IBS-CTPU Seminar, 21st, December, 2023

MeV-scale reheating or decaying particles at around MeV

Kawasaki, Kohri, Sugiyama, arXiv:astro-ph/9811437, arXiv:astro-ph/0002127
K. Kohri, arXiv:astro-ph/0103411
Kawasaki, Kohri, Moroi, arXiv:astro-ph/0408426
T.Hasegawa, Kohri, Hiroshima, Hansen, Tram, Hannestad, arXiv:1908.10189 [hep-ph]

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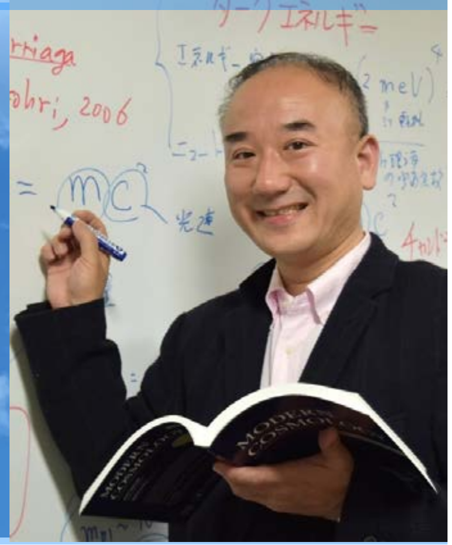


SOKENDAI KEK 理論センター THEORY CENTER KAVLI IPMU

Abstract

- After Inflation, the early matter dominated (MD) epoch follows
- In supergravity, we may expect MeV-scale reheating temperature, inducing flavor-dependent imperfect thermalizations of neutrinos
- Then, three flavor neutrino-oscillation in the early Universe is so important
- From BBN and CMB, we obtain the lower bound on reheating temperature to be $T_{RH} \gtrsim 5$ MeV
- This work of three active-flavors oscillations with hadronic decay scenario is the world's first!

Strong motivations for MeV-scale reheating in supergravity or superstring

- Gravitational decay rate for moduli, dilatons, gravitino, ... with O(1) – O(10) TeV masses

$$\Gamma_{\phi} \sim \frac{m_{\mathrm{heavy}}^3}{m_{\mathrm{Planck}}^2} = H(T_{\mathrm{RH}}) \sim \frac{T_{\mathrm{RH}}^2}{m_{\mathrm{Planck}}}$$

- Reheating temperature

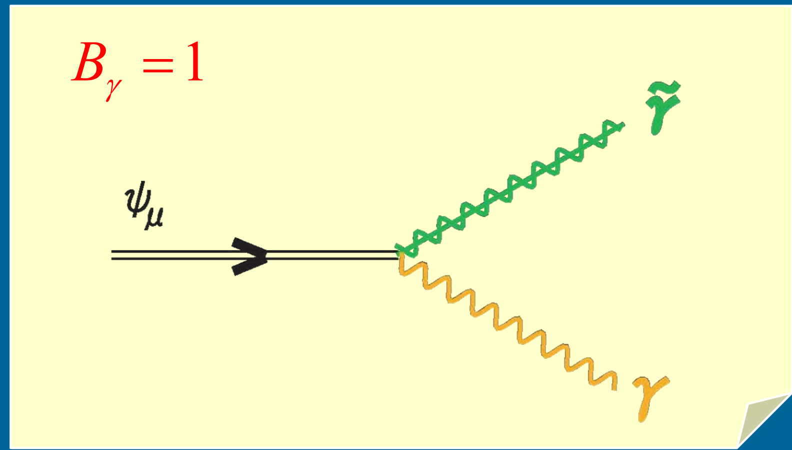
$$T_{\mathrm{RH}} \sim O(1)\mathrm{MeV}\left(\frac{m_{\mathrm{heavy}}}{10\mathrm{TeV}}\right)^{3/2}$$

Moduli/gravitino Decay and BBN

1. Moduli/gravitinos are unstable in Gravity Mediation ~~SUSY~~

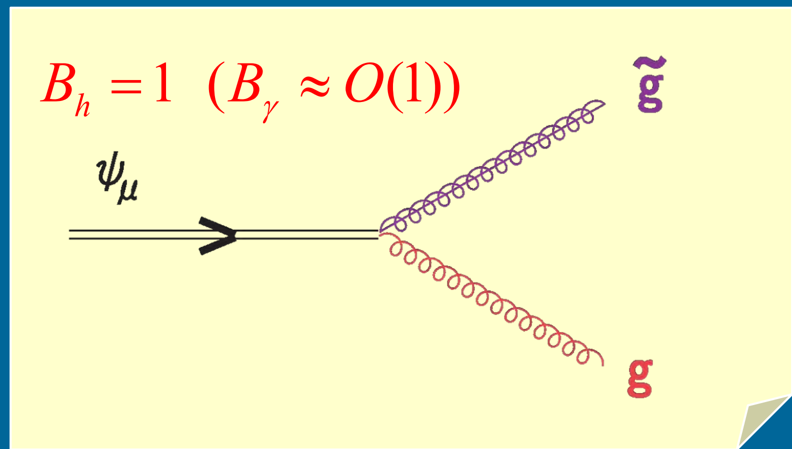
- Radiative decay

$$\tau(\psi_{3/2} \to \gamma + \tilde{\gamma}) = 4 \times 10^{8}\,\mathrm{sec}\left(\frac{\mathrm{m}_{3/2}}{100\ \mathrm{GeV}}\right)^{-3}$$

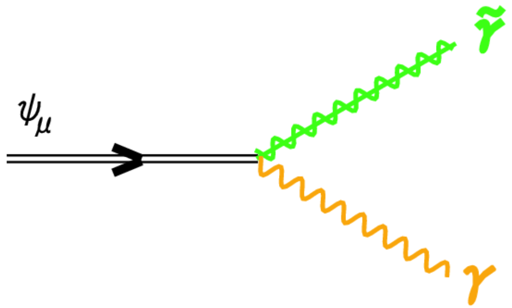


- Hadronic decay

$$\tau(\psi_{3/2} \to g + \tilde{g}) = 6 \times 10^{7}\,\mathrm{sec}\left(\frac{\mathrm{m}_{3/2}}{100\ \mathrm{GeV}}\right)^{-3}$$



Radiative decay of gravitino



1) Electro-magnetic cascade

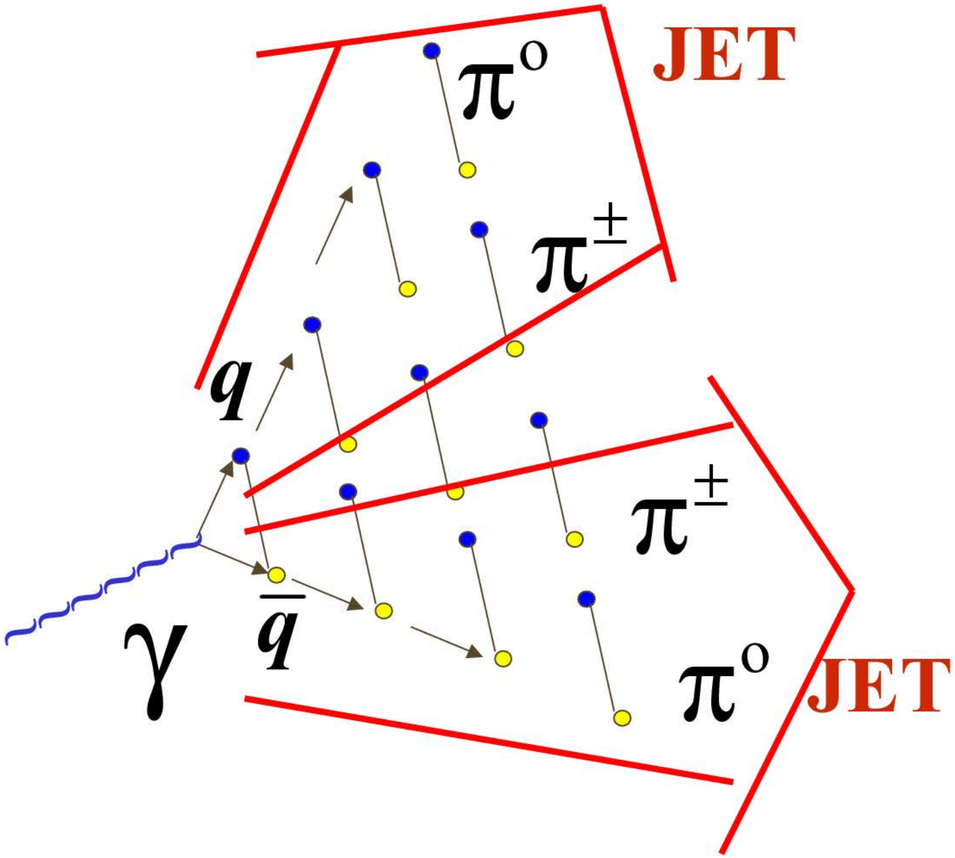
$$\gamma + \gamma_{\rm BG} \to e^+ + e^-$$
$$\gamma + e^-_{\rm BG} \to \gamma + e^-, \quad e^- + \gamma_{\rm BG} \to e^- + \gamma$$
$$\gamma + \gamma_{\rm BG} \to \gamma + \gamma$$

2) many soft photons are produced

3) Photo-dissociation of light elements

$$\mathrm{D} + \gamma \to p + n,$$
$${}^4\mathrm{He} + \gamma \to {}^3\mathrm{He} + n, \quad \mathrm{T} + p,$$
$${}^3\mathrm{He} + \gamma \to \mathrm{D} + p + n, \quad \mathrm{etc.}$$

Quark Emission and Hadron Jets



q = u, d, s,...

Kawasaki, Kohri, Moroi, arXiv:astro-ph/0408426

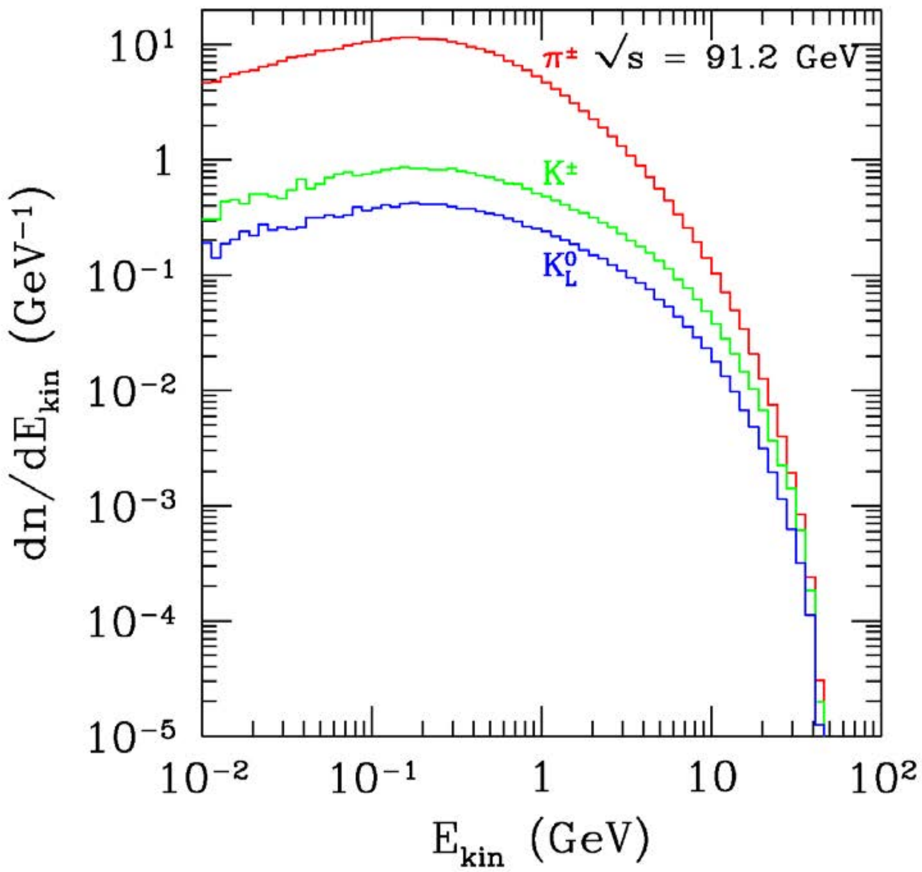
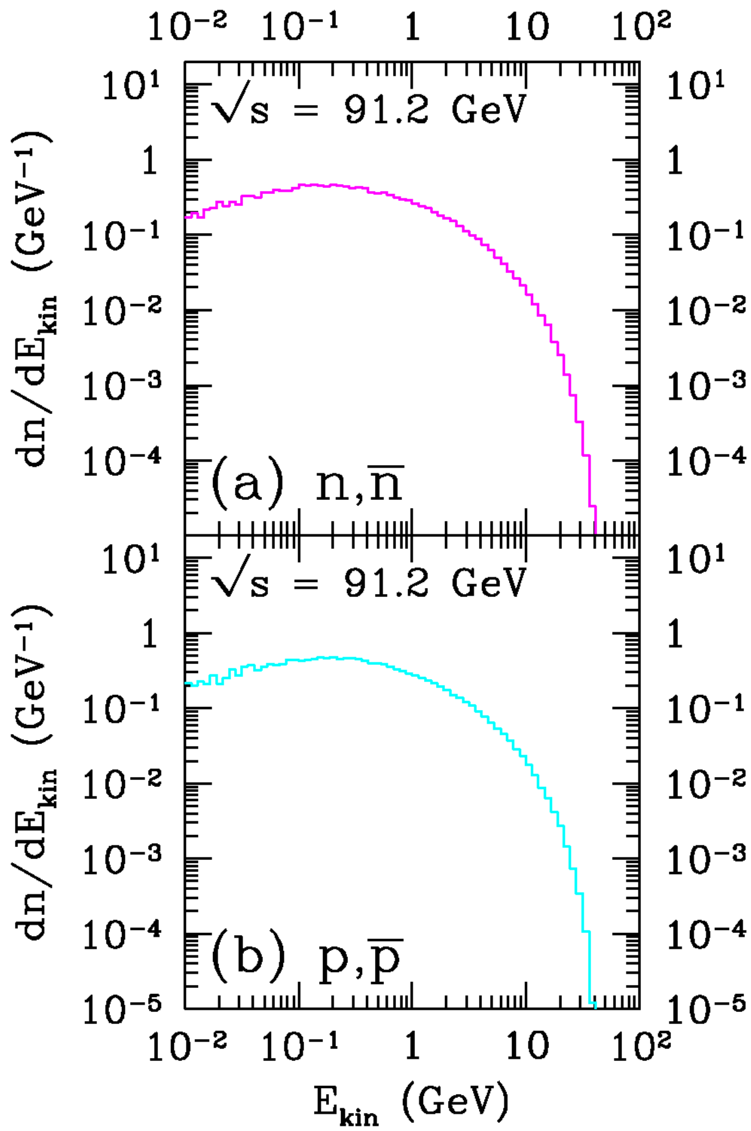
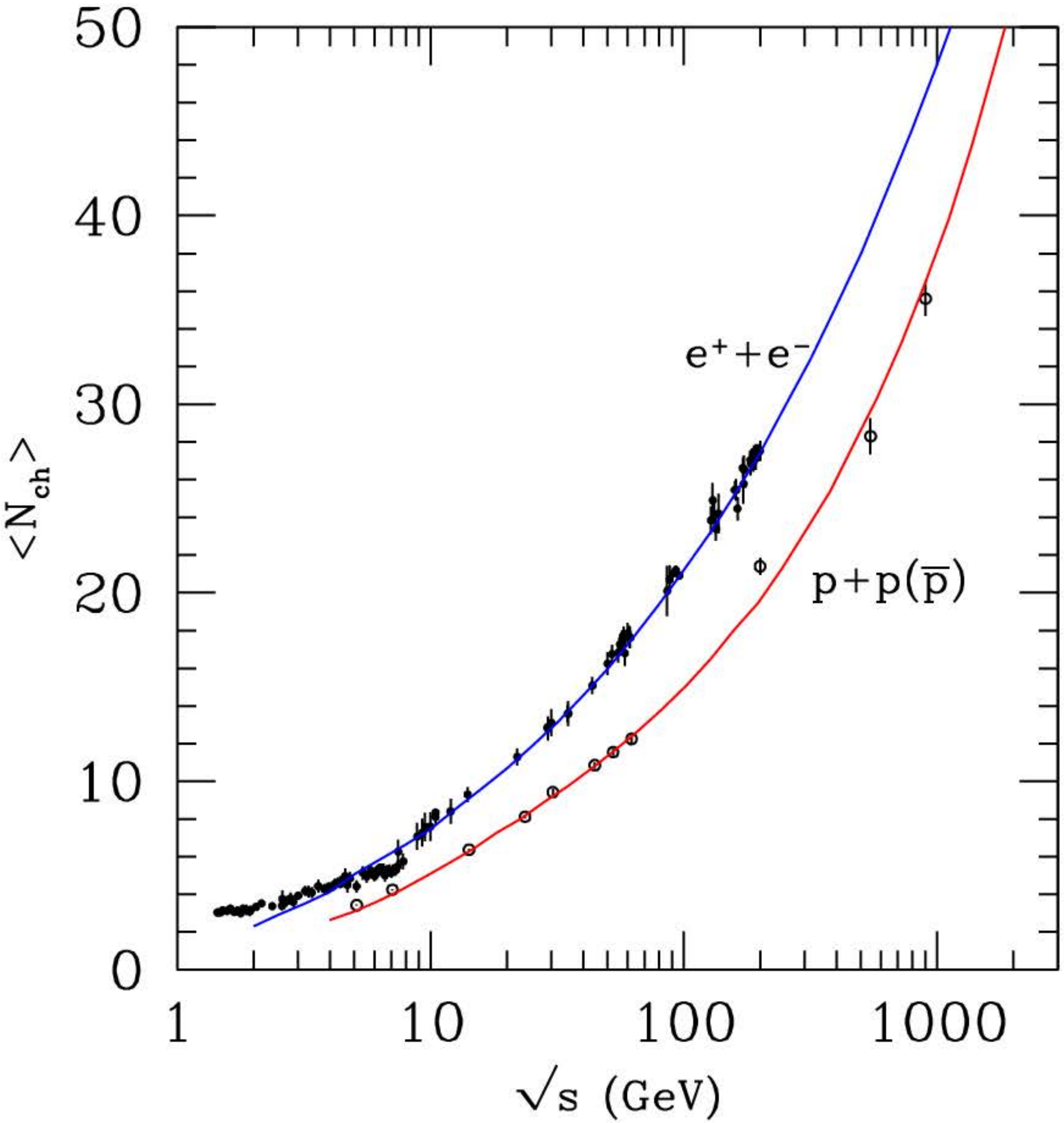


FIG. 3. Plot of the spectrum of the produced mesons ($\pi^+ + \pi^-$, $K^+ + K^-$, and K^0_L) as a function of the kinetic energy $E_{\rm kin}$. This is the case that the center of mass energy is $\sqrt{s} = 91.2$ GeV which corresponds to the Z^0 resonance. They are computed by using the JETSET 7.4 Monte Carlo event generator.



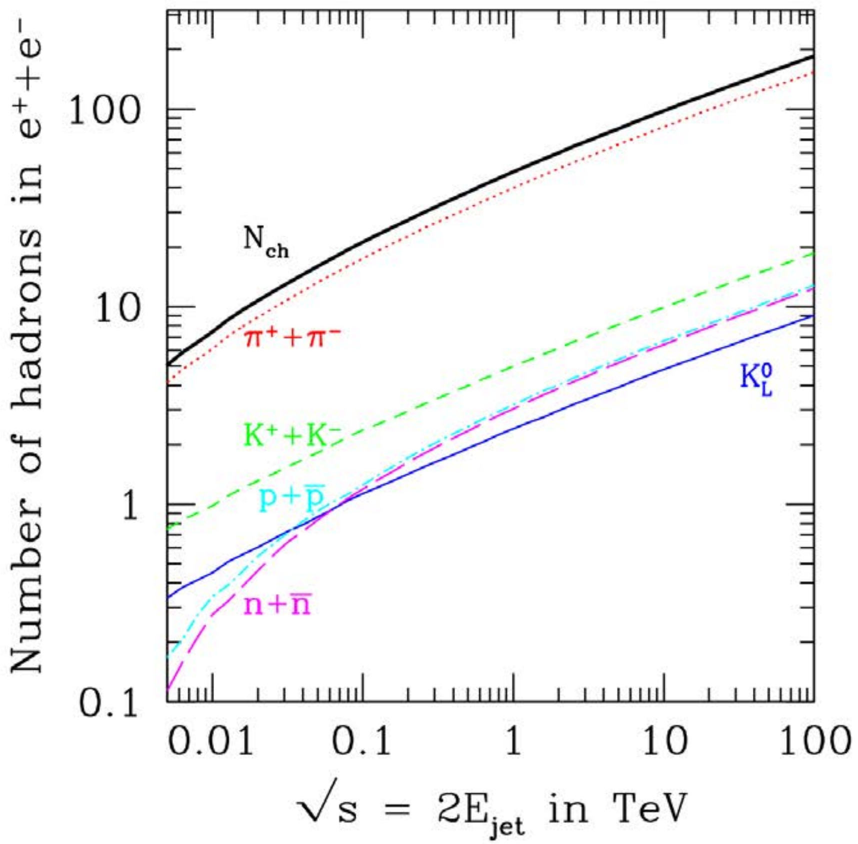
Kawasaki, Kohri, Moroi, arXiv:astro-ph/0408426

Charged particle multiplicity

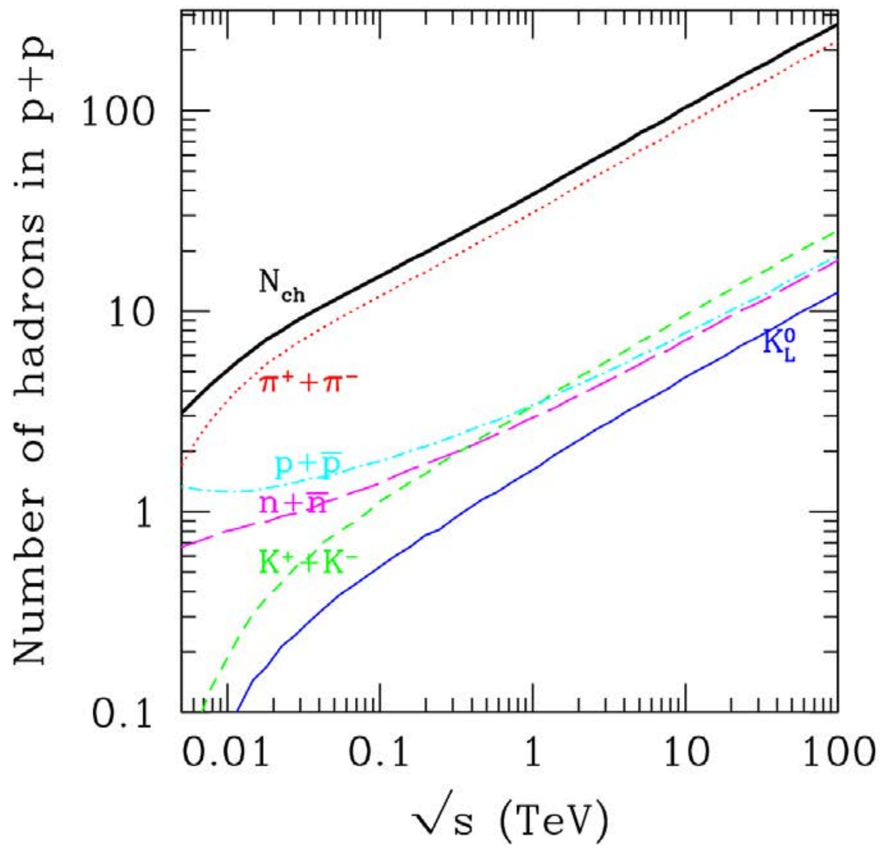


Kawasaki, Kohri, Moroi, arXiv:astro-ph/0408426

Number of hadrons in e+ e- scattering



Number of hadrons in pp scattering



K. Kohri, arXiv:astro-ph/0103411

Stopping of energetic hadrons

In the electromagnetic plasma of $e^{\pm}$ and γ, high energy hadrons are stopped until they scatter off the ambient nuclei?

$$R_{\rm stop}\left(E_i, T, Yp\right) \equiv n_N \int_{E_i}^{E_{\rm th}} \langle\sigma\beta\rangle \left(\frac{dE}{dt}\right)^{-1} dE$$

where,

$$\left(\frac{dE}{dt}\right) = \left(\frac{dE}{dt}\right)_{\rm Coulomb} + \left(\frac{dE}{dt}\right)_{\rm Compton} + \dots$$

(I) If $R_{\rm stop}\left(E_i, T, Yp\right) << 1$,

Hadrons are stopped electromagnetically

(II) If $R_{\rm stop}\left(E_i, T, Yp\right) >> 1$,

Hadrons scatter off the background nuclei with the energy E_f which is obtained by

$$\boxed{n_N \int_{E_i}^{E_f} \langle\sigma\beta\rangle \left(\frac{dE}{dt}\right)^{-1} dE = 1}$$

Coulomb Energy-Loss rate

1. <u>Non-relativistic charged nucleon</u> $(\beta < 1)$

i) $\beta_e < \beta$ (Bethe's formula, ionization loss rate, or plasma excitation, …)

$$\boxed{\frac{dE}{dt} = -\frac{4\pi\alpha^2 Z^2 \Lambda n_e}{m_e \beta}, \qquad \Lambda \sim O(1)}$$

velocity dependence

ii) $\beta < \beta_e$

$$\boxed{\frac{dE}{dt} = -\frac{4\pi\alpha^2 Z^2 \Lambda n_e \beta^2}{3 m_e \beta_e}, \qquad \Lambda \sim O(1)}$$

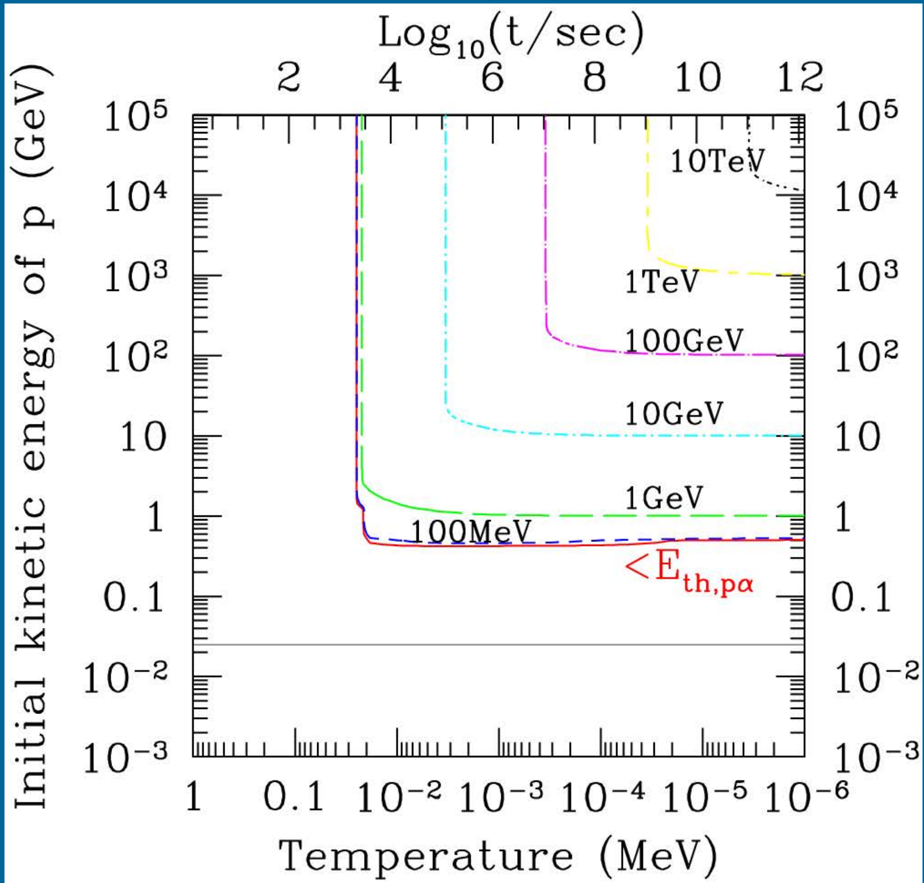
$$\left\langle \frac{dE}{dt} \right\rangle = \int \frac{dE}{dt} f_e(\beta_e) d\beta_e$$

$f_e(\beta_e)$: Maxwell-Boltzmann dist. func. of electrons

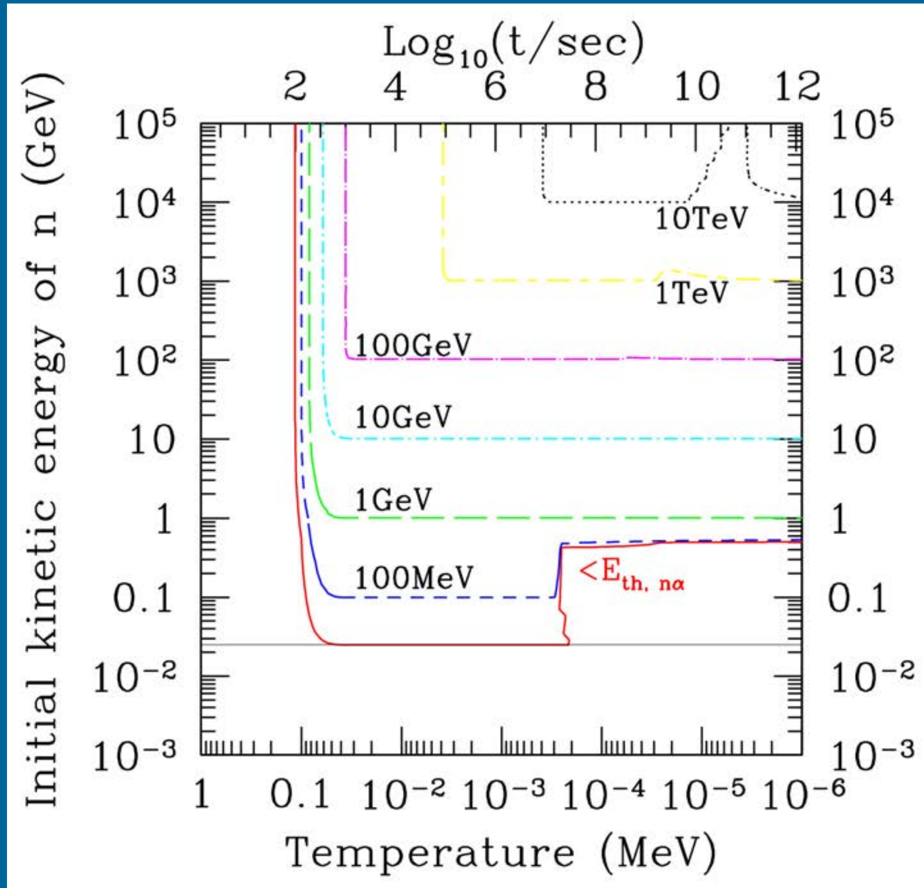
$$= \int_0^{\beta} \left.\frac{dE}{dt}\right|_{\beta_e < \beta} f_e(\beta_e) d\beta_e + \int_{\beta}^{\infty} \left.\frac{dE}{dt}\right|_{\beta < \beta_e} f_e(\beta_e) d\beta_e$$

Small!

Contours of final energy of energetic proton



Contours of final energy of energetic neutron



Kawasaki, Kohri, Moroi, arXiv:astro-ph/0408426

$$\text{(I) If } R_{\text{stop}}\left(E_i, T, Yp\right) \ll 1,$$

K. Kohri, arXiv:astro-ph/0103411

Only inter-conversion reactions between neutrons and protons by mainly mesons occur

Reno and Seckel (1988)

Kohri (2001)

$$\text{(II) If } R_{\text{stop}}\left(E_i, T, Yp\right) \gg 1,$$

Both inter-consersions between p and n, and destruction of Helium4 by energetic nucleons occur

Dimopoulos, Esmailzdeh, Hall, Starkman (1989)

K. Kohri, arXiv:astro-ph/0103411

(I) Early stage of BBN (before/during BBN)

Interaction between hadrons and nucleons

Pion

- $\pi^o \to 2\gamma$ $(\tau_{\pi^o} \cong 10^{-16}\ \mathrm{sec})$ Unimportant !
- $\pi^+ + n \to \begin{cases} p + \pi^o \\ p + \gamma \end{cases}$
- $\pi^- + p \to \begin{cases} n + \pi^o \\ n + \gamma \end{cases}$

kaon

- $K^- + p \to \begin{cases} \Sigma^- + \pi^+ \\ \Sigma^+ + \pi^- \\ \Sigma^o + \pi^o \end{cases}$
- $K^- + p \to \Lambda^o + \pi^o$
- $K^- + n \to \begin{cases} \Sigma^- + \pi^o \\ \Sigma^o + \pi^- \\ \Lambda^o + \pi^- \end{cases}$ $\Lambda^o \longrightarrow p + \pi^o$
- $K_L + N \to N' + \ldots$

Nucleon, Anti-nucleon

- $p\bar{p} + n(p) \to p + \ldots$
- $n\bar{n} + p(n) \to n + \ldots$

Inter-conversion between neutron and protons by mesons

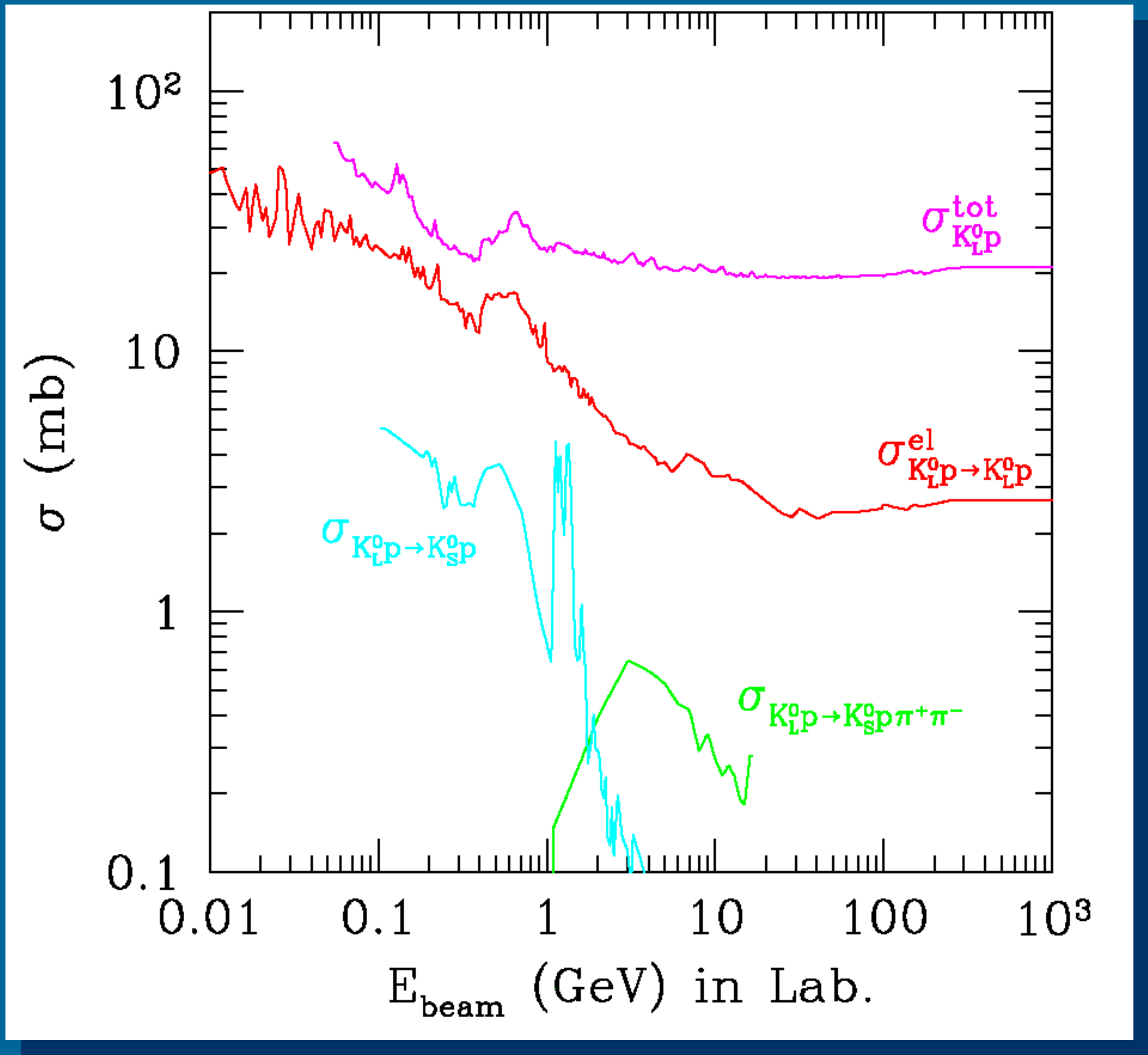
Reno and Seckel (1988)

Kohri (2001)

Here, conservatively we did not include anti-nucleon processes

Cross section of K0 + p scattering

K. Kohri, arXiv:astro-ph/0103411



Time scales

K. Kohri, arXiv:astro-ph/0103411

- Lifetime of Hadrons

  - $\tau_{\pi^\pm} = 2.6\times10^{-8}\,\mathrm{sec}$
  - $\tau_{K^\pm} = 1.2\times10^{-8}\,\mathrm{sec}$
  - $\tau_{K_L} = 5.2\times10^{-8}\,\mathrm{sec}$
  - $\tau_{n} = 887\,\mathrm{sec}$

- Hadron-Nucleon interaction rate

$$\boxed{\Gamma^{\mathrm{H_i}}_{\mathrm{N}\to\mathrm{N'}} = n_N \; \sigma^{\mathrm{H_i}}_{\mathrm{N}\to\mathrm{N'}} \; \beta \simeq \frac{1}{10^{-8}\,\mathrm{sec}}\left(\frac{T}{\mathrm{MeV}}\right)^3\left(\frac{\eta}{10^{-9}}\right)\left(\frac{\sigma^{\mathrm{H_i}}_{\mathrm{N}\to\mathrm{N'}}\;\beta}{10\mathrm{mb}}\right)}$$

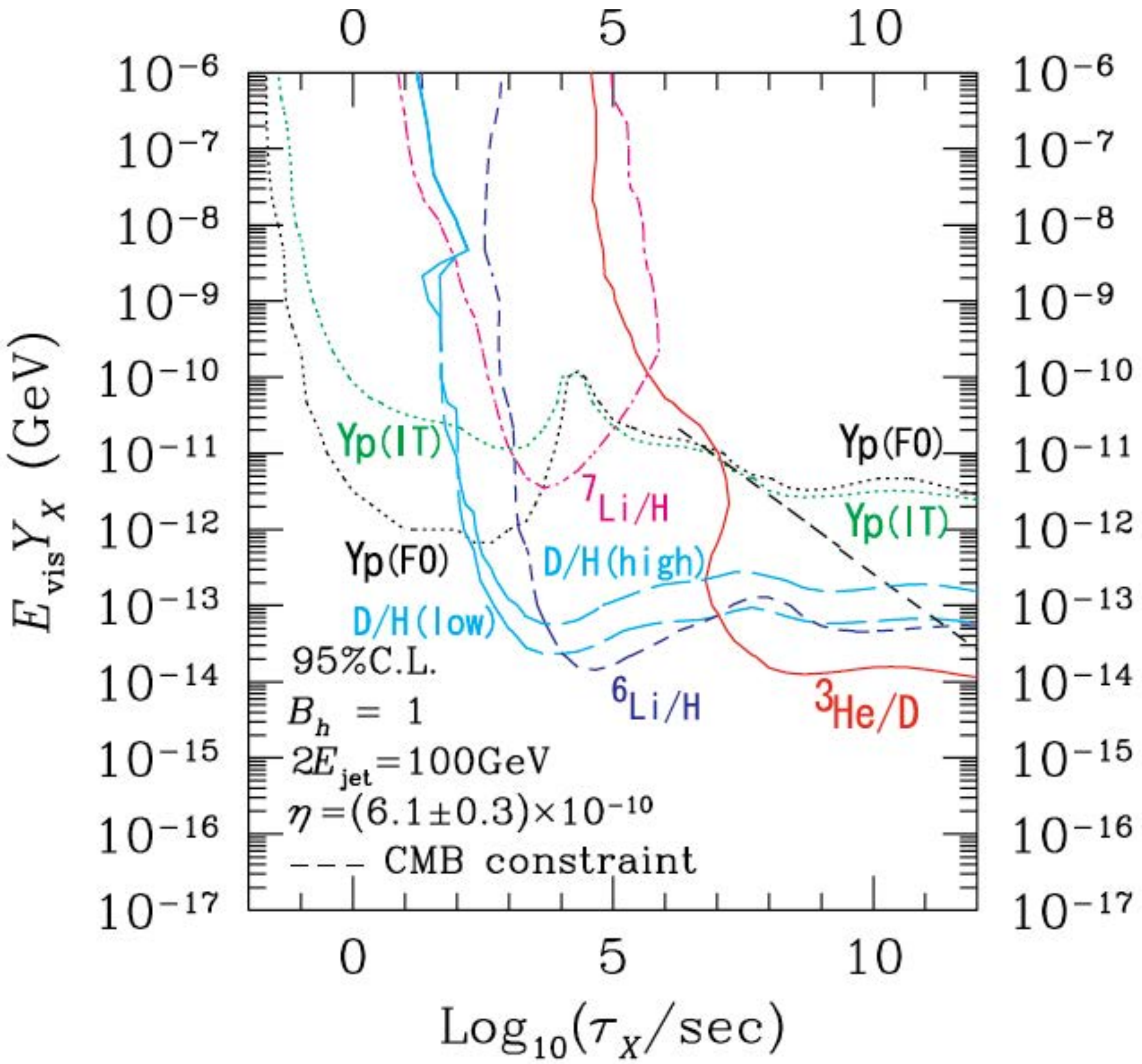
$$\frac{1}{\Gamma^{\mathrm{H_i}}_{\mathrm{N}\to\mathrm{N'}}} \simeq 10^{-8}\,\mathrm{sec}\left(\frac{T}{\mathrm{MeV}}\right)^{-3}$$

Sub-dominant case

$$\rho_{\phi} << \rho_{radiation}$$

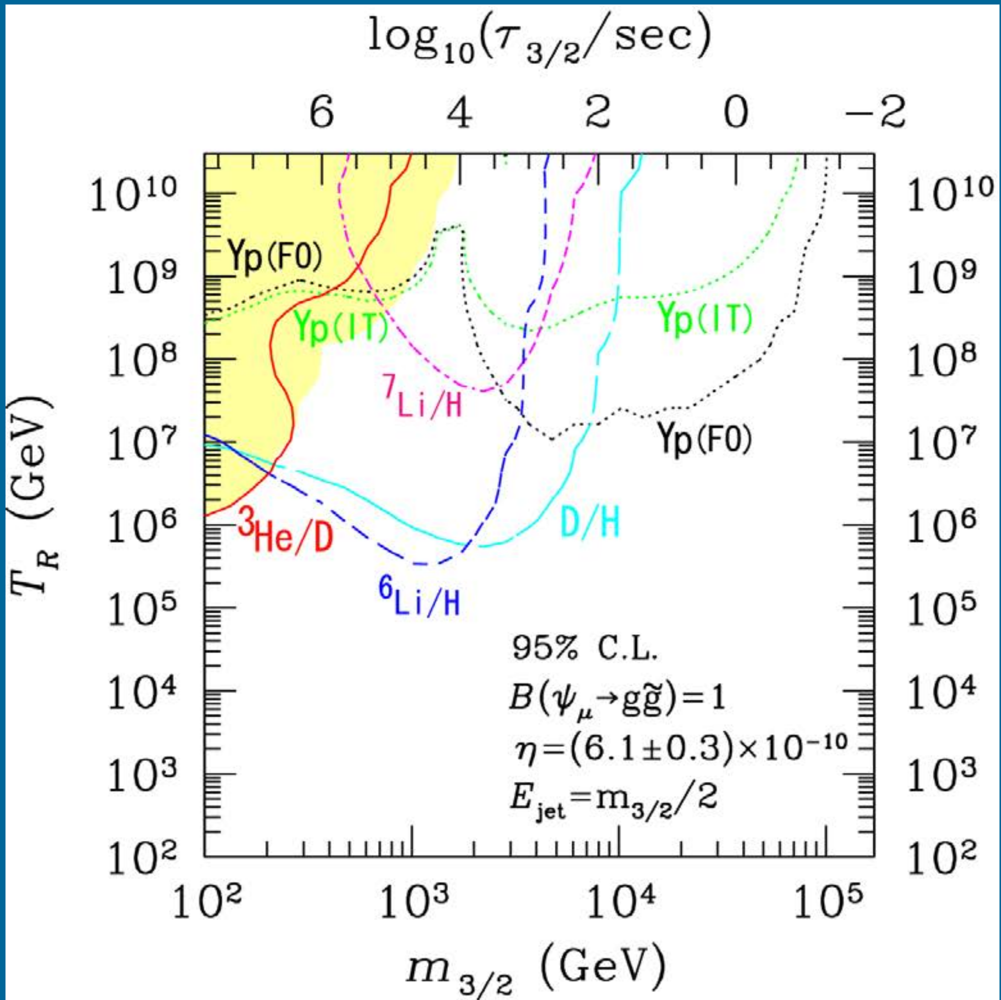
Bounds on hadronic injection

Kawasaki, Kohri, Moroi, arXiv: astro-ph/0408426



Upper bound on reheating temperature

Kawasaki, Kohri, Moroi, 2004



$$B_h(\psi_{3/2} \to g + \tilde{g}) = 1$$

$$T_R = 10^9\,\mathrm{GeV}\left(Y_{3/2}/10^{-12}\right)$$

$$m_{3/2} = 500\mathrm{GeV}\ (\tau_{3/2}/4\times10^5\,\mathrm{sec})^{-1/3}$$

Neutrino injection

Kanzaki, Kawasaki, Kohri, Moroi, hep-ph/0609246
Kanzaki, Kawasaki, Kohri, Moroi, arXiv:0705.1200 [hep-ph]

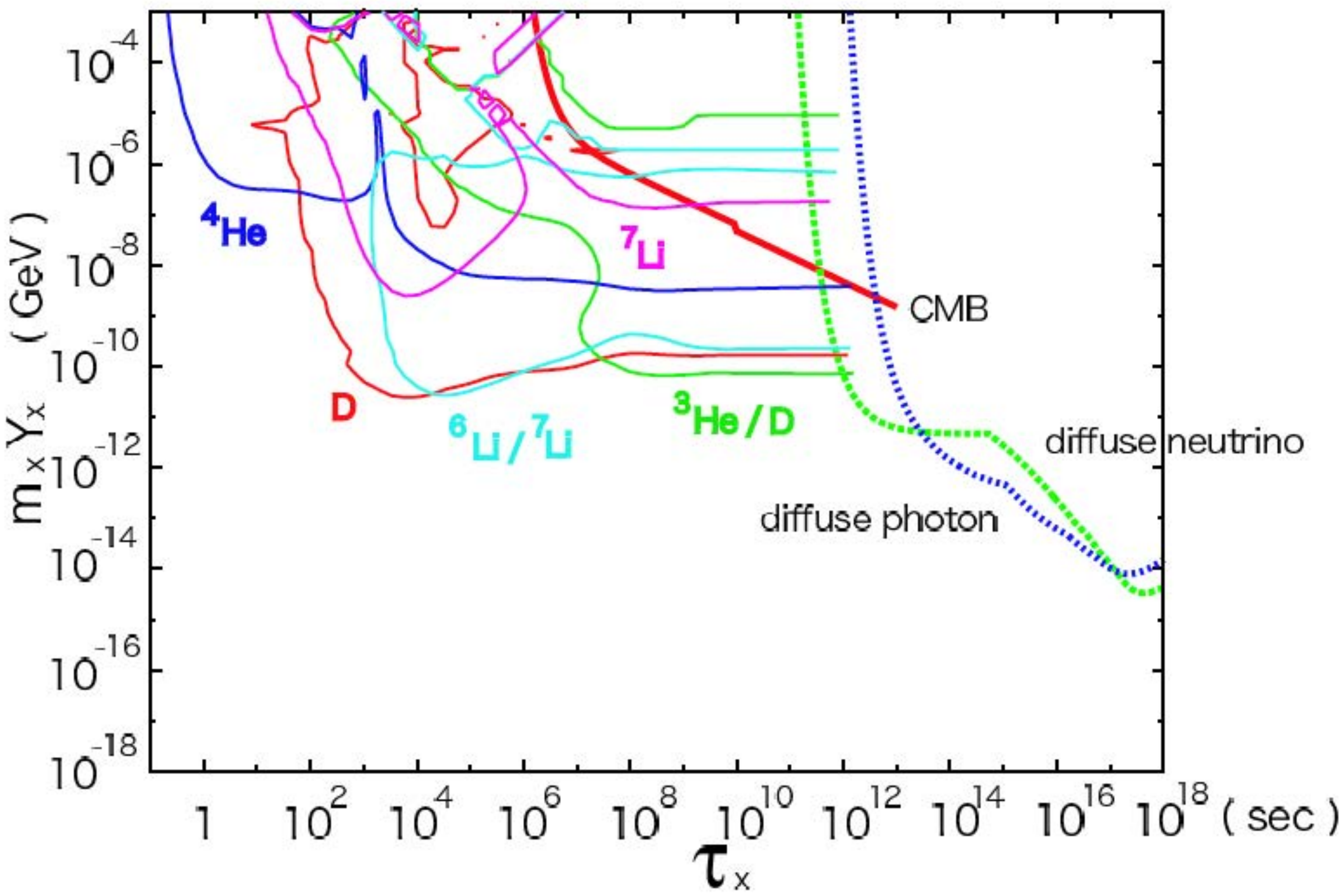
- $\nu^* + \nu_{BG} \rightarrow e^* + e^*$: electromagnetic injection
- $\nu^* + e_{BG} \rightarrow \nu^* + e^*$: electromagnetic injection

- $\nu^* + \nu_{BG} \rightarrow q^* + q^*$: hadronic injection

- $\nu^* + \nu_{BG} \rightarrow \nu^* + \nu^*$: Self-interaction (so slow)

Bounds on neutrino injections

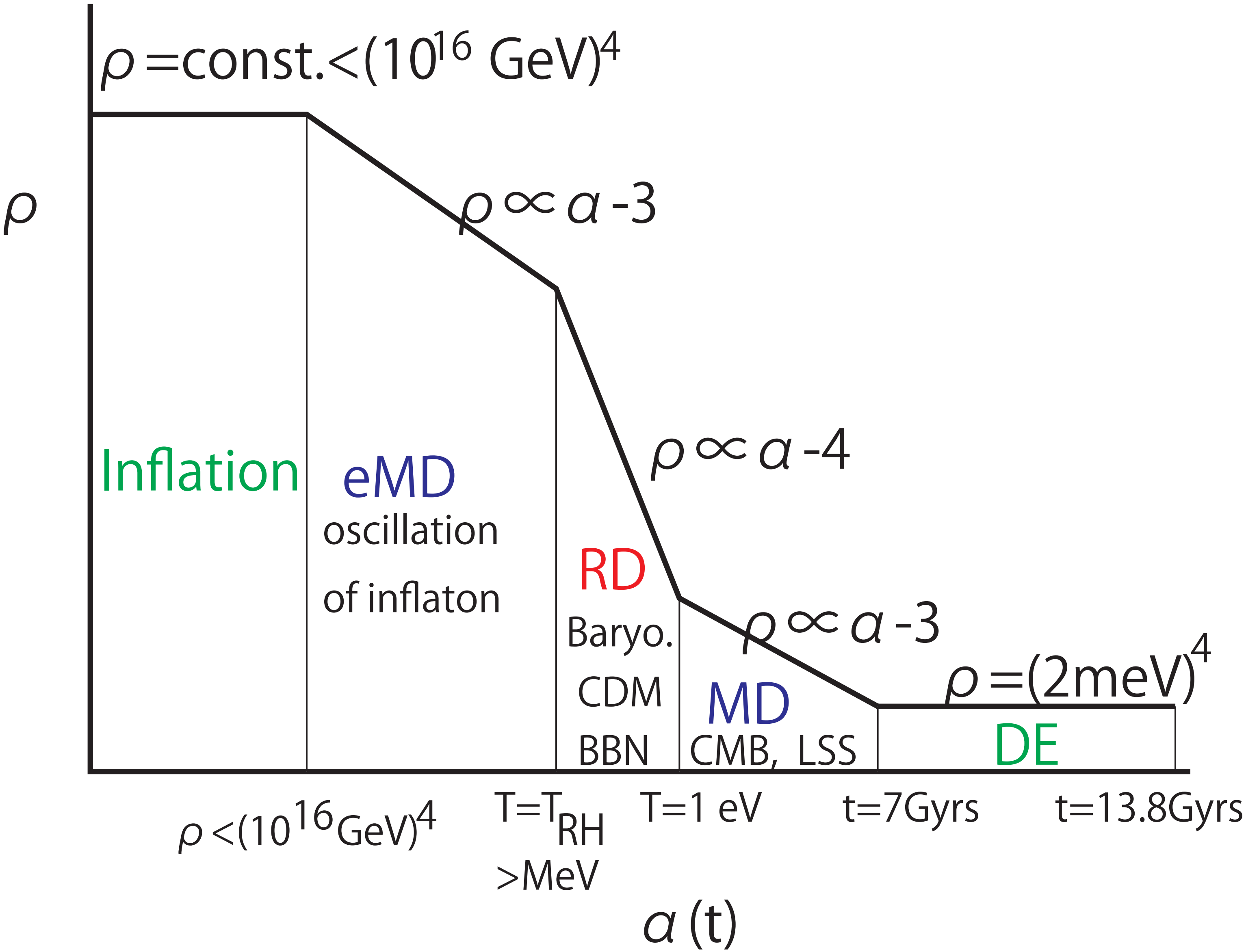
Kanzaki, Kawasaki, Kohri, Moroi, arXiv:0705.1200 [hep-ph]



Dominant case
(MeV-scale reheating)

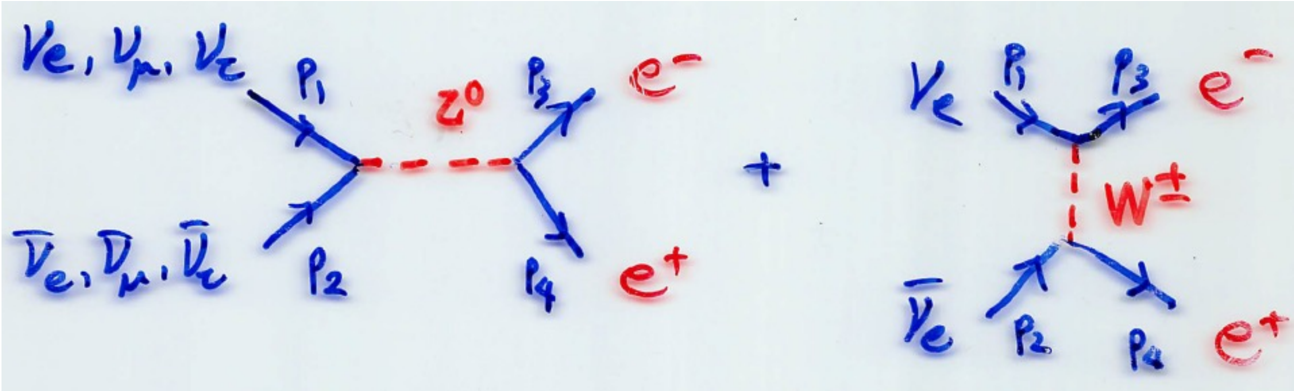
$$\rho_\phi >> \rho_{radiation}$$

Thermal History

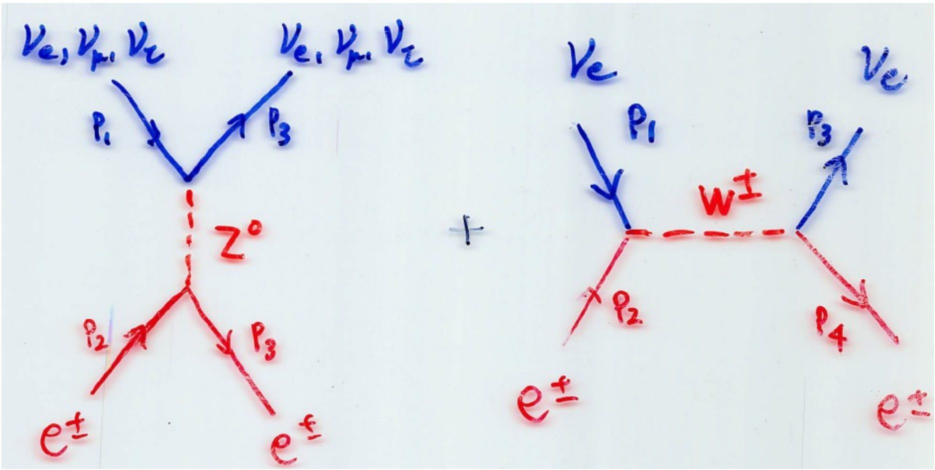


Time evolution of $f_{\nu i}(p)$

- Production and Annihilation



- Scattering



ν_e has a stronger interation with plasma through $W^\pm$

Feezeout of weak interaction

- Weak interaction rate

$$\Gamma \sim \sigma_{n\leftrightarrow p} n_e \sim T^5 / m_W^4$$

- Expansion rate

$$H = \frac{\sqrt{\rho}}{3m_{\text{planck}}} \sim \sqrt{g_*}\frac{T^2}{m_{\text{planck}}}$$

$$g_* \sim 3.36\left[1+0.14(N_{\nu,\text{eff}}-3)\right]$$

$$\boxed{\frac{\Gamma}{H} \sim \frac{T^3 m_{\text{planck}}}{\sqrt{g_*}m_W^4} \sim \left(\frac{T}{0.8\ \text{MeV}}\right)^3 \left[1+0.14(N_{\nu,\text{eff}}-3)\right]^{-1/2}}$$

Helium 4 mass fraction Y

- Analytically we obtain the primordial value

$$Y_p \sim \frac{1}{4} + 0.01\Delta N_\nu + 0.01\ln(\eta_{10}/6) + 0.1\left(\frac{\tau_n - 880\,sec}{880\,sec}\right)$$

N_ν : effective number of neutrino species

$\eta = \dfrac{n_B}{n_\gamma} = \eta_{10} \times 10^{-10}$: baryon to photon ratio

τ_n : neutron life time

Imperfect thermalization of neutrinos by MeV-scale reheating

Kawasaki, Kohri, and Sugiyama, 1998; 2000

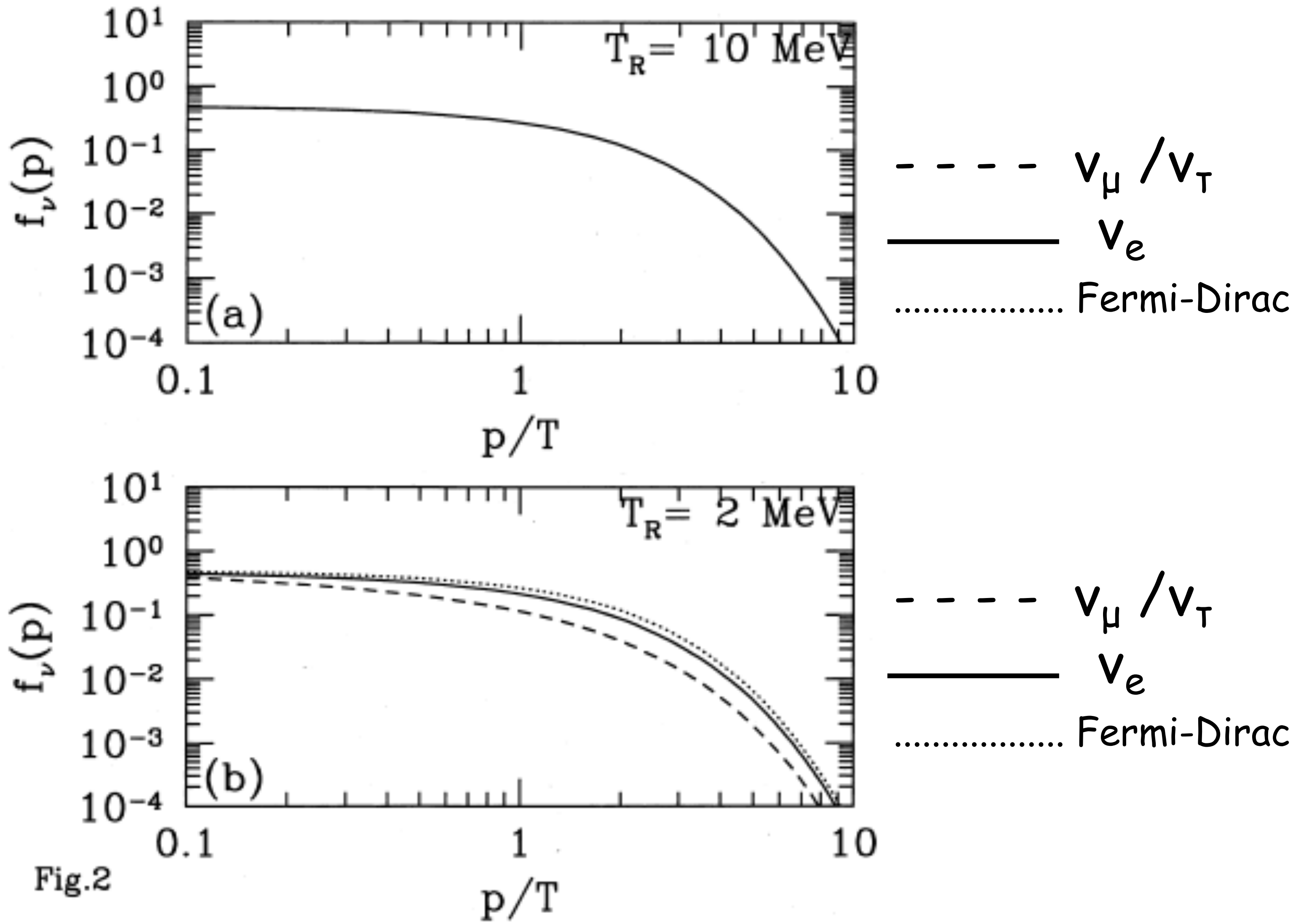
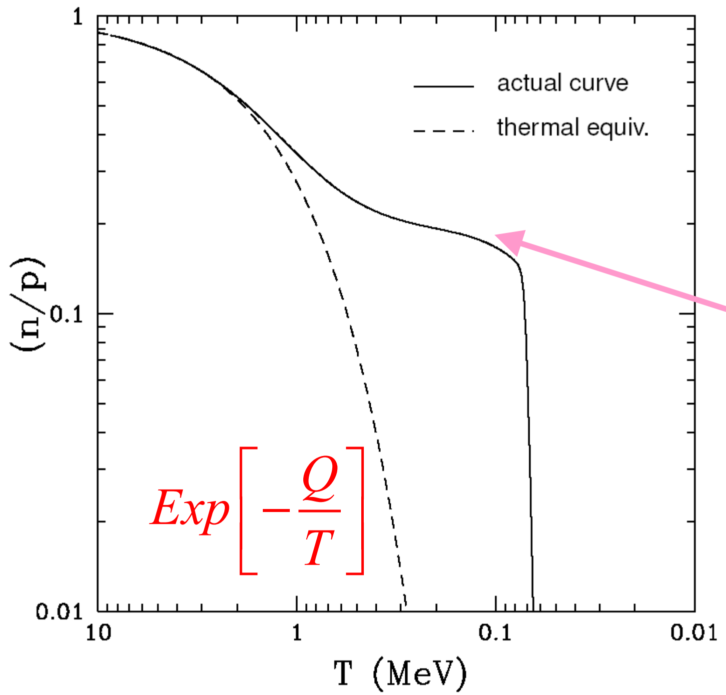


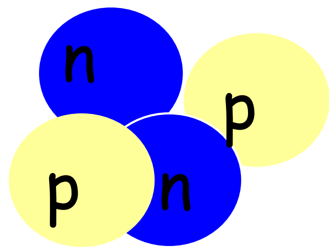
Fig.2

He4 mass fraction Y



$$\left(\frac{n_n}{n_p}\right)_{\text{freezeout}} \approx \frac{1}{7}$$

^4He



$$n_{^4\text{He}} = n_n / 2$$

$$Y_p \equiv \frac{\rho_{^4\text{He}}}{\rho_B} \approx \frac{4\times \cancel{m_N} \times n_{^4\text{He}}}{\cancel{m_N} \times (n_n + n_p)} \approx \frac{2(n_n / n_p)_{\text{freezeout}}}{(n_n / n_p)_{\text{freezeout}} + 1} \approx 0.25$$

Neutrino IMPERFECT thermalisation and Big Bang Nucleosynthesis

- Modifications on interaction rates due to MeV reheating and oscillations amog $\nu_e \leftrightarrow \nu_\mu$ and/or ν_τ

$$\Gamma_{n\nu_e \to pe^-} = K \int_0^\infty dp_{\nu_e} \left[\sqrt{(p_{\nu_e}+Q)^2 - m_e^2}\,(p_{\nu_e}+Q) \frac{p_{\nu_e}^2}{1+e^{-(p_{\nu_e}+Q)/T_\gamma}} f_{\nu_e}(p_{\nu_e}) \right]$$

$$\boxed{\Delta Y \simeq +0.19(-\Delta\Gamma_{n\leftrightarrow p}/\Gamma_{n\leftrightarrow p})}$$

- Modifications on energy density

$$N_\nu^{\rm eff} \equiv \frac{\rho_{\nu_e}+\rho_{\nu_\mu}+\rho_{\nu_\tau}}{\rho_{\rm std}} \ll 3?$$

$$\boxed{\Delta Y \simeq -0.1(-\Delta\rho_{tot}/\rho_{tot})}$$

Neutrino oscillation in the early Universe

Quantum Kinetic Equation

$$\frac{d\varrho_p}{dt} = \frac{\partial \varrho_p}{\partial t} - Hp\frac{\partial \varrho_p}{\partial p} = \boxed{-i\left[\mathcal{H}_p, \varrho_p\right]} \boxed{+ C\left(\varrho_p\right)}$$

ν oscillation $\quad$ ν production/collision

density matrix for ν (2 flavor) ν_e - ν_x $\qquad e^- + e^+ \to \nu_\alpha + \nu_\alpha$

$$\varrho_p = \begin{pmatrix} \rho_{ee} & \rho_{ex} \\ \rho_{ex}^* & \rho_{xx} \end{pmatrix}$$

diagonal: ν distribution

off-diagonal: flavor coherence

$$\mathcal{H}_p = \boxed{\frac{\mathrm{M}^2}{2p}} \boxed{- \frac{8\sqrt{2}G_{\mathrm{F}}p}{3}\left[\frac{\boldsymbol{E}_l}{m_W^2} + \frac{\boldsymbol{E}_\nu}{m_Z^2}\right]}$$

matter effect

$$\mathrm{M}^2 = U\mathcal{M}^2U^\dagger \quad \mathcal{M}^2 = \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \quad U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

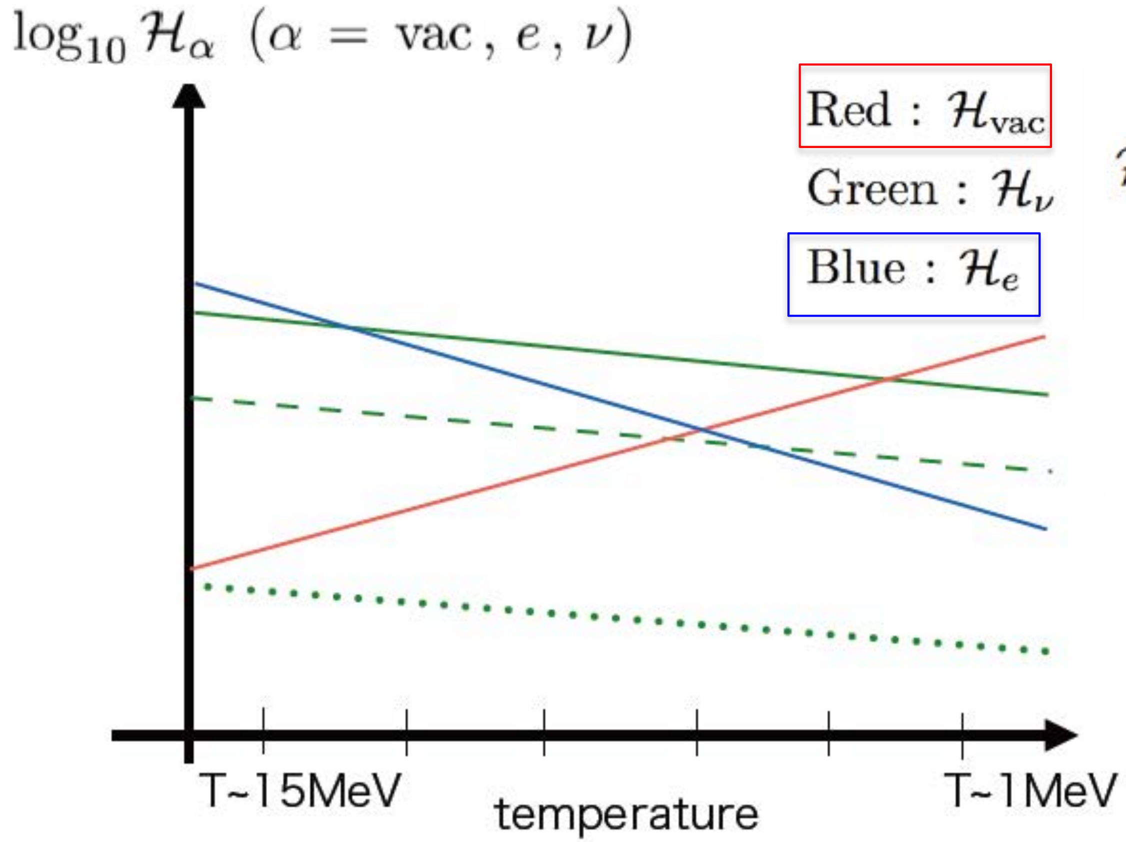
$$\boldsymbol{E}_l \sim \mathrm{diag}(\rho_e, 0) \quad \boldsymbol{E}_\nu \sim \mathrm{diag}(\rho_{\nu_e}, \rho_{\nu_x})$$

MSW-like effective mass difference in the early Universe

$$\frac{\delta m_M^2}{2p} = \sqrt{\left(\frac{\delta m^2}{2p}\right)^2 \sin^2 2\theta + (\mathcal{H}_{\rm vac} + \mathcal{H}_{\rm mat})^2}$$

$$\sin^2 2\theta_M = \frac{\left(\frac{\delta m^2}{2p}\right)^2 \sin^2 2\theta}{\left(\frac{\delta m^2}{2p}\right)^2 \sin^2 2\theta + (\mathcal{H}_{\rm vac} + \mathcal{H}_{\rm mat})^2}$$

MSW-type resonance (oscillation) in the early Universe



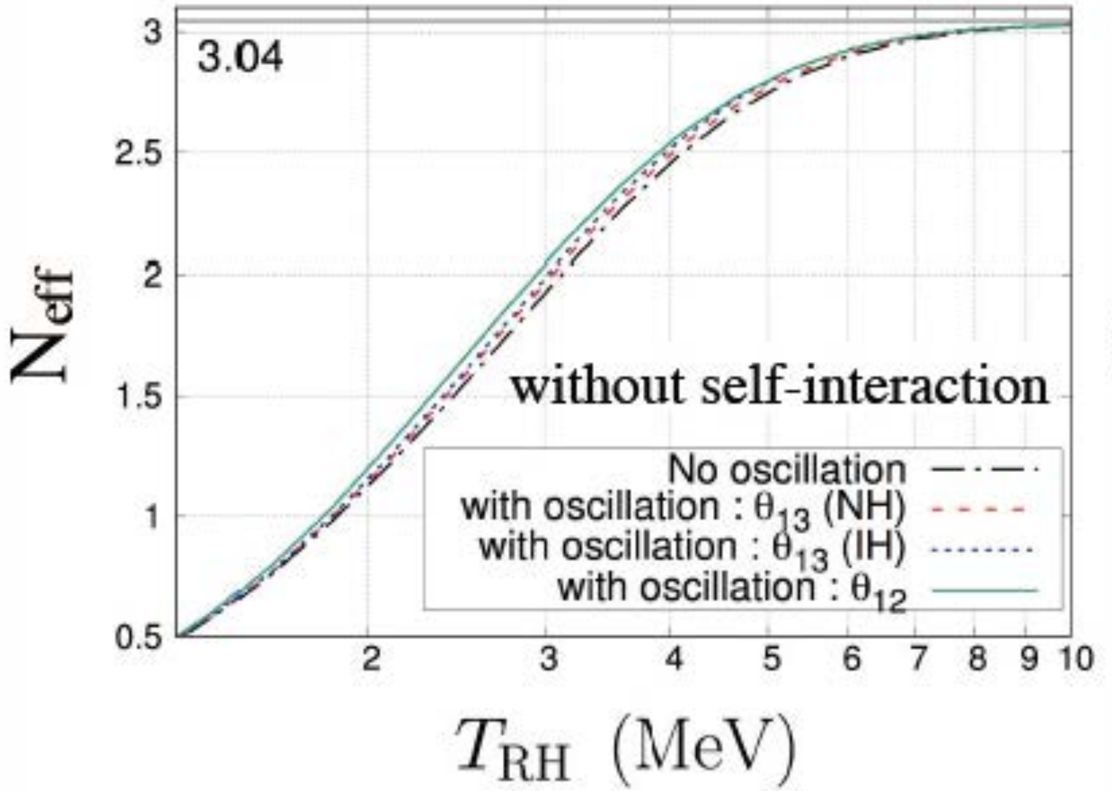
$$\mathcal{H} = \boxed{\mathcal{H}_{\mathrm{vac}}} + \boxed{\mathcal{H}_e} + \mathcal{H}_\nu$$
$$= \boxed{\frac{\delta m^2}{2E}\mathrm{B}} - \boxed{\frac{8\sqrt{2}G_F E \varrho_{e^\pm}}{3m_W^2}\mathrm{L}}$$
$$+ \frac{\sqrt{2}G_F}{2\pi^2}\int dE' E'^2 \left[\rho\left(E'\right) - \bar{\rho}^*\left(E'\right)\right]$$

$$\mathrm{B} = \mathrm{U}\left(\mathrm{diag}\left[-1/2, 1/2\right]\right)\mathrm{U}^\dagger, \mathrm{L} = \mathrm{diag}\left[1, 0\right]$$

$$|\mathcal{H}_{\mathrm{mat}}| \approx |\mathcal{H}_{\mathrm{vac}}| \;\Rightarrow$$
$$T_c \approx G_F^{-1/3}\left(\delta m^2 \cos 2\theta\right)^{1/6} \approx \begin{cases} 3\,\mathrm{MeV}\left(\dfrac{\delta m_{12}^2}{2.5\times 10^{-3}\,\mathrm{eV}^2}\right)^{1/6} \\ 5\,\mathrm{MeV}\left(\dfrac{\delta m_{13}^2}{7.5\times 10^{-5}\,\mathrm{eV}^2}\right)^{1/6} \end{cases}$$

Thermalization of three active neutrinos

T.Hasegawa, Kohri, Hiroshima, Hansen, Tram, Hannestad, arXiv:1908.10189 [hep-ph]



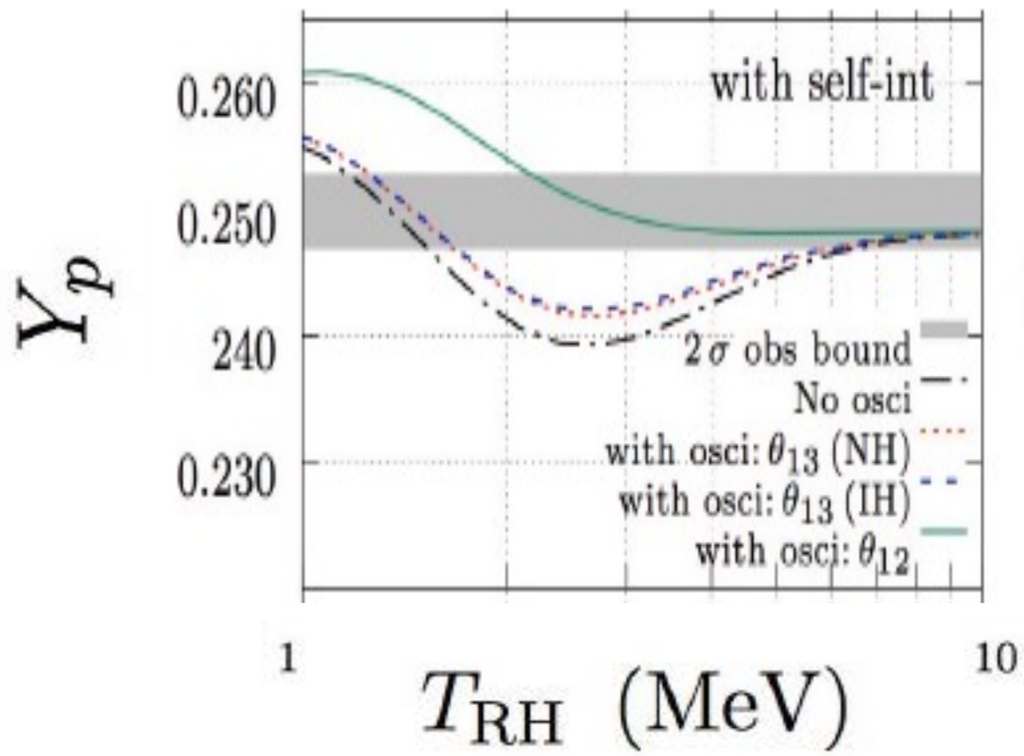
$T_{\mathrm{RH}} \searrow$ $\quad$ $\mathrm{N}_{\mathrm{eff}} \searrow$

with ν oscillation or self-int. $\rightarrow$ $\mathrm{N}_{\mathrm{eff}} \nearrow$

Helium 4 abundance Y

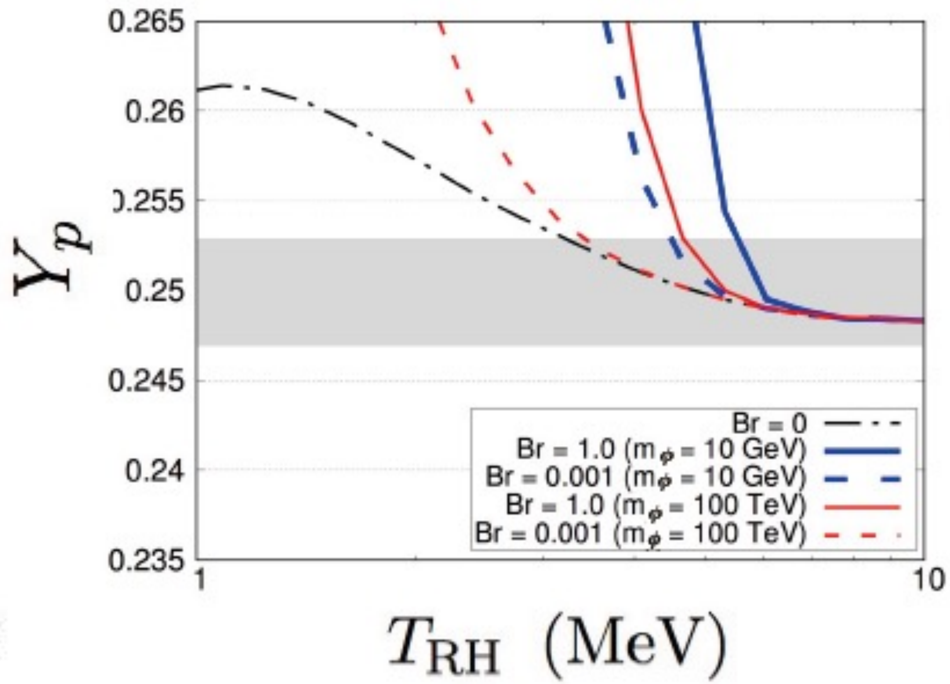
T.Hasegawa, Kohri, Hiroshima, Hansen, Tram, Hannestad, arXiv:1908.10189 [hep-ph]

Radiative decay



$\rightarrow \gamma, e^{\pm} \rightarrow \nu$'s

Hadronic decay



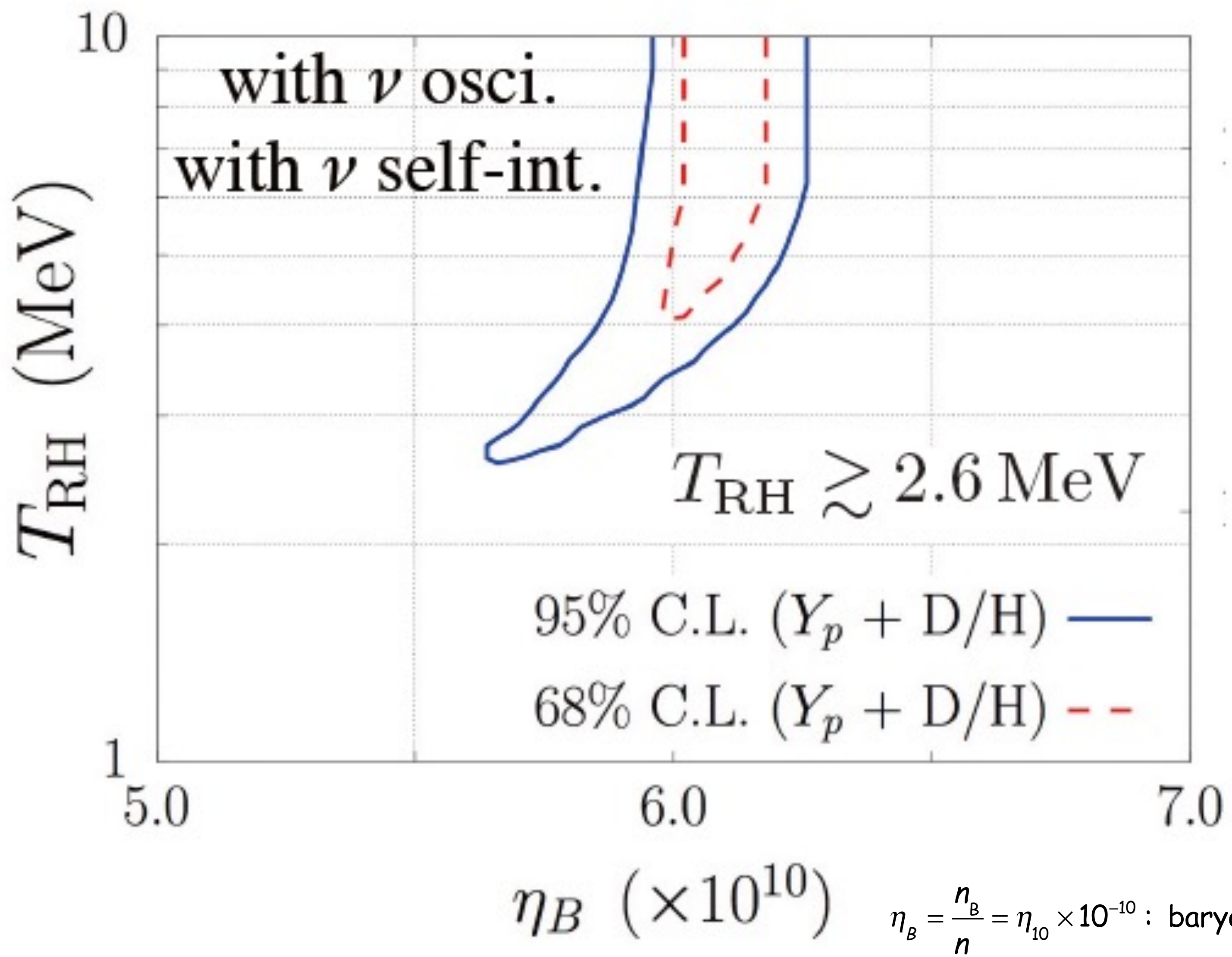
$\rightarrow$qq, gluon$\rightarrow \pi$'s

$$n + \pi^{+} \rightarrow p + \pi^{0}$$
$$p + \pi^{-} \rightarrow n + \pi^{0}$$

n/p ↗

Lower bound on T_{RH} for radiative decay

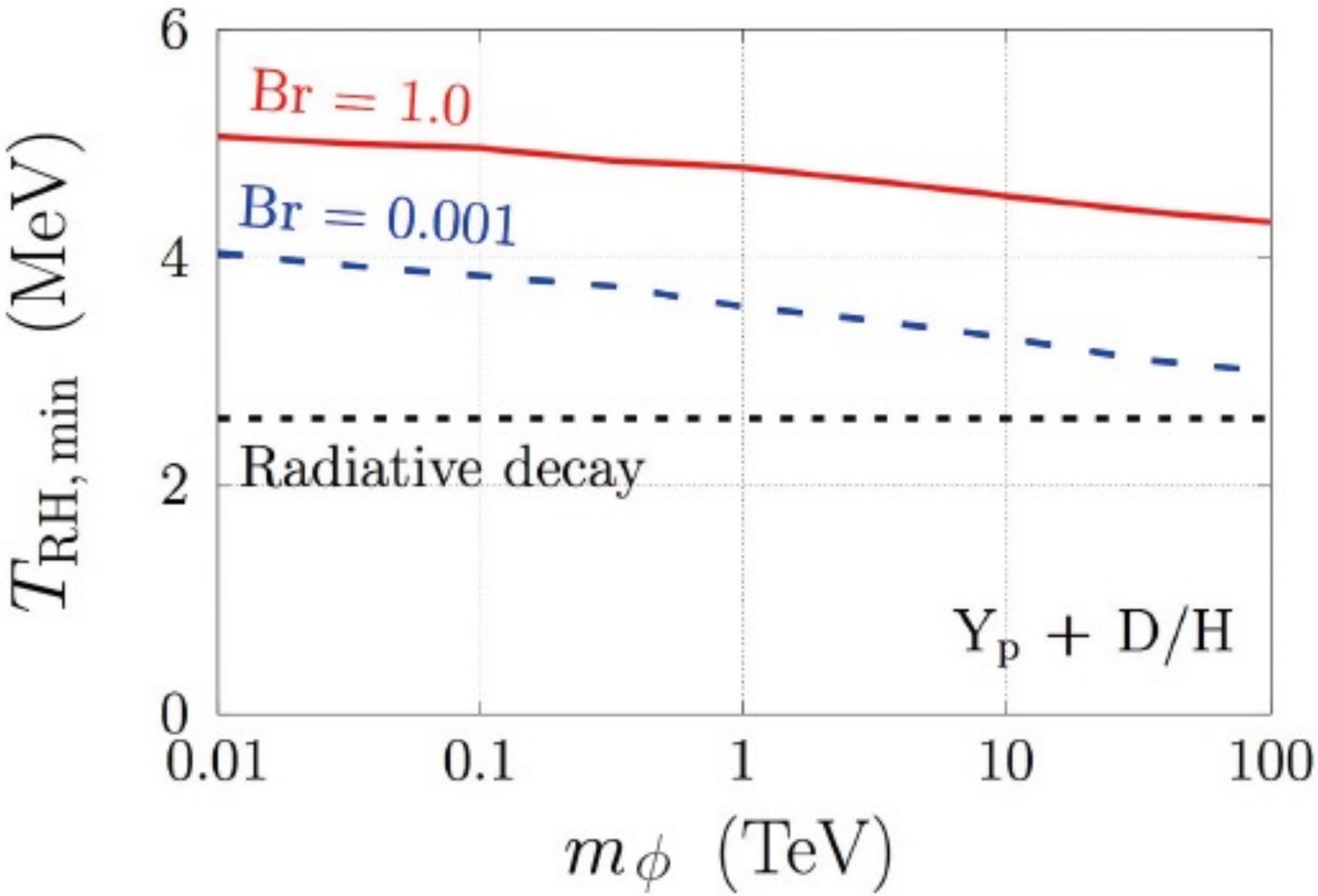
T.Hasegawa, Kohri, Hiroshima, Hansen, Tram, Hannestad, arXiv:1908.10189 [hep-ph]



$\eta_B = \frac{n_B}{n_\gamma} = \eta_{10} \times 10^{-10}$: baryon to photon ratio

Lower bounds on T_{RH} for hadronic decay

T.Hasegawa, Kohri, Hiroshima, Hansen, Tram, Hannestad, arXiv:1908.10189 [hep-ph]



What about thermalization of sterile neutrinos with a MeV-scale reheating?

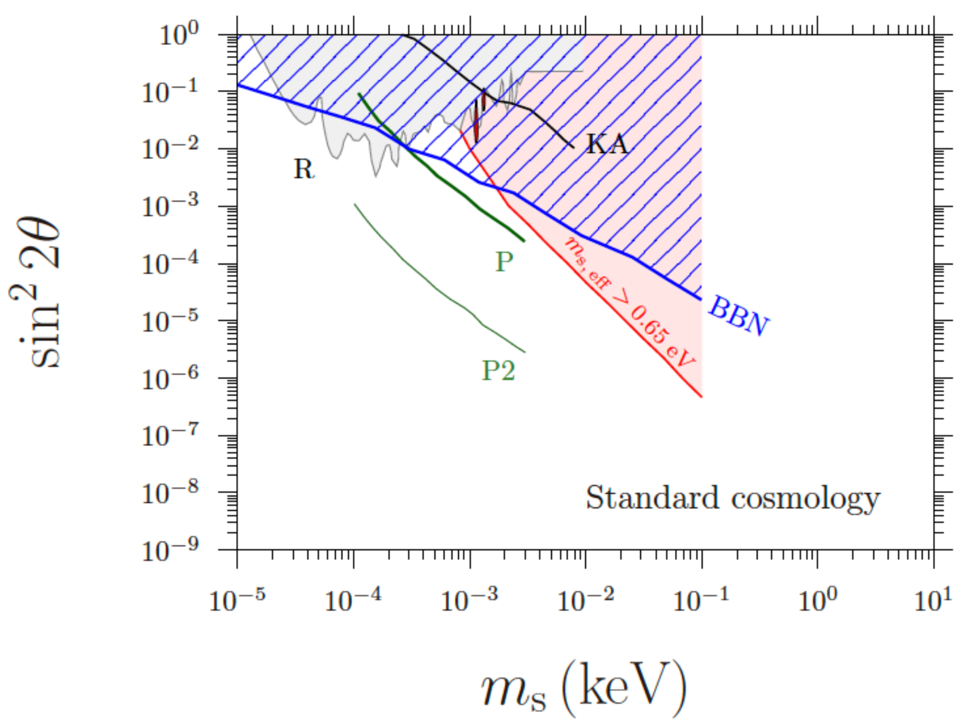
Outstanding Problem!

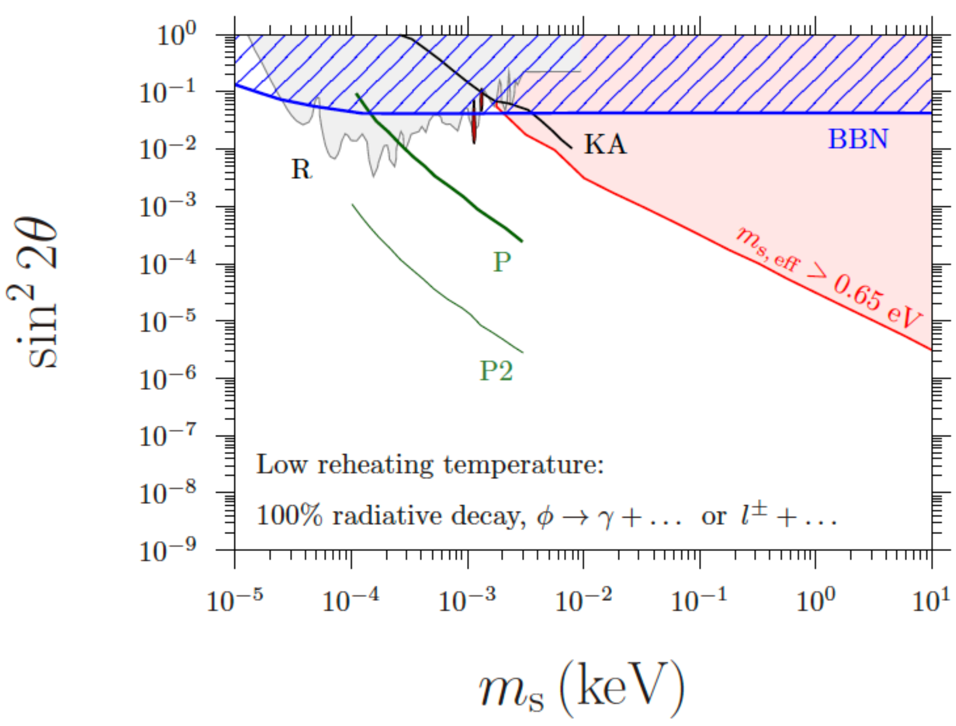
T.Hasegawa, Kohri, Hiroshima, Hansen, Tram, Hannestad, arXiv:2003.13302 [hep-ph]

A solution of reactor anomaly

$T_R \sim 5$MeV

T.Hasegawa, Kohri, Hiroshima, Hansen, Tram, Hannestad, arXiv:2003.13302 [hep-ph]





$T_R \gg 5$ MeV

$T_R \sim 5$MeV

Conclusion

- In supergravity, we may naturally expect a O(1) MeV scale reheating temperature. then Neutrino oscillations in the early Universe are so effective
- From BBN (and CMB), we can constrain the lower bound on T_R to be $T_{RH} >\sim 5$ MeV even for hadronic-decay scenarios
- From observations, we will obtain information of sterile neutrinos which couple to active neutrinos
- This work of three active-flavors oscillations with hadronic decay scenario is the world's first!