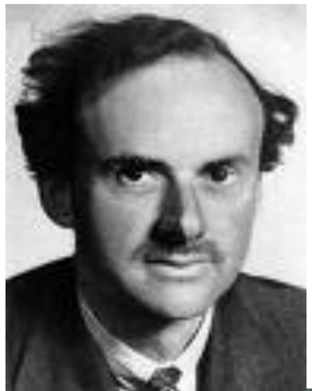
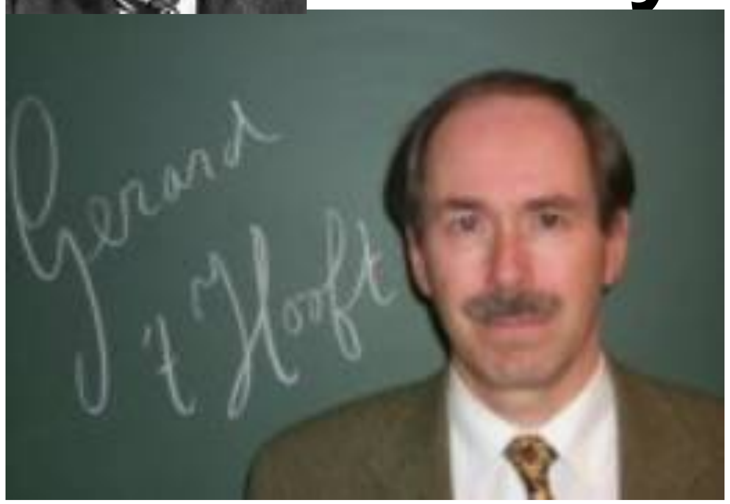
Magnetic plasma and (unusual) confinement

Edward Shuryak
Stony Brook

Confinement phenomenon for a long time was associated with Bose-Einstein condensation (BEC) of magnetic monopoles. In previous works we had shown that it is indeed the case for lattice monopoles, which in pure gauge theory are about as numerous near Tc as gluons.
We can now show that with **increasing number of quark flavors** to Nf=O(10) the deconfinement transition moves to much stronger coupling, and thus magnetic monopoles will dominate electric excitations. Quark zero modes create many states, most of them negatively affecting the BEC. We will also speculate that ``unusual" magnetic objects can undergo BEC, as they known to do so in supersymmetric analogs of multi-flavor QCD.



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

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

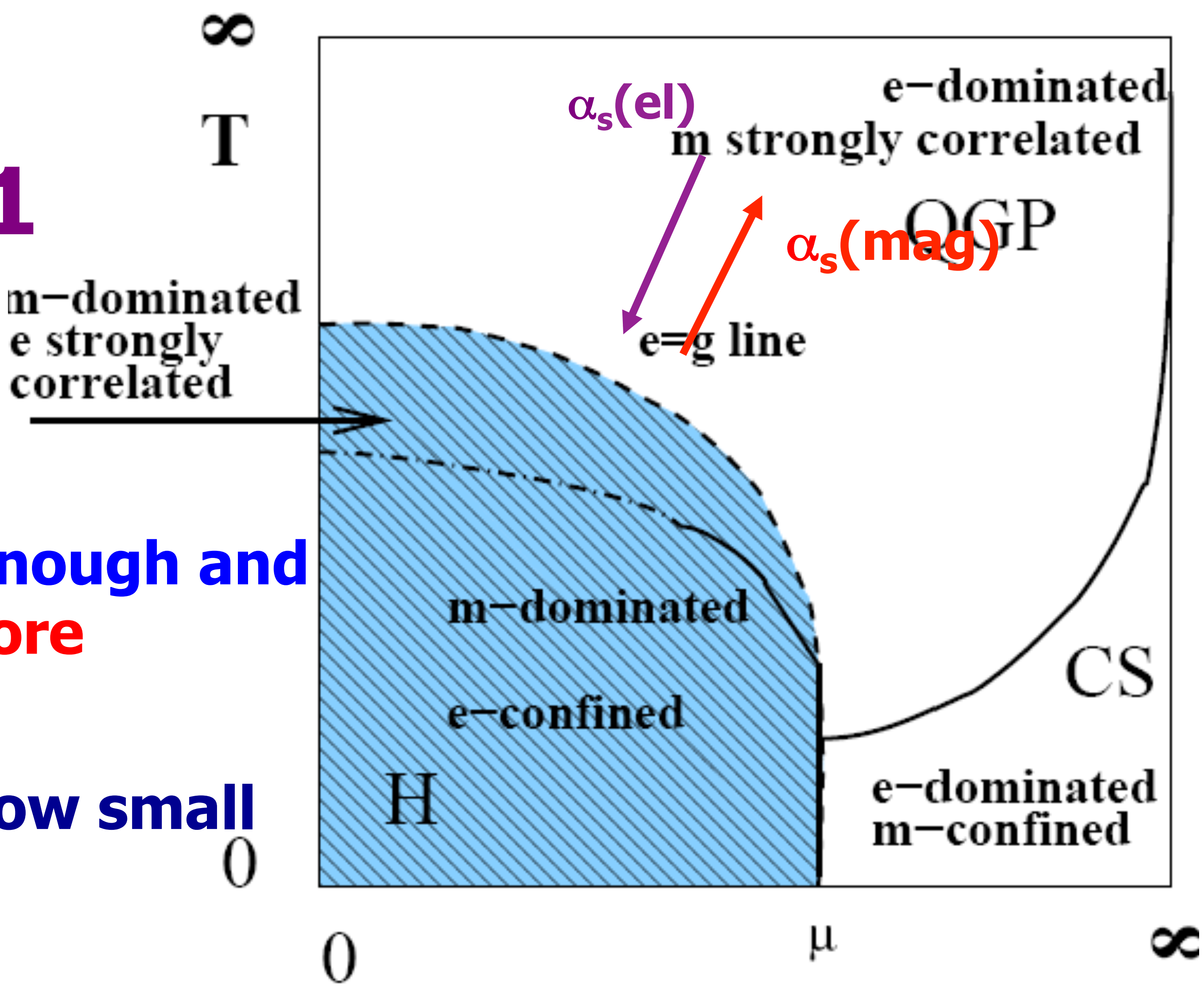
``magnetic scenario": Liao,ES hep-ph/0611131,Chernodub+Zakharov

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?

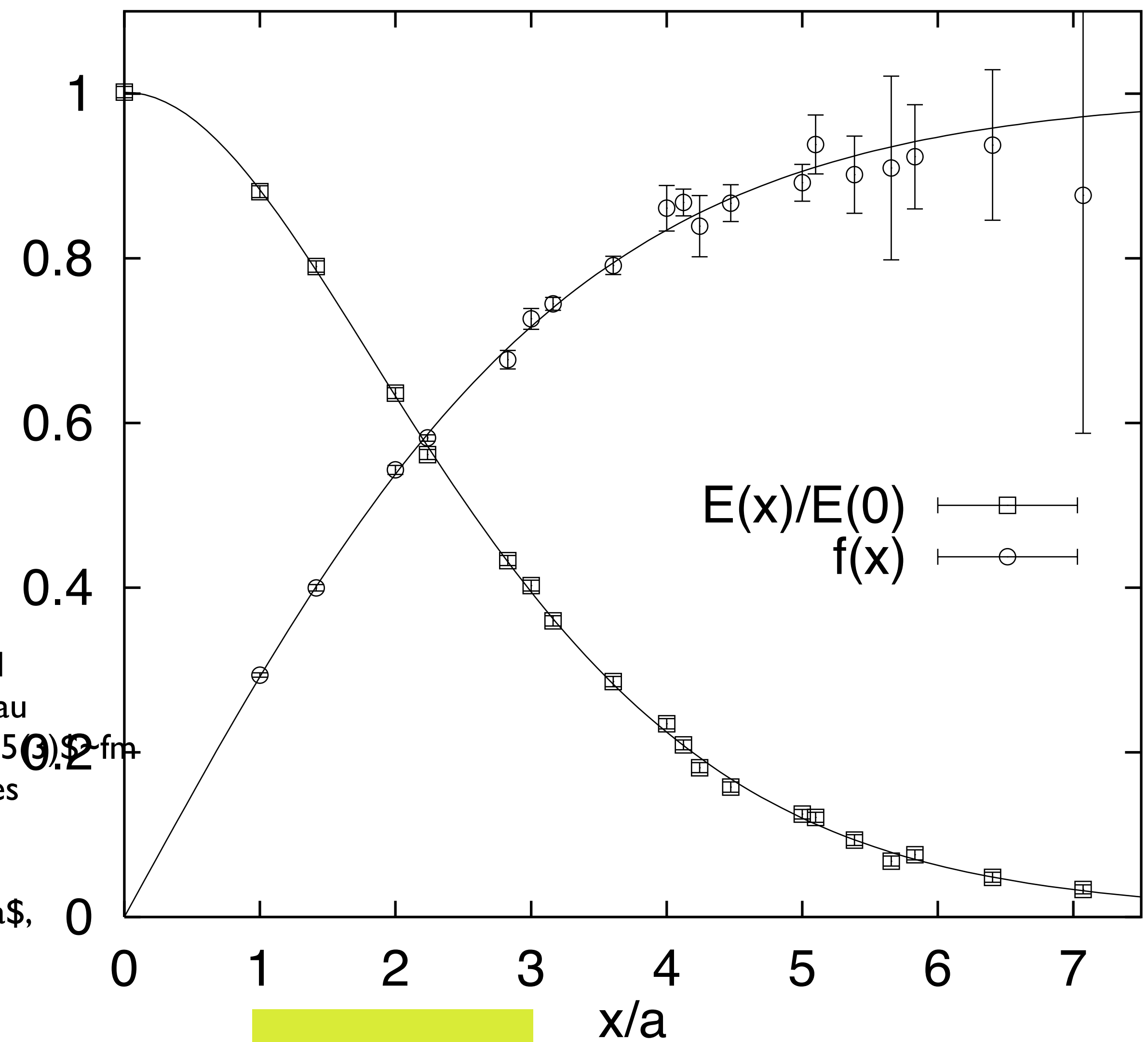
monopoles in QCD?

- there is no adjoint scalar
- yet there is e.g. <P> or <A_4> which can substitute in Euclidean formulation
- monopoles in corresponding gauges (which make at least one loop around the time tau) are identified and found to be lattice-independent (=physical?)

confinement=BEC of monopoles?

(Mandelstam,'tHooft)

- flux tubes can be studied on the lattice
- their profile matches well with the dual flux tube solution (curve)



The dual Maxwell equations have been verified in APSU(2) and the fields are adequately described by the dual Ginzburg-Landau equations with the values $\lambda=0.15(2)$~fm and $\xi=0.25(3)$~fm for penetration and coherence length, respectively. These values correspond to a (dual) photon mass $m_{\gamma}\approx 1.3$~GeV$\approx 3\sigma$ and a Higgs mass of $m_H\approx 0.8$~GeV$\approx 2\sigma$, the ratio of which, $\kappa=\lambda/\xi=0.59(13)$, indicates the vacuum of $SU(2)$ gauge theory to be a (weak) type I superconductor

G.Bali

GEF-TH 22/07

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

Spring 2008

A. D'Alessandro and M. D'Elia*
Dipartimento di Fisica, Università di Genova and INFN, Sezione di Genova, Via Dodecaneso 33, I-16146 Genova, Italy

x-Correlations
show it is a liquid
=> Magnetic
Coulomb coupling

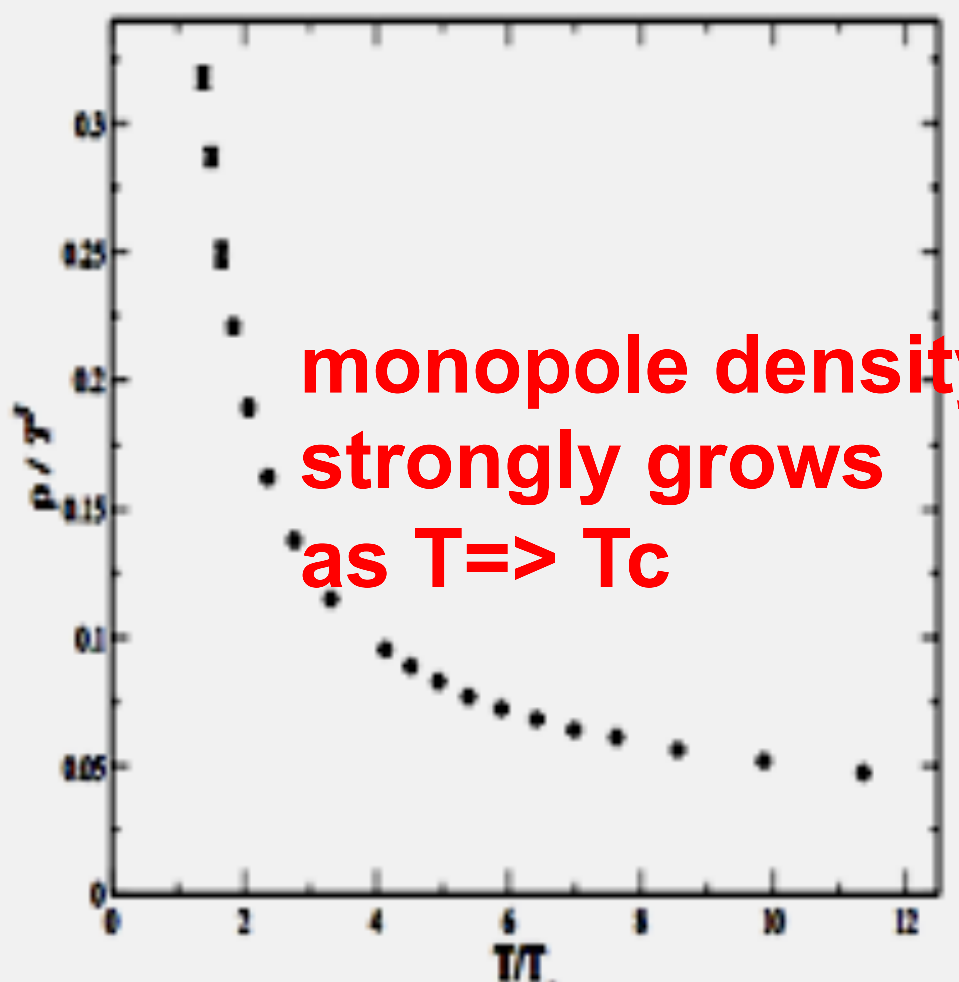


FIG. 3. $\rho(T)/T^3$ as a function of T/T_c. Data have been obtained on a $48^3 \times L_t$ lattice, with variable L_t and at $\beta = 2.75$ (first 9 points), and variable β at $L_t = 4$ (last 10 points).

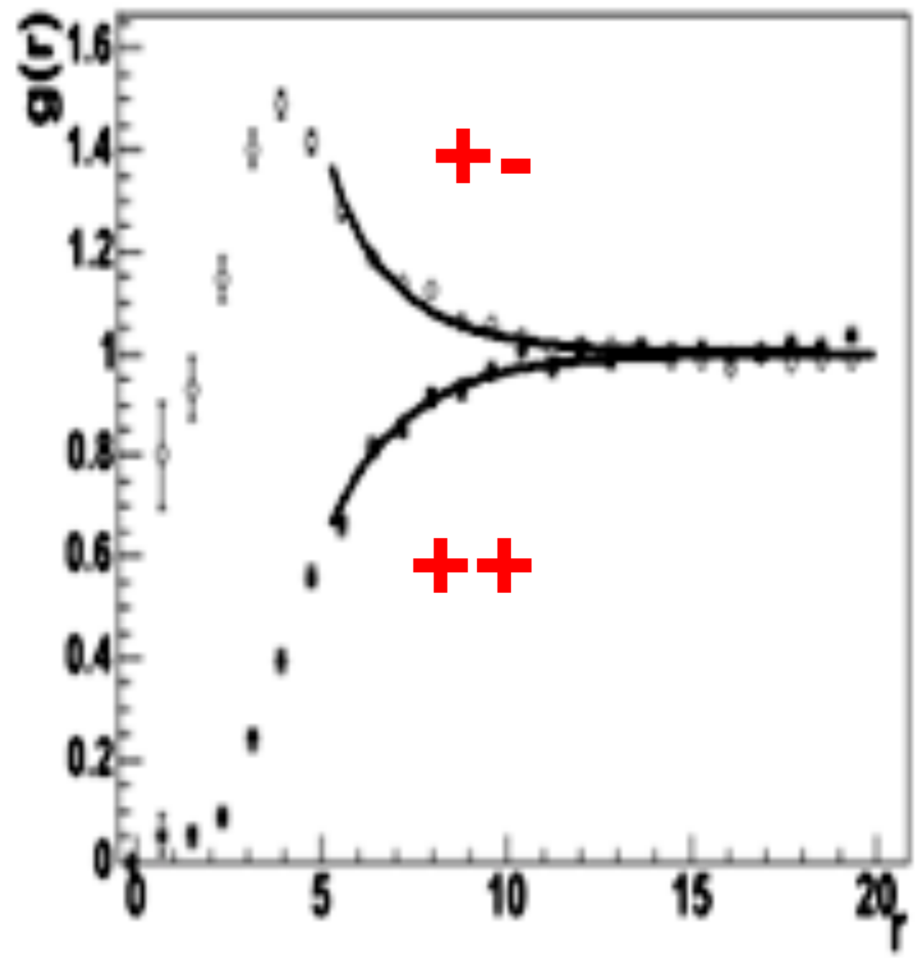


FIG. 5. $g(r)$ for the monopole-monopole (stars) and monopole-antimonopole (circles) case on a $0^3 \times 5$ lattice at $\beta = 2.7$ ($T \simeq 2.85\ T_c$). The reported curves correspond to fits according to $) = \exp(-V(r)/T)$ with $V(r)$ a Yukawa potential (see Eqs. (2.9) and (2.10)).

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

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

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

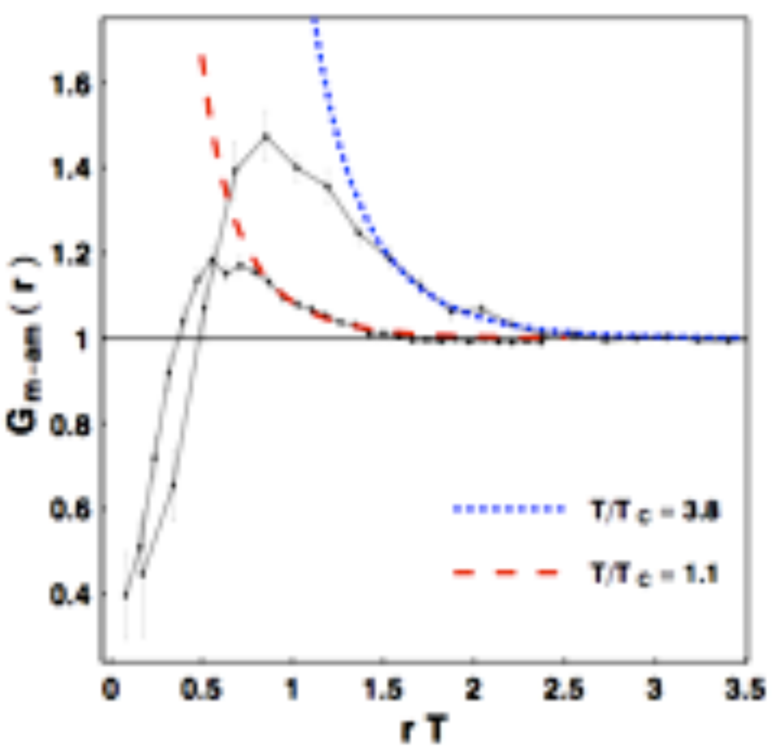
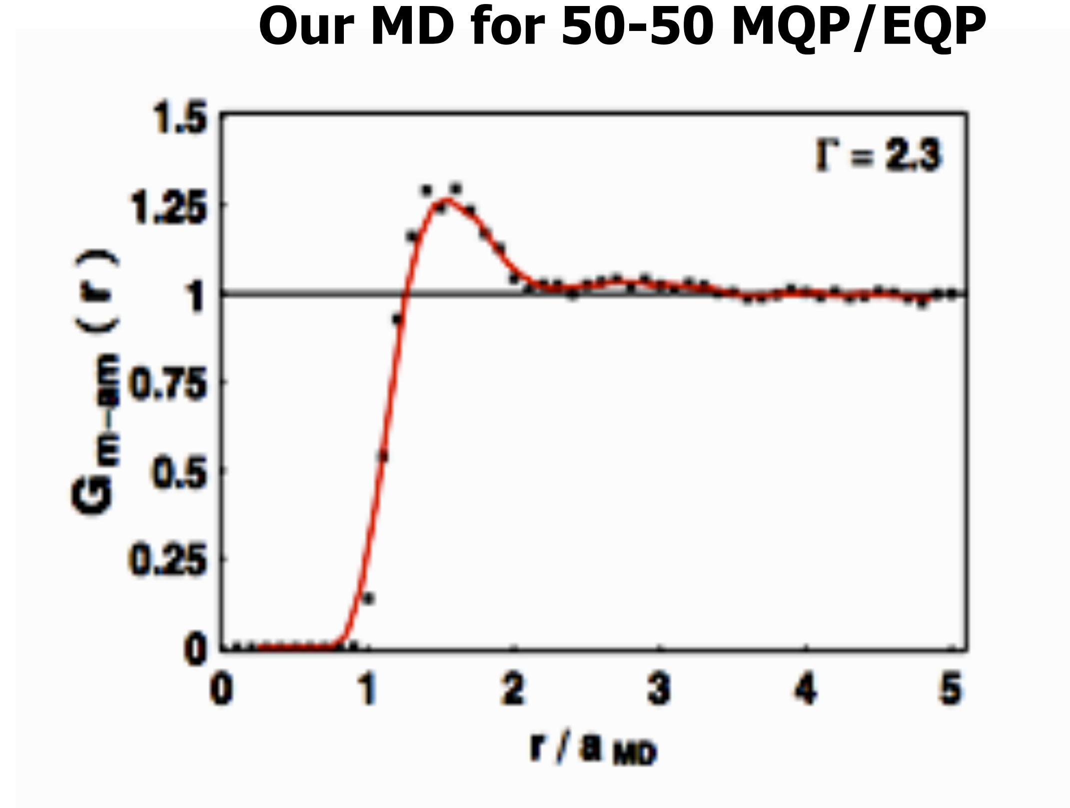


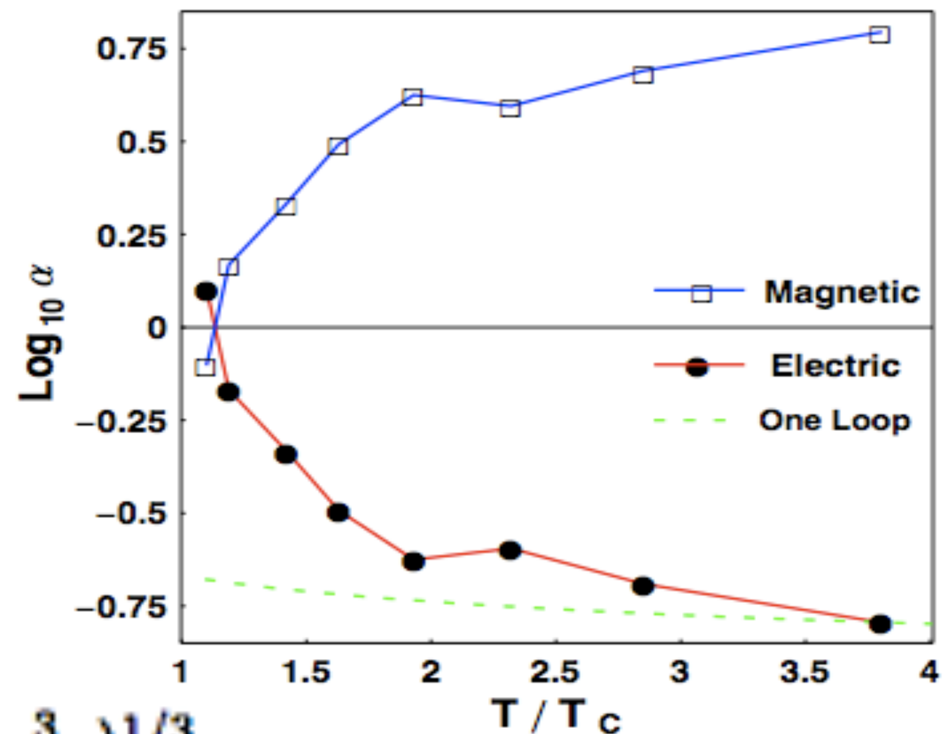
FIG. 2. (color online) Monopole-antimonopole correlators versus distance: points are lattice data [2], the dashed lines are our fits.

Our MD for 50-50 MQP/EQP



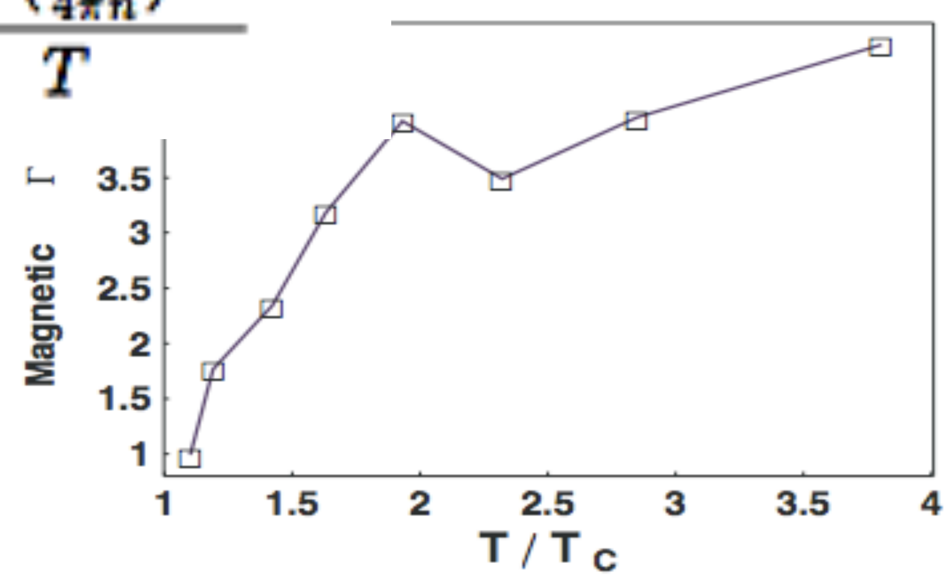
α_s(electric) and α_s(magnetic) do run in opposite directions!

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



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

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



Bose-Einstein condensation of interacting particles

[Bose-Einstein Condensation of strongly interacting bosons: From liquid He-4 to QCD monopoles.](#) **Marco Cristoforetti , Edward Shuryak**

[Phys.Rev. D80 (2009) 054013 e-Print: arXiv:0906.2019](#))

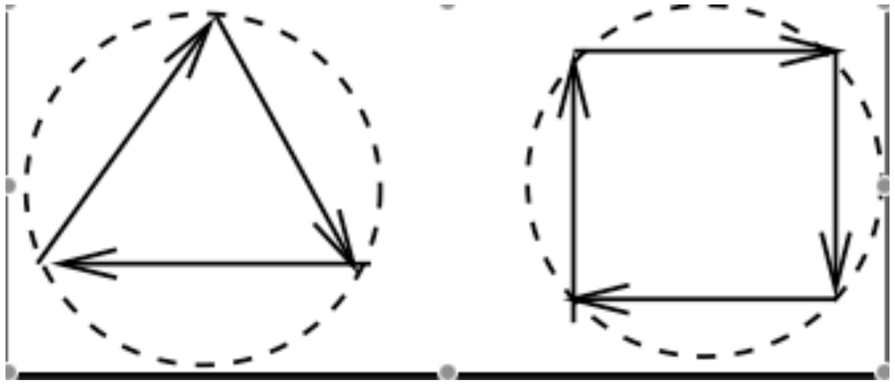
- Feynman theory (for liquid He4): polygons
  BEC if exp(-ΔS(jump))>.16 or so ($1/N_{naighbours}$)

We calculated ``instantons" for particles jumping paths in **a liquid and solid He4** incuding realistic atomic potentials and understood 2 known effects:

(i) Why Tc grows with repulsive interaction<= because a jump proceeds faster under the barrier

(ii) no supersolid He => density too large and action above critical

Marco is doing Path Integral simulations with permutations numerically, to refine conditions when **BEC transitions** take place

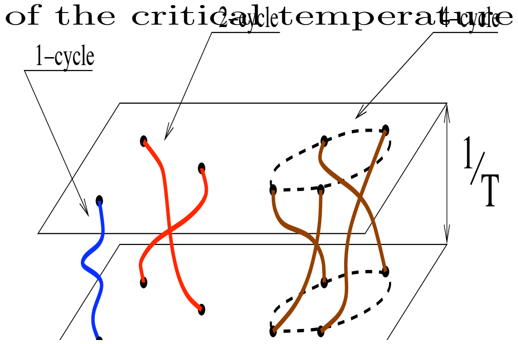


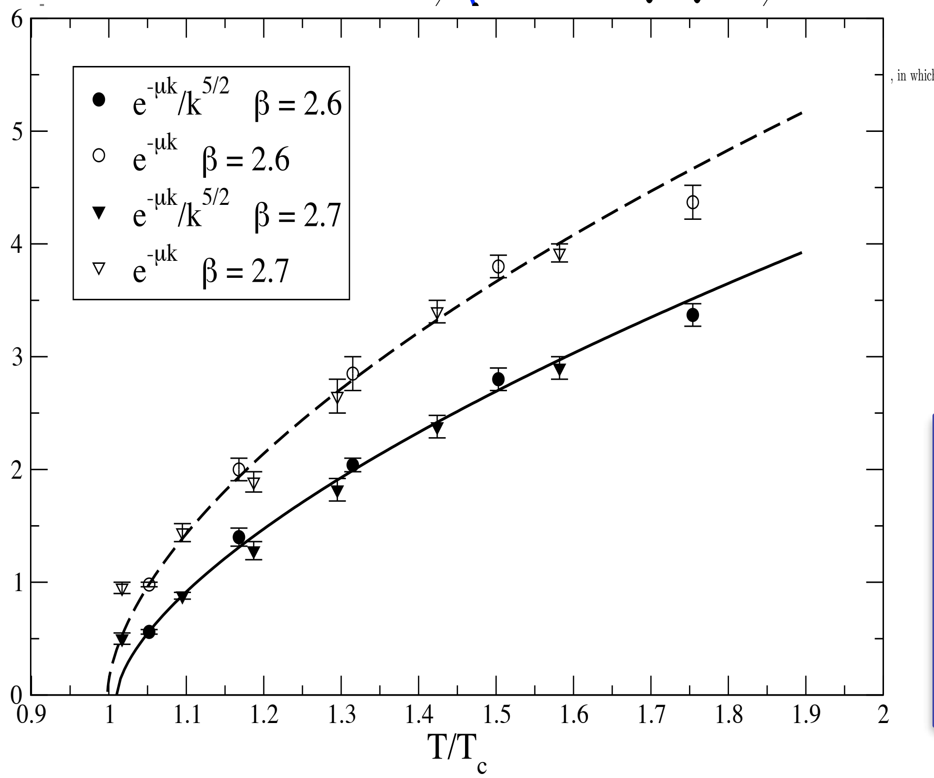
Jumping paths: Feynman, interacting

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.





, in which

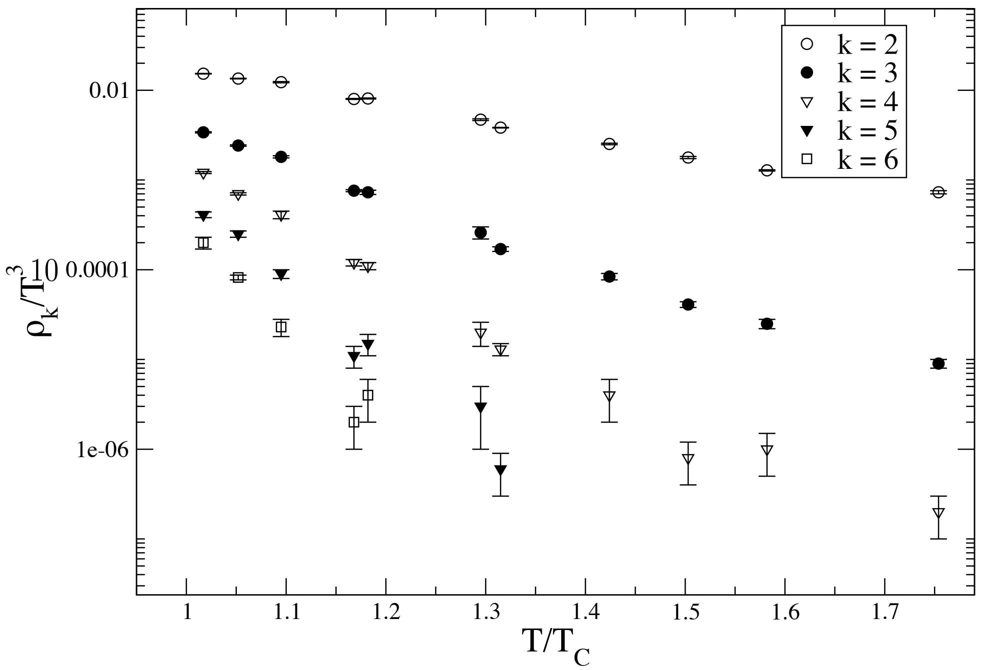


FIG. 2: Normalized densities ρ_k/T^3 as a function of T/T_c.

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

Effect of Light Fermions on the Confinement Transition in QCD-like Theories

Jinfeng Liao[1,2,*] and Edward Shuryak[3,†]

[1] Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA.
[2] RIKEN BNL Research Center, Bldg. 510A, Brookhaven National Laboratory, Upton, NY 11973, USA.
[3] Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794, USA.

Dependence of the deconfinement transition parameters on the fermion content provides information on the mechanism of confinement. Recent progress in lattice gauge theories has allowed to study it for light flavor number $N_f \sim O(10)$ and found this transition to shift toward significantly stronger coupling. We propose an explanation for that: light fermions can occupy the chromo-magnetic monopoles, via zero modes, making them "distinguishable" and unsuitable for Bose-Einstein Condensation. Such dilution of unoccupied monopoles is compensated by stronger coupling that makes them lighter and more numerous. We also suggest that flavor-carrying quark-monopole objects account for the density beyond quark Fermi sphere seen in cold dense phase of $N_c = 2$ lattice QCD.

The main idea: quarks "ride" on monopoles, due to their zero modes, making many types of differently flavored (but bosonic) objects, and this works against BEC. When only "empty" monopoles condense we call it the "usual confinement" condition will then be applied for the monopole condensation in QCD-like theories for the rest of our analysis:

$$\left(\frac{m^*}{T}\right)\left(\frac{n}{T^3}\right)^{-\frac{2}{3}} \le \tilde{S}_c \equiv 2\left(S_c - S_V\right) \tag{4}$$

The constant $\tilde{S}_c$ is of order one and its precise value is not needed as long as its N_f-dependence is negligible.

monopoles. Consider a monopole with one flavor of light quark added: for each of its allowed zero modes there is a probability for it to be occupied by a fermion or not. Let us assume the ratio of the probabilities (occupied/not-occupied) to be f (a kind of zero-mode fugacity), we then see that the overall probablitiy for a monopole (with N_M number of zero modes for *each fermion flavor*) to stay as a "pure" monopole is simply $1/(1+f)^{2N_M}$ (with the factor 2 accounting for both quark and anti-quark contributions for Dirac fermions). So effectively the available density for BEC condensation will be $n/(1+f)^{2N_f N_M}$. Combined with the BEC condition in Eq.(4) we obtain

$$\left(\frac{m^*}{T}\right)\frac{(1+f)^{4N_f N_M/3}}{(n/T^3)^{2/3}} \le \tilde{S}_c \tag{5}$$

This implies that with increasing N_f, the density n has to increase and mass m^* to decrease correspondingly so as to reach the same condensation condition. This pushes the transition to stronger coupling, therefore explaining the N_f-dependence of the critical coupling in Fig.1.

To make a semi-quantitative estimate, we use the following magnetic scaling relations that connect the monopole mass and density with gauge coupling: $m^*/T \sim 1/g$ and $n^{1/3}/T \sim g^2$ [18, 20, 30]. Combined with the above condition, we obtain the critical gauge coupling for monopole condensation to be: $g(N_f) = g_0\,(1+f)^{4N_f N_M/15}$ where g_0 is the corresponding critical coupling for pure gauge case. This can be further converted to the lattice couping $\beta = 2N_c/g^2$:

$$\beta_c(N_f) = \beta_0(1+f)^{-8N_f N_M/15} \tag{6}$$

Feynman condition of the BEC explains the critical line vs Nf

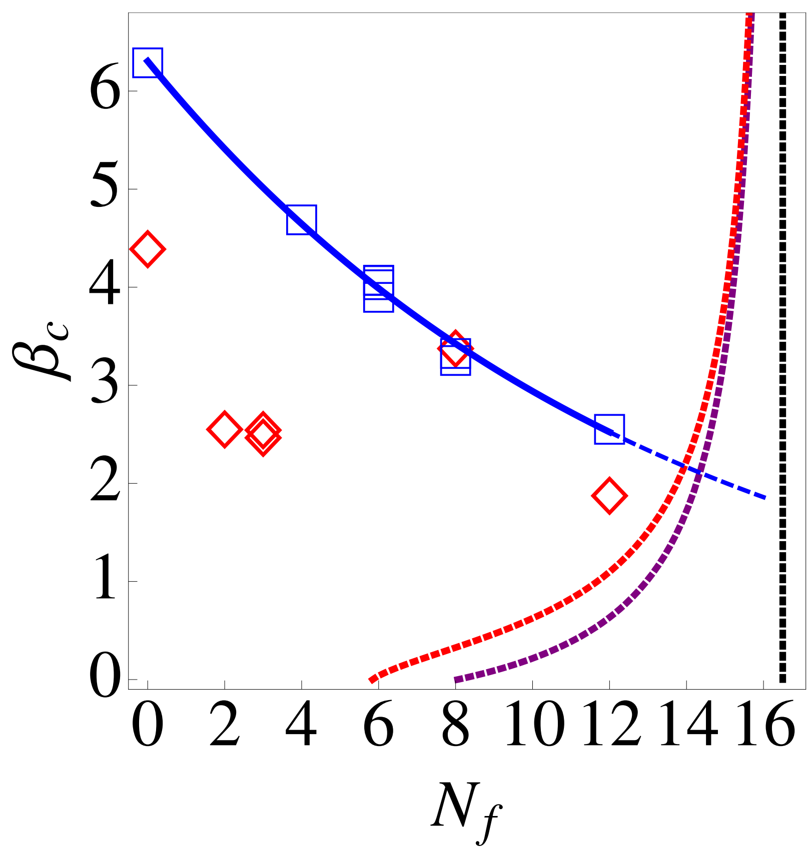


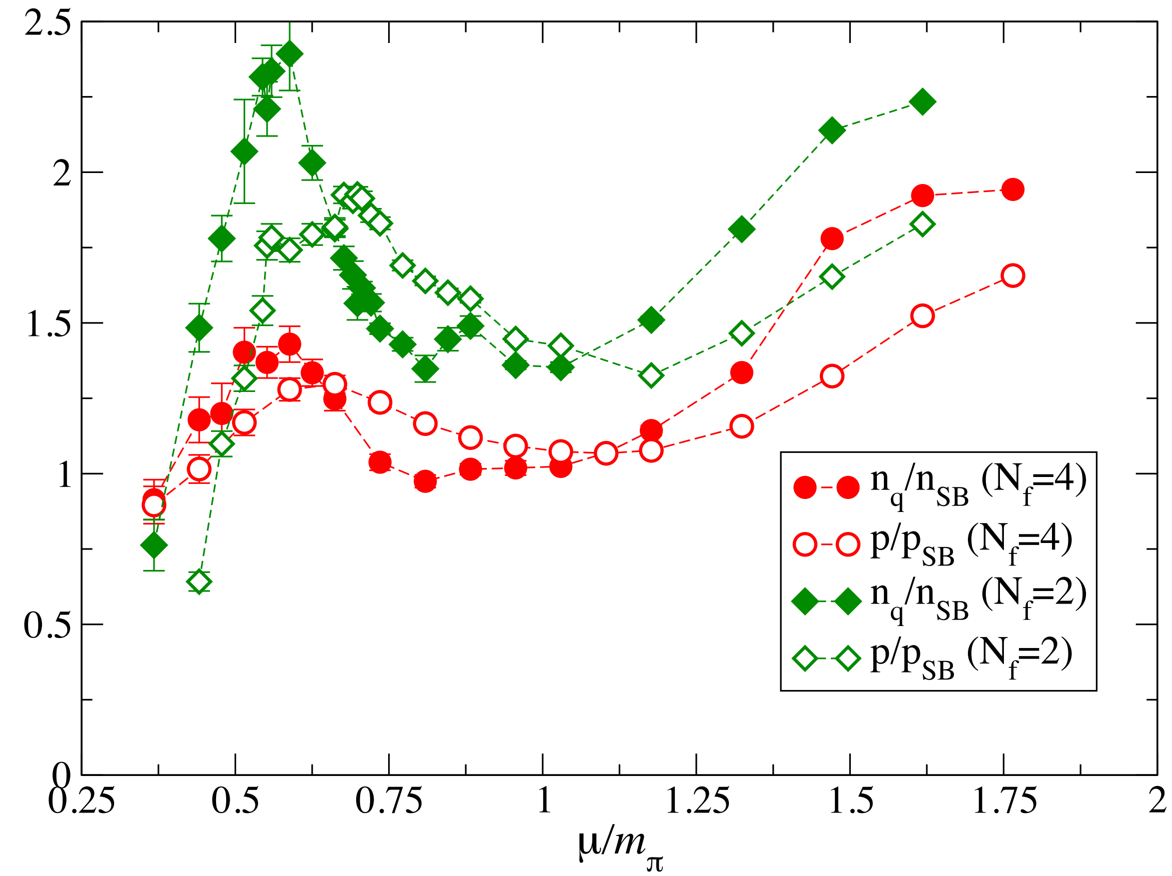
FIG. 1: Dependence of the critical lattice coupling β_c at scale T_c versus the number of fundamental quark flavors N_f in QCD-like theories. Blue boxes are from [9] fwith near-coincident boxs being lattice data for the same N_f with different N_τ which demonstrate lattice spacing consistency. Red diamonds are from various other literature. The thick blue line is the fitting curve, extended as dashed blue line beyond $N_f = 12$. The black/purple/red dased curves on the right are lines for vanishing beta function at 1,2,3-loop levels.

6. It is well known that the $N_c = 2$ theory is a very special case, with extra symmetry between quarks-antiquarks and mesons-diquarks. It also allows the finite density lattice simulations without the "sign problem". Lattice study of this theory was recently extended to the low-T finite-μ region with $N_f = 2, 4$ quarks by Hands, et al [33]. The quark density (per flavor) shown in their Fig.3 displays a number of features: (i) a structure at $\mu \approx m_\pi/2$ as predicted by the rotation from the $\psi\psi$ to diquark condensate [34, 35]; (ii) the usual quark Fermi sphere at higher μ; and (iii) an unexpected growth of quark density at still higher μ to about twice the value as expected from the Fermi sphere. The deconfinement as per the Polyakov loop appears concurrent with (iii).

We now propose that this extra quark density in (iii) is due to the condensate of the *monopole-quark* states. The high quark chemical potential strongly favors states with quark numbers and efficiently converts the pure monopoles into monopole-quark states, thus explaining the deconfinement at about the same density. At such low T the dominant monopole-single-quark objects, being bosonic, would appear mostly as a condensate, like the diquarks. Assuming standard effective potential with a repulsive binary interaction $V_{int} = \lambda n^2/4$, one gets the condensate density growing linearly with μ, $n_{BEC} \sim (\mu - m)/\lambda$ at $\mu > m$, which is consistent with observations of [33]. Furthermore, a similar density per flavor for both $N_f = 2$ and $N_f = 4$ is consistent with our view that these objects are dominantly states with only a *single* quark per monopole. States with multiple quark

Lattice Study of Dense Matter with Two Colors and Four Flavors

Simon Hands[1], Philip Kenny[1], Seyong Kim[2], and Jon-Ivar Skullerud[3]



quark fermi gas and then unexpected excess, which we interpret as q's on monos

Fermionic zero modes of the monopoles

- Starting in the simplest Nc = 2 theory we use the term "isospin" instead of the color. Thus the fundamental (adjoint) quarks have isospin T=1/2 (1), respectively.
- grandspin K = T + S takes values 1/2 + 1/2 = 0, 1 and 1 + 1/2 = 1/2, 3/2
- From the number of zero modes, 1 and 2 respectively, one can see that zero modes correspond to K = 0 and K = 1/2 in those two cases.

- path integral with one complex coefficient => in the operator language, a pair of creation/ annihilation operators with the algebra [aa+] = 1 requiring representation in the form of two states, the "empty" and "occupied" ones.
- Exponential proliferation of states 2^{N_f} !
- (for those in doubts, a homework: calculate quantum number and multiplicity of magnetic states in $\mathcal{N}$=4,N_f=0 SYM, as well as $\mathcal{N}$=2, N_f=4. You should find that both are E/M selfdual => thus conformal! No need to calculate loops…)

So, quarks on the monopoles create spin-0 bosons

Adjoint fermions (gluinos) create fermions and (if several) may create spin-1 (e.g. in N=4 SYM)

discussion

- Are there **different confinements?**
- e.g. BEC of monopoles in 3+1 versus vortices in 2+1. So what happens when 1dim is compactified? (**Cossu, D'Elia arXiv:0904.1353, Na=2 => two confining phases found, but they are separated by 2 deconfined ones, and we do not know if they can be continuously(?))**
- Or BEC of the Q_M=2 vs Q_M=1 objects in $\mathcal{N}$=2, N_f=3 SYM: can one find each of them and find out which is BE-Condenced?

Adjoint quarks and hints from SUSY

- Example 1: N_a=1,N_f=4 => like $\mathcal{N}$=2, N_f=4 SYM which is fully conformal. (The difference is only in scalars, so it is near-conformal; but if one starts from magnetic formulation, how these scalars not to appear?)
- Example 2: N_a=1,N_f=3 => like $\mathcal{N}$=2, N_f=3 SYM for which SW found two vacua: one 4-degenerate has confinement and chiral symm.breaking, another 1-degenerate has only confinement with an unusual magnetic charge Q_M=2

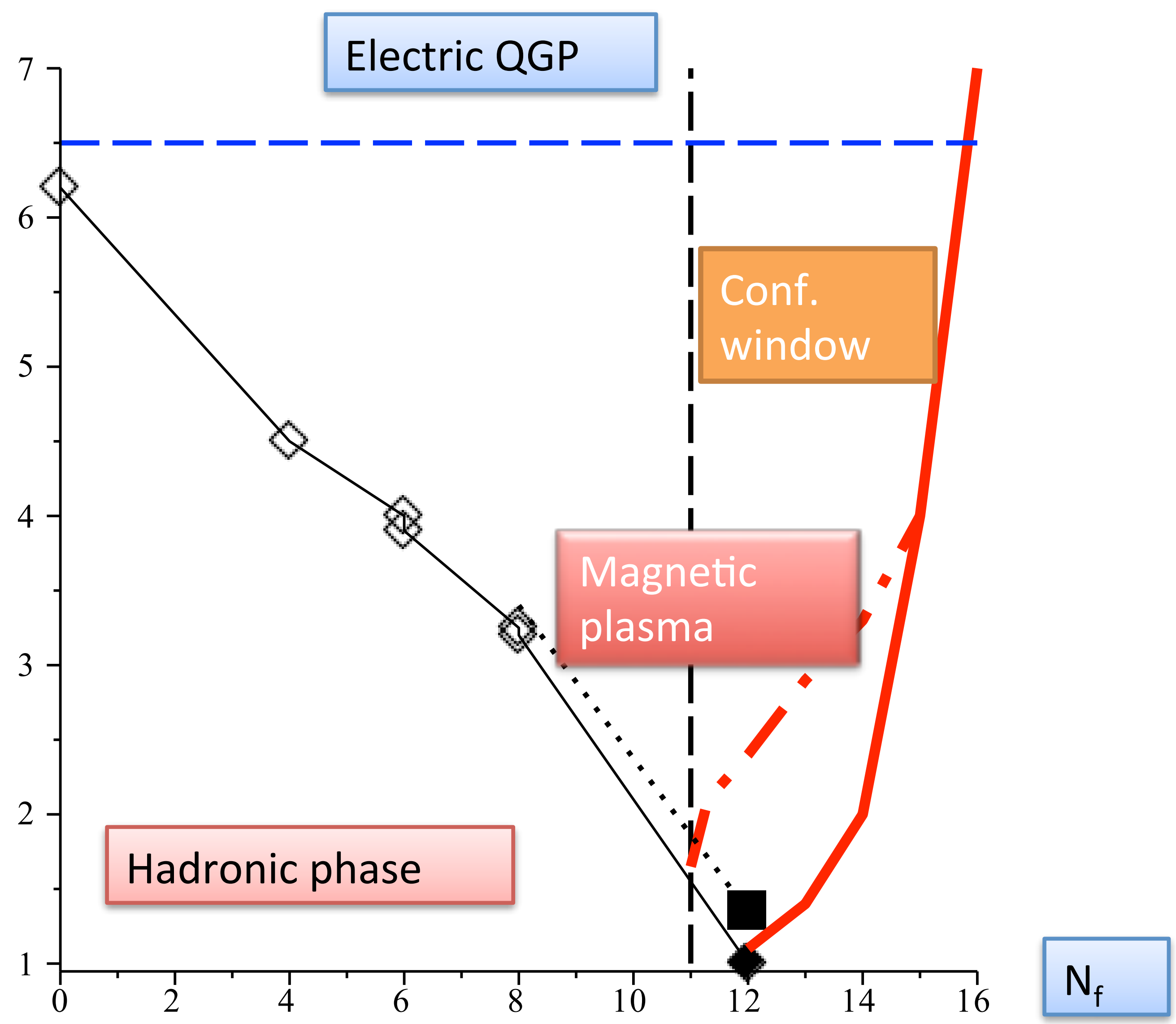
Unusual confinement is BEC of magnetic objects other than just magnetic monopoles: SW QCD with 3 flavors has two examples:
flavored monopoles or even composite di-monopole bound by all 3 quarks !

much stronger coupled QGP

News from the lattice world, due to GPU's clusters jump in flops

QCD with many quarks, $N_c=3$

- Plotted **$2N_c/g^2(T)$**
- Diamonds are for chiral transition
  Miura,Lombardo and Pallante, arXiv:1110.3152
- Dotted: the confinement line, with a new phase
  A. Cheng, A. Hasenfratz and D. Schaich, arXiv: 1111.2317
- Horizontal dashed is E/M equilibrium (LS)



summary

- magnetic excitations: monopoles and dyons
- well defined if adjoint scalar: is dual superconductor idea right for QCD
- monopoles found on the lattice, make a Coulomb liquid and BEC at Tc
- contribute dominantly to kinetics: novel plasmas of e and g
- fermions on monopoles and confinement is an emerging field