Quintessential Kination and Leptogenesis

Stefano Scopel

Korea Institute of Advanced Study, Seoul

KIAS
KOREA INSTITUTE FOR ADVANCED STUDY

Based on E.J. Chun and S.S., arXiv:0707.1544

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 → leptogenesis through out-of-equilibrium $\not{L}$ decay of heavy particle X
- sphaleron conversion to Baryon number
- <u>if X is not so heavy:</u> 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:

$$\mathbf{W} = \mathbf{Y}_N^{ij} N_i L_j H_2 + \frac{1}{2}\mathbf{M}_N^{ij} N_i N_j$$

$$\frac{\mathcal{K}}{M} = \frac{1}{M_L}\mathbf{Y}_\nu^{ij} = \mathbf{Y}_N^{Tik}\mathbf{M}_N^{-1kl}\mathbf{Y}_N^{lj} \longrightarrow \boxed{\mathbf{m}_\nu^{ij} = \frac{v_2^2}{M_L}\mathbf{Y}_\nu^{ij} = v_2^2\ \mathbf{Y}_N^{Tik}\mathbf{M}_N^{-1kl}\mathbf{Y}_N^{lj}}$$

- Type II: Higgs heavy triplet(s):

	non-SUSY	SUSY	~~SUSY~~
MINIMAL CONTENT:	2 scalar triplets or 1 triplet+1 ν_R	4 (triplet+striplet)	2 (triplet+striplet)

Type I + Type II…

Thermal leptogenesis (Fukugita and Yanagida, PLB174, 45)

requires Sakharov conditions:

✓ $\cancel{L}$ → neutrino mass op.

✓ $\cancel{C}$ and $\cancel{CP}$ → phases

✓ out of-equilibrium decay → $K(T=M) \equiv \underset{\text{decay rate}}{\Gamma}/\underset{\text{Hubble constant}}{H(M)}$

K=wash-out parameter: $\begin{cases} k>1 \text{ wash-out regime} \\ k<1 \text{ out-of-equilibrium decay} \end{cases}$

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 at al., PRD59,123504)
- kination ≡ 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: <u>to study how kination dominance can modify the predictions of thermal leptogenesis in type-I see-saw</u>

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:

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

if: $\frac{\dot{\phi}^2}{2} \gg V(\phi) \longrightarrow \boxed{w = 1}$

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

$$\begin{cases} \rho_{rad} \propto a^{-4} & \text{(radiation)} \\ \rho_{rad} \propto a^{-3} & \text{(matter)} \\ \rho_{kin} \propto a^{-6} & \text{(kination)} \end{cases}$$

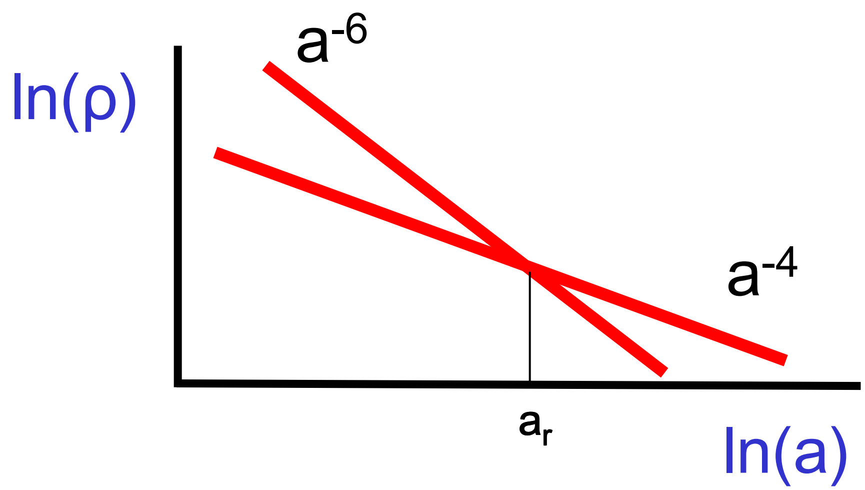
we know that radiation must dominate at the time of nucleosynthesis, however we have no observational constraint at earlier times. So setting T_r as the kination-radiation equality temperature for which:

$$\rho_{kin}(T_r) = \rho_{rad}(T_r)$$

T_r is a free parameter, with the only bound:

$$T_r \gtrsim 1 \text{ MeV}$$

Fix boundary conditions at T_r:



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

$$a_r \equiv a(T_r)$$

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

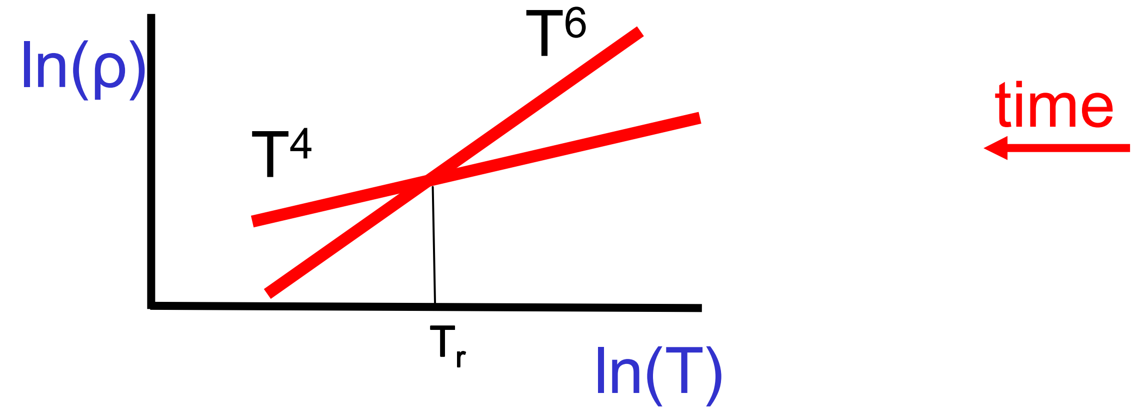
$$g_{*r} = \text{dof } \# \text{ at } T_r$$

+ isoentropic expansion (a^3 s=constant):

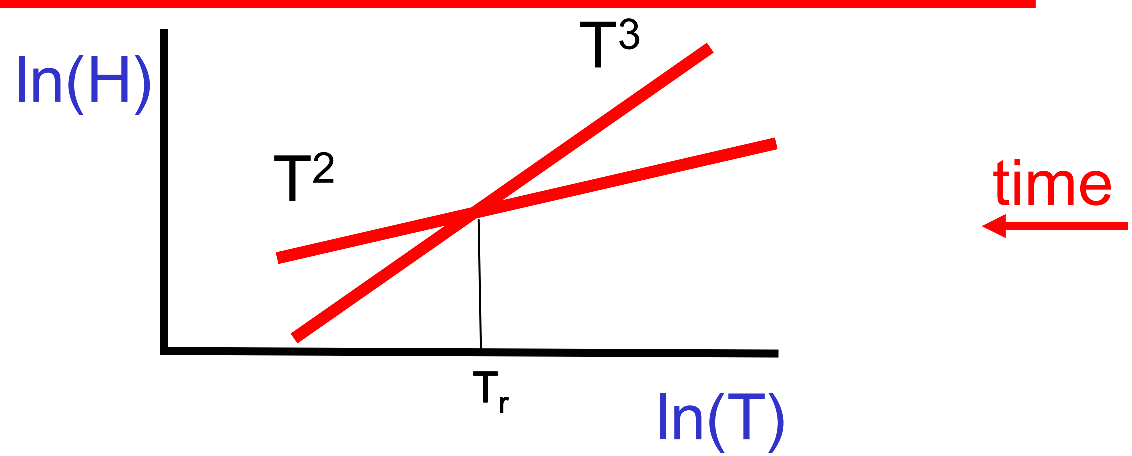
$$\left(\frac{a_r}{a}\right)^3 = \frac{g_*}{g_{*r}}\left(\frac{T}{T_r}\right)^3$$

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

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



$$H(T) = 1.66\sqrt{g_*}\frac{T^2}{m_{pl}}\sqrt{1 + \frac{g_*}{g_{*r}}\left(\frac{T}{T_r}\right)^2}$$



A useful parametrization:

$$H(z) = \sqrt{\frac{z^2 + z_r^2}{1 + z_r^2}\frac{H_1}{z^3}} \quad \begin{cases} z_r \gg 1 \to H(z) = \dfrac{H_1}{z^3} & \text{(kination)} \\ z_r \ll 1 \to H(z) = \dfrac{H_1}{z^2} & \text{(radiation)} \end{cases}$$

$$z \equiv \frac{M}{T}$$

$M \equiv$ heavy neutrino mass

$$H_1 \equiv H(z = 1)$$

$$\boxed{z_r \equiv \sqrt{\frac{g_*}{g_{*r}}} M/T_r}$$

Let's plug some numbers:

T_r= 1 MeV
g_{*r}=10.75
$g_*(T)$=228.75 (SUSY)

extreme situation (T_r~1 MeV):
✓low mass M (z_r<4.5 x 10^8)
✓sufficient window for sphaleron
✓standard picture recovered when T_r>>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:

$\Gamma_{gauge} \sim \alpha^2 T > H \rightarrow$

$$M \simeq T < 3.4 \times 10^5 \left(\frac{\sqrt{g_{*r}}\,T_r}{3.28 \text{ MeV}}\right)^{1/2} \text{GeV}$$

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

$\Gamma_{sphaleron} \sim \alpha^4 T > H \rightarrow$

$$T < 10^4 \left(\frac{\sqrt{g_{*r}}\,T_r}{3.28 \text{ MeV}}\right)^{1/2} \text{GeV}$$

(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) spermultiplets 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: $$\tilde{m} \equiv |y|^2 \frac{\langle H_2 \rangle^2}{M}$$

Wash-out parameter:

$$K \equiv \frac{\Gamma_d}{H(T=M)} = \frac{63.78}{\sqrt{1+z_r^2}} \left(\frac{\tilde{m}}{0.05 \text{ eV}} \right)$$

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~10, see later)

Boltzmann equations

N=heavy majorana neutrinos, Ñ=sneutrinos, l=leptons, $\tilde{l}$=sleptons

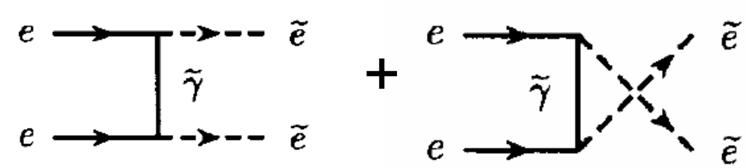
$$N(z) \equiv \frac{Y_N(z)}{Y_N^{eq}(z=0)} \,, \tilde{N}(z) \equiv \frac{Y_{\tilde{N}}(z)}{Y_{\tilde{N}}^{eq}(z=0)} \,, \tilde{N}^\dagger(z) \equiv \frac{Y_{\tilde{N}^\dagger}(z)}{Y_{\tilde{N}^\dagger}^{eq}(z=0)} \,,$$

$$\tilde{N}_\pm \equiv \tilde{N}(z) \pm \tilde{N}^\dagger(z) \,, L(z) \equiv \frac{Y_l(z) - Y_{\bar{l}}(z)}{Y_l^{eq}(z=0)} \,, \tilde{L}(z) \equiv \frac{Y_{\tilde{l}}(z) - Y_{\tilde{l}^\dagger}(z)}{Y_{\tilde{l}}^{eq}(z=0)}$$

$$Y_i\left(z = \frac{M}{T}\right) \equiv \frac{n_i}{s(z)}$$

(n_i=number densities, s=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:

$$\hat{N}(z) \equiv N(z) + \tilde{N}_+$$
$$\hat{L}(z) \equiv L(z) + \tilde{L}(z)$$

decay amplitude

L number violating scatterings proportional to the top yukawa coupling λ_t

one gets the simplified set of BE:

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

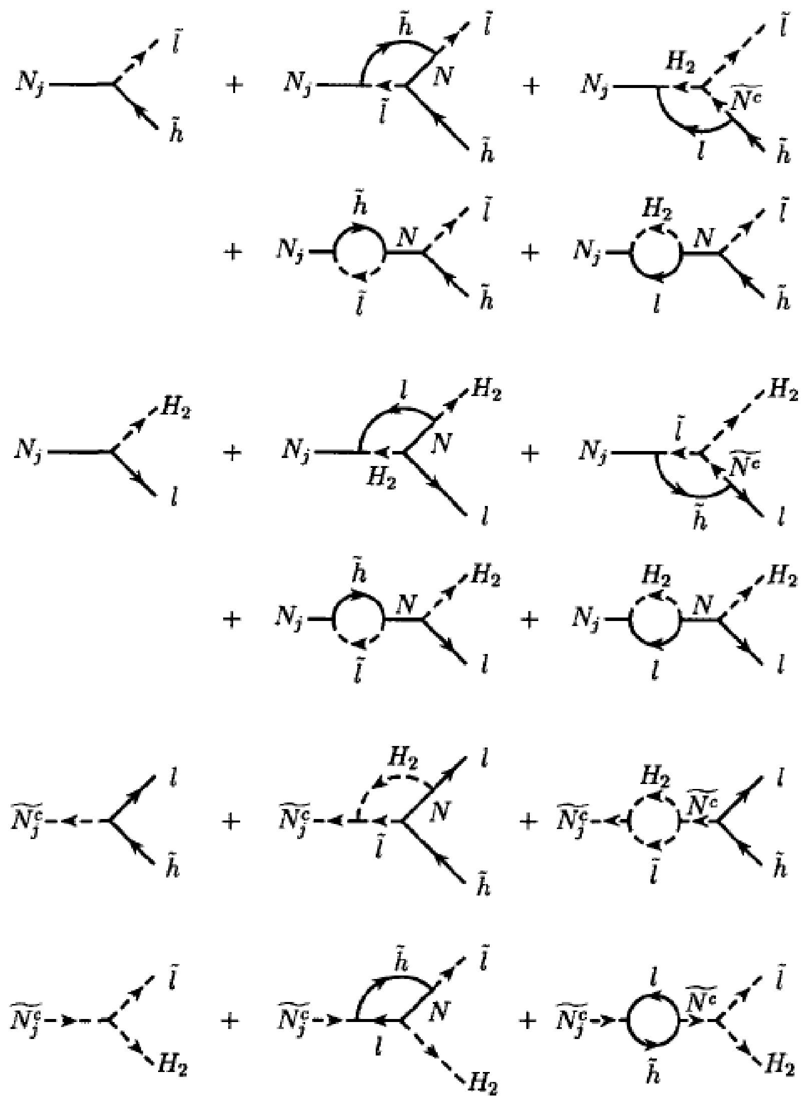
$$\frac{d\hat{L}}{dz}(z) = K\sqrt{\frac{1+z_r^2}{z^2+z_r^2}}\,z^2\left[\gamma_d(z)\epsilon(\hat{N}-\hat{N}_{eq}) - \frac{\gamma_d(z)\hat{N}_{eq}\hat{L}}{4} - \frac{1}{2}\gamma_s(z)\hat{L}\hat{N} - \gamma_t(z)\hat{L}\hat{N}_{eq}\right]$$

CP-violating parameter:

$$\epsilon \equiv \frac{\Gamma(N\to l+h_2)-\Gamma(N\to \bar{l}h_2^\dagger)}{\Gamma(N\to l+h_2)+\Gamma(N\to \bar{l}h_2^\dagger)} = \frac{\Gamma(N\to \tilde{l}+\tilde{h})-\Gamma(N\to \tilde{l}^\dagger\bar{\tilde{h}})}{\Gamma(N\to \tilde{l}+\tilde{h})+\Gamma(N\to \tilde{l}^\dagger\bar{\tilde{h}})}$$

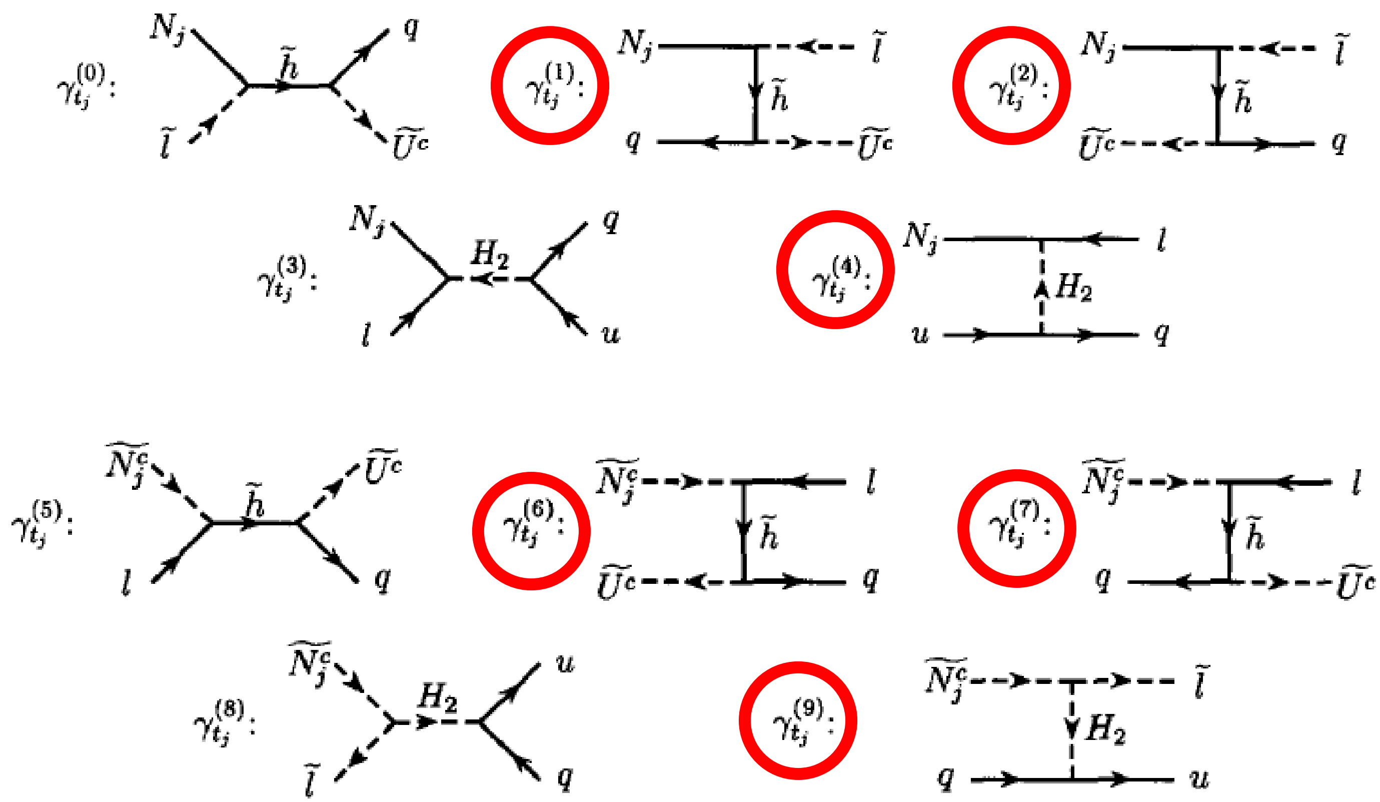
$$= \frac{\Gamma(\tilde{N}\to l+\tilde{h})-\Gamma(\tilde{N}^\dagger\to \bar{l}\bar{\tilde{h}})}{\Gamma(\tilde{N}\to l+\tilde{h})+\Gamma(\tilde{N}^\dagger\to \bar{l}\bar{\tilde{h}})} = \frac{\Gamma(\tilde{N}\to \tilde{l}+h_2)-\Gamma(\tilde{N}^\dagger\to \tilde{l}^\dagger h_2^\dagger)}{\Gamma(\tilde{N}\to \tilde{l}+h_2)+\Gamma(\tilde{N}^\dagger\to \tilde{l}^\dagger h_2^\dagger)}$$

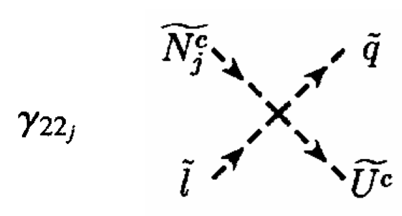
Decay amplitudes:



Plumacher, NPB530,207
Buchmuller at al., Annal.Phys.315,305

L number-violating scattering amplitudes proportional to λ_t:

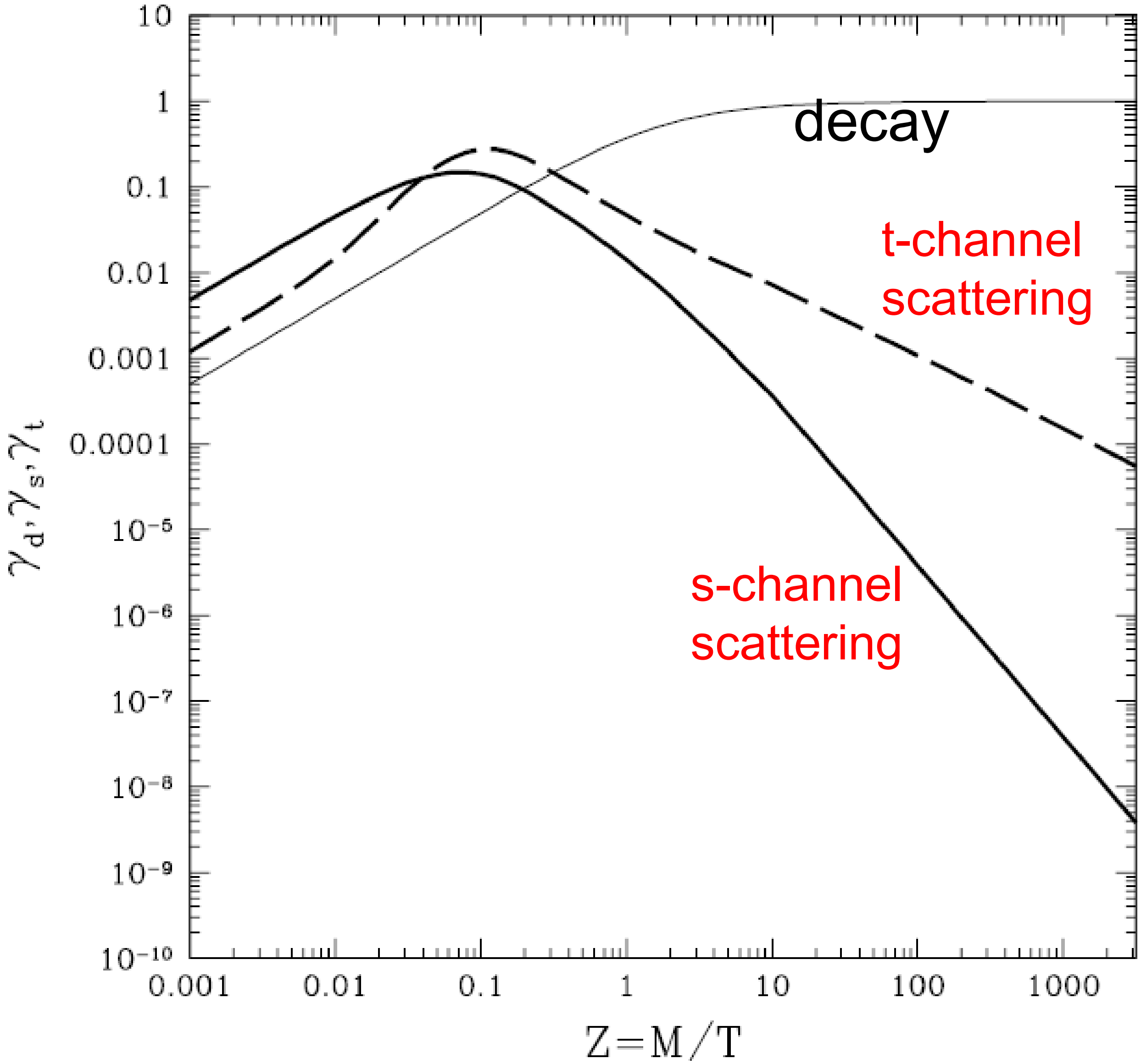




infrared divergence
in t-channel
regularized by
Higgs/higgsino
thermal mass

Plumacher, NPB530,207
Buchmuller at al., Annal.Phys.315,305

Decay and scattering rates



N.B.: scattering is important at high temperature, z<<1

$$\gamma_{s,t}(z) \equiv \frac{1}{n_{eq}\Gamma_d}\frac{T}{64\pi^4}\int ds\ \hat{\sigma}_{s,t}(s)\sqrt{s}K_1(\frac{\sqrt{s}}{T})$$

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

$K_i \equiv$ Bessel functions of the first kind

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

collecting all dominant terms:

$$\begin{aligned} f_s(x) &\equiv 3\left[f^{(0)}(x) + \frac{f^{(3)}(x)}{2} + f^{(5)(x)} + \frac{f^{(8)}(x)}{2} + \frac{f_{22}(x)}{2}\right] \\ f_t(x) &\equiv \frac{3}{2}\left[f^{(1)(x)} + f^{(2)}(x) + f^{(4)}(x) + f^{(6)}(x) + f^{(7)}(x)\right. \\ &\quad \left. + f^{(9)}(x) + f_{22}(x)\right] \end{aligned}$$

where:

$$f_t^{(0)} = \frac{1}{2}\frac{x^2-1}{x^2}; \qquad f_t^{(1)} = \frac{x-1}{x}\left[-\frac{2x-1}{x-1} + \frac{x}{x-1}\log\frac{x-1+a_h}{a_h}\right]$$

$$f_t^{(2)} = \frac{x-1}{x}\left[-1+\log\frac{x-1+a_h}{a_h}\right]; \quad f_t^{(3)} = \left(\frac{x-1}{x}\right)^2$$

$$f_t^{(4)} = \frac{x-1}{x}\left[\frac{x-2}{x-1} + \frac{1}{x-1}\log\frac{x-1+a_h}{a_h}\right]; \quad f_t^{(5)} = \frac{1}{2}\left(\frac{x-1}{x}\right)^2$$

$$f_t^{(6)} = \frac{x-1}{x}\left[-2+\log\frac{x-1+a_h}{a_h}\right]; \quad f_t^{(7)} = -1+\log\frac{x-1+a_h}{a_h}$$

$$f_t^{(8)} = \frac{x-1}{x^2}; \quad f_t^{(9)}\frac{1}{x}\left[-1+\log\frac{x-1+a_h}{a_h}\right]; \quad f_{22} = \frac{x-1}{x}.$$

$$a_h \equiv \frac{m_H(T)}{M}$$

$m_H(T)$~0.4 T Higgs/higgsino thermal mass

all other thermal masses are neglected

Final lepton asymmetry:

observation

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

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): <u>η=1</u>

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

Boltzmann equations don't depend on ε, solving BEs one gets η super-weak wash-out regime (K<<1)

vanishing initial RHN density ($\hat{N}(0)=0$)

semi-analitic solutions:

defining:

$$\Delta \equiv \hat{N} + \frac{\hat{L}}{\epsilon}$$

negligible, main contribution from z<<1

one has:

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

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

$$\text{with} \quad \hat{I}_1 \simeq 0.504, \text{ and } \hat{I}_2 \simeq 0.921$$

n=1 radiation, n=2 kination

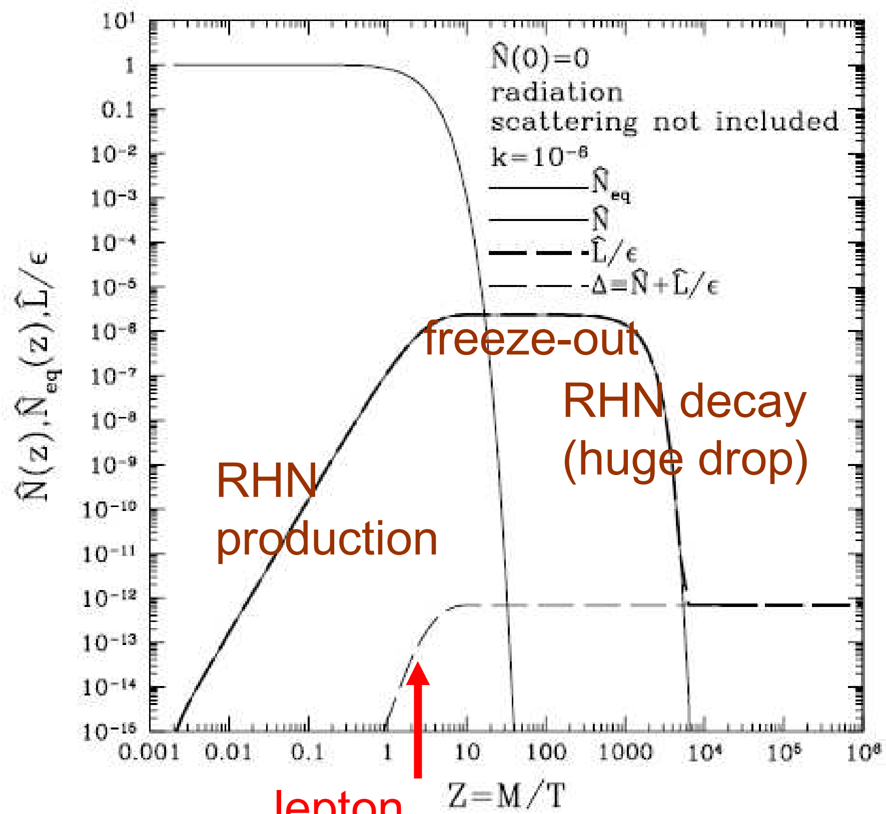
scattering dominates. Neglecting scattering: $\eta \sim K^2$

Numerical solutions of the Boltzmann equations

super-weak wash-out (K<<1)

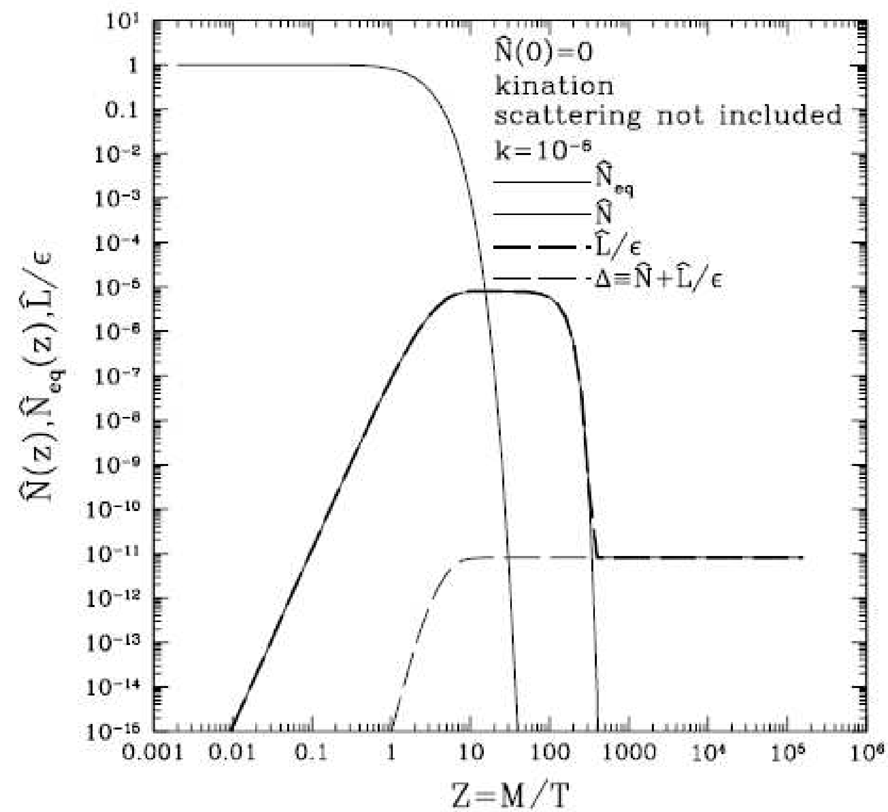
vanishing initial RHN density ($\hat{N}(0)=0$)

radiation



lepton
asymmetry
produced
early

kination



<u>scattering not included</u>

what is happening:

- at high temperature an initial population of RHNs and an early lepton asymmetry are built up
- at z~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 (Δ~0)
- however CP violation in inverse decays is slightly less than ε because of relative depletion of faster annihilators compared to slower ones
- CP violation in RHN decay is exactly ε, so that the produced L asymmetry slightly overshoots the initial one
- however, strong cancellation, second-order, back-reaction effect (~K^2)

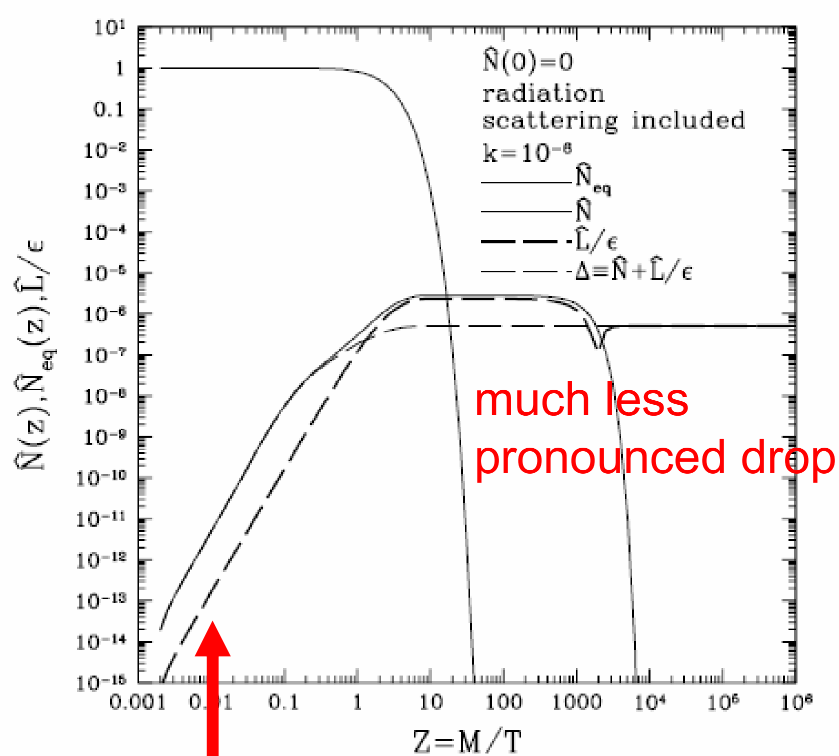
L number violating scatterings change this picture completely

Numerical solutions of the Boltzmann equations

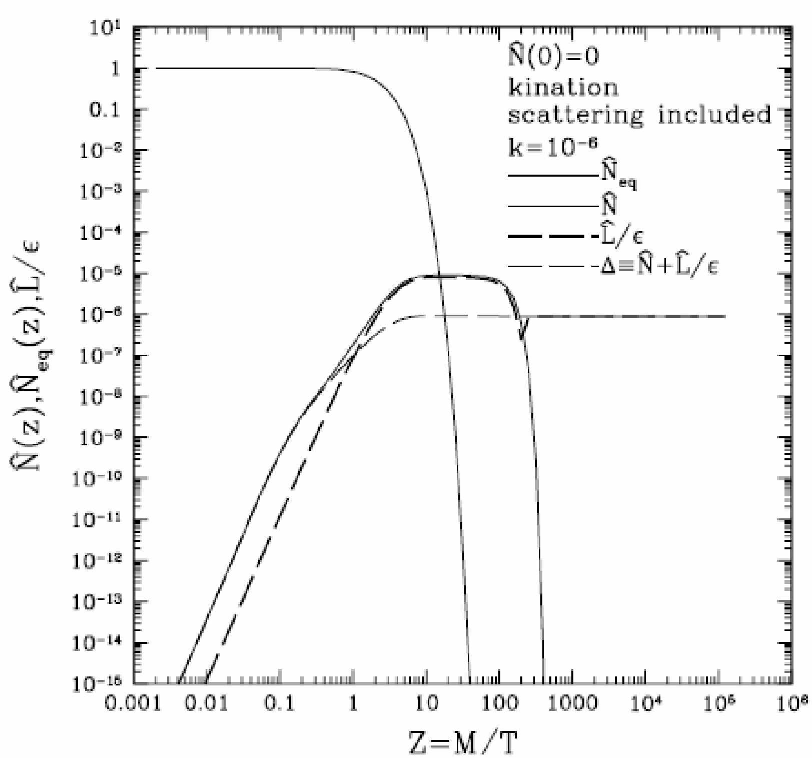
super-weak wash-out (K<<1)

vanishing initial RHN density ($\hat{N}(0)=0$)

radiation



kination



$\hat{L}/\varepsilon$ no longer tracks $\hat{N}$

scattering included

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 ($\hat{L}/\varepsilon$ no longer tracks $\hat{N}$)

strong enhancement, $L/\varepsilon \sim K$

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:

$$z_f^{n+\frac{3}{2}} e^{-z_f} = \frac{2^{\frac{7}{2}}}{K\pi^{1/2}}$$ (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:

$$z_f \simeq a_2 + b_2 \ln(K) < \sqrt{\left(\frac{63.78}{K}\frac{\tilde{m}}{0.05\ \mathrm{eV}}\right)^2 - 1} = z_r \begin{cases} \tilde{m} = 0.05 \rightarrow K \lesssim 7.6 \\ \tilde{m} = 0.01 \rightarrow K \lesssim 5.7 \end{cases}$$

strong wash-out regime (K>>1)

vanishing initial RHN density ($\hat{N}(0)=0$)

semi-analitic solutions:

integrating BEs using saddle-point technique:

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

$$\text{where} \quad \hat{N}_{eq}(z_f) = \frac{4}{K z_f^n},$$

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

n=1 radiation, n=2 kination

RHNs decouple late, when scatterings are negligible

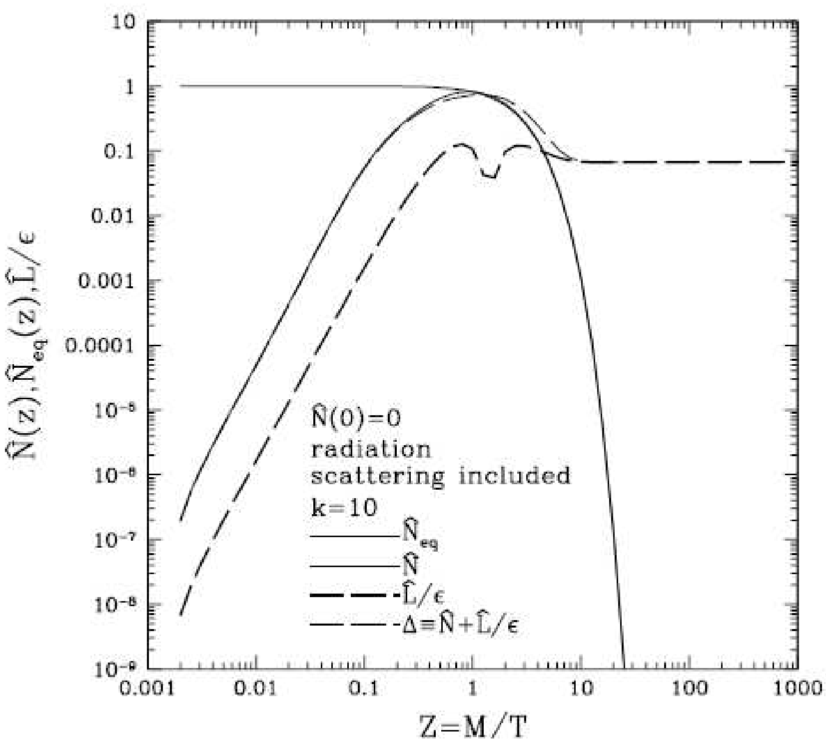
<u>at fixed K</u> RHNs decouple later for kination (same expansion rate at z=1, for z>1 kination implies a faster deceleration and a lower expansion rate)

Numerical solutions of the Boltzmann equations

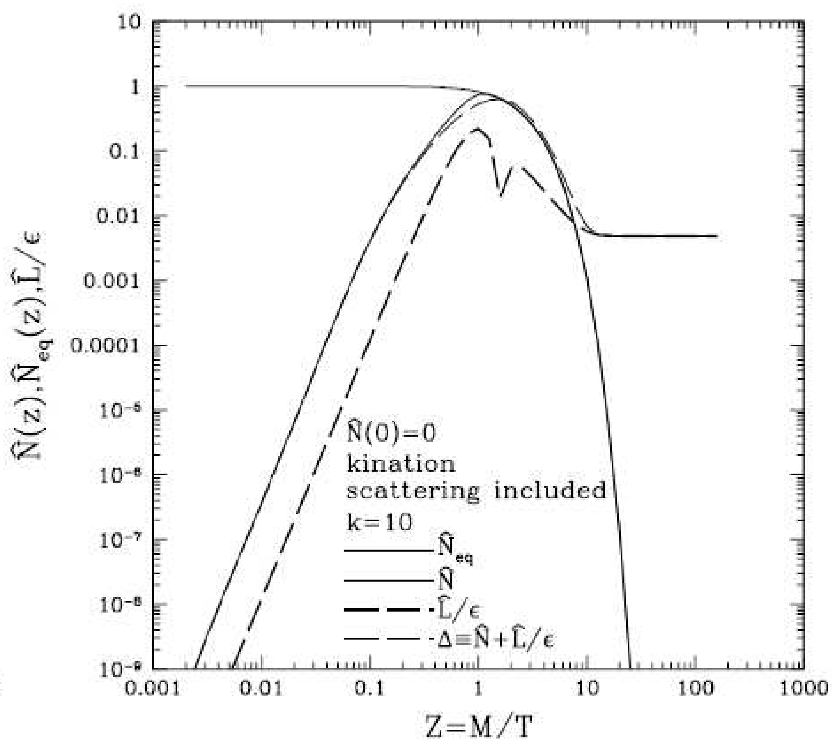
strong wash-out (K>>1)

vanishing initial RHN density ($\hat{N}(0)=0$)   same as $\hat{N}(0)=1$

radiation

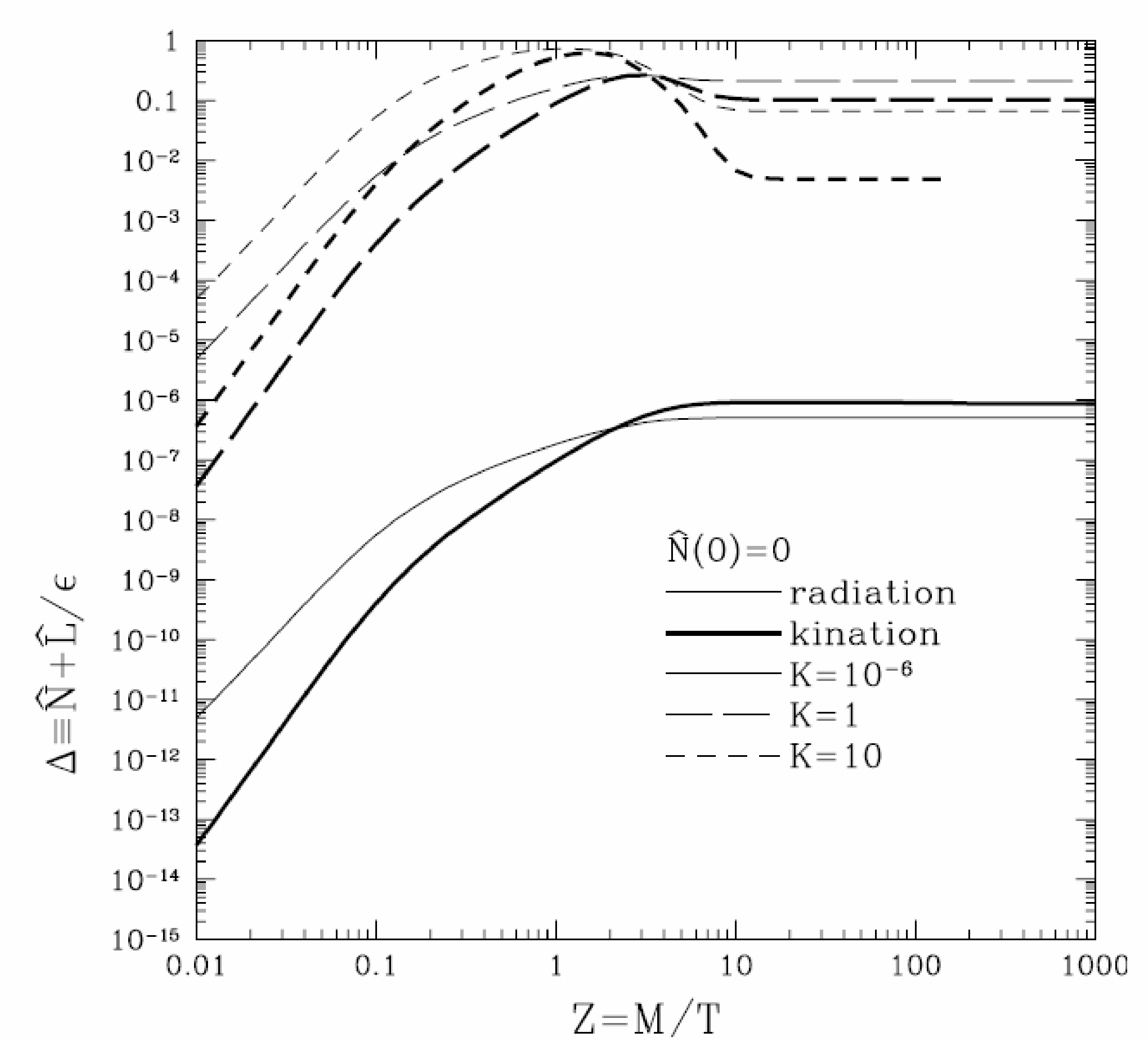


kination



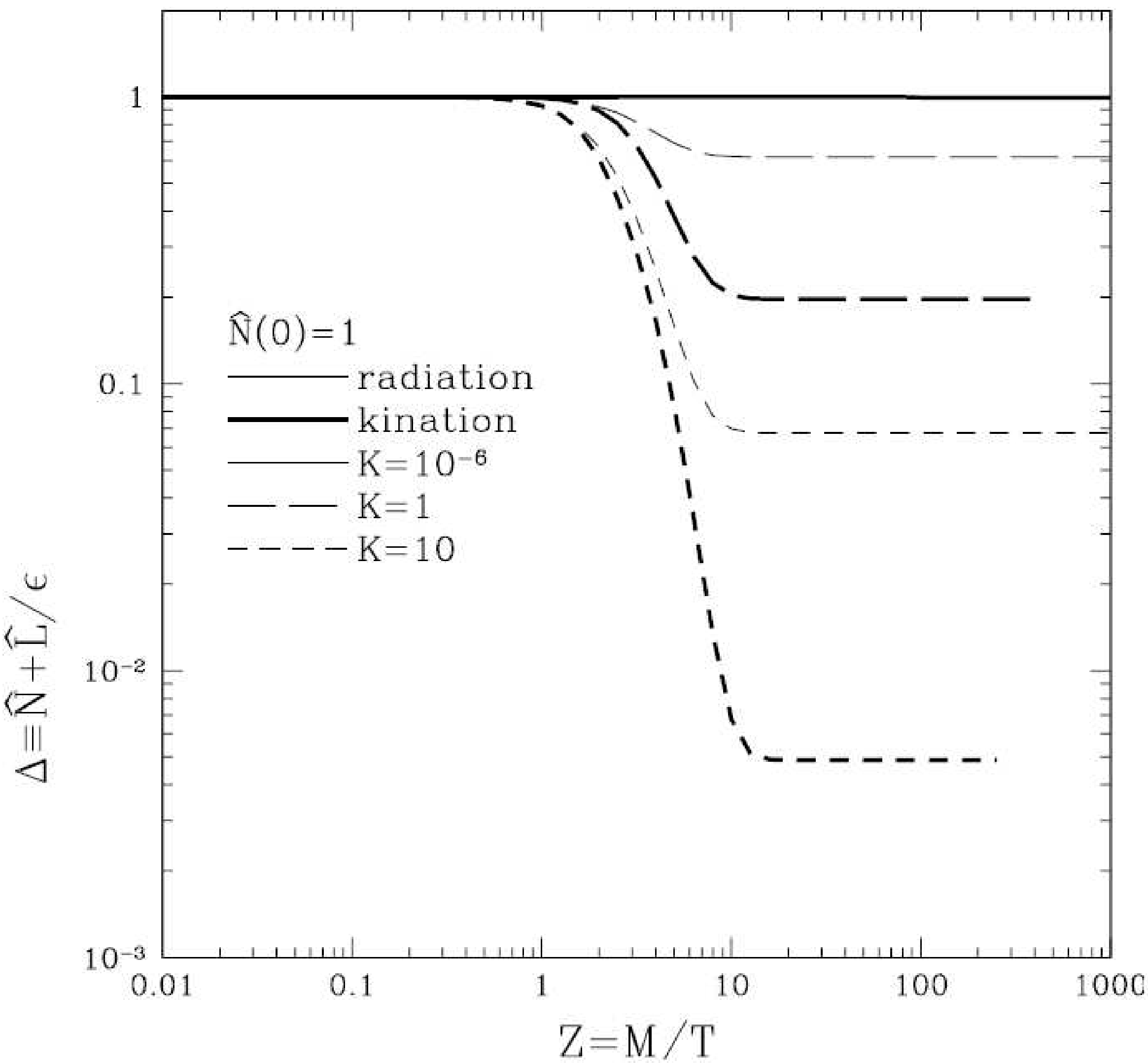
RHNs thermalize before z_f → thermal equilibrium erases any dependence on initial conditions

Δ vs. z:
vanishing initial RHN density ($\hat{N}(0)=0$)



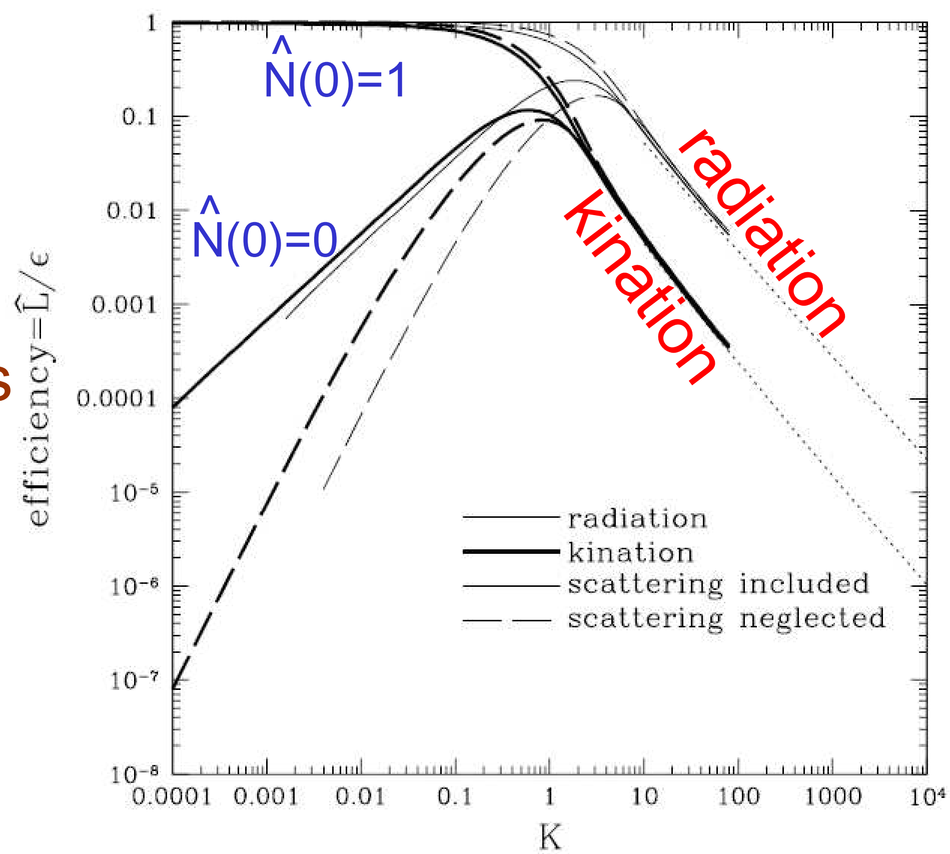
Δ vs. z:

thermal initial RHN density ($\hat{N}(0)=1$)



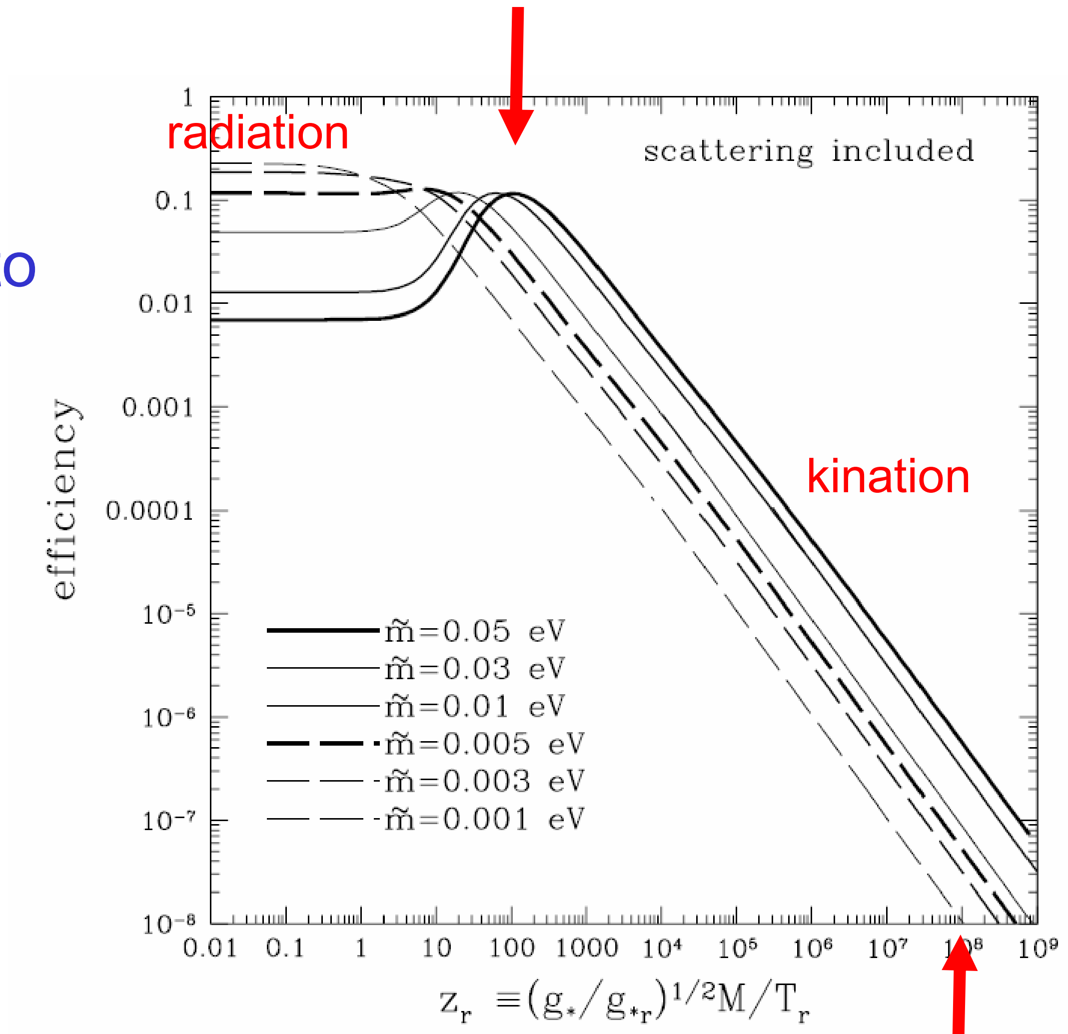
efficiency η vs. K

- for K>>1 curves with N(0)=0 and 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 η vs. z_r

- smooth transition from radiation dominance (z_r<1) to kination dominance (z_r>1)
- strong supression of the efficiency if z_r>>1
- increased efficiency for 1<z_r<100 if $\tilde{m}$>0.01 eV



T_r=1 MeV→z_r~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

Conclusions - 2

•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 <u>is even better</u> 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 $\tilde{m}$