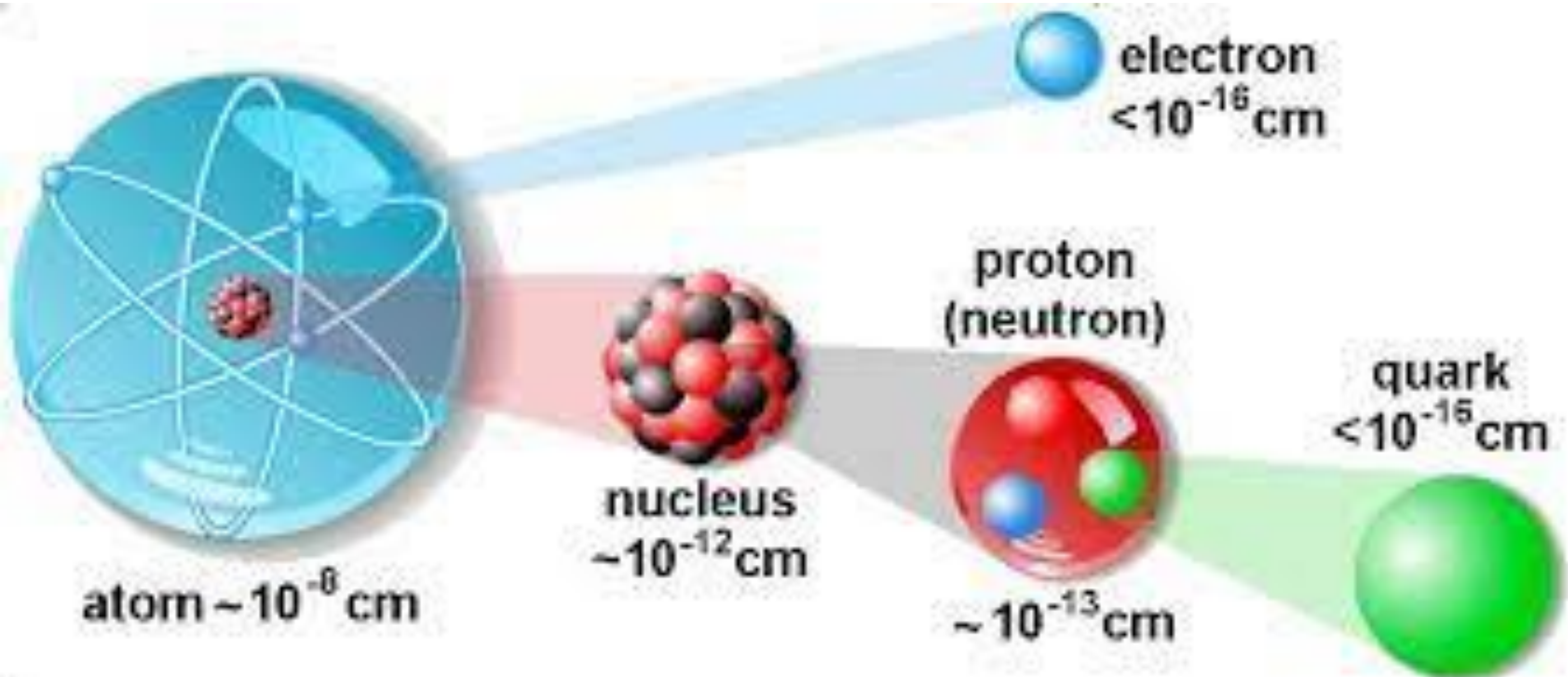
Quark Gluon Plasma:
From Laboratory to Cosmos
A brief overview

A. M. Srivastava
Institute of Physics
Bhubaneswar, India

Microstructure of matter: Length scales



Ref. https://quantumphysicsoverview.weebly.com/

With ultra high energy collisions using large accelerators, we probe structure at smaller length scales:

Smallest length scales probed so far ~ 10^{-16} cm.

quarks, gluons, electrons,… show no inner structure at this length scales. These are believed to be elementary constituents of matter.

Further sub-structure not ruled out: e.g. string theory…….

Confinement of quarks and gluons in QCD

Quantum Chromo Dynamics (QCD) is the theory of Strong Interactions (forces between quarks/gluons inside hadrons (protons,neutrons,pions,....)

Quarks, gluons carry **color** charge.

This color interaction between quarks, gluons is so strong that they remain confined inside hadrons

There are different types of hadrons:

Three quark bound states: Baryons, e.g. Protons, neutrons,..

Quark-antiquark bound states: Mesons, e.g. Pions, kaons,....

Other exotic possibilities: Glueballs (only composed of gluons)

larger number of quarks/antiquarks etc.

Some evidence for these....

Confinement of quarks and gluons in QCD ……

Color interaction between quarks/gluons is very strong

Very different from Coulomb interaction where potential energy between electrical charges **decreases** with distance.

For color interaction between quarks bound inside a hadron,

color potential energy **increases (linearly)** with distance.

So, quarks, gluons cannot be isolated

(unlike electrons, protons, which can be isolated by ionizing an atom).

This is called color confinement.

No isolated quarks/gluons exist in nature.

They are detected using probes penetrating the inner structure of hadrons, using ultra-high energy collisions.

Deconfinement in QCD

QCD shows another interesting behavior:

Color interaction energy bcomes very small at very short distances.

In some sense, when quarks/gluons are very close to each other, their effective color charge becomes very small.

Thus: Color Interaction becomes very weak at high energies/small length scales.

This is called **The Asymptotic Freedom of QCD.**

(2004 Nobel Prize: Gross, Politzer, Wilczek).

This suggests that if a hadronic system is at **very high density,**

so that quarks/gluons inside hadrons are forced to come very close to each other,

then these quarks/gluons should interact very little with each other.

Deconfinement in QCD ....

Similarly, if the system is at **very high temperature,**

then quarks/gluons inside hadrons will scatter with very high kinetic energy, scattering with large momentum transfer.

Small compton wavelengths, so can come very close to each other.

Again, they should behave almost as free particles.

This implies that in extreme conditions of high density and/or temperature

Quarks/gluons should not remain confined inside individual hadrons

There should be deconfinement of quarks and gluons

In this situation, hadrons should undergo a transition to a

Weakly Interacting Gas of quarks and gluons

This is known as: **Quark-Gluon Plasma (QGP)**

Quark-Gluon Plasma (QGP)

Various theoretical estimates show that if nuclear matter is in a state in which the nucleon (baryon) density and/or the energy density becomes about an order of magnitude larger than the normal density of a nucleus

$$\rho = (10-15)\rho_0 \approx (2-3) GeV / fm^3$$

then deconfinement should occur.

Expectation: Weakly interacting plasma of quarks/gluons

QGP expected to occur in the Early Universe, inside Neutron Stars,

and in Relativistic Heavy-ion Collision Experiments

Surprising result from these experiments:

Strong evidence for QGP , but **not a weakly interacting plasma**

Rather: **strongly coupled, like a perfect liquid, called - sQGP**

Process of defonfinement:

As discussed: This deconfined phase of QCD, **the QGP**, can arise in two different conditions.

(1) At high temperatures, (2) At high baryon density

High Temperature Deconfinement

Consider a system of hadrons which has temperature higher than about 10^{12} K (~ 100 - 200 MeV)

Note: Confinement of quarks and gluons inside protons and neutrons sets in when energy scale is less than about 200 MeV.

At such temperatures large amounts of pions are produced thermally (pion mass ~ 140 MeV) density of hadrons (protons, neutrons, pions,..) becomes very large and they start overlapping (typical size of hadron ~ 1 fm).

Quarks cannot belong to any given hadron, hadronic description breaks down. (Similar to electrons forming conduction band in a metal where electron clouds of neighboring atoms start overlapping).

Further, with very large thermal kinetic energy, interaction between quarks,gluons becomes very small (Asymptotic Freedom of QCD)

It results in a thermally equilibrated system of relatively free quarks and gluons

Transition to High Temperature QGP phase.

Such a system will consist of a hot plasma of quarks and gluons, instead of hadrons.

Note: this is very different from ionization of a gas where electrons get liberated from atoms when thermal energy becomes larger than the electron binding energy.

Quarks can never be liberated from hadrons in this sense (confinement of quarks).

Here quarks get liberated because different hadrons start overlapping when hadron density becomes very large.

Essentially, quarks do not know to which hadron they belong,

There are no more boundaries between hadrons

It is thus clear that exactly the same situation will occur when hadrons (baryons: protons, nucleons) are compressed together to form a high density system **(even at very low temperatures).**

This leads to: **Deconfined phase (QGP) at high baryon density**

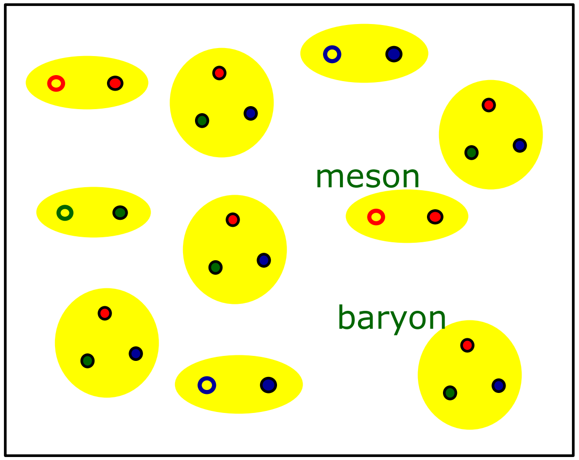
Such a system will also have deconfined quarks/gluons

Further, due to Low temperature it can exhibit highly non-trivial quantum correlations leading to exotic phases:

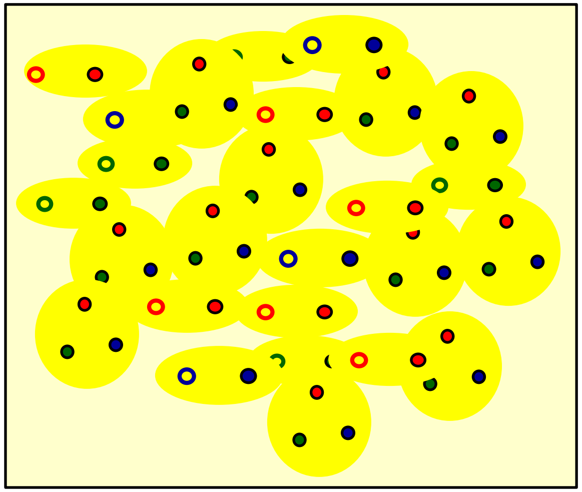
Condensed Matter QCD

Physical picture of deconfinement

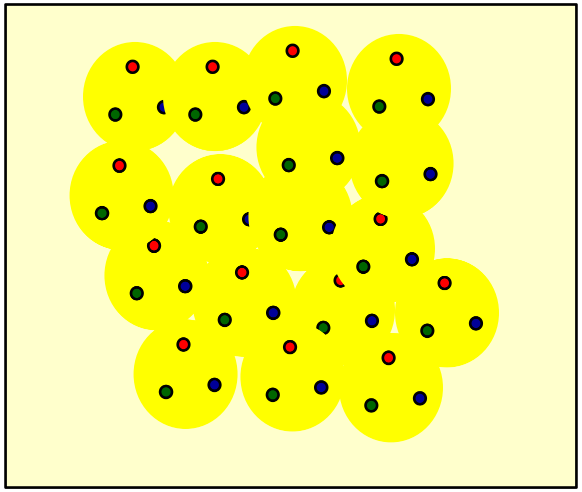
Dilute system of hadrons
at low temperature and density
Quarks-anti quarks confined
inside mesons, qqq in baryons



Higher temperatures,
Large density of hadrons
q qbar do not belong to
individual hadrons:
Transition to QGP phase



Same thing happens for a system
of nucleons at high baryon density,
Small temperature. q qbar do not belong
to individual hadrons : Again,
transition to QGP phase



Note: any concept of **unbinding** of
quarks or **ionization** not relevant here

SYSTEMS WHERE SUCH DECONFINED PHASES COULD OCCUR:

High temperature deonfinement:

In the Laboratory:

Ultra relativistic heavy-ion collision experiments –

Heavy nuclei are collided at ultra-relativistic energies.

Relativistic Heavy-Ion Collider **(RHIC)** at Brookhaven National Laboratory, USA: Collision of Pb-Pb , Au-Au at 200 GeV/A energy in center of mass system (CMS)

Large Hadron Collider **(LHC)** : CMS energies up to 5.5 TEV

It results in production of an extremely dense, hot system of quarks and gluons.

Thus in Lab one is able to create high temperature QGP system.

Correction: One is able to Re-Create .....QGP system

Re-create..... Because

Such a QGP system existed in the Universe long-long ago,
About 13.7 billion years ago, right after the birth of the Universe

The Early Universe:

Very hot stages of the early universe

$T > 100$ MeV (10^{12} K)

when age of the universe was less than few microseconds

during these early stages, it is expected that the universe consisted of QGP (along with plasma of other particles)

Let us take a brief tour of the early Universe to understand this stage

General picture of the evolution of the Universe

Observations made by Edwin Hubble showed(1929) that

All Galaxies are moving away from each other.

(Using Doppler shift of spectral lines).

The Universe is Expanding

The observation of the expansion of the universe, combined with Einstein’s theory of gravity (General Relativity), leads to remarkable Conclusion:

The universe was extremely small in the beginning

It started from a Singularity, with extremely high density

and kept expanding until now.

Initial expansion was very fast,

in some sense like a Gigantic Explosion .

This is: **The Big Bang Theory of the Universe**

Earliest stage of the Universe, which we can discuss with some confidence is known as **The Planck Stage**

This is when the universe was **10^{-43} sec** old after the Big Bang

Density ~ 10^{87} tons/cm^3 , Temperature ~ 10^{32} K

Largest density known in present universe: Neutron stars (density of nucleus): ~ **10^8 tons/cm^3** . Like compressing 10 km high mountain to a size of a cricket ball.

To understand stages earlier than the Planck stage we need a Quantum Theory of Gravity, still lacking (Superstring theory ?,…..)

Universe has been expanding since then, and cooling down:

Present age of the Universe: about 13.7 billion years

Present Temperature ~ **2.7 K,** average density ~ **10^{-29} grams/cm^3**

Planck Stage	**Present Stage**
Universe age t ~ 10^{-43} sec.	t=13.7 billion years
Temperature T ~ 10^{32} K	T = 2.7 K

Universe has been expanding and cooling during this period

We had just concluded that when temperature becomes higher than than 10^{12} K (~ 100 MeV), we should get deconfined QGP phase

From the above picture, we see that there must be some time $\mathbf{t_C}$ such that when Universe was younger than $\mathbf{t_C}$, its temperature must have been higher than 100 MeV

Thus for times earlier than $\mathbf{t_C}$

the Universe must have been in the QGP phase.

Calculating the evolution of the universe (using Einstein’s equations), **one finds that $\mathbf{t_C}$ ~ few microseconds**

Thus, when the universe was younger than few microseconds, it consisted of a hot plasma of quarks, gluons (QGP)

Along with the plasma of other elementary particles: electrons, muons, photons, neutrinos,..

Hadrons are the smallest compound structures we know.

Thus: when the Universe was younger than few microseconds, it was filled with plasma of elementary particles.

Note: Such highly dense, hot QGP has been created in laboratory with **Ultra-Relativistic Heavy-Ion Collision Experiments**

In this sense, one has re-created such an early stage of the universe in laboratory: Insight into the early universe

However: here, in Laboratory, only gets plasma of quarks and gluons only

Electrons, photons,…. do not form a thermally equilibrated plasma

Because mean free path for their scattering is much larger than the size of the system created.
So, there is a difference from the early Universe…….

Relativistic heavy-ion collision experiments (RHICE):

Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory, USA:

Collision of Pb-Pb , Au-Au at 200 GeV/A energy in center of mass system (CMS) for each colliding pair of proton/neutron (nucleons) .

Large Hadron Collider (LHC) :
CMS energies up to 5.5 TEV

RHIC estimates:
Energy density > 10 GeV/fm^3 , Temperature >~ 250 MeV

Lattice Gauge Theory Calculations:
Critical temperature ~ 170 MeV
Critical energy density ~ 1 GeV/fm^3

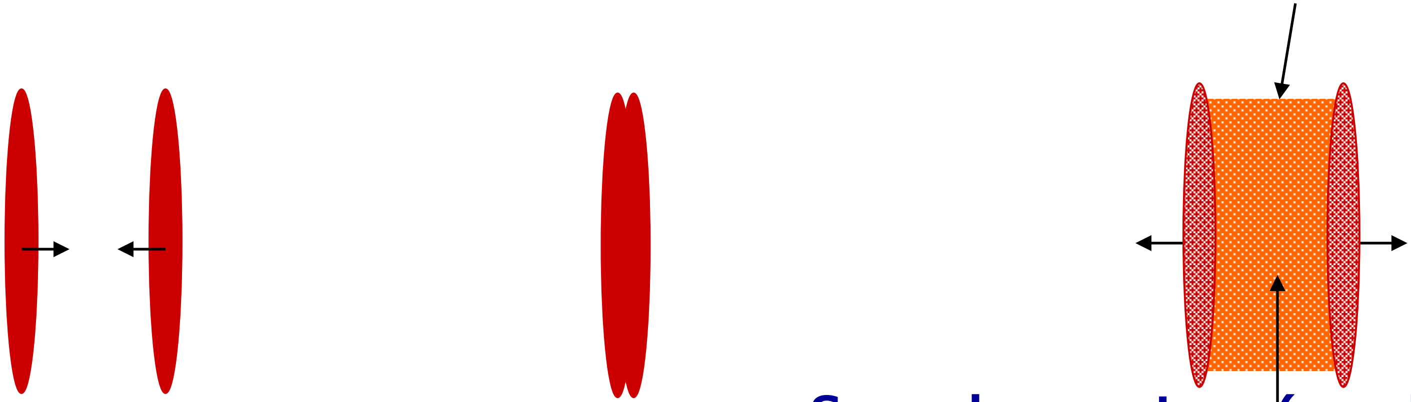
Thus expect that QGP created in these experiments

Basic Physical Picture of Relativistic Heavy-ion Collisions

Ultra relativistic heavy-ion collisions –
200 GeV energy for each colliding nucleon pair (for RHIC)

Mass of a nucleon ~ 1 GeV
So Lorentz Gamma factor for Length Contraction ~ 100

Nucleus diameter ~ 15 fm
Lorentz contraction flattens it
like a Chapati
(~ 1 fm, wee partons)



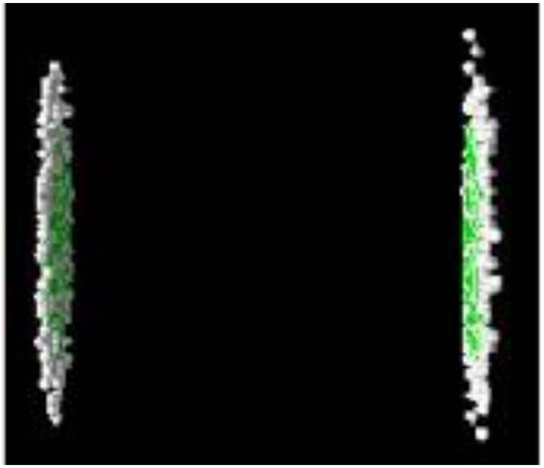
Initial **QGP**: Rapid Longitudinal expansion

Ultra-relativistic Nuclei approaching

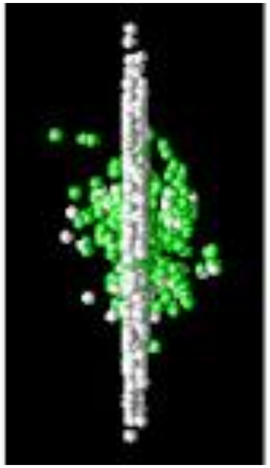
Overlap

Secondary partons (quarks, gluons) thermalize (in about 1 fm time) and form QGP between receding nuclei

A Pictorial View of Heavy-Ion Collicion at RHIC

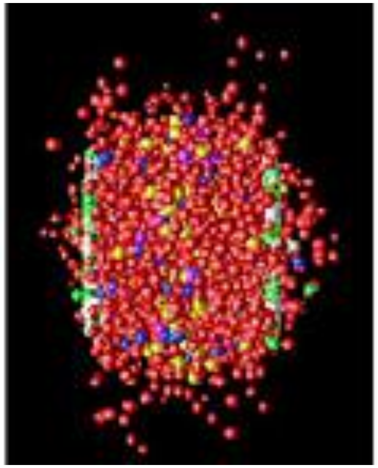


Thin Pancakes
Lorentz γ=100

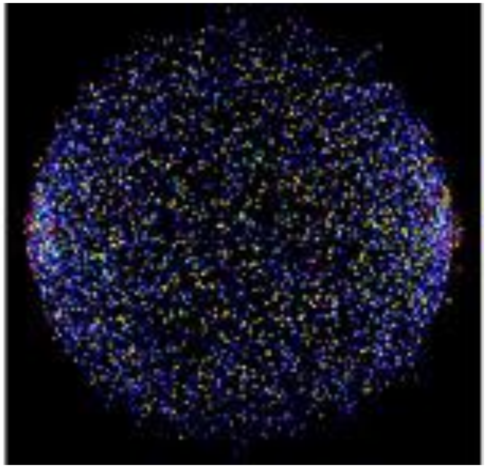


Nuclei pass
throuth each
other < 1 fm/c

(Asymptotic
freedom)



Huge Stretch
Transverse Expansion
High Temperature (?!)
QGP formation



Peter Steinberg, BNL

The Last Epoch:
Final Freezeout--
Large Volume

QGP phase in these experiments is only a transient stage,
lasts for ~ 10^{-22} sec.

As expanding QGP cools, quarks combine to form hadrons

Hadronic system keeps expanding. Eventually it is so dilute that Hadrons do not scatter with each other much and system falls out of equilibrium.

This is called the Freezeout stage

After this, hadron system keep expanding, freely, maintaining the values of their energies/momenta at the freezeout stage

These hadrons (or their decay products) are detected by Detectors surrounding the collision point.

Thus, the only information one has about early stages like QGP etc. has to be obtained from the properties of these detected particles.

By analyzing properties (energy, momentum etc.) of these particles, one has to infer the possibility of existence of QGP during early stages in these collisions.

Further, one has to determine properties of this QGP, such As equation of state, viscosity etc.

For this one looks for specific features of particle properties which contain such information.

These are known as signals for QGP:

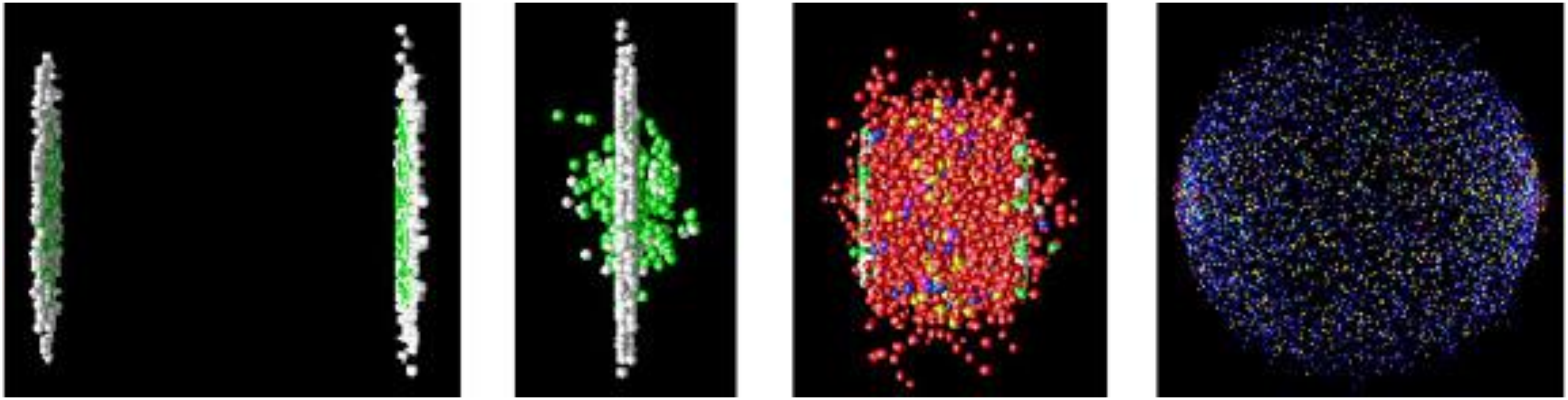
Photon production, lepton production, suppression of quarkonia (heavy quark-antiquark system), Strangeness enhancement, Elliptic flow, etc. are some such Signals.

All these signals have been detected, and they suggest very strong Possibility that QGP has been created in these experiments.

Most surprising observation relates to the signal: Elliptic Flow

Central Collisions: When nuclei collide head-on

Peter Steinberg, BNL



QGP undergoes azimuthally Symmetric hydrodynamic expansion

Final detected Particles

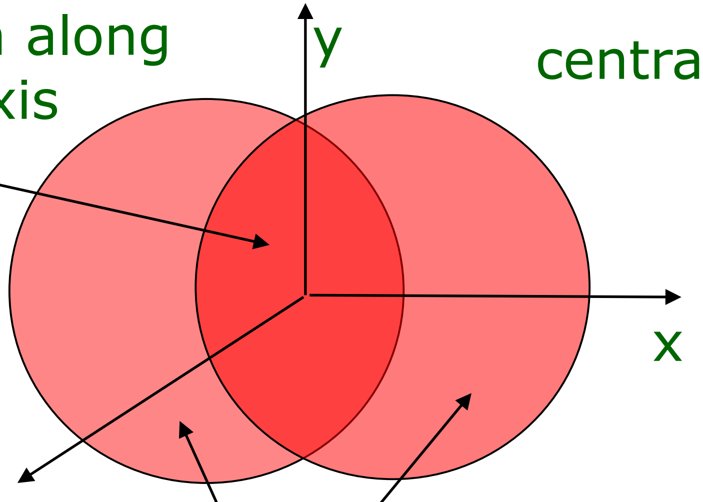
These are called Central Collisions.

Resulting QGP system initially expands with azimuthal symmetry in the transverse plane.

Eventually, it becomes almost spherically symmetric

Here: Momentum distribution of finally detected particles has perfect azimuthal symmetry

Elliptic Flow arises in non-central collisions: where resulting QGP region is anisotropic

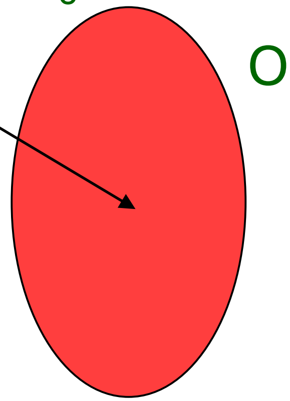


collision along
z axis

Collision
region

Spectators

central pressure = P_0



Outside
P = 0

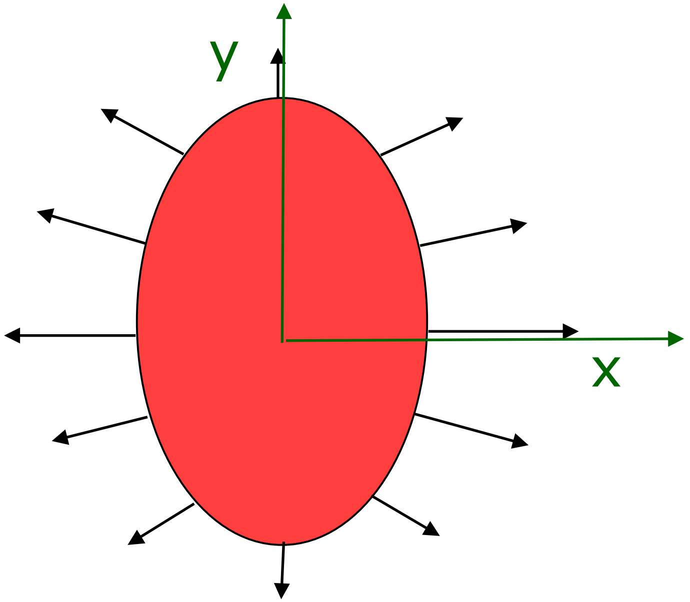
Anisotropic
shape implies:

$$\frac{\partial P}{\partial x} > \frac{\partial P}{\partial y}$$

Important: Initial particle momentum distribution isotropic :

Anisotropic pressure gradient implies: buildup of plasma flow larger in x direction than in y direction.

Momentum distribution develops anisortopy due to this larger flow in x direction



This momentum anisotropy is characterized by the **2nd Fourier coefficient V_2 (called Elliptic flow)**.

Higher Fourier coefficients denoted as V_n, the higher flow coefficients.

Note: Elliptic flow strong evidence for thermalization. Pressure Gradient necessary to give anisotropic momentum distribution

Observed value of V_2 fitted with hydrodynamic simulations

Startling results: Data consistent only with extremely low shear viscosity η

Value of shear viscosity to entropy ratio η/s found to be close to the AdS/CFT bound (from String theory) = $1/4\pi$.

Lower than any known liquid.

Why is such a low value of shear viscosity η surprising ?

Recall: Shear viscosity tells how fluid momentum diffuses
when velocity gradients are present.
Faster moving fluid molecules diffuse to other regions with slower velocity, thereby decreasing velocity gradients in time.

Thus, shear viscosity is larger when particles have large mean free path, means they do not scatter much, **e.g. Ideal Gas**

Small shear viscosity requires very small mean free path,
This means large particle scattering, strongly coupled system.

Ideal fluid has zero viscosity

Recall: Expectation of a QGP phase was based on the Asymptotic Freedom of QCD. At high temperature/density quarks/gluons Will be almost free, so they should be in a deconfined QGP phase

Thus QGP should be close to an Ideal Gas system with large η

Instead, observations show, it is close to ideal fluid, very small η

Deep connections between physics of heavy-ion collisions and The Early Universe

Recall: Properties of QGP phase have to be inferred from final hadrons reaching detectors after freezeout stage.

This is quite like using the **Cosmic Microwave Background Radiation (CMBR)**. By analyzing its properties, one determines properties of the Universe during its very early stages.

CMBR: the most important experimental probe in cosmology

Very early universe was filled with extremely hot and dense soup of quarks and gluons and other elementary particles.

Densities and temperatures were so high that photons were in (almost) perfect thermal equilibrium with other particles.

Note: This implies perfect black body spectrum for photons

As the universe expanded and cooled, the radiation in the universe (photons) also cooled, lost energy, and eventually decoupled from matter (when neutral hydrogen formed).

This Stage (surface) of Last scattering (of photons with matter) occurred when universe age ~ 300000 years

(present age of the universe is about 13.7 billion years)

Now the frequency of this radiation is in microwave range with a black body temperature of 2.7 K

This Radiation has been observed and is called:

The Cosmic Microwave Background Radiation: CMBR

CMBR makes it possible to make direct observations into the physics of the Universe at the Surface of Last Scattering

Not only that, precise measurements of CMBR fluctuations enable us to test models of the very early universe which are based on exotic theories of elementary particles: Namely

Inflationary stage: When universe expanded superluminally

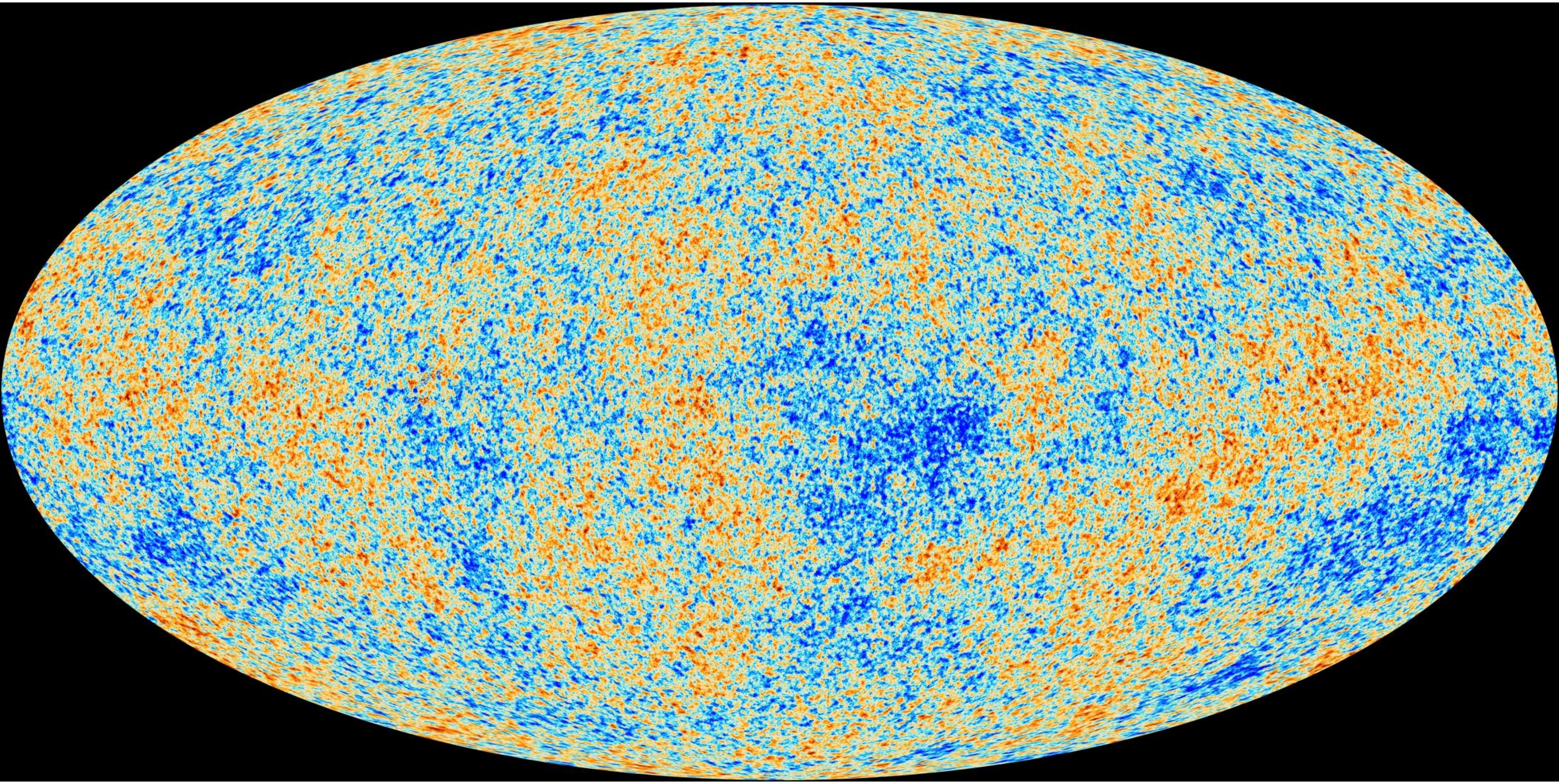
only 10^{-35} sec. after the birth of the universe

Stage of matter-radiation decoupling, t ~ 300,000 years

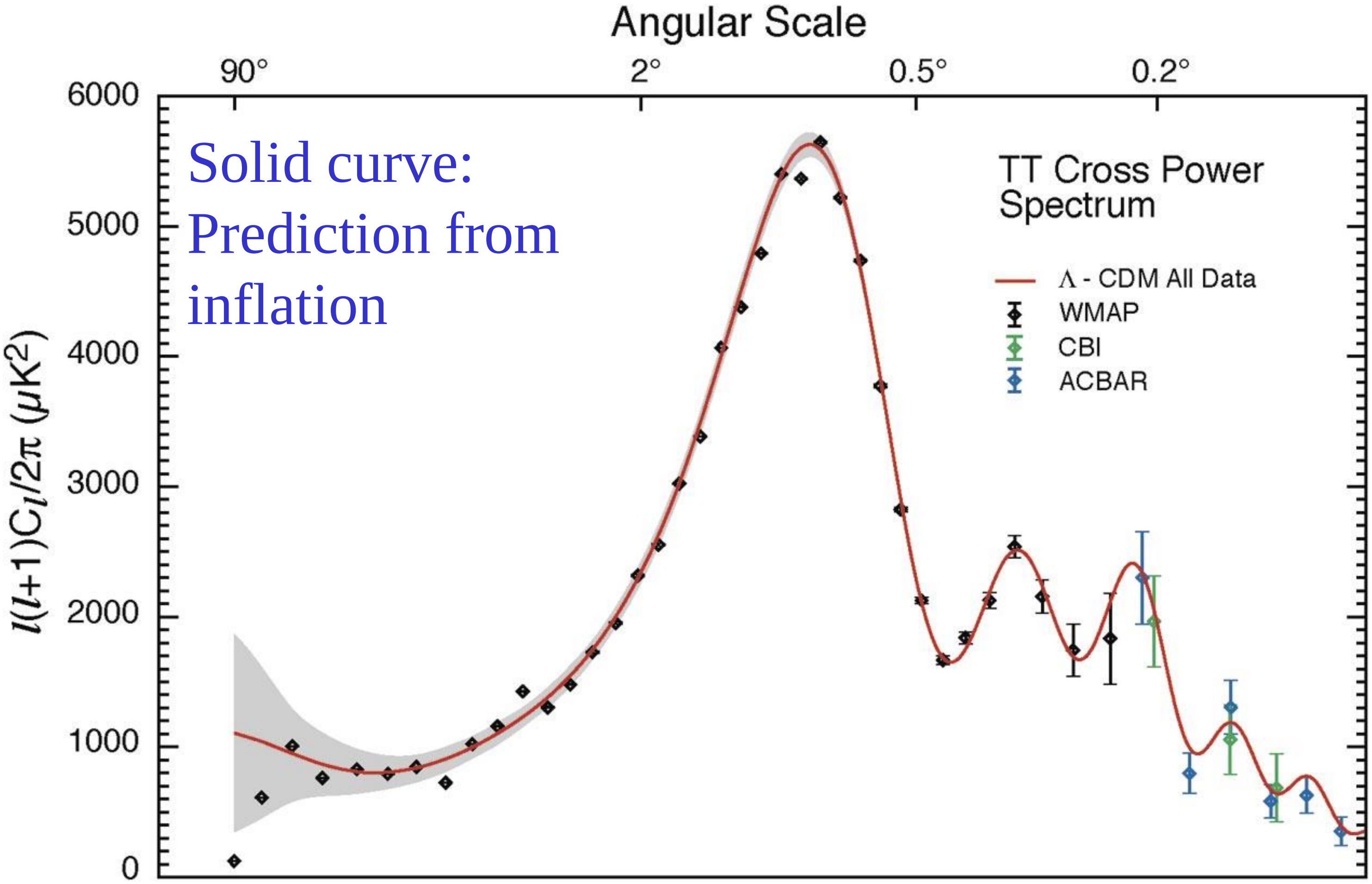
The universe couldn’t be completely homogeneous, otherwise galaxies etc. could not form. So: Initial gas (plasma) was LUMPY. Somewhere denser (hotter), somewhere lighter (cooler).

Thus CMBR should not have same temperature when we look in different directions. These are called CMBR fluctuations and they directly tell us about density fluctuations in the very early stages of the Universe: **Those generated during INFLATION**

Planck data: CMBR fluctuations ~ 0.001 %. Completely consistent with density fluctuations needed for formation of Galaxies etc.



Acoustic peaks in CMBR anisotropy power spectrum (Resulting from coherence and acoustic oscilations of density fluctuations).

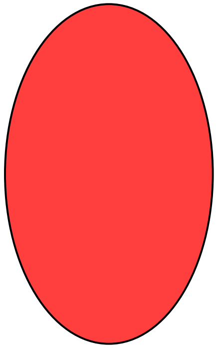


Solid curve: Prediction from inflation

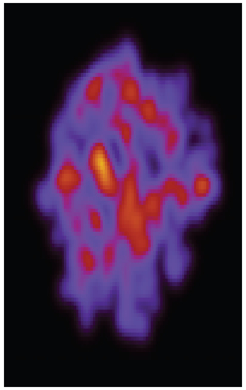
Now: look again at Elliptic Flow in Heavy-ion Collisions

It was known that there are fluctuations present at the initial stage itself.

Thus: situation is
not like this



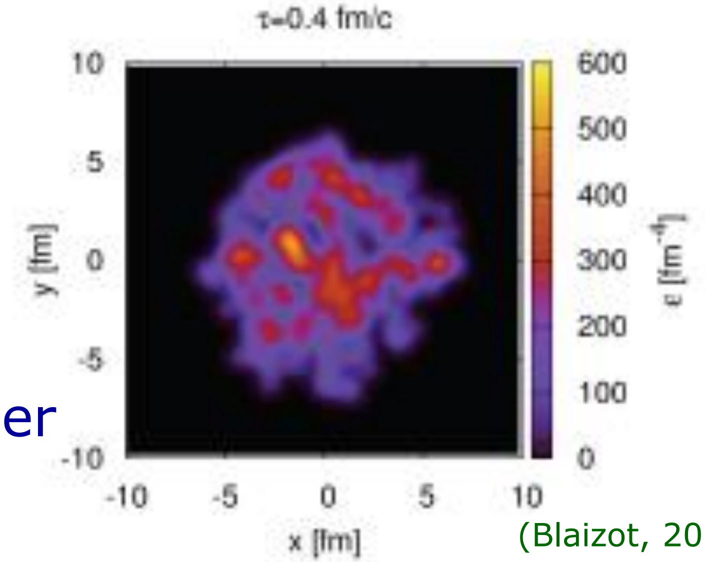
Rather, it
is like this



Even for central collisions, one has strong fluctuations present initially

Thus: Momentum distribution of final detected particles will always have strong anisotropies:

Should be contained in non-zero Fourier Coefficients V_n for large values of n



(Blaizot, 2014)

Note: Evolution of these fluctuations is governed by hydrodynamics,
Just the same way as for the Universe: Gravity only changes
Overall shape of the power spectrum, not the acoustic peaks

Initial state fluctuations and flow coefficients

Lesson: Initial state fluctuations are extremely important, originating from initial conditions (parton distributions) inside the colliding nuclei.

Due to these initial state fluctuations all flow coefficients V_n will be non-zero in general.

CMBR temperature anisotropies analyzed using Spherical Harmonics (As appropriate for the whole sky)

This gives the celebrated Power Spectrum of CMBR anisotropies

Important lesson for heavy-ion collisions from CMBR analysis:

Plot power spectrum for all Fourier Coefficients V_n for azimuthal momentum distribution of particles.

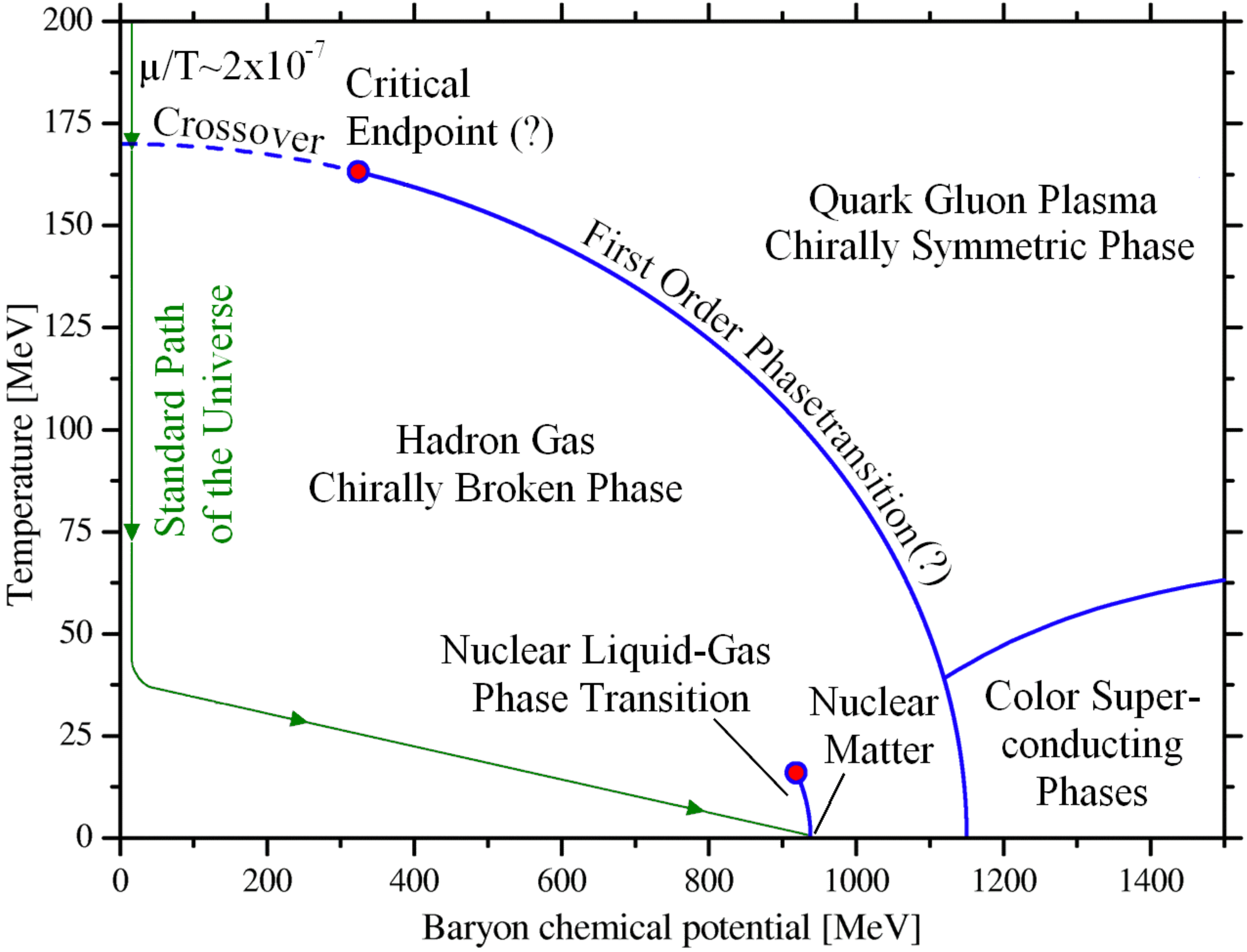
The whole plot will have important information about initial state fluctuations and their evolution.

Note: Physics of flow fluctuations very similar to Inflationary fluctuations. Similar plot as for CMBR expected

Hadrons to QGP: Some non-trivial predictions

Deconfinement transition: Z(3) Symmetry breaking, Walls, strings

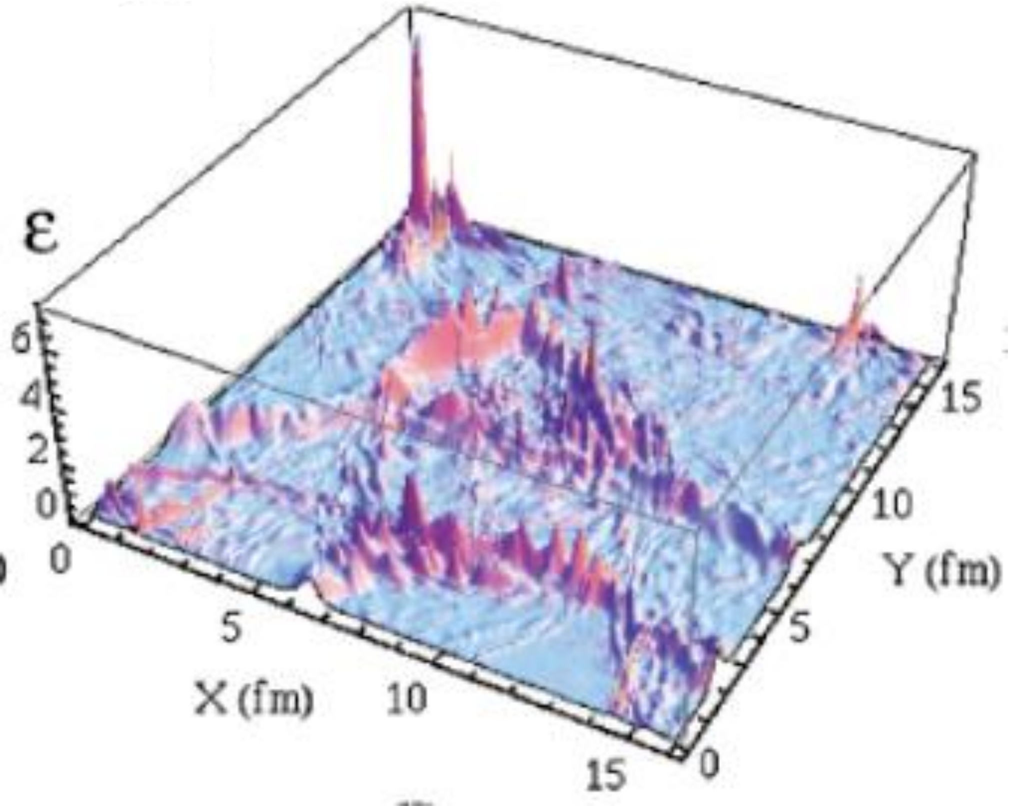
Chiral transition: Disoriented Chiral Condensates (DCC)

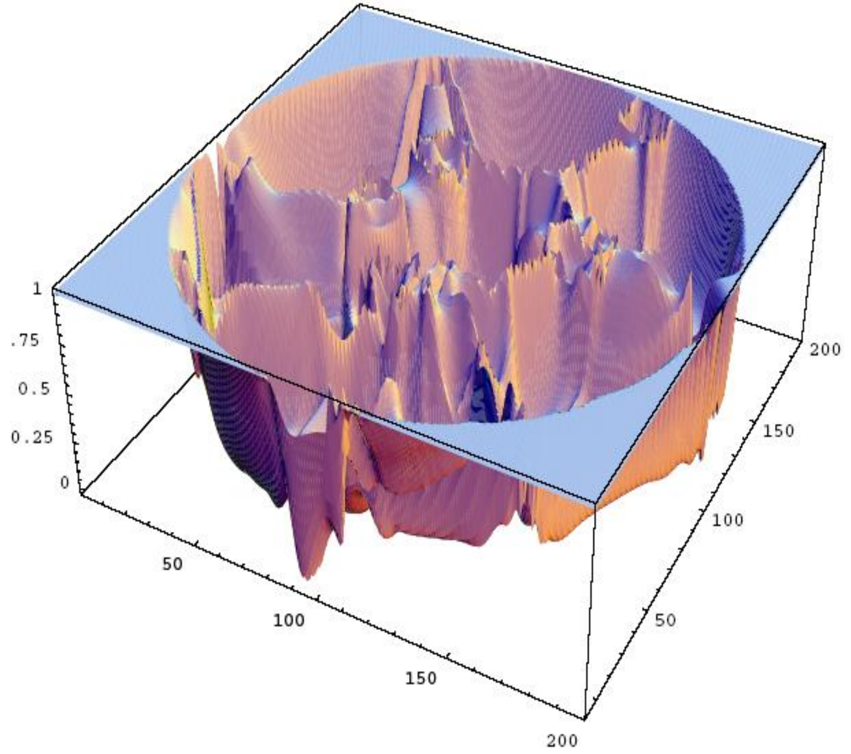


Deconfinment transition: Center Domains and domain walls

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
(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:

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

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)

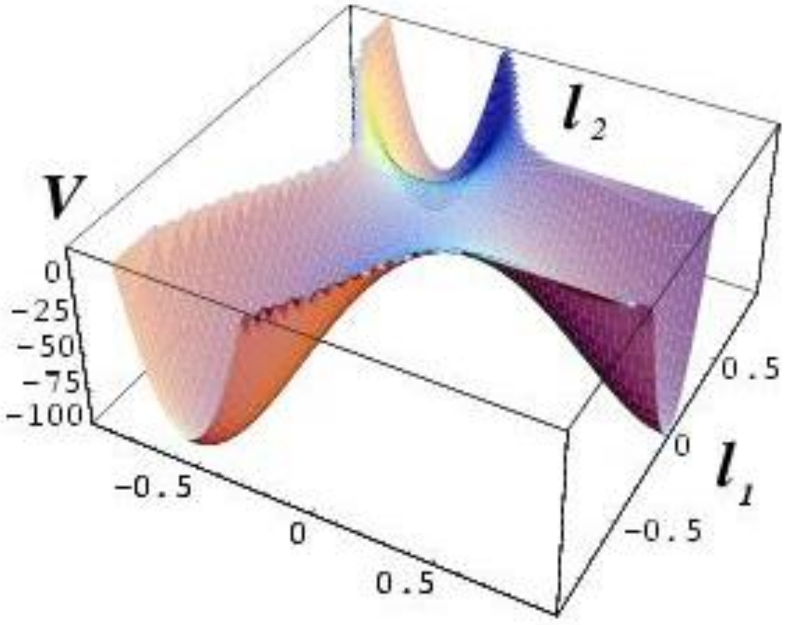
As l_0 transforms non-trivially under the Z(3) symmetry, its non-zero value breaks the Z(3) symmetry spontaneously in the QGP phase. The symmetry is restored in the confining phase.

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

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

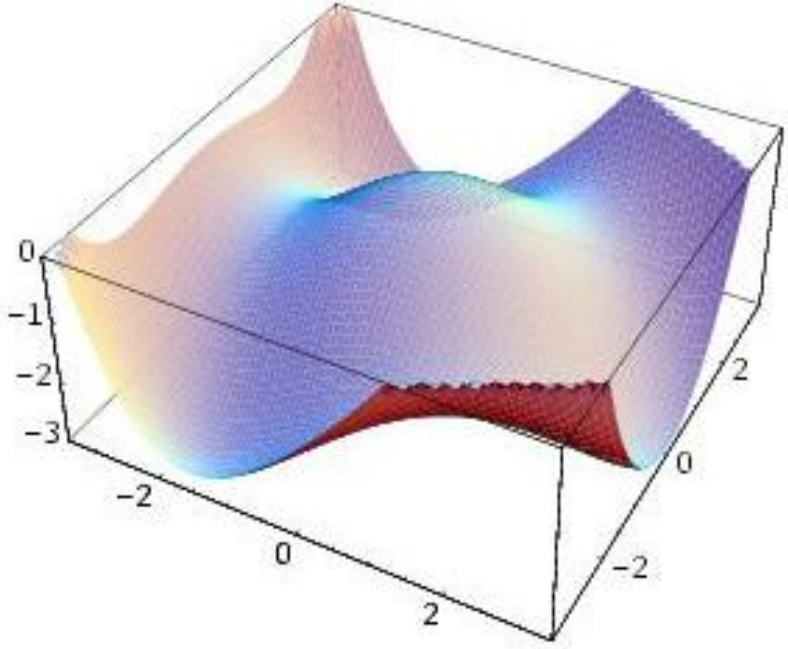
(The only difference is relative heights of barrier between Z(3) vacua)

Polyakov loop case



(a)

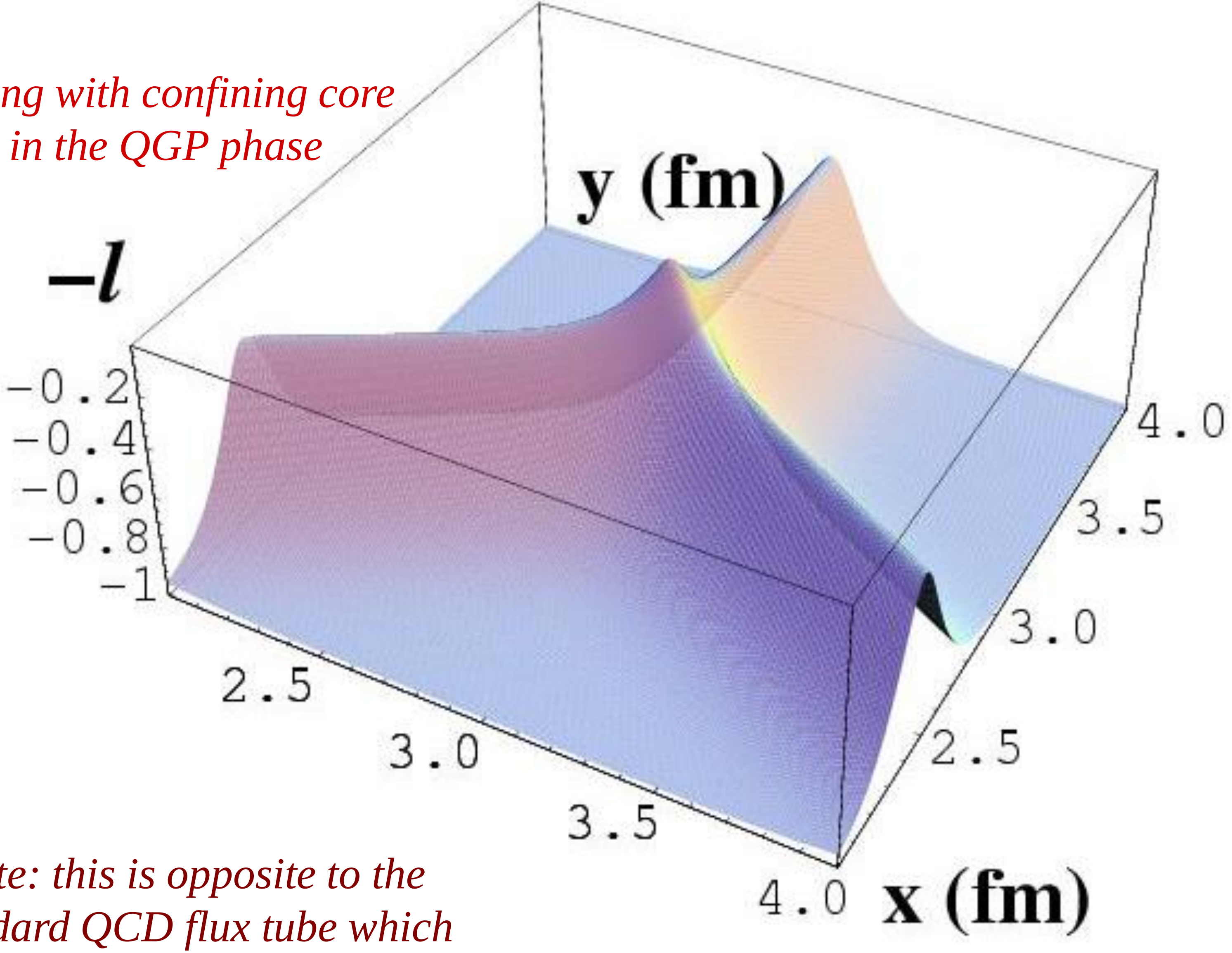
Axionic string case



(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.

Chiral phase transition in QCD: reminder

QCD Lagrangian has $SU(2)_L \times SU(2)_R$ chiral symmetry for two massless flavor case.

This symmetry is broken explicitly by non-zero quark masses.

Hadron spectrum does not reflect this (approximate) symmetry. It only shows approximate SU(2) isospin symmetry.

Conclusion: Vacuum of QCD does not respect chiral symmetry.

Chiral symmetry $SU(2)_L \times SU(2)_R$ *is spontaneously broken to the isospin* $SU(2)_V$ *symmetry*

The order parameter which respects this symmetry breaking pattern is an SU(2) matrix M, which, for linear realization of Chiral symmetry, can be written as:

$$M = \sigma + i \ \pi . \tau$$

Thus, (σ, π) becomes order parameter with O(4) transformations

Chiral phase transition and Disoriented Chiral Condensate (DCC)

Spontaneously broken chiral symmetry can get restored at high temperatures.

Using (σ,π) order parameter, we can write down the finite

temperature linear sigma model effective potential

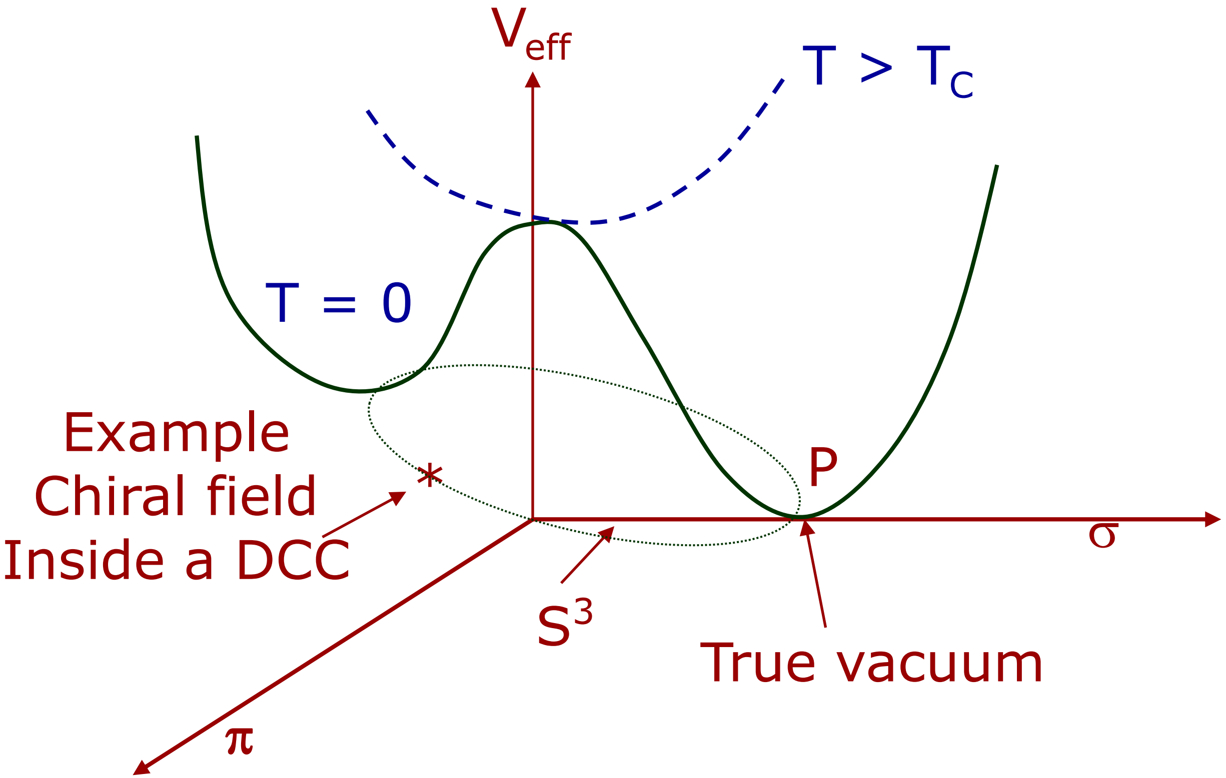
which describes the Chiral phase transition:

$$V_{eff} = m_\sigma^2 (\sigma^2 + \pi^2)(T^2/T_c^2 - 1)/4 + \lambda (\sigma^2 + \pi^2)^2 - H\sigma$$

The last term breaks the chiral symmetry explicitly, and leads to non-zero pion mass.

Parameter values: m_σ = 600 MeV, $\lambda \sim 4.5$, $H = (120$ MeV$)^3$,

$T_c \sim$ 200 MeV



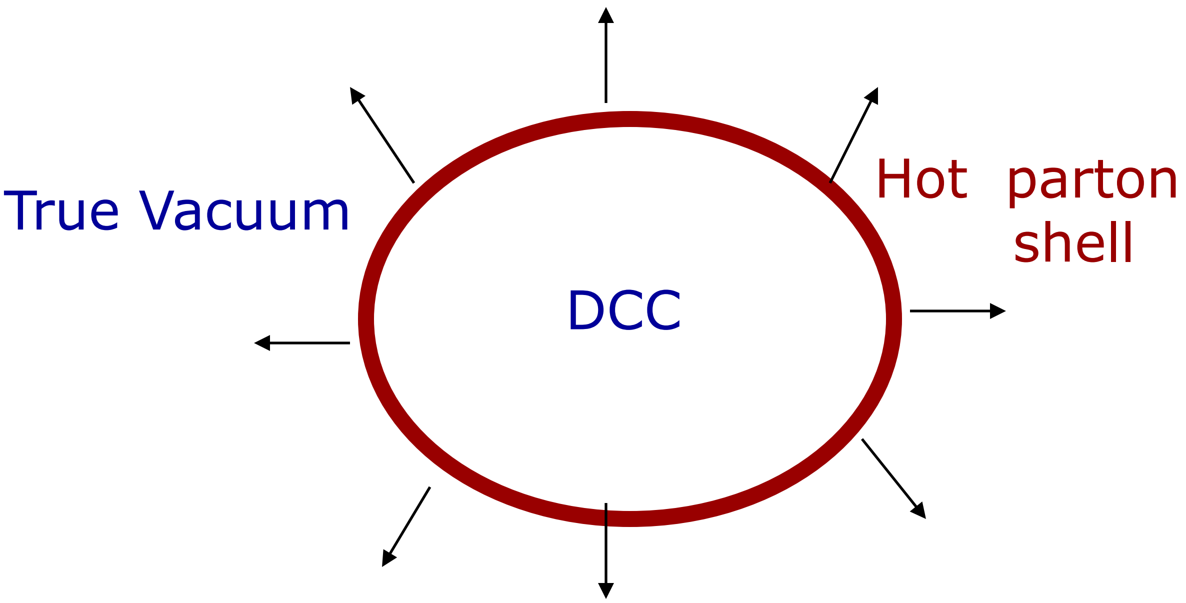
Bottom of V_{eff} tilted due to non-zero pion mass.
Inside a DCC domain, chiral field does not take value P. Due to higher potential energy, this field rolls down towards the true vacuum P and oscillates about it. Result: Coherent pions
Early works by – Anselm ('89), Blaizot and Krzywicki ('92)

DCC pions at very low P_T , basically given by inverse DCC domain size.

Bjorken, Kowalski, and Taylor ('93) suggested DCC formation
For high multiplicity hadronic collisions.

Motivation from Centauro Events in cosmic ray collisions –
(large fluctuations in neutral to charge pion ratio seen)

Baked Alaska Scenario



Inside a DCC domain, chiral field takes a well defined, uniform value

Observable consequences of DCC:

The most dramatic, and hence most discussed signature concerns the ratio of number of neutral pions to all pions

$$f \quad = \quad \frac{n_{\pi 0}}{n_{\pi 0} \;+\; n_{\pi +-}}$$

If pions are incoherently produced, then the probability distribution of f will be a Gaussian, peaked at 1/3.
For pions emitted from a DCC domain, the probability distribution of f is:

$$P(f) \quad = \quad \frac{1}{2\,(f)^{1/2}}$$

This follows as number of pions is proportional to square of field amplitude, and all points on the vacuum manifold S^3 are equally likely as initial conditions.

Assume $n_{\pi_i} \sim \pi_i^2$, then

$$f = \frac{\pi_3^2}{\pi_1^2 + \pi_2^2 + \pi_3^2}$$

To calculate this value, define angles on S^3 as,

$$(\sigma, \pi_3, \pi_1, \pi_2) = (\cos\theta, \sin\theta\cos\phi, \sin\theta\sin\phi\cos\eta, \sin\theta\sin\phi\sin\eta)$$

$$f = \frac{\sin^2\theta\cos^2\phi}{\sin^2\theta\,(\cos^2\phi + \sin^2\phi)} = \cos^2\phi$$

Assuming all values on S^3 to be equally probable, P(f) is determined by

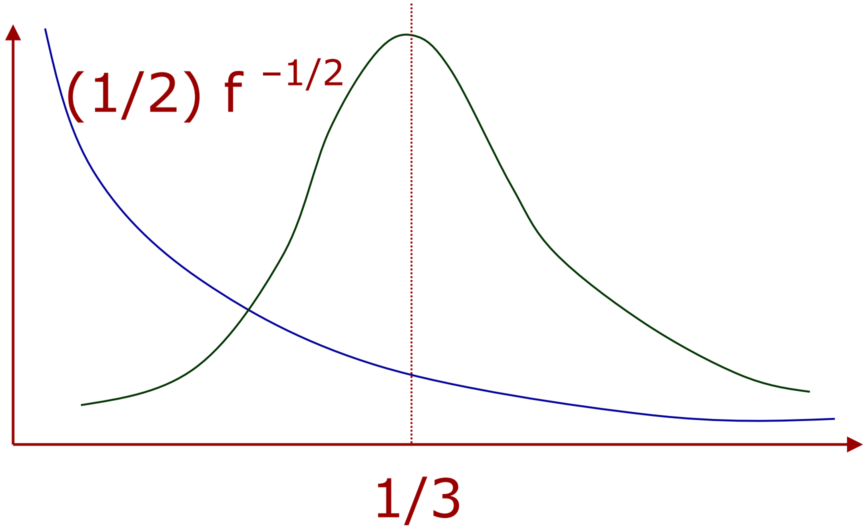
$$\int_{f_1}^{f_2} P(f)df = \frac{1}{\pi^2}\int_0^{2\pi} d\eta \int_0^{\pi} d\theta \sin^2\theta \int_{\cos^{-1}\sqrt{f_1}}^{\cos^{-1}\sqrt{f_2}} d\phi \sin\phi$$

$$\text{R.H.S.} \sim \sqrt{f_2} - \sqrt{f_1}$$

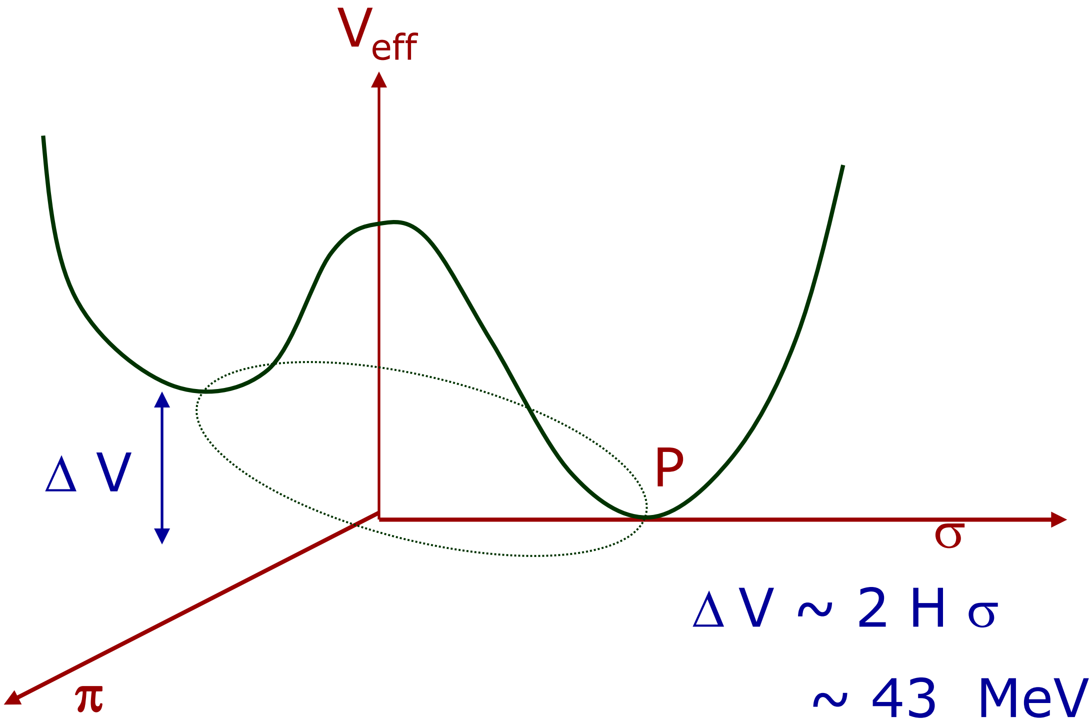
This implies, $P(f) = \dfrac{1}{2\sqrt{f}}$

Since then $\int P(f)df \sim \sqrt{f}$

$P(f) = (1/2)\, f^{-1/2}$ distribution, expected of DCC pions, differs Markedly from the Gaussian one, especially for small f.



Significant departure from the value 1/3 for P(f) can provide the Cleanest evidence for DCC formation,
Hence for chiral Symmetry restoration.



$\Delta V \sim 2 H \sigma$

~ 43 MeV/ fm^3

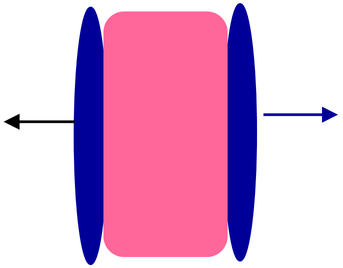
To get an idea of numbers, note that maximum energy density in A DCC domain is about $2 H \sigma$ (Symmetry breaking term in V_{eff} is $H \sigma$, and $\sigma \sim 100$ MeV, $H = (120 \text{ MeV})^3$

Thus number of pions emitted from a DCC domain of radius about 3 fm (which is very optimistic) is $\sim 43(4\pi/3)\, 3^3/140 \sim 30$

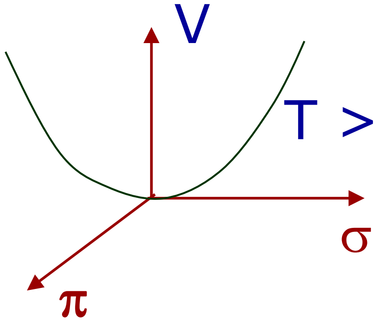
This is small compared to the large background of non-DCC pions. But DCC pions have low P_T .

Basic Picture of DCC Formation in Heavy-ion Collisions:
First take $m_\pi = 0$, similar picture valid for non-zero m_π

Receding nuclei



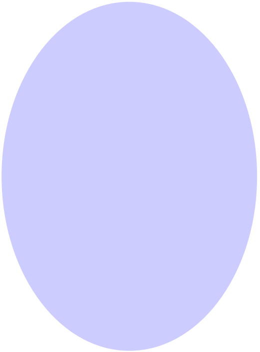
Hot QGP, $T >> T_C$



$T >> T_C$

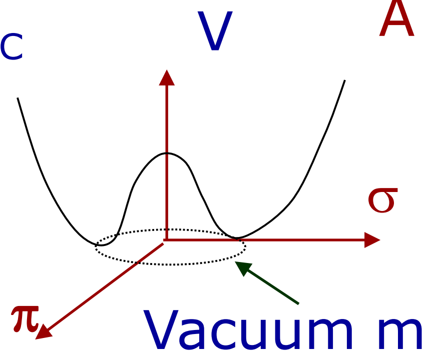
Chirally Symmetric phase

A portion of plasma



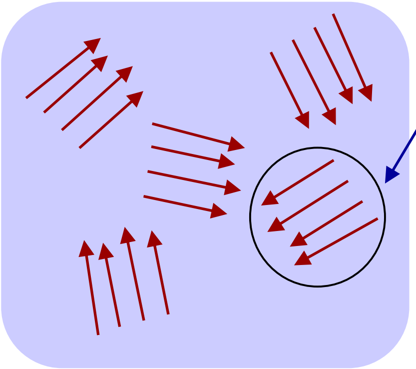
Expanded plasma, $T << T_C$

$T << T_C$



Vacuum manifold a 3-sphere S^3

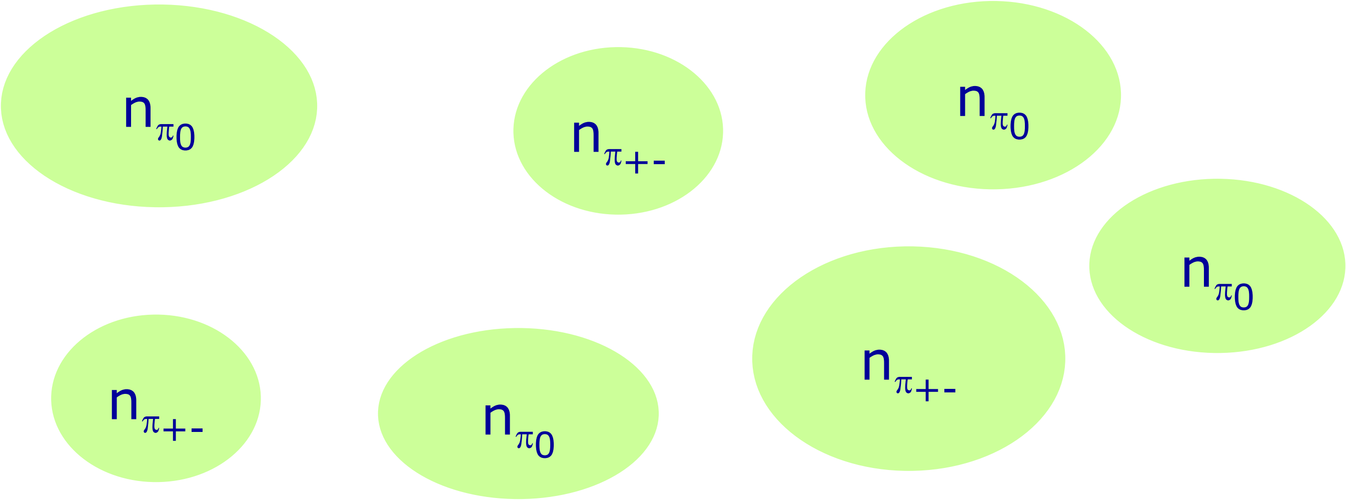
A DCC Domain



Chiral symmetry spontaneously broken

Thus: heavy-ion collisions necessarily give multiple DCC domains

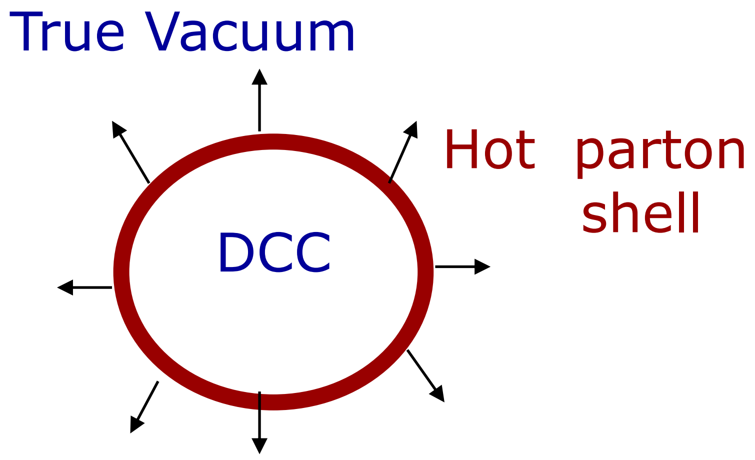
Signal is not expected to be clean if many DCC domains form:



Signals from many DCC domains will combine to give Gaussian distribution at 1/3. Though, the width of this Gaussian will increase with the number of pions from each DCC domains.

Difficult to get large and few DCC domains. If size smaller than 2-3 fm, it may be difficult to detect even from pion fluctuations.

Original Baked Alaska Scenario (hadron-hadron collisions) :



True Vacuum

Hot parton shell

DCC

Here, it is simply assumed that hot expanding partonic shell may leave behind a single DCC

Why ? Not clear. Also, what is meant By *hot parton shell* ?

If one is assuming QGP formation initially, then situation should be same as heavy-ion case (i.e. small DCC).

If not, then how does one Disorient the vacuum ?

For pp collisions, QGP formation was not expected (really ?)

New Possibilities with high multiplicity collisions at LHC:

Collective effects indicate equilibrium being achieved

Energy scales imply: Chiral symmetry restoration quite likely

pp collision: Small initial plasma volume, so small DCC

But likely to be only one DCC in a given event

Leading to clean signal of coherent pions.

This is much closer to the original picture of DCC

Much excitement about DCC earlier,

Renewed efforts needed now, with new possibilities
For these high multiplicity PP collisions.

So far we discussed QGP at high temperature:

Our search for such a QGP system started with Cosmos (early stages of the Universe), down to Laboratory searches

Now let us discuss the other extreme regime:
High Baryon Density QGP

Searches for this regime are being carried out in Heavy-ion collision experiments **at lower collision energies (?)**

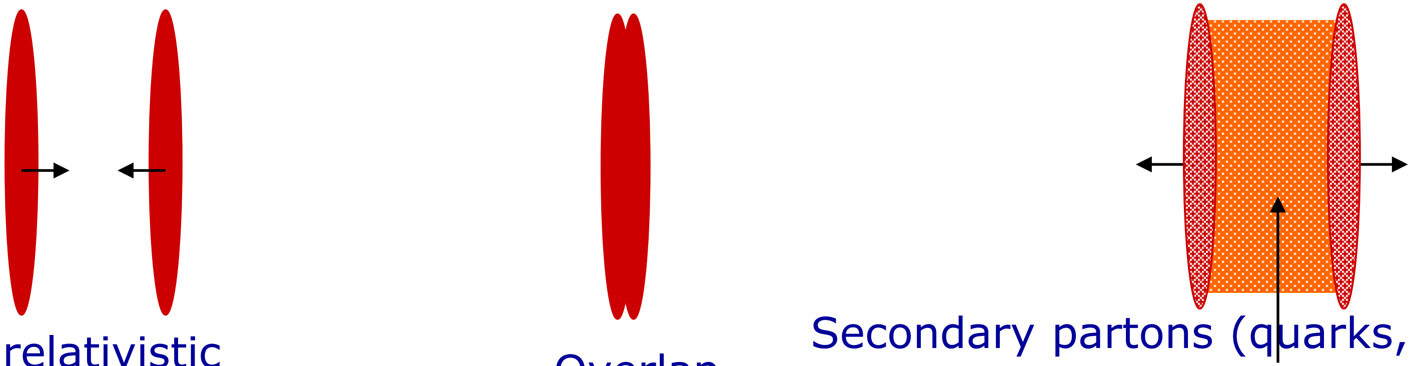
RHIC with low energy collisions (Beam Energy Scan program)
few tens of GeV center of mass energy

Dedicated experiments: **FAIR** in Germany and **NICA** in Russia
Attempts to create densities similar to that inside a neutron star

Largest possible baryon densities anywhere in the universe can occur inside neutron stars, or inside proto-black-holes.

Exotic phases of QCD may be realized in these cores.

Recall: Basic Picture of Relativistic Heavy-ion Collisions



Ultra-relativistic
Nuclei approaching

Overlap

Secondary partons (quarks, gluons)
thermalize (in about 1 fm time) and form
QGP between receding nuclei

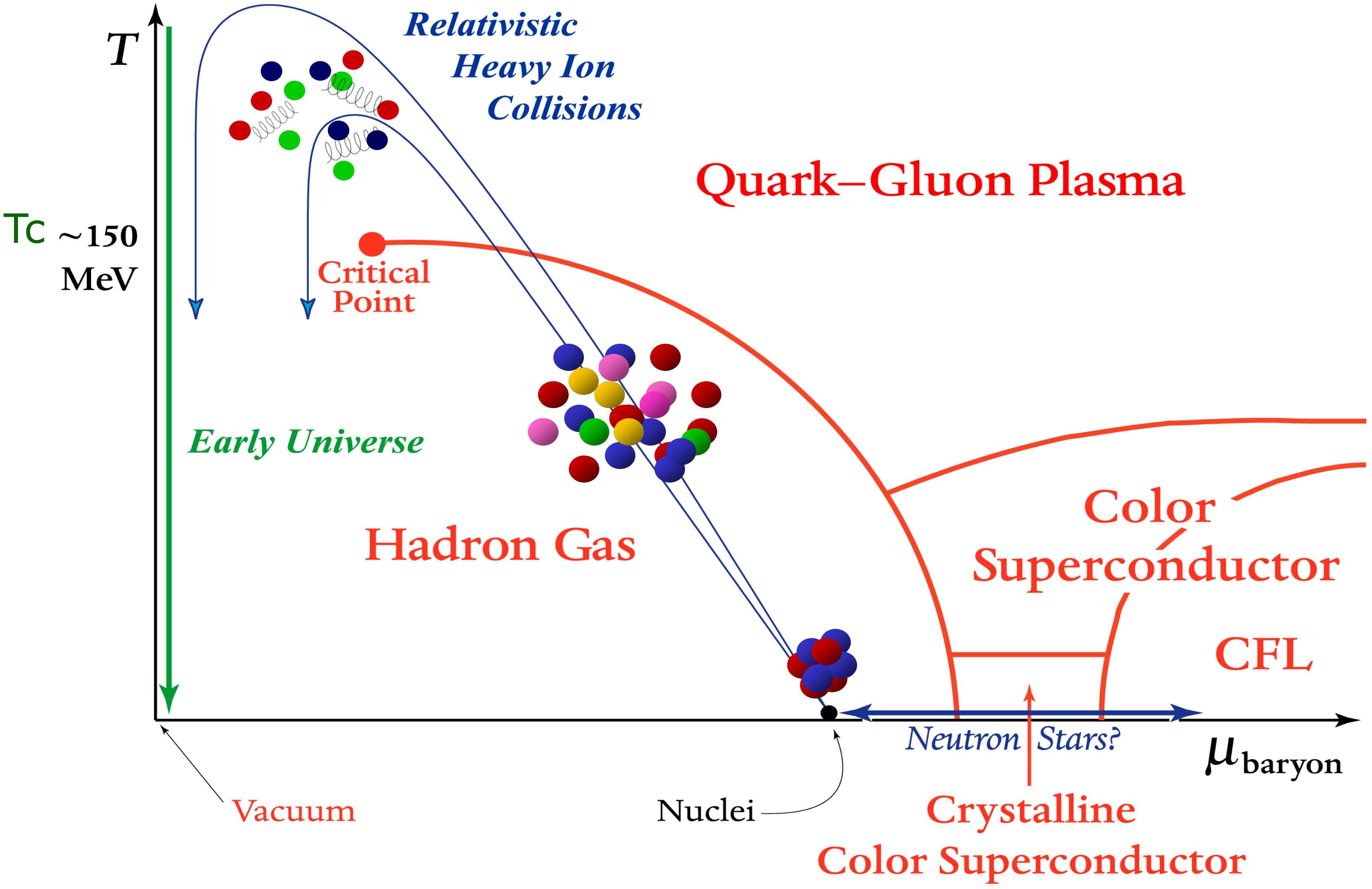
As the collision happens at ultra-relativistic energies, colliding Quarks (contained inside protons, neutrons of the two nuclei) interact very little with each other.

This is due to Asymptotic Freedom of QCD
Most colliding (primary) quarks basically go through each other

While scattering, they still create lot of other particles, gluons, quarks/antiquarks. This secondary parton system has almost zero baryon number (quarks have baryon number 1/3, antiquarks -1/3)

If we want high baryon number density, primary colliding quarks must stop in the middle. Low collision energy required.

Phase Diagram of Nuclear Matter



Neutron stars:

Neutron stars form in supernova explosions.
Mass *of the* order of 1 -2 solar mass; R*adius about 10 km*

Central density *as high as 5* to 10 times the nuclear equilibrium density *of* 0.16/fm^3. About 10^8 tons/cc.

Initial temperature ~ 10 -30 MeV (10^{11} K)
Rapidly cools to T below 0.1 MeV (10^9 K) within minutes by neutrino emission. Subsequent slow cooling.

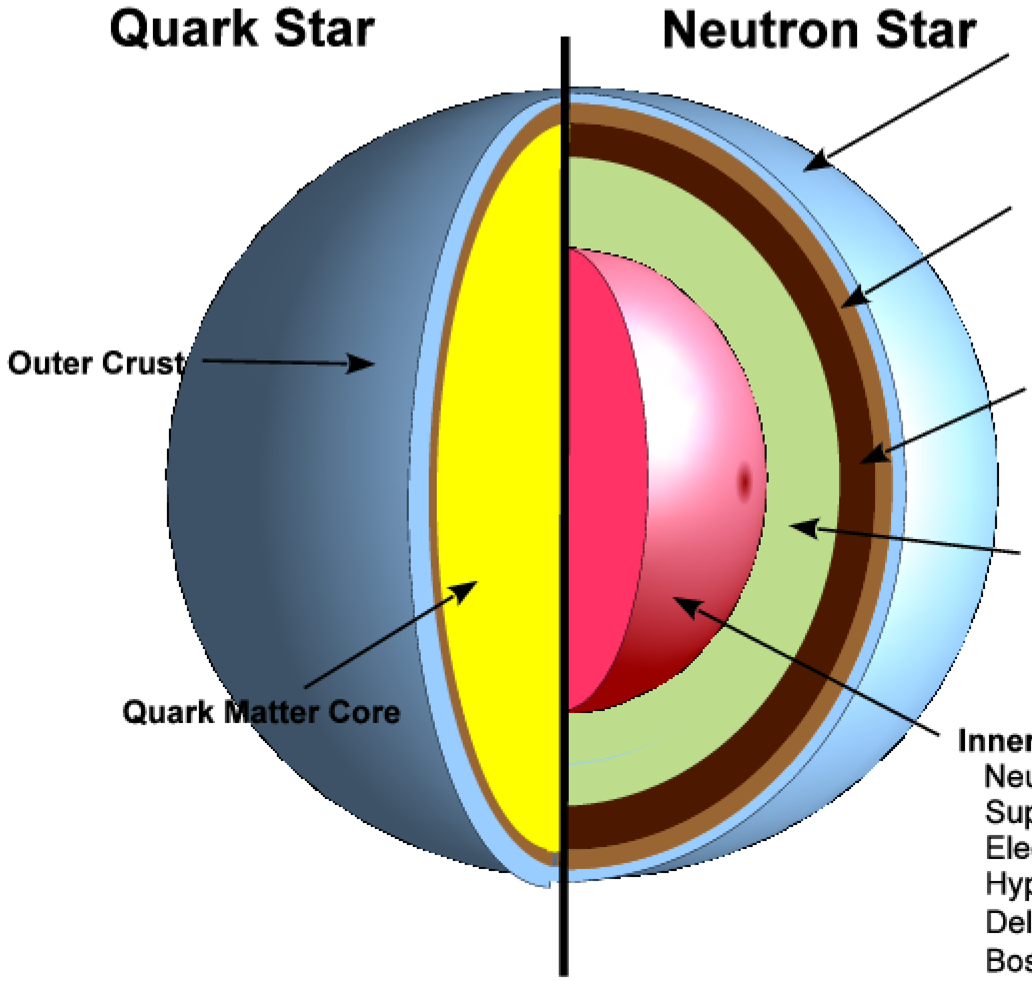
Excellent laboratory for detecting any new weakly interacting Particle: (axions, KK gravitons from superstring theory)

which can get out from the core with little scattering, further cooling the star)
Has been used to put strong constraints, e.g. on extra dimensions.

A neutron star is one of the densest forms of matter in the observable universe.

Possibilities for the core structure of a neutron/quark star

Radius about 10 km, mass 1 – 2 solar masses (from internet)



Quark Star

Neutron Star

Outer Crust

Quark Matter Core

Surface:
Hydrogen/Helium plasma
Iron nuclei

Outer Crust:
Ions
Electron gas

Inner Crust:
Heavy ions
Relativistic electron gas
Superfluid neutrons

Outer Core:
Neutrons, protons
Electrons, muons

Inner Core:
Neutrons
Superconducting protons
Electrons, muons
Hyperons (Σ, Λ, Ξ)
Deltas (Δ)
Boson (π, K) condensates
Deconfined (u,d,s) quarks / color-superconducting quark matter

Superfluid interior of neutron star:

Nucleons inside neutron star form a highly degenerate system.
(Temperature of few MeV << chemical potential ~ 1 GeV)

Yukava one pion exchange potential for N-N interaction is attractive:

Cooper problem:
Situation just like electrons in condensed matter systems forming
Cooper pairs and leading to Superconducting phase

Any attractive interaction destabilizes Fermi surface

Formation of Cooper pairs of neutrons at the Fermi surface.

leading to superfluid state for neutrons

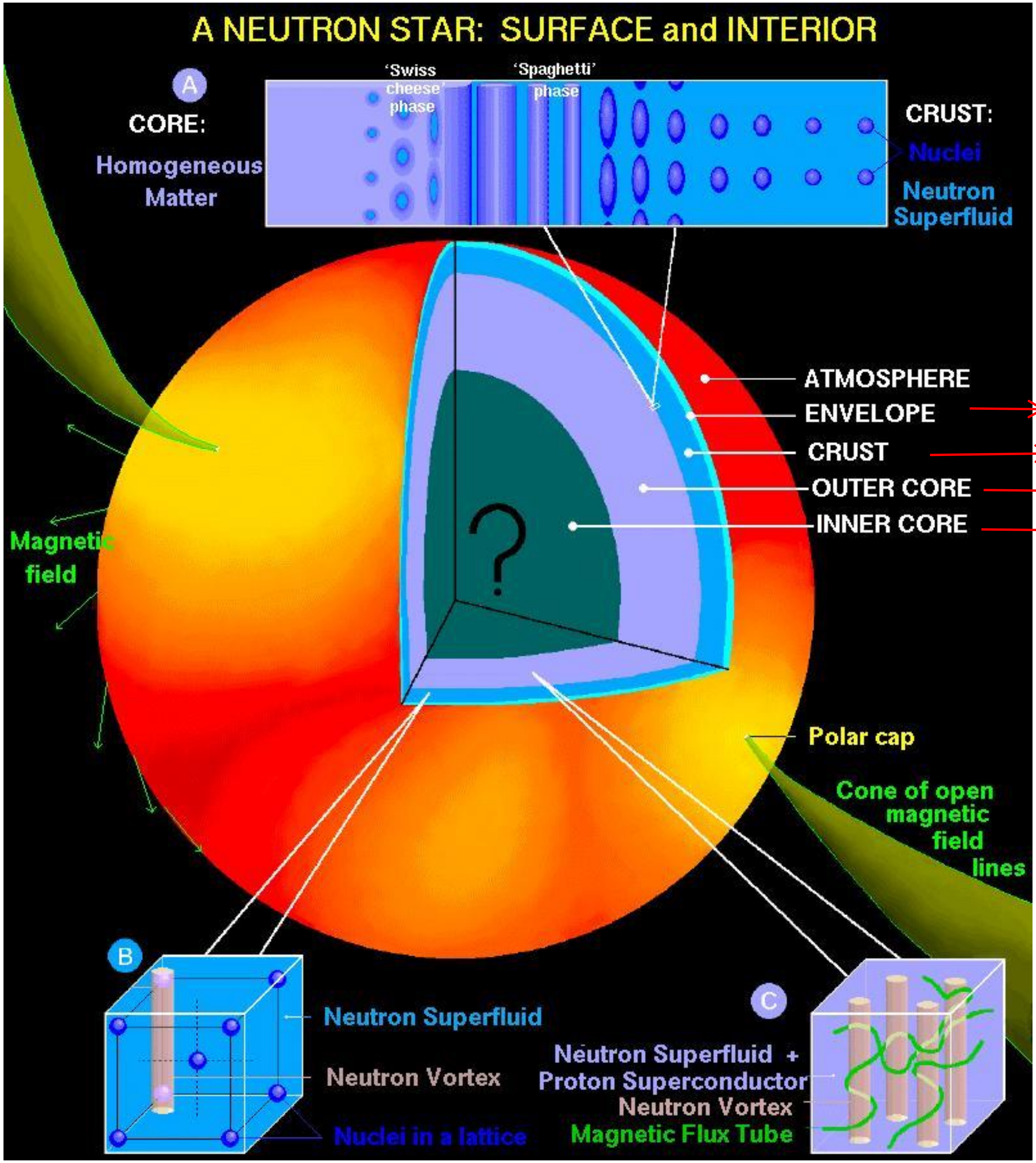
(superconducting state for protons).

Inevitable prediction: Superfluid vortices:
Strong observational evidence

Inner Core:
Size ~ 1 Km
QCD phases:
QGP, CFL, etc.

Outer Core:
Size ~ 9 Km
Superfluid
Phases of
Nucleons

Superfluid
Vortices play
Important role
in glitches



(from Internet)

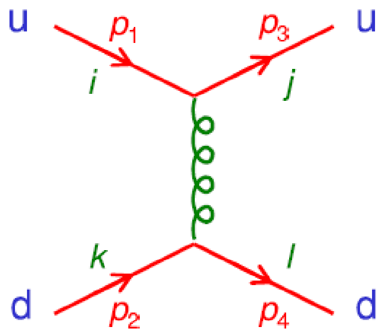
→ 0.2 km
→ 1 km
→ 9 km
→ 1 km

Exotic QCD phases at very high baryon density:

At ultra-high baryon density – very large chemical potential.
~ 500 MeV for quarks.
asymptotic freedom makes Perturbative calculations reliable.

Quark-quark interaction: One gluon exchange good approximation

i,j,k,l = 1,2,3 (or r,g,b) refer to colors of
u and d quarks



Note: Amplitude is the same as that for the QED process
$e^- \mu^- \longrightarrow e^- \mu^-$, with the following changes

1) Replace EM coupling e by strong coupling g_s (i.e. α by α_s)

1) Multiply by color factor $C_F\,(ik \rightarrow jl) = (1/4)\, \lambda^a_{ij}\, \lambda^a_{kl}$

quark-quark can combine as: 3 x 3 = 3* + 6

The color factors for the two representations are :

$$C_F(3^*) = -2/3 \quad \text{and} \quad C_F(6) = 1/3$$

As the EM potential between $e^- \mu^-$ is repulsive, the qq potential is attractive in the 3* channel, and repulsive in the 6 channel

Again, Cooper problem:
Any attractive interaction destabilizes Fermi surface

BCS pairing of quarks in 3* channel: **Color Superconductivity**

Quark Cooper pair: $< q^{\alpha}_{ia} q^{\beta}_{jb} >$, α,β color, i,j, flavor, a,b spin

Color-Flavor Locked (CFL) phase:

color antisymmetric, spin antisymmetric, ⇒ flavor antisymmetric

Consider most symmetric case: all flavors masssless
(not unreasonable for very high chemical potential)
Special pairing pattern ($^1S_0$ pairing):

$$< q_i^\alpha q_j^\beta > \sim \Delta_{CFL} (\delta_i^\alpha \delta_j^\beta - \delta_j^\alpha \delta_i^\beta) = \Delta_{CFL}\, \varepsilon^{\alpha\beta n} \varepsilon_{ijn}$$

Note: This is invariant under equal and opposite rotations of color and (vector) flavor:

Leads to following spontaneous symmetry breaking

$$SU(3)_{color} \times SU(3)_L \times SU(3)_R \times U(1)_B \rightarrow SU(3)_{C+L+R} \times Z_2$$

Color SU(3) spontaneously broken

Chiral symmetry spontaneously broken, beyond density where chiral symmetry was restored (standard QGP phase)

Spontaneous Breaking of SU(3) color symmetry:

Implies all gluons become massive, no long range color forces
Hence the name: Color superconductor
(Though: the new photon is the usual photon with a small admixture of gluon

$$A^{*}{}_{\mu} = \cos(\alpha) A_{\mu} + \sin(\alpha) G^{8}_{\mu}$$

$$\cos(\alpha) = \frac{g}{\sqrt{(e^2/3)+g^2}} \sim 1$$

α is like the Weinberg angle)

Spontaneous breaking of chiral symmetry,
not by a color neutral $< \bar{q} q >$ condensate

But by a colored condensate: (colored) hadron multiplets

Other possible pairings: 2 light flavors: 2SC pairing
Breaks Color SU(3) to color SU(2) symmetry.

5 out of 8 gluons become massive

Crystalline Color Superconducting phase:

Similar to the LOFF phases in condensed matter systems:

At somewhat lower chemical potentials, quark mass difference becomes important.

Cooper pairing of different quarks (having different Fermi momenta), leads to spatial modulation of the order parameter.
Spontaneous breaking of spatial translations
(and rotation) symmetries.

For SSB G broken to H:
The order parameter space *O* = G/H (The Quotient group, or The Coset space if H is not a normal subgroup of G)

Topological defects resulting from this SSB phase transition are determined by different homotopy groups

$$\pi_n(O) = \pi_n(\frac{G}{H})$$

Relevant values of n = 0, 1, 2,….d where d is space dimension
For d = 3 we have:

Zeroth homotopy group $\pi_0(O)$: Domain wall defects

1st homotopy group $\pi_1(O)$: String defects

2nd homotopy group $\pi_2(O)$: point (monopole) defects

3rd homotopy group $\pi_3(O)$: Skyrmions

Different types of defects lead to completely different density fluctuations, and also to different coarsening of defect network

Different QCD phase transitions correspond to different symmetry breaking patterns: Resulting in different defects.

(1) Transition from Normal to Nucleon Superfluid $^1S_0$ phase

SSB: G = U(1) group broken to H = 1 (the identity)

Order parameter space *O* = U(1)/1 = U(1) = S^1 (Circle)

Only non-trivial homotopy Group is 1st homotopy group: $\pi_1(O)$

Resulting topological defect: strings (superfluid vortices)
Exactly same as for superfluid ^{4}He case

This is believed to occur in the inner crust region of neutron Stars. Indirect observational evidence for vortices

This should be possible to achieve in low energy Heavy-ion collisions: Signal: Imprints on flow of hadrons

(Mod. Phys. Lett. A32, 1750170 (2017))

(2) Transition from Hadronic, confined, phase to deconfined QGP phase

SSB: G = Z(3) (cyclic) group broken to H = 1 (the identity)

Here, Z(3) is the Centre of the color group SU(3)

Order parameter space *O* = Z(3)/1 = Z(3)

Only non-trivial homotopy Group is : $\pi_0(O)$

Resulting topological defect: Domain walls – 3 kinds
Also: junction of three domain walls leads to strings

So, string-domain wall network will form.

Similar systems have been studied in cosmology as axion string-domain wall network.

We will present results for the formation of this network Using simulations of Polyakov loop model for the transition

Transition from the QGP phase to the Color Superconducting CFL phase:

Recall: Spontaneous symmetry breaking pattern

$$G \equiv SU(3)_{color} \times SU(3)_L \times SU(3)_R \times U(1)_B$$

$$\rightarrow SU(3)_{C+L+R} \times Z_2 \equiv H$$

Order parameter space *O* = $SU(3) \times SU(3) \times U(1)$

$\pi_0(O) = 1$ $\pi_2(O) = 1$

So: No domain wall,
or monopole defects

$\pi_1(O) = Z$ String defects: superfluid vortices

$\pi_3(O) = Z \otimes Z$ Doubling of colored Skyrmions (baryons)

Summary:

QCD phases have very rich structure

Even at heavy-ion collisions, many non-trivial possibilities

The Vacuum itself has rich possibilities,

High Temp. QGP phase: Z(3) domains, walls, strings
non-trivial quark scattering, new sources of fluctuations

Low Temp. Chiral symmetry broken phase: DCC

High Baryon density phases: Color superconductivity.

Then the Physics of fluctuations in QGP created in heavy-ion collisions: very similar to plasma fluctuations (hence CMBR anisotropies) in early universe. Deep inter-connections, concept of super-horizon fluctuations etc.

**Magnetic field (~ 10^{15} Tesla) in heavy ion collisions:
Chiral magnetic effect, effect on elliptic flow,……**

THANK YOU

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: $b = 2.0$, $c = 0.6061 \times 47.5/16$,
$a(x) = (1-1.11/x)(1+0.265/x)^2 (1+0.300/x)^3 - 0.487$
where, $x = T/T_c$

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

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

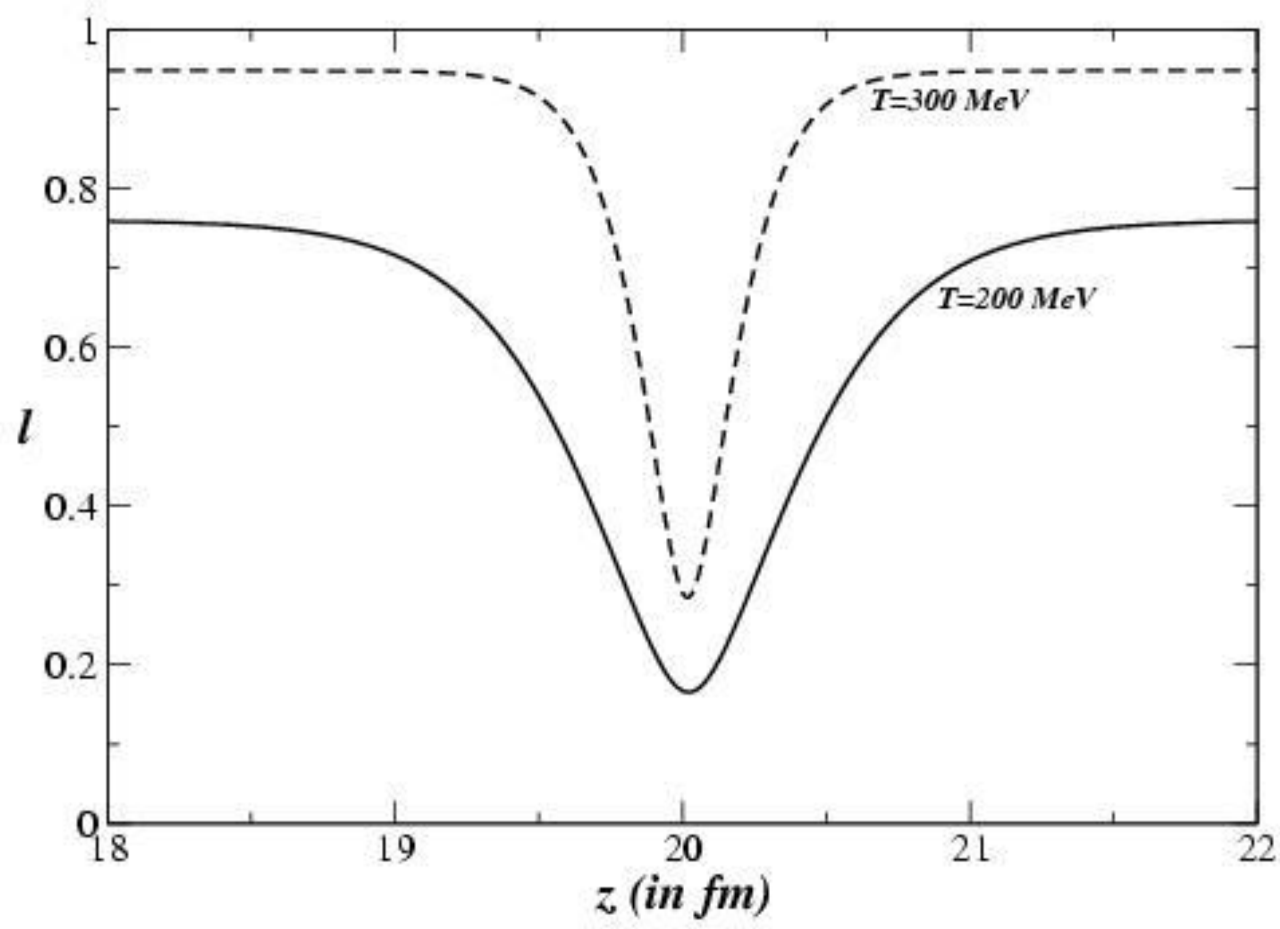
Note: b term gives $\cos 3\theta$, leading to Z(3) vacuum structure

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.

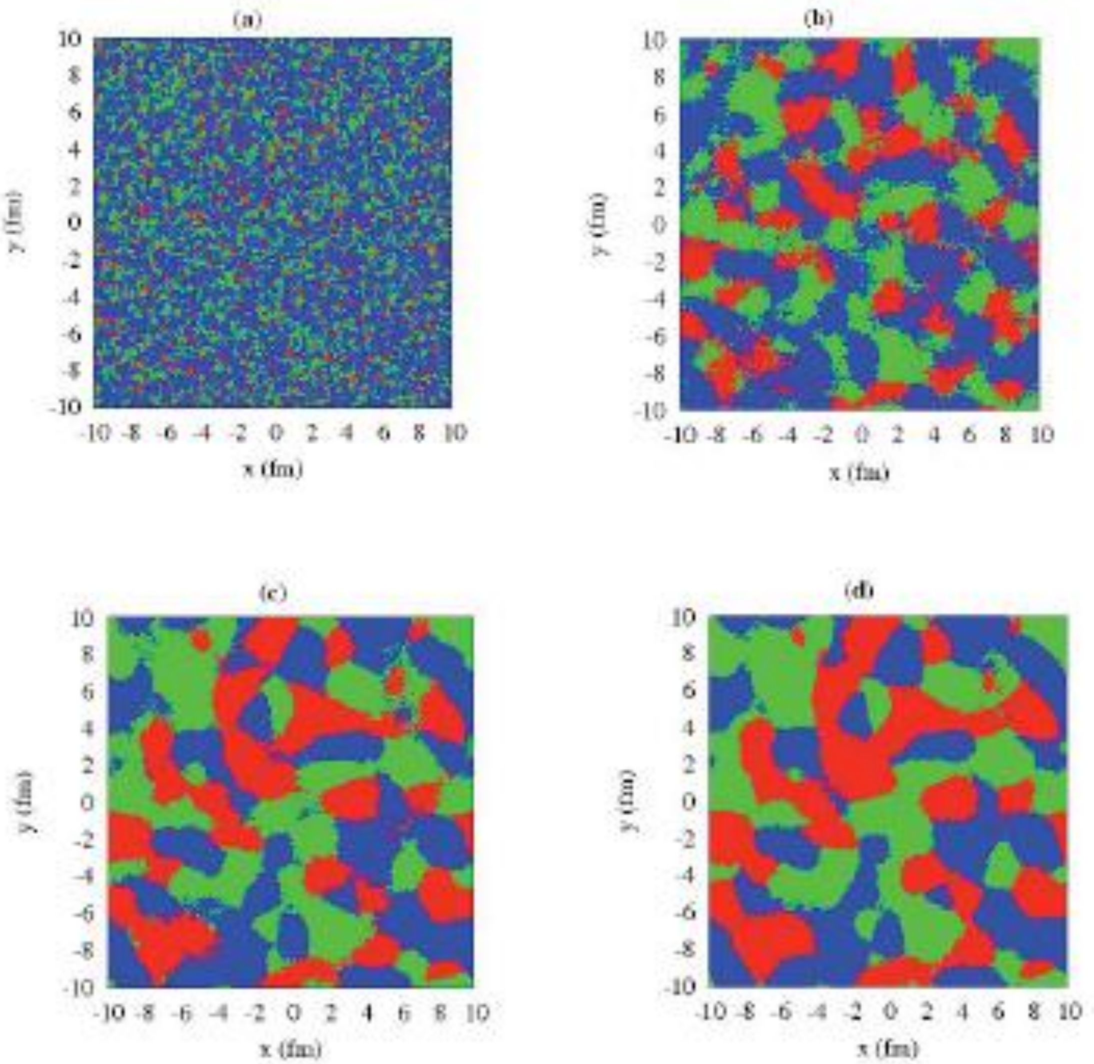
This is opposite to the standard case, where strings etc. form when system cools below Tc to symmetry broken phase.

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.

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)

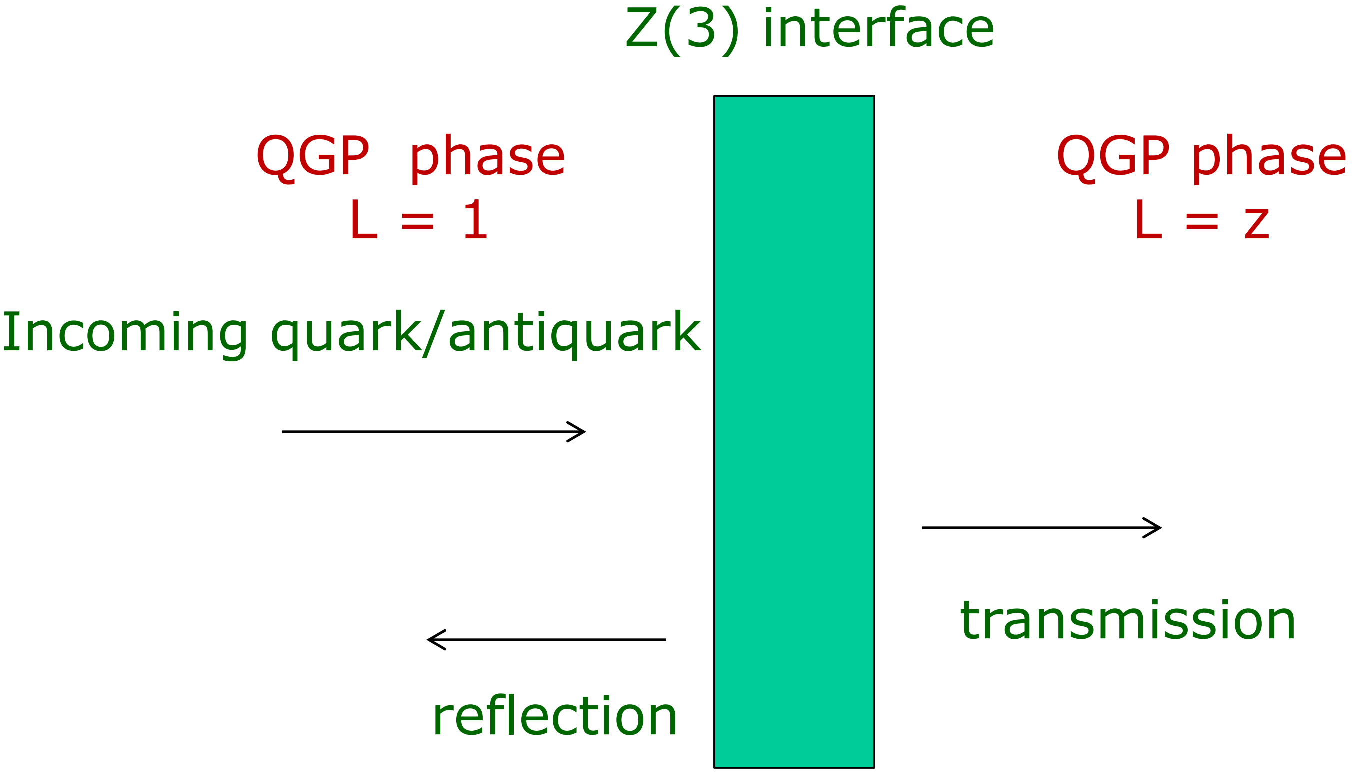
3) In QGP: Korthals Altes (1992)

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

Two 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.