QCD Preheating

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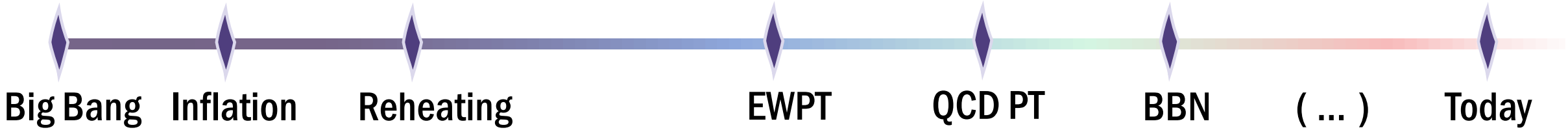
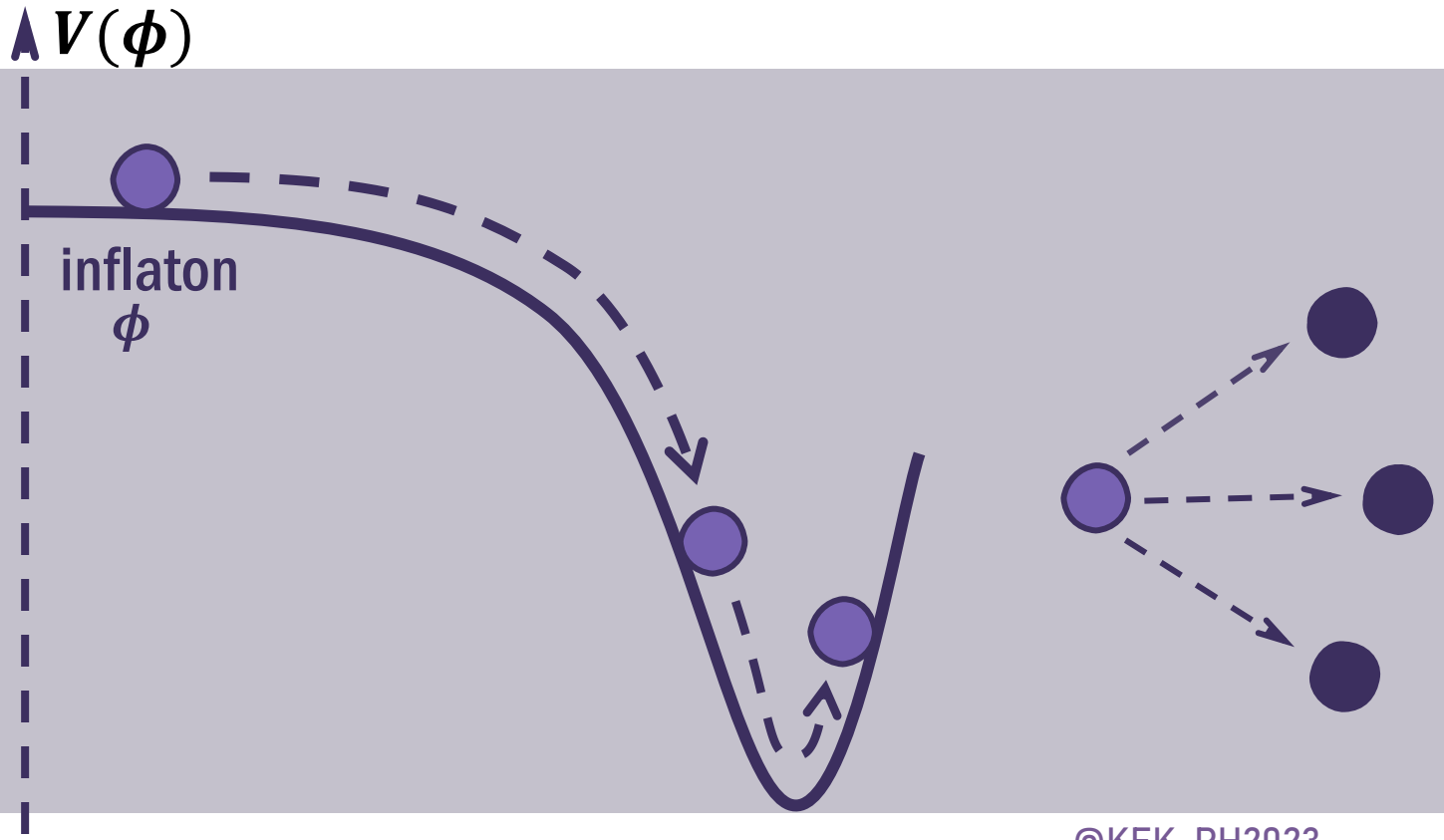
Based on:
Phys. Rev. D 108, 023512
In collaboration with S. Enomoto [Zhongshan U], H. Ishida [Toyama Prefecture U], J. Li [KEK], S. Matsuzaki [Jilin U]

KEK Theory Meeting on Particle Physics Phenomenology (KEK-PH2023)

7-10 November 2023
KEK

Reheating in Conventional thermal history



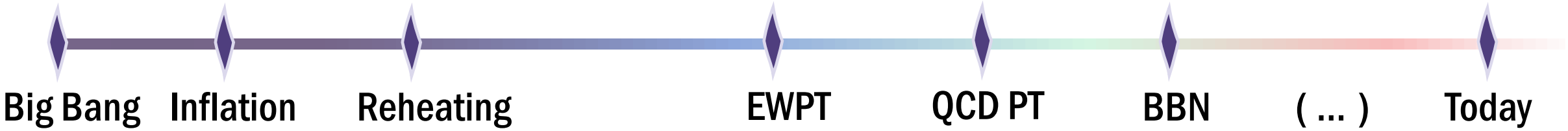


"Cosmic origin of matter"

"Production of cosmic relics"

e.g. baryogenesis accessible

Production mechanism of cosmic abundance



-- Perturbative production, decay processes

c.f. EW baryogenesis, leptogenesis, etc..

-- nonperturbative, nonadiabatic processes

c.f. Preheating – today's focus

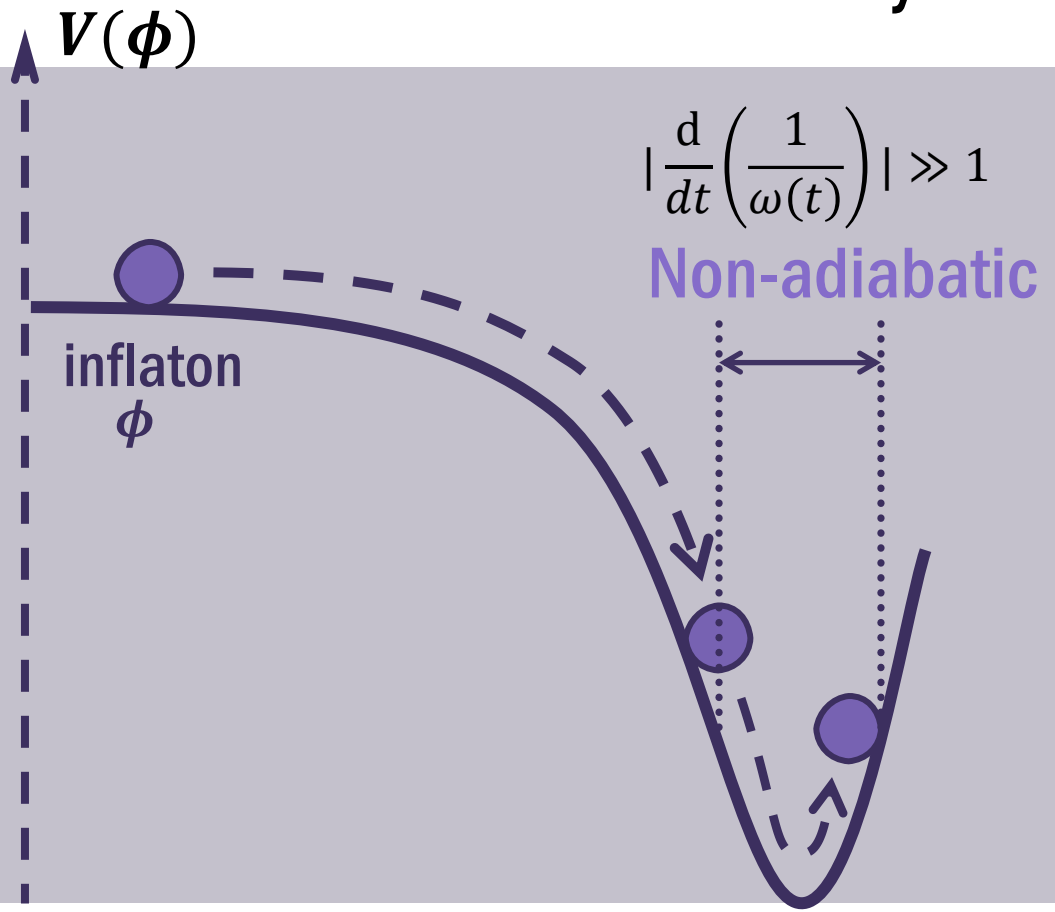
Production mechanism of cosmic abundance

[L. Kofman, A. D. Linde and A. A. Starobinsky, Phys. Rev. Lett. 73 (1994), Phys. Rev. D 56 (1997)]

Review of "conventional" preheating

Time-evolutionary inflaton field: $\phi(t)$

SM and/or
BSM scalar field: χ



$$V(\langle\phi(t)\rangle,\chi) = \frac{1}{2}m_\phi^2\langle\phi(t)\rangle^2 + \frac{1}{2}\lambda^2\langle\phi(t)\rangle^2\chi^2$$

Equation of motion for χ with osc. Inflaton $\phi(t)$

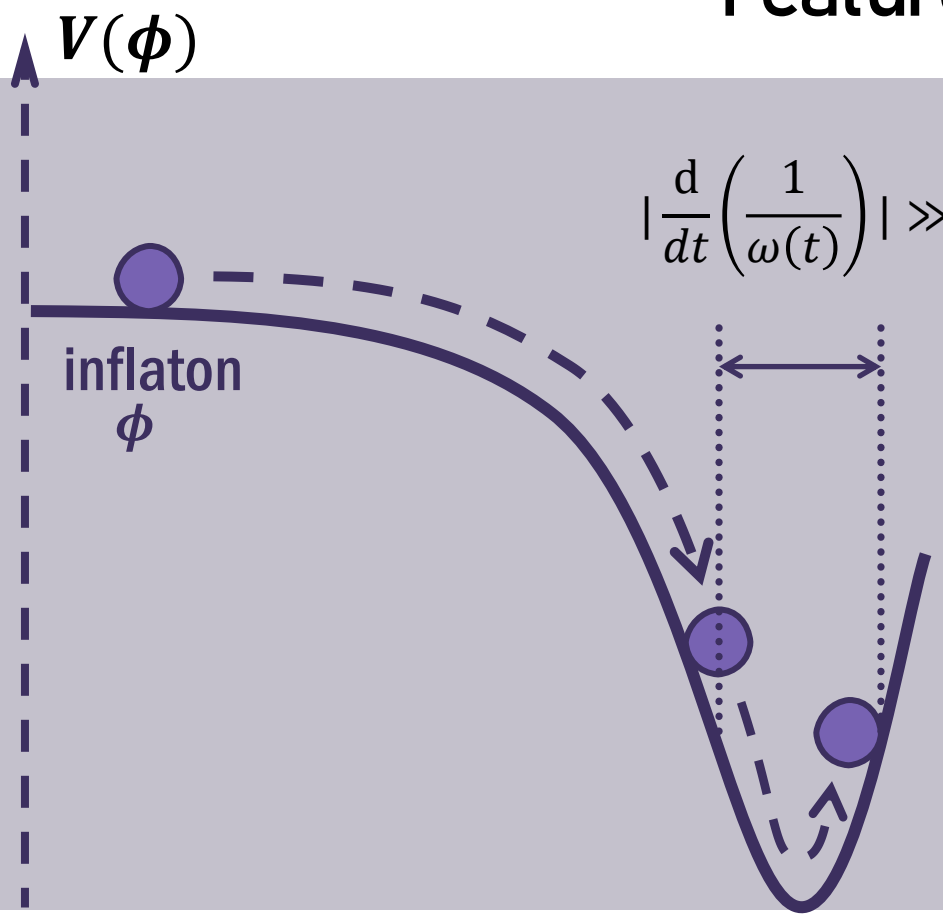
$$0 = \partial_t^2\chi_k + \omega_k(t)^2\chi_k \qquad \omega_k(t) \equiv \sqrt{|\mathbf{k}|^2 + \lambda^2\langle\phi(t)\rangle^2}$$

$$\chi(t,\mathbf{x}) = \sum_k \left[e^{i\mathbf{k}\cdot\mathbf{x}}\chi_k(t)a_k + (h.c.)\right]$$

$$n_{\chi k}(t) = \frac{1}{V}\langle\widehat{N}_{\chi\mathbf{k}}(t)\rangle = \frac{\langle\partial_t\chi_\mathbf{k}^\dagger\cdot\partial_t\chi_\mathbf{k}\rangle + \omega_k^2\langle\chi_\mathbf{k}^\dagger\chi_\mathbf{k}\rangle}{2\omega_k V} - \frac{1}{2}$$

Production mechanism of cosmic abundance

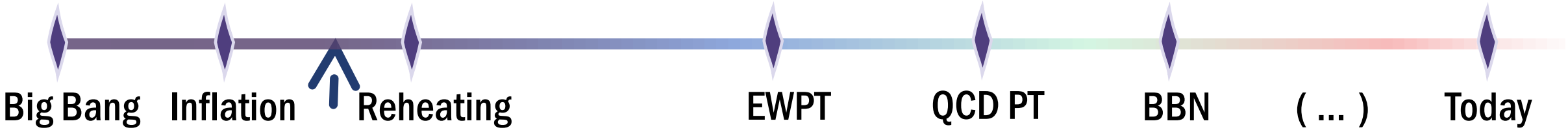
Features of Preheating summarized:



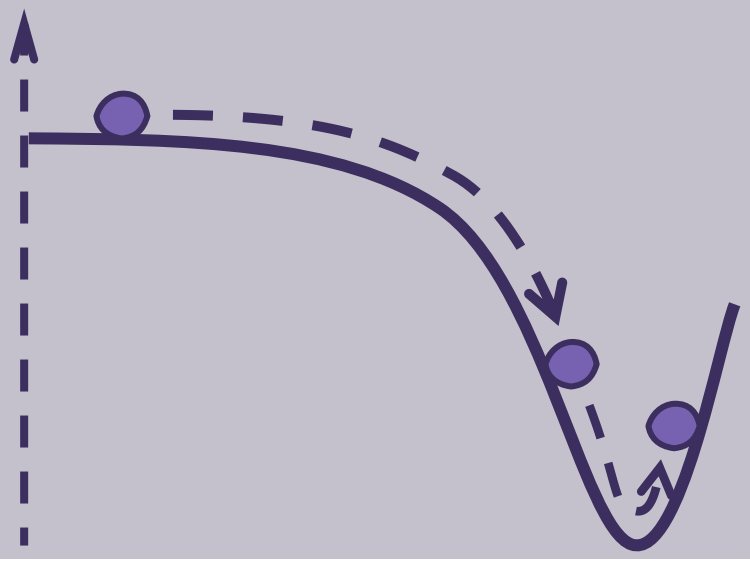
- Non-adiabaticity
- Population/production of particle
- Reheating the universe

Time-varying background field can pump the particle production!

Application to thermal history



conventional
Preheating epoch



"Cosmic origin of matter"

"Production of cosmic relics"

e.g. baryogenesis accessible

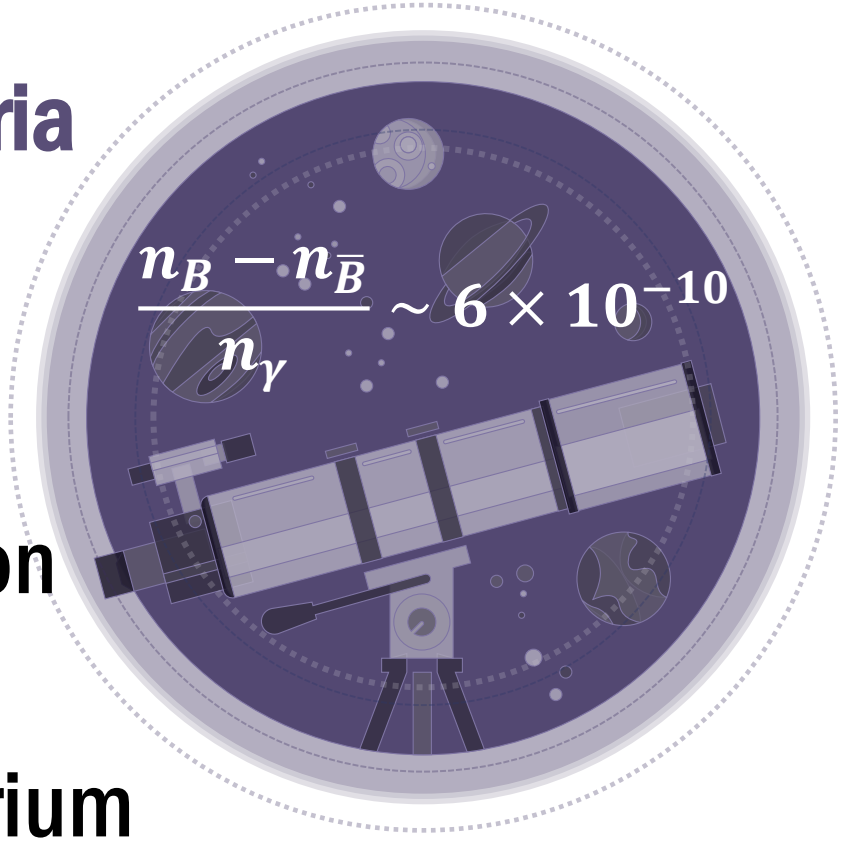
Yes, Baryogenesis

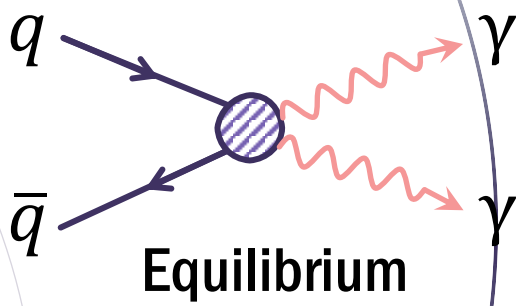
Sakharov's Criteria

01 B violation

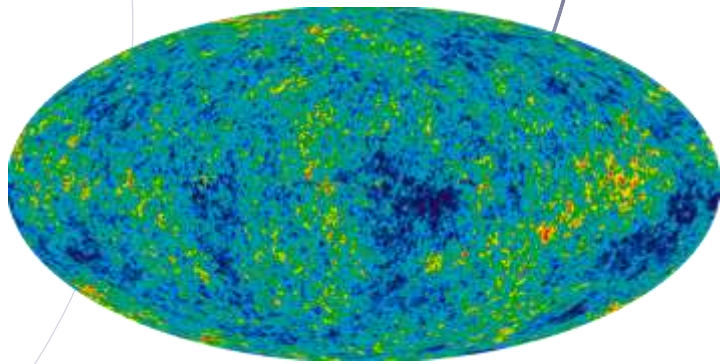
02 C and CP violation

03 Out of equilibrium





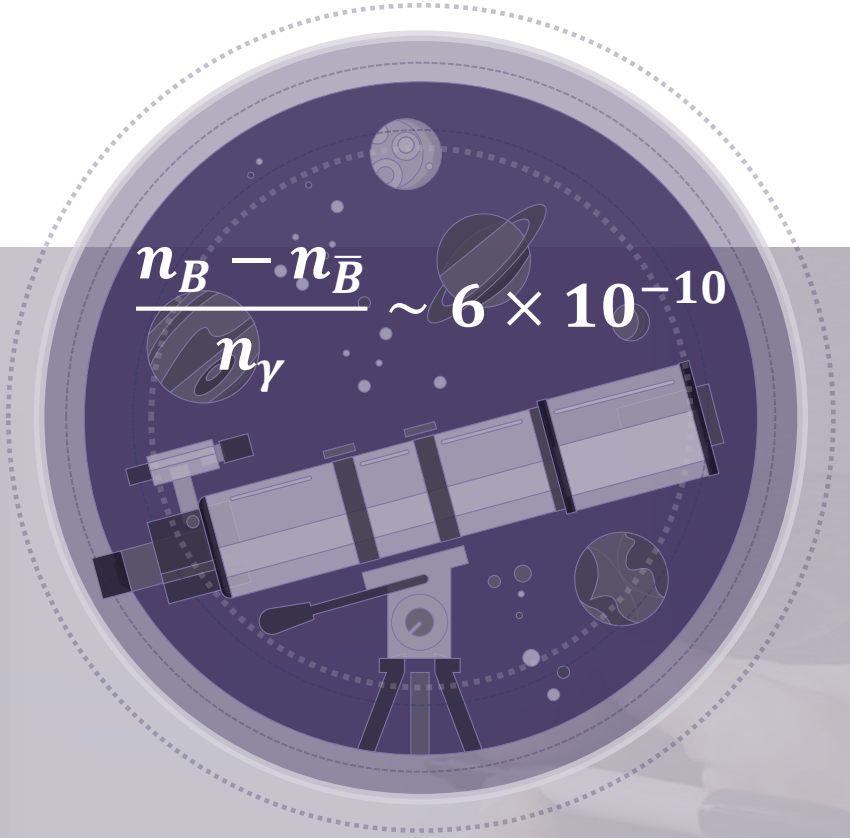
Equilibrium



Nine Year Microwave Sky
[Credit: NASA / WMAP Science Team]

[A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5 (1967)]

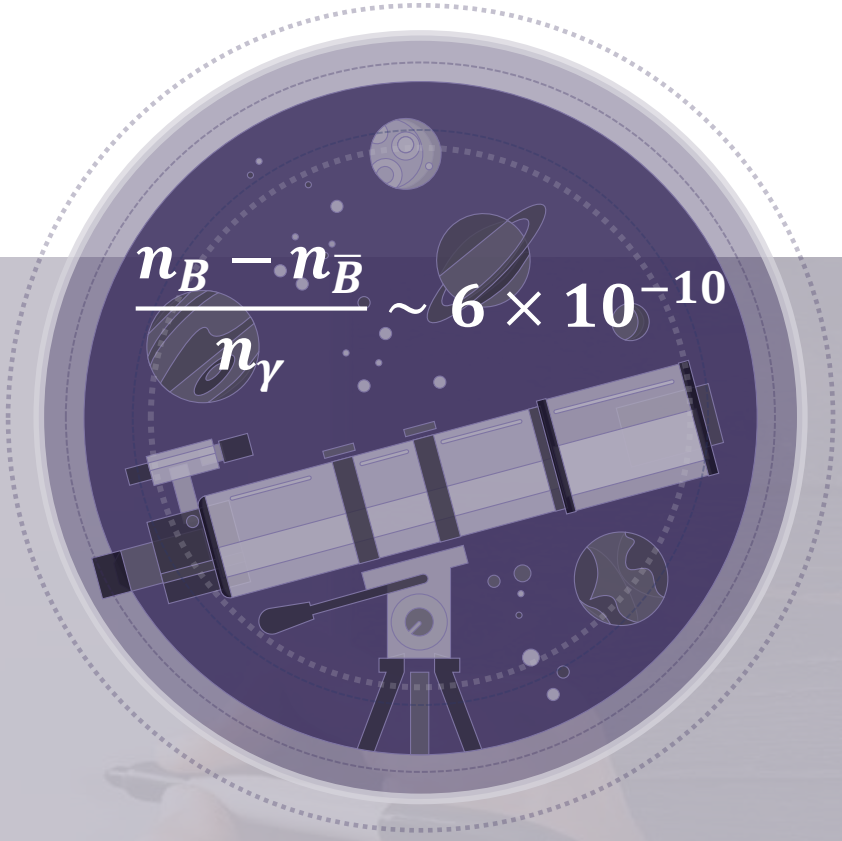
SM EW Baryogenesis:



In Standard Model

- B violation ---------- EW sphaleron
- C and CP violation ------ EW-CP phase in CKM
- Out of equilibrium ------ N/A (EWPT is not 1st order, but crossover)

SM EW Baryogenesis:

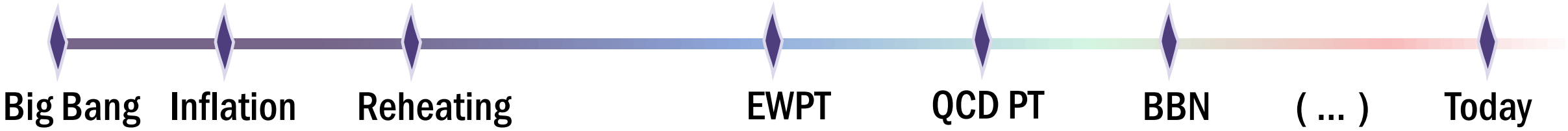


Naïve question, then….

How about QCD, not EW?

Character figure from https://www2.kek.jp/kids/accelerator/index.html

Application to thermal history

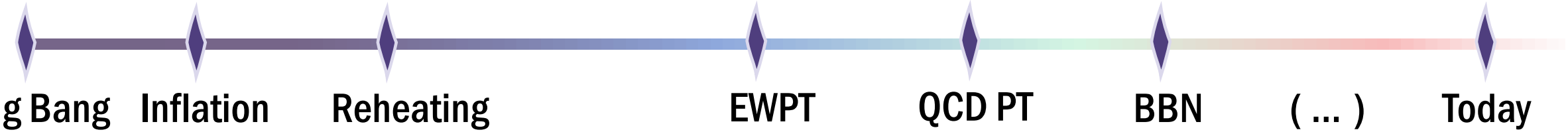


“Folklore”

QCD is considered that should not play major role of baryogenesis

- QCD sector does not have baryon number violation;
- nor large enough CP violation;
- and will never be out of thermal equilibrium at lower scales due to the strong coupling nature.

Application to thermal history



However...

QCD phase transition
=
the origins of mass
&
matter property for nucleon.

"Folklore"

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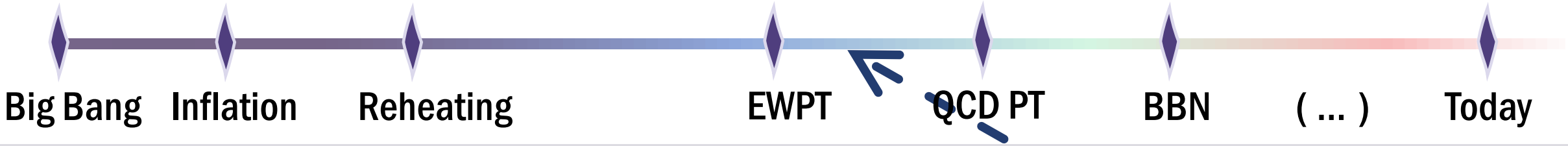
Application to thermal history



However...

Shouldn't baryogenesis be at QCD scale?

QCD phase transition
=
the origins of mass
&
matter property for nucleon.

"Folklore"

QCD is considered that should not play major role of baryogenesis

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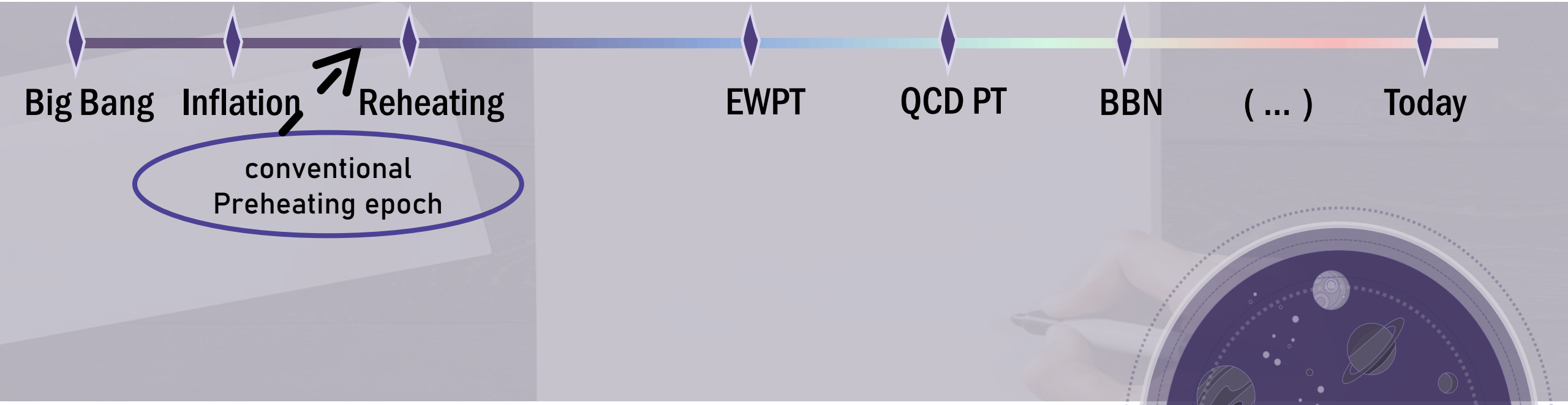
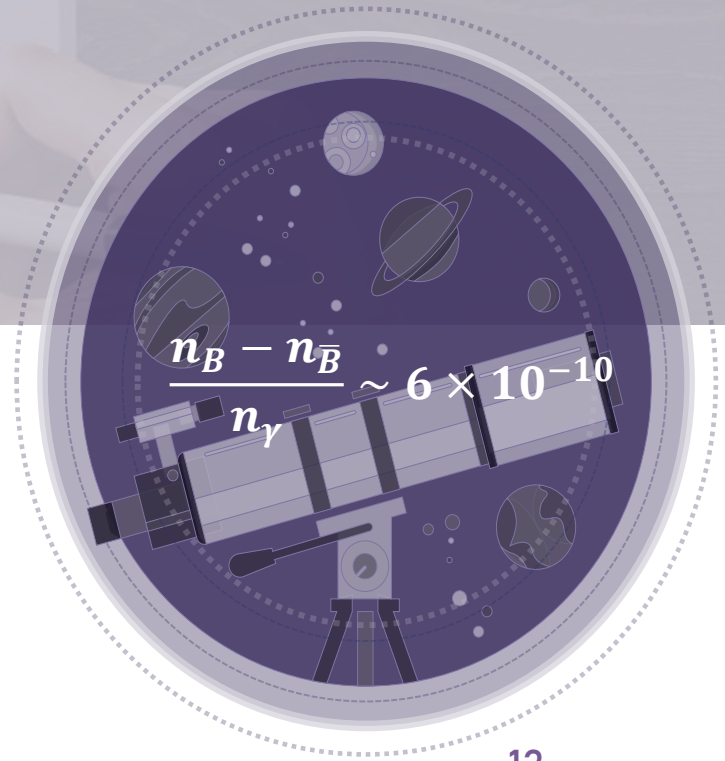
Our today's proposal: QCD Baryogenesis

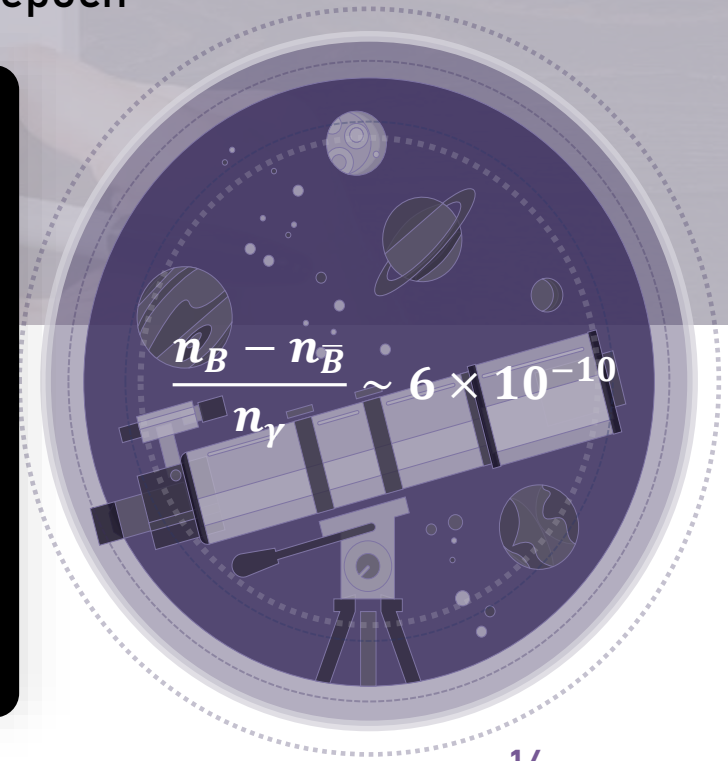




Our today's proposal: QCD Baryogenesis

(non-adiabaticity)

- Out of equilibrium ------ QCD preheating
- B violation ---------- Transport from a dark sector
- C and CP violation ------ Complex transport coupling

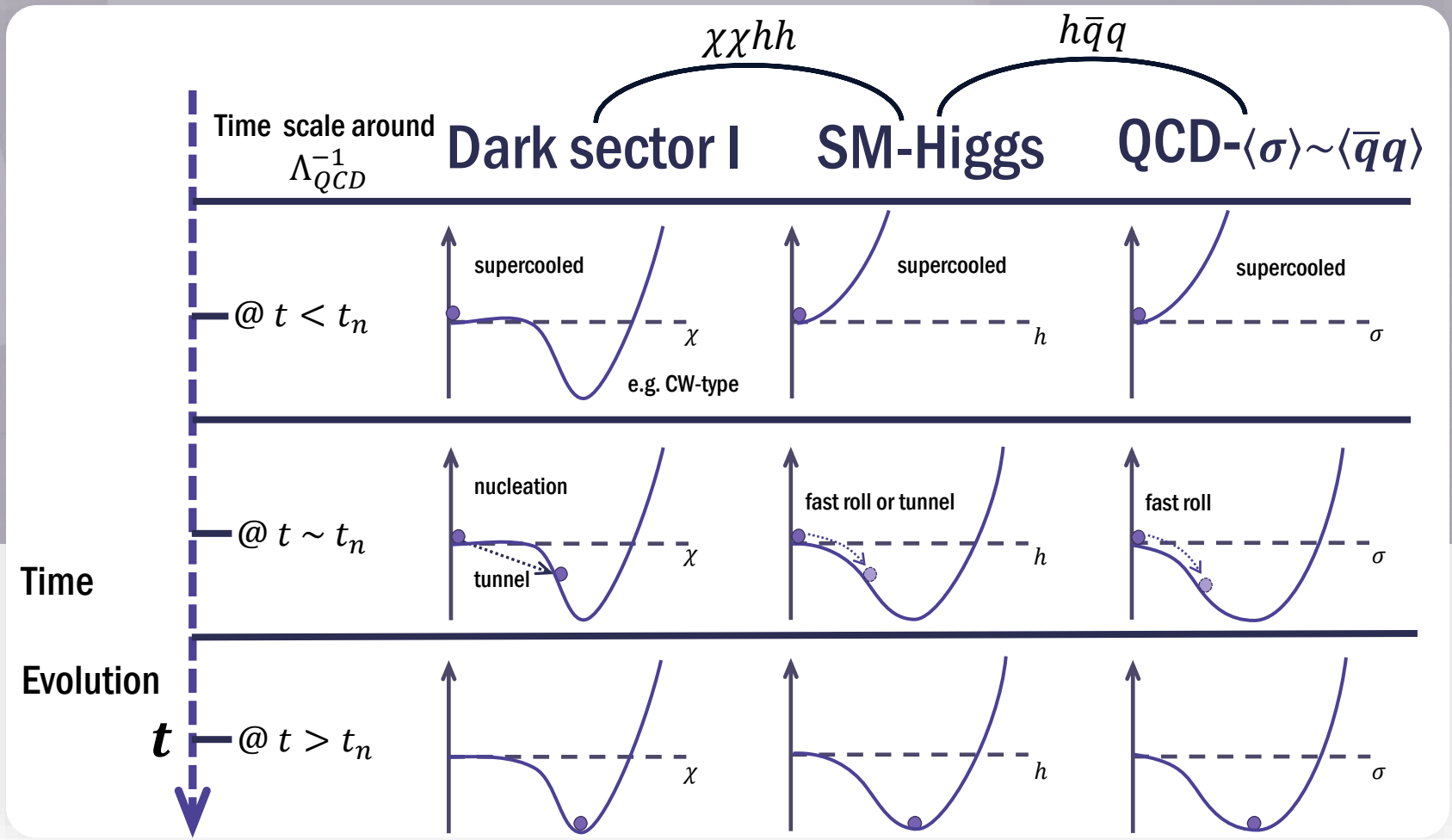


Preliminaries for QCD preheating

For detailed study upcoming:
X-R. Wang, et al, in progress
H-X.Zhang, et al, (arXiv:2311.xxxxx)

Required setup:

multiple of supercooling for
- Dark sector I
- SM-Higgs
- QCD-$\langle\sigma\rangle\sim\langle\bar{q}q\rangle$



Phenomenological setup ready for QCD Baryogenesis

An easy try with 2 flavor Linear Sigma Model

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

Note $\langle\sigma\rangle \sim \langle\bar{q}q\rangle$

$$M = \frac{\sigma + i\pi^a \tau^a}{2} \qquad N = \begin{pmatrix} n \\ p \end{pmatrix} : \text{nucleon doublet}$$

Input

$$f_\pi = 92.4\ \text{MeV} \qquad m_N = 940\ \text{MeV}$$
$$m_\pi = 140\ \text{MeV} \qquad M_\sigma = 500\ \text{MeV}$$

Phenomenological setup ready for QCD Baryogenesis

An easy try with 2f-LSM for QCD preheating epoch

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

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

(non-adiabaticity)

- Out of equilibrium ------ **QCD preheating**
- B violation ---------- Transport from a dark sector
- C and CP violation ------ Complex transport coupling

Interactions b/w neutron & SM_singlet dark fermion

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

n_D denotes dark fermion in **dark sector II**

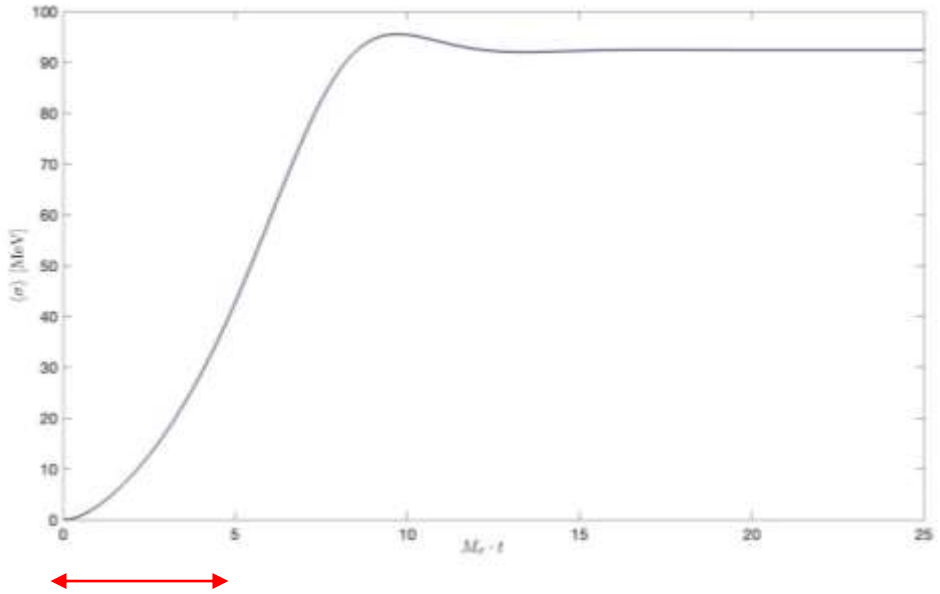
$$\mathcal{L}_{Dark\ Dirac} = -(m_D \bar{n}_{D_L} n_{D_R} + (h.c.))$$

$$m_D = 1050\ \text{MeV}$$

UV completion of the setup, in progress, to be reported elsewhere [X-R. Wang, et al, in progress]

Mechanism of particle production

Particle production area $\left|\dot{\tilde{m}}_N/\tilde{m}_N^2\right| \gtrsim 1$ $\quad \tilde{m}_N = m_N \cdot \dfrac{\langle\sigma(t)\rangle}{f_\pi}$



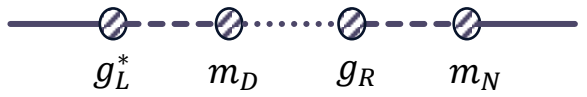
Particle production area $\quad |\sigma| \lesssim \sqrt{\dfrac{f_\pi\langle\dot{\sigma}\rangle}{m_N}} \simeq 42\ \mathrm{MeV}$

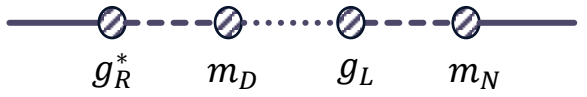
$(\ \Delta\sigma \sim 42\ \mathrm{MeV} \ \Rightarrow \ M_\sigma t \lesssim 5\ )$

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

where γ denotes sigma meson decay width ~550MeV

Schematic Feynman-graphical interpretation of BAU generation :

$\left\langle n_L^\dagger n_L \right\rangle \ni$  $\propto g_L^* g_R m_D m_N$

$\left\langle n_R^\dagger n_R \right\rangle \ni$  $\propto g_R^* g_L m_D m_N$

$$Y_B \propto \left|\left\langle n_L^\dagger n_L \right\rangle - \left\langle n_R^\dagger n_R \right\rangle\right|^2 \propto |g_L g_R|^2$$

Solve tedious 21 time-evolutionary equations.....

1 $$\partial_t\langle n^{s\dagger}_{L,\vec{k}} n^s_{L,\vec{k}}\rangle = -is\epsilon^{i\theta_{\vec{k}}}\left(\tilde{m}_N\langle n^s_{R,-\vec{k}} n^s_{L,\vec{k}}\rangle + g^*_R\langle D^s_{R,-\vec{k}} n^s_{L,\vec{k}}\rangle\right) + \text{h.c.}\,, \tag{A12}$$

2 $$\partial_t\langle n^s_{R,-\vec{k}} n^s_{L,\vec{k}}\rangle = 2is\left|\vec{k}\right|\langle n^s_{R,-\vec{k}} n^s_{L,\vec{k}}\rangle - is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}^*_N\langle n^{s\dagger}_{L,\vec{k}} n^s_{L,\vec{k}}\rangle + g^*_L\langle D^{s\dagger}_{L,\vec{k}} n^s_{L,\vec{k}}\rangle\right) + is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}^*_N\langle n^s_{R,-\vec{k}} n^{s\dagger}_{R,-\vec{k}}\rangle + g_R\langle n^s_{R,-\vec{k}} D^{s\dagger}_{R,-\vec{k}}\rangle\right), \tag{A13}$$

3 $$\partial_t\langle D^s_{R,-\vec{k}} n^s_{L,\vec{k}}\rangle = 2is\left|\vec{k}\right|\langle D^s_{R,-\vec{k}} n^s_{L,\vec{k}}\rangle + is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}^*_N\langle D^s_{R,-\vec{k}} n^{s\dagger}_{R,-\vec{k}}\rangle + g_R\langle D^s_{R,-\vec{k}} D^{s\dagger}_{R,-\vec{k}}\rangle\right) - is\epsilon^{-i\theta_{\vec{k}}}\left(m^*_D\langle D^{s\dagger}_{L,\vec{k}} n^s_{L,\vec{k}}\rangle + M^*_R\langle D^{s\dagger}_{R,\vec{k}} n^s_{L,\vec{k}}\rangle + g_R\langle n^{s\dagger}_{L,\vec{k}} n^s_{L,\vec{k}}\rangle\right), \tag{A14}$$

4 $$\partial_t\langle D^{s\dagger}_{L,\vec{k}} n^s_{L,\vec{k}}\rangle = is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}^*_N\langle D^{s\dagger}_{L,\vec{k}} n^{s\dagger}_{R,-\vec{k}}\rangle + g_R\langle D^{s\dagger}_{L,\vec{k}} D^{s\dagger}_{R,-\vec{k}}\rangle\right) - is\epsilon^{i\theta_{\vec{k}}}\left(m_D\langle D^s_{R,-\vec{k}} n^s_{L,\vec{k}}\rangle + M_L\langle D^s_{L,-\vec{k}} n^s_{L,\vec{k}}\rangle + g_L\langle n^s_{R,-\vec{k}} n^s_{L,\vec{k}}\rangle\right), \tag{A15}$$

5 $$\partial_t\langle n^{s\dagger}_{R,-\vec{k}} n^s_{R,-\vec{k}}\rangle = is\epsilon^{i\theta_{\vec{k}}}\left(\tilde{m}_N\langle n^s_{L,\vec{k}} n^s_{R,-\vec{k}}\rangle + g_L\langle D^s_{L,\vec{k}} n^s_{R,-\vec{k}}\rangle\right) + \text{h.c.}\,, \tag{A16}$$

6 $$\partial_t\langle D^{s\dagger}_{R,-\vec{k}} n^s_{R,-\vec{k}}\rangle = is\epsilon^{i\theta_{\vec{k}}}\left(m_D\langle D^s_{L,\vec{k}} n^s_{R,-\vec{k}}\rangle + M_R\langle D^s_{R,\vec{k}} n^s_{R,-\vec{k}}\rangle + g_R\langle n^s_{L,\vec{k}} n^s_{R,-\vec{k}}\rangle\right) - is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}^*_N\langle D^{s\dagger}_{R,-\vec{k}} n^{s\dagger}_{L,\vec{k}}\rangle + g^*_L\langle D^{s\dagger}_{R,-\vec{k}} D^{s\dagger}_{L,\vec{k}}\rangle\right), \tag{A17}$$

7 $$\partial_t\langle D^{s\dagger}_{R,-\vec{k}} D^s_{R,-\vec{k}}\rangle = is\epsilon^{i\theta_{\vec{k}}}\left(m_D\langle D^s_{L,\vec{k}} D^s_{R,-\vec{k}}\rangle + M_R\langle D^s_{R,\vec{k}} D^s_{R,-\vec{k}}\rangle + g^*_R\langle n^s_{L,\vec{k}} D^s_{R,-\vec{k}}\rangle\right) + \text{h.c.}\,, \tag{A18}$$

8 $$\partial_t\langle D^{s\dagger}_{R,\vec{k}} n^s_{L,\vec{k}}\rangle = -is\epsilon^{i\theta_{\vec{k}}}\left(m_D\langle D^s_{L,-\vec{k}} n^s_{L,\vec{k}}\rangle + M_R\langle D^s_{R,-\vec{k}} n^s_{L,\vec{k}}\rangle + g^*_R\langle n^s_{L,-\vec{k}} n^s_{L,\vec{k}}\rangle\right) + is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}^*_N\langle D^{s\dagger}_{R,\vec{k}} n^{s\dagger}_{R,-\vec{k}}\rangle + g_R\langle D^{s\dagger}_{R,\vec{k}} D^{s\dagger}_{R,-\vec{k}}\rangle\right), \tag{A19}$$

9 $$\partial_t\langle D^s_{L,\vec{k}} n^s_{R,-\vec{k}}\rangle = 2is\left|\vec{k}\right|\langle D^s_{L,\vec{k}} n^s_{R,-\vec{k}}\rangle + is\epsilon^{-i\theta_{\vec{k}}}\left(m^*_D\langle D^{s\dagger}_{R,-\vec{k}} n^s_{R,-\vec{k}}\rangle + M^*_L\langle D^{s\dagger}_{L,-\vec{k}} n^s_{R,-\vec{k}}\rangle + g^*_L\langle n^{s\dagger}_{R,-\vec{k}} n^s_{R,-\vec{k}}\rangle\right) - is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}^*_N\langle D^s_{L,\vec{k}} n^{s\dagger}_{L,\vec{k}}\rangle + g^*_L\langle D^s_{L,\vec{k}} D^{s\dagger}_{L,\vec{k}}\rangle\right), \tag{A20}$$

10 $$\partial_t\langle D^s_{R,\vec{k}} n^s_{R,-\vec{k}}\rangle = 2is\left|\vec{k}\right|\langle D^s_{R,\vec{k}} n^s_{R,-\vec{k}}\rangle - is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}^*_N\langle D^s_{R,\vec{k}} n^{s\dagger}_{L,\vec{k}}\rangle + g^*_L\langle D^s_{R,\vec{k}} D^{s\dagger}_{L,\vec{k}}\rangle\right) + is\epsilon^{-i\theta_{\vec{k}}}\left(m^*_D\langle D^{s\dagger}_{L,-\vec{k}} n^s_{R,-\vec{k}}\rangle + M^*_R\langle D^{s\dagger}_{R,-\vec{k}} n^s_{R,-\vec{k}}\rangle + g_R\langle n^{s\dagger}_{L,-\vec{k}} n^s_{R,-\vec{k}}\rangle\right), \tag{A21}$$

11 $$\partial_t\langle D^s_{R,-\vec{k}} D^s_{L,\vec{k}}\rangle = 2is\left|\vec{k}\right|\langle D^s_{R,-\vec{k}} D^s_{L,\vec{k}}\rangle - is\epsilon^{-i\theta_{\vec{k}}}\left(m^*_D\langle D^{s\dagger}_{R,-\vec{k}} D^s_{L,\vec{k}}\rangle + M^*_R\langle D^{s\dagger}_{R,\vec{k}} D^s_{L,\vec{k}}\rangle + g_R\langle n^{s\dagger}_{L,\vec{k}} D^s_{L,\vec{k}}\rangle\right) + is\epsilon^{-i\theta_{\vec{k}}}\left(m^*_D\langle D^s_{R,-\vec{k}} D^{s\dagger}_{R,-\vec{k}}\rangle + M^*_L\langle D^s_{R,-\vec{k}} D^{s\dagger}_{L,-\vec{k}}\rangle + g^*_L\langle D^s_{R,-\vec{k}} n^{s\dagger}_{R,-\vec{k}}\rangle\right), \tag{A22}$$

12 $$\partial_t\langle D^s_{L,-\vec{k}} n^s_{L,\vec{k}}\rangle = 2is\left|\vec{k}\right|\langle D^s_{L,-\vec{k}} n^s_{L,\vec{k}}\rangle + is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}_N\langle D^s_{L,-\vec{k}} n^{s\dagger}_{R,-\vec{k}}\rangle + g_R\langle D^s_{L,-\vec{k}} D^{s\dagger}_{R,-\vec{k}}\rangle\right) - is\epsilon^{-i\theta_{\vec{k}}}\left(m^*_D\langle D^{s\dagger}_{R,\vec{k}} n^s_{L,\vec{k}}\rangle + M^*_L\langle D^{s\dagger}_{L,\vec{k}} n^s_{L,\vec{k}}\rangle + g^*_L\langle n^{s\dagger}_{R,\vec{k}} n^s_{L,\vec{k}}\rangle\right), \tag{A23}$$

13 $$\partial_t\langle n^s_{L,-\vec{k}} n^s_{L,\vec{k}}\rangle = 2is\left|\vec{k}\right|\langle n^s_{L,-\vec{k}} n^s_{L,\vec{k}}\rangle - is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}^*_N\langle n^{s\dagger}_{R,\vec{k}} n^s_{L,\vec{k}}\rangle + g_R\langle D^{s\dagger}_{R,\vec{k}} n^s_{L,\vec{k}}\rangle\right) + is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}^*_N\langle n^s_{L,-\vec{k}} n^{s\dagger}_{R,-\vec{k}}\rangle + g_R\langle n^s_{L,-\vec{k}} D^{s\dagger}_{R,-\vec{k}}\rangle\right), \tag{A24}$$

14 $$\partial_t\langle D^s_{R,\vec{k}} D^s_{R,-\vec{k}}\rangle = 2is\left|\vec{k}\right|\langle D^s_{R,\vec{k}} D^s_{R,-\vec{k}}\rangle - is\epsilon^{-i\theta_{\vec{k}}}\left(m^*_D\langle D^s_{R,\vec{k}} D^{s\dagger}_{L,\vec{k}}\rangle + M^*_R\langle D^s_{R,\vec{k}} D^{s\dagger}_{R,\vec{k}}\rangle + g_R\langle D^s_{R,\vec{k}} n^{s\dagger}_{L,\vec{k}}\rangle\right) + is\epsilon^{-i\theta_{\vec{k}}}\left(m^*_D\langle D^{s\dagger}_{L,-\vec{k}} D^s_{R,-\vec{k}}\rangle + M^*_R\langle D^{s\dagger}_{R,-\vec{k}} D^s_{R,-\vec{k}}\rangle + g_R\langle n^{s\dagger}_{L,-\vec{k}} D^s_{R,-\vec{k}}\rangle\right), \tag{A25}$$

15 $$\partial_t\langle D^{s\dagger}_{L,-\vec{k}} n^s_{R,-\vec{k}}\rangle = is\epsilon^{i\theta_{\vec{k}}}\left(m_D\langle D^s_{R,\vec{k}} n^s_{R,-\vec{k}}\rangle + M_L\langle D^s_{L,\vec{k}} n^s_{R,-\vec{k}}\rangle + g_L\langle n^s_{R,\vec{k}} n^s_{R,-\vec{k}}\rangle\right) - is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}^*_N\langle D^{s\dagger}_{L,-\vec{k}} n^{s\dagger}_{L,\vec{k}}\rangle + g^*_L\langle D^{s\dagger}_{L,-\vec{k}} D^{s\dagger}_{L,\vec{k}}\rangle\right), \tag{A26}$$

16 $$\partial_t\langle D^{s\dagger}_{L,\vec{k}} D^s_{L,\vec{k}}\rangle = -is\epsilon^{i\theta_{\vec{k}}}\left(m_D\langle D^s_{R,-\vec{k}} D^s_{L,\vec{k}}\rangle + M_L\langle D^s_{L,-\vec{k}} D^s_{L,\vec{k}}\rangle + g_L\langle n^s_{R,-\vec{k}} D^s_{L,\vec{k}}\rangle\right) + \text{h.c.}\,, \tag{A27}$$

17 $$\partial_t\langle n^s_{R,\vec{k}} n^s_{R,-\vec{k}}\rangle = 2is\left|\vec{k}\right|\langle n^s_{R,\vec{k}} n^s_{R,-\vec{k}}\rangle + is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}^*_N\langle n^{s\dagger}_{L,-\vec{k}} n^s_{R,-\vec{k}}\rangle + g^*_L\langle D^{s\dagger}_{L,-\vec{k}} n^s_{R,-\vec{k}}\rangle\right) - is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}^*_N\langle n^s_{\cdot,-\vec{k}} n^{s\dagger}_{\cdot,\cdot}\rangle + g^*_L\langle n^s_{\cdot,-\vec{k}} D^{s\dagger}_{\cdot,\cdot}\rangle\right), \tag{A28}$$

18 $$\partial_t\langle D^s_{L,-\vec{k}} D^s_{L,\vec{k}}\rangle = 2is\left|\vec{k}\right|\langle D^s_{L,-\vec{k}} D^s_{L,\vec{k}}\rangle - is\epsilon^{-i\theta_{\vec{k}}}\left(m^*_D\langle D^{s\dagger}_{R,\vec{k}} D^s_{L,\vec{k}}\rangle + M^*_L\langle D^{s\dagger}_{L,\vec{k}} D^s_{L,\vec{k}}\rangle + g^*_L\langle n^{s\dagger}_{R,\vec{k}} D^s_{L,\vec{k}}\rangle\right) + is\epsilon^{-i\theta_{\vec{k}}}\left(m^*_D\langle D^s_{L,-\vec{k}} D^{s\dagger}_{R,-\vec{k}}\rangle + M^*_L\langle D^s_{L,-\vec{k}} D^{s\dagger}_{L,-\vec{k}}\rangle + g^*_L\langle D^s_{L,-\vec{k}} n^{s\dagger}_{R,-\vec{k}}\rangle\right), \tag{A29}$$

19 $$\partial_t\langle D^{s\dagger}_{L,\vec{k}} D^s_{R,\vec{k}}\rangle = is\epsilon^{-i\theta_{\vec{k}}}\left(m^*_D\langle D^{s\dagger}_{L,\vec{k}} D^{s\dagger}_{L,-\vec{k}}\rangle + M^*_R\langle D^{s\dagger}_{L,\vec{k}} D^{s\dagger}_{R,-\vec{k}}\rangle + g_R\langle D^{s\dagger}_{L,\vec{k}} n^{s\dagger}_{L,-\vec{k}}\rangle\right) - is\epsilon^{i\theta_{\vec{k}}}\left(m_D\langle D^s_{R,-\vec{k}} D^s_{R,\vec{k}}\rangle + M_L\langle D^s_{L,-\vec{k}} D^s_{R,\vec{k}}\rangle + g_L\langle n^s_{R,-\vec{k}} D^s_{R,\vec{k}}\rangle\right), \tag{A30}$$

20 $$\partial_t\langle n^{s\dagger}_{R,\vec{k}} n^s_{L,\vec{k}}\rangle = -is\epsilon^{i\theta_{\vec{k}}}\left(\tilde{m}_N\langle n^s_{L,-\vec{k}} n^s_{L,\vec{k}}\rangle + g_L\langle D^s_{L,-\vec{k}} n^s_{L,\vec{k}}\rangle\right) + is\epsilon^{-i\theta_{\vec{k}}}\left(\tilde{m}^*_N\langle n^{s\dagger}_{R,\vec{k}} n^{s\dagger}_{R,-\vec{k}}\rangle + g_R\langle n^{s\dagger}_{R,\vec{k}} D^{s\dagger}_{R,-\vec{k}}\rangle\right). \tag{A31}$$

QCD Baryogenesis works !!!

$$Y_B \propto |g_L g_R|^2$$

- Neutrons and anti-neutrons are produced **simultaneously** and **asymmetrically**
- Assuming the damping transport coupling:

$$|g_{L,R}(t)| = |g_{L,R0} \cdot \varphi(t)| = |g_{L,R0} \cdot e^{-\Gamma_\varphi t} \cos m_\varphi t|$$

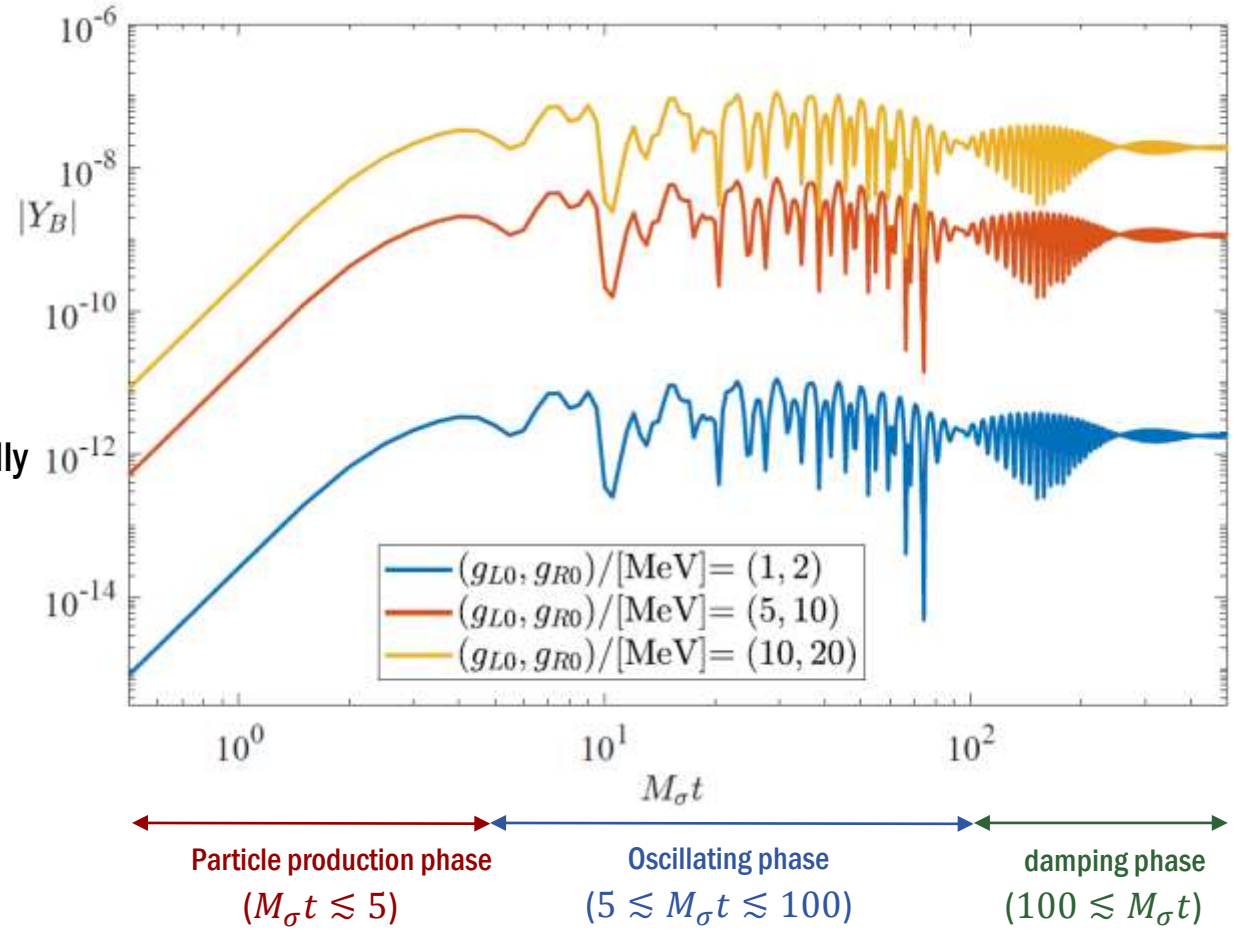
Otherwise, the net baryon continue its oscillating eternally

φ is interpreted as "would-be" ALP

$\Gamma_\varphi = 5$ MeV $\quad m_\varphi = 10$ MeV

Dark Fermion mass $m_D \sim 1$ GeV

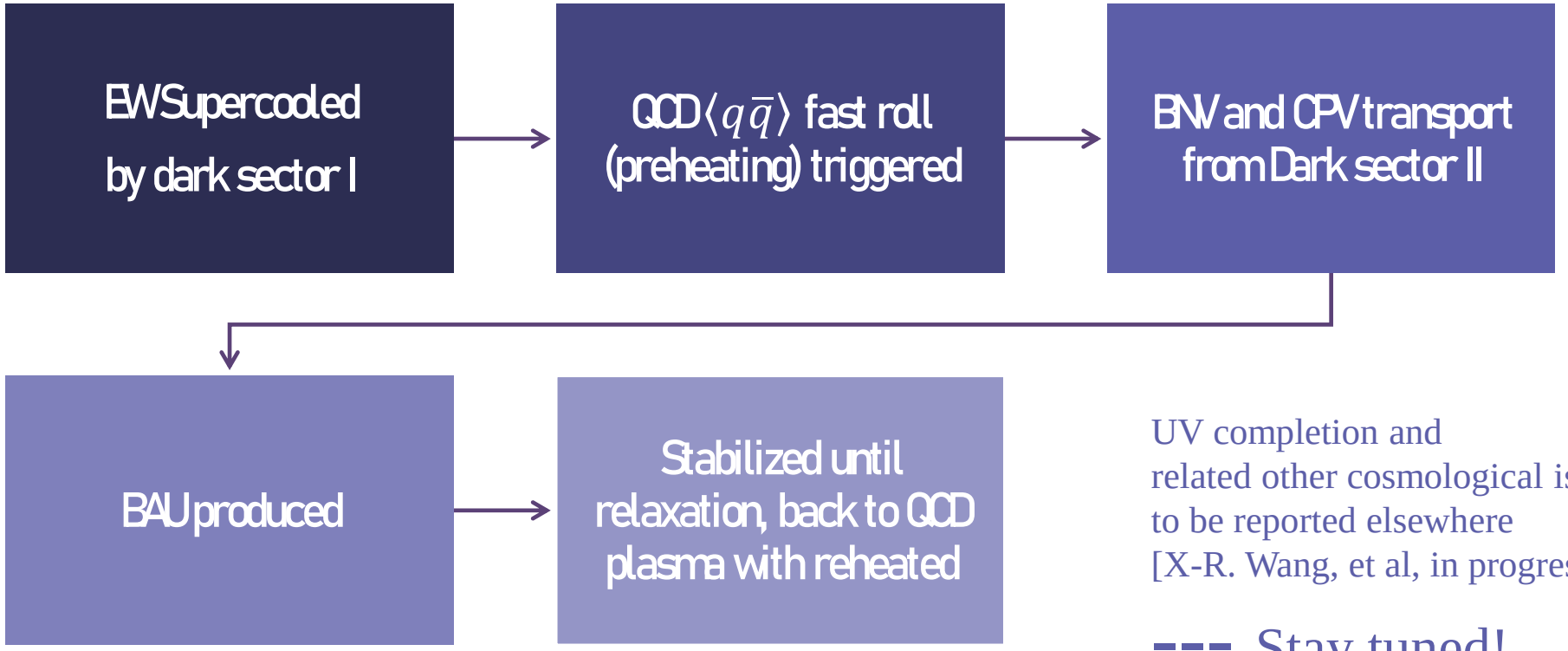
Origin of ALP to be addressed elsewhere
[X-R. Wang, et al, in progress]



Summary

New frontier open ,

involving variant Beyond the Standard Model candidates



UV completion and
related other cosmological issues,
to be reported elsewhere
[X-R. Wang, et al, in progress]

--- Stay tuned!

Character figure from https://www2.kek.jp/kids/accelerator/index.html

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Thanks for your attention !