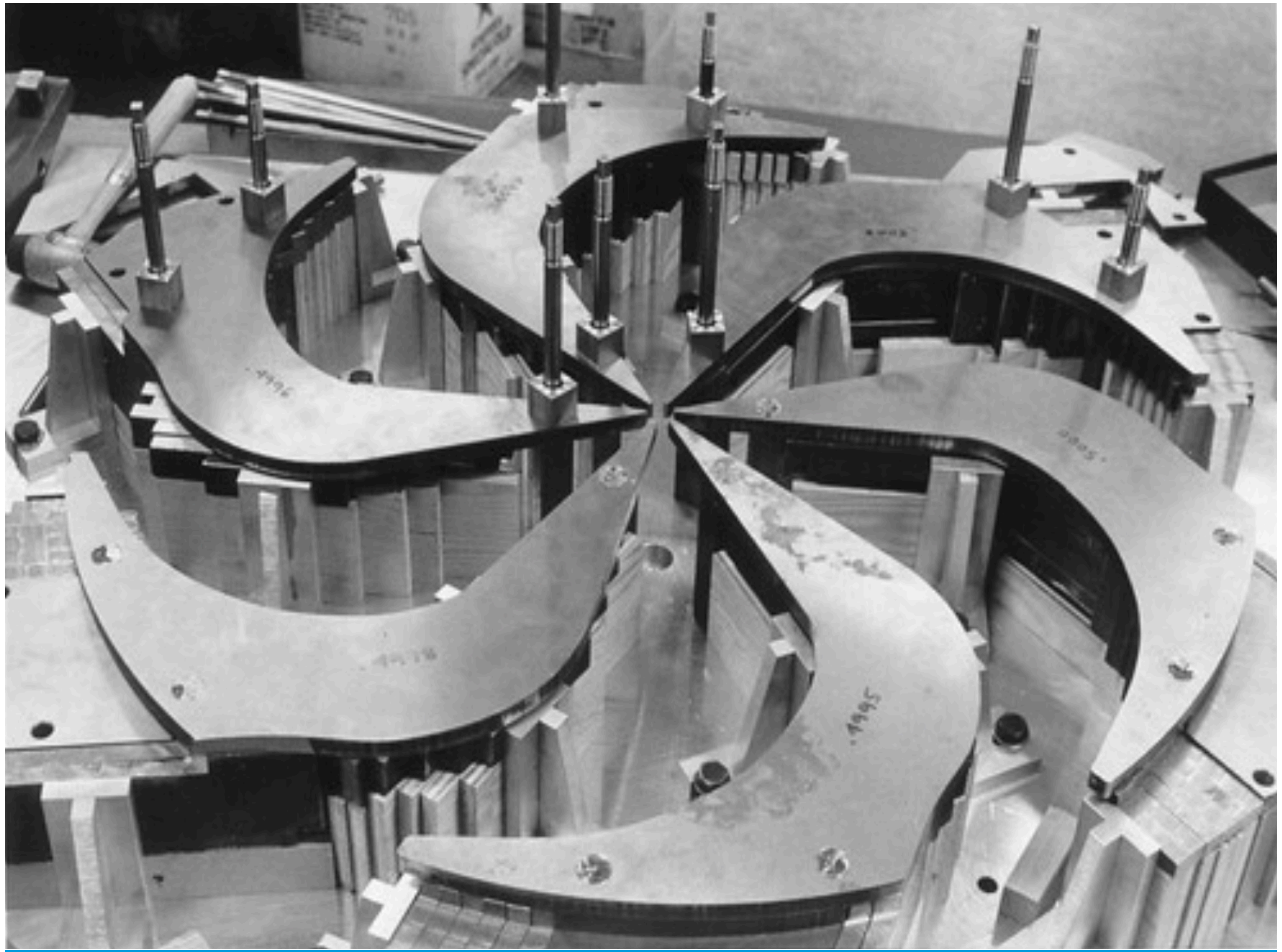
Cosmology of Dirac Neutrino Mass Models



TRIUMF
Canada's particle accelerator centre
Centre canadien d'accélération des particules

Michael Shamma (He/They)
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Neutrinos in Astrophysics and Cosmology
March 2024

Outline

- What we don't know about neutrinos
- It's really tough to produce and detect Dirac ν
- Example Dirac ν models which contribute detectably to ΔN_{eff}
- Terrestrial and cosmological ν probes
    - Correlating terrestrial and cosmological ν measurements
- Neutrinos in the bulk

Majorana or Dirac?

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- Dirac and Majorana masses permitted:
  $\mathscr{L}_\nu \supset -y_\nu \bar{L}\tilde{H}\nu_R - iM\bar{\nu}_R^c\nu_R + h.c.$

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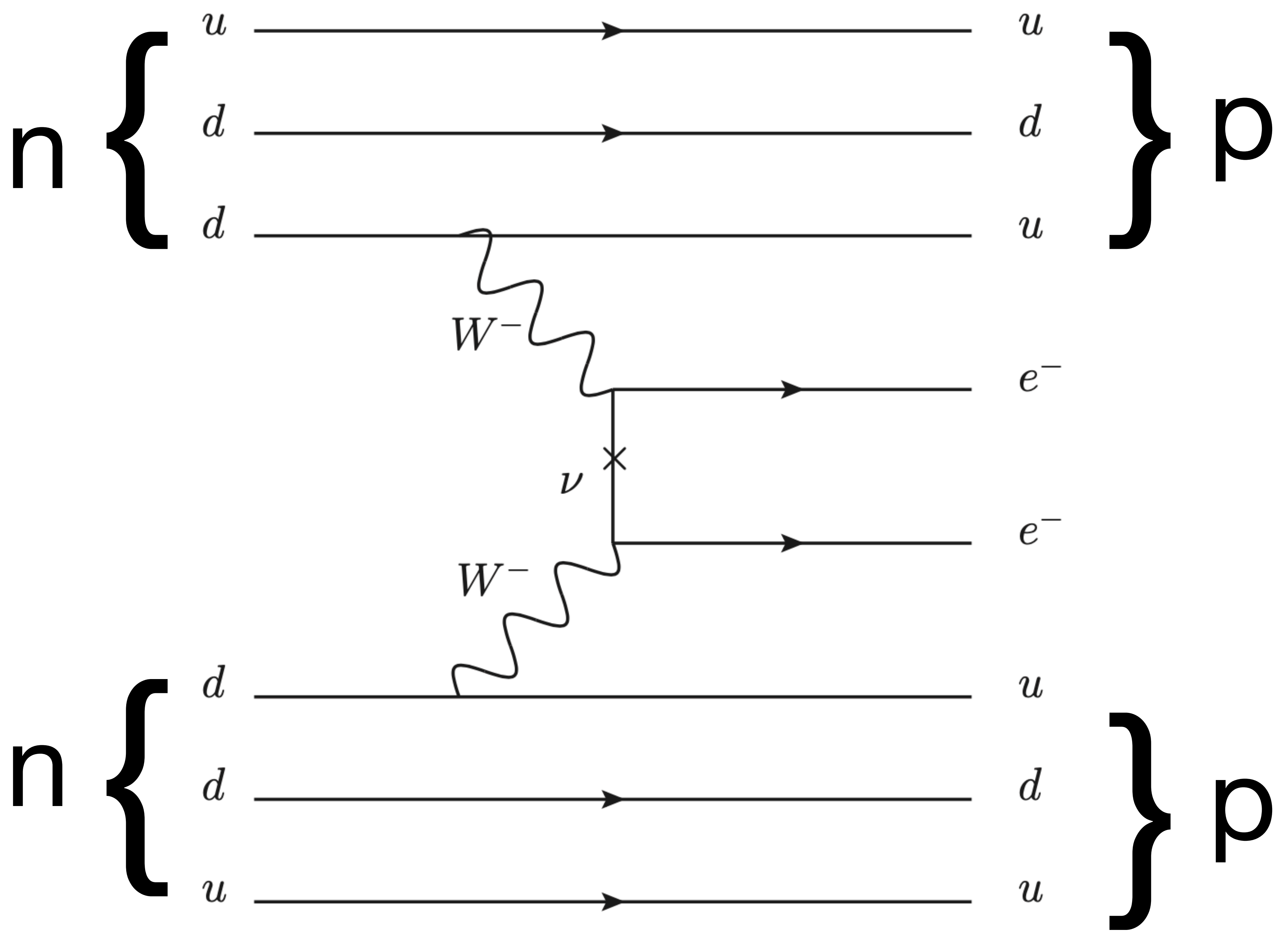

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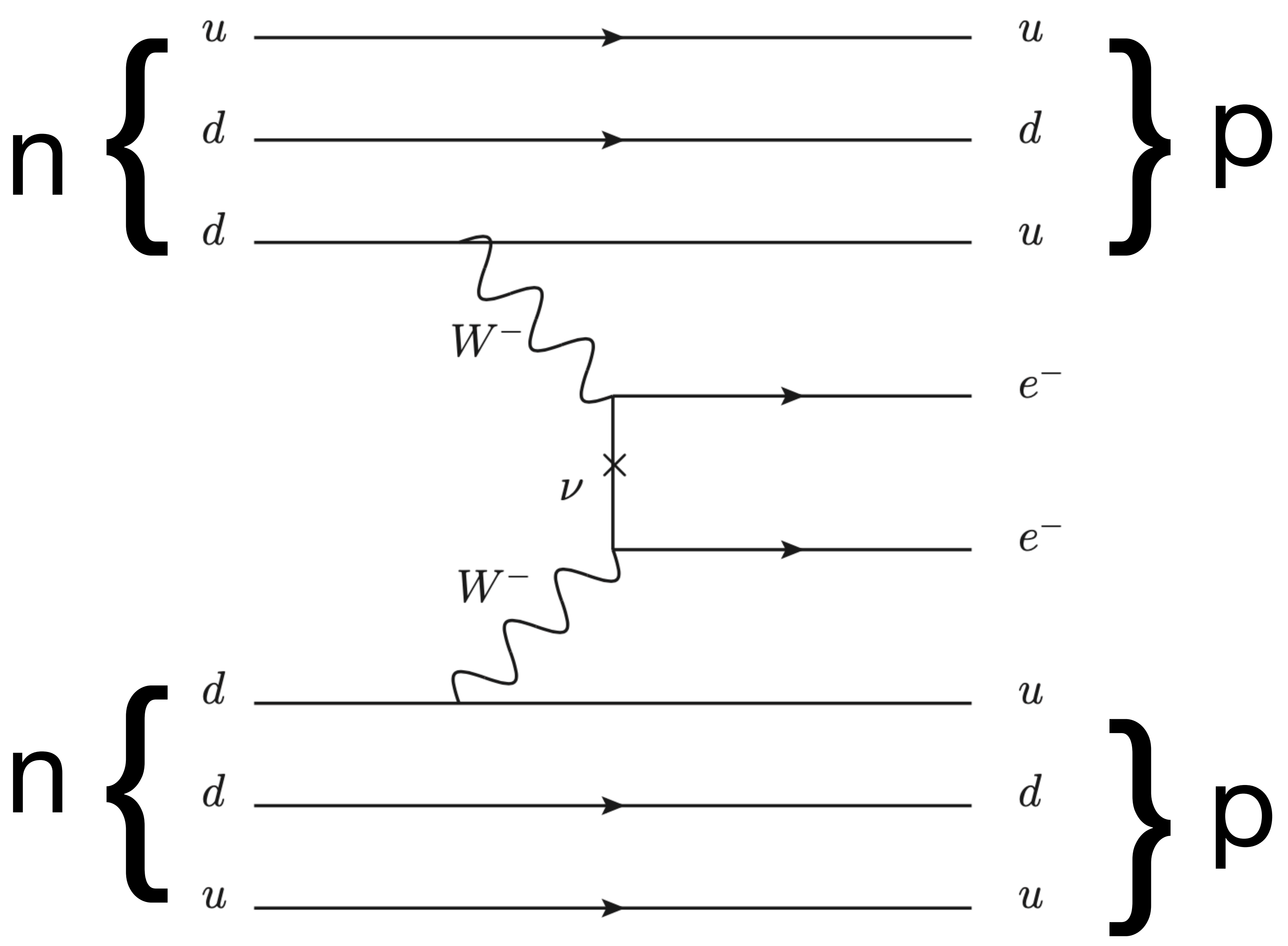

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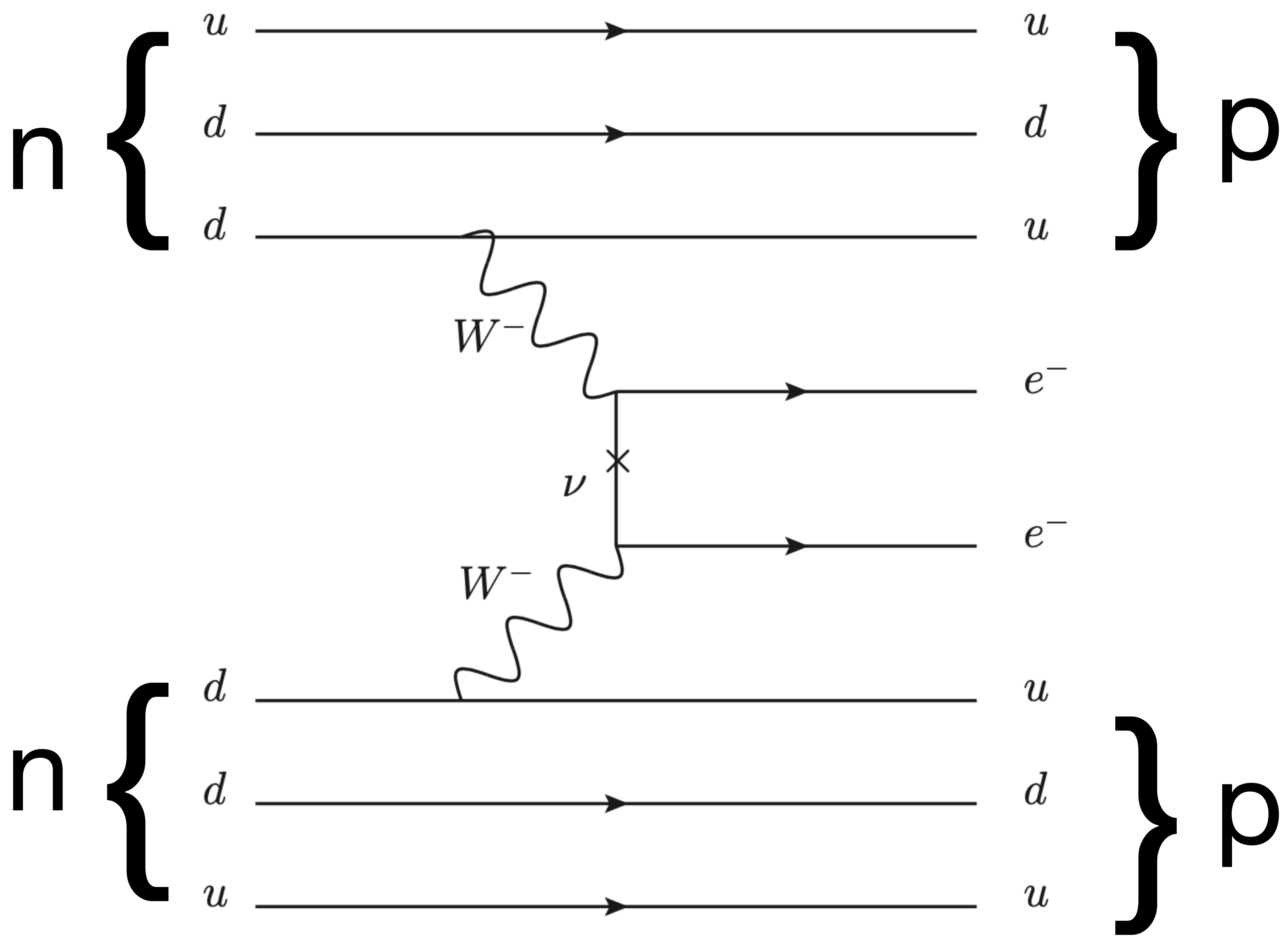

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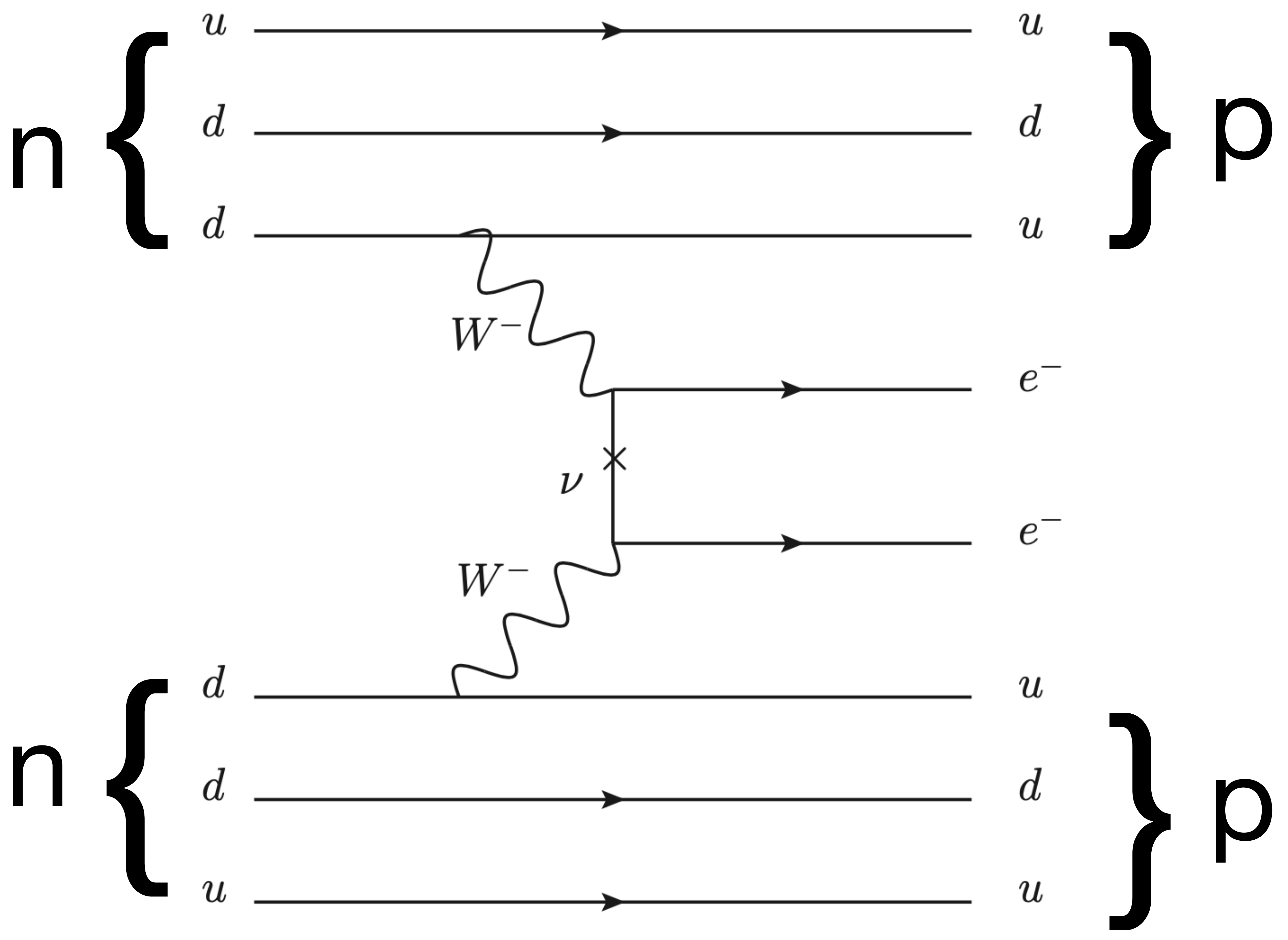

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Minimal SM Extension: $y_\nu \bar{L}\tilde{H}\nu_R$

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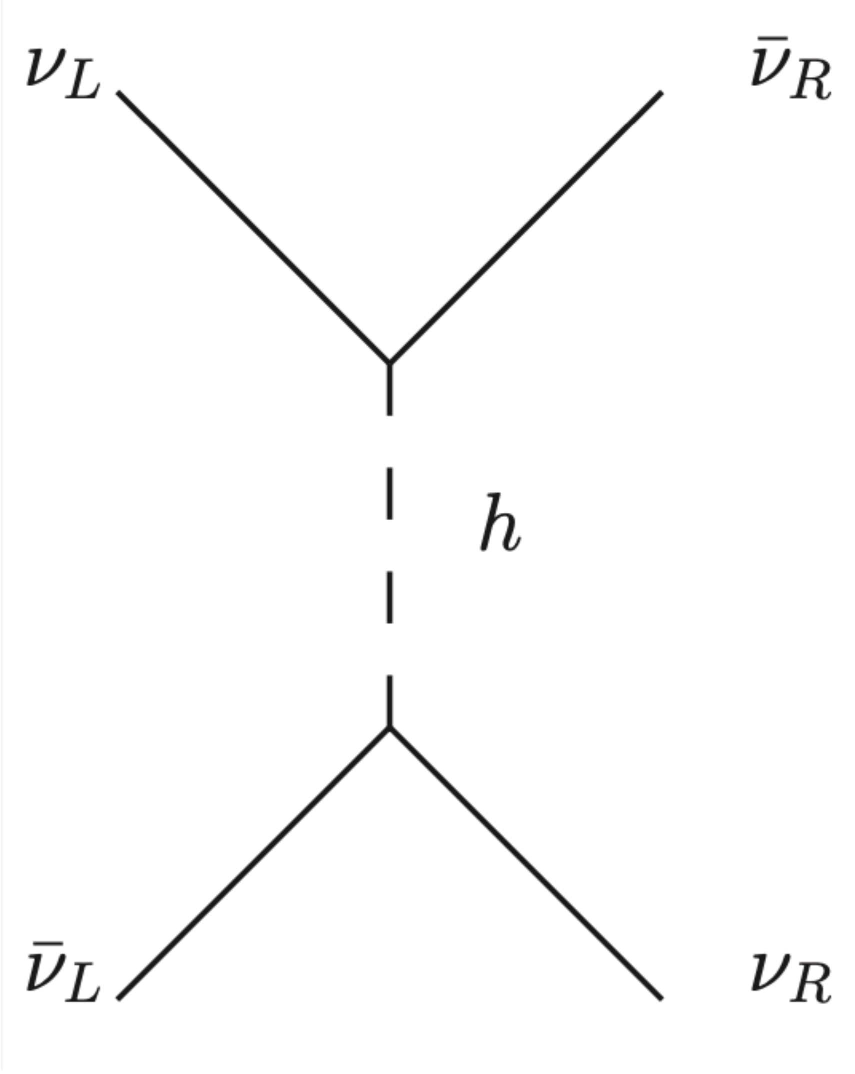

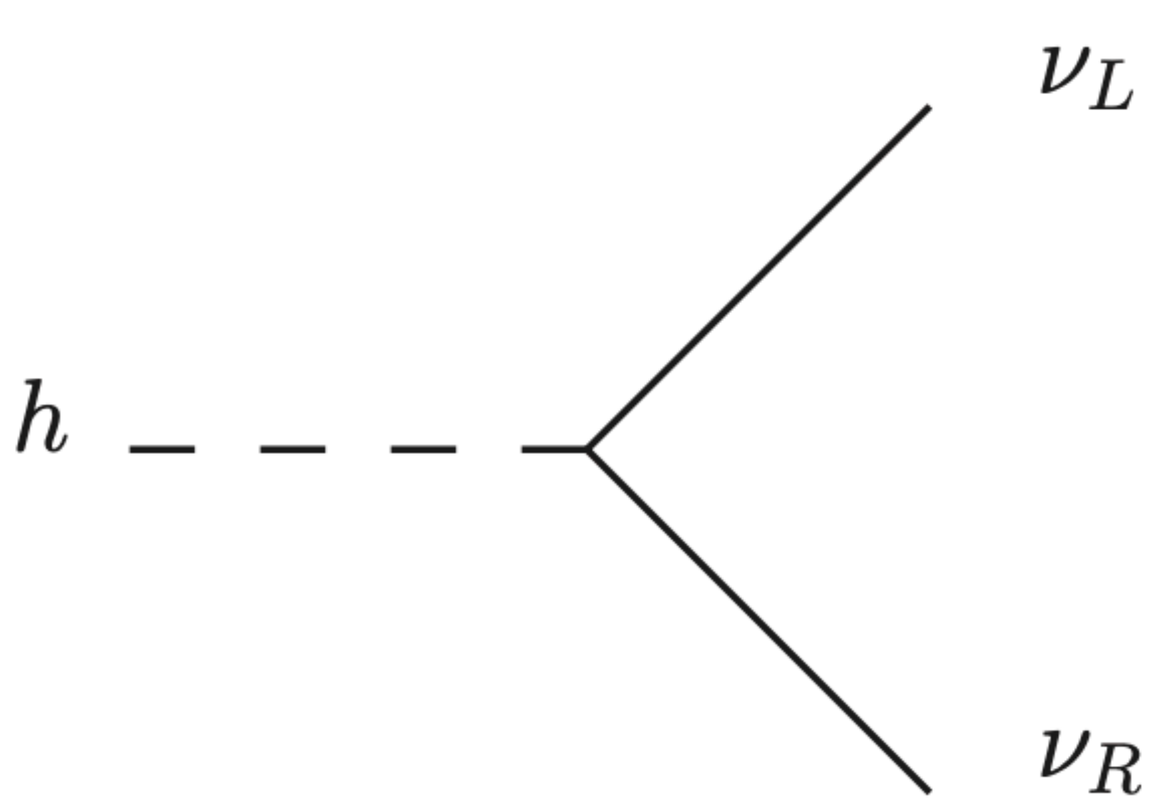

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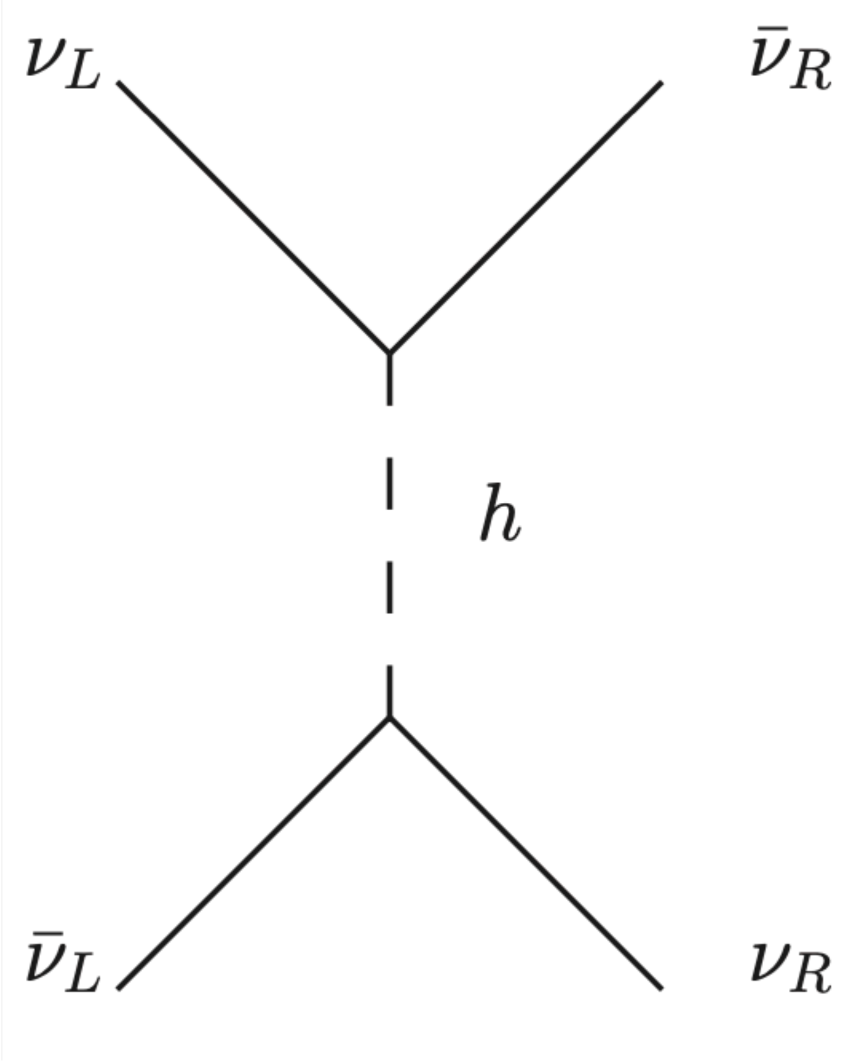

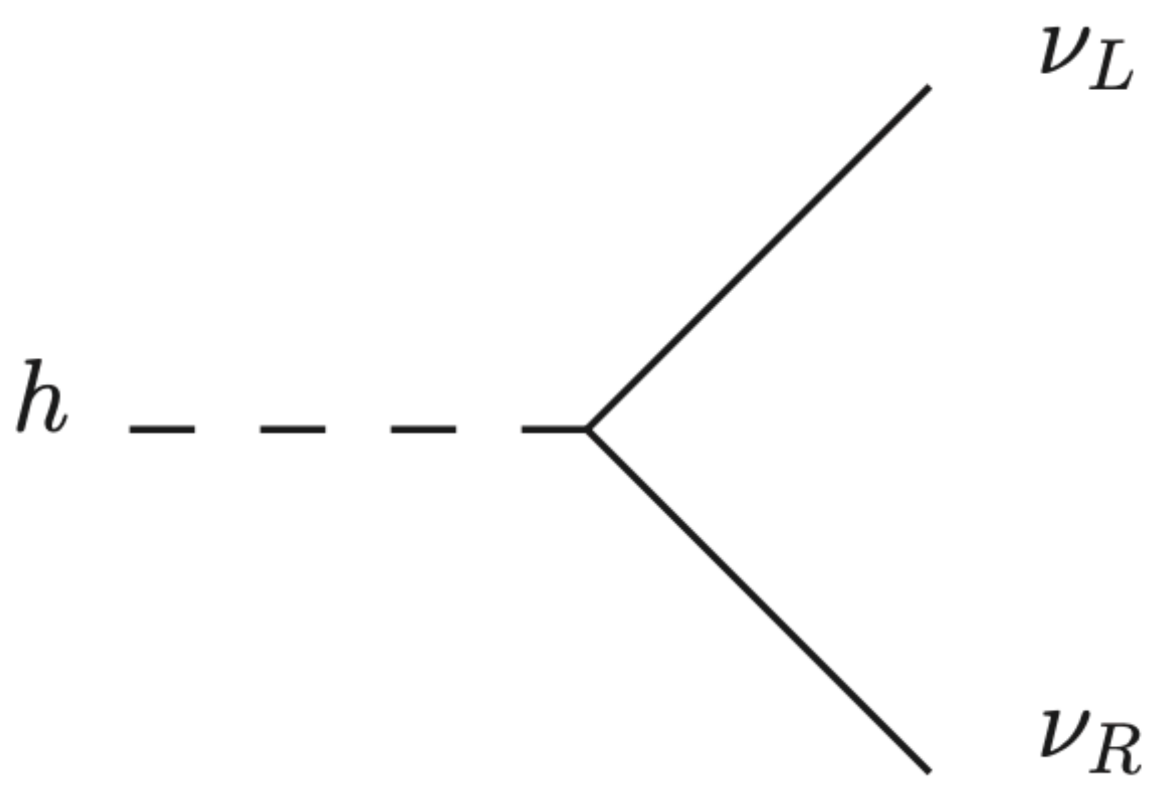

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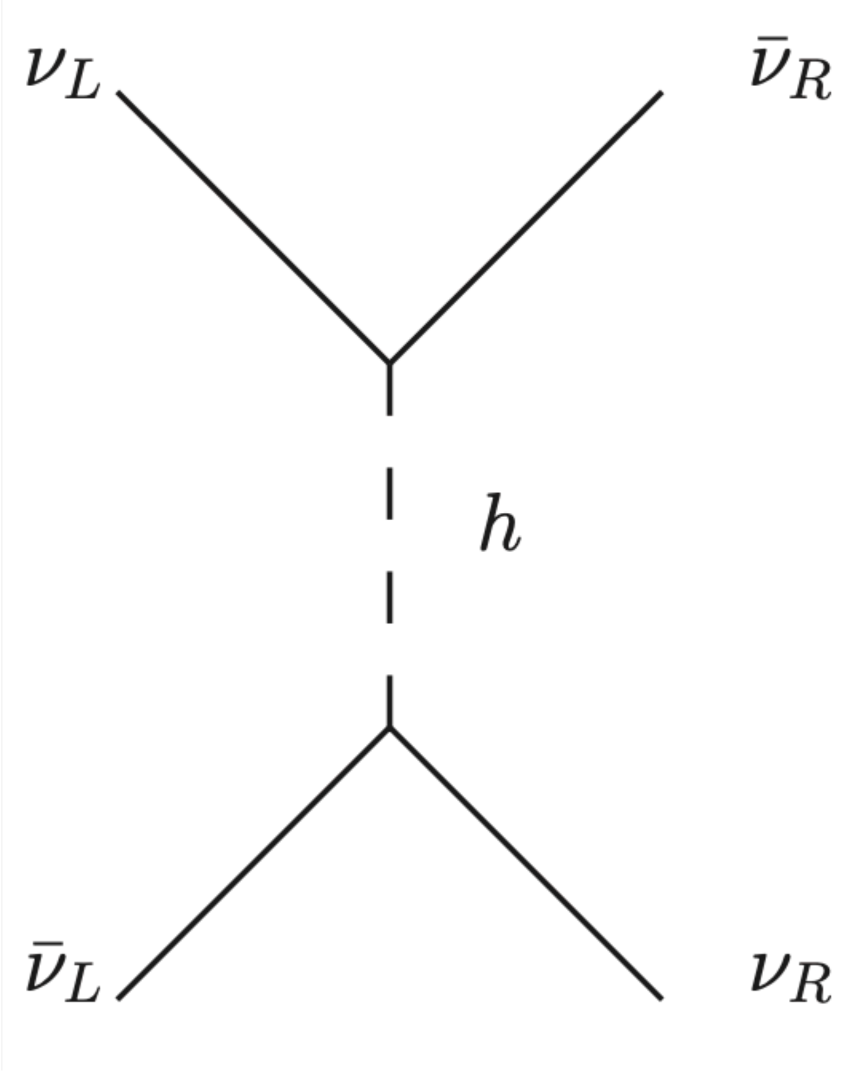

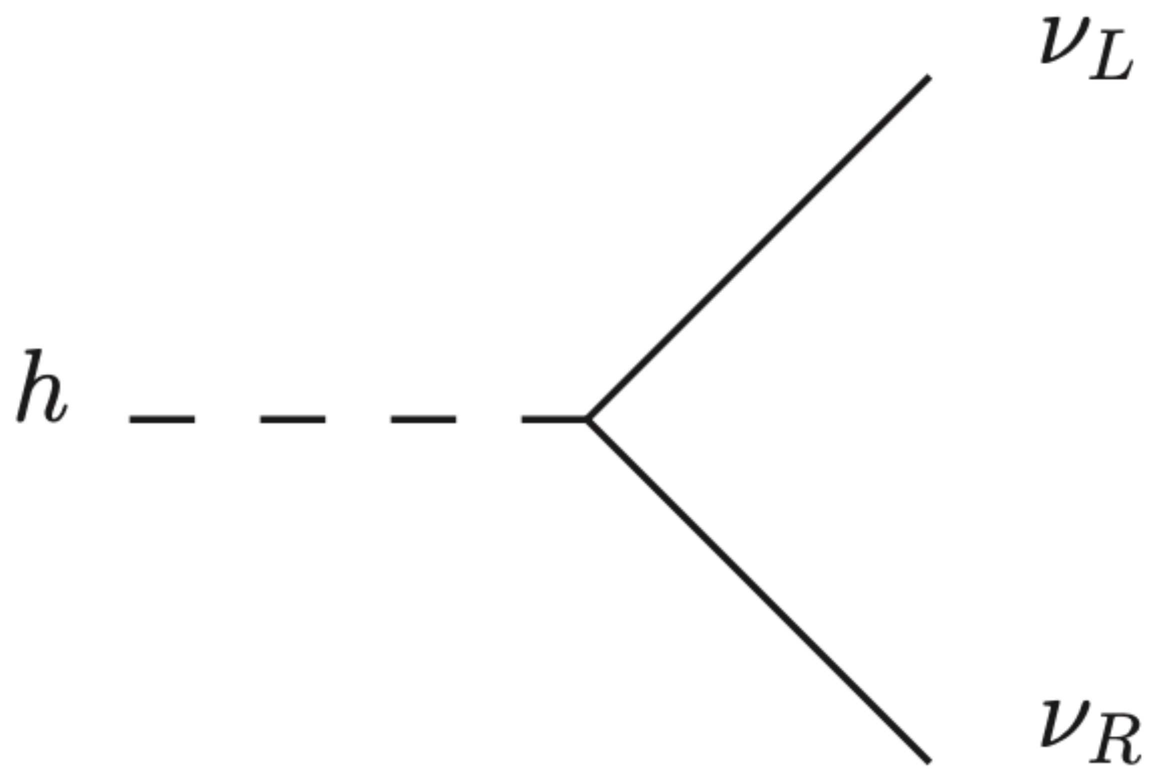

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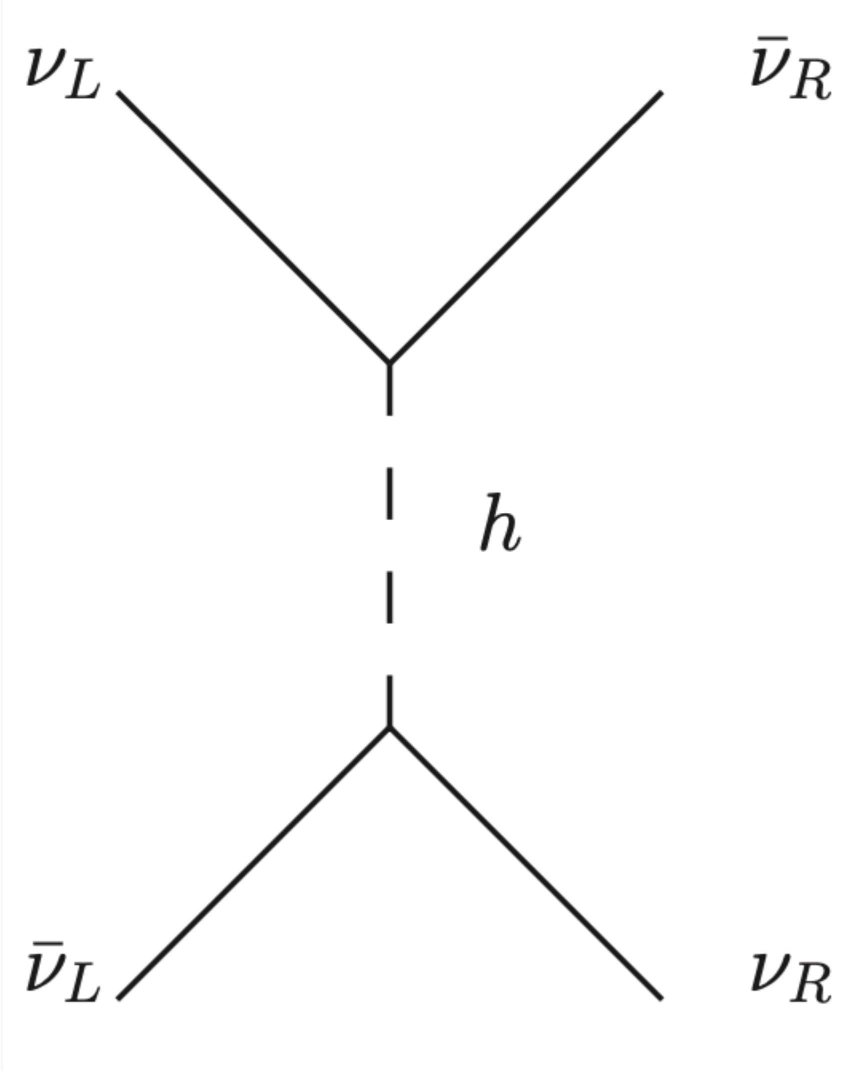
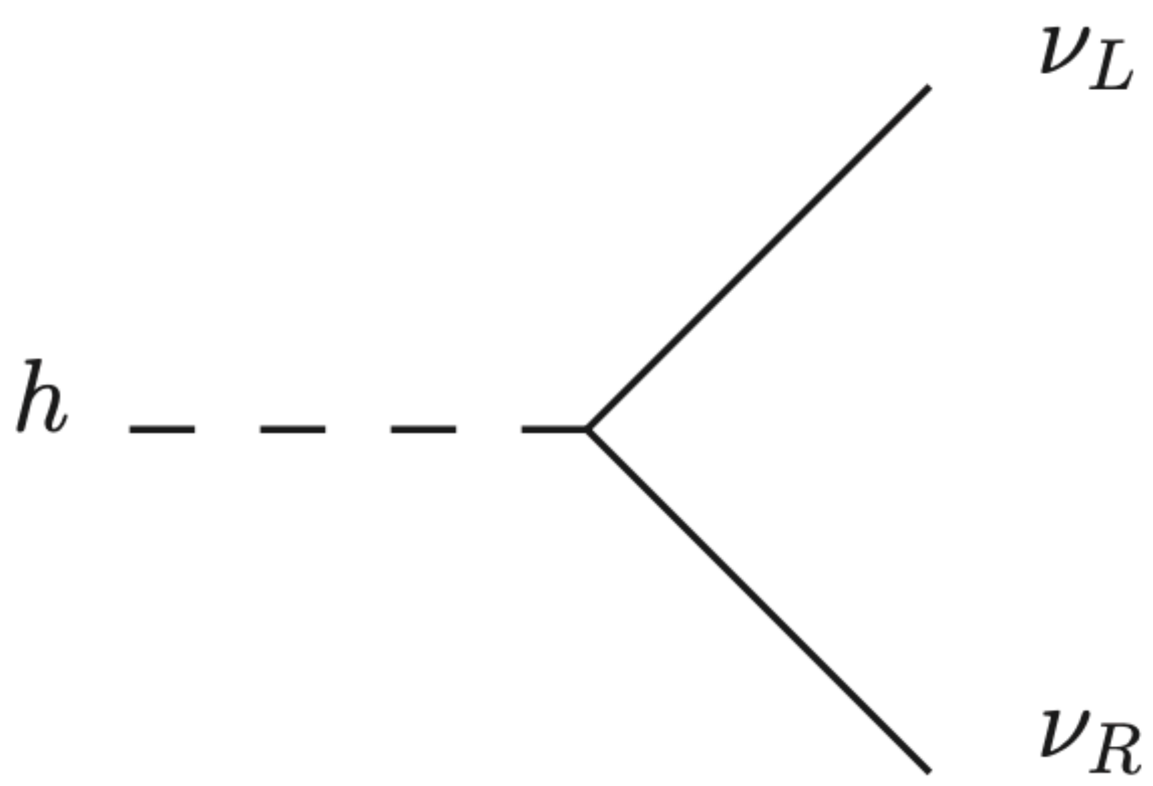


Predicted abundance is

$$\Omega_{\nu_R} \sim \frac{\rho_{\nu_R}}{T_{\mathrm{ew}}^4} \sim \frac{\Gamma(h \to \nu_L\nu_R)n_h}{HT_{\mathrm{ew}}^3} \sim 10^{-8}\left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)^2$$



[P. Adshead, Y. Cui, A. Long, **MS**, hep-ph/2009.07852
X. Luo, W. Rodejohann, X. Xu hep-ph/2011.13059]

BSM Dirac Neutrino Masses

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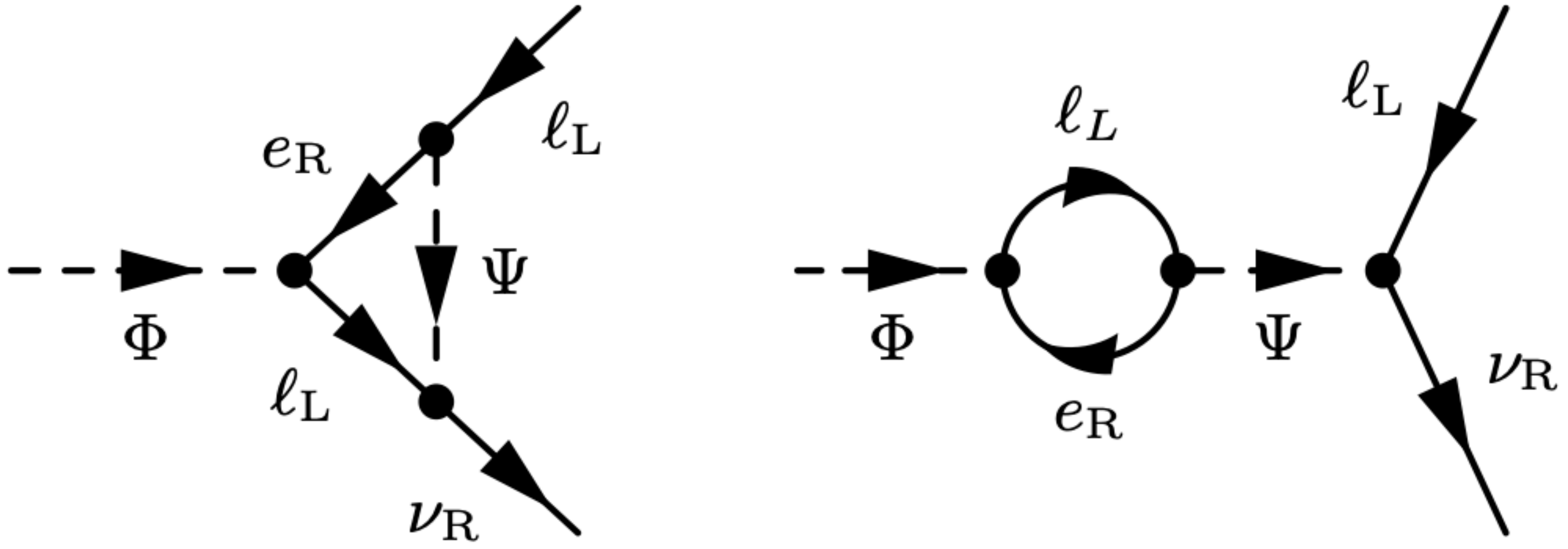
  - Model dependent $\Delta N_{\text{eff}} \sim 0.05 - 0.14$



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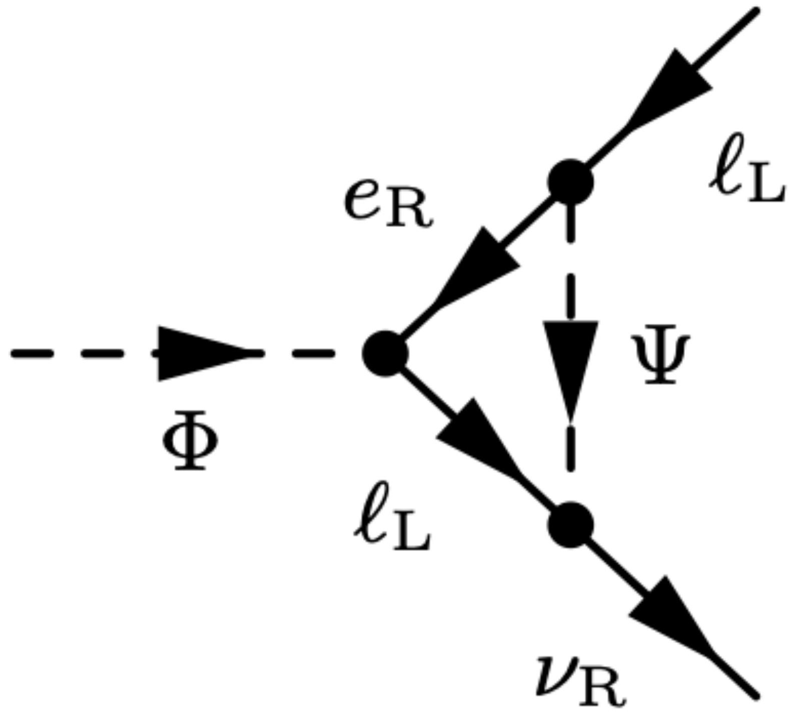
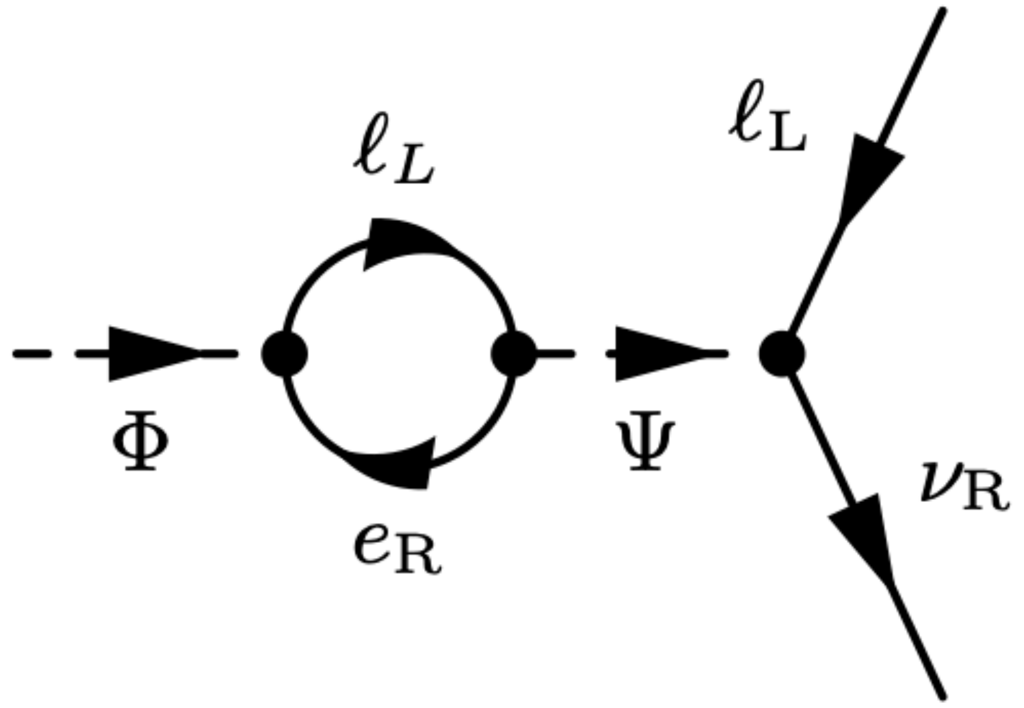
  - $T_{\text{dec}} \lesssim (m_{Z'}/g' M_{\text{pl}})^{4/3} M_{\text{pl}} \implies \Delta N_{\text{eff}} \simeq 0.13 - 0.23$





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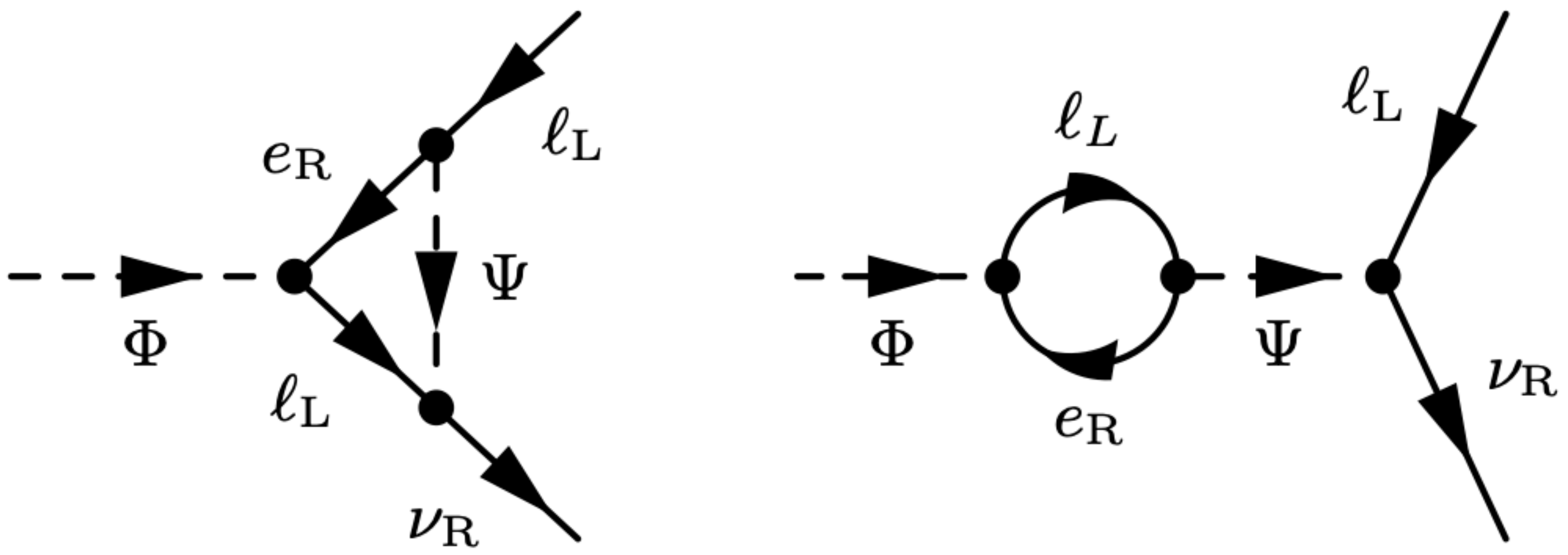
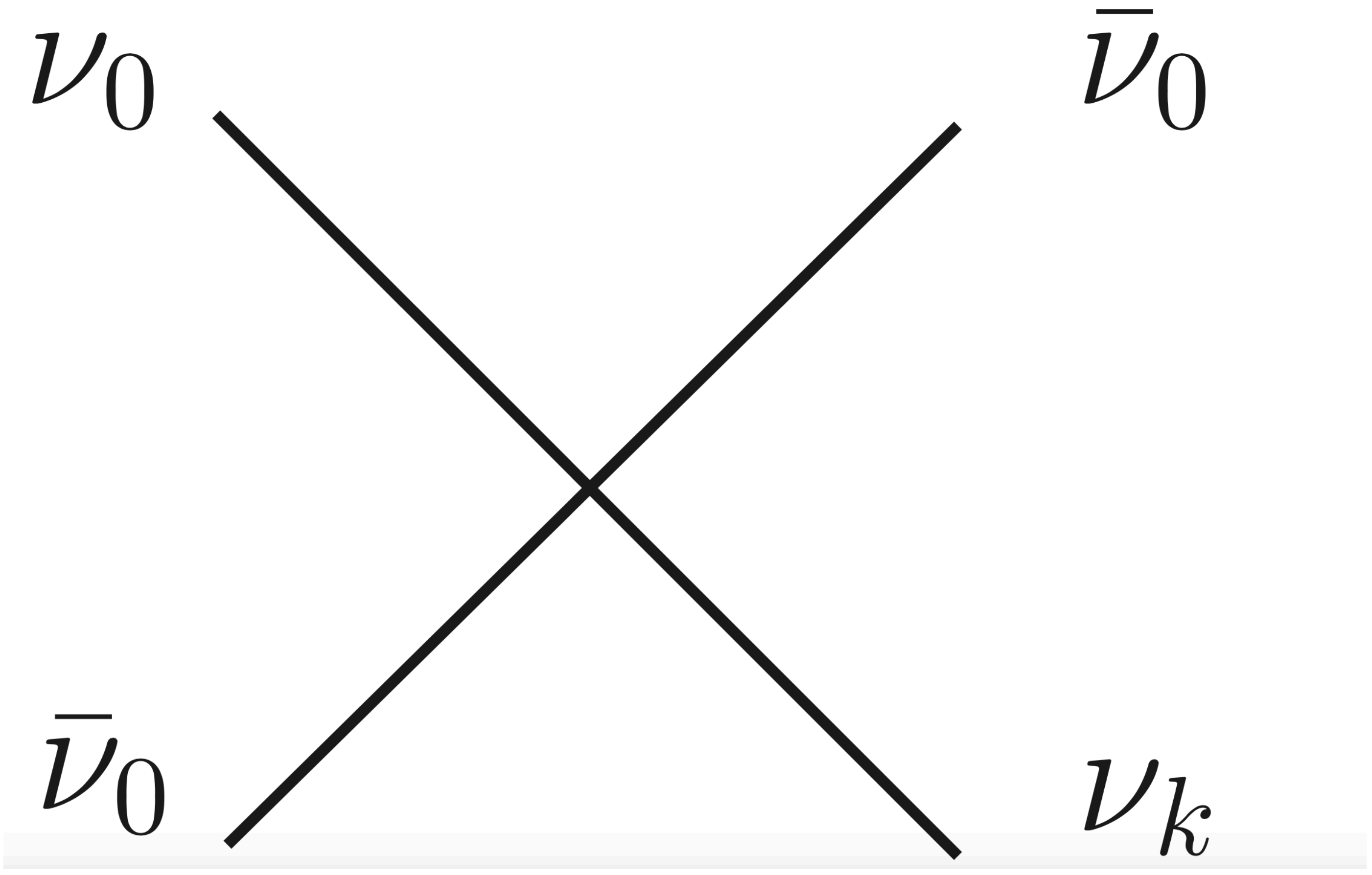
- Neutrino mass models have a home in an extra dimension [N. Arkani-Hamed, et. al. hep-ph/9811448, K.R. Dienes, et. al. hep-ph/9811428]:
  - Compactification generates Dirac ν mass

    $$\implies \mathscr{L} \supset -\frac{\lambda v}{\sqrt{2\pi R_{\text{ED}} M_*}} \bar{\nu}_L \nu_R^{(0)}$$

  - …also generates mixing of the ν_k modes with ν_L
  - And substantial number of relics, strong constraints [K. Abazajian, G. Fuller, M. Patel hep-ph/0011048]





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Terrestrial Probes of Neutrino Mass

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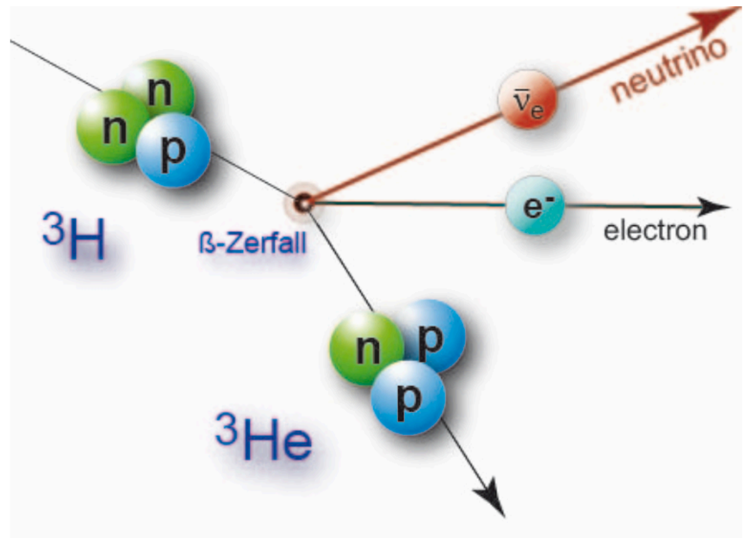
- Parametrize absolute neutrino mass scale with

$$m_{\nu_e} = \left[\sum_i m_i^2 \, |U_{ei}|^2 \right]^{1/2}$$

[M. Tanabashi, Phys. Rev. D, 98(3):030001, 2018.]



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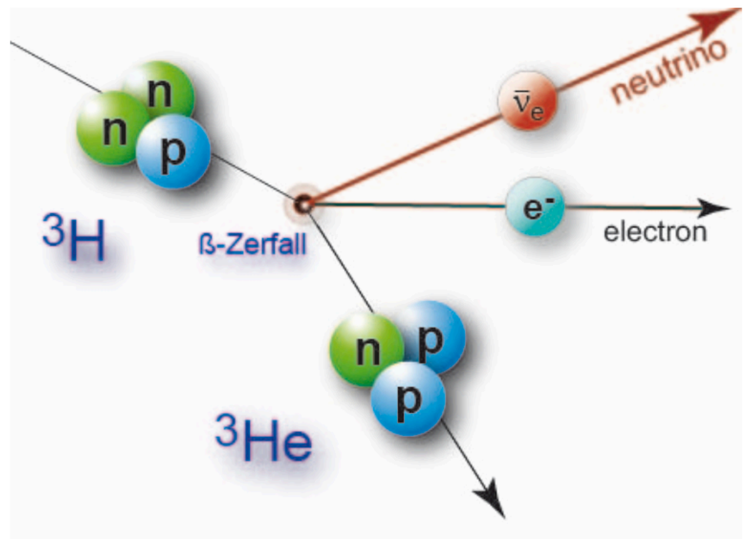

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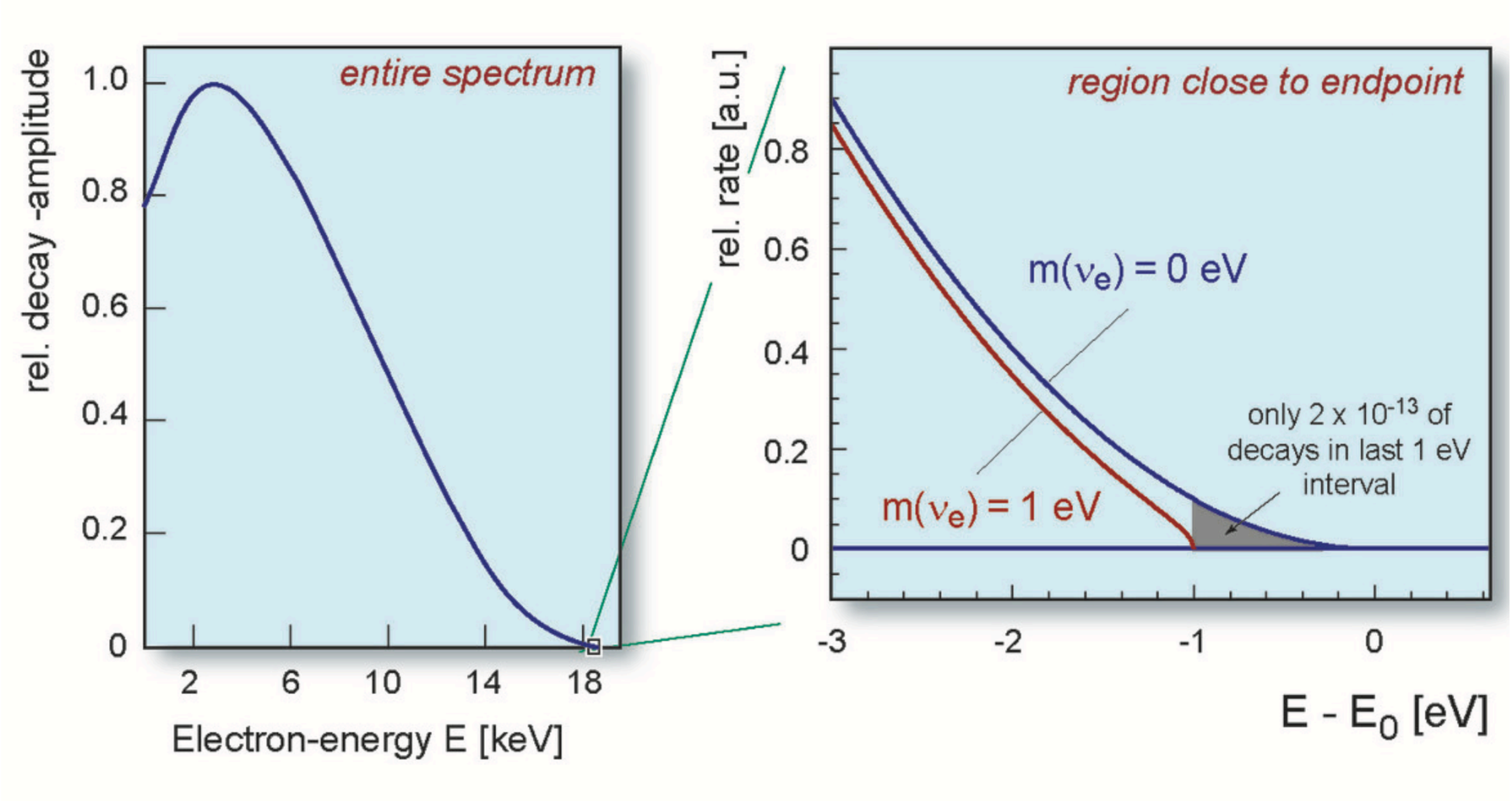

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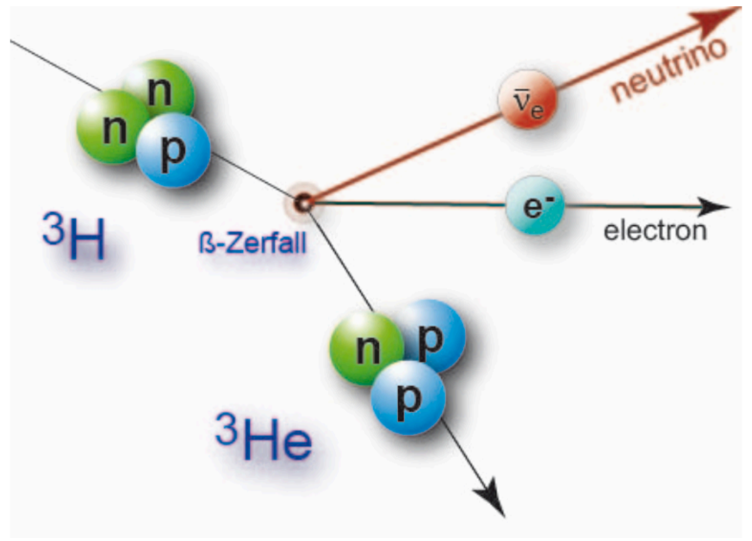

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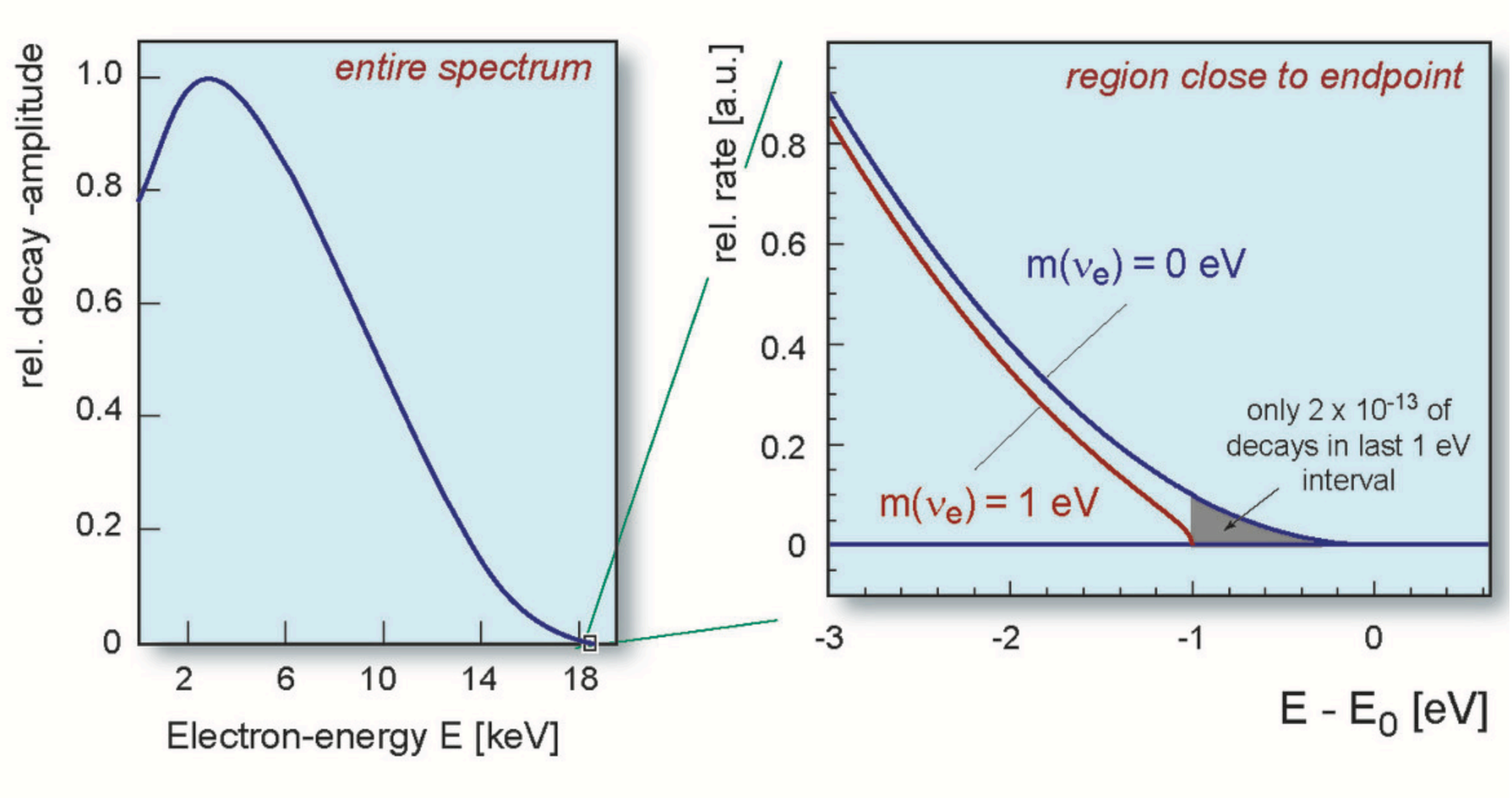

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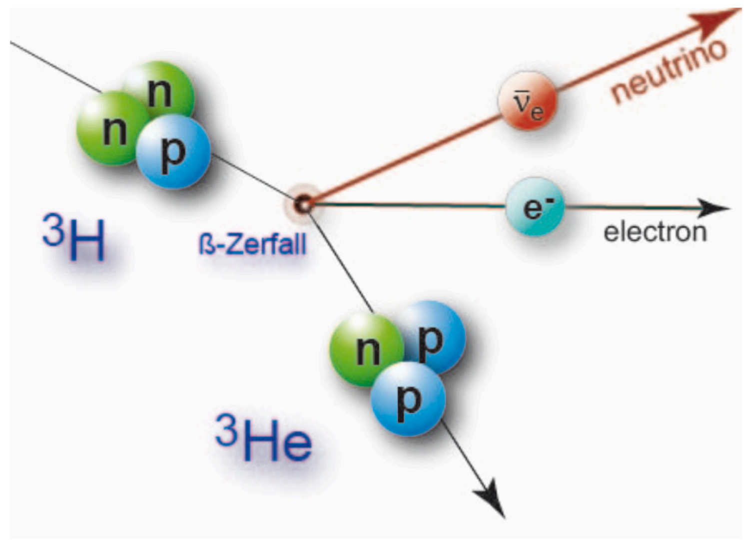

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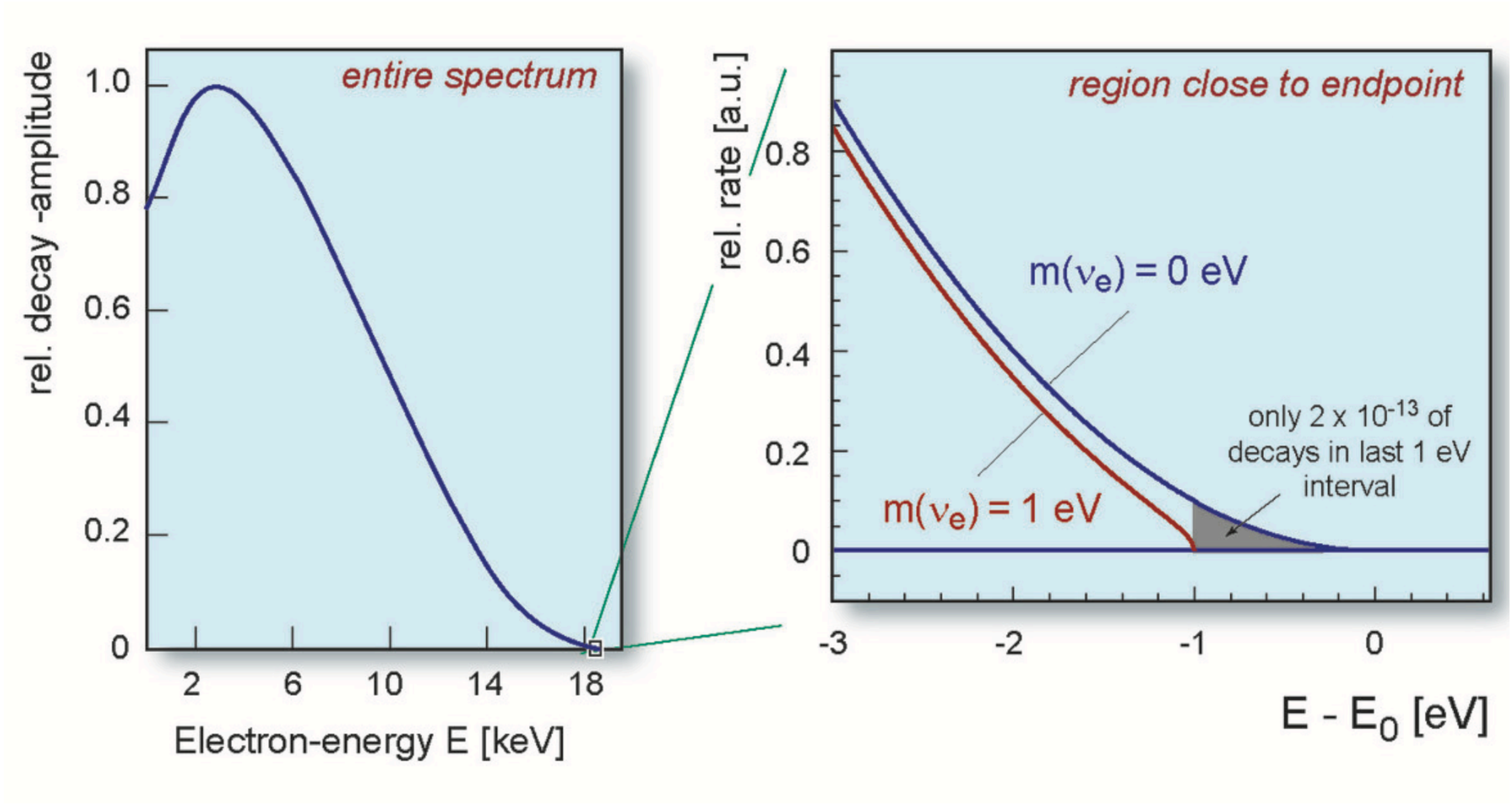

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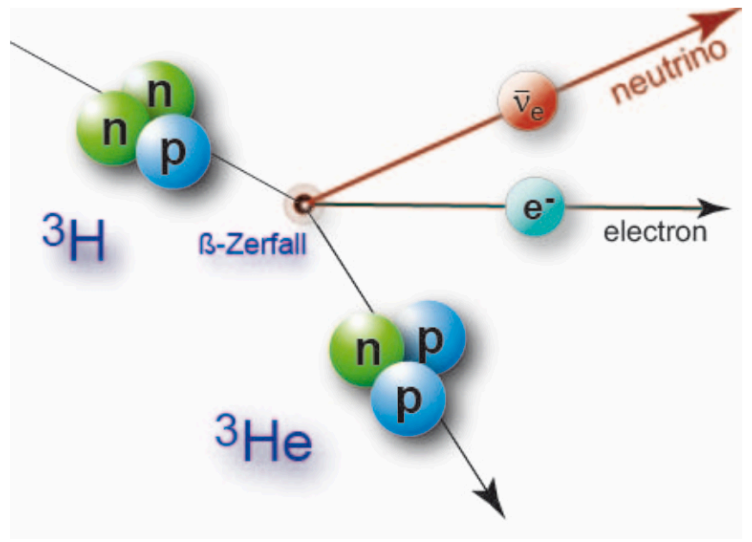

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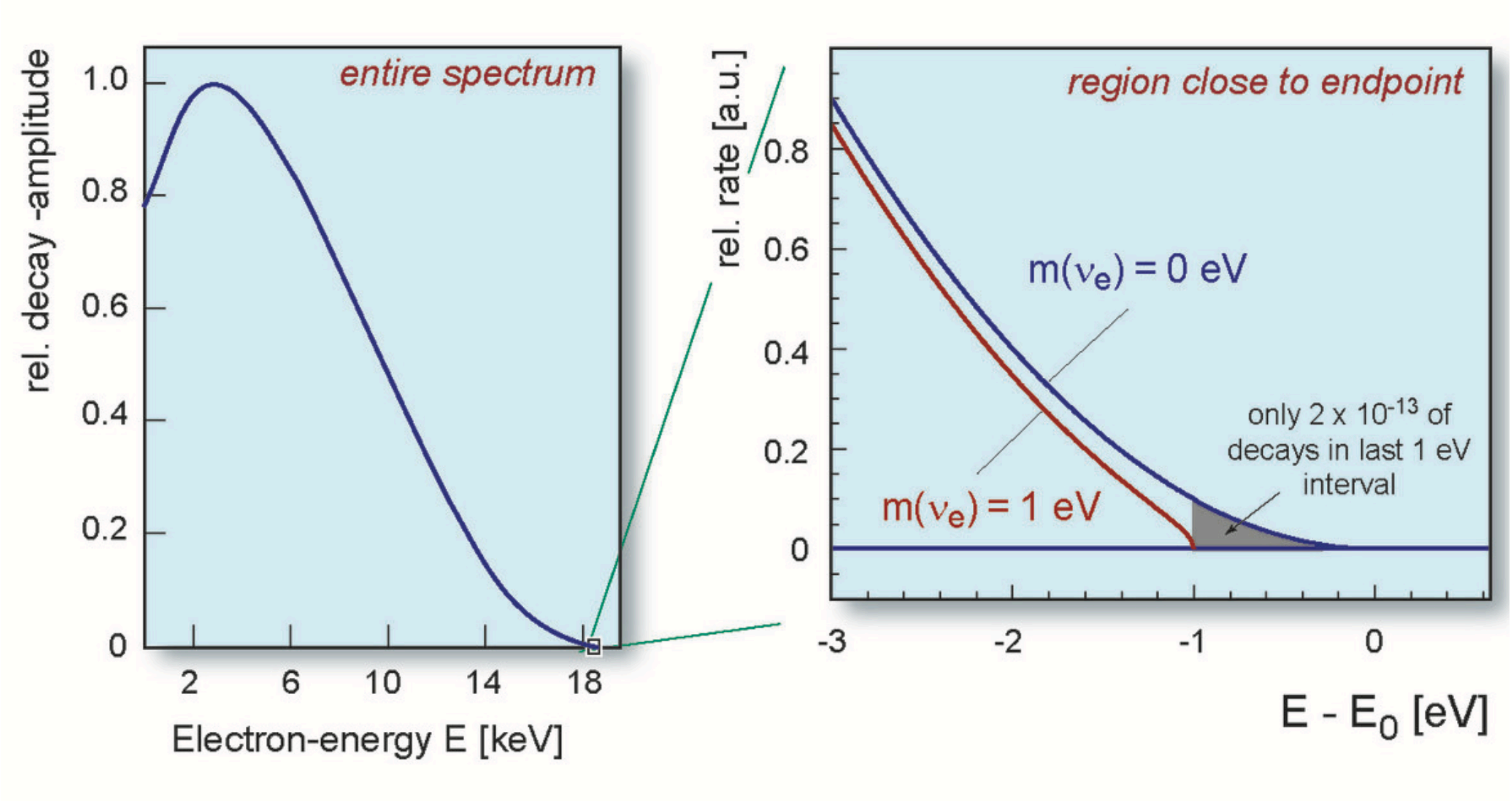

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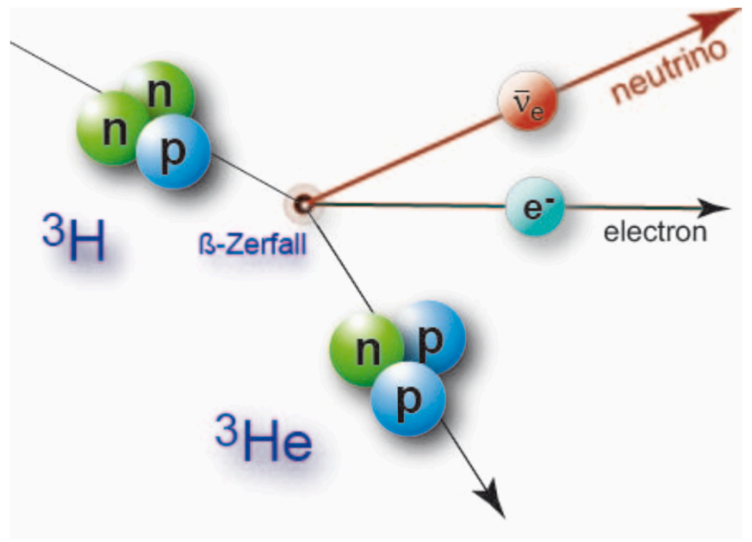
- Project 8 projected sensitivity: $m_{\nu_e} < 0.04$ eV

  $\implies \Sigma m_\nu \simeq 0.14$ eV (NO) and $\Sigma m_\nu \simeq 0.099$ eV (IO)

  [A.A. Esfahani et al. J. Phys. G, 44(5):054004]



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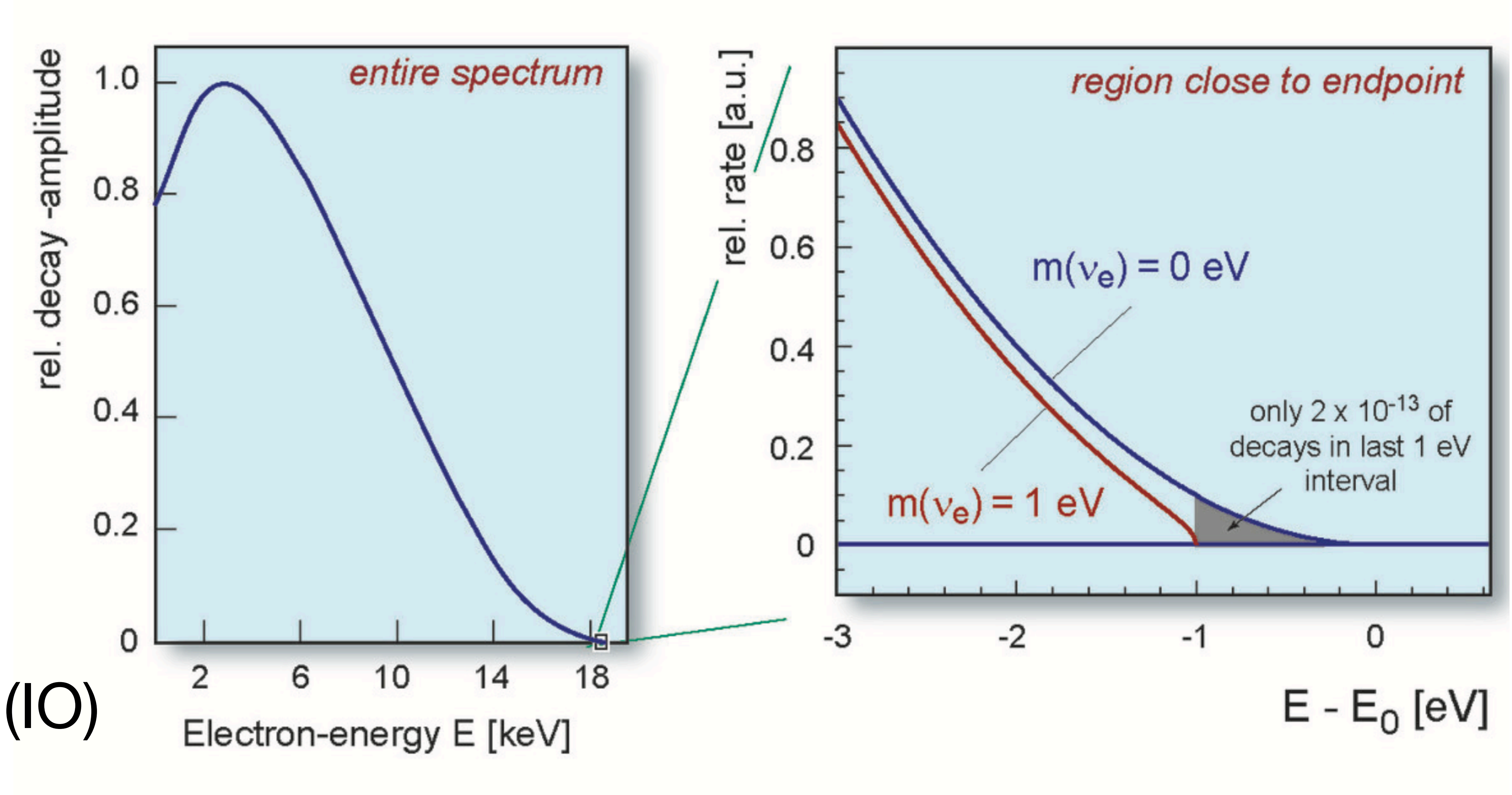

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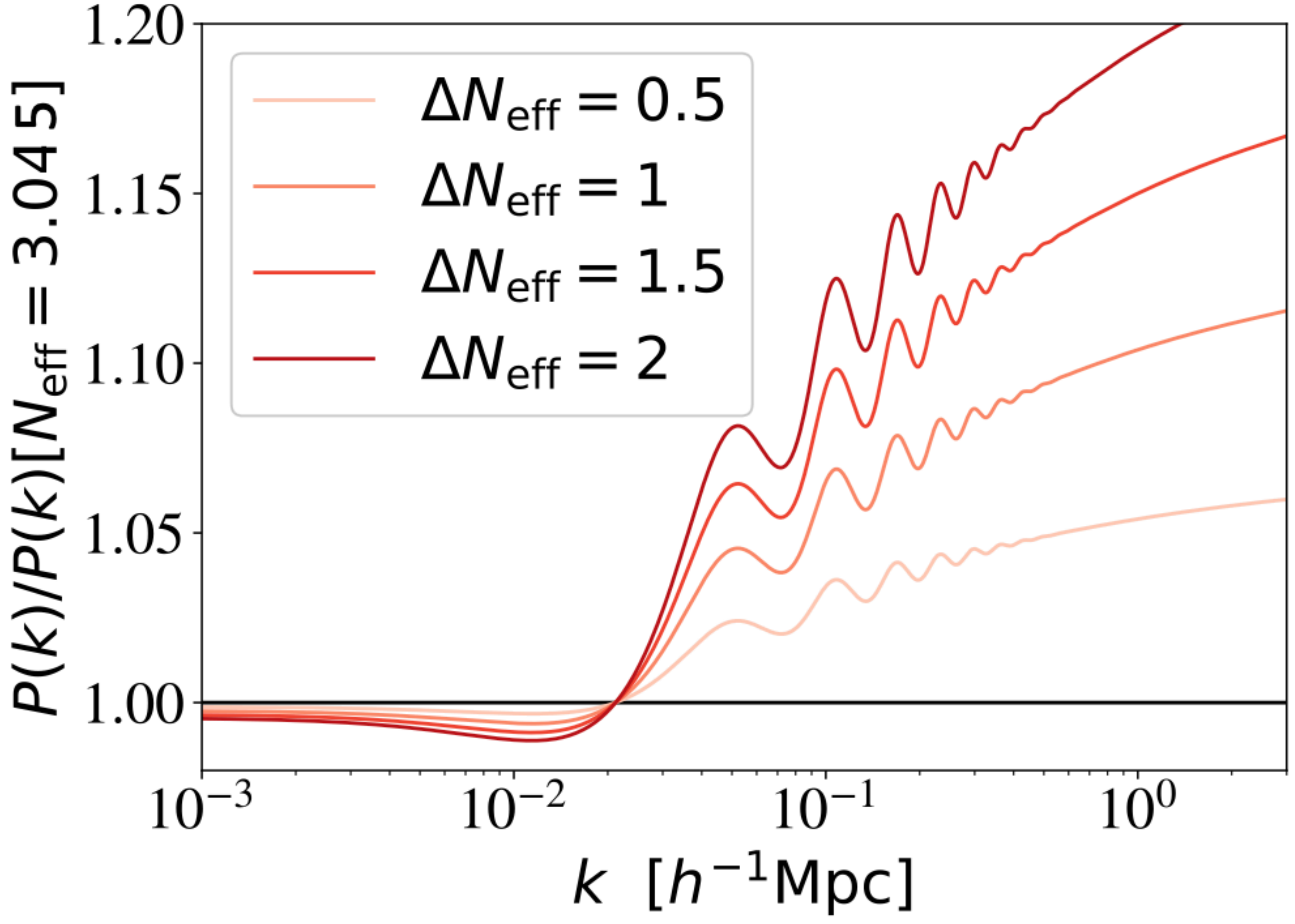

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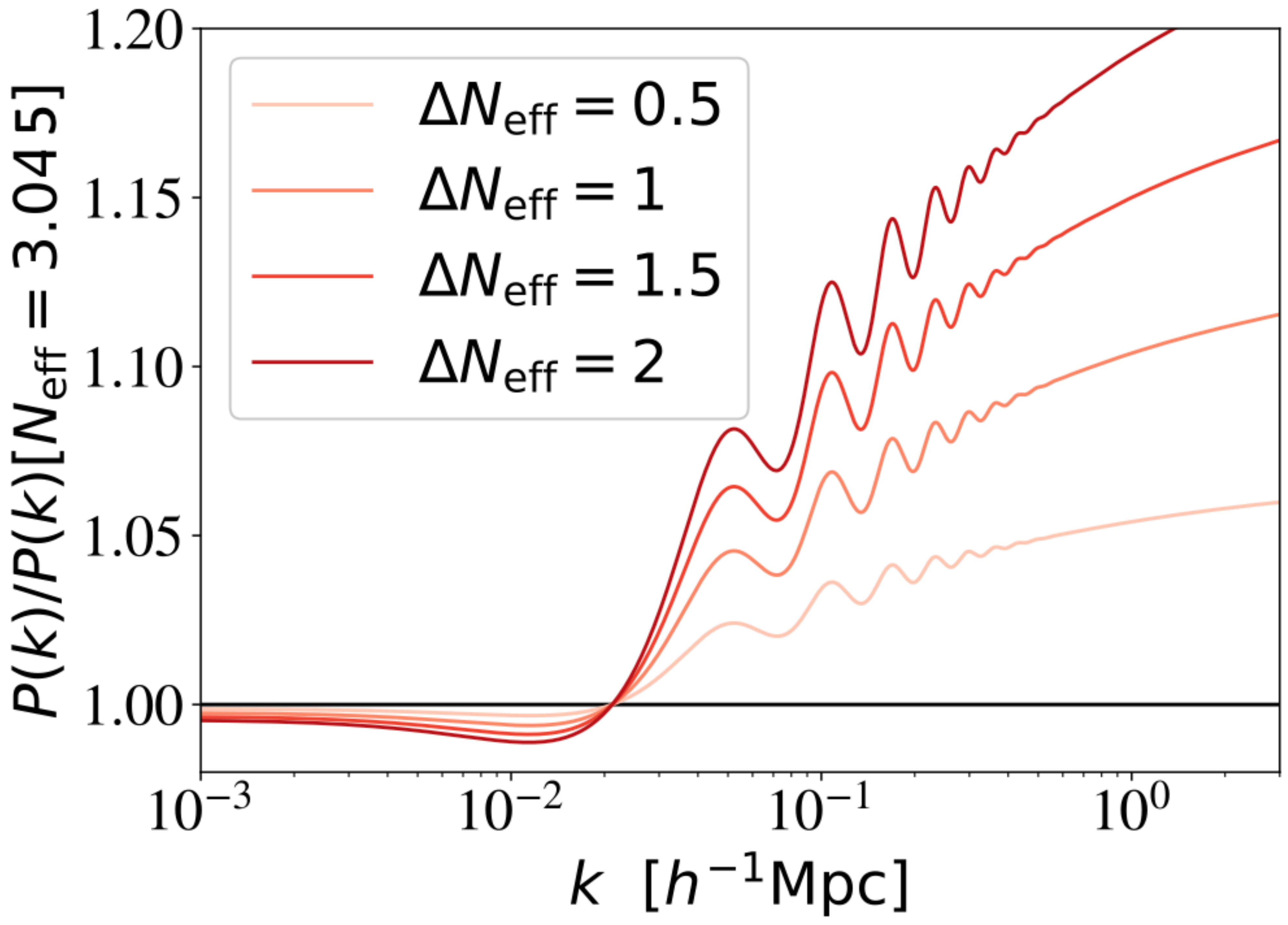
  [N. Aghanim, et. al. astro-ph.CO/1807.06209]



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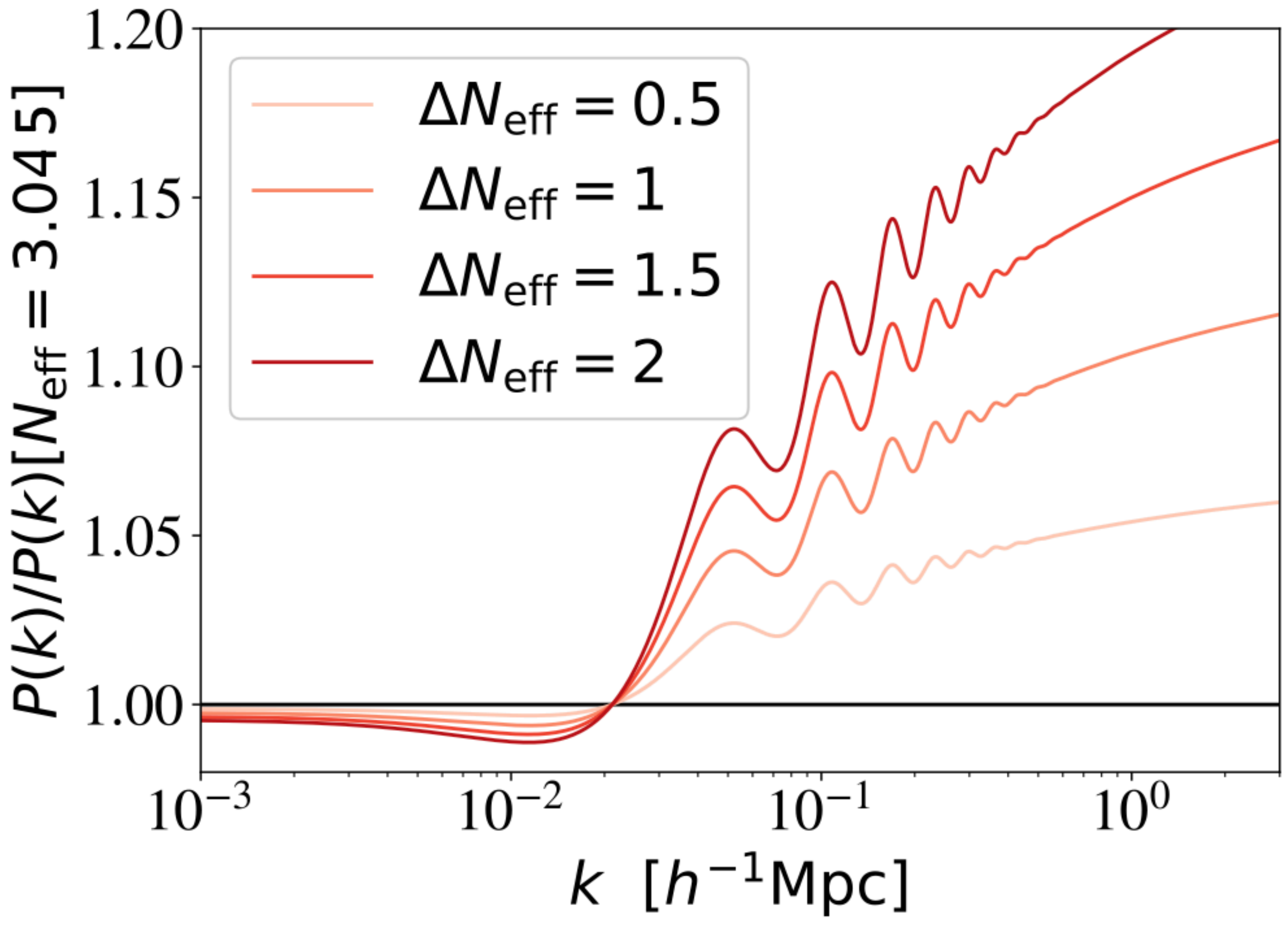
- CMB Stage-IV will constrain $\Delta N_{\text{eff}} < 0.06$

  [K. Abazajian, et. al. astro-ph.IM/1907.04473]



Cosmological Probes of Neutrino Masses

Michael Shamma (He/They)
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Neutrinos in Astrophysics and Cosmology
March 2024

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Thermalized Dirac ν_R

Can use conservation of entropy for thermalized ν_R

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$$\Delta N_{\text{eff}} = \frac{\rho}{\rho_\nu} = \frac{g}{(7/8)2}\left(\frac{T}{T_\nu}\right)^4 = \frac{4g}{7}\left[\frac{g'_\star}{g_\star(T_d)}\right]^{4/3}$$

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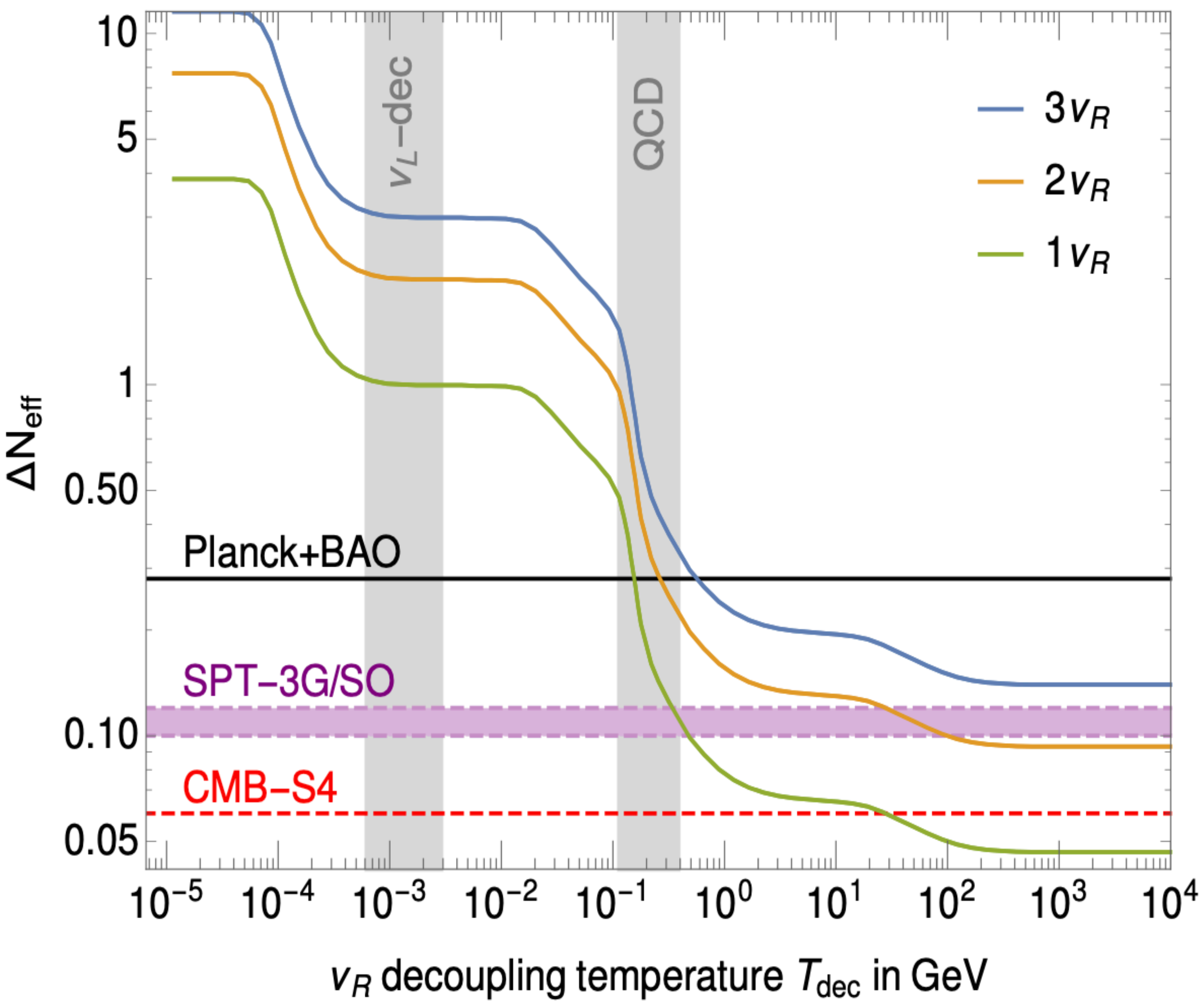

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Correlating Terrestrial and Cosmological Probes

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$$\frac{N_{\text{eff}}}{N_{\text{eff}}^{\text{SM}}} = (1 + \rho_R/\rho_L)\,\big|_{t=t_{\text{CMB}}}, \quad \frac{\Sigma m_\nu^{\text{tot}}}{\Sigma m_\nu} = (1 + \rho_R/\rho_L)\,\big|_{t=t_0},$$

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$$\boxed{\left(\frac{N_{\rm eff}}{N_{\rm eff}^{\rm SM}} - 1\right)^{1/4}\left(\frac{\Delta N_{\rm eff}}{N_{\rm eff}^{\rm SM}}\right)^{1/4} = \left(\frac{\sum m_\nu^{\rm tot}}{\sum m_\nu} - 1\right)^{1/3} = \left(\frac{m_{\nu,{\rm sterile}}^{\rm eff}}{\Sigma m_\nu}\right)^{1/3}}$$

[K. Abazajian, J. Heeck, hep-ph/1908.03286;
P. Adshead, Y. Cui, A. Long, **MS**, hep-ph/2009.07852]

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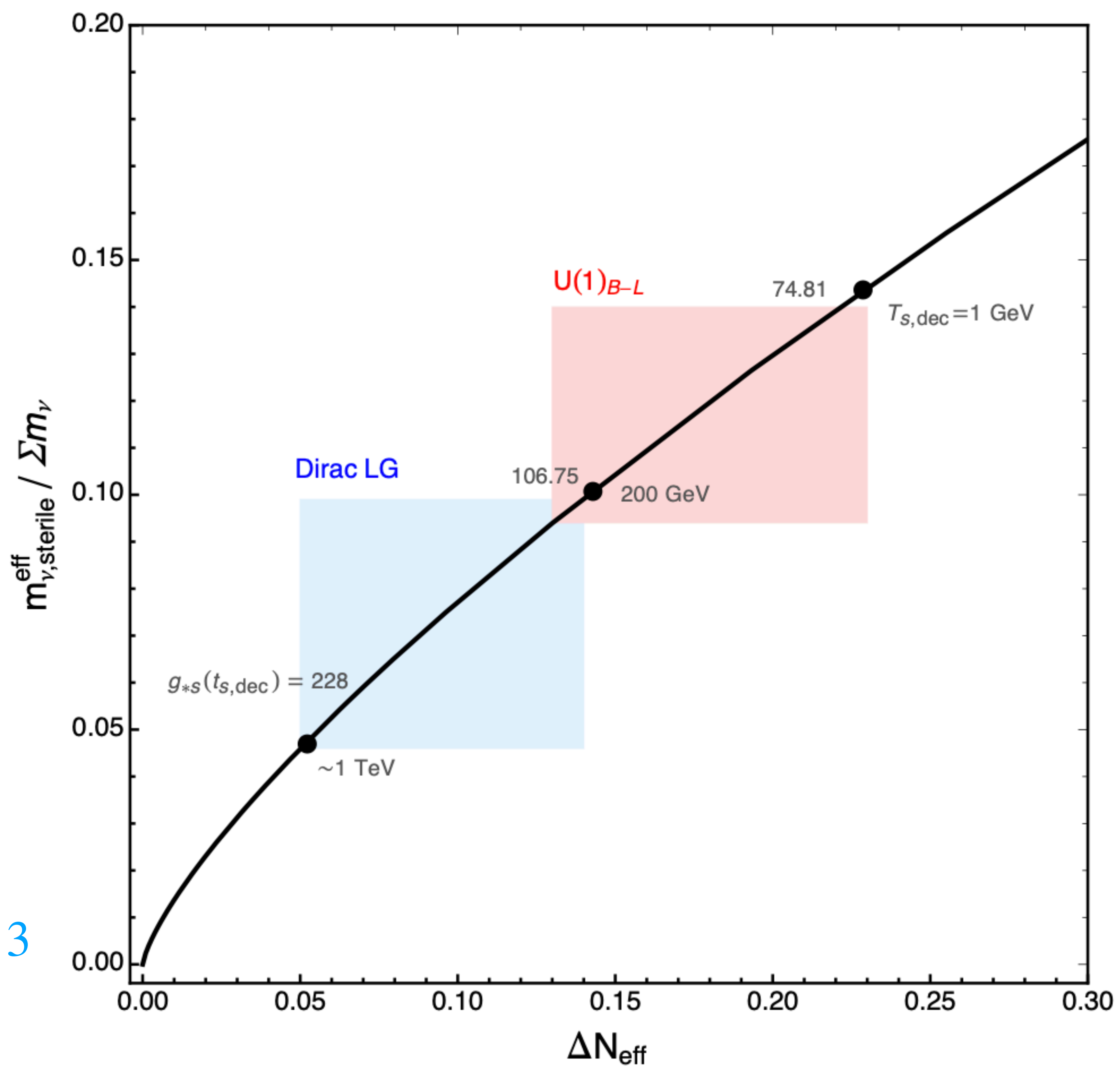

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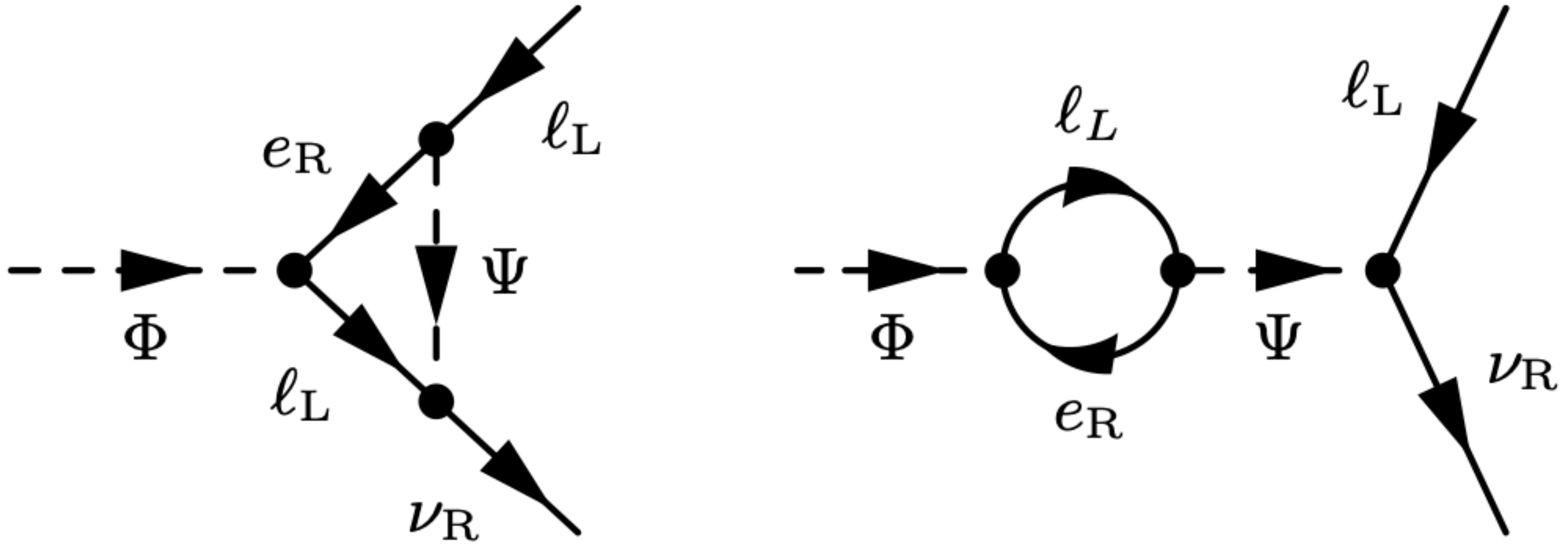
BSM Dirac Neutrino Masses

- Dirac Leptogenesis [K. Dick, et. al. Phys. Rev. Lett., 84:4039–4042, 2000…]
  - Model dependent $\Delta N_{\text{eff}} \sim 0.05 - 0.14$

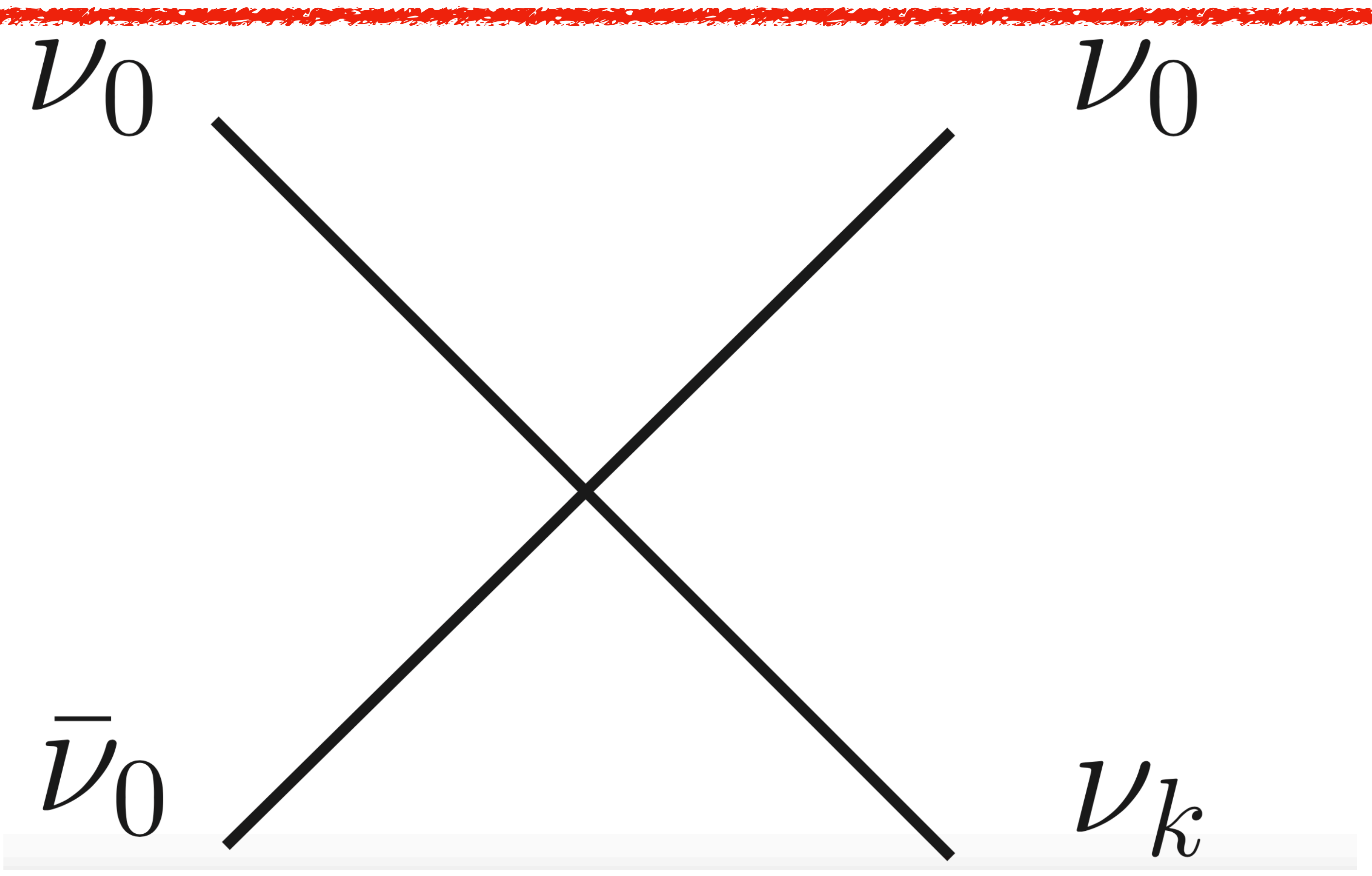


- Gauged $U(1)_{B-L}$ [V. Barger, et. al. Phys. Rev. D, 67:075009, 2003…]
  - $T_{\text{dec}} \lesssim (m_{Z'}/g' M_{\text{pl}})^{4/3} M_{\text{pl}} \implies \Delta N_{\text{eff}} \simeq 0.13 - 0.23$

- Neutrino mass models have a home in an extra dimension [N. Arkani-Hamed, et. al. hep-ph/9811448, K.R. Dienes, et. al. hep-ph/9811428]:
  - Compactification generates Dirac ν mass

$$\implies \mathscr{L} \supset -\frac{\lambda v}{\sqrt{2\pi R_{\text{ED}} M_*}} \bar{\nu}_L \nu_R^{(0)}$$

  - …also generates mixing of the ν_k modes with ν_L
  - And substantial number of relics, strong constraints [K. Abazajian, G. Fuller, M. Patel hep-ph/0011048]



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Bulk sterile neutrinos mix with active states:

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Produce a substantial number through freeze-in

$$\frac{dY_k}{dT} = -\frac{1}{4}\frac{\sin^2 2\theta_k}{\left[1+(T/T_V^k)^6\right]^2}\frac{M_{\text{Pl}}\Gamma_\nu Y_\nu}{\gamma T^3}$$

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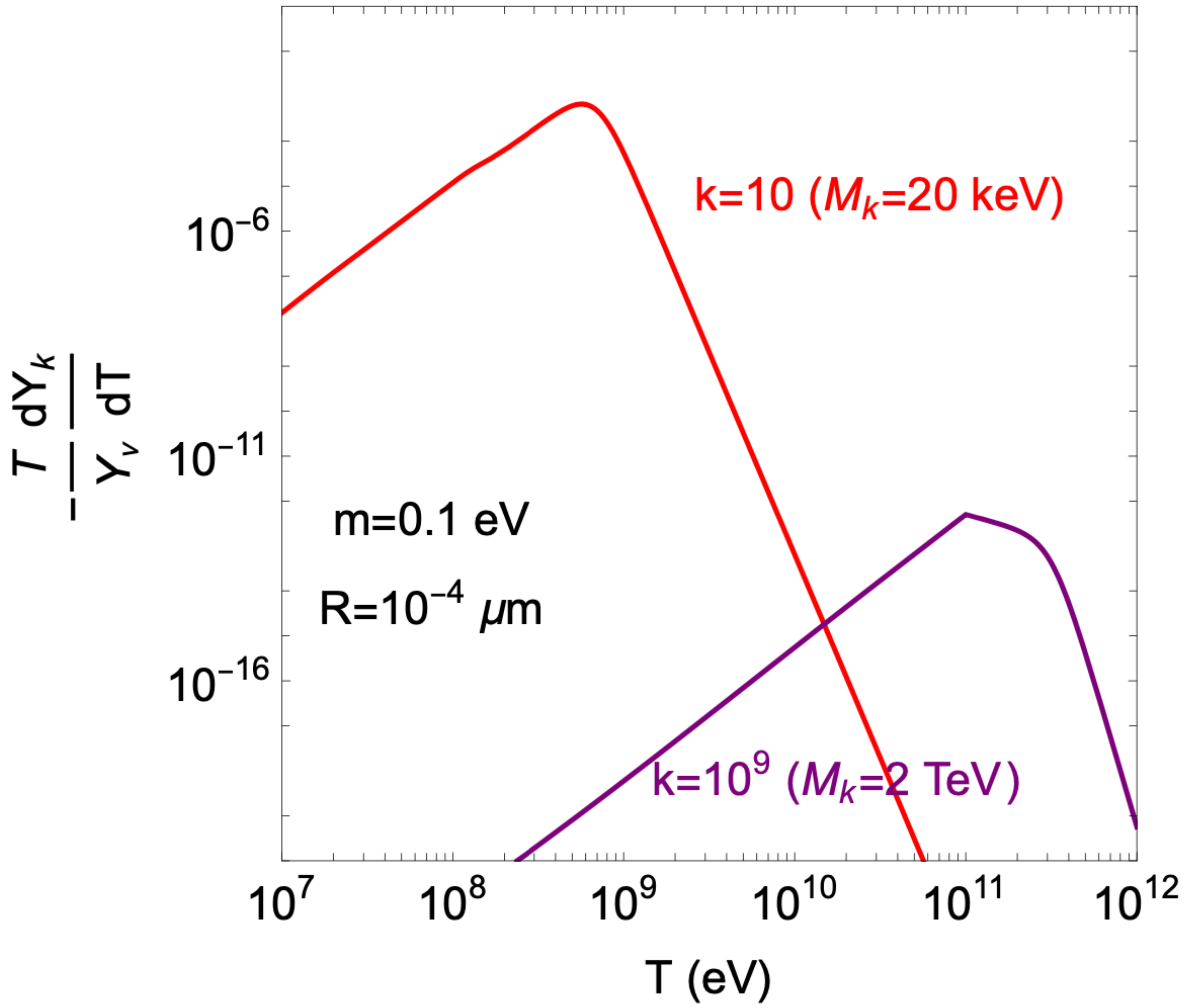

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High Reheat Universe, $T_{\mathrm{RH}} > T_{\mathrm{ew}}$:

$$\frac{n_k}{n_\nu} \simeq 2.32 \times 10^{-2} \left(\frac{m}{0.1\ \mathrm{eV}}\right)^2 \left(\frac{R}{10^{-4}\ \mu m}\right) \frac{1}{k} \left[\frac{10.75}{g_*(T_V^k)}\right]^{11/6}$$

$$\implies k_{\max} = \min\left[6.5 \times 10^7 \left(\frac{R}{10^{-4}\ \mu\mathrm{m}}\right), 5.1 \times 10^7 \left(\frac{R}{10^{-4}\ \mu\mathrm{m}}\right)\right]$$

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Low Reheat Universe, $T_{\mathrm{RH}} \sim \mathcal{O}(10\ \mathrm{MeV})$:

$$\frac{n_k}{n_\nu} \simeq 7.1 \times 10^{-7} \left(\frac{m}{0.1\ \mathrm{eV}}\right)^2 \left(\frac{R}{10^{-4}\ \mu m}\right)^2 \frac{1}{k^2} \left[\frac{10.75}{g_*(T_{\mathrm{RH}})}\right]^{1/2}$$

$$\implies k_{\mathrm{max}} = 5.07 \times 10^3 \left(\frac{R}{10^{-4}\ \mu\mathrm{m}}\right) \left(\frac{T_{\mathrm{RH}}}{10\ \mathrm{MeV}}\right)$$

High Reheat Universe, $T_{\mathrm{RH}} > T_{\mathrm{ew}}$:

$$\Delta N_{\mathrm{eff}} \simeq \sum_k 3.25 \times 10^6 \left(\frac{m}{0.1\ \mathrm{eV}}\right)\left(\frac{R}{10^{-4}\ \mu\mathrm{m}}\right)^{3/2} k^{-3/2}$$

$$\Omega_{DM} \simeq \sum_{k=1}^{k_{tU}} 0.5 \left(\frac{m}{0.1\ \mathrm{eV}}\right)^2 \left[\frac{10.75}{g_*(T_V^k)}\right]^{11/6}$$

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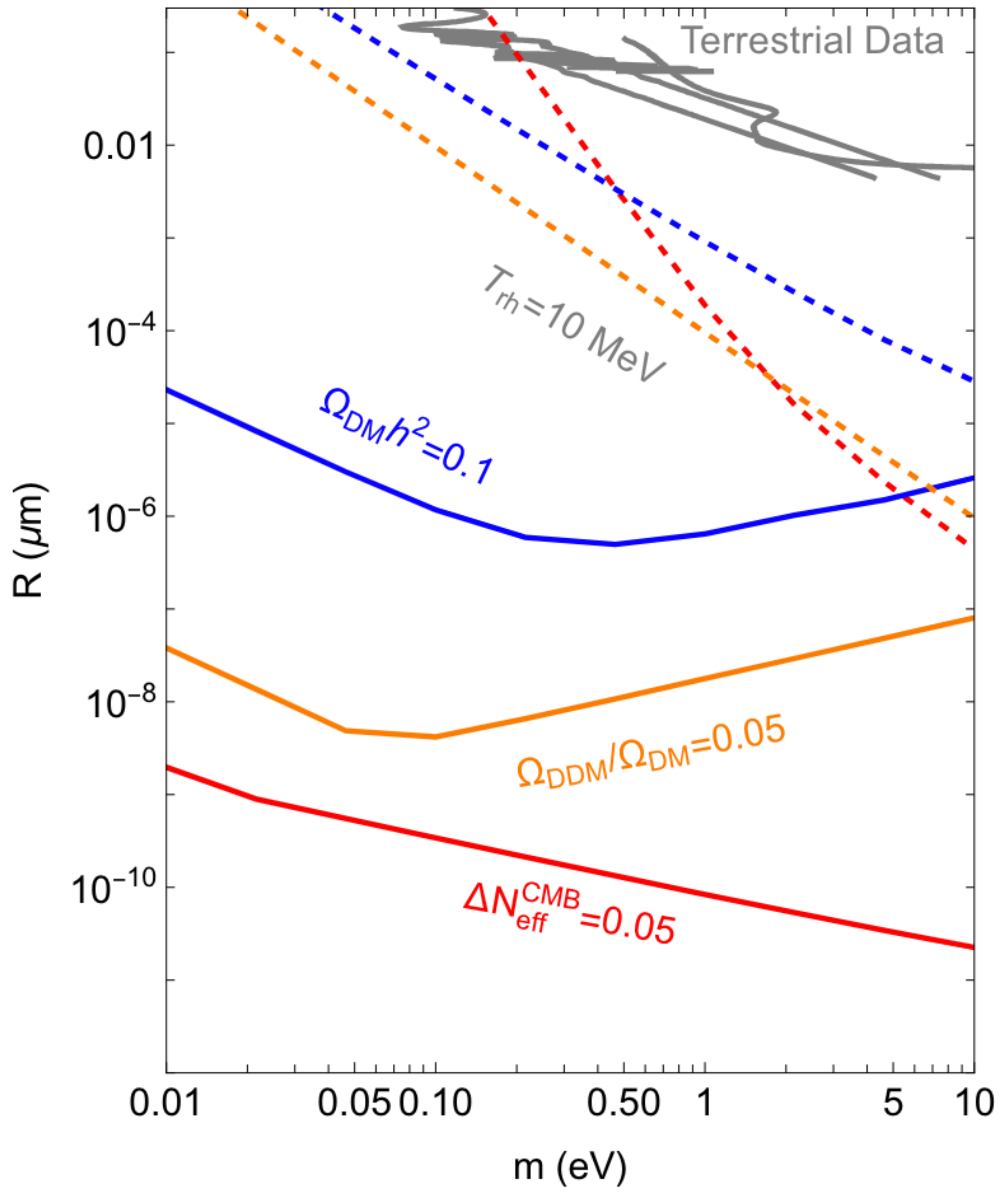

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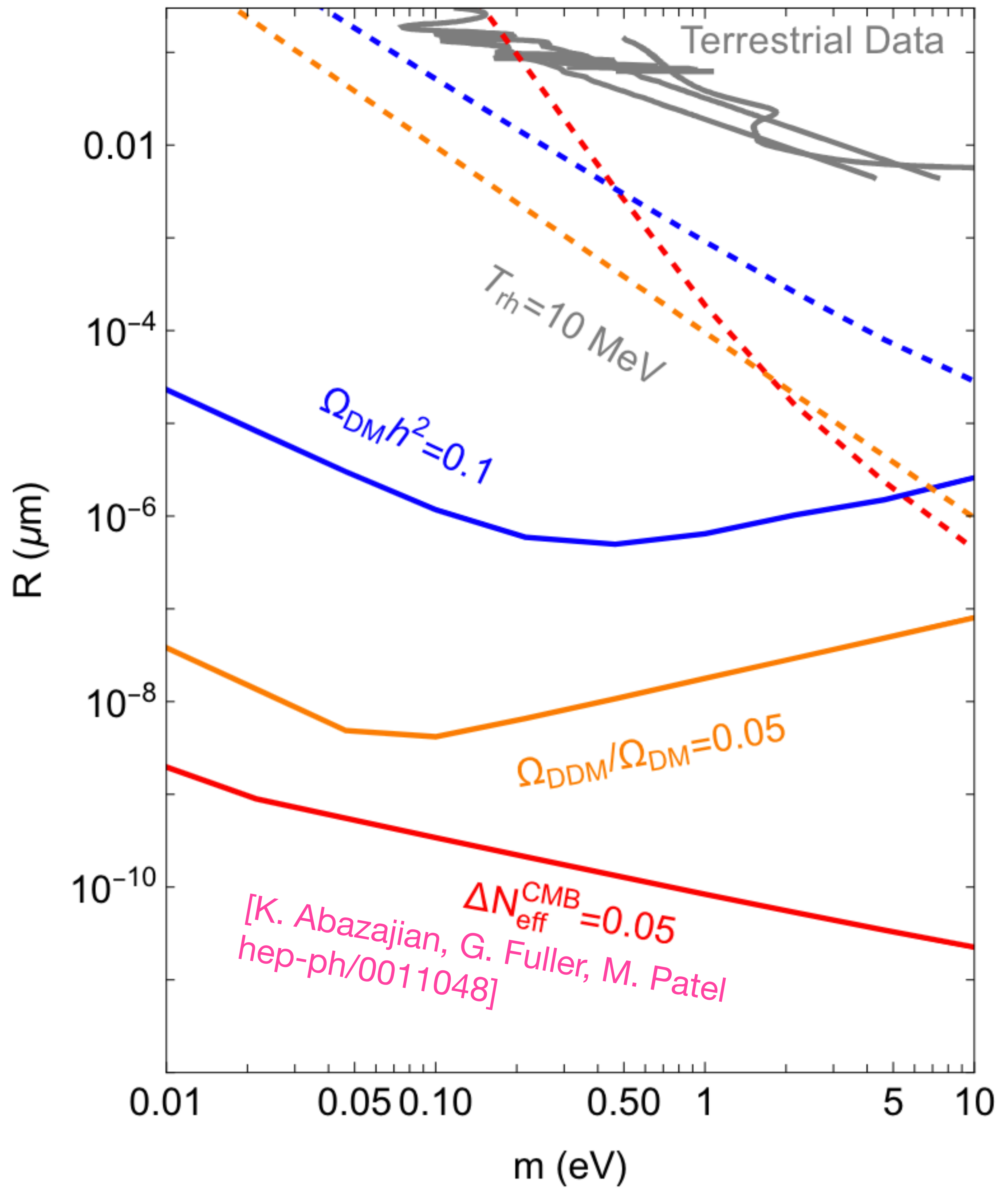
$$\Omega_{DM} \simeq \sum_{k=k_{tU}}^{k_{\rm CMB}} 0.5\left(\frac{m}{0.1\ {\rm eV}}\right)^2\left[\frac{10.75}{g_*(T_V^k)}\right]^{11/6}$$



High Reheat Universe, $T_{\rm RH} > T_{\rm ew}$:

$$\Delta N_{\rm eff} \simeq \sum_k 3.25 \times 10^6 \left(\frac{m}{0.1\ \rm eV}\right)\left(\frac{R}{10^{-4}\ \mu\rm m}\right)^{3/2} k^{-3/2}$$

$$\Omega_{DM} \simeq \sum_{k=1}^{k_{tU}} 0.5 \left(\frac{m}{0.1\ \rm eV}\right)^2 \left[\frac{10.75}{g_*(T_V^k)}\right]^{11/6}$$

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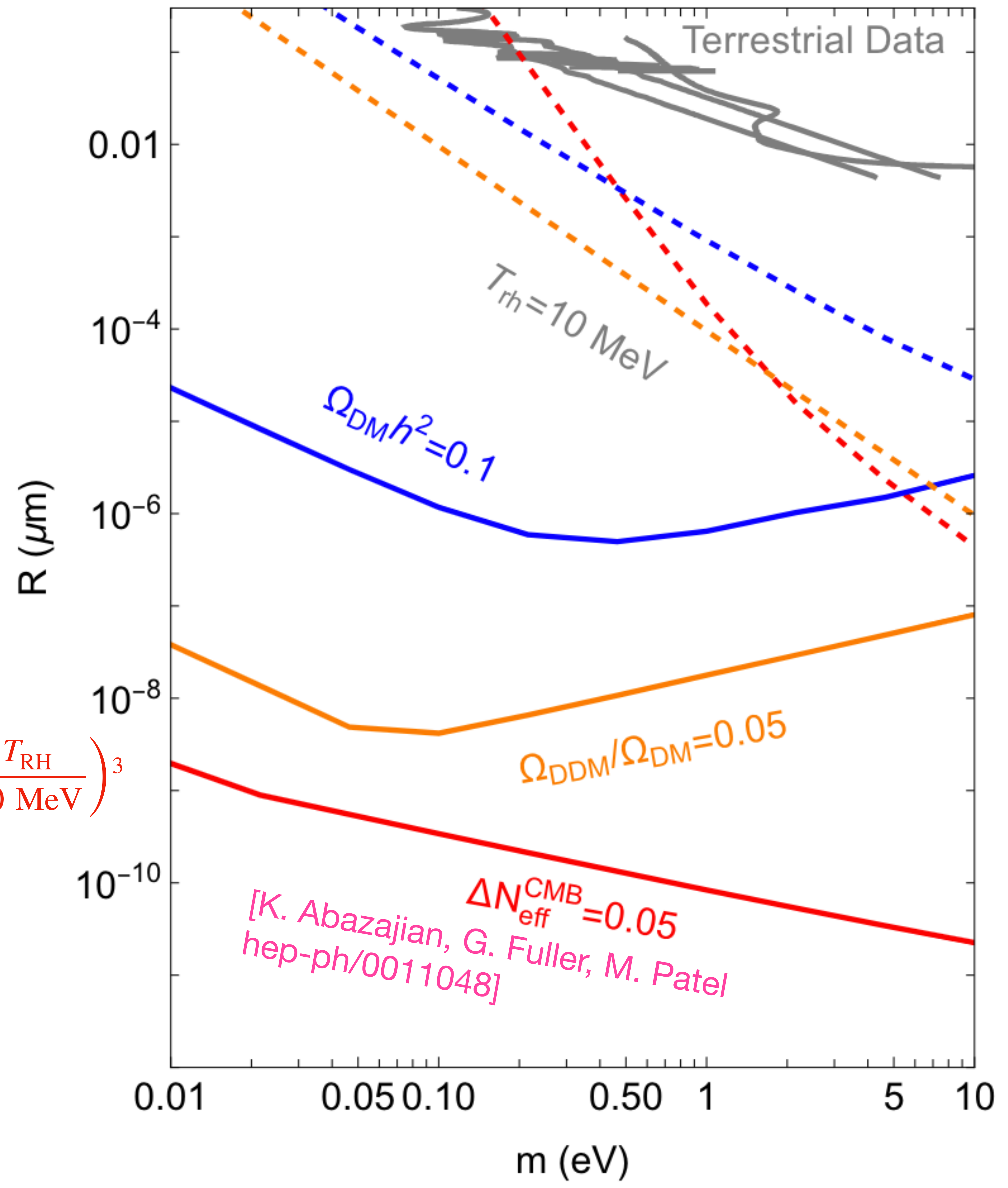
Low Reheat Universe, $T_{\rm RH} > T_{\rm ew}$:

$$\Delta N_{\rm eff} \simeq \sum_{k=1}^{k_{t_{\rm CMB}}} 7.9 \times 10^{-17} \left(\frac{m}{0.1\ \rm eV}\right)^4 \left(\frac{10^{-4}\ \mu\rm m}{R}\right)^2 k^2 \left(\frac{T_{\rm RH}}{10\ \rm MeV}\right)^3 + \sum_{k=k_{t_{\rm CMB}}}^{k_{\rm max}} 6.7 \times 10^3 \left(\frac{m}{0.1\ \rm eV}\right)\left(\frac{R}{10^{-4}\ \mu\rm m}\right)^{5/2} k^{-5/2} \left(\frac{T_{\rm RH}}{10\ \rm MeV}\right)^3$$

$$\Omega_{DM} \simeq \sum_{k=1}^{k_{tU}} 1.5 \times 10^{-5} \left(\frac{m}{0.1\ \rm eV}\right)^2 \left(\frac{R}{10^{-4}\ \mu\rm m}\right) k^{-1} \left[\frac{10.75}{g_*(T_{\rm RH})}\right]^{1/2} \left(\frac{T_{\rm RH}}{10\ \rm MeV}\right)^3$$

$$\Omega_{DM} \simeq \sum_{k=k_{tU}}^{k_{\rm CMB}} 1.5 \times 10^{-5} \left(\frac{m}{0.1\ \rm eV}\right)^2 \left(\frac{R}{10^{-4}\ \mu\rm m}\right) k^{-1} \left[\frac{10.75}{g_*(T_{\rm RH})}\right]^{1/2} \left(\frac{T_{\rm RH}}{10\ \rm MeV}\right)^3$$



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Summary

- New physics with Dirac ν provide well-motivated explanation of m_ν
- New interactions can produce substantial numbers of ν_R which potentially thermalize
  - Upcoming cosmological surveys can probe Dirac ν!
- Future surveys may probe BSM physics through correlated observables
  - This diagnostic test can distinguish generic eV-scale relics ($m_{\text{relic}} \neq m_{\nu_L}$) from the DNH ($m_{\nu_L} = m_{\nu_R}$)
- Upcoming work explores the scenario in which many possibly non-degenerate eV-keV scale relics are produced alongside the degenerate ν_R
  - E.g. will provide constraints on the size of dark dimensions, neutrino masses

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Thank you!