HEAVY ION COLLISIONS

AND

QUANTUM FIELDS IN AND OUT EQUILIBRIUM

EMMI Workshop on

"Prospects and Challenges for Future Experiments in Heavy Ion Collisions"
GSI, Darmstadt
February 15, 2013

European Research Council

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OUTLINE

Issues
Thermodynamics
Hydrodynamics
Thermalization
Jets and turbulent flow
Summary

ISSUES

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- Initial motivation (*QCD asymptotic freedom, quark-gluon plasma, deconfinement transition, restoration of chiral symmetry, etc*)
- Matter in equilibrium is described by QFT (*at finite temperature and density*)
- Wave functions of nuclei at high energy are given by QF d.o.f. (*partons, color glass fields, etc*)
- Many non equilibrium phenomena in HIC (*thermalization, fluctuations, jets, etc*)
- Theoretical tools (*pert. theory, lattice, 'analytic' non perturbative methods, AdS/CFT, etc*)

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Note: QCD is important mainly in early stages of high energy collisions

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- Temperature-density phase diagram not fully understood (*critical end point ?*)
- High temperature phase is well understood (T>3Tc) in terms of weak coupling expansions (*weakly coupled massive quasiparticles*).
- Vicinity of Tc : some understanding in terms of Euclidean concepts (*Polyakov loop, etc*). Physical d.o.f. ?
- Beyond perturbation theory with non perturbative RG, DSE. Also progress in 'IR QCD' (*Landau gauge*).

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Note: activity with its own 'dynamics'. Contact with HIC ?

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Plasma: *soft and hard modes, particles and fields*. Long wavelength modes can remain strongly coupled....

THERMALIZATION

- How do we go from the intial nuclear wave-functions to the locally equilibrated fluid seen in experiments ?
- What are the initial d.o.f.'s : partons ? color fields (CGC)? mixture of both ?
- Initial fields are typically unstable (e.g. if anisotric momentum distributions of particles). Instabilities provide 'fast' isotropization of momentum distributions
- Amplification of soft modes is a generic feature
- CGC picture suggests an overpopulation of soft modes

The overpopulated 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 $\quad n_0\, \epsilon_0^{-3/4} \sim 1/\alpha_s^{1/4}$

In equilibrated quark-gluon plasma

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

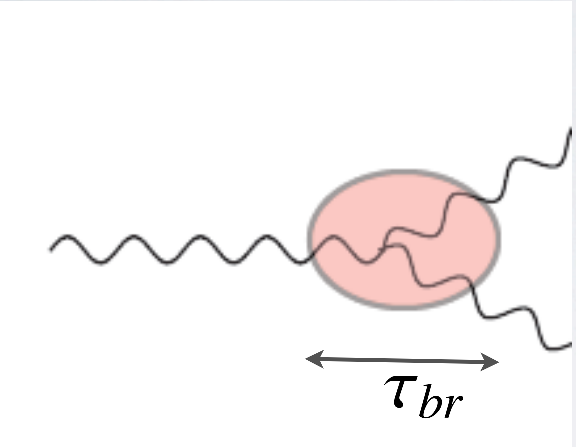
mismatch by a large factor (at weak coupling) $\quad \alpha_s^{-1/4}$

Will the system accommodate the particle excess by forming a Bose-Einstein condensate ?

(JPB, F. Gelis, J. Liao, L. McLerran, R. Venugopalan, 2012)

JETS AND TURBULENT FLOW

Medium induced gluon radiation (BDMPS-Z theory)



$\omega, k_\perp$

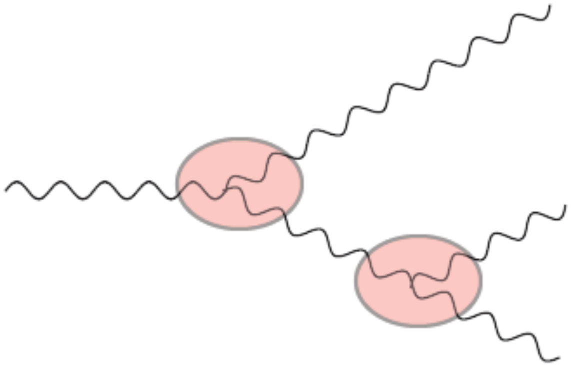
$$\frac{1}{\tau_{br}} \sim \frac{k_\perp^2}{2\omega} \qquad k_\perp^2 \sim \hat{q}\,\tau_{br}$$

$$\tau_{br} \sim \sqrt{\frac{2\omega}{\hat{q}}} \qquad \theta_{br} \sim \frac{k_\perp}{\omega} \sim \left(\frac{2\hat{q}}{\omega^3}\right)^{1/4}$$

Energy loss is dominated by a single emission with maximum energy

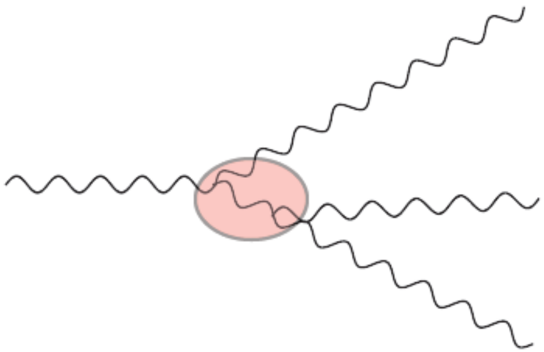
Multiple gluon branching can be important, and contribute to transport soft gluons towards large emission angles

Independent emissions are enhanced by a fator L/τ_f



$$\sim \left(\alpha_s \frac{L}{t_f}\right)^2$$

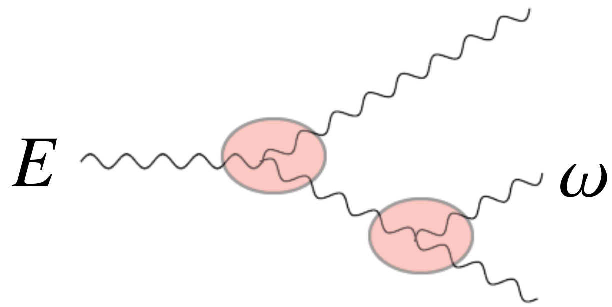
Interference effects are subleading



$$\sim \alpha_s^2 \frac{L}{t_f}$$

JPB, F. Dominguez, E. Iancu, Y. Mehtar-Tani, arXiv: 1209.4585

QCD cascade of a new kind



$$D(x,\tau) \equiv x\frac{\mathrm{d}N}{\mathrm{d}x}$$

$$x = \frac{\omega}{E}$$

$$\frac{\partial D(x,\tau)}{\partial \tau} = \int \mathrm{d}z\, \mathcal{K}(z) \left[\sqrt{\frac{z}{x}} D\left(\frac{x}{z},\tau\right) - \frac{z}{\sqrt{x}}\, D(x,\tau)\right]$$

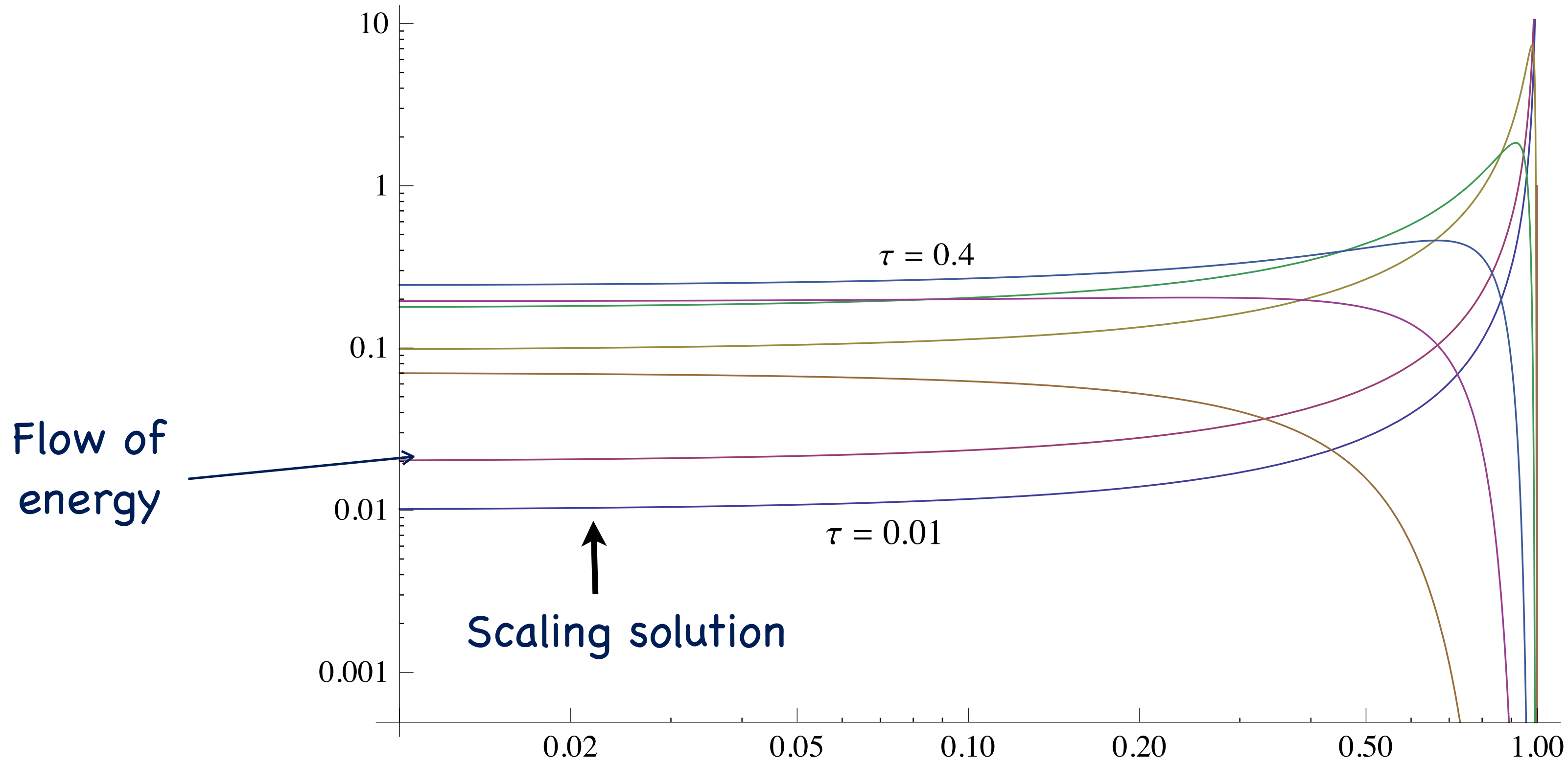
$$\mathcal{K}(z) = \frac{\bar{\alpha}}{2}\frac{f(z)}{[z(1-z)]^{3/2}}, \qquad f(z) = [1-z(1-z)]^{5/2}$$

Two features

- radiation (transport of momentum from hard to soft)

- turbulent flow (wave turbulence, nearly local interactions in momentum space = 'quasi-democratic' branching)

$\sqrt{x}D(x,\tau)$



$$\mathcal{E}_{\rm flow} = E\frac{\upsilon\tau^2}{2} = \frac{\upsilon}{2}\,\bar{\alpha}^2\omega_c \qquad \omega_c \equiv \frac{\hat{q}L^2}{2} \qquad \upsilon \simeq 5$$

Estimate

$\hat{q} = 1\,\mathrm{GeV}^2/\mathrm{fm}$ $\quad \omega_c \simeq 40$ Gev $\quad \bar{\alpha}^2 \simeq 0.1$ $\quad \mathcal{E}_{\rm flow} \simeq 15$ GeV

$L = 4$ fm

from J.-P. B., E. Iancu, Y. Mehtar-Tani, arXiv: 1301.6102

SUMMARY

- nice interplay between QFT and the physics of heavy ion collisions

- new phenomena are being predicted (and perhaps even seen)