Formation of high density domains at the QCD phase transition

Christoph Herold and Marcus Bleicher

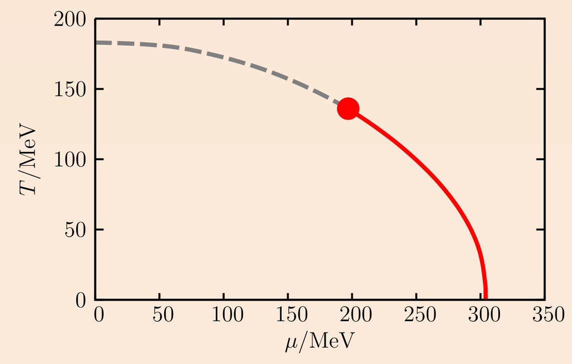
In collaboration with Marlene Nahrgang, Igor Mishustin, Stefan Schramm, Jan Steinheimer

Institute for Theoretical Physics, Goethe University Frankfurt
Frankfurt Institute for Advanced Studies (FIAS)

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

The QCD phase diagram - does a phase transition exist or not?

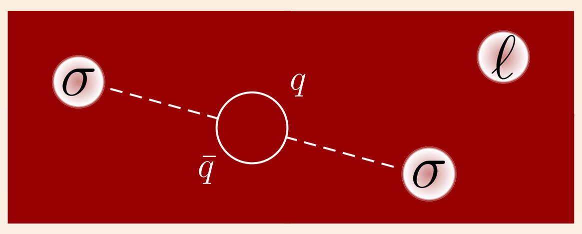
- Studies of effective models of QCD indicate the existence of a phase transition and a critical endpoint at large baryochemical potential [1]
- Event-by-event fluctuations are sensitive to the correlation length and could serve as a signal for a possible critical end point [2]
- Growth of the correlation length is limited by nonequilibrium effects: finite system size, finite time, critical slowing down [3]
- Spinodal instabilities at the first order phase transition might also lead to strong fluctuations if the system is out of equilibrium [4]



A dynamical model for the QCD phase transition in heavy ion collisions

- Couple chiral fields to hydrodynamically expanding fluid of quarks and antiquarks [5, 6]
- Include effects of dissipation and fluctuation that the fields encounter in the locally thermalized heat bath of quarks [7, 8]
- Ensure self-consistency and energy-momentum conservation [7]
- Include Polyakov loop dynamics on a phenomenological basis [9]

Chiral fluid dynamics with explicit propagation of the Polyakov loop



- We use the Polyakov-quark-meson model as the basis for our studies

$$\mathcal{L}=\bar{q}\left[\mathrm{i}\left(\gamma^\mu\partial_\mu-\mathrm{i}g_s\gamma^0A_0\right)-g\sigma\right]q+\frac{1}{2}\left(\partial_\mu\sigma\right)^2-U(\sigma)-\mathcal{U}(\ell,\bar{\ell})$$

- The coupled dynamics of fields and fluid have been derived self-consistently within the 2PI approach [7]
- For the sigma field this yields a Langevin equation with temperature dependent damping coefficient and stochastic noise term

$$\partial_\mu\partial^\mu\sigma+\eta_\sigma(T)\partial_t\sigma+\frac{\partial V_{eff}}{\partial\sigma}=\xi_\sigma\,,\quad \langle\xi_\sigma(t)\xi_\sigma(t')\rangle=\frac{1}{V}\delta(t-t')m_\sigma\eta_\sigma\coth\left(\frac{m_\sigma}{2T}\right)$$

- The dynamics of the Polyakov loop is described by a relaxation equation including dissipation and fluctuation

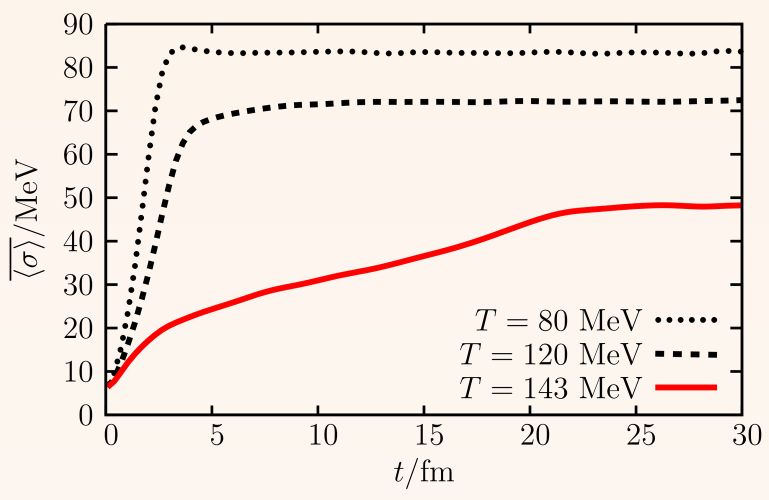
$$\eta_\ell\partial_t\ell+\frac{\partial V_{eff}}{\partial\ell}=\xi_\ell\,,\quad \langle\xi_\ell(t)\xi_\ell(t')\rangle T^2=\frac{1}{V}\delta(t-t')2\eta_\ell T$$

- For the energy-momentum tensor of the quarks we assume the structure of an ideal fluid

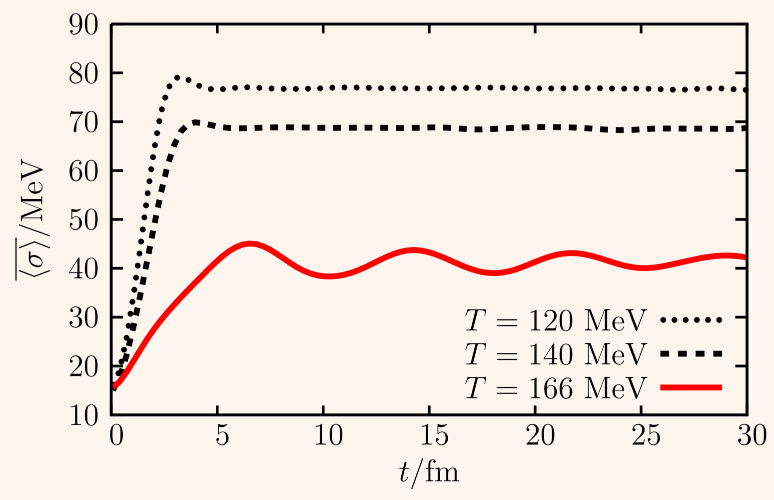
$$\partial_\mu T_q^{\mu\nu}=S_\sigma^\nu+S_\ell^\nu\,,\quad S_\sigma^\nu=\left(-\frac{\partial\Omega_{q\bar{q}}}{\partial\sigma}-\eta_\sigma\partial_t\sigma\right)\partial^\nu\sigma\,,\quad S_\ell^\nu=\left(-\frac{\partial\Omega_{q\bar{q}}}{\partial\ell}-\eta_\ell\partial_t\ell T^2\right)\partial^\nu\ell$$

Equilibration in a box

- Studies of the relaxational dynamics of the system after a temperature quench in a box [10]
- Results are not sensitive to the choice of the Polyakov loop damping coefficient η_ℓ
- We observe a delay in the relaxation time near the phase transition as well as critical slowing down near the critical point (see red curves)

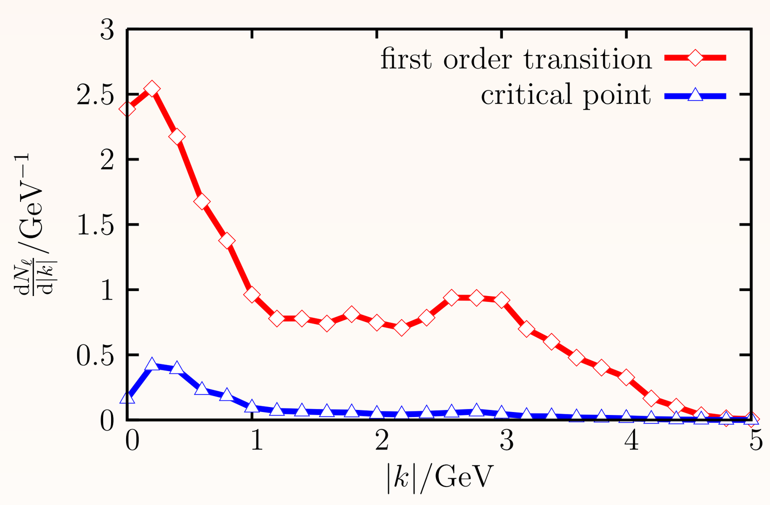


Evolution of volume and event averaged sigma field after several quenches in a first order transition scenario.

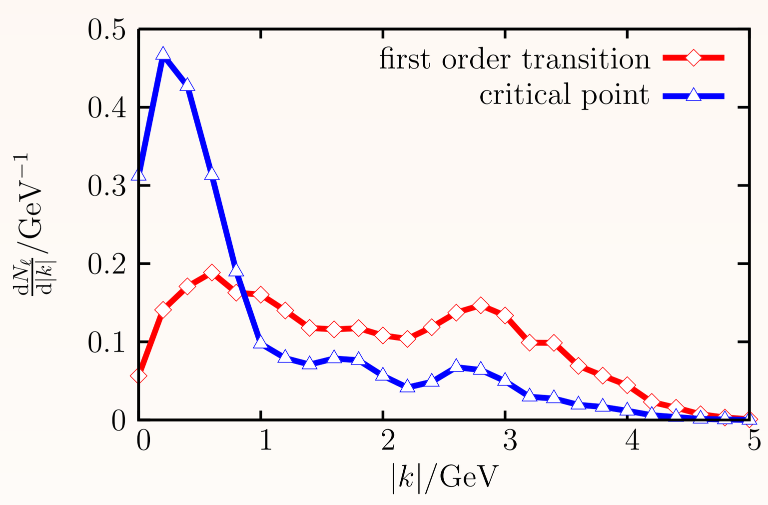


Evolution of volume and event averaged sigma field after several quenches in a critical point scenario.

- During the transition process the intensity of sigma and Polyakov loop fluctuations is stronger in a first order than in a critical point scenario
- After the system is equilibrated we find an enhancement of soft modes at the critical point



Histogram of the intensity of Polyakov loop fluctuations during transition process.



Histogram or the intensity of Polyakov loop fluctuations after equilibration.

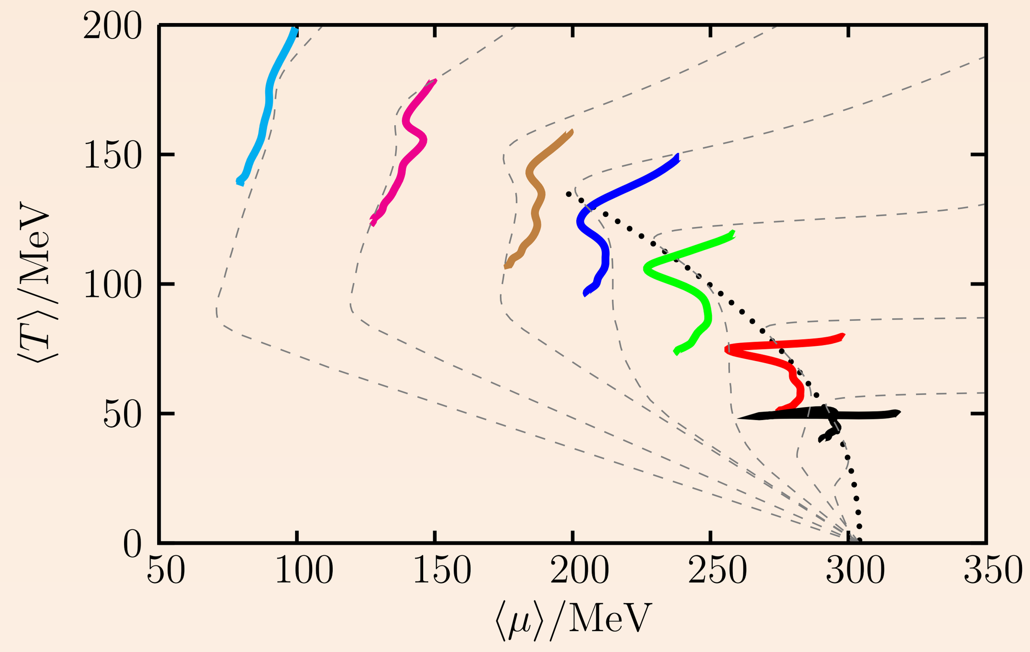
FIAS Frankfurt Institute for Advanced Studies

HIC for FAIR Helmholtz International Center

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

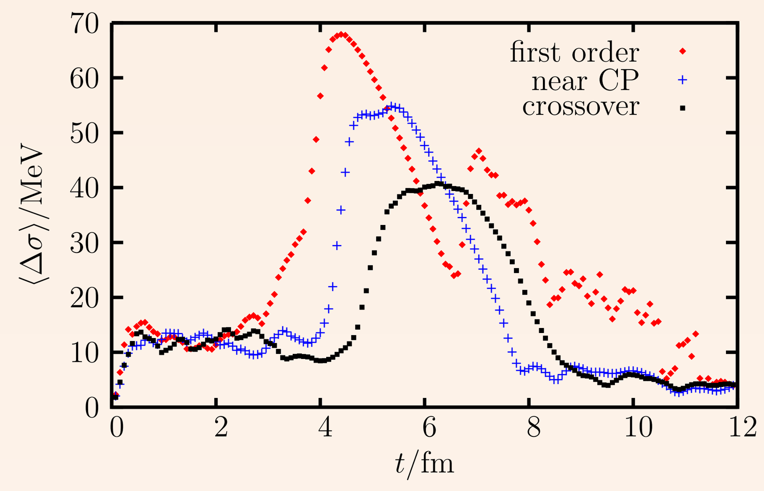
The expanding medium at finite densities

- With growing baryochemical potential μ the trajectories bend away from the isentropes

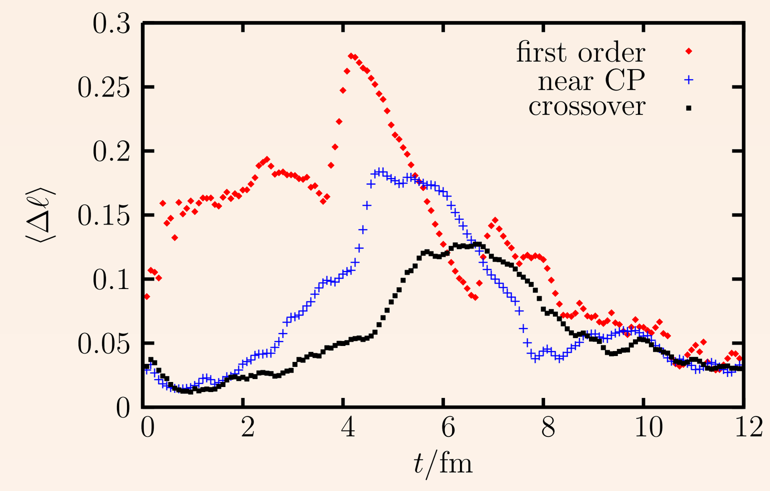


Solid lines: trajectories of simulations with different starting points in the T-μ-plane, dashed lines: isentropes, dotted line: phase boundary.

- Strong nonequilibrium fluctuations $\langle\Delta\sigma\rangle=\sqrt{\langle(\sigma(\vec{x})-\sigma_{\rm eq}(\vec{x}))^2\rangle}$, $\langle\Delta\ell\rangle=\sqrt{\langle(\ell(\vec{x})-\ell_{\rm eq}(\vec{x}))^2\rangle}$ at the first order phase transition hint at the formation of a supercooled phase

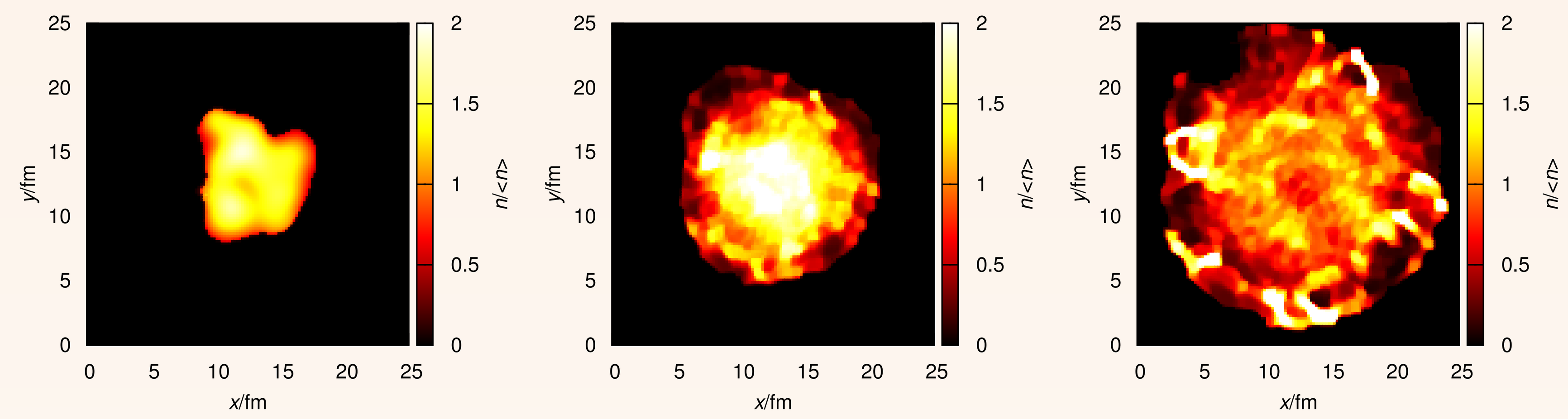


Evolution of sigma fluctuations for different trajectories.



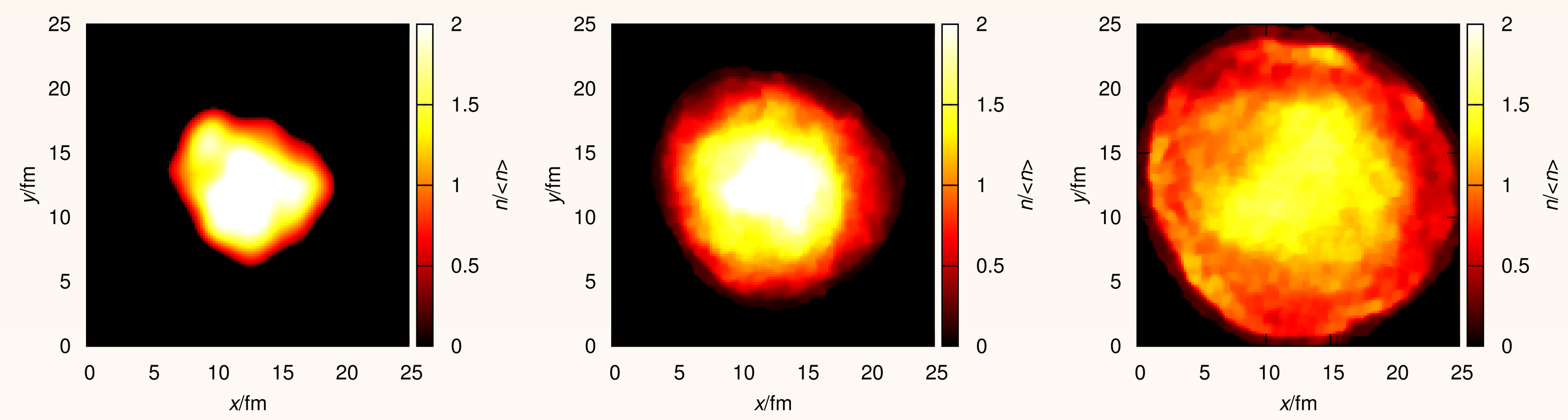
Evolution of Polyakov loop fluctuations for different trajectories

- Evolution of density fluctuations at the phase transition, formation of domains



initial density profile *after $t=6$ fm* *after $t=12$ fm*

- Evolution of density fluctuations near the critical point



initial density profile *after $t=6$ fm* *after $t=12$ fm*

Outlook

- Study event-by-event fluctuations of order parameters, baryon density, see Marlene Nahrgang's talk

References

[1] O. Scavenius, A. Mocsy, I. N. Mishustin and D. H. Rischke, Phys. Rev. C **64** (2001) 045202.
[2] M. A. Stephanov, K. Rajagopal and E. V. Shuryak, Phys. Rev. D **60** (1999) 114028
[3] B. Berdnikov and K. Rajagopal, Phys. Rev. D **61**, 105017 (2000)
[4] C. Sasaki, B. Friman and K. Redlich, Phys. Rev. D **77** (2008) 034024
[5] I. N. Mishustin and O. Scavenius, Phys. Rev. Lett. **83** (1999) 3134
[6] K. Paech, H. Stoecker and A. Dumitru, Phys. Rev. C **68** (2003) 044907
[7] M. Nahrgang, S. Leupold, C. Herold, M. Bleicher, Phys. Rev. C **84** (2011) 024912.
[8] M. Nahrgang, C. Herold, S. Leupold, I. Mishustin, M. Bleicher arXiv:1105.1962 [nucl-th].
[9] E. S. Fraga, G. Krein and A. J. Mizher, Phys. Rev. D **76** (2007) 034501
[10] C. Herold, M. Nahrgang, I. N. Mishustin and M. Bleicher, in prep.