[Lecture 1]

Heavy Ions

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QCD

QCD is the theory of strong interactions.

⇒ It describes interactions between hadrons (p, π, ...)

- Asymptotic states.
- *Normal* conditions of temperature and density.
- Nuclear matter (us).
- Colorless objects.

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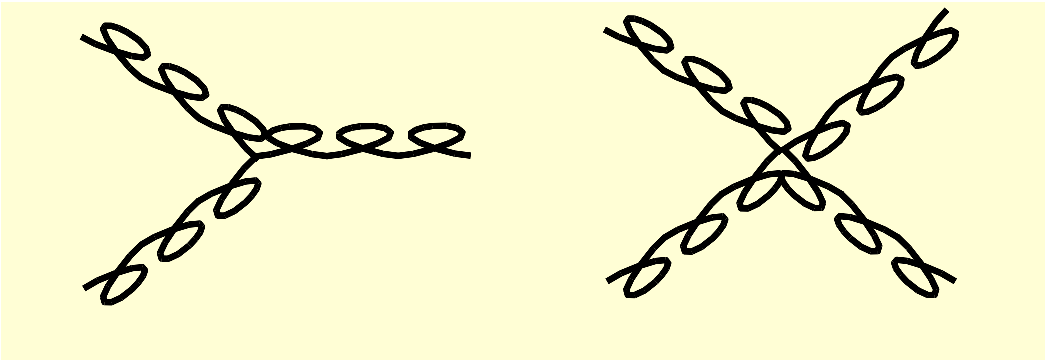
⇒ Quarks and gluons in the Lagrangian

- Fundamental particles.

charge=+2/3	u ($\sim$5 MeV)	c ($\sim$1.5 GeV)	t ($\sim$175 GeV)
charge=-1/3	d ($\sim$10 MeV)	s ($\sim$100 MeV)	b ($\sim$5 GeV)

- Colorful objects. color = charge of QCD $\longrightarrow$ vector
  Similar to QED, but gluons can interact among themselves



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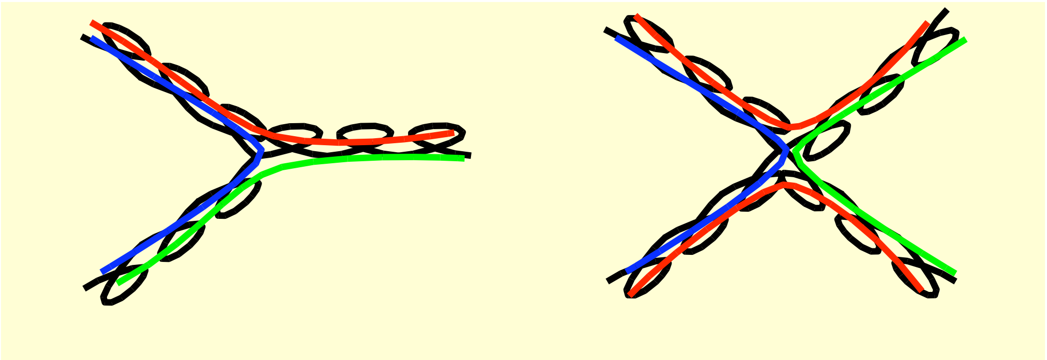

- Gluons carry color charge ⟶ This changes everything...

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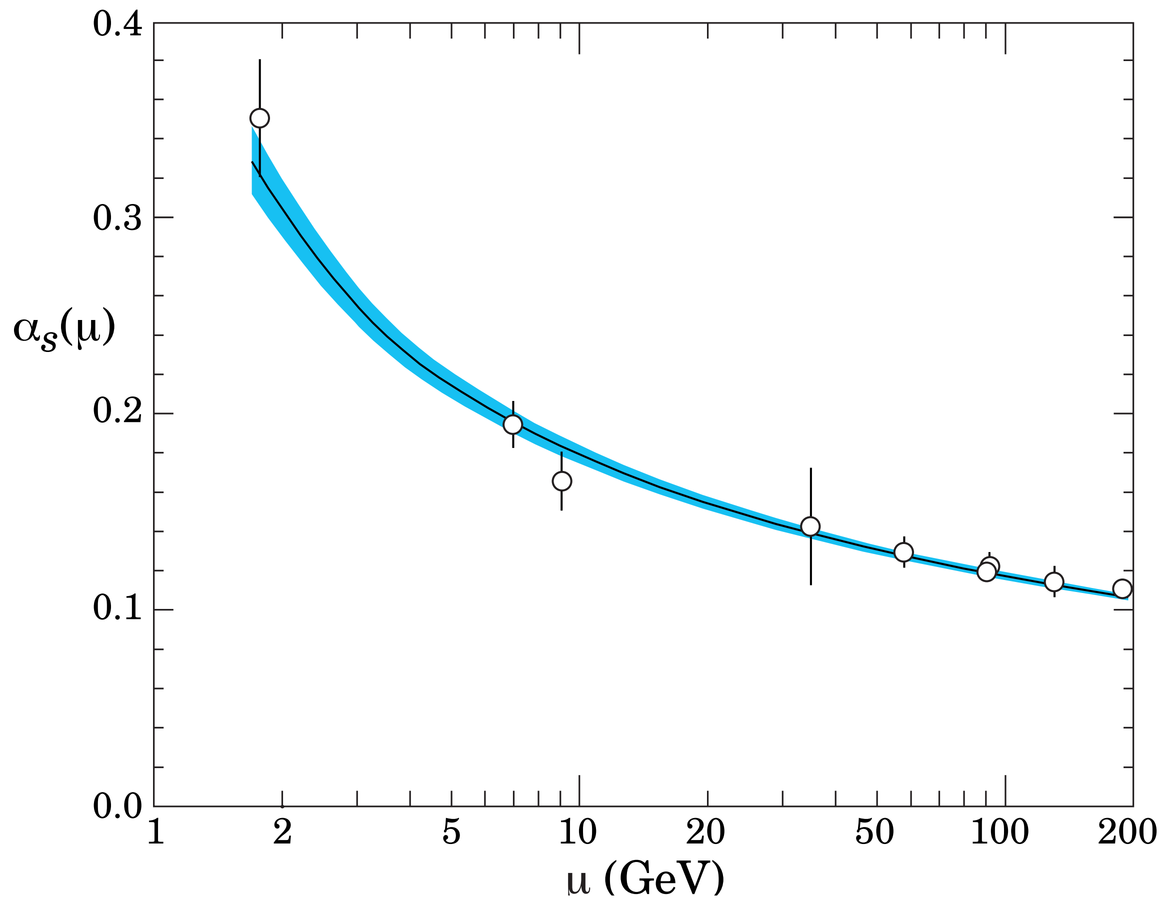
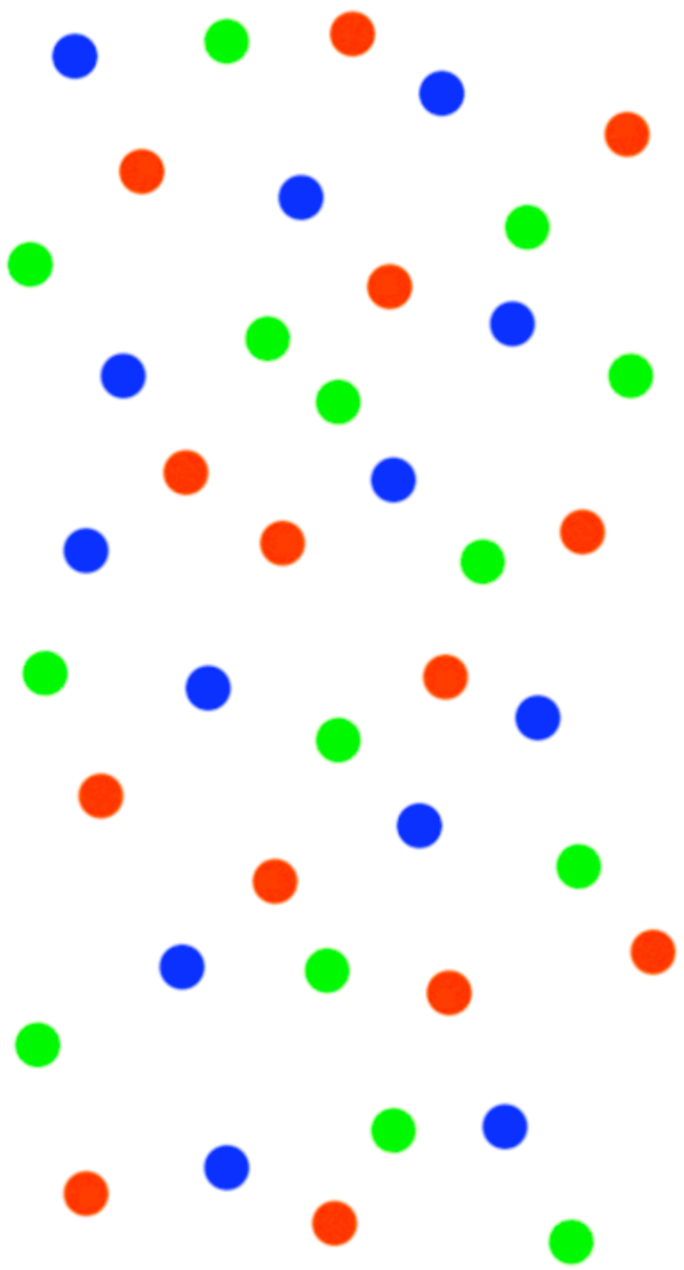
⇛ No free quarks and gluons: Confinement.

⇛ Strength smaller at smaller distances: Asymptotic freedom.



Picture

⇛ In quantum field theory, vacuum is a medium which can screen charge. (quarks or gluons disturb vacuum).



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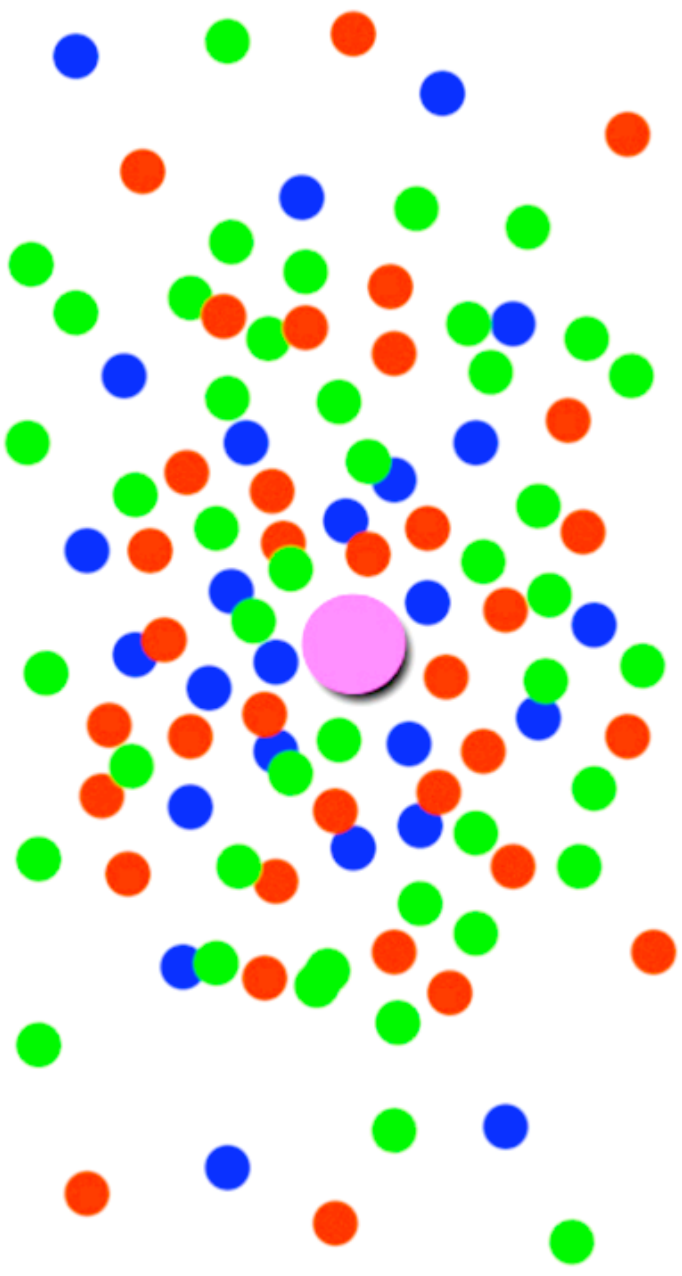
⇒ confinement $\Longrightarrow$ isolated quarks (gluons) = infinite energy



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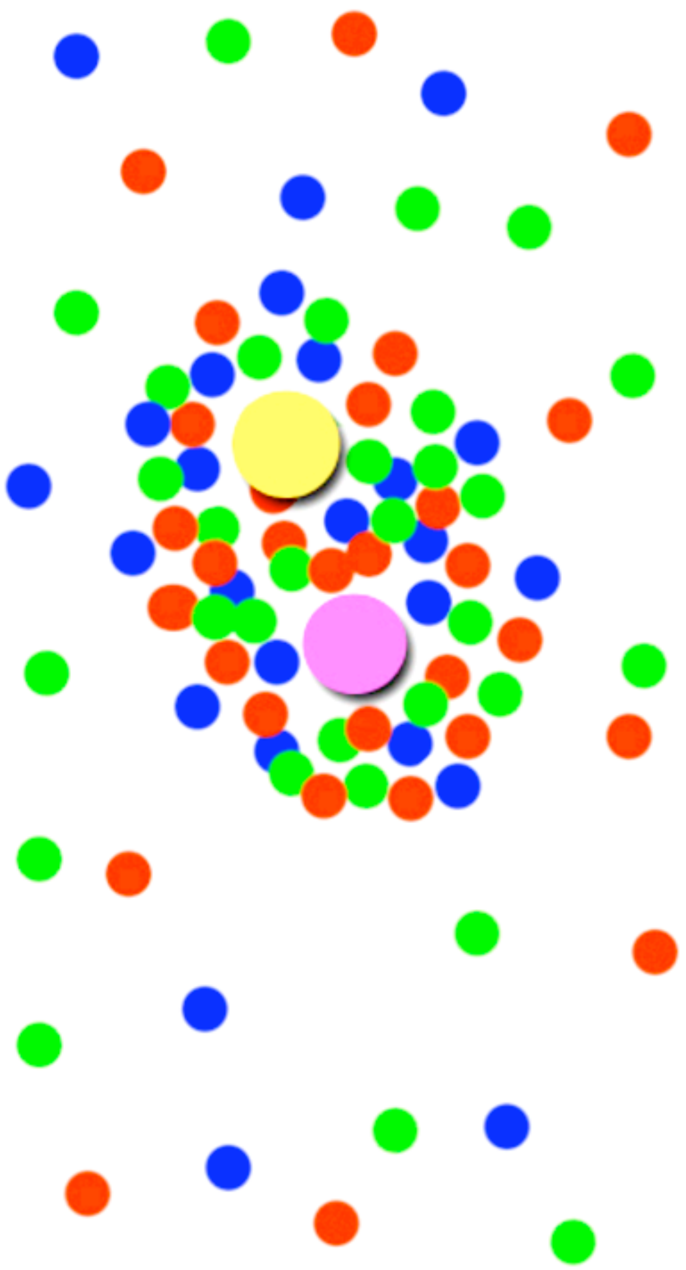

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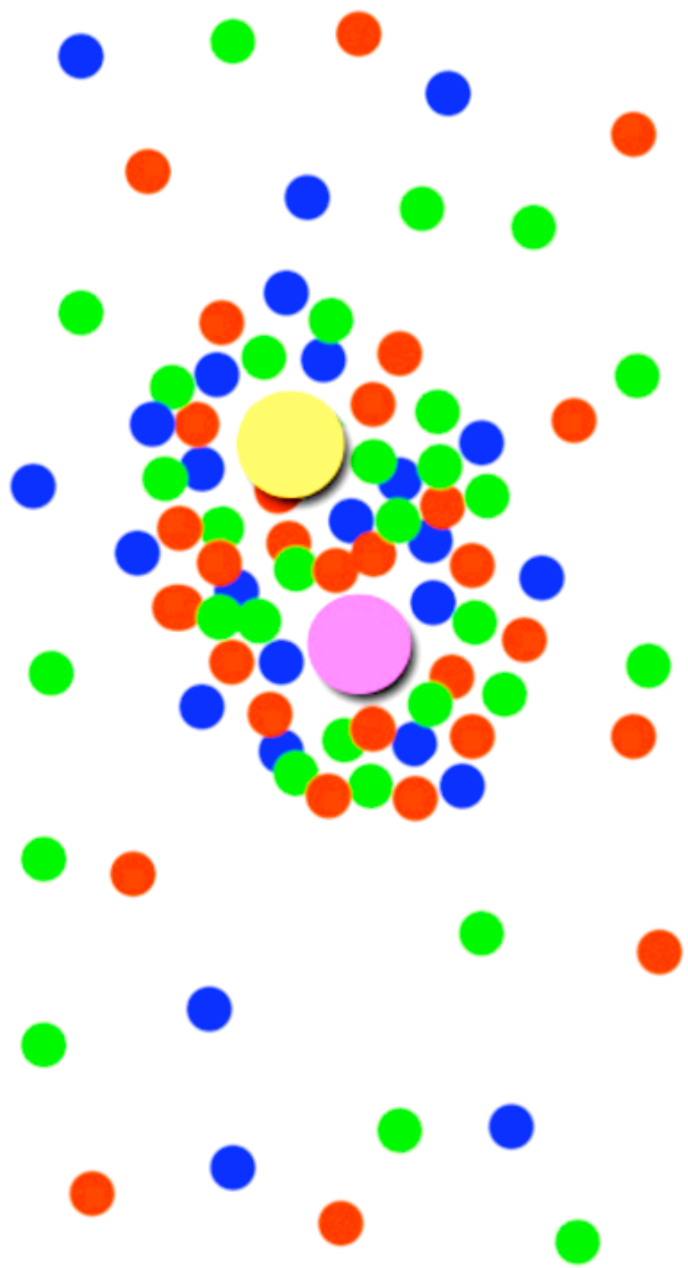
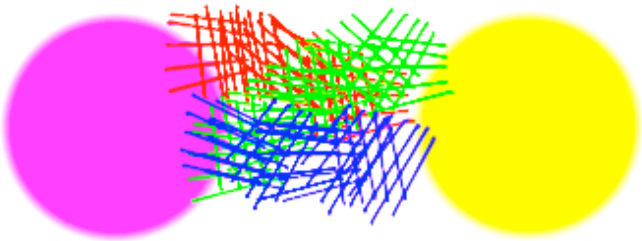
⇛ masses:

	mass (GeV)	$\sum q_m$ (GeV)
p	$\sim$1	$2m_u + m_d$ $\sim$0.03
π	$\sim$0.13	$m_u + m_d \sim$ 0.02



String picture

A way of visualizing a meson $\longrightarrow$ a $q\bar{q}$ pair join together by a string



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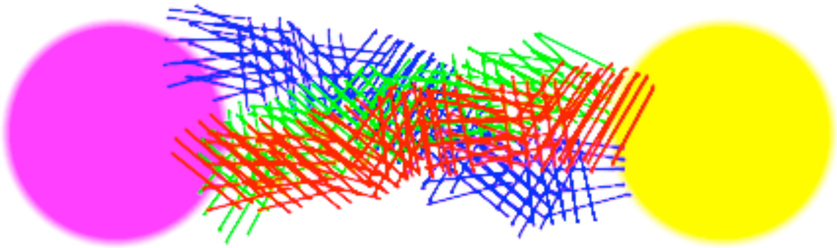

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⇛ The potential between a $q\bar{q}$ pair at separation r is

$$V(r) = -\frac{A(r)}{r} + Kr$$

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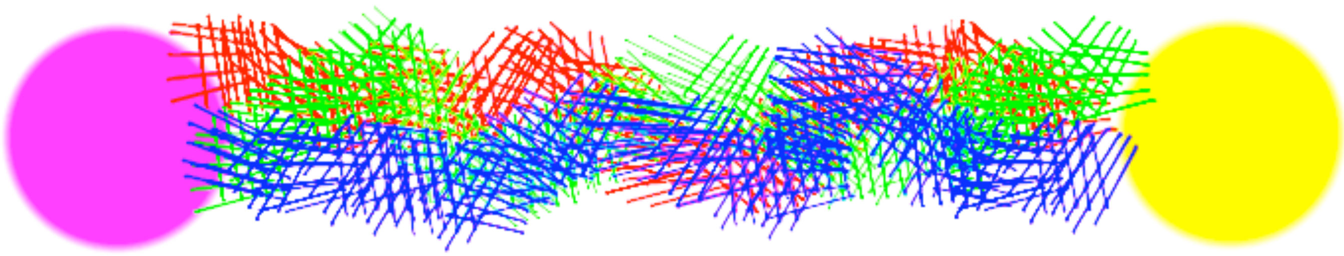

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⇛ In the limit $m_q \rightarrow \infty$ the string cannot break (infinite energy)

Chiral symmetry

In the absence of quark masses the QCD Lagrangian splits into two independent quark sectors

$$\mathcal{L}_{\rm QCD} = \mathcal{L}_{\rm gluons} + i\bar{q}_L\gamma^\mu D_\mu q_L + i\bar{q}_R\gamma^\mu D_\mu q_R$$

⇛ For two flavors $(i = u, d)$ $\mathcal{L}_{\rm QCD}$ is symmetric under $SU(2)_L \times SU(2)_R$

⇛ However, this symmetry is not observed

Solution: the vacuum $|0\rangle$ is not invariant

$$\langle 0|\bar{q}_L q_R|0\rangle \neq 0 \quad \longrightarrow \quad \text{chiral condensate}$$

⇛ Symmetry breaking

Golstone's theorem $\Longrightarrow$ massless bosons associated: pions

So, **properties of the QCD vacuum**

- Confinement
- Chiral symmetry breaking

Is there a regime where these symmetries are restored?

QCD phase diagram

Free quarks and gluons?

Asymptotic freedom: Quarks and gluons interact weakly at

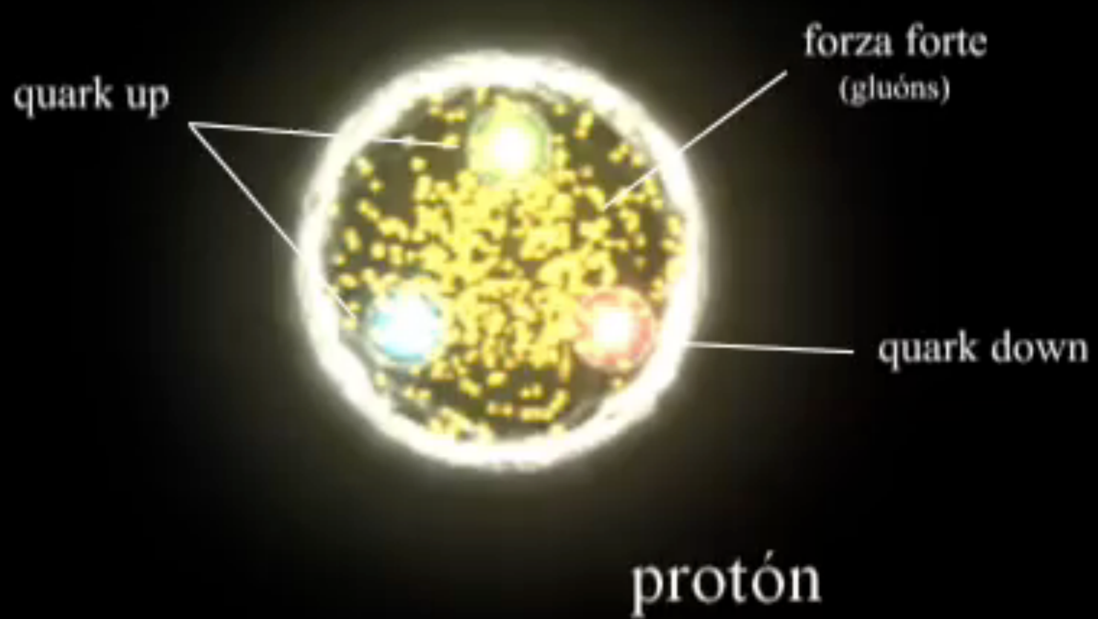
@ Small distances — **increase density**

@ Large momentum — **increase temperatures**

Heavy-ion collisions main goal

Study QCD under extreme conditions

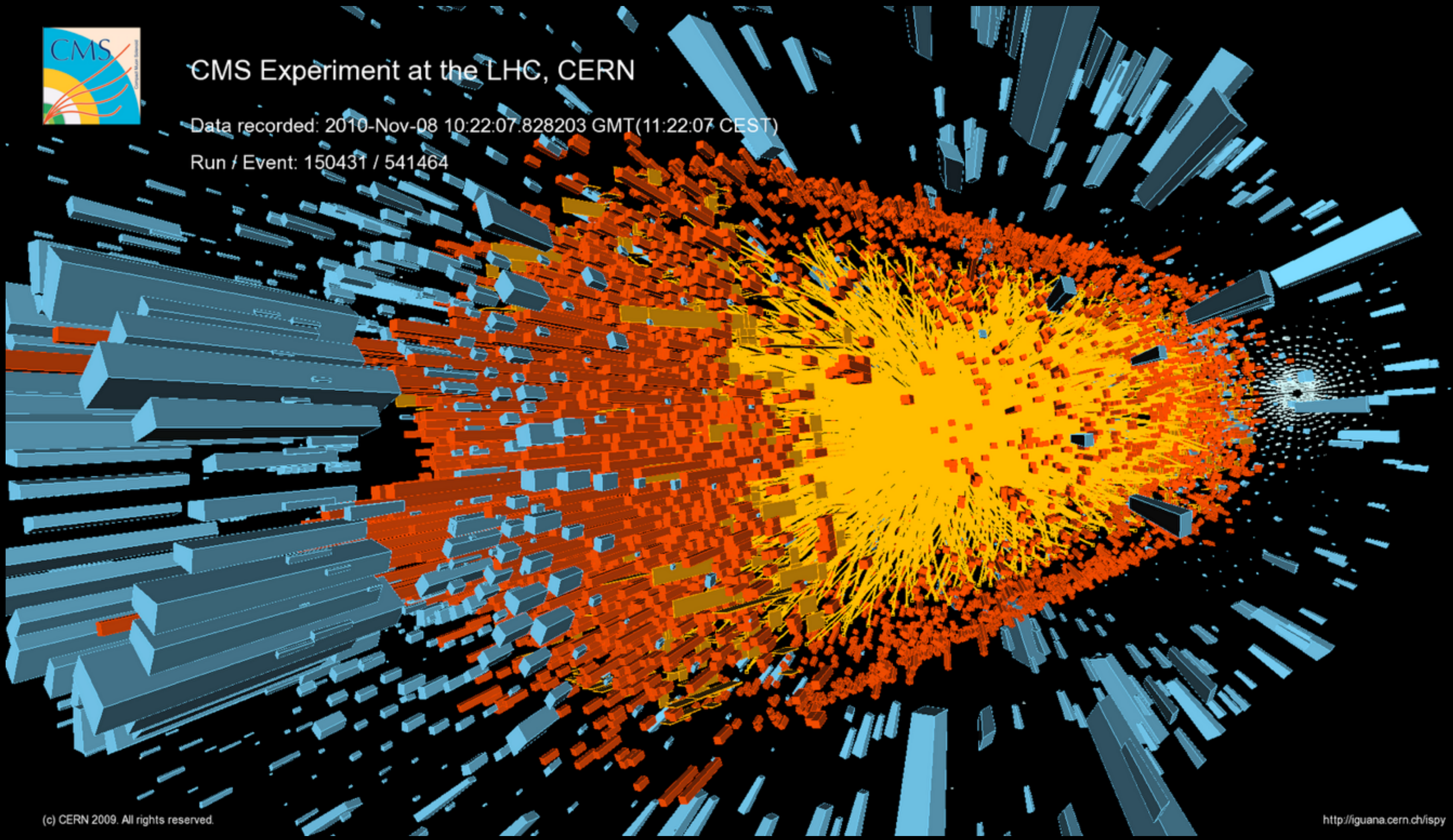
- → High density
- → High temperature



High-densities/temperatures

- ☐ In the early Universe
- ☐ Core of neutron stars
- ☐ Heavy-ion collisions

Needs large energy density deposited in a macroscopic (in QCD scales) region of space



Real data - event from first collisions recorded with by in 2010

HIC: some history

Landau (1953) applies fluid dynamics to hadronic collisions

Assumptions

- Large amount of the energy deposited in a short time in a small region of space (**little fireball**) with the size of a Lorentz-contracted nucleus
- Created matter treated as a relativistic (classical) fluid

Equation of state $P = \epsilon/3$

- The hydrodynamical flow stops when the mean free path becomes of the order of the size of the system: freeze out

Hydrodynamics is nowadays the main tool to check the degree of thermalization in HIC

Hydrodynamics $\partial_\mu T^{\mu\nu} = 0$

$$T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu} + \text{viscosity corrections}$$

(+ Equation of State)

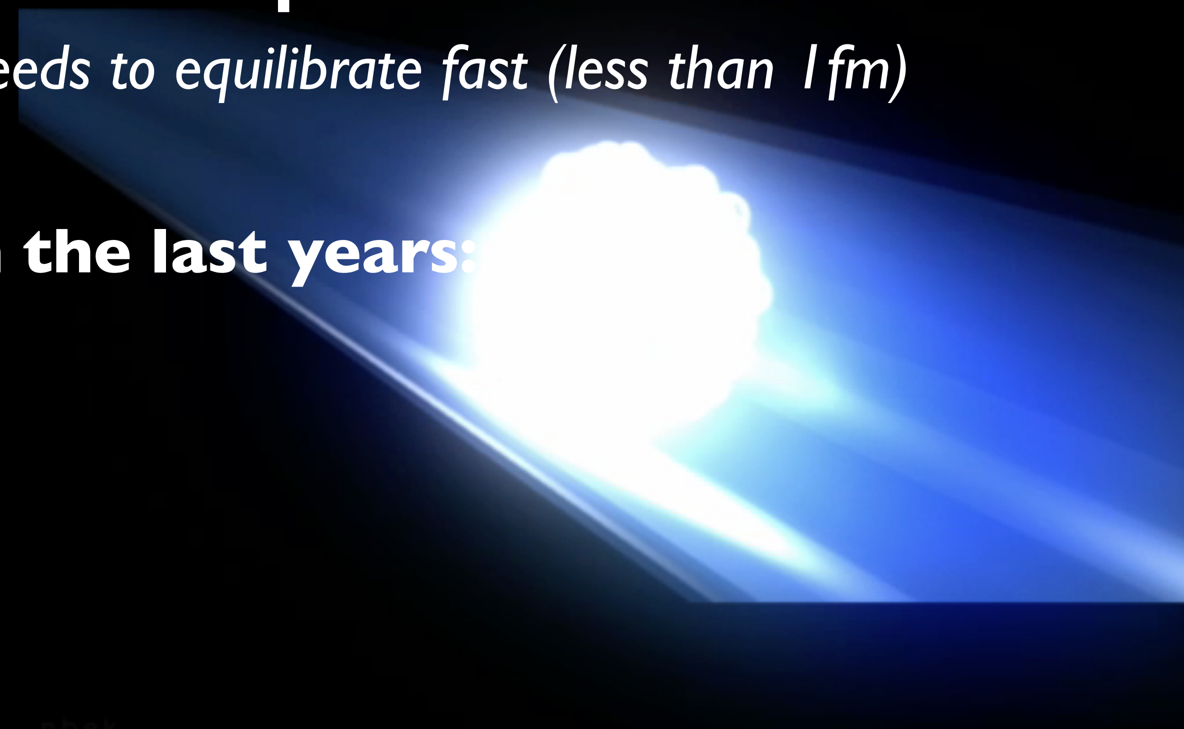
Does not address the question on **how thermal equilibrium is reached**

— *Far from equilibrium initial state needs to equilibrate fast (less than 1fm)*

Most of the theoretical progress in the last years:

— *Viscosity corrections*

— *Fluctuations in initial conditions*



The golden measurement

Remember the Euler eq.

$$\frac{\partial \beta}{dt} = -\frac{c^2}{\epsilon + P} \nabla P$$

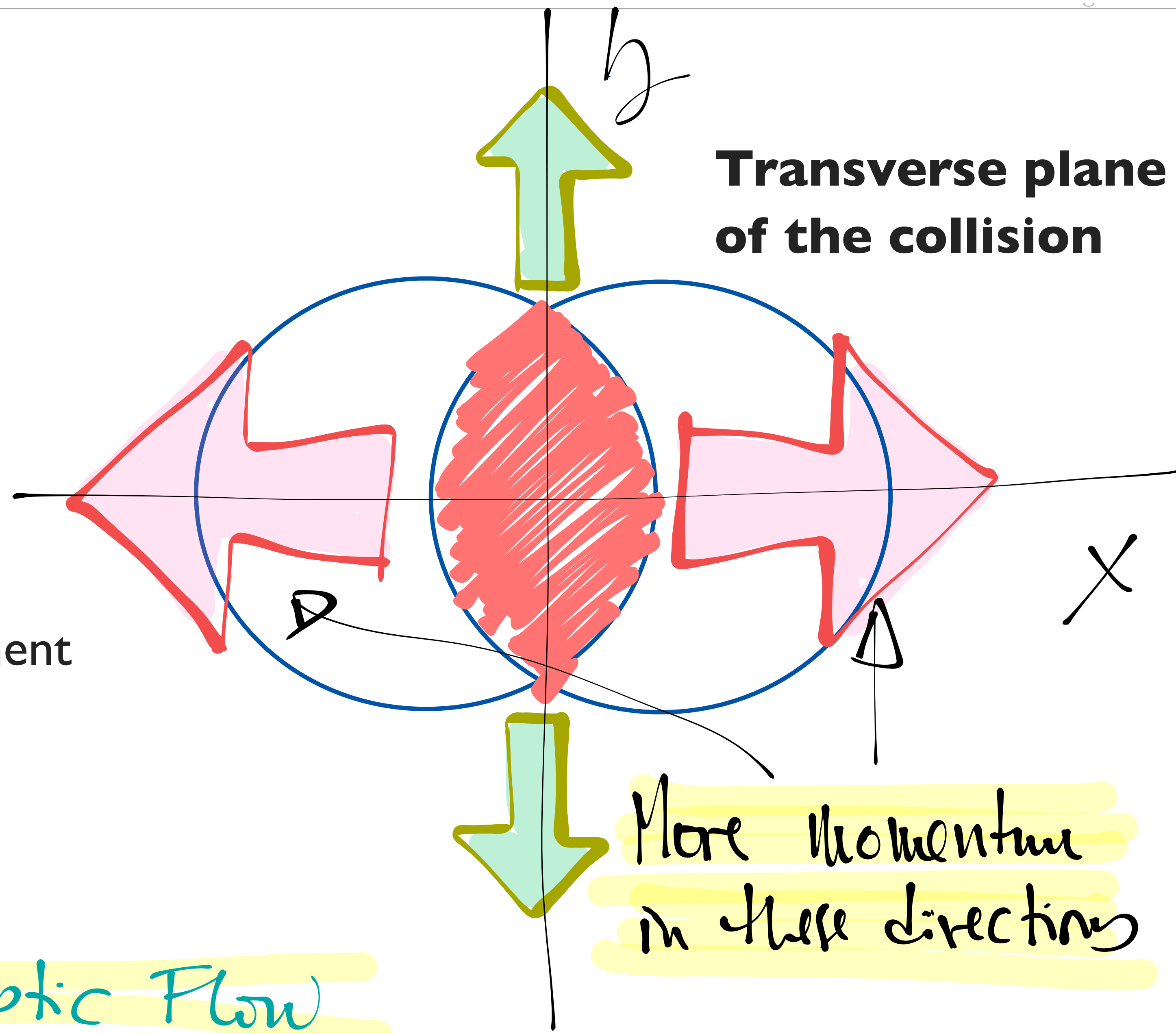
$$\epsilon = 3P \implies \partial_x P > \partial_y P$$

Make a Fourier decomposition

- Elliptic flow is the second component

$$\frac{dN}{d\phi} \propto 1 + 2 v_2 \cos 2\phi$$

v_2 → Elliptic Flow

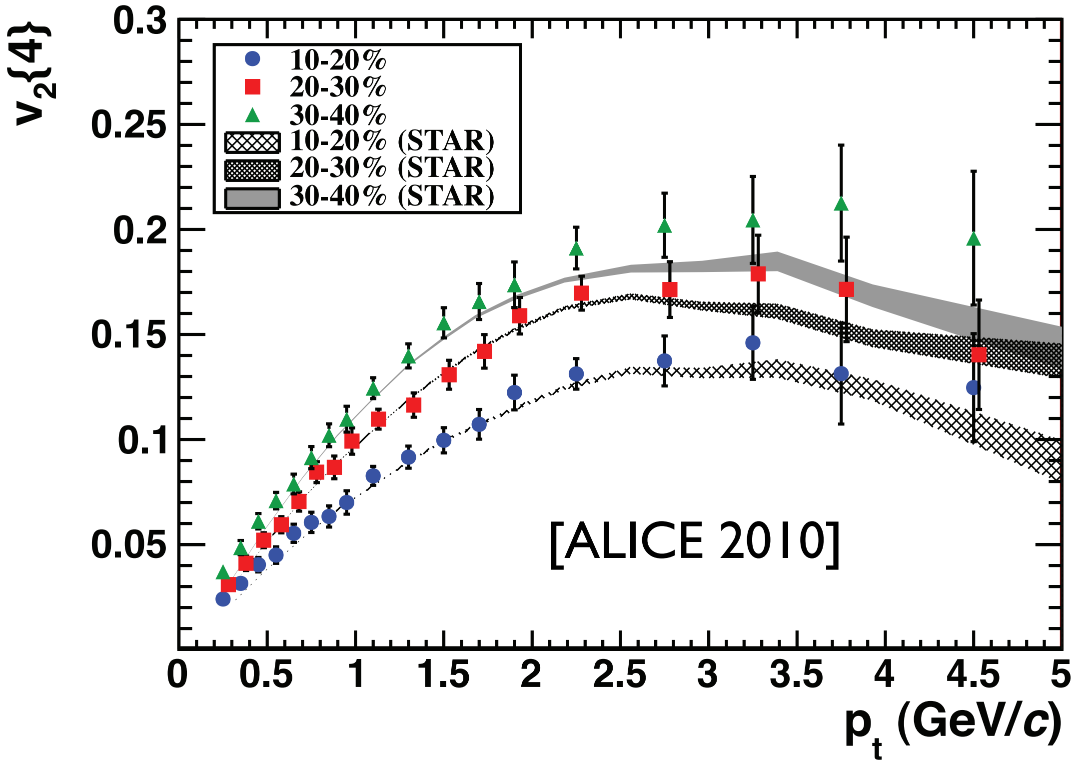


Anisotropies in the initial spacial distributions - geometry - translate into anisotropies in the momentum distributions

- Impossible with instantaneous, point-like, interactions unless initial- or final-state correlations

Viscosity from data

LHC flow similar to RHIC



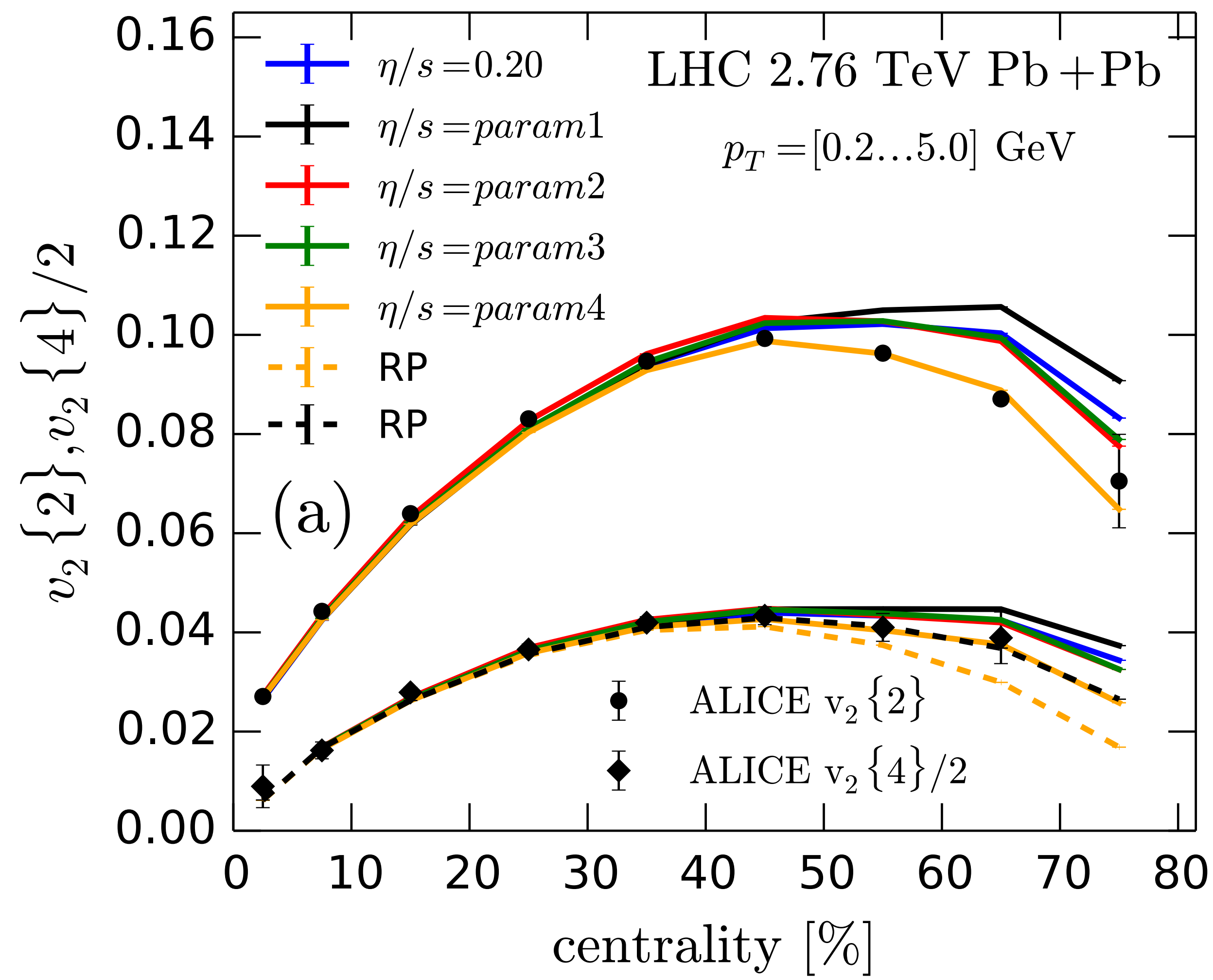
Lowest viscosity known

- "Perfect liquid": sQGP
- AdS/CFT bound

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

[Policastro, Son, Starinets, 2001]

Well described by hydro



[Niemi, Eskola, Paatelainen 2015]

QCD phase diagram

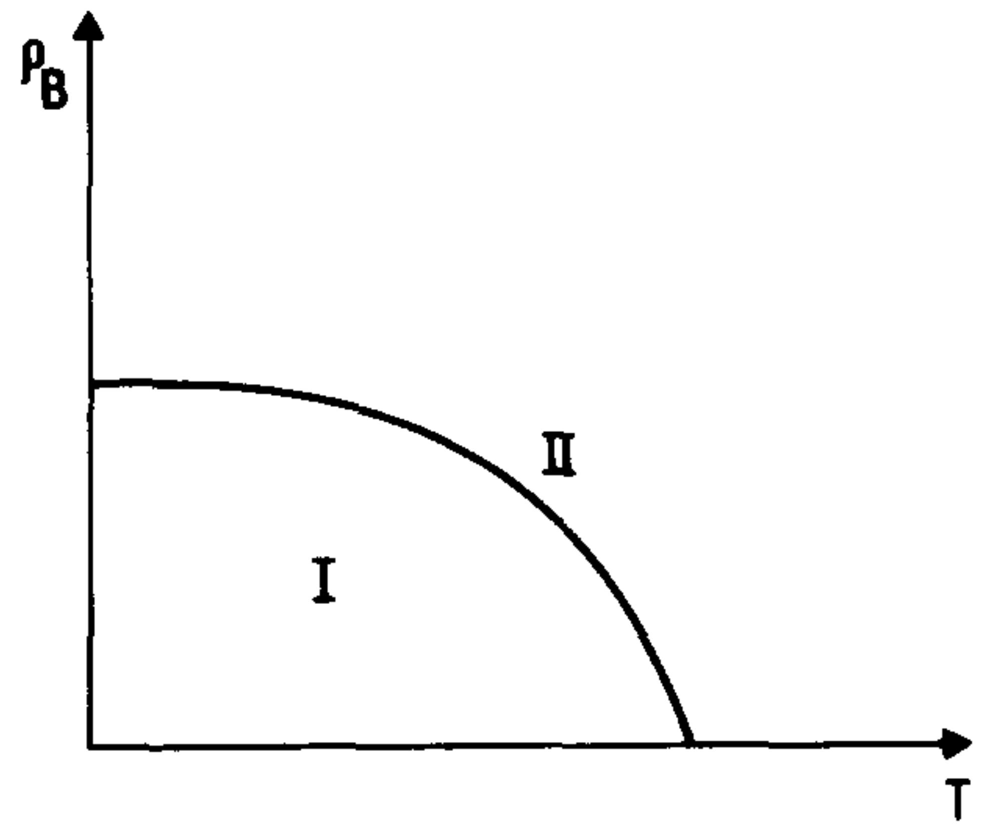
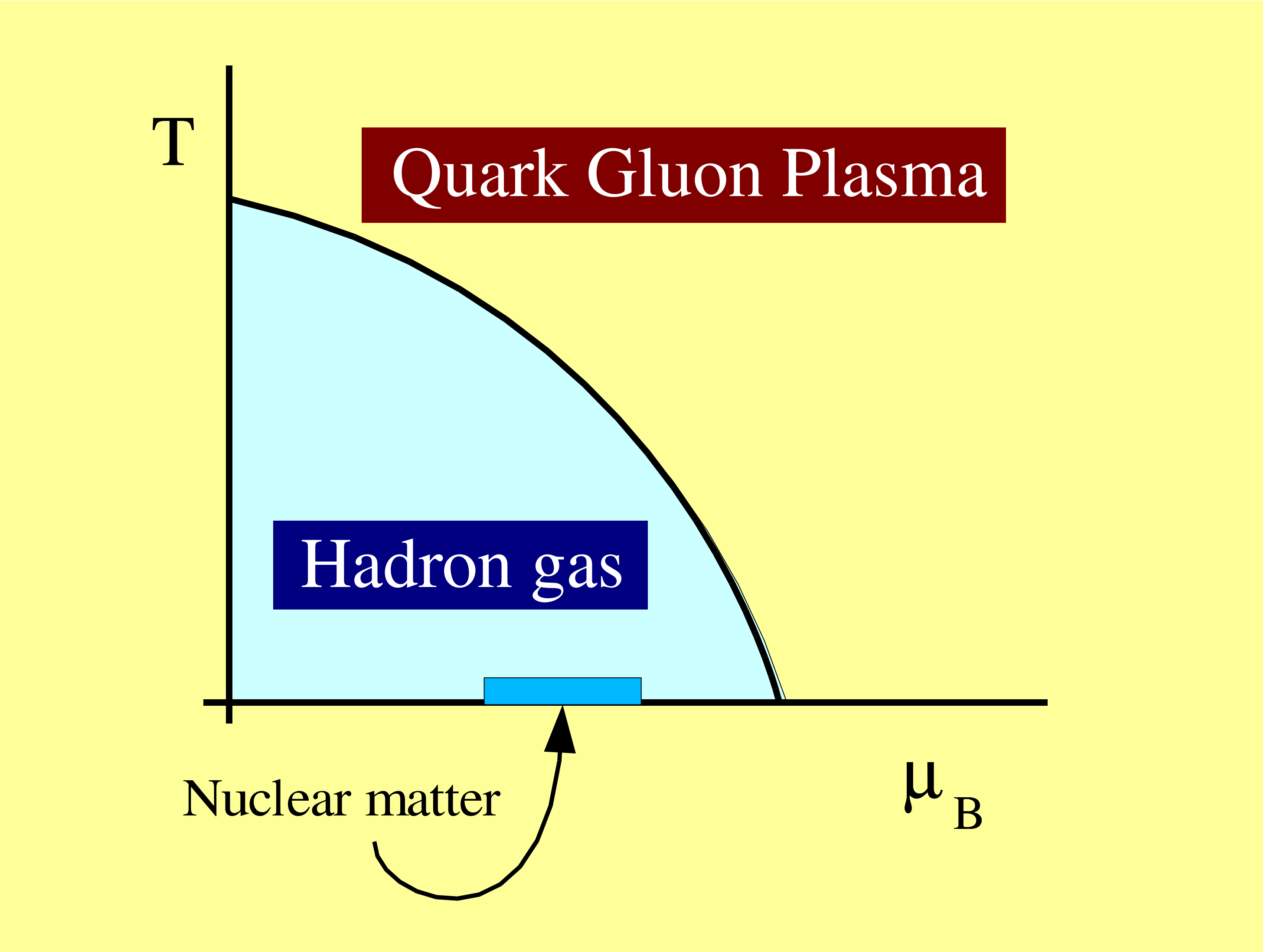


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

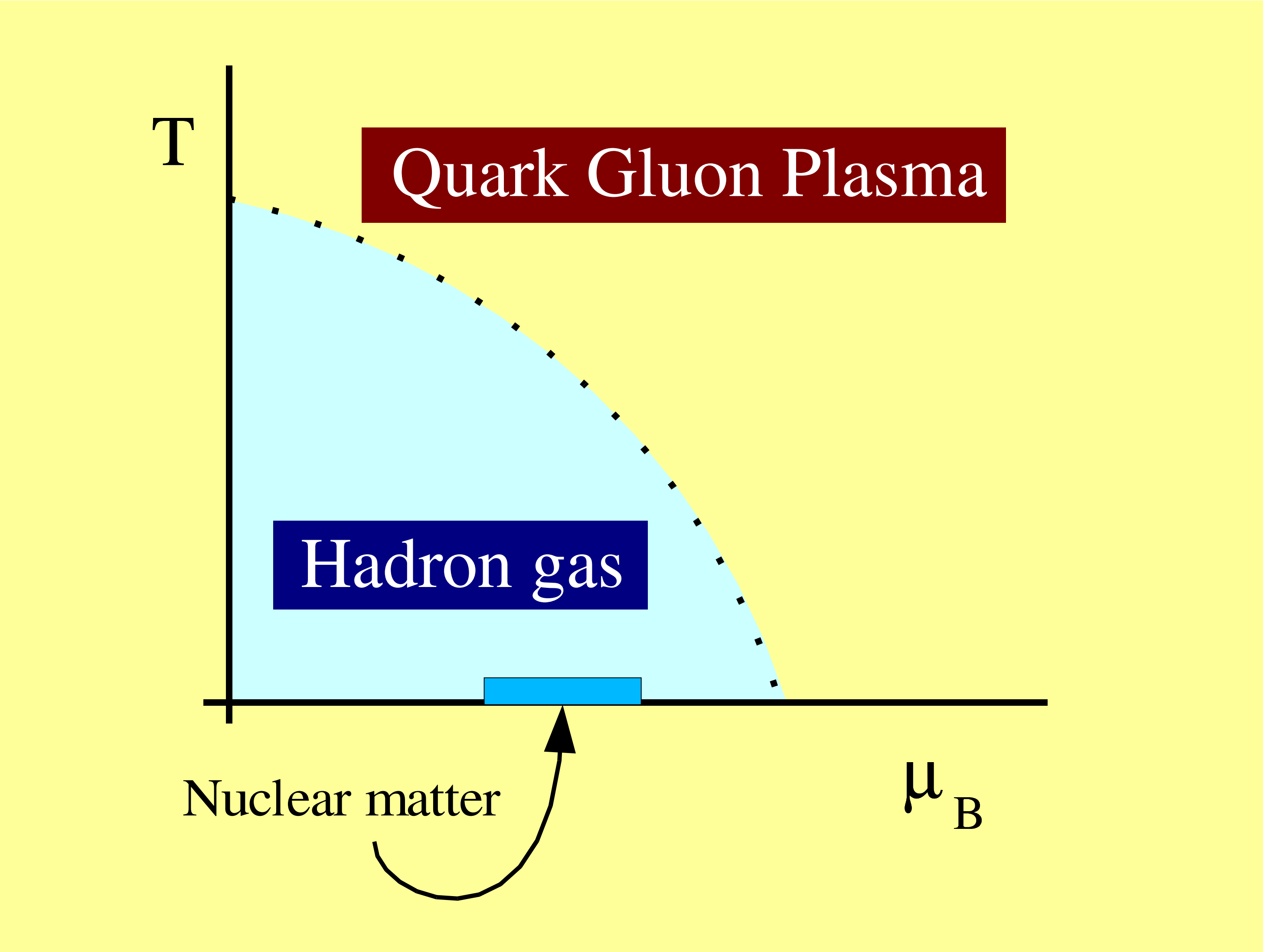
[Cabibbo and Parisi 1975]

QCD phase diagram



⇛ First lattice calculation found a first order phase transition

QCD phase diagram



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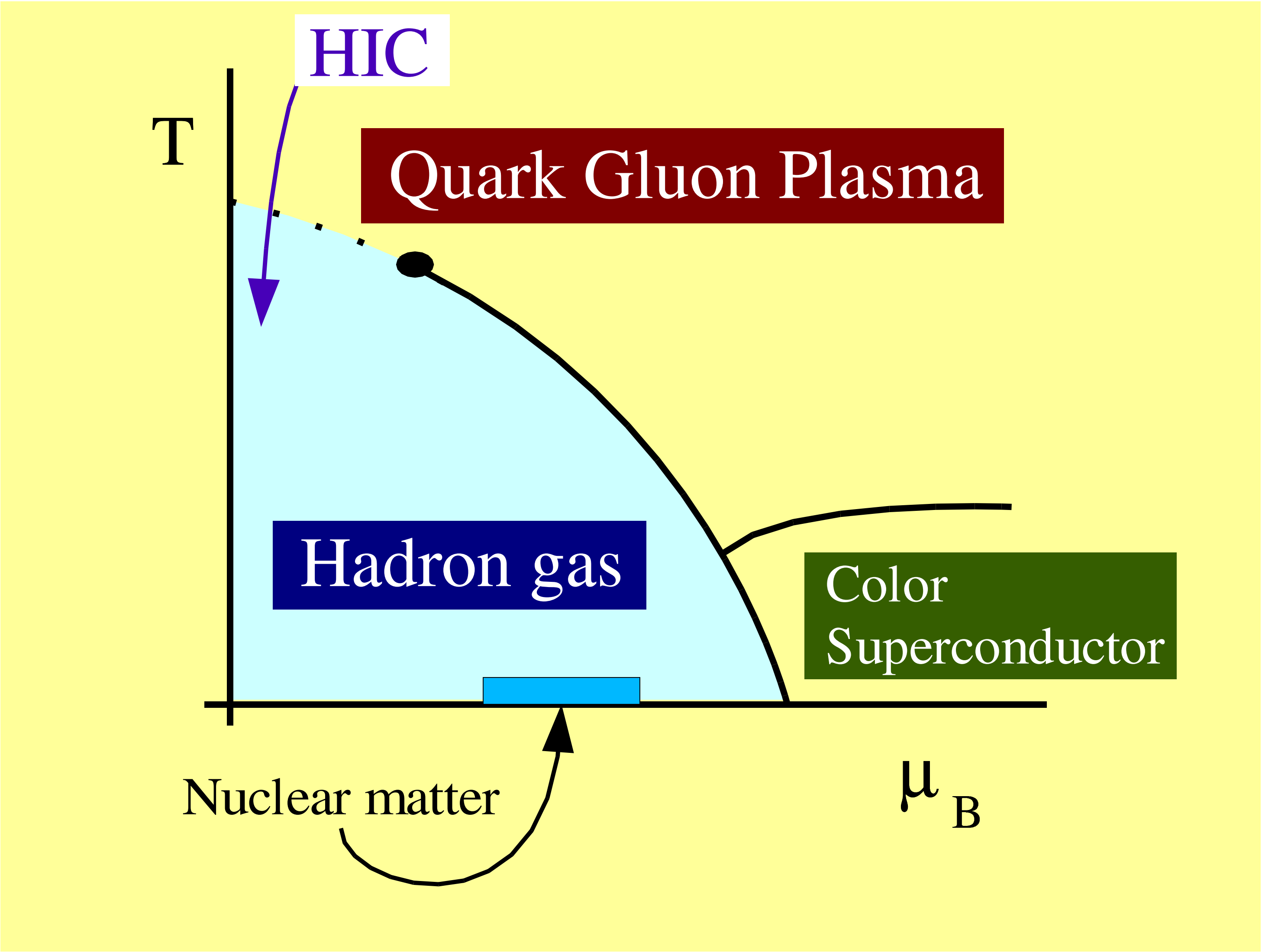

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- Present status: several different phases found.

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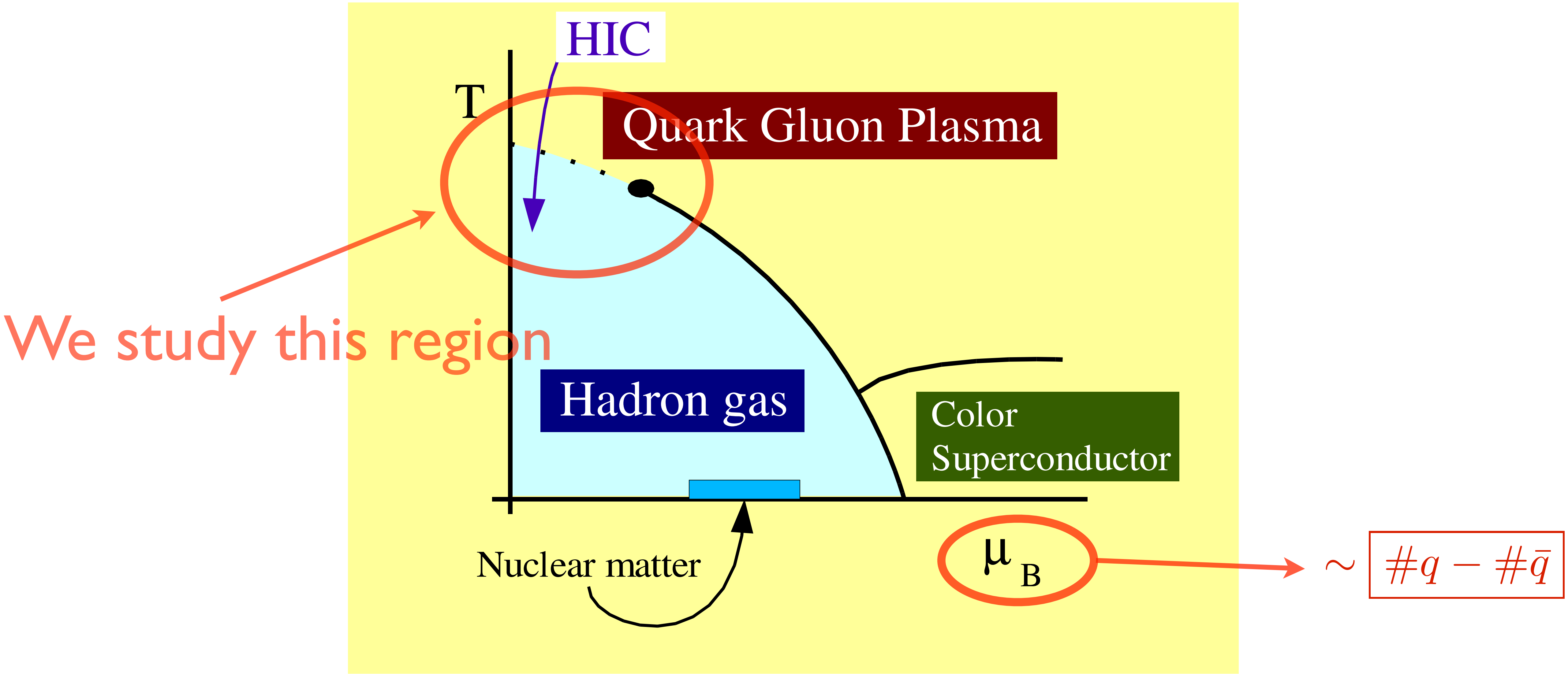

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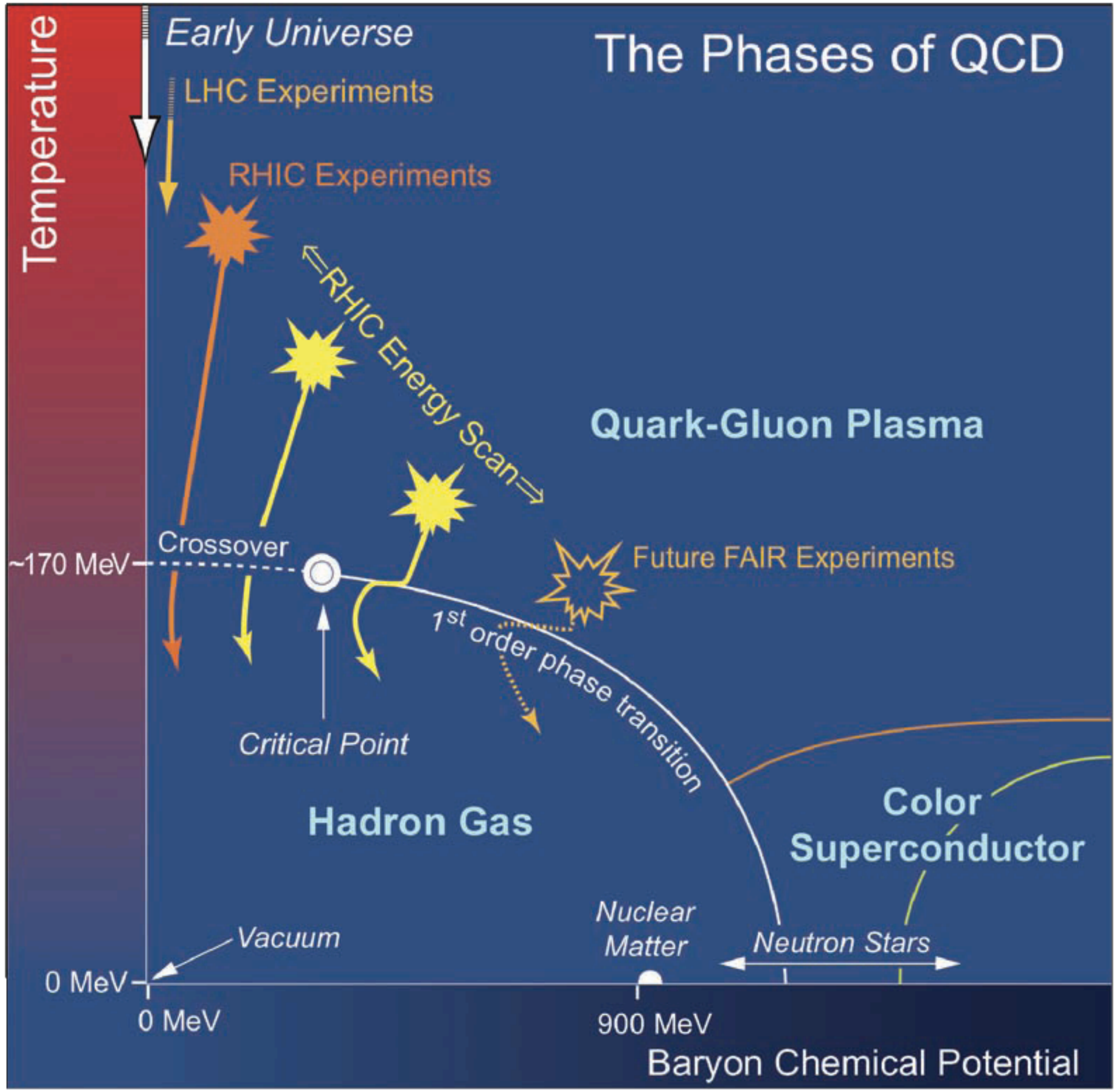


[More cartoon-like]

QCD thermodynamics I

- In the grand canonical ensemble, the thermodynamical properties are determined by the (grand) partition function

$$Z(T,V,\mu_i) = \mathrm{Tr}\exp\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\}$$

where $k_B = 1$, H is the Hamiltonian and N_i and μ_i are conserved number operators and their corresponding chemical potentials.

- The different thermodynamical quantities can be obtained from Z

$$P = T\frac{\partial \ln Z}{\partial V}\,, \quad S = \frac{\partial (T\ln Z)}{\partial T}\,, \quad N_i = T\frac{\partial \ln Z}{\partial \mu_i}$$

- Expectation values can be computed as

$$\langle \mathcal{O} \rangle = \frac{\mathrm{Tr}\mathcal{O}\exp\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\}}{\mathrm{Tr}\exp\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\}}$$

QCD thermodynamics II

In order to obtain Z for a field theory with Lagrangian $\mathcal{L}$ one normally makes the change $-it = 1/T$, with this, the action

$$iS \equiv i \int dt \mathcal{L} \longrightarrow S = -\int_0^{1/T} d\tau \mathcal{L}_E$$

and the grand canonical partition function can be written (for QCD) as

$$Z(T,V,\mu) = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A^\mu \exp\{-\int_0^{1/T} dx_0 \int_V d^3x(\mathcal{L}_E - \mu\mathcal{N})\},$$

where $\mathcal{N} \equiv \bar{\psi}\gamma_0\psi$ is the number density operator associated to the conserved net quark (baryon) number.

Additionally, (anti)periodic boundary conditions in $[0, 1/T]$ are imposed for bosons (fermions)

$$A^\mu(0,\mathbf{x}) = A^\mu(1/T,\mathbf{x})\,, \quad \psi(0,\mathbf{x}) = -\psi(1/T,\mathbf{x})$$

QCD thermodynamics III

In order to solve these equations

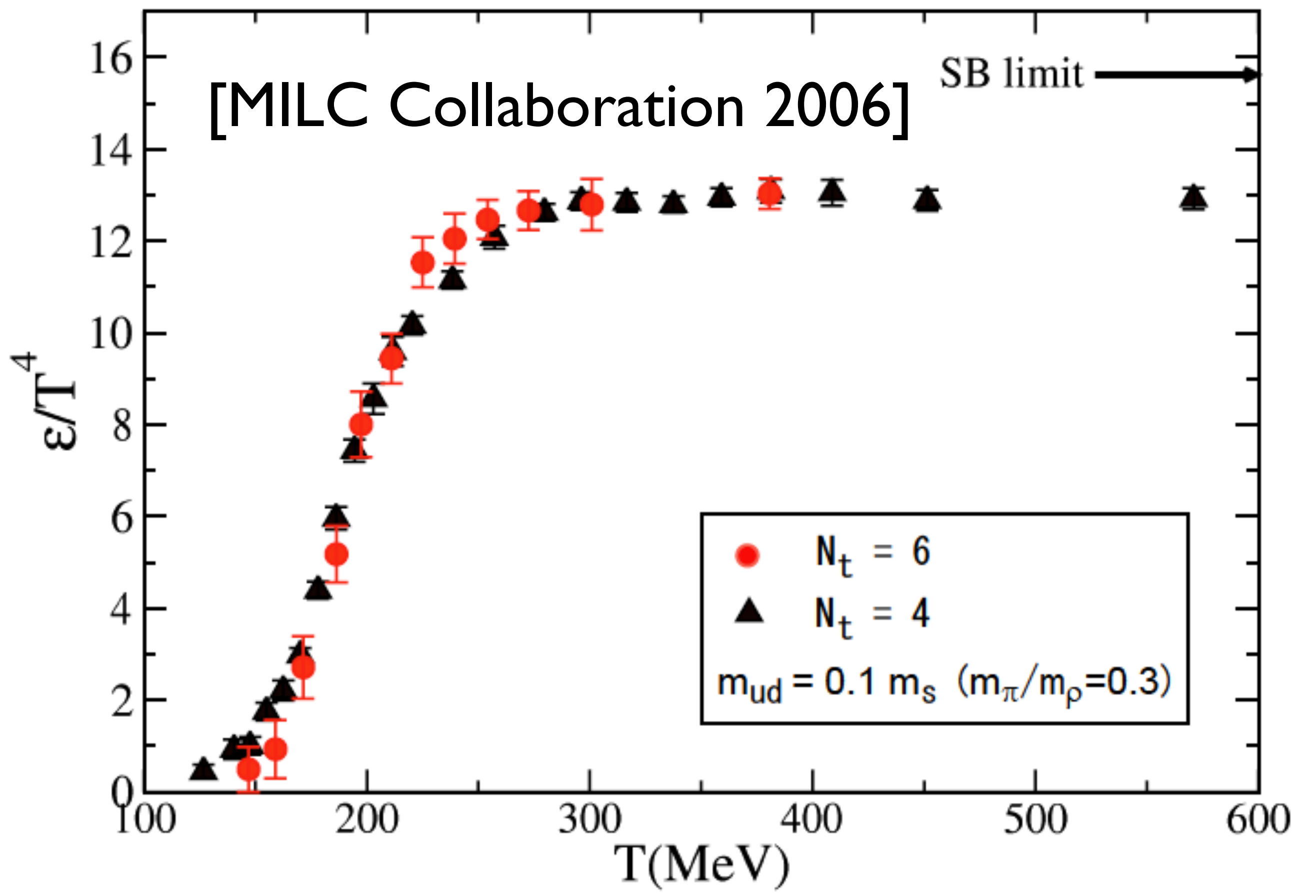
- Perturbative expansion
  - $\alpha_S(T)$ small for large $T \longrightarrow$ bad convergence, but some results obtained.
- Lattice QCD
  - Discretization in $(1/T, V)$ space
  - Contributions to Z are computed by random configurations of fields in the lattice
  - Most of the results for $\mu = 0$

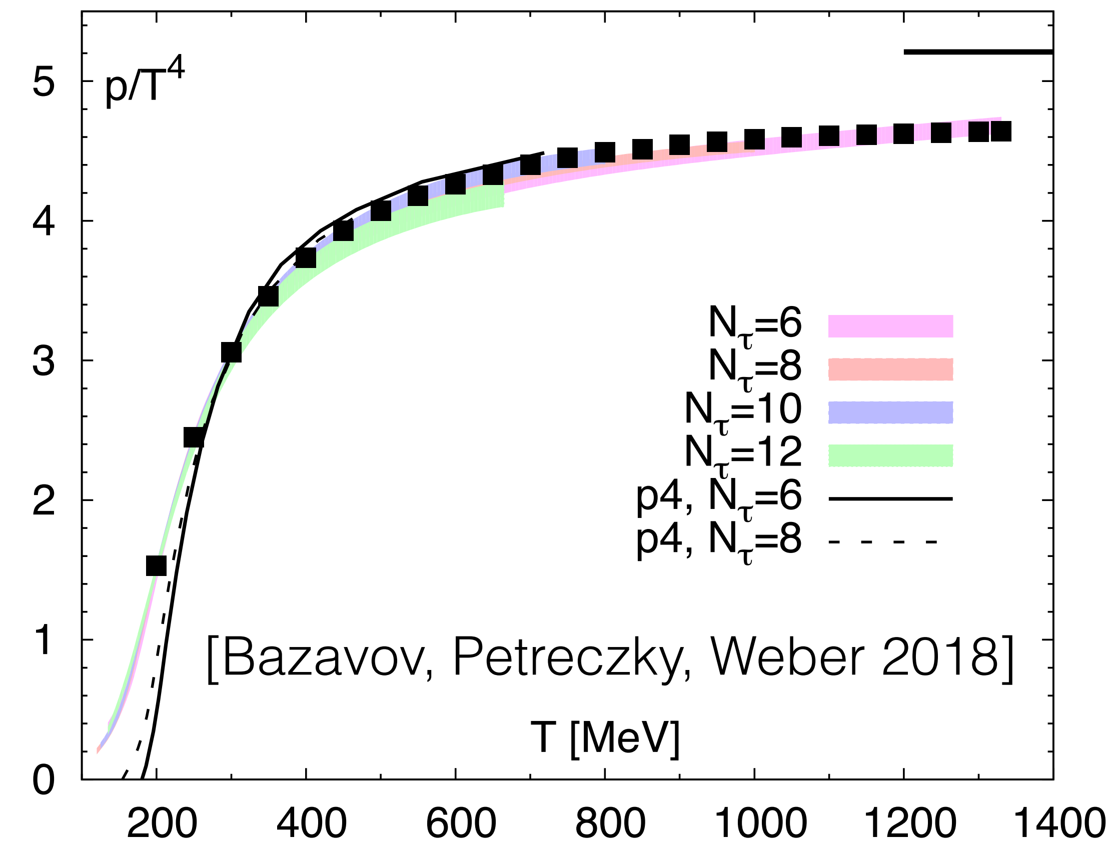
First example: EoS

Naïve estimation: Let's fix $\mu = 0$, the pressure of an ideal gas (of massless particles) is proportional to the number of d.o.f: $P \propto NT^4$

$$P_\pi \propto 3 \times T^4 \, ; \qquad P_{QGP} \propto (\underbrace{2 \times 2 \times 3}_{\text{quarks}} + \underbrace{2 \times 8}_{\text{gluons}}) \times T^4$$

[notice that proportionality factors are different, Fermi/Bose-Einstein statistics]

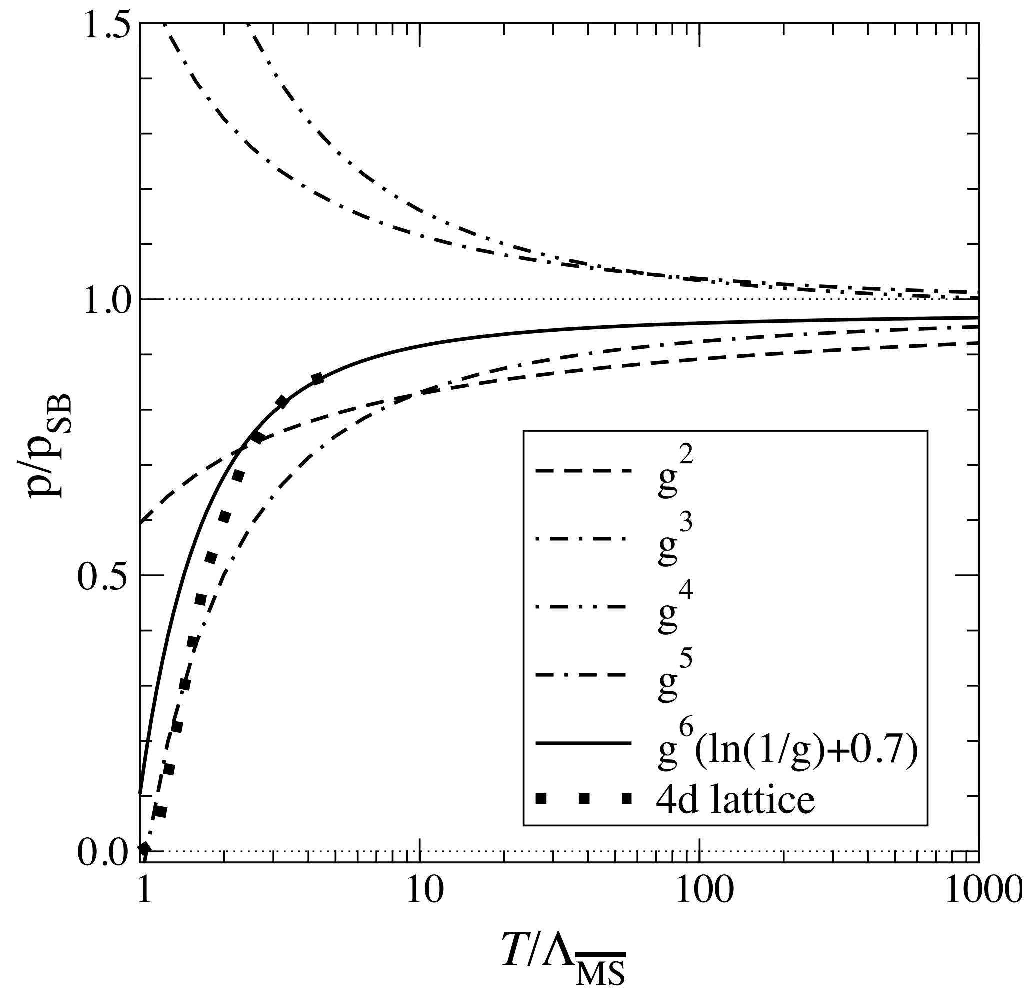




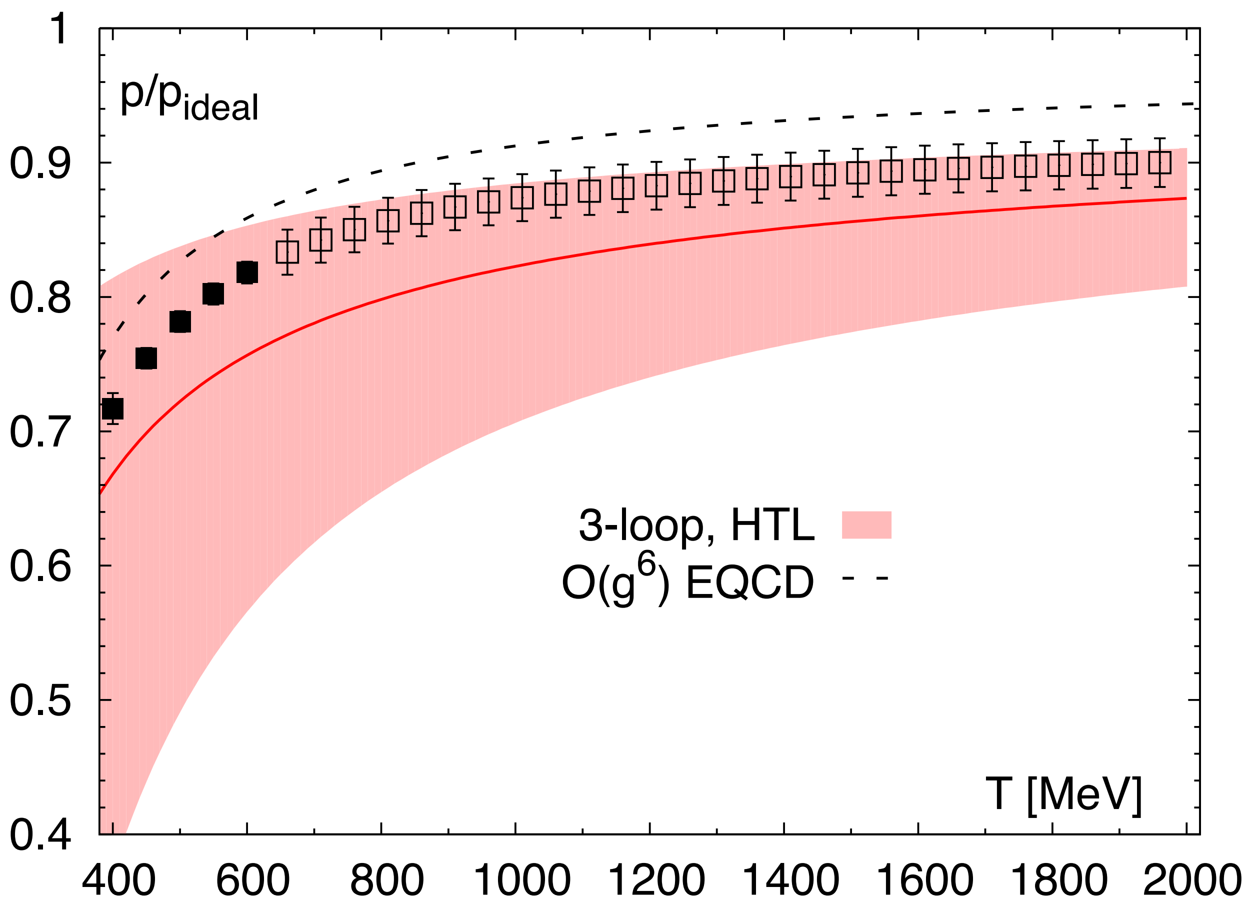
Perturbative calculations

Different orders in PT compared to lattice results

[Kajantie, Laine, Rummukainen, Schroder 2003]



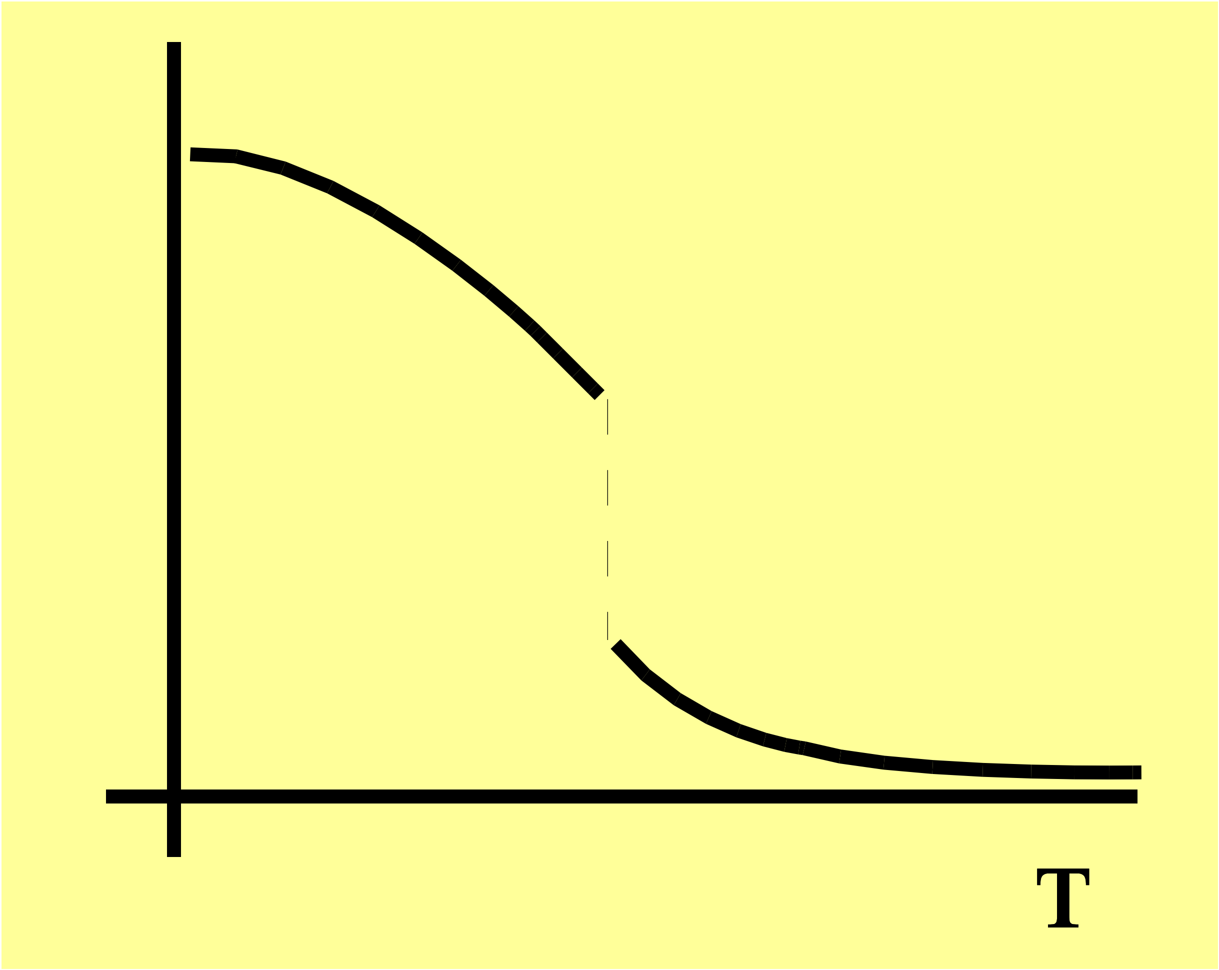
[Plot from Bazavov, Petreczky, Weber 2018]



Convergence for very large temperature

Order parameters

In order to know whether the change from a hadron gas to a QGP is a phase transition or a rapid cross-over order parameters are needed



First order: discontinuity in the order parameter

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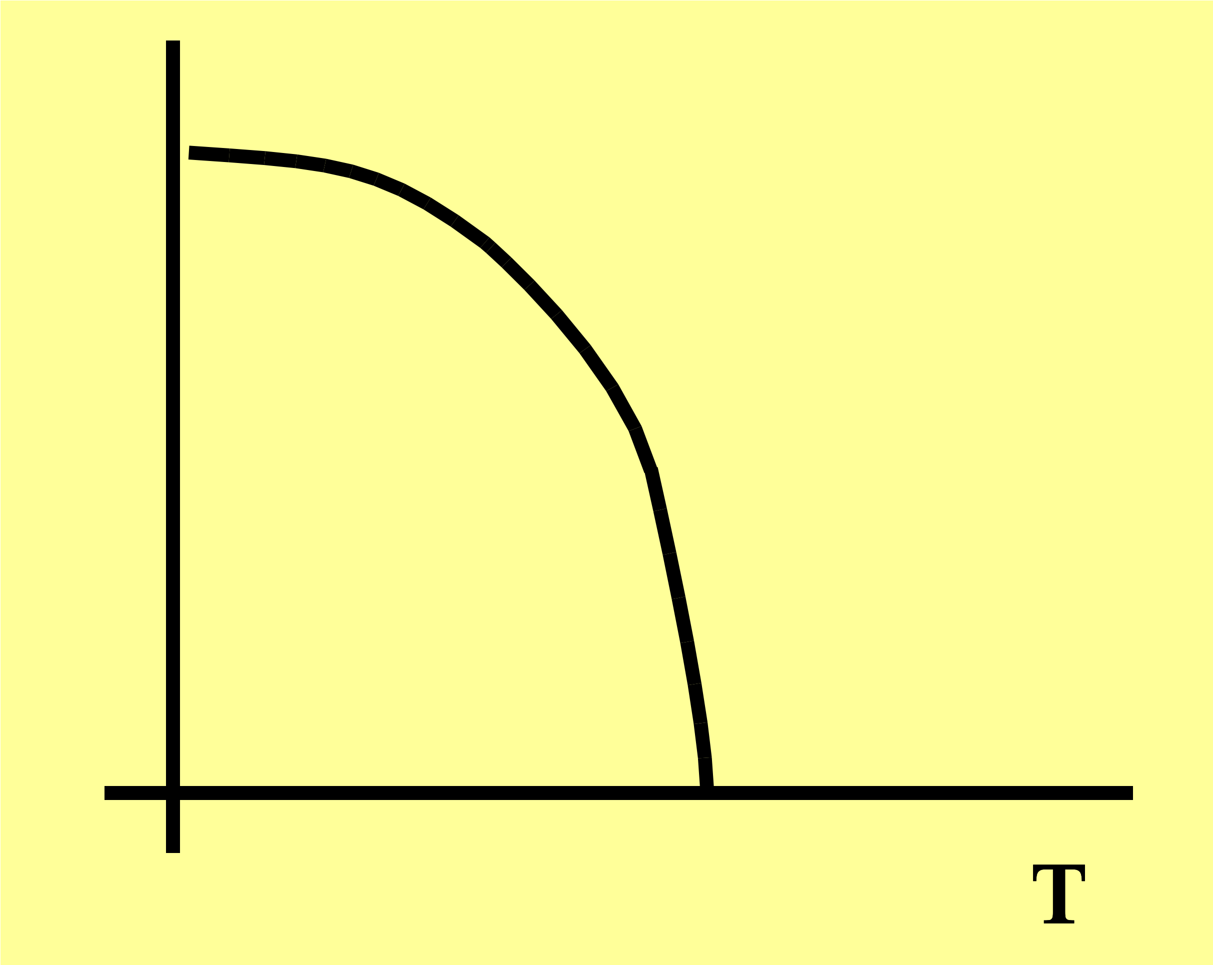

Second order: discontinuity in the derivative

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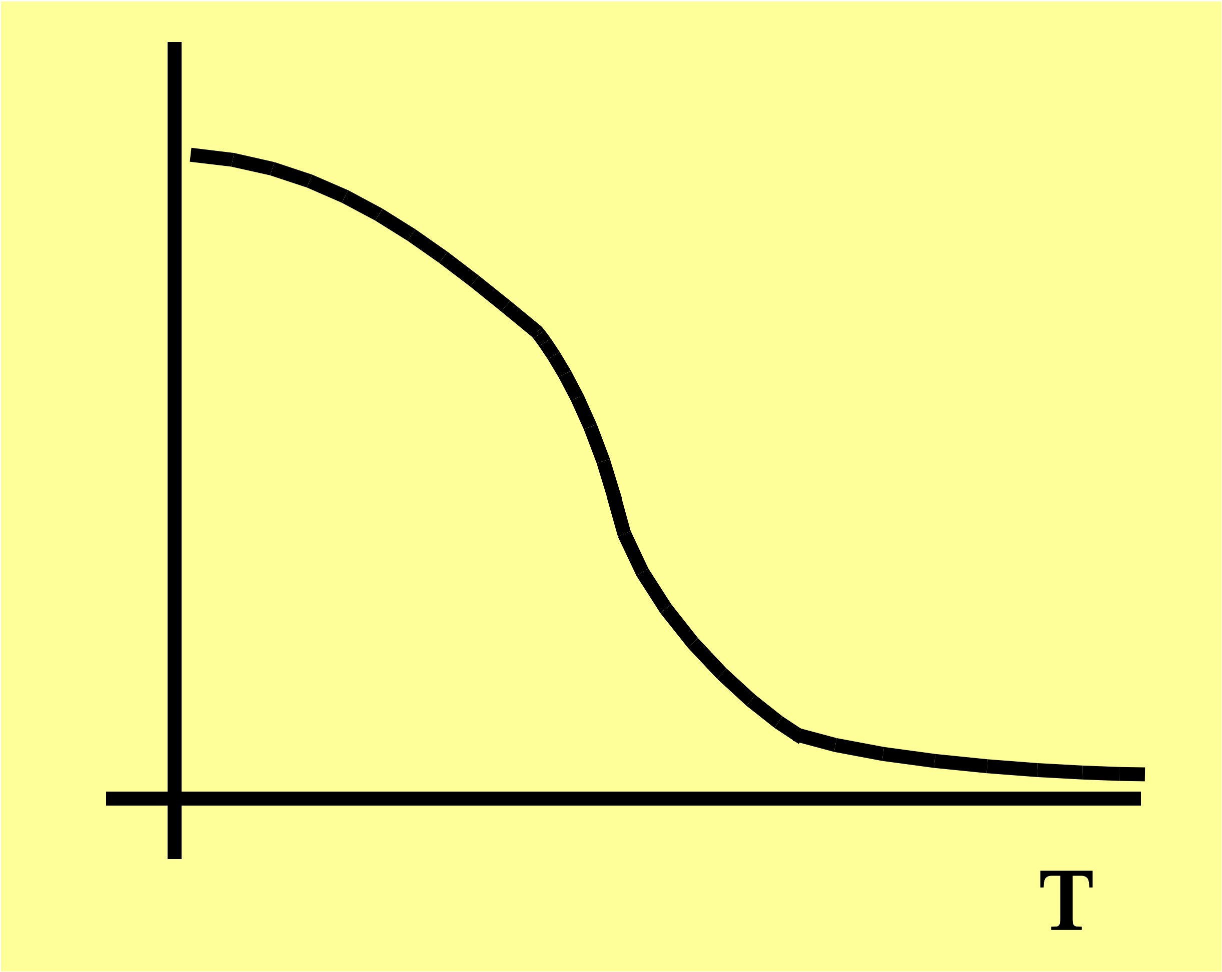


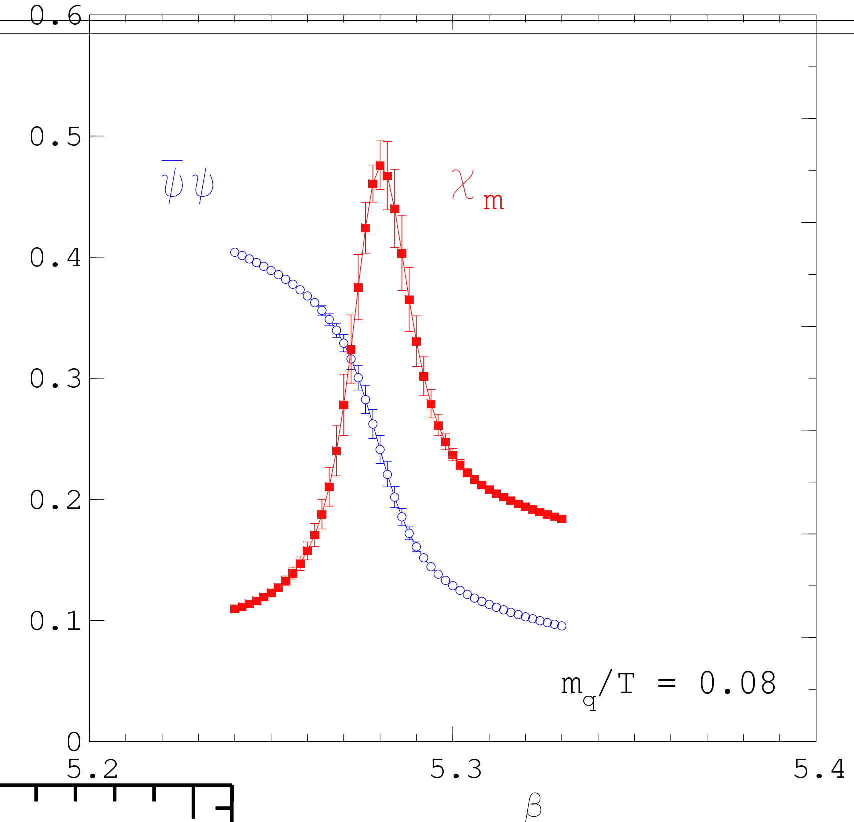
Cross-over: continuous function

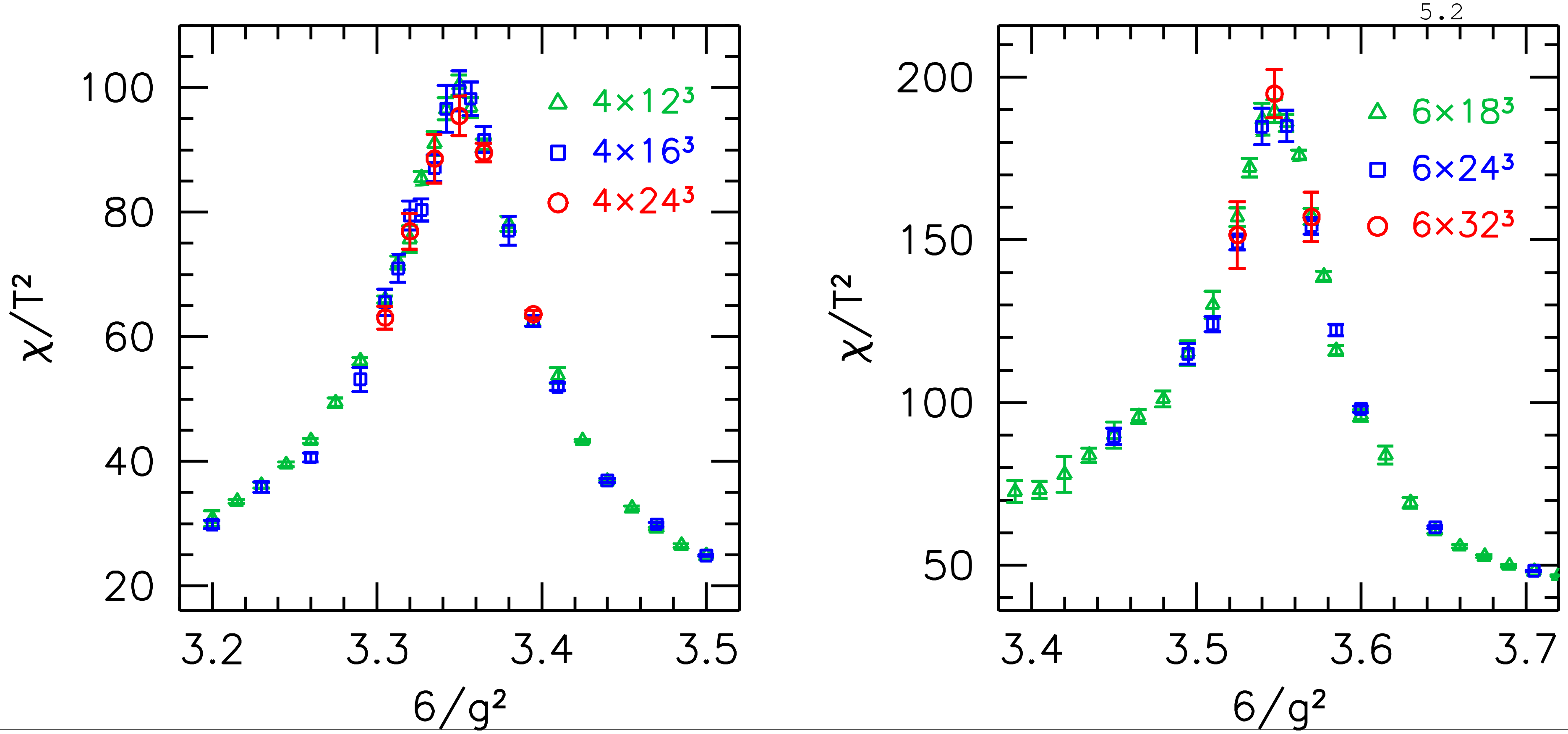
QCD order parameters I

Chiral symmetry restoration: for $m_q = 0$
chiral condensate is the order parameter

$$\langle 0|\bar{q}_L q_R|0\rangle \neq 0 \quad \xrightarrow[T\to\infty]{} \quad \langle 0|\bar{q}_L q_R|0\rangle = 0$$

Susceptibility: $\chi_m = \frac{\partial}{\partial m_q}\langle \bar{q}q\rangle$

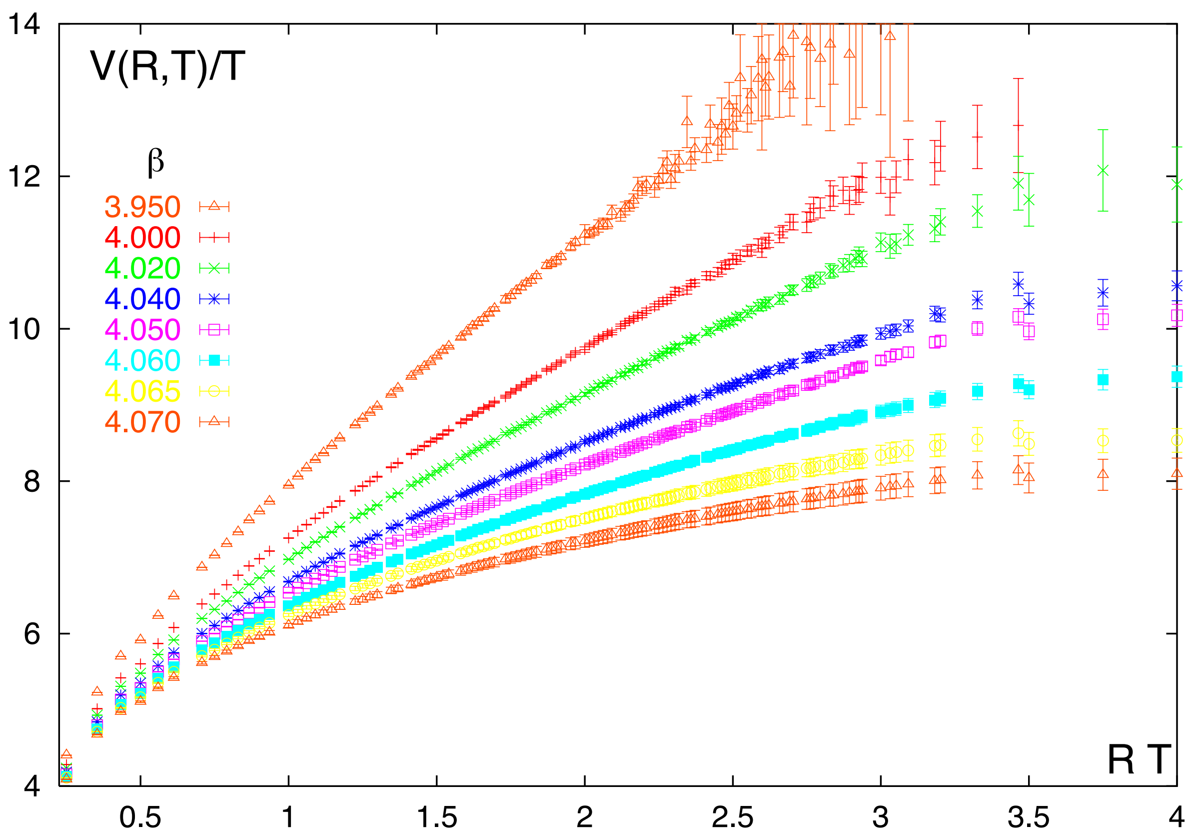




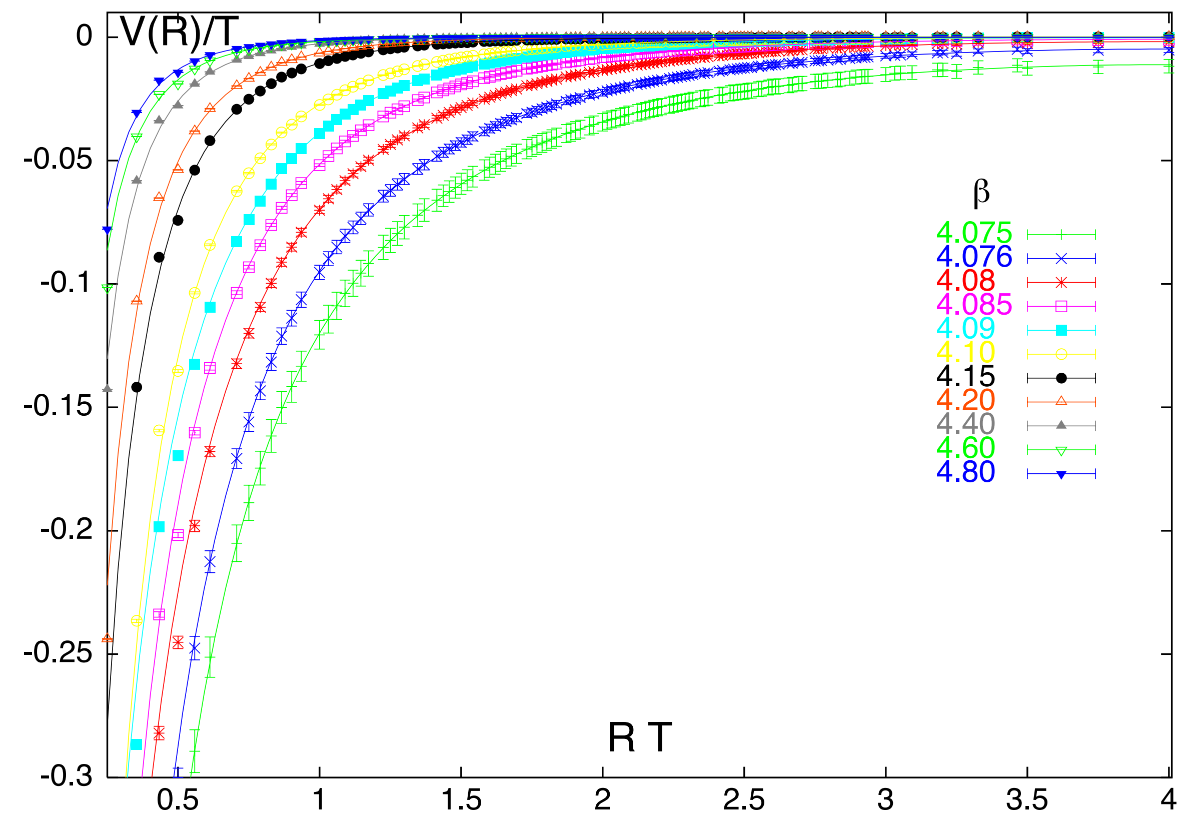
[Aoki et al 2006]

QCD order parameters II

<u>Confinement</u>: for $m_q \to \infty$ the order parameter is the potential



$T < T_c$

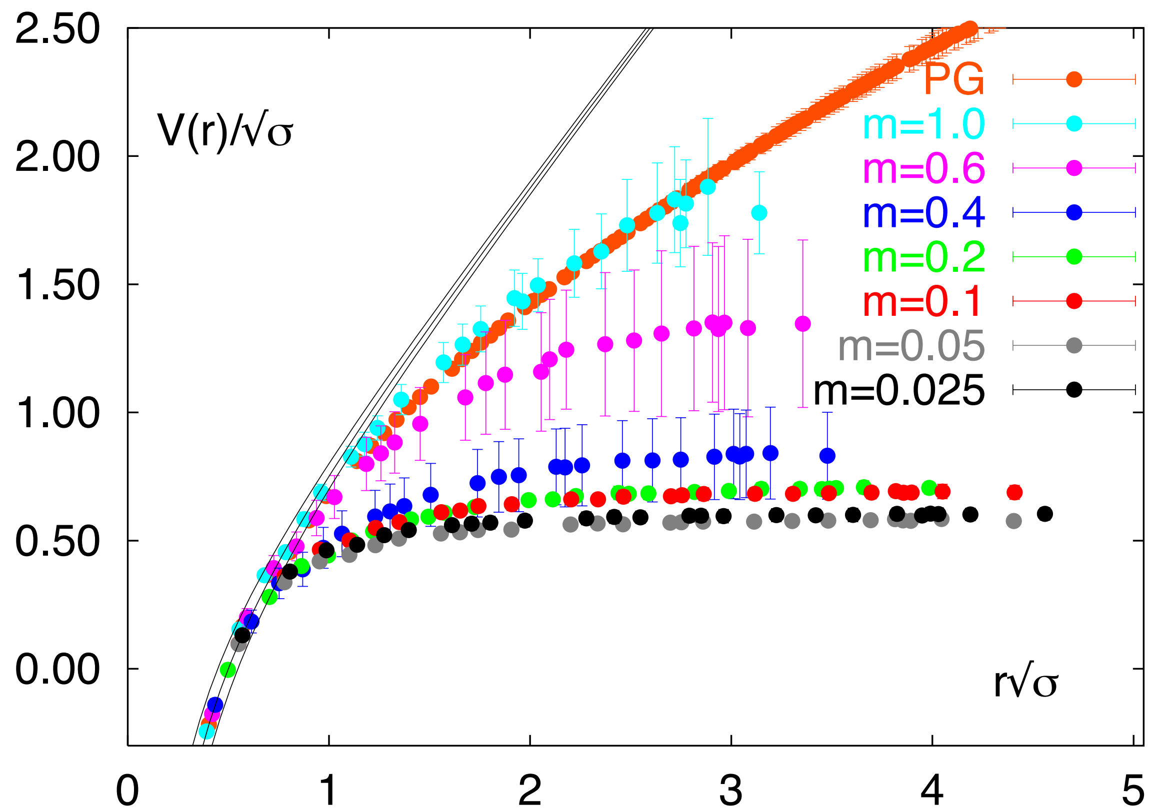


$T > T_c$

[Kaczmarek et al 2000]

However…

When masses are taken into account the potential is screened even below T_c



[Karsch, Laermann, Peikert 2001]

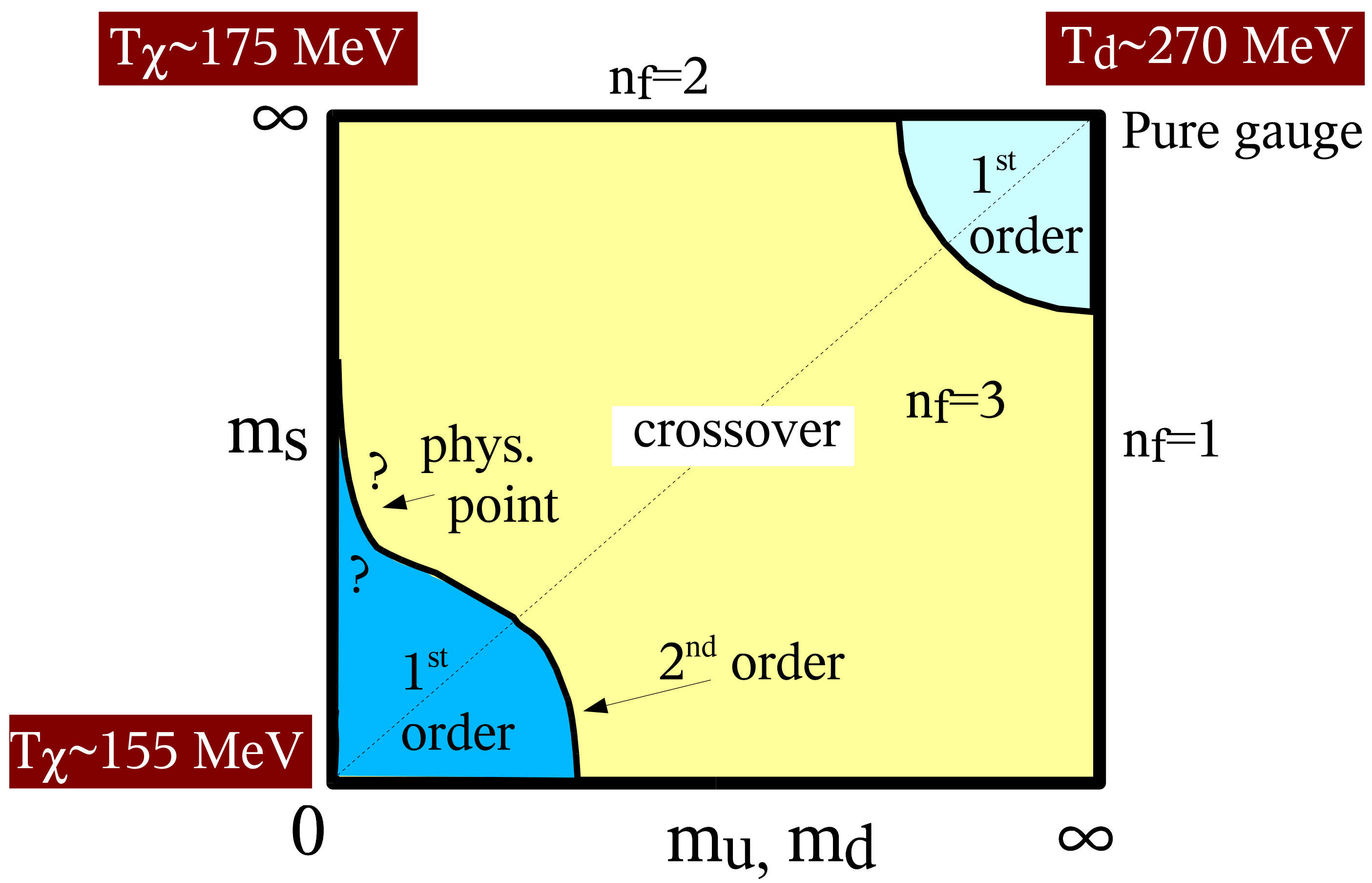
Light $\bar{q}q$ pair creation breaks the string

Physical quark masses

Two order parameters

$\Rightarrow m_q = 0 \longrightarrow$ Chiral condensate

$\Rightarrow m_q = \infty \longrightarrow$ Potential

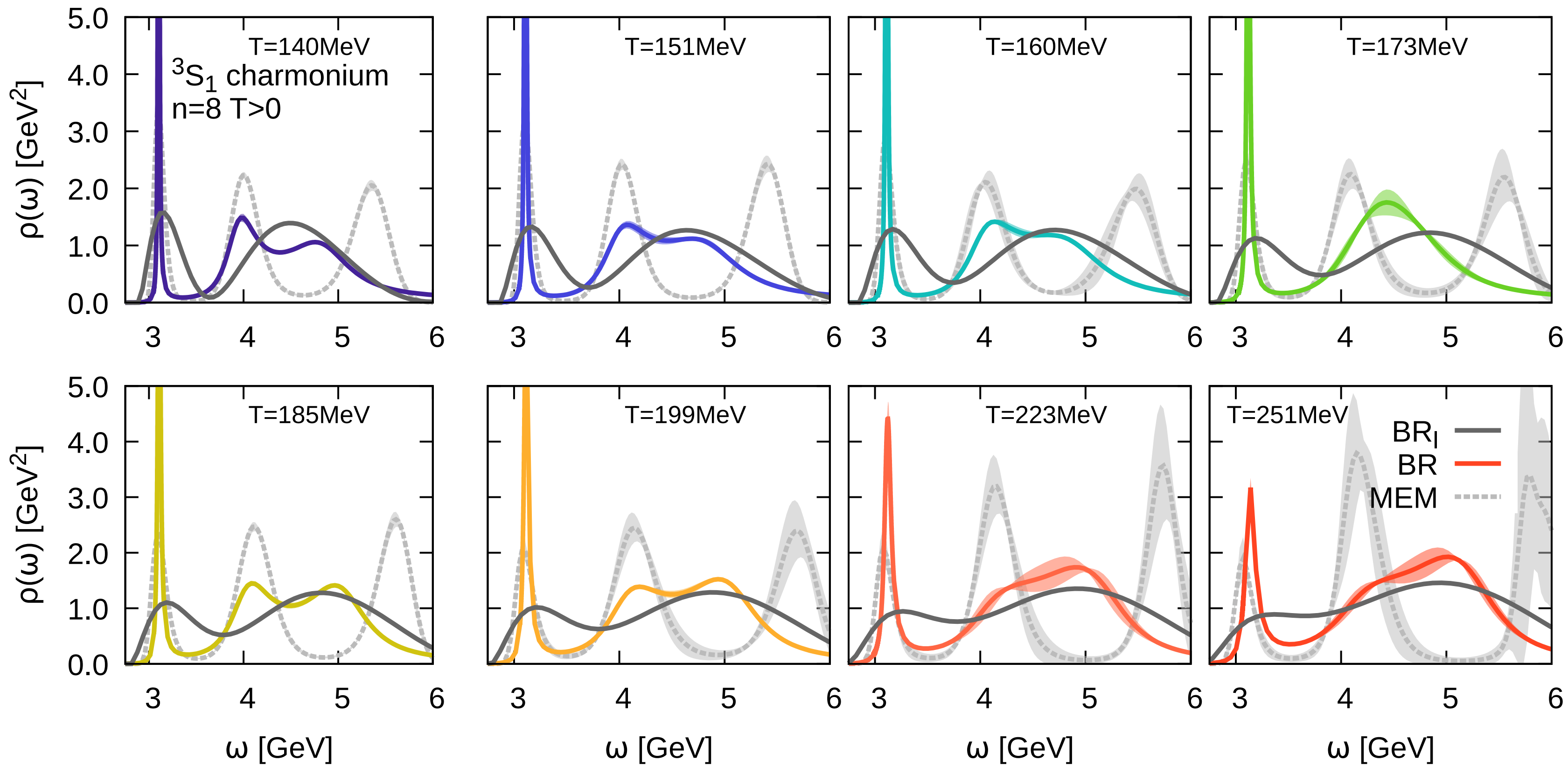


For physical masses, all results indicate a cross over at present

Quarkonia spectral functions

Naively, all bound states are destroyed in deconfinement. Quarkonia should then disappear in HIC [Matsui, Satz 1986]. The situation is, however, more complicated

[Kim, Petreczky, Rothkopf 2018]

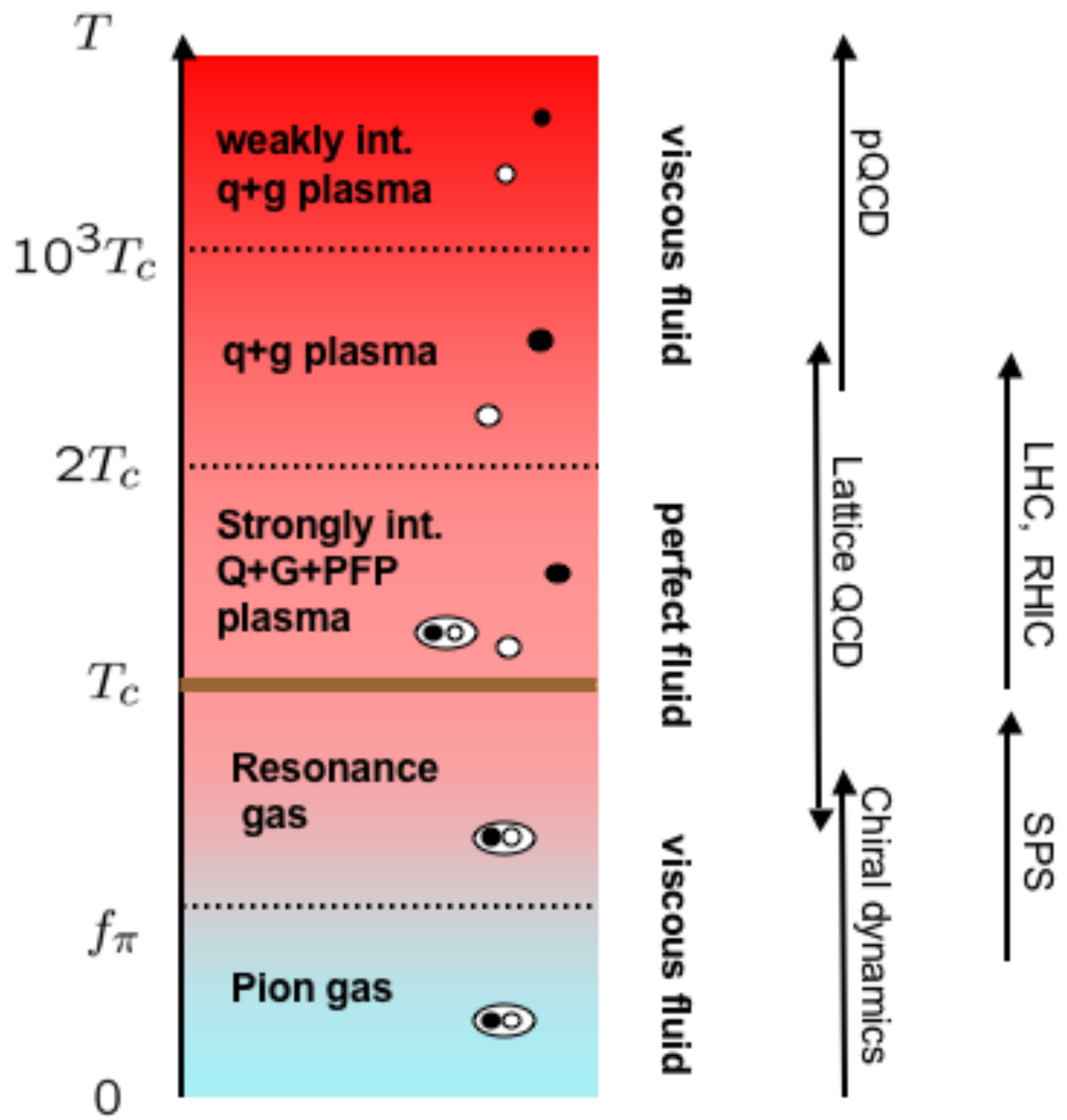


Different quarkonia states melt at different temperatures
[some bound states survive transition]

Sequential suppression

Υ	>2.63Tc
χ_{b1}	1.19 — 1.44 Tc
J/Ψ	1.29 — 1.35 Tc
χ_{c1}	1.19 Tc

A possible picture of hot QCD



[Taken from Hatsuda, J/Ψ workshop BNL, May 2006]

Conclusions - lecture 1

QCD has a **rich dynamical content**

- Confinement and chiral symmetry breaking in vacuum
- New phases of matter at high energies/densities
- Quark gluon plasma universal form of matter at high enough energies

Heavy ion collisions are the experimental tools

However, QGP is only one of the manifestations of a **wider and richer accessible physics**

QCD is the only sector in the Standard Model where studies of collectivity at the fundamental level are experimentally possible