

Gluons at Finite Temperature

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Universidade de São Paulo**

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São Carlos**

Overview

- Of QCD and Yang-Mills Theory

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- Aspects of the Method

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- The Vacuum

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- Of QCD and Yang-Mills Theory
- Aspects of the Method
- The Vacuum
- Finite Temperature
- Summary: The Early Universe

[For an introduction: See R. Alkofer & L. von Smekal, Phys. Rept. 353:281, 2001
A. Maas, MPLA A20, p1797, 2005]

Part I: QCD in the Vacuum

Quantumchromodynamics (QCD)

- (Quantized) Theory of strong interactions

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- (Quantized) **Theory of strong interactions**
- Describes the structure of hadrons and (ultimately) nuclei

Quantumchromodynamics (QCD)

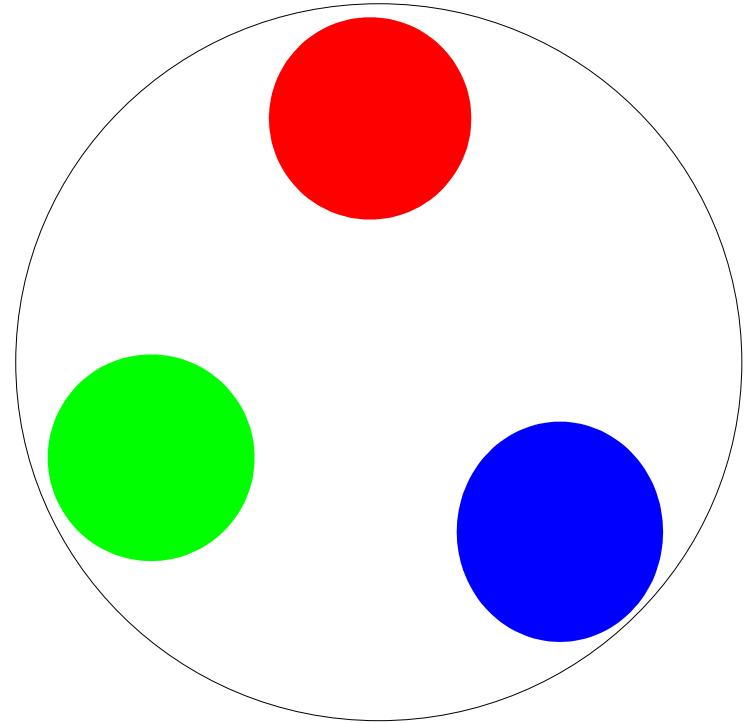
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- Elementary degrees of freedom are **quarks and gluons**
 - Carry new charge: Color charge

Quantumchromodynamics (QCD)

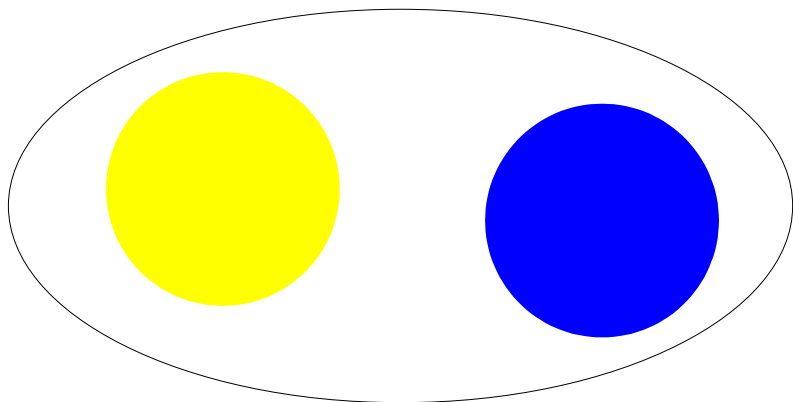
- (Quantized) **Theory of strong interactions**
- Describes the structure of hadrons and (ultimately) nuclei
- Elementary degrees of freedom are **quarks and gluons**
 - Carry new charge: Color charge
 - Quarks come in **red**, **green**, **blue**, and anti-colors

QCD degrees of freedom

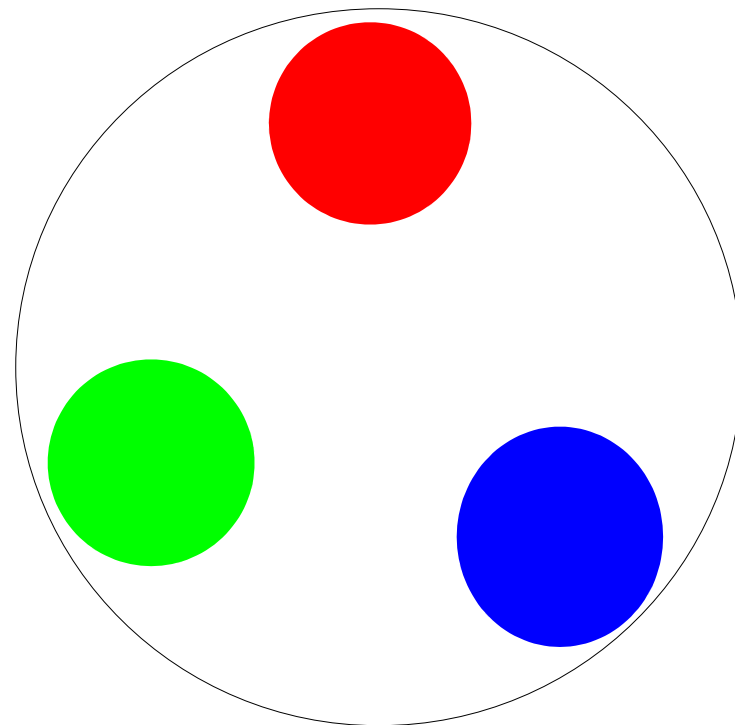
- Baryon: 3 (valence-)quarks



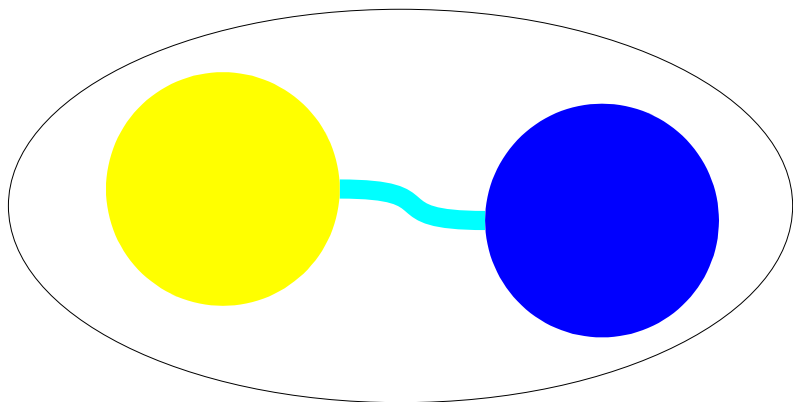
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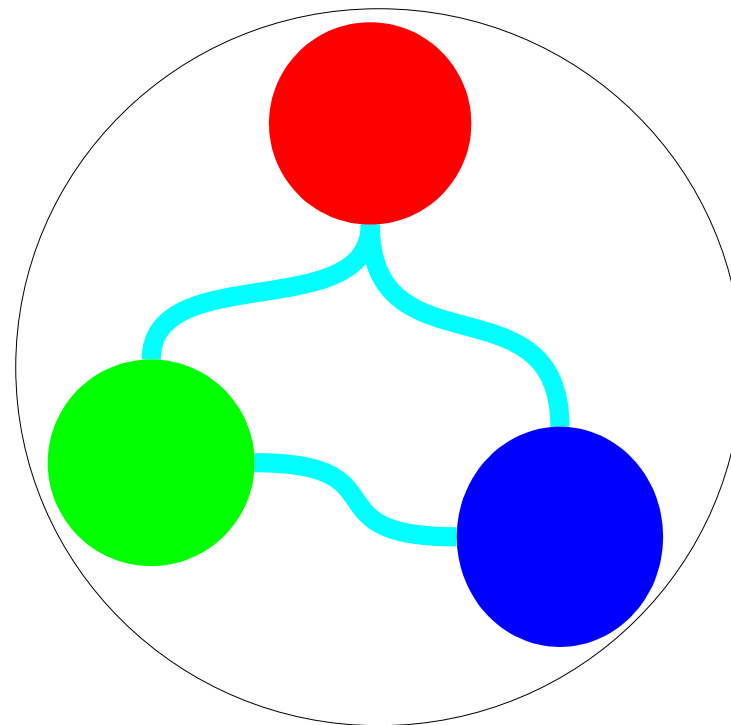
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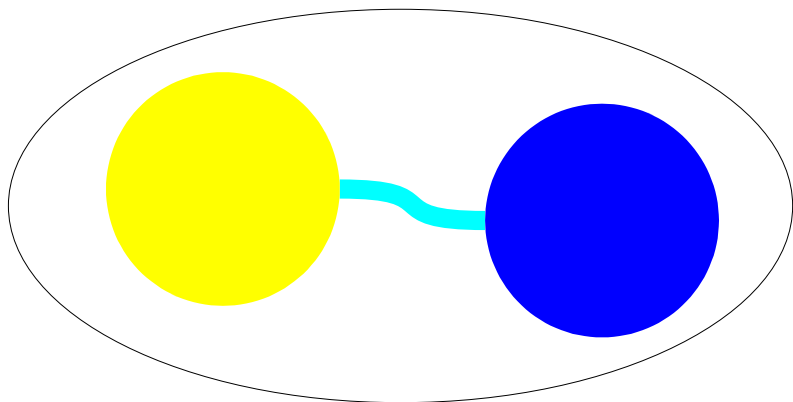
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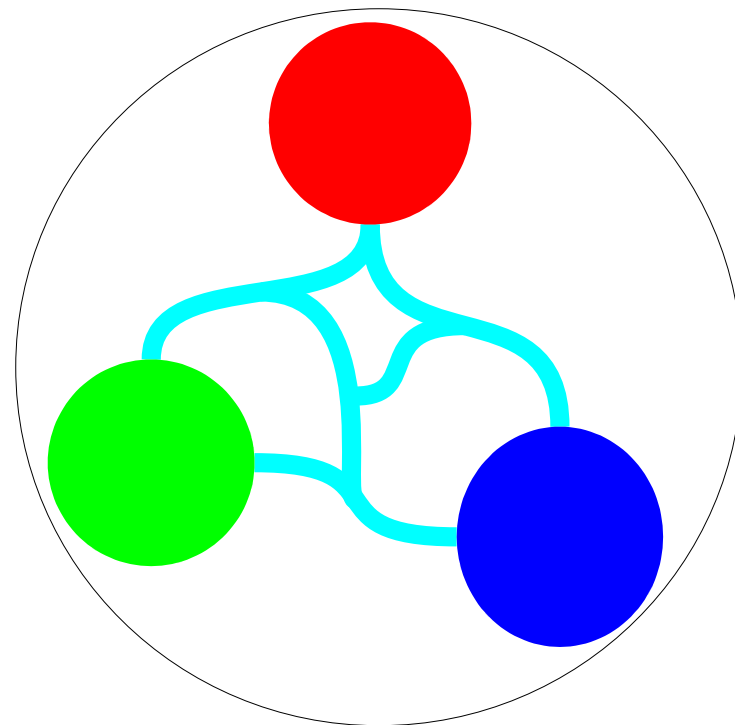
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QCD degrees of freedom



- Baryon: 3 (valence-)quarks
- Meson: 1 quark and 1 antiquark
- Interactions mediated by gluons
- Gluons are also charged
 - Pure glue theory: Yang-Mills theory



Properties of QCD I

- **Weakly interacting** at high energies
($>$ a few GeV)
 - Asymptotic freedom
 - Accessible by perturbation theory

Properties of QCD I

- **Weakly interacting** at high energies (> a few GeV)
 - Asymptotic freedom
 - Accessible by perturbation theory
- **Strongly interacting** at low energies
 - Perturbation theory fails
 - Genuine non-perturbative effects

Properties of QCD II

- **Chiral symmetry**
 - Connects left- and right-handed quarks
 - Exact symmetry if quarks are massless
 - (Weak) explicit breaking by quark masses

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- **Chiral symmetry**
 - Connects left- and right-handed quarks
 - Exact symmetry if quarks are massless
 - (Weak) explicit breaking by quark masses
- **Chiral symmetry spontaneously broken**
 - Nucleon mass of ~ 1 GeV although bare quark masses ~ 5 - 10 MeV
 - “Constituent” quark mass of ~ 330 MeV

Properties of QCD III

- **Confinement**

- Free quarks and gluons not observed
- In general: No colored objects observed

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 - Unique signature due to fractal electric charge

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- **Connected to topological excitations?**

Properties of QCD III

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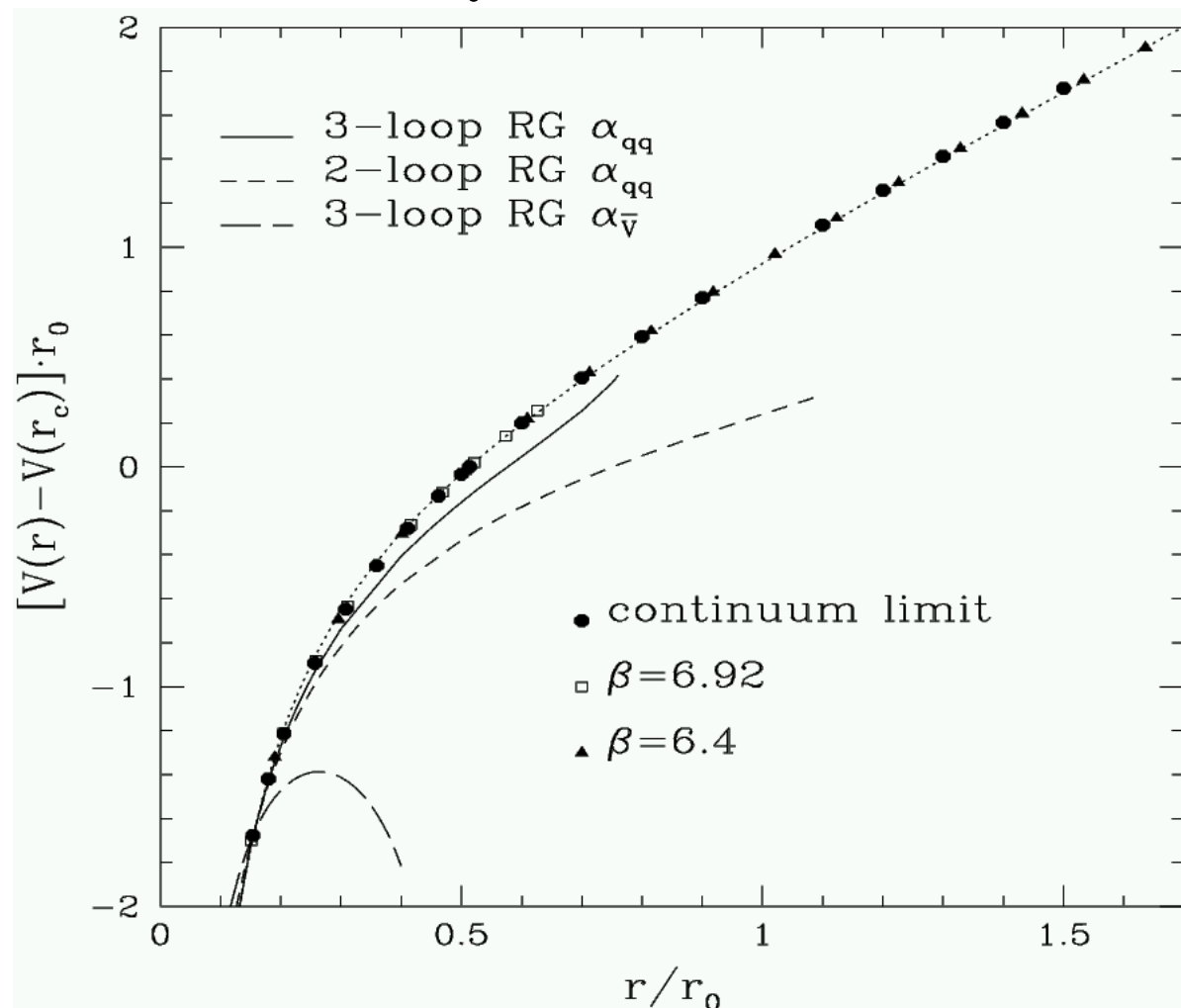
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- **Effect of main interest here**

Properties of QCD IV

- **Inter-quark potential** confining (“Cornell potential”): $V = a/r + \sigma r$ (σ string tension)

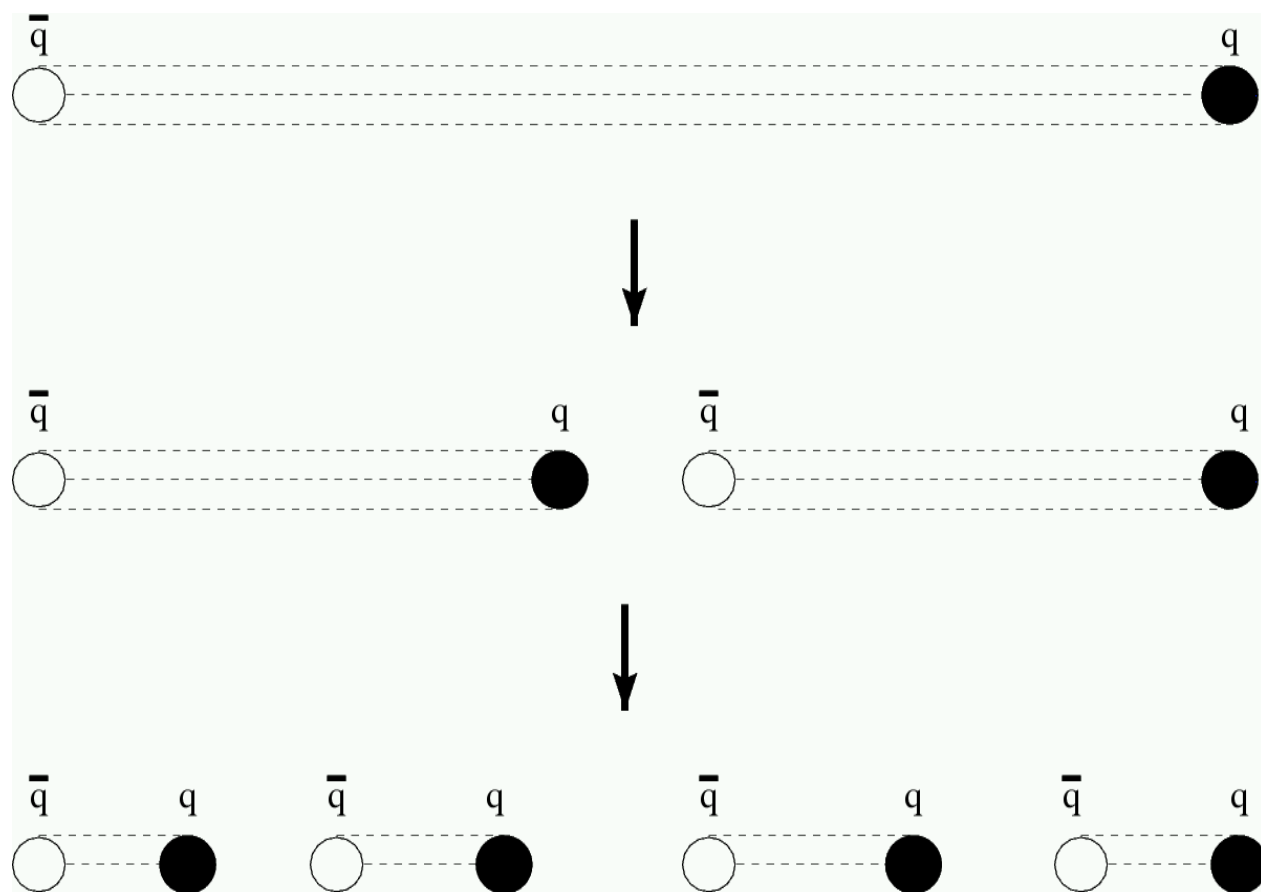


[Figure from Sommer et al., 2001]

Properties of QCD IV

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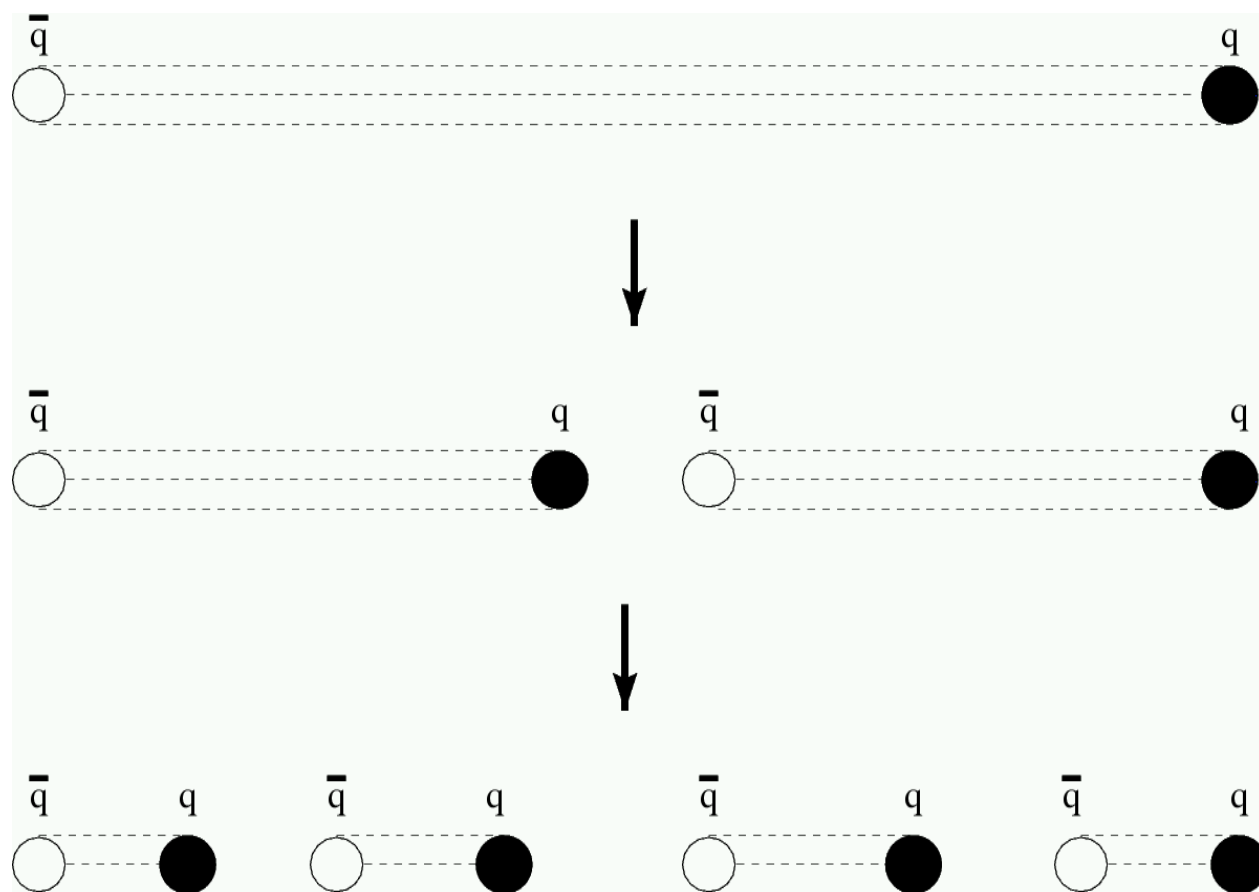


[Figures from Greensite, 2003]

Properties of QCD IV

- **Inter-quark potential** confining
 (“Cornell potential”): $V = a/r + \sigma r$ (σ string tension)

- Flattened by
string breaking
- Gluon string
always breaks



[Figures from Greensite, 2003]

QCD Theory

- Gauge theory: **Landau gauge**

$$L = -\frac{1}{4} F_{\mu\nu}^a F^{\mu\nu,a} + \bar{\psi} (iD_{\mu} \gamma^{\mu} - m) \psi - \bar{c}^a \partial^{\mu} D_{\mu}^{ab} c^b$$

$$F_{\mu\nu}^a = \partial_{\mu} A_{\nu}^a - \partial_{\nu} A_{\mu}^a + gf^{abc} A_{\mu}^b A_{\nu}^c$$

$$D_{\mu} = \partial_{\mu} - ieA_{\mu}^a \tau^a \quad D_{\mu}^{ab} = \delta^{ab} \partial_{\mu} - g f^{abc} A_{\mu}^c$$

- $\psi, \bar{\psi}$: **Quarks**
- A_{μ}^a : **Gluons**
- c^a, \bar{c}^a : **Ghosts** (Pure intermediate states)

Green's Functions

- Green's functions describe a theory completely
- **Propagators** are the (inverse) 2-point Green's functions
- Full **propagators** contain **non-perturbative information**
 - How can they be accessed?
- Restrict to Yang-Mills theory
 - Full QCD has also been treated in the vacuum

Propagators

- **Ghost propagator:**
 - G dressing function

$$D_G(q^2) = \frac{-G(q^2)}{q^2}$$

Propagators

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$$D_G(q^2) = \frac{-G(q^2)}{q^2}$$

- **Gluon propagator:**
 - Z dressing function

$$D_{\mu\nu}(q) = \left(\delta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2} \right) \frac{Z(q^2)}{q^2}$$

Confinement in propagators

- **Sufficient criterion:**

$$D(p^2=0)=0$$

- D is the propagator of a particle (gluon)
- Massless particle: No on-shell propagation

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- Massless particle: No on-shell propagation

- **Different scenarios:**

- Kugo-Ojima and Gribov-Zwanziger predict:

$$G(p^2=0)=\infty$$

- **Long-range correlations**
- **Ghost: Carrier of confining forces**

Methods

- **Lattice gauge theory**
 - Monte Carlo method
 - Finite volume: Hard to reach infrared

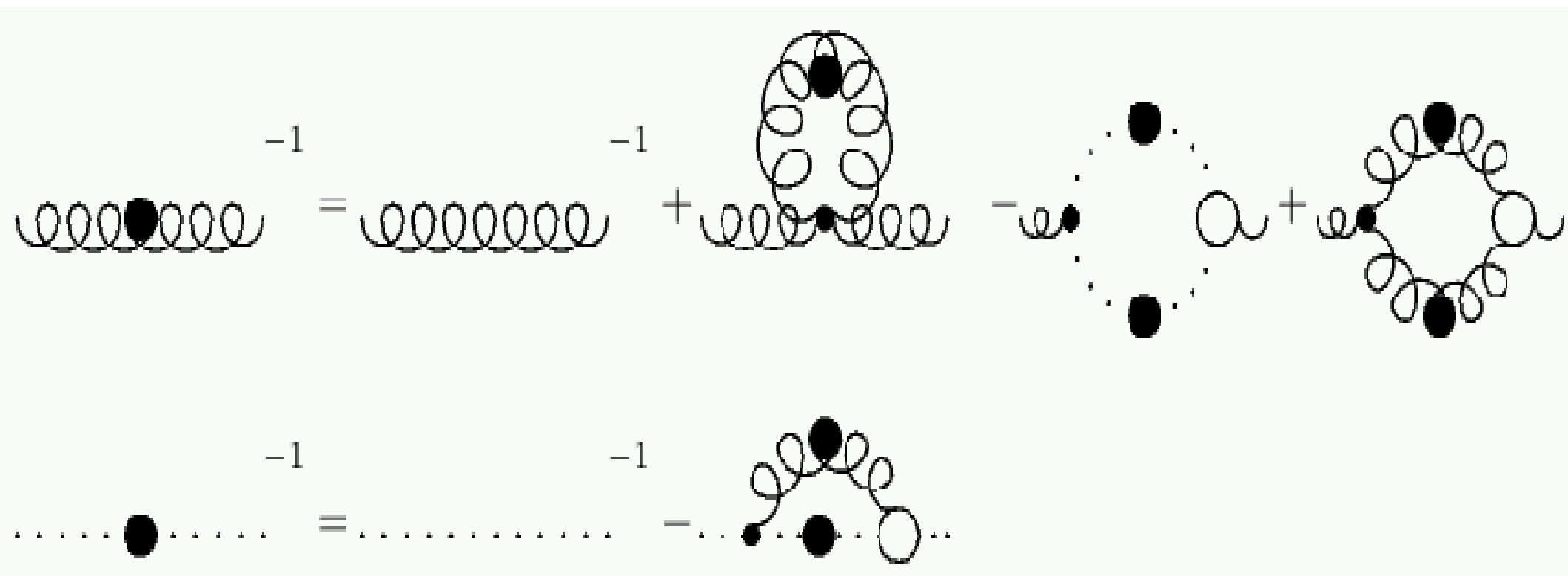
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- **Functional methods**
 - Renormalization group methods
 - (Quantum) Equations of motions:
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 - Need approximations

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- **Complementary**

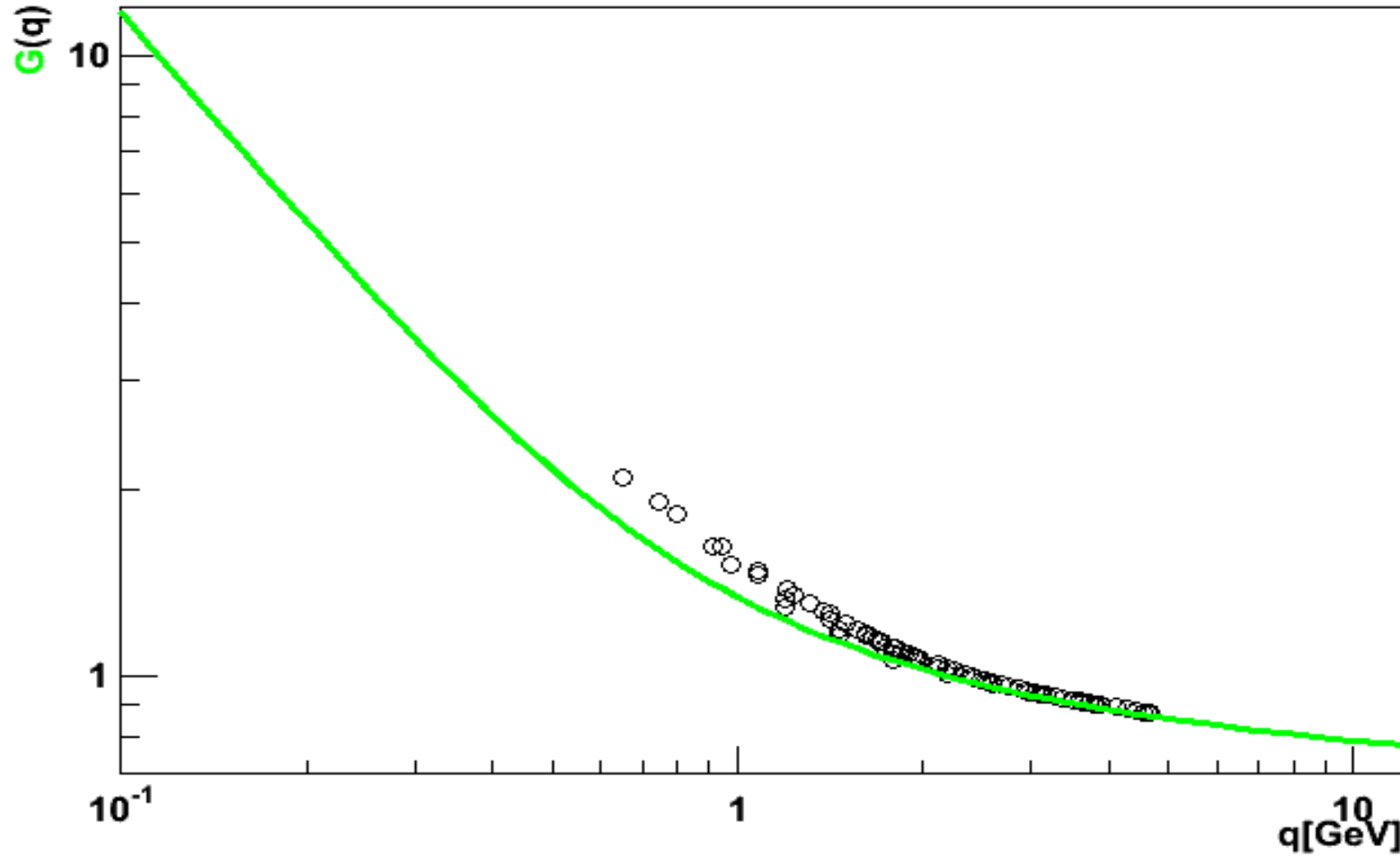
(Truncated) Dyson-Schwinger Equations



- Infinite set of coupled equations
- **Truncation necessary:** Ansätze for the vertices
- **Induces several problems:** Under control

Ghost

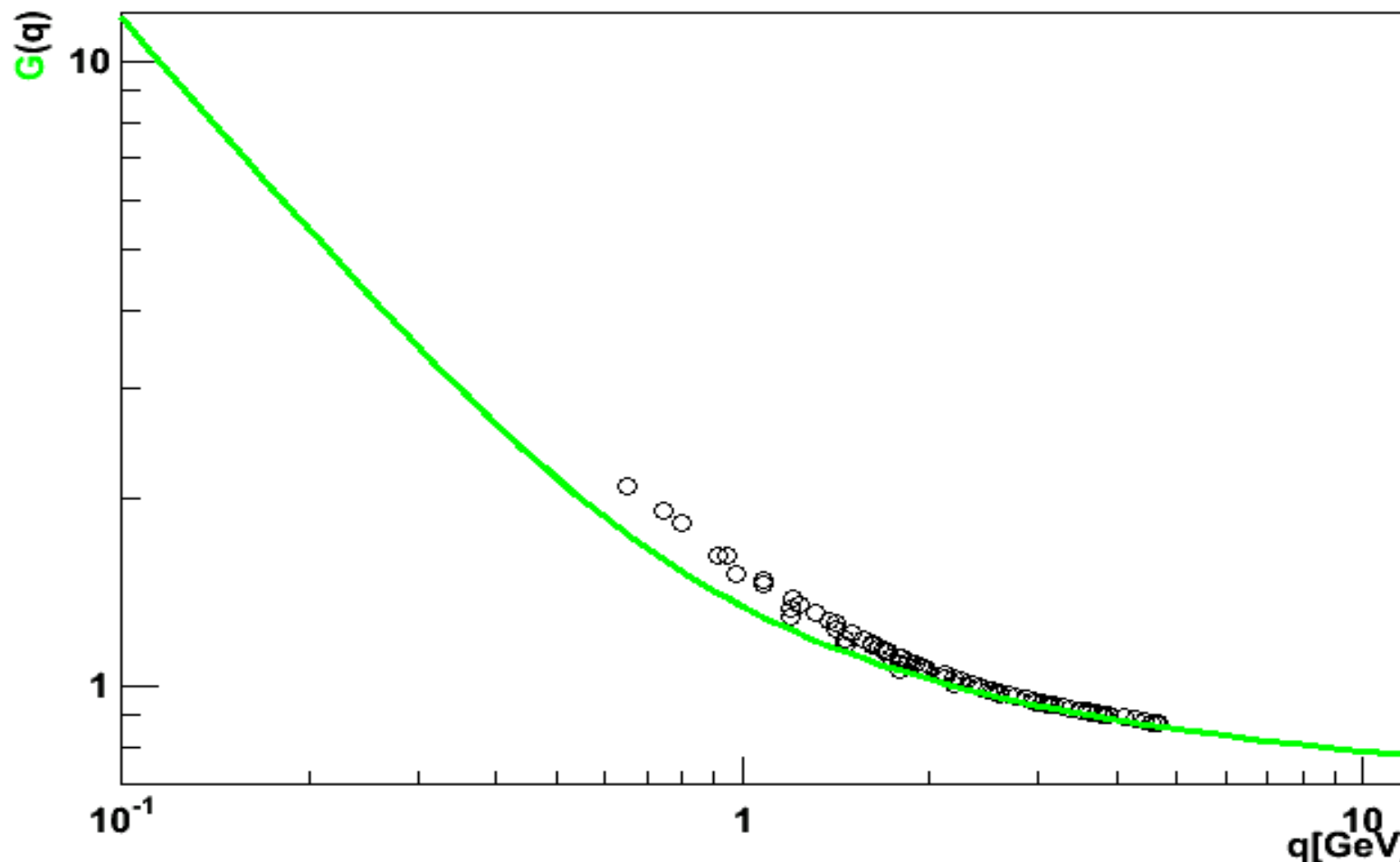
[DSE: Fischer et al., PLB 2002,
Lattice: Langfeld et al., 2002]



- IR strongly divergent: Mediates long-range forces

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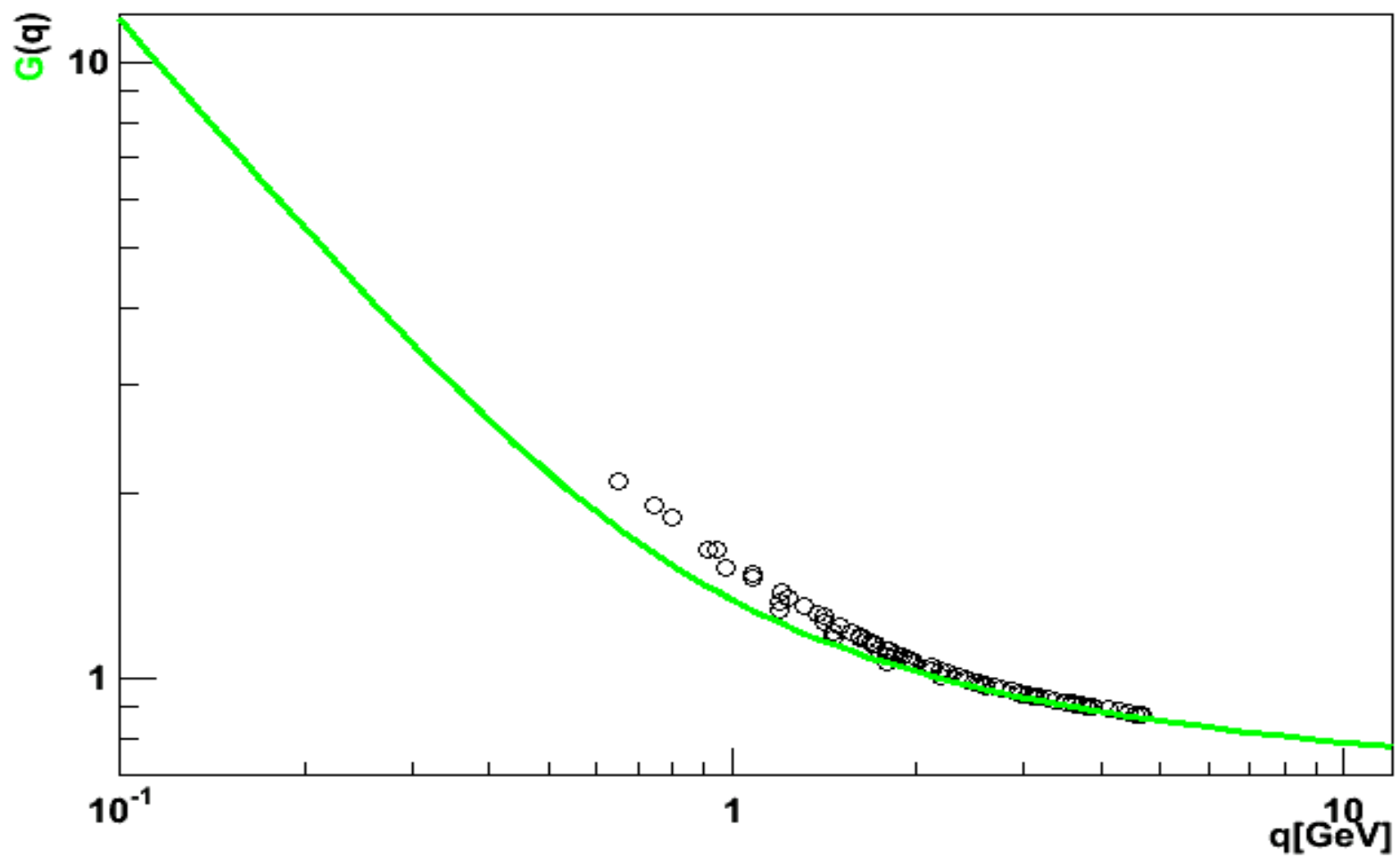


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- DSEs gives power-law: $G(p) \sim (p^2)^{-0.595}$ [von Smekal et al., PRL 1997; Zwanziger PRD 2002, Lerche PRD 2002]

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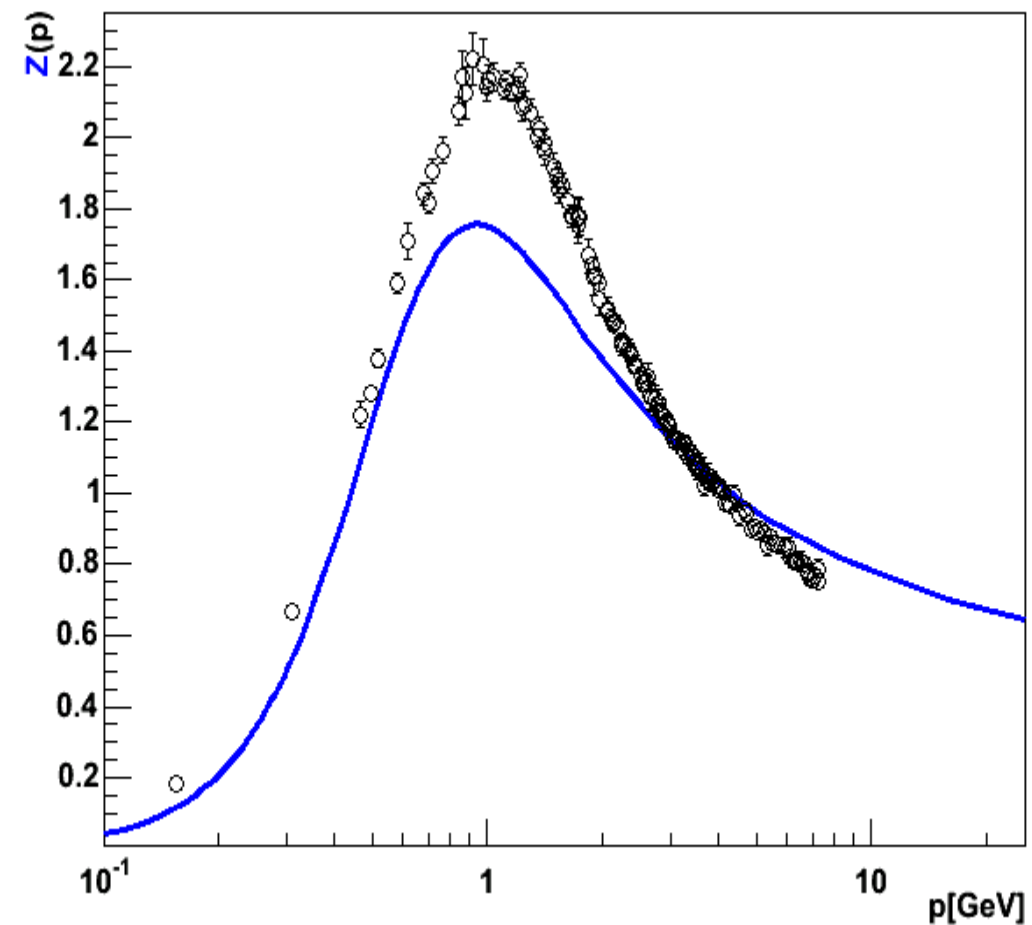
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- DSEs gives power-law: $G(p) \sim (p^2)^{-0.595}$ [von Smekal et al., PRL 1997; Zwanziger PRD 2002, Lerche PRD 2002]
- Confirmed by RG calculations [Gies, PRD 2002; Fischer et al. JHEP 2004; Pawłowski et al., PRL 2004]

Gluon on $20^3 \times 64$

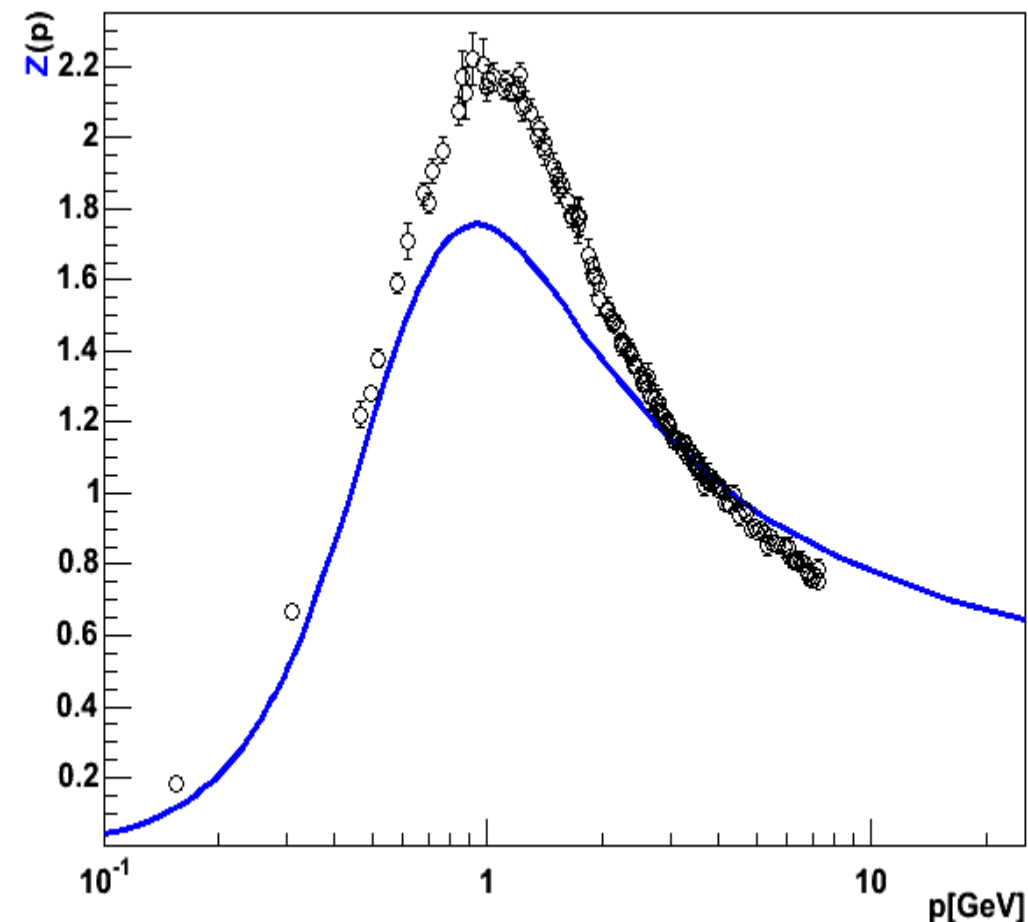
[DSE: Fischer et al., PLB 2002, Lattice: Bowman et al., PRD 2004]



• Infrared vanishing – confined

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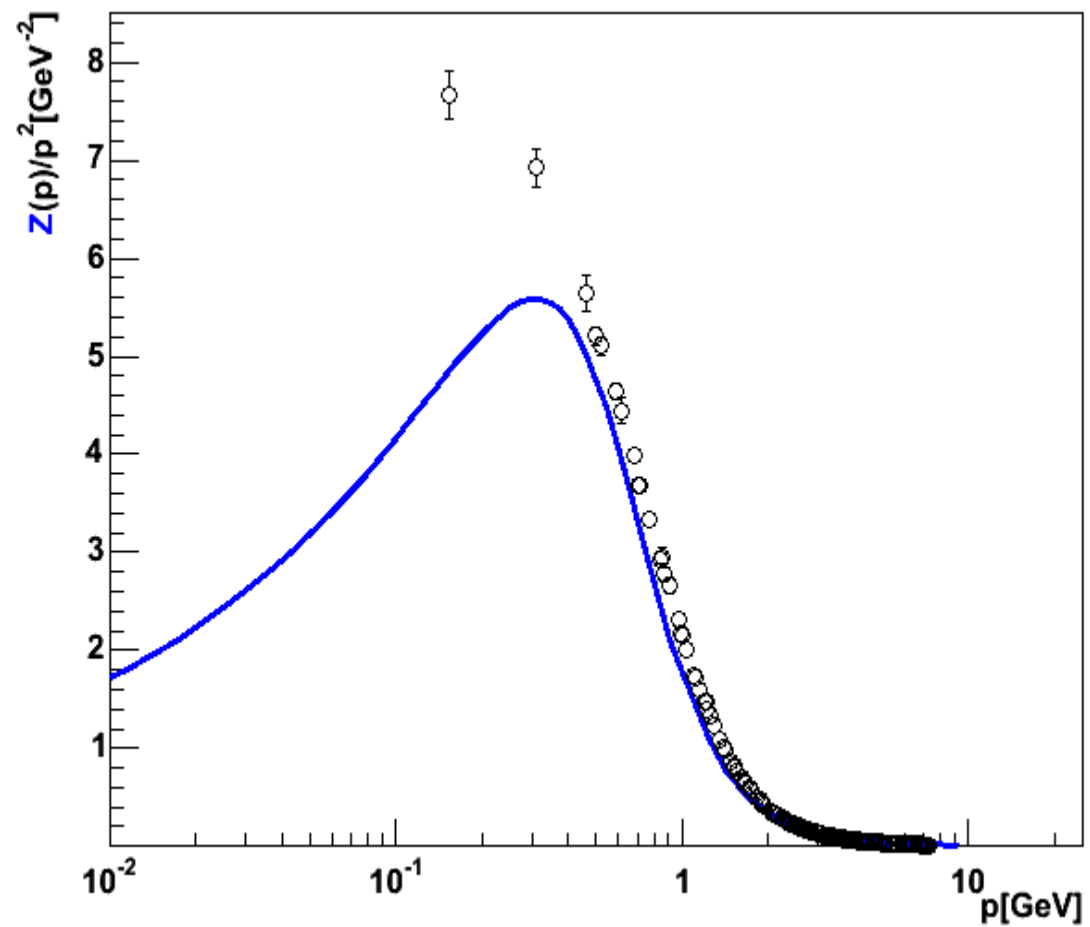
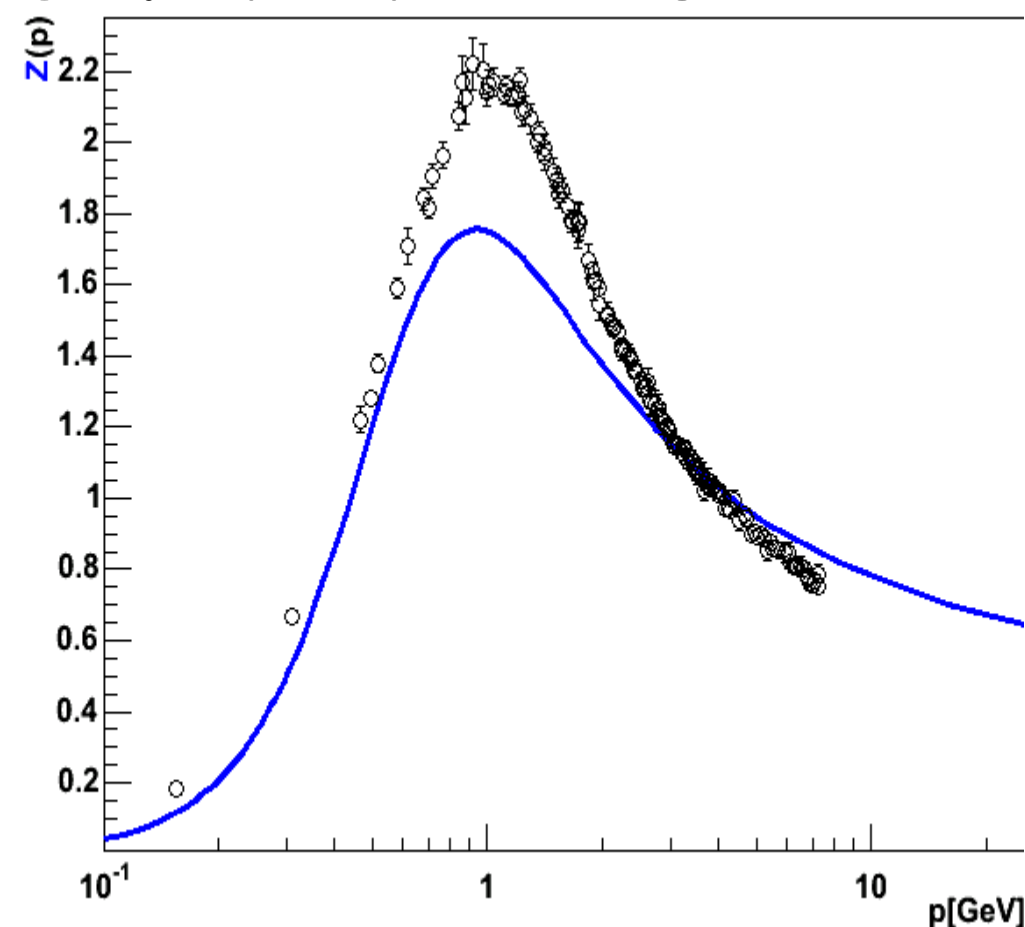


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- DSEs and RG gives $Z(p) \sim (p^2)^{1.19}$ [von Smekal et al., PRL 1997, Zwanziger PRD 2002, Lerche et al. PRD 2002; Gies, PRD 2002; Fischer et al., JHEP 2004; Pawłowski et al., PRL 2004]

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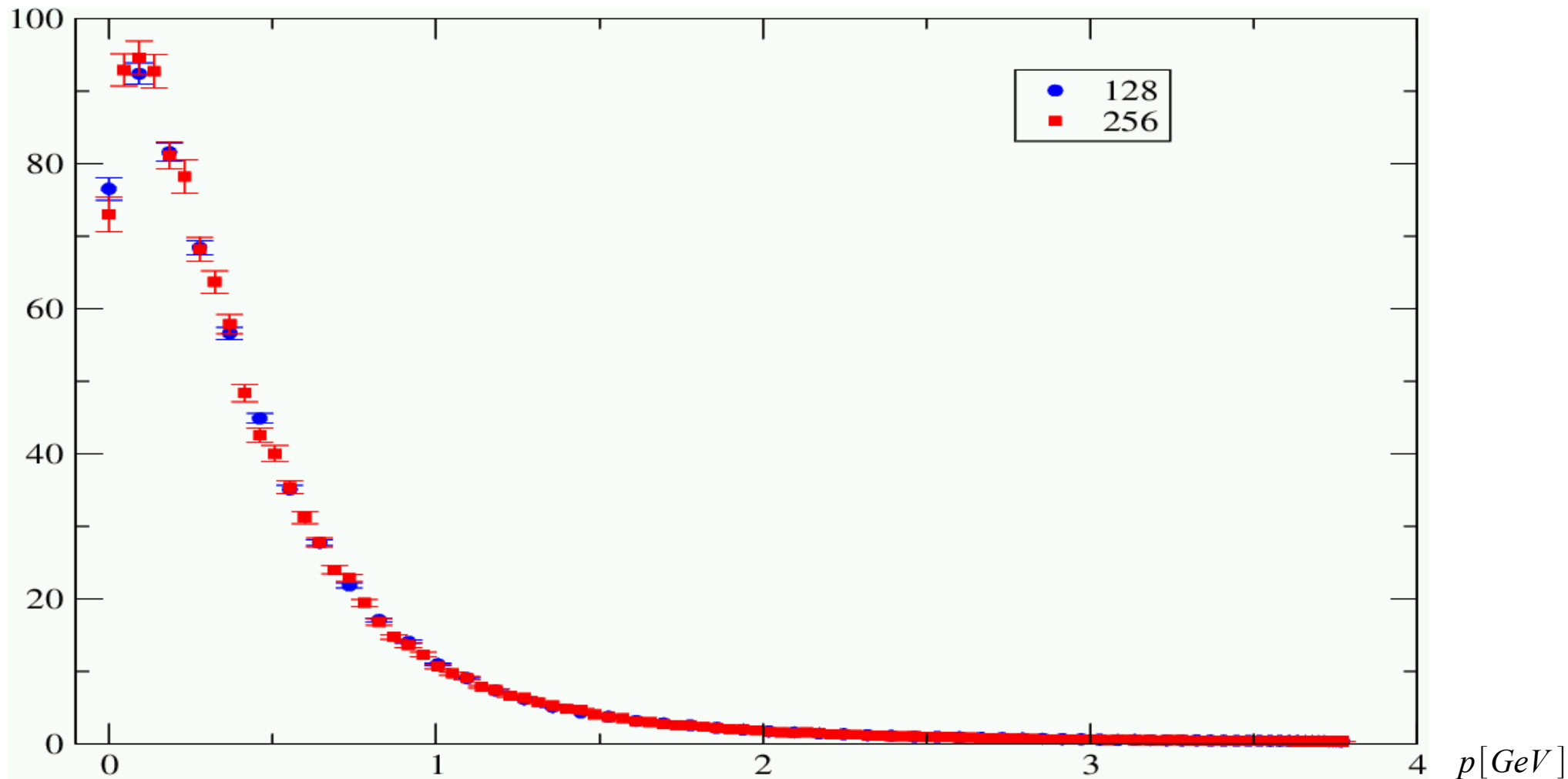
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- Lattice data strongly affected by finite volume

Gluon - large lattice volumes needed

$Z(p)/p^2 [a.u.]$

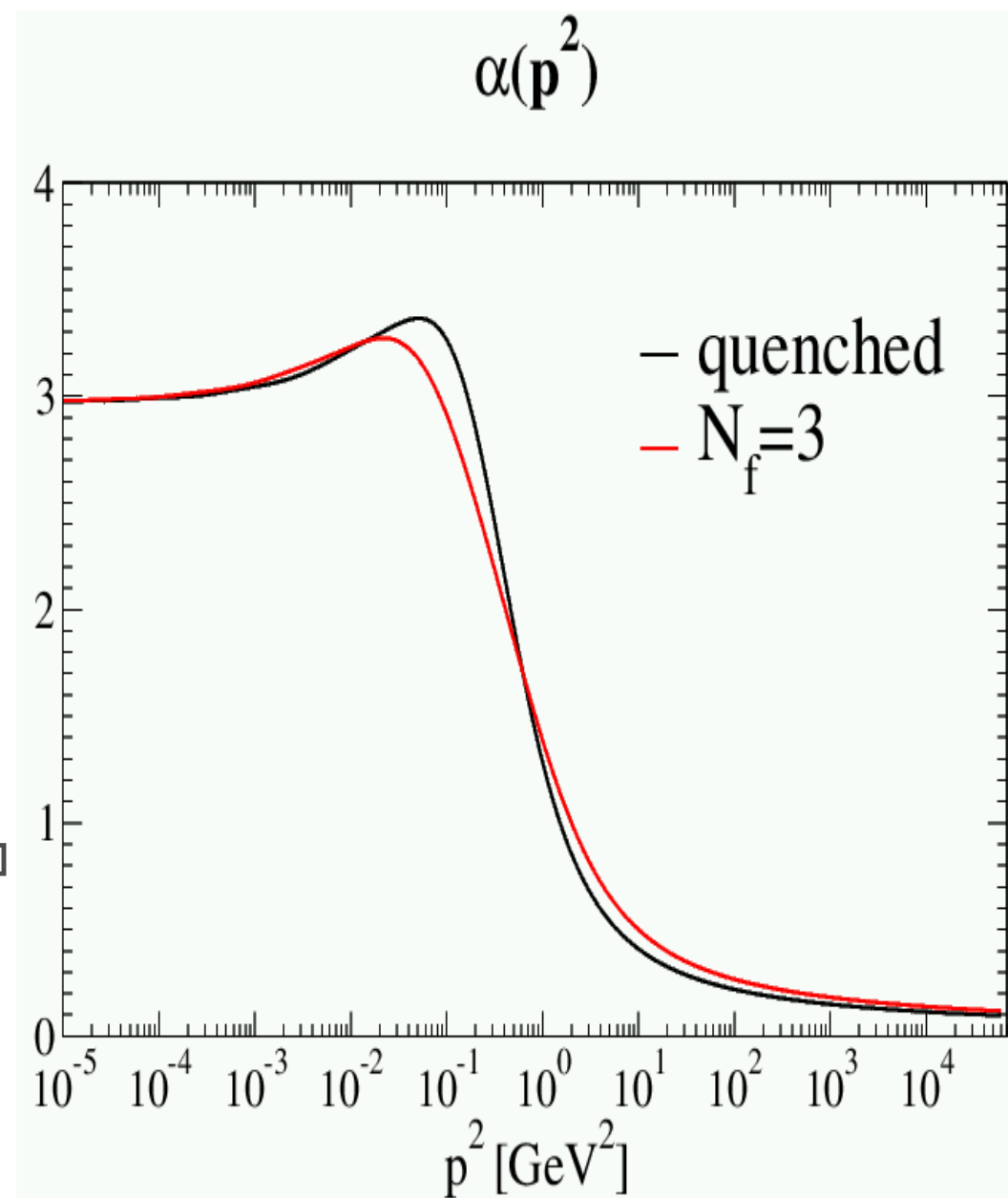


- 4d - Asymmetric lattice $16^3 \times 128$ and $16^3 \times 256$

[Oliveira et al., 2004]

Running coupling

- Fixed point in the infrared, agrees with perturbative strong coupling in the UV
- Agrees with recent calculations using exact renormalization group
[Gies, PRD 2002; Fischer et al., Pawłowski et al., 2003]
- Physical interpretation as a coupling constant?



[Fischer et al., PRD 2003]

Systematic dependences

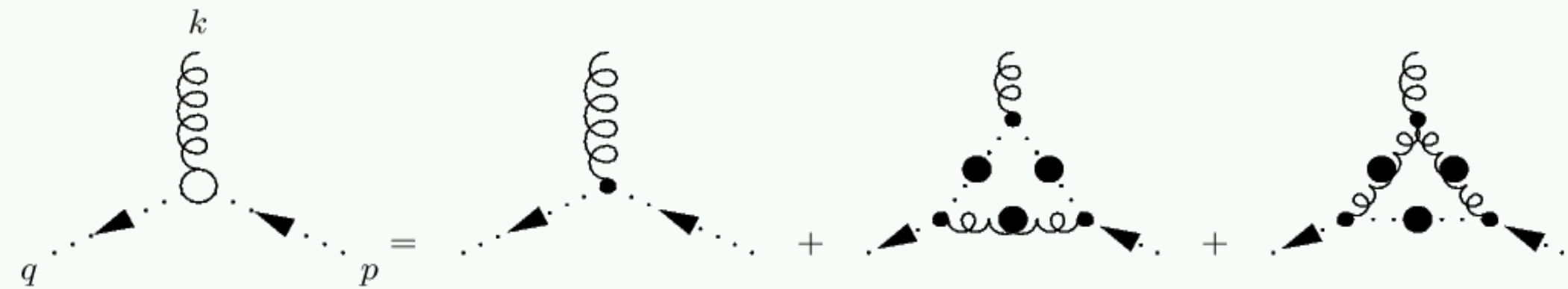
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 - **Explicitly verify ansatz** [Schleifenbaum et al., 2004]

Systematic dependences

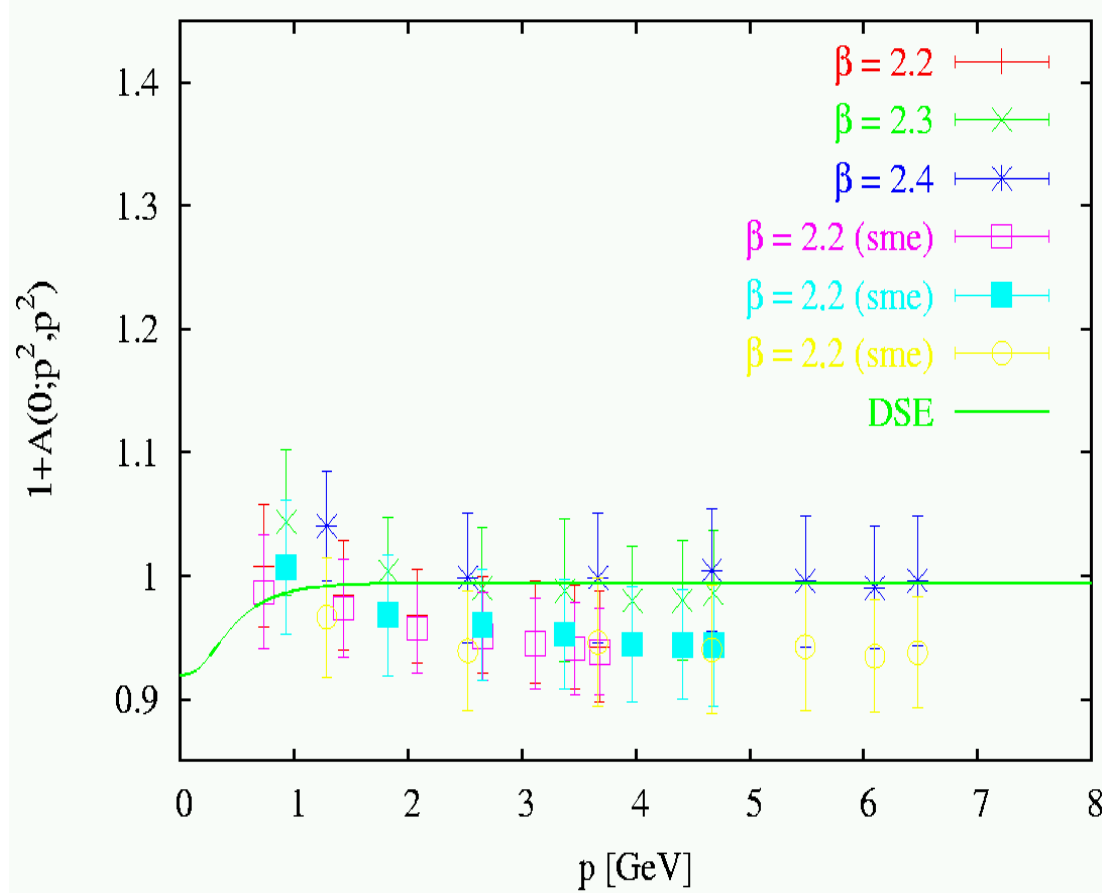
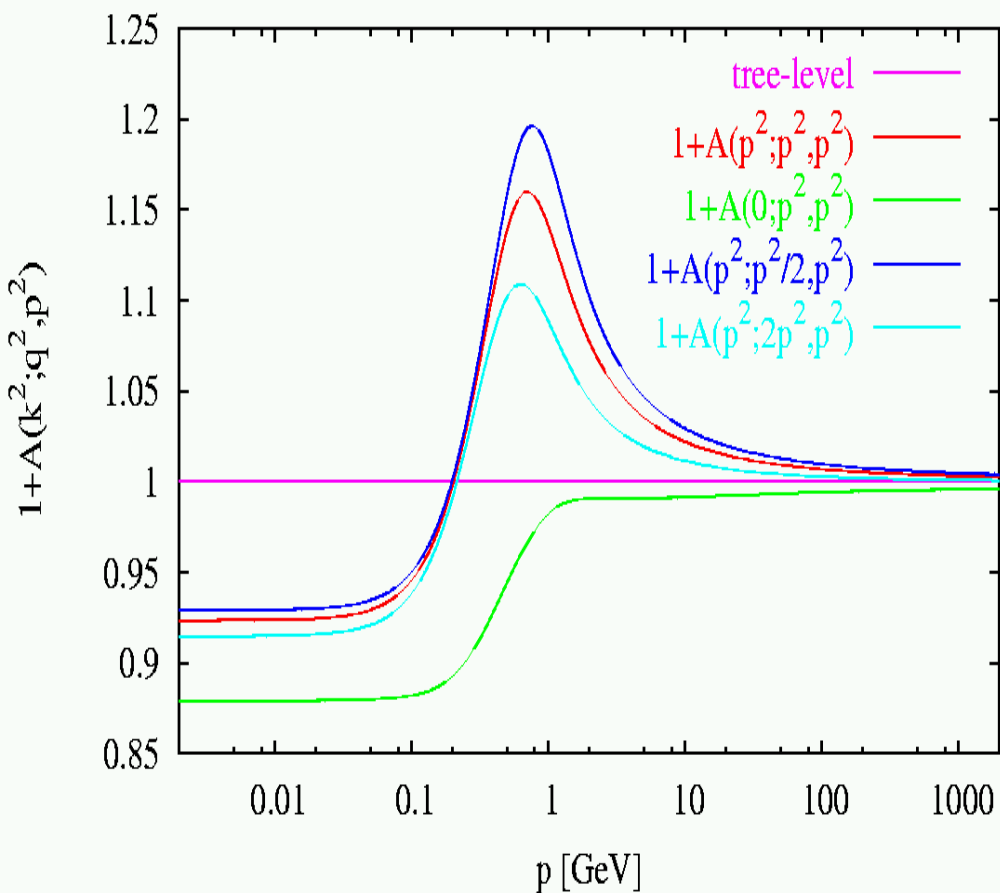
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Ghost-Gluon Vertex

[DSE: Schleifenbaum et al., 2004
Lattice: Cucchieri et al., 2004]

Transverse part of the 4d ghost-gluon vertex

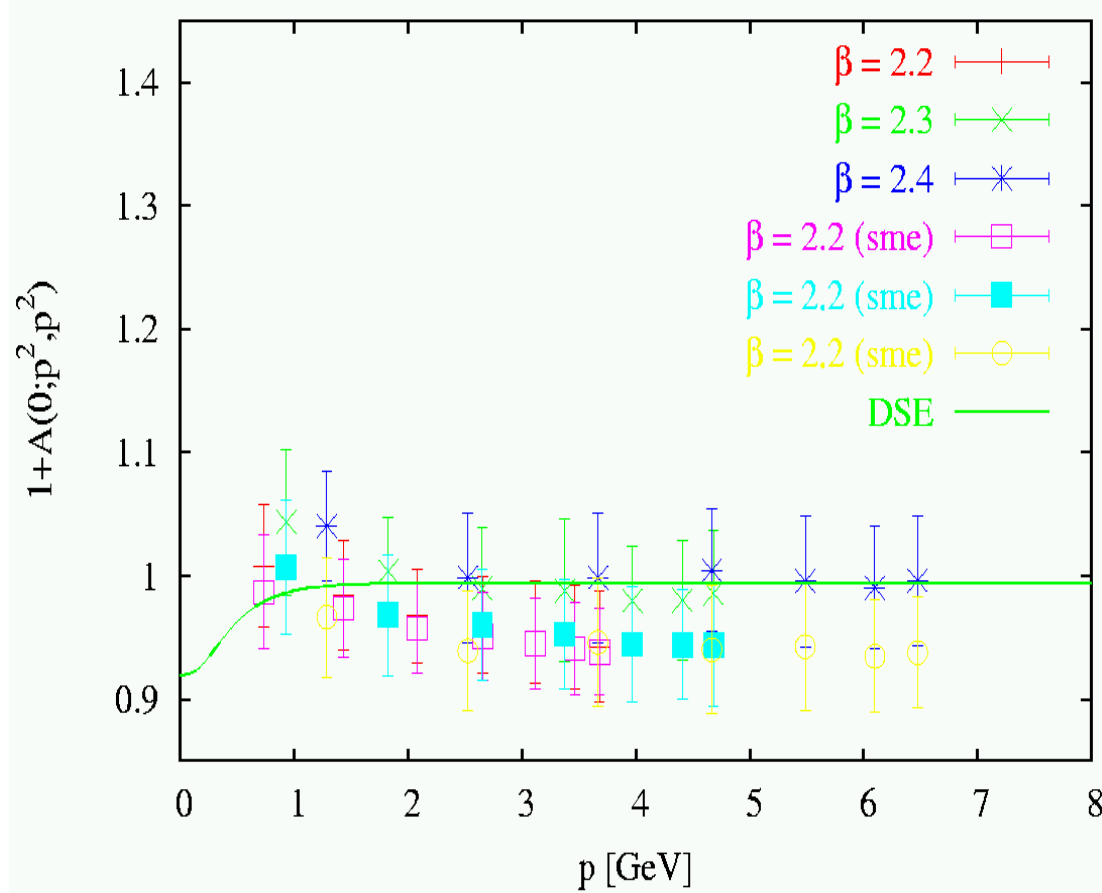
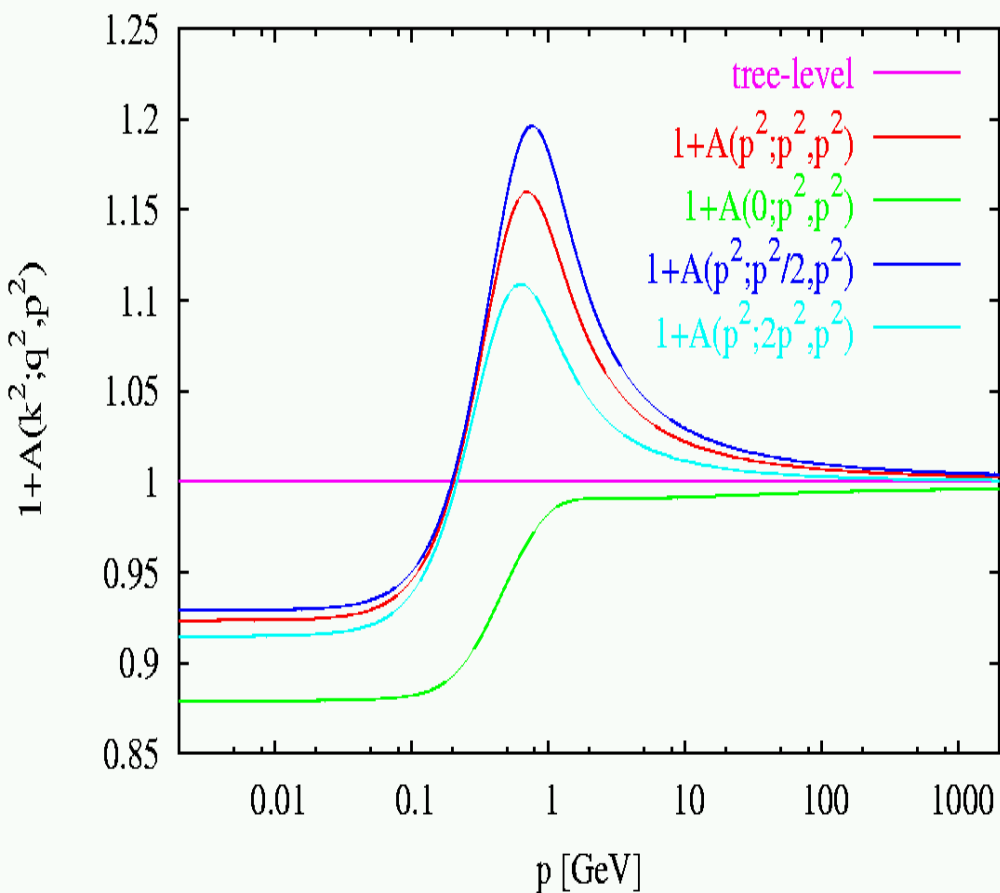


- Results compatible with a **bare ghost-gluon vertex**
- **Supports** bare ansatz in **DSE** calculations

Ghost-Gluon Vertex

[DSE: Schleifenbaum et al., 2004
Lattice: Cucchieri et al., 2004]

Transverse part of the 4d ghost-gluon vertex



- Results compatible with a **bare ghost-gluon vertex**
- **Supports** bare ansatz in **DSE calculations**
- Other vertices likely infrared subleading

[Alkofer et al., PLB 2004]

Part II: Finite Temperature

Finite Temperature QCD I

- Can the properties of QCD change?

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- Old idea: QCD weakly coupled at high temperature

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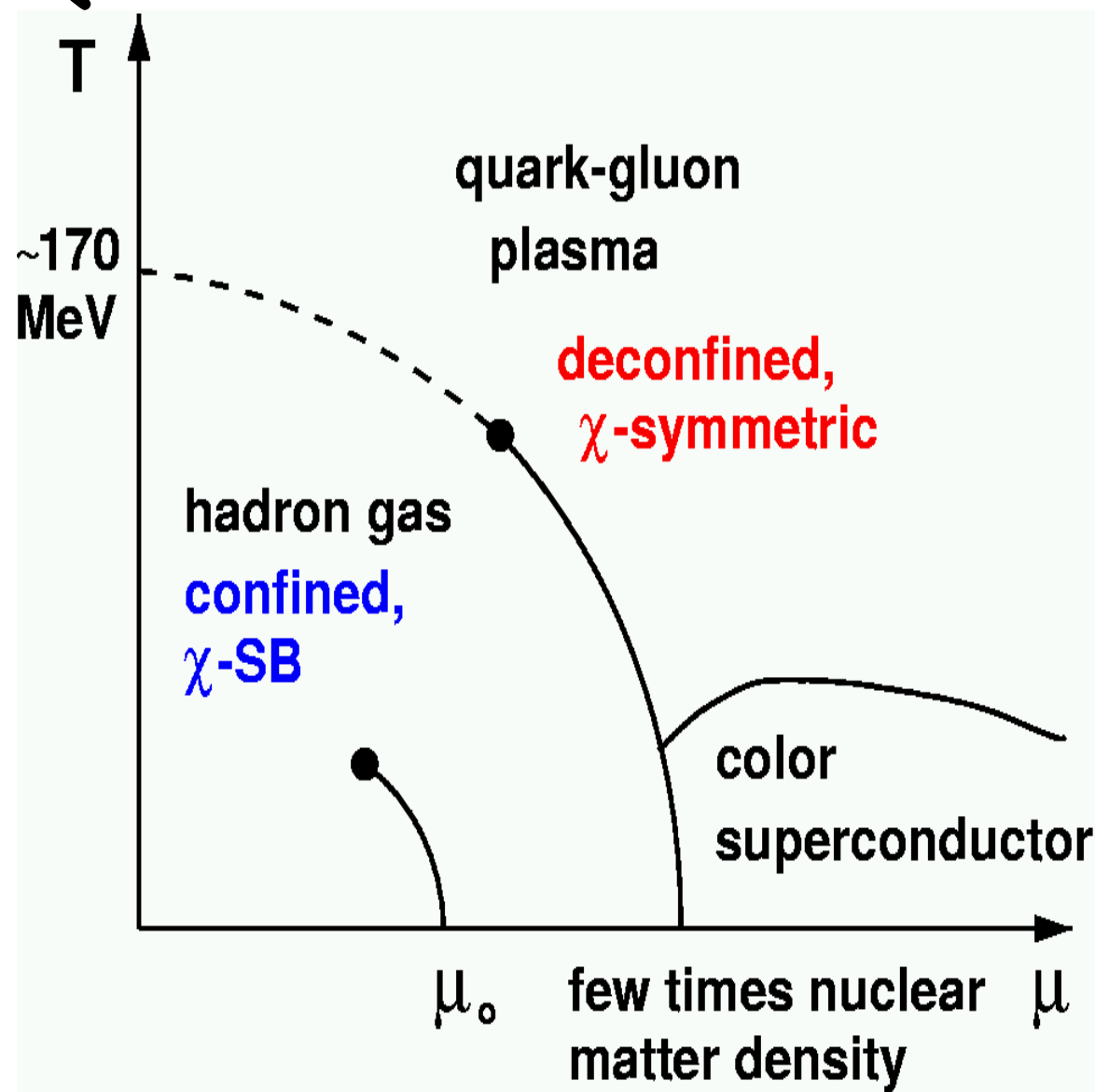
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- Phase diagram of QCD
 - Phase transition at high temperature and densities

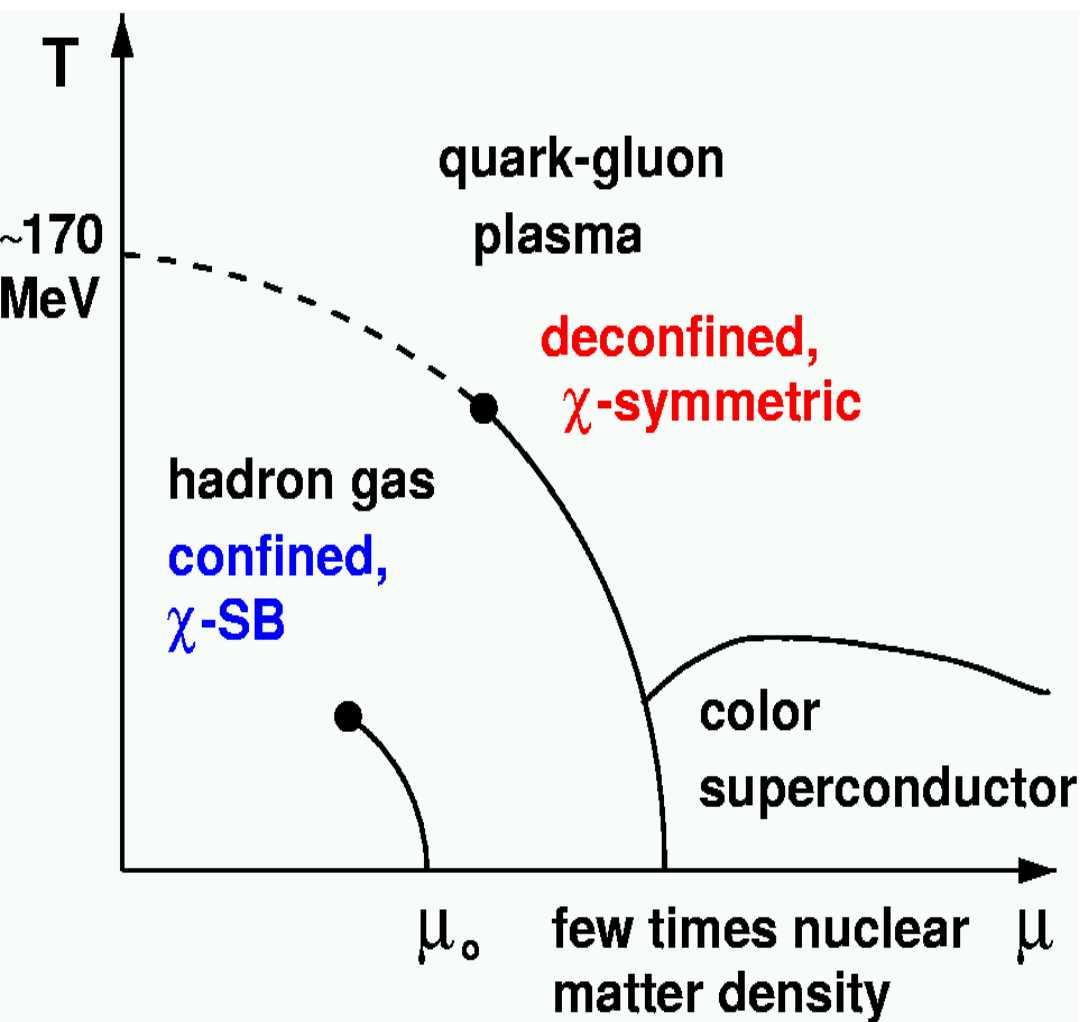
Finite Temperature QCD I

[Figure from Karsch et al., 2003]

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Finite Temperature QCD II

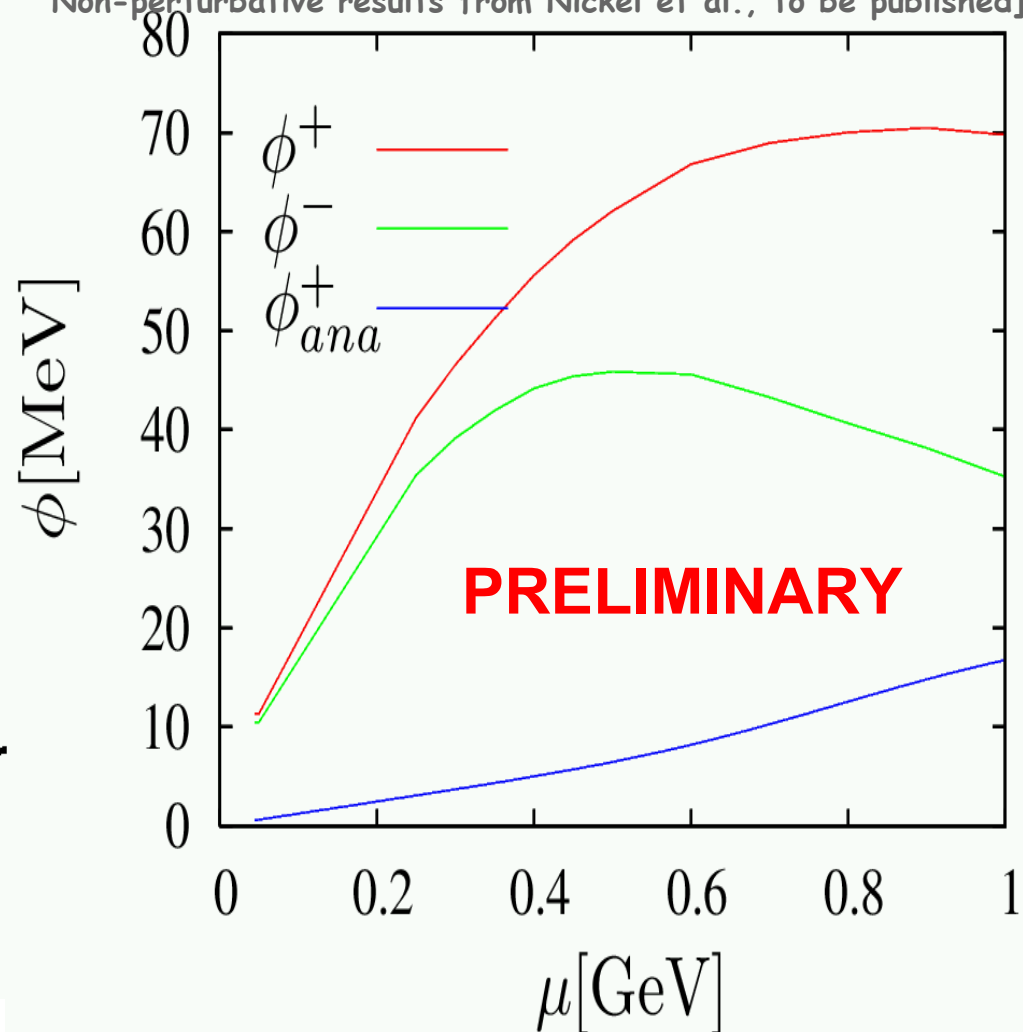
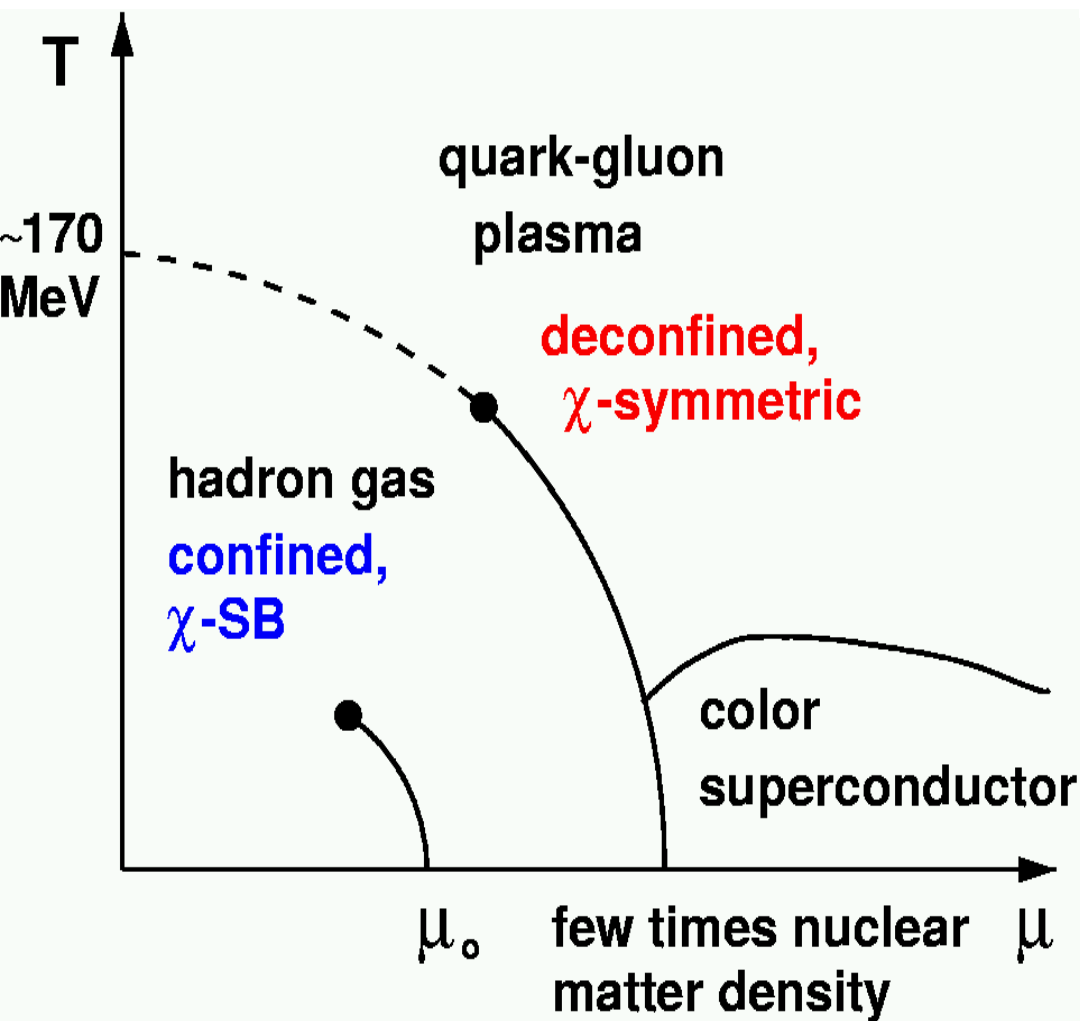


- Relevant for the early universe

Finite Temperature QCD II

[Perturbative analytic result from Rischke & Wang, PRD 2002

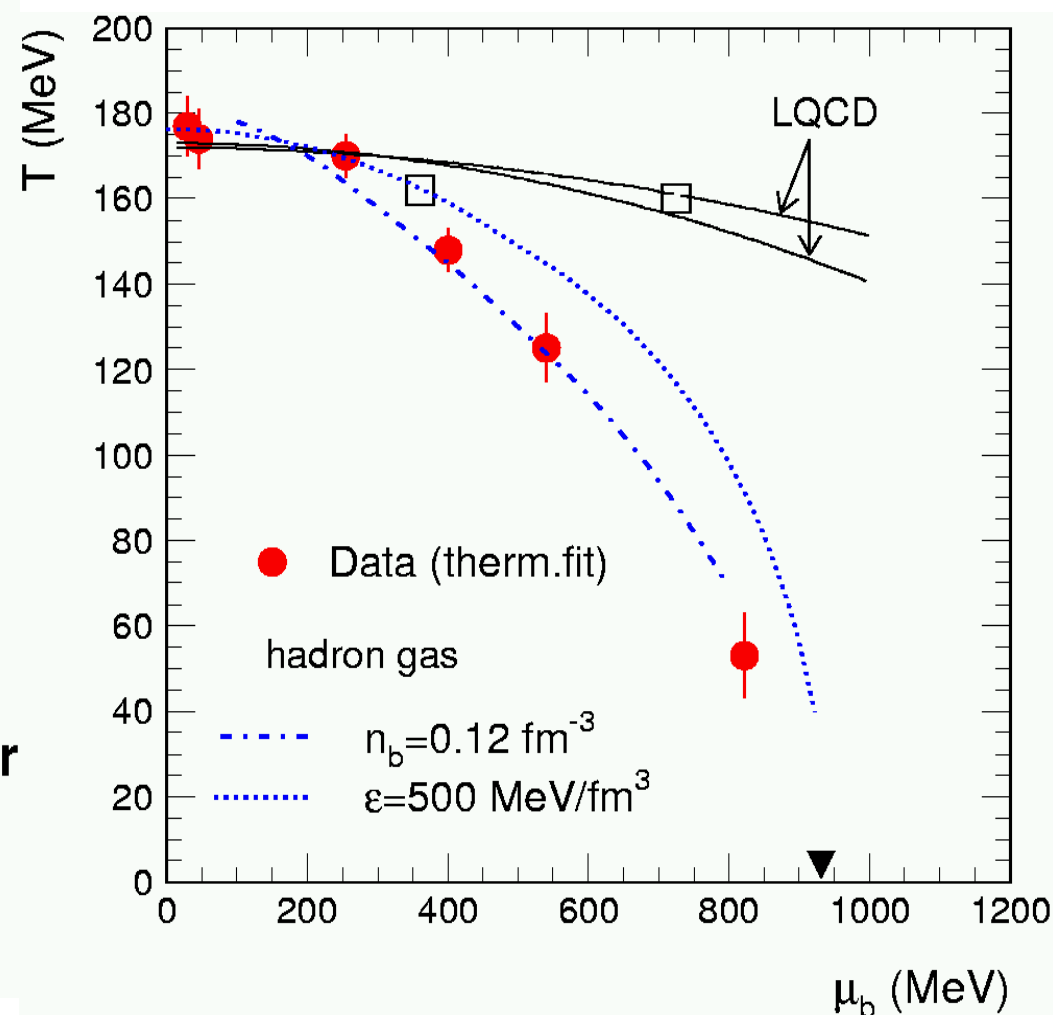
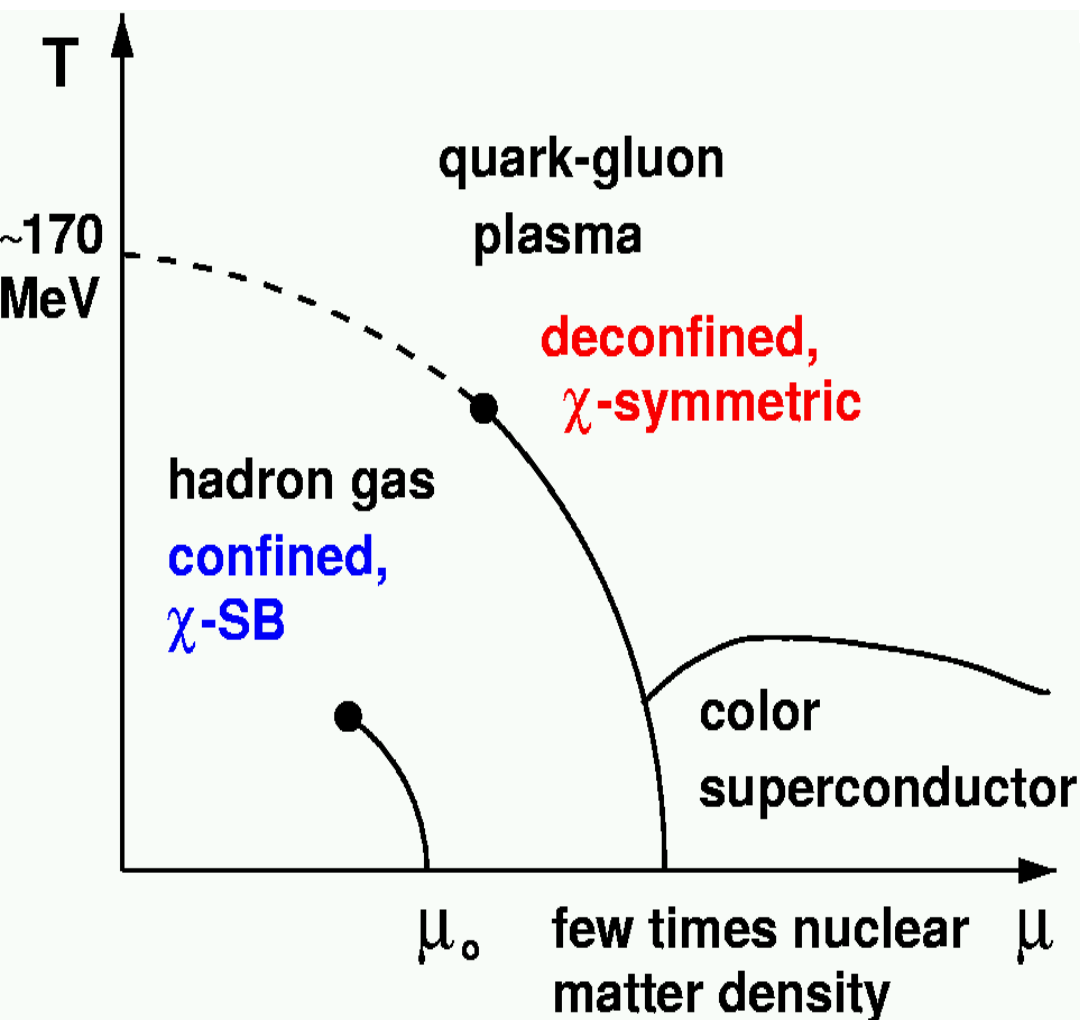
Non-perturbative results from Nickel et al., to be published]



- Relevant for the early universe and neutron-stars (?)
- Significant effects expected!

Finite Temperature QCD II

[Figure from Andronic et al., 2004]



- Relevant for the early universe and neutron-stars
- Experimentally investigated in heavy-ion collisions

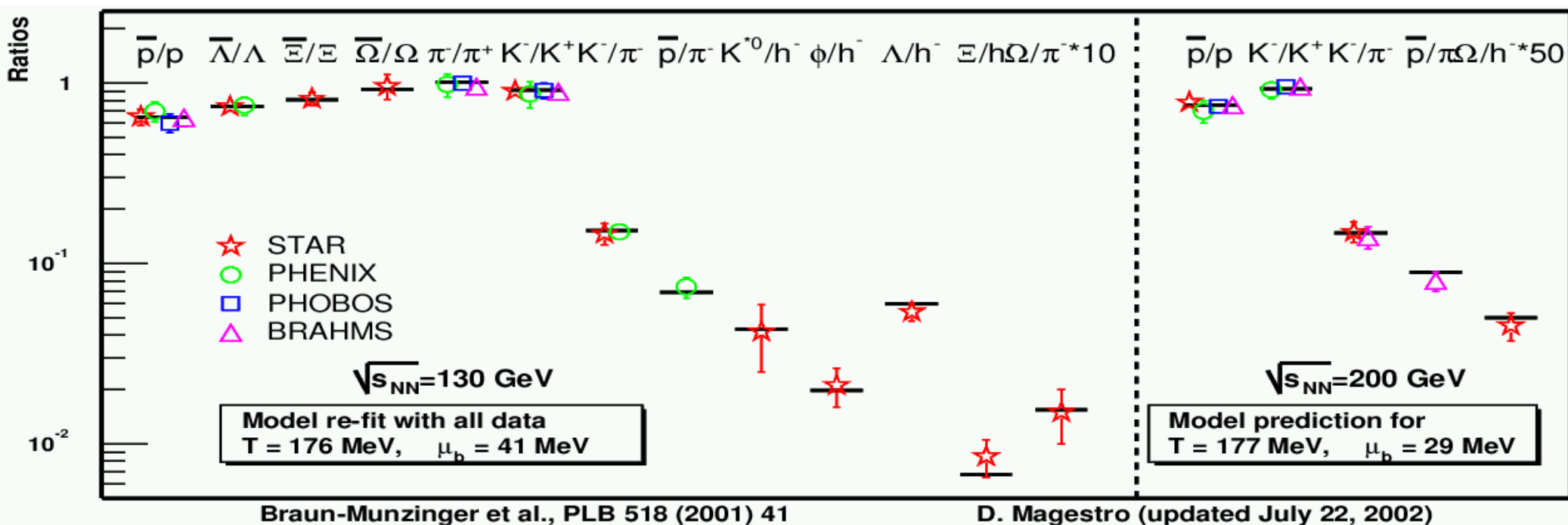
Temperature from Experiment

- Temperature and chemical potential **cannot be measure directly**

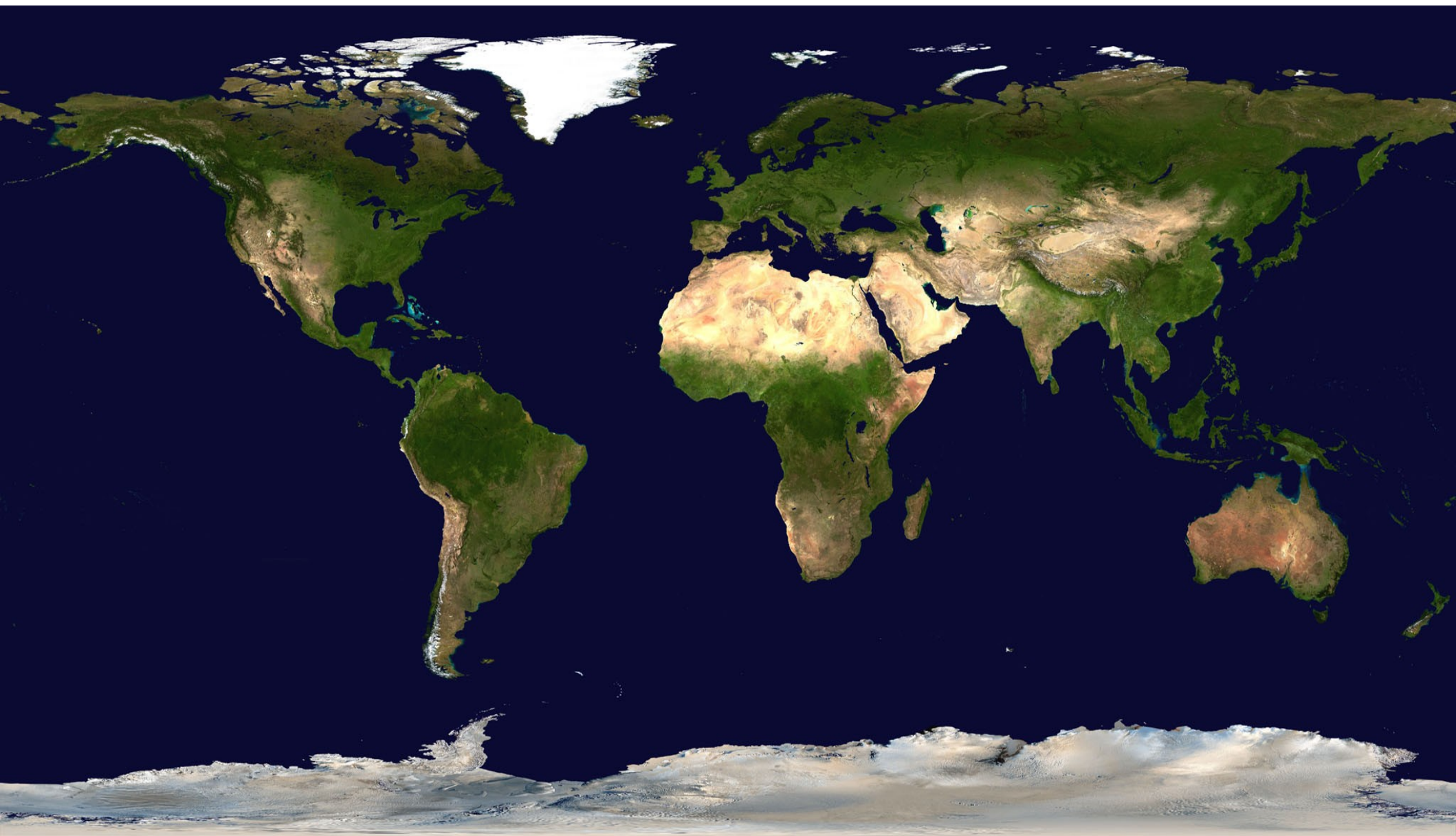
Temperature from Experiment

- Temperature and chemical potential **cannot be measure directly**
- Indirect extraction from a **fit** of the hadron production ratios

- Idealized model of a free hadron gas

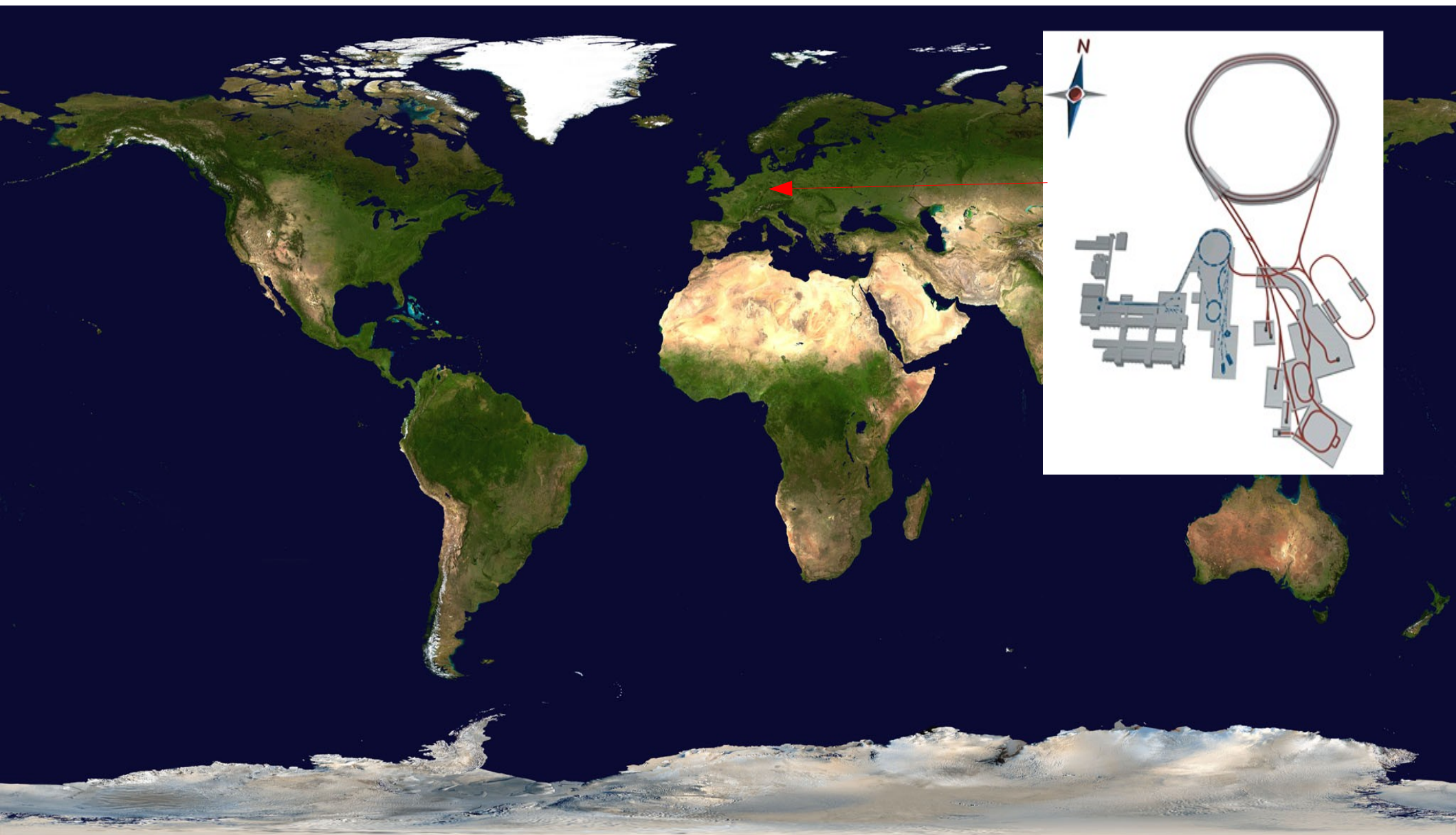


Research centers for Heavy-Ion physics



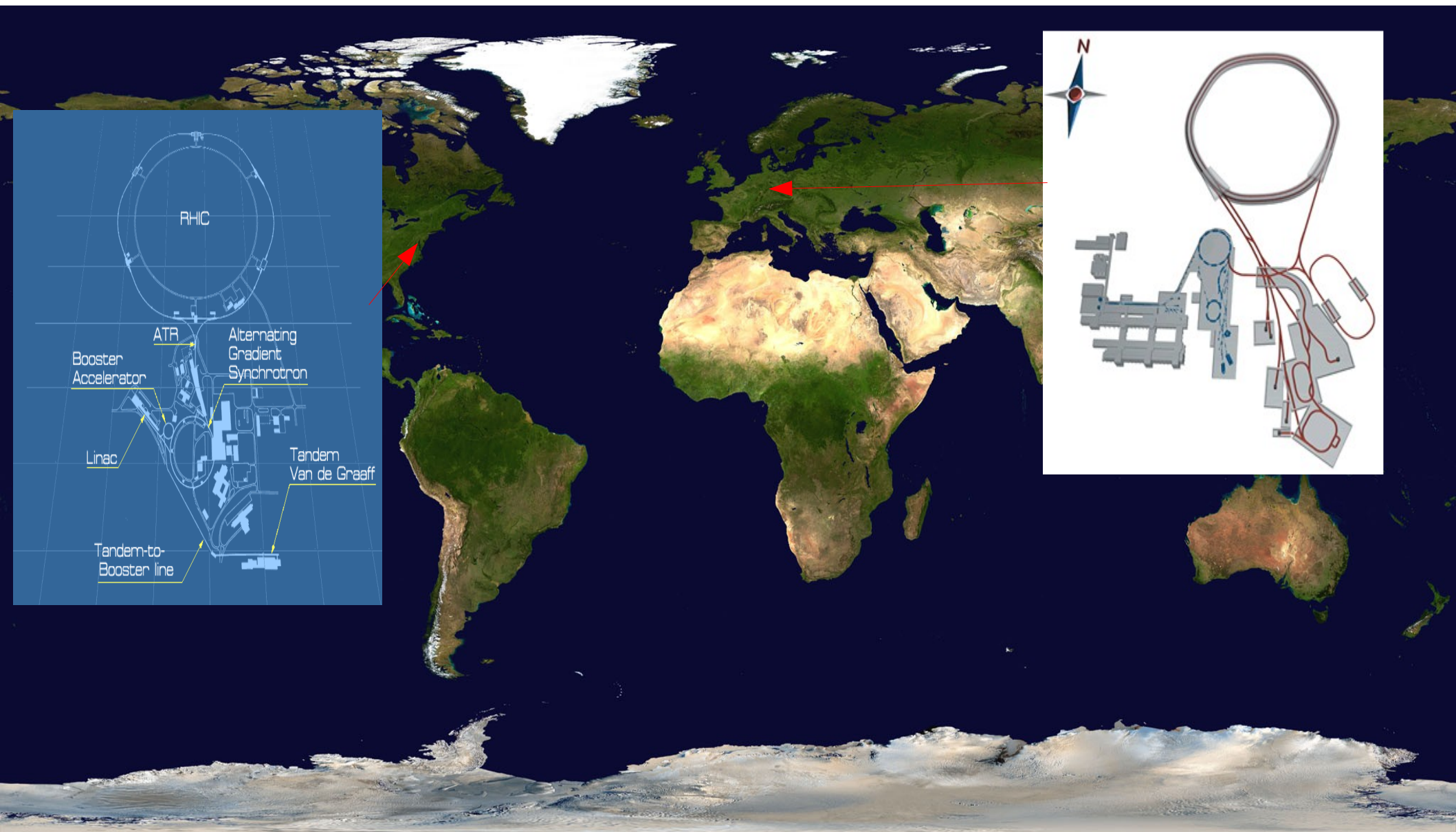
[Earth picture from NASA]

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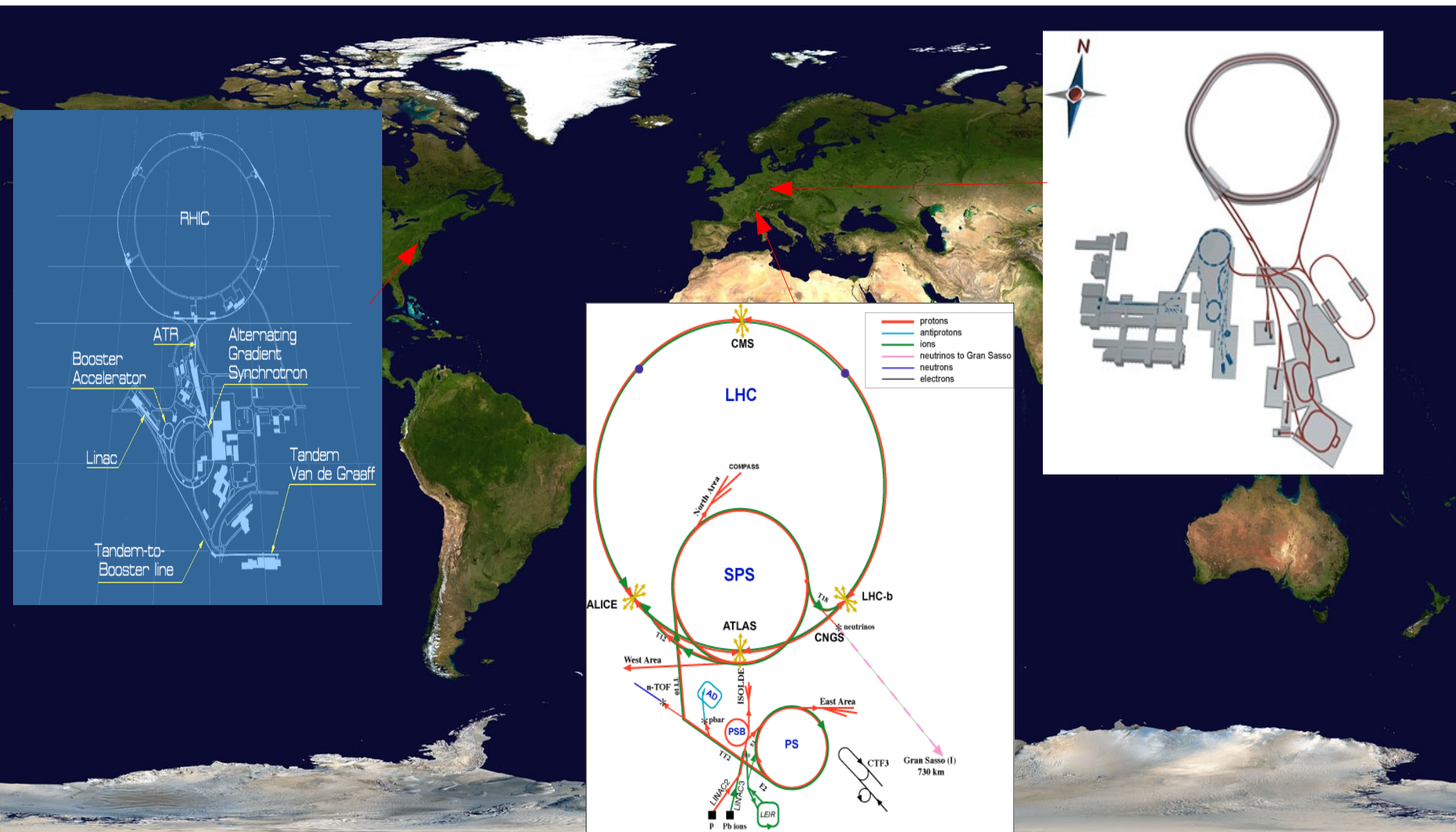
[Earth picture from NASA, research center picture from the homepage]

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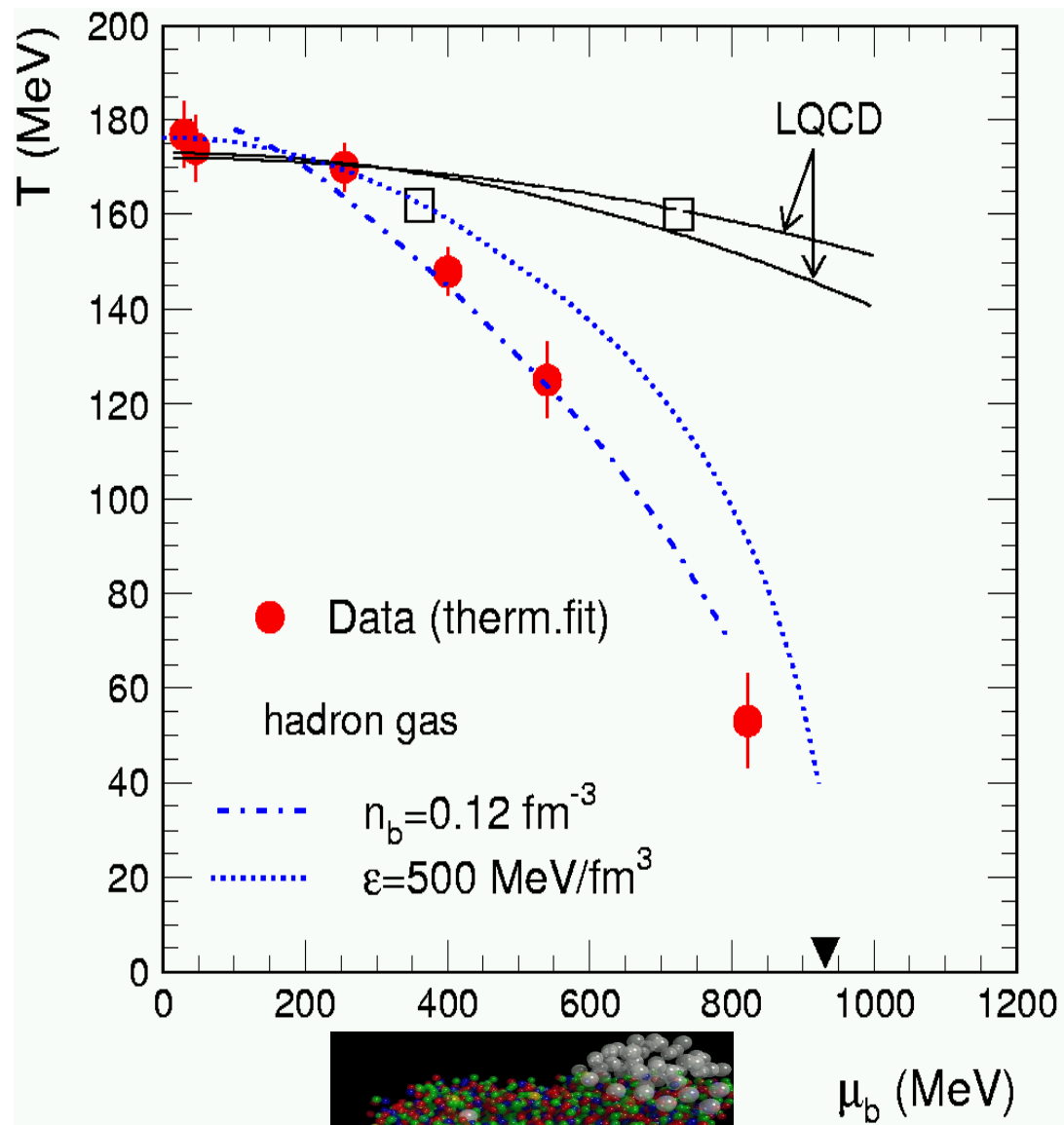
[Earth picture from NASA, research center pictures from their respective homepages]

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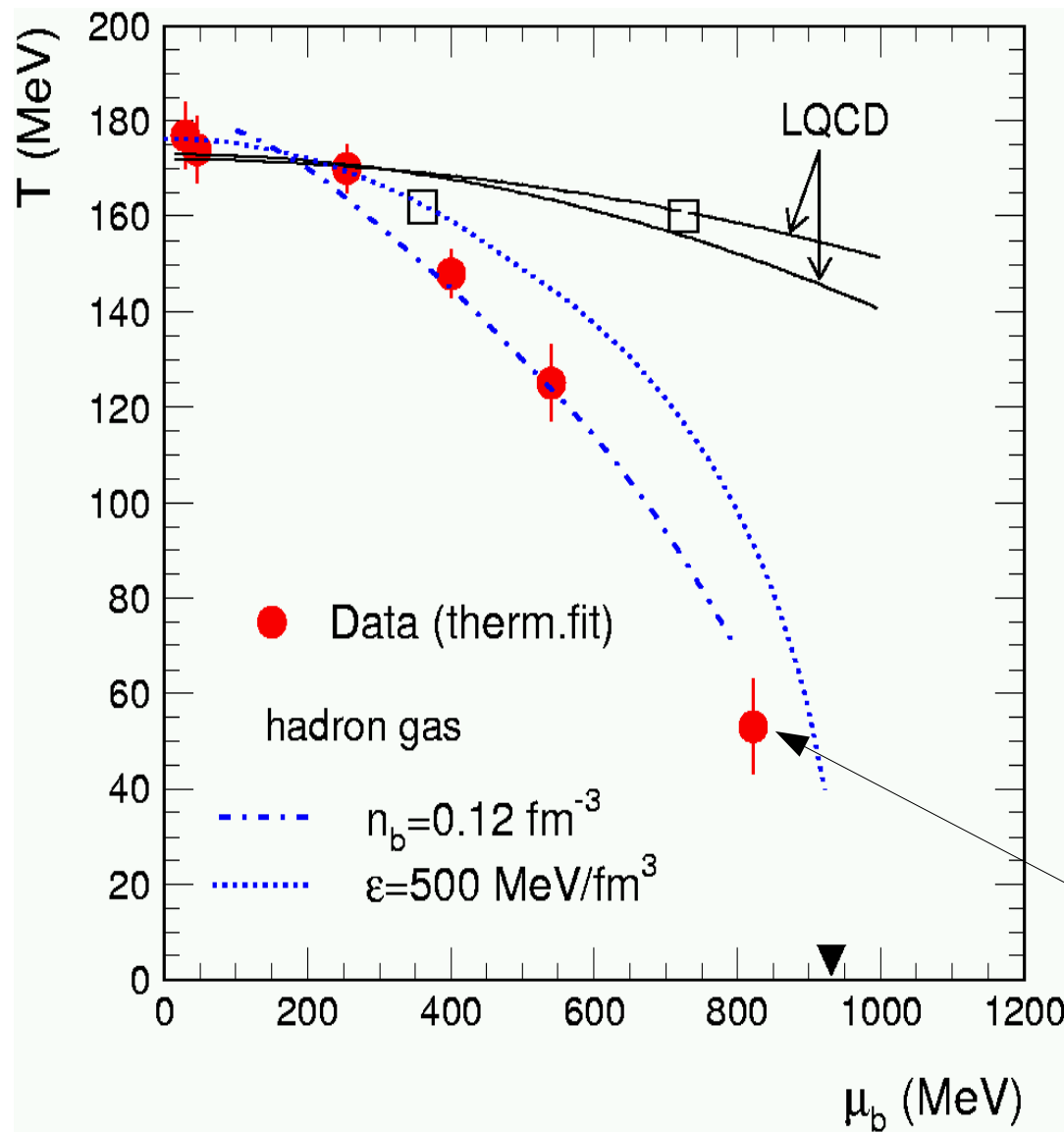
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Experiments



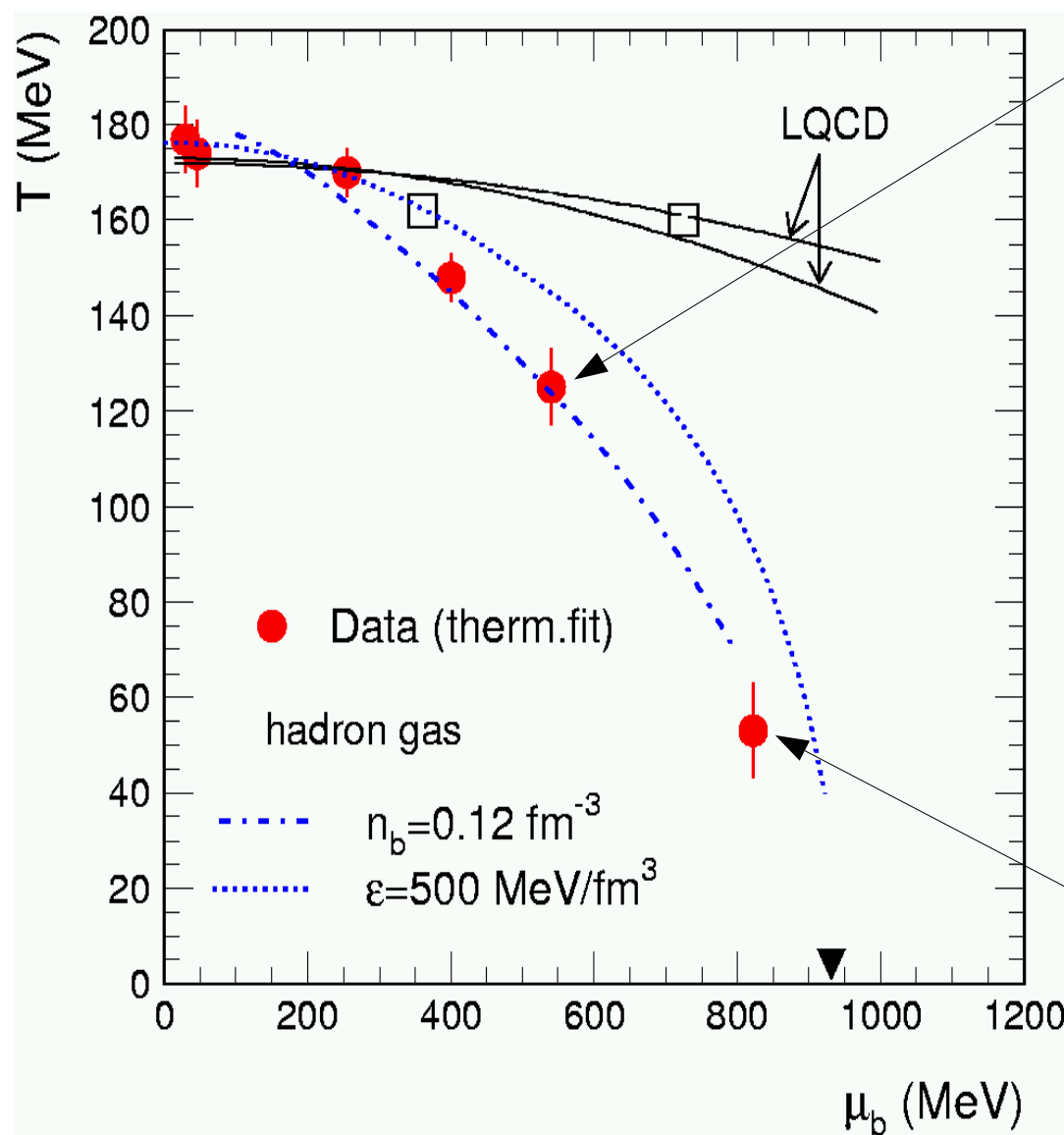
[From CERN press release]

Experiments



SIS: ~1 GeV/A
(Kaos, Fopi, Hades)
Ongoing

Experiments



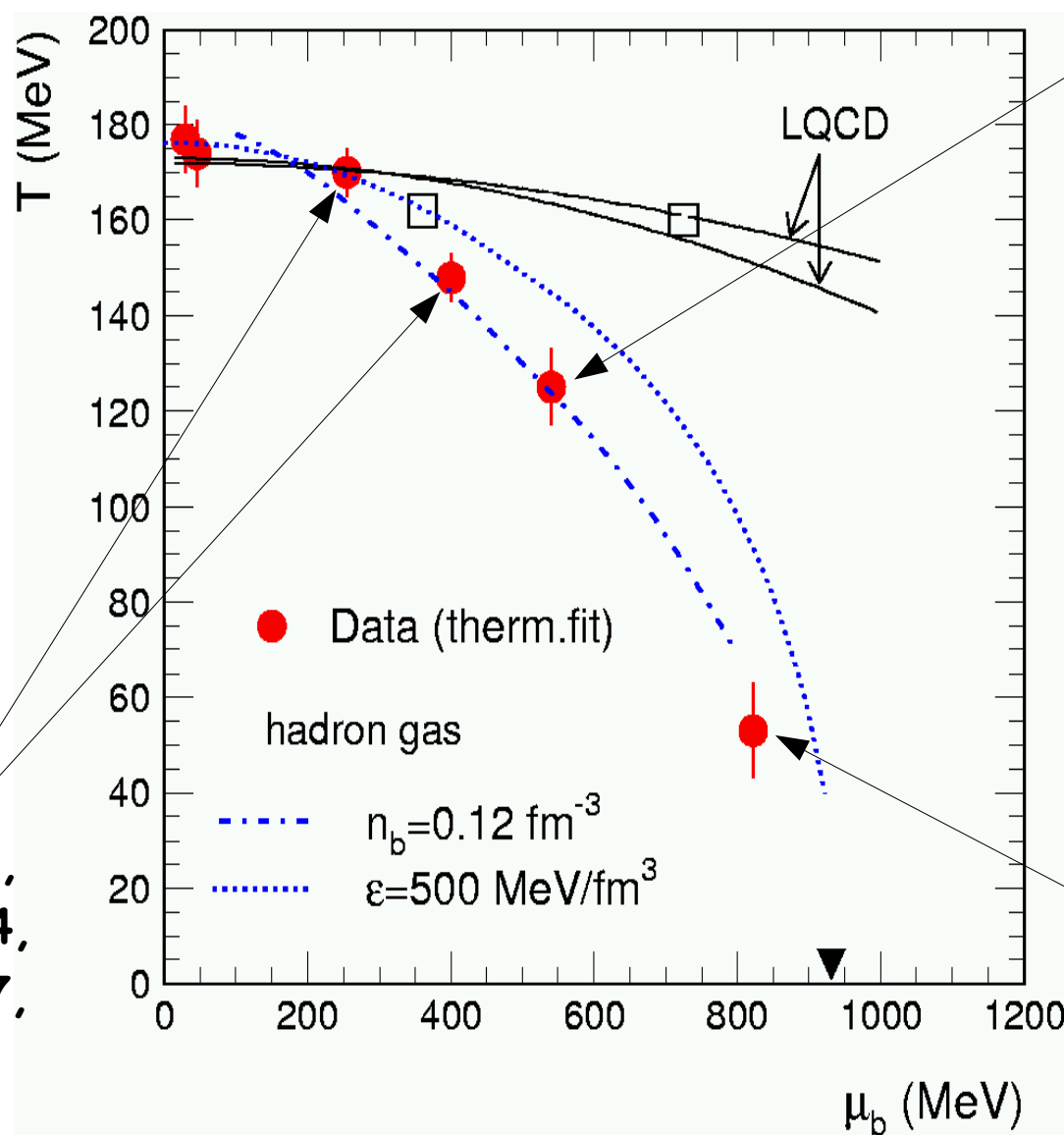
AGS: 5 GeV/A
(E802/864, E917,
E810, E814/877,
E864, E895)
Completed

SIS: ~1 GeV/A
(Kaos, Fopi, Hades)
Ongoing

Experiments

SPS: <17 GeV/A
(WA80/98, NA35/49,
NA 38/50/60, NA 44,
CERES, WA97, NA57,
NA52)

Nearly completed



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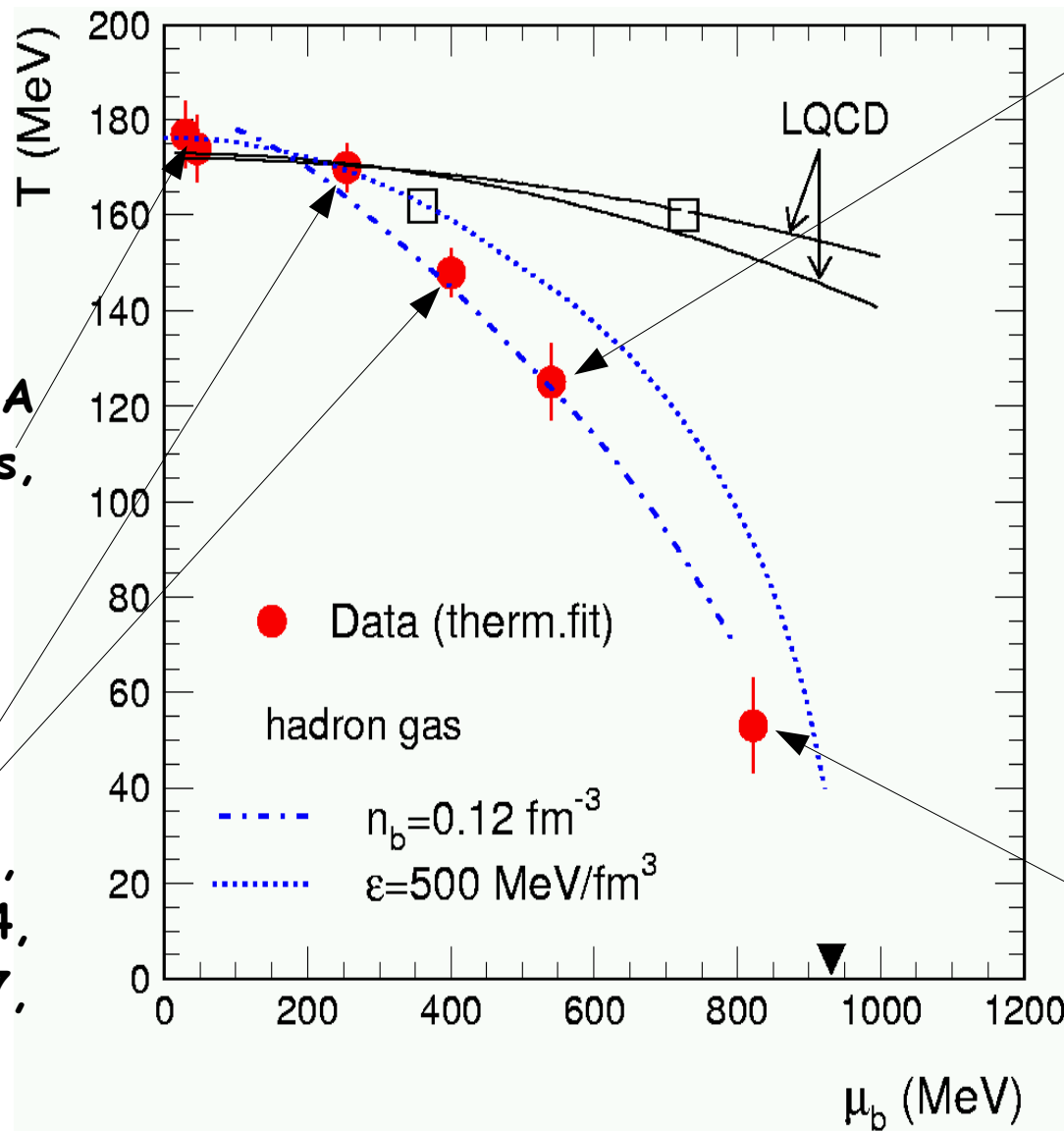
Experiments

RHIC: 200/130 GeV/A
(Star, Phenix, Brahms, Phobos)
Ongoing

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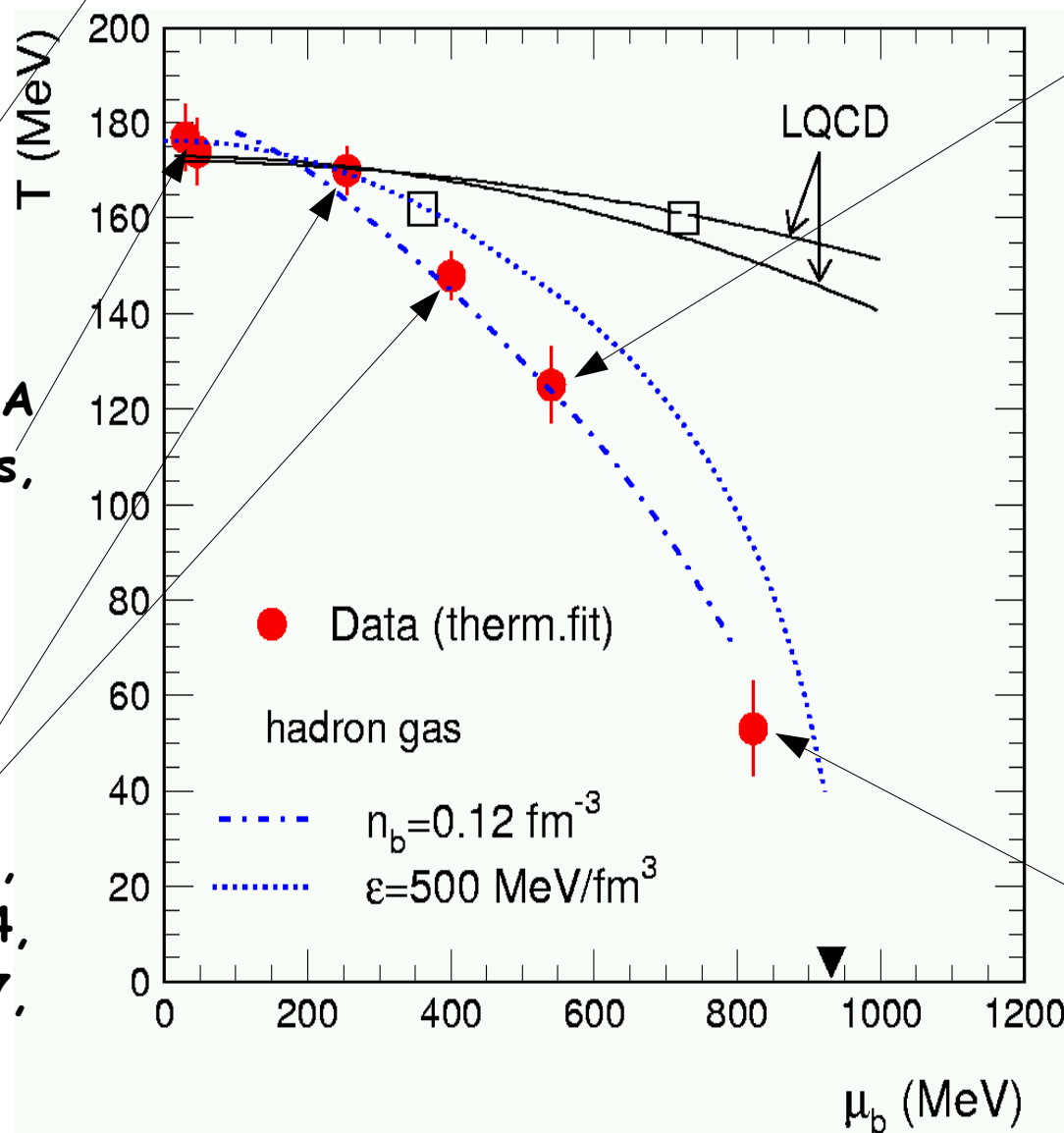
LHC: 2700 GeV/A
(Alice, CMS, Atlas)
Under construction

RHIC: 200/130 GeV/A
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(Alice, CMS, Atlas)
Under construction

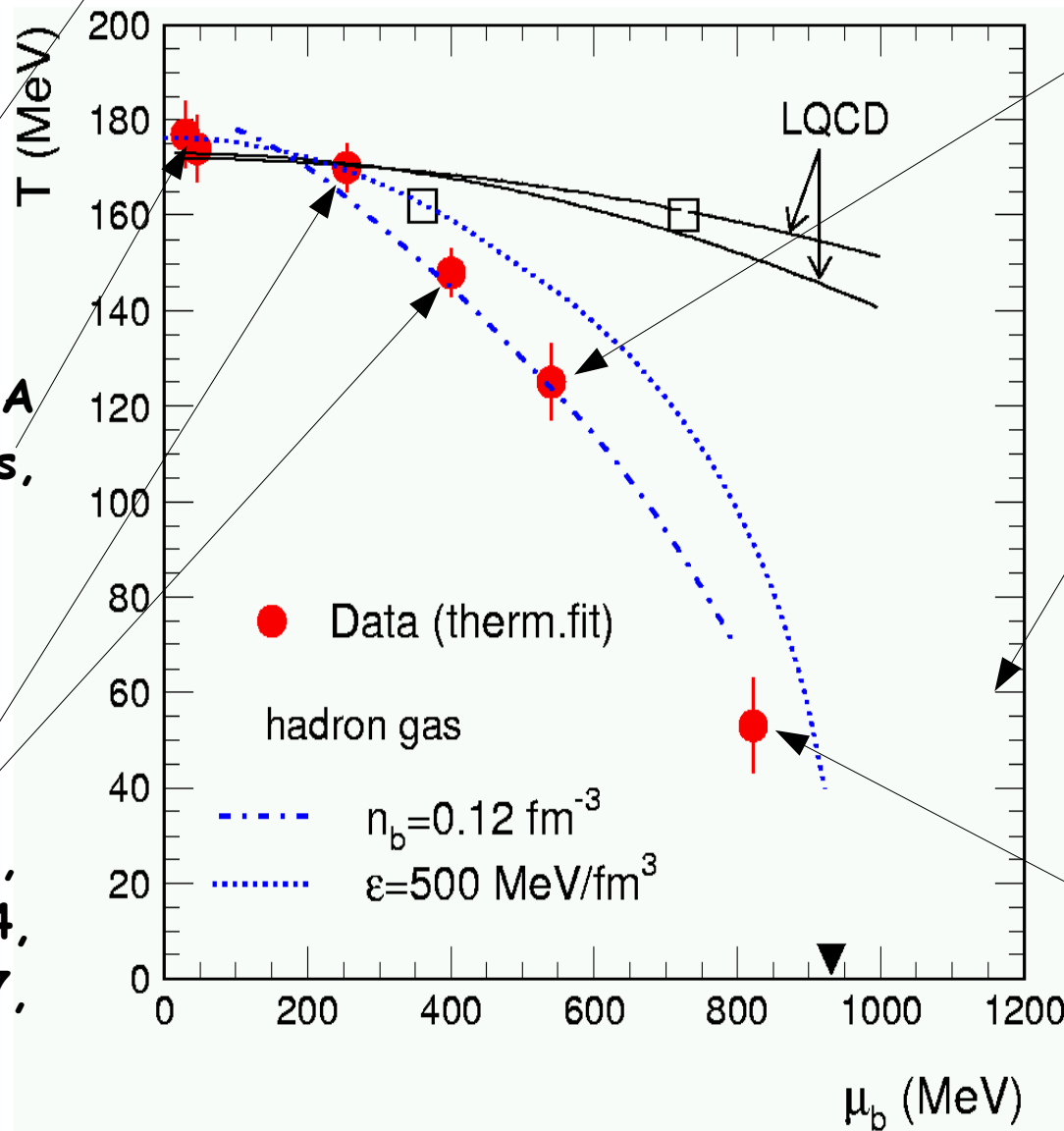
RHIC: 200/130 GeV/A
(Star, Phenix, Brahms, Phobos)
Ongoing

SPS: <17 GeV/A
(WA80/98, NA35/49, NA 38/50/60, NA 44, CERES, WA97, NA57, NA52)
Nearly completed

AGS: 5 GeV/A
(E802/864, E917, E810, E814/877, E864, E895)
Completed

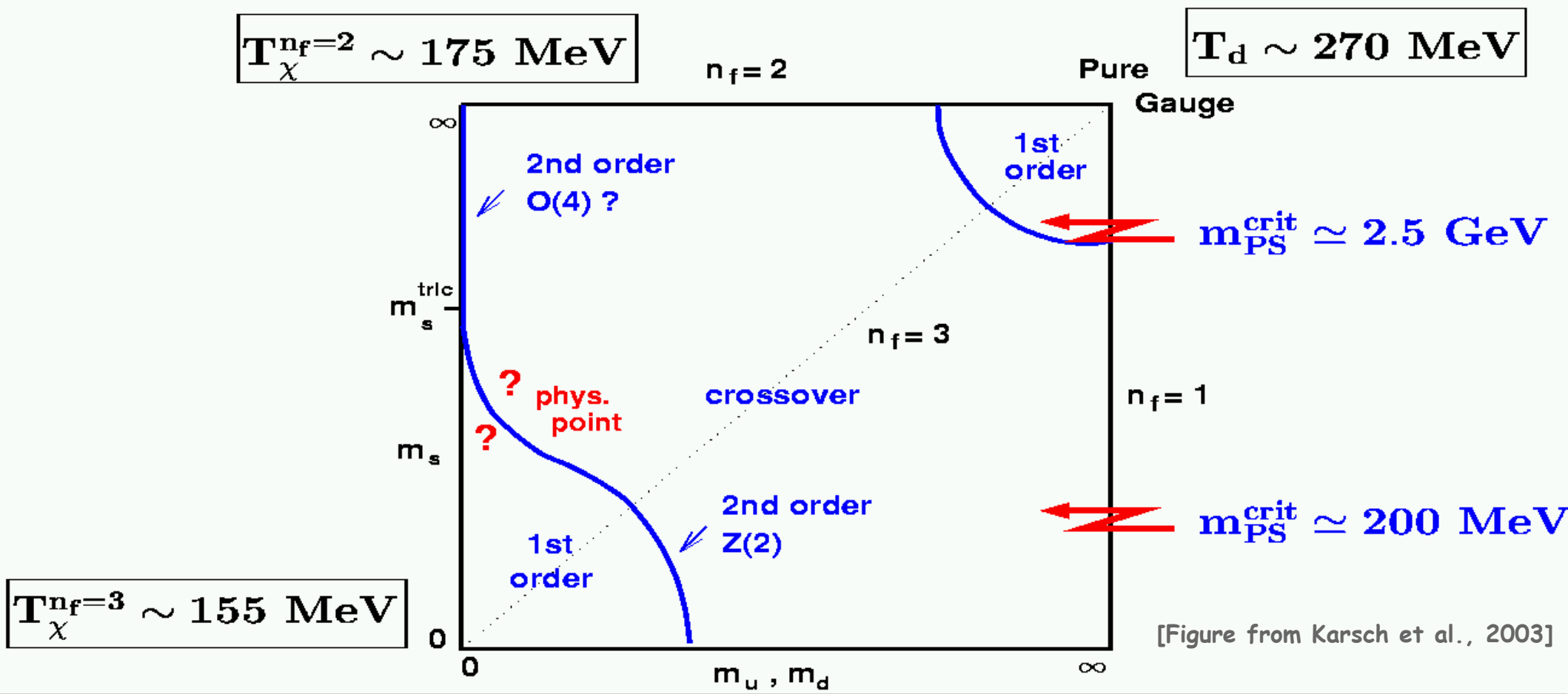
FAIR: High density (CMB)
Under construction

SIS: ~1 GeV/A
(Kaos, Fopi, Hades)
Ongoing



Order of the phase transition

- Order of the phase transition depends on the quark masses
 - Currently not possible to calculate at physical quark masses



[Figure from Karsch et al., 2003]

The fate of hadrons

- **Hadrons broaden**

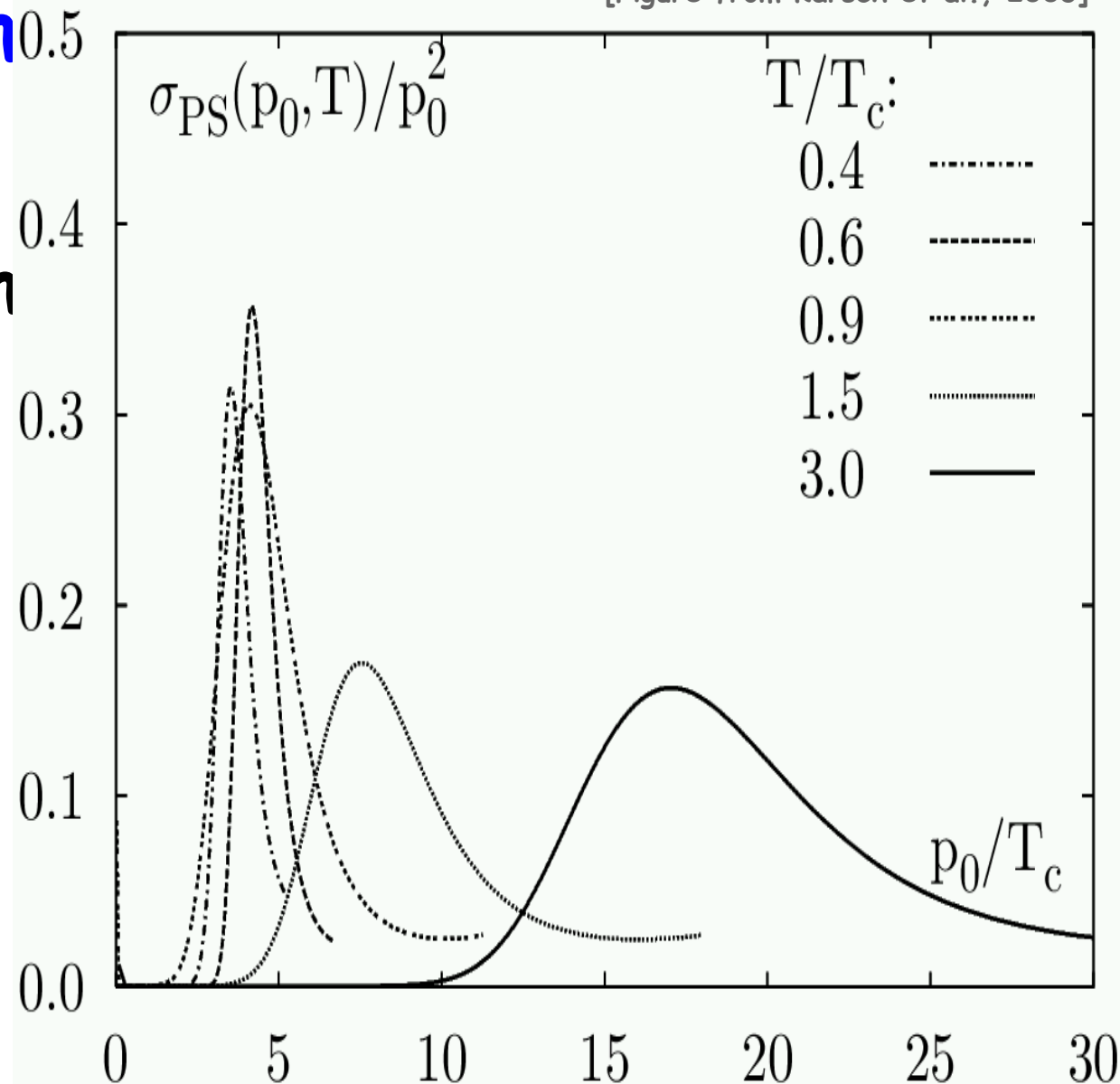
- Observable in spectral function

- “Dissolving”?

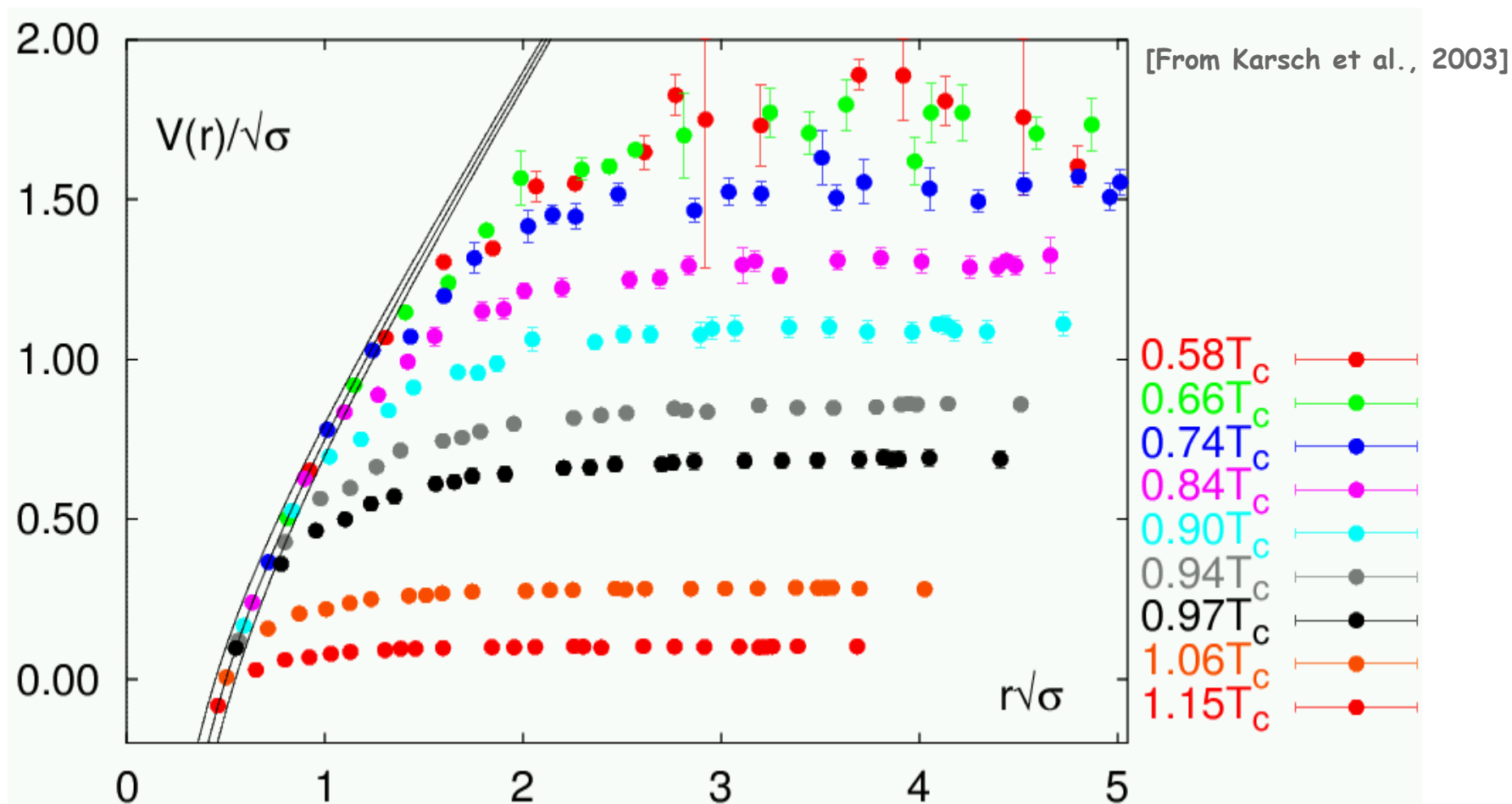
- Consequences on (production) cross-sections

- **Experimental consequences**

[Figure from Karsch et al., 2003]



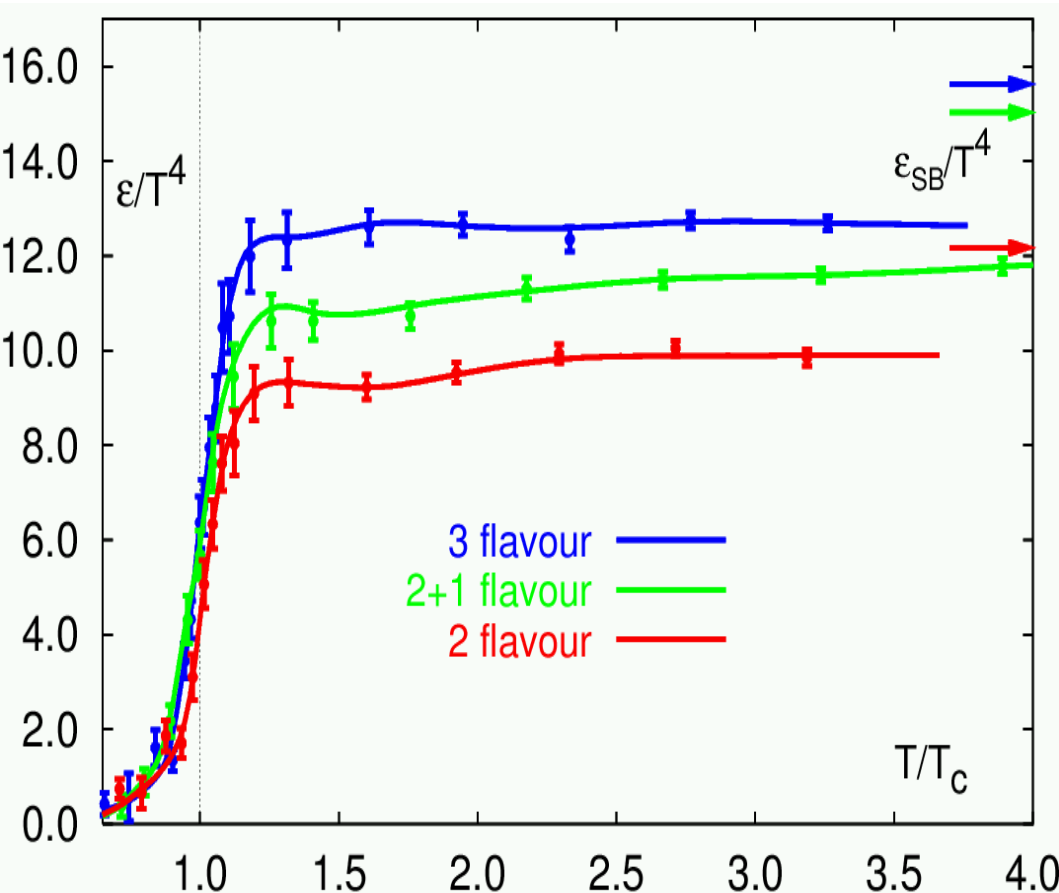
Deconfinement



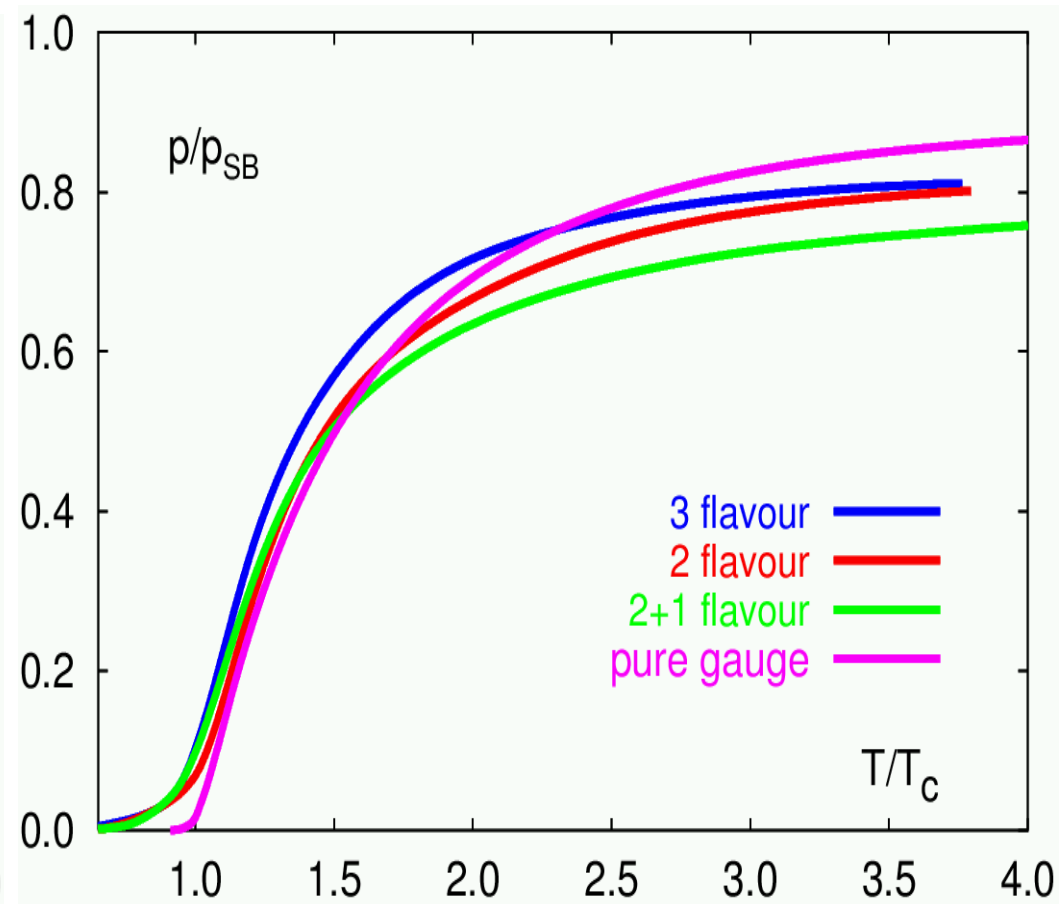
- String tension vanishes at phase transition
- Not observable in full QCD

Thermodynamic potential

- Thermodynamic potential not simple
- Significantly different from a Stefan-Boltzmann-law at phase transition and beyond

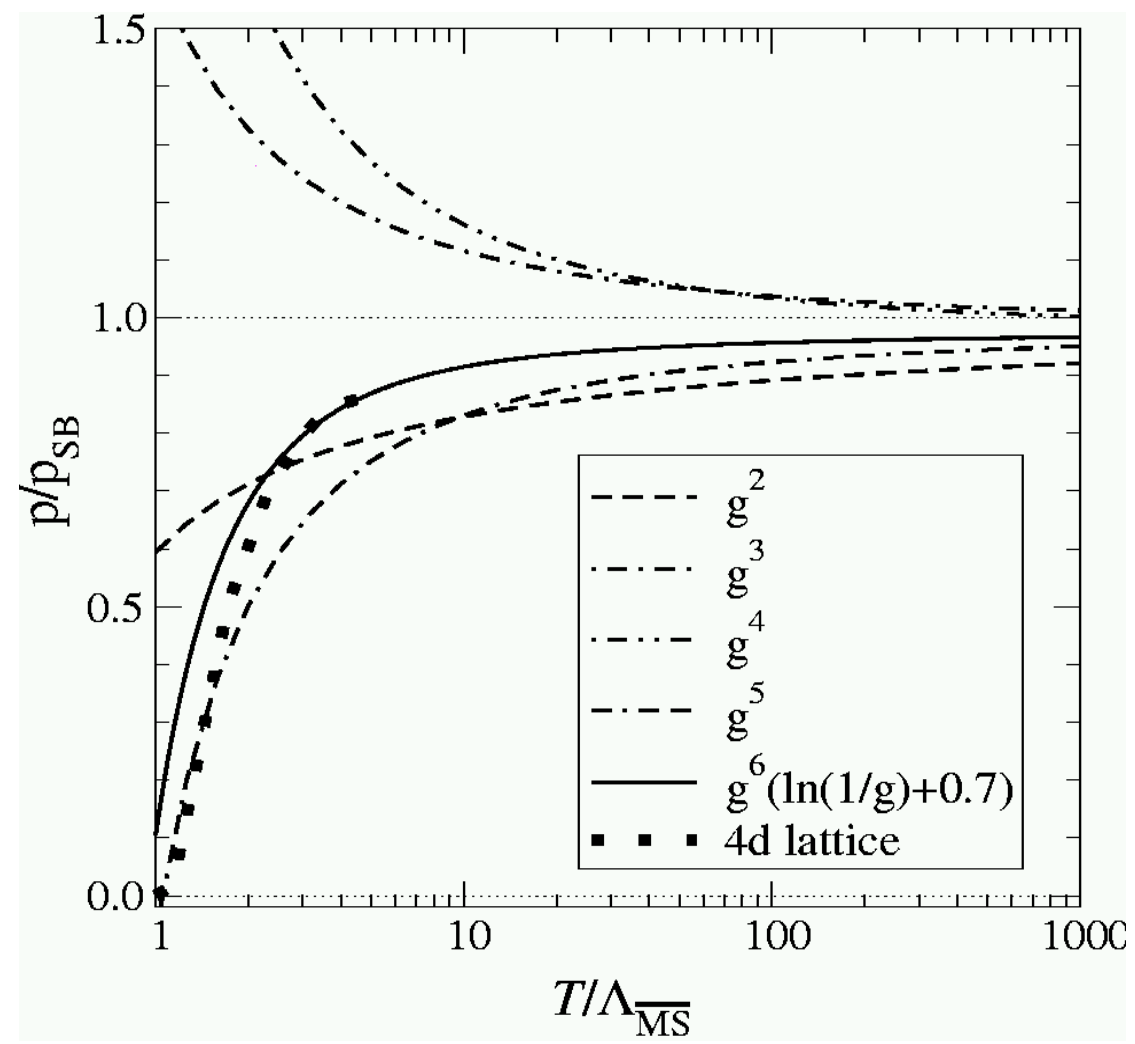


[Left: From Karsch et al. 2000, Right: From Karsch 2001]



Finite Temperature (perturbation theory)

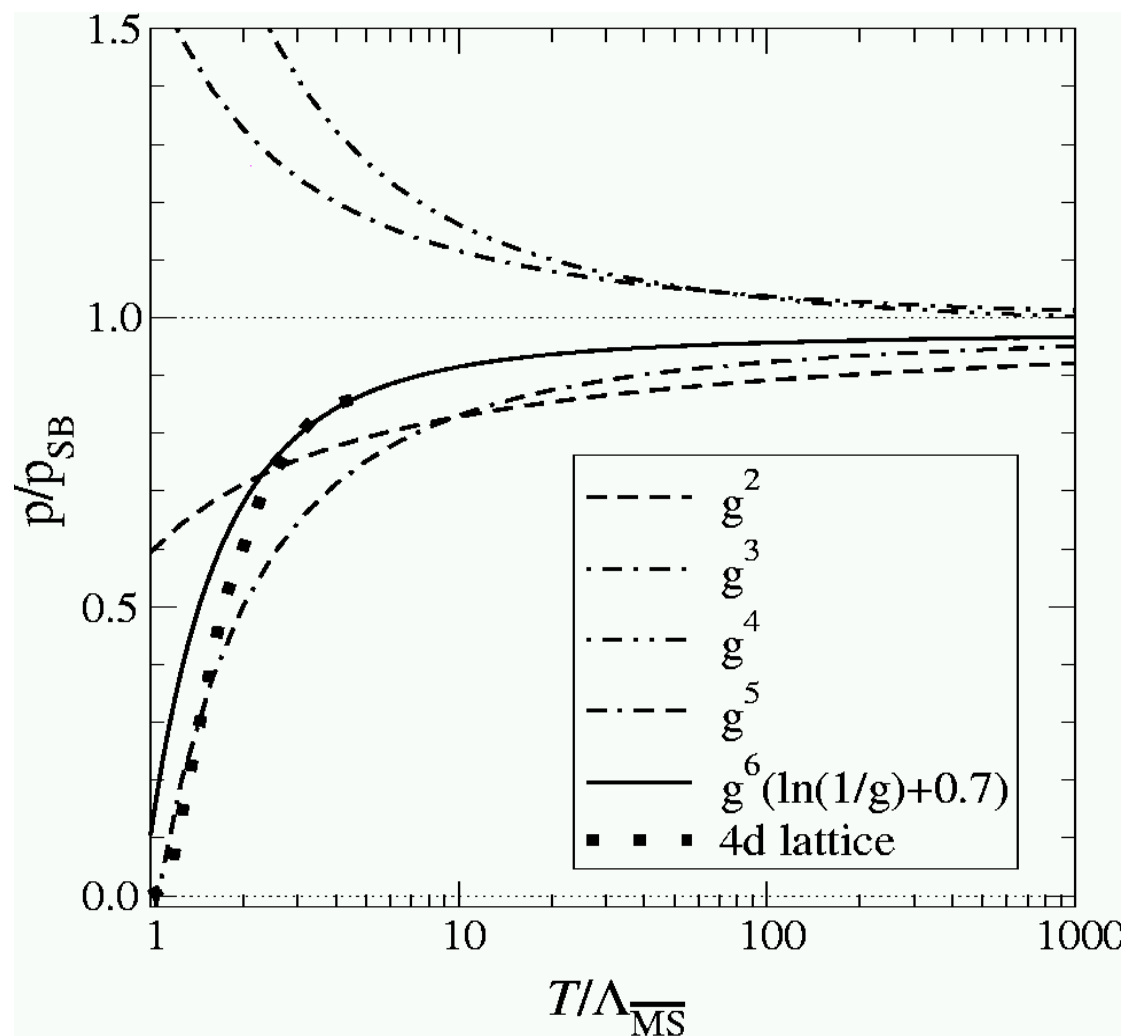
[Figure from Rischke 2004]



Finite Temperature (perturbation theory)

- (Ordinary) **Perturbation theory fails**

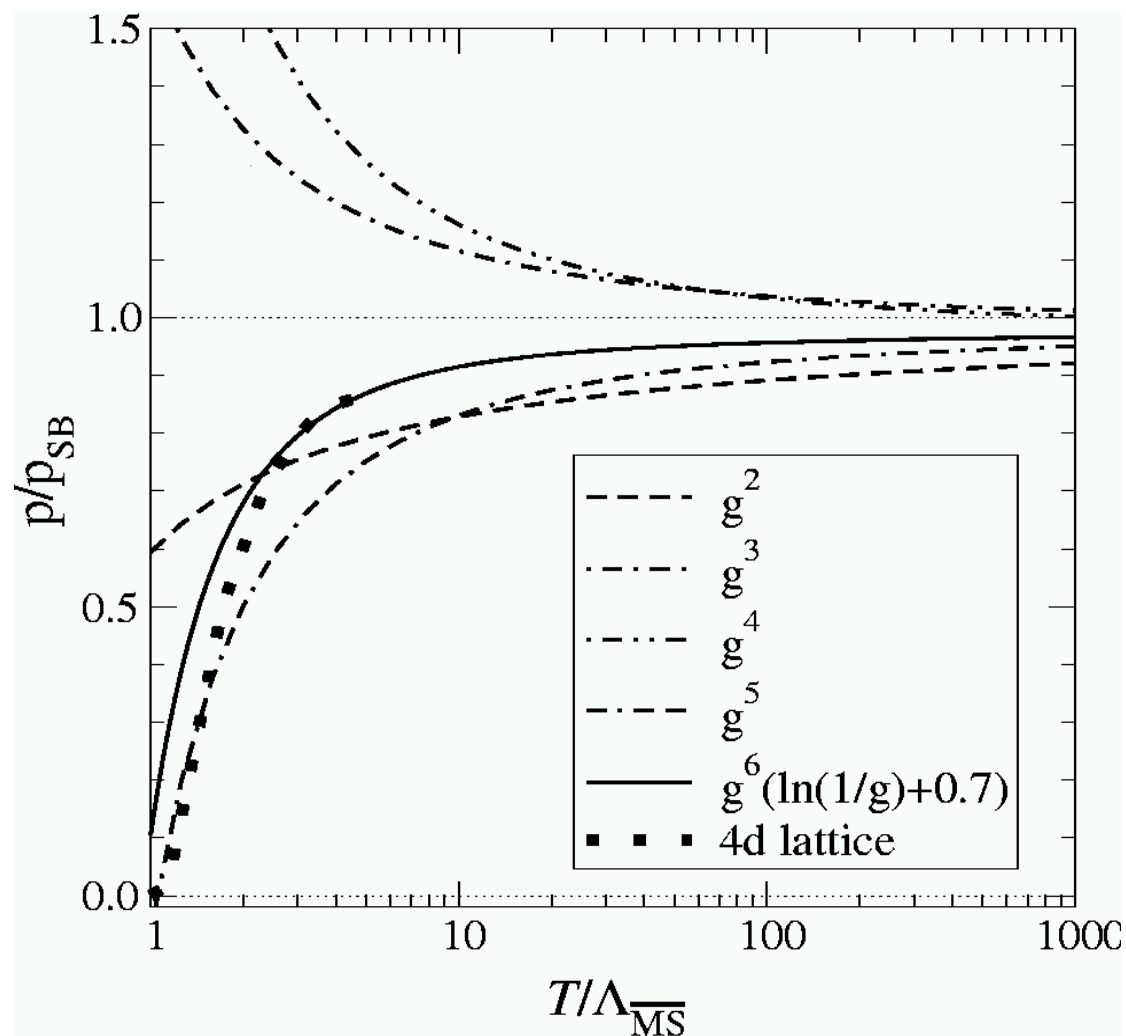
[Figure from Rischke 2004]



Finite Temperature (perturbation theory)

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 - Similar to the vacuum
- Most problems for chromomagnetic interactions

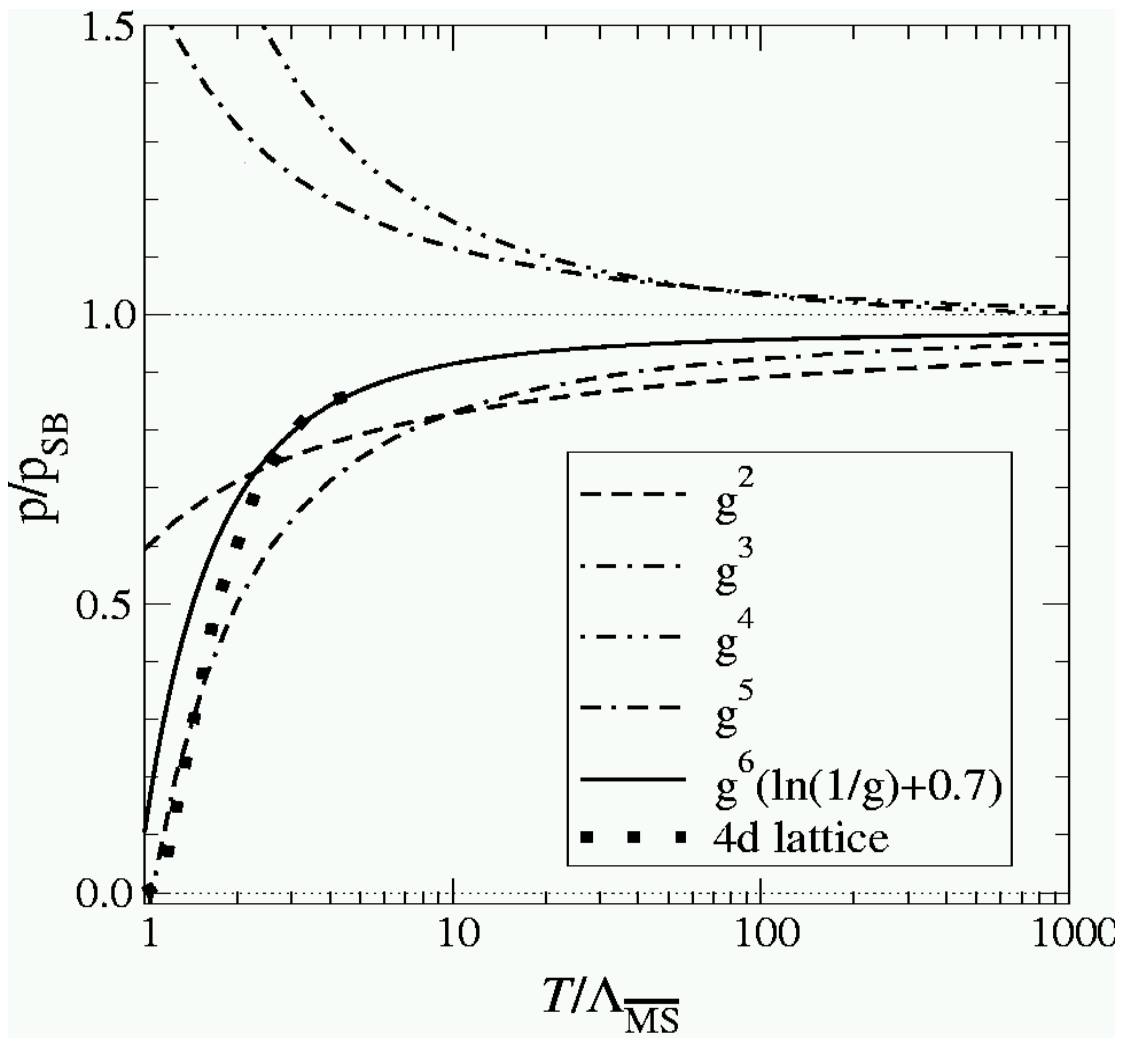
[Figure from Rischke 2004]



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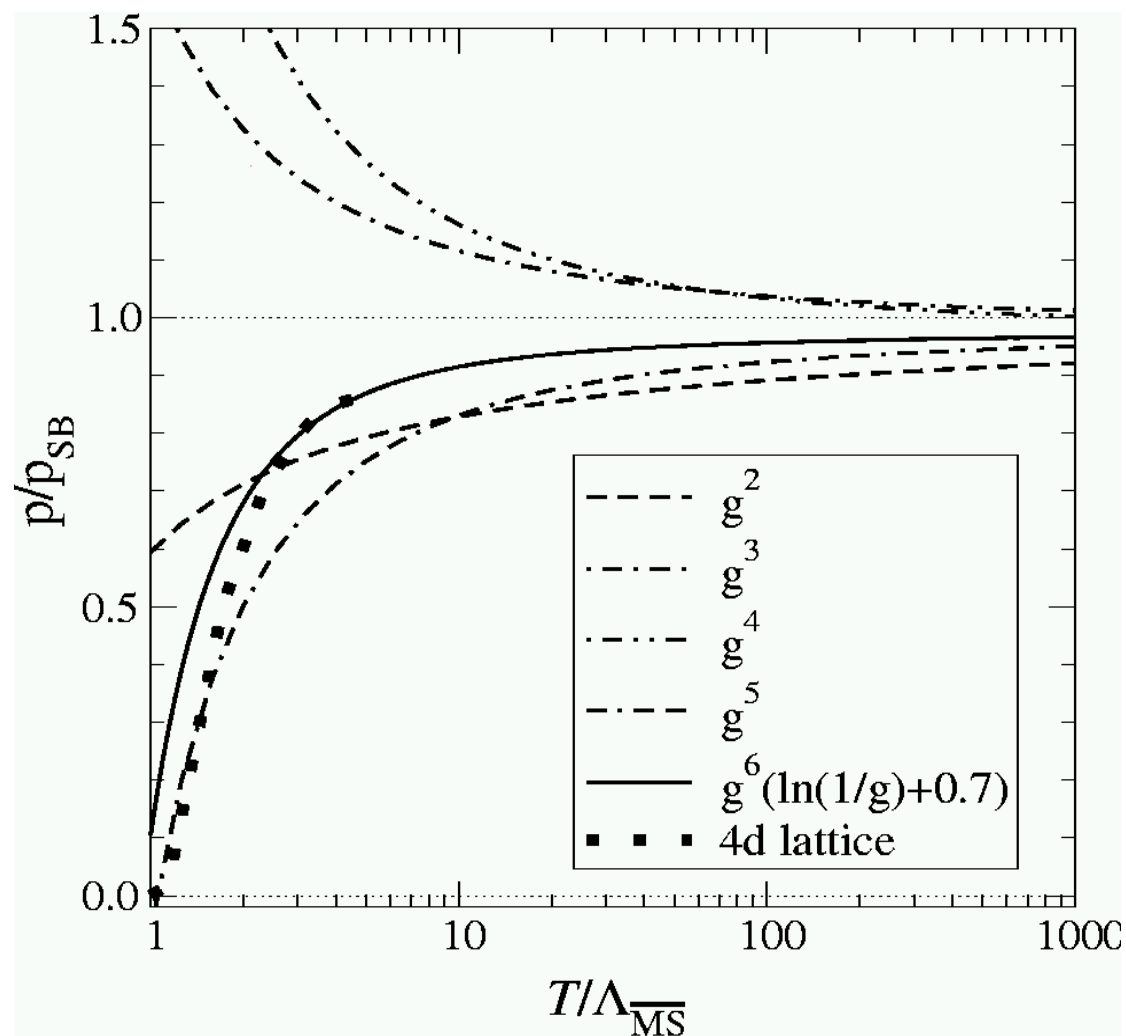
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Finite Temperature (perturbation theory)

- (Ordinary) **Perturbation theory fails**
- Infrared divergences
 - Similar to the vacuum
- Most problems for chromomagnetic interactions
- Reason for this?
- **How can one treat this problem?**

[Figure from Rischke 2004]



Finite-Temperature Propagators

- Equilibrium Physics: Matsubara formalism

Finite-Temperature Propagators

- Equilibrium Physics: Matsubara formalism

- **Ghost**
$$D_G(p_0^2, \vec{p}^2) = \frac{-G(p_0^2, \vec{p}^2)}{p^2}$$

Finite-Temperature Propagators

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- Gluon

$$D_{\mu\nu}(p_0, \vec{p}) = P_{\mu\nu}^T \frac{Z(p_0^2, \vec{p}^2)}{p^2} + P_{\mu\nu}^L \frac{H(p_0^2, \vec{p}^2)}{p^2}$$

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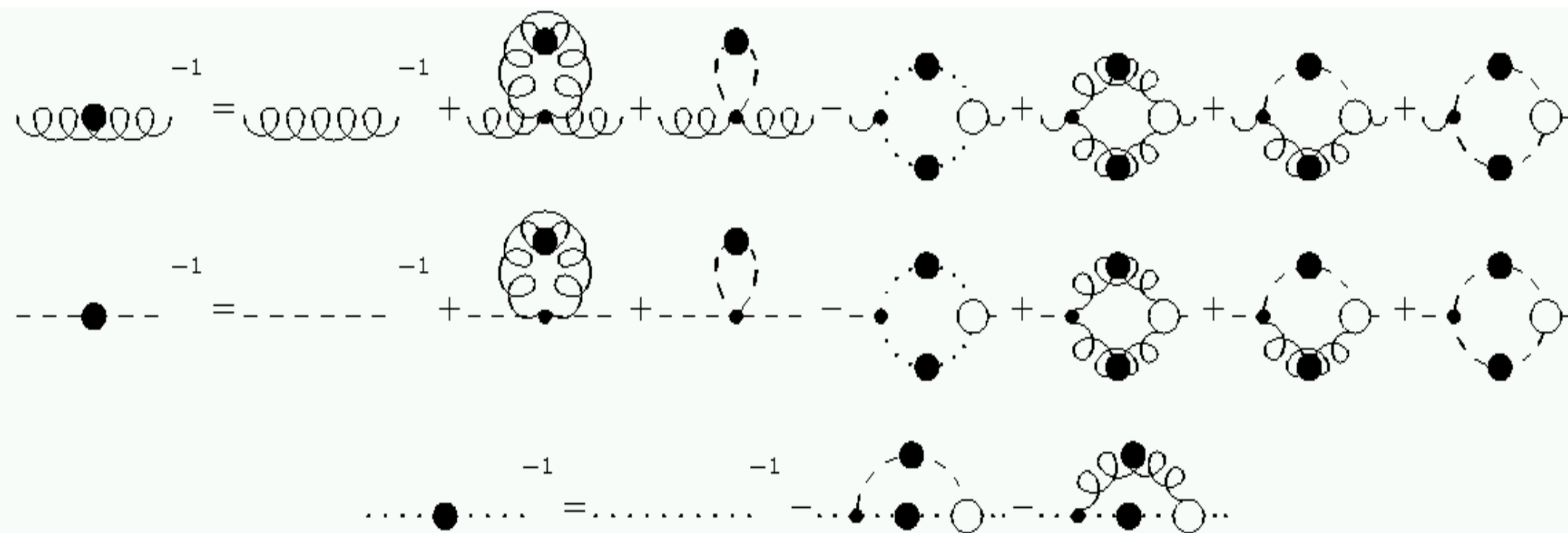
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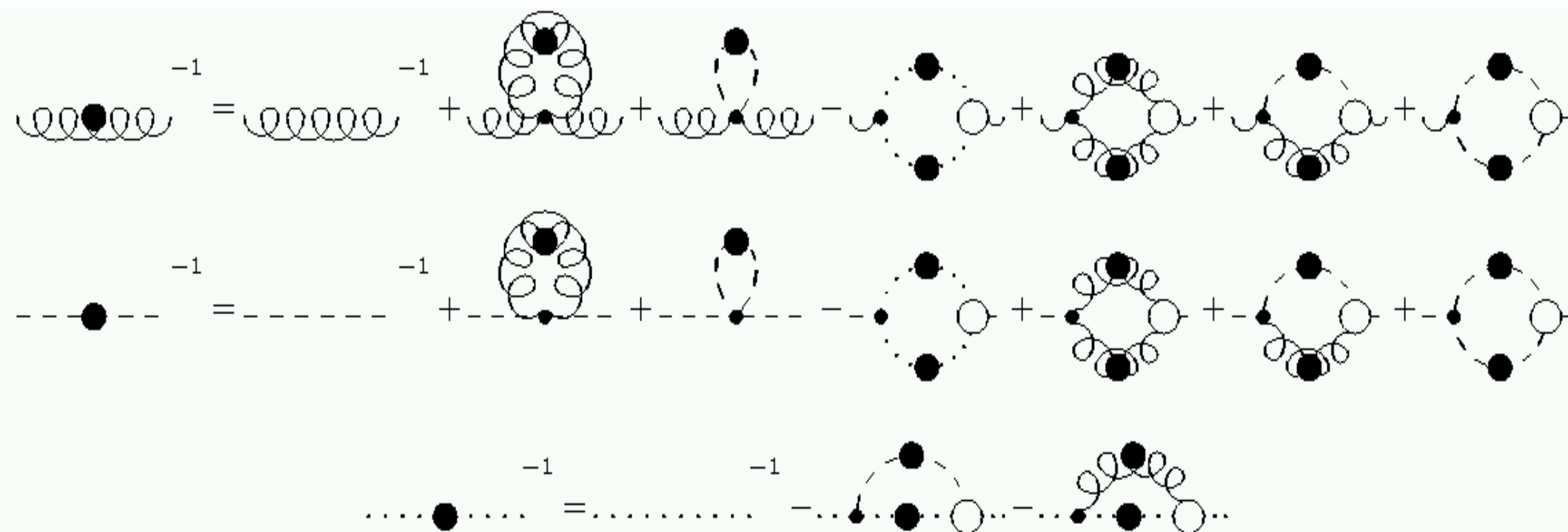
– p_0 **discrete**, $p_0=0$: **soft**, $p_0 \neq 0$: **hard**

(Truncated) Dyson-Schwinger Equations



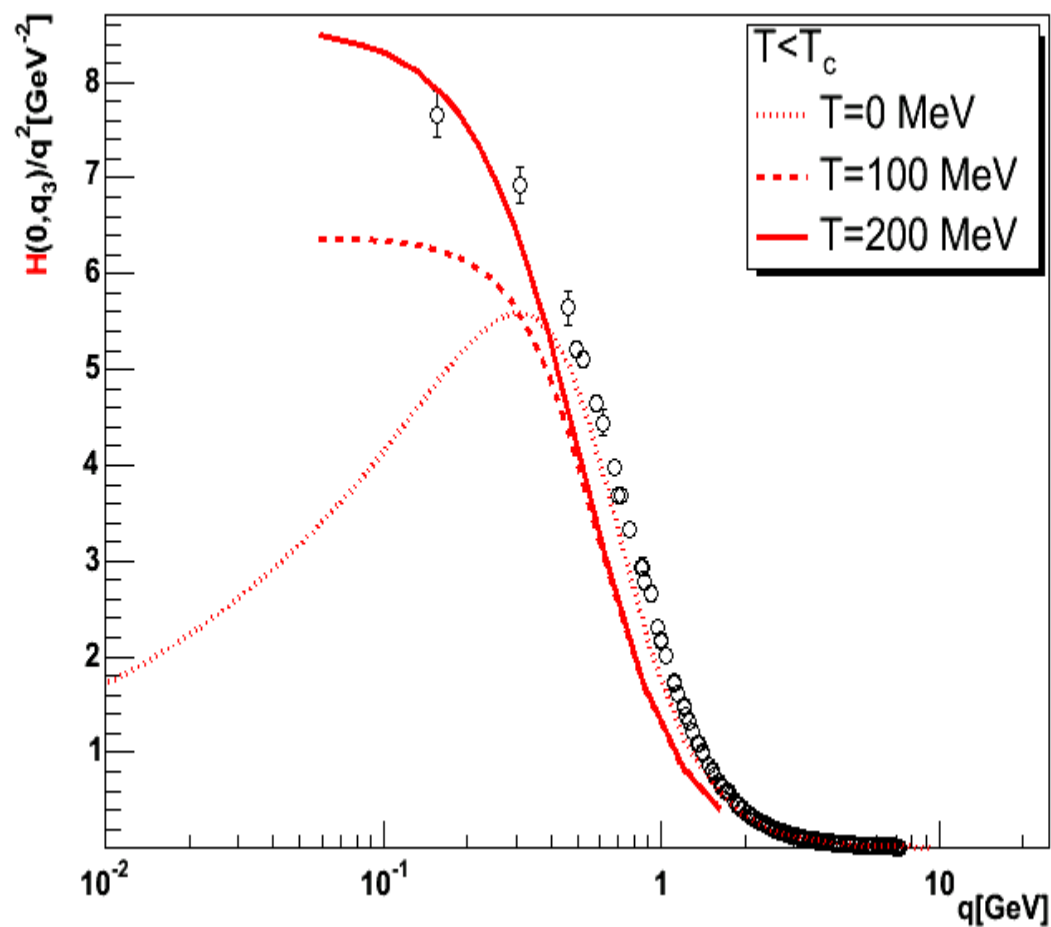
- Significantly **increased complexity**
- Similar problems as in the vacuum: **Under control**

(Truncated) Dyson-Schwinger Equations



- Significantly **increased complexity**
- Similar problems as in the vacuum: **Under control**
- Ghost-gluon vertex nearly bare in the infinite temperature limit [W. Schleifenbaum et al., 2004]

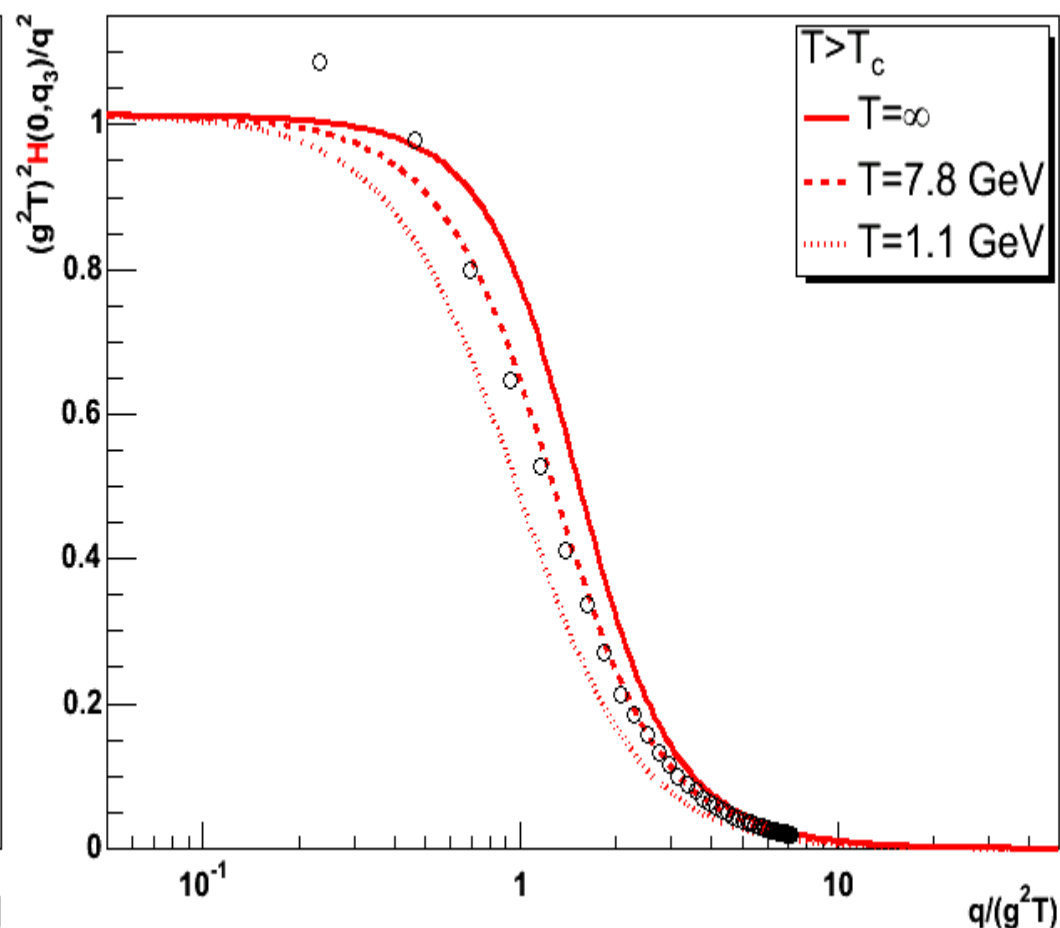
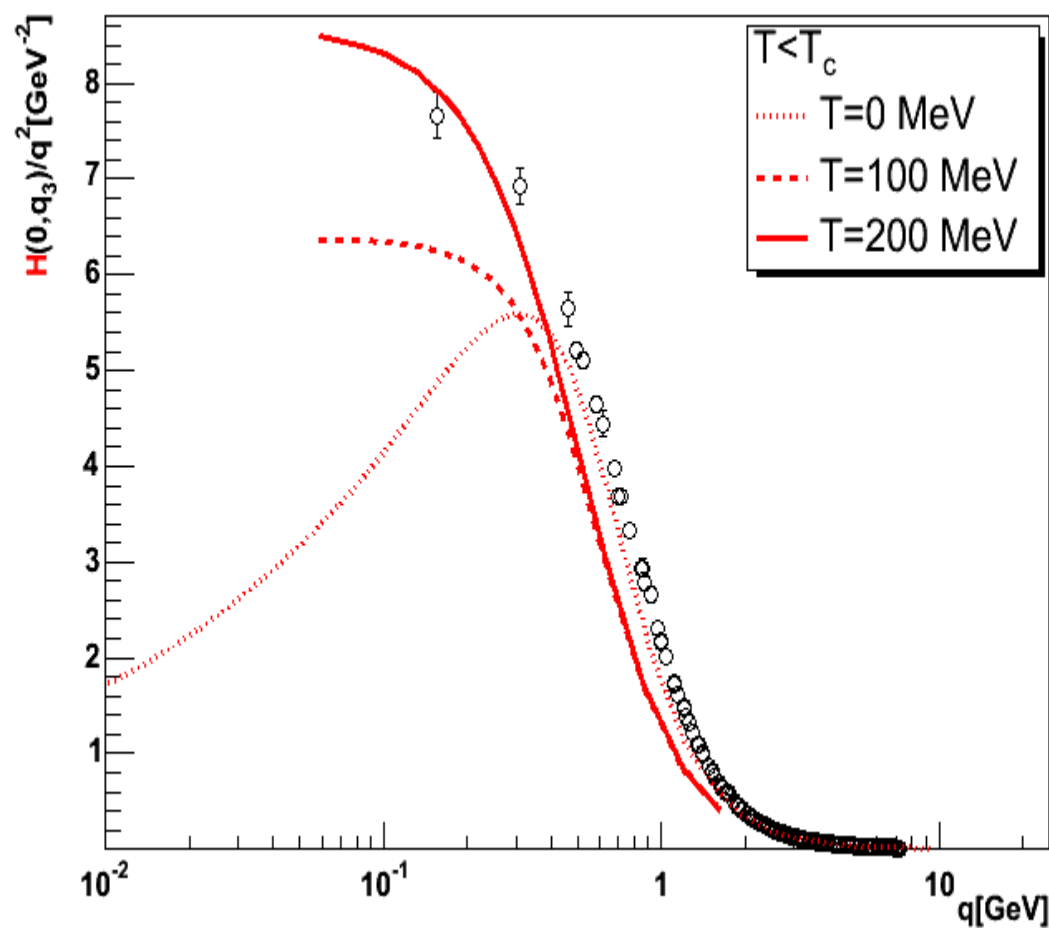
Chromoelectric Gluon



[T=0 DSE: Fischer et al., PLB 2002,
 $T < T_c$ DSE: Grüter et al., 2004
 Lattice at T=0: Bowman et al., 2004]

- **Confined** at small temperatures

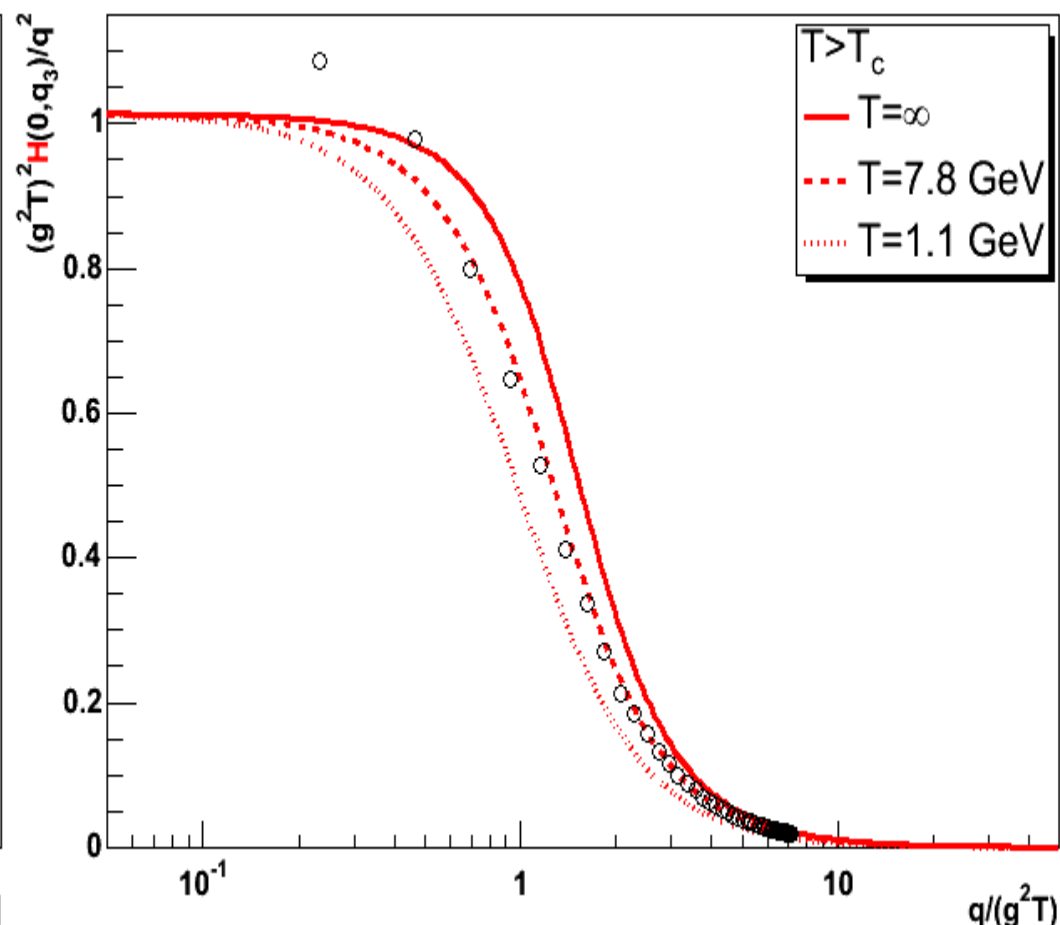
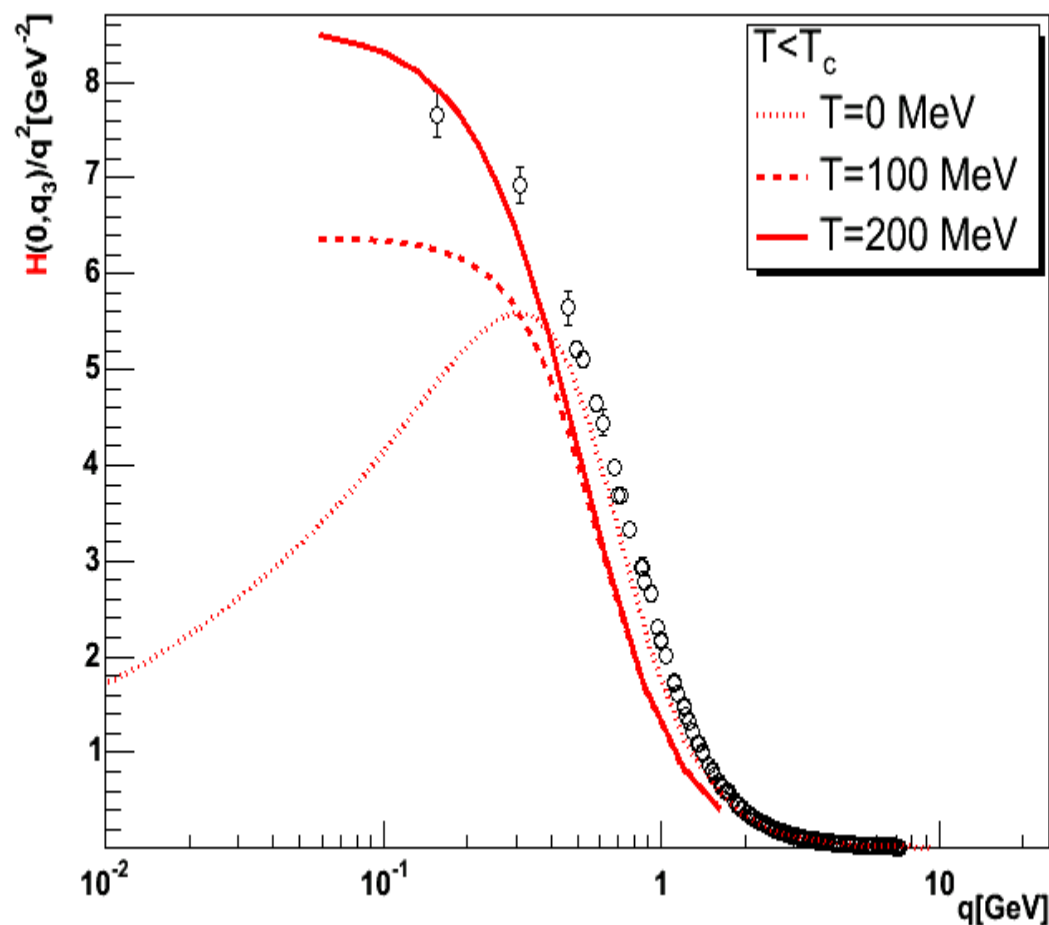
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 Lattice at $T=0$: Bowman et al., 2004
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- **Confined** at small temperatures
- **Screened** at high temperatures

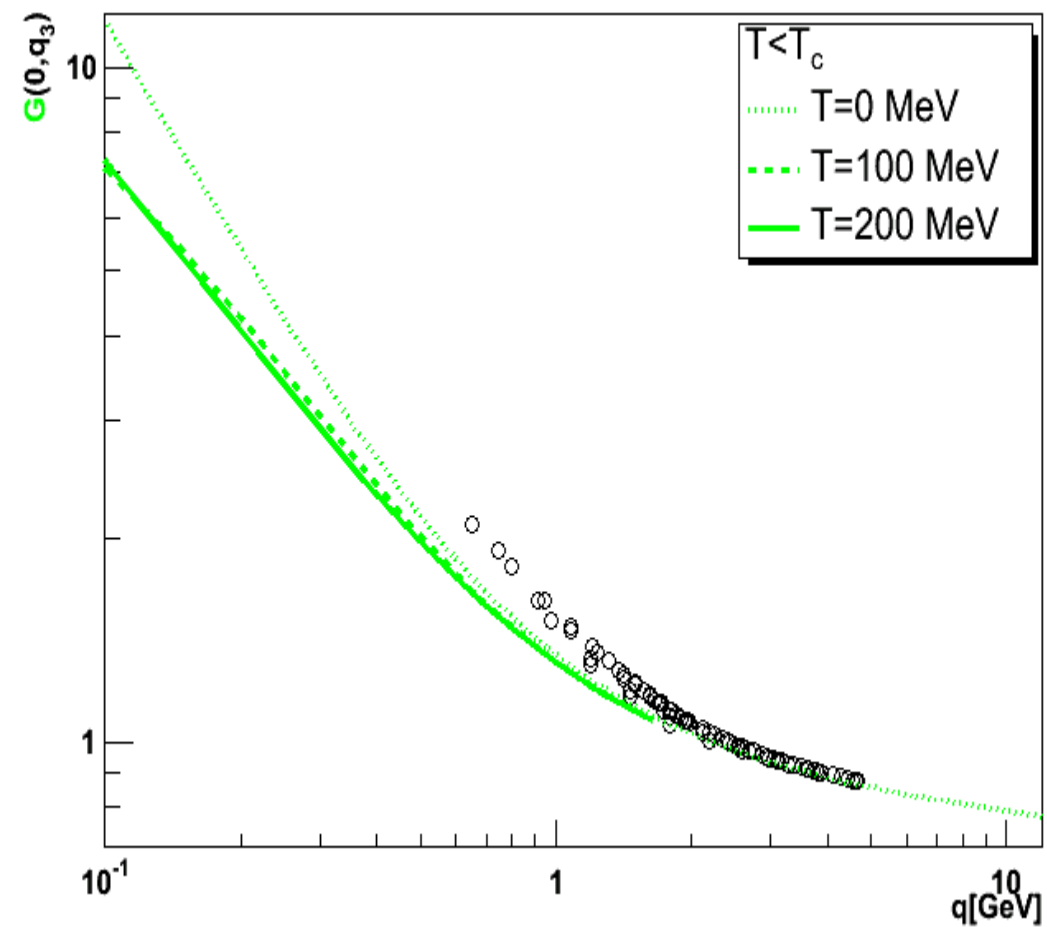
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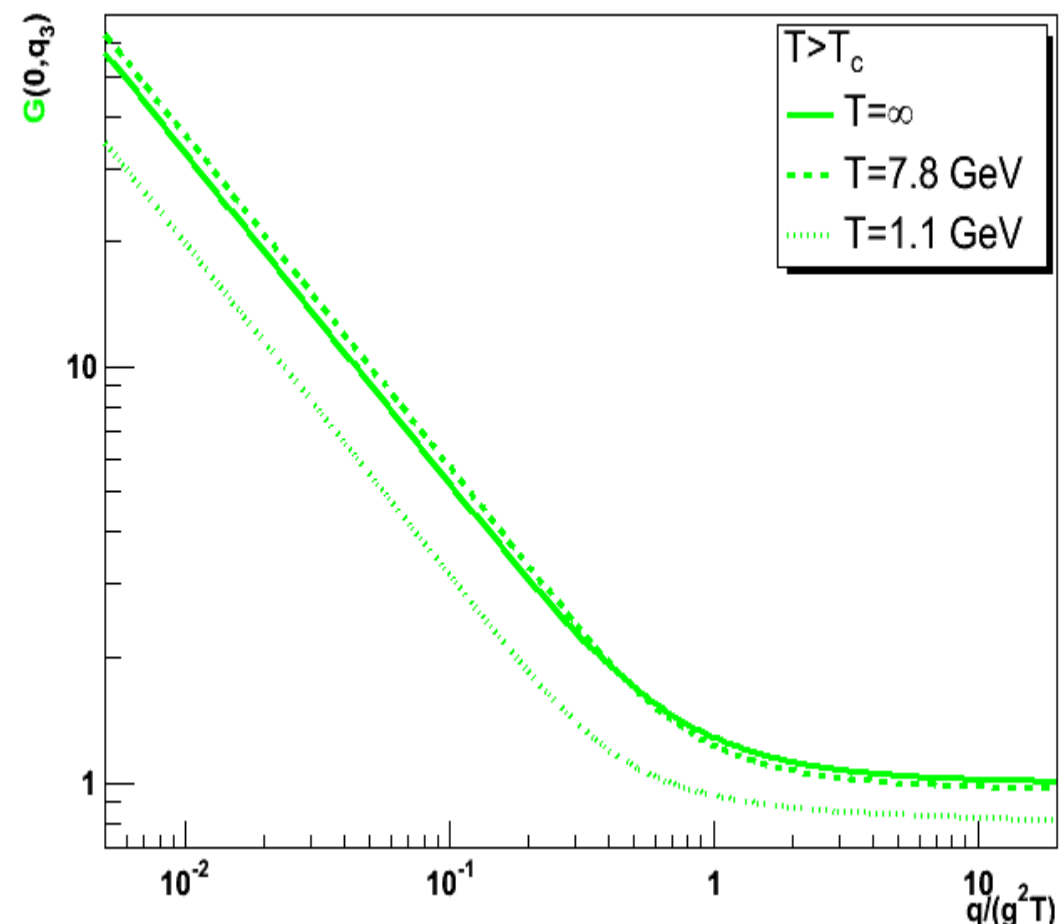
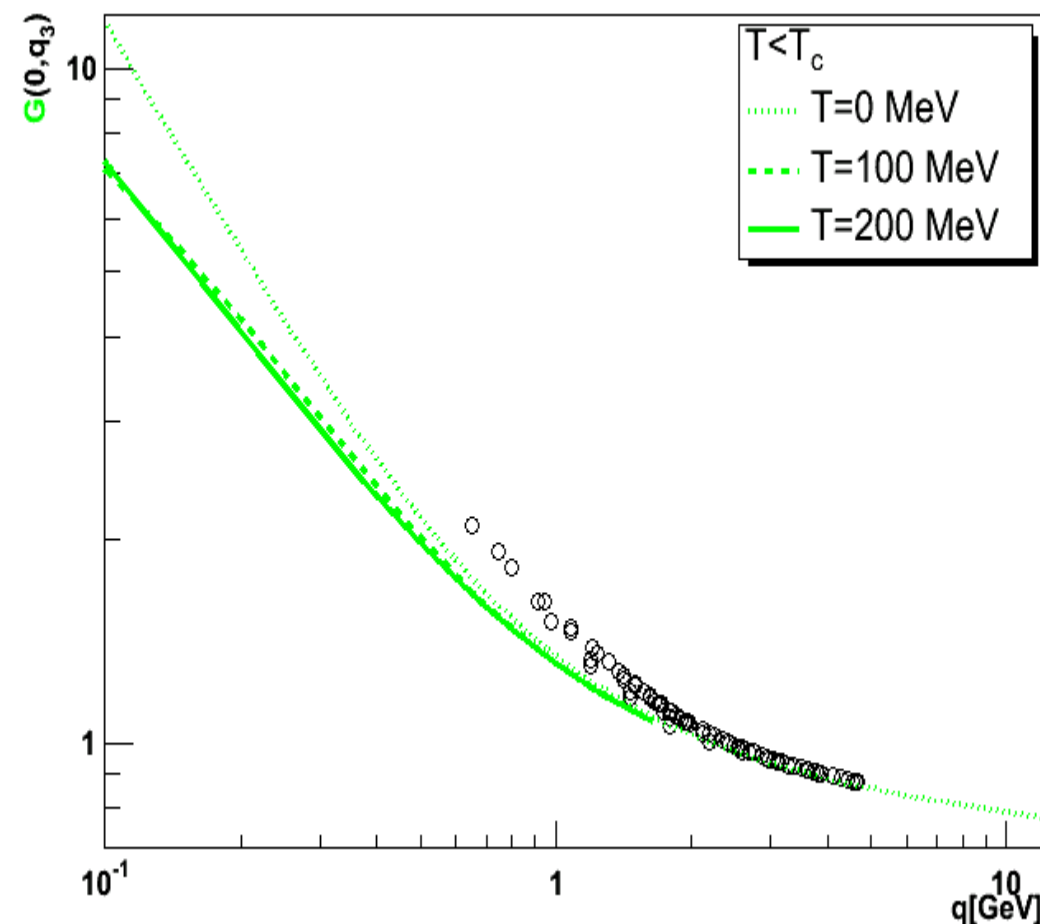
- **Confined** at small temperatures
- **Screened** at high temperatures
- **Non trivial**, possibly confined

Ghost



[T=0 DSE: Fischer et al., PLB 2002
 T<T_c DSE: Grüter et al., 2004
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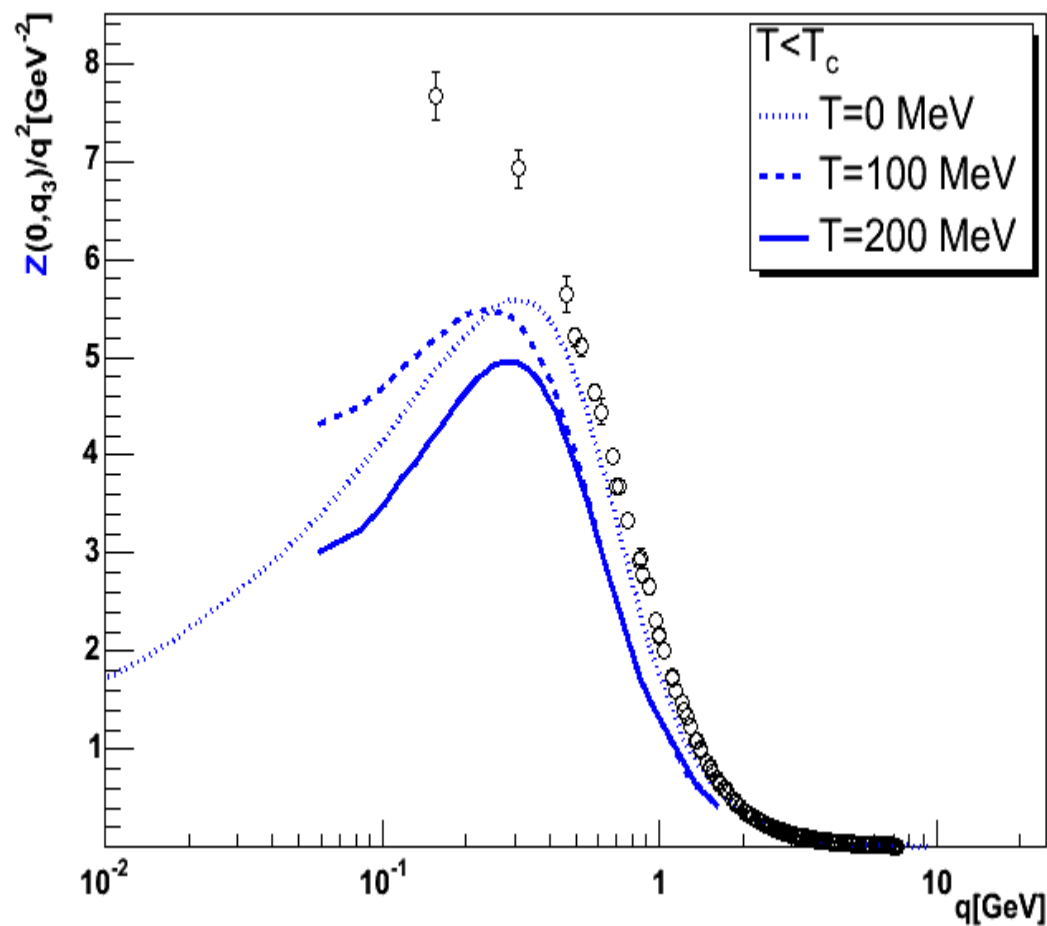
Ghost



- IR qualitatively **independent of temperature**
- Can always **mediate long-range forces**

[$T=0$ DSE: Fischer et al., PLB 2002
 $T < T_c$ DSE: Grüter et al., 2004
 $T > T_c$ DSE: Maas et al., EPJC 2005
 $T=\infty$ DSE: Maas et al., EPJC 2004
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Chromomagnetic Gluon



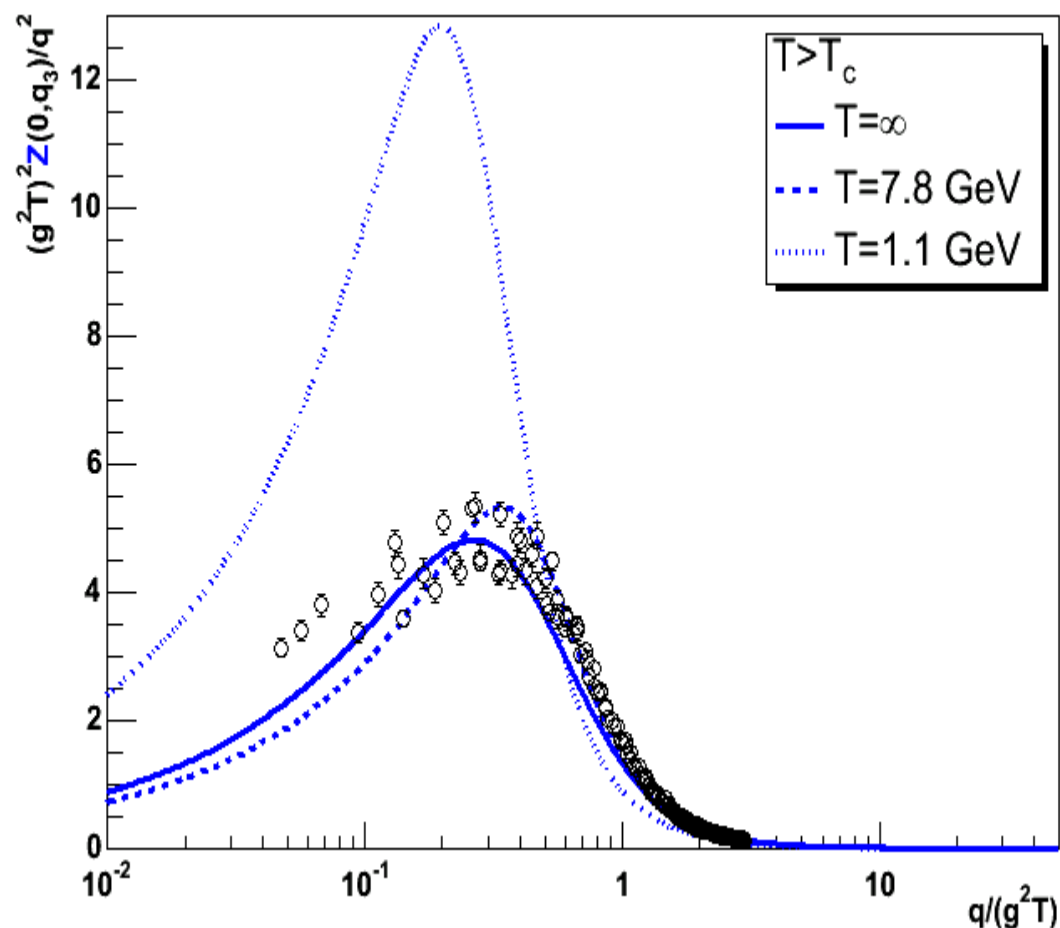
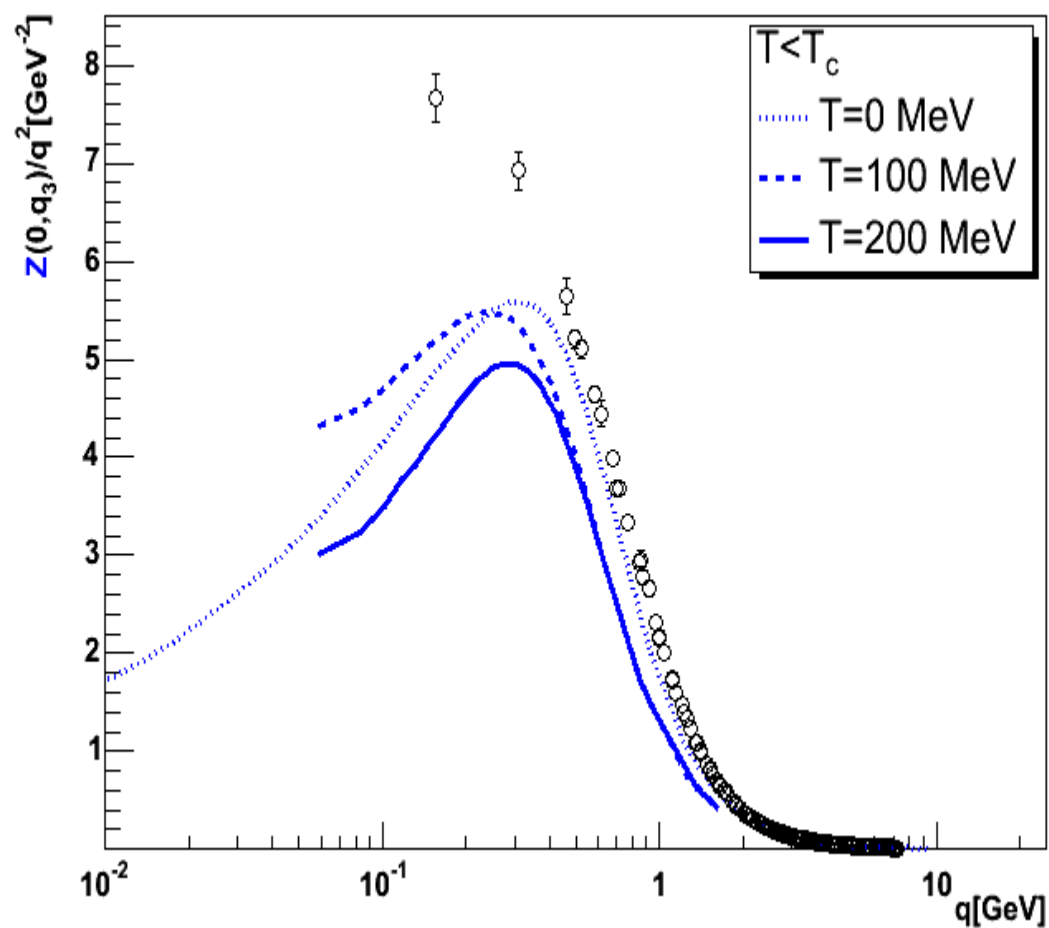
[$T=0$ DSE: Fischer et al., PLB 2002

$T < T_c$ DSE: Grüter et al., 2004

Lattice at $T=0$: Bowman et al., 2004]

- **Confined** at low temperatures

Chromomagnetic Gluon



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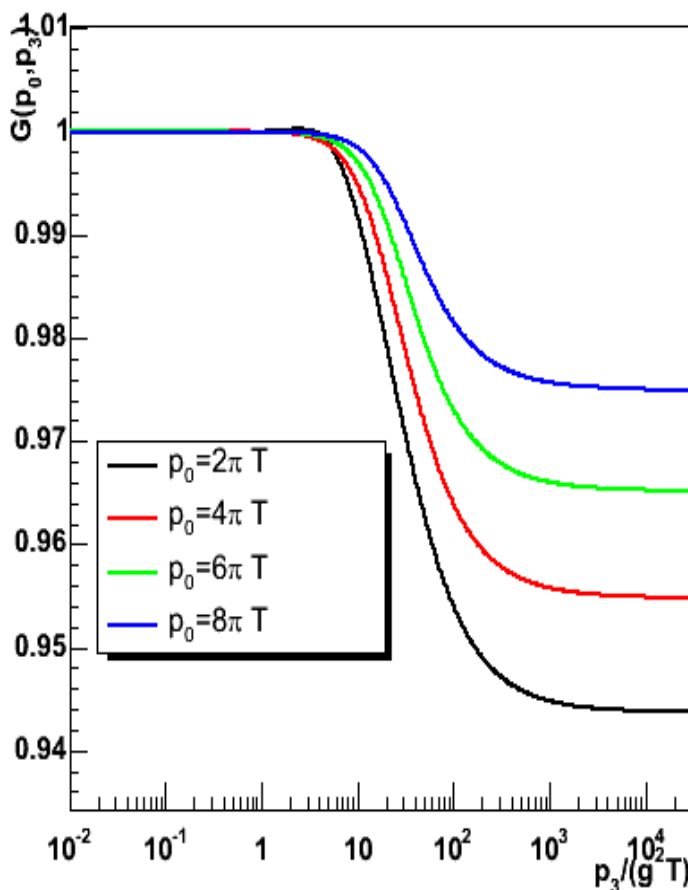
- **Confined** at low temperatures
- Still **confined** at high temperatures
- **Non-trivial phase!**

Hard Modes

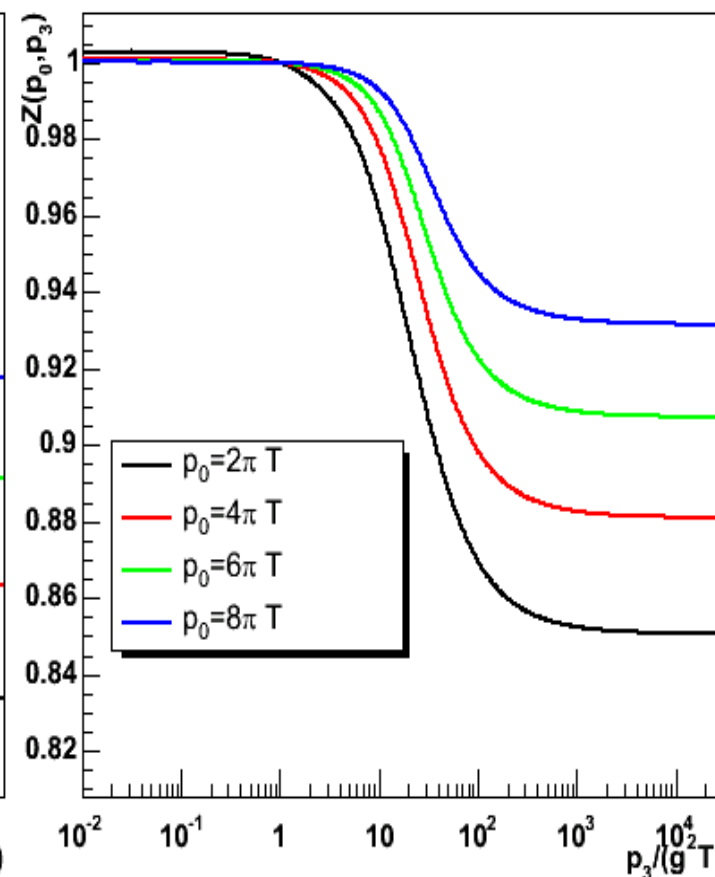
$T=1.5 \text{ GeV}$

[Maas et al., EPJC 2005]

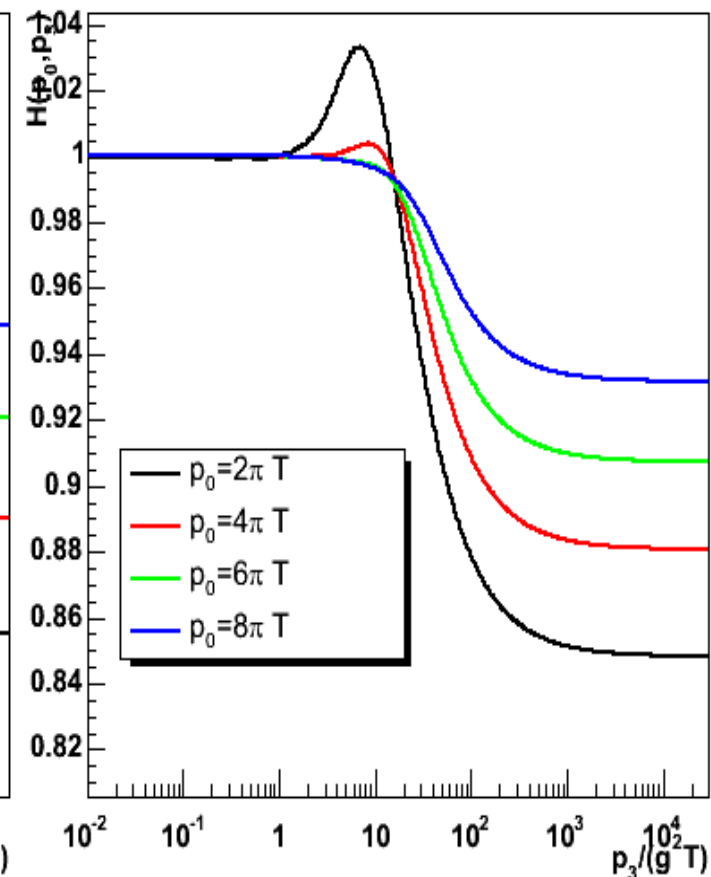
$p_0 \neq 0$ ghost dressing function



$p_0 \neq 0$ transverse dressing function



$p_0 \neq 0$ longitudinal dressing function



- Hard modes **nearly free** down to the phase transition
 - Possibly also non-trivial

Thermodynamic Potential

- Dominated at high temperatures by hard modes

Thermodynamic Potential

- **Dominated at high temperatures by hard modes**
- **Hard modes nearly free: Stefan-Boltzmann-like in agreement with lattice**
 - **Soft modes contribute sub-leading**

Thermodynamic Potential

- **Dominated at high temperatures by hard modes**
- **Hard modes nearly free: Stefan-Boltzmann-like in agreement with lattice**
 - Soft modes contribute sub-leading
- **Soft mode contribution likely relevant at the phase transition** [Zwanziger, 2004]
 - **Important to experiments!**

Interpretation

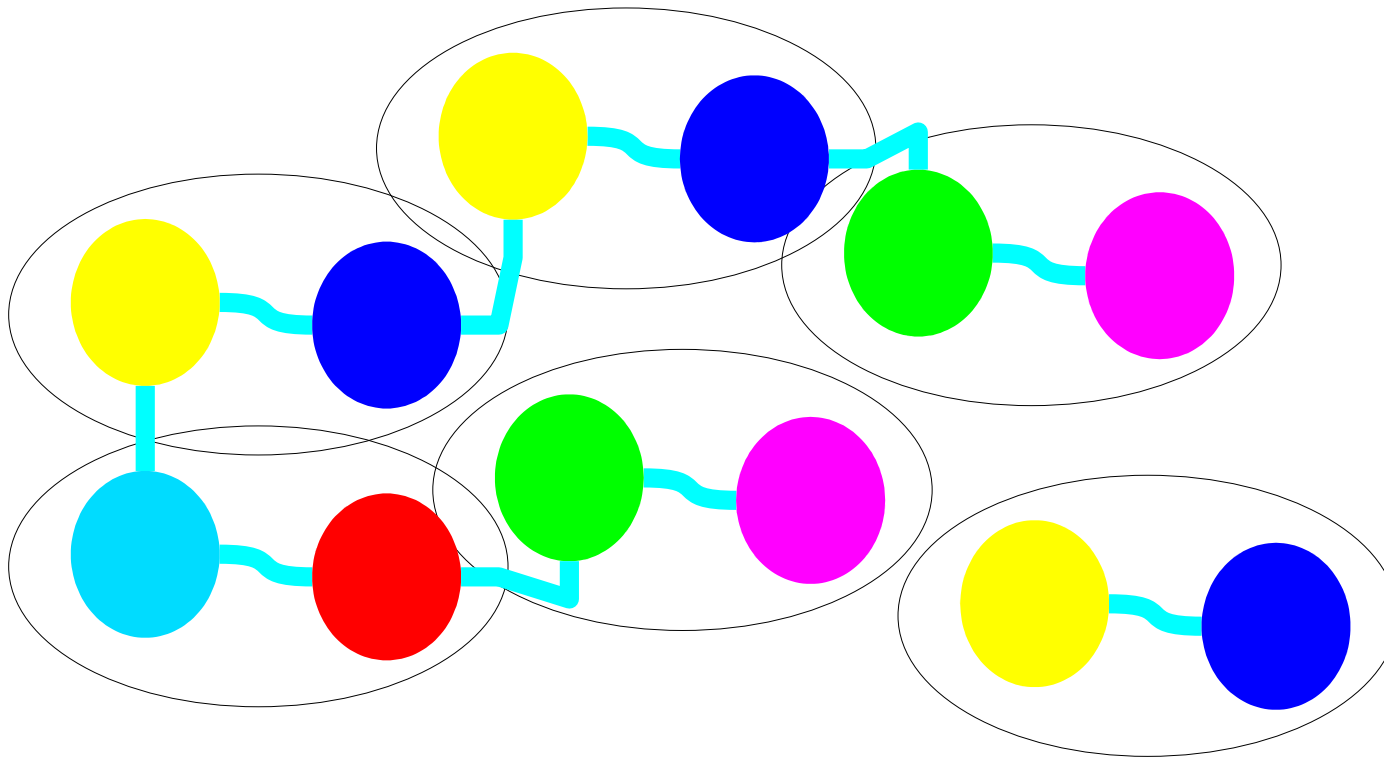
- Results are consistent with other observations on the lattice
 - Spatial string tension, absence of chromomagnetic screening, Z_3 -symmetry restoration
 - Time-like becomes simple, but not space-like

Interpretation

- Results are consistent with other observations on the lattice
 - Spatial string tension, absence of chromomagnetic screening, Z_3 -symmetry restoration
 - Time-like becomes simple, but not space-like
- **Microscopic interactions** dominated by soft modes
 - Quantum fluctuations dominate thermal fluctuations
- **Macroscopic bulk properties** dominated by hard modes
 - Hard modes responsible for chromoelectric screening
- Hints to a **consistent description of the high-temperature phase**

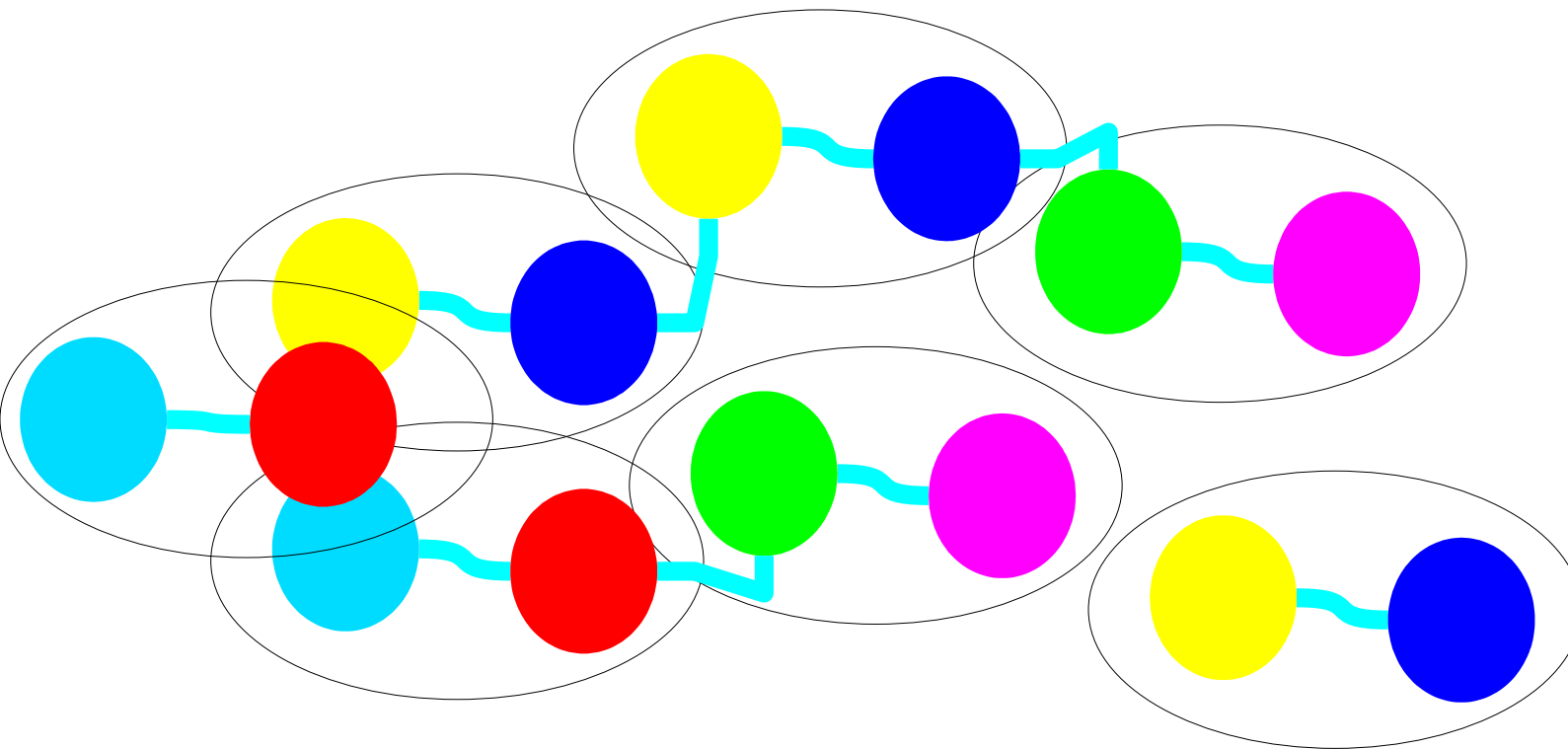
Picture of the high-temperature phase

- How does the high-temperature phase look?



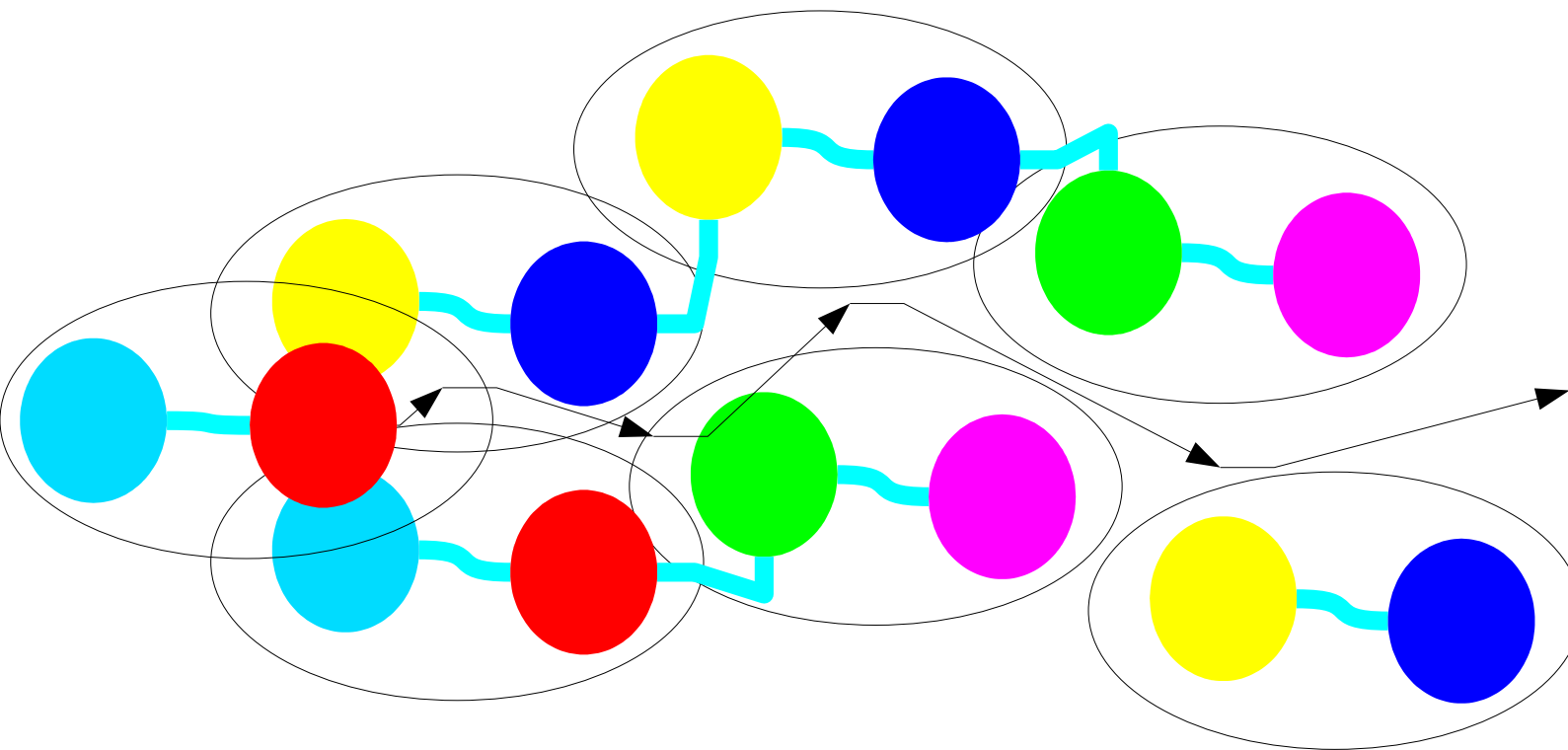
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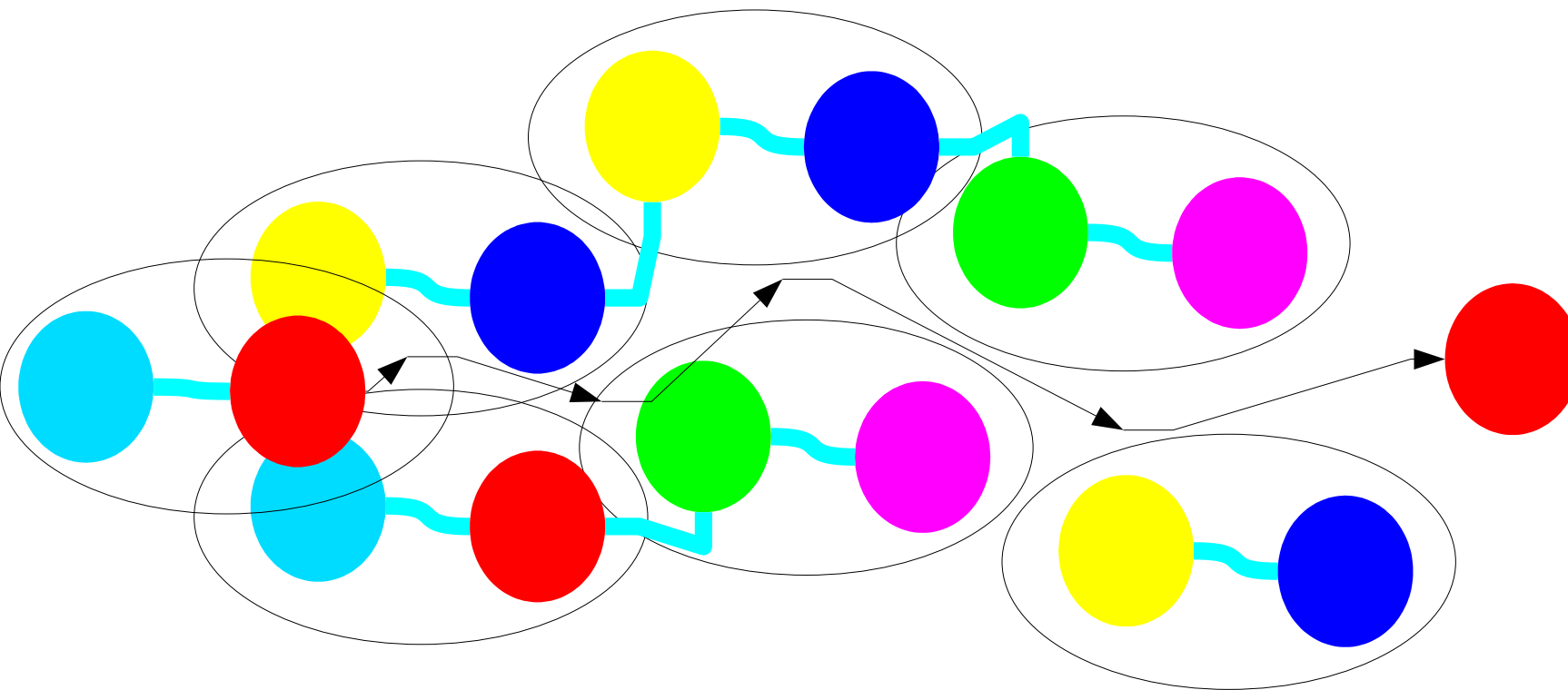
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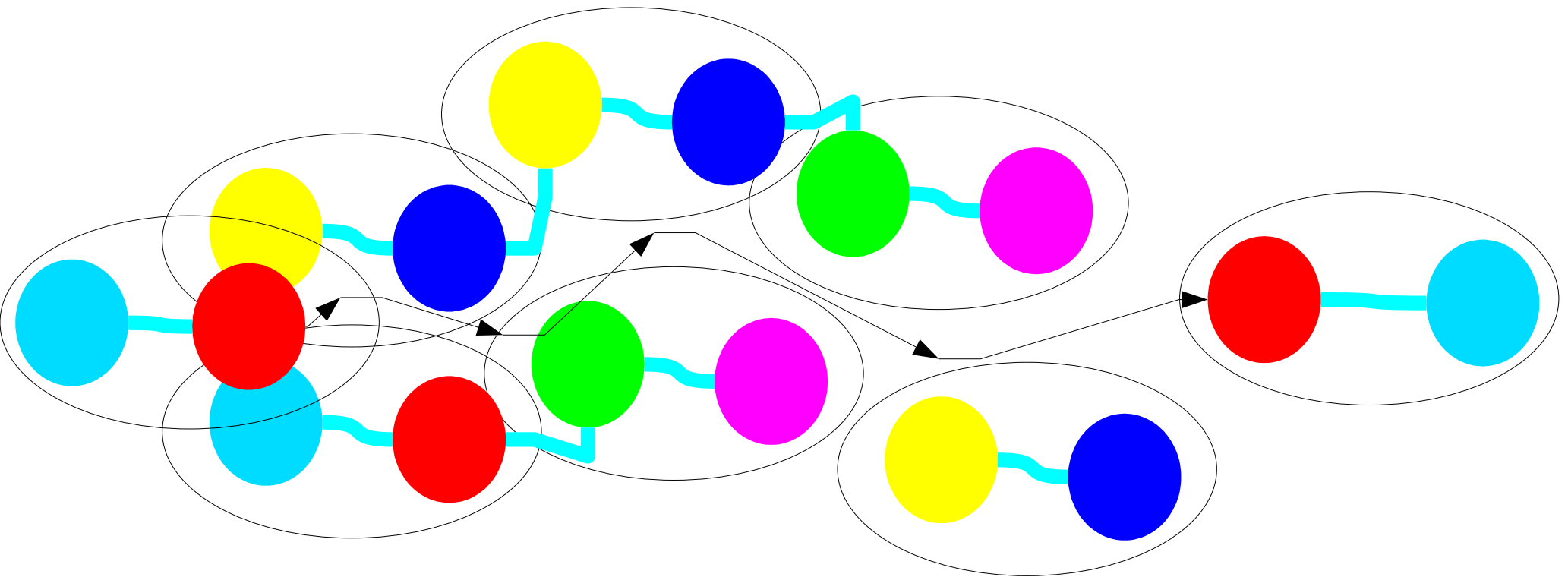
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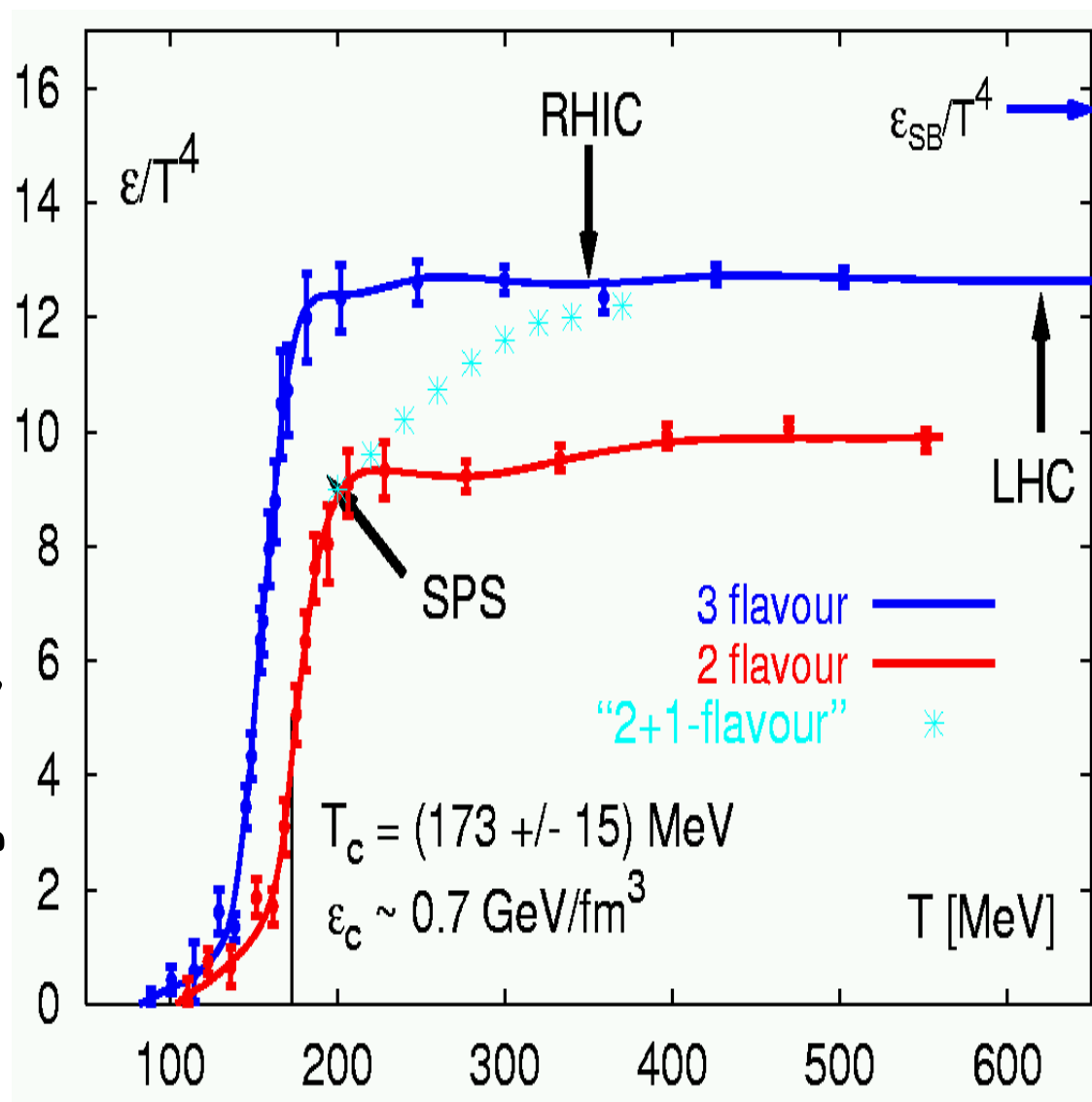
- How does the high-temperature phase look?



- Strongly interacting ("ionic") liquid with delocalized quarks and gluons

Importance for the early universe

- Unclear if a phase transition
- Even if not a drastic change occurs
- Large jump in energy
- **Practical** very similar effects
- **Assume** a 1st order transition



Impact on Nucleosynthesis

- **Baryon-to-photon ratio** is influenced by QCD phase transition

Impact on Nucleosynthesis

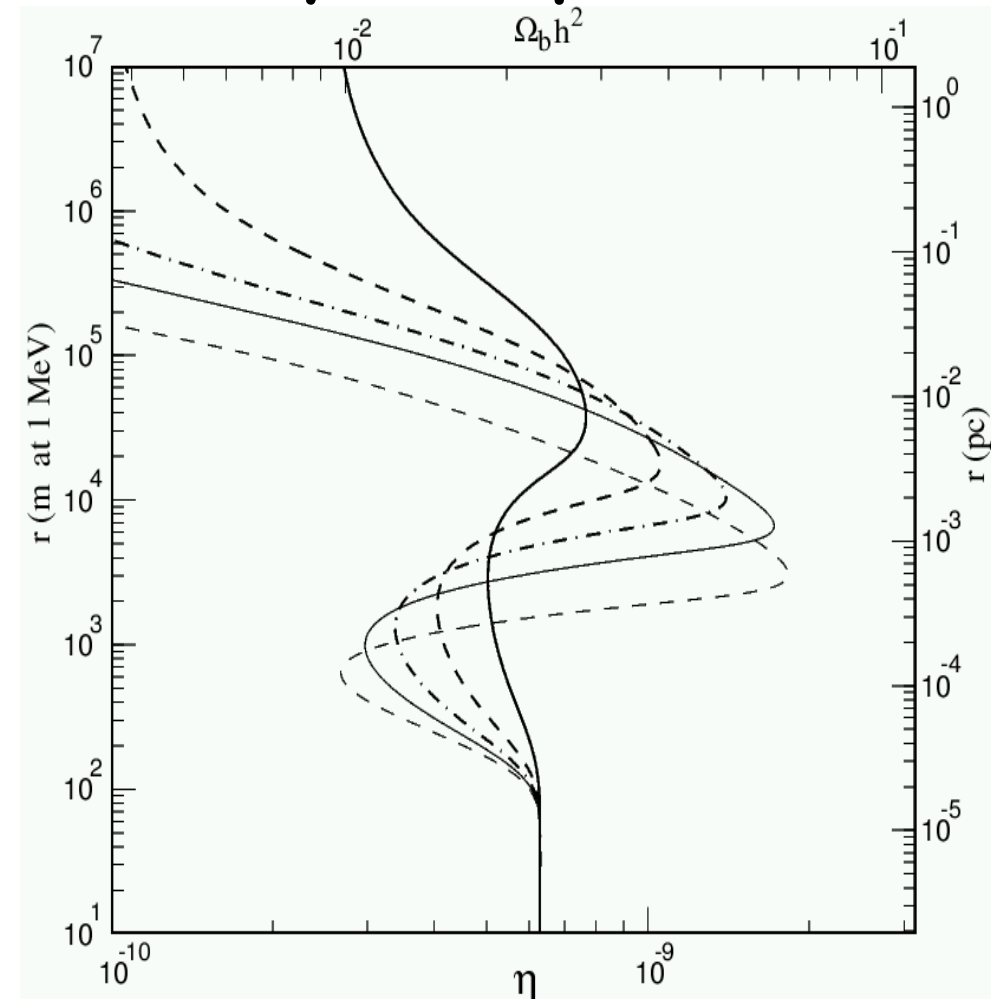
- **Baryon-to-photon ratio** is influenced by QCD phase transition
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Impact on Nucleosynthesis

- **Baryon-to-photon ratio** is influenced by QCD phase transition
 - Quarks electrically charged
 - 1st order phase transition
leads to bubble formation
 - Spatial inhomogeneities

Impact on Nucleosynthesis

- **Baryon-to-photon ratio** is influenced by QCD phase transition
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 - Effect at ~ 150 m initial bubble separation

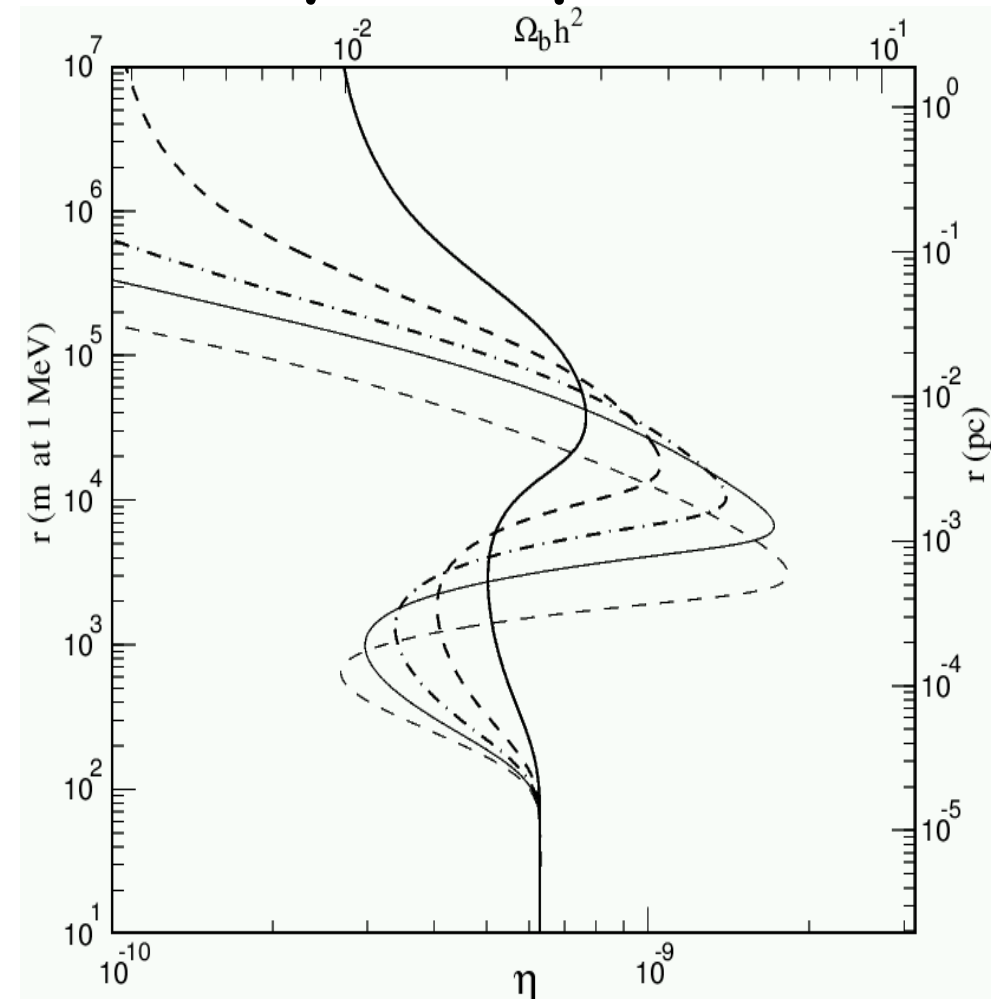


[Figure from Kainulainen, 1999]

Impact on Nucleosynthesis

- **Baryon-to-photon ratio** is influenced by QCD phase transition

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 - **Likely only** ~ 0.01 m



[Figure from Kainulainen, 1999]

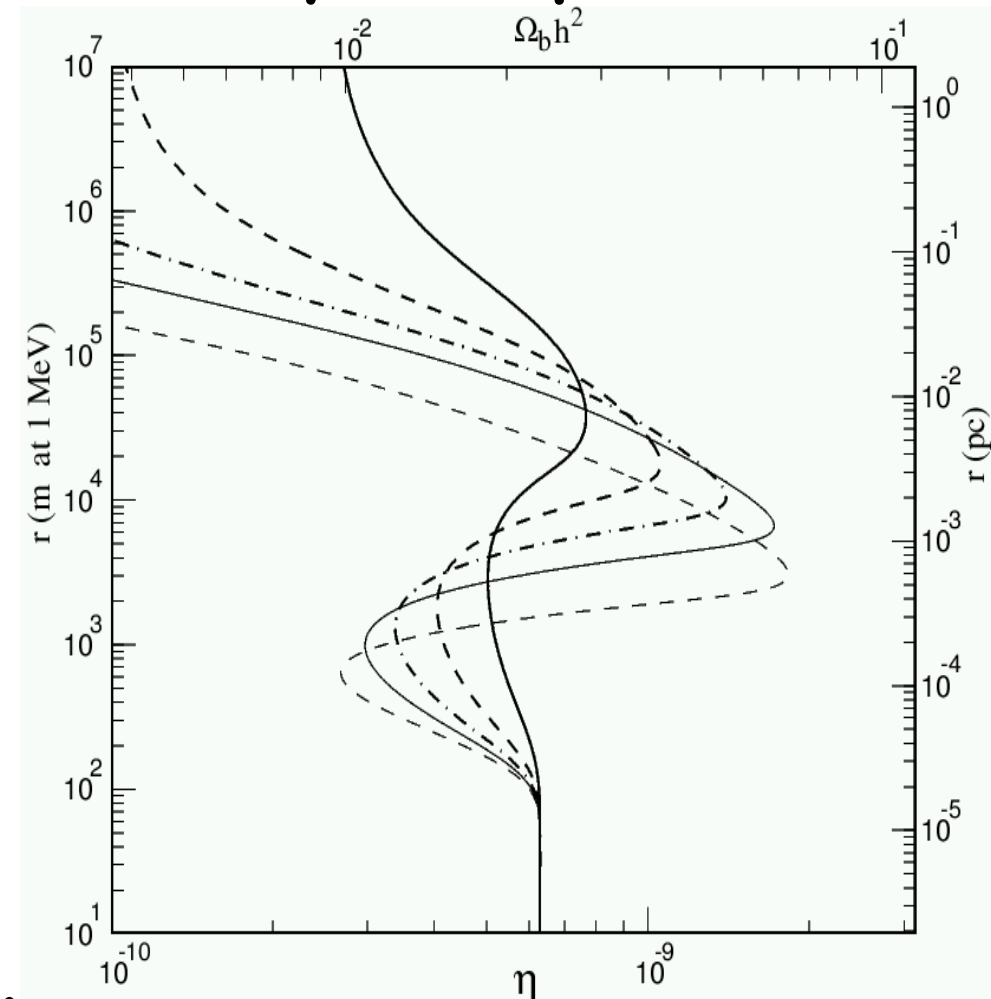
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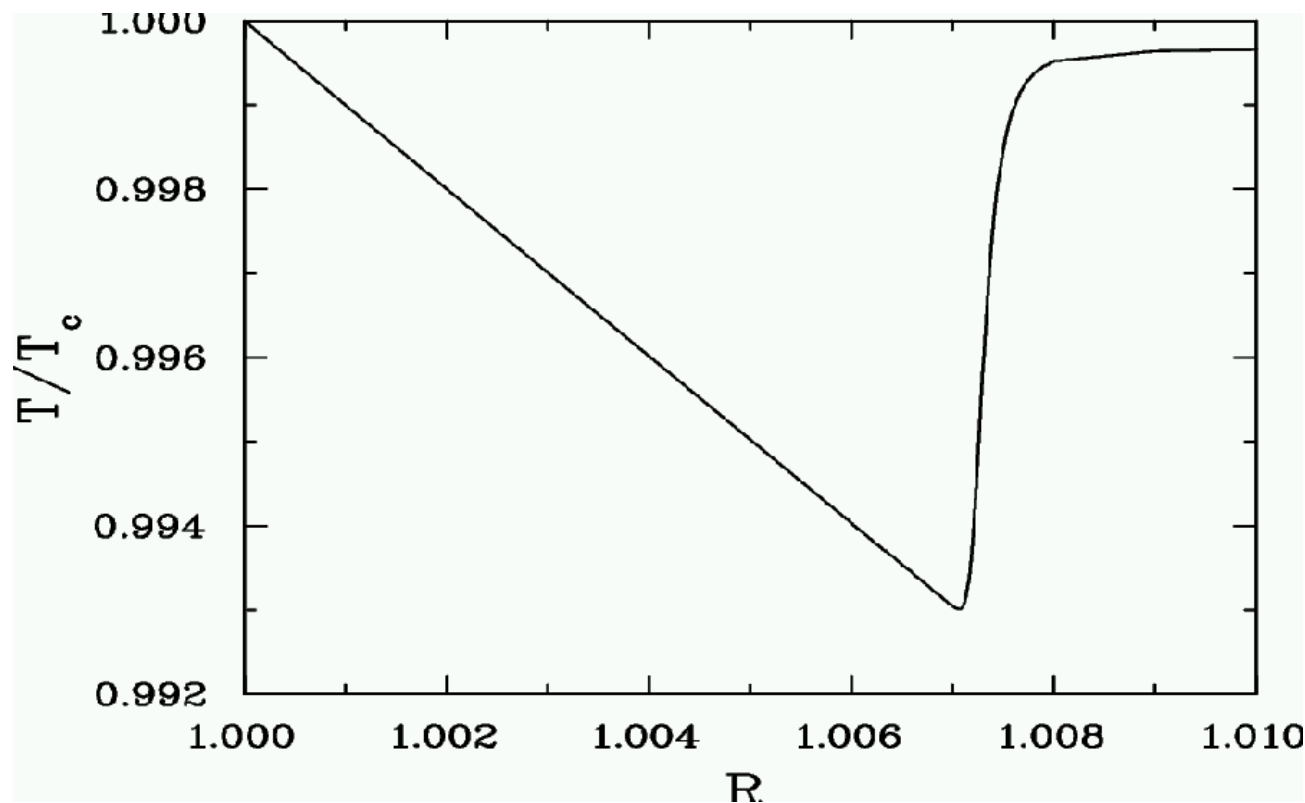
- Importance for chemical composition
 - Cosmological models



[Figure from Kainulainen, 1999]

QCD inflation

- Chiral symmetry restoration similar to inflation transition
- Allows in principle for an **inflationary era** with **reheating**
- QCD phase transition not strong enough to give a measurable effect – too small surface tension (0.03-0.5?)



[Figure from Kapusta, 2001]

Other Consequences

- Much stronger nucleations: **Primordial black hole formation**
- **Strangelets**: Nuggets of strange matter
- Large scale **chromomagnetic walls**
 - Would be observable in CMB for $l > 1000$

Other Consequences

- Much stronger nucleations: **Primordial black hole formation**
- **Strangelets**: Nuggets of strange matter
- Large scale **chromomagnetic walls**
 - Would be observable in CMB for $l > 1000$
- Important for physics beyond the SM
 - Possible trace in cosmological observables
 - Detectable only if high temperature behavior of QCD/standard model is known well enough

Summary

- **High-temperature phase is non-trivial**
- Confinement of soft chromomagnetic modes
 - Probably also chromoelectric (and hard?) modes
- Interactions dominated by soft modes
- Thermodynamics dominated by hard modes
- Basis for a **consistent description** of the **high-temperature phase**
- Necessary to understand experiments and the early universe

Outlook

- Reliability of the method?
- Phase diagram
 - Quarks at finite density and temperature
 - Phase transition
- Connection to the vacuum structure
 - What are the relevant degrees of freedom?
 - How do they behave above the phase transition?
- Hadrons
- Experimental and cosmological signatures

Collaboration

- R. Alkofer (Graz university)
- A. Maas (IFSC USP/previous GSI)
- J. Wambach (GSI & TU Darmstadt)
- Work supported by the BMBF, Helmholtz association, the graduate school Basel-Tübingen and the DFG
- Some e-prints on this topic:
hep-ph/0504019, 0501150, 0411052, 0408282, 0408074
- Previous collaborators:
 - B. Grüter (Now D-fine)
 - W. Schleifenbaum (Now University of Tübingen)