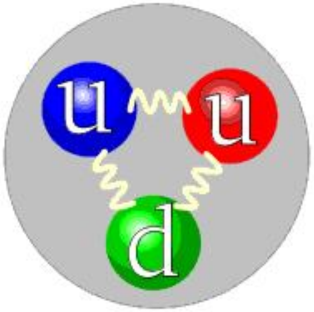
QGP production from the quantum ground-state of QCD: Hamiltonian picture

beautiful math or "New Physics" of QCD?



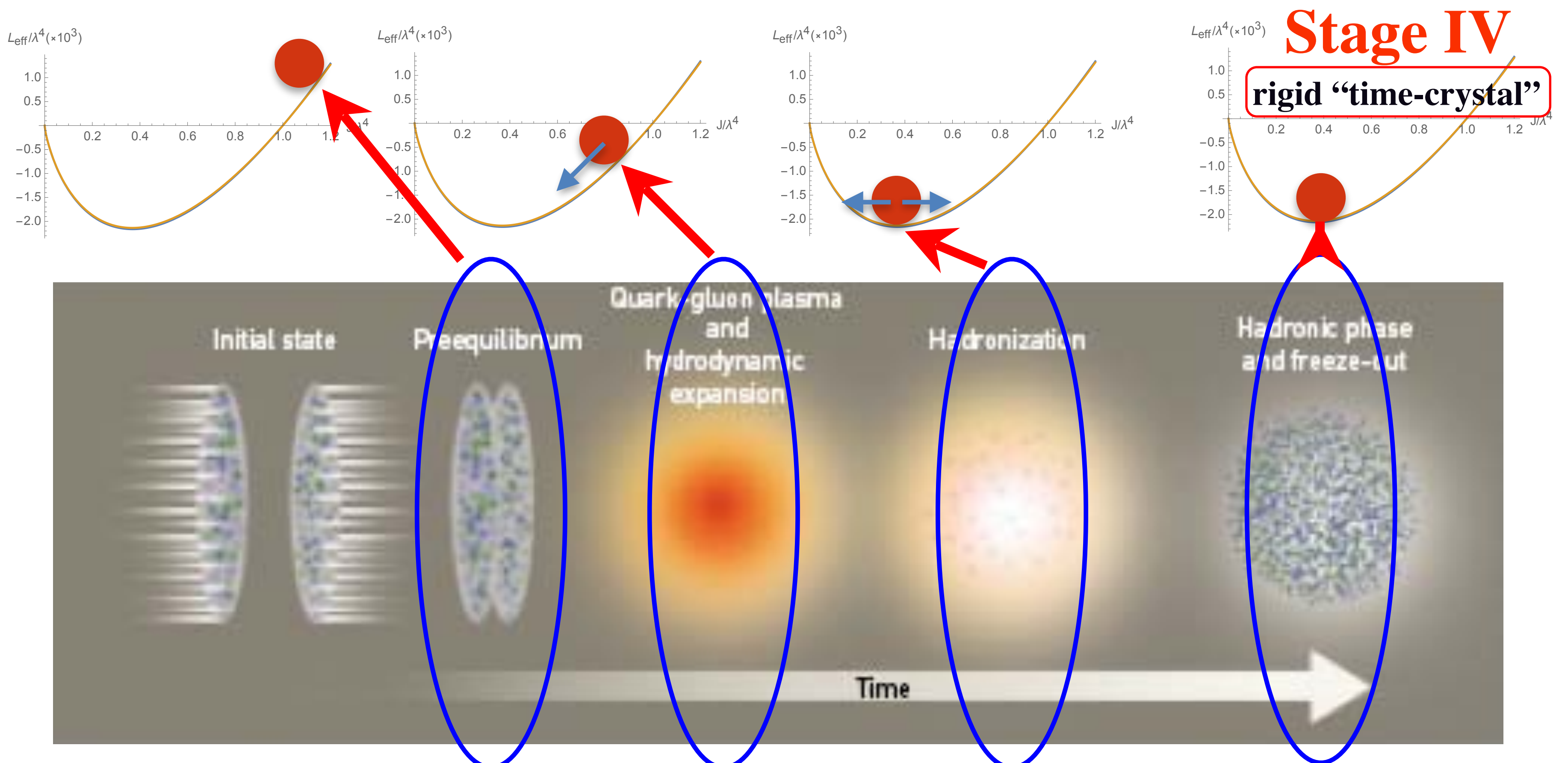
Roman Pasechnik

"The greatest adventure my generation will ever have - the confined field theory of QCD"

Bo Andersson

EPS-HEP 2019, Ghent

Outlook: stages of the “micro Big Bang”



Stage I

- (almost) classical homogeneous CE gluon condensate evolution
- small inhomogeneities
- perturbative regime (short distances)

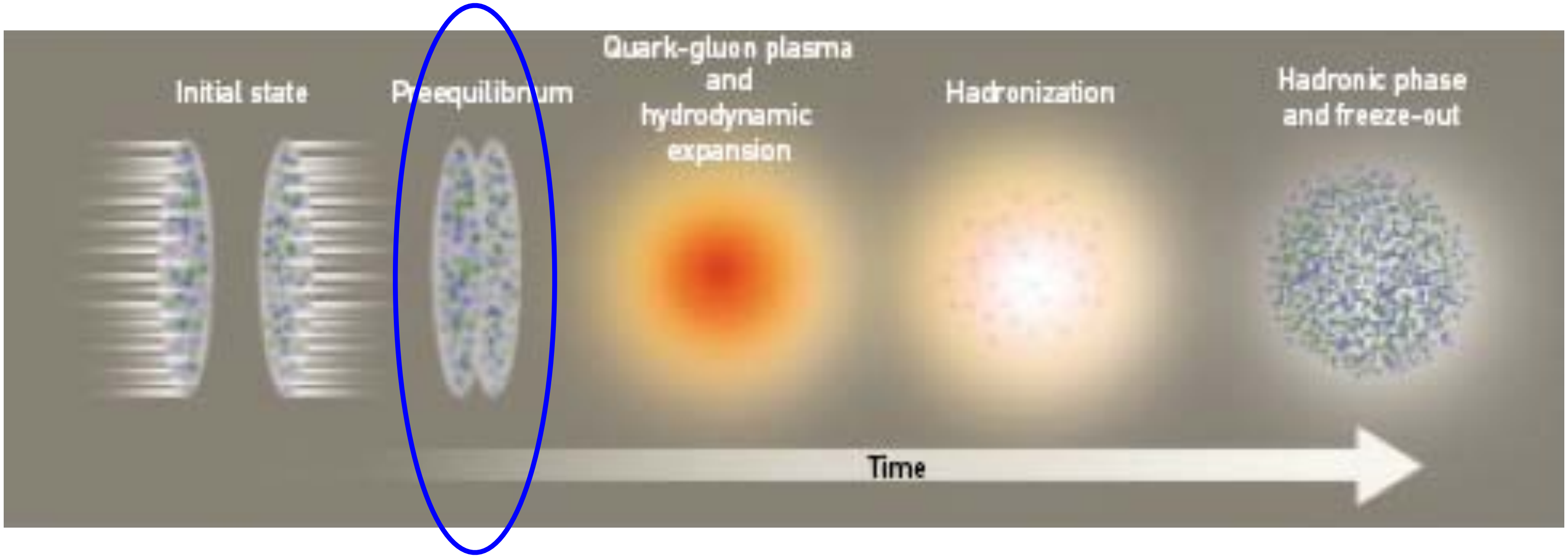
Stage II

- energy “swap” from condensate to the fluctuations (quasiclassical pic.)
- large inhomogeneities (plasma modes)
- parametric resonance effect (particle production mechanism)

Stage III

- quantum ground state formation (CE mostly + initiation of CM)
- large distances/essentially quantum dynamics
- domain-wall formation

Stage I



Initial state
Preequilibrium
Quark-gluon plasma and hydrodynamic expansion
Hadronization
Hadronic phase and freeze-out
Time

Homogeneous gluon condensate: semi-classics

R. Pasechnik, G. Prokorov & G.Vereshkov JHEP '14

Corrections are small for g_{YM}<<1
(short distances!)

Classical YM Lagrangian:

$$\mathcal{L}_{\rm cl} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a \qquad F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_{\rm YM}\, f^{abc} A^b_\mu A^c_\nu$$

Basis for canonical (Hamiltonian) quantisation of "condensate+waves" system:

temporal (Hamilton) gauge $\quad A^a_0 = 0 \qquad e^a_i A^a_k \equiv A_{ik} \qquad e^a_i e^a_k = \delta_{ik} \qquad e^a_i e^b_i = \delta_{ab}$

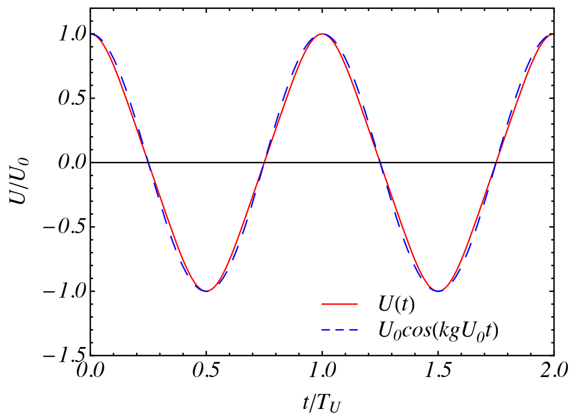
due to local SU(2) ~ SO(3) isomorphism $\quad A_{ik}(t,\vec{x}) = \delta_{ik} U(t) + \widetilde{A}_{ik}(t,\vec{x})$

$$U(t) \equiv \frac{1}{3}\delta_{ik}\langle A_{ik}(t,\vec{x})\rangle_{\vec{x}}\,, \qquad \langle A_{ik}(t,\vec{x})\rangle_{\vec{x}} = \frac{\int_\Omega d^3x\, A_{ik}(t,\vec{x})}{\int_\Omega d^3x}$$

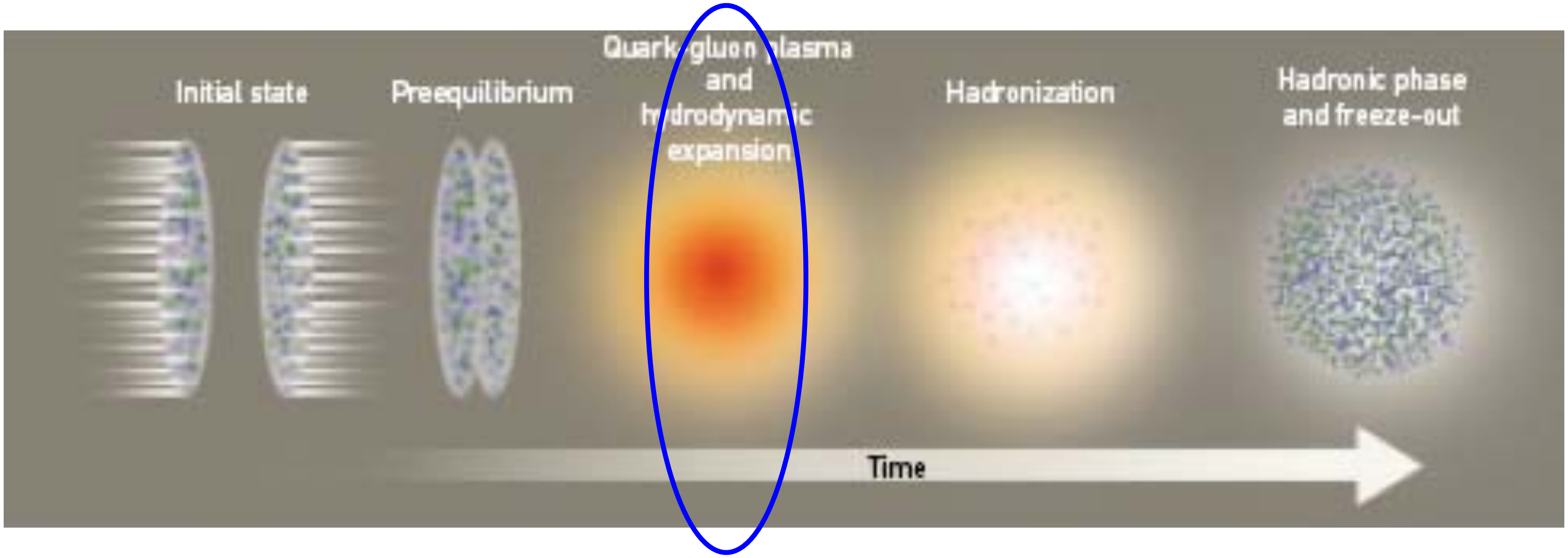
Zeroth-order in waves = "pre-quilibrium state"?

$$\mathcal{H}_{\rm YM} \simeq \mathcal{H}_{\rm YMC} = \frac{3}{2}\Big[(\partial_0 U)^2 + g^2 U^4\Big]\,, \qquad \partial_0\partial_0 U + 2g^2\, U^3 = 0$$

$$t = -\int_{U_0}^{U} \frac{dU}{\sqrt{g^2 U_0^4 - g^2 U^4}}\,, \qquad U(0) = U_0\,, \qquad U'(0) = 0$$



Stage II



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Condensate+waves semi-classical system

R. Pasechnik, G. Prokorov & G.Vereshkov JHEP '14

"condensate+waves" system evolution:

$$- \delta_{lk}(\partial_0\partial_0 U + 2g^2U^3) + (-\partial_0\partial_0 \widetilde{A}_{lk} + \partial_i\partial_i \widetilde{A}_{lk} - \partial_i\partial_k \widetilde{A}_{li} - g e_{lmk}\partial_i \widetilde{A}_{mi} U - 2g e_{lip}\partial_i \widetilde{A}_{pk} U$$
$$- g e_{lmi}\partial_k \widetilde{A}_{mi} U + g^2 \widetilde{A}_{kl} U^2 - g^2 \widetilde{A}_{lk} U^2 - 2g^2 \delta_{lk} \widetilde{A}_{ii} U^2) + (-g e_{lmp}\partial_i \widetilde{A}_{mi} \widetilde{A}_{pk}$$
$$- 2g e_{lmp} \widetilde{A}_{mi}\partial_i \widetilde{A}_{pk} - g e_{lmp}\partial_k \widetilde{A}_{mi} \widetilde{A}_{pi} + g^2 \widetilde{A}_{li}\widetilde{A}_{ik} U + g^2 \widetilde{A}_{li}\widetilde{A}_{ki} U + g^2 \widetilde{A}_{ik}\widetilde{A}_{il} U$$
$$- 2g^2 \widetilde{A}_{ii}\widetilde{A}_{lk} U - g^2 \delta_{lk}\widetilde{A}_{pi}\widetilde{A}_{pi} U) + g^2(\widetilde{A}_{li}\widetilde{A}_{pk}\widetilde{A}_{pi} - \widetilde{A}_{pi}\widetilde{A}_{pi}\widetilde{A}_{lk}) = 0$$

tensor basis decomposition

$$\chi_l^{\vec{p}} = s_l^\sigma \eta_\sigma^{\vec{p}} + n_l \lambda^{\vec{p}}$$

$$\widetilde{A}_{ik} = \psi_{ik} + e_{ikl}\chi_l$$

$$\psi_{ik}^{\vec{p}} = \psi_\lambda^{\vec{p}} Q_{ik}^\lambda + \varphi_\sigma^{\vec{p}}(n_i s_k^\sigma + n_k s_i^\sigma) + (\delta_{ik} - n_i n_k)\Phi^{\vec{p}} + n_i n_k \Lambda^{\vec{p}}$$

Full Hamiltonian

$$\mathcal{H}_{\rm YM}^{\rm waves} = \frac{1}{2}\Big\{\partial_0\psi_\lambda\,\partial_0\psi_\lambda^\dagger + \partial_0\phi_\sigma\,\partial_0\phi_\sigma^\dagger + \partial_0\Phi\,\partial_0\Phi^\dagger + \frac{1}{2}\,\partial_0\Lambda\,\partial_0\Lambda^\dagger + \partial_0\eta_\sigma\,\partial_0\eta_\sigma^\dagger$$
$$+ \partial_0\lambda\,\partial_0\lambda^\dagger + p^2\,\psi_\lambda\psi_\lambda^\dagger + \frac{p^2}{2}\,\phi_\sigma\phi_\sigma^\dagger + p^2\,\Phi\Phi^\dagger + \frac{p^2}{2}\,\eta_\sigma\eta_\sigma^\dagger + p^2\,\lambda\lambda^\dagger$$
$$- \frac{p^2}{2}\,e^{\gamma\sigma}(\eta_\sigma\phi_\gamma^\dagger + \phi_\gamma\eta_\sigma^\dagger) + igp\,U\,e^{\sigma\gamma}\eta_\sigma\eta_\gamma^\dagger - igp\,U\,Q^{\lambda\gamma}\psi_\lambda\psi_\gamma^\dagger$$
$$- igpU e^{\sigma\gamma}\phi_\sigma\phi_\gamma^\dagger - igp\,U\,(2\Phi\lambda^\dagger - 2\lambda\Phi^\dagger + \Lambda\lambda^\dagger - \lambda\Lambda^\dagger)$$
$$+ 2g^2\,U^2\,\eta_\sigma\eta_\sigma^\dagger + 2g^2\,U^2\,\lambda\lambda^\dagger + g^2\,U^2\,(4\Phi\Phi^\dagger + 2\Phi\Lambda^\dagger + 2\Lambda\Phi^\dagger + \Lambda\Lambda^\dagger)\Big\}$$

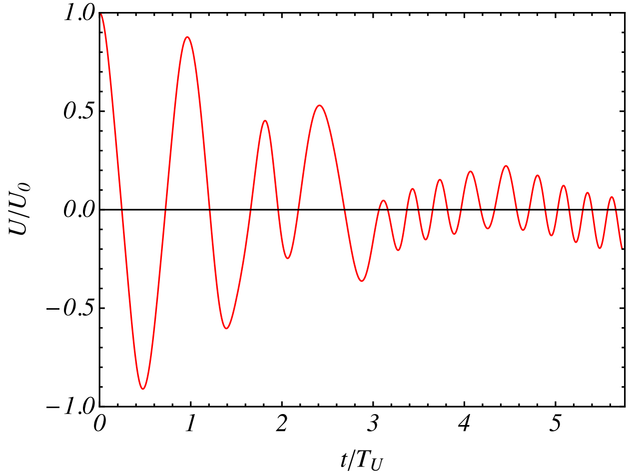
$$\mathcal{H}_{\rm YM} = \mathcal{H}_{\rm YMC} + \sum_{\vec{p}} \mathcal{H}_{\rm YM}^{\rm waves}$$

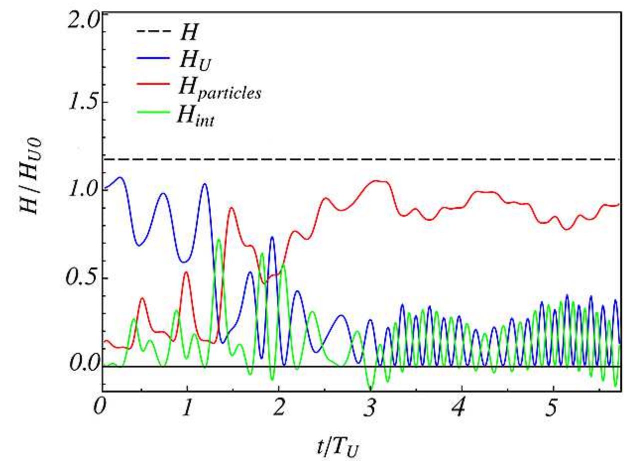
Longitudinally polarised (plasma) mode becomes physical due to interactions with the homogeneous condensate!

Decay of the homogeneous condensate

R. Pasechnik, G. Prokorov & G.Vereshkov JHEP '14

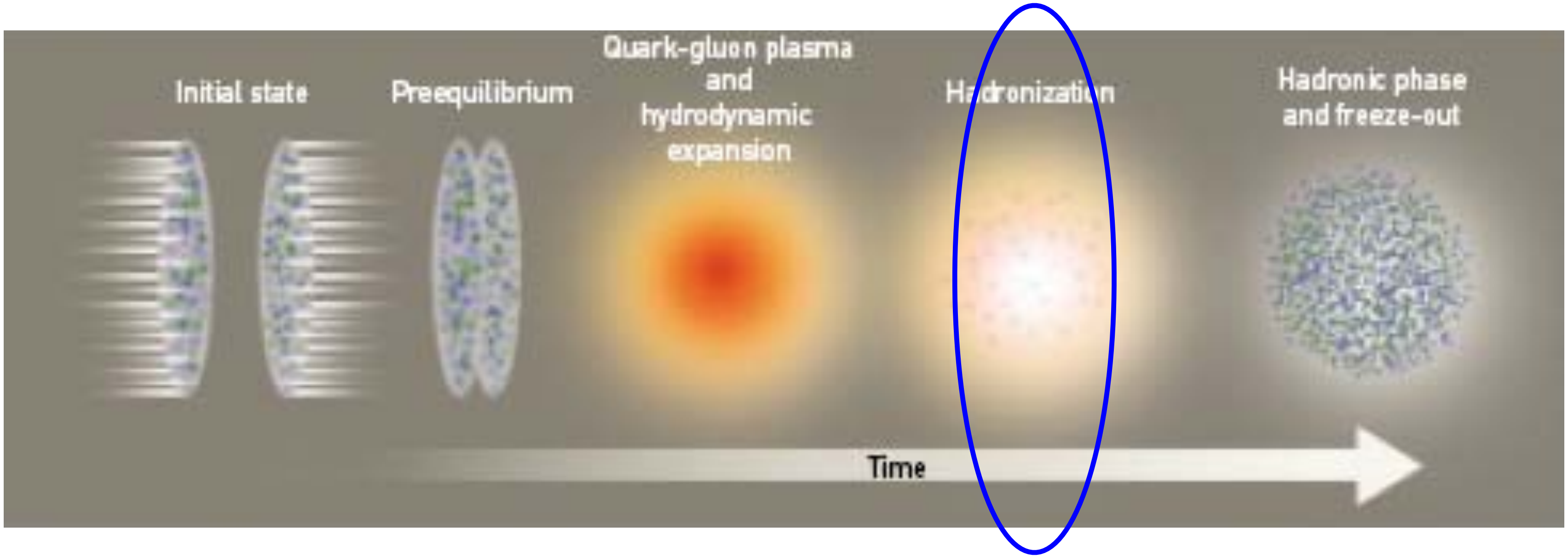
$$
\begin{aligned}
\mathcal{H}_{\rm U} &= \frac{3}{2}\left(\partial_0 U \partial_0 U + g^2\, U^4\right)\,,\\
\mathcal{H}_{\rm particles} &= \frac{1}{2}\sum_{\vec p}\,\Big(\partial_0\psi_\lambda\,\partial_0\psi^\dagger_\lambda + \partial_0\phi_\sigma\,\partial_0\phi^\dagger_\sigma + \partial_0\Phi\,\partial_0\Phi^\dagger + \frac{1}{2}\,\partial_0\Lambda\,\partial_0\Lambda^\dagger + \partial_0\eta_\sigma\,\partial_0\eta^\dagger_\sigma\\
&+\partial_0\lambda\,\partial_0\lambda^\dagger + p^2\,\psi_\lambda\psi^\dagger_\lambda + \frac{p^2}{2}\,\phi_\sigma\phi^\dagger_\sigma + p^2\,\Phi\Phi^\dagger + \frac{p^2}{2}\,\eta_\sigma\eta^\dagger_\sigma + p^2\,\lambda\lambda^\dagger\\
&-\frac{p^2}{2}\,e^{\gamma\sigma}\left(\eta_\sigma\phi^\dagger_\gamma + \phi_\gamma\eta^\dagger_\sigma\right)\Big)\,,\\
\mathcal{H}_{\rm int} &= \frac{1}{2}\sum_{\vec p}\,\Big[igp\,U\,e^{\sigma\gamma}\eta_\sigma\eta^\dagger_\gamma - igp\,U\,Q^{\lambda\gamma}\psi_\lambda\psi^\dagger_\gamma\\
&- igpU\,e^{\sigma\gamma}\phi_\sigma\phi^\dagger_\gamma - igp\,U\,(2\Phi\lambda^\dagger - 2\lambda\Phi^\dagger + \Lambda\lambda^\dagger - \lambda\Lambda^\dagger)\\
&+ 2g^2\,U^2\,\eta_\sigma\eta^\dagger_\sigma + 2g^2\,U^2\,\lambda\lambda^\dagger + g^2\,U^2\,(4\Phi\Phi^\dagger + 2\Phi\Lambda^\dagger + 2\Lambda\Phi^\dagger + \Lambda\Lambda^\dagger)\Big]\,.
\end{aligned}
$$





Ultra-relativistic gluon plasma production!

Stage III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Long distances: chromo-magnetic condensate

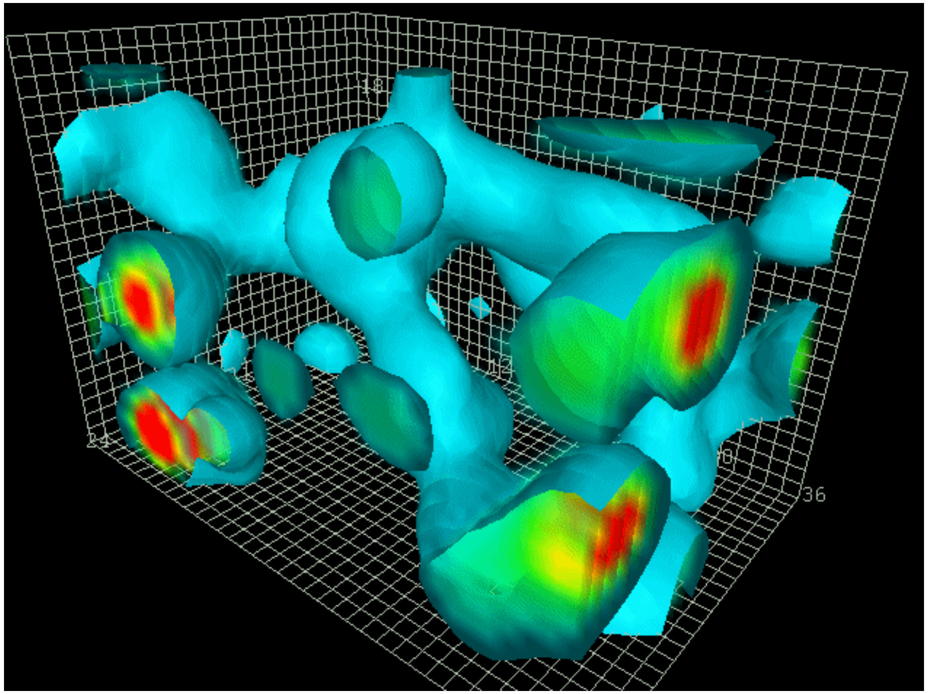
Quantum-topological (chromomagnetic) vacuum in QCD

$$\varepsilon_{vac(top)} = -\frac{9}{32}\langle 0| : \frac{\alpha_s}{\pi} F^a_{ik}(x) F^{ik}_a(x) : |0\rangle + \frac{1}{4}\left(\langle 0| : m_u \bar{u} u : |0\rangle + \langle 0| : m_d \bar{d} d : |0\rangle + \langle 0| : m_s \bar{s} s : |0\rangle\right)$$

$$\simeq -(5 \pm 1) \times 10^9\ \mathrm{MeV}^4.$$

CM condensate:

$\epsilon_{vac} \sim 10^{-2} \mathrm{GeV}^4$



Ground-state at long distances:

$\Lambda_{\mathrm{cosm}} \sim 10^{-47}\ \mathrm{GeV}^4$

Vacuum in QCD has incredibly wrong energy scale… or

We must be missing something very important!?

Effective YM action

A. Addazi, A. Marciano, R. Pasechnik & G. Prokorov, EPJC '19

At least, for SU(2) gauge symmetry, the all-loop and one-loop effective Lagrangians are practically indistinguishable (by FRG approach)

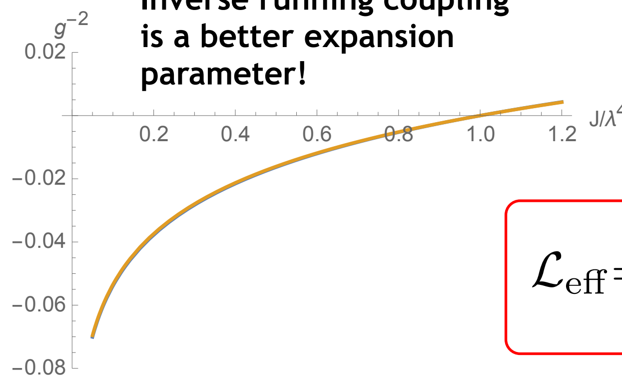
P. Dona, A. Marciano, Y. Zhang and C. Antolini, Phys. Rev. D **93** (2016) no.4, 043012.

A. Eichhorn, H. Gies and J. M. Pawlowski, Phys. Rev. D **83** (2011) 045014 [Phys. Rev. D **83** (2011) 069903].

H. Pagels and E. Tomboulis, Nucl. Phys. B **143**, 485 (1978).

$$\mathcal{L}_{\rm cl} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a \qquad \mathcal{A}^a_\mu \equiv g_{\rm YM} A^a_\mu \qquad \mathcal{F}^a_{\mu\nu} \equiv g_{\rm YM} F^a_{\mu\nu}$$

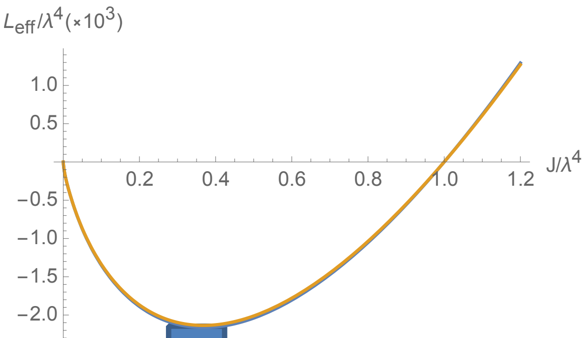
Inverse running coupling is a better expansion parameter!



Effective YM Lagrangian:

$$\boxed{\mathcal{L}_{\rm eff} = \frac{\mathcal{J}}{4\bar{g}^2(\mathcal{J})}, \qquad \mathcal{J} = -\mathcal{F}^a_{\mu\nu}\mathcal{F}^{\mu\nu}_a}$$

Effective Lagrangian:



chromoelectric (CE) condensate (Savvidy vacuum) $\quad \mathcal{J}^* > 0$

G. K. Savvidy, Phys. Lett. **71B**, 133 (1977)

The energy-momentum tensor:

$$T^\nu_\mu = \frac{1}{\bar{g}^2}\left[\frac{\beta(\bar{g}^2)}{2} - 1\right]\left(\mathcal{F}^a_{\mu\lambda}\mathcal{F}^{\nu\lambda}_a + \frac{1}{4}\delta^\nu_\mu \mathcal{J}\right) - \delta^\nu_\mu \frac{\beta(\bar{g}^2)}{8\bar{g}^2}\mathcal{J}$$

Equations of motion:

$$\overrightarrow{\mathcal{D}}^{ab}_\nu \left[\frac{\mathcal{F}^{\mu\nu}_b}{\bar{g}^2}\left(1 - \frac{\beta(\bar{g}^2)}{2}\right)\right] = 0,$$

$$\overrightarrow{\mathcal{D}}^{ab}_\nu \equiv \left(\delta^{ab}\overrightarrow{\partial}_\nu - f^{abc}\mathcal{A}^c_\nu\right),$$

trace anomaly:

$$T^\mu_\mu = -\frac{\beta(\bar{g}^2)}{2\bar{g}^2}\mathcal{J}$$

NOTE: the RG equation

$$\frac{d\ln|\bar{g}^2|}{d\ln|\mathcal{J}|/\mu_0^4} = \frac{\beta(\bar{g}^2)}{2}$$

appears to be invariant under

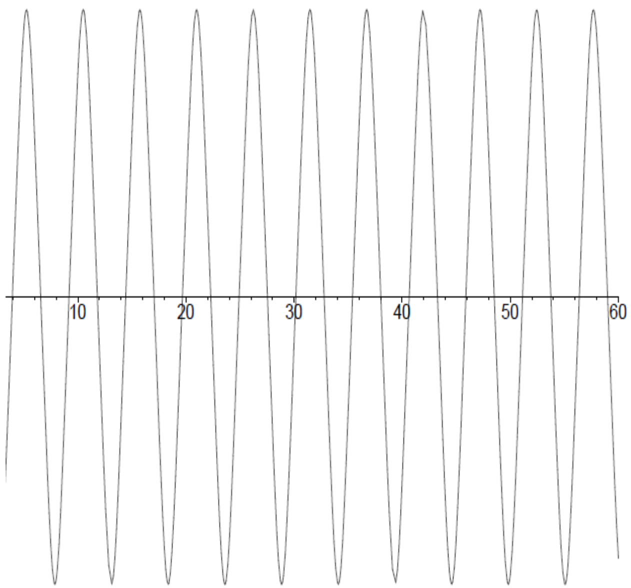
$$\boxed{\mathcal{J} \longleftrightarrow -\mathcal{J} \qquad \bar{g}^2 = \bar{g}^2(|\mathcal{J}|)}$$

Chromo-electric condensate solution

A. Addazi, A. Marciano, R. Pasechnik & G. Prokorov, EPJC '19

$$Q \equiv \frac{32}{11}\pi^2 e(\xi\Lambda_{\rm QCD})^{-4} T^{\mu}_{\mu}[U]$$
$$= 6e\left[(U')^2 - \frac{1}{4}U^4\right] a^{-4}(\xi\Lambda_{\rm QCD})^{-4}$$

Classical YM condensate



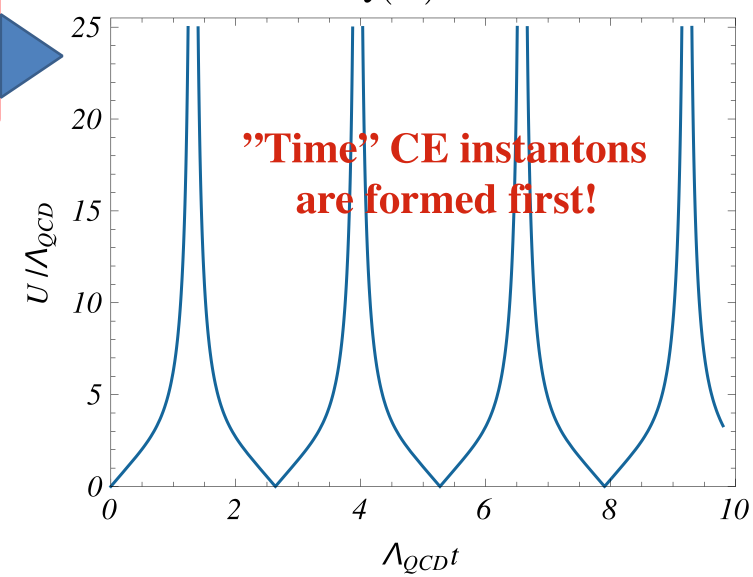
Exact partial solution:

$$|Q| = 1$$

Quantum corrections

Savvidy (CE) vacuum

$$Q(U) = 1$$



"Radiation" medium

$$\epsilon_{\rm YM} \propto 1/a^4$$

Unstable solution!

QCD vacuum:
a ferromagnetic undergoing spontaneous magnetisation (Pagels&Tomboulis)

Asymptotic tracker solution!

$$\epsilon_{\rm CE} \to +\text{const} \quad t \to \infty$$

Stable solution!

- **In fact, both chromoelectric and chromomagnetic condensates are stable on non-stationary (FLRW) background of expanding Universe**

"Mirror" symmetry of the ground state

A. Addazi, A. Marciano, R. Pasechnik & G. Prokorov, EPJC '19

In a vicinity of the ground state, the effective Lagrangian

$$\mathcal{L}_{\rm eff} = \frac{\mathcal{J}}{4\bar{g}^2} \qquad \mathcal{J} \simeq \mathcal{J}^*$$

is invariant under

$$\boxed{\mathbb{Z}_2: \qquad \mathcal{J}^* \longleftrightarrow -\mathcal{J}^*, \quad \bar{g}^2(\mathcal{J}^*) \longleftrightarrow -\bar{g}^2(\mathcal{J}^*), \quad \beta(\bar{g}_*^2) \longleftrightarrow -\beta(\bar{g}_*^2)}$$

For pure gluodynamics at one-loop: $\beta_{(1)} = -\frac{bN}{48\pi^2}\,\bar{g}^2_{(1)} \qquad b = 11$

$$\alpha_s = \frac{\bar{g}^2}{4\pi} \qquad \alpha_{\rm s}(\mu^2) = \frac{\alpha_{\rm s}(\mu_0^2)}{1 + \beta_0\,\alpha_{\rm s}(\mu_0^2)\ln(\mu^2/\mu_0^2)} \qquad \mu^2 \equiv \sqrt{|\mathcal{J}|}$$

Choosing the ground state value of the condensate $\mu_0^2 \equiv \sqrt{|\mathcal{J}^*|}$ **as the physical scale**

we observe that the mirror symmetry, indeed, holds provided

$$\mathcal{J} \simeq \mathcal{J}^* \qquad \alpha_s(\mu_0^2) \longleftrightarrow -\alpha_s(\mu_0^2)$$

i.e. in the ground state only!

Heterogenic quantum YM ground state: two-scale vacuum

The running coupling at one-loop

$$\bar{g}_1^2(\mathcal{J}) = \frac{\bar{g}_1^2(\mu_0^4)}{1+\frac{bN}{96\pi^2}\bar{g}_1^2(\mu_0^4)\ln(|\mathcal{J}|/\mu_0^4)} = \frac{96\pi^2}{bN\ln(|\mathcal{J}|/\lambda_\pm^4)}$$

$$\mathcal{L}_{\rm eff}^{(1)} = \frac{bN}{384\pi^2}\mathcal{J}\ln\left(\frac{|\mathcal{J}|}{\lambda_\pm^4}\right)$$

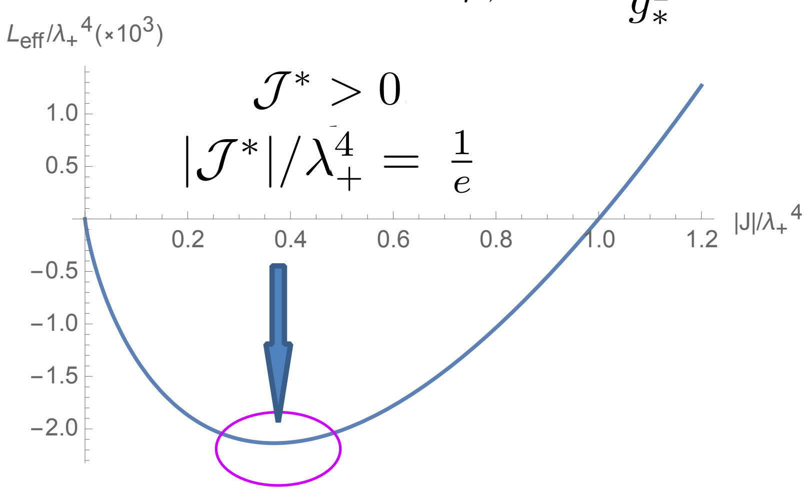
with two energy scales

$$\boxed{\lambda_\pm^4 \equiv |\mathcal{J}^*|\exp\left[\mp\frac{96\pi^2}{bN|\bar{g}_1^2(\mathcal{J}^*)|}\right] \qquad |\mathcal{J}^*| = \lambda_+^2\lambda_-^2}$$

CE vacuum: $\beta(\bar{g}_*^2) = 2$

e.o.m. is automatically satisfied!

Trace anomaly: $T^\mu_{\mu,\rm CE} = -\frac{1}{\bar{g}_*^2}\mathcal{J}^*$



Cosmological CE attractor

Mirror symmetry

One-loop:

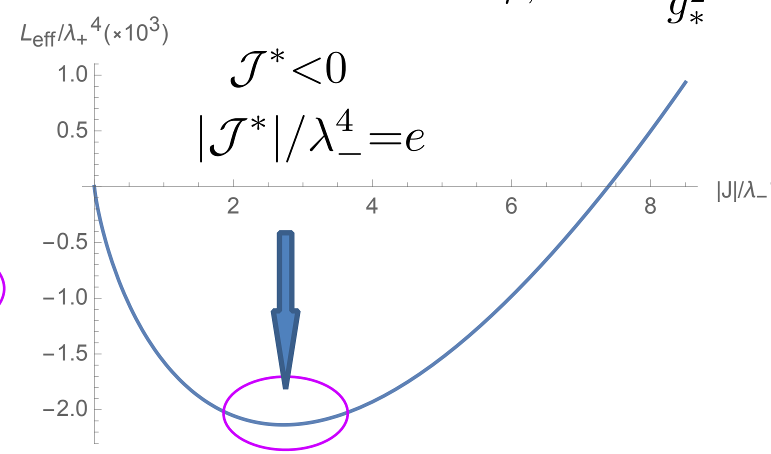
$$\lambda_+^2/\lambda_-^2 = e$$

CM vacuum: $\beta(\bar{g}_*^2) = -2$

Reduces to the standard YM e.o.m. discussed in e.g. in instanton theory

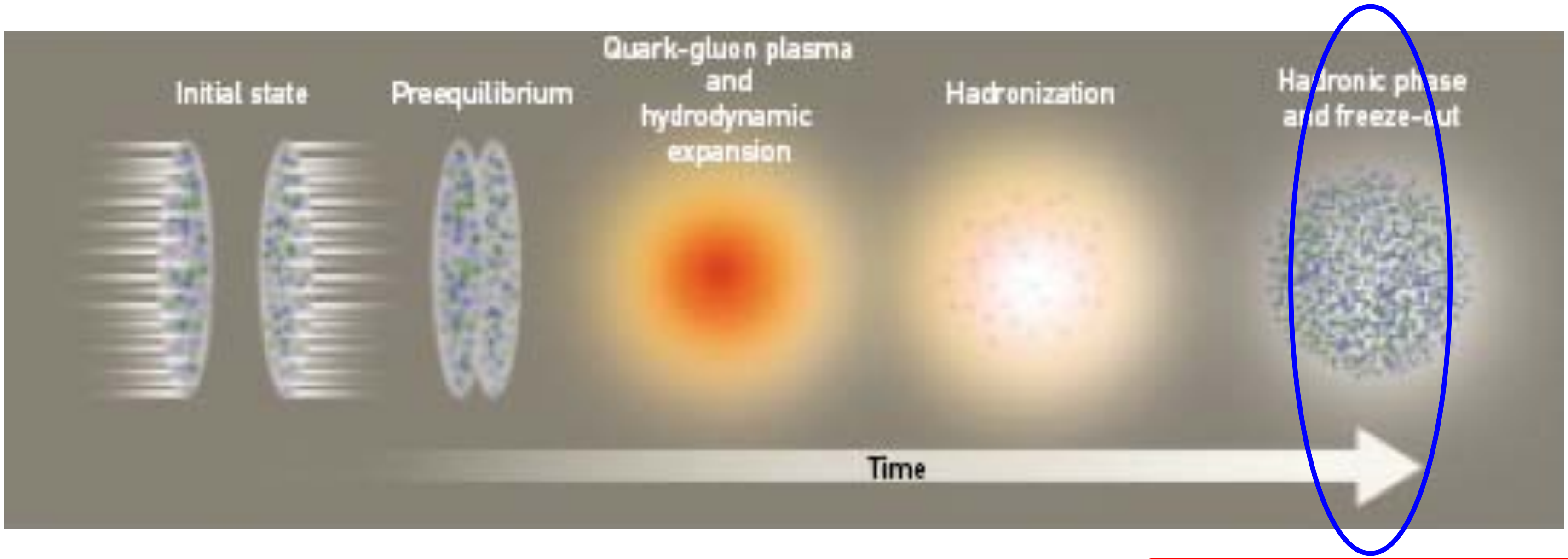
$$\overrightarrow{\mathcal{D}}_\nu^{ab}\left[\frac{\mathcal{F}_b^{\mu\nu}}{\bar{g}^2}\right] = 0, \quad \bar{g}^2 \simeq \bar{g}_*^2$$

Trace anomaly: $T^\mu_{\mu,\rm CM} = +\frac{1}{\bar{g}_*^2}\mathcal{J}^*$



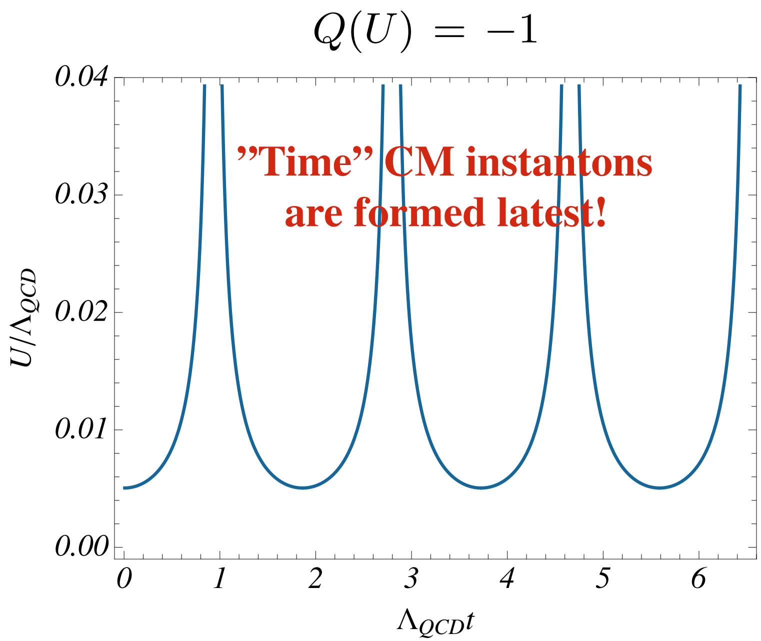
Cosmological CM attractor

Post-confinement: stage IV



- **Both CE and CM reach their attractors**
- **CM/CE domains "crystallisation"**
- **rigid "time-crystal" (no fluctuations)**
- **CC is formed**

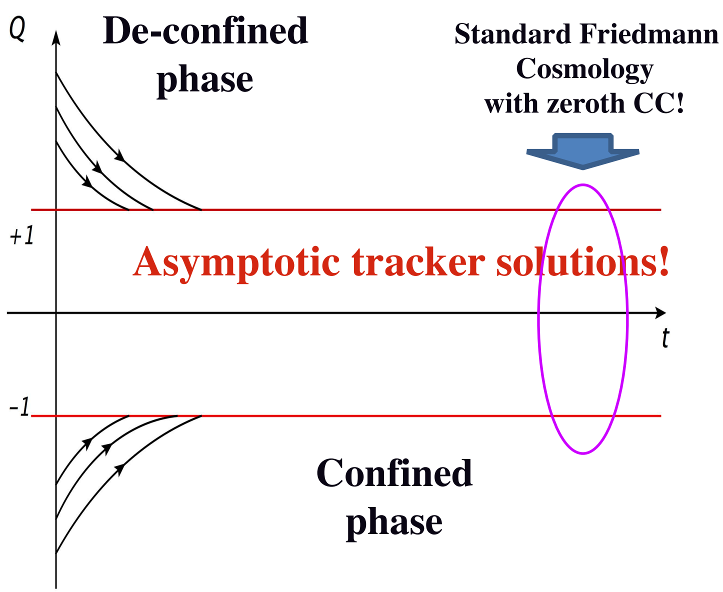
Macroscopic evolution and vacua cancellation



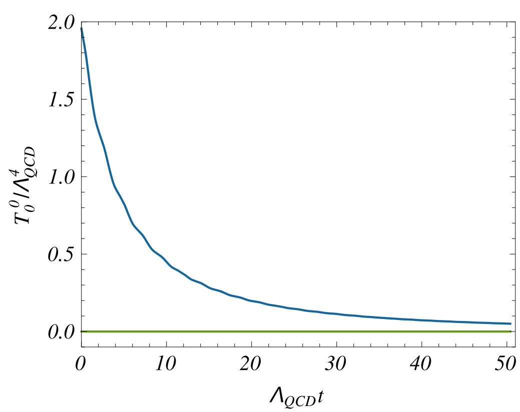
$$\epsilon_{\rm vac} \equiv \frac{1}{4}\langle T^{\mu}_{\mu}\rangle_{\rm vac} = \mp\mathcal{L}_{\rm eff}(\mathcal{J}^*)$$

$$\boxed{\epsilon^{\rm CE}_{\rm vac}\Big|_{\mathcal{J}^*>0} + \epsilon^{\rm CM}_{\rm vac}\Big|_{\mathcal{J}^*<0} \equiv 0}$$

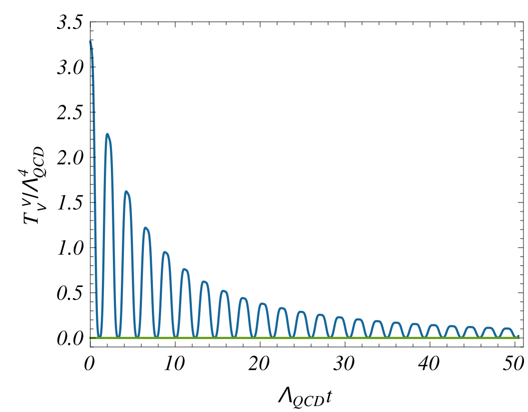
Exact compensation of CM and CE vacua
as soon as the cosmological attractor is achieved!



CE energy density



CE EMT trace



System with very unusual dynamical properties!

Summary

- **Hamiltonian (real-time) picture in temporal gauge offers a novel look at physical evolution of "micro-Big Bang" events in heavy-ion collisions that is not reachable in Lattice QCD (Maiani-Testa theorem PLB '90)**

- **Semi-classical dynamics of the homogeneous gluon condensate (with small inhomogeneities) represent the initial (pre-equilibrium) state in a typical such event**

- **Real-time evolution of such pre-equilibrium state unavoidably leads to a decay of the gluon condensate and resonant-like production of inhomogeneous quantum-wave fluctuations. This provides a consistent dynamical mechanism of QGP production from the ground state in QCD**

- **While semi-classical picture above is approximately valid at small times/distances, at large separation scales, quantum corrections to the ground state become crucial. The vacuum polarisation dramatically modifies the e.o.m for the homogeneous gluon condensate, leading to the ground-state solutions of a new type (obeying the vacuum e.o.s)**

For more information, please, come to my next talk today:

Quantum Yang-Mills vacua in expanding Universe: Do we live in a time crystal?

11 Jul 2019, 14:53
22m
ICC - Baeckeland 2 (Ghent)

Parallel talk | Quantum Field and Str... | Quantum Field and String...