CERN, Summer Theory Institute, Aug.2010

Fluctuations and sounds, The magnetic side of the sQGP

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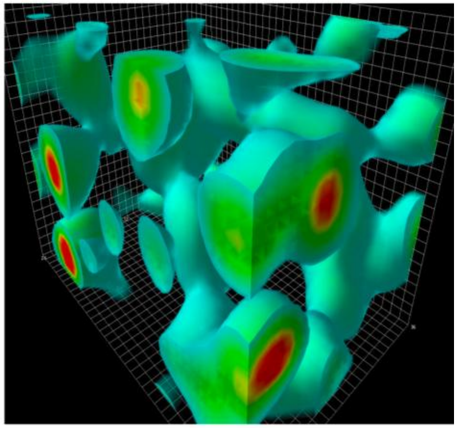
Outline: (3 hard pieces)

1. Initial fluctuations => Sound waves, Modified Mach cones from jets
2. magnetic plasma at RHIC => monopoles behave as Coulomb classical plasma, explain small viscosity. Confinement as monopole BEC
3. Jet quenching in magnetic plasma, flux tubes, "ridges"

(ES, CERN lectures 1982)

The vacuum vs QGP



Visualization by Derek Leinweber

- **The vacuum is very complicated, dominated by ``topological objects"**

Vortices, monopoles and instantons

- **Among other changes it shifts its energy down compared to an**

"empty" vacuum, known as the Bag terms, p=#T^4-B

e=#T^4+B

- The QGP, as any plasma, screens them, and thus is nearly free from them
- => when QGP is produced, **the vacuum tries to expel it**

Magdeburg hemispheres 1656

"We cannot pump the QCD vacuum out, but we can pump in something else, namely the Quark-Gluon Plasma and measure the pressure difference…"

- **Now we found a lot of topology in QGP as well, especially near Tc**

Part 1:The fluctuations and the sounds

PHYSICAL REVIEW C **80**, 054908 (2009)

Fate of the initial state perturbations in heavy ion collisions

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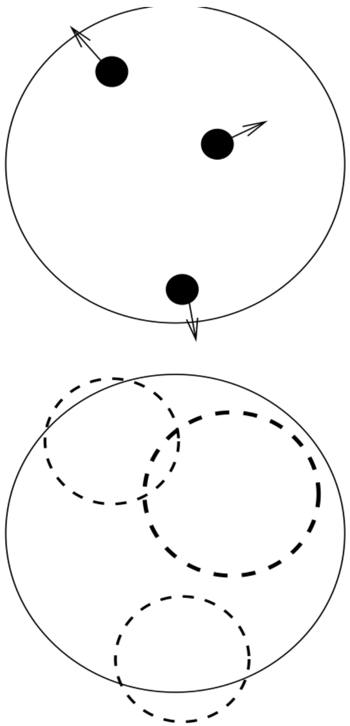
(Received 20 July 2009; revised manuscript received 14 October 2009; published 13 November 2009)



Naively, ``spots" should excite a wave and get expanded to a spherical (or conical, or cylindrical) wave

Like in the case of stone thrown into the pond, nothing is left at the original position**: so how can they be observed?**

Its size =>**the sound horizon** => is about twice smaller than the fireball size (at freezeout) 8 fm/c

And thus large angular size 2 H/R about 1 rad

$$R_h = \int_0^{\tau_f} d\tau c_s(\tau)$$

If one wants to get large radial flow, one has to wait the time needed for it to develop. The sound speed during this time creates large rings.

Two new fundamental scales, describing fluctuations **at freezeout**

(V.Khachatryan,ES)

1. The sound horizon: radius

$$H_s = \int_0^{\tau_f} d\tau c_s(\tau)$$

2.The viscous horizon: the Width of the circle

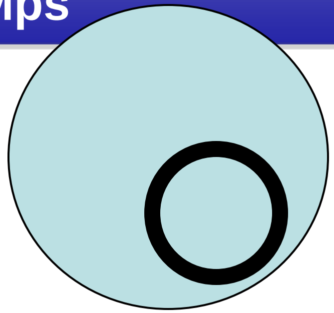
$$\delta T_{\mu\nu}(t) = exp\left(-\frac{2}{3}\frac{\eta}{s}\frac{k^2 t}{3T}\right)\delta T_{\mu\nu}(0)$$

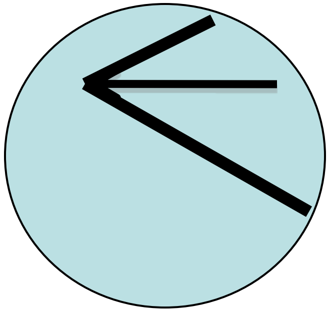
$$k_v = \frac{2\pi}{R_v} = \sqrt{\frac{3Ts}{2\tau_f \eta}} \sim 200MeV$$

Let us finish this section by pointing our the hierarchy relation between all those four scales which we assume is true

$$R > H_s > R_v > l \qquad (2.8)$$

For the Big Bang it was introduced by Sunyaev-Zeldovich about 40 years ago, was observed in CMB and galaxy correlations, it is about 150 Mps





Visible shape of the sound

cylinder (at freezeout, boosted by radial flow)

Peak at +- 1 rad, 60º?
Have I done it correctly?

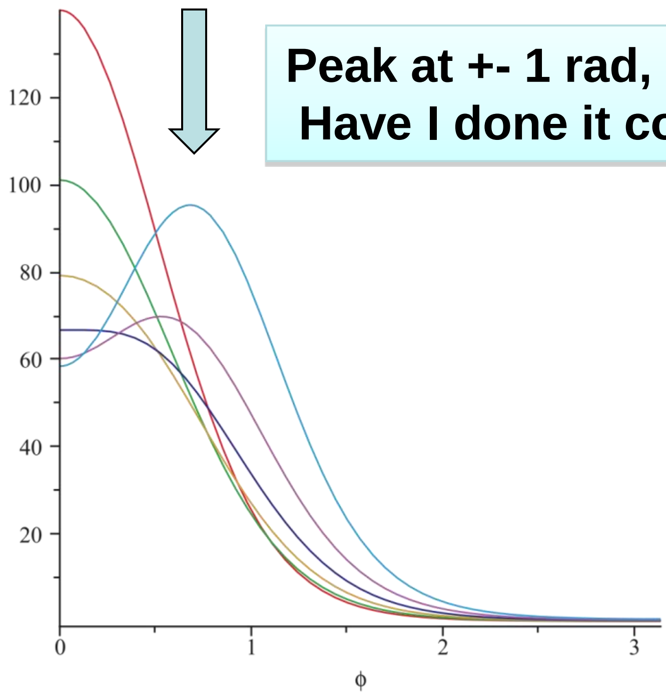


FIG. 5. (Color online) Dependence of the visible distribution in the azimuthal angle on the width of the (semi)circle at the time of freeze-out. Six curves, from the most narrow to the widest ones, correspond to the radius of the circle of 1, 2, 3, 4, 5, and 6 fm, respectively. The original spot position is selected to be at the edge of the nuclei. The distribution is calculated for a particle of $p_t = 1$ GeV and fixed freeze-out $T_f = 165$ MeV.

- The blue line is how asimuthal distribution would look like **for sound cylinders, double peak because part of the circle is outside of the fireball**
- comparing with data, I concluded that there no ridges at such angle
- Thus I argued it is a flux tube

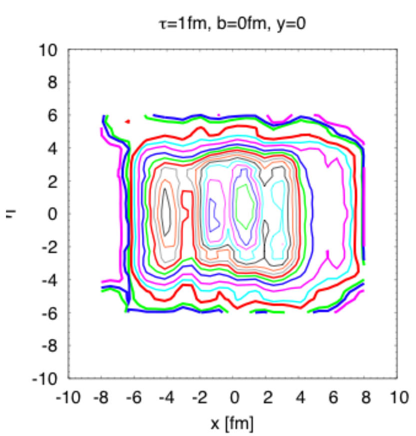
Here is a study of F.Grassi and her student

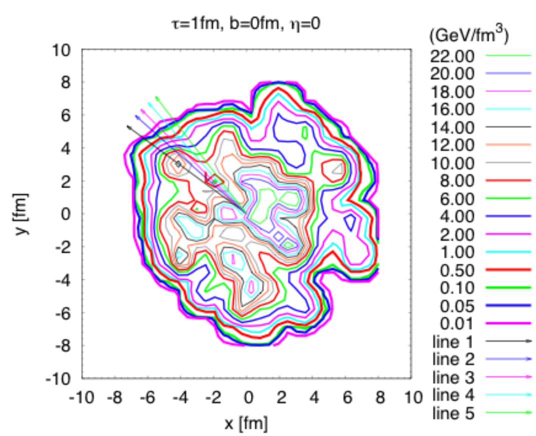
2+1 hydrodynamics: one tube model (R.Andrade Ph.D. Thesis)

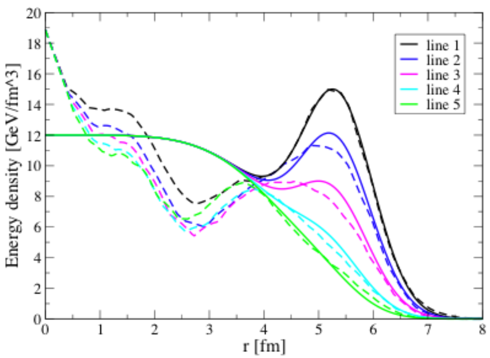
WHY 3+1 HYDRO GIVES GOOD RESULTS?

$\longrightarrow$ Study transverse expansion of a slice with one tube

- longitudinal boost invariance assumed
- central collision
- profile inspired by NeXus initial conditions



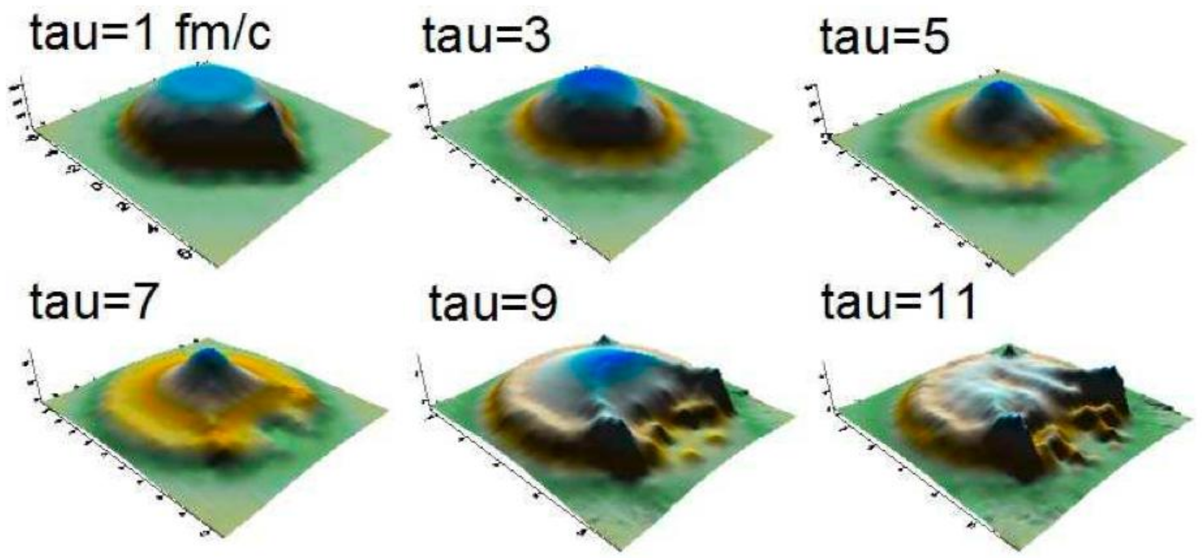




The sound cylinders and two peaks are also seen

Origin of the two peaks

Tube "sinks" and matter around "rises" forming a hole+two horns

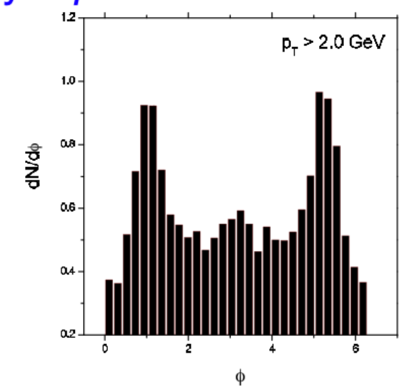


Temporal evolution of energy density for the one tube model.

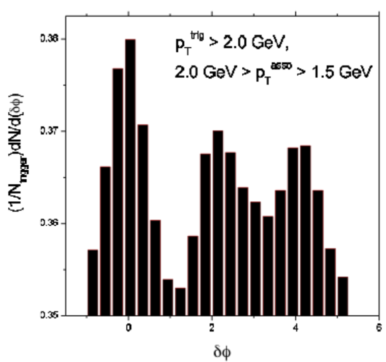
The peaks are at the same angles +- 1 rad (as I got) from perturbation but **+-2 rad in correlations**

One tube model

MAIN RESULT: single particle angular distribution has TWO PEAKS separated by $\Delta phi \sim 2$



CONSEQUENCE: two particle angular distribution has three peaks



Fluctuations from Glauber

B. Alver, G. Roland, **Phys.Rev.C81:054905,2010. e-Print: arXiv:1003.0194 [nucl-th] => triangular flow paper**

- ε_{mn}=< r^m cos(n($\phi-\psi_{mn}$))>
- The dipole $\varepsilon_{11}=0$ by definition but not ε_{31}
- Are angles of different harmonics correlated? Odd ones are quite correlated ψ_{31}, ψ_{33}, ψ_{55} pointing in y direction, to the tips of the almond
- (Pilar Staig, ES, archive:**1008.3139**, aug.18th, 2010)

Glauber fluctuations up to 6^{th} are all comparable

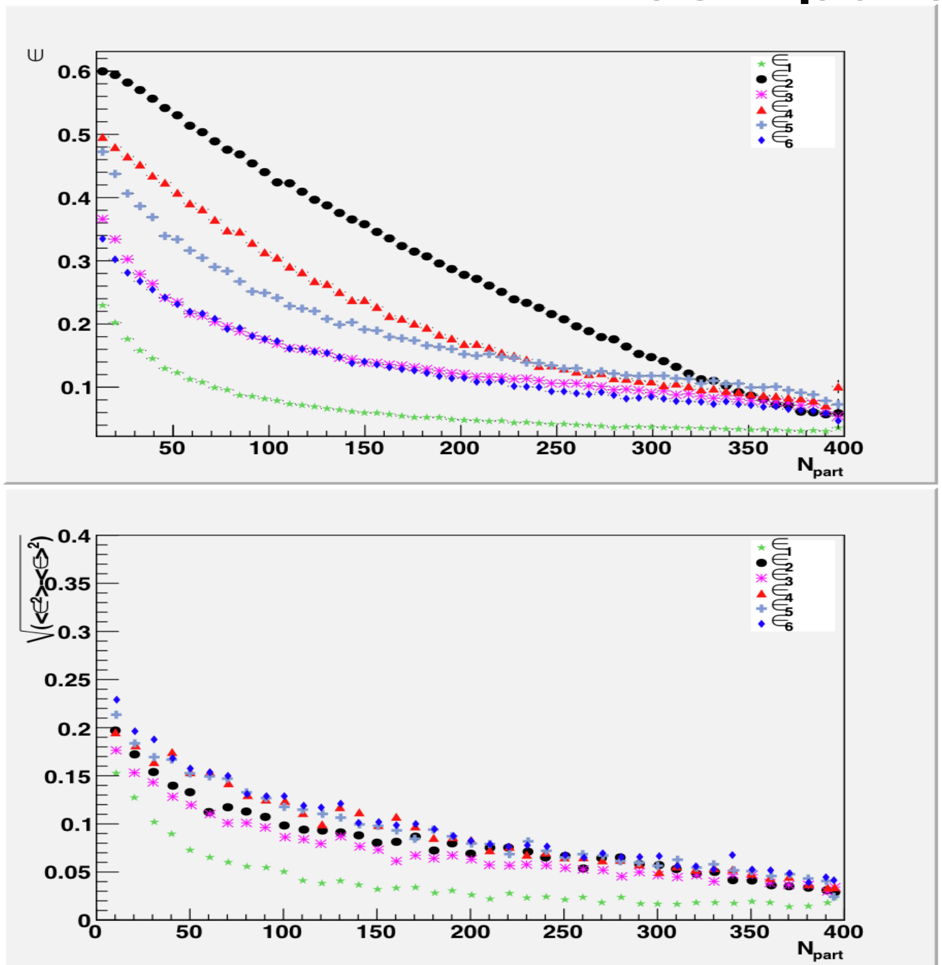


FIG. 5: Average anisotropies (upper plot) and their variations (lower), as a function of centrality expressed via the number of participants N_{part}

$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \cos(n\phi)\rangle^2}}{\langle r^n \rangle}$$

$$\epsilon_1 = \frac{\sqrt{\langle r^3 \cos(\phi)\rangle^2 + \langle r^3 \cos(\phi)\rangle^2}}{\langle r^3 \rangle}$$

The angles ψ_n are defined by:

$$\tan(n\psi_n) = \frac{\langle r^n \sin(n\phi)\rangle}{\langle r^n \cos(n\phi)\rangle}$$

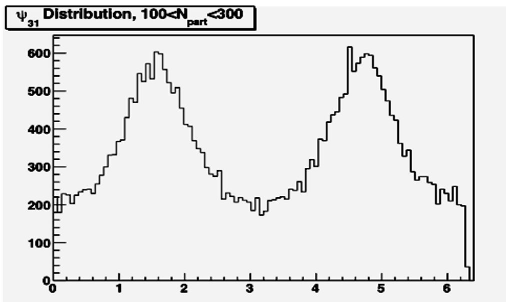
and to calculate ψ_1 we use:

$$\tan(\psi_1) = \frac{\langle r^3 \sin(\phi)\rangle}{\langle r^3 \cos(\phi)\rangle}$$

Distribution of the angles

1[st] : tips and waist

1



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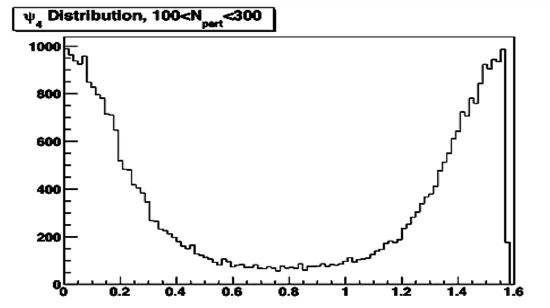

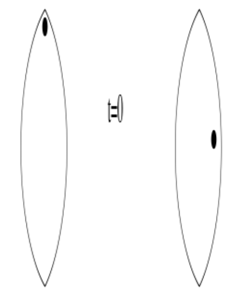

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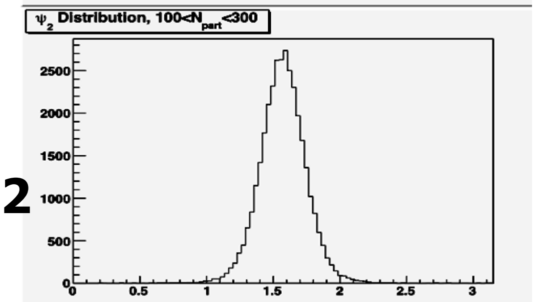

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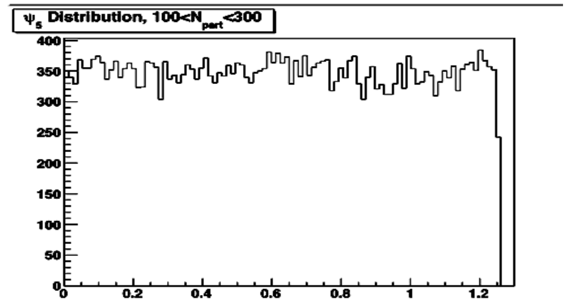
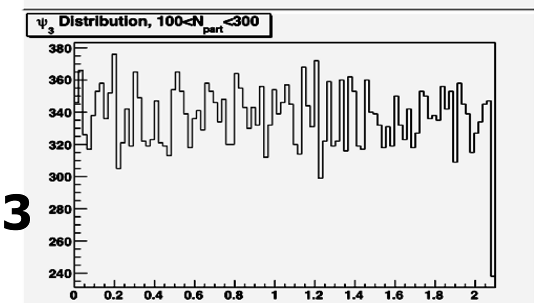


3ed and 5[th] Uncorrelated?

3



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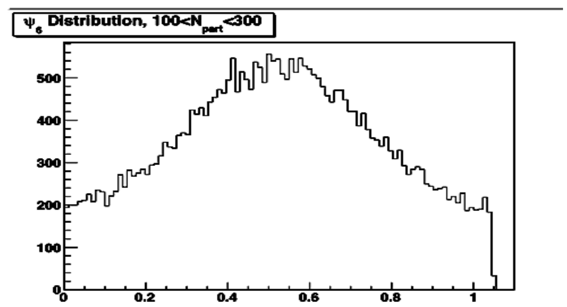


•The odds are **all** correlated!
There are “tips” and ”waist” peaks geometry tells us that peripheral events would be 3-peaks

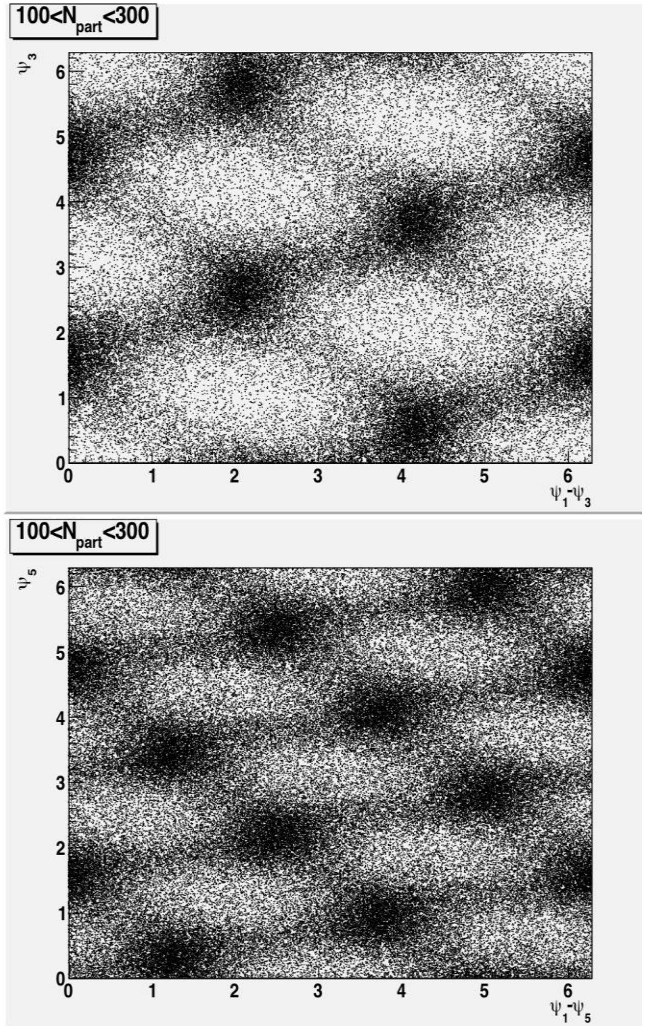


FIG. 8: Scatter plot of the ψ_3 vs $\psi_3 - \psi_1$ (above), and of the ψ_5 vs $\psi_5 - \psi_1$ (below), the same centrality

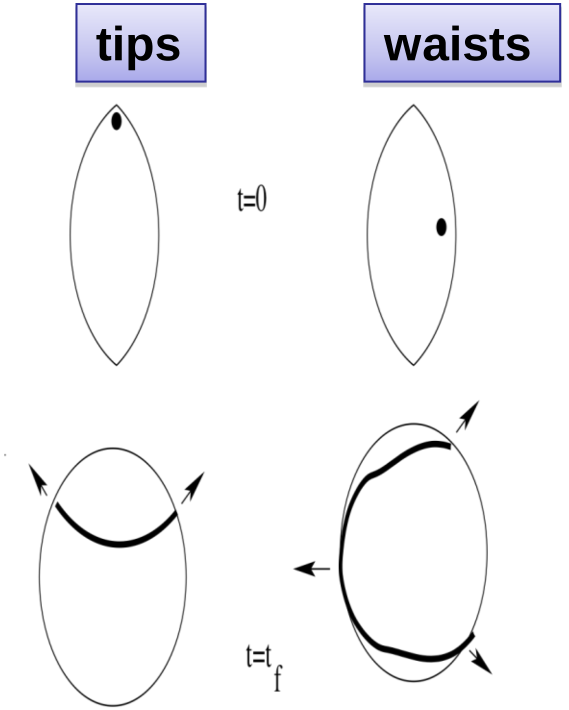


FIG. 4: Two upper picture correspond to initial time $t = 0$: the system has almond shape and contains perturbations (black spots). Two lower pictures show schematically location and diffuseness of the sound fronts at the freezeout time t_f. The arrows indicate the angular direction of the maxima in the angular distributions, 2 and 3 respectively.

Both calculations agree, but they both ignored viscosity!

Thus the rms width has therefore increased as

$$\sqrt{< x^2(t) >} = \sqrt{r_0^2 + \frac{2}{k_v^2(t)}}\,, \tag{3.3}$$

which is $\sim t^{1/2}$ at large time. This is because of the diffusive nature of the viscosity. The amplitude has decreased by the factor

$$\frac{\delta T_{\mu\nu}(t, x = 0)}{\delta T_{\mu\nu}(t = 0, x = 0)} = \left(1 + \frac{2}{r_0^2 * k_v^2(t)}\right)^{-1/2}. \tag{3.4}$$

$$k_v = \frac{2\pi}{R_v} = \sqrt{\frac{3Ts}{2\tau_f \eta}} \sim 200MeV$$

r_0=.2 fm

Suppression is serious, by about factor 4

The observed recoil tells us the volume of the region where the sound is

- Conditional probability to get p_2 provided the trigger is p_1 (Borghini 0707.0436)

$$f(\vec{p_2}|p_1) = f_0(\vec{p_2})\left(1 - \frac{2p_1 p_{2,x}}{N < p_t^2 > (1+\bar{v}_2)}\right)$$

where the trigger by definition is in the x direction,

$$\bar{v}_2 =< p_x^2 - p_y^2 > / < p_x^2 + p_y^2 >$$

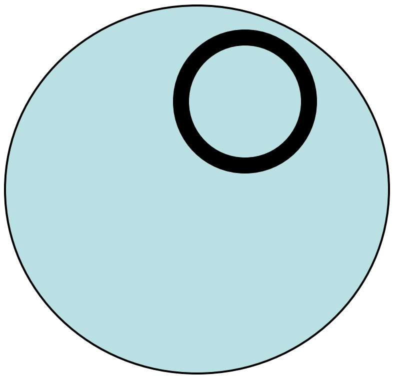
- **N is the number of particles which takes the recoil**.

What is it?

- **we argue it is the black region:**

Outside cannot be by causality

Inside not because sound does not live any momentum



- **$N = N_{tot}\, H^2/k_v/V_{tot}$ or about $N_{tot}/10$ or 500 particles for central AuAu at RHIC**
- **This explains the magnitude of the first dipole harmonics in the correlation function** (see e.g. 1003.0194, Alver and Roland)

Geometric acoustics can describe modification of shapes by flow

$$\frac{d\vec{r}}{dt} = \frac{\partial \omega(\vec{k},\vec{r})}{\partial \vec{k}} \,,$$
$$\frac{d\vec{k}}{dt} = -\frac{\partial \omega(\vec{k},\vec{r})}{\partial \vec{r}} \,,$$

In this case the dispersion relation is obtained from that in the fluid at rest by a local Galilean transformation, so that

$$\omega(\vec{k},\vec{r}) = c_s k + \vec{k}\vec{u} \,. \tag{4.3}$$

In the simplest case of constant flow vector $\vec{u} = const(r)$ the first of these eqn just obtains an additive correction by flow

$$\frac{d\vec{r}}{dt} = c_s \vec{n}_{\vec{k}} + \vec{u} \,, \tag{4.4}$$

where $\vec{n}_{\vec{k}} = \vec{k}/k$ is the unit vector in the direction of the momentum. The second eqn gives $\frac{d\vec{k}}{dt} = 0$ as there is no

a (generalized) Hubble-like flow

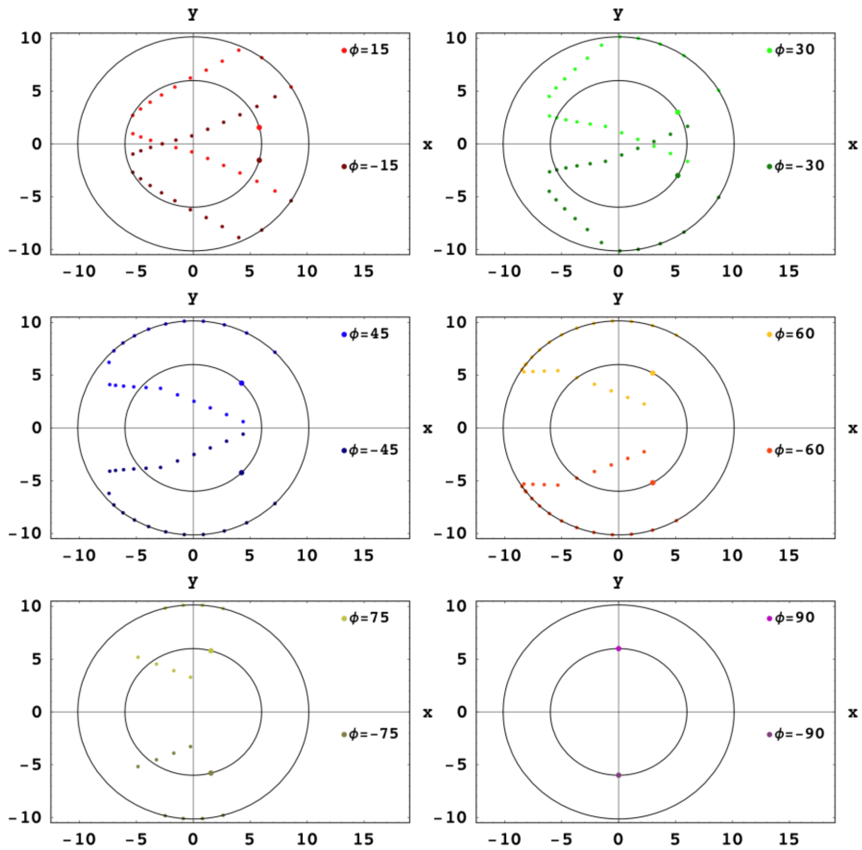
$$u_i(r) = H_{ij} r_j \,, \tag{4.5}$$

with some time and coordinate independent Hubble tensor. The eqn (4.2) now reads

$$\frac{dk_i}{dt} = -H_{ij} k_j \,, \tag{4.6}$$

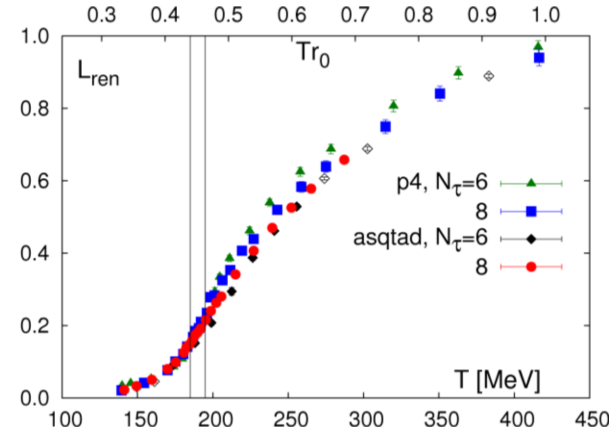
$$k_i(t) = exp(-H_i t) k_i(0). \quad \vec{r}(t) = t c_s \vec{n}_{\vec{k}} + \vec{r}(0) exp(+Ht) \,.$$

Relativistic flow brings in Lorentz factor, easily solvable numerically: e.g.



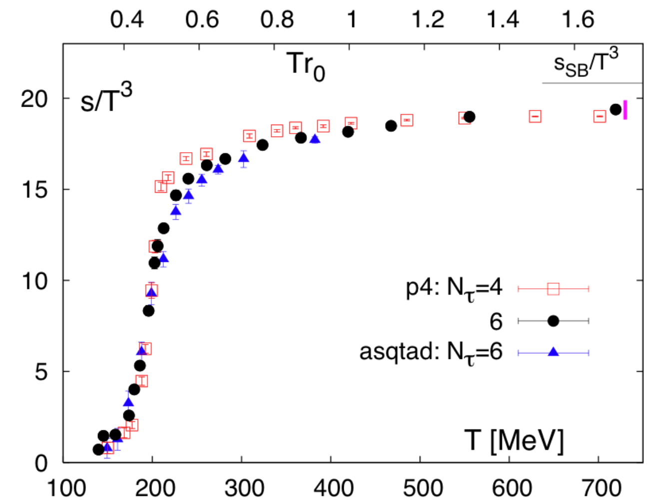
Part 2: E/B duality and the magnetic plasma(?)

The “**semi**-QGP puzzle” at T=>Tc (Pisarski)



- Electric objects are suppressed by the Polyakov line

$$L = \frac{1}{N_c} Tr P exp(i \int A_0 d\tau)$$

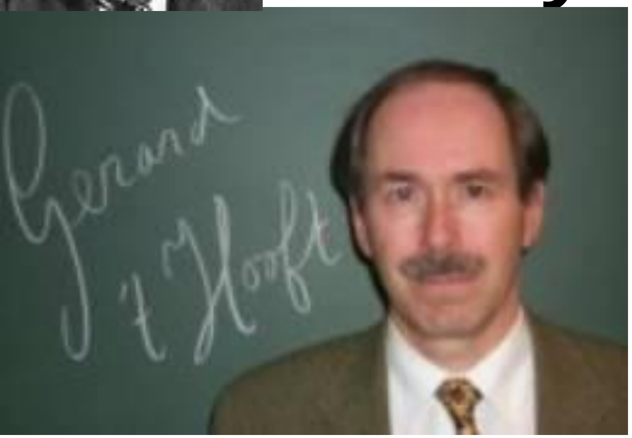


- Quarks should scale as <L>, gluons as <L^2>, and they are (PNJL,Wilson-tHooft loops)

- and yet the entropy near Tc is large…

what is the other half?
Hadrons or monopoles?
(no electric charge => no L suppression)

Magnetic objects and their dynamics: classics



- Dirac explained how magnetic charges may coexists with quantum mechanics (1934)
- ‘t Hooft and Polyakov discovered **monopoles** in Non-Abelian gauge theories (1974) : VEV of adjoint scalar is needed
- ‘t Hooft and Mandelstamm suggested “dual superconductor” mechanism for confinement (1982), monopole BEC
- Seiberg and Witten shown how it works, in the **N=2 Super - Yang-Mills theory (1994)**

“magnetic scenario”: (color) magnetic monopoles are important excitations near Tc

Four lectures on strongly coupled Quark Gluon Plasma. Edward Shuryak, (SUNY, Stony Brook) . 2009. 46pp. Published in Nucl.Phys.Proc.Suppl.195:111-156,2009.

- **Strongly coupled plasma with electric and magnetic charges. Liao,ES, Phys.Rev.C75:054907,2007. hep-ph/0611131**
- **Magnetic component of Yang-Mills plasma**,M.N.Chernodub and V.I.Zakharov, 98, 082002 (2007) [arXiv:hep-ph/0611228].
- **Electric Flux Tube in Magnetic Plasma.** Liao,ES, Phys.Rev.C77:064905,2008. arXiv:0706.4465
- Magnetic monopoles in the high temperature phase of Yang-Mills theories, A.D'Alessandro and M.D'Elia, Nucl.Phys.B 799, 241 (2008) [arXiv:0711.1266
- **Magnetic Component of Quark-Gluon Plasma is also a Liquid!** Liao,ES, Phys.Rev.Lett.101:162302,2008. e-Print: arXiv:0804.0255
- **Angular Dependence of Jet Quenching Indicates Its Strong Enhancement Near the QCD Phase Transition. Jinfeng Liao,, Edward Shuryak Phys.Rev.Lett.102:202302,2009. e-Print: arXiv:0810.4116**
- **Thermal Monopole Condensation and Confinement in**

``magnetic scenario": Liao,ES hep-ph/0611131,Chernodub+Zakharov

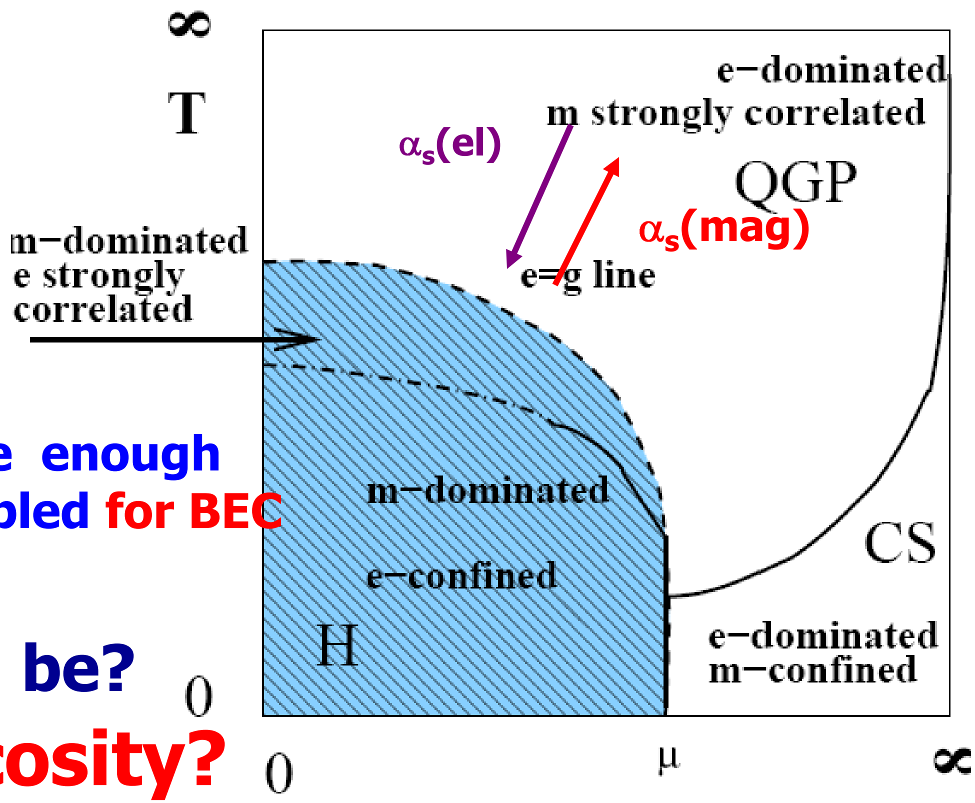
Old good Dirac condition =>

α_s(electric) α_s(magnetic)=1

=>electric/magnetic couplings

must run in the **opposite directions**!

Where is the "equilibrium line" α_s(el)= α_s(mag) =1 ?
Is there the famous wall at which density of states jumps but F does not?



monopoles should be (i) dense enough and (ii) sufficiently weakly coupled for BEC to happen.

how small can α_s(mag) be?

Can it upset the viscosity?

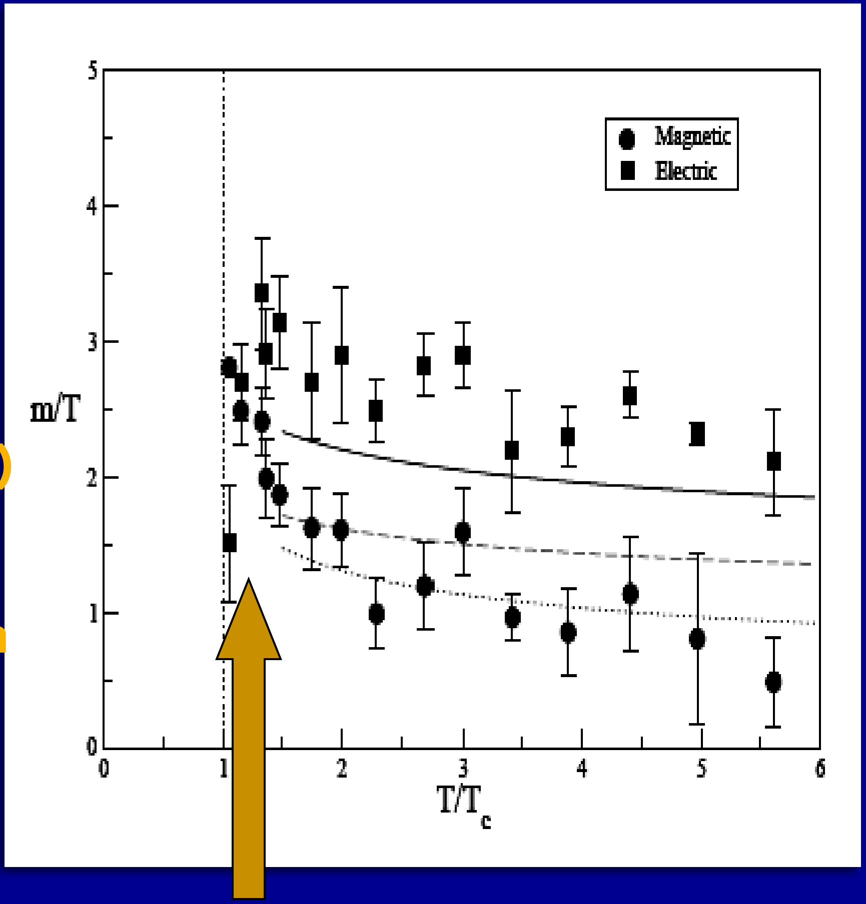
Electric and magnetic screening masses (inverse screening lengths) from numerical simulation in lattice gauge theory Nakamura et al, 2004

arrow shows the ``equilobrium" E=M point

Me<Mm
Magnetic
Dominated

At T=0 magnetic
Screening mass
Is about 2 GeV
(de Forcrand et al)
(a glueball mass)

(Other lattice data
-Karsch et al-
show how Me
Vanishes at Tc in
more detail)

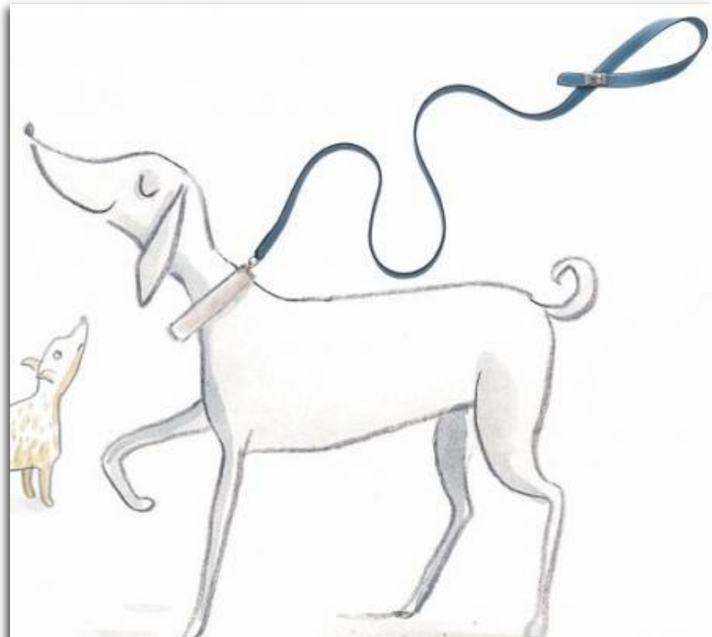


Me>Mm
Electrric
dominated

$M_E/T=O(g)$
ES 78
$M_M/T=O(g^2)$
Polyakov 79

Is QGP really getting magnetic as T<1.4Tc?

magnetic objects are seen on the lattice, but we do not yet understand what they are



The density of monopoles which wrap at least once around time is lattice-independent ! (D'Elia)

The leash= Dirac string is
gauge dependent, can be directed as one wishes

The collar (string end) is detectable,
It is the 3-d cube from which magnetic
flux is going out

The dog=magnetic object, studied but not understood yet.
Many possibilities (e.g. dyons .. Fermionic zero modes)
E^2 and B^2 are correlated with monopole path
But so far statistically, not on event-by-event

Experimentation with monopoles use many Gauges. It was shown that if one puts monopoles by hand "nearly all of them have collars"
But not in some gauges

The monopole density (vs T/Tc)

in confined and deconfined phases (Ratti,ES.08)

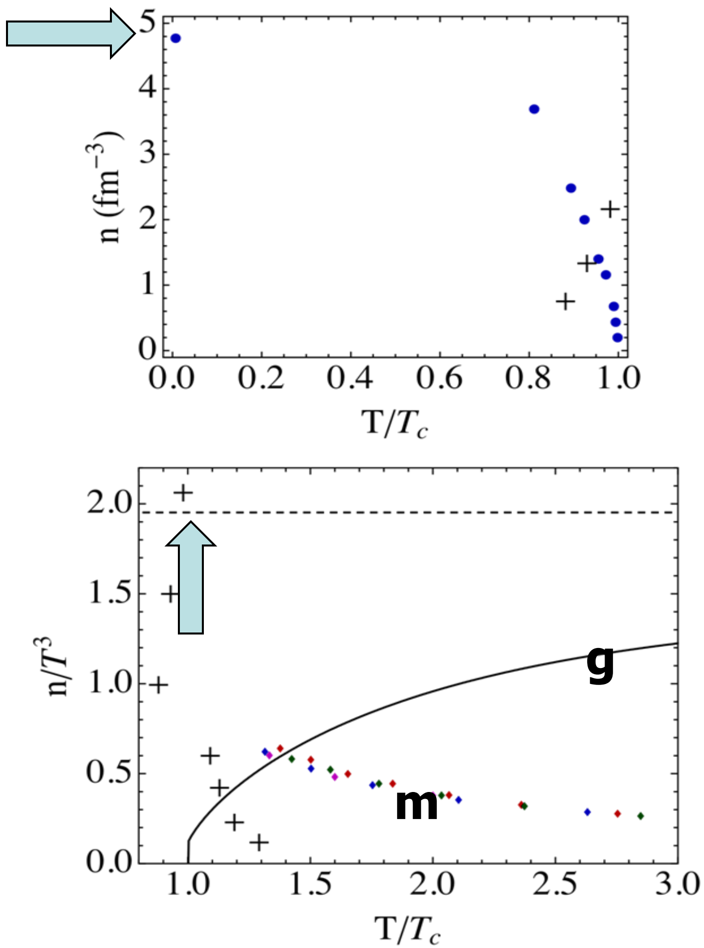


Figure 1: (a) The monopole density n_m in units of $[\mathrm{fm}^{-3}]$ versus T/T_c for the confined phase $T < T_c$. (b) The normalized density n/T^3 versus T/T_c for the deconfined phase $T > T_c$.

- The T=0 lattice point: from Bornyakov,Ilgenfritz et al
- Near-Tc: condenced and uncondenced monopoles, from flux tubes (Liao ES)
- The solid line represent the density of **gluons** suppresed by <P>
- Note that the sum (g+mono) is about const(T) except the peak at Tc (the peak is not due to dyons, as their density is flat)

Magnetic Component of Quark-Gluon Plasma is also a Liquid!

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(April 1, 2008)

The so called magnetic scenario recently suggested in [1] emphasizes the role of monopoles in strongly coupled quark-gluon plasma (sQGP) near/above the deconfinement temperature, and specifically predicts that they help reduce its viscosity by the so called "magnetic bottle" effect. Here we present results for monopole-(anti)monopole correlation functions from the same classical molecular dynamics simulations, which are found to be in very good agreement with recent lattice results [2]. We show that the magnetic Coulomb coupling does run in the direction *opposite* to the electric one, as expected, and it is roughly inverse of the asymptotic freedom formula for the electric one. However, as T decreases to T_c, the magnetic coupling never gets weak, with the plasma parameter always large enough ($\Gamma > 1$). This nicely agrees with empirical evidences from RHIC experiments, implying that magnetic objects cannot have large mean free path and should also form a good liquid

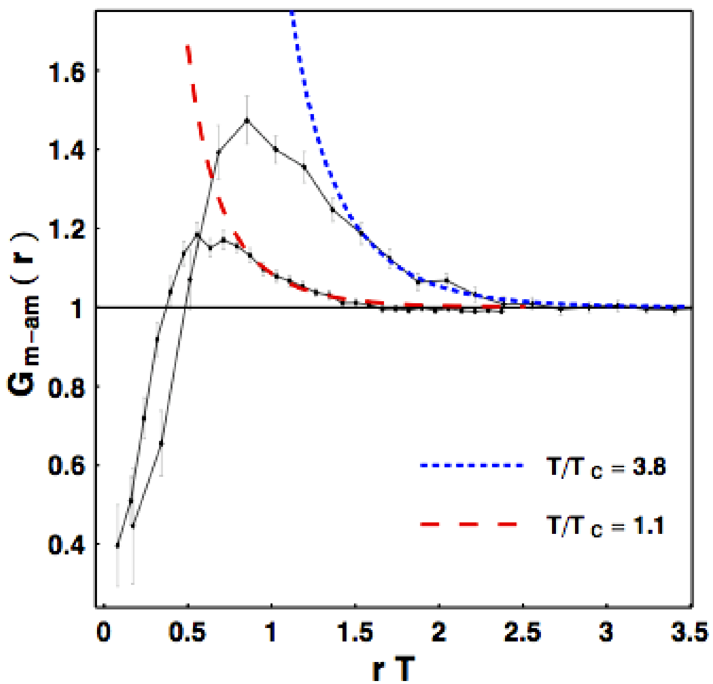
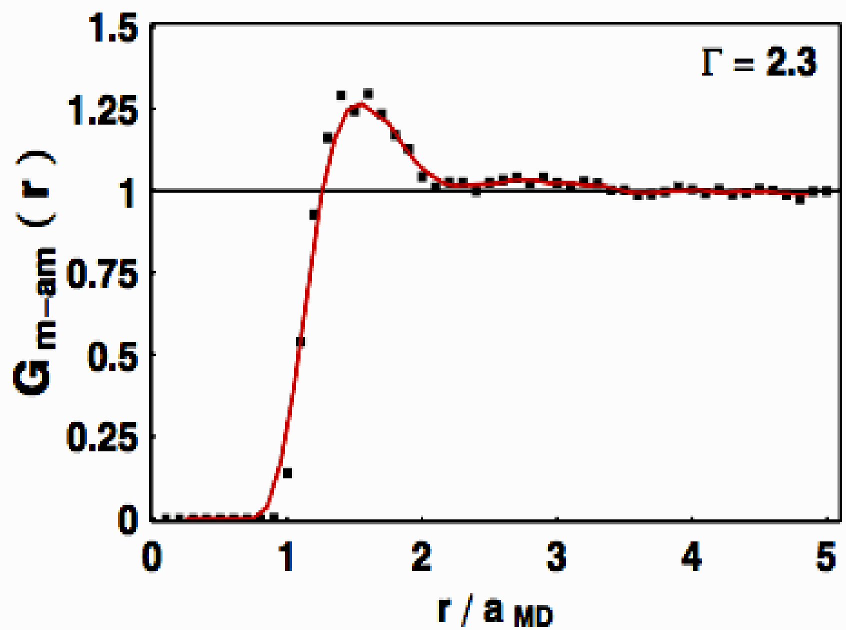


FIG. 2. (color online) Monopole-antimonopole correlators versus distance: points are lattice data [2], the dashed lines are our fits.

Our MD for 50-50 MQP/EQP

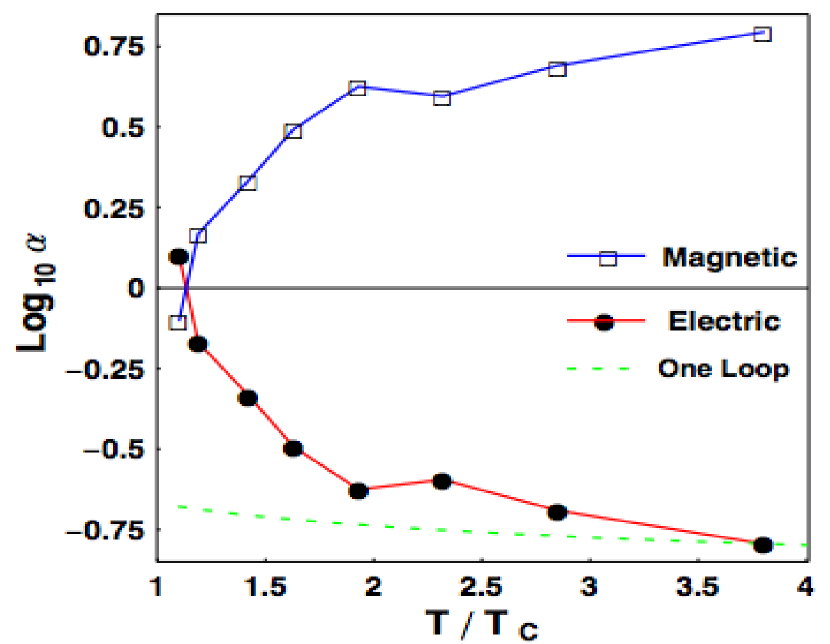


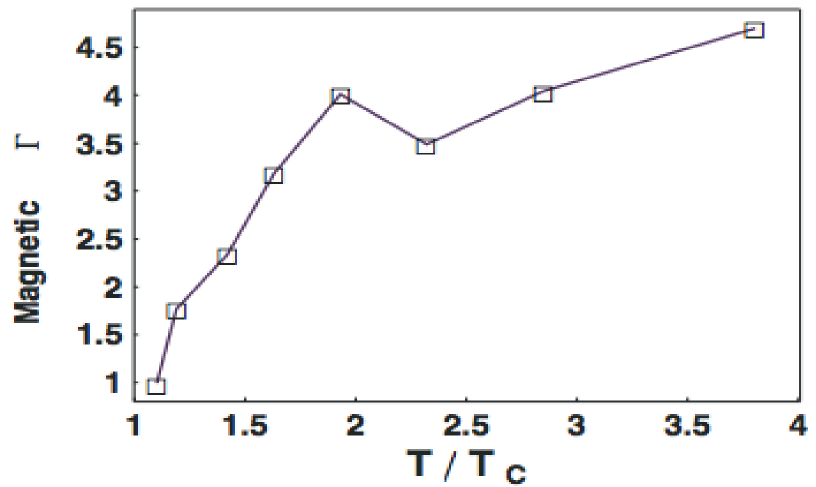
α_s(electric) and α_s(magnetic) do run in opposite directions!

- Squares: fitted magnetic coupling, circles: its inverse compared to asymptotic freedom (dashed)
- Effective plasma parameter (here for magnetic)

$$\Gamma \equiv \frac{\alpha_C / (\frac{3}{4\pi n})^{1/3}}{T}$$

- So, the monopoles are **never weakly coupled!**
- **(just enough to get Bose-condenced)**





Thermal Monopole Condensation and Confinement in finite temperature Yang-Mills Theories

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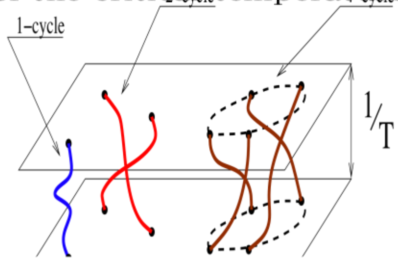
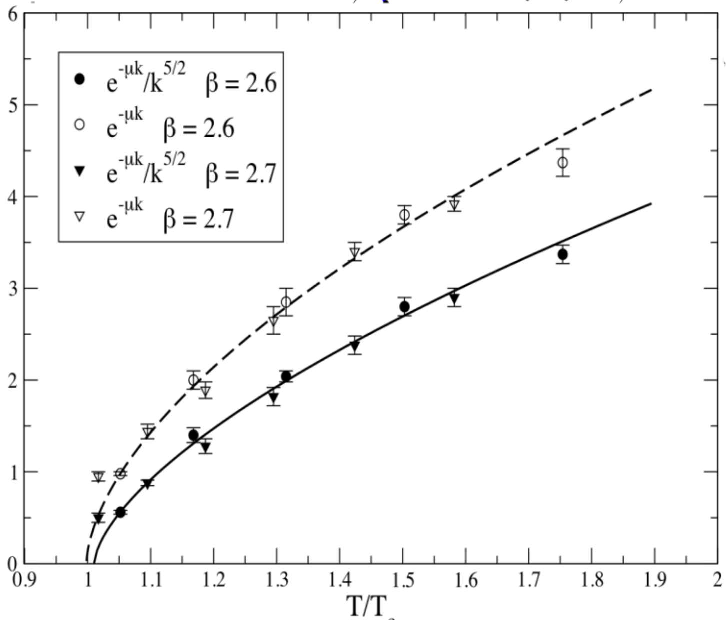
We investigate the connection between Color Confinement and thermal Abelian monopoles populating the deconfined phase of SU(2) Yang-Mills theory, by studying how the statistical properties of the monopole ensemble change as the confinement/deconfinement temperature is approached from above. In particular we study the distribution of monopole currents with multiple wrappings in the Euclidean time direction, corresponding to two or more particle permutations, and show that multiple wrappings increase as the deconfinement temperature is approached from above, in a way compatible with a condensation of such objects happening right at the deconfining transition. We also address the question of the thermal monopole mass, showing that different definitions give consistent results only around the transition, where the monopole mass goes down and becomes of the order of the critical temperature itself.





, in which

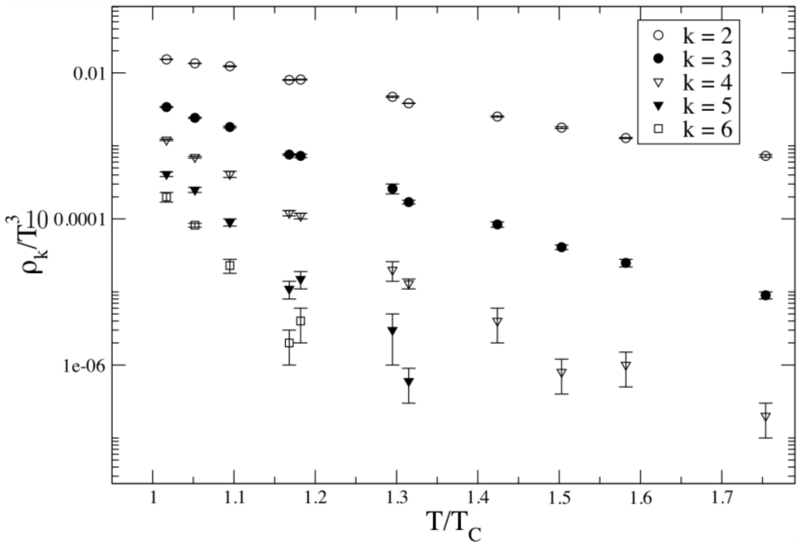


FIG. 2: Normalized densities ρ_k/T^3 as a function of T/T_c.

The lesson: monopoles at T_c, behave as He^4 =>Bose-Einstein condensation

Not surprising, large correction to transport (Ratti,ES,09)

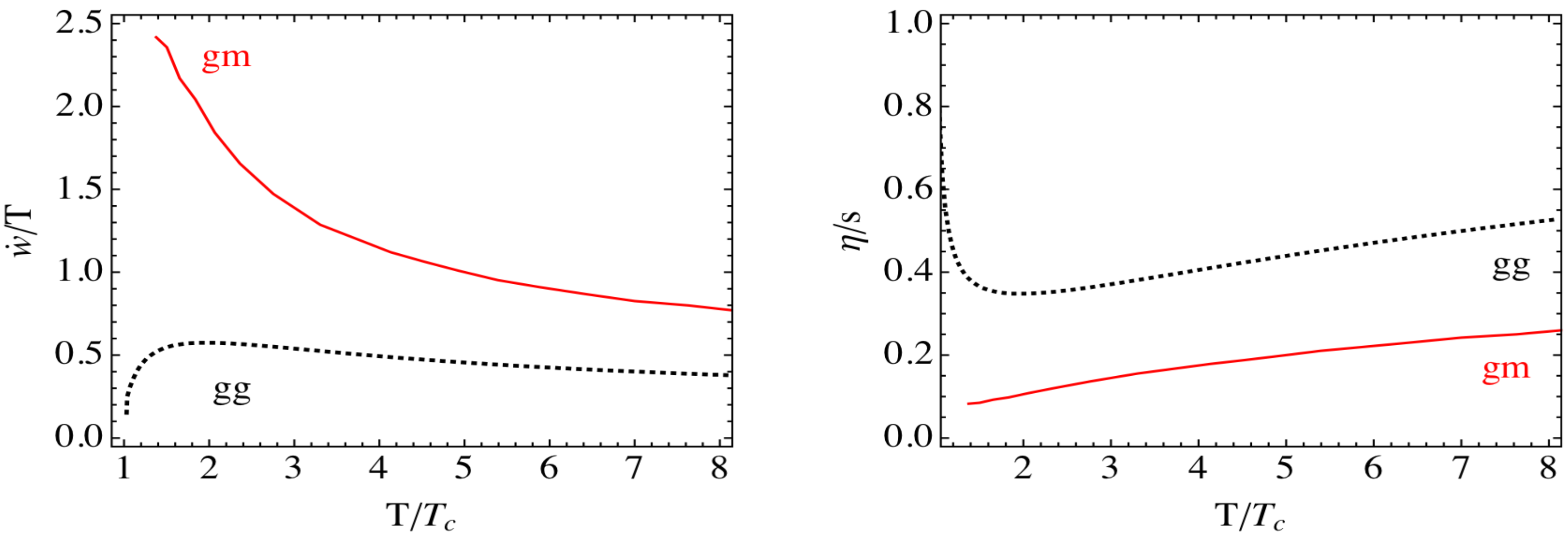
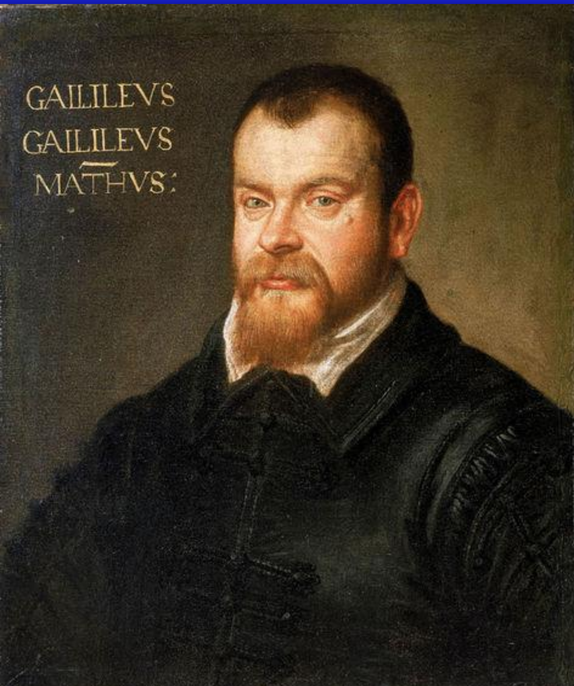


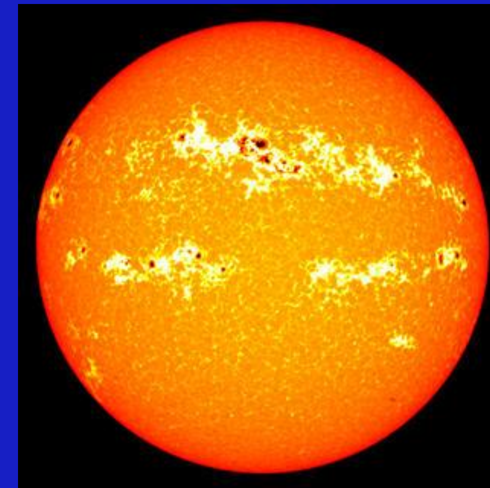
Figure 14: Left panel: gluon-monopole and gluon-gluon scattering rate. Right panel: gluon-monopole and gluon-gluon viscosity over entropy ratio, η/s.

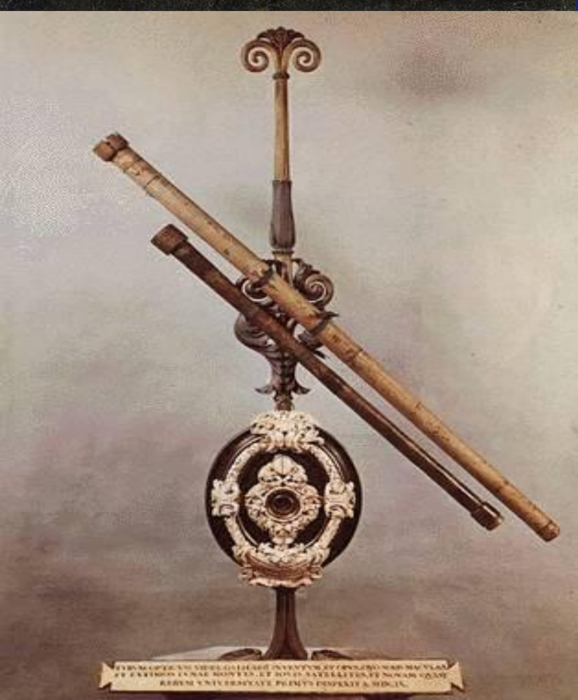
- **RHIC: T/Tc<2, LHC T/Tc<4**: we predict hydro will still be there, with η/s about .2

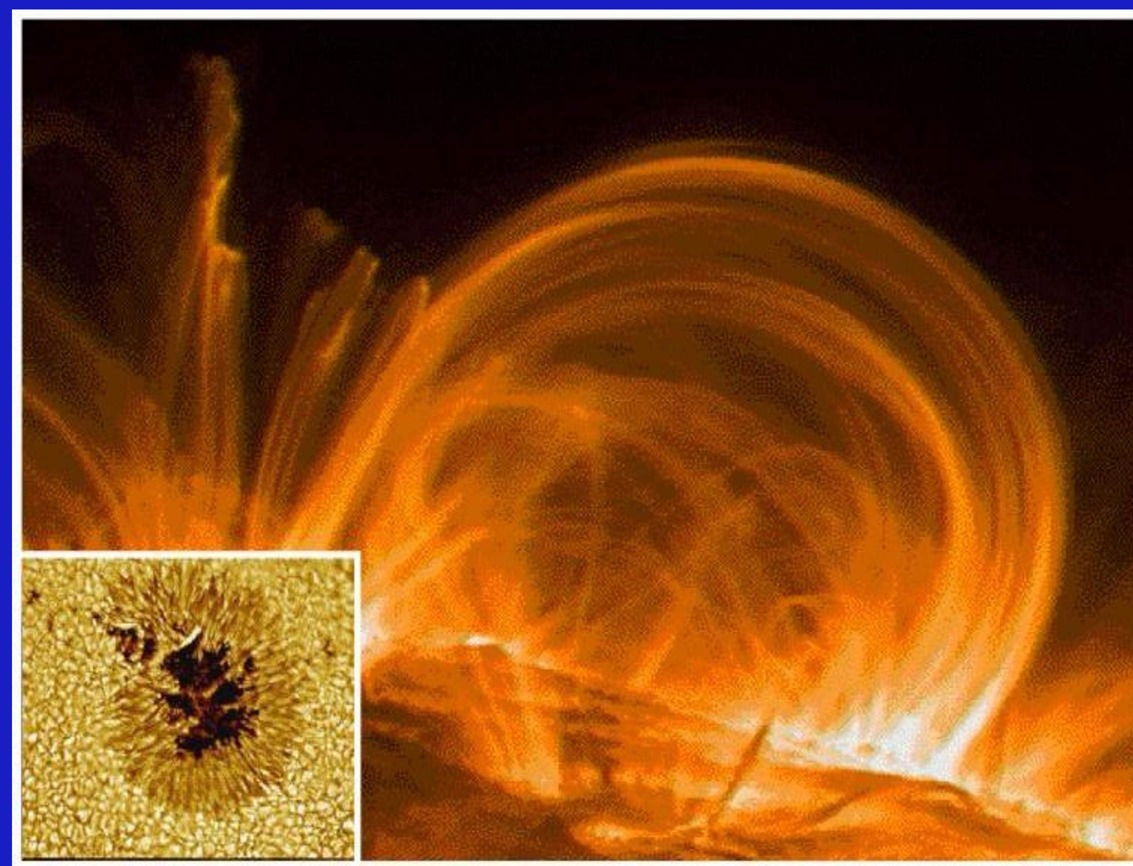
Part 3: electric flux tubes

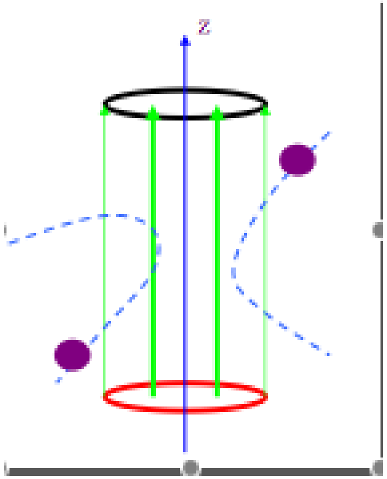


1612: Galileo discovered what we now call solar corona



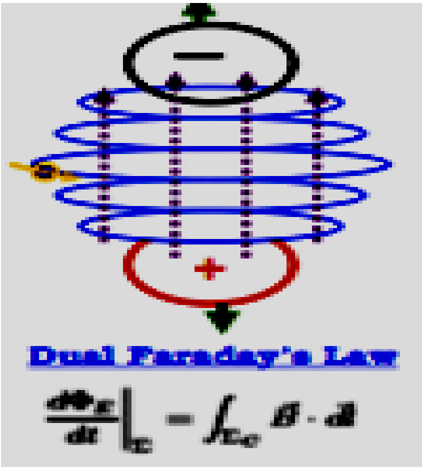






Moving e-charge leads to magnetic coil => e-flux tubes above Tc?

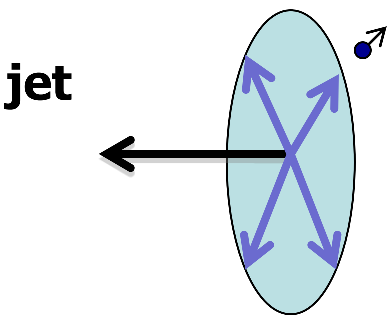
(with J.F.Liao, archive 0706.4465)



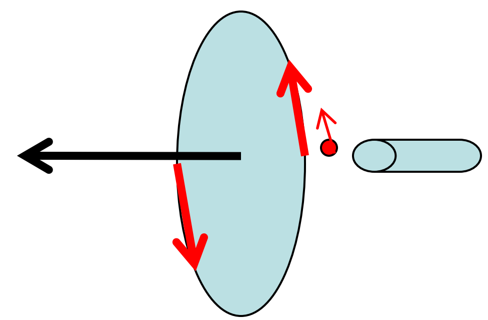
- **Dual superconductivity** at T<Tc as a confinement mechanism ('tHooft, Mandelstam 1980's) => monopole Bose condensation => electric flux tubes (dual to Abrikosov-Nielsson-Olesen vortices)
- **Dual magnetohydrodynamics** at T>Tc ? Electric flux tubes in magnetic plasma (M=phase)
- monopoles are reflected from E field => pressure => metastable flux tubes

Jet quenching is different in electric and magnetic plasmas

- Nonzero E_r => radial kicks to charges

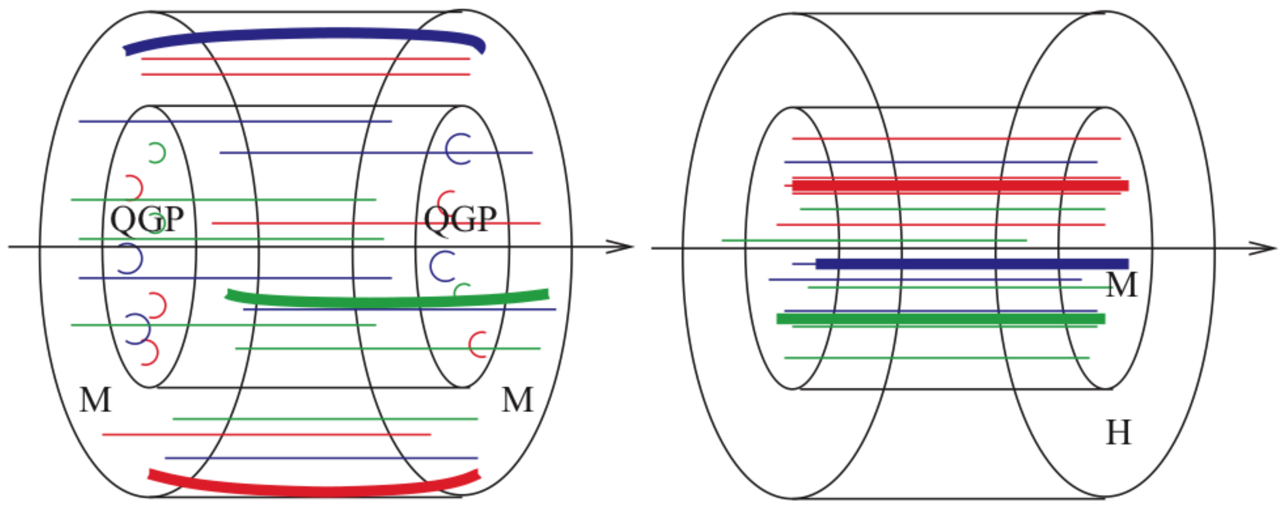


Nonzero B_ϕ => Tangential kicks of the monopoles



This creates vorticity, magnetic coil and (possibly) an electric flux tube behind the jet

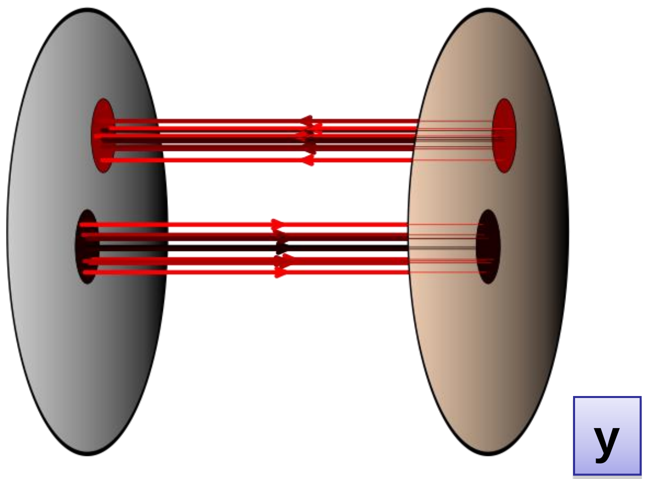
Here is my view of the “QGP corona”

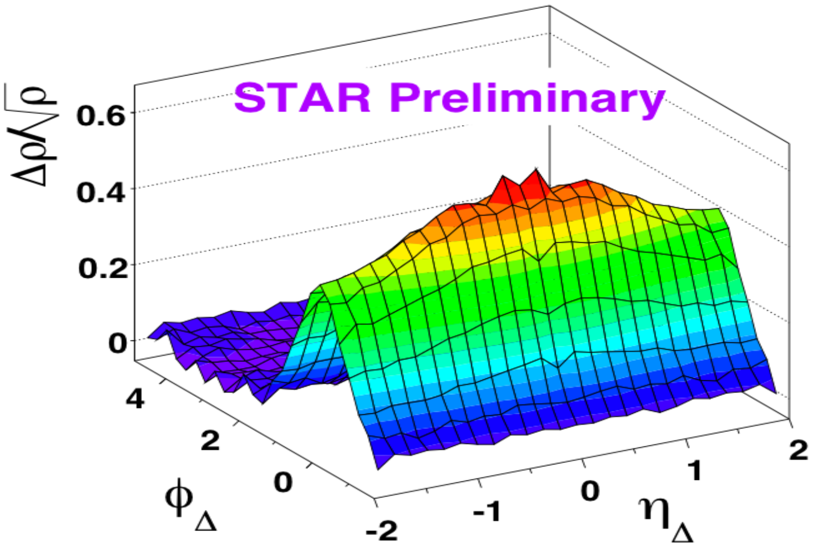


(a) (b)

FIG. 1. (Color online) Snapshot of unscreened electric (dual-magnetic) field in the M (near-T_c) region of the fireball. (a) Full RHIC energy; (b) reduced energy (analogous to SPS).

the``soft ridge" exists even **without** any hard trigger





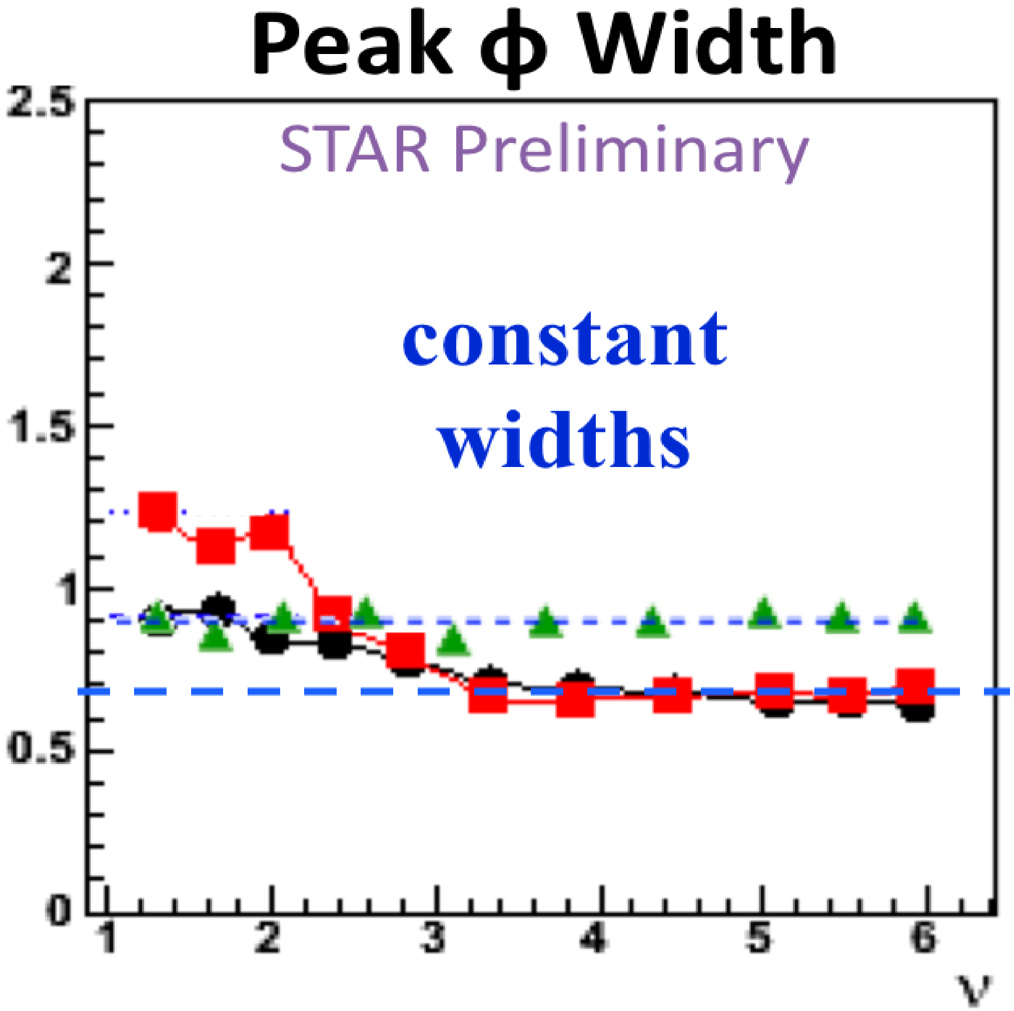
McLerran,Venugopalan et al: Fluctuations of color charges at early time

$$1/Q_s \sim .2fm/c$$

(Phobos further observed that ridge extends at least till |y|=4)

What happens next, till freezeout (>10 fm), is quite nontrivial

The peak width decreases for central collisions



- L.Ray

The decay products of the ridge are clusters which are **larger** than in pp!

they have up to 10 pions and they decay unisotropically

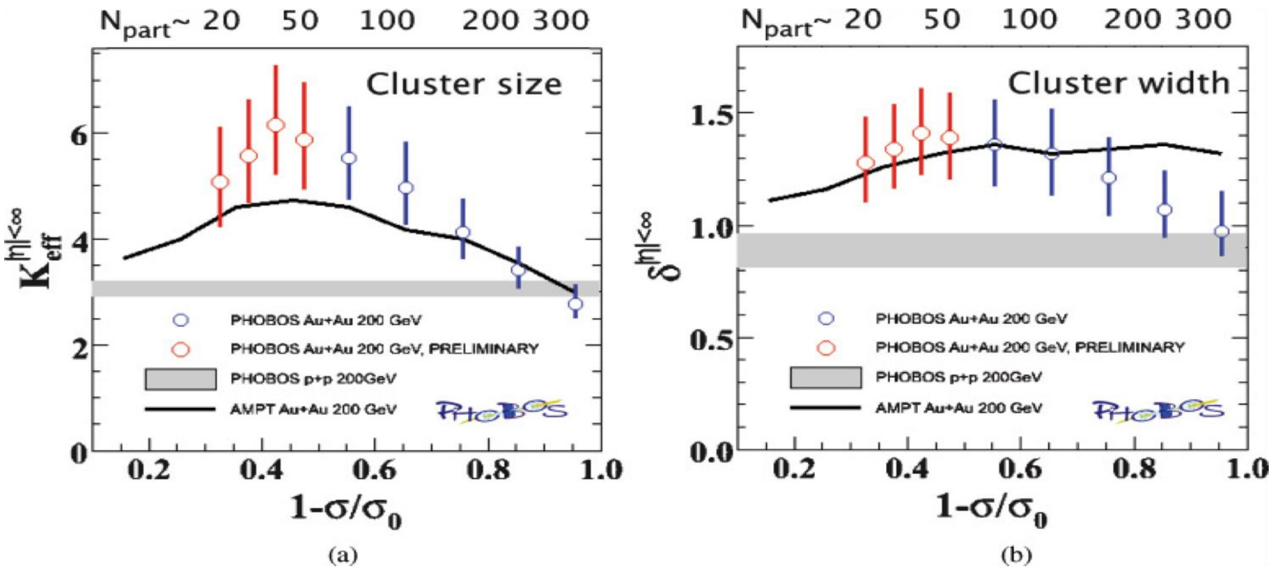
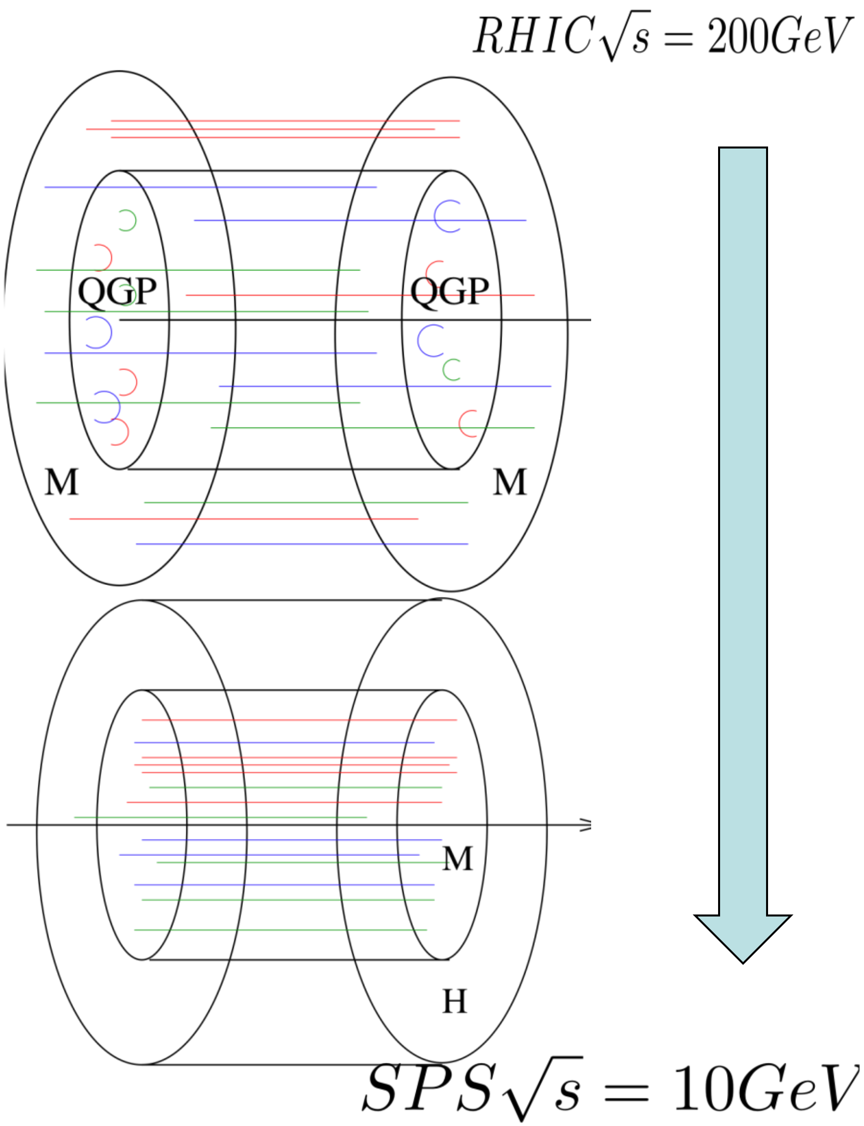


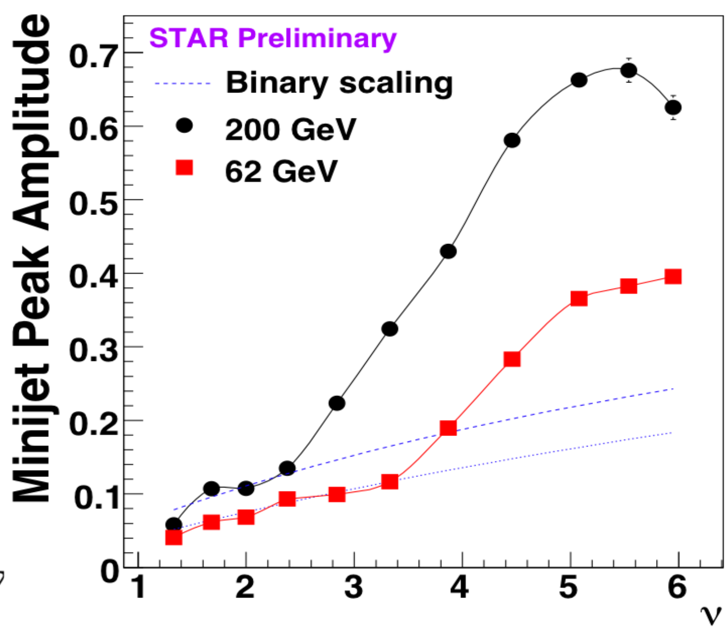
FIG. 13. (Color online) Cluster size (a) and width (b) as functions of centrality (cross section fraction) in Au-Au collisions at RHIC full energy, from PHOBOS [41]. The size is the number of charged particles associated with the cluster, and the width is in rapidity.

G.Stephens

Predictions for energy dependence: ridges



As energy decreases, M phase
Goes inside the fireball =>
Much smaller radial flow =>
Disappearance of the ridge
happens at fixed density of matter!



STAR AuAu

L.Ray: Also in CuCu

``metastable flux tube" option for ``cone" and ``ridge":

- there are enough monopoles to stabilize the flux tubes **mechanically** up to 1.4Tc:
- They can **survive for a long time**, 5-10 fm/c due to **heavy electric quasiparticles (q,g,dyons) at Tc**

$$P_{breaking} \sim exp(-\frac{\pi M^2}{E})$$

Mq=300 MeV at T=0 but about 600 MeV at Tc (lattice disp.curves)

summary

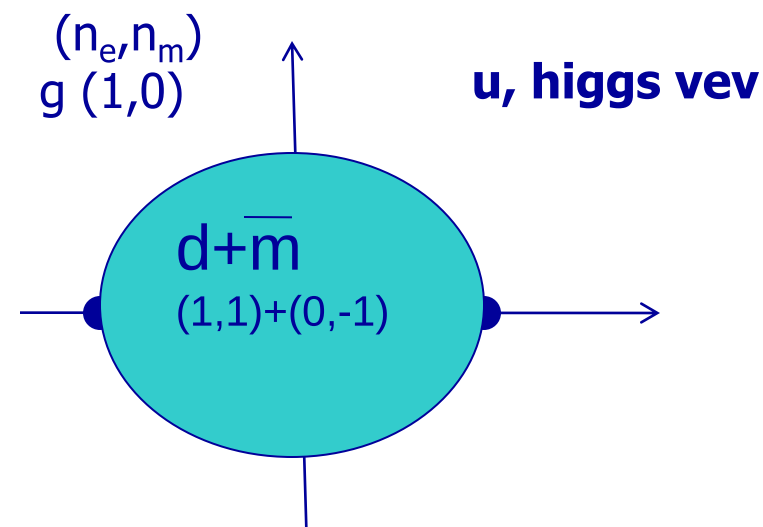
- **Fluctuations create perturbations => sound cylinders and cones. Sound horizon and viscous spread are to be measured, by (very distorted) cylinders,"Mach peaks" and recoil**
- **Color magnetic monopoles are found on the lattice, they behave as physical objects: the Coulomb plasma, running coupling,BEC at Tc**
- **What we called m-phase (from mixed) is magnetic-dominated. Different jet quenching,**

indications to corona made of flux tubes which are even more stable in magnetic plasma than in vacuum!

Recent development: the wall crossing formulae

- Black dots: SW (1994) singularities in which mono and dyon gets massless
- Blue oval is strong coupling region separated by "the wall" at which the **spectrum changes discontinuously** but not metric or charges:

(states disapper into IR)



Dyons were promoted to dyonic black holes in N=2 supergravity and their bound states have been studied

Recently "wall crossing formula" =>

M. Kontsevich and Y. Soibelman, "Motivic Donaldson-Thomas invariants:summary of results," arXiv:0910.4315

T. Dimofte, S. Gukov and Y. Soibelman, "Quantum Wall Crossing in N=2 Gauge Theories," arXiv:0912.1346 [hep-th].