Dirac Neutrinos and N_{eff}

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Talk based on 2005.01629, 2011.13059

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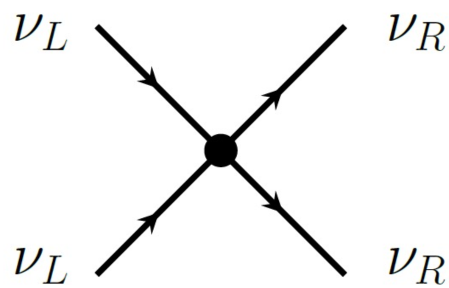
Motivation

- Question: Neutrino, Dirac or Majorana?
  - neutrino is Dirac → light right-handed neutrinos ν_R → $N_{\rm eff}$
  - In SM there's no problem ν_R is decoupled from SM
  - In BSM, ν_R could be thermalized
- "Neutrino Portal"
- Weak Lab Constrain
- Rich cosmological phenomenology

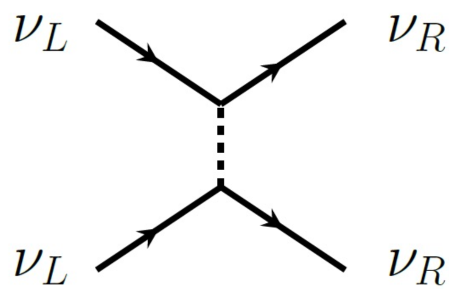
  Future CMB experiment (CMB-S4) → percent level determination of $N_{\rm eff}$

Dirac Neutrinos and N_{eff}

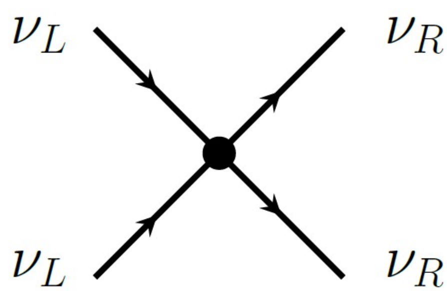
- Contact Interaction
  - X. Luo, W. Rodejohann, X. Xu, JCAP, 2005.01629
  - "Freeze-out"



- Non-Contact Interaction
  - X. Luo, W. Rodejohann, X. Xu, JCAP, 2011.13059
  - Freeze-in



Contact Interaction



Consider the most general interaction form

$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_a \overline{\nu}\Gamma^a \nu \left[\overline{\nu}\Gamma^a(\epsilon_a + \tilde{\epsilon}_a i_a \gamma^5)\nu\right],$$

$$\Gamma^a = \{I,\ i\gamma^5,\ \gamma^\mu,\ \gamma^\mu\gamma^5,\ \sigma^{\mu\nu} \equiv \frac{i}{2}[\gamma^\mu, \gamma^\nu]\}.$$

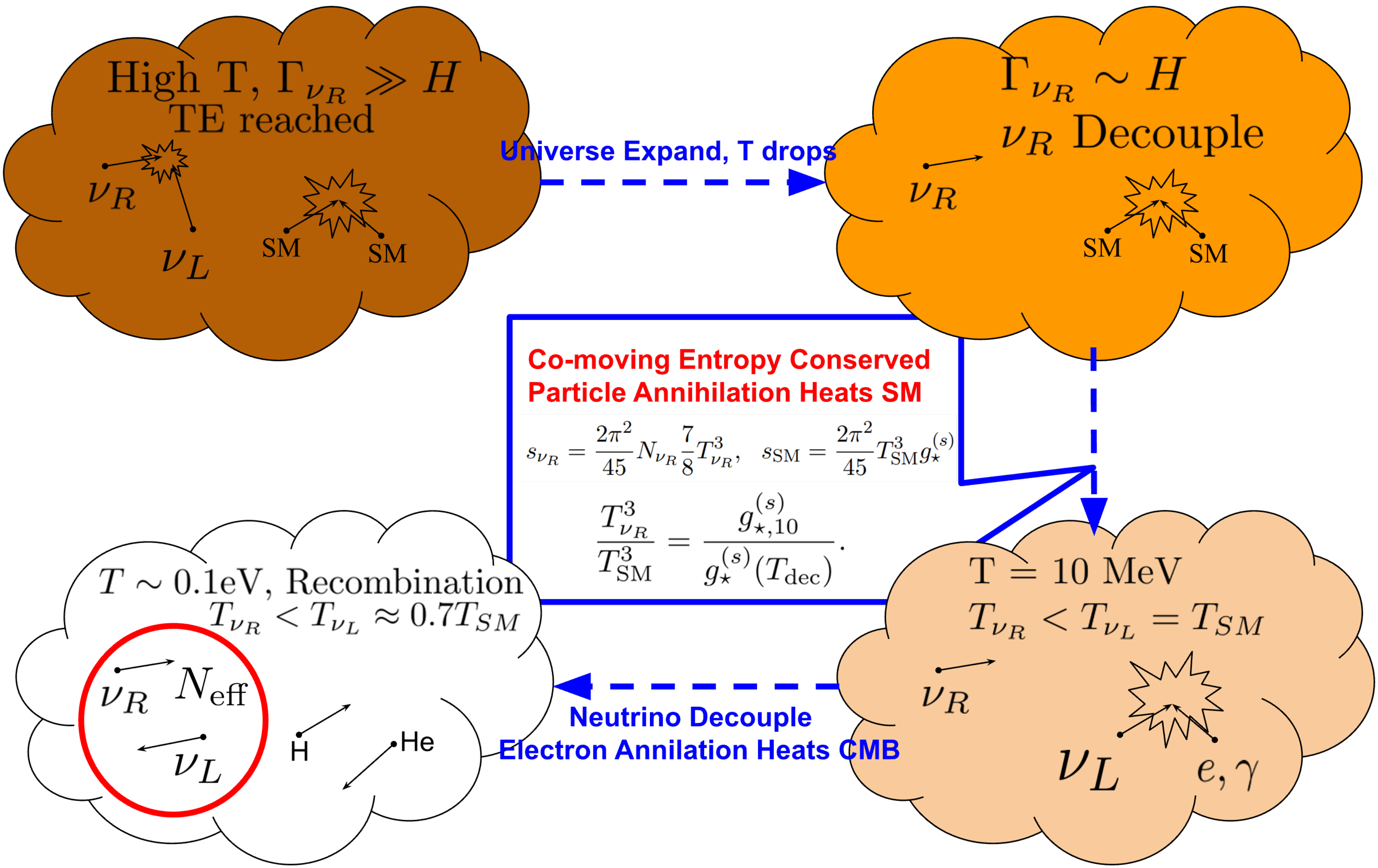
- In the chiral basis, they are

$$\begin{aligned}\mathcal{L} \supset\ & G_S\,\overline{\nu_L}\nu_R\overline{\nu_L}\nu_R + G_S^*\,\overline{\nu_R}\nu_L\overline{\nu_R}\nu_L \\ & + \tilde{G}_S\,\overline{\nu_L}\nu_R\overline{\nu_R}\nu_L \\ & + G_V\,\overline{\nu_L}\gamma^\mu\nu_L\overline{\nu_R}\gamma_\mu\nu_R \\ & + G_T\,\overline{\nu_L}\sigma^{\mu\nu}\nu_R\overline{\nu_L}\sigma_{\mu\nu}\nu_R + G_T^*\,\overline{\nu_R}\sigma^{\mu\nu}\nu_L\overline{\nu_R}\sigma_{\mu\nu}\nu_L\end{aligned}$$

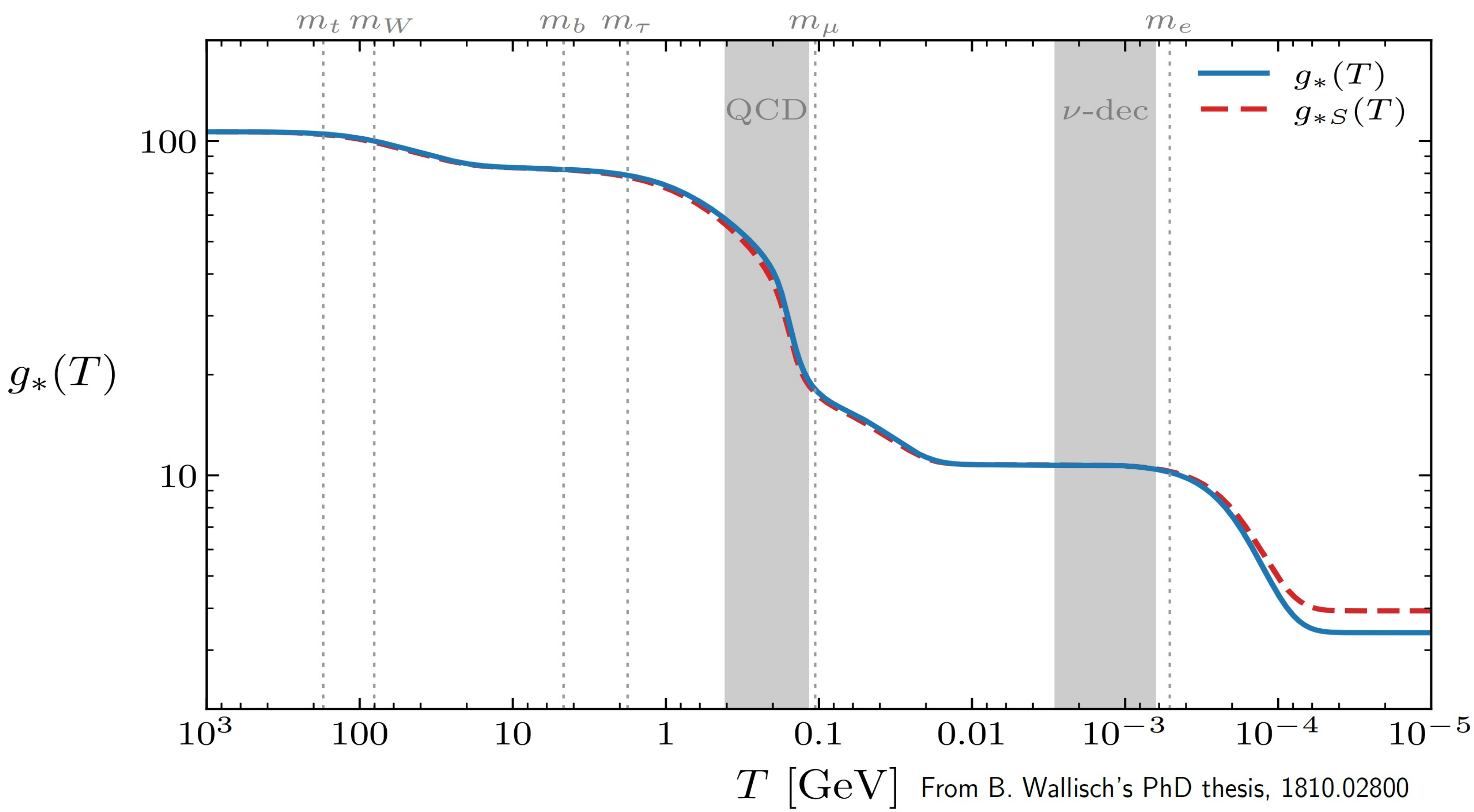
- Dimensional Analysis

$$\Gamma_{\nu_L \leftrightarrow \nu_R} \sim G_s^2 T^5 \gg H \sim T^2/m_{pl}, \quad \text{(For sufficiently large T.)}$$

Very High T → ν_R in thermal equilibrium, low T → ν_R decouple



High T, $\Gamma_{\nu_R} \gg H$
TE reached
ν_R
ν_L
SM
SM
Universe Expand, T drops
$\Gamma_{\nu_R} \sim H$
ν_R Decouple
ν_R
SM
SM
Co-moving Entropy Conserved
Particle Annihilation Heats SM
$s_{\nu_R} = \frac{2\pi^2}{45} N_{\nu_R} \frac{7}{8} T_{\nu_R}^3, \quad s_{\rm SM} = \frac{2\pi^2}{45} T_{\rm SM}^3 g_\star^{(s)}$
$\frac{T_{\nu_R}^3}{T_{\rm SM}^3} = \frac{g_{\star,10}^{(s)}}{g_\star^{(s)}(T_{\rm dec})}.$
$T \sim 0.1$eV, Recombination
$T_{\nu_R} < T_{\nu_L} \approx 0.7 T_{SM}$
ν_R $N_{\rm eff}$
ν_L
H
He
Neutrino Decouple
Electron Annilation Heats CMB
T = 10 MeV
$T_{\nu_R} < T_{\nu_L} = T_{SM}$
ν_R
ν_L
e, γ



From B. Wallisch's PhD thesis, 1810.02800

- Quick Example: If ν_R decouples sufficiently early ($g_\star = 106.75$), then when the universe cools down to 10MeV $(g_\star = 10.75)$ we have:

$$\frac{T_{\nu_R}^3}{T_{\rm SM}^3} = \frac{g_{\star,10}^{(s)}}{g_\star^{(s)}(T_{\rm dec})}. \rightarrow \quad \frac{T_{\nu_R,10}}{T_{\rm SM,10}} = 0.46, \quad \frac{T_{\nu_R,10}^4}{T_{\rm SM,10}^4} = 0.047. \quad \rightarrow 3\nu_R \Rightarrow \Delta N_{\rm eff} = 3 \times 0.0468 = 0.14$$

- Later the decouple → higher $\frac{T_{\nu_R,10}}{T_{\rm SM,10}}$ → higher $N_{\rm eff}$
- Still approximation, solve Boltzmann equation → accurate answer

Brief Intro of Boltzmann Equation

- Boltzmann Equation governs evolution of particle distribution f_ψ

$$\left[\frac{\partial}{\partial t} - H\,\vec{p}\cdot\nabla_{\vec{p}}\right] f_\psi(\vec{p},\ t) = C_\psi^{(f)}.$$

- The collision term $C_\psi^{(f)}$ is a large integral of … everything

$$C_\psi^{(f)} = -\frac{1}{2E_\psi}\int d\Pi_a d\Pi_b \cdots d\Pi_i d\Pi_j \cdots (2\pi)^4 \delta^4(p_\psi + p_a + p_b + \cdots - p_i - p_j - \cdots)$$
$$\times S\left[|\mathcal{M}|^2_{\psi+a+b+\cdots\to i+j+\cdots} f_\psi f_a f_b \cdots (1\pm f_i)(1\pm f_j)\cdots\right.$$
$$\left. -|\mathcal{M}|^2_{i+j+\cdots\to\psi+a+b+\cdots} f_i f_j \cdots (1\pm f_\psi)(1\pm f_a)(1\pm f_b)\cdots\right],$$

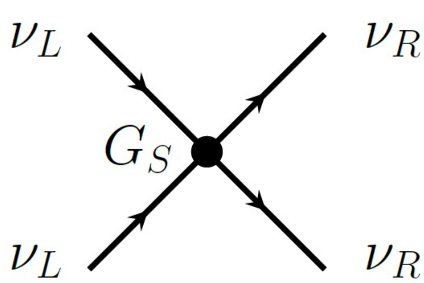
$$d\Pi_x \equiv \frac{g_x}{(2\pi)^3}\frac{d^3p_x}{2E_x}\,,\quad x\in\{\psi,\ a,\ b,\ \cdots i,\ j,\ \cdots\}$$

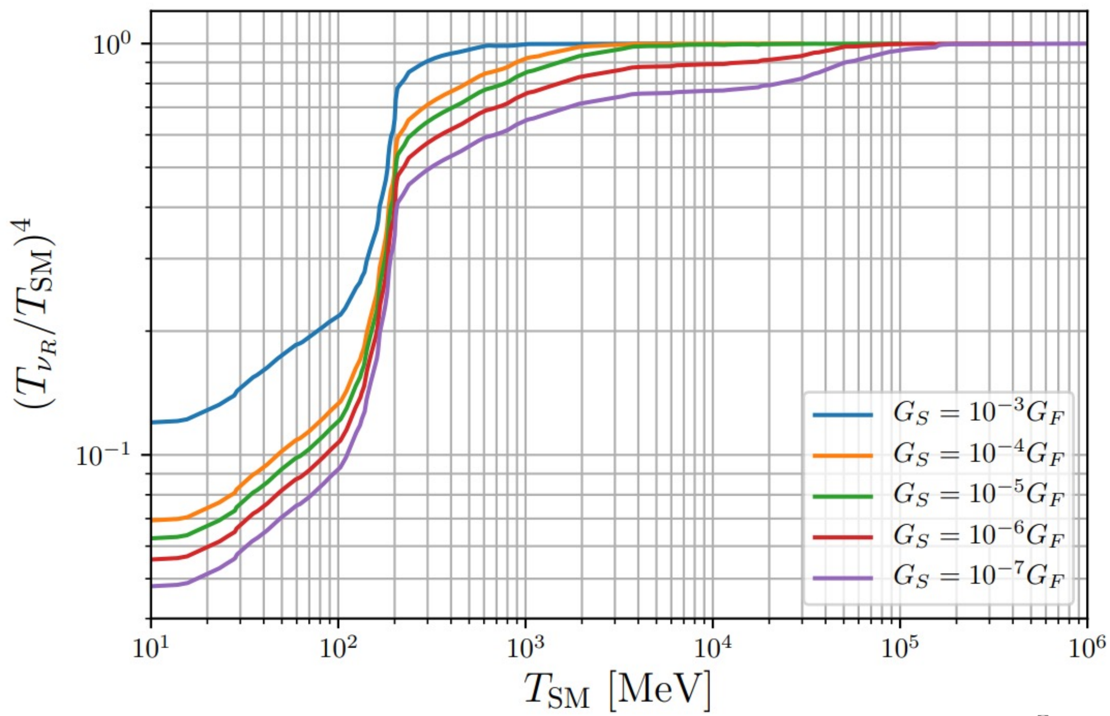
- Method: Dolgov et al [hep-ph/9703315]. TLDR, what's the result?

Results

process	S	$C_{\nu_R}^{(\rho)}$ from MB statistics	$1-\delta_{\rm FD}$
$\nu_R(p_1)+\nu_R(p_2)\leftrightarrow\nu_L(p_3)+\nu_L(p_4)$	$\frac{2}{2!2!}$	$\frac{12}{\pi^5}\lvert G_S-12G_T\rvert^2 N_{\nu_R}\left(T_{\rm SM}^9-T_{\nu_R}^9\right)$	0.8840
$\nu_R(p_1)+\overline{\nu_R}(p_2)\leftrightarrow\nu_L(p_3)+\overline{\nu_L}(p_4)$	1	$\frac{2}{\pi^5}\lvert\tilde G_S-2G_V\rvert^2 N_{\nu_R}\left(T_{\rm SM}^9-T_{\nu_R}^9\right)$	0.8841
$\nu_R(p_1)+\nu_L(p_2)\leftrightarrow\nu_R(p_3)+\nu_L(p_4)$	1	$\frac{1}{2\pi^5}\lvert\tilde G_S-2G_V\rvert^2 N_{\nu_R}T_{\rm SM}^4T_{\nu_R}^4\left(T_{\rm SM}-T_{\nu_R}\right)$	0.8518
$\nu_R(p_1)+\overline{\nu_L}(p_2)\leftrightarrow\nu_R(p_3)+\overline{\nu_L}(p_4)$	1	$\frac{3}{\pi^5}\lvert\tilde G_S-2G_V\rvert^2 N_{\nu_R}T_{\rm SM}^4T_{\nu_R}^4\left(T_{\rm SM}-T_{\nu_R}\right)$	0.8249
$\nu_R(p_1)+\overline{\nu_L}(p_2)\leftrightarrow\overline{\nu_R}(p_3)+\nu_L(p_4)$	1	$\frac{6}{\pi^5}\lvert G_S-12G_T\rvert^2 N_{\nu_R}T_{\rm SM}^4T_{\nu_R}^4\left(T_{\rm SM}-T_{\nu_R}\right)$	0.8118

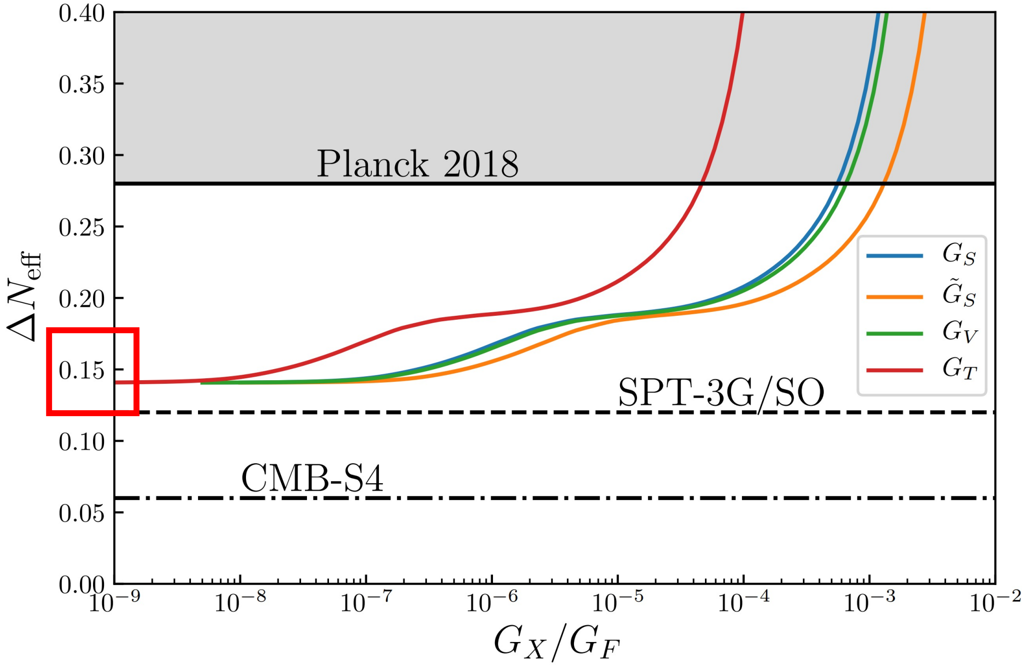
Find out $C_{\nu_R}^{(\rho)}$
→ Boltzmann equation
→ Solve Evolution of T_{ν_R}
→ $N_{\rm eff}$



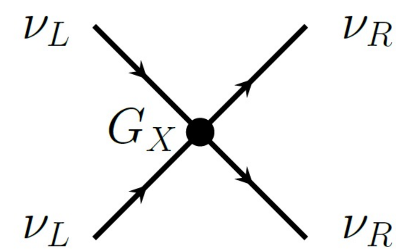


Results

From the temperature calculate N_{eff}



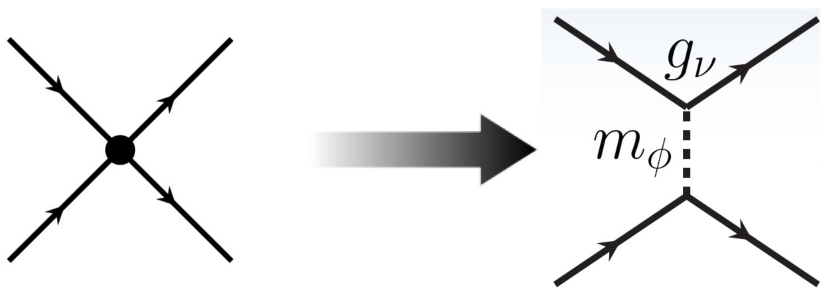
$$\mathcal{L} \supset G_S\, \overline{\nu_L}\nu_R\overline{\nu_L}\nu_R + G_V\, \overline{\nu_L}\gamma^\mu\nu_L\overline{\nu_R}\gamma_\mu\nu_R + G_T \cdots$$

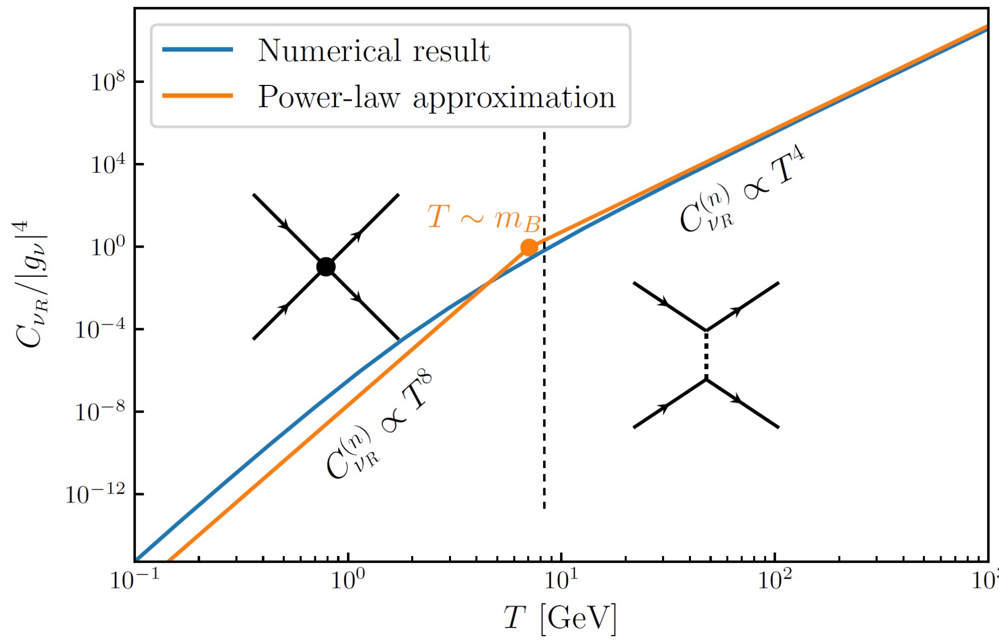


Current: $10^{-3} \sim 10^{-5} G_F$ Excluded → probe $1/\sqrt{G_X} \sim 50\text{TeV}$ physics

Future: Exclude any small G_X → probe infinite energy? No

Freeze-out → Freeze-in



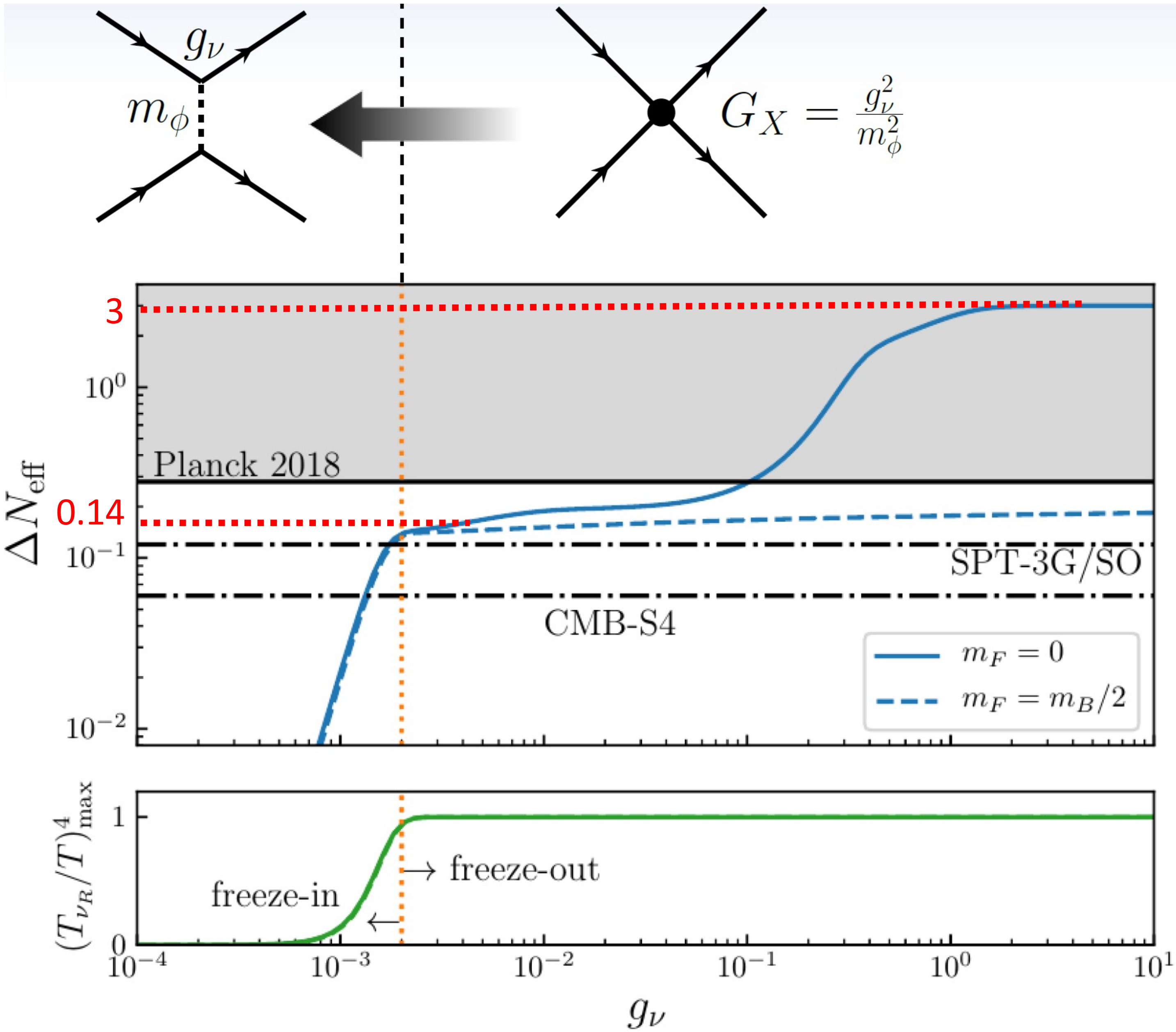


- Low energy EFT fails at high T, open the vertex
- Dimensional Analysis

$$\Gamma_{\nu_R} \sim g^4 T \ll H \sim T^2/m_{pl}, \quad \text{(For sufficiently large T.)}$$

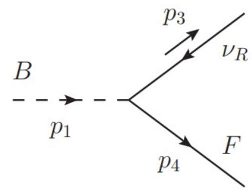
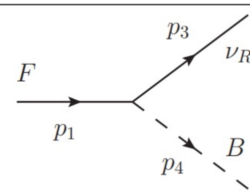
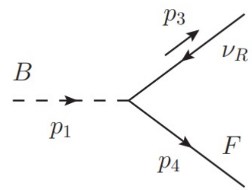
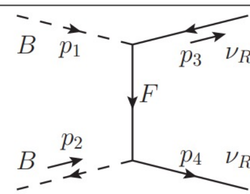
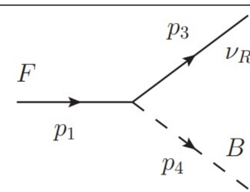
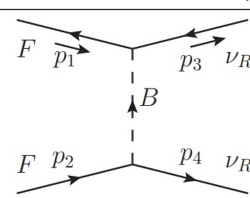
High T → ν_R not thermal equilibrium
Low T → model dependent → Boltzmann

Results

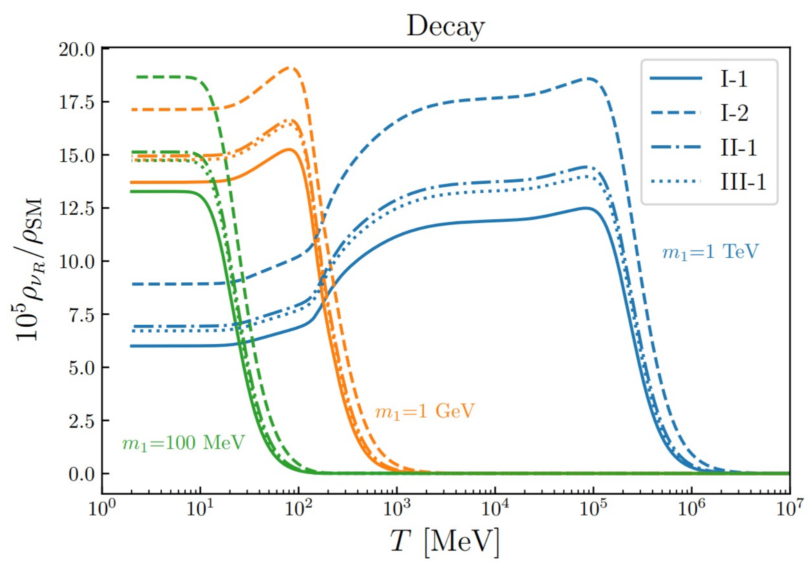


g_ν
m_ϕ
$G_X = \frac{g_\nu^2}{m_\phi^2}$
3
10^0
Planck 2018
$\Delta N_{\rm eff}$
0.14
10^{-1}
SPT-3G/SO
CMB-S4
10^{-2}
$m_F = 0$
$m_F = m_B/2$
$(T_{\nu_R}/T)^4_{\rm max}$
1
0
freeze-in
←
→ freeze-out
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
g_ν

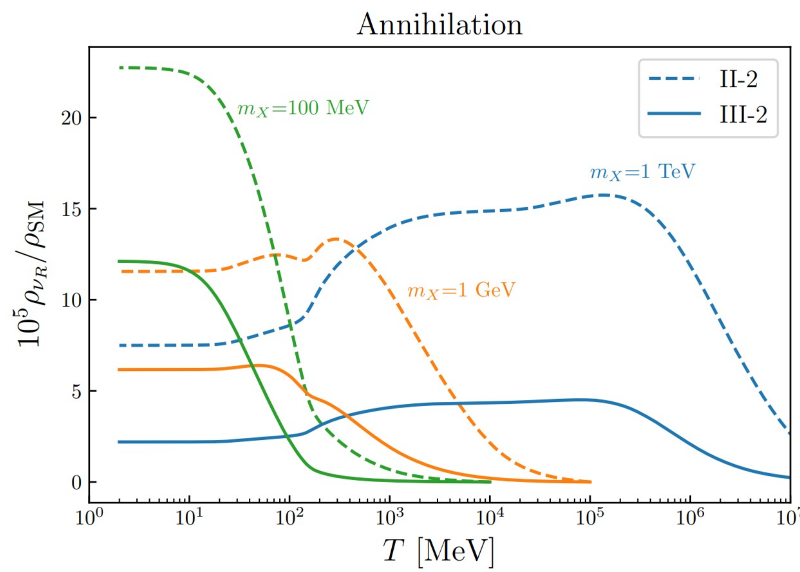
Results

Cases	Dominant processes for ν_R-genesis	$S\|\mathcal{M}\|^2$
(I-1) F and B in thermal equilibrium, $m_B > m_F$		scalar B: $\|g_\nu\|^2(m_B^2 - m_F^2)$ vector B^μ: $\|g_\nu\|^2\left(2m_B^2 - m_F^2 - \frac{m_F^4}{m_B^2}\right)$
(I-2) F and B in thermal equilibrium, $m_F > m_B$		scalar B: $\|g_\nu\|^2(m_F^2 - m_B^2)$ vector B^μ (for $16\pi^2 m_B^2 \gtrsim g_\nu^2 m_F^2$): $\|g_\nu\|^2(m_F^2 - m_B^2)(2m_B^2 + m_F^2)m_B^{-2}$
(II-1) B in thermal equilibrium, F not, $m_B > m_F$		scalar B: $\|g_\nu\|^2(m_B^2 - m_F^2)$ vector B^μ: $\frac{\|g_\nu\|^2}{3m_B^2}(m_B^2 - m_F^2)(2m_B^2 + m_F^2)$
(II-2) B in thermal equilibrium, F not, $m_F > m_B$		complex scalar B: $\|g_\nu\|^4 \frac{tu - m_B^4}{\|t - m_F^2\|^2}$ for real scalar B, see Eq. (25) for vector B, see Eqs. (27) and (29)
(III-1) F in thermal equilibrium, B not, $m_F > m_B$		scalar B: $\|g_\nu\|^2(m_F^2 - m_B^2)$ vector B^μ (for $16\pi^2 m_B^2 \gtrsim g_\nu^2 m_F^2$): $\|g_\nu\|^2(m_F^2 - m_B^2)(2m_B^2 + m_F^2)m_B^{-2}$
(III-2) F in thermal equilibrium, B not, $m_B > m_F$		scalar B: $\|\mathcal{M}\|^2 = \|g_\nu\|^4(t - m_F^2)^2/(t - m_B^2)^2$ vector B^μ: $4\|g_\nu\|^4(m_F^2 - u)^2/(t - m_B^2)^2$

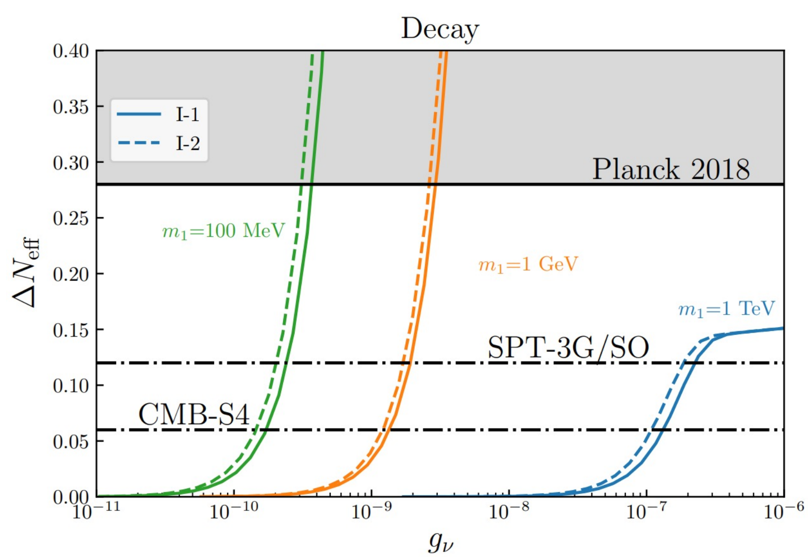
Results



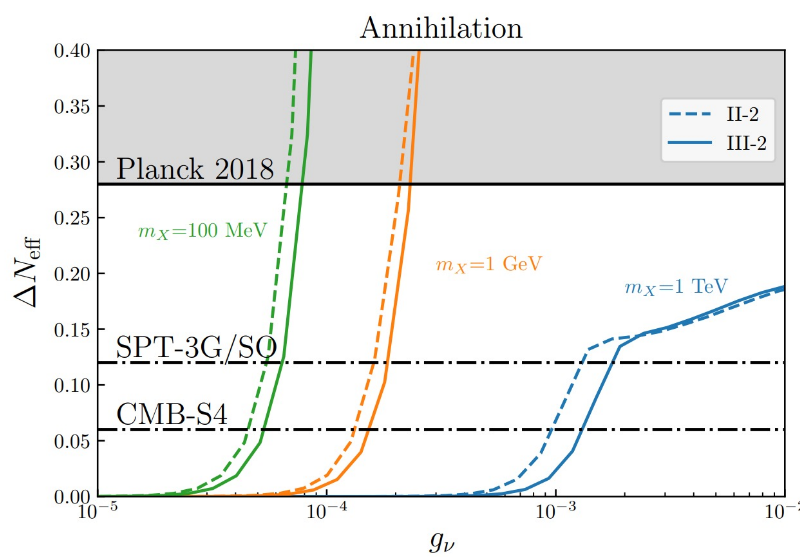
Decay
I-1
I-2
II-1
III-1
m_1=1 TeV
m_1=1 GeV
m_1=100 MeV
$10^5\rho_{\nu_R}/\rho_{SM}$
T [MeV]



Annihilation
II-2
III-2
m_X=100 MeV
m_X=1 TeV
m_X=1 GeV
$10^5\rho_{\nu_R}/\rho_{SM}$
T [MeV]



Decay
I-1
I-2
Planck 2018
m_1=100 MeV
m_1=1 GeV
m_1=1 TeV
SPT-3G/SO
CMB-S4
$\Delta N_{\rm eff}$
g_ν



Annihilation
II-2
III-2
Planck 2018
m_X=100 MeV
m_X=1 GeV
m_X=1 TeV
SPT-3G/SO
CMB-S4
$\Delta N_{\rm eff}$
g_ν

Summary

- Interactions of neutrinos (ν_L) with ν_R in the early universe

- Resolve Dirac/Majorana
  - ν_R could be thermalized → $N_{\rm eff}$

- Constraint on $N_{\rm eff}$ → Constrain coupling strength
  - Freeze-out: Planck2018 → $1/\sqrt{G_X} \sim 50{\rm TeV}$
    Future CMB → exclude
  - Freeze-in