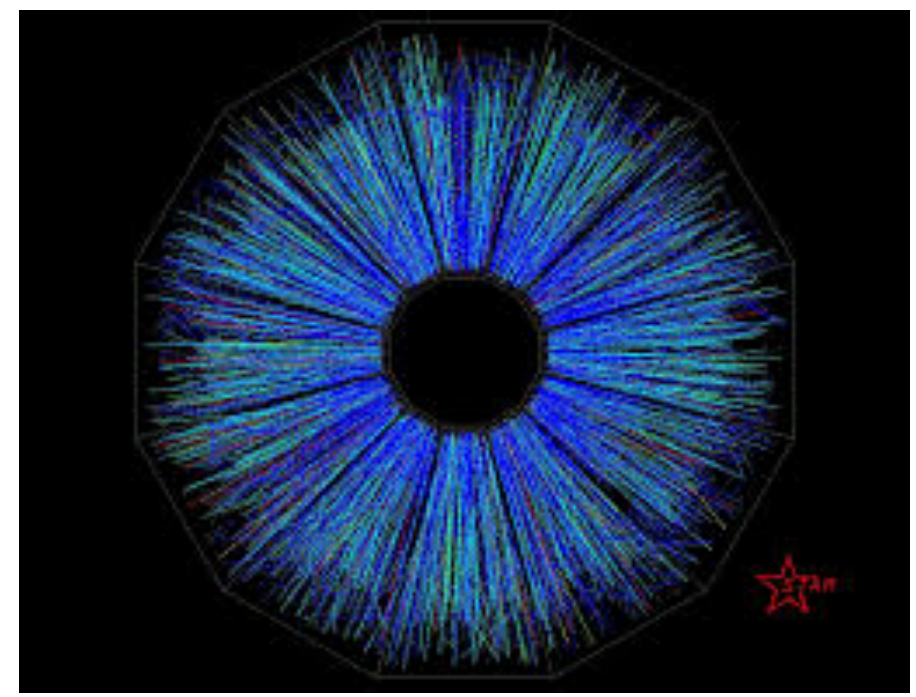
Gauge topology and heavy ion physics

Edward Shuryak
Stony Brook University



Xtreme QCD workshop 2018, Frankfurt

outline

Why is sQGP so unusual? The "magnetic scenario"

- Kinetic coefficients (viscosity and jet quenching)
- Both indicate very strong rescatering peaking at
- T=(1-2)Tc
- Only the monopole density peaks there!
- More on the dual plasmas

The interrelation of topological objects: instants, instanton-dyons and monopoles

- Brief summary of instanton-dyons
- Relation between instanton-dyons and monopoles
- Monopoles explain not only confinement (BEC)
- But chiral symmetry breaking as well

matter composition, by d.o.f.

quarks

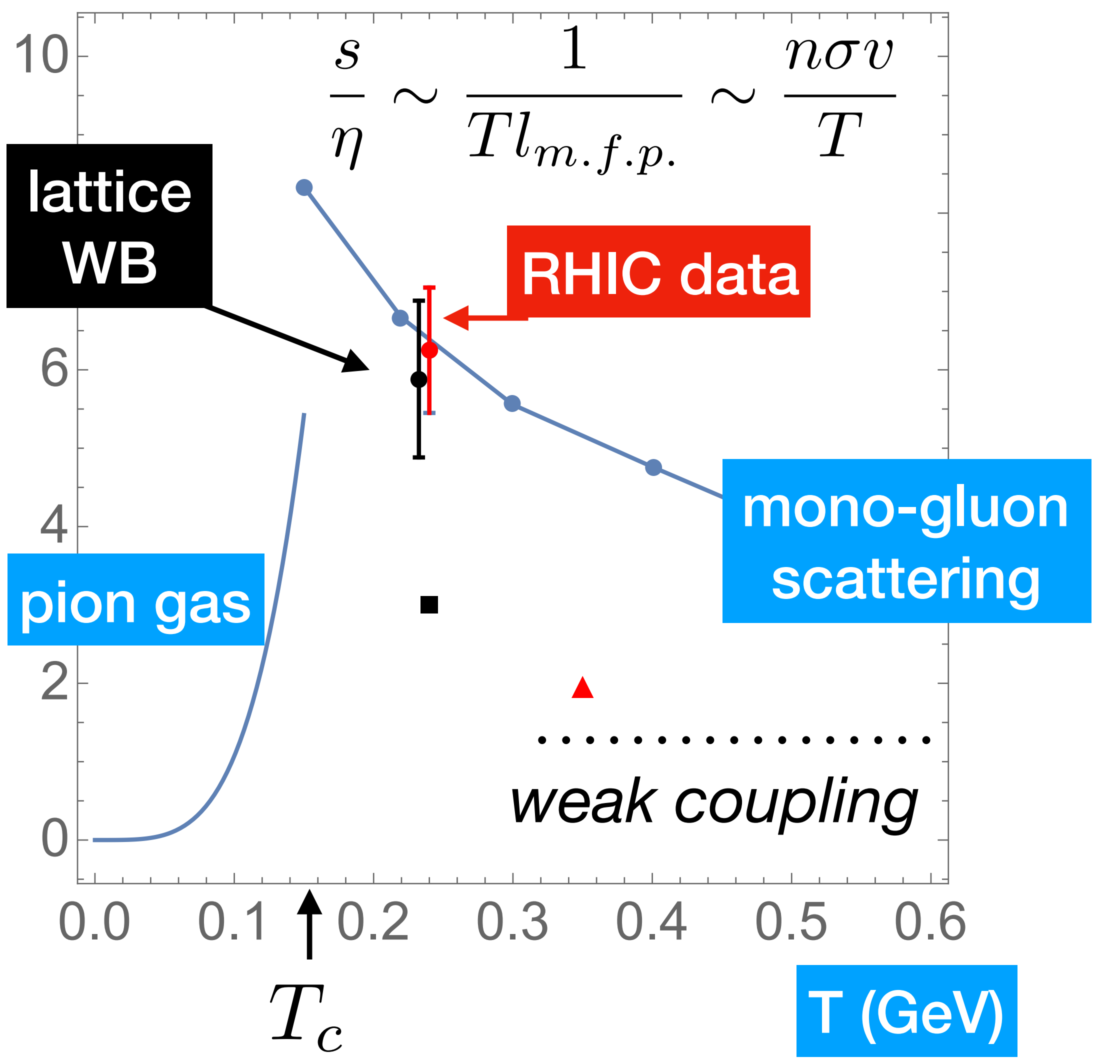
monopoles

gluons

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**

T/Tc

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



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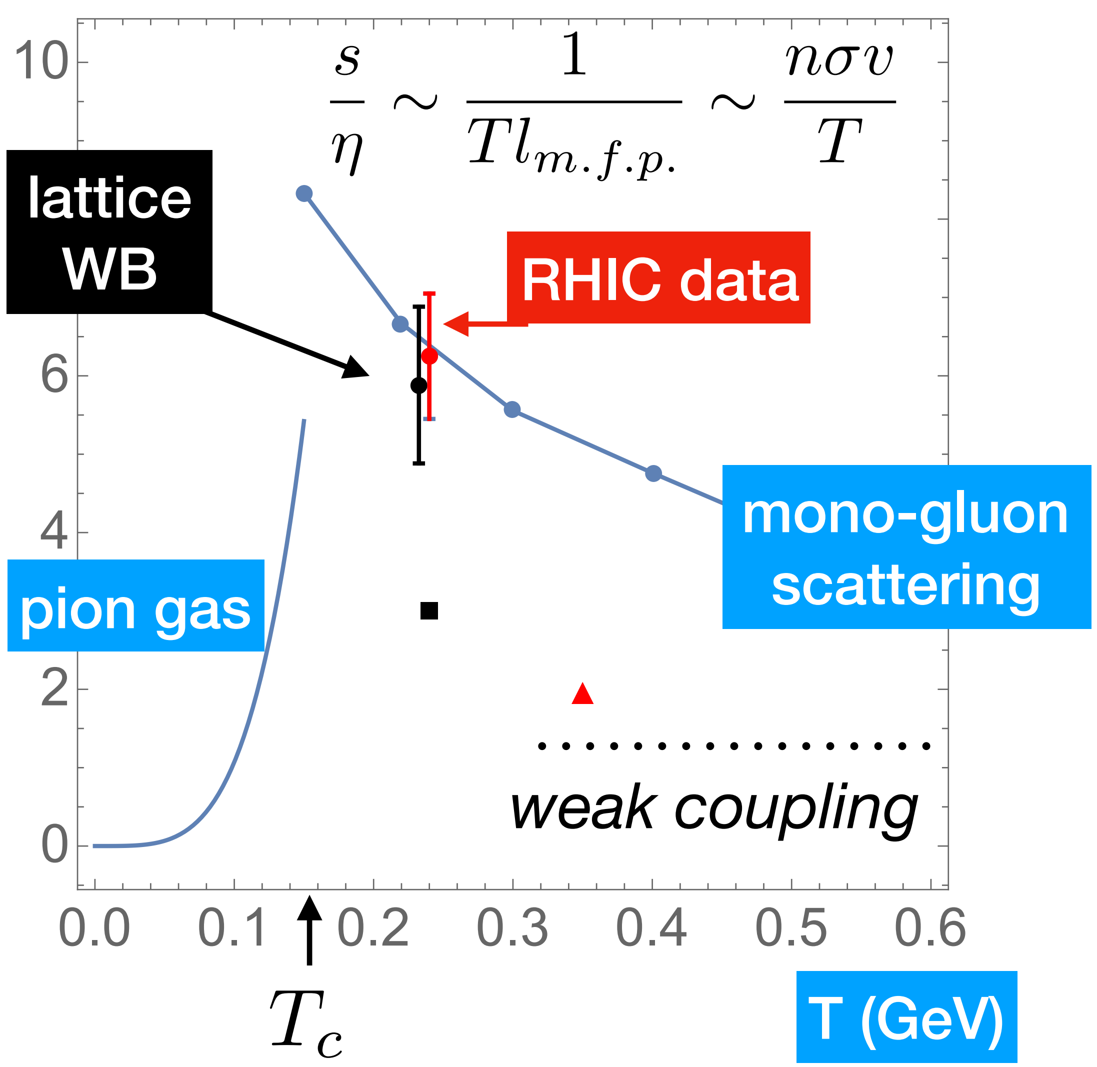

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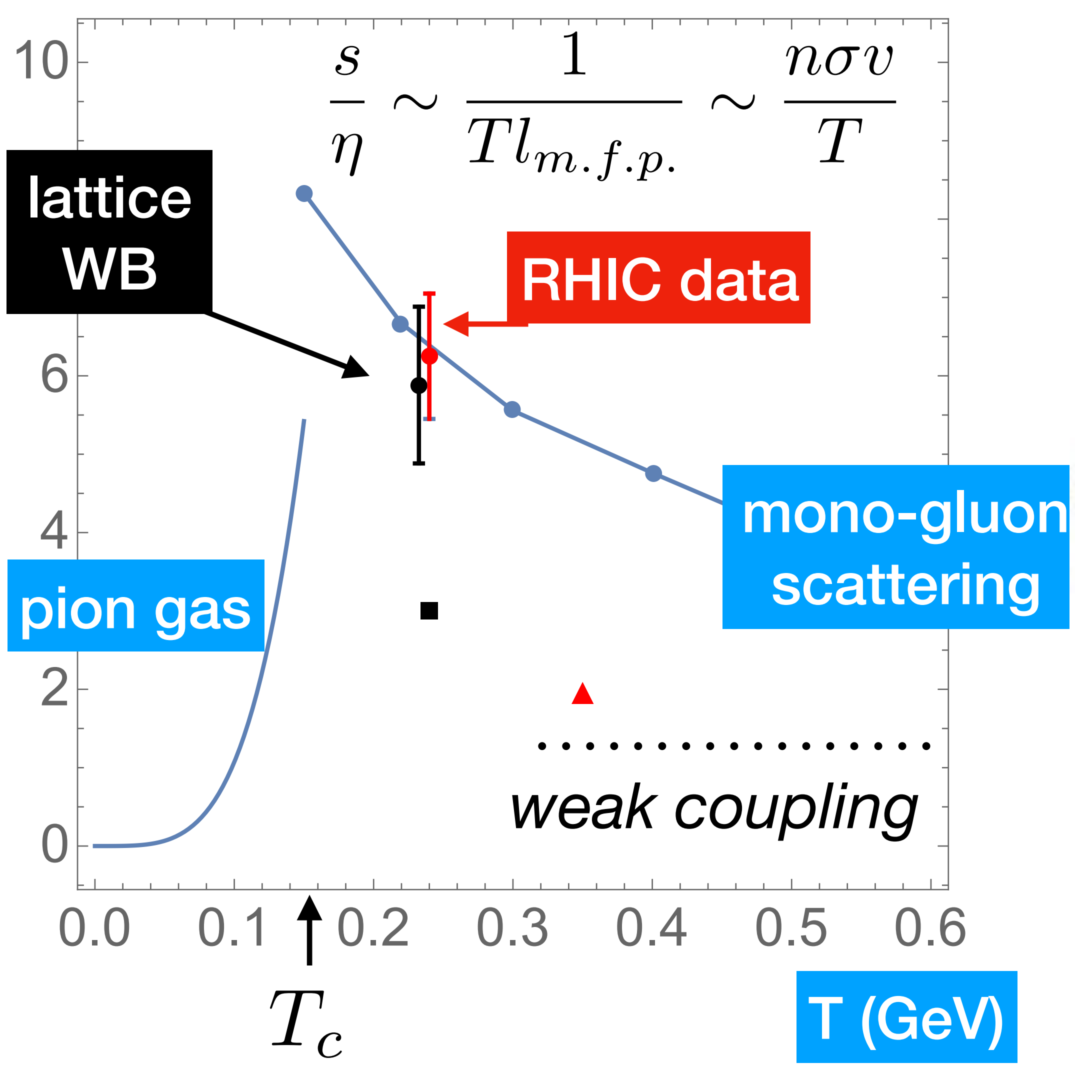

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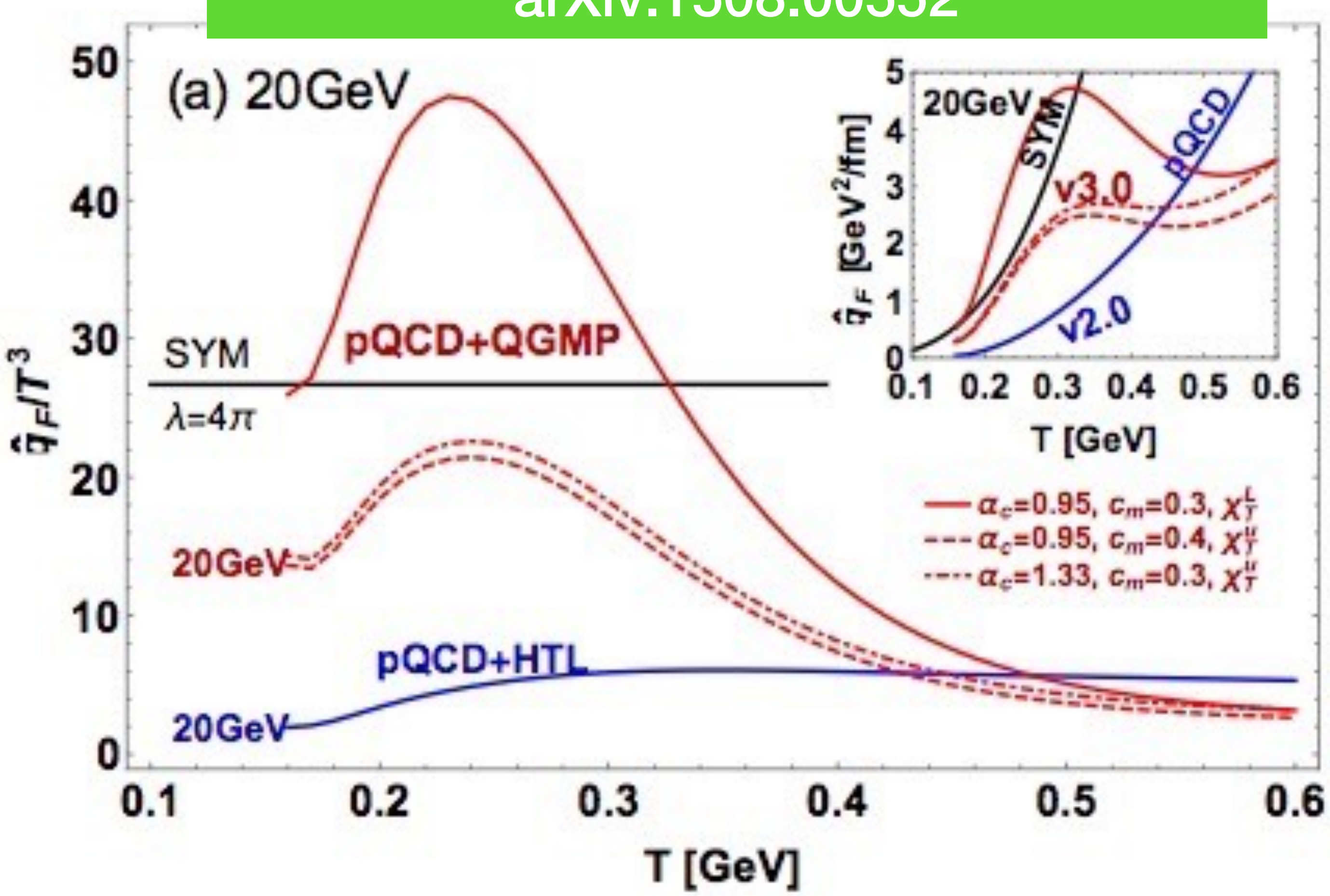

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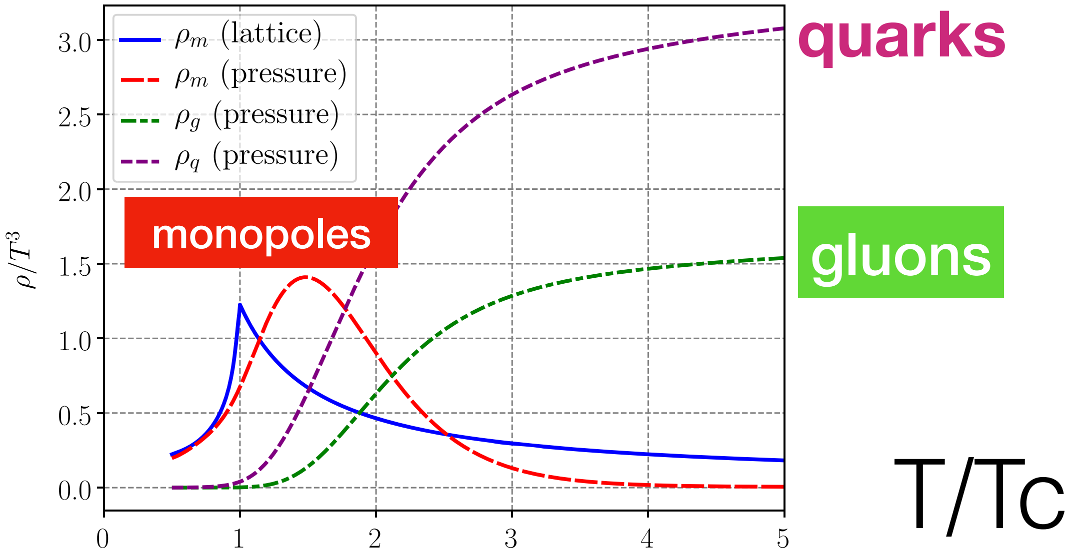

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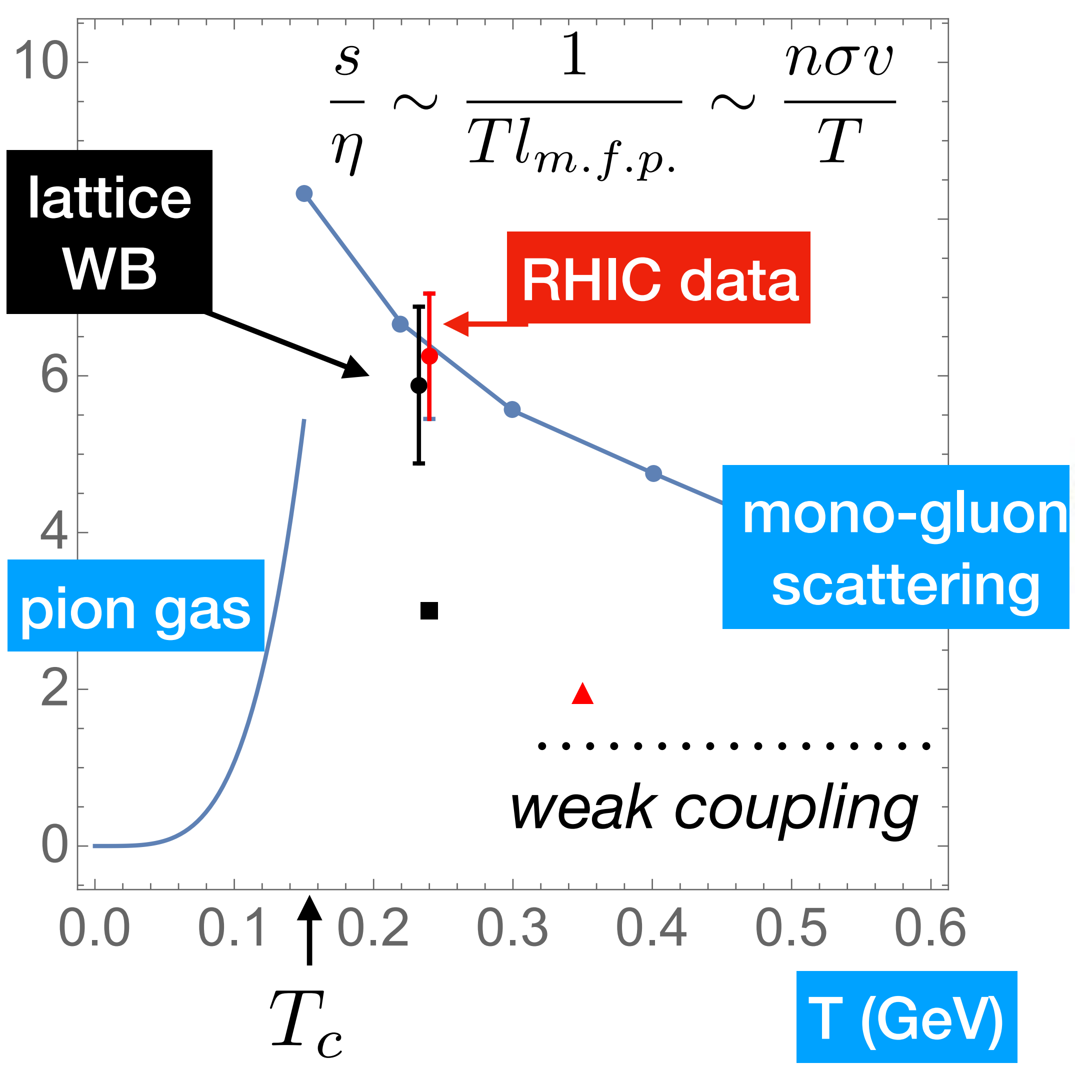

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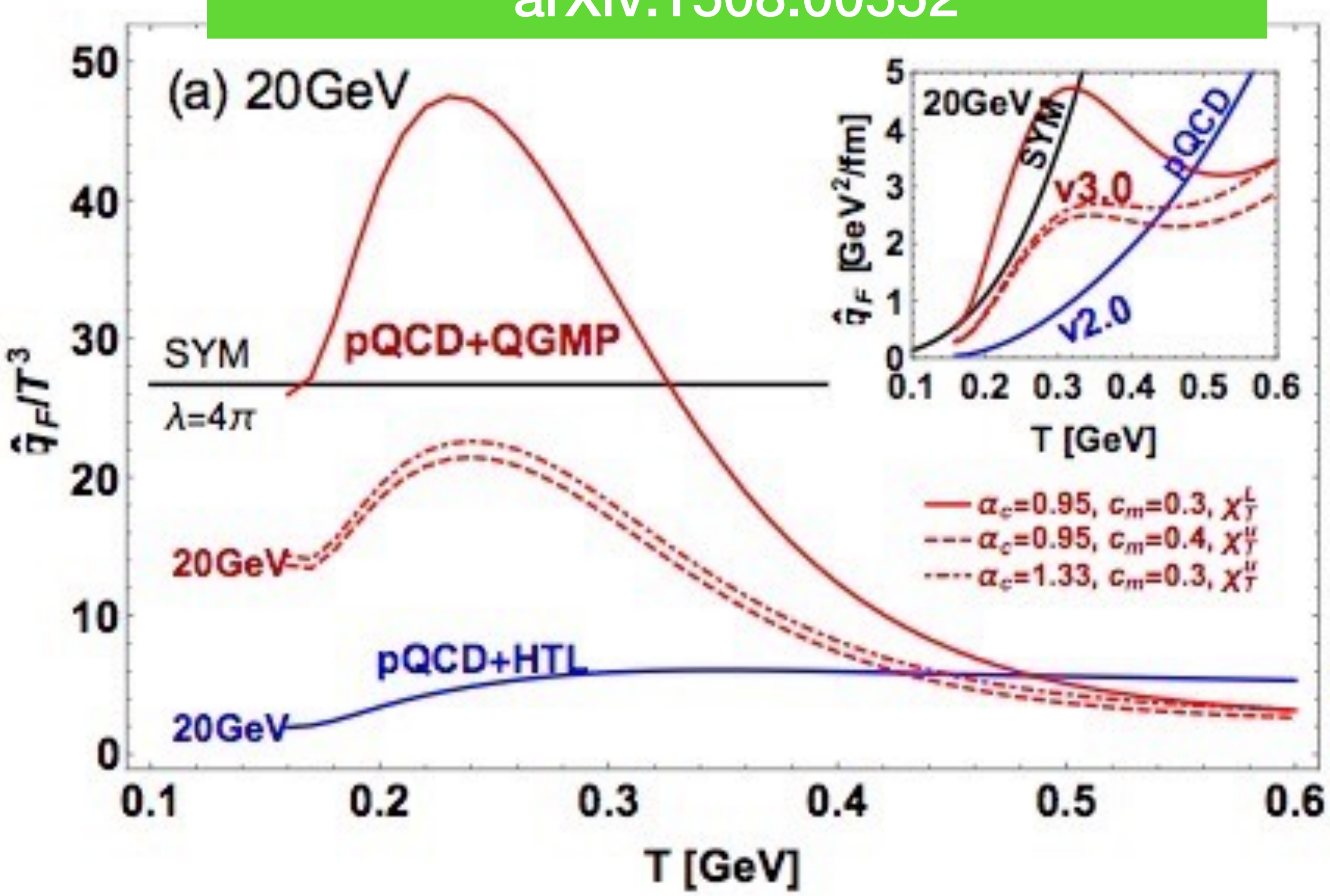

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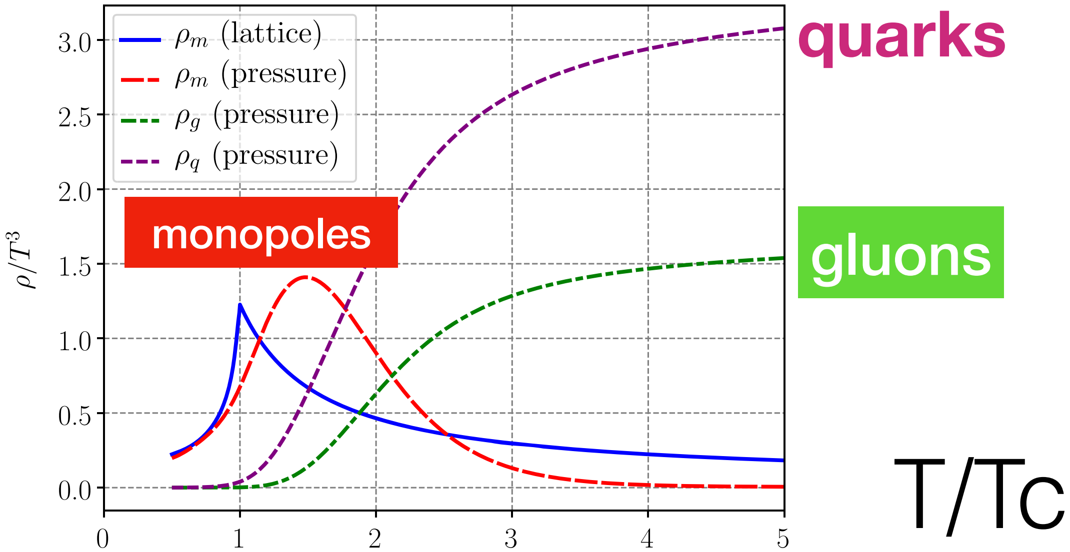

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only the monopole density peaks near Tc!

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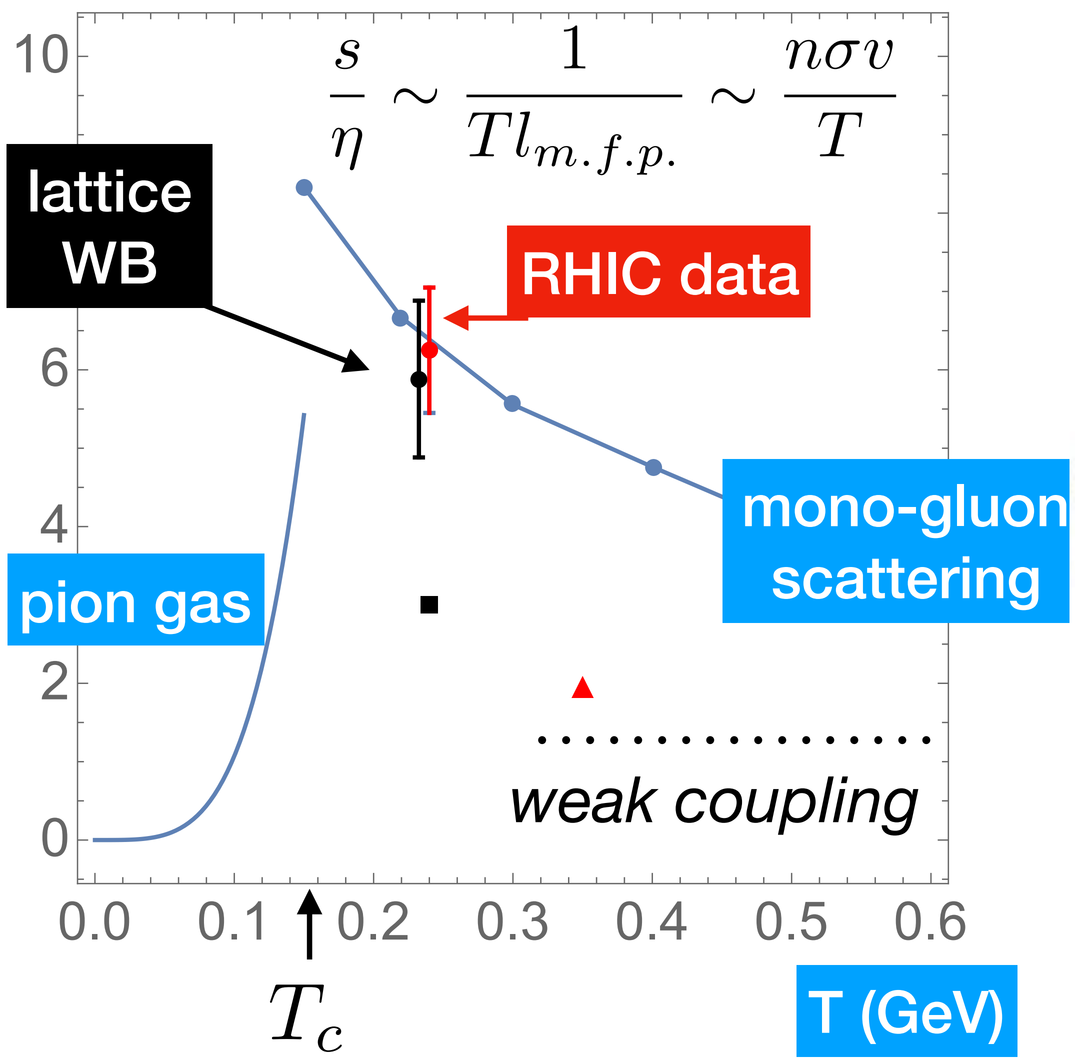

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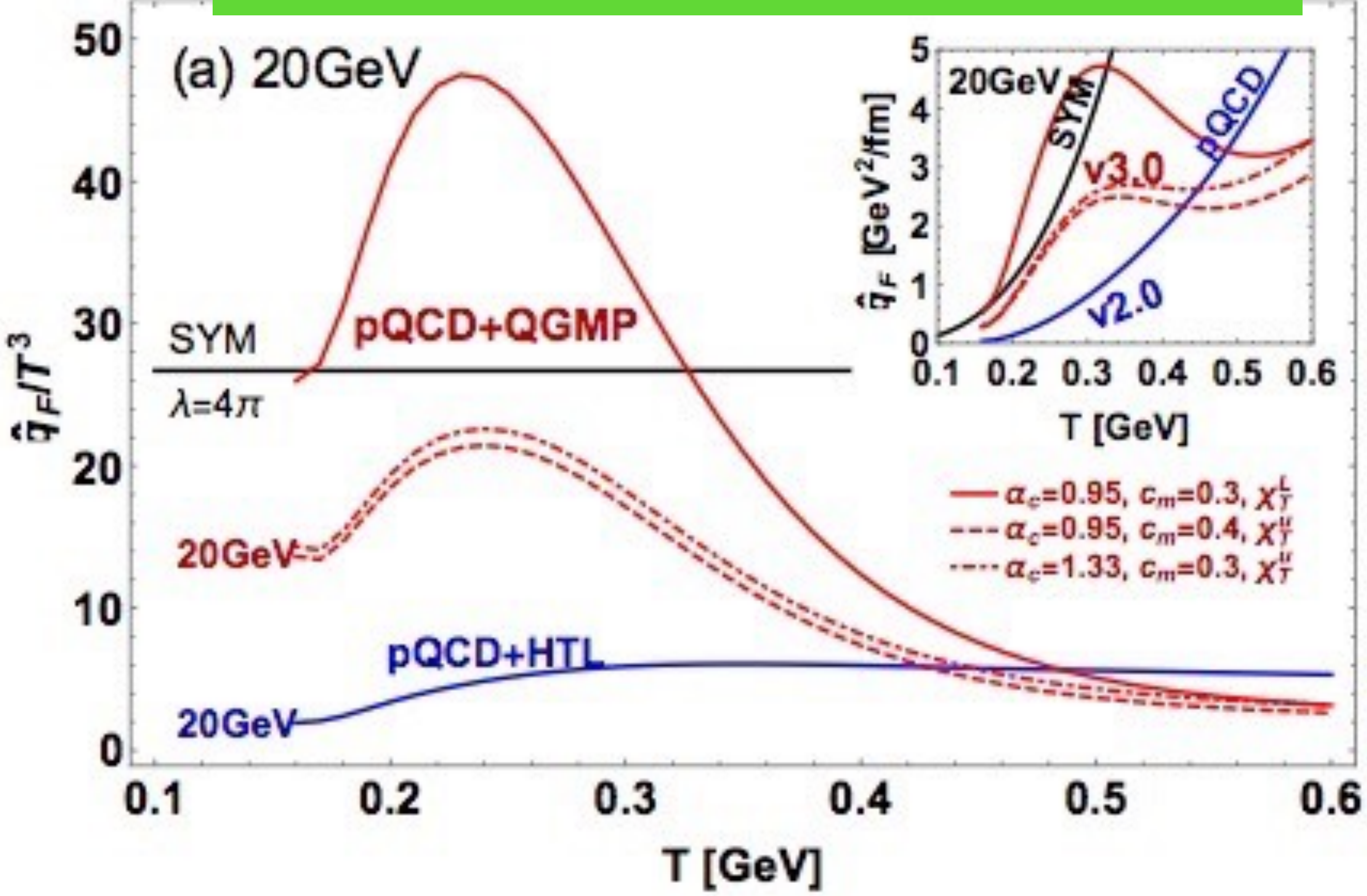
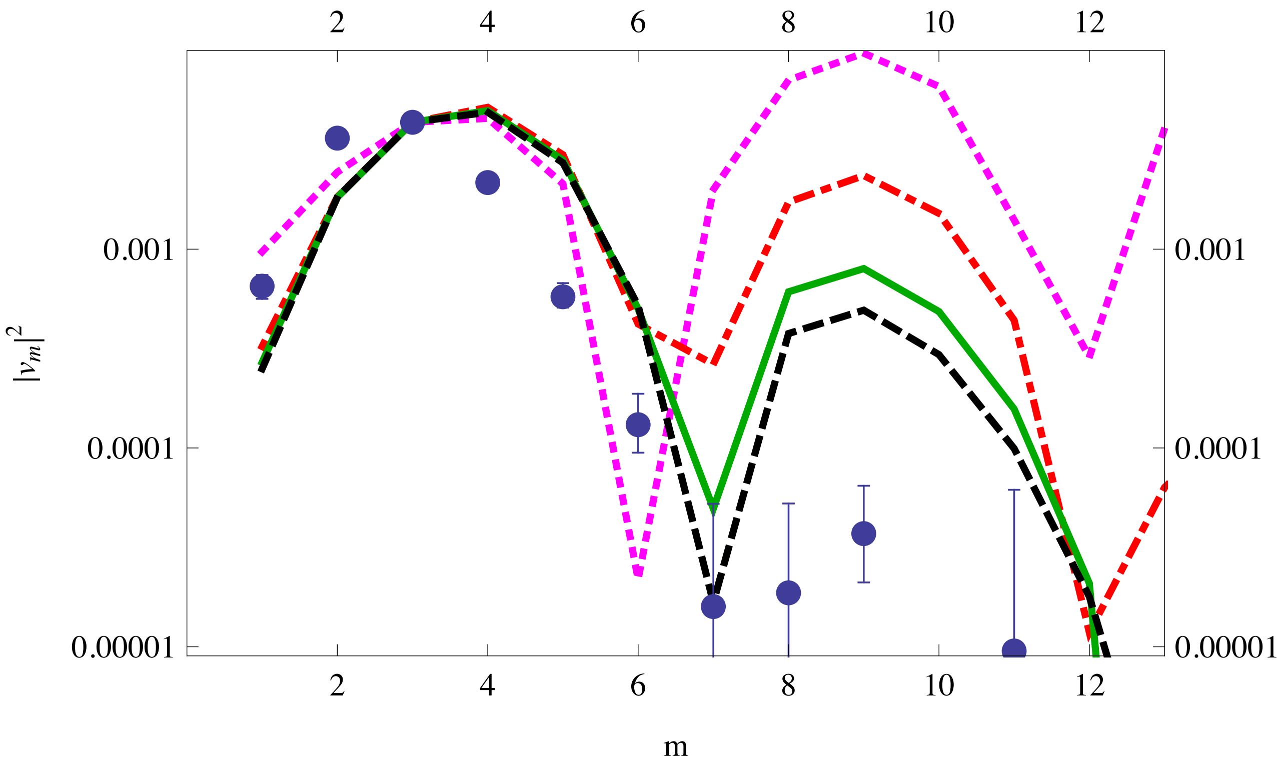
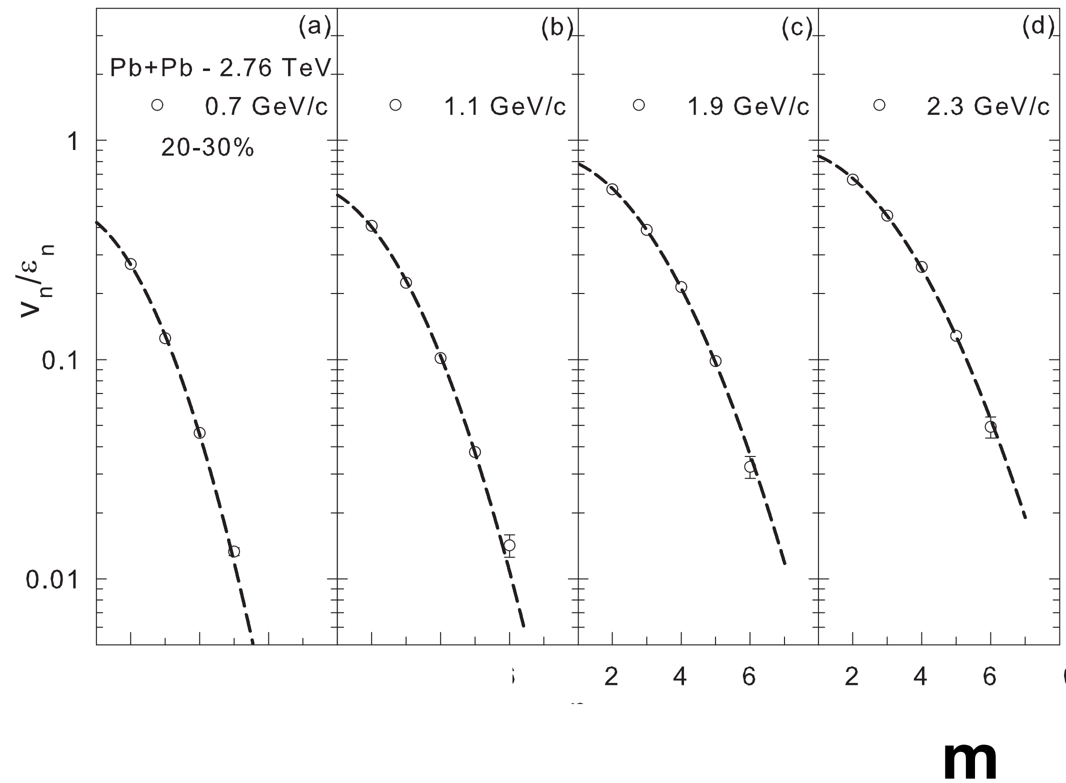


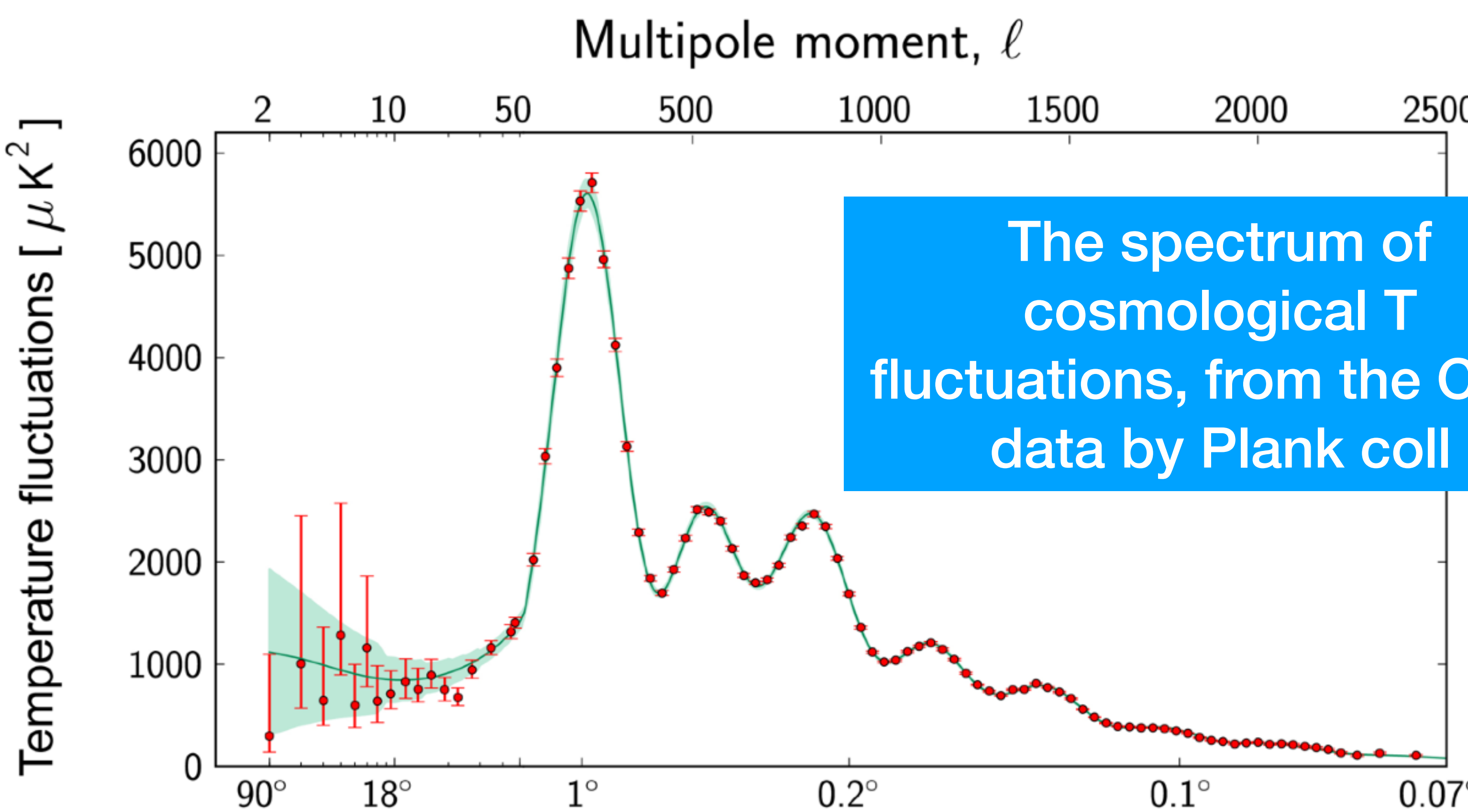
the spectrum of azimuthal harmonics show the effect of viscous damping much more clearly

data from ATLAS coll

$$P_m = \exp\left[-m^2 \frac{4}{3}\left(\frac{\eta}{s}\right)\left(\frac{1}{TR}\right)\right]$$



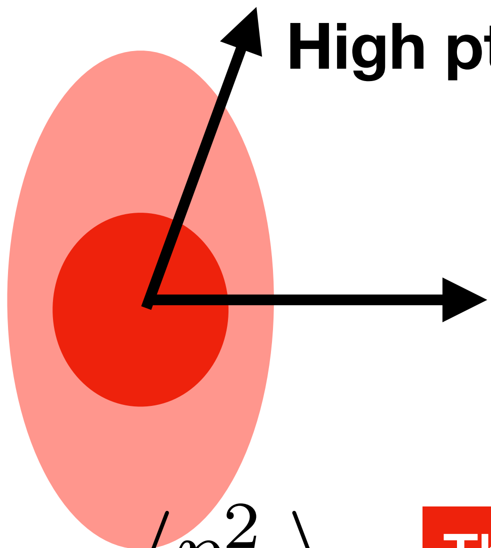




The spectrum of cosmological T fluctuations, from the CMB data by Plank coll

the sounds of the Little and Big Bang

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



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

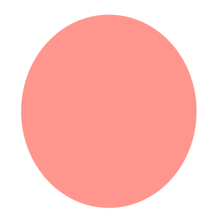
A jet in shorter x direction suffers less quenching by matter

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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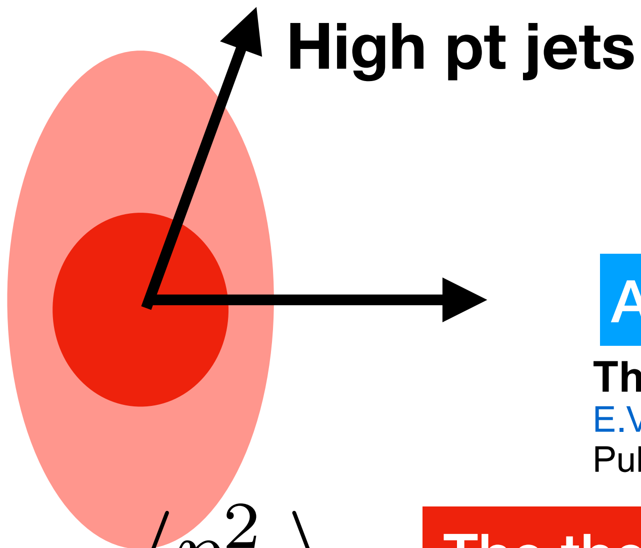

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the quenching is proportional to the density.
And the most dense region (shown by the dark red)
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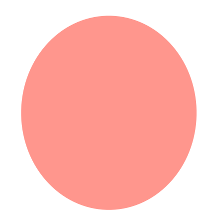
Perhaps quenching peaks at intermediate density?



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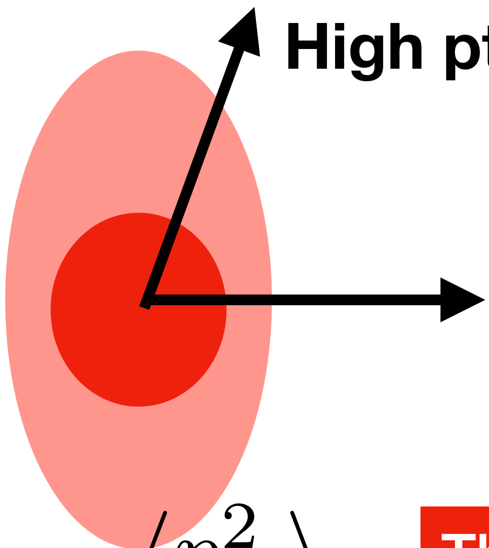

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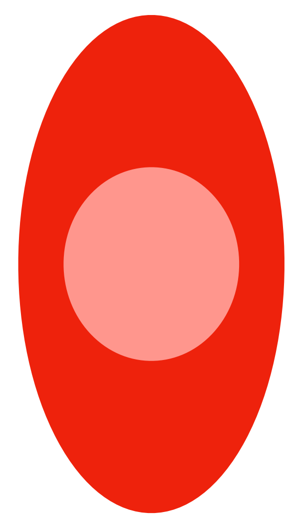

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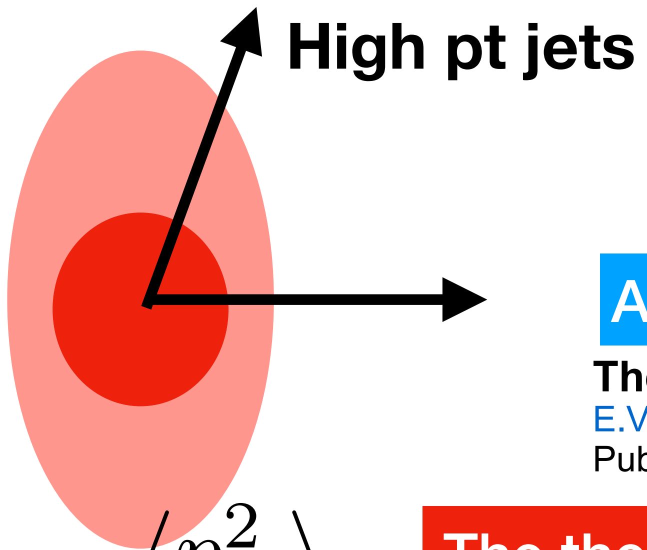

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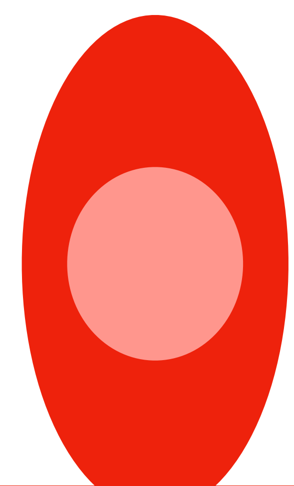
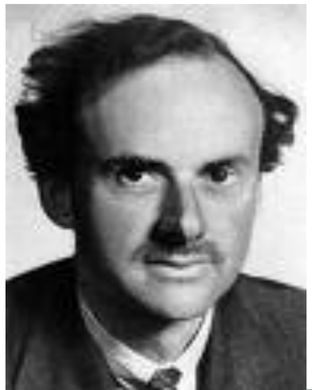
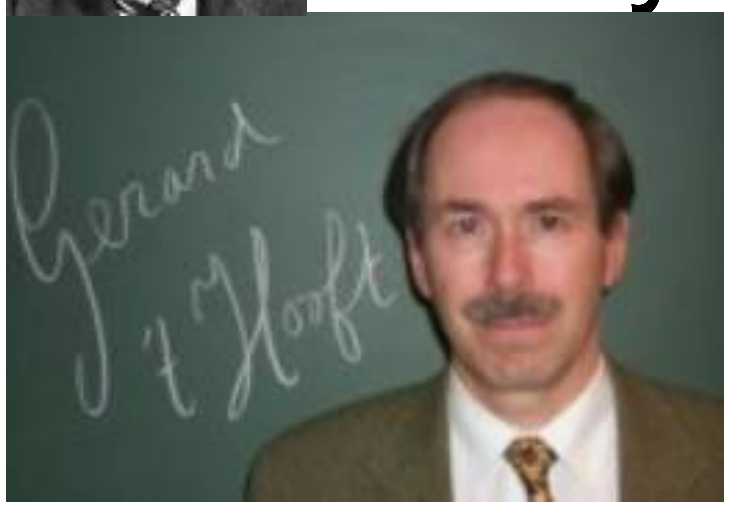


this reproduces
the azimuthal distribution of jet quenching.
BUT WHY ? => scattering on monopoles



Particle - monopoles and their dynamics: classics

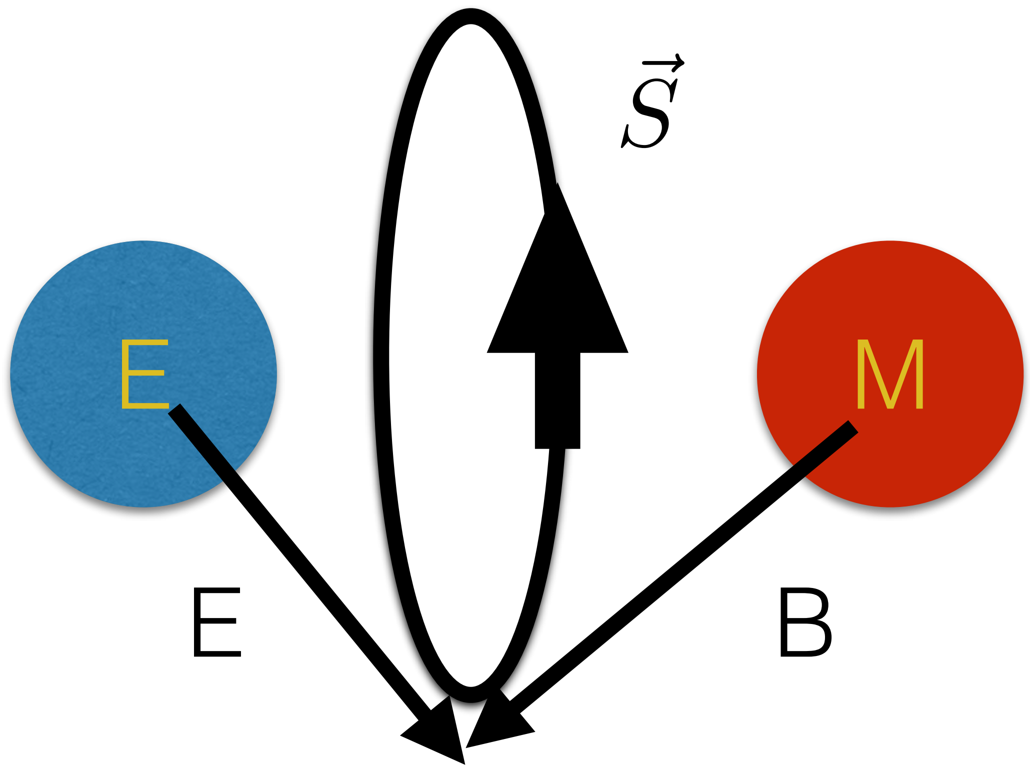


- Dirac explained how magnetic charges may coexists with quantum mechanics (1934)
- ‘t Hooft and Polyakov discovered **monopoles** in Non-Abelian gauge theories (1974)
- ‘t Hooft and Mandelstam suggested “dual superconductor” mechanism for confinement **(1976)**
- Seiberg and Witten shown how it works, in the **N=2 Super - Yang-Mills theory (1994)**

Understanding the ``dual plasmas”
(with both electric and magnetic charges)

a monopole and a charge: classical motion

hints from the 19-th cent.



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

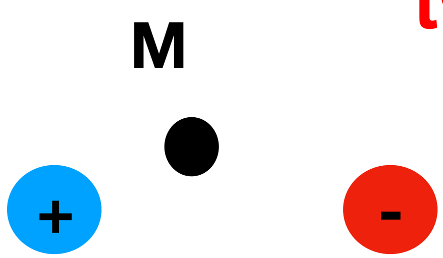
Pointing vector rotates

Observation by J.J.Thompson:

even static charge+monopole lead to rotating electromagnetic field

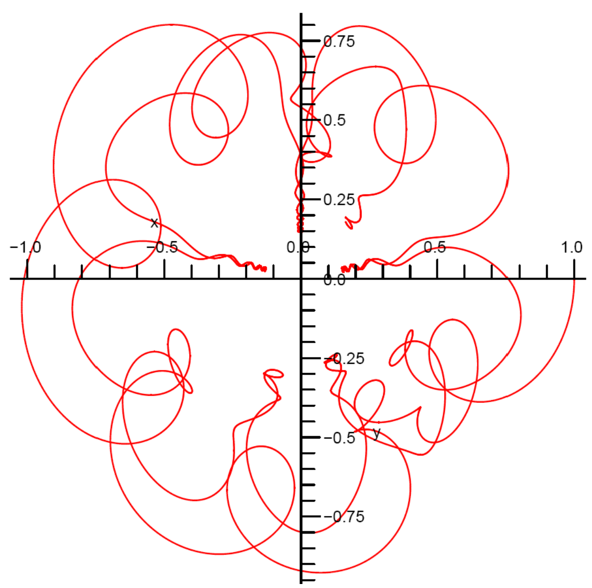
A.Poincare:
angular momentum of the particle plus that of the field is conserved => motion on a cone, not plane as usual

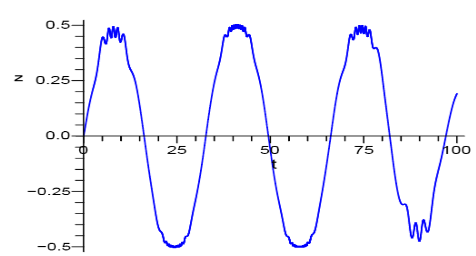
H. Poincare´, C. R. Acad. Sci. Ser. B. 123, 530 (1896).



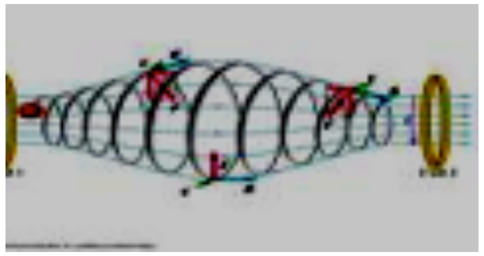
two charges play ping-pong with a monopole without even moving!

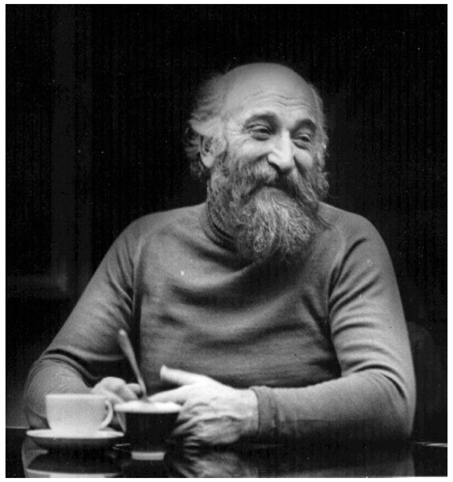
Indeed, collisions are much more frequent than in cascades

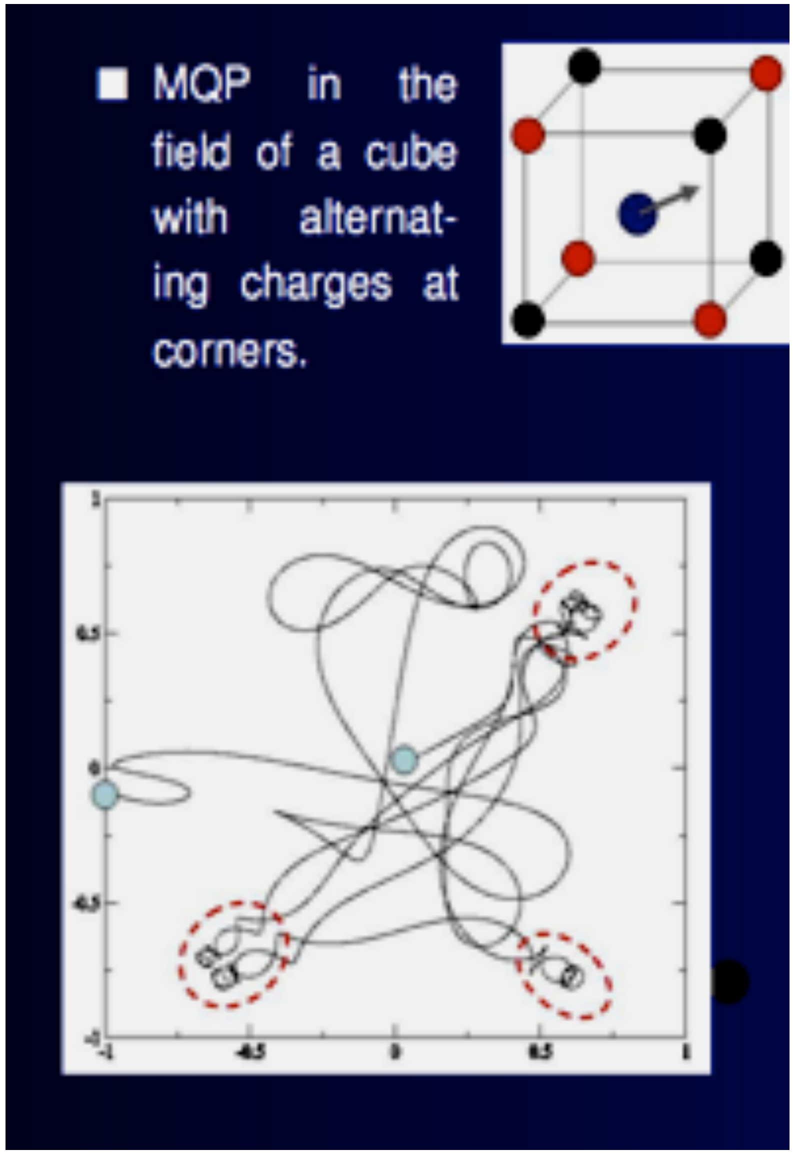


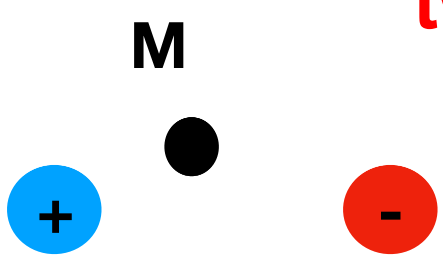


Dual to Budker's magnetic bottle









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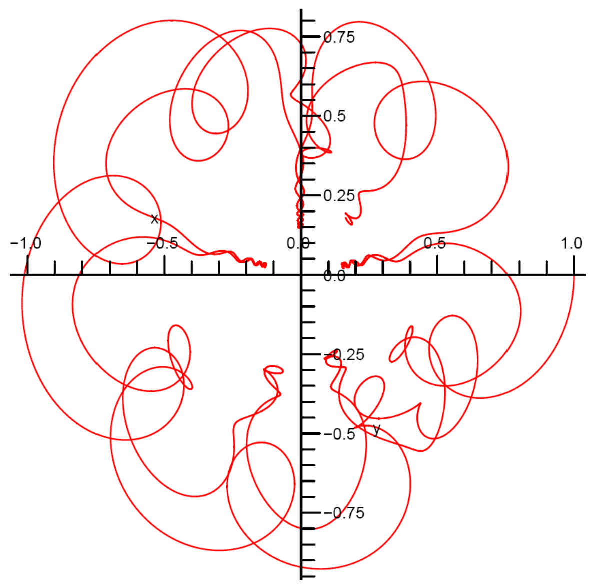

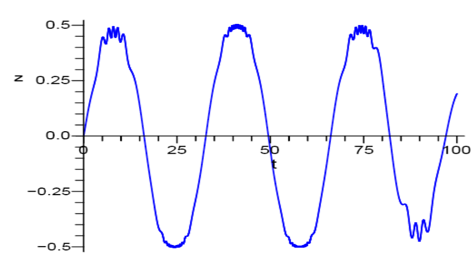

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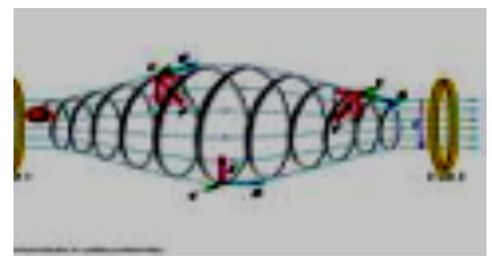
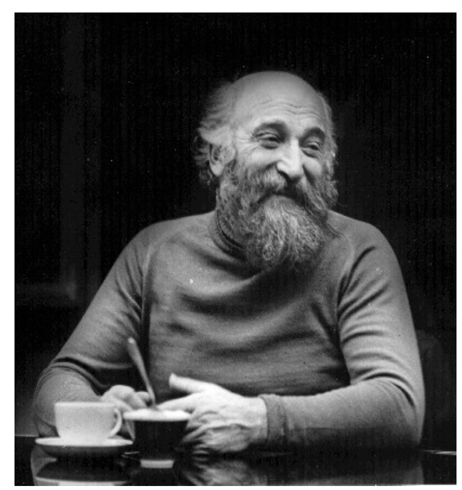
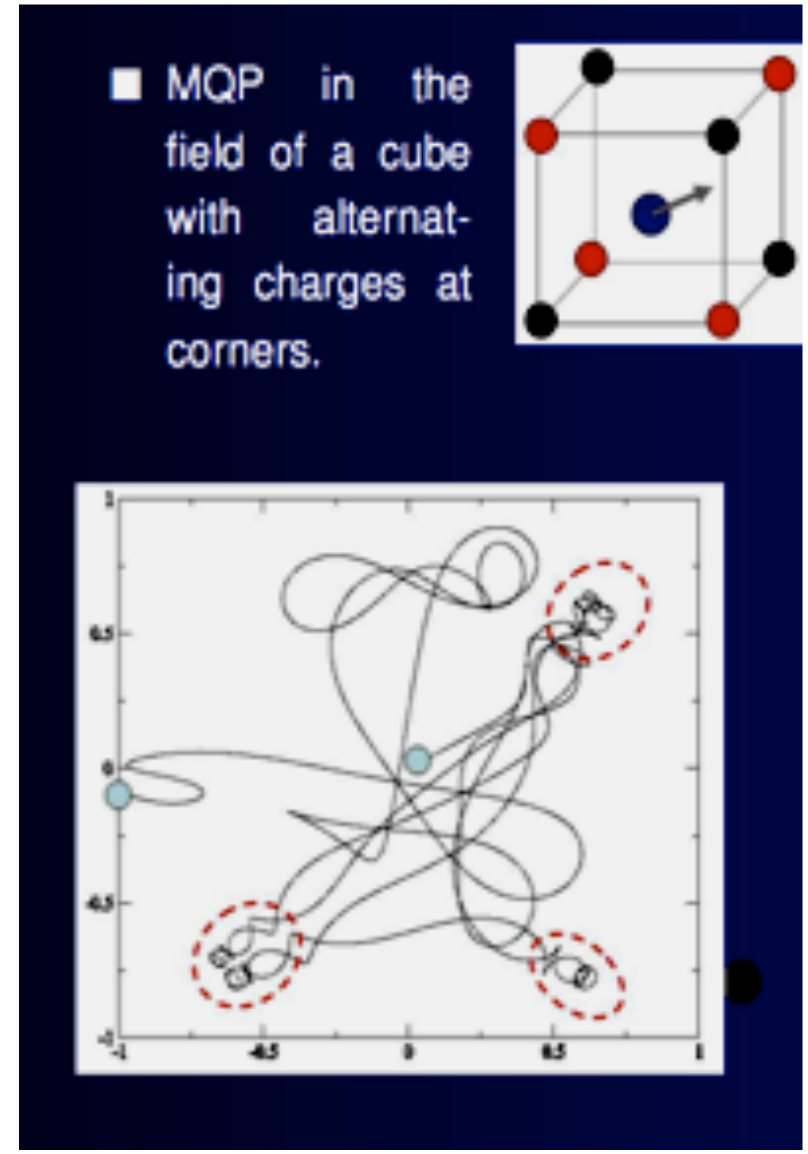
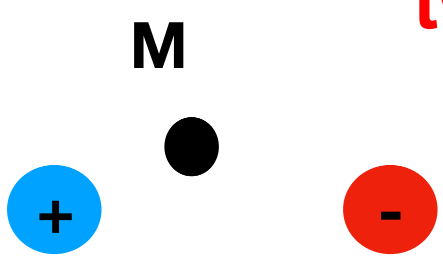






like a proverbial drunkard cannot go home colliding with few lamp posts



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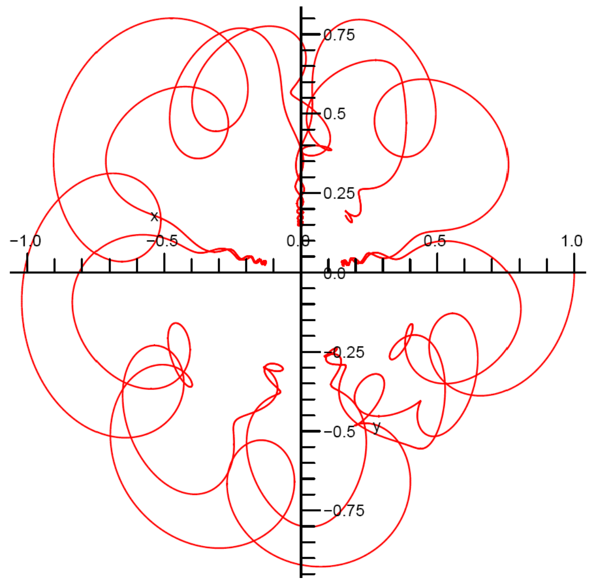

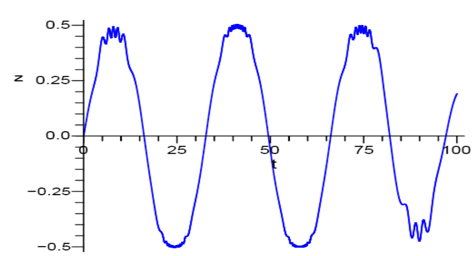

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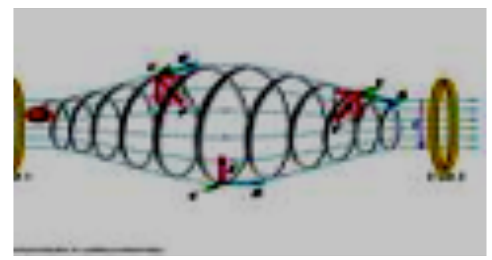
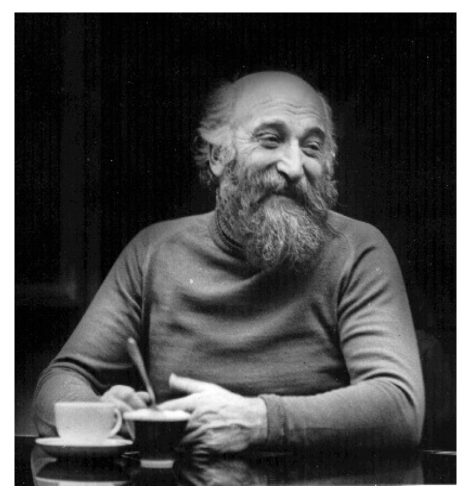
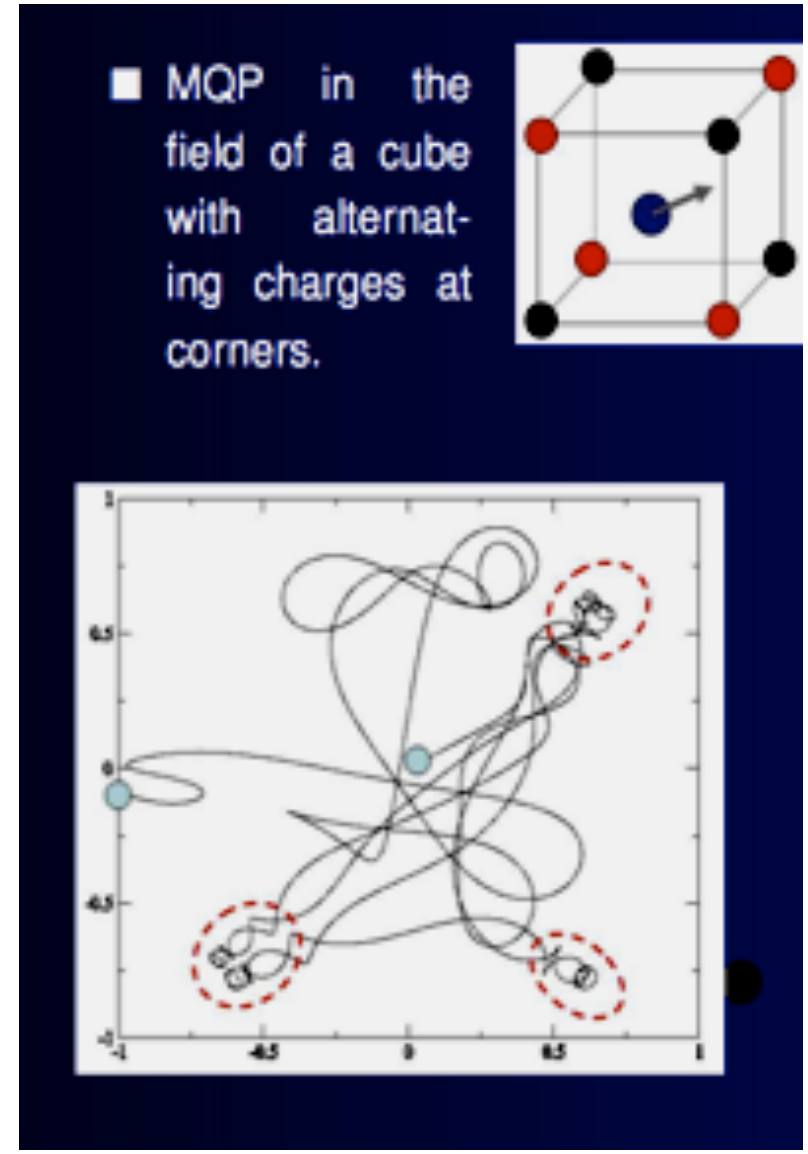






like a proverbial drunkard cannot go home colliding with few lamp posts

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)

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

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

$$\boxed{\delta_j = \pi j'}$$

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

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).

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

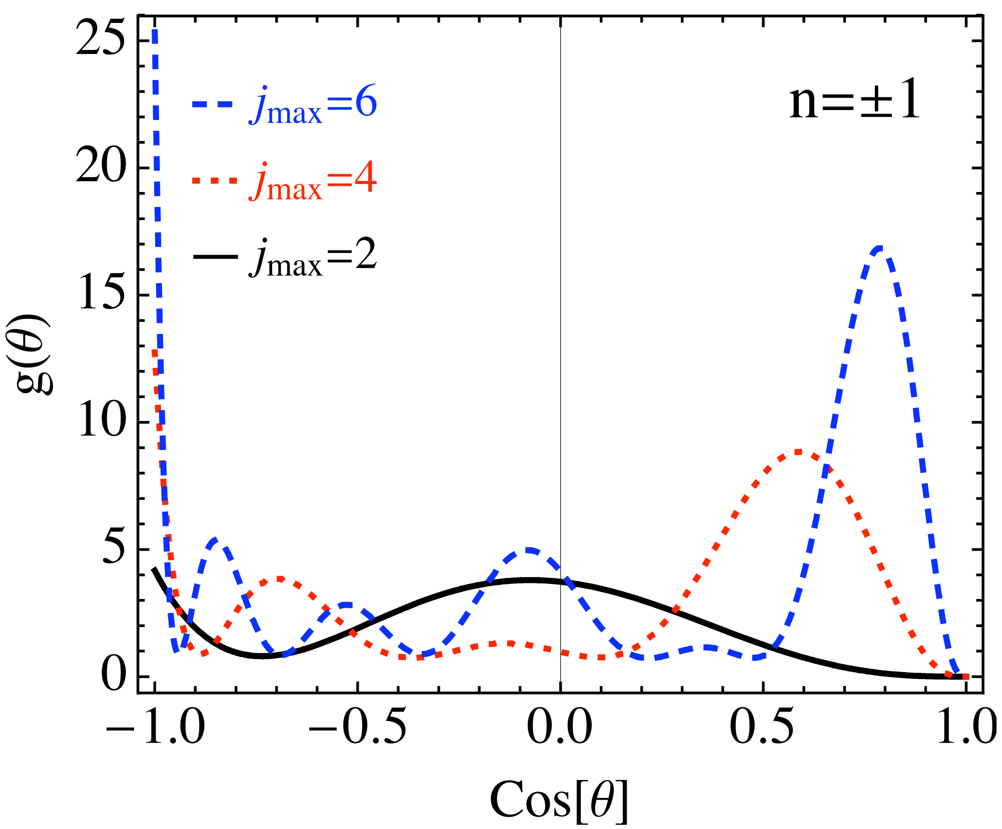
gluon-monopole scattering explains small viscosity!

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

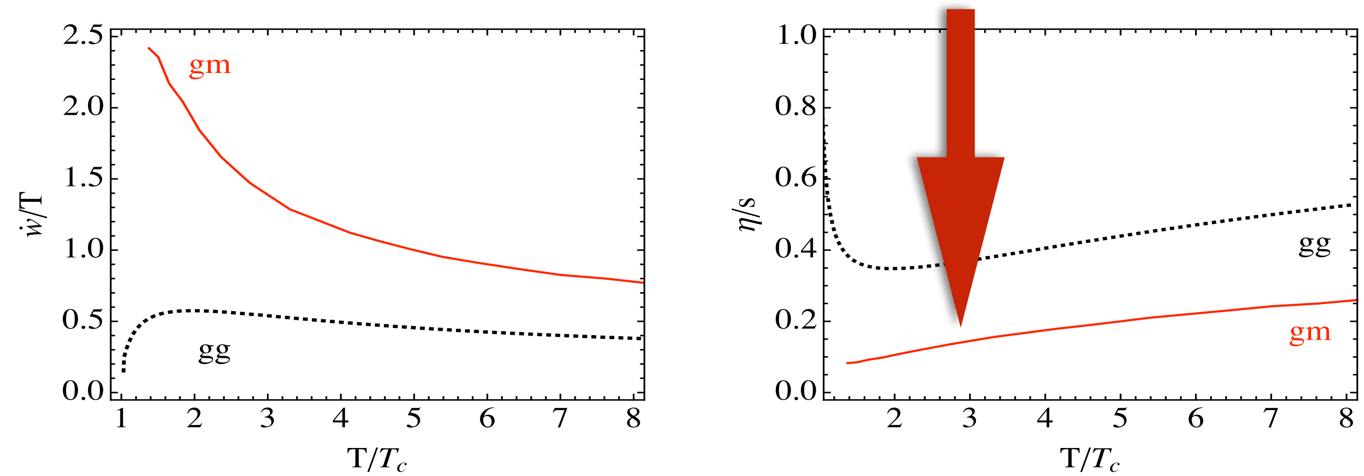


Figure 14: Left panel: gluon-monopole and gluon-gluon scattering rate. Right panel: gluon-monopole and gluon-gluon viscosity over entropy ratio, η/s.

- **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

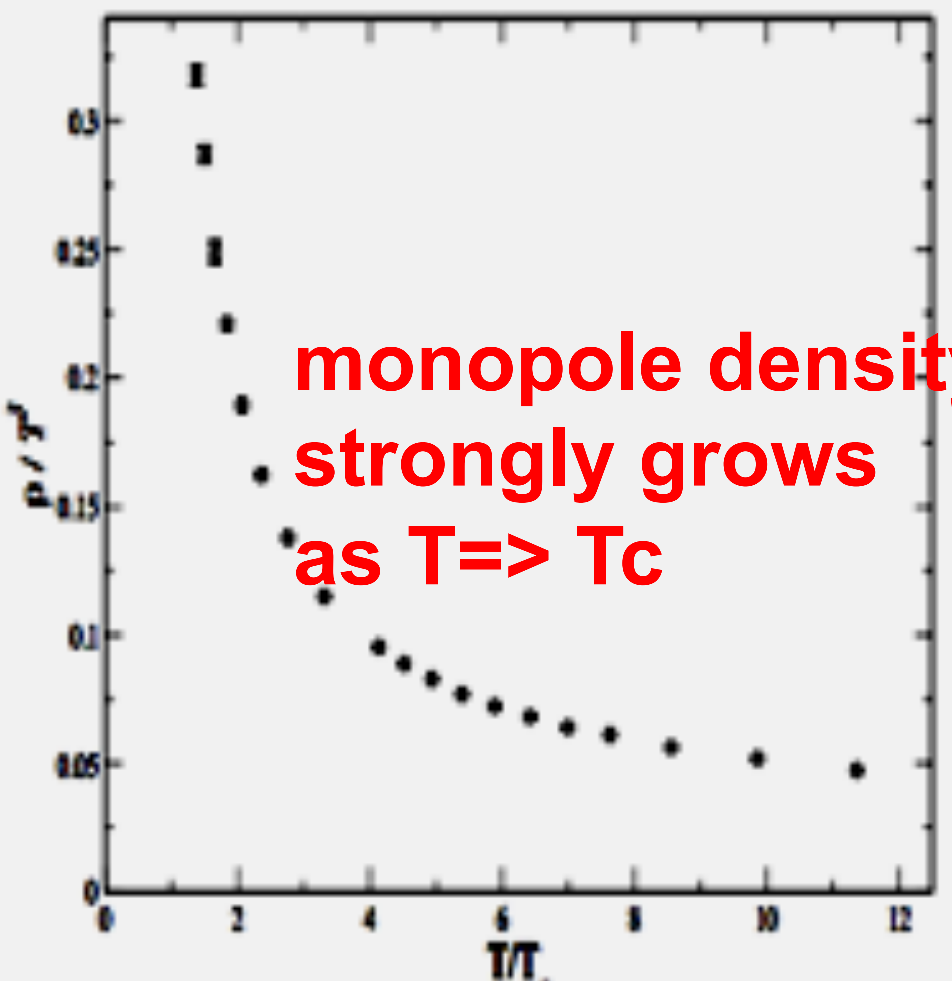


FIG. 3. $\rho(T)/T^3$ as a function of T/T_c. Data have been obtained on a $48^3 \times L_t$ lattice, with variable L_t and at $\beta = 2.75$ (first 9 points), and variable β at $L_t = 4$ (last 10 points).

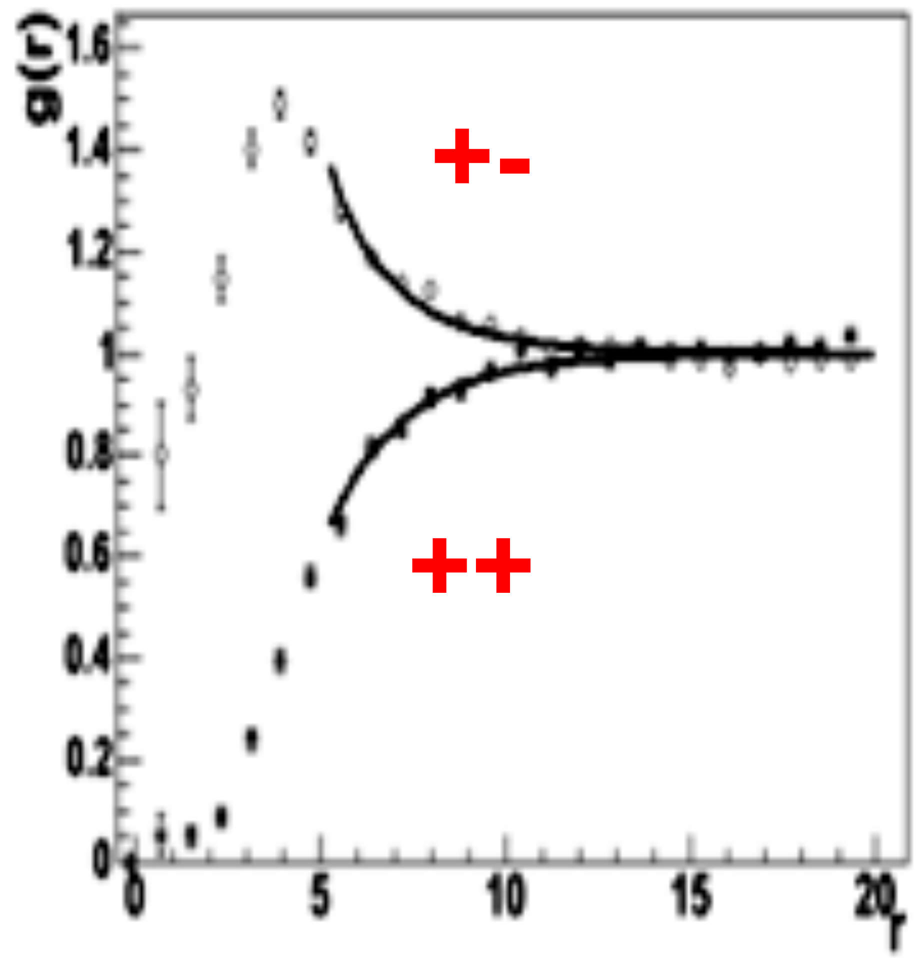


FIG. 5. $g(r)$ for the monopole-monopole (stars) and monopole-antimonopole (circles) case on ...$0^3 \times 5$ lattice at $\beta = 2.7$ ($T \simeq 2.85\, T_c$). The reported curves correspond to fits according to ...$) = \exp(-V(r)/T)$ with $V(r)$ a Yukawa potential (see Eqs. (2.9) and (2.10)).

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

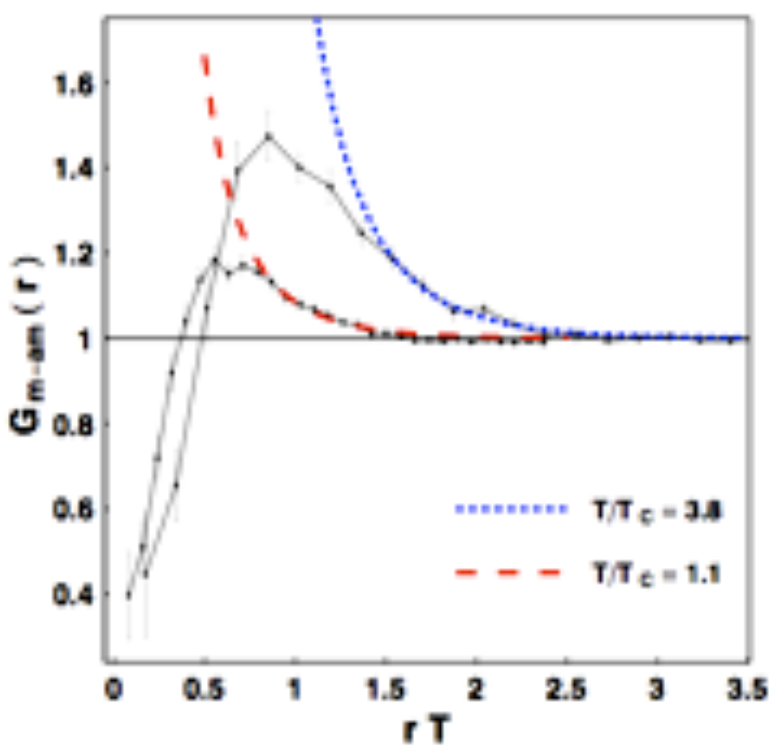
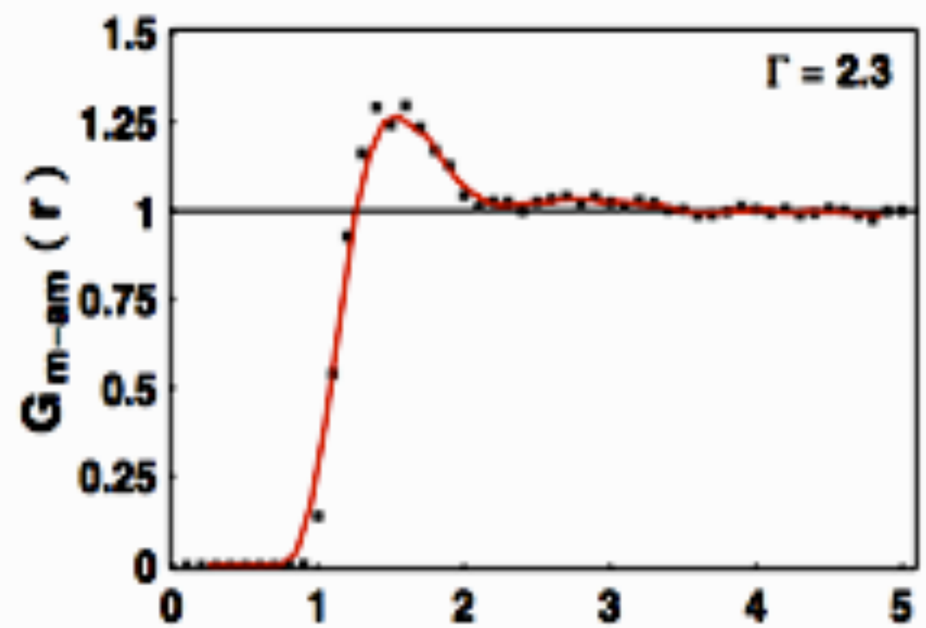


FIG. 2. (color online) Monopole-antimonopole correlators versus distance: points are lattice data [2], the dashed lines are our fits.

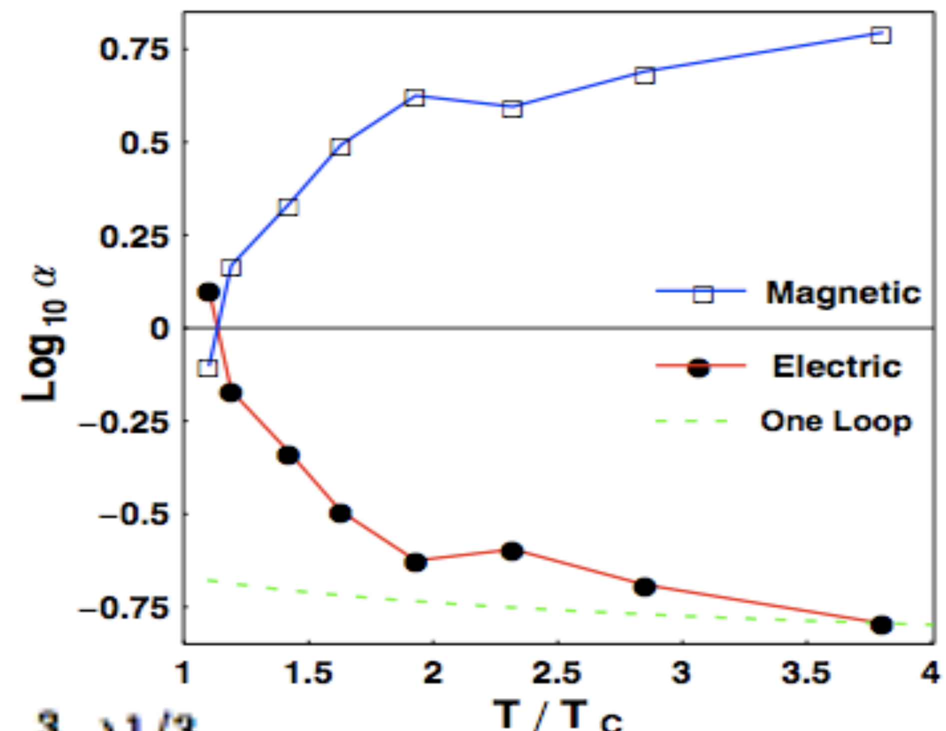
Our MD for 50-50 MQP/EQP



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

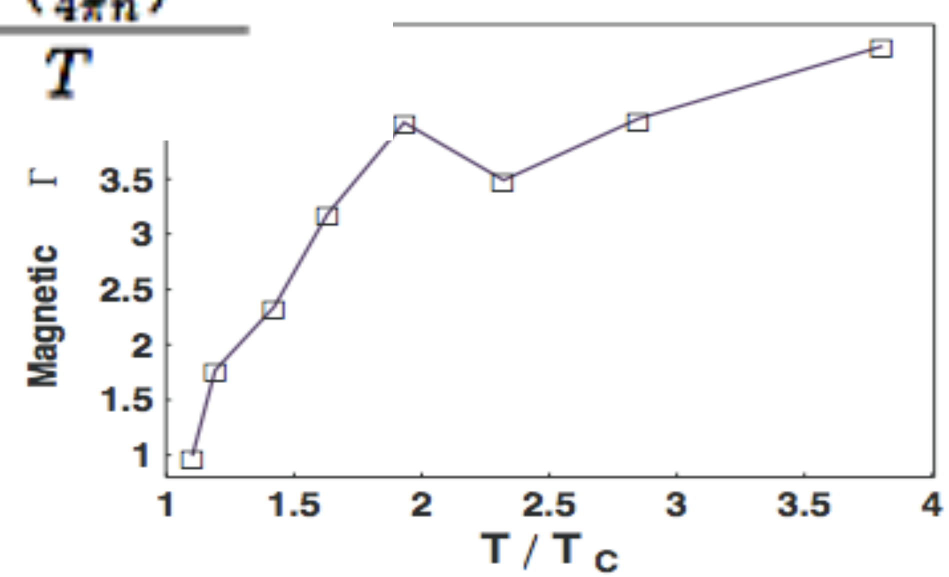
α_s(electric) and α_s(magnetic) do run in opposite directions!

- 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!

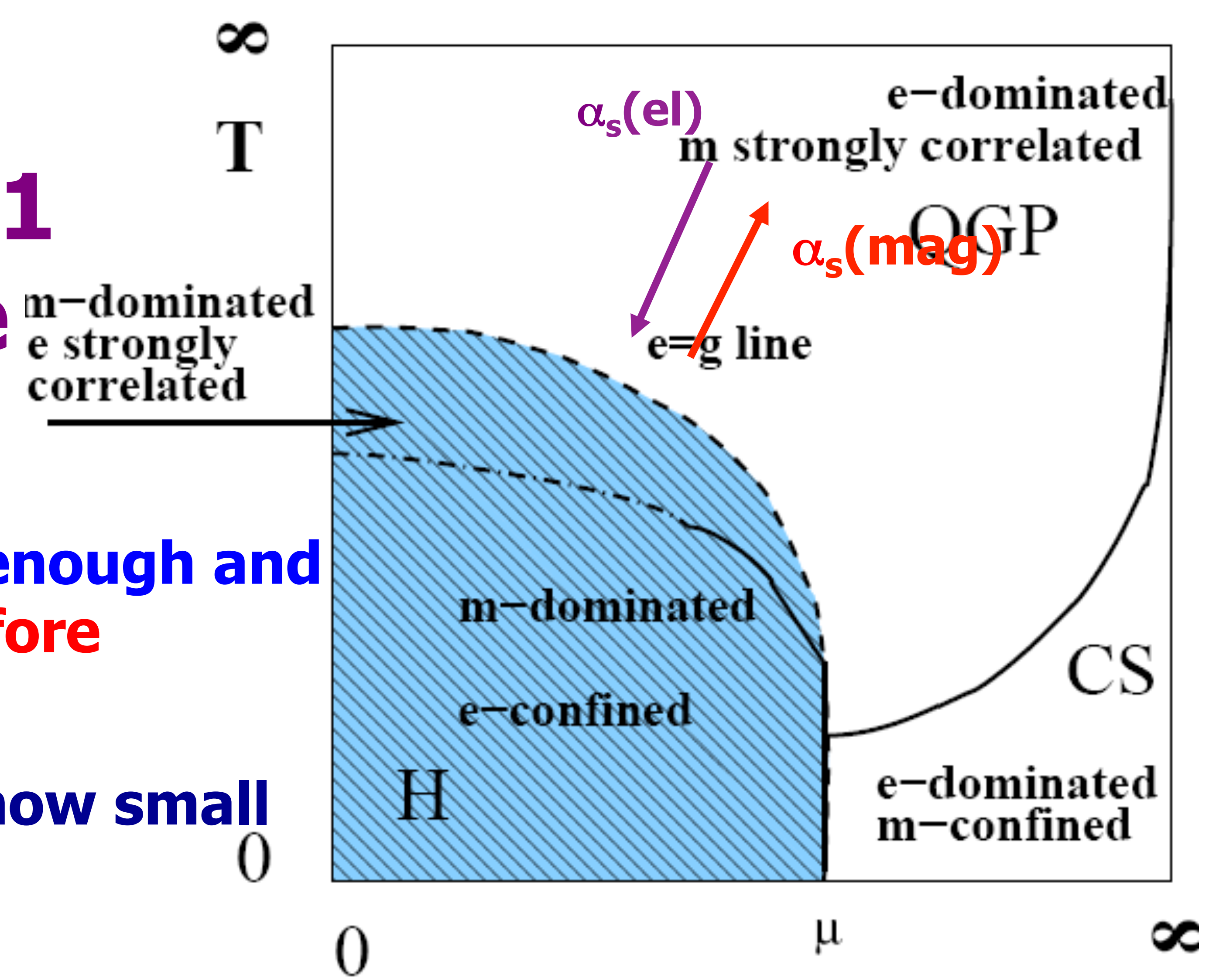
the "equilibrium line"

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?



Understanding the inter-relation
Between various topological objects

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

Explain mismatch of quark condnesate in SUSY QCD

V.Khoze (jr) et al 2001

Explain confinement by back reaction to F

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

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*

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 Higgled 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
Z look different, and yet they are related
by the Poisson sum 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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arXiv:1802.10509v1 [hep-ph] 28 Feb 2018

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

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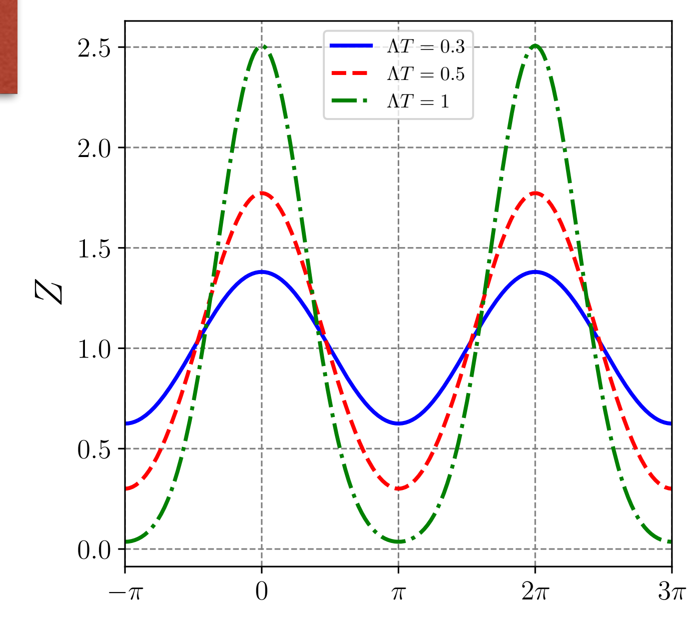

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instanton-dyons with winding number n

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 sume

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

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

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

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

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

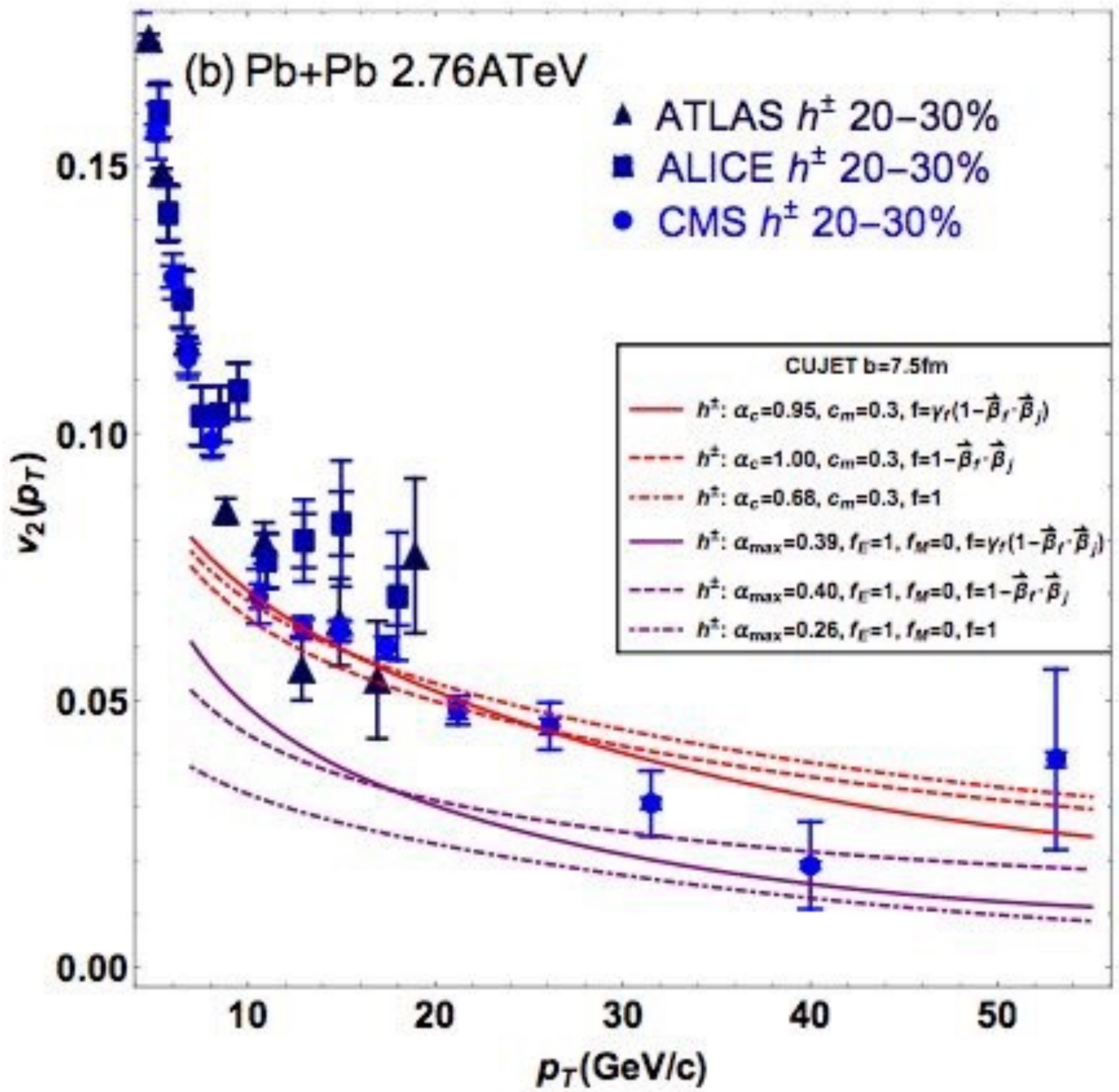
Summary

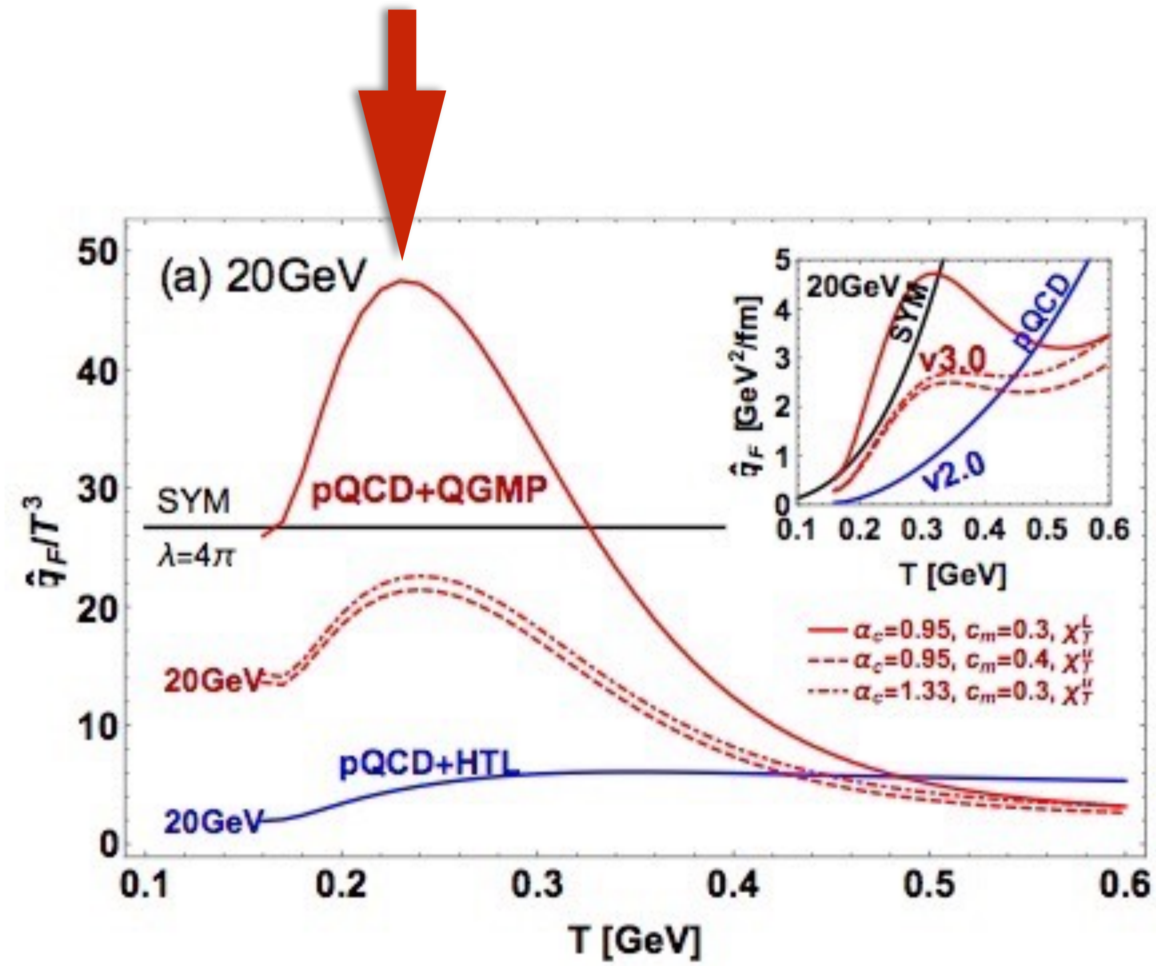
- sQGP is unusual because it is a dual plasma, with both electrically and magnetically charged quasiparticles
- As T cools, and electric coupling increases, the magnetic coupling decreases
- As monopoles get lighter, their density grows till BEC (confinement)
- Chiral condensate is due to collectivization of topological zero modes
- Instanton-dyons and monopoles look different but lead to the same partition function

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