Probing Axion Couplings to Matter with N_{eff} Measurements

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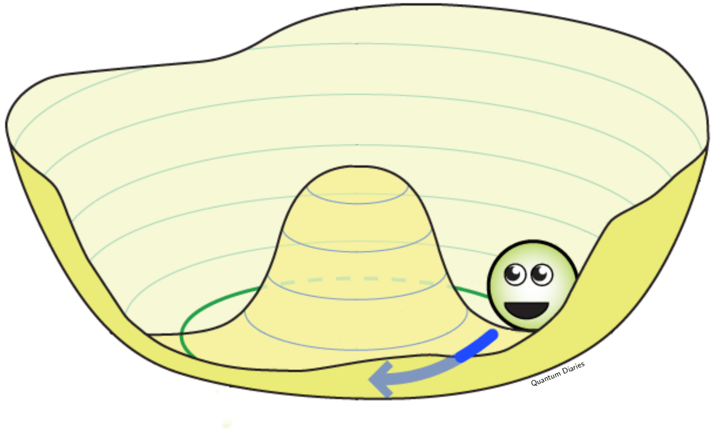
Based on work in progress with:
Daniel Green & Yi Guo

CMB-S4 Collaboration Meeting, August 2021

Extra Light Species



Light and weakly interacting particles arise in many BSM models, e.g. from spontaneously broken global symmetries.

Classification of their interactions with the Standard Model in effective field theory:

$$\mathcal{L} \supset \sum \frac{\mathcal{O}_X \mathcal{O}_{\mathrm{SM}}}{\Lambda^{\Delta}}$$

allowed interactions constrained by symmetry

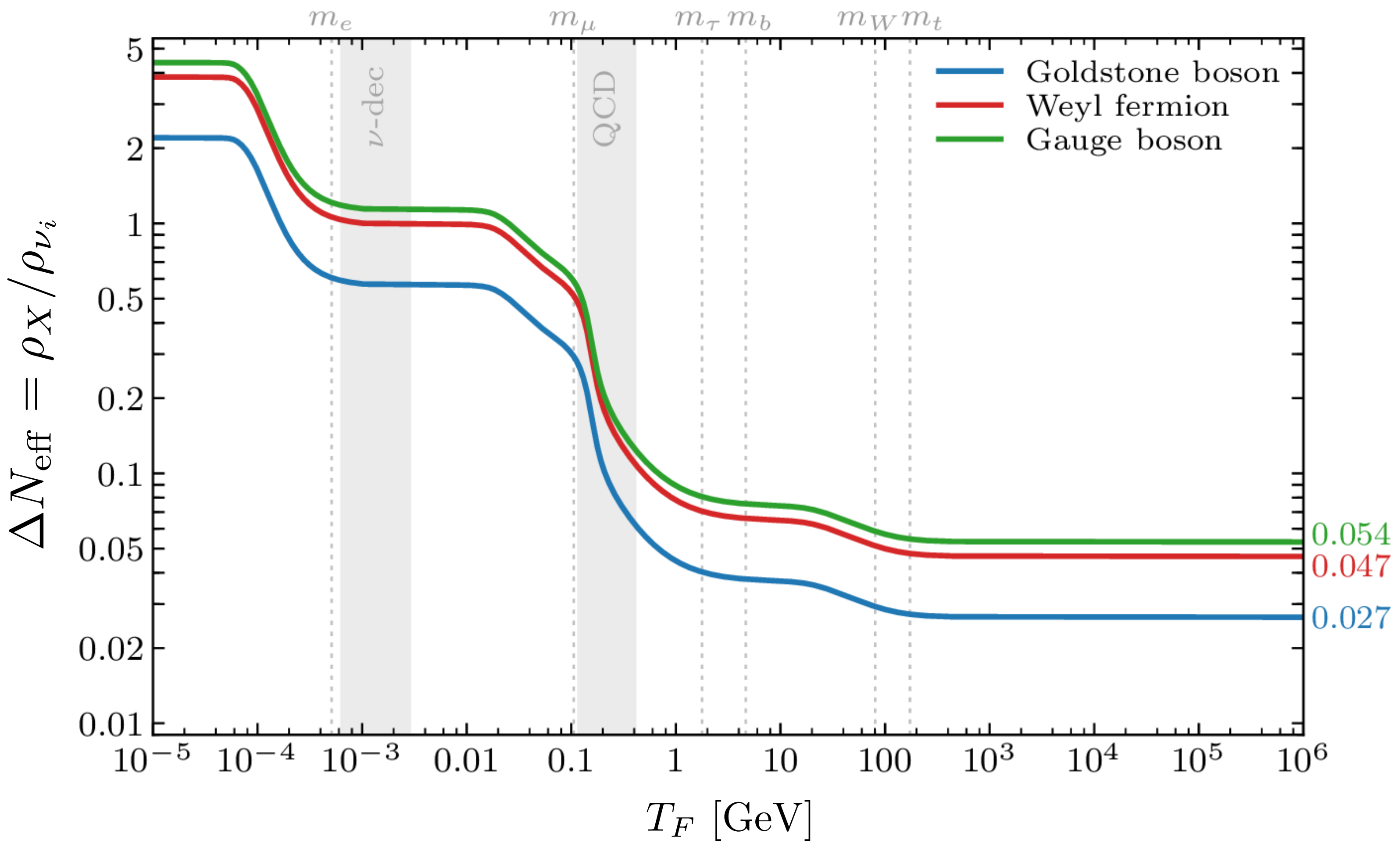
symmetry breaking scale
(in the following: $\Delta = 1$)

Useful to classify according to spin
$\rightarrow$ dark scalars (e.g. axions), dark fermions, dark forces, gravitinos.

Brust, Kaplan & Walters (2013)

Light Thermal Relics

Relic density in units of the neutrino density



Freeze-out temperature

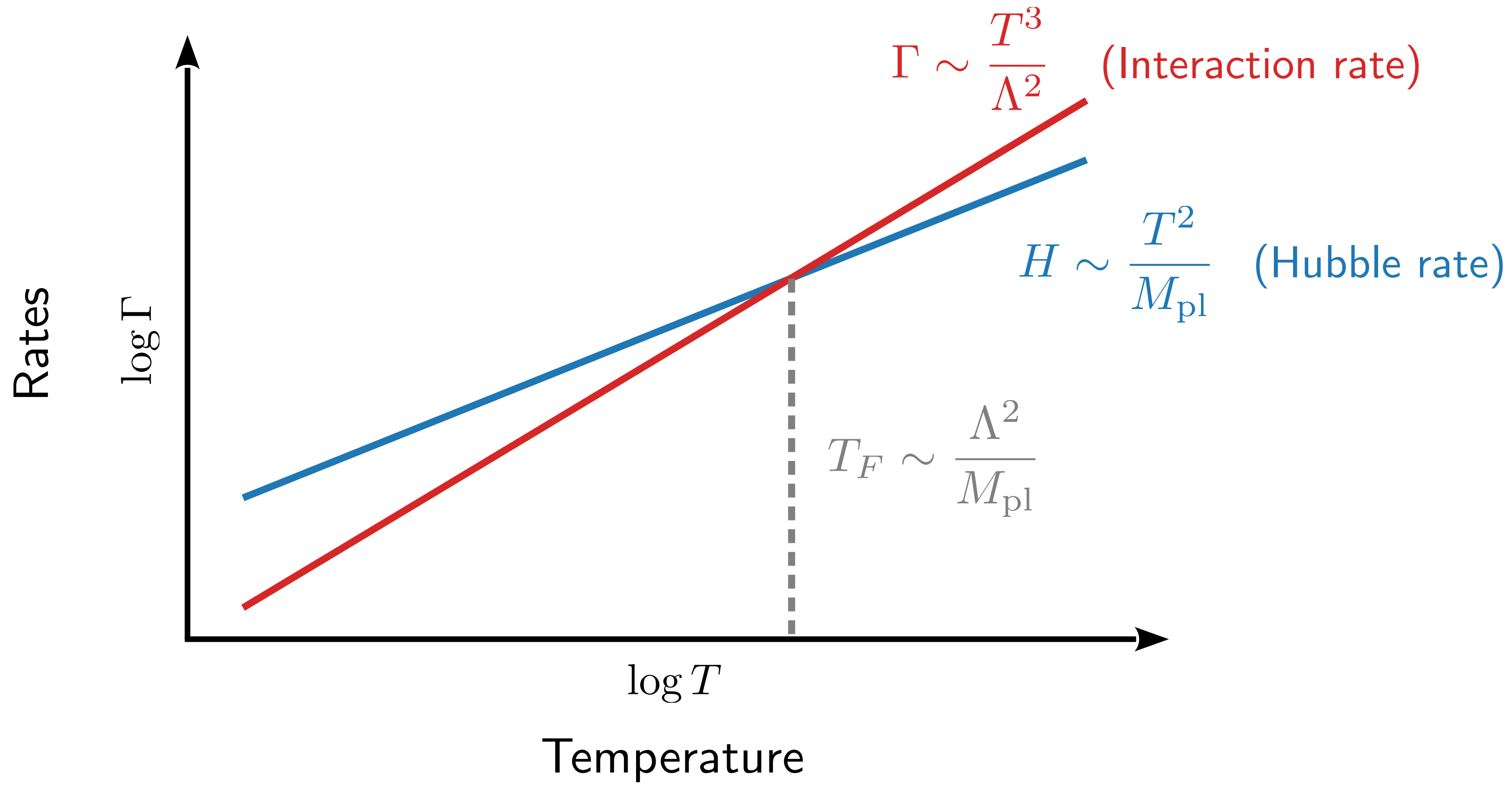
Depends on coupling Λ

$$\Delta N_{\rm eff}(T_F) = 0.027\, g_{*,X} \left(\frac{g_{*,\rm SM}}{g_*(T_F)} \right)^{4/3}$$

For a detailed discussion on assumptions, see e.g. BW (2018)

Freeze-Out

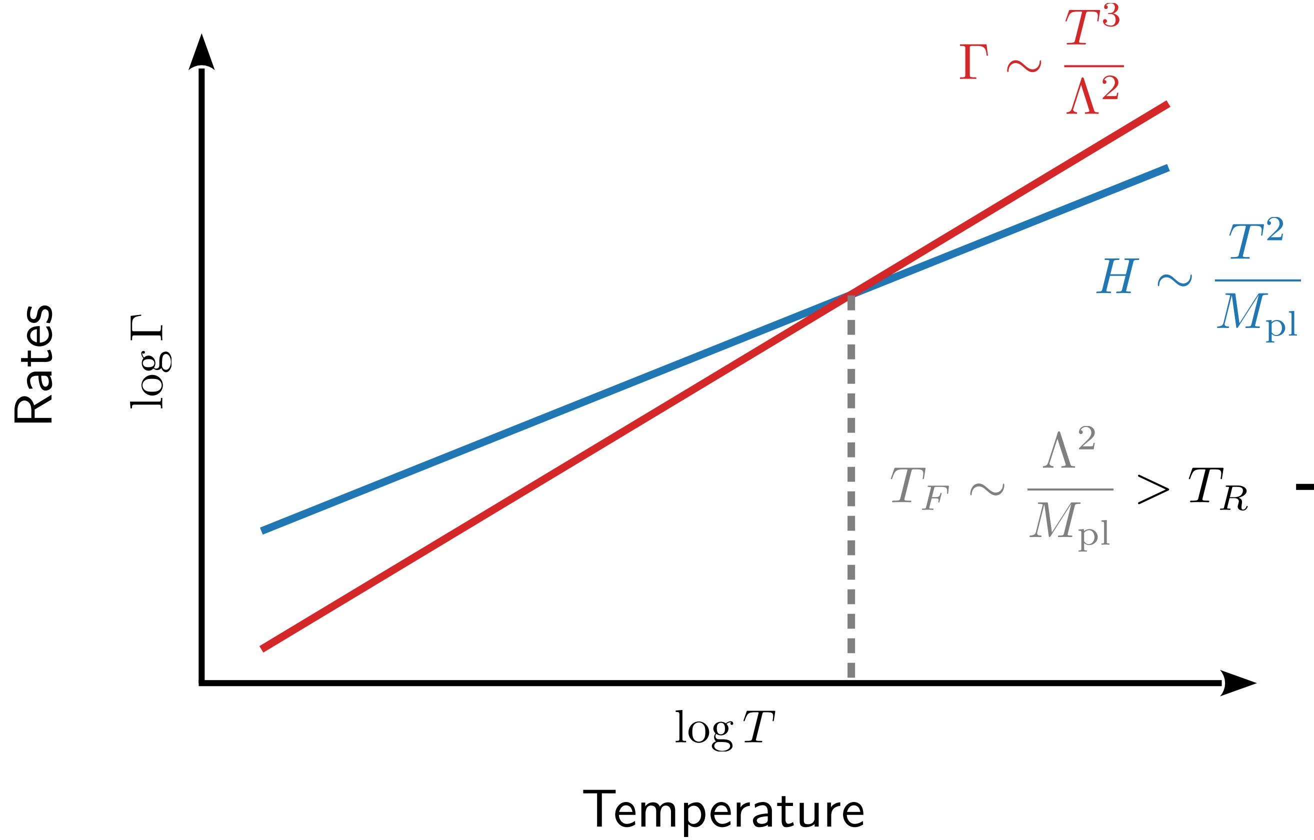
For dimension-5 couplings to massless SM particles (photons, gluons or prior to the electroweak phase transition):



Remember: freeze-out at $H(T) \sim \Gamma(T)$.

Avoid Freeze-Out Abundance

Suppress the freeze-out abundance by requiring the would-be freeze-out temperature to be below reheating temperature*:



$$T_F \sim \frac{\Lambda^2}{M_{\rm pl}} > T_R \longrightarrow \Lambda > c\sqrt{T_R\, M_{\rm pl}}$$

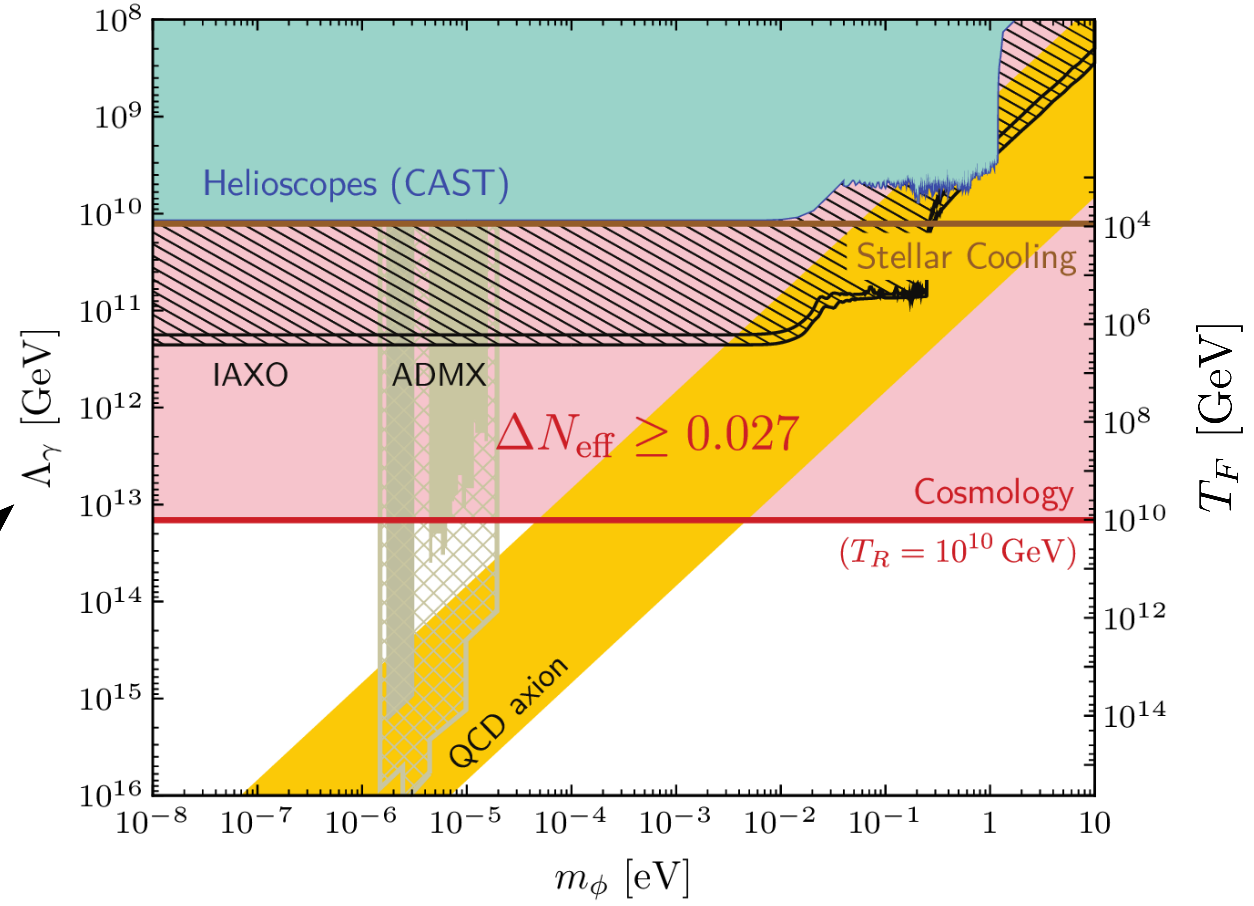
* Alternatively, weaker constraints can be derived by excluding a given freeze-out temperature.

Baumann, Green & BW (2016)

Constraints on the Axion Coupling to Photons

Exclusion of $\Delta N_{\rm eff} = 0.027$ implies strong constraints on couplings to the Standard Model:

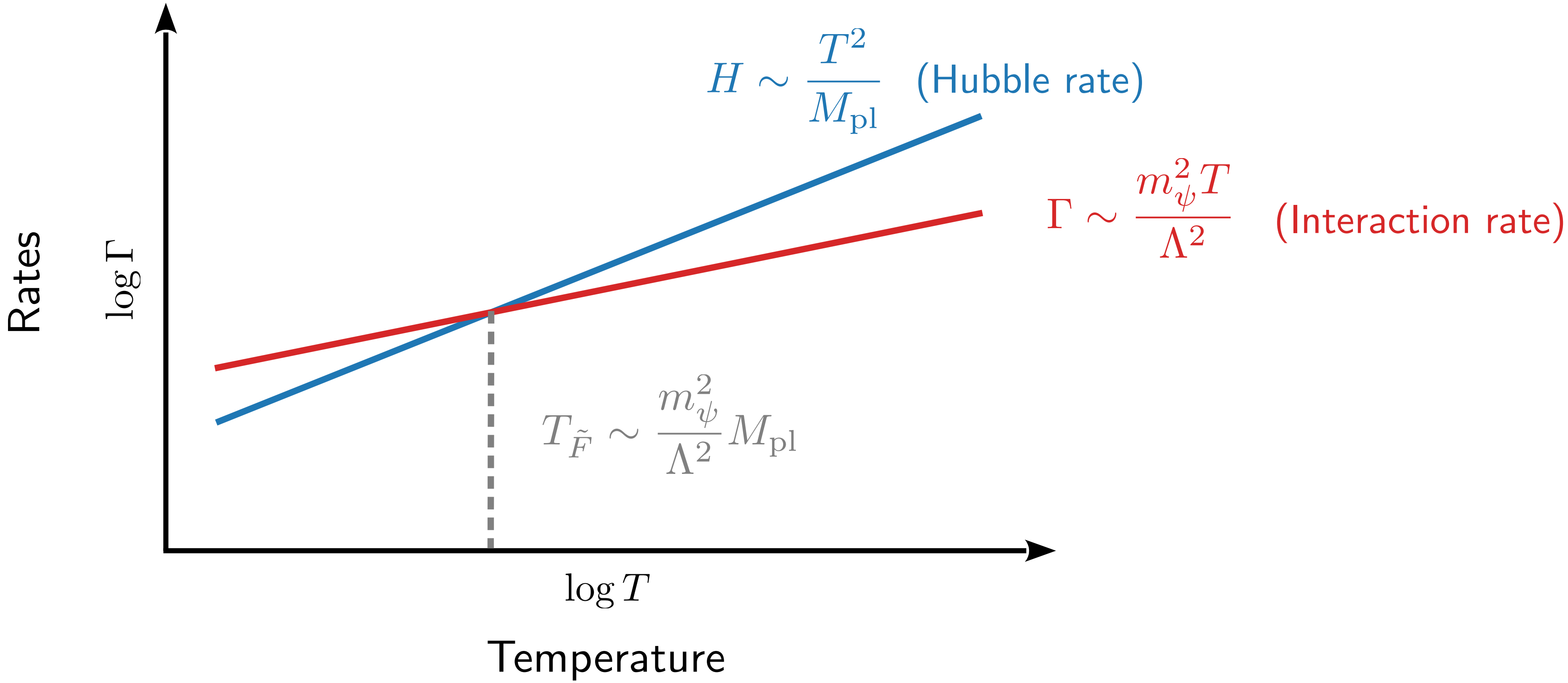
$$-\frac{\phi}{4\Lambda_\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Baumann, Green & BW (2016)

Freeze-In

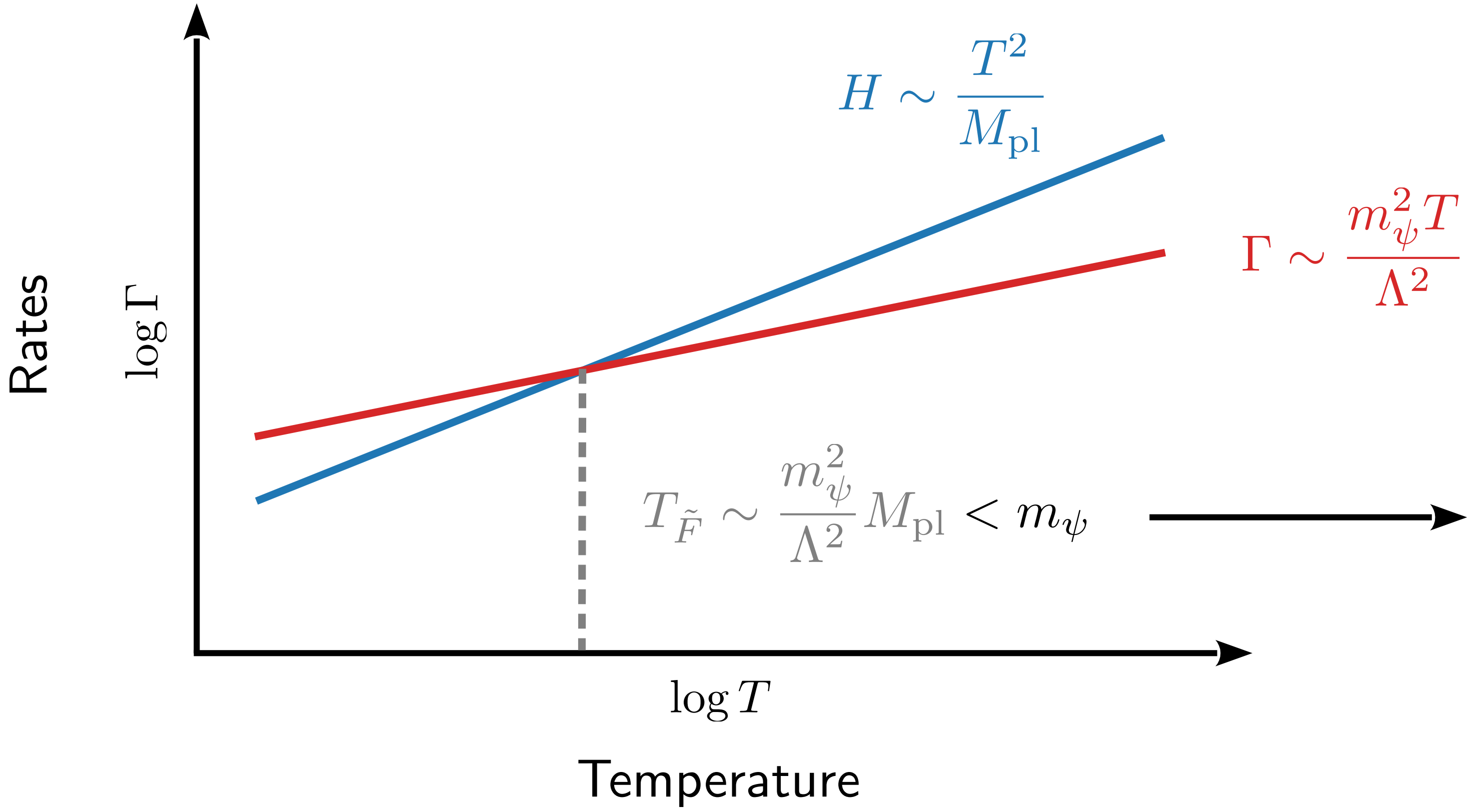
For couplings to SM fermions after the electroweak phase transition (in addition):



Remember: freeze-in at $H(T) \sim \Gamma(T)$.

Avoid Freeze-In Abundance

Boltzmann-suppress the freeze-in abundance by requiring the would-be freeze-in temperature to be below the mass of the coupled SM fermion:

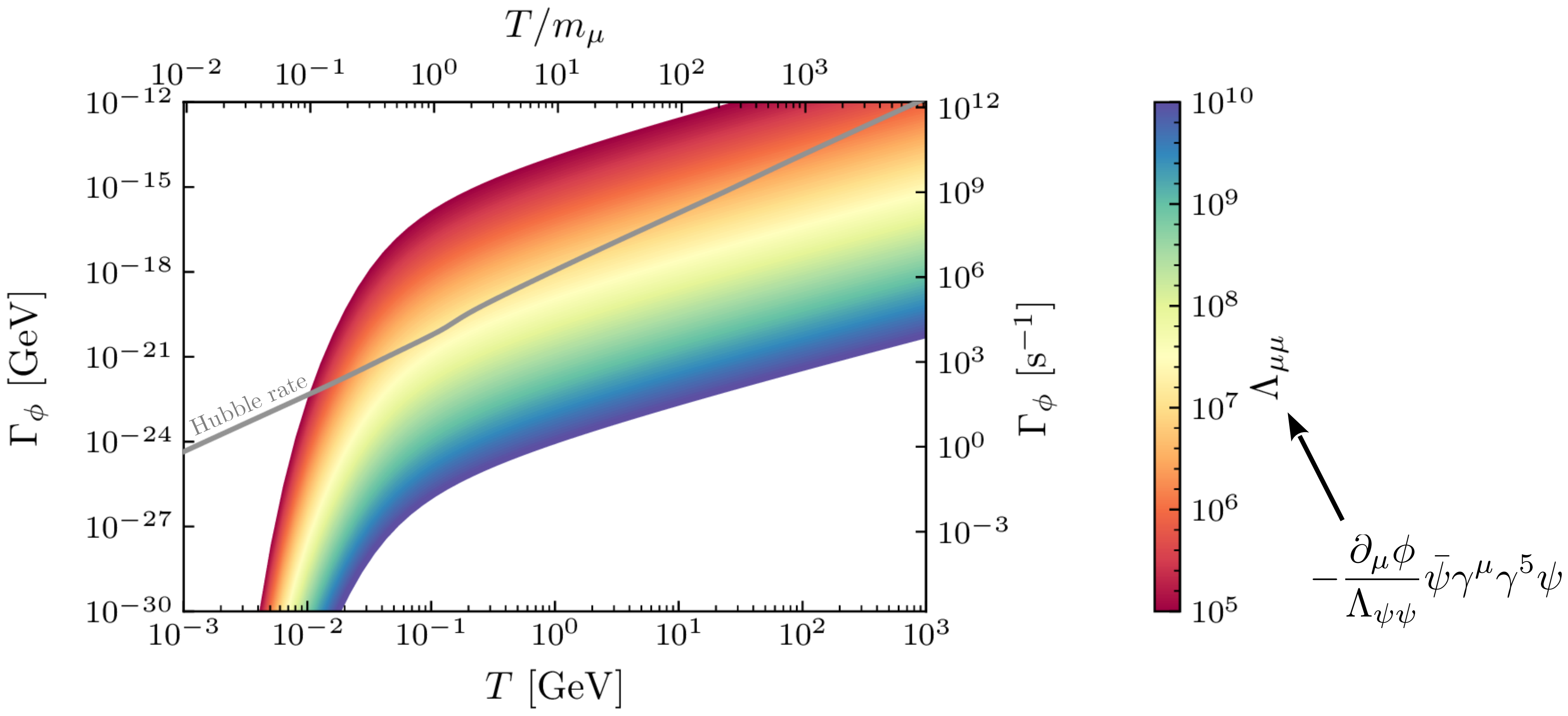


$$\Lambda \gtrsim c\sqrt{m_\psi M_{\rm pl}}$$

Baumann, Green & BW (2016)

Axion-Fermion Interaction Rate

Numerical calculation of the interaction rate without approximations:

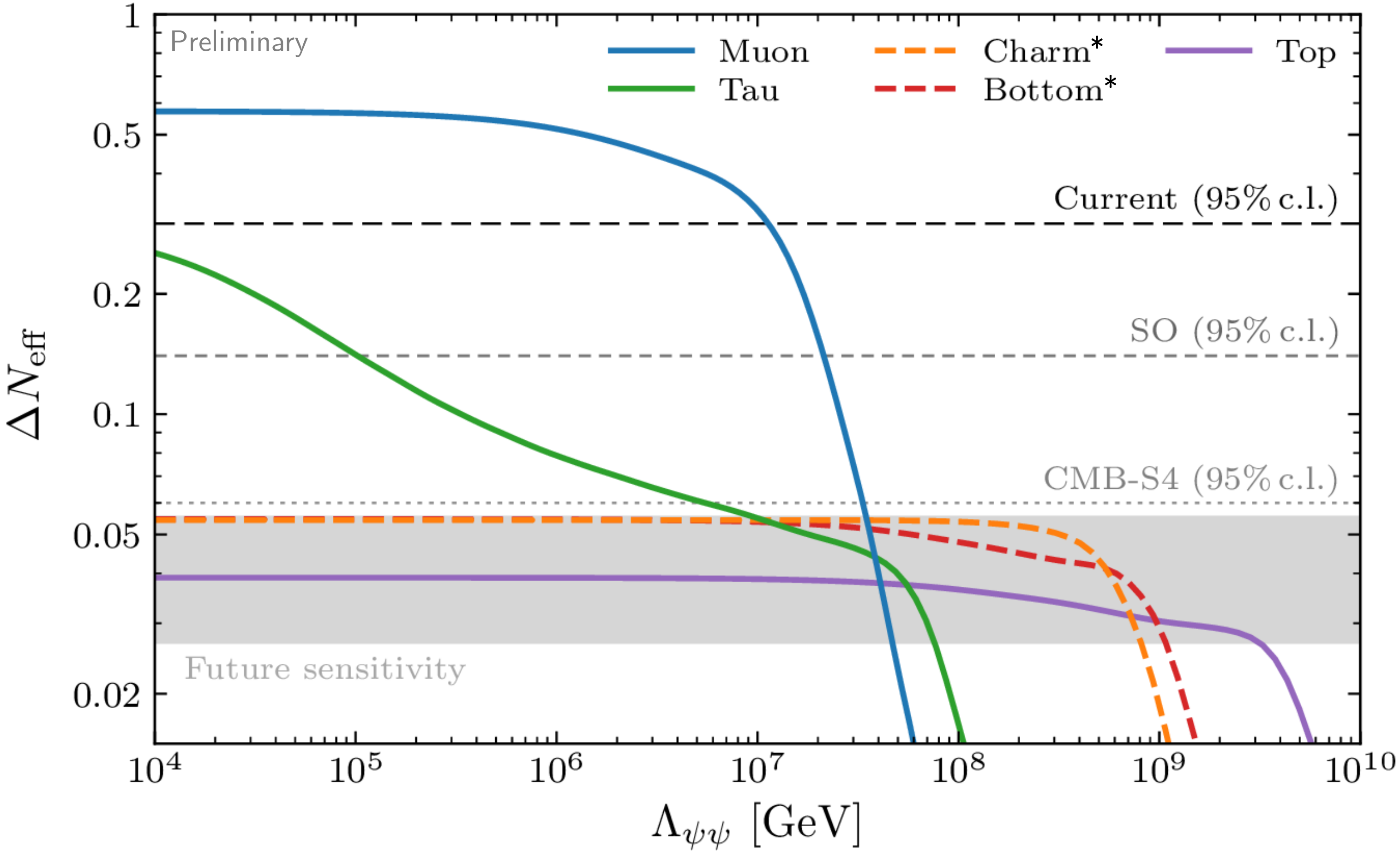


Here: muons, but similar for couplings to other massive SM fermions.

Green, Guo & BW (to appear)

Predictions for ΔN_{eff}

Solving the Boltzmann equation, we predict:

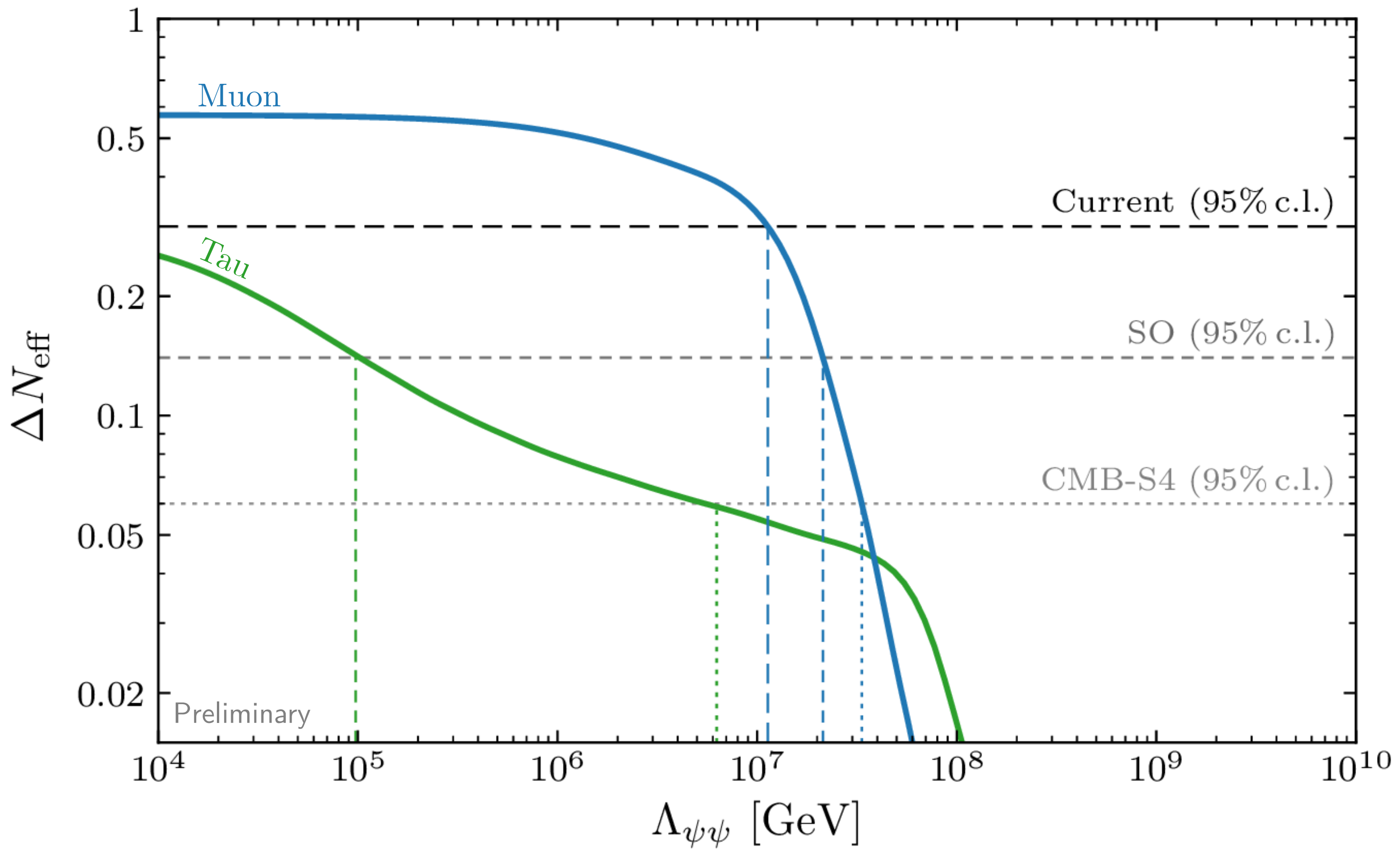


* Calculations for charm and bottom couplings are impacted by the QCD phase transition. Here: conservative estimate, might be larger.

Green, Guo & BW (to appear)

Updated Constraints on Axion Couplings to Matter Fields

Exclusion of certain levels of $\Delta N_{\rm eff}$ leads to constraints on these axion couplings:



Current:

$\Lambda_{\mu\mu} > 10^{7.1}$ GeV

$\Lambda_{\tau\tau} > 10^{3.2}$ GeV

SO:

$\Lambda_{\mu\mu} > 10^{7.3}$ GeV

$\Lambda_{\tau\tau} > 10^{5.0}$ GeV

CMB-S4:

$\Lambda_{\mu\mu} > 10^{7.5}$ GeV

$\Lambda_{\tau\tau} > 10^{6.8}$ GeV

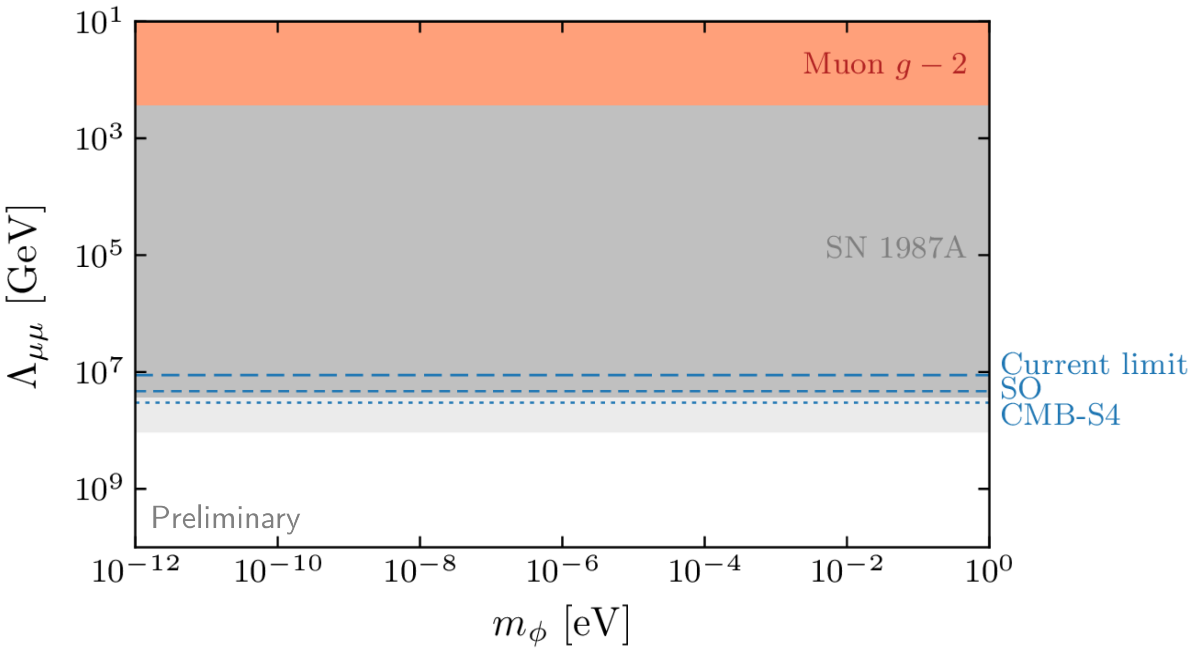
(Preliminary)

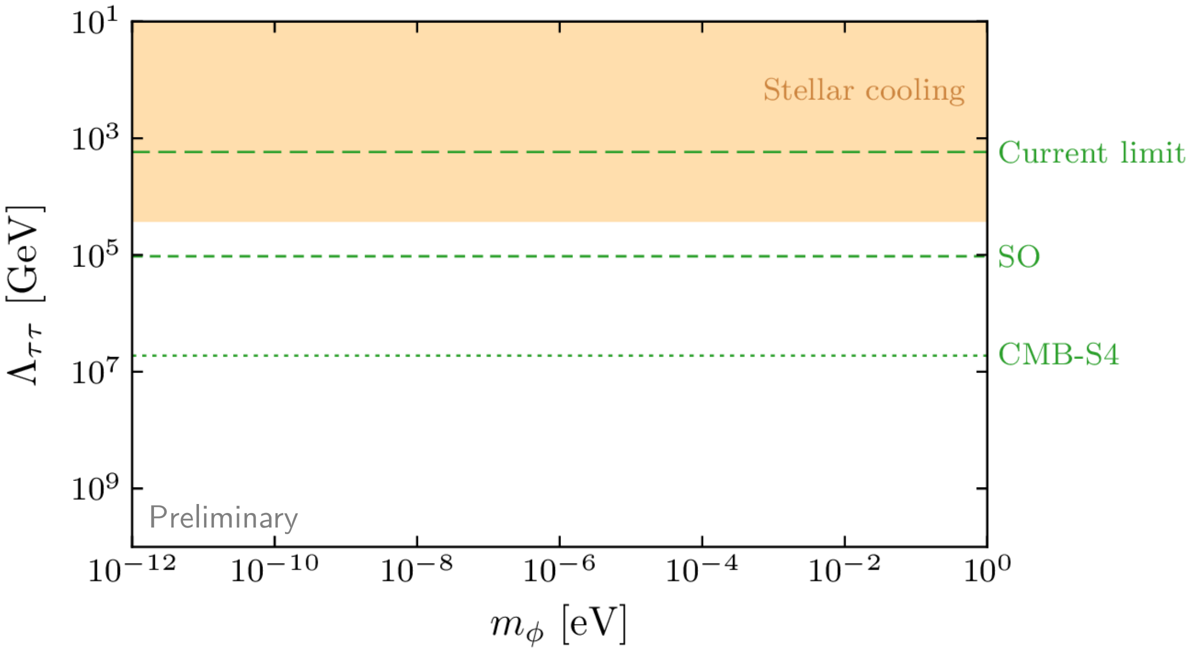
Green, Guo & BW (to appear)

Conclusions

- Constraints on $\Delta N_{\rm eff}$ do not only have implications on particle physics via freeze-out.

- Current and upcoming CMB surveys (including CMB-S4) can put complimentary and competitive constraints on axion-fermion couplings by avoiding freeze-in:

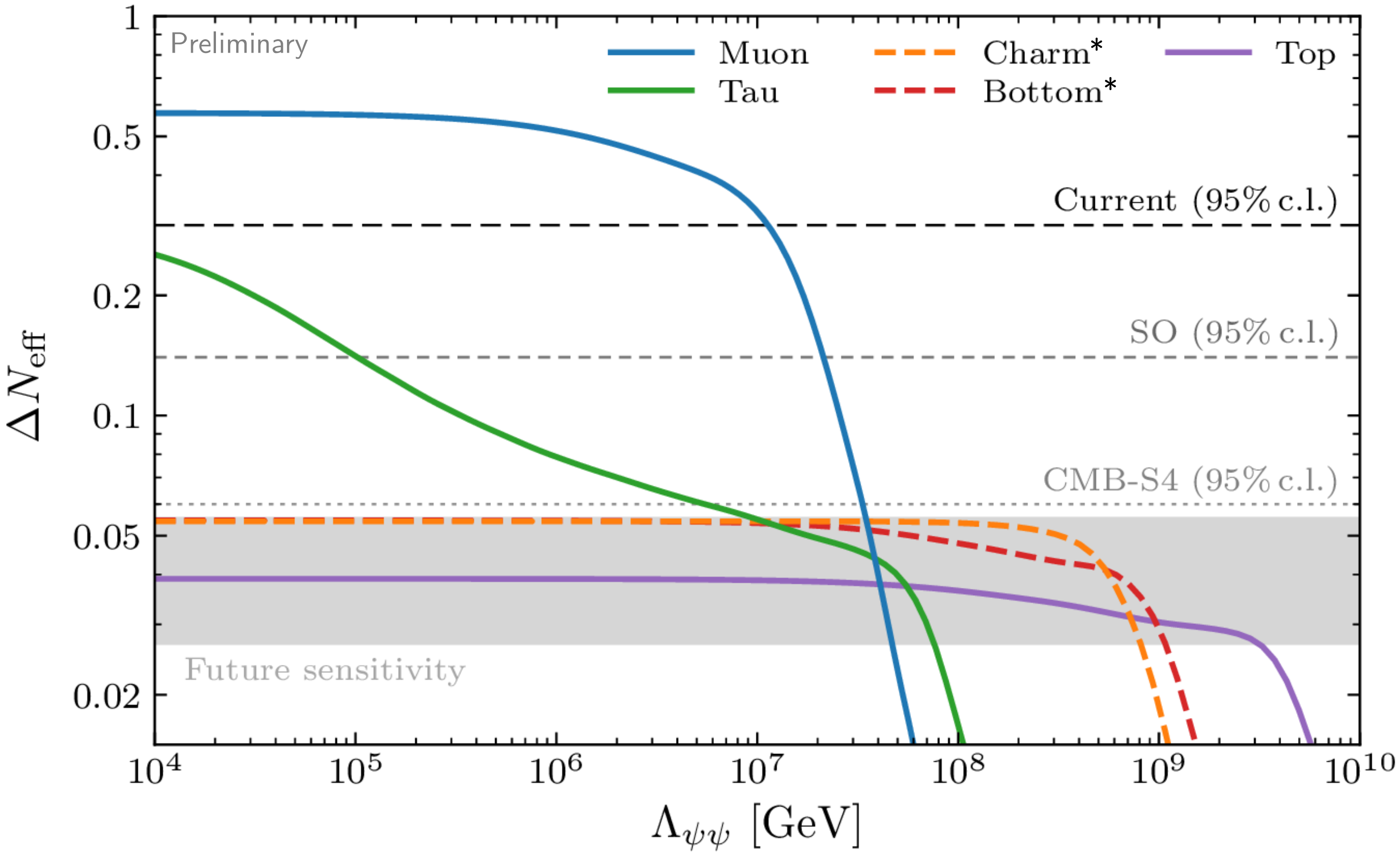




Feng et al. (1998); Andreas et al. (2010); Bollig et al. (2020); Croon et al. (2021)

Green, Guo & BW (to appear)

Thank you!



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(To appear soon – stay tuned!)

Backup Slides

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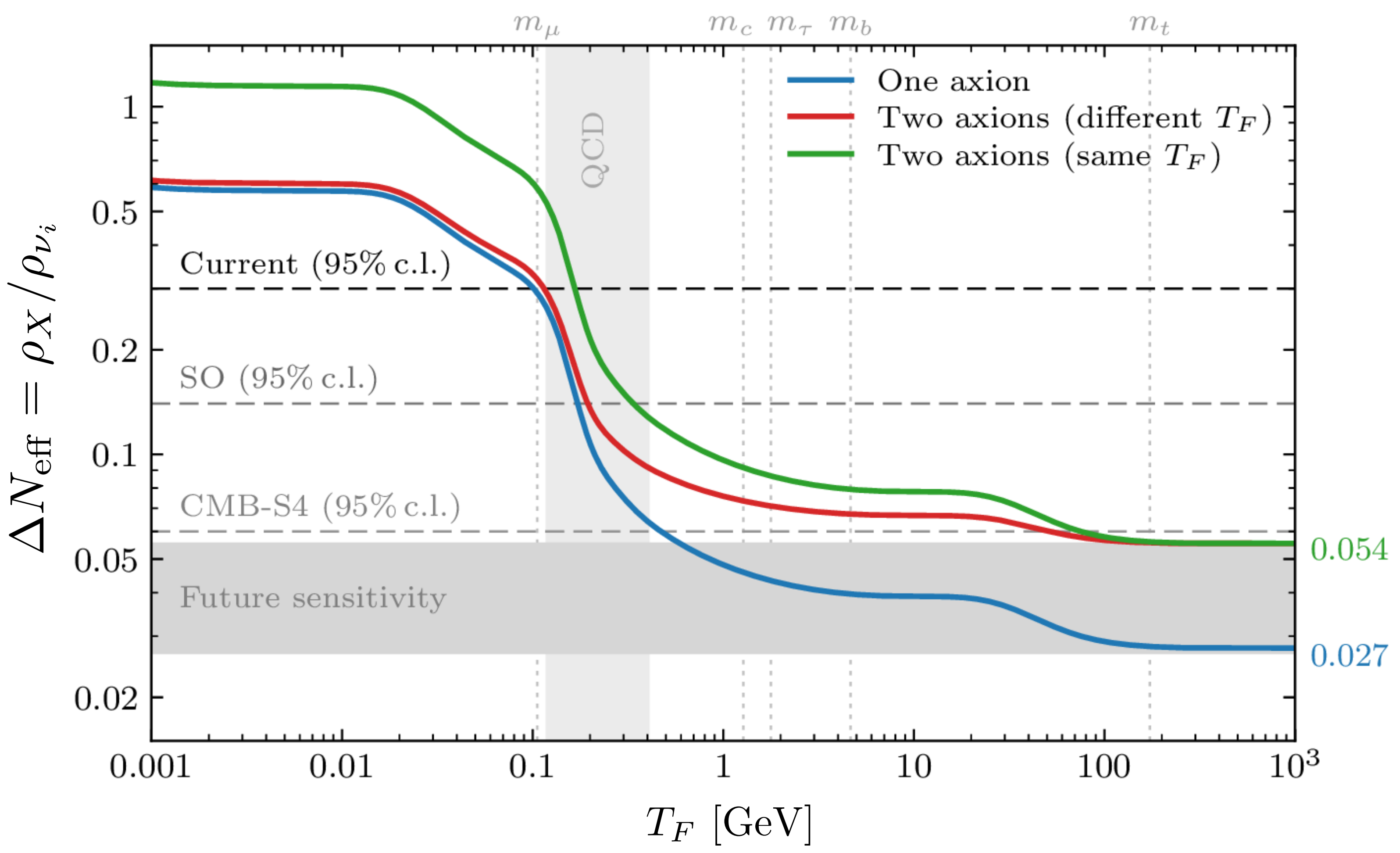

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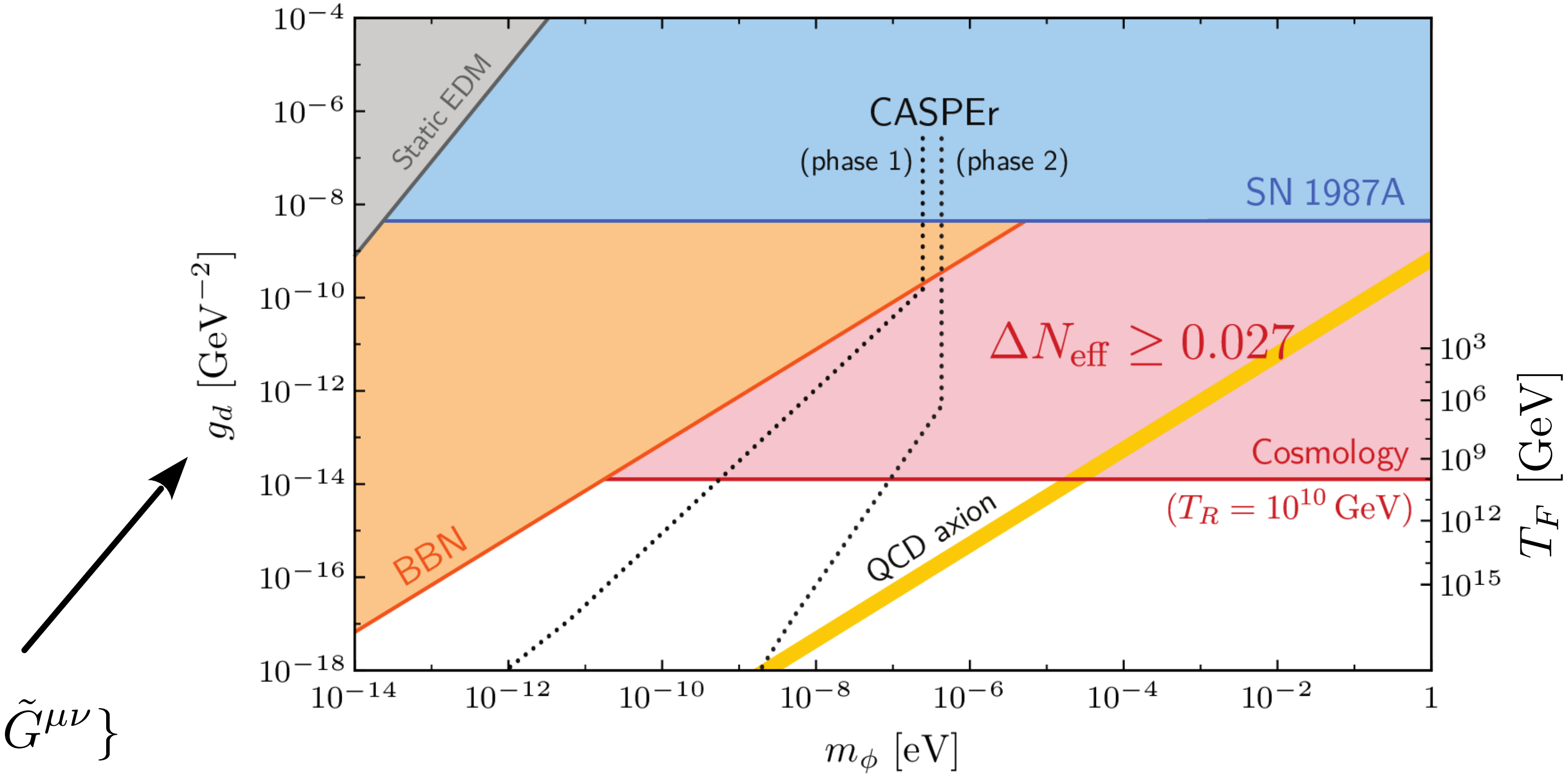

$$-\frac{\phi}{4\Lambda_g}{\rm tr}\{G_{\mu\nu}\tilde{G}^{\mu\nu}\}$$

$$g_d \approx \frac{2\pi}{\alpha_s} \times \frac{3.8\times 10^{-3}\,{\rm GeV}^{-1}}{\Lambda_g}$$

Baumann, Green & BW (2016)

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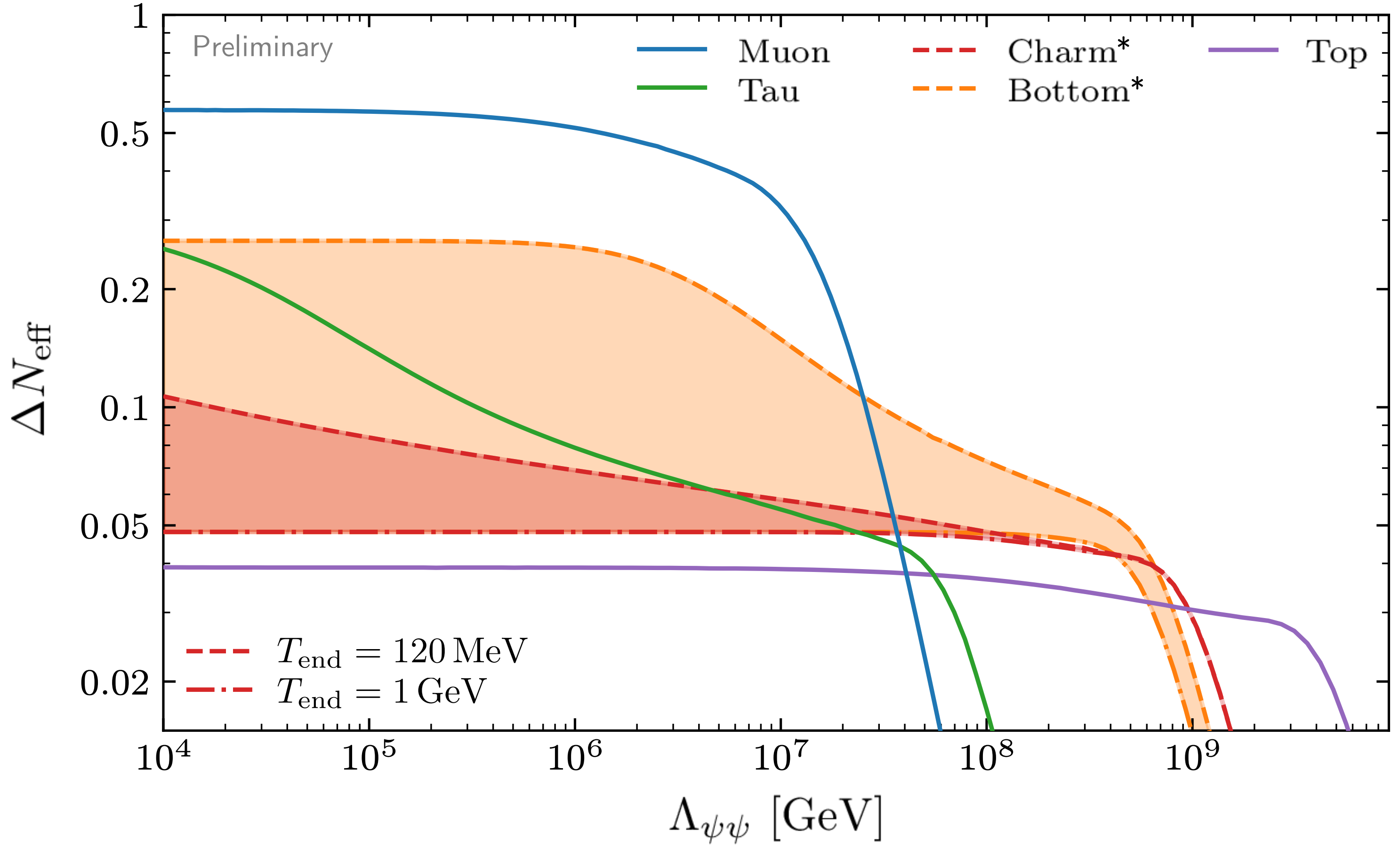
Solving the Boltzmann equation, we predict:



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