Discussion on thermalization in heavy ion collisions

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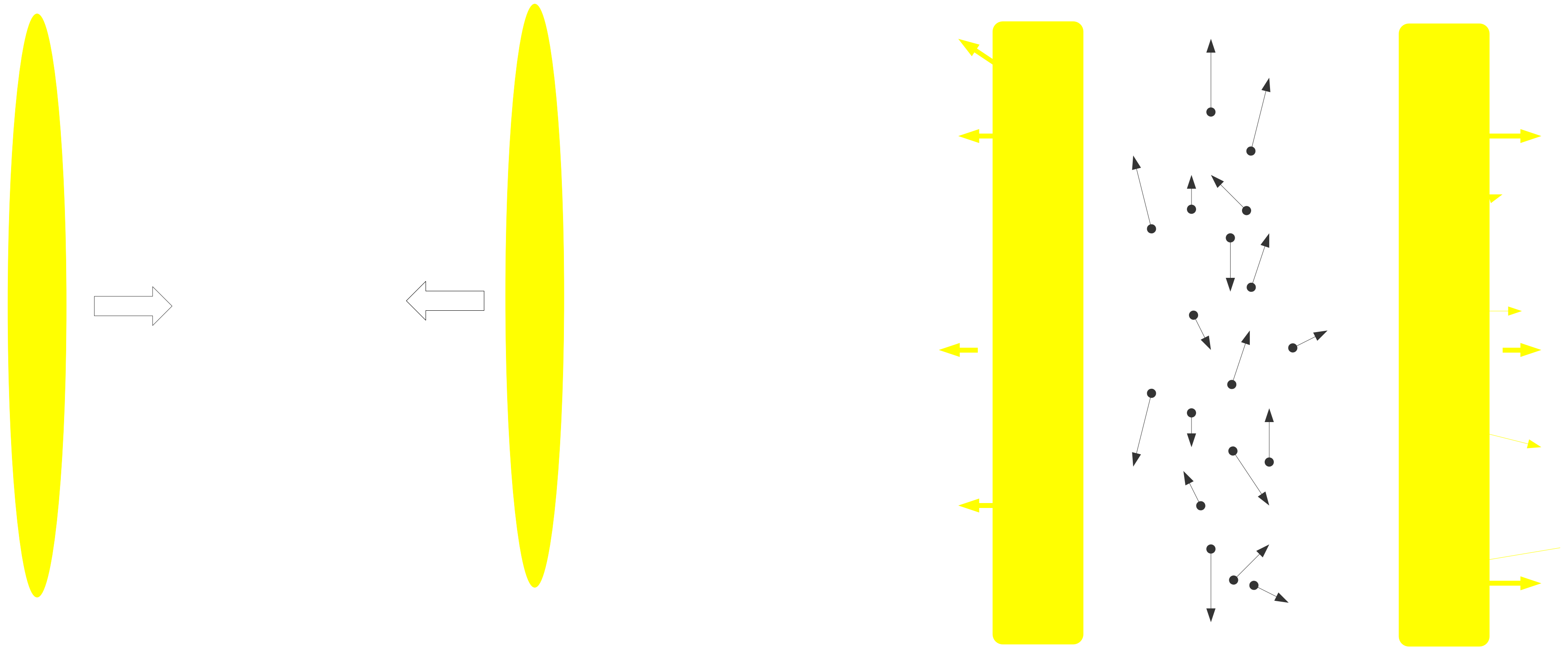
Relativistic heavy ion collisions



quarks and gluons are knocked out of nuclei

subsequent expansion, initially quasi 1-dimensional

Thermalization?

expansion, finite lifetime

thermalization requires $\Gamma_{\text{interaction}} \gg \Gamma_{\text{expansion}}$

RHIC: lifetime $< 10\text{fm}$

boost invariant expansion: $\Gamma_{\text{expansion}} \sim \tau^{-1}$

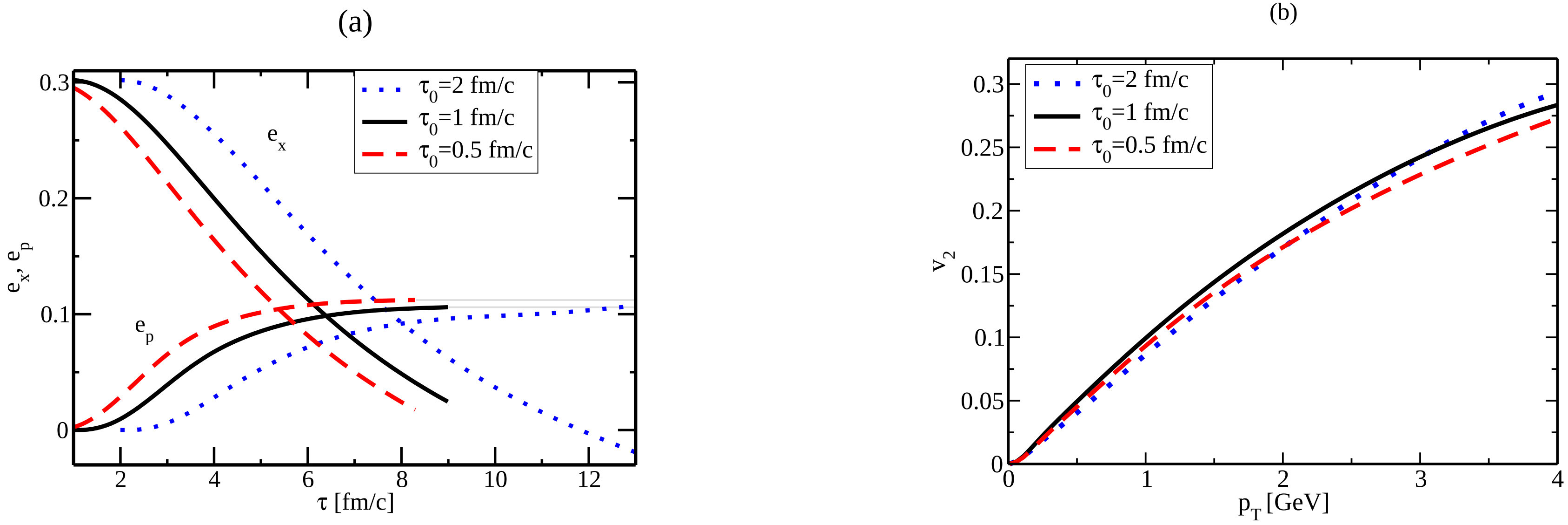
$\Gamma_{\text{interaction}} \sim (0.5\text{fm})^{-1}$ für $T \sim 500\text{MeV}$?

Thermalization?

hydrodynamics gives experimentally observed elliptic flow v_2

only for early thermalization $\tau_0 \sim 0.5$ fm [Heinz]

τ_0 need not be that small (for appropriate initial conditions) [Luzum, Romatschke]



Thermalization?

experiments give no indication for longitudinal pressure p_z

$$T^{ij} = \begin{pmatrix} p_{\rm t} & 0 & 0 \\ 0 & p_{\rm t} & 0 \\ 0 & 0 & p_z \end{pmatrix}$$

Theoretical framework

weak coupling limit $\alpha_s(Q) \ll 1$

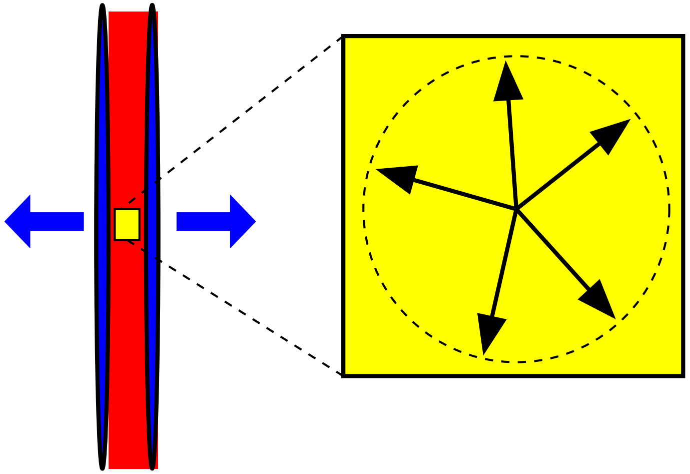
- theoretical control
- valid for momenta, (density)$^{1/3} \sim Q \gg \Lambda_{\rm QCD}$

occupation number $f(Q) \ll 1/g^2$

- weakly interacting “hard” quarks and gluons

maximal temperature: $T_{\rm max} \sim g^{2/3} Q$

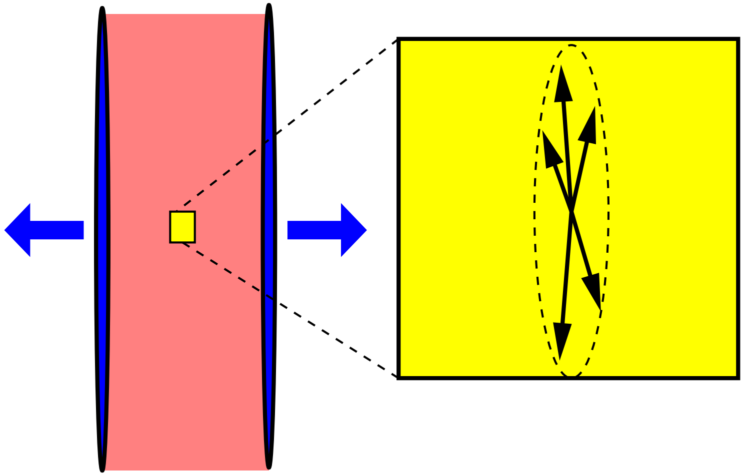
Momentum anisotropy



$\tau \lesssim Q^{-1}$: production of "hard" gluons with

$$p_\perp \sim Q$$

(isotropic momentum distribution)



free expansion in z-direction →

$$p_z \ll p_\perp$$

while $p_z \sim p_\perp$ in equilibrium

Momentum anisotropy

Bottom up thermalization

at some point $p_z \sim gQ$

weak coupling $g \ll 1$

$\Rightarrow p_z \ll Q$

understanding isotropization in weak coupling requires studying extreme anisotropy

other scenario:

$p_z \gg p_\perp$ initially [Mrowczynski]

Interactions

only $2 \rightarrow 2$ scattering:

$\tau_0 \sim \exp(1/\alpha_s)$ [Mueller]

ineleastic processes: $2 \leftrightarrow 3$ gluons

soft $(k \ll Q)$ gluon production speeds up thermalization

“bottom up thermalization” [Baier, Mueller, Son, Schiff]

$$\tau_0 \sim \alpha_s^{-13/5} Q^{-1}, \qquad T_0 \sim \alpha_s^{2/5} Q$$

additional mechanism: plasma instabilities

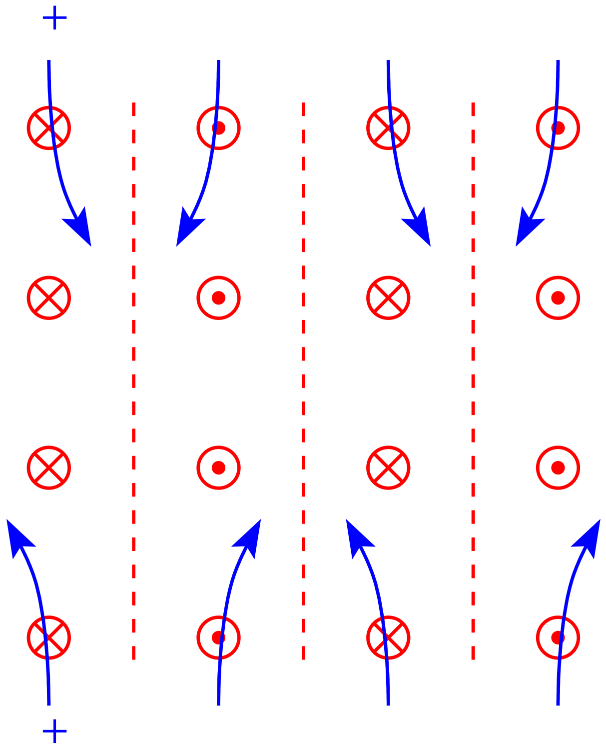
collective effect

known from (QED) plasma physics

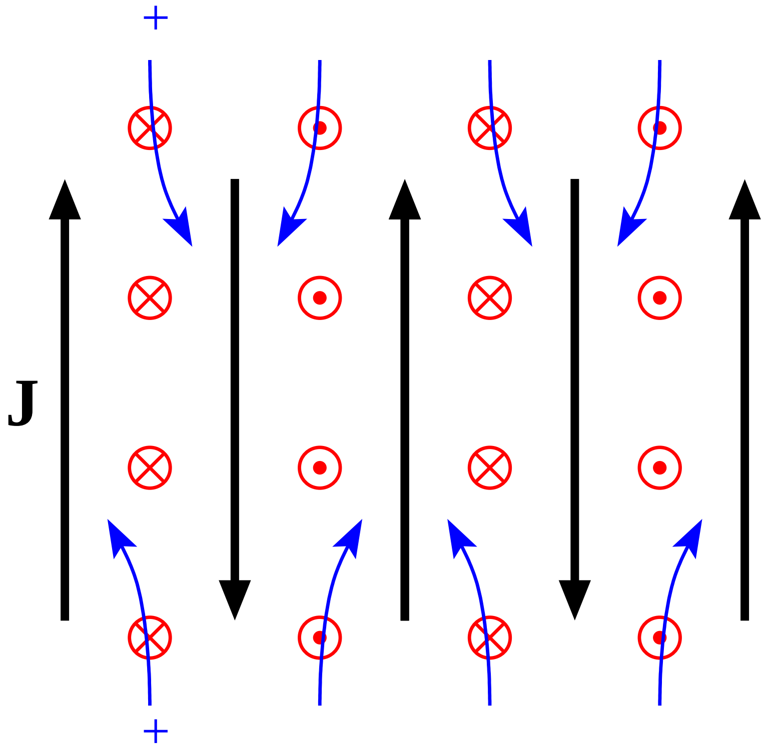
affect bottom up thermalization [DB]

Plasma instabilties

anisotropic plasmas are unstable [Weibel,...], small fluctuations grow exponentially



(a)



(b)

wave vector $\boldsymbol{k}^2 \sim m_0^2 \sim g^2 \int d^3p \frac{\partial f(\boldsymbol{p})}{\partial p} \sim g^2 f Q^2$

Multi-scale problem

hard scale Q

$$p_\perp \sim Q$$

soft scale m

$$\begin{aligned} m^2 &\sim \text{polarization tensor} \\ &\sim g^2 \int d^3p \frac{\partial f_\mathrm{h}}{\partial p} \\ &\sim g^2 Q p_z f_h \end{aligned}$$

m/v_z

relevant for strong anisotropy $p_z/p_\perp \sim v_z \ll 1$

difficult to accomodate on one lattice

Which modes are unstable

unstable modes $k^2 \sim m^2$, $m^2 \sim g^2 f Q^2$

$$m \ll Q \qquad \text{for} \qquad f \ll \frac{1}{g^2}$$

unstable modes are soft

strong anisotropy, $v_z = p_z/Q \ll 1$:

$\exists$ unstable modes with

$$k \sim \frac{m}{v_z} \gg m$$

$\boldsymbol{k}$ mainly in z-direction

QED vs QCD

weak fields: non qualitative difference between QED and QCD

exponential growth must saturate, non-linear effect

QED: saturation when $\Delta p \sim p \sim Q$ within $t \sim k^{-1}$

$\Leftrightarrow$ amplitude $e\boldsymbol{B}k^{-1} \sim Q \quad \Leftrightarrow \quad g\boldsymbol{A} \sim Q$

$\longrightarrow$ fast isotropization (?)

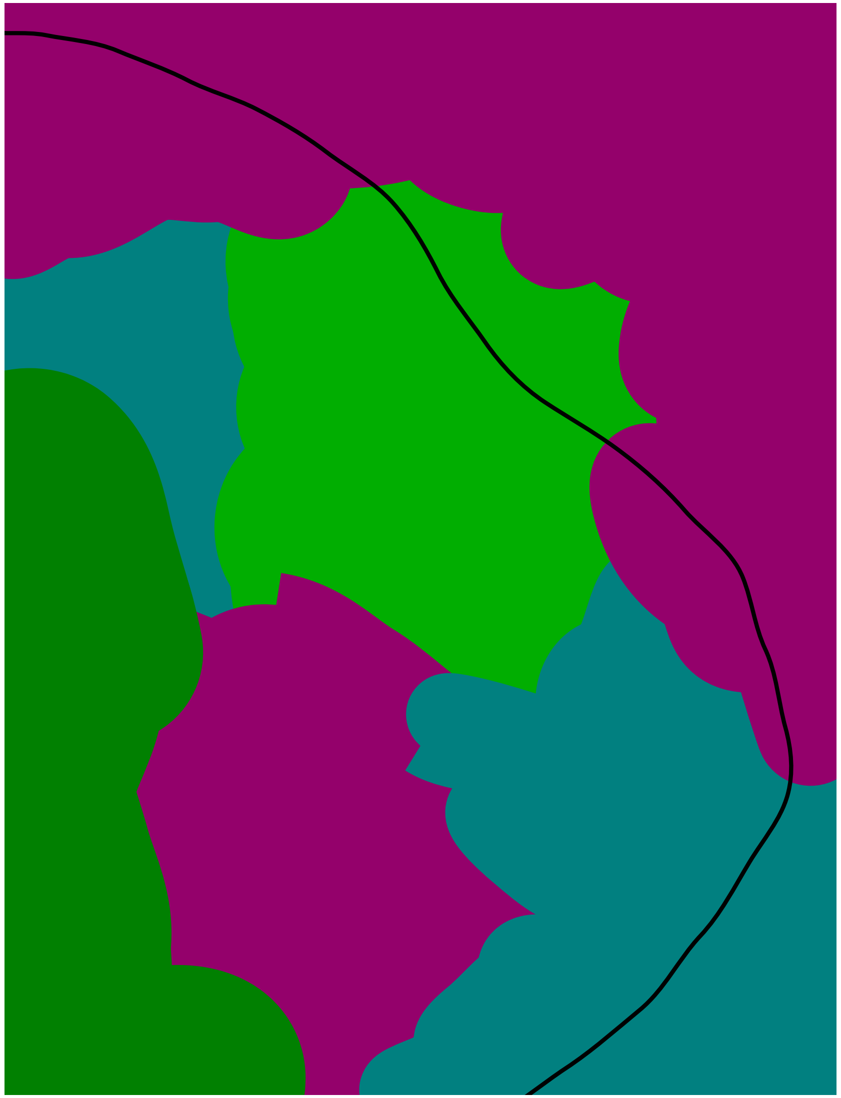
QCD: non-linear when

$$g\boldsymbol{A} \sim \nabla \quad \Leftrightarrow \quad g\boldsymbol{A} \sim \boldsymbol{k} \ll Q$$

then effect on hard gluons is still small

or maybe not? nonperturbative problem

Effect of unstable modes on hard gluons



randomly oriented domains of long wavelength gluon fields

hard gluon momenta perform random walk

$\Rightarrow$ p_z-broadening, isotropization

more efficient than elastic scattering

Effect of unstable modes on hard gluons

Boost-invariant 1-dimensional expansion of free particles:

$$p_z \sim Q(Qt)^{-1}$$

elastic scattering:

$$p_z \sim Q(Qt)^{-1/3}$$

abelian saturation:

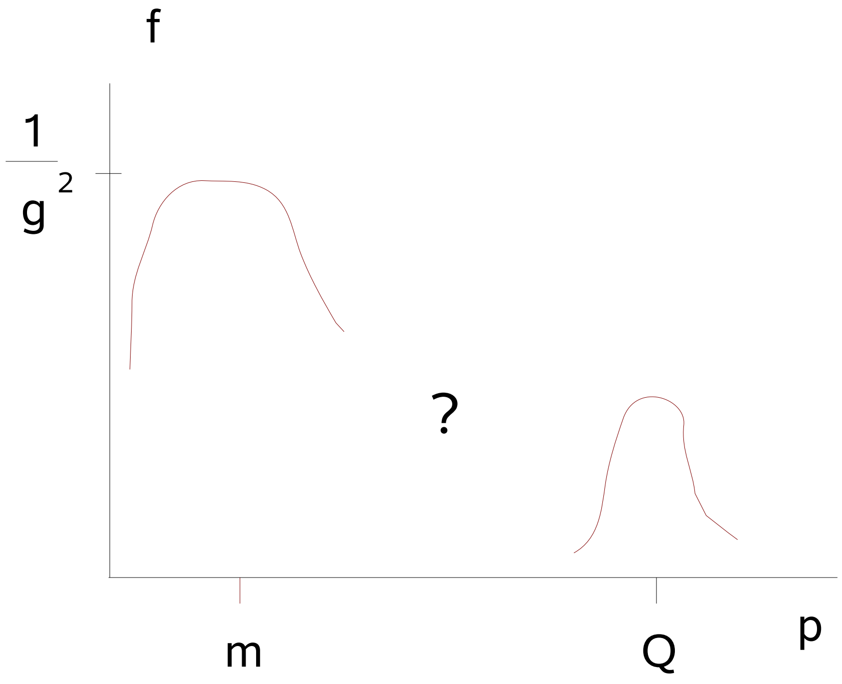
$$p_z \sim Q$$

non-abelian saturation:

$$p_z \sim Q(Qt)^{-1/8}$$

We need to know a lot more

what is the spectrum of the UV cascade?



how is energy transferred from unstable to stable modes for $k \gg m$?

Open questions

- what is the mechanism for saturation?
- at which amplitude does saturation occur for strong anisotropy?
- what is the spectrum of the UV cascade?
- is there a universal parametric result for the thermalization time and temperature?
- experimental signature of instabilities?
- experimental signature of longitudinal pressure?