Baryogenesis with relativistic walls arxiv ~~...~~ 2106 : 14913

initial model : $\mathcal{L} = |\partial_\mu \phi|^2 + i \bar{X} \not{\partial} X + i \bar{N} \not{\partial} N - M \bar{N} N$
$- Y \phi \bar{N} X - V(\phi)$

light (X) heavy (N)

$\langle \phi \rangle = 0 \rightarrow v_\phi$, $M \gg v_\phi$ (one or two orders of magnitude)

$P_X = (E, 0, 0, E)$
$P_N = (E, 0, 0, \sqrt{E^2 - M^2})$ violation of conservation of mom.

$\mathcal{P}(X \rightarrow N)$?

$v_\phi \neq 0$ W ← ← X

we will work in the wall frame.

- intuitively : $\mathcal{P} \propto Y^2 \left(\frac{v}{M}\right)^2$ ← proportional to the mixing angle, and non adiabatic regime $\boxed{\Delta p_z L < 1}$

$\Delta p_z = p_0 - \sqrt{p_0^2 - M^2} \cong \frac{M^2}{2p_0}$ X —×— N

$\mathcal{P}_{X \rightarrow N} \approx \left(\frac{Yv}{M}\right)^2 \Theta(1 - \Delta p_z L) = \left(\frac{Yv}{M}\right)^2 \Theta\left(1 - \frac{M^2}{2p_0} L\right)$

$= \left(\frac{Yv}{M}\right)^2 \Theta\left(2p_0 - \frac{M^2}{v}\right)$ ($1/v$)

- Rigorous way : correlation function $\langle 0 | T\{ \bar{X}(x_1) N(x_2) \} | 0 \rangle$

X Y N, x_1 × x_2, $\langle \phi \rangle$

$= \int d^4x \; S_X(x_1 - x) \, Y \langle \phi \rangle \, S_N(x - x_2)$

1 VEV insertion

Going to Fourier space :

$\int d^4x \, d^4k \, d^4q \; e^{ik(x_1 - x)} e^{iq(x - x_2)} S_X(k) S_N(q)$
$\times Y \langle \phi(x) \rangle$

$= \int d^4k \, d^4q \; e^{ikx_1 - iqx_2} S_X(k) S_N(q)$
$(2\pi)^3 \delta^3(k - q) \int dz \; e^{iz(k_z - q_z)} Y \langle \phi(z) \rangle .$

$\delta^1(k_x - q_x) \delta(k_y - q_y) \delta(k_0 - q_0)$

Application of LSZ formula for $\langle N, q | X, k \rangle$ scattering matrix

$\langle N, q | X, k \rangle = (2\pi)^3 \delta^{(3)}(k - q) \int dz \; e^{-iz\Delta p_z} \langle \phi(z) \rangle$
$\times \underbrace{\bar{u}_N(q) u_X(k) Y}_{X \rightarrow \phi N}$

$\Delta p_z = q_z - k_z$

$\mathcal{P}_{X \rightarrow N} = \int \frac{d^3q}{(2\pi)^3 2q_0 2k_0} (2\pi)^3 \delta^{(3)}(k - q) \, |\mathcal{M}_{X \rightarrow \phi N}|^2$
$\times \underbrace{\left| \int dz \; e^{-iz\Delta p_z} \langle \phi(z) \rangle \right|^2}_{\text{wall effects}}$

- $|\mathcal{M}_{X \rightarrow N\phi}|^2 = \frac{|Y|^2 k_z}{2k_0} \times \frac{\Delta p_z}{\sqrt{k_z^2 - M^2}}$

- Take a tanh wall : $\langle \phi \rangle = \frac{v_\phi}{2}\left[\tanh\left(\frac{z}{L}\right) + 1\right]$

$\rightarrow \left(\frac{\pi L}{2 \sinh\left(\frac{L \Delta p_z \pi}{2}\right)}\right)^2 v_\phi^2 \xrightarrow{\Delta p_z > L} e^{-L \Delta p_z \pi} (\pi L)^2 \ldots$

exponential decay for $\underline{L \Delta p_z \gg 1}$!

$$\xrightarrow{\Delta p_z L < 1} \left(\frac{\pi L/2}{1 + \frac{L\Delta p_z \pi}{2} - 1 + \frac{L\Delta p_z}{2}} \right)^2 v_\phi^2$$

$$= \frac{v_\phi^2}{\Delta p_z^2}$$

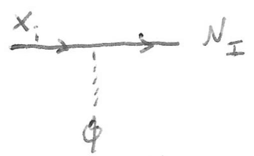
$$\Rightarrow \boxed{P_{x\to N} \simeq \frac{Y^2 v_\phi^2}{M^2} \, \theta(1 - \Delta p_z L) \,.}$$

$$1 > L \frac{M^2}{2k_0} \Rightarrow \underset{\overset{\|}{2\gamma T}}{2k_0} > LM^2 \Rightarrow \boxed{2\gamma > \frac{LM^2}{T}}$$

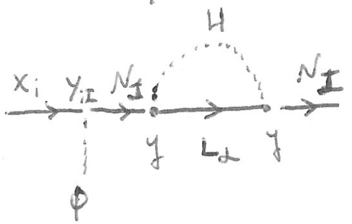
- we have clearly an out-of equilibrium situation.

- CP violation: Restart from the previous $\mathcal{L}$ and add pieces:

$$\mathcal{L} = i\bar{X}_i P_R \not{\partial} X_i + i\bar{N}_I \not{\partial} N_I - M_I \bar{N}_I N_I$$
$$- Y_{iI} \phi \bar{N}_I P_R X_i - y_{I\alpha} (H\bar{L}_\alpha) P_R N_I + \text{h.c.}$$



$$\propto A^0(X_i \to N_I) \propto Y_{iI}$$



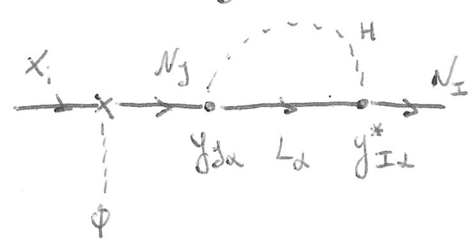
$$\propto A^1(X_i \to N_I) \propto \sum_{KJ} Y_{iJ} Y^*_{KJ} Y_{KI} f^{(X\phi)}_{IJ}$$
$$+ \sum_{\alpha J} Y_{iJ} y^*_{\alpha J} y_{\alpha I} f^{(HL)}_{IJ}$$

$$\varepsilon_{Ii} = \frac{|M_{i\to I}|^2 - |M_{\bar{i}\to\bar{I}}|^2}{\sum_i |M_{i\to I}|^2 + |M_{\bar{i}\to\bar{I}}|^2}$$

loop of $X\phi$

$$\varepsilon_I = \sum_i \varepsilon_{Ii} = \frac{2}{\sum_i |Y_{iI}|^2} \Bigg(\underbrace{\sum_{k,J,i} \mathrm{Im}(Y_{iI} Y^*_{iJ} Y_{kJ} Y^*_{kI}) \,\mathrm{Im} f^{(X\phi)}_{IJ}}_{=0}$$
$$+ \sum_{\alpha,I,J} \underbrace{\mathrm{Im}(Y_{iI} Y^*_{iJ} y_{\alpha J} y^*_{\alpha I})}_{\neq 0 \text{ if imag part in } y \text{ or } Y} \mathrm{Im} f^{(HL)}_{IJ} \Bigg)$$

what is $\mathrm{Im} f^{(HL)}_{IJ}$?



To be computed using one vev insertion going $\left(\frac{Y_v}{M}\right)$

$$\mathrm{Im} f_{IJ} = \frac{1}{16\pi} \frac{\sqrt{x}}{1-x} \qquad x = \frac{M_J^2}{M_I^2}$$

Dynamics: flux of X: $J = \int \frac{d^3p}{(2\pi)^3} \frac{p_z}{p_0} f_X(p,T)$

$$n = \frac{\Delta N}{\Delta A \Delta z} = \frac{\Delta N}{\Delta A \Delta t} \frac{\Delta t}{\Delta z} = J/v_w$$

$$n_{N_I} = \frac{1}{\gamma_w v_w} \int \frac{d^3p}{(2\pi)^3} P_{x\to N} \times f$$

$$= \sum_i \frac{|Y_{iI}|^2 T^3}{\pi^2 M_I^2} v_\phi^2 \, e^{-\frac{M_I^2}{2v_\phi T \gamma}}$$

non adiabatic $\simeq \sum \theta^2_{iI} \, n_{X_i}(T)$.

$\Rightarrow$ Some abundance of X has been removed and N has been created.

$$\Rightarrow \sum_I \Delta m_{NI} = - \sum_i \Delta m_{X^i}$$

CP violation: $\sum_I \left(\Delta m_{NI} - \Delta m_{\bar{N}I} \right) = - \sum_i \left(\Delta m_{X^i} - \Delta m_{\bar{X}^i} \right)$

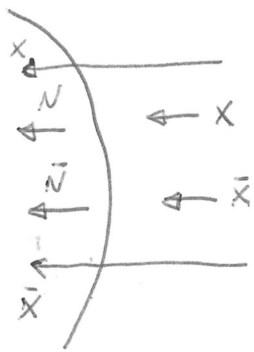
Separation into heavy and light species.

Models: 1) Phase transition induced leptogenesis.

$$\mathcal{L} = \sum_I \left(Y_I (\phi^+ \bar{X}) P_L N_I + Y_I^* \bar{N}_I P_R (\phi X) \right) - V(\phi)$$
$$+ \frac{1}{2} \lambda_X \phi \bar{X}^c X + \sum_I M_I \bar{N}_I N_I + \sum_{\alpha I} y_{\alpha I} (H \bar{L}_\alpha) P_R N_I$$

Assignment of Lepton number: $L(X) = -1$, $L(N) = 1$
$L(\phi) = 2$

ϕ: $v_\phi = 0 \rightarrow v_\phi \neq 0$ breaks lepton number.



$- \Delta m_N = \Delta m_X \propto \underset{\substack{\downarrow \\ CP}}{\varepsilon} \times \underset{\substack{\downarrow \\ prod}}{\theta^2} \times m_X$

- Δm_N inside of bubble

$\lambda_X v_\phi \bar{X}^c X$

$\bar{X} \longrightarrow \times \longrightarrow X$ $\Bigg]$ $\boxed{\Delta m_X \rightarrow 0}$

$\langle \phi \rangle$

- Δm_N: $N \rightarrow X\phi$ erased
$N \rightarrow HL$ transported to SM.

$$\frac{m_L - m_{L^c}}{s} \cong \frac{135 \zeta(3) g_X}{8 \pi^4 g_*} \left(\frac{T_m}{T_{reh}} \right)^3 \times \frac{\sum_\alpha |y_{\alpha I}|}{\sum_\alpha |y_{\alpha I}|^2 + |Y_I}$$

$$\times \sum_I \theta_I^2 \varepsilon_I$$

$$\frac{\Delta m_B}{s} \simeq - \frac{28}{79} \frac{m_L - m_{L^c}}{s} \Rightarrow \boxed{\theta^2 y^2 \left(\frac{T_m}{T_{reh}} \right)^2 \sim 10^-}$$

Constraints on the model:

1) matching light neutrino masses:

Weinberg op: $\theta_I^2 \frac{y_{\alpha I} y_{\beta I} (L_\alpha H)(L_\beta H)}{m_X}$

$\hookrightarrow m_\nu \sim y^2 \theta^2 \frac{v_{EW}^2}{m_X} \simeq y^2 \theta^2 \frac{v_{EW}^2}{\lambda_X v_\phi}$

$\rightarrow v_\phi > 10^9$ GeV.

(Possibility of Loop-induced neutrino masses).

2) Wash-outs:

- $LH \rightarrow X$: $\frac{m_X}{T_{reh}} \gtrsim \log \frac{M_P}{m_X} - 10$

$\Rightarrow \boxed{\frac{m_X}{T_n} \gtrsim 15}$

- $H\bar{L} \Leftrightarrow H^c L \Rightarrow \Gamma \propto T^3$
Efficient at high T.

$\Rightarrow T_{reh} < 10^{13}$ GeV.

<u>Summary</u>: $\left\{ \begin{array}{l} \cdot\ v_\phi \in [10^9, 10^{14}] \\ \cdot\ \dfrac{m_X}{T_{reh}} \gtrsim 15 \text{ (flat potential)} \\ \qquad\qquad\quad \text{small } T_{reh}. \\ \cdot \text{ Relativistic walls.} \end{array} \right.$

2) Second model: baryogenesis with relativistic walls.

$$\mathcal{L} = \sum_{I=1,2} M_I \bar{B}_I B_I + \sum_{I=1,2} Y_I (\bar{B}_I H) P_L Q$$

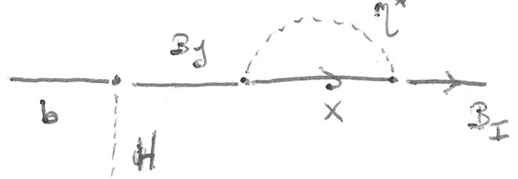
$$+ y_I \eta^* \bar{B}_I P_R X + \kappa \underbrace{\eta^c}_{\downarrow} du + \frac{1}{2} m_X \bar{X}^c X$$

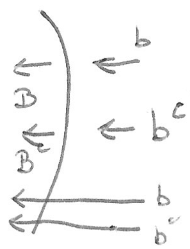
$$+ m_\eta^2 |\eta|^2$$

- Dangerous $(LH) X^c$
- B number assignments: fundamental rep of QCD

$M_I \sim m_\eta$. $B(\eta) = 2/3$, $B(X) = 1$.

- CP violation:





$\Delta m_b = -\Delta m_B \propto \varepsilon\, \theta^2 m_b$

$B \rightarrow bH$ erase

$B \rightarrow X \eta^c \rightarrow X d^c u^c$

$\rightarrow \left\{ \begin{array}{l} b\eta\ d^c u^c \\ b^c \eta^c\ d^c u^c \end{array} \right.$

<u>Wash out</u>: $B_I \rightarrow X d^c u^c \rightarrow bdu\, d^c u^c$, $B_I^c \rightarrow b^c d^c u^c d$

asym gen: $B_I \rightarrow b^c d^c u^c d^c u^c$, $B_I^c \rightarrow bdu\, du$.

$\Rightarrow m_q - m_{\bar{q}} = -3 \sum_I \Delta m_{B_I}\ \mathrm{Br}(B_I \rightarrow X \eta^c)$

Matching observation: $\boxed{\theta^2 \left(\dfrac{T_m}{T_n}\right)^2 \sim 10^{-(6-7)}}$

Wash-out: $b\eta \rightarrow X$

$$\boxed{\frac{m_{B, X, \eta}}{T_{reh}} \gtrsim 30}$$

Experimental signatures:

- Neutron oscillations: $n \leftrightarrow \bar{n}$

$$\delta m_{n \leftrightarrow \bar{n}} \sim \frac{\Lambda_{QCD}^6}{M_\eta^4 m_X} \left(\sum_I \kappa\, \theta_I y_I\right)^2 V_{bu} < 10^{-33} \text{ GeV}$$

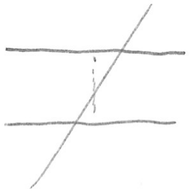
$\theta^2 \sim 10^{-5}$, $y \sim 1$, $V_{bu} \sim 1 \Rightarrow \dfrac{\Lambda_{QCD}^6}{\text{GeV}} < 10^{-26} M_\eta^4 m_X$

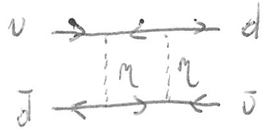
$\Rightarrow M_\eta \sim m_X \Rightarrow \boxed{\dfrac{\Lambda_{QCD}}{M_\eta} \lesssim 10^{-5}}$ ✗ significant

if $V_{bu} \sim 10^{-2} \Rightarrow \boxed{\dfrac{\Lambda_{QCD}}{M_\eta} \lesssim 10^{-3}}$ <u>ok</u>.

- Flavor violation and FCNC

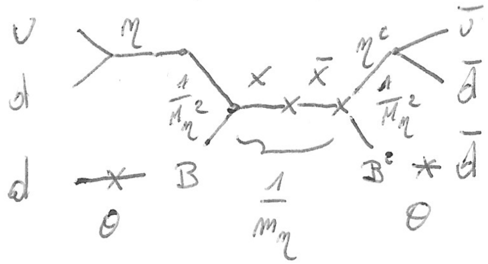
$\eta^c\, du$ type VI of 1105.3161





Antisymmetrically coupled.

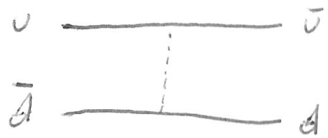
- EDM : { chromo-electric, electron } not stringent.



$n \leftrightarrow \bar{n}$

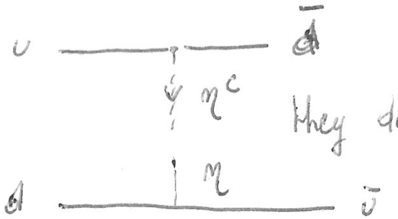
- collecting we have : $\theta^2 \frac{1}{m_X} \frac{1}{M_\eta^4}$ ok.

FCNC :



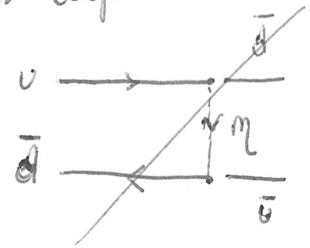
tree-level FCNC. allowed for many BSM.

own $\eta^c d_R u_R + \eta\, \bar{d}_R \bar{u}_R$ we cannot write

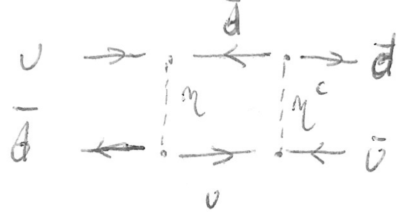


they do not connect.

At loop level :



forbidden



This is allowed. but suppressed by heavy masses of b and t.