From Quark-Gluon Plasma to the Perfect Liquid

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Part I

Quark-Gluon Plasma

Matter at extreme conditions

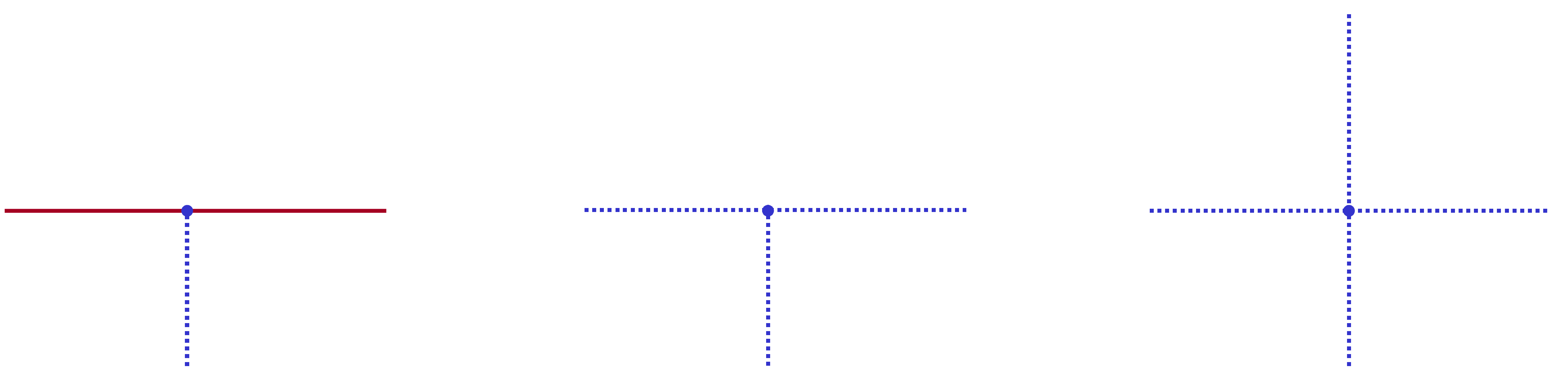
- Squeeze slowly $\rightarrow$ Cold, dense matter
- Squeeze fast $\rightarrow$ Hot, "dense" matter

(1) is much more difficult to do than (2):
Cold matter beyond nuclear matter density ($\rho_B > \rho_0 = 0.15\ \mathrm{fm}^{-3}$) exists only in the core of collapsed (neutron) stars.

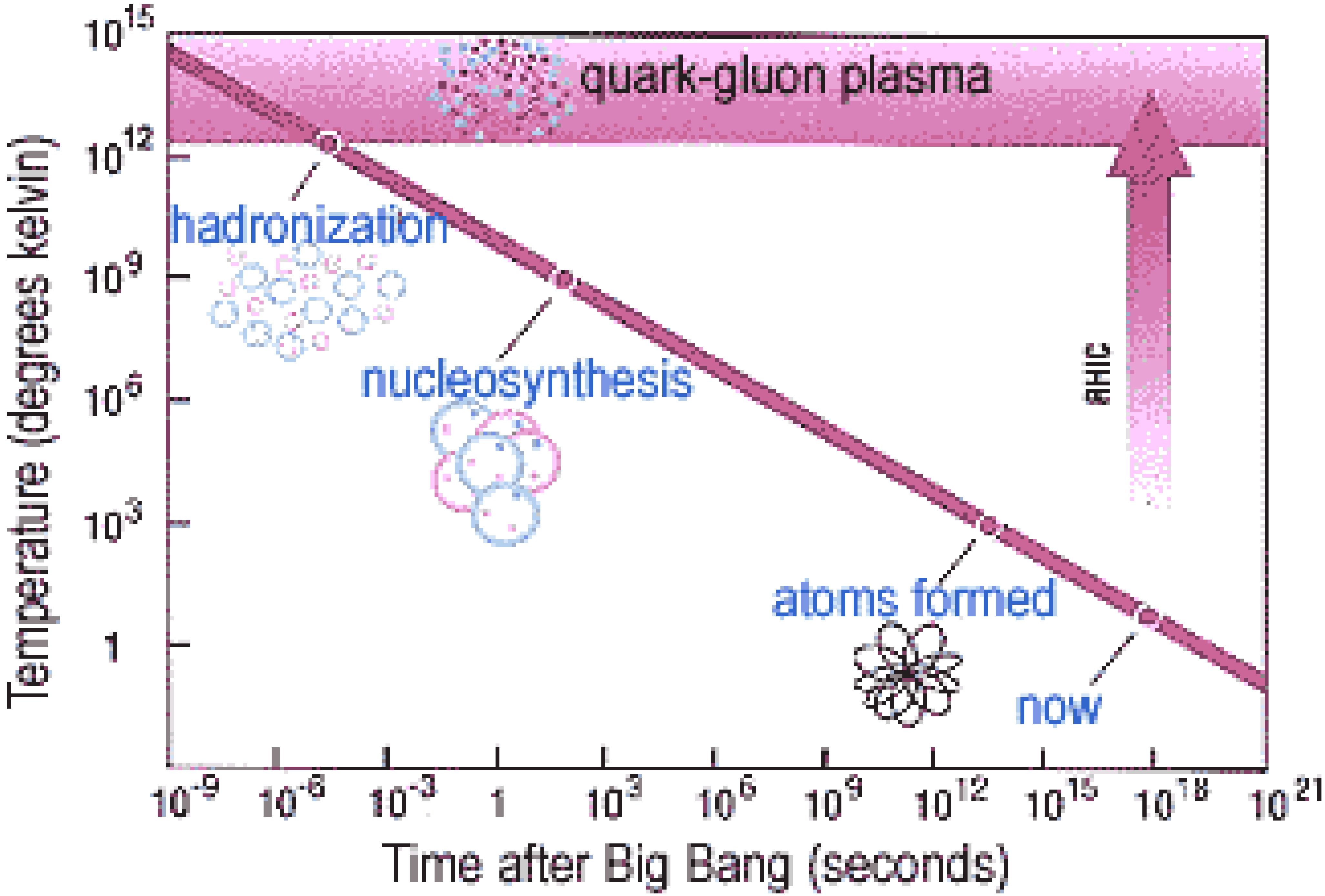
(2) Happened once: $t < 20\ \mu s$ after inflation.
Can also be achieved by colliding nuclei at high energy.
30 years of history: Bevalac, AGS, SPS, RHIC $\rightarrow$ LHC.
Goal: energy density $\varepsilon \gg M_N \rho_0 = 0.14\ \mathrm{GeV/fm}^3$.

Quantum chromodynamics

$$L_{\text{QCD}} = -\tfrac{1}{4}\sum_a G^a_{\mu\nu} G^{a\mu\nu} + \sum_f \bar{\Psi}\gamma^\mu \left(\partial_\mu + g\sum_a A^a_\mu t^a\right)\Psi + \sum_f m_f \bar{\Psi}\Psi$$



Cosmic Connection



Degrees of freedom

- At extreme (energy) density, particle masses can be neglected relative to the kinetic energy:

$$\varepsilon = \nu \int \frac{\delta^3 \pi}{(2\pi)^3} \frac{E}{\varepsilon^{E/T} \pm 1} \quad \omega\iota\tau\eta \quad E = \sqrt{\pi^2 + \mu^2}$$

$$\varepsilon = \nu \frac{\pi^2}{30} a T^4 \quad \text{with} \quad a = \begin{cases} 7/8 \, (\text{fermions}) \\ 1 \;\; (\text{bosons}) \end{cases}$$

$$\text{Quarks:} \quad \nu = 2 \times 2 \times N_C \times N_F = 12 N_F$$

$$\text{Gluons:} \quad \nu = 2 \times (N_C^2 - 1) = 16$$

Hadrons or partons?

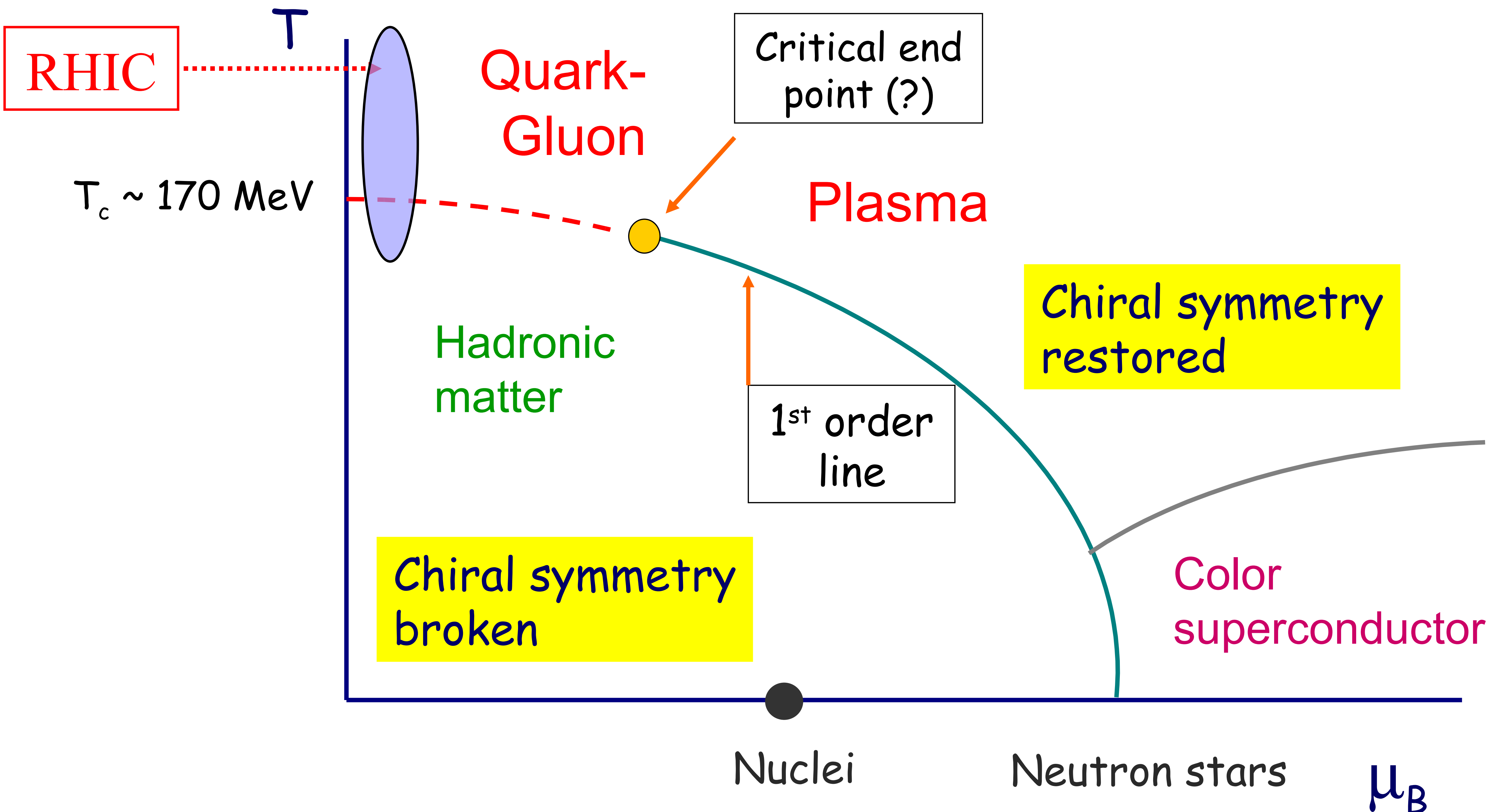
If QCD had N_F light quark flavors, there would be (N_F^2-1) nearly massless Goldstone bosons ("pions"):

$$\nu_\pi = N_F^2 - 1$$

For large N_F the pions win out over quarks, but for N_F=3 the quarks and gluons win out:

→ at high T matter is composed of a colored plasma of quarks and gluons, not of hadrons!

QCD phase diagram

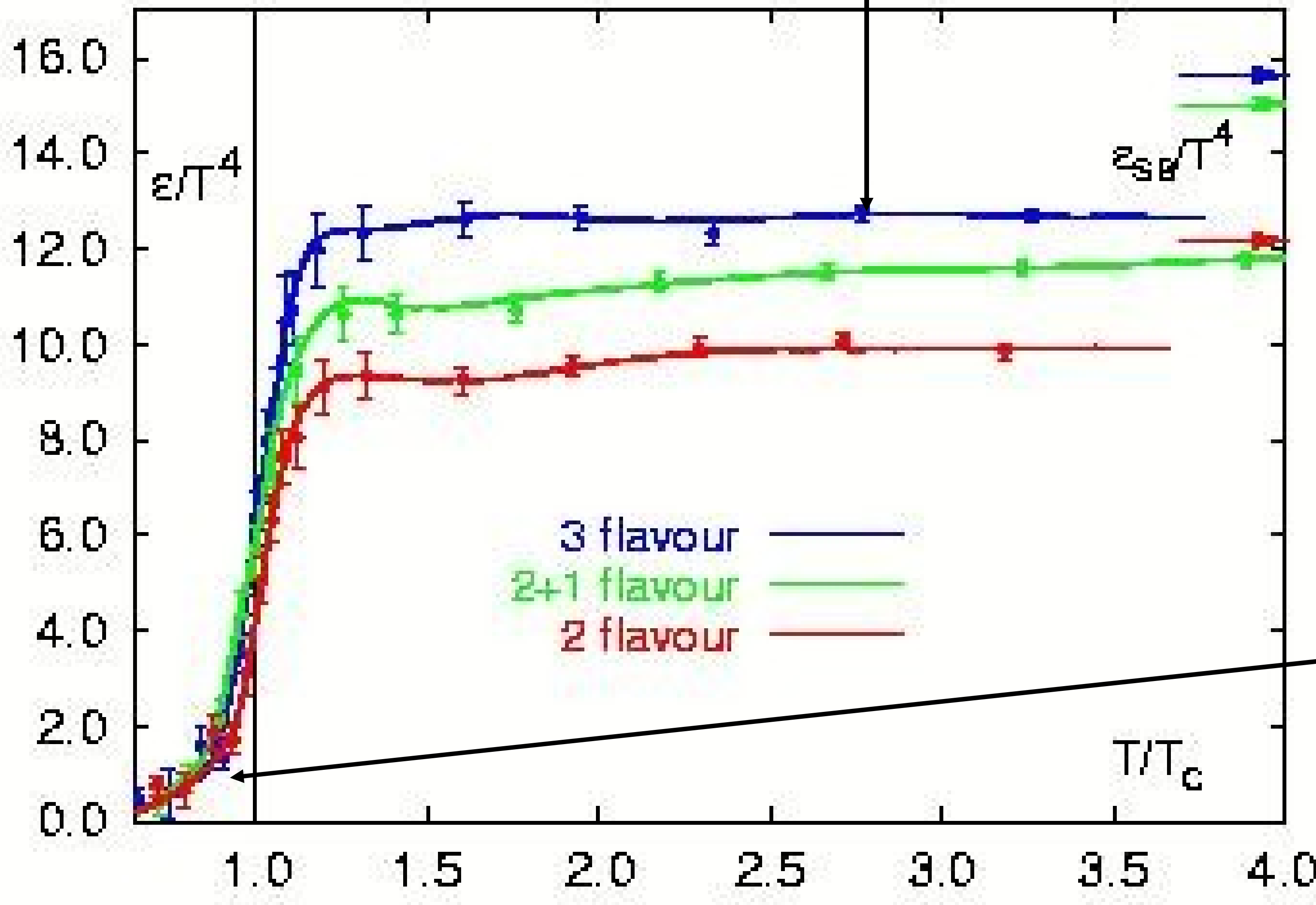


From hadrons to QGP

$$\varepsilon = \frac{\pi^2}{30} \nu T^4$$

QGP = quark-gluon plasma

$\langle \bar{\psi}\psi \rangle \approx 0$



QCD equation of state from lattice QCD

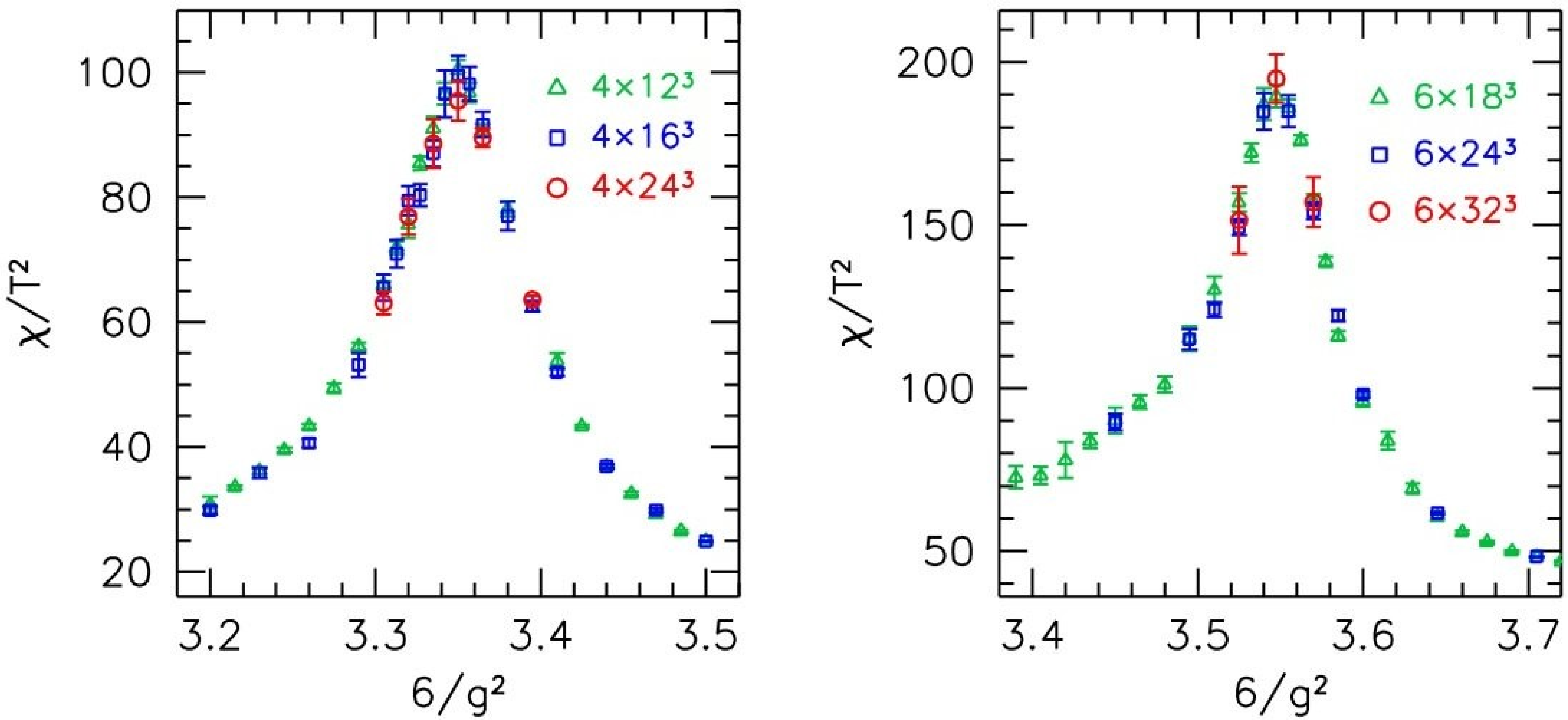
Hadron gas

$\langle \bar{\psi}\psi \rangle_0$

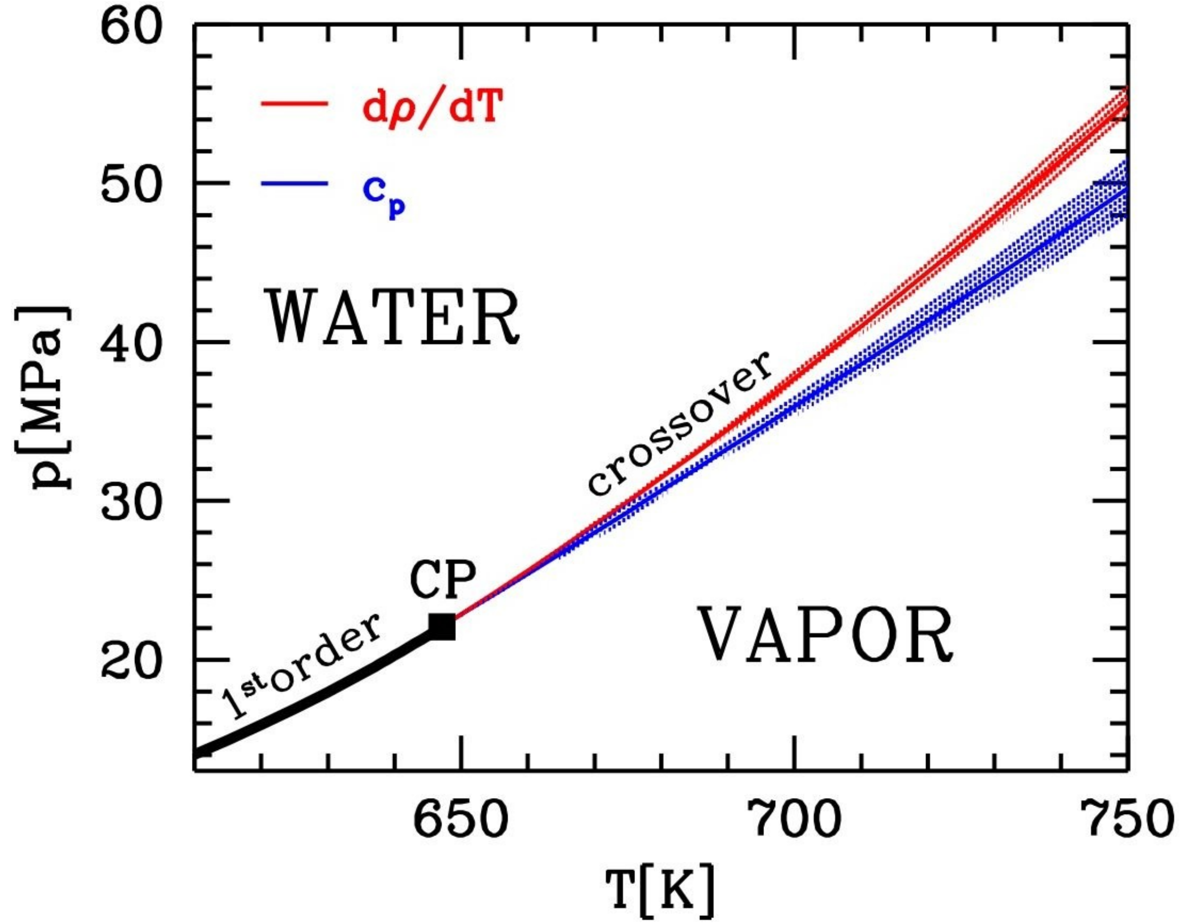
Crossover of phases

Susceptibilities peak at T_c, but do not diverge. Vacuum properties change smoothly, but rapidly → "crossover"

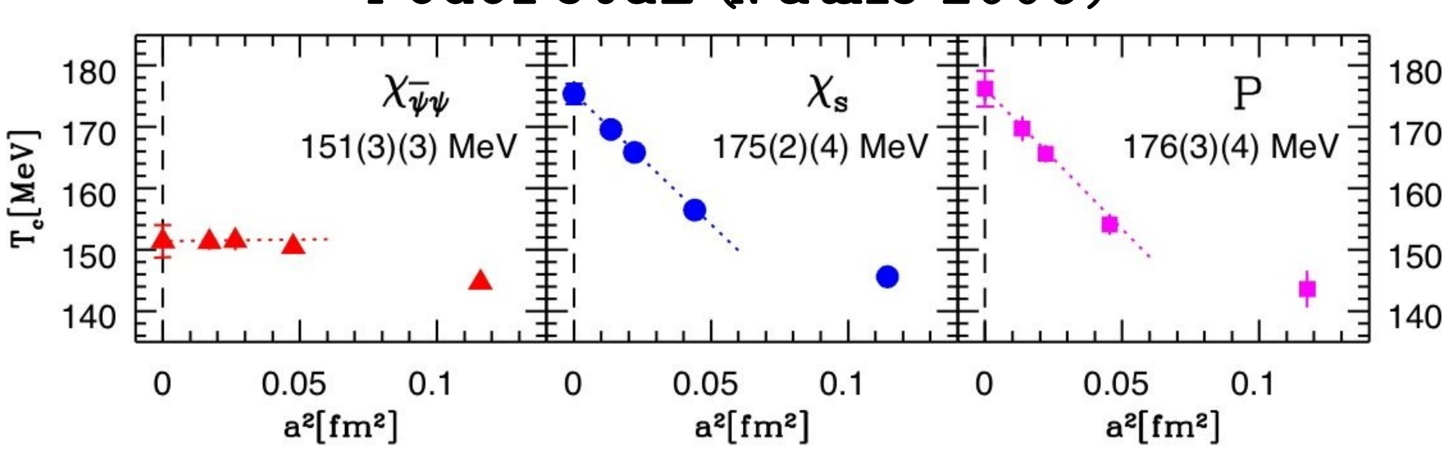
Aoki et al. (Nature 2006)

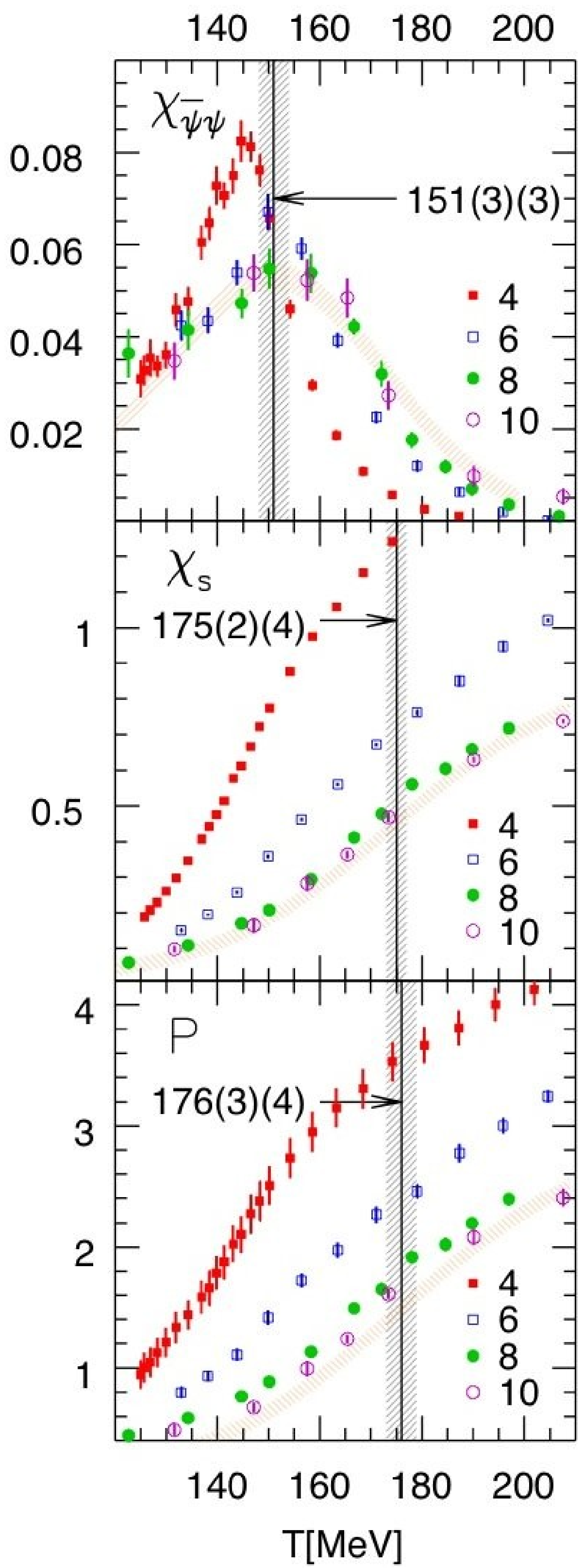


A fuzzy transition?



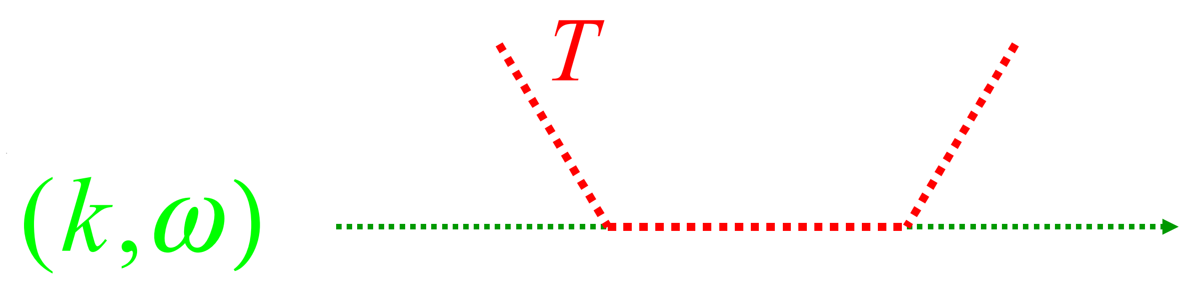
Fodor et al (Nature 2006)





Quasi-particles in the QGP

Physical excitation modes at high *T* are not elementary quarks and gluons, but "dressed" quarks and gluons:



Compton scattering on a thermal gluon!

Propagator of transversely polarized gluons

$$D(k,\omega)^{-1} = \omega^2 - k^2 - \frac{1}{2}(gT)^2 \left[1 - \frac{1}{2}\left(\frac{\omega}{k} - \frac{k}{\omega} \right) \ln \frac{\omega + k}{\omega - k} \right]$$

$\rightarrow$ Effective mass of gluon:

$$m_G^* \longrightarrow \frac{1}{\sqrt{3}} gT$$

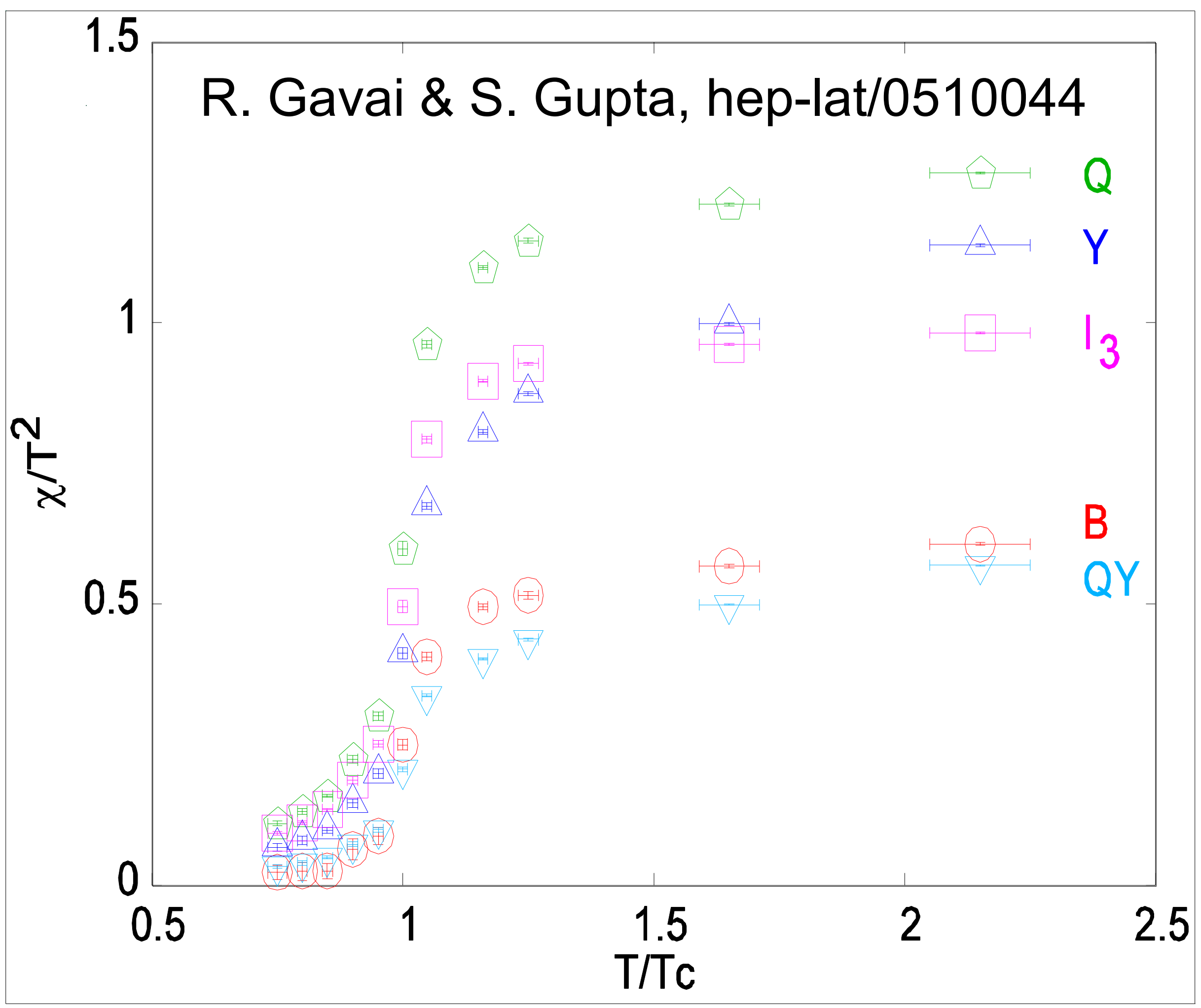
$$m_G^* \longrightarrow \frac{1}{\sqrt{2}} gT$$

Lattice - susceptibilities

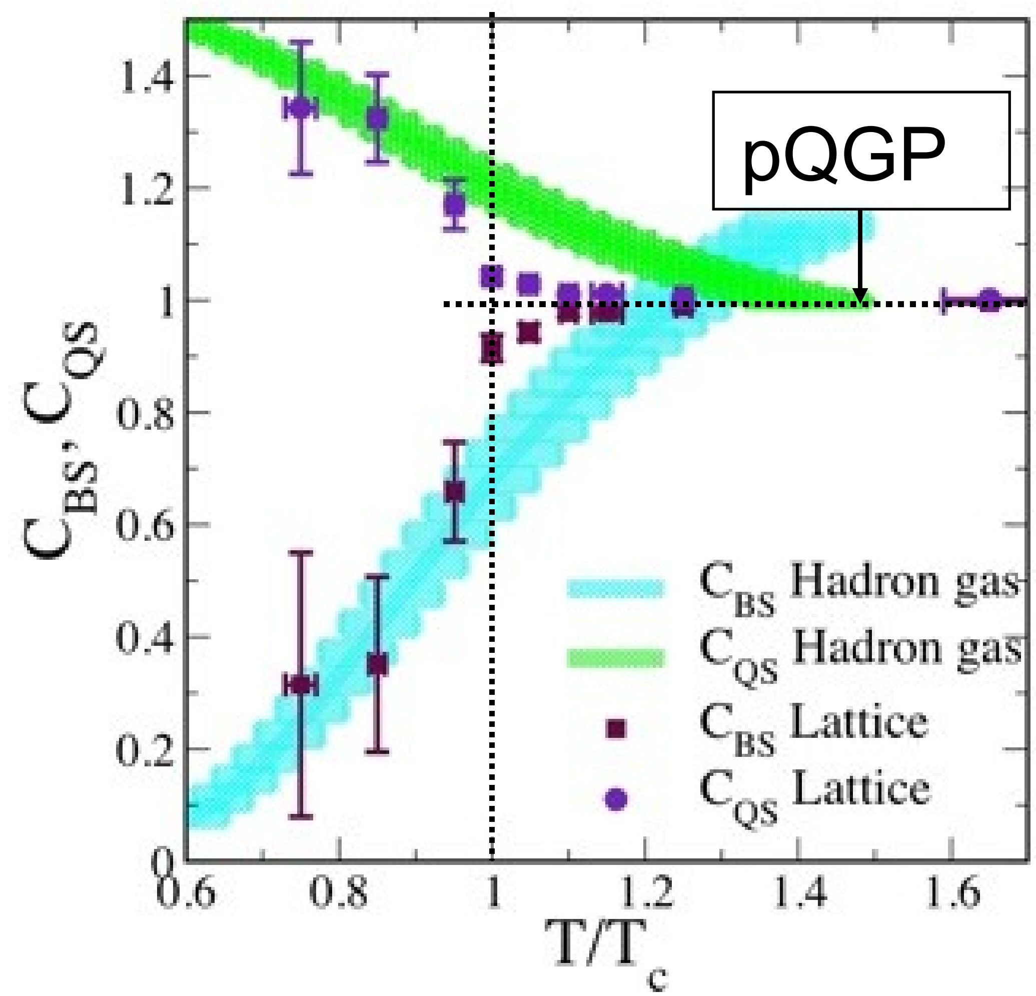
$$\chi_{XY} = \frac{\partial^2}{\partial \mu_X \partial \mu_Y} \ln Z(T, \mu_i) = \langle XY \rangle - \langle X \rangle \langle Y \rangle$$

$$C_{XS} = \# \frac{\langle XS \rangle - \langle X \rangle \langle S \rangle}{\langle S^2 \rangle - \langle S \rangle^2}$$

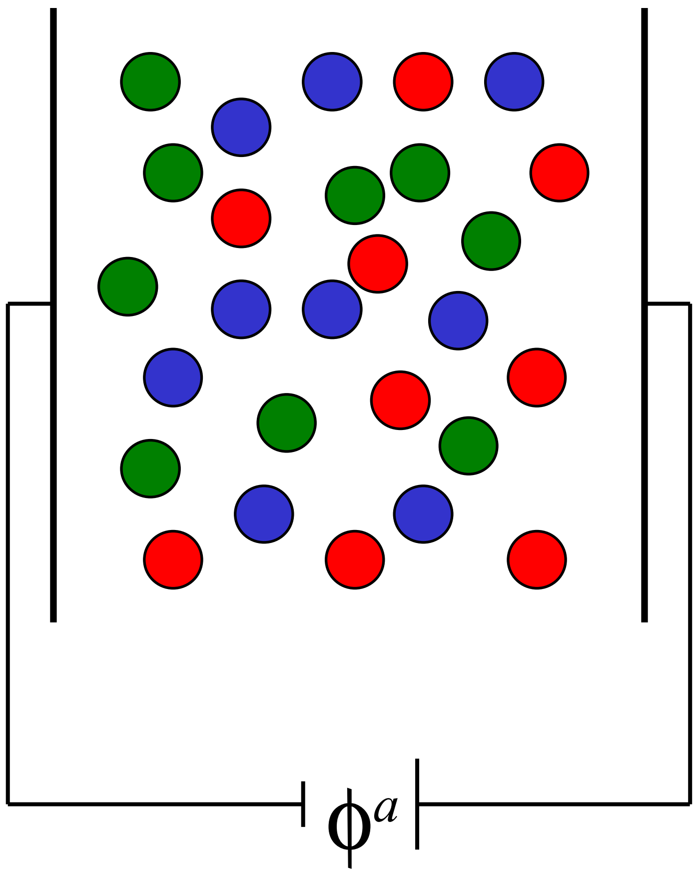
$$\langle XS \rangle \approx \sum_i x_i s_i n_i$$



A.Majumder



Color screening



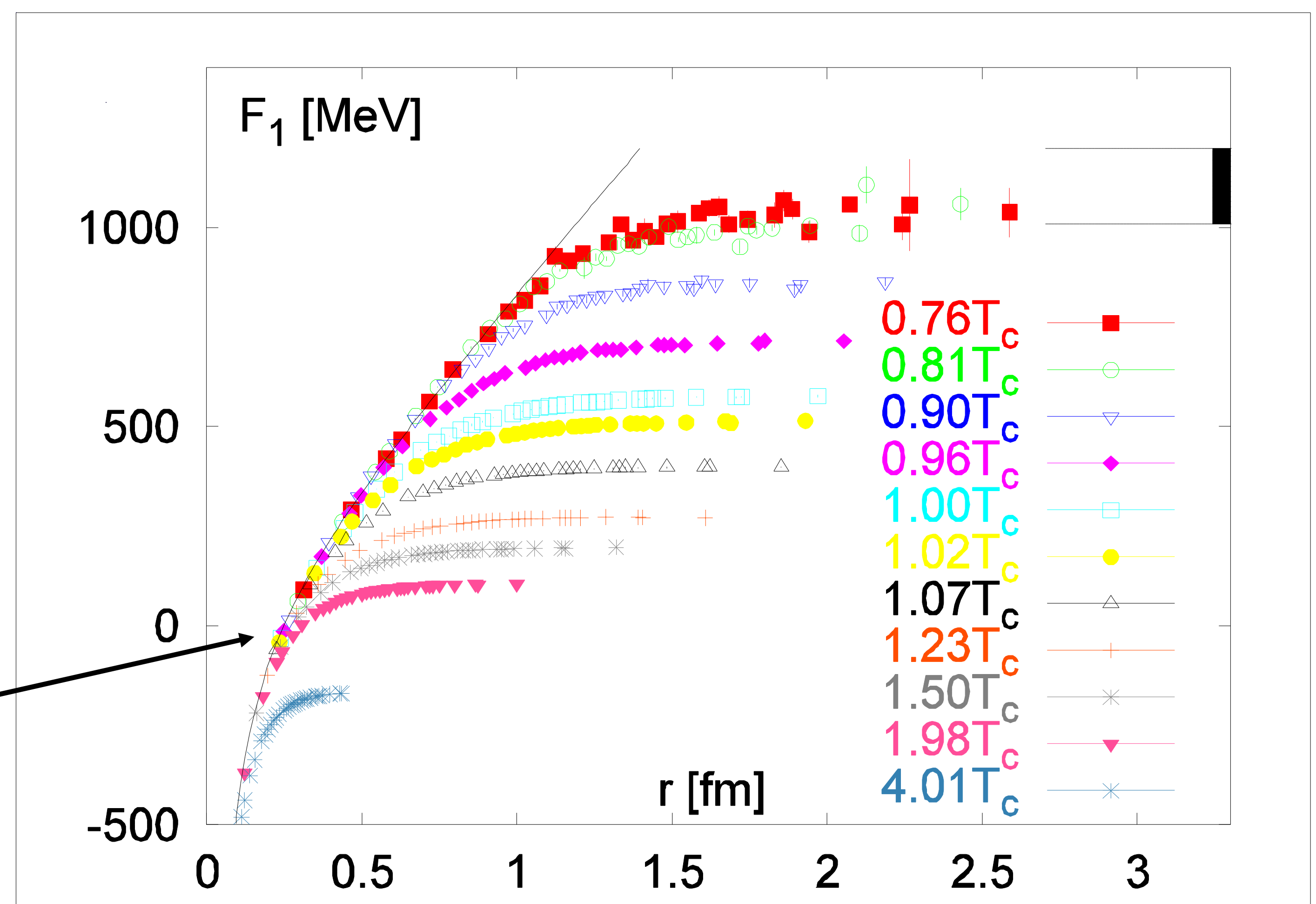
$$-\nabla^2 \phi^a = g\rho_G^a(\phi^b) + g\rho_Q^a(\phi^b)$$

Induced color density $\rho^a = -\mu^2 \phi^a$

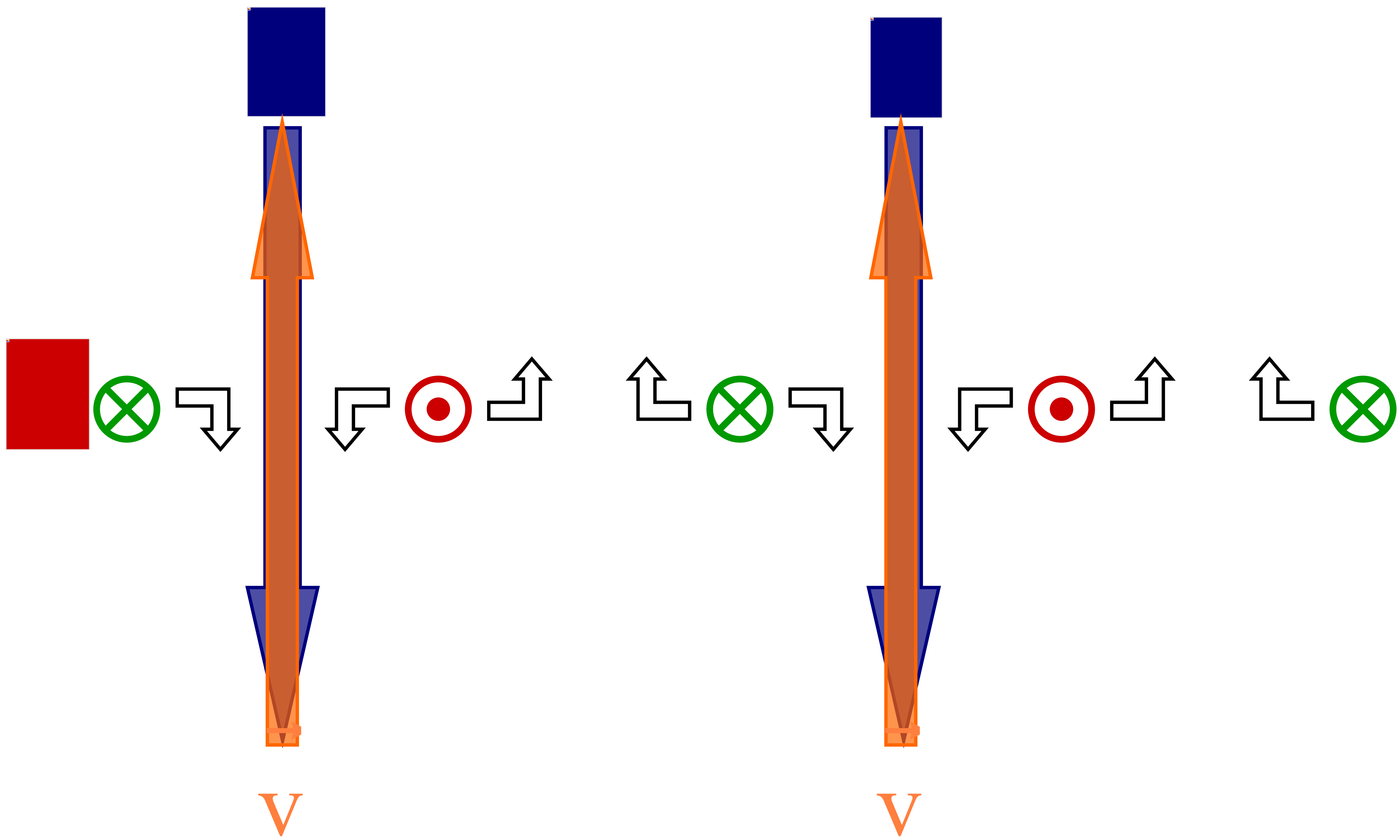
with $\mu_G^2 = (gT)^2, \quad \mu_Q^2 = \frac{N_F}{6}(gT)^2$

Static color charge (heavy quark) generates screened potential

$$\phi^a = t^a \frac{\alpha_s}{r} e^{-\mu r}$$

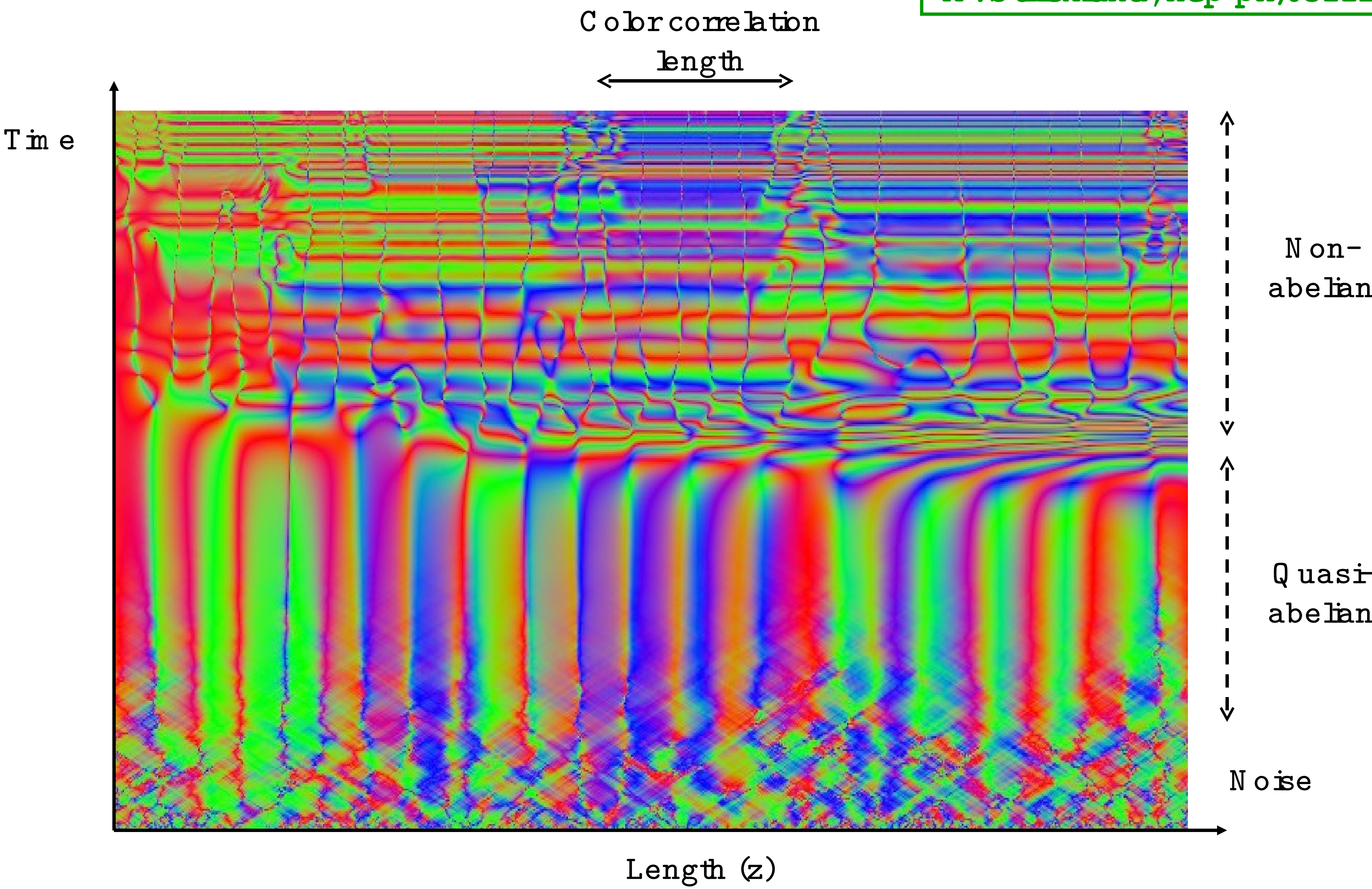


Plasma two-stream instability

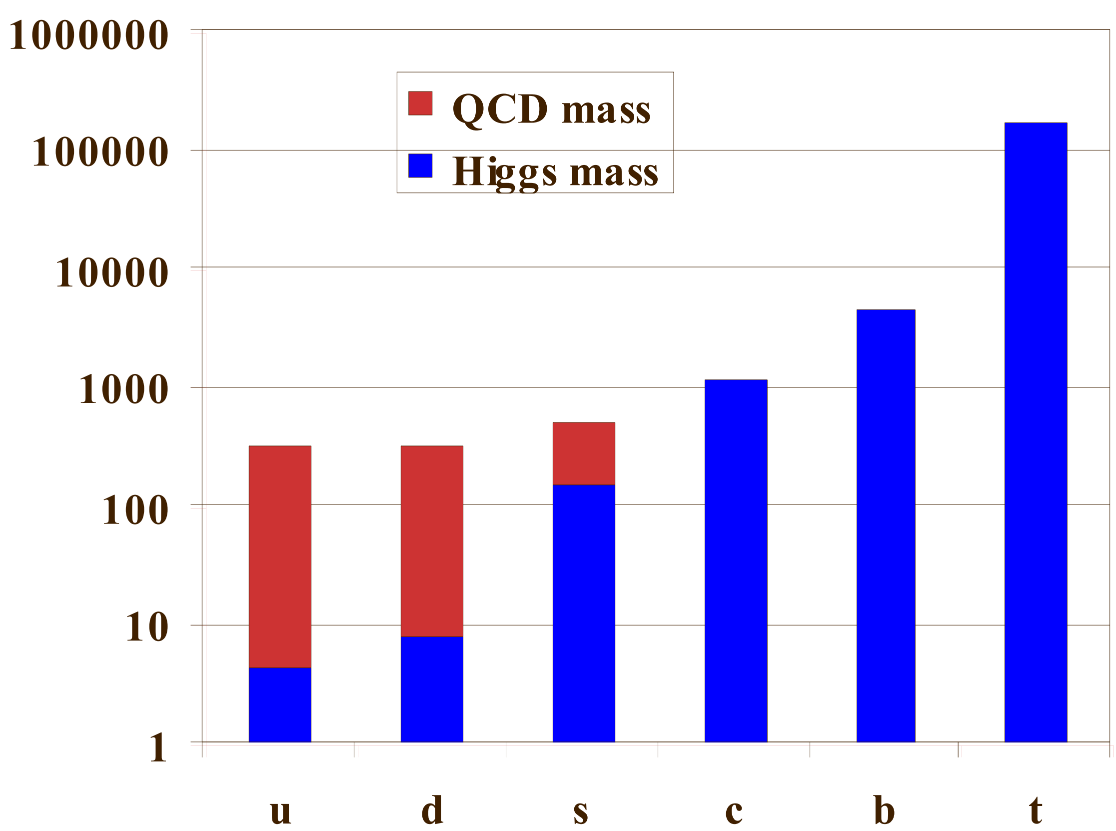


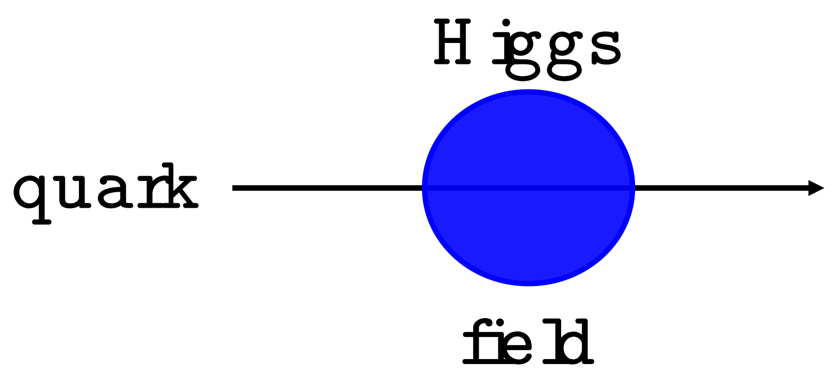
Turbulent color fields

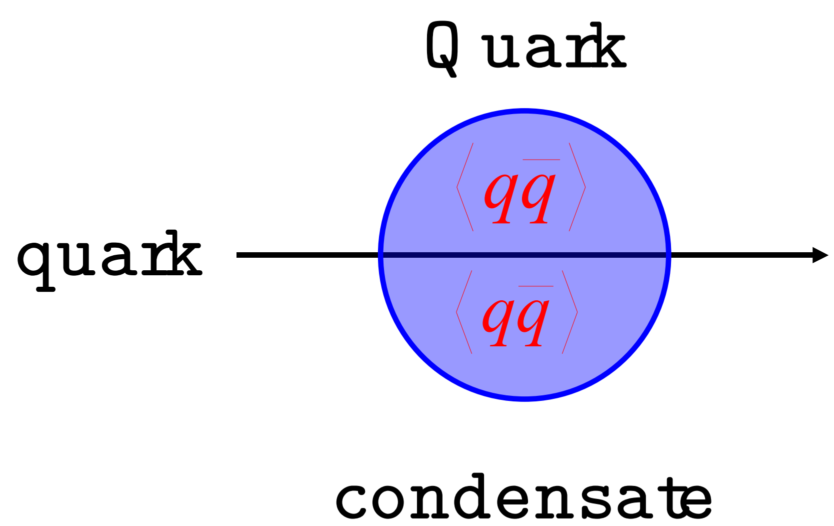
M. Strickland, hep-ph/0511212



Quark masses



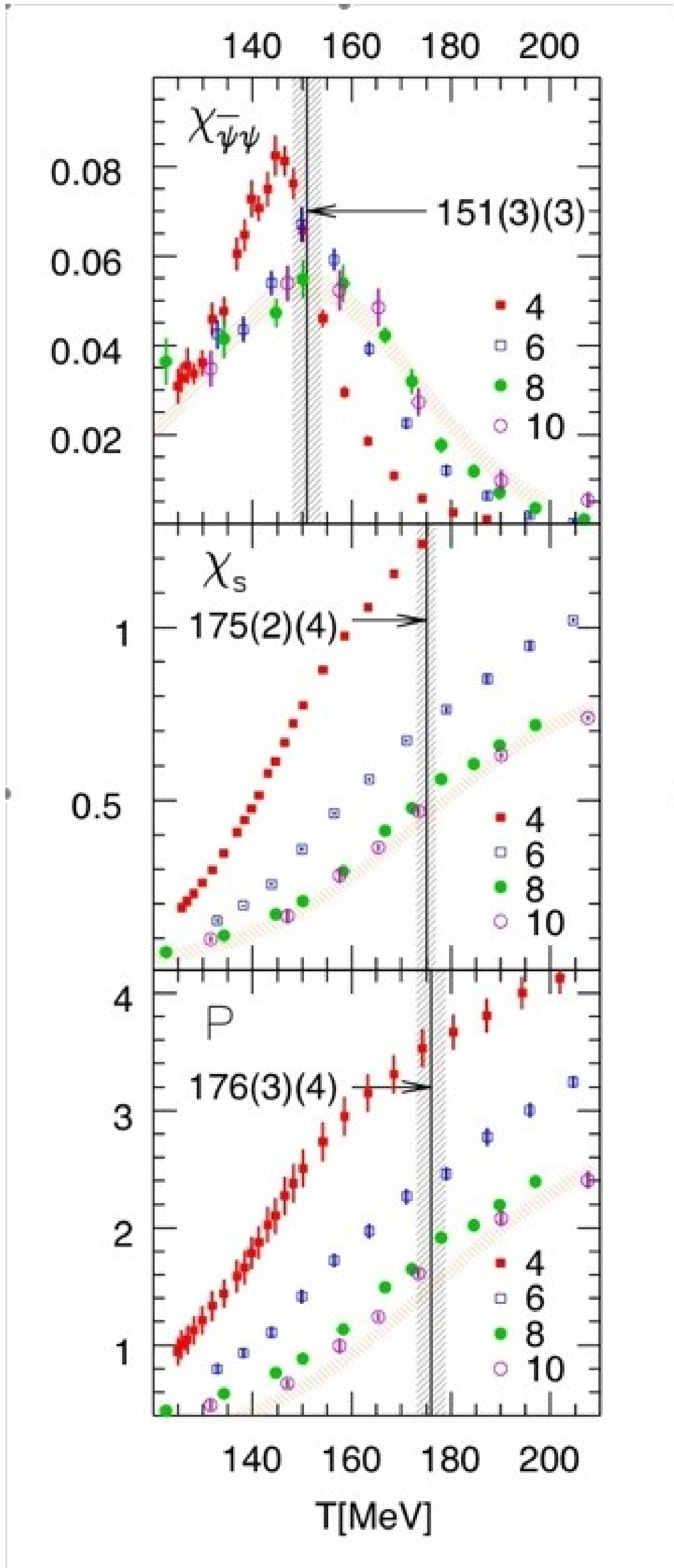




QCD mass disappears above T_c:

(partial) chiral symmetry restoration

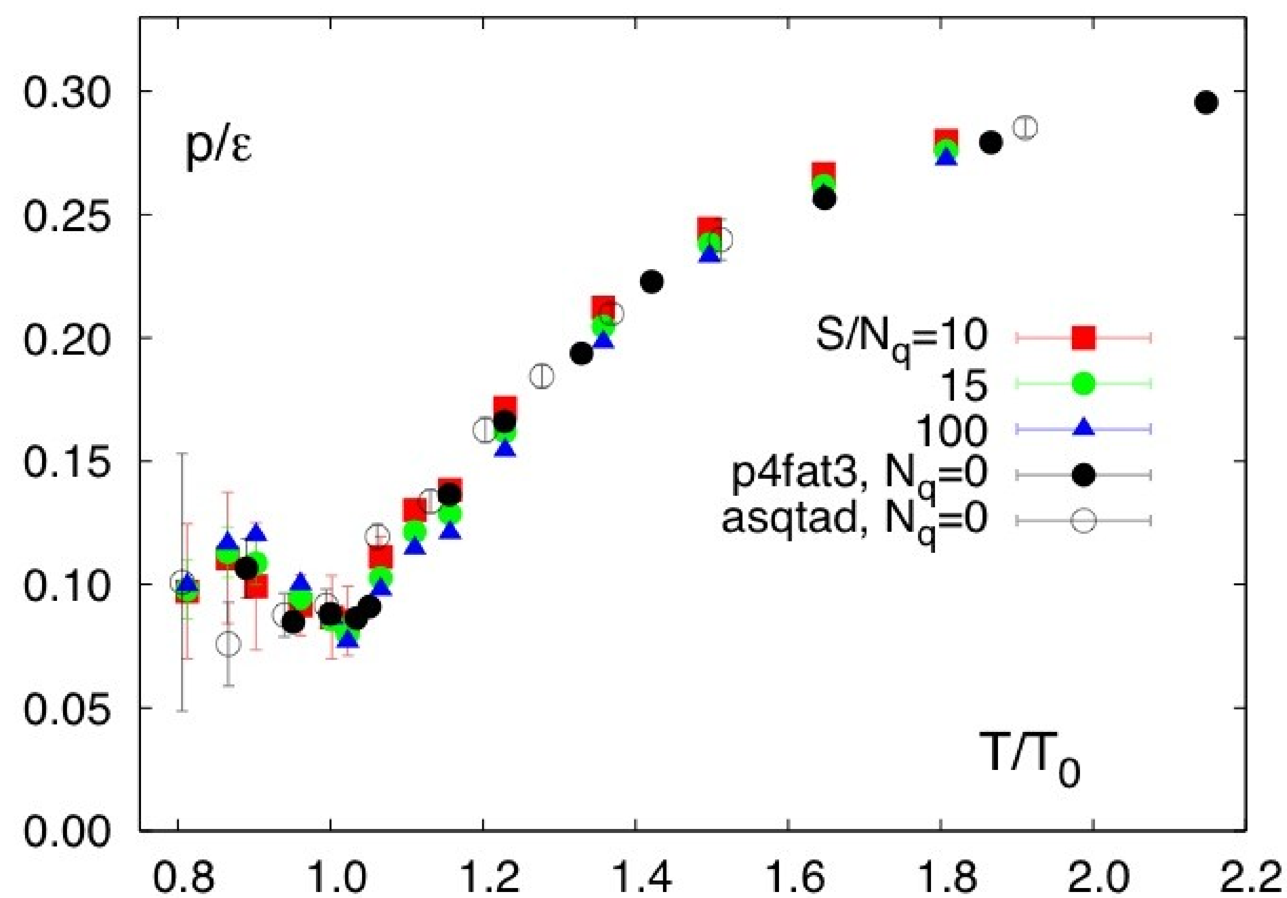
The QCD EoS (at μ=0)



The precise value of T_c is still under debate:

T_c = 170 ± 20 MeV with 20 - 30 MeV width.

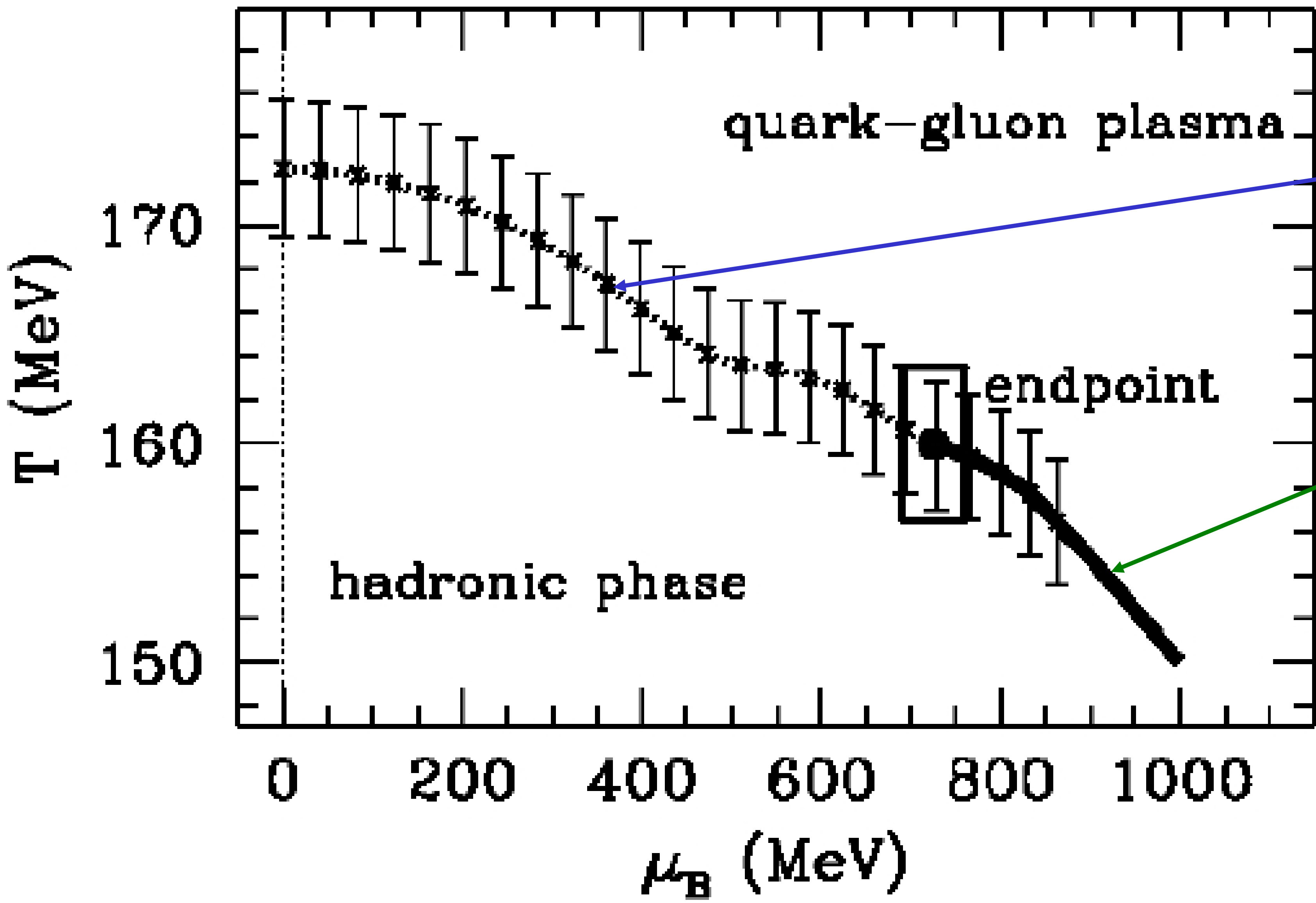
EoS near T_c is far from ideal ultrarelativistic gas!
Sound velocity $c_s^2 = \partial P/\partial\varepsilon << 1/3$.



Into the T-μ_B plane

$T_c(\mu_B)$

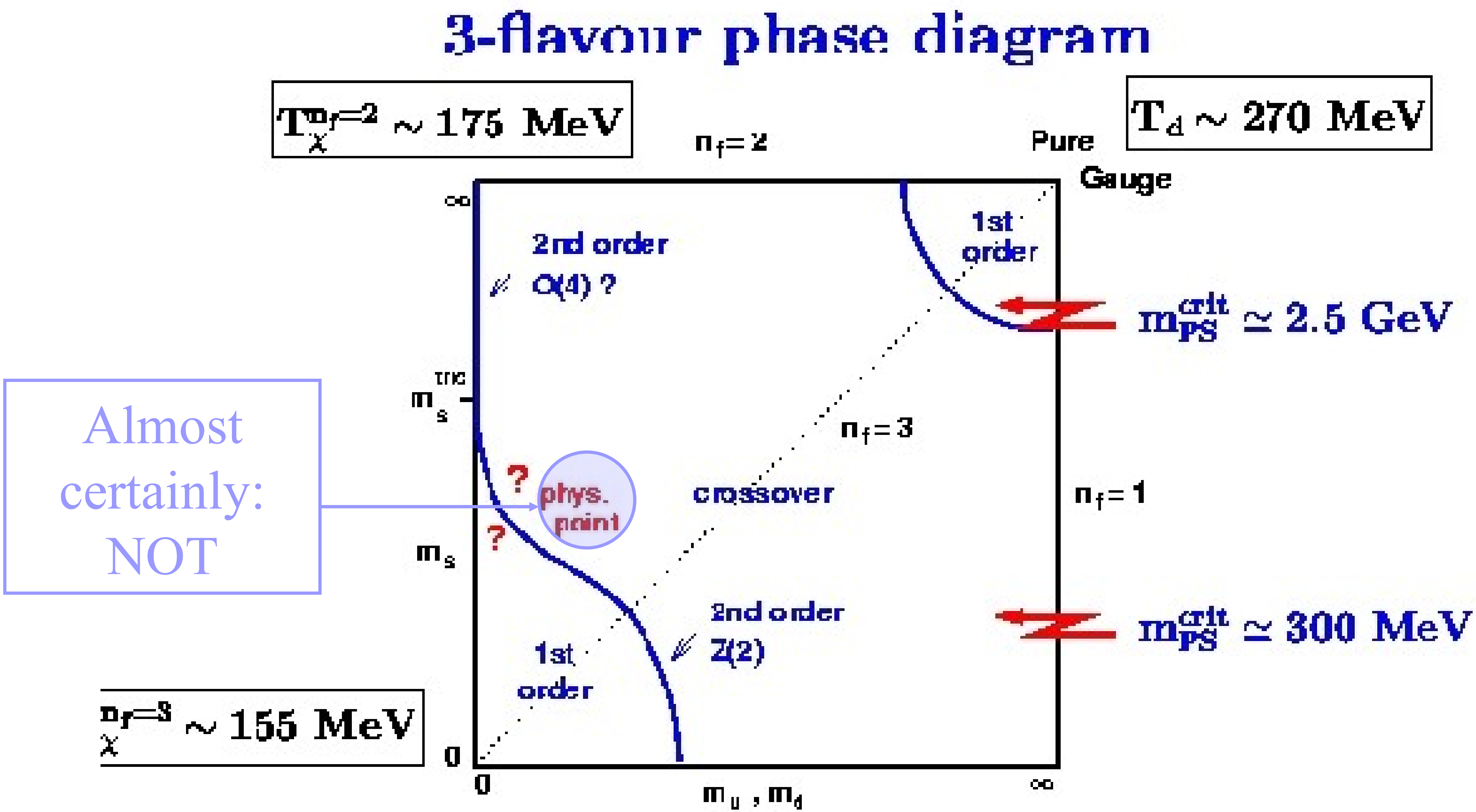
First order phase transition line



Fodor & Katz (2001)

Controls net baryon density

Is there a phase transition?



A triple point ?

Fodor et al. hep-lat/0701022