Quark-gluon-monopole plasma production by glasma decay

A. Iwazaki
Nishogakusha University

Our main concern in this talk is a **pre thermalized state of plasma**, that is, a state of quark gluon monopole plasma produced just after the decay of glasma.

We show that **the pre thermalized state is very similar to a thermalized state**, which is achieved by the thermalization of the pre thermalized state.

First, we note the pressure of the thermalized gluon plasma.

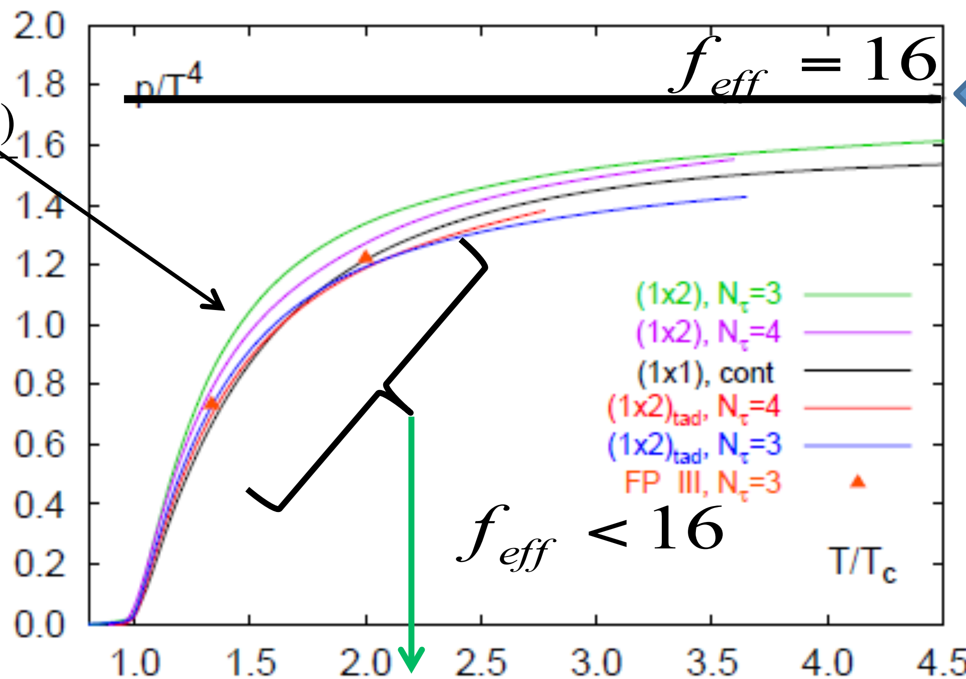
Pressure of ideal gluon gas (SU(3) gauge theory)

$$\frac{P}{T^4} = \frac{\pi^2 f_g}{90} \cong 1.75 \qquad \boxed{f_g = 2 \times 8}$$

number of dynamical degree of freedom of gluons

spin (2), color (8)

$$\frac{P}{T^4} = \frac{\pi^2 f_{eff}(T)}{90}$$



ideal gluon gas

$\frac{T}{T_c}$

Philipsen (2013)

The decrease of the pressure implies suppression of <u>*effective*</u> gluonic degrees of freedom $f_{eff} < 2 \times 8$

The suppression of the effective gluonic degrees of freedom has been theoretically understood in the following.

semi-quark gluon plasma

A model of suppression of gluonic degrees of freedom has been proposed

Hidaka and Pisarski (2008)

Effective number n_{gluon} of gluons (quarks) decreases with Polyakov loop $\langle L \rangle = \exp(-\varepsilon / T)$,

ε; extra energy of a quark added

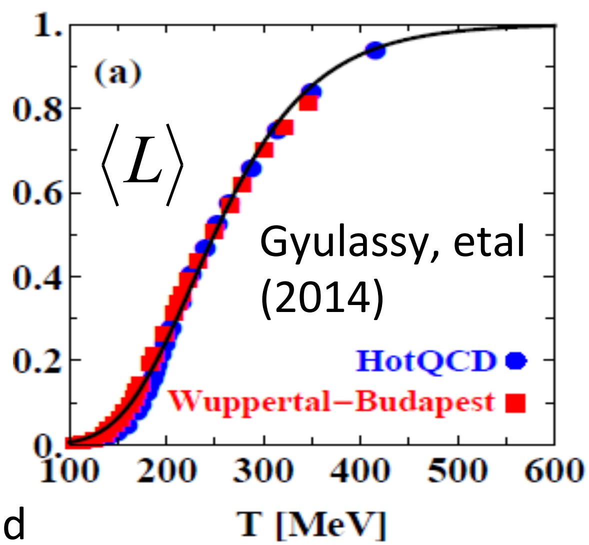
which decreases with the decrease of temperature

$$dn_{gluon} \propto \exp(-E/T) d^3 p \langle L \rangle^2; \qquad L = \frac{1}{3} Tr(P \exp(ig \int_0^{1/T} A_0 d\tau))$$

$\langle L \rangle$ represents a rate of a quark excitation.

$\langle L \rangle = 0$ represents no quark excitation. (confinement)

$\langle L \rangle = 1$ represents a quark easily excited



n_{gluon}; **number density of gluons**

$$\frac{n_{gluon}}{T^3} \cong \frac{1.2 f_{eff}}{\pi^2} \propto \langle L \rangle^2$$

namely

$$f_{eff}(T) = f \langle L \rangle^2$$

According to the model, the effective number of quark degrees of freedom is given by

$$\frac{n_{quark}}{T^3} \cong \frac{0.9 f_q}{\pi^2} \quad \text{(ideal quark gas)}$$

$$f_q = \underset{\uparrow \atop \text{flavor}}{3} \times \underset{\uparrow \atop \text{color}}{3} \times \underset{\uparrow \atop \text{spin}}{2}$$

$$\frac{n_{quark}}{T^3} \equiv \frac{0.9 f_{eff}(T)}{\pi^2} \quad \text{(realistic quark gas)}$$

$$f_{eff}(T) \equiv f_q \langle L \rangle$$

triplet

$$f_q = 18$$

In the case of realistic gluon gas

$$\frac{n_{gluon}}{T^3} = \frac{1.2 f_g \langle L \rangle^2}{\pi^2} \equiv \frac{1.2 f_{eff}(T)}{\pi^2}$$

octet

$$f_{eff}(T) \equiv f_g \langle L \rangle^2$$

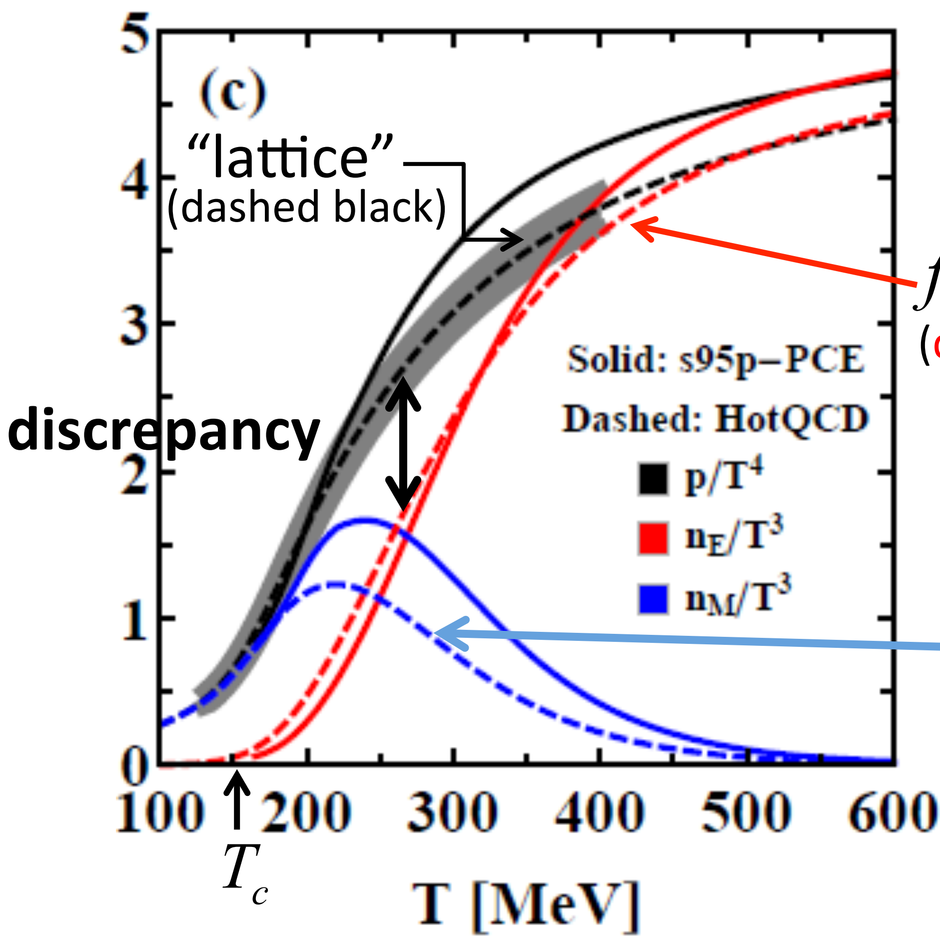
$$f_g = 16$$

The suppression of dynamical degrees of freedom can be understood by using Polyakov loop

But,

pressure obtained in the lattice gauge are still bigger than the one in the “phenomenological model ” when $T = (1 \sim 3) \times T_c$

$$f_{eff} \propto \langle L \rangle^2$$



$f_{eff} \propto \langle L \rangle^2$ (dashed red)

$$\frac{n_{gluon}}{T^3} \cong \frac{1.2 f_{eff}}{\pi^2}$$

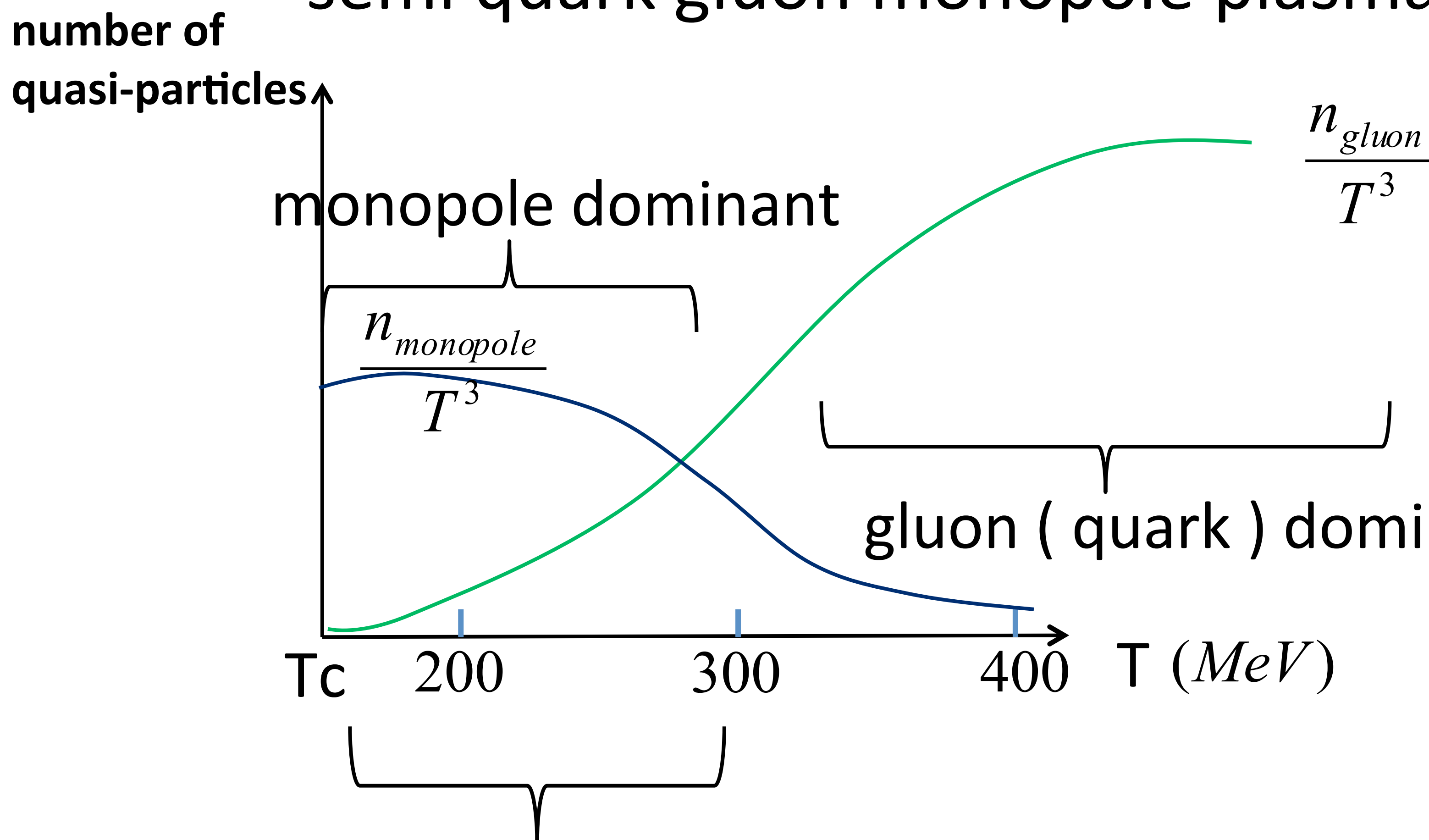
This **discrepancy** is compensated by **monopoles**

Liao and E. Shuryak (2007)
Gyulassy, etal (2014, 2015)

$$\frac{n_{monopole}}{T^3}$$

The monopoles emerge in low temperatures $T = (1 \sim 3) \times T_c$

Schematic picture of quasi-particles in strong coupled gauge plasma (called as semi quark gluon monopole plasma)



Monopoles give rise to small shear viscosity

$$\frac{\eta}{s} << 1$$

Liao and E. Shuryak (2007)
Gyulassy, etal (2014, 2015)

Up to now, we have made a brief review
of quasi particles arising in **thermalized**
quark gluon plasma discussed by Hidaka et al. and
proposed by Gyulassy et al.

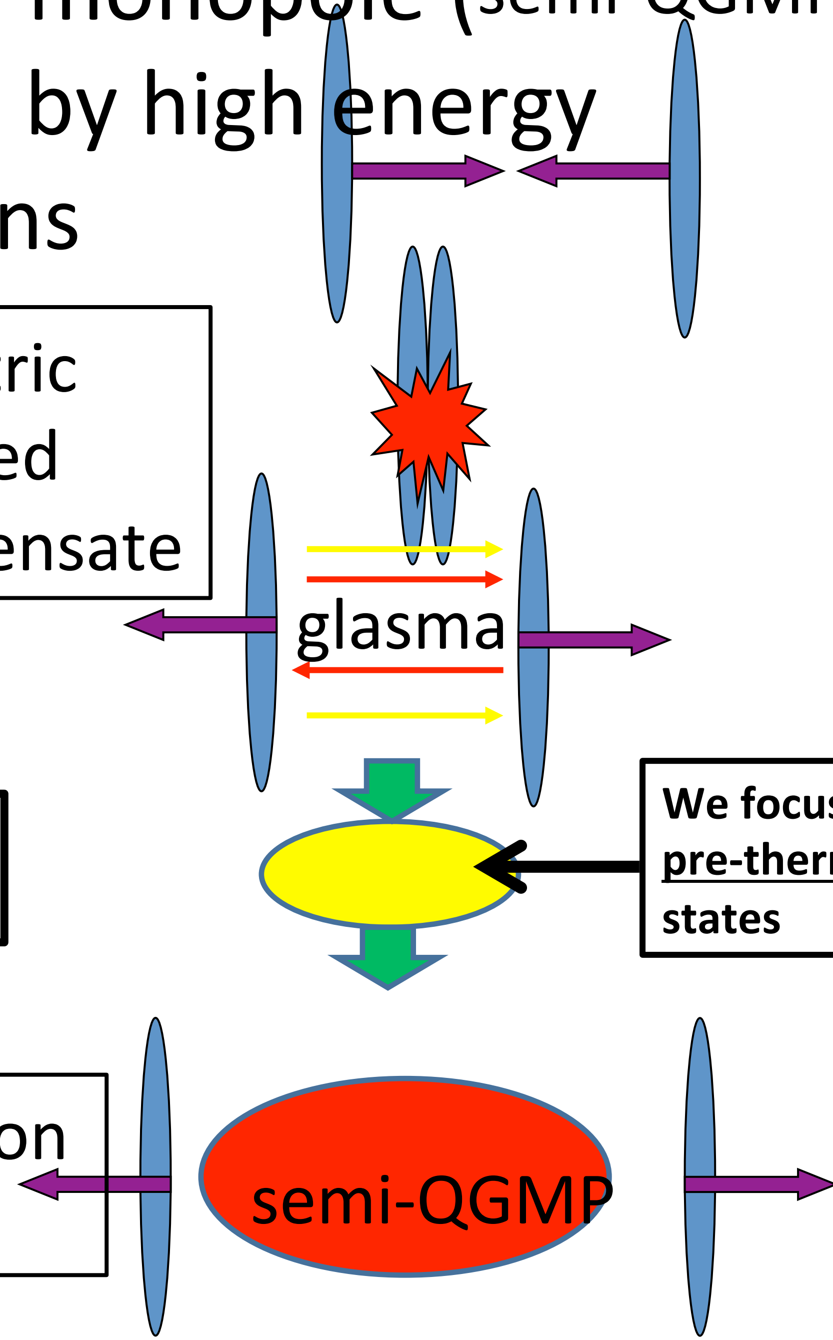
We now talk a **pre-thermalized state** of gluons
and monopoles produced by the decay
of the glasma.

semi-quark gluon monopole (semi-QGMP) plasma produced by high energy heavy ion collisions

Glasma; classical color electric and magnetic fields predicted in a model color glass condensate

Glasma decays into <u>pre thermalized</u> quark gluon plasma

thermalized semi-quark gluon monopole plasma



We focus on <u>pre-thermalized</u> states

Question?

What amount of gluons and monopoles are produced in the decay of glasma?

We do not address with the question how they are thermalized.

We assume that color electric and magnetic fields of glasma are **spatially homogeneous**.

Production mechanism

Gluons and monopoles are produced by the **Schwinger mechanism** under the classical color electric E and magnetic B fields (glasma)

We note

The most produced gluons are Nielsen-Olesen unstable modes. They have imaginary mass ; $i\sqrt{gB}$; B color magnetic field

Monopoles causing confinement also have imaginary mass; $i\mu$, $\mu \approx 700MeV$ dual superconducting model

Production of gluons and monopoles

Energy conservation

energy obtained by gluons accelerated by electric field E in a time interval $d\tau$

$$d\tau \times n_{gluon} \times gE = \frac{-1}{2} d(E^2)$$

n_{gluon}; number density of gluons

$$d\tau \times n_{monopole} \times g_m E = \frac{-1}{2} d(B^2)$$

$n_{monopole}$;number density of monopoles

τ; time

$g\,g_m = 4\pi$; Dirac quantization of magnetic charge g_m

Evolution equations of gauge fields

$$\frac{d(gE)}{d\tau} = -4\pi\alpha_s n_{gluon}$$

$$\frac{d(gB)}{d\tau} = -4\pi n_{monopole}$$

Initial conditions

$$gB(\tau = 0) = gE(\tau = 0) = Q_s^2$$

Q_s **is a parameter representing a temperature after thermalization; effective saturation momentum less than real saturation momentum**

Number densities produced in Schwinger mechanism

We use approximate explicit formulae

Tanji (2009) Tanji, and Itakura (2012) Iwazaki (2014)

imaginary mass

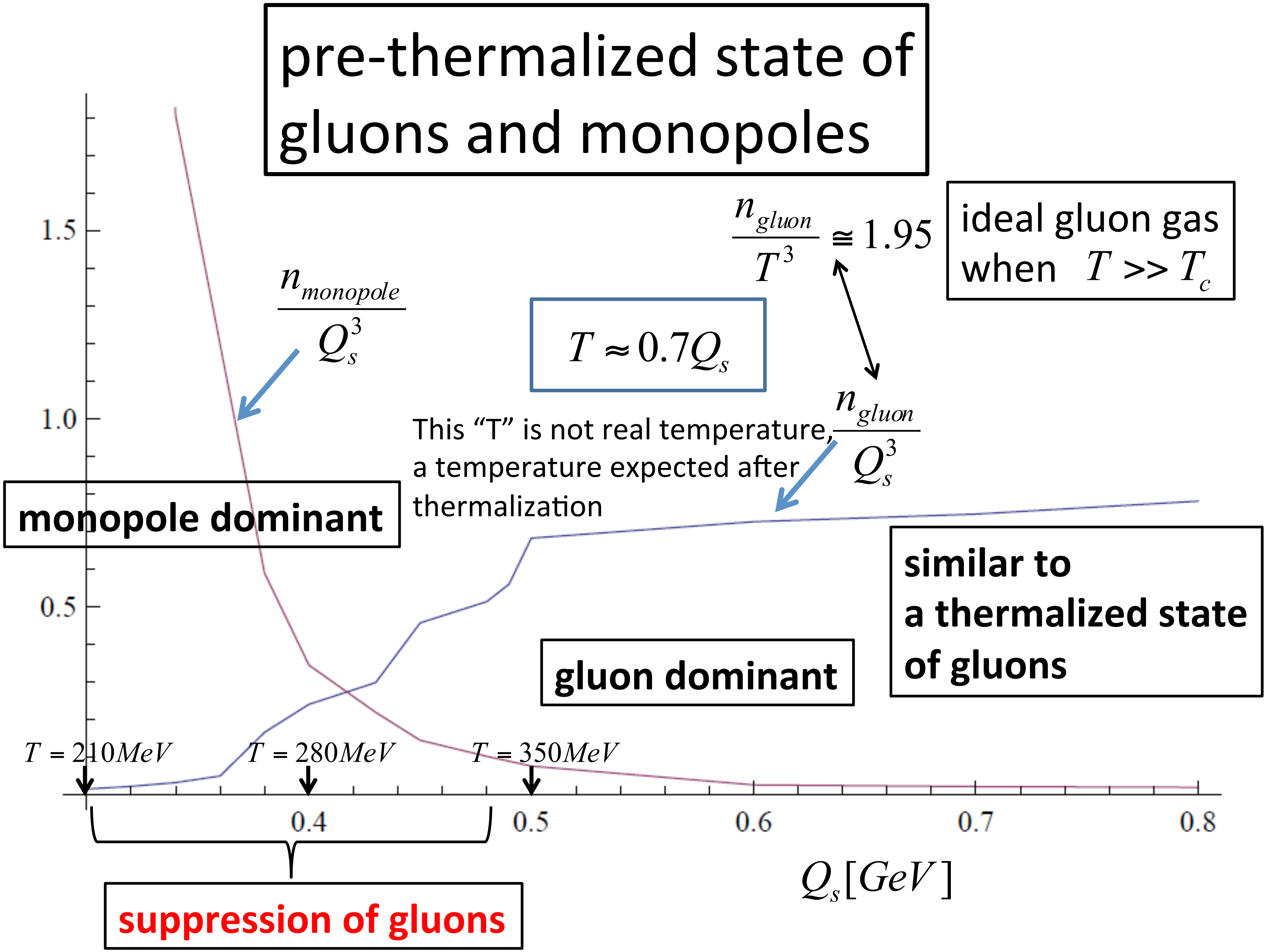
$$n_{gluon} \cong \frac{gB}{2\pi}\frac{gE\tau}{2\pi}\left(\exp(\frac{\pi B}{E}) + \exp(\frac{-3\pi B}{E})\right)\frac{1}{1-\exp(-\frac{2\pi B}{E})}$$

$$n_{monopole} \cong \frac{g_m B}{2\pi}\frac{g_m E\tau}{2\pi}\exp(\frac{\pi\mu^2}{g_m B} - \frac{\pi E}{B})\frac{1}{1-\exp(-\frac{2\pi E}{B})}$$

$$g_m = \frac{4\pi}{g}, \qquad \alpha_s(Q_s) = \frac{g^2}{4\pi} \cong \frac{\alpha_c}{1+\frac{9\alpha_c}{4\pi}\log(\frac{Q_s^2}{T_c^2})}, \qquad \alpha_c = 0.95, \quad T_c = 160MeV$$

(magnetic charge)

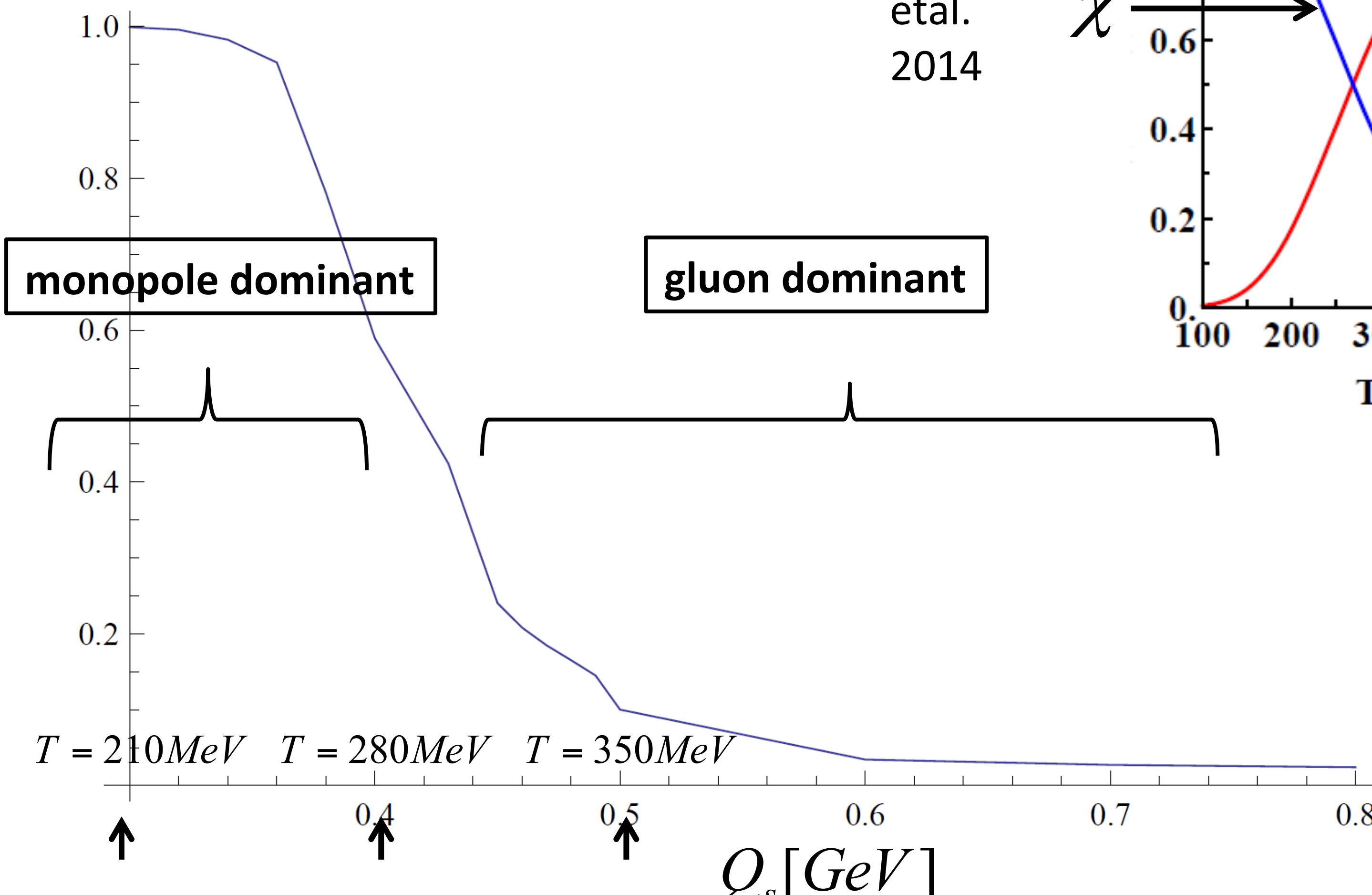
Used by Gyulassy, etal (2014)



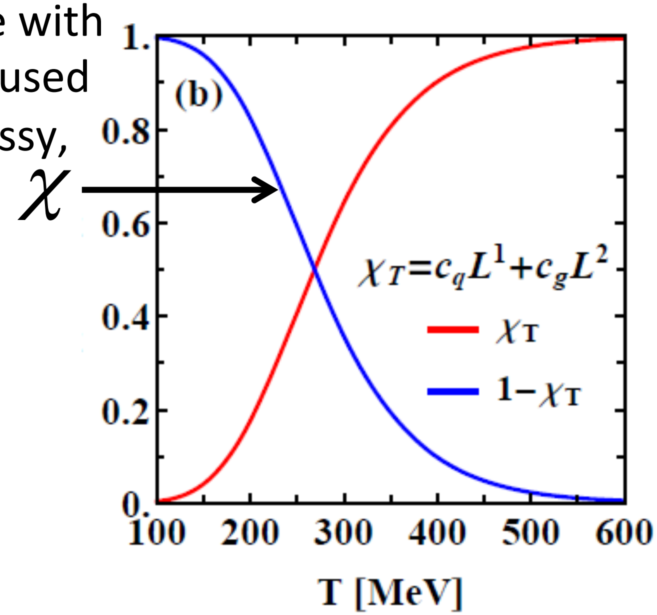
pre-thermalized state of gluons and monopoles
$\frac{n_{gluon}}{T^3} \cong 1.95$
ideal gluon gas when $T >> T_c$
$\frac{n_{monopole}}{Q_s^3}$
$T \approx 0.7 Q_s$
This "T" is not real temperature, a temperature expected after thermalization
$\frac{n_{gluon}}{Q_s^3}$
monopole dominant
similar to a thermalized state of gluons
gluon dominant
1.5
1.0
0.5
$T = 210 MeV$
$T = 280 MeV$
$T = 350 MeV$
0.4
0.5
0.6
0.7
0.8
$Q_s [GeV]$
suppression of gluons

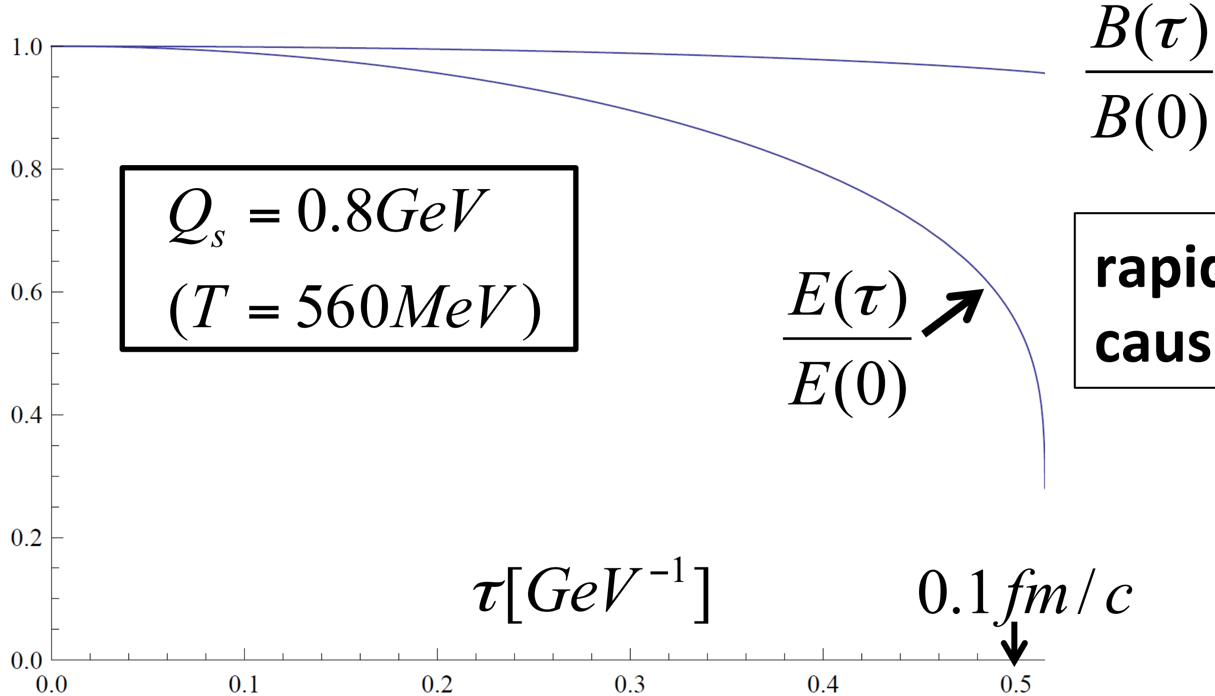
Fraction of monopoles

$$\chi \equiv \frac{n_{monopole}}{n_{gluon} + n_{monopole}}$$

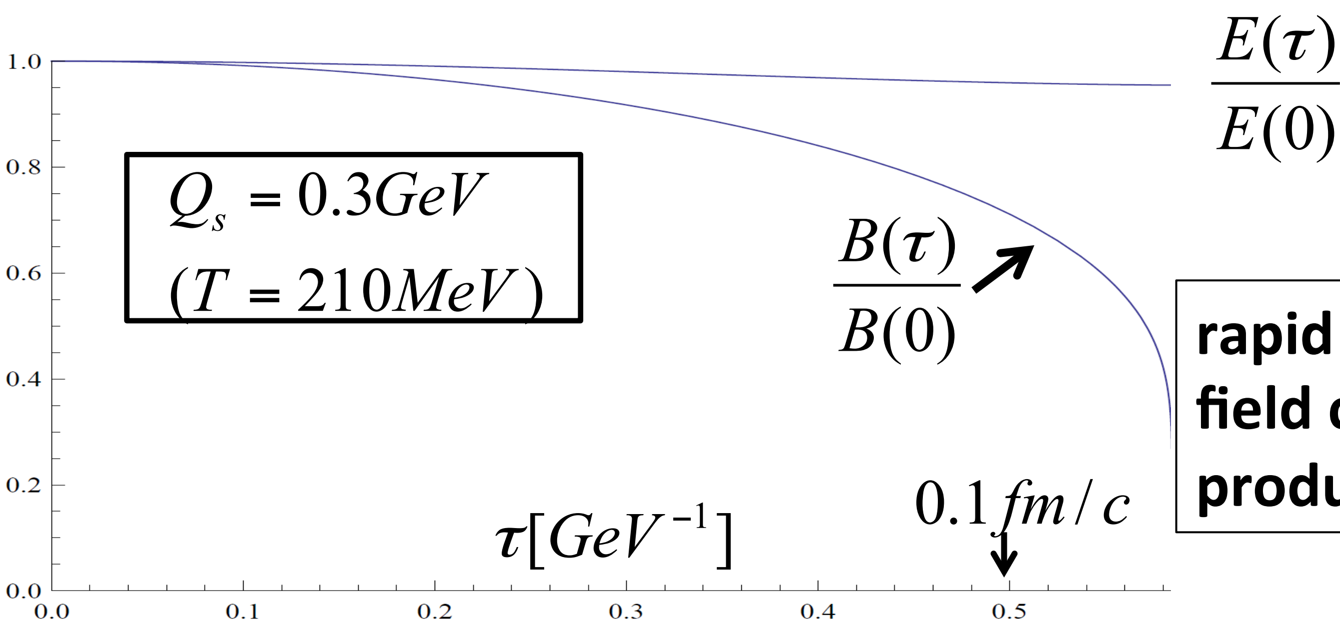


Compare with a model used by Gyulassy, etal. 2014

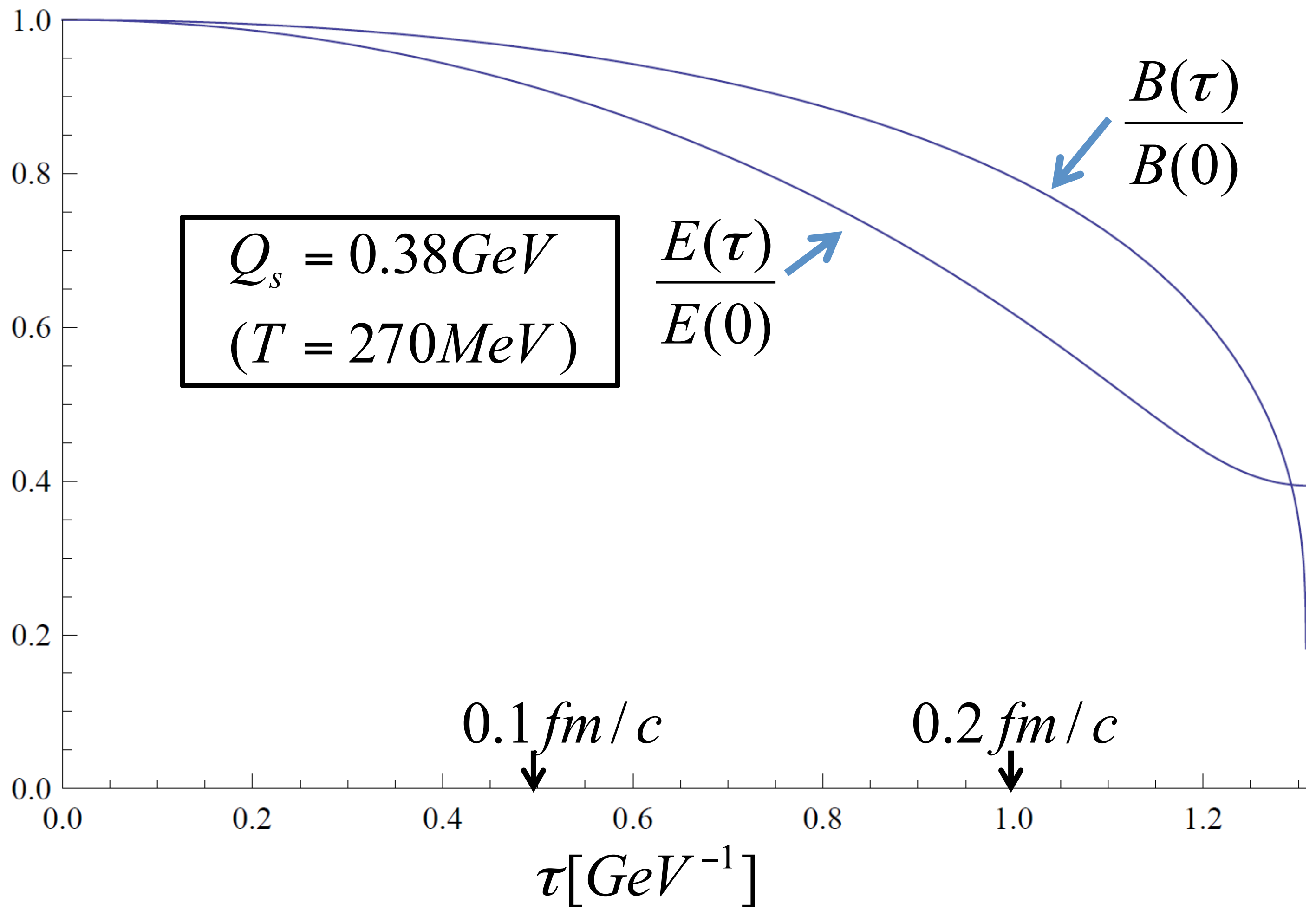




rapid decay of electric field causing gluon production

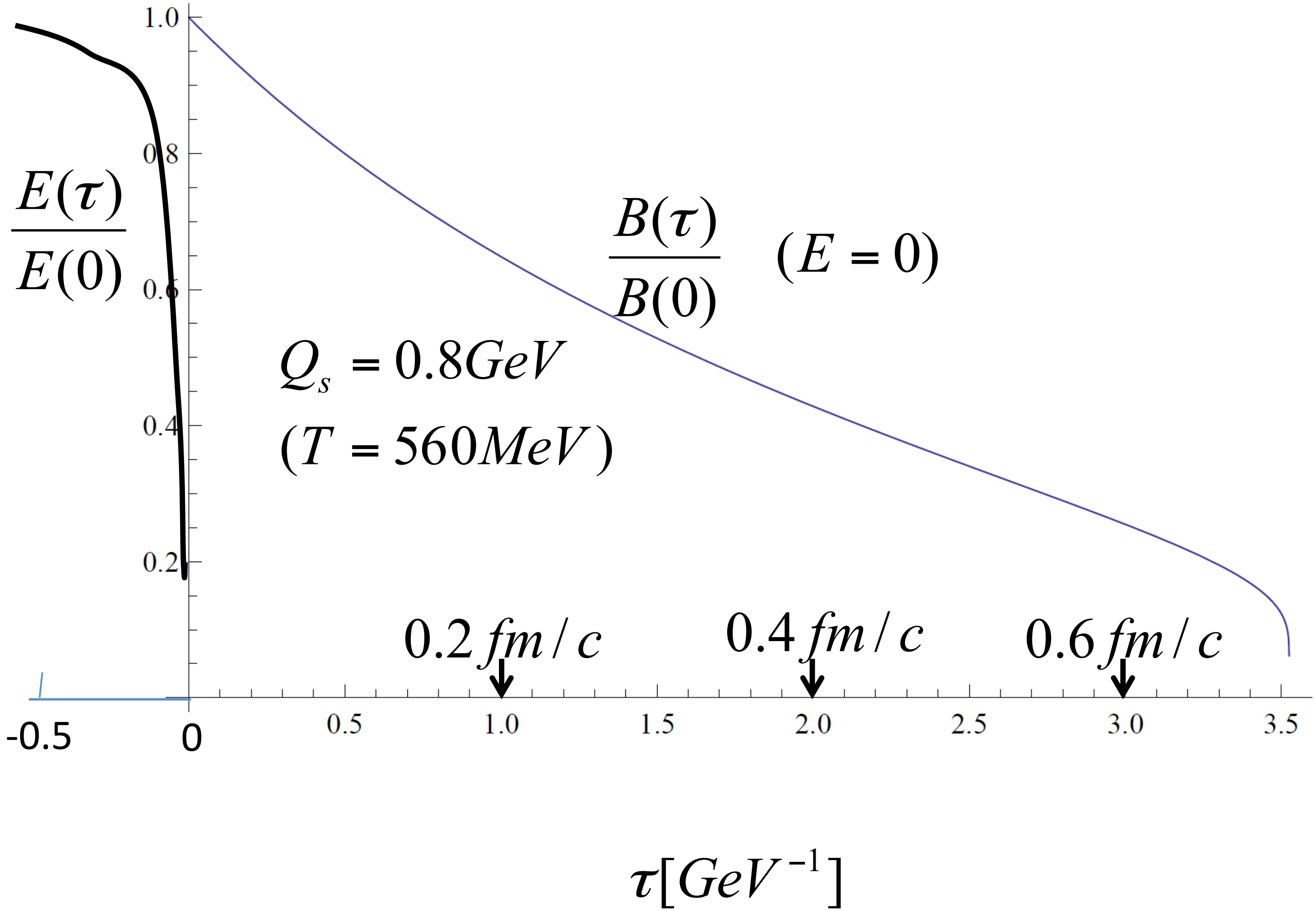


rapid decay of magnetic field causing monopole production

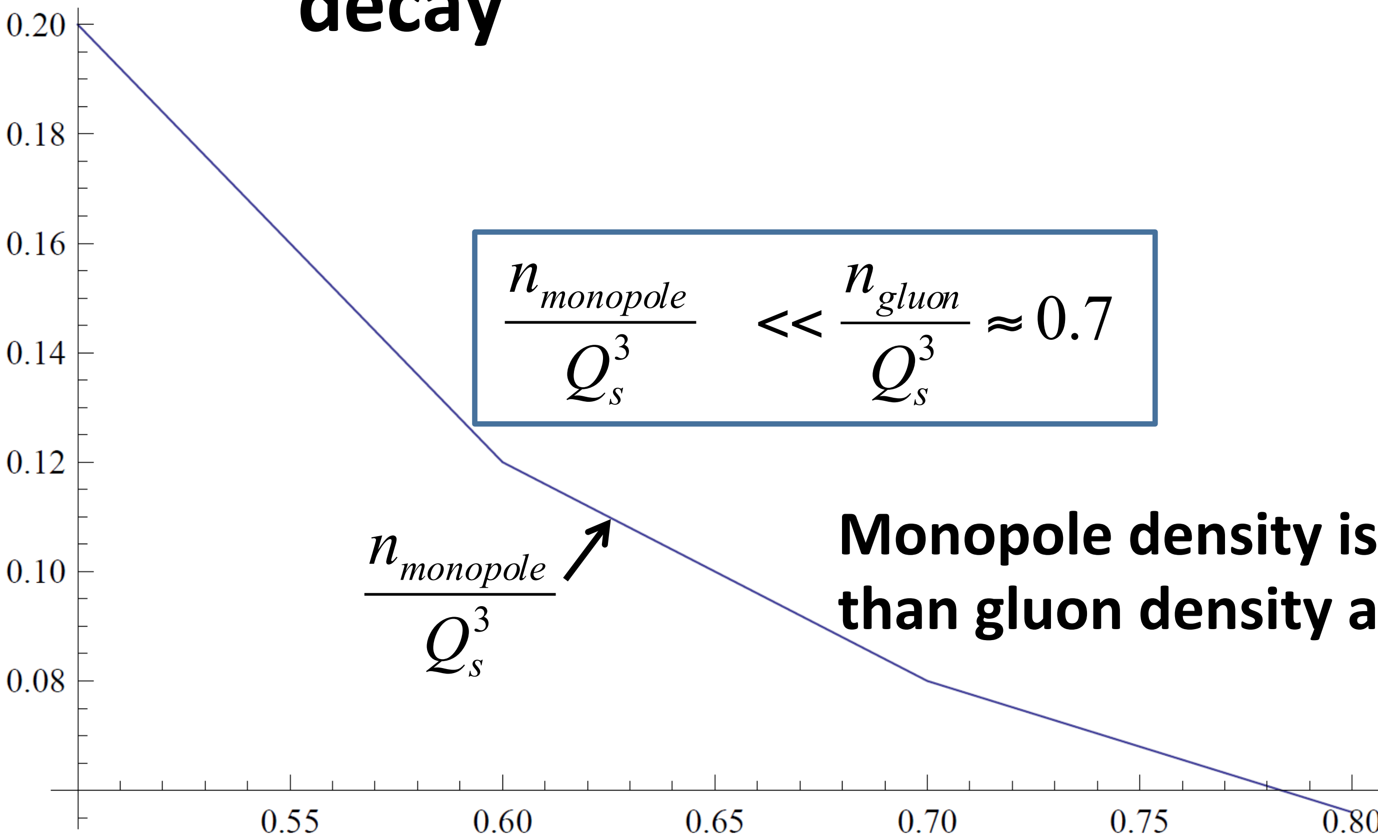


1.0
0.8
0.6
0.4
0.2
0.0
$\frac{B(\tau)}{B(0)}$
$\frac{E(\tau)}{E(0)}$
$Q_s = 0.38GeV$
$(T = 270MeV)$
$0.1\,fm/c$
$0.2\,fm/c$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
$\tau[GeV^{-1}]$

Magnetic field slowly decays after the rapid decay of electric field



Monopole production by the decay of the magnetic field after the electric field decay



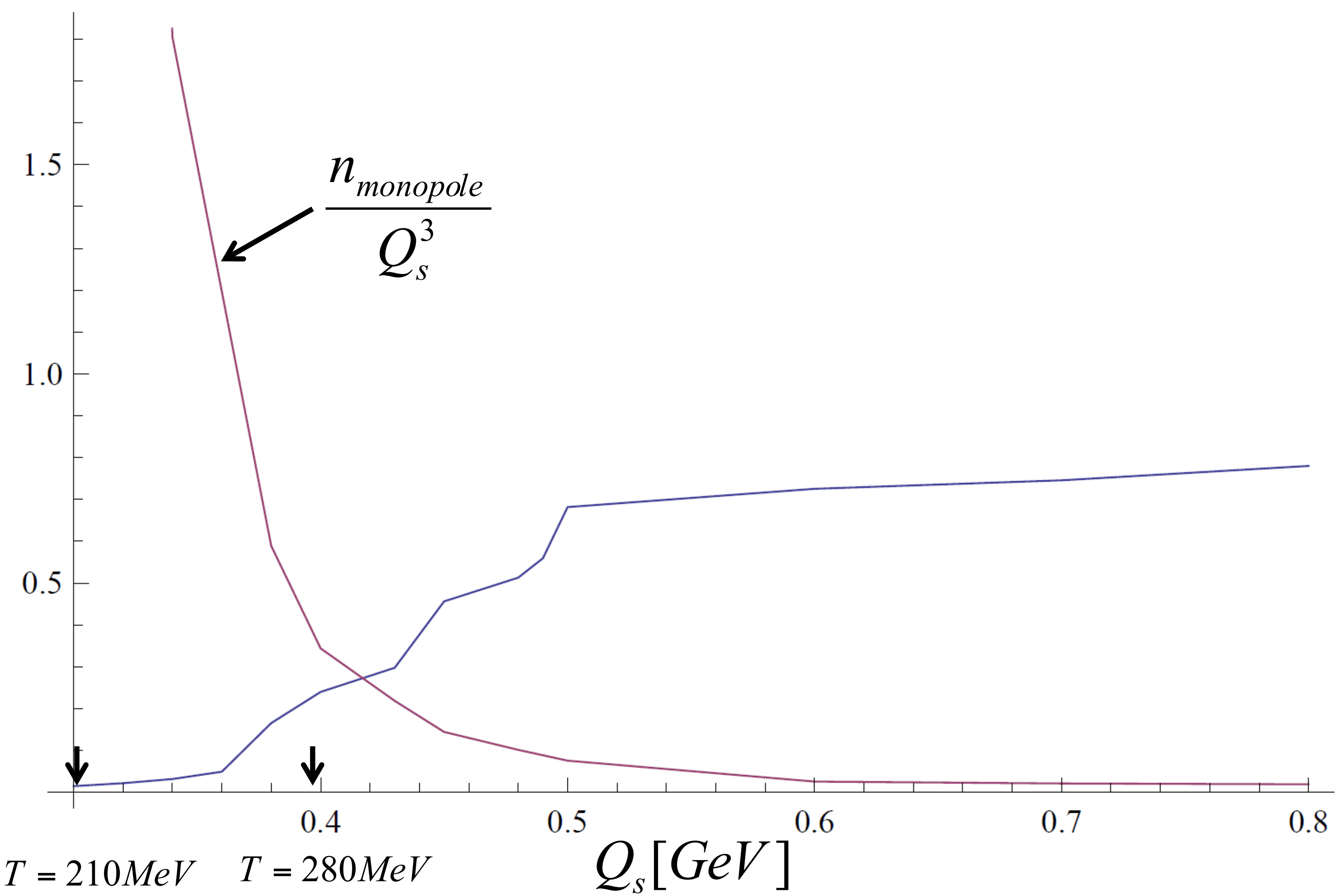
$$\frac{n_{monopole}}{Q_s^3} << \frac{n_{gluon}}{Q_s^3} \approx 0.7$$

$$\frac{n_{monopole}}{Q_s^3}$$

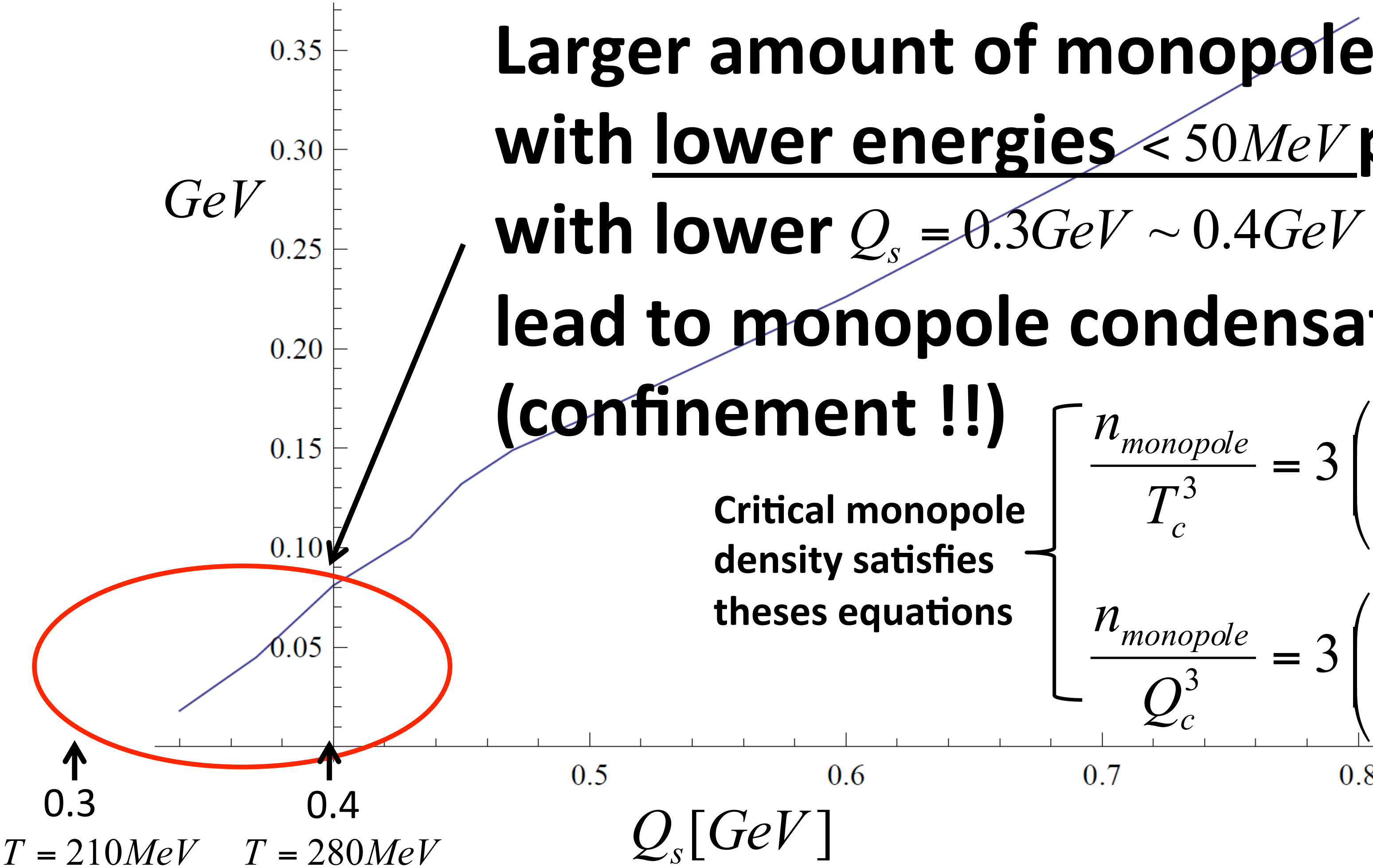
$Q_s[GeV]$

Monopole density is still much less than gluon density at large $Q_s > 0.5GeV$

number density of a monopole



energy of a monopole



Larger amount of monopoles with lower energies $< 50MeV$ produced with lower $Q_s = 0.3GeV \sim 0.4GeV$ lead to monopole condensation (confinement !!)

Critical monopole density satisfies theses equations

$$
\begin{cases}
\dfrac{n_{monopole}}{T_c^3} = 3\left(\dfrac{m_{monopole}}{3.31T_c}\right)^{3/2} \\[2ex]
\dfrac{n_{monopole}}{Q_c^3} = 3\left(\dfrac{0.7m_{monopole}}{3.31Q_c}\right)^{3/2}
\end{cases}
$$

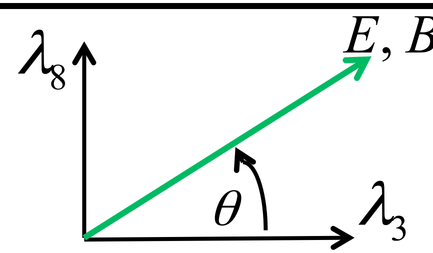
Technical detail

In these calculations of SU(3) gauge theory
We have taken into account
three types of Nielsen-Olesen unstable modes
and **three types of magnetic monopoles**.

Furthermore,
the background gauge fields are in **maximal Abelian two dimensional space**.
We have **taken average over the direction of the background gauge fields in the space**

Production of gluons and monopoles in SU(3) gauge theory

Background electric and magnetic fields in maximal Abelian space $\{\lambda_3, \lambda_8\}$



$$B = |B|(\cos\theta\,\lambda_3 + \sin\theta\,\lambda_8), \quad E = |E|(\cos\theta\,\lambda_3 + \sin\theta\,\lambda_8), \quad -\frac{\pi}{6} \leq \theta \leq \frac{\pi}{6}$$

3 types of Nielsen-Olesen unstable modes

A_a ← color, $a = 1 \sim 8$

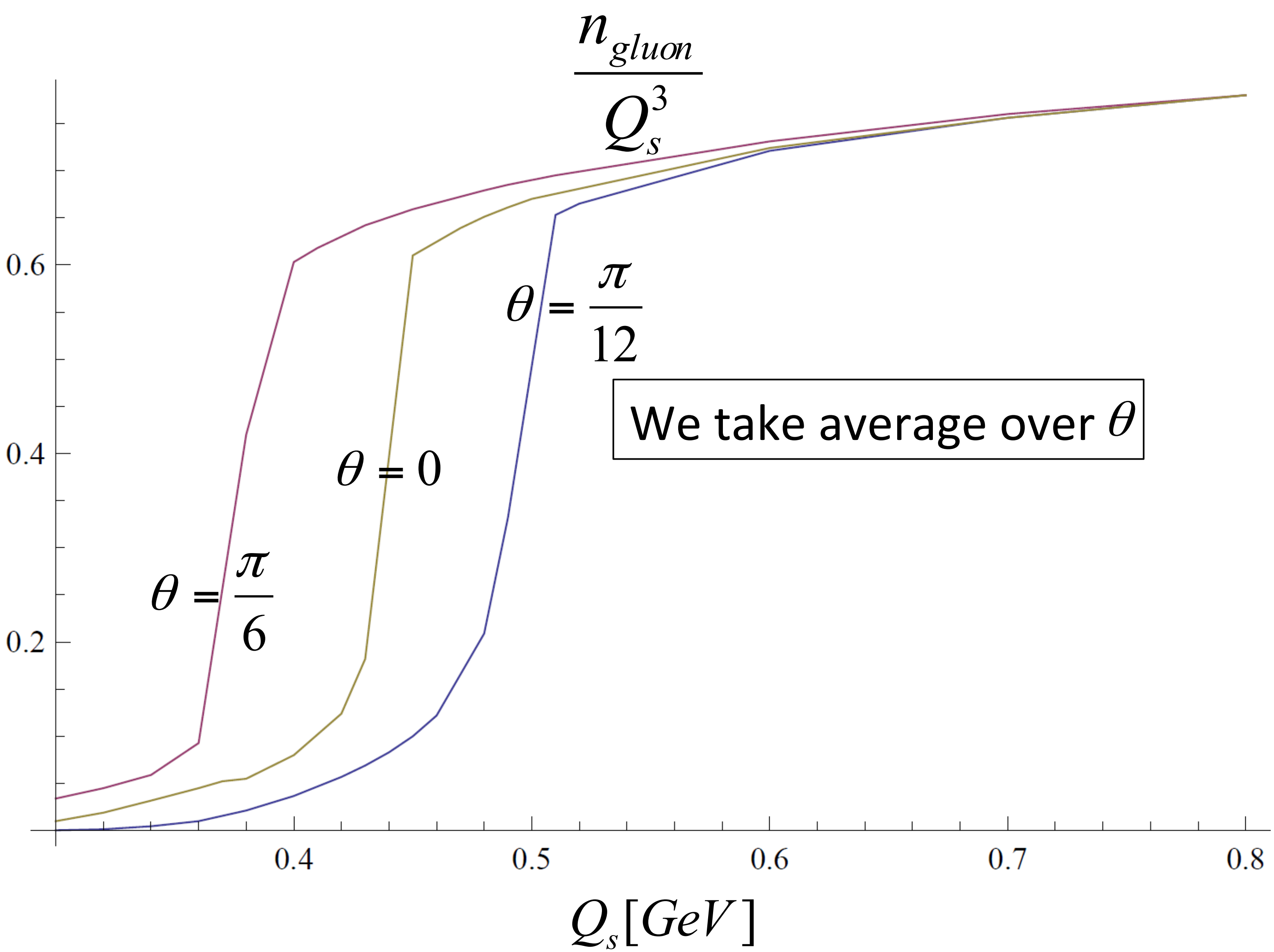
$$\Phi_1 \equiv \frac{A_1 + iA_2}{\sqrt{2}}, \qquad \Phi_2 \equiv \frac{A_4 + iA_5}{\sqrt{2}}, \qquad \Phi_3 \equiv \frac{A_6 + iA_7}{\sqrt{2}}$$

$$g_1 = g\cos\theta \qquad g_2 = g(\cos\theta + \sqrt{3}\sin\theta)/2 \qquad g_3 = g(\cos\theta - \sqrt{3}\sin\theta)/2$$

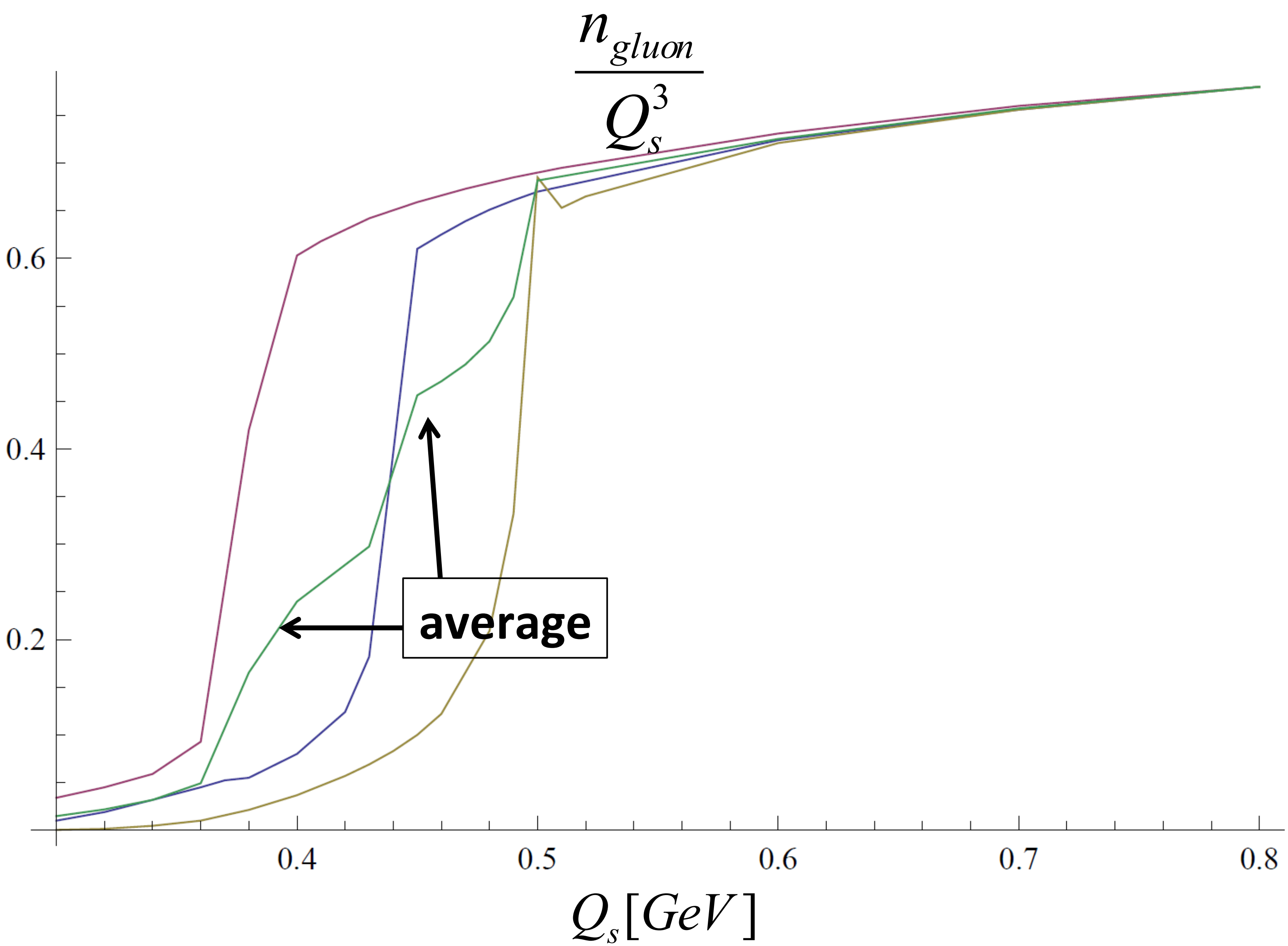
3 types of magnetic monopoles with magnetic charges

$$g_m^1 = g_m\cos\theta, \quad g_m^2 = g_m(\cos\theta + \sqrt{3}\sin\theta)/2, \quad g_m^3 = g_m(\cos\theta - \sqrt{3}\sin\theta)/2$$

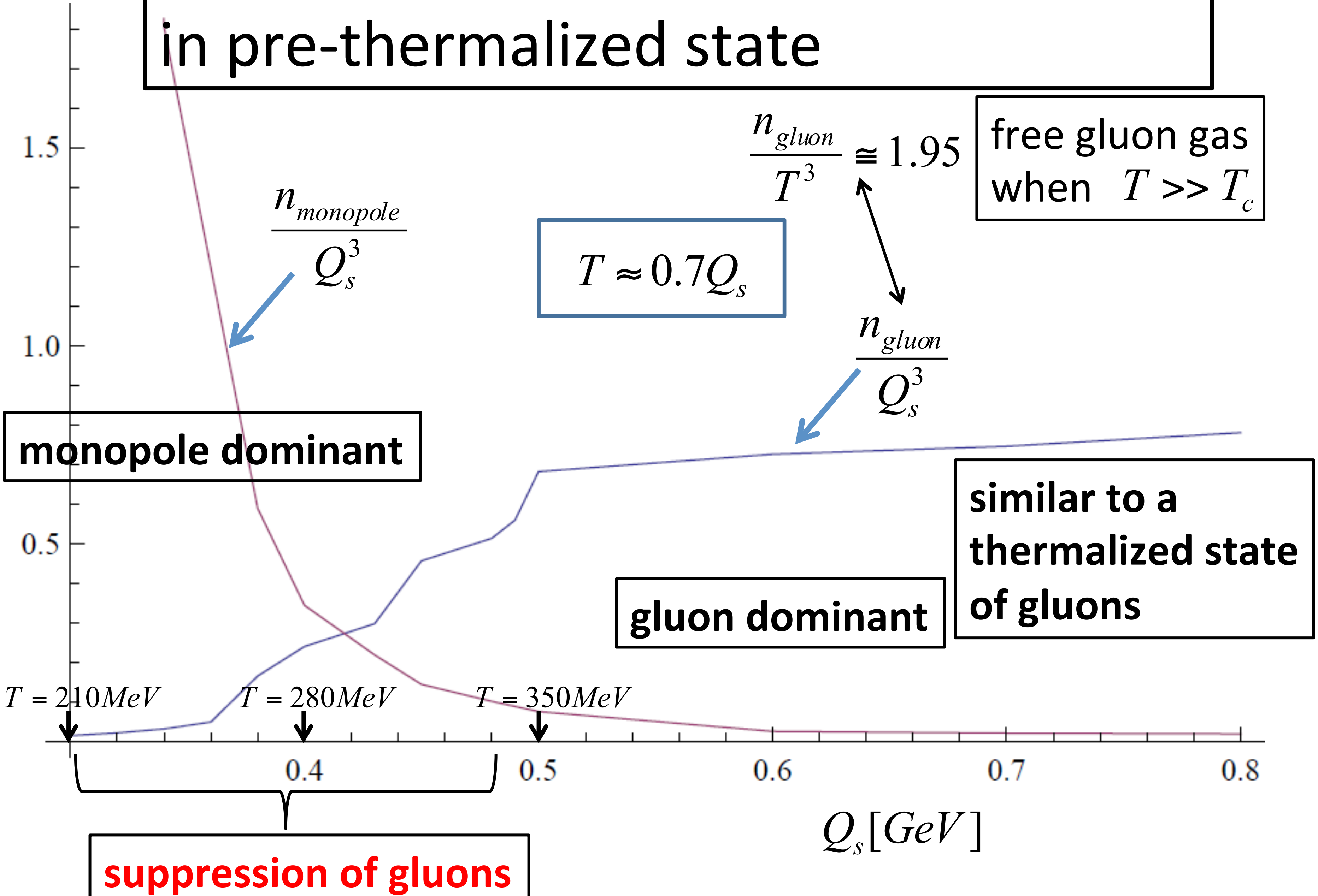
gluon production



gluon production



Production of gluons and monopoles in pre-thermalized state



Conclusion

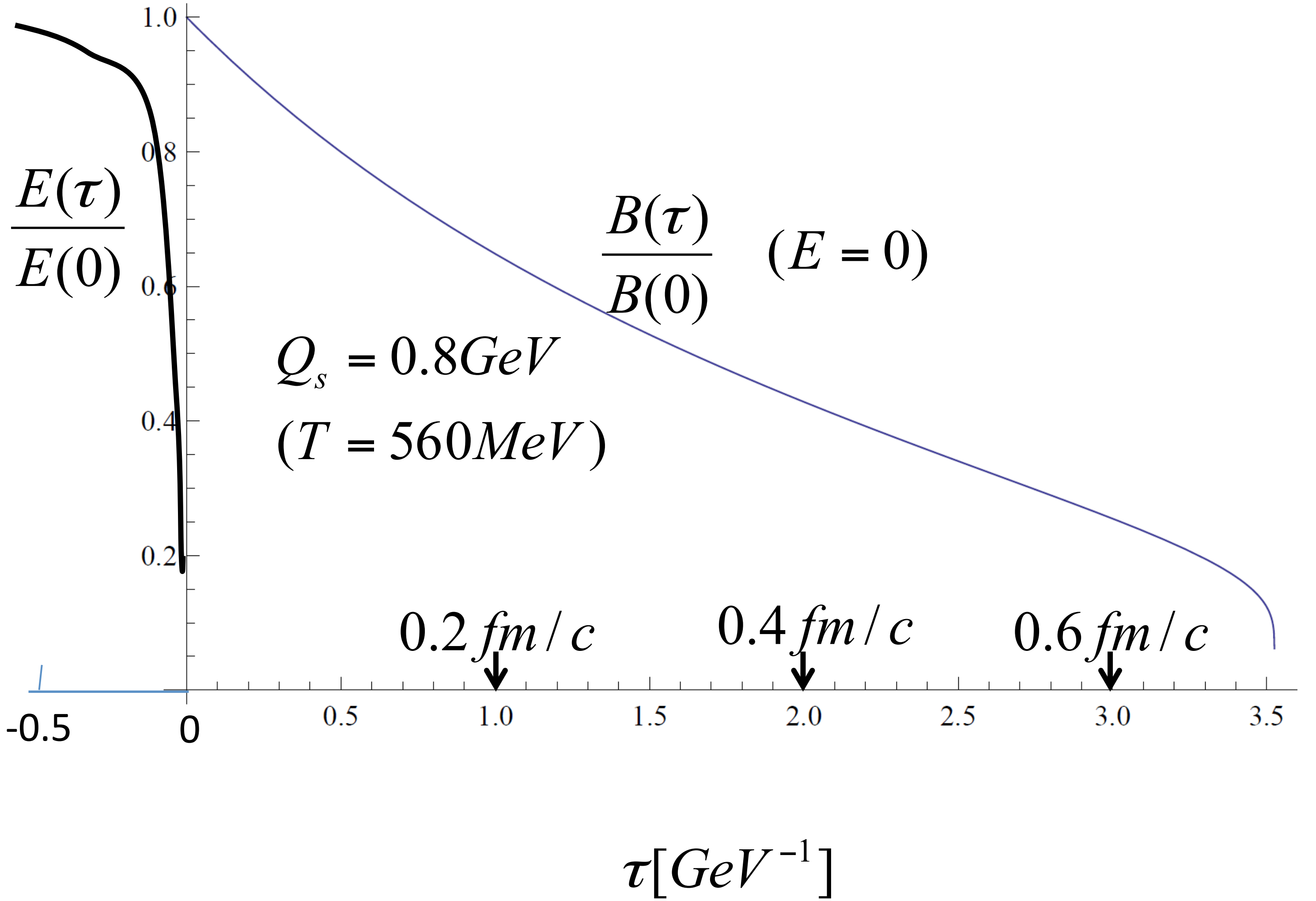
We have discussed the production of gluon and monopole by using Schwinger mechanism.

We have found that

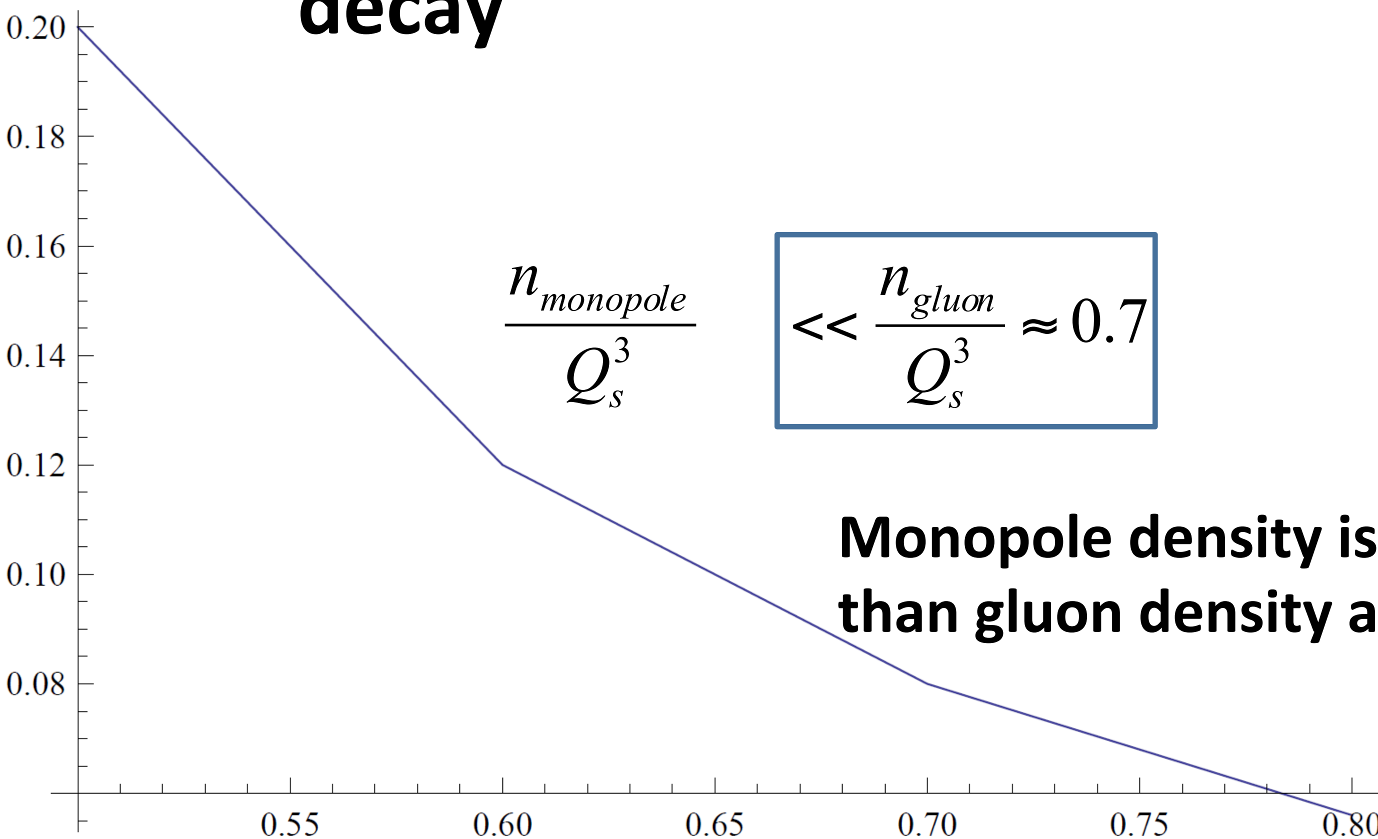
a pre thermalized state of gluons and monopoles is very similar to a thermalized state of semi-quark gluon monopole plasma.

The fact would lead to **fast thermalization of the pre thermalized plasma.**

Magnetic field slowly decays after the rapid decay of electric field



Monopole production by the decay of the magnetic field after the electric field decay



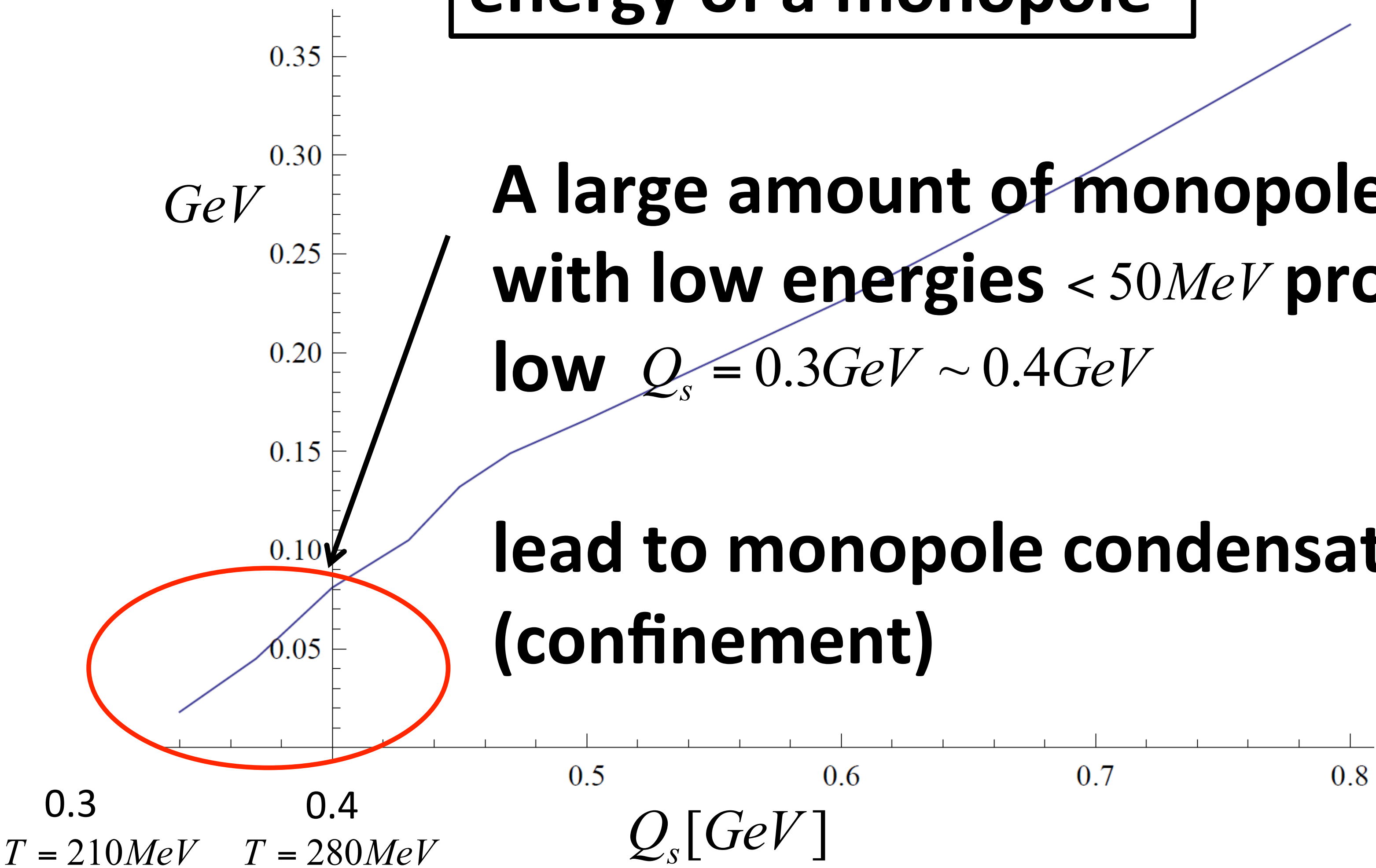
$$\frac{n_{monopole}}{Q_s^3}$$

$$<< \frac{n_{gluon}}{Q_s^3} \approx 0.7$$

$Q_s[GeV]$

Monopole density is still much less than gluon density at large $Q_s > 0.5GeV$

energy of a monopole



A large amount of monopoles with low energies $< 50 MeV$ **produced in low** $Q_s = 0.3 GeV \sim 0.4 GeV$

lead to monopole condensation (confinement)