Domain growth and Fluctuations during Quenched Transition to QGP

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Motivation

: To study about non-trivial Z(3) vacuum structure, Z(3) domains and their consequences in QGP phase.

Z(3) CENTER SYMMETRY OF QCD AND POLYAKOV LOOP ORDER PARAMETER

Partition function for a system of gluons in terms of path integral formalism

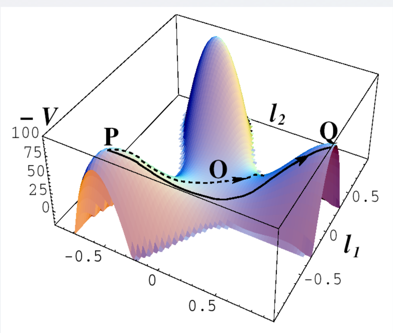
$$Z = \int D[A]\exp(-S[A]) \qquad S[A] = \int_0^\beta d\tau \int d^3x\,(\;TrF^{\mu\nu}F_{\mu\nu}\;)$$

- Gauge fields obey periodic boundary condition $A_\mu(x,\beta) = A_\mu(x,0)$
- Action is invariant under gauge transformation $A_\mu \to U\left(A_\mu + i\partial_\mu\right)U^{-1}$
- Gauge transformations are also periodic $U(x,\beta) = U(x,0)$
- Extra symmetry of the theory $U(x,\beta) = ZU(x,0)$
- Where Z(N) is the centre group of SU(N). (ZU = UZ)

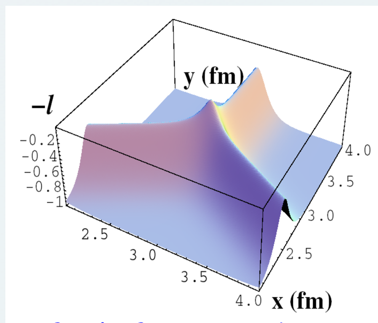
$$Z = e^{2\pi i n/N} \quad n = 0, 1, 2 \ldots\ldots N-1$$

- Finite temperature SU(N) gauge theory has Z(N) symmetry as the Euclidean action is invariant under Z(N) transformation.
- Z(3) symmetry is restored below T_c in the confined phase and spontaneously broken in the deconfined phase giving rise to 3 Z(3) vacua.
- Polyakov Loop Order Parameter : $l(x) = \frac{1}{N}Tr(P\exp(ig\int_0^\beta A_0(x,\tau)d\tau))$ $\qquad \langle l(x)\rangle \sim e^{-\beta\Delta F}$
- ΔF : change in free energy of the pure glue theory due to addition of an isolated quark
- Under Z(3) symmetry : $l(x) \to Z\,l(x)$
- In confined phase, Z(3) symmetry is restored corresponding to $\langle l(x)\rangle = 0$
- In deconfined phase, Z(3) symmetry is spontaneously broken corresponding to finite $\langle l(x)\rangle$

Domain Wall and String



Plot of inverted potential –V (l) in (l_1,l_2) plane



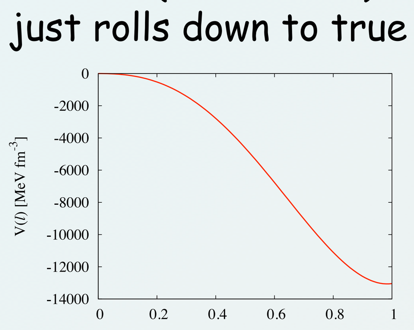
Surface plot of -l for two-dimensional lattice in x-y plane. String (l =0) is attached to the three interfaces.

- Domain walls are the solution while going from one vacuum to another vacuum.The solution (solid curve) can never go through origin i.e l is never zero inside the wall. The intersection of three different interfaces gives rise to string like structure.

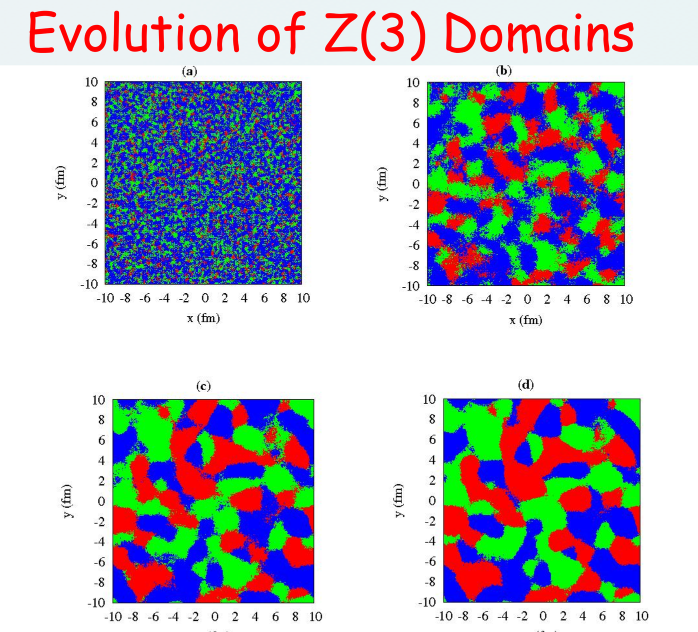
Domain Growth during Quenched transition to QGP

- The phase transition can be viewed as a quench due to the early thermalization to a QGP state.
- The barrier between true vacuum and false vacuum (l = 0) vanishes at temperature above 250 MeV.
- Quench the system from low temperature to high temperature (~ 400 MeV) in very short time (less than 1 fm), but the field still sits *around* l = 0 and just rolls down to true vacuum after that. Z(3) domains form and coarsens.

Plot of V(l) in θ = 0 direction for T = 400MeV
No barrier between true and false vacuum.



Evolution of Z(3) Domains



Red → θ =0 vacuum
Green → θ =2π/3
Blue → θ =4π/3

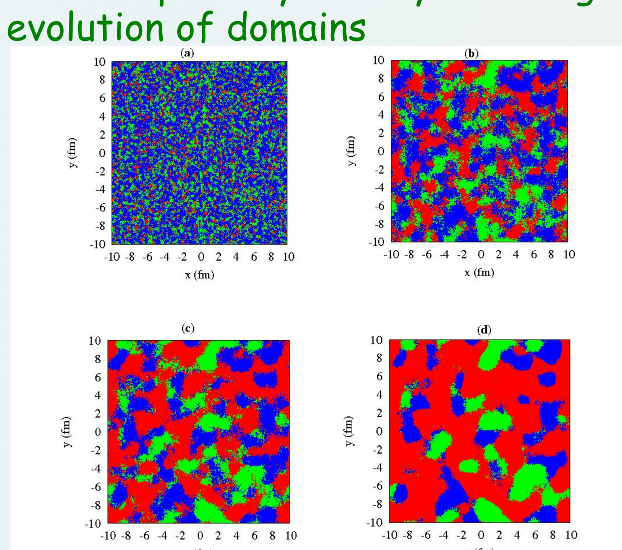
- At τ = 1.2, 2.0, 2.4 and 2.8 fm respectively. Here Temp are 376, 317, 298 and 283 MeV and corresponding magnitudes of l are 0.04, 0.08, 0.2 and 0.4 respectively.
- Small η/s due to small size of domains (M Asakawa et al,PRL 110, 202301, 2013)

Small vs large explicit symmetry breaking

Small explicit symmetry breaking : Initial patch of l shifts towards θ =0 vacuum, still overlapping with the initial equilibrium value of l. l rolls down to every vacuum, but θ = 0 vacuum is more dominant.

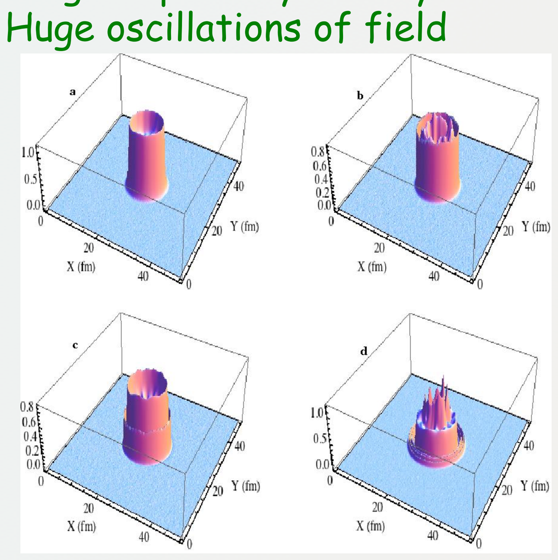
- Large explicit symmetry breaking : l shifts more towards θ = 0 vacuum, so initial patch rolls down entirely θ = 0 direction. No formation of Z(3) domains or interfaces or strings.
- However, we see huge oscillations of the field before reaching to true vacuum.
- This may affect elliptic flow anisotropy.

Small explicit symmetry breaking : evolution of domains



θ = 0 domain is dominant compared to other 2 domains
At τ = 1.2,1.6,2.0 and 2.4 fm (temp 376, 342, 317 and 298 MeV) respectively.

Large explicit symmetry breaking : Huge oscillations of field



Field rolls down everywhere towards θ = 0 vacuum. Plots are at τ = 2.6, 3.6, 4.4 and 6.2 fm respectively. Huge oscillations of field will affect flow anisotropy.

Conclusion

- During quench, Z(3) domains are produced and coarsens in time with small explicit symmetry breaking.
- Due to large explicit symmetry breaking, field roll down to true vacuum only and no Z(3) domains appear.
- There are huge oscillations of the field and it would affect the flow anisotropy.
- Huge oscillations in flow anisotropy in quench case compared to equilibrium case.
So, effect of quench should be taken care of in hydrodynamic simulations.

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Effective potential based on Polyakov loop

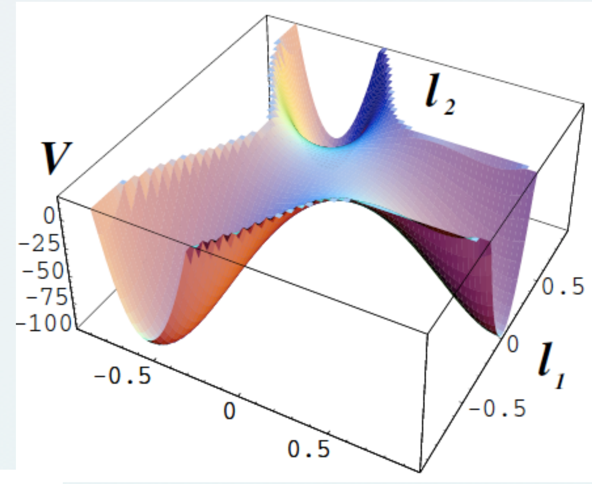
- Effective Lagrangian density $L = \frac{N}{g^2}|\partial_\mu l|^2 T^2 - V(l)$ $\quad V(l) = \left(-\frac{b_2}{2}|l|^2 - \frac{b_3}{6}\left(l^3 + l^{*3}\right) + \frac{1}{4}|l|^4\right) b_4 T^4$
- Normalized such that $l_0 \to 1$ as $T \to \infty$. With $l = |l|e^{i\theta}$ b_3 gives $\cos(3\theta)$ leading to Z(3) degenerate vacuum structure.
- Coefficients b_2, b_3, b_4 are chosen to fit lattice results for energy density and pressure in pure SU(3) gauge theory.

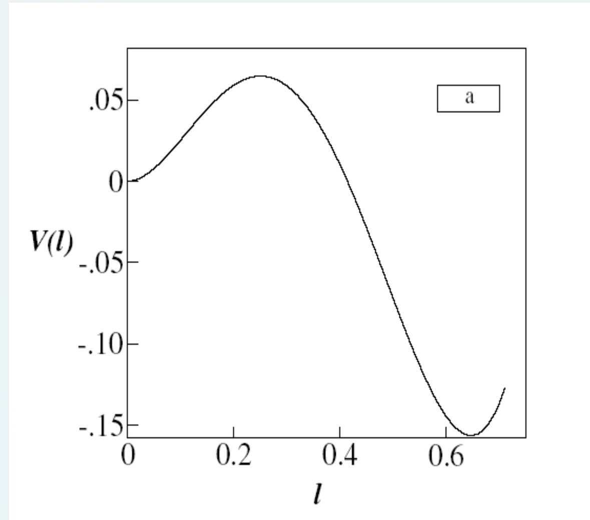
$$b_2(r) = \left(1 - \frac{1.11}{r}\right)\left(1 + \frac{0.265}{r}\right)^2\left(1 + \frac{0.300}{r}\right)^3 - 0.487$$

b_3 = 2.0, b_4 = 0.6
$r = T/T_c$

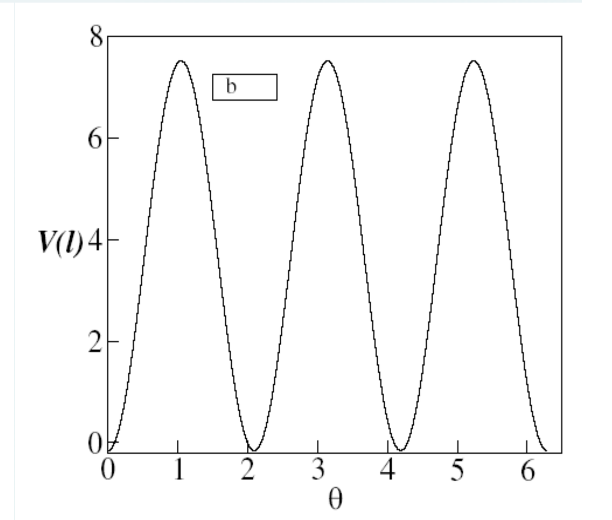
R Pisarski, Phys Rev D,62,111501(2000)

- This potential represents a weakly first order phase transition with Tc =182 MeV.
- There are 3 degenerate vacua corresponding to the phases at θ =0, 2π/3, 4π/3.





Plot of V(*l*) in θ = 0 direction



Plot of V(*l*) w.r.t θ

- Plots of V(l) (in units of Tc^4) for T=185 MeV.
- Barrier vanishes at T = 250 MeV

Numerical Techniques:

- We carry out 2+1 dimensional simulation of C-D phase transition as a quench.
- We use 2000X2000 lattice (physical size 20 fm).
- Quench the system from low temp to 400 MeV in 1 fm time and then the temp decreases due to longitudinal expansion.

$$T(\tau) = T(\tau_0)\left(\frac{\tau_0}{\tau}\right)^{1/3}$$

- Initial field configuration constitutes a small patch around l = 0.
- Field evolution is numerically implemented by a stabilized Leapfrog algorithm of 2nd order accuracy both in space and time.

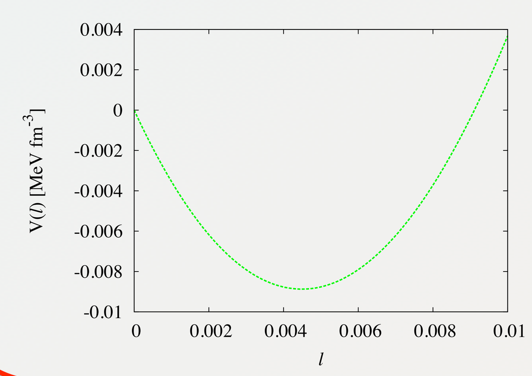
$$\ddot{l}_i + \frac{\dot{l}_i}{\tau} - \frac{\partial^2 l_i}{\partial x^2} - \frac{\partial^2 l_i}{\partial y^2} = \frac{-\partial V(l)}{\partial l_i}, \qquad i = 1,2 \quad \text{with } \dot{l} = 0 \text{ at } \tau = 0$$

Effect of Quarks

- Z(N) symmetry is explicitly broken giving rise to one true vacuum and two meta stable vacua in presence of quarks.
- The effect of explicit symmetry breaking is realized by adding a linear term in the effective potential.

$$V(l) = \left(-b_1\left(\frac{l + l^*}{2}\right) - \frac{b_2}{2}|l|^2 - \frac{b_3}{6}\left(l^3 + l^{*3}\right) + \frac{1}{4}|l|^4\right) b_4 T^4$$

Shift of l = 0 vacuum



The false vacuum shifts by a small amount ε= 0.0044
For b_1= 0.005 and T=190 MeV

Plot of V(l) in θ = 0 direction

Modeling of transverse expansion

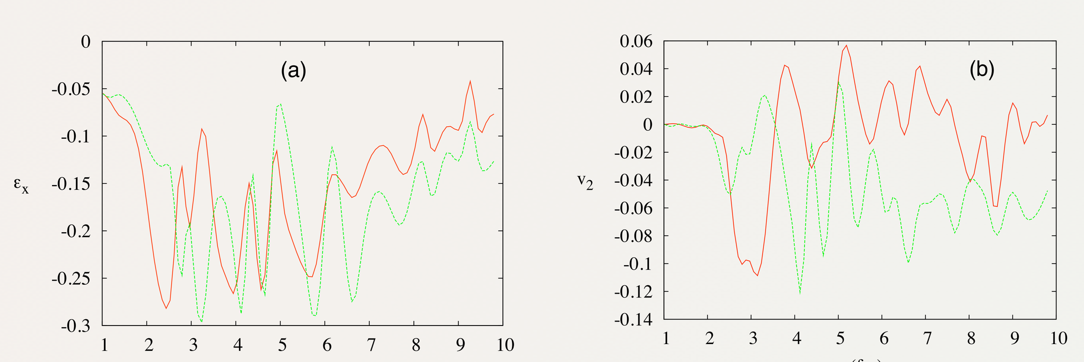
- A study of momentum anisotropy development with (quench) and without (equilibrium) the presence of large oscillations of the order parameter field.
- Wood Saxon temp profile with X and Y elliptical shape for non central collision.
- Transverse size increases with uniform acceleration of 0.015c per fm.
- This expanding background of temp profile represents expanding QGP in which the evolution of the order parameter field is studied.
- Interpretation of the simulation is that we study long wavelength modes of l which are coupled to a background of short wavelength modes which are in thermal equilibrium.
- In case of equilibrium, the field sits at the vacuum expectation value.

Elliptic flow anisotropy

Spatial eccentricity $\varepsilon_x = \frac{\int \rho(y^2 - x^2)dxdy}{\int \rho(y^2 + x^2)dxdy}$

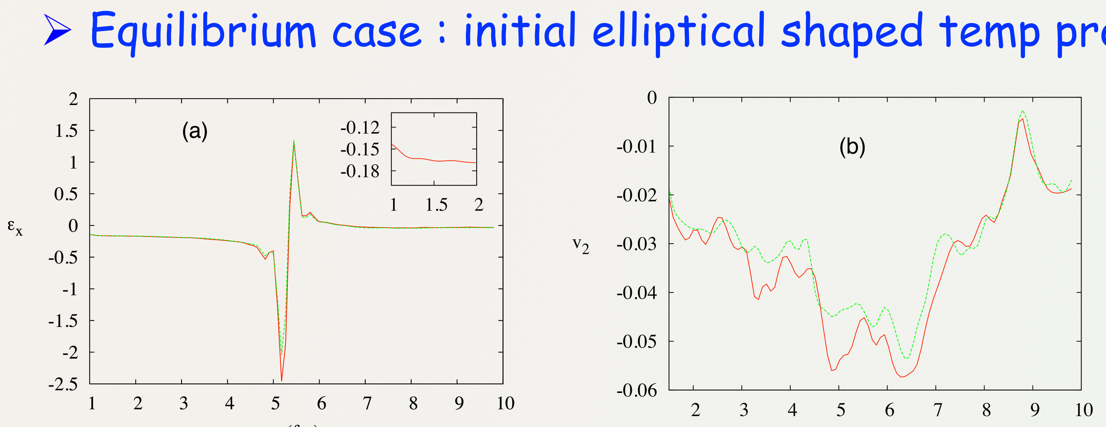
- Calculate T_{0x} and T_{0y} components of energy momentum tensor.
- Calculate θ = $\tan^{-1}$ (T_{0y} /T_{0x}) and Net momentum density=Sqrt(T_{0x}^2 +T_{0y}^2)
- Now calculate elliptic flow coefficient by Fourier expanding net momentum density w.r.t θ.

➢ Quench case : initial elliptical shaped temp profile with eccentricity 0.5



Corresponds to two different realizations of the initial random field configuration.

➢ Equilibrium case : initial elliptical shaped temp profile with eccentricity 0.5



Initial value of ε_x= -0.14