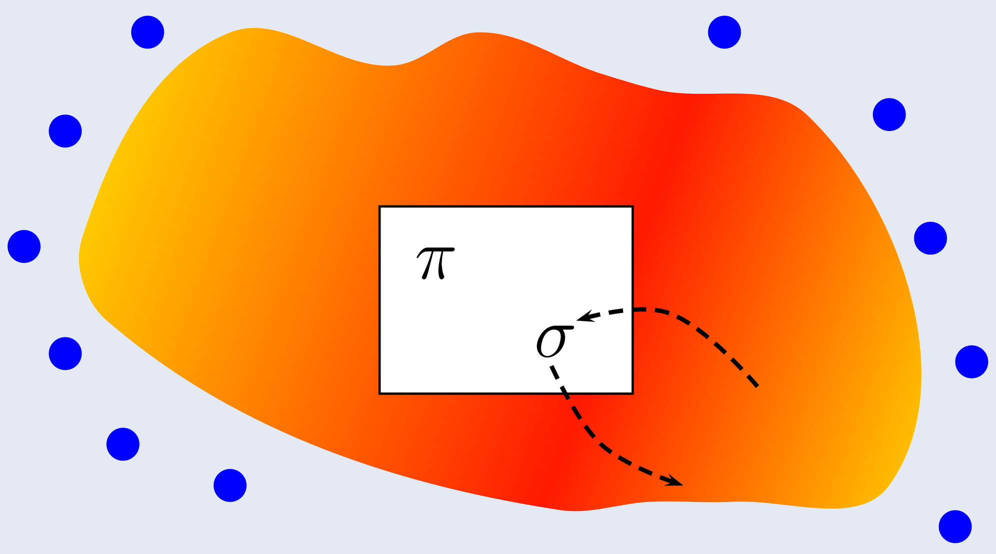
Phase transitions in chiral fluid dynamics including dissipation and noise

Marlene Nahrgang[1,2], Marcus Bleicher[1,2] and Stefan Leupold[3]

(1) Institute for Theoretical Physics, Goethe-University Frankfurt,
(2) Frankfurt Institute for Advanced Studies (FIAS),
(3) Department of Physics and Astronomy, Uppsala University

Motivation

- The system created in a heavy-ion collision is finite, very dynamic and inhomogeneous.
- Nonequilibrium effects play an important role at the phase transition in heavy-ion collisions.
- We propagate the order parameter of chiral symmetry explicitly. It is coupled to a realistic fluid dynamical description of the expansion of the fireball. These models are called chiral fluid dynamics [1,2].
- We extend chiral fluid dynamics by consistently including dissipation and noise and existing Langevin studies of chiral symmetry [3,4,5] by consistently taking the back reaction of the fields on the finite and dynamic heat bath into account.



The quark-meson model

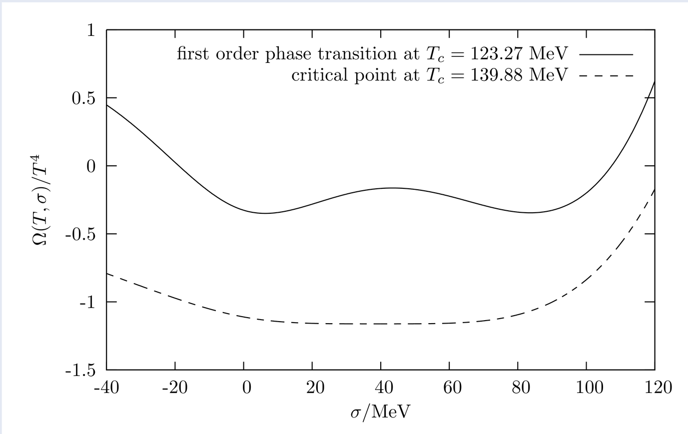
The starting point for the coupled system is the quark-meson model

$$\mathcal{L} = \overline{q}\left[i\gamma^\mu\partial_\mu - g\left(\sigma + i\gamma_5\vec{\tau}\vec{\pi}\right)\right]q + \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma) + \frac{1}{2}(\partial_\mu\vec{\pi}\partial^\mu\vec{\pi}) - U(\sigma,\vec{\pi})\,.$$

In the mean-field approximation the thermodynamic potential to one-loop level at $\mu = 0$ is given by

$$\Omega(\sigma,\vec{\pi},T) = U(\sigma,\vec{\pi}) - 2d_qT\int\frac{d^3p}{(2\pi)^3}\ln\left(1+\exp\left(-\frac{E}{T}\right)\right)\,,$$

For a small coupling the transition is a crossover, for $g = 3.63$ the potential becomes flat at $T_c = 139.88$ MeV (critical point). For $g = 5.5$ one finds two degenerate minima at $T_c = 123.27$ MeV (first order phase transition).



Coupled dynamics

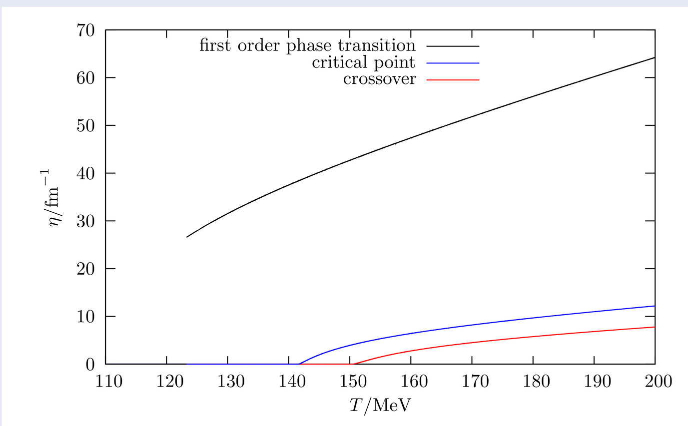
Within the formalism of the 2PI effective action one can selfconsistently [6,7] derive the dynamics of the σ mean field and the quark fluid [8]. The σ field is propagated according to a Langevin equation

$$\partial_\mu\partial^\mu\sigma + \frac{\delta U}{\delta\sigma} + g\rho_s + \eta\partial_t\sigma = \xi$$

with a damping term η and the noise field ξ. For $\mathbf{k} = 0$

$$\eta = g^2\frac{d_q}{\pi}\left(1 - 2n_{\rm F}\left(\frac{m_\sigma}{2}\right)\right)\frac{\left(\frac{m_\sigma^2}{4} - m_q^2\right)^{\frac{3}{2}}}{m_\sigma^2}$$

$$\langle\xi(t)\xi(t')\rangle = \frac{1}{V}\delta(t-t')m_\sigma\eta\coth\left(\frac{m_\sigma}{2T}\right)\,.$$



Below T_c: damping by the interaction with the hard pions $\eta = 2.2/\mathrm{fm}$ [4]. The quark fluid evolves according to energy-momentum conservation. Here, approximation of an ideal fluid:

$$\partial_\mu T_{\rm q}^{\mu\nu} = S^\nu$$

The source term describes the energy dissipation from the field to the fluid

$$\partial_\mu T_\sigma^{\mu\nu} = -(g\rho_s + \eta\partial_t\sigma)\partial^\nu\sigma$$

and the energy flow from the fluid to the field provided by the noise field ξ. It is obtained from the total energy of the field [9]

$$E_\sigma = 1/2\partial_t\sigma^2 + 1/2\vec{\nabla}\sigma^2 + U(\sigma)$$

Time evolution of the coupled system

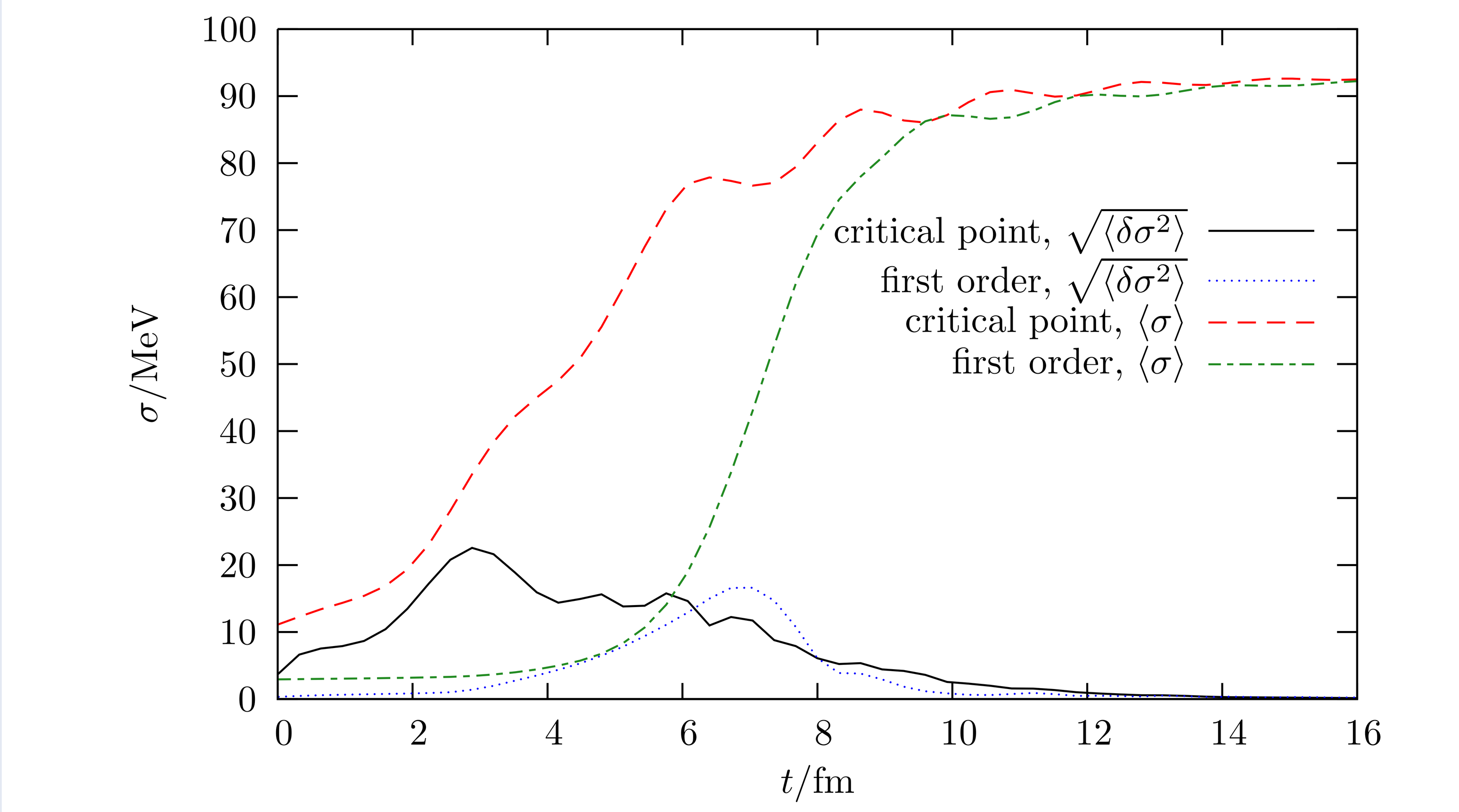


Figure: The relaxation of the σ field and its fluctuations averaged over an inner sphere. In a scenario with a first order phase transition the σ field relaxes more slowly than for a scenario with a critical point, where we see oscillations due to the vanishing damping at the phase transition [10].

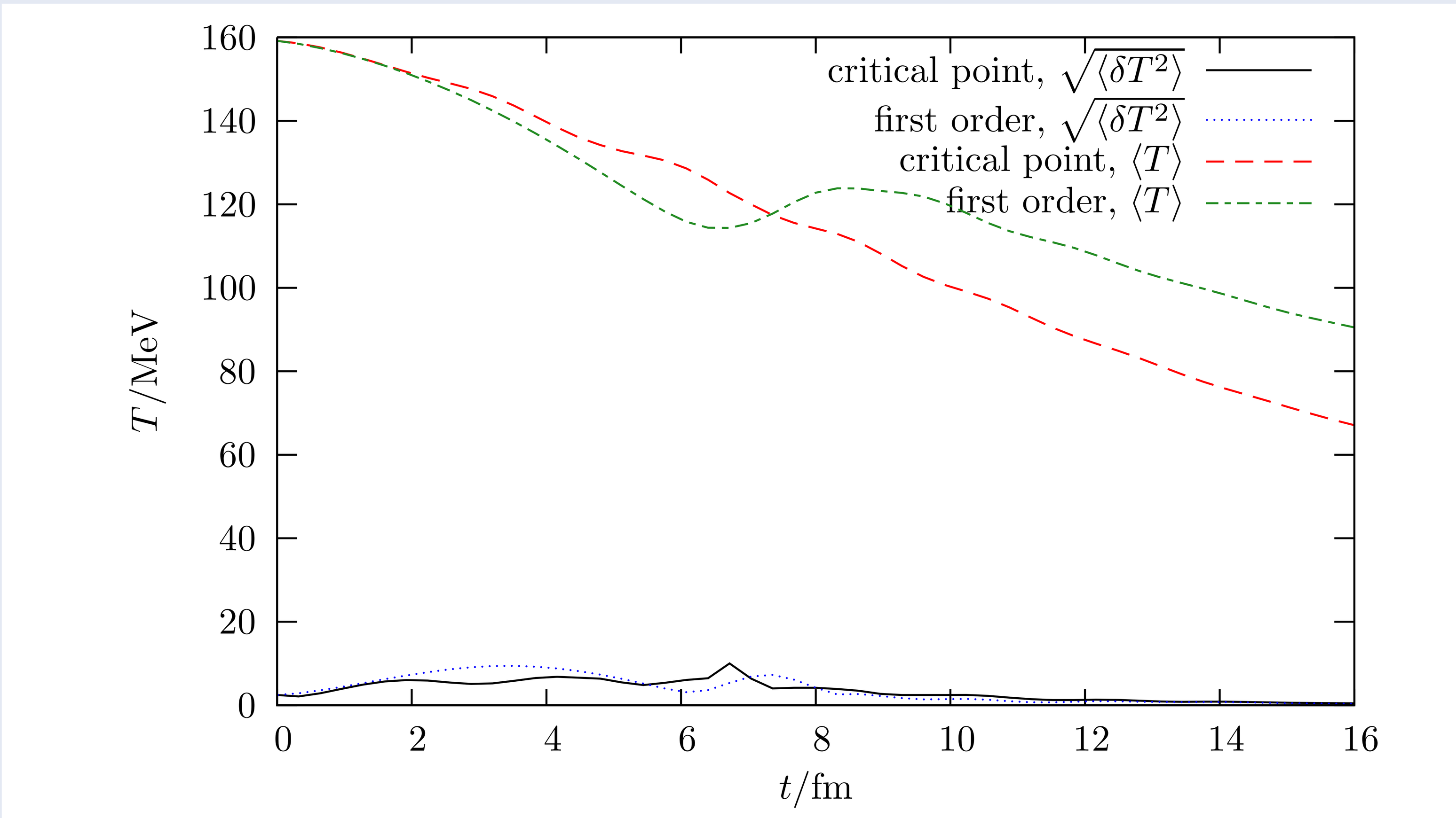


Figure: The time evolution of the temperature of the quark fluid and its fluctuations averaged over an inner sphere. During the relaxational process of the σ field one observes the reheating effect in a scenario with a first order phase transition [10].

Intensity of σ fluctuations

$$\frac{dN_\sigma}{d^3k} = \frac{(\omega_k^2|\sigma_k|^2 + |\partial_t\sigma_k|^2)}{(2\pi)^3 2\omega_k}$$

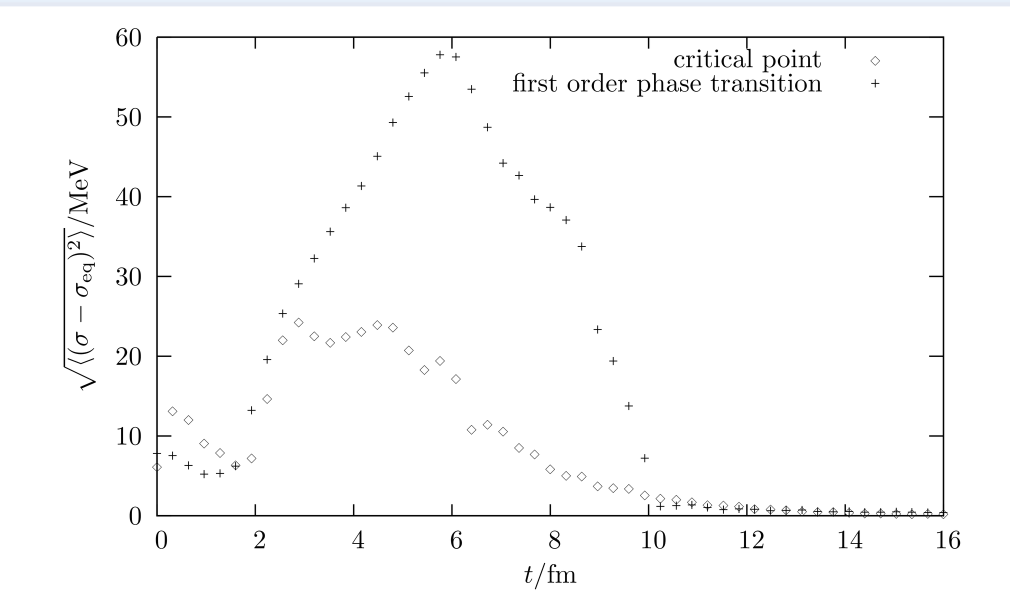


Figure: Deviation of the σ field from equilibrium for a scenario with a critical point and a first order phase transition [10].

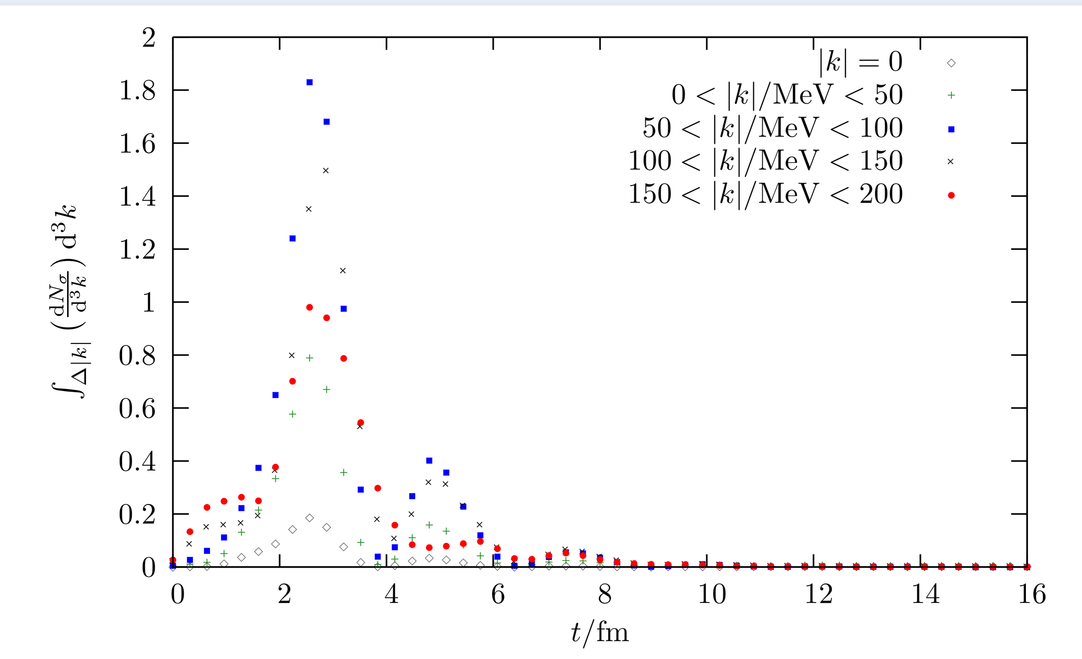


Figure: The intensity of σ fluctuations in a critical point scenario [10].

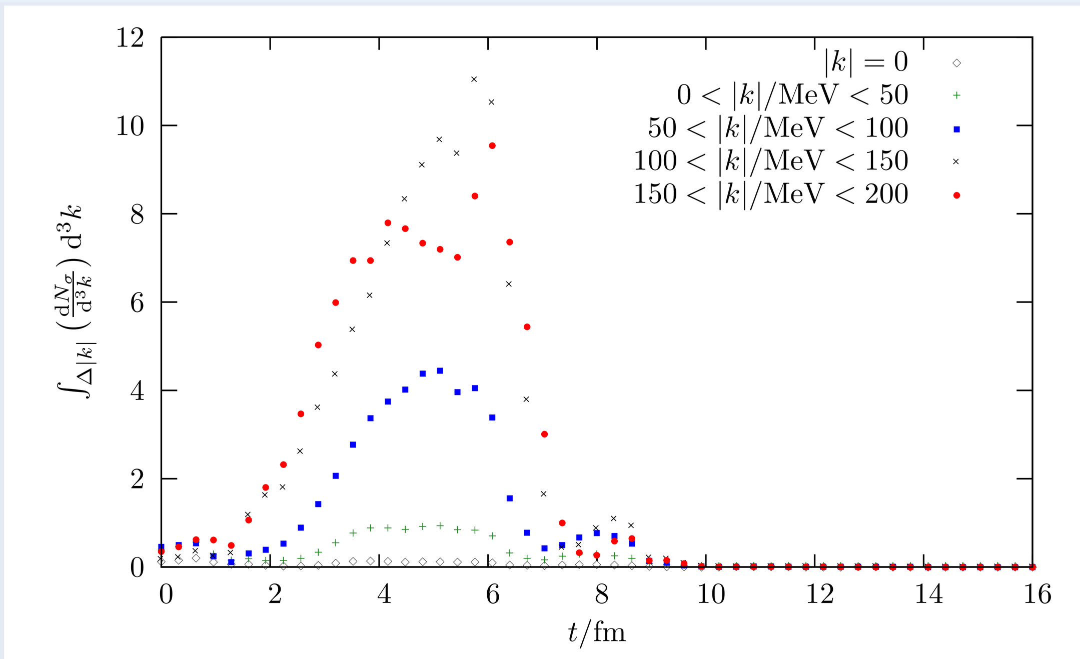


Figure: The intensity of σ fluctuations in a scenario with a first order phase transition [10].

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Summary

- We presented a model of chiral fluid dynamics which consistently includes damping and noise.
- Energy-momentum conservation is obtained by taking the back reaction on the heat bath into account.
- We observed the nonequilibrium effects of supercooling and reheating.
- Enhanced σ fluctuations at the first order phase transition were found.

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