Compressed Baryonic Matter experiment at FAIR: Theory overview

Marlene Nahrgang

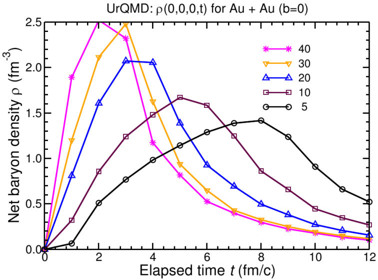
Duke University & Frankfurt Institute for Advanced Studies (FIAS)

FAIRNESS 2013

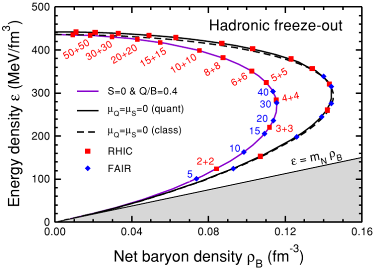
Berlin, September 16$^{\mathrm{th}}$, 2013

The Compressed Baryonic Matter (CBM) experiment

- Beam energies in the range $2 - 35\,A$ GeV (SIS100/300).
- Reaches highest net-baryon densities ⇒ explores new regions in the QCD phase diagram, complementary to the BES program at RHIC.



(I. Arsene et al PRC**75** (2007)



(J. Randrup, J. Cleymans PRC**74** (2006)

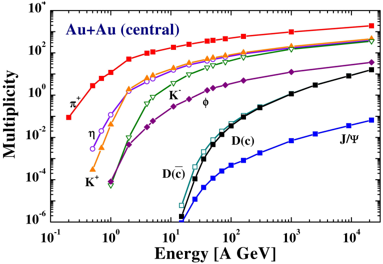
- Highest beam intensities ⇒ ability to measure rare probes with high statistics.

The CBM experiment - in this (theory) talk

- Charm production and propagation of open charm.
- Electromagnetic probes: dileptons.
- The equation of state at high baryonic densities.
- The phase structure and phase transition of QCD at high baryonic densities.

Charm production at FAIR energies

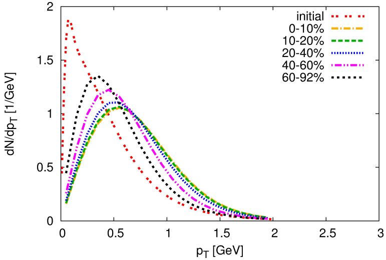
- $c\bar{c}$-quark pairs are predominantly produced in the initial hard nucleon-nucleon scatterings.
- Production and propagation of charm (and bottom) quarks have extensively been studied at top-RHIC/LHC energies.
- Production cross sections fall off rapidly towards lower beam energies.
- In the energy range for CBM, charm production occurs at the threshold.

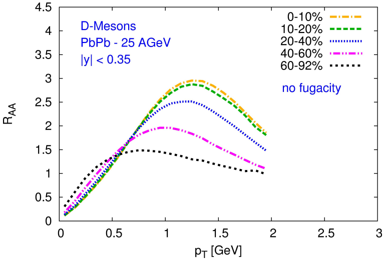


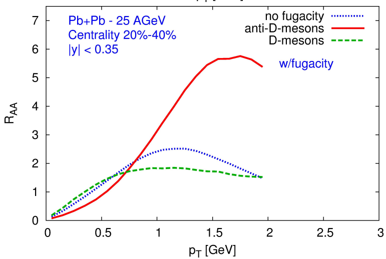
(HSD, W. Cassing et al., Nucl. Phys. A**691** (2001))

Charm propagation in the medium at FAIR energies

- Initial spectra from HSD-parametrization.
- Langevin propagation + UrQMD hybrid approach.
- Transport coefficients from pQCD+resonance scattering
  (Rapp, Hees, PRC**71** (2005))







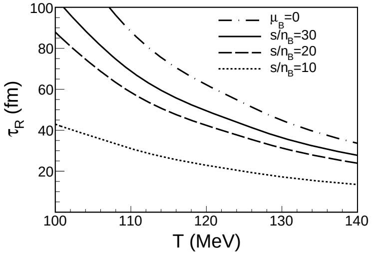
(T. Lang et al., arXiv:1305.1797)

$\Rightarrow$ Clear differences between D and $\bar{D}$-mesons expected in the resonance scattering approach!

D-meson propagation in the medium

- Hadronic interactions (D-hadron) might become more important!
- Effective Lagrangian consistent with chiral and heavy-quark spin symmetries.
- Included interactions: D - mesons $= \{\pi, K, \eta\}$ and D-baryons $= \{N, \Delta\}$.

$\Rightarrow$ Due to additional D-baryon contributions to the drag- and diffusion coefficient, the relaxation time is reduced at FAIR energies!



(L. Tolos and J. M. Torres-Rincon, arXiv:1306.5426)

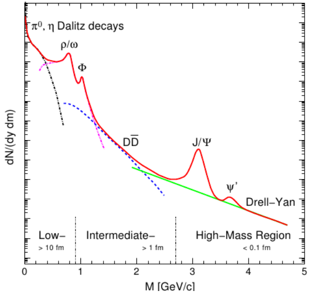
Talks by D. Cabrera and J. M. Torres-Rincon on Wednesday!

Electromagnetic probes

Photons γ and dileptons $\ell^+ \ell^-$...

... do not interact with the medium via the strong interaction $\Rightarrow$ penetrating probes.

... are produced during all stages of the collision:



(Fig. by A. Drees)

$\rightarrow$ from initial hard scatterings (Drell-Yan, high mass region).

$\rightarrow$ from the thermalized medium - hadronic or partonic.

$\rightarrow$ from hadronic decays in the late phase $\rightarrow$ cocktail.

... are measured as time integrals over the collision history.

Electromagnetic probes

- A dilepton is a timelike, virtual photon $M^2_{\gamma^*} = M^2_{e^+e^-} > 0$!
- Real photon ($M^2_\gamma = 0^+$) emission and dilepton emission are given by the same electromagnetic current-current correlation function

$$\Pi^{\mu\nu}_{\text{ret}} = -i \int \mathrm{d}^4 x \exp(iq \cdot x) \langle [j^\mu(x), j^\nu(0)] \rangle_{T,\mu}$$

in different kinematic regimes:

$$\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4x \mathrm{d}^4 q} = -\frac{\alpha^2_{\text{em}}}{3q^2\pi^3} g^{\mu\nu} \Im \Pi^{\mu\nu}_{\text{ret}}(q)\Big|_{q^2 = M^2_{e^+e^-}} n_B(q_0)$$

$$q_0 \frac{\mathrm{d}N_\gamma}{\mathrm{d}^4x \mathrm{d}^3 q} = \frac{\alpha_{\text{em}}}{2\pi^2} g^{\mu\nu} \Im \Pi^{\mu\nu}_{\text{ret}}(q)\Big|_{q_0 = |\vec{q}|} n_B(q_0)$$

- In the vacuum the em spectral function is dominated by the ρ, ω and ϕ resonances at low mass and a quark-antiquark continuum at high mass.

Dileptons and chiral symmetry

- The QCD Lagrangian is symmetric under chiral transformations (up to the small current quark masses).
- Under axial transformations $\psi \to \exp\left(-i\gamma_5 \frac{\vec{\tau}}{2}\vec{\Theta}\right)\psi$:

  a pion-like state rotates into a sigma-like state: $\vec{\pi} \to \vec{\pi} + \vec{\Theta}\sigma$

  a rho-like state rotates into a a_1-like state: $\vec{\rho} \to \vec{\rho} + \vec{\Theta} \times \vec{a}_1$

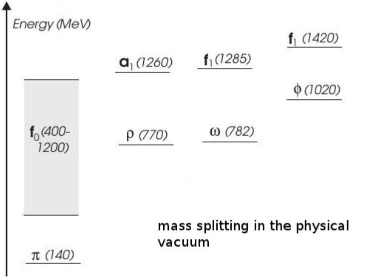
$\Rightarrow$ naive assumption: chiral partners are degenerate, they should have the same eigenvalues, e. g. the same masses

BUT...

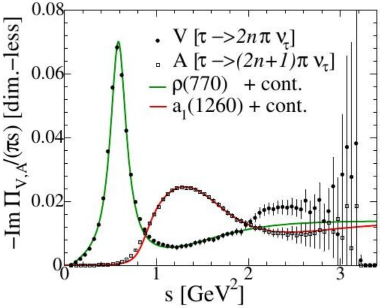
Dileptons and chiral symmetry

... chiral symmetry is spontaneously broken in the vacuum
$\Rightarrow$ mass splitting

$q\bar{q}$ excitations in vacuum



spectral functions of ρ and a_1 in vacuum

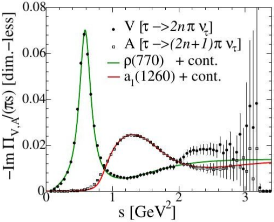


(ALEPH data from τ decay)

Expectation: chirally restored phase in hot and dense matter.

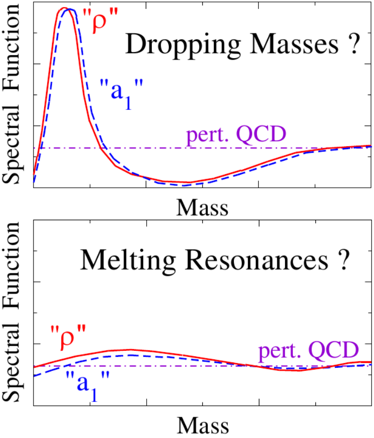
Dileptons and chiral symmetry

There are different possible scenarios for in-medium modifictions of the spectral functions:



⟹

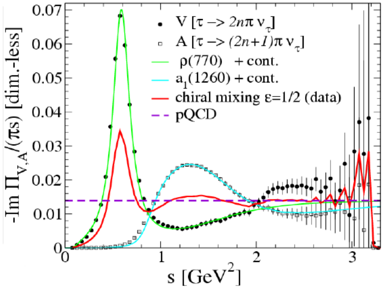
⟹



(CBM physics book)

Problem: only the vector part of the spectral function is accessible via dileptons.

Chiral mixing



(R. Rapp)

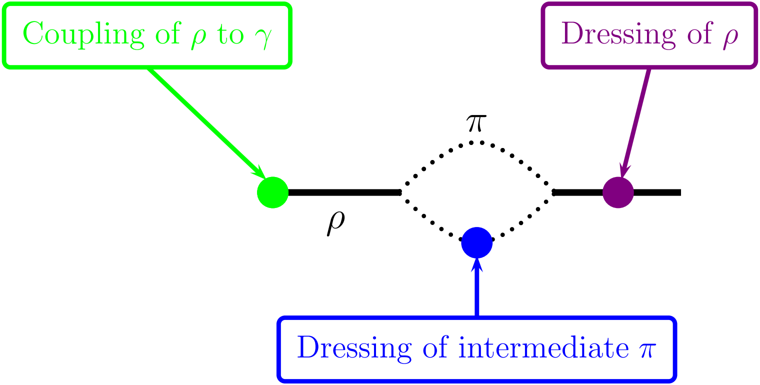
- In low-density expansion and to leading-order in T:

$$\Pi_{\mathrm{V,A}}(q) = (1-\epsilon)\Pi^0_{\mathrm{V,A}}(q) + \epsilon\Pi^0_{\mathrm{A,V}}(q)$$

with $\epsilon = \frac{T^2}{6f_\pi^2}$. (M. Dey et al, PLB**252**, 1990)

- Further calculations of medium-modified spectral functions require models for the...

In-medium correlator



Overview (by far not exhaustive)

- QCD and Weinberg sum rules $\Rightarrow$ can only give constraints on spectral functions from models: shift and/or width (Leupold et al. ...)

  Talk by Thomas Buchheim, this afternoon!

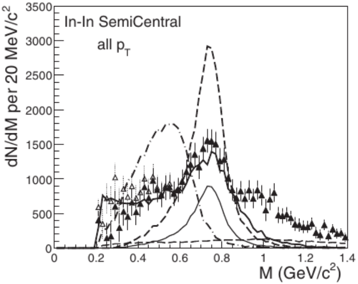
- Mean-field dynamics (Brown and Rho...) $\Rightarrow$ dropping mass scenario

- Hadronic many-body theory (Ko et al, Chanfray et al, Hermann et al, Rapp et al. ...) $\Rightarrow$ in-medium broadening

  $\rightarrow$ $\pi\pi$-interactions and baryonic excitations

NA60 data of $\mu^+\mu^-$ seems to favor the broadening scenario:

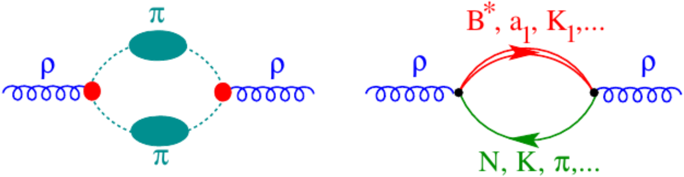
dashed: vacuum
dashed-dotted: dropping mass
solid: in-medium broadening



(NA60 collaboration, PRL **96**, 2006)

Hadronic many-body theory

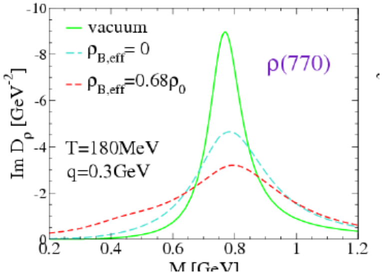
Fig. by H. Hees



in-medium propagator:

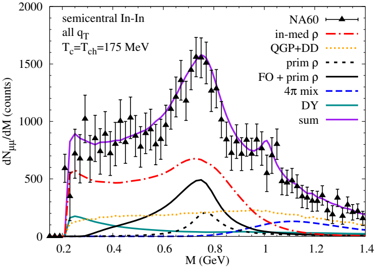
$$D_\rho(M, q; T, \mu_B) = (M^2 - (m_\rho^0)^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M})^{-1}$$

- Baryon contributions to the broadening are large.
- Baryon effects are important even at $n_{B-\bar{B}} = 0$.
- Sensitive to $n_B + n_{\bar{B}}$ due to CP-invariance of the strong interaction ($\rho - N = \rho - \bar{N}$).

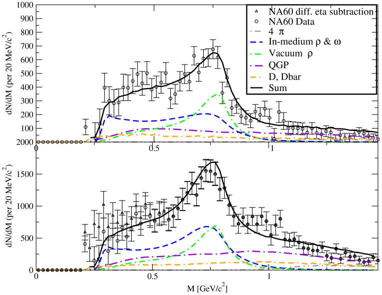


(Rapp and Wambach, 1999)

Hadronic or partonic?



(van Hees and Rapp, 2008)



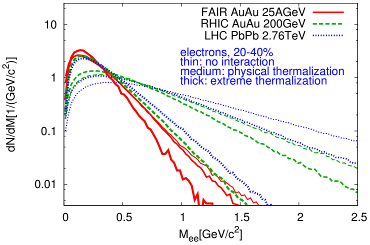
(Ruppert and Renk, 2008)

- Parton-hadron duality of rates $\propto \exp(-E_\gamma / T)$.
- Could the dilepton v_2 distinguish between multipion and $q\bar{q}$ processes?

Correlated $D\bar{D}$-decay into lepton-pairs

Correlated $D\bar{D}$-meson decay into dileptons is the main background for the thermal radiation from the QGP/hadronic medium.

- Softer spectra at lower energies.
- Dependence on the diffusion coefficient.
- Difference to experimental data is a measure for thermal radiation.



(T. Lang et al, arxiv:1305.7377)

Convolution with the medium evolution

As with (probably) all observables:

Quantitative predictions for dilepton yields in heavy-ion collisions depends on the evolution of the medium!

Talks during this conference:

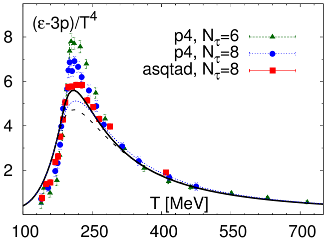
- Dileptons from UrQMD $\rightarrow$ Stephan Endres, Saturday
- UrQMD plus fluid dynamics $\rightarrow$ Jussi Auvinen, Thursday
- UrQMD plus viscous fluid dynamics $\rightarrow$ Iurii Karpenko, Thursday

What is fluid dynamics?

- Two time scales:
  - fast processes $\Rightarrow$ local equilibration
  - slow processes $\Rightarrow$ change of conserved charges (energy, momentum, charge)
- General dynamics: $\partial_\mu T^{\mu\nu} = 0$ and $\partial_\mu N^\mu = 0$.
- Properties of the system enter via the equation of state and transport coefficients.

- The equation of state at $\mu_B = 0$ can be calculated on the lattice.
- Little is known about the equation of state at finite (high) baryonic densities...

  Talk by Sylvain Mogliacci, this morning!



P. Huovinen, P. Petreczky, NPA**837** (2010)

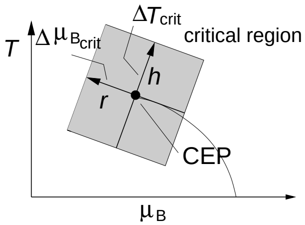
Equation of state - critical point

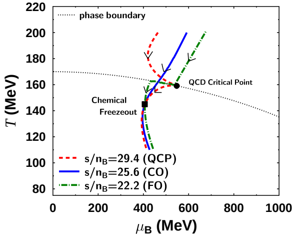
- Construct an eos with CP from the universality class of the 3d Ising model.
- Map the temperature and the external magnetic field (r, h) onto the (T, μ)-plane $\Rightarrow$ critical part of the entropy density S_c.
- Match with nonsingular entropy density from QGP and the hadronic phase:

$$s = 1/2(1 - \tanh S_c)s_H + 1/2(1 + \tanh S_c)s_{QGP}$$

- Focussing of trajectories $\Rightarrow$ Different behavior of $\bar{p}/p$ yields.

not confirmed in similar studies, e.g. M. Bluhm, B. Kampfer PoS CPOD2006 (2006)





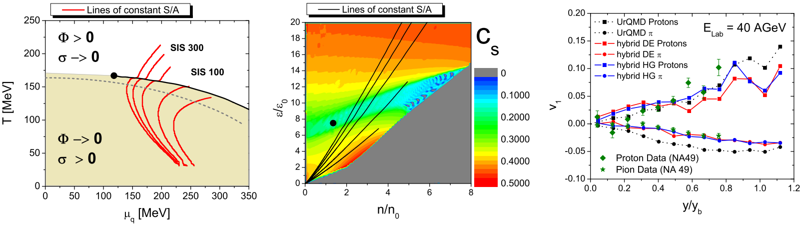
C. Nonaka, M. Asakawa PRC**71** (2005); M. Asakawa, S. Bass, B. Mueller, C. Nonaka PRL**101** (2008)

Equation of state - effective models

- Equations of state can be obtained from effective model Lagrangians.
- Hadronic SU(3) non-linear sigma model including quark degrees of freedom yields a realistic structure of the phase diagram and phenomenologically acceptable results for saturated nuclear matter.

  V. Dexheimer, S. Schramm, PRC**81** (2010)

- The influence of the eos on the directed flow or mean transverse momentum spectra is negligible.

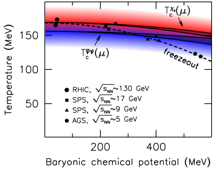


J. Steinheimer, V. Dexheimer, H. Petersen, M. Bleicher, S. Schramm, H. Stoecker, PRC**81** (2010)

Approaches to the QCD phase diagram

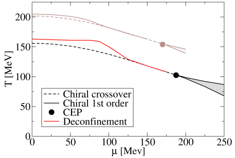
- QCD calculations in the nonperturbative regime:
  Talk by Gergely Endrodi, Saturday morning!

LQCD Wuppertal-Budapest
JHEP **0203** (2002), JHEP **1104** (2011)

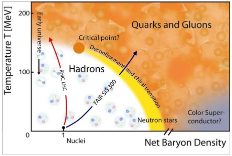


Dyson-Schwinger equations

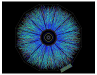
C. Fischer, J. Luecker, PLB**718** (2013)



- Effective models of QCD:



- Heavy-ion collisions:



SHINE NA61

FAIR

NICA

Fluctuations at the critical point

- In thermal systems the correlation length ξ diverges at the CP.
- Coupling of the order parameter to pions $g\sigma\pi\pi$ and protons $G\sigma\bar{p}p \Rightarrow$ fluctuations in multiplicity distributions

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

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

- Higher cumulants are more sensitive to the CP

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

  kurtosis: $\langle(\delta N)^4\rangle - 3\langle(\delta N)^2\rangle^2 \propto \xi^7$

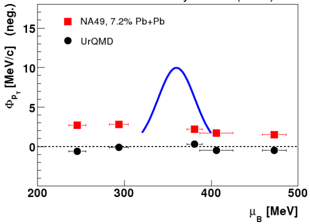
M. Stephanov, PLB **102** (2009), PRL **107** (2011)

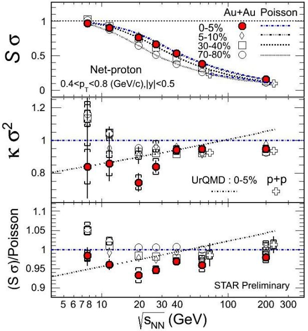
- Experimental difficulties, baryon number conservation

MN et al. EPJ C**72** (2012)

A. Bzdak, V. Koch, PRC**86** (2012), PRC**87** (2013)

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





STAR collaboration, QM2012

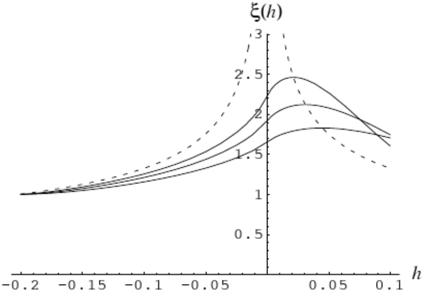
Fluctuations at the critical point

- Long relaxation times near a critical point
  $\Rightarrow$ the system is driven out of equilibrium (critical slowing down)!
- Phenomenological equation:

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

with $\Gamma(m_\sigma) = \frac{A}{\xi_0}(m_\sigma \xi_0)^z$
$z = 3$
(dynamical) critical exponent from model H in Hohenberg-Halperin

$\Rightarrow \xi \sim 1.5 - 2.5$ fm



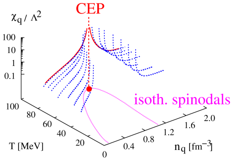
B. Berdnikov and K. Rajagopal, PRD **61** (2000)); D. Son, M. Stephanov, PRD **70** (2004); M. Asakawa, C. Nonaka, Nucl. Phys. A774 (2006)

Fluctuations at the phase transition

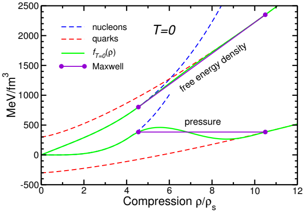
- Large nonstatistical fluctuations in nonequilibrium situations of single events.
- Instability of slow modes in the spinodal region (spinodal decomposition)

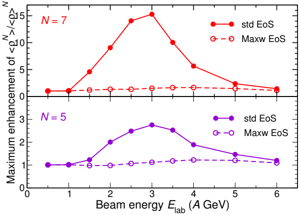
  I. Mishustin, PRL **82** (1999)

  C. Sasaki, B. Friman, K. Redlich, PRD **77** (2008)



- Significant amplification of initial density irregularities





J. Steinheimer, J. Randrup, PRL **109** (2012), arXiv:1302.2956

Heavy-ion collisions are

- inhomogeneous
- finite in space and time
- and highly dynamical.

? 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?

Goal:
Combine the fluid dynamical description of heavy-ion collisions with fluctuation phenomena at the phase transition!

- Explicit propagation of the order parameter(s) – NχFD
- Fluid dynamical fluctuations

Nonequilibrium chiral fluid dynamics - NχFD

- Langevin equation for the sigma field: damping and noise from the interaction with the quarks (quark-meson model)

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

- For PQM: phenomenological dynamics for the Polyakov-loop
- Fluid dynamical expansion of the quark fluid = heat bath, including energy-momentum exchange

$$\partial_\mu T_{\mathrm{q}}^{\mu\nu} = S^\nu = -\partial_\mu T_\sigma^{\mu\nu}$$

$\Rightarrow$ includes a stochastic source term!

- Nonequilibrium equation of state $p = p(e, \sigma)$

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, C. Herold, S. Leupold, I. Mishustin, M. Bleicher, JPG**40** (2013); C. Herold, MN, I. Mishustin, M. Bleicher PRC **87** (2013)

Talks by Alex Meistrenko, Christoph Herold, after the coffee break!

Relativistic theory of fluid dynamical fluctuations

- Conventional fluid dynamics propagates thermal average.
- If there was no noise $\Rightarrow \langle T^{\mu\nu} T^{\alpha\beta} \rangle = 0$, give viscosity via the Kubo-formalism.
- Fast processes lead to local equilibration AND to noise.

$\Rightarrow$ stochastic fluid dynamics by Landau, 1957
$\Rightarrow$ extention to relativistic fluid dynamics in the QCD:

$$\partial_\mu T^{\mu\nu} = 0 \qquad \partial_\mu N^\mu_B = 0$$

$$\begin{aligned} T^{\mu\nu} &= T^{\mu\nu}_{\mathrm{eq}} + \Delta T^{\mu\nu}_{\mathrm{visc}} && \text{on average} \\ T^{\mu\nu} &= T^{\mu\nu}_{\mathrm{eq}} + \Delta T^{\mu\nu}_{\mathrm{visc}} + S^{\mu\nu} \end{aligned}$$

$\langle S^{\mu\nu} \rangle = 0$: noise

J. Kapusta, B. Mueller, M. Stephanov PRC**85** (2012)

Relativistic theory of fluid dynamical fluctuations

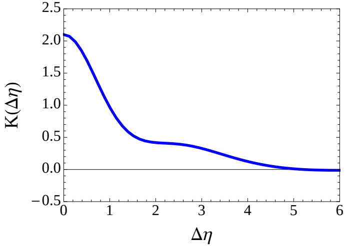
- Magnitude of the noise correlator from the fluctuation-dissipation theorem, it matches noise and dissipation (viscosity!)

$$\langle S^{\mu\nu}(x) S^{\alpha\beta}(y)\rangle = 2T[\eta(\Delta^{\mu\alpha}\Delta^{\nu\beta} + \Delta^{\mu\beta}\Delta^{\nu\alpha}) + (\zeta - 2/3\eta)\Delta^{\mu\nu}\Delta^{\alpha\beta}]\delta^4(x-y)$$

- Noise is local but the fluid dynamical modes transport correlations over macroscopic distances.
- Example: boost-invariant Bjorken expansion:

Particle number correlations extend over more than one unit in rapidity.

J. Kapusta, B. Mueller, M. Stephanov PRC**85** (2012)



- Colored noise in second order viscous fluid dynamics in

K. Murase, T. Hirano, arxiv:1304.3243

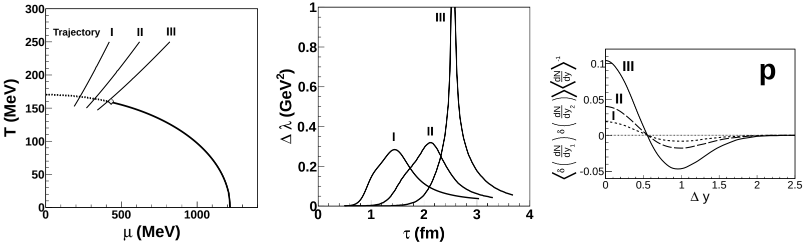
Fluid dynamical fluctuations at a critical point

- Focus on thermal conductivity and set viscosities to zero.
- Use a background equation of state with a CP

$$P = A_4 T^4 + A_2 \mu_B^2 T^2 + A_0 \mu_B^4 - C T^2 - B$$

J. Kapusta PRC**81** (2010)

- Example: boost-invariant Bjorken expansion:



- On the flyby near the CP the thermal conductivity is enhanced ⇒ enhancement of the rapidity correlator of protons.

J. Kapusta, J. Torres-Rincon PRC**86** (2012)

Summary

At CBM...

- The phase diagram can be studied at high net-baryon densities:
  - Fluctuation phenomena at the critical point.
  - Spinodal instabilities in the region of the first-order phase transition.
  - More exotic phases? Color superconductor? Quarkyonic matter?
- What is the equation of state at high net-baryon densities?
- Study rare probes in dense nuclear matter:
  - Electromagnetic probes, dileptons and direct photons $\rightarrow$ chiral symmetry restoration? Hadronic or partonic sources?
  - Charm production and dynamics: what are the underlying production and interaction mechanisms?