ES70 @ CCNU *Oct. 9, 2018*

A Long Quest for the Degrees of Freedom

Jinfeng Liao

IU/CCNU

Happy 70th!

The magnificent achievements of Edward can only be toasted with the most perfect liquid
— RHIC & LHC serve the perfect liquid!
— We will celebrate with a different kind of perfect liquid!

"Flying with Eagle"

From ***Michael Lublinsky***
I spent fantastic three years in Stony Brook where I had the privilege of learning from you. I always admire your so broad knowledge and deep vision. You taught me many things in physics and beyond and I consider you as one of my Teachers… I am forever grateful for this! … Happy living until 120, as is commonly wished here in Israel!

From ***Ho-Ung Yee***
Edward, my warm congratulations for your 70'th Birthday! I have always been impressed by your enthusiasm for physics and open-mindedness and support towards young people. I have really felt privileged and lucky to be with you while in Stony Brook. See you around in many future years and keep healthy!

From ***Claudia Ratti***
I am truly grateful for everything you did for me and all the things you taught me: the years in Stony Brook, working in your group, have been a great professional and human experience that I will never forget. … I am very privileged for having had the possibility of working with a scientist of your stature…. you played a very important role in my life and I hope that you will continue to inspire the minds of young physicists for many more years.

We were so blessed and privileged to be pupils of such a great master!

“Flying with Eagle”

In Chinese:
“鸟随鸾凤飞腾远，
人伴贤良品自高!”

A (Long) Quest

The Degrees of Freedom (DoF)

EM Plasma: electrons, ions $\longrightarrow$ Crystal lattice + electrons in periodic potential

Atoms / Molecules

Electrons in metal $\longrightarrow$ Cooper pairs in superconductor

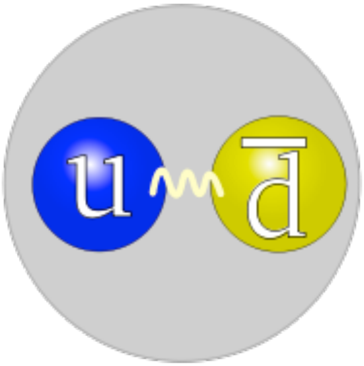
Quarks/Gluons $\longrightarrow$ Hadrons $\longrightarrow$ Nuclei

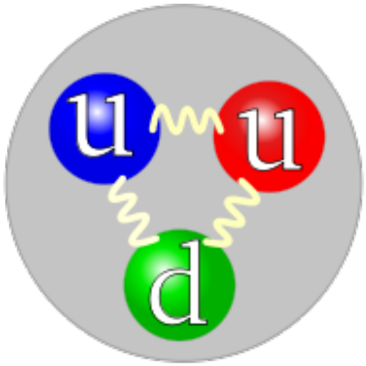
S. Weinberg:
"If you start with the wrong degrees of freedom, you will be very sorry."

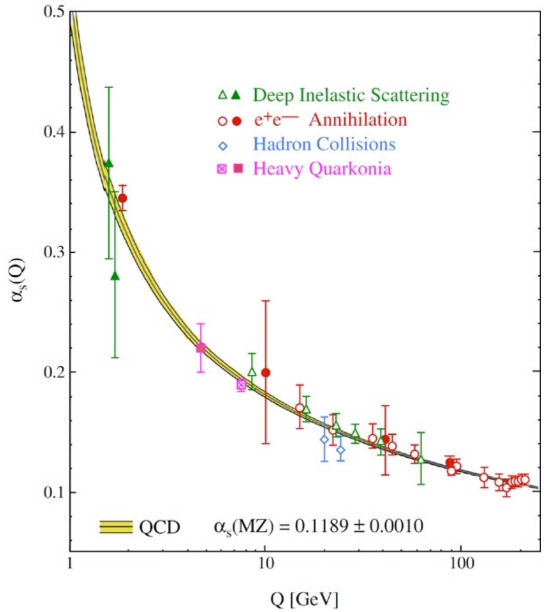
Quarks & Hadrons

Around 1960': lots of hadrons, quark model

Late 60' / early 70': DIS/partons, QCD







However: quarks & gluons are deeply hidden in hadrons.

QCD is "anti-screening" in the vacuum, opposite to QED.

Is this a feature of "simple" quarks & gluons or is it due to structure that is emergent?

The Early Days

. **Theory of Hadronic Plasma**
Edward V. Shuryak (Novosibirsk, IYF). Feb 1977. 23 pp.
Published in **Sov.Phys.JETP 47 (1978) 212-219, Zh.Eksp.Teor.Fiz. 74 (1978) 408-420**
IYF-77-34

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

Detailed record - Cited by 280 records 250+

Quark-Gluon Plasma and Hadronic Production of Leptons, Photons and Psions
Edward V. Shuryak (Novosibirsk, IYF). Jan 1978. 4 pp.
Published in **Phys.Lett. 78B (1978) 150, Sov.J.Nucl.Phys. 28 (1978) 408, Yad.Fiz. 28 (1978) 796-808**
IYF-78-24
DOI: 10.1016/0370-2693(78)90370-2

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

Detailed record - Cited by 709 records 500+

. **Quantum Chromodynamics and the Theory of Superdense Matter**
Edward V. Shuryak (Novosibirsk, IYF). 1980. 88 pp.
Published in **Phys.Rept. 61 (1980) 71-158**
DOI: 10.1016/0370-1573(80)90105-2

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; AMS MathSciNet

Detailed record - Cited by 960 records 500+

QCD at high T is screening, too— a plasma like QED!

The vacuum must have highly nontrivial structures.

Ahead of One's Time

QUARK–GLUON PLASMA AND HADRONIC PRODUCTION OF LEPTONS, PHOTONS AND PSIONS

E.V. SHURYAK
Institute of Nuclear Physics, Novosibirsk, USSR

Received 16 March 1978

QCD calculations of the production rate in a quark–gluon plasma and account of the space–time picture of hadronic collisions lead to estimates of the dilepton mass spectrum, $p_\perp$ distributions of $e^\pm$, $\mu^\pm$, γ, $\pi^\pm$, production cross sections of charm and psions.

Hadronic reactions, taking place at small and large distances, are treated on quite different theoretical grounds. While the former are well described by the parton model based on asymptotic freedom of QCD, the latter are still discussed in more phenomenological way. I should like to argue in this paper, that a very important intermediate region exists, namely reactions taking place far from the collision point and not obeying the parton model, but at the same time treatable by perturbative QCD methods. This region corresponds to production of particles with mass M or transverse momentum $p_\perp$ such that 1 GeV $\lesssim M, p_\perp \ll \sqrt{s}$ ($\lesssim$ 4–5 GeV at ISR energies).

The best known example is dilepton production ($\mu^+\mu^-$, e^+e^-), in which deviations from the Drell–Yan model [1] for dilepton mass $M \lesssim 5$ GeV reach a factor 10^1–10^2. Bjorken and Weisberg [2] proposed a qualitative explanation for it: such pairs are produced at later stages of the collision, when antiquarks are more numerous and can interact repeatedly. Much earlier, Feinberg [3] ascribed them to the charge-current fluctuations in the hydrodynamical model [4] and also stressed the importance of the space–time aspect of the problem.

We assume that in hadronic collisions after some time a *local* [7] *thermal equilibrium* is established in the sense that all properties are determined by a single parameter, the temperature T, depending on time and coordinates. The schematic space–time picture of the collisions is shown in fig. 1. We are interested in the final state interaction region, limited by two lines: $T(x, t) = T_i$, the initial temperature at which the thermodynamical description becomes reasonable, and $T(x, t) = T_f \sim m_\pi$, where the system breaks into secondaries [4,7]. The medium is assumed to be the quark–gluon

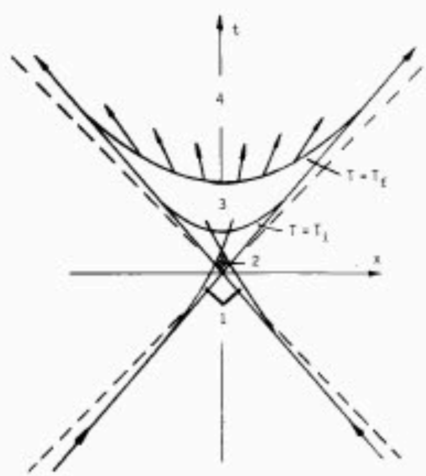


Fig. 1. The space–time picture of hadronic collisions, proceeding through the following stages: (1) structure function formation; (2) hard collisions; (3) final state interaction; (4) free secondaries.

What Are the DoFs?

$$\mathcal{Z} = \int \mathcal{D}[A_\mu] e^{-S}$$

Two strategies:
1. Use real computers with brute force
2. Effective models that start with the right DoFs

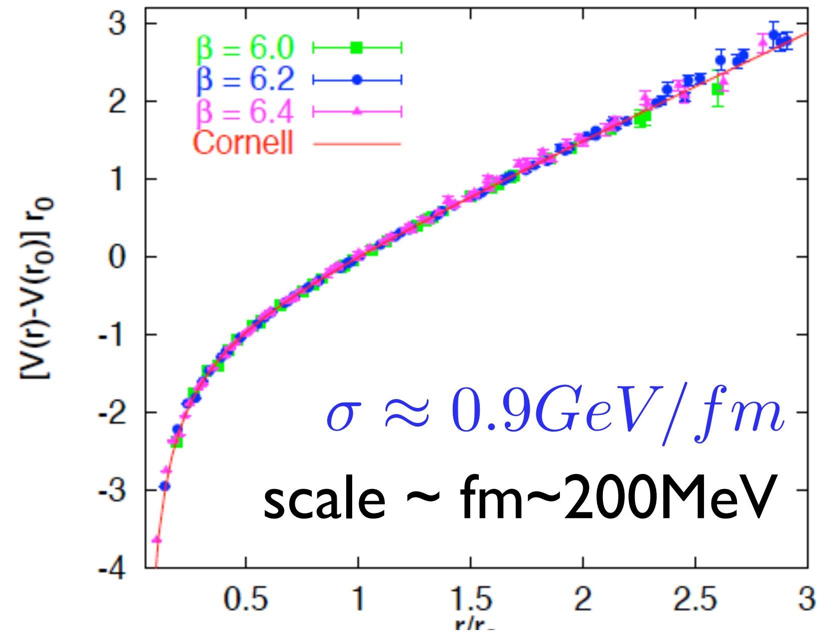
What are the most important/relevant configurations/DoFs?

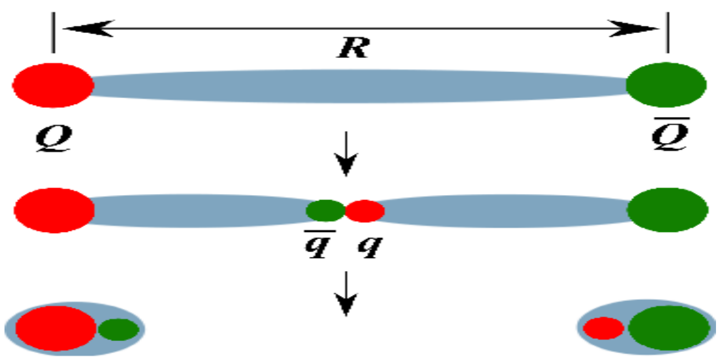
The Complicated Vacuum

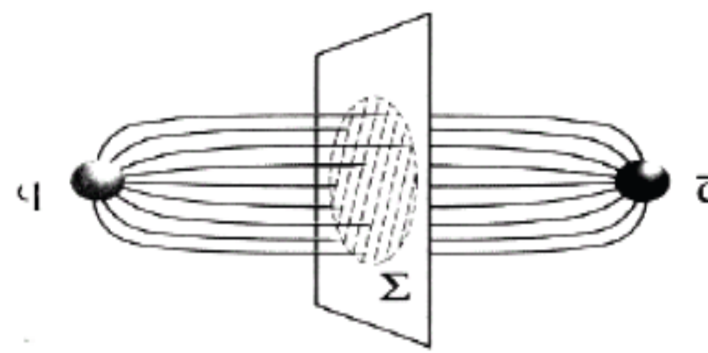
$$V(r) = -\frac{\alpha_s}{r} + \sigma r$$

linear potential at large distance
~ 1 fm ~ 1/Lambda_QCD:
it costs infinite energy to
separate Q-bar-Q

Origin of linear potential:
flux tube of chromo-E field





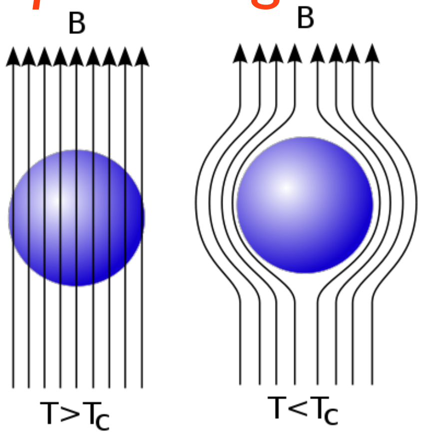


QCD dipole field $V \sim r$

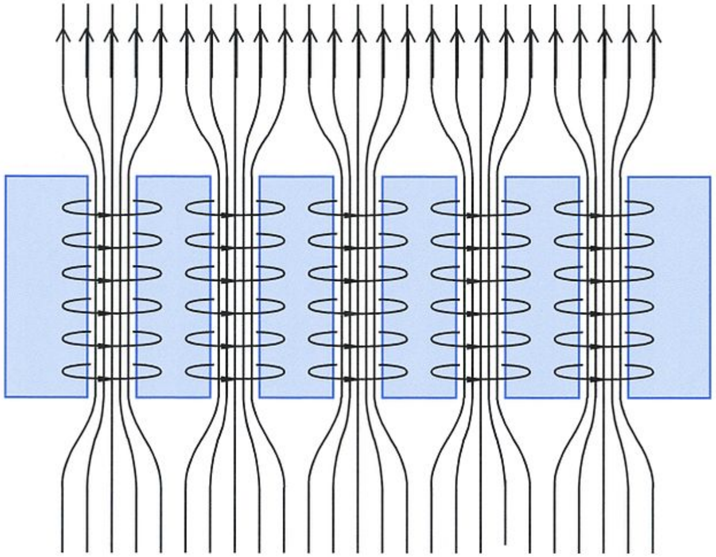
Emergent stringy behavior!

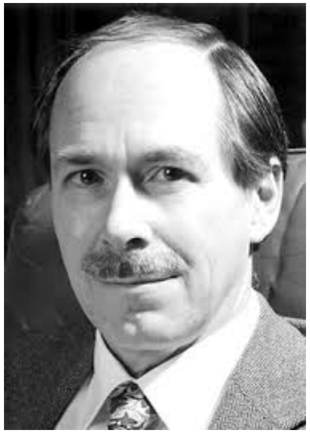
Meissner Effect in Superconductor

Meissner effect: electric (cooper-pair) condensate expels magnetic fields, and squeezes them into flux tube.



$$B_z(x) = B_0 e^{-x/\lambda}.$$

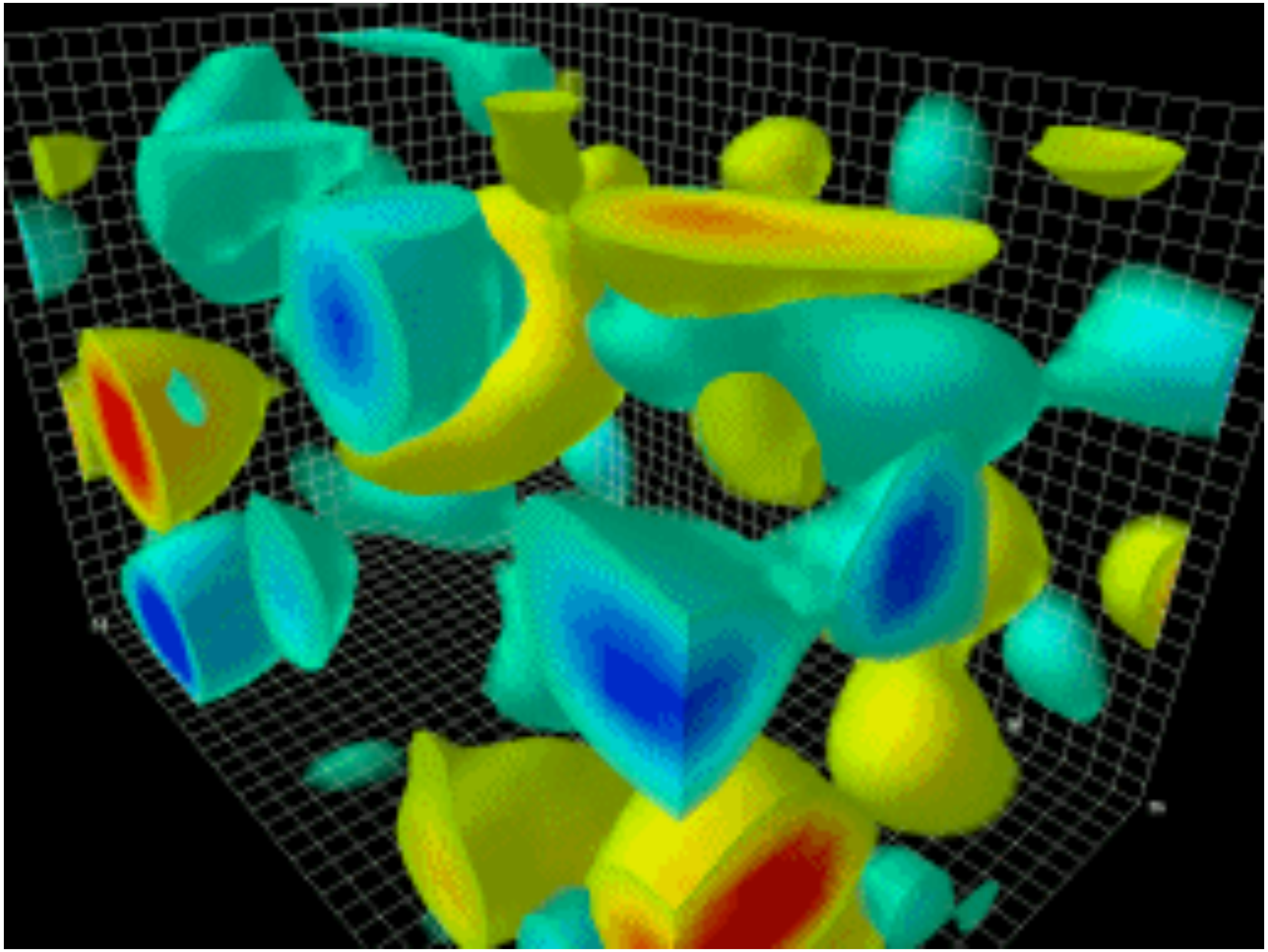




’t Hooft, Mandelstamm, Nambu —> transforming this insight into QCD

Difficulty: no “higgs” to make monopoles (easily)

Vacuum & Instanton



Instantons must be there and important.
Ed was convinced long before the supercomputers.

Vacuum & Instanton

1. **The Role of Instantons in Quantum Chromodynamics. 2. Hadronic Structure**
   Edward V. Shuryak (Novosibirsk, IYF). Mar 1982. 24 pp.
   Published in **Nucl.Phys. B203 (1982) 116-139**
   IYF-81-134
   DOI: 10.1016/0550-3213(82)90479-5
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   Detailed record - Cited by 323 records 250+

2. **The Role of Instantons in Quantum Chromodynamics. 3. Quark - Gluon Plasma**
   Edward V. Shuryak (Novosibirsk, IYF). Jan 1982. 17 pp.
   Published in **Nucl.Phys. B203 (1982) 140-156**
   IYF-82-03
   DOI: 10.1016/0550-3213(82)90480-1
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   Detailed record - Cited by 231 records 100+

3. **The Role of Instantons in Quantum Chromodynamics. 1. Physical Vacuum**
   Edward V. Shuryak (Novosibirsk, IYF). Oct 1981. 23 pp.
   Published in **Nucl.Phys. B203 (1982) 93**
   IYF 81-118
   DOI: 10.1016/0550-3213(82)90478-3
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   Detailed record - Cited by 556 records 500+

Vacuum as Instanton Liquid

Correlation functions in the QCD vacuum
Edward V. Shuryak (SUNY, Stony Brook). 1993. 46 pp.
Published in **Rev.Mod.Phys. 65 (1993) 1-46**
DOI: 10.1103/RevModPhys.65.1
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 341 records 250+

Instantons in QCD
Thomas Schäfer (Washington U., Seattle), Edward V. Shuryak (SUNY, Stony Brook). Oct 1996. 133 pp.
Published in **Rev.Mod.Phys. 70 (1998) 323-426**
DOE-ER-40561-293, INT-96-00-150
DOI: 10.1103/RevModPhys.70.323
e-Print: **hep-ph/9610451** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 1275 records 1000+

The ILM successfully explains chiral dynamics and hadron properties in vacuum.
It though did not explain confinement.
Nevertheless, it led Ed to the color superconductivity!

Diquark Bose condensates in high density matter and instantons
R. Rapp (SUNY, Stony Brook), Thomas Schäfer (Washington U., Seattle), Edward V. Shuryak (SUNY, Stony Brook), M. Velkovsky (Brookhaven). Nov 1997. 4 pp.
Published in **Phys.Rev.Lett. 81 (1998) 53-56**
SUNY-NTG-97-30
DOI: 10.1103/PhysRevLett.81.53
e-Print: **hep-ph/9711396** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI.gov Server
Detailed record - Cited by 982 records 500+

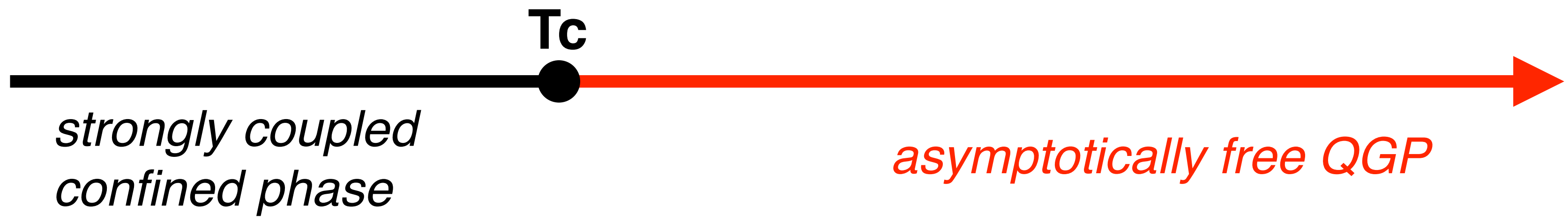
The Big Machines

Boiling a quark-gluon plasma in lab routinely

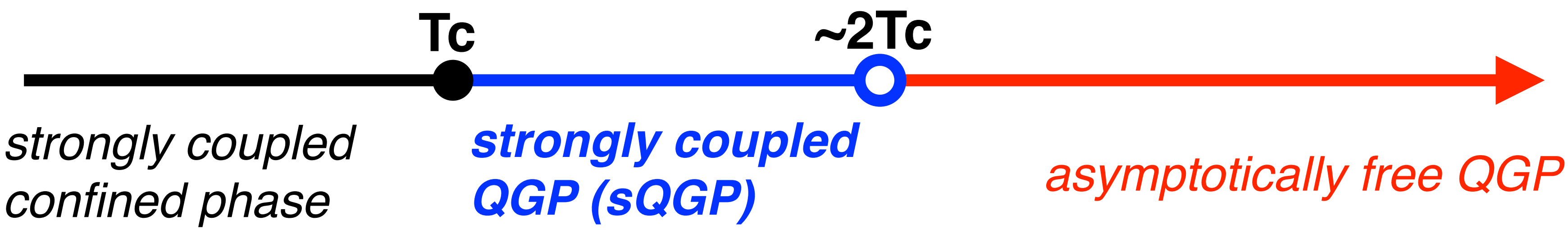
A nearly perfect liquid — strongly coupled, sQGP

So, what are the right degrees of freedom?

The old belief



The new paradigm thanks to discoveries at RHIC and LHC (1~3Tc):



The matter just above confinement (in 1~2Tc), is more closely related to the confined world, rather than to the asymptotic QGP!

A"<u>postconfinement</u>" regime?!
What are the DoFs???

Surviving Hadrons

Shuryak, Zahed, …: bound states surviving into hot phase!

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics A 775 (2006) 224–234

NUCLEAR PHYSICS A

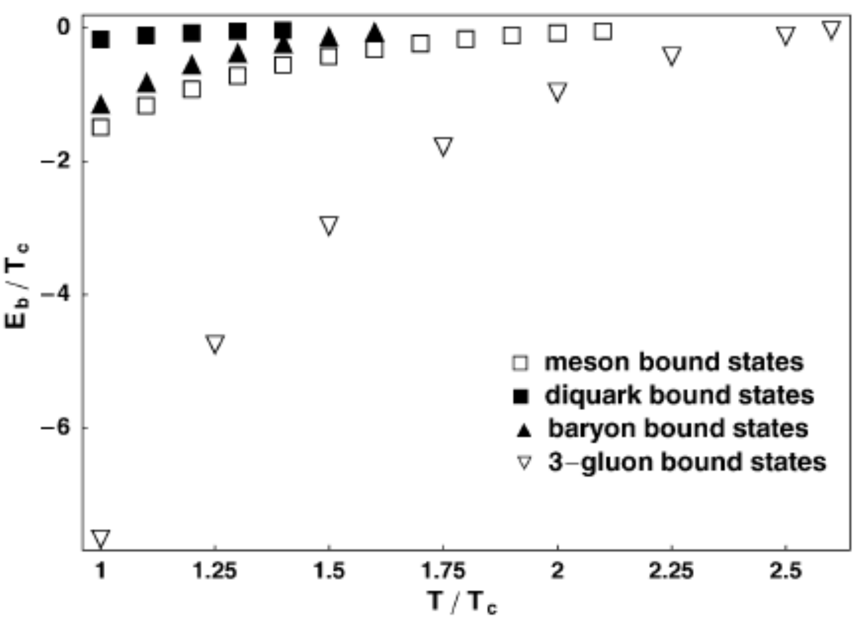
Polymer chains and baryons in a strongly coupled quark–gluon plasma

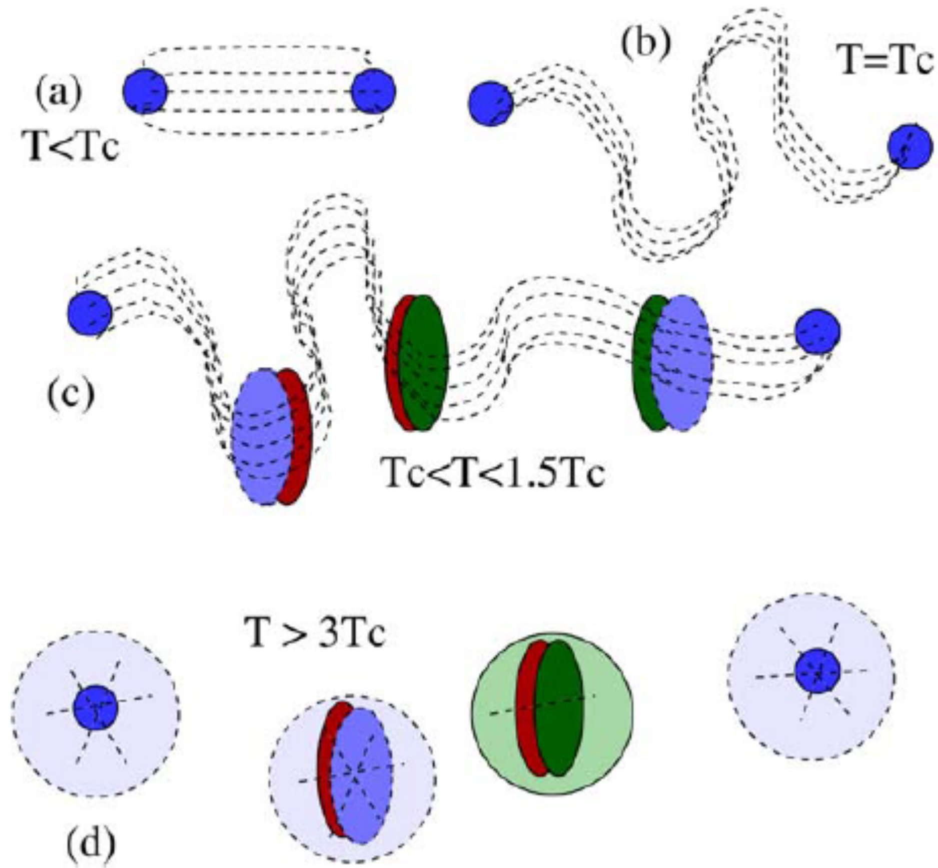
Jinfeng Liao *, Edward V. Shuryak

Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794-3800, USA

Received 14 October 2005; received in revised form 21 March 2006; accepted 29 June 2006

Available online 18 July 2006





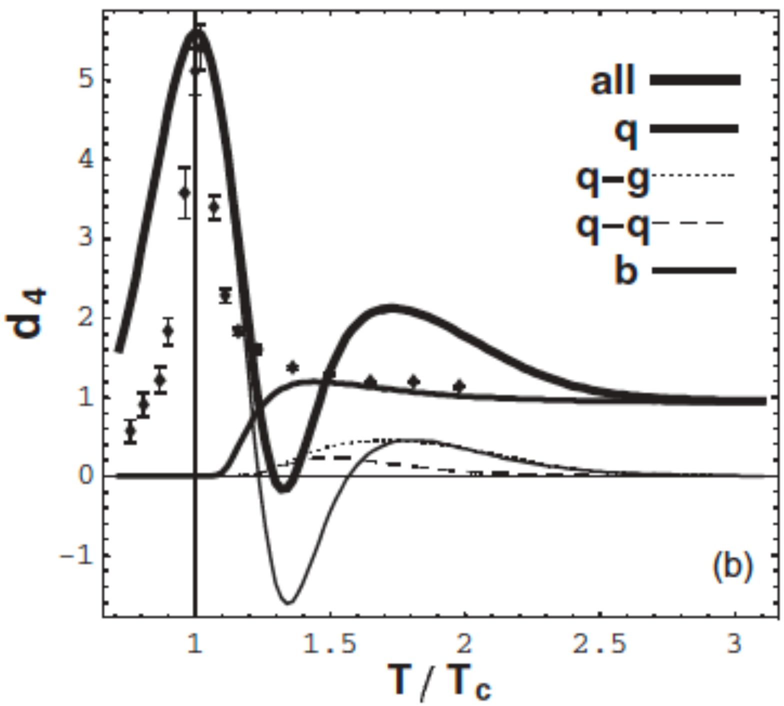
Surviving Hadrons: Susceptibilities Know Them!

PHYSICAL REVIEW D **73**, 014509 (2006)

What do lattice baryonic susceptibilities tell us about quarks, diquarks, and baryons at $T > T_c$?

Jinfeng Liao and Edward V. Shuryak
Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794-3800, USA
(Received 3 November 2005; published 17 January 2006)

Lattice data on QCD thermodynamics, especially recent study of high order susceptibilities by UK-Bielefeld Collaboration, have provided valuable information about matter properties around and above the critical temperature T_c. In this work we tried to understand what physical picture would explain these numerical data. We found two scenarios which will do it: (i) a quark quasiparticle gas, with the effective mass which is strongly *decreasing* near the phase boundary into the quar (ii) a picture including baryons at $T > T_c$, with the mass rapidly *increa* toward QGP. We further provide several arguments in favor of the latter sc continuity with the baryon gas picture at $T < T_c$.



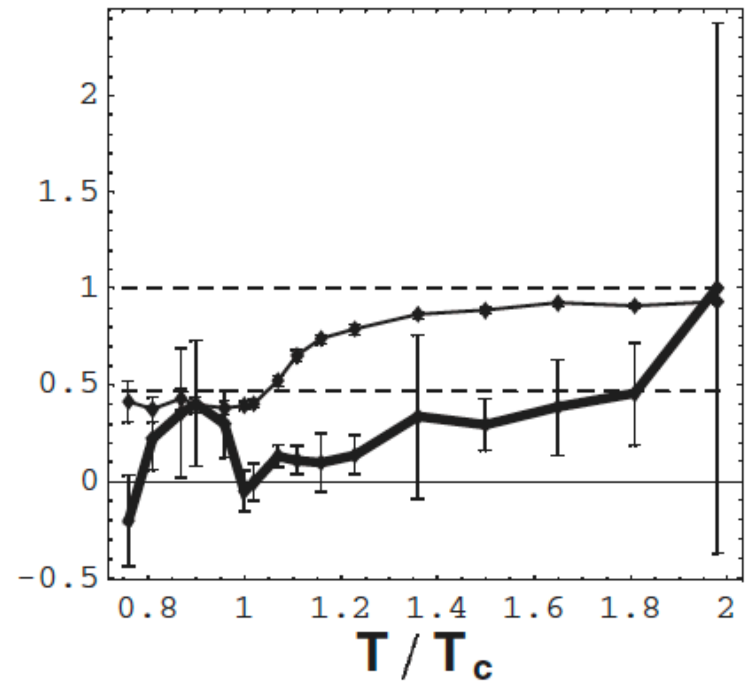
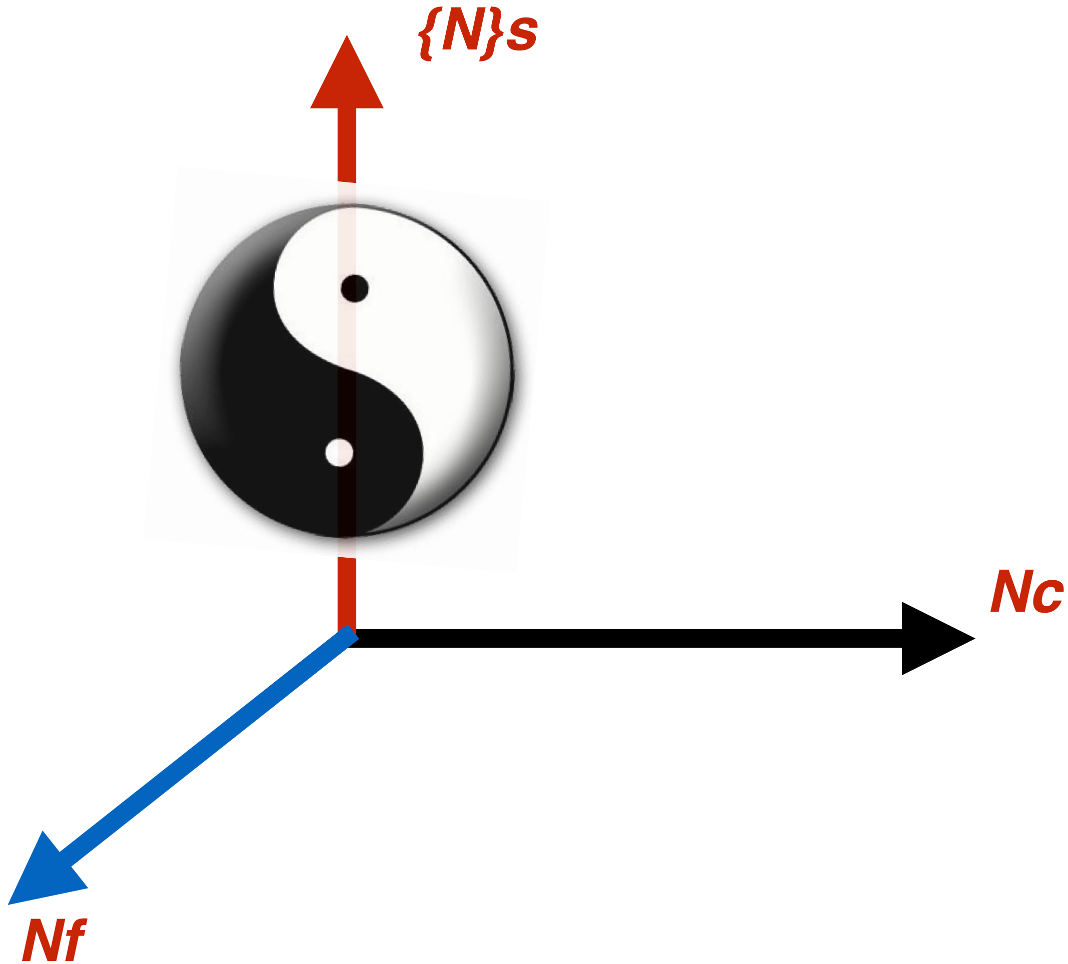


FIG. 6. The susceptibilities ratios d_4^l/d_4 (the thin solid line) and d_6^l/d_6 (the thick solid line). The dashed lines correspond to ideal quark gas (upper) and ideal baryonic gas (lower).

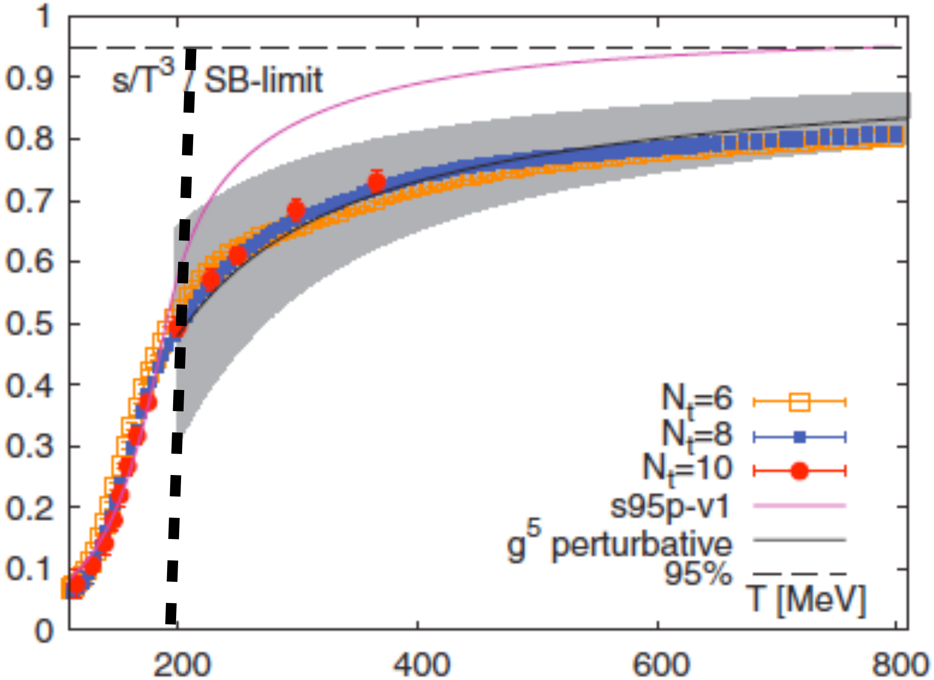
Thinking Harder About DoFs



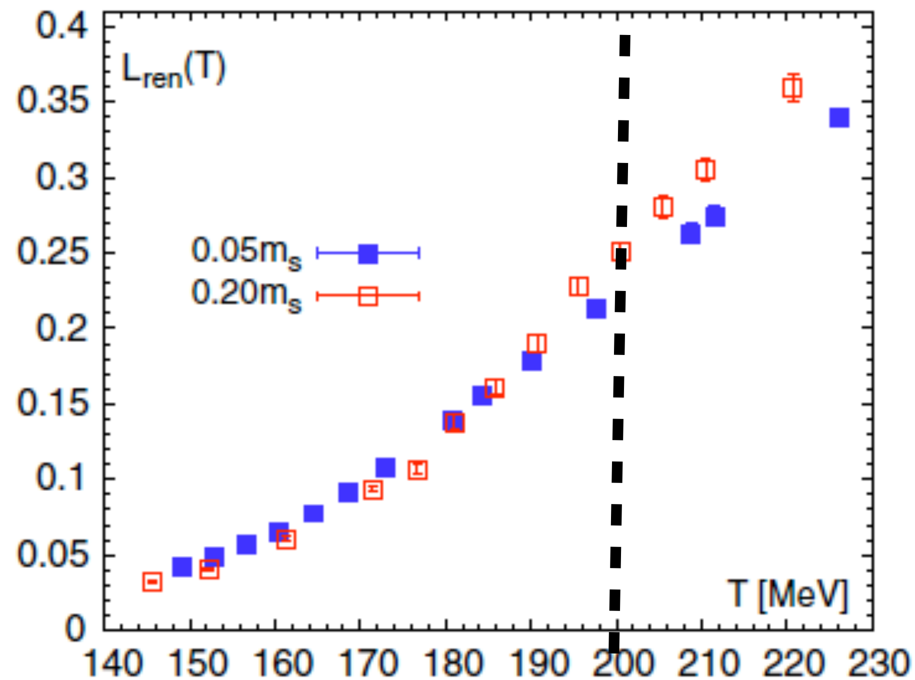
Electric-Magnetic Duality?!

Liberation of Color? Missing DoF?

Degrees of freedom



Degree of color liberation



A region around Tc with liberated degrees of freedom but only partially liberated color-electric objects.

(Pisarski & collaborators: semi-QGP)

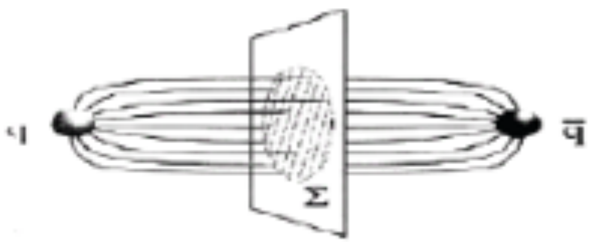
Then what are the "extra" dominant DoF here???

Thermal monopoles evaporated from vacuum condensate!

Chromo-Magnetic Monopoles in sQGP

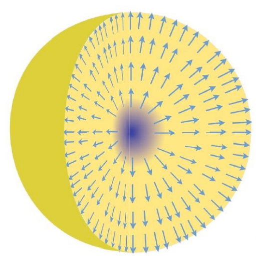
T<< Lambda_QCD | T ~ Lambda_QCD | T>> Lambda_QCD

Vacuum: confined | Tc | sQGP | ***wQGP: screening*** | T

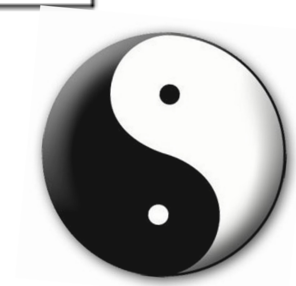


Emergent plasma with <u>E & M</u> charges:
chromo-magnetic monopoles are the "missing DoF"

Plasma of E-charges
E-screening: g T
M-screening: g^2 T



$$\alpha_E * \alpha_M = 1.$$



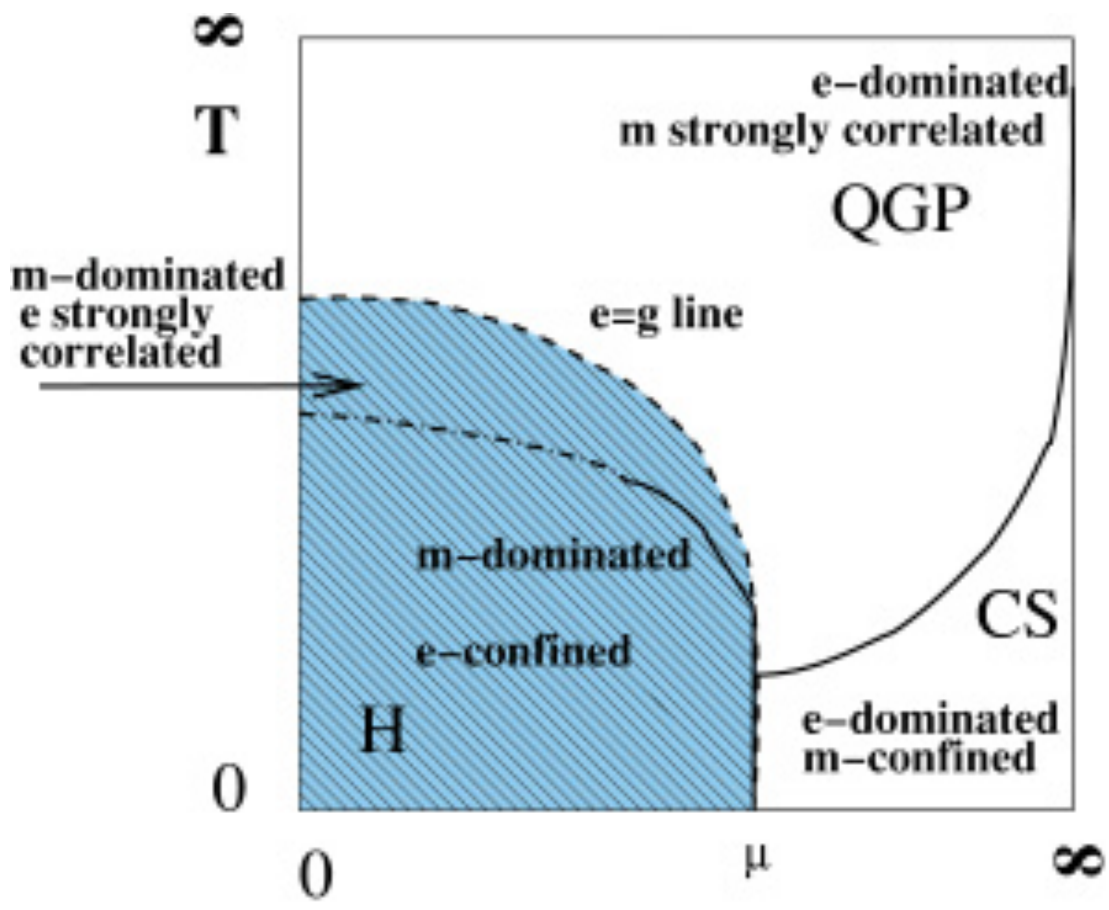
Condensate monopoles —> dense thermal monopoles 1-2Tc: thermal monopoles play key role in this regime.

PHYSICAL REVIEW C **75**, 054907 (2007)

Strongly coupled plasma with electric and magnetic charges

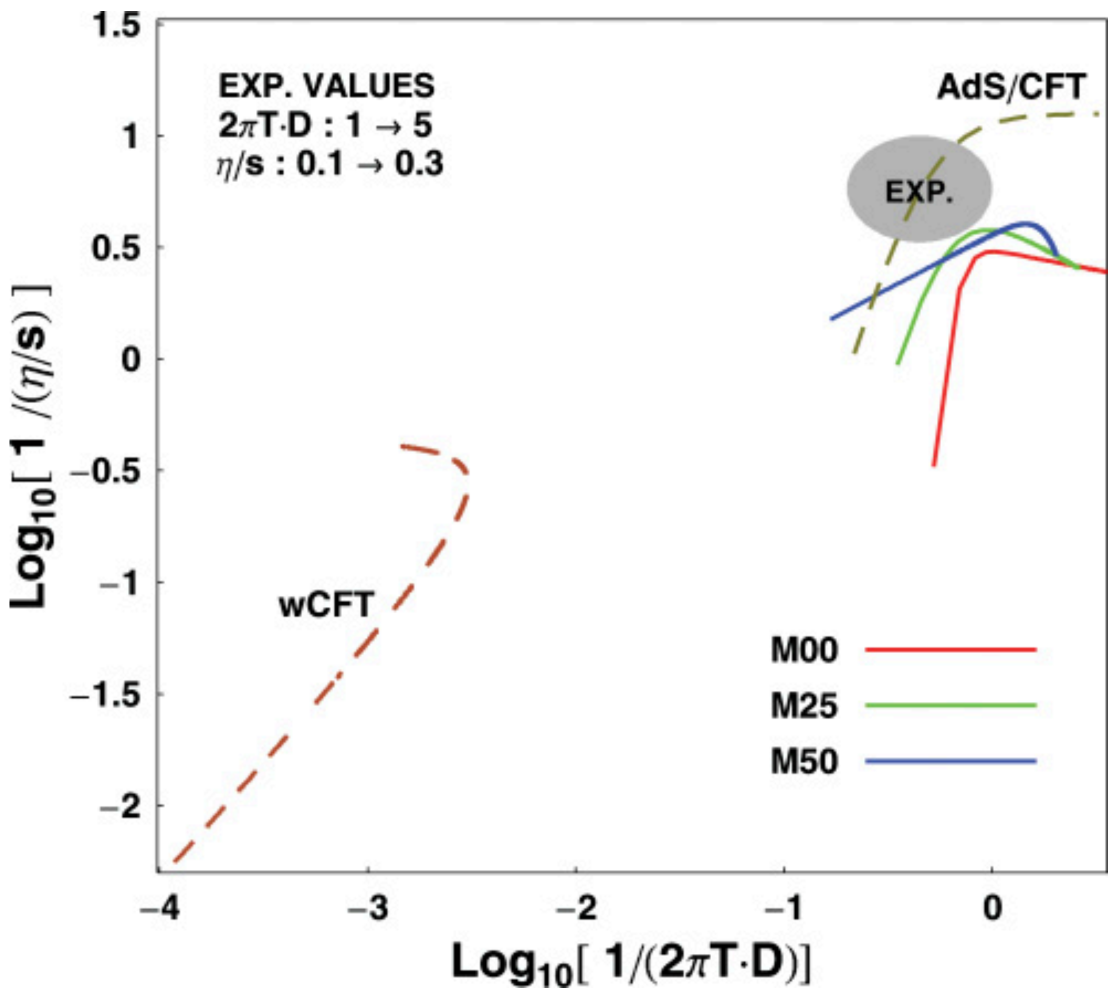
Jinfeng Liao and Edward Shuryak

A New Look at the Phase Diagram



Transport Properties from Magnetic Component

The magnetic component significantly enhances the scattering, needed for understanding the perfect fluidity.



A Chromo-Magnetic Liquid

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

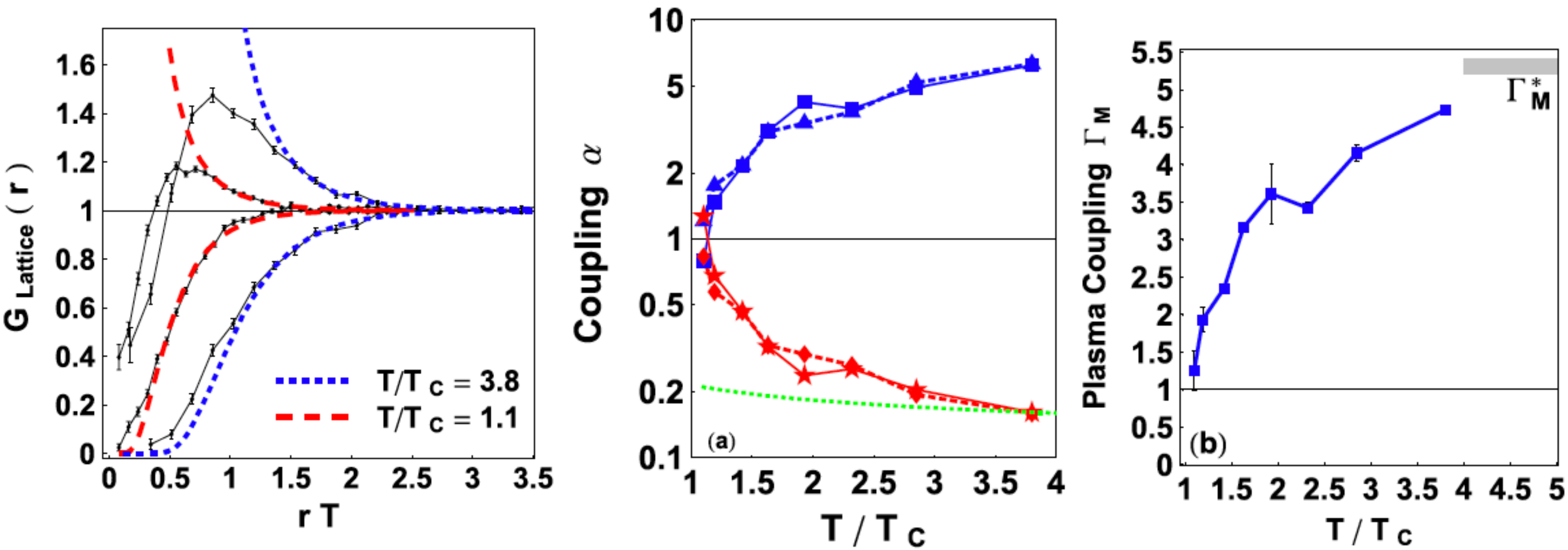
Jinfeng Liao and Edward Shuryak

Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794, USA

(Received 17 April 2008; revised manuscript received 26 August 2008; published 15 October 2008)

The magnetic scenario for strongly coupled quark-gluon plasma (sQGP) emphasizes the role of monopoles near or above the deconfinement temperature, and specifically predicts that they help reduce its viscosity by the "magnetic bottle" effect. Here we present results for monopole-(anti)monopole correlation functions from our classical molecular dynamics simulations, which are in good agreement with the lattice results. By analysis of the correlation functions, we show that the magnetic Coulomb coupling runs in the direction *opposite* to the electric one. However, as T decreases to T_c, the magnetic coupling never gets too weak, with the plasma parameter always large enough ($\Gamma > 1$). This nicely agrees with empirical evidence from the BNL Relativistic Heavy Ion Collider experiments, implying that magnetic objects should also form a good liquid with low viscosity.

DOI: 10.1103/PhysRevLett.101.162302 PACS numbers: 12.38.Mh, 12.38.Aw, 14.80.Hv, 52.27.Gr

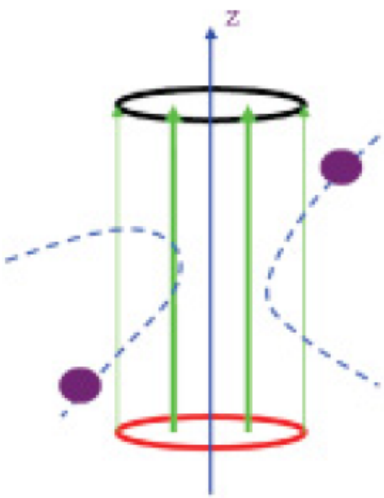


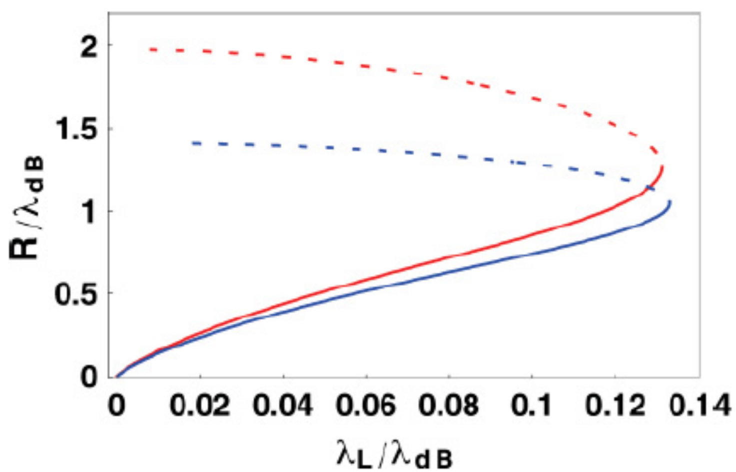
Flux Tubes Above Tc

PHYSICAL REVIEW C 77, 064905 (2008)

Electric flux tube in a magnetic plasma

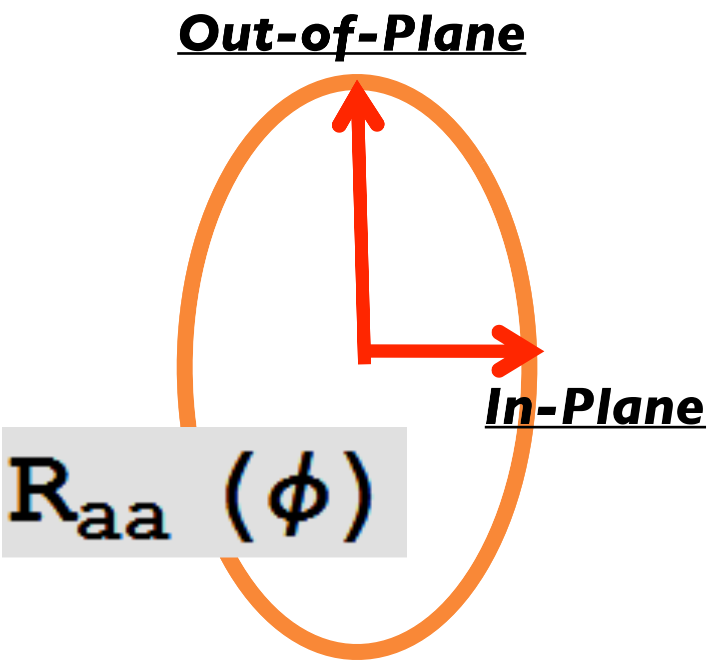
Jinfeng Liao and Edward Shuryak
Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794, USA
(Received 6 July 2007; published 11 June 2008)



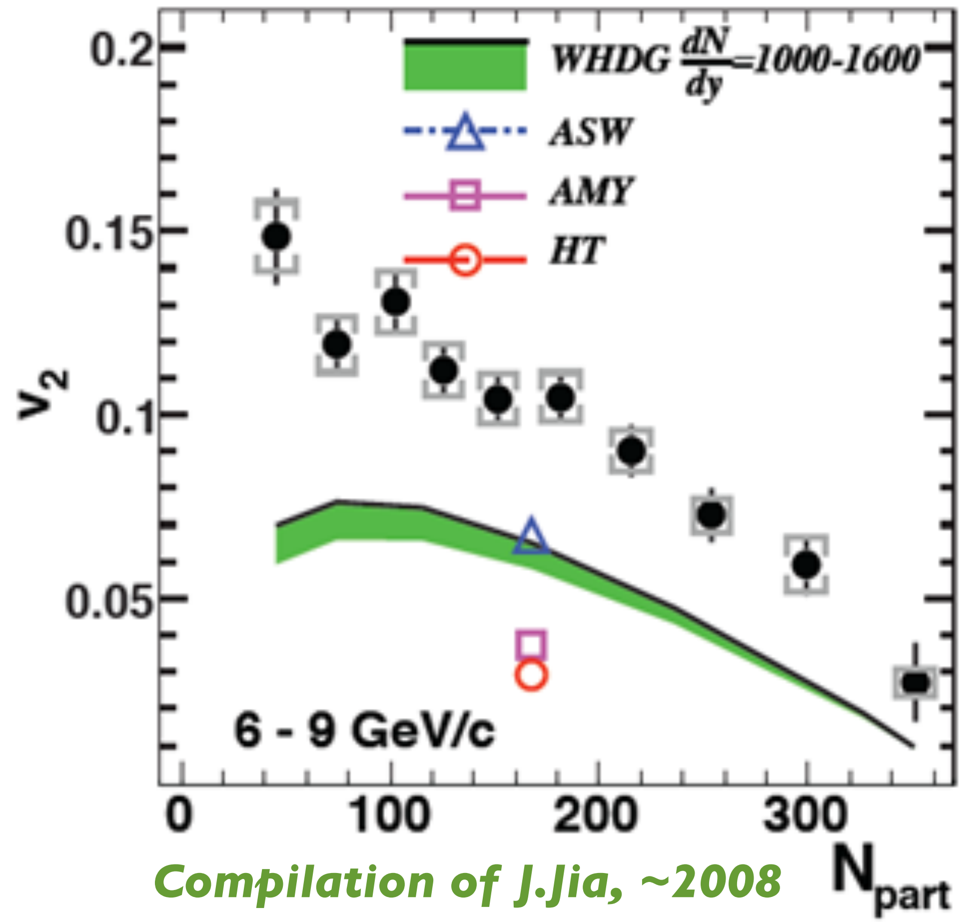


$$\frac{g^2}{4\pi}\left(\frac{n}{T^3}\right) \geqslant 2.0 \left(\frac{\bar{k}_T}{T}\right)^2 \frac{M}{T}.$$

Jet Energy Loss



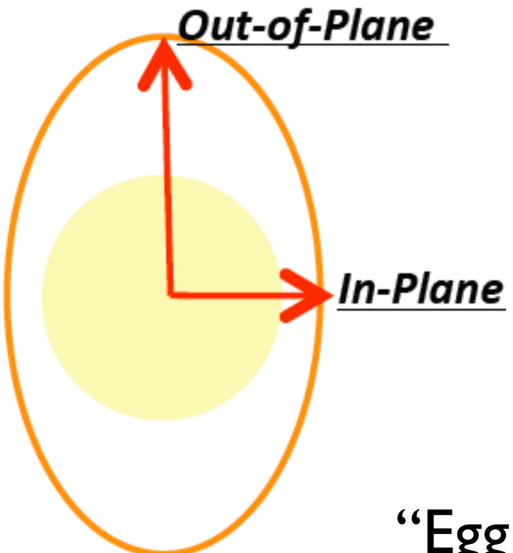
$I_{in} < I_{out} \Rightarrow (R_{aa})_{in} > (R_{aa})_{out}$



Compilation of J.Jia, ~2008

Till ~ 2008, there was clear discrepancy between accurate data and model predictions.

Where Are Jets Quenched (More Strongly)?



Taken for granted in all previous models: "waterfall" scenario.

We realized the puzzle may concern more radical questions:

Where are jets quenched (more strongly)?

Geometry is a sensitive feature:
"Egg yolk" has one geometry,"Egg white" has another.

PRL **102**, 202302 (2009) PHYSICAL REVIEW LETTERS week ending 22 MAY 2009

Angular Dependence of Jet Quenching Indicates Its Strong Enhancement near the QCD Phase Transition

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

[1]*Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794, USA*
[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
(Received 22 October 2008; revised manuscript received 19 February 2009; published 22 May 2009)

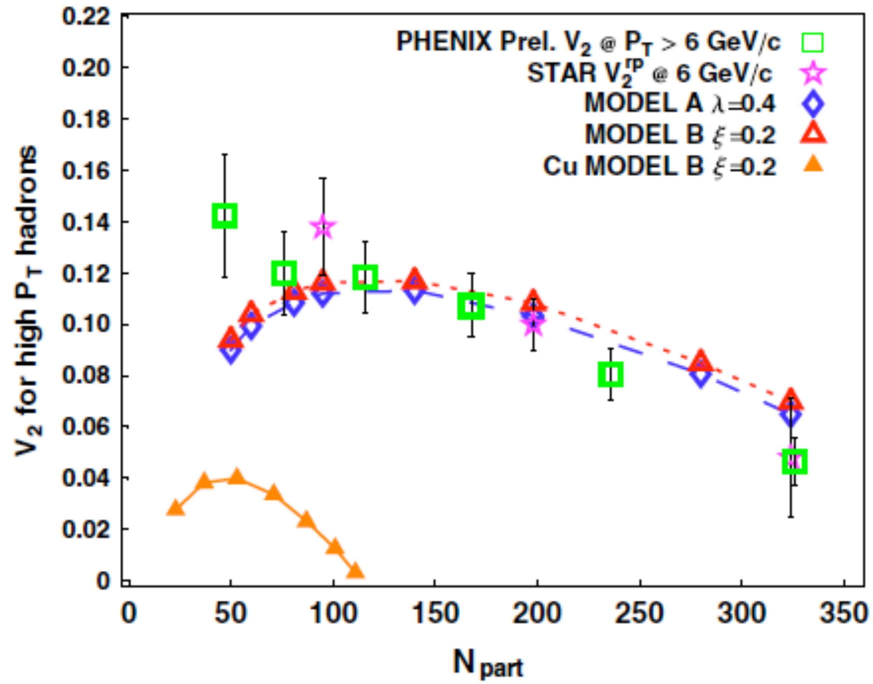
Near-Tc Enhancement of Jet-Medium Coupling

Three major findings:

(1) With fixed Raa, the jet v2 is VERY sensitive to the T-dependence of jet-medium coupling;

(2) Energy loss around Tc region enhances the jet v2;

(3) RHIC data suggests a very strong enhancement near Tc.



In the paper PRL(2009) we concluded:

"In relativistic heavy ion collisions the jets are quenched about **2--5 times stronger** in the near-Tc region than the higher-T QGP phase."

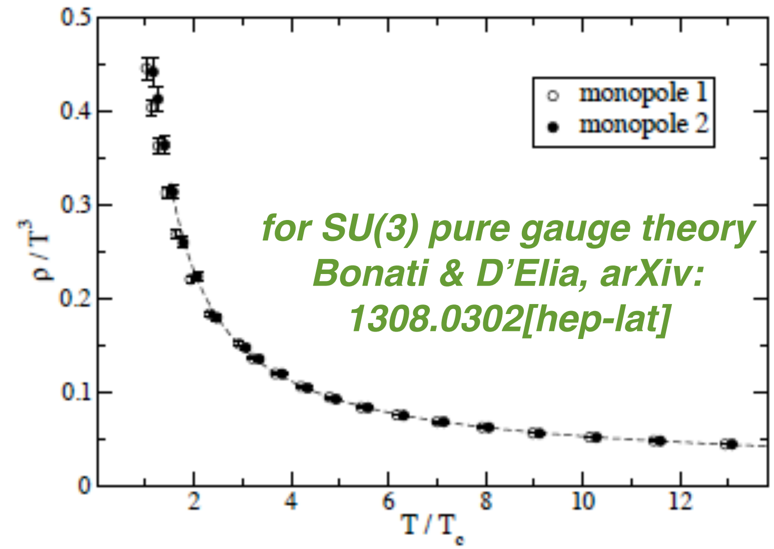
— Evidence for Magnetic DoFs!

Magnetic DoF Prevails Near Tc

$$\alpha_E * \alpha_M = 1.$$

Electric and magnetic charges always scatter strongly with each other!

Magnetic charges become copious in the plasma near Tc



An entirely new era of jet energy loss modeling: CUJET3 based on semi-Quark-Gluon-Monopole Plasma (sQGMP)

— See talk by Miklos Gyulassy tomorrow!

J. Xu, JL, M. Gyulassy, CPL2015; JHEP2016.
S. Shi, J. Xu, JL, M. Gyulassy, arXiv:1704.04577; to appear soon.

ES60 @ Stony Brook

A New Chapter:
Ensemble of Instanton-Dyons

Significant developments by Stony Brook group (Shuryak, Zahed, et al)

M.LopezRuiz, J. Jiang, JL, arXiv:1611.02539(PRD).
M.LopezRuiz, J. Jiang, JL, in preparation.

What Are the DoFs?

$$\mathcal{Z} = \int \mathcal{D}[A_\mu] e^{-S}$$

Two strategies:
1. Use real computers with brute force
2. Effective models that start with the right DoFs

What are the most important/relevant configurations/DoFs for confinement?

Polyakov Loop & Holonomy

- $\frac{1}{2}\mathrm{Tr}L$ is gauge invariant
  $\Longrightarrow$ can be parametrized $L(|\vec{x}| \to \infty) = \begin{pmatrix} e^{2\pi i \mu_1} & 0 \\ 0 & e^{2\pi i \mu_2} \end{pmatrix}$
- The set of eigenvalues $\{\mu_i\}$ is called *Holonomy* with $\mu_1 + \mu_2 = 0$

  And the difference $\nu \equiv \mu_2 - \mu_1$ $\longrightarrow$ *Holonomy parameter*

$$L_\infty = \lim_{|\vec{x}|\to\infty} \frac{1}{2} Tr \mathcal{P} e^{i\int_0^\beta d\tau A_4} = \cos(\pi\nu) \qquad \nu \in [0,1]$$

$\nu = \frac{1}{2} \to L_\infty = 0:$ Confining, maximally nontrivial holonomy

$\nu = 0 \to L_\infty = 1:$ Deconfined, trivial holonomy

In QCD it is holonomy that can play the role of the "Higgs" mechanism.

Polyakov Loop & Holonomy

Classifying gauge field configurations according to holonomy:

$$\mathcal{Z} = \int \mathcal{D}[A_\mu] e^{-S} \to \int d\nu \left[\int \mathcal{D}[(A_\mu)|_\nu] e^{-S} \right]$$

$$\to \int d\nu e^{-\beta V F(\nu)}$$

Holonomy Potential

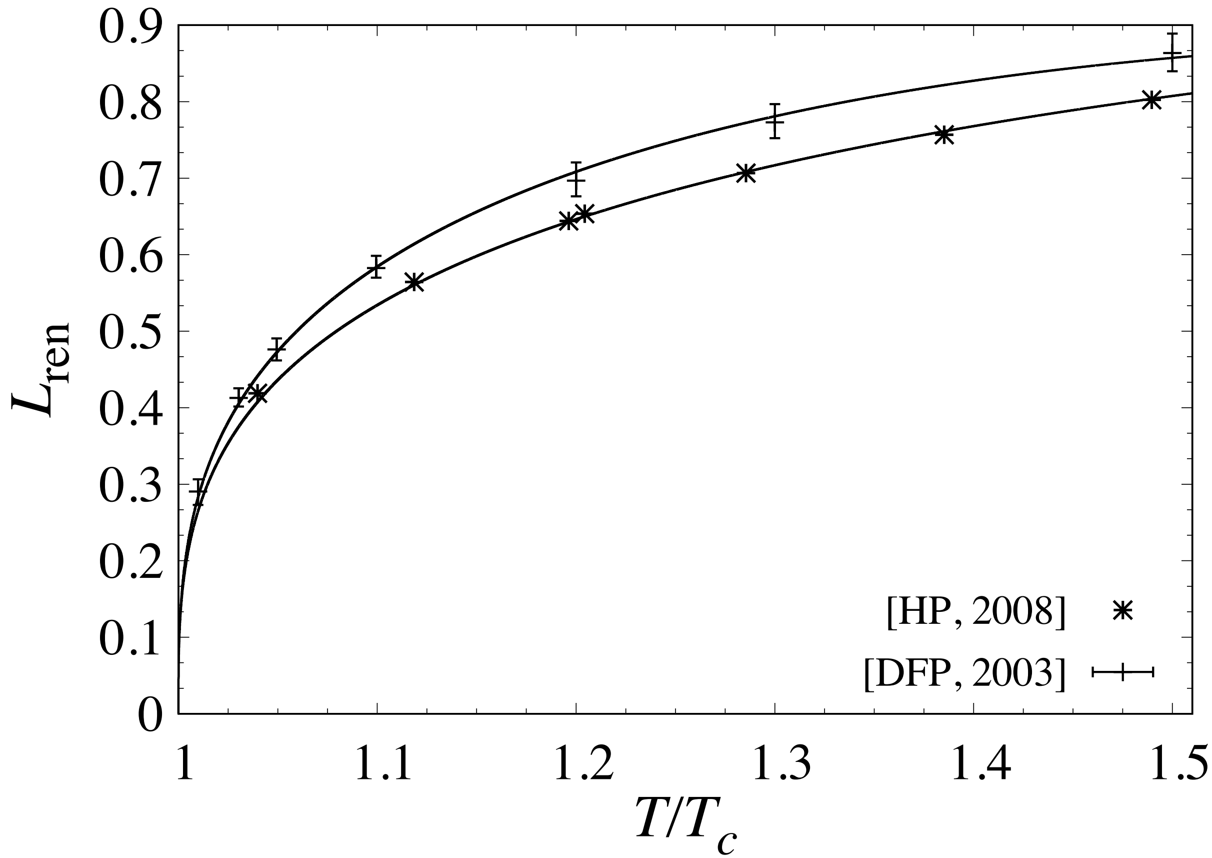
In the thermodynamic limit (V->infinity), the minimum of holonomy potential is physically realized.

Perturbative contributions always favor trivial holonomy (famous Gross-Pisarski-Yaffe potential):

$$F_p(\nu) = \frac{(2\pi)^3 T^4}{3} \nu^2 \bar{\nu}^2 \qquad \bar{\nu} \equiv 1 - \nu$$

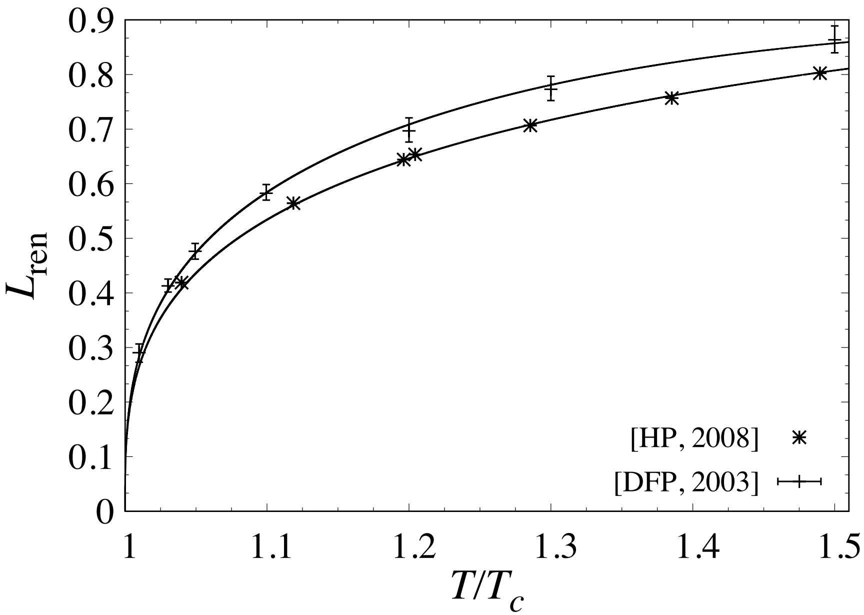
Lattice Results

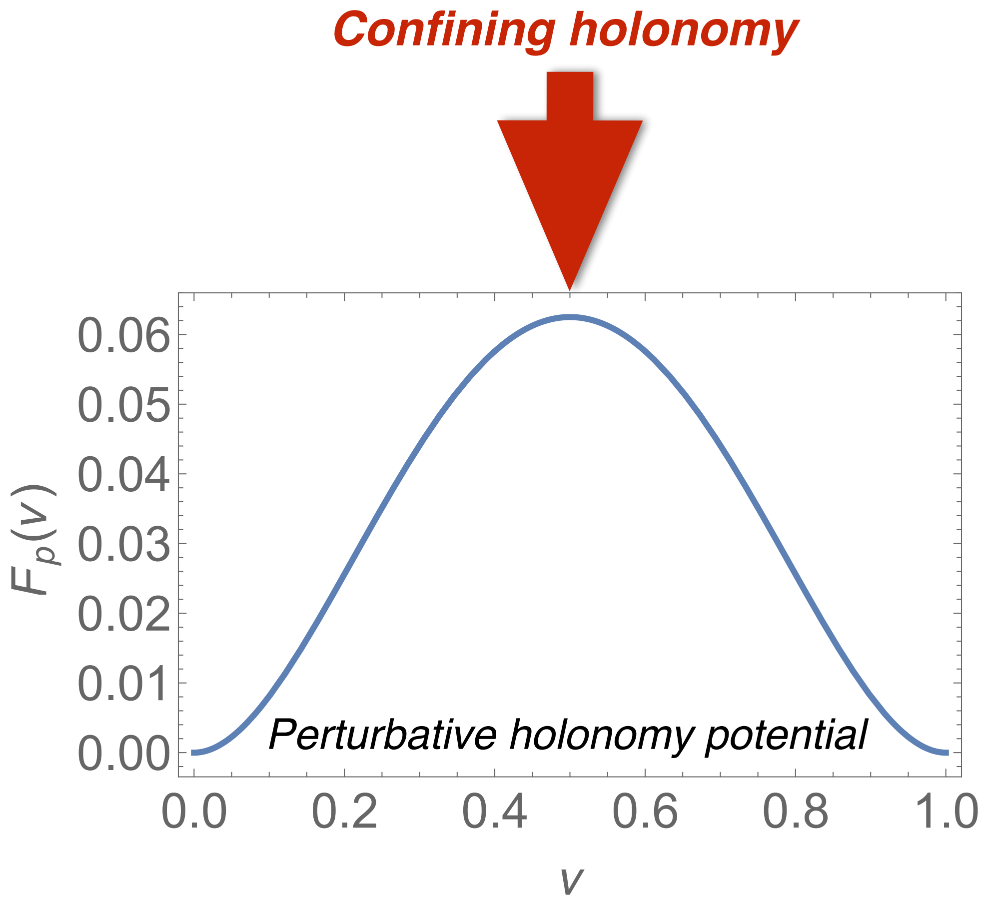
* ***2nd order phase transition***
* ***RAPID increase just above Tc***



Digal, Fortunato, Petreczky, PRD68(034008)2003
Huebner, Pica, PoS2008, arXiv:0809.3933[hep-lat]

Polyakov Loop & Holonomy





It must be nonperturbative, topological configurations that drive the system toward confining nontrivial holonomy!

Ensemble of Topological Objects

Classifying gauge field configurations according to holonomy:

$$\mathcal{Z} = \int \mathcal{D}[A_\mu]e^{-S} \to \int d\nu \left[\int \mathcal{D}[(A_\mu)|_\nu]e^{-S}\right]$$

Perturbative contributions

$$F_p(\nu) = \frac{(2\pi)^3 T^4}{3}\nu^2\bar{\nu}^2$$

$$\bar{\nu} \equiv 1 - \nu$$

Nonperturbative contributions from topological sector

$$\simeq \sum_{N_{topo}} e^{-S_{N_{topo}}}$$

[But, what types of topological objects???]

$$\to \int d\nu e^{-\beta V F(\nu)}$$

Holonomy Potential

What Are the Right DoFs?

**** Topological object***
(—nonperturbative, important at strong coupling)

**** Magnetically charged***

**** Sensitive to holonomy***

Instantons with nontrivial holonomy
— KvBLL calorons! (constructed ~1998)

KvBLL Calorons

$$S_{\mathrm{YM}} = \frac{1}{2g^2}\int \mathrm{d}^4x\, \mathrm{Tr}\, F_{\mu\nu}F_{\mu\nu}$$ where $$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - i[A_\mu, A_\nu]$$

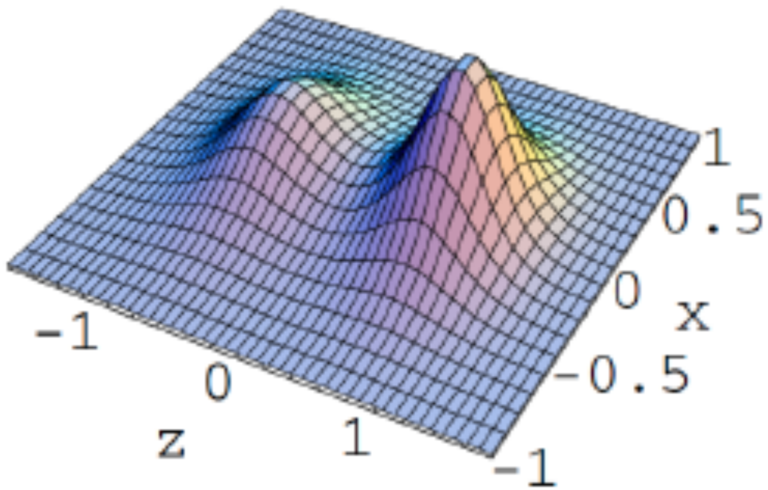
$$Q_T = \frac{1}{16\pi^2}\int \mathrm{d}^4x\, \mathrm{Tr}\, F_{\mu\nu}\tilde{F}_{\mu\nu} = \pm 1$$

$$S = \frac{8\pi^2}{g^2}$$

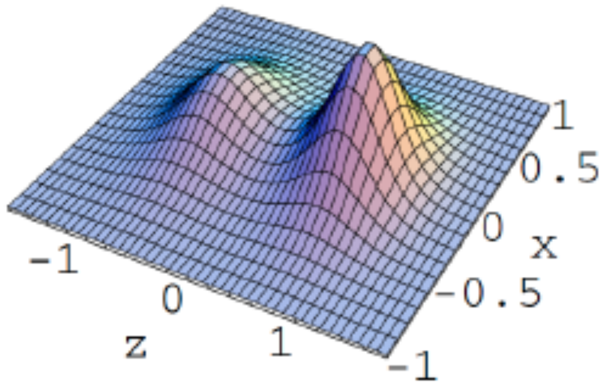
$$\boxed{A_\mu^{\mathrm{KvBLL}} = \delta_{\mu 4} v \frac{\tau^3}{2} + \frac{\tau^3}{2}\bar{\eta}^3_{\mu\nu}\partial_\nu \log\Phi + \frac{\Phi}{2}\mathrm{Re}\left[\left(\bar{\eta}^1_{\mu\nu} - i\bar{\eta}^2_{\mu\nu}\right)\left(\tau^1 + i\tau^2\right)\left(\partial_\nu + iv\delta_{\nu 4}\right)\tilde{\chi}\right]}$$

Non-trivial holonomy $v = 2\pi T\nu$ with $\nu \in [0,1]$

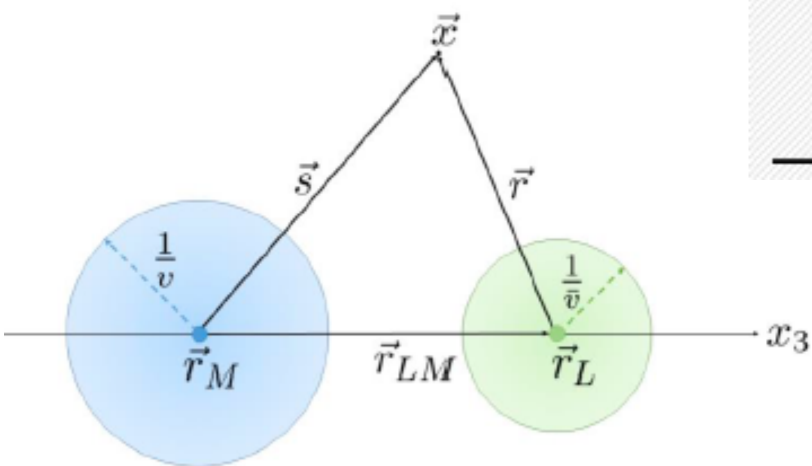
Most interestingly: this object is made of Nc constituent dyons (monopoles)!!!



Instanton-Dyons



	M	$\bar{M}$	L	$\bar{L}$
Electric charge	1	1	-1	-1
Magnetic charge	1	-1	-1	1
Action	$\nu\frac{8\pi^2}{g^2}$	$\nu\frac{8\pi^2}{g^2}$	$\bar{\nu}\frac{8\pi^2}{g^2}$	$\bar{\nu}\frac{8\pi^2}{g^2}$
Radius	v^{-1}	v^{-1}	$\bar{v}^{-1}$	$\bar{v}^{-1}$



$$v = 2\pi T\nu \,,\; \bar{v} = 2\pi T\bar{\nu}$$

Holonomy as effective "Higgsing"

The dyons inside KvBLL instantons hold the promise of driving confinement!

Building Ensemble of Instanton-Dyons

$$\mathcal{Z} = \int \mathcal{D}[A_\mu] e^{-S} \to \int d\nu \left[\int \mathcal{D}[(A_\mu)|_\nu] e^{-S} \right]$$

$$\to \int d\nu e^{-\beta V F(\nu)}$$

$$\mathcal{Z} = e^{-VP(\nu)} \sum_{\substack{N_M, N_L, \\ N_{\bar{L}}, N_{\bar{M}}}} \frac{1}{N_L! N_M! N_{\bar{L}}! N_{\bar{M}}!} \int \prod_{l=1}^{N_L} f_L T^3 \, \mathrm{d}^3 r_{L_l} \prod_{m=1}^{N_M} f_M T^3 \, \mathrm{d}^3 r_{M_m}$$
$$\times \prod_{\bar{l}=1}^{N_{\bar{L}}} f_{\bar{L}} T^3 \, \mathrm{d}^3 r_{\bar{L}_{\bar{l}}} \prod_{\bar{m}=1}^{N_{\bar{M}}} f_{\bar{M}} T^3 \, \mathrm{d}^3 r_{\bar{M}_{\bar{m}}} \det(G_D) \det(G_{\bar{D}}) \, e^{-V_{D\bar{D}}}$$

In short: sum over a statistical ensemble of many L & M Instanton-dyons with interactions (with 1-loop perturbative quantum fluctuations included)

Dyon-anti-Dyon Correlations

"Gas" ensemble: negligible correlations;
"Liquid" ensemble: significant short range correlations
—> —> Properties of the ensemble crucially depend on such correlations!

$$\mathcal{Z} = e^{-VP(\nu)} \sum_{\substack{N_M, N_L, \\ N_{\bar{L}}, N_{\bar{M}}}} \frac{1}{N_L! N_M! N_{\bar{L}}! N_{\bar{M}}!} \int \prod_{l=1}^{N_L} f_L T^3 \, \mathrm{d}^3 r_{L_l} \prod_{m=1}^{N_M} f_M T^3 \, \mathrm{d}^3 r_{M_m}$$

$$\times \prod_{\bar{l}=1}^{N_{\bar{L}}} f_{\bar{L}} T^3 \, \mathrm{d}^3 r_{\bar{L}_{\bar{l}}} \prod_{\bar{m}=1}^{N_{\bar{M}}} f_{\bar{M}} T^3 \, \mathrm{d}^3 r_{\bar{M}_{\bar{m}}} \det(G_D) \det(G_{\bar{D}}) \, e^{-V_{D\bar{D}}}$$

Implemented via interaction potential energy term

The Correlation Potential

$$V_{D\bar{D}} = \begin{cases} \sum_{i,\bar{j}} \frac{S}{\pi T r_{i\bar{j}}} e^{-M_D r_{i\bar{j}}} & \text{for } \bar{M}L, \bar{L}M \\ \sum_{i,\bar{j}} \frac{-S}{\pi T r_{i\bar{j}}} e^{-M_D r_{i\bar{j}}} & \text{if } \zeta_j > \zeta_j^c, \text{ for } LL, M\bar{M} \\ \sum_{\substack{i>j \\ j,\bar{j}}} V_{ij}^C & \text{if } \zeta_j < \zeta_j^c, \text{ for } \begin{array}{l} LL, MM, \\ \bar{L}\bar{L}, \bar{M}\bar{M}, \\ L\bar{L}, M\bar{M} \end{array} \\ 0 & \text{for } LM, \bar{L}\bar{M}. \end{cases}$$

Long range correlations are dictated by the charges of the objects.

Short range correlations are mimicked with repulsive core

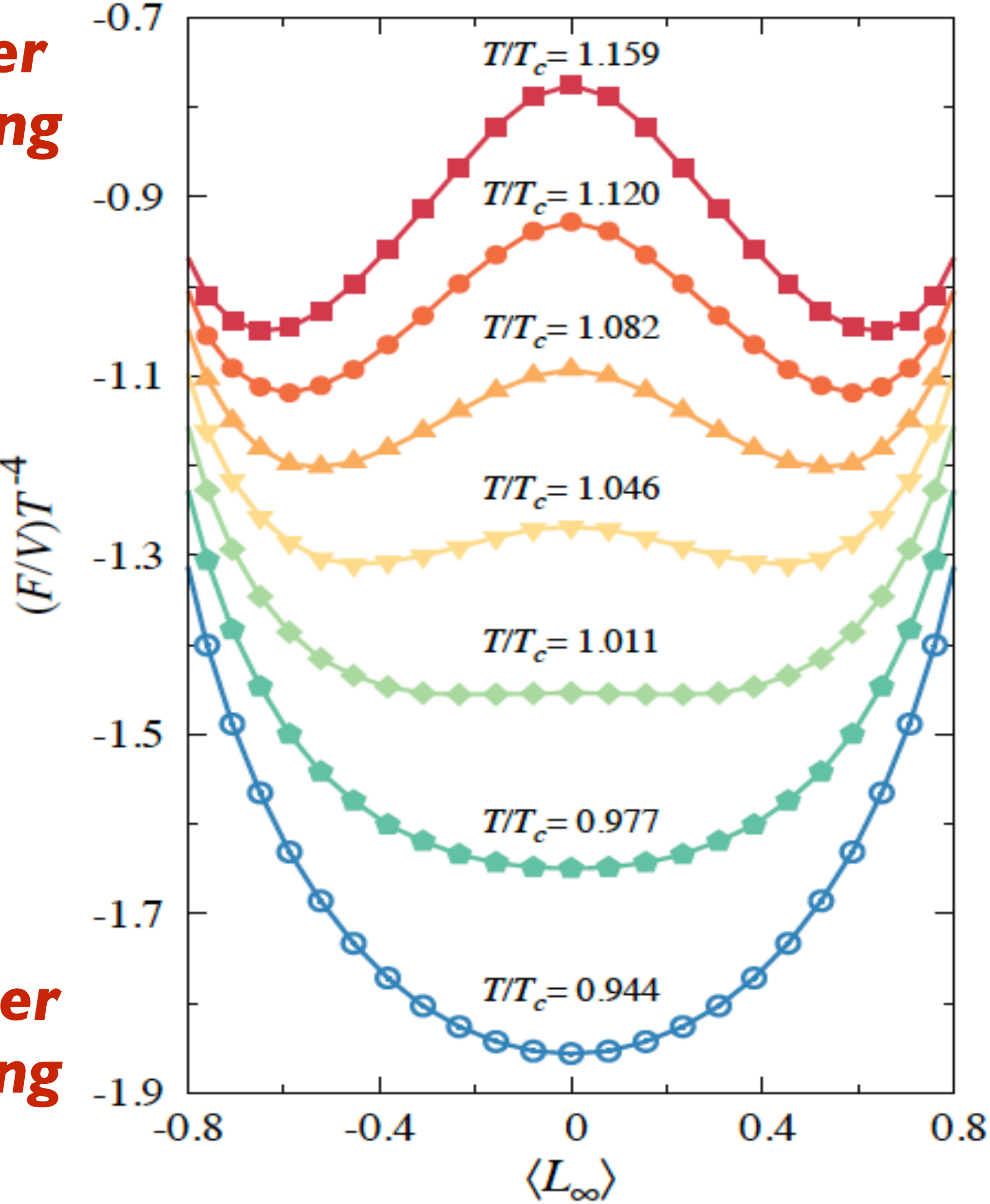
$$V_{j\bar{j}}^C = \frac{\nu_j V_c}{1 + e^{(\zeta_j - \zeta_c)}}, \quad \zeta_j = 2\pi \nu_j T r_{j\bar{j}}$$

A repulsive core potential is crucial for enforcing confinement!
[first shown by Shuryak and collaborators]

The Holonomy Potential

Weaker coupling

Stronger coupling

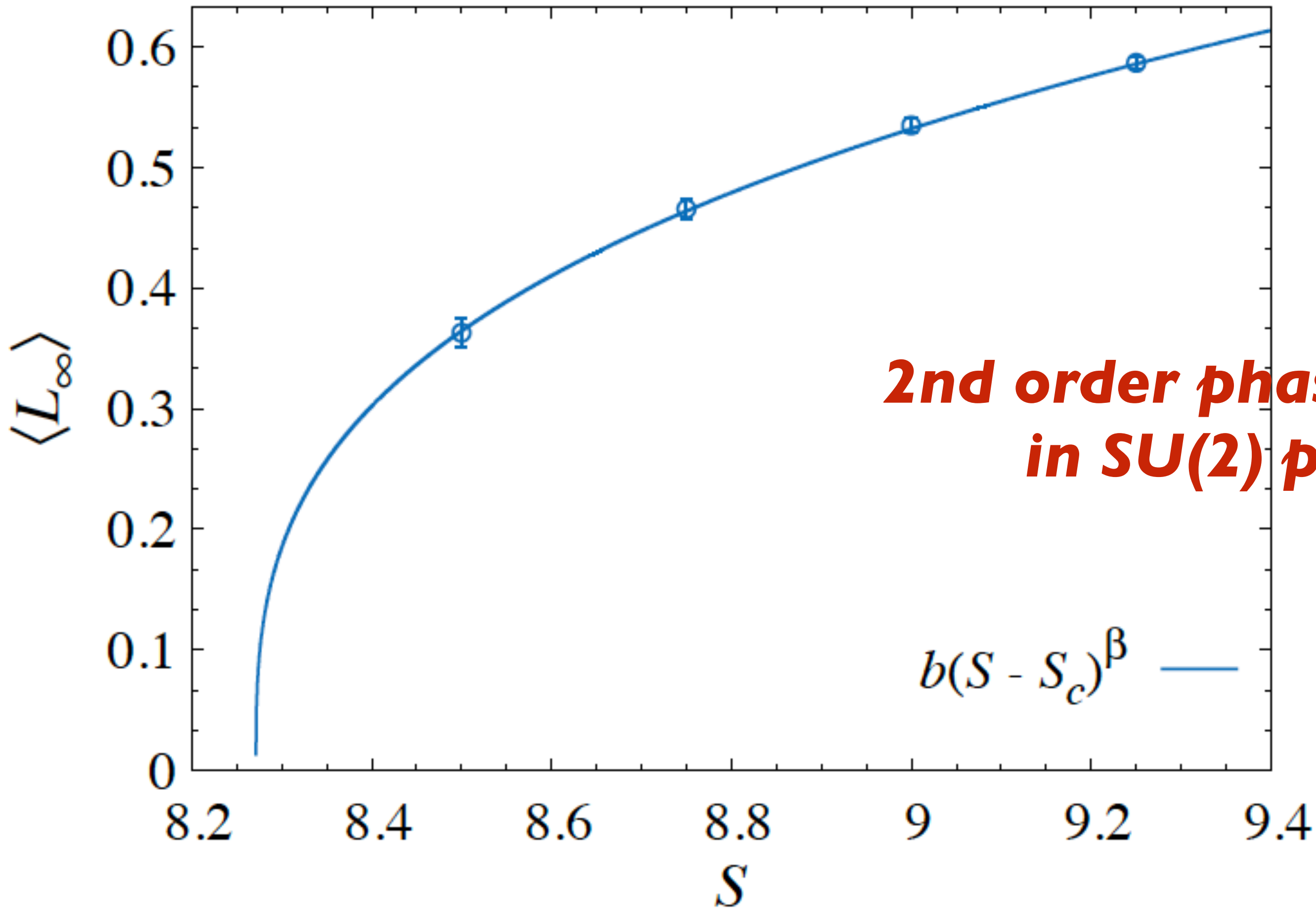


Diluter

A change of shape from high to low T!

Denser —> Short range correlations become really important!

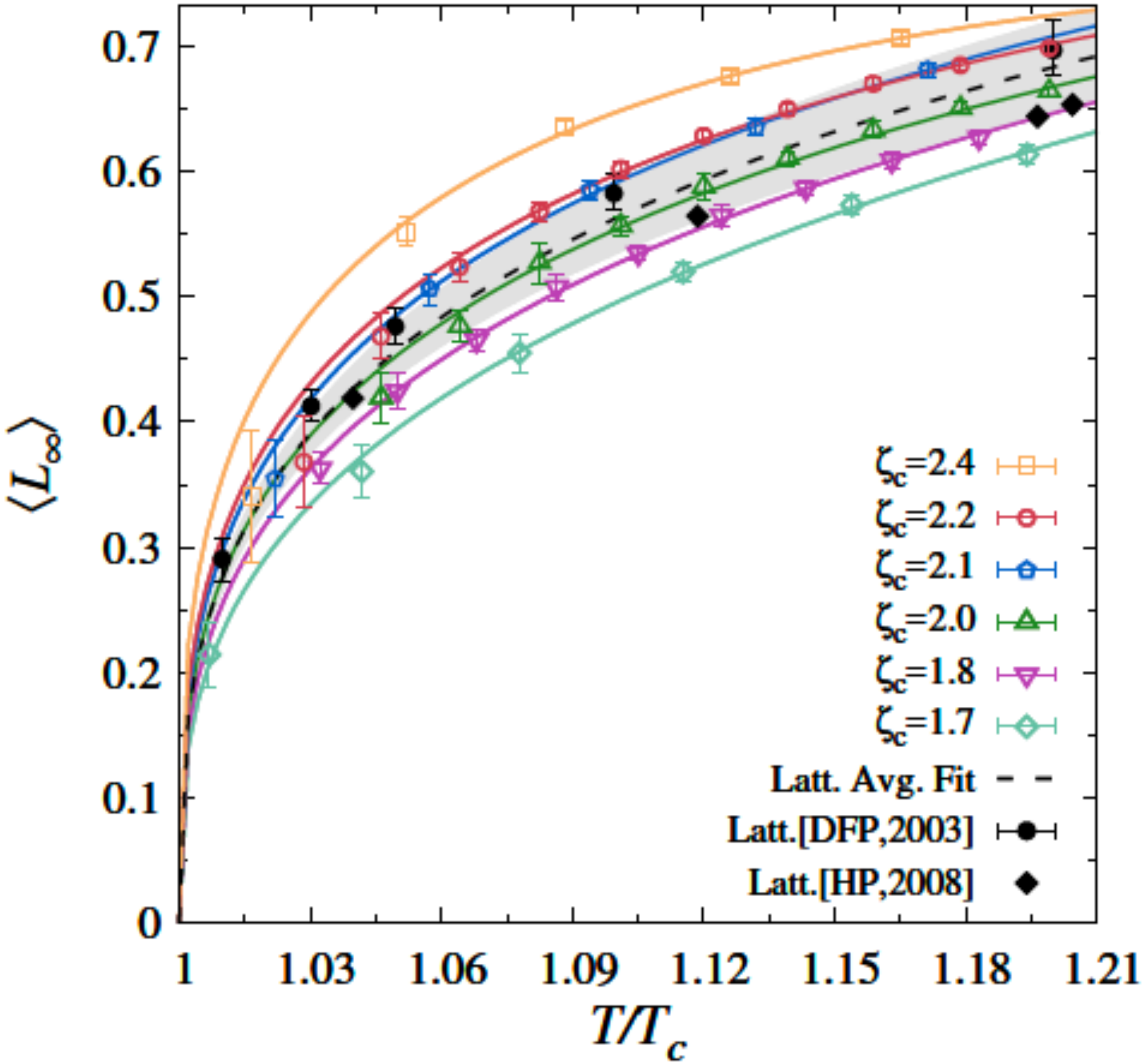
Confinement Driven by Instanton-Dyons



2nd order phase transition in SU(2) pure YM

$$\langle L_\infty \rangle \propto (S - S_c)^\beta, \quad \beta = 0.3265(3)$$

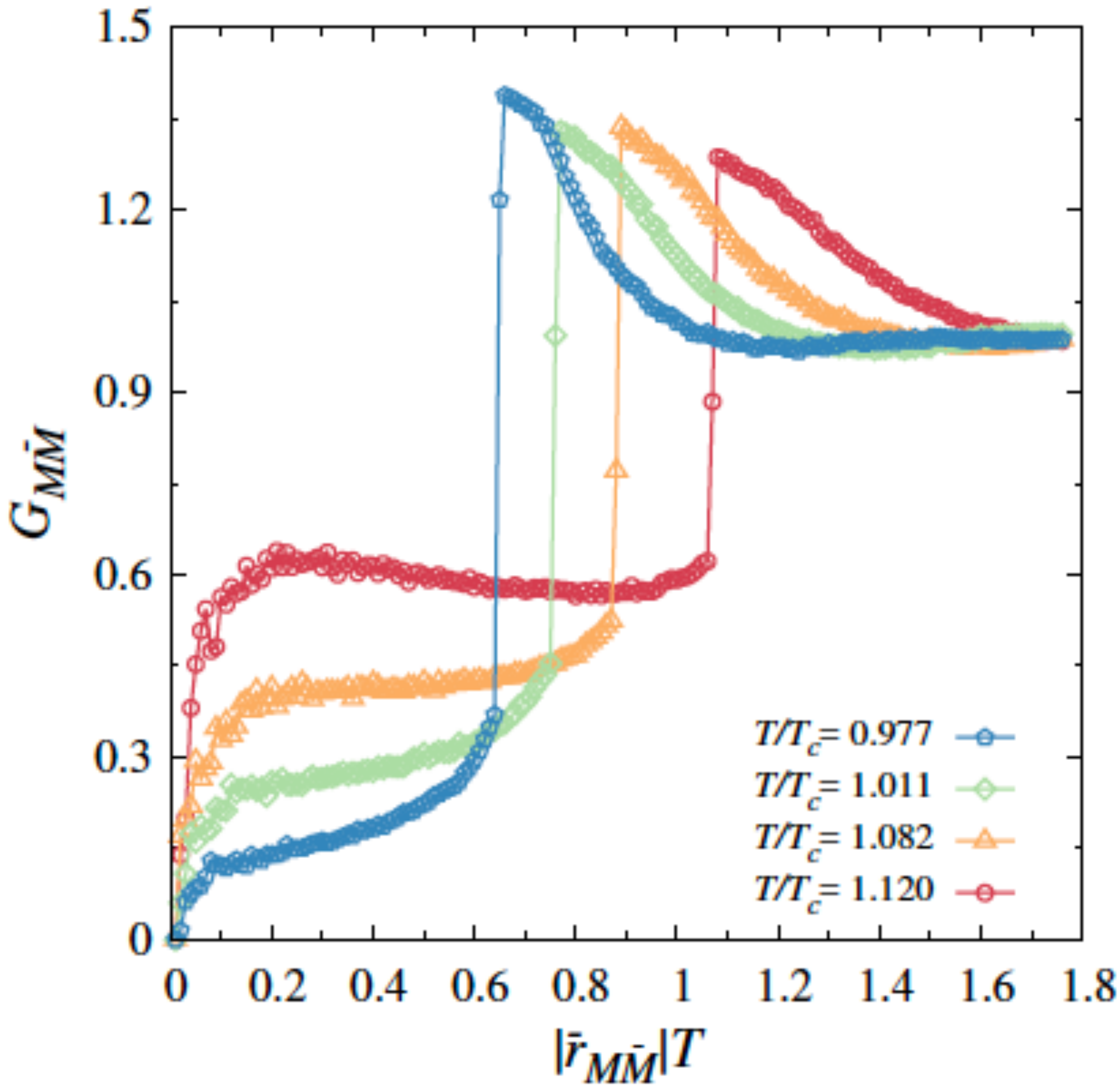
Confinement Driven by Instanton-Dyons



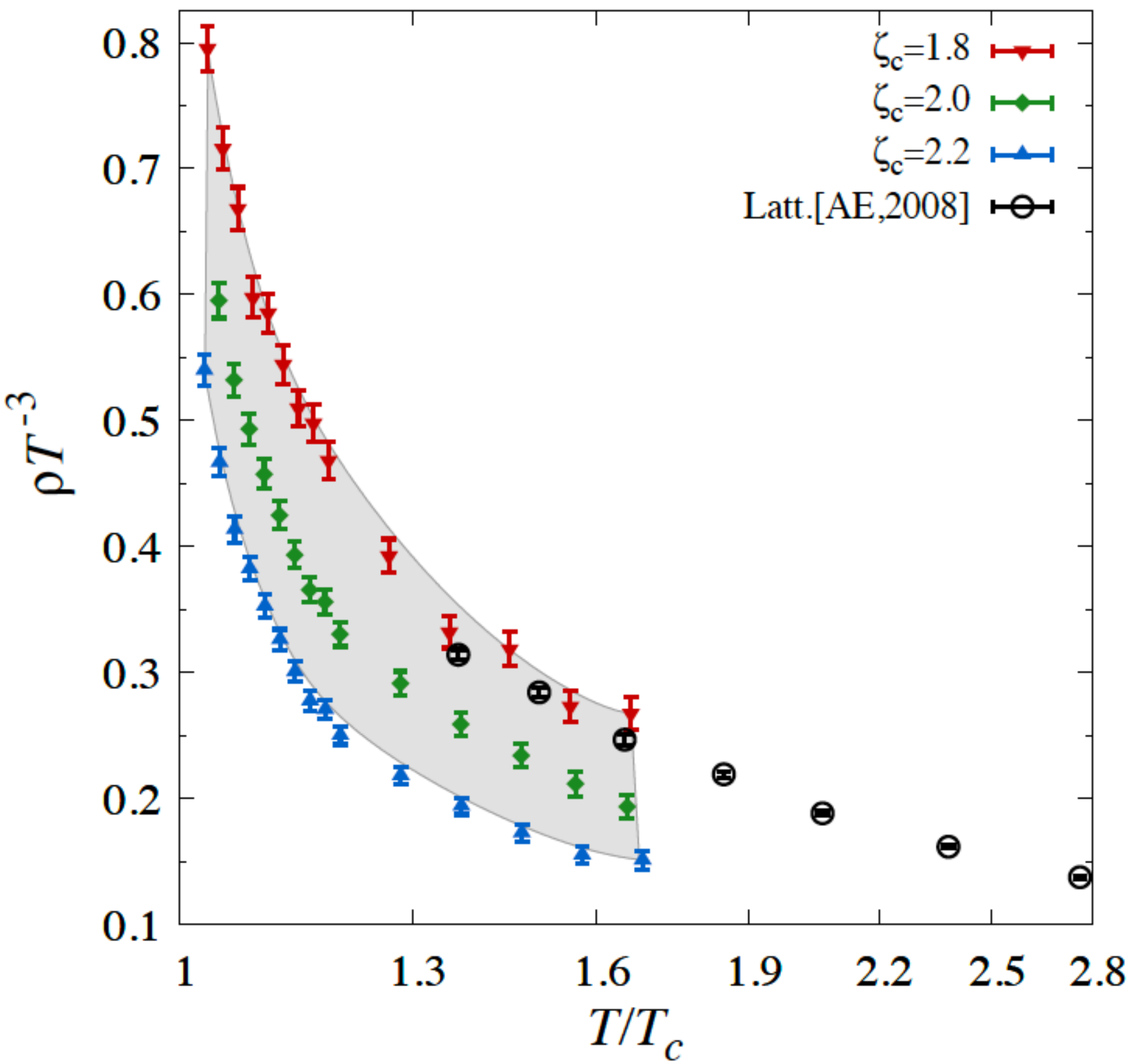
Confinement dynamics is sensitive to the short range correlations

Key parameter: the range parameter of the core

Strongly Correlated Ensemble



Emergent DoF Toward Tc



Summary

Quest for DoFs

T<< Lambda_QCD

T ~ Lambda_QCD

T>> Lambda_QCD

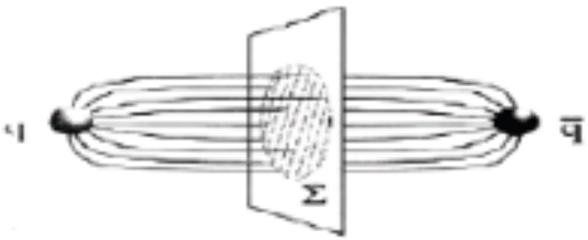
Vacuum: confined

Tc

sQGP

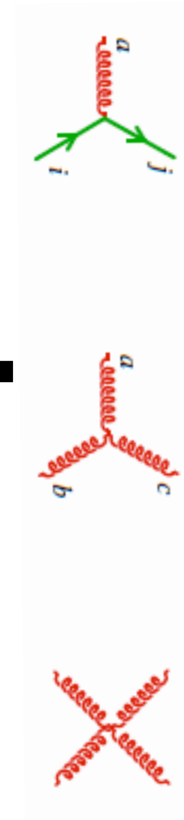
wQGP: screening

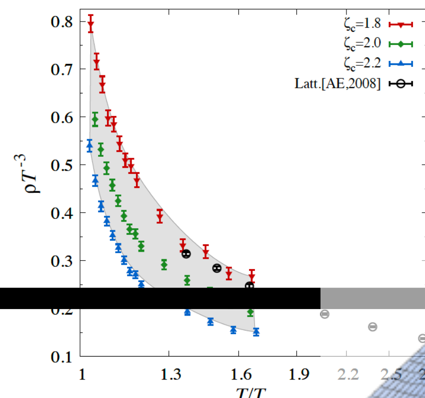
T

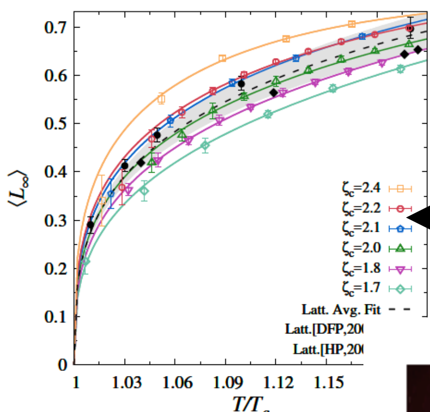


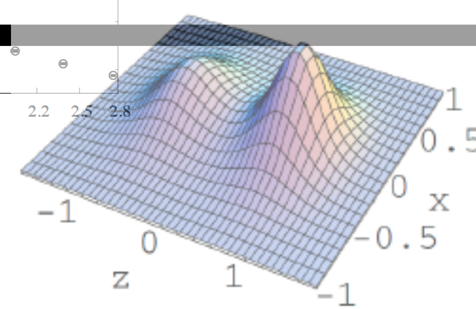
Emergent plasma
with E & M charges:
chromo-magnetic monopoles
are the "missing DoF"

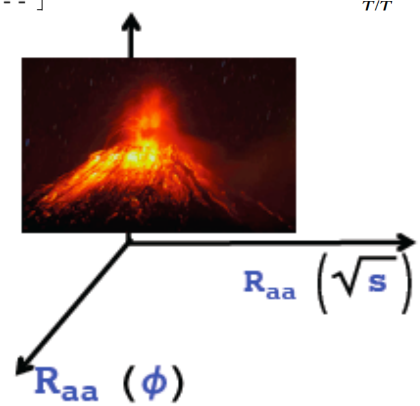
Plasma of E-charges
E-screening: g T
M-screening: g^2 T











Quest for DoFs: Are We There Yet?

Edward: hope this keep you busy for many more creative years ahead!
We will check progress at your 80th celebration!