Constraining UV freeze-in of light relics with current and next-generation CMB observations

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Based on JCAP10(2024)106,
with P. Stengel, M. Gerbino, M. Lattanzi

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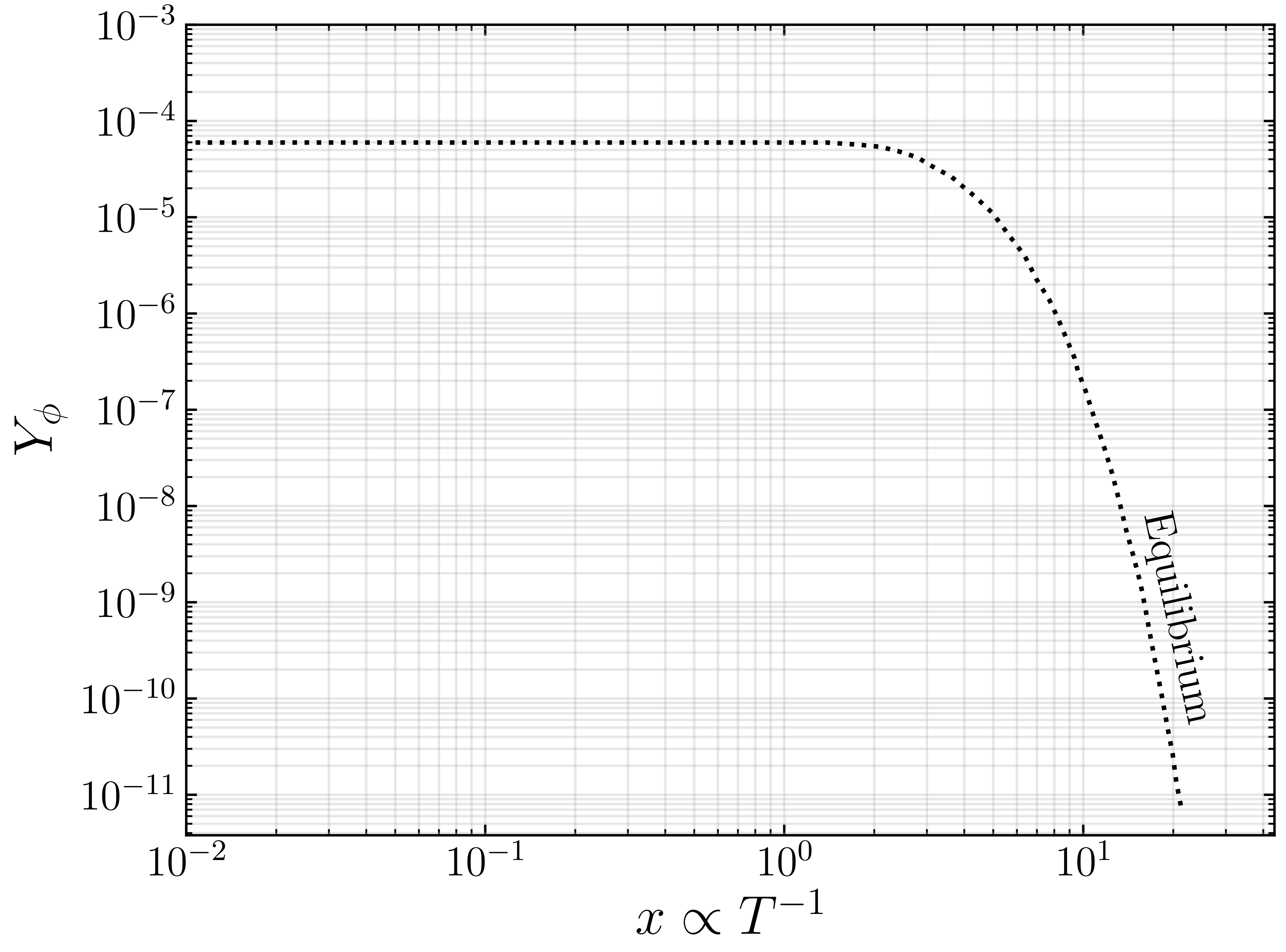
UV freeze-in production of light relics

$(Y_\phi \equiv n_\phi / s)$

$$\frac{dY_\phi}{d\log x} - \left(1 - \frac{1}{3}\frac{d\log g_{*s}}{d\log x}\right)\frac{\Gamma_\phi(x)}{H(x)}\left[Y_\phi^{\rm eq} - \left(\frac{Y_\phi}{Y_\phi^{\rm eq}}\right)^{l-1} Y_\phi\right] = 0$$



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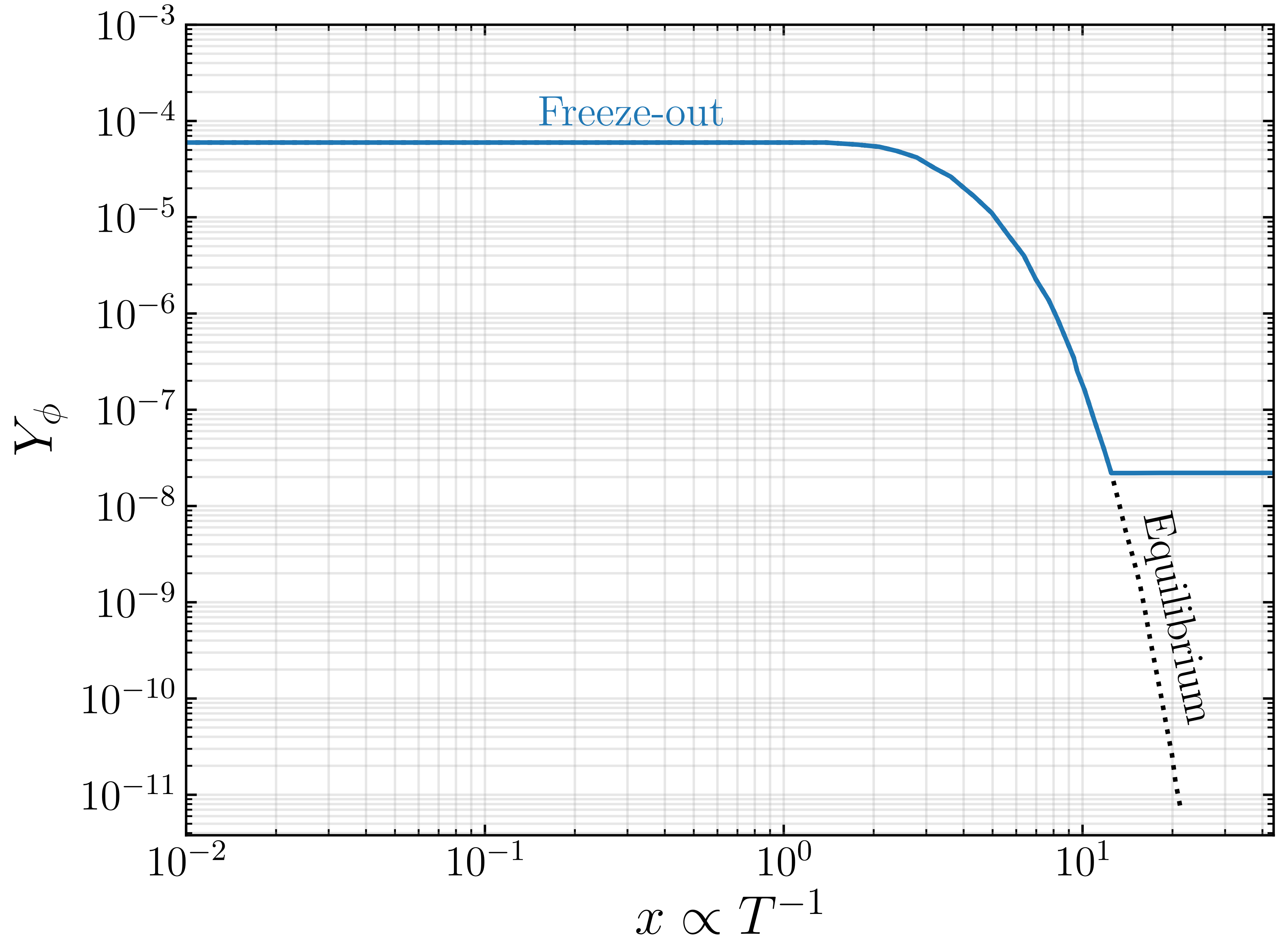
$\Delta N_{\rm eff}$:

Effective number of relativistic species



- Freeze-out production: $\Gamma(T_d) \simeq H(T_d)$

$$\Delta N_{\rm eff}^{\rm FO} \propto g_{*\phi}\left(\frac{g_{*s}^{\rm SM}(T_d)}{106.75}\right)^{-4/3}$$

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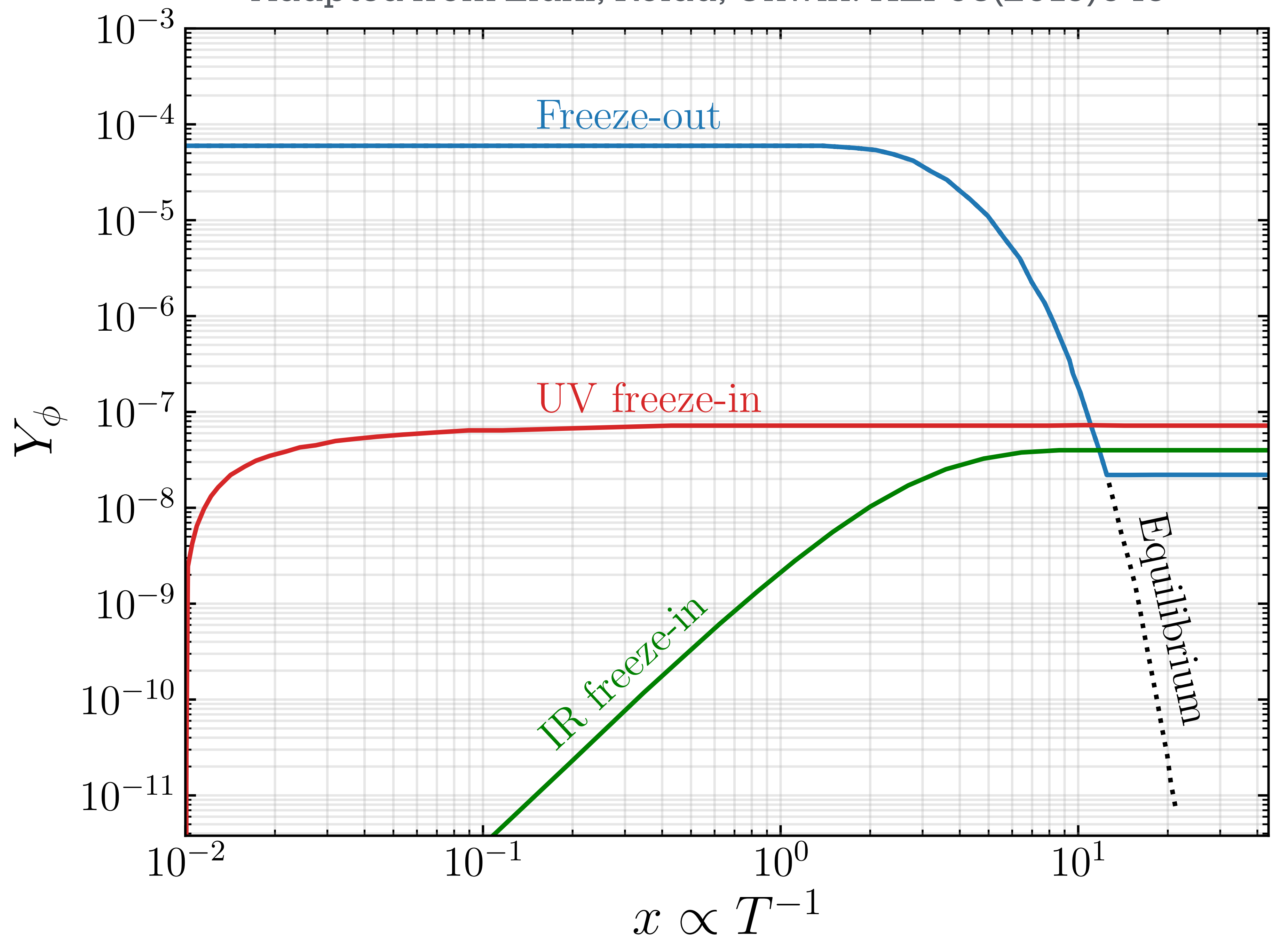
Adapted from Elahi, Kolda, Unwin: HEP03(2015)048



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- UV freeze-in production via dimension $4+n$ interaction:

$$\Delta N_{\rm eff}^{\rm UV} \propto g_{*\phi}\left(\frac{M_{\rm Pl} T_{\rm reh}^{2n-1}}{\Lambda^{2n}}\right)^{4/3}$$

Strongly dependent on the highest temperature at which SM species are thermalized (reheating temperature)

UV freeze-in production of light relics

Several BSM scenarios explored:

LC, Stengel, Lattanzi, Gerbino: JCAP10(2024)106

- ALPs from Primakoff production
- Massless dark photons
- Light right-handed neutrinos in gauged B-L model
- Light right-handed neutrinos with non-vanishing charge radius

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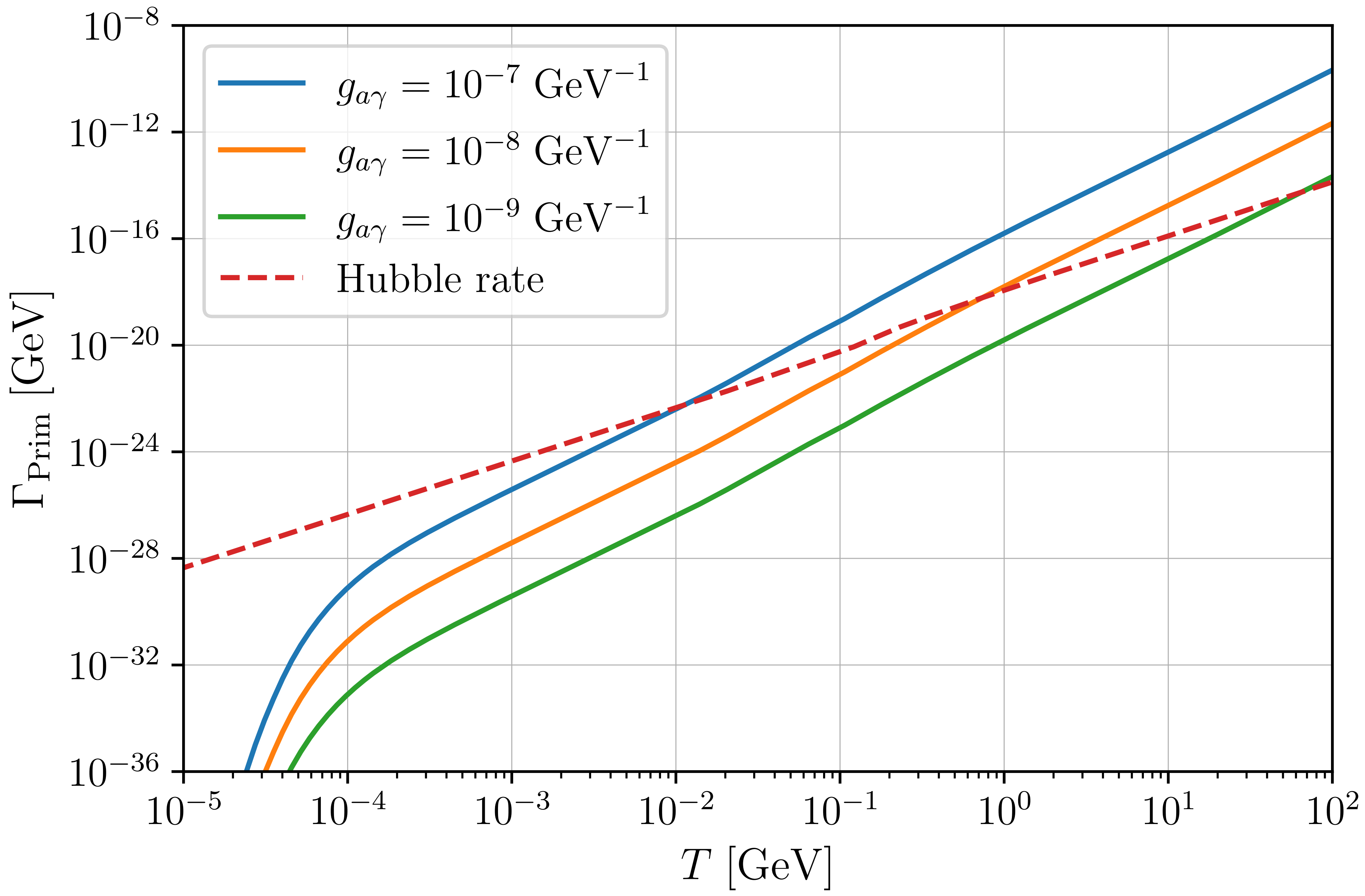
UV freeze-in of ALPs from Primakoff production

- **ALPs**: pseudo Nambu-Goldstone bosons arising from the spontaneous breaking of global symmetries in scenarios BSM. Dimension-5 coupling to photons:

$$\mathscr{L}_{a\gamma} = \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

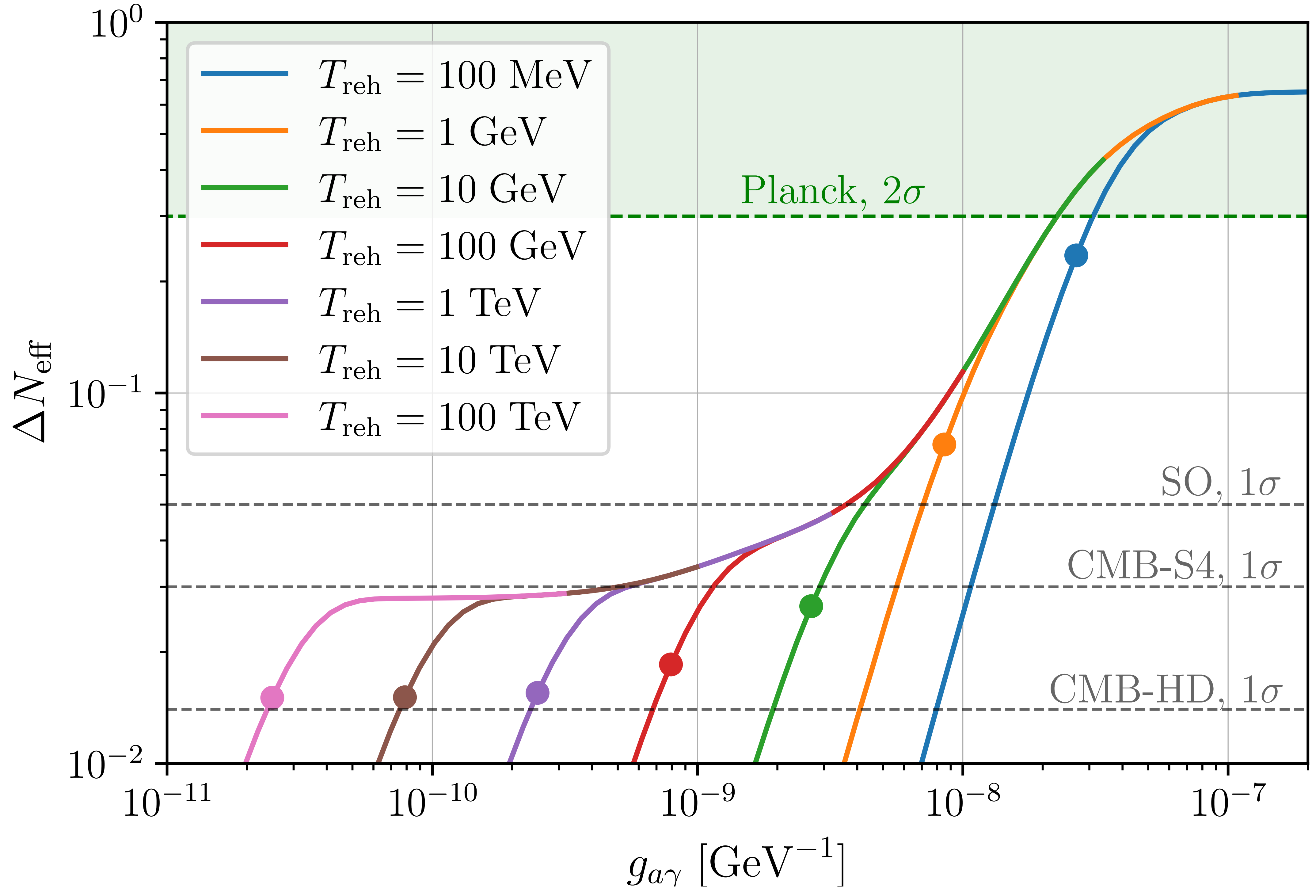
- **Primakoff production**: conversion of photons into ALPs in presence of the magnetic fields generated by charged particles in the primordial plasma

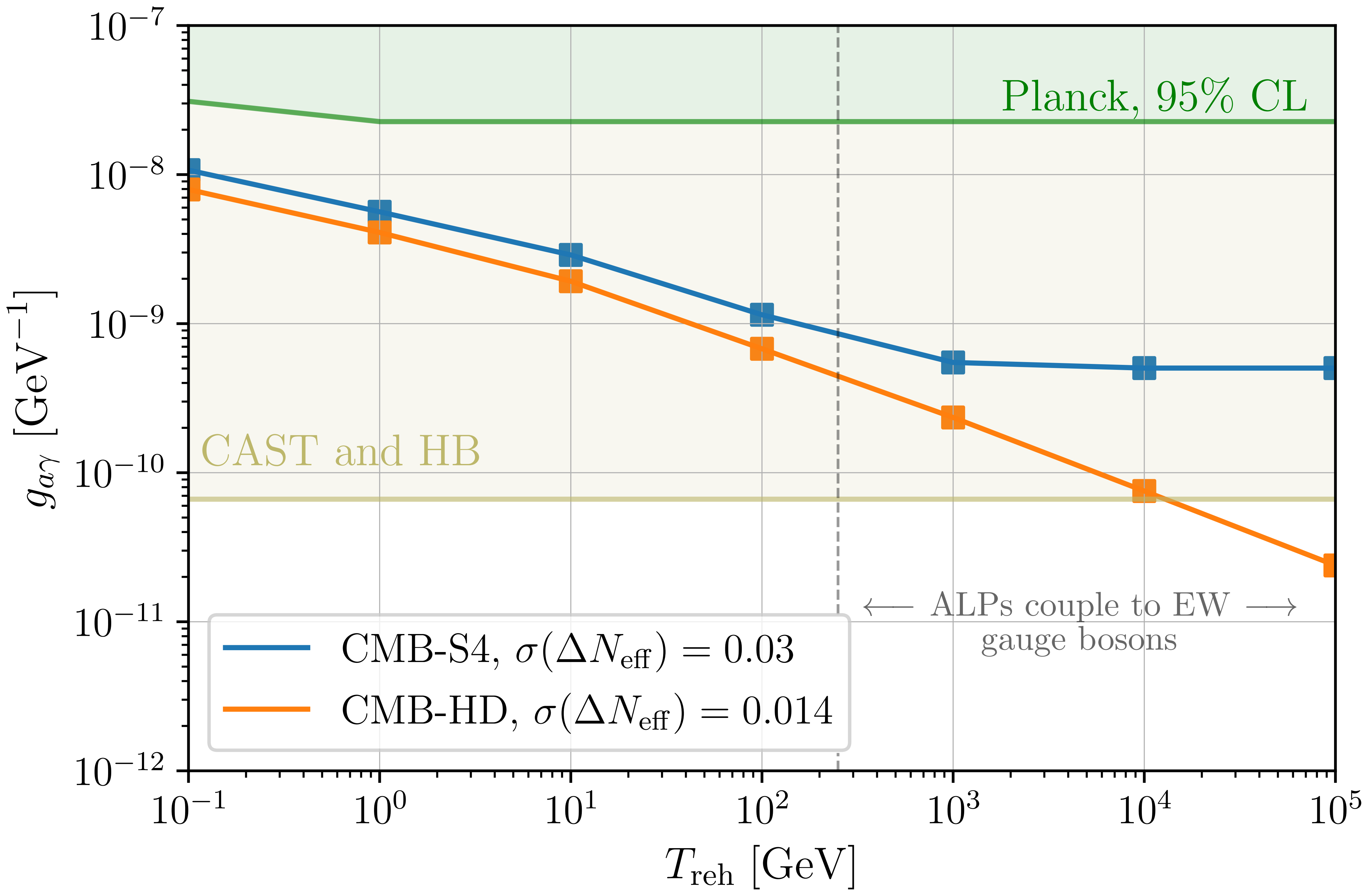
$$\Gamma_{\text{Prim}}(T) = \frac{\alpha_{\text{em}} g_{a\gamma}^2}{36} g_q(T) \left[\ln\left(\frac{T^2}{m_\gamma^2}\right) + 0.8194 \right] T^3$$



Bolz, Brandenburg, Buchmuller: Nucl. Phys. B 606 (2001) 518–544
Cadamuro, Redondo: JCAP02(2012)032

UV freeze-in of ALPs from Primakoff production





Next-generation CMB experiments can probe the freeze-in regime

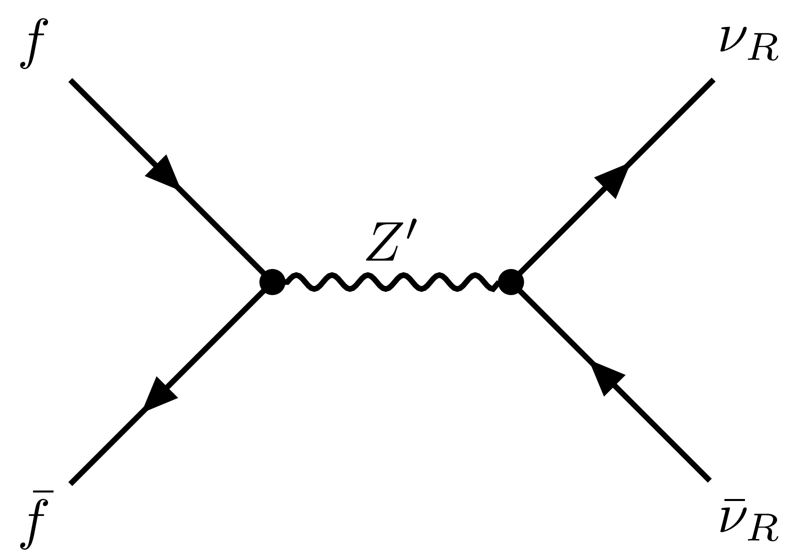
Strong constraints for high enough reheating temperatures!

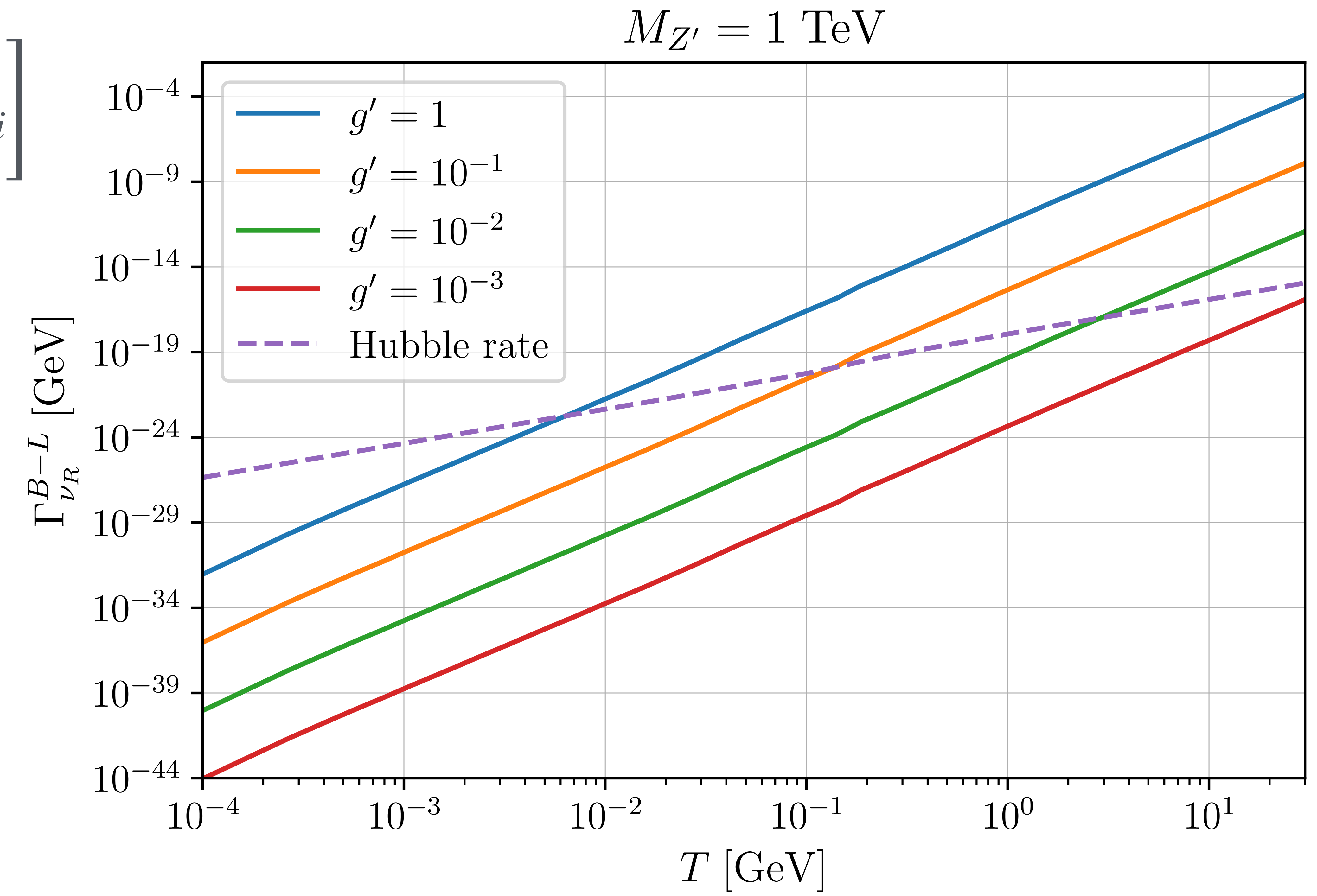
UV freeze-in of light RH neutrinos in gauged B-L model

- This model includes 3 RH neutrinos and a new Z' boson:

$$\mathscr{L} = g' Z'_\mu \sum_i \left[\frac{1}{3} \left(\bar{u}_i \gamma^\mu u_i + \bar{d}_i \gamma^\mu d_i \right) - \bar{e}_i \gamma^\mu e_i - \bar{\nu}_{L,i} \gamma^\mu \nu_{L,i} - \bar{\nu}_{R,i} \gamma^\mu \nu_{R,i} \right]$$

- RH neutrinos produced from fermion-antifermion annihilations:





- In the limit $M_{Z'} \gg T_{\text{reh}}$ this becomes a point interaction: $\Gamma_{\nu_R}^{B-L} \propto \frac{g'^4}{M_{Z'}^4} T^5$

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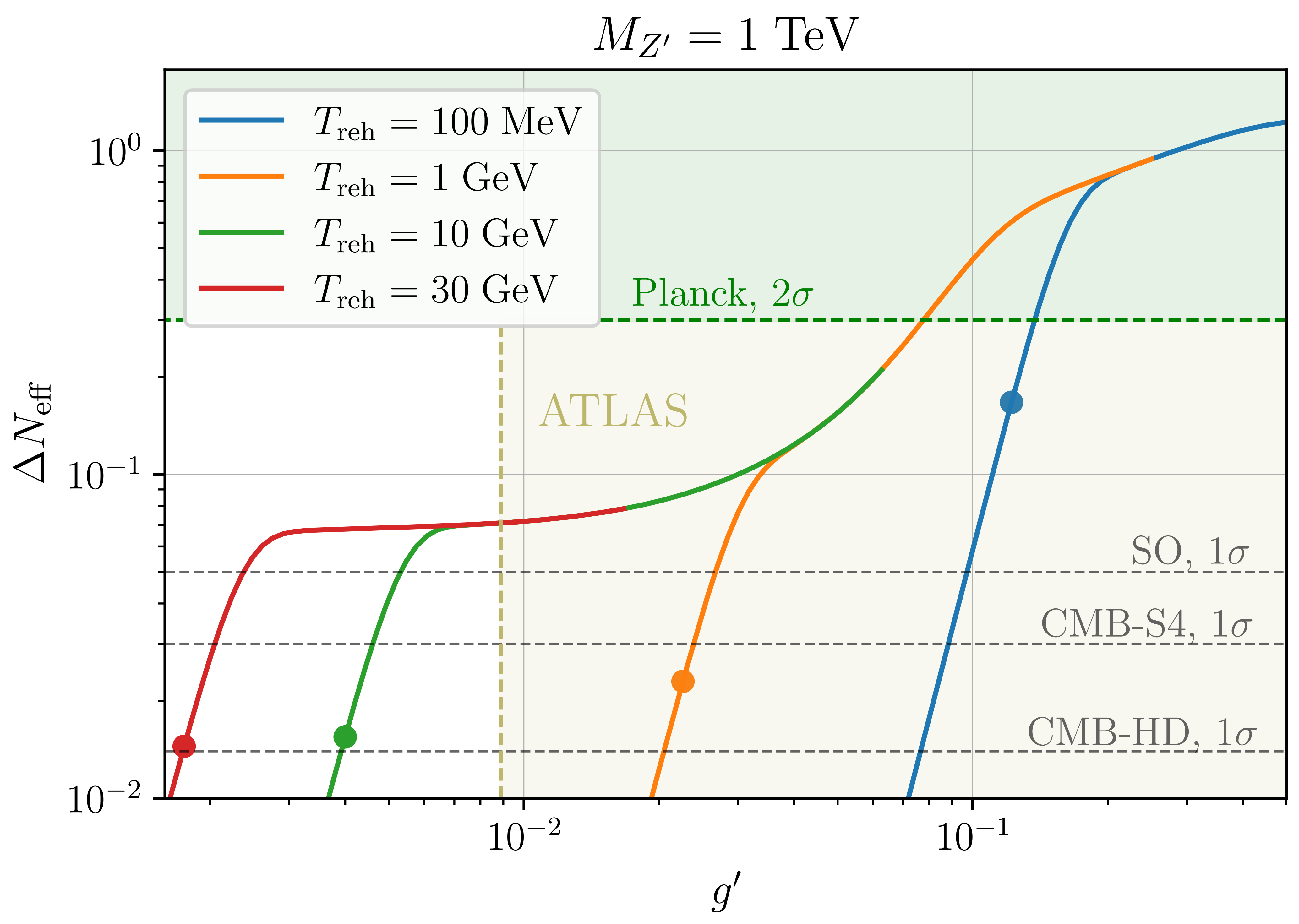

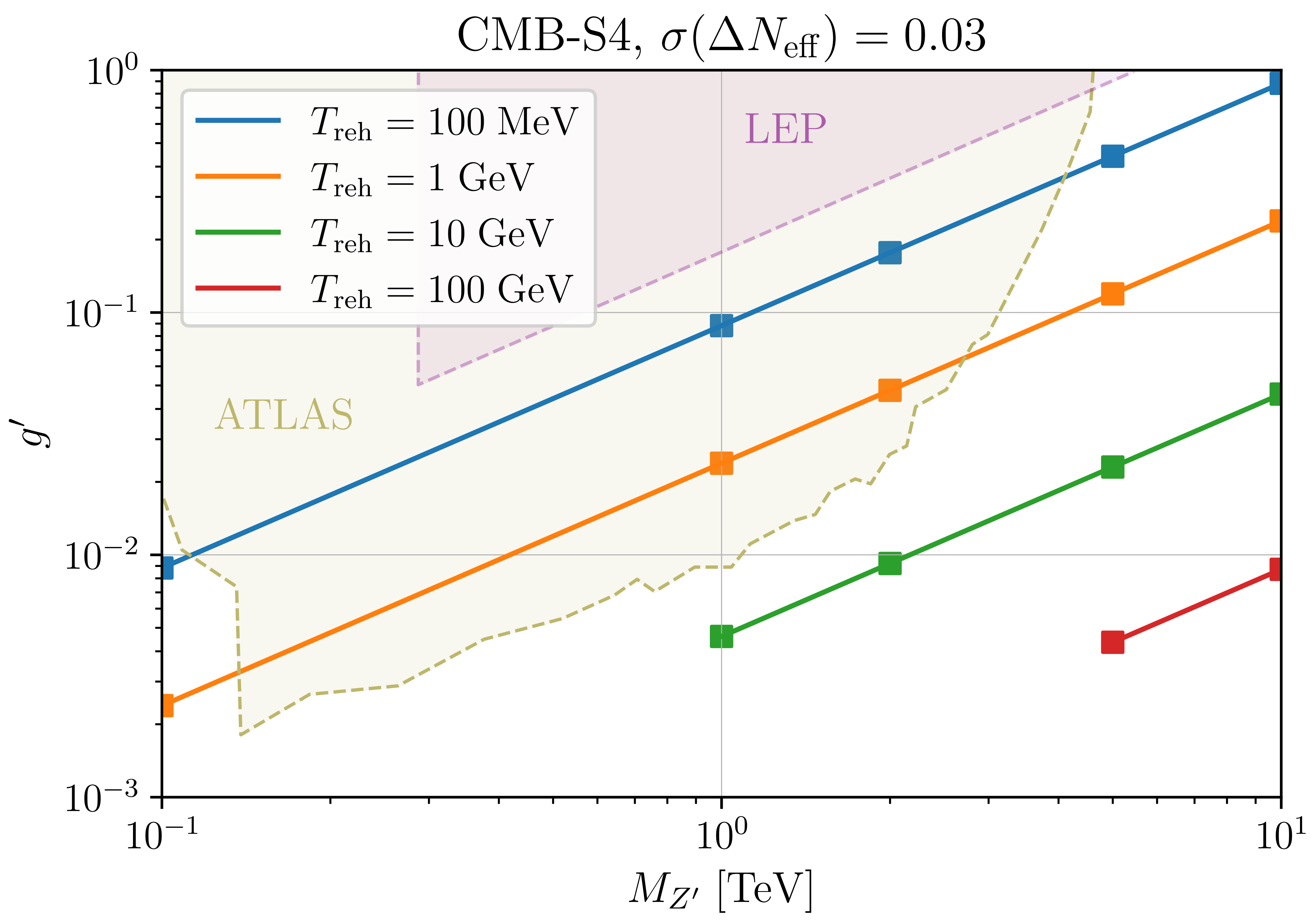

CMB observations allow us to probe higher masses of the Z' boson

Conclusions

- The CMB is a powerful observable to constrain the presence of light species BSM
- In particular, the improved sensitivity of next-generation experiments will allow us to probe regions of parameter space where the light relics are produce via freeze-in
- For high enough reheating temperatures, strong bounds on light relics produced via UV freeze-in. These will complement, or surpass, astrophysical and laboratory bounds

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Thank you!