For Heavy Ions, will LHC be "*like*" RHIC?

1. *Yes:* small increase in elliptic flow, (appropriately scaled) multiplicity
   (Nearly) ideal hydro works
   Consensus view?

2. *Sorta*: elliptic flow smaller, (scaled) multiplicity higher
   Viscous hydro applies: how much does η/s increase?
   "Semi"-QGP: *partial* deconfinement near T_c: this talk today

3. *Nothing* like it: elliptic flow *much* larger; (scaled) multiplicity - *much* higher?
   Not "Wit-less": Busza, arXiv: 0907.4719
   Terra incognita: *non*-equilbrium distribution
   "Abandon all hope ye who enter here"?
   Perhaps: use kinetic theory to evolve Color Glass to "jetty" final state?

With Y. Hidaka, arXiv:0803.0453, 0906.1751, 0907.4609, 0912.0940
With A. Dumitru, Y. Guo, Y. Hidaka, C. Korthals-Altes (DGHKP), 1010....
Related: T. Zhang, T. Brauner, & D. Rischke, 1005.2928.
O. Philipsen et al., 1010....

Before, in Frankfurt....

Threw pile of string theory books in the trash

Obi-Wan Ken-Robbie said to Miklos Gyulassy:

"Don't go over to the Dark Side (AdS/CFT), no, don't do it!"

I was the "most reactionary physicist on earth"

If RHIC is in a conformally invariant regime, and

if AdS/CFT is relevant for QCD, then

unique predictions for LHC: in AdS/CFT, η/s is *constant*, even if "s" changes!

Juggled three balls (to illustrate triple point)

Today: Soon, a *second* Golden Era begins

First Golden Era: RHIC

Like high T_c superconductivity, *wealth* of data,

but we *still* don't know what's going on

LHC: like RHIC, or not? We'll know by Xmas! Ho ho ho!

The semi-, versus the complete, Quark Gluon Plasma

Typical plasma in QED: e.g., H atoms

No ionization: gas of H atoms

Completely ionized plasma, e^-'s and p's move freely of one another

Partially ionized plasma: *some* H atoms, *some* free charges.

QCD: deconfinement is the ionization of *color* charge

No color charge ionized: confined phase.

"*Complete*" Quark-Gluon Plasma (QGP): *total* ionization of color

"*Semi*"-QGP: *partial* ionization of color

Complete QGP: above a "few" times T_c (= temperature for deconfinement)

Semi-QGP: from a little bit *below* T_c, to a "few" times T_c

What is a "few" times times T_c? *What is the width of the semi-QGP?*

If RHIC starts in the semi-QGP, and LHC starts in the complete QGP, then for heavy ions, LHC will *not* be like RHIC.

(Many, many qualifications: LHC always cools through semi-QGP, etc....)

Summary

Elementary model for confinement

Integrating over an *imaginary* chemical potential
Matrix model of the semi-QGP, versus Polyakov-Nambu-Jona-Lasino models
How to compute: perturbation theory with "birdtrack" diagrams

Fun and games with birdtracks

Dilepton production: not realistic, but illustrative
Energy loss in the semi-QGP: plus *uniform* suppression of color charge
Shear viscosity in the semi-QGP:
shear viscosity *decreases*, even though the cross section does as well

So how wide *is* the semi-QGP?
Lattice: renormalized Polyakov loops indicate *wide* semi-QGP, to ~ 4 T_c.
DGHKP, 1010.... : indirect measures indicate *narrow* semi-QGP, to ~ 1.5 T_c.

Experimentalists will know before we (theorists) will.

Elementary model for confinement

Consider the Boltzmann distribution
at a nonzero chemical potential, μ:

$$n_{\mathrm{B}}(E-\mu) = \mathrm{e}^{-(E-\mu)/T}$$

Let μ be imaginary, μ = i Q:

$$n_{\mathrm{B}}(E-iQ) = \mathrm{e}^{-(E-iQ)/T}$$

Q is clearly periodic, and runs from 0 to 2 π T.
Now assume that the distribution in Q is *flat*. Then the integral over Q vanishes,

$$\int_0^{2\pi T} n_{\mathrm{B}}(E-iQ)\, dQ = \mathrm{e}^{-E/T} \int_0^{2\pi T} \mathrm{e}^{iQ/T}\, dQ = 0$$

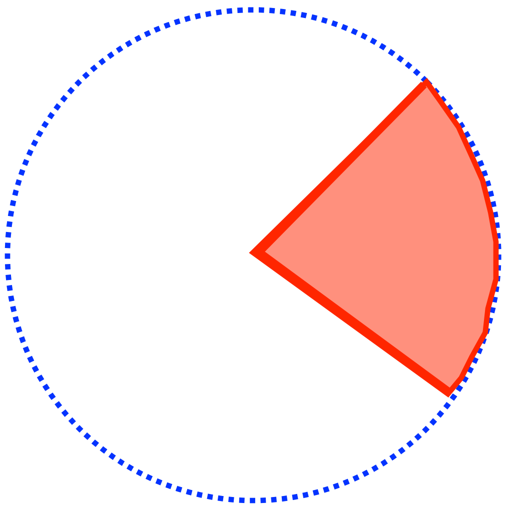
which is confinement.
For Bose-Einstein (+) or Fermi-Dirac (-) statistics, do Boltzmann expansion:

$$n_{\pm}(E-iQ) = \frac{1}{\mathrm{e}^{-(E-iQ)/T} \mp 1} = \mathrm{e}^{(E-iQ)/T} \pm \mathrm{e}^{-2(E-iQ)/T} \ldots$$

For a flat distribution, the integral of *every* term vanishes, so $\langle n_{\pm}(E-iQ) \rangle = 0$.

Elementary model for partial *de*confinement

Take a distribution which is flat, but only in a wedge:



$$\rho_x(Q) = \frac{1}{2\pi x}\,\theta\left(\pi x - \frac{|Q|}{T}\right)$$

This is a normalized density,

$$\int_0^{2\pi T} \rho_x(Q)\, dQ = 1$$

x=0: only Q = 0. "*Complete*" Quark-Gluon Plasma.

x=1: flat distribution of Q's. Confined phase, all distribution functions vanish.

1 < x < 0. Q's flop around. *Partial* suppression of distribution functions.
"Semi"-QGP, partial deconfinement.

N.B.: The suppression of colored fields is *independent* of mass or momentum:
why R_{AA} for charm quarks is ~ R_{AA} for light quarks (pions)?

Matrix model for semi-QGP

Color? Thermal Wilson line **L** →

L is gauge variant, eigenvalues gauge *in*variant.

For SU(N_c), N_c-1 eigenvalues.

$$\mathbf{L} = \mathcal{P} \exp \left(ig \int_0^{1/T} A_0 \, d\tau \right)$$

To represent non-trivial **L**, perform a semi-classical expansion in *intermediate* coupling about →

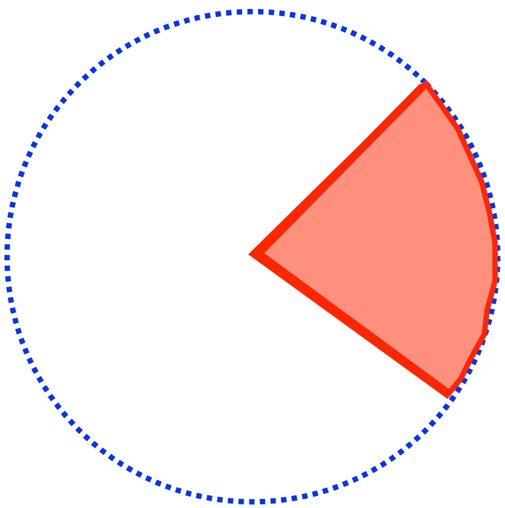
$$(A_0^{cl})^{ab} = \delta^{ab} \frac{Q^a}{g}$$

Q^a : a= 1...N_c. with $\Sigma_{a=1}{}^{N_c}$ Q^a = 0, mod 2 π T.

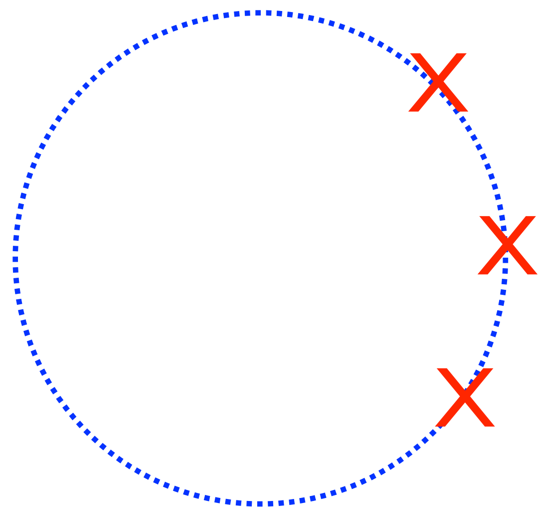
At infinite N_c, the sum over eigenvalues becomes an *integral* over Q.

Matrix model of the semi-QGP. (Like SU(∞) on femtosphere:
Sundborg, hep-th/9908001; Aharony, Marsano, Minwalla, Papadodimas, & Van Raamsdonk, hep-th/0310285 & 0502149)

$N_c = \infty$



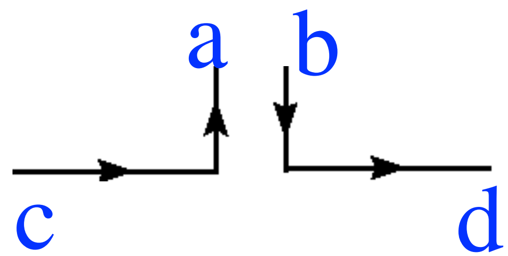
$N_c = 3$



Computing in the semi-QGP: energies with color

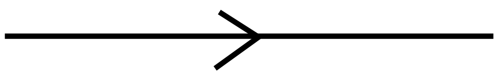
Generalize 't Hooft's double line notation to finite N_c.
BTW, can derive *any* group theory identity by drawing "birdtracks"
P. Cvitanovic, http://www.birdtracks.dk/

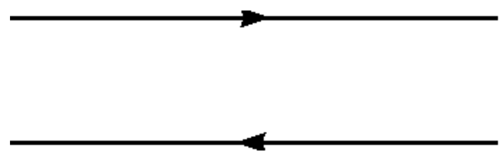
$(t^{ab})_{cd} =$



$- \frac{1}{N}$

Computing semi-class.'y about A_0^{cl} is *easy*: energy p_0 acquires color indices:
one for fields in the fundamental representation, two for those in the adjoint.





$- \frac{1}{N}$

quark:

$p_0^a = p_0 - Q^a$

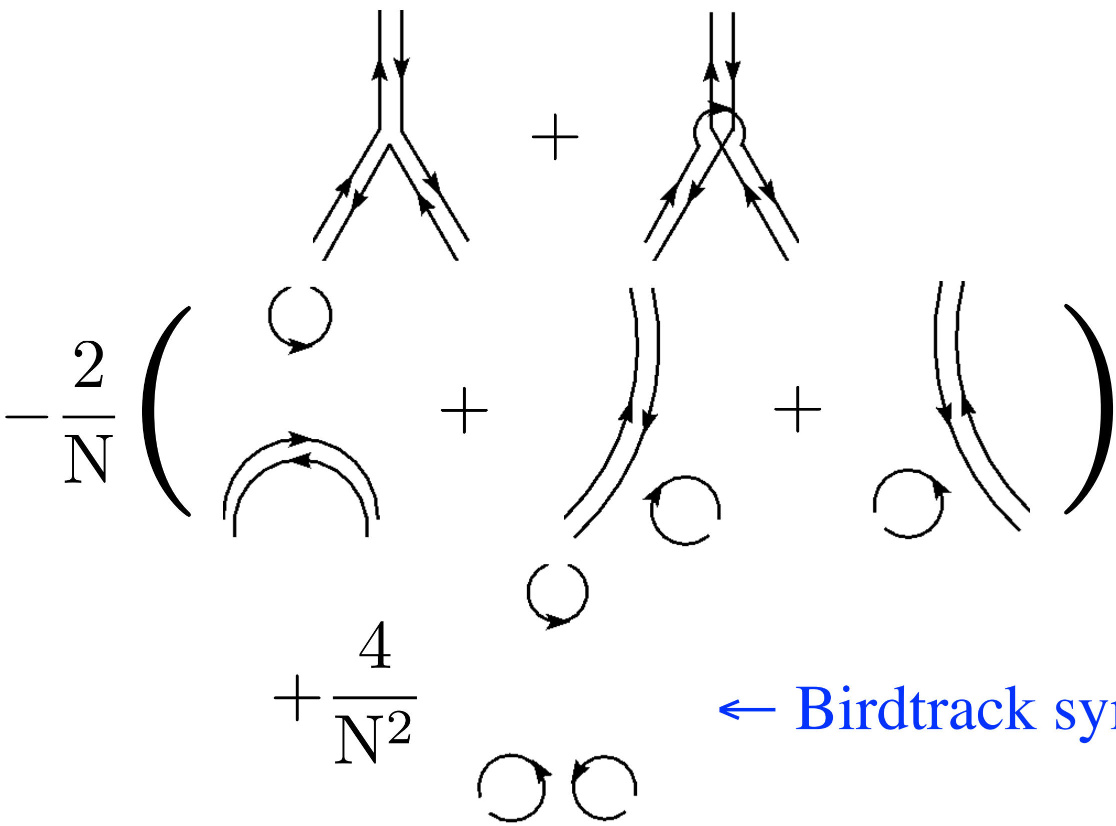
gluon:

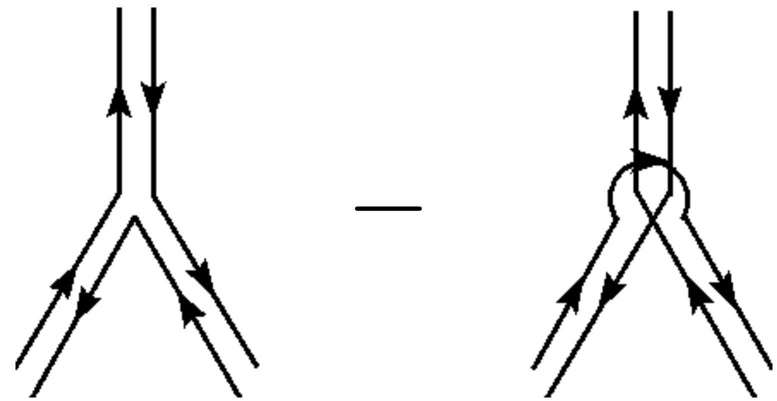
$p_0^{ab} = p_0 - Q^a + Q^b$

Computing with ease in the semi-QGP

Perturbation theory is as usual, except there is an imaginary (color) chemical potential, which shifts the energy, p_0. Propagators in imaginary time, τ:
energy $p_0 = 2\,\pi\,n\,T$, $n = 0, \pm 1, \pm 2 \ldots$

$$\Delta_Q(\tau, E) = T \sum_{n=-\infty}^{+\infty} \frac{\mathrm{e}^{-ip_0\tau}}{(p_0+Q)^2+E^2} = \sum_{s=\pm} \frac{s}{2E}\,(1+n(sE-iQ))\;\mathrm{e}^{-sE\tau}$$



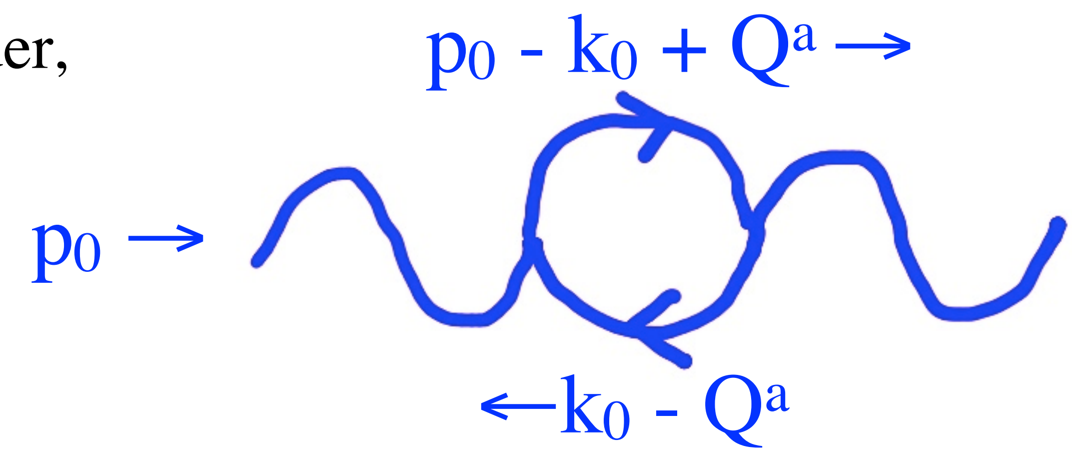


Birdtrack three gluon vertex ↑

← Birdtrack symmetric structure constant

Dilepton production in the semi-QGP, 1

Compute the usual diagram at lowest order, just adding Q's to the propagators:



Loop momenta = k; $E_1 = E_k$, $E_2 = E_{k-p}$.
Result is ~ $\int d^3k \, R_Q$:

$$R_Q = \; n_-(E_1 - iQ)\, n_-(E_2 + iQ)$$

Standard identity:

$$R_Q = n_+(E_1 + E_2)\, (1 - n_-(E_1 - iQ) - n_-(E_2 + iQ))$$

Doing Boltzmann expansion,

$$R_Q = n_+(E_1 + E_2) \left(1 - \sum_{j=1}^{\infty} \frac{(-1)^{j+1}}{N_c} \left(\mathrm{e}^{-jE_1}\, \mathrm{tr}\, \mathbf{L}^j + \mathrm{e}^{-jE_2}\, \mathrm{tr}\, (\mathbf{L}^\dagger)^j \right) \right)$$

Still have to integrate over Q's. Easy to evaluate for arbitrary Q-distribution.

Dilepton production in the semi-QGP, 2

Complete QGP: Q = 0, usual product of Fermi-Dirac distribution functions

$$R_{Q=0} = n_-(E_1)\, n_-(E_2)$$

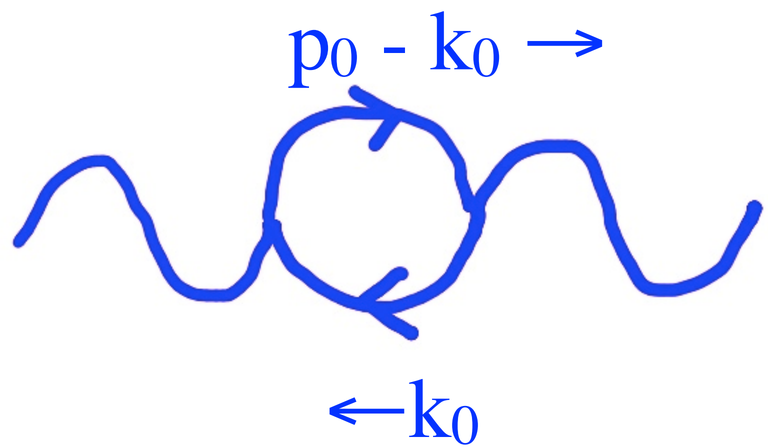
Confined phase: flat Q-distribution.
At $N_c = \infty$, tr $\mathbf{L}^j = 0$ for $j \geq 1$, so

$$R_{\rm confined} = n_+(E_1 + E_2)$$

At low momenta, $E_1 + E_2 << T$, $R_{\rm confined} \sim (E_1+E_2)/T$, while $R_{Q=0} \sim 1$
Bose enhancement in the confined phase, but *not* in the complete QGP.
Confined phase gives *more* (very soft) dileptons than the QGP!

Contrast to FWpPNJL model
(Fukushima-Weise-pisarski-Polyakov)NJL:

Each quark line $\sim l = \text{tr}\, \mathbf{L}/N_c$,
so R suppressed, $\sim l^2$ as $l \to 0$.



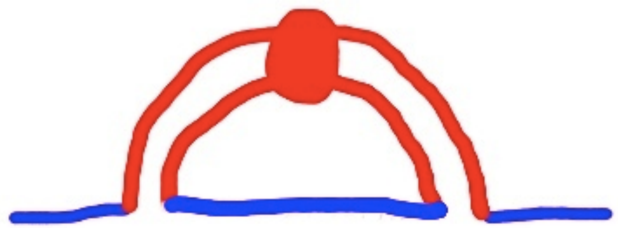
Not like a matrix model, where there is *enhancement*

Energy loss in the semi-QGP

Damping rate for a fast or heavy quark: add Q's to the propagators.

Need Hard Thermal Loops (HTLs) in background Q-field:

Blue: hard momenta, p ~ T. Red:soft momenta, p ~ g T. Blob = HTL resummed



Again, result is a function of the Q's, *F*(Q) times the perturbative result:

$$\gamma = c\, g^2\, N_c\, \log(1/g)\, \mathcal{F}(Q)$$

By definition, in the complete QGP, Q = 0, *F*(0) = 1.

Near T_c, where $l \to 0$, *F*(Q) ~ *l*.

Energy loss ~ damping rate, so it is suppressed *linearly* near T_c.

Suppression of energy loss very different from dilepton production!

Plus: uniform suppression of color charge, ~ < *loop* >: R_{AA} for heavy quarks?

Shear viscosity in the semi-QGP, 1

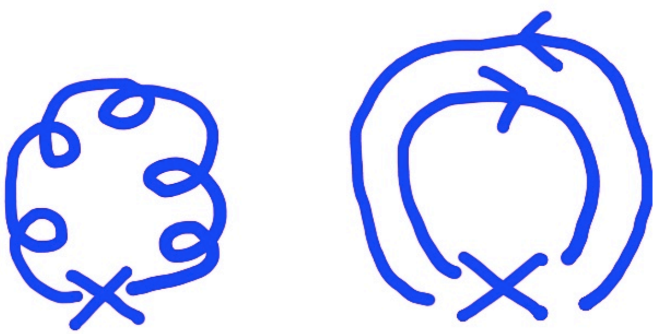
Shear viscosity, η, in the complete QGP: Arnold, Moore & Yaffe, hep-ph/0302165

In the semi-QGP: Boltzmann equation in a *background* field, Q ≠ 0.

$$\eta = \frac{\mathcal{S}^2}{\mathcal{C}}$$

S = source term , C = collision term.

Start first with pure glue, for *small* values of the Polyakov loop, l = tr **L**/N_c:



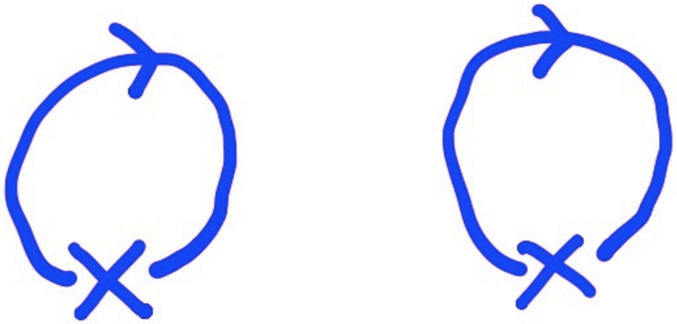
$$\mathcal{S}_{\rm glue} \sim \ell^2$$

$$\mathcal{C}_{\rm glue} \sim \ell^2$$

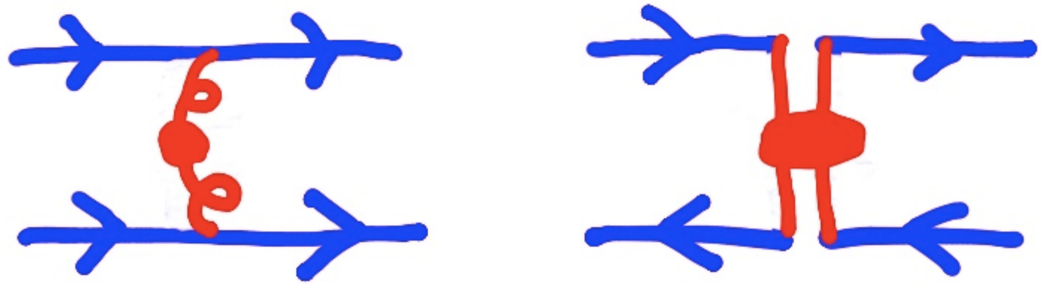
$$\eta_{\rm glue} \sim \frac{\mathcal{S}^2_{\rm glue}}{\mathcal{C}_{\rm glue}} \sim \frac{(\ell^2)^2}{\ell^2} \sim \ell^2$$

Shear viscosity in the semi-QGP, 2

With N_f flavors of dynamical quarks, taking $N_f \sim N_c \to \infty$:



$$\mathcal{S}_{\rm qk} \sim \ell$$



$$\mathcal{C}_{\rm qk} \sim 1$$

$$\eta_{\rm qk} \sim \frac{\mathcal{S}^2_{\rm qk}}{\mathcal{C}_{\rm qk}} \sim \frac{\ell^2}{1} \sim \ell^2$$

Thus $\eta \sim l^2$ as $l \to 0$ in all cases.

Away from small l, quark and gluon scattering enter, terms mix.

Not like ordinary kinetic theory: η small not because of large coupling, but because density of fields vanishes. *Special* to deconfining transition.

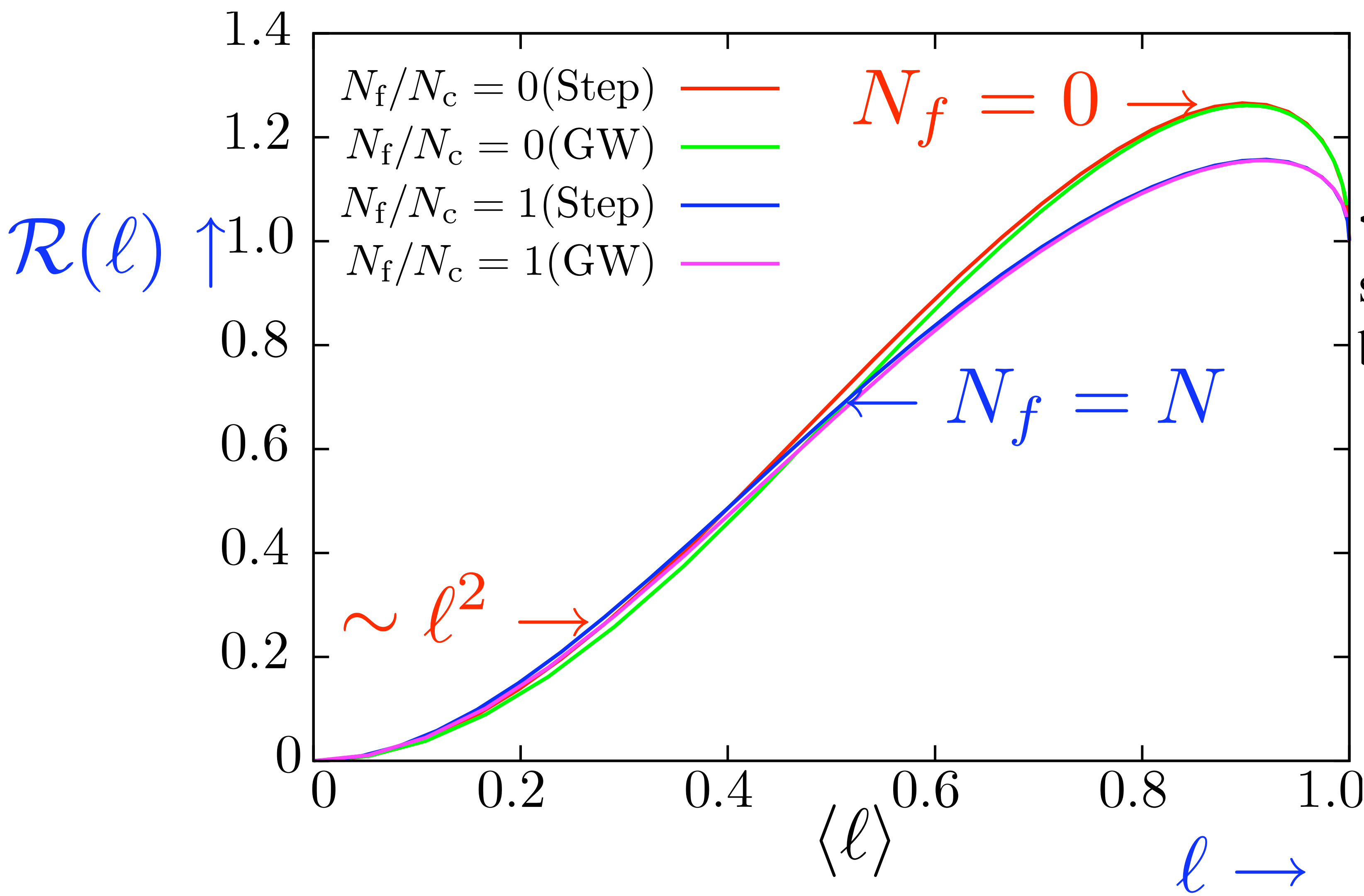
Shear viscosity in the semi-QGP, 3

R(l) = ratio of shear viscosity in semi-QGP/pert.-QGP for the *same* value of g

c_1, c_2 #'s from Arnold, Moore, & Yaffe

As $l \to 0$, $R(l) \sim l^2$. e.g., $R \sim 0.3$ for $l \sim 0.3$

$$\eta = \frac{c_1 \, T^3}{g^4 \, \log(c_2/g)} \, \mathcal{R}(\ell)$$



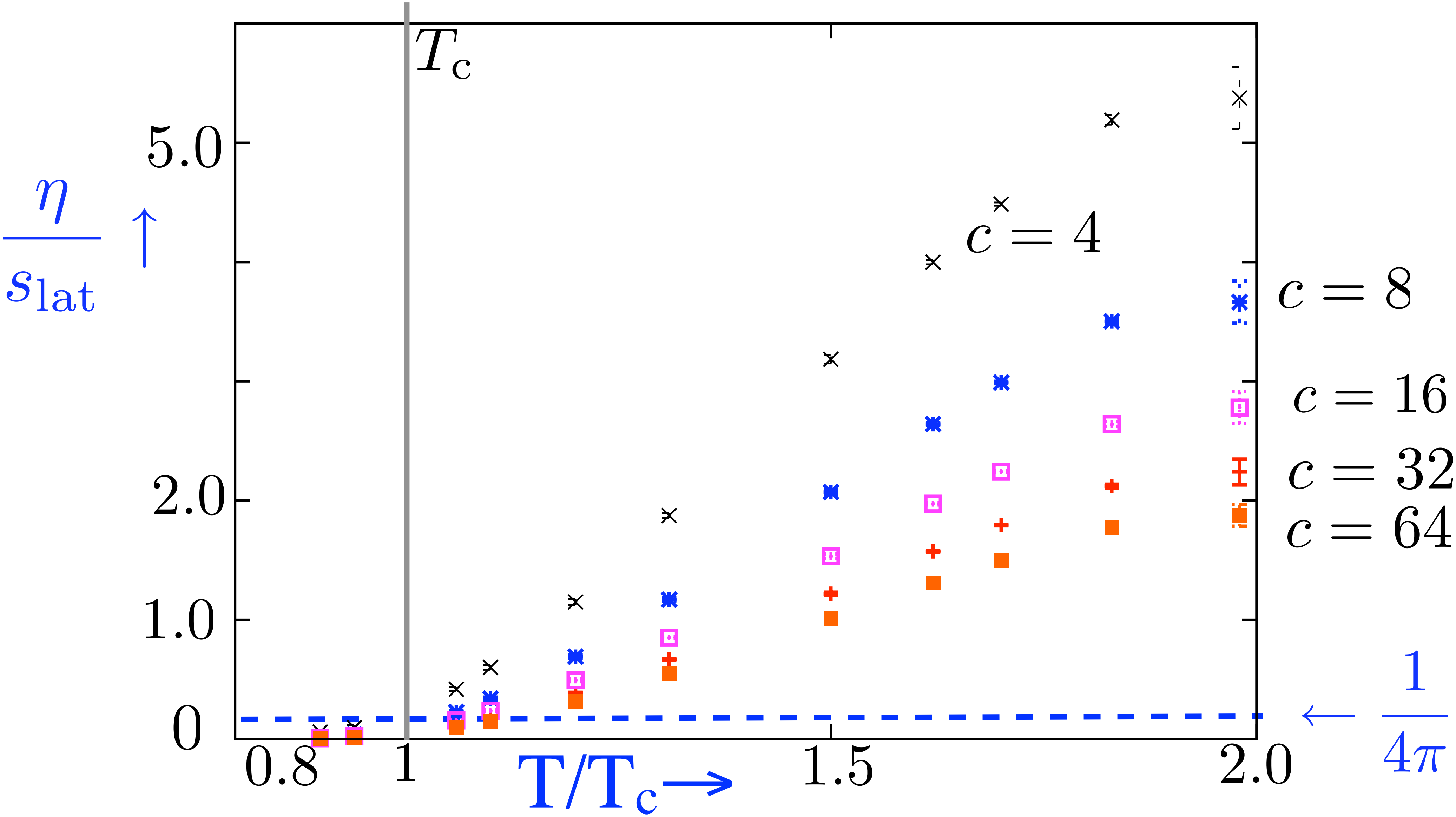
←Cusp near 1: smoothed out by Q ~ g T?

Shear viscosity in the semi-QGP, 4

Leading log shear viscosity/lattice entropy. $\alpha_s(T_c) \sim 0.3$.

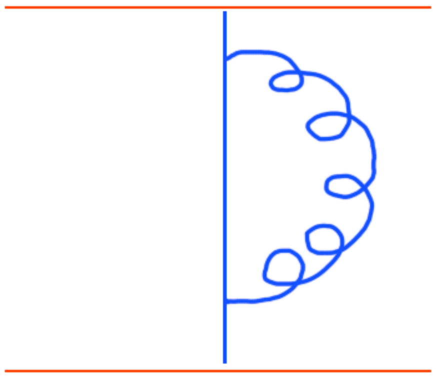
Large increase from T_c to 2 T_c. *Clearly* need results beyond leading log.

Also need to include: quarks and gluons *below* T_c, hadrons *above* T_c. *Not* easy.



Renormalized loops

Polyakov '80, Dotsenko & Vergeles '81 +...
Dumitru, Hatta, Lenaghan, Originos, & RDP hep-ph/0311223
Gupta, Hubner & Kaczmarek 0711.2251 = GHK



Bare loop UV divergent. At one loop =>
In 3+1 dim.'s, linear divergence with lattice spacing "a":
(R = representation, Casimir C_R)

$$\langle \ell_R^{\mathrm{bare}} \rangle = \exp\left(- \# \, C_R \, g^2 (1 + \ldots) \, \frac{1}{aT} \right) \, \langle \ell_R^{\mathrm{ren}} \rangle$$

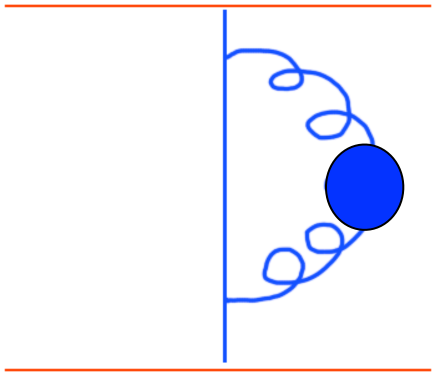
Renormalized loop:
N_t = 1/aT = # time steps:

$$\langle \ell_R^{\mathrm{bare}} \rangle = \mathcal{Z}_R(g^2)^{N_t} \, \langle \ell_R^{\mathrm{ren}} \rangle$$

Can choose $\langle \ell \rangle \to 1 \quad , \; T \to \infty$

Also choose zero point energy $E_0 = 0$: RDP & YK 0907.4609

At high T, ren'd loops approach 1 from above



Gava & Jengo '81:

Compute perturbatively,

fold Debye mass, m_D , into propagator for A_0:

$$\langle \ell_R^{\rm ren} \rangle - 1 \sim (-) \, \frac{C_R \, g^2}{T} \int d^3k \, \frac{1}{k^2 + m_{\rm D}^2} \sim (-) \, \frac{C_R \, g^2}{T} \, (-) \, \sqrt{m_{\rm D}^2}$$

Sign of the integral is *negative*; like subtracting $1/k^2$ propagator.

$$\langle \ell_R^{\rm ren} \rangle - 1 \sim (+) \, \frac{C_R}{N} \, \frac{(g^2 \, N)^{3/2}}{8\pi\sqrt{3}}$$

Zero point energy & renormalized loops

RDP & YK 0907.4609: renormalization valid for arbitrary Wilson loops:

$$\mathcal{W} = \mathrm{tr}\,\mathcal{P}\; e^{ig\oint A_\mu dx^\mu} \quad ; \quad \mathcal{W}_{\rm bare} = \mathcal{Z}_{\rm div}\,\mathcal{W}_{\rm ren}$$

Two ambiguities:

$$\mathcal{Z}_{\rm div} = \mathrm{e}^{E_0 L}\;\mathcal{Z}_0\;\mathcal{Z}(g^2\ldots)^{L/a} \quad ; \quad \mathcal{W}_{\rm ren} \to \mathrm{e}^{-E_0 L}\;\mathcal{Z}_0^{-1}\,\mathcal{W}_{\rm ren}$$

Overall scale trivial: $Z_0 = 1$ by requiring <*loop*> $\rightarrow$ 1 as T $\rightarrow \infty$.

E_0 = ground state energy for potential from Wilson loop: $E_0 = \# \sqrt{\sigma}$. # ?

Can *define* $E_0 = 0$ order by order in perturbation theory with *any* regulator.

$E_0 = 0$ also in string model: Nambu-Goto *plus* extrinsic curvature terms.

Ambiguity present also for calc.'s on small sphere

Lattice provides *non*-perturbative way to *define* $E_0 = 0$.

However, $E_0 = 0$ *only* for straight loops, and *not* for "smeared" loops.

Renormalization of smeared loops: S. Capitani and O. Kaczmarek, in progress.

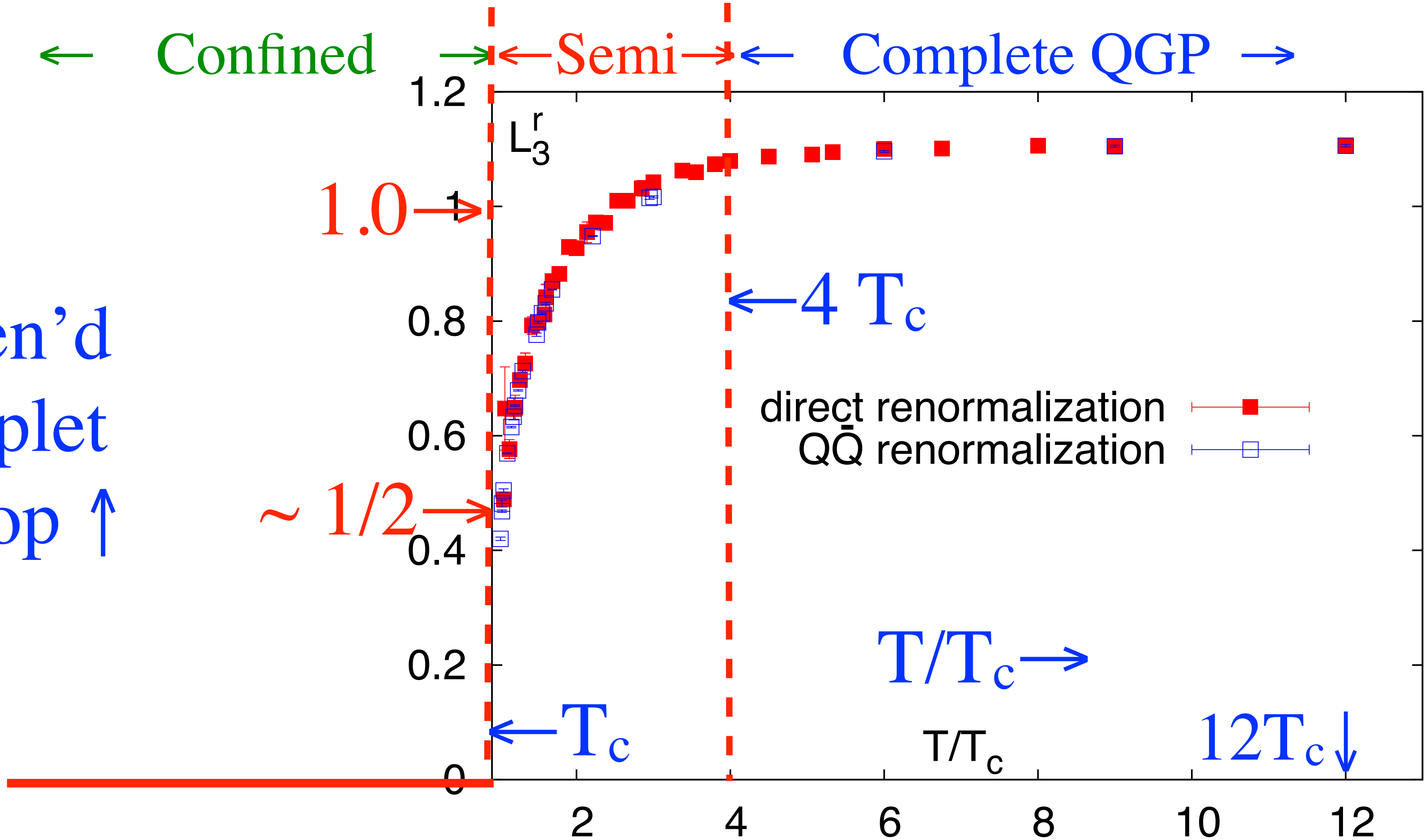
Lattice: renormalized loop, c/o quarks

GHK: Lattice SU(3), *no* quarks. Two ways of getting ren'd loop agree.

<*triplet loop*> ~ 1/2 at T_c^+. N=3 close to Gross-Witten point?

semi-QGP: from (*exactly*) T_c^+ to 2 - 4 T_c (?). <*loop*> ~ constant above 4 T_c.

<*adjoint loop*> ~ 0.01 just below T_c . *Only* natural in matrix model.

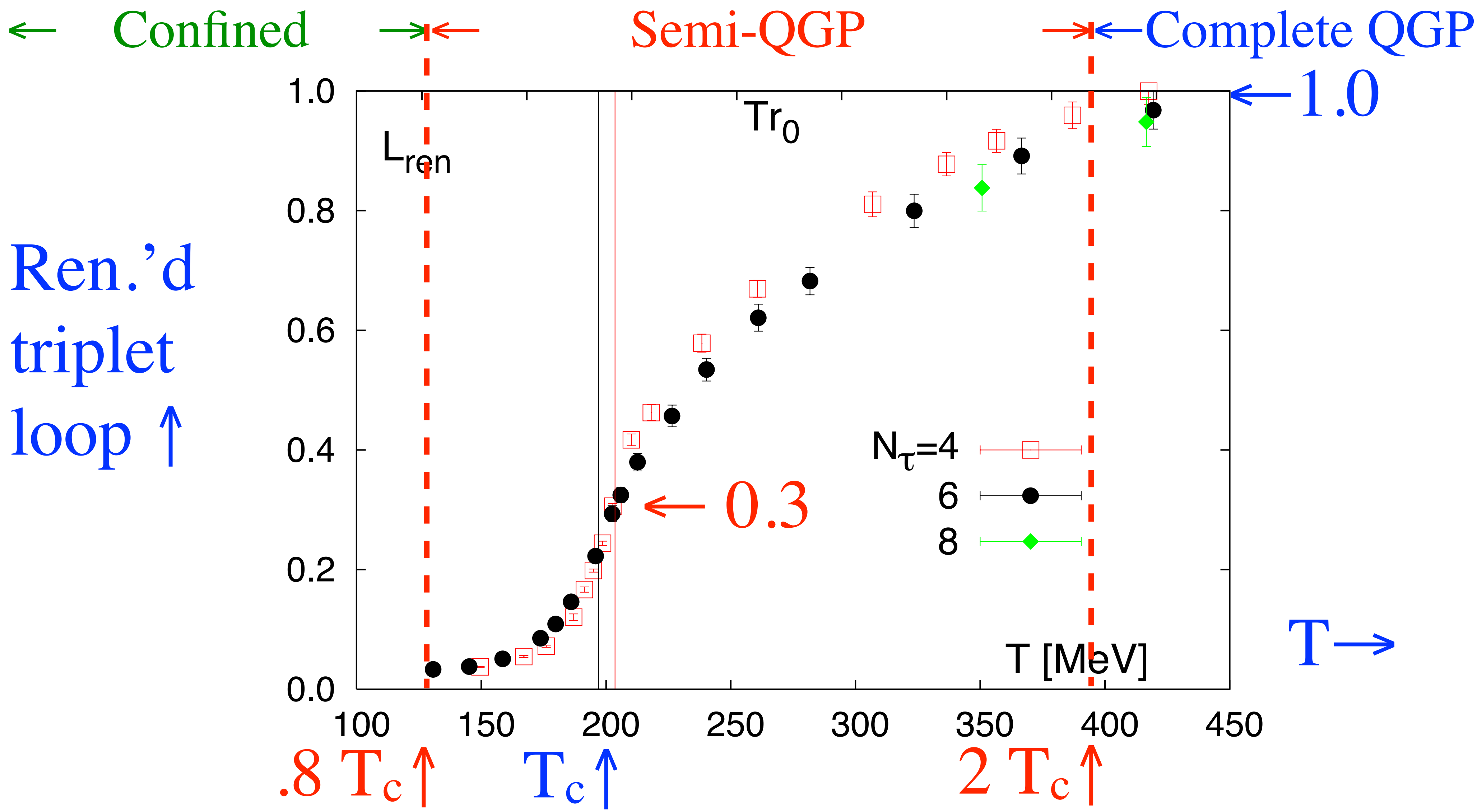


Lattice: renormalized loop, with quarks

Cheng et al, 0710.0354: ~ QCD, 2+1 flavors. T_c ~ 190 MeV, crossover.

<loop>: nonzero from ~ 0.8 T_c; ~ 0.3 at T_c; ~ 1.0 at 2 T_c.

Semi-QGP from ~ 0.8 T_c (*below* T_c) to ~ 2-3 T_c (?). *<loop> small* at T_c .



Effective potential for the semi-QGP, 1

At one loop order, there is a potential for $A_0^{cl} = Q/g$:
Gross, Yaffe, & RDP, '81; N. Weiss, '81

$$\mathcal{V}_{\rm pert.} = \# \, T^4 \, q^2 (1-q)^2 \; , \; Q = 2\pi T q$$

Necessary: in the pure glue theory, lifts the degeneracy in q.
This potential enters the computation of the tunneling between $Z(N_c)$ vacua,
= $Z(N_c)$ interface tension.

Meisinger, Miller, & Ogilvie (MMO), hep-ph/0108009:
add a *non*-perturbative potential, ~ T^2
Terms ~ T^2 "Fuzzy Bag": RDP, hep-ph/0612191

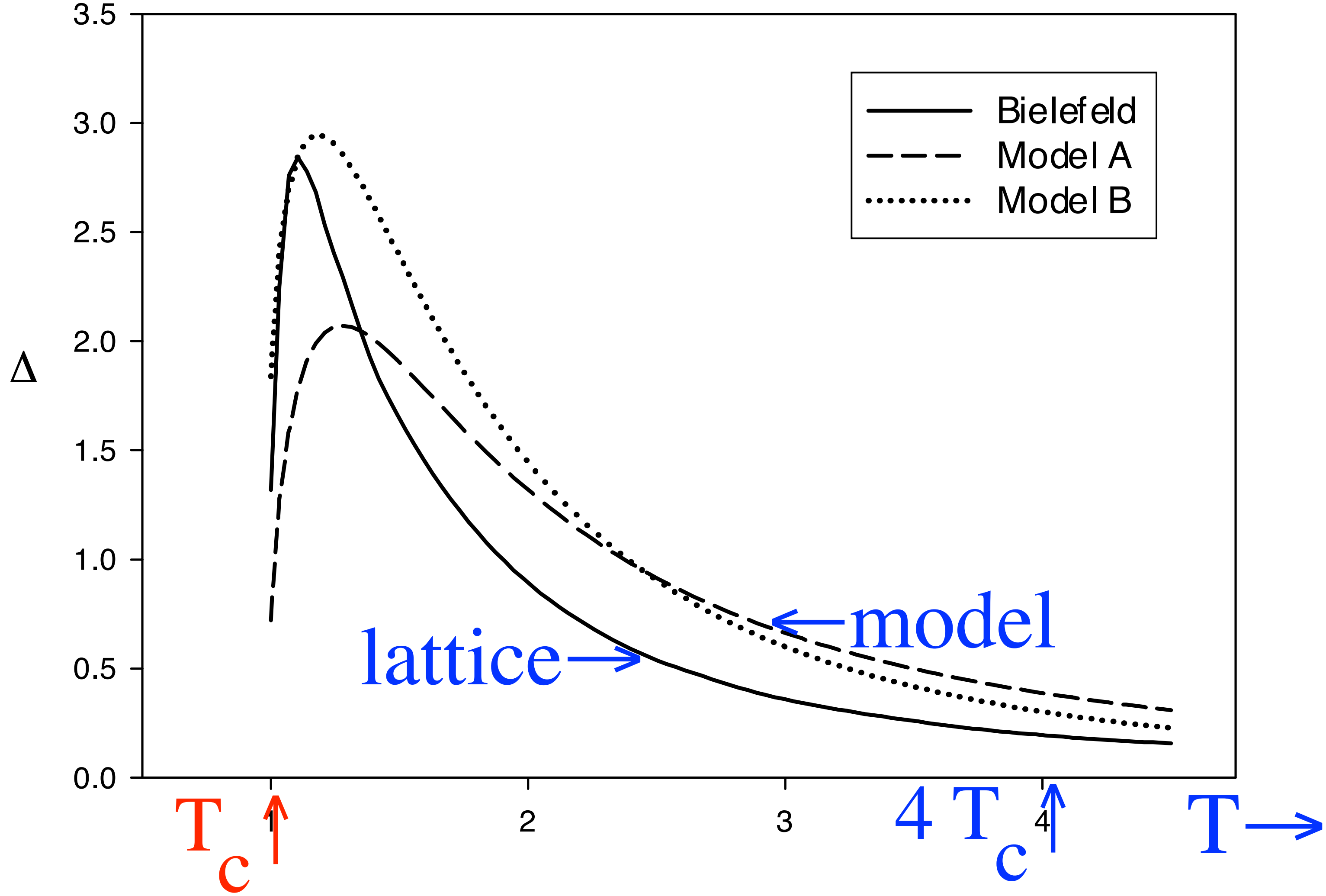
$$\mathcal{V}_{\rm non-pert.} = \# \, T^2 \, q (1-q)$$

Must have terms ~ q as q → 0: else have a phase transition
(either 1st or 2nd order), in going from the *complete* QGP, to the semi- QGP.
Lattice finds only *one* transition, at T_c, and *not* a second transition above T_c.

Effective potential for the semi-QGP, 2

MMO fit the pressure with reasonable accuracy:

$$\frac{e-3p}{T^4}\uparrow$$



But the renormalized Polyakov loop is *nothing* like the lattice:
it is near one by ~ 1.5 T_c!

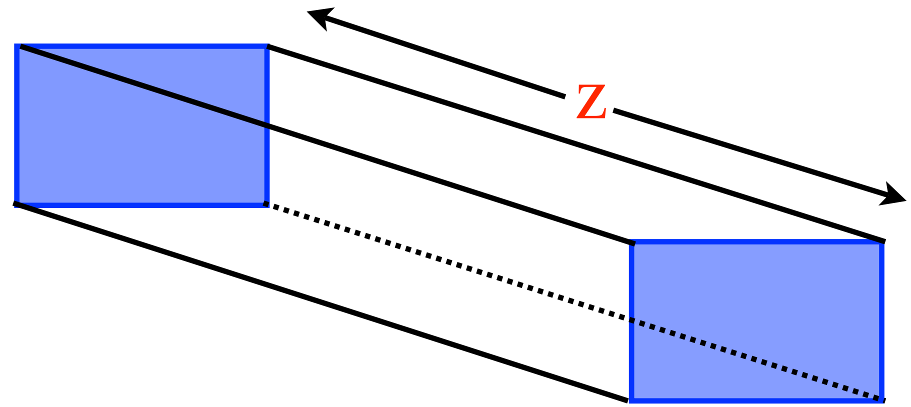
Dumitru, RDP, & Zschiesche, '05, unpublished: *no* effective potential fits *both* the pressure *and* the renormalized loop.

Z(N) interfaces = ‘t Hooft loop

Z(N) interface: Z(N) “twist” in z-direction. A_{tr} = transverse area.

$$A_0^{\rm cl} = \frac{2\pi T}{gN}\, q(z)\, t_N$$

$\langle L \rangle = \mathbf{1}$



$\langle L \rangle = \mathrm{e}^{2\pi i/N}\,\mathbf{1}$

$t_N = \mathrm{diag}(1_{N-1}, -N+1)$. $A_0 \sim$ “coordinate” q(z).

$L_{\rm eff}$ = classical + 1 loop potential, for *constant* A_0

$$\mathcal{L}_{\rm eff} = \frac{4\pi^2 (N-1) T^3}{\sqrt{3 g^2 N}}\, \mathrm{A}_{\rm tr} \int dz \left(\left(\frac{dq}{dz} \right)^2 + q^2 (1-q)^2 \right)$$

Bhattacharya, Gocksch, Korthals-Altes & RDP, hep-ph/9205231

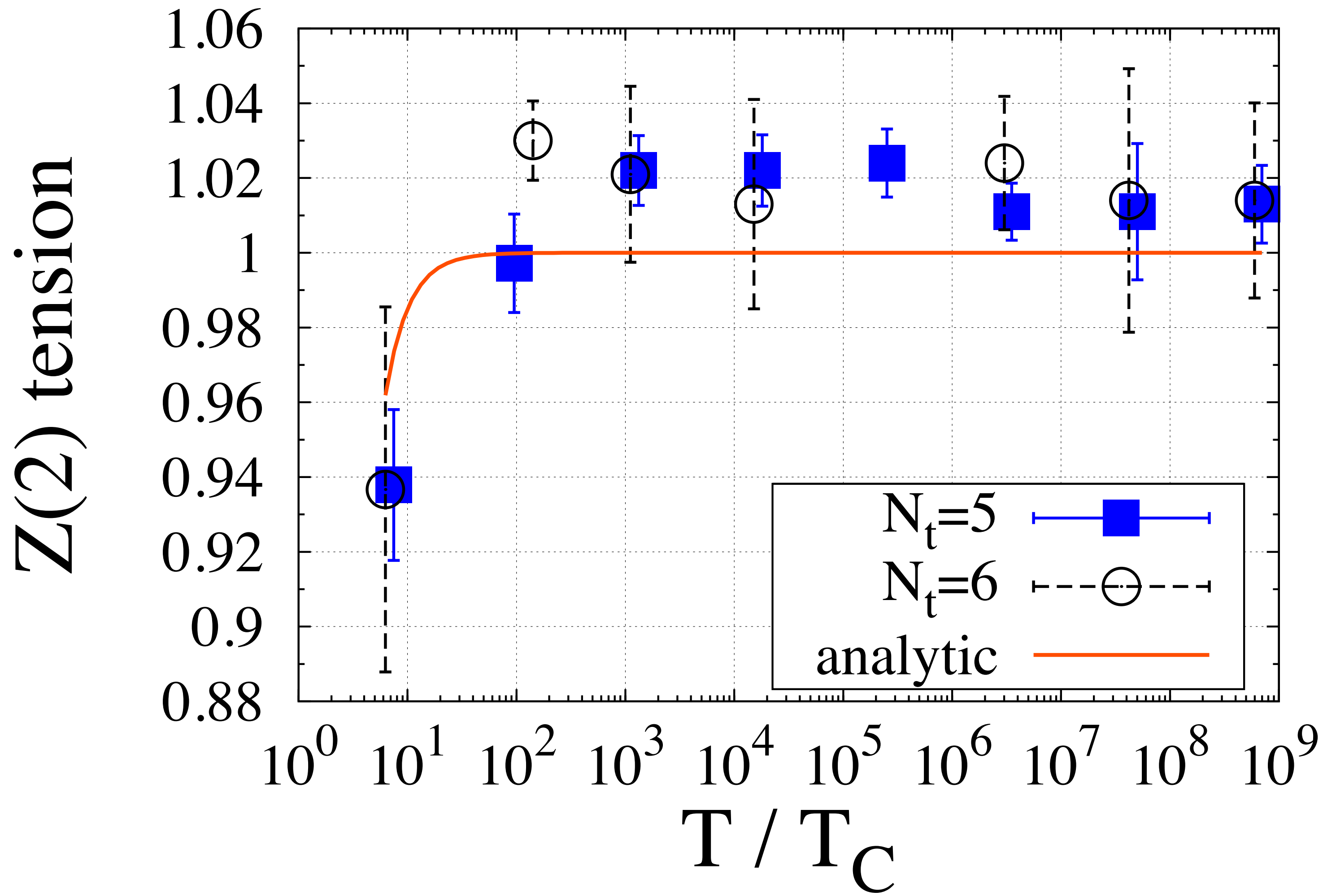
Interface = ‘t Hooft loop: Korthals-Altes, Kovner & Stephanov, hep-ph/9909516

Corrections ~ g^3: Giovannangeli & Korthals-Altes hep-ph/0412322

~ g^4: Korthals-Altes, Schroder, & Vuorinen, in progress

Interface tension for the semi-QGP

In pure glue SU(N_c) theory, global Z(N_c) symmetry implies N_c degenerate vacua
Tunneling between degenerate N_c vacua is interface tension (aka 't Hooft loop)
Semi-classical computation of interface tension works *well* above ~ 10 GeV,
but *not* below: SU(2) lattice, de Forcrand & Noth hep-lat/0506005
DGHKP, 1010....: With "fuzzy bag" term of MMO, works well right down to T_c!



Two types of gluon masses in the semi-QGP

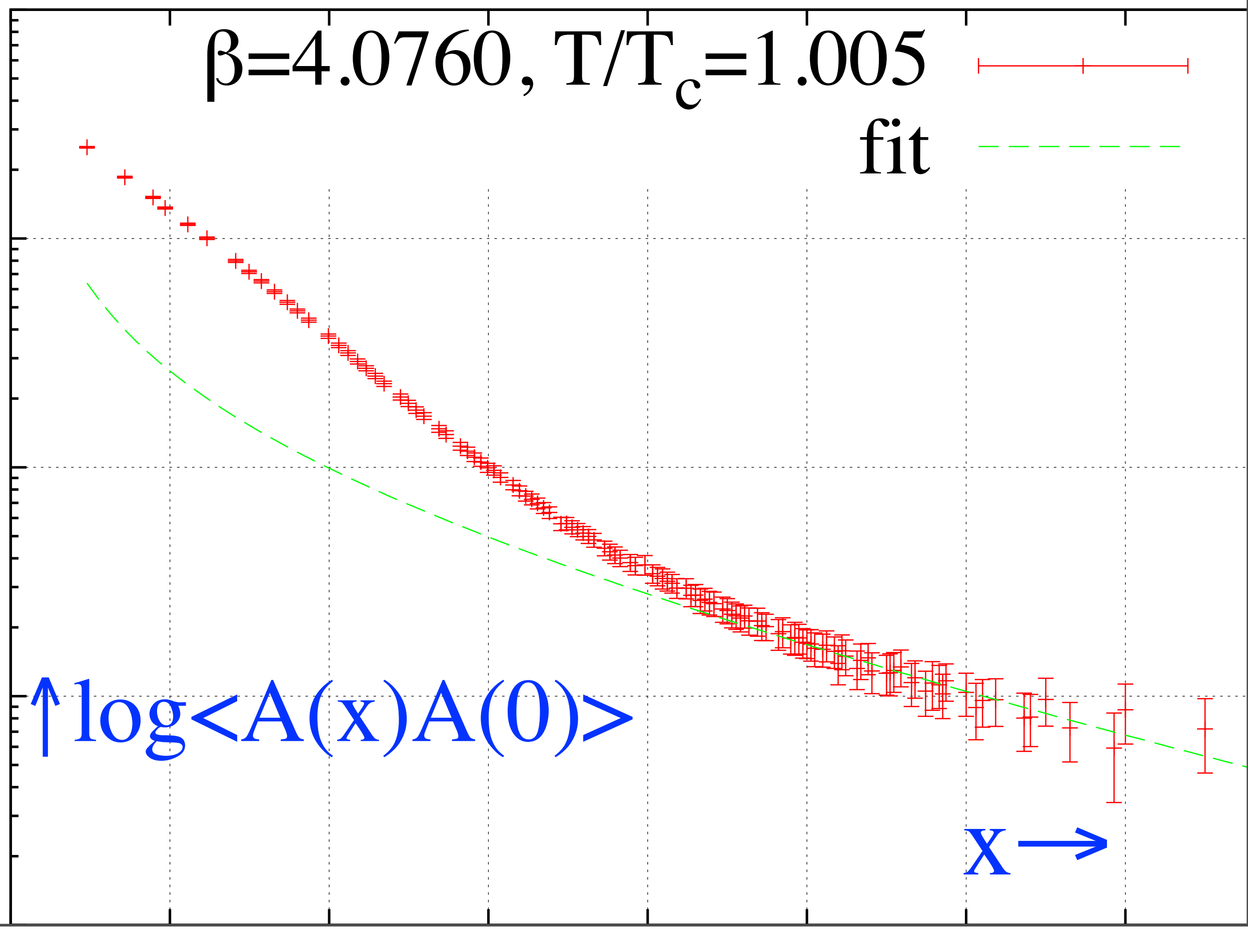
DGHKP, 1010....: two point function of gluons. In coordinate space,
(energy $p_0 = 2\pi n T$, $n = 0, \pm 1, \pm 2...$)

$$\langle A_0^{ab}(\vec{x})\, A_0^{ba}(0)\rangle \sim \int \frac{d^3p}{(2\pi)^3}\, \mathrm{e}^{i\vec{p}\cdot\vec{x}} \sum_{n=-\infty}^{+\infty} \frac{\mathrm{e}^{-ip_0\tau}}{(\vec{p})^2 + (p_0 + Q^a - Q^b)^2 + m_{\mathrm{D}}^2(Q)}$$

Off-diagonal color fields *heavy*:
$\sim |p_0 + Q^a - Q^b| \sim 2\pi T$
Diagonal color fields *light*:
$\sim$ Debye mass, $m_D(Q) \sim g\,T$

Unique prediction in semi-QGP:
two types of gluon masses

O. Kaczmarek, unpublished:
evidence from lattice SU(3):
two slopes in log<A(x)A(0)>
Only *below* $\sim 1.5\ T_c$, *not* above



Conclusions

RHIC: (mainly) in the semi-QGP?

LHC: deep in the complete QGP?

Shear viscosity *increases* going from the semi- QGP,
to the complete QGP.

Today: the width of the semi-QGP is *narrow*, from $\sim T_c$ to $\sim 1.5\, T_c$,
and *not* broad, $\sim T_c$ to $\sim 4\, T_c$.

John Harris: "Expect the Unexpected"