The Role of Noise and Dissipation in the Hadronization of the QGP

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QGPTH 2005 - Vienna, August 10-12

Outline

- Introduction and motivation
- Langevin dynamics and dissipation effects
- Improved Langevin description (work in progress)
  - Multiplicative noise
  - Non-Markovian corrections
- Final remarks

Introduction and Motivation

- Depending on the nature of the QCD transition, phase conversion can occur in a number of ways:

  nucleation vs. spinodal decomposition

- Time scales in HIC -> hadronization via explosive decomp.

- Most theoretical attempts: rapid change in effective potential (Polyakov loop model, effective chiral models, etc) -> very fast spinodal decomposition

  ("explosive phase conversion")

- Signatures: e.g., Scavenius, Dumitru & Jackson (2001); Dumitru & Pisarski (2002); Randrup (2004), Rafelski (talk here).

Questions:

- What are the effects of dissipation and noise on the evolution of the order parameter for the chiral transition?
- Can dissipation prevent explosive decomposition in high-energy heavy ion collisions?

Method: Langevin description inspired by microscopic nonequilibrium field theory results (real-time lattice simulations)

Main point: even if the system quickly reaches the unstable (spinodal) region there is still no guarantee that it will explode!

Langevin dynamics and dissipation effects

[ESF & G. Krein (2005)]

Microscopic QFT -> noise and dissipation terms from thermal & quantum fluctuations - self-interaction or coupling to other fields [e.g., Gleiser & Ramos (1994); Rischke (1998)]

$$\partial^2\phi + \Gamma\frac{\partial\phi}{\partial t} + U'_{eff}(\phi) = \xi(\vec{x},t)$$

$\Gamma=\Gamma(T)$: response coefficient ("intensity of dissipation")

$\phi(x,t)$: non-conserved order parameter (σ field for χPT)

Stochastic (noise) force [assumed Gaussian and white (*)]:

$$\langle\xi(\vec{x},t)\rangle = 0 \qquad \langle\xi(\vec{x},t)\xi(\vec{x'},t')\rangle = 2\Gamma T\delta(\vec{x}-\vec{x'})\delta(t-t')$$

Effective theory

- Assumptions: 1st order χ phase trans. (+ exp. system + finite size)

- Framework: coarse-grained Landau-Ginzburg effective potential
[from linear σ model + quarks , N_f=2]
[Csernai & Mishustin (1995); Scavenius & Dumitru (1999); …]

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

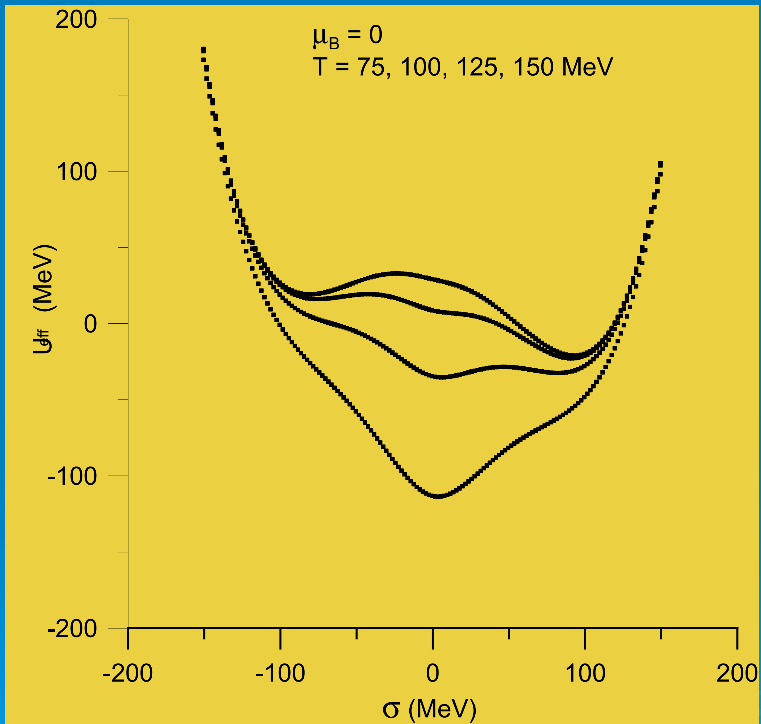
$$U(\sigma,\pi) = \frac{\lambda^2}{4}(\sigma^2 + \pi^2 - v^2)^2 - h_q\,\sigma$$

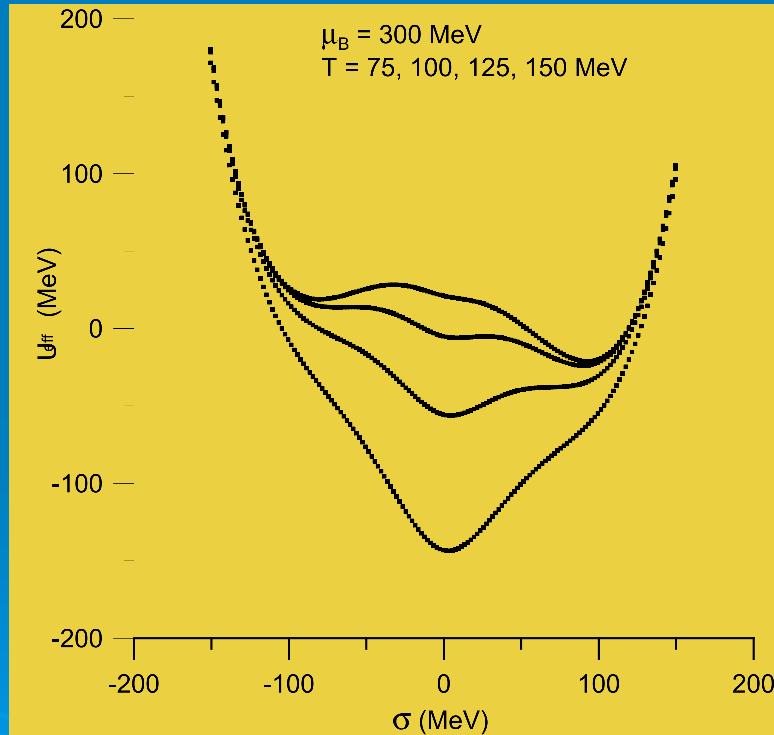
Parameters such that SU(2) ⊗ SU(2) broken in the vacuum,
$\langle\sigma\rangle = f_\pi$, $\langle\pi\rangle = 0$, h_q from PCAC, masses, etc

Integrate over fermions (heat bath for the chiral fields)

⇓

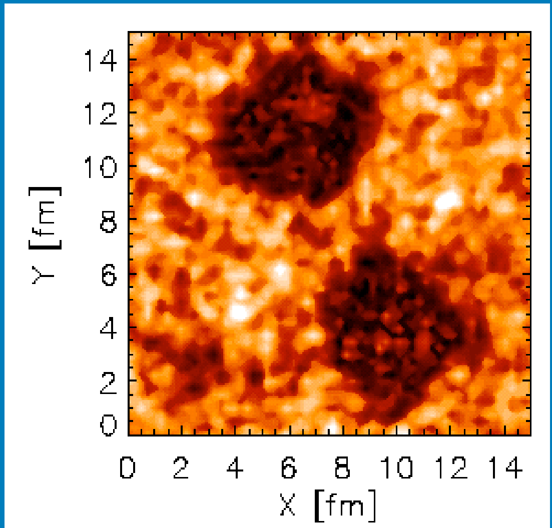
effective potential for $\phi=(\sigma,\pi)$

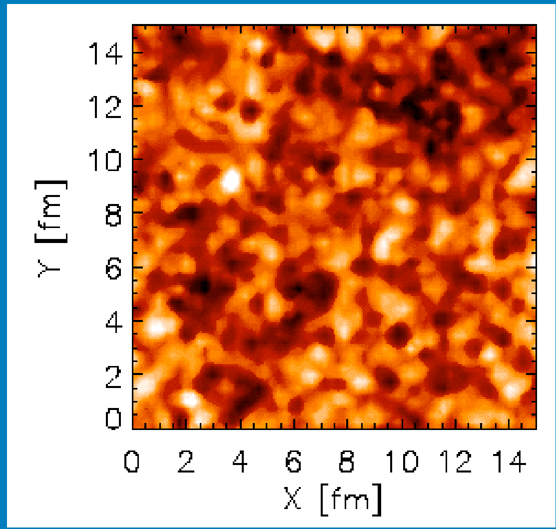




Some questions:

- Time scales: expansion rate, decay rate, domain coarsening – nucleation vs. spinodal decomposition (explosion?)





[Scavenius, Dumitru & Jackson (2001)]

- Length scales: radius of the critical bubble, correlation length, size of the system

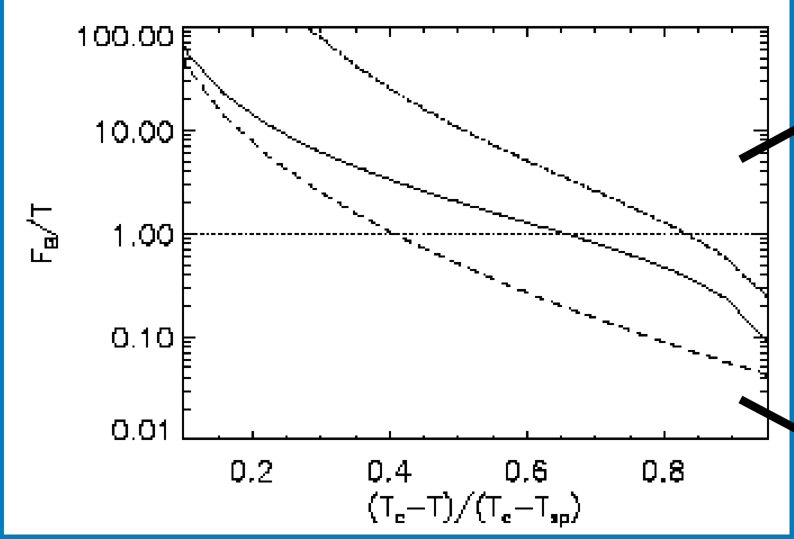
  N.B.: finite size can affect decay rate and late-stage growth

- Inhomogeneities: chiral field inhomogeneities vs. fermionic det

  [ESF, A. Mócsy & B.G. Taketani, work in progress]

Explosive scenario:

Time scales (for nucleation):



[Scavenius, Dumitru, ESF, Lenaghan & Jackson (2001)]

$$\Gamma_{nucl} \sim e^{-F_B/T}$$

Phase conversion is likely to proceed via "explosive" spinodal decomposition!

+ similar results for instabilities from:

Rafelski & Letessier (2000)
Dumitru & Pisarski (2001)
Scavenius, Dumitru & Jackson (2001)
Paech, Stoecker & Dumitru (2003)
Randrup (2004)
...

System would go directly to spinodal and explode, mostly bypassing bubble nucleation... -> Very short time scales

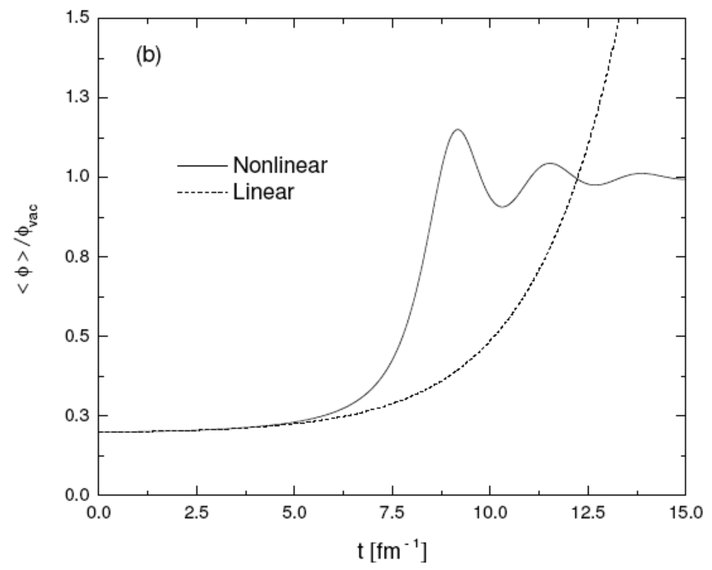
However, shouldn't dissipation effects be relevant?

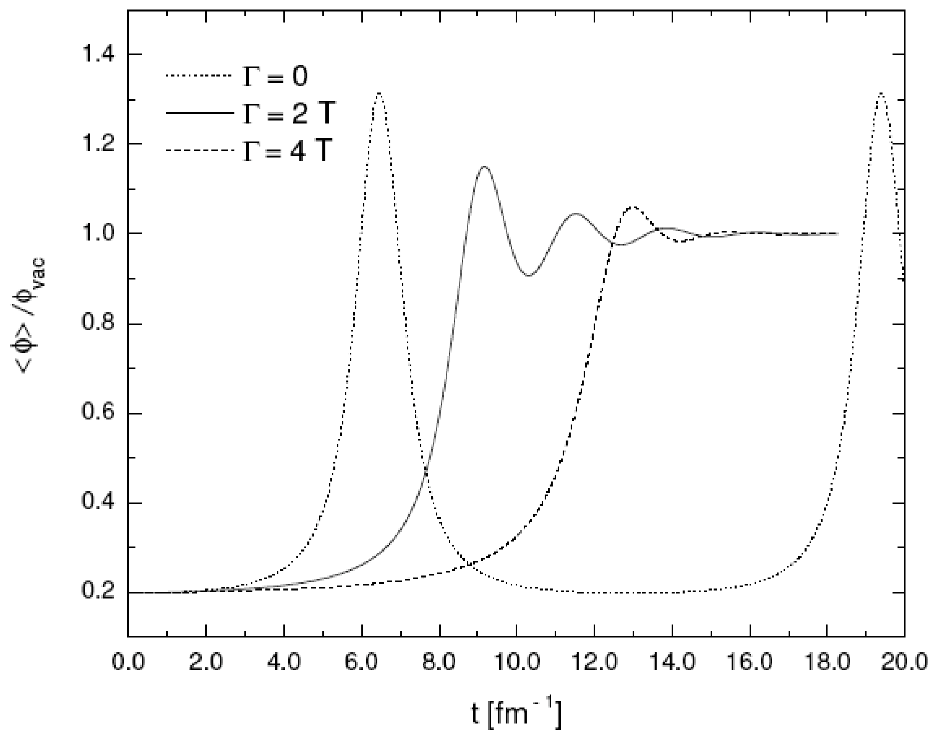
Solving the Langevin dynamics on a lattice:

- Cubic space-like lattice with 64^3 sites under p.b.c.'s
- Semi-implicit finite-difference scheme for time evolution (now using leap-frog)
- FFT for spatial dependence
- Temperature fixed to spinodal
- Lattice spacing: $a = 0.91$ fm
- Average over several realizations

Results:

For t < 5 fm/c the solution for the linearized eqn is very close to the complete one, then is "delayed" -> O(2) potential much shallower than complete V_{eff}





Even for conservative dissipation Γ=2T, the retardation effect for exponential growth is ~ 100% !!

For expansion times ~ 5 fm/c (~ RHIC times scales) there might be not enough time for the onset of the spinodal explosion !

Still missing:

- Finite-size effects: important right from the start in heavy-ion collisions
  [ESF and R. Venugopalan (2004)]

- Expansion of the fluid (more “dissipation”)
  [Scavenius, Dumitru & Jackson (2001)]

- Effects from “Polyakov loop sector”
  [ESF, G. Krein & A.J. Mizher, work in progress]

- Non-Markovian (memory) effects
  [ESF, T. Kodama, G. Krein & L. Palhares, to appear soon]

- More complicated noise and dissipation from QFT
  [ESF, G. Krein & R.O. Ramos, to appear soon]

Improved Langevin description [work in progress]

Multiplicative noise:

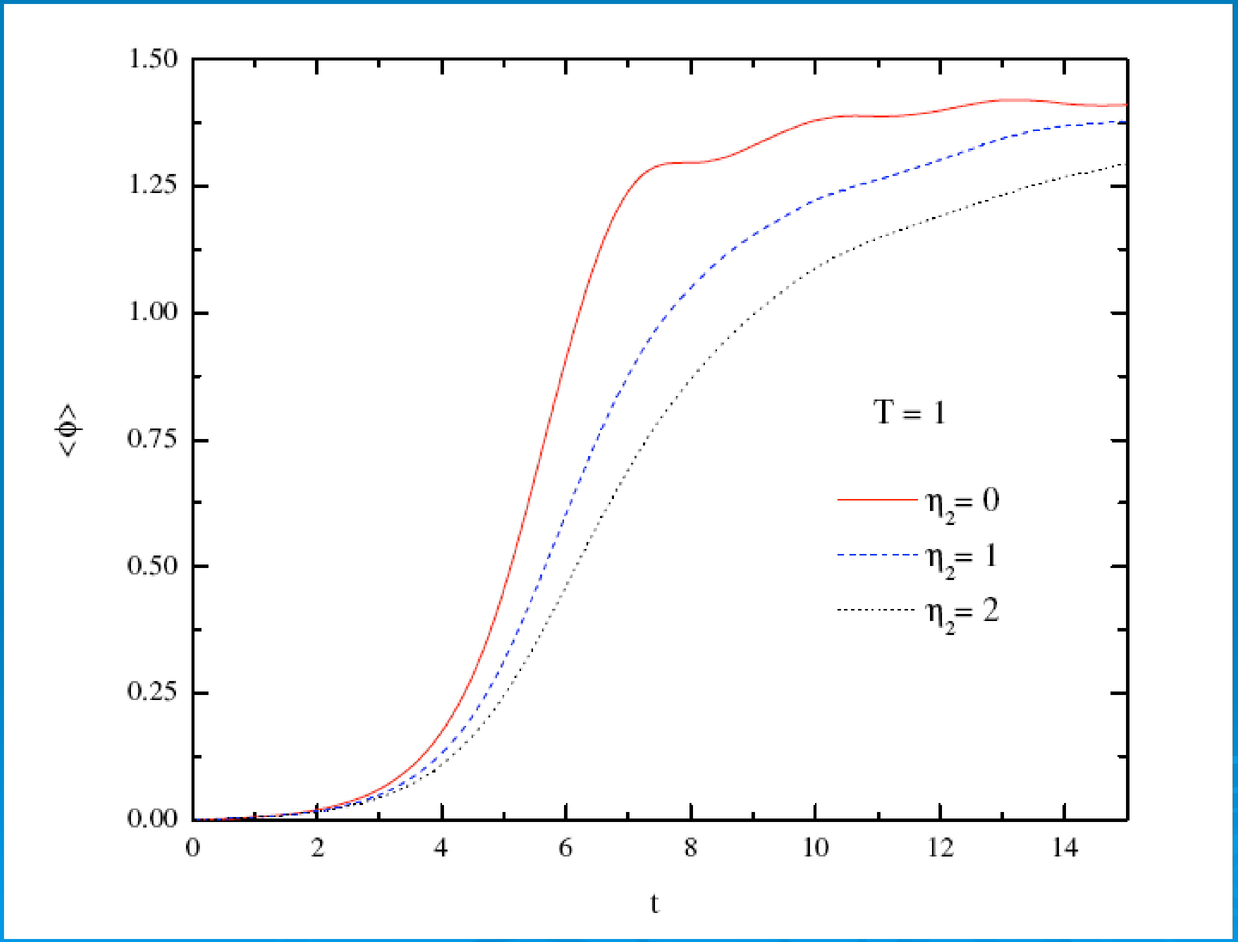
- A more complete QFT description of nonequilibrium dissipative dynamics predicts the existence of additional terms in the Langevin equation.
- In fact, dissipation effects should depend on the local density and, accordingly, the noise should contain a multiplicative term (fluctuation-dissipation theorem).
- Effects of multiplicative noise seem to be rather significant (e.g., in the Kibble-Zurek scenario of defect formation in one spatial dimension)
  [Antunes, Gandra & Rivers (2005)]

$$\partial^2 \phi + [\Gamma_1 + \Gamma_2 \ \phi^2] \frac{\partial \phi}{\partial t} + V'(\phi) = \xi_1(\vec{x}, t) + \xi_2(\vec{x}, t) \ \phi$$

$$\langle \xi_a(\vec{x}, t) \xi_a(\vec{x'}, t') \rangle = 2 \, \Gamma_a T \delta(\vec{x} - \vec{x'}) \delta(t - t')$$

Preliminary results:

- For degenerate double-well potential at given T
- Still in arbitrary units
- Thermalization is clearly retarded!



Non-Markovian corrections:

- Linear response nonequilibrium QFT provides complicated memory kernels associated with dissipation instead of a simple Markovian term. The latter corresponds to a drastic simplification of the dissipation kernel.
- We obtain a systematic expansion in which higher-order terms correspond to more non-local contributions.
- We start with the much simpler case of dissipative metastable quantum mechanics, where the memory kernel has its origin in the Feynman influence functional of the heat bath, and derive a (derivative) expansion for non-local corrections.

  (approximations and important scales under control)
- In the case of field theory, we phenomenologically generalize our results for quantum mechanics, obtaining a Langevin equation that incorporates the first (radiation) non-local correction.

Final remarks

- Effects of dissipation seem to be important in the process of hadronization of the QGP. In particular, it could dramatically modify the *explosive behavior*.

- Multiplicative noise (and density-dependent dissipation) do play a role, and retard even more thermalization.

- Non-Markovian corrections can, in principle, be incorporated systematically in the Langevin evolution (simpler structure).

- Still to include: chiral + Polyakov loop effective theory; expansion; finite-size effects; more realistic microscopic treatment of dissipation; connection to hydro evolution.