Primordial lepton oscillations and baryogenesis

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CP violation

CP violation can happen in neutrino oscillation phenomena.

$$P(\nu_i \to \nu_j) \neq P(\bar{\nu}_i \to \bar{\nu}_j)$$

Discovery soon?

responsible for **baryogenesis**???

sounds interesting, but …

neutrino masses are produced after the electroweak phase transition (Higgs mechanism).

neutrino is extremely light —> small effect at high energy.

CP violation in the vacuum appears at a very higher order

$$A_{\rm CP}^{(\mu e)} = - A_{\rm CP}^{(\tau e)} = A_{\rm CP}^{(\tau\mu)} =$$
$$4\, J_{\rm CP} \left(\sin\frac{\Delta m_{32}^2}{2p}\, L + \sin\frac{\Delta m_{21}^2}{2p}\, L + \sin\frac{\Delta m_{13}^2}{2p}\, L\right),$$

$$J_{\rm CP} = {\rm Im}\left(U_{\mu 3}\, U_{e3}^*\, U_{e2}\, U_{\mu 2}^*\right)$$

no hope?

We think,

we found an interesting possibility.

inflation

↓

Inflaton decays into leptons

↓ CP violating oscillation in thermal plasma

flavor dependent lepton asymmetry

↓ flavor dependent washing out

converted into net lepton number

↓ spharelon

baryon asymmetry

neutrino oscillations + some details

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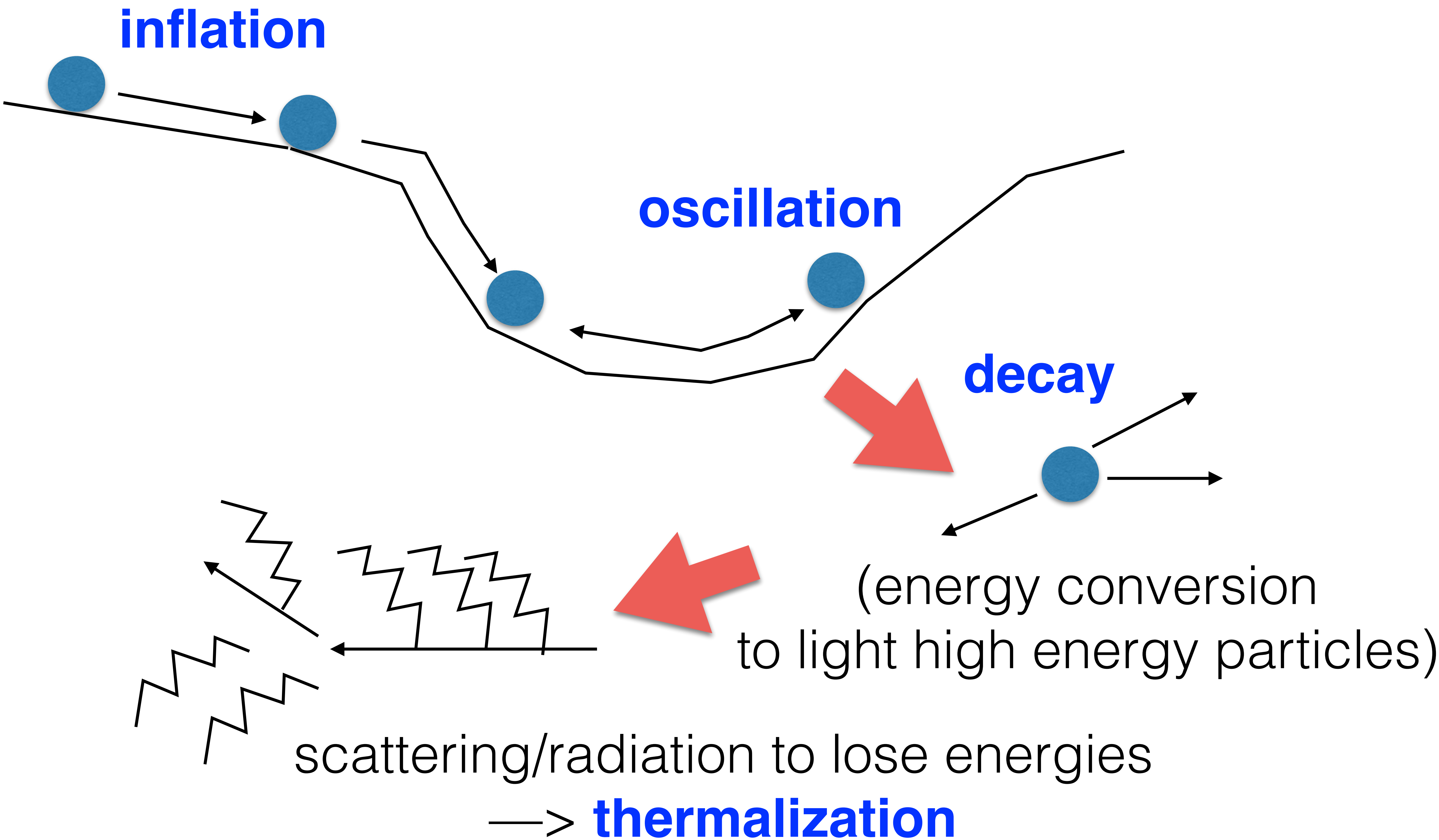
inflation and reheating



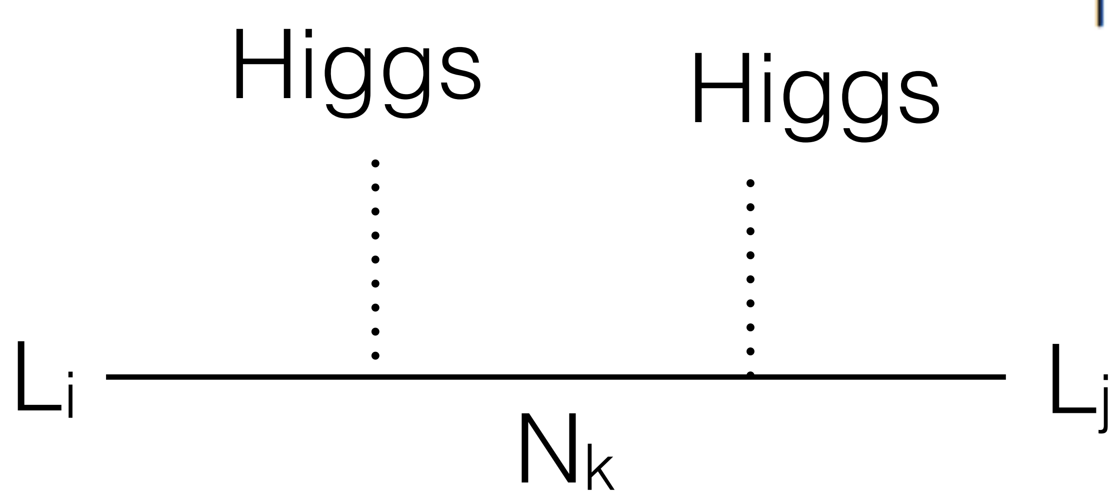
this is clearly a **one-way** process.

a good opportunity for baryogenesis!

Almost automatic!

Seesaw model:

$$
\begin{aligned}
\mathcal{L}_{\rm int} = & -y_\nu^{ij}\bar{N}_i P_L(l_j\cdot\tilde{H}) + \text{h.c.} \\
& + \frac{M_i}{2}\bar{N}_i^c N_i + \text{h.c.} \\
& + y_e^l \bar{e}_l P_L(l_l\cdot H) + \text{h.c.}
\end{aligned}
$$



In the early Universe, there are lots of Higgs bosons.

propagation becomes **flavor** dependent!

modified speed of light

$$w = k - \boxed{\mathrm{Re}\left[b_{ll'}\right]}$$

thermal correction

$$b_{ll'} \simeq -\frac{T^2}{16k}(y_e^l)^2\delta_{ll'} + \frac{\pi^2 T^4}{9M_k^4} y_\nu^{kl*} y_\nu^{kl'} k,$$

flavor diagonal
(charged lepton Yukawa)

flavor **non**-diagonal

(not quite a mass,
but anyway non-diagonal)

the second term gets important at high energy!

primordial lepton oscillation

phase difference

$$|t = \Delta t\rangle = e^{-i\omega_i \Delta t} e^{ik_i \Delta x} |t = 0\rangle$$

$$\begin{aligned}\delta\phi_{jk} &= (\omega_j - \omega_k)\Delta t - (k_j - k_k)\Delta x \\ &= (k_j - k_k)(\Delta t - \Delta x) - \Delta b_{jk}\Delta t \\ &\simeq -\Delta b_{jk}\Delta t,\end{aligned}$$

$$U^\dagger b U = b^{\rm diag}$$

$$\Delta b_{jk} = b_j^{\rm diag} - b_k^{\rm diag},$$

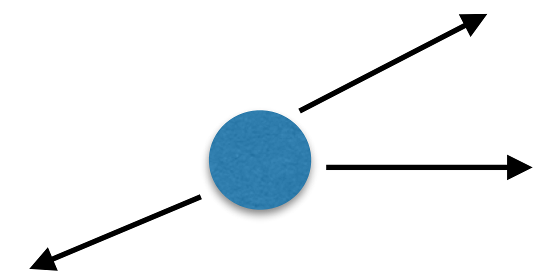
$$\Delta t \simeq \Gamma^{-1},$$

$$\Gamma \sim \frac{g_2^2}{4\pi} T.$$

(mean free time of leptons)

baryogenesis

step 1: inflaton decay



$$\phi \rightarrow l_i + X$$

(and its CP conjugate process)

a particular combination of the "mass" eigenstates is produced.

$$|l_\phi\rangle = \sum_{j=1,2,3} V_j^* |j\rangle.$$

basis where "b" is diagonalized

the energy of the leptons is O(m_ϕ)

(inflaton mass)

baryogenesis

step 2: oscillating into flavor eigenstates

CP asymmetry

$$P_l - P_{\bar{l}} = 4\sum_{j>k} \mathrm{Im}\left(U_{lj}V_j^* V_k U_{lk}^*\right) \int dk\, f(k) \sin\frac{\Delta b_{jk}(k)}{\Gamma}.$$

$$\simeq 4\mathrm{Im}\left(U_{l3}V_3^* V_2 U_{l2}^*\right) \frac{\Delta b_{32}(m_\phi)}{\Gamma}. \quad (V_1 = 0 \text{ for simplicity.})$$

$$|l(e,\mu,\tau)\rangle = \sum_{j=1,2,3} U_{jl}^\dagger |j\rangle, \qquad |l_\phi\rangle = \sum_{j=1,2,3} V_j^* |j\rangle.$$

(note: asymmetry is not yet physical. It becomes physical at the stage where the tau lepton Yukawa becomes important, i.e., T < 10^{12}GeV.)

baryogenesis

step 3: converting to lepton number asymmetry

$$P_l - P_{\bar{l}} \simeq 4\mathrm{Im}\left(U_{l3} V_3^* V_2 U_{l2}^*\right) \frac{\Delta b_{32}(m_\phi)}{\Gamma}.$$

this is **zero** if we sum over “l” index.

—> no net lepton asymmetry

lepton number violating process (llHH interaction):

$$\Gamma_l^{\mathrm{w.o.}} \simeq \frac{|U_{l3}^{\mathrm{PMNS}}|^2}{\pi^2} \frac{m_{\nu 3}^2}{v^4} T_R^3, \qquad \frac{\Gamma_l^{\mathrm{w.o.}}}{H} = \frac{T}{10^{12}\ \mathrm{GeV}} \times \begin{cases} 0.03, & l = \tau \\ 0.02, & l = \mu + e \end{cases}$$

flavor dependent! net lepton asymmetry is produced!

estimation

branching fraction

washout efficiency

$$\frac{n_L}{s} \sim \frac{n_\phi}{s} \times B_{\phi \to l} \times A_{CP} \times \frac{\Delta b_{23}}{\Gamma} \times \left(\frac{\Gamma_\tau^{\mathrm{w.o.}}}{H} - \frac{\Gamma_{\mu+e}^{\mathrm{w.o.}}}{H} \right)$$

$$\sim \frac{n_\phi}{s} \times B_{\phi \to l} \times A_{CP} \times \frac{\Delta b_{23}}{\Gamma} \times 0.01 \times \left(\frac{T_R}{10^{12}\ \mathrm{GeV}} \right)$$

number of inflaton

$$A_{CP} = \mathrm{Im}(U_{l3} V_3^* V_2 U_{l2}^*),$$

$$\frac{n_\phi}{s} \simeq \frac{T_R}{m_\phi}, \qquad \frac{\Delta b_{23}}{\Gamma} \sim \frac{4\pi^3 m_\phi T_R^3}{9 g_2^2 M_k^4} |y_\nu^{k3}|^2,$$

$$\boxed{\frac{n_B}{s} \sim \frac{n_L}{s} \sim 10^{-7} \times B_{\phi \to l} \times A_{CP} \times \left(\frac{T_R}{10^{12}\ \mathrm{GeV}} \right)^2 \left(\frac{10}{M/T_R} \right)^{-3}}$$

Looks OK! (independent of inflaton mass)

Summary

It is quite natural that baryogenesis happened
at the **reheating** era.

inflaton decay and **lepton oscillation**
can explain the baryon asymmetry.

I’d like to work out more detail especially the relation
between the observable phase and the one for baryogenesis.