Happy Birthday, Joe!

e-mail: kapusta@physics.umn.edu or kapusta@umn.edu

Birthdate

21 June 1952 Antigo, Wisconsin

Antigo, Wisconsin

From Wikipedia, the free encyclopedia

Coordinates: 45°8′28″N 89°9′12″W

Antigo (/ˈæntɪɡoʊ/ *AN-ti-goh*)[1] is a city in and the county seat of Langlade County, Wisconsin, United States.[2] The population was 8,560 at the 2000 census. Antigo is the center of a farming and lumbering district, and its manufactures consist principally of lumber, chairs, furniture, sashes, doors and blinds, hubs and spokes, and other wood products.

Contents [hide]

Antigo
Nequi-Antigo-sebi

— **Town** —

Location of Antigo, Langlade County in Wisconsin

Notable residents

- Justin Berg, Chicago Cubs baseball players (pitcher)
- James Bradley, son of John Bradley, author of *Flags of Our Fathers* and *Flyboys: A True Story*
- John Bradley, Navy corpsman who took part in the Raising the Flag on Iwo Jima
- James Randall Durfee, U.S. federal court judge
- Charles Gowan, former Antigo Mayor
- Jon Hohman, professional football player
- Alfred J. Lauby, Wisconsin State Assemblyman
- D. Wayne Lukas, U.S. Racing Hall of Fame horse trainer
- Thomas Lynch, U.S. Representative
- Francis J. McCormick, NFL player
- Elmer Addison Morse, U.S. Representative
- Joe Piskula, Los Angeles Kings hockey player (defenseman)
- Ray Szmanda, radio and television personality/spokesperson
- Margaret Turnbull, astronomer and graduate of Antigo High School
- James M. Vande Hey, U.S. Air Force general
- Clair H. Voss, Presiding Judge of the Wisconsin Court of Appeals
- Clarence E. Wagner, Mayor of Long Beach, California
- Joseph I. Kapusta, Professor of Physics at the University of Minnesota

http://www.anti-powerpoint-party.com

Punchline

Effective theory for deconfinement, *near* T_c.

There's always *some* effective theory.

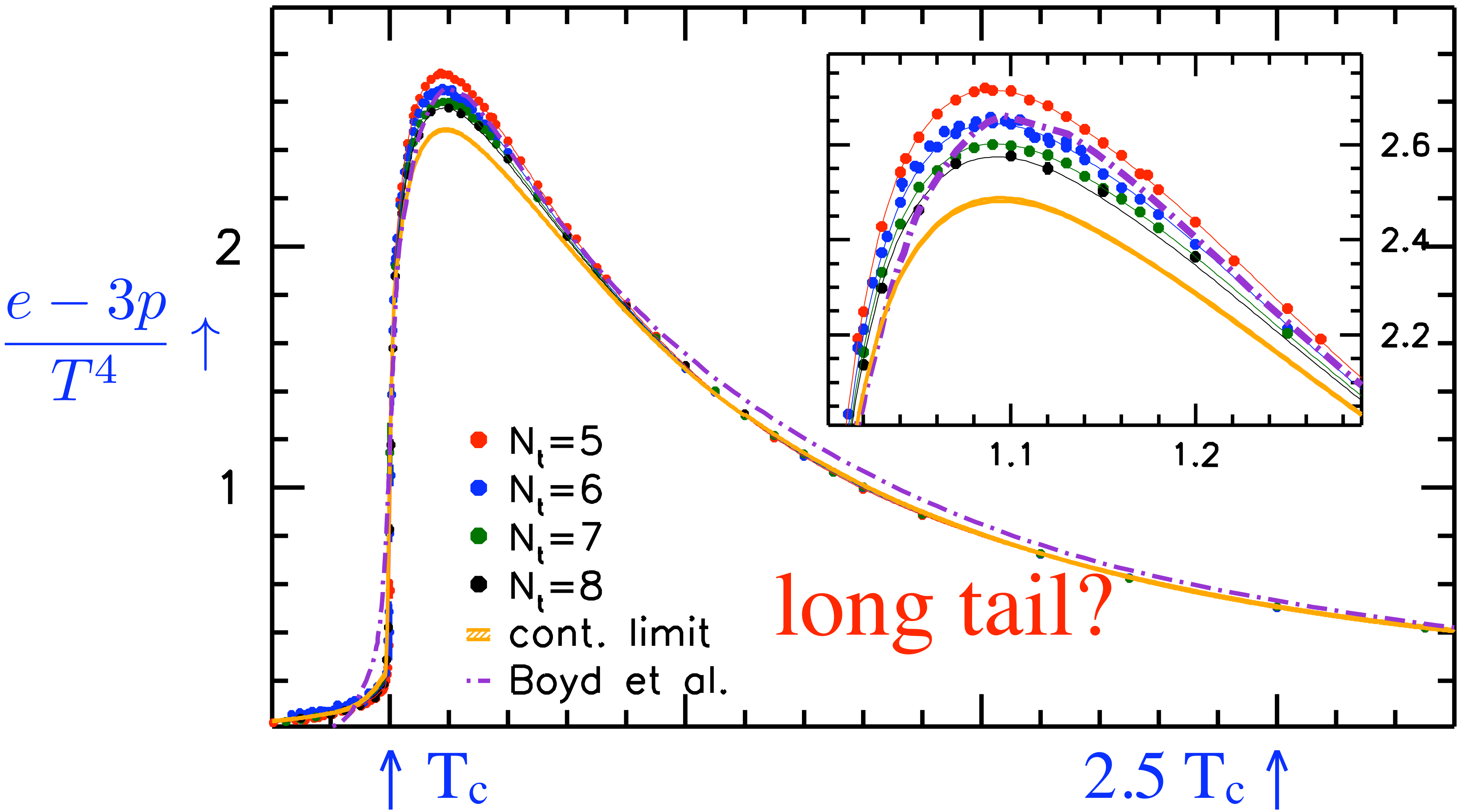
Only possible because of lattice simulations

Moderate coupling. *Versus* AdS/CFT = strong coupling

Lattice: what you know

"Pure" SU(3), no quarks. Peak in (e-3p)/T^4, just above T_c.

Borsanyi, Endrodi, Fodor, Katz, & Szabo, 1204.6184

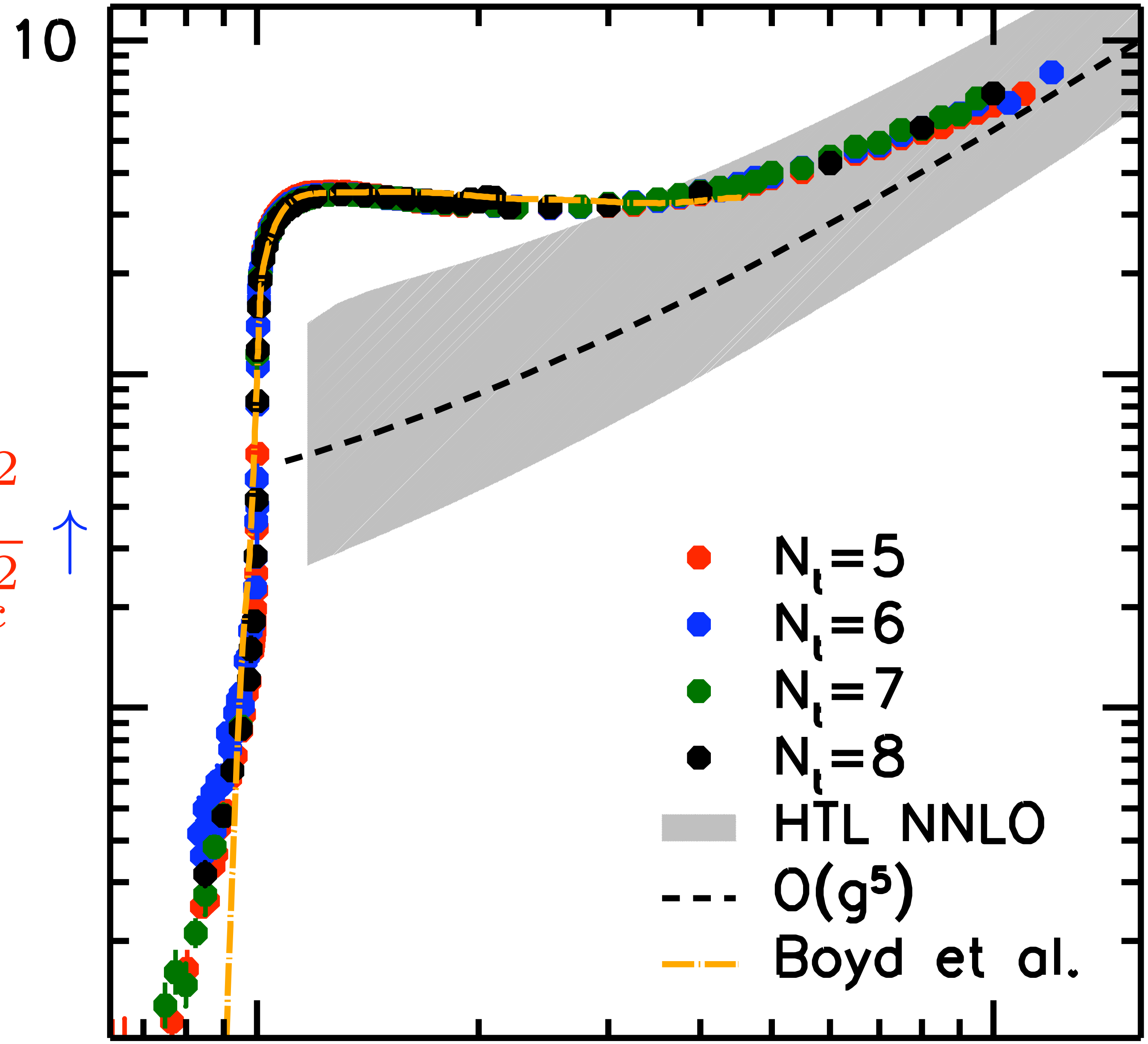


Lattice: what you should know

$T_c \to 4\, T_c$:

For pressure, leading corrections to ideality, T^4, are *not* a bag constant, T^0, but $\sim T^2$ - ? Take as *given*.

$$\frac{e-3p}{T^4}\;\frac{T^2}{T_c^2}\uparrow$$



$\uparrow T_c$ $\quad$ $10\, T_c \uparrow$

Borsanyi +... 1204.6184

In 2+1 dim.s, T^3 & T^2, *not* T

Caselle +... 1111.0580

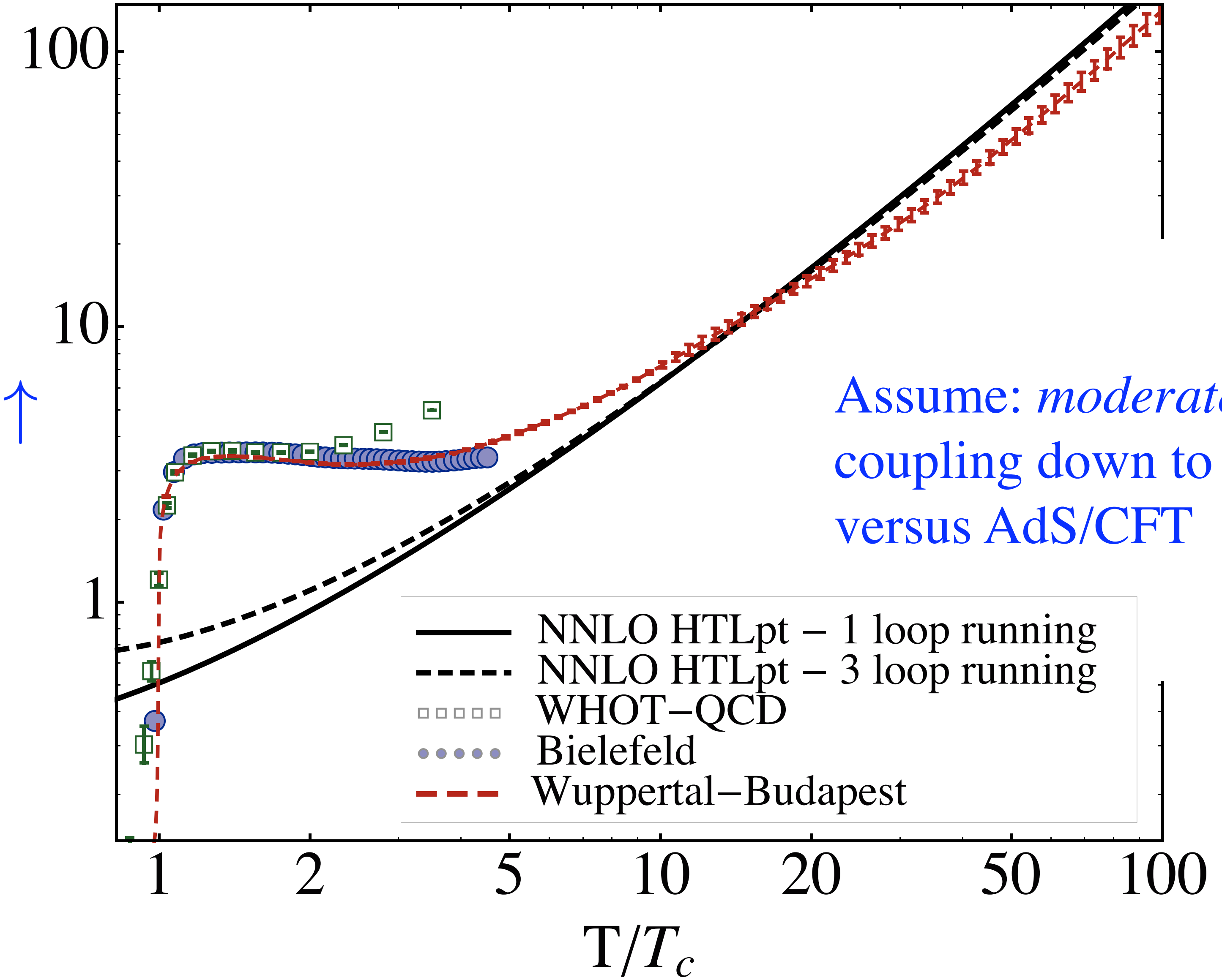
Not a gluon “mass”

Moderate coupling, even at T_c

QCD coupling is *not* so big at T_c, $\alpha(2\pi T_c) \sim 0.3$ (runs like $\alpha(2\pi T)$)

HTL perturbation theory at NNLO: Andersen, Leganger, Strickland, & Su, 1105.0514

$$\frac{e-3p}{T^4} \; \frac{T^2}{T_c^2} \uparrow$$



Assume: *moderate* coupling down to T_c versus AdS/CFT

The competition: models for the "s"QGP T_c to ~ 4 T_c

Unrelated

Massive gluons: Peshier, Kampfer, Pavlenko, Soff '96...Castorina, Miller, Satz 1101.1255
Castorina, Greco, Jaccarino, Zappala 1105.5902

Mass decreases pressure, so adjust m(T) to fit p(T) with *three* parameters.

$$p(T) = \# T^4 - m^2 T^2 + \ldots$$

Polyakov loops: Fukushima ph/0310121...Hell, Kashiwa, Weise 1104.0572

Effective potential of Polyakov loops.
Potential has *five* parameters

$$V_{eff}(T) \sim m^2 \ell^* \ell + T \log f(\ell^* \ell)$$

$$m^2 = T^4 \sum_{i=0}^{3} a_i (T_c/T)^i$$

AdS/CFT: Gubser, Nellore 0804.0434...Gursoy, Kiritsis, Mazzanti, Nitti, 0903.2859

Add potential for dilaton, φ, to fit pressure.
Only infinite N, *two* parameters

$$V(\phi) \sim \cosh(\gamma\phi) + b\,\phi^2$$

Related

Linear model of Wilson lines: Vuorinen & Yaffe, ph/0604100;
de Forcrand, Kurkela, & Vuorinen, 0801.1566; Zhang, Brauer, Kurkela, & Vuorinen, 1104.0572

$$V_{eff}(\mathbf{Z}) = m^2 \,\mathrm{tr}\mathbf{Z}^\dagger\mathbf{Z} + \kappa\,(\det\mathbf{Z} + c.c.) + \lambda\,\mathrm{tr}(\mathbf{Z}^\dagger\mathbf{Z})^2 + \ldots$$

Z is not unitary; *four* parameters. ‘t Hooft loop *approximate*.

Above models comparable to our model with *one* free parameter.

Deriving the effective theory from QCD:

Monopoles: Liao & Shuryak, ... + 0804.0255.

Dyons: Diakonov & Petrov, ... + 1011.5636: explain 1st order for SU(N) > 4 & G(2)

Bions: ... + Poppitz, Schaefer, & Unsal 1205.0290: term ~ q(1-q) about SUSY limit

Preliminaries

Order parameters

Thermal Wilson line:

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

Under global Z(3) rotations:

$$\mathbf{L} \to e^{2\pi i/3}\, \mathbf{L}$$

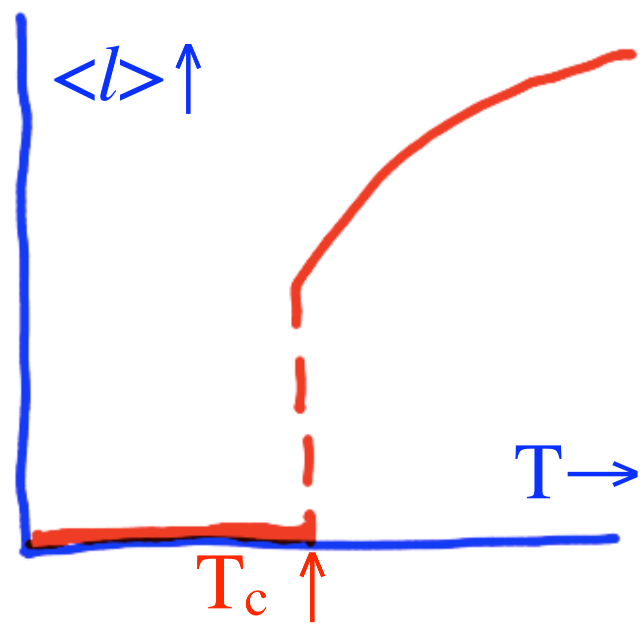
Wilson line gauge variant.
Trace = Polyakov loop gauge *in*variant

$$\ell = \frac{1}{3}\, \mathrm{tr}\, \mathbf{L}$$

Eigenvalues of **L** are also gauge *in*variant:
basic variables of matrix model

$\langle$ *loop* $\rangle$ measures *partial* ionization of color:
when $0 < \langle$ *loop* $\rangle < 1$, “semi”-QGP

(Loop models: confinement = Z(3) symmetry
Matrix models: confinement =
complete eigenvalue repulsion)



Matrix model

Matrix model: SU(2)

Simple approximation: *constant* $A_0 \sim \sigma_3$.

For SU(2), single field q

$$A_0^{cl} = \frac{\pi T}{g} \, q \, \sigma_3$$

Wilson line **L**:

$$\mathbf{L}(q) = \begin{pmatrix} \mathrm{e}^{i\pi q} & 0 \\ 0 & \mathrm{e}^{-i\pi q} \end{pmatrix}$$

Polyakov loop *l*:

$$\ell = \cos(\pi q)$$

Z(2) symmetry: q → 1 - q, L → - L

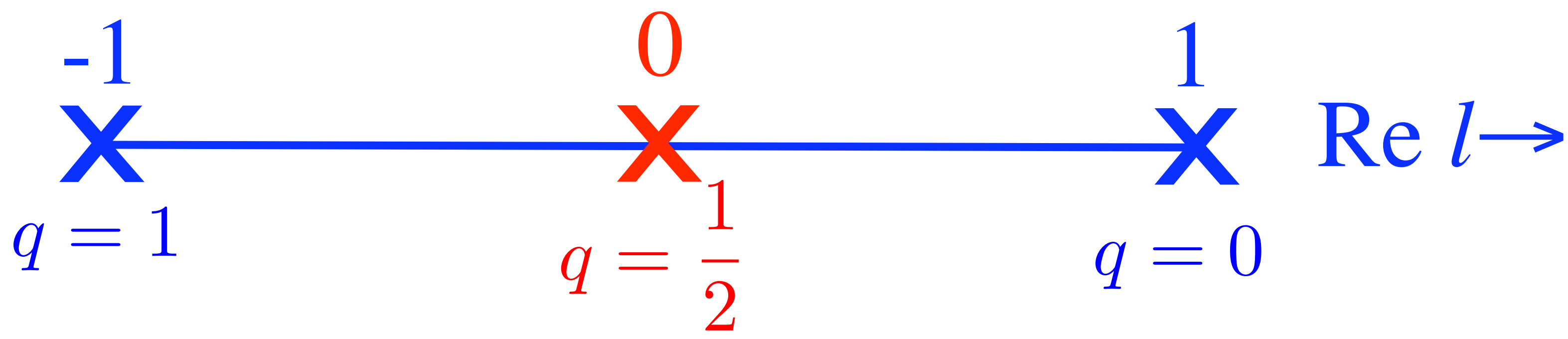
Perturbative vacua: q = 0 and 1, **L = ± 1**

Point *half*way in between: q = ½ :
Confined vacuum, **L**$_c$, $l = 0$.

$$\mathbf{L}_c = \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}$$

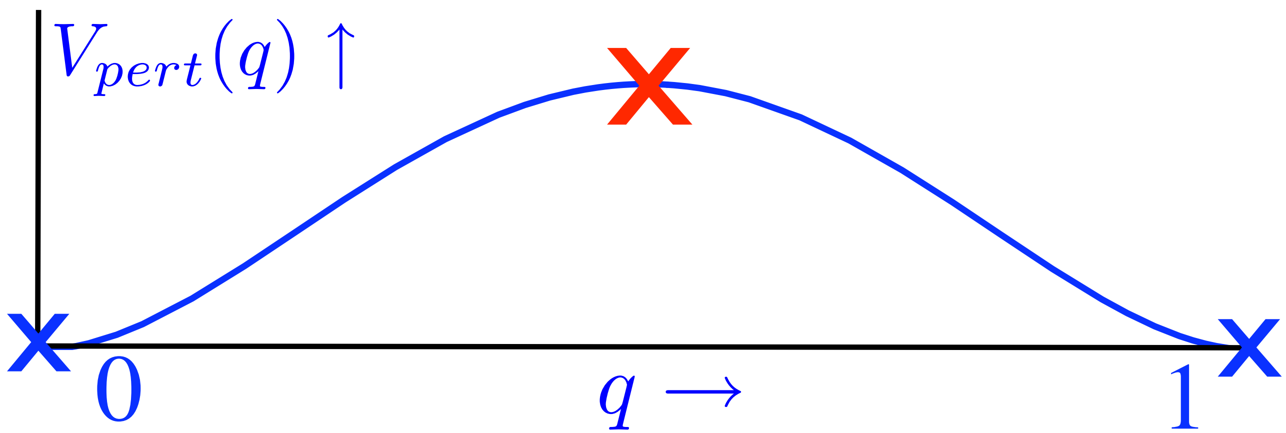
Perturbative potential for q

Classically, *no* potential:



One loop order: potential (Gross, RDP, & Yaffe, ’81)

$$V_{pert}(q) = \frac{4\pi^2}{3} T^4 \, q^2 (1 - q)^2$$

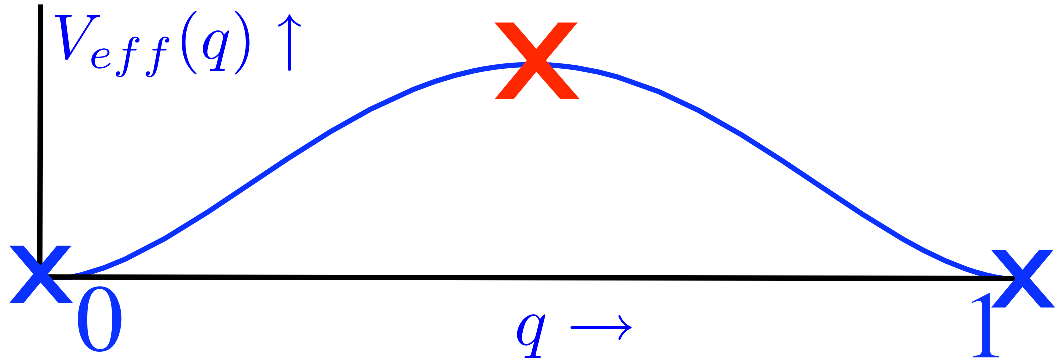


Non-perturbative potential

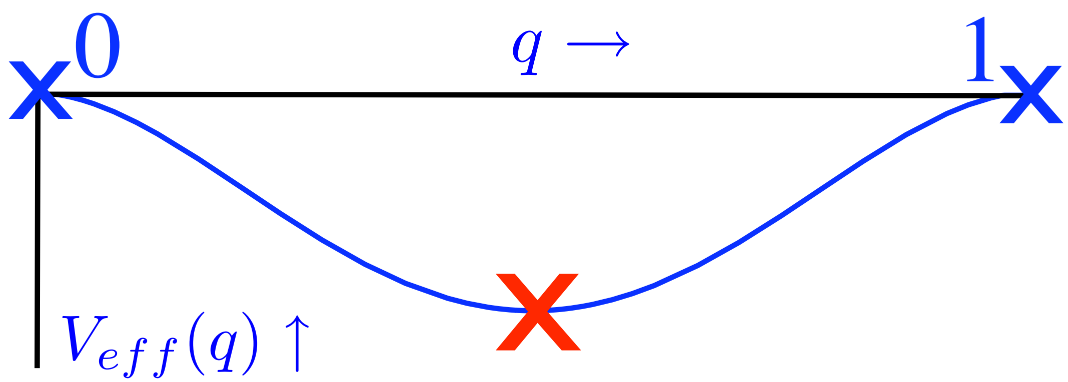
By *fiat*, add *non*-perturbative terms, to get <q> ≠ 0 :

$$V_{eff}(q) = V_{pert}(q) + V_{non}(q)$$

T >> T_c: $\langle q \rangle = 0,1 \rightarrow$



T < T_c: $\langle q \rangle = ½ \rightarrow$

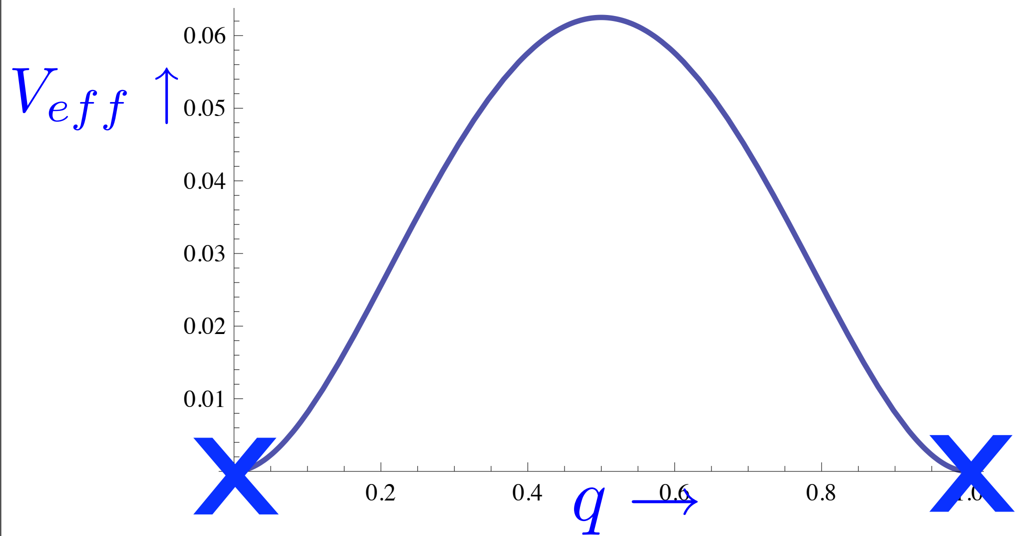


Cartoons

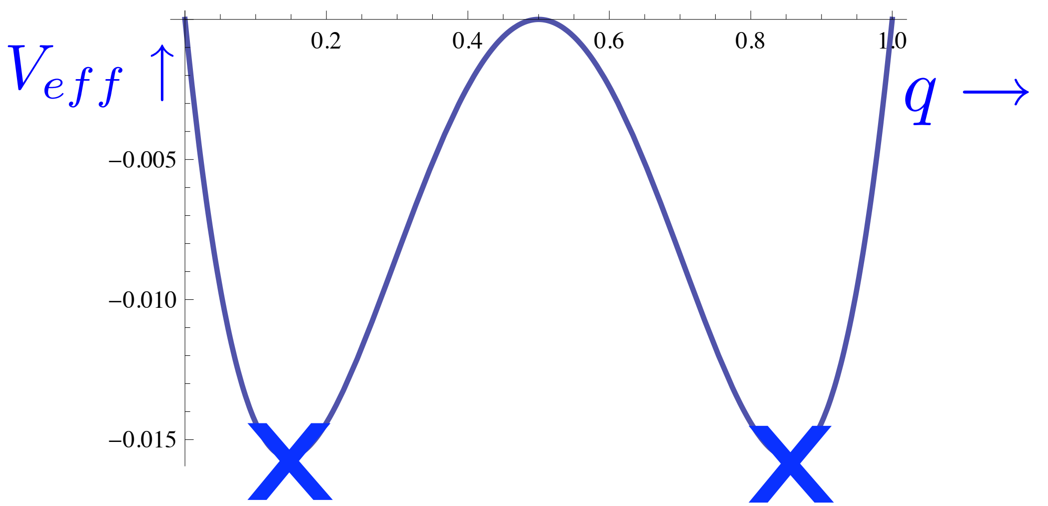
Consider:

$$V_{eff} = q^2(1-q)^2 - \; a\, q(1-q)\,,\; a \sim T_c^2/T^2$$

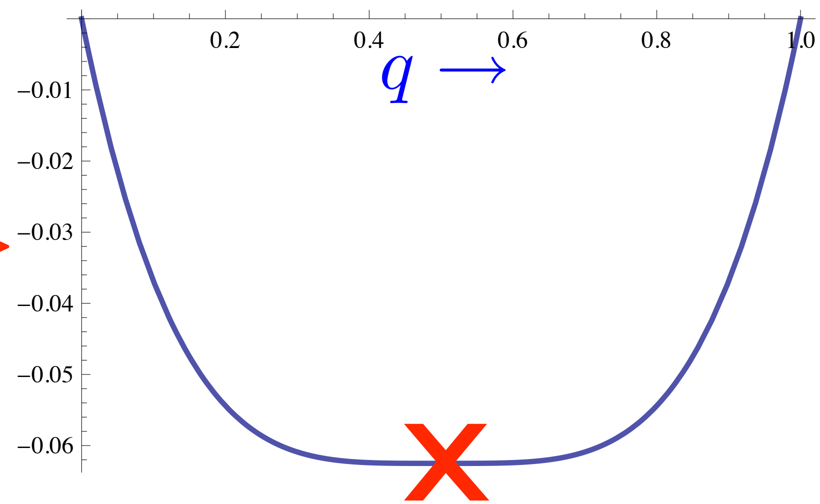
$\Downarrow$ T >> T$_c$: complete QGP



$\Downarrow$ T > T$_c$: semi QGP



T = T$_c$ =>



Matrix models, two colors

Zero parameter model: Meisinger, Miller, & Ogilvie, ph/0108009

1 parameter: Dumitru, Guo, Hidaka, Korthals-Altes, & RDP, 1011.3820; 2 parameter: 1205.0137

Effective potential sum of pert. and non-pert. terms:

$$V_{pert}(q) = \frac{4\pi^2}{3} T^4 \left(-\frac{1}{20} + q^2 (1-q)^2 \right)$$

$$V_{non}(q) = \frac{4\pi^2}{3} T^2 \, T_c^2 \left(-\frac{c_1}{5} q(1-q) - c_2 \, q^2 (1-q)^2 + \frac{c_3}{15} \right) + B \, T_c^4$$

Typical mean field theory:

$$\left. \frac{d}{dq} V_{eff}(q) \right|_{q=\langle q \rangle} = 0$$

Pressure:

$$p(T) = -V_{eff}(\langle q \rangle)$$

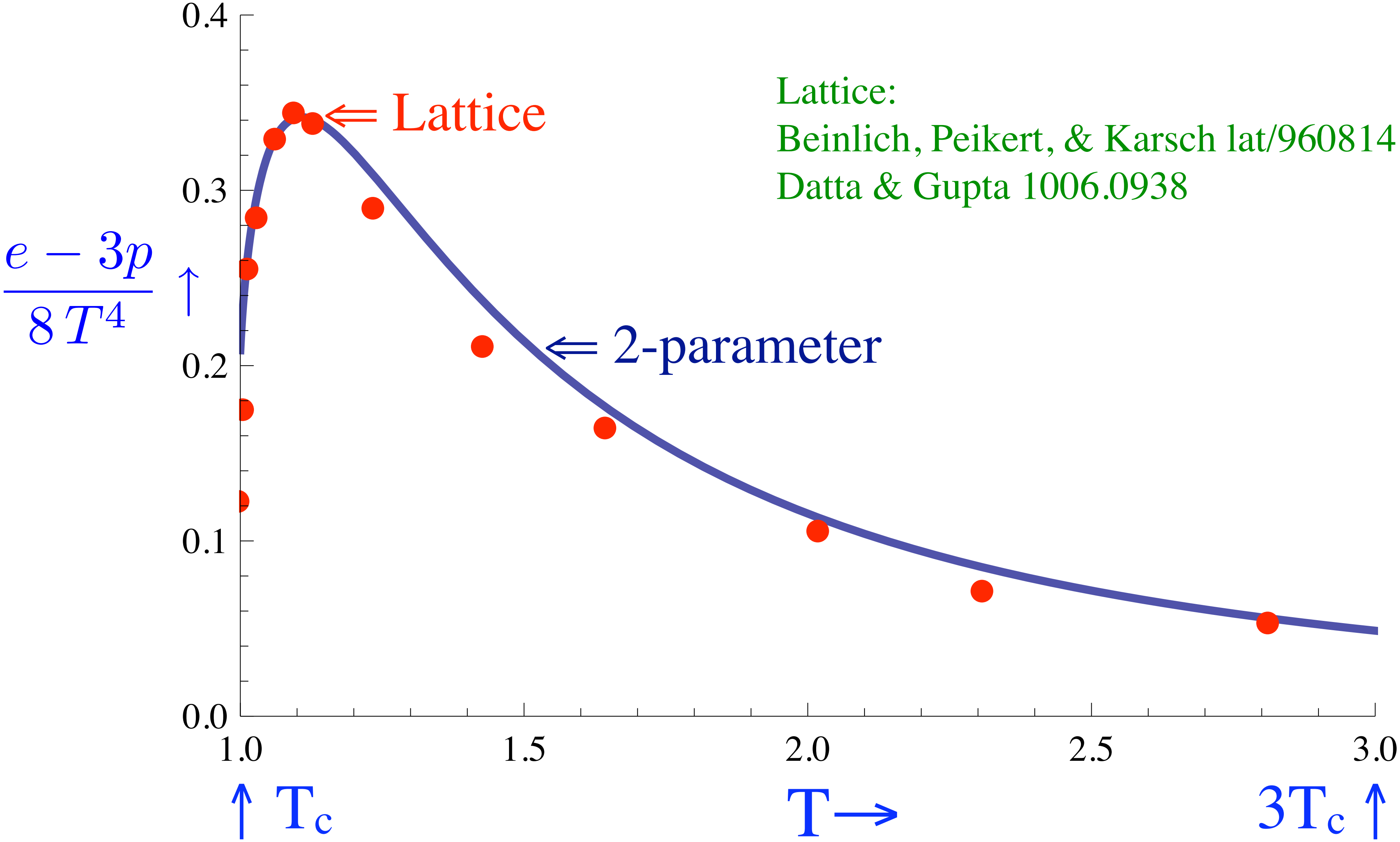
Start with four parameters: c_1, c_2, c_3, & MIT bag constant B.

Require: transition at T_c; pressure(T_c) = 0. *Two* free parameters.

Matrix model, three colors

Fix two parameters by fitting to latent heat and e-3p:

$c_1 = .83 \; , c_2 = .55 \; , c_3 = 1.3 \; , B = (262 \text{ MeV})^4 \; .$

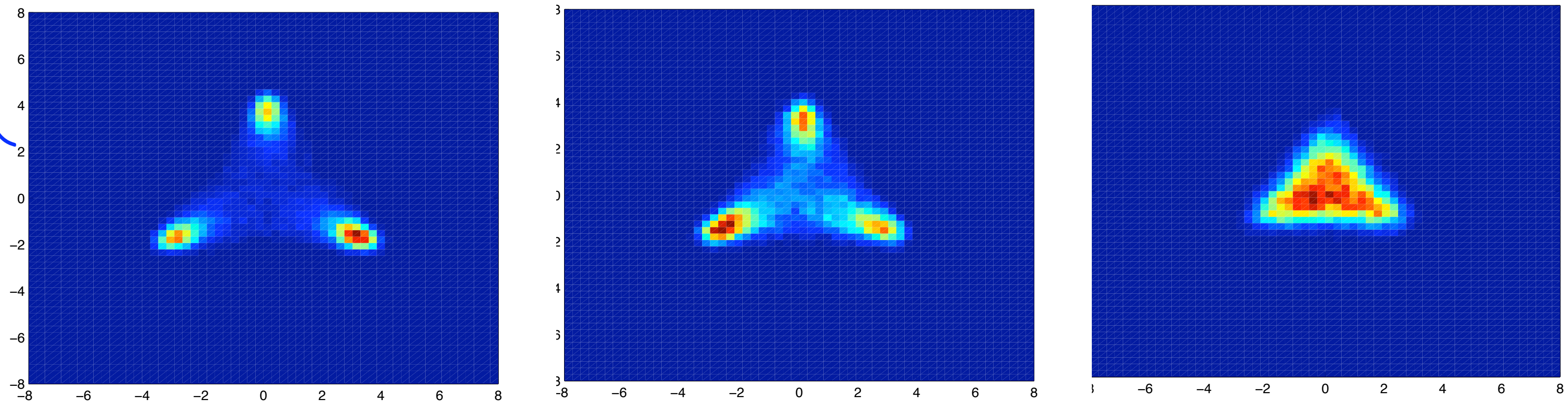


‘t Hooft loop

Lattice, A. Kurkela, unpub.’d: 3 colors, loop l complex.

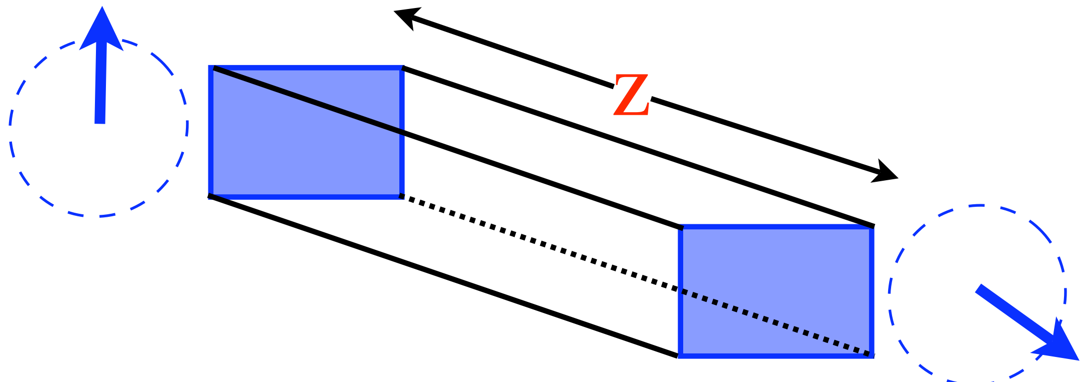
Distribution of loop shows Z(3) symmetry:

$\mathrm{Re}\,\ell \uparrow$



$\mathrm{Im}\,\ell \rightarrow$

$T \gg T_c$ $\qquad$ $T \sim T_c$ $\qquad$ $T < T_c$



Interface tension: take long box.

Each end: distinct but *degenerate*

In between: interface, action ~ interface tension, σ:

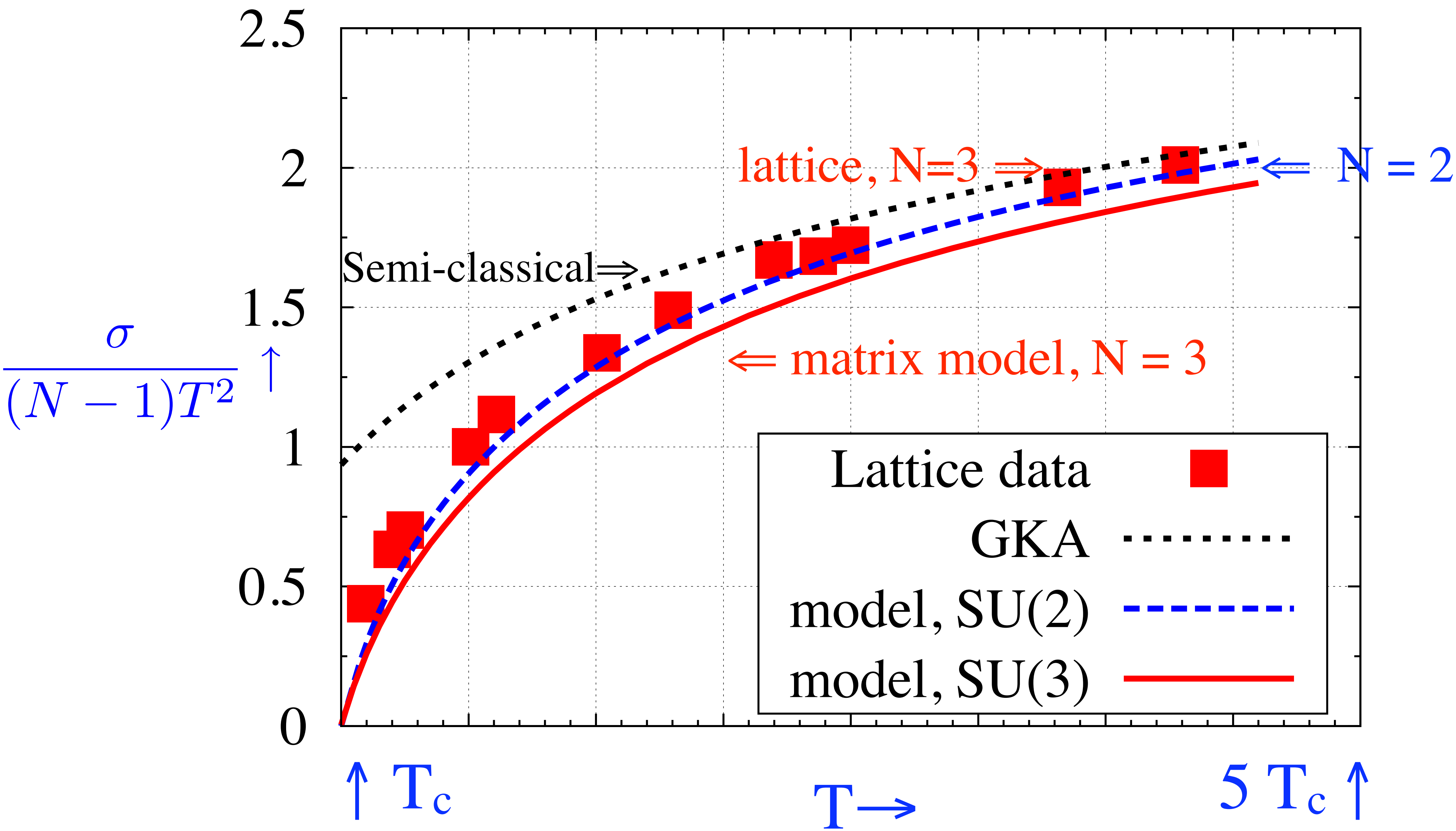
$$Z \sim e^{-\sigma V_{tr}}$$

$T > T_c$: order-order interface = ‘*t Hooft loop*:

Success: 't Hooft loop

Matrix model works well:

Lattice: de Forcrand, D'Elia, & Pepe, lat/0007034; de Forcrand & Noth lat/0506005

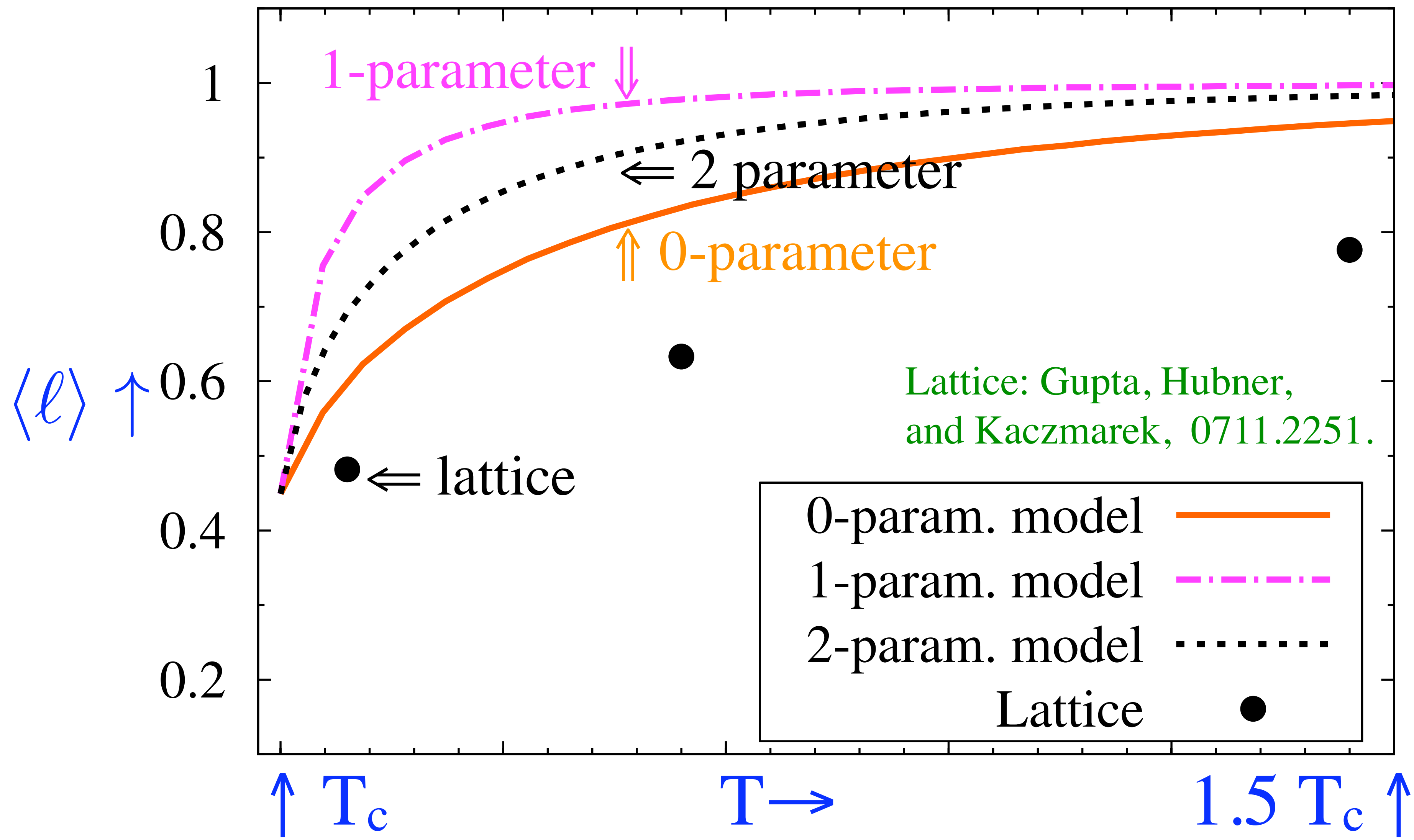


Failure: Polyakov loop

Renormalized Polyakov loop from lattice *nothing* like matrix model

Model: transition region *narrow*, to ~ 1.2 T_c; lattice loop *wide*, to ~ 4.0 T_c.

Does the ren.'d Polyakov loop reflect the eigenvalue distribution?



G(2) gluons: the "law" of maximal eigenvalue repulsion

G(2) group: confinement with*out* a center

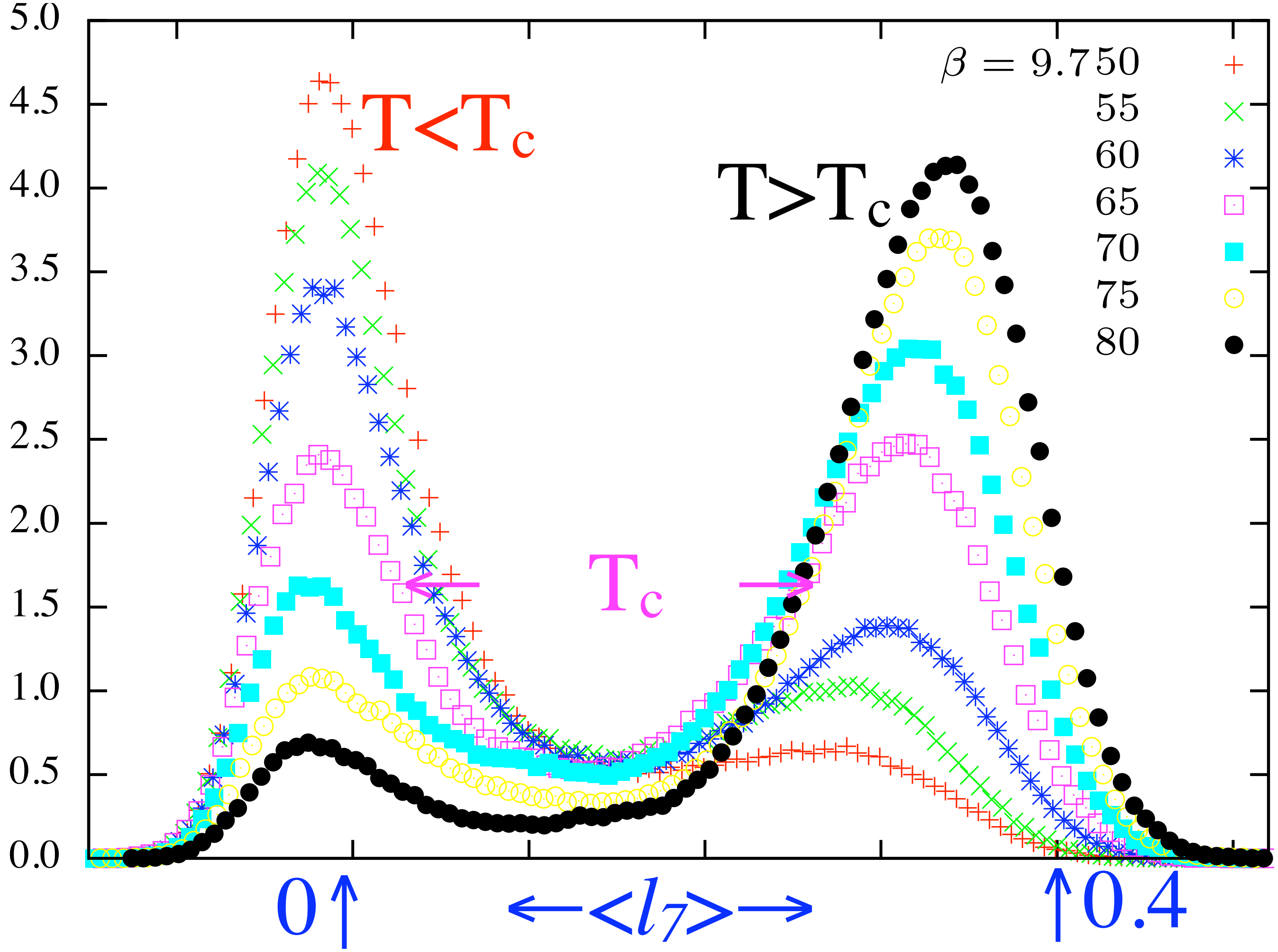
Holland, Minkowski, Pepe, & Wiese, lat/0302023...

Exceptional group G(2) has *no* center, so in *principle*, *no* "deconfinement"

With no center, $\langle loop_7 \rangle$ can be *non*zero at *any* T > 0.

Lattice: 1st order transition, $\langle l_7 \rangle \sim 0$ for $T < T_c$, $\langle l_7 \rangle \neq 0$ for $T > T_c$: deconfinement!

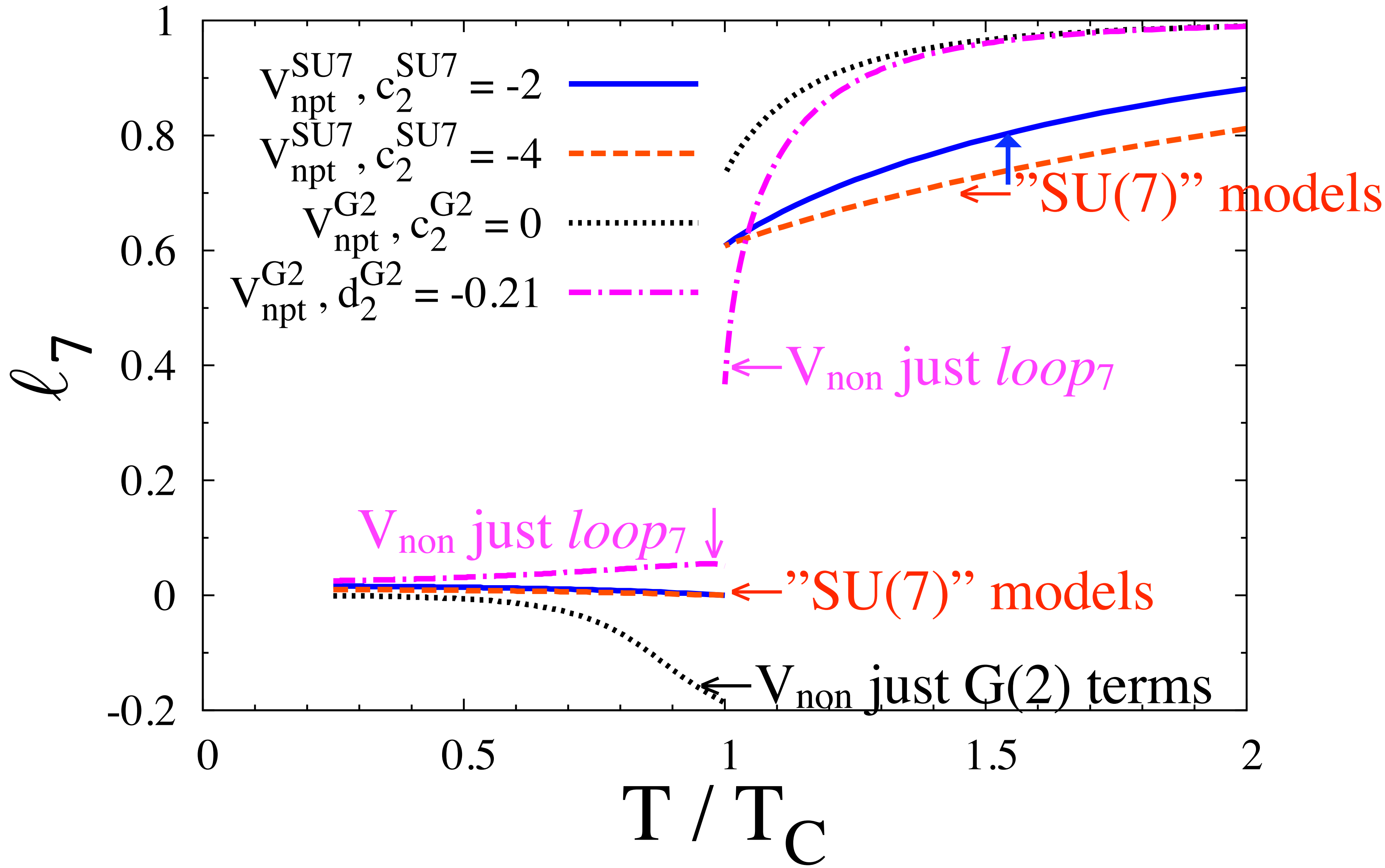
Welleghausen, Wipf, & Wozar 1102.1900.



Law of maximal eigenvalue repulsion

Generically, *easy* to find 1st order transitions. *Most* have $\langle l_7 \rangle$ *non*zero below T_c.

To get $\langle l_7 \rangle \sim 0$ below T_c, *must* add terms to generate maximal eigenvalue repulsion

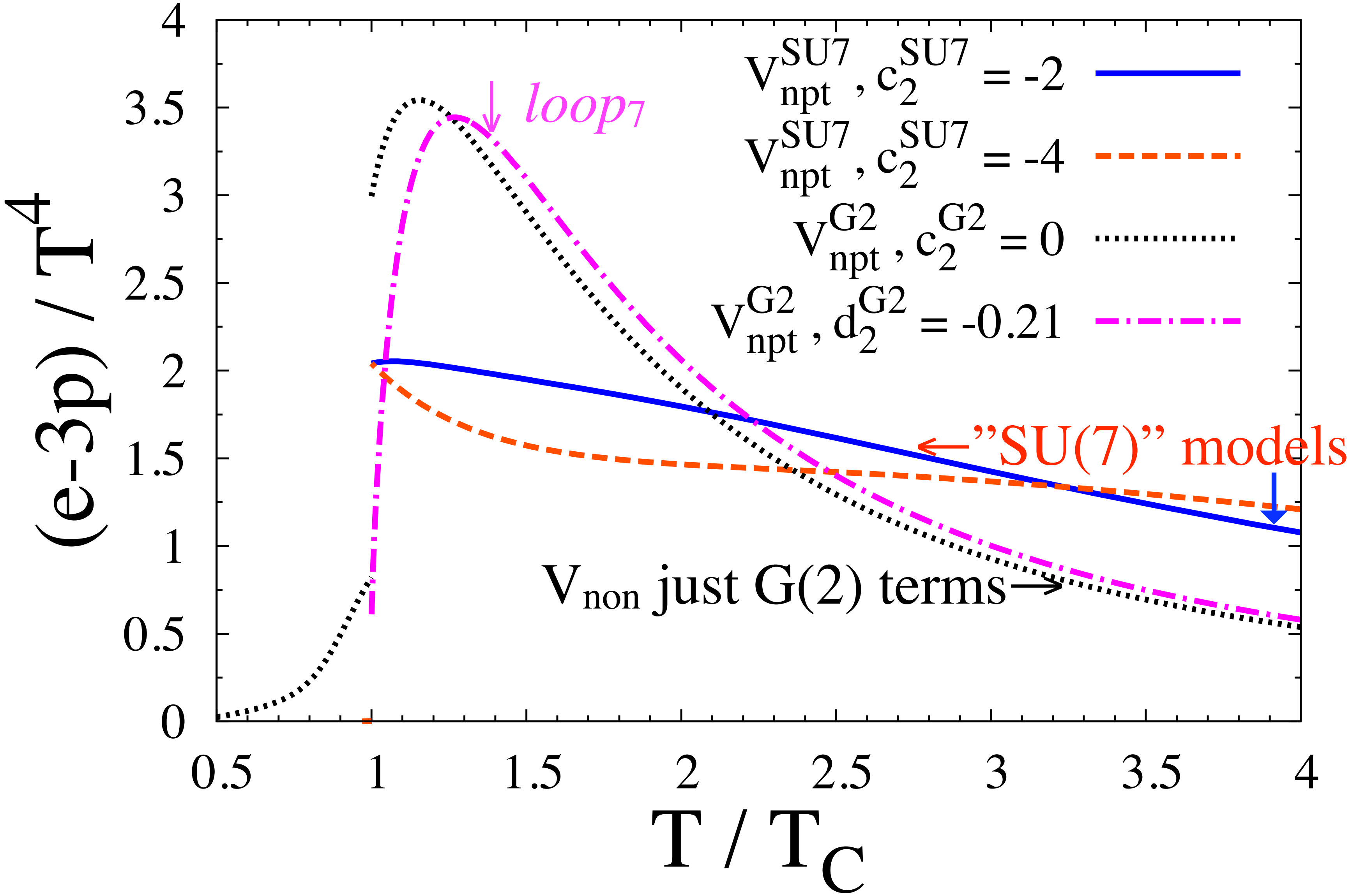


Predictions for G(2)

Start with model with 3 parameters

Requiring $\langle l_7 \rangle \sim 0$ below T_c *greatly* restricts the possible parameters.

Yields *dramatic* differences in the behavior of $(e-3p)/T^4$.



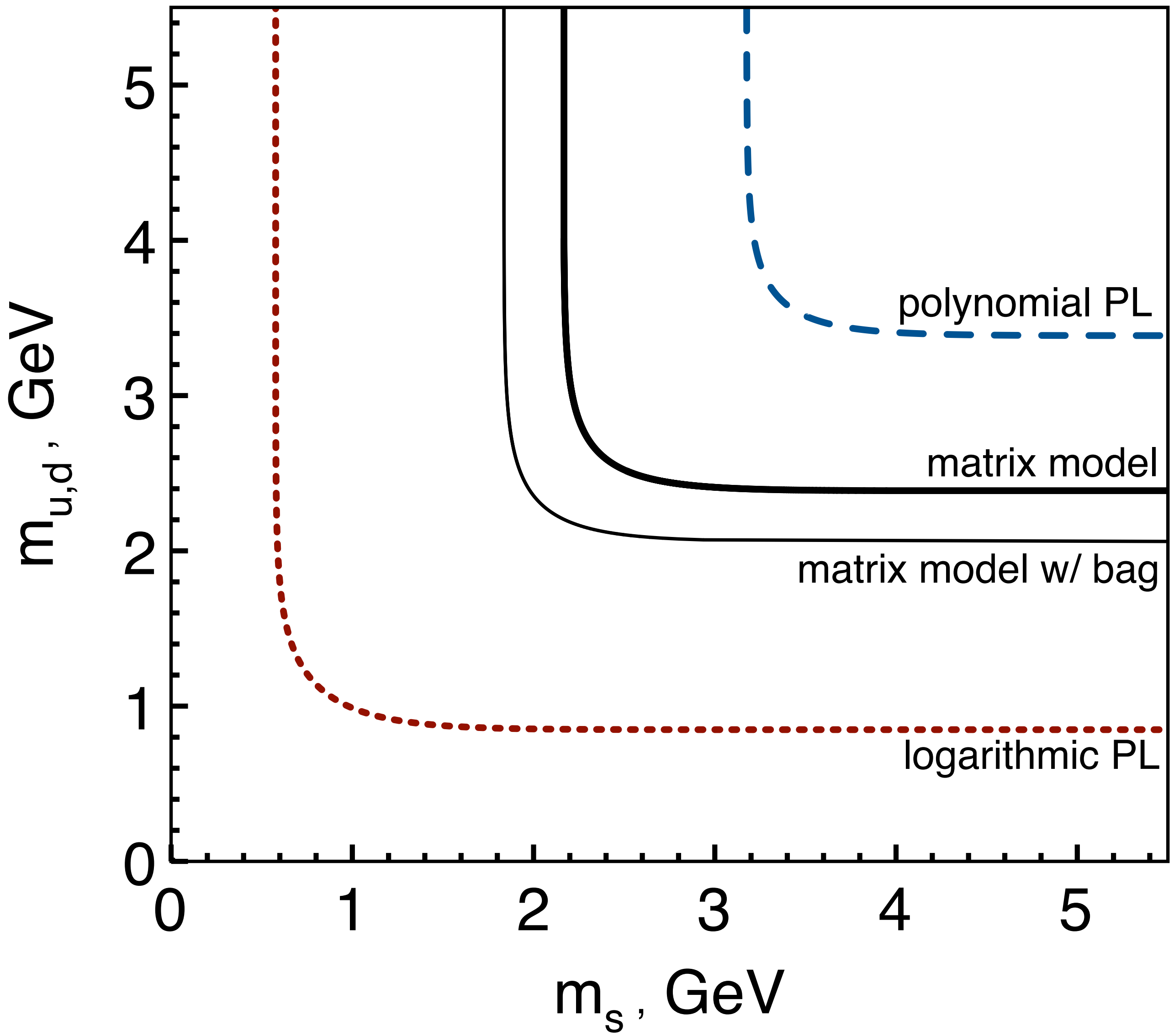
Testing the model: heavy quarks

Predictions for upper corner of Columbia plot

Add heavy quarks: critical endpoint for deconfinement, T_{ce}.

Matrix model: $T_{ce} \sim 0.99\ T_c$. Polyakov loop models: $T_{ce} \sim 0.90\ T_c$.

Kashiwa, RDP, & Skokov 1205.0545



Novel thermodynamics at infinite N

Gross-Witten transition at infinite N

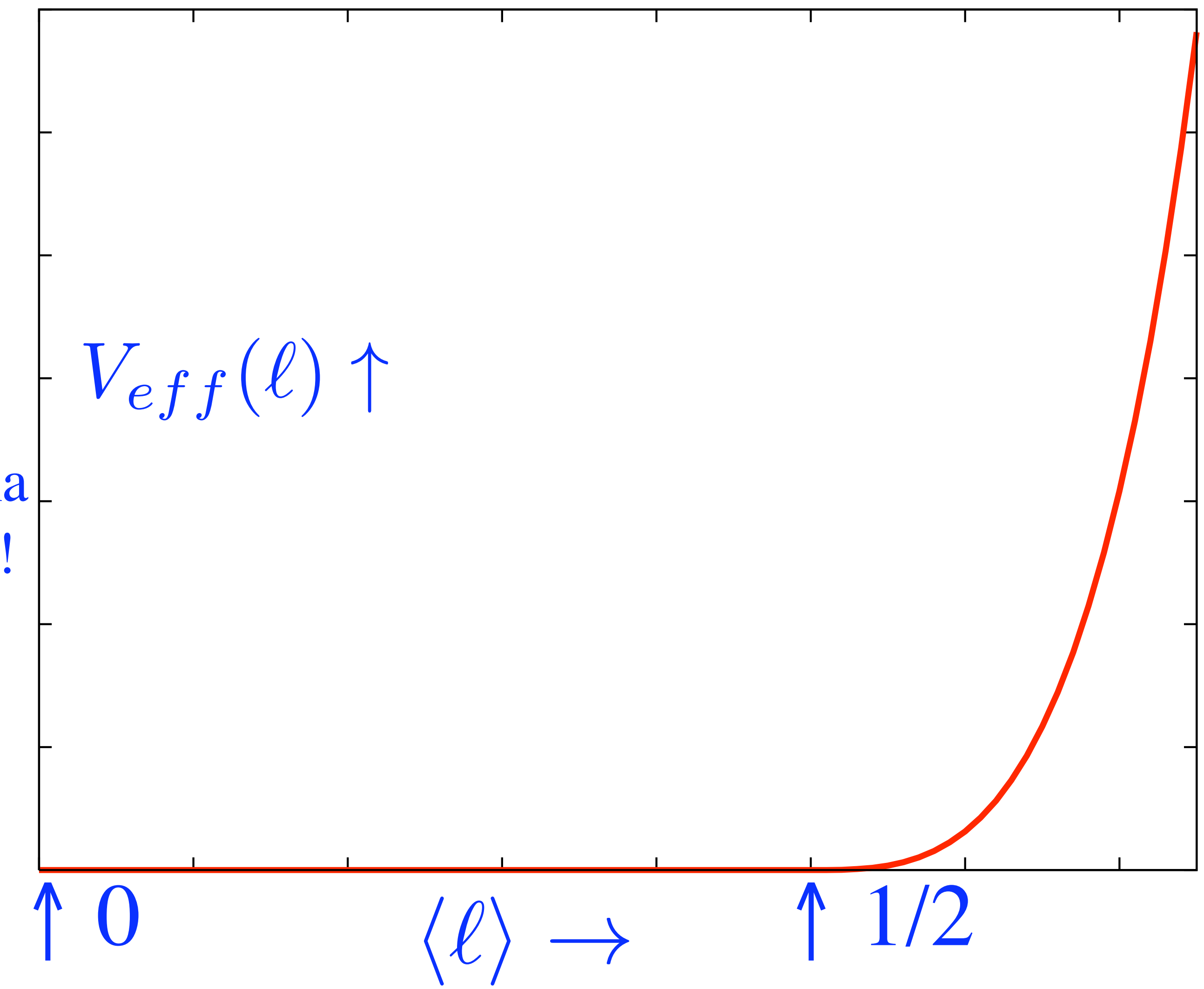
Solve at N=∞: RDP & Skokov 1206.1329. Find "critical first order" transition:
Latent heat *nonzero* ~ N^2, *and* specific heat diverges ~ $1/(T-T_c)^{3/5}$
Like femtosphere: ... + Aharony... th/0310825; Dumitru, Lenaghan, RDP, ph/0410294

$$\ell(T_c^-) = 0$$

$$\ell(T_c^+) = \frac{1}{2}$$

At T_c, 2 degenerate minima
But V_{eff} *flat* between them!

Special to N = ∞:
need to look at N > 40



Summary

Pure gauge: T: 1.2 to 4.0 T_c, pressure dominated by *constant* ~ T^2 : *stringy?*

Tests: discrepancy with Polyakov loop; heavy quarks; large N

Need to include quarks! *Is there a single "T_c"?*

Standard kinetic theory: strong coupling gives *small* η and *large* $\hat{q}$

Majumder, Muller, & Wang, ph/0703082; Liao & Shuryak, 0810.4116

Semi-QGP: naturally *small* η near T_c:

σ ~ *loop*^{2}, but ϱ = density ~ *loop*^{2} T^3:

Y. Hidaka & RDP, 0803.0453, 0906.1751, 0907.4609, 0912.0940:

$$\eta \sim \frac{\rho^2}{\sigma} \sim \ell^2$$

(Relation to anomalous viscosity? Asakawa, Bass, & Muller, ph/0603092 & ph/0608270)

But energy loss also *small*: $\hat{q} \sim \ell$ for quarks