Quintessential Kination and Leptogenesis

Stefano Scopel

Korea Institute of Advanced Study, Seoul

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Introduction

• Non-zero neutrino masses and mixing angles provide a convincing evidence of physics beyond the Standard Model
• **See-saw mechanism**: a paradigm to understand neutrino masses
• The see-saw scenario involves a high-energy scale where lepton number $L$ is not conserved $\rightarrow$ **leptogenesis through out-of-equilibrium** $\mathcal{L}$ decay of heavy particle $X$
• sphaleron conversion to Baryon number
• **if $X$ is not so heavy**: direct measurement of neutrino parameters at accelerators?
Different types of see-saw

Dimension-5 effective operator: \( \frac{\mathcal{K}}{M} LLHH \)
with \( M \) typical scale of lepton number violation.

- **Type I**: 3 singlet heavy fermions \( N \):

  \[
  W = Y_{N}^{ij} N_i L_j H_2 + \frac{1}{2} M_N^{ij} N_i N_j
  \]

  \[
  \frac{\mathcal{K}}{M} = \frac{1}{M_L} Y_{\nu}^{ij} = Y_N^{Tik} M_N^{-1kl} Y_N^{lj}
  \]

  \[
  m^{ij} = \frac{\nu^2}{M_L} Y_{\nu}^{ij} = \nu^2 Y_N^{Tik} M_N^{-1kl} Y_N^{lj}
  \]

- **Type II**: Higgs heavy triplet(s):

  - non-SUSY
  - SUSY

  **MINIMAL CONTENT:**
  - 2 scalar triplets
  - 4 (triplet+striplet)
  - 2 (triplet+striplet)
  - or 1 triplet+1 \( v_R \)

  Type I + Type II...
Thermal leptogenesis (Fukugita and Yanagida, PLB174, 45) requires Sakharov conditions:

- □ $\mathcal{C}$
- □ $\mathcal{P}$ and $\mathcal{CP}$
- □ out of-equilibrium decay

→ neutrino mass op.
→ phases

$K(T=M) \equiv \frac{\Gamma}{H(M)}$

$sphaleron$ interactions before electroweak phase transition
convert the lepton asymmetry into a baryon asymmetry
The case of quintessence – the possibility of kination

- $\Omega_{\text{Dark Energy}} \sim 0.7$
- Dark Energy can be explained by quintessence (slowly evolving scalar field) (Caldwell et al., PRL80,1582)
- quintessence has “tracking solutions” which explain why today: $\Omega_{\text{Dark Energy}} \sim \Omega_{\text{background}} = \Omega_{\text{radiation}} + \Omega_{\text{matter}}$ although they evolve very differently with time (Stenhardt et al., PRD59,123504)
- kination $\equiv$ epoch during which the energy density of the Universe is dominated by the kinetic energy of the quintessence field
- during kination the Universe expands faster than during radiation domination
- a thermal Cold Dark Matter particle decouples earlier and its relic density can be enhanced (Salati, PLB571,121)
- our goal: to study how kination dominance can modify the predictions of thermal leptogenesis in type-I see-saw
Cosmological behaviour of kination

the energy-momentum tensor of quintessence:

\[ T_{\mu\nu} = \partial_{\mu} \phi \frac{\partial \mathcal{L}}{\partial \partial_{\nu} \phi} - g_{\mu\nu} \mathcal{L} \]

equation of state:

\[ w \equiv \frac{p}{\rho} = \frac{\dot{\phi}^2}{2} - V(\phi) \]

\[ \frac{\dot{\phi}^2}{2} + V(\phi) \]

if:

\[ \frac{\dot{\phi}^2}{2} \gg V(\phi) \]

\[ w = 1 \]
The energy density of the Universe scales as $\rho \propto a^{-3(1+w)}$, so:

\[
\begin{align*}
\rho_{\text{rad}} & \propto a^{-4} \quad \text{(radiation)} \\
\rho_{\text{rad}} & \propto a^{-3} \quad \text{(matter)} \\
\rho_{\text{kin}} & \propto a^{-6} \quad \text{(kination)}
\end{align*}
\]

we know that radiation must dominate at the time of nucleosynthesis, however we have no observational constraint at earlier times. So setting $T_r$ as the kination-radiation equality temperature for which:

\[
\rho_{\text{kin}}(T_r) = \rho_{\text{rad}}(T_r)
\]

$T_r$ is a free parameter, with the only bound:

\[
T_r \gtrsim 1 \text{ MeV}
\]
Fix boundary conditions at $T_r$:

$$\ln(\rho)$$

$$a^{-6}$$

$$a^{-4}$$

$$\ln(a)$$

$$\rho(T) = \rho_{rad}(T) + \rho_{rad}(T_r) \left( \frac{a_r}{a} \right)^6$$

$$\rho_{rad}(T) = \frac{\pi^2}{30} g_* T^4$$

$$a_r \equiv a(T_r)$$

$$g_{*r} = \text{dof} \# \text{ at } T_r$$

+ isoentropic expansion ($a^3 s=\text{constant}$):

$$s = 2 \frac{\pi^2}{45} g_* T^3$$

$$\left( \frac{a_r}{a} \right)^3 = \frac{g_*}{g_{*r}} \left( \frac{T}{T_r} \right)^3$$
\[ \rho(T) = \frac{\pi^2}{30} g_* T^4 \left( 1 + \frac{g_*}{g_{*r}} \left( \frac{T}{T_r} \right)^2 \right) \]

\[ H(T) = 1.66 \sqrt{g_* \frac{T^2}{m_{pl}}} \sqrt{1 + \frac{g_*}{g_{*r}} \left( \frac{T}{T_r} \right)^2} \]
A useful parametrization:

\[ H(z) = \sqrt{\frac{z^2 + z_r^2}{1 + z_r^2}} \frac{H_1}{z^3} \]

\[
\begin{align*}
\text{(kination)} & \quad z_r \gg 1 \rightarrow H(z) = \frac{H_1}{z^3} \\
\text{(radiation)} & \quad z_r \ll 1 \rightarrow H(z) = \frac{H_1}{z^2}
\end{align*}
\]

\[ z \equiv \frac{M}{T} \]

\[ H_1 \equiv H(z = 1) \]

\[ z_r \equiv \sqrt{\frac{g_*}{g^* r}} \frac{M}{T_r} \]

M=heavy neutrino mass
Let’s plug some numbers:

- \( T_r = 1 \text{ MeV} \)
- \( g_{*r} = 10.75 \)
- \( g_*(T) = 228.75 \) (SUSY)

**extreme situation** (\( T_r \sim 1 \text{ MeV} \)):
- ✓ low mass \( M \) (\( z_r < 4.5 \times 10^8 \))
- ✓ sufficient window for sphaleron
- ✓ standard picture recovered when \( T_r \gg M \) (\( z_r \to 0 \))

\[
H(T) \simeq 0.95 \times 10^4 \text{ GeV} \left( \frac{3.28 \text{ MeV}}{\sqrt{g_{*r} T_r}} \right) \left( \frac{T}{10^6 \text{ GeV}} \right)^3
\]

in order to allow thermalization after reheating:

\[
\Gamma_{\text{gauge}} \sim \alpha^2 T > H \rightarrow M \simeq T < 3.4 \times 10^5 \left( \frac{\sqrt{g_{*r} T_r}}{3.28 \text{ MeV}} \right)^{1/2} \text{ GeV}
\]

in order to allow conversion of lepton asymmetry to baryon asymmetry, sphaleron interactions must be in thermal equilibrium before the electroweak phase transition:

\[
\Gamma_{\text{sphaleron}} \sim \alpha^4 T > H \rightarrow T < 10^4 \left( \frac{\sqrt{g_{*r} T_r}}{3.28 \text{ MeV}} \right)^{1/2} \text{ GeV}
\]

(worst case scenario, still enough)
We wish to discuss leptogenesis in the Minimal Supersymmetric extension of the Standard Model supplemented by right-handed neutrino (RHN) spermparticles N, i.e.:

\[ \mathcal{W} = \mathcal{W}_{MSSM} + \frac{1}{2} N^c M N^c + y H_2 L N^c \]

\( y = \) Yukawa coupling

(similar results in non-susy case)

RHN decay rate:

\[ \Gamma_d = \frac{|y|^2 M}{4\pi} \]

Effective neutrino mass scale:

\[ \tilde{m} \equiv |y|^2 \langle H_2 \rangle^2 / M \]

Wash-out parameter:

\[ K \equiv \frac{\Gamma_d}{H(T = M)} = \frac{63.78}{\sqrt{1 + \frac{z_r^2}{0.05 \text{ eV}}}} \]

\( K >> 1 \) (\( z_r << 1 \), radiation)

\( K << 1 \) (\( z_r >> 1 \), kination)

wide range of possibilities depending on \( z_r \), from strong to super-weak wash-out at fixed neutrino mass scale
In particular, when kination dominates:

$$K = 1.38 \times 10^{-6} \left( \frac{10^4 \text{ GeV}}{M} \right) \left( \frac{\tilde{m}}{0.05 \text{ eV}} \right) \left( \frac{\sqrt{g_* r} T_r}{3.28 \text{ MeV}} \right)$$

typically $K$ is very small, however can be larger depending on $T_r$ (but kination dominance implies an upper bound $K \sim 10$, see later)
Boltzmann equations

\( N = \text{heavy majorana neutrinos}, \ \tilde{N} = \text{sneutrinos}, \ l = \text{leptons}, \ \tilde{l} = \text{sleptons} \)

\[
N(z) \equiv \frac{Y_N(z)}{Y_N^{\text{eq}}(z = 0)}, \quad \tilde{N}(z) \equiv \frac{Y_{\tilde{N}}(z)}{Y_{\tilde{N}}^{\text{eq}}(z = 0)}, \quad \tilde{N}^\dagger(z) \equiv \frac{Y_{\tilde{N}^\dagger}(z)}{Y_{\tilde{N}^\dagger}^{\text{eq}}(z = 0)}, \quad \tilde{N}_\pm \equiv \tilde{N}(z) \pm \tilde{N}^\dagger(z), \quad L(z) \equiv \frac{Y_l(z) - Y_{\tilde{l}}(z)}{Y_l^{\text{eq}}(z = 0)}, \quad \tilde{L}(z) \equiv \frac{Y_{\tilde{l}}(z) - Y_{\tilde{l}^\dagger}(z)}{Y_{\tilde{l}}^{\text{eq}}(z = 0)}
\]

\( Y_i \left( z = \frac{M}{T} \right) \equiv \frac{n_i}{s(z)} \) (\( n_i = \text{number densities}, \ s = \text{entropy density} \))

fast gaugino-mediated interactions imply:

\[
\begin{cases}
\tilde{N}_- = 0 \\
L = \tilde{L}
\end{cases}
\]

Higgs & higgsinos same as leptons & sleptons
other degrees of freedom assumed in thermal equilibrium
Setting:

\[ \hat{N}(z) \equiv N(z) + \hat{N}_+ \]
\[ \hat{L}(z) \equiv L(z) + \hat{L}(z) \]

one gets the simplified set of BE:

\[ \frac{d\hat{N}}{dz}(z) = -K \sqrt{\frac{1 + z^2_r}{z^2 + z^2_r}} z^2 (\hat{N} - \hat{N}_{eq}) \left[ \gamma_d(z) + 2 \gamma_s(z) + \gamma_t(z) \right] \]
\[ \frac{d\hat{L}}{dz}(z) = K \sqrt{\frac{1 + z^2_r}{z^2 + z^2_r}} z^2 \left[ \gamma_d(z) \epsilon(\hat{N} - \hat{N}_{eq}) - \frac{\gamma_d(z) \hat{N}_{eq} \hat{L}}{4} - \frac{1}{2} \gamma_s(z) \hat{L} \hat{N} - \gamma_t(z) \hat{L} \hat{N}_{eq} \right] \]

CP-violating parameter:

\[ \epsilon \equiv \frac{\Gamma(N \rightarrow l + h_2) - \Gamma(N \rightarrow \bar{l}h^\dagger_2)}{\Gamma(N \rightarrow l + h_2) + \Gamma(N \rightarrow \bar{l}h^\dagger_2)} = \frac{\Gamma(N \rightarrow \bar{l} + \tilde{h}) - \Gamma(N \rightarrow \bar{l}\tilde{h})}{\Gamma(N \rightarrow \bar{l} + \tilde{h}) + \Gamma(N \rightarrow \bar{l}\tilde{h})} \]

\[ = \frac{\Gamma(\tilde{N} \rightarrow l + \tilde{h}) - \Gamma(\tilde{N}^\dagger \rightarrow \tilde{l}\tilde{h})}{\Gamma(\tilde{N} \rightarrow l + \tilde{h}) + \Gamma(\tilde{N}^\dagger \rightarrow \tilde{l}\tilde{h})} = \frac{\Gamma(\tilde{N} \rightarrow \bar{l} + h_2) - \Gamma(\tilde{N}^\dagger \rightarrow \bar{l}h^\dagger_2)}{\Gamma(\tilde{N} \rightarrow \bar{l} + h_2) + \Gamma(\tilde{N}^\dagger \rightarrow \bar{l}h^\dagger_2)} \]
Decay amplitudes:

\[ N_j \rightarrow h \]
\[ N_j \rightarrow N \]
\[ N_j \rightarrow N' \]
\[ N_j \rightarrow H_2 \]
\[ N_j \rightarrow \bar{N} \]

Plumacher, NPB530,207
Buchmuller at al., Annal.Phys.315,305
L number-violating scattering amplitudes proportional to $\lambda_t$:

\[ \gamma^{(0)}_{t_j} : \]
\[ \gamma^{(1)}_{t_j} : \]
\[ \gamma^{(2)}_{t_j} : \]
\[ \gamma^{(3)}_{t_j} : \]
\[ \gamma^{(4)}_{t_j} : \]
\[ \gamma^{(5)}_{t_j} : \]
\[ \gamma^{(6)}_{t_j} : \]
\[ \gamma^{(7)}_{t_j} : \]
\[ \gamma^{(8)}_{t_j} : \]
\[ \gamma^{(9)}_{t_j} : \]
\[ \gamma^{(10)}_{t_j} : \]

infrared divergence in t-channel regularized by Higgs/higgsino thermal mass

Plumacher, NPB530,207
Buchmuller at al., Annal.Phys.315,305
Decay and scattering rates

N.B.: scattering is important at high temperature, $z << 1$
\[
\gamma_{s,t}(z) \equiv \frac{1}{n_{eq} \Gamma_d} \frac{T}{64\pi^4} \int ds \hat{\sigma}_{s,t}(s) \sqrt{s} K_1\left(\frac{\sqrt{s}}{T}\right)
\]

\[
n_{eq}(z) = \frac{g}{2\pi^2} \frac{M^3}{z} K_2(z)
\]

\[K_i \equiv \text{Bessel functions of the first kind}\]

\[
\hat{\sigma}_{s,t}(s) \equiv 3 \frac{\alpha_u}{4\pi} f_{s,t} \left(\frac{s}{M^2}\right), \quad \alpha_u = \frac{\chi_t^2}{4\pi}
\]

Collecting all dominant terms:

\[
f_s(x) \equiv 3 \left[f^{(0)}(x) + \frac{f^{(3)}(x)}{2} + f^{(5)}(x) + \frac{f^{(8)}(x)}{2} + \frac{f_{22}(x)}{2}\right]
\]

\[
f_t(x) \equiv \frac{3}{2} \left[f^{(1)}(x) + f^{(2)}(x) + f^{(4)}(x) + f^{(6)}(x) + f^{(7)}(x) + f^{(9)}(x) + f_{22}(x)\right]
\]
where:

\[
\begin{align*}
    f_t^{(0)} &= \frac{1}{2} \frac{x^2 - 1}{x^2}; \\
    f_t^{(1)} &= \frac{x - 1}{x} \left[ -\frac{2x - 1}{x - 1} + \frac{x}{x - 1} \log \frac{x - 1 + a_h}{a_h} \right]; \\
    f_t^{(2)} &= \frac{x - 1}{x} \left[ -1 + \log \frac{x - 1 + a_h}{a_h} \right]; \\
    f_t^{(3)} &= \left( \frac{x - 1}{x} \right)^2; \\
    f_t^{(4)} &= \frac{x - 1}{x} \left[ \frac{x - 2}{x - 1} + \frac{1}{x - 1} \log \frac{x - 1 + a_h}{a_h} \right]; \\
    f_t^{(5)} &= \frac{1}{2} \left( \frac{x - 1}{x} \right)^2; \\
    f_t^{(6)} &= \frac{x - 1}{x} \left[ -2 + \log \frac{x - 1 + a_h}{a_h} \right]; \\
    f_t^{(7)} &= -1 + \log \frac{x - 1 + a_h}{a_h}; \\
    f_t^{(8)} &= \frac{x - 1}{x^2}; \\
    f_t^{(9)} &= \frac{1}{x} \left[ -1 + \log \frac{x - 1 + a_h}{a_h} \right]; \\
    f_{22} &= \frac{x - 1}{x}.
\end{align*}
\]

\[a_h \equiv \frac{m_H(T)}{M}\]

\[m_H(T) \sim 0.4 \ T \text{ Higgs/higgsino}\]

thermal mass

all other thermal masses are neglected
Final lepton asymmetry:

$$Y_{\hat{L}} = 4 \times 10^{-3} \hat{L}(z = \infty) = 4 \times 10^{-3} \epsilon \eta \simeq 10^{-10}$$

Definition of efficiency:

$$\eta \equiv \frac{\hat{L}(z = \infty)}{\epsilon}$$

If RHNs thermalize early and decay out-of-equilibrium when they are still relativistic ($K<1$): $\eta=1$

Depending on initial conditions (start with vanishing or equilibrium RHN distribution) and on wash-out effect ($K>1$): $\eta<1$

Boltzmann equations don’t depend on $\epsilon$, solving BEs one gets $\eta$
super-weak wash-out regime (K<<1)
vanishing initial RHN density (\(\hat{N}(0)=0\))

semi-analitic solutions:

defining:

\[ \Delta \equiv \hat{N} + \frac{\hat{L}}{\epsilon} \]

one has:

\[ \eta \equiv \frac{\hat{L}(\infty)}{\epsilon} = \Delta(\infty) \simeq K \int_0^\infty z^n \hat{N}_{eq}(z) \left[ \gamma_d + 2\gamma_s + 4\gamma_t \right] \, dz \]

\[ \simeq K \int_0^\infty z^{n+2} K_2(z) (\gamma_s + 2\gamma_t) = K\hat{I}_n \]

with \( \hat{I}_1 \simeq 0.504 \), and \( \hat{I}_2 \simeq 0.921 \)

n=1 radiation, n=2 kination

scattering dominates. Neglecting scattering: \( \eta \sim K^2 \)
Numerical solutions of the Boltzmann equations
super-weak wash-out ($K<<1$)
vanishing initial RHN density ($\hat{N}(0)=0$)

radiation

kination

lepton asymmetry produced early

scattering not included
what is happening:

• at high temperature an initial population of RHNs and an early lepton asymmetry are built up
• at $z \sim 1$ the RHN density and the lepton asymmetry are frozen, until the RHNs decay (plateau)
• RHN decays cancel most of the lepton asymmetry $\hat{L}/\varepsilon$ tracks $\hat{N}$ very closely ($\Delta \sim 0$)
• however CP violation in inverse decays is slightly less than $\varepsilon$ because of relative depletion of faster annihilators compared to slower ones
• CP violation in RHN decay is exactly $\varepsilon$, so that the produced L asymmetry slightly overshoots the initial one
• however, strong cancellation, second-order, back-reaction effect ($\sim K^2$)

L number violating scatterings change this picture completely
Numerical solutions of the Boltzmann equations
super-weak wash-out ($K<<1$)
vanishing initial RHN density ($\dot{N}(0)=0$)

\begin{align*}
\text{radiation} \quad & N(0)=0 \\
\text{kination} \quad & \dot{N}(0)=0 \\
\text{scattering included} \quad & k=10^{-6}
\end{align*}

\begin{align*}
\dot{N}(z), \dot{N}_{eq} & \text{ radiation} \\
\dot{N} & \text{ scattering included} \\
\frac{L}{\epsilon} & = \dot{N} + \frac{\dot{L}}{\epsilon}
\end{align*}

much less pronounced drop

\begin{align*}
\dot{N}(z), \dot{N}_{eq} & \text{ kination} \\
\dot{N} & \text{ scattering included} \\
\frac{L}{\epsilon} & = \dot{N} + \frac{\dot{L}}{\epsilon}
\end{align*}

\begin{align*}
\dot{N}(0)=0 \\
\text{scattering included} \quad & k=10^{-6}
\end{align*}

\[ \frac{\dot{L}}{\epsilon} \text{ no longer tracks } \dot{N} \]
the effect of scattering

• due to the higher overall interaction rate RHNs are more populated in the first place
• however, the main effect is due to the presence of (approximately) CP-conserving s-channel scatterings of the type:

\[ Q + U \rightarrow N + L \]

This process populates N without affecting L, since, for instance:

\[ \Gamma(Q + U \rightarrow N + L) = \Gamma(\bar{Q} + \bar{U} \rightarrow N + \bar{L}) \]

so when RHNs decay they produce a lepton asymmetry that is not canceled by an earlier, specular one (\( \hat{L}/\epsilon \) no longer tracks \( \hat{N} \))

strong enhancement, \( \hat{L}/\epsilon \approx K \)
strong wash-out regime (K>>1)
vanishing initial RHN density (N(0)=0)

semi-analitic solutions:
in this case the bulk of the lepton asymmetry is produced at the
decoupling temperature \( z_f > 1 \), given by the relation:

\[
\frac{\frac{3}{2} z_f^{n+\frac{3}{2}} e^{-z_f}}{K \pi^{1/2}} = \frac{2^{\frac{7}{2}}}{K} \quad \text{(n=1 radiation, n=2 kination)}
\]

useful fit:

\[
z_f \simeq a_n + b_n \ln(K)
\]

\[
a_1 = 1.46; \quad b_1 = 1.40
\]

\[
a_2 = 4.66; \quad b_2 = 1.41
\]

requiring that \( z_f < z_r \) (i.e., that decoupling happens when
kination still dominates) implies an upper bound on K:

\[
z_f \simeq a_2 + b_2 \ln(K) < \sqrt{\left( \frac{63.78}{\tilde{m}} \left( \frac{\tilde{m}}{0.05 \text{ eV}} \right)^2 - 1 \right)} = z_r
\]

\[
\begin{cases}
\tilde{m} = 0.05 \rightarrow K \lesssim 7.6 \\
\tilde{m} = 0.01 \rightarrow K \lesssim 5.7
\end{cases}
\]
strong wash-out regime \((K >> 1)\)
vanishing initial RHN density \((\hat{N}(0) = 0)\)

semi-analitic solutions:

integrating BEs using saddle-point technique:

\[
\eta = \frac{\hat{L}(\infty)}{c} = \hat{N}_{eq}(z_f) F_{wash-out}(n, z_f),
\]

where \(\hat{N}_{eq}(z_f) = \frac{4}{K \hat{z}^n_f}\),

and \(F_{wash-out}(n, z_f) \simeq \sqrt{\frac{2\pi}{1 - \frac{n}{z_f}}} \exp \left[ - \left( 1 + \frac{3}{2} + n \right) \right] \)

\(n=1\) radiation, \(n=2\) kination

RHNs decouple late, when scatterings are negligible

at fixed \(K\) RHNs decouple later for kination (same expansion rate at \(z=1\), for \(z>1\) kination implies a faster deceleration and a lower expansion rate)
Numerical solutions of the Boltzmann equations for strong wash-out ($K \gg 1$) with vanishing initial RHN density ($\hat{N}(0) = 0$), same as $\hat{N}(0) = 1$.

RHNs thermalize before $z_f \rightarrow$ thermal equilibrium erases any dependence on initial conditions.
Δ vs. z: 
vanishing initial RHN density (\(\hat{N}(0)=0\))
Δ vs. z:
thermal initial RHN density ($\hat{N}(0)=1$)
efficiency $\eta$ vs. $K$

- For $K \gg 1$ curves with $\hat{N}(0)=0$ and $\hat{N}(0)=1$ coincide.
- Scattering is only important for $K < 1$.
- For $K > 1$ efficiency for kination is about one order of magnitude smaller than for radiation.
- For $K < 1$ efficiencies are comparable in the two cases.
efficiency $\eta$ vs. $z_r$

- Smooth transition from radiation dominance ($z_r < 1$) to kination dominance ($z_r > 1$)
- Strong suppression of the efficiency if $z_r >> 1$
- Increased efficiency for $1 < z_r < 100$ if $\tilde{m} > 0.01$ eV

$T_r = 1$ MeV $\rightarrow$ $z_r \sim 10^8$
Conclusions

• If kination dominates until nucleosynthesis, gauge interactions can thermalize only at a temperature $T \sim 10^5$ GeV, so the RHN mass $M \sim T$ needs to be relatively light. This constraint is relaxed for higher $T_r$.

• Sphaleron interactions thermalize above the temperature of electroweak phase transition → conversion of lepton number to baryon number is allowed.

• In standard cosmology, when the RHN Yukawa coupling is fixed to provide the atmospheric neutrino mass scale one has $K \gg 1$. With kination any situation between strong to super-weak wash-out is possible.

• When $z_r > 100$ the super-weak wash-out regime is attained, and efficiency is strongly suppressed compared to the standard case: $\eta \sim K \sim (64/z_r)(\tilde{m}/0.05 \text{ eV})$. In this case s-channel scatterings driven by the top Yukawa coupling strongly enhance the efficiency in models with a vanishing initial RHN density.
•when $1<z_r<100$ kination stops to dominate shortly after leptogenesis takes place. In this case, for $m>0.01$ eV, leptogenesis proceeds with $0.1<K<1$ in a regime where the efficiency is even better than that for the case of radiation domination

a wide range of possibilities described by only two parameters: $z_r$ and the neutrino mass scale $\tilde{m}$