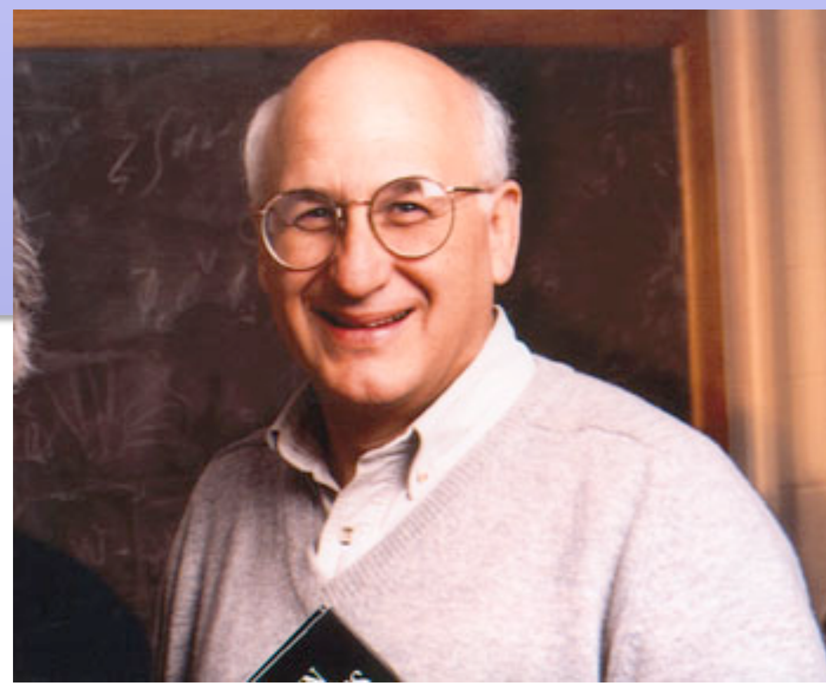
Deconfinement, monopoles and new phenomena in heavy ion collisions

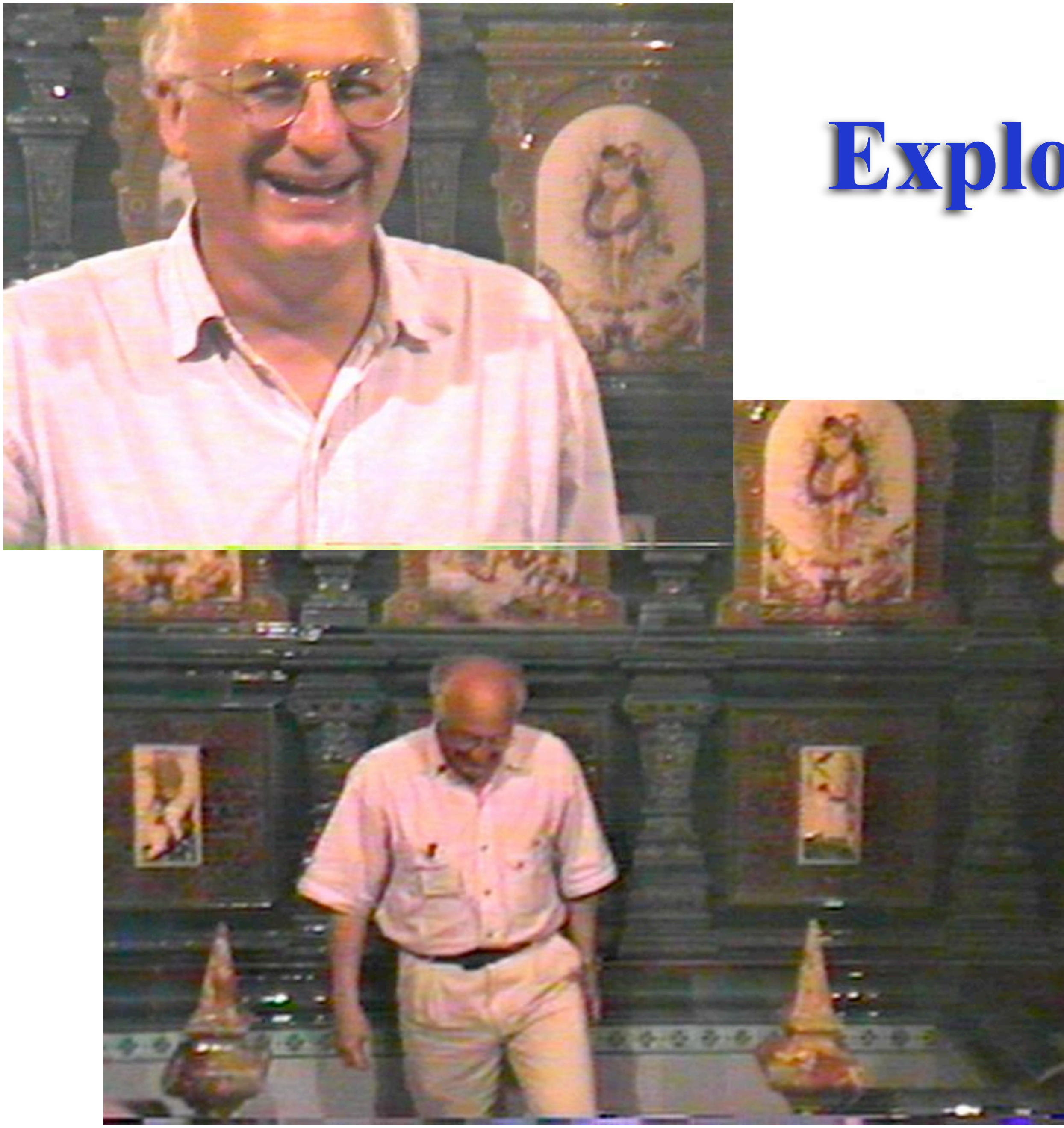
Edward Shuryak
(Shifmania,
May 2009)



"… a very long lived excited state"
(compressed, by me, version of Voloshin introduction)

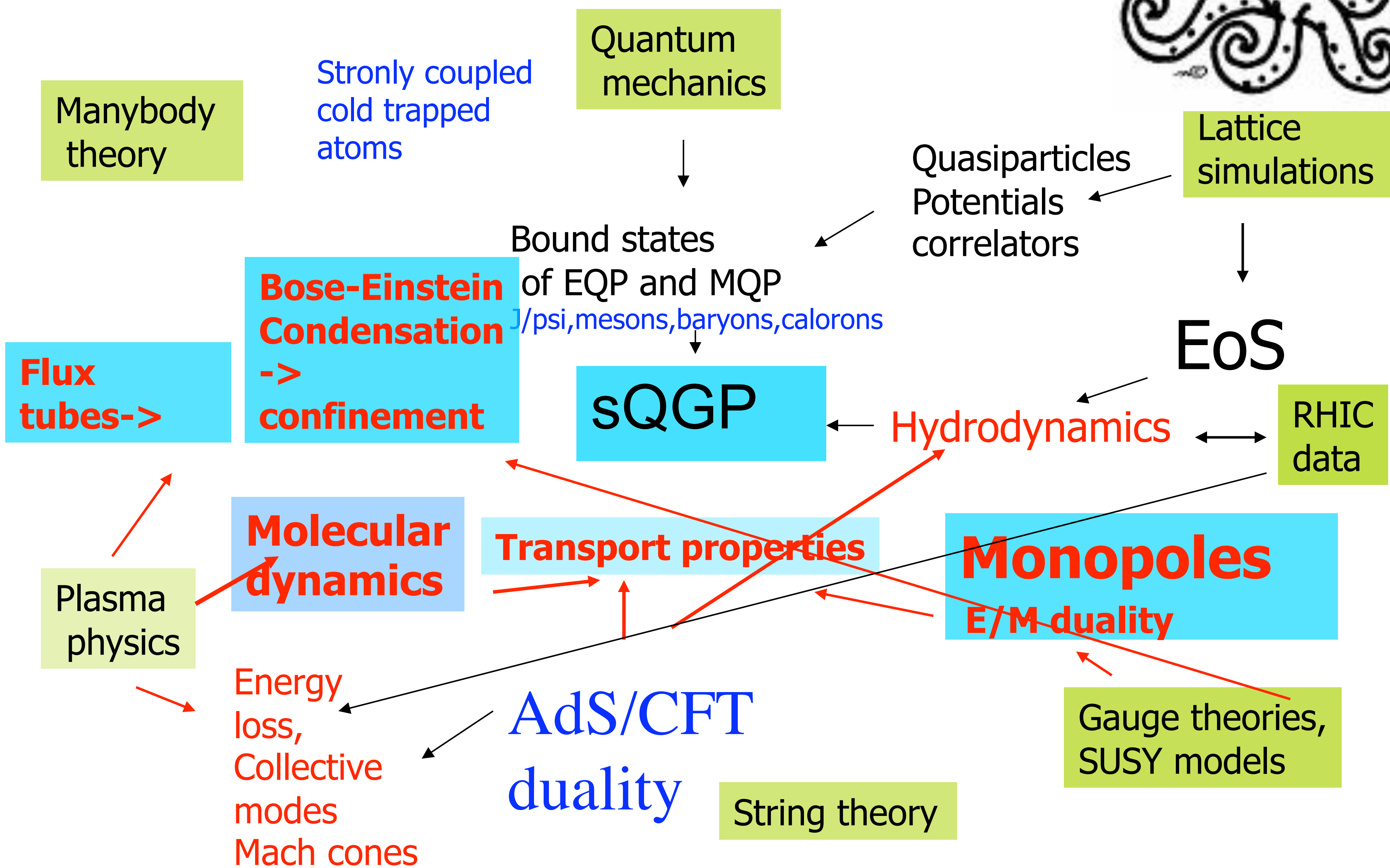
Nor-Amberd, 1980's

Exploring bathing



Como, 1990’s

The emerging theory of sQGP



The talk has many pictures but not so much text and eqns: one may find some of them in archive 0807.3033

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Physics of strongly coupled quark–gluon plasma

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A R T I C L E I N F O

Keywords:
Quark–gluon plasma
Finite temperature QCD
Heavy-ion collisions
AdS/CFT

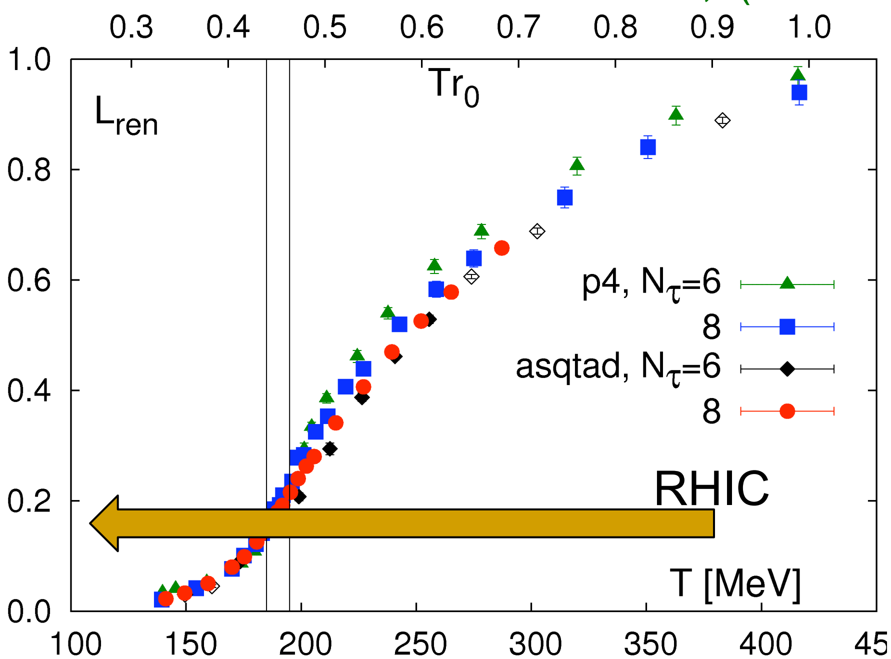
A B S T R A C T

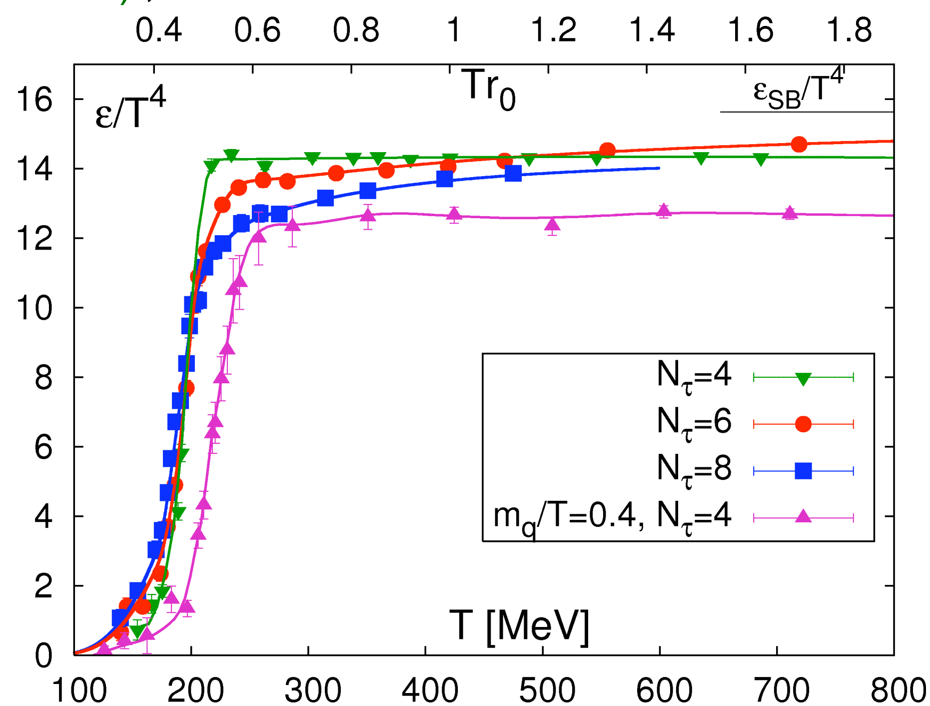
This review covers our current understanding of strongly coupled Quark–Gluon Plasma (sQGP), especially theoretical progress in: (i) explaining the RHIC data by hydrodynamics; (ii) describing lattice data using electric–magnetic duality; (iii) understanding of gauge-string duality known as AdS/CFT and its application for "conformal" plasma. In view of the interdisciplinary nature of the subject, we include a brief introduction into several topics "for pedestrians". Some fundamental questions addressed are: Why is sQGP such a good liquid? What is the nature of (de)confinement and what do we know about "magnetic" objects creating it? Do they play any important role in sQGP physics? Can we understand the AdS/CFT predictions, from the gauge theory side? Can they be tested experimentally? Can AdS/CFT duality help us understand rapid equilibration/entropy production? Can we work out a complete dynamical "gravity dual" to heavy ion collisions?

Deconfinement/the energy density

Is the transition 20 or 200 MeV wide?

Bazavov et al, (HotQCD Coll.) , arXiv:0903.4379

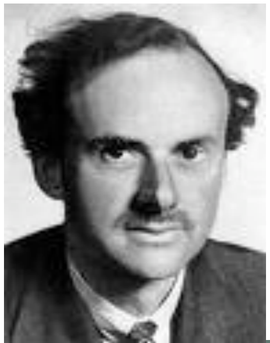




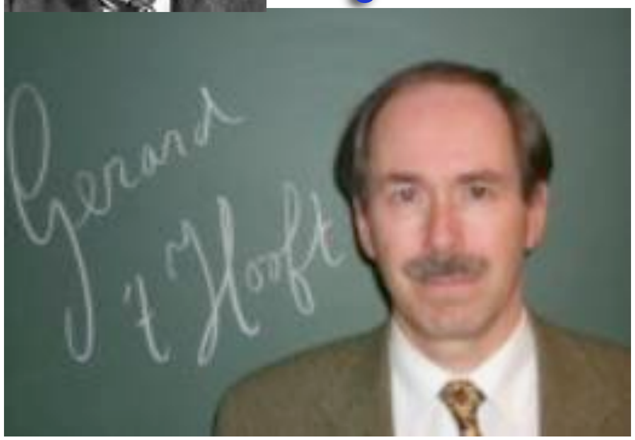
Renormalized Polyakov loop

QCD ``Higgsing”=> nonzero A_0=> imaginary chemical potential for electric charge

- Quark density **must be proportional to L** (well checked using quark susceptibilities by Ratti,Weise, 06) : **gluons to L^2**
- Pisarski called the region T=(1-2) Tc **semi**-QGP
- And yet, **no such suppression in entropy and energy density**: **what is missing there? <= Magnetic objects, unsuppressed by L**



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)

Electric and magnetic screening masses (inverse screening lengths) from numerical simulation in lattice gauge theory

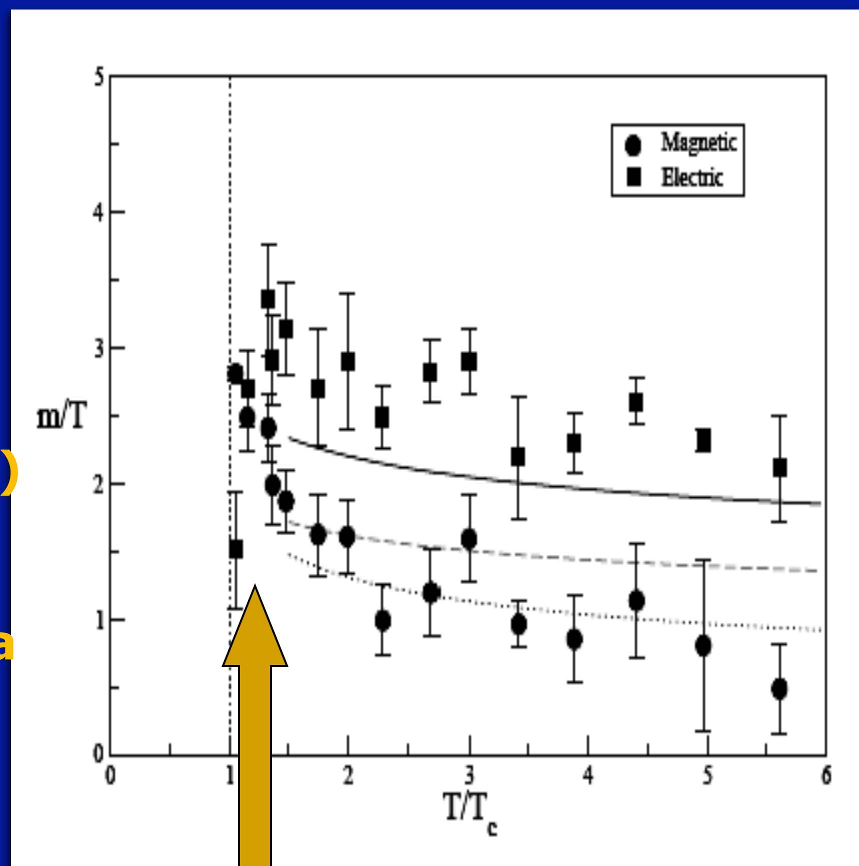
Nakamura et al, 2004

arrow shows the ``self-dual" 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
$M_M/T=O(g\hat{}2)$
Polyakov 79

Is QGP really getting magnetic as T<1.4Tc?

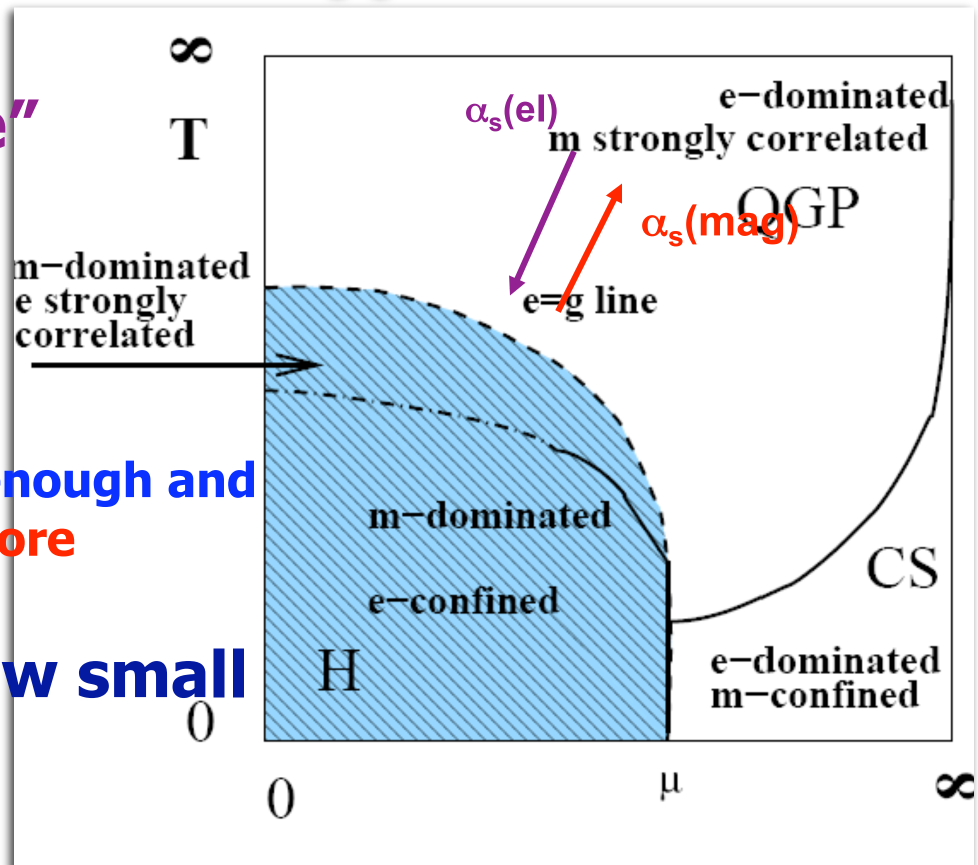
``magnetic scenario": Liao,ES hep-ph/0611131,Chernodub+Zakharov

Old good Dirac condition

α_s(electric) α_s(magnetic)=1

=>electric/magnetic couplings (e/g) must run in the opposite directions!

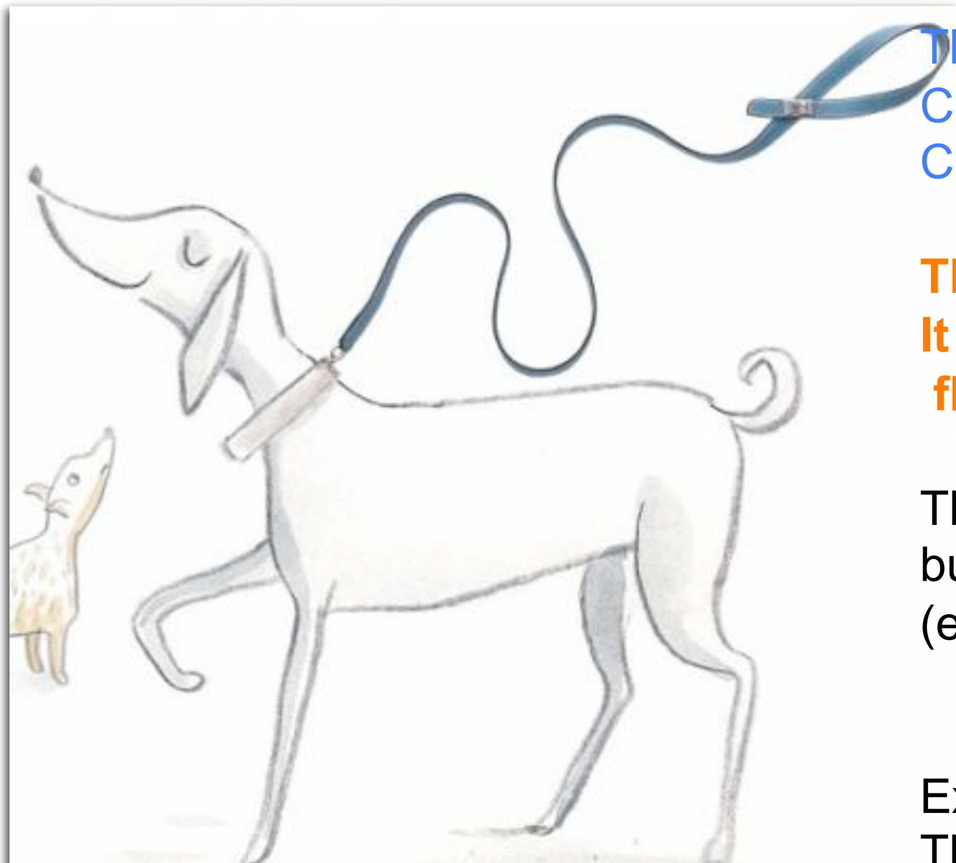
the "equilibrium line"
α_s(el)= α_s(mag) =1
needs to be in the plasma phase



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

=>α_s(mag) < α_s(el): how small can α_s(mag) be?

Which magnetic objects are seen on the lattice?



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

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

The dog=magnetic object, to be studied
but not understood yet. Many possibilities
(e.g. dyons ..Unsals 3 mono+12 q's),

Experimentation with monopoles put on
The lattice in many gauges have shown
That nearly all of them ``have collars"
In nearly all gauges

GEF-TH 22/07

Magnetic monopoles in the high temperature phase of Yang–Mills theories

Spring 2008

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x-Correlations
show it is a liquid
=> We extract
magnetic
Coulomb coupling

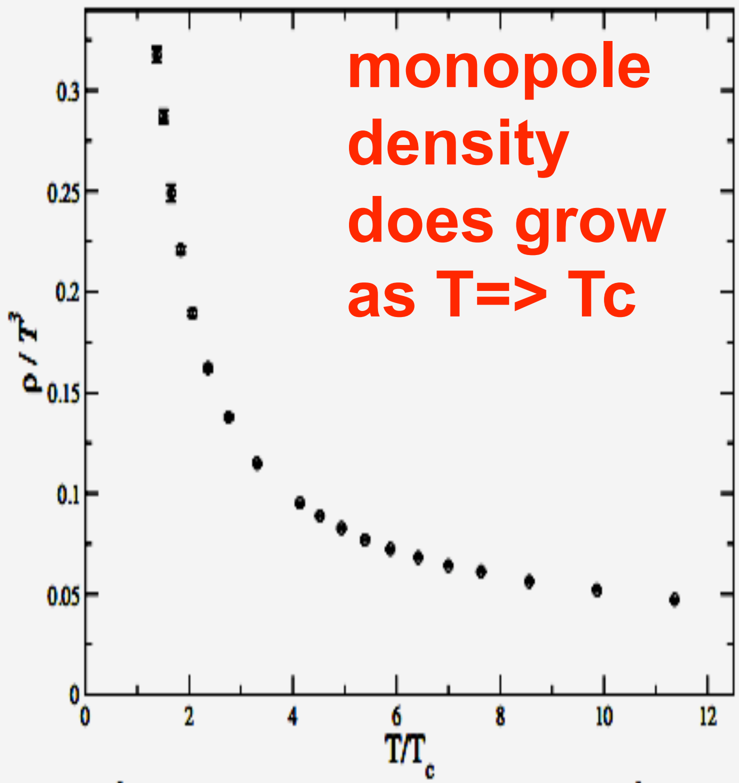

FIG. 3. $\rho(T)/T^3$ as a function of T/T_c. Data have been obtained on a $48^3 \times L_t$ lattice, with variable L_t and at $\beta = 2.75$ (first 9 points), and variable β at $L_t = 4$ (last 10 points).

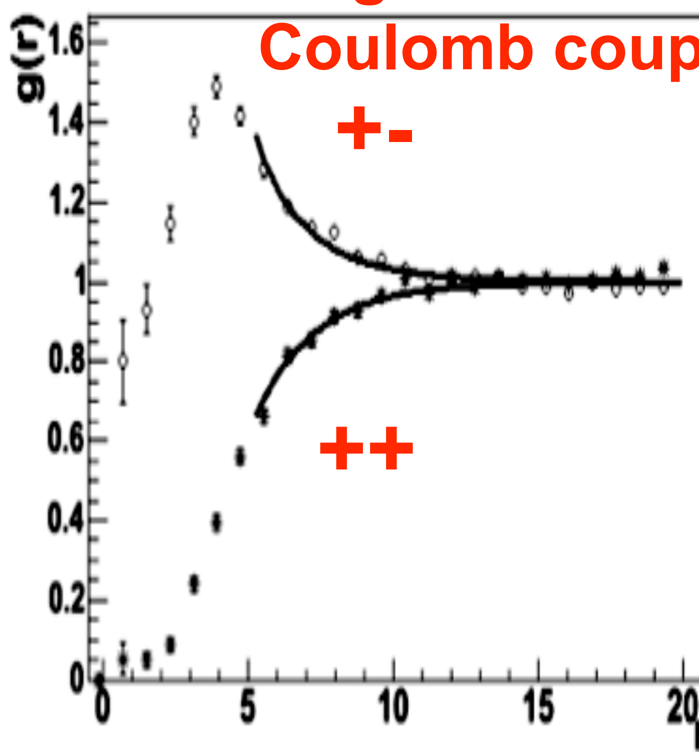

FIG. 5. $g(r)$ for the monopole-monopole (stars) and monopole-antimonopole (circles) case on $0^3 \times 5$ lattice at $\beta = 2.7$ ($T \simeq 2.85\ T_c$). The reported curves correspond to fits according to $) = \exp(-V(r)/T)$ with $V(r)$ a Yukawa potential (see Eqs. (2.9) and (2.10)).

Lattice SU(2) gauge theory, monopoles found and followed by Min.Ab.gauge

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

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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

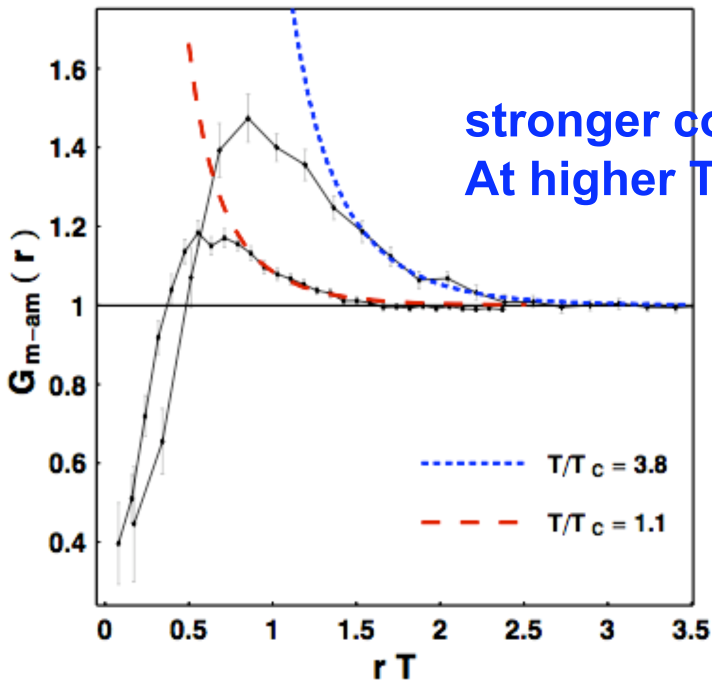
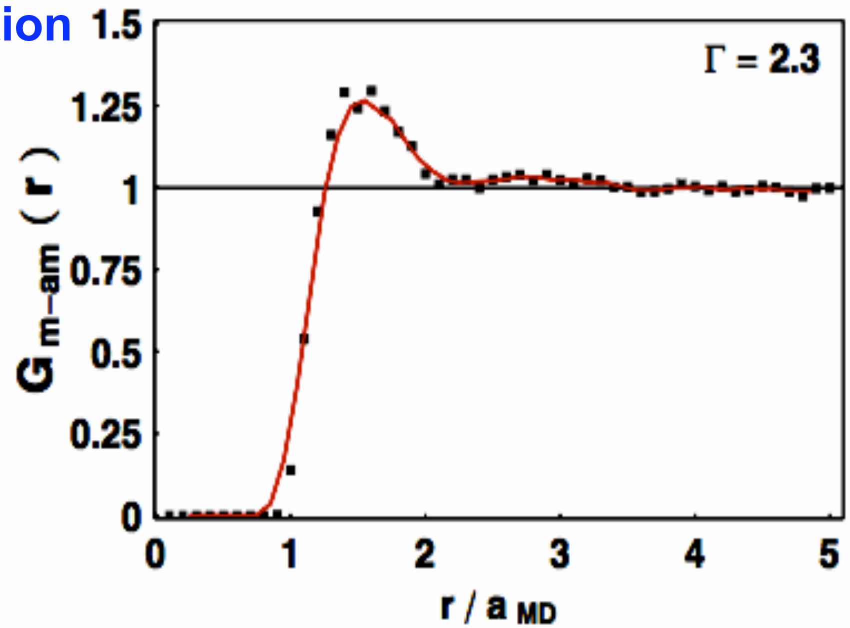


FIG. 2. (color online) Monopole-antimonopole correlators versus distance: points are lattice data [2], the dashed lines are our fits.

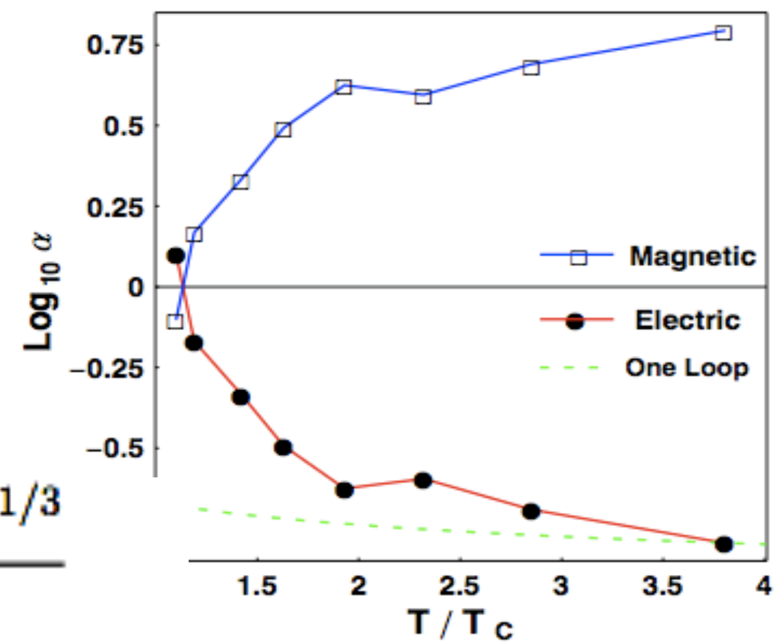
stronger correlation At higher T!

Our MD for 50-50 MQP/EQP

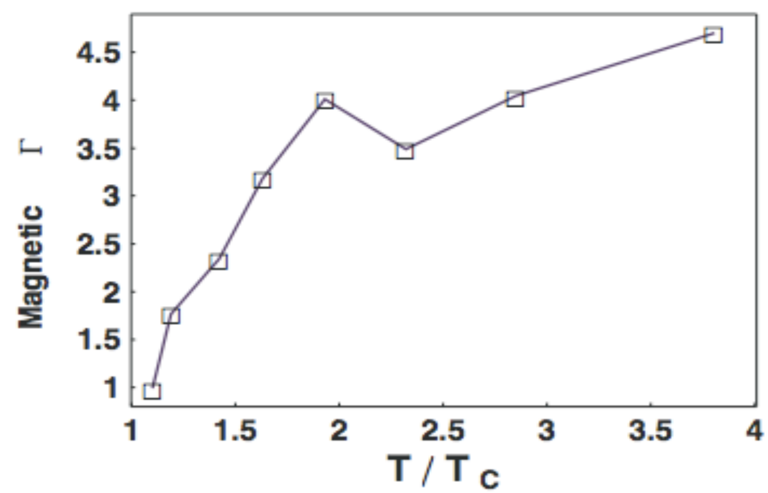


α_s(electric) and α_s(magnetic) do run in opposite directions!

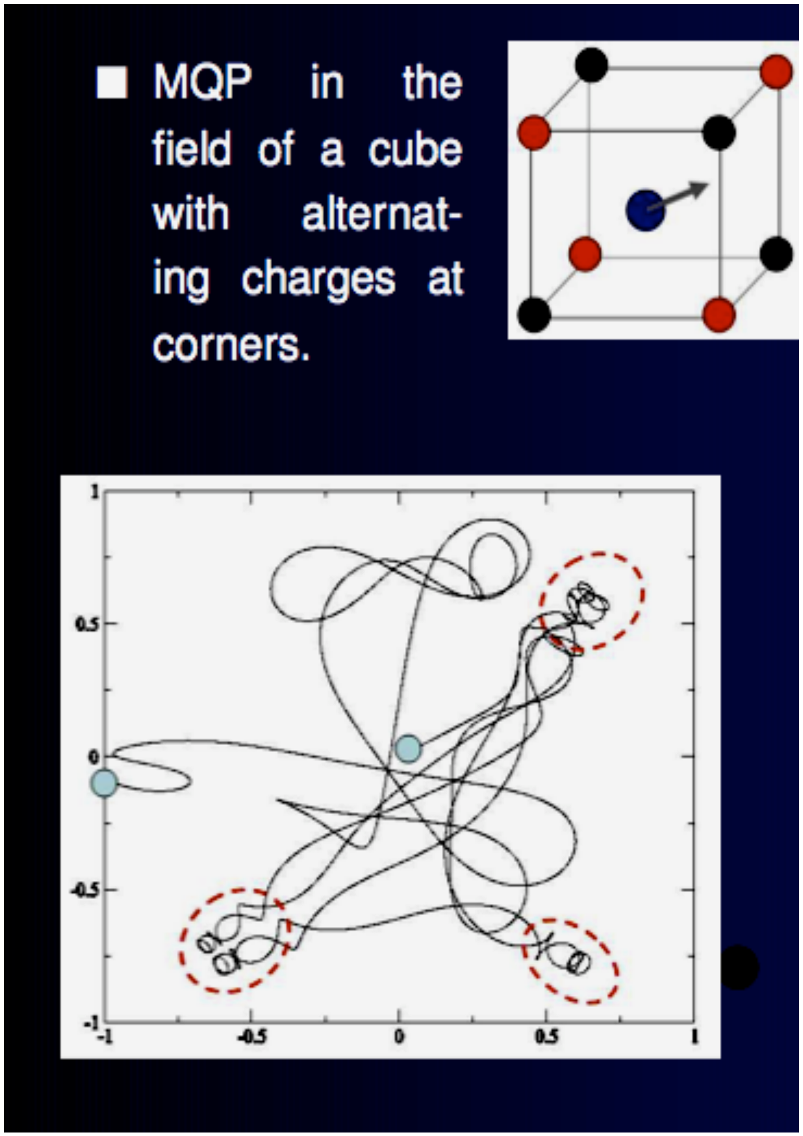
- Squares: fitted magnetic coupling, circles: its inverse compared to asymptotic freedom (dashed)
- Effective magnetic plasma parameter $\Gamma \equiv \frac{\alpha_C / (\frac{3}{4\pi n})^{1/3}}{T}$

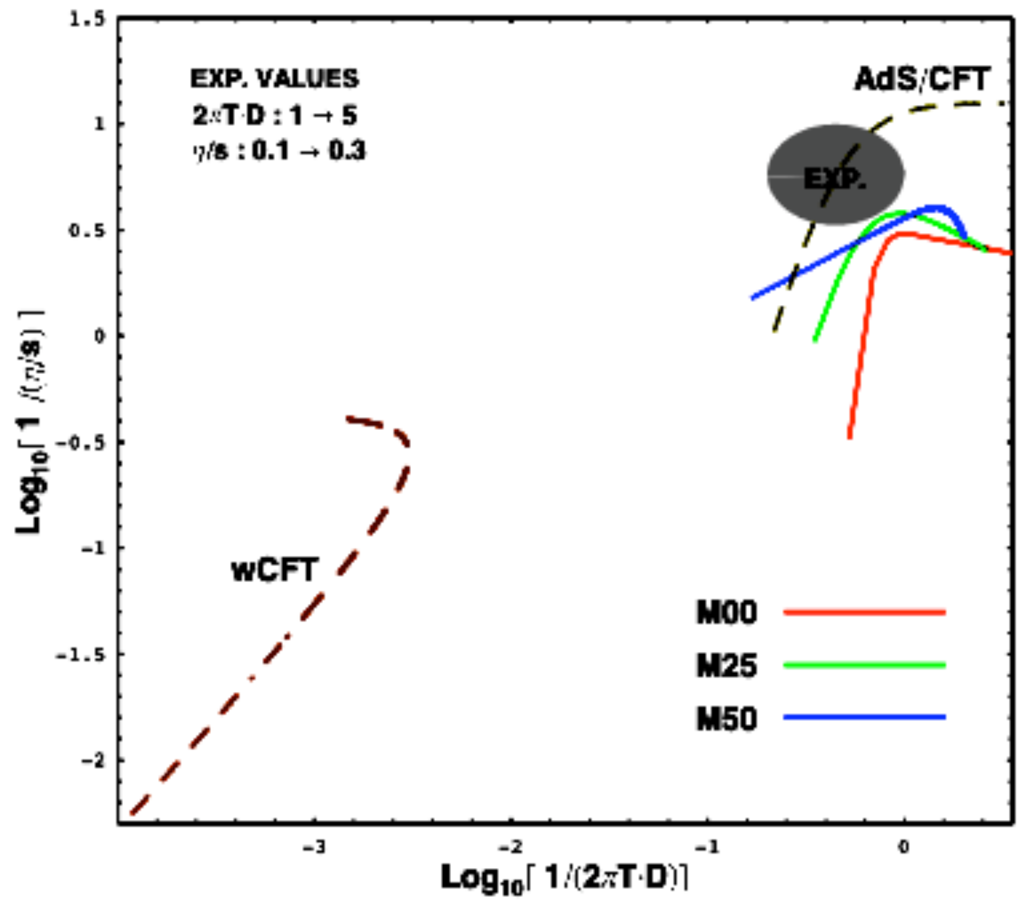


- So, the monopoles are never weakly coupled!
- (just enough to get Bose-condenced, see later)



``caging" and (classical MD) transport





Monopoles in electric Quark-Gluon Plasma

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November 24, 2008

- Quantum problem of gluon-monopole scattering
- n=eg (=1) is the only parameter, if we ignore the monopole core and keep only Coulomb B field

We denote the vector harmonics by $\Phi^{m,\sigma}_{j,n}(\theta,\varphi)_{ai}$. They obey the following eigenvalue equations

$$\left\{\begin{array}{c} \vec{J}^2 \\ J_3 \\ (\hat{r}\cdot\vec{I}) \\ (\hat{r}\cdot\vec{S}) \end{array}\right\} \Phi^{m,\sigma}_{j,n}(\theta,\varphi)_{ai} = \left\{\begin{array}{c} j(j+1) \\ m \\ n \\ \sigma \end{array}\right\} \Phi^{m,\sigma}_{j,n}(\theta,\varphi)_{ai}. \qquad (55)$$

$$\begin{aligned}\phi^{(+)}(\vec{r}) &= e^{-i\pi n}\sum_{j=|n|}^{j_{max}}(2j+1)e^{i\pi j}e^{-i\pi j'/2}j_{j'}(kr)\left[U(-\varphi,\theta,\varphi)\,\chi_i^n\right]\mathcal{D}^{(j)}_{n,-n}(-\varphi,\theta,\varphi)\\ &= \left[U(-\varphi,\theta,\varphi)\,\chi_i^n\right]\psi^{(+)}(\vec{r}). \qquad (91)\end{aligned}$$

We recall that the index j' in the above formula is the positive root of

$$j'(j'+1) = j(j+1) - n^2. \qquad (92)$$

j' is not an integer!

A surprize: no corrections to thermodynamics

$$\delta M_m = \frac{T}{\pi}\sum_j (2j+1)\int dk \frac{d\delta_j}{dk} f(k,T)$$

- **Beth-Uhlenbeck correction** (extra states in a box) is zero because there is no dependence on k

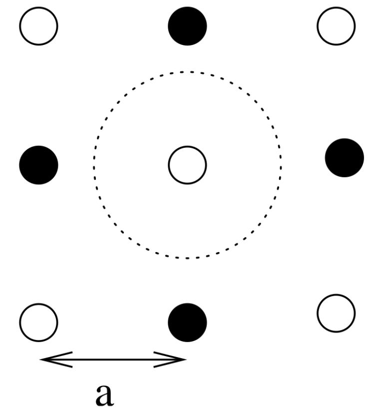
The origin of this somewhat unexpected result can be traced to the fact that the Beth-Uhlenbeck expression was derived from a semiclassical counting of the density of states in a large (spherical) box containing the monopole. However the semiclassical density of states, related to classical phase space, is insensitive to magnetic fields because the corresponding integral

$$\Omega_{cl}(E) = \int \frac{d^3p d^3x}{(2\pi)^3}\delta\left(E - H(p,x)\right) \qquad (82)$$

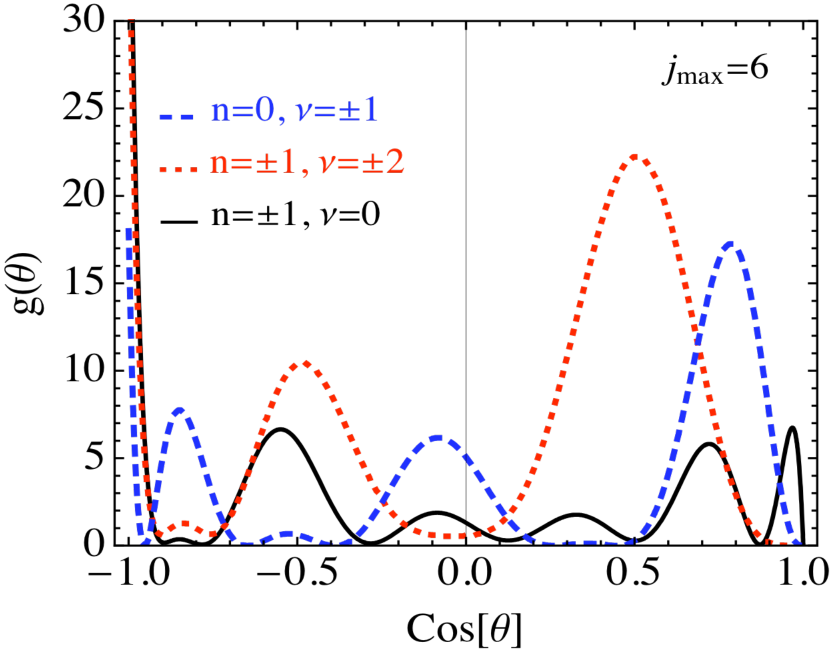
for an electric particle in any magnetic field $H = (\vec{p} - e\vec{A}(x))^2/2m$ does not depend on the field at all (in order to see that this explanation is correct, consider for

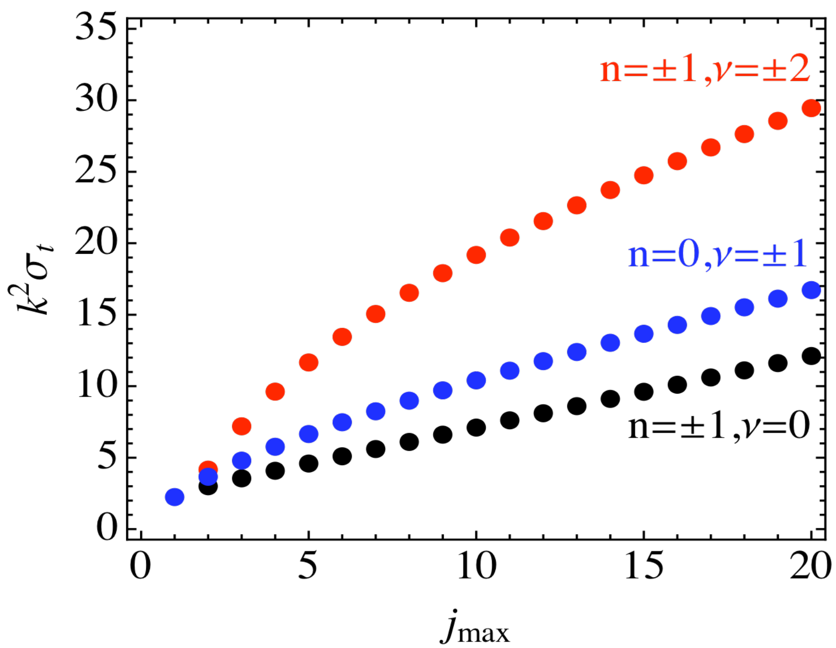
Scattering amplitude

vs maximal impact parameter or j_{max}



Transport cross section: results





$$g(\theta) = (1 - \cos\theta)|f(\theta)|^2$$

Not surprising, large correction to transport

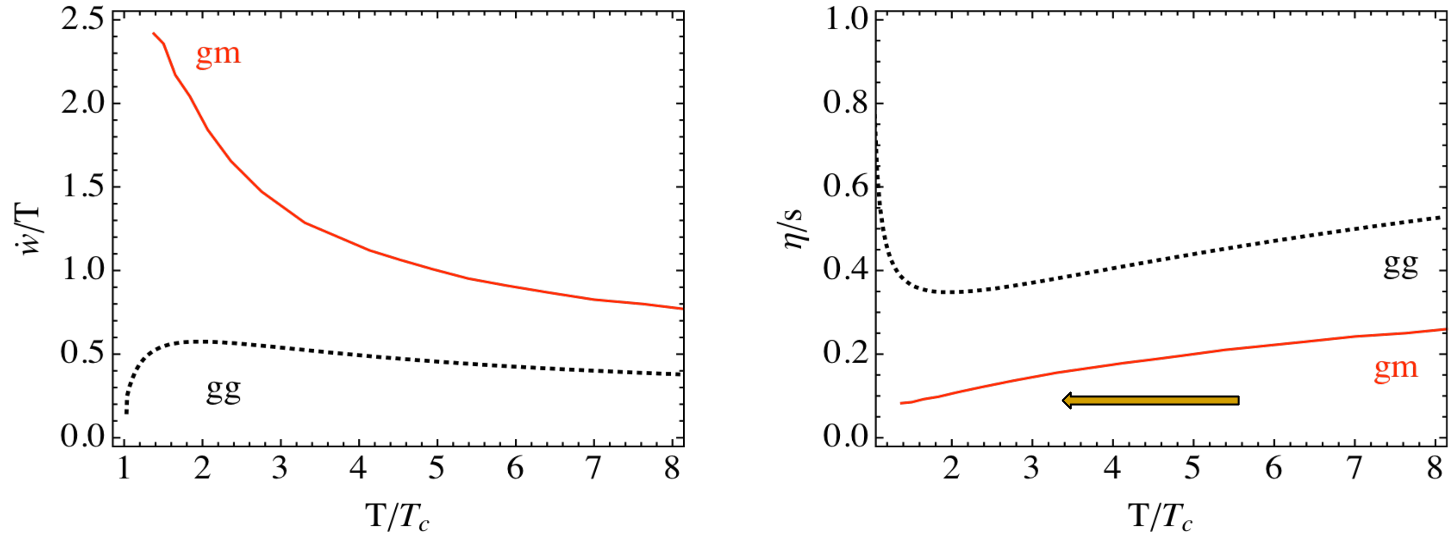


Figure 14: Left panel: gluon-monopole and gluon-gluon scattering rate. Right panel: gluon-monopole and gluon-gluon viscosity over entropy ratio, η/s.

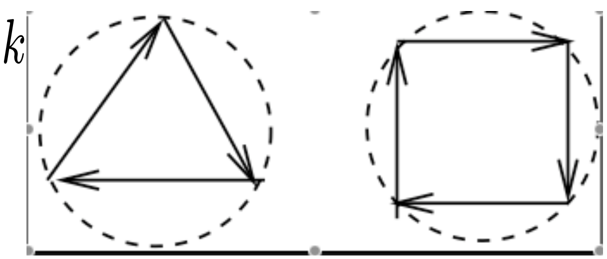
Son et al
AdS/CFT
1/4pi=0.08

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

Reviving Feynman theory of BEC for He4

- Feynman (1950's): sum over the polygon jumps diverges when **ΔS(jump)<Sc universally!**

$$Z = \sum_k C_k(geometr)exp(-k\Delta S) = \sum_k (ce^{-\Delta S})^k$$



PIMC done in 1980-1990 and is still going (Ceperley, RMP) explained many things accurately, still not elucidated if Feynman was completely right

Crossing the Boundaries…

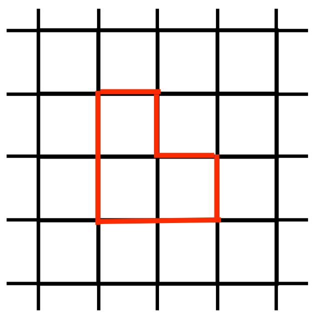
Bose-Einstein Condensation of strongly interacting bosons: from liquid He4 to QCD monopoles

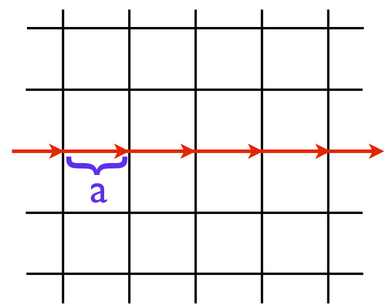
Marco Cristoforetti[1] and Edward V. Shuryak[2]

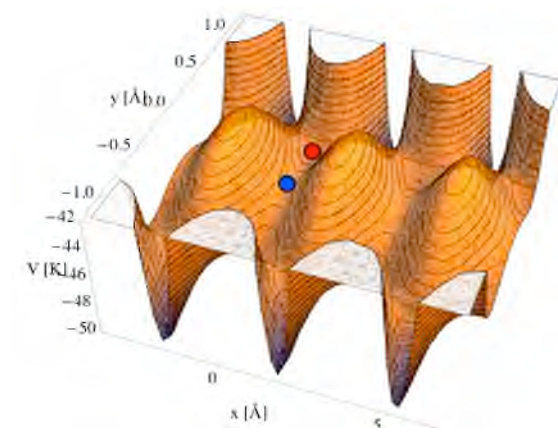
[1] *Physik Department, Technische Universität München, D-85747 Garching, Germany*
[2] *Department of Physics and Astronomy, State University of New York, Stony Brook NY 11794-3800, USA*

(Dated: April 8, 2009)

Starting from classic work of Feynman on the λ-point of liquid Helium, we have developed a simple “moving string model” which can rather accurately predict the critical temperature for liquid He4. It approximates Feynman’s “polygons” by an infinite line of particles, simultaneously jumping to its neighbor’s place. The action needed for that per atom is calculated both semiclassically and numerically: we then follow Feynman’s idea that this action should be some universal constant. This treatment also explains why high density (solid) He is *not* a BEC state. We then use this model for deconfinement phase transition of QCD-like gauge theoris, relating it to BEC of (color)magnetic monopoles. We start with Feynman-like approach without interaction, estimating the monopole mass at T_c. Then we discuss the role of monopole’s Coulomb repulsion, and end up proposing certain lattice studies of monopole “polygons” (or clusters).







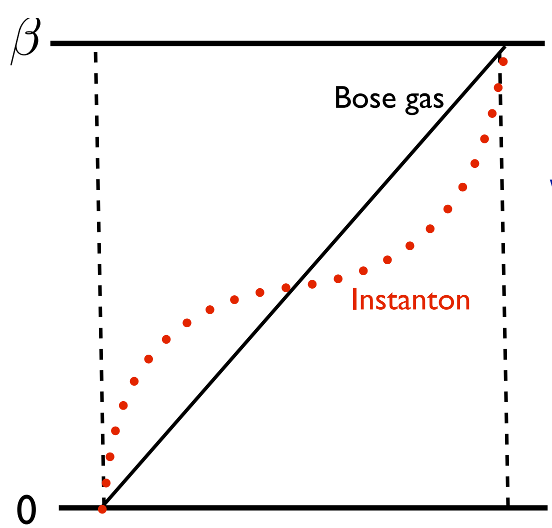
Large polygons => moving line model studied semiclassically and by the 1d path integral numerically

Making instantons practical, Once again

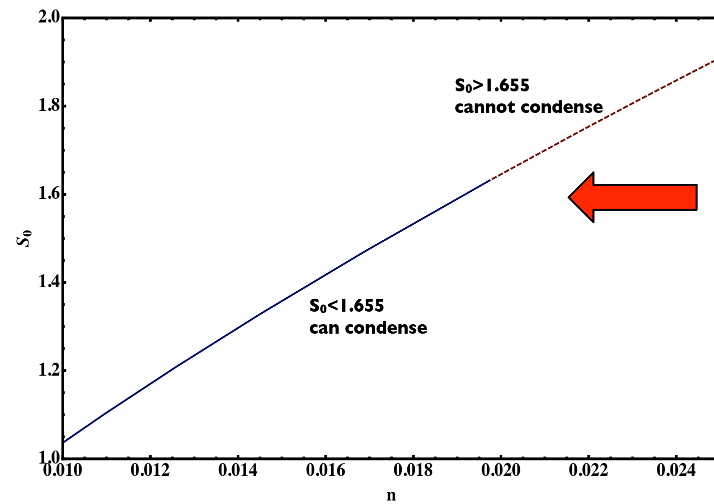
$$T_c[d, V_0, E_E] = \left(\sqrt{\frac{m}{2E_E}}\frac{d}{\pi}\mathrm{F}[\pi, -V_0/E_E]\right)^{-1}$$
$$= \sqrt{\frac{m}{2E_E}}\frac{d}{\pi}2\mathrm{K}[-V_0/E_E])^{-1}. \qquad (19)$$

provided the energy is substituted from the Feynman condition, which say that the Euclidean action

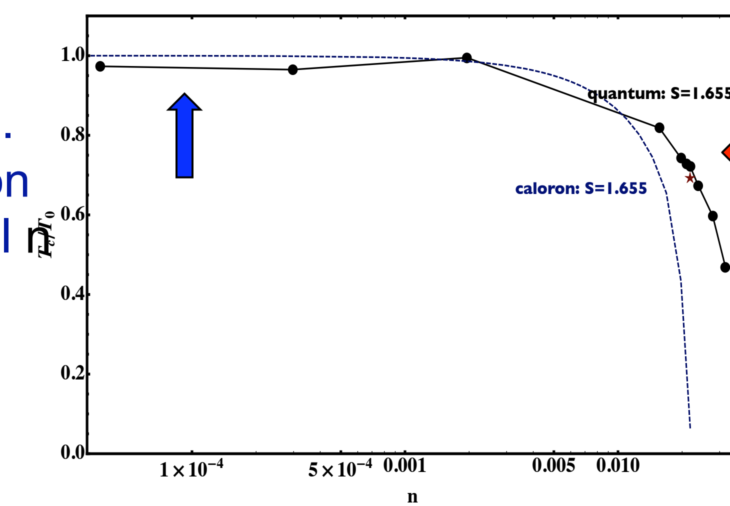
$$S_E[d, V_0, E_E] = \int_0^\beta d\tau \left(\frac{m}{2}\dot{x}_{cl}^2 + V(x)\right)$$
$$= \frac{d}{\pi}\sqrt{\frac{mE_E}{2}}2\left(2\mathrm{E}\left[-\frac{V_0}{E_E}\right] - \mathrm{K}\left[-\frac{V_0}{E_E}\right]\right), \qquad (20)$$



Baym,Blaizot..
pert.calculaiton
works at small n



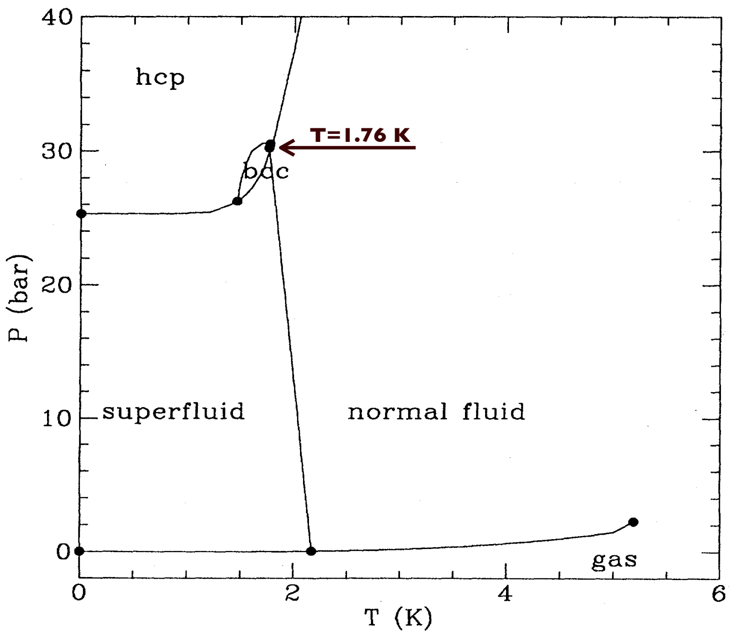
Sc=
1.655



He4

FIG. 10: (a) The action for the instanton solution as a function of the density. When the action is larger than the critical value $S = 1.655$ (dashed line) the system cannot be Bose-Einstein condensed phase.
(b) The critical temperature obtain from the caloron/instanton solution (dashed line) and from the 1-d PIMC simulation (points). The red star shows the

As density grows, Feynman condition cannot be satisfied:
=> solid He4 is not supersolid



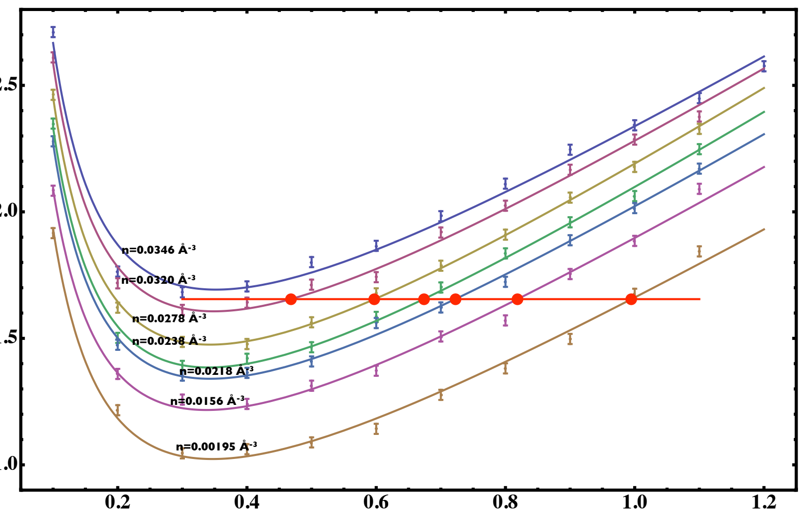


FIG. 13: Action as a function of the temperature for different densities.

BEC (confinement) condition for monopoles

For charged Bose gas (monopoles) the action for the jump can be calculated similarly, but relativistically; jumps in space d and in time
Comparable)

$\Delta S = M\ \mathrm{sqrt}(d^2 + (1/Tc)^2) + \Delta S(\mathrm{interaction}) = Sc = 1.655$

=> Upper bound on the monopole mass M at Tc

M(Tc) < 300 MeV

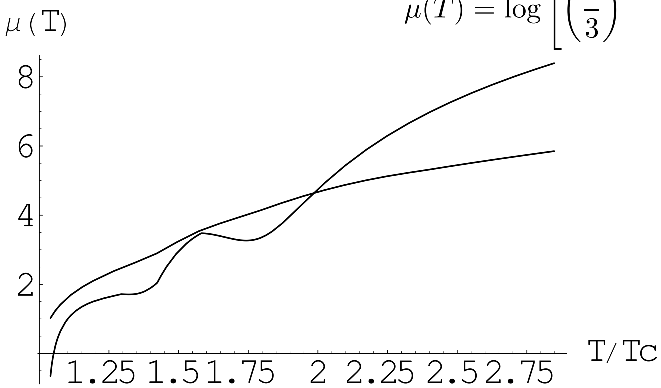
Lattice studies of monopole clusters near Tc

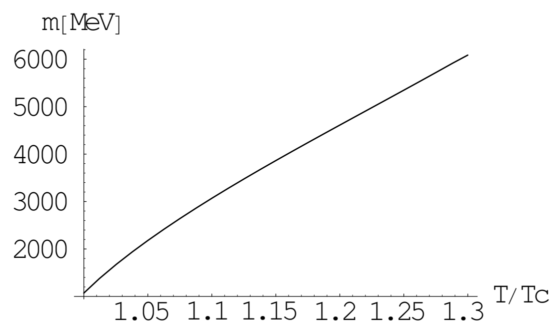
(M.D’Ellia,A.D’Alessandro)

$$\mu(T) = \log\left[\left(\frac{1}{2}\right)^{5/2}\frac{n_1(T)}{n_2(T)}\right] \qquad (8)$$

or equivalently from the same (5) applied to trajectories wrapped twice n_2 and three times n_3

$$\mu(T) = \log\left[\left(\frac{2}{3}\right)^{5/2}\frac{n_2(T)}{n_3(T)}\right] \qquad (9)$$





M(T=Tc) =>.3 GeV.
As predicted

T/Tc	m[GeV]=$1/(2 < x^2 > T)$
1.095	0.617(16)
1.187	0.907(16)
1.295	1.229(29)
1.424	1.671(12)
1.582	2.163(19)
1.780	2.736(15)
2.035	3.360(14)
2.374	4.047(13)
2.848	4.856(11)
7.000	15.59(2)

- Clusters with k<4 behave like in He
- mu and monopole masses consistently determined, they are lighter than dyons (M(dyon)/T=S(inst)/Nc=4)

New phenomena in heavy ion collisions:

the ``cone" and ``ridges" are seen

they are "too bright"

=> flux tubes seem to survive for long time

Three main jet correlations :

- ``Shoulder” on the away side => ``conical flow”

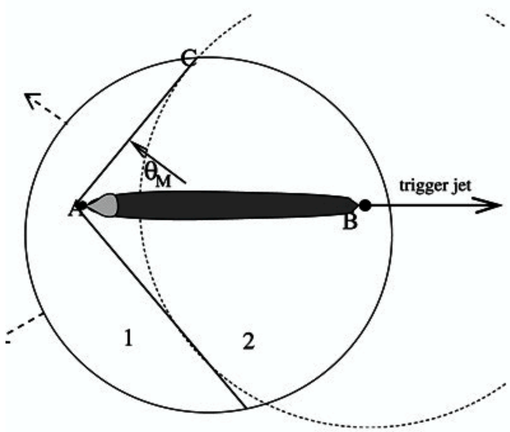
(H.Stoecker,J.Casalderrey+ES, 2005)

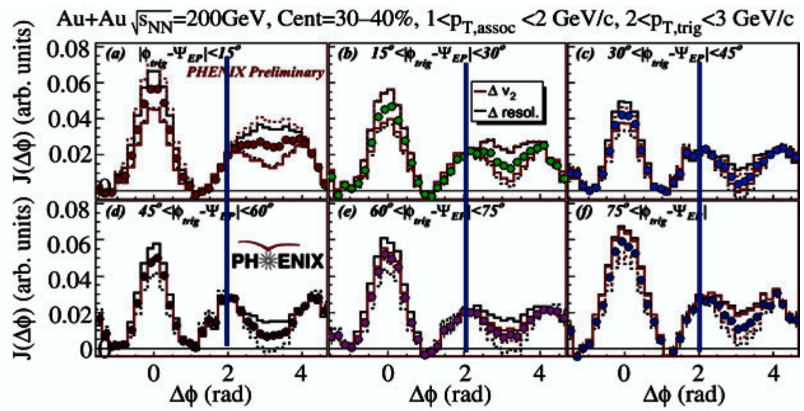
- ``Hard ridge” => forward-backward bremmstrahlung cones kicked out by hydro radial flow

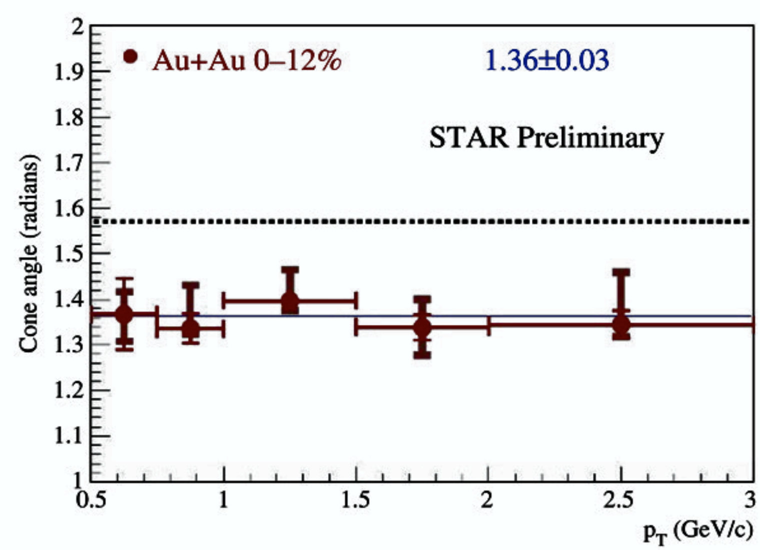
(ES 0706.3531, PRC76)

- ``Soft ridge” => initial stage fluctuation of the color changes
  (Dumitru,Gelis,McLerran,Venugopalan, 0804.3858, Gavin et al 0806.4718)

The 3-particle correlations confirmed conical shape. The cone angle seems to be universal,
but large => c_s=.2, why?
Why cone is so bright? and why there is no wake?
Why does it exists at SPS? (CERES)

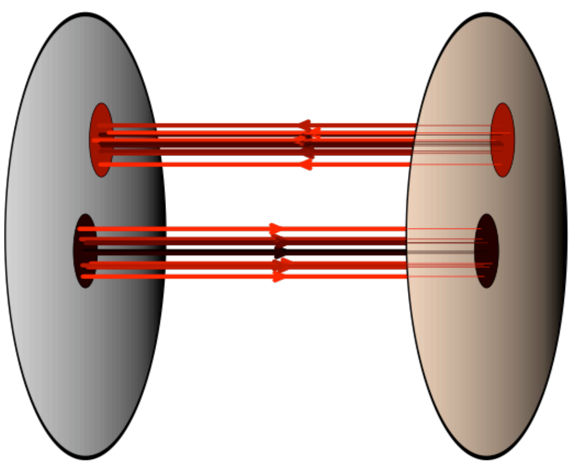


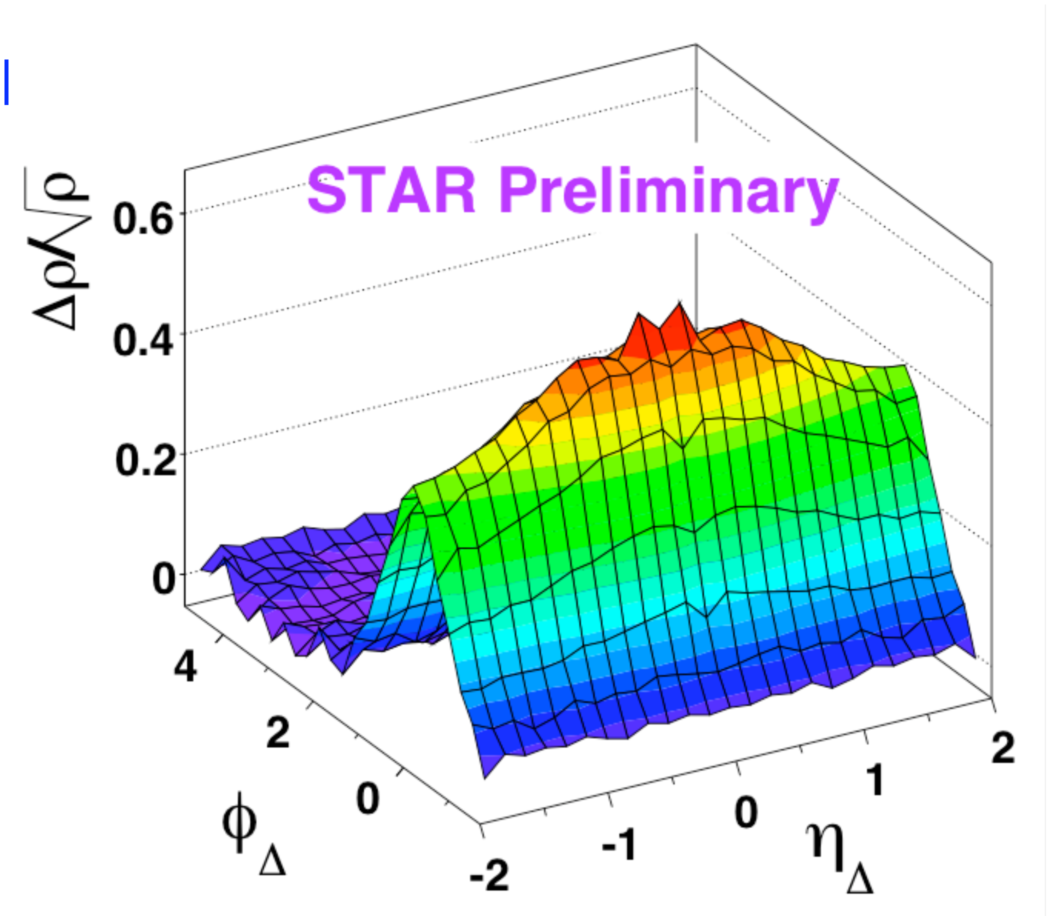




STAR found that the``ridge” exists even **without** any hard trigger (=>good statitics)

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





The Fate of the Initial State Fluctuations in Heavy Ion Collisions

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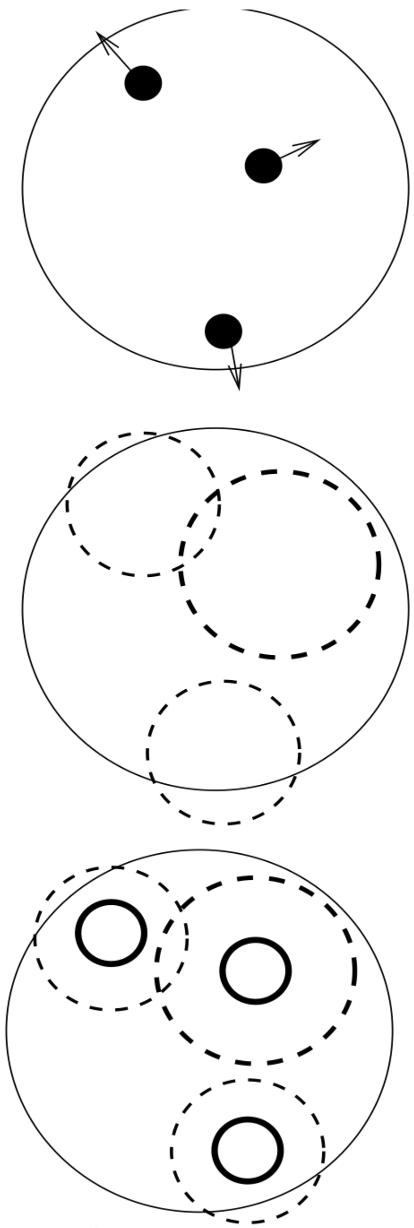
(February 20, 2009)

We study the propagation of local density fluctuations created in heavy ion collisions (either due to hard collisions or color charge separation) through the hydrodynamical evolution, which is modeled by overall Hubble flow. While naively they should expand to spherical waves of sound with the radius given by sound horizon, making them delocalized and hardly observable, the real solution is much more interesting. The interplay of time-dependent speed of sound and Hubble expansion leads to recreation of a fluctuations at original location and even their amplification.



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

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

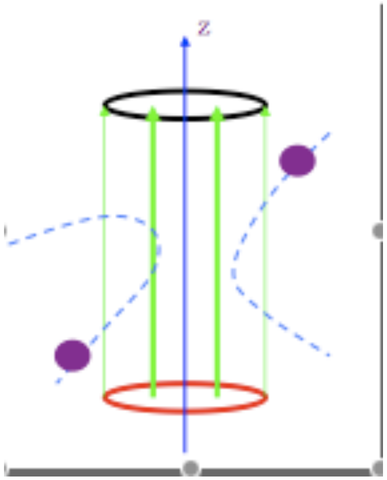
And thus large angular size

But the actual solution to the problem reveals **creation of smaller-brighter second waves which we may see**

Dilemma:

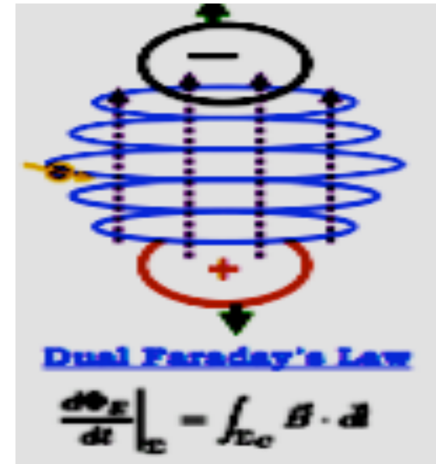
- Either ``acoustic solution” : the second wave of sound due to rapid $c_s(t)$ dependence
- **Or the flux tube solution : a ``coil” preventing expansion of the (electric) flux tube**

(possible if matter is basically magnetic plasma, with very few electric charges)



e-flux tubes above Tc?

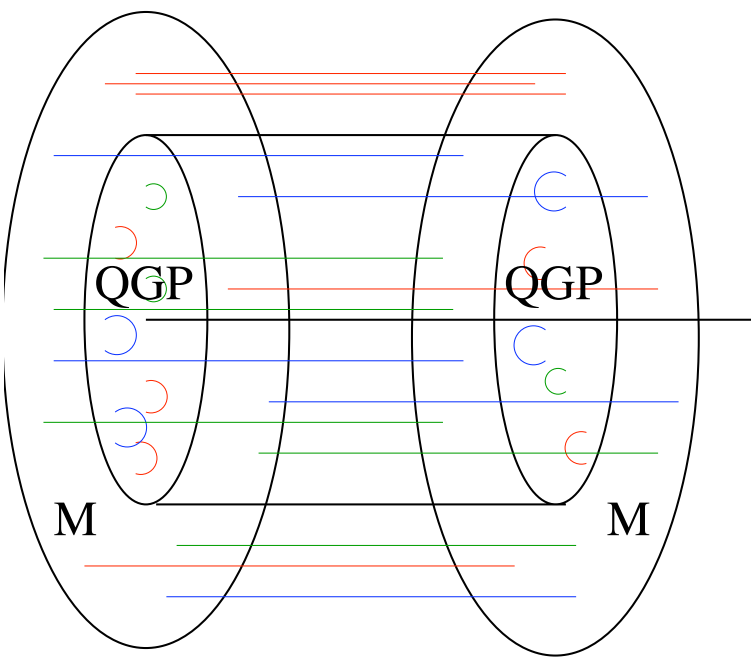
(with J.F.Liao, archive 0706.4465)

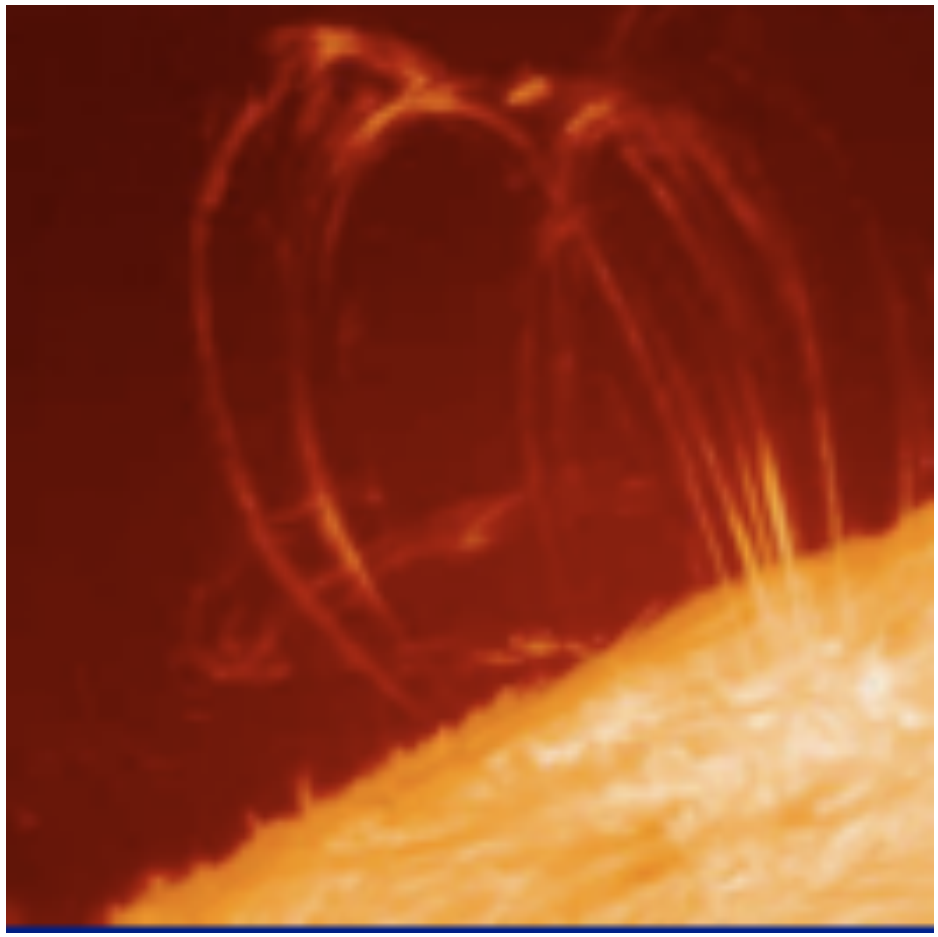


- **Dual superconductivity** at T<Tc as a confinement mechanism ('tHooft, Mandelstam 1980's) => monopole Bose condensation => electric flux tubes (dual to Abrikosov-Nielsson-Olesen vortices)
- **Dual magnetohydrodynamics** at T>Tc ? Electric flux tubes in magnetic plasma
- monopoles are reflected from E field => pressure => metastable flux tubes up to 1.4 Tc

My favorite example of flux tubes without super/quantum

- **metastable with normal current**





Summary on monopoles

- as T decreases, electric coupling grows and magnetic decreases
- e/m equilibrium is around 1.4 Tc

Monopole density peaks at Tc where their mass < 300 MeV
(While q,g and dyons are all much heavier, around 4 Tc=800 MeV)

- Correlators are very similar to that in strongly coupled Coulombic liquids: **must be real objects**
- Scattering between e- and m-charges is large and has backward peak. Classical caging => **small viscosity and diffusion**

Quantum g+m scattering produces reasonable viscosity eta/s for RHIC and predicts eta/s =.2 at LHC

- Monopoles behave as Bose-condenced atoms (He4) at Tc <= Feynman universality and equality of clusters: **must be real objects**

Summary on jet quenching, the ``cone” and the two ``ridges”

- tomography => jet quenching is enhanced at Tc
- A long-time stability puzzle of the cone and two ``ridges” (with and without the jet)
- dilemma: metastable flux tubes or ``acoustic solution” (the second wave due to rapid change of $c_s(t)$)
- Why does it all happen? => plasma is magnetic near Tc => dual MHD