Nonequilibrium meson production in strong fields.

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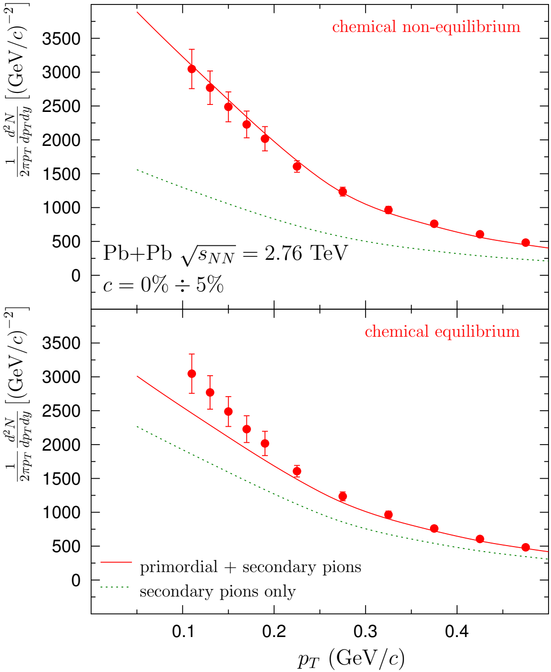
Compact stars in the QCD Phase Diagram VI,
Dubna, September 27, 2017



V.Begun, arXiv:1512.09157

Time dependent mass and dispersion relation

- Dispersion relation for σ and π

$$\omega_\sigma(t,\vec{p}) = \sqrt{m_\sigma(T(t))^2 + \vec{p}^2}\,, \quad \omega_\pi(\vec{p}) = \sqrt{m_\pi^2 + \vec{p}^2}\,,$$

- The mass evolution of σ is governed by

$$m_\sigma(T(t)) = [m_\sigma(0) - m_\pi]\sqrt{1 - \frac{T(t)}{T_c}} + m_\pi\,, \quad T(t) = \frac{T_0\ t_0}{t}\,, \quad t \geq t_0\,,$$

- Temperature is given by

$$T(t) = \frac{T_0\ t_0}{t}\,, \quad t \geq t_0\,,$$

$$T(t) \leq T_c$$

Kinetic equation - assumptions

- Spatial homogeneity of distribution function $f_i(t, \vec{p})$

$$\frac{\partial f_i}{\partial \vec{x}} = 0$$

- Spatial isotropy
- The 3-dim expansion is governed by

$$\frac{df_i}{dt} = \frac{\partial f_i}{\partial t} - \frac{\dot{R}}{R}\mathbf{p} \cdot \frac{\partial f_i}{\partial \mathbf{p}}$$

- $R(t) = V \cdot t$ is radius of expanding fireball

J. Bernstein *Kinetic theory in the expanding universe* Cambridge Press 1988

Kinetic equation for π

$$\frac{\partial f_\pi}{\partial t}(t,\vec{p_1}) - \frac{\dot{R}(t)}{R(t)} \cdot \vec{p_1}\frac{\partial f_\pi}{\partial \vec{p_1}} =$$

$$(1+f_\pi(t,\vec{p_1}))\left(\int d^3p_\sigma \frac{d^3p_2}{(2\pi)^3 4 w_\sigma w_2}\Gamma_{\sigma\to\pi\pi}(\vec{p}_\sigma,\vec{p_1},\vec{p_2})\,(1+f_\pi(t,\vec{p_2}))\,f_\sigma(t,\vec{p}_\sigma)\right)$$

$$-f_\pi(t,\vec{p_1})\left(\int d^3p_\sigma \frac{d^3p_2}{(2\pi)^3 4 w_\sigma w_2}\Gamma_{\pi\pi\to\sigma}(\vec{p}_\sigma,\vec{p_1},\vec{p_2})f_\pi(t,\vec{p_2})\,(1+f_\sigma(t,\vec{p}_\sigma))\right)$$

$R(t) = v_R \cdot t$ is radius of expanding fireball

J. Bernstein *Kinetic theory in the expanding universe* Cambridge Press 1988

Ł.Juchnowski, D.B.Blaschke, T.Fischer, S. A. Smolyansky, J.Phys.Conf.Ser. 673 (2016) 1, 012009

Kinetic equation for σ

$$\frac{\partial f_\sigma}{\partial t}(t,\vec{p}_\sigma) - \frac{\dot{R}(t)}{R(t)} \cdot \vec{p}_\sigma \frac{\partial f_\sigma}{\partial \vec{p}_\sigma} =$$

$$= \frac{\Delta_\sigma(t,\vec{p}_\sigma)}{2} \int_{t_0}^{t} dt' \Delta_\sigma(t',\vec{p}_\sigma)\left(1 + f_\sigma(t',\vec{x},\vec{p}_\sigma)\right)\cos\left(2\theta_\sigma(t,t',\vec{p}_\sigma)\right)$$

$$+ \left(1 + f_\sigma(t,\vec{p}_\sigma)\right)\left(\int d^3p_1 \frac{d^3p_2}{(2\pi)^6 4w_1w_2} \Gamma_{\pi\pi\to\sigma}(\vec{p}_\sigma,\vec{p}_1,\vec{p}_2) f_\pi(t,\vec{p}_1) f_\pi(t,\vec{p}_2)\right)$$

$$- f_\sigma(t,\vec{p}_\sigma)\left(\int d^3p_1 \frac{d^3p_2}{(2\pi)^6 4w_1w_2} \Gamma_{\sigma\to\pi\pi}(\vec{p}_\sigma,\vec{p}_1,\vec{p}_2)\left(1 + f_\pi(t,\vec{p}_1)\right)\left(1 + f_\pi(t,\vec{p}_2)\right)\right)$$

The vacuum transition amplitude and dynamical phase

$$\Delta_\sigma(t,\vec{p}_\sigma) = \frac{m_\sigma}{w_\sigma^2}\frac{\partial m_\sigma}{\partial t}, \qquad \theta_\sigma(t,t',\vec{p}_\sigma) = \int_{t'}^{t} dt'' w_\sigma(t'',\vec{p}_\sigma)$$

A.V Filatov, *et al.* , Phys. Part. Nucl. **39** 1116 (2008)

Schmidt, Blaschke *et al.* Int.J.Mod.Phys. E7 (1998) 709-722

Reaction rate

For the σ decay and regeneration we assume a constant matrix element $|M|^2 = \mathrm{const}$ so that the momentum dependence of $\Gamma_{\sigma\to\pi\pi}$ is simply given by the momentum conserving delta-function

$$\begin{aligned} \Gamma_{\sigma\to\pi\pi}(\vec{p}_\sigma, \vec{p}_1, \vec{p}_2) &= (2\pi)^4\delta^4(p_\sigma - p_1 - p_2)|M|^2 \\ &\to (2\pi)^4\delta(w_\sigma - w_1 - w_2)\delta^3(\vec{p}_\sigma - \vec{p}_1 - \vec{p}_2)\,. \end{aligned}$$

Elastic scattering

$$\frac{df_\pi(\varepsilon_1)}{dt} = \frac{|M_{fi}|^2}{64\pi^3\varepsilon_1}\int\int F(f)\frac{D}{p_1}d\varepsilon_1' d\varepsilon_2',$$

$$F(f) = [1+f_1]\,[1+f_2]f_1'f_2' - [1+f_1']\,[1+f_2']f_1 f_2 \ ,$$

$$D \equiv \min[p_1, p_2, p_1', p_2']$$

Semikoz, Tkachev, Phys. Rev. D 55, 489

Thermal initial conditions (LHC)

$$f_i(t_0, \vec{p}) = g_i \left[\exp(\sqrt{p^2 + m_i^2(T_0)}/T_0) - 1 \right]^{-1} \ , \quad i = \pi, \sigma \ .$$

$$T_0 = Tc = 170 \text{ MeV}$$

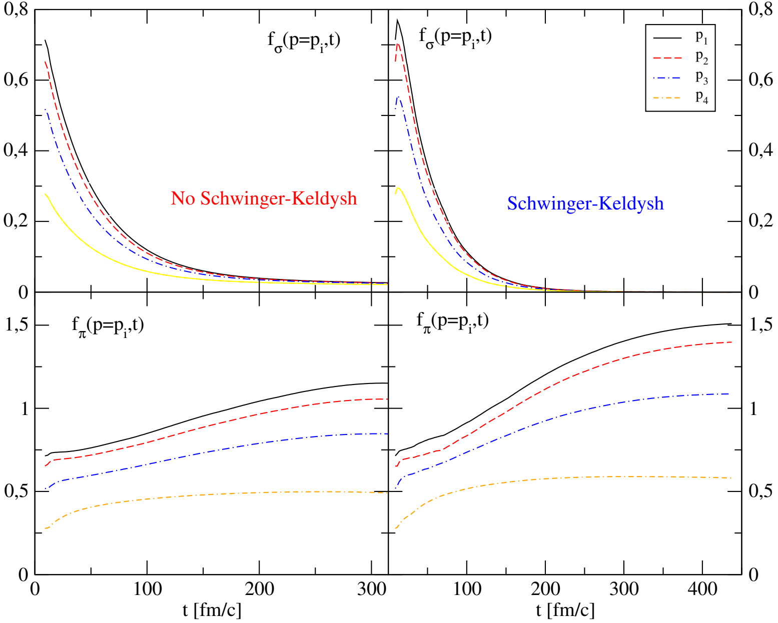
$$\mu = 0$$

$$t_0 = 9 \text{ fm/c}$$

$$m_\pi = 140 \text{ MeV}$$

$$m_\sigma(0) = 550 \text{ MeV}$$

Value of t_0 corresponding to a Hubble flow velocity of $v_R = 0.72$ c for gold nuclei with radius $R_0 = 6.5$ fm



$p_1 = 5$ MeV, $p_2 = 50$ MeV, $p_3 = 100$ MeV, $p_4 = 200$ MeV

Enhancement factor

$$r = \frac{n_{\text{final}}}{n_{\text{initial}}} = \int_0^\infty dpp^2 f_\pi(t_f, \vec{p}) \Big/ \int_0^\infty dpp^2 f_\pi(t_0, \vec{p}) \quad (1)$$

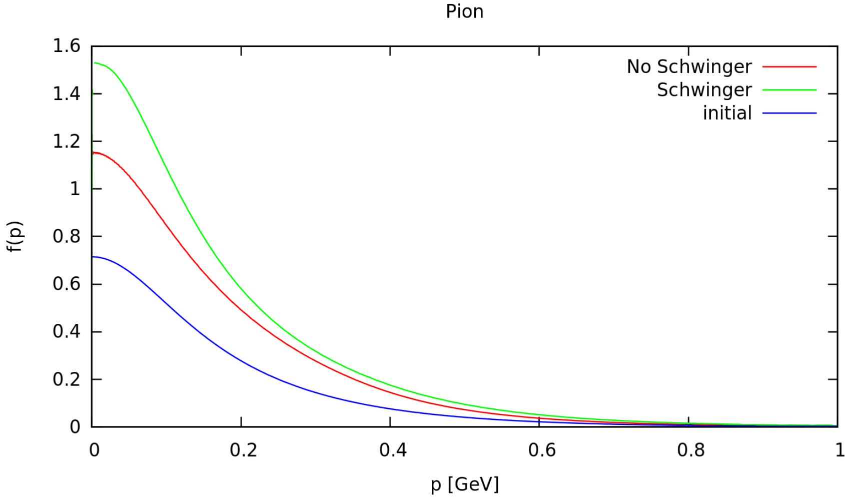
- in the presence of Keldysh-Schwinger process

$$r_+ = 2.57$$

- in the absence of Keldysh-Schwinger process

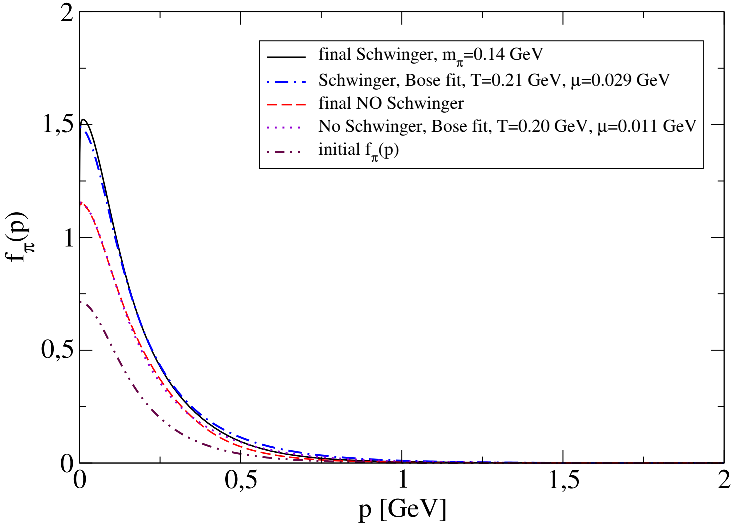
$$r_- = 2.08$$

Pion distribution function



$$r_+ = \frac{n_{\text{final}}}{n_{\text{initial}}} = 2.57 \qquad r_- = 2.08$$

Pion distribution function



$$r_+ = \frac{n_{\text{final}}}{n_{\text{initial}}} = 2.57 \qquad r_- = 2.08$$

Summary & Conclusion

- Expansion term

$$\frac{\dot{R}}{R}\mathbf{p}\cdot\frac{\partial f_i}{\partial \mathbf{p}}$$

and time dependent dispersion relation

$$\omega_\sigma(t,\vec{p}) = \sqrt{m_\sigma(T(t))^2 + \vec{p}^2}$$

seems to be main driving "force"

- Production ratio is not high $\Rightarrow$ enhancment in partonic phase (?)
- More chiral physics is needed
- There is a need to study B-E condensation

$$\tilde{f} = f(\vec{\mathbf{p}},t) + (2\pi)^3 N_c(t)\delta^3(\vec{\mathbf{p}})$$

To the future

- Full 3D solver instead of the expansion term
- Collision integrals evaluation with minimal number of approximations/assumptions
- Study of non-equilibrium effects in HIC/Supernovae
- Study dynamical Schwinger effect/inertial mechanism in HIC and supernovae

THE END

The resulting system of kinetic equations

$$
\begin{aligned}
\frac{\partial f_\sigma}{\partial t}(t, p_\sigma) &= \frac{\Delta_\sigma(t, p_\sigma)}{2} \int_{t_0}^{t} dt' \Delta_\sigma(t', p_\sigma) \left(1 + f_\sigma(t', p_\sigma)\right) \cos\left(2\theta_\sigma(t, t', p_\sigma)\right) \\
&+ \frac{1}{8\pi} \left(1 + f_\sigma(t, p_\sigma)\right) \frac{1}{p_\sigma w_\sigma} \int_{p_1^-}^{p_1^+} p_1 dp_1 \frac{|M|^2}{w_1} f_\pi(t, p_1) f_\pi(t, p_2) \\
&- \frac{1}{8\pi} f_\sigma(t, p_\sigma) \frac{1}{p_\sigma w_\sigma} \int_{p_1^-}^{p_1^+} p_1 dp_1 \frac{|M|^2}{w_1} \left(1 + f_\pi(t, p_1)\right) \left(1 + f_\pi(t, p_2)\right)
\end{aligned}
$$

$$
\begin{aligned}
\frac{\partial f_\pi}{\partial t}(t, p_1) &= \frac{1}{8\pi} \left(1 + f_\pi(t, p_1)\right) \frac{1}{p_1 w_1} \int_{p_\sigma^-}^{p_\sigma^+} p_\sigma dp_\sigma \frac{|M|^2}{w_\sigma} f_\sigma(t, p_\sigma) \left(1 + f_\pi(t, p_2)\right) \\
&- \frac{1}{8\pi} f_\pi(t, p_1) \frac{1}{p_1 w_1} \int_{p_\sigma^-}^{p_\sigma^+} p_\sigma dp_\sigma \frac{|M|^2}{w_\sigma} f_\pi(t, p_2) \left(1 + f_\sigma(t, p_\sigma)\right) \ ,
\end{aligned}
$$

$p_2 = p_2(\vec{p_1}; \vec{p_\sigma})$

$$
p_1^\pm = \frac{1}{2} \left| p_\sigma \pm w_\sigma \sqrt{1 - \frac{4m_\pi^2}{m_\sigma^2}} \right|, \qquad p_\sigma^\pm = \frac{m_\sigma^2}{m_\pi^2} \frac{1}{2} \left| p_1 \pm w_1 \sqrt{1 - \frac{4m_\pi^2}{m_\sigma^2}} \right|
$$