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Non-equilibrium phase transitions in relativistic heavy-ion collsions

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FIAS Frankfurt Institute for Advanced Studies

HIC for FAIR Helmholtz International Center

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Importance of fast dynamics

I.N. Mishustin, Phys. Rev. Lett. 82 (1999) 4779; Nucl. Phys. AA681 (2001) 56

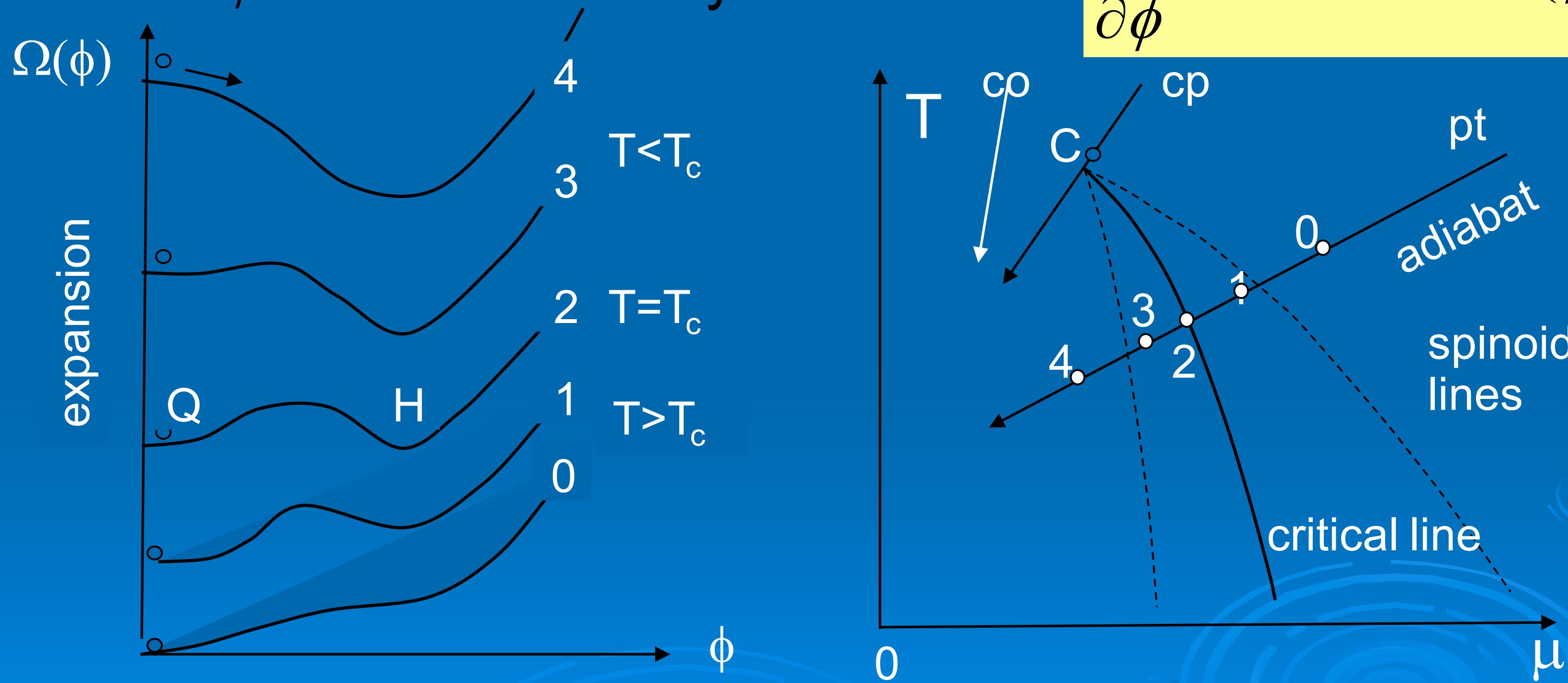
Effective thermodynamic potential leading to a 1st order transition

$$\Omega(\phi;T,\mu) = \Omega_0(T,\mu) + \frac{a}{2}\phi^2 + \frac{b}{4}\phi^4 + \frac{c}{6}\phi^6$$

a,b,c are functions of T and μ

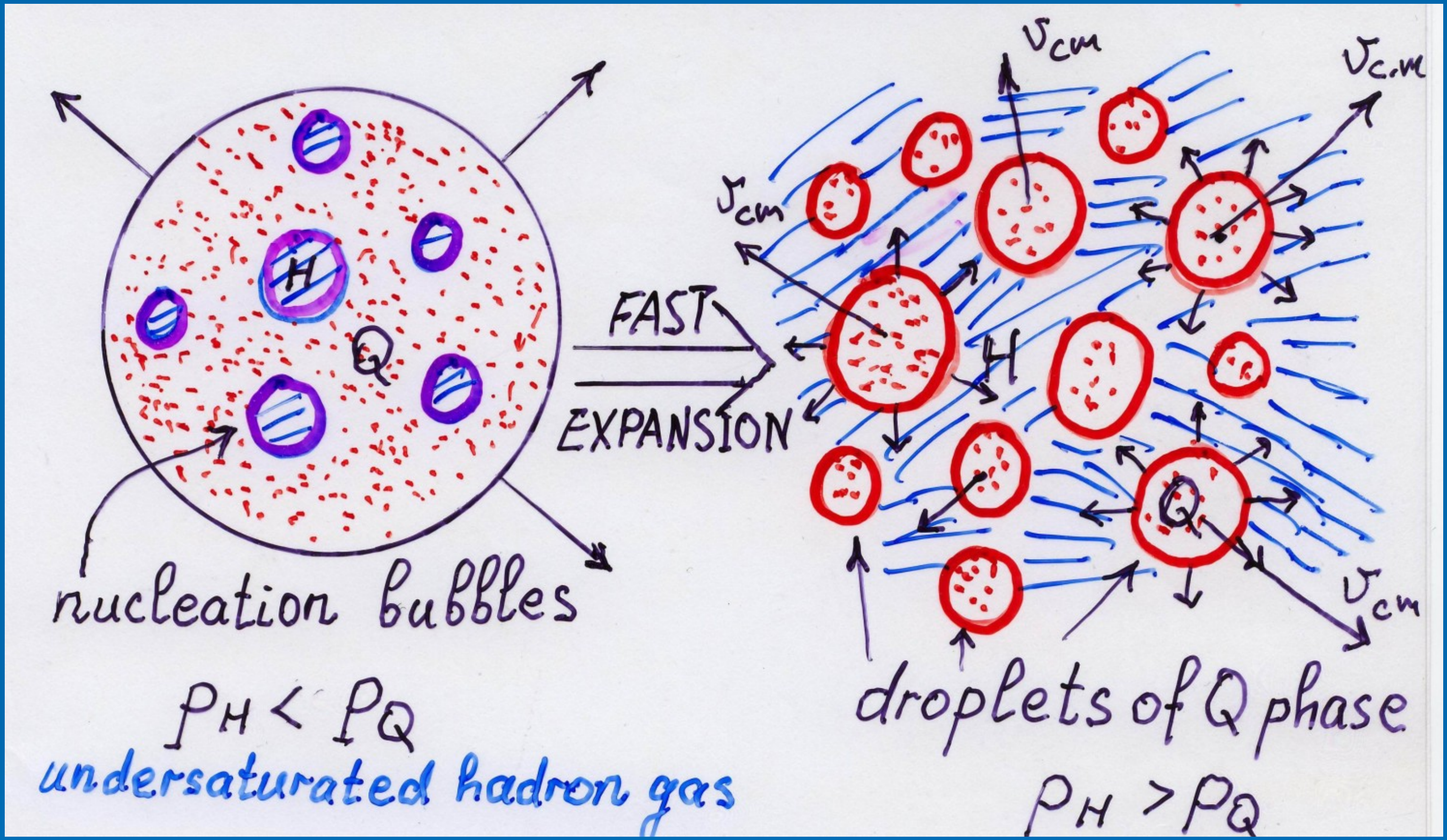
Equilibrium ϕ is determined by

$$\frac{\partial\Omega}{\partial\phi} = 0 \Rightarrow P = -\Omega(\phi_{eq})$$



In rapidly expanding system 1-st order transition is delayed until the barrier between two phases disappears

Dynamical fragmentation 1

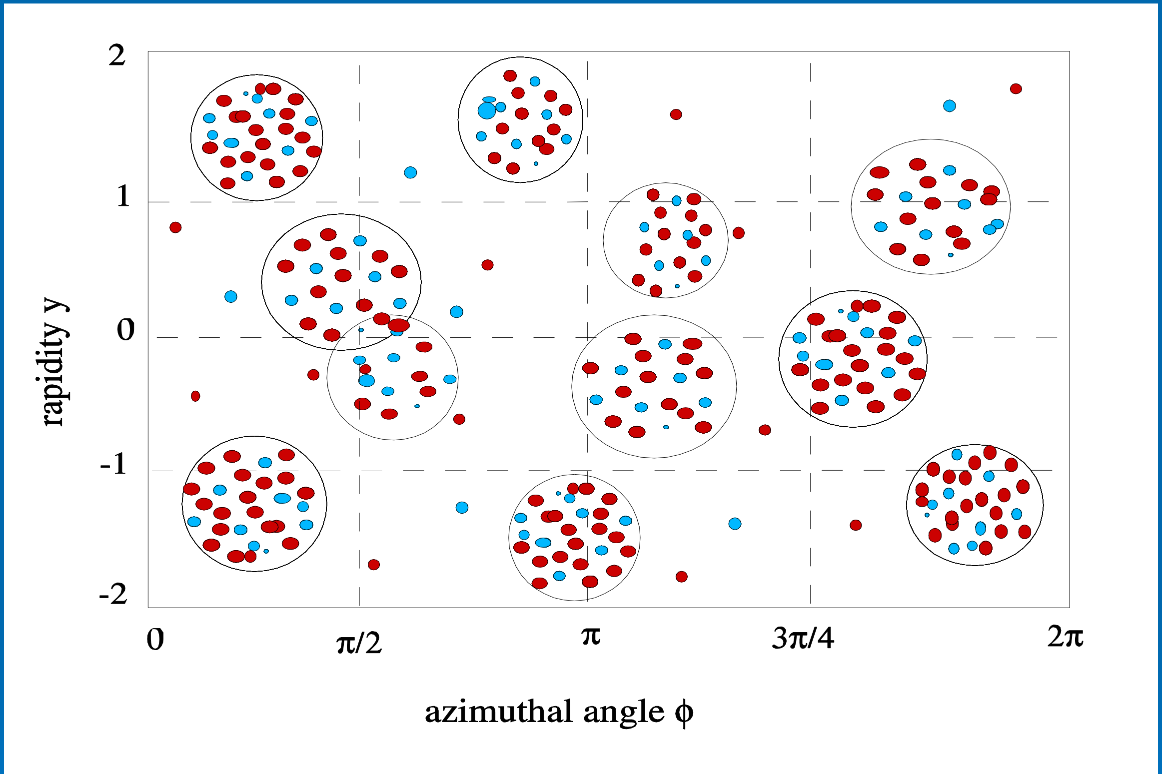


In the course of fast expansion the system enters spinodal instability when Q phase becomes unstable and splits into quark droplets/hadron resonances

Csernai&Mishustin 1995, Mishustin 1999, Rafelski et al. 2000, Randrup et al.2003

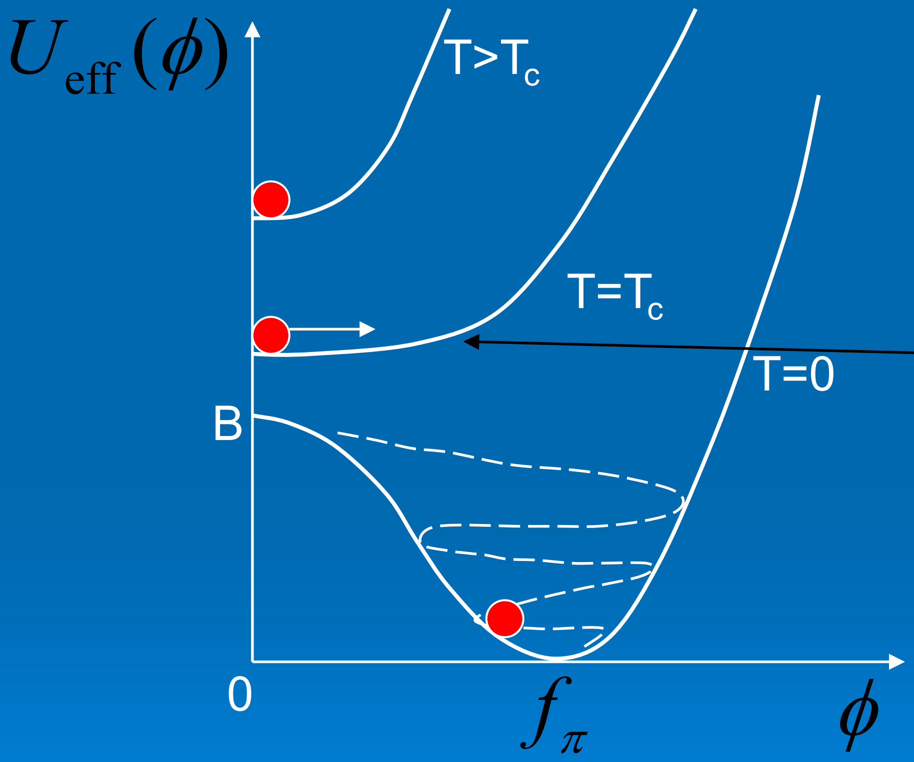
Extreme possibility - direct transition from quarks to hadrons without mixed phase

Experimental signal of droplets in the rapidity-azimuthal angle plane



Look for event-by-event fluctuations of hadron distributions in momentum space associated with emission from quark droplets. Such measurerments should be done in the broad energy range!

Critical slowing down in the 2nd order phase transition



Transition goes through the spinodal decomposition (Csernai&Mishustin 1995)

Fluctuations of the order parameter evolve according to the equation

$$\frac{d\delta\phi}{dt} = -\gamma\frac{\partial\Omega}{\partial\phi} \approx -\frac{\delta\phi}{\tau_{\rm rel}}$$

In the vicinity of the critical point the relaxation time for the order parameter diverges-no restoring force

$$\tau_{\rm rel}(T) \sim \frac{1}{\left|T-T_c\right|^{\nu}} \to \infty, \quad \nu \approx 2$$

Critical fluctuations do not develop due to the “critical slowing down” (Berdnikov, Rajagopal)

Dynamical fluctuations of the order parameter

Work in collaboration with M. Nahrgang, M. Bleicher, C. Greiner, S. Leupold,…

Linear sigma model (LσM) with constituent quarks:

$$L = \bar{q}[i\gamma\partial - g(\sigma + i\gamma_5 \boldsymbol{\tau\pi})]q + \frac{1}{2}[\partial_\mu \sigma \partial^\mu \sigma + \partial_\mu \boldsymbol{\pi} \partial^\mu \boldsymbol{\pi}] - U(\sigma, \boldsymbol{\pi}),$$

$$U(\sigma, \boldsymbol{\pi}) = \frac{\lambda^2}{4}(\sigma^2 + \boldsymbol{\pi}^2 - v^2)^2 - H\sigma, \ \ <\sigma>_{\mathrm{vac}} = f_\pi \rightarrow H = f_\pi m_\pi^2$$

Mean σ field is the order parameter for the chiral phase transition.

Thermodynamics of LσM on the mean-field level was studied in

Scavenius, Mocsy, Mishustin&Rischke, Phys. Rev. C64 (2001) 045202

CO, 2nd and 1st order chiral transitions are obtained in T-μ plane.

Here we consider μ=0 system by tune the strength of the chiral phase transition by changing the coupling constant g.

Chiral fluid dynamics (CFD)

I.N. Mishustin, O. Scavenius, Phys. Rev. Lett. 83 (1999) 3134

Fluid is formed by constituent quarks and antiquarks with interact with the chiral field via effective mass

$$m^2 = g^2(\sigma^2 + \pi^2)$$

CFD equations are obtained from the energy momentum conservation

$$\partial_\nu (T_{\text{fluid}}{}^{\mu\nu} + T_{\text{field}}{}^{\mu\nu}) = 0 \Rightarrow \partial_\nu T_{\text{fluid}}{}^{\mu\nu} = -\partial_\mu T_{\text{field}}{}^{\mu\nu} = -(\partial_\mu \partial^\mu + \frac{\partial U}{\partial \sigma})\partial^\nu \sigma$$

We solve generalized e. o. m. with friction (η) and noise (ξ):

$$\partial_\mu \partial^\mu \sigma + \frac{\partial U}{\partial \sigma} + g < \bar{q}q > + \eta \partial_t \sigma = \xi$$

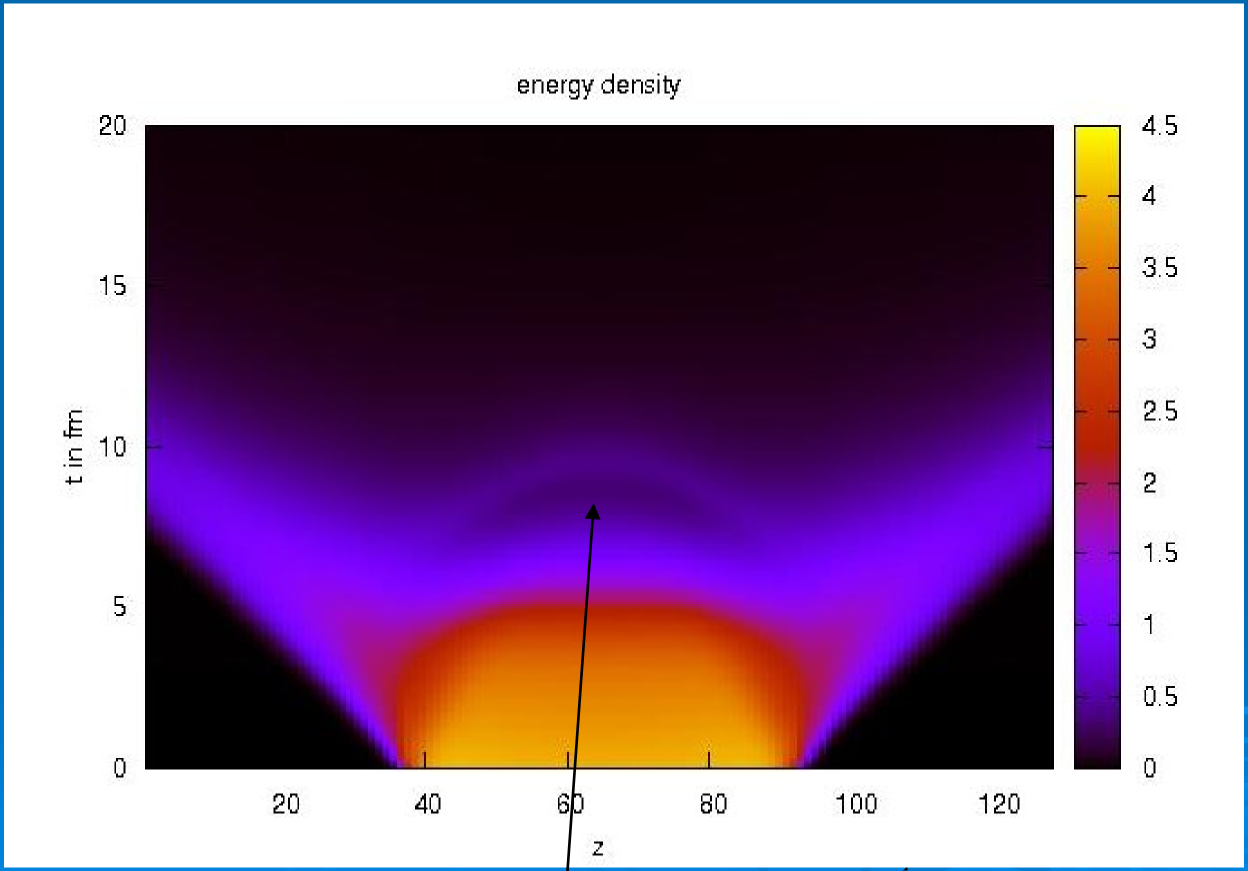
(relaxation equation)

$$< \xi(t) >= 0, \quad < \xi(t)\xi(t') >= \frac{2T}{V}\eta\delta(t - t')$$

(fluctuation-dissipation theorem)

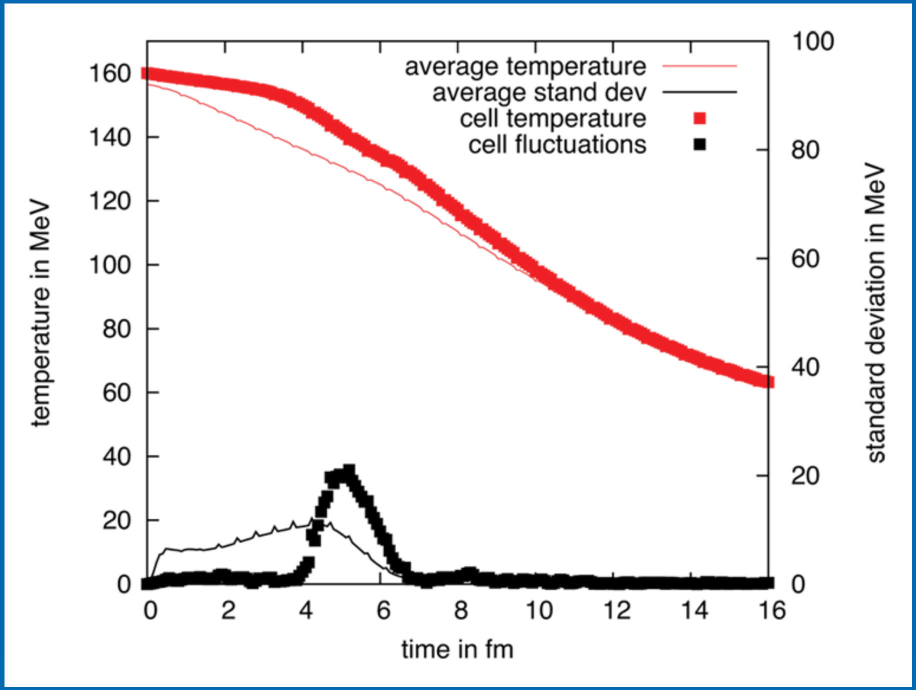
Dynamical evolution of chiral fluid in Bjorken-like expansion

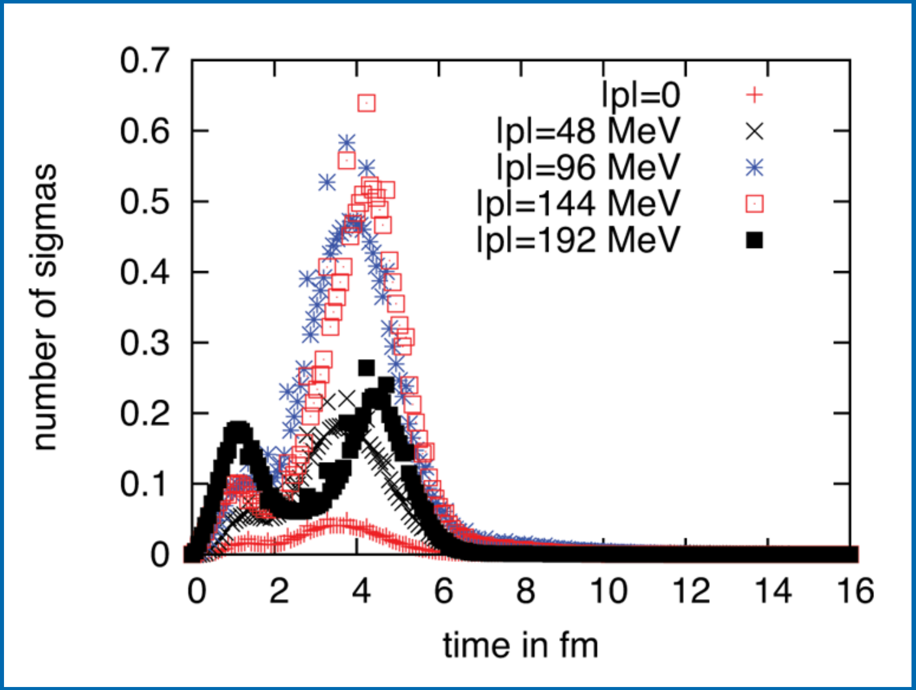
$\eta = 2.2 / fm, \quad g=5.5$ (1st order transition}



Reheating

Crossover transition

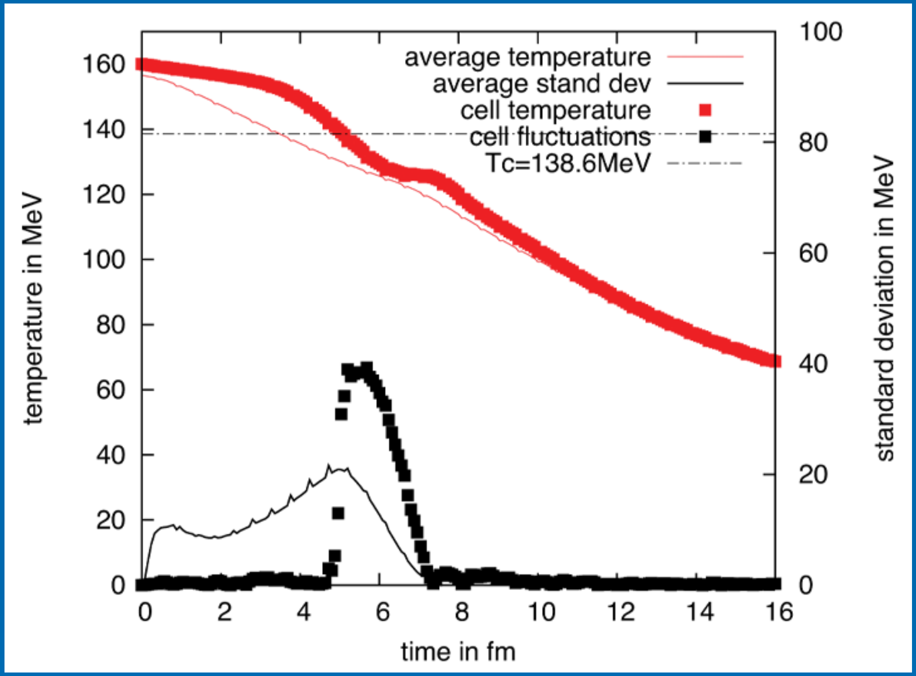


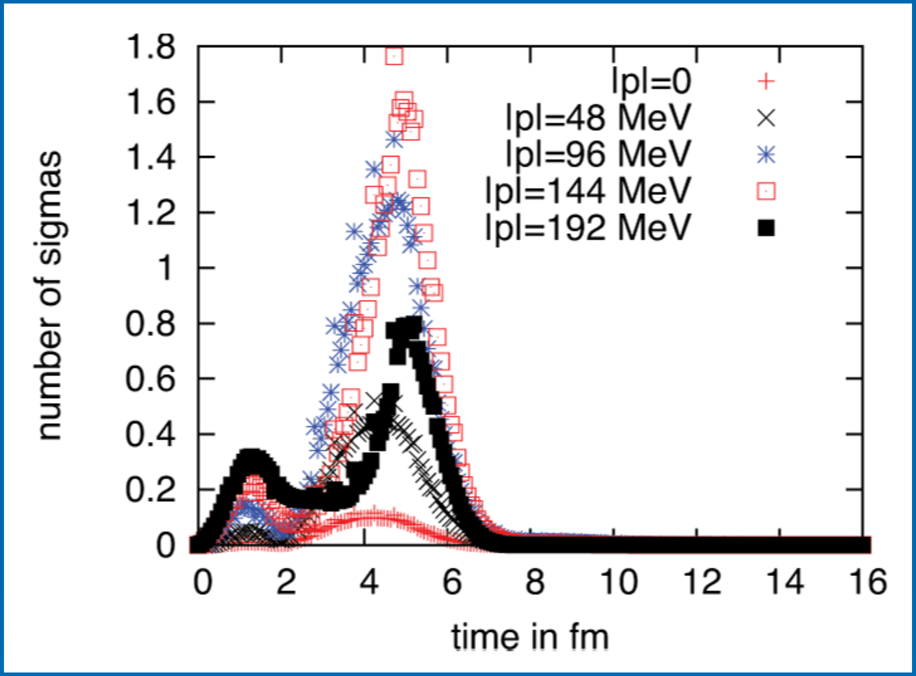


Fluctuations are rather weak, effective number of sigmas is small

$$\frac{dN_\sigma}{d^3k} = \frac{1}{(2\pi)^3}\frac{1}{2\omega_k}[\omega_k^2 |\sigma_k|^2 + |\dot{\sigma}_k|^2]$$

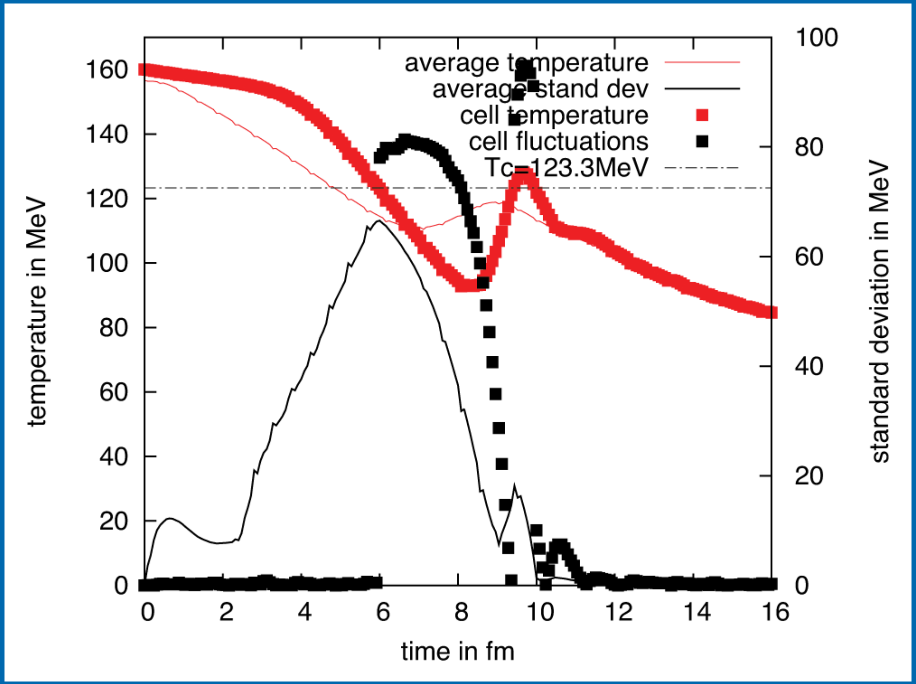
Second order transition with critical point (g=3.63)

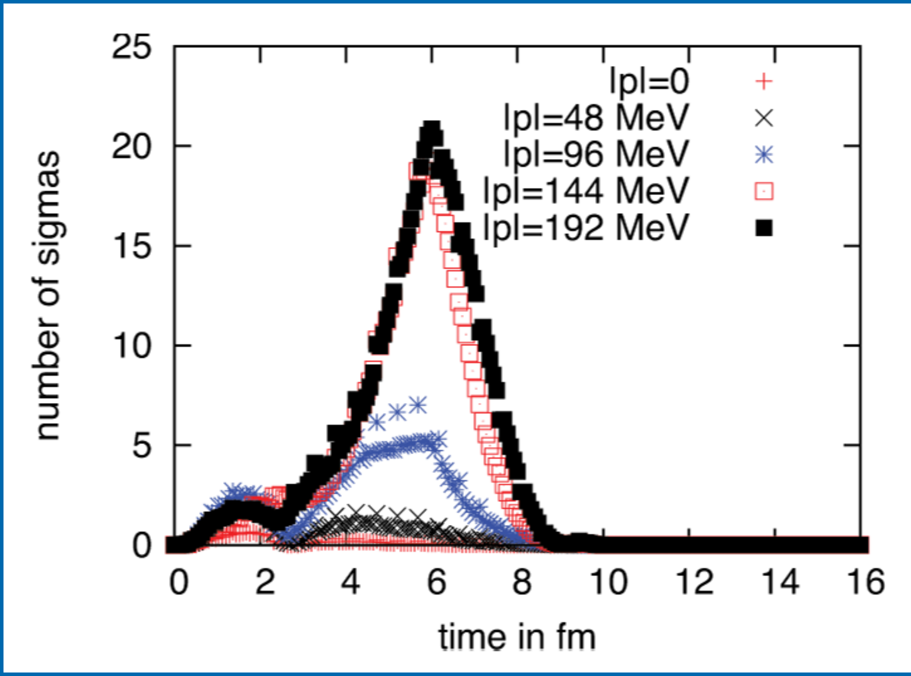




Fluctuations are stronger, but no traces of divergence are seen

Strong first order transition (g=5.5)





- Strong supercooling and reheating effects are clearly seen.
- Sharp rise of fluctuations after 6 fm/c, when the barrier in thermodynamic potential disappears. Effective number of sigmas increases by two orders of magnitude!

Conclusions

- Phase transitions in relativistic heavy-ion collisions will most likely proceed out of equilibrium
- 2^{nd} order phase transitions (with CEP) are too weak to produce significant observable effects
- Non-equilibrium effects in a 1^{st} order transition (spinodal decomposition, strong fluctuations of order parameter) may help to identify the phase transition