Heavy Ion Physics

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@CASSalgado @HotLHC

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An apparently simple lagrangian hides a plethora of emerging phenomena

Nucleus-nucleus collisions provide optimal conditions for these QCD studies - extended object in the transverse plane

Heavy-ion collisions <u>main goal</u>

Study QCD under extreme conditions

↳ High density

↳ High temperature

1. QCD matter

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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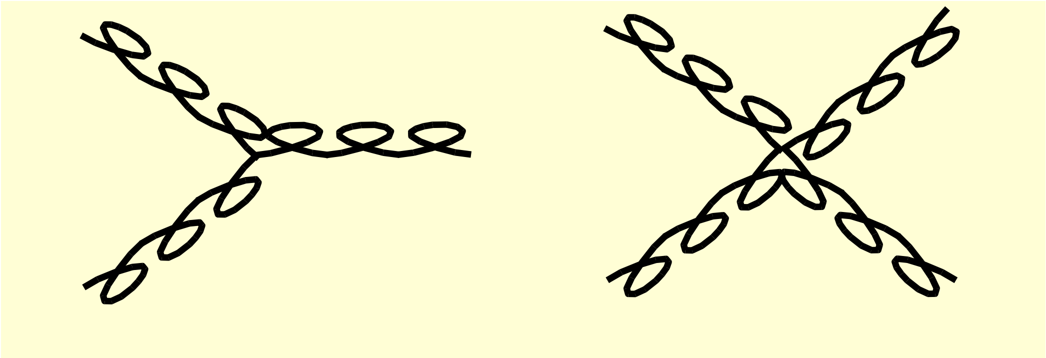
⇒ Quarks and gluons in the Lagrangian

- 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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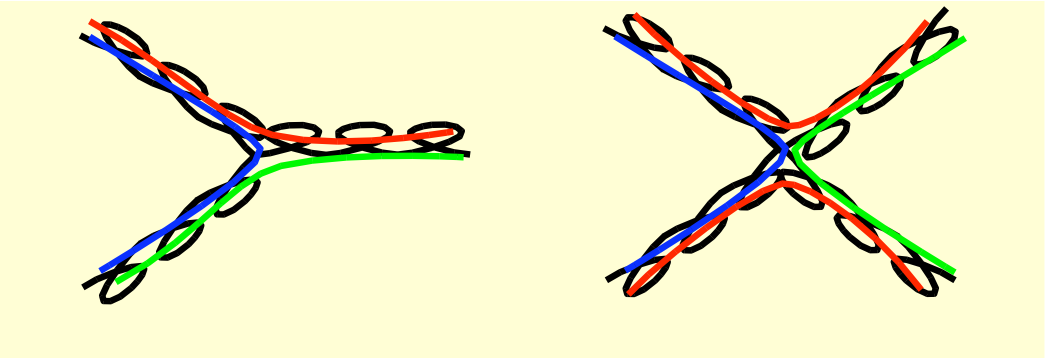

- Gluons carry color charge $\longrightarrow$ This changes everything...

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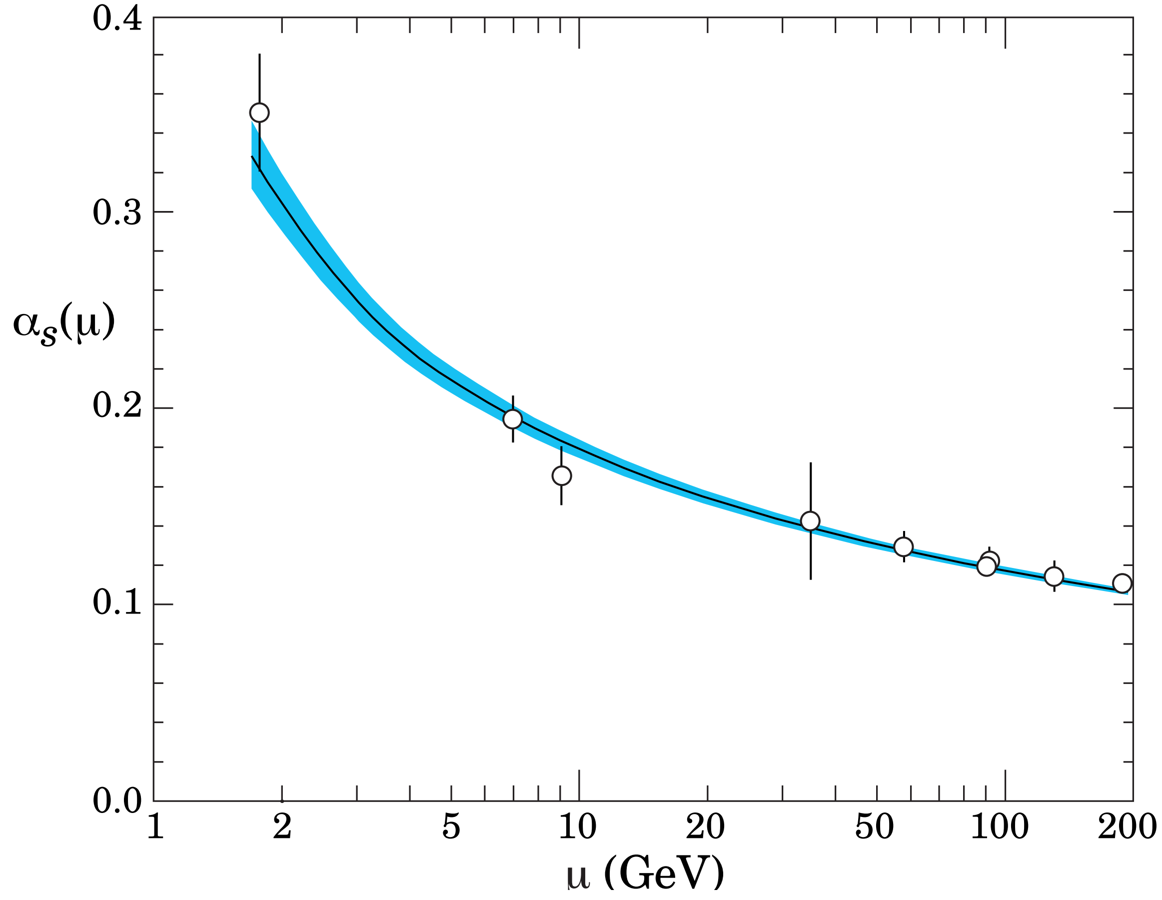
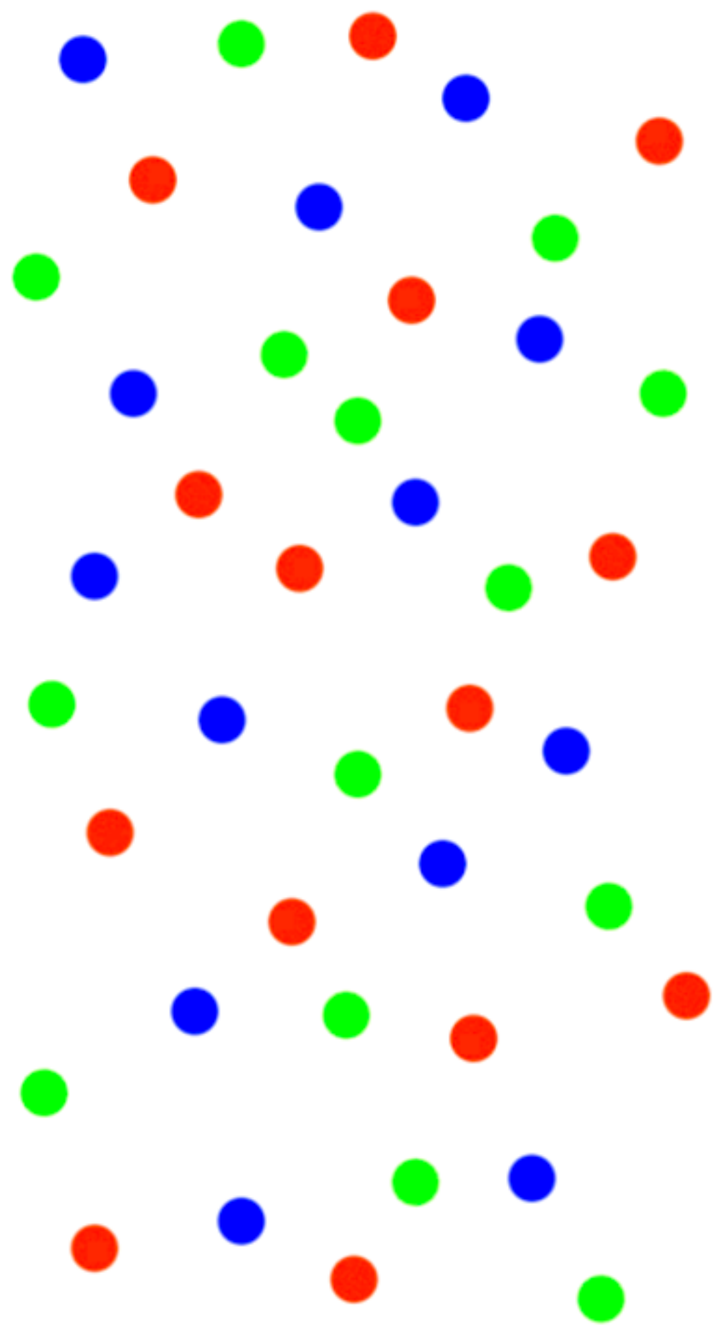
⇛ No free quarks and gluons: Confinement.

⇛ Strength smaller at smaller distances: Asymptotic freedom.



Picture

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



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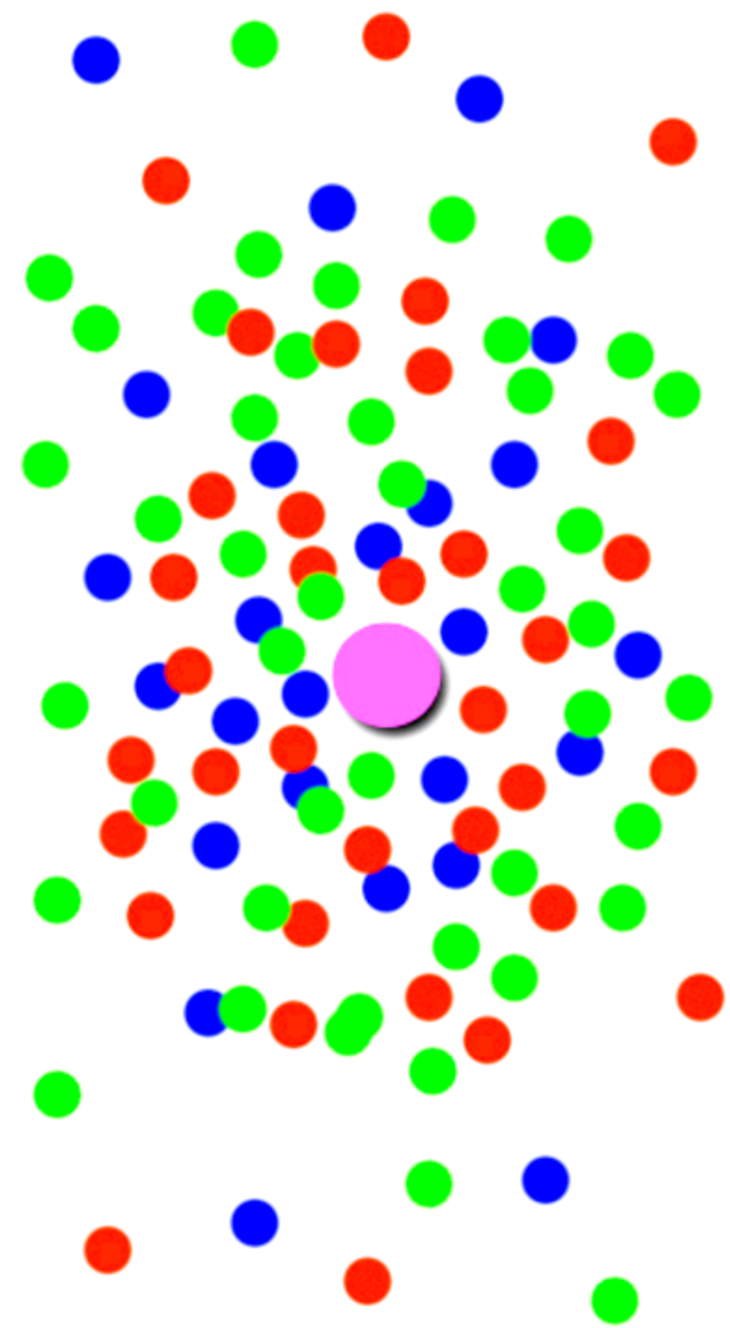
⇛ Confinement ⇒ isolated quarks or gluons = infinite energy



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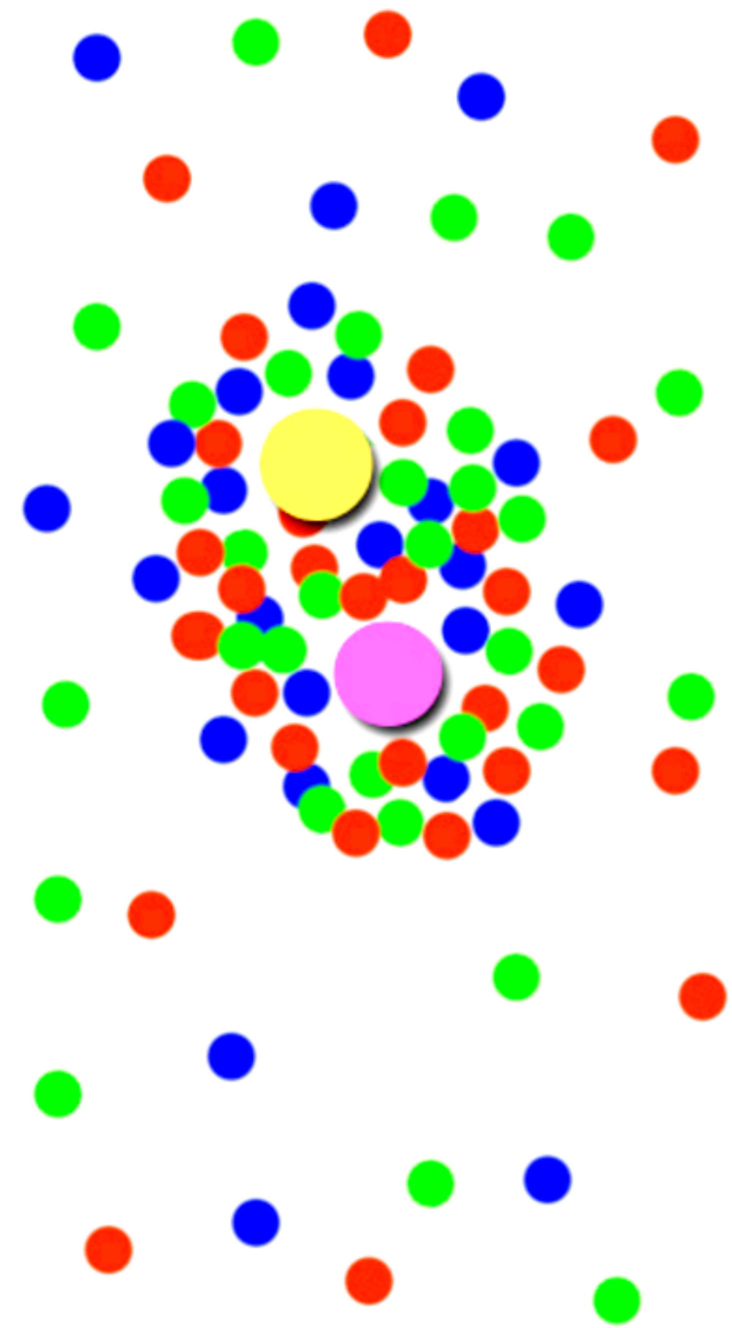
⇒ Colorless packages (hadrons)
↘ vacuum excitations



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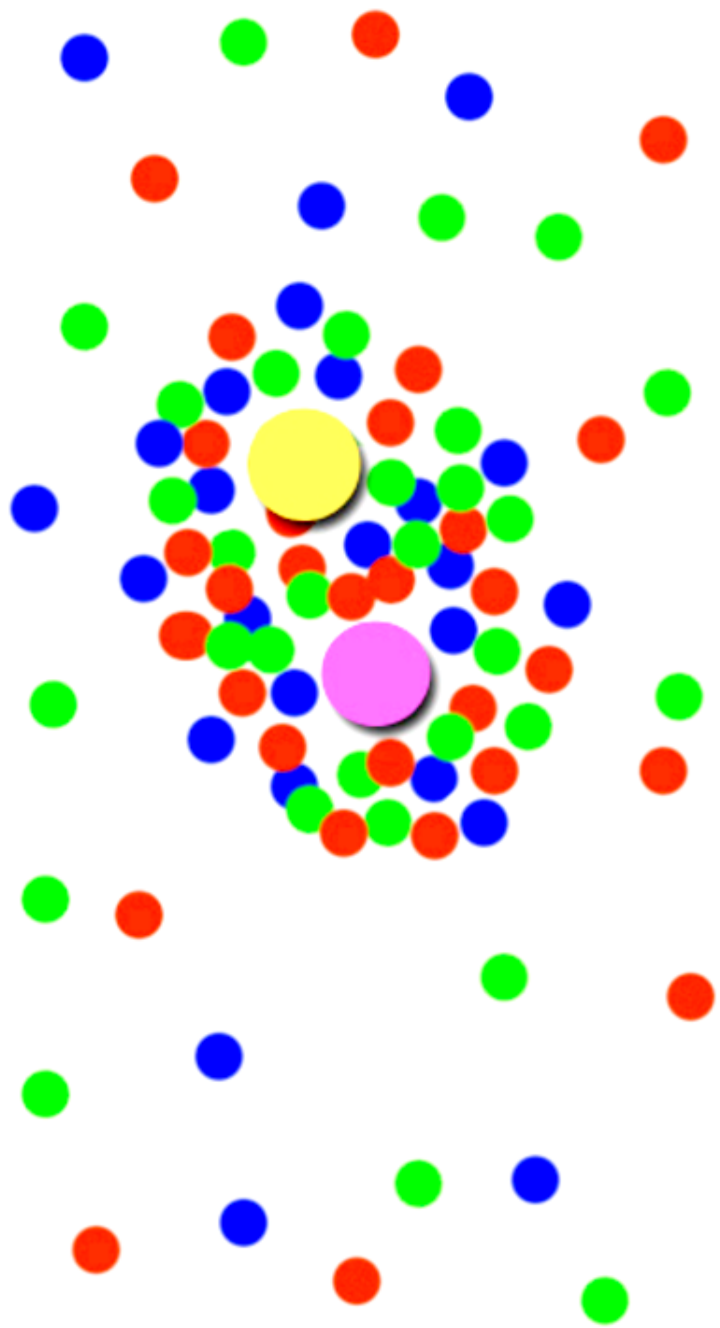
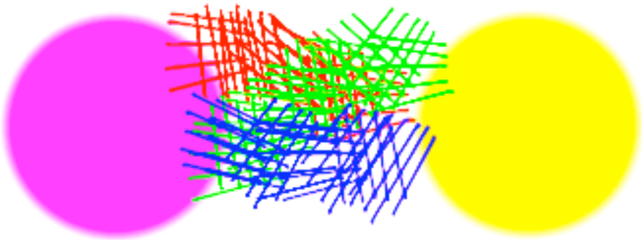
⇛ Masses

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



⇛ Colorless object

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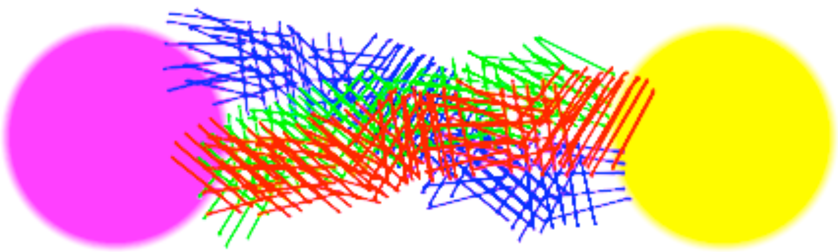

⇛ Colorless object

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

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

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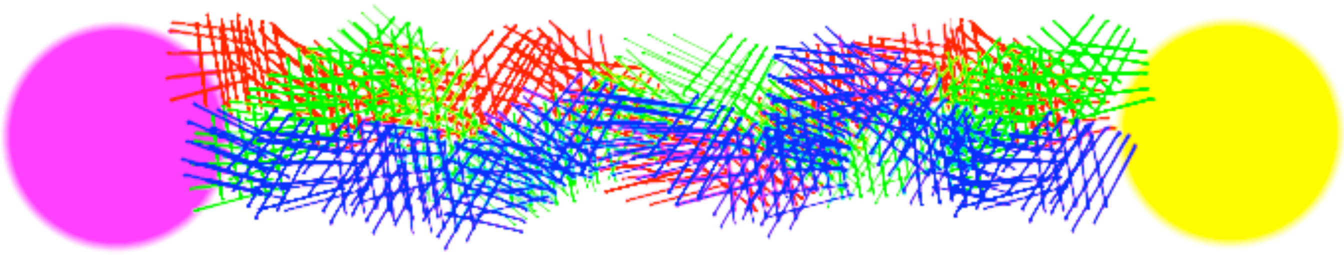

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⇛ In the limit $m_q \to \infty$ the string cannot break (infinite energy)

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:

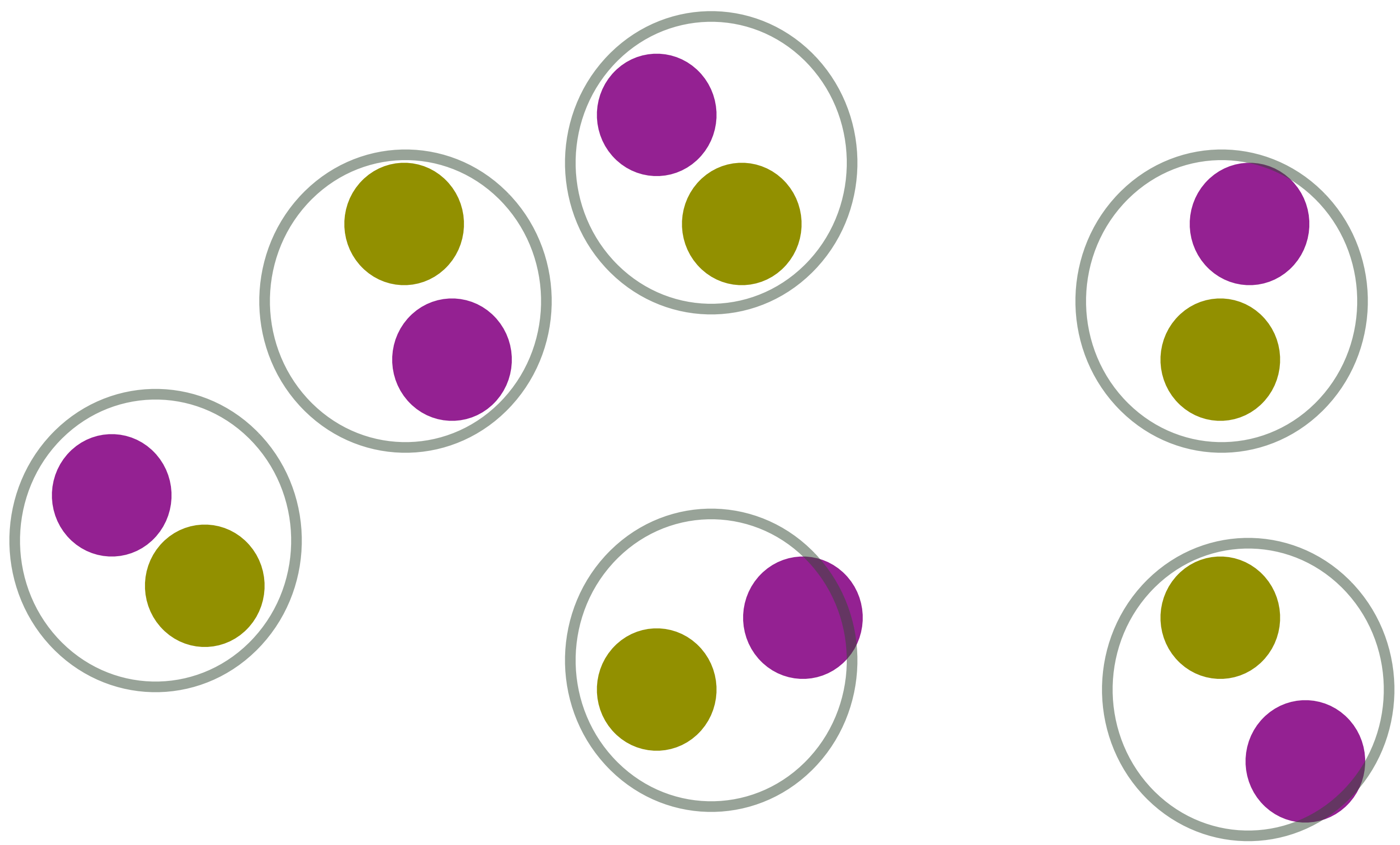
- → Confinement
- → chiral symmetry breaking

Is there a regime where these symmetries are restored? → **QCD phase diagram**

Free quarks and gluons?

Asymptotic freedom: quarks & gluons interact weakly

* at small distances → increase density
* at large momenta → increase temperature



Phase transition?

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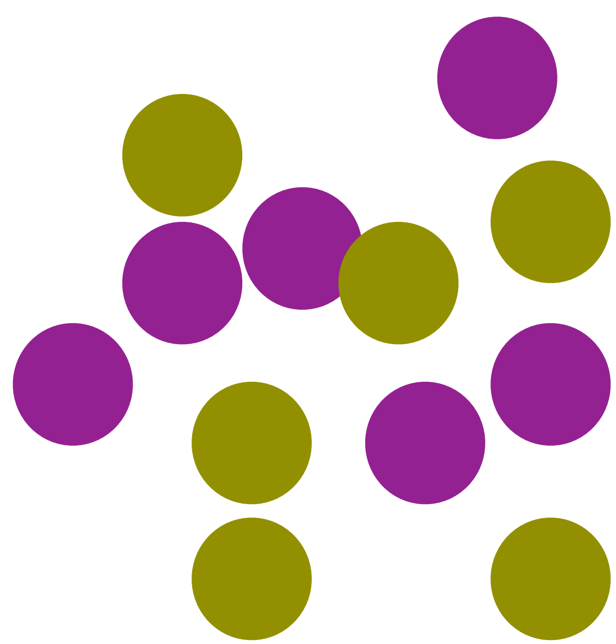


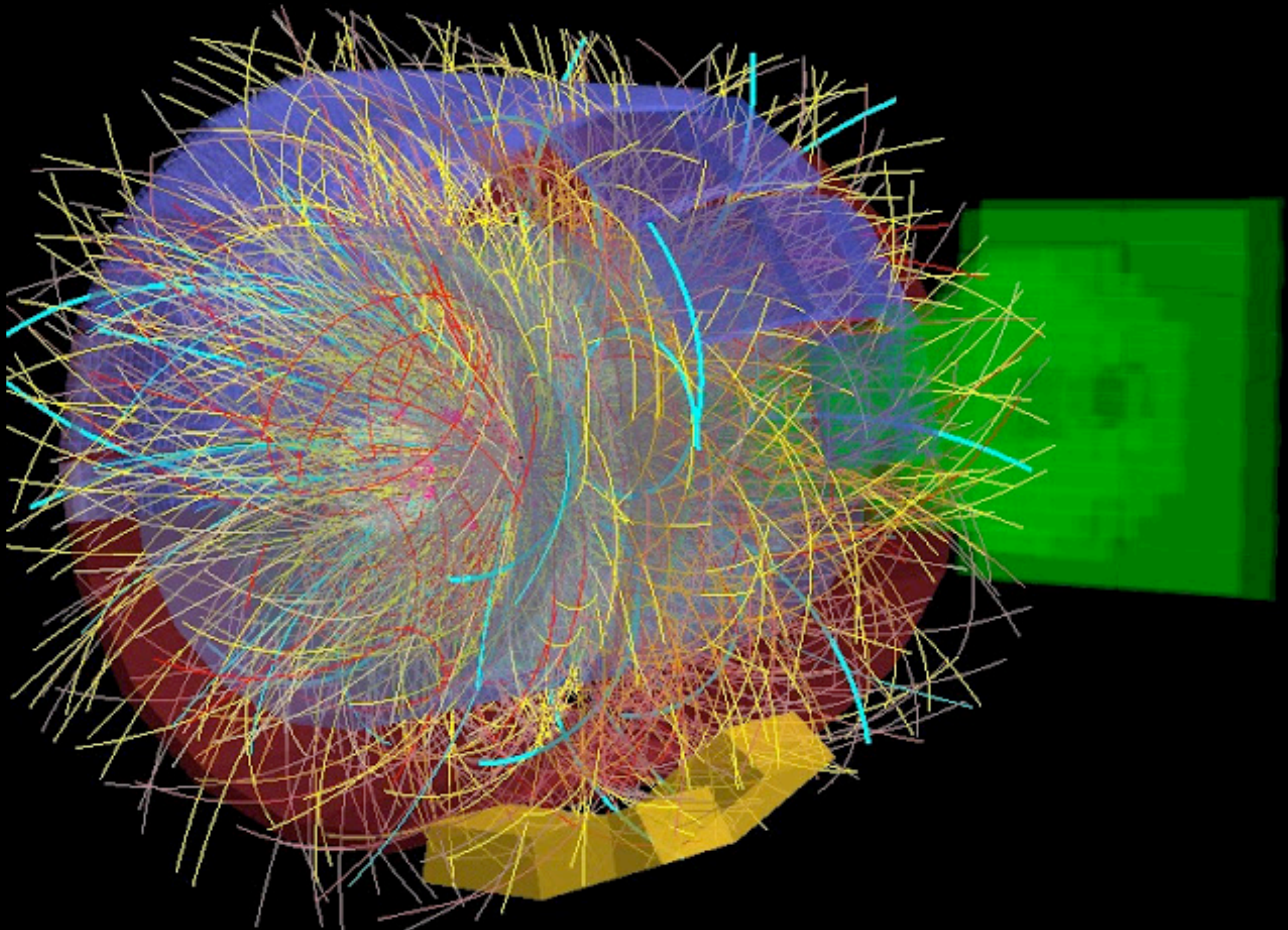
Phase transition?

How? Where?

These phases could exist in several situations

- ⇛ The early Universe some μs after the Big-Bang
  - ↘ order of the transition has cosmological consequences
- ⇛ In the core of neutron stars
- ⇛ In experiments of heavy-ion collisions

Real data from the LHC PbPb@2.76 ATeV



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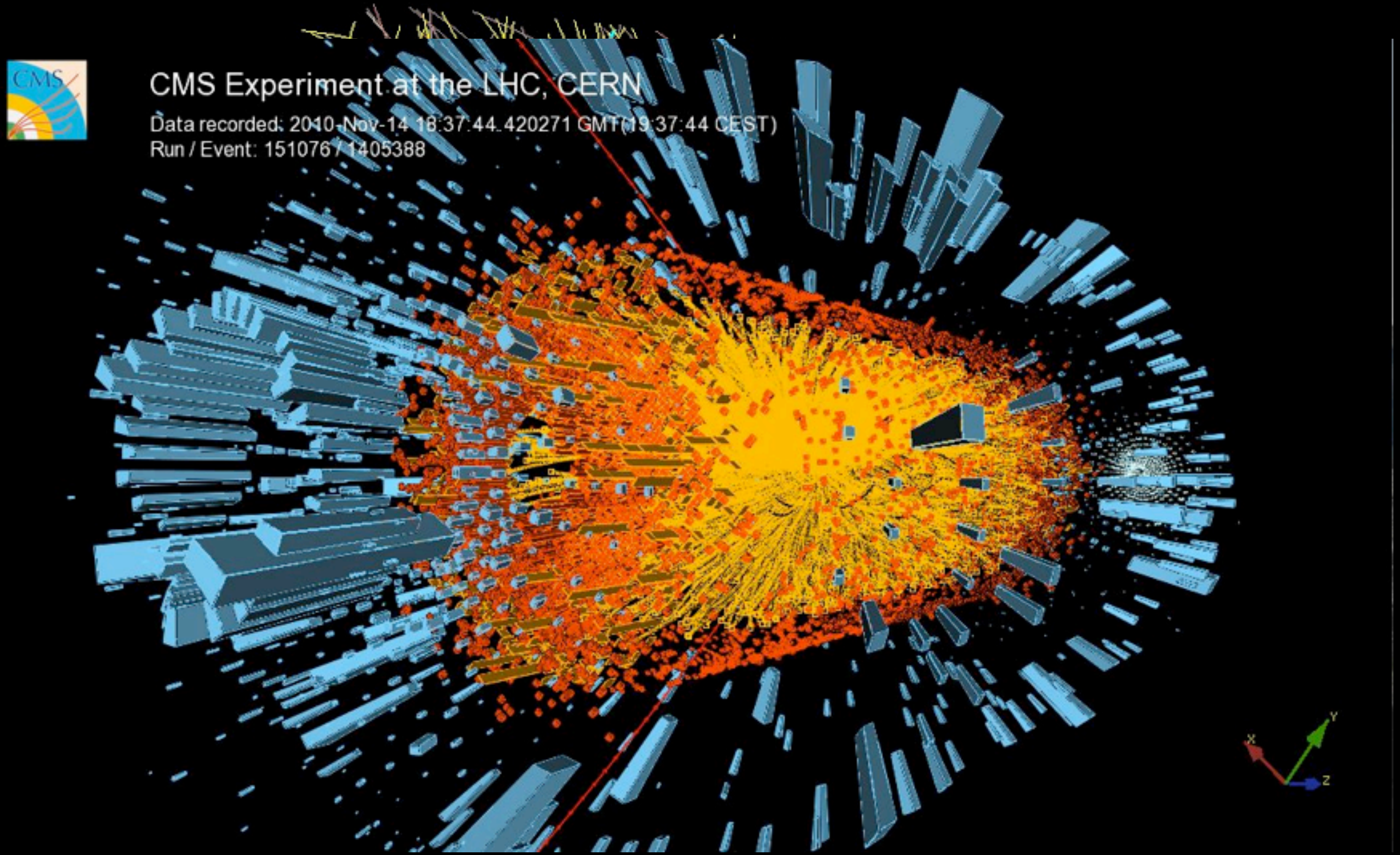


Heavy-ion collisions, some history...

Landau (1953) applies hydrodynamics to hadronic collisions.

Assumptions

- ⇛ Large amount of the energy deposited in a short time in a small region of space (**little fireball**) of the size of a Lorentz-contracted nucleus
- ⇛ Created matter is treated as a relativistic (classical) **perfect 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**
  - Normally, the condition is $T \sim m_\pi$

More on hydrodynamics

⇛ Equations of motion of a relativistic fluid

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

⇛ Where, the energy-momentum tensor for an perfect fluid is

$$T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - pg^{\mu\nu}$$

here ϵ is the energy density, p the pressure and u^μ the flow velocity

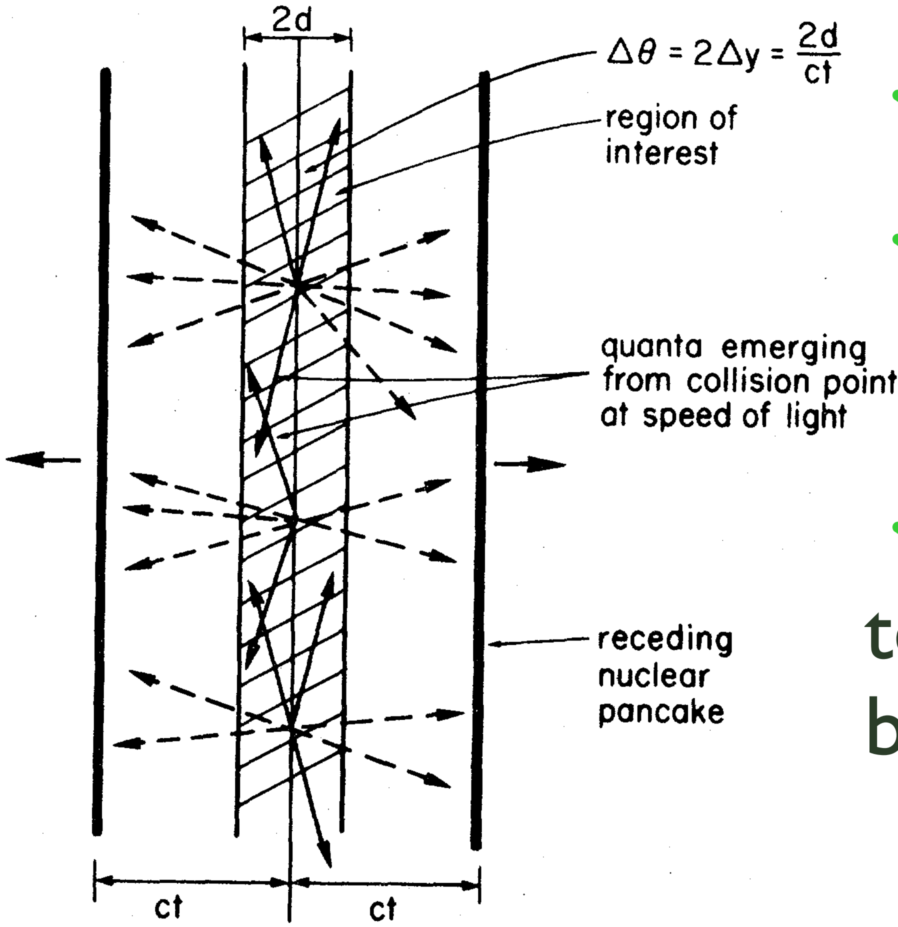
⇛ The system is closed with an equation of state, ex. $P = \epsilon/3$

⇛ The initial conditions need to be fixed

Hydrodynamics is one of the most active field of research in HIC

Main goal: check the degree of thermalization of the system

Bjorken model (1982)



- Assume infinite nuclei (in transverse plane)
- Define rapidity

$$y = \frac{1}{2}\log\frac{t+z}{t-z}$$

- At asymptotic energies, boost invariance tells that properties cannot depend on rapidity, but only on proper time. So, initial conditions

$$p(\tau);\ \epsilon(\tau);\ u^\mu = \gamma^2(1,0,0,z/t)$$

⇛ The hydrodynamic equation is now $\frac{d\epsilon}{d\tau} + \frac{\epsilon + p}{\tau} = 0$

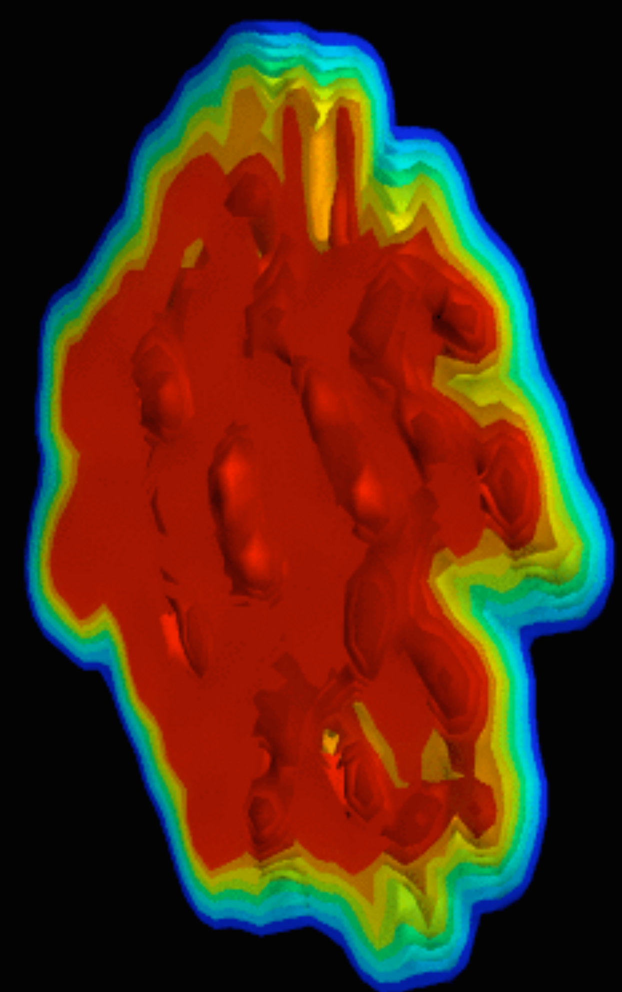
⇛ And the solutions are

$$\epsilon(\tau) = \frac{\epsilon_0}{\tau^{4/3}}$$

Ex. Check these equations; check that the entropy per unit rapidity is constant; check that the temperature drops as $\tau^{-1/3}$

Gold-gold collisions at RHIC ($\sqrt{s} = 200$ AGeV)

Evolution of temperature with time



http://quark.phy.bnl.gov/~bschenke/

QCD thermodynamics

QCD phase diagram

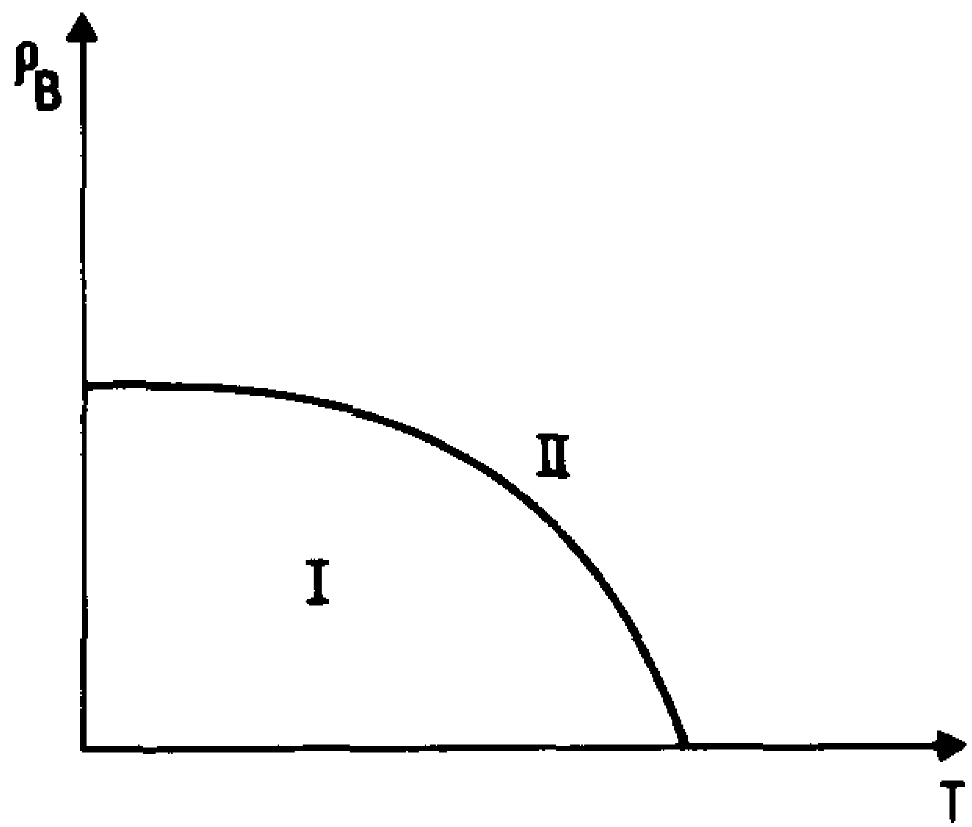
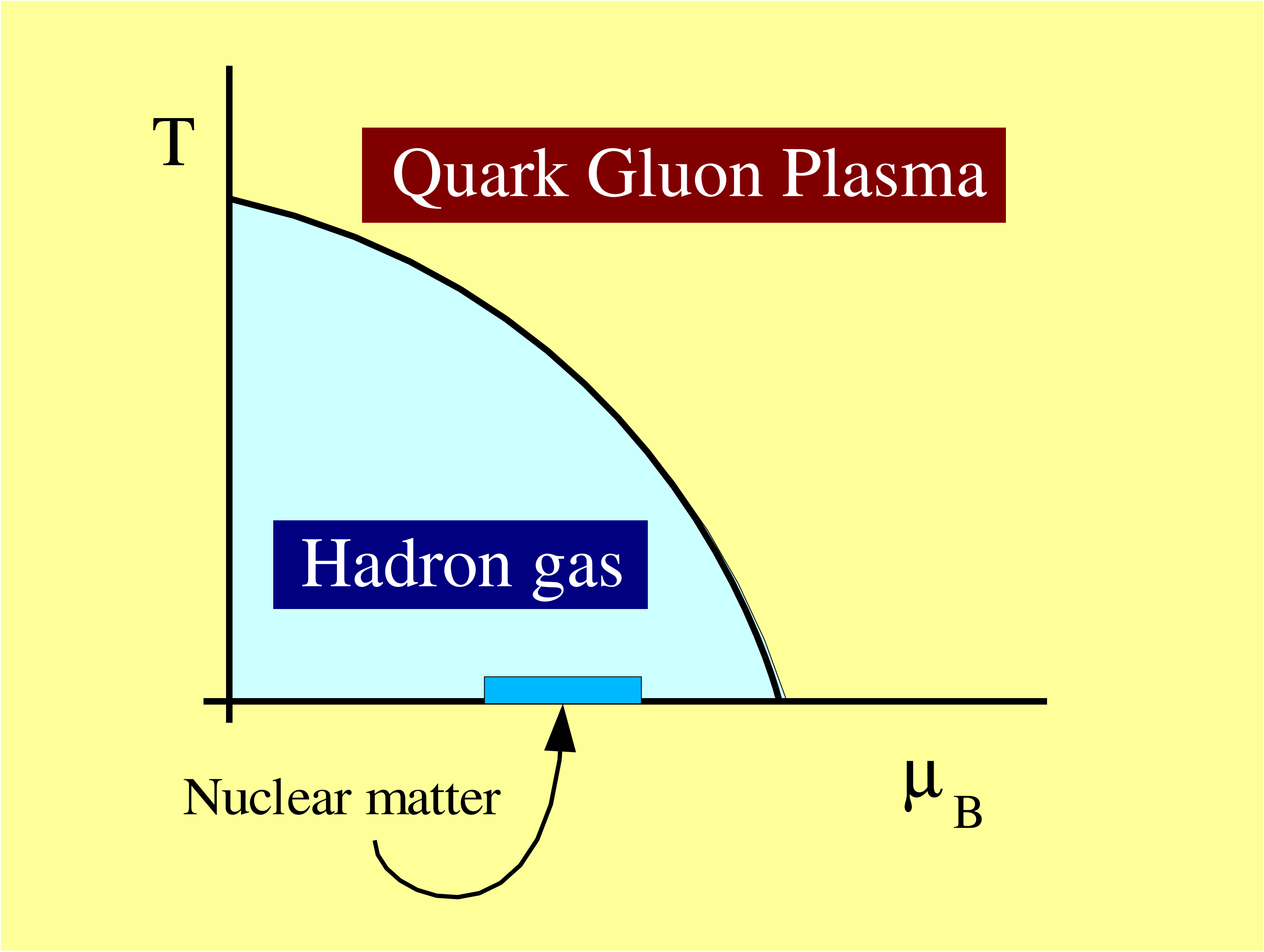


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

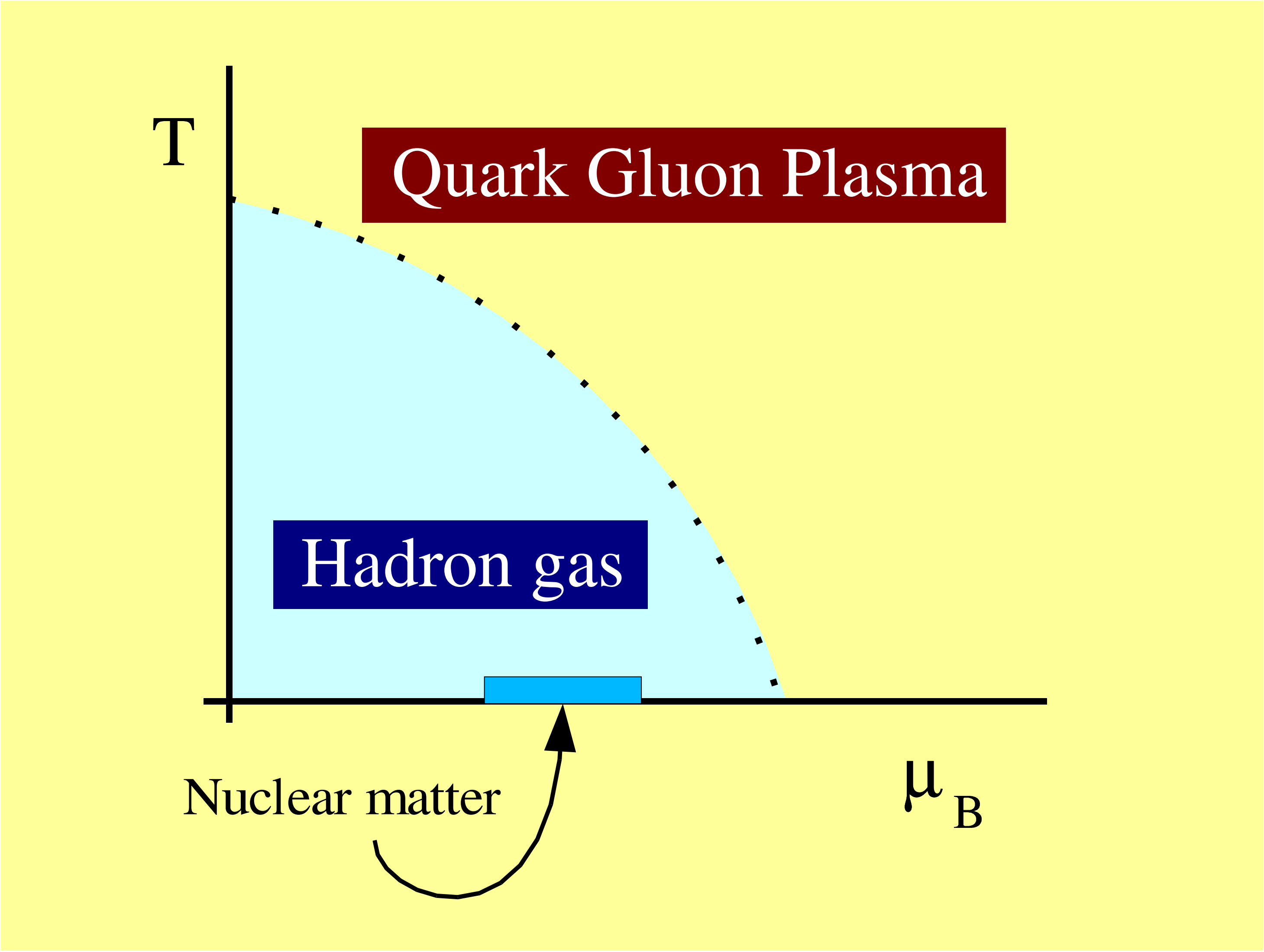
[Cabibbo and Parisi 1975]

QCD phase diagram



⇒ First lattice calculation found a first order phase transition

QCD phase diagram



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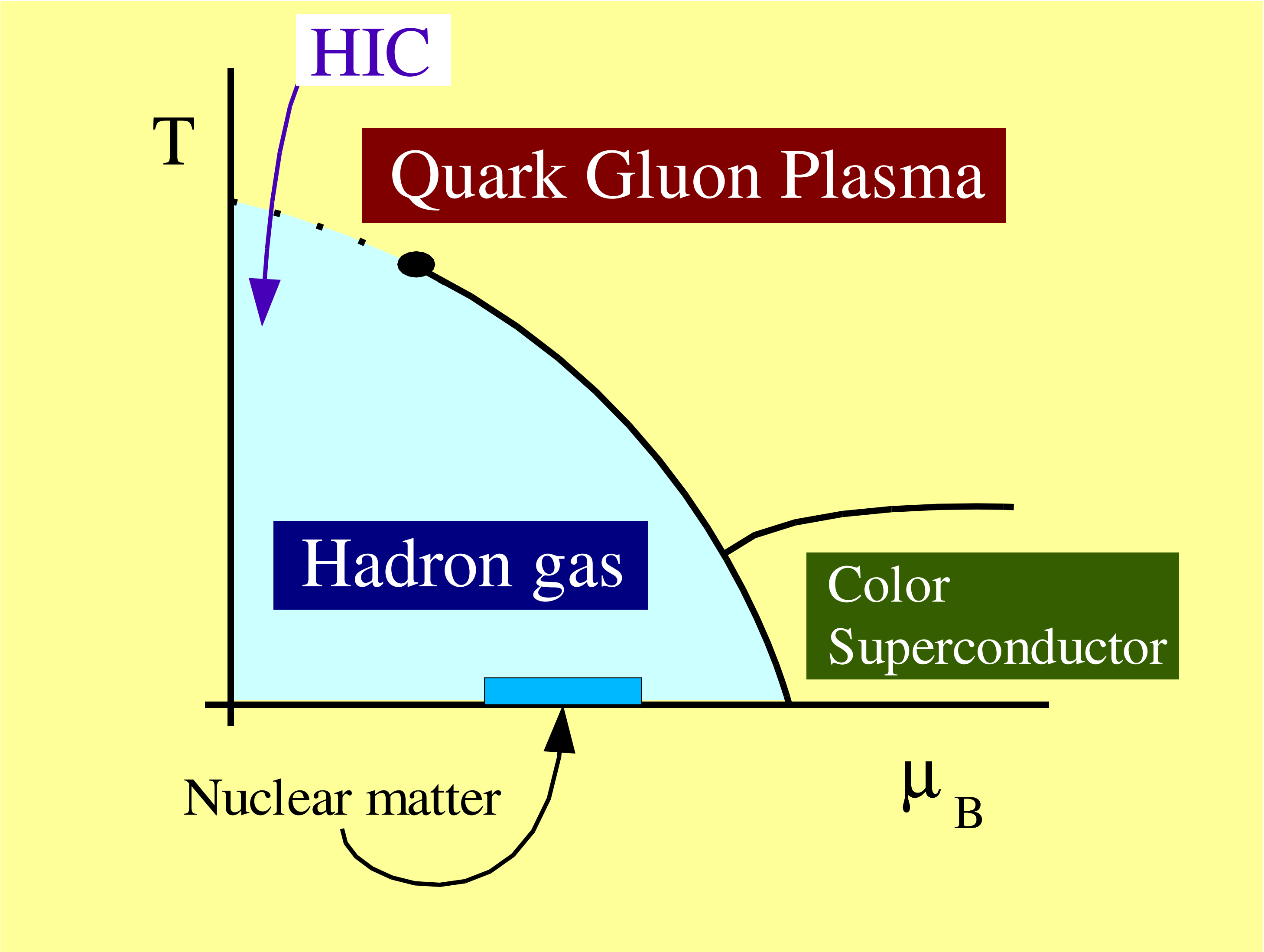

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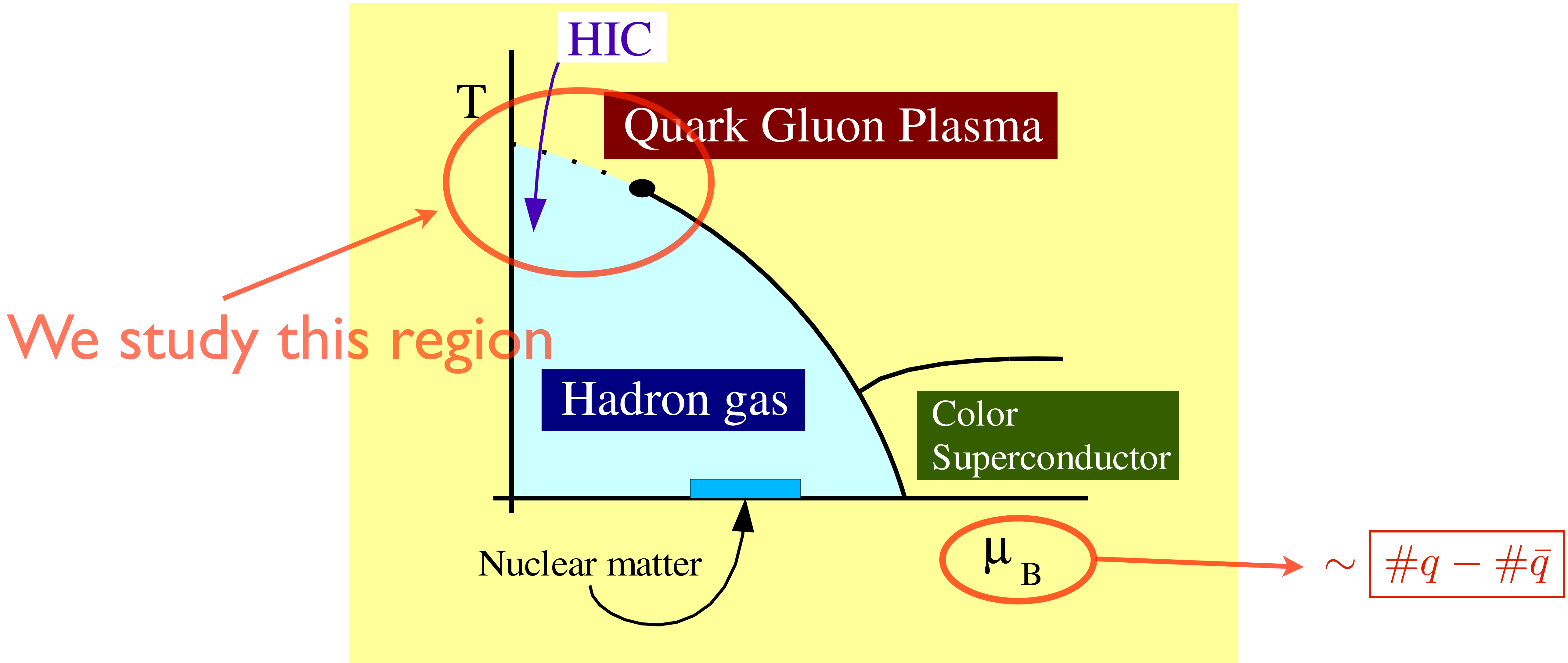

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QCD thermodynamics I

⇛ 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

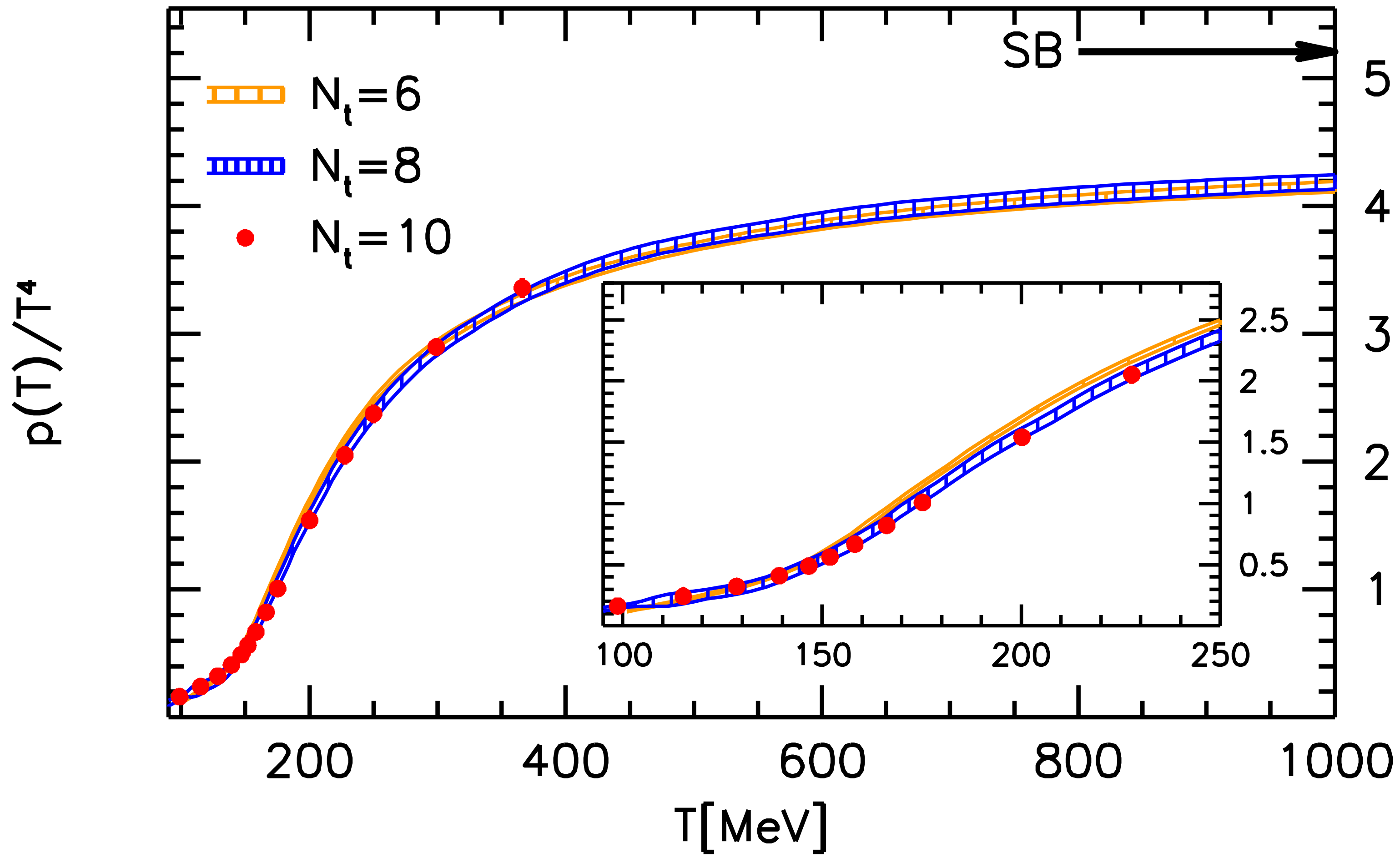
In order to solve these equations

- ⇛ 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 $\mu = 0$, results for small μ only recently available.

First example: equation of state

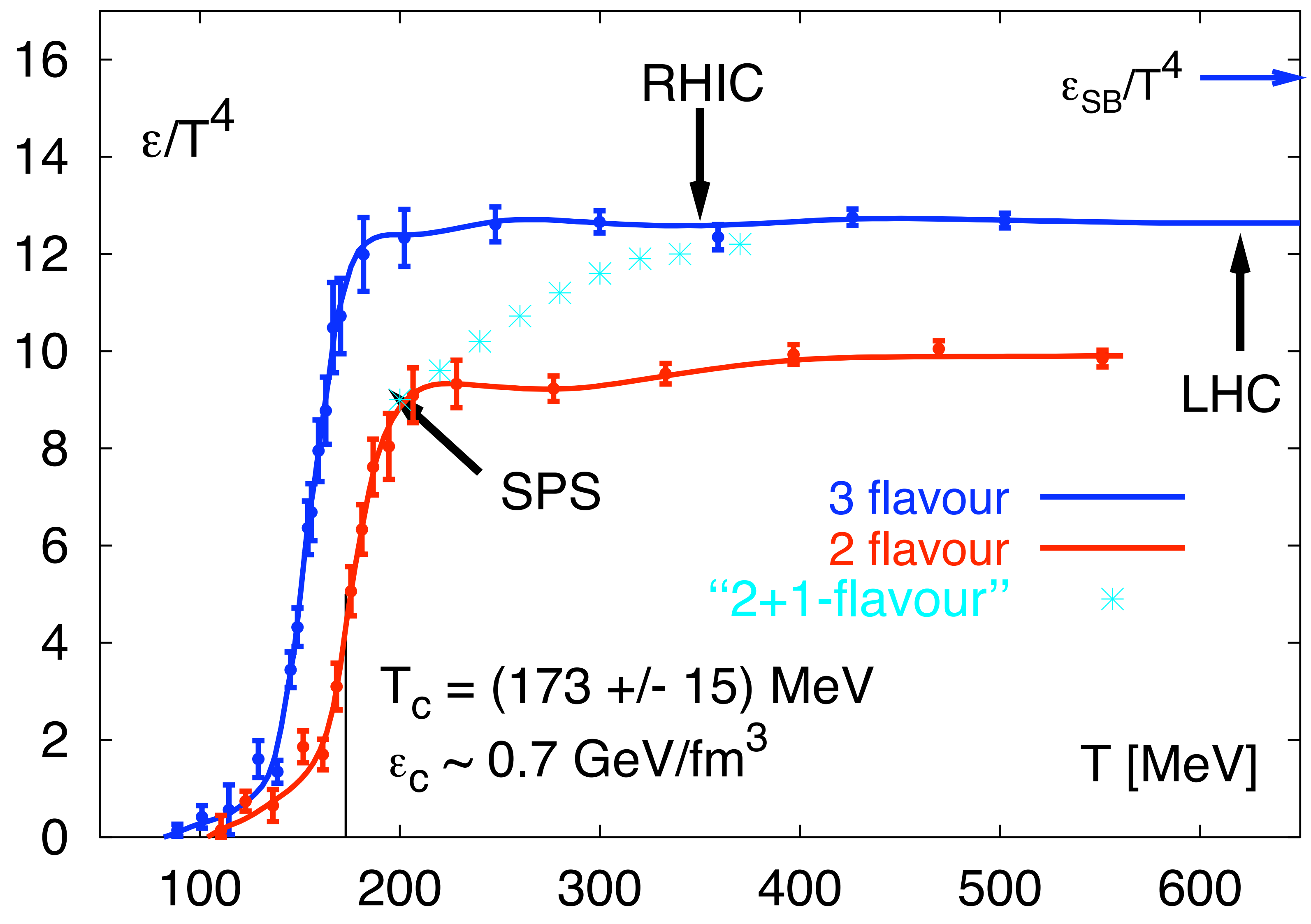
Naïve estimation: Let's fix $\mu = 0$, the pressure of an ideal gas (of massless particles) is proportional to the number of d.o.f: $P \propto NT^4$

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



[Borsanyi et al 2010]

EoS and experiments



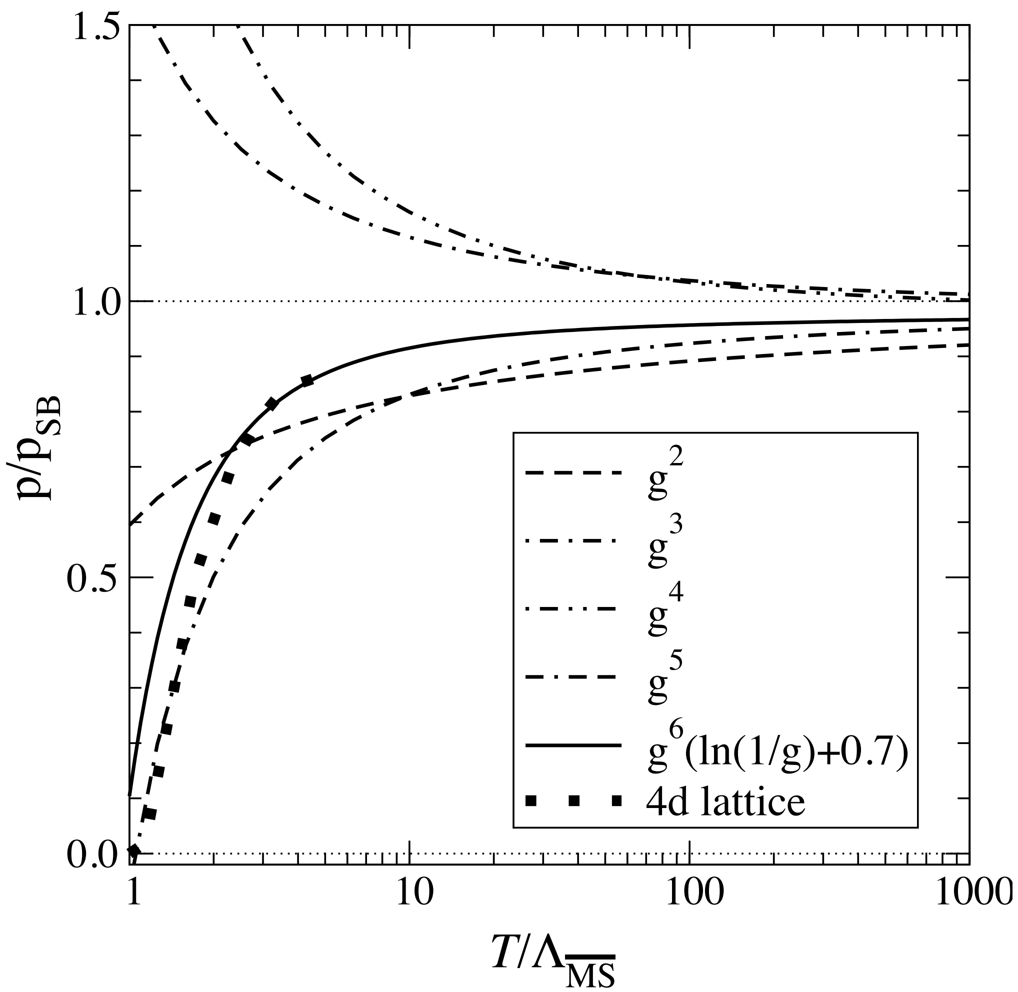
(Karsch *et al.*)

This is just an estimate!

Perturbative calculations

Different orders in PT compared to lattice results

[Kajantie et al. 2003]

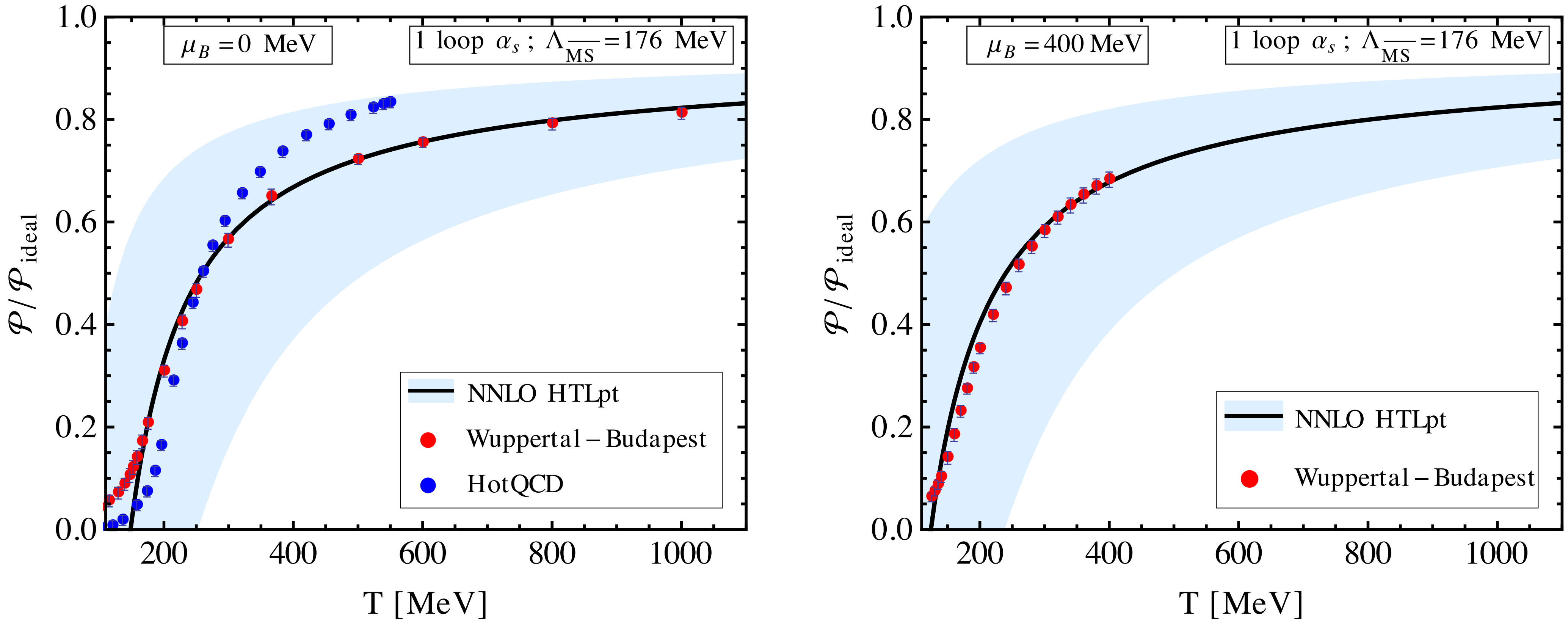


Convergence for very large temperature

Perturbative calculations

New results in NNLO - HTL

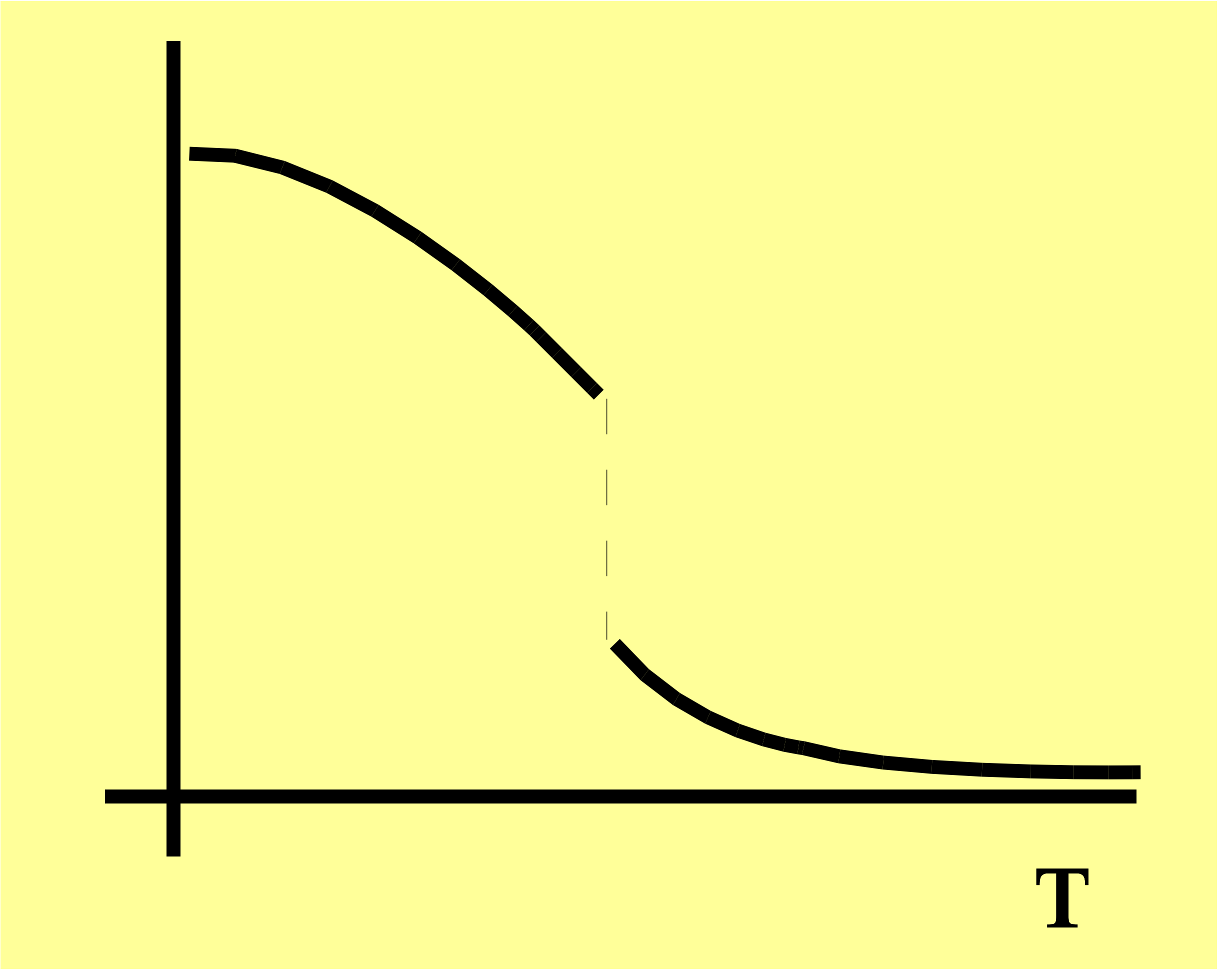
[Haque et al. 2014]



Impressive improvement

Phase transition: 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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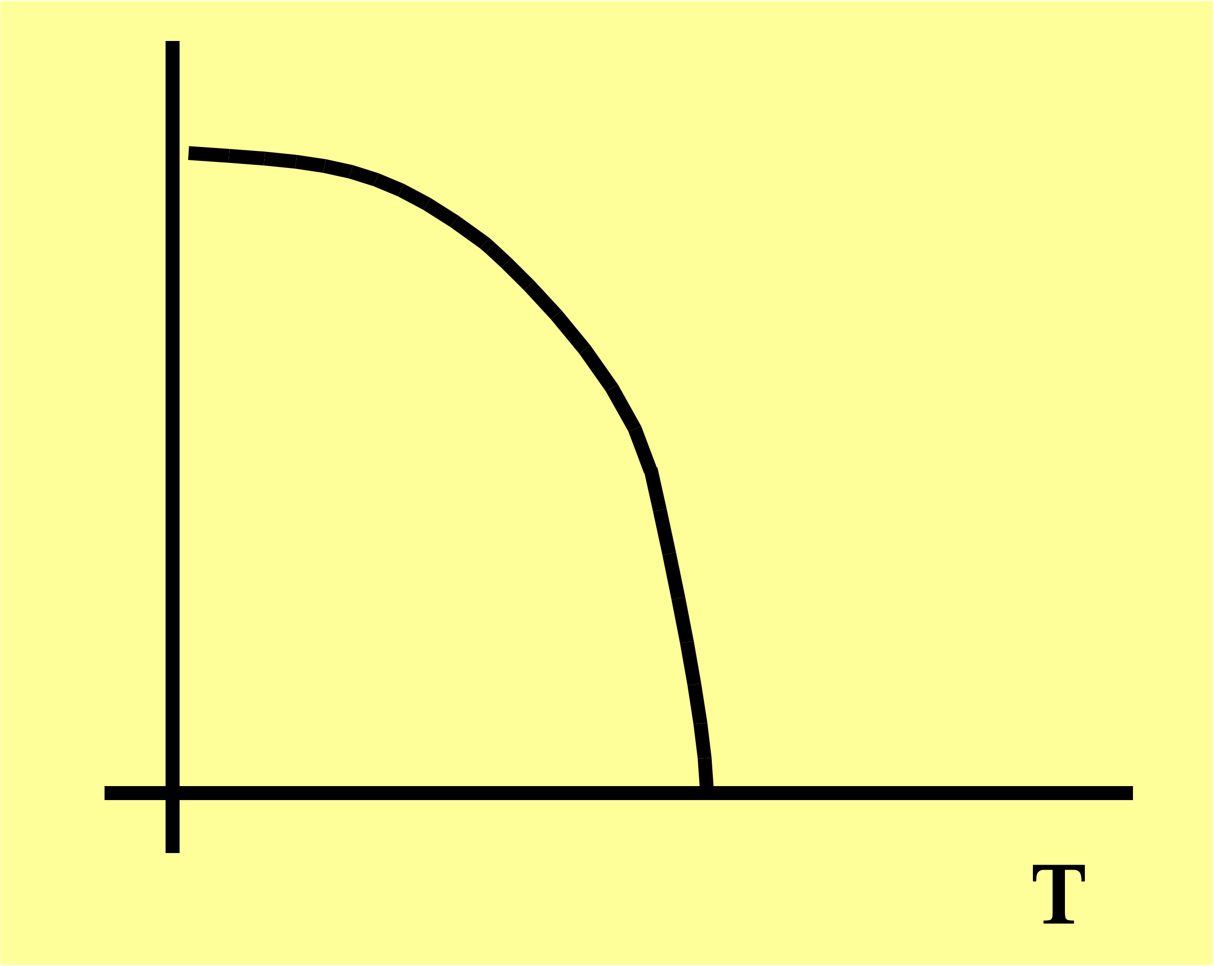

Second order: discontinuity in the derivative

Phase transition: order parameters

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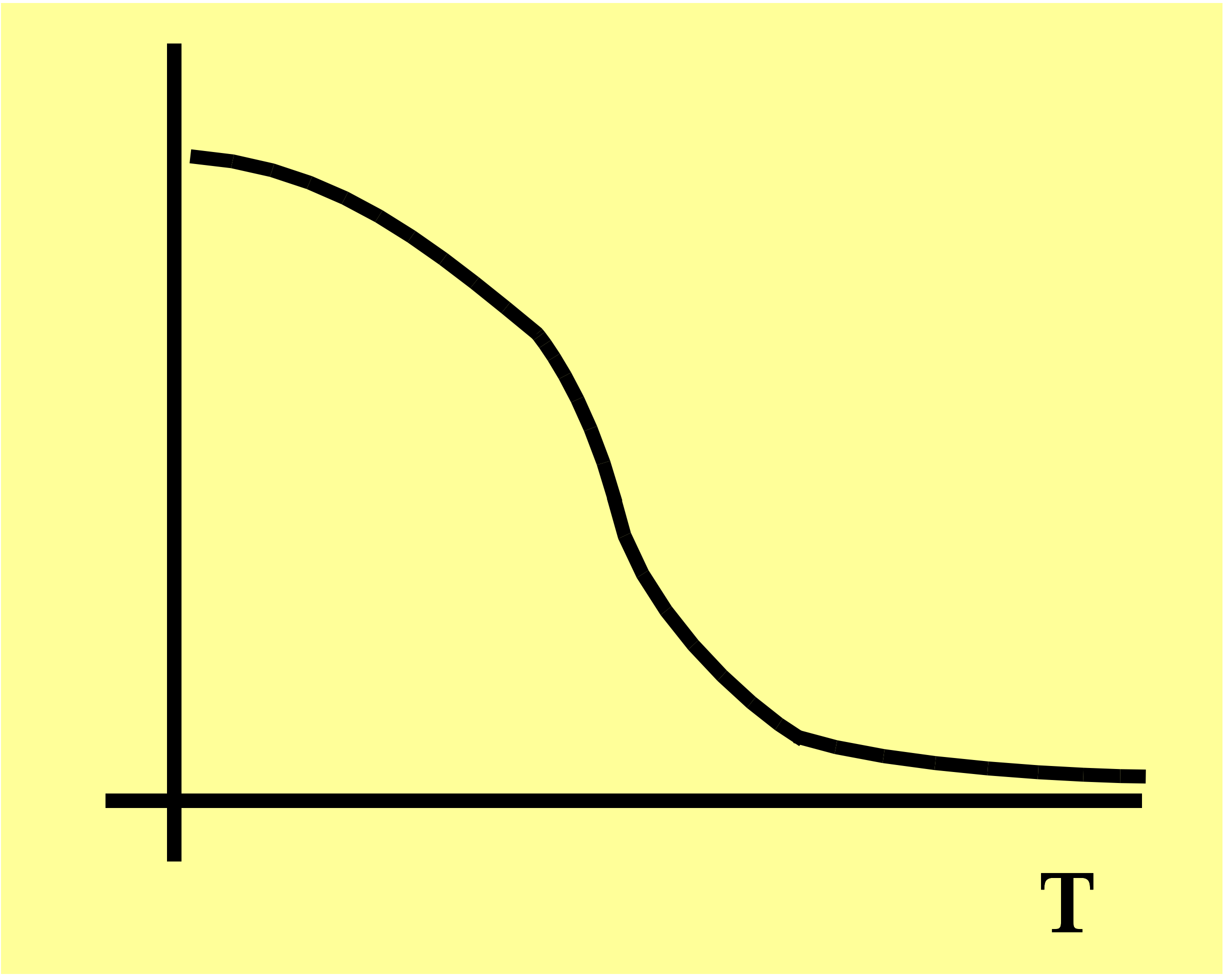


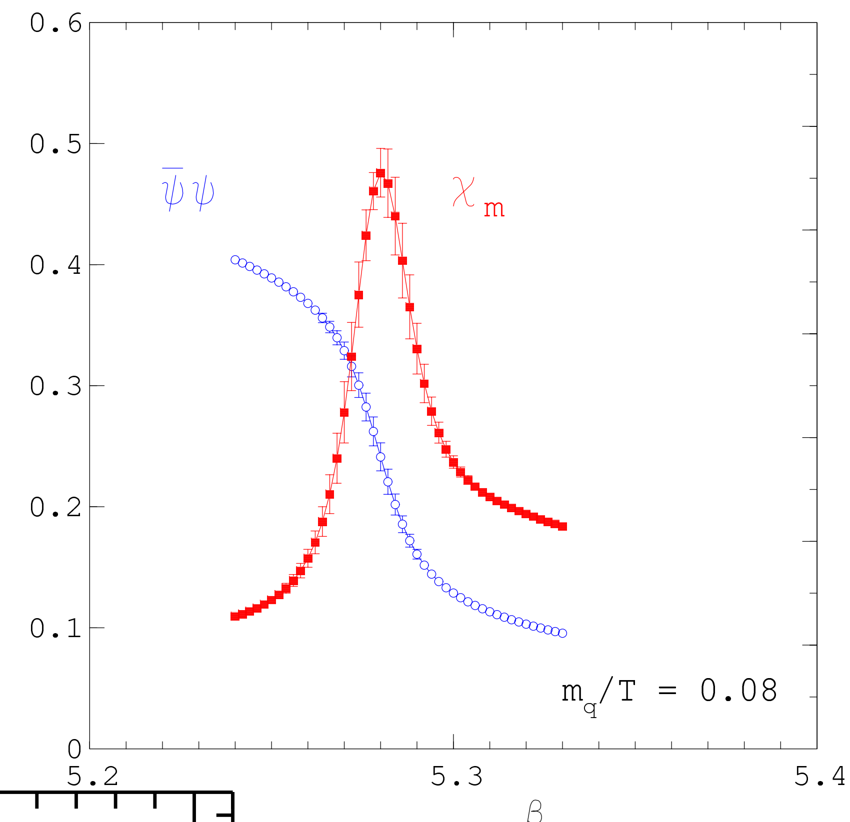
Cross-over: continuous function

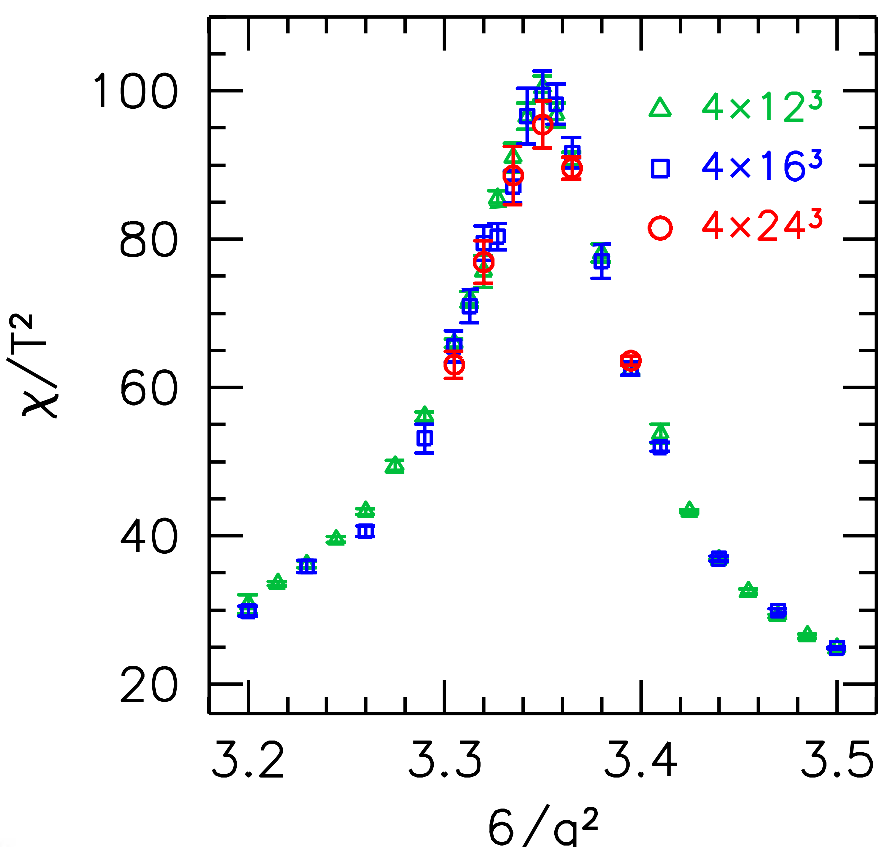
Order parameters in QCD I

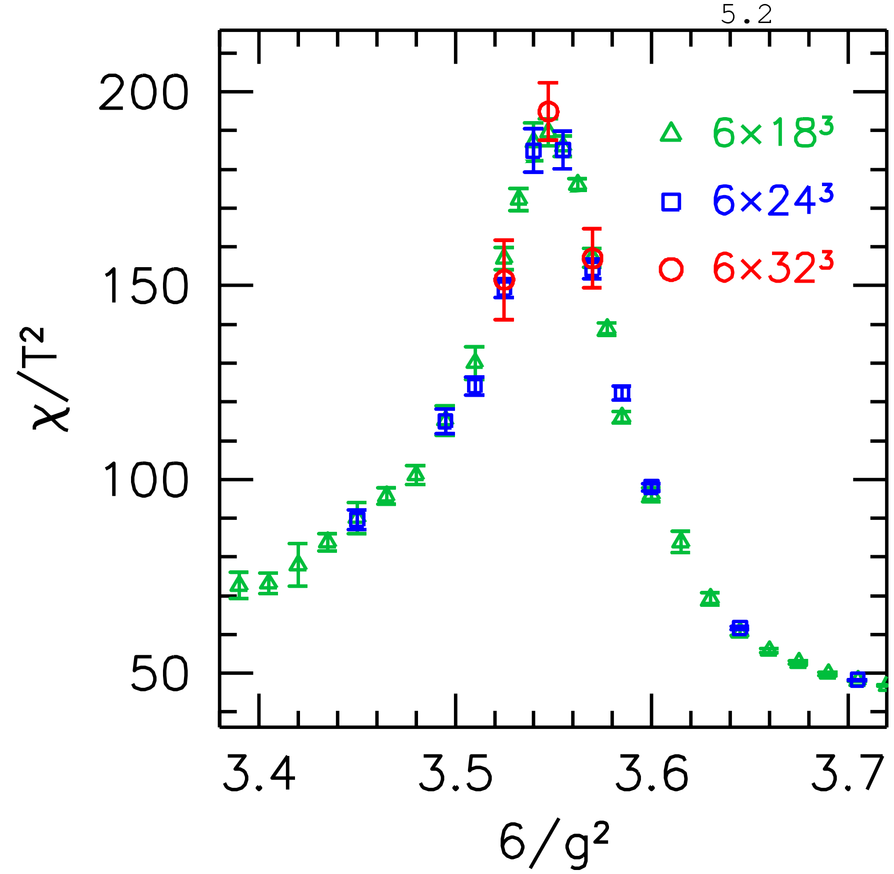
<u>Chiral symmetry restoration</u>: for $m_q = 0$ chiral condensate is the order parameter

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

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



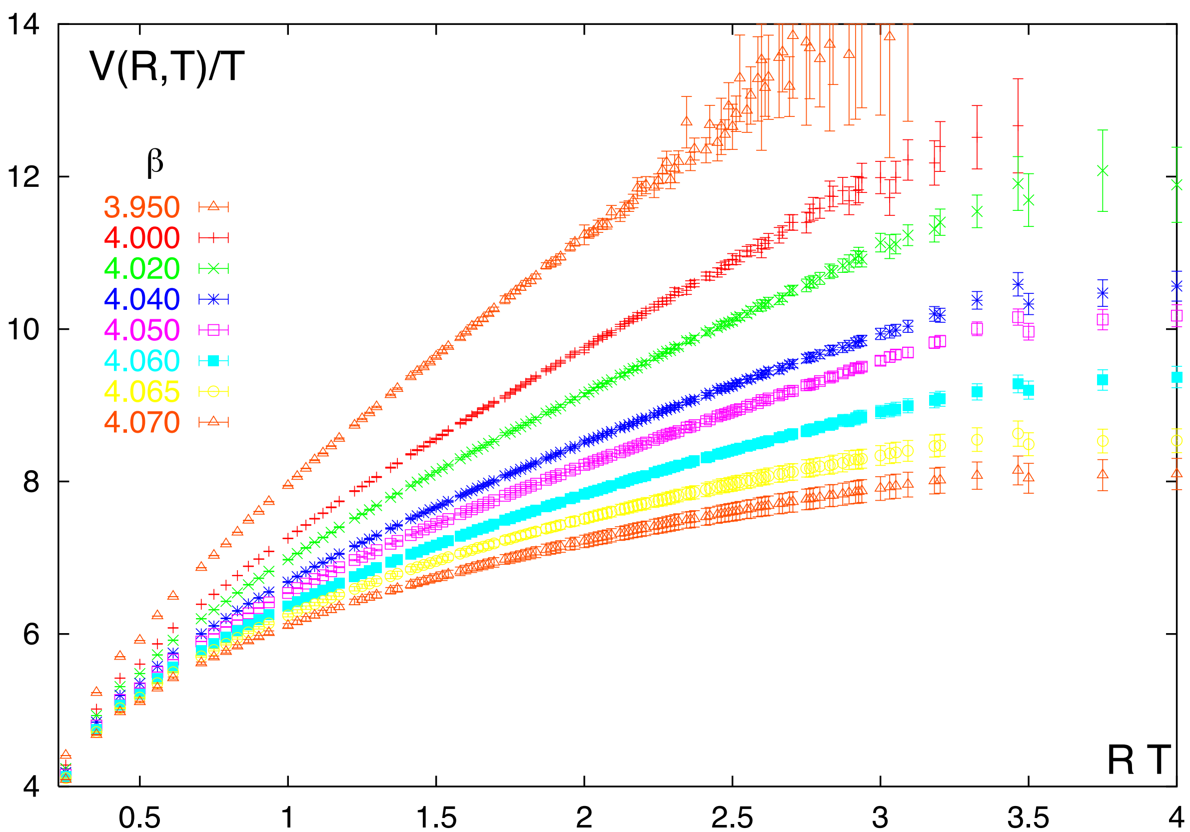


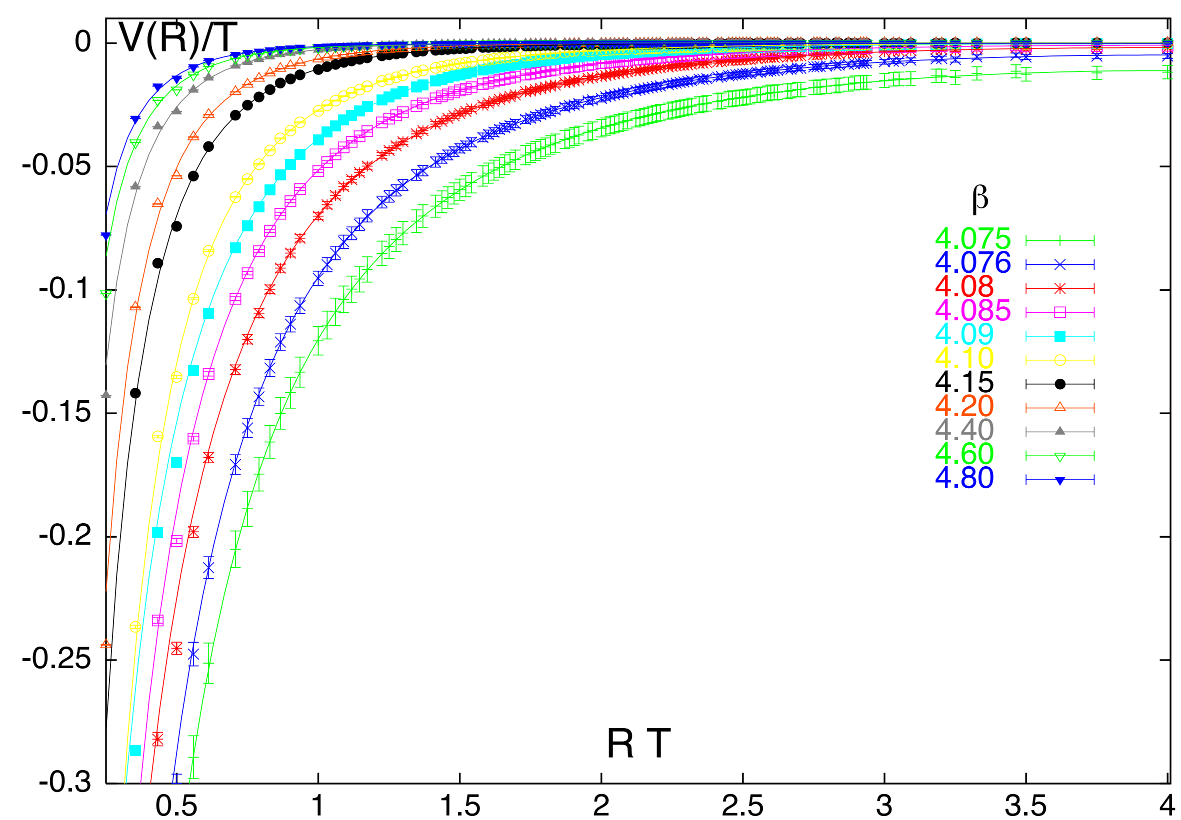


[Aoki et al 2006]

Order parameters in QCD II

Confinement: for $m_q \to \infty$ the order parameter is the potential



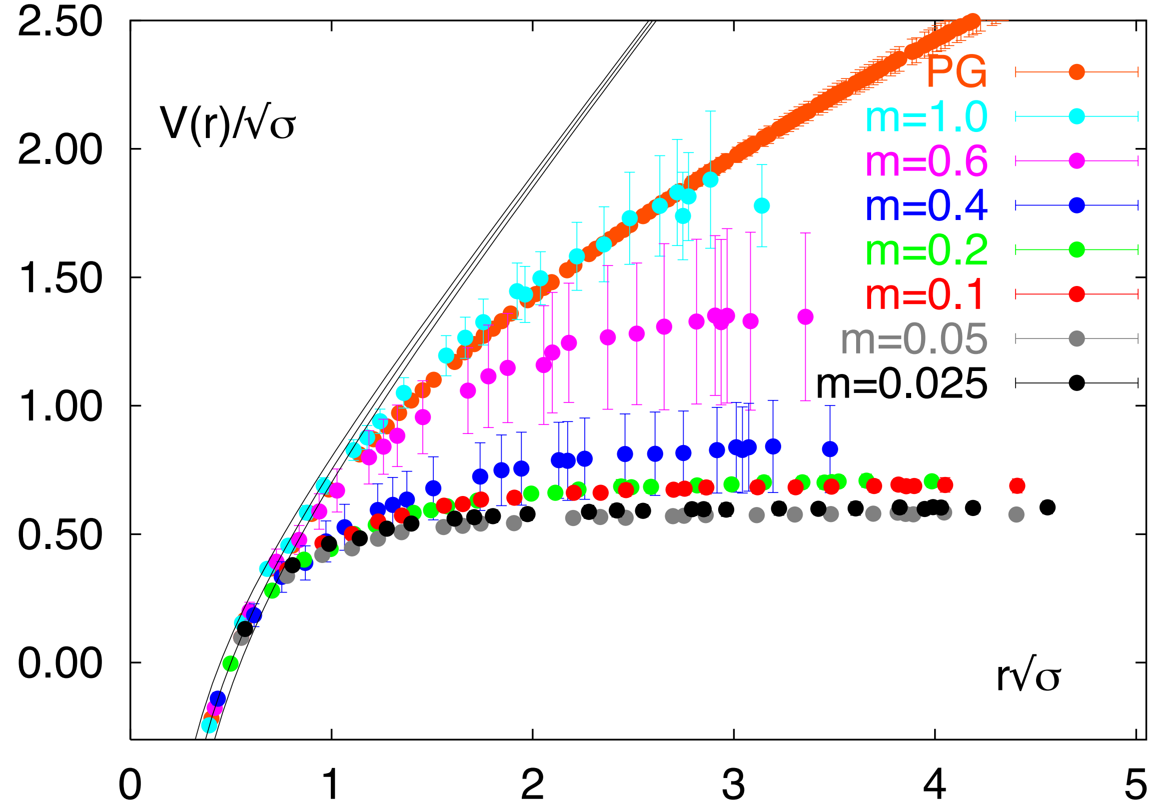


$T < T_c$ $\qquad$ $T > T_c$

[Kaczmarek et al 2000]

However...

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



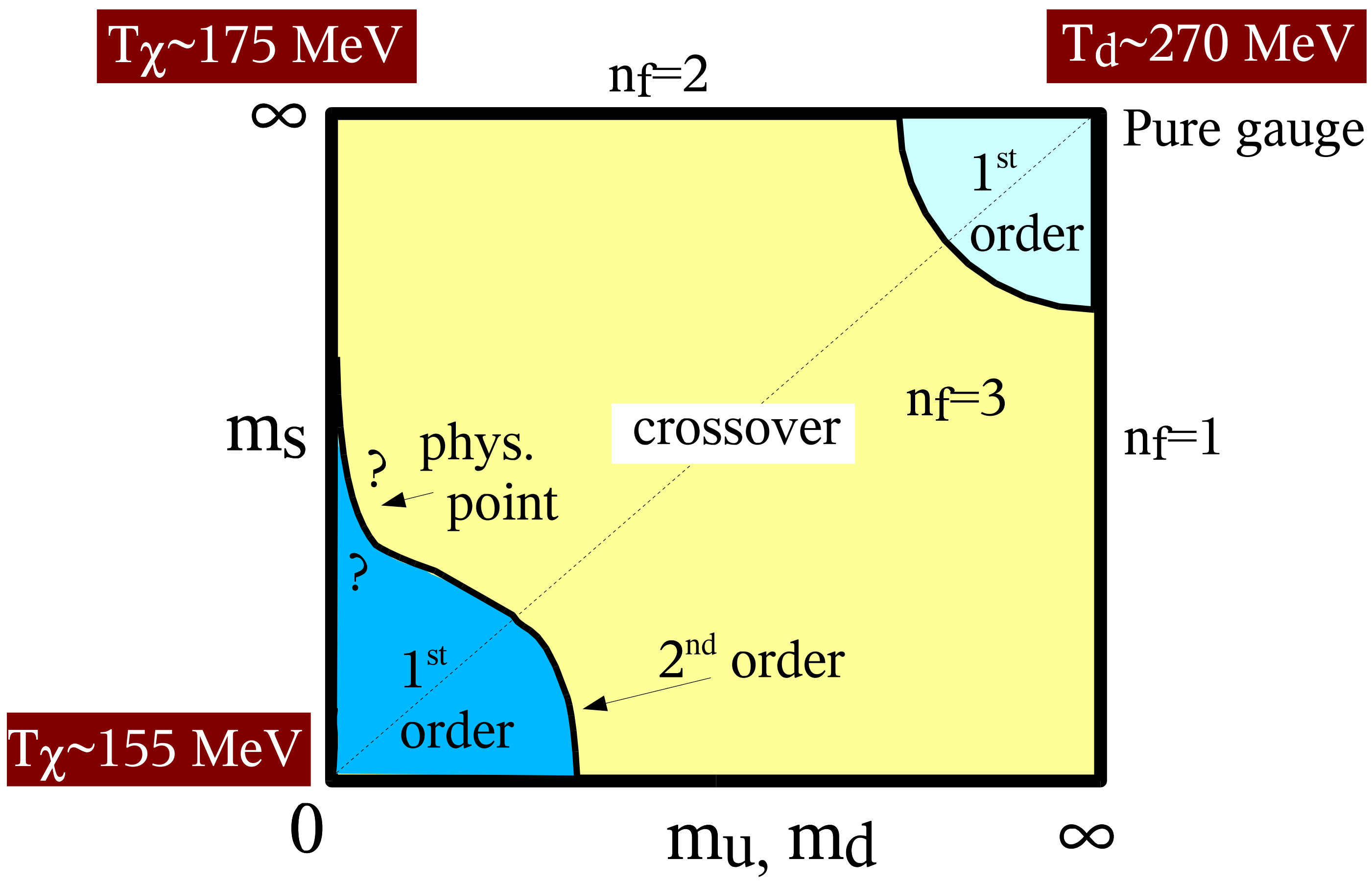
[Karsch, Laermann, Peikert 2001]

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

Influence of the quark masses

Two order parameters

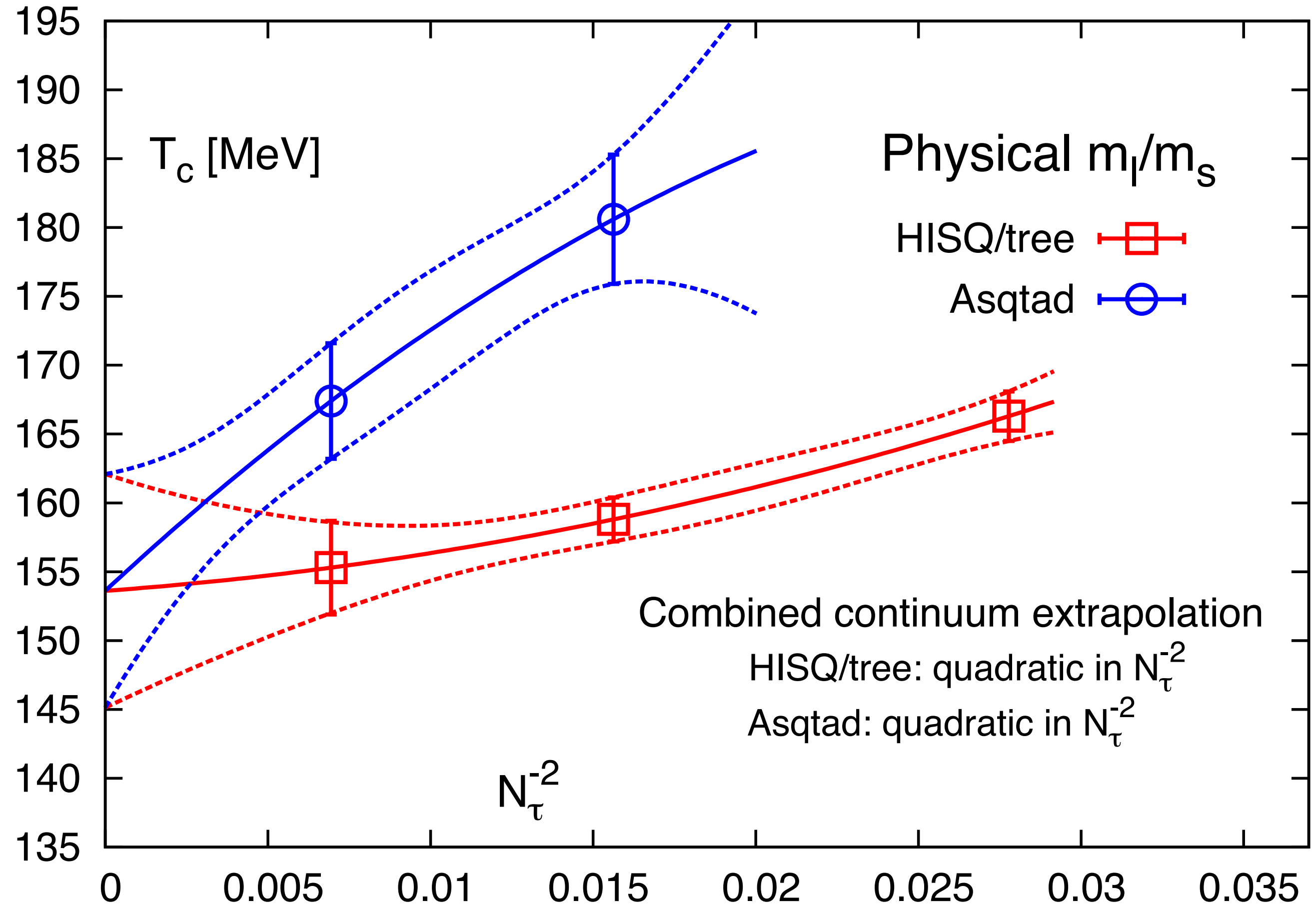
- $m_q = 0 \longrightarrow$ Chiral condensate
- $m_q = \infty \longrightarrow$ Potential



For physical masses, most likely cross-over

The critical temperature

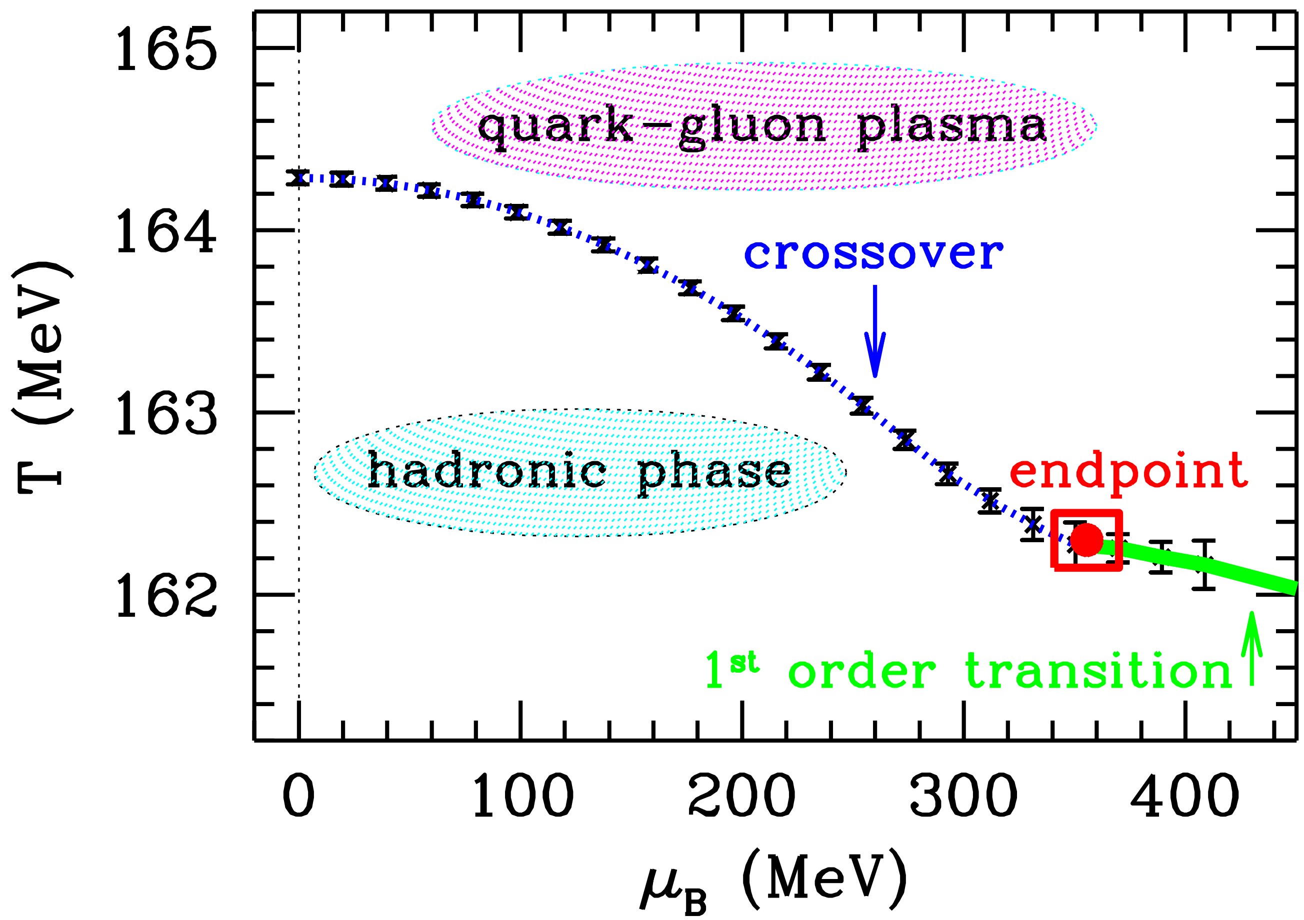
$$T_c = 154 \pm 9\text{MeV}$$



HotQCD Coll. 2012, in agreement with previous results from Wuppertal-Budapest

Finite baryochemical potential

Lattice calculations very challenging at finite μ_B

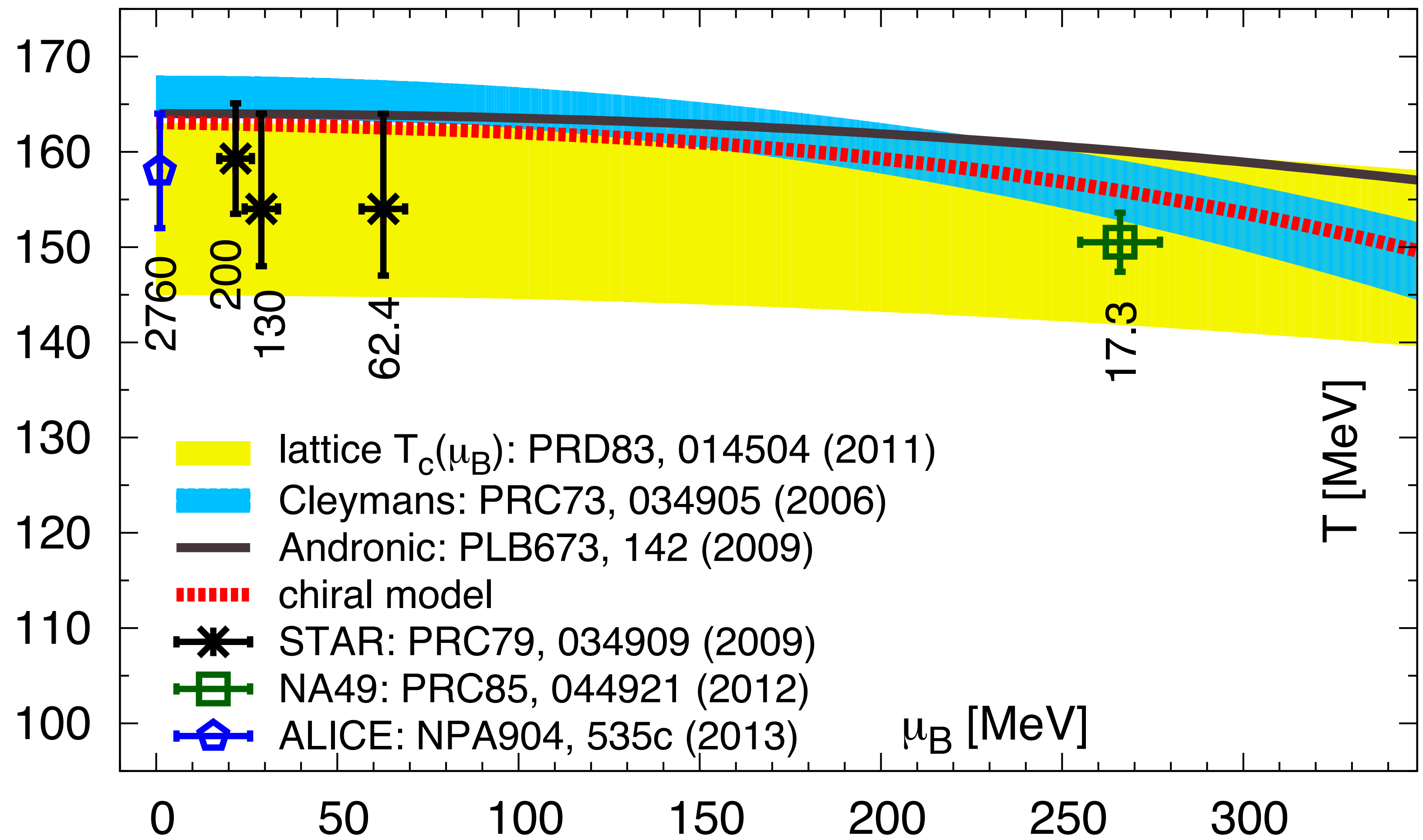


[Fodor et al 2004]

- ⇛ Order of the transition depends on μ_B
- ⇛ Possible critical point at experimental reach
- ⇛ Still a lot of uncertainties exist

Where are the HIC?

Statistical models fit particle abundances and obtain (T, μ_B) at freeze-out



model dependent

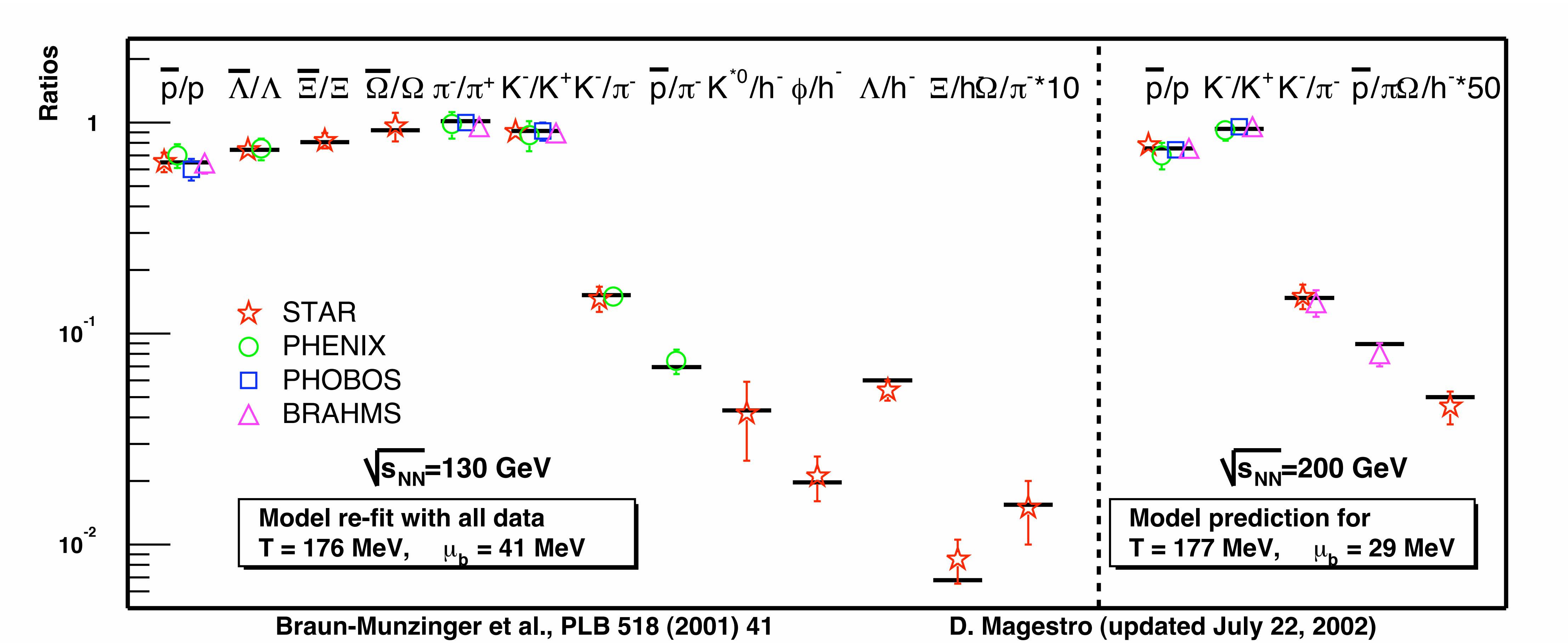
[Rau et al 2013]

Statistical description of particle yields

Assuming an ideal gas of particles, the number densities are

$$n_i = -\frac{T}{V}\frac{\partial \ln Z}{\partial \mu_i} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_i)/T] \pm 1}$$

Only two independent parameters, μ_B and T (+some assumptions)

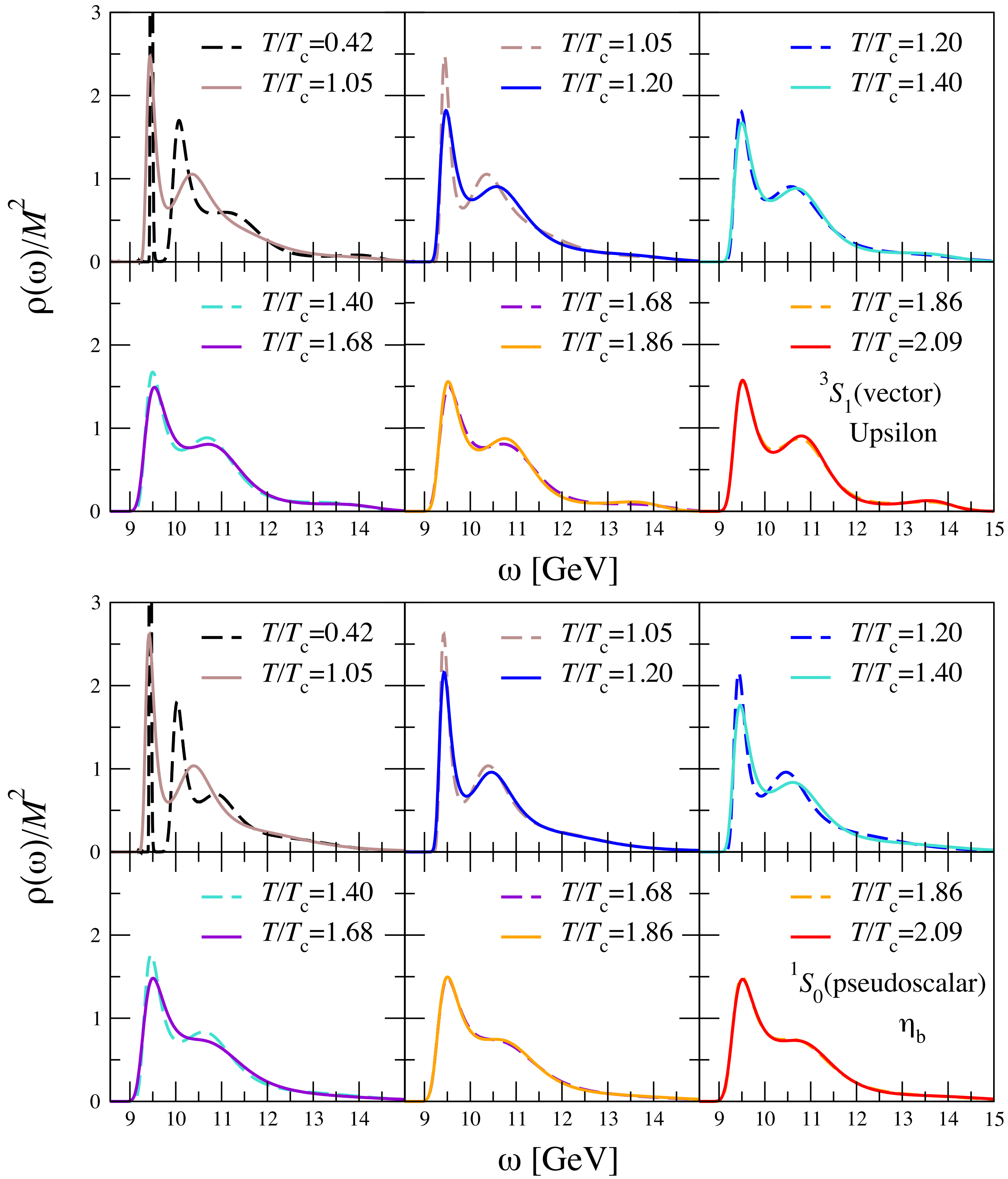


Estimates in the previous slide made with these models

Some extra results and interpretations

Bound states above T_C

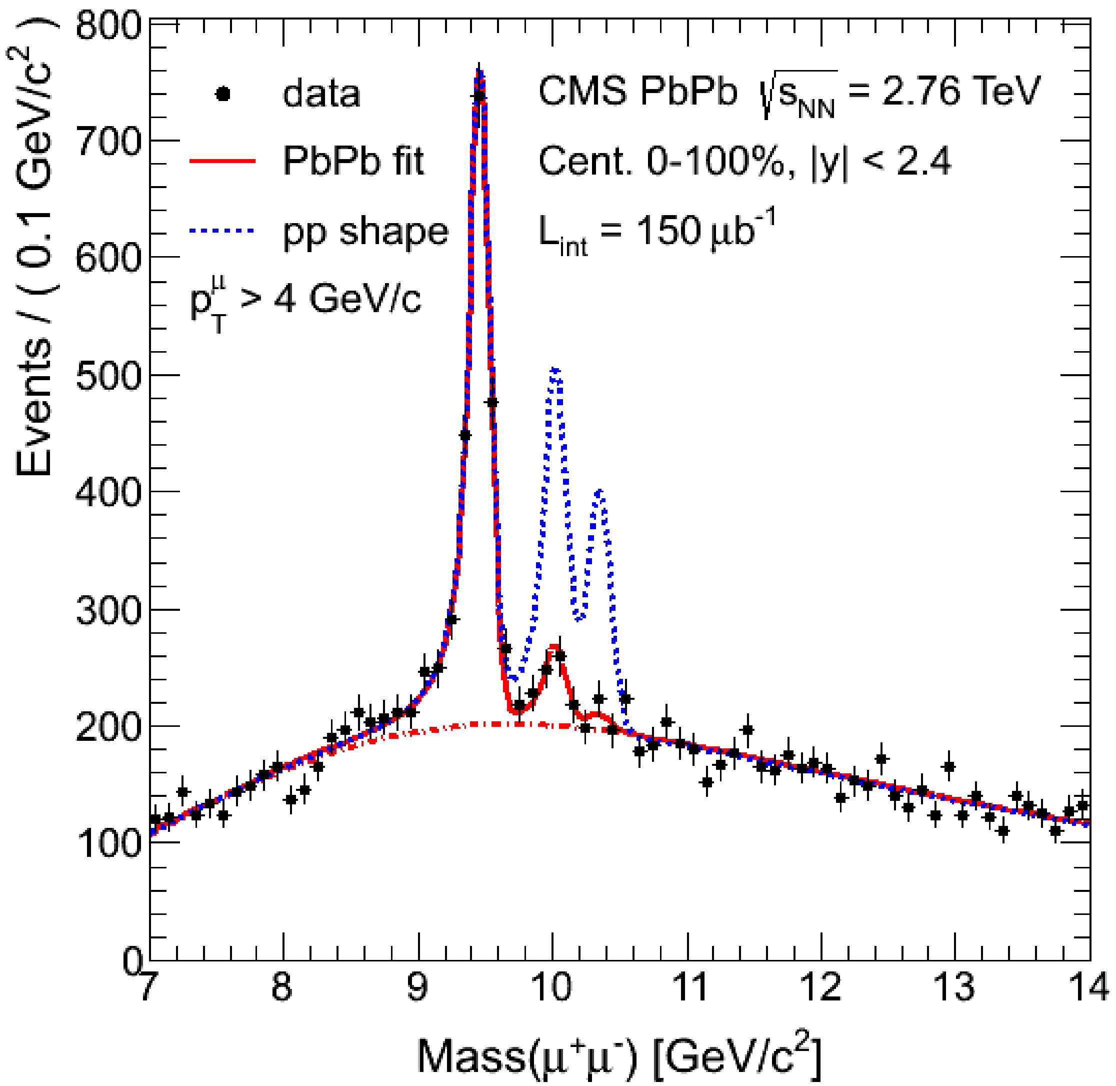
Υ, η_b survive upto $2T_c$

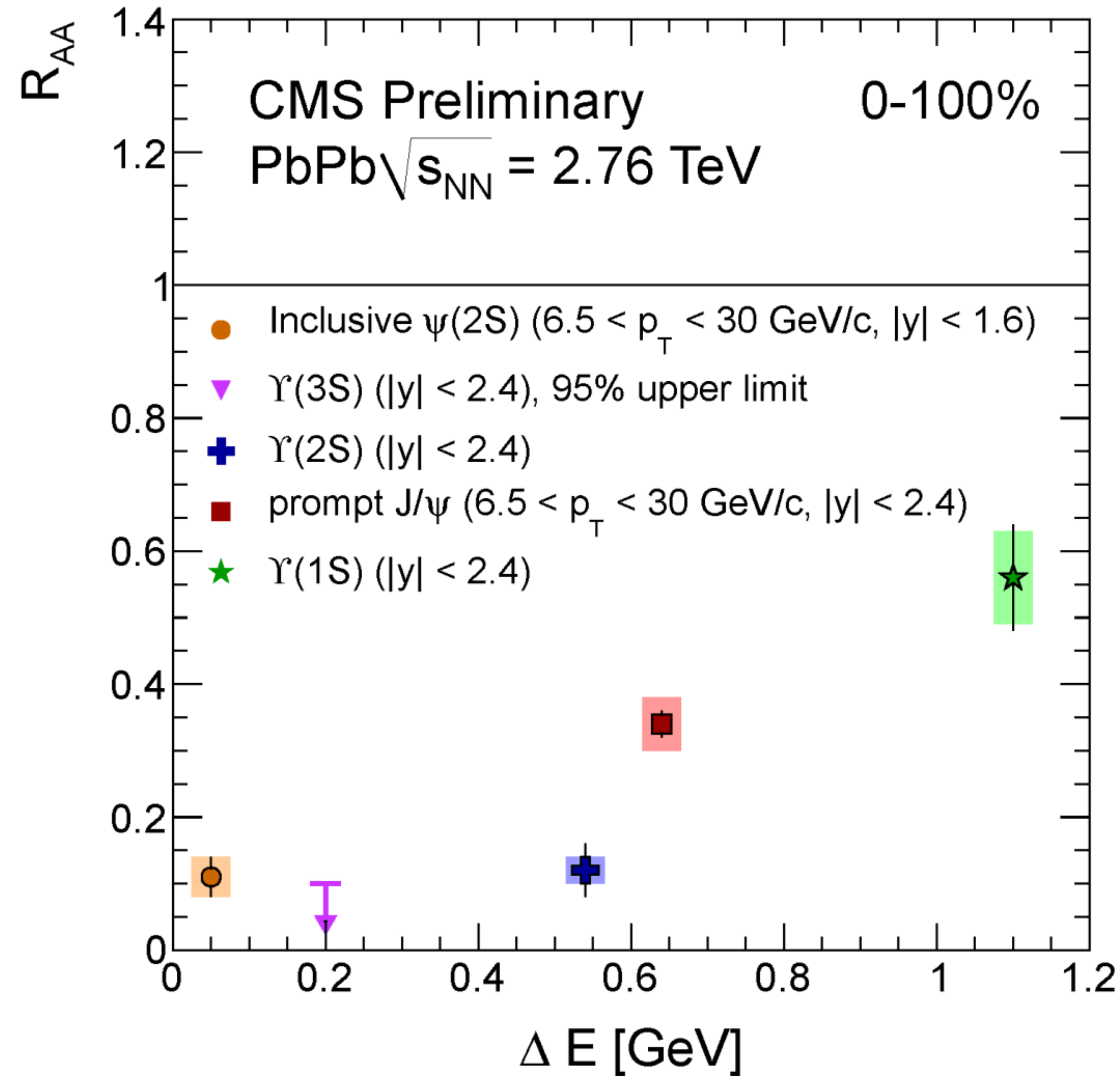


[Aarts et al 2014]

Suppression of quarkonia

[J Velkovska Hard Probes 2013]



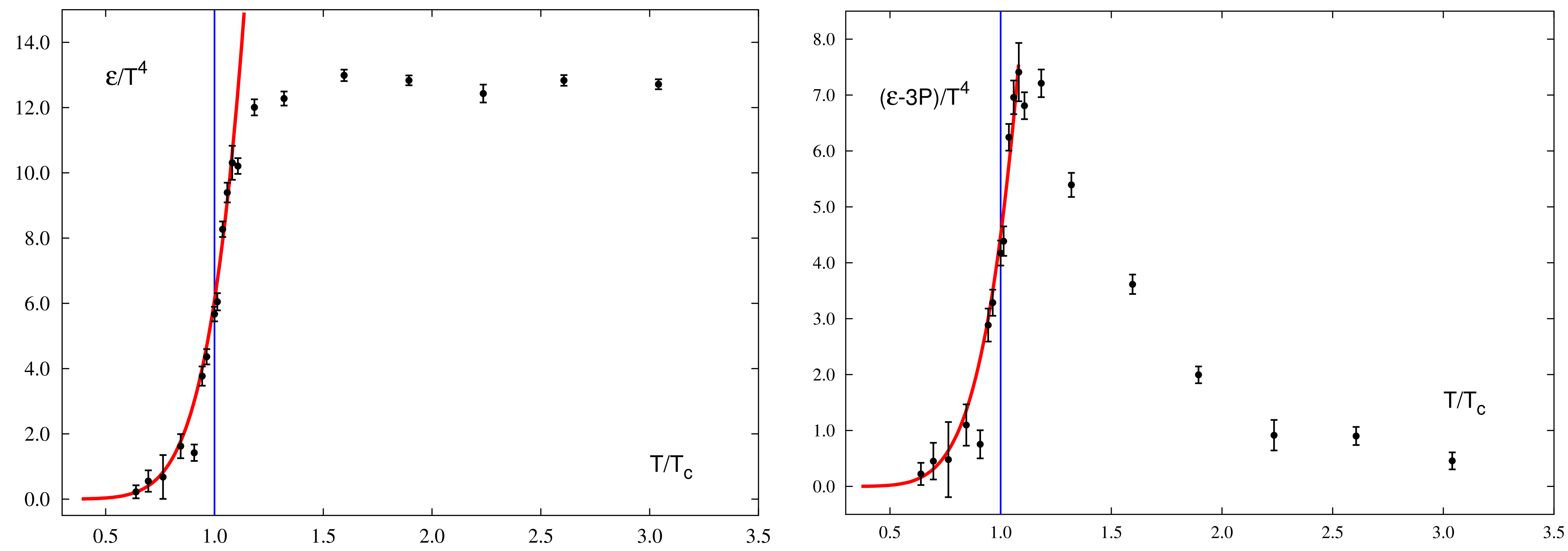


Suppression ordered by binding energy

- **Quarkonia as a termometer**
- **Consistent with suppression of only excited states**

Below T_C

A hadron resonance gas can describe the lattice results

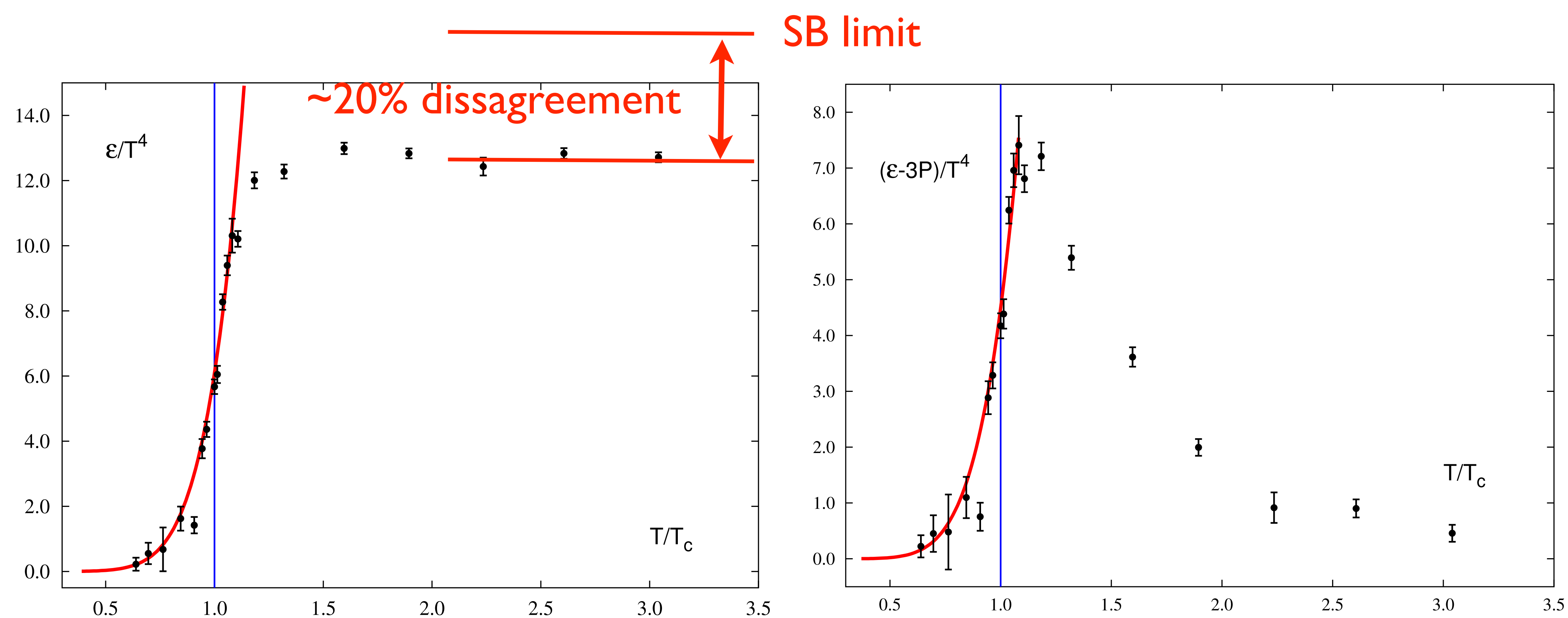


[Karsch, Redlich, Tawfik 2003]

Notice that including more and more particles and resonances in the partition function increases the number of degrees of freedom

Below T_C

A hadron resonance gas can describe the lattice results

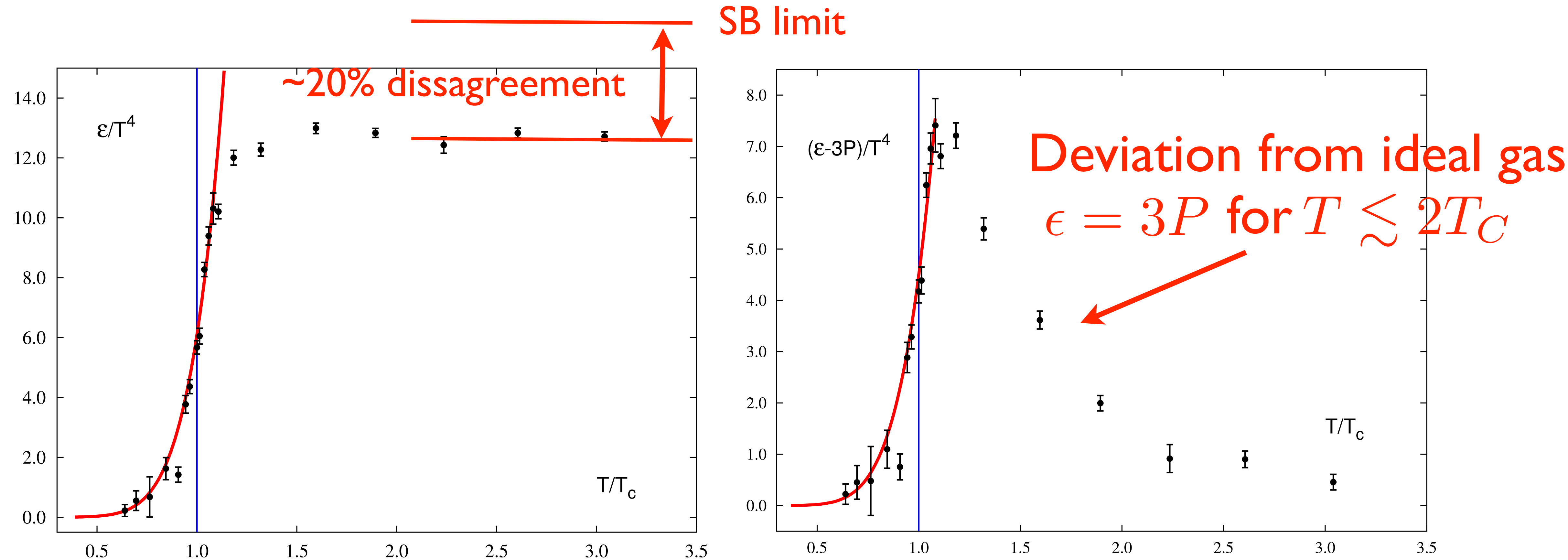


[Karsch, Redlich, Tawfik 2003]

Notice that including more and more particles and resonances in the partition function increases the number of degrees of freedom

Below T_C

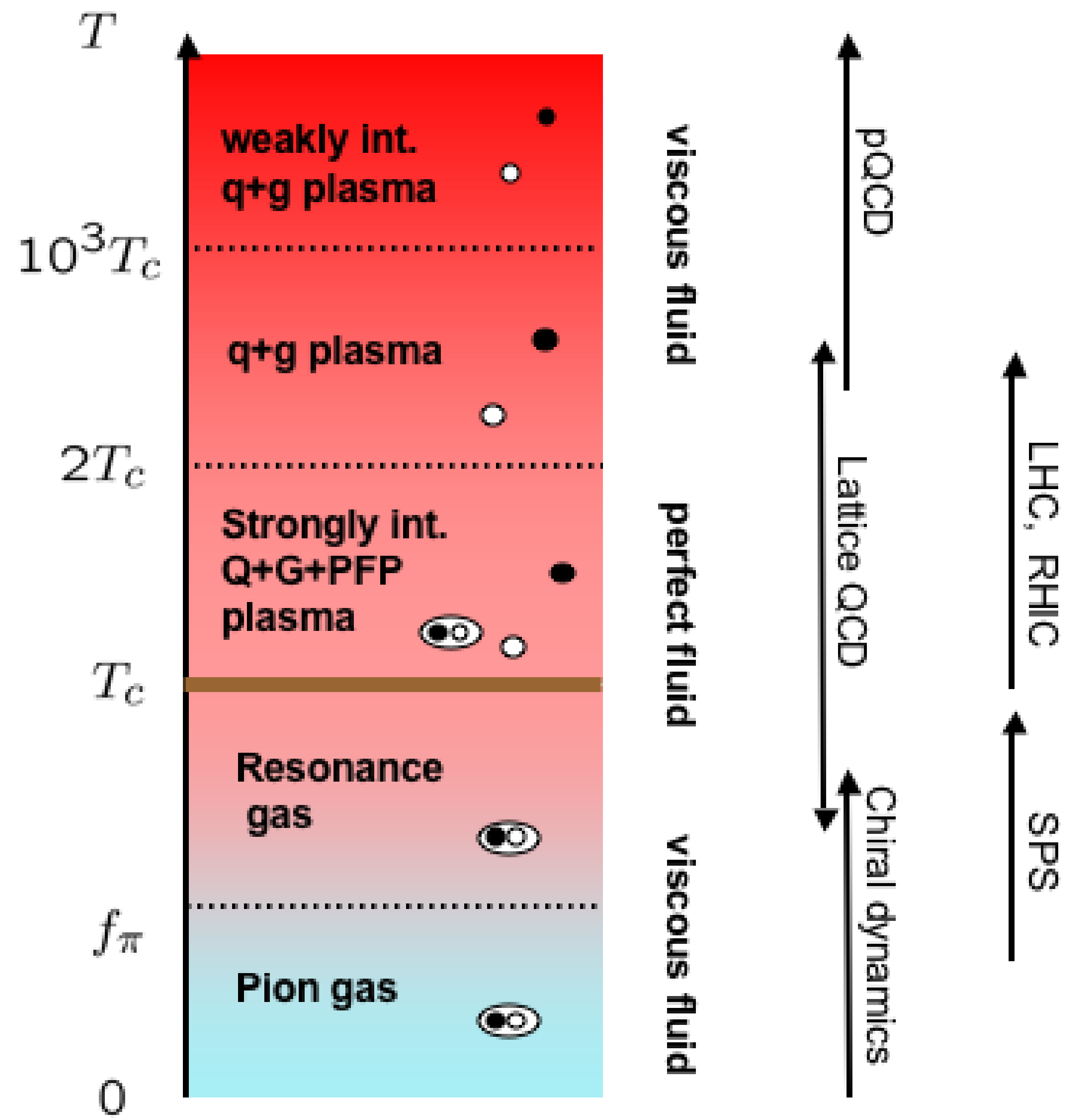
A hadron resonance gas can describe the lattice results



[Karsch, Redlich, Tawfik 2003]

Notice that including more and more particles and resonances in the partition function increases the number of degrees of freedom

A possible picture of hot QCD



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

Summary I

⇛ QCD vacuum:
Confinement & chiral symmetry breaking

⇛ Other states of matter possible?

⇛ Theory $\longrightarrow$ Different phases exist!

(for small μ_B)
Lattice + perturbative + models

⇛ Transition hadron gas $\leftrightarrow$ quark gluon plasma.

⇛ Order of the transition depends on quarks masses. For realistic masses, most probably crossover at $\mu_B = 0$.

⇛ Properties close to T_c different from a gas: Strongly coupled QGP? Indications of bound states above T_c

⇛ Heavy ion collisions experiments attempt to study this region.