The hedghog is the mascot of the SB Nuclear Theory group for 20 years, selected for its cute topology!

# QCD Topology at RHIC

**Edward Shuryak**
**Department of Physics and Astronomy**
**Stony Brook**

# Outline: 5 hot topics in QCD topology

1. Chiral symmetry breaking, fermionic quasizero modes =>instanton liquid => dyon plasma?
2. Dyons also have a role in confinement => effective potential for <P> (Diakonov)? Composite monopoles (Unsal)?
3. Going real: sphalerons and their explosion => diffractive clusters in pp at RHIC
4. CP-odd domains should lead to CP-forbidden decays e.g. eta=> 2pi
5. magnetic plasma at RHIC => flux tubes, dual MHD, "ridges", Confinement as monopole BEC,

# The vacuum vs QGP, in 1970's

ES, **Phys.Lett.B79:135,1978**

- **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

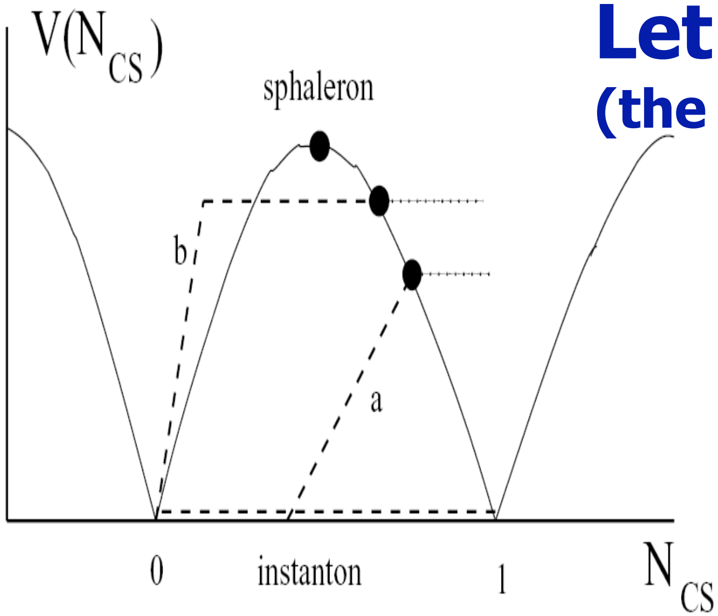
**“We cannot pump the QCD vacuum out, but we can pump in something else, namely the Quark-Gluon Plasma and measure the pressure difference…” ES**

**Now we found a lot of topology in QGP as well:**

**Perhaps the easiest way to understand topology is right above Tc…**

# Let us start at the beginning

## (the potential will be explained later)

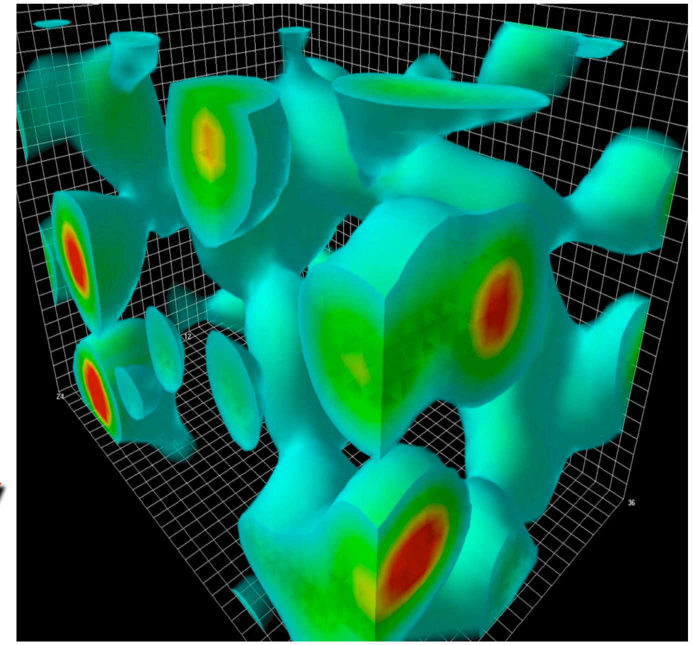



- The energy of Yang-Mills field versus the Chern-Simons number $N_{CS} = \int d^3x K_0$ is a periodic function, with zeros at integer points.

- The *instanton* (the lowest dashed line) describes tunneling between vacua. It is a path at E=0, it starts and ends at no field strength
- If energy is deposited, the paths (the dashed lines) goes up and emerge from ''under the barrier'' into real (Minkowskian) world at the turning points, where momenta (in the $A_0 = 0$ gauge) "$\vec{p}$" $= \frac{d\vec{A}}{dt} = \vec{E} = 0 \Rightarrow$ the field is magnetic
- Real time motion outside the barrier (shown by horizontal dotted lines) => explosions
- The maximal cross section corresponds to the top of the barrier, called the sphaleron =''ready to fall'' in Greek, according to Klinkhammer and Manton

# The QCD vacuum and instantons

(Schaefer, ES, RMP 1996)



- Chiral symmetry breaking
- Chiral U(1) breaking
- **No confinement in 3+1,**

**(Unlike 2+1, Polyakov)**

**"Instantons are not toys!" (P.van Baal)**

# Nambu-Jona-Lasinio versus the instanton liquid model

- NJL (1961) introduced hypothetical 4-fermion interaction (chirally symmetric)
- 2 parameters, G and cutoff Lambda (about 1 GeV)
- Good chiral physics, const.quarks pions etc (no confinement)
- Eta' also massless
- Other particles like sigma, rho,N not too well defined <=Higher orders basically undefined

**The Instanton Liquid Model ES (1982) also has 2 parameters**

$$n \approx 1 fm^{-4}, \rho \approx 1/3 fm, n\rho^4 \sim 10^{-2}$$

**It also describes all the chiral physics correctly**

**It can be and was solved to all orders**
**Rho and nucleon are bound and many correlators are well described**

**eta' is now heavy, due to repulsive 4-fermi term from 't Hooft!**

# Instantons emerging from vacuum quantum noise by ``cooling” (MIT group, 1993), S and Q

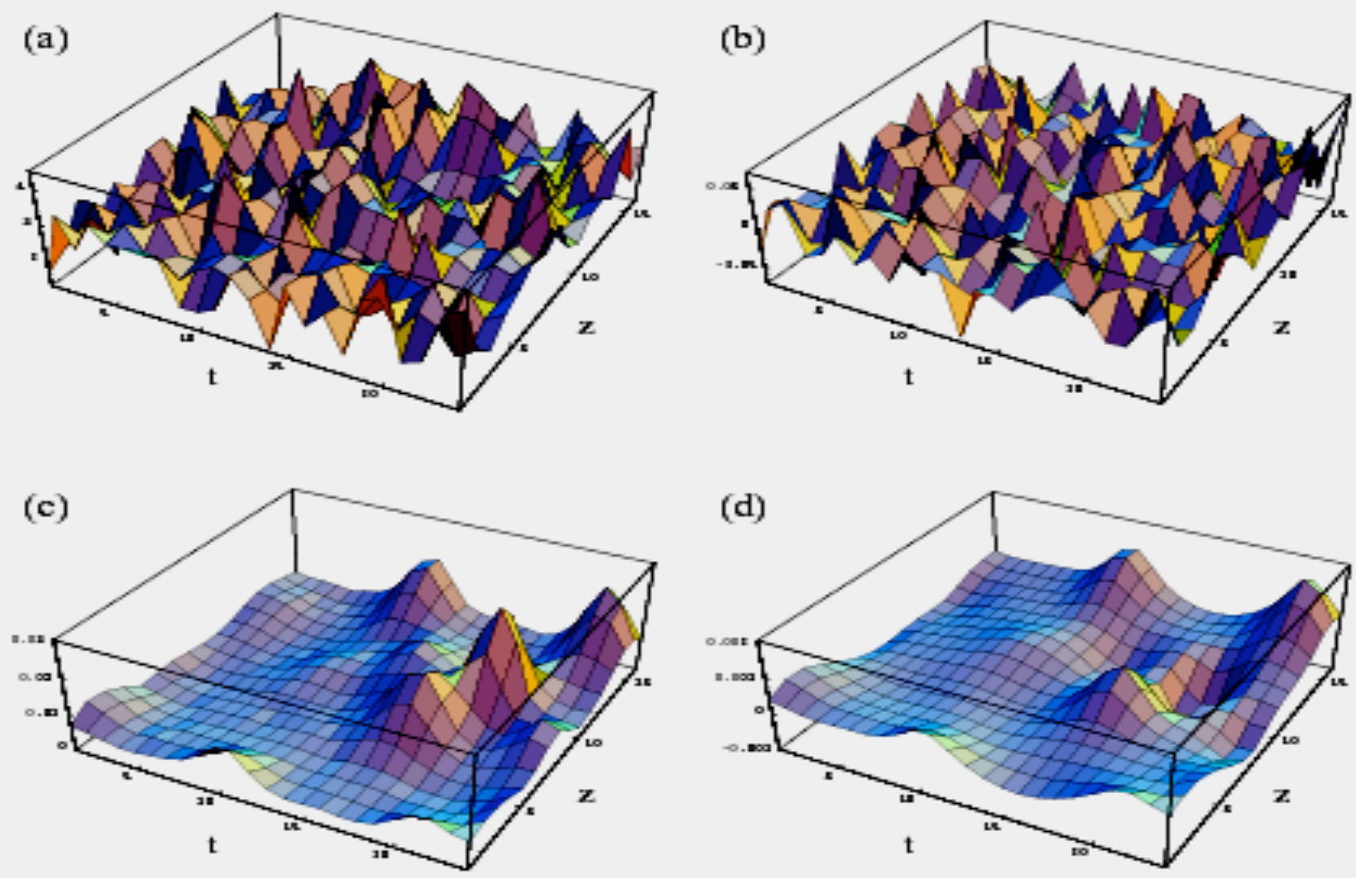



Fig. 5.8 Examples of cooling of lattice configurations

# Instantons induce forces between light quarks which are qualitatively different from gluon exchanges

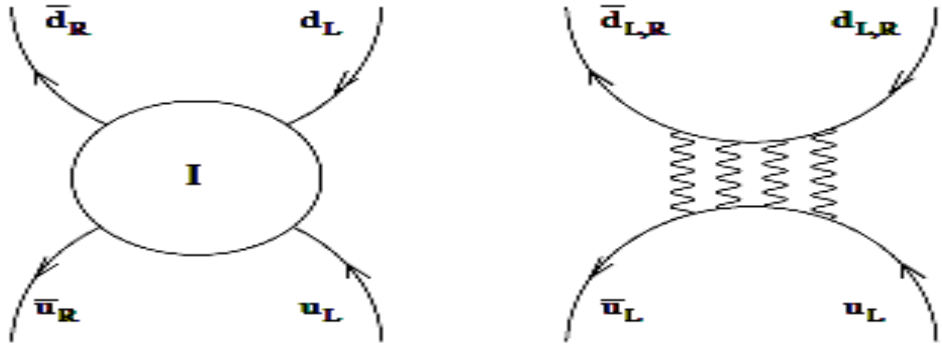
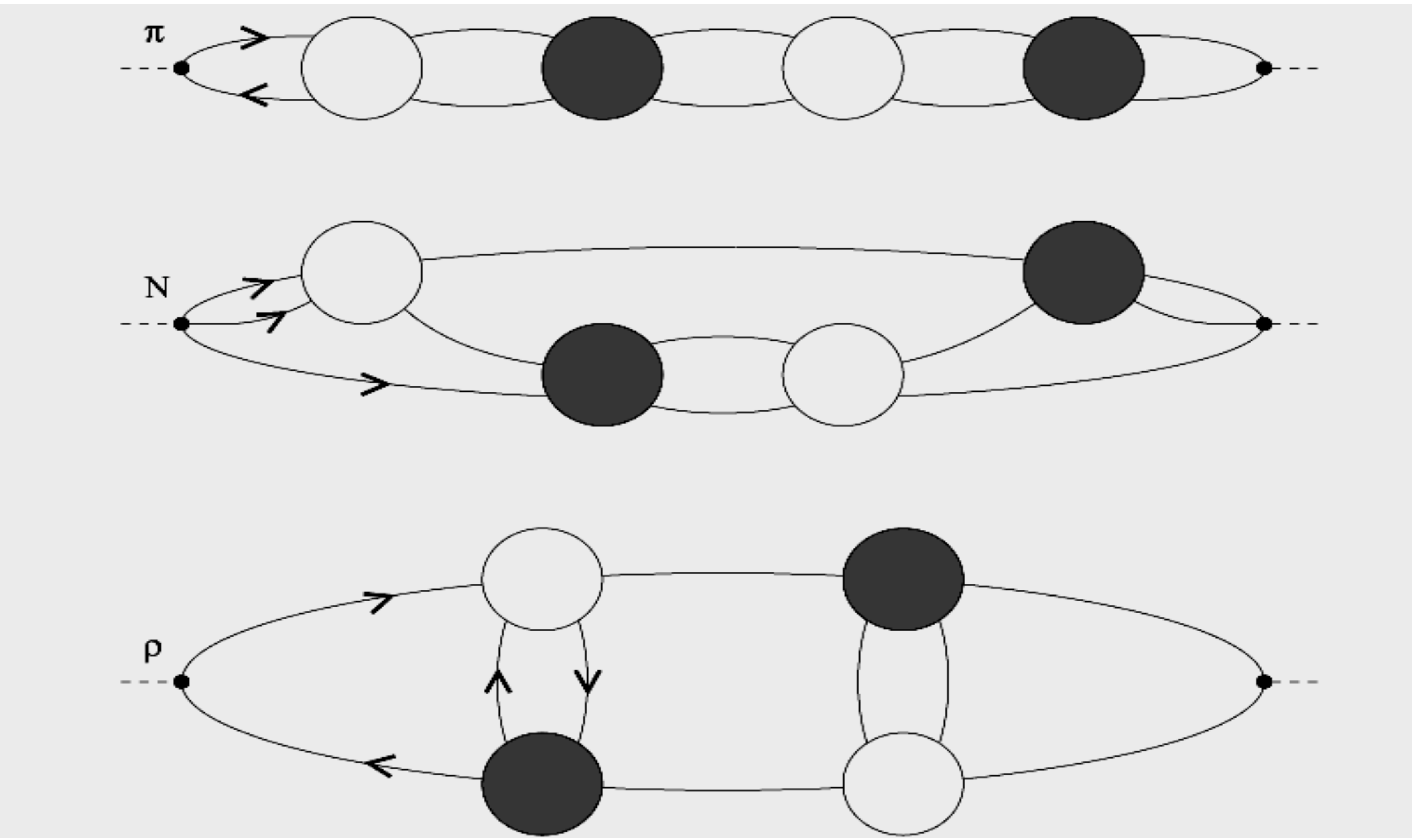



Fig. 4.1 The instanton-induced 't Hooft vertex (a) for 2 flavor QCD versus the ordinary gluon exchange diagrams (b). Note a very different chiral structure of the two: the latter does not violate any chiral symmetry because chirality is conserved along each line.

For $N_f = 2$, the result is

$$\mathcal{L}_{N_f=2} = \int d\rho\, n_0(\rho) \left[ \prod_f \left( m\rho - \frac{4}{3}\pi^2\rho^3 \bar{q}_{f,R} q_{f,L} \right) + \frac{3}{32} \left( \frac{4}{3}\pi^2\rho^3 \right)^2 \left( \bar{u}_R \lambda^a u_L \bar{d}_R \lambda^a d_L - \frac{3}{4} \bar{u}_R \sigma_{\mu\nu} \lambda^a u_L \bar{d}_R \sigma_{\mu\nu} \lambda^a d_L \right) \right], \qquad (4.14)$$

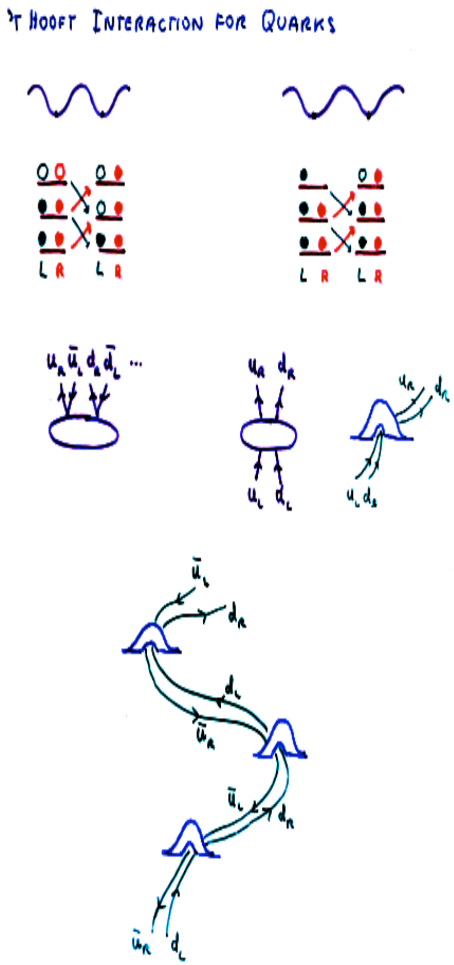
# correlation functions as (4th order) diagrams in 't Hooft interaction, 2 flavors

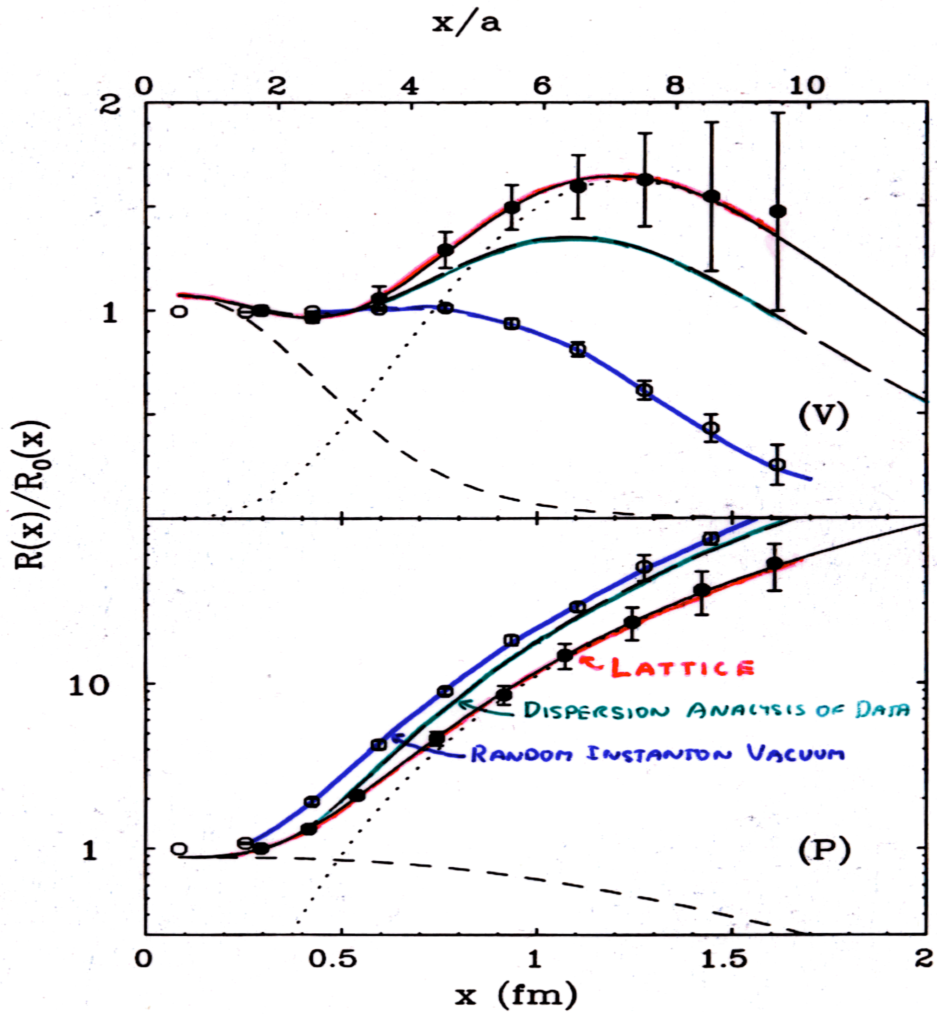


# A pion as a quark pair tunneling together

(from France to Britain)

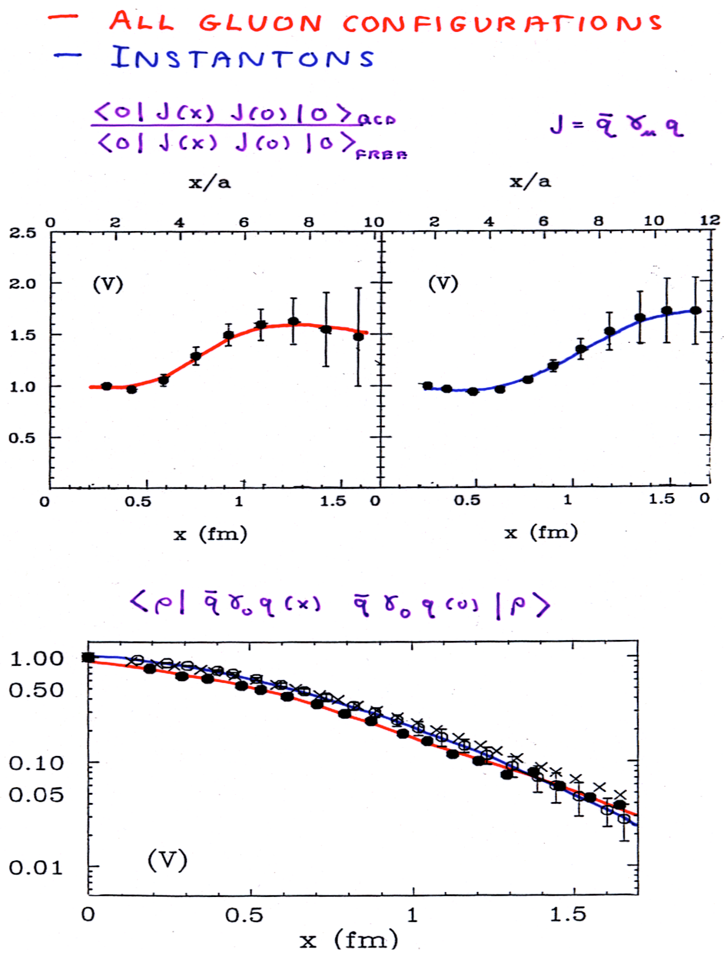
**ES,RMP,1993**

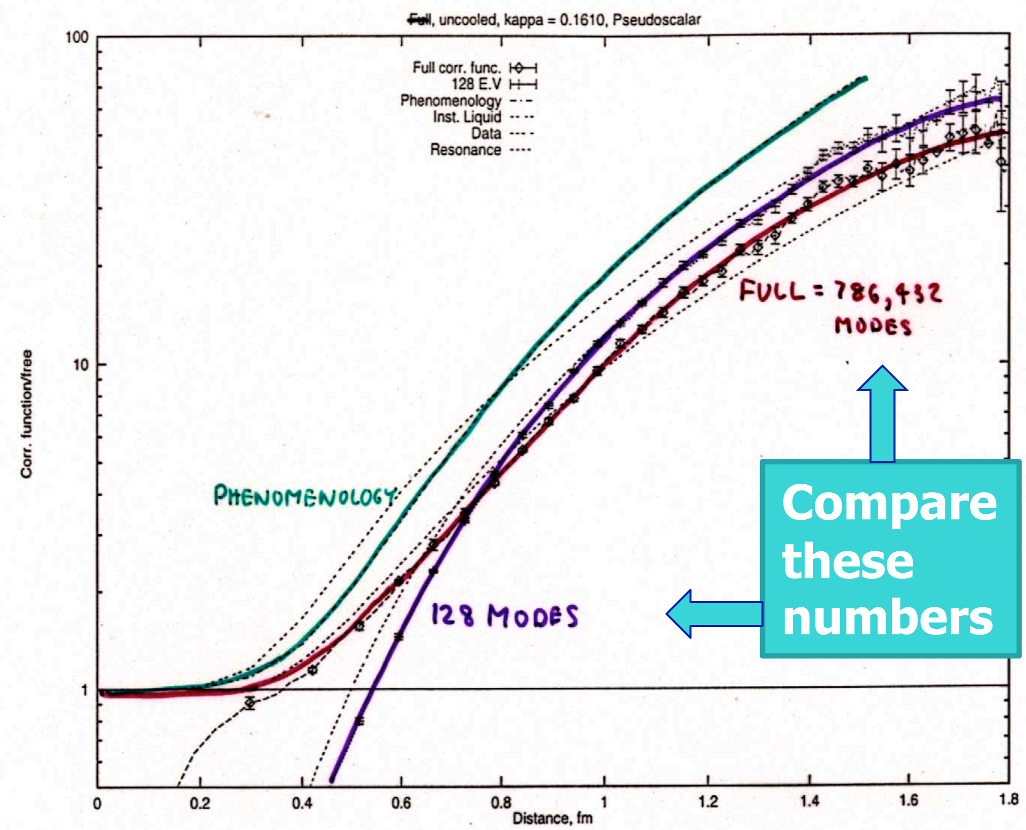


**The tiny fraction 0.01% of fermionic states (about 1 per instanton) is indeed enough to reproduce most of light quark hadronic physics**

J.Negele,T.DeGrand,A.Hazenfratz



# topological objects have zero modes which are chiral!

- $(D_\mu \gamma_\mu)^2 \psi=(D^2+G_{\mu\nu}\sigma_{\mu\nu})\psi=0$
- To get zero in the r.h.s. one needs the spin term since $D^2>0$
- Instantons/dyons are (anti)selfdual =>

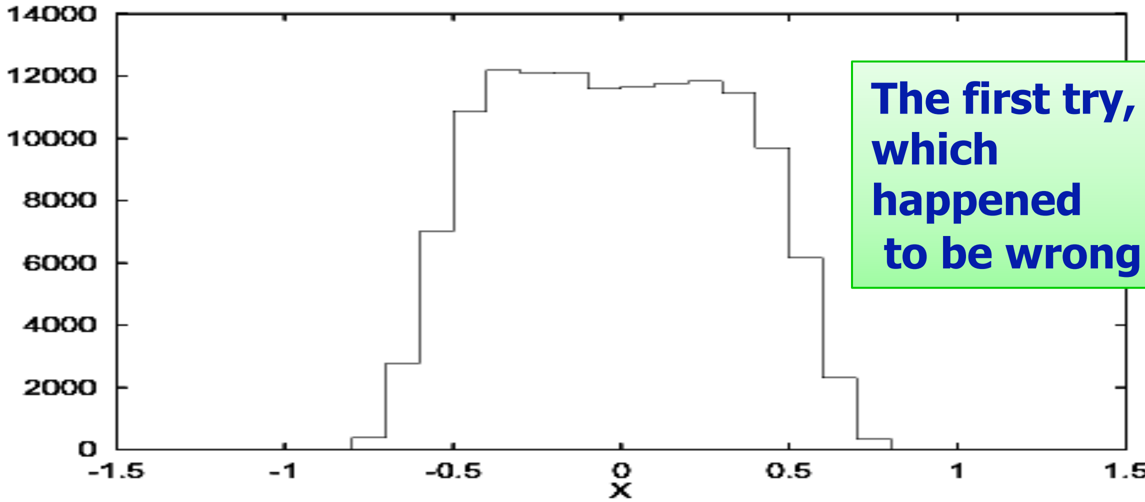
the spin term is nonzero for **a specific chirality only!**

- **If the quark condesate is made of (collectivised) zero modes it must be locally chiral (pure L or R)**

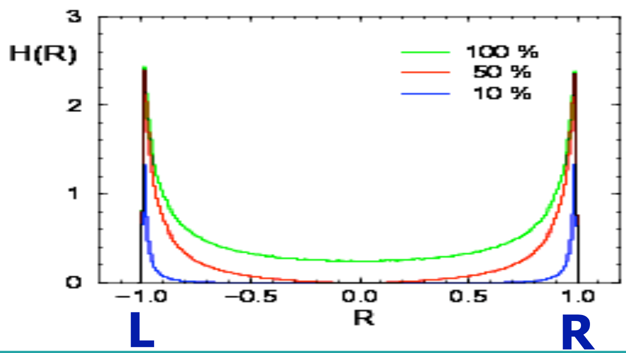
Comment on "Evidence Against Instanton Dominance of Topological Charge Fluctuations in QCD" by I. Horváth *et al.*

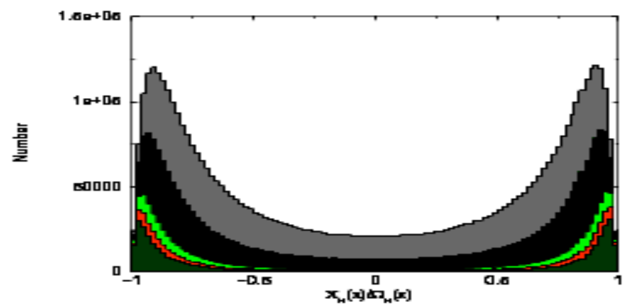
Thomas DeGrand, Anna Hasenfratz
*Department of Physics, University of Colorado, Boulder, CO 80309 USA*
(February 1, 2008)

We comment on the recent paper (hep-lat/0102003) by Horváth, Isgur, McCune, and Thacker, which concludes that the local chiral structure of fermionic eigenmodes is not consistent with instanton dominance. Our calculations, done with an overlap action, suggest the opposite conclusion.




The first try, which happened to be wrong




**So the states making the quark condensate are locally (anti) selfdual, thus topological!**

# At nonzero holonomy ($A_0$) the instantons are made of **Nc (anti) selfdual dyons** (also known as instanton quarks)

T.C. Kraan and P. van Baal, Phys. Lett. B435 (1998) 389 [hep-th/9806034].

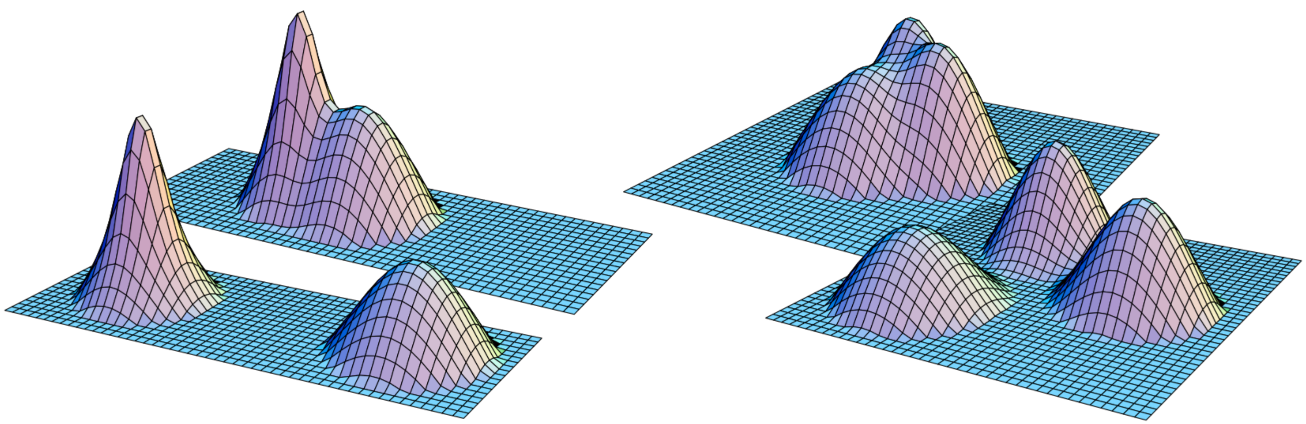
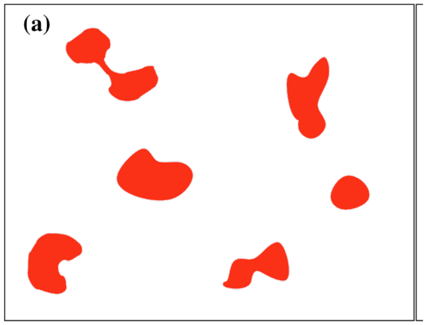


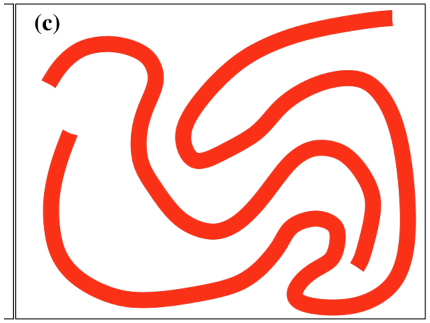
**Figure 2:** On the left are shown two charge one SU(2) caloron profiles at $t = 0$ with $\beta = 1$ and $\mu_2 = -\mu_1 = 0.125$, for $\rho = 1.6$ (bottom) and 0.8 (top) on equal logarithmic scales, cutoff below an action density of $1/(2e^2)$. On the right are shown two charge one SU(3) caloron profiles at $t = 0$ and $(\nu_1, \nu_2, \nu_3) = (1/4, 7/20, 2/5)$, implemented by $(\mu_1, \mu_2, \mu_3) = (-17/60, -1/30, 19/60)$. The bottom configuration has the location of the lumps scaled by 8/3. They are cutoff at $1/(2e)$.

**So, the instanton liquid => dyon plasma**

# the geometric shape of the zero modes is not yet clear…

- Istantons give 4-d localized modes
- Dyons and monopoles have zero modes which are lines in 4d
- Vortices produce 2d surfaces




**Understanding of the transition from the "instanton liquid" to "dyonic plasma" is badly needed !**

# QCD sphalerons and their explosion => diffractive clusters at RHIC

**Semiclassical Theory of High Energy Collisions based on Instantons and Sphalerons**

- ''pomeron from instantons'':

ES, Zahed PRD62:085014,2000 hep-ph/0005152

D. E. Kharzeev, Y. V. Kovchegov and E. Levin Nucl. Phys. A **690**, 621 (2001) [hep-ph/0007182].

M. A. Nowak, ES and Zahed, PRD 64, 034008 (2001) [hep-ph/0012232].

G.W.Carter,D.Ostrovsky and ES, Phys. Rev. D **65**, 074034 (2002) [hep-ph

- the turning states and their explosion

D.Ostrovsky, G.W.Carter and ES, hep-ph/0204224,PRD

- Landau method for cross section - rescaled YM sphalerons are produced

D. Diakonov and V. Petrov, Phys. Rev. D **50**, 266 (1994) R. A. Janik, ES and Zahed, hep-ph/0206005.

- Explicit solution of the Dirac eqn in the exploding field background: an end of ''the fermion puzzle''?

ES and Zahed, hep-ph/0206022.

- Gluonic cluster production in double-Pomeron processes (e.g. $pp->pp\eta'; pp f_0(1600), pp+$cluster) compared to data; ES and Zahed,2002
- Instanton-induced Double DIS $\gamma^*\gamma^*$)ES and Zahed,2003

## Earlier developments:

• (Baryon-number violating) instanton-induced processes in electroweak theory A.Ringwald, Nucl.Phys. B330 (1990) 1, O.Espinosa, Nucl.Phys. B343 (1990) 310; L.McLerran, A.Vainshtein V.I.Zakharov, A.Muller, M.Maggiore and M.Shifman, : extremely insightful works, but the effect is too small to be seen!

# Carter-Ostrovsky,ES 2001: the potential and the QCD sphalerons

- What is the minimal potential energy of static Yang-Mills field, consistent with the constraints:

(i) the given value of (corrected) Chern-Simons number.

(ii) the given value of the r.m.s. size $< r^2 >= \int d^3 x r^2 \mathcal{B}^2 / \int d^3 x \mathcal{B}^2$

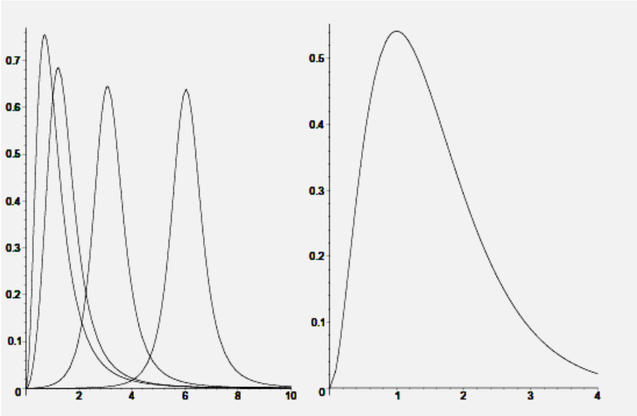
- Solution (found by D.Ostrovsky) is a ball made of three magnetic gluon fields (out of 8 in SU(3)) rotated around x,y,z axes

$B^2/2 = 24(1-\kappa^2)^2 \rho^4/(r^2+\rho^2)^4$

$E_{stat} = 3\pi^2(1-\kappa^2)^2/(g^2\rho)$ $\tilde{N}_{CS} = \mathrm{sign}(\kappa)(1-|\kappa|)^2(2+|\kappa|)/4.$

Eliminating $\kappa$ one gets the topological potential energy,

$\kappa = 0$ gives the sphaleron



# Explosion of the Turning States

**Left: the snapshots of the r^2 energy**
**Right: the spectrum of the produced fermions**

- Solved both numerically (G.Carter) and analytically (by D.Ostrovsky based on work by Luescher and Schehter from 1977 which can also be via conformal transformation -Zahed)
- Sphalerons at $t=0 =>$ (at large t) into a spherical transverse wave $4\pi e(r,t) = \frac{8\pi}{g^2\rho^2}(1-\kappa^2)^2\left(\frac{\rho^2}{\rho^2+(r-t)^2}\right)^3$

- ES+Zahed: new solution to the Dirac equation in exploding backgroun obtained by inversion of the fermionic O(4) zero mode of O(4) symmetric solution.

It explicitly shows how the quark acceleration occurs, starting from zero energy at t=0 to the final spectrum

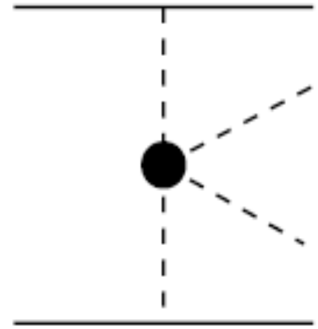
- The sphalerons produce one level crossing $N_F \bar{L}R$ quarks, and the antisphaleron-like clusters the chirality opposite.

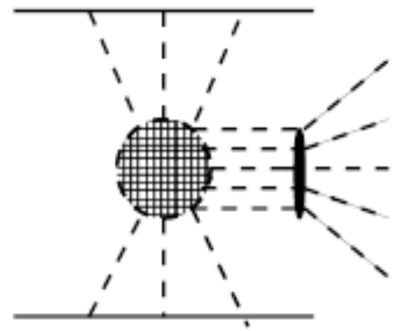
# Pomeron from instantons

• Soft Pomeron with ''instanton ladder'' provides reasonable intercept and slope

•No Odderon SU(3) allows for a colorless combination of 3 gluons.

Perturbatively, the odderon/pomeron ratio is $O(\alpha_s)$ and not as suppressed as the data shows. Instantons are SU(2) beasts and do not allow it.





• Instanton is the only nontrivial field for which straight Wilson lines can be easily analytically calculated

$\int \tau^a A^a_\mu dx_\mu \sim (\tau^a \eta^a_{\mu\nu} e^t_\nu e^l_\mu) \int F(x^2) dt$

• The trick with rotating cross section to Minkowski seem to work perturbatively and in general (Meggiolaro): we tried it for instanton

# Example of the cleanest process: the double DIS, no hadrons, just excitation of one cluster (sphaleron)

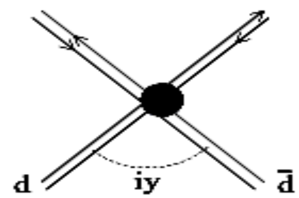
Double-DIS $\gamma^*\gamma^*$ (Next linear collider?)

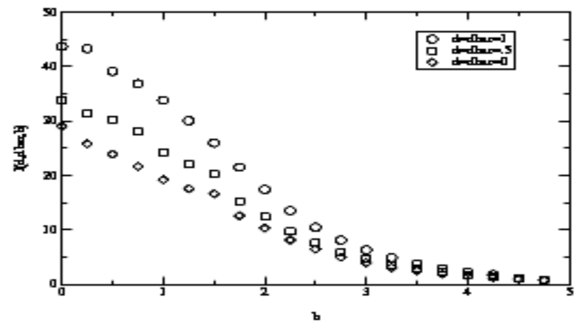
About the same small gluonic spot without any nucleon

ES, I.Zahed hep-ph/0307103, PRD in press

Two dipoles cross the instanton, the angle is changed to $iy$ at the end of the calculation

$\sigma \sim d_1^2 d_2^2$ times the dimensionless function of the three 2-d vector variables $\mathbf{I}(\vec{d1}/\rho, \vec{d2}/\rho, \vec{b}/\rho)$ explicitly given and tabulated: see b-profile



# Semiclassical Double-Pomeron Production of Glueballs, $\eta'$ and clusters

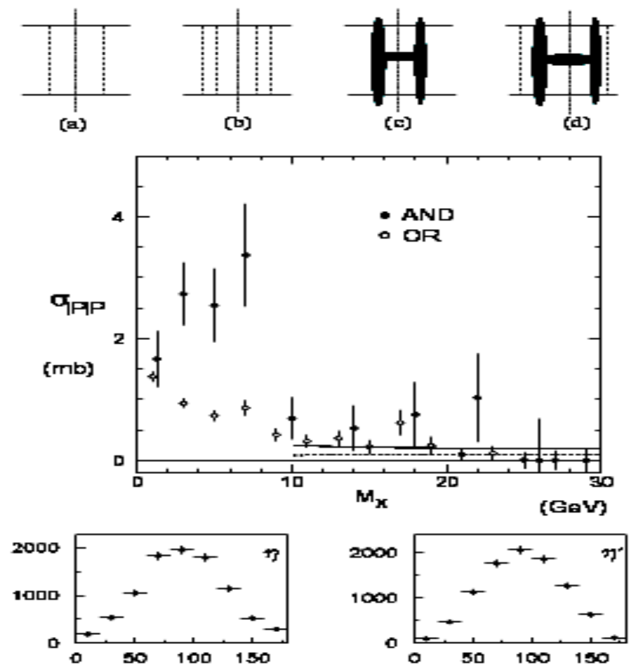
ES and I.Zahed,Phys.Rev. D68 (2003) 034001

Pomeron-Pomeron into cluster, cross section from UA8 collaboration: heavy gluonic clusters with isotropic decay. What are they?

Note: a cross section that is an order of magnitude larger than the one predicted by Pomeron factorization

WA102 collaboration at CERN, $pp$ Double-Pomeron into identified central hadron: strong dependence of the cross section on the azimuthal angle $\phi$ (between two kicks to two protons), not expected from standard Pomeron phenomenology.

we get $cos^2(\phi)$ for P=+ and $sin^2(\phi)$ for P=-1.



# sphalerons in pp:

- Double-diffractive cluster production in STAR+"Roman pots" => proposal pending
- Sphaleron produces 6 units of chirality!
- Expected exclusive channels which are well observed like $KK\pi$ etc (but not $\pi\pi\pi$) like it was in $\eta_c$ decays (Bjorken,Schafer)
- Because pp has magnetic field => charge

asymmetry in final states (Kharzeev)

**Rafaelle Millo is Ph.D.student of my former student P.Faccioli who is professor at University of Trento. He visited in Dec. 09 for a week and we made (in 2 days) the following paper**

### Macroscopic Chirality Fluctuations in Heavy Ion Collisions should induce CP forbidden Decays

Raffaele Millo[1] and Edward V. Shuryak[2]

[1] *Universitá degli Studi di Trento and I.N.F.N. Via Sommarive 14, Povo (Trento), Italy.*
[2] *Department of Physics and Astronomy, State University of New York, Stony Brook NY 11794-3800, USA*
(Dated: December 24, 2009)

**arXiv: 0912.4894**

If large fluctuations of quark chirality occur in heavy ion collisions, they result in macroscopic CP-odd "spots" of the so called theta-vacua, with a non-zero $\theta(x)$. We consider particular decays of mesons, CP-forbidden in the vacuum with zero $\theta$, like $\eta \to \pi\pi$. We evaluate their rates for such decays near hadronic freezeout. These rates, as well as charge asymmetries already observed, are proportional to square of the CP-violating parameter $\langle \theta^2 \rangle$ averaged over the fireball and events. With such input, we found that the forbidden decay rates are likely to be orders of magnitude larger than CP-allowed ones. We further estimated that up to about one per mill of $\eta$ mesons produced in heavy ion collisions should decay in this way. We further discuss how those can be observed. We argue using STAR data on charge asymmetries for AuAu and CuCu collisions that the size of CP-odd spots at freezeout is as large as Cu nuclei: this fortunate fact (not explained so far by itself) suggests that the two-pion invariant mass is modified by only about a percent, which is comparable to experimental resolution. If so, we think experimental observation of these decays is within the reach of current dataset. If those decays are found, it would confirm that CP-odd interpretation of charge asyymetry is correct, even without complication related to geometry, impact parameter or magnetic field induced on the fireball.

- We since have learned that A.R.Zhitnitsky had the same idea before us , he also calculated such decay in hep-ph/0003191
- All the parameters in the answer coinside, but he considered 2 flavors and we did 3 with eta-eta' mixing., amplitude different by factor 3
- (At that time Kharzeev, Pisarski and Tytgut proposed **metastable minima,** domains of theta vacua: this is a different Idea which did not worked out. Now we all consider just the CP-odd fluctuations which do not require any new minima)

- Decays which were forbidden are now allowed:

$\eta \Rightarrow \pi^+\pi^-$, $\eta' \Rightarrow \eta\pi$, $\eta' \Rightarrow \pi^+\pi^-$

- in the CP-odd spot <theta> is nonzero => disbalance between instantons and anti-instantons even at freezeout in the near-vacuum state
- Calculated from the chiral Lagrangian at nonzero theta

The CP-odd part of the ChPT Lagrangian in the leading chiral order and at leading order in the $1/N_c$ expansion, is equal to[18]

$$L_{eff} = -i\frac{\chi_{top}N_f}{2N_c}\bar{\theta}\left[\mathrm{Tr}[U(x) - U^\dagger(x)] - 2\log\det U(x)\right] \quad (5)$$

where $\bar{\theta}$ is an *effective $\theta$ parameter.*

$$\bar{\theta} \simeq \frac{F_\pi^2 N_c m_\pi^2}{4N_f\chi_{top}}\theta \quad (6)$$

**it is clear that any theta effect can only be visible if no quarks is massless: thus theta-bar variable.**

$$\bar{\theta} \approx 0.06\theta$$

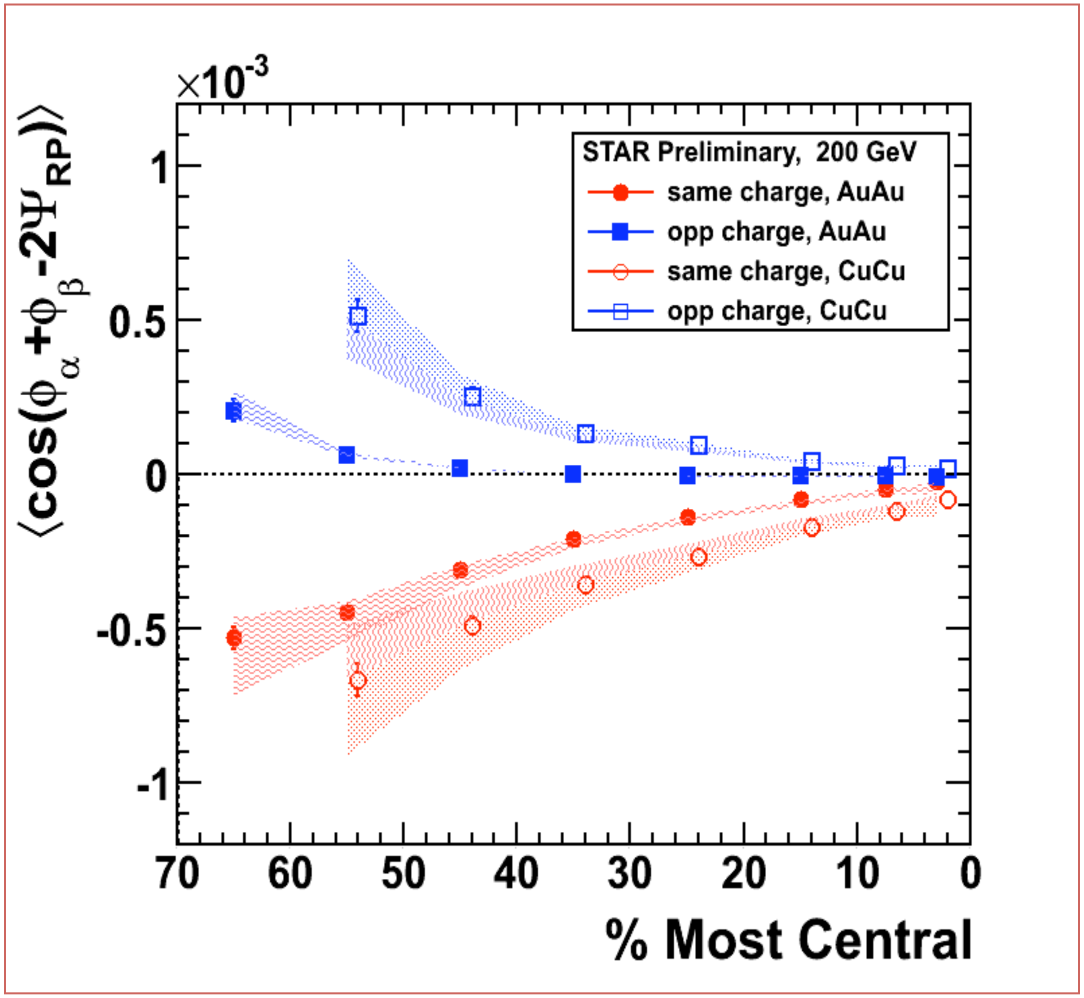
**So, for theta=O(1) thetabar is few percents**

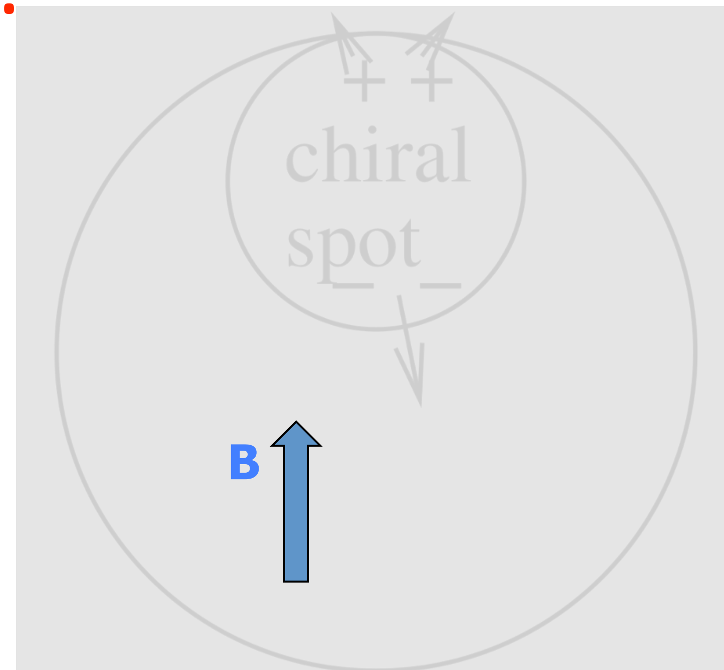
$$\Gamma_{\eta\to\pi^+\pi^-} = \frac{1}{32\pi^2}|A_{\eta\to\pi^+\pi^-}|^2\frac{|\bar{p}_\pi|}{m_\eta^2}\mathrm{d}\Omega$$

$$\simeq \frac{1}{24\pi}\frac{\chi_{top}^2}{F_\pi^6}\bar{\theta}^2\frac{\sqrt{m_\eta^2 - 4m_\pi^2}}{m_\eta^2} \approx 140MeV\bar{\theta}^2$$

$$P_{\eta\to\pi^+\pi^-} = \Gamma_{\eta\to\pi^+\pi^-}\Delta\tau_f\frac{V_{spot}}{V_f} \sim 0.1\theta^2\frac{\Delta\tau_f}{1fm}\frac{V_{spot}}{V_f}$$

# What is the size of the "chiral spot" at freezeout?




**+- is strongly quenched in AuAu,**
**but it is nearly symmetric in CuCu**

**⇒At freezeout the spot size seem to be comparable to the Cu nucleus**

# Can forbidden decays be observed?

- Because the chiral spot is so large, theta(x)contributes relatively small momentum
- $k=O(1/R_{spot})$

As a result, the invariant mass of the final state is modified by

$$M_{inv} = \sqrt{m_\eta^2 - \vec{k}^2} \approx m_\eta[1 - \frac{\vec{k}^2}{2m_\eta^2}] \quad (14)$$

The magnitude of the spot size and the corresponding momenta will be discussed in the next section, for estimate we will use $k = 50 - 100\,MeV$. From the formula above we see that the correction to the mass is then in the range of $-(0.005..0.02)$.

Which is comparable to best experimental resolution in the invariant mass.

Small signal but with 10^9 events and about 10^6 pairs/event perhaps doable

**No magnetic field needed**, if it gives the same $\theta$ as charge asymmetry, it will prove that it is CP-odd

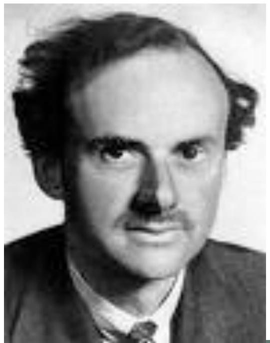
# How many sphalerons (CP-odd fluctuations) are there in AuAu event? (Not all virtual objects are exited into rel ones, so RHIC fireball has much less topology than vacuum…)

The estimate of the number of sphalerons produced in Au Au collisions have been estimated in [7]. If we only consider the number of vacuum instantons in an initial state "pancake" then we get a so called minimal number

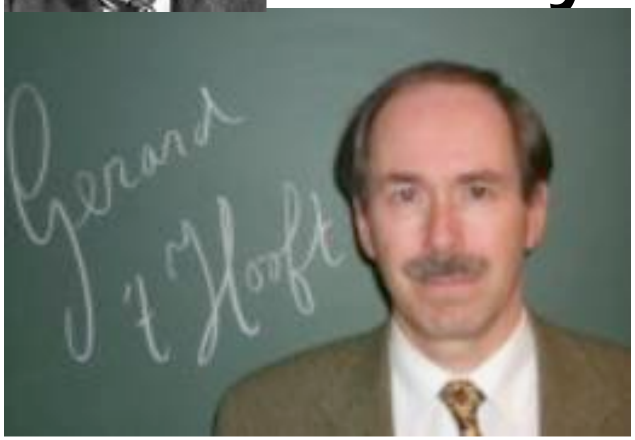
$$N_{sphalerons} > n\rho^2 \pi R_{Au}^2 \sim 10 \qquad (2)$$

while the maximal number in [7] is an order of magnitude larger. This implies that the asymmetry of the fireball is $Q_{top} \sim \sqrt{N_{sphalerons}} = 3 - 10$. As the size of the sphalerons is $\sim \rho \ll R_{Au}$, each of them exploding leads to some chirally asymmetric spots.

[7] E. V. Shuryak, Nucl. Phys. A **717**, 291 (2003).



# Magnetic objects and their dynamics: classics



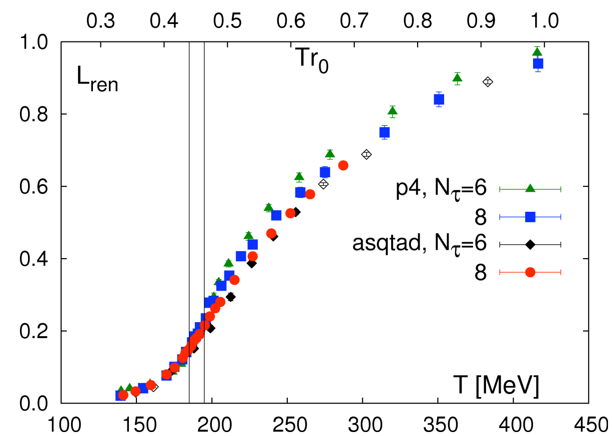

- Dirac explained how magnetic charges may coexists with quantum mechanics (1934)
- ‘t Hooft and Polyakov discovered **monopoles** in Non-Abelian gauge theories (1974)
- ‘t Hooft and Mandelstamm suggested “dual superconductor” mechanism for confinement (1982)
- Seiberg and Witten shown how it works,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

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

- **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 finite temperature Yang-Mills Theories.**
  **Alessio D'Alessandro, Massimo D'Elia, Edward Shuryak, . Feb 2010. 17pp.**

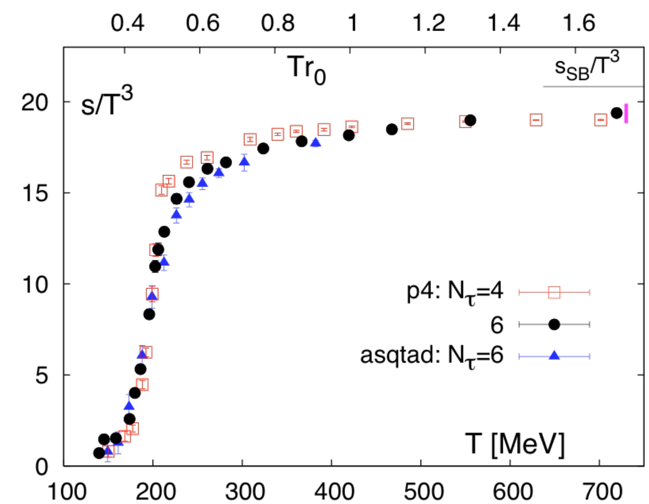
**Four lectures on strongly coupled Quark Gluon Plasma. Edward Shuryak, (SUNY, Stony Brook) . 2009. 46pp. Published in Nucl.Phys.Proc.Suppl. 195:111-156,2009.**

# The "semi-QGP puzzle" (Pisarski) as T=>Tc




- Electric objects are suppressed by the Polyakov line

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




- Quarks as <L>, gluons as <L$^2$>, and they are…PNJL
- and yet the entropy near Tc is large…

**what is the other half?**

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

Old good Dirac condition

**$\alpha_s$(electric) $\alpha_s$(magnetic)=1**

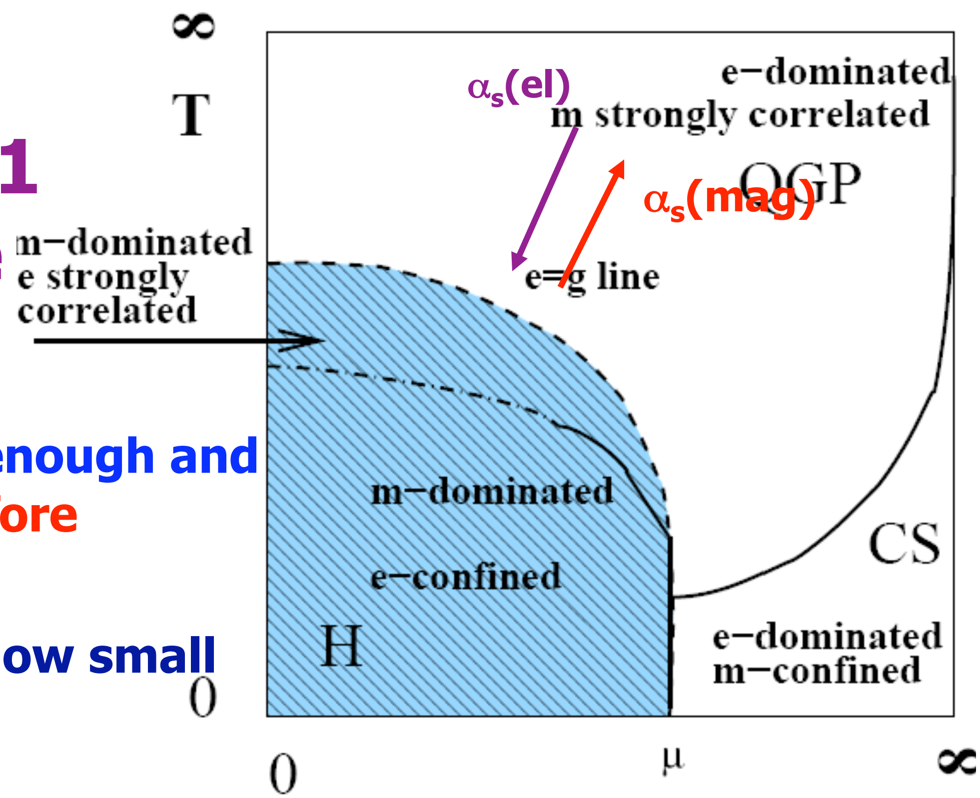
=>electric/magnetic couplings (e/g)

must run in the opposite directions!

the "equilibrium line"

**$\alpha_s$(el)= $\alpha_s$(mag) =1**

**needs to be in the plasma phase**

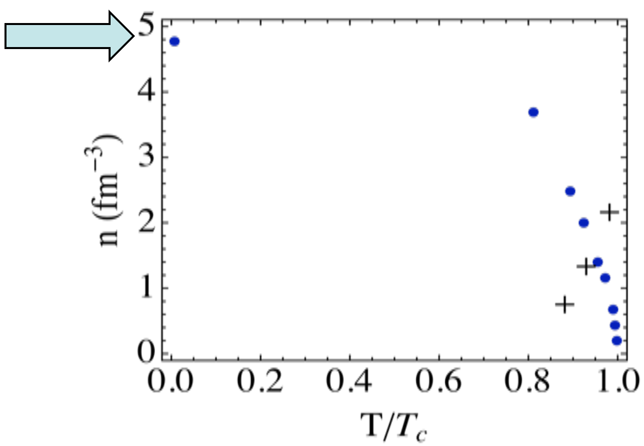



monopoles should be dense enough and sufficiently weakly coupled before deconfinement to get BEC

=>$\alpha_s$(mag) < $\alpha_s$(el): how small can $\alpha_s$(mag) be?

# The monopole density (vs T/Tc)

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



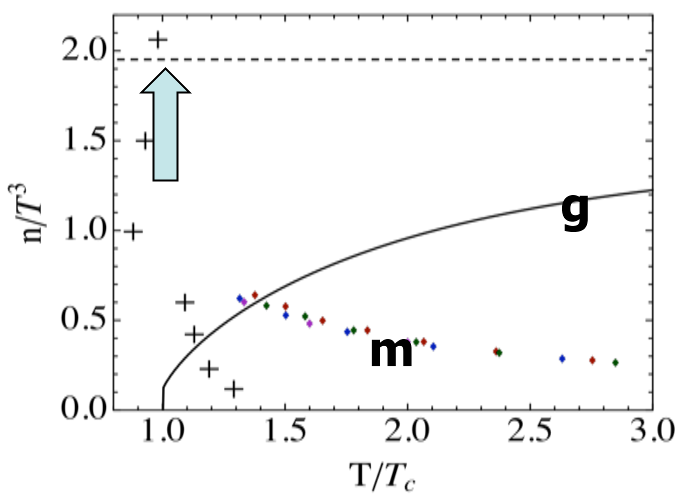




Figure 1: (a) The monopole density $n_m$ in units of [fm$^{-3}$] versus $T/T_c$ for the confined phase $T < T_c$. (b) The normalized density $n/T^3$ versus $T/T_c$ for the deconfined phase $T > T_c$.

- 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!

Jinfeng Liao and Edward Shuryak
*Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794*
(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

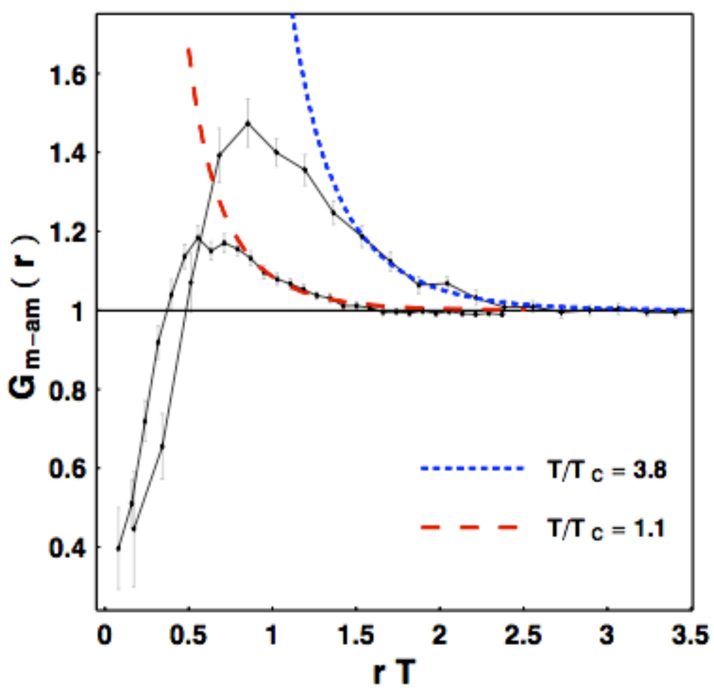
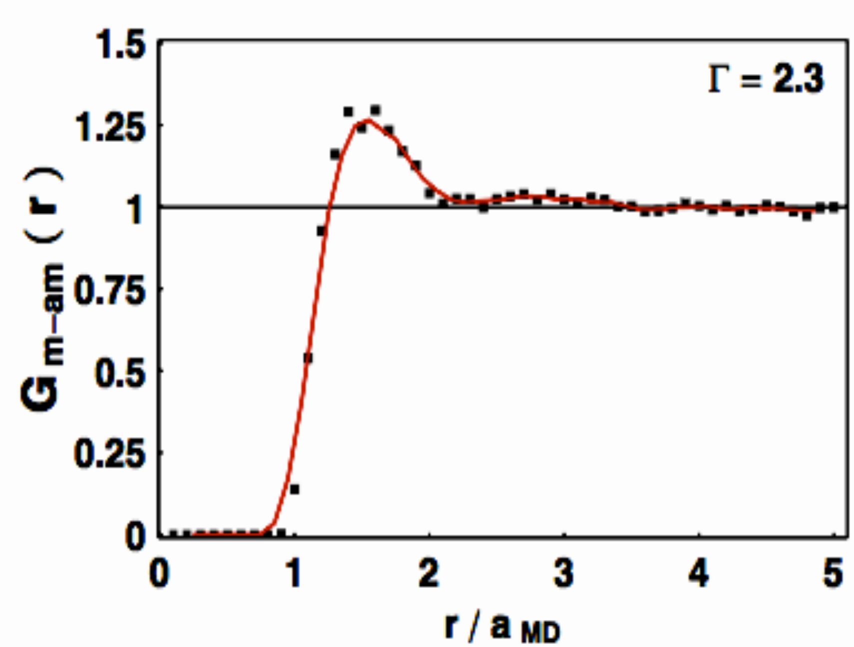



FIG. 2. (color online) Monopole-antimonopole correlators versus distance: points are lattice data [2], the dashed lines are our fits.

**Our MD for 50-50 MQP/EQP**

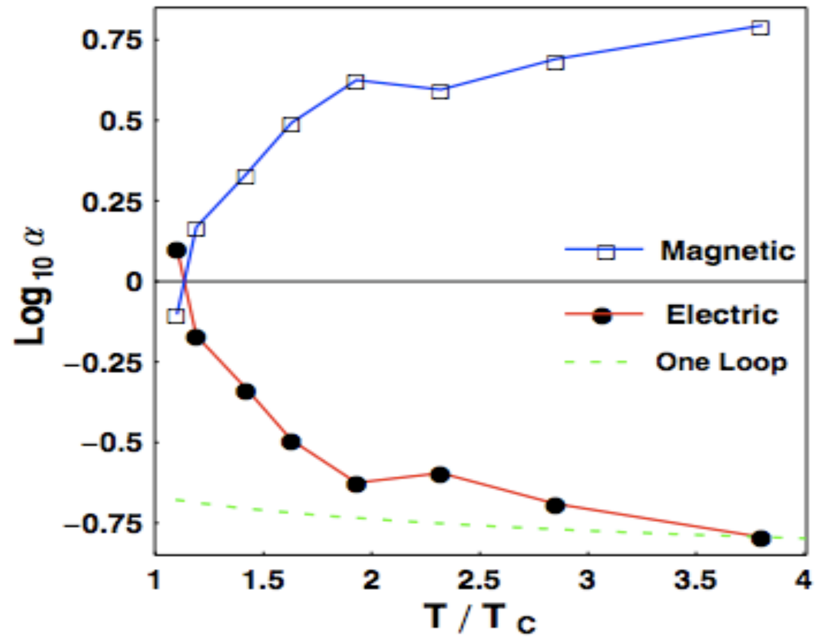


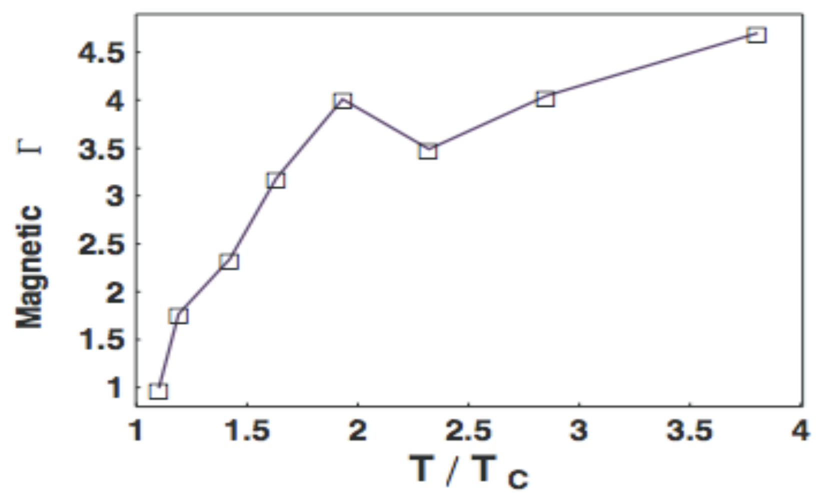
# $\alpha_s$(electric) and $\alpha_s$(magnetic) do run in opposite directions!

- 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)**



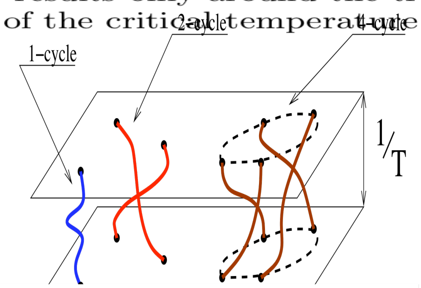



# Thermal Monopole Condensation and Confinement in finite temperature Yang-Mills Theories

Alessio D'Alessandro, Massimo D'Elia[1] and Edward V. Shuryak[2]
[1] *Dipartimento di Fisica, Università di Genova and INFN, Via Dodecaneso 33, 16146 Genova, Italy*
[2] *Department of Physics and Astronomy, State University of New York, Stony Brook NY 11794-3800, USA*
(Dated: February 22, 2010)



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.



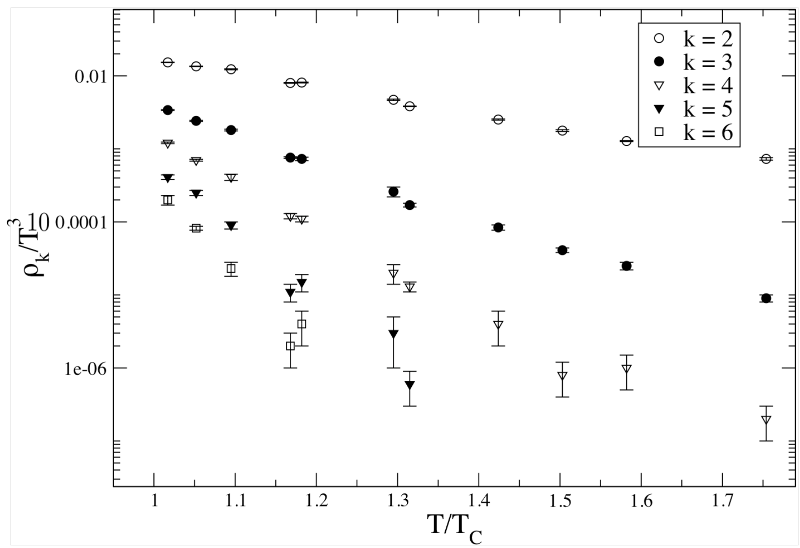
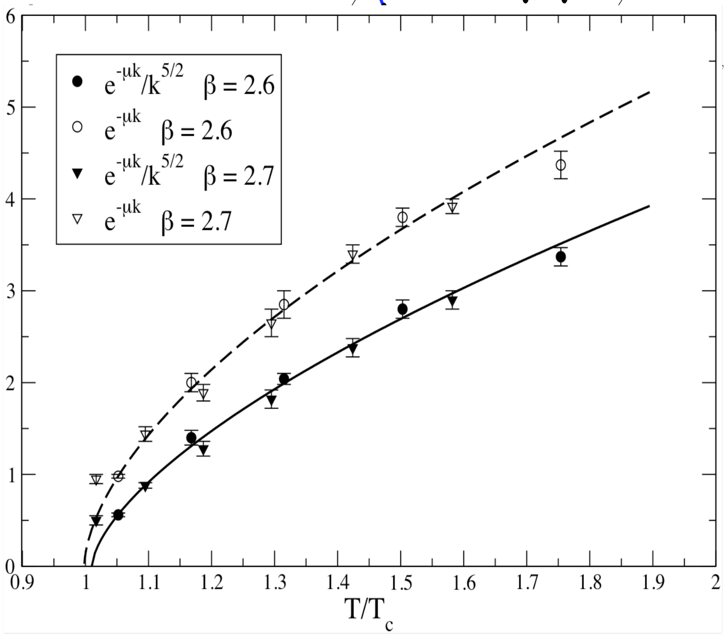




FIG. 2: Normalized densities $\rho_k/T^3$ as a function of $T/T_c$.




, in which

IG. 4: Chemical potentials reported in Table II for $\alpha = 0$ and $\alpha = 2.5$ and two different lattice spacings, together with a fit f them according to Eq. (24).

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

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

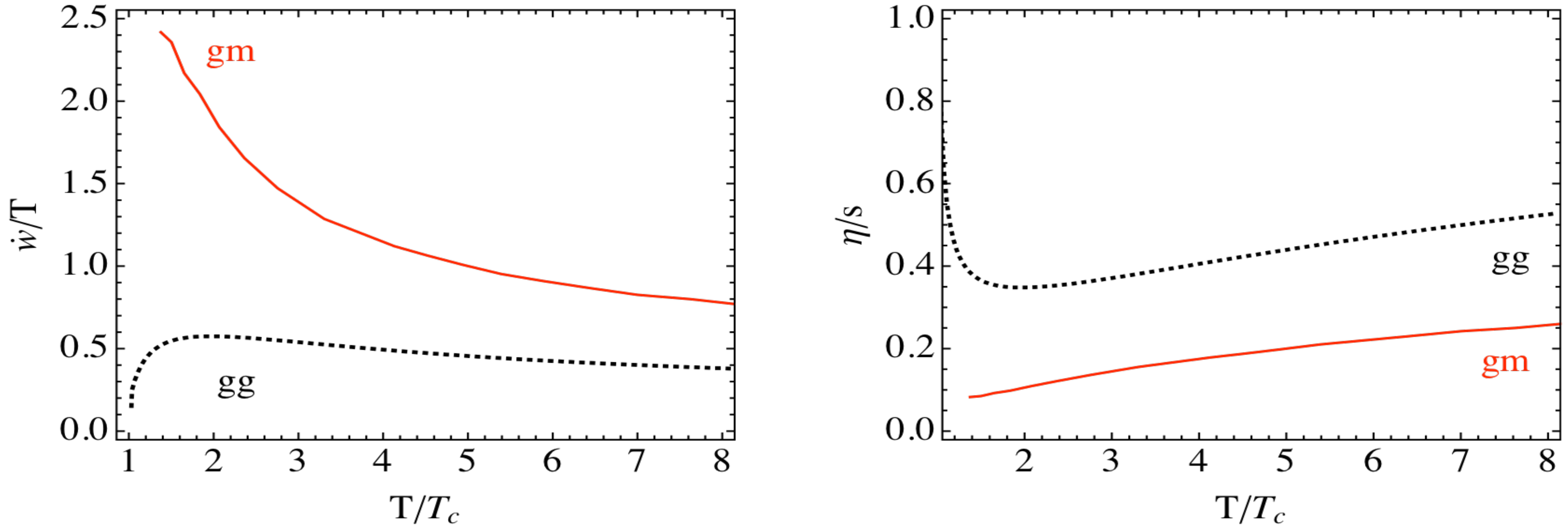
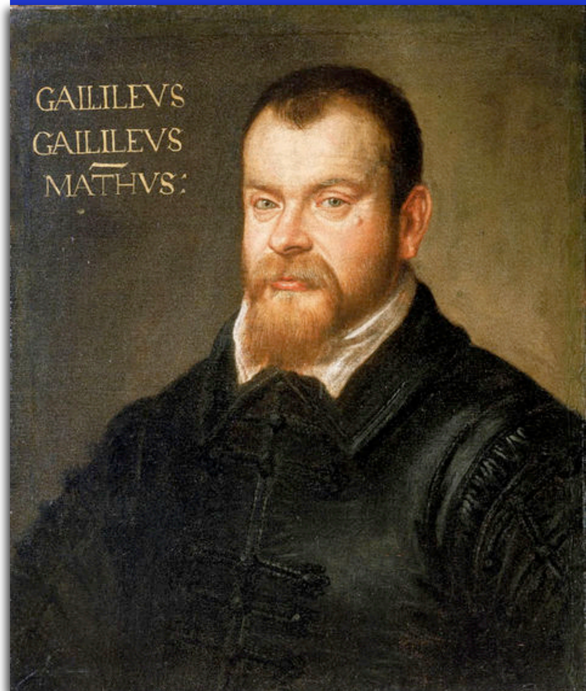
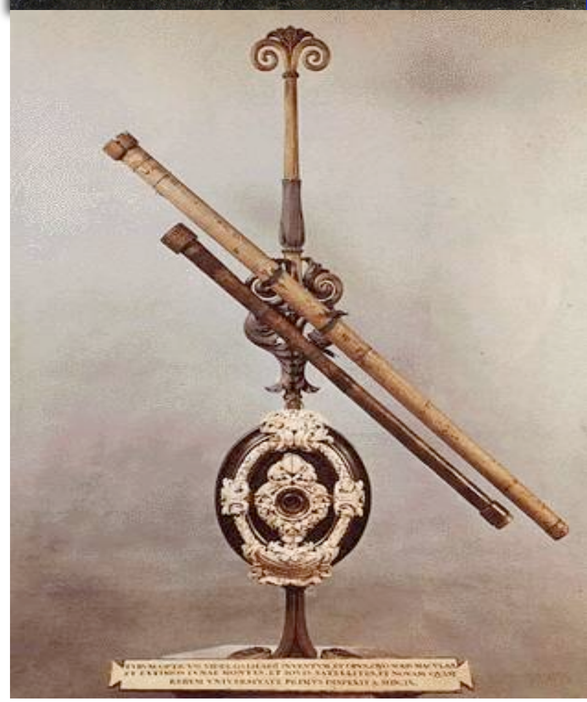


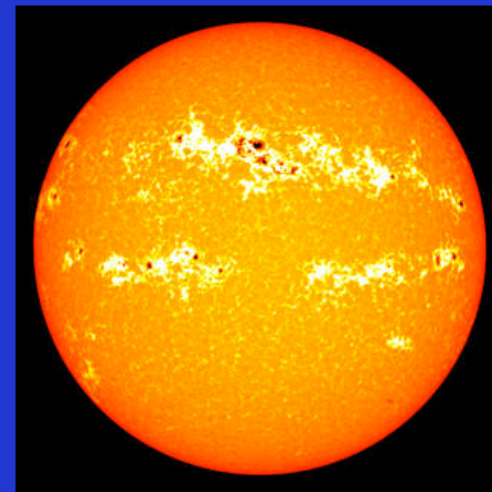

Figure 14: Left panel: gluon-monopole and gluon-gluon scattering rate. Right panel: gluon-monopole and gluon-gluon viscosity over entropy ratio, $\eta/s$.

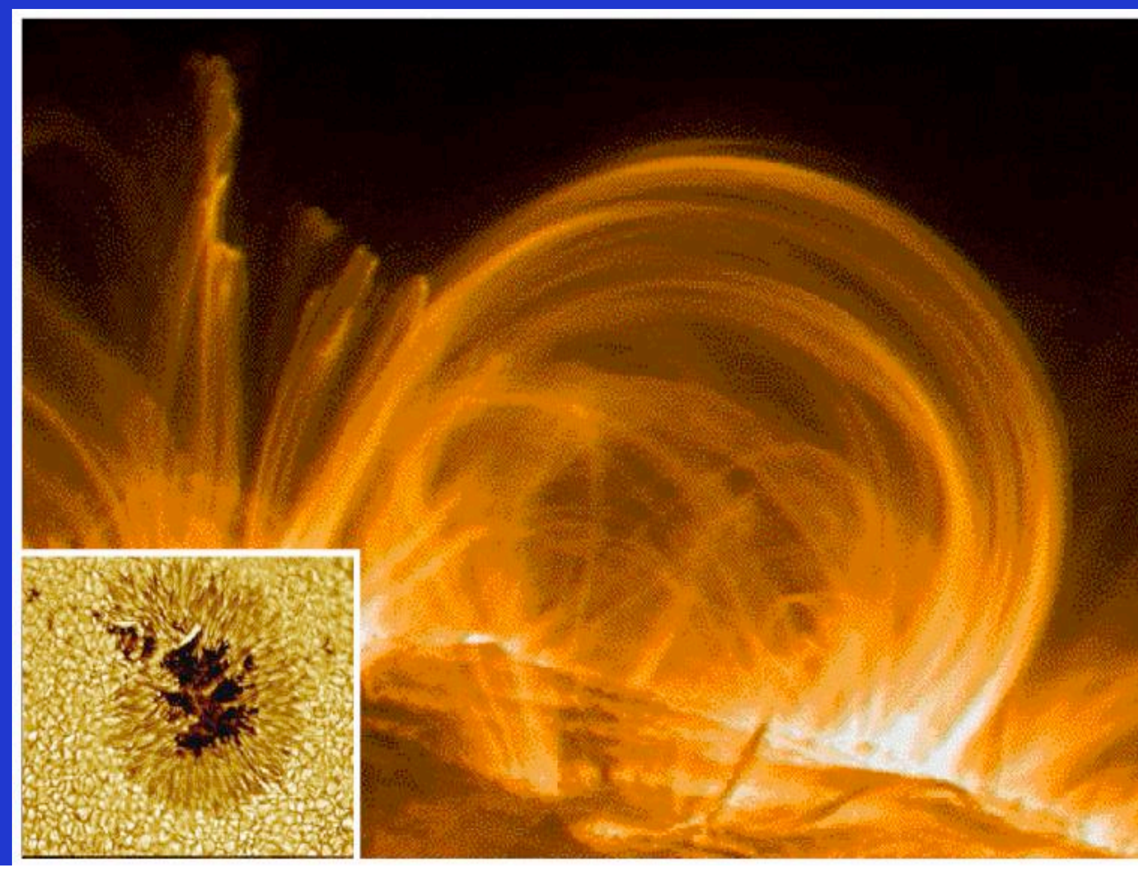
- **RHIC: T/Tc<2, LHC T/Tc<4**: we predict hydro will still be there, with η/s about .2



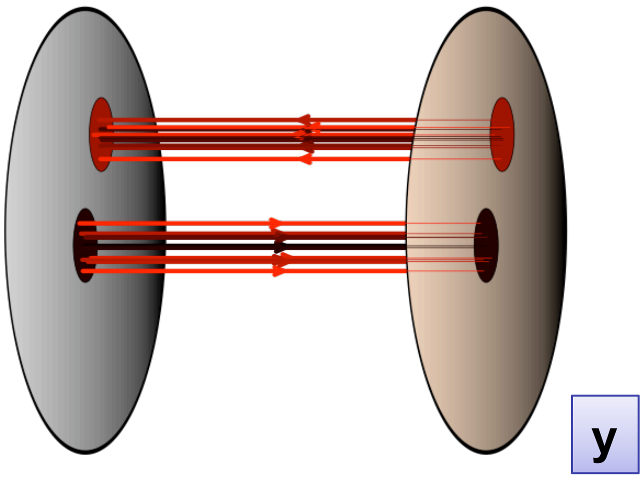


# 1612: Galileo discovered what we now call solar corona

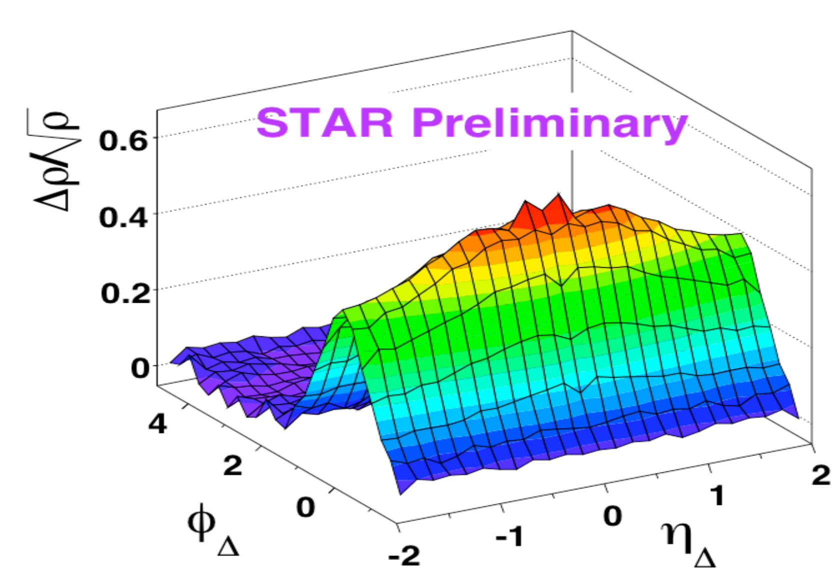




# the``soft ridge" exists even **without** any hard trigger




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

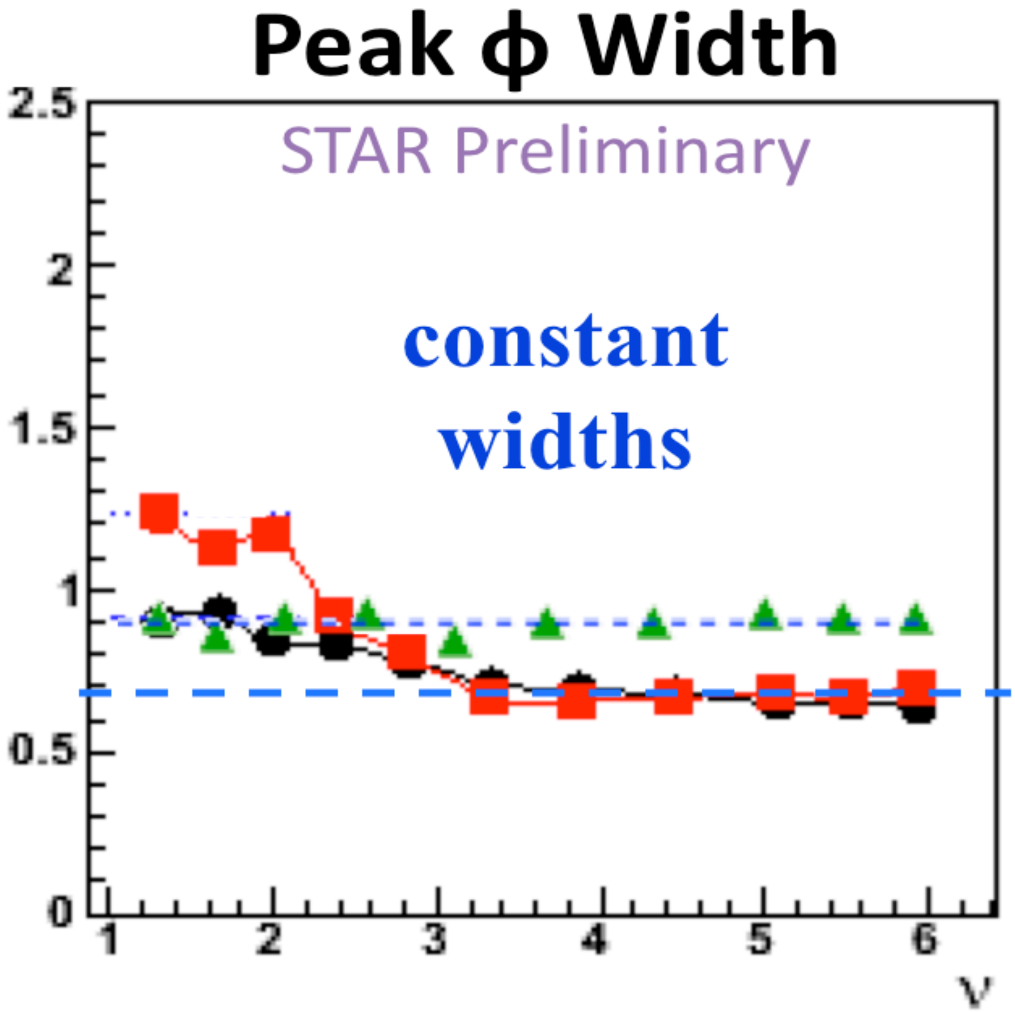



$$1/Q_s \sim .2fm/c$$

**(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

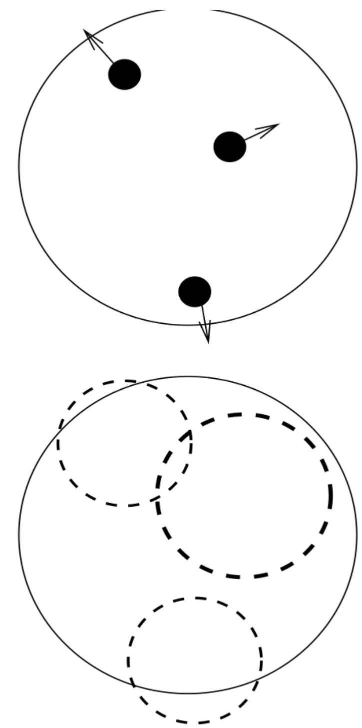



- L.Ray

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

**Fate of the initial state perturbations in heavy ion collisions**

Edward Shuryak
*Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794, USA*
(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 comparable to fireball size 6-8 fm/c

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

And thus large angular size

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.

# Can we restrict its size (at freezeout) from the data?

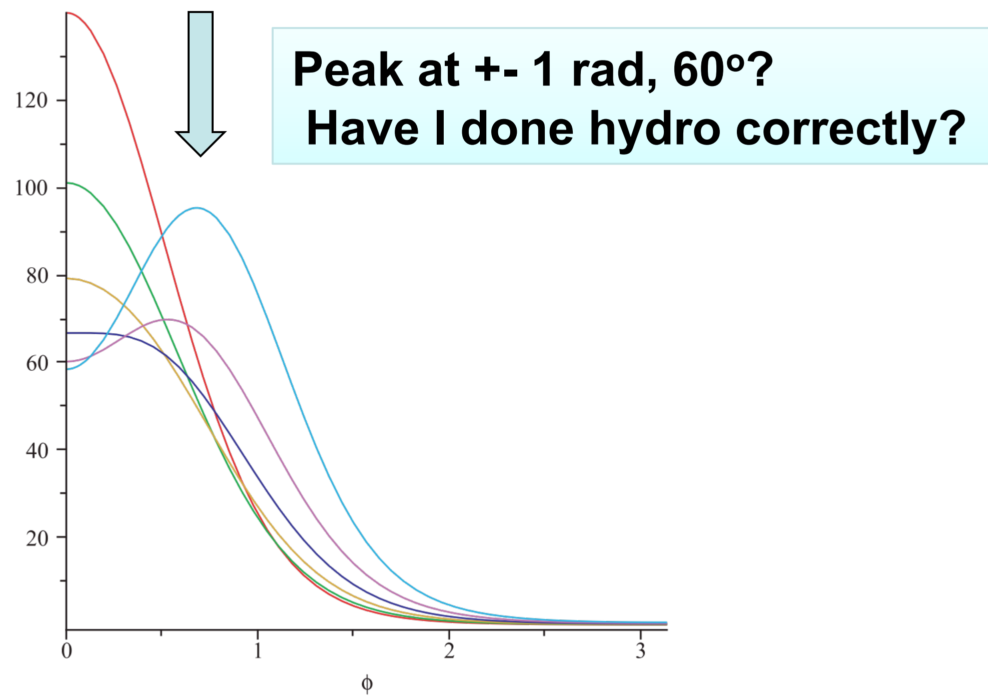



FIG. 5. (Color online) Dependence of the visible distribution in the azimuthal angle on the width of the (semi)circle at the time of freeze-out. Six curves, from the most narrow to the widest ones, correspond to the radius of the circle of 1, 2, 3, 4, 5, and 6 fm, respectively. The original spot position 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, we concllude that there no ridges at such angle

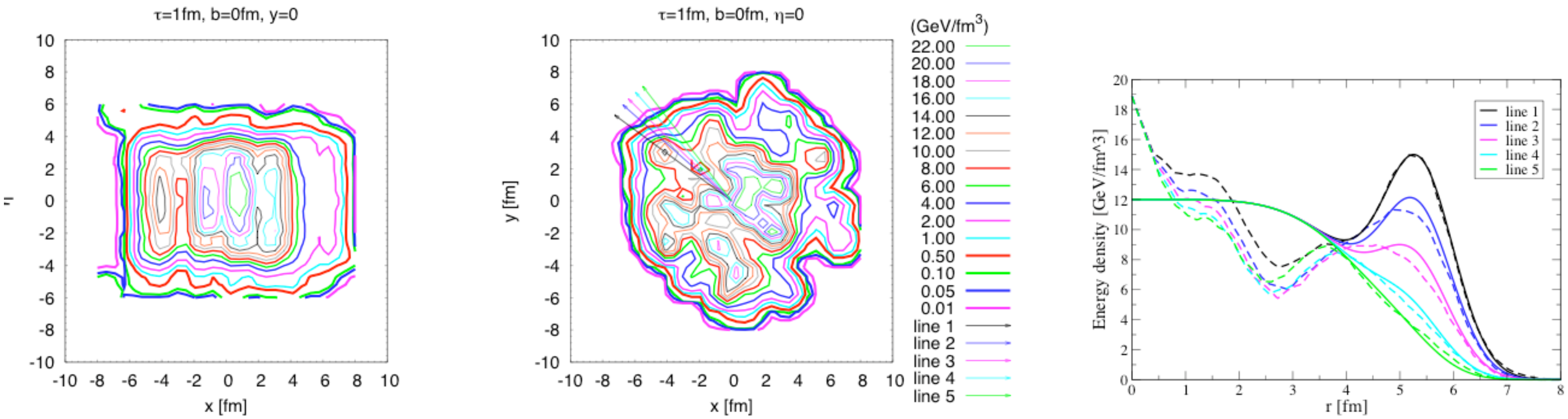
$$R(\tau_{\text{freeze-out}}) < 3\,\text{fm or so.}$$

# 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?
⟶ Study transverse expansion of a slice with one tube

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

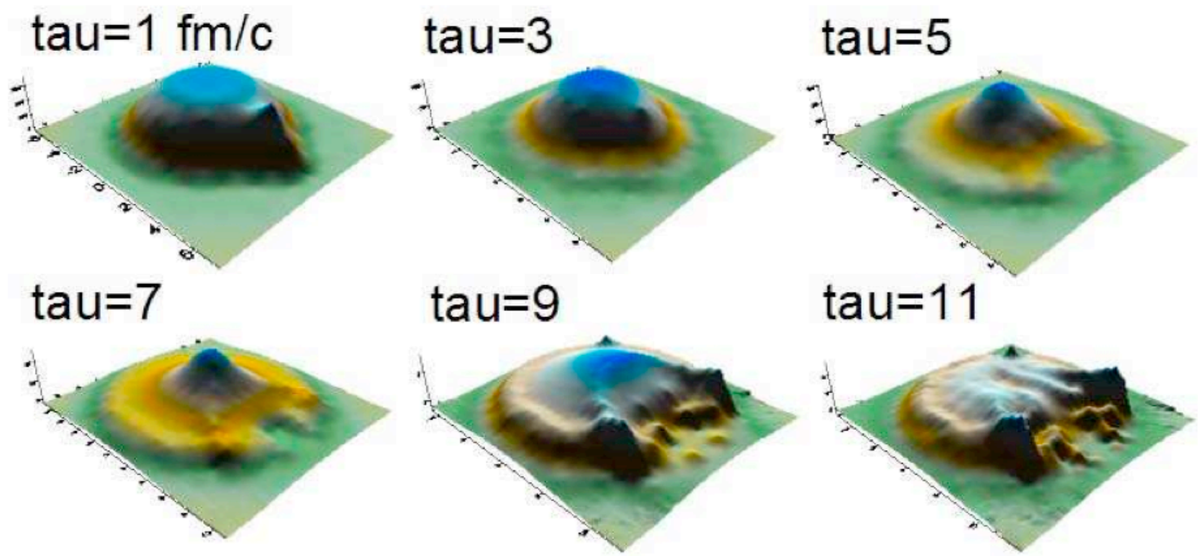



Choice of a realistic slice.

# 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

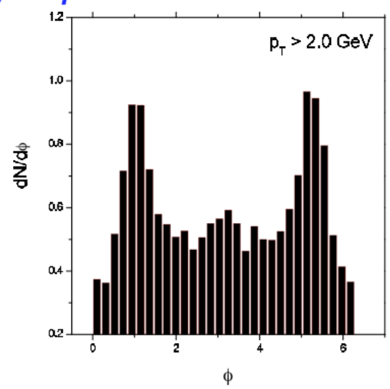



Temporal evolution of energy density for the one tube model.

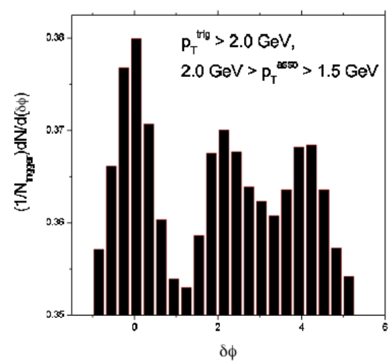
# The peaks are at the same angles +- 1 rad as I got!

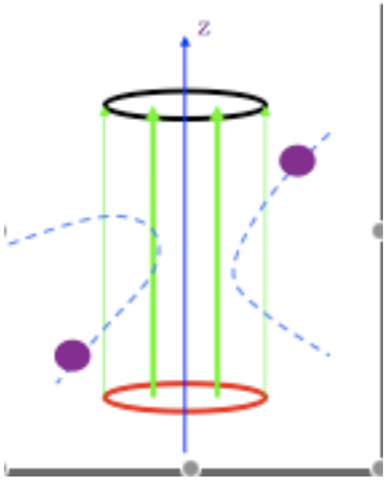
One tube model

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



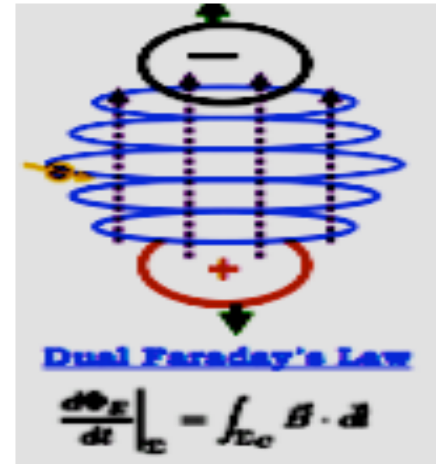

CONSEQUENCE: two particle angular distribution has three peaks





# 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

# Here is my view of the "QGP corona"

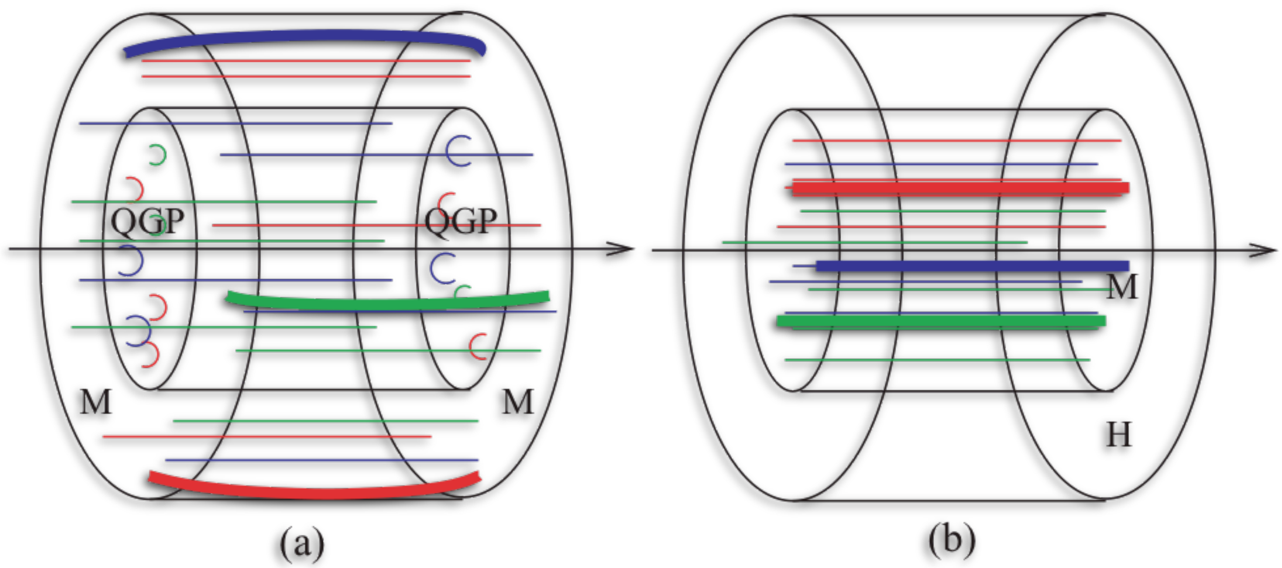
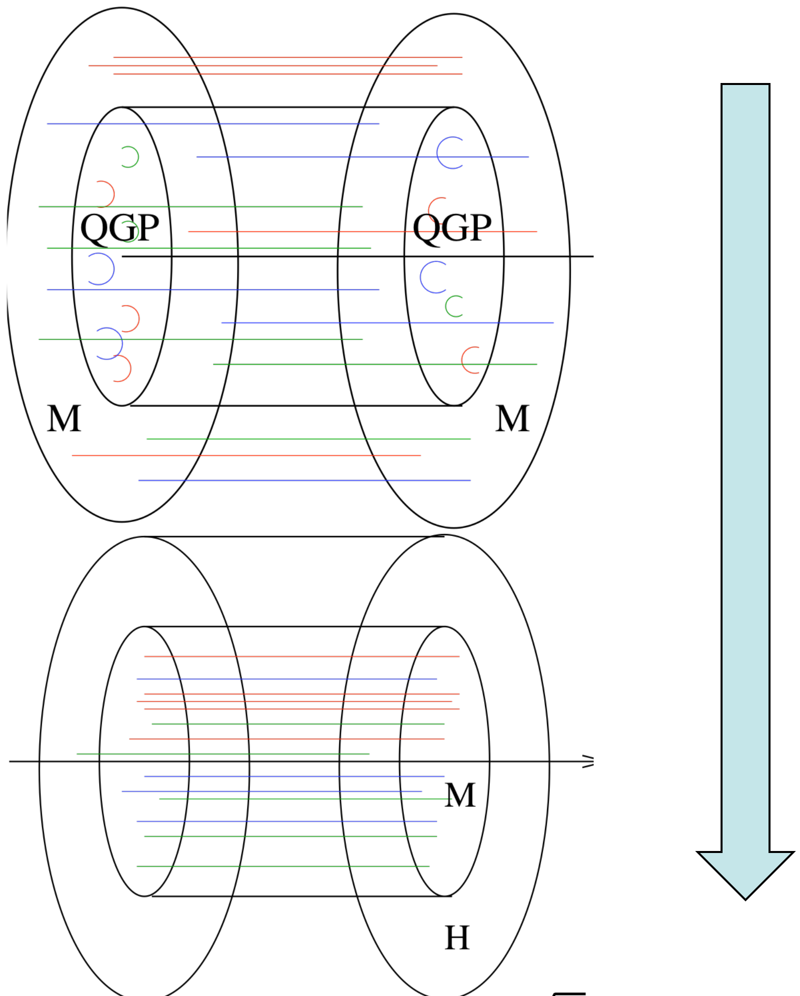



FIG. 1. (Color online) Snapshot of unscreened electric (dual-magnetic) field in the M (near-$T_c$) region of the fireball. (a) Full RHIC energy; (b) reduced energy (analogous to SPS).

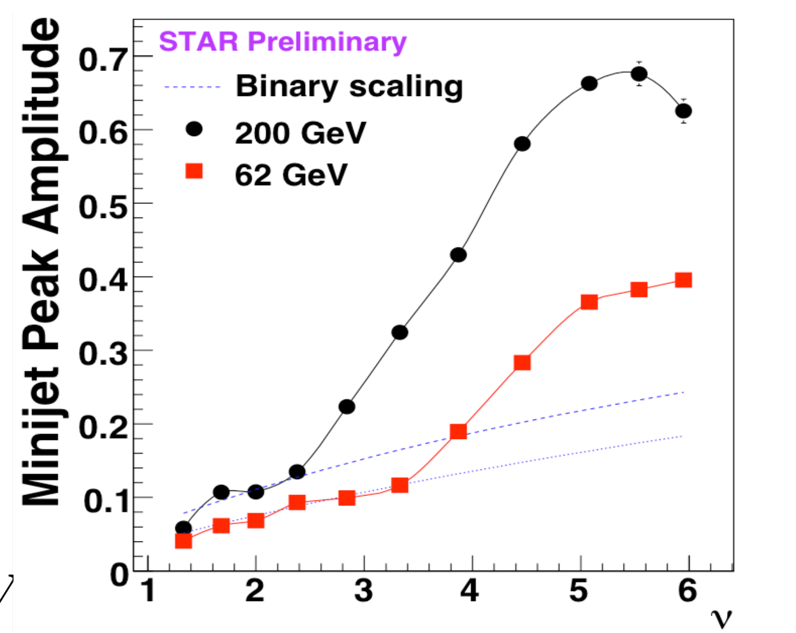
# Predictions for energy dependence: ridges

$RHIC \sqrt{s} = 200 GeV$




$SPS \sqrt{s} = 10 GeV$

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




**L.Ray,**
**Also in**
**CuCu**

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

they have up to 10 pions and they decay unisotropically

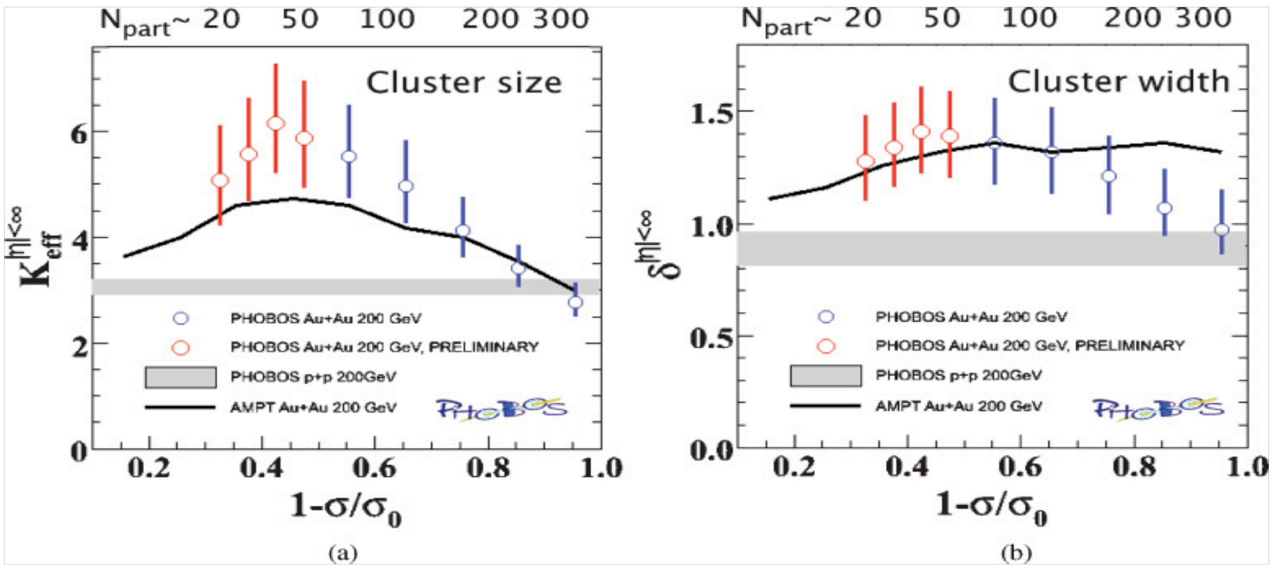



FIG. 13. (Color online) Cluster size (a) and width (b) as functions of centrality (cross section fraction) in Au-Au collisions at RHIC full energy, from PHOBOS [41]. The size is the number of charged particles associated with the cluster, and the width is in rapidity.

G.Stephens

# ``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 800 MeV at Tc**

# summary

- Instantons provide quantiative description of chiral symmetry breaking, solve the U(1) problem and produce good correlators: but do not explain confinement. => would dyon plasma do it?
- Prompt excitation instanton=>sphaleron in diffractive pp should be studied at RHIC
- CP effects at AuAu collisions come from O(10) exploding sphalerons at early time <= magnetic field strongly decreases with (subject of the workshop)
- Color magnetic monopoles found in MAG behave as physical objects: the Coulomb plasma, BEC at Tc
- "RHIC ridges" are the "QGP corona" made of

flux tubes, which are even more stable in magnetic plasma than in vacuum!