Generation of baryon fluctuations in the QGP phase

Outline :

1. Baryon fluctuations from a first order quark-hadron transition :
   Conventional picture for the universe and heavy-ion collisions
   None of this works if quark-hadron transition is a cross-over

   A new approach :

2. Polyakov loop order parameter, Spontaneous breaking of Z(3) symmetry in QGP phase, explicit breaking with quarks

3. Z(3) interfaces, Strings with confining core

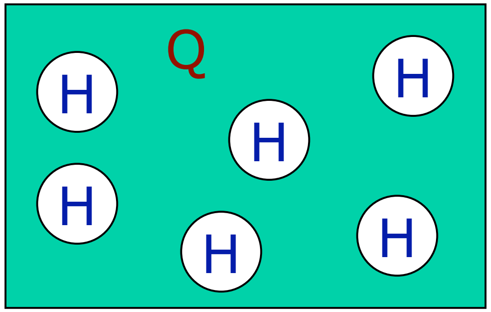
4. Baryon fluctuations due to Z(3) interfaces, strangeness enhancement: For the universe

5. Relativistic heavy-ion case: in progress

Important: Nature of quark-hadron transition completely irrelevant

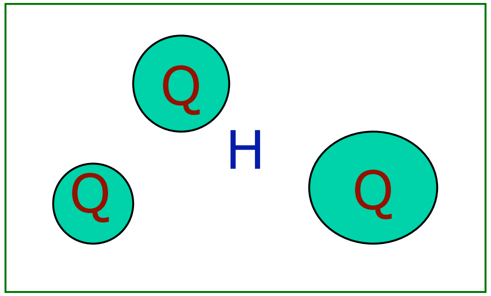
Biswanath Layek, Ananta P. Mishra, Vivek K. Tiwari, AMS

A first order quark-hadron transition 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 QGP phase and by heavy baryons in 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

Problems with the conventional scenario:

1. All this requires a first order quark-hadron transition,
   It will not work for a cross-over, which is likely the case

2. Even for a first order transition, distance scales for baryon
   Fluctuations are too small for the universe (of order few cm)

   Such fluctuations dissipate away quickly without any
   observational effects.

   Even though inhomogeneous nucleosynthesis is tightly
   constrained, formation of quark nuggets would have
   been interesting as that could have provided dark matter,
   without affecting nucleosynethsis.

For relativistic heavy-ion collisions also, baryon fluctuation generation, Strangelet formation, all that requires first order Transition (in this scenario).

We discuss a new possibility: Consider 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, b = 1/ T, with T being the temperature, A_0 (x,t) is the time component of the vector potential at spatial position x and Euclidean time t .

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

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

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

Let us first discuss the properties of these walls, and a new string like structure in the QGP phase.

For numerical estimates, we use the following Lagrangian for $l(x)$, proposed by Pisarski:

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

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

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,

$a(x) = (1-1.11/x)(1+0.265/x)^2 (1+0.300/x)^3 - 0.487$

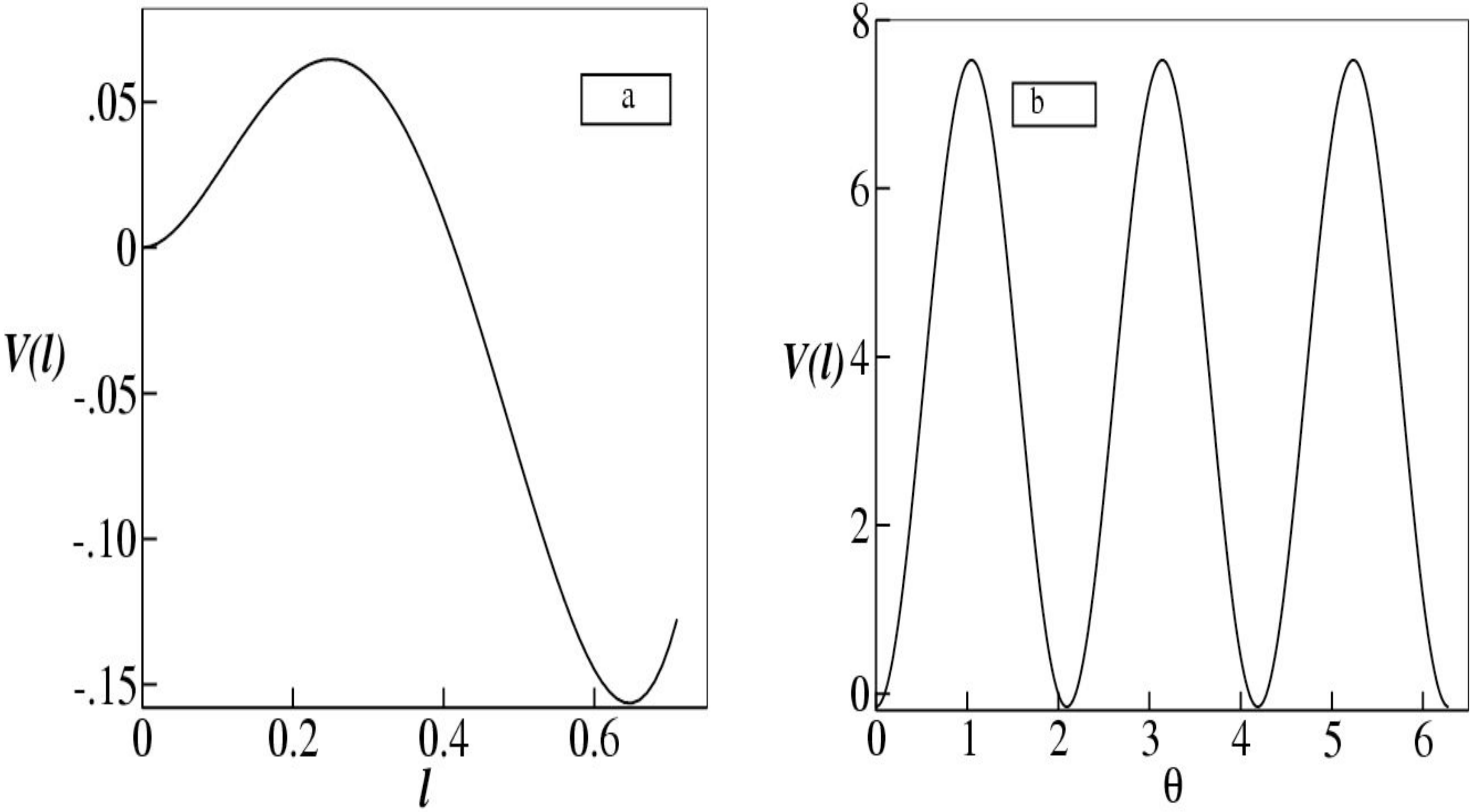
where, $x = T/T_c$

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

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

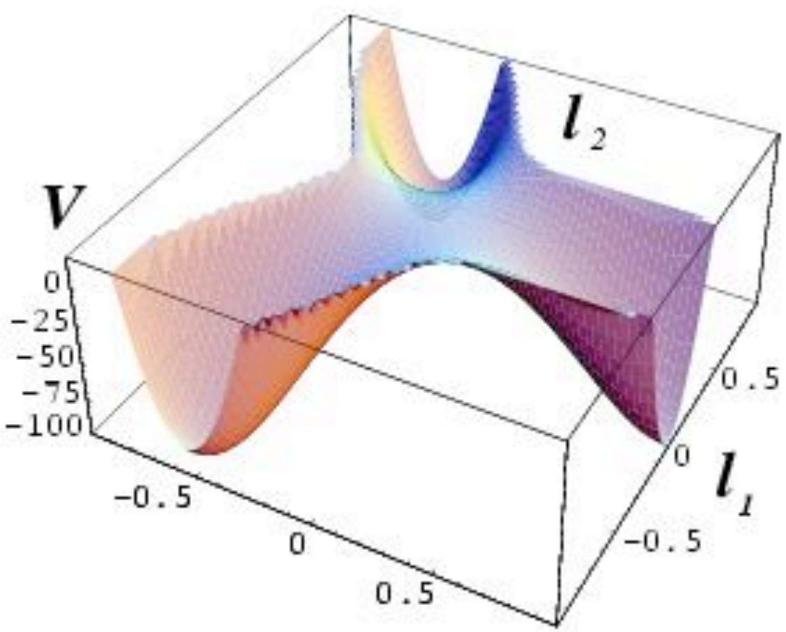
Note: b term gives cos 3q , leading to Z(3) vacuum structure

Plot of V*(l)* for T = 185 MeV, *l* = |*l*| exp(iq)



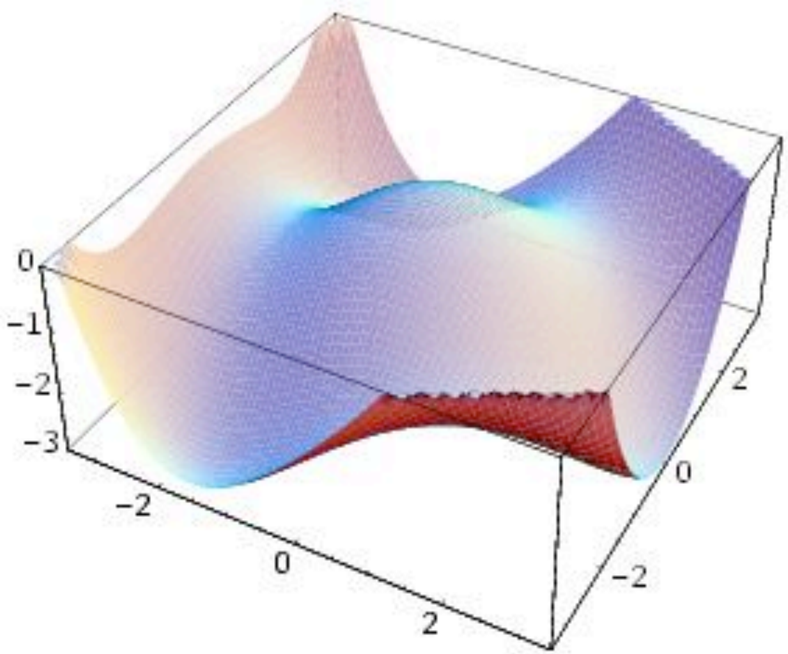
Note: relative heights of barriers

Polyakov loop case



(a)

Axionic string case



(b)

Lowest potential energy path
Between two vacua goes
Through the origin.

Here, lowest potential energy
Path joining two vacua
remains in the valley.

Does it mean that l = 0 inside the wall ? Not true, we show later

Domain wall solution: Field equations for a planar wall-

$$\frac{d^2 l_j}{dz^2} = \frac{g^2}{NT^2}\frac{\partial V(l_1, l_2)}{\partial l_j}, \quad l = l_1 + i l_2 \;, \quad j = 1,2$$

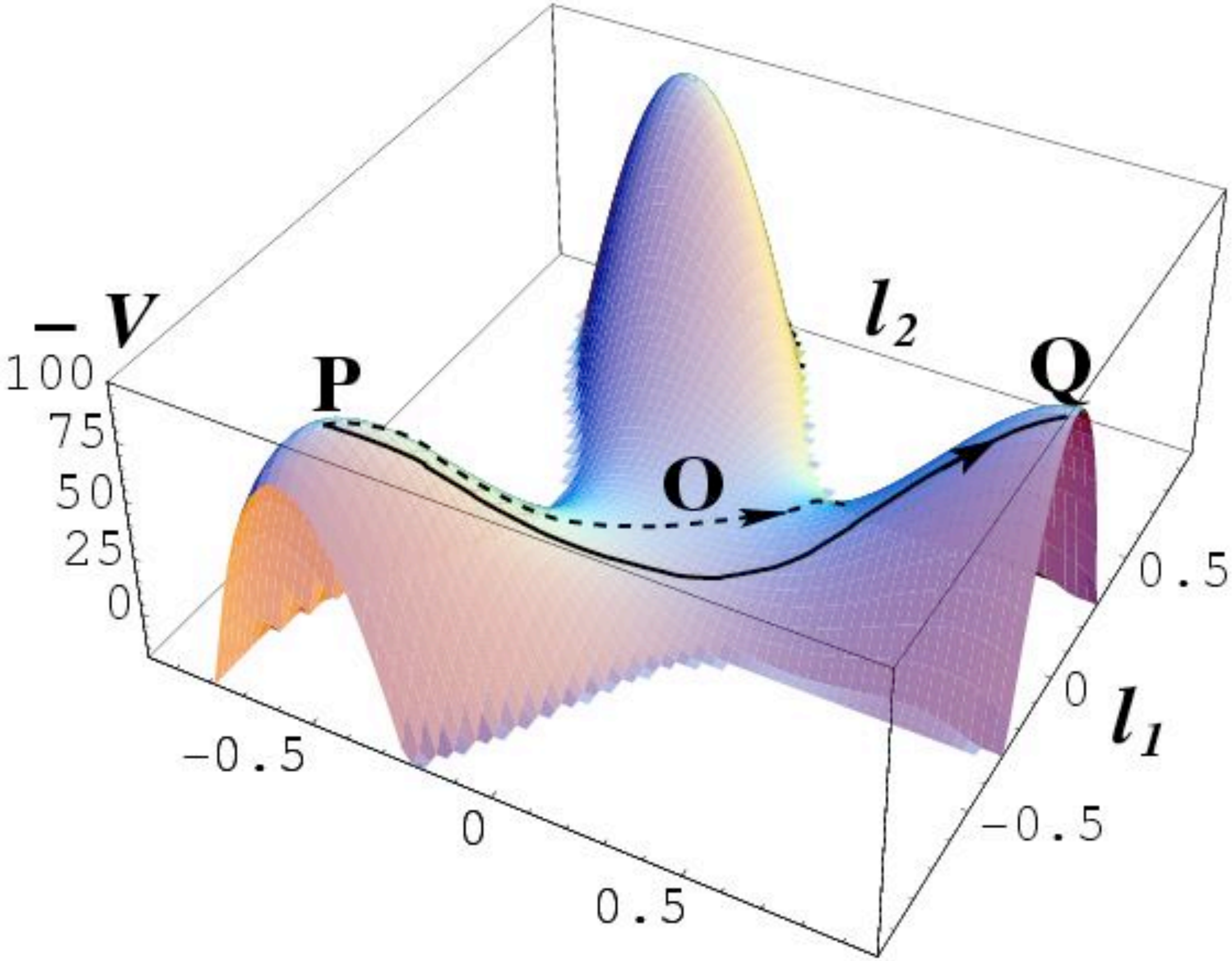
Use standard technique for bounce solution:

interpret Z as time, l_1 and l_2 as the 2-d position space

For a particle moving under potential $= -V(l_1, l_2)(g^2 / NT^2)$

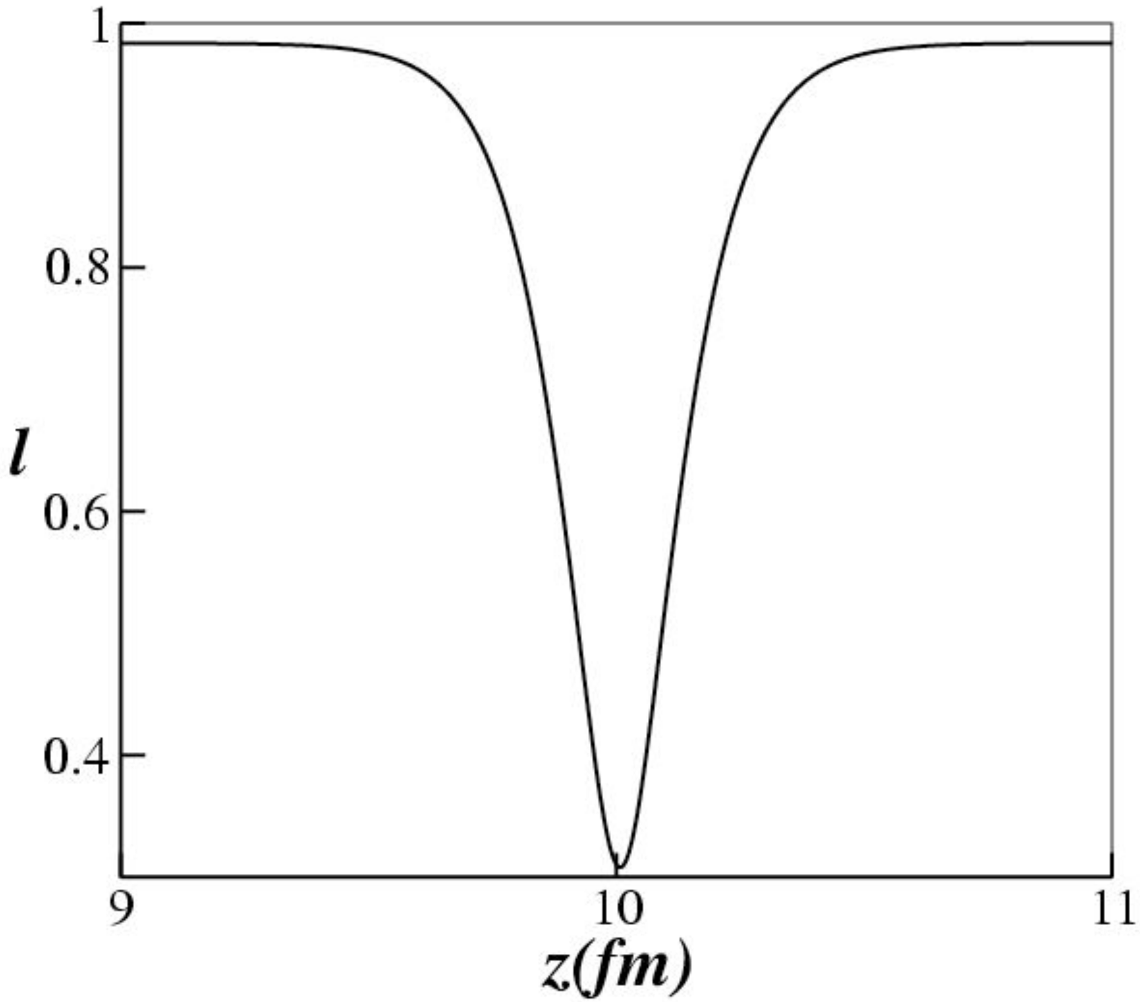
Domain wall solution corresponds to a particle trajectory
Which starts from one minima of V for large – Z, and
Approaches another minima of V for large + Z.

Note: Solution (solid curve) can never go through origin for SU(2N+1), So, l cannot be zero inside the wall. Though, the curve can go through origin for SU(2N)



Unfortunately, bounce technique difficult to apply here (work With A.P.Mishra). So, we use energy minimization technique

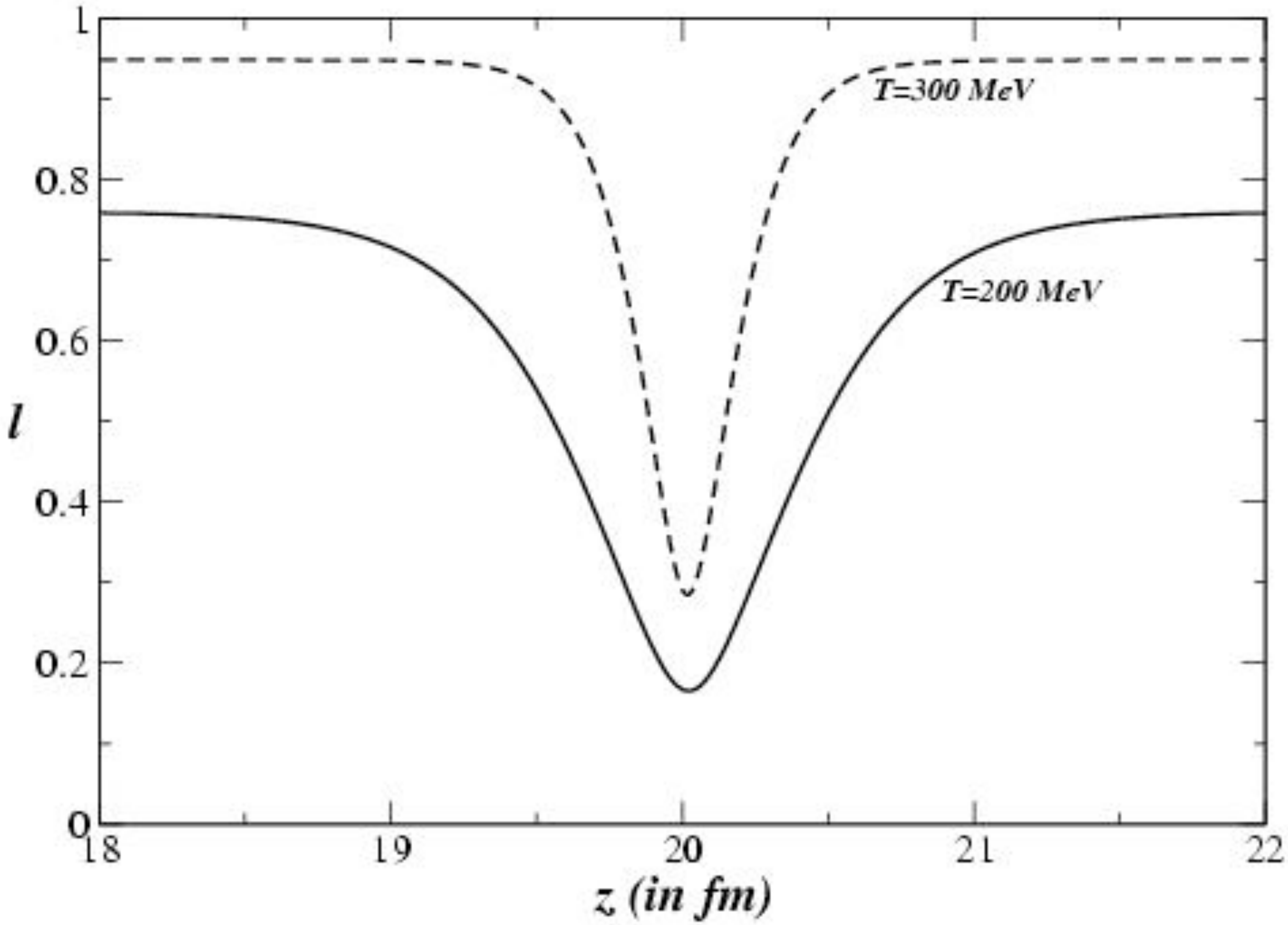
Domain wall profile for T = 400 MeV, Note: $|l|$ small, But non-zero inside the wall.



Surface tension = 7 , 2.61 , 0.34 GeV/ fm^2

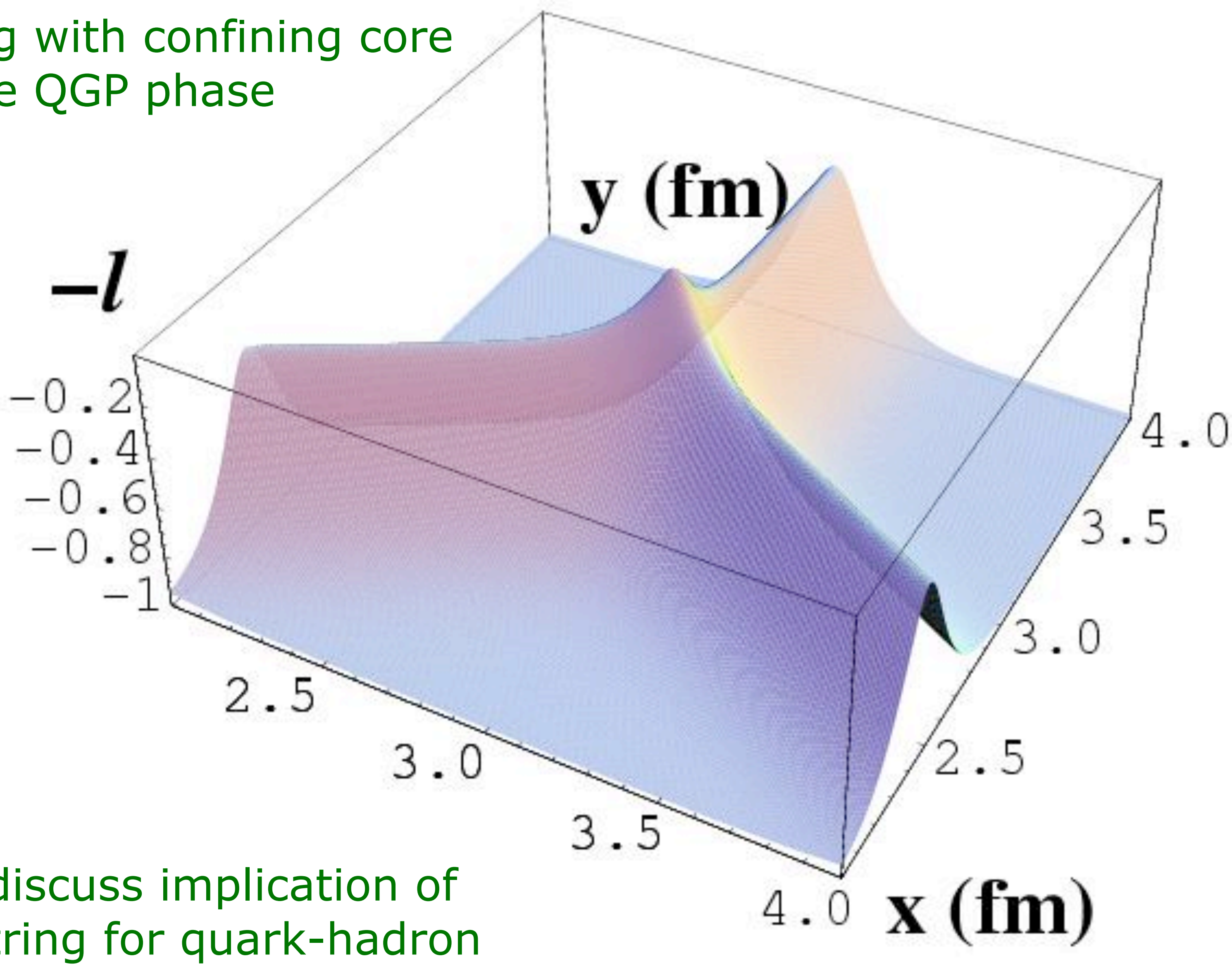
For T = 400, 300, 200 MeV, close to analytical estimates

For high T : $\sigma \sim \frac{8\pi^2}{9g} T^3$ Bhattacharya, …



Junction of three walls ,   String with l = 0 inside it.

String with confining core
In the QGP phase

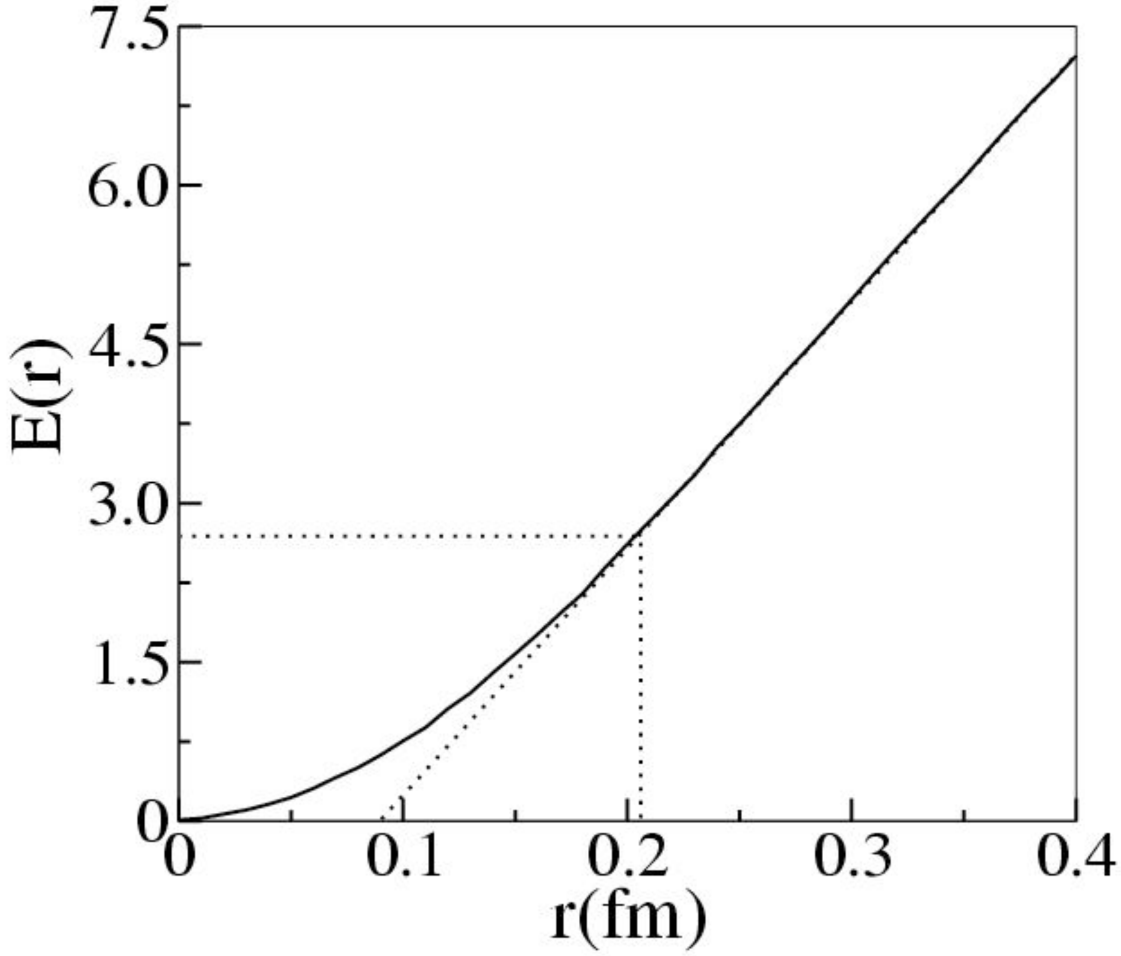


Later discuss implication of
This string for quark-hadron
transition

String energy: $E(r) = E_c(r)$, $0 < r < r_c$

$E(r) = E_c(r_c) + 3\,s\,(r - r_c)$, $r > r_c$

This gives, $s \sim 7.7$ GeV / fm^2 , $E_c(r_c) \sim 2.7$ GeV / fm



Note: These Z(3) walls, and the string, 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 the universe, they could form at the end of inflationary phase

For heavy-ion collisions, they will form when system thermalizes

First consider the case of the universe:

A network of Z(3) domain walls, and strings will form at some Early stage. It may reach scaling solution near QCD scale when the tension forces become large .

We will study the effects of collapsing Z(3) walls on baryon Number distribution.

Proposal : as the Polyakov loop l is the order parameter for confinement –deconfinement transition, various physical quantities should depend on l .

In particular : effective quark mass should depend on l .

we write for effective quark mass:

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

(Note: linear term expected for quarks, but we neglect explicit symmetry breaking)

Here, m_q is the current quark mass as appropriate for QGP Phase with $|l(x)| = l_0$. We take,

m_u , $m_d \sim$ 10 MeV , $m_s \sim$ 140 MeV

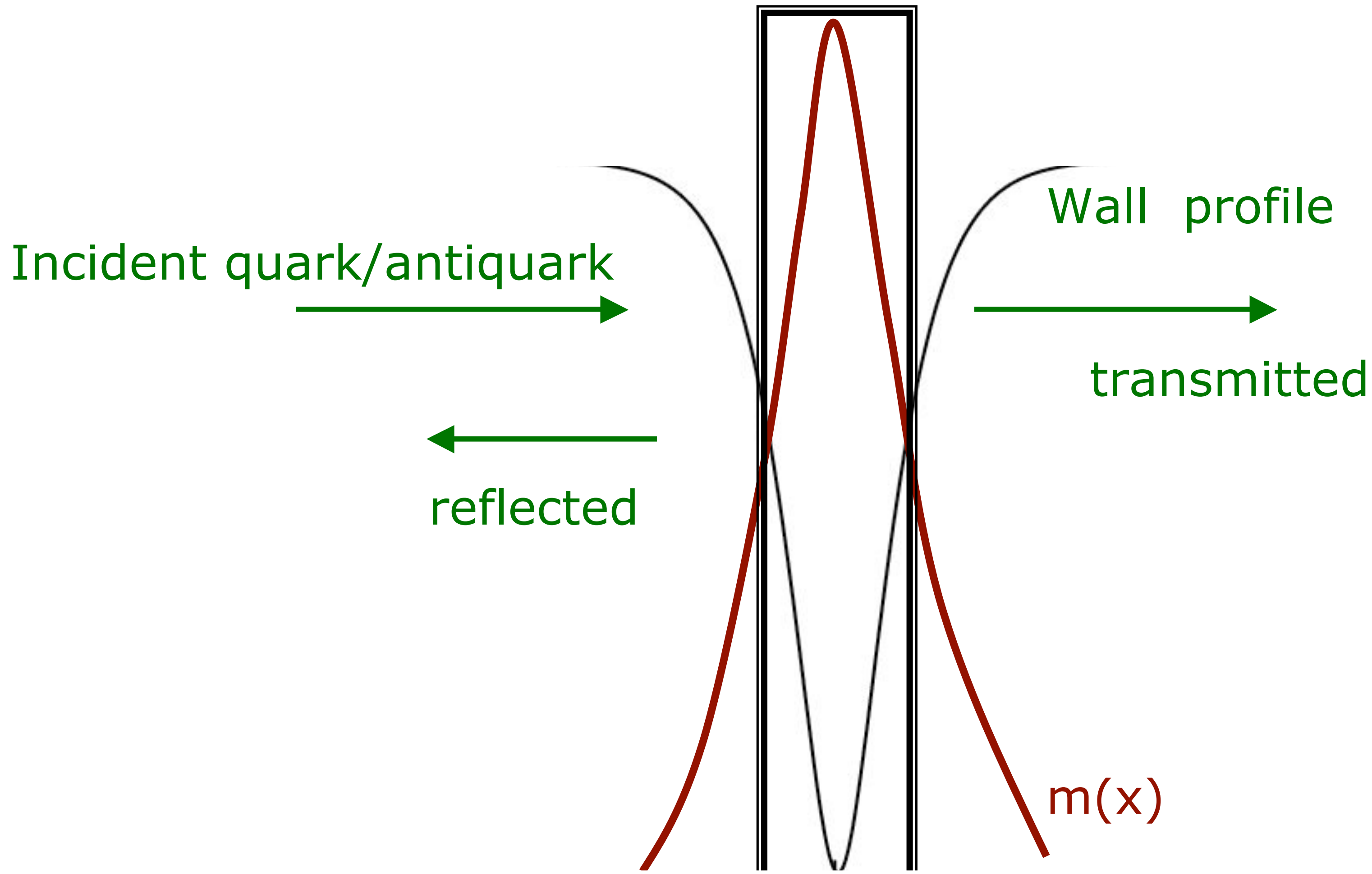
We take $m_0 \sim$ 300 MeV as the constituent mass contribution for the quark

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

Transmission coefficient:

$$T = \frac{4r^2}{4r^2 + (1 - r^2)^2 \sin^2(pd)}$$

$$r = \frac{p(E + m_q)}{q(E - V_0 + m_q)}, \quad q^2 = E^2 - m_q^2, \quad p^2 = (E - V_0)^2 - m_q^2$$

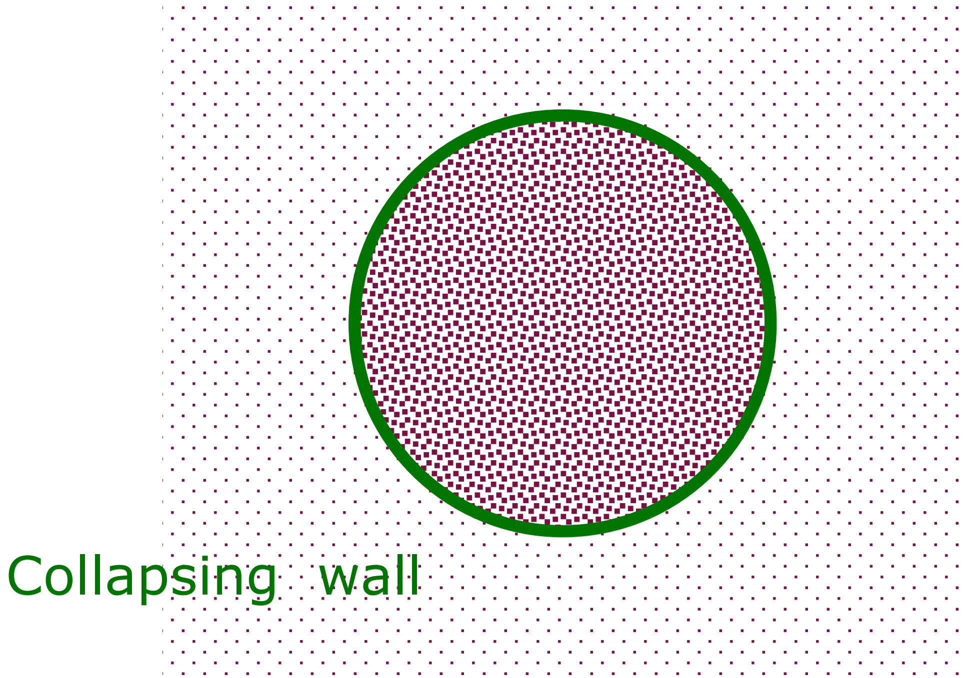
Here, V_0 is the height of the rectangular potential barrier,

E is the energy of the incident quark, and d is the width

of the barrier, which we take as the width of the wall

d = 0.5 fm, and 1 fm, for T = 300, and 200 MeV

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 Overdense region (as in the conventional scenario).

As 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. Also, collapse should be fast so we can neglect The expansion of the universe (should be fine for N_d = 10).

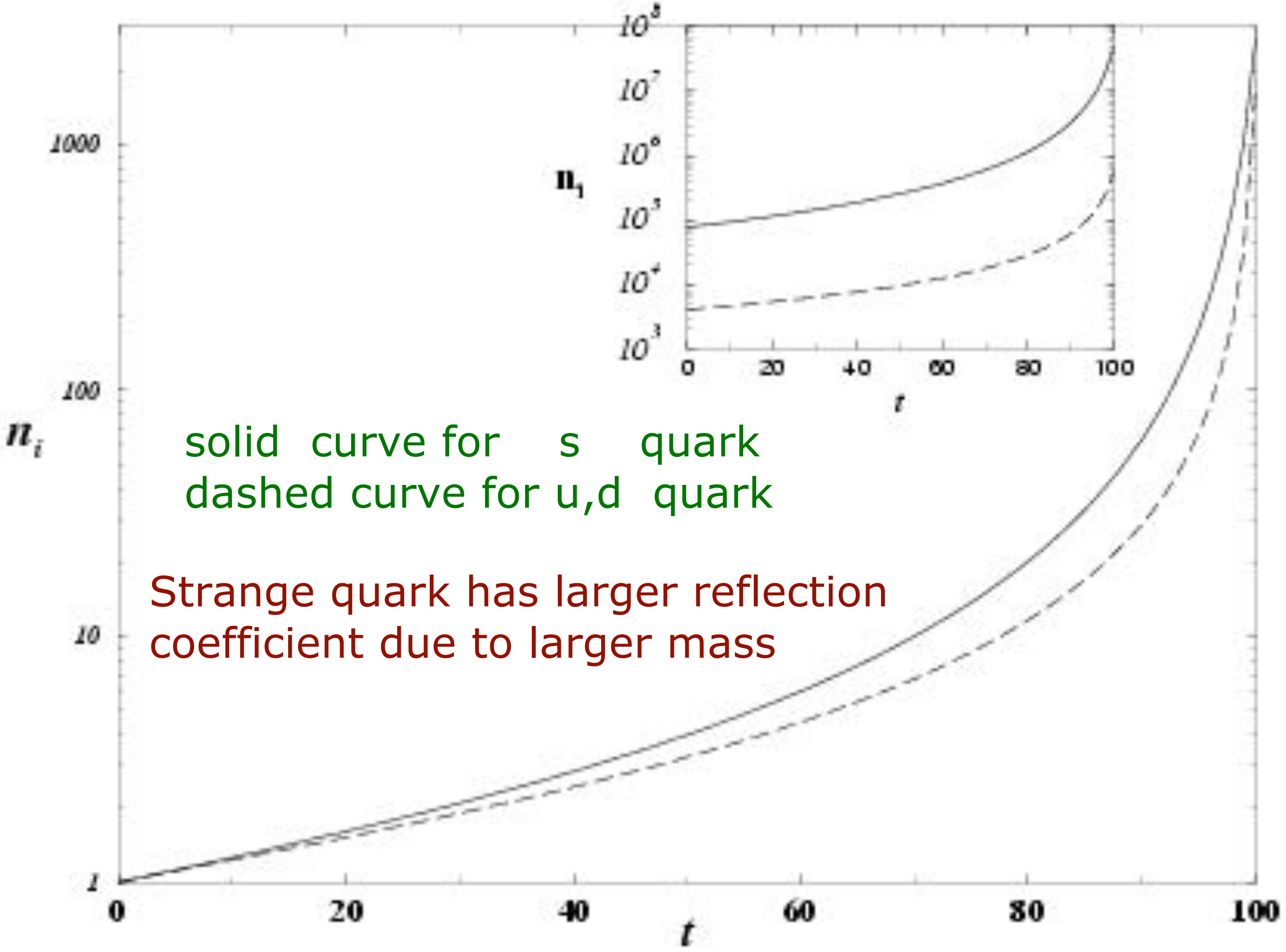
This simplifies the task as a fixed potential barrier can be Used for calculations. (we plan to do for temperature Dependent barrier).

Baryon density profile r (R) is calculated as follows

Total umber of baryons inside $N_i = n_i \; V_i$

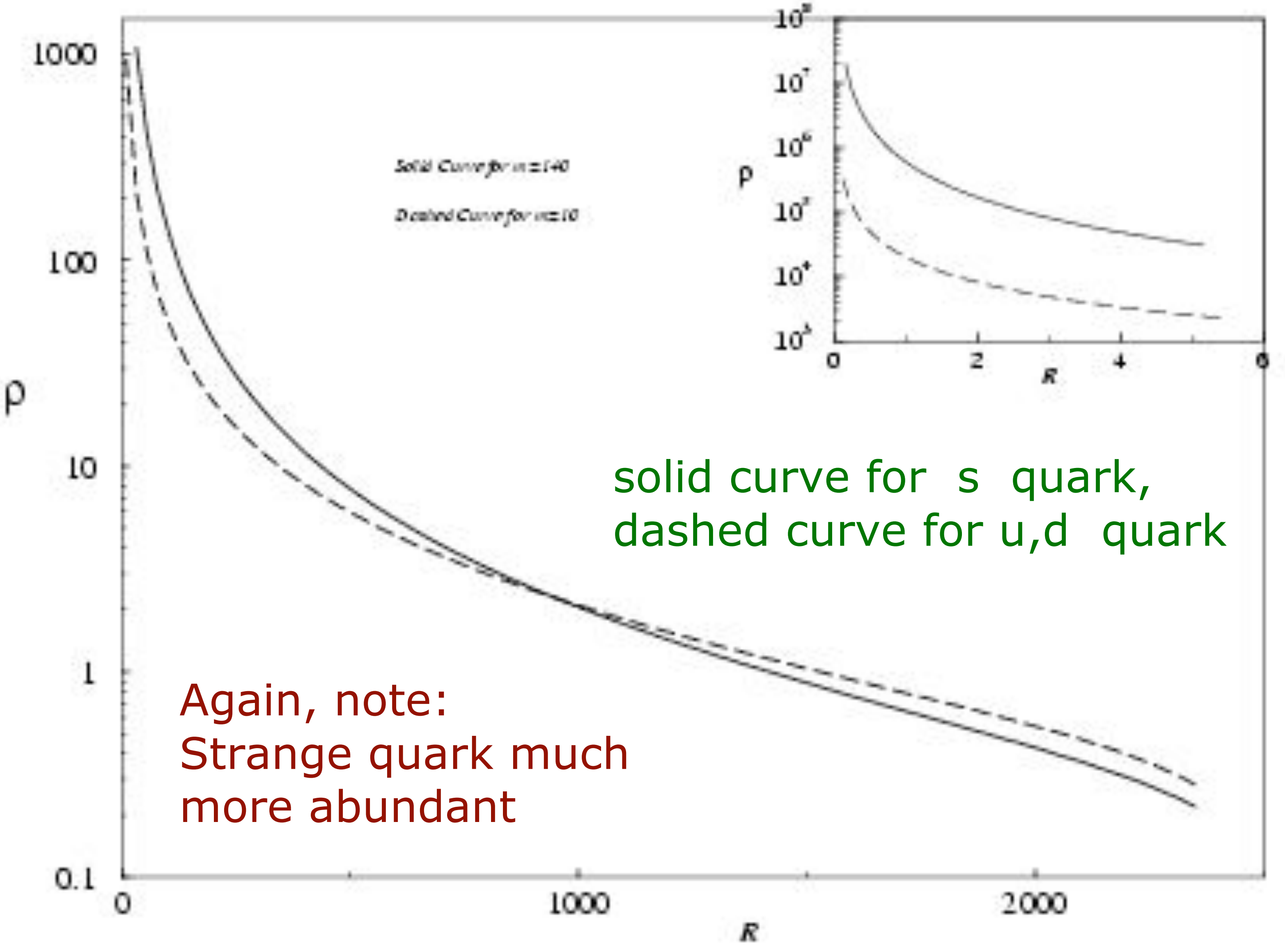
$$N_i(R + dR) - N_i(R) = \rho(R) 4\pi R^2 dR$$

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


1000
100
10
1
n_i
0
20
40
60
80
100
t
10^8
10^7
10^6
10^5
10^4
10^3
n_1
0
20
40
60
80
100
t
solid curve for s quark
dashed curve for u,d quark
Strange quark has larger reflection
coefficient due to larger mass

~ 15 msec

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



solid curve for s quark,
dashed curve for u,d quark

Again, note:
Strange quark much
more abundant

Important points:

1. Distance between inhomogeneities is given by separation between collapsing walls. For any domain wall models, this is a 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.

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

Role of strings:

Note: strings have order parameter = 0 inside, so should Have larger potential barrier for quarks.

Collapsing string network should also contribute to baryon overdensities.

Due to small tensions, string network may be dense Enough to make significant contributions to baryon Inhomogeneities (though still walls should dominate).

As strings and walls are inter-connected here, one needs To study the whole network together.

We know that Z(3) symmetry is explicitly broken due to quarks This makes two of the Z(3) vacua metastable. This only means That true vacuum will expand and others will shrink (as in the Conventional case). There will also be false vacuum energy Release. Order of magnitudes presented here should not change.

Relativistic heavy-ion collisions:

Here, a dense wall-string network will form during initial stages of thermalization.

Its evolution will be completely dominated by expansion, and associated changing temperature.

Any assumptions of simple spherical geometry will be invalid here.

Thus: can be handled only using 3-D numerical simulations

We have earlier studied (in 2-D) formation and evolution of String defects. Those simulations have to be extended for The present case and for 3-D.

We should be able to study baryon density fluctuations produced Because of shrinking wall-string network, and any possible Strangelet production

Effect of wall-string network on quark-hadron transition:

With $l(x)$ being small or zero inside walls/strings, the transition
To confining phase should proceed in an inhomogeneous way.

Especially if the transition happens to be a first order transition
(even weak one). Bubbles will then nucleate on top of
these strings, leading to inhomogeneous nucleation picture.

This should be prominent in the case of heavy-ion collisions
Because of dense evolving string/wall network.

Also, for the universe dynamics of any first order transition
Will be strongly modified.

Summary:

1. Collapsing Z(3) walls and strings in the QGP phase act as potential barriers for quarks/antiquarks.

2. Reflection from collapsing walls leads to baryon number concentration inside, leading to baryon fluctuation production.

3. For the universe, large amplitude baryon fluctuations with distance scales ~ 1 km are formed. These can strongly affect nucleosynthesis.

4. Quark nuggets may form which may be stable. These can then provide dark matter, without affecting nucleosynthesis.

5. Same mechanism will lead to baryon fluctuations and strangelet formation in heavy-ion collisions.

All of this is completely insensitive to quark-hadron transition