# Color Instabilities in Relativistic Heavy-Ion Collisions

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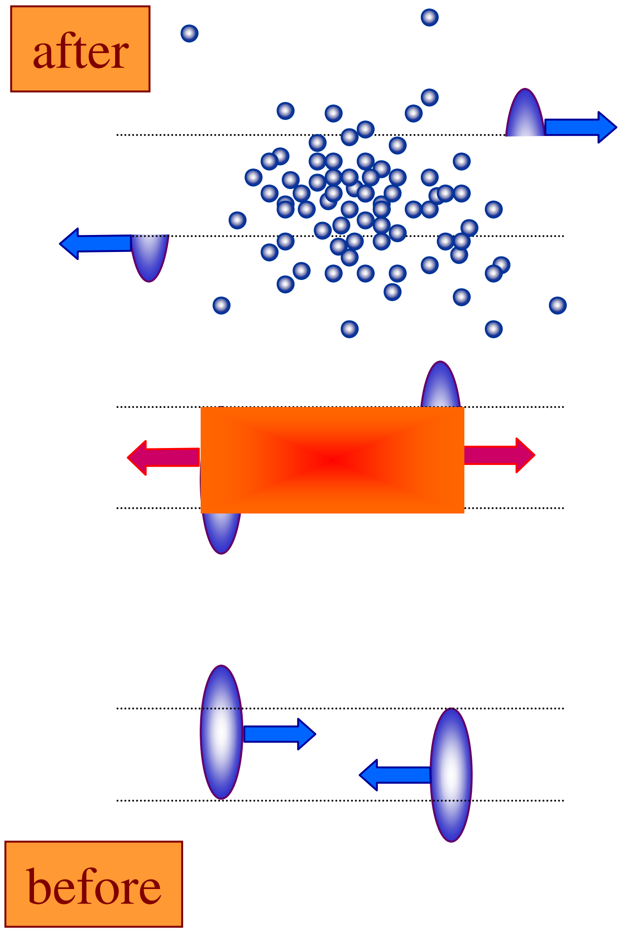
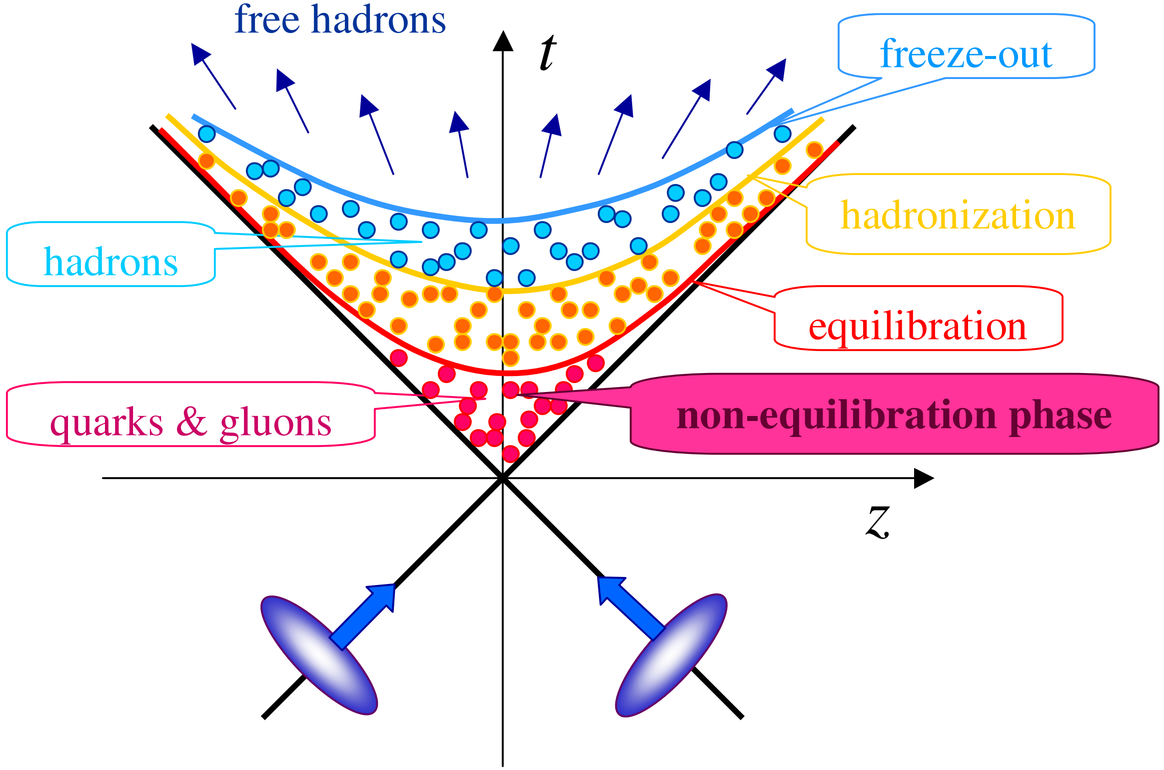
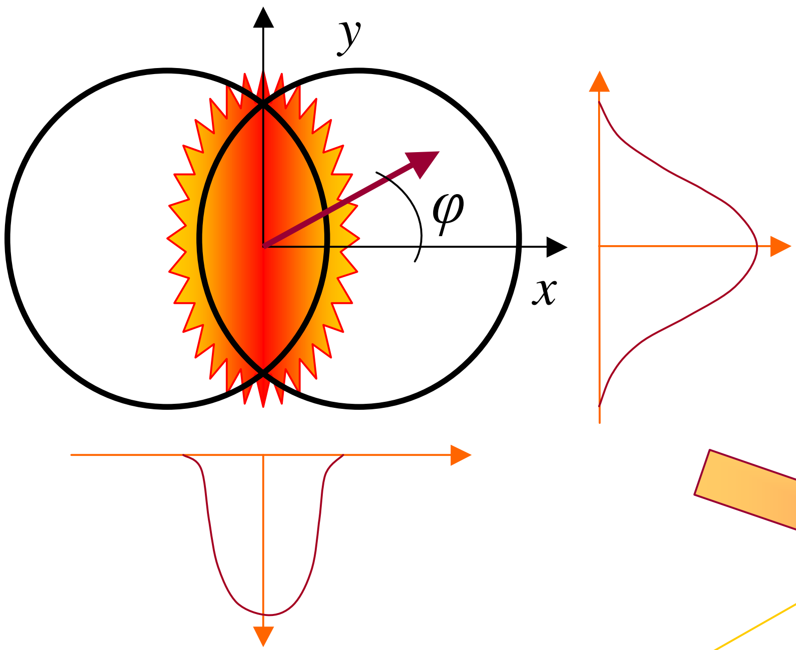
# Course of relativistic heavy-ion collisions



# Early stage equilibration @ RHIC

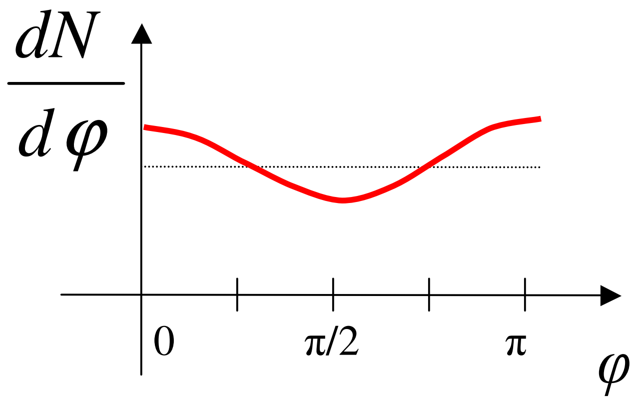
**Success of hydrodynamic models in describing elliptic flow**




Hydrodynamics

$$\left(\frac{\partial}{\partial t} + \mathbf{v}\nabla\right)\mathbf{v} = -\frac{\nabla p}{\rho}$$

Hydrodynamics requires local thermodynamical equilibrium!



# Equilibration is fast

$$v_2 \sim \varepsilon = \left\langle \frac{x^2 - y^2}{x^2 + y^2} \right\rangle$$

**Eccentricity decays due to the free streaming!**

$\varepsilon \searrow \;\Rightarrow\; v_2 \searrow$ ➡ $t_{eq} \le 1\ \text{fm}/c$

time of equilibration

U. Heinz, AIP Conf. Proc. **739,** 163 (2004)

# Collisional equilibration

**If QGP is weakly coupled:** $\alpha_s \equiv \frac{g^2}{4\pi} << 1$ – QCD coupling constant

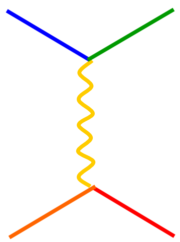
**Time of equilibration driven by parton-parton collisions**

$$t_{\mathrm{eq}} \sim \frac{1}{g^4 \ln(1/g)\, T}$$

$T$ – characteristic momentum

either single hard scattering
or multiple soft scatterings

dominated by



**Collisions are too slow !**

# Possible conclusion & objection

**QGP is strongly coupled: QGP → sQGP**

**But . . .**

**asymptotic freedom @ high-energy density**

… $\alpha_s \approx 0.3$

**FAQ**

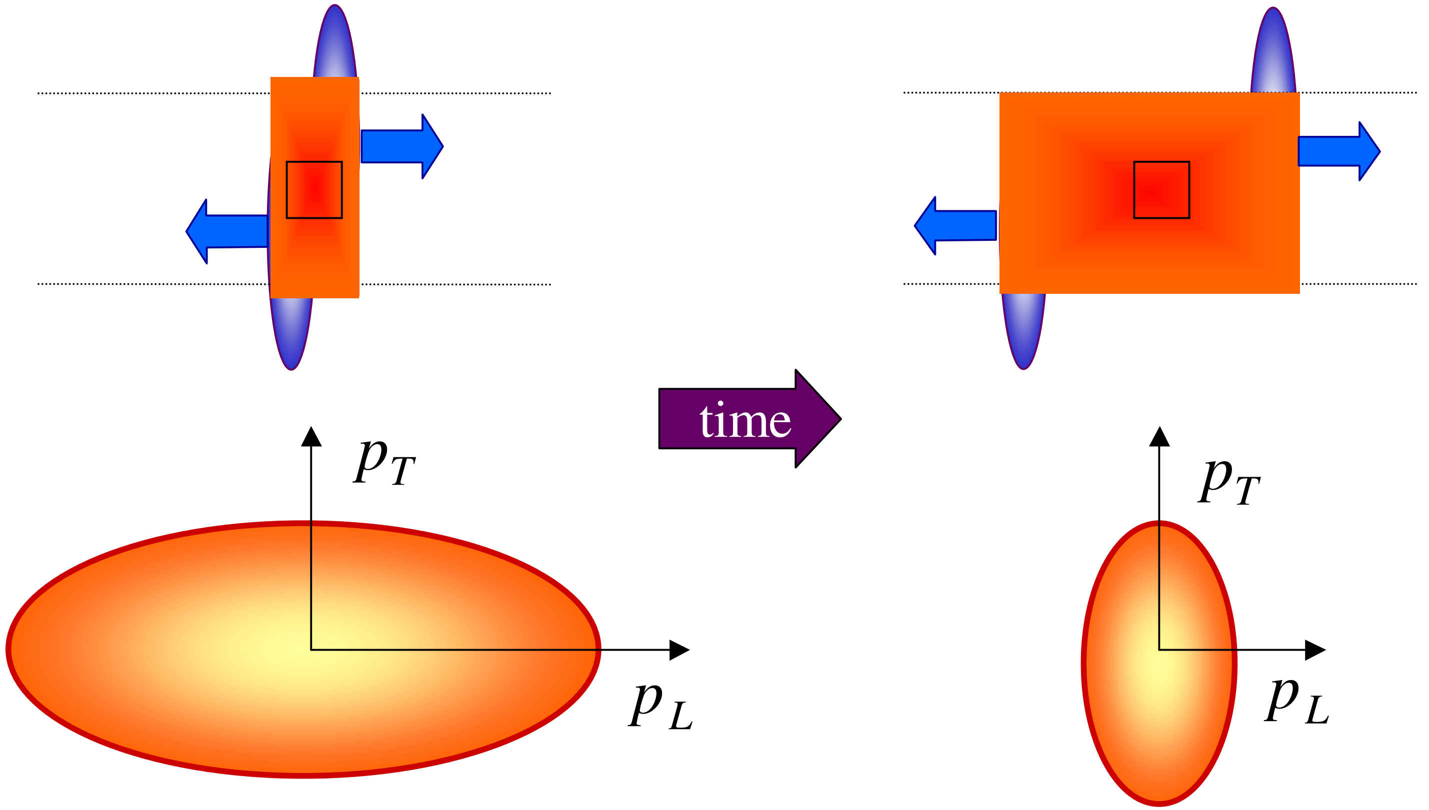
**Q: Can weakly coupled QGP equilibrate fast?**

**A: Yes, due to chromomagnetic instabilities!**

# Chromomagnetic instabilities

**The instabilities occur due to anisotropy of the momentum distribution**

Parton momentum distribution is initially anisotropic

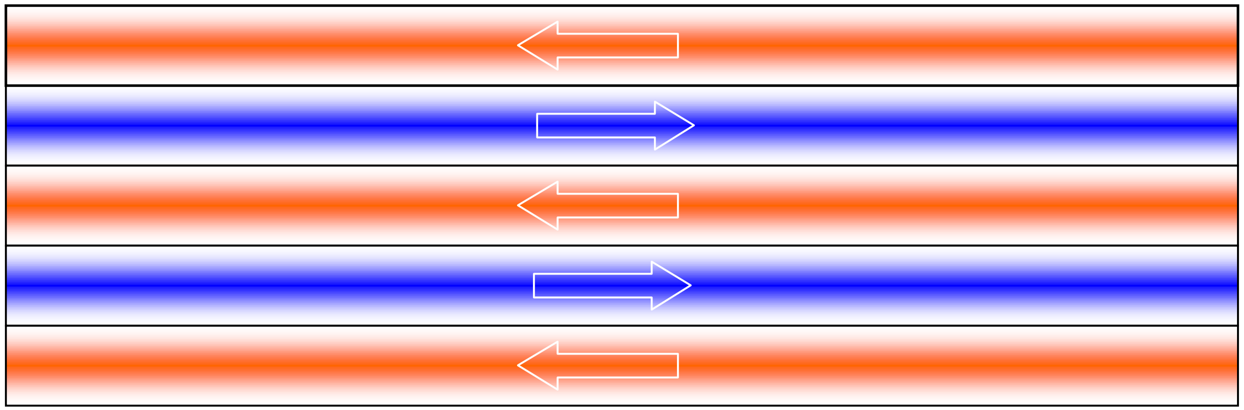


# Seeds of instability

$\left\langle j_a^{\mu}(x) \right\rangle = 0$ **but current fluctuations are finite**

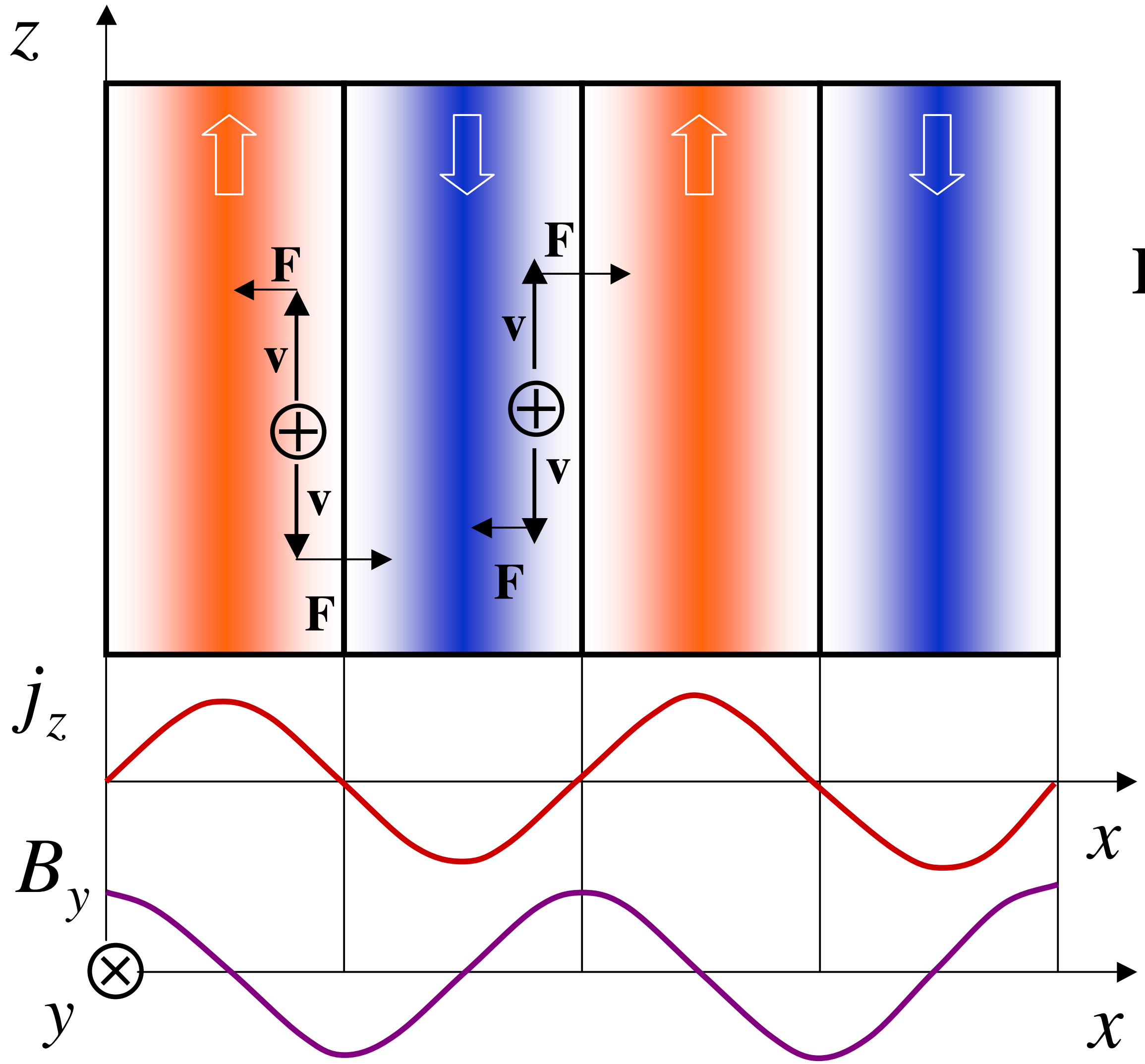
$$\left\langle j_a^{\mu}(x_1)\, j_b^{\nu}(x_2) \right\rangle = \frac{1}{2}\delta^{ab} \int \frac{d^3p}{(2\pi)^3} \frac{p^{\mu} p^{\nu}}{E_p^2} f(\mathbf{p}) \delta^{(3)}(\mathbf{x} - \mathbf{v}t) \neq 0$$

$$x_1 = (t_1, \mathbf{x}_1), \quad x_2 = (t_2, \mathbf{x}_2), \quad x = (t_1 - t_2, \mathbf{x}_1 - \mathbf{x}_2)$$



**Direction of the momentum surplus**

# Mechanism of filamentation




Lorentz force

$$\mathbf{F} = q\,\mathbf{v}\times\mathbf{B}$$

Ampere's law

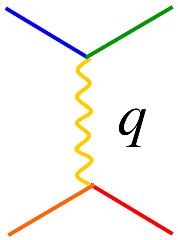
$$\nabla\times\mathbf{B} = \mathbf{j}$$

# Instabilities are fast

Time scale of processes driven by parton-parton scattering

$$t_{\text{hard}} \sim \frac{1}{g^4 \ln(1/g)\, T}$$

$$t_{\text{soft}} \sim \frac{1}{g^2 \ln(1/g)\, T}$$




hard scattering: $q \sim T$

soft scattering: $q \sim gT$

Time scale of collective phenomena

$$t_{\text{collec}} \sim \frac{1}{g\, T}$$

$$g^2 << 1 \quad \Rightarrow \quad t_{\text{hard}} >> t_{\text{soft}} >> t_{\text{collec}}$$

**The instabilities are fast!**

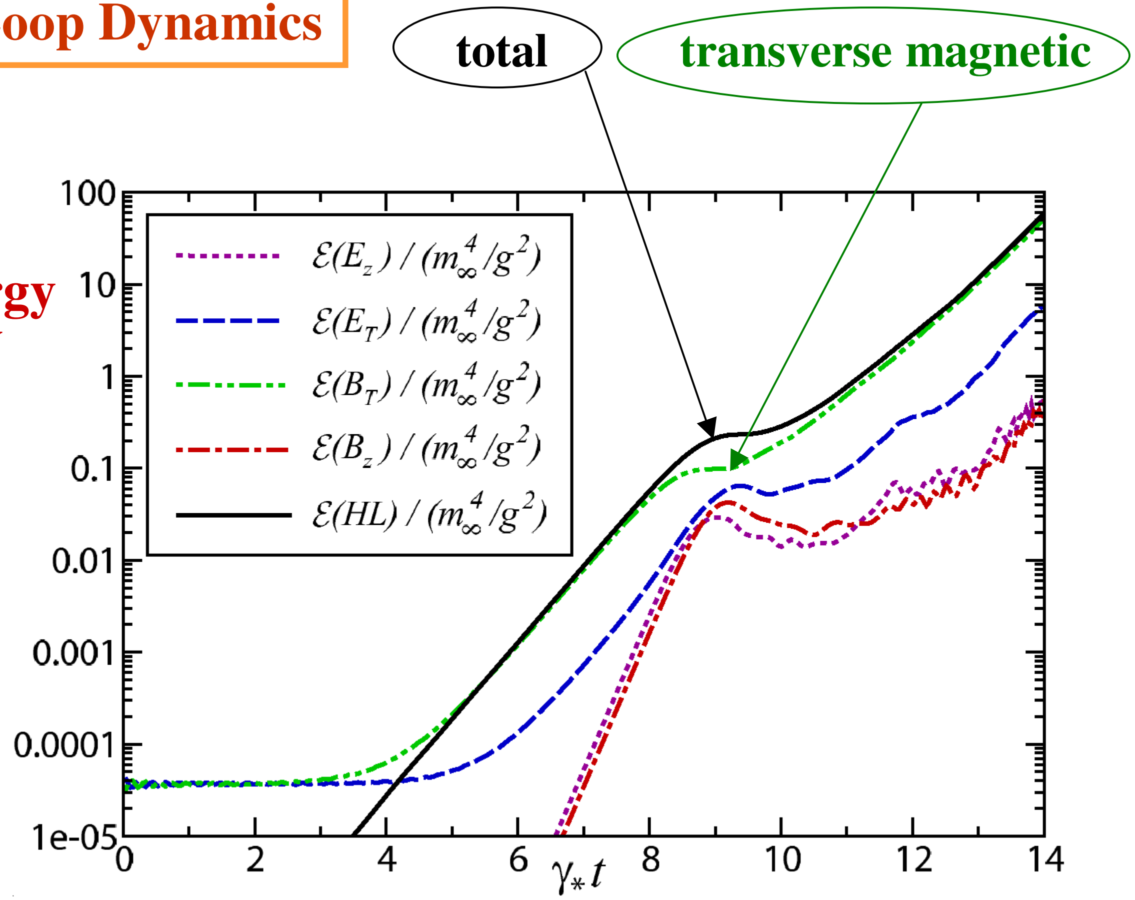
# Growth of instabilities – 1+1 numerical simulations

**SU(2) Hard Loop Dynamics**

**1+1 dimensions**

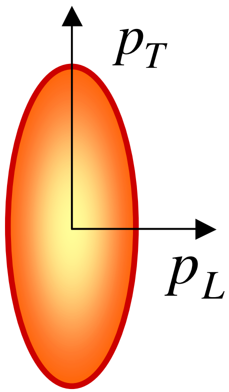
$$A_a^\mu = A_a^\mu(t, z)$$

**Scaled field energy density**




$\gamma_*$ - maximal growth rate

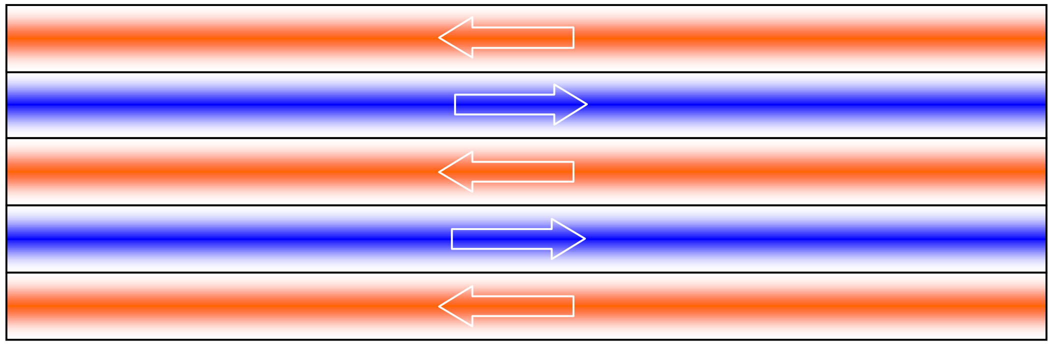
**Anisotropic particle's momentum distribution**



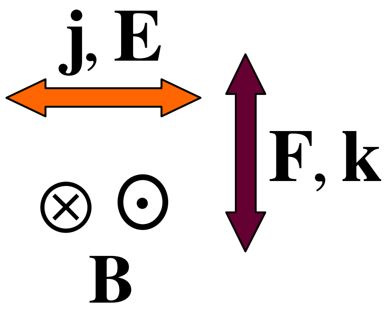

oblate

A. Rebhan, P. Romatschke & M. Strickland, Phys. Rev. Lett. **94**, 102303 (2005)

# Isotropization



**Direction of the momentum surplus**




**momentum change of particles**

$$\Delta \mathbf{p} = \int dt\, \mathbf{F}$$

**momentum of fields**

$$\mathbf{P}_{\text{fields}} \sim \mathbf{B}^a \times \mathbf{E}^a \sim \mathbf{k}$$

# Isotropization – numerical simulation

**Classical system of colored particles & fields**

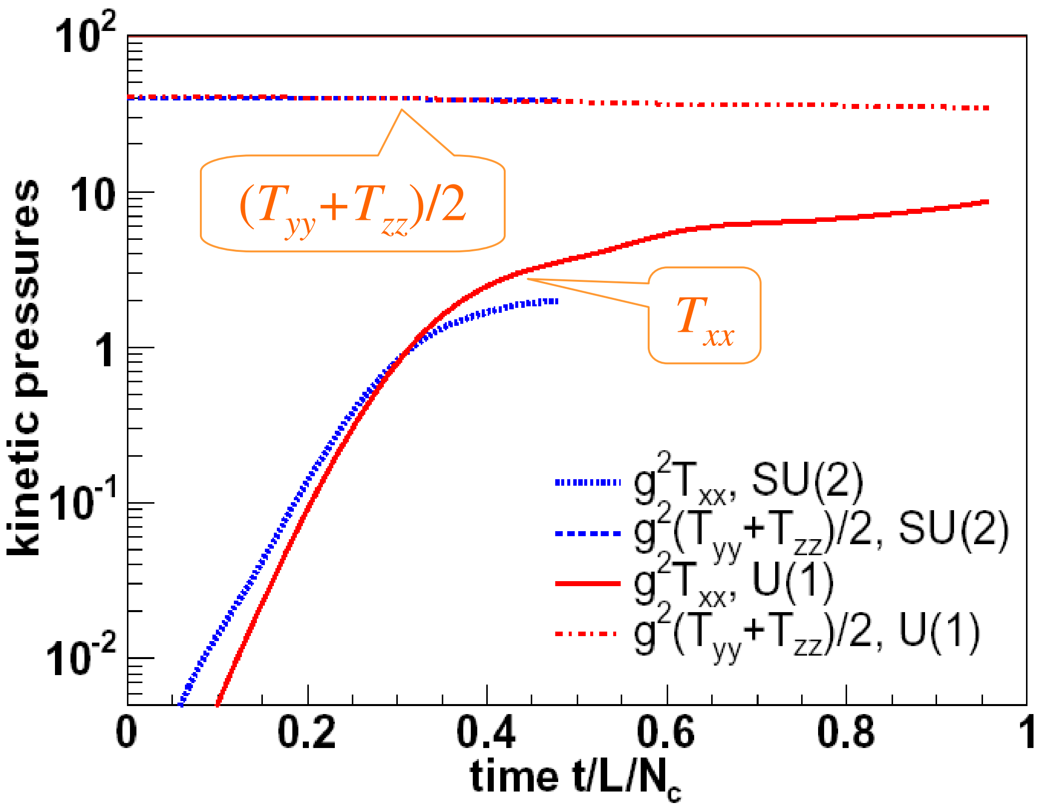
$$T_{ij} = \int \frac{d^3p}{(2\pi)^3} \frac{p_i p_j}{E} f(\mathbf{p})$$

**Initial anisotropy:**

$$T_{xx} = 0$$

**Isotropy:**

$$T_{xx} = (T_{yy} + T_{zz})/2$$




A. Dumitru & Y. Nara, Phys. Lett. **B621**, 89 (2005).

# Conclusion

**The scenario of instabilities driven equilibration provides a plausible solution to the fast equilibration problem of weakly coupled plasma**