Berndt Müller: hunting for the Quark Gluon Plasma

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Some of Berndt's notable contributions

'86: Müller & Rafelski, strangeness enhancement in AA: first *real* signal for QGP!

'86: Plunien, Müller & W. Greiner, Casimir effect

'92: Geiger & Müller, *seminal* work on parton cascades

'03: Fries, Müller, Nonaka & Bass, recombination - *amazingly* successful

Former post-docs:

Tenured:

- Alec Schramm (Occidental College)
- Klaus Kinder-Geiger (Deceased)
- Xin-Nian Wang (LBL)
- Sen-Ben Liao (National Chung-Cheng Univ, Taiwan)
- Carsten Greiner (Frankfurt)
- Dirk Rischke (Frankfurt)
- Steffen Bass (Duke)
- Chiho Nonaka (Nagoya)
- Rainer Fries (Texas A&M)

TBT (to be tenured):

- Thorsten Renk (Jyväskyla)
- Abhijit Majumder (Ohio State Univ.)

Industry: Jörg Ruppert

A recent example: chiral magnetic effect

Asakawa, Majumder, & Müller, arXiv:1003.2436; Müller & Schäfer, 1009.1053

Considered anomalous π-γ-ϱ coupling $\mathcal{L}_{eff} \sim \epsilon^{\alpha\beta\gamma\delta}\, F_{\alpha\beta}\, \partial_\gamma \pi^0\, \rho^0_\delta$

Wess-Zumino-Witten model: general effective Lagrangian for anomalous couplings

$$\mathcal{L}_{eff} \sim \frac{e^2 N_c}{48\pi^2 f_\pi}\, \epsilon^{\alpha\beta\gamma\delta}\pi^0\, F_{\alpha\beta}\, F_{\gamma\delta} \;-\; \frac{2ieN_c}{\pi^2 f_\pi^3}\, \epsilon^{\alpha\beta\gamma\delta} A_\alpha\, \partial_\beta \pi^0\, \partial_\gamma \pi^+\, \partial_\delta \pi^- + \ldots$$

First term: $\pi^0 \to \gamma\,\gamma$. Second term: $\omega \to \gamma\,\gamma\,\gamma$. Integrate 2nd term by parts

$$\pi^0 \epsilon^{\alpha\beta\gamma\delta}\, F_{\alpha\beta}\, \partial_\gamma (\pi^+ \partial_\delta \pi^-) \sim \pi^0\, B_i\, \partial_0 J_i + \pi^0\, \epsilon^{ijk}\, E_i\, \partial_j J_k$$

J is the pion e.m. current; J ~ ϱ by VMD

B ∂ J is the chiral magnetic effect; E · ∂ × J , is the chiral electric effect.

AMM: need domains of $< \pi^0 >$. Too small to explain STAR data by ~ 10^{-4}.

See, also, Schlichting & Pratt, arXiv:1005.5431 & 1009.4283.

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

1. *Yes:* small increase in elliptic flow, (appropriately scaled) multiplicity
   (Nearly) ideal hydro works
   Approach from *strong* coupling. Gyulassy: "Diving into the Black Hole"

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

With A. Dumitru, Y. Guo, Y. Hidaka, C. Korthals Altes (DGHKP), 1011....
With Y. Hidaka, 0803.0453, 0906.1751, 0907.4609, 0912.0940

Semi-classical approach in *intermediate* coupling:
Hietenan, Kajantie, Laine, Rummukainen, & Schröder, ph/0503061...0811.4664
Andersen, Leganger, Strickland, & Su: ...0911.0676, 1005.1603, 1009.4644

3. *Nothing* like it: elliptic flow *much* larger; (scaled) multiplicity - *much* higher?
   Not "Wit-less": Busza, arXiv: 0907.4719
   Terra incognita: *non*-equilbrium distribution

The semi-, versus the complete, Quark Gluon Plasma

Typical plasma in QED: e.g., 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 ionization: confined phase: below T_c

Total ionization: "*complete*" Quark-Gluon Plasma

Lattice: complete QGP above a "few" times T_c

Partial ionization: "semi"-QGP

From a little bit *below* T_c, to a "few" times T_c

What is a "few" times times T_c?

Conclusion: used to think semi-QGP *broad*, T_c^+ to ~ 4.0 T_c

Today: *narrow*, T_c^+ to ~ 1.5 T_c .

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....)

SU(3) gauge theory as a 3-state "clock" model

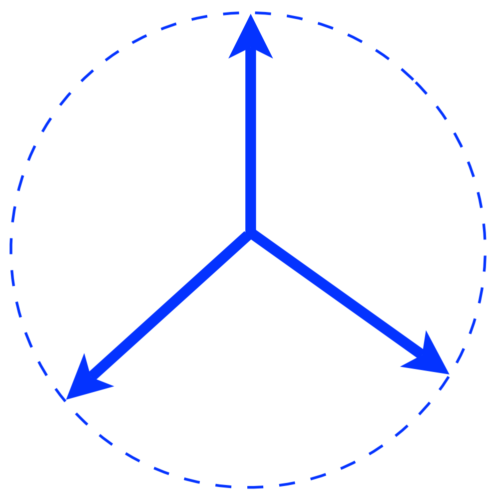
Let U_c = gauge transf. = *constant* phase.

SU(3): det $U_c = 1$, so U_c *third* root of unity:

$$U_c = \left(e^{2\pi i/3}\right)^j \ , \ j = 0, 1, 2$$

Under U_c, gluons *invariant*: $A_\mu \to e^{-2\pi i/3}\, A_\mu\, e^{2\pi i/3} = A_\mu$

but quarks *not*. $\psi \to e^{2\pi i/3}\, \psi$

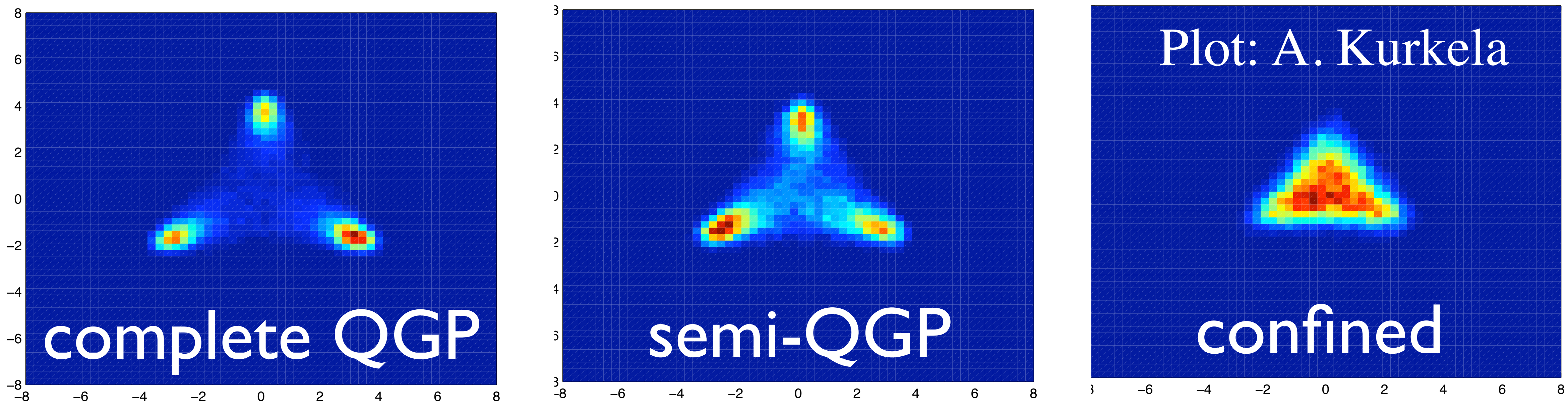


'**t Hooft: Z(3) spin from SU(3) color**

Lattice: Z(3) spin symmetry ~ ok with three light flavors.

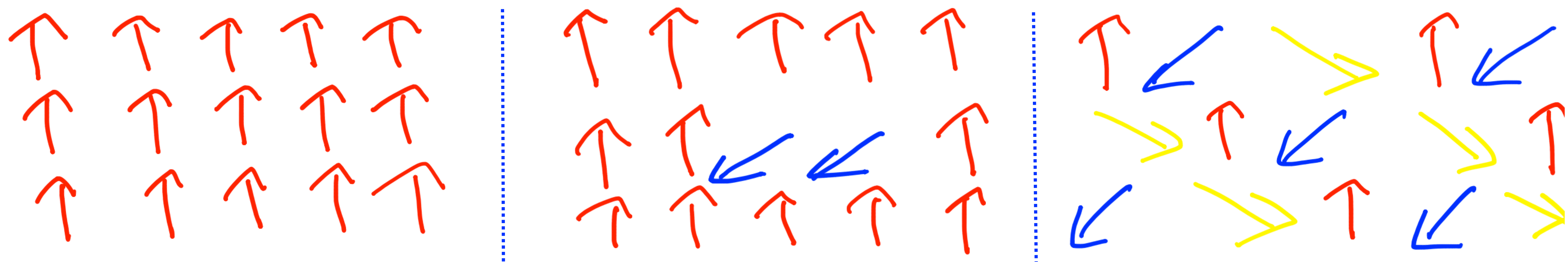
Measure with thermal Wilson line

$$\mathbf{L} = e^{ig \int_0^{1/T} A_0 \, d\tau}$$



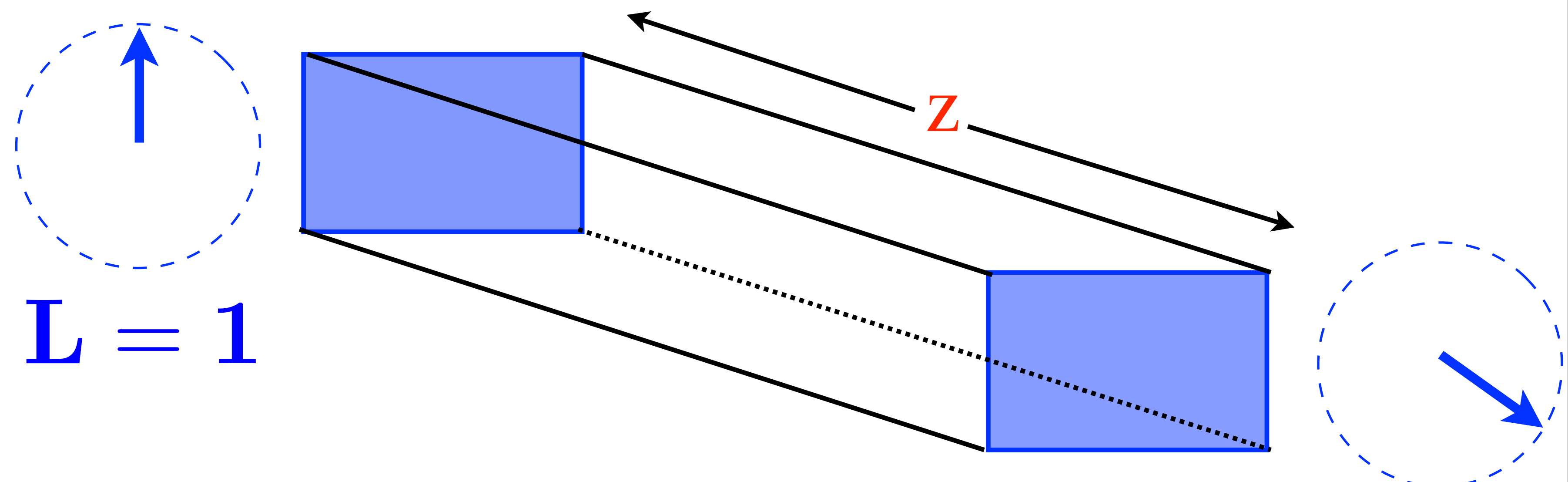
T >> T$_c$ **T ~ T$_c$** **T < T$_c$**

Deconfining transition as a clock model



Complete QGP ↑	“Semi”-QGP ↑	Confined Phase ↑
ordered spin system	Some spin defects	completely disordered spins
$T \gg T_c$	$T > T_c$	$T < T_c$

How to compute defects? Consider a box, long in one spatial direction.
Put one spin at one end, another spin at the other.



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

$$\mathbf{L} = e^{\frac{2\pi i}{3}}\,\mathbf{1}$$

Degenerate vacua at both ends. In between, an interface forms, tunnel between degenerate vacua.
Can compute this (order-order) “interface tension”.

Path for Z(3) interface

Consider a background field,

$$A_0^{cl} = \frac{2\pi T}{3g}\, q\, t_8 \qquad t_8 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

Along this t_8 direction,

$$\mathbf{L}(q) = \mathrm{e}^{\frac{2\pi i}{3}\, q\, t_8} \qquad \mathbf{L}(1) = \mathrm{e}^{2\pi i/3}\, \mathbf{1}$$

Hence the boundary conditions are q = 0 at one end of the box, q = 1 at the other.

Compute one loop determinant in background field:

$$V_{eff} \sim \#\, T^4 \, (ct. + q^2 (1-q)^2)$$

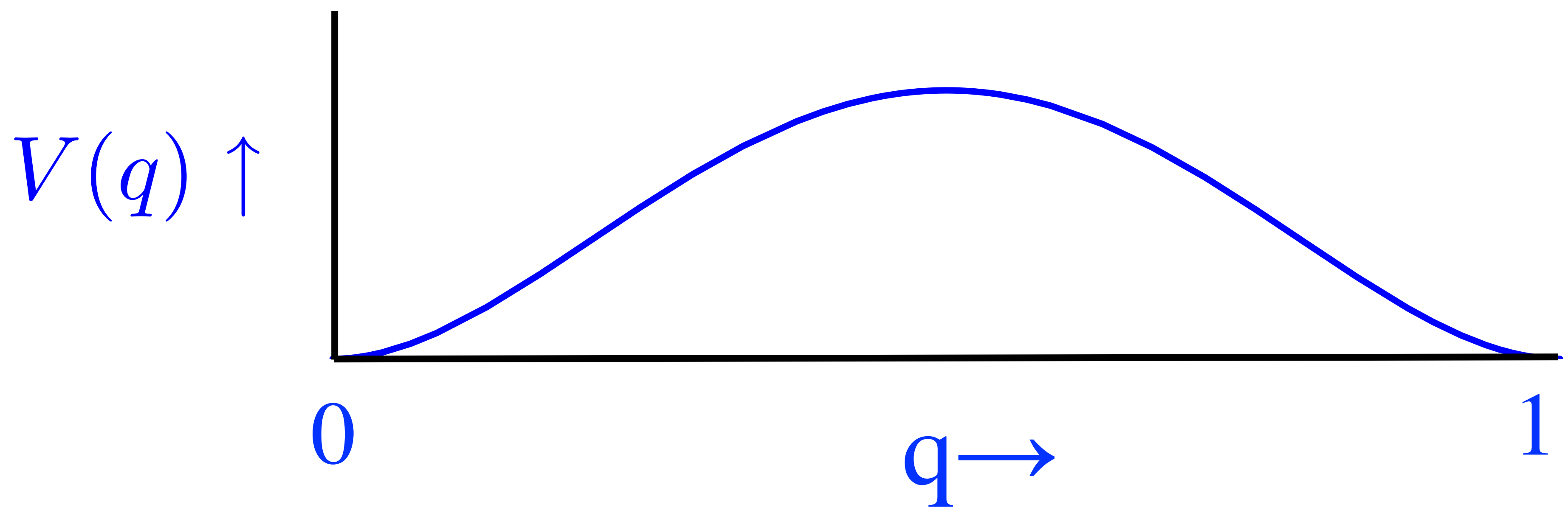
Constant = ideal gas term for gluons.

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

Interface tension

Electric field $\partial_i A_0 \sim (1/g)\, dq/dz$,
so effective Lagrangian

$$L_{eff} \sim \frac{T^2}{g^2}\left(\frac{dq}{dz}\right)^2 + \# T^4 q^2 (1-q)^2$$



Standard tunneling problem in 1 dimension.
Action for tunneling interface tension:

$$\alpha_{inter} \sim \frac{T^3}{\sqrt{g^2}}$$

Interface tension equivalent to ‘t Hooft loop,
wrapping around center of box: measures response to Z(3) magnetic charge
Korthals-Altes, Kovner & Stephanov, hep-ph/9909516

Path to confinement

Now consider another background field

$$A_0^{cl} = \frac{2\pi T}{3g}\, q_c\, t_3 \qquad t_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Along the t_3 direction,

$$\mathbf{L}(q_c) = \mathrm{e}^{\frac{2\pi i}{3} q_c t_3} \qquad \mathbf{L}(q_c = 1) = \mathrm{e}^{\frac{2\pi i}{3}\, t_3} = \begin{pmatrix} \mathrm{e}^{2\pi i/3} & 0 & 0 \\ 0 & \mathrm{e}^{-2\pi i/3} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Note: $\mathbf{L}(1) = \mathrm{e}^{\frac{2\pi i}{3}}\, \mathbf{L}(1)$ Hence: $\mathrm{tr}\, \mathbf{L}(1) = \mathrm{tr}\, \mathbf{L}^2(1) = 0$

Thus $q_c = 1$ is the *confined* vacuum for SU(3).

$q_c = 0$ is the usual perturbative vacuum.

$$V_{eff} \sim \#\, T^4\, (ct. + q_c^2 (1 - q_c)^2)$$

$V_{\rm eff}$ to $\sim g^3$: Giovannangeli & Korthals Altes, hep-ph/0412322

$\sim g^4$: Korthals-Altes, Schroder, & Vuorinen, in progress

Effective matrix model for confinement

In pert. thy, perturbative vacuum stable: need *new* terms to drive confinement.
Meisinger, Miller, & Ogilvie (MMO), hep-ph/0108009:
Add, *by hand,* a non-pert. potential, ~ T^2 ("Fuzzy Bag": RDP, hep-ph/0612191)

$$V_{\rm non-pt} = T^2 \, \Lambda^2 \left(c_1 \, q(1-q) + c_2 \, q^2 (1-q)^2 + c_3 \right)$$

Λ mass parameter; c_1, c_2, c_3 dim.'less parameters. Fix one by $p(T_c) = 0$.
MMO: only one parameter, c_1. Can add ∞ series of polynomials in q(1-q).

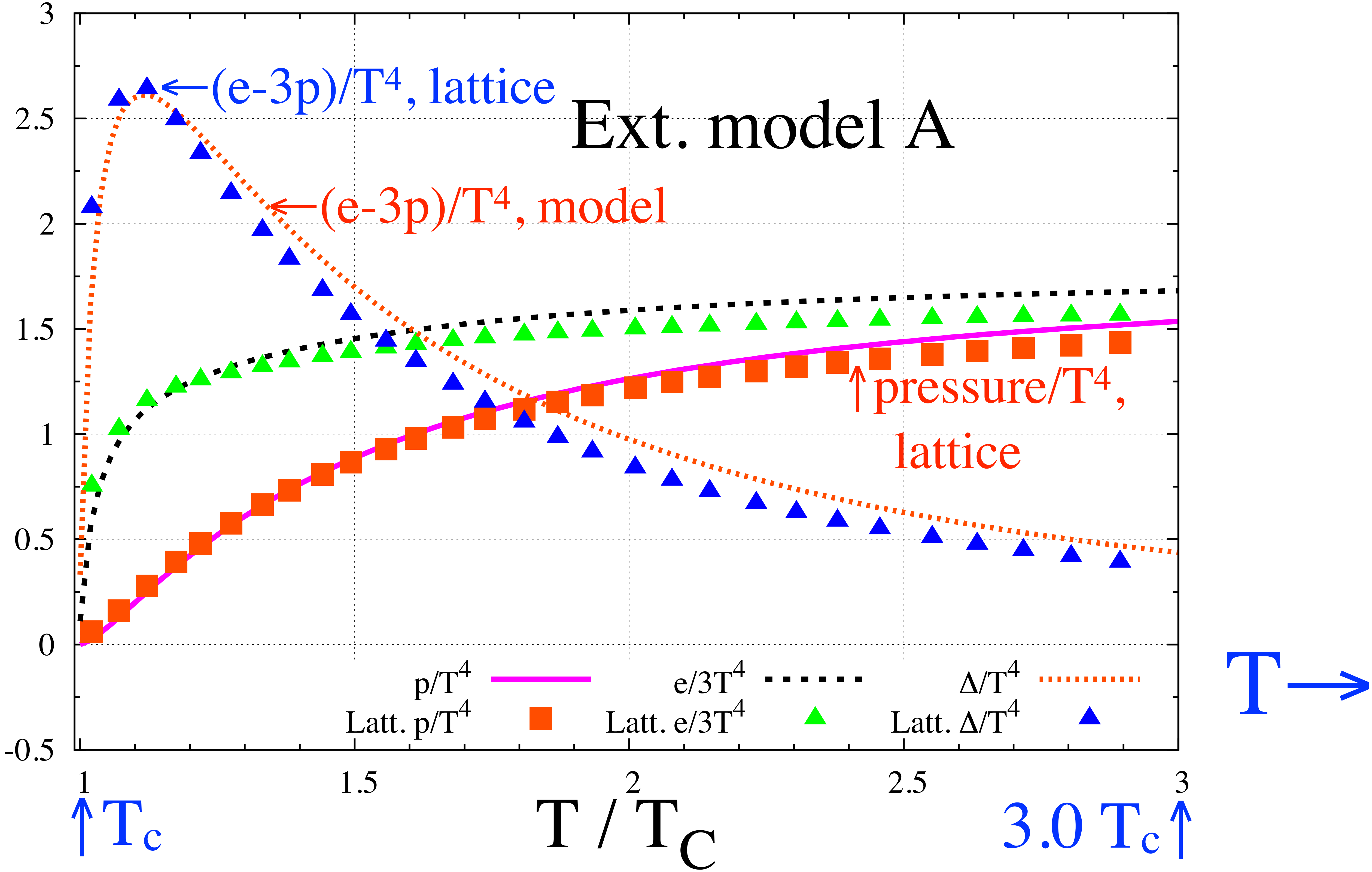
Need term ~ c_1 : with c_1, $< q > \sim 1/T^2$.
Otherwise, phase *transition* from complete ($<q> = 0$) to semi- ($<q> \neq 0$) QGP

$$V_{\rm pt} = \# T^4 \, q^2 (1-q)^2$$

$V_{\rm eff} = V_{\rm pt} + V_{\rm non\text{-}pt}$. $V_{\rm eff}$ function of q, q ε Lie *algebra*, not Lie group.
Fit parameters from pressure (or better, interaction measure, $(e-3p)/T^4$)
Then compute interface tension and gluons masses. Only *effective* theory, *not* complete: vs Liao & Shuryak: ph/0611131,0804.0255,0804.4890,0810.4116

Effective matrix model, pure SU(3) glue

Can tune parameters of eff. model to obtain reasonable agreement with pressure:



Results: ‘t Hooft loop, two colors

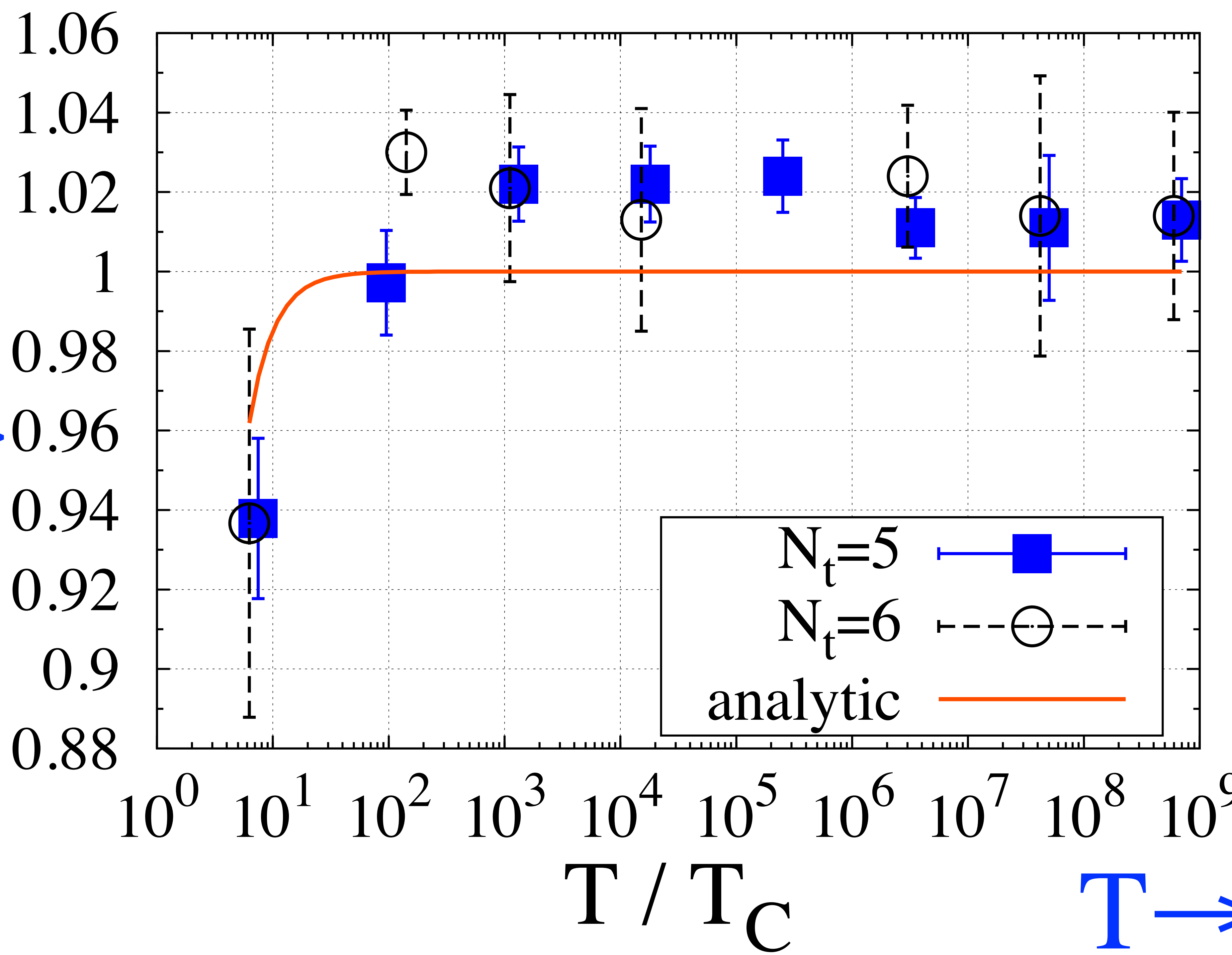
Pure SU(2): ‘t Hooft loop on lattice, de Forcrand & Noth hep-lat/0506005

Below: comparison between lattice and effective model: good, need better data.

‘t Hooft loop =
Z(2) interface
tension:

Ratio
lattice/semi-class.→
in complete QGP

~ agreement.



T→

Two types of gluon modes near T_c

Compute quantum fluctuations above background field,
(energy $p_0 = 2\pi n T$, $n = 0, \pm 1, \pm 2 \ldots$)

$$\left(A_0^{cl}\right)_{ab} = \frac{2\pi T}{g} q_a \delta_{ab}$$

$$\langle A_0^{ab}(\vec{x})\, A_0^{ba}(0)\rangle$$

$$\sim \int \frac{d^3p}{(2\pi)^3}\, \mathrm{e}^{i\vec{p}\cdot\vec{x}} \sum_{n=-\infty}^{+\infty} \frac{\mathrm{e}^{-ip_0\tau}}{(\vec{p})^2 + ((2\pi T)(n + q_a - q_b))^2 + m_{\mathrm{D}}^2(Q)}$$

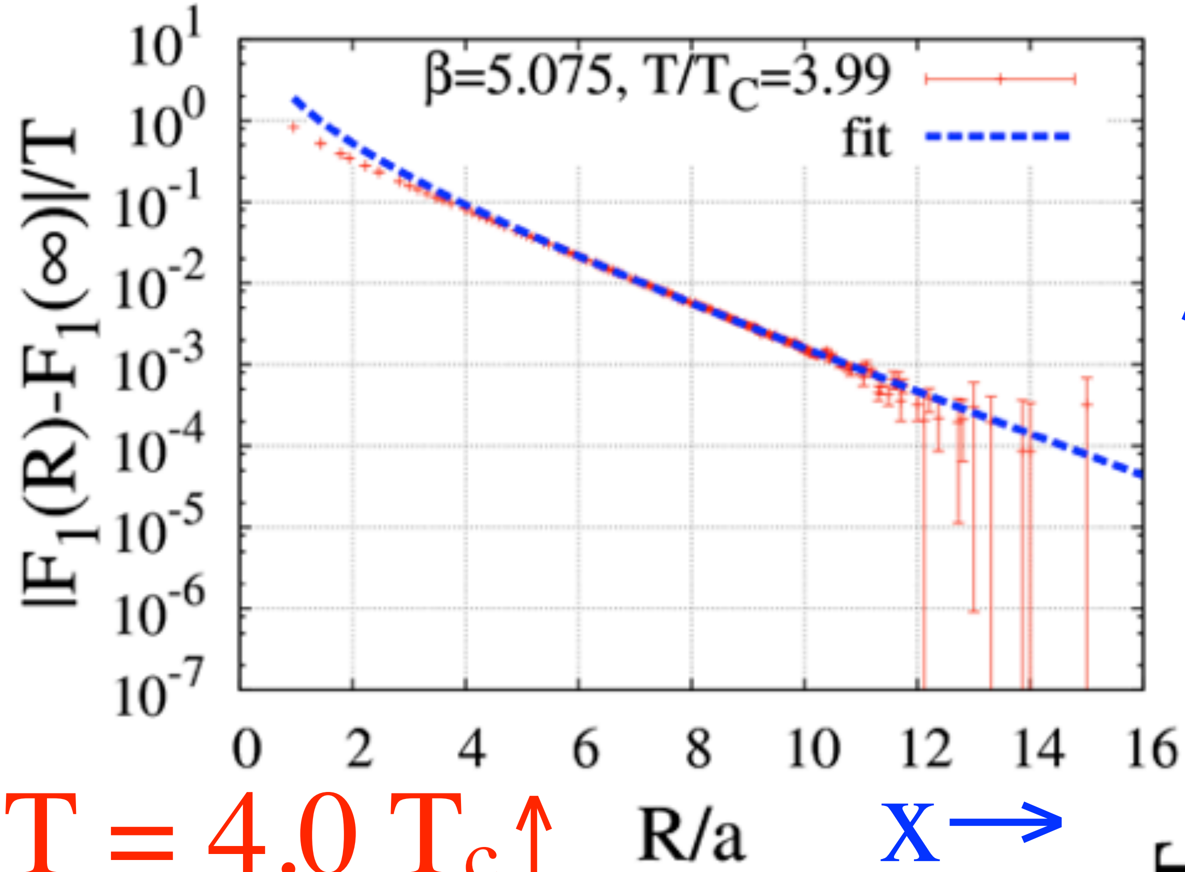
Off-diagonal color fields, $q_a \neq q_b$ *heavy*: "mass"~ $(2\pi T)(n + q_a - q_b) \sim 2\pi T$

Diagonal color fields, $q_a = q_b$ *light*: "mass" ~ Debye mass, $m_D(Q) \sim g T$

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

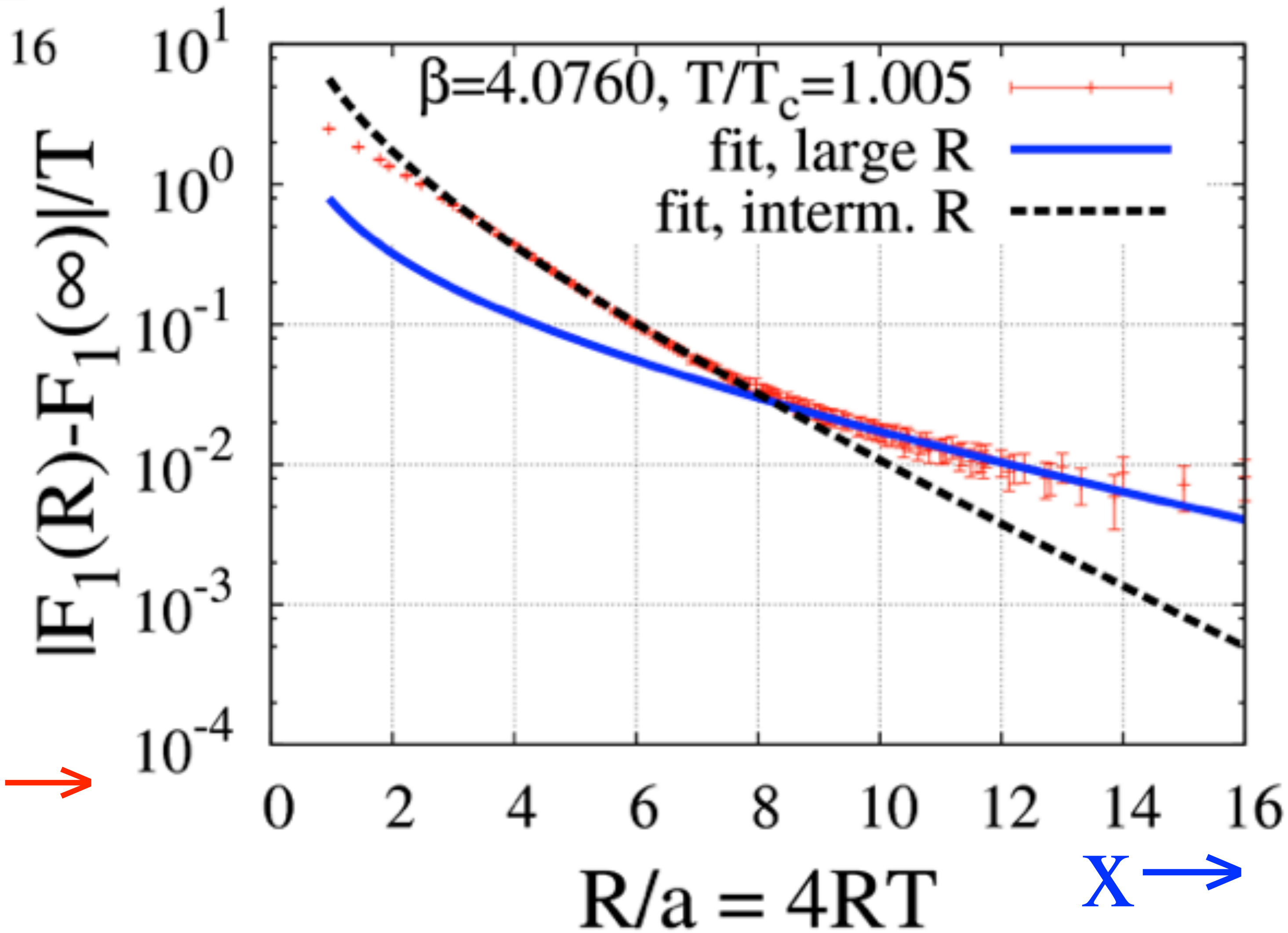
Lattice data, pure SU(3): two masses near T_c?

O. Kaczmarek, arXiv: 0710.0498



$\uparrow \log\langle A(x)A(0)\rangle$

$T = 4.0\ T_c \uparrow$ $x \rightarrow$

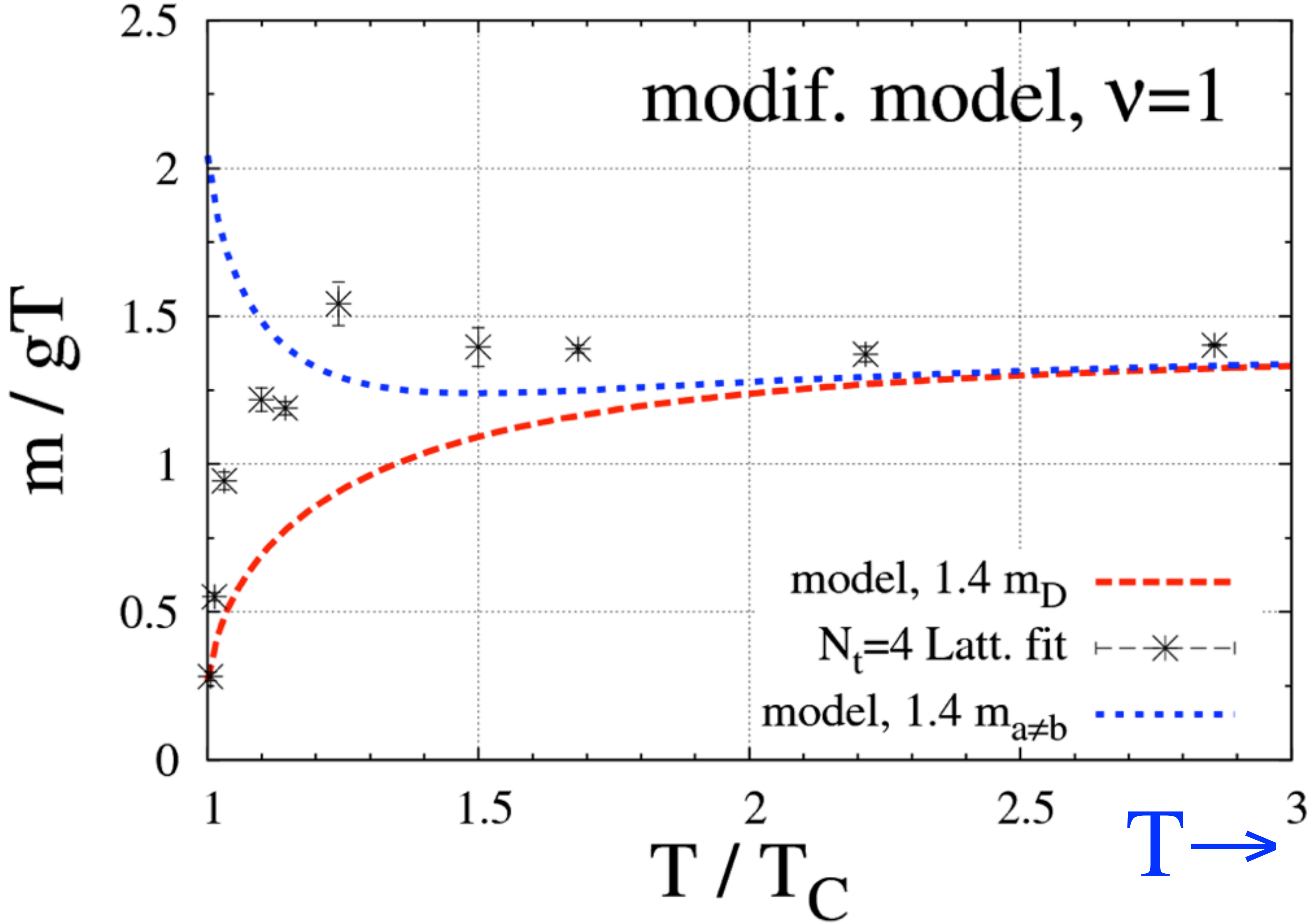


$\uparrow \log\langle A(x)A(0)\rangle$

$T = 1.005\ T_c \rightarrow$

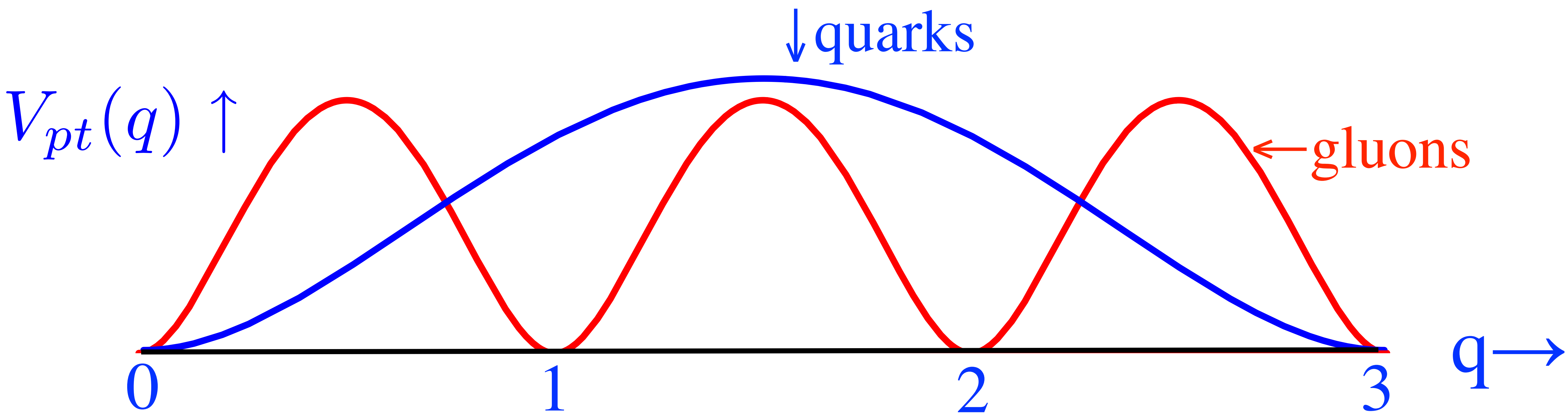
$x \rightarrow$

Comparison: lattice vs model



Adding quarks

Compute potential for constant A_0 with quarks: $$A_0^{cl} = \frac{2\pi T}{3g}\, q\, t_8$$



Red: potential for constant A_0 from SU(3) gluons

<L> = exp(2 π i q/3) **1**. q = 0, 1, 2 are degenerate Z(3) vacua.

Blue: potential from quarks. Potential at q = 1, 2 ≠ q = 0 , 3.

True test: compute effects of dynamical quarks, see how T_c shifts, etc.

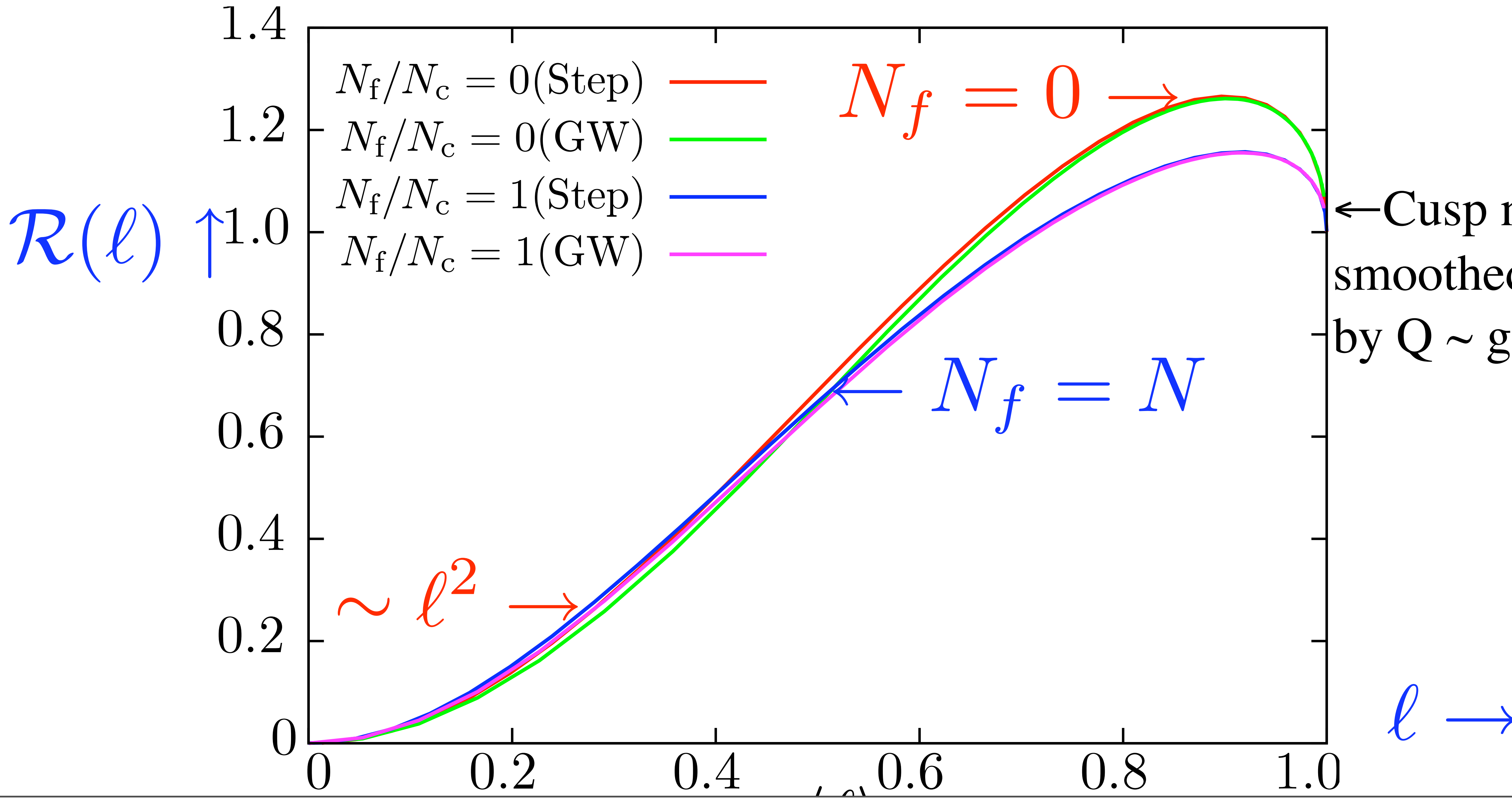
Shear viscosity in the semi-QGP, 1

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

c_1, c_2 #'s from
Arnold, Moore, & Yaffe, hep-ph/0302165

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

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



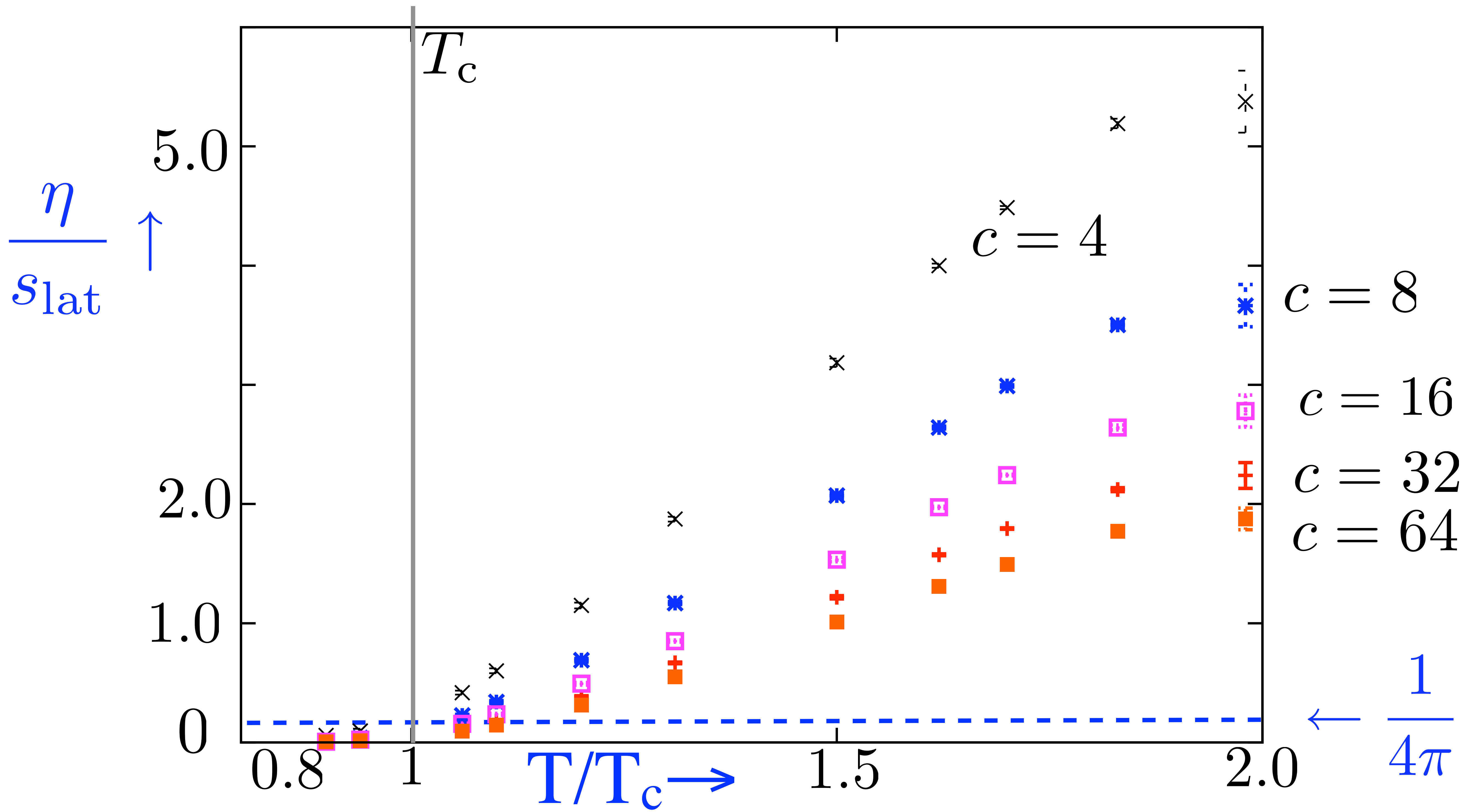
←Cusp near 1: smoothed out by Q ~ g T?

Shear viscosity in the semi-QGP, 2

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.



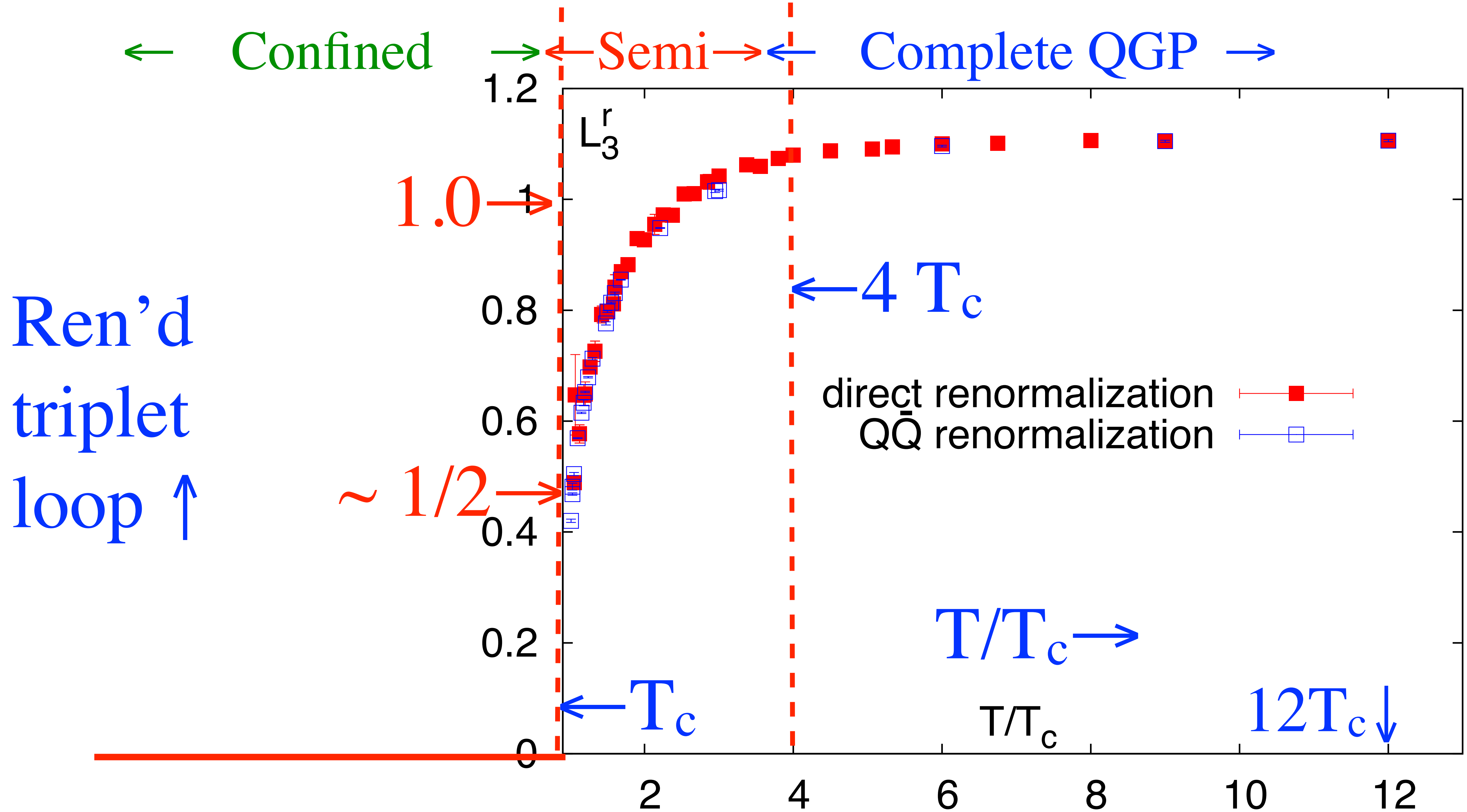
Lattice: renormalized loop, c/o quarks

Gupta, Hubner & Kaczmarek 0711.2251: Lattice SU(3), no quarks.

Above: semi-QGP *narrow*, T_c^+ to ~ 1.5 T_c . Lattice: *broad*, T_c^+ to ~ 4 T_c .

Above agrees with Schwinger-Dyson: Marhauser & Pawlowski, 0812.1144

Our analysis does *not* agree with lattice ren.'d loop: reason for discrepancy?



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 ~ T_c to ~ 1.5 T_c,
and *not* broad, ~ T_c to ~ 4 T_c.

Conclusions

RHIC: (mainly) in the semi-QGP?

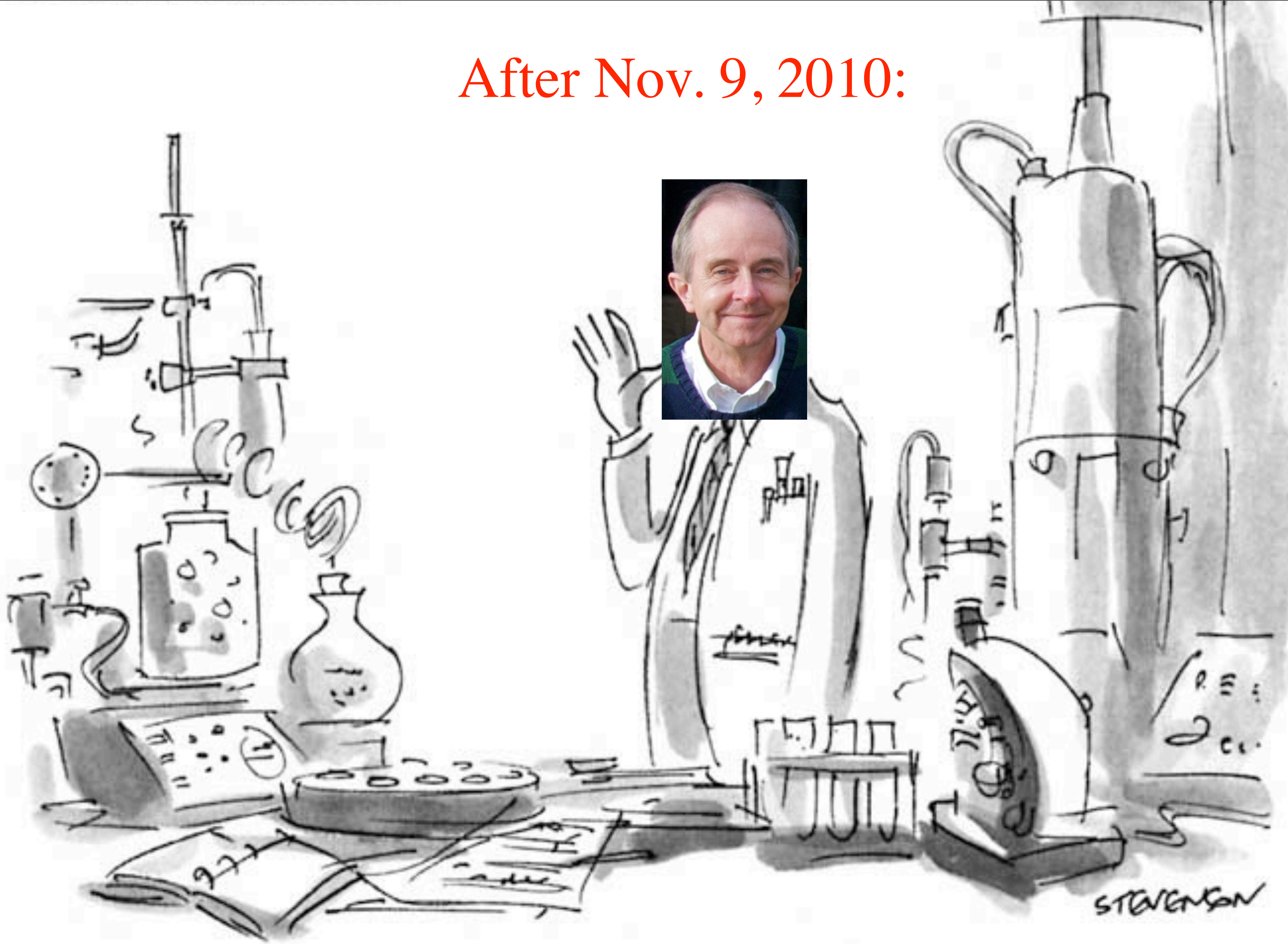
LHC: deep in the complete QGP?

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”

After Nov. 9, 2010:



"A possible eureka."