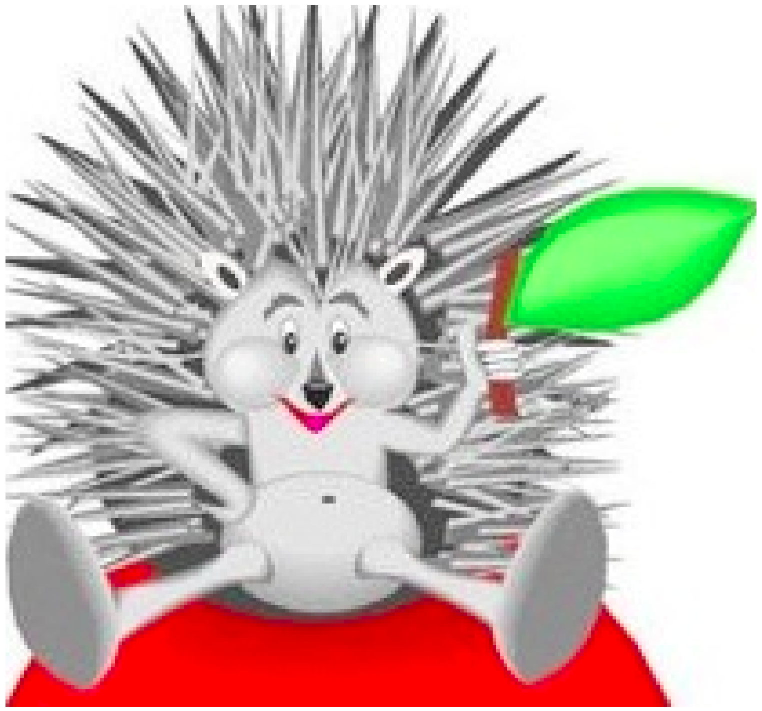
Confinement,
Instanton-dyons and Monopoles

Edward Shuryak
Stony Brook University



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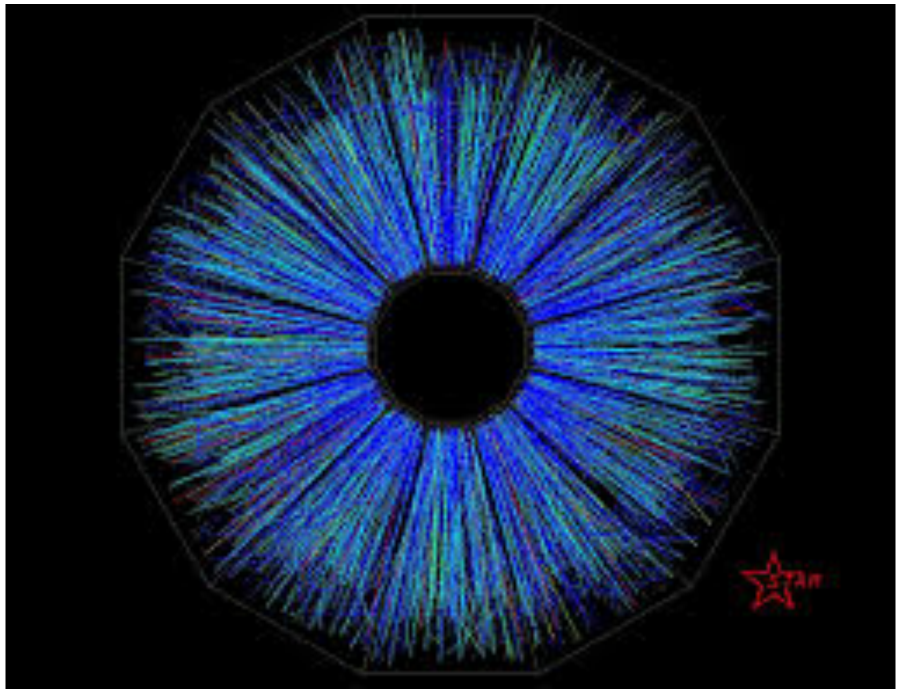


topology,semiclassics,instantons

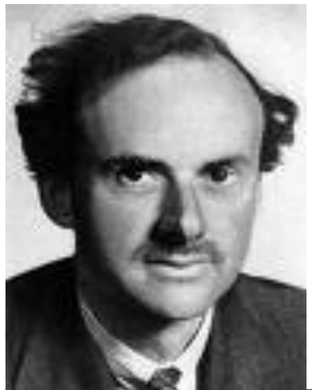
Heavy ion collisions, QGP

Quark confinement and hadron spectrum,
Aug.3, 2018, Maynooth, Ireland

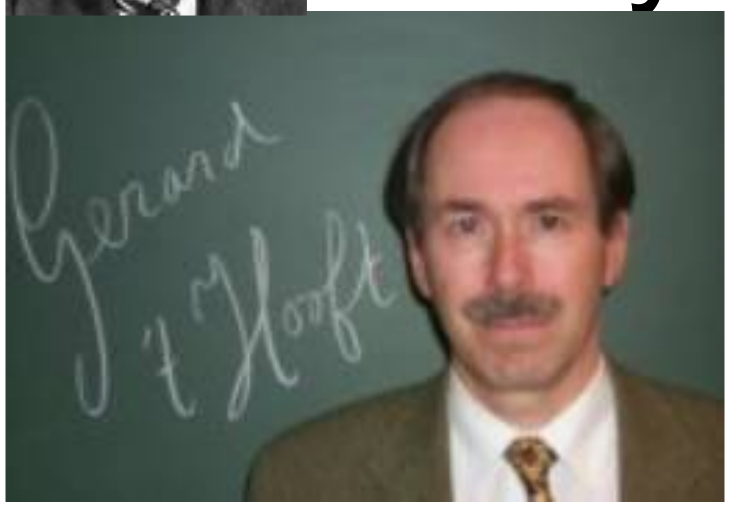
outline

Instanton-dyons <=> Monopoles
Euclidean semiclassical theory <=>time-dependent dynamics

- Confinement=Bose-Einstein condensation of
- monopoles. Kinetic coefficients -viscosity,
- jet quenching parameter, can be explained by
- “dual QGP” with monopoles. But, what are
- these monopoles in QCD?
- instanton-dyons => confinement, chiral symmetry breaking and nontrivial quark periodicity
- Relation between instanton-dyons and monopoles
- Chiral symmetry breaking with monopoles



Particle - monopoles 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 Mandelstam suggested “dual superconductor” mechanism for confinement **(1976)**
- Seiberg and Witten shown how it works, in the **N=2 Super - Yang-Mills theory (1994)**

matter composition, by d.o.f.

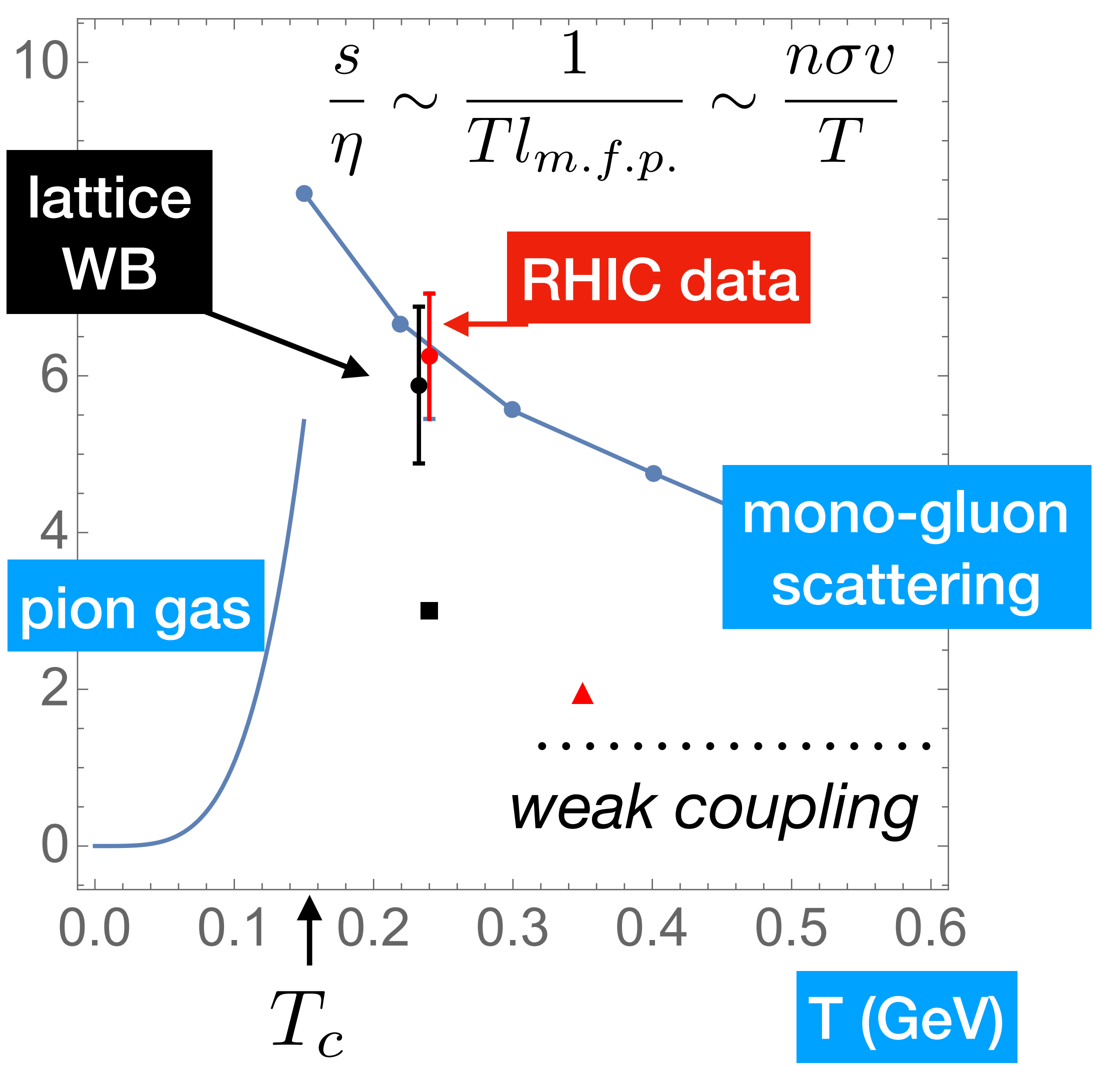
quarks

Role of QCD monopoles in jet quenching
Adith Ramamurti, Edward Shuryak (SUNY, Stony Brook). Aug 14, 2017. 16 pp.
Published in **Phys.Rev. D97 (2018) no.1, 016010**

monopoles

gluons

Strongly coupled quark-gluon plasma in heavy ion collisions
Edward Shuryak Rev.Mod.Phys. 89 (2017) 035001



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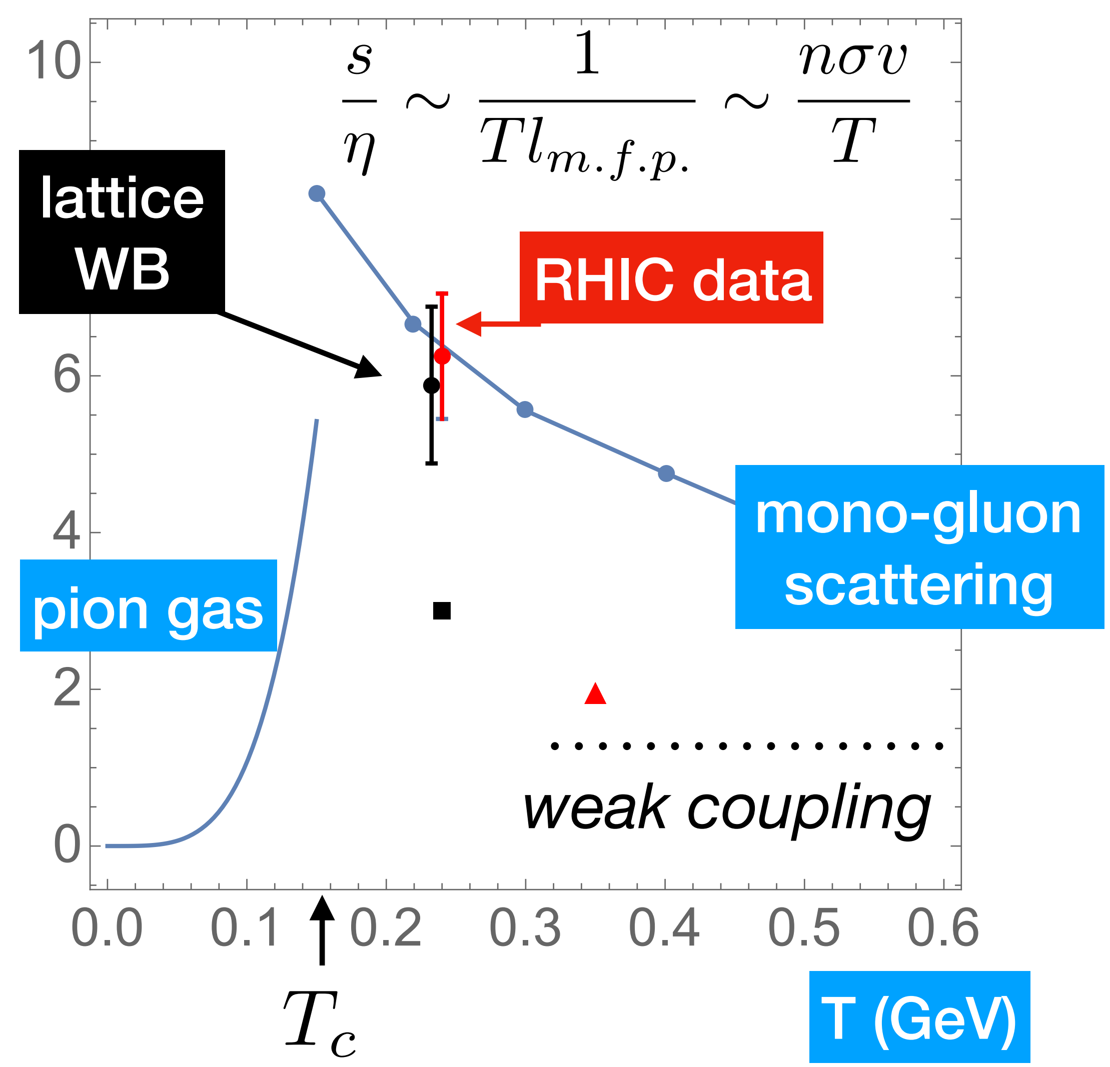

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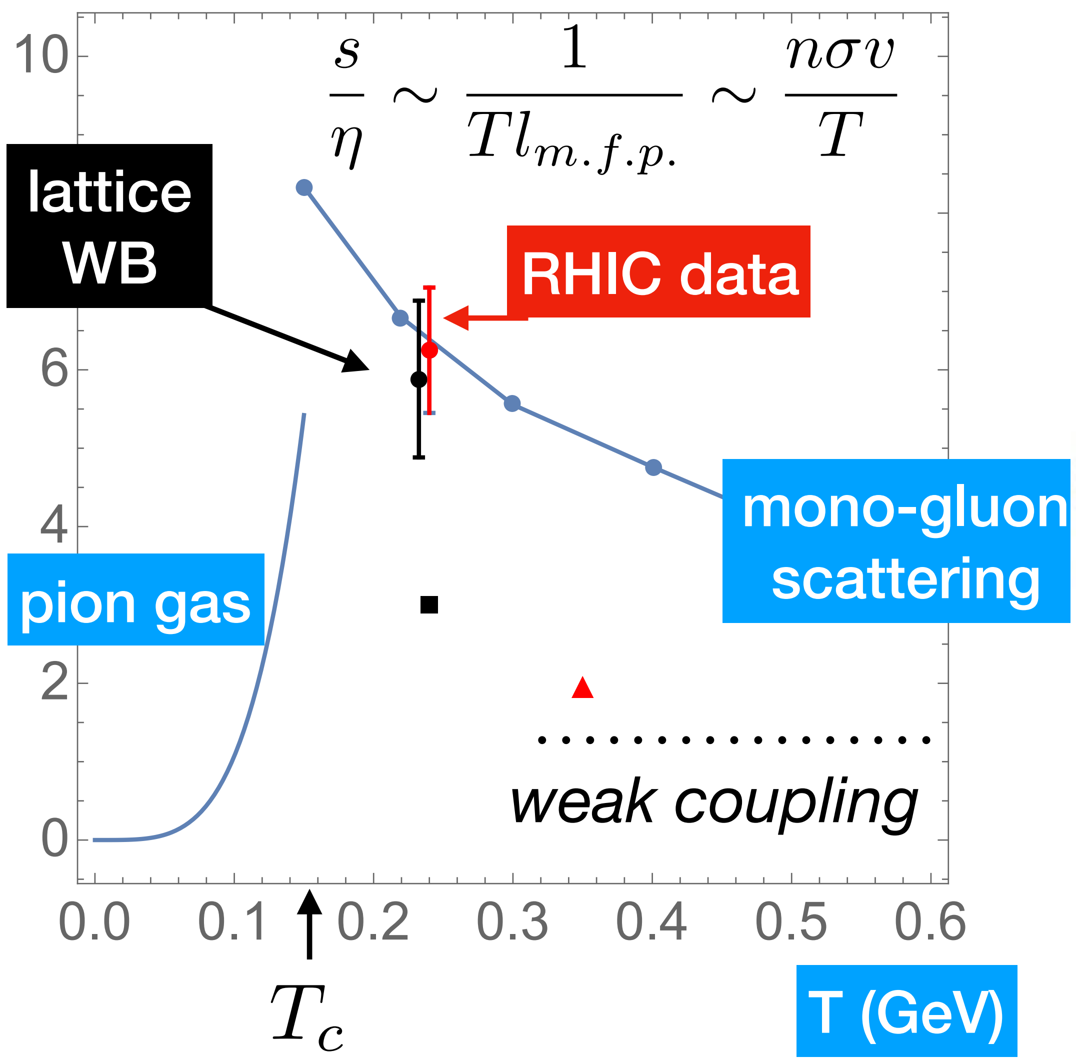

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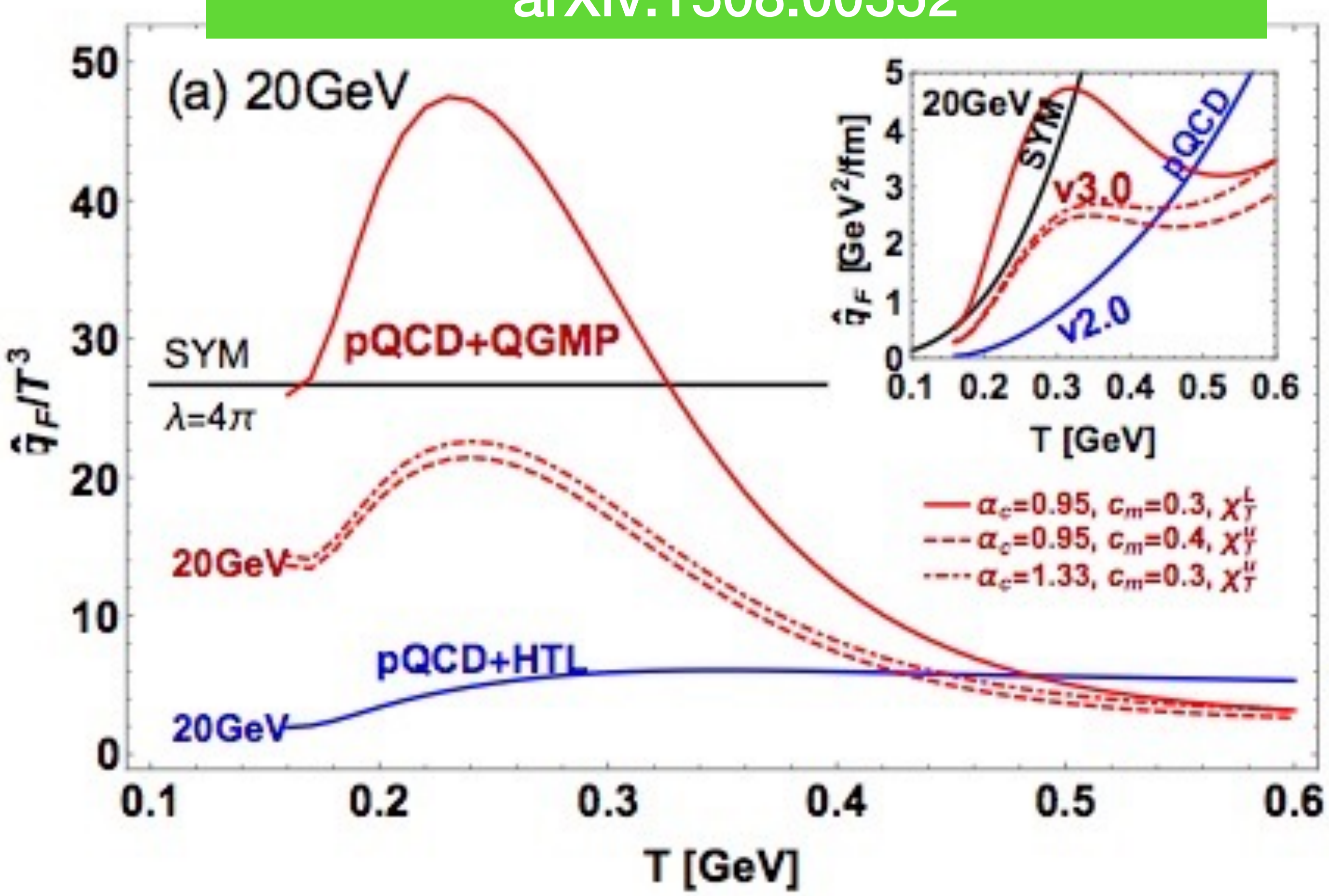

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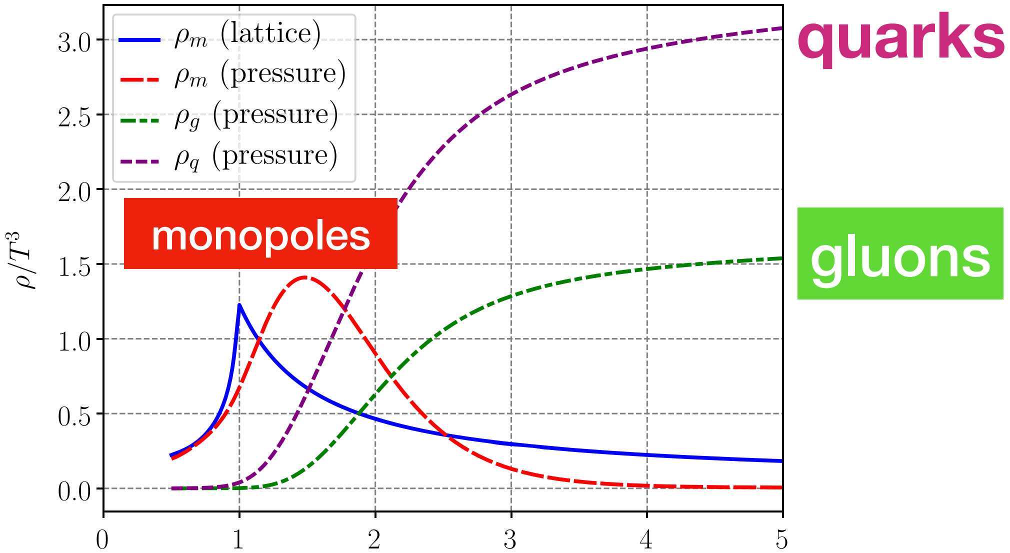

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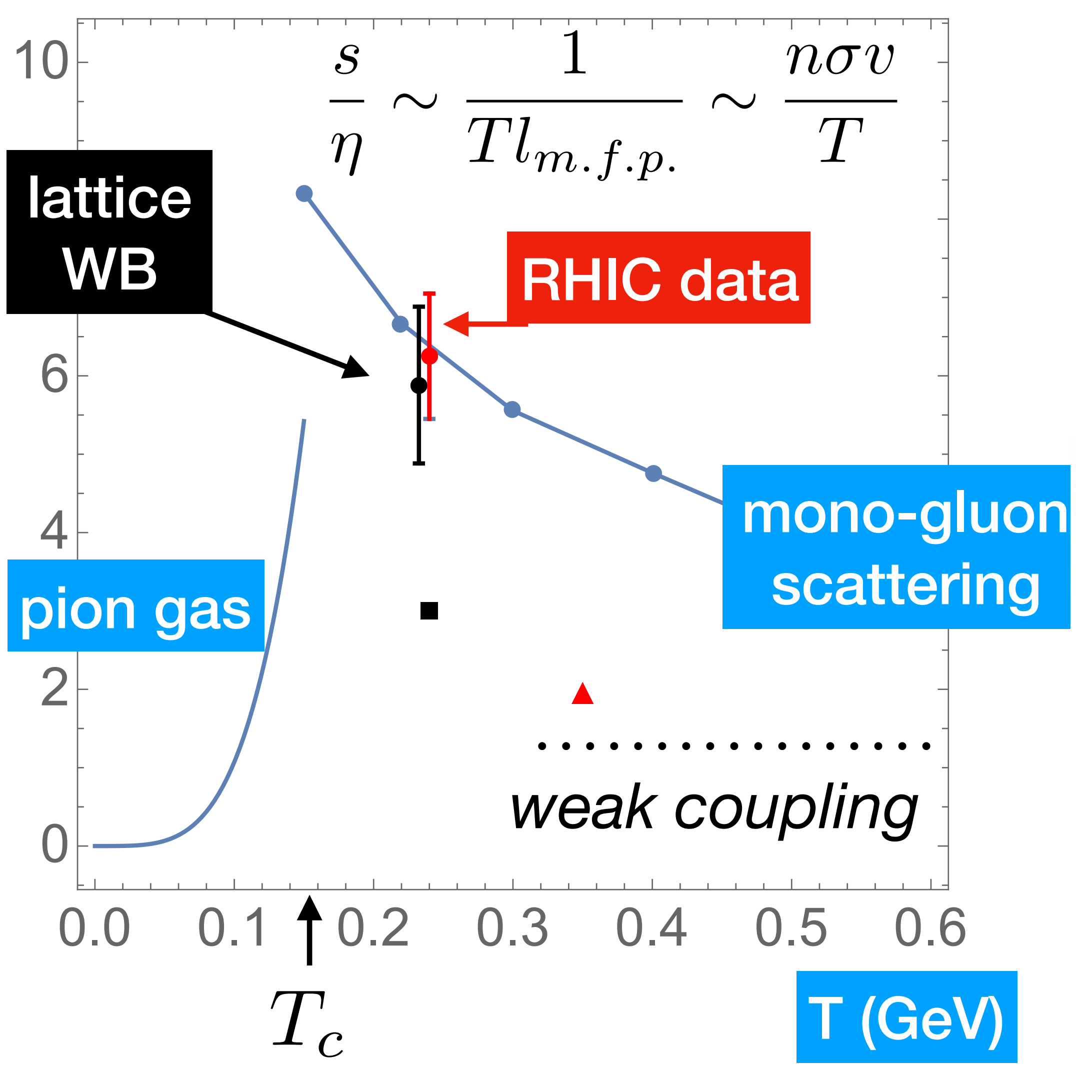

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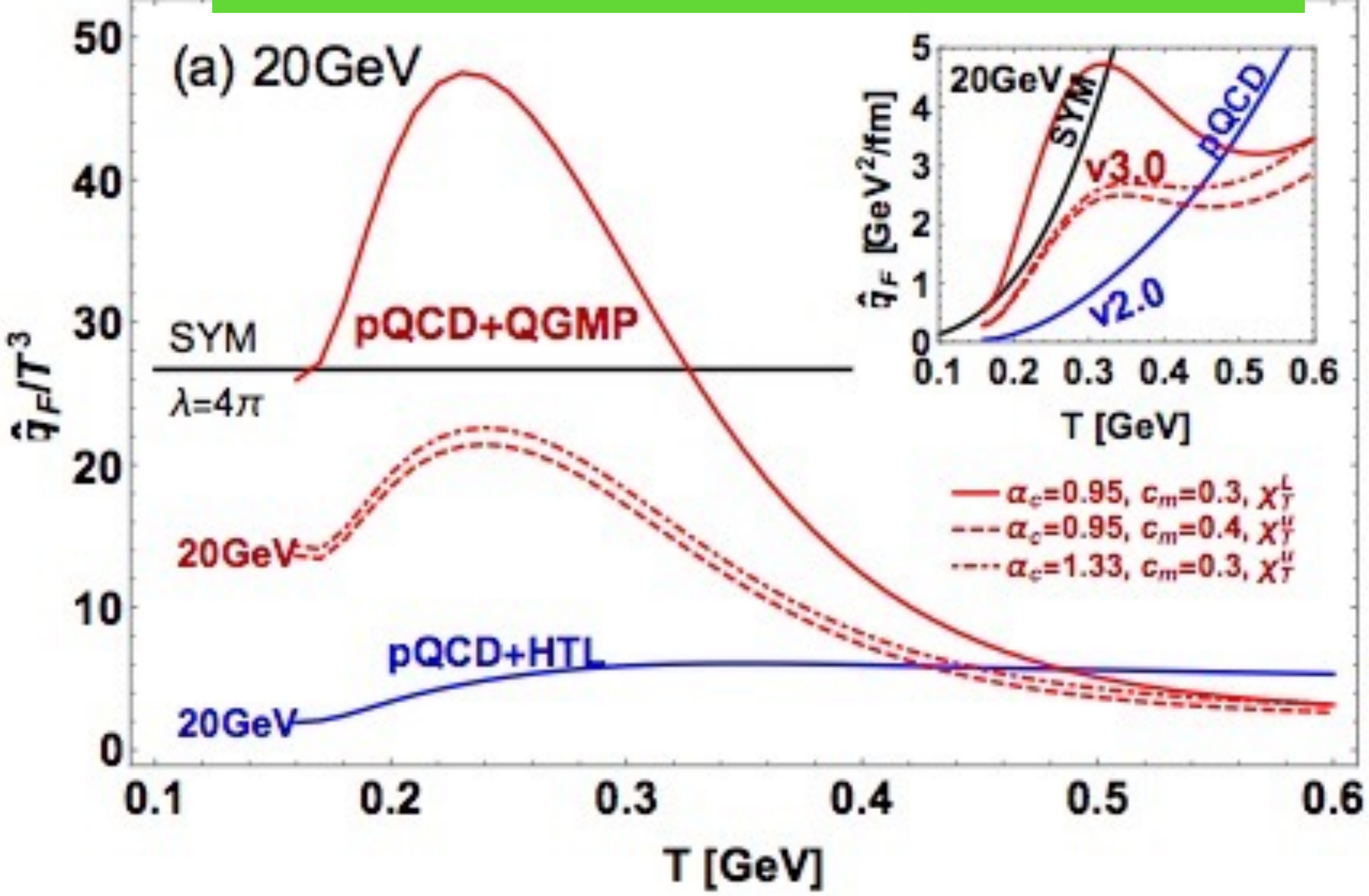

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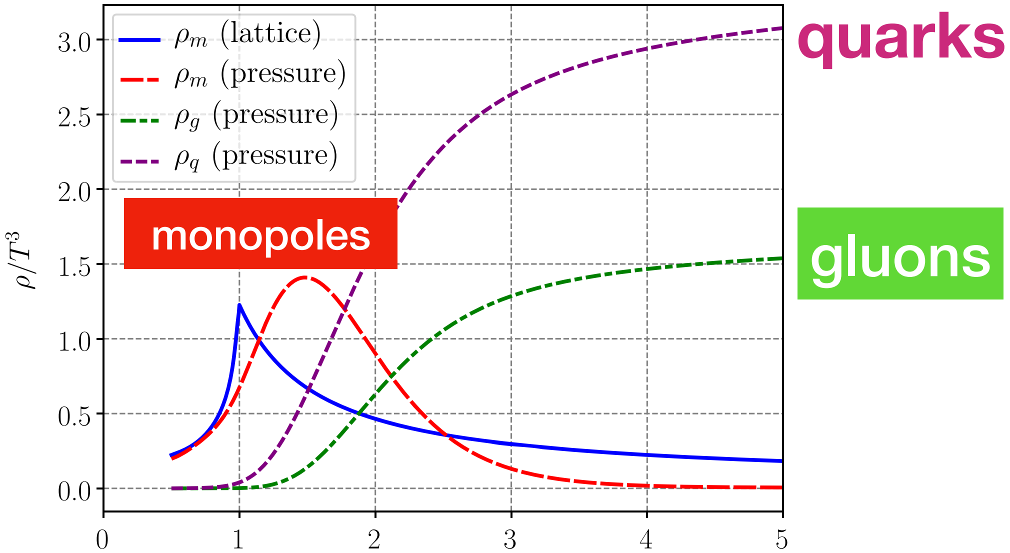

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only the monopole density peaks near Tc!

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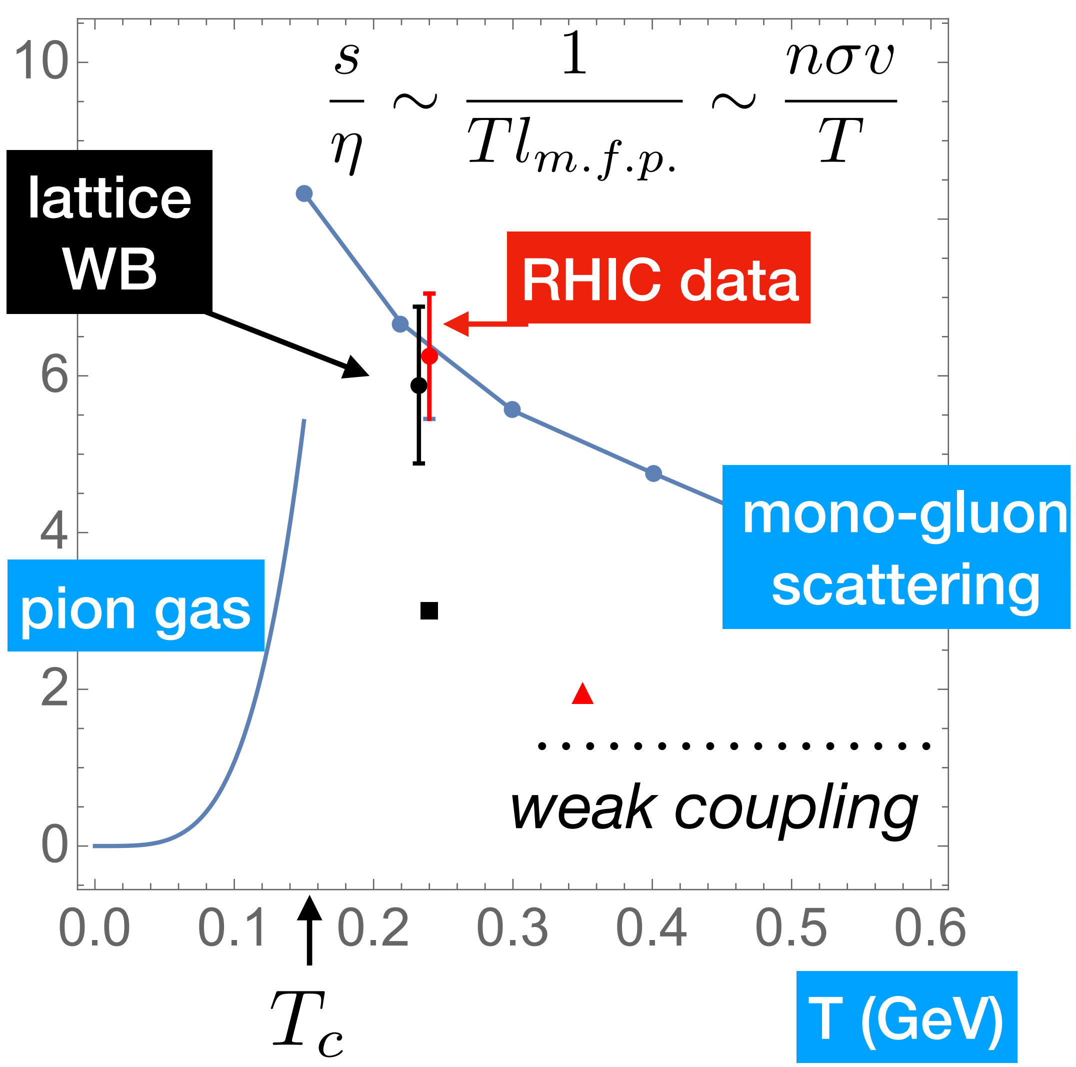

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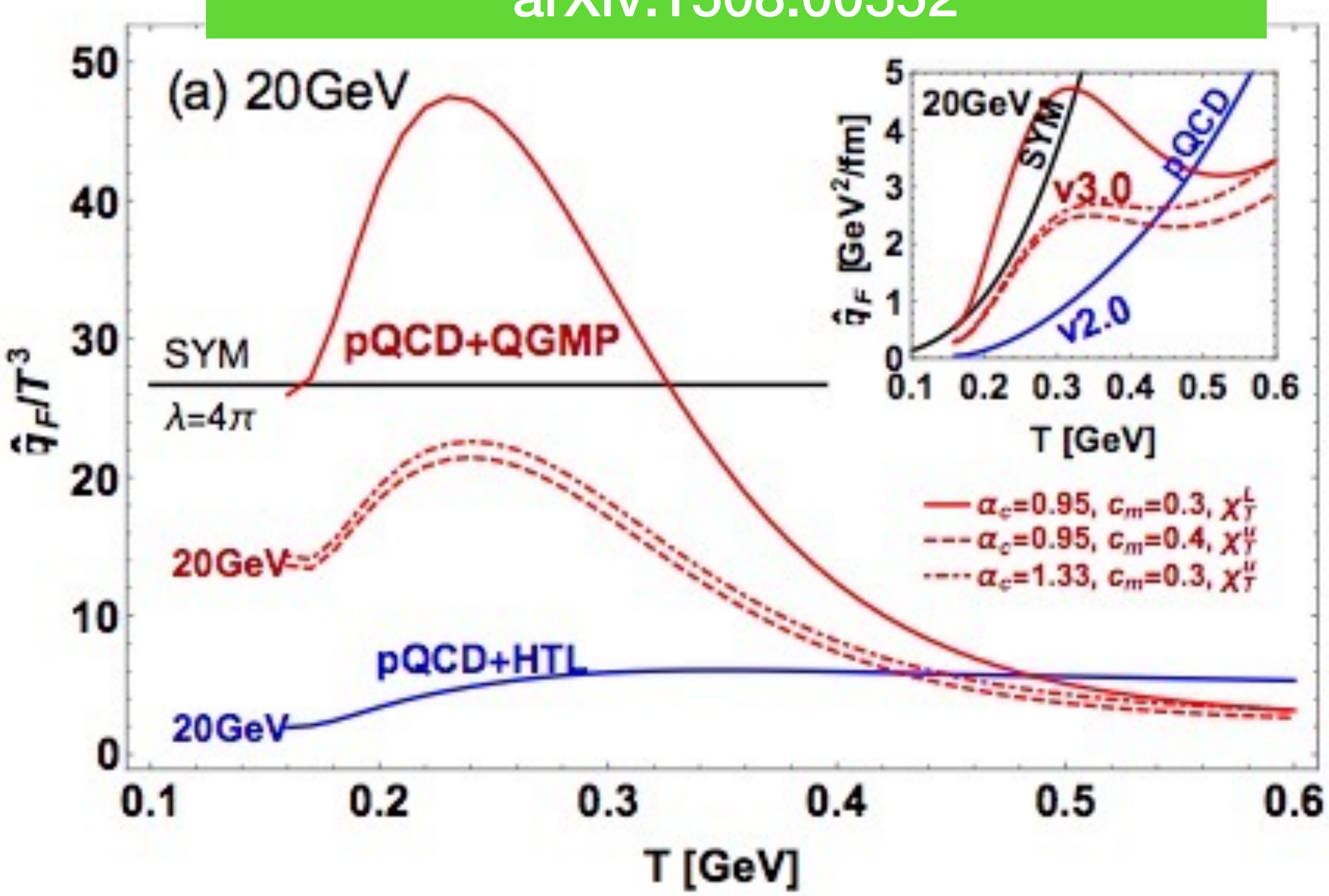


Are there monopoles in QCD?

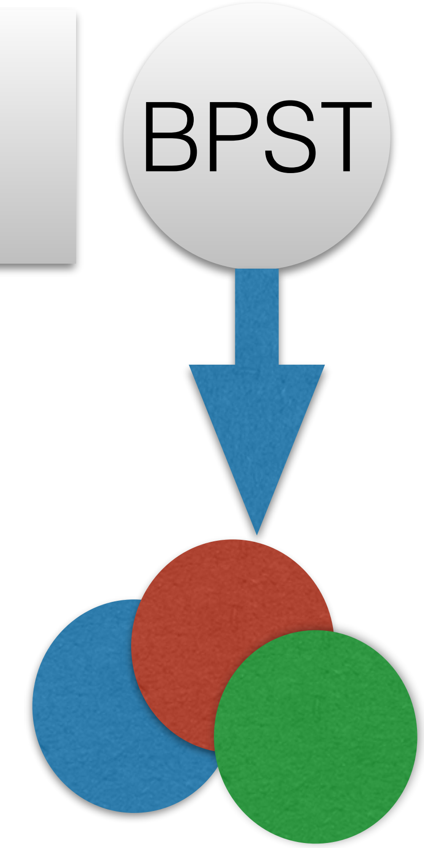
- they are not ’t Hooft-Polyakov monopoles because we do not have adjoint scalars
- Yes, lattice people learned how to find and trace them
- but one would want some analytic control

We do have **instantons** and **instanton-dyons** **with good semiclassical control (S>>hbar)**

but

- *those are Euclidean objects, which cannot be taken out of Matsubara time*
- *for example we cannot calculate rescattering of quasiparticles or jets*

Non-zero Polyakov line splits instantons into Nc instanton-dyons (Kraan,van Baal, Lee,Lu 1998)



Explained mismatch of quark condensate in SUSY QCD

V.Khoze (jr) et al 2001

Explained confinement by back reaction to free energy

D.Diakonov 2012, Larsen+ES,Liu,Zahed+ES 2016

Explain chiral symmetry breaking in QCD and in setting with modified fermion periodicities

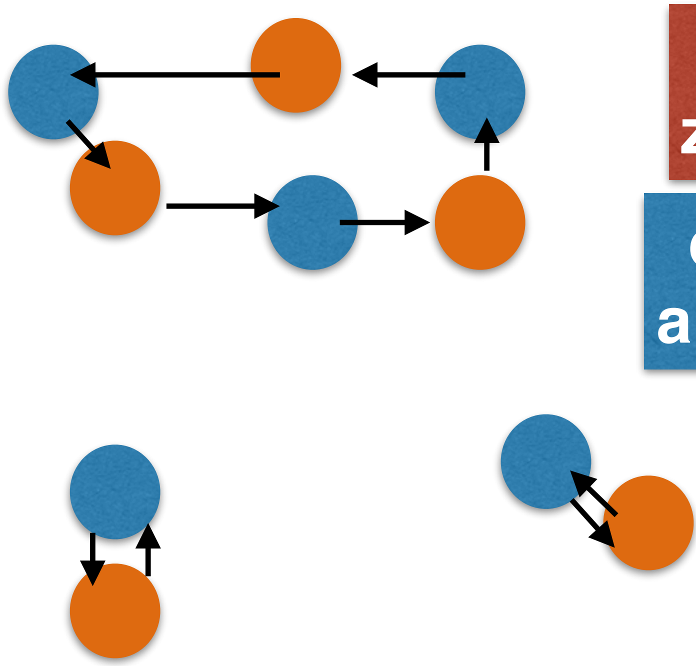
R.Larsen+ES 2017, Unsal et al 2017

Instanton-dyon Ensemble with two Dynamical Quarks: the Chiral Symmetry Breaking

Rasmus Larsen and Edward Shuryak
Department of Physics and Astronomy, Stony Brook University, Stony Brook NY 11794-3800, USA

This is the second paper of the series aimed at understanding of the ensemble of the instanton-dyons, now with two flavors of light dynamical quarks. The partition function is appended by the fermionic factor, $(detT)^{N_f}$ and Dirac eigenvalue spectra at small values are derived from the numerical simulation of 64 dyons. Those spectra show clear chiral symmetry breaking pattern at high dyon density. Within current accuracy, the confinement and chiral transitions occur at very similar densities.

$$|<\bar{\psi}\psi>| \;=\; \pi\rho(\lambda)_{\lambda\to 0, m\to 0, V\to\infty}$$



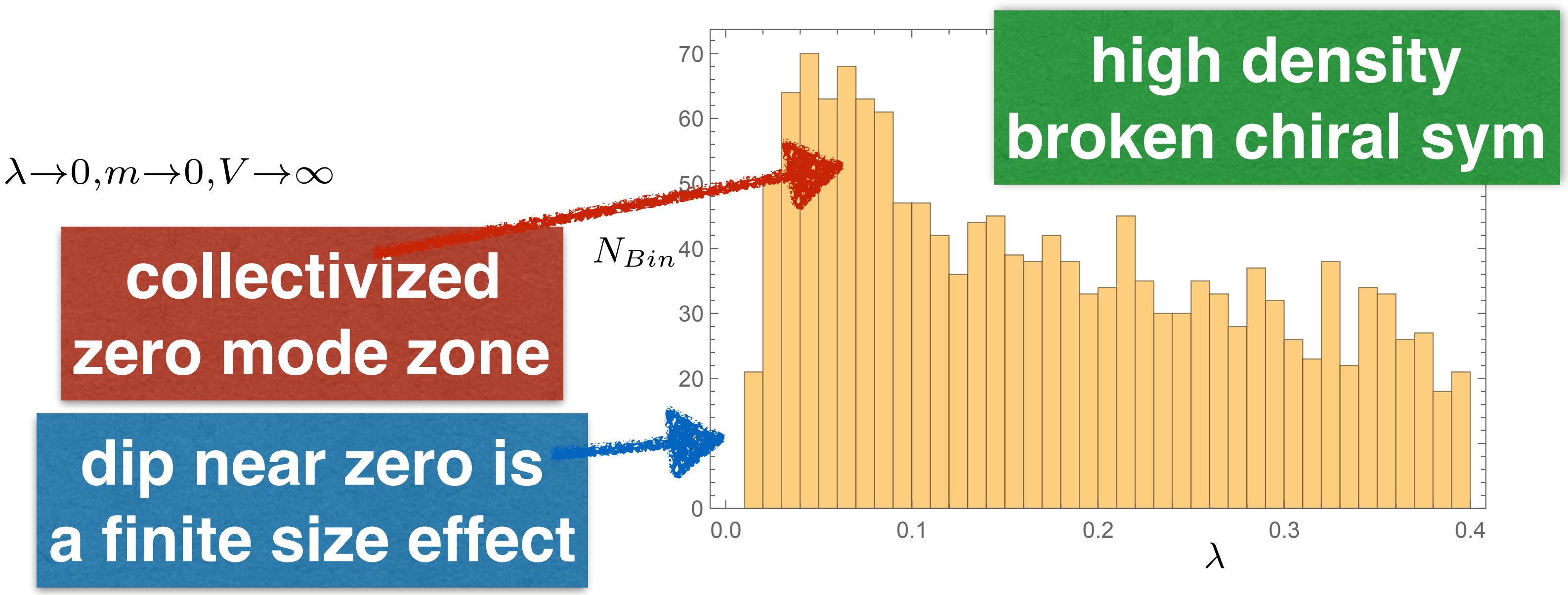
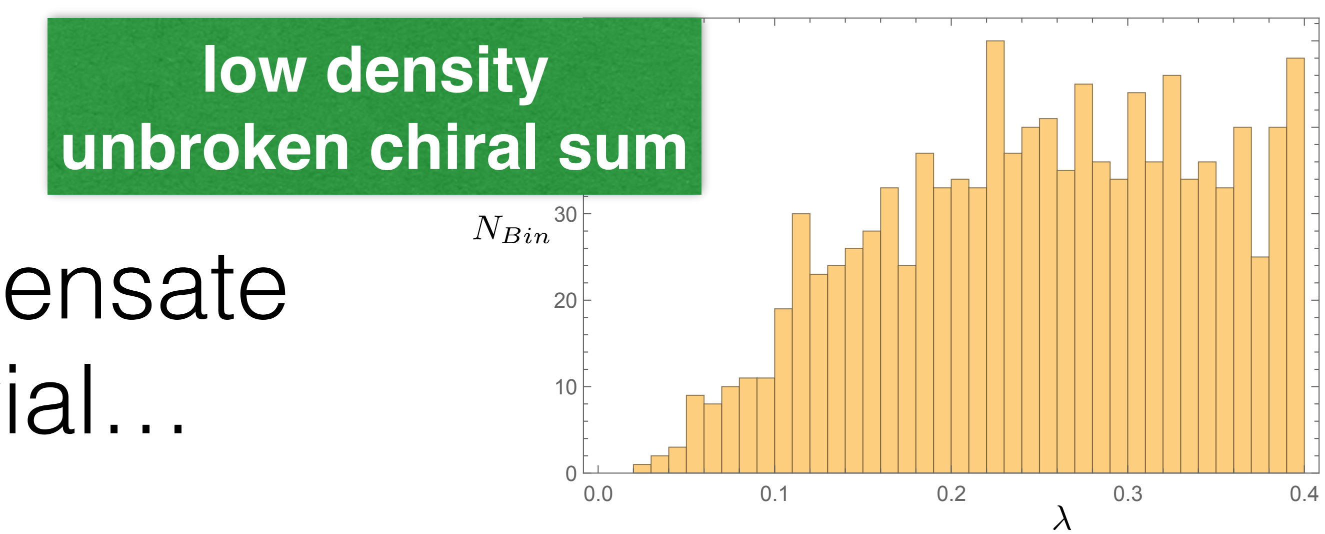


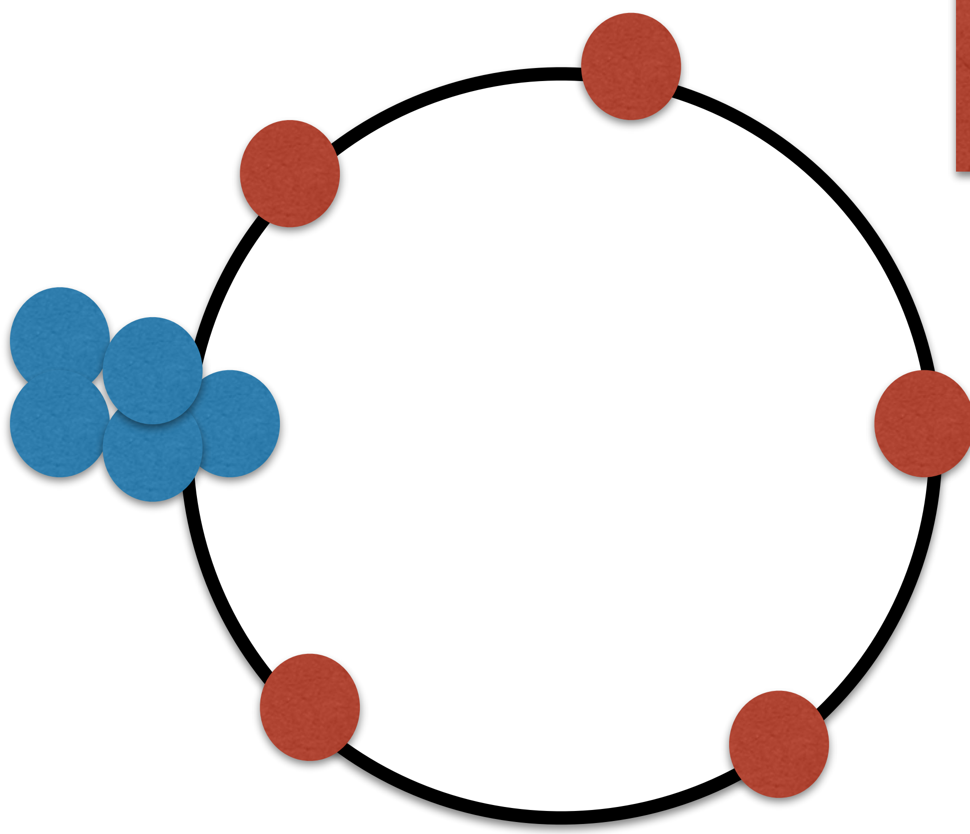
FIG. 1: Eigenvalue distribution for $n_M = n_L = 0.47$, $N_F = 2$ massless fermions.



extracting condensate
is far from trivial…

FIG. 2: Eigenvalue distribution for $n_M = n_L = 0.08$, $N_F = 2$ massless fermions.

Ordinary Nc=Nf=5 QCD



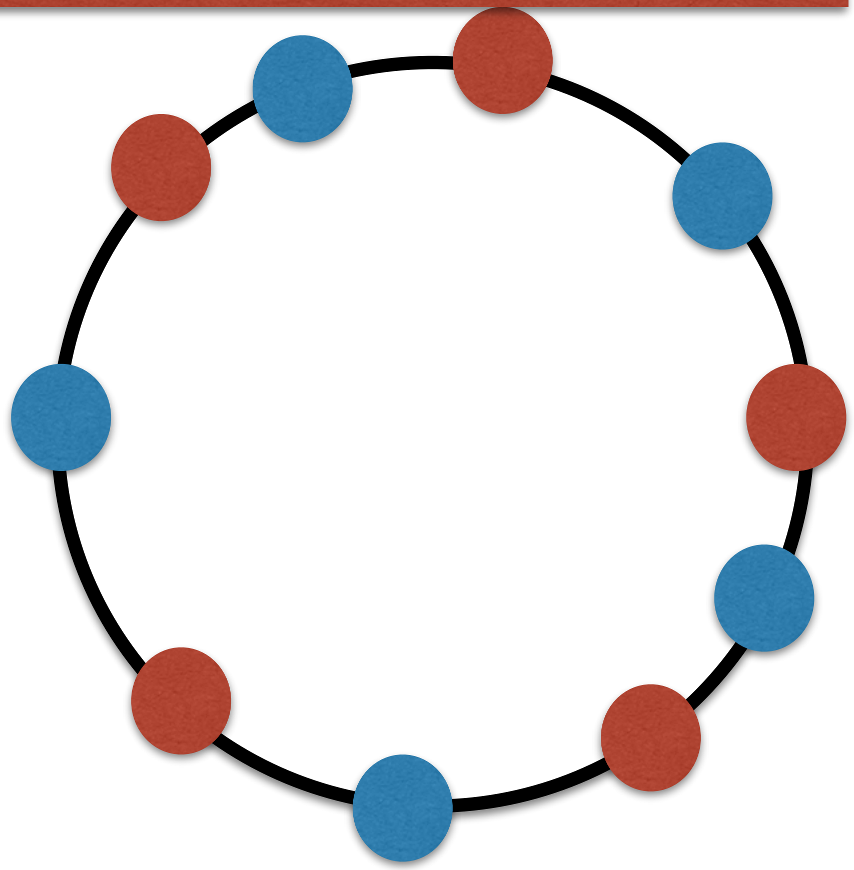
P without a trace
is a diagonal unitary matrix
=> Nc phases (red dots)

quark periodicity
phases => Nf blue dots
are in this case all =pi
quarks are fermions

**as a consequence,
out of 5 types of instanton-dyons
only one L has zero modes**

still Nc=Nf=5 but with
"most democratic" arrangement
ZN-symmetric QCD

H. Kouno, Y. Sakai, T. Makiyama, K. Tokunaga, T. Sasaki and M. Yahiro, J. Phys. G 39, 085010 (2012).



quark periodicity phases => Nf blue dots are in this case flavor-dependent

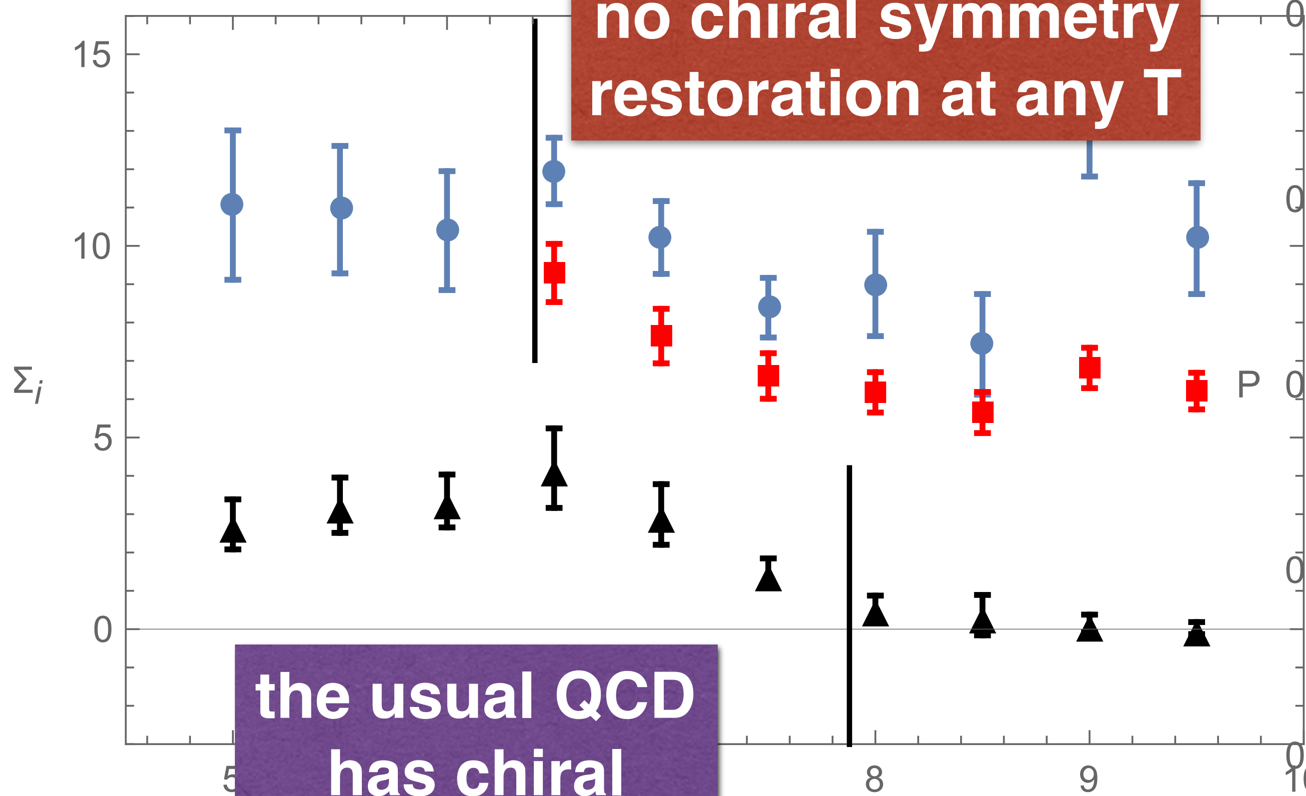
In this case each dyon type has one zero mode with one quark flavor =>N independent topological ZMZ's!

Both transitions are dramatically different!

symmetric phase

u=>M
d=>L
$< \bar{u}u > \neq < \bar{d}d >$

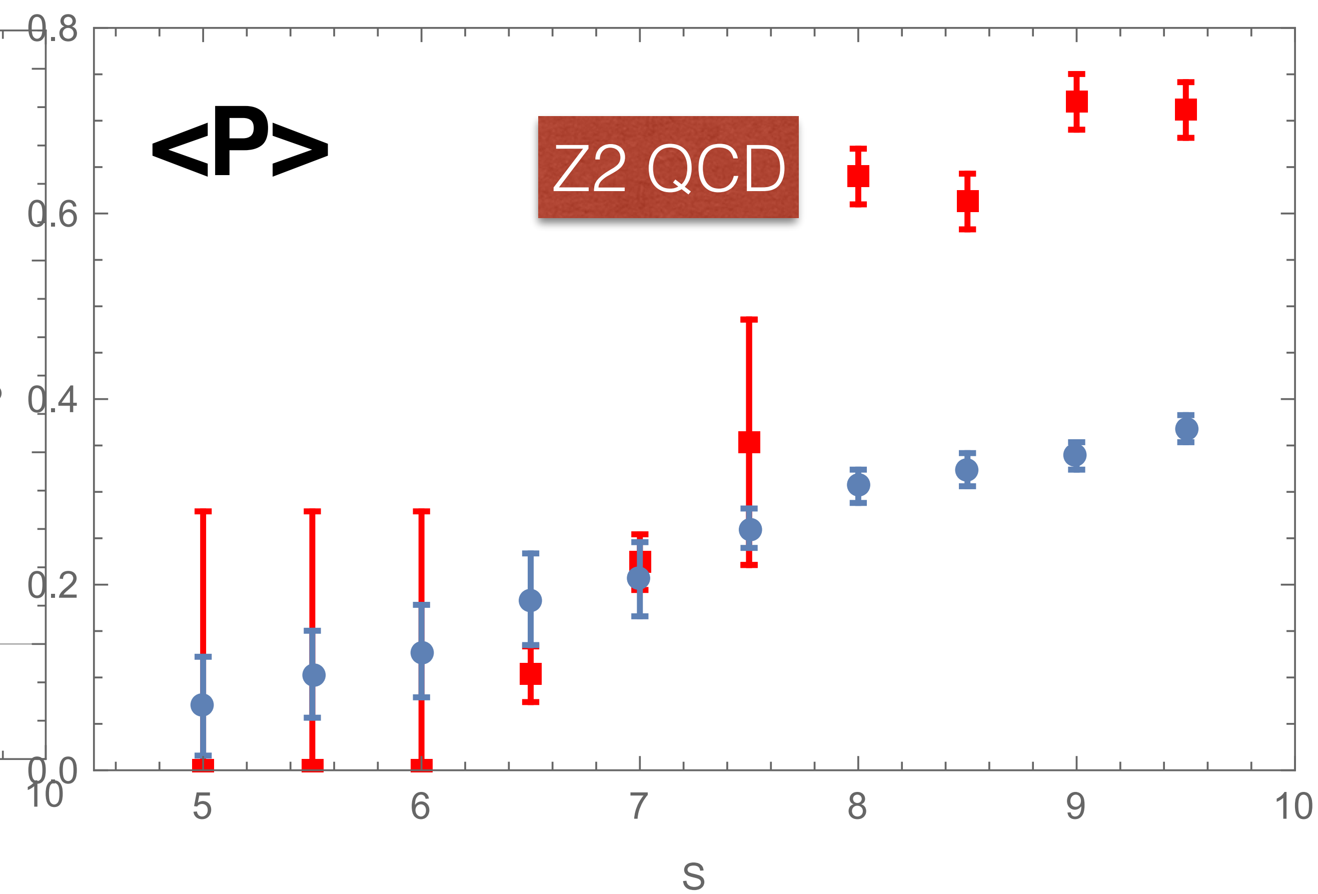
no chiral symmetry restoration at any T



the usual QCD has chiral restoration

FIG. 6: Chiral condensate generated by u quarks and L dyons (red squares) and d quarks interacting with M dyons (blue circles) as a function of action S, for the Z_2-symmetric model. For comparison we also show the results from II for the usual QCD-like model with $N_c = N_f = 2$ by black triangles.

Note that the condensate Is much larger for Z2QCD



confining phase gets much more robust: strong first order mixed phase (flat F) is observed at medium densities

Are instanton-dyons related to monopoles?

One can however start in the theory in which there is a complete theoretical control **on both** and **compare two approaches directly**

N.Dorey and A.Parnachev
JHEP 0108, 59 (2001)
hep-th/0011202]

N=4 extended supersymmetry with Higgsed scalar compactified on a circle

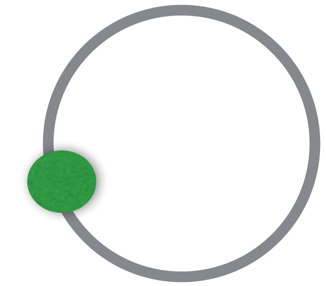
Partition function calculated in terms of monopoles

Partition function calculated in terms of instanton-dyons

Configurations are obviously very different
Zs also look different,
and yet they are related
by the Poisson summation formula
and thus are the same!!!

Is there any relation between the semiclassical instanton-dyons and QCD monopoles?

Adith Ramamurti,[*] Edward Shuryak,[†] and Ismail Zahed[‡]



The same phenomenon in much simpler setting: quantum particle on a circle at finite T

$$Z_1 = \sum_{l=-\infty}^{\infty} \exp\left(-\frac{l^2}{2\Lambda T} + il\omega\right)$$

moment of inertia

Aharonov-Bohm phase

$$Z_2 = \sum_{n=-\infty}^{\infty} \sqrt{2\pi\Lambda T}\, \exp\left(-\frac{T\Lambda}{2}(2\pi n - \omega)^2\right).$$

Matsubara winding number

$$\alpha_n(\tau) = 2\pi n \frac{\tau}{\beta},$$

based on classical paths

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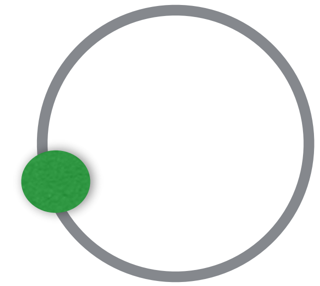

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Note completely different dependence on T and holonomy omega

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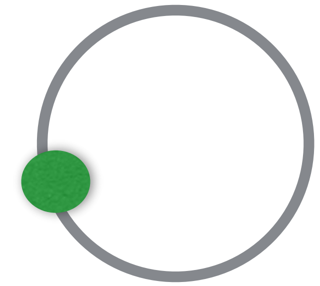

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And yet, they are the same!
(elliptic theta function of the 3 type)

$$Z_1 = Z_2 = \theta_3\left(-\frac{\omega}{2}, \exp\left(-\frac{1}{2\Lambda T} \right) \right)$$

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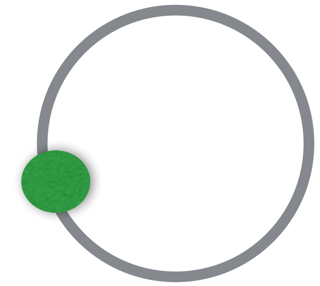

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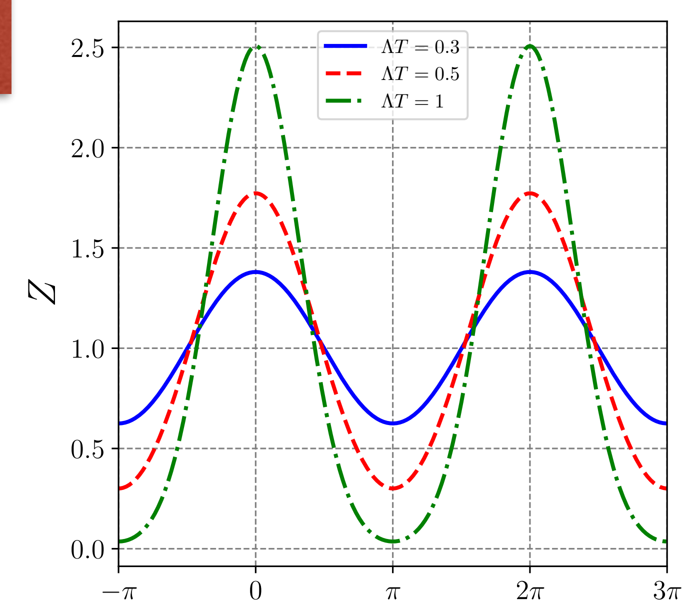

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Adith Ramamurti,* Edward Shuryak,† and Ismail Zahed‡

instanton-dyons with winding number n

The twisted solution is obtained in two steps. The first is the substitution

$$v \to n(2\pi/\beta) - v\,, \tag{13}$$

and the second is the gauge transformation with the gauge matrix

$$\hat{\Omega} = \exp\left(-\frac{i}{\beta} n\pi\tau\hat{\sigma}^3 \right), \tag{14}$$

where we recall that $\tau = x^4 \in [0, \beta]$ is the Matsubara time. The derivative term in the gauge transformation adds a constant to A_4 which cancels out the unwanted $n(2\pi/\beta)$ term, leaving v, the same as for the original static monopole. After "gauge combing" of v into the same direction, this configuration – we will call L_n – can be combined with any other one. The solutions are all

$$S_n = (4\pi/g^2)|2\pi n/\beta - v|$$

$$\sum_{n=-\infty}^{\infty} f(\omega + nP) = \sum_{l=-\infty}^{\infty} \frac{1}{P} \tilde{f}\left(\frac{l}{P}\right) e^{i2\pi l\omega/P}$$

Poisson summation formula can be used to derive the monopole sum

$$Z_{\text{inst}} = \sum_n e^{-\left(\frac{4\pi}{g_0^2}\right)|2\pi n - \omega|}$$

$$Z_{\text{mono}} \sim \sum_{q=-\infty}^{\infty} e^{iq\omega - S(q)}$$

$$S(q) = \log\left(\left(\frac{4\pi}{g_0^2}\right)^2 + q^2\right)$$

$$\approx 2\log\left(\frac{4\pi}{g_0^2}\right) + q^2\left(\frac{g_0^2}{4\pi}\right)^2 + \dots$$

q is angular momentum of rotating monopole, so it is electric charge

Can chiral symmetry breaking be understood via monopoles?

arXiv:1801.06922v1 [hep-ph] 22 Jan 2018

Chiral symmetry breaking and monopoles in gauge theories

Adith Ramamurti* and Edward Shuryak†
Department of Physics and Astronomy,
Stony Brook University,
Stony Brook, NY 11794, USA
(Dated: January 23, 2018)

Fermionic zero modes of monopoles are in 3d
So they are q-m bound states

Chiral symmetry breaking is based on 4d near-zero eigenmodes

Monopole mode leaves out the tau dependence
And with anti-periodic quarks, it leads to Matsubara eigenvalues +- pi*T
Can collectivization of eiegenstates fill in the gap?

$$U = \oint_\beta d\tau e^{iH\tau} = -\mathbb{1} \,.$$

$$\lambda_i + \omega_{i,n} = \left(n + \frac{1}{2}\right)\frac{2\pi}{\beta} \,,$$

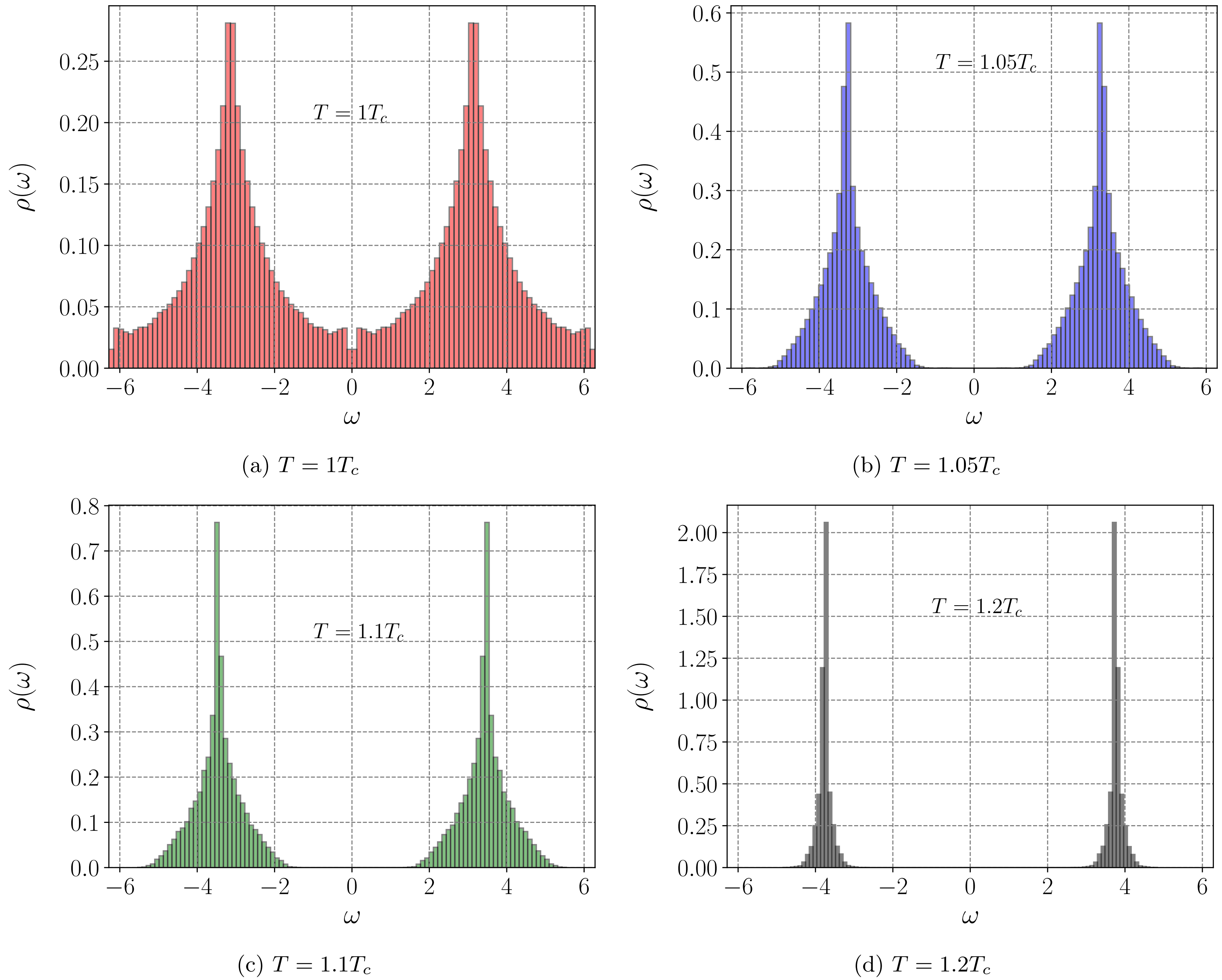


FIG. 4: Distributions of Dirac eigenvalues for $T/T_c =$ (a) 1 , (b) 1.05 , (c) 1.1, and (d) 1.2, respectively.

Yes, the gap at zero can be filled
And this happens exactly at Tc!

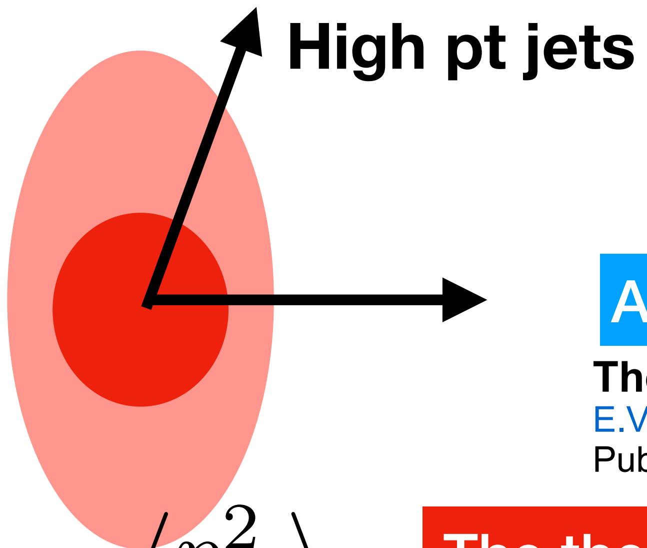
Summary

- Instanton-dyons and monopoles look different but lead to the same partition function. High and low T series.
- Chiral condensate is due to collectivization of topological zero modes, for monopole as well

- sQGP is unusual because it is a dual plasma, with both electrically and magnetically charged quasiparticles
- As T cools, and electric coupling increases, the magnetic coupling decreases
- As monopoles get lighter, their density grows till BEC (confinement)

Extra slides

A relatively recent story: the angular distribution of jet quenching and monopoles



$$\frac{dN}{dy d^2 p_\perp} \sim [1 + 2v_2(p_\perp) cos(2\phi)]$$

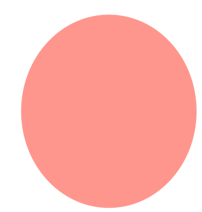
A jet in shorter x direction suffers less quenching by matter

The Azimuthal asymmetry at large p(t) seem to be too large for a `jet quenching'
E.V. Shuryak (SUNY, Stony Brook). Dec 2001. 3 pp.
Published in **Phys.Rev. C66 (2002) 027902**

$$\hat{q} = \frac{\langle p_\perp^2 \rangle}{length}$$

The theory gave reasonably good description of quenching itself
But experiment stubbornly gave v2 about twice larger than
all theories predicted

Angular Dependence of Jet Quenching Indicates Its Strong Enhancement Near the QCD Phase Transition
Jinfeng Liao, Edward Shuryak Phys.Rev.Lett. 102 (2009) 202302



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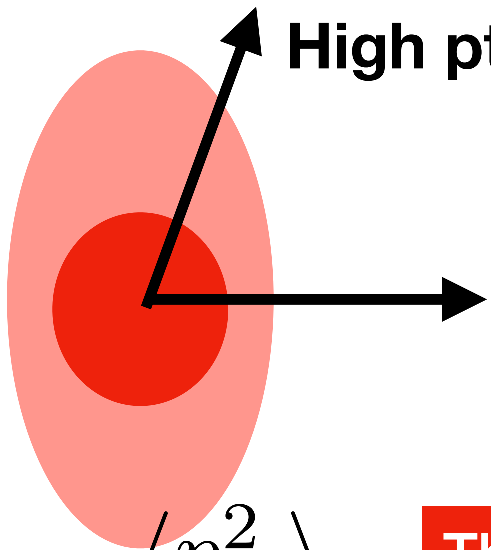

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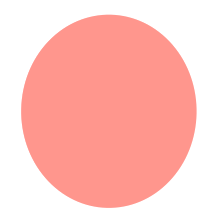
An explanation proposed: in these theories
the quenching is proportional to the density.
And the most dense region (shown by the dark red)
is much "more round" than less dense (pink) region.
Perhaps quenching peaks at intermediate density?



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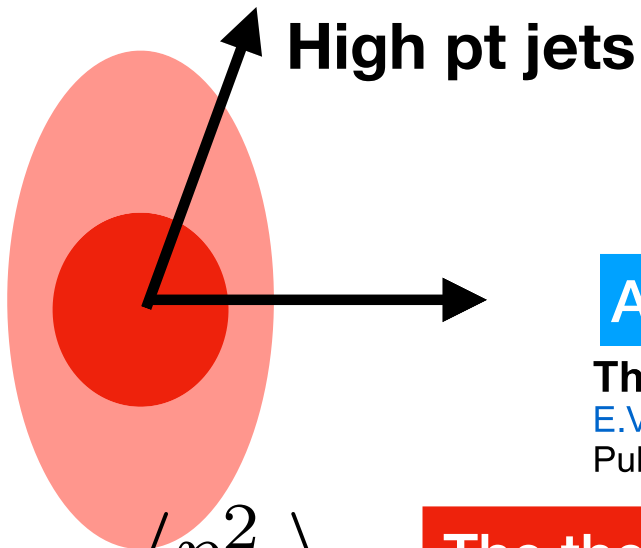

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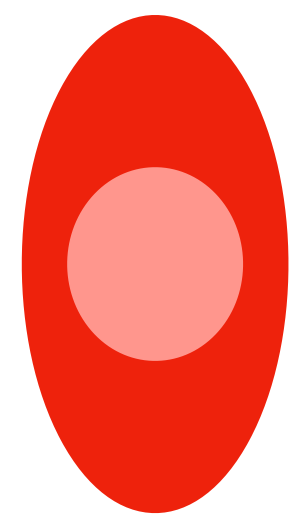
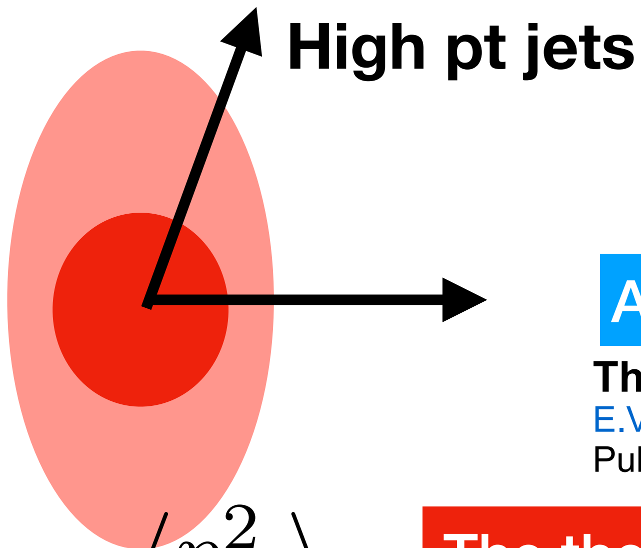
all theories predicted

Angular Dependence of Jet Quenching Indicates Its Strong Enhancement Near the QCD Phase Transition
Jinfeng Liao, Edward Shuryak Phys.Rev.Lett. 102 (2009) 202302

An explanation proposed: in these theories
the quenching is proportional to the density.
And the most dense region (shown by the dark red)
is much “more round” than less dense (pink) region.
Perhaps quenching peaks at intermediate density?



A relatively recent story: the angular distribution of jet quenching and monopoles



$$\frac{dN}{dyd^2p_\perp} \sim \left[1 + 2v_2(p_\perp)cos(2\phi)\right]$$

A jet in shorter x direction suffers less quenching by matter

The Azimuthal asymmetry at large p(t) seem to be too large for a `jet quenching'
E.V. Shuryak (SUNY, Stony Brook). Dec 2001. 3 pp.
Published in **Phys.Rev. C66 (2002) 027902**

$$\hat{q} = \frac{\langle p_\perp^2 \rangle}{length}$$

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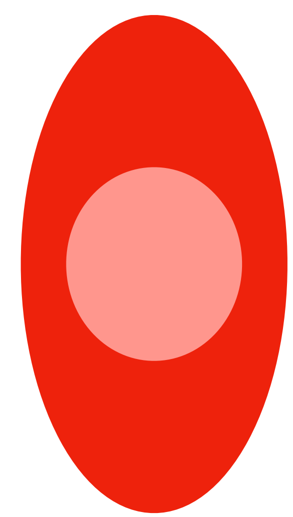
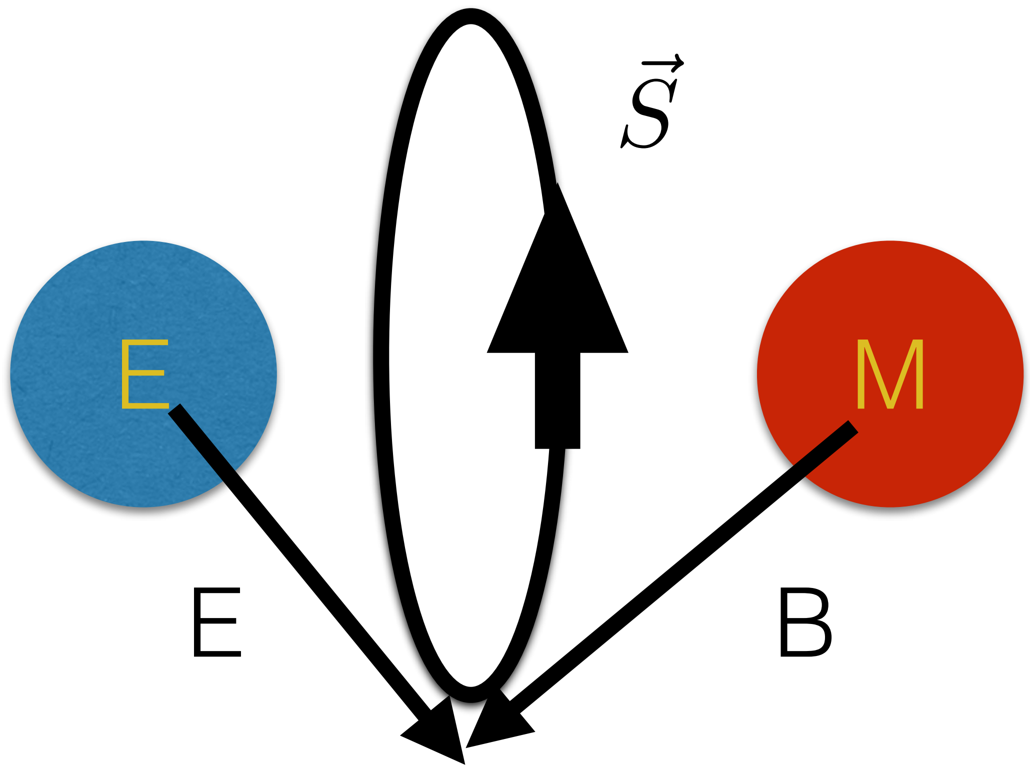


this reproduces
the azimuthal distribution of jet quenching.
BUT WHY ?

a monopole and a charge: classical motion

hints from the 19-th cent.



$$\vec{S} = [\vec{E} \times \vec{B}]$$

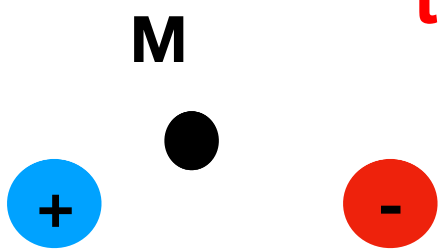
Pointing vector rotates

Observation by J.J.Thompson:

even static charge+monopole lead to rotating electromagnetic field

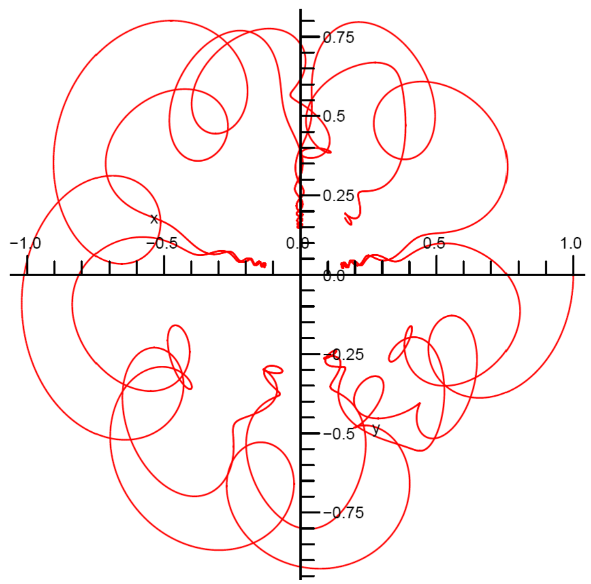
A.Poincare:
angular momentum of the particle plus that of the field is conserved => motion on a cone, not plane as usual

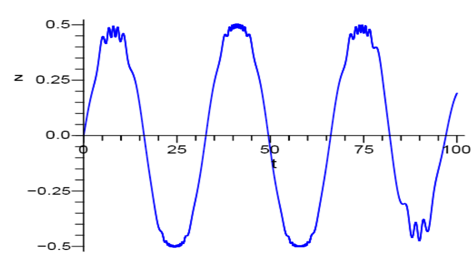
H. Poincare´, C. R. Acad. Sci. Ser. B. 123, 530 (1896).



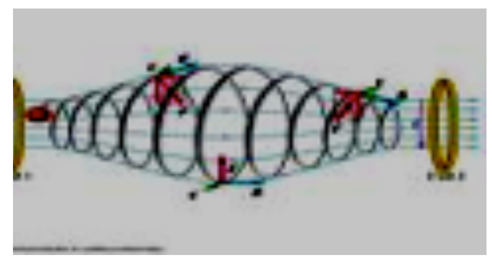
two charges play ping-pong
with a monopole without
even moving!

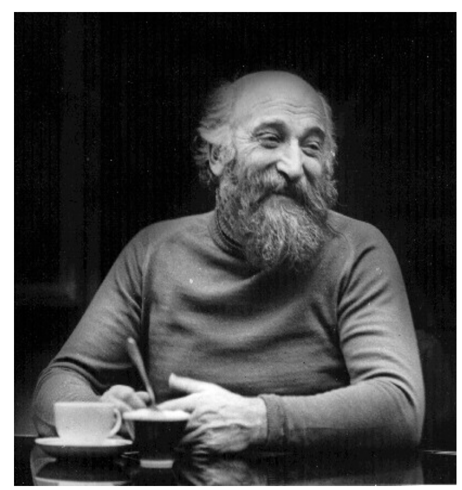
Indeed, collisions are much
more frequent than in cascades

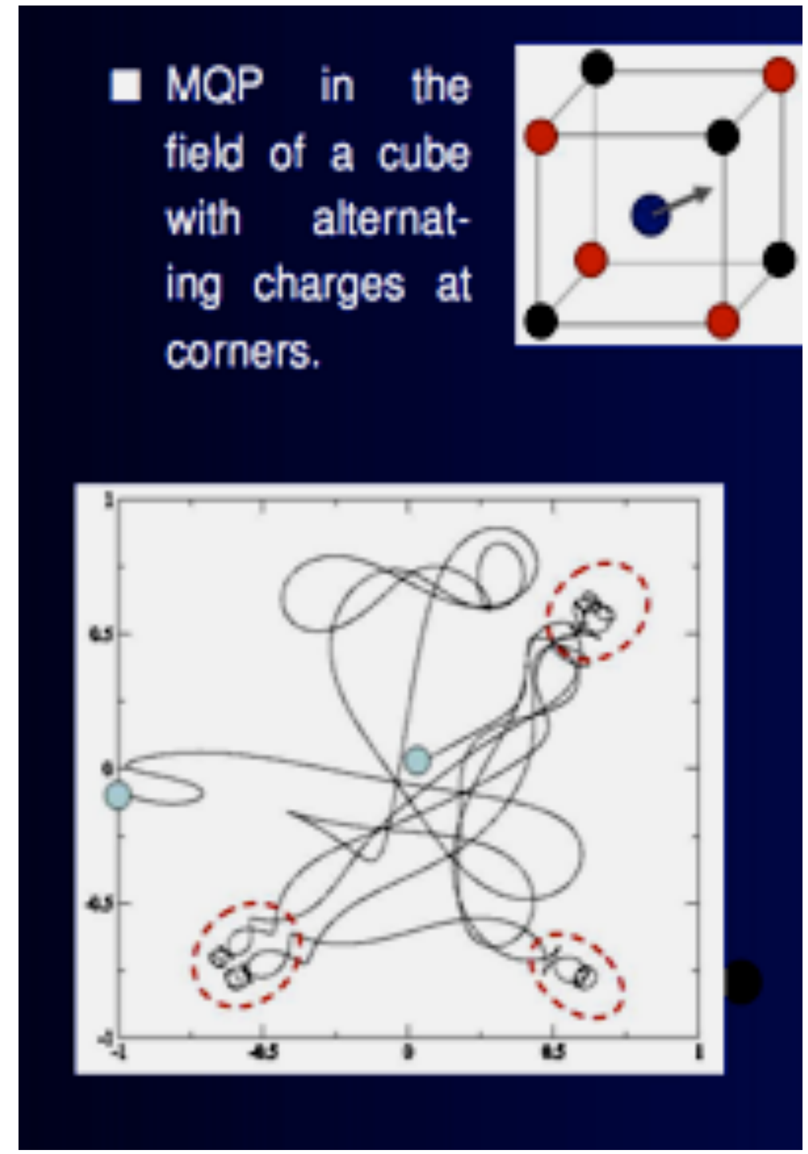


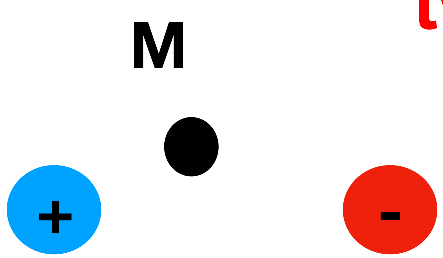


Dual to Budker's magnetic bottle









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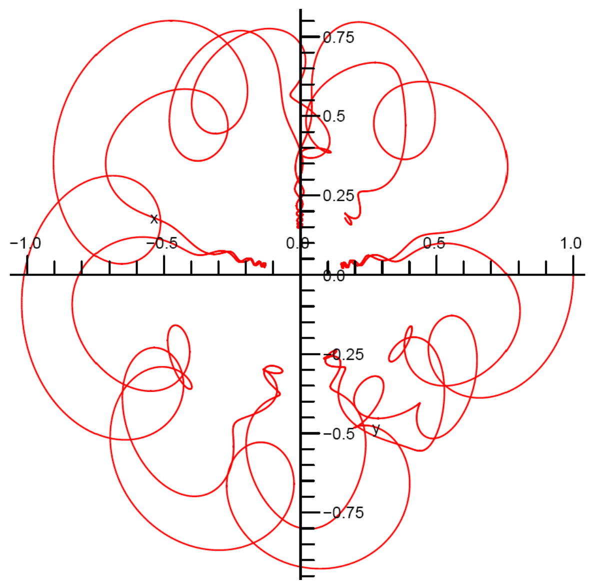

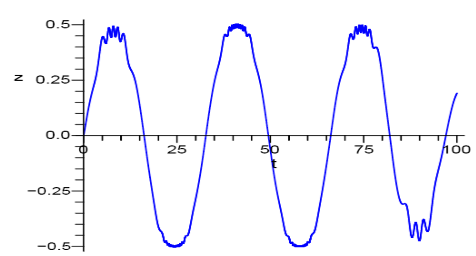

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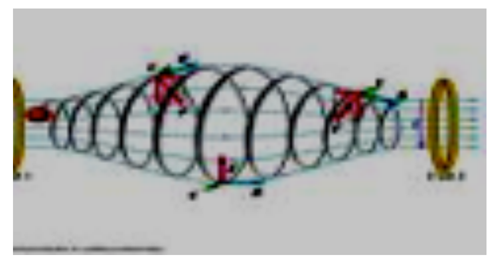
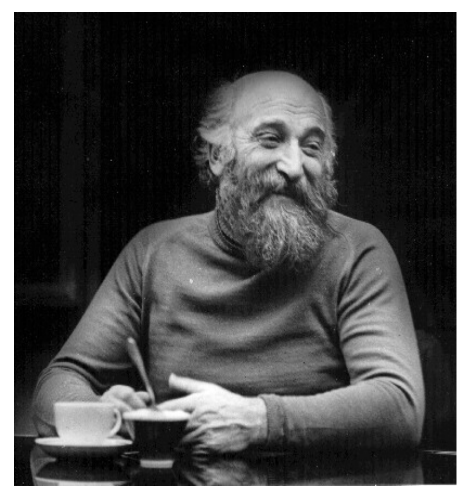
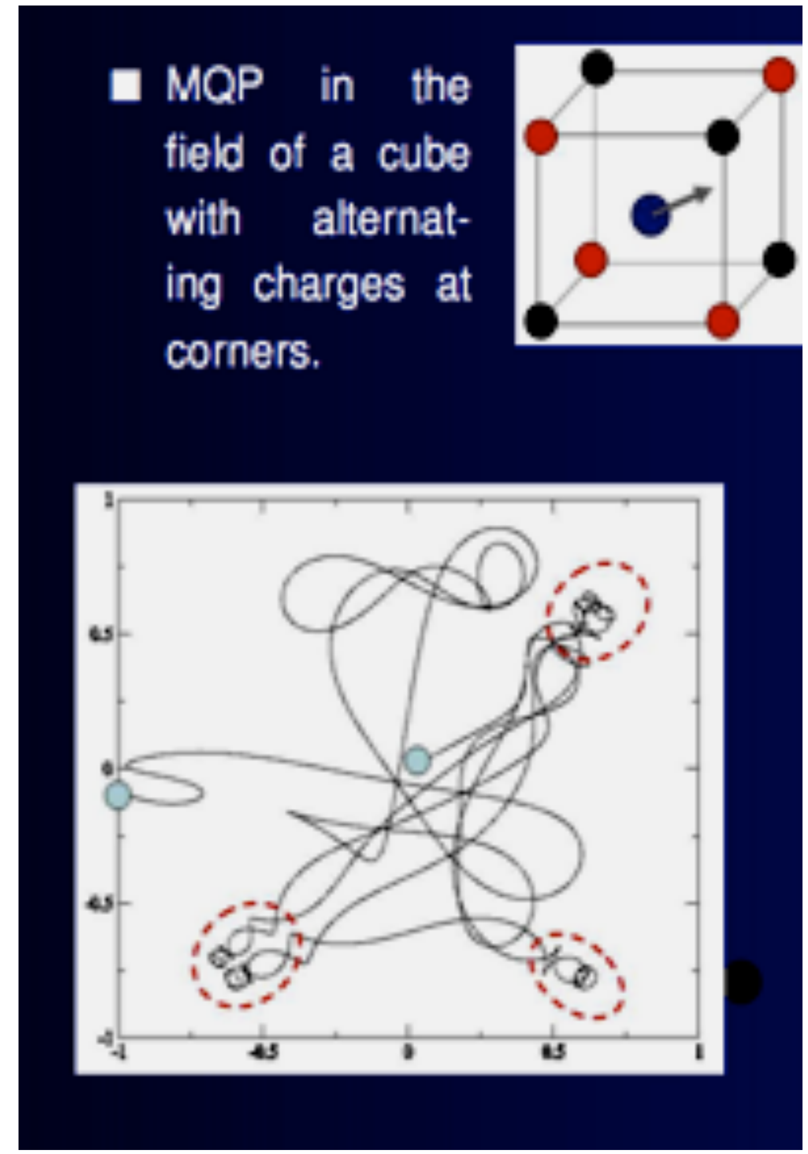
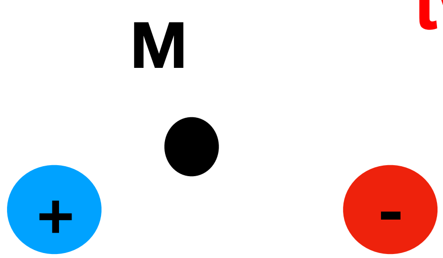




Indeed, collisions are much more frequent than in cascades



like a proverbial drunkard cannot go home colliding with few lamp posts



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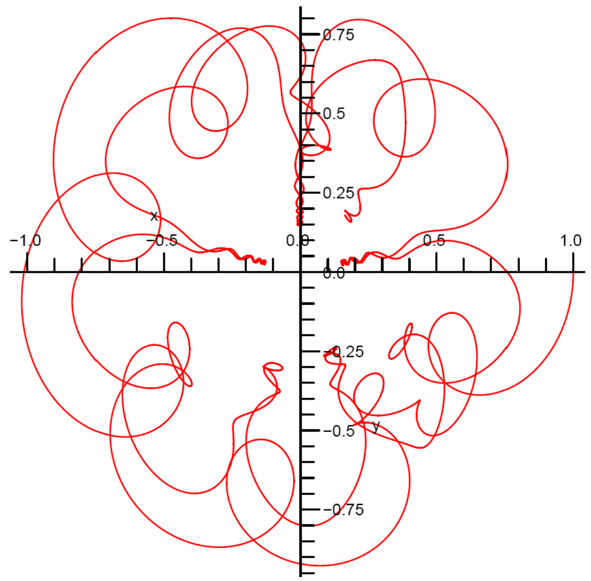
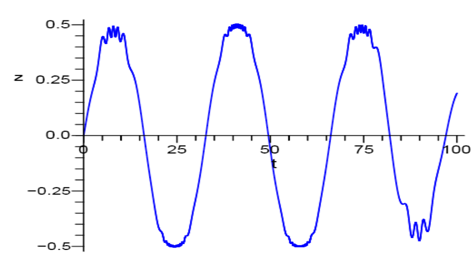
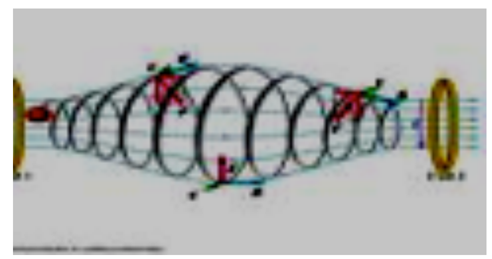
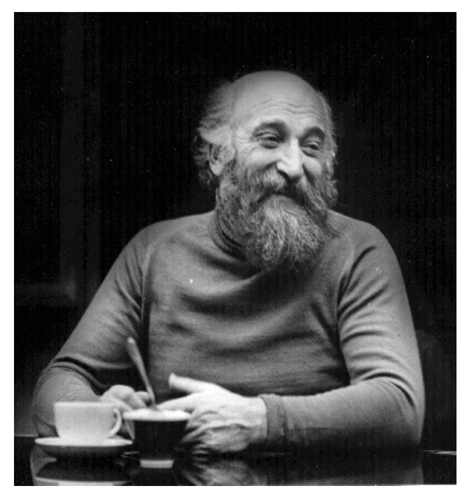
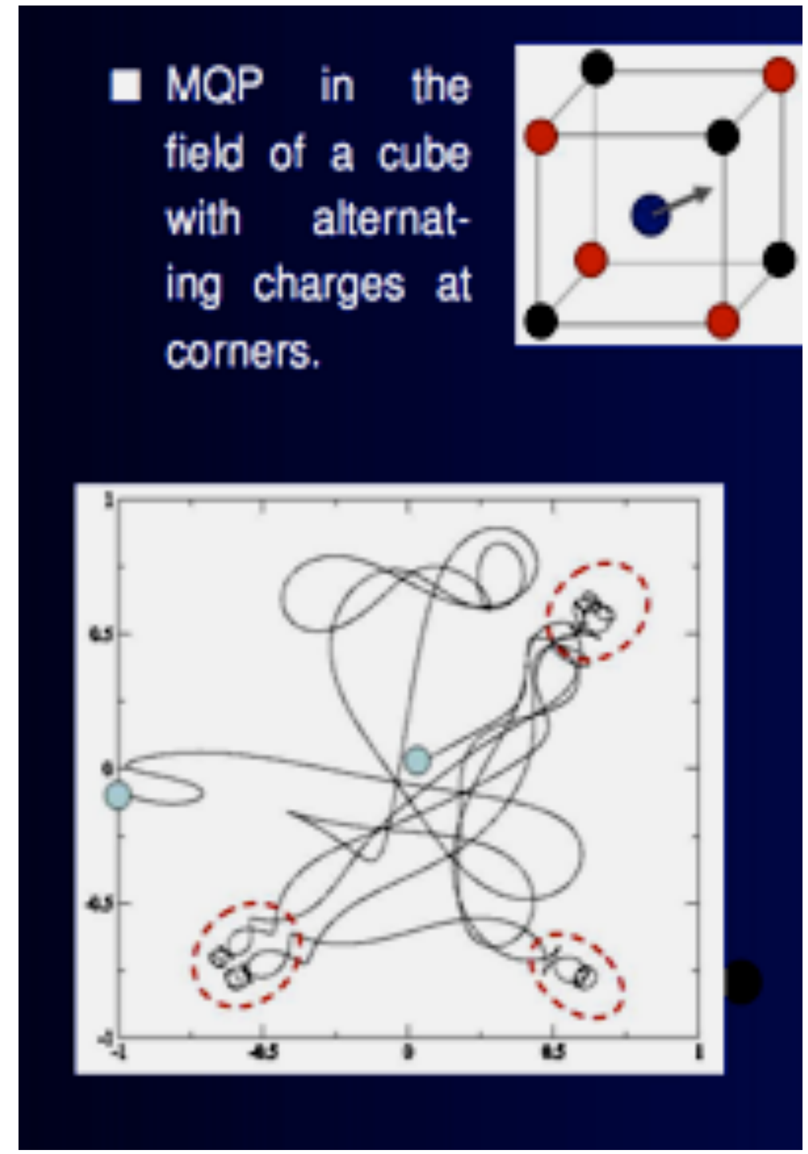




Dual to Budker's
magnetic bottle







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colliding with few lamp posts

classical kinetics of the "dual plasma", with E and M charges was simulated by molecular dynamics, diffusion coefficient and viscosity calculated

Quantum-mechanical problem of a charge-monopole scattering (should belong to QM textbooks but is not there)

$$e \cdot g \equiv n \quad integer$$

$$\delta_j = \pi j'$$

$$j'(j'+1) = j(j+1) - n^2$$

is the only parameter
It is dimesionless
so the scattering phase
cannot depend on momenta

Both j (total orbital mom.)
and n (that of the field) are integers
but j' is not!!!!! Thus complicated
angular distribution

Unlike in a standard scattering problem
Ylm angular functions cannot be used:
At large l,m>>1 those describe a scattering plane
But we know in classical limit it is the Poincare cone

D. G. Boulware, L. S. Brown, R. N. Cahn, S. D. Ellis, and C. k. Lee, Phys. Rev. D 14, 2708 (1976).
J. S. Schwinger, K. A. Milton, W. Y. Tsai, L. L. DeRaad, and D. C. Clark, Ann. Phys. (N.Y.) 101, 451 (1976).

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Note that ddelta/dk=0
So no new states and thus no corrections to thermodynamics,
Only to kinetics

quantum scattering of quarks and gluons on monopoles and viscosity of strongly coupled QGP

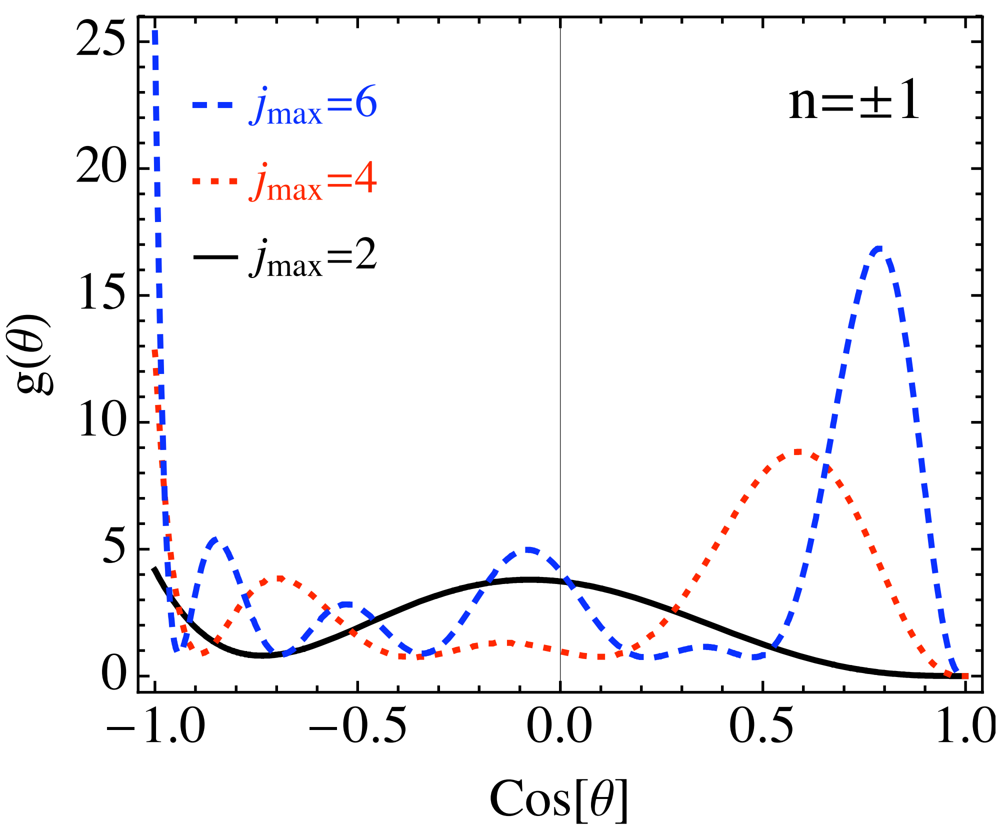
gluon-monopole scattering explains small viscosity!

PHYSICAL REVIEW D **80,** 034004 (2009)

Role of monopoles in a gluon plasma

Claudia Ratti and Edward Shuryak*

backward peak important for transport cross section



Not surprising, large correction to transport

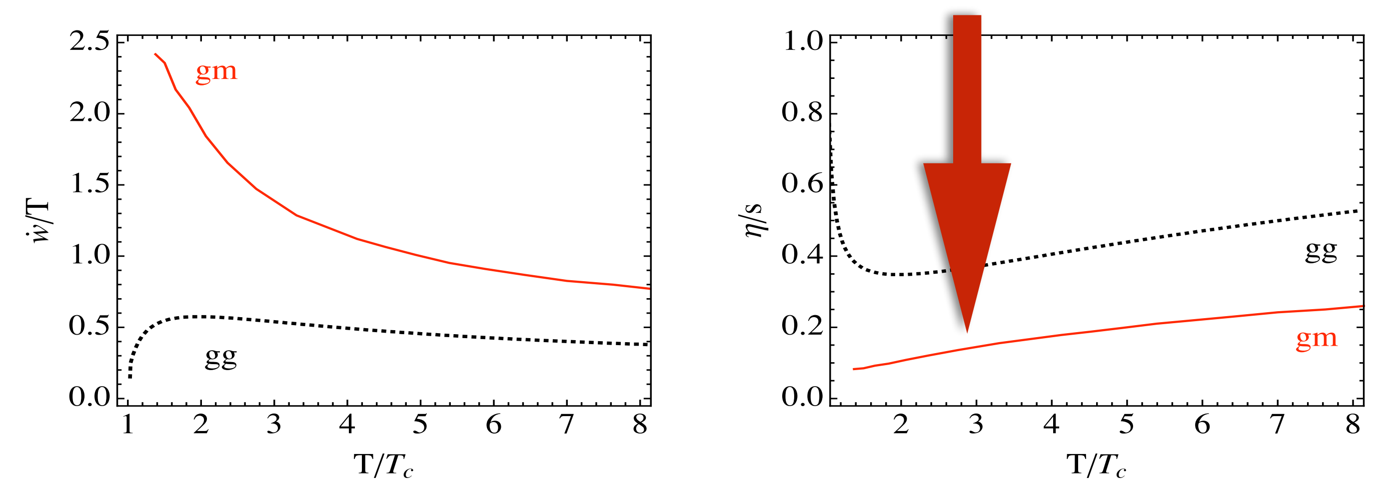


Figure 14: Left panel: gluon-monopole and gluon-gluon scattering rate. Right panel: gluon-monopole and gluon-gluon viscosity over entropy ratio, η/s.

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

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

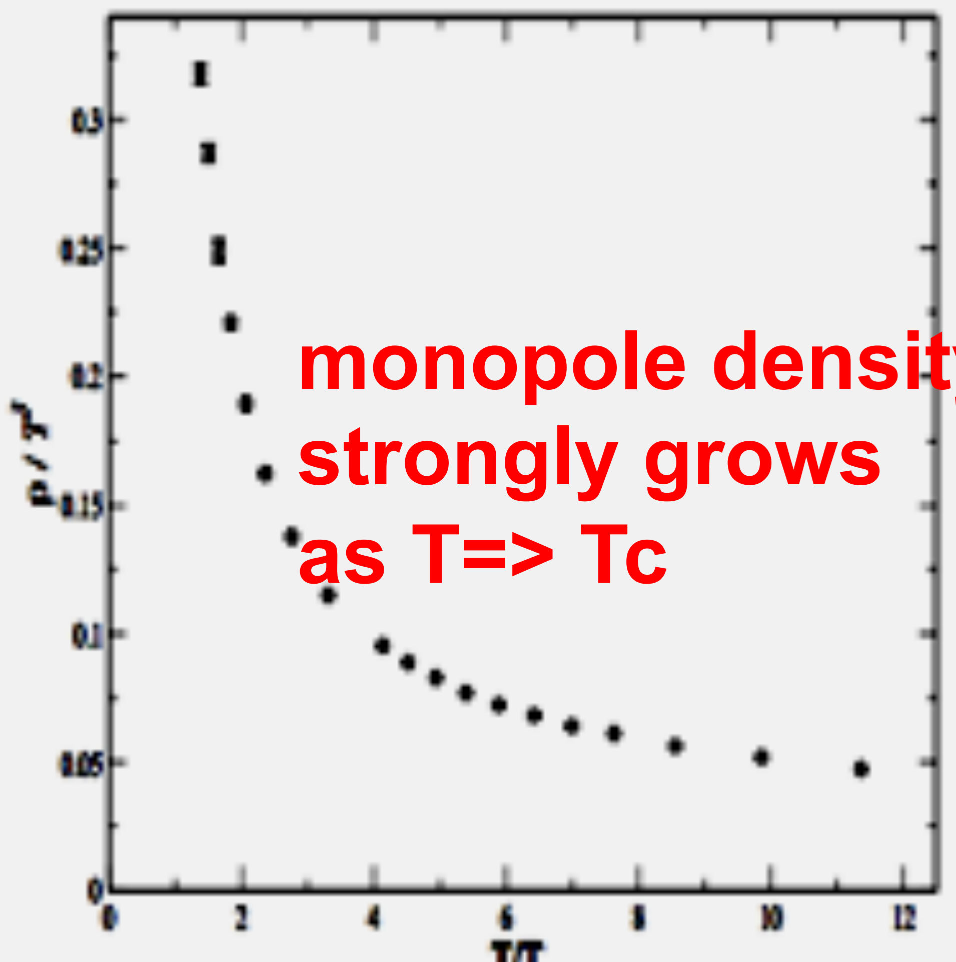


FIG. 3. $\rho(T)/T^3$ as a function of T/T_c. Data have been obtained on a $48^3 \times L_t$ lattice, with variable L_t and at $\beta = 2.75$ (first 9 points), and variable β at $L_t = 4$ (last 10 points).

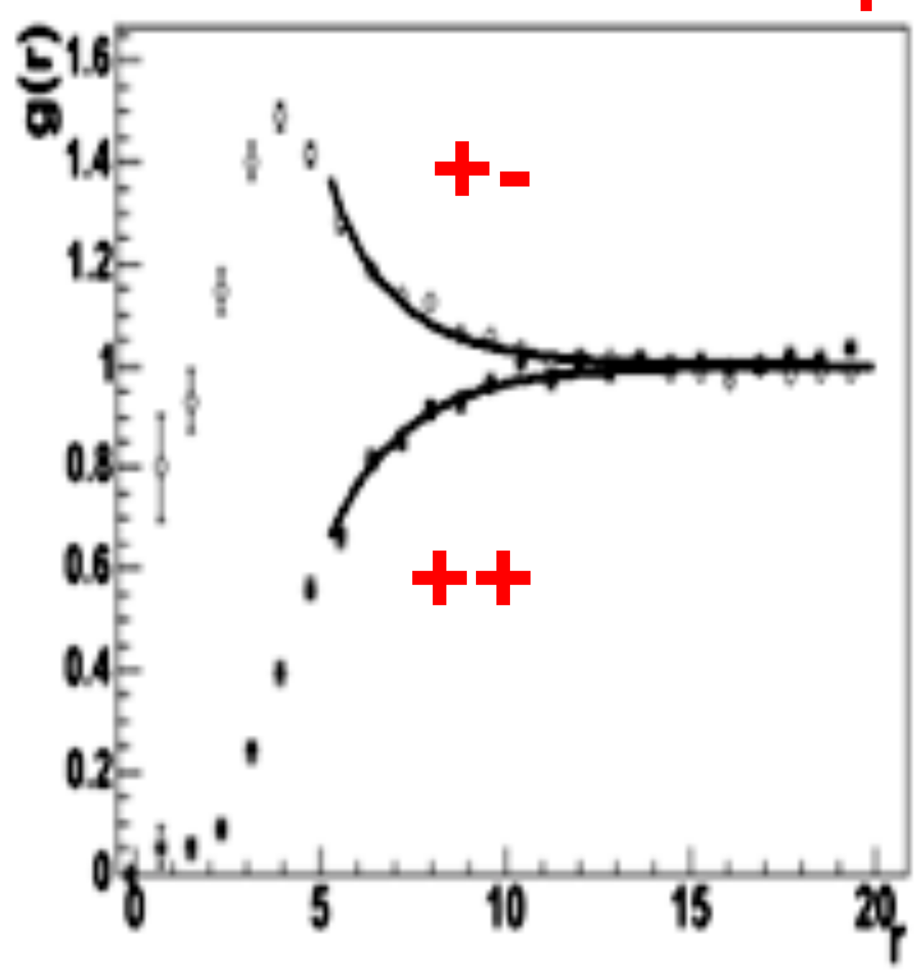


FIG. 5. $g(r)$ for the monopole-monopole (stars) and monopole-antimonopole (circles) case on ...$0^3 \times 5$ lattice at $\beta = 2.7$ ($T \simeq 2.85\, T_c$). The reported curves correspond to fits according to ...$) = \exp(-V(r)/T)$ with $V(r)$ a Yukawa potential (see Eqs. (2.9) and (2.10)).

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

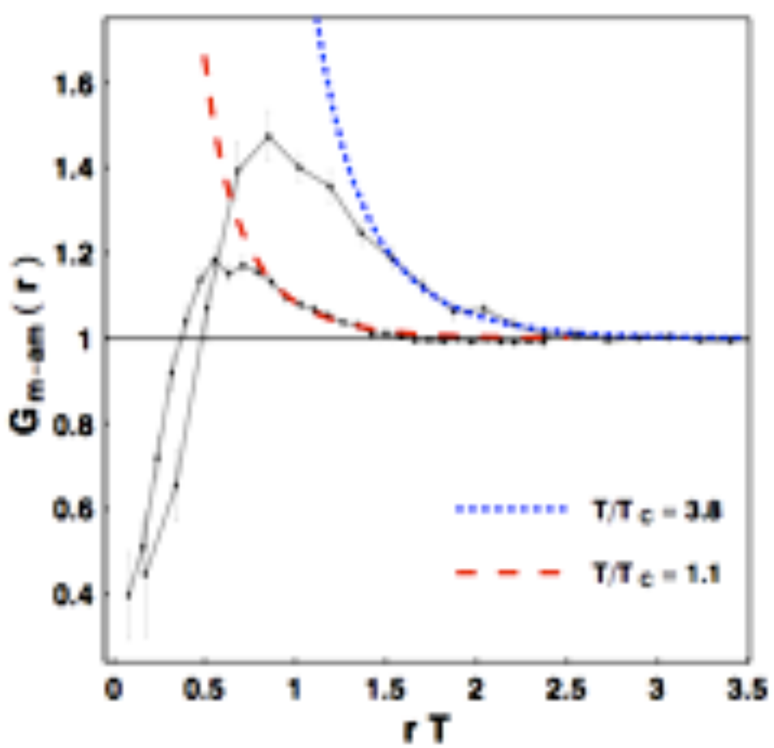
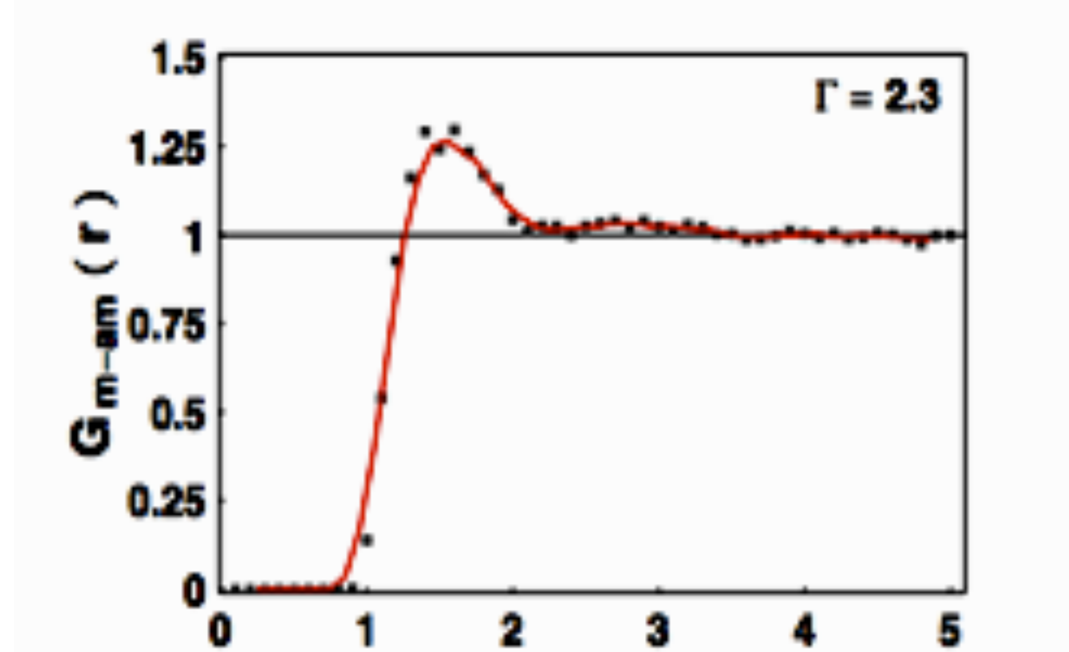


FIG. 2. (color online) Monopole-antimonopole correlators versus distance: points are lattice data [2], the dashed lines are our fits.

Our MD for 50-50 MQP/EQP

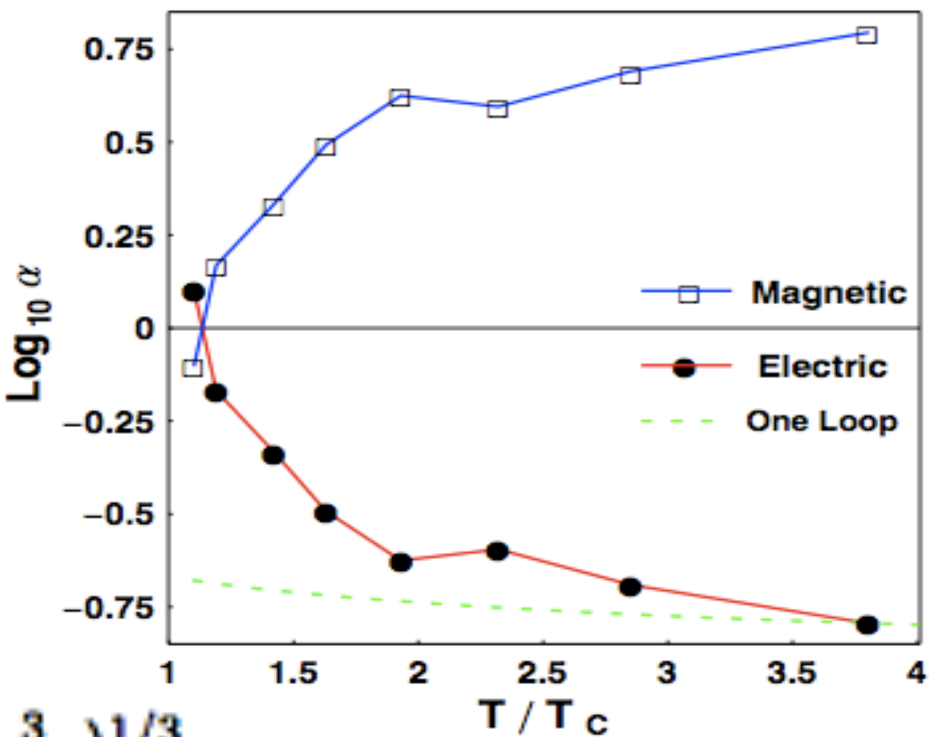


I would not bother you with this plot
If not one observation:
The correlation increases with T

α_s(electric) and α_s(magnetic)

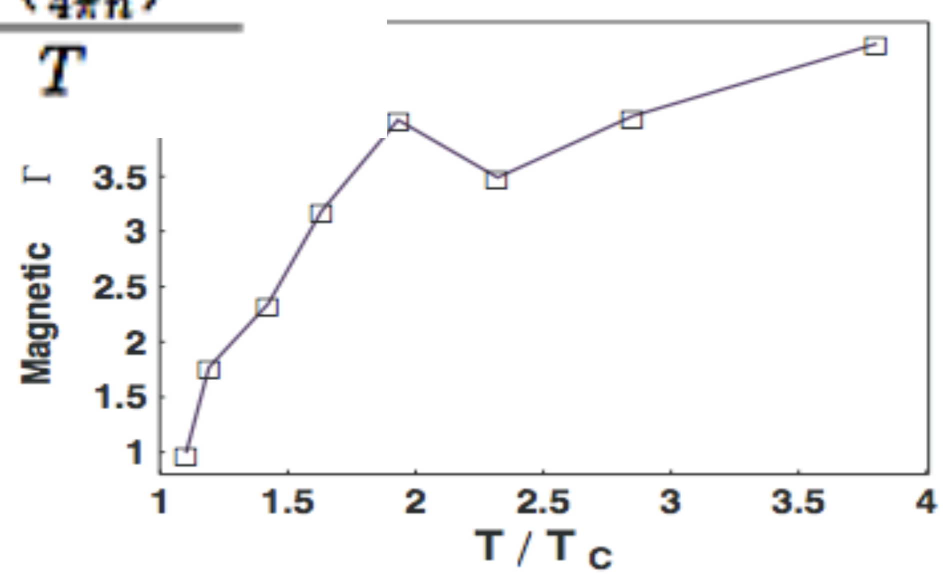
do run in opposite directions!

- 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)**

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



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

Old good Dirac condition

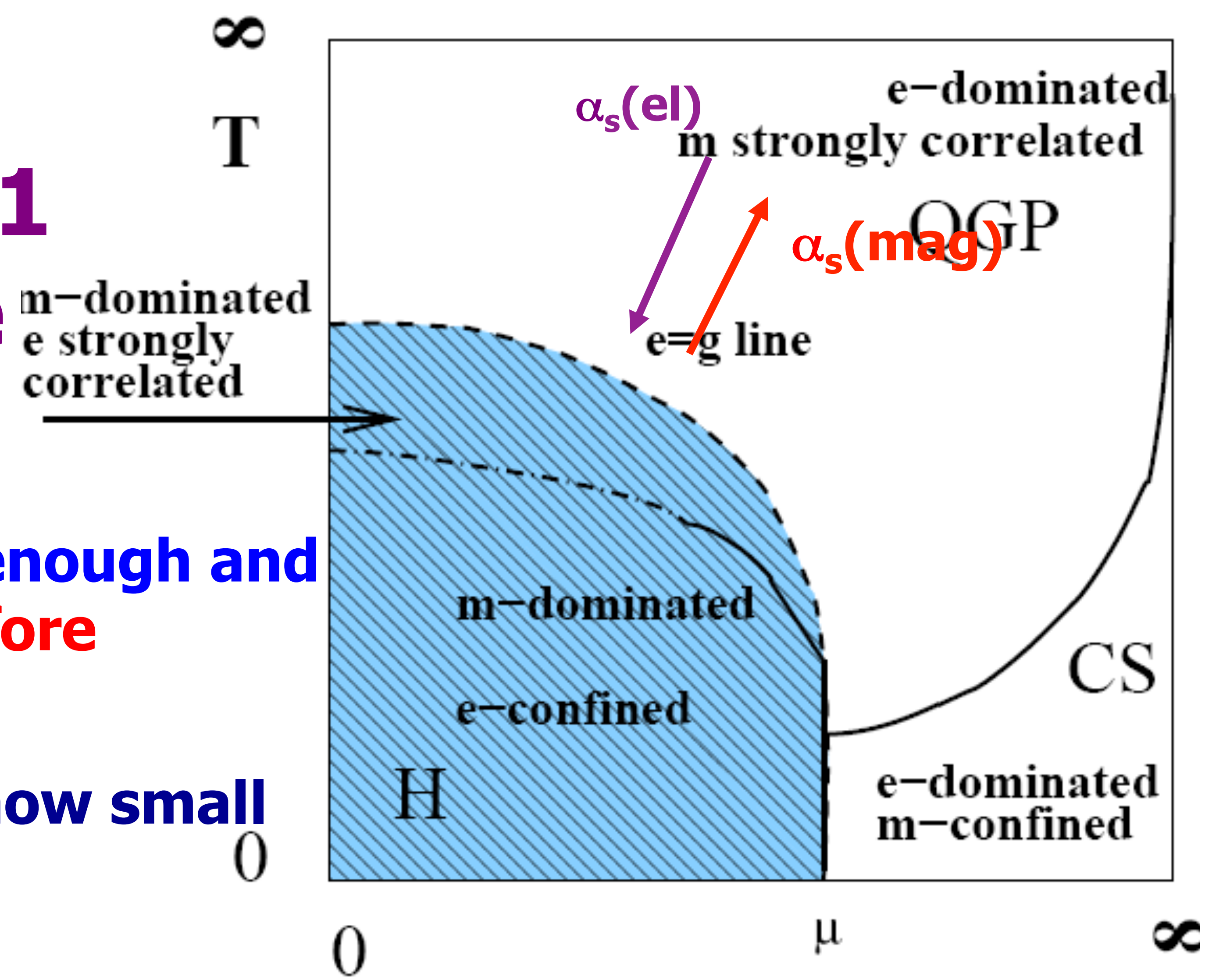
α_s(electric) α_s(magnetic)=1

=>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?

PHYSICAL REVIEW D **82,** 094007 (2010)

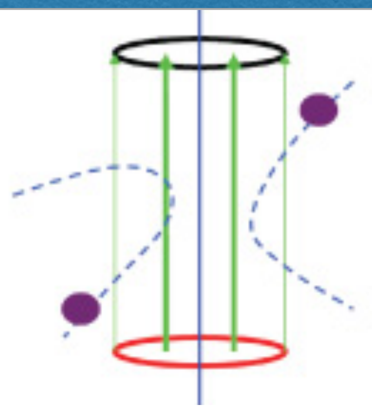
Static $\bar{Q}Q$ potentials and the magnetic component of QCD plasma near T_c

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

and earlier works

Flux tubes can exist even without "dual superconductor"
At T>Tc

E.g. there are plenty of flux tubes on the Sun



Some density of monopoles
Is enough to provide pressure
On the electric flux tube

The only difference is such flux tubes
are not stable forever
Because of Ohmic losses

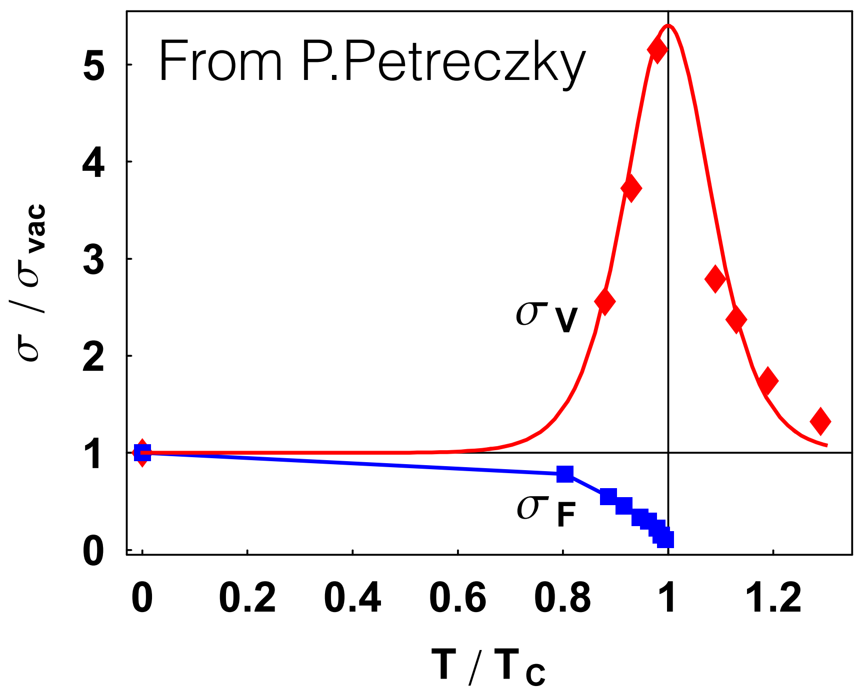
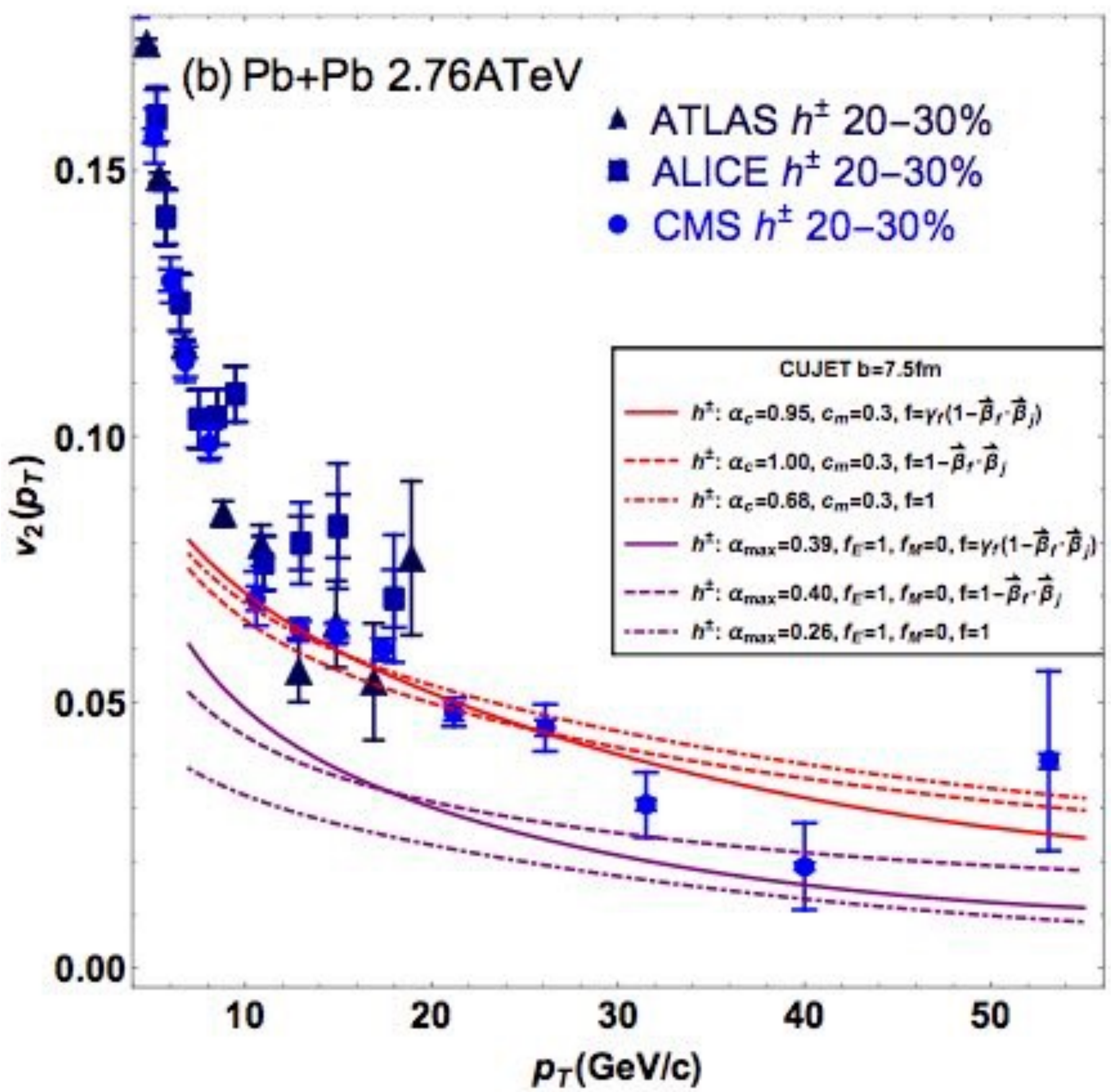


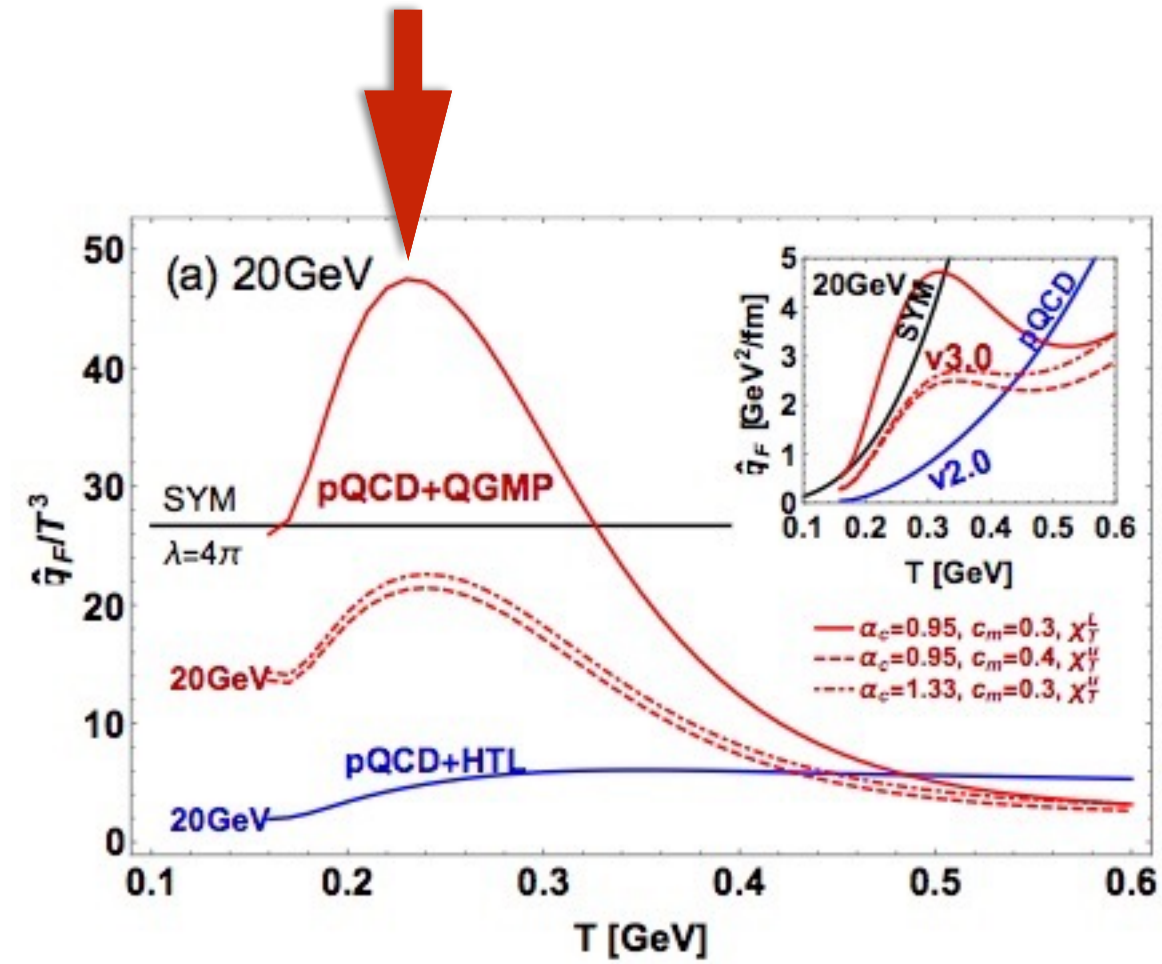
FIG. 2 (color online). Effective string tensions in the free energy $\sigma_F(T)$ (from [4]) and the internal energy $\sigma_V(T)$ (extracted from [3]).

on the lattice one cannot study
unstable objects
But one can have string tension
For free energy and potential energy

We argued that free energy corresponds
To very slow processes, while in quarkonia
One should use potential energy

peak of the density of monopoles at Tc
explains not only a **dip in viscosity (m.f.p.)**
but also other things such as jet quenching





Xu, J., J. Liao, and M. Gyulassy (2015), arXiv:1508.00552