(Non)-perturbative properties of high-T QCD

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- Introduction:
  - thermal scales in QCD: $T$, $gT$, $g^2T$, ...

- Heavy quark free energies
  - screening and running couplings

- Bulk thermodynamics
  - the equation of state: QCD and SU(3)

- Hadronic fluctuations
  - quark number and charge fluctuations

- Conclusions
Introduction: sQGP

- matter created at RHIC is a dense, strongly interacting system
- Does the coupling at finite temperature become large?
- Are exotic bound states in the QGP responsible for large interaction cross sections?
- Is the QGP a liquid?
- Can the QGP be described in terms of a conformal field theory?

overview on perturbative and non-perturbative features of the QGP
Thermal scales in QCD

- **the hard scale:** \( p \sim T \)
  thermal modes, bulk thermodynamics, eg. pressure
  \[
  \frac{p}{T^4} = a_{SB} f_p(g(T))
  \]

- **the soft scale:** \( p \sim gT \)
  static color-electric modes, eg. Debye screening
  \[
  \frac{m_D(T)}{g(T)T} = \sqrt{\frac{N_c}{3} + \frac{n_f}{6} + \frac{n_f}{2\pi^2} \left( \frac{\mu_q}{T} \right)^2} \cdot f_E(g(T))
  \]

- **the ultra-soft scale:** \( p \sim g^2 T \)
  static color-magnetic modes, eg. spatial string tension
  \[
  \frac{\sqrt{\sigma_s}}{g^2(T)T} = c_M f_M(g(T))
  \]
Non-thermal scales in thermal QCD

- even harder scales: $p \gg T$, $r^{-1} \gg T$, $M \gg T$

  short distance physics, eg. quarkonium

  $g^2(r, T')$

- quantitative questions, eg.

  When does $T$ become the dominant scale?
  (i.e. controls the running of $g^2$)
Hierachy of scale?

Perturbation theory provides a hierachy of length scales

\[ T \gg gT \gg g^2T \ldots \Rightarrow \text{guiding principle for effective theories, resummation, dimensional reduction...} \]

These scales are not well separated close to \( T_c \)!!
Hierachy of scale?

- Perturbation theory provides a hierarchy of length scales

\[ T \gg gT \gg g^2T \ldots \Rightarrow \text{guiding principle for effective theories, resummation, dimensional reduction...} \]

These scales are not well separated close to \( T_c \) !

- Early lattice results show that \( g^2(T) > 1 \) even at \( T \sim 5T_c \)

G. Boyd et al, NP B469 (1996) 419: SU(3) thermodynamics..

...one has to conclude that the temperature dependent running coupling has to be large, \( g^2(T) \sim 2 \) even at \( T \sim 5T_c \)

- the Debye screening mass is large close to \( T_c \)

- the spatial string tension does not vanish above \( T_c \)

\[ \sqrt{\sigma_s} \neq 0 \Rightarrow \text{the QGP is “non-perturbative” up to very high } T \]
Screening of heavy quark free energies
– remnant of confinement above $T_c$ –

singlet free energy
(in Coulomb gauge)

$T \approx T_c$ : screening for $r \gtrsim 0.5 \text{fm}$

$F_1(r, T) \sim \frac{\alpha(T)}{r} e^{-\mu(T)r} + \text{const.}$

$F_1(r, T)$ follows linear rise of $V_{\bar{q}q}(r, T = 0) = -\frac{4\alpha(r, T = 0)}{3r} + \sigma r$

for $T \lesssim 1.5T_c, r \lesssim 0.3 \text{ fm}$


F. Karsch, xQCD, July 2008 – p. 6/32
Non-perturbative Debye screening

- leading order perturbation theory: \( m_D = g_D(T)T \sqrt{1 + \frac{n_f}{6}} \)

- \( T_c < T \lesssim 10T_c \): non-perturbative effects are well represented by an ”A-factor”: \( m_D \equiv Ag_D(T)T, \ A \simeq 1.5 \)

- perturbative limit is reached very slowly (logarithms at work!!)

\[ m_D/T = Ag(T) \]
\[ A = 1.42(2) \]
Non-perturbative Debye screening

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- \( T_c < T \lesssim 10T_c \): non-perturbative effects are well represented by an "A-factor": \( m_D \equiv A g_D(T)T, \; A \sim 1.5 \)

- Perturbative limit is reached very slowly (logarithms at work!!)

\[ g_D^2(T_c) \approx 4, \; g_D^2(4T_c) \approx 2 \]
Non-perturbative Debye screening

$\mu_q$-dependence

leading order perturbation theory:

$$m_D = g(T)T \sqrt{1 + \frac{n_f}{6} + \frac{n_f}{2\pi^2} \left(\frac{\mu_q}{T}\right)^2}$$

Taylor expansion, 2-flavor QCD:

$$m_D(T) = m_0(T) + m_2(T) \left(\frac{\mu_q}{T}\right)^2 + \mathcal{O}(\mu_q^4)$$

$$\frac{m_2}{m_0} = \frac{3}{8\pi^2}:$$ agrees with perturbation theory for $T \gtrsim 1.5T_c$

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\]

non-perturbative effects are in the glue quark sector
"perturbative" above $T \gtrsim 1.5T_c$?

The spatial string tension
Does dimensional reduction work with light quarks?

Non-perturbative, vanishes in high-T perturbation theory:

\[ \sqrt{\sigma_s} = - \lim_{R_x, R_y \to \infty} \ln \frac{W(R_x, R_y)}{R_x R_y} \]

\[ \frac{\sqrt{\sigma_s}}{g_\sigma^2(T)T} = c_\sigma , \quad c_\sigma \equiv c_3 , \quad g_E^2 \equiv g_\sigma^2 T \]

\( c_3 \): 3-d SU(3), LGT
\( g_\sigma^2 \): 2-loop dim. red. pert. th.

4-d SU(3), LGT data:

3-d SU(3), dimensional reduction:
M. Laine, Y. Schröder, JHEP 0503 (2005) 067
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\( c_3 \): 3-d SU(3), LGT
\( g_\sigma^2 \): 2-loop dim. red. pert. th.

\[ g_\sigma^2(T_c) \simeq 3.7 , \quad g_\sigma^2(5T_c) \simeq 2 \]

dimensional reduction works for \( T \gtrsim 2T_c \)

- \( c_M \) (almost) flavor independent
- \( g_\sigma^2(T) \) shows 2-loop running

\[ c_\sigma = 0.553(1) [\text{SU}(3)] \]
\[ c_\sigma = 0.54(1) [\text{QCD}] \]

M. Cheng et al (RBC-Bielefeld), arXiv:0806.3264

F. Karsch, xQCD, July 2008 – p. 9/32
Screening of heavy quark free energies
– remnant of confinement above $T_c$ –


- singlet free energy
  (in Coulomb gauge)

- $T \simeq T_c$: screening for $r \gtrsim 0.5\text{fm}$

$$F_1(r, T) \sim \frac{\alpha(T)}{r} e^{-\mu(T)r} + \text{const.}$$

- $F_1(r, T)$ follows linear rise of $V_{\bar{q}q}(r, T = 0) = -\frac{4\alpha(r, T = 0)}{3r} + \sigma r$
  for $T \lesssim 1.5T_c$, $r \lesssim 0.3\text{ fm}$
Singlet free energy and asymptotic freedom


Singlet free energy defines a running coupling:

$$\alpha_{\text{eff}} = \frac{3r^2}{4} \frac{dF_1(r, T)}{dr}$$

(in Coulomb gauge)
Singlet free energy and asymptotic freedom


\[ \alpha_{\text{eff}} = \frac{3r^2}{4} \frac{dF_1(r, T)}{dr} \]
(in Coulomb gauge)

large distance: constant Coulomb term (string model)
short distance: running coupling \( \alpha(r) \) from \( T = 0 \), 3-loop

short distance physics \( \Leftrightarrow \) vacuum physics

T-dependence starts in non-perturbative regime for \( T \lesssim 3T_c \)
Singlet free energy and asymptotic freedom


Singlet free energy defines a running coupling:

\[ \alpha_{\text{eff}} = 3r^2 \frac{dF_1(r, T)}{4 dr} \]

(in Coulomb gauge)

large distance: constant Coulomb term (string model)

short distance: running coupling \( \alpha(r) \) from \( T = 0 \), 3-loop

short distance physics \( \Leftrightarrow \) vacuum physics

T-dependence starts in non-perturbative regime for \( T < \frac{3}{3} T_c \)

\[ \alpha_{qq}(r, T) \]

rise due to confinement \( \alpha_{\text{eff}} \sim \sigma r^2 \)
two prominent features of EoS that characterize the non-perturbative structure of QCD at high temperature

- strong deviations from ideal gas behavior ($\epsilon = 3p$) for $T_c \leq T \lesssim 3T_c$
- deviations from Stefan-Boltzmann limit persist even at high $T$
QCD equation of state

- two prominent features of EoS that characterize the non-perturbative structure of QCD at high temperature
  - strong deviations from ideal gas behavior ($\epsilon = 3p$) for $T_c \leq T \lesssim 3T_c$
  - deviations from Stefan-Boltzmann limit persist even at high $T$

- structure of EoS is 'universal', i.e. shows little quark mass dependence in $\epsilon/\epsilon_{SB}$ vs. $T/T_c$
- quark content changes only 'details'
SU(3) Equation of State
pressure: LGT vs. HTL

High $T$ part of the pressure calculated on the lattice is in good agreement with HTL-resummed perturbation theory for $T \gtrsim 3T_c$

No need for AdS/QCD to explain 'pressure gap'

HTL: J.P. Blaizot,
E. Iancu, A. Rebhan,
PL B470 (99) 181

F. Karsch, xQCD, July 2008 – p. 13/32
The pressure revisited

- $T \gtrsim (2-3)T_c$: deviations from ideal gas understood in terms of HTL-resummed perturbation theory
- $T \lesssim 2T_c$: strong deviations from ideal gas
- deviations from $p_{SB}$ almost flavor independent

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(2+1)-flavor QCD: ...towards the cont. limit ($N_\tau = 8$) with light quarks ($m_\pi \simeq 220$ MeV)

- non-conformal:
  $[(\epsilon - 3p)/T^4]_{max} \simeq (6 - 7)$ at $T_{max} \simeq 200$ MeV ($\sim$ softest point of EoS)

- some cut-off effects in the peak region; p4 and asqtad agree

- $T \gtrsim 300$ MeV: good agreement between $N_\tau = 6$ and 8 results

- non-perturbative:
  $(\epsilon - 3p)/T^4 \sim A/T^2 + B/T^4$
  for $1.5T_c \lesssim T \lesssim 4T_c$
EoS: low $T$ regime

LGT vs resonance gas

approach to physical quark masses:

$m_q = 0.1m_s \rightarrow m_q = 0.05m_s$

($m_\pi \simeq 220$ MeV $\rightarrow 150$ MeV)
**EoS: low $T$ regime**

**LGT vs resonance gas**

- Approach to physical quark masses:
  - $m_q = 0.1 m_s \rightarrow m_q = 0.05 m_s$
  - ($m_\pi \simeq 220$ MeV $\rightarrow$ 150 MeV)

  $\rightarrow O(5\text{MeV})$ shift of $T$-scale

- Good agreement with HRG model in the transition region;
  still need to control cut-off effects
Pressure, Energy and Entropy

\( p/T^4 \) from integration over \((\epsilon - 3p)/T^5\);
\( p(T_0) = 0 \) at \( T_0 = 0 \) MeV
(exponential extrapolation);

systematic error on \( 3p/T^4 \) \( \approx 0.33 \)

good scaling behavior; good agreement between different discretization schemes
Pressure, Energy and Entropy

- \( \frac{p}{T^4} \) from integration over \( (\epsilon - 3p)/T^5 \);
- \( p(T_0) = 0 \) at \( T_0 = 0 \) MeV
  (exponential extrapolation);
- systematic error on \( \frac{3p}{T^4} \approx 0.33 \)
- good scaling behavior; good agreement between different discretization schemes

\begin{align*}
\text{p4: } N_t = 6 \\
\text{asqtad: } N_t = 8
\end{align*}
Hadronic fluctuations at $\mu > 0$ from Taylor expansion coefficients at $\mu = 0$

$n_f = 2, \ m_\pi \simeq 770$ MeV: S. Ejiri, FK, K.Redlich, PLB633 (2006) 275

$n_f = 2 + 1, \ m_\pi \simeq 220$ MeV: RBC-Bielefeld, preliminary

- Taylor expansion of bulk thermodynamics in terms of $\mu_{u,d,s}$

\[
\frac{p}{T^4} \equiv \frac{1}{VT^3} \ln Z(V, T, \mu_u, \mu_d, \mu_s) \\
= \sum_{i,j,k} c_{i,j,k} \left( \frac{\mu_u}{T} \right)^i \left( \frac{\mu_u}{T} \right)^j \left( \frac{\mu_s}{T} \right)^k
\]

- Expansion coefficients evaluated at $\mu_{u,d,s} = 0$ are related to fluctuations of $B$, $S$, $Q$ at $\mu_{B,S,Q} = 0$:

$\uparrow$ baryon number, strangeness, charge fluctuations

event-by-event fluctuations at RHIC and LHC
Hadronic fluctuations at \( \mu > 0 \) from
Taylor expansion coefficients at \( \mu = 0 \)

\[ n_f = 2, \ m_\pi \simeq 770 \text{ MeV}: \text{S. Ejiri, FK, K.Redlich, PLB633 (2006) 275} \]
\[ n_f = 2 + 1, \ m_\pi \simeq 220 \text{ MeV}: \text{RBC-Bielefeld, preliminary} \]

- higher derivatives \( \Rightarrow \) higher moments
- mixed derivatives \( \Rightarrow \) correlations

\[
2c_2^x = \frac{\partial^2 p/T^4}{\partial (\mu_x/T)^2} = \frac{1}{VT^3} \langle (\delta N_x)^2 \rangle_{\mu=0} = \frac{1}{VT^3} \langle N_x^2 \rangle_{\mu=0}
\]

\[
24c_4^x = \frac{\partial^4 p/T^4}{\partial (\mu_x/T)^4} = \frac{1}{VT^3} \langle (\delta N_x)^4 \rangle - 3 \langle (\delta N_x)^2 \rangle^2 \rangle_{\mu=0} = \frac{1}{VT^3} \langle N_x^4 \rangle - 3 \langle N_x^2 \rangle^2 \rangle_{\mu=0}
\]

\[
4c_{22}^{xy} = \frac{\partial^4 p/T^4}{\partial (\mu_x/T)^2 \partial (\mu_y/T)^2} = \frac{1}{VT^3} \left[ \langle N_x^2 N_y^2 \rangle - 2 \langle N_x N_y \rangle^2 - \langle N_x^2 \rangle \langle N_y^2 \rangle \right]_{\mu=0}
\]

with \( x = q, s \)
• Results for expansion coefficients $c_{i,j,k}^{u,d,s}$

Cut-off dependance:

- Small cut-off effects in the transition region (similar to p, e-3p, ...)

Mass dependance:

- $T_c$ decreases with decreasing mass
- Fluctuations increase with decreasing mass

red: RBC-Bielefeld, preliminary
**Baryon number fluctuations ($\mu_B = 0$)**

\[ 2c_2^B = \langle B^2 \rangle \]

- $n_f=2+1$, $m_{\pi}=220$ MeV
- $n_f=2$, $m_{\pi}=770$ MeV

\[ 24c_4^B = \langle B^4 \rangle - 3 \langle B^2 \rangle^2 \]

- $n_f=2+1$, $m_{\pi}=220$ MeV
- $n_f=2$, $m_{\pi}=770$ MeV

- filled: $nt=4$
- open: $nt=6$

- red: RBC-Bielefeld, preliminary

- fluctuations increase with decreasing mass
- fluctuations increase over the resonance gas value
Quark number in Boltzmann approximation

baryonic sector of pressure in a hadron resonance gas;

\[ m_B \gg T \Rightarrow \text{Boltzmann approximation: } p_B/T^4 = \sum_{m \leq m_{\text{max}}} p_m/T^4 \]

with \( p_m/T^4 = F(T, m, V) \cosh(B\mu_B/T) \)

\[ \chi^B_2 \equiv \frac{\partial^2 p_m/T^4}{\partial(\mu_B/T)^2} = B^2 F(T, m, V) \cosh(B\mu_B/T) \]

\[ \chi^B_4 \equiv \frac{\partial^4 p_m/T^4}{\partial(\mu_B/T)^4} = B^4 F(T, m, V) \cosh(B\mu_B/T) \]

ratio of fourth (\( \chi^B_4 \)) and second (\( \chi^B_2 \)) cumulant of quark number fluctuation gives "unit of charge" carried by the particle with mass "m":

\[ m \gg T \Rightarrow R^B_{4,2} \equiv \frac{\chi^B_4}{\chi^B_2} = B^2 \]
Charge fluctuations in Boltzmann approximation

**hadronic resonance gas:** contributions from isosinglet \( (G^{(1)} : \eta, \ldots) \) and isotriplet \( (G^{(3)} : \pi, \ldots) \) mesons as well as isodoublet \( (F^{(2)} : p, n, \ldots) \) and isoquartet \( (F^{(4)} : \Delta, \ldots) \) baryons

\[
\frac{p(T, \mu_q, \mu_I)}{T^4} \simeq G^{(1)}(T) + G^{(3)}(T) \frac{1}{3} \left( 2 \cosh \left( \frac{2\mu_I}{T} \right) + 1 \right) + F^{(2)}(T) \cosh \left( \frac{3\mu_q}{T} \right) \cosh \left( \frac{\mu_I}{T} \right) + F^{(4)}(T) \frac{1}{2} \cosh \left( \frac{3\mu_q}{T} \right) \left[ \cosh \left( \frac{\mu_I}{T} \right) + \cosh \left( \frac{3\mu_I}{T} \right) \right]
\]

**charge fluctuations** at \( \mu_q = \mu_I = 0 \);

isospin quartet \( F^{(4)} \) contains baryons carrying charge 2

\[
R_{4,2}^Q \equiv \frac{\chi_4^Q}{\chi_2^Q} = \frac{4G^{(3)} + 3F^{(2)} + 27F^{(4)}}{4G^{(3)} + 3F^{(2)} + 9F^{(4)}} \rightarrow 1 \text{ for } T \rightarrow 0
\]

contribution of doubly charged baryons increases quartic relative to quadratic fluctuations
Ratios of quartic and quadratic fluctuations of charges in (2+1)-flavor QCD

RBC-Bielefeld, preliminary

baryon number fluctuation

charge fluctuation

chiral limit: ratios $\sim |T - T_c|^{-\alpha} + \text{regular}$

\[ \Rightarrow \text{enhancement over resonance gas values} \]

\[ \Rightarrow \text{may be observable in event-by-event fluctuations} \]

(valence) quark sector quickly ($T \gtrsim 1.5T_c$) behaves perturbative
Hadronic fluctuations and chiral symmetry restoration

- expect 2\textsuperscript{nd} order transition in 3-d, O(4) symmetry class;

scaling field: \[ t = \left| \frac{T - T_c}{T_c} \right| + A \left( \frac{\mu_q}{T_c} \right)^2, \quad \mu_{crit} = 0 \]

singular part: \[ f_s(T, \mu_u, \mu_d) = b^{-1} f_s(t b^{1/(2 - \alpha)}) \sim t^{2 - \alpha} \]

\[ \frac{\partial^2 \ln Z}{\partial \mu_q^2} \sim t^{1 - \alpha}, \quad \frac{\partial^4 \ln Z}{\partial \mu_q^4} \sim t^{-\alpha} \quad (\mu = 0) \]

- O(4)/O(2): \( \alpha < 0 \), small \( \Rightarrow \)

\[ \langle (\delta N_q)^2 \rangle \text{ dominated by T-dependence of regular part} \]

\[ \langle (\delta N_q)^4 \rangle \text{ develops a cusp} \]
Quadratic fluctuations of baryon number charge & strangeness in (2+1)-flavor QCD

vanishing chemical potentials:

\[ \chi_{Q}^{2} = \frac{1}{VT^3} \langle Q^2 \rangle \]

\[ \chi_{B}^{2} = \frac{1}{VT^3} \langle N_{B}^2 \rangle \]

\[ \chi_{S}^{2} = \frac{1}{VT^3} \langle N_{S}^2 \rangle \]

rapid approach to SB limit

⇒ smooth change of quadratic fluctuations across transition region

chiral limit: \( \chi_{2}^{B}, \chi_{2}^{Q} \sim |T - T_c|^{1-\alpha} + \text{regular} \)
Quartic fluctuations of baryon number charge & strangeness in (2+1)-flavor QCD

vanishing chemical potentials:

\[ \chi_Q^4 = \frac{1}{V T^3} \left( \langle Q^4 \rangle - 3\langle Q^2 \rangle^2 \right) \]

\[ \chi_B^4 = \frac{1}{V T^3} \left( \langle N_B^4 \rangle - 3\langle N_B^2 \rangle^2 \right) \]

\[ \chi_S^4 = \frac{1}{V T^3} \left( \langle N_S^4 \rangle - 3\langle N_S^2 \rangle^2 \right) \]

rapid approach to SB limit

⇒ large light quark number & charge fluctuations across transition region

chiral limit: \( \chi_B^4, \chi_Q^4 \sim |T - T_c|^{-\alpha} + \text{regular} \)
**Deconfinement and χ-symmetry**

- The chiral phase transition (i.e. at $m_q = 0$) is deconfining
- True in QCD, i.e. SU(3) + fermions in the fundamental representation
- SU(3) + fermions in the adjoint representation: $T_{decon} < T_\chi$
- The transition in QCD with physical quark masses is a crossover

In which sense is the transition deconfining and chiral symmetry restoring?

- **deconfinement:** heavy hadrons $\Rightarrow$ light quarks and gluons; liberation of many new light degrees of freedom $\Rightarrow$ rapid change in $\epsilon/T^4$, $s/T^3$, ....

- **chiral symmetry restoration:** vanishing mass splittings, no new degrees of freedom $\Rightarrow$ minor effect on bulk thermodynamics, but rapid change of chiral condensate
Deconfinement and $\chi$-symmetry

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- chiral symmetry restoration: vanishing mass splittings,
  no new degrees of freedom
  $\Rightarrow$ minor effect on bulk thermodynamics, but
  rapid change of chiral condensate
$\chi$-symmetry restoration: drop in condensate; peak in susceptibilities

\[
\Delta_{l,s}(T) = \frac{\langle \bar{\psi}\psi \rangle_{l,T} - \frac{m_l}{m_s} \langle \bar{\psi}\psi \rangle_{s,T}}{\langle \bar{\psi}\psi \rangle_{l,0} - \frac{m_l}{m_s} \langle \bar{\psi}\psi \rangle_{s,0}}
\]

$\chi_{\text{singlet}}/T^2$

hotQCD preliminary

0.75*p4fat3

asqtad: $m_l/m_s=0.1$

p4: $m_l/m_s=0.1$

0.05

$\Delta_{l,s}$

$\text{Tr}_0$

$N_\tau=8$

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Deconfinement and $\chi$-symmetry restoration and bulk thermodynamics

$\chi$-symmetry restoration: drop in condensate; peak in susceptibilities

$\Delta_{l,s}(T) = \frac{\langle \bar{\psi}\psi \rangle_{l,T} - \frac{m_l}{m_s} \langle \bar{\psi}\psi \rangle_{s,T}}{\langle \psi\psi \rangle_{l,0} - \frac{m_l}{m_s} \langle \psi\psi \rangle_{s,0}}$

Illustrative fit:
$A(T-T_c)^{-1.32}$
Deconfinement and $\chi$-symmetry and bulk thermodynamics

- Most prominent features of bulk thermodynamics are related to deconfinement.
- $\chi$-symmetry restoration: drop in condensate; peak in susceptibilities.

Do they stay closely related in the continuum limit?
Conclusions

- **glue sticks**

  the interesting non-perturbative physics in QCD happens in the gluon sector

- **quarks add flavor**

  quarks add to the picture by ’modifying prefactors’ (in accord with dimensional reduction approach)

- **no glue ⇒ no binding**

  ’glue-free’ observables show early onset of perturbative behaviour
Conclusions

- non-perturbative QCD-EoS $\sim$ pure gauge theory EoS
  
  the interesting non-perturbative physics in QCD happens in the gluon sector

- nothing qualitatively new in QCD with light quarks
  
  quarks add to the picture by 'modifying prefactors' (in accord with dimensional reduction approach) except close to $T_c$!!

- quantum numbers are carried by ”quarks” already close to $T_c$
  
  ’glue-free’ observables show early onset of perturbative behaviour
Finally...

the regime $T_c \leq T \lesssim (1.5 - 2.0)T_c$ differs from
the regime $T \gtrsim (1.5 - 2.0)T_c$

It is more difficult (impossible?) to describe it quantitatively
in terms of conventional theoretical high-T concepts:
perturbation theory, resummation, dimensional reduction
Finally...

- the regime \( T_c \leq T \lesssim (1.5 - 2.0) T_c \) differs from the regime \( T \gtrsim (1.5 - 2.0) T_c \)

  It is more difficult (impossible?) to describe it quantitatively in terms of conventional theoretical high-T concepts: perturbation theory, resummation, dimensional reduction

- Do we see new physics? \( \Rightarrow \) Quark Gluon Liquid

- or, remnants of old physics? \( \Rightarrow \) confinement