When FIMPs decay into neutrinos: the *Neff* story

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In collaboration with


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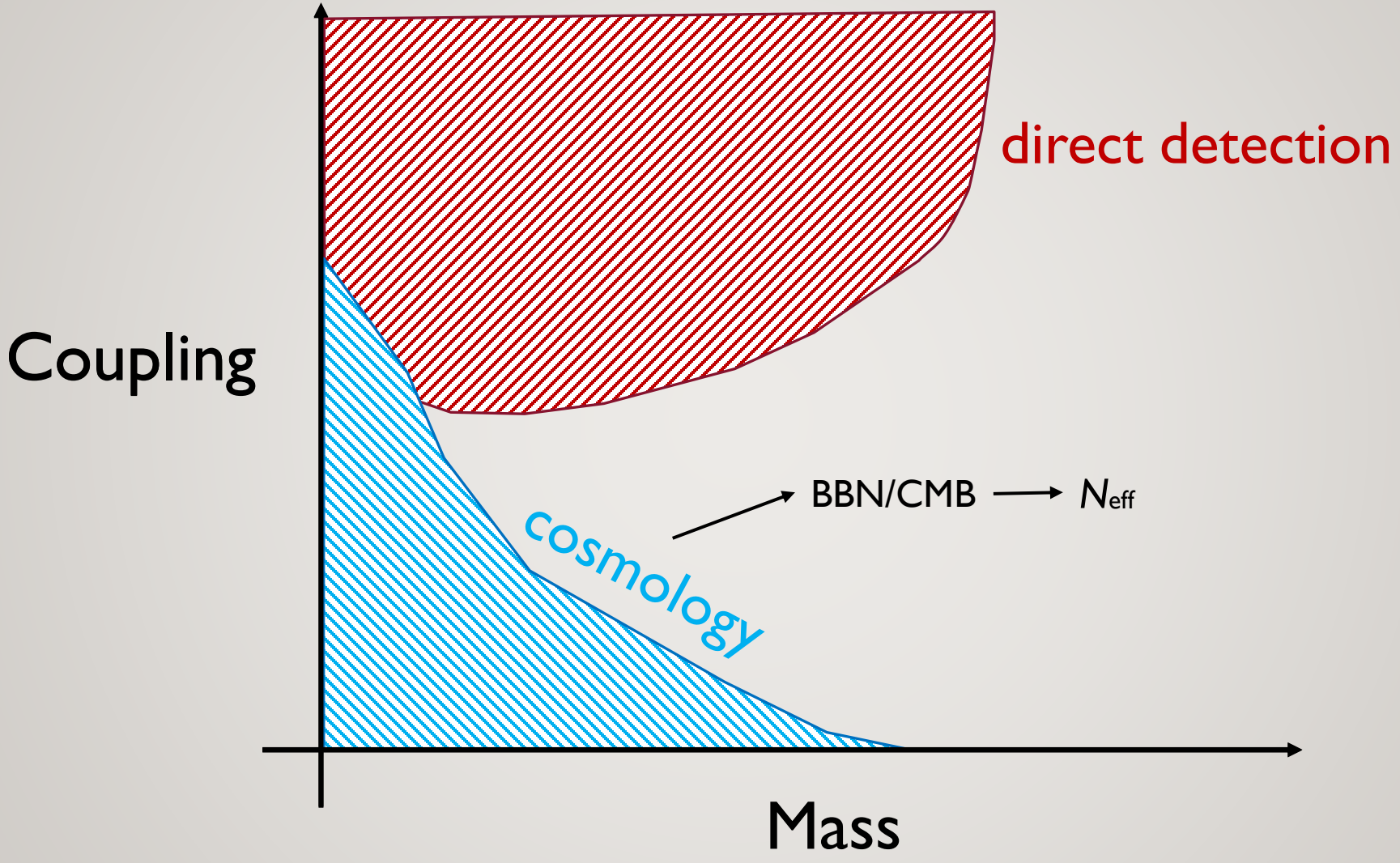
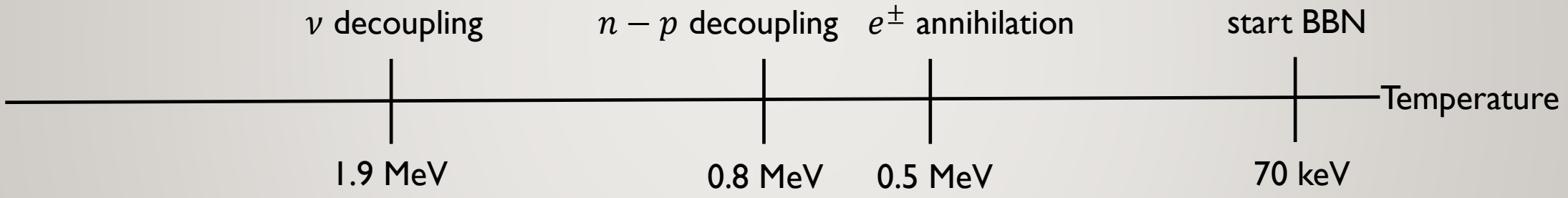
Based on arXiv:2103.09831

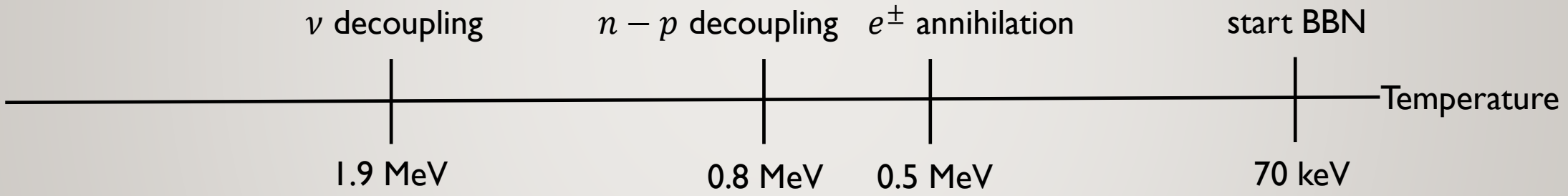
How do FIMPs that decay mostly into neutrinos affect N_{eff} ?


direct detection
Coupling
BBN/CMB → N_{eff}
cosmology
Mass

Timeline of relevant events in the early Universe



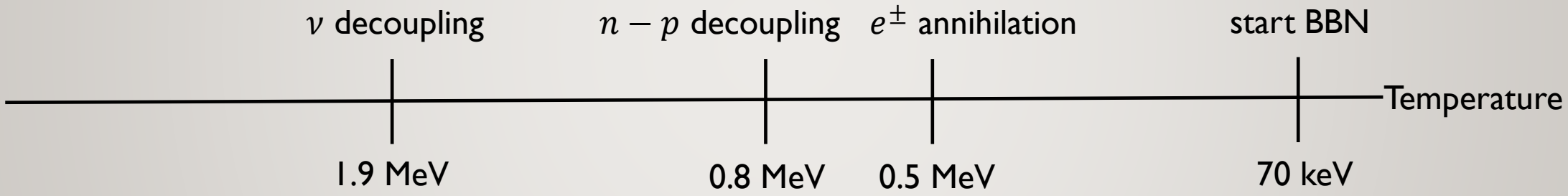
Timeline of relevant events in the early Universe



$$N_{\mathrm{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\mathrm{rad}} - \rho_{\gamma}}{\rho_{\gamma}}\right) \rightarrow N_{\mathrm{eff}}^{\mathrm{SM}} = 3.044$$

What happens if a FIMP decays into ν before ν decoupling?

$$N_{\mathrm{eff}}^{\mathrm{SM}}$$



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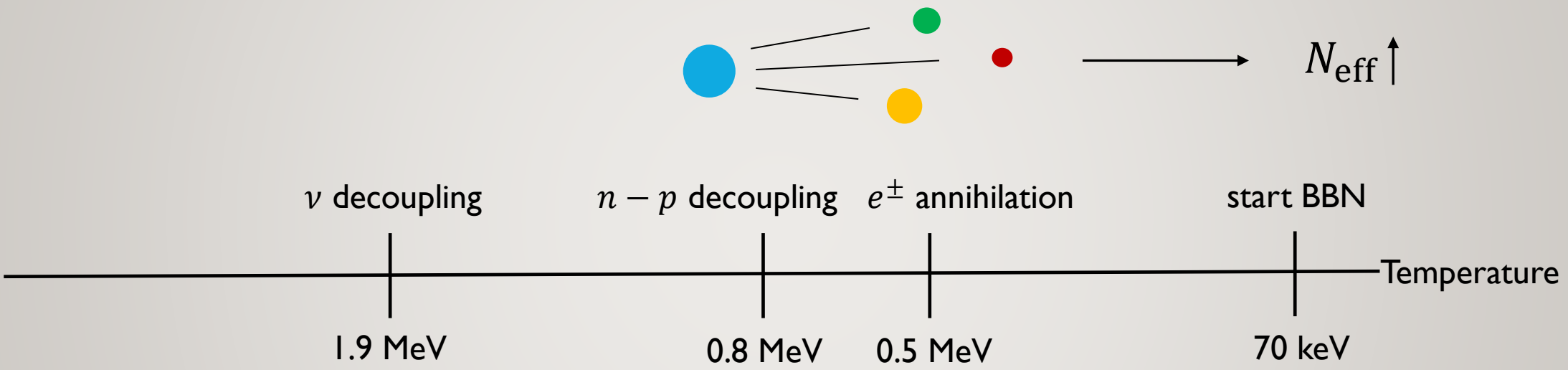

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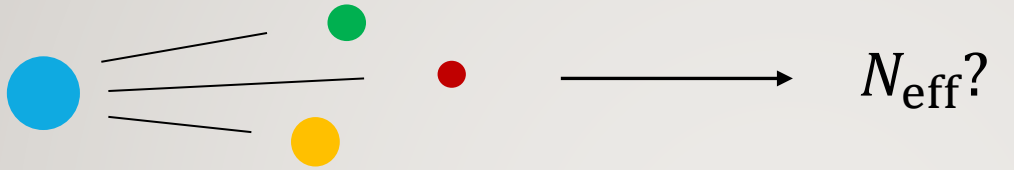
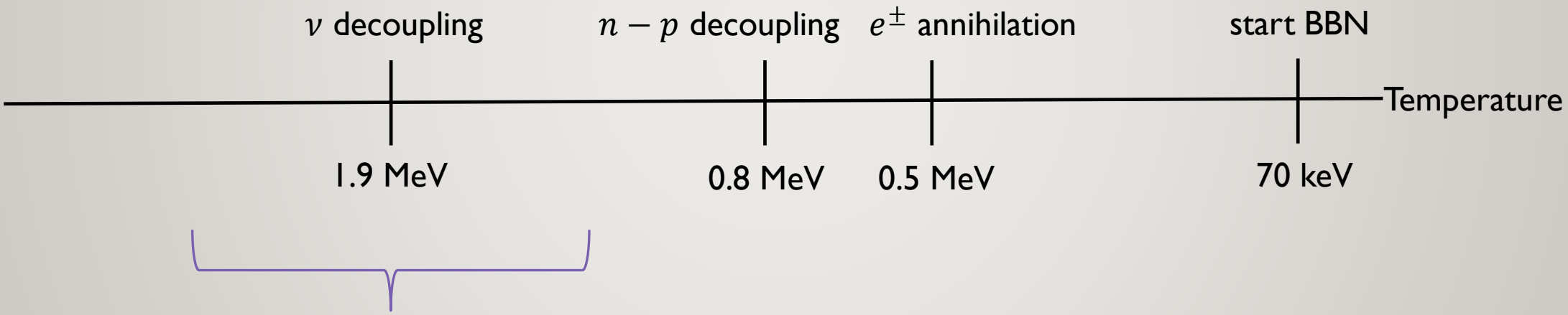


N_{eff}?



- ν decoupling not instantaneous
- cross-section $\sigma \propto E_\nu^2$
- νs with higher energies stay longer in equilibrium

What are the relevant reactions?

Around decoupling: $\frac{\Gamma_{\text{non-eq}}}{\Gamma_{\text{therm}}} \sim \frac{G_F^2 T^4 E_\nu^{\text{inj}}}{G_F^2 T^5} = \frac{E_\nu^{\text{inj}}}{T} \gg 1$ ⟶

$$\nu_{\text{non-eq}} + \nu_{\text{therm}} \rightarrow \nu_{\text{non-eq}} + \nu_{\text{non-eq}}$$
$$\nu_{\text{non-eq}} + \bar{\nu}_{\text{therm}} \rightarrow e^+ + e^-$$
$$\nu_{\text{non-eq}} + e^\pm \rightarrow \nu_{\text{non-eq}} + e^\pm$$

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$$\xi_{\text{EM,eff}}\left(E_\nu^{\text{inj}}, T\right) = \xi_{\text{EM}} + \xi_\nu \times \epsilon\left(E_\nu^{\text{inj}}, T\right)$$

Total fraction of FIMP energy to EM plasma

Fraction of FIMP energy directly to EM plasma

Fraction of FIMP energy from neutrinos to EM plasma

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$$\xi_{\text{EM,eff}}\left(E_\nu^{\text{inj}}, T\right) = \xi_{\text{EM}} + \xi_\nu \times \epsilon\left(E_\nu^{\text{inj}}, T\right)$$

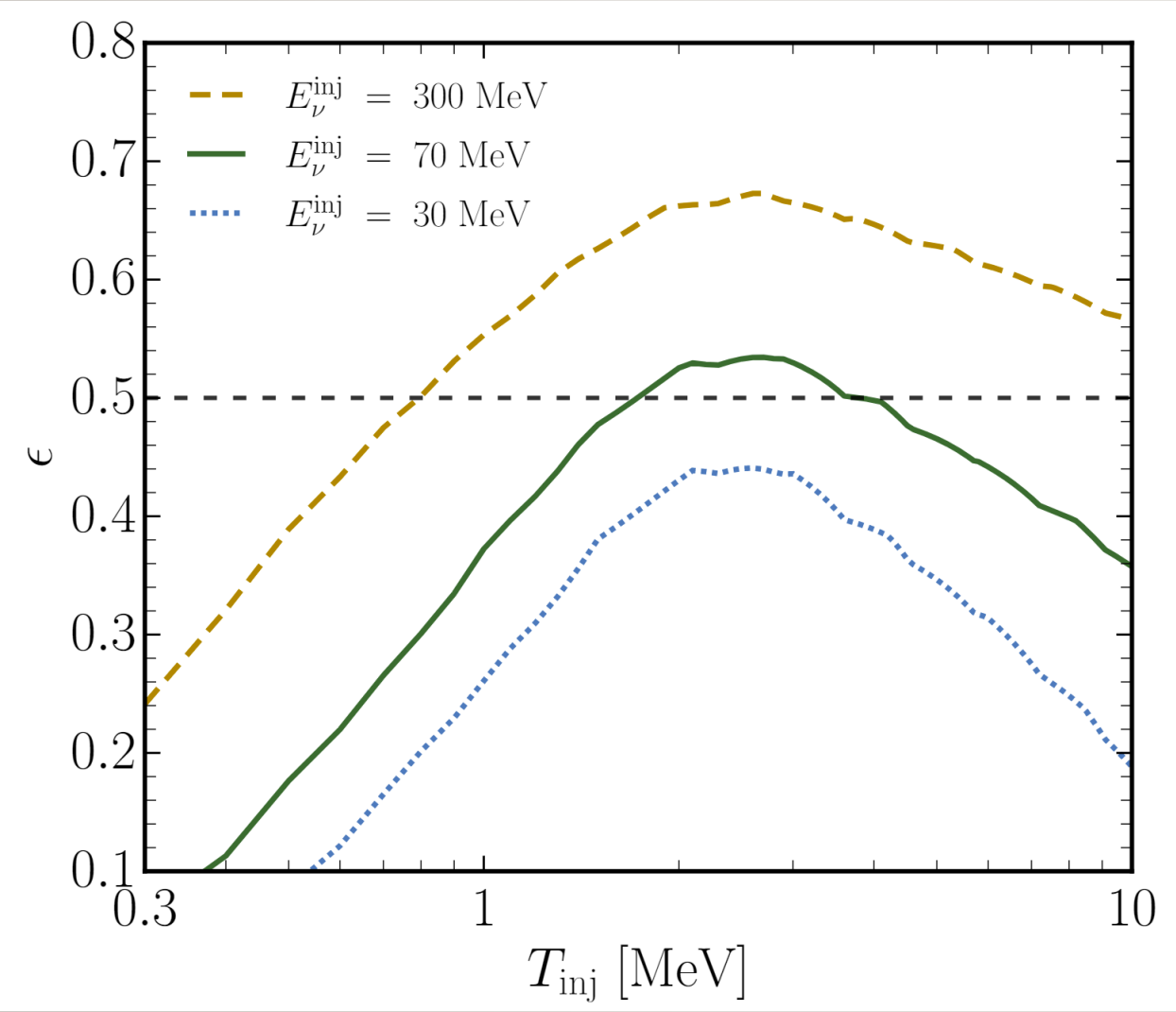
If $\epsilon > 0.5$ then $\xi_{\text{EM,eff}} > 0.5$, independently of ξ_{EM}

Total fraction of FIMP energy to EM plasma

Fraction of FIMP energy directly to EM plasma

Fraction of FIMP energy from neutrinos to EM plasma

How does $N_{\rm eff}$ change?



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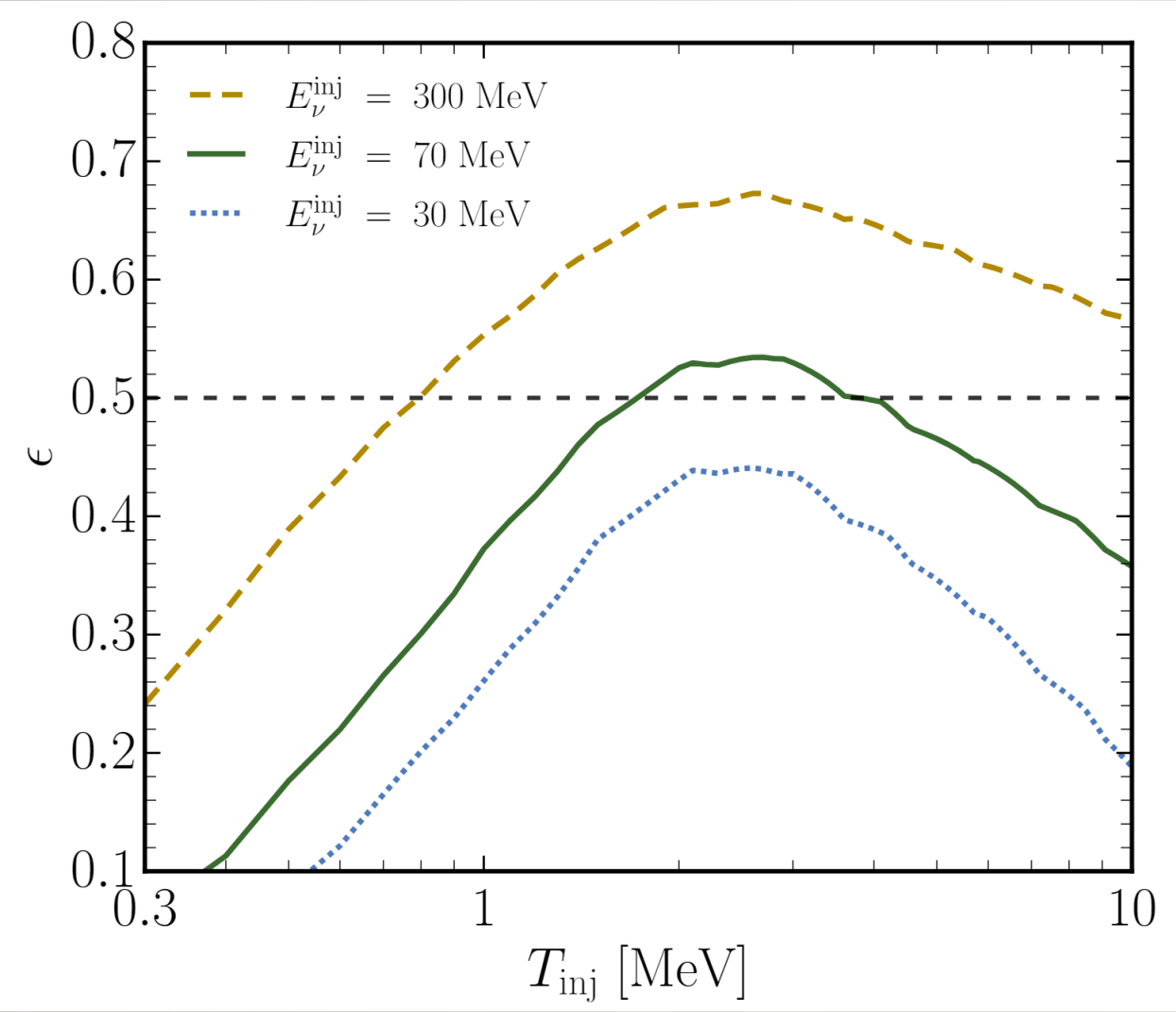
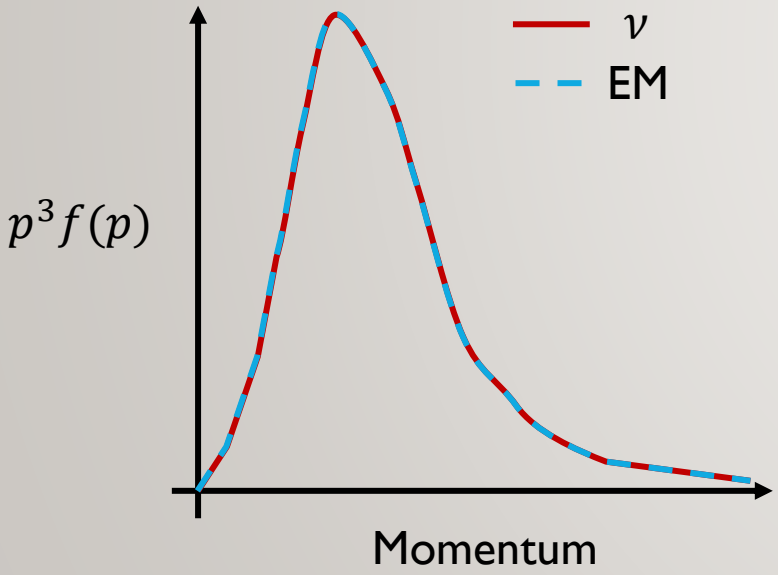


- More than half of FIMP energy ends up in EM plasma
- EM plasma heats up more than ν plasma
- $N_{\rm eff}$ decreases

$$N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_\nu}{\rho_\gamma}\right) \propto \left(\frac{T_\nu}{T_\gamma}\right)^4$$

What is the actual mechanism behind this effect?

Before FIMP decay



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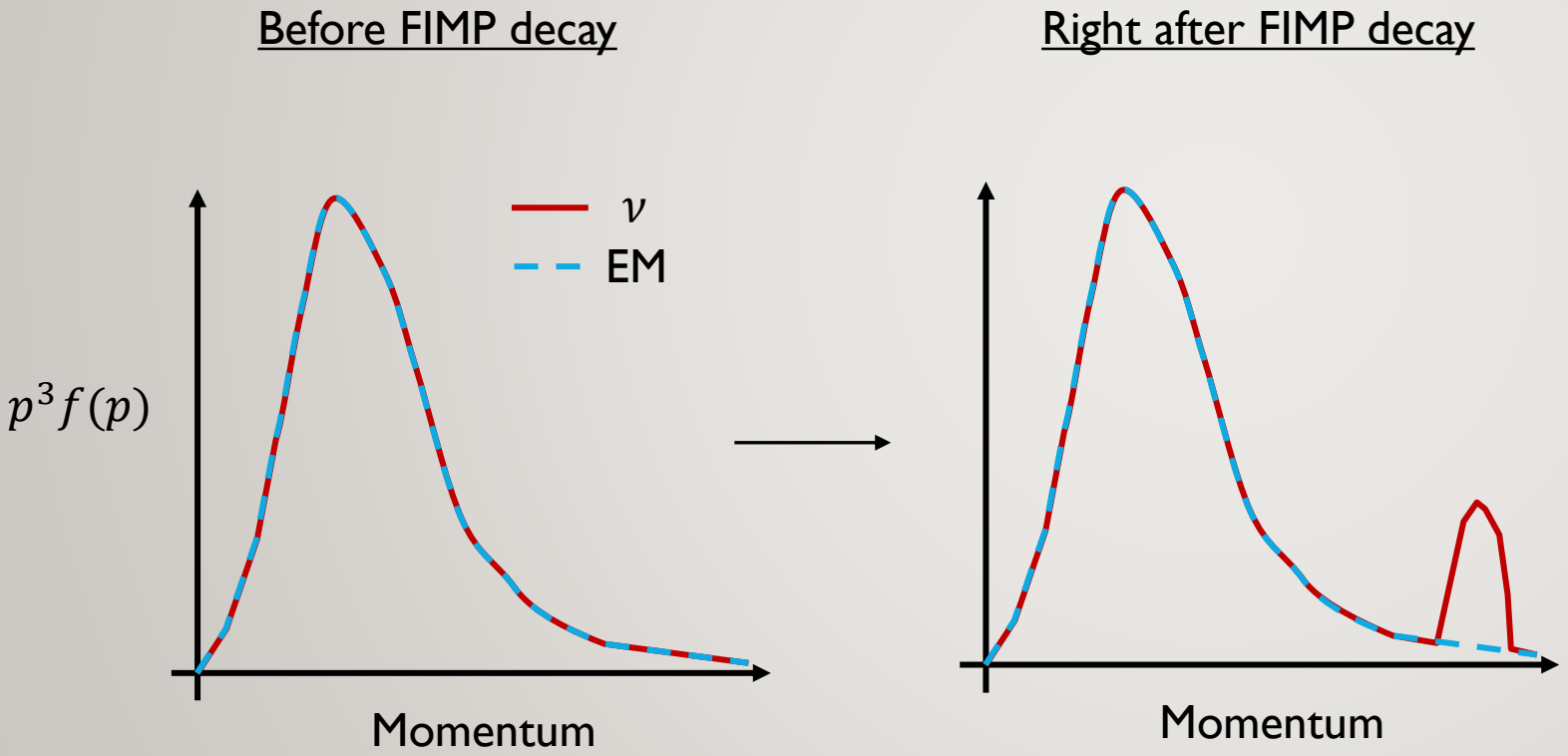

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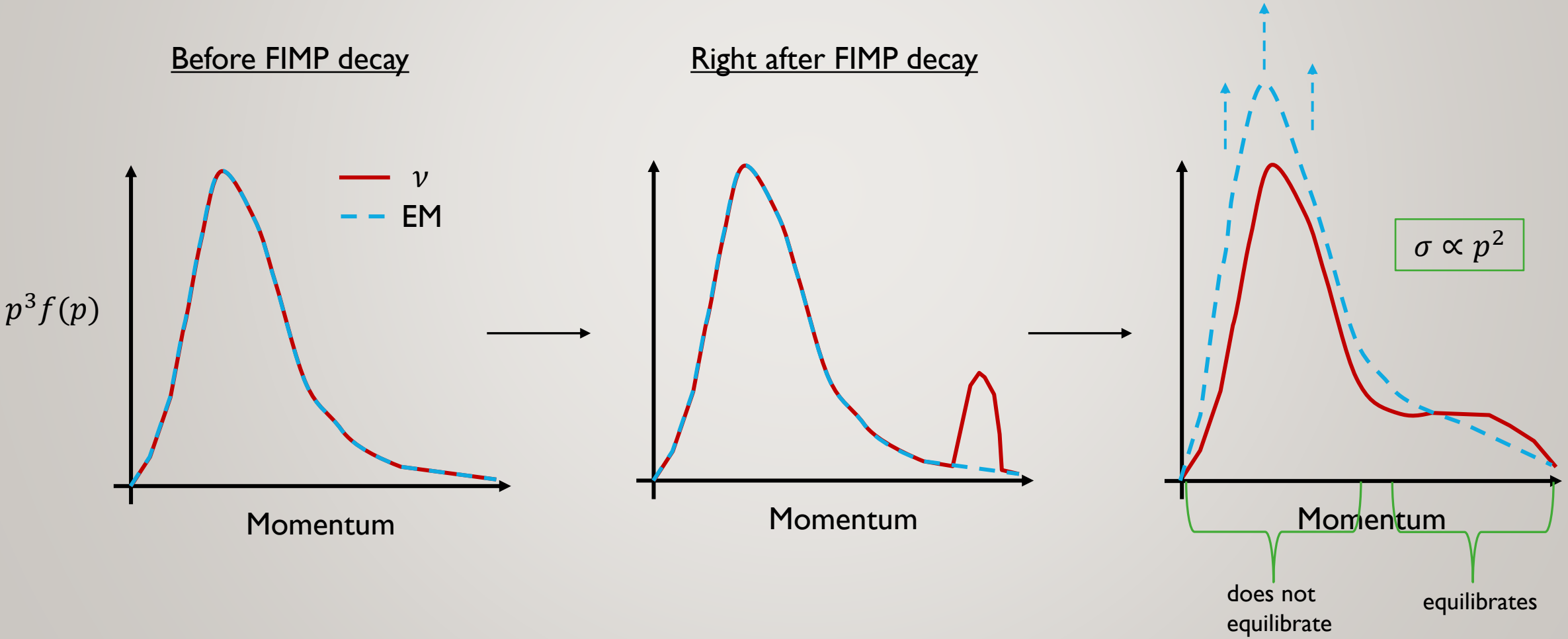
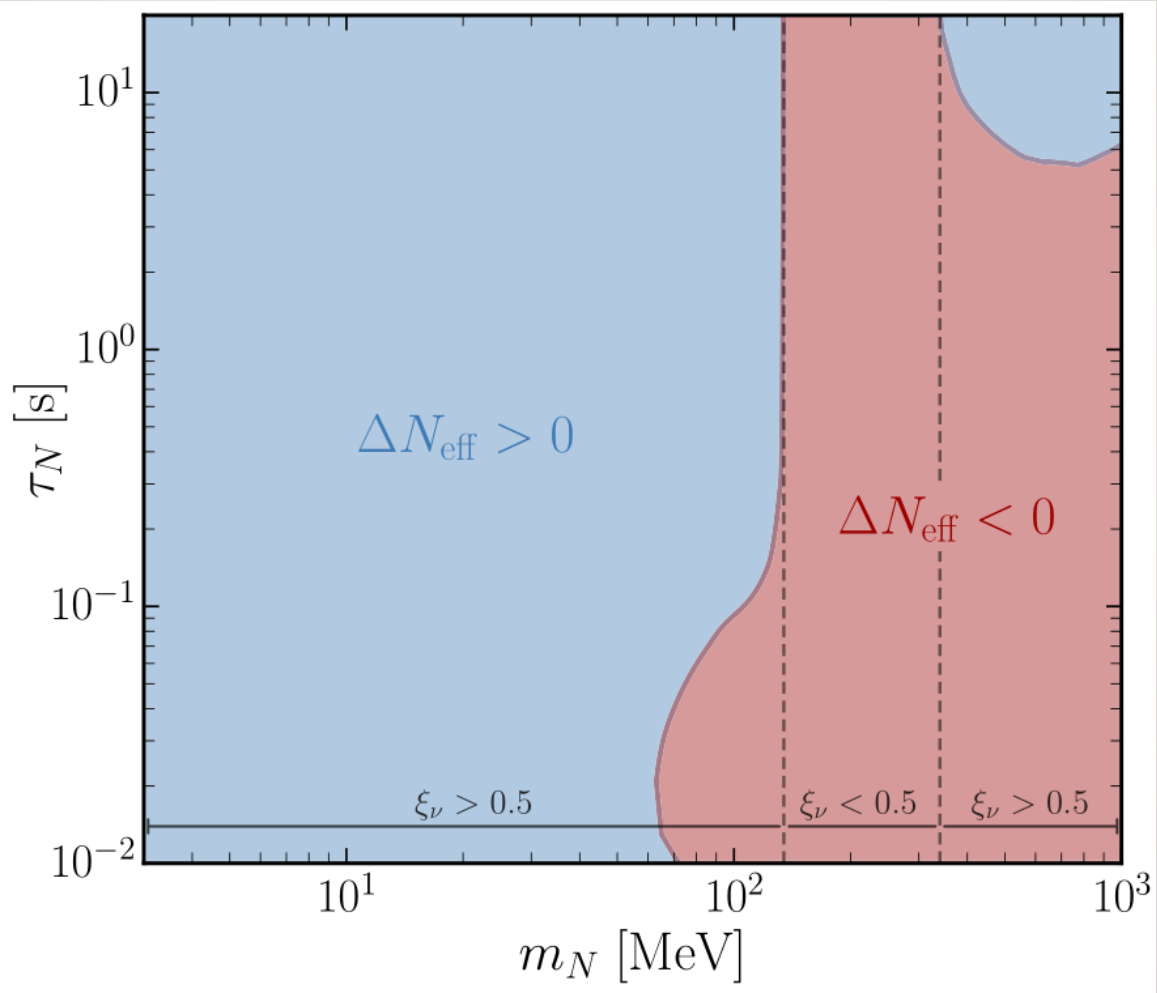


Case study: Heavy Neutral Leptons



Summary

Conclusion: even if unstable FIMPs inject most of their energy into neutrinos around neutrino decoupling, they may still decrease Neff

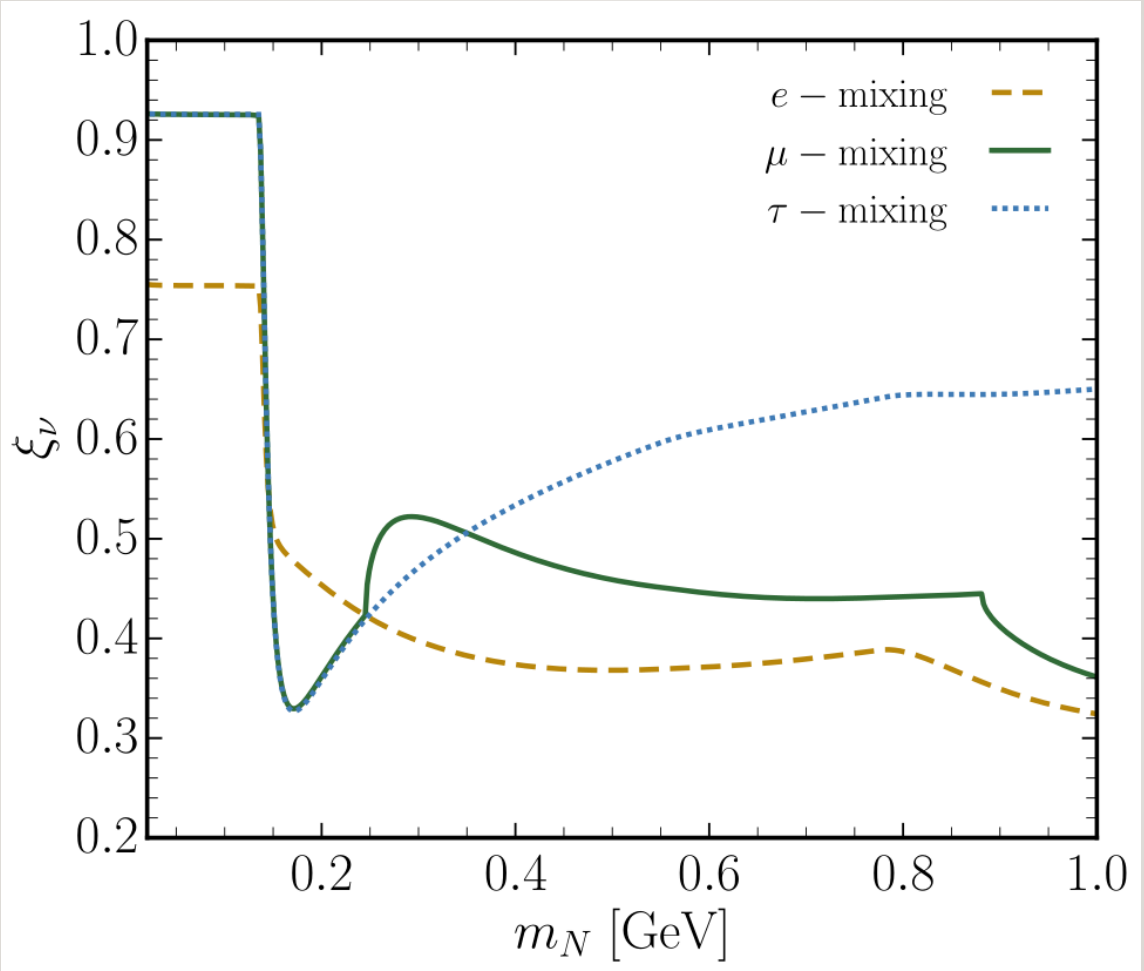
How: high-energy neutrinos created from FIMP decays transfer more energy to the EM plasma than neutrino plasma

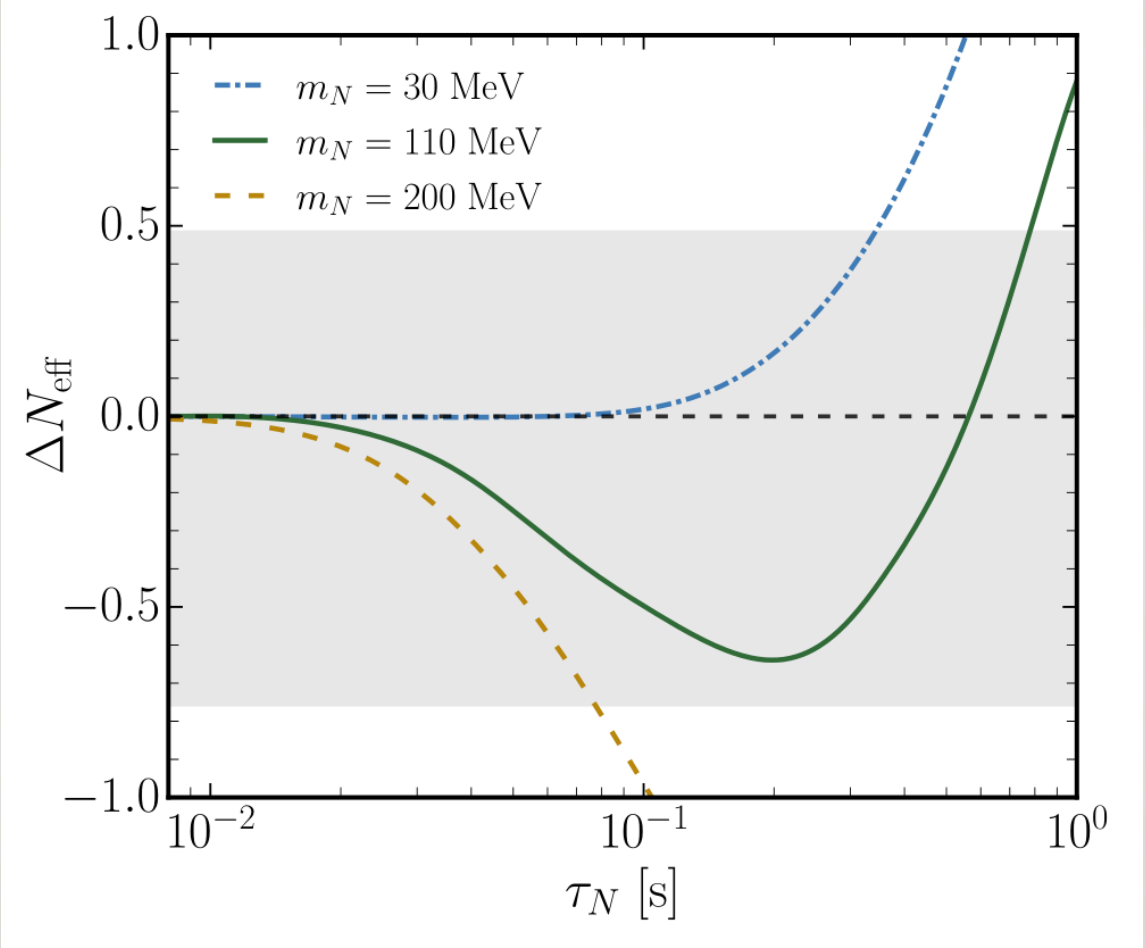
Why: thermal neutrinos cannot efficiently equilibrate through weak reactions anymore, while EM particles can still equilibrate through EM interactions and trap the transferred energy in that sector

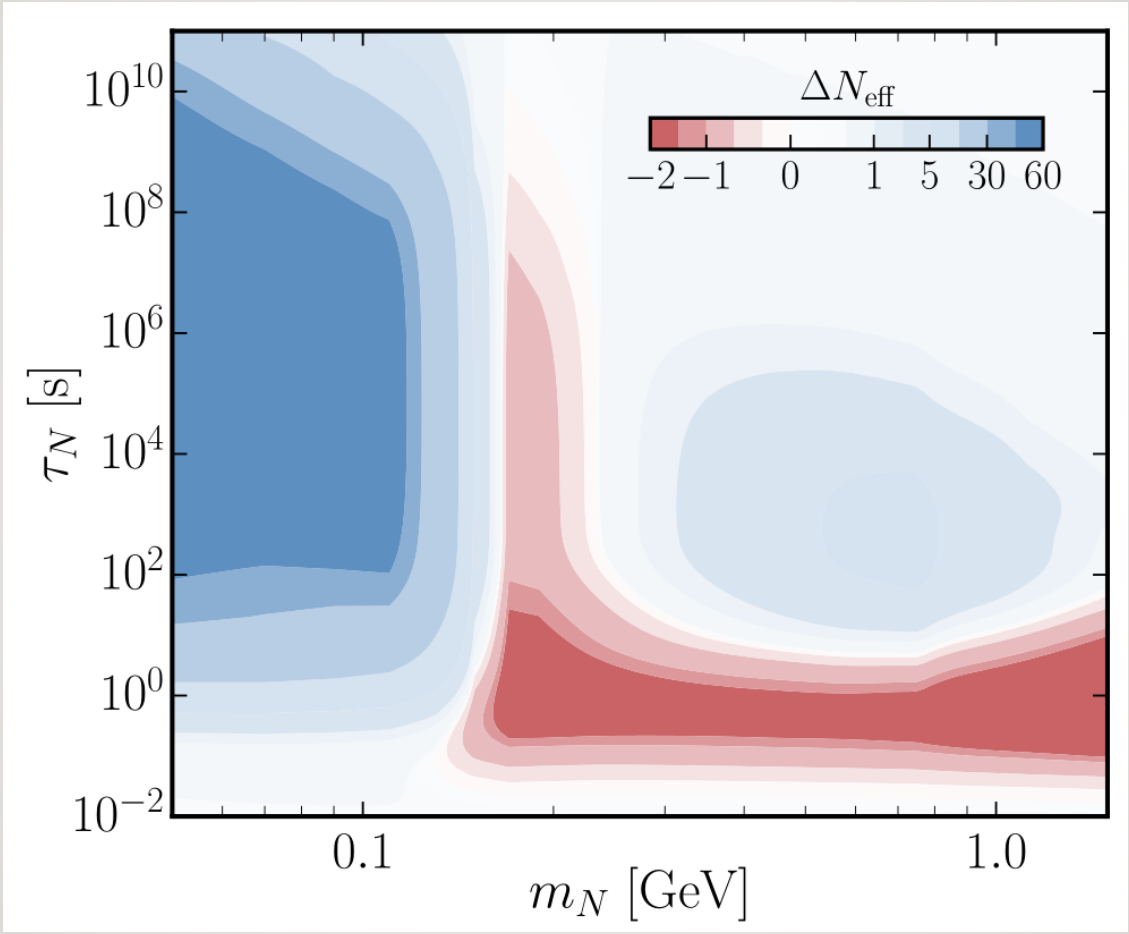
When: if neutrinos are created with energies greater than $E_\nu^{\rm inj} \gtrsim 25$ MeV

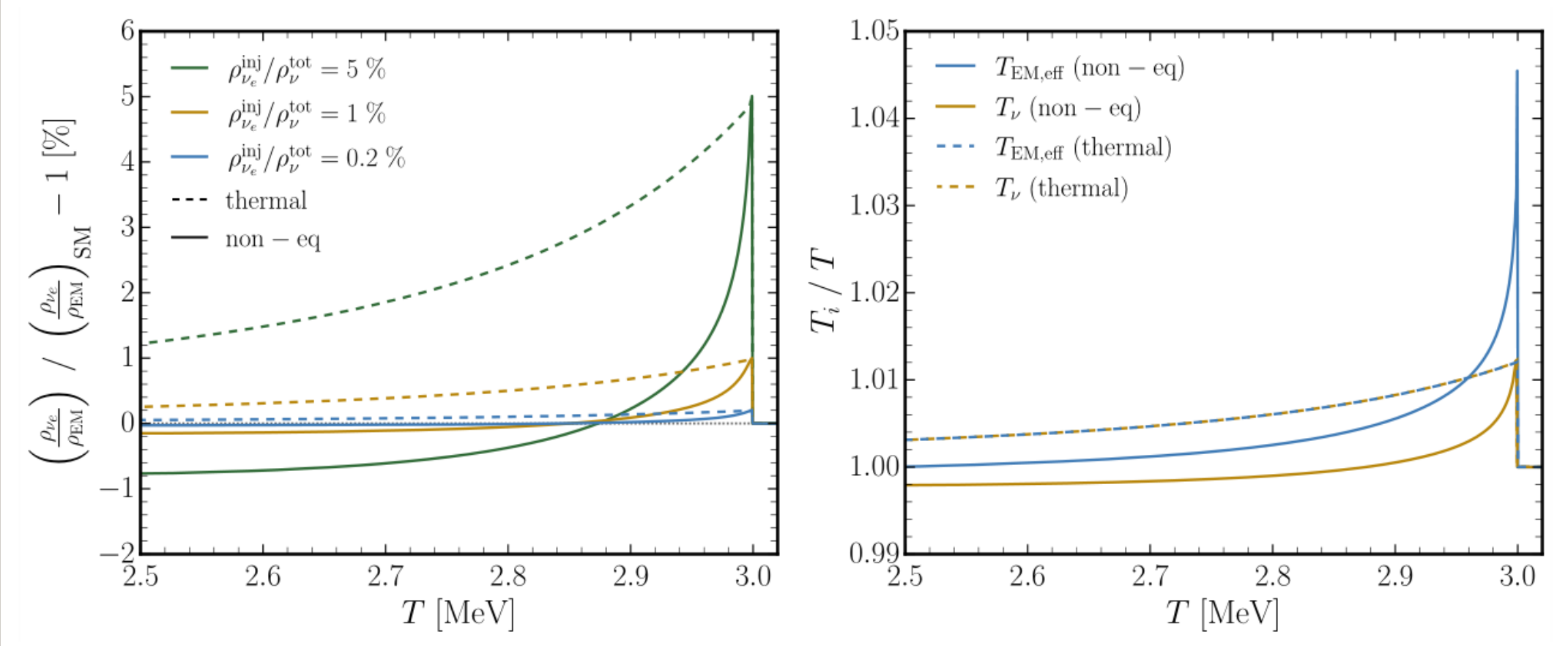
THANK YOU ☺

Appendix

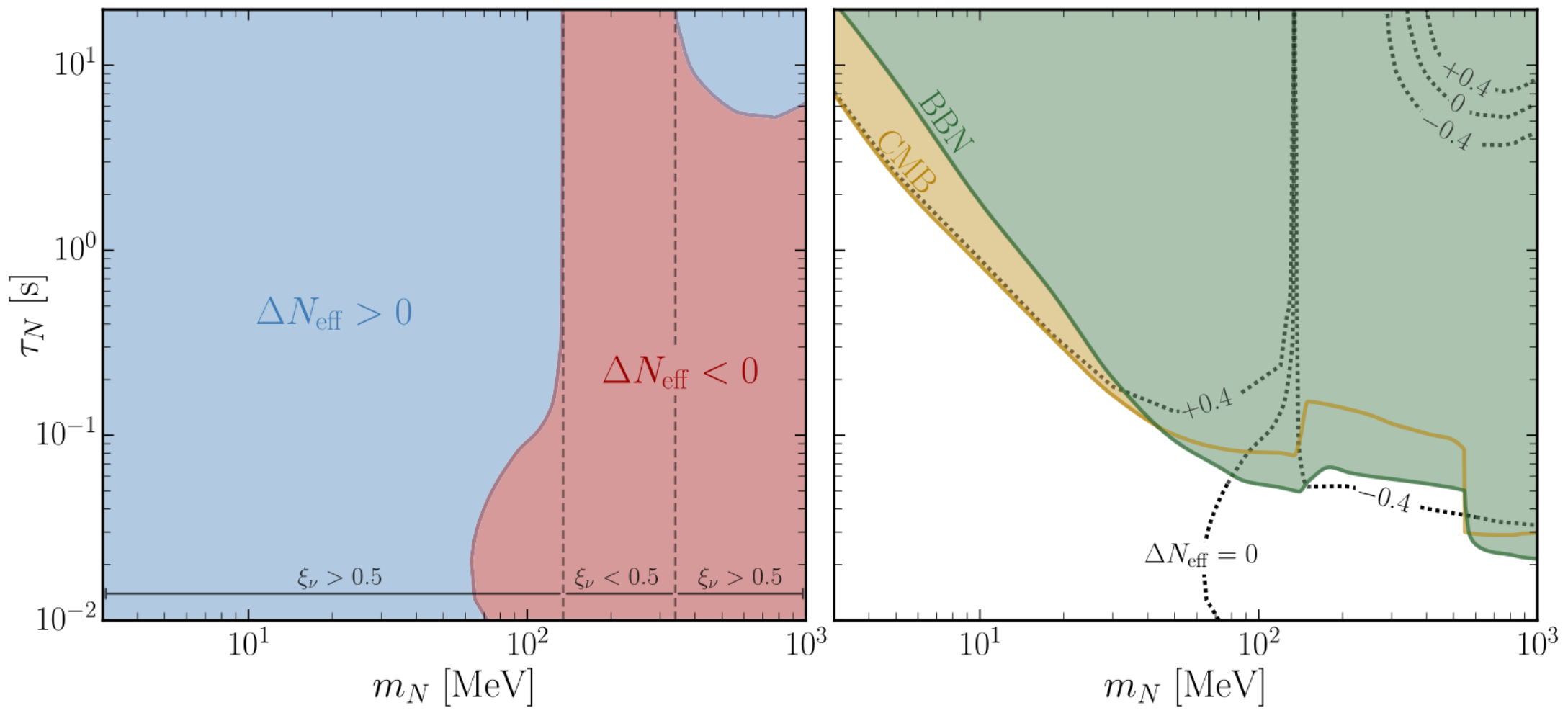

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
ξ_ν
0.2
0.4
0.6
0.8
1.0
m_N [GeV]
$e-$ mixing
$\mu-$ mixing
$\tau-$ mixing


1.0
0.5
0.0
−0.5
−1.0
$\Delta N_{\rm eff}$
$m_N = 30$ MeV
$m_N = 110$ MeV
$m_N = 200$ MeV
10^{-2}
10^{-1}
10^{0}
τ_N [s]


$\Delta N_{\rm eff}$
−2 −1 0 1 5 30 60
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
τ_N [s]
0.1
1.0
m_N [GeV]


$\rho_{\nu_e}^{\rm inj}/\rho_\nu^{\rm tot} = 5\ \%$
$\rho_{\nu_e}^{\rm inj}/\rho_\nu^{\rm tot} = 1\ \%$
$\rho_{\nu_e}^{\rm inj}/\rho_\nu^{\rm tot} = 0.2\ \%$
thermal
non − eq
$\left(\frac{\rho_{\nu_e}}{\rho_{\rm EM}}\right) / \left(\frac{\rho_{\nu_e}}{\rho_{\rm EM}}\right)_{\rm SM} - 1\ [\%]$
T [MeV]
$T_{\rm EM,eff}$ (non − eq)
T_ν (non − eq)
$T_{\rm EM,eff}$ (thermal)
T_ν (thermal)
$T_i\ /\ T$
T [MeV]

Case study: Heavy Neutral Leptons



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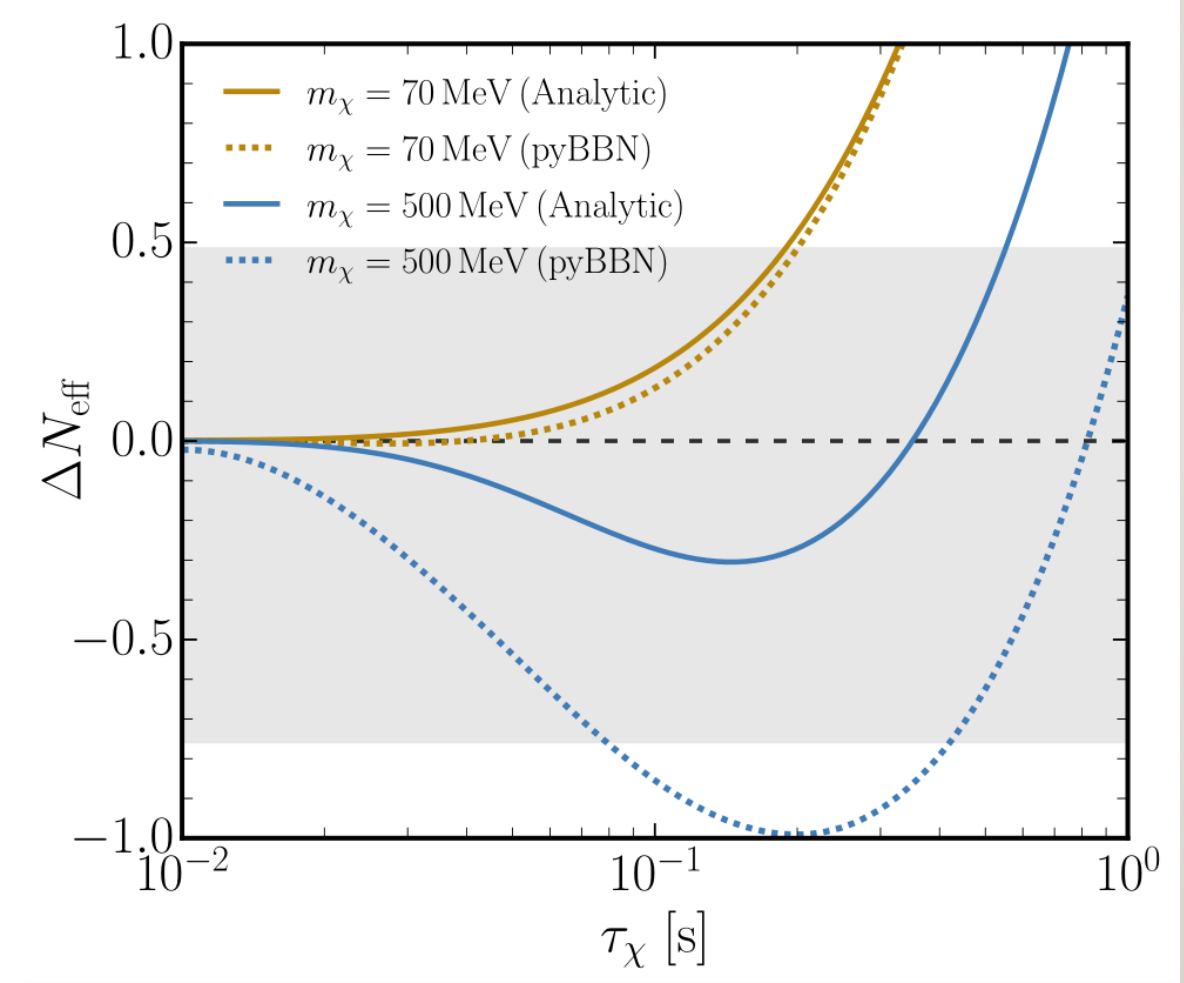

$$\chi \rightarrow \nu_e + \nu_\mu + \bar{\nu}_\mu$$

$$E_\nu^{\rm inj} \gtrsim \frac{70}{3} \approx 25 \text{ MeV}$$