Marco Ruggieri
Catania University, Physics and Astronomy Department

YANG-MILLS THERMODYNAMICS

Quasiparticles and Z(3) lines condensates

QCD@Work 2012, Lecce

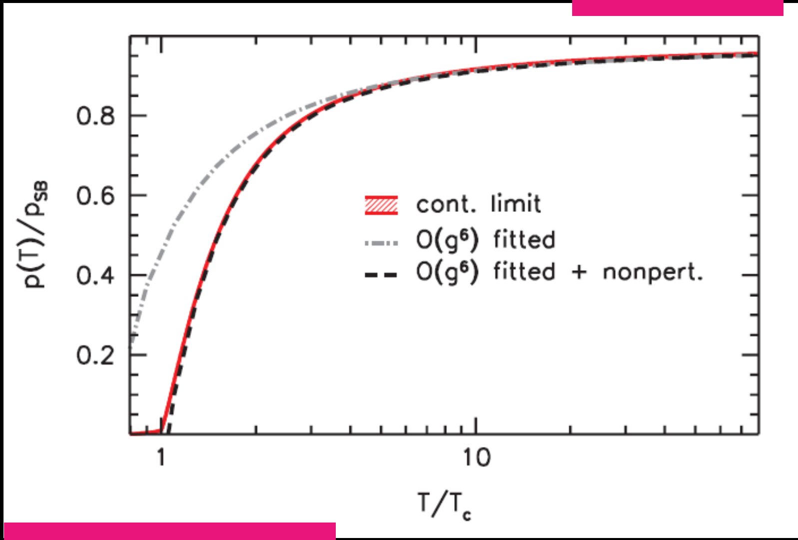
In this talk:

- Salient features of SU(3) Yang-Mills thermodynamics
- Quasiparticles picture of plasmas
- Z(3) lines condensate picture of plasmas
- Merging the two pictures
- Conclusions and Outlook

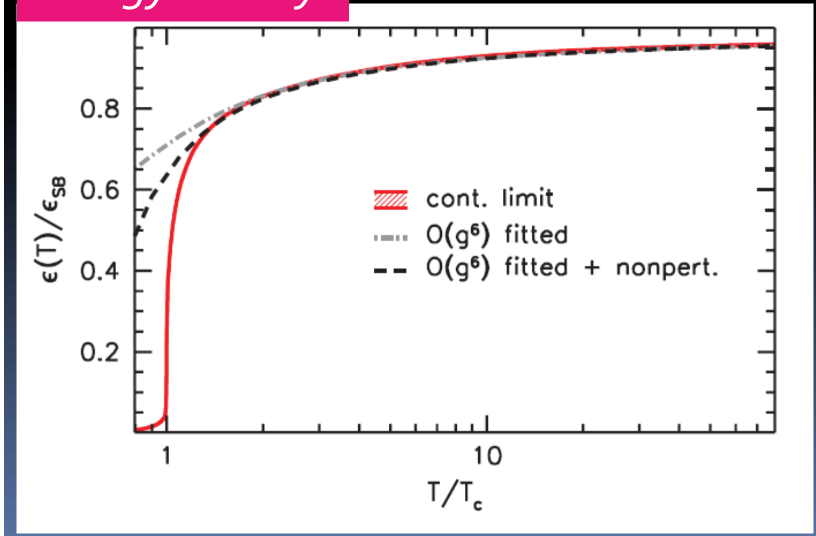
WUB collaboration , **arXiv:1204.6184 [hep-lat]**

Yang-Mills Data

Pressure



Energy density



Hot SU(3) pure Yang-Mills theory

First order phase transition, from hadron phase to deconfinement phase.

Critical temperature: Tc = 270 MeV

Latent heat (energy density jump): about 9×10^9 MeV^4

Non-perturbative regime

Similar results obtained in:

G. Boyd *et al.*, **Nucl.Phys. B469 (1996)**

S. Datta and S. Gupta, **Phys. Rev. D82 (2010)**

G. Endrodi *et al.*, **arXiv:1104.0013**

WUB collaboration , **arXiv:1204.6184 [hep-lat]**

Yang-Mills Data

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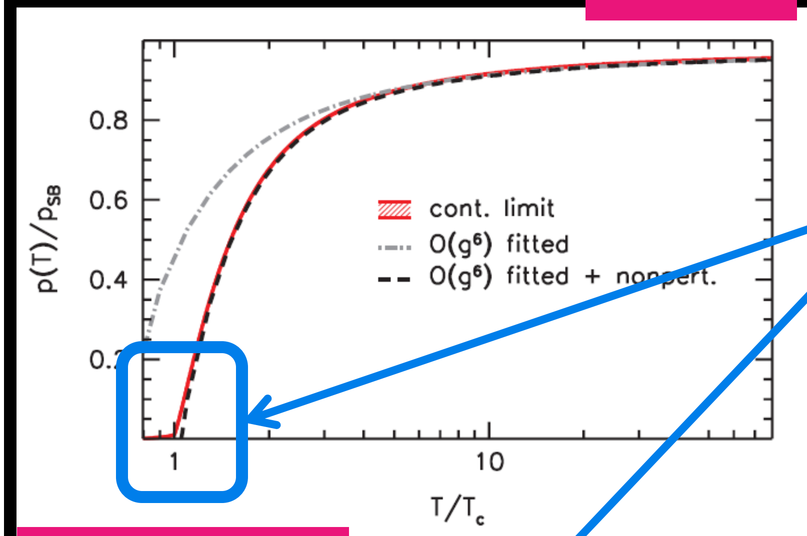
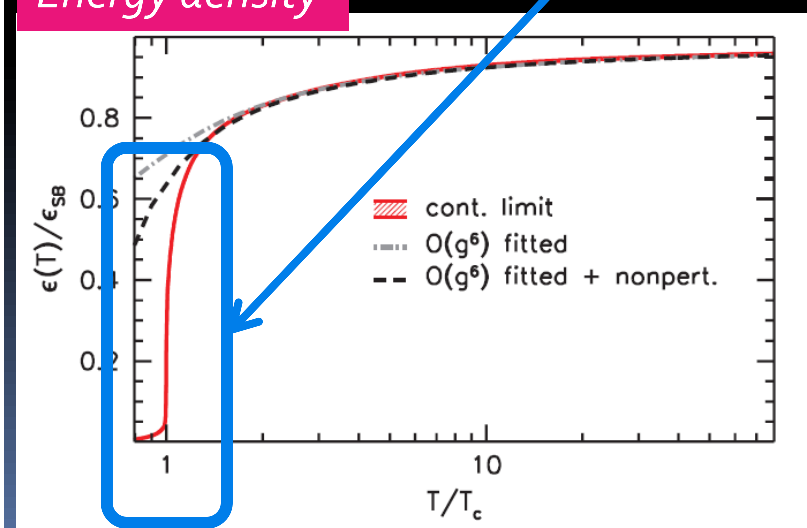


Energy density



Hot SU(3) pure Yang-Mills theory

First order phase transition, from hadron phase to deconfinement phase.

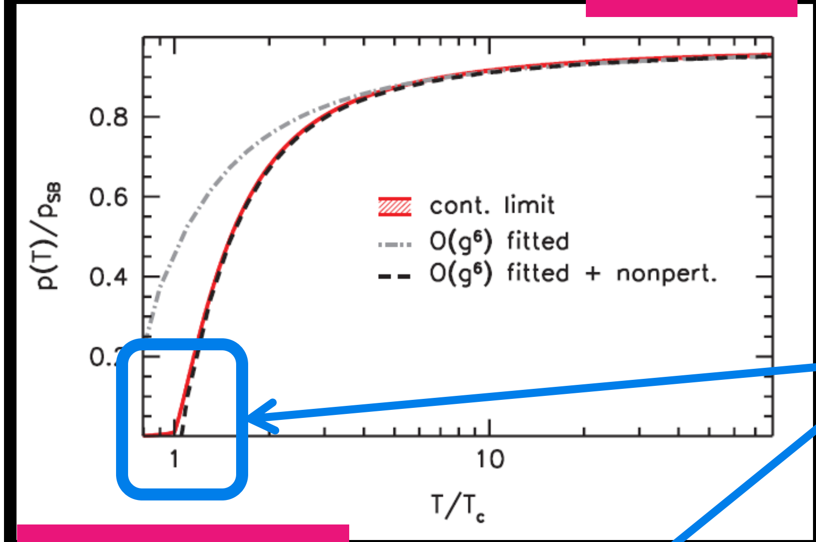
Hadron (Confinement) Phase:
Glueballs + Hagedorn Spectrum
(WUB collaboration , **arXiv:1204.6184**
H. B. Meyer, **Phys. Rev. D80 (2009)**)

Deconfinement Phase:
Gluon Quasiparticles
Z(3) Lines Condensate

WUB collaboration , **arXiv:1204.6184 [hep-lat]**

Yang-Mills Data

Pressure



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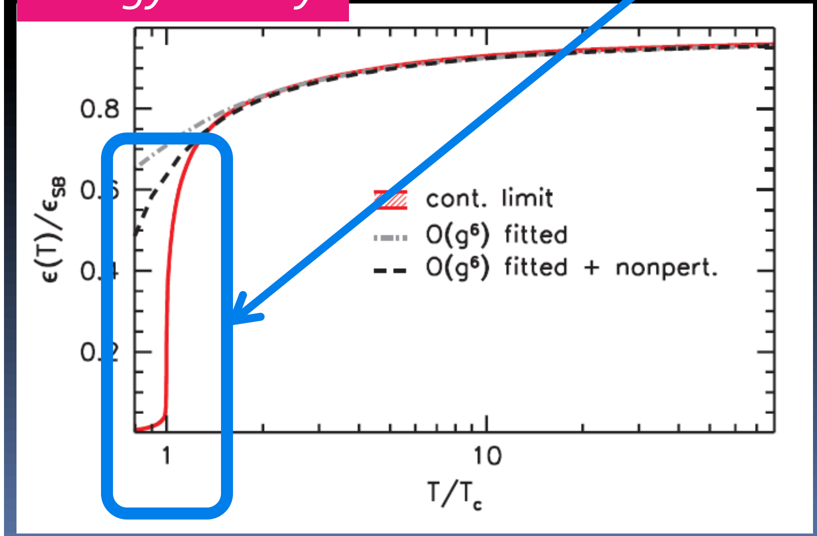
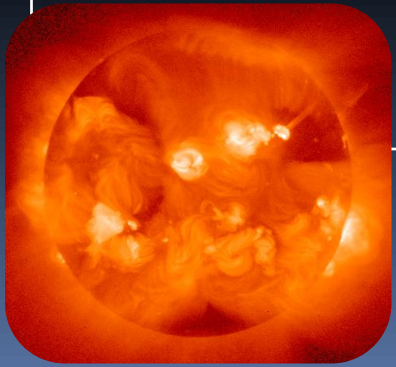


Hot SU(3) pure Yang-Mills theory

First order phase transition, from hadron phase to deconfinement phase.

Critical temperature: Tc = 270 MeV (about 3×10^{12} Kelvin)

For comparison:
Sun core temperature: about **10^7 Kelvin**
Supernova core: about **5×10^{11} Kelvin**
(from NASA website)



WUB collaboration , **arXiv:1204.6184 [hep-lat]**

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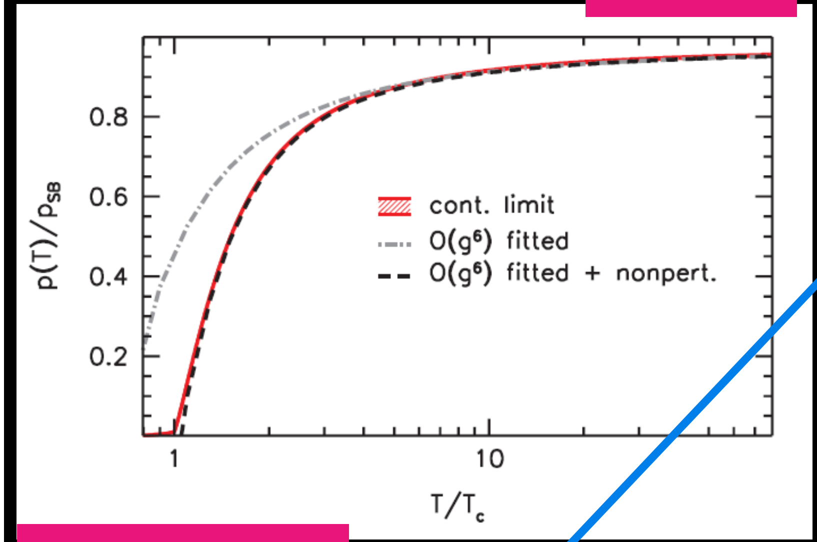

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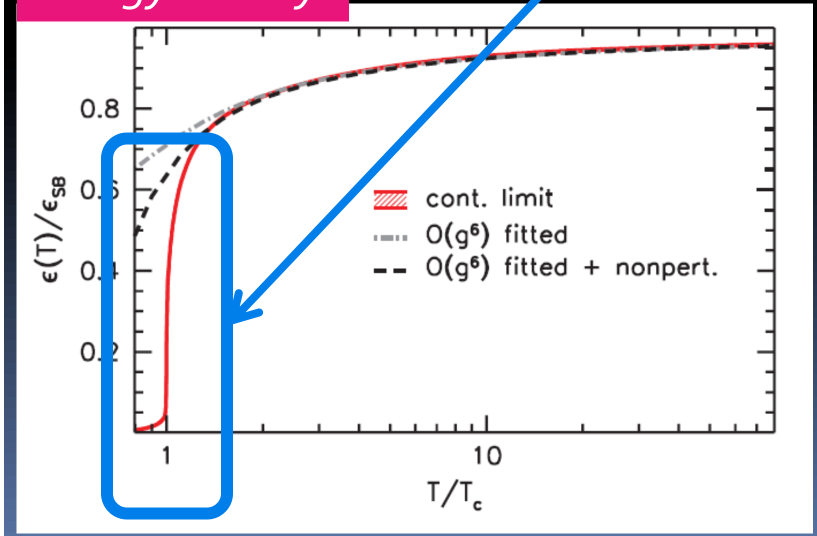


Hot SU(3) pure Yang-Mills theory

Latent heat (energy density jump):
about 9×10^9 MeV^4

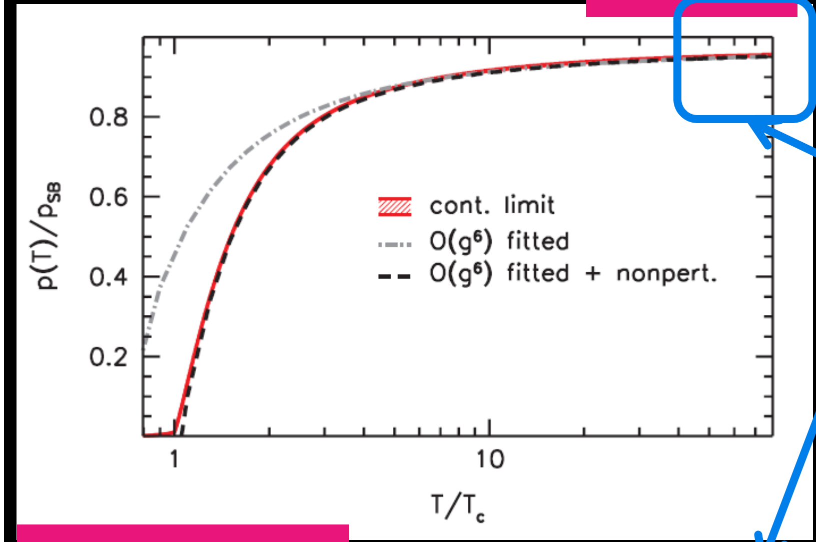
About 10^{26} times larger than boiling water:

SU(3): about **10^{29} J/cm^3**
Boiling water: about **10^3 J/cm^3**

WUB collaboration , **arXiv:1204.6184 [hep-lat]**

Yang-Mills Data

Pressure



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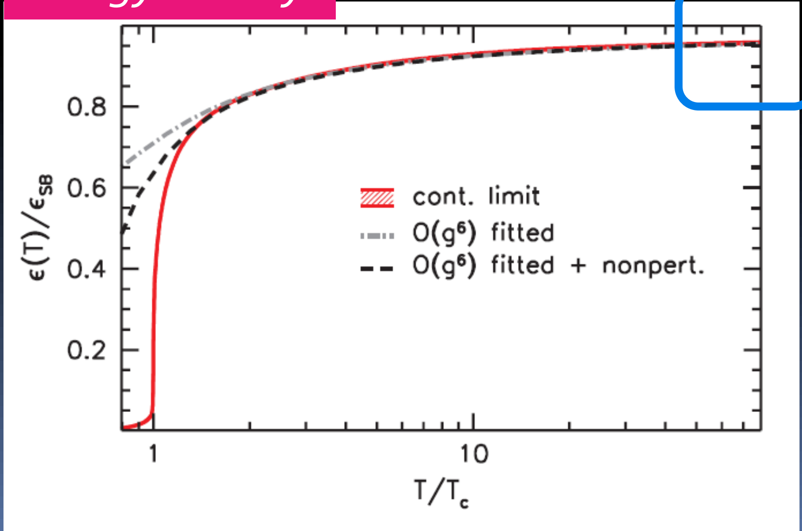


Hot SU(3) pure Yang-Mills theory

"Non-perturbative" regime

Data below **Stefan-Boltzmann limit** (gas made of free massless particles)

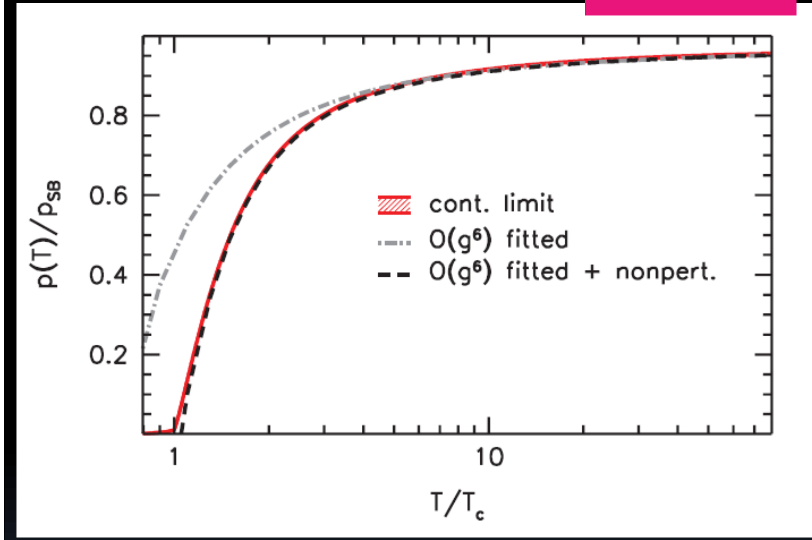
$$P = v_b \frac{\pi^2 T^4}{90} \qquad \varepsilon = v_b \frac{\pi^2 T^4}{30}$$

(for example, at T=100 Tc, p/pSB = 0.95)

Yang-Mills Thermodynamics

<u>Scope</u>: understand Lattice data about thermodynamics, in terms of the relevant degrees of freedom.

Pressure



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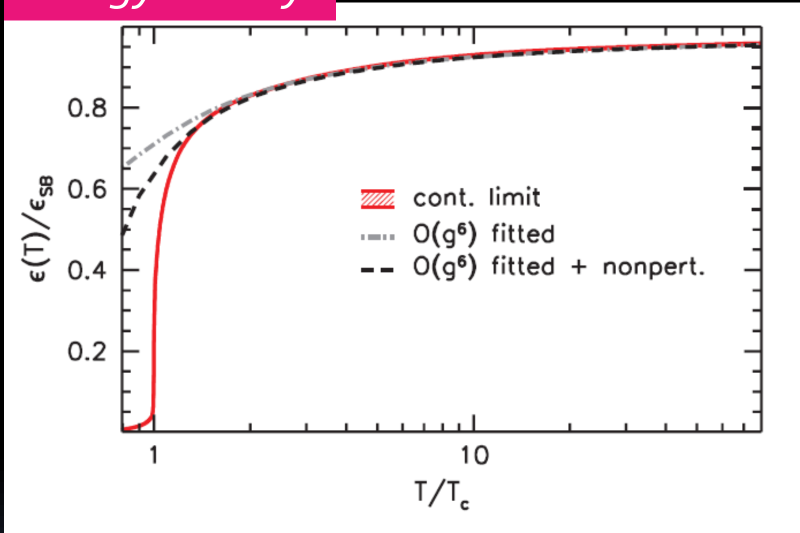


Microscopic/Phenomenological description of Lattice data is interesting for (at least) two reasons:

1.) Better theoretical understanding of hot and deconfined Yang-Mills system.

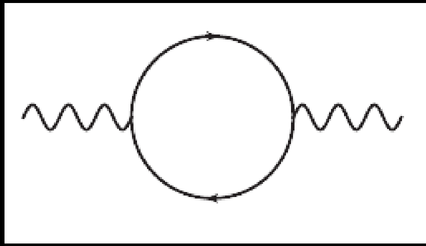
2.) Applications to heavy ion collision simulations.

Collective excitations in a QCD plasma

Retarded gluon propagator at finite temperature:

$$D^R_{\mu\nu} = \frac{i}{Q^2 - G} P^T_{\mu\nu} + \frac{i}{Q^2 - F} P^L_{\mu\nu} - i\frac{\xi}{Q^2}\frac{Q_\mu Q_\nu}{Q^2}$$

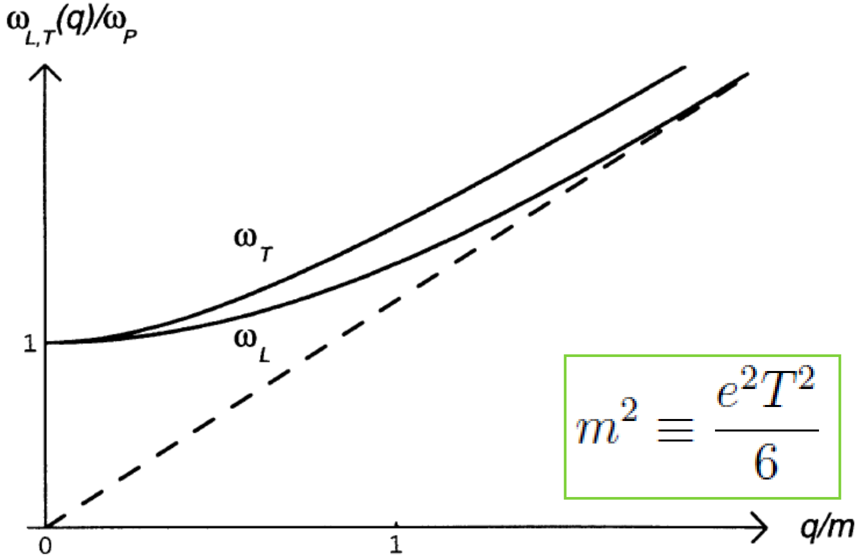
G = *Transverse* self-energy
F = *Longitudinal* self-energy



Poles of transverse and longitudinal parts of the gluon propagator give the *dispersion laws* for the transverse and longitudinal *damped travelling waves* in the plasma.

$$\omega_T^2(\boldsymbol{q}) = \boldsymbol{q}^2 + \mathrm{Re}G(q_0 = \omega_T(\boldsymbol{q}), \boldsymbol{q})$$

$$\omega_L^2(\boldsymbol{q}) = \boldsymbol{q}^2 + \mathrm{Re}F(q_0 = \omega_L(\boldsymbol{q}), \boldsymbol{q})$$



$$m^2 \equiv \frac{e^2T^2}{6}$$

H. Arthur Weldon, **Phys. Rev. D26 (1982)**
See also:
Le Bellac textbook

Collective excitations in a QCD plasma

G = *Transverse* self-energy
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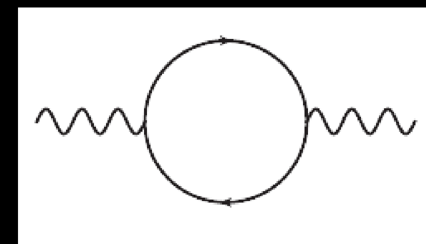

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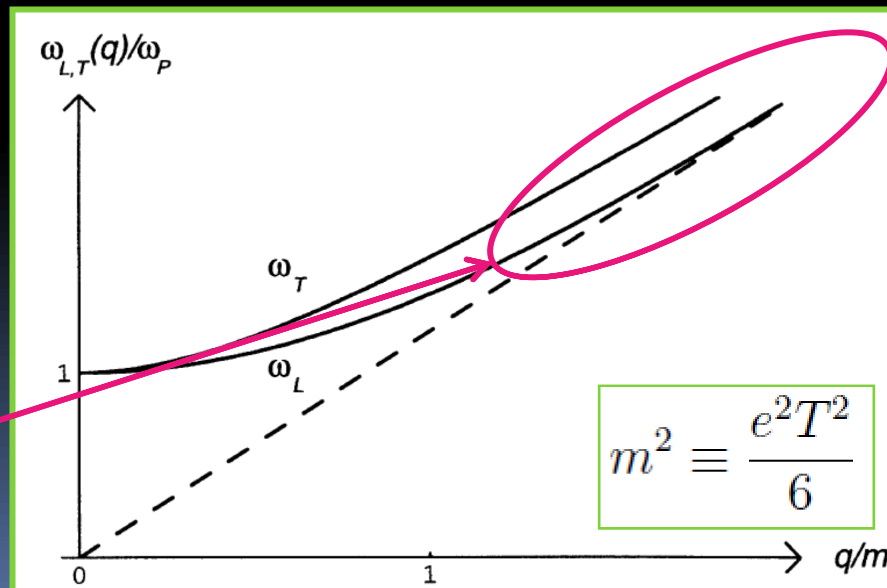
$|\boldsymbol{q}| \gg m :$

Transverse (Gluons) $\omega_T^2 \approx \boldsymbol{q}^2 + m^2$

Longitudinal (Plasmon) $\omega_L^2 \approx \boldsymbol{q}^2$



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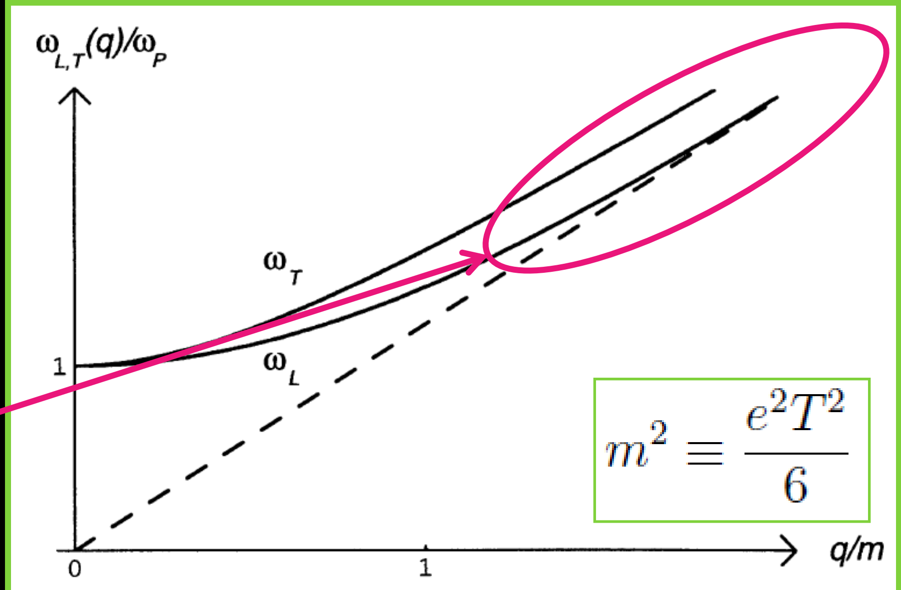

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Longitudinal (Plasmon) $\omega_L^2 \approx \boldsymbol{q}^2$

$$D_{pole} \approx \frac{Z(q_0, \boldsymbol{q})}{q_0^2 - \boldsymbol{q}^2 - m^2}$$

$|\boldsymbol{q}| \gg m:$

$$Z_T \approx \frac{1}{2|\boldsymbol{q}|}$$

$$Z_L \approx \frac{2|\boldsymbol{q}|}{m^2} \exp\left(-\frac{\boldsymbol{q}^2 + m^2}{m^2}\right)$$

Large momentum *longitudinal* mode does NOT propagate .

Thermodynamics is dominated by transverse modes.

Transverse Quasiparticles and Thermodynamics

Idea: Extend the high temperature, transverse quasiparticle picture of the plasma down to deconfinement temperature.

$$p \propto T \int \frac{d^3q}{(2\pi)^3} \log\left(1 - e^{-\beta\omega}\right)$$

Perfect, massive gas of transverse QPs

$$\omega = \sqrt{\boldsymbol{q}^2 + m^2} \; ,$$

Dispersion relation

$$m(T) = \frac{A}{(t-\delta)^c} + Bt \; , \quad t \equiv \frac{T}{T_c} \; .$$

(nonperturbative) Thermal mass

M. I. Gorenstein and S. N. Yang, **Phys. Rev. D52 (1995)**
A. Peshier et al., **Phys. Rev. D54 (1996)**
P. Levai and U. W. Heinz, **Phys. Rev. C57 (2001)**
M. Bluhm et al., **Phys. Lett. B709 (2012)**
P. N. Meisinger et al., **Phys. Lett. B585 (2004)**
P. Castorina et al., **Eur. Phys. J. C71 (2011)**
S. Plumari et al., **Phys. Rev. D84 (2011)**
P. Castorina and M. Mannarelli, **Phys. Lett. B644 (2007)**

Transverse Quasiparticles and Thermodynamics

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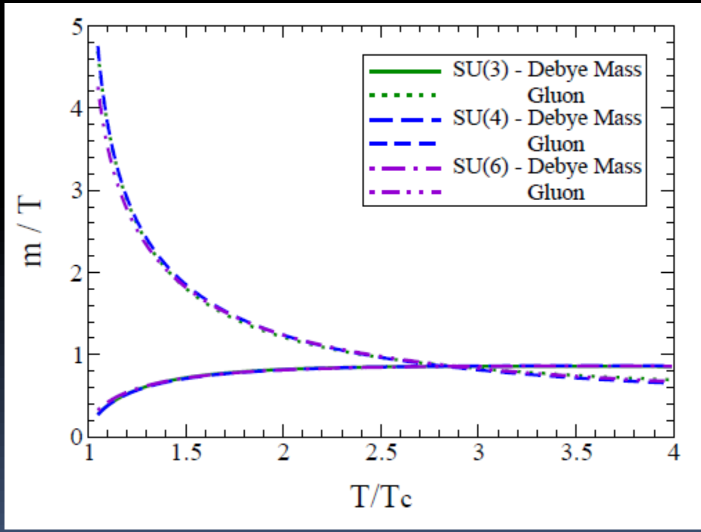

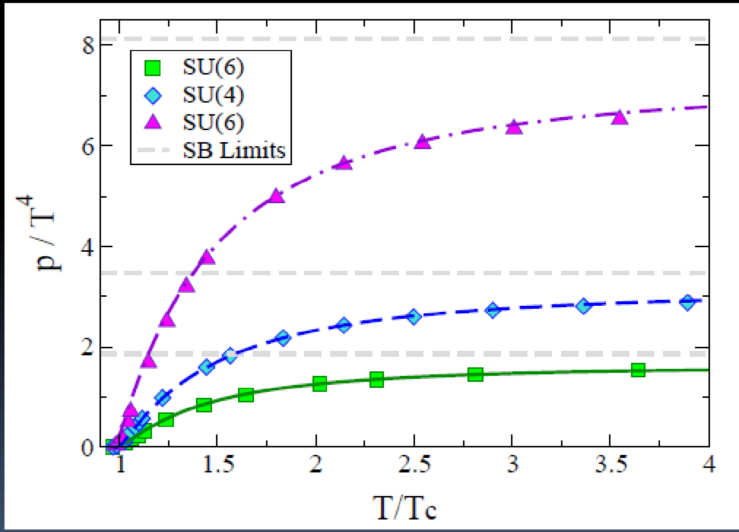

P. Castorina *et al.*, **Eur. Phys. J. C71 (2011)**

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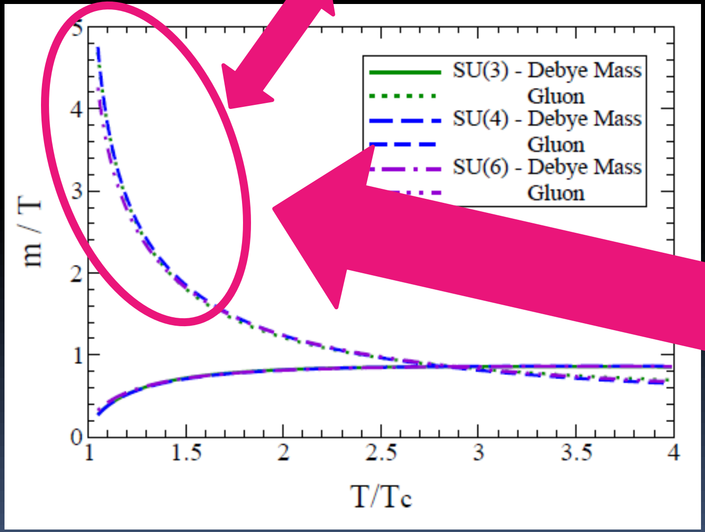

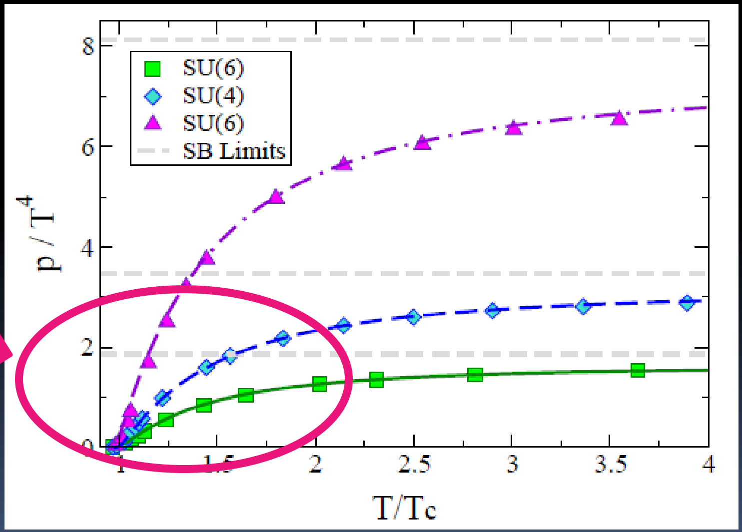

P. Castorina *et al.*, **Eur. Phys. J. C71 (2011)**

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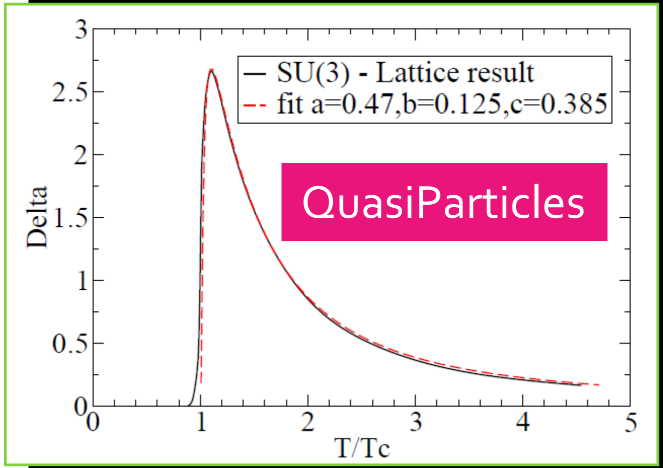
QPs vs "Perturbative"



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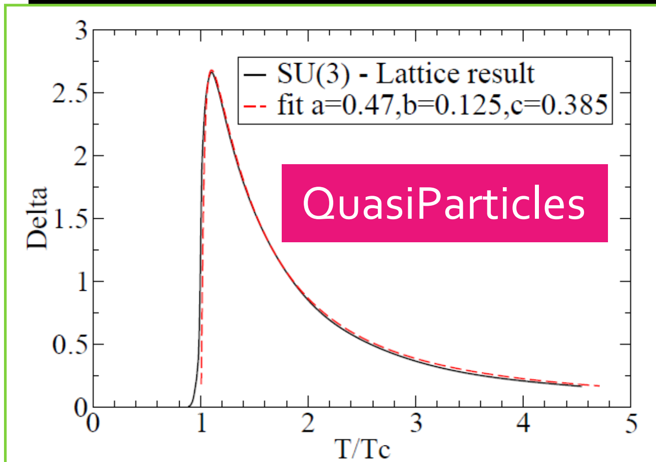
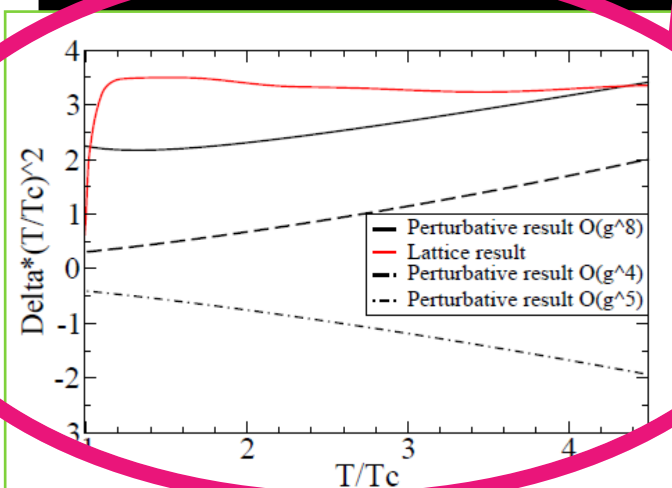
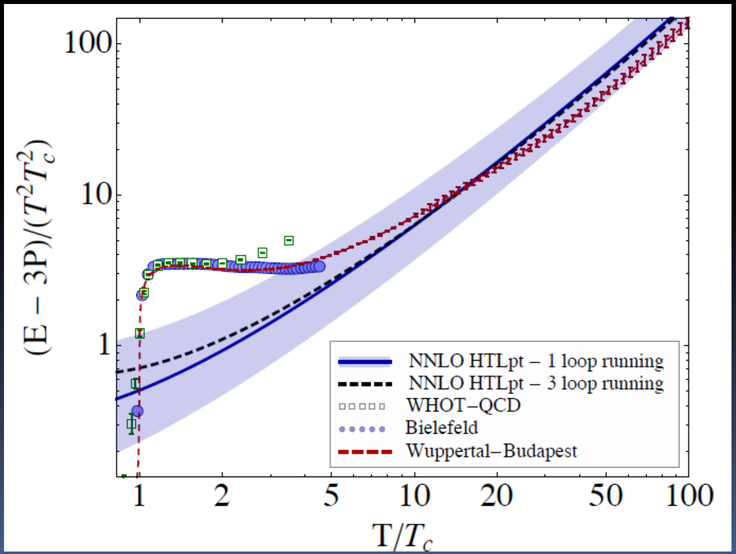


Perturbative Computation



K. Kajantie *et al.*, **Phys. Rev. D67 (2003)**



N. Su *et al.*, **Phys. Rev. D84 (2011)**

P. Castorina *et al.*, **Eur. Phys. J. C71 (2011)**

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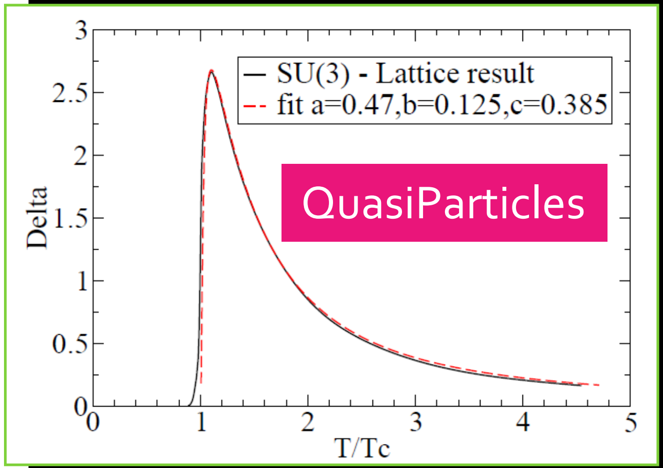
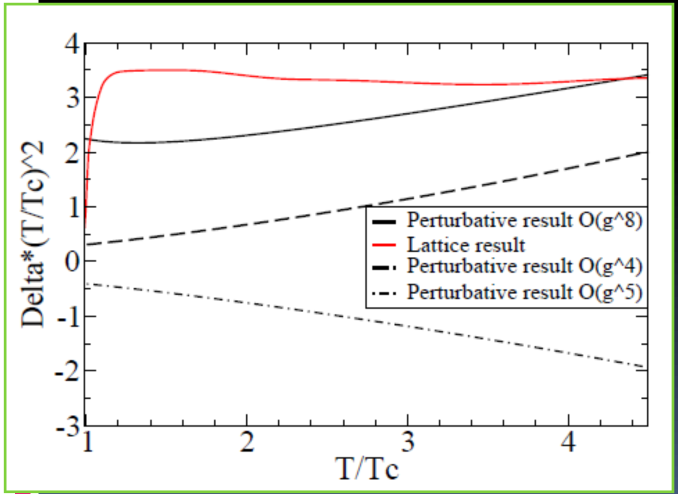
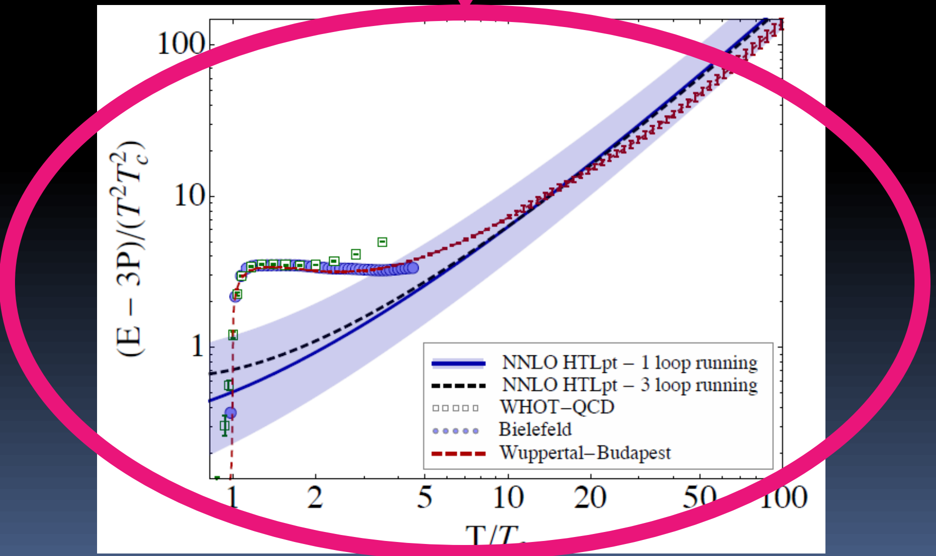


Hard Thermal Loop





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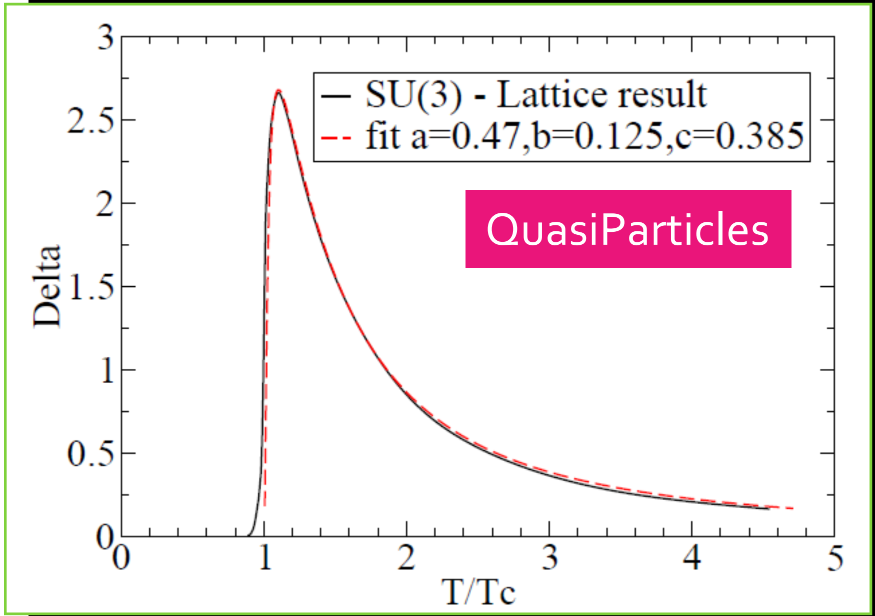


Advantage of QPs:
Offer a ***simple interpretation*** of the ***non-perturbative*** gluon plasma, where perturbative methods do not work.

Alternative description: *Holographic QCD.*
See for example:

U. Gursoy *et al.*, **JHEP 0905:033 (2009)**
P. Colangelo *et al.*, **Phys. Rev. D80 (2009)**
F. Bigazzi *et al.*, **Comm. Theor. Phys.57 (2012)**
E. Megias *et al.*, **Phys. Rev. D83 (2011)**
O. Andreev, **Phys. Rev. D76 (2007)**
F. Xu and M. Huang, **arXiv:1111.5152 [hep-ph]**

A.M. Polyakov , **Phys. Lett. B72 (1978)**

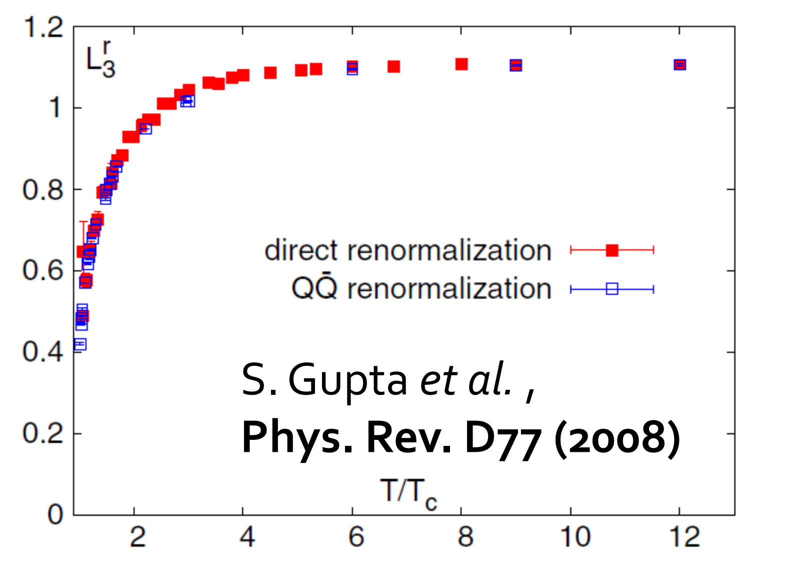
Polyakov loop

Consider the following order parameter for the confinement-deconfinement phase transition:

$$\ell_F(\boldsymbol{x}) = \frac{1}{N_c}\mathrm{Tr}L_F(\boldsymbol{x})$$

$$L_{\mathcal{R}}(\boldsymbol{x}) = \mathcal{P}\exp\left[i\int_0^{1/T} d\tau\;\; A_4^a(\boldsymbol{x},\tau)T_{a,\mathcal{R}}\right]$$

Confinement phase corresponds to vanishing Polyakov loop expectation value.



S. Gupta *et al.* ,
Phys. Rev. D77 (2008)

High temperature phase of the pure gauge theory is like the low temperature phase of a spin model, where the Polyakov loop takes the role of magnetization.

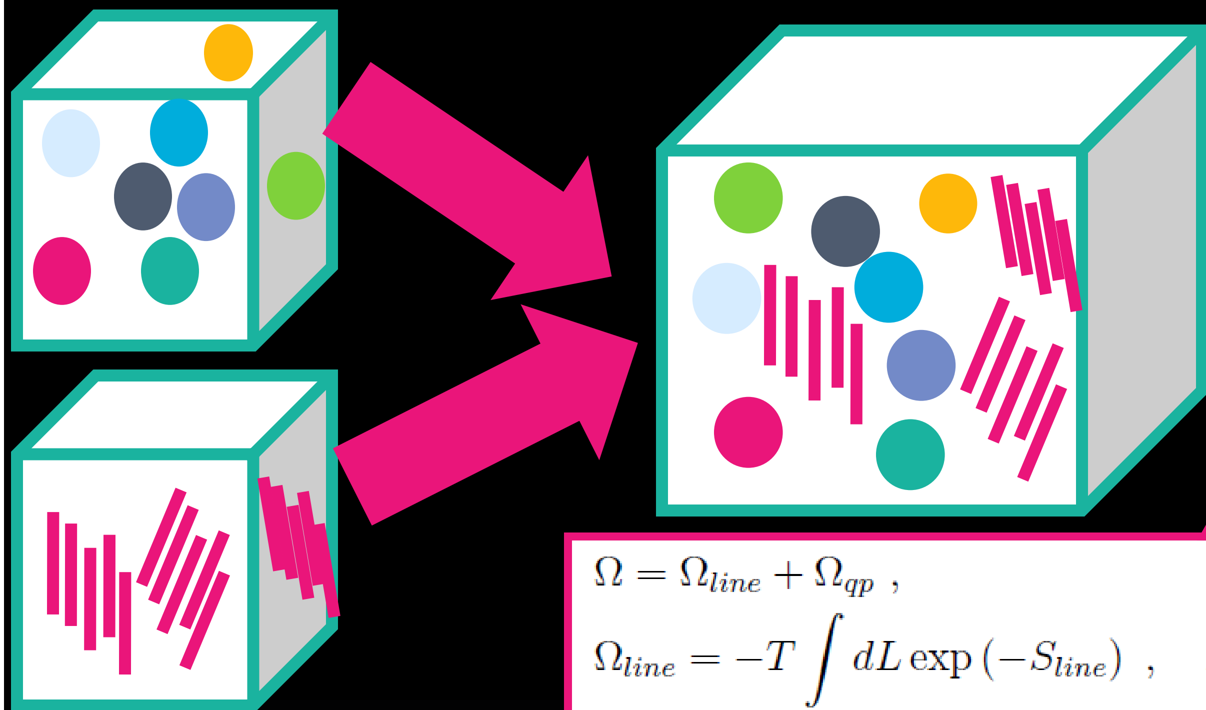
Condensate of Z(3) lines.

R. Pisarski, **Phys.Rev. D62 (2000)**
A. Dumitru *et al.*, **Phys.Rev. D70 (2004)**
R. Pisarski and V. Skokov, **arXiv:1206.1329**

Similar results on the Lattice obtained in:
M. Panero *et al.*, **JHEP 1205 (2012)**
O. Kaczmarek *et al.*, **Phys.Lett. B543 (2002)**

M. Ruggieri *et al.*, **arXiv:1204.5995 [hep-ph]**

Z(3) condensates and QPs



Unified view:
Transverse quasiparticles propagating in a *Z(3) lines condensate*.

$$\Omega = \Omega_{line} + \Omega_{qp} \ ,$$

$$\Omega_{line} = -T \int dL \exp\left(-S_{line}\right) \ , \quad S_{line} \propto \int d\boldsymbol{x} d\boldsymbol{y}\ \ell_F(\boldsymbol{x}) \ell_F^*(\boldsymbol{x}+\boldsymbol{y}) \ ,$$

$$\Omega_{qp} = 2T \int \frac{d}{(2\pi)^3} \mathrm{Tr} \log \left[1 - L_A \exp\left(-\beta\sqrt{\boldsymbol{q}^2 + m^2}\right)\right] \ .$$

S_{line} inspired by:
H. Abuki and K. Fukushima, **Phys.Lett. B676 (2009)**
T. Zhang *et al.*, **JHEP 1006 (2010) 064**
Ω_{qp} inspired by:
P. Meisinger *et al.*, **Phys.Lett. B676 (2009)**

M. Ruggieri *et al.*, **arXiv:1204.5995 [hep-ph]**

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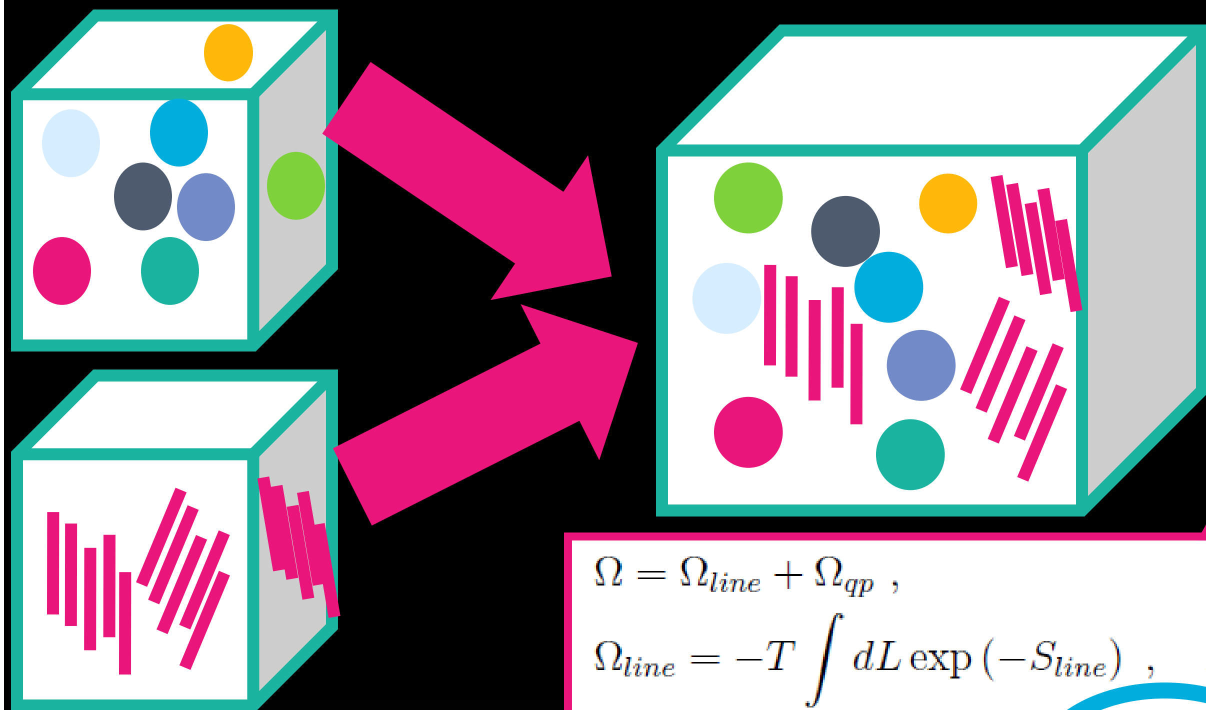

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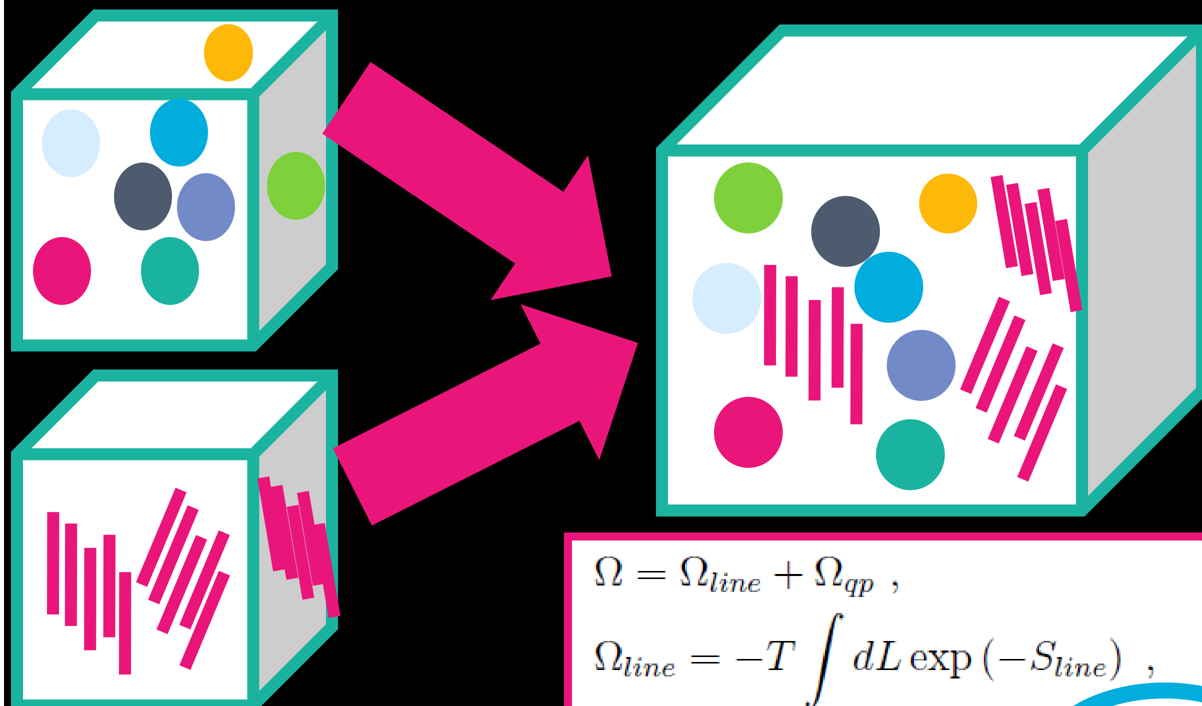
Coupling

S_{line} inspired by:
H. Abuki and K. Fukushima, **Phys.Lett. B676 (2009)**
T. Zhang *et al.*, **JHEP 1006 (2010) 064**
Ω_{qp} inspired by:
P. Meisinger *et al.*, **Phys.Lett. B676 (2009)**

N. Weiss,
Phys.Rev. D24 (1981) 475

M. Ruggieri *et al.*, **arXiv:1204.5995 [hep-ph]**

Z(3) condensates and QPs



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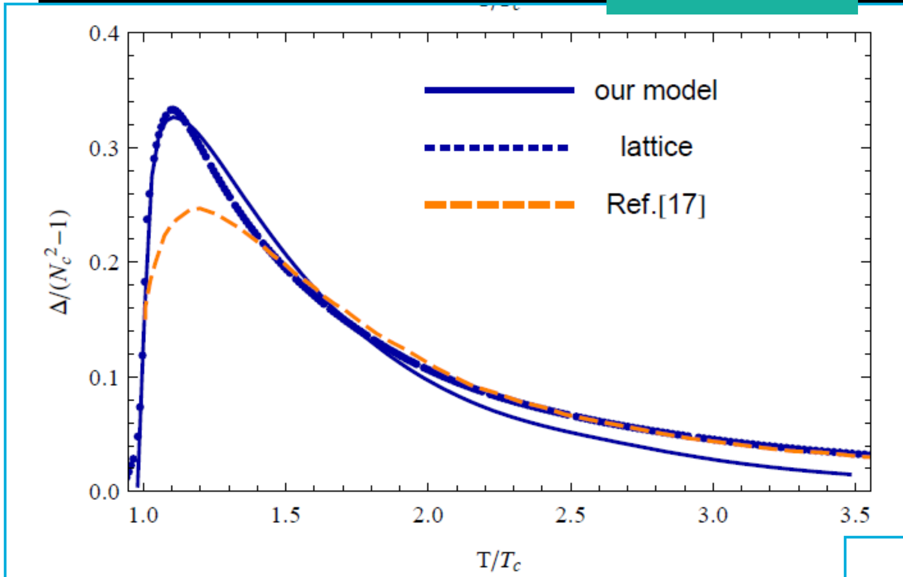
Coupling

<u>**4 free parameters:**</u>
2 in the pure matrix model potential
2 in the gluon quasiparticle mass
They are fixed by a best fit of pressure computed on the Lattice

M. Ruggieri *et al.*, **arXiv:1204.5995 [hep-ph]**

Results

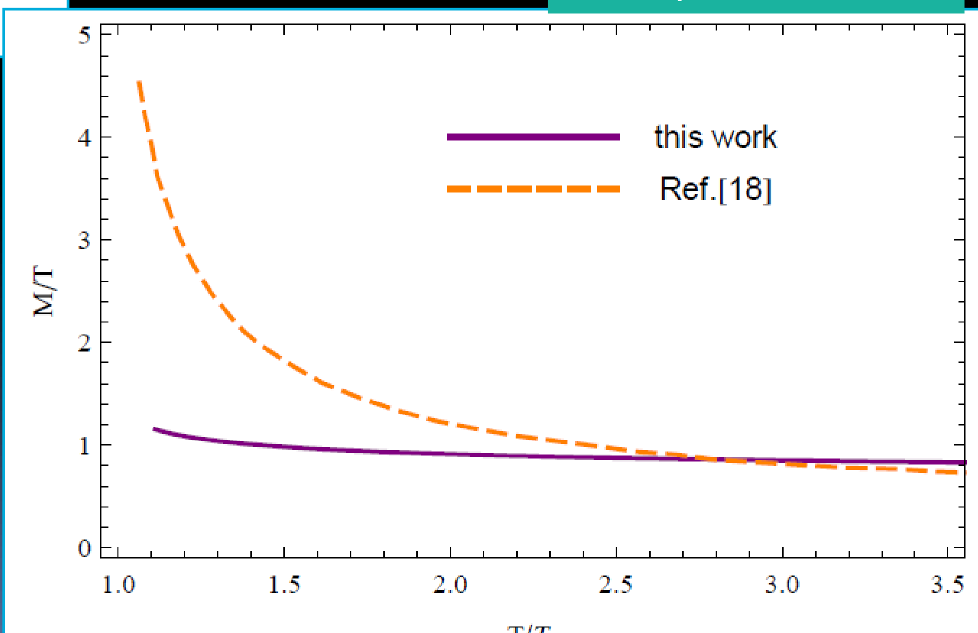
Interaction Measure



Lattice data from:
WUB collaboration , **arXiv:1204.6184 [hep-lat]**

[17] P. Meisinger *et al.*, **Phys.Lett. B676 (2009)**
[18] P. Castorina *et al.*, **Eur. Phys. J. C71 (2011)**

Quasiparticle Mass



The indigo line corresponds to the mass which offers the *best fit to* Lattice data for pressure.

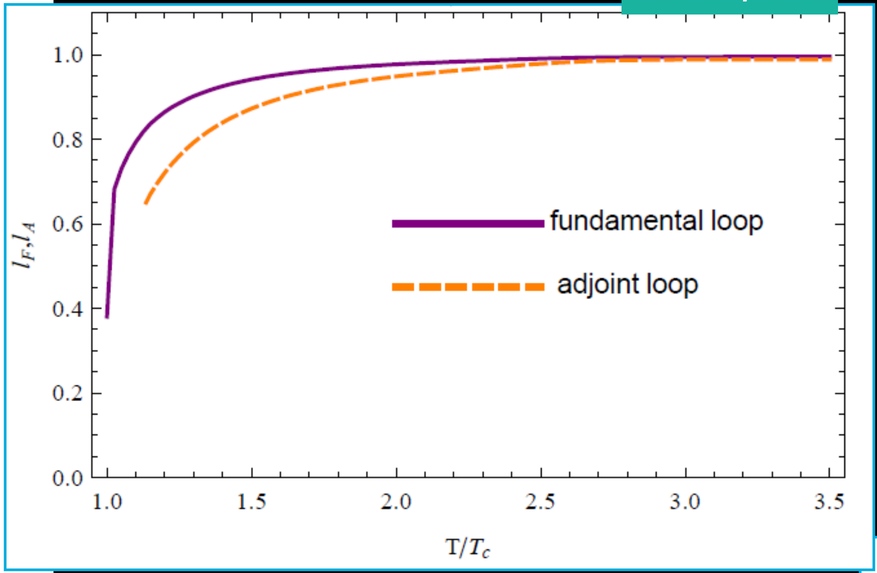
Main effect of Polyakov loops:
QP mass does no longer diverge at the deconfinement temperature.

Relevant for HICs simulations

M. Ruggieri *et al.*, **arXiv:1204.5995 [hep-ph]**

Results

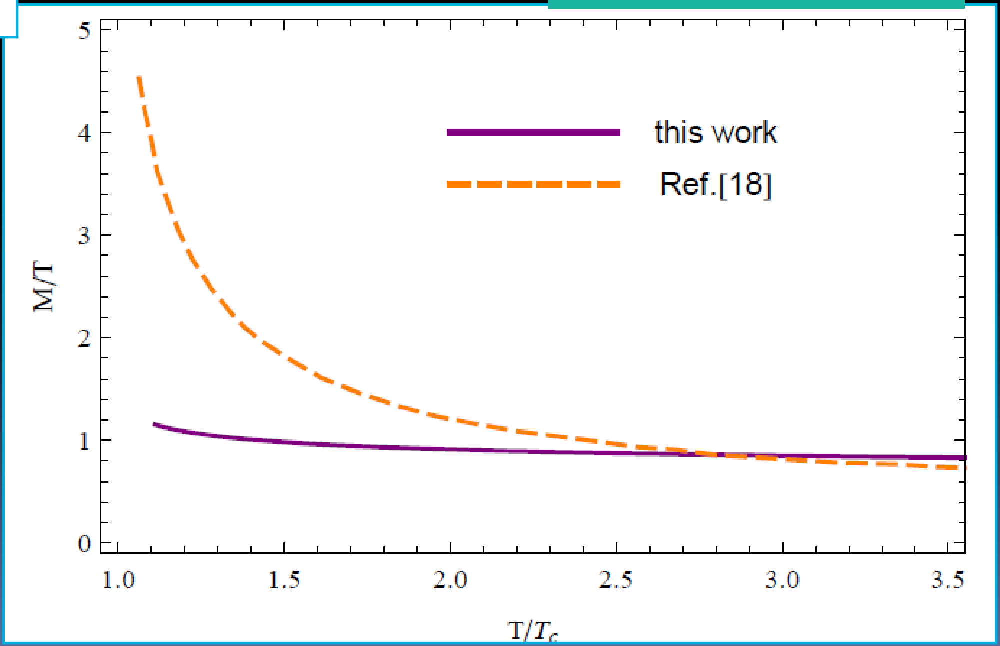
Polyakov Loops



Lattice data from:
WUB collaboration , **arXiv:1204.6184 [hep-lat]**

[17] P. Meisinger *et al.*, **Phys.Lett. B676 (2009)**
[18] P. Castorina *et al.*, **Eur. Phys. J. C71 (2011)**

Quasiparticle Mass



The indigo line corresponds to the mass which offers the *best fit to* Lattice data for pressure.

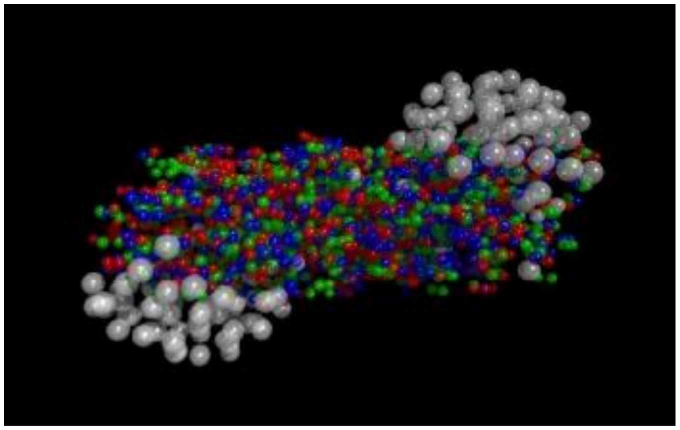
Main effect of Polyakov loops:
QP mass does no longer diverge at the deconfinement temperature.

Relevant for HICs simulations

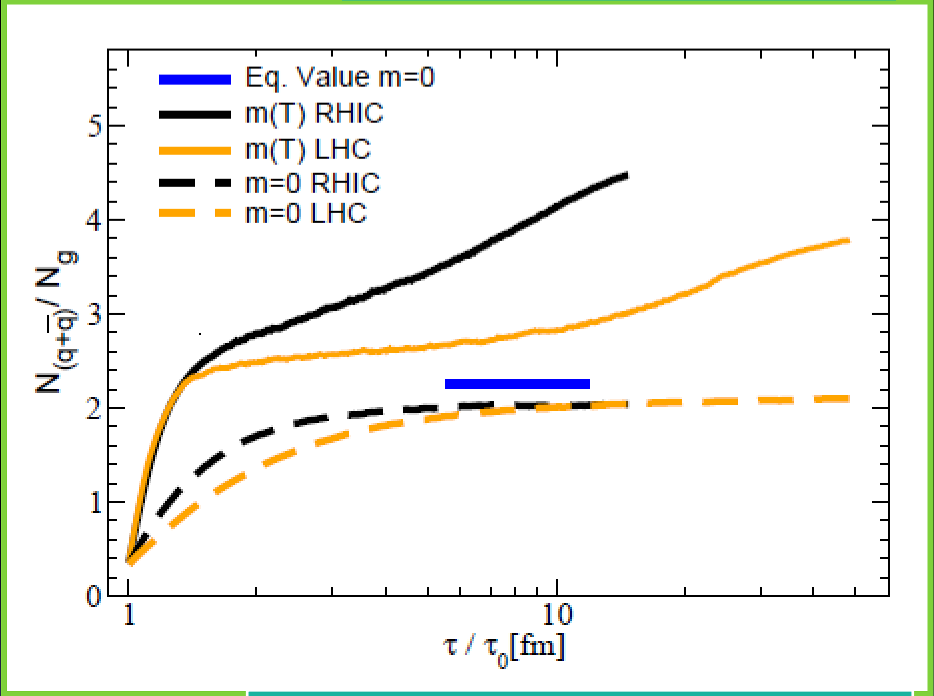
F. Scardina et *al.*, **arXiv:1202.2262 [nucl-th]**

QPs and the Fireball

Quasiparticles have considerable application to the study of the chemical composition of the expanding fireball produced in a heavy ion collision .



(Quark+Antiquark)/Gluons

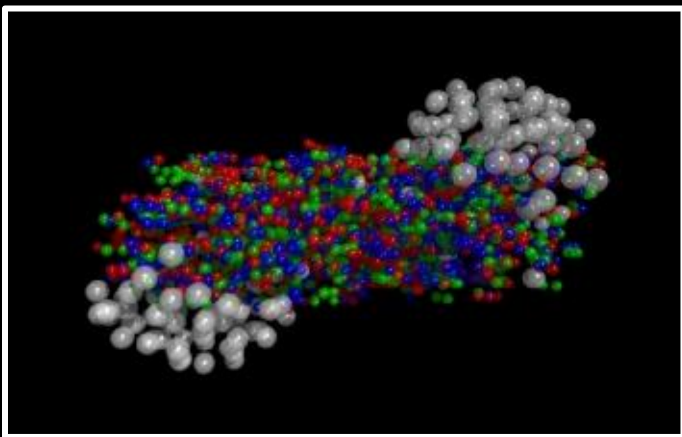


.) *QP-Quarks* beside QP-gluons.
.) Polyakov loops *neglected*.

F. Scardina et *al.*, **arXiv:1202.2262 [nucl-th]**

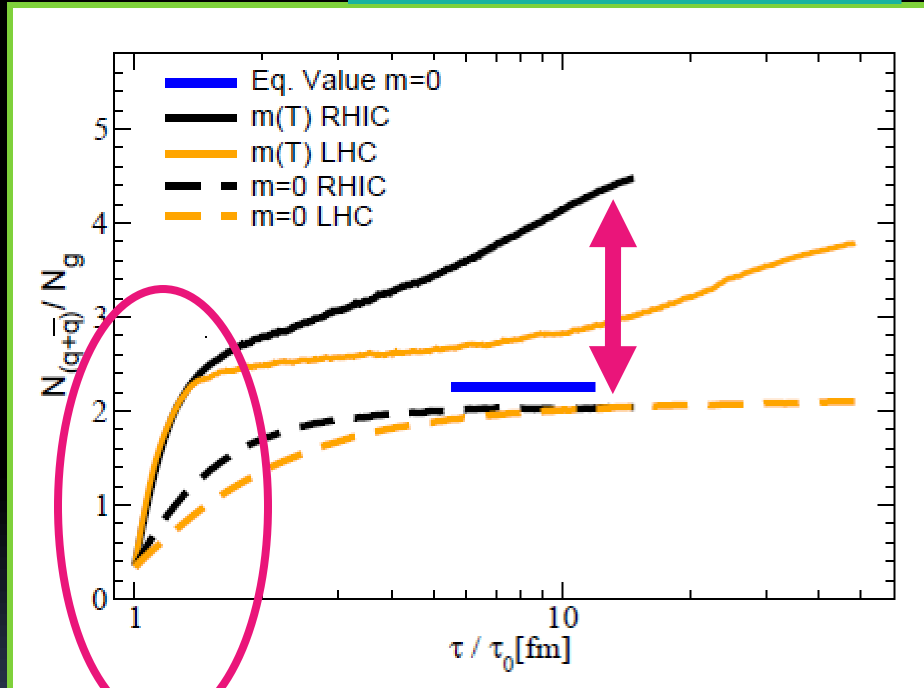
QPs and the Fireball

Quasiparticles have considerable application to the study of the chemical composition of the expanding fireball produced in a heavy ion collision .



Quasiparticles have a strong effect on the ratio of fermions over gluons number: *Fermions* are produced *faster*, and in a *larger amount* than in the case in which *massles particles* are considered.

(Quark+Antiquark)/Gluons



.) *QP-Quarks* beside QP-gluons.
.) Polyakov loops *neglected*.

Improvement of the results including the Polyakov loops is under investigation.

Conclusions and Outlook

- Yang-Mills Thermodynamics is well understood in terms of QPs and condensates of Z(3) lines
- Results are relevant for HICs simulations: QP mass and Polyakov loops affect thermalization

- Introducing dynamical quarks (*wip*)
- Computation of transport coefficients
- Computation of susceptibilities
- QPs, Z(3) lines and transport code

Acknowledgements

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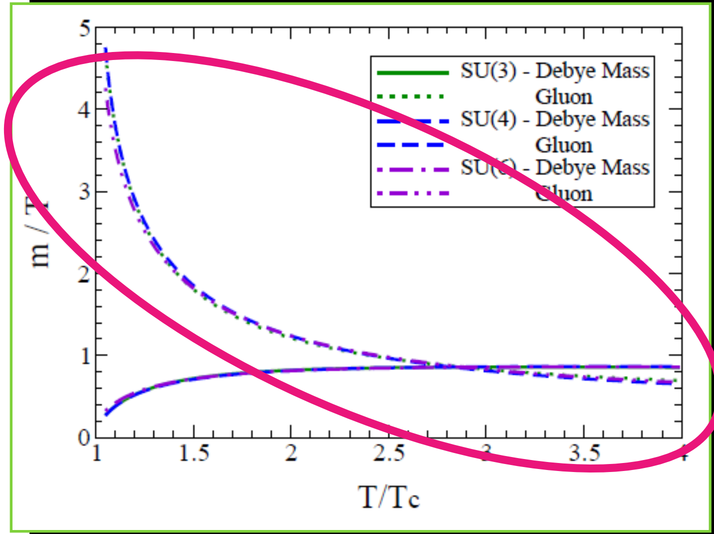
P. Alba, P. Castorina, S. Plumari, C. Ratti *and* ***V. Greco***
for the fruitful collaboration. I also acknowledge discussions with:
M. Frasca *and* ***D. Zappalà*****.**

Chi ha paura muore ogni giorno. Chi non ha paura muore una sola volta.
(Who is afraid dies every day. Who is not afraid dies only once.)

P. Borsellino (19 Gennaio 1940 – 19 Luglio 1992)

Transverse Quasiparticles and N_c^2-1 scaling

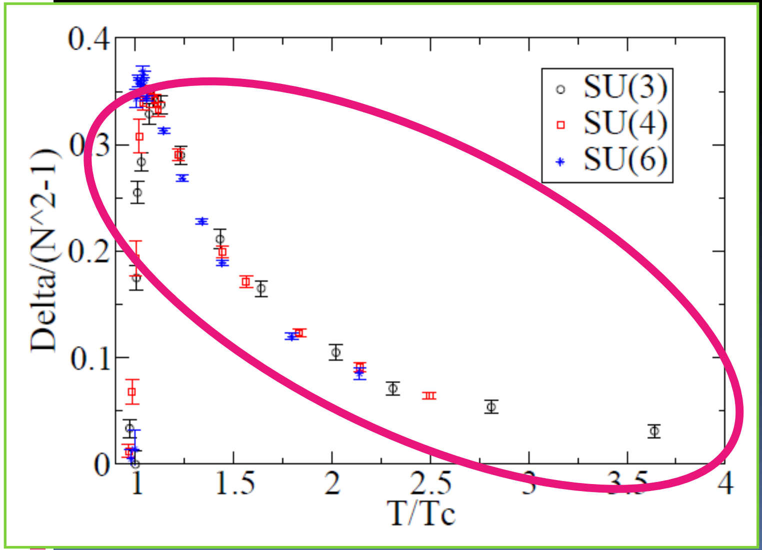
P. Castorina *et al.*, **Eur. Phys. J. C71 (2011)**



Thermal mass turns out to be *independent* on the number of colors. Noticing that:

$$\Delta(T) \approx \frac{N_c^2-1}{6\pi^2}\frac{m^2}{T^2}K_1(m/T)\left[\frac{m}{T}-\left(\frac{dm}{dT}\right)\right]$$

one has the simple interpretation of the N_c^2-1 scaling observed on the lattice.



N_c^2- 1 scaling | gluon mass independent on N_c

Lattice data from:
M. Panero, **Phys. Rev. Lett. 103 (2009)**