Dynamic event-by-event fluctuations and domain formation at the phase transition of QCD

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with:

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Quark Matter 2012, Washington DC

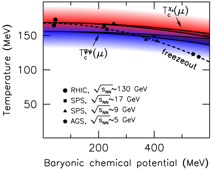
Subatech

HIC for FAIR
Helmholtz International Center

FIAS Frankfurt Institute for Advanced Studies

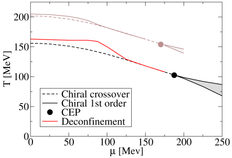
Approaches to the QCD phase diagram

- QCD calculations in the nonperturbative regime:



LQCD

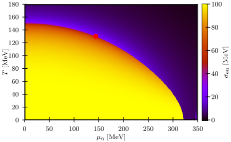
(Z. Fodor, S.D. Katz, JHEP **0203** (2002))



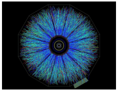
DSE

(C. S. Fischer, J. Luecker, arXiv:1206.5191)

- Effective models of QCD:



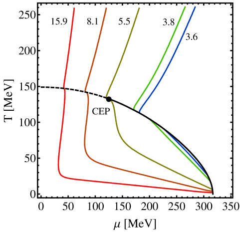
- Heavy-ion collisions:



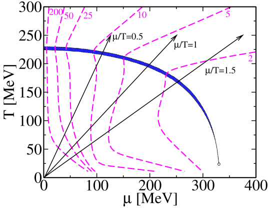
FAIR

Phase diagrams and fluctuations in effective models

QM MF



PQM MF

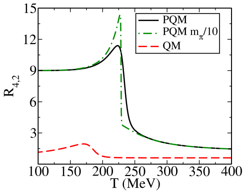


- Crossover (CO), critical point (CP), first order phase transition (FO) in (P)QM models.
- Location (T_c, μ_c) of the CP depends on model parameters, it is non-universal.
- At $\mu_B = 0$ the phase transition can be tuned from CO to FO by changing the quark-meson coupling constant.

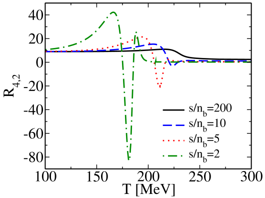
(E. Nakano, B. -J. Schaefer, B. Stokic, B. Friman, K. Redlich, PLB **682** (2010))

Phase diagrams and fluctuations in effective models

QM MF



PQM MF



- Crossover (CO), critical point (CP), first order phase transition (FO) in (P)QM models.
- Location (T_c, μ_c) of the CP depends on model parameters, it is non-universal.
- At $\mu_B = 0$ the phase transition can be tuned from CO to FO by changing the quark-meson coupling constant.
- Enhanced fluctuations in the quark number susceptibilities/kurtosis, increasing from CO to CP.

(V. Skokov, B. Stokic, B. Friman and K. Redlich, PRC **82** (2010), V. Skokov, B. Friman and K. Redlich, PRC **83** (2011), V. Skokov, B. Friman and K. Redlich, PLB **708** (2012))

Phase diagram and fluctuations in heavy-ion collisions

Coupling of the order parameter to pions $g\sigma\pi\pi$ and protons $G\sigma\bar{p}p \Rightarrow$ fluctuations in multiplicity distributions

$$\langle(\delta N)^2\rangle \propto \langle(\Delta\sigma)^2\rangle \propto \xi^2$$

ξ: correlation length of fluctuations of the order parameter, diverges at the CP

(M. Stephanov, K. Rajagopal, E. Shuryak, PRL **81** (1998), PRD **60** (1999))

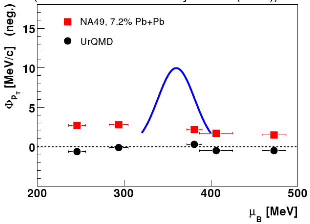
Higher cumulants are more sensitive to the CP

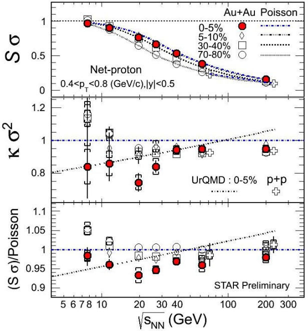
$$\langle(\delta N)^3\rangle \propto \xi^{4.5}$$

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

(M. Stephanov, PLB **102** (2009), PRL **107** (2011))

(NA49 collaboration J. Phys. G **35** (2008))



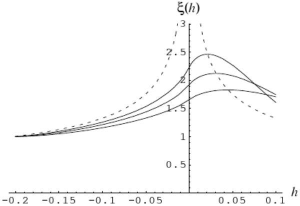


(STAR collaboration, QM2012)

Phase transitions in dynamic systems

- Critical point:
  large relaxation times limit the growth of ξ
  (**critical slowing down**)

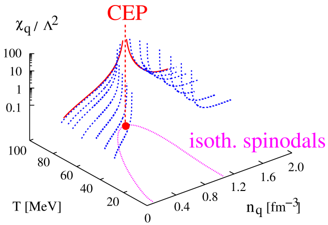
  (B. Berdnikov, K. Rajagopal, Phys. Rev. D **61** (2000))



- First order phase transition:
  instability of slow modes at the spinodal lines
  (**spinodal decomposition**)

  (I. Mishustin, PRL **82** (1999); C. Sasaki, B. Friman,

  K. Redlich, PRD **77** (2008))



Fluctuations are different, but all are interesting!

- Crossover: remnants of the $\mathcal{O}(4)$ criticality.
- Critical point: divergent event-by-event fluctuations in thermodynamic equilibrium.
- First order phase transition: large nonstatistical fluctuations in η/p_T spectra in individual events.

Motivation: Heavy-ion collisions are dynamic, inhomogeneous and finite in space and time.

? Can nonequilibrium effects become strong enough to develop signals of the first order phase transition?

? Do enhanced equilibrium fluctuations at the critical point survive the dynamics?

Nonequilibrium chiral fluid dynamics - NχFD

- Langevin equation for the sigma field: damping and noise from the interaction with the quarks

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

- For PQM: phenomenological dynamics for the Polyakov-loop (poster by C. Herold).
- Fluid dynamic expansion of the quark fluid = heat bath, including energy-momentum exchange $\partial_\mu T^{\mu\nu}_{\mathrm{q}} = S^\nu = -\partial_\mu T^{\mu\nu}_\sigma$
- Nonequilibrium equation of state $p = p(e, \sigma)$.
- Fluid dynamic initial conditions from UrQMD (www.urqmd.org).

Selfconsistent approach within the 2PI effective action!

(MN, S. Leupold, C. Herold, M. Bleicher, PRC **84** (2011); MN, S. Leupold, M. Bleicher, PLB **711** (2012); MN, M. Bleicher, S. Leupold, I. Mishustin, arXiv:1105.1962; and work in progress)

(related work: I. Mishustin, O. Scavenius, PRL **83** (1999); K. Paech, H. Stoecker, A. Dumitru, PRC **68** (2003))

Not included (yet)

- Simulations with pion fields
- Quantum dynamics (e. g. J. Berges et al., PRL **107** (2011) 061301)
- Fluid dynamic fluctuations and viscosities

  (J. Kapusta, B. Mueller, M. Stephanov, PRC **85** (2012); Acta Phys. Polon. B **43** (2012))
- Final state interaction

Results - overview

- $\mu_B = 0$ (no fluctuations in net quark number)
  - Domain formation at the first order phase transition.
  - Event-by-event fluctuations at the critical point.
- $\mu_B \neq 0$
  - Trajectories in the phase diagram.
  - Formation of domains of high quark number density at the first order phase transition.

Dynamic domain formation

First order phase transition

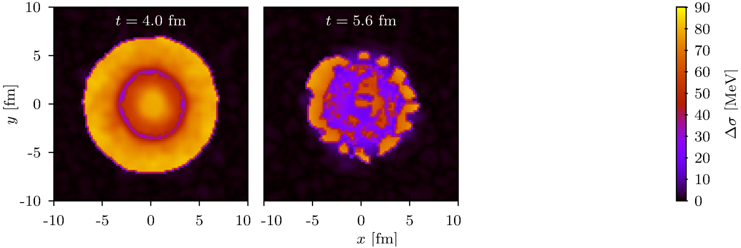
Sigma field fluctuations: $\Delta\sigma = \sqrt{(\sigma - \sigma_{\rm eq})^2}$

- Highly supercooled state at $t = 4.0$ fm/c.

Dynamic domain formation

First order phase transition

Sigma field fluctuations: $\Delta\sigma = \sqrt{(\sigma - \sigma_{\mathrm{eq}})^2}$

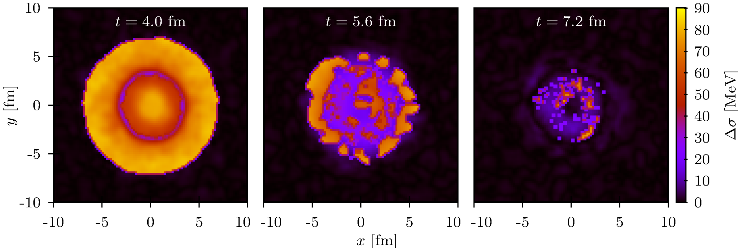


- Highly supercooled state at $t = 4.0$ fm/c.
- Dynamic formation of domains at $t = 5.6$ fm/c.

Dynamic domain formation

First order phase transition

Sigma field fluctuations: $\Delta\sigma = \sqrt{(\sigma - \sigma_{\mathrm{eq}})^2}$

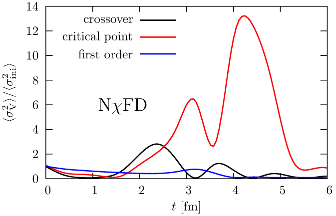


- Highly supercooled state at $t = 4.0$ fm/c.
- Dynamic formation of domains at $t = 5.6$ fm/c.
- Dynamic decay of domains at $t = 7.2$ fm/c.

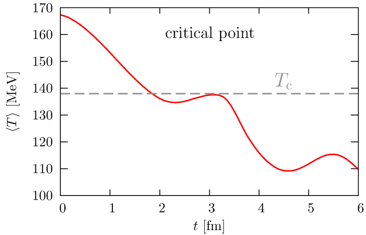
This could lead to non-statistical fluctuations in hadron multiplicities.

Dynamic enhancement of event-by-event fluctuations

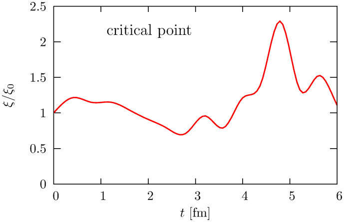
Event-by-event fluctuations



temperature



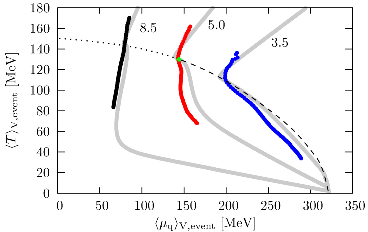
correlation length from
$G(r) \propto \exp(-r/\xi)$



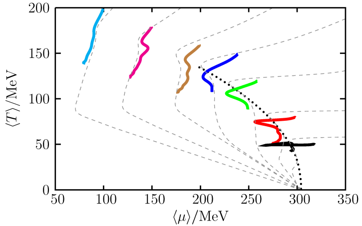
- Dynamic correlation length grows up to $\simeq 2.5$ fm.
- Enhanced event-by-event fluctuations of the order parameter, $\langle\sigma_{\rm V}^2\rangle \propto \xi^2$.
- Initial fluctuations are washed out during the first 1 fm.
- Delay between the averaged $T_{\rm c}$ and the peak in ξ and $\langle\sigma_{\rm V}^2\rangle$.

Trajectories and isentropes at finite μ_B

QM, event averaged



PQM, one individual event

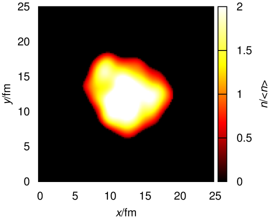


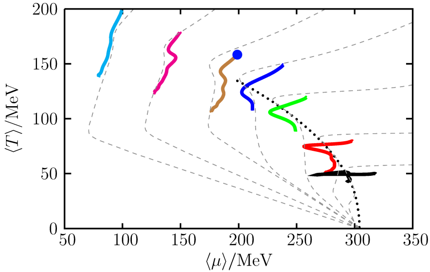
- Grey: equilibrium isentropes, color: T-μ_B trajectories from simulations.
- Fluid trajectories differ from the (equilibrium) isentropes due to interaction with the fields.
- Including the effective Polyakov-loop field leads to more structure of the trajectories, in particular at the first order phase transition (Poster by C. Herold).

Evolution of quark number density

Crossover - critical point

initial density



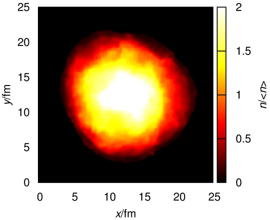


(Poster by C. Herold)

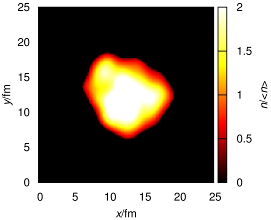
Evolution of quark number density

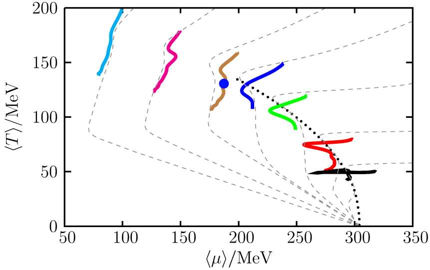
Crossover - critical point

during the evolution



initial density





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Evolution of quark number density

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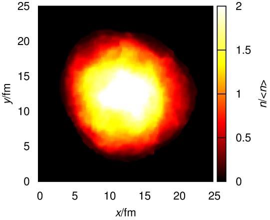
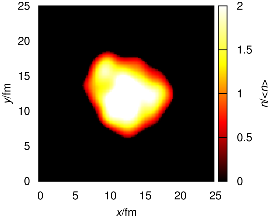
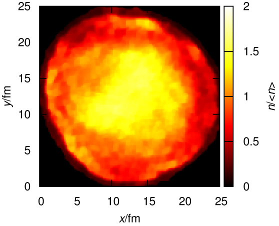
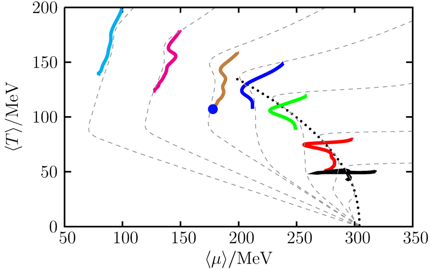


initial density



after $t = 12$ fm



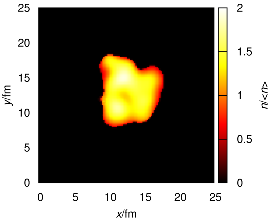


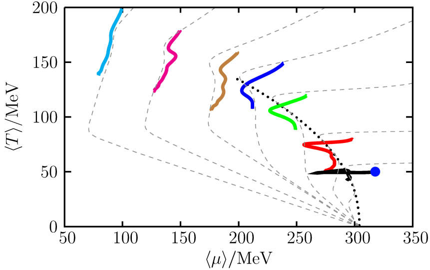
(Poster by C. Herold)

Formation of high quark number density domains

First order phase transition

initial density





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Formation of high quark number density domains

First order phase transition

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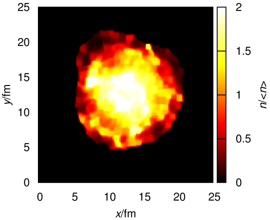
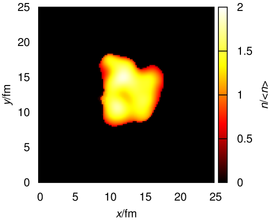
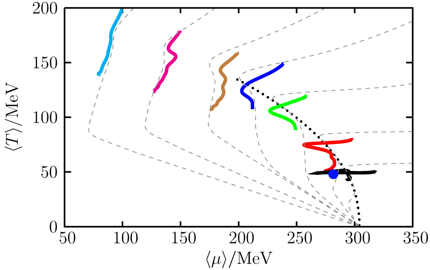


initial density





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Formation of high quark number density domains

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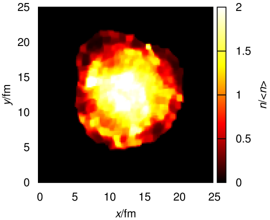
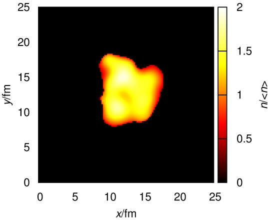
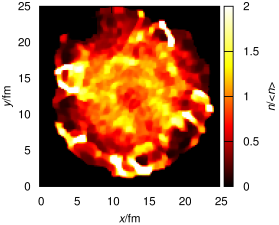
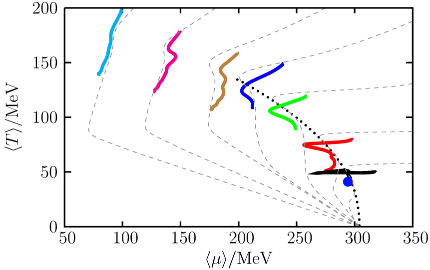


initial density



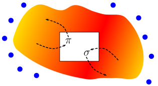
after $t = 12$ fm





(Poster by C. Herold)

Summary

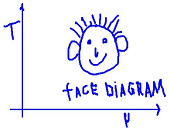


- Dynamic domain formation (σ and *n*) at the first order phase transition.

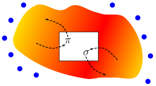
? Can nonequilibrium effects become strong enough to develop signals of the first order phase transition?

- Dynamic correlation length ξ grows up to $\simeq$ 2.5 fm.
- Dynamic enhancement of event-by-event-fluctuations of the order parameter (σ) at the critical point.

? Do enhanced equilibrium fluctuations at the critical point survive the dynamics?



Summary



- Dynamic domain formation (σ and n) at the first order phase transition.

✓ Yes, nonequilibrium dynamics can lead to signals at the first order phase transition!

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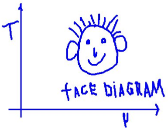
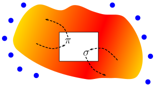


Summary



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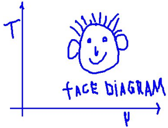
✓ Yes, the critical fluctuations develop even in the situation of a nonequilibrium, dynamic simulation of heavy-ion collisions!



BACKUP

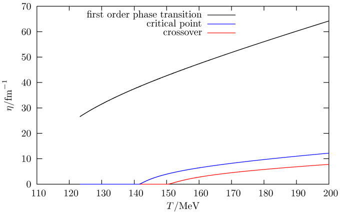
Semiclassical equation of motion for the sigma field

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

damping term η and noise ξ for $\mathbf{k} = 0$

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

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

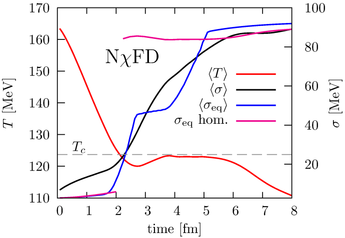


below T_c damping by the interaction with the hard pion modes, apply $\eta = 2.2/\mathrm{fm}$

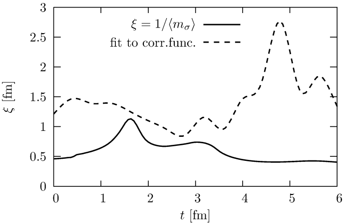
(T. S. Biro and C. Greiner, PRL **79** (1997))

Influence of the inhomogeneous system

first order phase transition



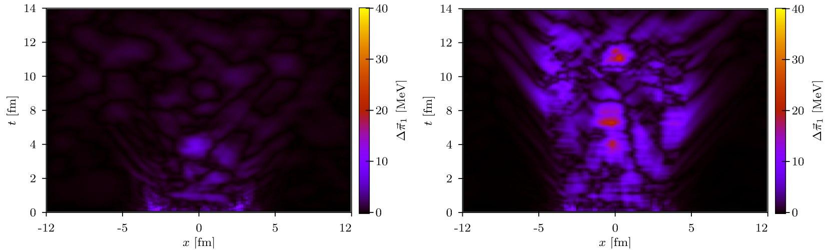
correlation length, critical point



Pion fluctuations

So far: pion fluctuations were not considered and $\vec{\pi} = \langle \vec{\pi} \rangle = 0$.
Propagate pion fluctuations, too:

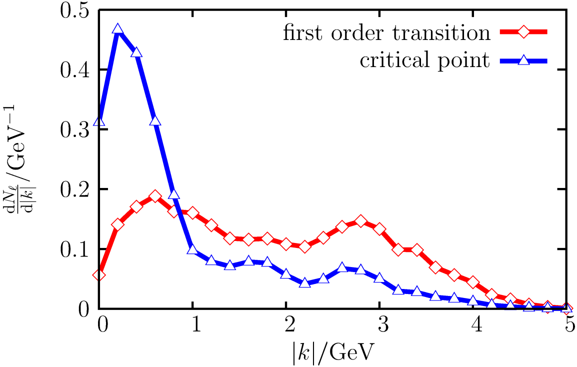
critical point | first order phase transition



Larger pion fluctuations in a scenario with a first order phase transition!

Box: after equilibration

Low mode fluctuations of the Polyakov-loop are enhanced in a CP scenario.



(Poster by C. Herold)