Propagation of Heavy Quarks in QGP in the Presence of Spatially and Temporally Varying Potential

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Outline :

1. Heavy quark propagation through QGP: Record on its trajectory

2. QGP in heavy-ion collisions not a smooth region, presence of large fluctuations and inhomogeneous regions

3. Heavy quarks and quarkonia most sensitive to this: Not ultra-relativistic, so strongly affected by changing potential

4. Rapid early thermalization provides sharp temporal variation of environment: violation of adiabaticity for quarkonia evolution
   (talk of Partha Bagchi later on in this workshop)

5. Focus on specific inhomogeneities: Center domains and Domain walls, effects on heavy quark propagation

6. Heavy quark propagation through fluctuating regions: imprints on adiabaticity due to critical slowing down in the critical regime

7. Summary: Using heavy quarks to probe fluctuations in QGP

Heavy quark propagation through QGP:

Heavy quarks are produced during early hard collisions, propagate through the QGP

Record of the entire propagation imprinted on the final state

Energy loss during propagation: sensitive to energy density of hot and dense medium,
Langevin-based transport models

Mostly such approaches consider average effects of thermal medium.

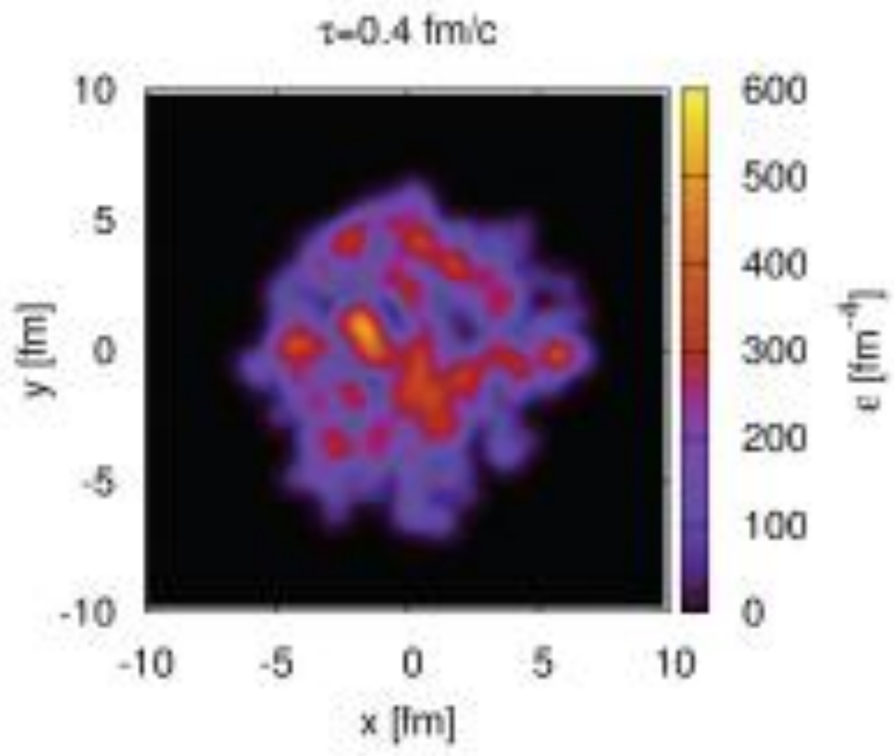
Not suitable for describing effects of large isolated fluctuations, localized in space and/or time.

QGP contains such inhomogeneous regions, also, in heavy-ion collisions there are large scale initial state density fluctuations

Non-trivial effects on propagation of heavy quarks

QGP in heavy-ion collisions not a smooth region :

Initial state fluctuations are always present in QGP produced in Heavy-ion collisions. (Blaizot's talk, Matter at extreme conditions, 2014)



Note: Large fluctuations in energy density, hence temperature
Heavy quark propagates through all this

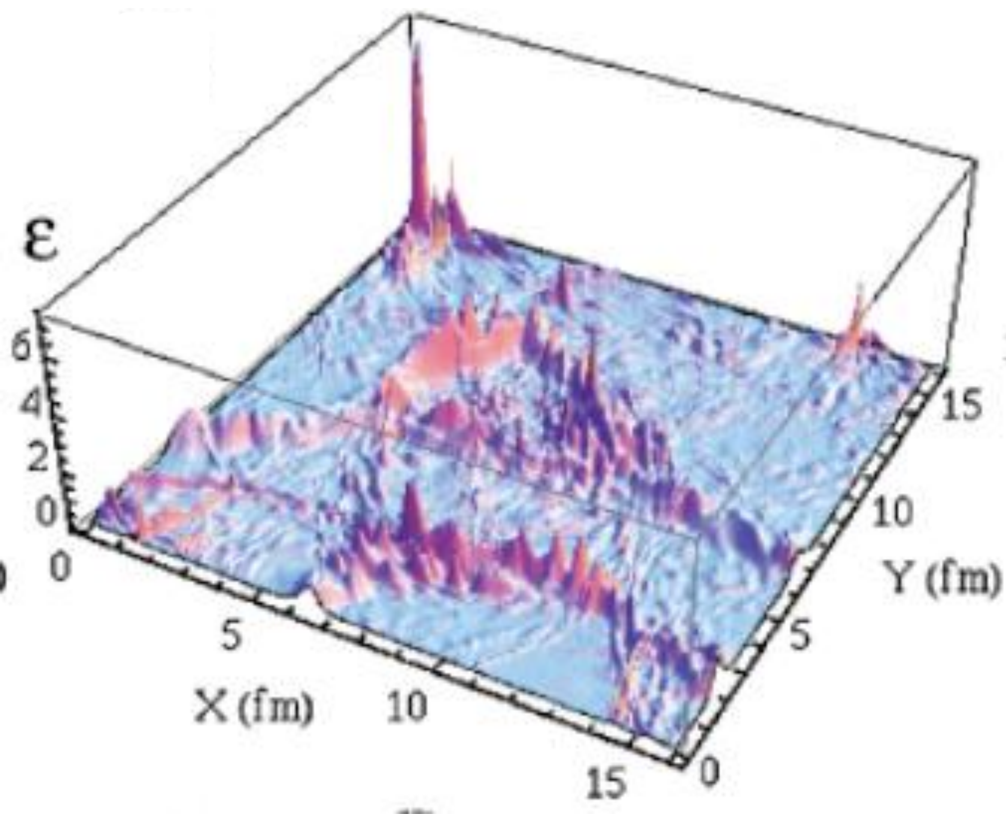
Can get significantly affected

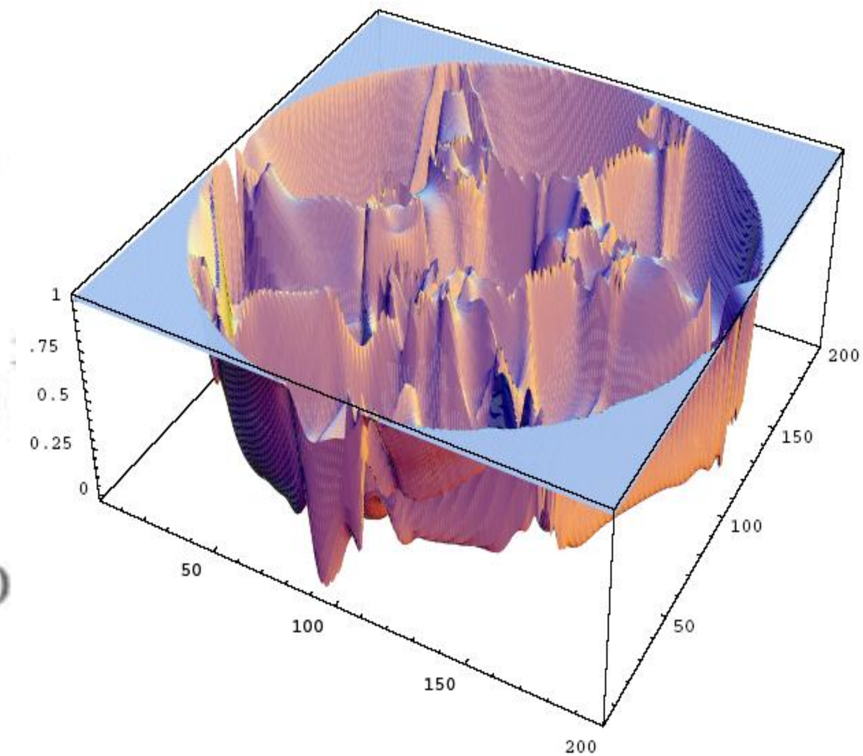
Other possibilities: Center Domains and domain walls

Z(3) center symmetry is spontaneously broken in the QGP phase
This leads to formation of Z(3) center domains and associated Z(3) center domain walls.

Heavy quarks scatter significantly from these

Simulation results modeling formation of Z(3) center domain walls
(Gupta, Mohapatra, AMS, Tiwari, PRD, 82, 074020 (2010)





Briefly: spontaneous breaking of Z(3) symmetry in the QGP phase

For the confinement-deconfinement phase transition in a SU(N) gauge theory, the Polyakov Loop Order Parameter is defined as:

$$l(x) = \tfrac{1}{N} tr\left(P \exp\left[ig \int_0^\beta A_0(x,\tau) d\tau \right]\right)$$

Here, P denotes path ordering, g is the coupling, $\beta = 1/T$, with T being the temperature, $A_0(x,\tau)$ is the time component of the vector potential at spatial position x and Euclidean time τ.

Under a global Z(N) transformation, $l(x)$ transforms as:

$$l(x) \to \exp\left(\frac{2\pi i n}{N}\right) l(x), \qquad n = 0,1,\ldots(N-1)$$

The expectation value of the Polyakov loop l_0 is related to the Free energy F of a test quark

$$l_0 \sim \exp(-F/ T)$$

l_0 is non-zero in the QGP phase corresponding to finite energy of quark, and is zero in the confining phase.

Thus, it provides an order parameter for the QCD transition, (with N = 3)

As l_0 transforms non-trivially under the Z(3) symmetry, its non-zero value breaks the Z(3) symmetry spontaneously in the QGP phase. The symmetry is restored in the confining phase.

Thus, there are Z(3) domain walls in the QGP phase

For numerical estimates, we use the following Lagrangian for $l(x)$, proposed by Pisarski: (our results do not depend crucially on this choice of parameterization, same results for potential due to Fukushima)

$$L = \frac{N}{g^2} |\partial_\mu l|^2 T^2 - V(l)$$

$$V(l) = \left(-\frac{a}{2} |l|^2 - \frac{b}{6}(l^3 + l^{*3}) + \frac{1}{4} |l|^4 \right) cT^4$$

Here, $V(l)$ is the effective potential. Values of various parameters are fixed by making correspondence with Lattice results: *b = 2.0, c = 0.6061* x 47.5/16,
a(x) = (1-1.11/x)(1+0.265/x)^2 (1+0.300/x)^3 – 0.487
where, $x = T/T_c$

With these parameters, $T_c \sim 182$ MeV.

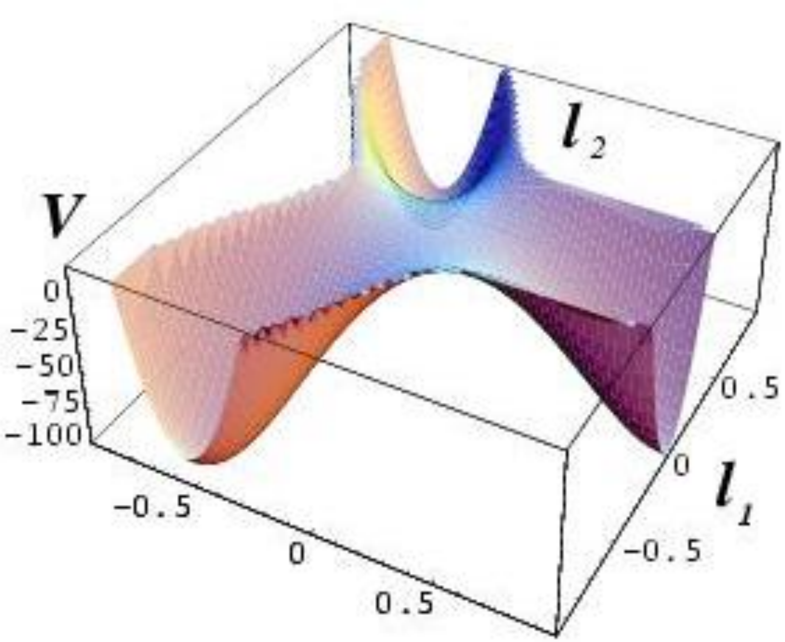
With suitable re-scaling, $l_0 \rightarrow 1, \ \ as \ \ T \rightarrow \infty$

Note: b term gives $\cos 3\theta$, leading to Z(3) vacuum structure

Interestingly, Z(3) effective potential, hence the resulting Z(3) domain structure, very similar to the axionic strings in the universe proposed to solve strong CP problem in QCD

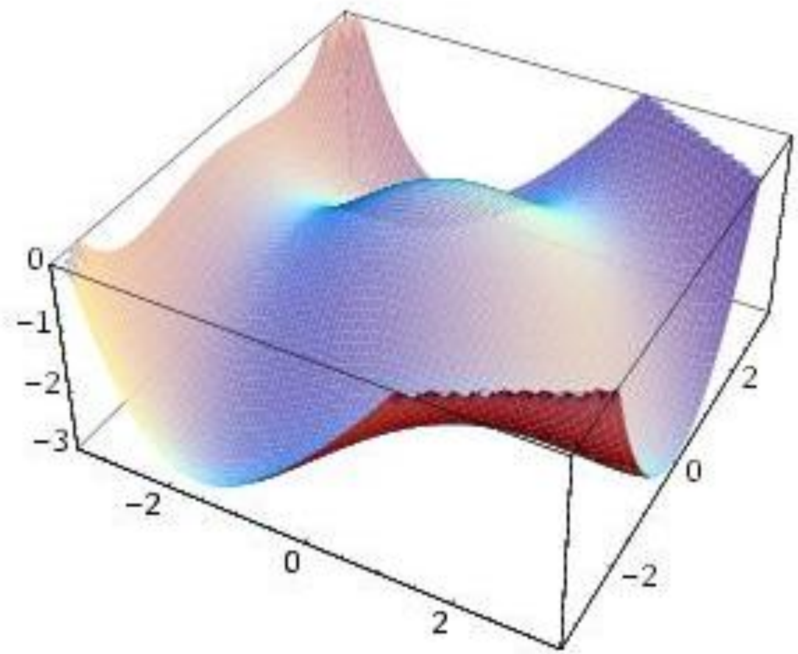
(The only difference is relative heights of barrier between Z(3) vacua)

Polyakov loop case



(a)

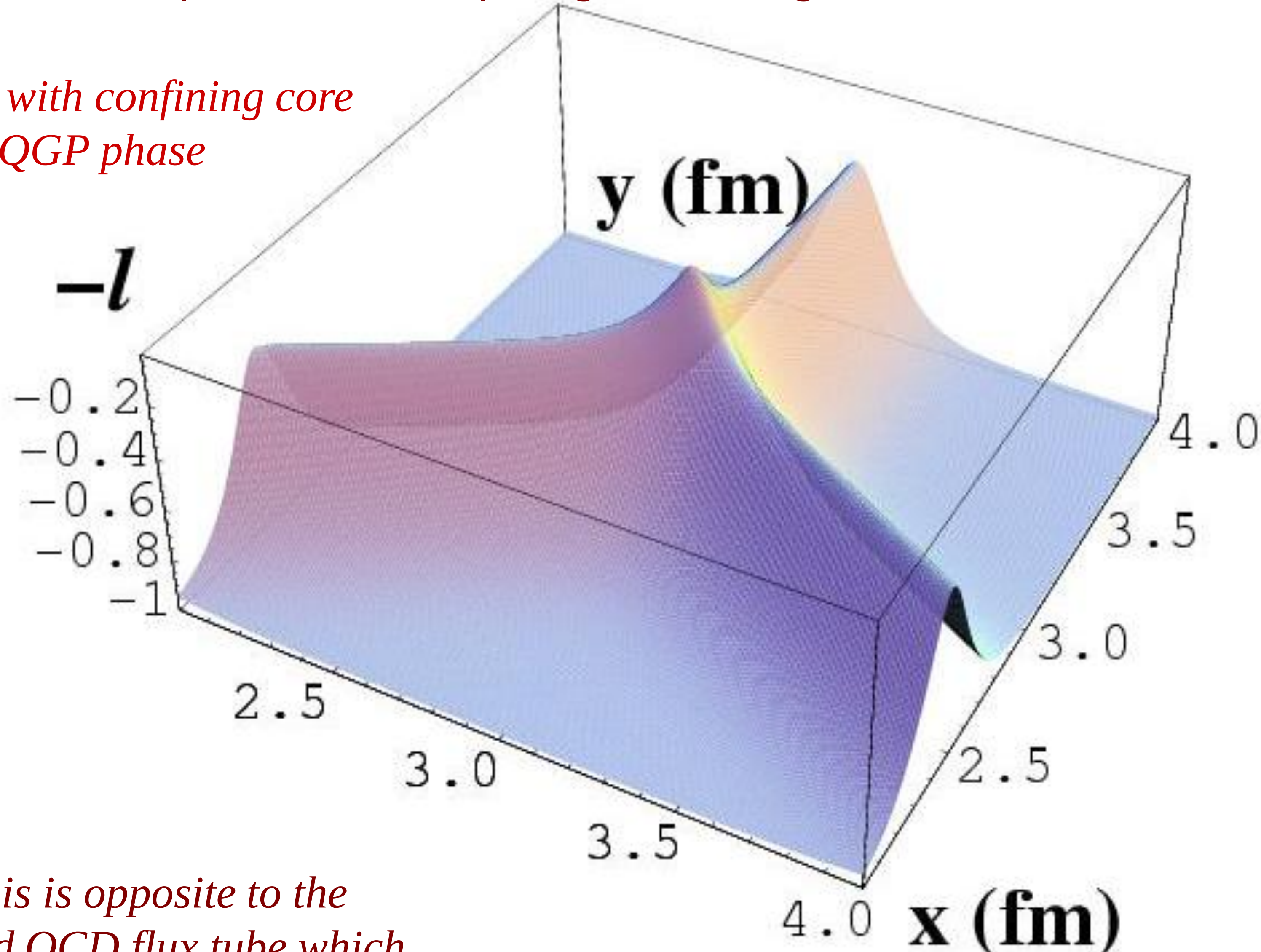
Axionic string case



(b)

Profiles of Z(3) walls: Importantly, junction of the three walls corresponds to a topological string.

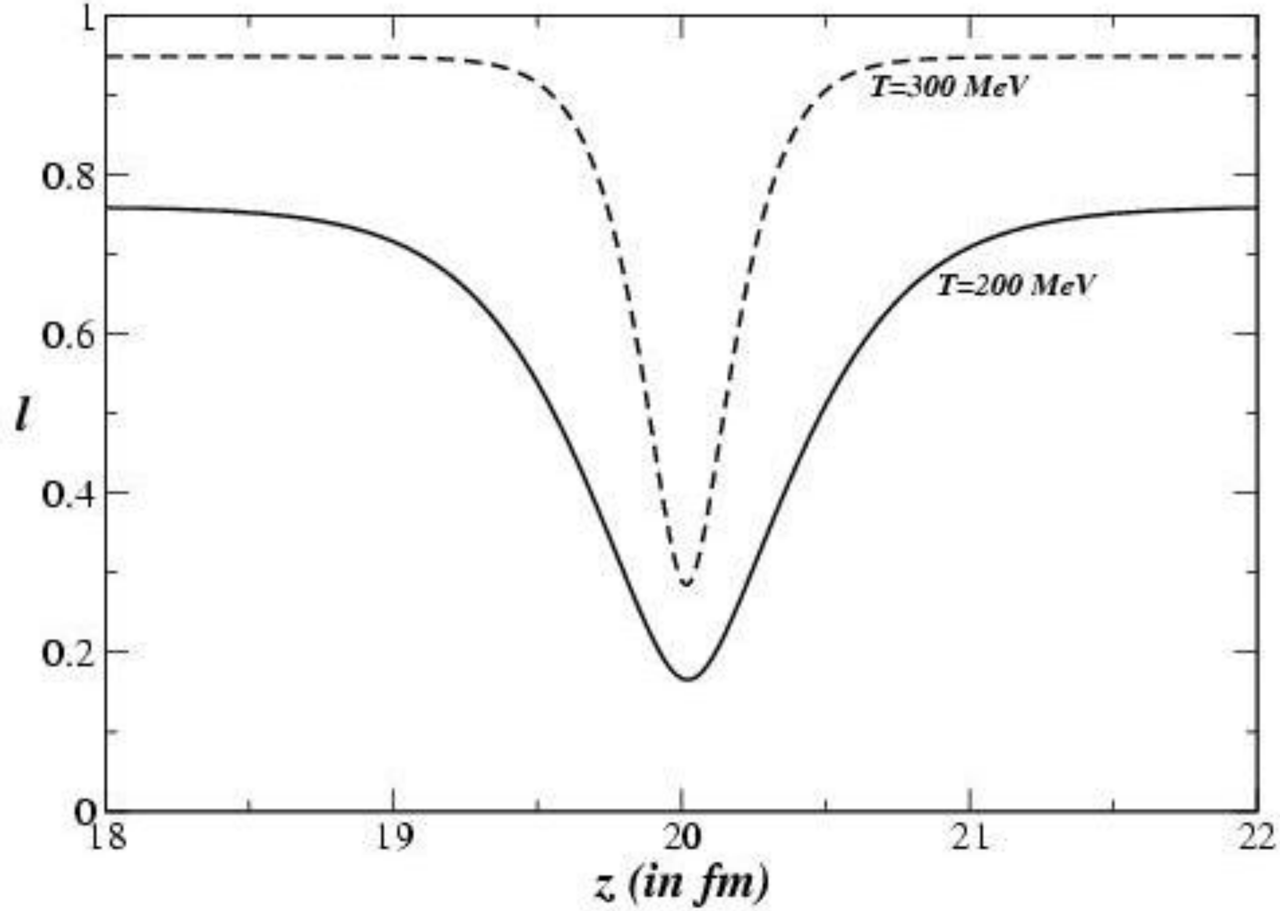
String with confining core in the QGP phase



Note: this is opposite to the standard QCD flux tube which exists in the confining phase.

Domain wall profile, Note: $|l|$ small, but non-zero inside the wall.

Surface tension = 7 , 2.61 , 0.34 GeV/ fm^2
for T = 400, 300, 200 MeV, close to analytical estimates for high T : $\sigma \sim \frac{8\pi^2}{9g} T^3$ Bhattacharya, …



Important to note: *l(x)* vanishes in the confined phase. Thus, its small value in the center of domain wall indicates closeness to the confined phase, while away from the wall, well defined deconfined phase exists.

Formation of Z(3) Walls and Strings

Note: These Z(3) walls, and the strings, exist in the QGP phase, at temperatures above Tc.

Here we have a situation where Z(3) symmetry is broken spontaneously at high temperatures, and is restored below Tc.

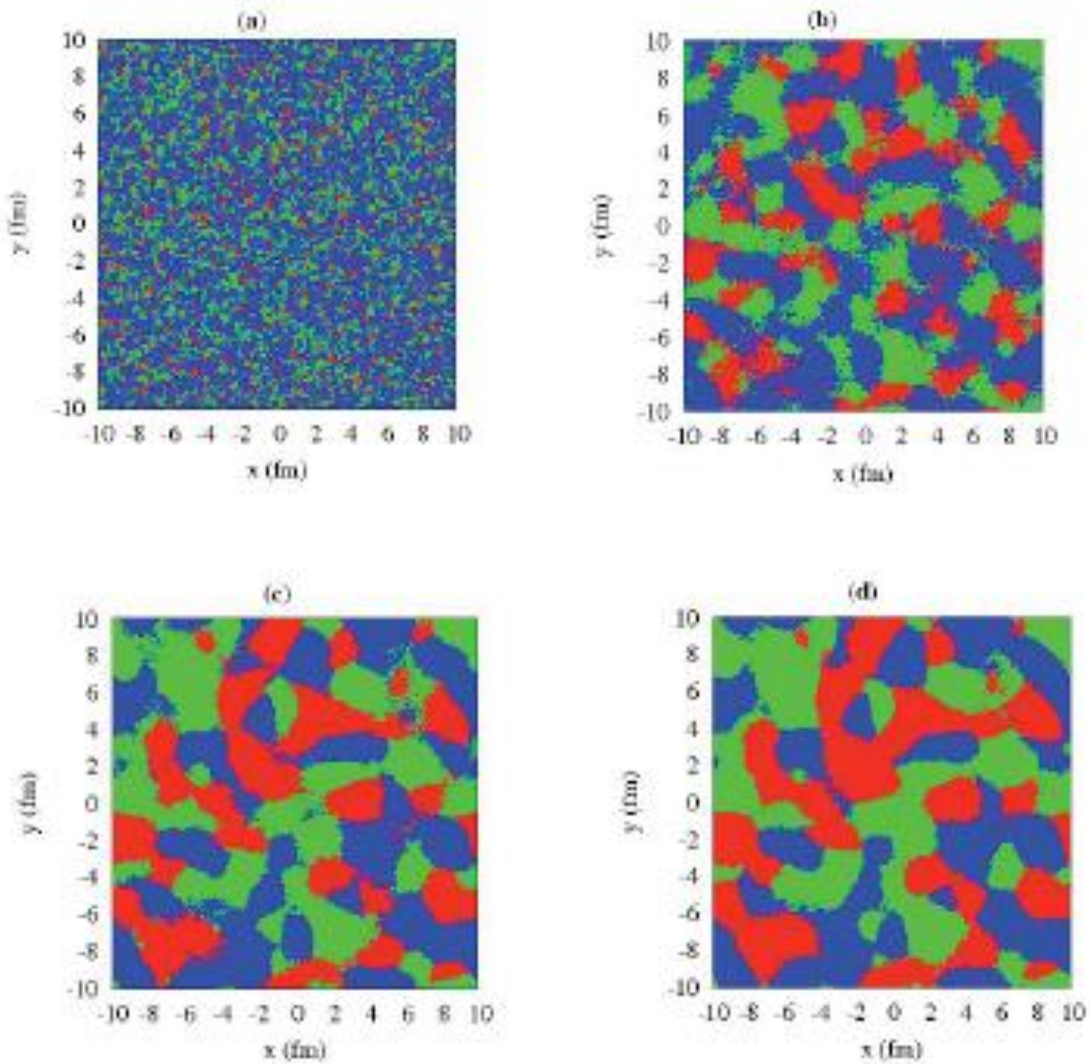
This is opposite to the standard case, where strings etc. form when system cools below Tc to symmetry broken phase.

For QCD, Z(3) walls and string will be pre-existing in the QGP phase , and they will melt away below Tc.

For heavy-ion collisions, they will form when system thermalizes at the initial stage.

(this raises serious questions about formation of such objects in the universe where temperature was always higher than Tc during early stages.)

Evolution of Z(3) Domains



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.

Mohapatra and AMS, PRC 88, 044901 (2013)

Z(3) Center domains and domain walls discussed in Literature :

1) Scattering of partons from Z(3) walls may account for small viscosity Asakawa, Bass, and Muller, arXiv: 1208.2426

(Though, very small domains used here, not supported by our simulation results)

CP violation associated with center domain walls (due to A_0 field in the definition of l(x)) leads to quarks or antiquark Bound states on the wall:

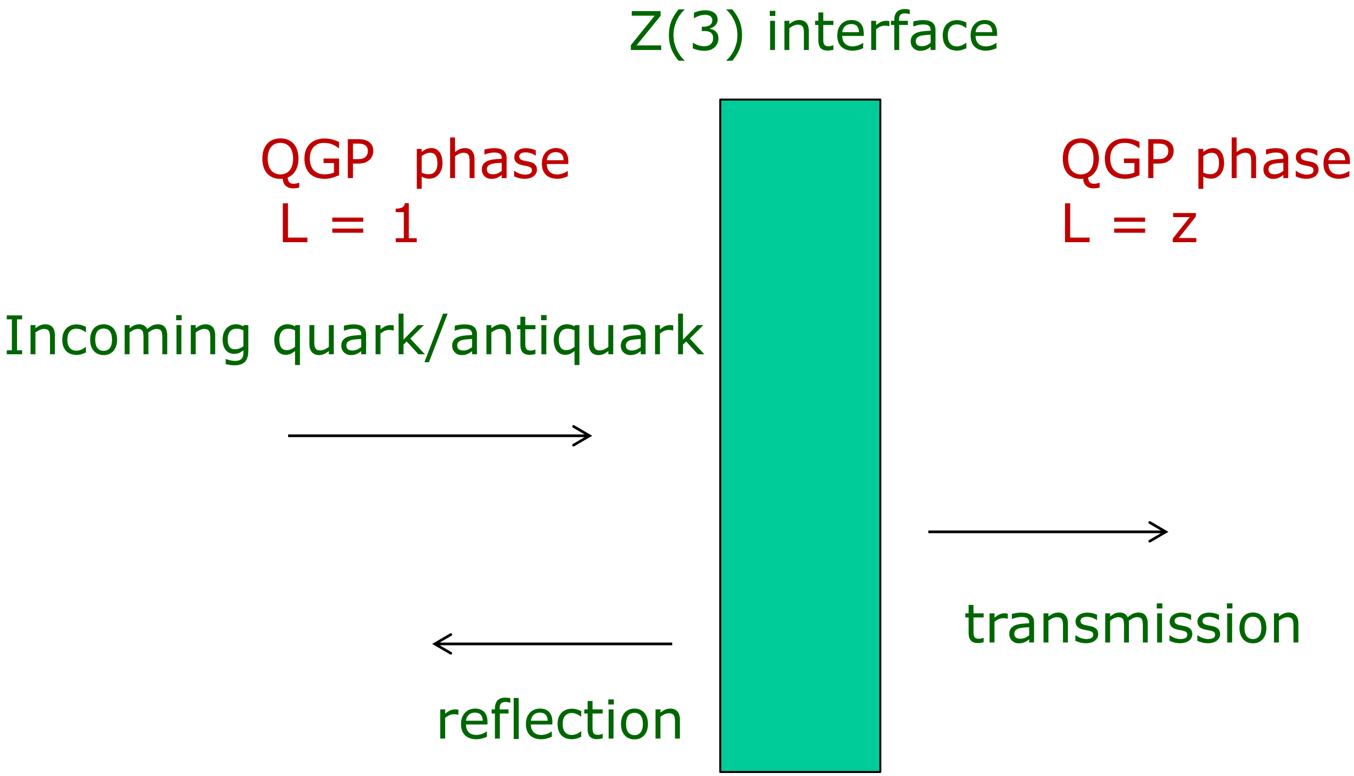
2) For standard model: Korthals Altes and Watson, PRL 75, 2799 (1995)
3) In QGP: Korthals Altes (1992)

Mostly, these discussions focus on light quarks.

We consider scattering of quarks from such structures
Strong effects for heavy quarks

Light quarks ultra-relativistic, so mostly unaffected by such structures (though interesting new possibilities remain to be explored for light quarks also).

Simple picture of quark scattering from a Z(3) interface



Z(3) interface provides a potential for the scattering of quark

Its effect is strongest for non-relativistic case, thus heavy quarks with relatively low momentum most affected by such structures

*T*wo different ways in which quarks can scatter from these Z(3) walls.

1) As the magnitude of the Polyakov loop (l(x)) varies across the wall, it should lead to variation of constituent quark mass across the wall (since l(x) is the order parameter for confinement-deconfinement transition).

   Thus the wall will provide a potential barrier for quark s leading to non-zero reflection.

2) Recall: l(x) is defined in terms of color potential A_0. Thus spatially varying l(x) will lead to color electric field leading to scattering of quarks and antiquarks.

   Note: for possibility (2), wall configuration breaks CP spontaneously leading to very different reflection coefficients for quarks and antiquarks.

First Consider : scattering from Z(3) walls with mass modification

we model the effective quark mass as:

$$m(x) = m_q + m_0 (l_0 - |l(x)|)$$

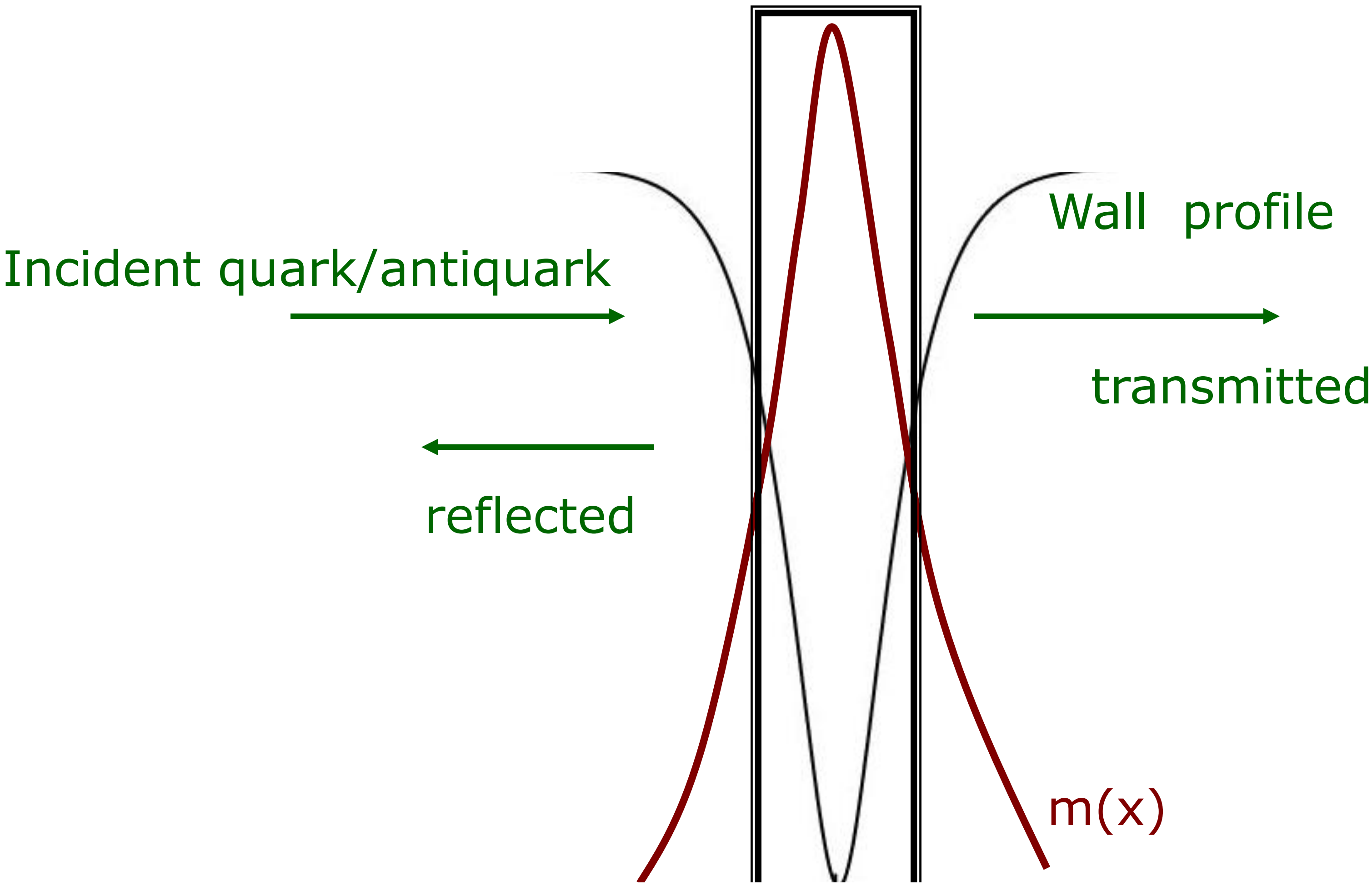
Here, m_q is the current quark mass as appropriate for QGP phase with $|l(x)| = l_0$, and $m_0 \sim 300$ MeV is taken as the constituent mass contribution for the quark

Thus : quark mass varies if $l(x)$ varies spatially, $m(x)$ is small when $l(x) = l_0$, and becomes large when $l(x)$ becomes small, as happens inside the Z(3) wall.

In other words: Z(3) wall behaves as a potential barrier for a quark crossing the wall.

$m(x)=m_q + m_0\,(l_0 - |l(x)|\,)$

Rectangular barrier approximation



We solve Dirac equation with this potential barrier and determine transmission coefficients

2nd Possibility: Spontanesous CP violation due to Z(3) wall:
Calculate back A_0 from l(x) profile:

Atreya, Sarkar., AMS, PRD 85, 014009 (2012)

Determination of A_0 profile of Polyakov loop

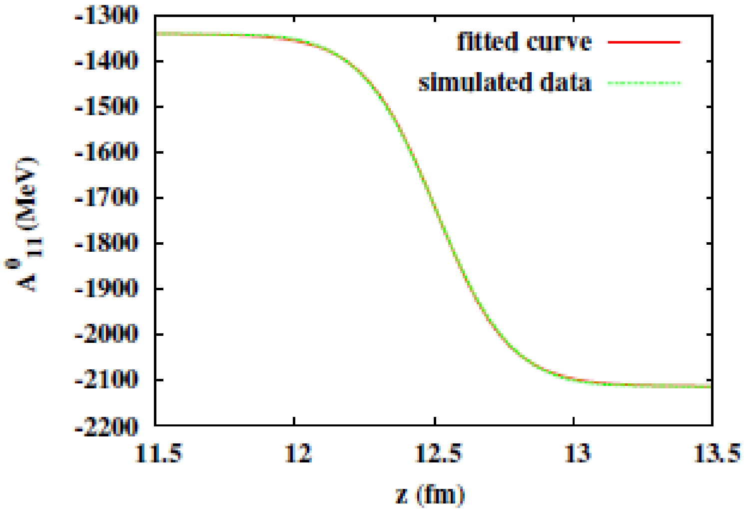
- $L(x) = (1/3)\, Tr\left[\mathbf{P} exp\left(ig \int_0^\beta A_0(\vec{x},\tau) d\tau\right)\right]$
- Gauge Choice

$$A_0 = \frac{2\pi T}{g}(a\lambda_3 + b\lambda_8)$$

a and b are constants, λ_3 and λ_8 are Gell-Mann Matrices

A_0 Profile

- The a and b profiles are then calculated from the $L(x)$ profile demanding that the variation of A_0 is continuous .



- Gradient of this A_0 profile will give color electric field.

Note: Again we have potential barrier. Except that, the sign of the potential changes from quark to antiquark. Thus if quarks are reflected strongly, antiquarks reflect very little.

CP violating effect of Z(3) wall (via associated A_0 field) is negligible for light quarks, but strong for heavy quarks:

	u	d	s	c
$E(\mathrm{GeV})$	3.0	3.0	3.0	3.0
$m(\mathrm{MeV})$	2.5	5.0	100	1270
R_q	1.73×10^{-7}	6.76×10^{-7}	2.8×10^{-4}	0.14
$R_{\bar{q}}$	1.92×10^{-8}	7.55×10^{-8}	3.2×10^{-5}	6.5×10^{-3}

Differences between heavy quark and antiquark spectra can directly signal such CP violating effects present in the QGP medium.

Note: Z(3) wall not necessary for this. Any long wavelength fluctuation in the color field will lead to similar (spontaneous) CP violating effect.

Thus heavy quark-antiquark momenta differences can probe the presence of long wavelength color field fluctuations

Spontaneous CP violating scattering has important implications
For quarkonia propagation:

As quarkonia passes through the region of color electric field (either associated with a Z(3) wall, or arising from long wavelength color field fluctuation), quarks and antiquarks feel opposite potential.

This leads to the possibility of direct breaking of quarkonia, or its excitation to higher states, which can melt easily.

Thus, even if temperature remains smaller than the dissociation temperature (from Debye screening) for quarkonia, such CP violating scattering can dissociate quarkonia.

(Atreya, Bagchi, AMS, PRC 90 (2014) 3, 034912)

This raises an important issue about propagation of quarkonia through QGP. This is about the assumption of adiabaticity in the evolution of quarkonia state as it passes through evolving QGP.

Bagchi, AMS, Mod.Phys.Lett. A30 (2015)1550162

Dutta, Borghini, Mod.Phys.Lett. A30 (2015)1550205

(Partha Bagchi's talk later on in the meeting)

CP violating scattering from the A_0 field leads to excitation of quarkonia to excited colored state, which is unbound, and can easily melt in QGP.

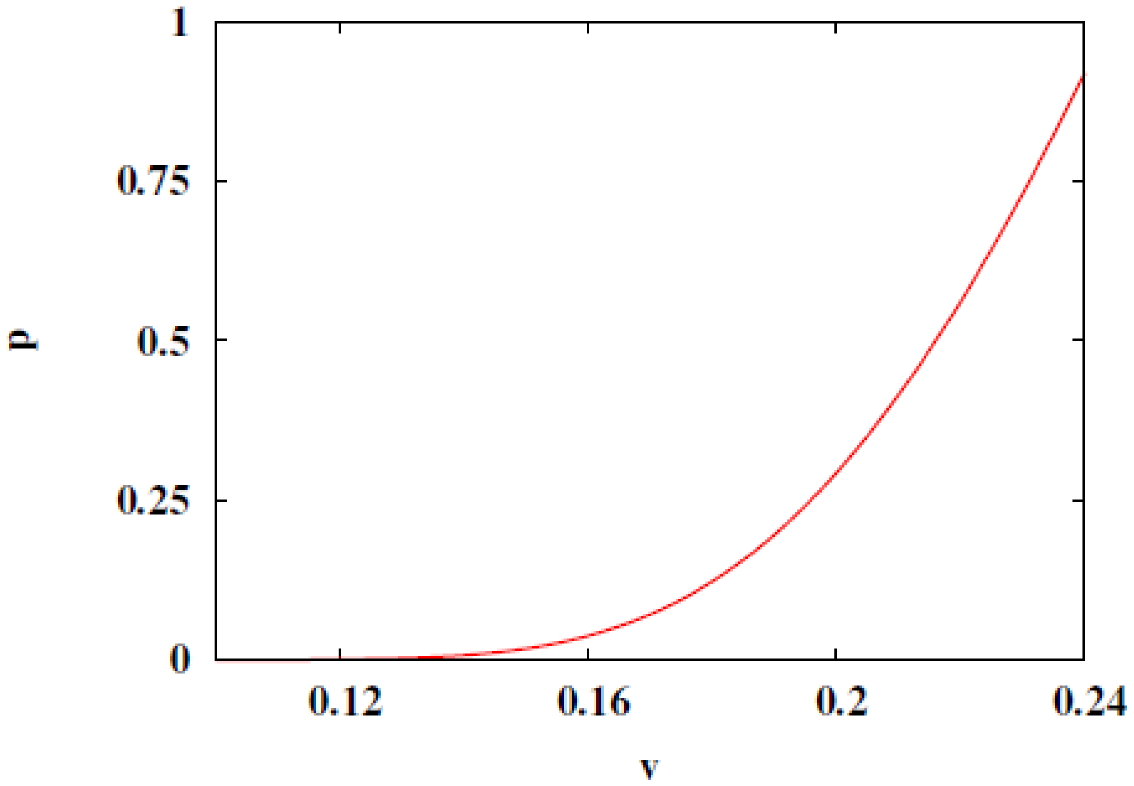


Figure : Probability p of transition of J/ψ to color octet χ states vs. its velocity v. Note that the probability rapidly rises with v.

Quarkonia excitation to higher states (which will subsequenetly melt easily) occurs also due to quark mass dependence on the Polyakov loop (without any CP violating A_0 field). Interestingly , the probability shows very different behavior as a function of quarkonia velocity through the wall.

- we have calculated transition probability to several excited states for charmonium and also for for bottomonium.

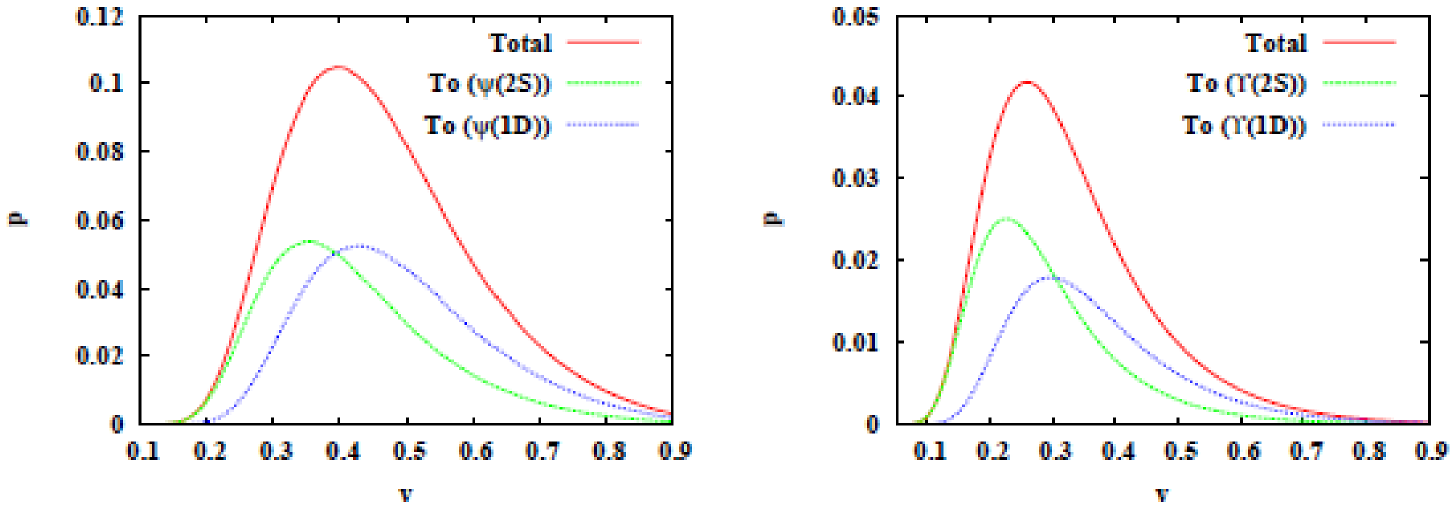
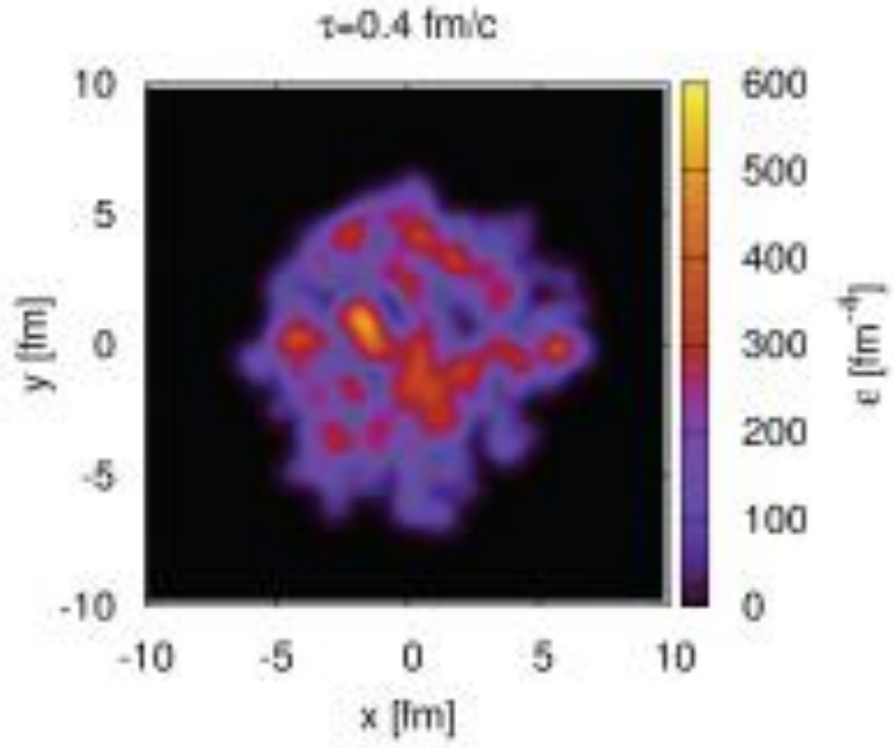


Figure : Above figure shows probability of transition from J/ψ and Υ to other excited states of charmonium and bottomonium

We come back to initial state fluctuations:



Such large fluctuations in energy density, (hence temperature) will necessarily provide spatially varying potential for propagation of heavy quarks (for example, through variation in the magnitude of the Ployakov loop order parameter affecting the consituent mass contribution to the quark).

Same thing will happen due to fluctuation regions arising from thermal effects. This raises an interesting possibility:

Fluctuations in the critical regime:

Many signals have been discussed to detect passage of the QGP system through the critical regime.

This is done by focusing on critical fluctuations.

An important feature of critical regime is The Critical Slowing Down Can one probe that ? One needs a probe which is sensitive to the time scale of fluctuations.

From our earlier discussions we see that the evolution of quarkonia state is precisely such a probe, when one focuses on the adiabaticity of the evolution.

Away from the critical regime, fluctuating regions will lead to fluctuating potential for propagating quarkonia. The adiabatic evolution will get seriously violated due to rapidly fluctuating regions. This will lead to frequent transitions to excited states hence melting of quarkonia (even at relatively lower temperatures)

In the critical regime:

Critical slowing down will affect the time scales of all fluctuations.

Closer one gets to the critical point, slower the fluctuations become (time scale diverging at the critical point).

Adiabaticity of quarkonia evolution will now only be affected by the spatial variation of potential, not by temporal variations.

For low momentum quarkonia, adiabatic evolution will work better and better, closer one gets to the critical point.

Thus quarkonia melting (and extra contributions to the excited states of quarkonia) due to violation of adiabaticity will be suppressed in the critical regime.

Summary and discussion:

Heavy quarks provide an excellent probe for fluctuations in the QGP fluctuations provide potential barriers leading to non-trivial scattering of heavy quarks, leaving imprints on quark momenta.

Evolution of quarkonia is very sensitive to presence of fluctuations, either in the presence of domain walls, or arising from initial state fluctuations, or from thermal fluctuations. Adiabatic evolution violated due to rapidly changing environment, especially during early thermalization stage

Color field fluctuations (from thermal effects, or arising from Z(3) walls) lead to spontaneous CP violation, affecting quarks and antiquarks differently.

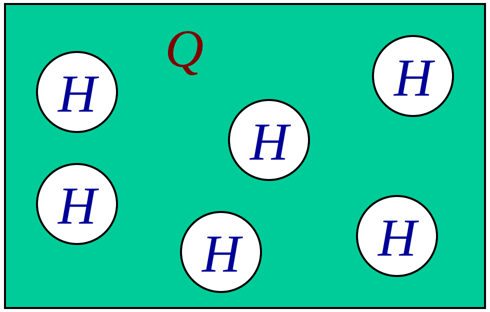
There are exciting possibilities of generation of inhomogeneities of heavy quarks/antiquarks due to collapsing Z(3) walls in QGP.

This can revive scenarios of strangeness distillation discussed earlier in heavy-ion collisions. It has important implications for the formation of quark/antiquark Nuggets in the universe. Most dominant contribution coming from Charm quark.

Formation of Strange quark nuggets in the universe

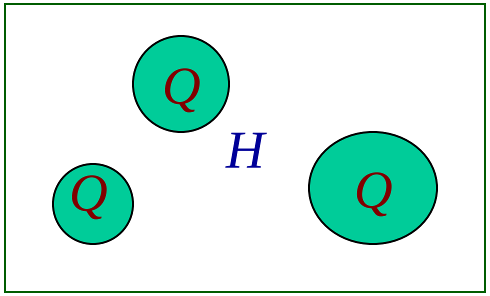
For comparison: Recall the conventional scenario of a first order quark-hadron transition in the universe which can produce baryon number fluctutions (Witten)

Hadronic bubbles are nucleated in the background of QGP phase.



Bubbles expand, coalesce, leaving pockets of QGP phase which shrink

Baryon number is carried by light quarks in the QGP phase and by heavy baryons in the hadronic phase.

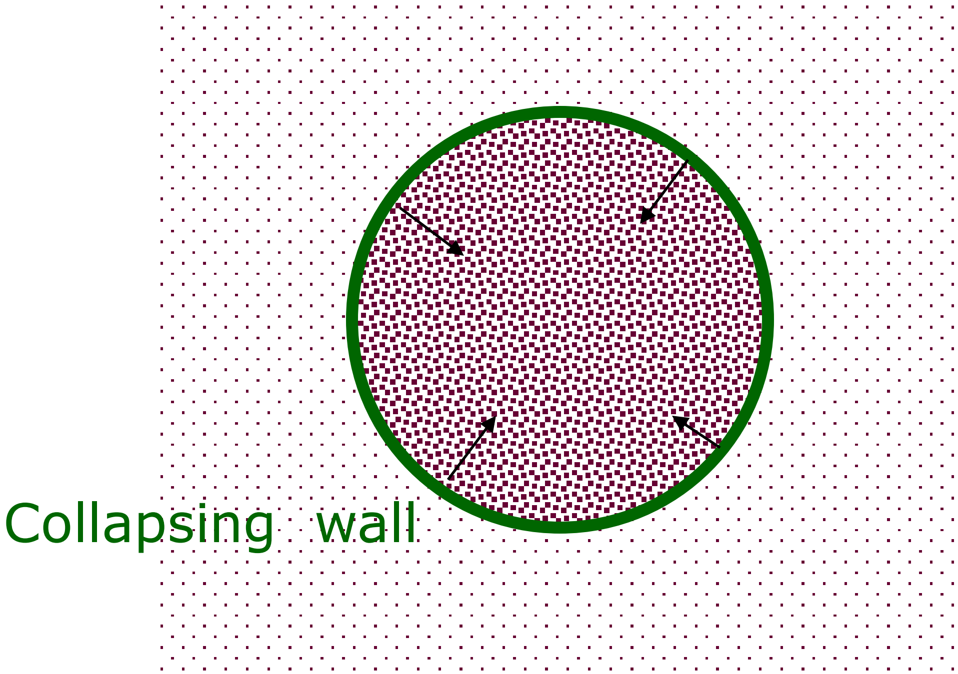


Result: Baryon number in shrinking QGP regions grows compared to hadronic regions

Large baryon fluctuations generated

For large baryon overdensities, stable quark nuggets may form
However: This does not work when the transition is a cross-over

Physical picture of the model



As the wall collapses, quarks and antiquarks are reflected as the wall sweeps through them, trapping a fraction of Baryon number inside

Baryon number inside the collapsing wall keeps growing. Eventually the wall disappears, leaving behind baryon over dense region (as in the conventional scenario).

These walls melt away below T_C : Last surviving inhomogeneities will be formed by the walls which collapse just above T_C .

Solve for the growth of baryon number overdensity:

$$\dot{n}_i = \left[-\frac{2}{3} u_w T(u_w) n_i + \frac{n_o T(u_q^-) - n_i T(u_q^+)}{6} \right] \frac{S}{V_i} - n_i \frac{\dot{V}_i}{V_i}$$

$$\dot{n}_o = \left[\frac{2}{3} u_w T(u_w) n_i - \frac{n_o T(u_q^-) - n_i T(u_q^+)}{6} \right] \frac{S}{V_o} + n_o \frac{\dot{V}_i}{V_o}$$

$n_{i,o}$ are baryon densities inside, and outside the collapsing wall.
S is the area of the wall, $V_{i,o}$ are inside, outside volumes.
We normalize densities to average baryon density of universe

T's are various transmission coefficients, u_w is the wall velocity which we take to be sound velocity.

We take the number of domain walls within horizon to be 1, 10

Note, these walls are not phase boundaries, so there is no Latent heat. (With explicit symmetry breaking, one should include that). Also, assuming collapse to be fast, we neglect the expansion of the universe (should be fine for $N_d = 10$).

This simplifies the task as a fixed potential barrier can be used for calculations. (This can not be assumed for relativistic Heavy-ion collision case: Rapid expansion dynamics).

Baryon density profile $\rho(R)$ is calculated as follows

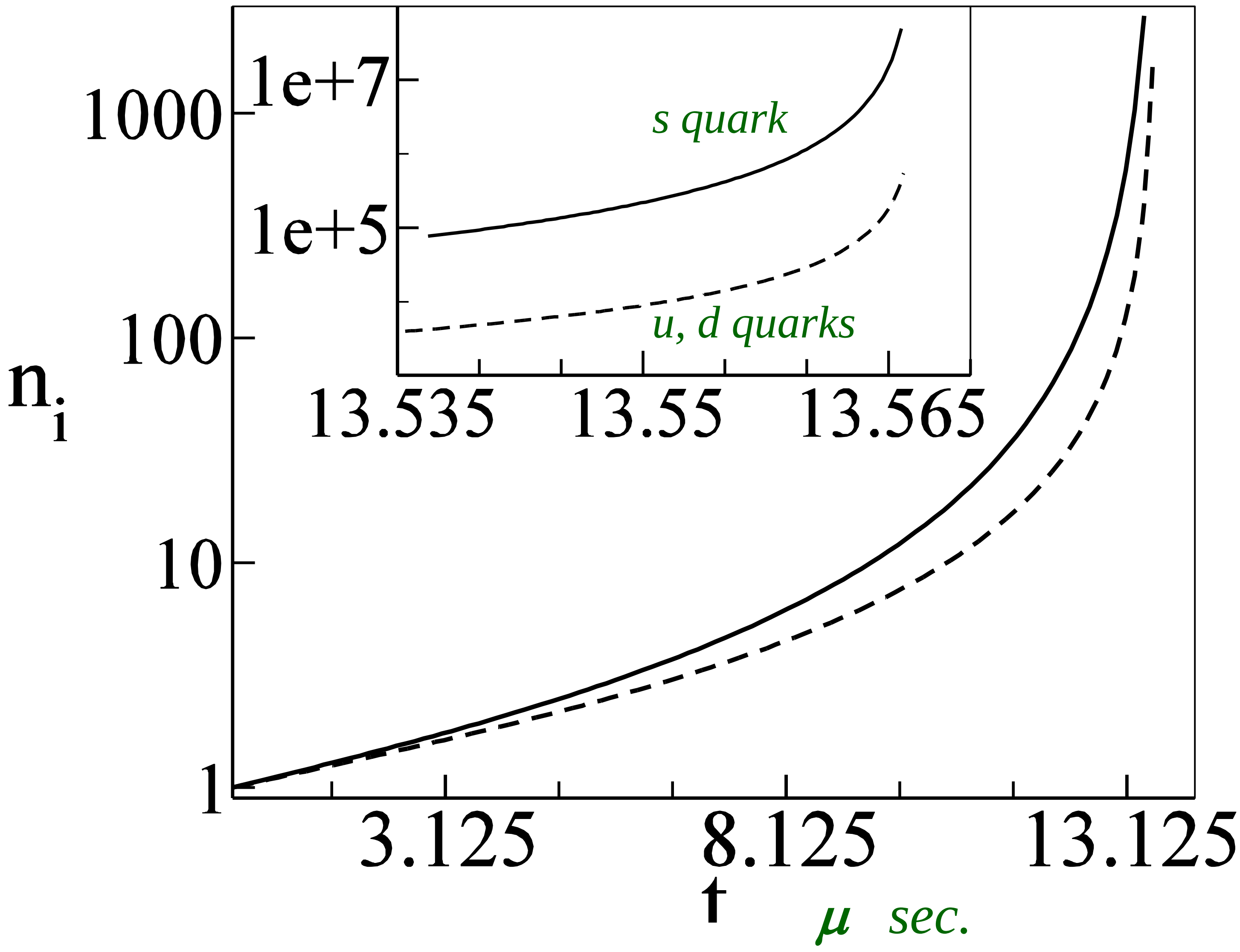
Total umber of baryons inside $N_i = n_i V_i$

$$N_i(R+dR) - N_i(R) = \rho(R) 4\pi R^2 dR$$

$$\rho(R) = \frac{dN_i}{dR}\frac{1}{4\pi R^2} = -\frac{\dot{N}_i}{4u_w \pi R^2}$$

Relative baryon density inside collapsing wall

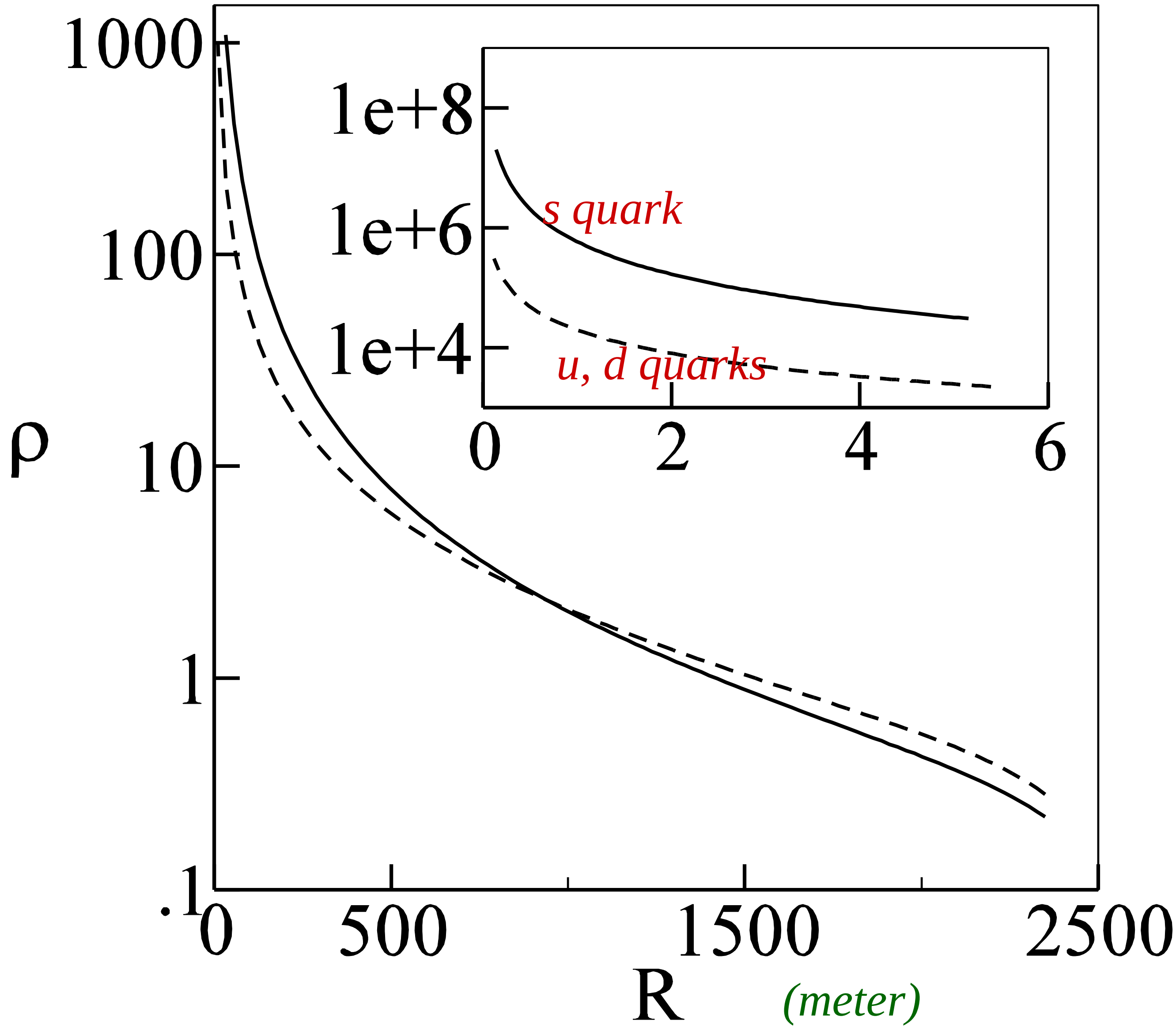
Strange quark has larger reflection coefficient due to larger mass



Overdensity evolution: overdensities by factor > 1000 and sizes more than ~ 1 m will survive until nucleosynethsis *(Jedamzik, Fuller)*

ρ *is the relative baryon density left behind by collapsing wall*

Again, note: Strange quark much more abundant



(meter)

Important points:

1. Distance between inhomogeneities is given by separation between collapsing walls. For our model, with low energy inflation: there may be only few walls in each horizon: Size ~ fraction of horizon size, i.e. about 1 km (much larger than conventional case of few cm).

2. Due to larger mass, strange quark has larger reflection coefficient leading to strangeness rich overdensities.

Quark nugget formation :

We find baryon number of order 10^{44} can get trapped inside a region of size less than 1 meter. These are favorable conditions for forming quark nuggets (which are naturally strangeness rich here). If they survive till present, they can provide dark matter, without ruining nucleosynthesis or CMBR observations.

All of this is completely insensitive to quark-hadron transition.