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Baryogenesis via QCD preheating driven by QCD Higgs

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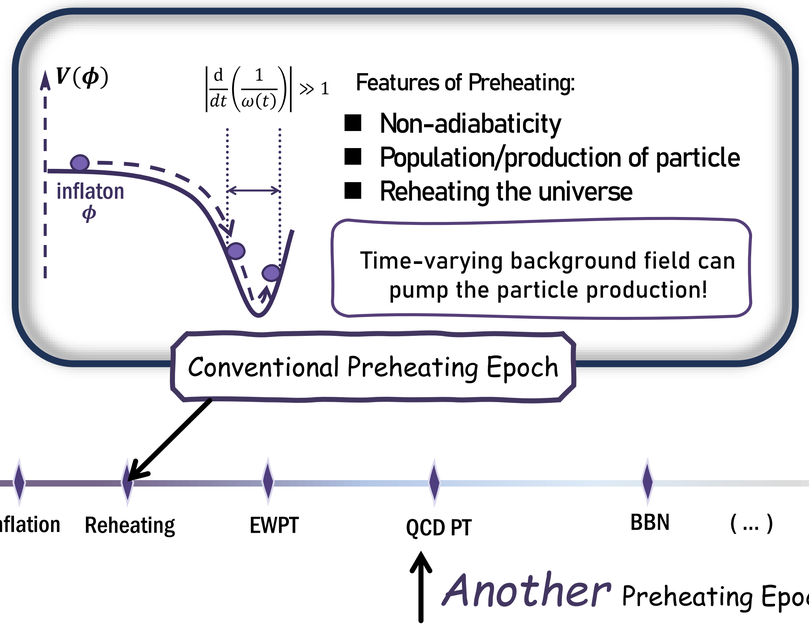


QCD Preheating

◆Phenomenological setup: 2 flavor Linear Sigma Model

$$\mathcal{L}_{LSM} = tr[\partial_\mu M^\dagger \partial^\mu M] + \frac{1}{2}m_\pi^2 f_\pi tr[M+M^\dagger] - m^2 tr[M^\dagger M] + \bar{N}i\partial\!\!\!/ N - \frac{2m_N}{f_\pi}(\bar{N}_L M N_R + \bar{N}_R M^\dagger N_L)$$

Meson Field $M = \frac{\sigma + i\pi^a\tau^a}{2}$ Nucleon Field $N = \begin{pmatrix} n \\ p \end{pmatrix}$

$\langle\sigma\rangle \rightarrow$ osscilating field $n \rightarrow$ populated field

◆Particle production area

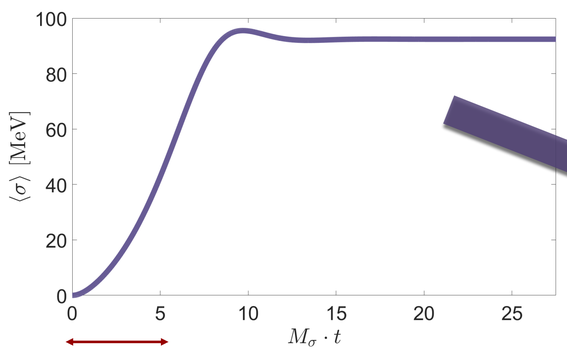
Non-adiabatic condition:

$$\left|\frac{d}{dt}\left(\frac{1}{\omega(t)}\right)\right| \gg 1 \rightarrow \left|\dot{\tilde{m}}_N/\tilde{m}_N^2\right| \gtrsim 1$$

$$\tilde{m}_N = m_N \cdot \frac{\langle\sigma(t)\rangle}{f_\pi}$$

$$|\sigma| \lesssim \sqrt{\frac{f_\pi\langle\dot{\sigma}\rangle}{m_N}} \simeq 42\ \text{MeV}$$

($\Delta\sigma \sim 42$ MeV $\Rightarrow$ $M_\sigma t \lesssim 5$)



Particle production phase $(M_\sigma t \lesssim 5)$

E.o.M. of $\langle\sigma\rangle$:

$$0 = \langle\ddot{\sigma}\rangle + \gamma\langle\dot{\sigma}\rangle - m_\pi^2 f_\pi + m^2\langle\sigma\rangle + \lambda\langle\sigma\rangle^3 + \cdots$$

QCD Induced Chemical Potential

Consider higher dimensional interaction induced from QCD

$$\mathcal{L}_{\mu_{dyn}} = -\frac{c}{(4\pi f_\pi)^2}\cdot\partial_\mu\left(\text{tr}\left[M^\dagger M\right]\right)J_B^\mu$$

References:
Kusenko:2014uta,Ibe:2015nfa,Daido:2015gqa,Takahashi:2015waa, Adshead:2015jza,Takahashi:2015ula,Kusenko:2016vcq,Maleknejad:2016dci, DeSimone:2016ofp,DeSimone:2016juo,Son:2018avk,Dasgupta:2018eha, Bae:2018mlv,Domcke:2019qmm,Wu:2020pej,Berbig:2023uzs

With spatial homogeneity

$$\mathcal{L}_{\mu_{dyn}} = -\mu_{dyn}(t)\cdot n_B(t) \qquad \mu_{dyn}(t) \equiv \frac{c}{(4\pi f_\pi)^2}\partial_0 tr\left[M(t)^\dagger M(t)\right] = \frac{c}{32\pi^2 f_\pi^2}\frac{d}{dt}\langle\sigma^2(t)\rangle$$

Inside the Standard Model !

◆Nonzero dynamic $\mu_{dyn}(t)$ breaks the C and CP symmetries as well as the T symmetry.

◆In the analysis of particle production and GW production, time-evolutionary μ_{dyn} also plays the role of the *regulator* of two-point/four-point function, to avoid the UV divergence.

Baryogenesis Realization

Sakharov's Criteria

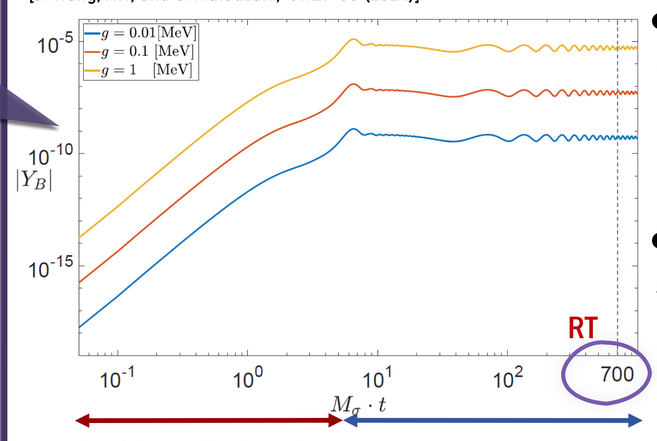
◆ Out of equilibrium ------ QCD preheating (non-adiabaticity)

◆ B violation ---------- Transport from a dark sector II n_D

$$\mathcal{L}_{n-D} = -g\,(\bar{n}_R n_{D_L} + \bar{n}_{D_R} n_L) + h.c.$$

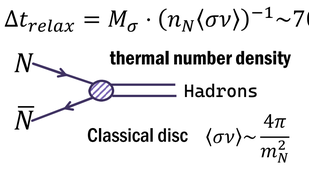
◆ C and CP violation ------ QCD induced chemical potential

[J. Wang, XW, and S. Matsuzaki, JHEP 08 (2024)]



● Relaxation time(RT)

$M_\sigma \cdot \Delta t_{relax} = M_\sigma \cdot (n_N\langle\sigma v\rangle)^{-1} \sim 700$



● Particle production region

$\Delta\sigma \sim 42$ MeV $\Rightarrow$ $M_\sigma t \lesssim 5 \ll 700$ (Relaxation Time)

B asymmetry is not washed out!

● Reference value of coupling g relates to the leptoquark mass in UV scale.

● The number density is expressed with two-point function

$$n_B(t) = \frac{1}{V}\int\frac{d\vec{k}}{(2\pi)^3}\sum_{s=\pm}\left(\left\langle n_{L,\vec{k}}^{s\,\dagger} n_{L,\vec{k}}^{s}\right\rangle - \left\langle n_{R,\vec{k}}^{s\,\dagger} n_{R,\vec{k}}^{s}\right\rangle\right).$$

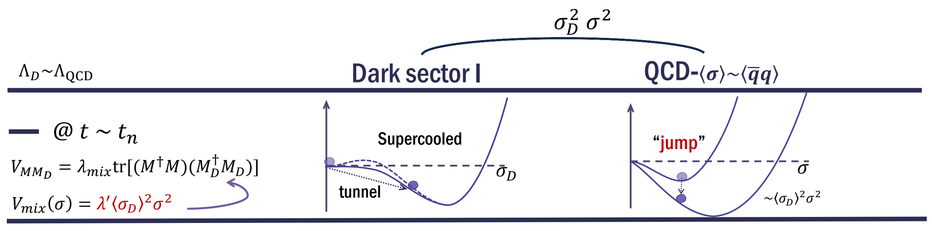
$$Number = \frac{Total\ kinetic\ energy}{one\ particle\ kinetic\ energy}$$

The UV divergence of the two-point function is *regularized* by chemical potential μ_{dyn}.

● Neutrons and anti-neutrons are produced *simultaneously* and *asymmetrically*.

● Y_B gets *stabilized* with the decreasing chemical potential μ_{dyn}.

Supercooling



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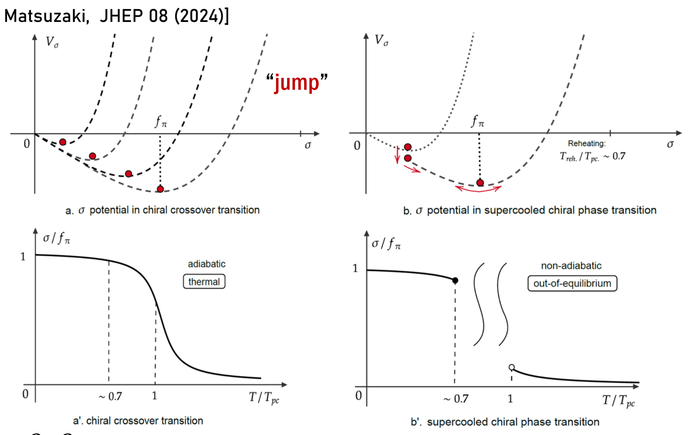


The term $\langle\sigma_D\rangle^2\sigma^2$ suddenly contributes and modifies the potential $V(\sigma)$ at $t = t_n$.

"Jump" plays a role of fast roll ~ 1st order phase transition!

Overall Scenario

Supercooled by Dark sector I → QCD $\langle\bar{q}q\rangle$ fast roll (preheating) triggered → BNV transport from Dark sector II → BAU produced GW generated → Stabilized until relaxation, back to QCD plasma with reheated

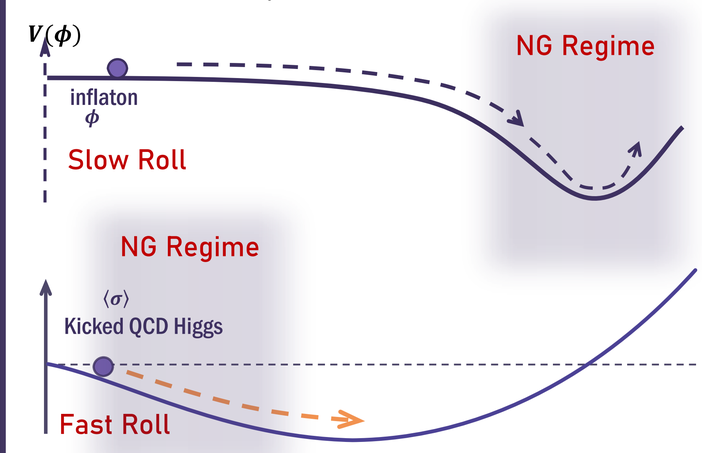
New frontier open, involving variant Beyond the Standard Model candidates

Gravitational Wave Generation(Ongoing!)

E.o.M. of GW:

$$h_{ij}'' + 2\frac{a'}{a}h_{ij}' - \nabla^2 h_{ij} = 16\pi G a^2 \Pi_{ij}^{TT},$$

The anisotropic source Π_{ij}^{TT} is originated from the *Non-Gaussianity (NG)* during the QCD preheating epoch.



The difference of evolution period in traditional preheating and QCD preheating.

The 1st Stage of QCD preheating is the non-adiabatic evolution.

$$\Pi_{ij}^{TT}(\mathbf{k},t) \ni \Lambda_{ij,lm}(\hat{k})\int\frac{d\mathbf{p}}{(2\pi)^3}\frac{1}{a(t)^2}\left\{\left[\sum_{s=\pm}\left(e_{\mathbf{k}+\mathbf{p}}^{s}\right)_\alpha\left(-n_{L,\mathbf{k}+\mathbf{p}}^{s\dagger} + n_{R,\mathbf{k}+\mathbf{p}}^{s\dagger}\right)\right](\sigma_l p_m + p_l\sigma_m)\left[\sum_{s'=\pm}\left(e_{\mathbf{p}}^{s'}\right)_\alpha\left(n_{L,\mathbf{p}}^{s'} + n_{R,\mathbf{p}}^{s'}\right)\right]\right\}$$

$$\left\langle\Pi_{ij}^{TT}(\mathbf{k},t)\Pi_{ij}^{TT}(\mathbf{k}',t)\right\rangle \ni \left\langle n_{L,\mathbf{k}+\mathbf{p}}^{s\dagger}(t)\, n_{L,\mathbf{p}}^{s'}(t)\, n_{L,\mathbf{k}+\mathbf{p}}^{r\dagger}(t')\, n_{L,\mathbf{p}}^{sr'}(t')\right\rangle$$

The UV divergence of the four-point function is *regularized* by the induced chemical potential μ_{dyn}.