Multiplicity fluctuations within nonequilibrium chiral fluid dynamics

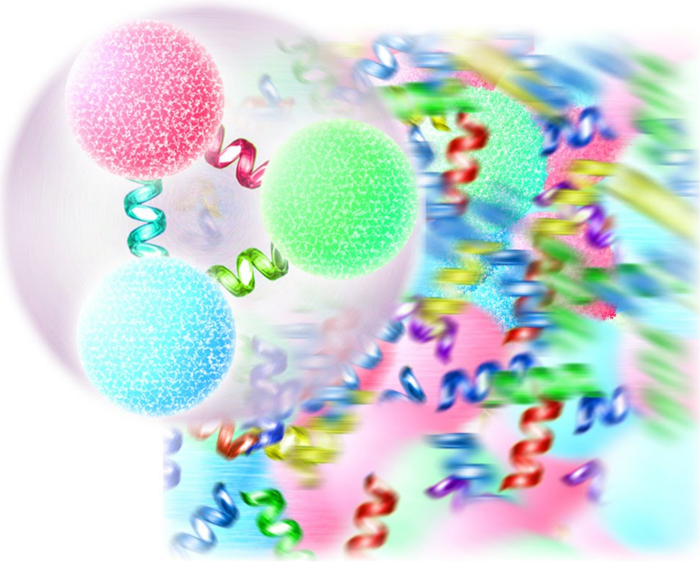
Christoph Herold

based on CH, Nahrgang, Yan, Kobdaj, arXiv: 1407.8277, accepted by JPG

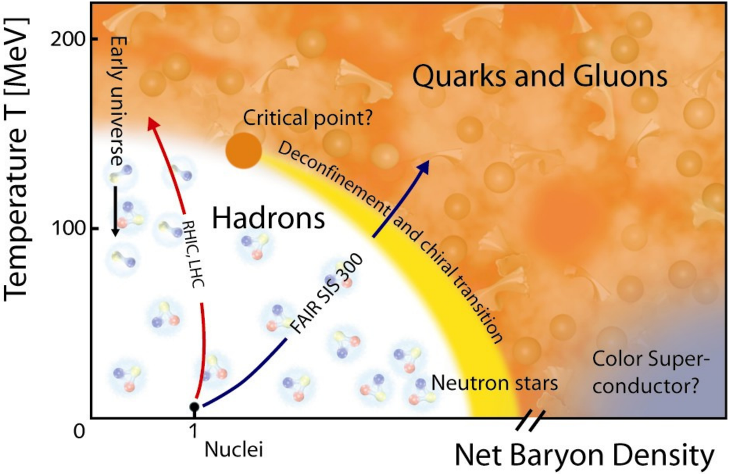
School of Physics, Suranaree University of Technology

Fairness, September 22, 2014

Nucleons and Quark-gluon-plasma



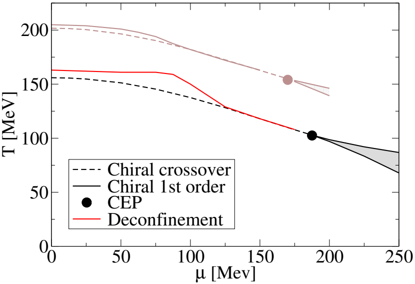
The QCD critical point

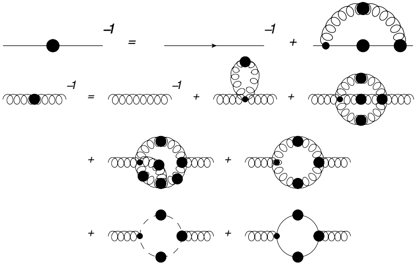


Finding the CP - I

1. From the QCD Lagrangian

- Solve partition function $\mathcal{Z}$ on a lattice (sign problem)
- Solve Dyson-Schwinger equations



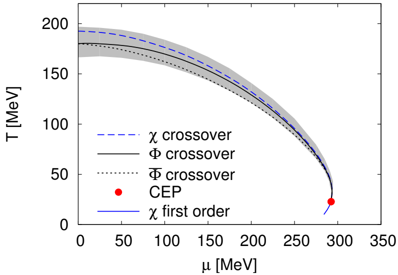


(Fischer, Luecker, Phys. Lett. B **718** (2013) 1036-1043)

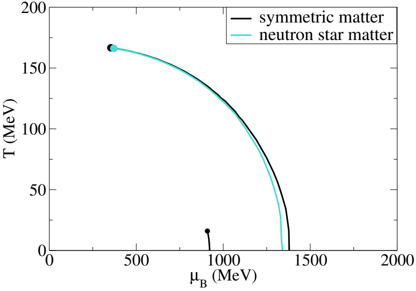
Finding the CP - II

2. From effective models

- Respect chiral symmetry (Sigma model, NJL model, ...)
- Existence/location of CP not universal!



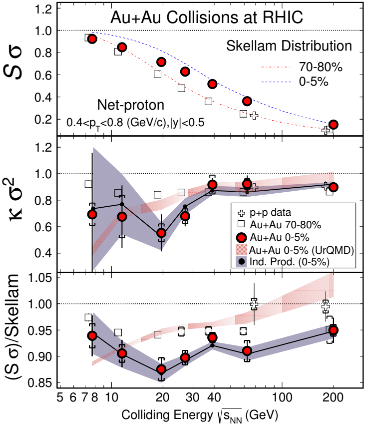
(Herbst, Pawlowski, Schaefer, Phys. Lett. B **696** (2011) 58-67)



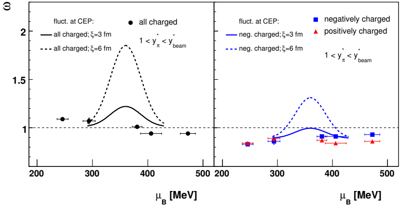
(Dexheimer, Schramm, Phys. Rev. C **81** (2010) 045201)

3. From experiment

- Fluctuations sensitive to critical region



(STAR collaboration, Phys. Rev. Lett. **112** (2014) 032302)



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

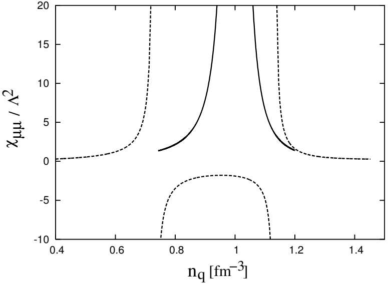
$$\sigma^2 = \langle \delta N^2 \rangle \sim \xi^2$$

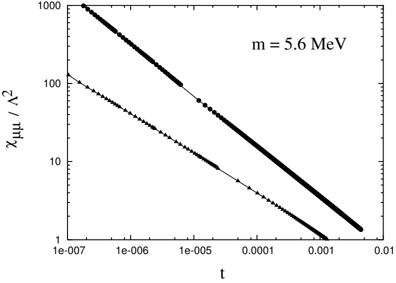
$$S\sigma = \frac{\langle \delta N^3 \rangle}{\langle \delta N^2 \rangle} \sim \xi^{2.5}$$

$$\kappa\sigma^2 = \frac{\langle \delta N^4 \rangle}{\langle \delta N^2 \rangle} - 3\langle \delta N^2 \rangle \sim \xi^5$$

(Stephanov, Phys. Rev. Lett. **102** (2009))

CP and first-order phase transition



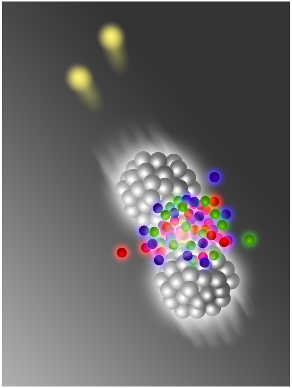


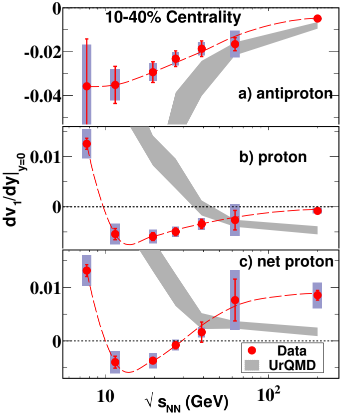
- Net quark number suscpetibility at CP (solid) and first-order phase transition (dashed) from NJL model
- Change of universality class, $\gamma = 2/3$ for CP, $\gamma = 1/2$ for first-order

$$\chi_{\mu\mu} \sim (\mu - \mu_0)^{-\gamma}$$

(Sasaki, Friman, Redlcih, Phys. Rev. D **77** (2008))

Latent heat in heavy-ion collisions?





- Latent heat might influence directed flow v_1, strength of expansion
- Measured by STAR collaboration

(STAR collaboration, Phys. Rev. Lett. 112 (2014) 162301)

Scope of this work

Start from effective chiral model with CEP and first-order phase transition

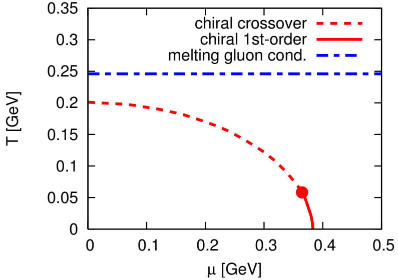
1. Study thermodynamics:
   - Calculate susceptibility and compare with NJL
   - Calculate kurtosis
   - Determine critical indices
2. Study fluid dynamics (heavy-ion collisions):
   - Quark and chiral fields $\rightarrow$ quark fluid and explicitly propagated fields
   - **Ensemble fluctuations event-by-event**

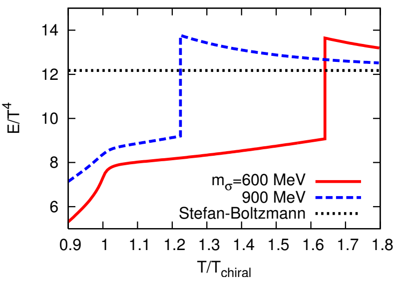
A chiral model with dilatons

Potential and equation of state from

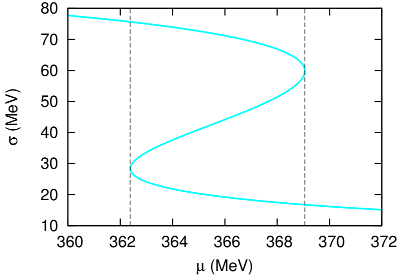
$$\mathcal{L} = \overline{q}\left[\mathrm{i}\left(\gamma^\mu\partial_\mu - \mathrm{i}g_s\gamma^0 A_0\right) - g\sigma\right]q + 1/2\left(\partial_\mu\sigma\right)^2 + 1/2\left(\partial_\mu\chi\right)^2 - U\left(\sigma\right) - \mathcal{U}(\chi)$$

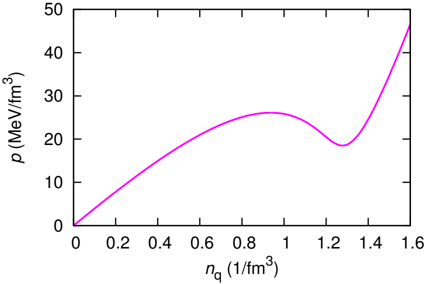
(Sasaki, Mishustin, Phys. Rev. C 85 (2012) 025202)





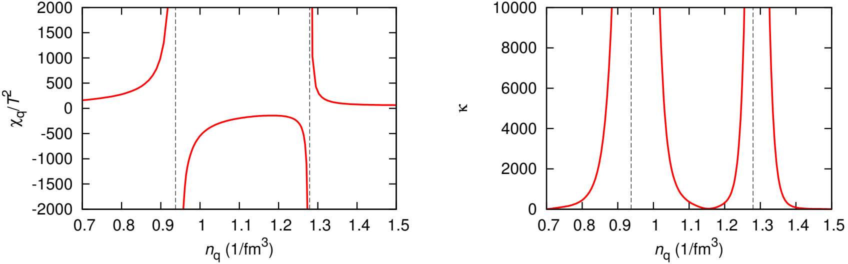
Spinodal instabilities at $T = 40$ MeV





- Phase transition in the presence of spinodal instabilities
- Mechanically instable region in the equation of state

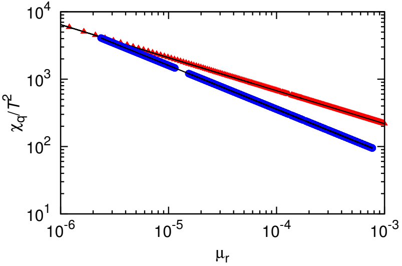
Spinodal instabilities at $T = 40$ MeV

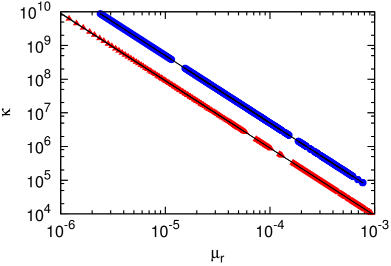


- $\frac{\chi_q}{T^2} = \frac{1}{VT^3}\langle \delta N_q^2 \rangle$ proportional to quark number fluctuations
- $\kappa = \frac{\langle \delta N_q^4 \rangle}{\langle \delta N_q^2 \rangle} - 3\langle \delta N_q^2 \rangle$

Expect: Enhancement of fluctuations at CP AND 1st order transition

Critical indices





$$\chi_q \sim (\mu - \mu_0)^{-\gamma}$$

with $\gamma = 1/2$ for first-order
and $\gamma = 2/3$ for CEP

$$\kappa \sim (\mu - \mu_0)^{-\zeta}$$

with $\zeta = 2$ for first-order
and $\zeta = 2$ for CEP

A chiral model with dilatons ... dynamically

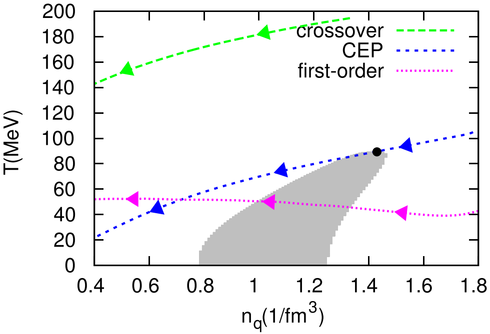
Ingredients for fully dynamical model:

- Hot medium (quarks)
- Fluctuations (chiral fields)

Chiral fluid dynamics

$$-\frac{\delta S_{\mathrm{cl}}}{\delta\sigma} - D = \xi\ , \quad \partial_\mu T_{\mathrm{q}}^{\mu\nu} = S_\sigma^\nu$$

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

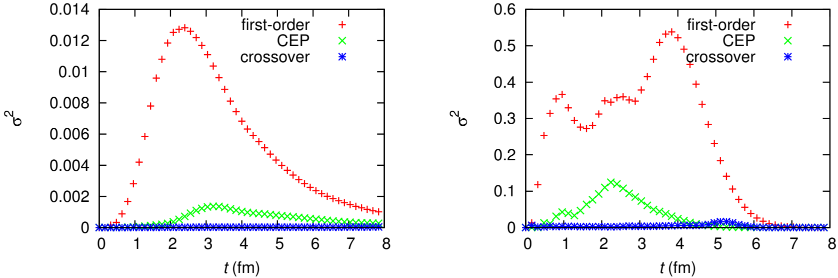


Potential and equation of state from

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

(Sasaki, Mishustin, Phys. Rev. C 85 (2012) 025202)

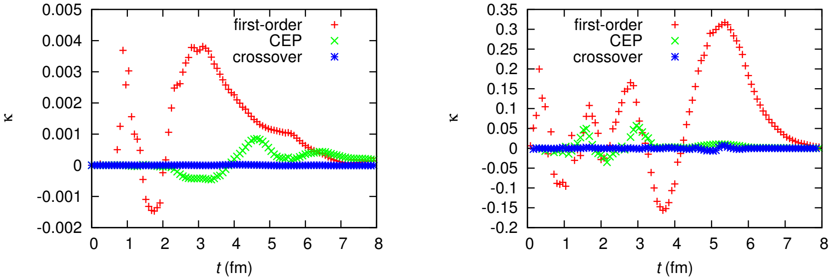
Event-by-event fluctuations: variance



Fixed volume vs. rapidity ($y < 0.5$) and p_T cut ($100\ \mathrm{MeV/fm^3} < p_T < 500\ \mathrm{MeV/fm^3}$)

- Different scales due to different volumes
- Fluctuating volume for rapidity and momentum cut

Event-by-event fluctuations: kurtosis



Fixed volume vs. rapidity ($y < 0.5$) and p_T cut (100 MeV/fm$^3 < p_T <$ 500 MeV/fm^3)

- Different scales due baryon number conservation
- Ratios of cumulants depend on fraction of measured to total baryons

From fluctuations to observables ...

... some more things need to be considered in the future

- Freeze out over hypersurface with constant energy density or temperature
- Final state interactions
- Evolution of fluctuations in the hadronic phase

SU(3) chiral quark-hadron (QH) model

include

- 3 quarks (u, d, s), baryon octet
- scalar mesons σ, ζ, vector meson ω

$$\mathcal{L} = \sum_i \overline{\psi}_i \left(\mathrm{i}\gamma^\mu \partial_\mu - \gamma^0 g_{i\omega}\omega - M_i \right) \psi_i + \frac{1}{2} \left(\partial_\mu \sigma \right)^2 - U\left(\sigma, \zeta, \omega\right) - \mathcal{U}(\ell)$$

with effective masses generated by σ and ℓ

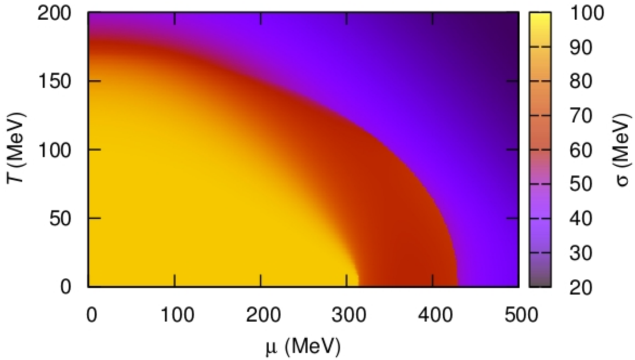
$$\begin{aligned} M_q &= g_{q\sigma}\sigma + g_{q\zeta}\zeta + M_{0q} + g_{q\ell}(1-\ell) \\ M_B &= g_{B\sigma}\sigma + g_{B\zeta}\zeta + M_{0B} + g_{B\ell}\ell^2 \end{aligned}$$

(Dexheimer, Schramm, Phys. Rev. C 81 (2010), 045201)

Improves equation of state, plus:

- Chiral phase transition at larger chemical potentials
- Disentangled from liquid-gas phase transition

QH model - phase diagram



- Chiral phase transition at larger chemical potentials
- Disentangled from liquid-gas phase transition

(Herold, Limphirat, Kobdaj, Yan, SPC 2014)

Summary and Conclusions

- Event-by-event fluctuations become enhanced in hydrodynamic phase for CEP and first-order phase transition
- Effects of hadronic phase have to be taken into account for reliable predictions

THANK YOU