# Leptogenesis and Low Reheating Temperatures

Stephen E. Henrich

**Co-authors:** Marcos Garcia, Wenqi Ke, and Keith Olive
**Based on:** 2607.08663

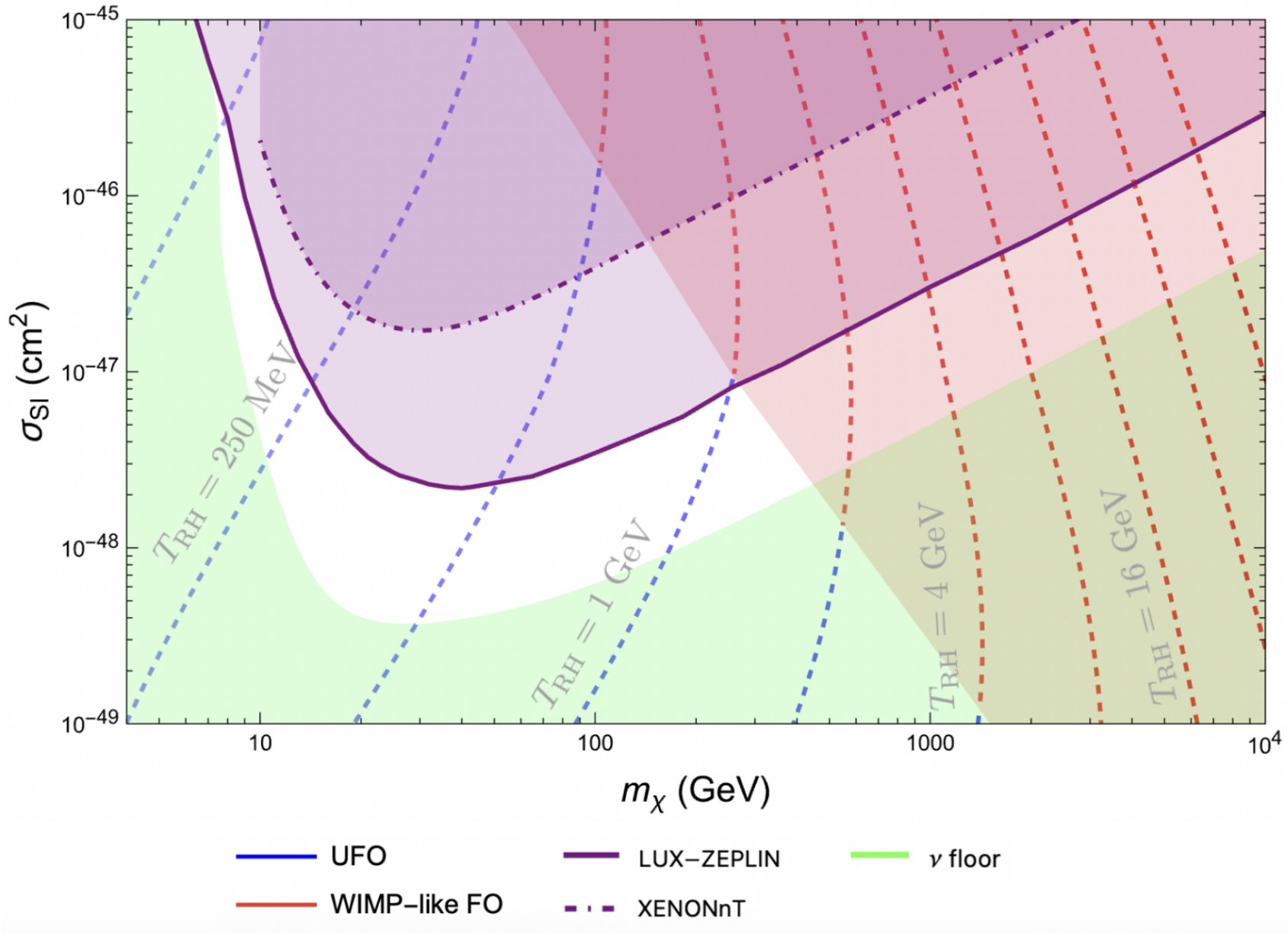


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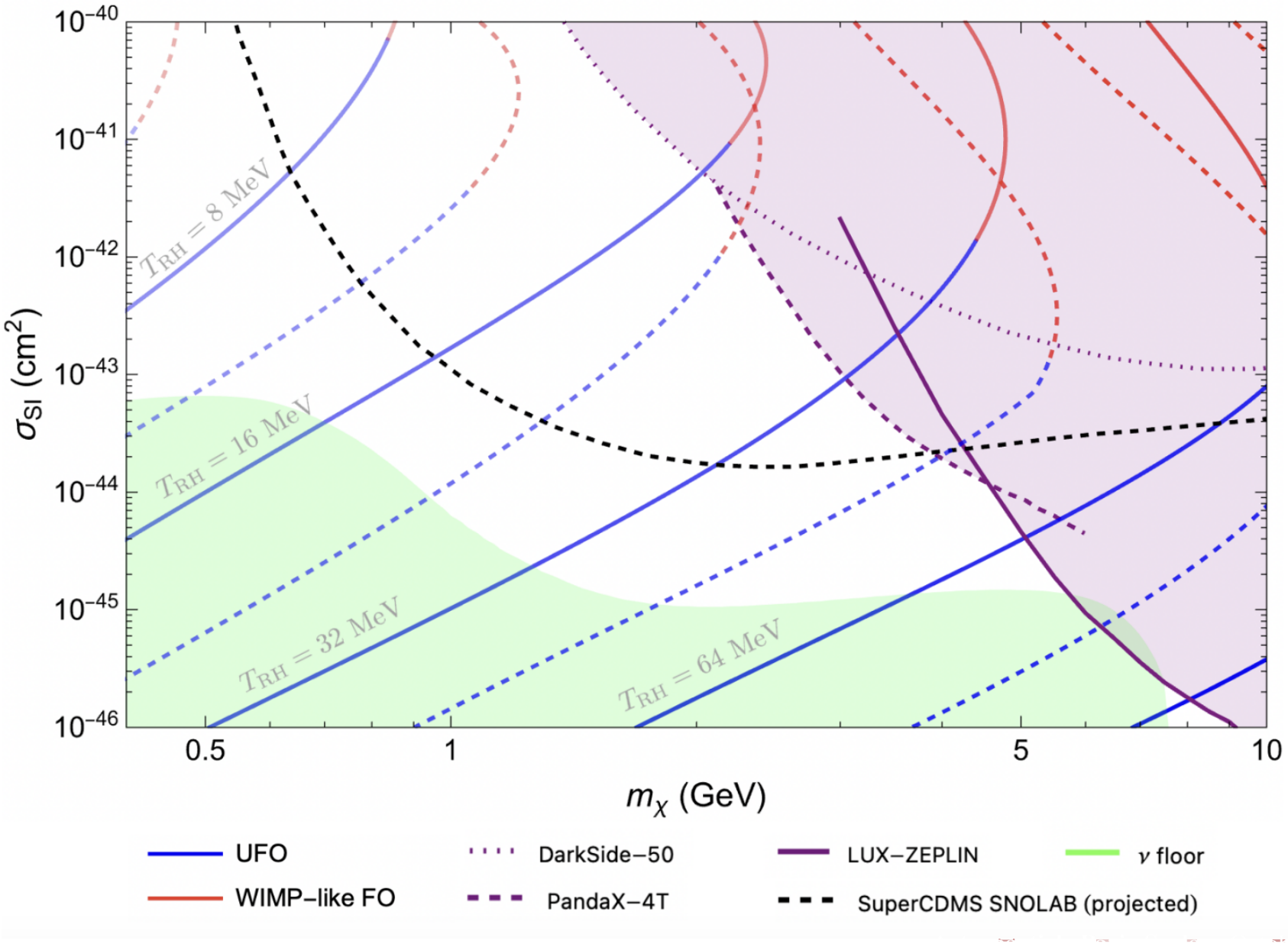
Department of Physics

**Astroparticle Paris-Saclay:** October 28th, 2026

# Low $T_{\rm RH}$ dark matter: (ultra)relativistic freeze-out



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# Non-thermal leptogenesis during reheating

1. Inflaton decays to both RHNs and SM particles

$$\Gamma_{\phi\to NN} = \frac{y^2_{\phi NN}}{8\pi} m_\phi \sqrt{1 - \frac{4M_N^2}{m_\phi^2}}, \qquad \Gamma_{\phi\to \bar{f}f} = \frac{y^2_{\phi \bar{f} f}}{8\pi} m_\phi$$

2. RHNs decay during reheating $\Rightarrow$ lepton asymmetry
3. Sphalerons $\Rightarrow$ baryon asymmetry, which becomes fixed near $T \sim T_{\rm sph}$
4. Reheating takes place via $\phi \to \bar{f} f$, $T_{\rm RH} \ll 100$ GeV

Consider $V(\phi) \propto \phi^k$. We will study $k = 2$ and $k = 4$.

*Thermal processes such as RHN inverse decays are included in our numerics, but are sub-dominant

* Giudice, Riotto et. al. 2003 found a lower bound of $T_{\rm RH} \gtrsim 2 \times 10^9$ GeV for thermal leptogenesis

# Parameters and Constraints

Five parameters: $(M_N, y_N, T_{\rm RH}, y_{\phi NN}, |\epsilon|)$

1. $M_N$ : mass of the lightest RHN
2. $y_N$: effective Yukawa for $M_1 \sim M_N$, determines RHN decay rate
3. $T_{\rm RH}$: determined by $y_{\phi ff}$
4. $y_{\phi NN}$: determines $\phi \longrightarrow NN$ efficiency
5. $|\epsilon|$: CP violating parameter

Assumptions

- Hierarchical type I seesaw, with
$$M_2, M_3 \gg M_1 \sim M_N = 10^{12}\ \text{GeV}$$
- RHNs decay prior to sphaleron decoupling ($a_{\rm end} < a_N < a_{\rm sph}$), which constrains $y_N$
- High scale inflation: $H_{\rm end} \sim 10^{13}$ GeV
- $T_{\rm RH} \ll 100$ GeV

# Boltzmann System

**1) Inflaton:** $$aH\rho_\phi' + 3(1+w_\phi)H\rho_\phi = -(\Gamma_{\phi\to ff} + \Gamma_{\phi\to NN})(1+w_\phi)\rho_\phi\,,$$

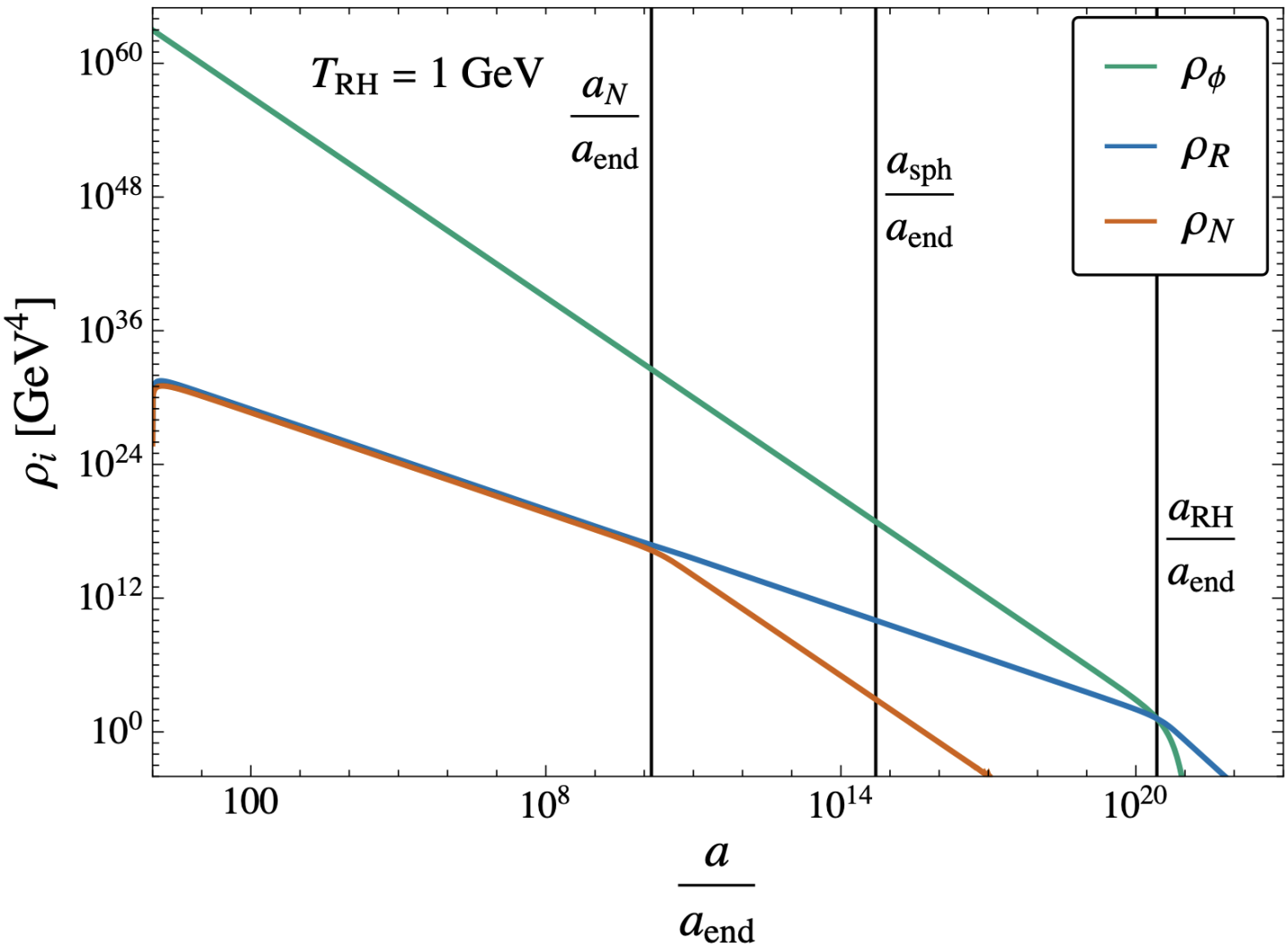
**2) Radiation:** $$aH\rho_{\rm R}' + 4H\rho_{\rm R} = \Gamma_{\phi\to ff}(1+w_\phi)\rho_\phi + \langle\Gamma_N\rangle\,(\rho_N - \rho_N^{\rm eq})\,,$$

**3) RHN:** $$aHn_N' + 3Hn_N = (1+w_\phi)\Gamma_{\phi\to NN}\frac{\rho_\phi}{m_\phi} - \langle\Gamma_N\rangle\left(n_N - n_N^{\rm eq}\right)\,,$$

**4) *B-L*:** $$aHn_{B-L}' + 3Hn_{B-L} = -\langle\Gamma_N\rangle\left[\epsilon(n_N - n_N^{\rm eq})\right] - \frac{1}{2}\langle\Gamma_{\rm ID}\rangle\, n_{B-L}\,,$$

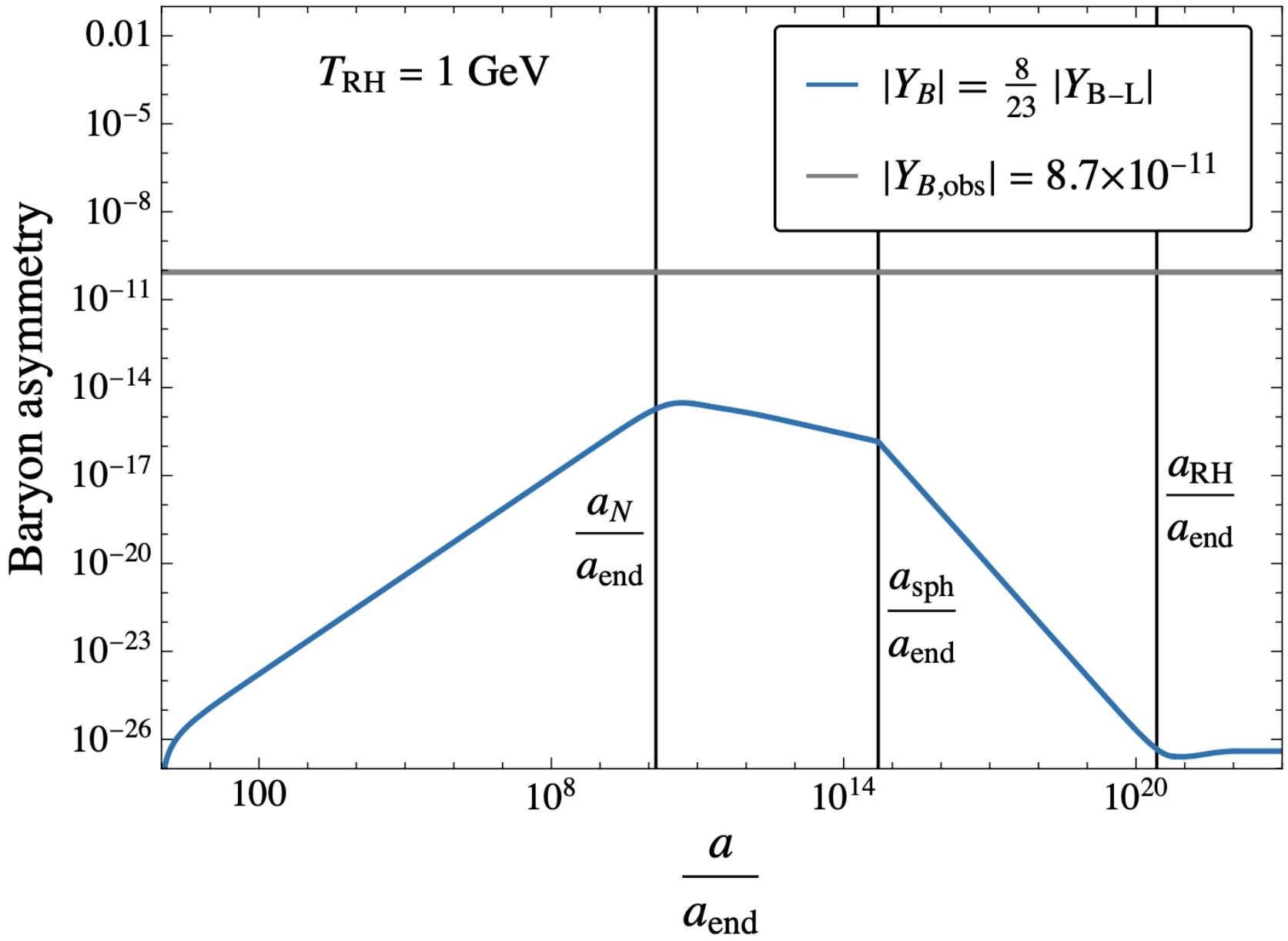
**5) Hubble:** $$3M_P^2H^2 = \rho_\phi + \rho_{\rm R} + \rho_N\,,$$

# Matter-like reheating ($w_\phi = 0$), Low $T_{\rm RH}$




Requiring RHNs to decay prior to sphaleron decoupling ($a_N \ll a_{\rm sph}$) leads to a simple constraint on $y_N$

# Matter-like reheating ($w_\phi = 0$), Low $T_{\rm RH}$



# Challenges for low $T_{\rm RH}$

- Severe dilution of the asymmetry from $T_{\rm sph}$ to $T_{\rm RH}$

$$\left(\frac{a_{\rm sph}}{a_{\rm RH}}\right)^3 \sim \left(\frac{T_{\rm RH}}{T_{\rm sph}}\right)^8$$

- Solution? Enhance $\phi \to NN$ to generate more RHNs and a larger lepton asymmetry
  - $\Rightarrow$ will often reheat too early
  - $\Rightarrow$ or generate a transient RHN-dominated epoch

# Baryon asymmetry for $k = 4$

Consider $V(\phi) \propto \phi^k$ and take $k = 4$.

The inflaton's mass ($m_{\phi,\mathrm{eff}}(a) \sim V''(a)$) is no longer constant, which fundamentally changes leptogenesis.

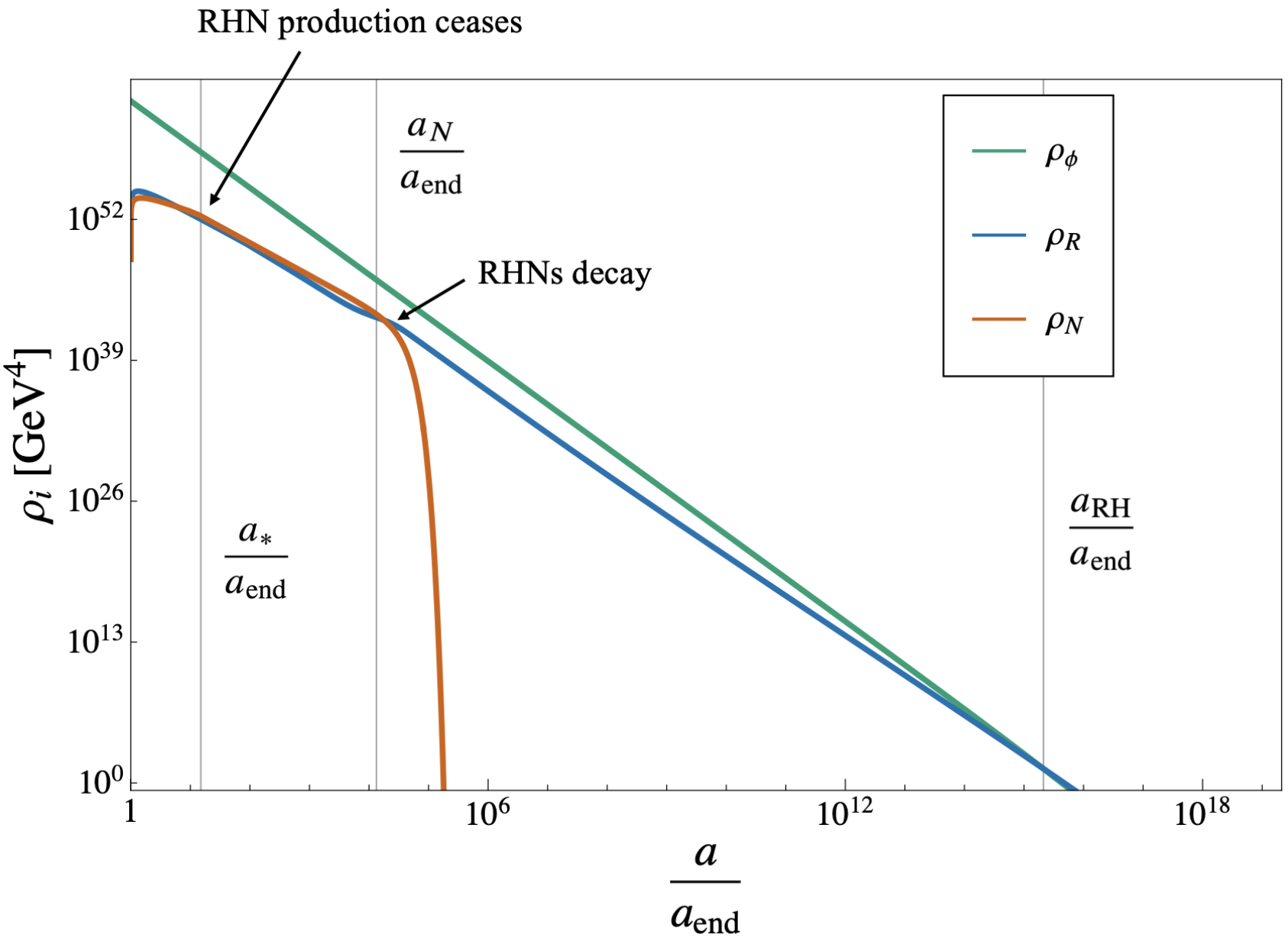
$$m_{\phi,\mathrm{eff}}(a) = m_{\phi,\mathrm{eff}}(a_{\mathrm{end}}) \left(\frac{a_{\mathrm{end}}}{a}\right) \tag{1}$$

$\Rightarrow$ RHN decay becomes kinematically inaccessible shortly after the end of inflation when $m_\phi(a) < 2M_N$, which occurs at

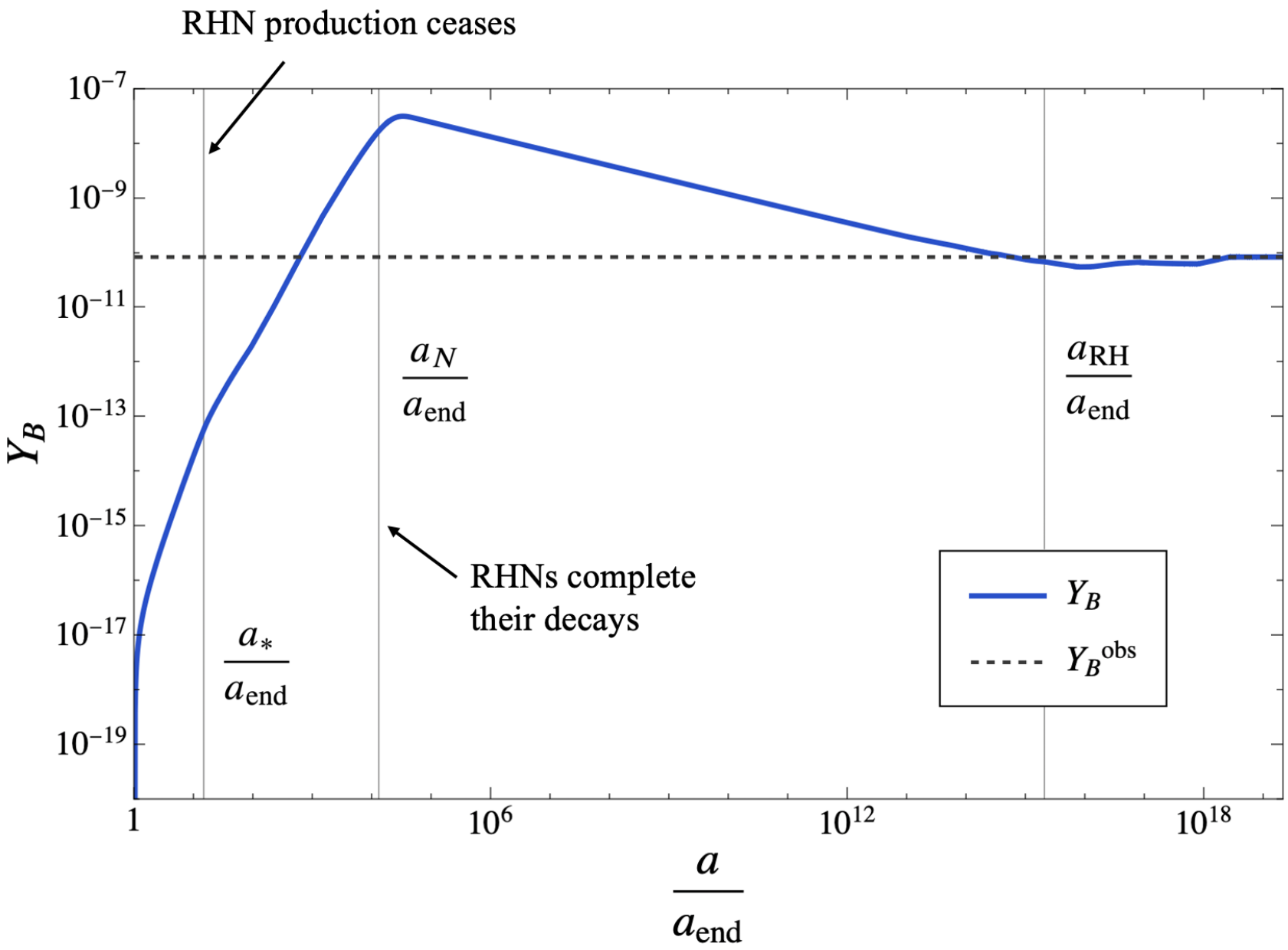
$$\frac{a_*}{a_{\mathrm{end}}} \simeq \frac{m_{\phi,\mathrm{eff}}(a_{\mathrm{end}})}{2M_N}. \tag{2}$$

For $M_N = 10^{12}$ GeV, we find $a_*/a_{\mathrm{end}} \sim 15$.
Thus, ***RHN production ceases almost immediately after the end of inflation, and the final baryon asymmetry can be traced directly to this early population***

# $k = 4$, Energy densities



# $k = 4$, Baryon asymmetry



# Baryon asymmetry ($k = 4$)

$$n_B(a_{\rm RH}) \simeq \underbrace{c_{\rm sph}|\epsilon|}_{\text{Baryon asymmetry per RHN decay}} \underbrace{n_N(a_*)}_{\text{RHN number density at } a_*} \underbrace{\left(\frac{a_*}{a_{\rm RH}}\right)^3}_{\text{Dilution from } a_* \text{ to } a_{RH}}$$

$$n_B(a_{\rm RH}) \simeq c_{\rm sph}|\epsilon| \underbrace{\frac{\rho_\phi(a_*)}{m_\phi(a_*)}}_{\text{Inflaton number density at } a_*} \underbrace{\frac{\Gamma_{\phi NN}}{H(a_*)}}_{\text{Fraction decayed to RHNs}} \left(\frac{a_*}{a_{\rm RH}}\right)^3$$

Recall that $a_*$ corresponds to when $\phi \to NN$ becomes kinematically forbidden

# Comparing $k = 2$ vs. $k = 4$ analytic results

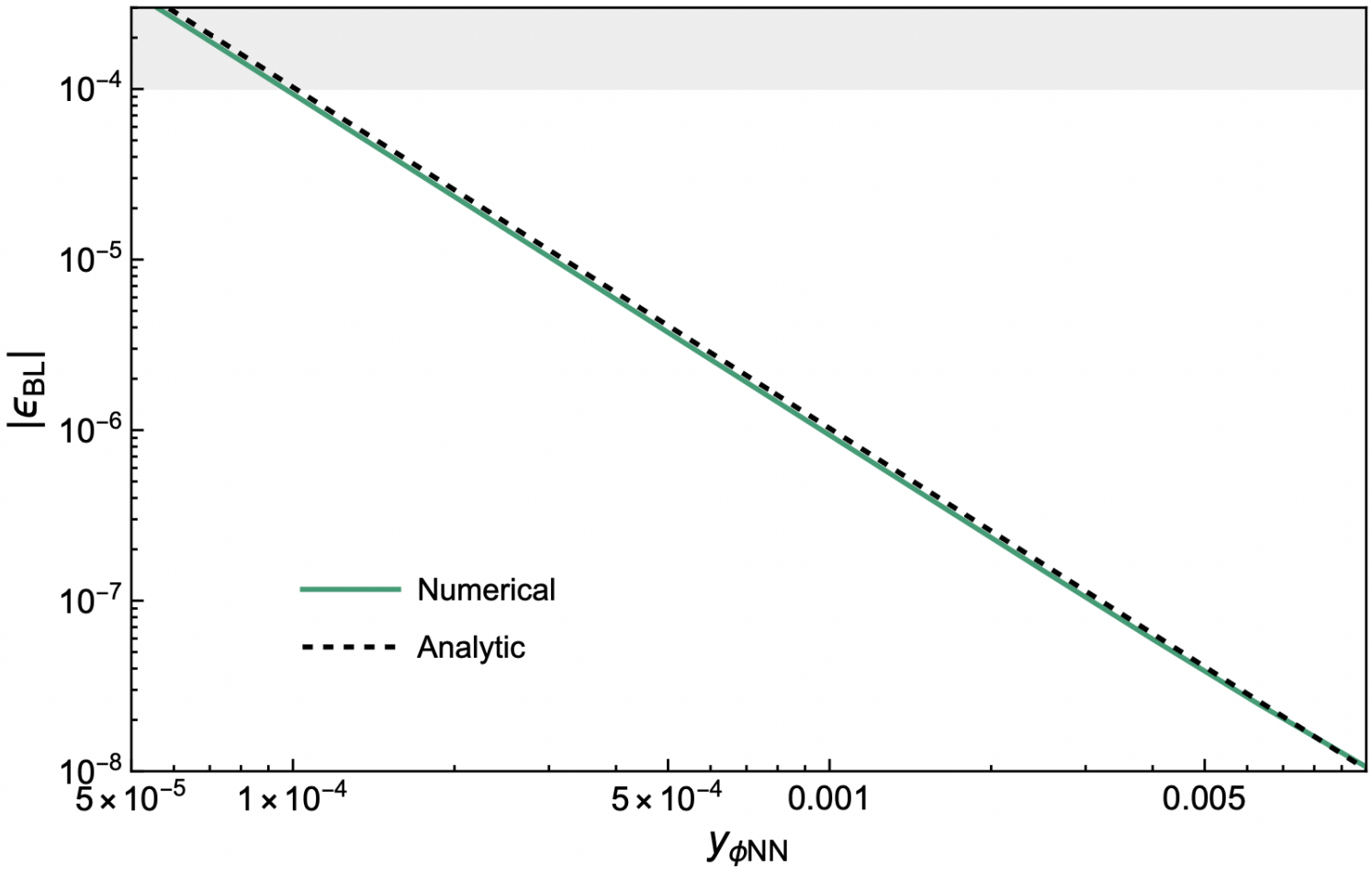
For $k = 2$, cosmological constraints (i.e. pre-mature reheating or transient RHN domination) on $y_{\phi NN}$ yield

$$Y_B \lesssim c_{\rm sph}|\epsilon| \left(\frac{T_{\rm RH}}{T_{\rm sph}}\right)^4 \left(\frac{T_{\rm RH}}{m_\phi}\right)$$
$$Y_B \lesssim 10^{-16} \tag{3}$$

For $k = 4$, analogous constraints are much less restrictive:

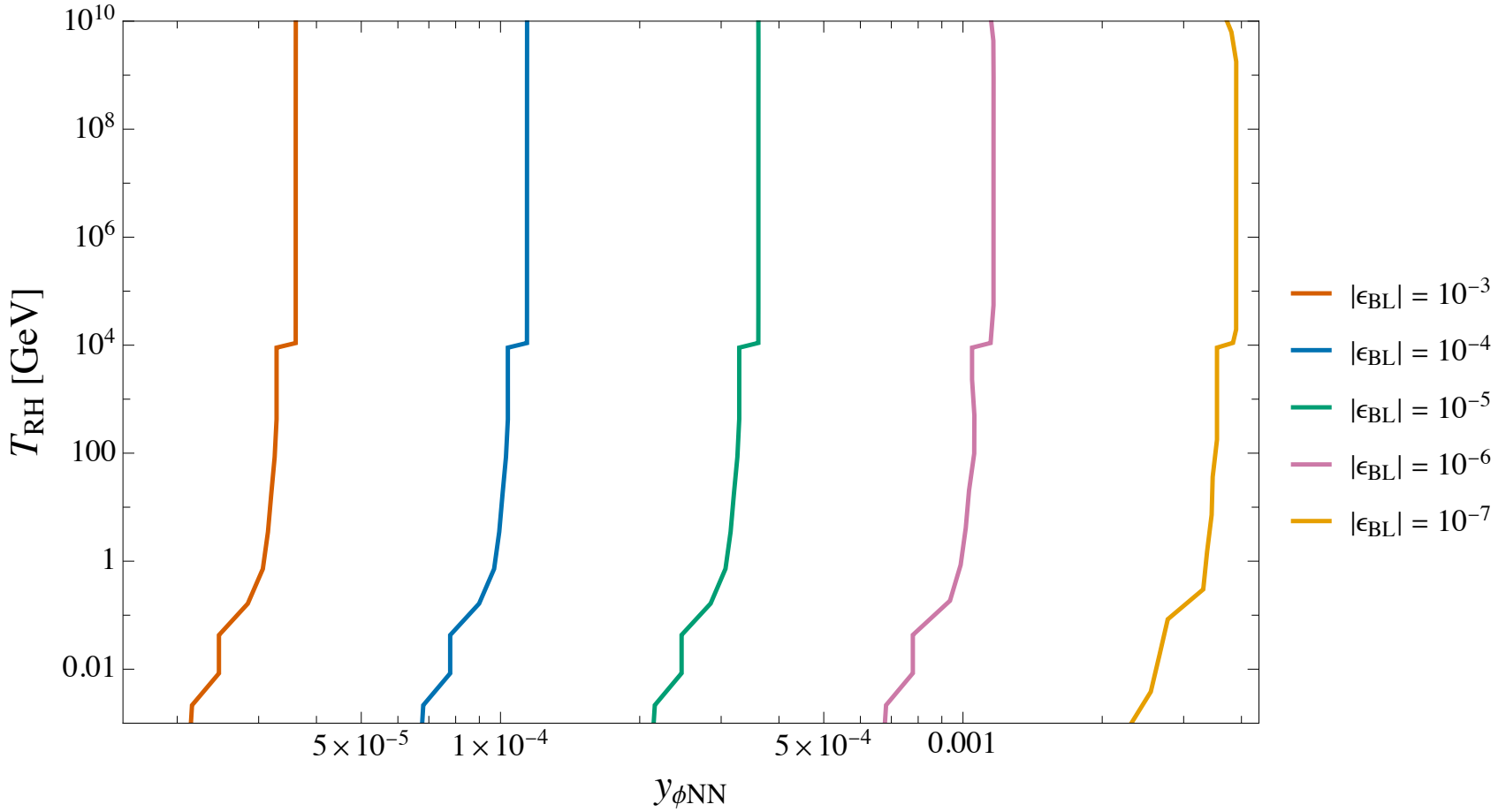
$$Y_B \lesssim c_{\rm sph}|\epsilon| \left(\frac{M_P}{\rho_{\rm end}^{1/4}}\right) \left(\frac{m_\phi}{2M_N}\right)$$
$$Y_B \lesssim 10^{-2} \tag{4}$$

# Parameter space in the $(y_{\phi NN}, |\epsilon|)$ plane




$$|\epsilon| \simeq 10^{-6} \left(\frac{1.1\times10^{-3}}{y_{\phi NN}}\right)^2 \left(\frac{\widehat{m}}{3.0\times10^{13}\,\mathrm{GeV}}\frac{10^{12}\,\mathrm{GeV}}{M_N}\right)^{-1} \left(\frac{4g_*(T_{\mathrm{RH}})}{247}\right)^{1/4}$$

# Parameter space in the $y_{\phi NN}$ vs. $T_{\rm RH}$ plane




$$Y_B(a_{\rm RH}) = \frac{n_B(a_{\rm RH})}{s(a_{\rm RH})} \simeq \frac{c_{\rm sph}|\epsilon| n_N(a_*)\left(\frac{a_*}{a_{\rm RH}}\right)^3}{s(a_{\rm RH})} = \frac{c_{\rm sph}|\epsilon| n_N(a_*)\left(\frac{a_*}{a_{\rm end}}\right)^3 \alpha^{3/4} T_{\rm RH}^3 \rho_{\rm end}^{-3/4}}{\frac{2\pi^2 g_*(a_{\rm RH})}{45} T_{\rm RH}^3}$$

# Conclusions

- Leptogenesis is challenging for $T_{\rm RH} < T_{\rm EW}$ due to
  1. Severe entropy dilution
  2. Cosmological constraints on $y_{\phi NN}$

- Matter-like reheating ($w_\phi = 0$) is incompatible with leptogenesis with standard type I see-saw for $T_{\rm RH} \lesssim 10$ GeV

- $k \geq 4$ solves the problem
  - $m_{\phi,\rm eff}(a)$ quickly drops below the RHN mass, leading to kinematic shutoff of $\phi \to NN$
  - This permits higher $y_{\phi NN}$ values, and thus higher baryon asymmetry for a fixed choice of low $T_{\rm RH}$

- Scalar reheating is also viable

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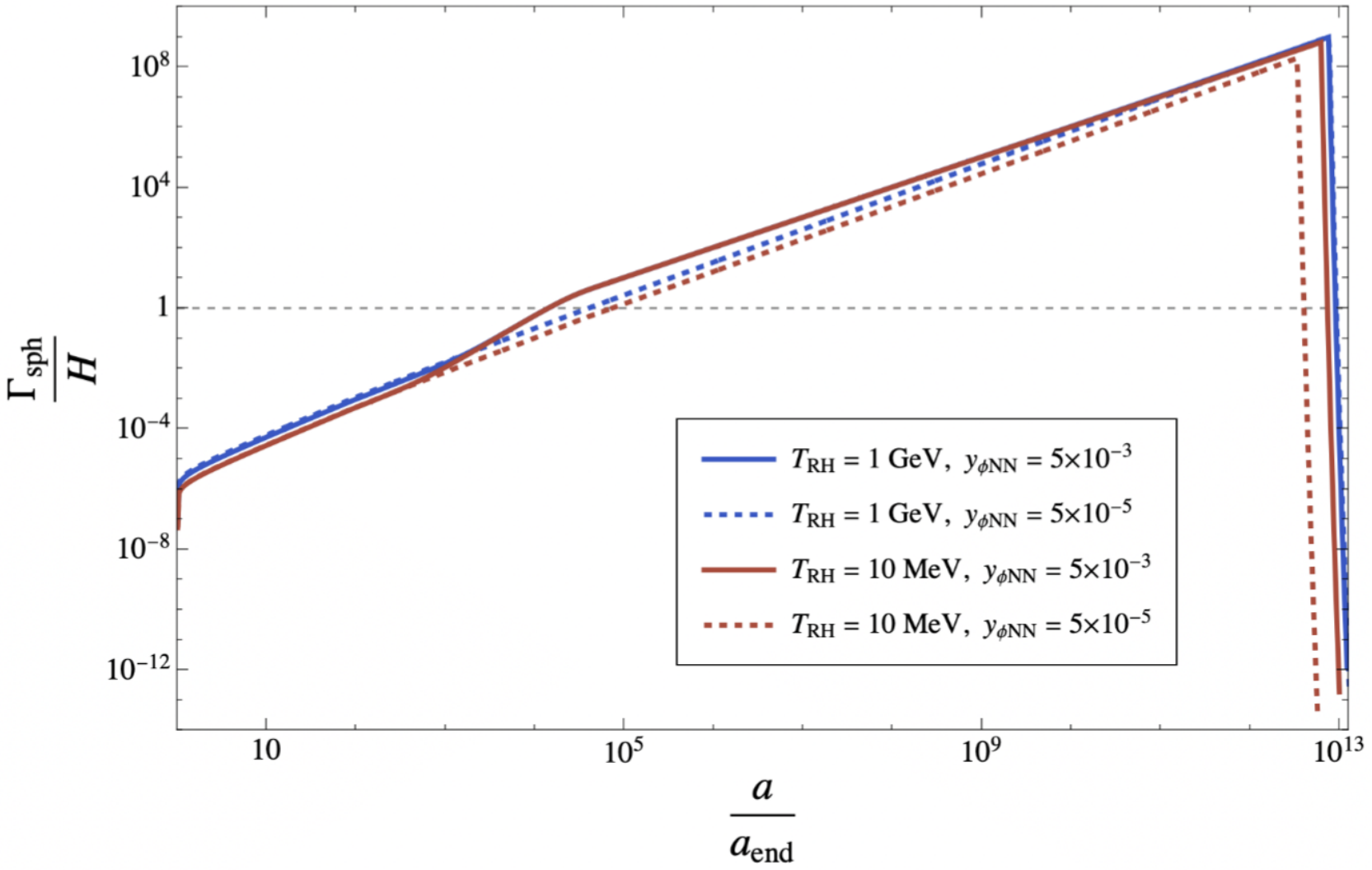


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# Sphaleron Equilibration

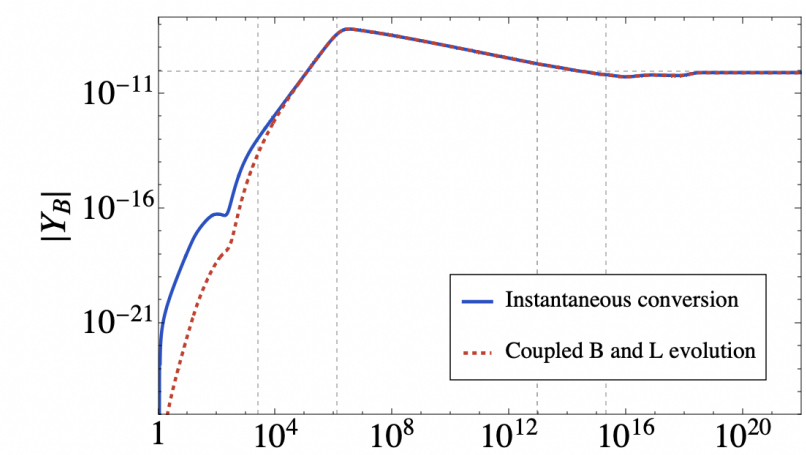


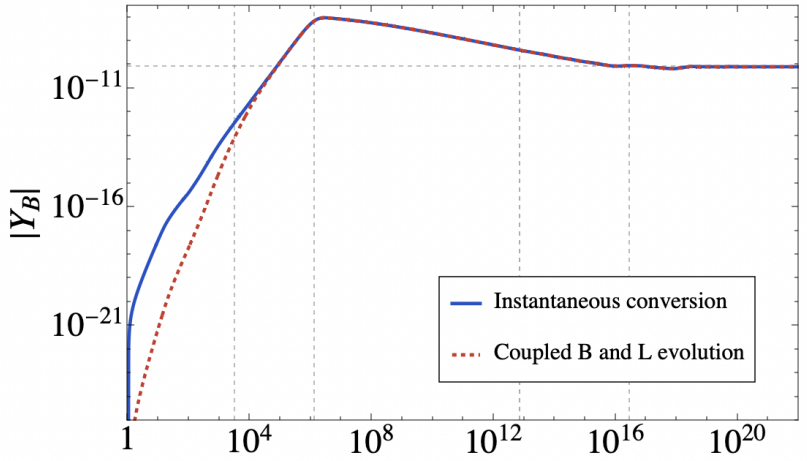
# Boltzmann System, Explicit $B$ and $L$

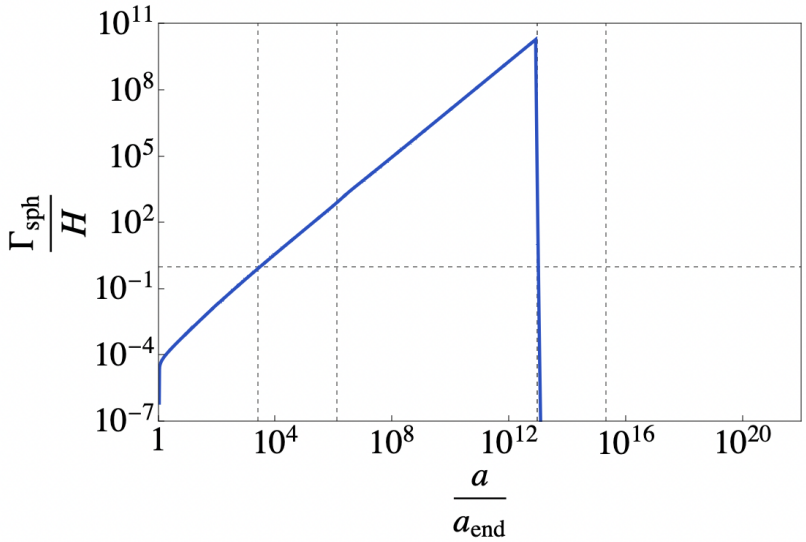
$$aH\rho_\phi' + 3(1+w_\phi)H\rho_\phi = -(\Gamma_{\phi\to ff} + \Gamma_{\phi\to NN})(1+w_\phi)\rho_\phi\,,$$
$$aH\rho_{\rm R}' + 4H\rho_{\rm R} = \Gamma_{\phi\to ff}(1+w_\phi)\rho_\phi + \langle\Gamma_N\rangle\,(\rho_N - \rho_N^{\rm eq})\,,$$
$$aHn_N' + 3Hn_N = (1+w_\phi)\Gamma_{\phi\to NN}\frac{\rho_\phi}{m_\phi} - \langle\Gamma_N\rangle\left(n_N - n_N^{\rm eq}\right)\,,$$
$$aHn_B' + 3Hn_B = \Gamma_B\left[c_{\rm sph}(n_B - n_L) - n_B\right]\,,$$
$$aHn_L' + 3Hn_L = \Gamma_B\left[c_{\rm sph}(n_B - n_L) - n_B\right] + \langle\Gamma_N\rangle\left[\epsilon(n_N - n_N^{\rm eq})\right] + \frac{1}{2}\langle\Gamma_{\rm ID}\rangle\,(n_B - n_L)\,,$$
$$3M_P^2H^2 = \rho_\phi + \rho_{\rm R} + \rho_N\,,$$

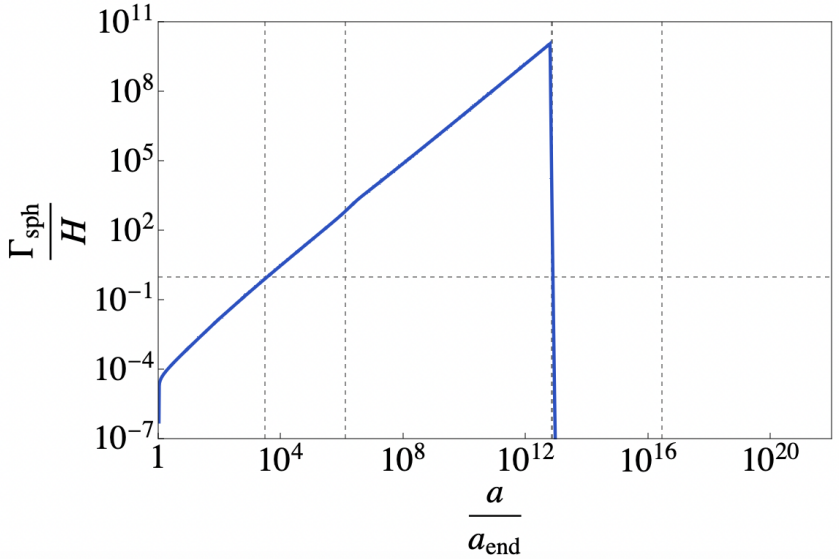
$$\Gamma_B \equiv \kappa R_{\rm sph}(T)/T^3 \qquad R_{\rm sph}(T) = T^4\begin{cases}\exp[0.83\left(\frac{T}{1\text{ GeV}}\right) - 147.7], & \text{for } T < T_c\\ 18\alpha_W^5, & \text{for } T > T_c\end{cases}$$

# Evolving $(n_B, n_L)$ vs. $n_{B-L}$ are equivalent



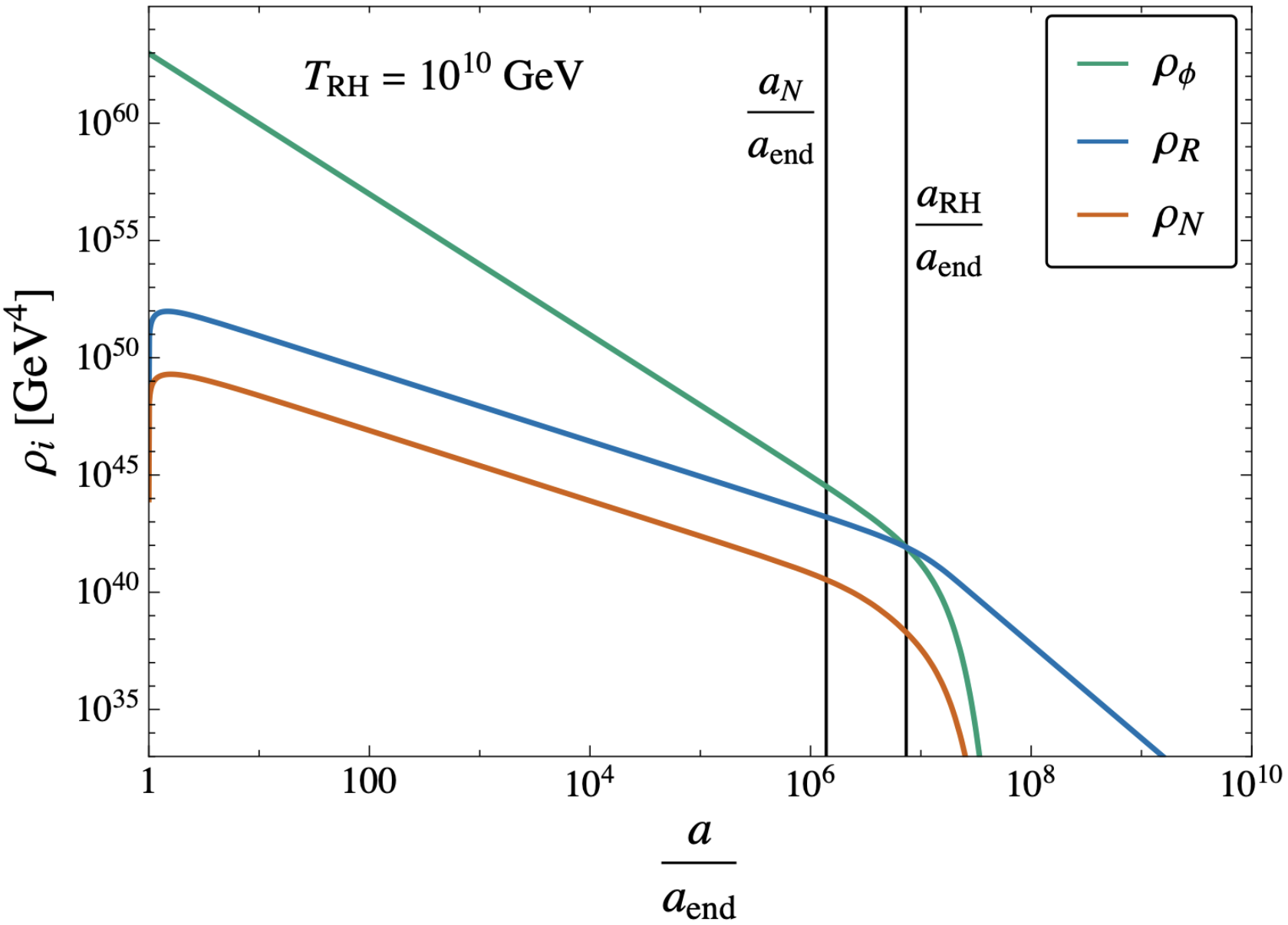



# Davidson-Ibarra Bound

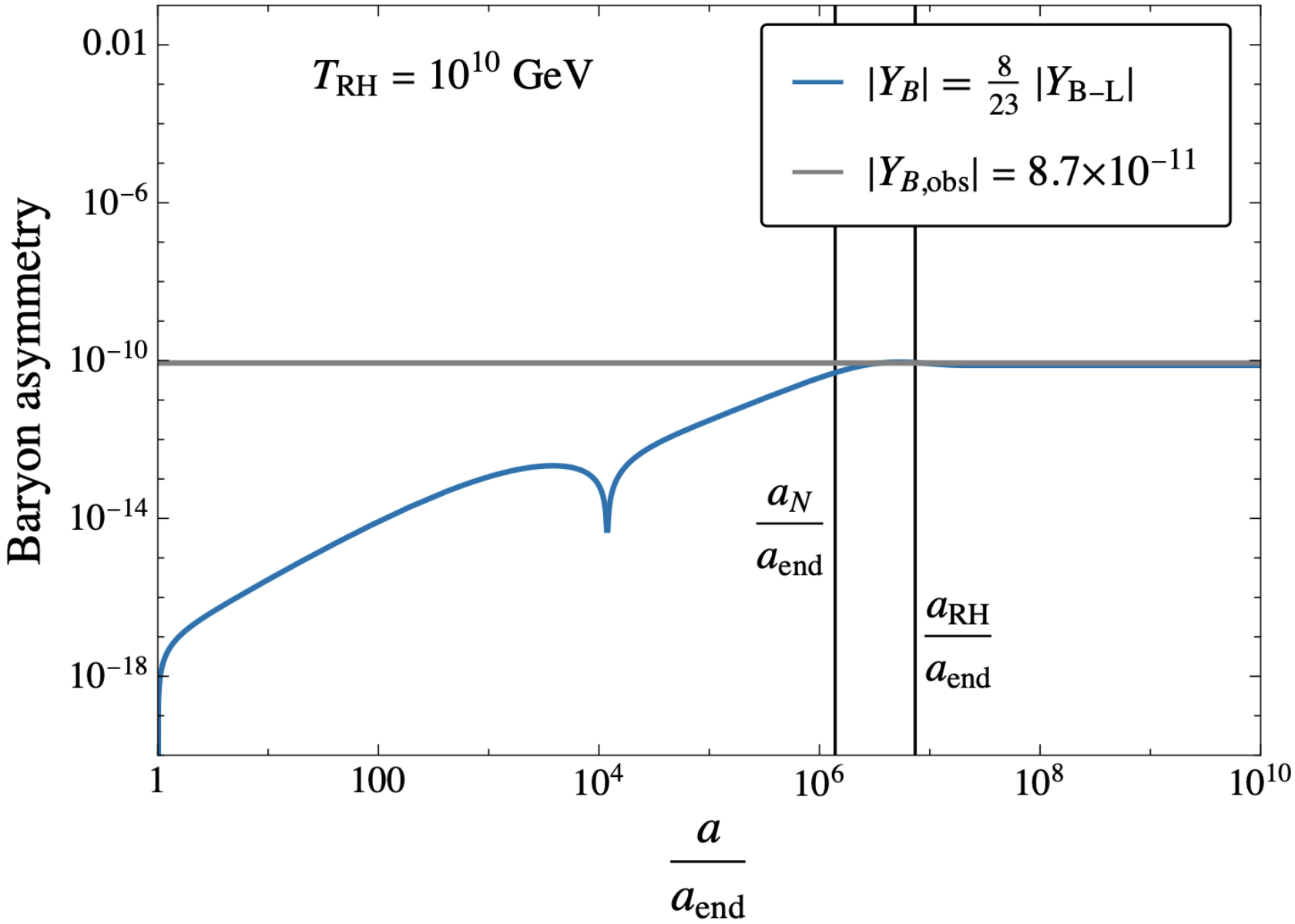
$$
\begin{aligned}
|\epsilon| &\leq \frac{3}{16\pi} \frac{M_1 (m_3 - m_1)}{v^2} \\
&\leq 9.9 \times 10^{-5}
\end{aligned}
$$

for $m_3 - m_1 = 0.05$ eV, $v = 174$ GeV, and $M_N = 10^{12}$ GeV.

# Matter-like reheating ($w_\phi = 0$), High $T_{\rm RH}$



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# Baryon Asymmetry (analytic) for Matter-like Reheating

Planck 2018 found: $|Y_B^{\rm obs}| = 8.7 \times 10^{-11}$

$$Y_B \approx c_{\rm sph} Y_{B-L}, \qquad c_{\rm sph} = \frac{8N_f + 4N_H}{22N_f + 13N_H} = \begin{cases} \frac{28}{79}, & \text{SM} \\ \frac{8}{23}, & \text{MSSM} \end{cases}$$

If $T_{\rm RH} < T_{\rm sph}$, then $Y_B(a_{\rm RH}) \approx Y_B(a_0)$, so we simply need to compute $Y_B(a_{\rm RH})$.

$$Y_B(a_{\rm RH}) = \frac{n_B(a_{\rm RH})}{s(a_{\rm RH})} \propto \frac{n_{B-L}(a_{\rm sph})}{T_{\rm RH}^3} \left(\frac{a_{\rm sph}}{a_{\rm RH}}\right)^3 . \tag{5}$$

# Baryon Asymmetry for Matter-like Reheating

$$n_B(a_{\rm RH}) \simeq c_{\rm sph}|\epsilon| n_N^{\rm prod}(a_{\rm sph}) \left(\frac{a_{\rm sph}}{a_{\rm RH}}\right)^3$$

$$\simeq \underbrace{c_{\rm sph}|\epsilon|}_{\text{Baryon asymmetry per RHN decay}} \underbrace{\frac{\rho_\phi(a_{\rm sph})}{m_\phi}}_{\text{Inflaton number density at } a_{sph}} \underbrace{\frac{\Gamma_{\phi\to NN}}{H(a_{\rm sph})}}_{\text{Fraction decayed to RHNs}} \underbrace{\left(\frac{a_{\rm sph}}{a_{\rm RH}}\right)^3}_{\text{Dilution from } a_{sph} \text{ to } a_{RH}}$$

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$$\begin{aligned} Y_B(a_{\rm RH}) &= \frac{n_B(a_{\rm RH})}{s(a_{\rm RH})} \\ &\simeq \frac{15 y_{\phi NN}^2}{4\sqrt{10}\pi^2} c_{\rm sph} |\epsilon| \frac{M_P T_{\rm RH}^3}{T_{\rm sph}^4} \frac{\sqrt{g_*(T_{\rm RH})}}{g_*(T_{\rm sph})}. \end{aligned} \tag{6}$$

Doesn't look too bad right? $M_P$ in the numerator should make it easy to get $Y_B \sim 8.7 \times 10^{-11}$. Wrong.

# Boltzmann System

**1) Inflaton:** $$aH\rho_\phi' + 3(1+w_\phi)H\rho_\phi = -(\Gamma_{\phi\to ff} + \Gamma_{\phi\to NN})(1+w_\phi)\rho_\phi\,,$$

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**3) RHN:** $$aHn_N' + 3Hn_N = (1+w_\phi)\Gamma_{\phi\to NN}\frac{\rho_\phi}{m_\phi} - \langle\Gamma_N\rangle\left(n_N - n_N^{\rm eq}\right)\,,$$

**4) *B-L*:** $$aHn_{B-L}' + 3Hn_{B-L} = -\langle\Gamma_N\rangle\left[\epsilon(n_N - n_N^{\rm eq})\right] - \frac{1}{2}\langle\Gamma_{\rm ID}\rangle\, n_{B-L}\,,$$

**5) Hubble:** $$3M_P^2H^2 = \rho_\phi + \rho_{\rm R} + \rho_N\,,$$

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# Baryon Asymmetry (analytic) for Matter-like Reheating

For reheating via $\phi \to \bar{f} f$, we require $y_{\phi NN} \lesssim y_{\phi ff}$. This implies

$$y_{\phi NN} \lesssim \frac{4\pi^2}{3}\sqrt{\frac{5g_*(T_{\rm RH})}{2}}\left(\frac{T_{\rm RH}^2}{m_\phi M_P}\right) \tag{7}$$

From the previous slide, this gives

$$Y_B(a_{\rm RH}) \lesssim \frac{5}{2}\left(\frac{g_*(T_{\rm RH})}{g_*(T_{\rm sph})}\right) c_{\rm sph}|\epsilon|\frac{T_{\rm RH}^5}{T_{\rm sph}^4 m_\phi} \tag{8}$$

Even taking $T_{\rm RH} = T_{\rm sph}$, the maximum allowed baryon asymmetry is approximately $Y_B \sim 10^{-16}$.

# Inflation → reheating

We consider T attractors as a specific example, but our results don't depend on this model.

$$V(\phi) = \lambda M_P^4 \left| \sqrt{6} \tanh\left( \frac{\phi}{\sqrt{6} M_P} \right) \right|^k$$

which when expanded about the minimum gives

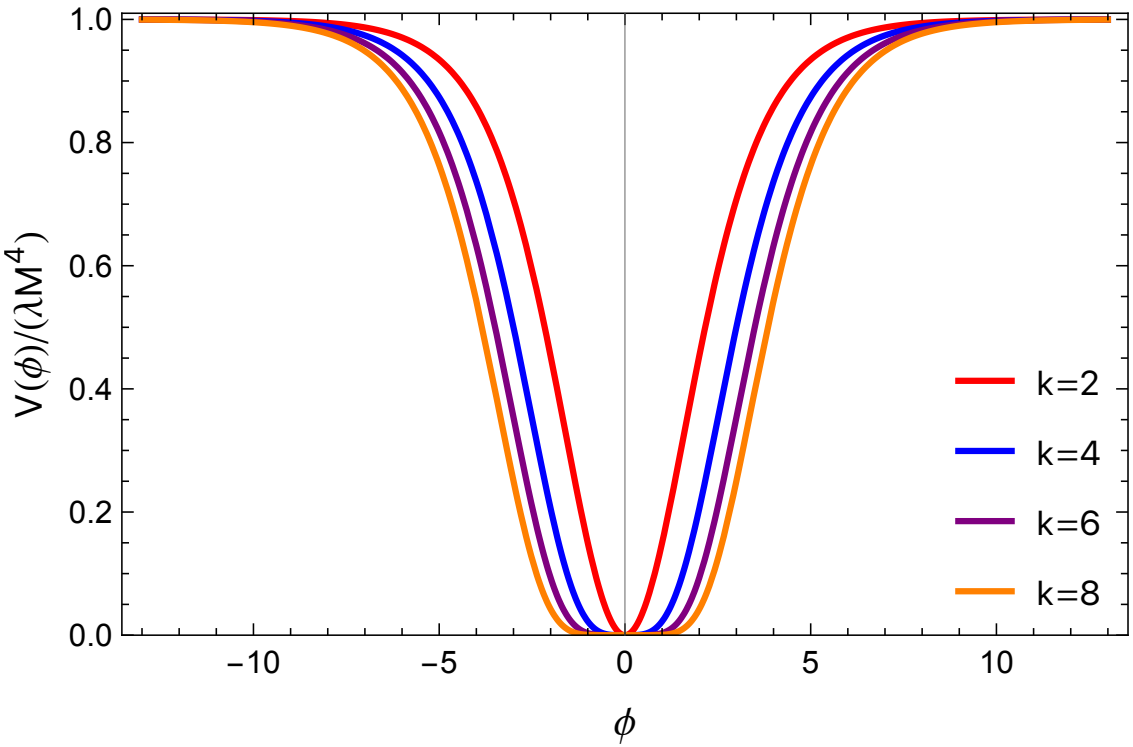
$$V(\phi) = \lambda \frac{|\phi|^k}{M_P^{k-4}}, \qquad \phi \ll M_P$$

We can find a time-averaged equation of state for the inflaton oscillations

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi), \quad p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$w = \frac{\langle p_\phi \rangle}{\langle \rho_\phi \rangle} = \frac{k-2}{k+2} \Rightarrow \begin{cases} k = 2, & w = 0 \text{ (matter)} \\ k = 4, & w = 1/3 \text{ (radiation)} \\ k = 6, & w = 1/2 \end{cases}$$

# T-attractor potentials



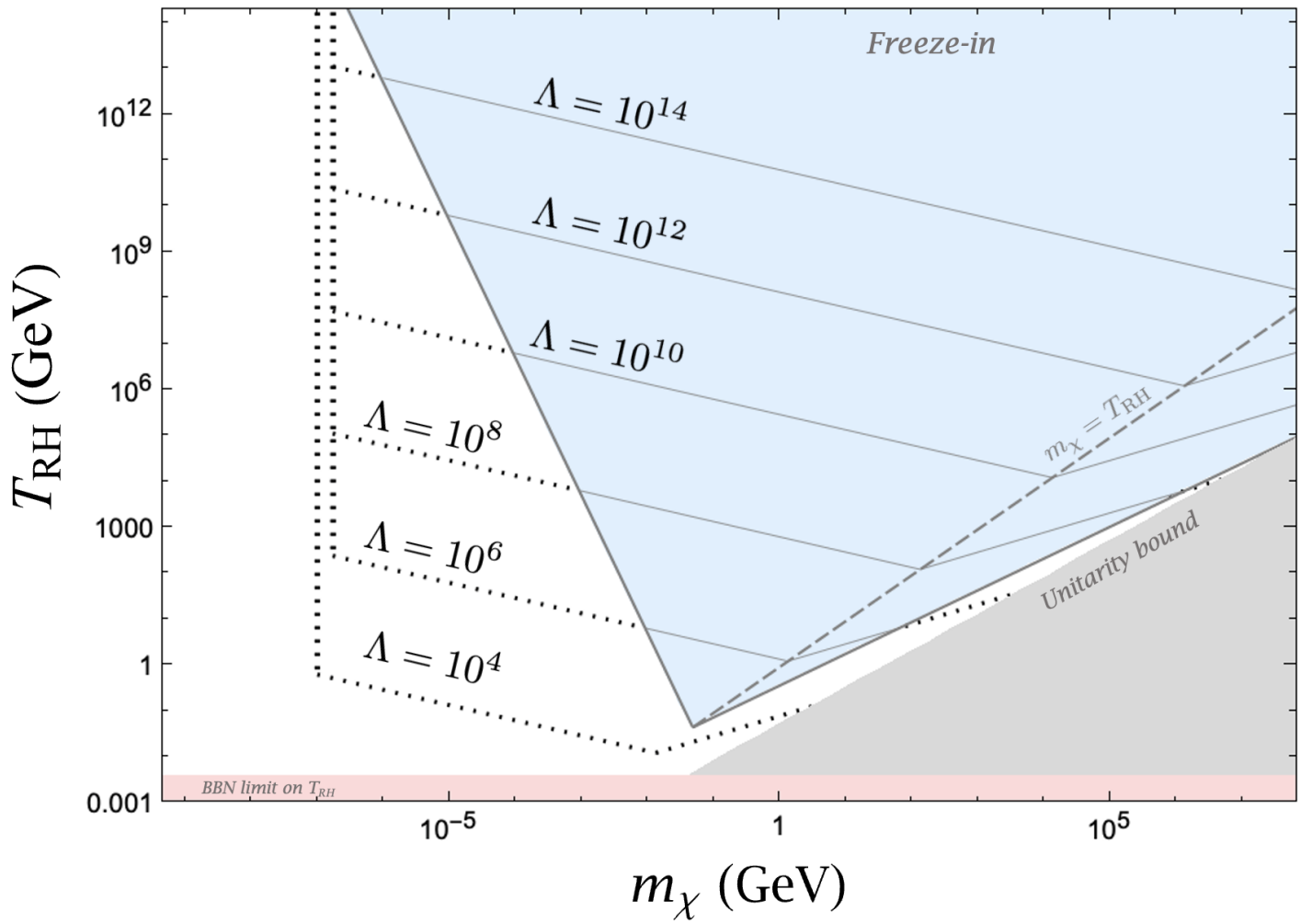

$$V(\phi) = \lambda M_P^4 \left| \sqrt{6} \tanh\left(\frac{\phi}{\sqrt{6} M_P}\right) \right|^k, \quad k \neq 2 \text{ yields anharmonic oscillations}$$

T-models generally predict $n_s$ and $r$ in close agreement with CMB measurements. Different $k$ generate different reheating dynamics.

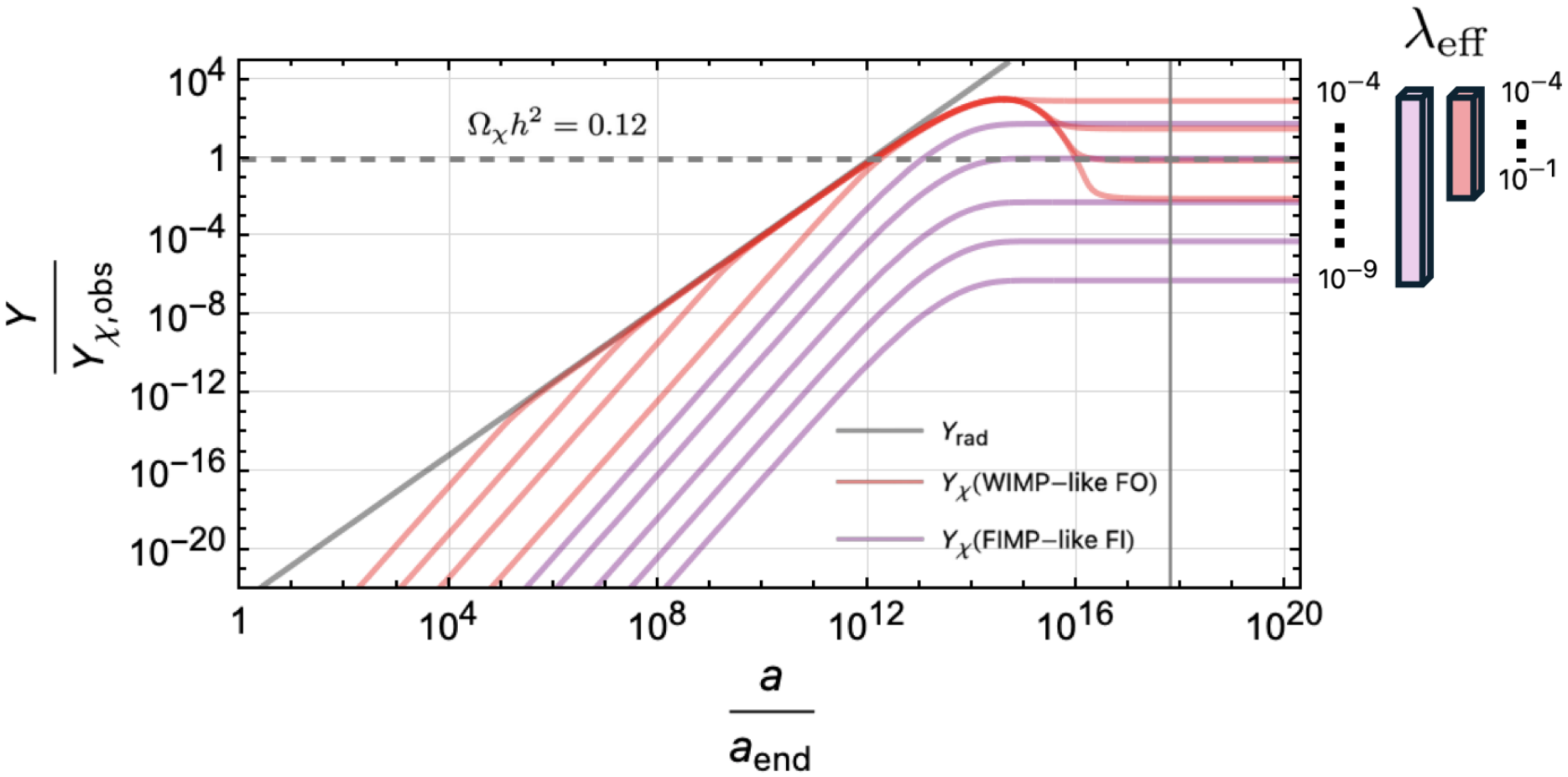
# Dark matter production during non-instantaneous reheating

- Since $T_{\max} > T_{\rm RH}$, we can have $m_\chi > T_{\rm RH}$
- Hubble will depend on equation of state of inflaton oscillations
- BSM interactions can be sensitive to various UV or IR scales (e.g. $T_{\max}, T_{\rm RH}, m_\chi, M_{Z'}$)
- Dilution of DM number density $n_\chi$ relative to $n_R$ due to entropy injection
- DM from the inflaton decays or gravitational scattering
- Typical WIMP and FIMP couplings are altered
- UFO becomes viable

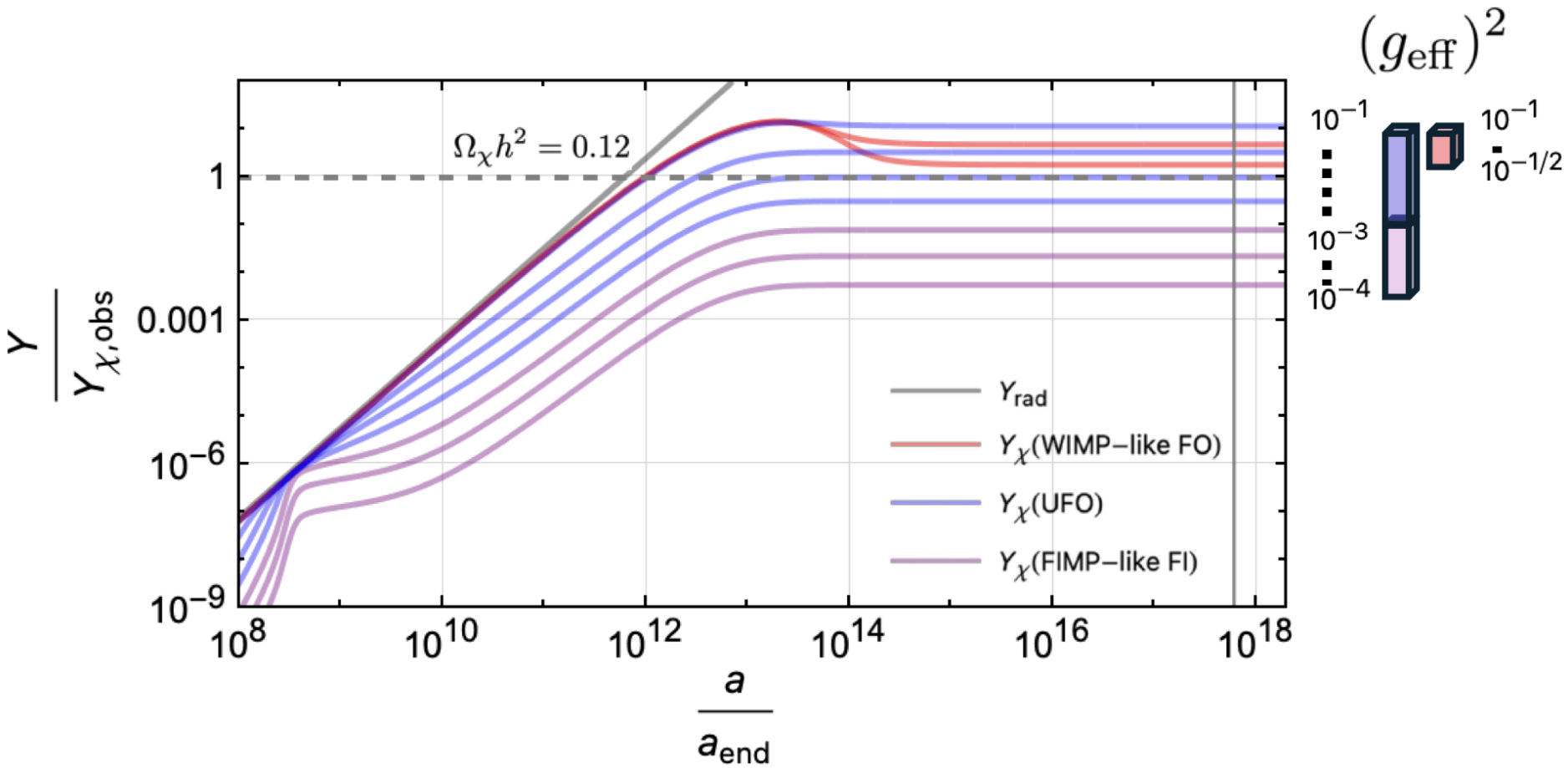
# $\Omega_\chi h^2 = 0.12$, UFO parameter space ($k = 2, n = 2$)



# Two distinct WIMP-to-FIMP Transitions



# Two distinct WIMP-to-FIMP Transitions



# Two distinct WIMP-to-FIMP Transitions

