Production of Entropy at the Chiral Phase Transition from Dissipation and Noise

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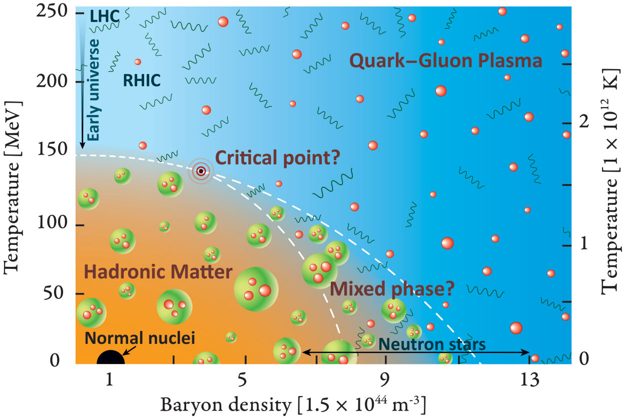
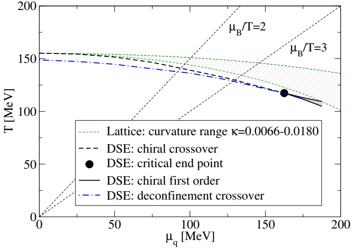
The QCD Phase Diagram

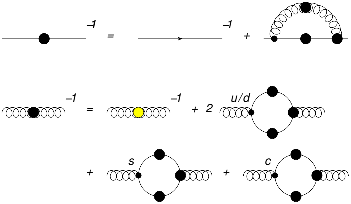


Finding the Critical Point - Theory

1. First principle calculations

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



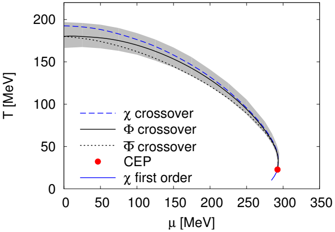


(Fischer, Luecker, Welzbacher, Phys. Rev. D **90** (2014))

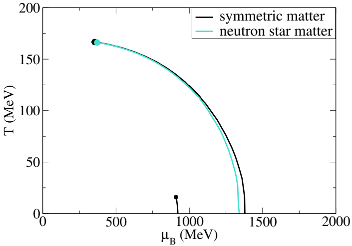
Finding the Critical Point - Theory

2. Effective models

- Extension with Polyakov loop, baryonic degrees of freedom
- Existence/location of CP not universal!



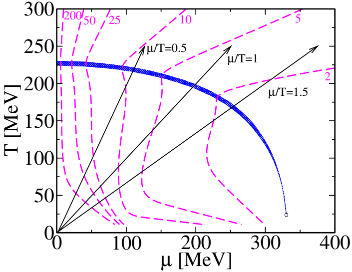
(Herbst, Pawlowski, Schaefer, Phys. Lett. B **696** (2011) 58-67)



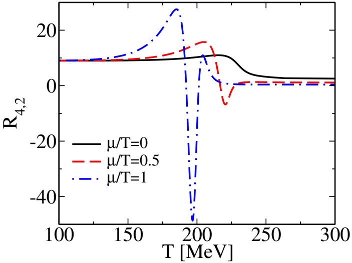
(Dexheimer, Schramm, Phys. Rev. C **81** (2010) 045201)

Finding the Critical Point - Theory

3. Susceptibilities



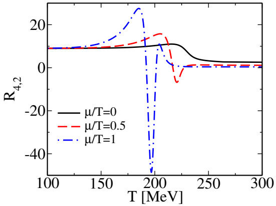
(Skokov, Friman, Redlich, Phys. Rev. C. **83** (2011))



(Skokov, Friman, Redlich, Phys. Rev. C. **83** (2011))

Finding the Critical Point - Theory

4. Susceptibilities and cumulants



(Skokov, Friman, Redlich, Phys. Rev. C. **83** (2011))

- Generalized susceptibilities:

$$c_2 = \frac{\partial^2 (p/T^4)}{\partial(\mu/T)^2} = \frac{1}{VT^3}\langle \delta N^2 \rangle$$

$$c_4 = \frac{\partial^4 (p/T^4)}{\partial(\mu/T)^4} = \frac{1}{VT^3}\left[\langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2\right]$$

- Independent of volume and temperature

$$\kappa\sigma^2 = c_4/c_2 = \frac{\langle \delta N^4 \rangle}{\langle \delta N^2 \rangle} - 3\langle \delta N^2 \rangle$$

Finding the Critical Point - Experiment

1. Higher order cumulants: beam energy scan (BES) at STAR

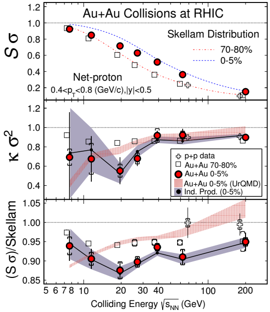
- Higher order cumulants

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

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

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

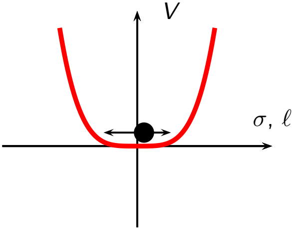
(Stephanov, Phys. Rev. Lett. **102** (2009))



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

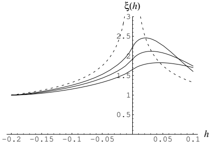
Finding the Critical Point - Experiment

2. ξ-sensitive observables: caveats



- Finite size effects
- Finite time effects
- Critical slowing down

Will influence potential signals



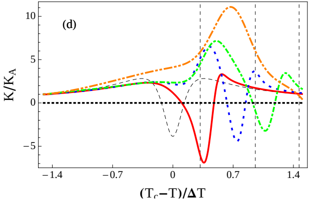
Phenomenologically

$$\frac{\mathrm{d}}{\mathrm{d}t} m_\sigma(t) = \Gamma(m_\sigma(t)) \left(m_\sigma(t) - \frac{1}{\xi_{\mathrm{eq}}(t)} \right)$$

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

Finding the Critical Point - Experiment

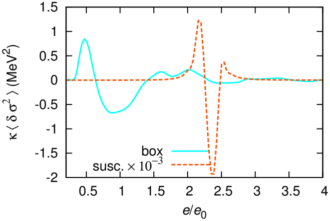
3. A dynamical kurtosis

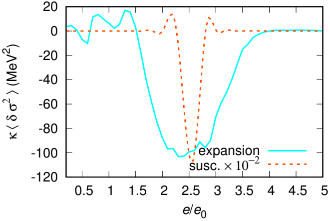


(Mukherjee, Venugopalan, Yin, Phys. Rev. C **92**, (2015))

Cumulants are influence by:

- Relaxation time
- Homogeneous medium
- Inhomogeneous medium





(CH, Nahrgang, Bleicher et al., EPJ A**54**, (2018))

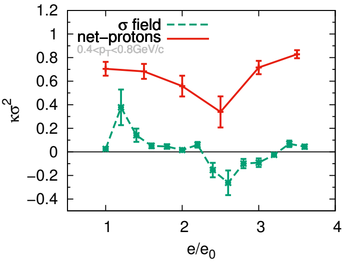
Finding the Critical Point - Experiment

- Nonequilibrium evolution

$$\frac{\partial^2\sigma}{\partial t^2}-\nabla^2\sigma+\eta\frac{\partial\sigma}{\partial t}+\frac{\delta\Omega}{\delta\sigma}=\xi$$

- Net-proton kurtosis follows sigma kurtosis

(CH, Nahrgang, Yan, Kobdaj, PRC **93** (2016))



- Corresponds with

$$\langle \delta N^4 \rangle = \langle N \rangle + \kappa_4 \left(\frac{gd}{T} \int_p \frac{n_p}{\gamma_p} \right)^4 + \ldots$$

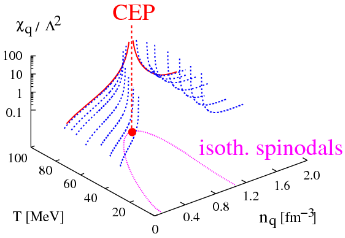
(Stephanov, Phys. Rev. Lett. **107**, (2011))

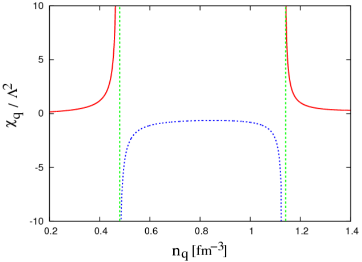
- **Cumulants of sigma determine evolution of experimental observables**

Finding a First-order Phase Transition

1. Nonequilibrium enhancement of fluctuations

- Nonequilibrium fluctuations interesting at first-order transition
- Spinodal decomposition
- Amplification of inhomogeneities

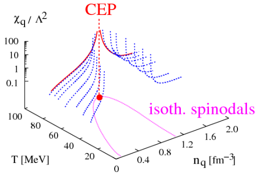




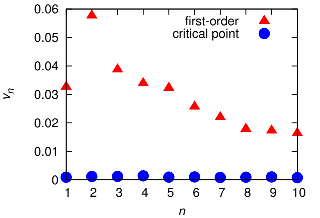
(Sasaki, Friman and Redlich, J. Phys. G **35** (2008))

Finding a First-order Phase Transition

2. Dynamical model

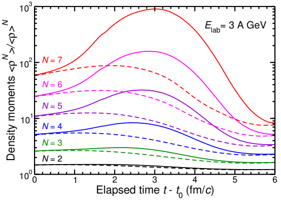


(Sasaki, Friman, Redlich, PRD 77 (2008))



(CH, Nahrgang, Mishustin, Bleicher, NPA 925 (2014))

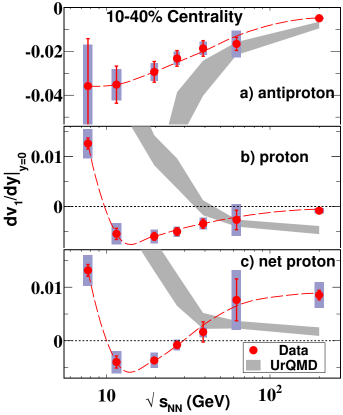
- Formation of metastable phase
- Dynamical fragmentation
- Droplets
- Non-statistical multiplicity fluctuations



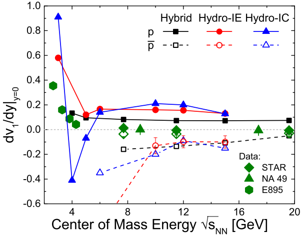
(Steinheimer, Randrup, PRL 109 (2012))

Finding a First-order Phase Transition

3. Directed flow



(STAR collaboration, PRL 112 (2014))



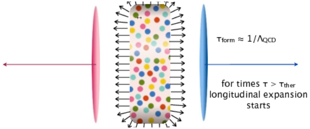
(Steinheimer et al., PRC 89 (2014))

- v_1 sensitive to EoS
- Possible signal for first-order phase transition

NχFD - Idea

Ingredients for Nonequilibrium Chiral Fluid Dynamics **NχFD** model

- Nonequilibrium dynamics and Bjorken expansion
- damping and stochastic fluctuations



(G. Martinez, arXiv:1304.1452)

$$\ddot{\sigma} + \eta\dot{\sigma} + \frac{\delta\Omega}{\delta\sigma} = \xi$$

$$\dot{e} = -\frac{e+P}{\tau} + \left(\frac{\delta\Omega}{\delta\sigma} + \eta\dot{\sigma}\right)\dot{\sigma}\ , \quad \dot{n} = -\frac{n}{\tau}$$

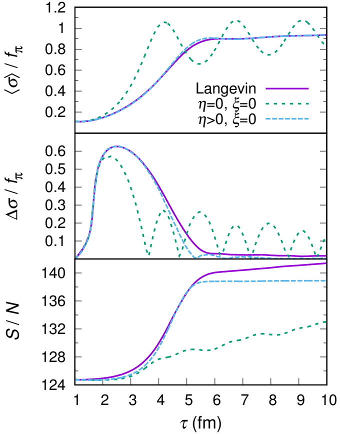
(Herold, Kittiratpattana, Steinheimer, Nahrgang, in prep. (2018))

Based on LσM

$$\mathcal{L} = \bar{q}\left(i\gamma^\mu\partial_\mu - g\sigma\right) + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma)\ ,$$ possibly extended with ℓ, χ

- Successfully describes: **spinodal dynamics, criticality**

NχFD - Entropy production



- Full Langevin:

$$\ddot{\sigma} + \eta\dot{\sigma} + \frac{\delta\Omega}{\delta\sigma} = \xi$$

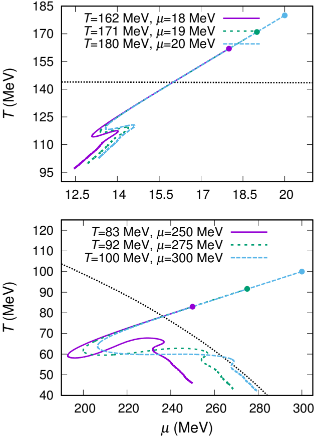
- W/o dissipation and noise:

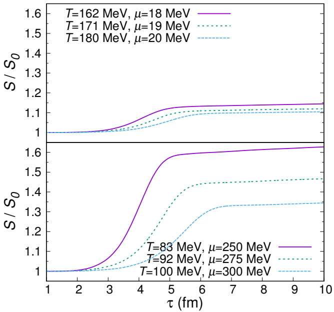
$$\ddot{\sigma} + \frac{\delta\Omega}{\delta\sigma} = 0$$

- W/ dissipation, w/o noise:

$$\ddot{\sigma} + \eta\dot{\sigma} + \frac{\delta\Omega}{\delta\sigma} = 0$$

NχFD - Initial Conditions

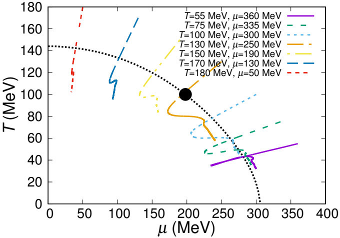


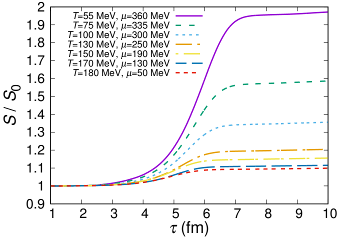


Impact of expansion rate $1/\tau$:

- Trajectory
- Amount of reheating
- Entropy production

NχFD - QCD Phase Diagram





- Entropy production becomes stronger at higher μ_B
- Possible signal for first-order phase transition?
- Search for steps in π multiplicities or π/p ratio

Summary

- Dissipation and noise produce entropy
- Relevant effect for first-order chiral phase transition
- Possibly observable in π/p ratio