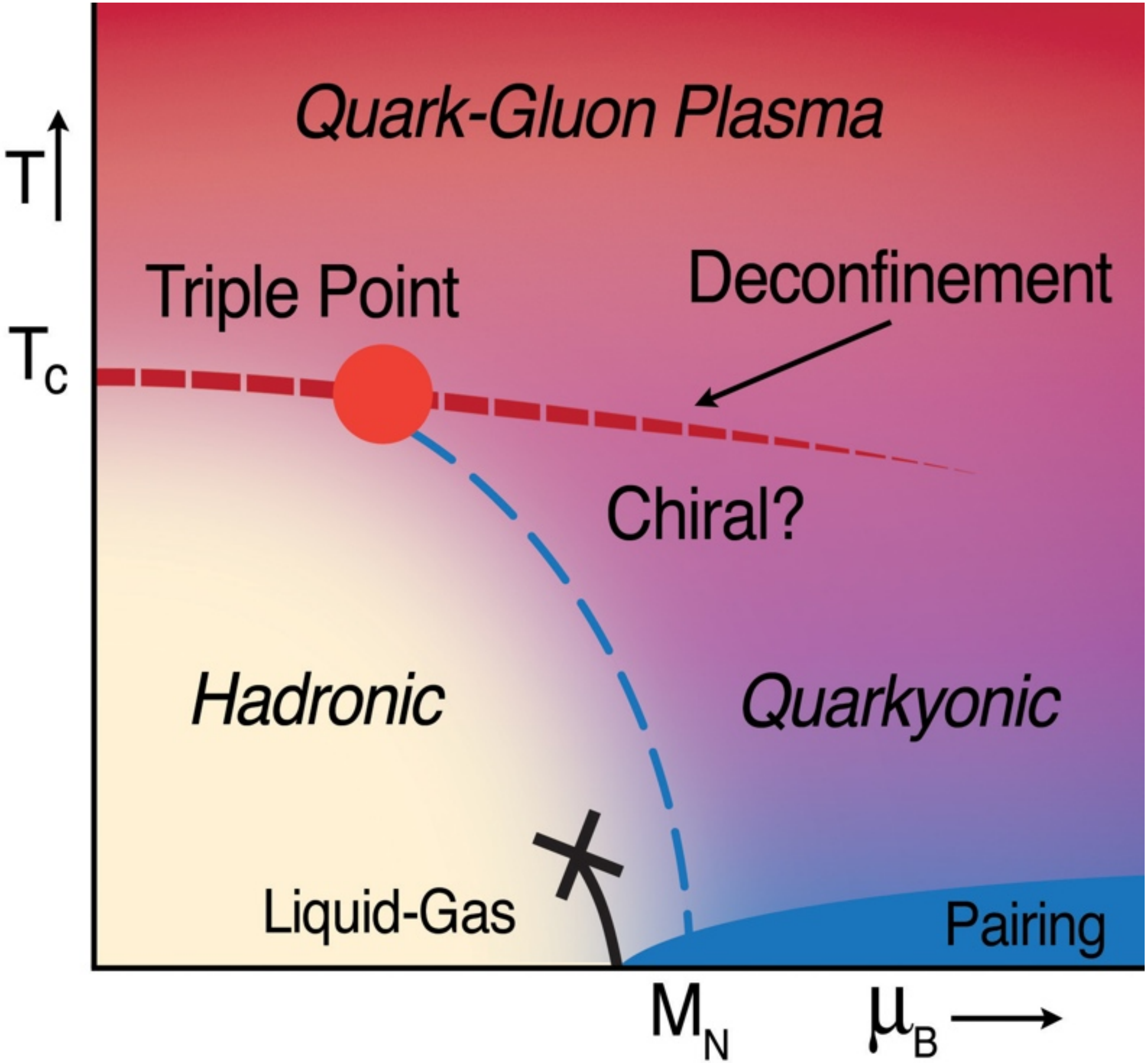
QCD Phase Diagram: 2009



$T\uparrow$

$\mu_B \longrightarrow$

Ionizing Color in the Quark Gluon Plasma

1. Quantum ChromoDynamics (*QCD*):

    How the coupling constant in QCD "runs": *asymptotic freedom*

    Ionizing Color Charge in a Quark Gluon Plasma at a temperature T_c.

2. Debye screening and the Random Phase Approximation in Plasmas,

    Electron Positron and Quark Gluon

    In QCD: how to go from $T = \infty$ down to $\sim 3\ T_c$. But *not* down to T_c!

3. Strongly Coupled Plasmas:

    Supersymmety vs. *Partial* Color Ionization in a "semi" Quark Gluon Plasma

4. Confinement: from 3 Colors in QCD to a 3-state Potts Model

    Quark Gluon Plasma as the *broken* phase of a Potts model.

5. Dynamics of the semi Quark Gluon Plasma: "Bleaching" Color near T_c

6. New Phase Diagram for QCD

    "Quarkyonic" Matter and their Chiral Spirals

QCD,

and Ionizing Charge in a Plasma

QCD,

and Ionizing $\Uparrow$ Charge in a $\Uparrow$ Plasma

Color *Quark Gluon*

Electrons & Photons in QED

Quantum ElectroDynamics, QED: electrons ψ, photons A_μ, coupling constant "e"

Local U(1) symmetry - *arbitrary* changes in the phase of ψ, $\theta(x)$:

$$U = \mathrm{e}^{ie\theta} \;:\; \psi \to U\psi \;;\; A_\mu \to A_\mu - \partial_\mu \theta$$

Gauge invariance:
use covariant, instead
of ordinary derivative:

$$D_\mu = \partial_\mu - ieA_\mu \to U^\dagger D_\mu U$$

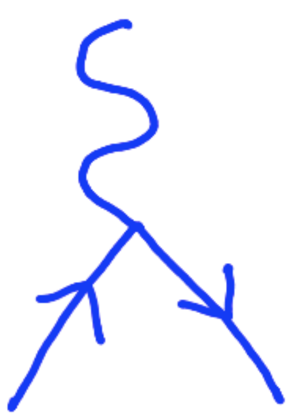
For massless electrons, Lagrangian

$$\mathcal{L} = \overline{\psi}\,\gamma^\mu D_\mu\,\psi + \frac{1}{4}\,F_{\mu\nu}^2$$

QED: photon field strength gauge invariant

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu = \frac{1}{-ie}\,[D_\mu, D_\nu]$$

Only interaction between a photon and electrons:



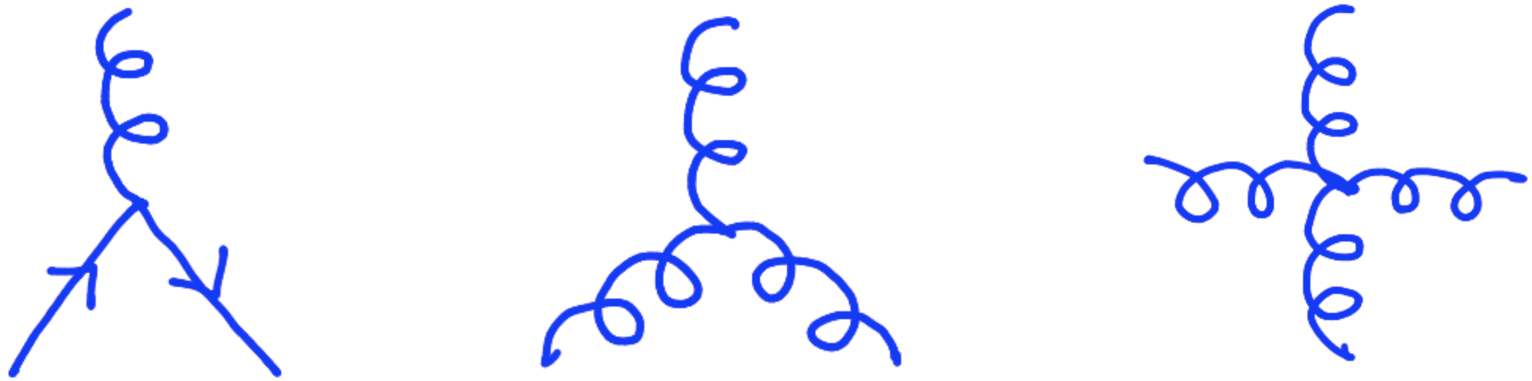
Quarks and Gluons in QCD

Quantum ChromoDynamics, QCD: quarks ψ and gluons A_μ , coupling const. "g"
"Strong" interactions: protons, neutrons, pions +... = quarks & gluons.

Local SU(3) symmetry: three "colors", $\theta \Rightarrow$ 3 by 3 (traceless) matrix.
Quarks: complex valued, 3 component column vector. 3 colors of quarks.
Gluons: real, traceless 3 by 3 matrix. $3^2 - 1 = 8$ types of gluons.

$$\mathcal{L} = \overline{\psi}\gamma^\mu D_\mu \psi + \frac{1}{2}\mathrm{tr}\, G^2_{\mu\nu} \; ; \; D_\mu = \partial_\mu - igA_\mu \; ; \; G_{\mu\nu} = \frac{1}{-ig}[D_\mu, D_\nu]$$

Lagrangian just like QED, but D_μ *and* $G_{\mu\nu}$ gauge *co*variant: $G_{\mu\nu} \rightarrow U^\dagger G_{\mu\nu} U$.
Local SU(N) symmetry: N quarks & $N^2 - 1$ gluons: *gluons dominate at large N*.
Interactions: quarks with gluons, *and* gluons with one another:



Asymptotic Freedom in QCD

Classically, QCD has *no* mass scale, only one dimensionless coupling, which "runs" with momentum.

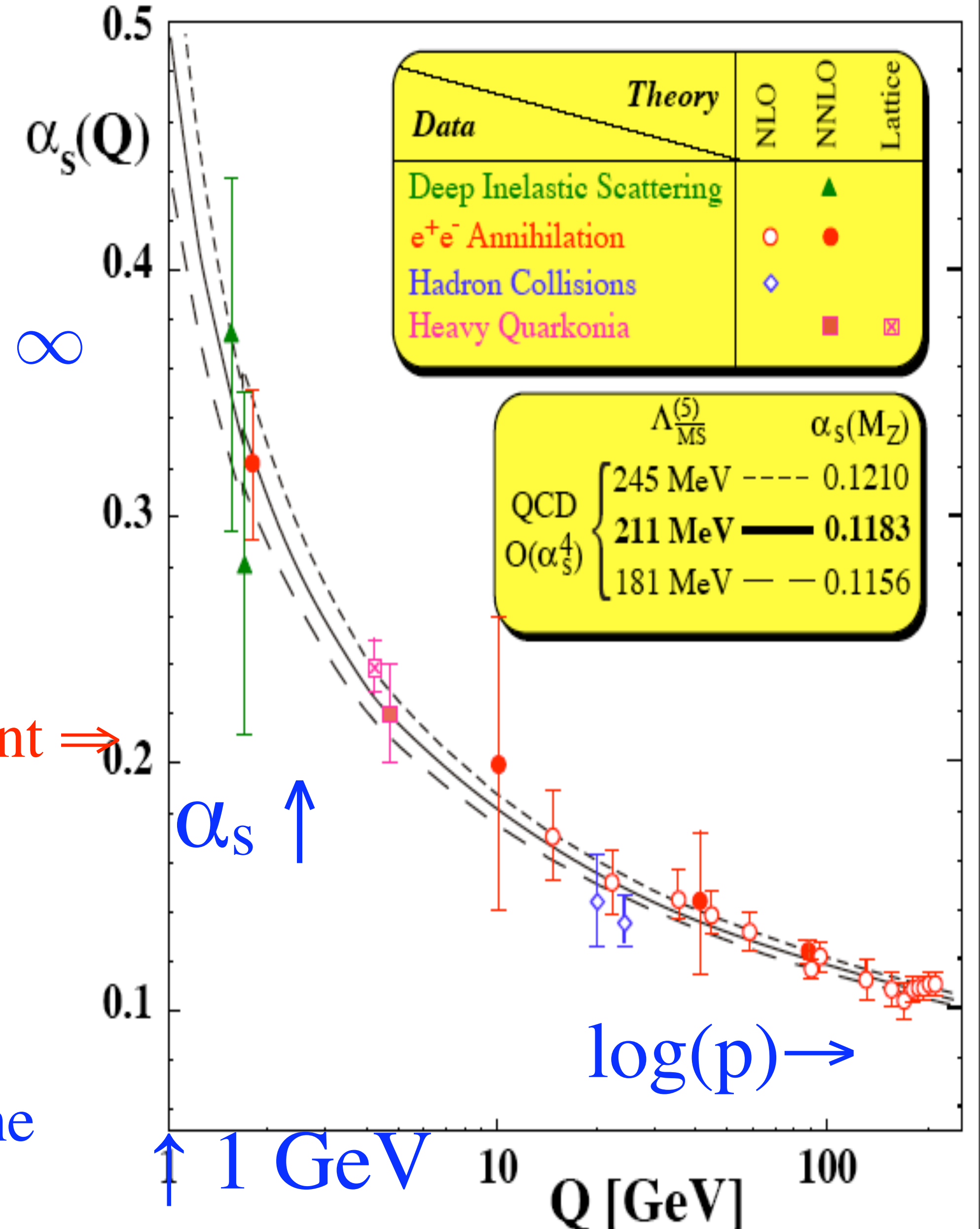
Asymptotic freedom: coupling *vanishes* at infinite momenta

$$\alpha_s(p) = \frac{g^2}{4\pi} \approx \frac{2\pi/9}{\log(p)} + \ldots \; ; \; p \to \infty$$

(Nobel: Gross, Politzer, & Wilczek, 2004)

When mass scale > 1 GeV, pert. thy ok.

(1 GeV ~ mass proton), $\alpha_s < 0.3$. Experiment ⇒



Long distances difficult: "confinement".

Short distances: ~ free field theory!

Theory *uniquely* specified by the value of the coupling constant at *one* momentum scale.

Ionizing Color Charge in a Quark Gluon Plasma

As temperature $T \to \infty$, by asymptotic freedom, $g^2(T) \to 0$, so *ideal* gas of eight gluons & quarks. Pressure:

$$p_{ideal}(T) = \left(8 + \frac{7}{8}\cdot 18\right)\frac{\pi^2}{45}\,T^4$$

At high T, familiar plasma physics: Debye screening.
Corrections to pressure, etc, power series in $\sqrt{g^2(T)}$ (not $g^2(T)$)

Low temperature: color is *not* ionized, "confinement". Hadronic "liquid".

Expect "deconfining" transition at $T=T_c$: i.e., color *ionized* above T_c.

Large increase in the pressure at T_c: consider large N = # colors, 3 in QCD

Plasma phase: pressure ~ N^2 from ionized (deconfined) gluons.

Hadronic "liquid": pressure ~ 1, since color can't ionize, confined hadrons.

Ionizing Color on a Lattice

Discretize QCD on lattice, with spacing "a". Since QCD has only one dimensionless coupling constant, results *unique* as "a" → 0.

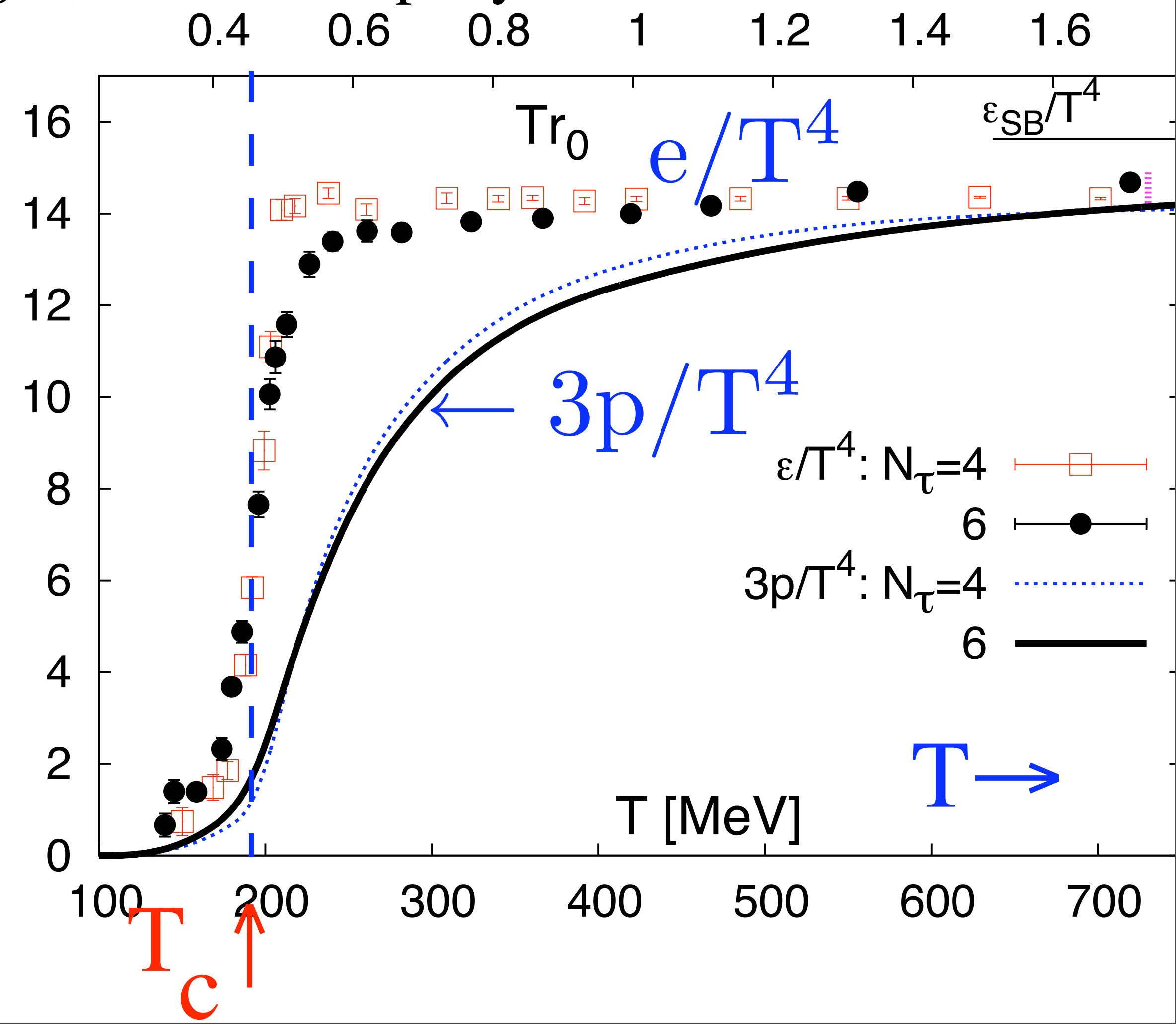
Cheng et al, arXiv:0719.0354. e = energy density, p = pressure. *Rapid* approach to (nearly) ideal gas, where e = 3p, by ~ 3 T_c .

Ionize color at *low* T_c ~ 200 MeV, ~ 1/5 m_{proton} = 0.2 * 10^{13} ^oK!

No true phase transition, crossover.

But *huge* increase in pressure at T_c.

Results similar for more colors: *large* increase in pressure due to ionization of color



Debye Screening and the Random Phase Approximation in Plasmas, Electron Positron & Quark Gluon

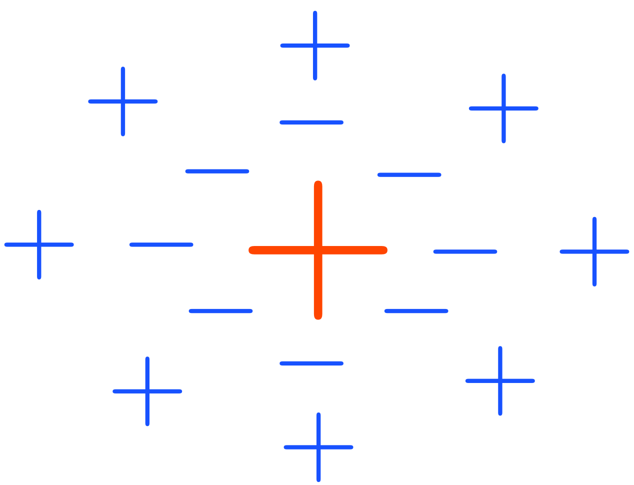
Debye Screening in a Coulombic Plasma

Ordinary matter (gas, liquid, solid) composed of electrically neutral objects.
"Fourth" state: plasma. No net charge, but charges *free* to move about.

Consider interaction with a fixed, test charge, +.

Ordinary matter: without ionization, interaction with test charge is the usual Coulomb interaction, ~ e^2/r.

Plasma: Coulomb interactions with test charge, +, *shielded* by free charges, – +, over distance $1/m_{Debye}$, m_{Debye} = Debye mass. Density of plasma = "n":



$$\frac{e^2}{r} \rightarrow e^{-m_{Debye} r}\,\frac{e^2}{r} \quad ; \quad m^2_{Debye} \sim \frac{e^2\, n}{T}$$

Random Phase Approximation (*RPA*)

Landau & Lifschitz, Vol. 10, “Physical Kinetics”, Lifshitz & Pitaevskii, pg 132.

PROBLEM 3. Determine the permittivity of an ultra-relativistic electron plasma, with the temperature $T_e \gg mc^2$ (V. P. Silin, 1960).

SOLUTION. The transport equation retains its form (27.9) even in the relativistic case. Accordingly, such formulae as (29.9) and (2) in Problem 2 remain valid. In the ultra-relativistic case, the electron speed $v \approx c$, the electron energy is cp, and the equilibrium distribution function is

$$f(p) = (N_e c^3/8\pi T_e^3) e^{-cp/T_e}.$$

The longitudinal permittivity is found to be

$$\epsilon_l - 1 = \frac{4\pi e^2 c}{kT_e} \int_{-1}^{1} \int_0^{\infty} \frac{f(p) \cos\theta \,.\, 2\pi p^2 \,dp\,d\cos\theta}{kc\cos\theta - \omega - i0}, \tag{6}$$

where θ is the angle between **k** and **v**. Integration of f over $2\pi p^2\,dp$ gives $\frac{1}{2}N_e$, and then integration over $d\cos\theta$, passing below the pole $\cos\theta = \omega/k$, leads to the result

$$\left.\begin{aligned} \epsilon_l'(\omega, k) - 1 &= \frac{4\pi N_e e^2}{k^2 T_e}\left[1 + \frac{\omega}{2kc}\log\left|\frac{\omega - ck}{\omega + ck}\right|\right], \\ \epsilon_l''(\omega, k) &= \pi\omega/2kc \quad \text{when} \quad \omega/k < c, \\ &= 0 \quad \text{when} \quad \omega/k > c. \end{aligned}\right\} \tag{7}$$

Similarly, starting from (2), we find for the transverse permittivity

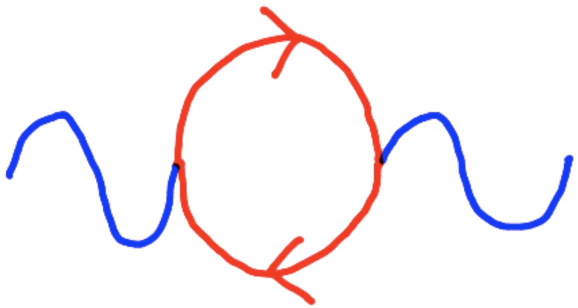
$$\epsilon_t'(\omega, k) - 1 = \frac{\pi e^2 N_e c}{\omega k T_e}\left[\left(1 - \frac{\omega^2}{c^2k^2}\right)\log\left|\frac{\omega - ck}{\omega + ck}\right| - \frac{2\omega}{ck}\right].$$

Photons in a Electron Positron Plasma

Hot QED: $T > 2\, m_{\text{electron}} \sim 10^{10}\ {}^oK$.

E.g.: γ-ray bursters… Exawatt lasers @ 10^{18}W: ExtremeLaserInfrastructure (ELI)

Photon self energy gives *Random Phase Approximation* (RPA). Density $n \sim T^3$:



$$m_D^2 = \frac{e^2\, n}{T} = \frac{e^2\, T^2}{9}$$

$$\mathcal{L}^{\gamma}_{\rm RPA} = \frac{3}{4}\, m_{\rm D}^2 \int_{\hat{k}^2=1} \frac{d\Omega_{\hat{k}}}{4\pi}\, F^{\mu\alpha}\, \frac{K^\alpha K^\beta}{-(\partial \cdot K)^2}\, F^{\mu\beta}\Big|_{K^\mu=(i,\hat{k})\,,K^2=0}$$

Loop momenta red: "*hard*" ~ T. Extneral momenta ∂_μ, blue "*soft*" ~ m_D ~ e T .

Debye screening of static electric, but not static magnetic fields.

"Landau damping": scatter off of particles in the thermal bath, $\omega < p$.

Time dependent electric *and* magnetic fields screened by electric charges:

Photon "mass": just index of refraction < 1.

Electrons in a Electron Positron Plasma

In EPP, also need electron self energy, like that of photons: thermal "mass" ~ e T:

$$m^2_{\rm elec} = \frac{1}{8}\, e^2 T^2$$

$$\mathcal{L}^{\rm el,self}_{\rm RPA} = m^2_{\rm elec} \int_{\hat{k}^2=1} \frac{d\Omega_{\hat{k}}}{4\pi}\, \overline{\psi}\, \frac{\gamma^\mu K^\mu}{K\cdot\partial}\, \psi \Big|_{K^\mu=(i,\hat{k})\,,\, K^2=0}$$

Like electron "mass", does not violate chiral symmetry of massless quarks.

RPA: add self energies to original Lagrangian:

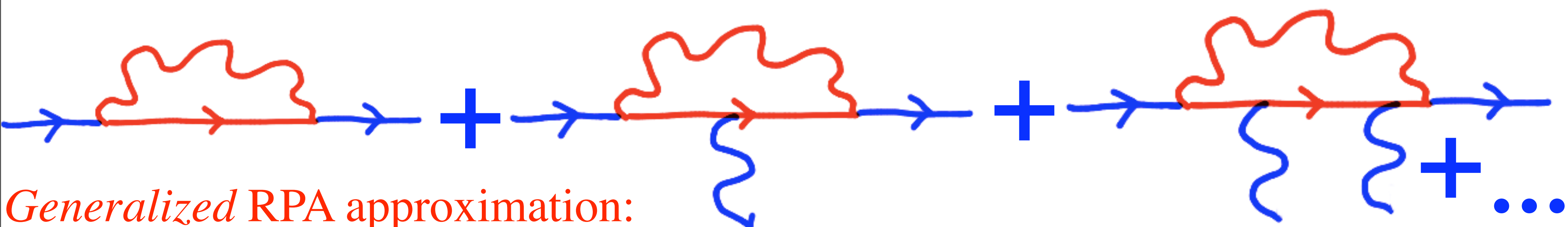
But: electrons are *not* gauge invariant, so neither is $L^{\rm el,\,self}_{\rm RPA}$ - ?

Complete RPA in a Electron Positron Plasma

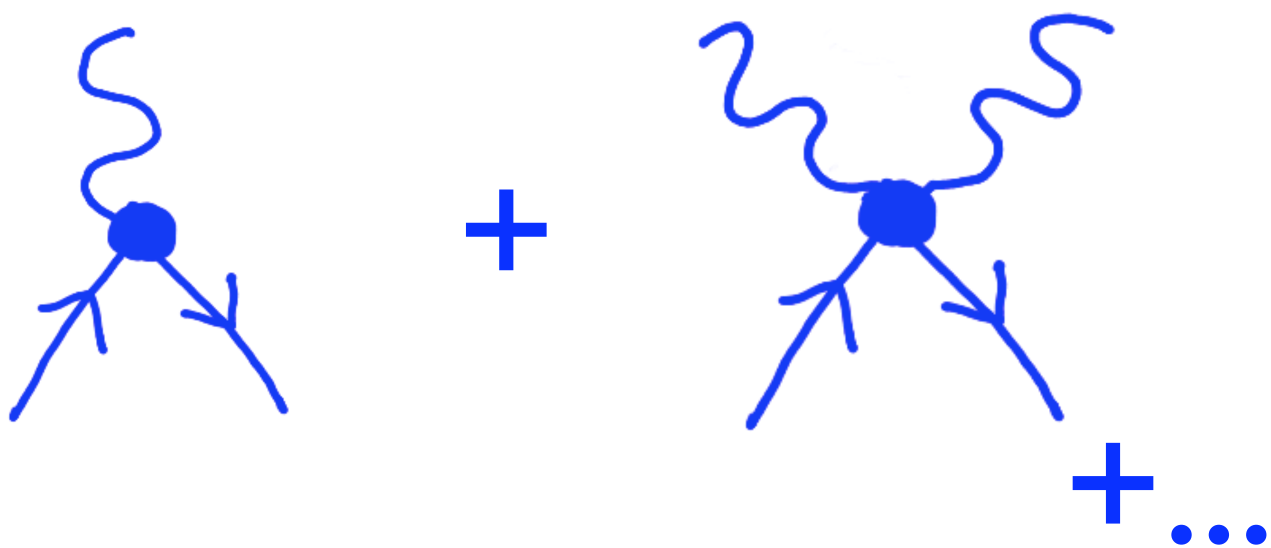
Gauge invariance: just replace
ordinary derivative, ∂_μ ,
with *covariant* derivative, D_μ :

$$\mathcal{L}^{\mathrm{el}}_{\mathrm{RPA}} = m^2_{\mathrm{elec}} \int \frac{d\Omega_{\hat{k}}}{4\pi}\, \overline{\psi}\, \frac{\gamma^\mu K^\mu}{K \cdot D}\, \psi$$

Diagramatically, represents an *infinite* series of vertices between an electron, positron, and any number of photons:



Generalized RPA approximation:
Effective propagators as before,
plus infinite series of
effective vertices:
photon and e^+e^-,
two photons and e^+e^-, etc.
All built up by using covariant, instead of ordinary, derivative.



RPA in a Quark Gluon Plasma

In weak coupling, g < 1, results in QCD very like QED! Quarks:

$$\mathcal{L}^{\mathrm{qk}}_{\mathrm{RPA}} = m^2_{\mathrm{qk}} \int \frac{d\Omega_{\hat{k}}}{4\pi} \, \overline{\psi} \, \frac{\gamma^\mu K^\mu}{K \cdot D} \, \psi \qquad m^2_{\mathrm{qk}} = \frac{1}{6} \, g^2 T^2$$

Gluons: make gauge invariant L_{RPA}
by replacing $F_{\mu\nu} \rightarrow G_{\mu\nu}$, and ∂_μ with D_μ!

$$m^2_{\mathrm{D}} = \frac{1}{3} \, g^2 T^2$$

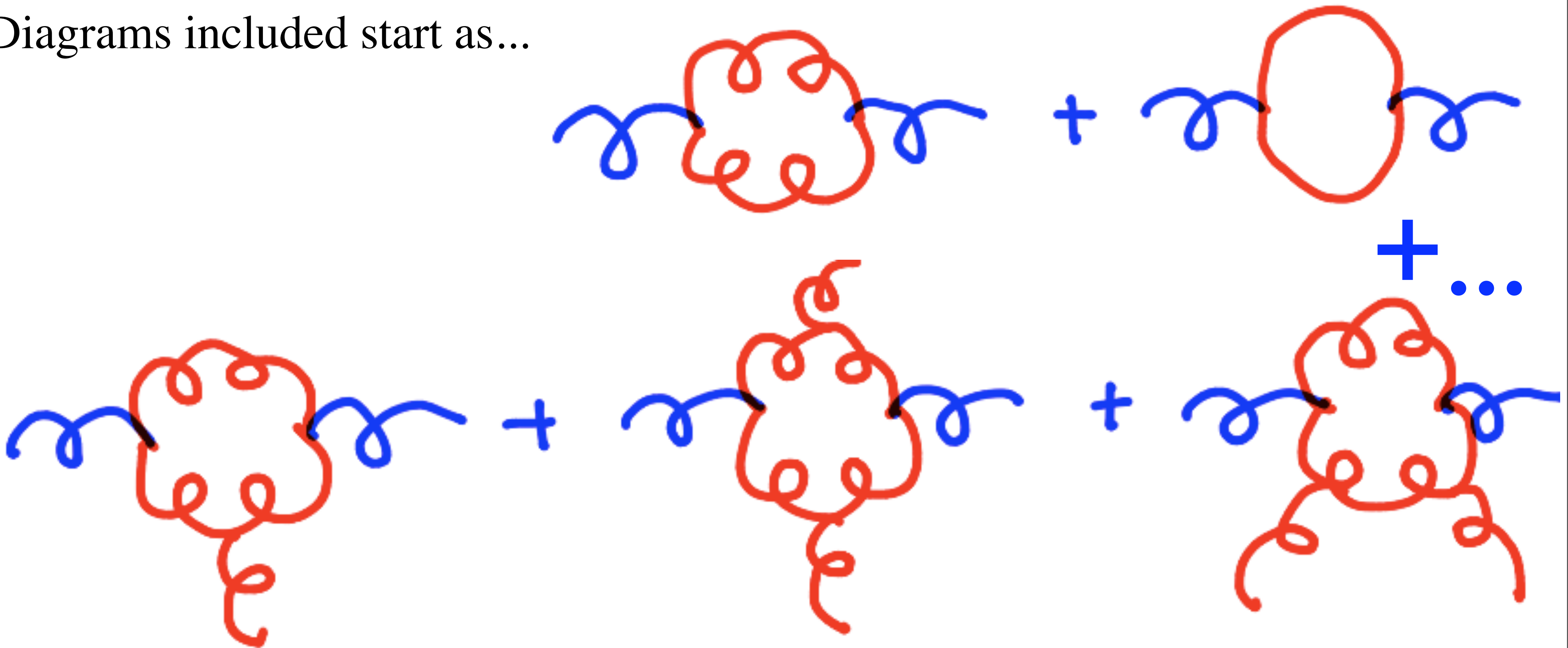
$$\mathcal{L}^{gluon}_{\mathrm{RPA}} = \frac{3}{2} \, m^2_{\mathrm{D}} \int \frac{d\Omega_{\hat{k}}}{4\pi} \, \mathrm{tr} \, \left(G^{\mu\alpha} \, \frac{K^\alpha K^\beta}{-(K \cdot D)^2} \, G^{\mu\beta} \right)$$

RPA in hot QCD = “Hard thermal loops”.
Braaten & RDP + Taylor & Wong + ...‘89-92.

Need effective propagators *plus* effective vertices. Can compute efficiently.

Diagrams for a Quark Gluon RPA

Diagrams included start as…



RPA *necessary* to treat "soft" momenta, ~ g T, consistently in weak coupling.

Why is the RPA gauge invariant? Simplest derivation: kinetic theory.
Leading order = only forward scattering processes, are gauge invariant.

Not true beyond leading order: consistent expansion to all orders?

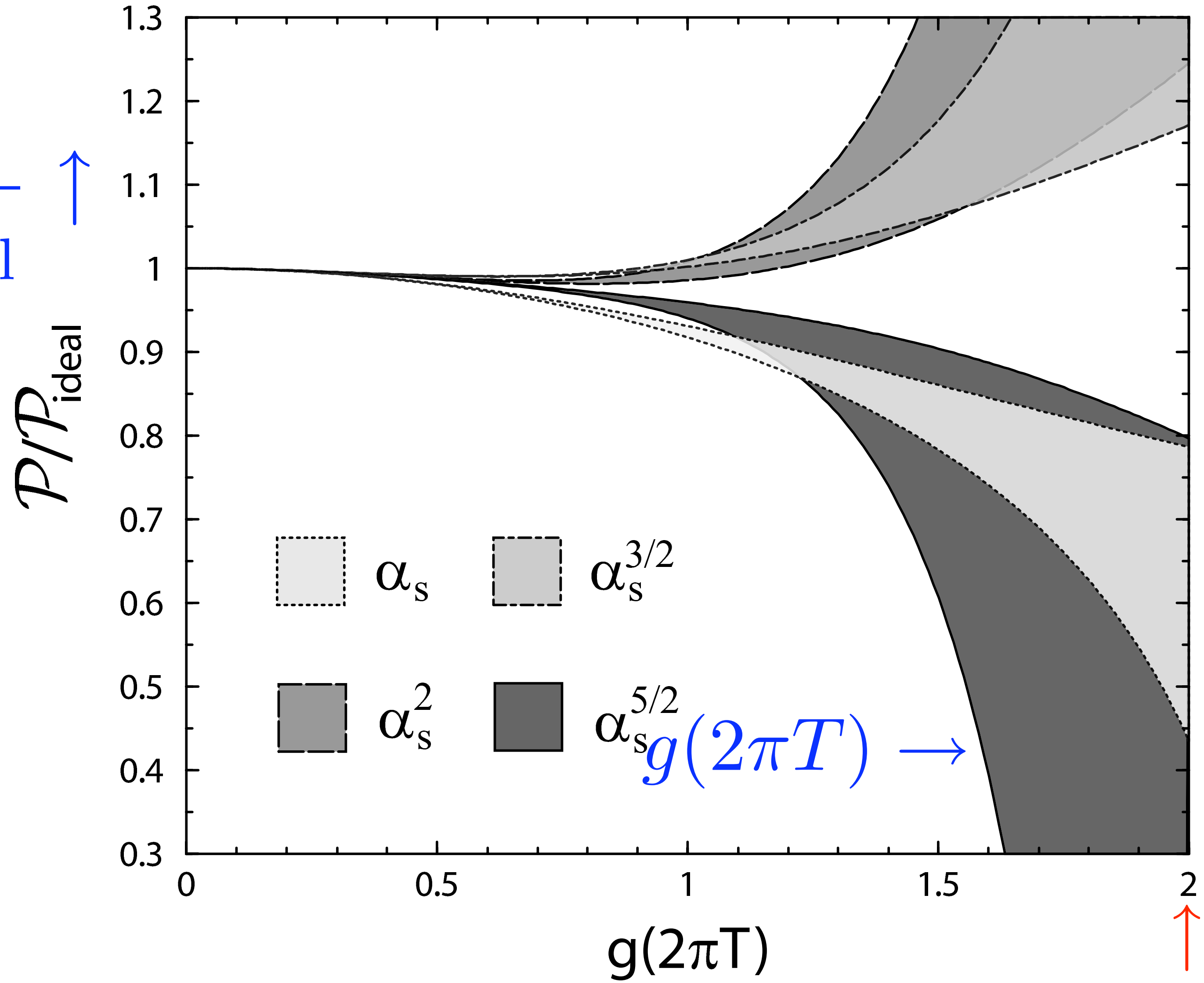
QCD: Naive Perturbation Theory fails *badly* at $T \neq 0$

$T=0$: perturbation thy. in $\alpha_s = g^2/4\pi$. Works well for momenta > 1 GeV, $\alpha_s < 0.3$.

$T \neq 0$: Debye screening $\Rightarrow$ expansion in $\sqrt{\alpha_s}$.

For pressure, perturbation thy. *fails* at *very* high temperature, $\sim 10^7$ GeV!

$\dfrac{p}{p_{ideal}} \uparrow$



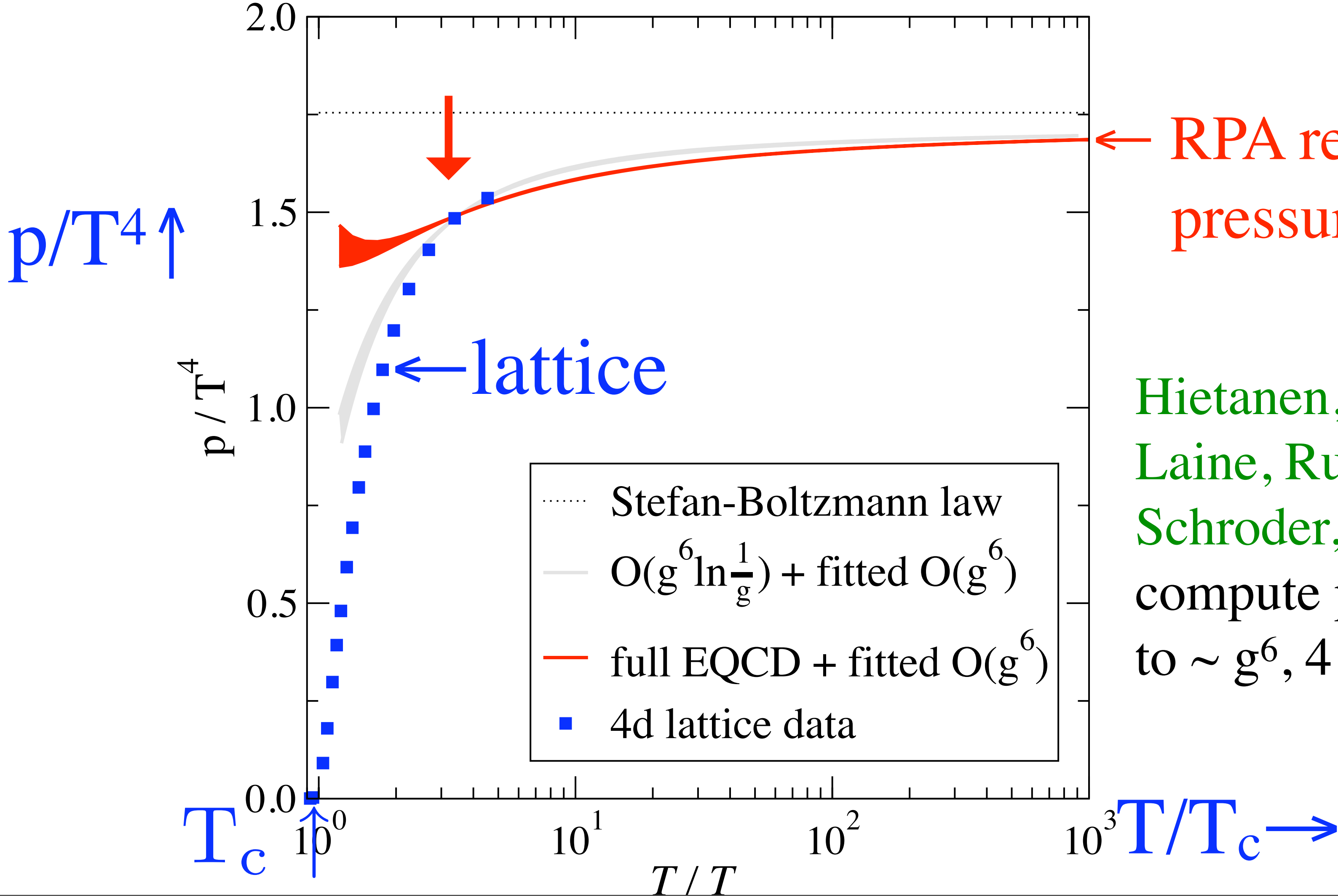
Andersen & Strickland, hep-ph/0404164

$\uparrow \alpha_s \sim 0.3$

QCD: Resummed RPA Pressure works down to ~ 3 T_c

Resum pressure using (generalized) RPA: works to ~ 3 T_c, but *not* below.

Strong decrease in the pressure near from ~ 3 T_c down to T_c: *new* physics.



Hietanen, Kajantie, Laine, Rummukainen, Schroder, 0811.4664: compute perturbatively to ~ g^6, 4 loop order.

Strongly Coupled Plasmas:
Supersymmetry vs.
Partial Color Ionization in the “semi” Quark Gluon Plasma

Plasmas in QED

Plasma of density "n".

Dimensionless coupling:

Γ_D = potential/kinetic energy

$$m_D^2 = \frac{e^2\, n}{T} \; ; \; \Gamma_D = \frac{e^2}{m_D T}$$

particles in "Debye sphere", radius $1/m_{Debye}$, = $1/\Gamma_D$

Dilute plasma, $\Gamma_D < 1$: *many* particles in Debye sphere.

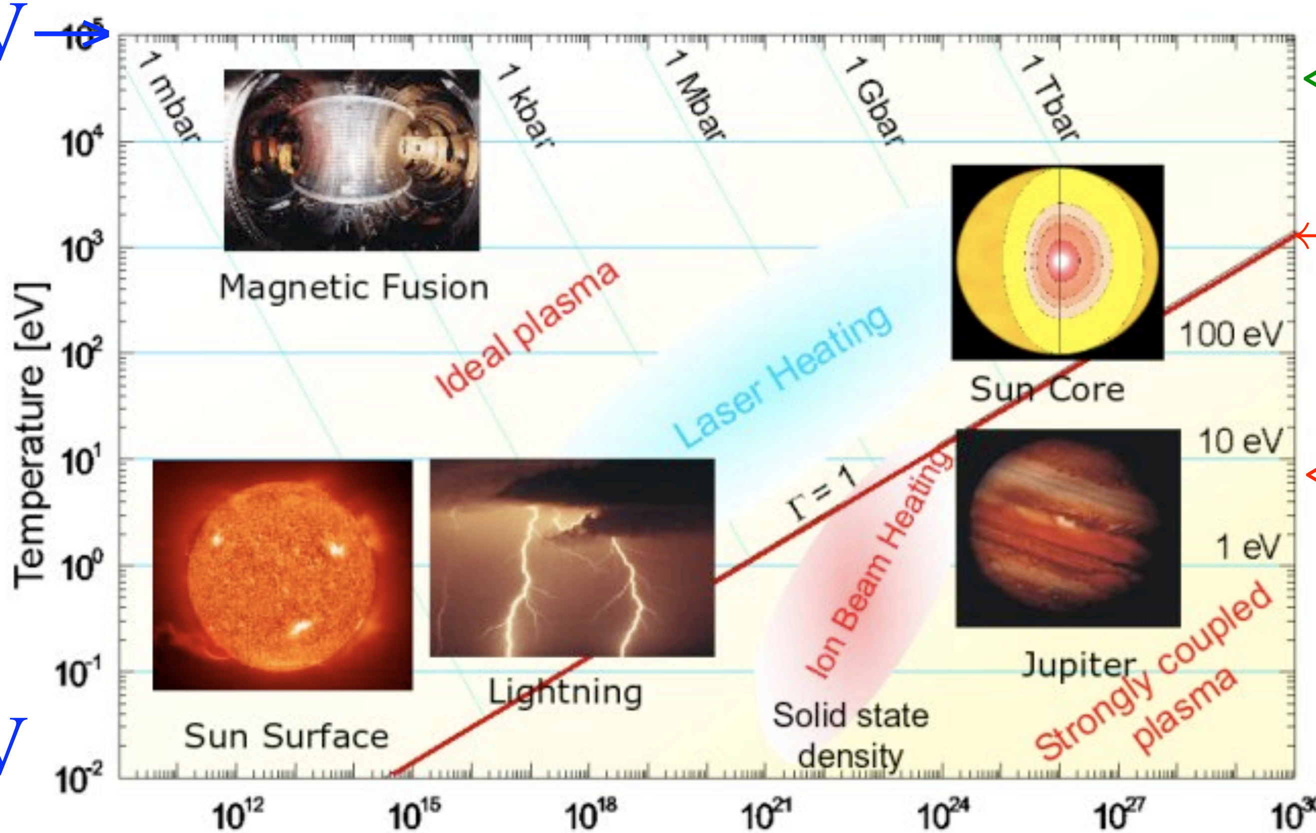
Dense plasma, $\Gamma_D \geq 1$: *few* particles in Debye sphere. Strongly coupled plasma.

10^5 eV→

T ↑

QGP:

10^9 eV



⇐ Prof. Jacoby

← $\Gamma = \#\,\Gamma_D^{2/3} = 1$

⇐ High density: "*strongly coupled*" plasma

Density→

Supersymmetry & AdS/CFT Plasma

Density in QCD is $n \sim T^3$, so $\Gamma_D \sim g^3$. *A strongly coupled plasma?*

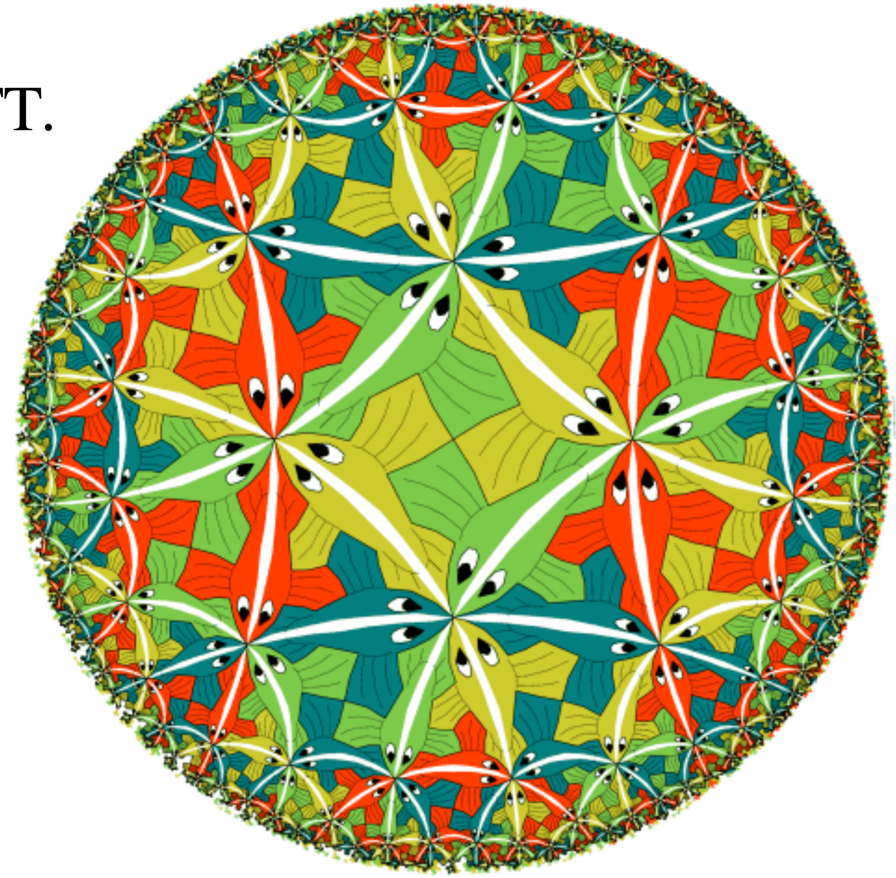
Maldacena, hep-th/9711200: $\mathcal{N} = 4$ supersymmetry for SU(N) gauge group

"Most" supersymmetric: gluons, gluinos, & Higgs, no quarks.

One dimensionless coupling, α_s, but does *not* run!

Can compute in limit of *infinite* coupling, *infinite* # of colors.

Anti deSitter/Conformal Field Theory, AdS/CFT.



Many results from AdS/CFT:
dominant paradigm

Conformal: pressure/ideal gas is
constant with T, > 3/4!

How to explain *small* pressure *near* T_c?

Ionizing Color in the QGP: Complete and Partial

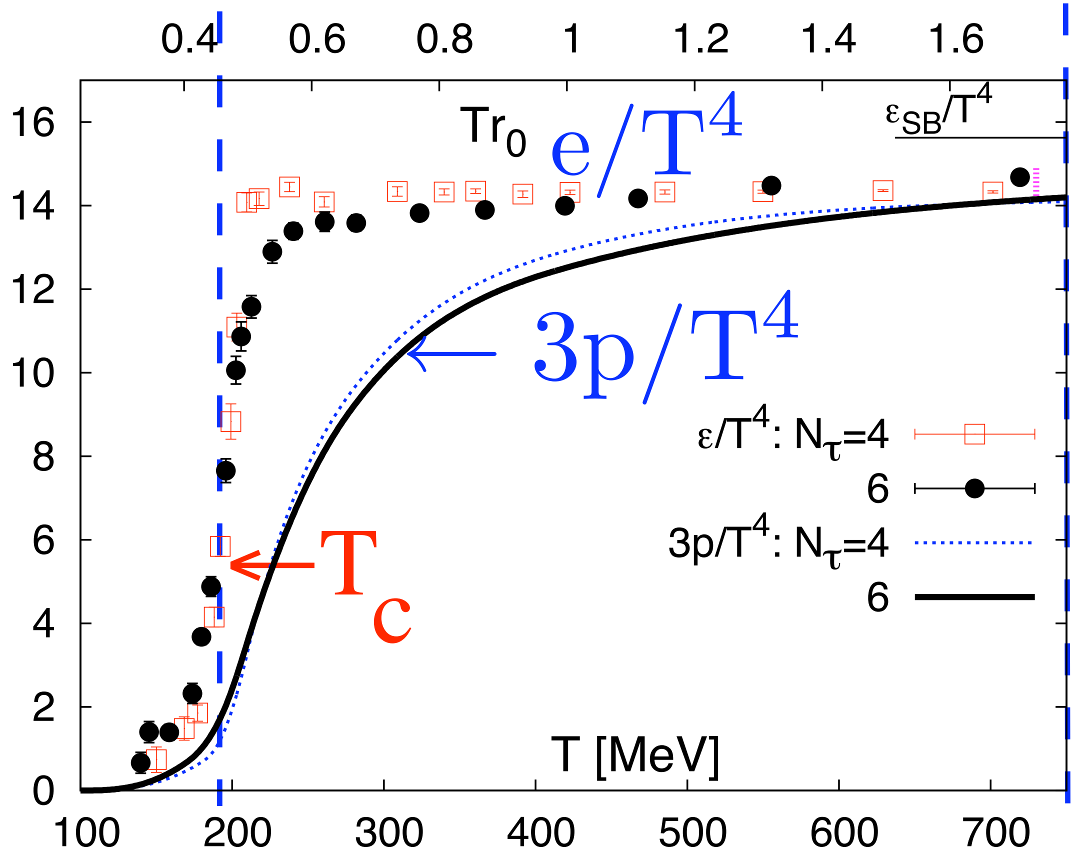
$T > 3\text{-}4\ T_c$: *complete* ionization of color, perturbative QGP. RPA pressure ~ ideal.

T: T_c to ~ $3\text{-}4\ T_c$: *partial* ionization of color. "*Semi*" QGP. Pressure intermediate.

$T < T_c$: no ionization of color, *confined*. Small pressure.

← Confined → ← "Semi"-QGP → ← Complete QGP →

Pressure/T^4 from lattice:



T→

Y. Hidaka & RDP, 0811.1202, 0906.1751, 0907.4609, 0909...

Confinement:
from 3 Colors to a 3-state Potts Model.
Polyakov Loops and Color Ionization.

Potts Model "hidden" in QCD

Let U_c = gauge transf. = *constant* phase.
$U_c \in SU(3)$, so det $U_c = 1$.
U_c *must* be one of *three* roots of unity:

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

Under U_c, gluons *invariant*:

$$A_\mu \rightarrow e^{-2\pi i/3} A_\mu \, e^{2\pi i/3} = A_\mu$$

but quarks are *not*.

$$\psi \rightarrow e^{2\pi i/3} \psi$$

't Hooft: "hidden" 3-state Potts model, or Z(3) spin, in SU(3) color

Measure using (Wegner-)Wilson loop. At $T \neq 0$, Polyakov loop:

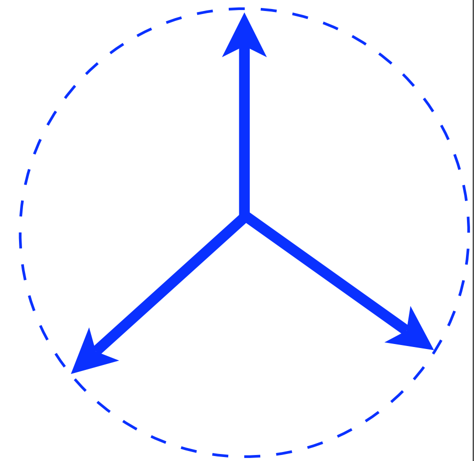
$$\ell = \frac{1}{3} \, \mathrm{tr} \, \exp\left(ig \int_0^{1/T} A_0 \, d\tau \right) \rightarrow e^{2\pi i/3} \, \ell$$

τ = imaginary time: $0 \rightarrow 1/T$.

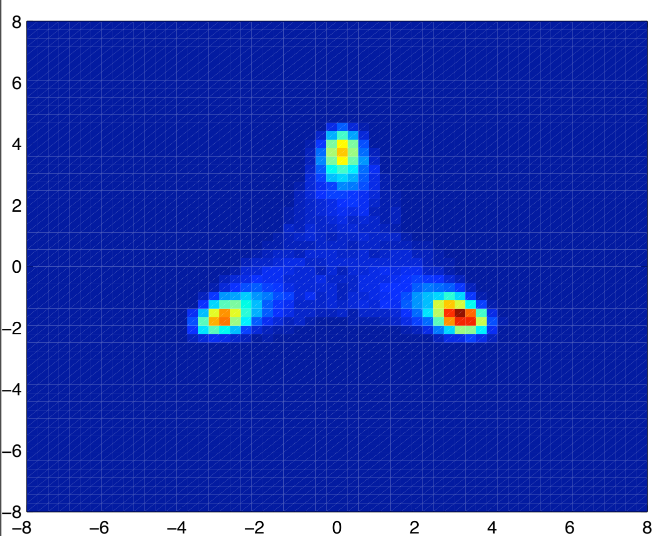
Polyakov loop measures Z(3) "spin".

Polyakov Loop as a Potts Model Spin

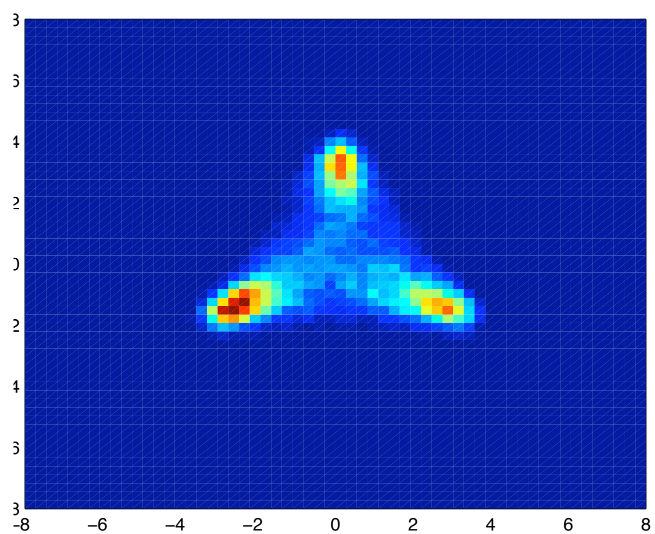
Purely gluonic plasma, no quarks: asymptotic freedom =>
hot gluons nearly ideal gas, $g^2(T) \to 0$ as $T \to \infty$.



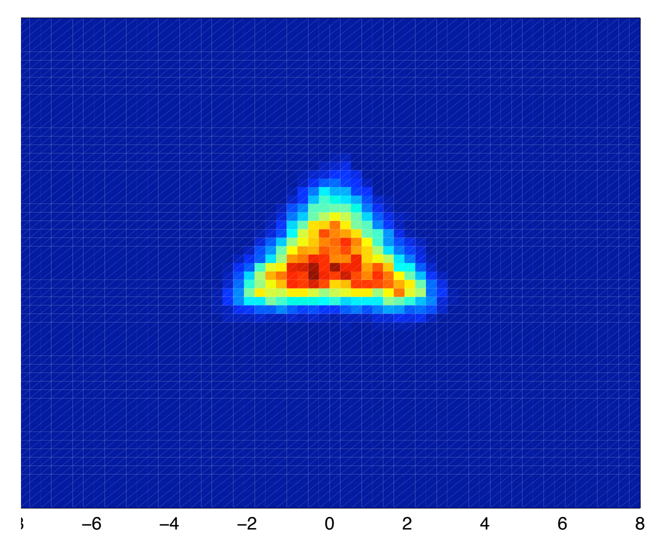
Fluctuations in A_0 small, so Polyakov loop is near one,
times $\exp(2\pi i/3)$! Three *degenerate* vacua: 3 state Potts model



$T \gg T_c$



$T \sim T_c$

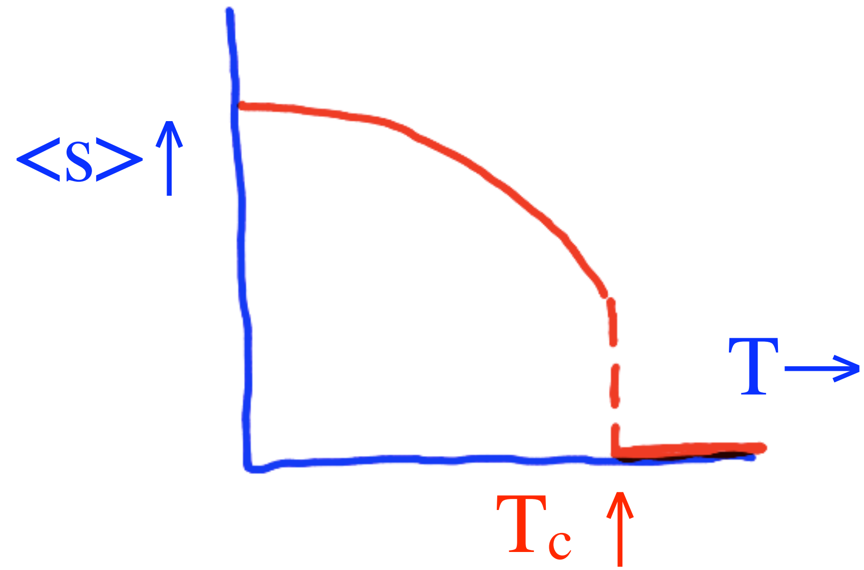


$T < T_c$

A. Kurkela, unpublished

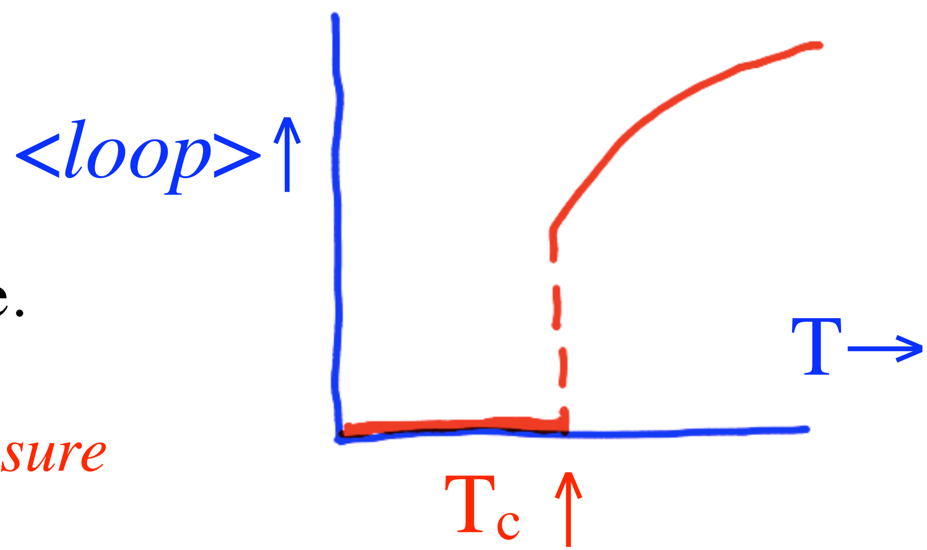
Potts Magnetization vs Polyakov Loop

Ordinary magnets:
symmetry (spontaneously) broken at low T,
restored above T_c.
For first order transition, magnetization:



QGP: Z(3) symmetry *broken* at high T, *restored* at low T.

$\langle \text{loop} \rangle = \exp(-F_{\text{test quark}}/T)$
$\qquad = 0$ when $T < T_c$:
Confinement = *no* Z(3) magnetization;
color cannot be ionized in the confined phase.



Polyakov loop provides gauge invariant measure of color ionization.

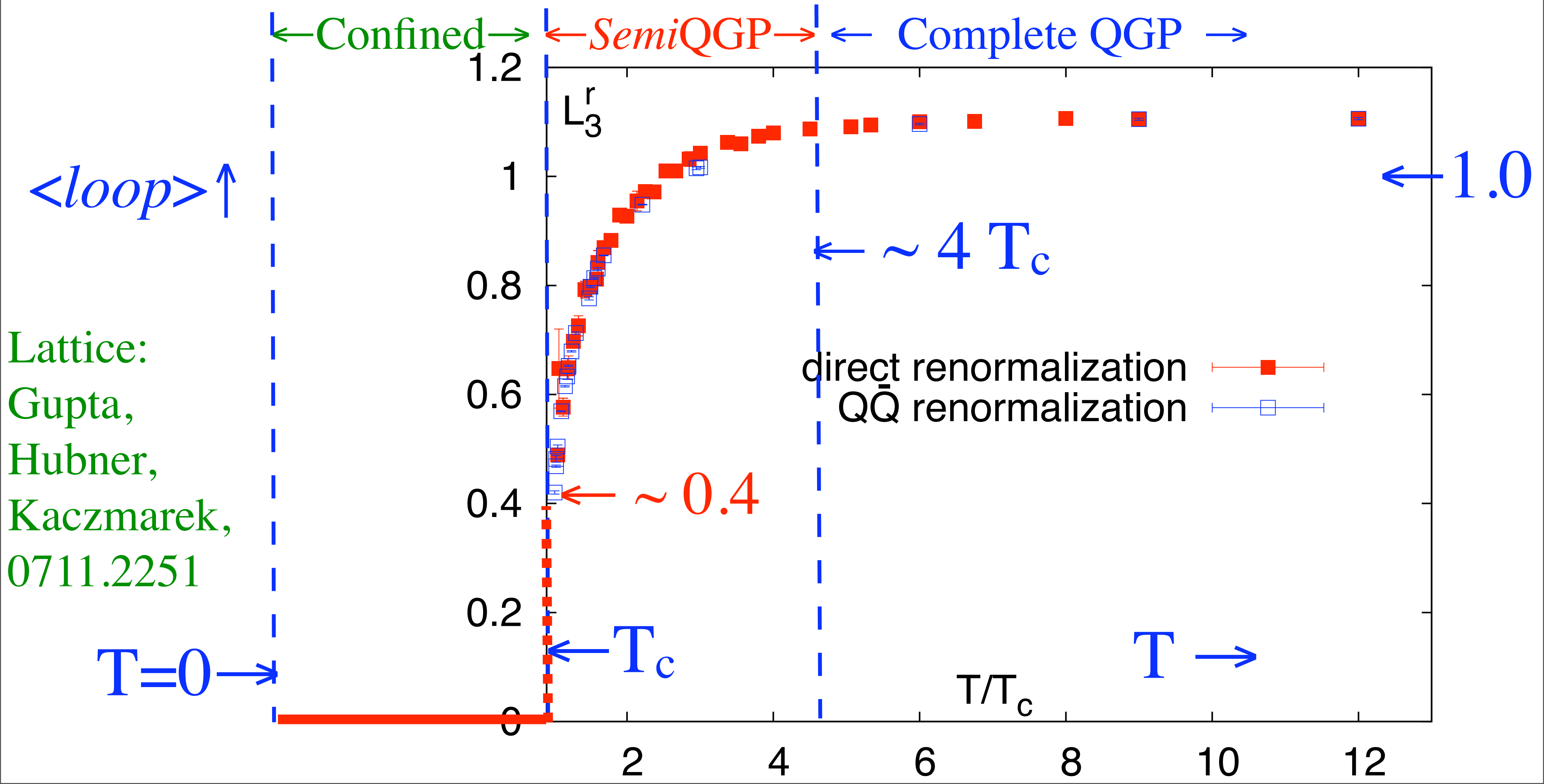
Polykov Loop from Lattice: pure Glue, no Quarks

Lattice: (renormalized) Polyakov loop. *Looks like pressure:*

Semi-QGP: <*loop*> < 1, T: T_c → 4 T_c Complete QGP: <*loop*> ~ 1, T > 4 T_c

Effective theory for Polyakov loop(s)?

RDP & ...: hep-ph/0006205, 0311223, 0410294, 0505256, 0512245, 0608242 + ...

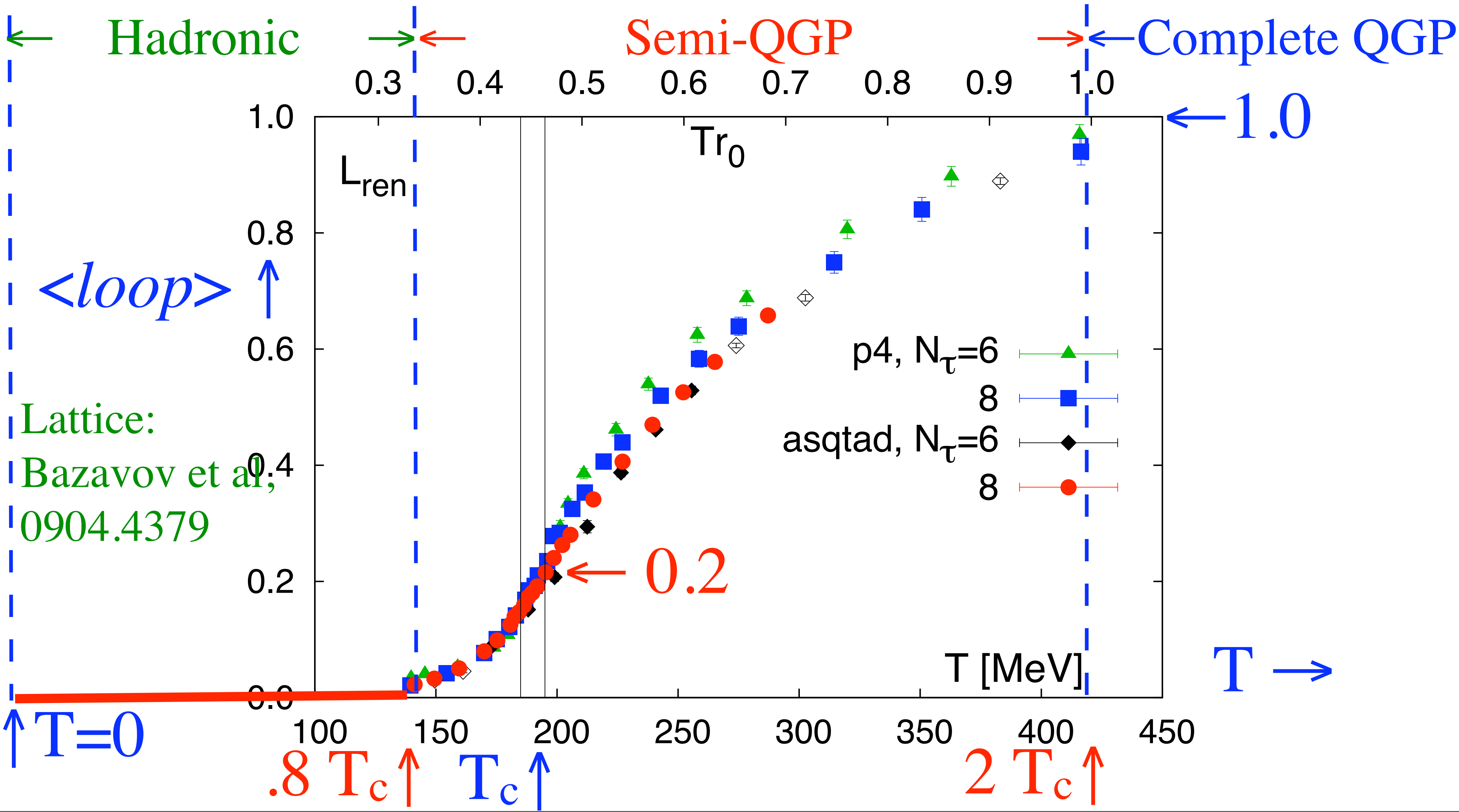


Polyakov Loop from Lattice: Glue plus Quarks

Quarks ~ background Z(3) field. *Lattice*: quarks do *not* wash out loop in QCD!

Semi-QGP: <*loop*> nonzero above 0.8 T_c (< T_c !), < 1 up to ~ 2-3 T_c .

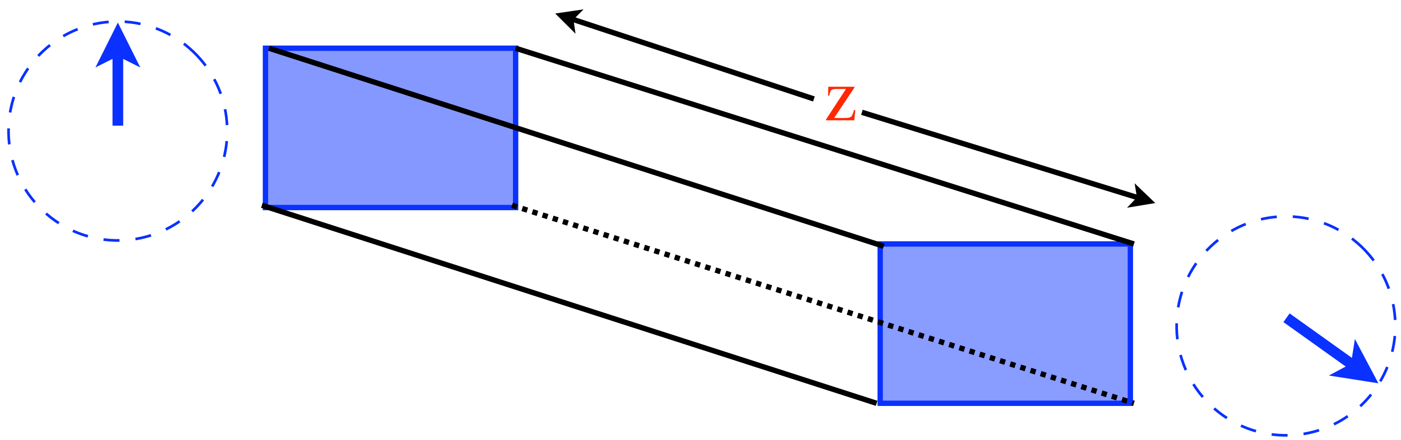
Hadronic phase below semi-QGP, T < 0.8 T_c . Complete QGP above , T > 2-3 T_c



Dynamics of the semi Quark Gluon Plasma: Bleaching Color near T_c

Interface Tension between two Z(3) Phases

In pure SU(3) (no quarks), consider a box which is long in the z-direction.
Vacuum at each end, but *different* Z(3) vacua. Domain wall forms.



Compute by taking z-dependent A_0 field:
RDP+... hep-ph/9205231.

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

Action proportional to transverse area times interface tension:
Tunneling between Z(3) vacua ↑ as T ↓.

$$\sigma_{\mathrm{inter}} = \frac{8\pi^2}{9}\,\frac{T^3}{\sqrt{g^2}}$$

What matters are *matrix* degrees of freedom.

Matrix Model for the QGP

Polyakov loop = 1/3 trace of SU(3) matrix:
L = thermal Wilson line

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

L = gauge variant, eigenvalues are gauge invariant.

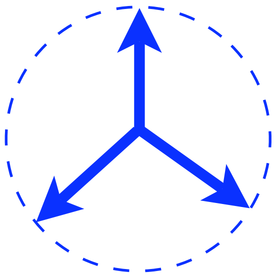
$\mathbf{L}^\dagger \mathbf{L} = \mathbf{1}$, so eigenvalues phases, = $\exp(i\, q_a)$, a = 1,2,3; $\Sigma_a q_a = 0$, mod 2π

Deconfinement is like a random matrix model (RMM):

complete QGP: all phases identical. E.g., all $q_a = 0$.

confined phase: uniform distribution over all Z(3) vacua:

$q_a = 0, \pm 2\pi/3$



semi-QGP: *non*-uniform distribution of eigenvalues.

Small volume: effective Lagrangian Vandermonde determinant, like RMM.

Large volume: no simple form - *yet* - for effective Lagrangian.

Hints from lattice: Dumitru & Smith, 0711.0868, Velytsky, 0805.4450

Assume a given eigenvalue distribution: *physics*?

Shear Viscosity in the semi-QGP

Shear viscosity, η: in kinetic theory, $\eta \sim 1/\text{cross section}$.

AdS/CFT: Kovtun, Son & Starinets hep-th/0405231.

Conjectured lower bound. (s = entropy density)

Reasonable, since computed for *infinite* coupling in SUSY QCD.

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

Semi-QGP: semi-classical expansion about background field $A^0_{cl} = Q/g$.

Q = diagonal matrix, *imaginary* chemical potential for color. .

Near T_c, as <*loop*> $\rightarrow$ 0,

perturbative η *times* <*loop*>^{2}:

Hidaka & RDP, '08,'09....

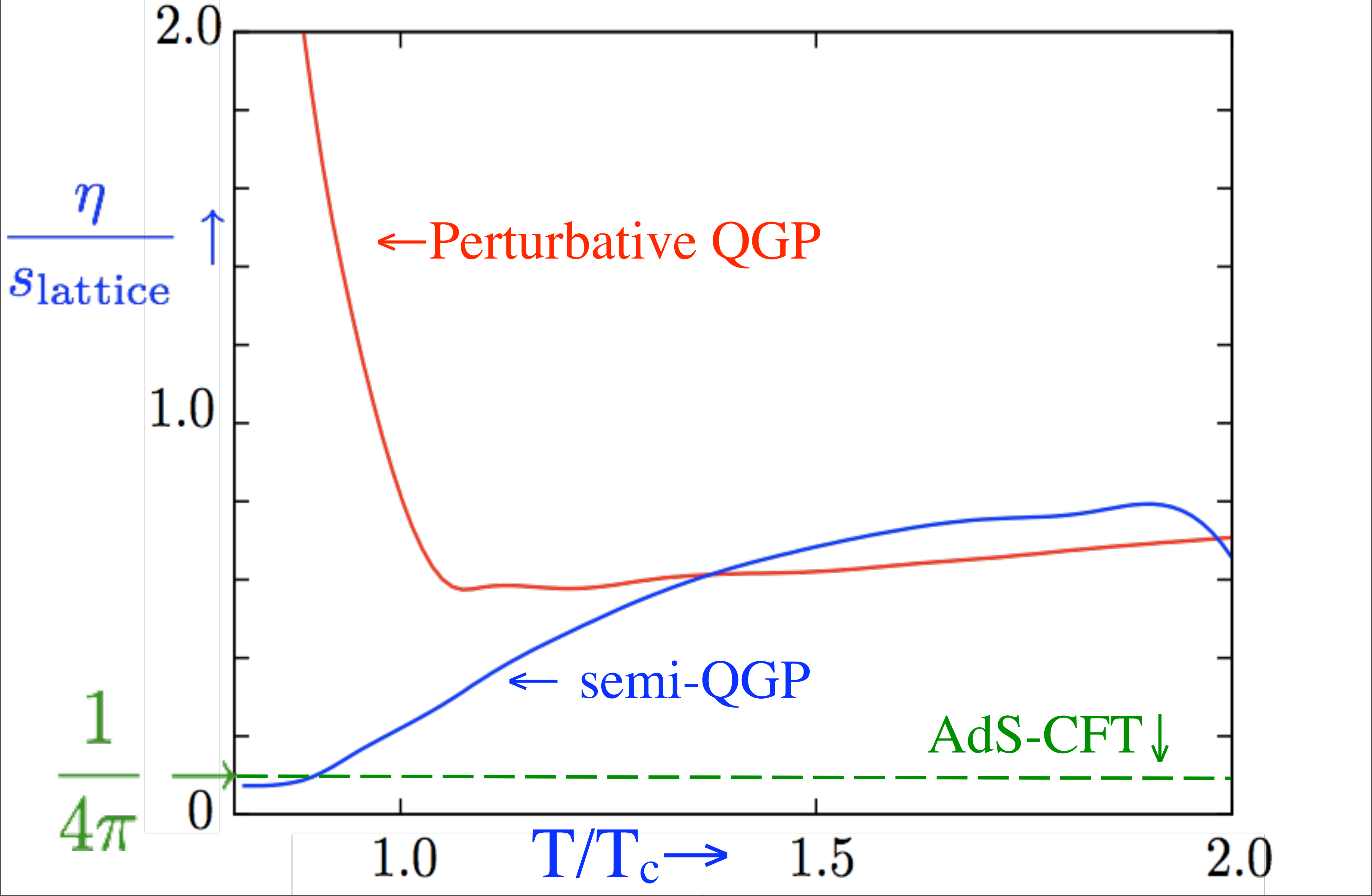
$$\frac{\eta}{T^3} = \frac{\#}{g^4 \log(c/g)} |\ell|^2 \; , \; \ell \rightarrow 0$$

η = (source term ~ <*loop*>^{2})^2/(cross section ~ <*loop*>^{2}) ~ <*loop*>^{2}

"Bleaching" of color: probability to produce color particles ~ <*loop*>.

Of course! If color can't be ionized, you can't produce colored particles.

Bleaching Shear Viscosity in the semi-QGP



AdS/CFT vs. semi-QGP @ LHC

Collisions of heavy ions at RHIC (Brookhaven, AuAu) and LHC (CERN, PbPb):
Quark Gluon Plasma?

RHIC: center of mass energy 200 GeV.
Shear viscosity appears very small, η/s near $1/4\pi$

LHC: > 2010, center of mass energy 5500 GeV.
pressure ~ T^4, so *perhaps LHC a factor of two higher in temperature than RHIC?*

AdS/CFT: if RHIC in conformal regime, so is the LHC.
η/s small at RHIC, stays small at the LHC. LHC *very* similar to RHIC.

Semi-QGP: Assume RHIC is in the semi-QGP, near T_c. η/s small.
LHC starts in the Complete QGP, well above T_c. η/s large.
Should be *numerous* differences between RHIC and LHC:
"bleaching" of color at RHIC, not (*initially*) at the LHC.

So: is LHC ≈ RHIC (AdS/CFT), or is LHC ≠ RHIC (Semi-QGP)?

Towards *NARPA*:
a Non-Abelian Random Phase Approximation

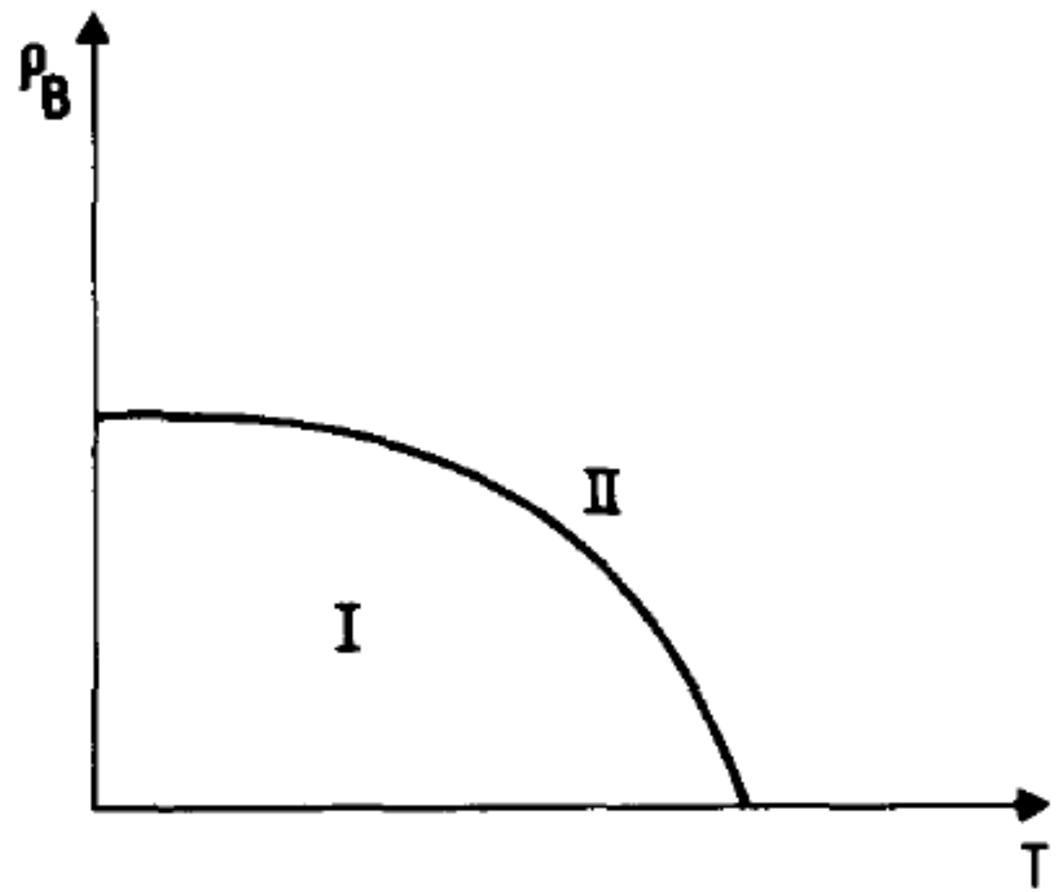
New Phase Diagram for QCD:
“Quarkyonic” Matter and their Chiral Spirals

QCD Phase Diagram: 1975

Cabibbo and Parisi '75: Transition to "unconfined" phase. *One* transition.

But QCD has *two* (possible) transitions: deconfinement and chiral symmetry.

ϱ_{Baryon} ↑



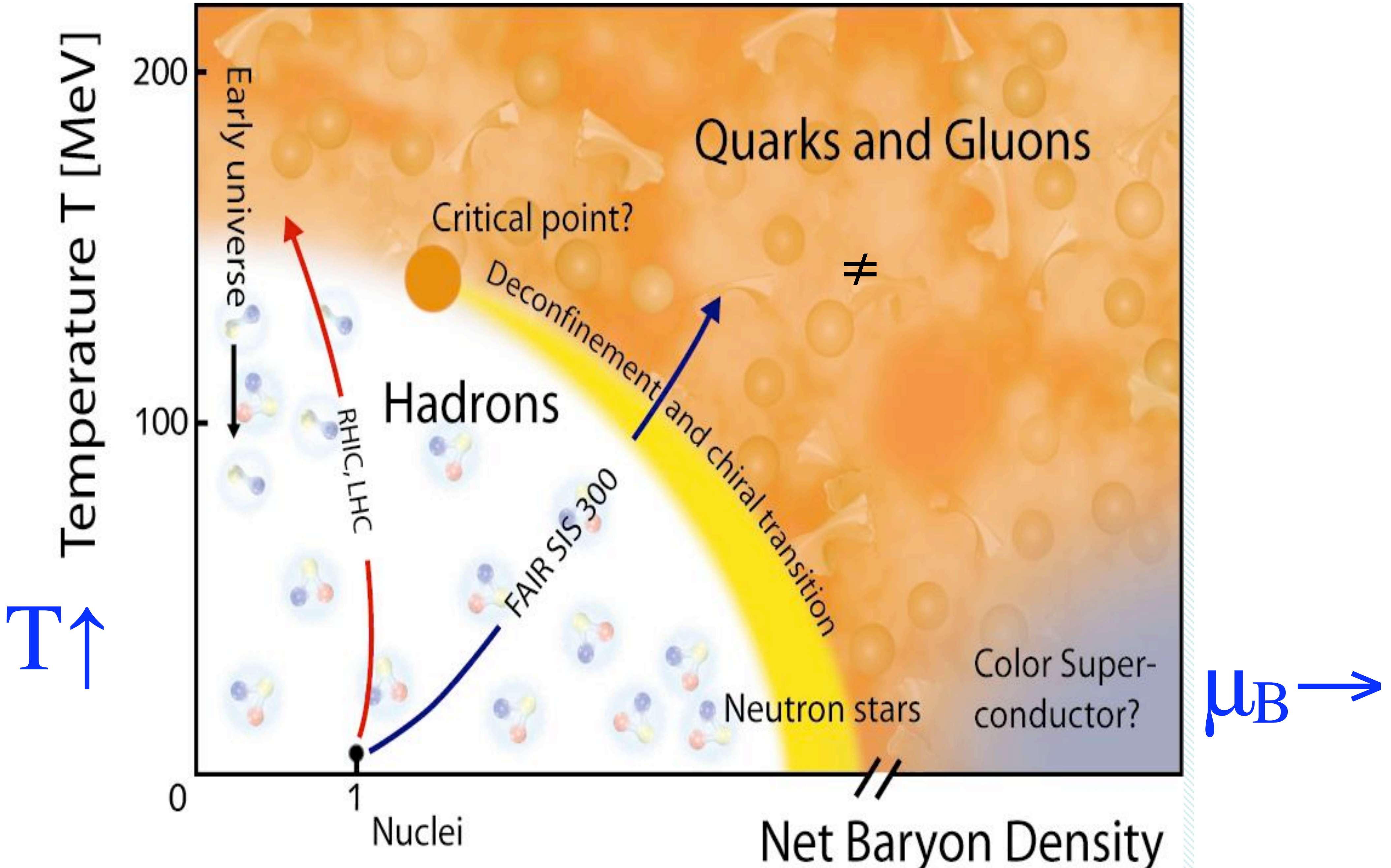
T →

Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

QCD Phase Diagram: 2007

Lattice: at $T \neq 0$, zero quark density, $\mu = 0$, *one* “transition”, crossover.

Rajagopal, Stephanov, & Shuryak ’99: critical endpoint at $\mu \neq 0$?



QCD Phase Diagram: 2009

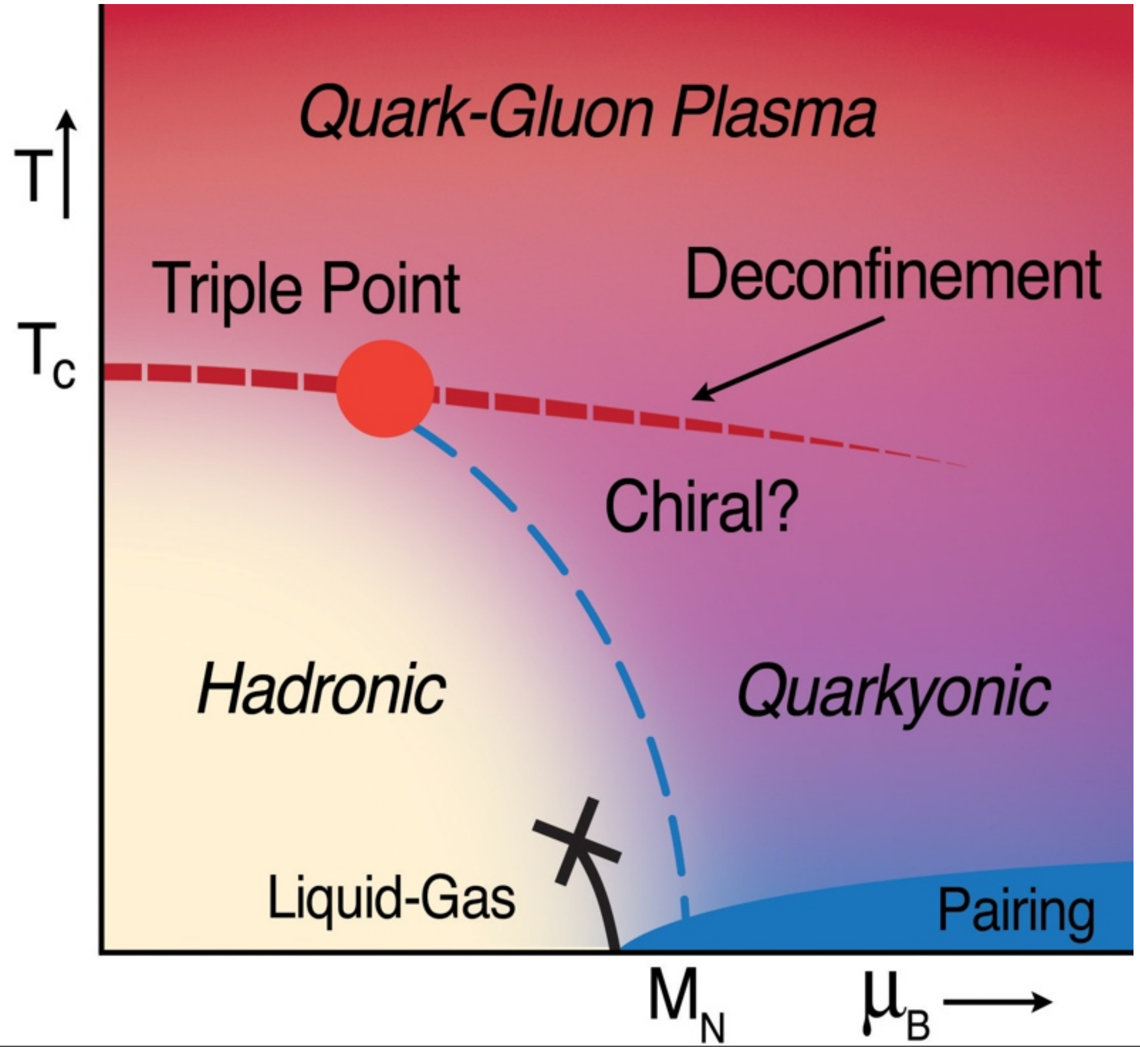
L. McLerran & RDP 0706.2191; 0803.0279; & et al... 0909....; & T. Kojo 0909...

Large N_c suggests: deconfining and chiral phase transitions *split* at $\mu \neq 0$.

"Quark-yonic" matter: quark Fermi sea + confined (bary-onic) Fermi surface

Implies *Triple Point* in T-μ plane. Related to experiment @ SPS, RHIC?

T↑

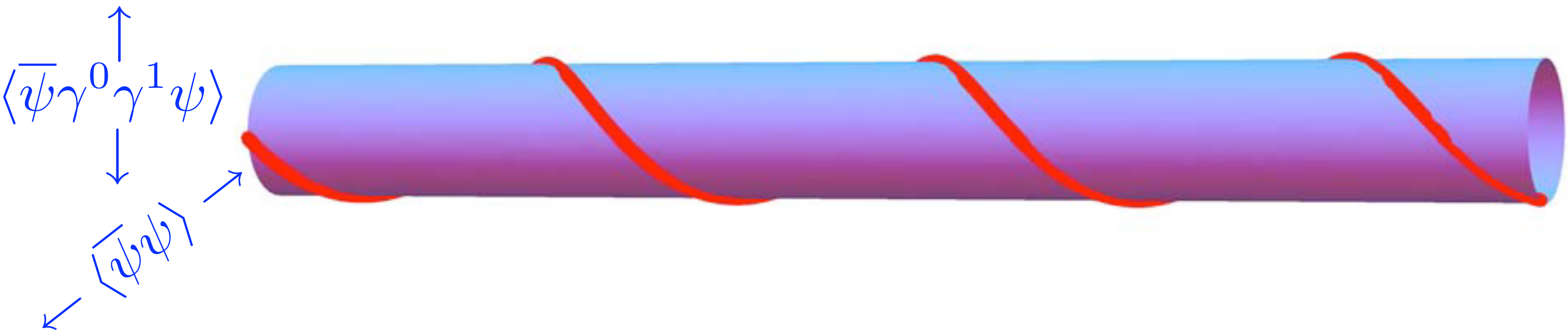


$\mu_B \longrightarrow$

“Chiral Spirals” in Quarkyonic Matter

RDP et al 0909...: using confining potential, find:
crystalline structure, with chiral density wave for (helicity) condensate:

$$\langle \overline{\psi}\psi \rangle^2 \; + \; \langle \overline{\psi}\gamma^0\gamma^1\psi \rangle^2 = \text{const}$$



Like, but *not* identical, to pion condensation, which rotates into $\langle \overline{\psi}\psi \rangle$ & $\langle \overline{\psi}\gamma_5\psi \rangle$

Directly analogous to polarons in polyacytelene. Thies, hep-th/0601049

Chiral Gross-Neveu model in 1+1 dimensions: Basar, Thies, & Dunne, 0903.1868

All in all...

"A possible eureka."