EMMI 'Rapid Reaction Task Force' on Thermalization in non-abelian plasmas

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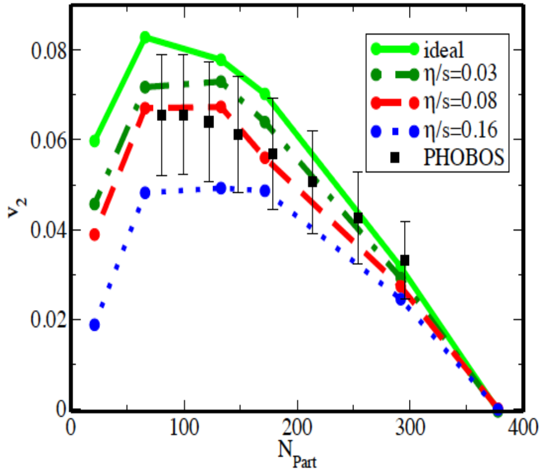
Phenomenological perspective

Empirical evidence from RHIC (and LHC):

- Matter produced in heavy ion collisions exhibit fluid behavior from very early time on (elliptic flow, sensitivity to fluctuations in initial conditions, etc)

- The fluid has very special transport properties, in particular a small value of the shear viscosity to entropy density ratio



Fluid behavior requires (some degree of) local equilibration. How is this achieved?

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

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

What is the fluid made of ?
What are the important degrees of freedom ?

(quasi) particles ? massive quarks and gluons ?

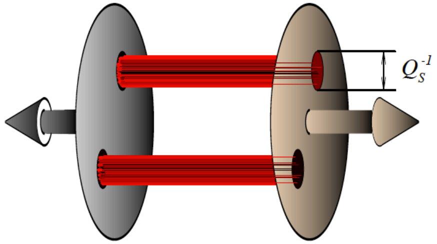
(classical) fields (color field, or AdS)

in a plasma, at weak coupling, separation of hard (particles) and soft (collective) modes, that are coupled together (hard loops)

$$j^{\mu}_{ind}(x) = \int \frac{d^3p}{(2\pi)^3} v^{\mu} \delta f(x,p) = \int dy \Pi^{\mu\nu}(x,y) A_{\nu}(y)$$

How is matter produced ?
Initial conditions

CGC assumes separation of charges (hard partons frozen during collision) and classical fields that dominate the interaction process



initial stages of collision dominated by longitudinal classical fields (glasma), with peculiar energy momentum tensor

saturation fixes the initial scale

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

related issue: entropy production

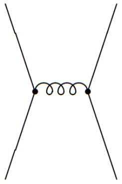
Many-body dynamics

Particles (f) and mean fields (E, B) giving rise to force

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \wedge \mathbf{B})$$

Particles move under influence of force, and collide with each other. Typical kinetic equation:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + \mathbf{F} \cdot \frac{\partial f}{\partial \mathbf{r}} = C[f]$$



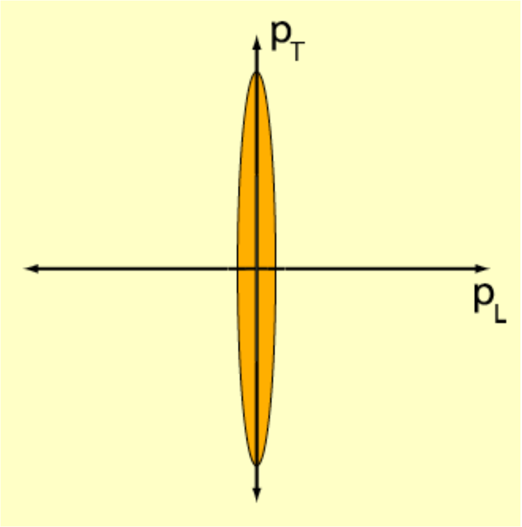
Note: F is force, derives from mean field, depends non linearly on phase space density f, that is $\mathbf{F} = \mathbf{F}[f]$

longitudinal expansion

Simple (boost invariant) expansion (ignoring mean field)

$$\partial_t f - \frac{p_z}{t}\partial_{p_z} f = \left.\frac{df}{dt}\right|_{p_z t} = C[f] \qquad\qquad \partial_t \epsilon + \frac{\epsilon + P_L}{t} = 0$$

in case of free streaming,
the momentum distribution
becomes rapidly very anisotropic



Mean field instabilities
Isotropization

Collective modes in anisotropic plasmas can become instable (e.g. Weibel instability)

Instabilities contribute to restore/maintain isotropy

Instabilities populate low momentum modes, leading to large occupation of soft field/modes

Overpopulation of the initial partonic state
Thermodynamical considerations

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

(when elastic processes dominate)

Most particles are in the BEC

$$n_{\mathrm{c}} \sim \frac{Q_{\mathrm{s}}^3}{\alpha}\left(1-\alpha^{1/4}\right) \qquad n_c = n - n_g$$

BEC contributes little to the energy density

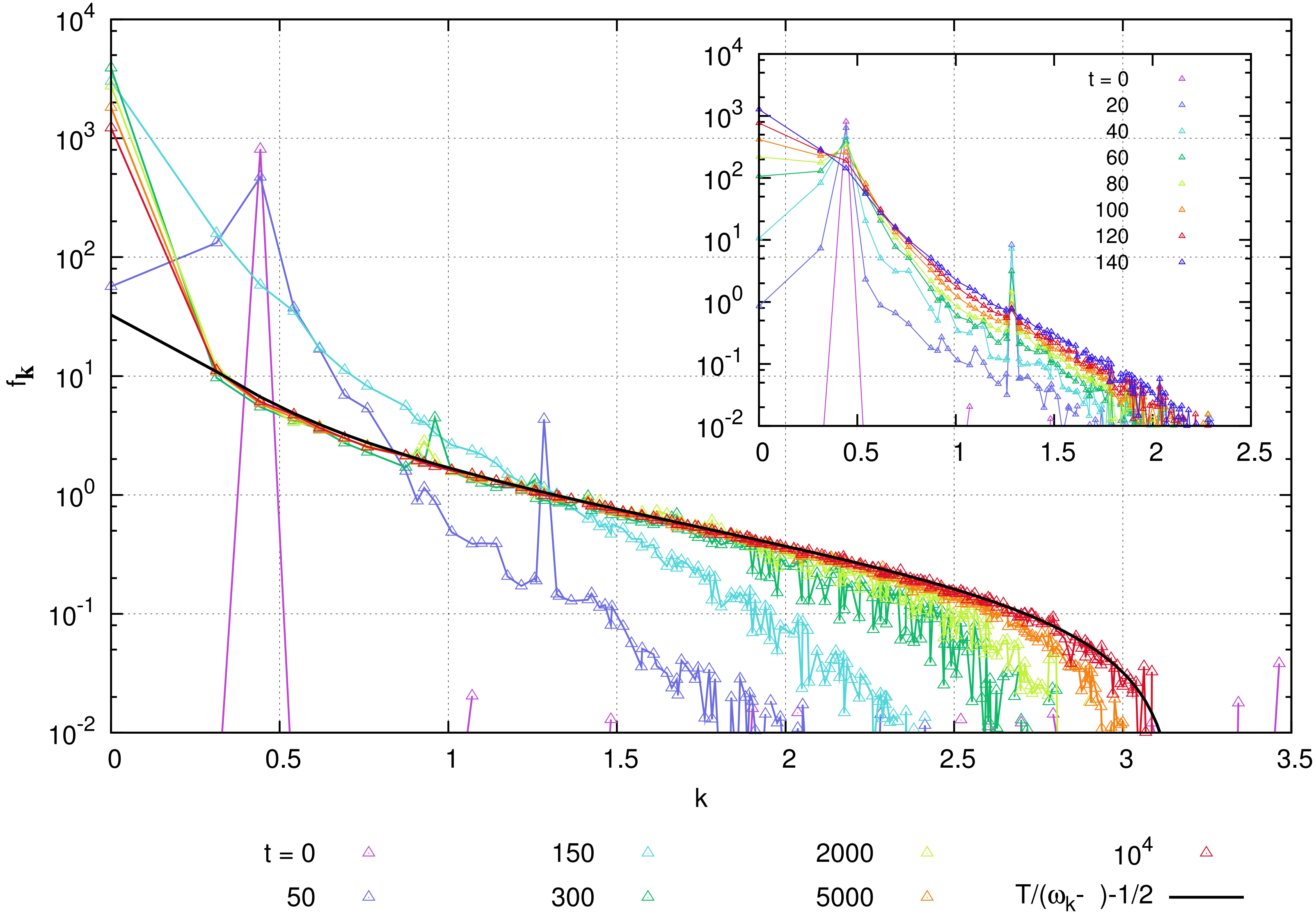
$$n_{\mathrm{c}}\, m \sim \frac{Q_{\mathrm{s}}^3}{\alpha_{\mathrm{s}}}\, \alpha_{\mathrm{s}}^{1/4} Q_{\mathrm{s}} \sim \alpha^{1/4} T^4 \ll \epsilon_0$$

Entropy considerations

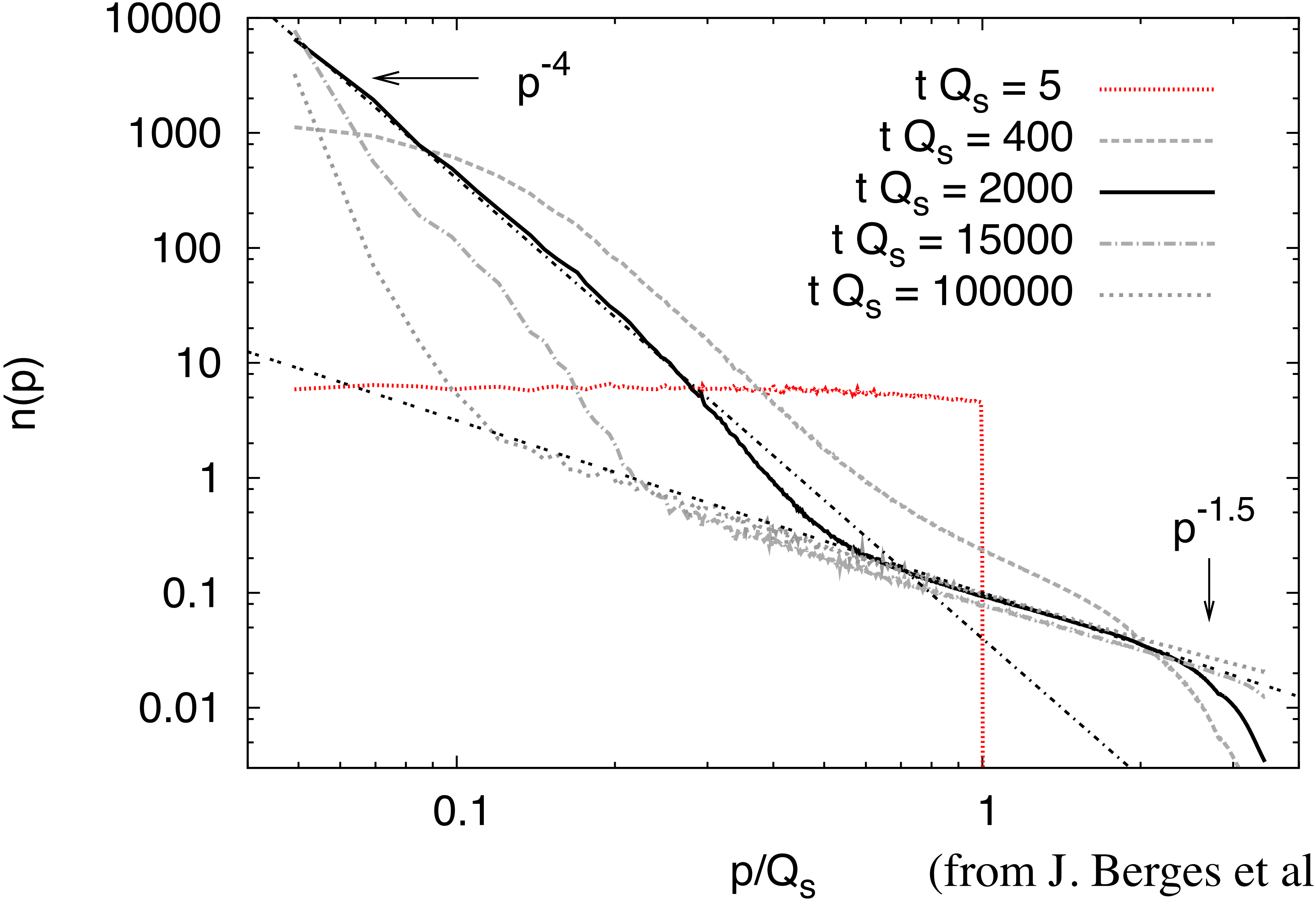
$$s \sim \int_{\boldsymbol{p}} \ln f_{\boldsymbol{p}} \qquad s_0 \sim Q_s^3 \qquad s_{eq} \sim T^3 \sim Q_{\mathrm{s}}^3/\alpha^{3/4}$$

Note: when $f \sim 1/\alpha_{\mathrm{s}}$ all dependence on coupling disappears -> classical field dynamics

Classical simulation (scalar theory)



(T. Epelbaum and F. Gelis, 2011)



(from J. Berges et al)

Towards a scenario for thermalization in heavy ion collisions

-Initial dynamics described by **classical color fields** (CGC), with characteristic **saturation scale** Qs

- instabilities play an important role: **isotropization**, cascade towards the infrared leading to **large occupancy** of (very) **soft modes**
- because of the large occupation, the system remains **strongly coupled** in spite of the small coupling constant
- a transient **Bose condensate** may form if particle number conserving processes dominate. This may be accompanied by fromation of **turbulent cascades**....

- inspiration from other fields (cold atoms, cosmology)