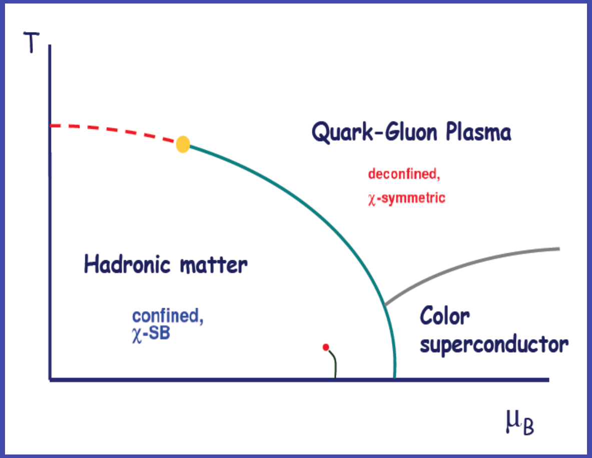
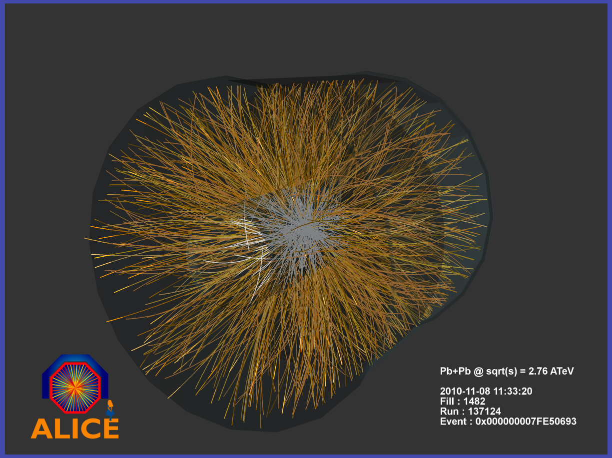
Extreme states of matter
and
ultra-relativistic heavy ion collisions

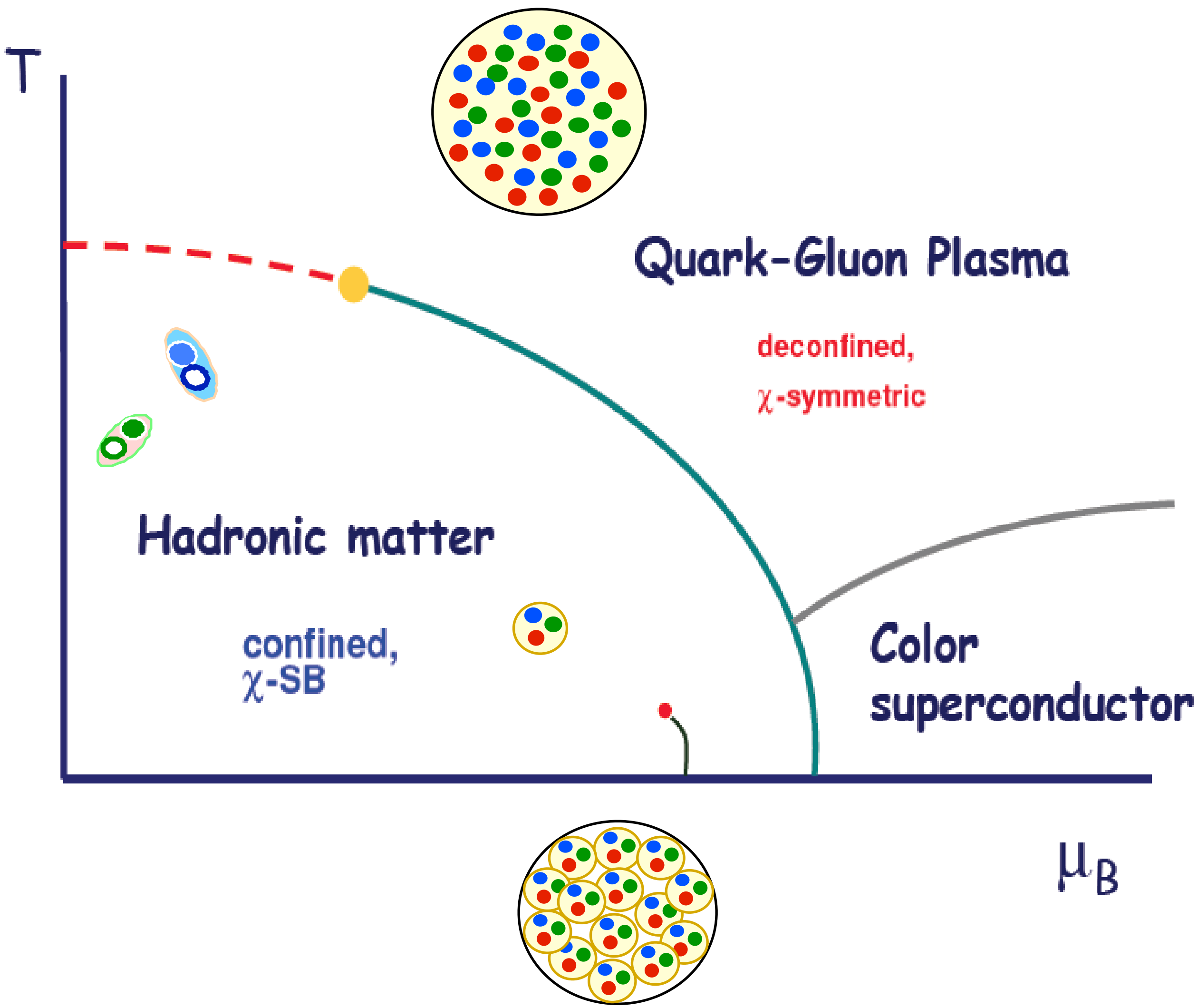


Rencontres du Vietnam
Qui Nhon
Vietnam
20/12/2011

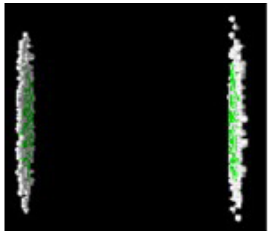


Jean-Paul Blaizot, IPhT- Saclay CEA & CNRS

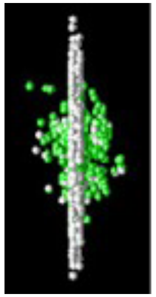
The QCD phase diagram



Colliding heavy nuclei

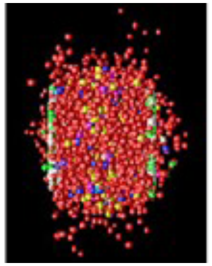


Initial conditions. Fluctuations (geometry, nucleus wave function and its parton content)

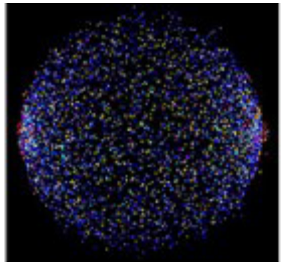


Particle (entropy) production. Involves mostly small x partons $(x = p_\perp / \sqrt{s} \sim 10^{-2} - 10^{-4} \quad \text{for} \quad p_\perp \simeq 2\text{GeV})$

One characteristic scale: saturation momentum Q_s



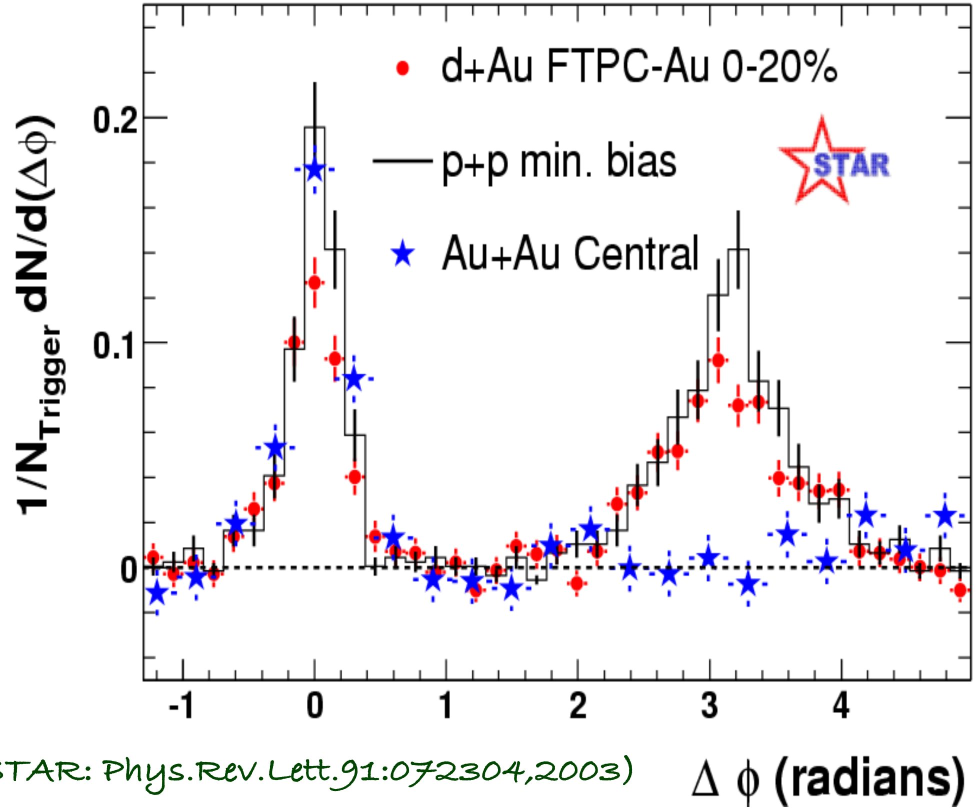
Thermalization. Quark-gluon plasma. Hydrodynamical expansion



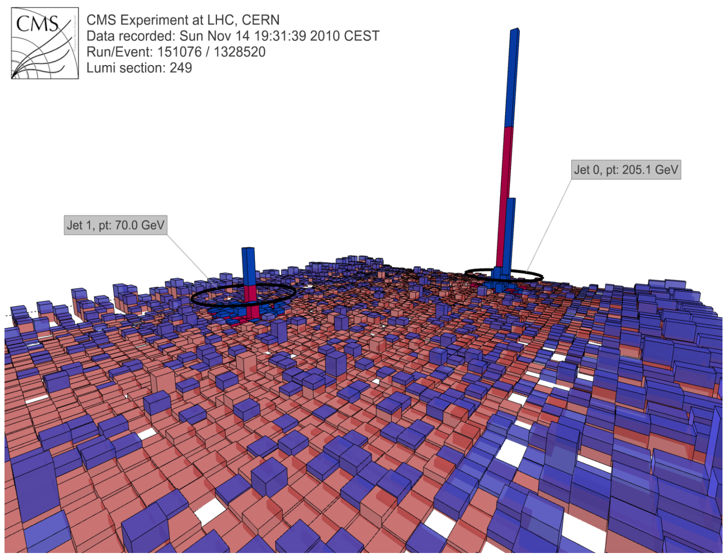
Hadronization. Hydrodynamic expansion continues till freeze-out. Apparent chemical equilibrium at freeze-out

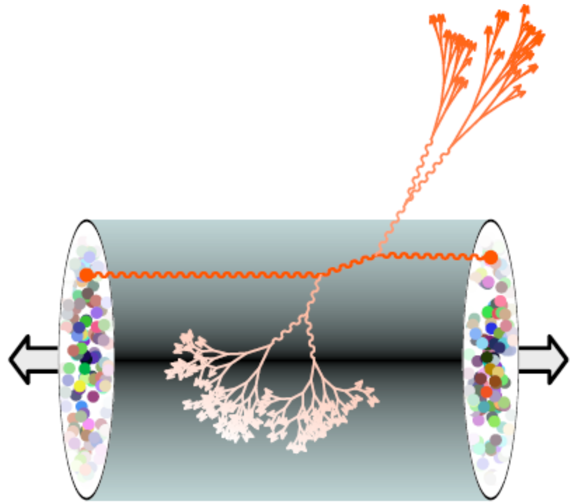
Main surprises from RHIC
(confirmed by LHC)
concern matter before freeze-out

Matter is opaque to the propagation of jets



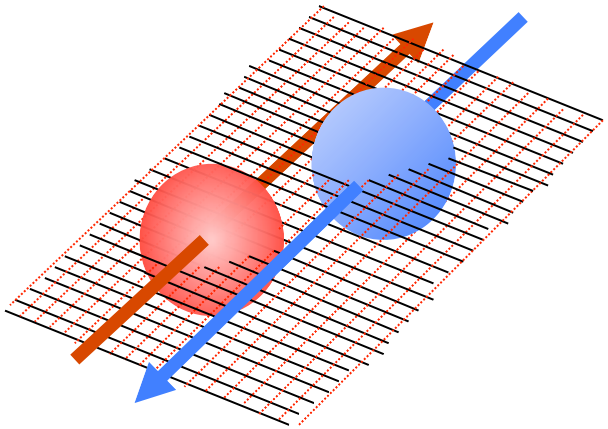
(STAR: Phys.Rev.Lett.91:072304,2003)

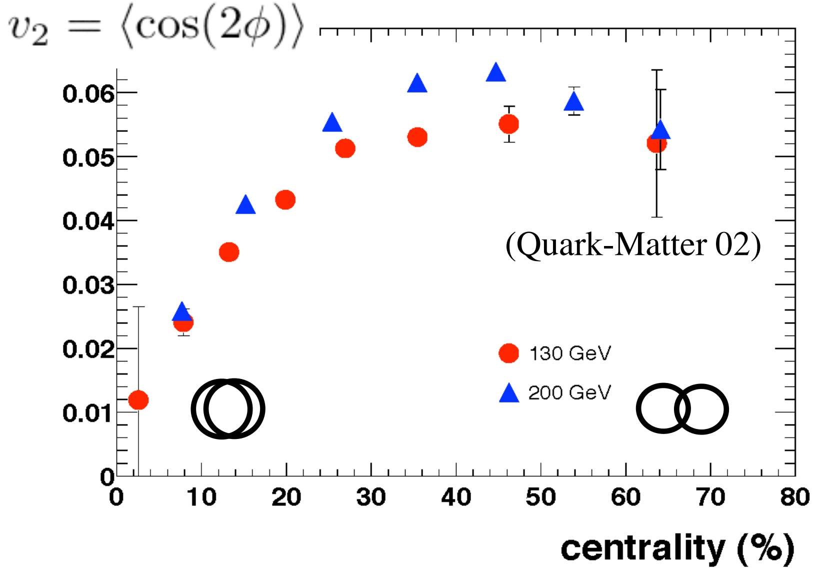


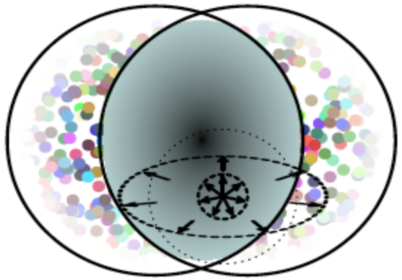


The jet produced near the surface 'escapes' normally. Its partner is absorbed in the produced plasma.

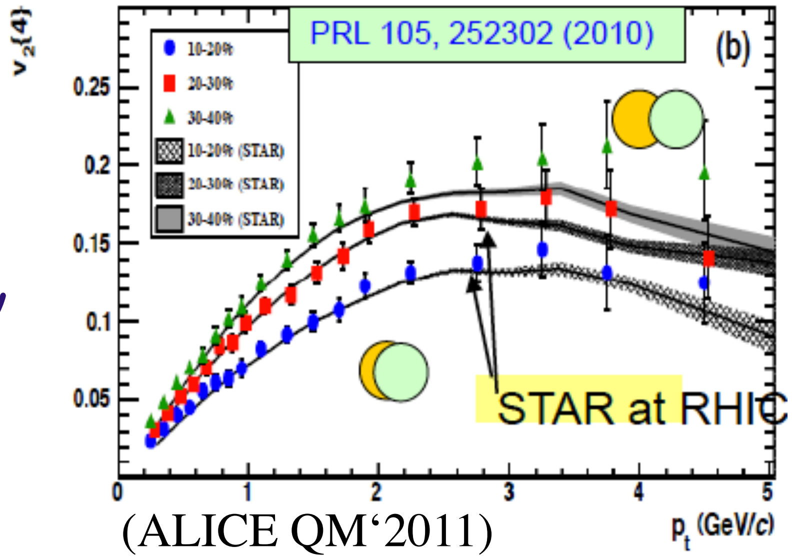
Produced matter flows like a fluid



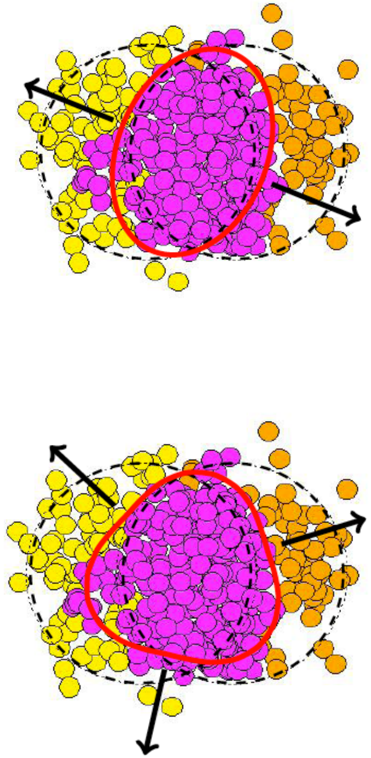


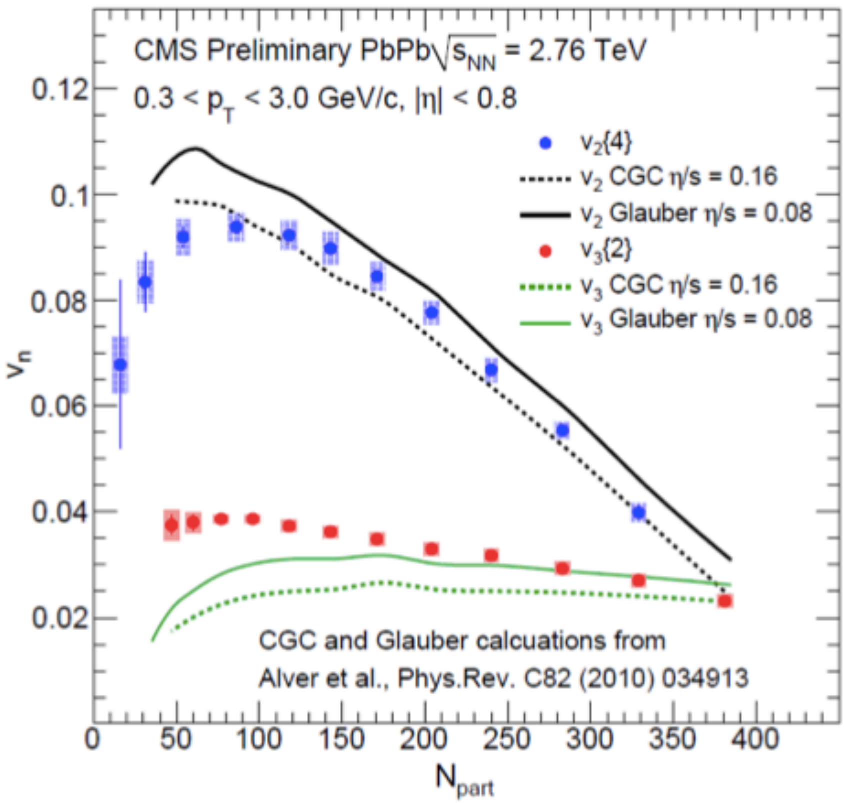


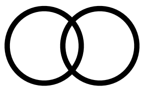
The flow takes place preferentially in the reaction plane rather than away from it.



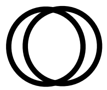
The flow is sensitive to initial nuclear density fluctuations







peripheral



central

J. Velkowska,

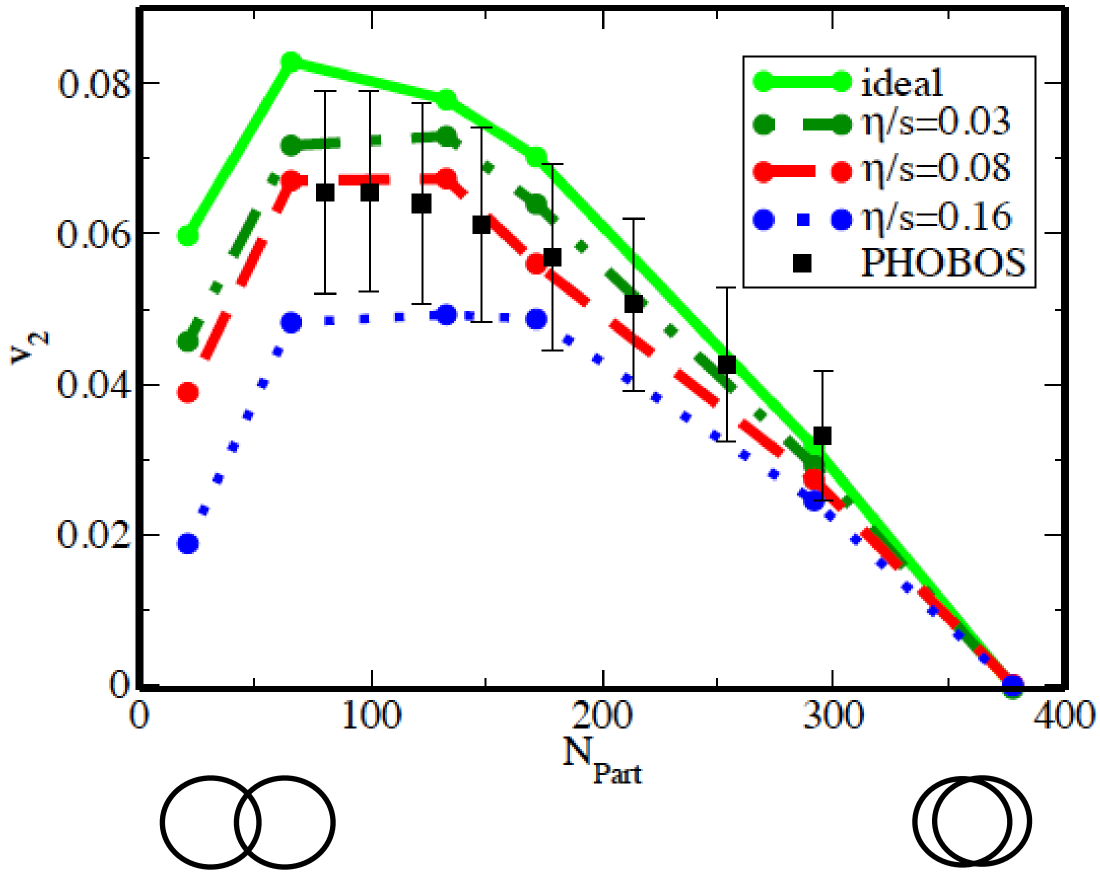
QM2011

and

Luzum,

arXiv:1011:5173

The low viscosity of the quark-gluon plasma

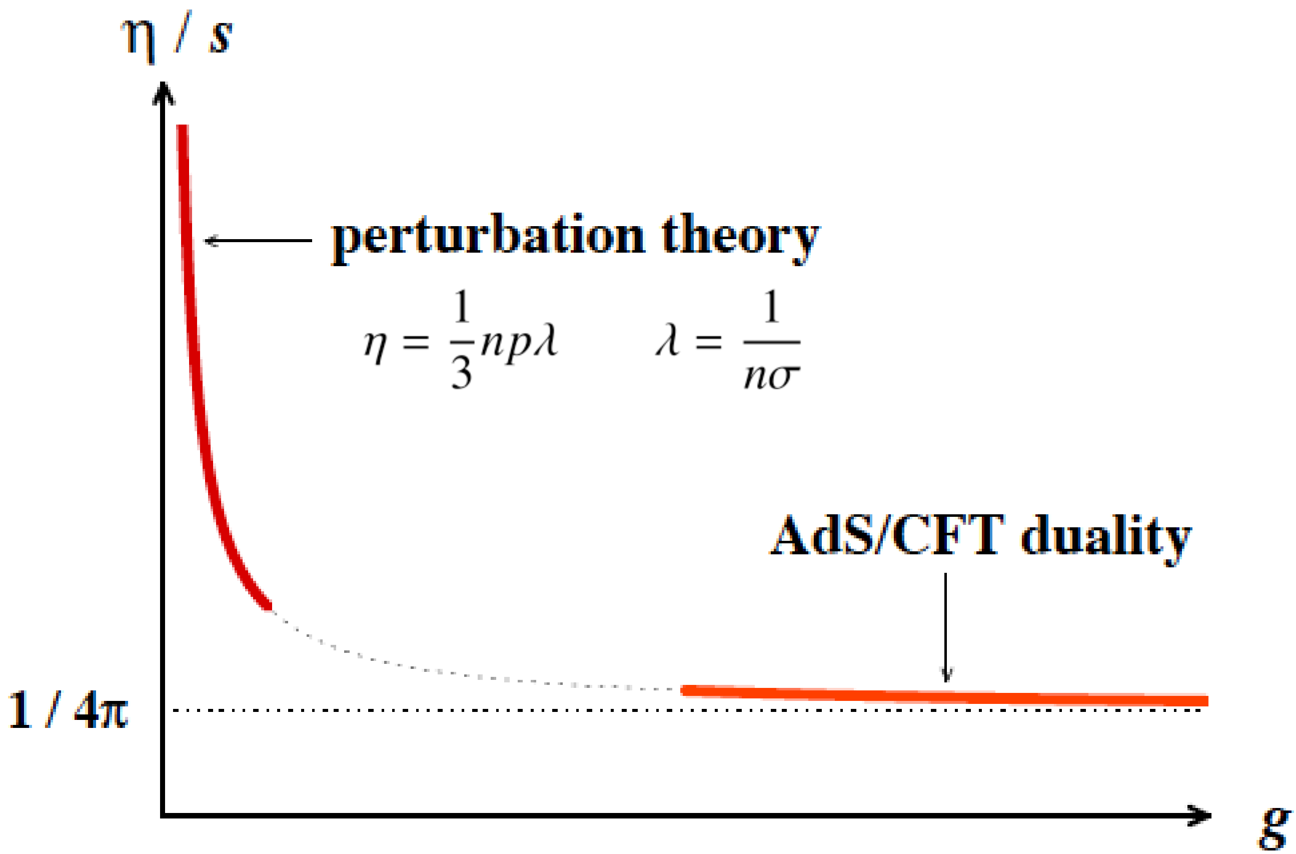


peripheral

central

(Luzum, Romatschke, 2007)

Viscosity at weak and strong coupling



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

(Policastro, Son, Starinet, 2001)

Theoretical puzzle

Small η/s and short equilibration time seem incompatible with weak coupling

However

- the coupling is not huge ($\alpha_s \sim 0.3 \div 0.4$)

- our present understanding of initial stages of heavy ion collisions is based on weak coupling (for asymptotically large nuclei and large energies)

$$Q_s^2 \approx \alpha_s \frac{xG(x,Q^2)}{\pi R^2}$$

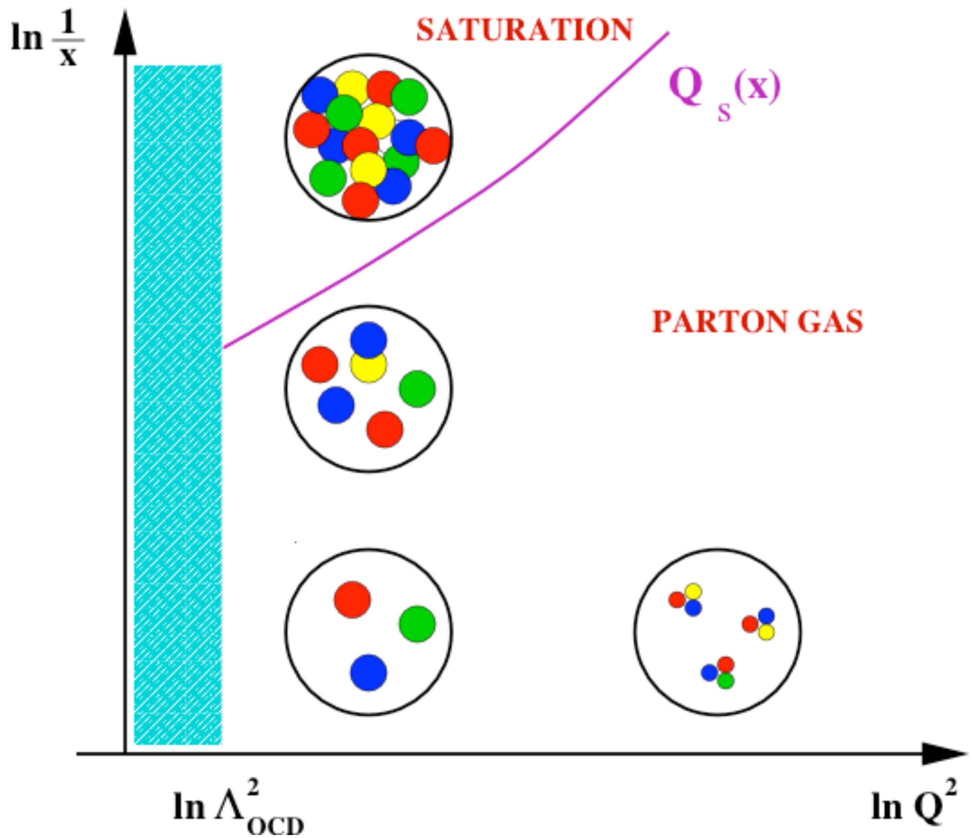
High density partonic systems

$$Q_s^2 \approx \alpha_s \frac{xG(x,Q^2)}{\pi R^2}$$

At saturation, occupation numbers are large

$$\frac{xG(x,Q^2)}{\pi R^2 Q_s^2} \sim \frac{1}{\alpha_s}$$

Description in terms of classical fields possible (CGC, etc)



The overpopulated quark-gluon plasma

Initial conditions $(t_0 \sim 1/Q_s)$

$$\epsilon_0 = \epsilon(\tau = Q_s^{-1}) \sim \frac{Q_s^4}{\alpha_s} \qquad n_0 = n(\tau = Q_s^{-1}) \sim \frac{Q_s^3}{\alpha_s} \qquad \epsilon_0/n_0 \sim Q_s$$

Overpopulation parameter $n_0\, \epsilon_0^{-3/4} \sim 1/\alpha_s^{1/4}$

In equilibrated quark-gluon plasma

$$\epsilon_{eq} \sim T^4 \qquad n_{eq} \sim T^3 \qquad n_{eq}\, \epsilon_{eq}^{-3/4} \sim 1$$

Mismatch by a large factor (at weak coupling) $\alpha_s^{-1/4}$

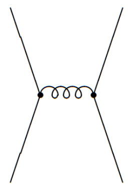
Formation of a Bose-Einstein condensate?

As a result of their interactions, gluons acquire a 'mass', and can condense.

Evidences for this phenomenon in classical scalar field theories (Epelbaum, Gelis, NPA 872 (2011) 210). Non abelian gauge theories ?

Note: when $f \sim 1/\alpha_s$ all dependence on the coupling constant disappears from kinetic equations

$$\partial_t f = C[f] \sim \alpha^2 f^3 \sim \frac{1}{\alpha}$$



(J.-P. B, F. Gelis, J. Liao, L. McLerran and R. Venugopalan, arXiv:1107.5296)

Conclusions

- the field of ultra-relativistic heavy ion collisions is a very rich one, it addresses fundamental issues (hot and dense QCD matter, high density partonic systems, etc)

- exciting developments in recent years, both experimentally and theoretically (RHIC, LHC; CGC, AdS/CFT, etc), many open questions/puzzles (weak vs strong coupling, thermalization, etc)

- future of the field looks bright, with many facilities allowing for such studies: LHC, RHIC2, FAIR, NICA