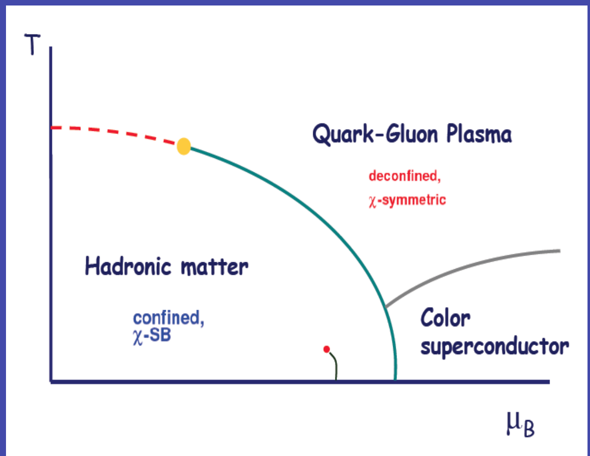
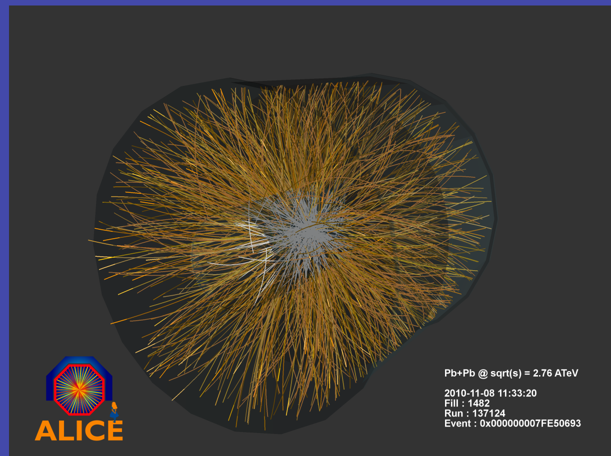
Extreme states of matter
and
ultra-relativistic heavy ion collisions





TIFR - Mumbai

January 24, 2012

Jean-Paul Blaizot, IPhT- CEA Saclay & CNRS

Outline

- Early concept, asymptotic freedom, thermodynamics from lattice calculations

- Lessons from RHIC and LHC

- From the 'ideal gas' to the 'perfect liquid'

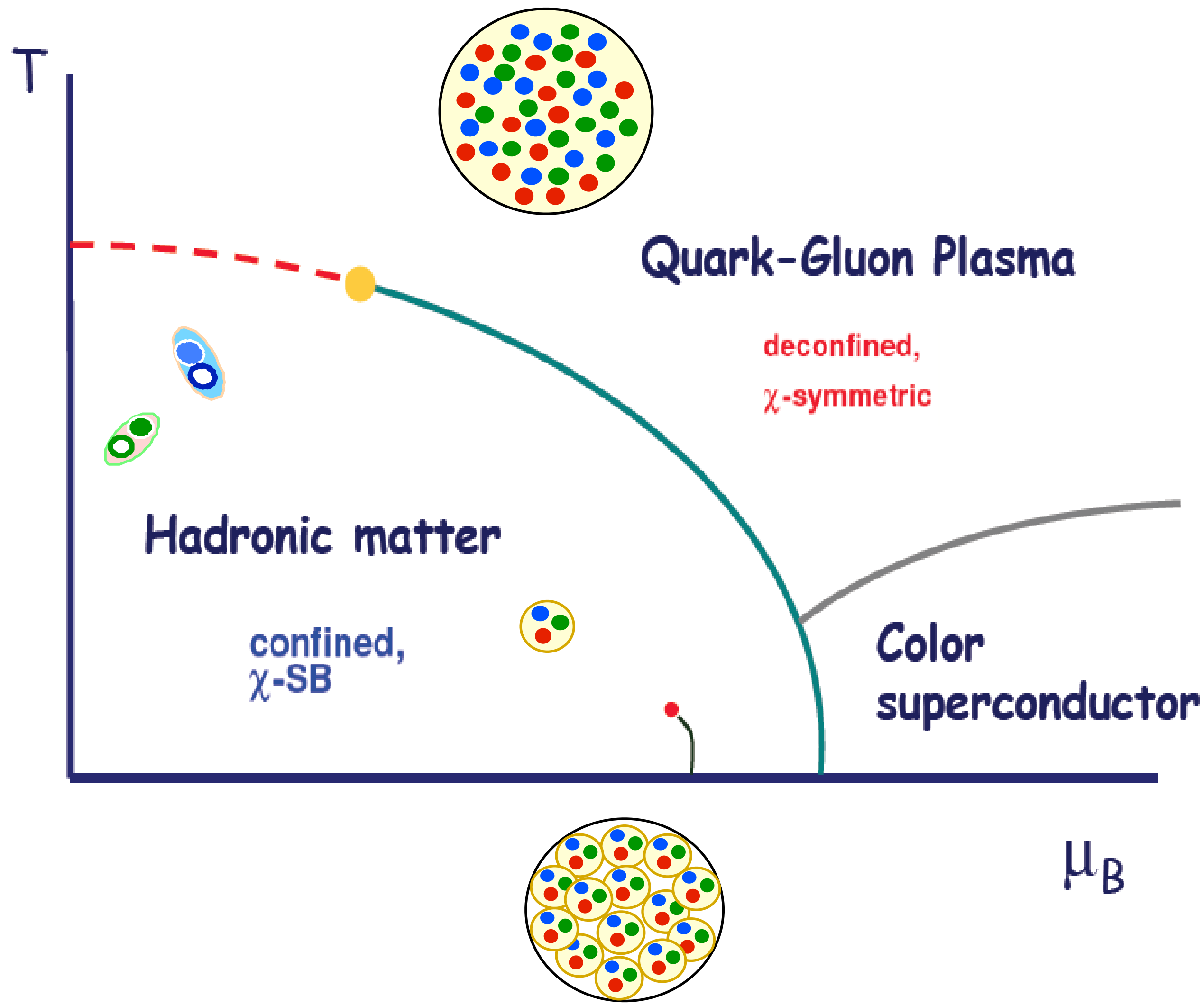
- How matter is produced, and thermalizes

QCD asymptotic freedom

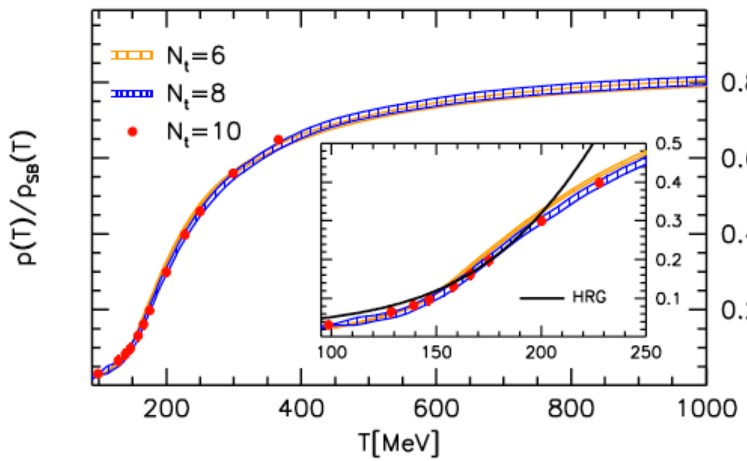
$$\alpha_s = \frac{g^2}{4\pi} \approx \frac{2\pi}{b_0 \ln\left(\mu / \Lambda_{QCD}\right)} \qquad \left(\mu \approx 2\pi T\right)$$

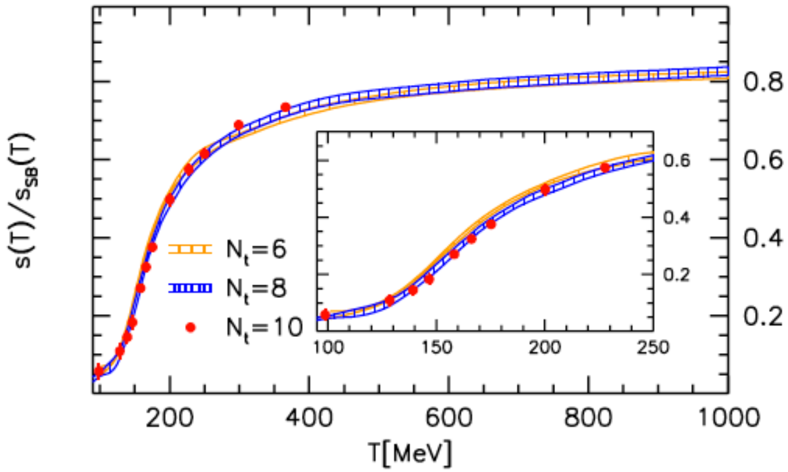
Matter is « simple » at high temperature:
an ideal gas of quarks and gluons

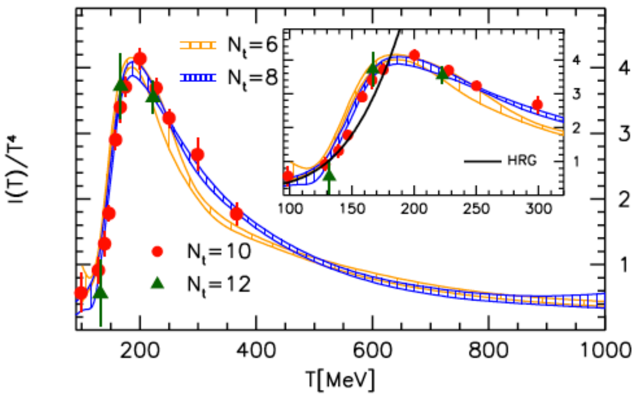
The QCD phase diagram



The crossover from the hadron gas to the quark-gluon plasma

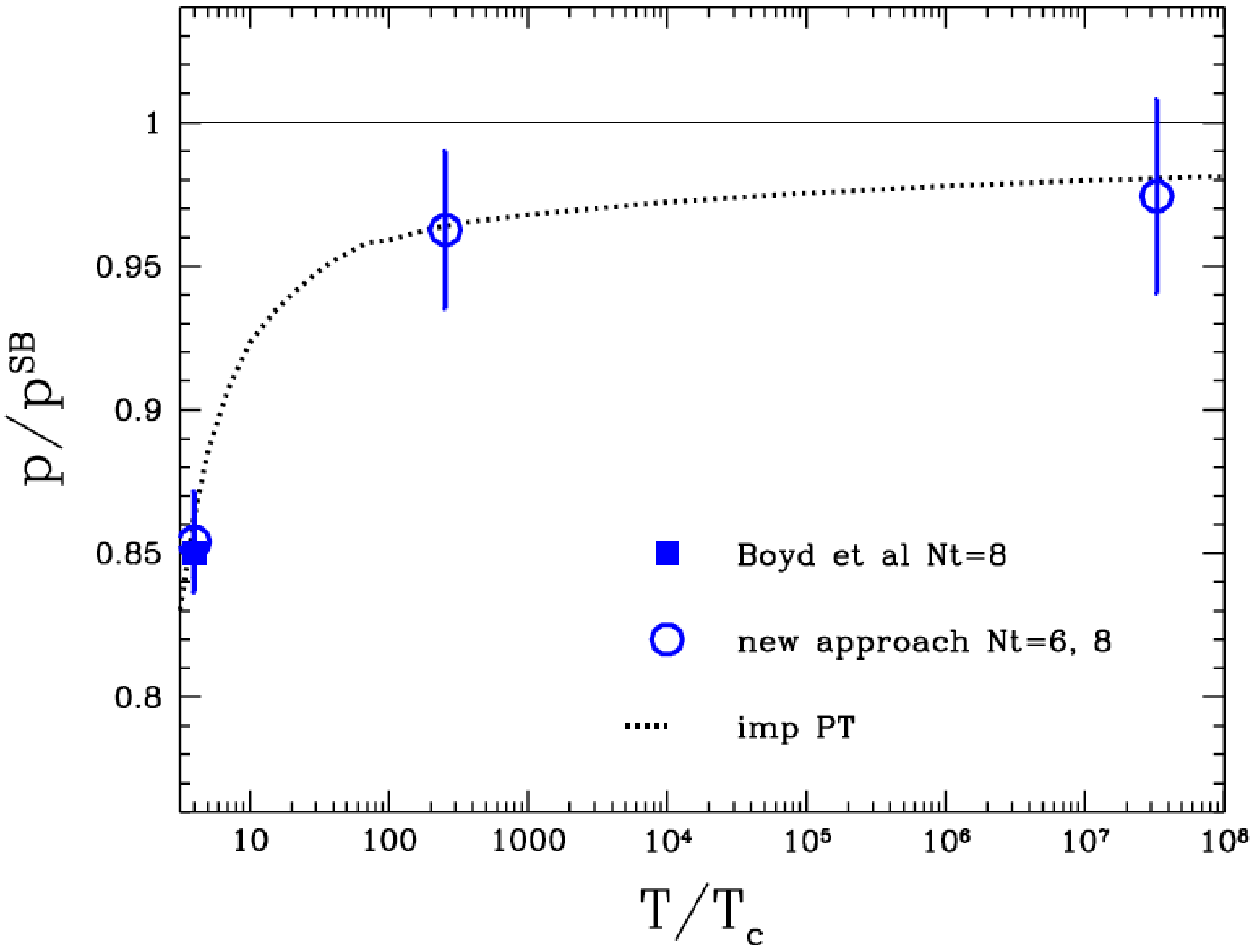






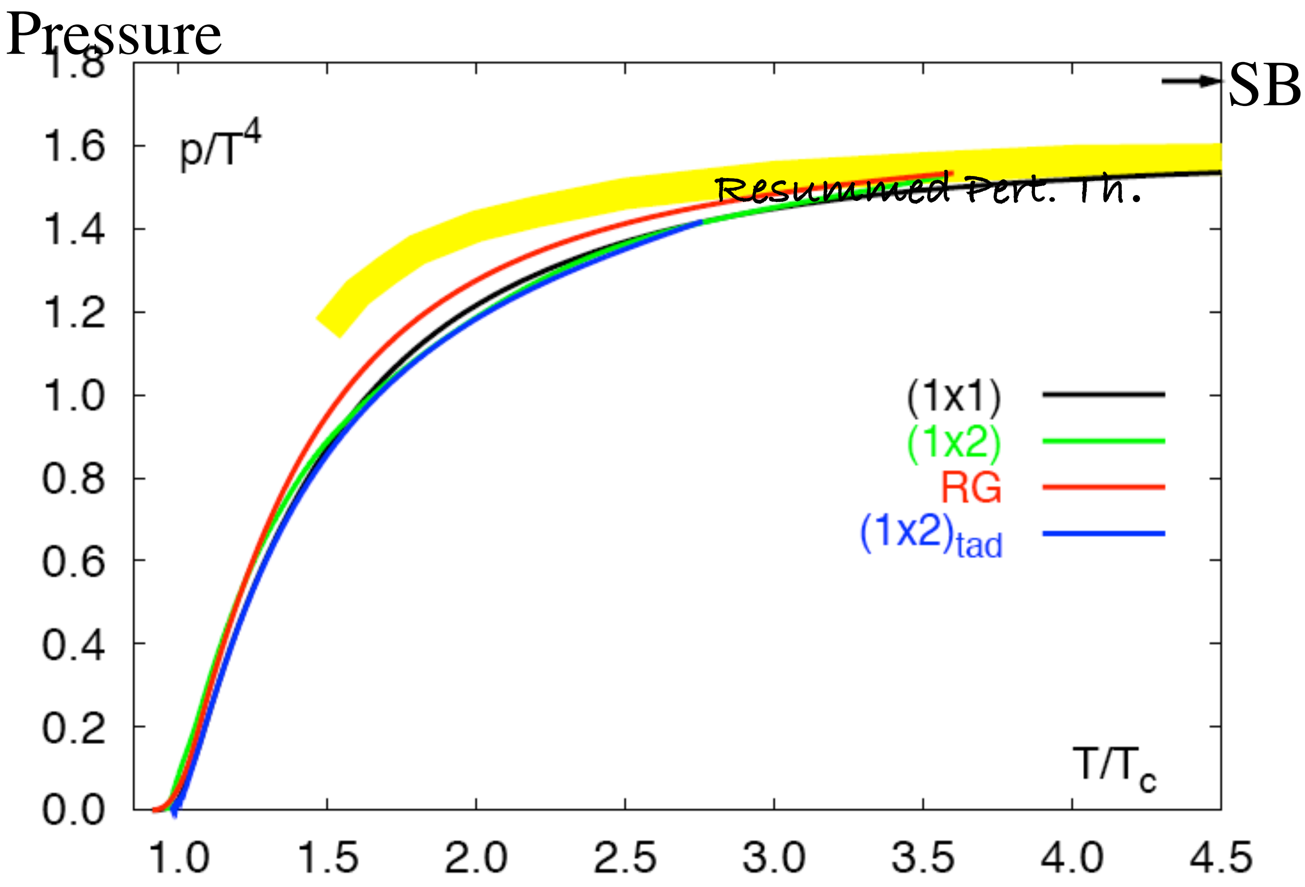
(Borsanyi et al, arXiv:1007.2580)

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



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

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)

«It's not what you don't know that gets you in trouble, it's what you think you know.»
Mark Twain

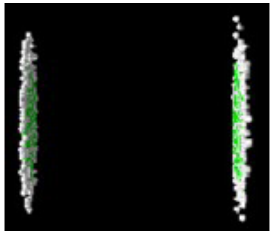
Colliding heavy nuclei

From AGS to SPS to RHIC to LHC

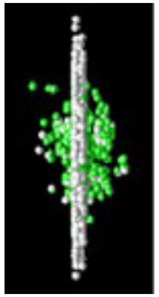
Bevalac

SPS-LHC

Colliding heavy nuclei

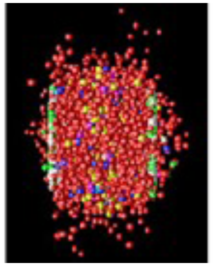


Initial conditions. Fluctuations (geometry, nucleus wave function and its parton content)

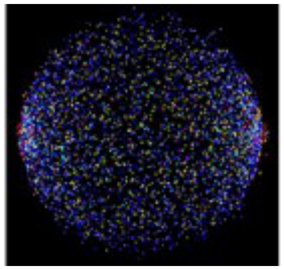


Particle (entropy) production. Involves mostly small x partons $(x = p_\perp / \sqrt{s} \sim 10^{-2} - 10^{-4} \quad \text{for} \quad p_\perp \simeq 2\text{GeV})$

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

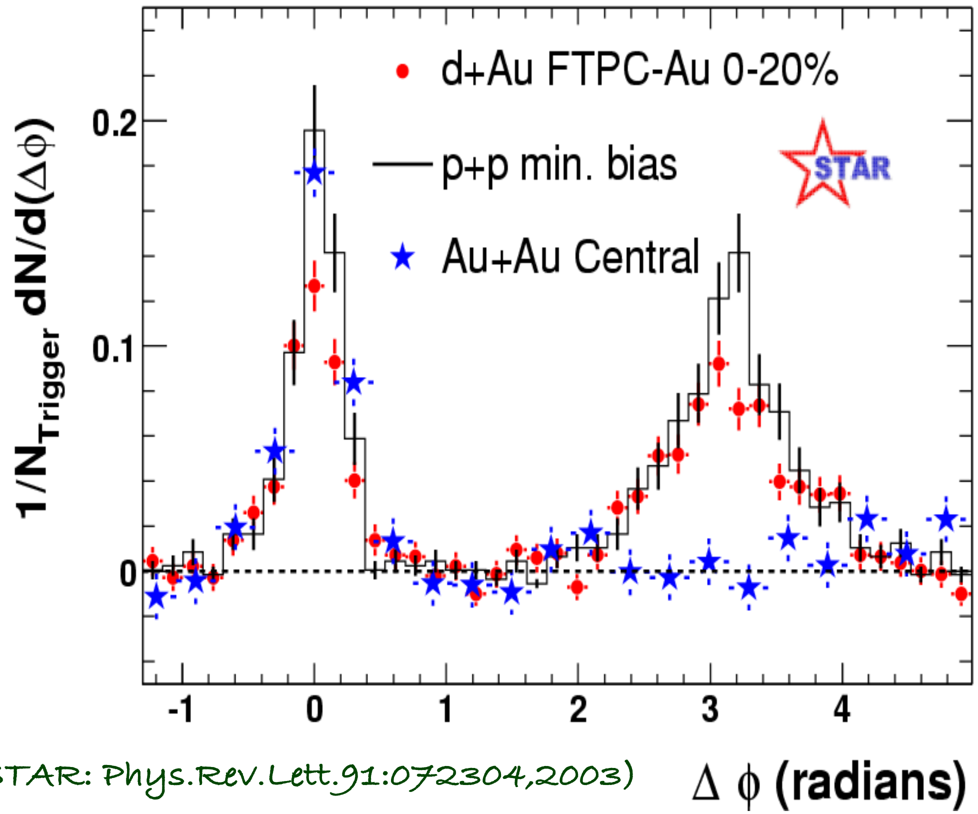
From the

« ideal gas »

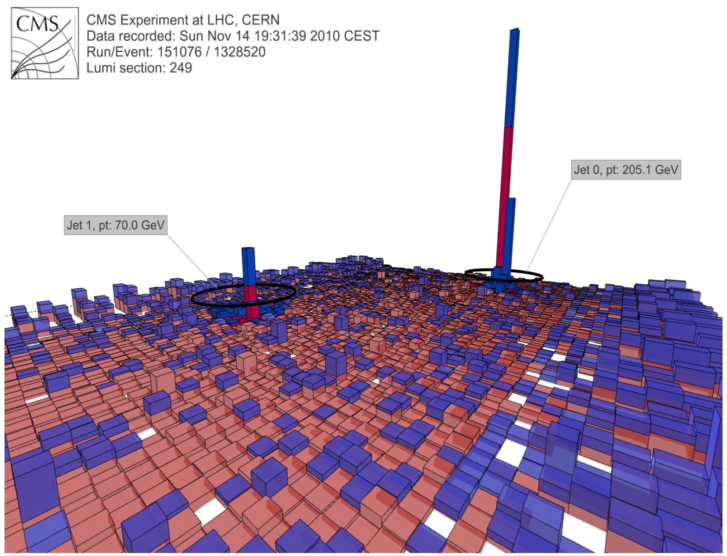
to the

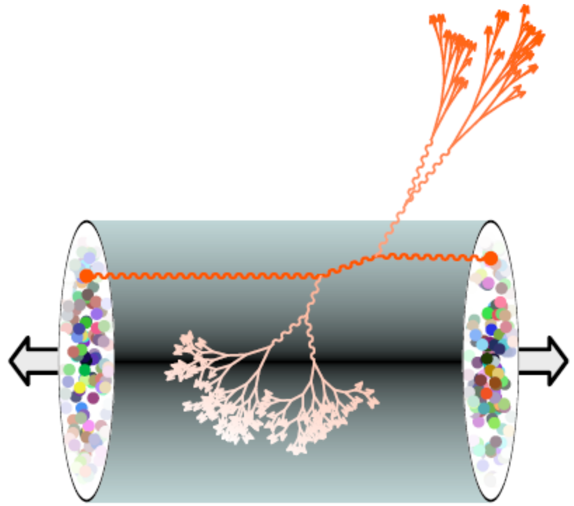
« perfect liquid »

Matter is opaque to the propagation of jets



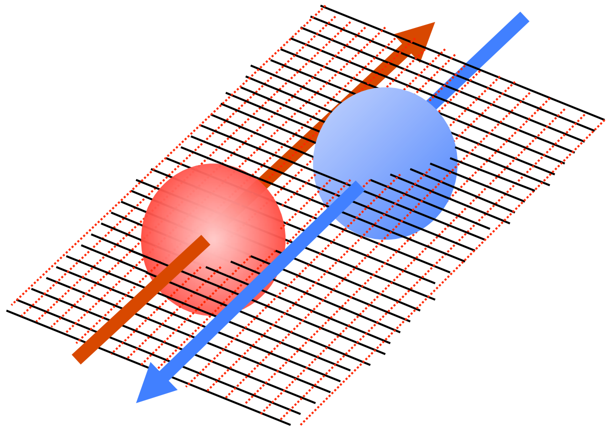
(STAR: Phys.Rev.Lett.91:072304,2003)

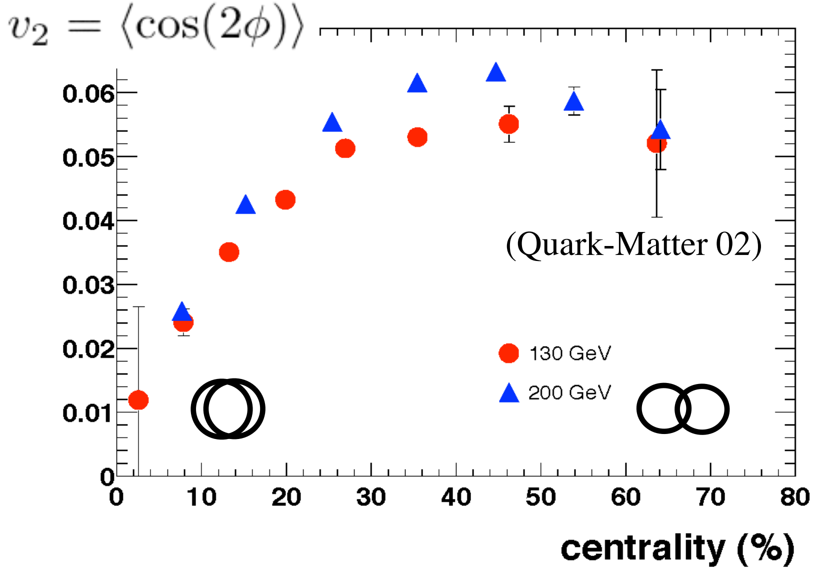


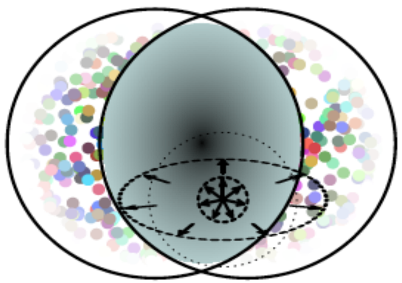


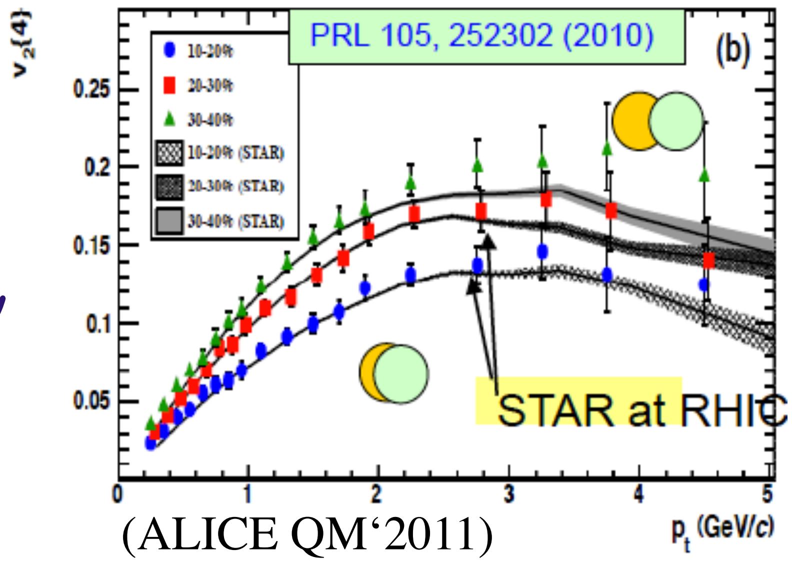
The jet produced near the surface 'escapes' normally. Its partner is absorbed in the produced plasma.

Produced matter flows like a fluid



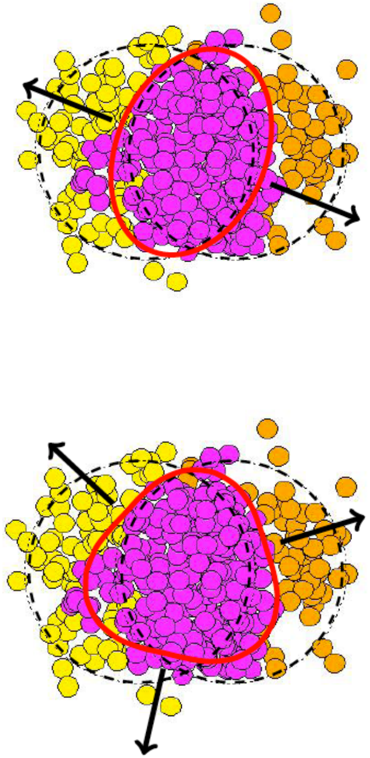


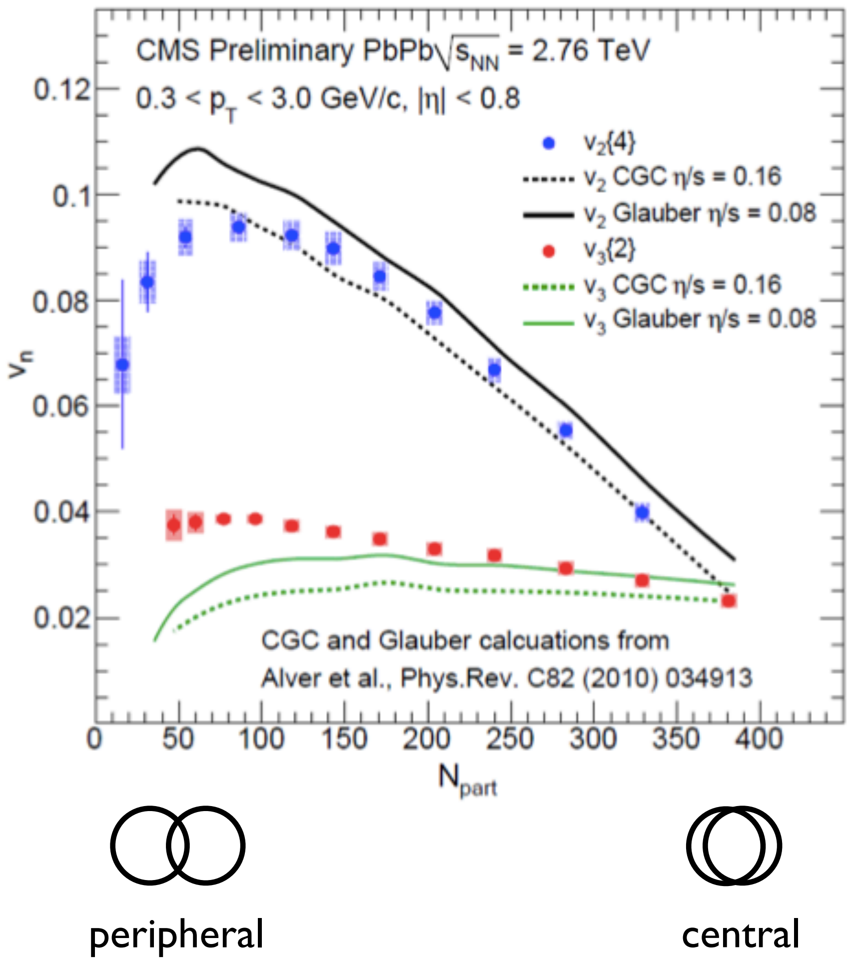




The flow takes place preferentially in the reaction plane rather than away from it.

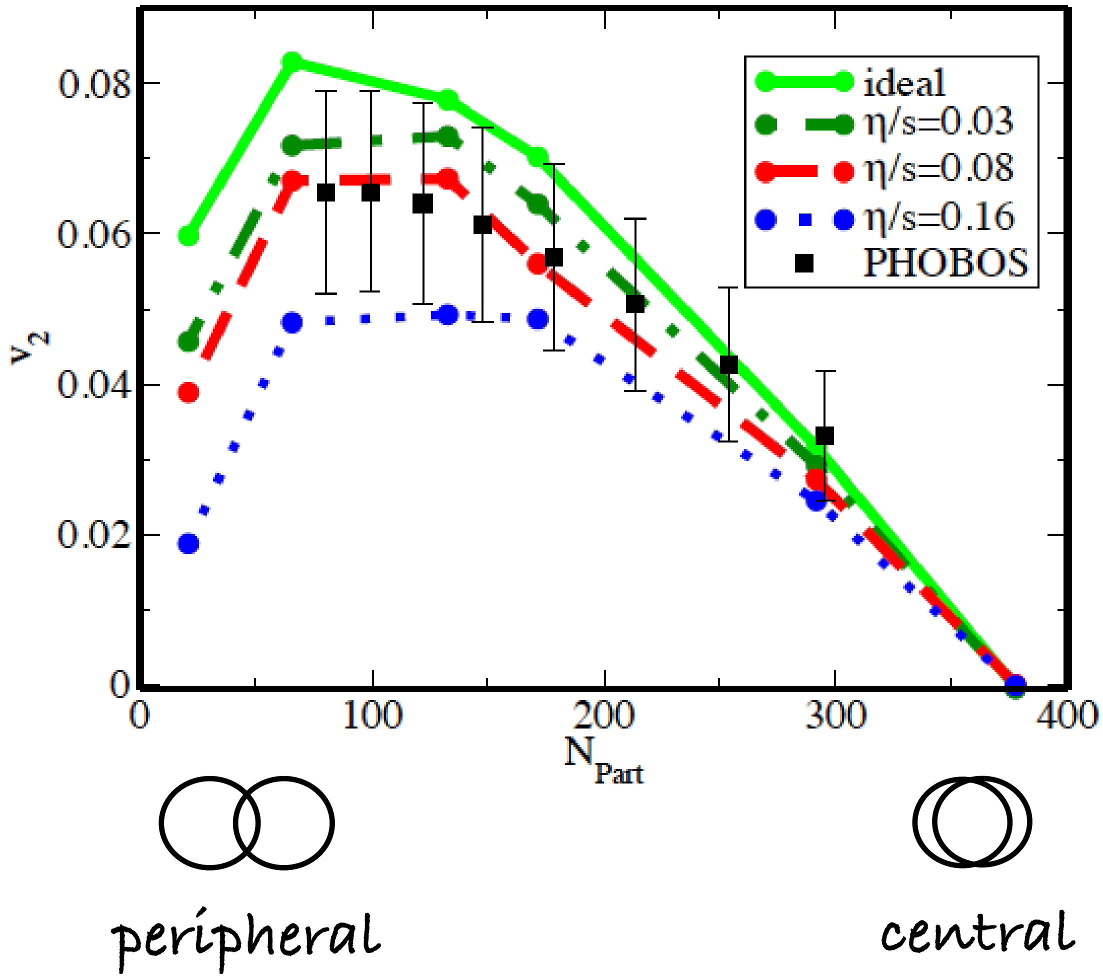
The flow is sensitive to initial nuclear density fluctuations





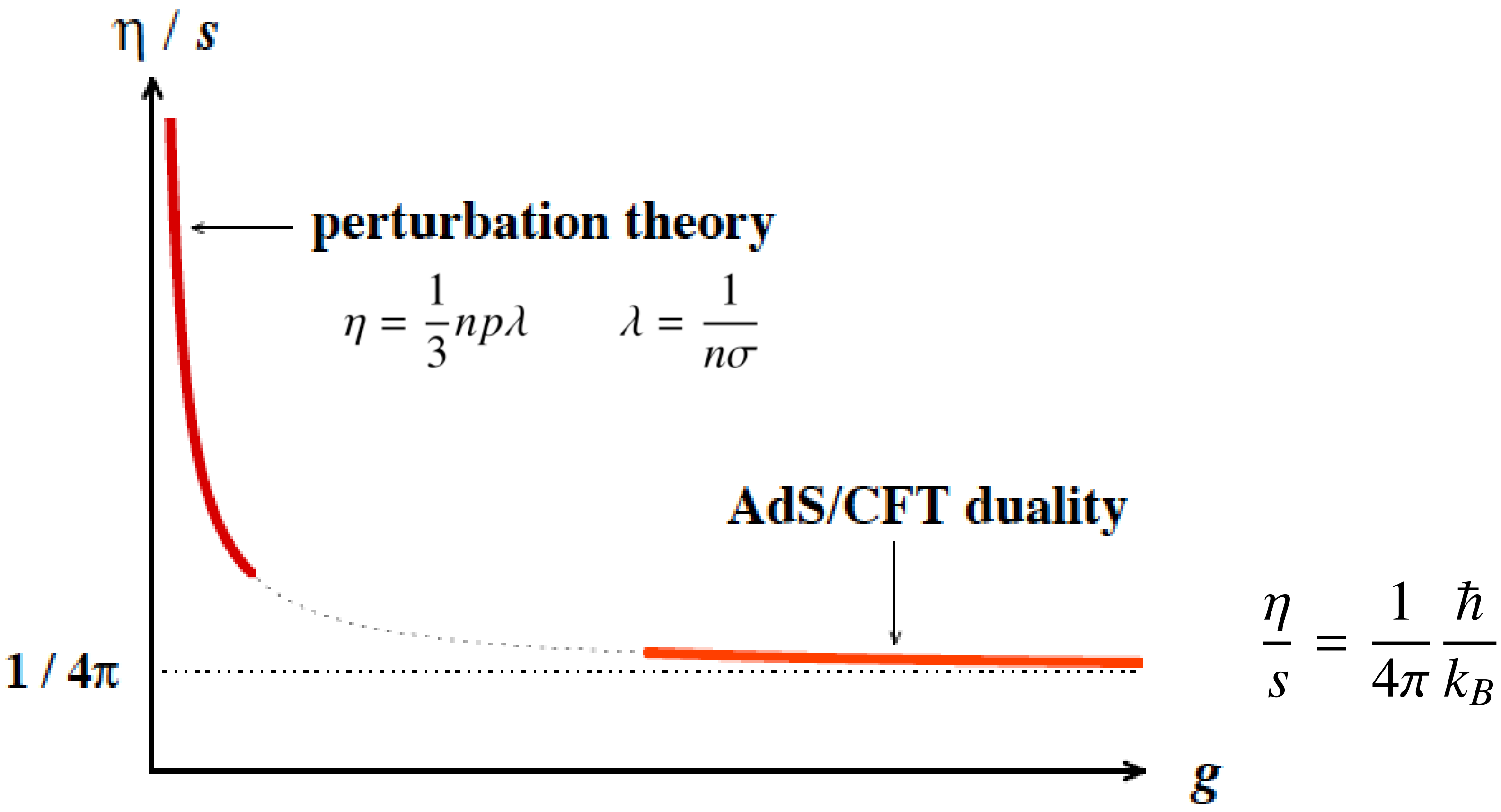
J. Velkowska, QM2011 and Luzum, arXiv:1011:5173

The low viscosity of the quark-gluon plasma



(Luzum, Romatschke, 2007)

Viscosity at weak and strong coupling



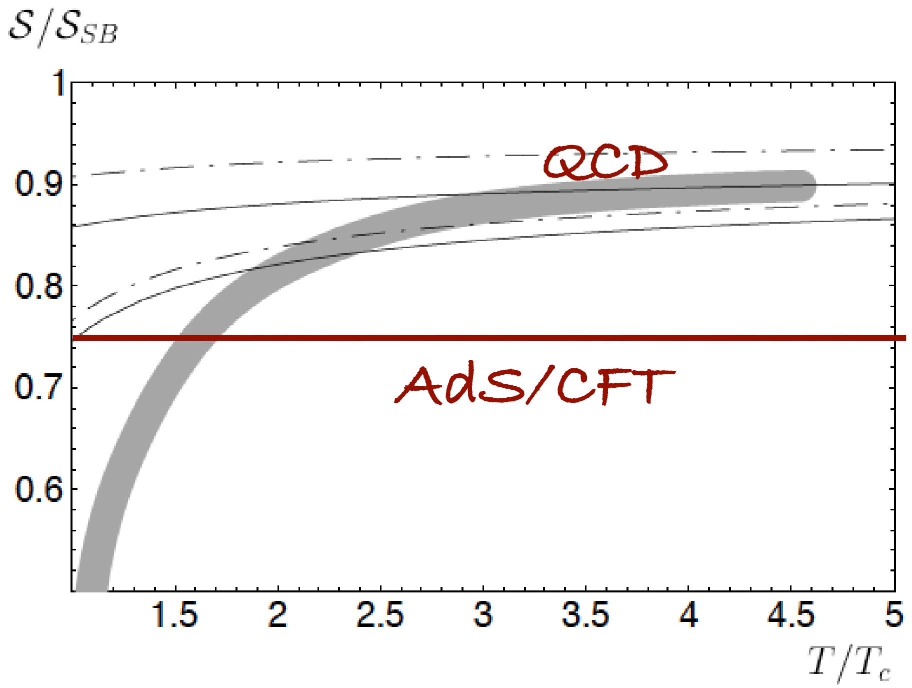
(Policastro, Son, Starinet, 2001)

Another strong coupling result

Simple limit of the entropy density at strong coupling

$$\frac{S}{S_0} = \frac{3}{4} + \frac{45}{32}\varsigma(3)\frac{1}{\lambda^{3/2}}$$

$$\left(\lambda \equiv g^2 N_c\right)$$



A new 'reference' system: the strongly coupled quark-gluon plasma (the `perfect liquid')

What is the origin of the strongly coupled character of the quark-gluon plasma?

A puzzling situation

- The coupling constant is not small, but not huge $\alpha_s \sim 0.3 \div 0.4$
- Strict perturbation does not work, but successful resummations exist
- Understanding of early stages of HI collisions relies on weak coupling

Clue

- «Strong coupling» behavior may appear at weak coupling, when many degrees of freedom contribute coherently (e.g. collective phenomena, BCS, CGC, etc)

Weakly AND strongly coupled ...

The asymptotically free qgp and the strongly coupled qgp are incomplete idealizations

Degrees of freedom with different wavelengths are differently coupled.

Expansion parameter

$$\gamma_\kappa = \frac{g^2 \langle \phi^2 \rangle_\kappa}{\kappa^2} \qquad \langle \phi^2 \rangle_\kappa \sim \kappa T \quad (\kappa \lesssim T) \qquad \gamma_\kappa = \frac{g^2 T}{\kappa}$$

Dynamical scales

$$\kappa \sim T \qquad \gamma_\kappa \sim g^2$$

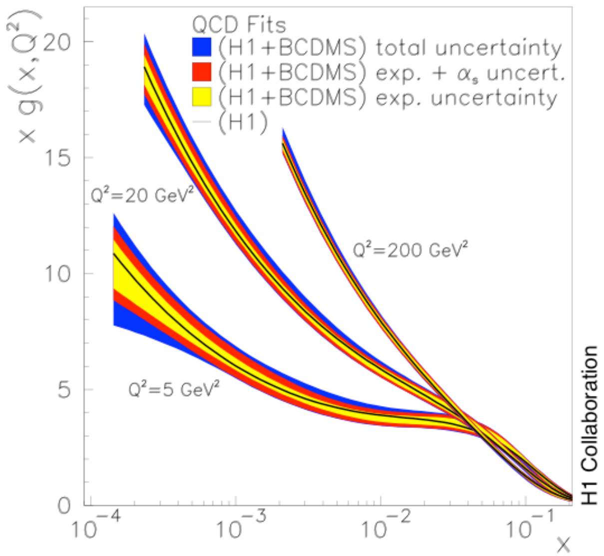
$$\kappa \sim gT \qquad \gamma_\kappa \sim g$$

$$\kappa \sim g^2 T \qquad \gamma_\kappa \sim 1$$

How is matter produced?

How does it thermalize?

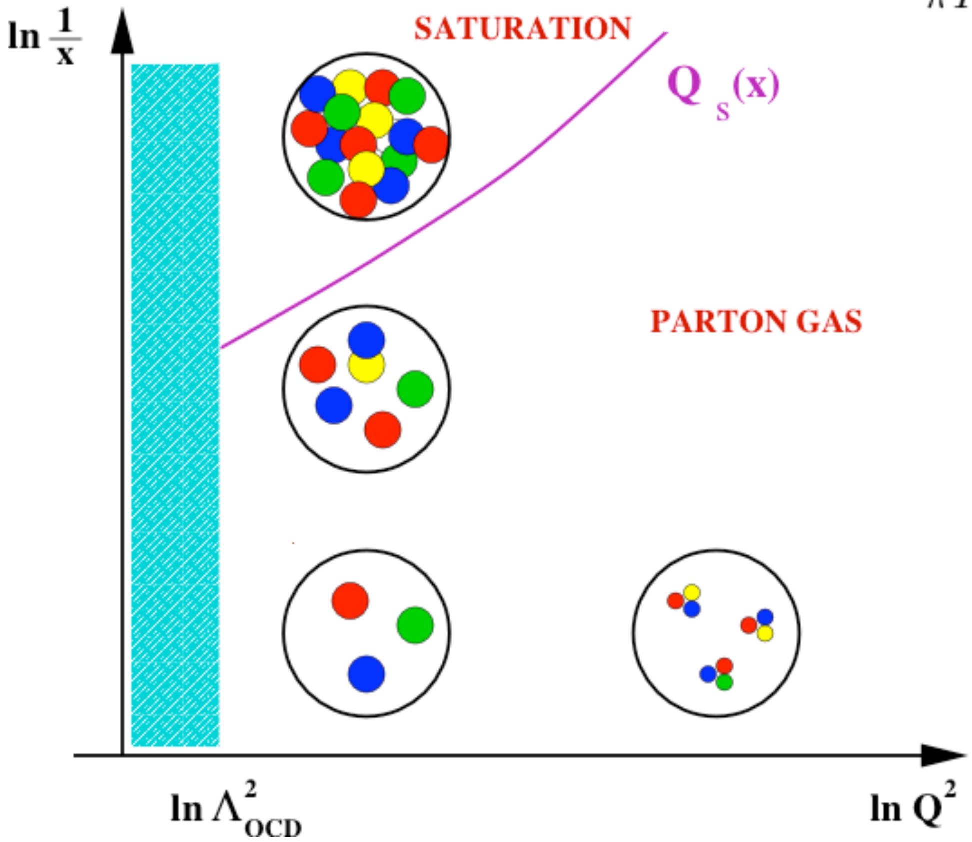
High density partonic systems



Large occupation numbers

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

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



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) $\alpha_s^{-1/4}$

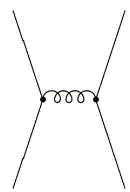
Formation of a Bose-Einstein condensate?

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 ?**

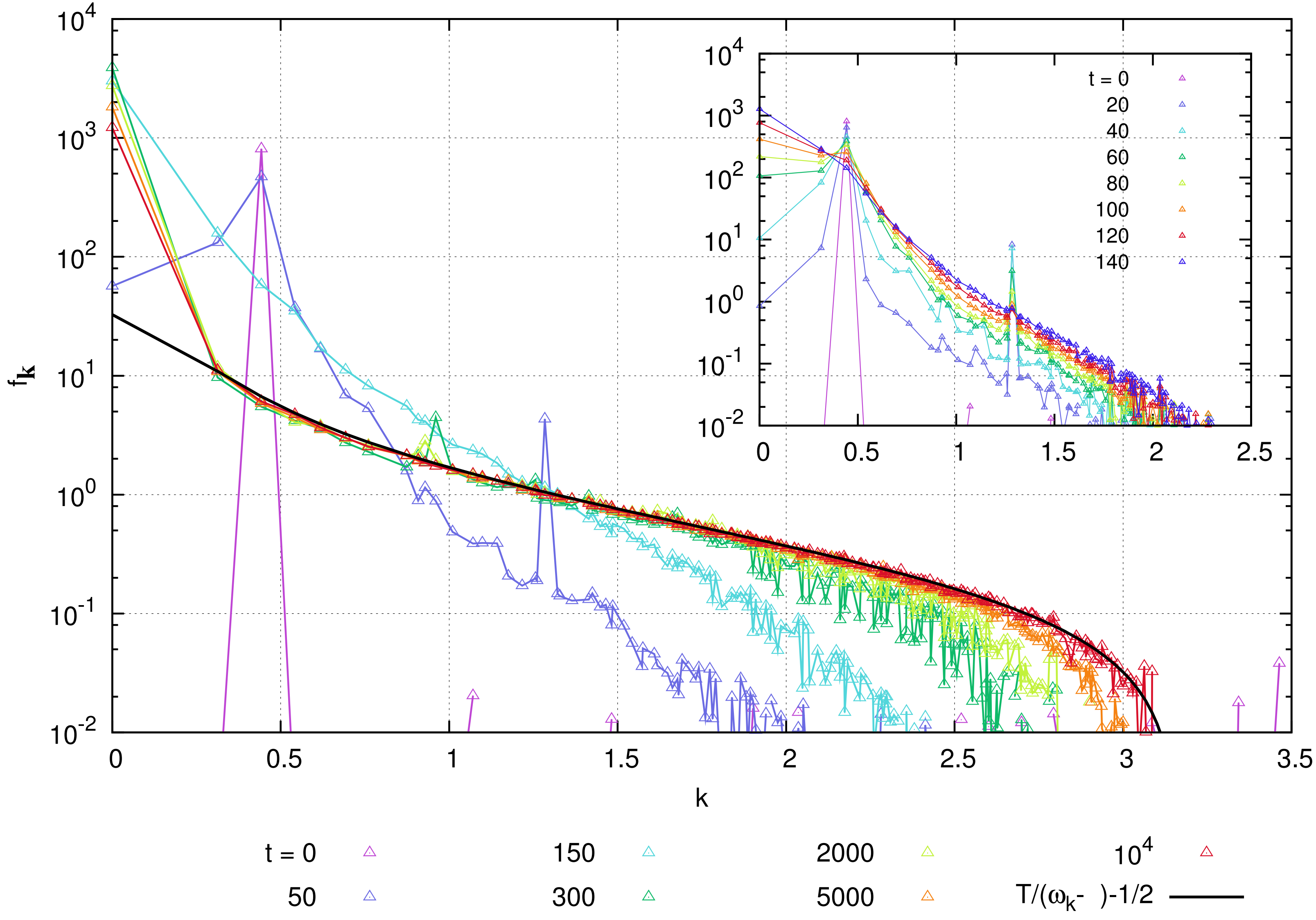
Note: when $f \sim 1/\alpha_s$ all dependence on the coupling constant disappears from kinetic equations

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

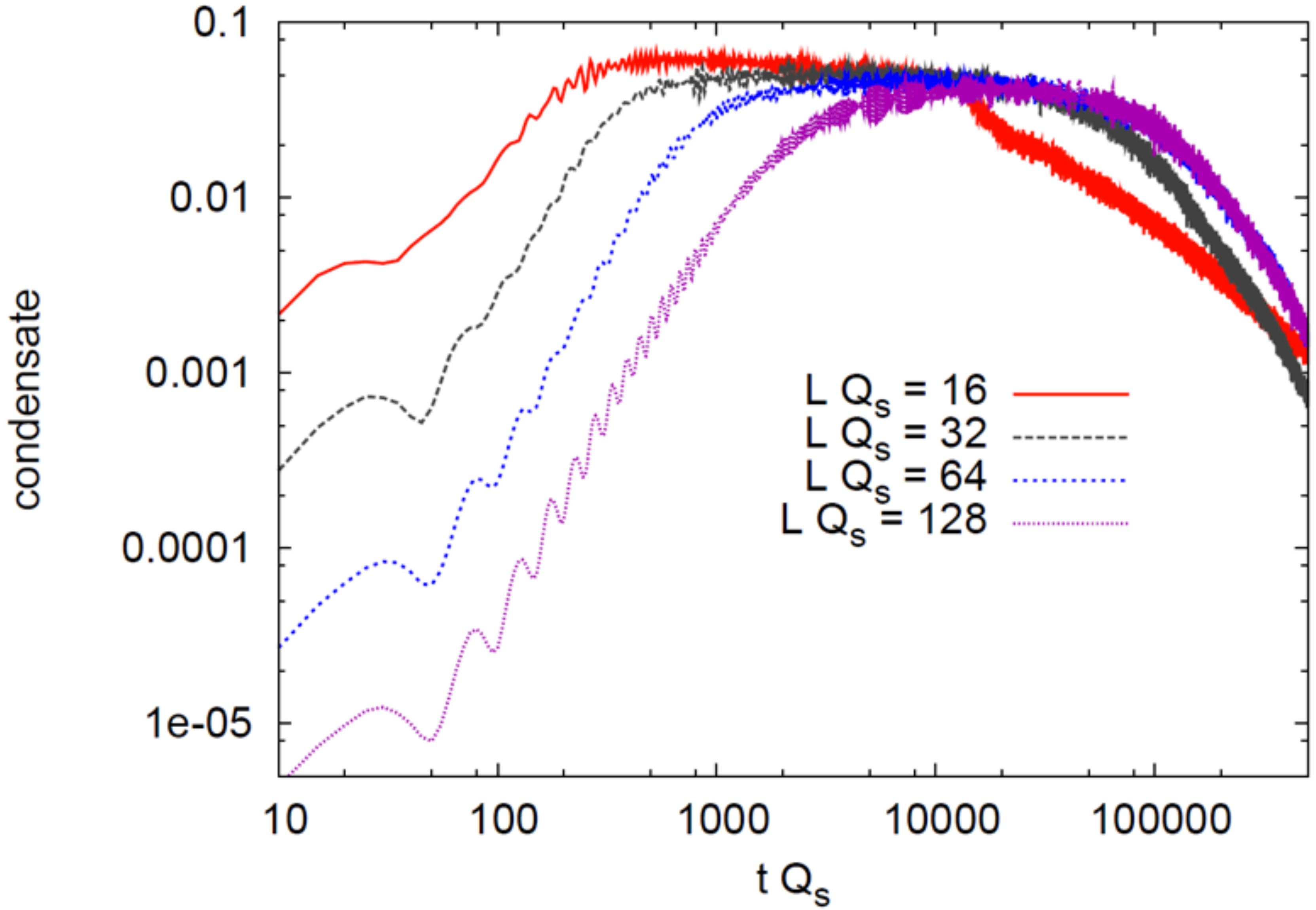


(J.-P. B, F. Gelis, J. Liao, L. McLerran and R. Venugopalan, arXiv:1107.5296)

Classical simulation (scalar theory)



(T. Epelbaum and F. Gelis, 2011)



(from J. Berges and D. Sexty, arXiv:1201.0687)

Conclusions

- the field of ultra-relativistic heavy ion collisions is a very rich one (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