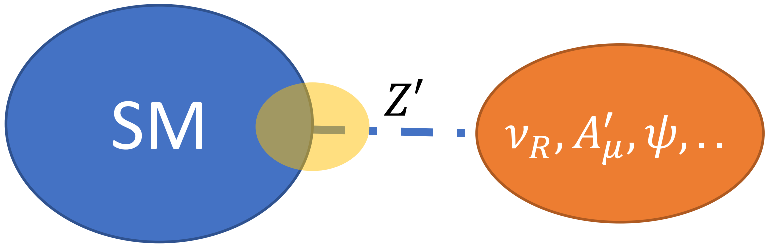


Leaked energy independent of details within HS: Depends only on one BSM coupling

Be



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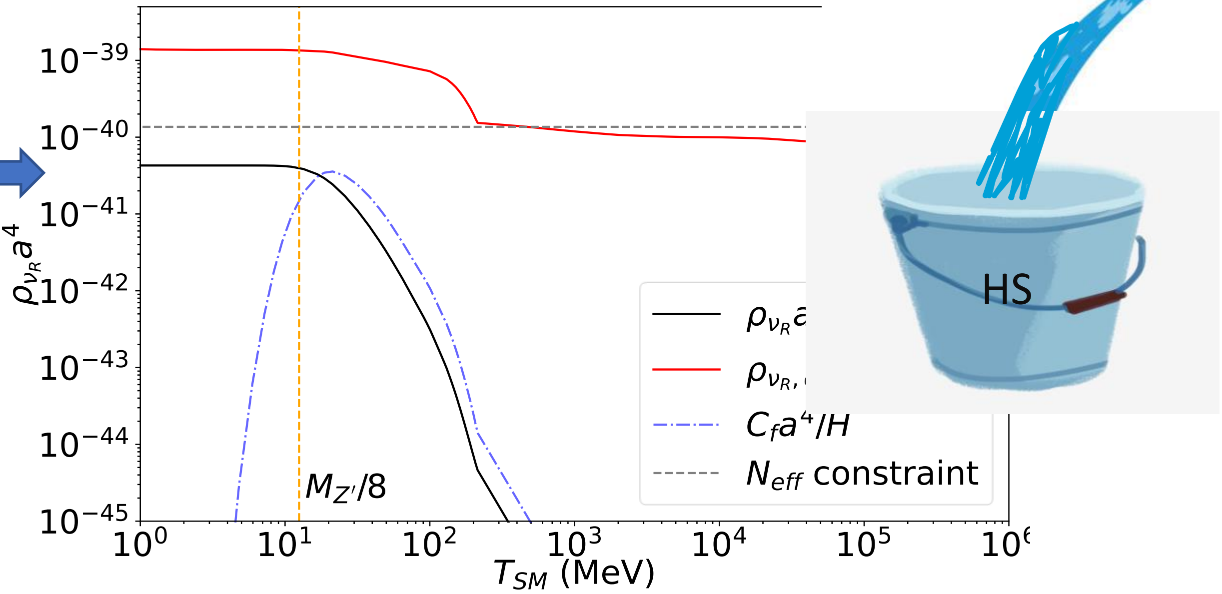
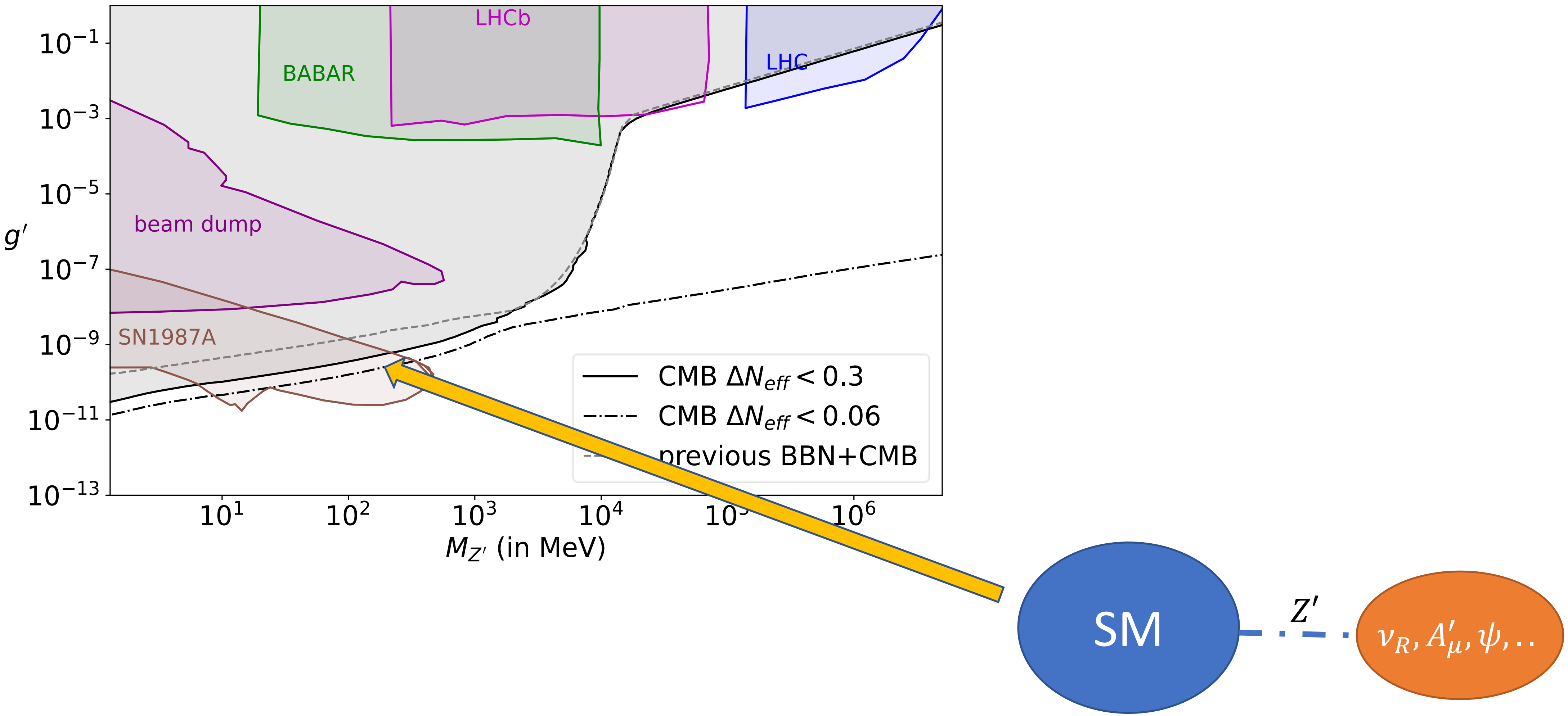
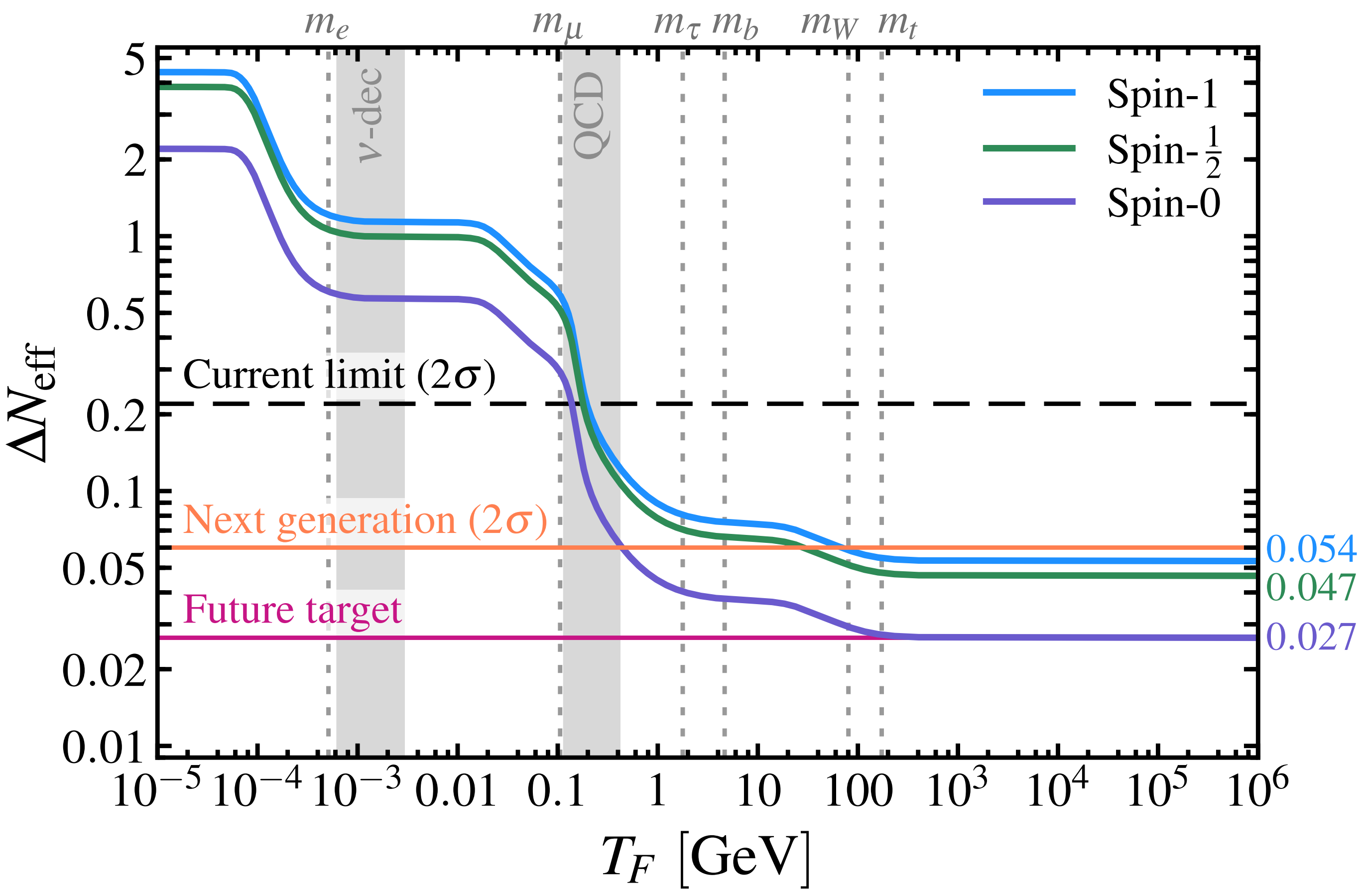


Neff constraints applicable for wide class of hidden sectors



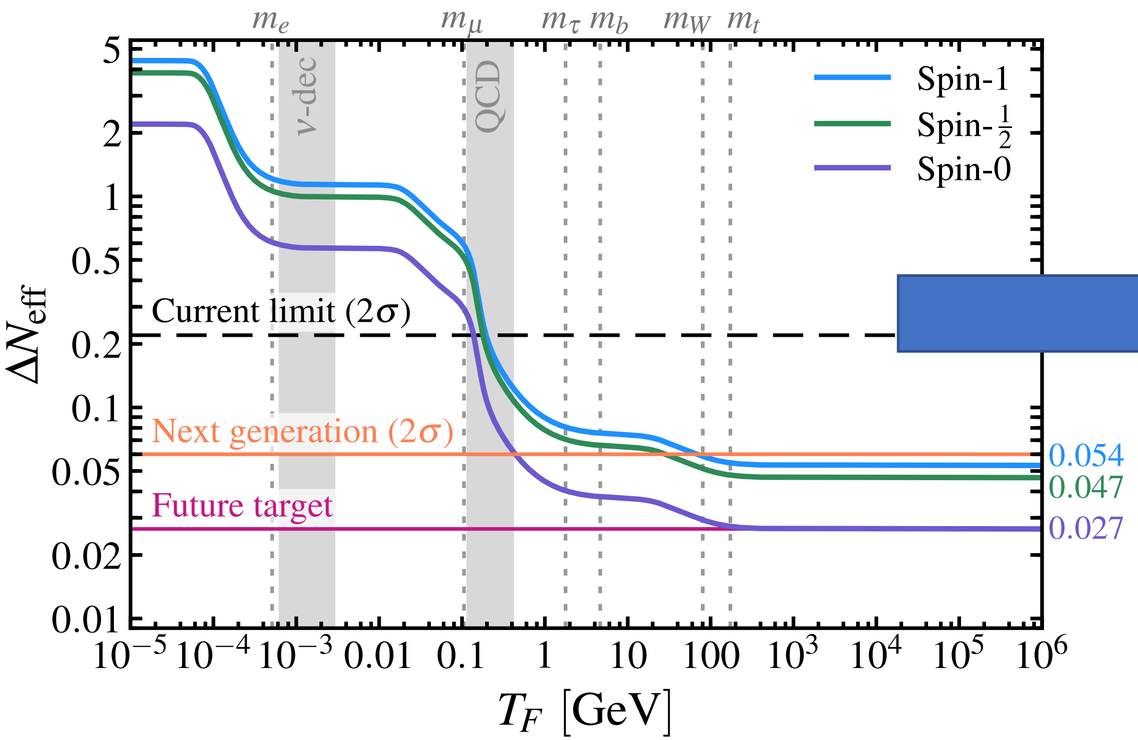
Reinterpreting the utility of Neff: Typically discussed as constraint on decoupling temperature



Decoupling temperature of new light particle

arxiv:1903:04763

Reinterpreting the utility of Neff: Instead think of as constraint on a wide class of hidden sectors



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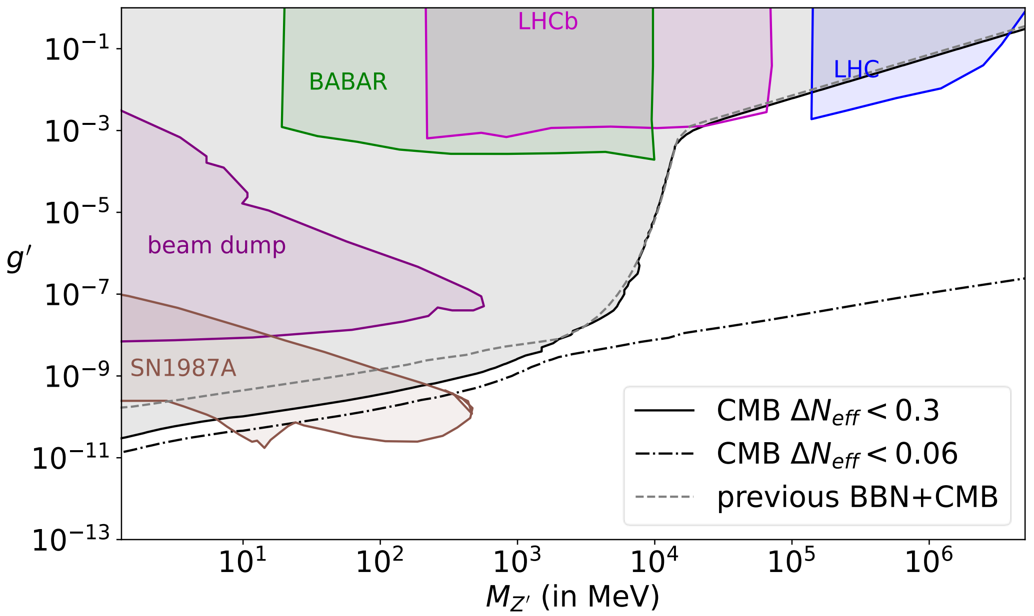
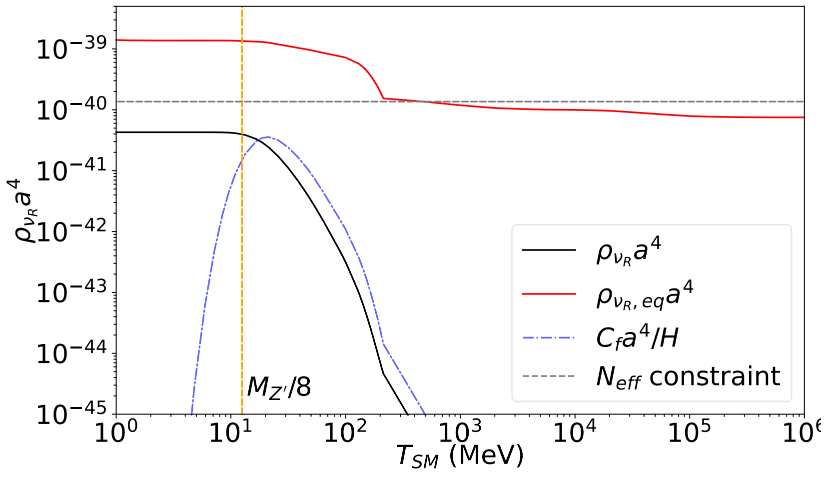


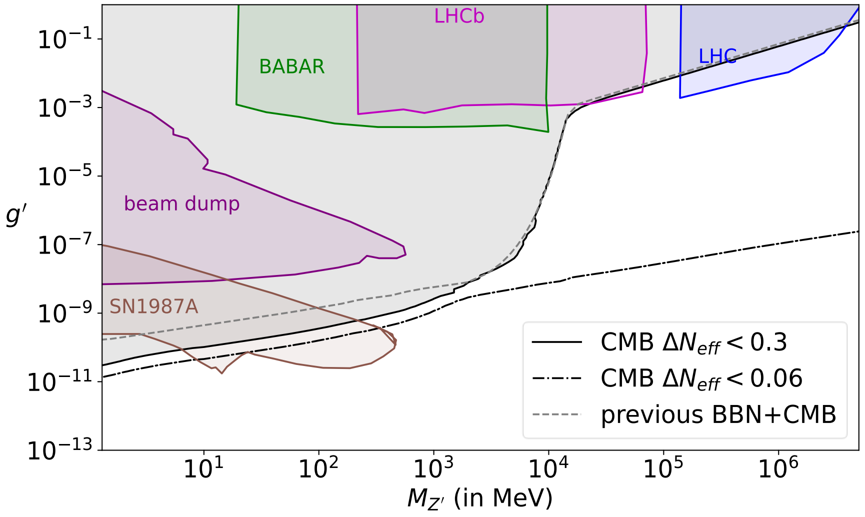
Summary

- Neff constraints are most relevant when the relativistic particles remain out-of-equilibrium with the Standard Model plasma

- As Neff measurements improve, the thermalization threshold will be pushed further away

- Neff measurements can provide conservative constraints on the portal couplings that are applicable for a large class of thermally decoupled hidden sectors.





Backup slides

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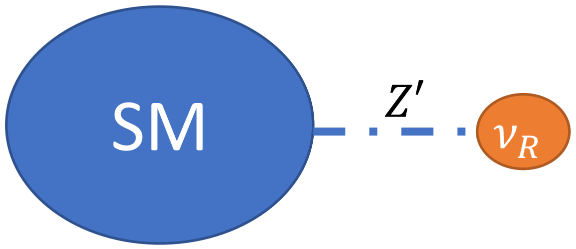
Standard Model B-L current

Right handed neutrinos

Stueckelberg mass



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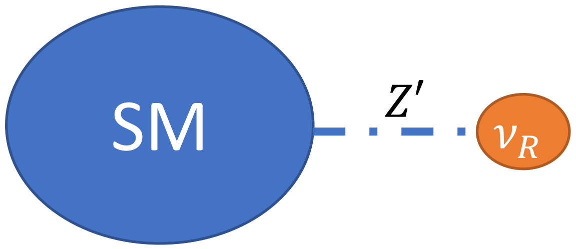

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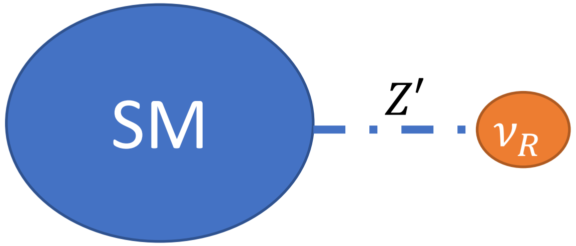

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Integral over Mandelstam s (or centre of mass energy)

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

Energy transfer collision term

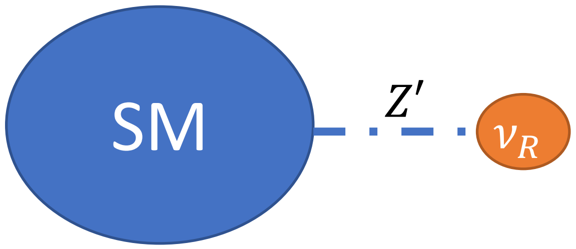
Physics behind Neff constraints: Boltzmann equations

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

Standard Model B-L current

Right handed neutrinos

Stueckelberg mass



Boltzmann equations:

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

$$\frac{d\rho_{\nu_R}}{dt} + 4H\rho_{\nu_R} = C$$

$$H = \frac{\sqrt{\rho_{SM} + \rho_{\nu_R}}}{\sqrt{3}M_{pl}}$$

CM frame cross-section

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

Energy transfer collision term

Physics behind Neff constraints: Boltzmann equations

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

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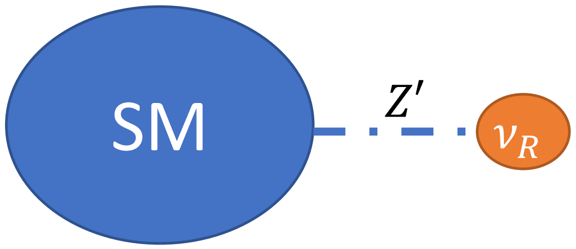

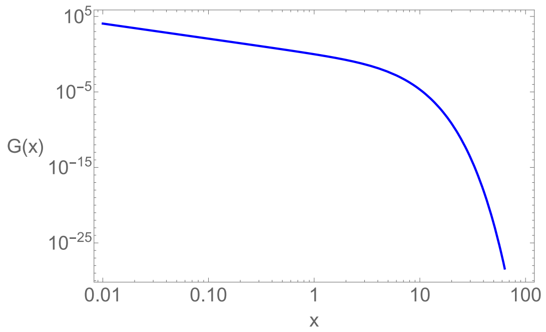

Phase-space factor encoding Fermi-Dirac distribution

Boltzmann equations:

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

$$\frac{d\rho_{\nu_R}}{dt} + 4H\rho_{\nu_R} = C$$

$$H = \frac{\sqrt{\rho_{SM} + \rho_{\nu_R}}}{\sqrt{3}M_{pl}}$$

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

Energy transfer collision term