Overview of hot and dense QCD matter

Strongly Interacting Matter
under Extreme Conditions

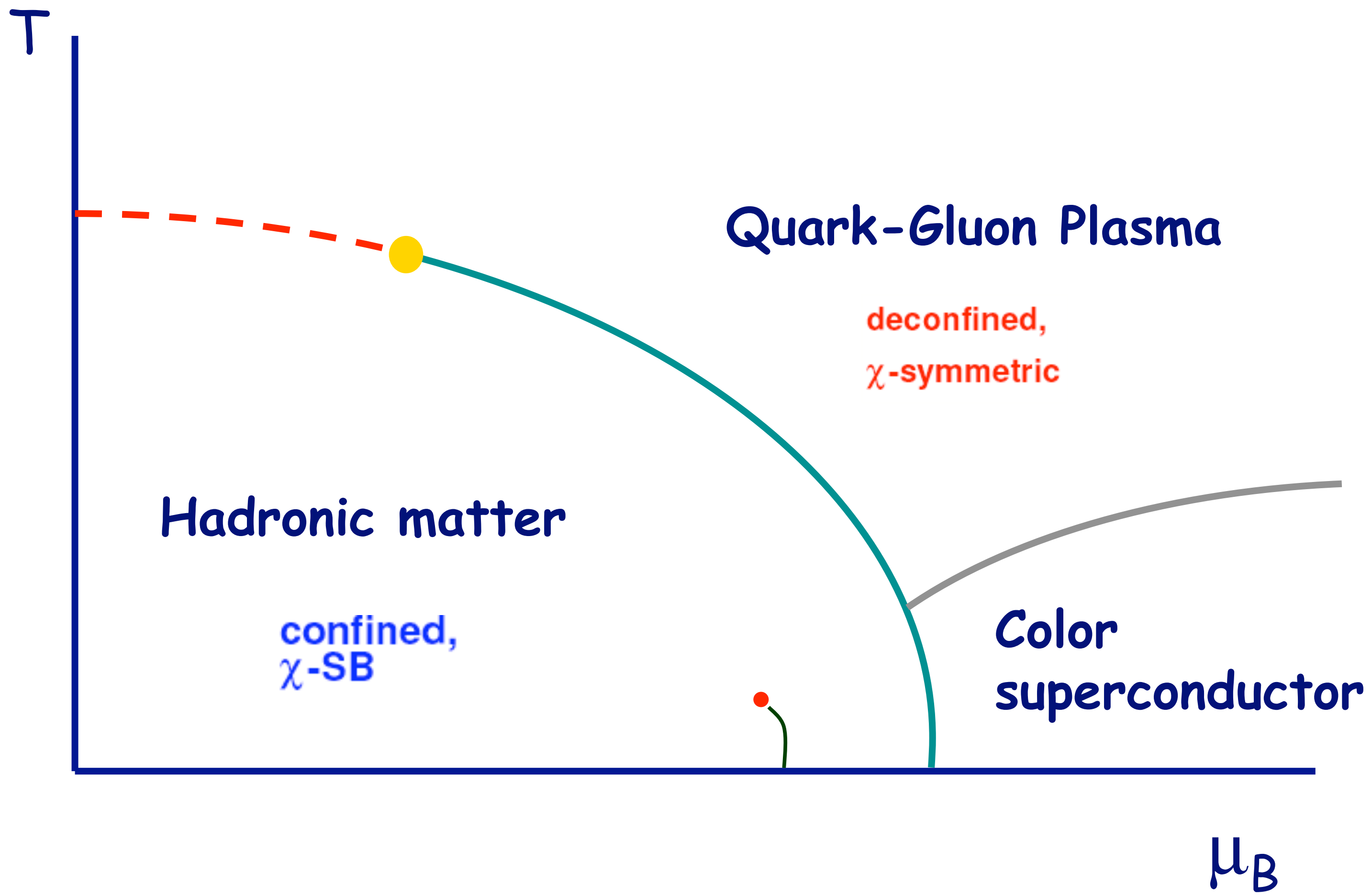
Hirschegg

January 18, 2010

Jean-Paul Blaizot, IPhT- Saclay

The QCD phase diagram

(« low resolution »)



The ideal baryonless Quark-Gluon Plasma

Asymptotic freedom

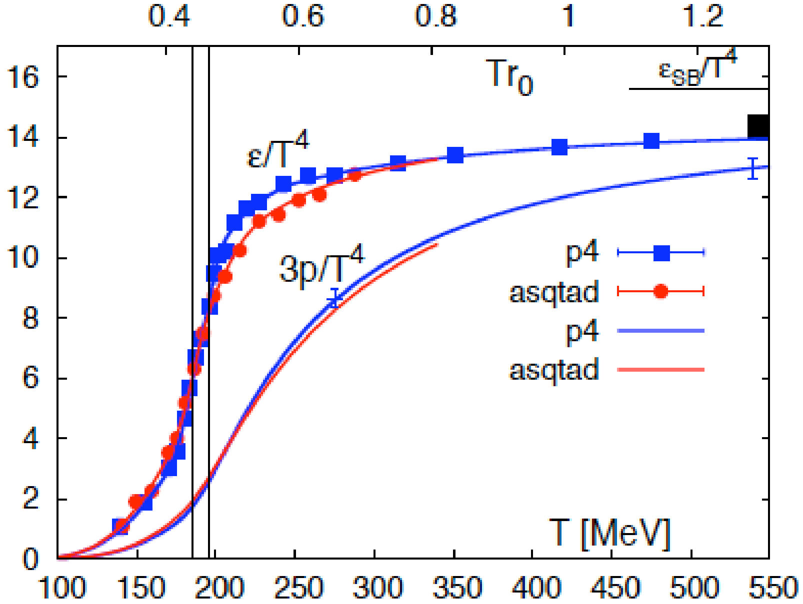
$$\alpha_s = \frac{g^2}{4\pi} \approx \frac{2\pi}{b_0 \ln\left(\mu / \Lambda_{QCD}\right)} \qquad \left(\mu \approx 2\pi T\right)$$

Matter is « simple » at high temperature:

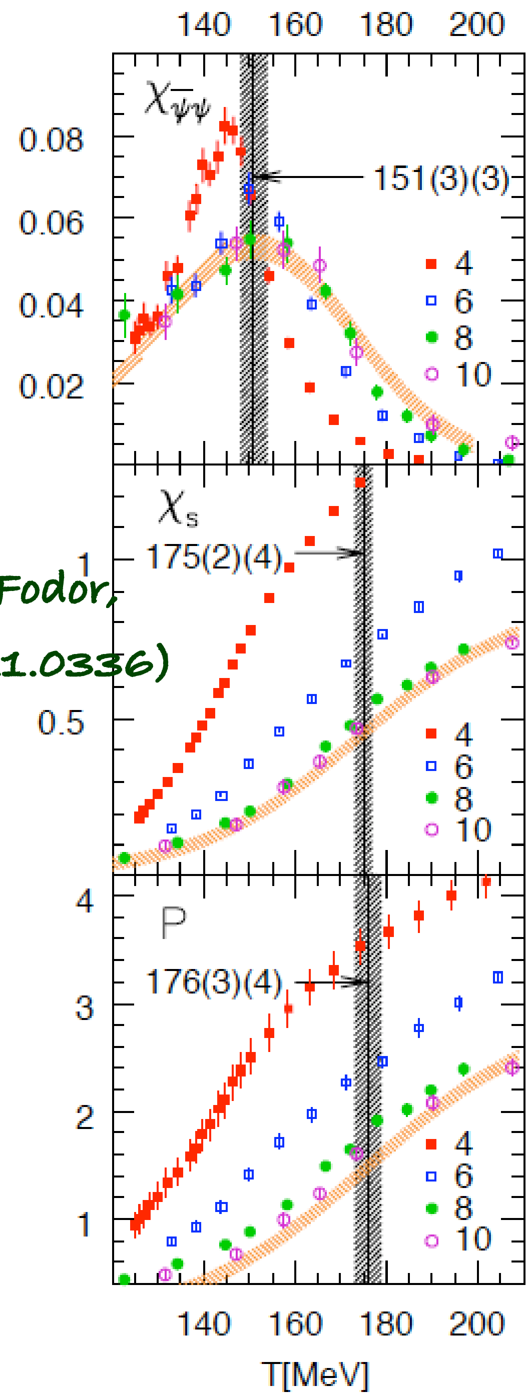
- an ideal gas of quarks and gluons
- the dominant effect of interactions is to turn (massless) quarks and gluons into weakly interacting (massive) quasiparticles.

Phase transition(s)

(crossover)

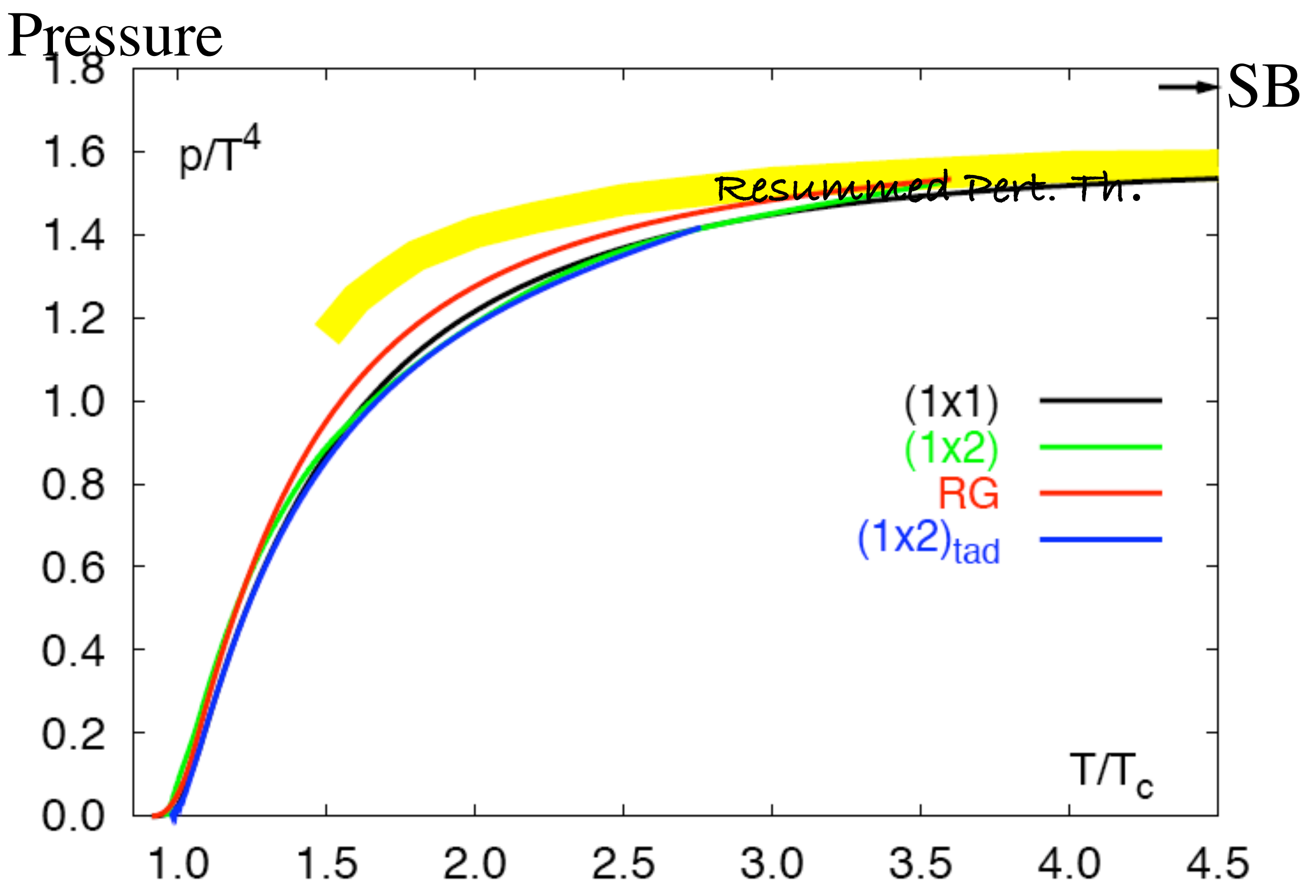


(from M. Bazavov et al, arXiv:0903.4379)



(from Z. Fodor, arXiv:0711.0336)

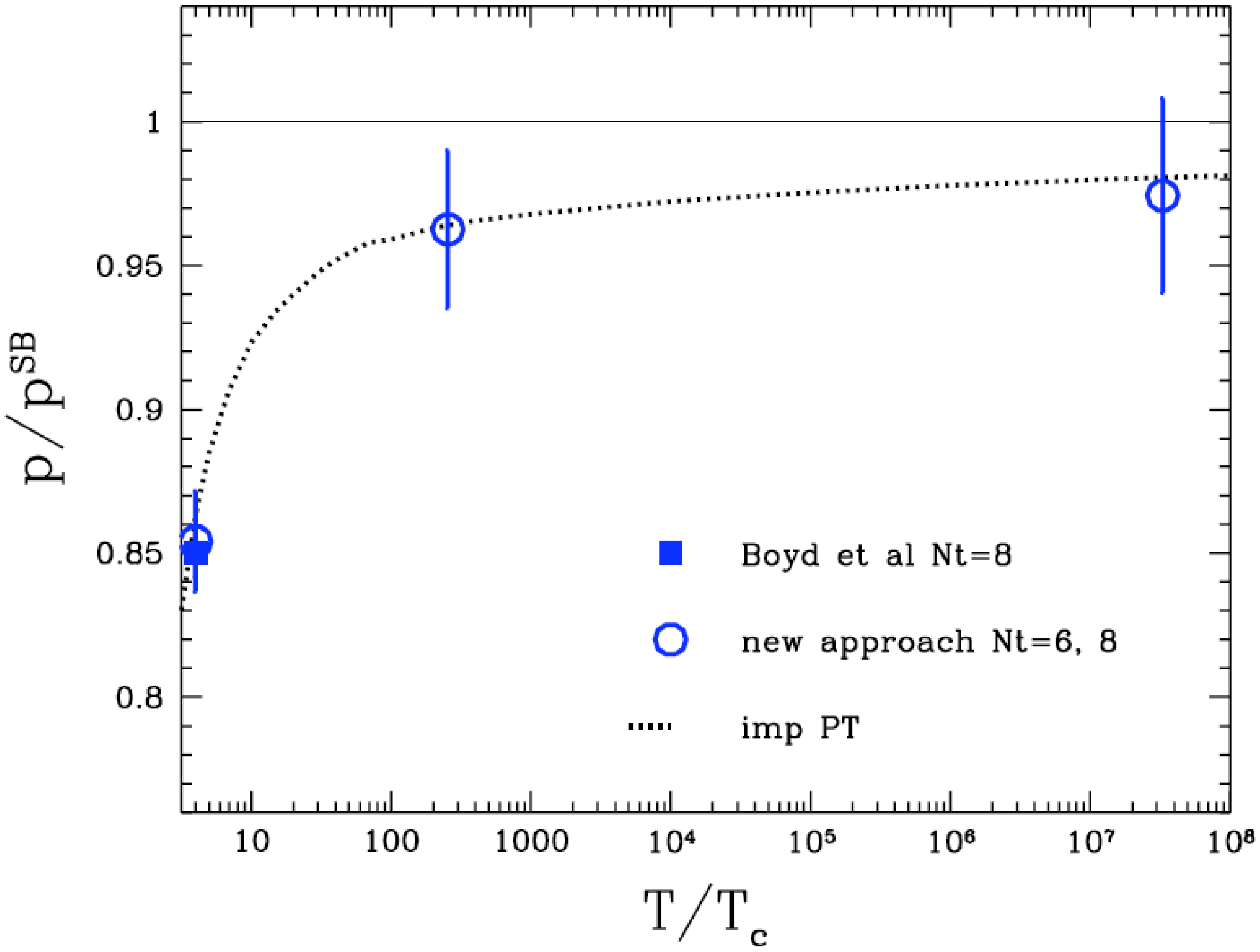
At T>3Tc Resummed Pert. Theory accounts for lattice results



(SU(3) lattice gauge calculation from Karsch et al, hep-lat/0106019)

(resummed pert. th. from J.-P. B., E. Iancu, A. Rebhan: Nucl.Phys.A698:404-407,2002)

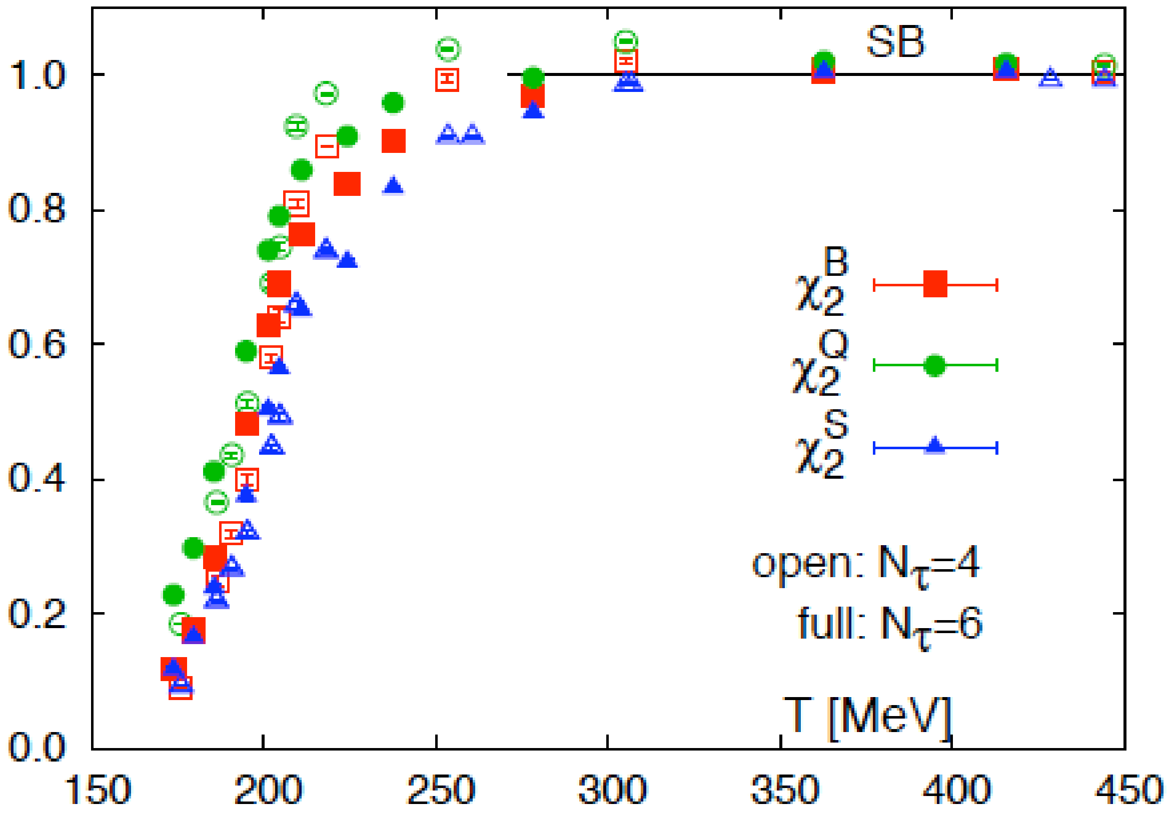
Pressure for SU(3) YM theory at (very) high temperature



(from G. Endrodi et al, arXiv: 0710.4197)

Conserved charge susceptibilities

$$\chi_C \sim < C^2 > \qquad C = B, Q, S$$

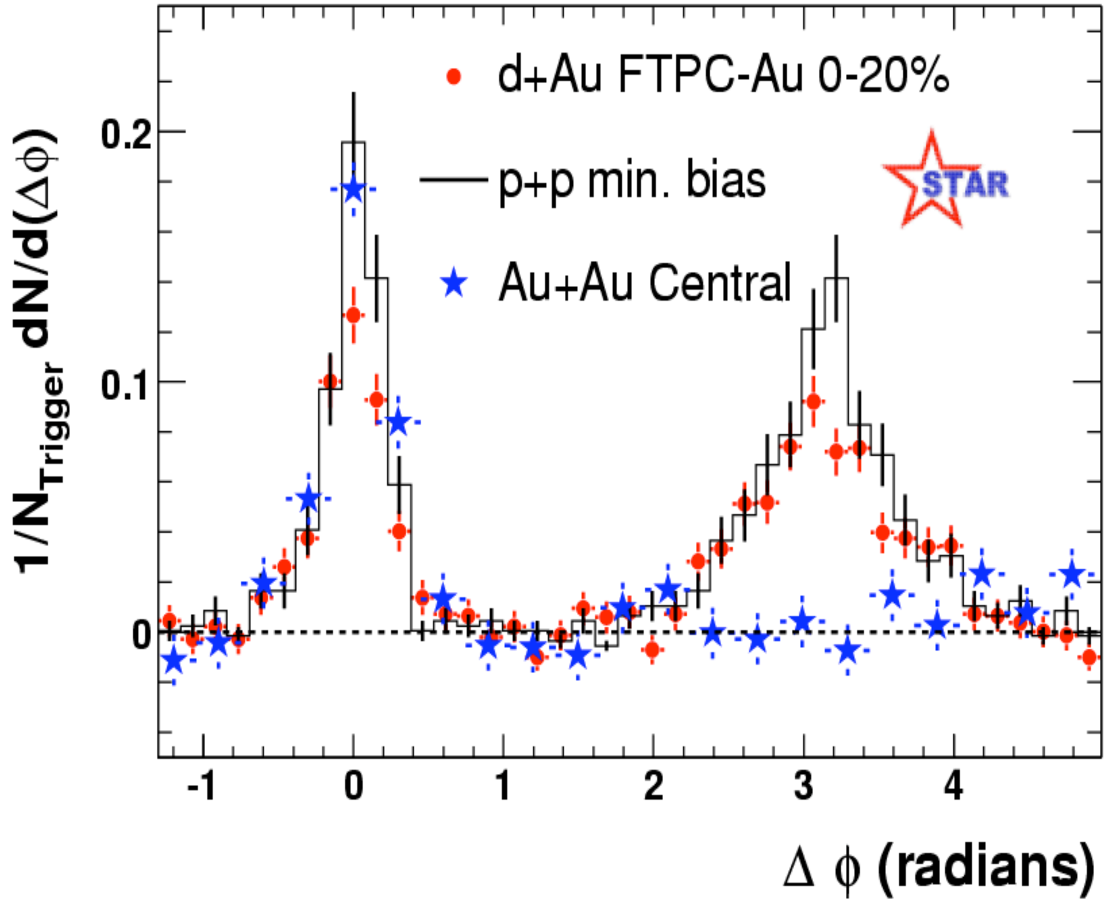


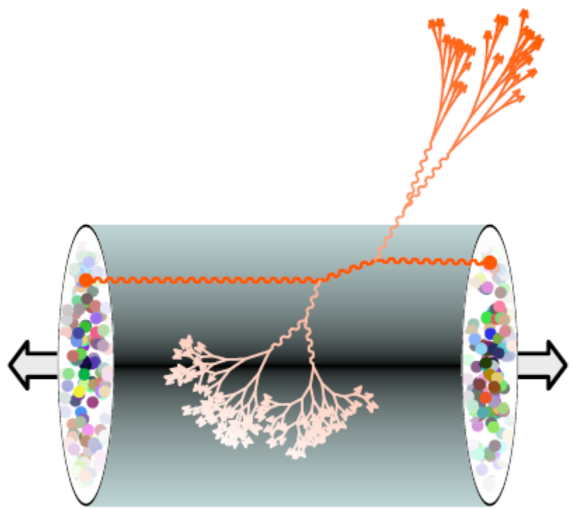
(from M. Cheng et al, arXiv: 0811.1006)

From the
« ideal gas »
to the
« perfect liquid »

Lessons from RHIC

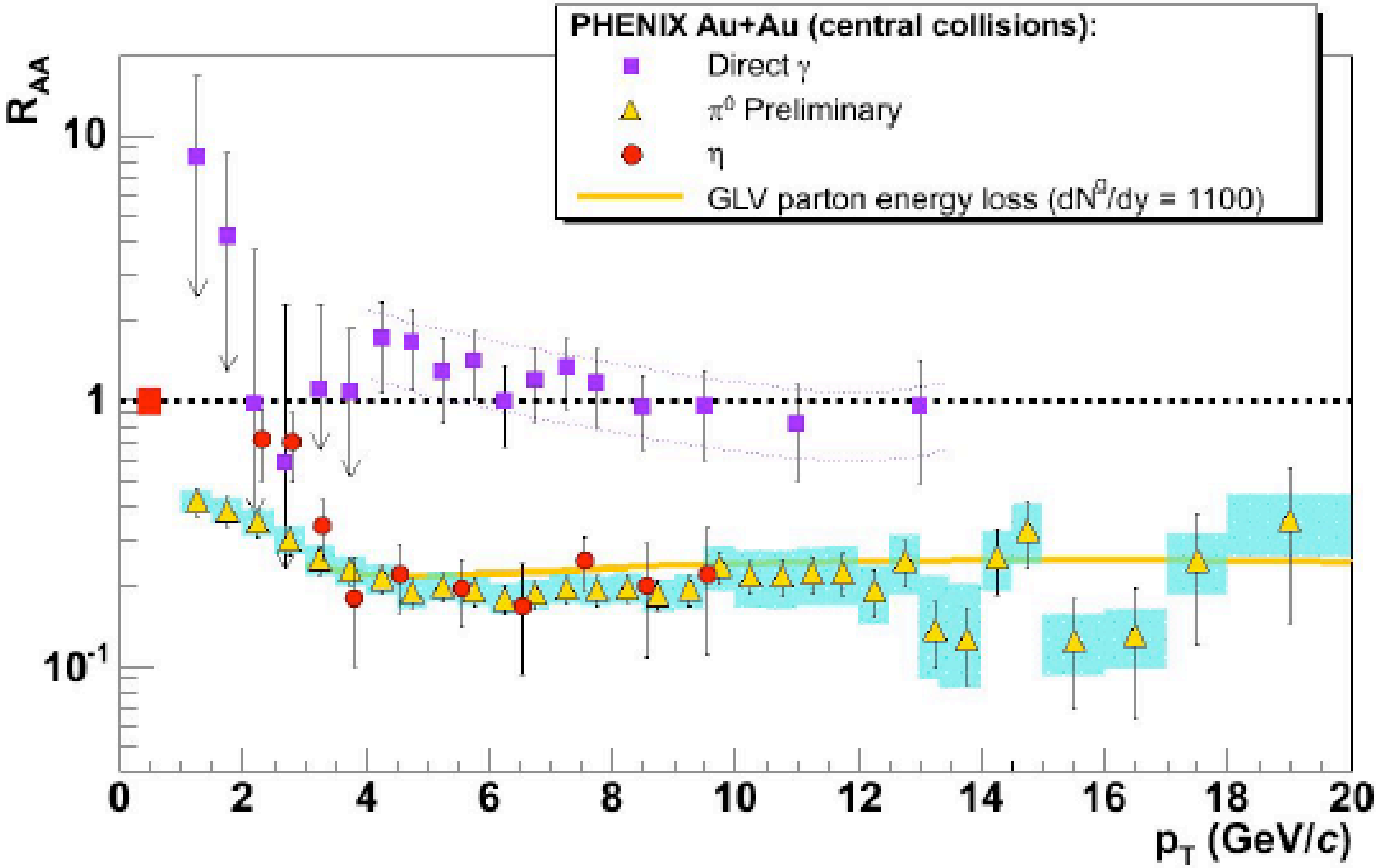
Matter is opaque to the propagation of jets



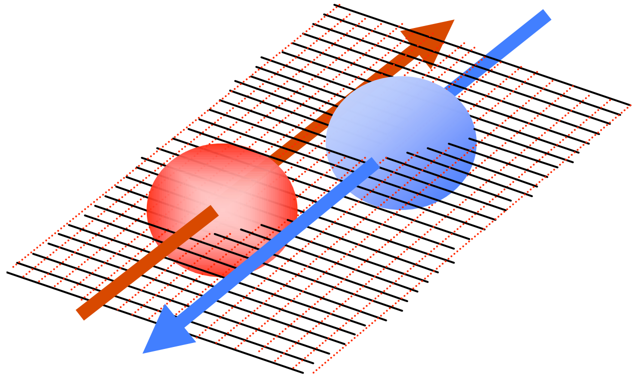


(STAR: Phys.Rev.Lett.91:072304,2003)

$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$

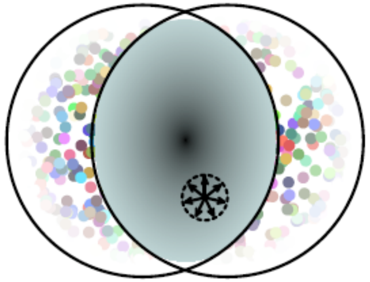


(from Akiba et al, NPA 774 (2006) 403)

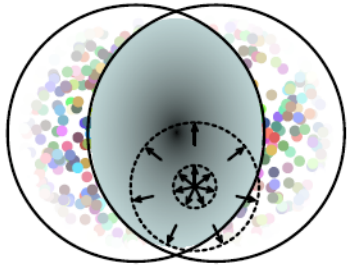


Matter flows like a fluid

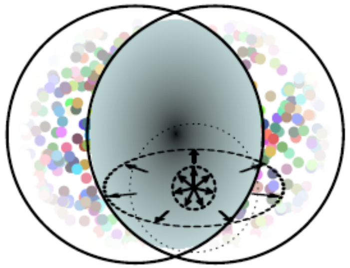
Initial momentum
distribution isotropic



Without interactions, the particles
would escape isotropically, irrespective
of the shape of the interaction zone

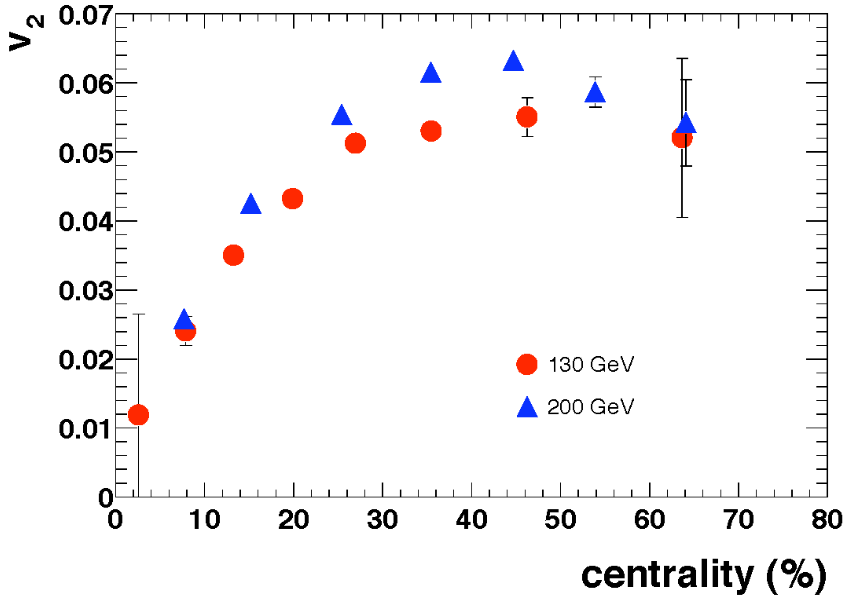


Strong interactions induce pressure gradients.
The expansion becomes anisotropic, and
the momentum distribution reflects the anisotropy
of the initial interaction region

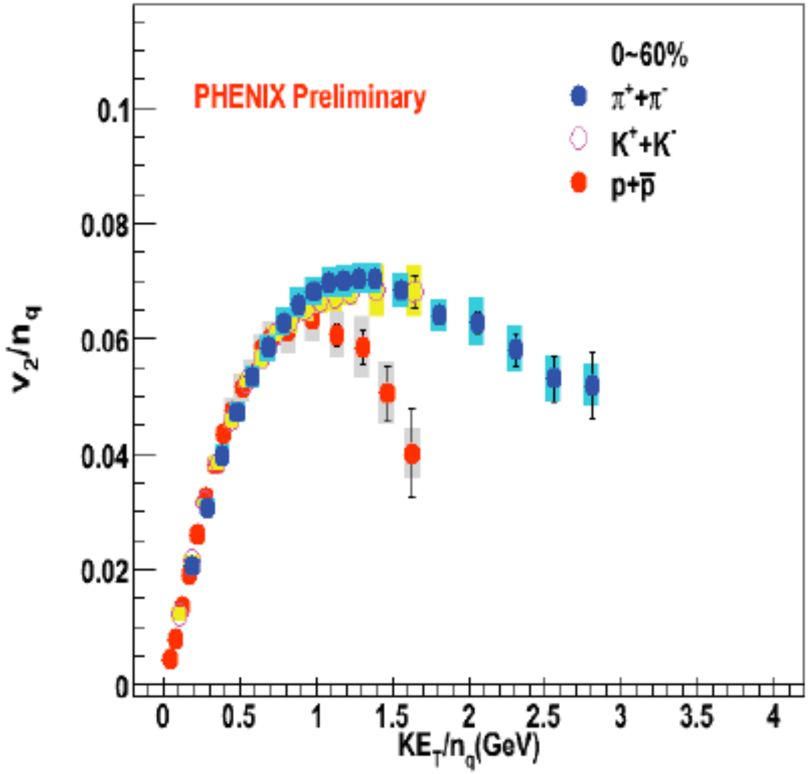


Elliptic flow

$$v_2 = \langle \cos(2\phi) \rangle$$

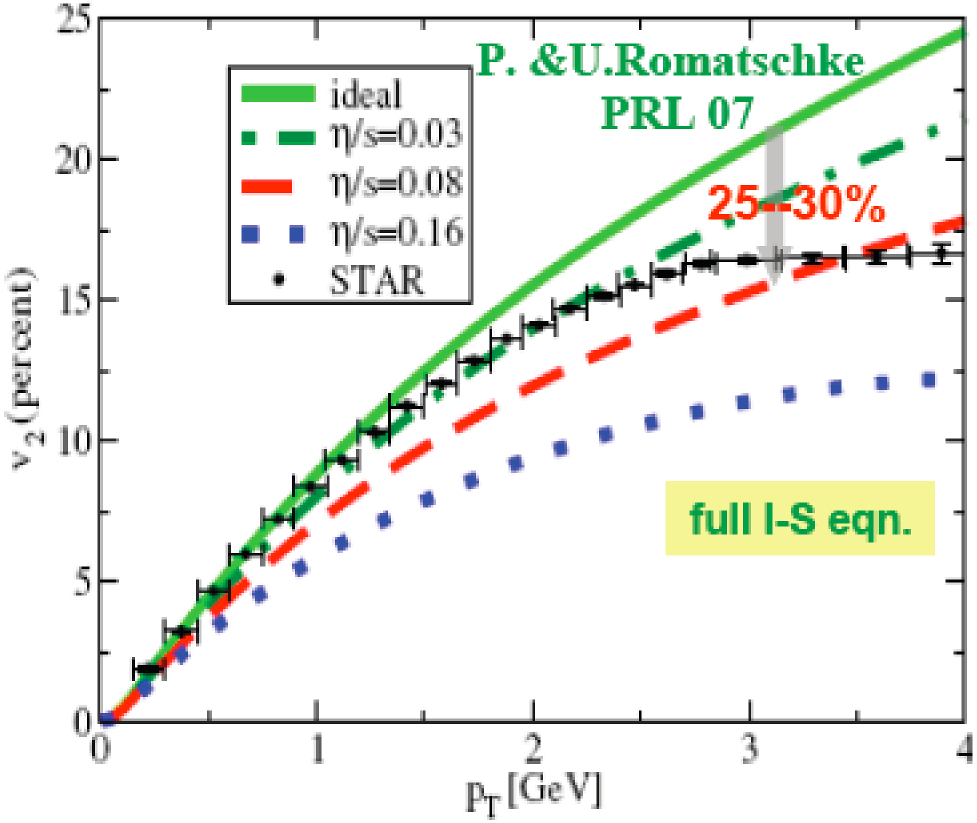


(Quark-Matter 02)



(Quark Matter 09)

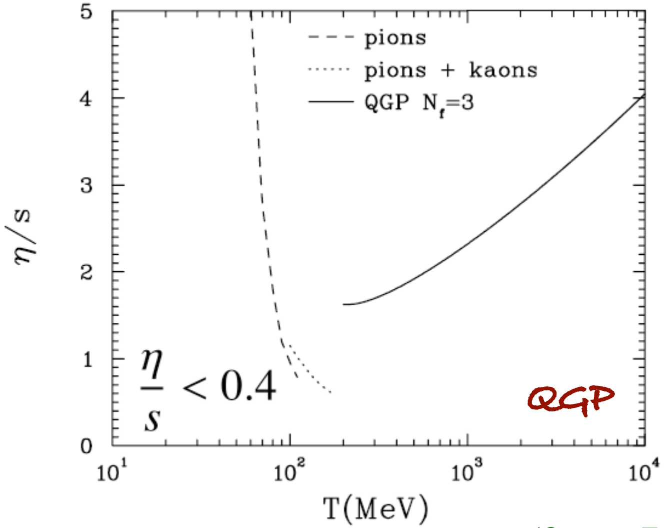
The low viscosity of the quark-gluon plasma

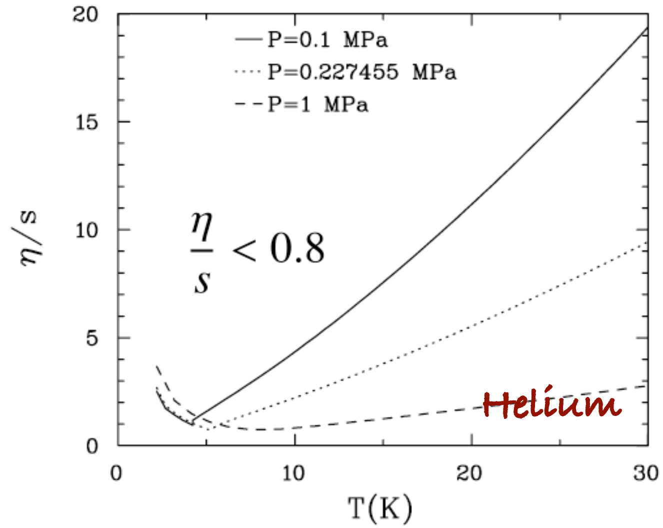


$$\frac{\eta}{s} < 5 \times \frac{1}{4\pi}$$

(M. Luzum and P. Romatschke, arXiv: 0804.4015)

Low viscosity, phase transition and strong coupling

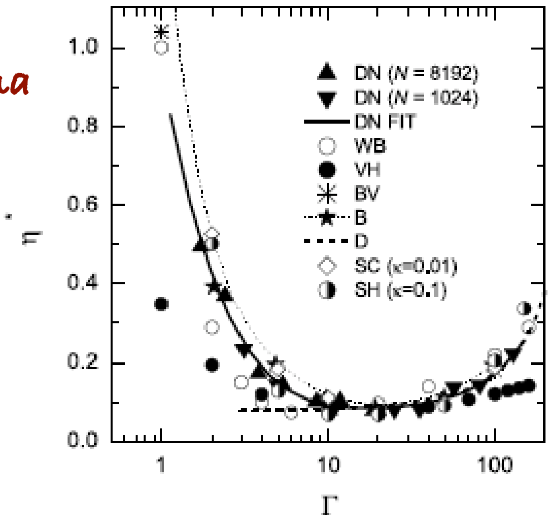




(from L. Csernai et al, nucl-th/0604032)

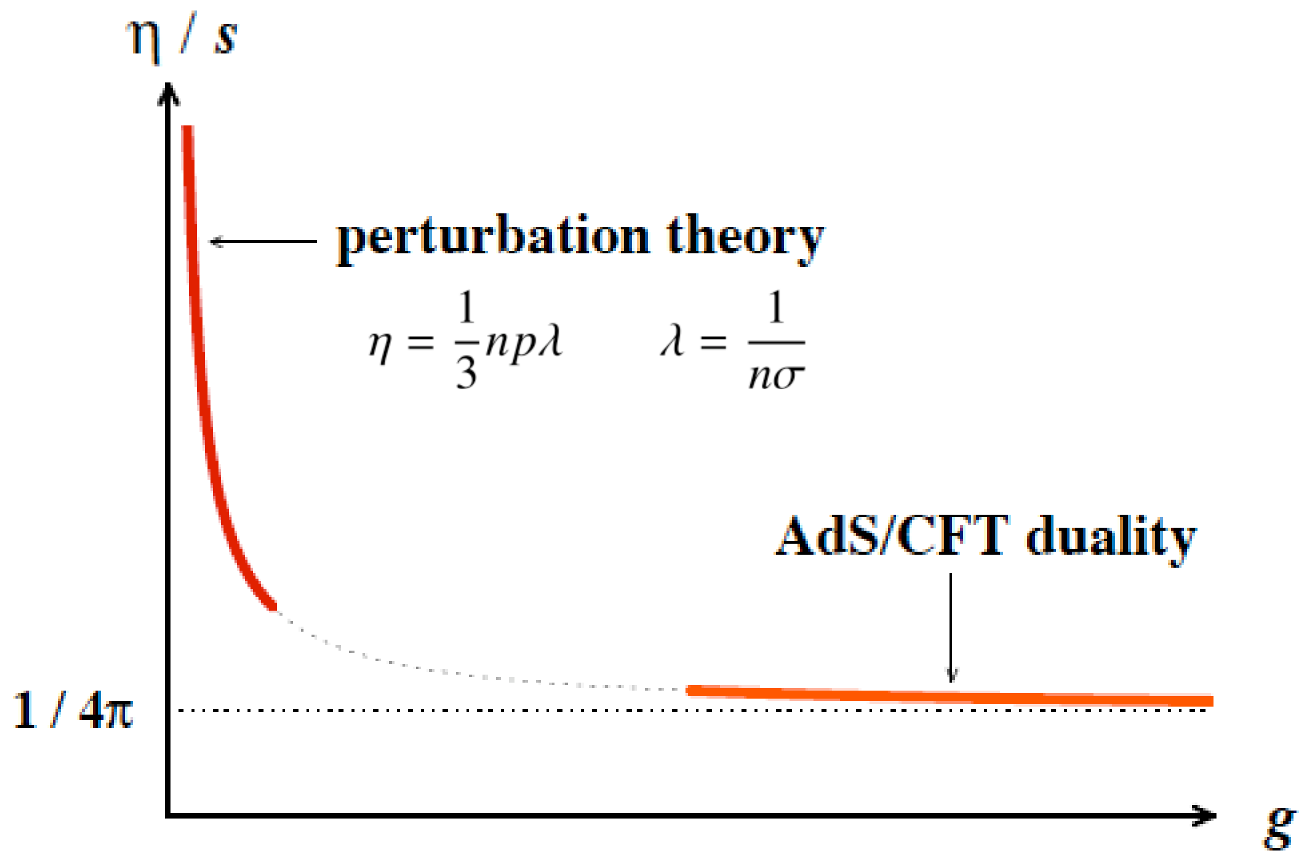
Strongly correlated plasma

(from Z. Donko et al, arXiv: 0710.5229)



Also, cold fermionic gas at unitarity $\frac{\eta}{s} \sim 0.5$

Viscosity at weak and strong coupling



The Ideal strongly coupled Quark-Gluon Plasma

A new 'reference' system

A theoretical breakthrough
AdS/CFT Duality

New techniques (borrowed from string theory) allow calculations in (some) strongly coupled gauge theories .

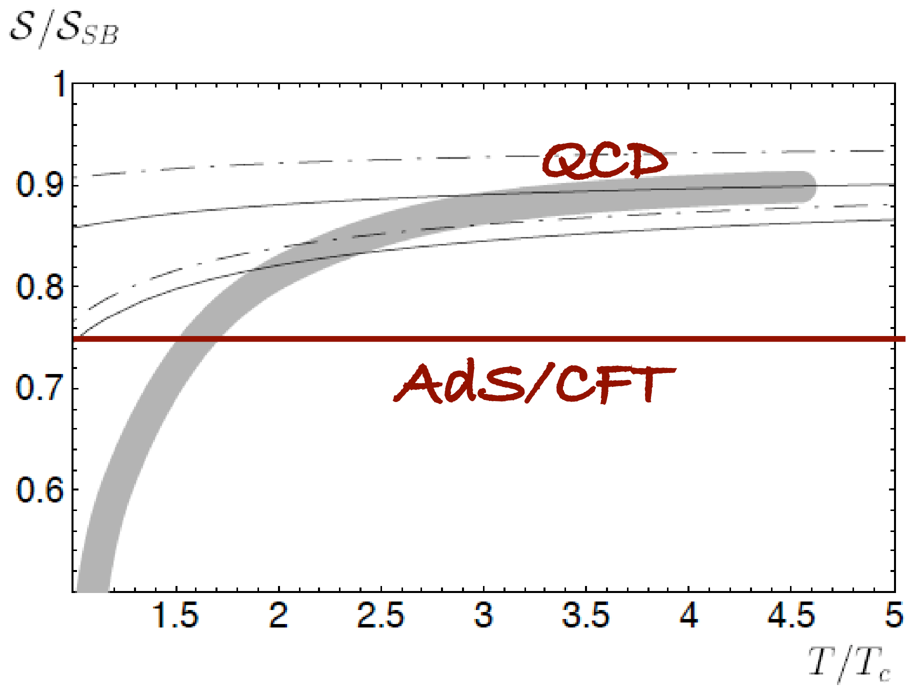
Rely on a mapping between a strongly coupled gauge theory and a weakly coupled (i.e. classical) gravity theory.

New reference state: the strongly coupled quark-gluon plasma (instead of the weakly coupled one).
New ideal system, allowing for many explicit calculations.

Some strong coupling results

Simple limit of the entropy density at strong coupling

$$\frac{S}{S_0} = \frac{3}{4} + \frac{45}{32}\varsigma(3)\frac{1}{\lambda^{3/2}} \qquad \left(\lambda \equiv g^2 N_c\right)$$



Simple result for the viscosity

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

(G. Policastro et al, PRL87 (2001))

A puzzling situation

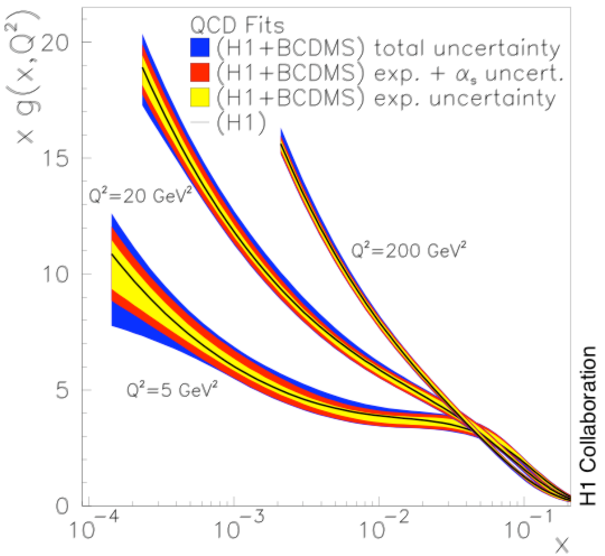
Weakly or strongly coupled ?

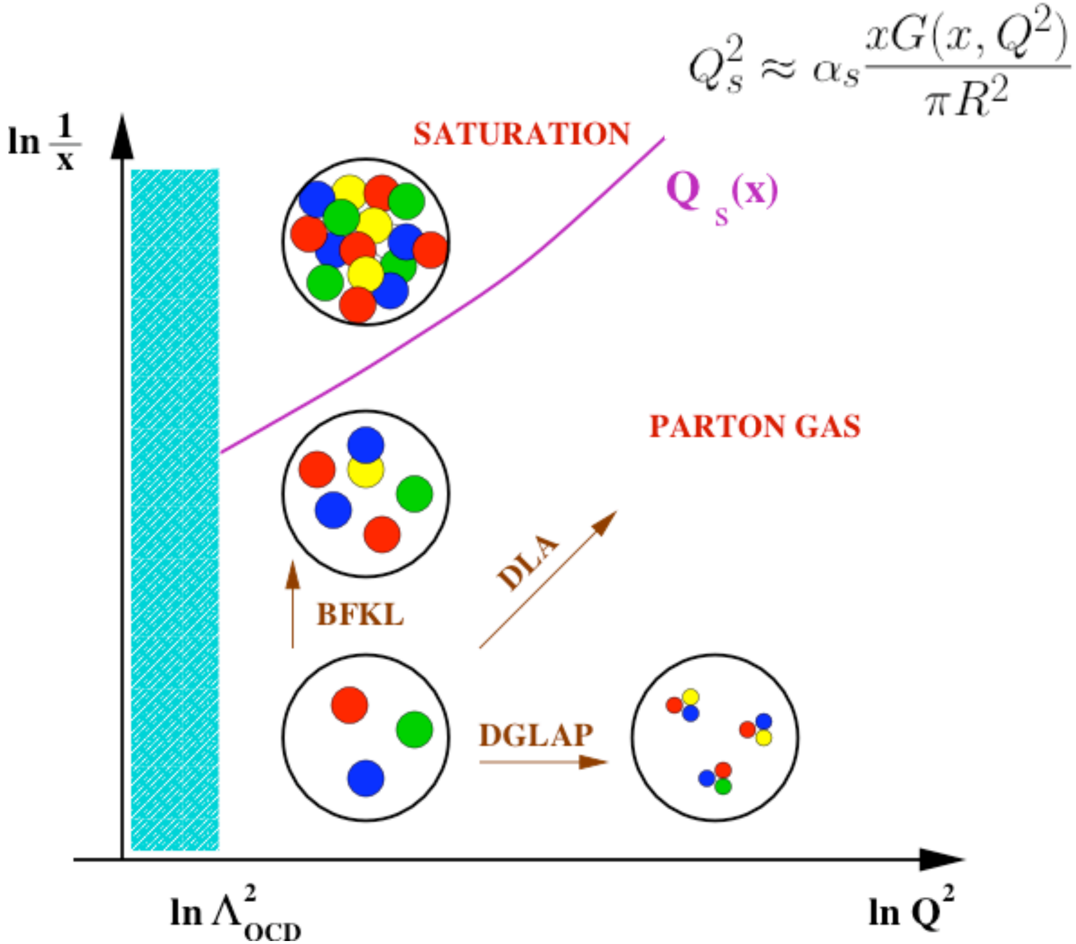
Weakly AND strongly coupled ...

In the qgp coexist degrees of freedom with different wavelengths. Whether these degrees of freedom are weakly or strongly coupled depends on their wavelength.

Non perturbative features arise from the cooperation of many degrees of freedom, or strong classical fields. An example: the color glass condensate.

High density partonic systems





Large occupation numbers

$$n \sim \frac{xG(x,Q^2)}{\pi R^2}$$

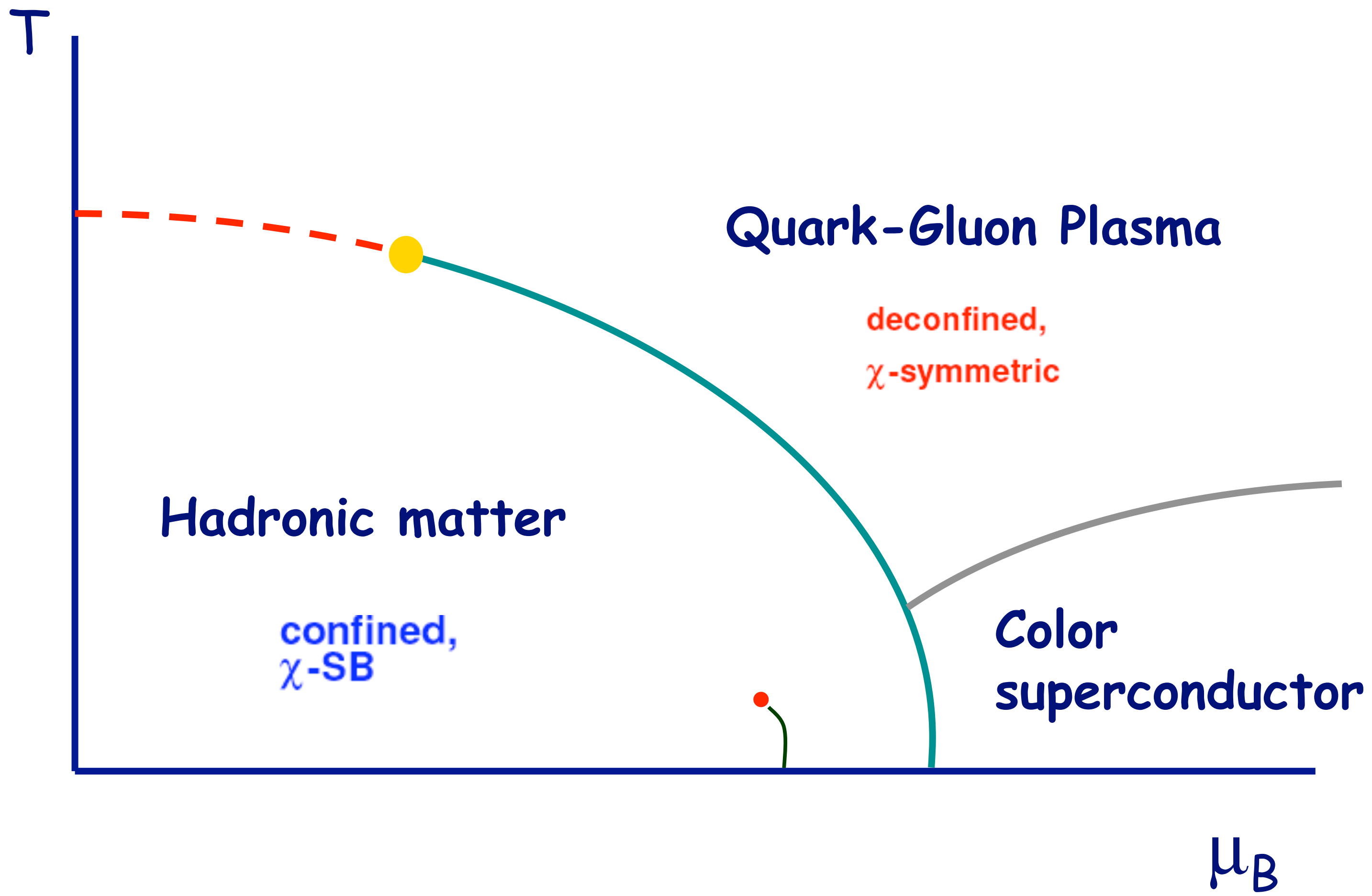
$$\frac{\pi}{Q_s^2} n \sim \frac{\pi}{\alpha_s}$$

=> classical fields

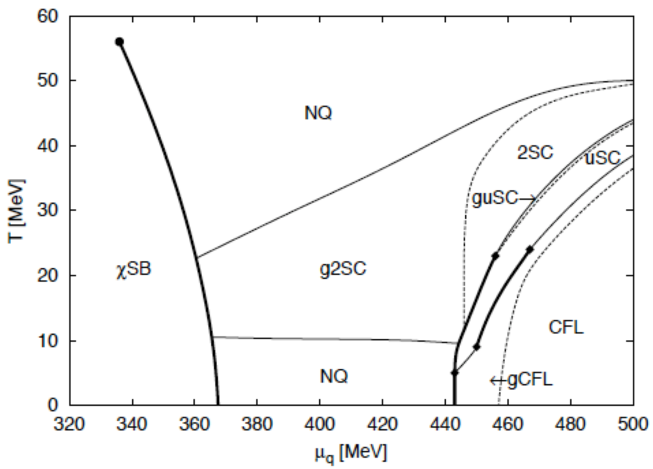
Exploring the (μ, T) plane

The QCD phase diagram

(« low resolution »)

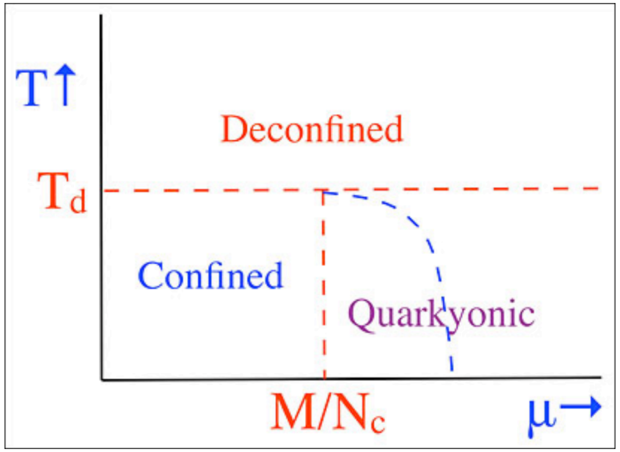


A better resolution phase diagram (model dependent)



(from Ruester et al, PRD72 (2005))

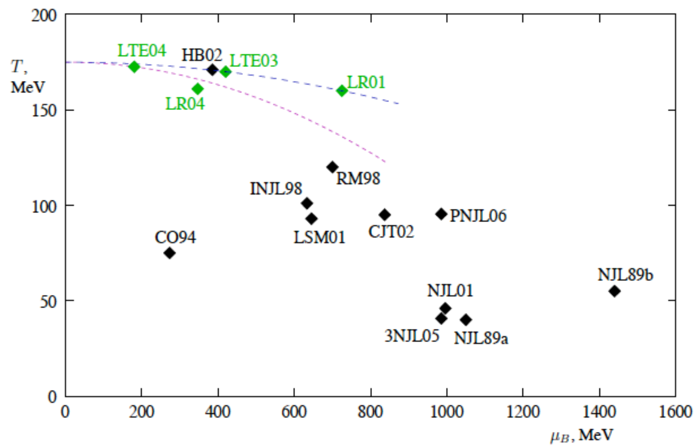
Speculation about new phases at high density



(from R. Pisarski and L. McLerran)

Much uncertainty about the existence and location of the critical point

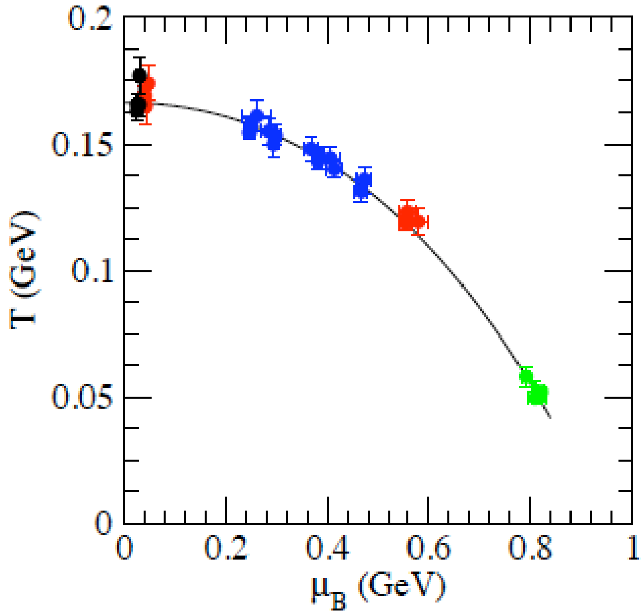
(from M. Stephanov)

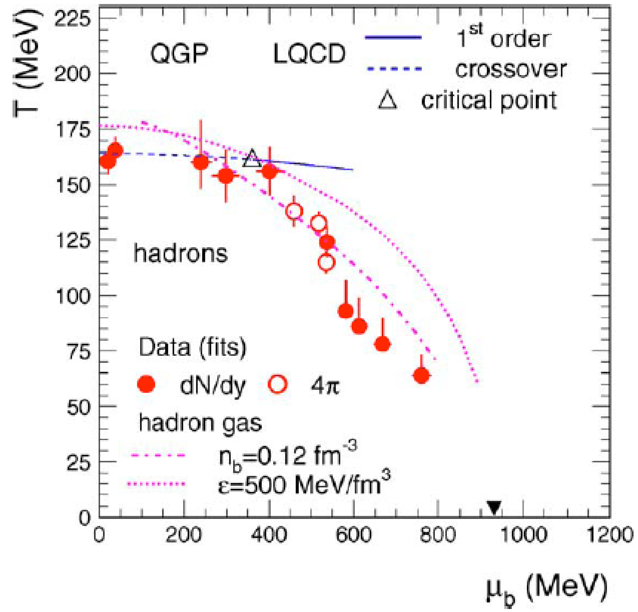


Matter at « freeze-out »

well described by statistical picture

$$n \sim \frac{1}{e^{(\varepsilon_k - \mu)/T} \pm 1}$$





(from J. Cleymans et al, hep-ph/0511094)

(from P. Braun-Munzinger et al)

Conclusions

- ultra-relatvistic heavy ion collisions allow us to study fundamental questions concerning the phase diagram of hot and dense matter, or the nuclear wave functions at very high energy.

-exciting developments in recent years, many open questions/puzzles : phase diagram ? strongly/weakly coupled plasma ? detailed mechanisms leading to thermalisation and collective flow ? What can we learn from heavy quarks ?