How spinodal instabilities influence observables at FAIR

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Frankfurt Institute for Advanced Studies

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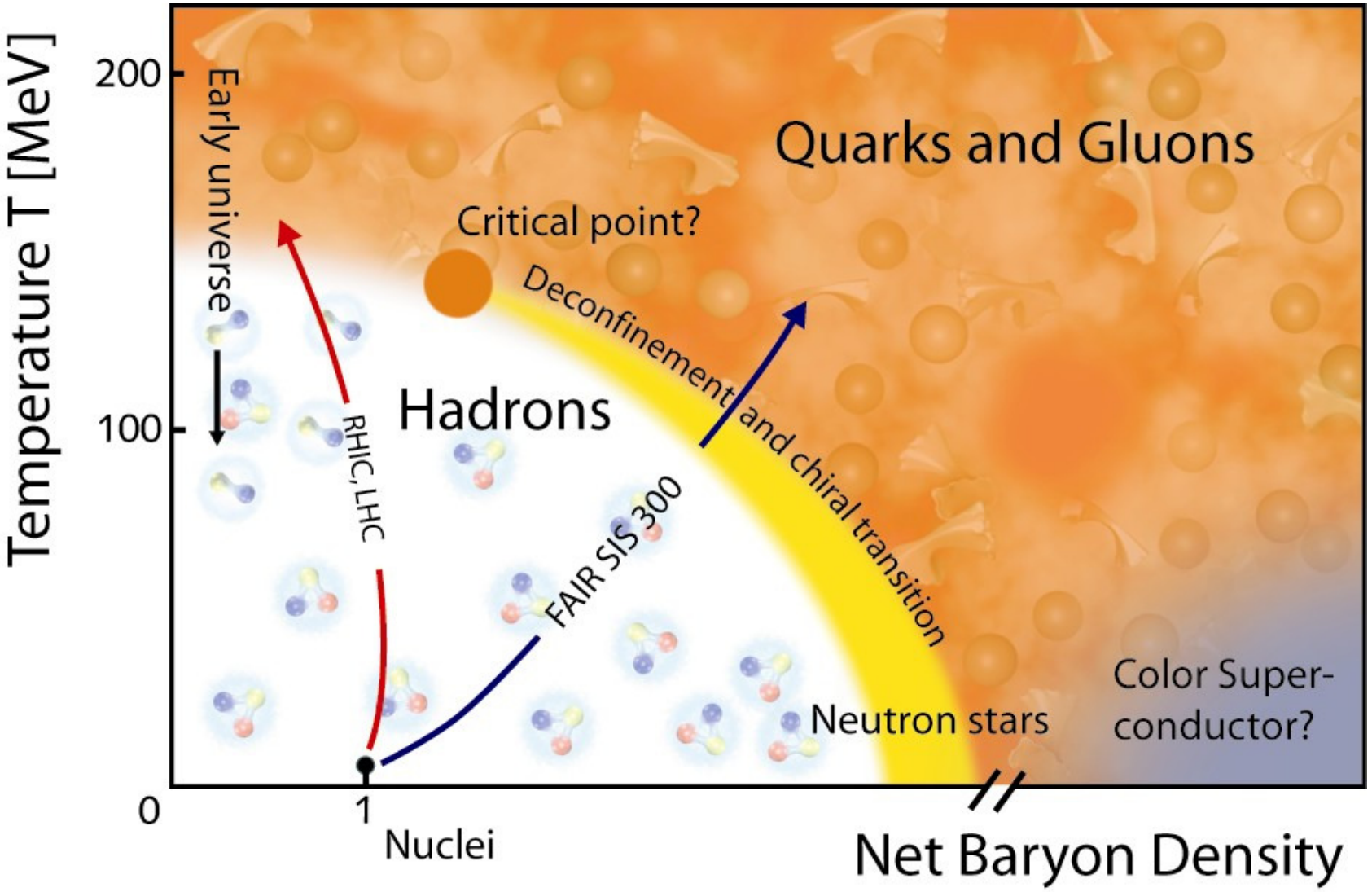
FIAS Frankfurt Institute for Advanced Studies

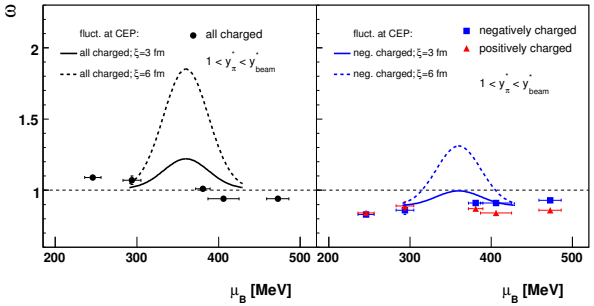
HIC for FAIR
Helmholtz International Center

GSI

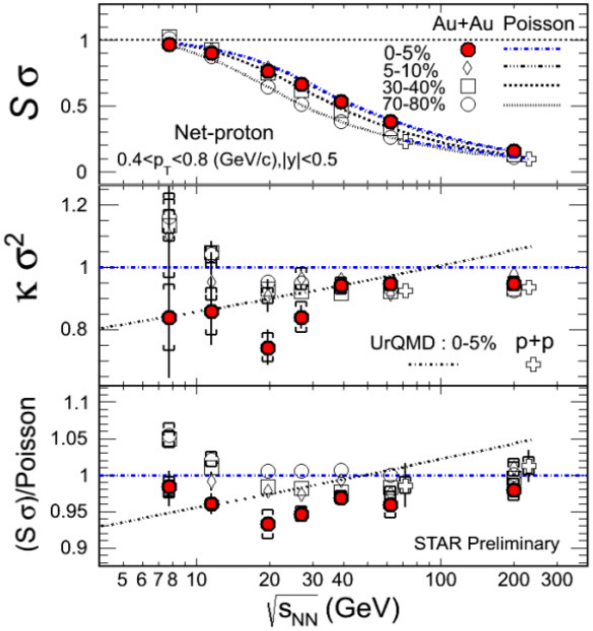
The QCD phase diagram



The critical point in heavy-ion collisions



(NA49 collaboration, Nucl. Phys. A **830** (2009))



(STAR collaboration, Quark Matter 2012)

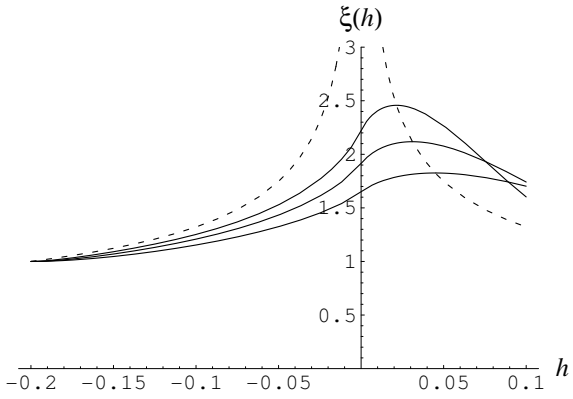
Moments/cumulants of particle distribution are sensitive to correlation length

$$\langle(\delta N)^2\rangle \sim \xi^2$$

$$\langle(\delta N)^3\rangle \sim \xi^{4.5}$$

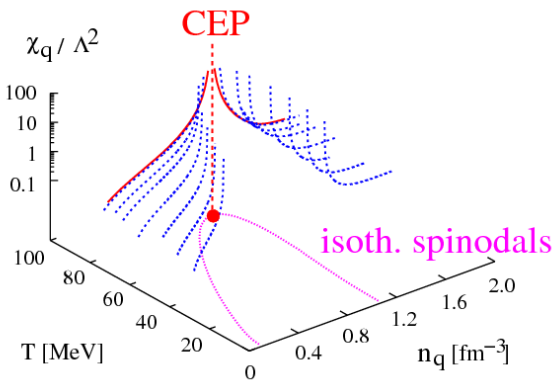
$$\langle(\delta N)^4\rangle - 3\langle(\delta N)^2\rangle^2 \sim \xi^7$$

(Stephanov, PRL **102** (2009))



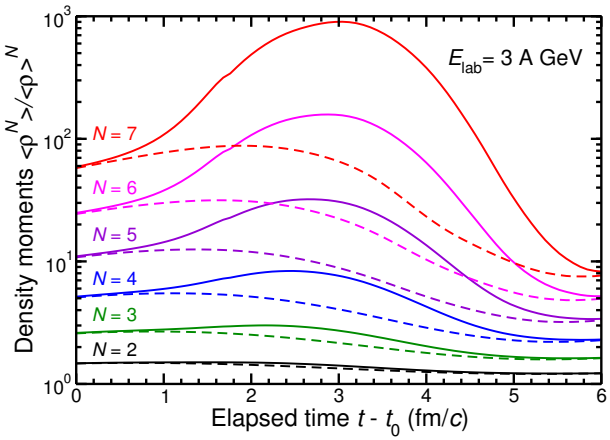
(Berdnikov, Rajagopal, PRD 61 (2000))

The first-order phase transition in heavy-ion collisions

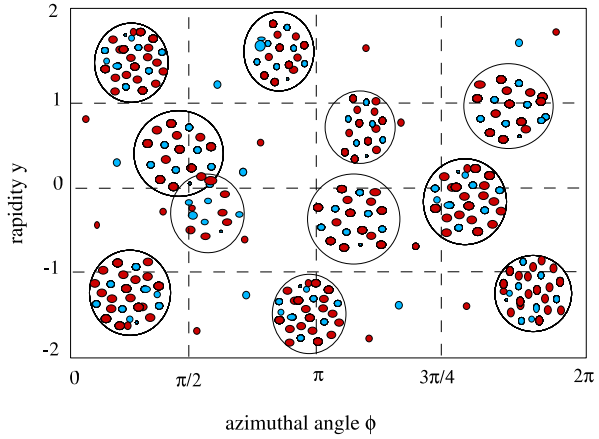


(Sasaki, Friman, Redlich, PRD 77 (2008))

- Formation of metastable phase
- Dynamical fragmentation
- Droplets
- Non-statistical multiplicity fluctuations



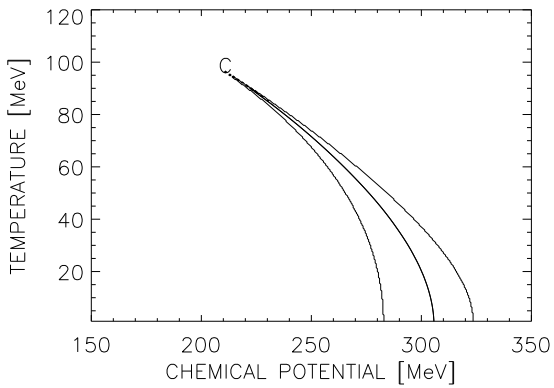
(Steinheimer, Randrup, PRL 109 (2012))



(Mishustin, PoS CPOD (2007))

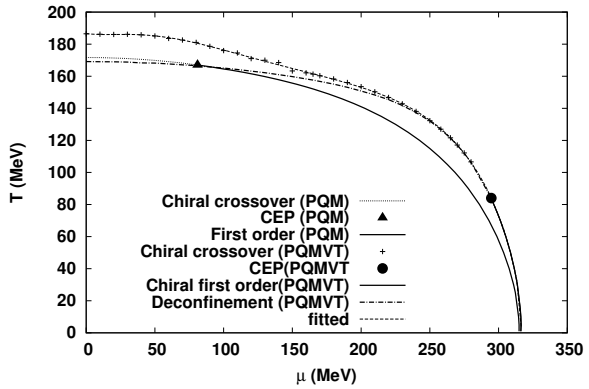
Effective models of QCD

Sigma model



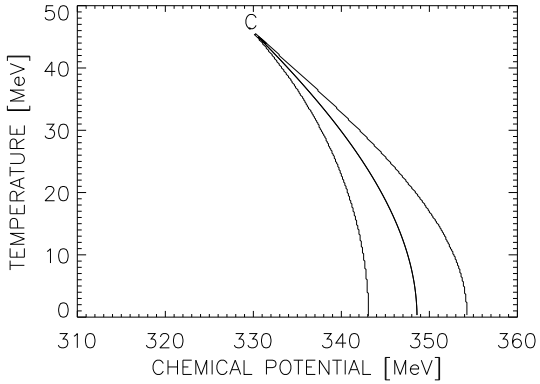
(Scavenius, Mocsy, Mishustin, Rischke, PRC **64** (2001))

Polyakov-quark-meson model



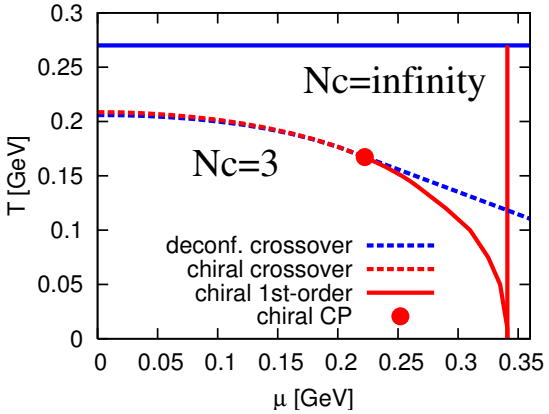
(Gupta, Tawari,arXiv:1107.1312v1 [hep-ph] (2011))

Nambu-Jona-Lasinio model



(Scavenius, Mocsy, Mishustin, Rischke, PRC **64** (2001))

Polyakov-NJL model



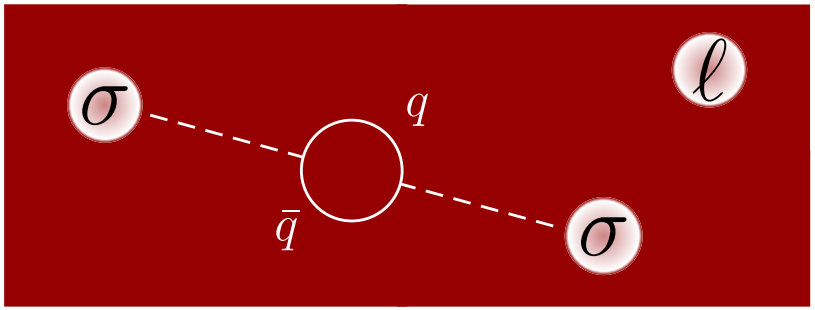
(C. Sasaki, APPS.3:659-668 (2010))

The NPχFD model

Ideal quark fluid

- + Sigma field
- + Polyakov loop

Explicit Langevin dynamics



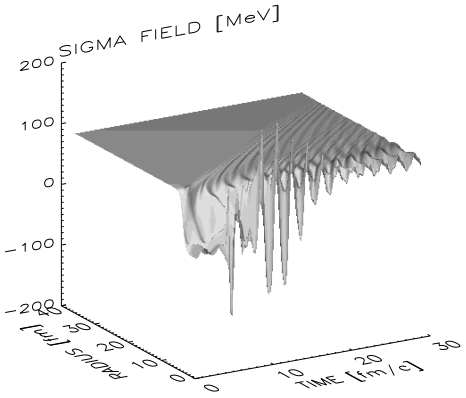
$$\mathcal{L} = \overline{q}\left[\mathrm{i}\left(\gamma^{\mu}\partial_{\mu} - \mathrm{i}g_s\gamma^0 A_0\right) - g\sigma\right] q + {}^1\!/_2\left(\partial_{\mu}\sigma\right)^2 - U\left(\sigma\right) - \mathcal{U}(\ell,\bar{\ell})$$

Fields and fluid are coupled via

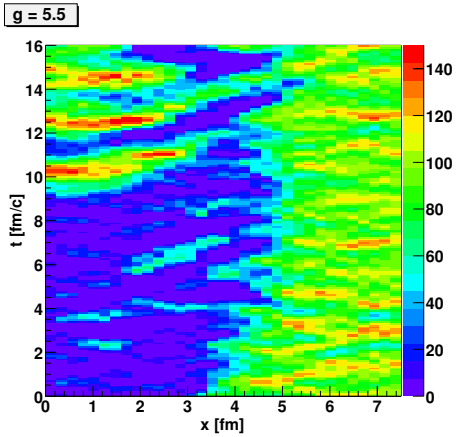
- Mean-field potential $V_{\mathrm{eff}} = U + \mathcal{U} + \Omega_{q\bar{q}}$
- Local pressure of quark fluid $p = p(\sigma, \ell, T, \mu)$
- Damping of sigma field due to interaction with quarks
- Energy-momentum exchange between fields and fluid

(M. Nahrgang, S. Leupold, CH and M. Bleicher, PRC **84** (2011), CH, M. Nahrgang, I. N. Mishustin and M. Bleicher, PRC **87** (2013))

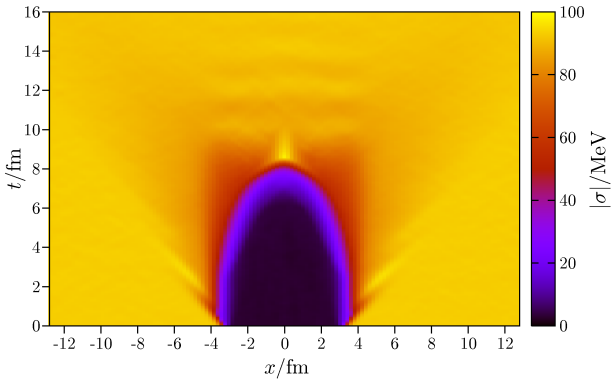
The Chiral fluid dynamics model



(I. N. Mishustin and O. Scavenius, Phys. Rev. Lett. **83** (1999))



(K. Paech, H. Stöcker and A. Dumitru, Phys. Rev. C **68** (2003))



(M. Nahrgang, C. H., S. Leupold, I. N. Mishustin and M. Bleicher, arXiv:1105.1962v2)

1. quark fluid coupled to chiral fields
2. inclusion of fluctuations
3. dissipation and noise

The coupled dynamics of fields and fluid

Langevin equation for the sigma field

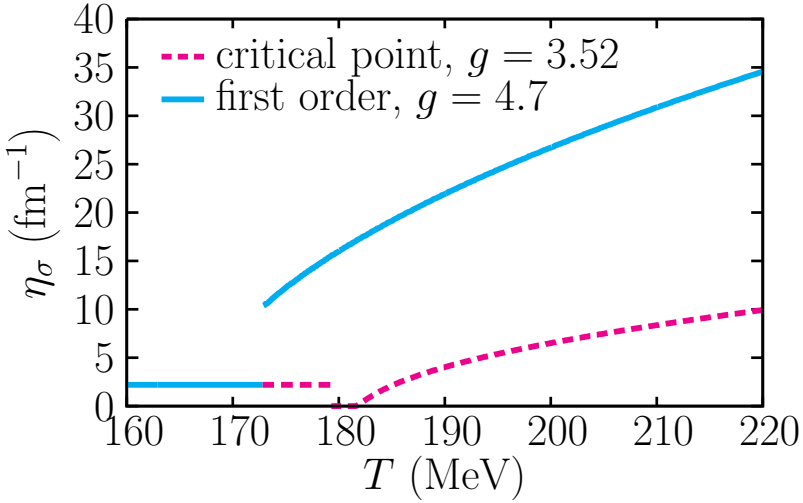
$$\partial_\mu \partial^\mu \sigma + \eta_\sigma(T)\partial_t \sigma + \frac{\partial V_{eff}}{\partial \sigma} = \xi_\sigma \ , \quad \langle \xi_\sigma(t)\xi_\sigma(t')\rangle = \frac{1}{V}\delta(t-t')m_\sigma \eta_\sigma \coth\left(\frac{m_\sigma}{2T}\right)$$

(Nahrgang, Leupold, C. H., Bleicher, Phys. Rev. C **84** (2011))

Relaxation equation for the Polyakov loop, constant η_ℓ=5/fm

$$\eta_\ell \partial_t \ell + \frac{\partial V_{eff}}{\partial \ell} = \xi_\ell$$

$$\langle \xi_\ell(t)\xi_\ell(t')\rangle T^2 = \frac{1}{V}\delta(t-t')2\eta_\ell T$$



Energy momentum and baryon number conservation in ideal quark fluid

$$\partial_\mu T_q^{\mu\nu} = S_\sigma^\nu + S_\ell^\nu, \quad \partial_\mu N^\mu = 0$$

A dynamical model for the Polyakov loop

Phenomenological kinetic term and biquadratic coupling to chiral fields

$$\mathcal{L} = \mathcal{L}_\phi + \frac{N_c}{g^2}|\partial_\mu \ell|^2 T^2 - \mathcal{U}(\ell) - \frac{h^2}{2}\phi^2|\ell|^2 T^2$$

(Dumitru, Pisarski, Phys. Lett. B **504** (2001))

Problem when $T = T(x^\mu)$ due to

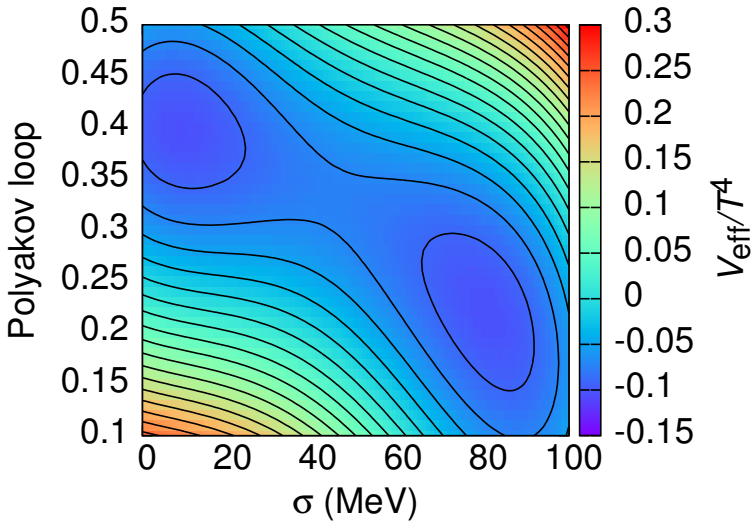
$$\frac{\partial}{\partial x^\mu}\left[\frac{N_c}{g^2}|\partial_\mu \ell|^2 T(x^\mu)^2\right]$$

in Euler-Lagrange equation

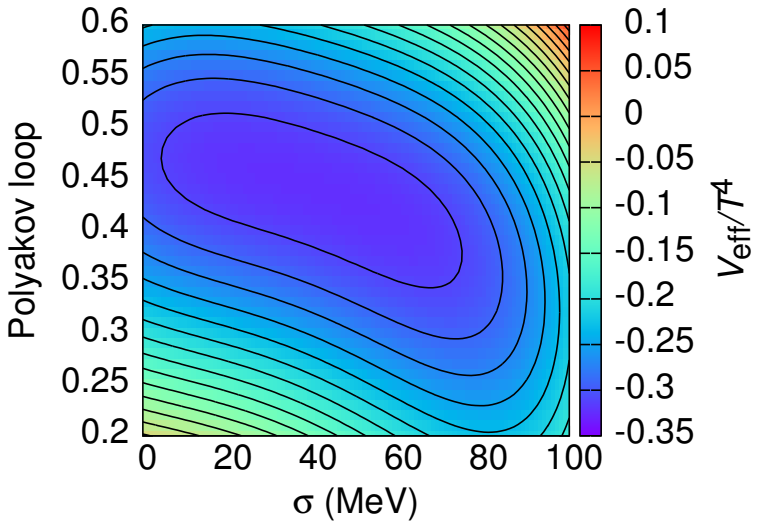
Possible solutions

- replace T by T_0
- Polyakov loop always in equilibrium
- use simple relaxation equation

Results at zero baryochemical potential



first order transition,
$g = 4.7$, $T_c = 172.9$ MeV

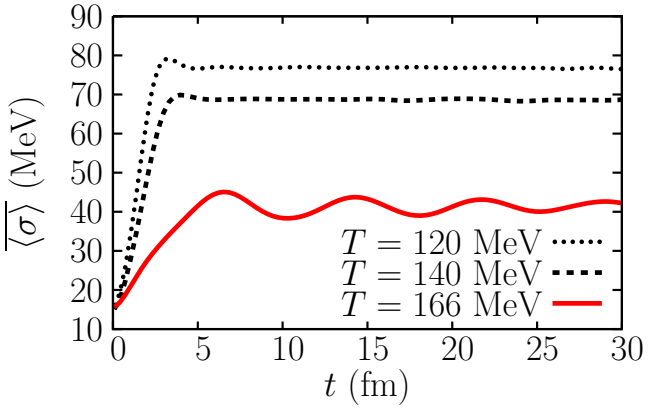


critical point,
$g = 3.52$, $T_c = 180.5$ MeV

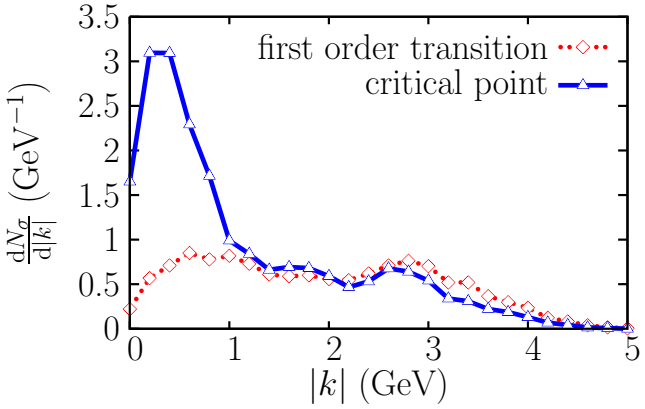
Study CP and FO by varying quark-meson coupling g

- Relaxational dynamics in a box
- Fluid dyamical expansion

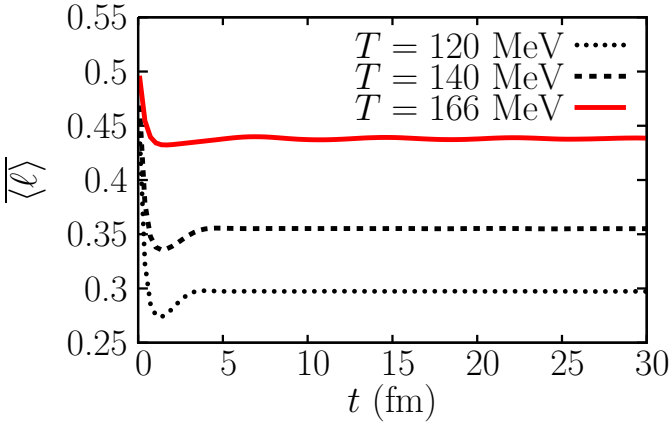
Box: Critical slowing down



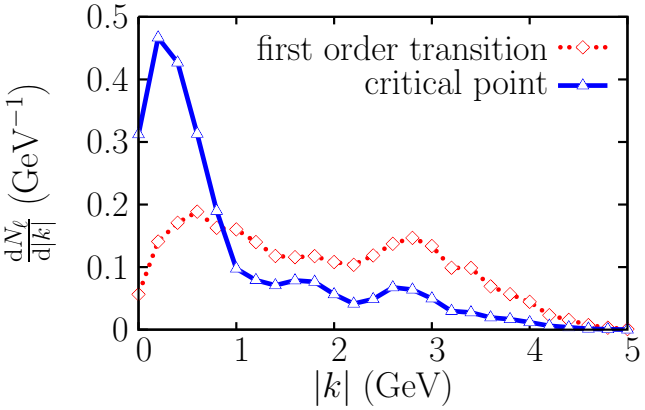
Relaxation of sigma field



Sigma fluctuations



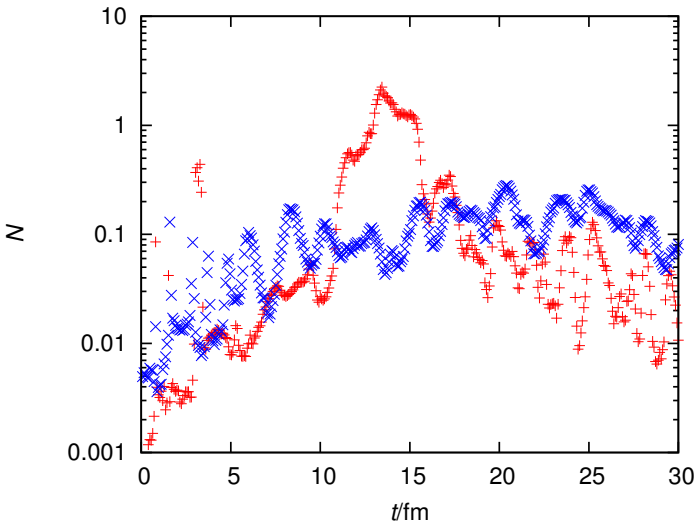
Relaxation of Polyakov loop



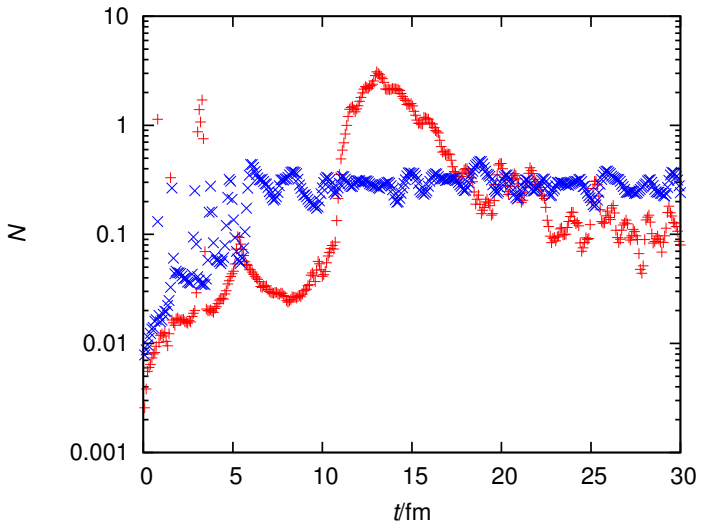
Polyakov loop fluctuations

(CH, M. Nahrgang, I. N. Mishustin and M. Bleicher, PRC **87** (2013))

Box: Fourier analysis of sigma fluctuations



$0 \leq |k| < 100$ MeV

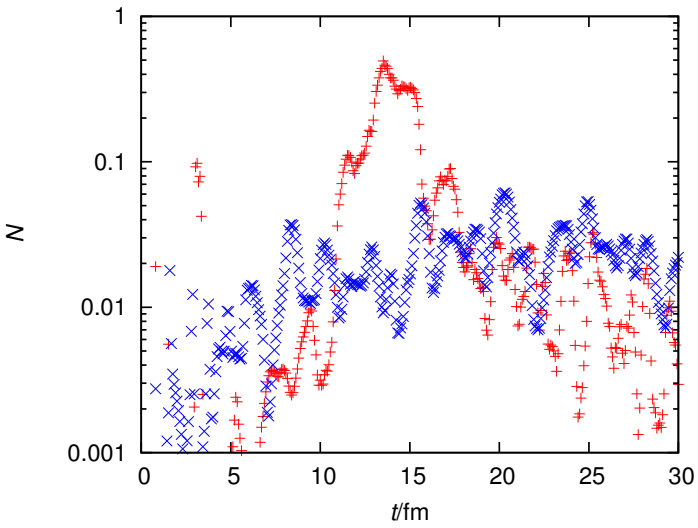


$100 \leq |k| < 200$ MeV

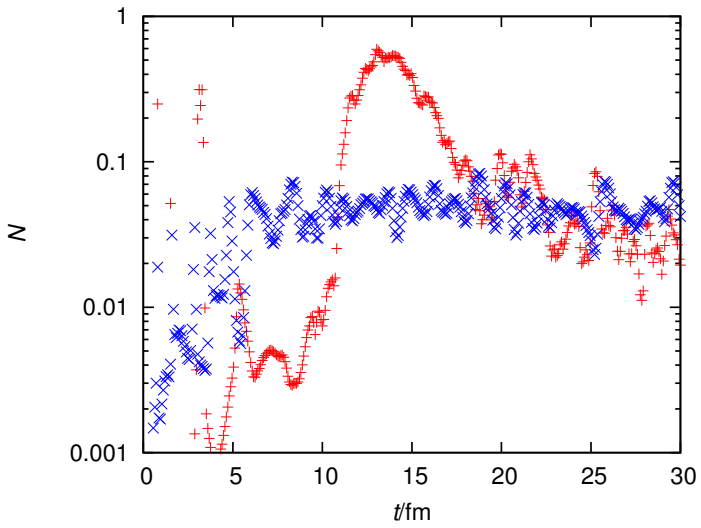
Intensity of sigma fluctuations:

$$N = \int_{\Delta k} \mathrm{d}^3 k \; N_k = \int_{\Delta k} \mathrm{d}^3 k \frac{a_k^\dagger a_k}{(2\pi)^3 2\omega_k} = \int_{\Delta k} \mathrm{d}^3 k \frac{\omega_k^2 |\sigma_k|^2 + |\dot{\sigma}_k|^2}{(2\pi)^3 2\omega_k}$$

Box: Fourier analysis of Polyakov loop fluctuations



$0 \leq |k| < 100$ MeV

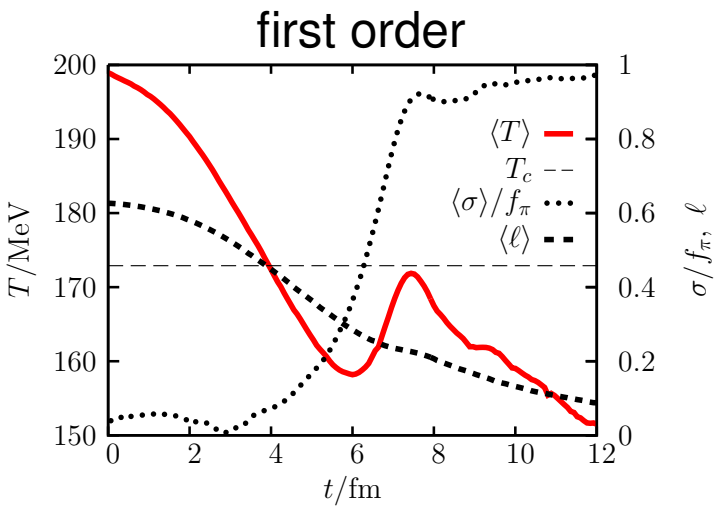


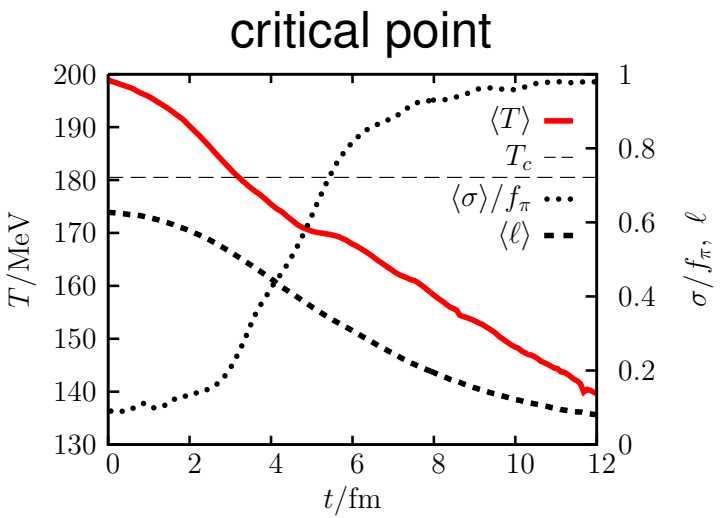
$100 \leq |k| < 200$ MeV

Intensity of Polyakov loop fluctuations:

$$N = \int_{\Delta k} \mathrm{d}^3 k \; N_k = \int_{\Delta k} \mathrm{d}^3 k \frac{a_k^\dagger a_k}{(2\pi)^3 2\omega_k} = \int_{\Delta k} \mathrm{d}^3 k T^2 \frac{\omega_k^2 |\ell_k|^2 + |\dot{\ell}_k|^2}{(2\pi)^3 2\omega_k}$$

Expansion: first order vs. critical point



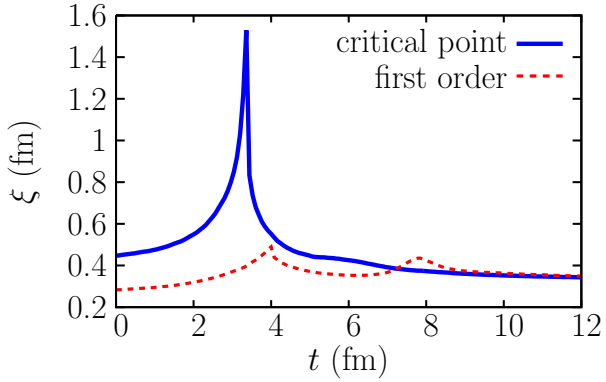


- Formation of supercooled phase
- Decay after $\sim$ 2 fm
- Reheating of the quark fluid

- Smooth transition
- Saddle point in $\langle T \rangle$ near T_c
- Slowing down

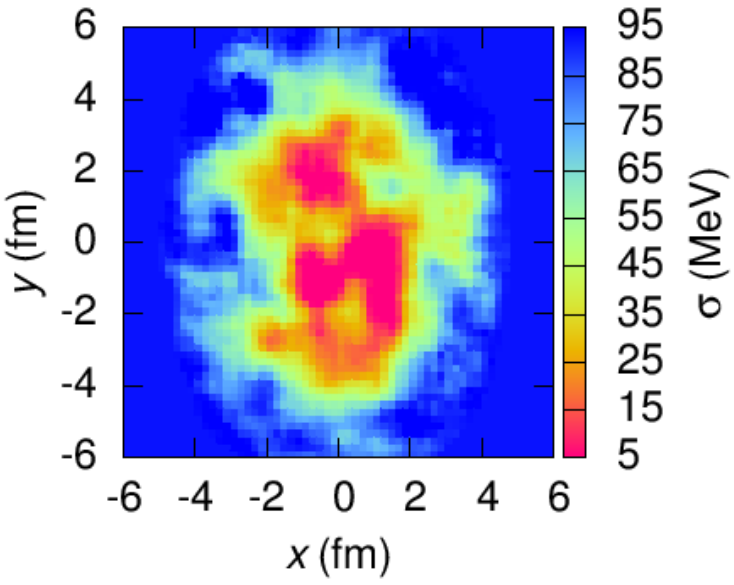
(CH, M. Nahrgang, I. N. Mishustin and M. Bleicher, PRC **87** (2013))

Expansion: Domain formation

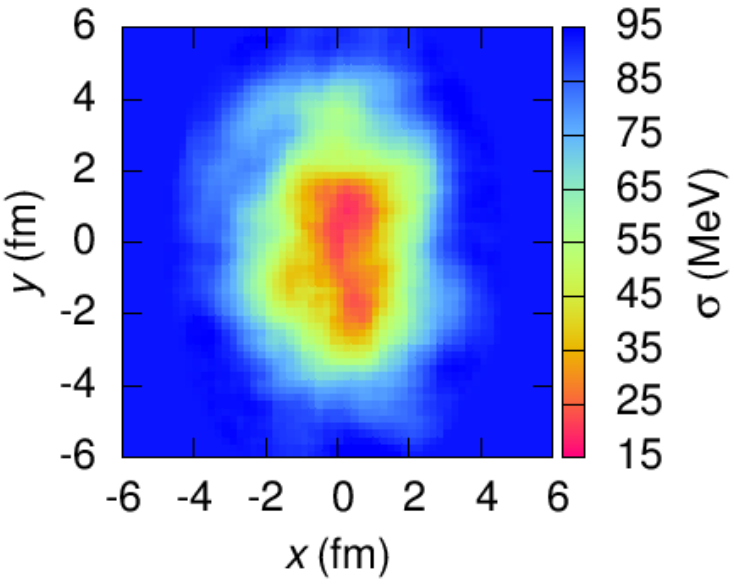


Correlate stochastic noise fluctuations over volume

$$V^{\mathrm{corr}} = \xi^3 = \frac{1}{m(\langle T \rangle)^3}$$



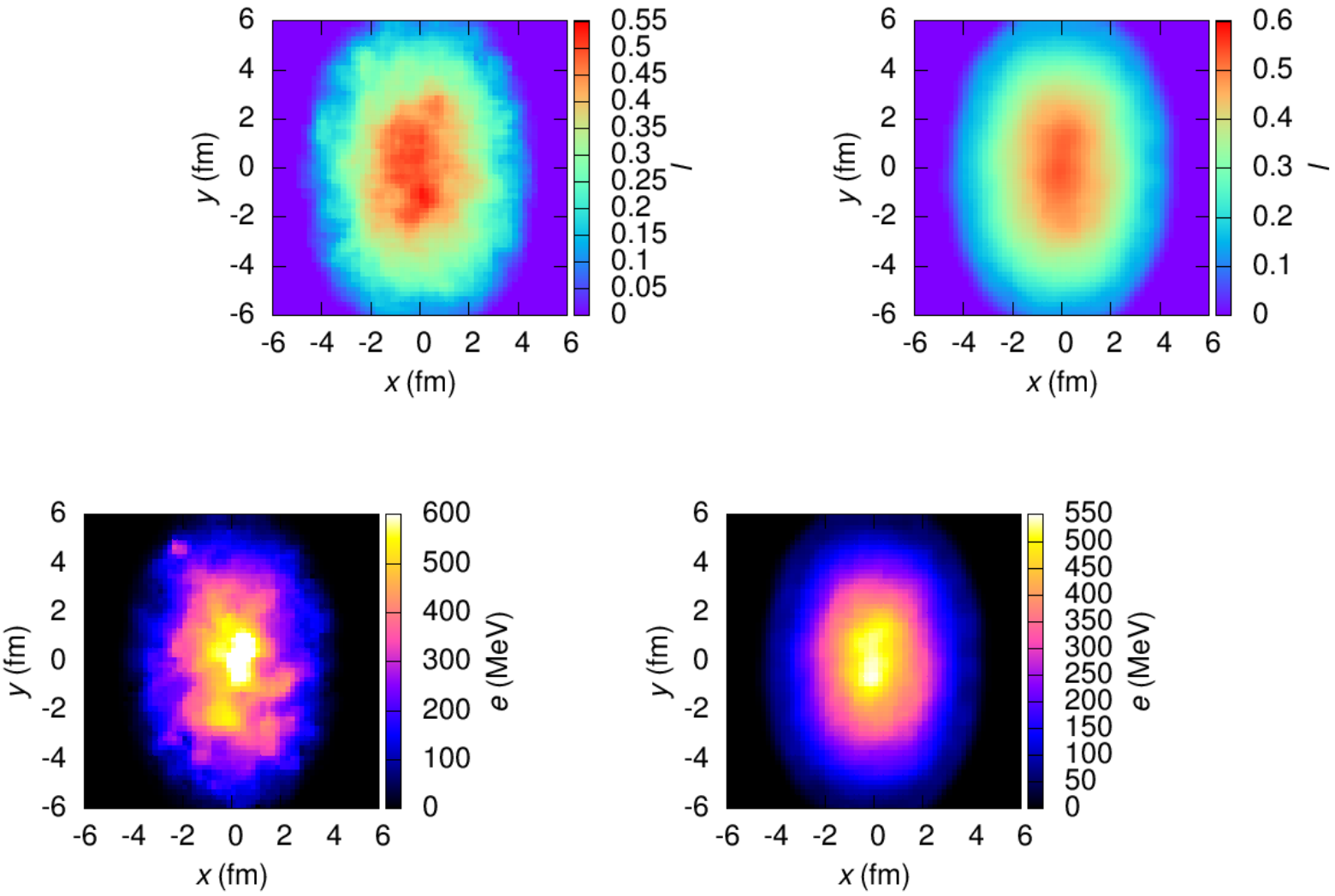
at first-order



at CP

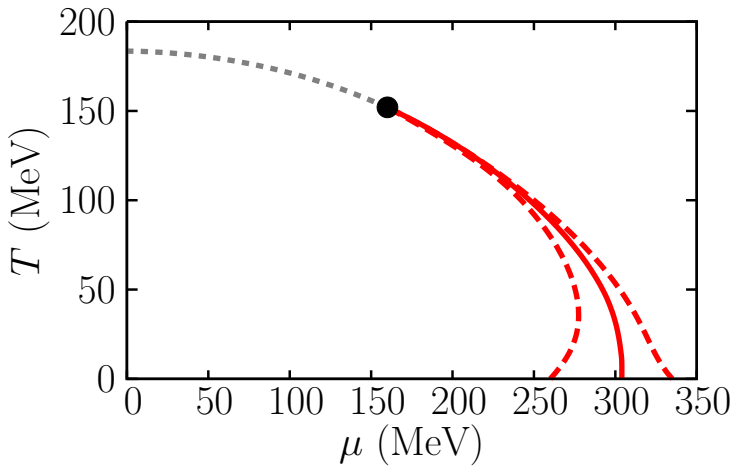
(CH, M. Nahrgang, I. N. Mishustin and M. Bleicher, PRC **87** (2013))

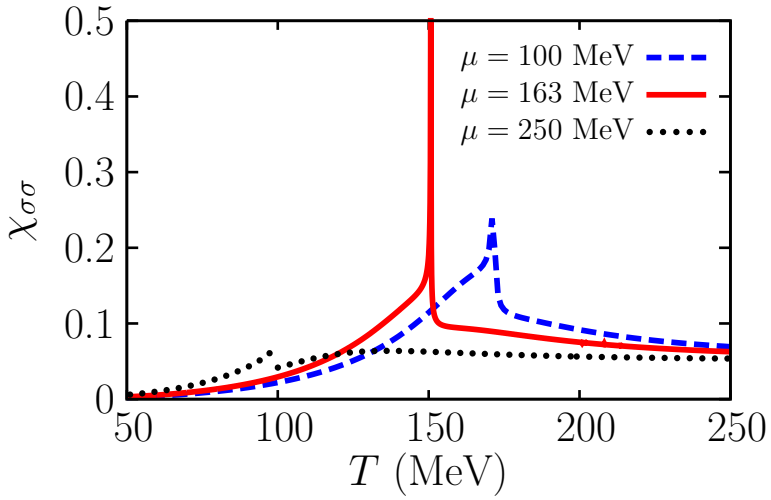
Free expansion: Domain formation



(C. H., M. Nahrgang, I. N. Mishustin and M. Bleicher, PRC **87** (2013))

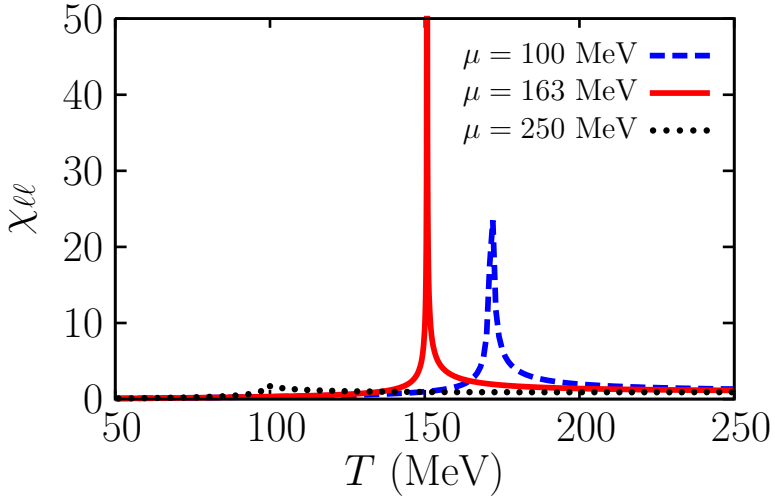
Results at finite baryochemical potential



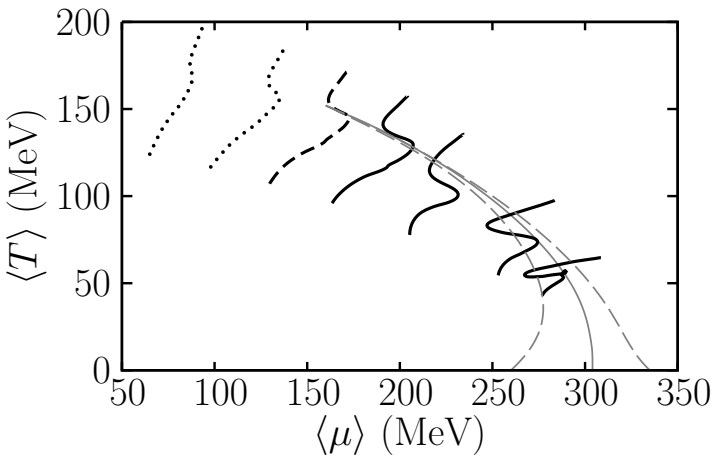


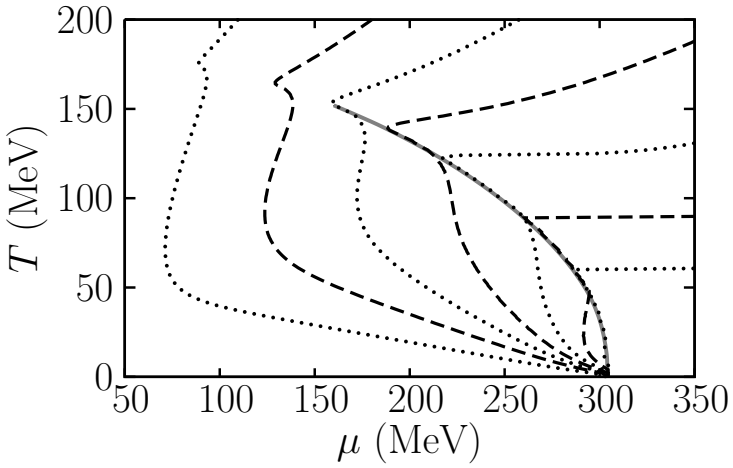
Phase diagram of Polyakov-Quark-meson model

- Common phase transition
- Common CEP



Expansion: Nonequilibrium trajectories





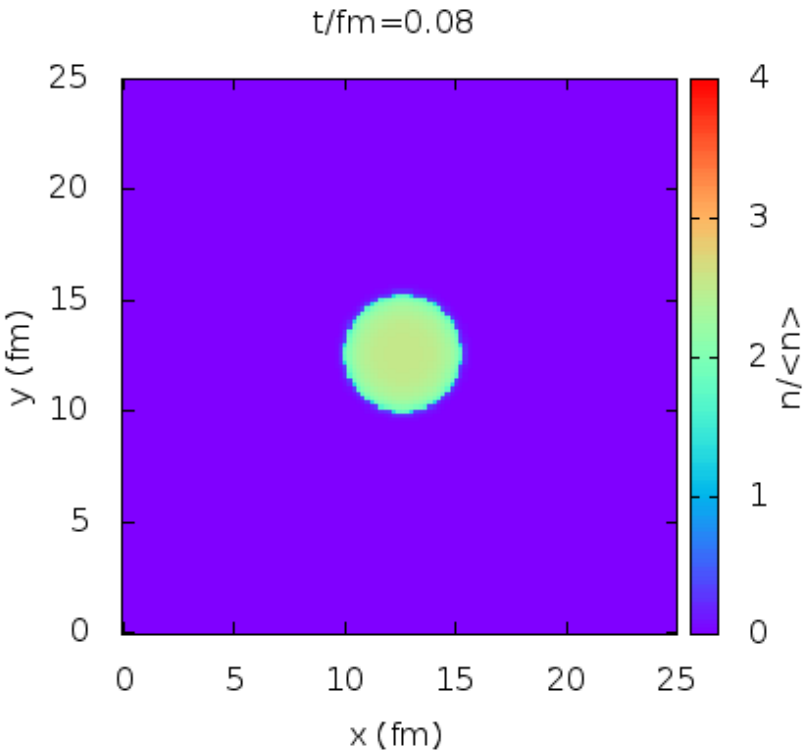
- Trajectories close to isentropes at crossover and CEP
- Trajectories influenced by nonequilibrium effects at first-order transition
- At high densities system remains in spinodal region for long time

Possibility for domain formation?

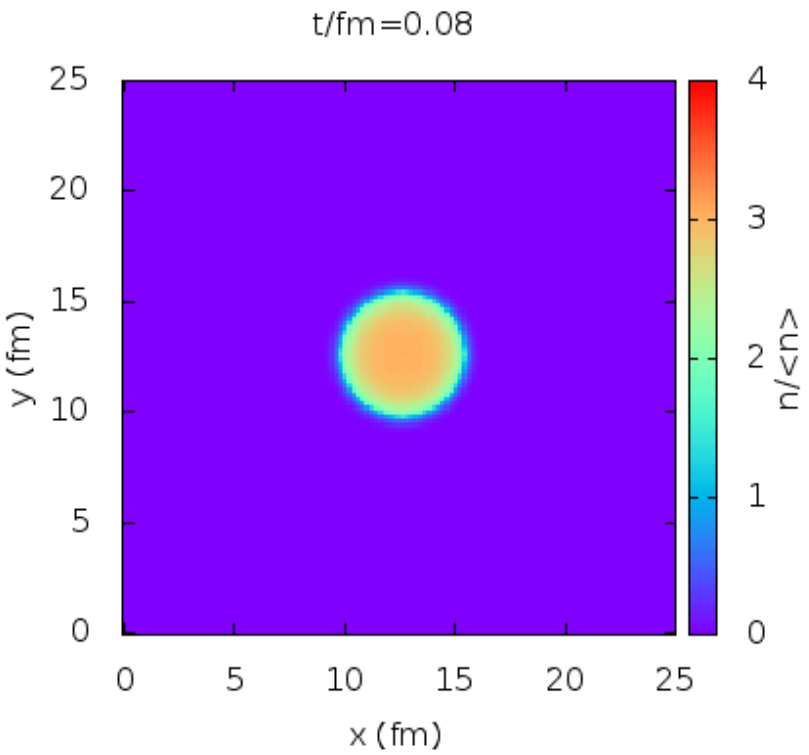
(CH, M. Nahrgang, I. Mishustin, M. Bleicher, in preparation)

Expansion: High-density domains

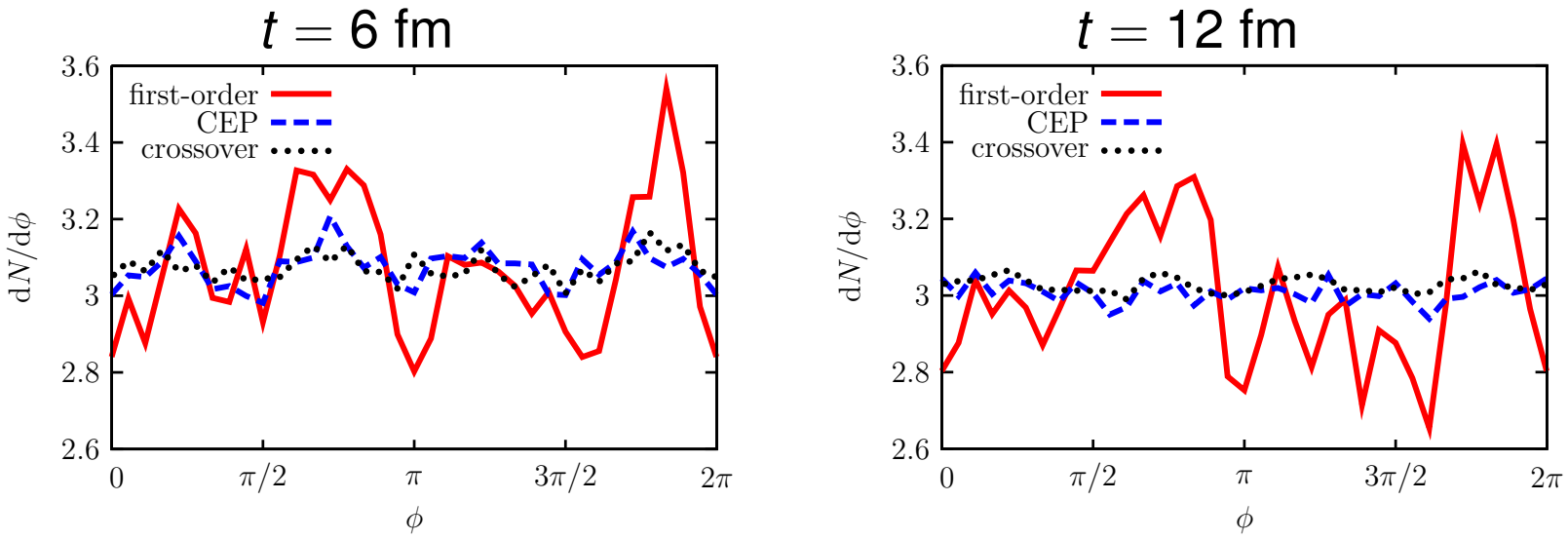
First-order



CEP



Expansion: High-density domains

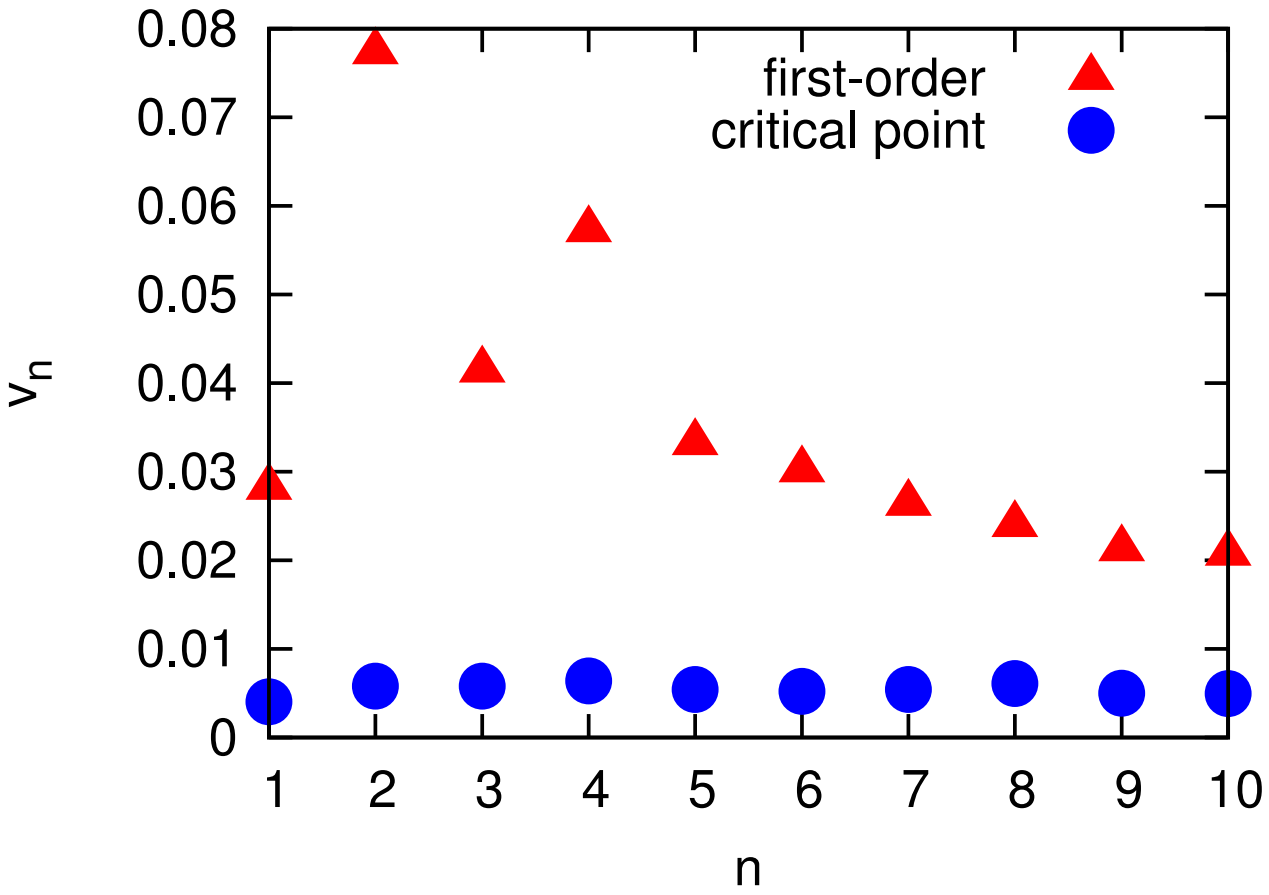


Azimuthal distribution of net baryon number $\frac{\mathrm{d}N}{\mathrm{d}\phi}$

- Strong fluctuations at first-order transition
- Signal remains and is not washed out

(CH, M. Nahrgang, I. Mishustin, M. Bleicher, in preparation)

Expansion: High-density domains

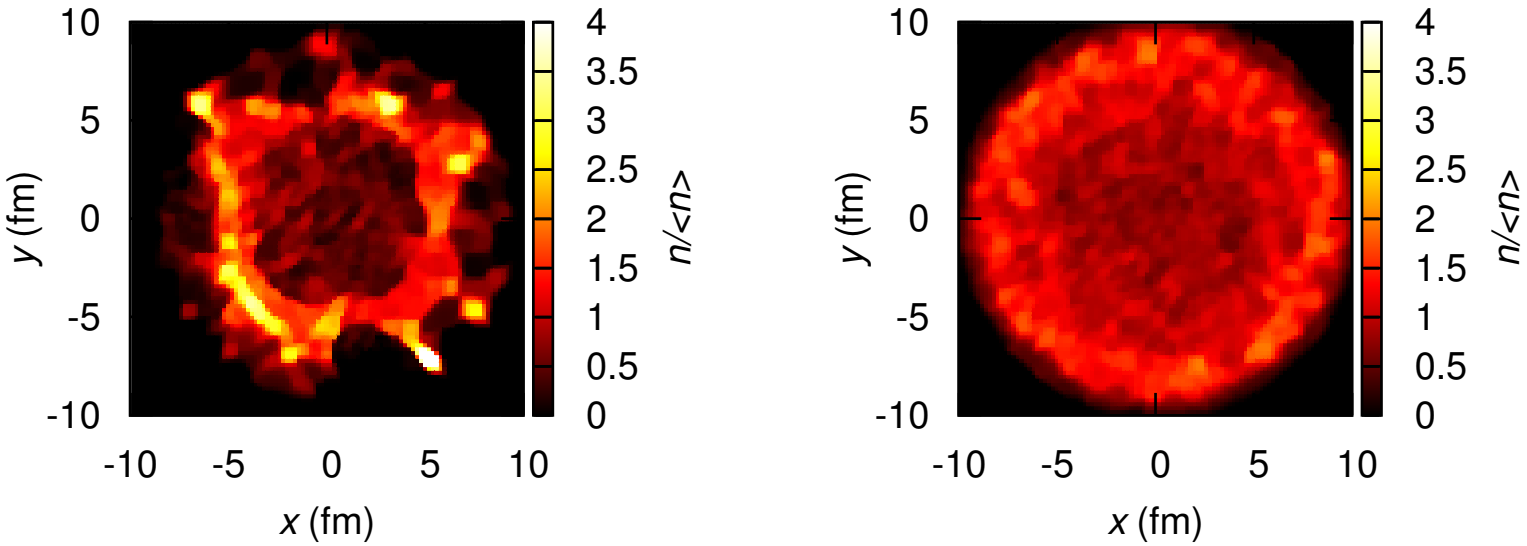


Fourier coefficients $v_n = \langle \cos[n(\phi - \psi_n)] \rangle$

- Strong enhancement at first-order transition

(CH, M. Nahrgang, I. Mishustin, M. Bleicher, in preparation)

Conclusions



- Nonequilibrium effects crucially influence a dynamical QCD phase transition
- Domain formation is observable in the order parameter fields
- Density profile evolve inhomogeneously
- Formation of baryon density domains may serve as experimental signal