Cosmology in Mirror Twin Higgs and Neutrinos

Patrick Fox

Fermilab

3rd PIKIO Meeting, Bloomington

With Z. Chacko, N. Craig, R. Harnik
arXiv:1611.07975
See also N. Craig, S. Koren, T. Trott
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νMTH

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Plan of talk

Twin Higgs and its variants
Cosmology and its issues
A solution
Connection to neutrinos
Conclusions

Twin Higgs

[Chacko, Goh, Harnik]

$$\mathrm{SM}_A \times \mathrm{SM}_B \times \mathbb{Z}_2$$

$$\mathcal{L} \supset y\, Q_A H_A U_A^c + y\, Q_B H_B U_B^c$$

Higgs is a PNGB, and Higgs potential is O(8) symmetric

$$V = -m^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$$

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} = e^{ih^a t^a / f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

Higgs portal between A and B sectors

Twin Higgs

[Chacko, Goh, Harnik]

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SM Higgs

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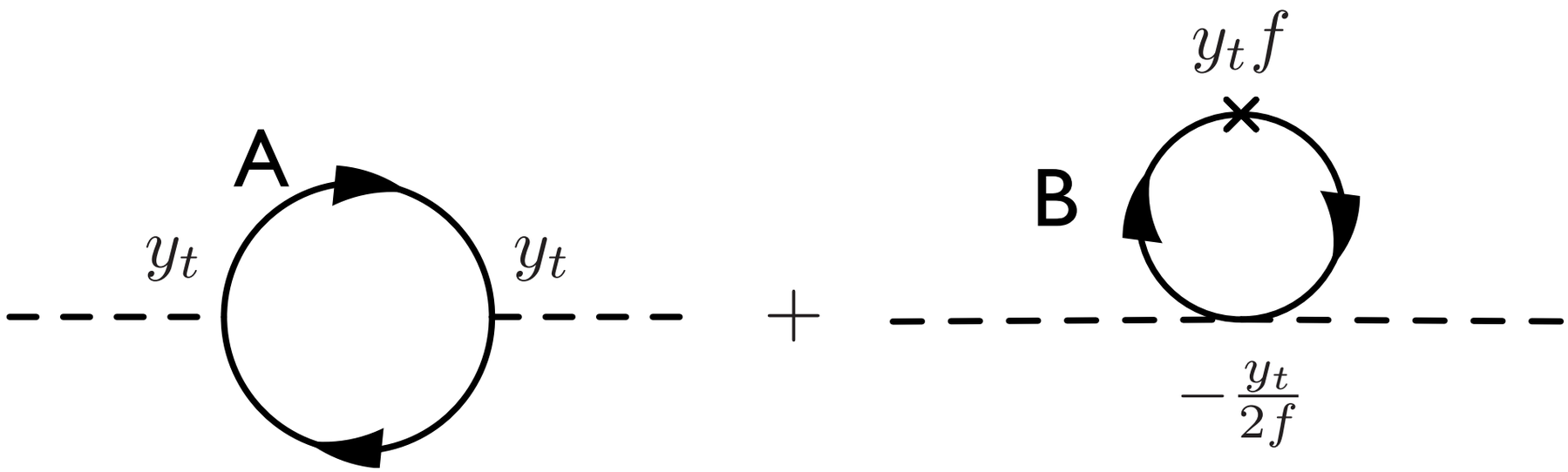
Higgs portal between A and B sectors

$$\mathcal{L} \sim y\, Q_A H U_A^c + y\, Q_B \left(f - \frac{|H|^2}{2f^2} \right) U_B^c$$



Quadratic divergences cancel, but states running in loop have <u>no</u> SM charge

$\mathbb{Z}_2$ invariant $|H_A|^2 + |H_B|^2$ is independent of Higgs

Log divergences generated at 1 loop e.g.

$$\frac{g^4}{16\pi^2}\log\frac{\Lambda^2}{f^2}\left(|H_A|^4+|H_B|^4\right)$$

Cutoff $\Lambda\sim 5\mathrm{TeV}$

To separate v and f and make the SM Higgs lie mostly in A introduce soft breaking $\mu_A^2|H_A|^2$

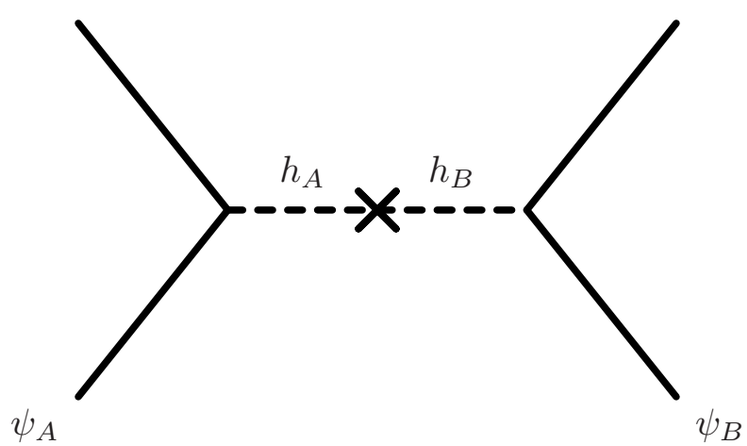
$$\delta m_h^2 \sim \frac{3y_t m_t^2}{4\pi^2}\left(\frac{f}{v}\right)^2\log\frac{\Lambda v}{m_t f}$$

f/v~3-5

SM and its Twin coupled through portals

$|H_A|^2|H_B|^2$ Inevitable, integral part of model

$F^A_{\mu\nu}F^{B\,\mu\nu}$ Ignore, not generated till high loop order



$$\langle \sigma v \rangle \simeq \left(y_A^i y_B^j\right)^2 \frac{v^2}{f^2}\frac{T^2}{m_h^4}$$

In equilibrium down to ~3 GeV

Variants, and ways out

Lots of new relativistic degrees of freedom in the B sector

Violates $N_{\rm eff}$ bounds

- Remove all light degrees of freedom in twin sector but keep those needed for naturalness e.g.
  - Fraternal Twin Higgs [Craig, Katz, Strassler, Sundrum]
  - Explicit $\mathbb{Z}_2$ breaking in the Yukawas [Barbieri, Hall, Harigaya]
- Decoupling of A-B occurs when more light stuff in A than B [Farina]

Prelude

New long-lived species that decouples relativistically

Dominates energy density at late times

Matter dominated epoch

Preferentially decays to SM, so dilutes Twin's contributions

No extra $\mathbb{Z}_2$ breaking

Role naturally played by RH neutrinos, of Type I seesaw

Observable effects on $N_{\rm eff}$ and $\sum m_\nu$ at CMB-S4, LSS

Estimate the problem

$$\frac{m_f^B}{m_f^A} = \frac{f}{v} \sim 3$$

$$\frac{\Lambda_{\rm QCD}^B}{\Lambda_{\rm QCD}^A} \sim \left(\frac{f}{v}\right)^{2/9}$$

Effective # degrees of freedom

$$g_* = \sum \left(N_{\rm bosons} + \frac{7}{8} N_{\rm fermions} \right)$$

At A-B decoupling

$$\frac{\rho_B}{\rho_A} = \frac{\sum_{\gamma,g,\nu,e,\mu,u,d,s}}{\sum_{\gamma,g,\nu,e,\mu,\tau,u,d,c,s}} \approx 0.8$$

Comoving entropy is conserved so as a particle leaves the bath (g decreases) the energy density increases

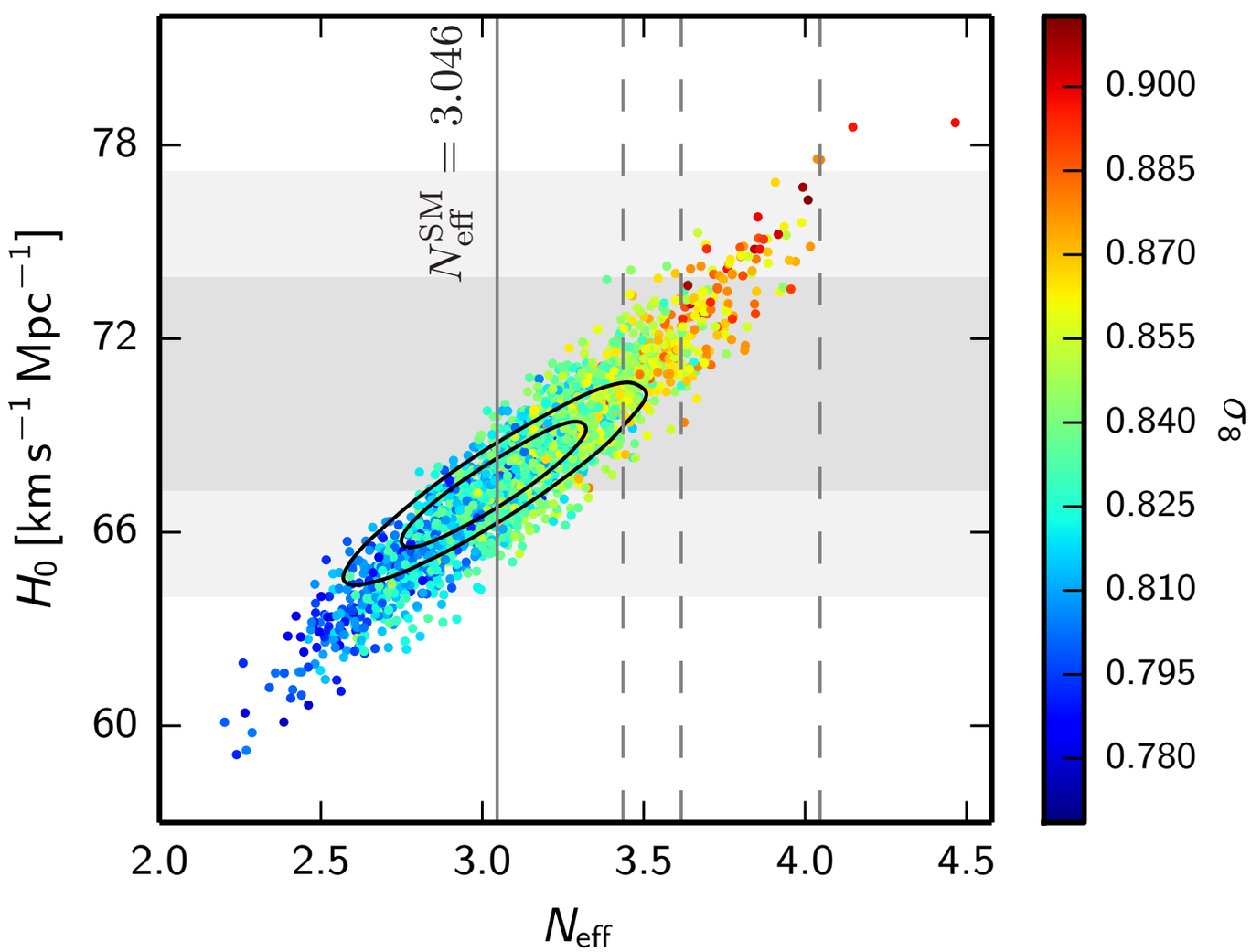
At CMB

$$\left.\frac{\rho_B}{\rho_A}\right|_{\rm BBN} \simeq \left(\left.\frac{g_{*B}}{g_{*A}}\right|_{T_D}\right)^{1/3} \left.\frac{\rho_B}{\rho_A}\right|_{T_D} = \left(\left.\frac{g_{*B}}{g_{*A}}\right|_{T_D}\right)^{4/3} \approx 0.75$$

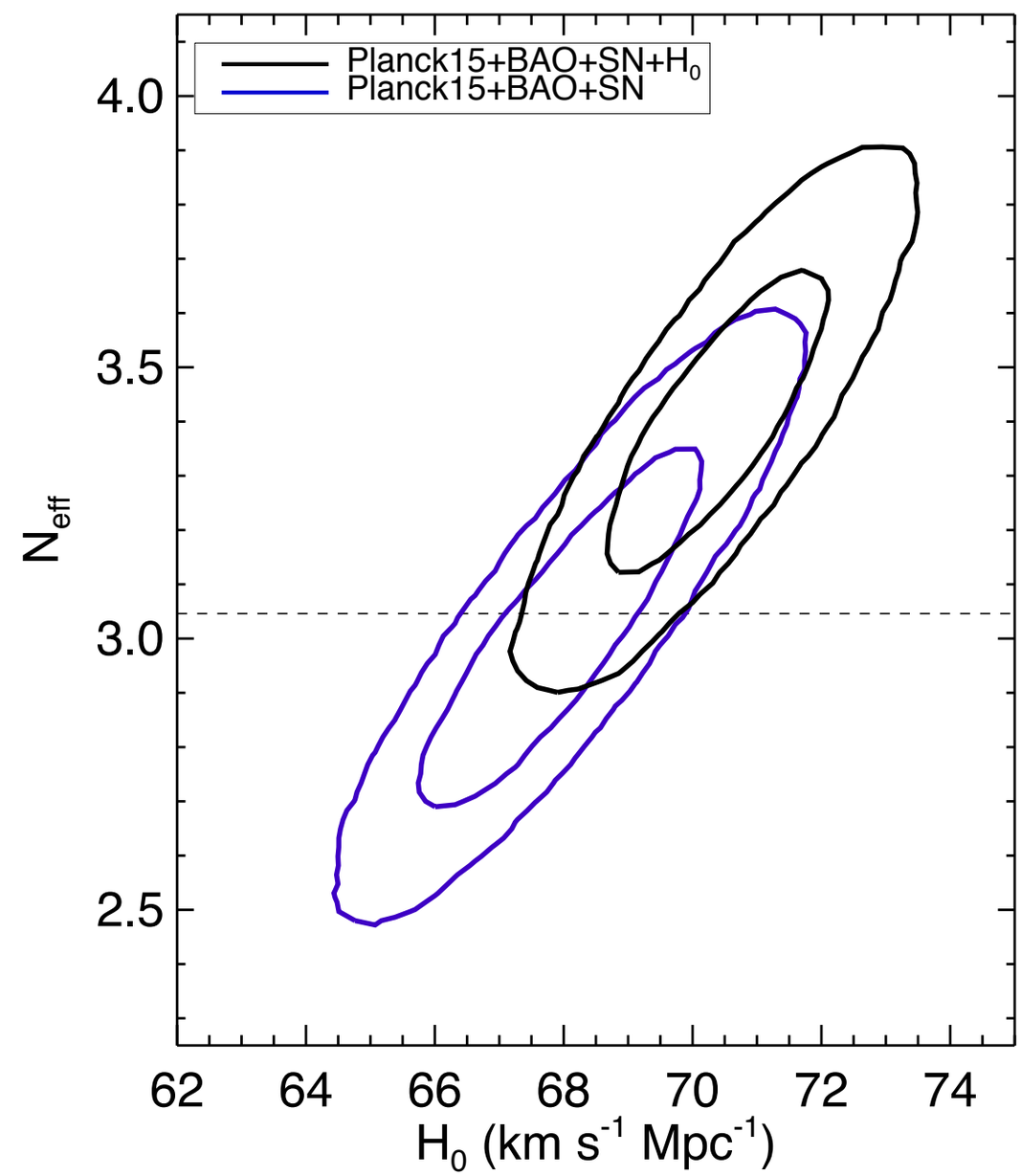
B-sector contribution to energy density is typically compared to additional number of neutrino species, $N_{\rm eff}$

$$\Delta N_{\rm eff} = 3\,\frac{\rho_B}{\rho_\nu}\bigg|_{\rm BBN} \approx 7.4\,\frac{\rho_B}{\rho_A}\bigg|_{\rm BBN} \approx 5.6\,!!$$

[Planck]



[Riess et al.]

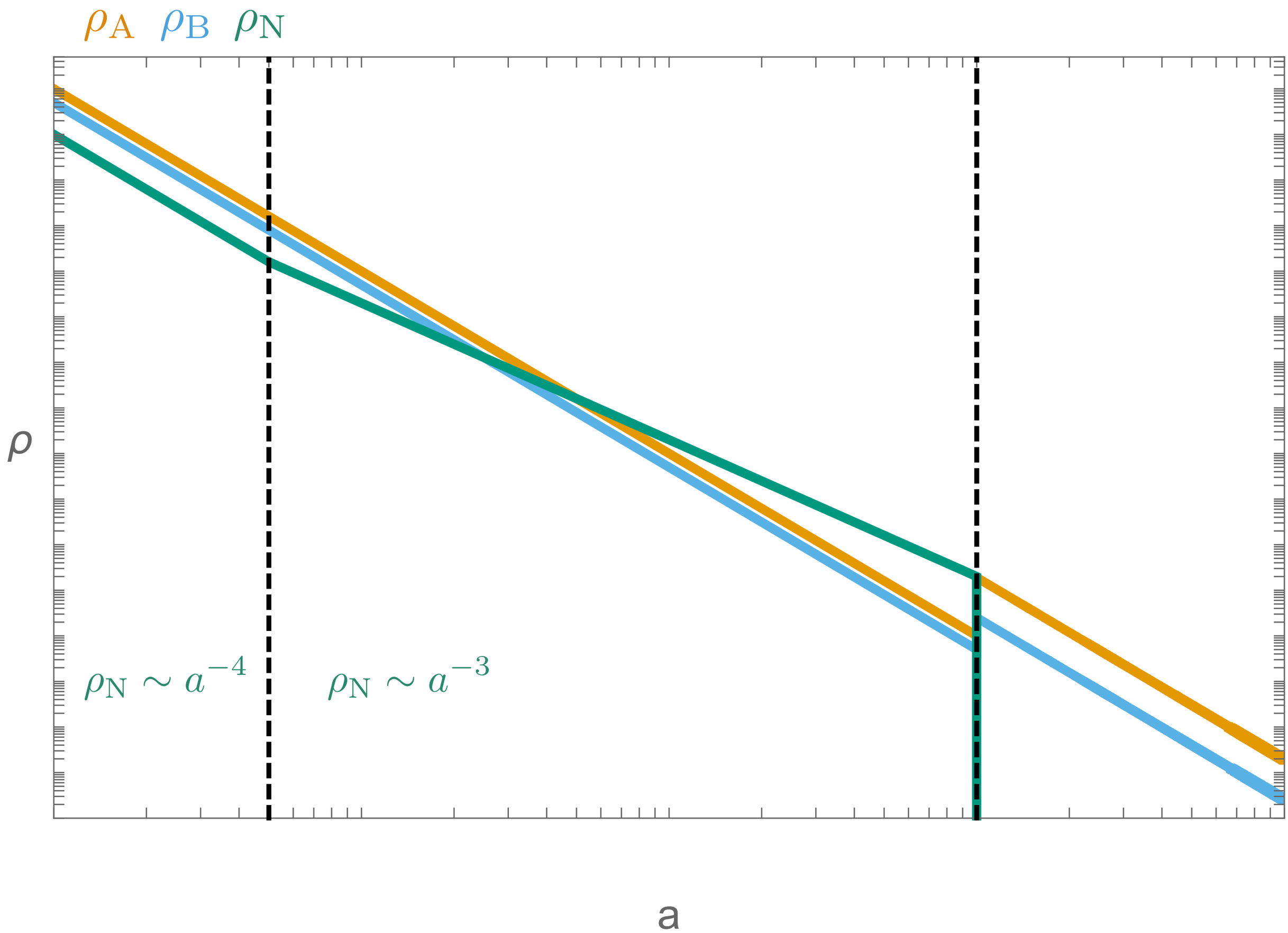


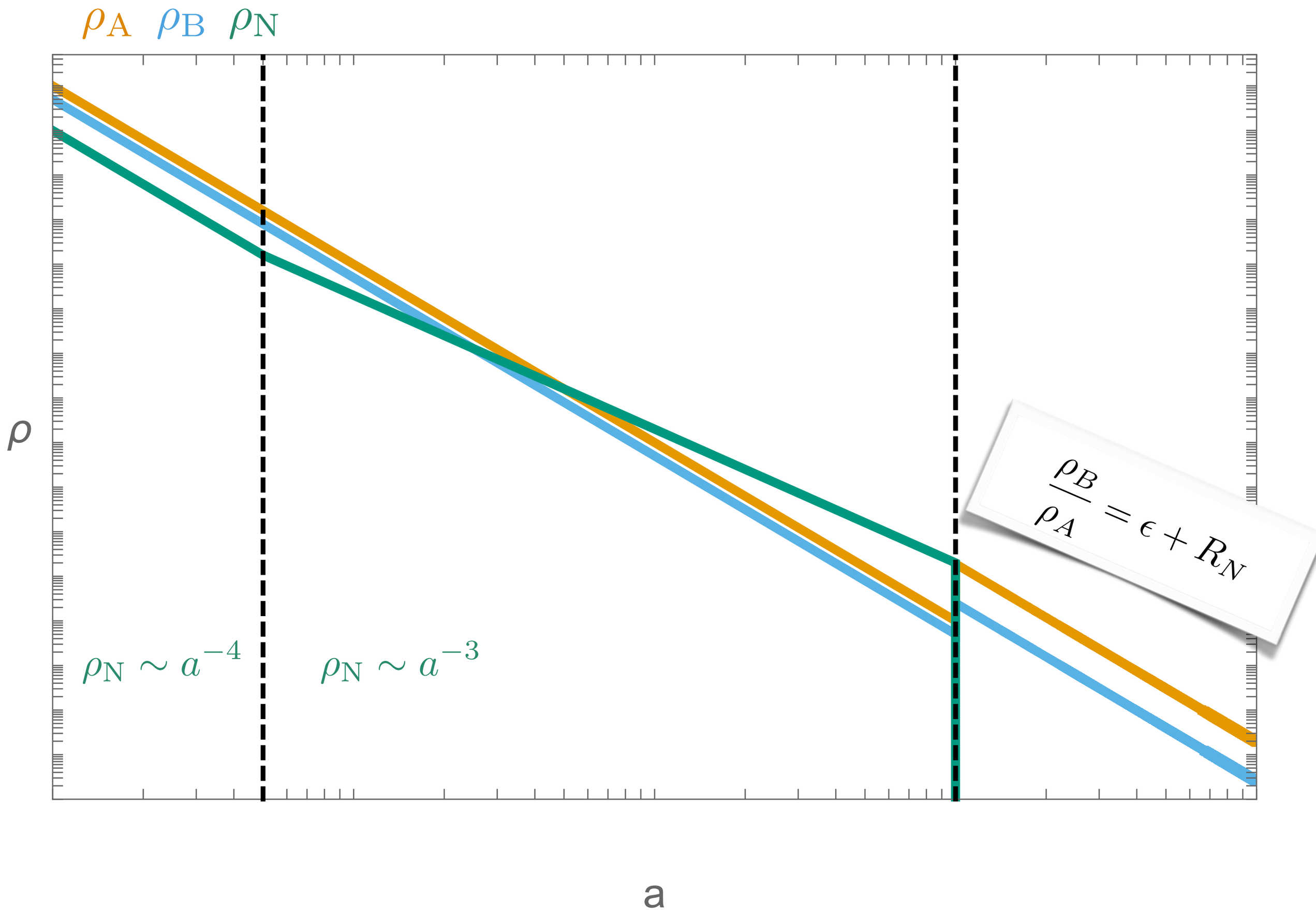
Solve the problem

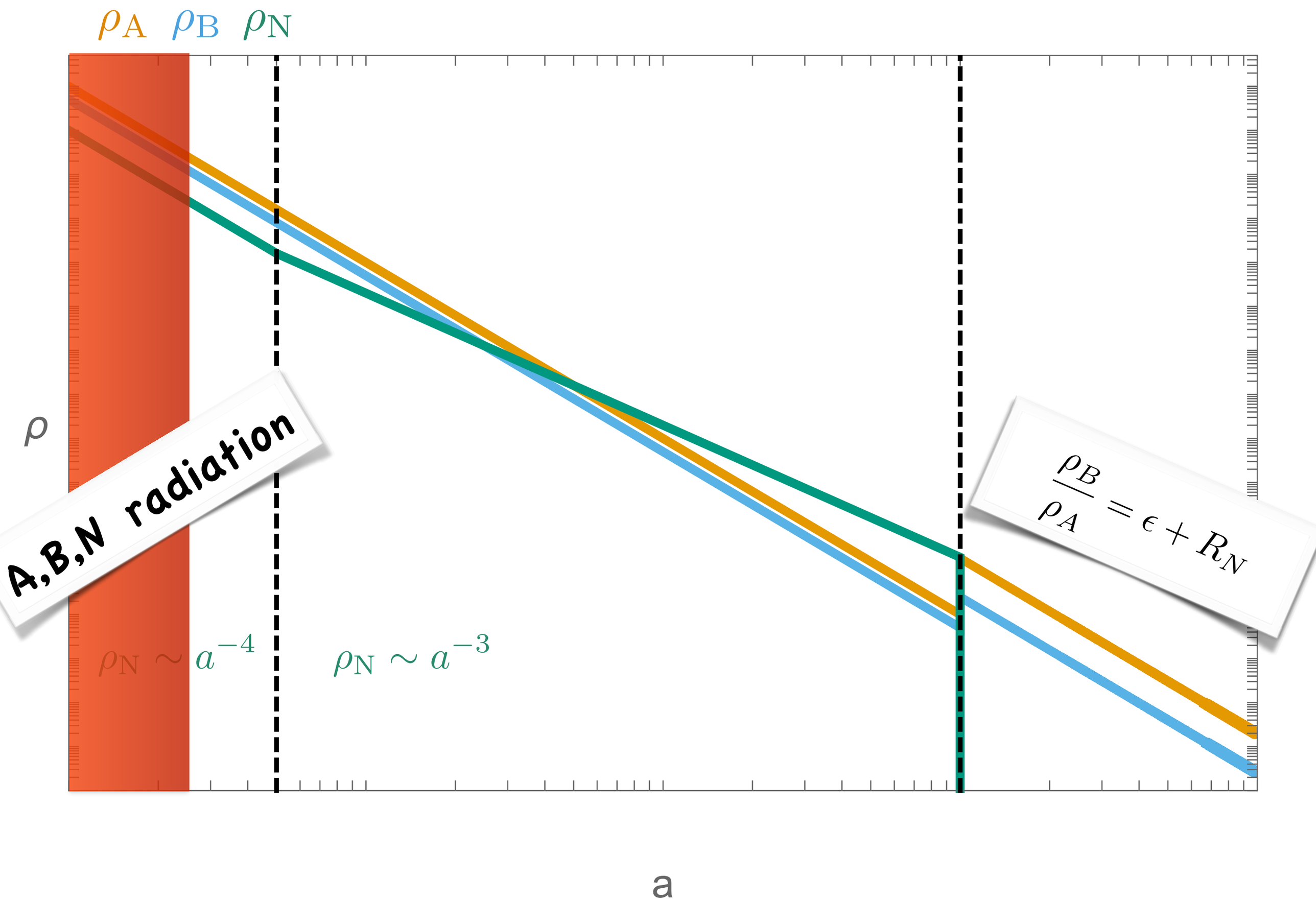
New very weakly coupled particle N $m_N \gtrsim 1\,\mathrm{GeV}$

- decouples relativistically
- long lived, but decays before ν_{SM} decoupling and after AB decoupling
- decays predominantly to A $\epsilon \equiv \frac{\Gamma_{N\to B}}{\Gamma_N} \ll 1$

What is N_{eff}?


$\rho_{\rm A}$ $\rho_{\rm B}$ $\rho_{\rm N}$
ρ
$\rho_{\rm N} \sim a^{-4}$
$\rho_{\rm N} \sim a^{-3}$
a


ρ_A ρ_B ρ_N
ρ
$\rho_N \sim a^{-4}$
$\rho_N \sim a^{-3}$
$\frac{\rho_B}{\rho_A} = \epsilon + R_N$
a


$\rho_{\rm A}$ $\rho_{\rm B}$ $\rho_{\rm N}$
ρ
A,B,N radiation
$\rho_{\rm N} \sim a^{-4}$
$\rho_{\rm N} \sim a^{-3}$
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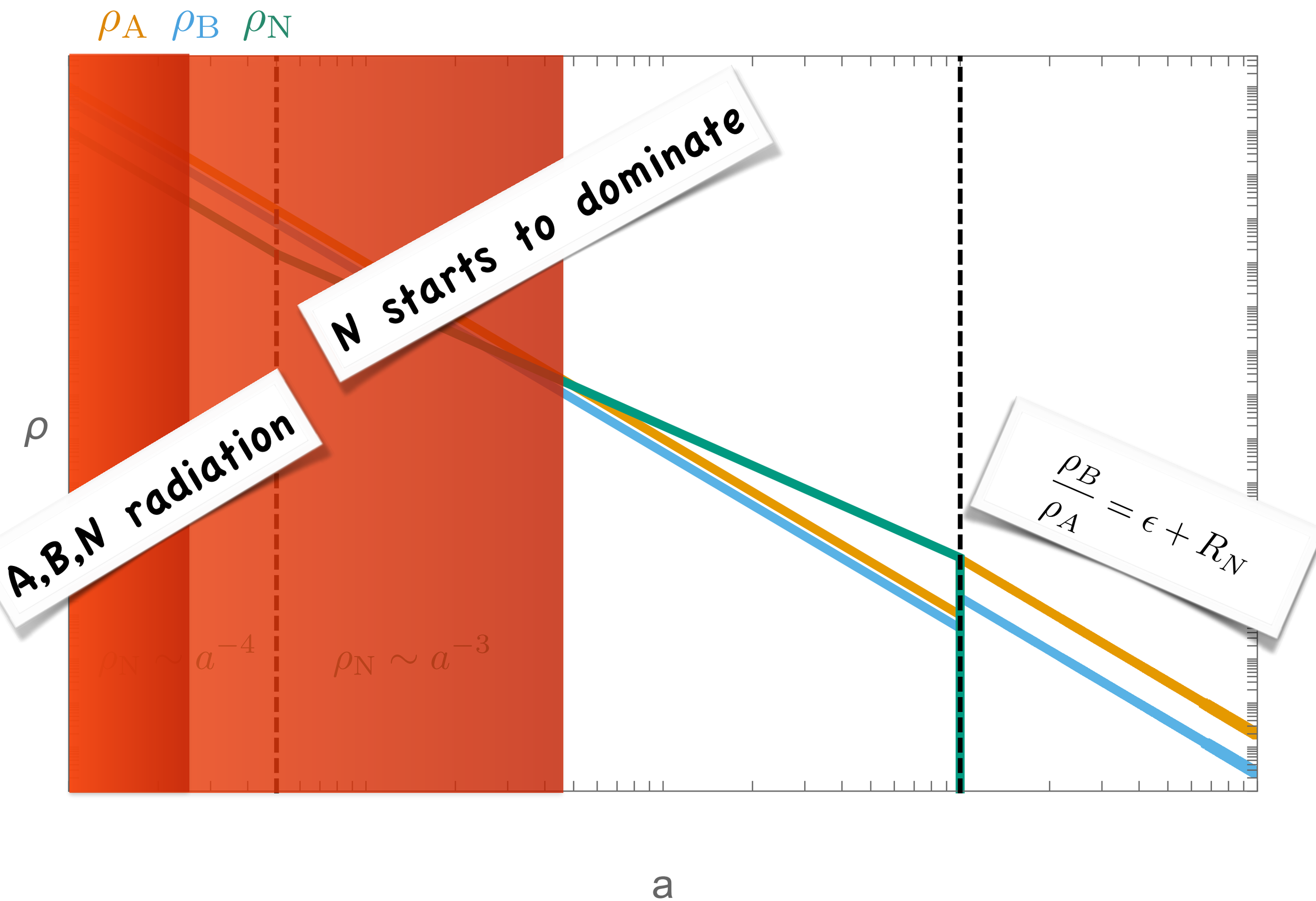
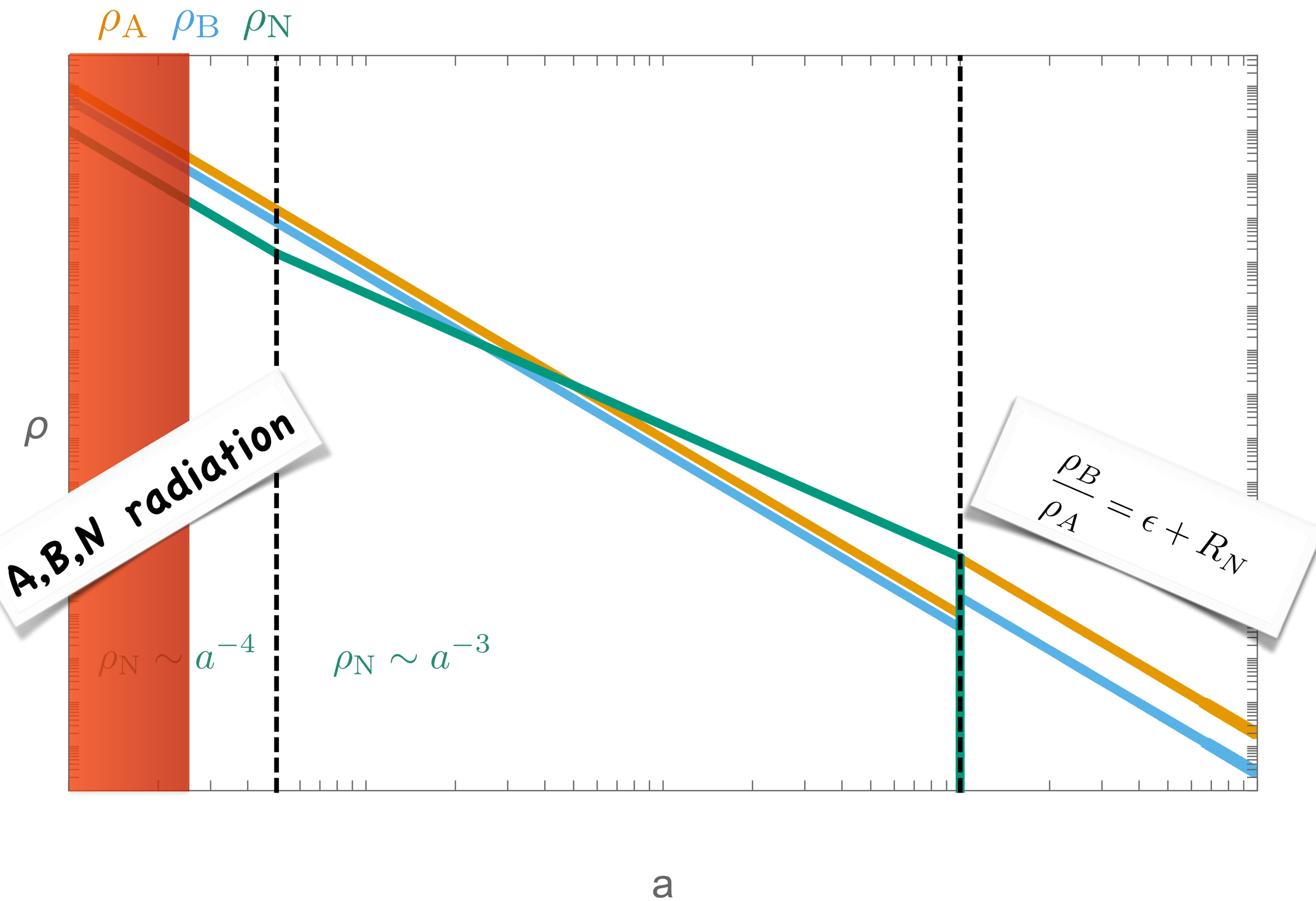
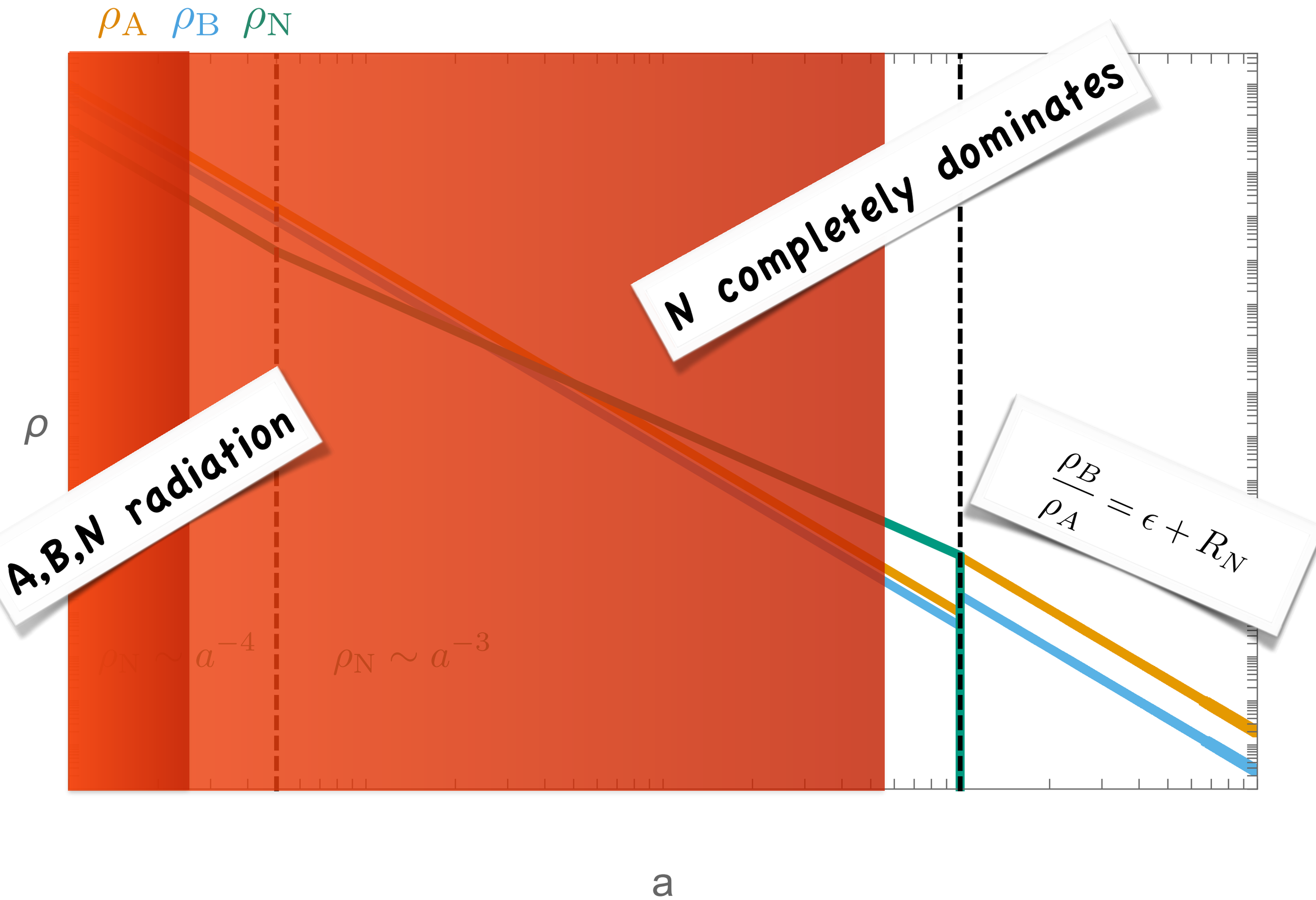
a


ρ_A ρ_B ρ_N
N starts to dominate
A,B,N radiation
$\frac{\rho_B}{\rho_A} = \epsilon + R_N$
$\rho_N \sim a^{-4}$
$\rho_N \sim a^{-3}$
ρ
a


$\rho_{\rm A}$ $\rho_{\rm B}$ $\rho_{\rm N}$
ρ
A,B,N radiation
$\rho_{\rm N} \sim a^{-4}$
$\rho_{\rm N} \sim a^{-3}$
$\frac{\rho_B}{\rho_A} = \epsilon + R_N$
a


ρ_A ρ_B ρ_N
ρ
A,B,N radiation
N completely dominates
$\rho_N \sim a^{-4}$
$\rho_N \sim a^{-3}$
$\frac{\rho_B}{\rho_A} = \epsilon + R_N$
a

N_{eff}

"Primordial" abundance of B

$$R_N = \frac{\pi^2}{90}\left(\frac{4\pi^2}{\zeta(3)}\right)^{4/3}\left(\frac{g_{*B,D}}{g_{*N}}\right)^{4/3}\left(\frac{g_{*,0}}{g_{*,D}}\right)^{4/3}\left(\frac{\Gamma_N^2 M_{Pl}^2}{g_{*B,R}M_N^4}\right)^{1/3}$$

+ decay contribution ε

$$\Delta N_{\rm eff} \approx 7.4\left(\frac{g_{*B,R}}{g_{*A,R}}\right)^{1/3}(\epsilon + R_N)$$

If N lives long enough and decays largely to A sector then evade CMB bound on new relativistic degrees of freedom

B-sector neutrinos

B neutrinos contribute to mass density in neutrinos $\sum m_\nu$

B neutrinos heavier than SM by $\frac{f}{v}$ or $\frac{f^2}{v^2}$ but are cooler

(ν, e, γ)

At SM neutrino decoupling # d.o.f. in both sectors the same

$$\frac{n_{\nu,B}}{n_{\nu,A}} = \frac{T_B^3}{T_A^3}$$

Conservation of entropy allows us to relate this to earlier times

$$\frac{m_{\nu,B} n_{\nu,B}}{m_{\nu,A} n_{\nu,A}} \approx \frac{m_{\nu,B}}{m_{\nu,A}} \left(\frac{\Delta N_{\rm eff}}{7.4} \right)^{3/4}$$

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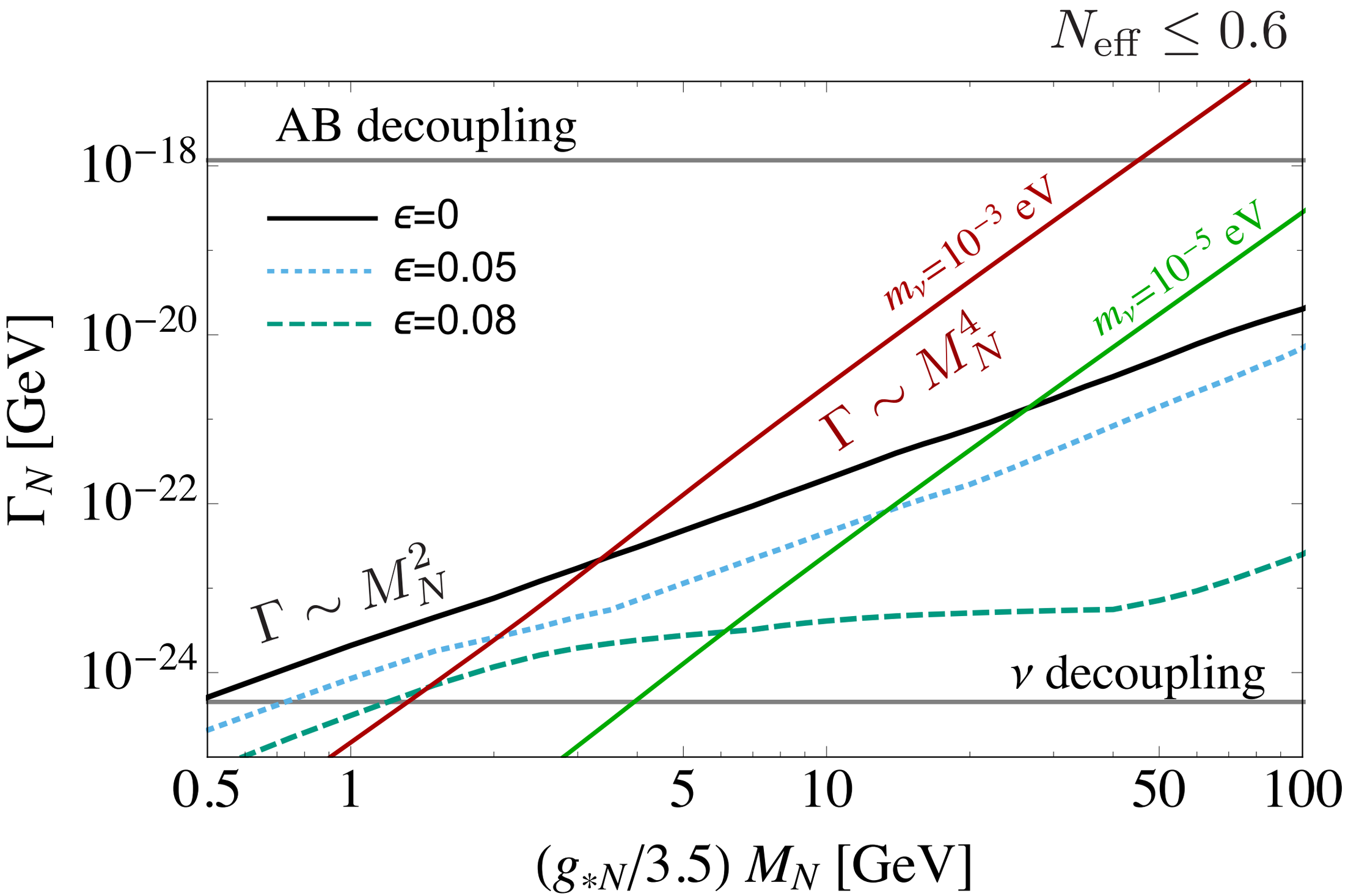
Taking into account varying g_*



Dial "N" for neutrino

For simplicity consider 1 flavour, for now

$$\mathcal{L} \supset -y\left(L_A H_A N_A + L_B H_B N_B\right) - \frac{1}{2} M_N \left(N_A^2 + N_B^2\right) - M_{AB} N_A N_B + \text{h.c.}$$

$$M_N \gg M_{AB} \gg y\langle H\rangle$$

$\mathbb{Z}_2$ means mass eigenstates are a (nearly) degenerate 50-50 mixture of A and B

$$N_+ = \frac{1}{\sqrt{2}}\left(N_A + N_B\right)$$

$$N_- = \frac{1}{\sqrt{2}}\left(N_A - N_B\right)$$

$$M_\pm = M_N \pm M_{AB}$$

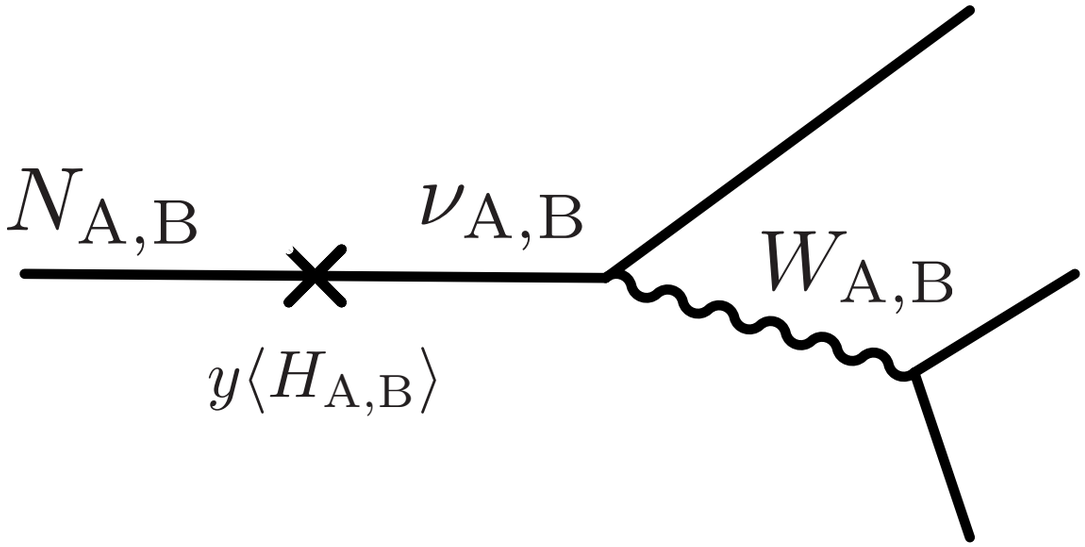
Dial "N" for neutrino

Integrate out to get Neutrino masses a la Type-I seesaw:

$$m_{\nu,A} = \frac{y^2 \langle H_A \rangle^2}{M_N} \left\{ 1 + \mathcal{O}\left(\frac{M_{AB}}{M_N} \right) \right\}$$

$$m_{\nu,B} = \frac{y^2 \langle H_B \rangle^2}{M_N} \left\{ 1 + \mathcal{O}\left(\frac{M_{AB}}{M_N} \right) \right\}$$

N decays



(+ Z modes)

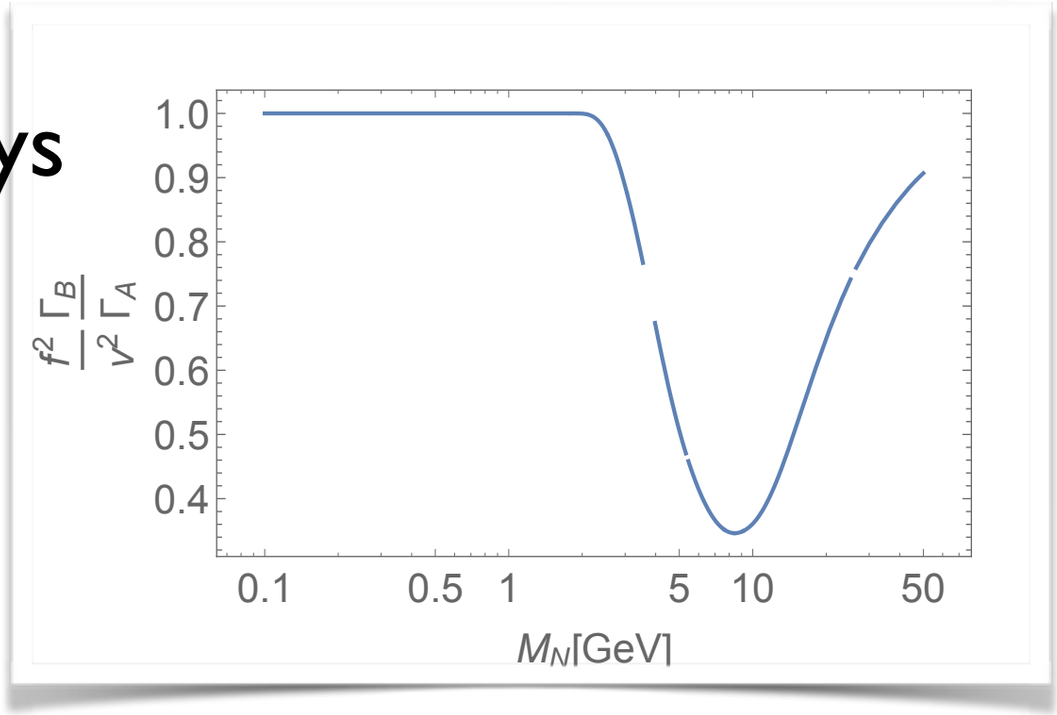
Ignoring final state masses, interference etc (include these in numerics)

$$\Gamma_{N\to A} \approx C_A \frac{G_F^2}{192\pi^3}\left(\frac{m_{\nu,A}}{M_N}\right) M_N^5$$

$$\Gamma_{N\to B} \approx C_B \frac{G_F^2}{192\pi^3}\left(\frac{m_{\nu,B}}{M_N}\right)\left(\frac{v}{f}\right)^4 M_N^5$$

Easily have suppressed B-sector decays

$$\epsilon = \frac{\Gamma_{N\to B}}{\Gamma_N} \approx \frac{v^2}{f^2}$$



(Even smaller ε)

- Hard $\mathbb{Z}_2$ breaking in the neutrino sector, y=0

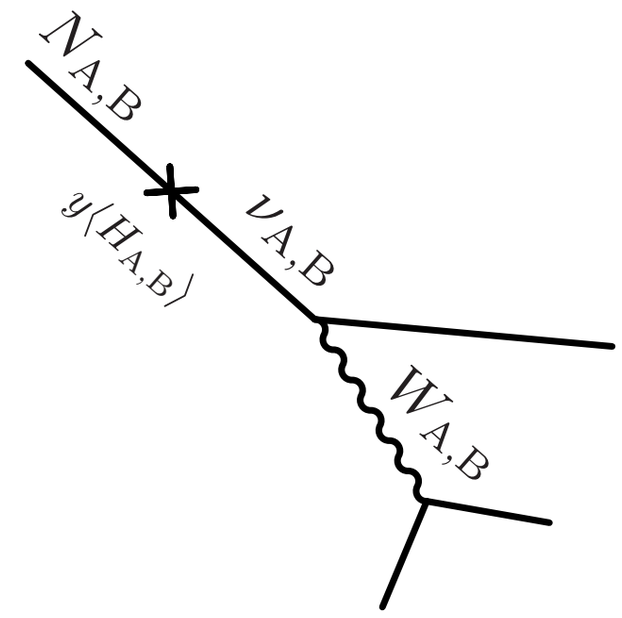
- Soft $\mathbb{Z}_2$ breaking in N masses $\mathcal{L} \supset \frac{1}{\Lambda}\left(|H_A|^2 N_A^2 + |H_B|^2 N_B^2\right)$

$$\mathcal{L} \supset -\frac{1}{2} M_{N_A} N_A^2 - \frac{1}{2} M_{N_B} N_B^2 - M_{AB} N_A N_B + \text{h.c.}$$

No longer maximally mixed, lighter N decays preferentially to A, heavier to B, but heavier is shorter lived

Does N decouple while relativistic?

N kept in equilibrium through weak interactions e.g. $N + e \to \nu + e$



$$\frac{\sigma(N + e^- \to \nu + e^-)}{\sigma(\nu + e^- \to \nu + e^-)} \sim \frac{m_\nu}{M_N}$$

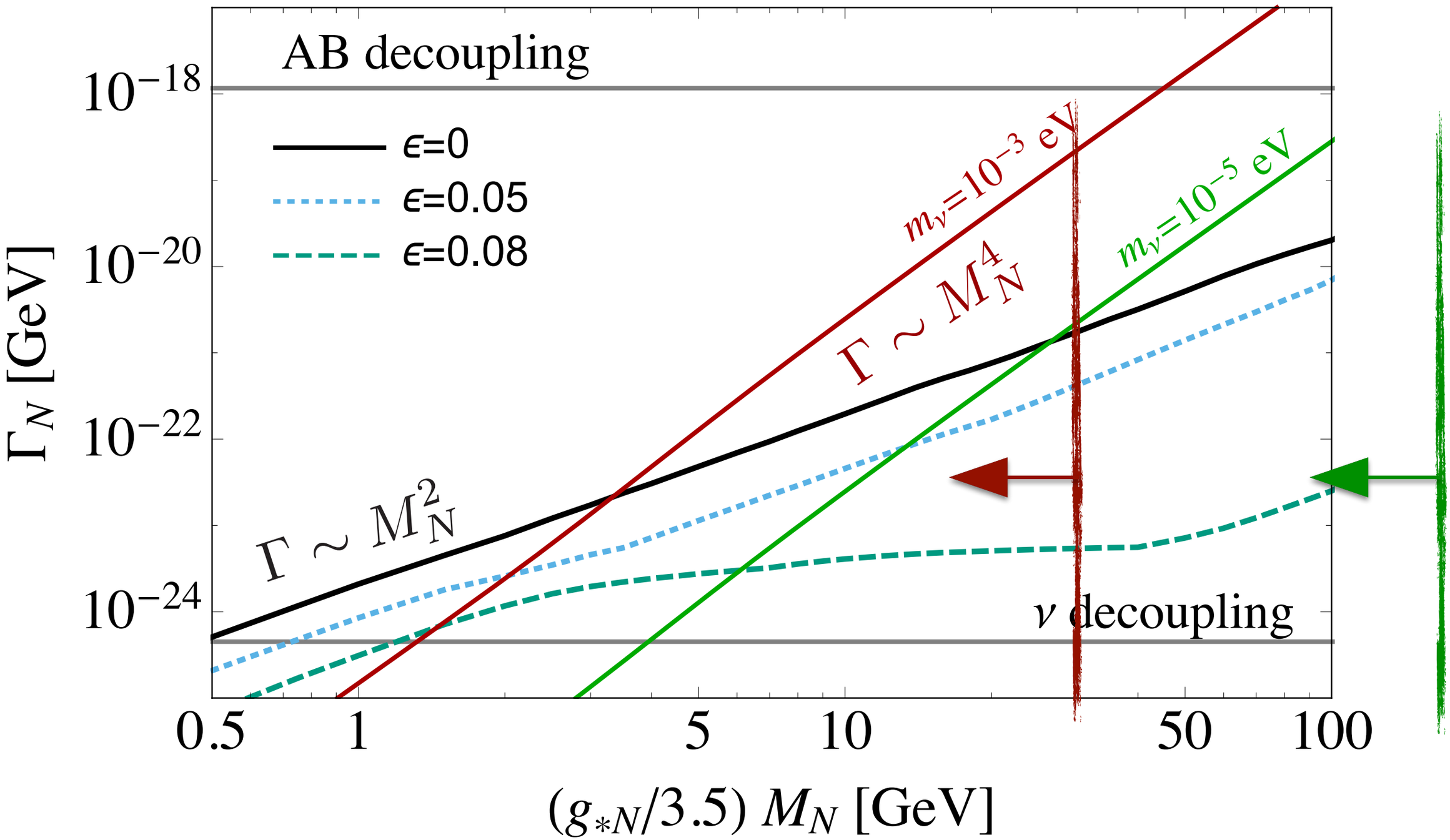
SM neutrinos freeze out at T~1 MeV

$$T_0 \sim \left(\frac{M_N}{m_\nu}\right)^{1/3} T_{\nu,\mathrm{SM}}$$

Decouple hot:

$$M_N < 10 \text{ GeV} \left(\frac{0.01 \text{ eV}}{m_\nu}\right)^{1/2}$$

Weaker constraint than dominating energy density



νMTH

Real model has 3 flavors of neutrinos, and PMNS matrix, CP etc

$$
\begin{aligned}
2.23 \times 10^{-3}\,\mathrm{eV}^2 \leq\ & \Delta m^2_{atm} \leq 2.61 \times 10^{-3}\,\mathrm{eV}^2 \\
6.99 \times 10^{-5}\,\mathrm{eV}^2 \leq\ & \Delta m^2_{sol} \leq 8.18 \times 10^{-5}\,\mathrm{eV}^2 \\
0.259 \leq\ & \sin^2\theta_{12} \leq 0.359 \\
0.374 \leq\ & \sin^2\theta_{23} \leq 0.628 \\
0.0176 \leq\ & \sin^2\theta_{13} \leq 0.0295\ .
\end{aligned}
$$

Decorate with indices

$$
\mathcal{L} \supset -y_{ij}\left(L^i_A H_A N^j_A + L^i_B H_B N^j_B\right) - \frac{1}{2}(M_N)_{ij}\left(N^i_A N^j_A + N^i_B N^j_B\right) - (M_{AB})_{ij} N^i_A N^j_B + \mathrm{h.c.}
$$

- Universal RH neutrinos
- Pseudo μ - τ anarchy [Altarelli, Feruglio, Masina]

νMTH—Universal

$$M_N \propto \mathbb{1} \qquad \text{and} \qquad M_{AB} \propto \mathbb{1} \qquad \text{and} \qquad y_{ij} \in \mathbb{R}$$

LH and RH neutrinos aligned

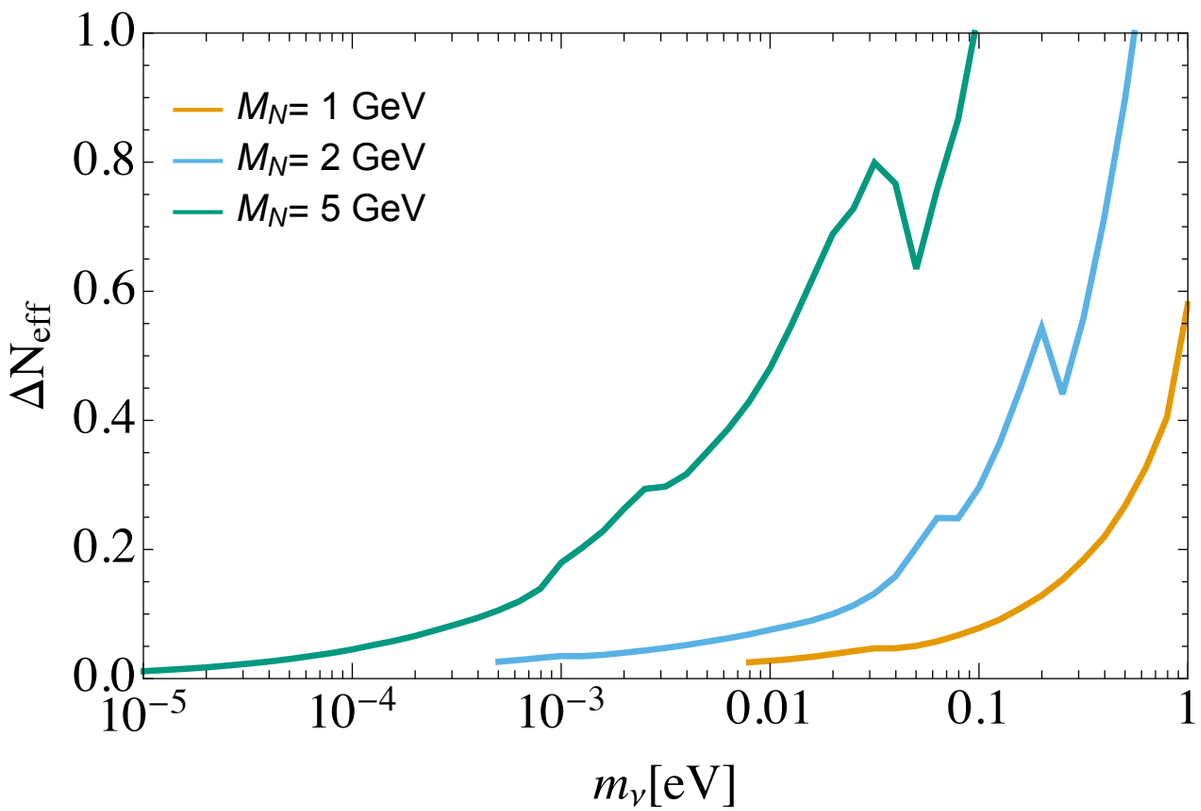
$$\Gamma_{N_i \to A} \approx C_A \frac{G_F^2}{192\pi^3} \left(\frac{m_{\nu,A}^i}{M_N} \right) M_N^5$$

By lowering mass of lightest SM neutrino can make 1 N arbitrarily long lived

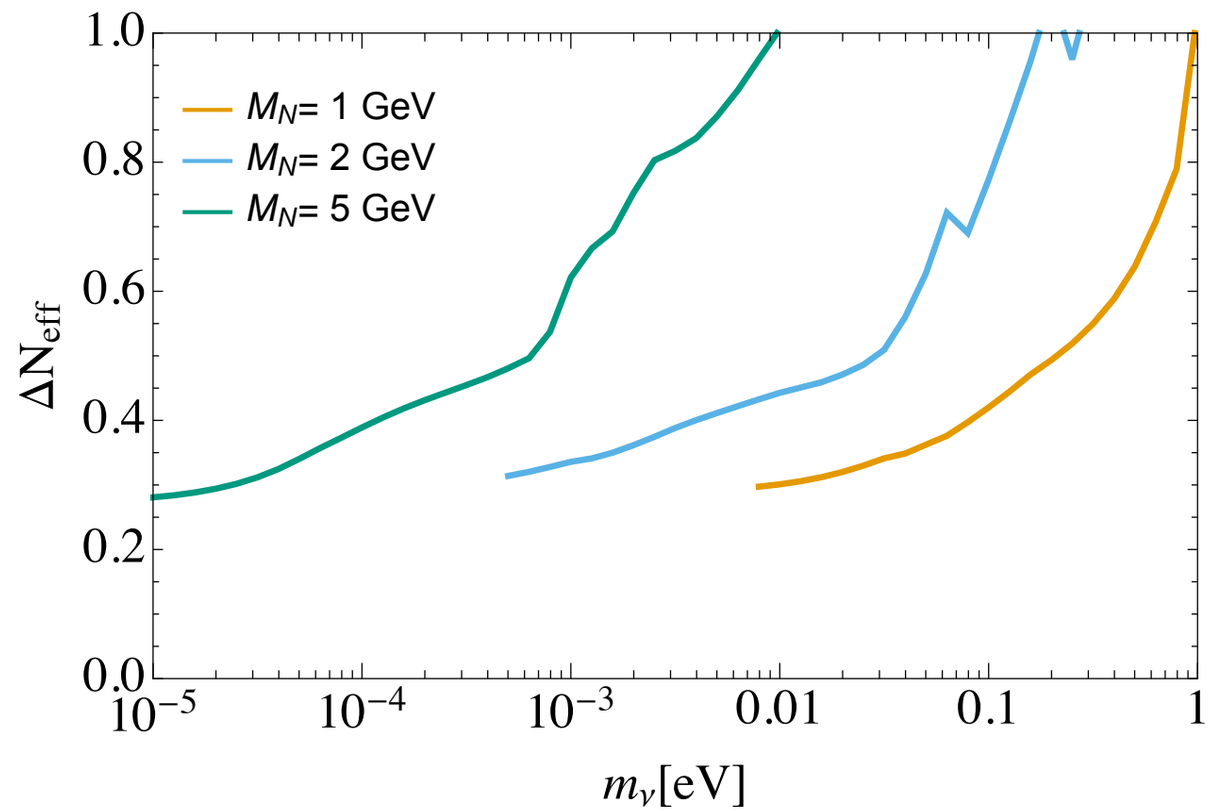
Solve cosmology numerically

$$\frac{f}{v} = \frac{m_f^B}{m_f^A} = 3$$

$\epsilon = 0$



$\epsilon = 0.05$



νMTH—Anarchic

Froggatt Nielsen charges of LH and RH neutrinos s.t.

$$m_D = \overline{m}_D \begin{pmatrix} \lambda^3 & \lambda & \lambda^2 \\ \lambda & \lambda & 1 \\ \lambda & \lambda & 1 \end{pmatrix}, \quad M_N = \overline{M}_N \begin{pmatrix} \lambda^2 & 1 & \lambda \\ 1 & \lambda^2 & \lambda \\ \lambda & \lambda & 1 \end{pmatrix}$$

$\lambda \approx 0.35$

Random entries with random phases

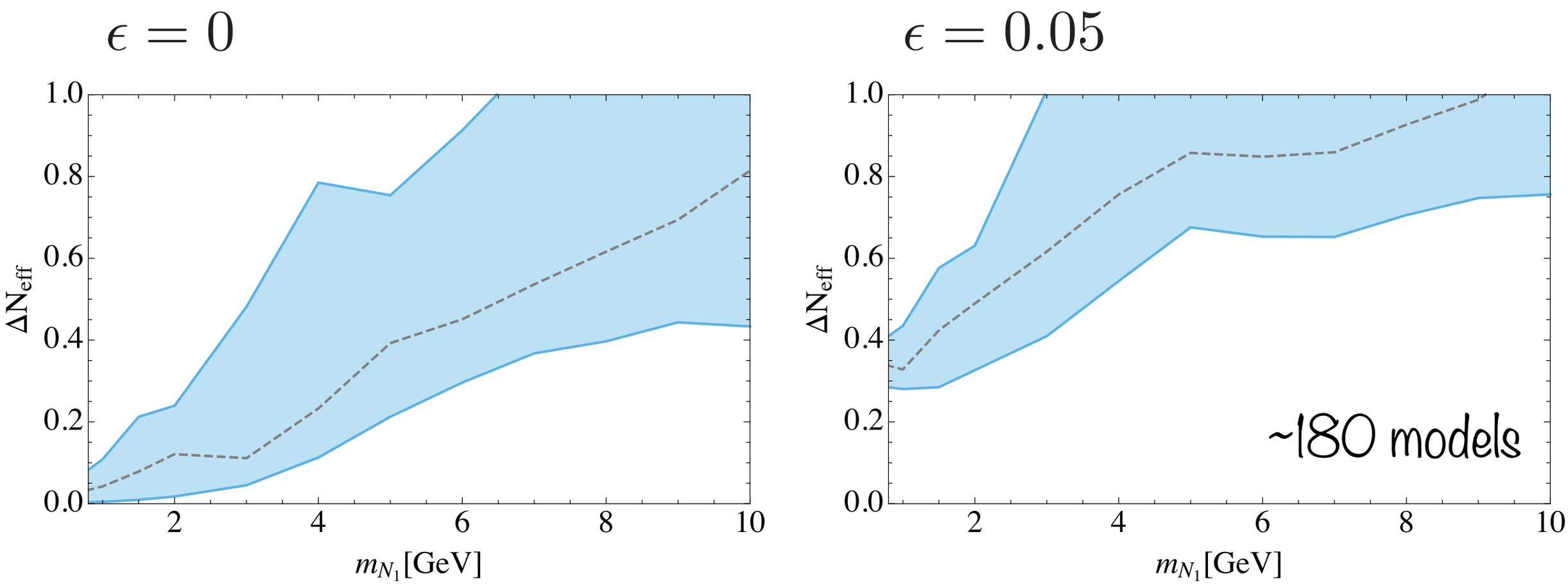
$[0.5, 2] \times t_{ij}$ $\qquad$ $[0, 2\pi]$

1-parameter family $\quad M_N \to r M_N$

$$m_D \to r^{1/2} m_D$$

Solve cosmology numerically

$$\frac{f}{v} = \frac{m_f^B}{m_f^A} = 3$$



Conclusions

- Simple solution to cosmological problems of original MTH
- Weakly coupled new state decouples early and decays late
- GeV scale RH neutrinos can simultaneously generate SM neutrino masses and fix MTH cosmology …. νMTH
- New contributions to relativistic d.o.f. and neutrino's
    - Observable in CMS-S4 and LSS measurements
- c.f. N(=2)Naturalness
- Connecting cosmology to Naturalness solution
- Long lived N's at colliders?

BACKUP

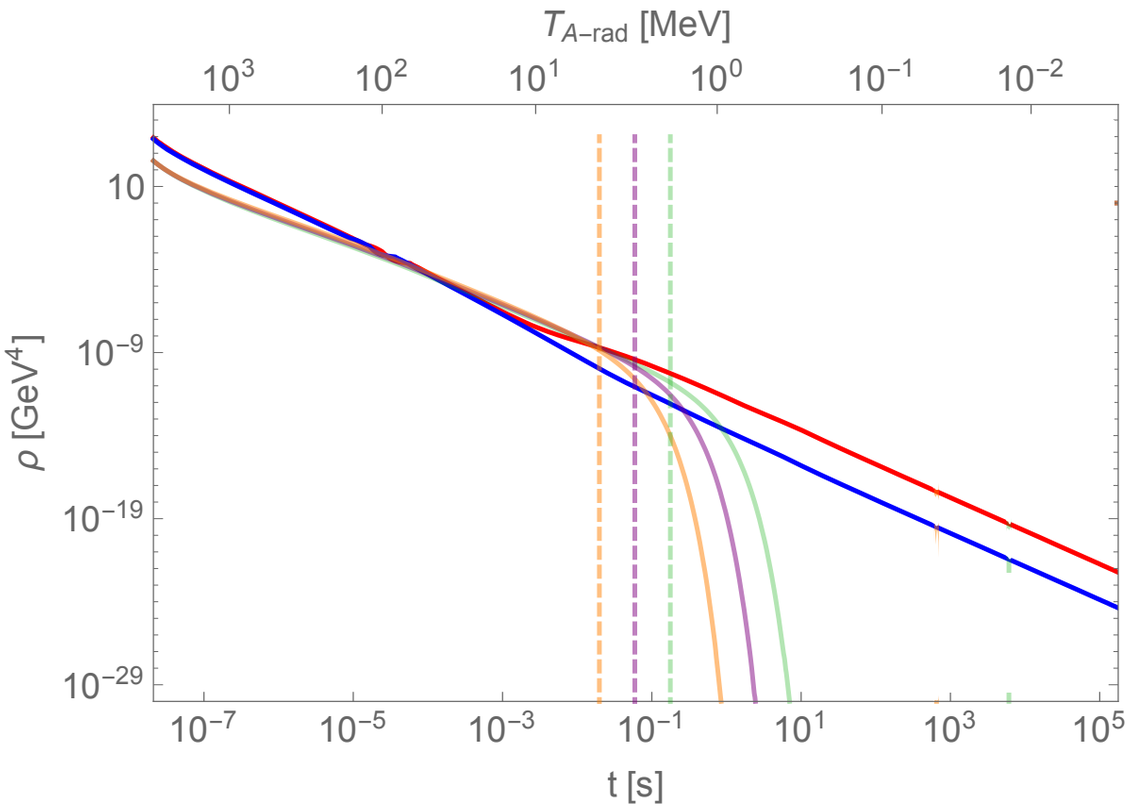
- Real models have 3 neutrinos with different masses & widths
- Decays not instantaneous
- Multiple thresholds in both sectors
- A, B baths and N's:

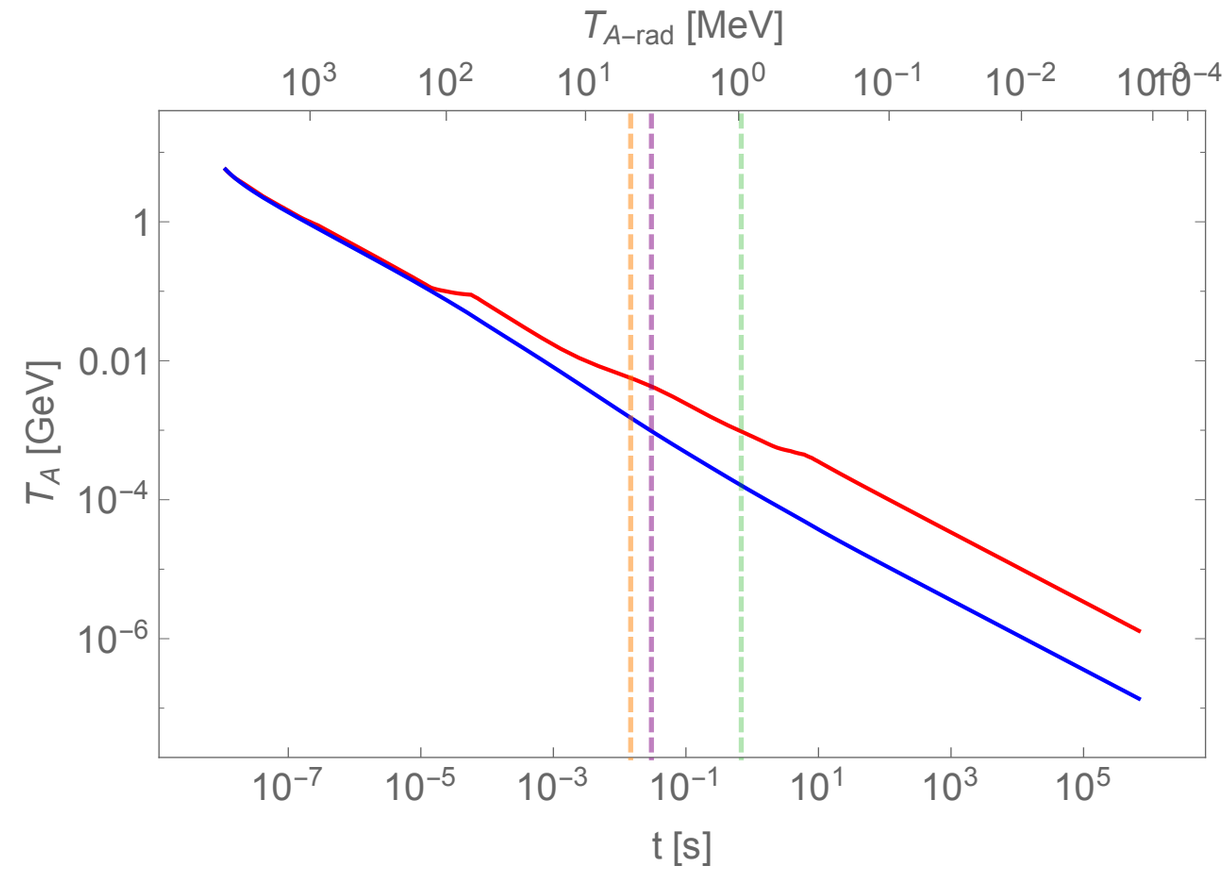
$$\dot{S}_A = \left(\frac{2\pi^2 g_{*A}}{45\, S_A}\right)^{1/3} a^4 \sum_i (1-\epsilon)(n_i - n_i^{eq})\langle E\,\Gamma_i\rangle \approx \left(\frac{2\pi^2 g_{*A}}{45\, S_A}\right)^{1/3} a^4 \sum_i (1-\epsilon)\Gamma_i \rho_i \ ,$$

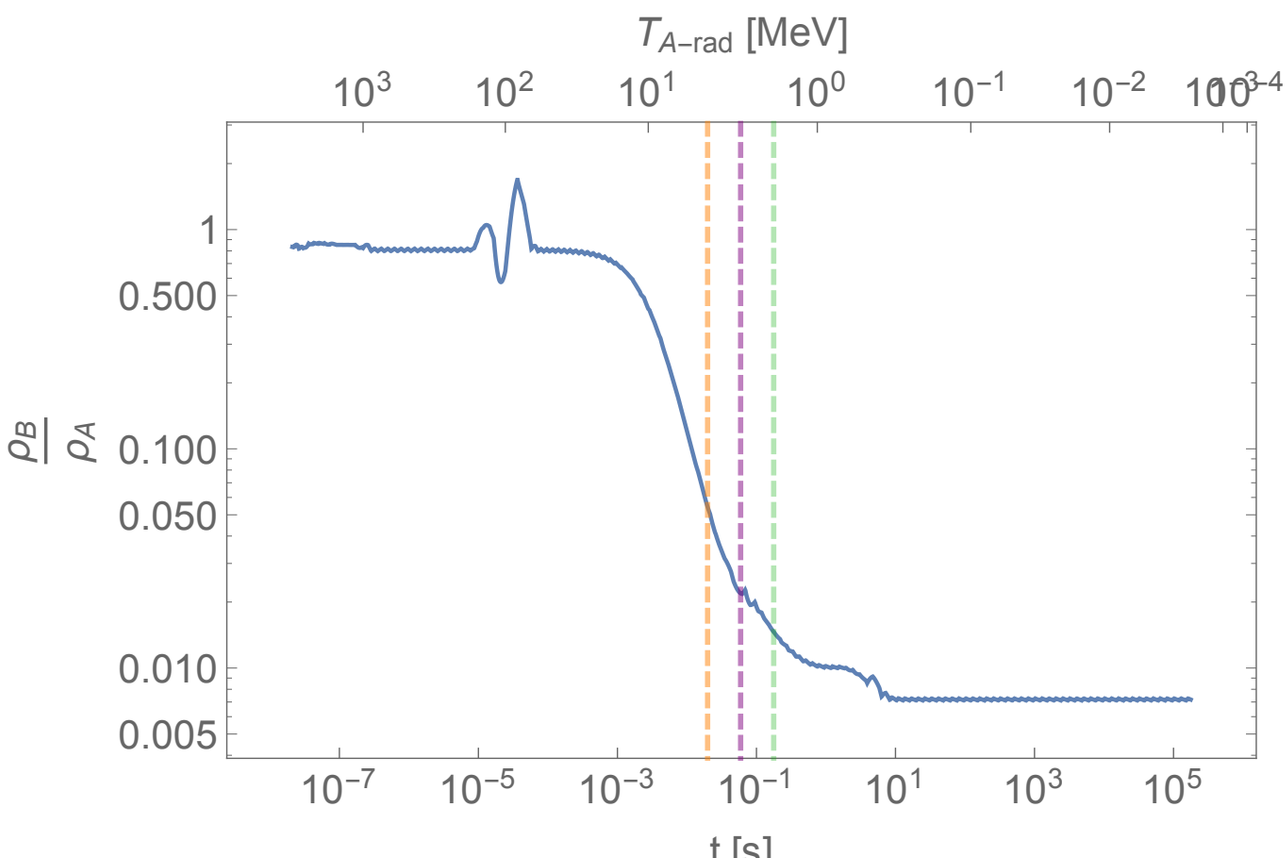
$$\dot{S}_B = \left(\frac{2\pi^2 g_{*B}}{45\, S_B}\right)^{1/3} a^4 \sum_i \epsilon\,(n_i - n_i^{eq})\langle E\,\Gamma_i\rangle \approx \left(\frac{2\pi^2 g_{*B}}{45\, S_B}\right)^{1/3} a^4 \sum_i \epsilon\,\Gamma_i \rho_i \ .$$

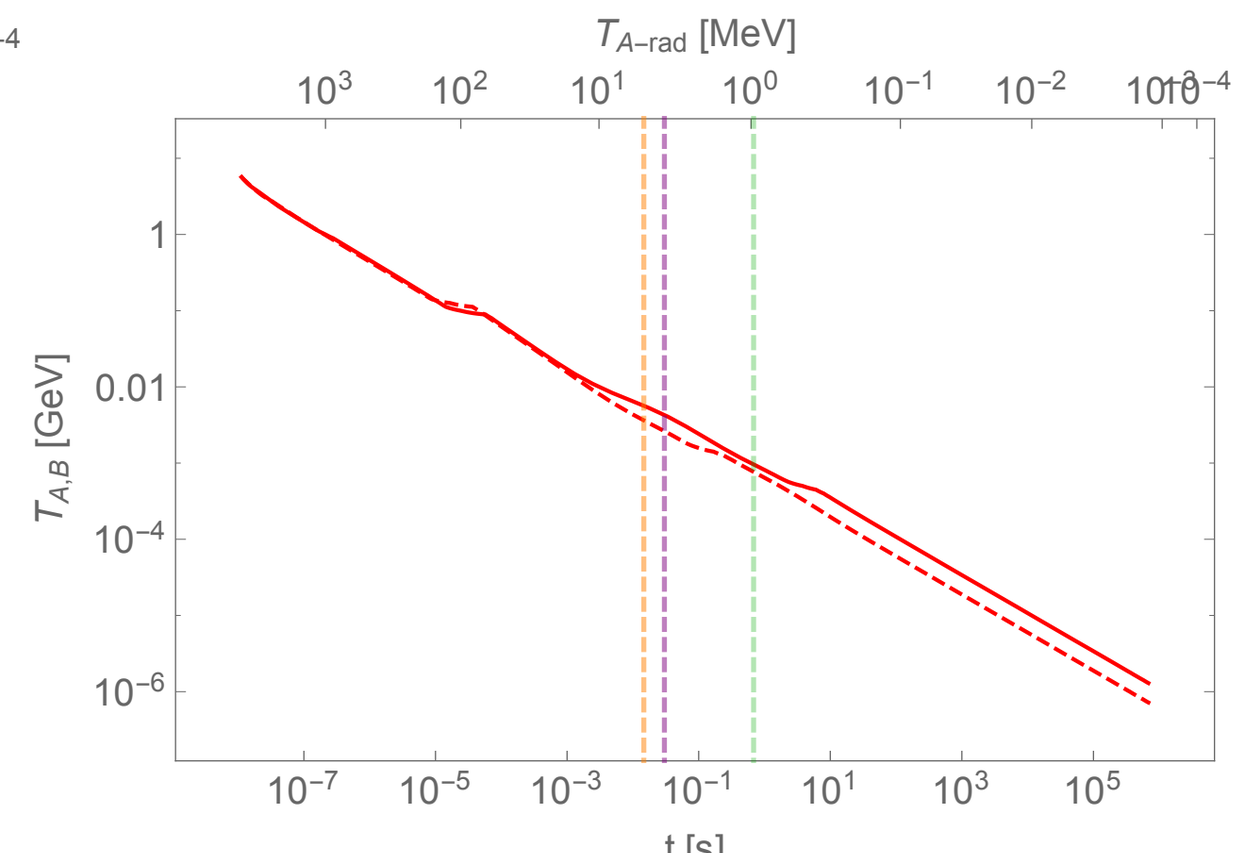
$$\dot{\rho}_i = -3H\,(\rho_i + p_i) - (n_i - n_i^{eq})\langle E\,\Gamma_i\rangle \approx -3H\,(\rho_i + p_i) - \Gamma_i \rho_i$$

Start w/ thermal abundance at largest N decoupling temperature


$T_{A\text{-rad}}$ [MeV]
10^3 10^2 10^1 10^0 10^{-1} 10^{-2} 10^{-3} 10^{-4}
ρ [GeV^4]
10
10^{-9}
10^{-19}
10^{-29}
10^{-7} 10^{-5} 10^{-3} 10^{-1} 10^1 10^3 10^5
t [s]


$T_{A\text{-rad}}$ [MeV]
10^3 10^2 10^1 10^0 10^{-1} 10^{-2} 10^{-3} 10^{-4}
T_A [GeV]
1
0.01
10^{-4}
10^{-6}
10^{-7} 10^{-5} 10^{-3} 10^{-1} 10^1 10^3 10^5
t [s]


$T_{A\text{-rad}}$ [MeV]
10^3 10^2 10^1 10^0 10^{-1} 10^{-2} 10^{-3} 10^{-4}
$\frac{\rho_B}{\rho_A}$
1
0.500
0.100
0.050
0.010
0.005
10^{-7} 10^{-5} 10^{-3} 10^{-1} 10^1 10^3 10^5
t [s]


$T_{A\text{-rad}}$ [MeV]
10^3 10^2 10^1 10^0 10^{-1} 10^{-2} 10^{-3} 10^{-4}
$T_{A,B}$ [GeV]
1
0.01
10^{-4}
10^{-6}
10^{-7} 10^{-5} 10^{-3} 10^{-1} 10^1 10^3 10^5
t [s]