Relativistic Heavy-Ion Collisions

– a subjective overview for AdS/CFT enthusiasts –

Stanisław Mrówczyński

Jan Kochanowski University, Kielce, Poland
& Institute for Nuclear Studies, Warsaw, Poland

Experimental Programs

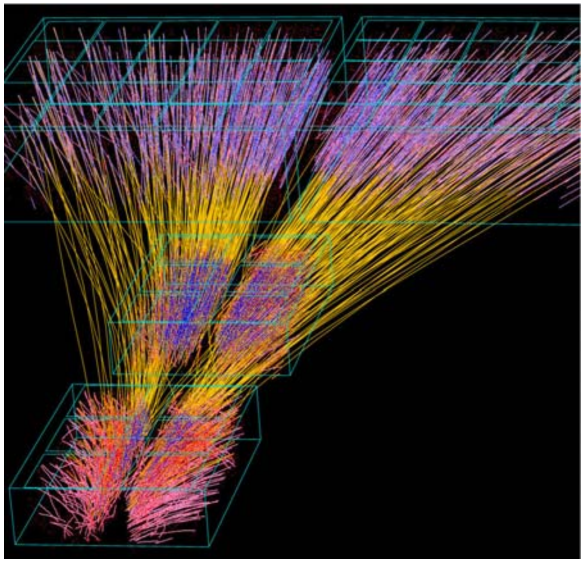
- **AGS** – Alternating Gradient Synchrotron, BNL
  fixed target experiments, energy 15 AGeV

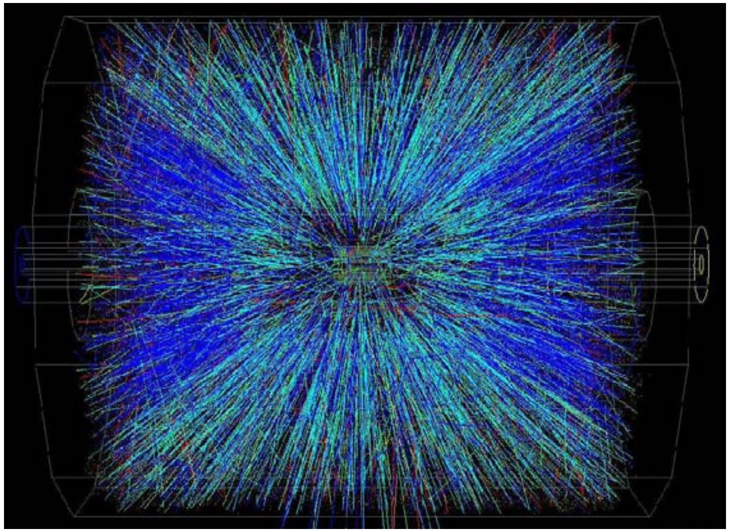
- **SPS** – Super Proton Synchroton, CERN
  fixed target experiments, energy 20-160 AGeV

- **RHIC** – Relativistic Heavy-Ion Collider Collider, BNL
  energy up to 100+100 AGeV

NA49 experiment @ SPS

$\mathrm{Pb}-\mathrm{Pb}\ @\ 158\ A\,\mathrm{GeV}$

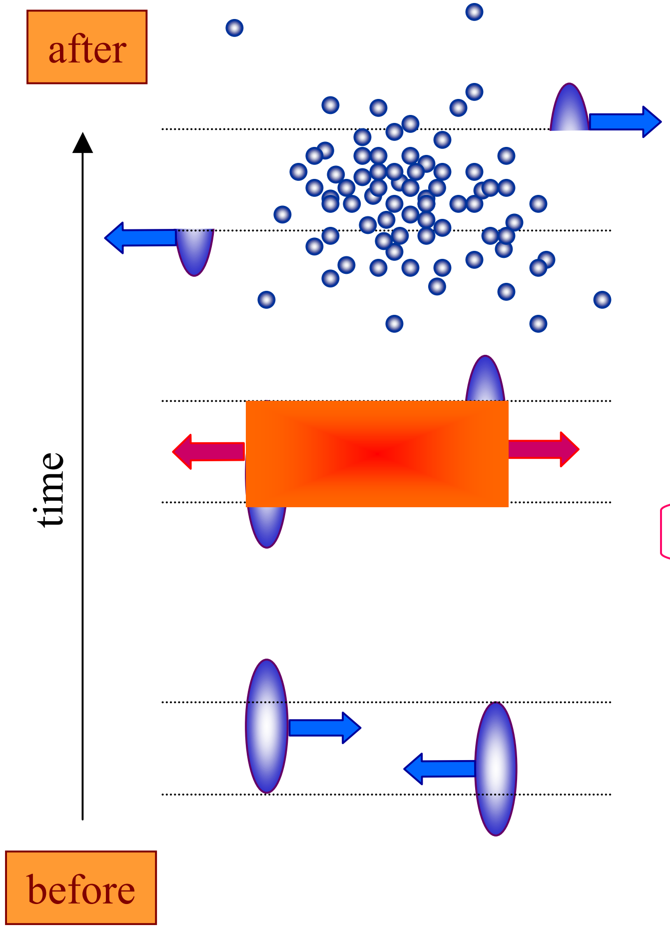




STAR experiment @ RHIC

$\mathrm{Au}-\mathrm{Au}\ @\ \sqrt{s_{NN}} = 200\ \mathrm{GeV}$

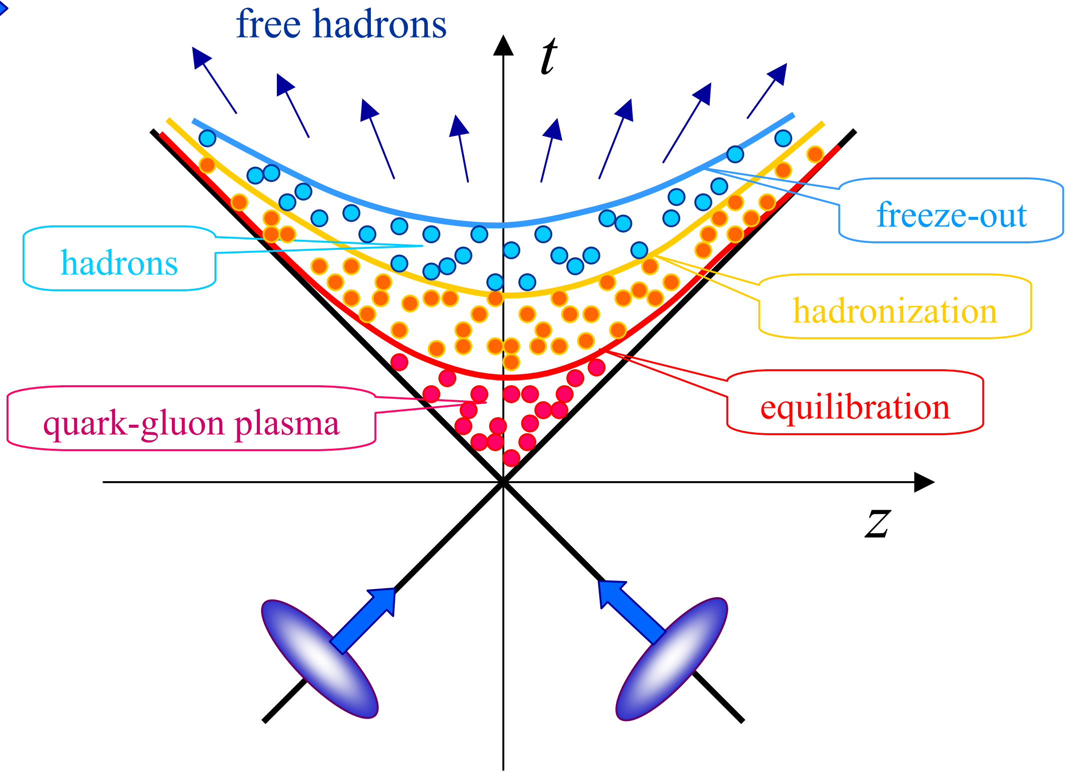
Scenario of relativistic heavy-ion collisions



after

time

before



free hadrons

t

freeze-out

hadrons

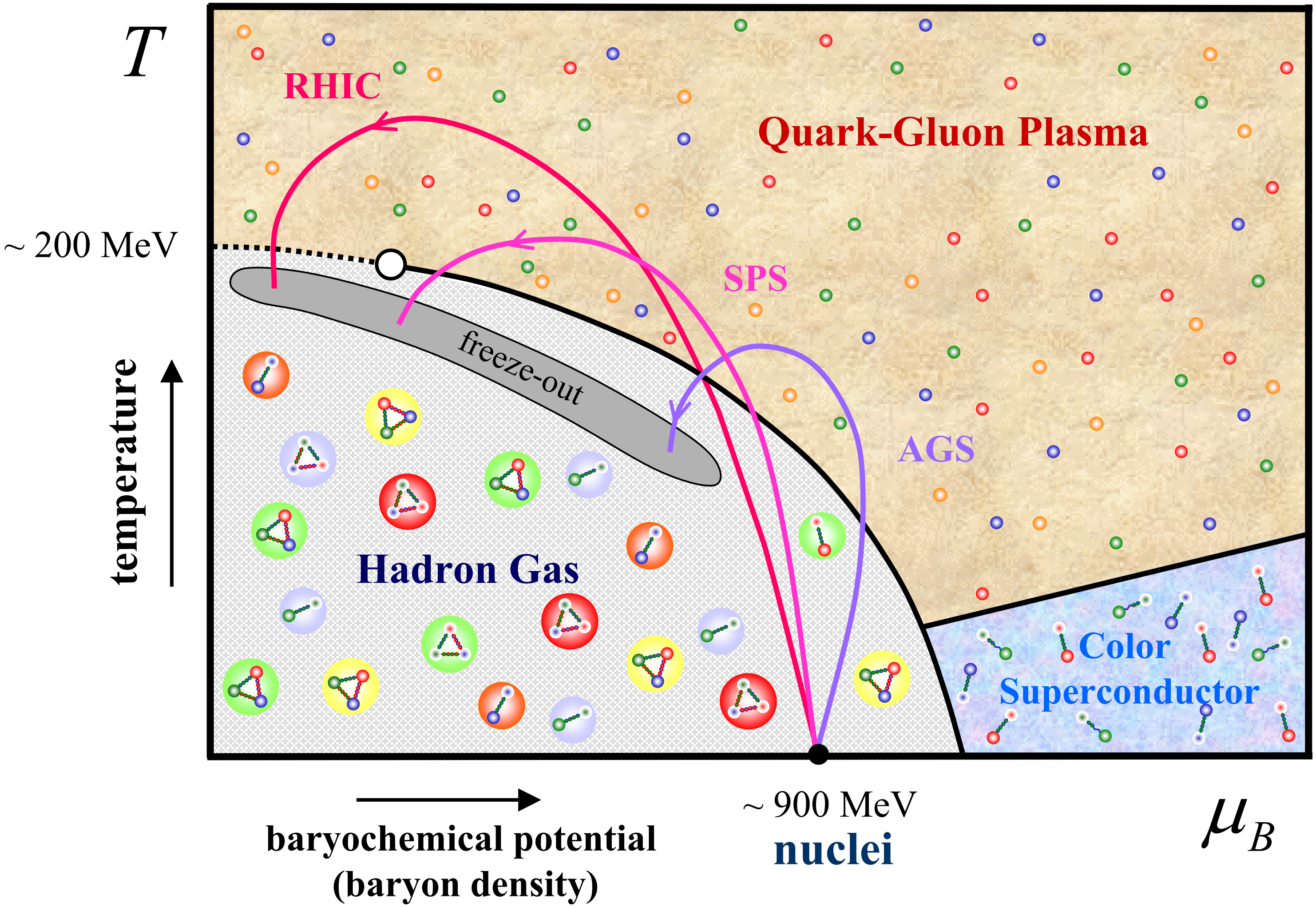
hadronization

equilibration

quark-gluon plasma

z

Phase diagram



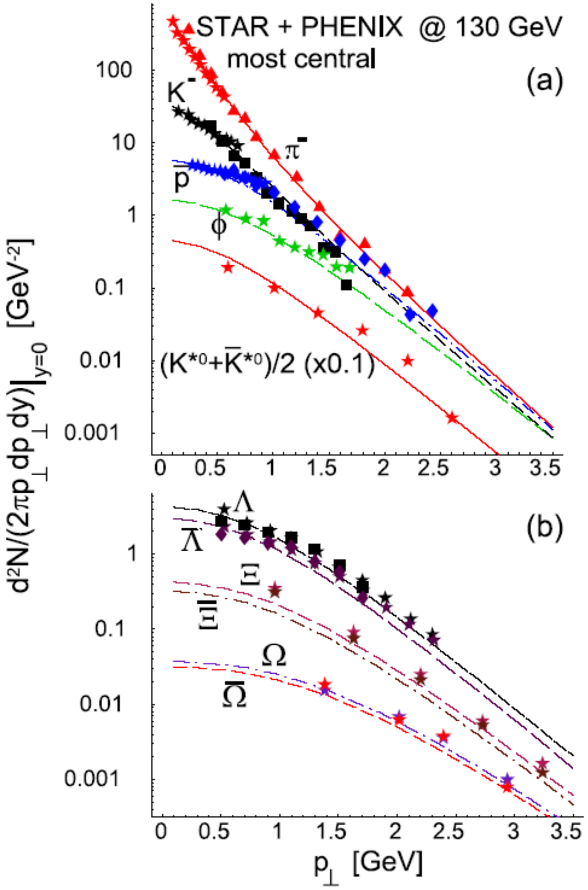
Equilibrium

Matter produced at RHIC appears to be in local thermal equilibrium

Late stage equilibrium

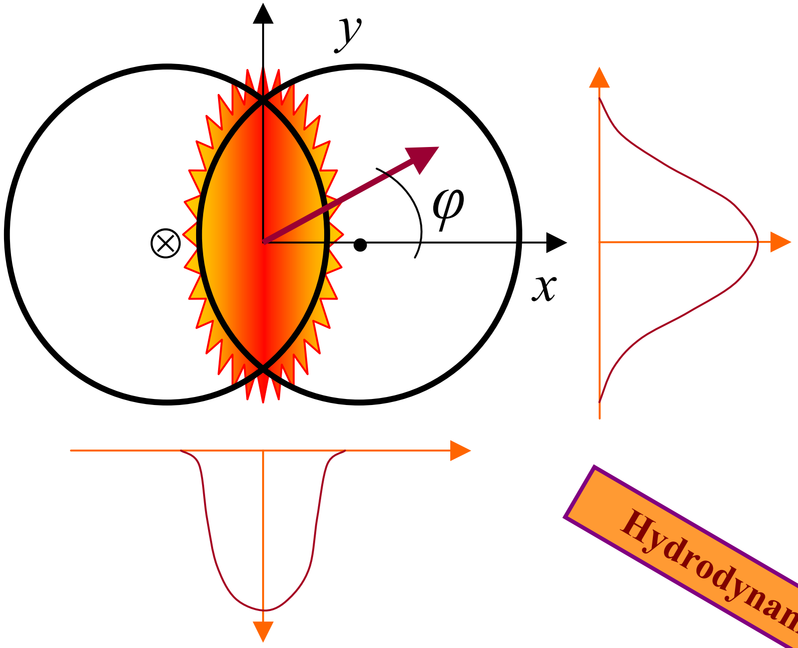
Au-Au @ 130 GeV within Cracow Thermal Model

	Model	Experiment
Fitted thermal parameters		
T [MeV]	165±7	
μ_B [MeV]	41±5	
μ_S [MeV]	9	
μ_I [MeV]	-1	
χ^2/n	0.97	
Ratios used for the fit		
π^-/π^+	1.02	1.00 ± 0.02 [47], 0.99 ± 0.02[48]
$\overline{p}/\pi^-$	0.09	0.08 ± 0.01 [49]
K^-/K^+	0.92	0.88 ± 0.05 [50], 0.78 ± 0.12 [51] 0.91 ± 0.09 [47], 0.92 ± 0.06 [48]
K^-/π^-	0.16	0.15 ± 0.02 [50]
K_0^*/h^-	0.046	0.060 ± 0.012 [50, 52] later: 0.042 ± 0.011 [41]
$\overline{K_0^*}/h^-$	0.041	0.058 ± 0.012 [50, 52] later: 0.039 ± 0.011 [41]
$\overline{p}/p$	0.65	0.61 ± 0.07 [49], 0.54 ± 0.08 [51] 0.60 ± 0.07 [47], 0.61 ± 0.06 [48]
$\overline{\Lambda}/\Lambda$	0.69	0.73 ± 0.03 [50]
$\overline{\Xi}/\Xi$	0.76	0.82 ± 0.08 [50]
Ratios predicted		
ϕ/h^-	0.019	0.021 ± 0.001 [53]
ϕ/K^-	0.15	$0.1 - 0.16$ [53]
Λ/p	0.47	0.49 ± 0.03 [54, 55]
Ω^-/h^-	0.0010	0.0012 ± 0.0005 [56]
Ξ^-/π^-	0.0072	0.0085 ± 0.0020 [57]
Ω^+/Ω^-	0.85	0.95 ± 0.15 [56]



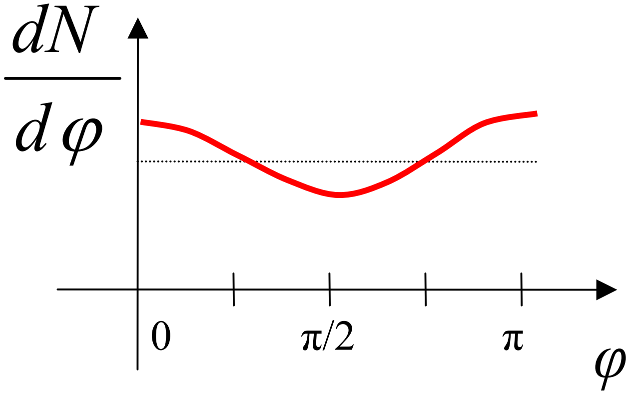
W. Broniowski, A. Baran and W. Florkowski, Acta Phys. Polon. **B33**, 4235 (2002)

Elliptic Flow & Early Stage Equilibrium



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

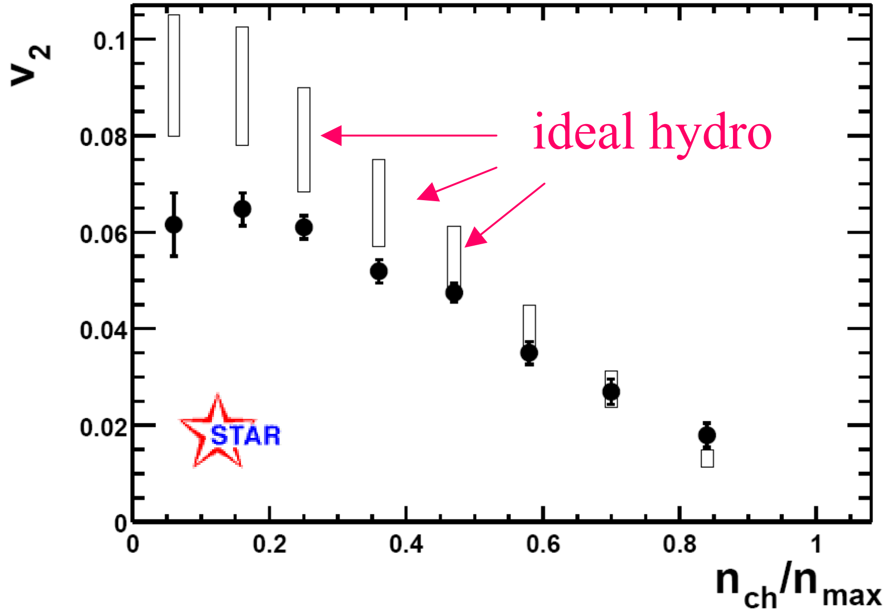
Hydrodynamics



Hydrodynamics requires local thermodynamical equilibrium!

Elliptic Flow & Early Stage Equilibrium

Au-Au @ 130 GeV



peripheral
collisions

central
collisions

$$\frac{dN}{d\varphi} = \frac{1}{2\pi}\left[1 + \sum_{n=0}^{\infty} v_n \cos\left(n(\varphi - \varphi_R)\right)\right]$$

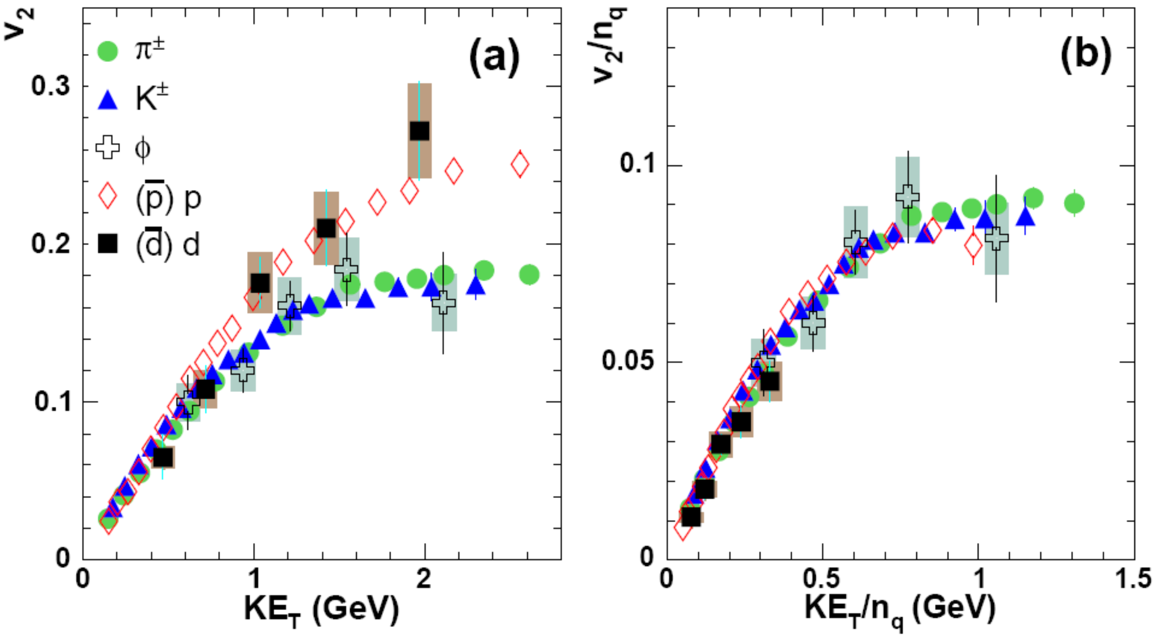
Ideal hydro works very
well for central collisions

K.H. Ackermann et al. [STAR Collaboration], Phys. Rev. Lett. **86**, 402 (2001)

Elliptic Flow & Early Stage Equilibrium

Au-Au @ 200 GeV

$$\frac{dN}{d\varphi}=\frac{1}{2\pi}\left[1+\sum_{n=0}^{\infty}\mathrm{v}_n\cos\left(n(\varphi-\varphi_R)\right)\right]$$



$$KE_T\equiv\sqrt{p_T^2+m^2}-m$$

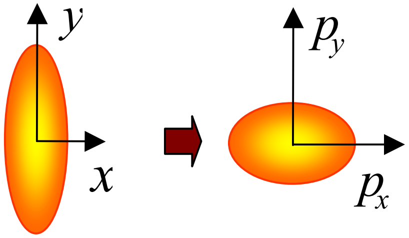
n_q – number of constituent quarks

Elliptic flow is generated
at quark phase

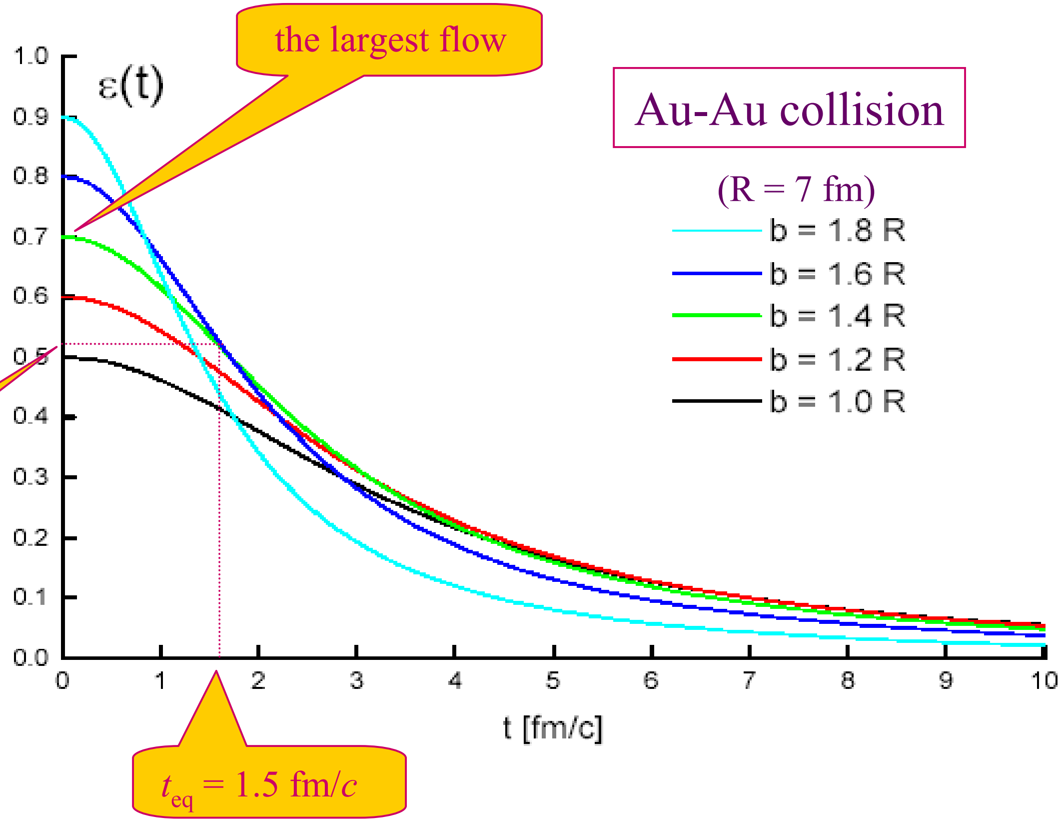
S. Afanasiev et al. [PHENIX Collaboration], Phys. Rev. Lett. **99**, 052301 (2007)

Equilibration Time

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



Eccentricity decay due to the free streaming



the largest flow

$0.75\ v_2$

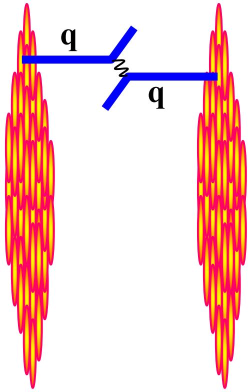
$t_{eq} = 1.5$ fm/c

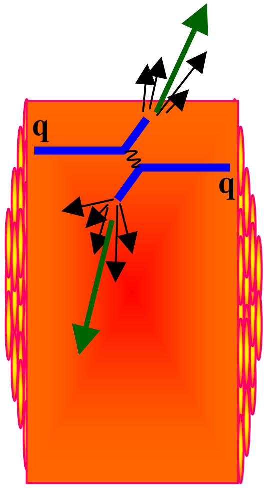
W. Jas and St. Mrówczyński, Phys. Rev. **C76**, 044905 (2007)

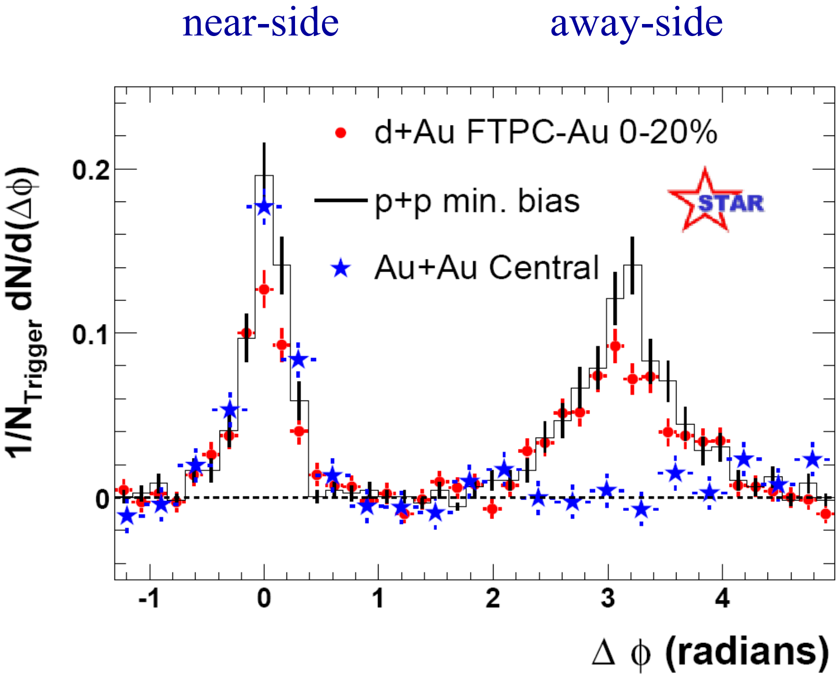
Opaqueness

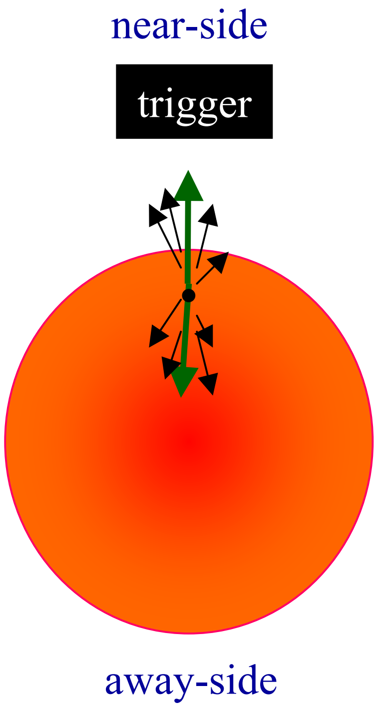
Matter produced at RHIC
appears to be very opaque

Hard Jets @ RHIC







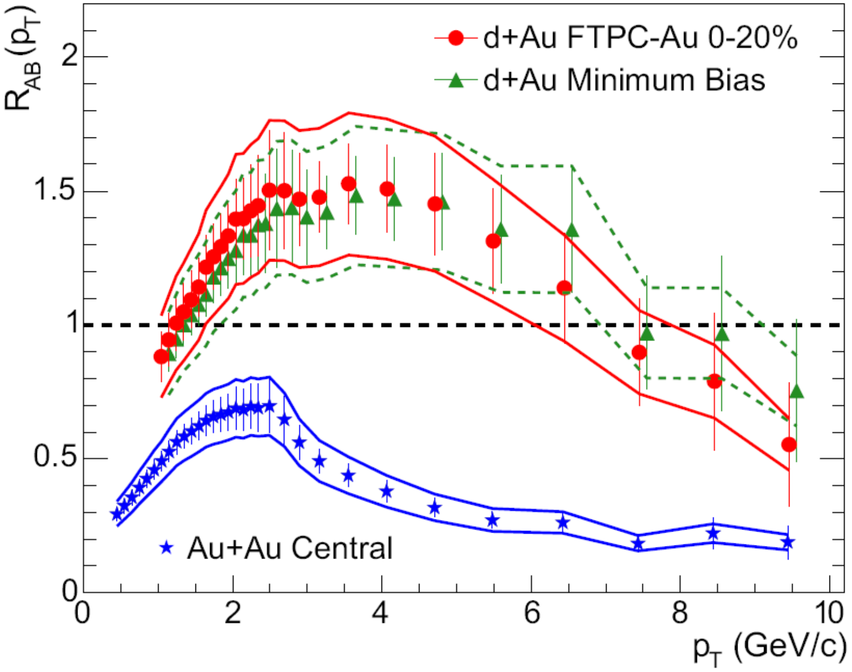


Away-side jet is suppressed
in central collisions

J. Adams et al. [STAR Collaboration], Nucl. Phys. **A757**, 102 (2005)

Hard Jets @ RHIC

Inclusive π^0 production



$$R_{AB}(p_T) = \frac{\dfrac{dN_{AB}}{d\eta\, d^2 p_T}}{\dfrac{\langle N_{bin}\rangle}{\sigma_{NN}^{\text{inel}}} \dfrac{d\sigma_{NN}}{d\eta\, d^2 p_T}}$$

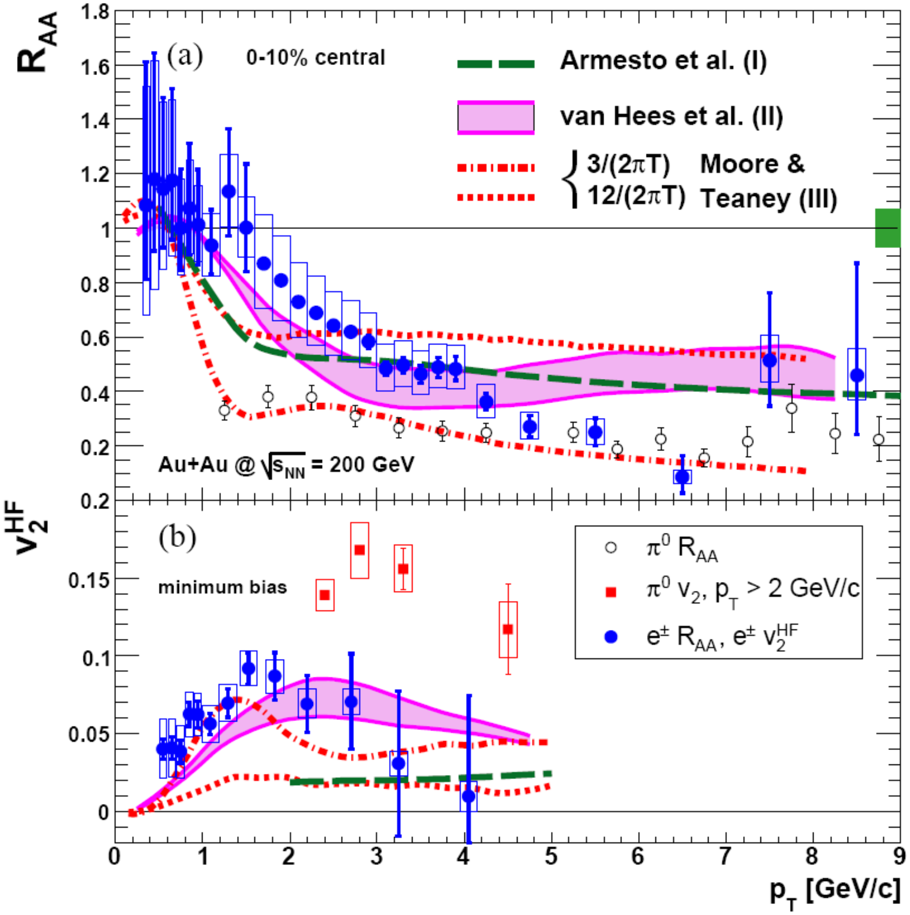
suppression

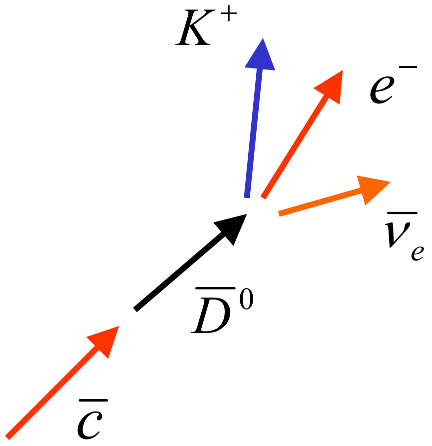
Production of high p_T pions is suppressed

J. Adams et al. [STAR Collaboration], Nucl. Phys. **A757**, 102 (2005)

Heavy-Flavours @ RHIC

$e^{\pm}$ from charm & bottom





Heavy quarks behave in QGP as light ones

A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. **98**, 172301 (2007)

Experimental features

- Matter produced at RHIC is in local equilibrium
- Equilibration time is short $\sim 1\mathrm{fm}/c$
- Viscosity of the matter is low
- Matter produced at RHIC is opaque

What does it mean ‘short’, ‘low’, ‘opaque’?

Weakly coupled quasi-equilibrium QGP

- Equilibration time due to collisions: $t_{\text{eq}} \sim \dfrac{1}{T\alpha_s^2 \ln(1/\alpha_s)}$

- Shear viscosity: $\eta \sim \dfrac{T^3}{\alpha_s^2 \ln(1/\alpha_s)}$

- Collisional energy loss: $\dfrac{dE}{dx} \sim \alpha_s^2 T^2 \ln(1/\alpha_s)$

- Radiative energy loss of $\begin{cases} \text{light quark: } \dfrac{dE}{dx} \sim \alpha_s^2 ET \ln(1/\alpha_s) \\ \text{heavy quark: } \dfrac{dE}{dx} \sim \dfrac{\alpha_s^3 ET^3}{M^2} \ln(1/\alpha_s) \qquad (M >> T) \end{cases}$

α_s – coupling constant, T – temperature, E – quark energy, M – heavy quark mass

Provisional Conclusion

QGP is strongly coupled

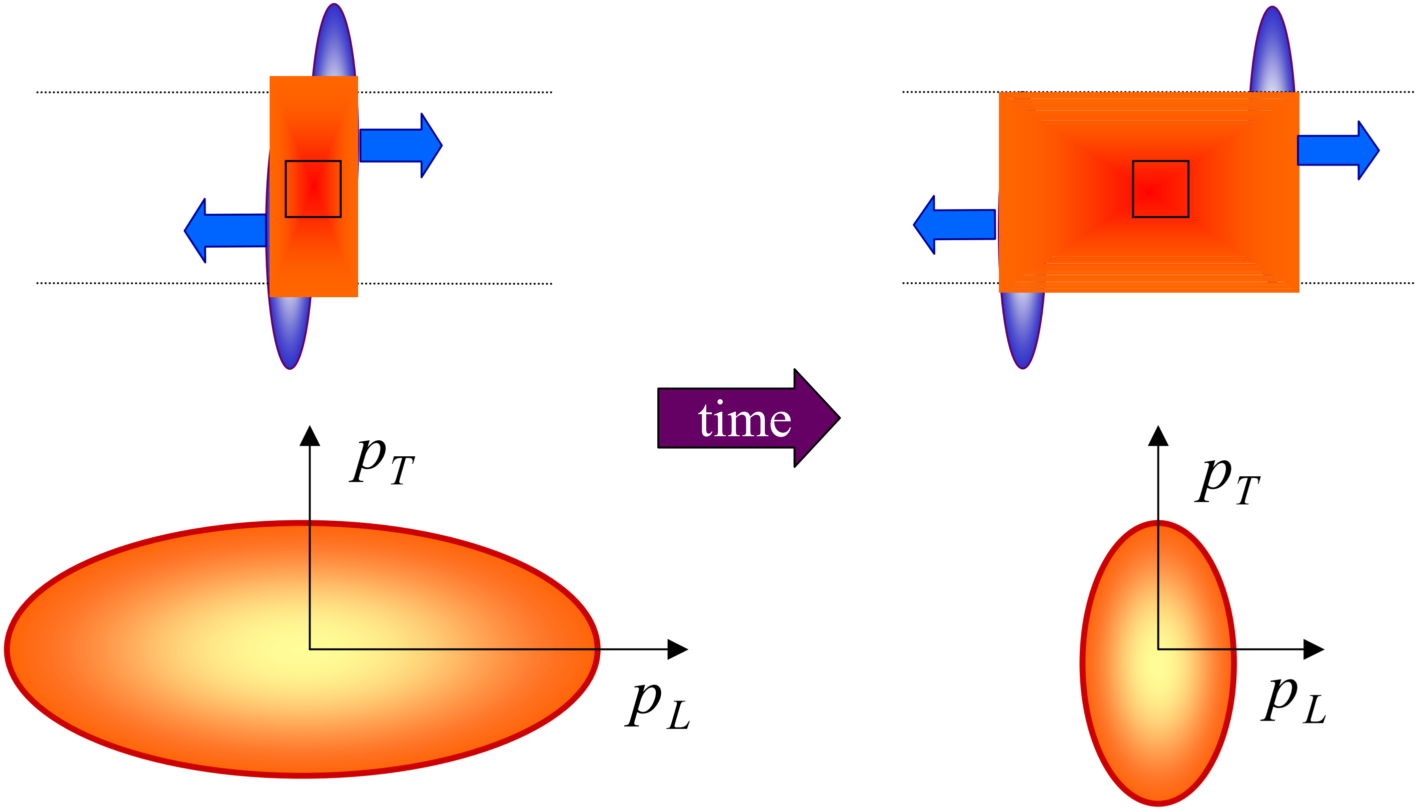
or

QGP behaves as strongly coupled but $\alpha_s \leq 0.3$?

Chromomagnetic instabilities

The instabilities occur due to anisotropy of the momentum distribution

Parton momentum distribution is initially anisotropic

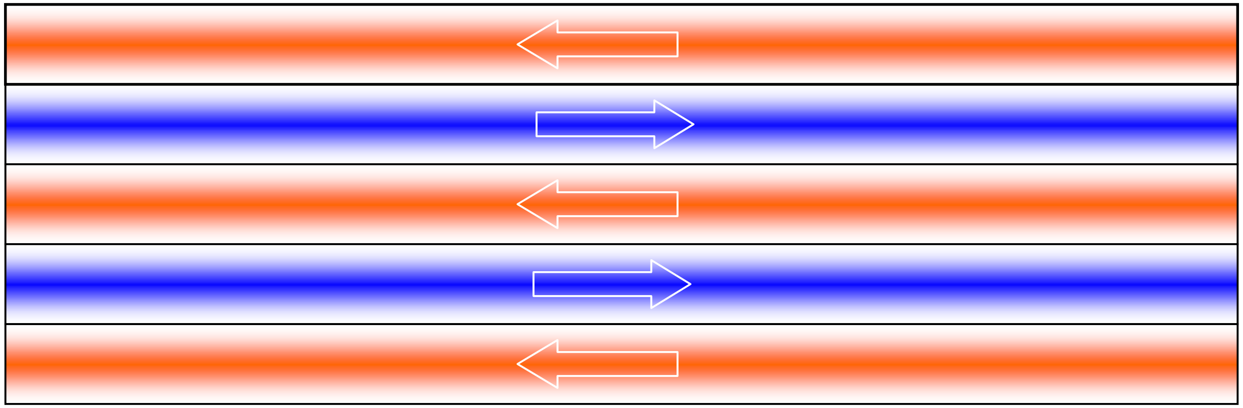


Seeds of instability

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

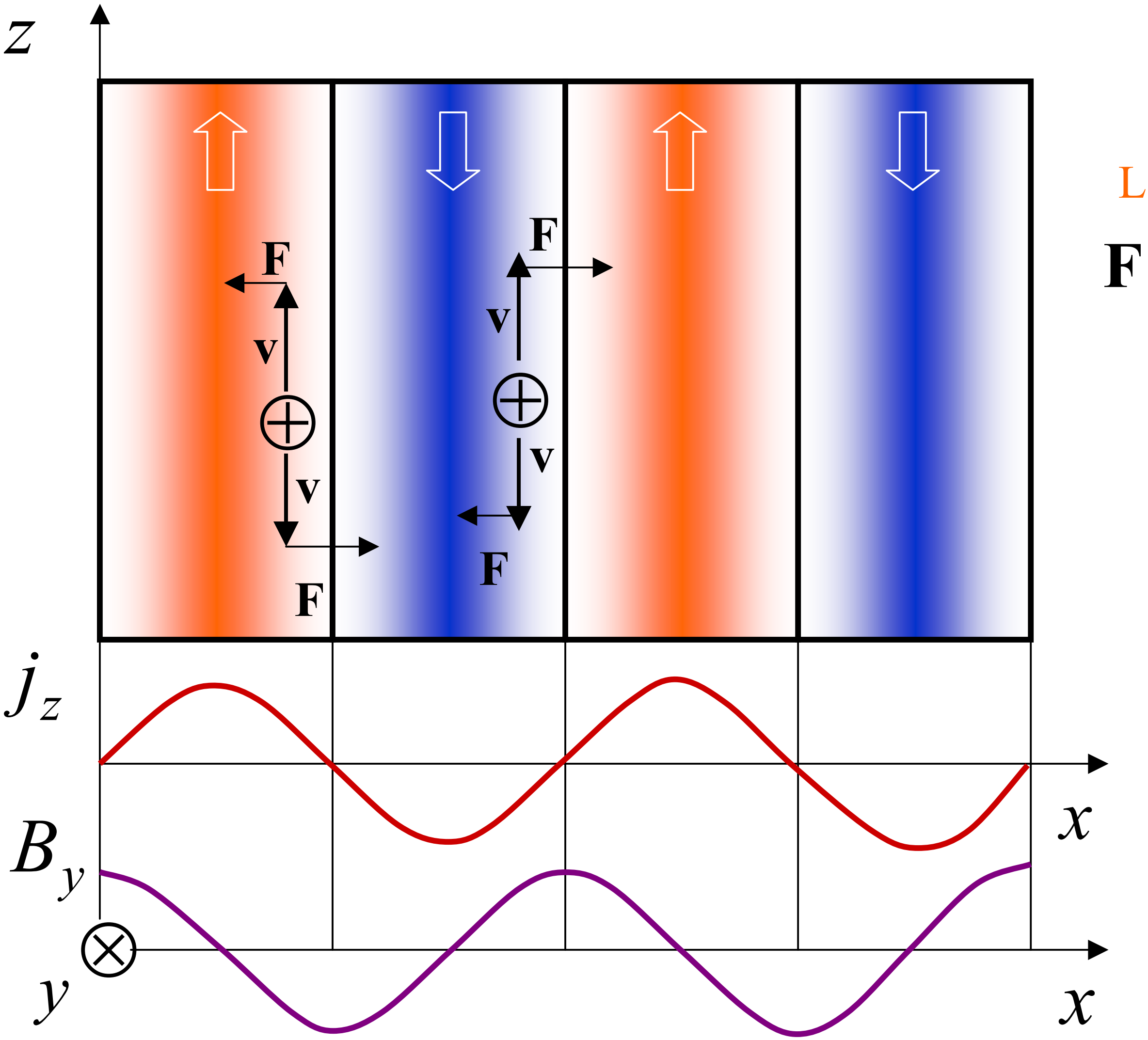
$$\boxed{\left\langle j_a^{\mu}(x_1)\, j_b^{\nu}(x_2) \right\rangle = \frac{1}{2}\delta^{ab} \int \frac{d^3p}{(2\pi)^3} \frac{p^{\mu} p^{\nu}}{E_p^2} f(\mathbf{p}) \delta^{(3)}(\mathbf{x} - \mathbf{v}t) \neq 0}$$

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



Direction of the momentum surplus

Mechanism of filamentation



Lorentz force

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

Ampere's law

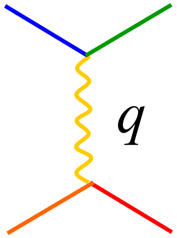
$$\nabla \times \mathbf{B} = \mathbf{j}$$

Instabilities are fast

Time scale of processes driven by parton-parton scattering

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

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



hard scattering: $q \sim T$

soft scattering: $q \sim gT$

Time scale of collective phenomena

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

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

The instabilities are fast!

Growth of instabilities – 1+1 numerical simulations

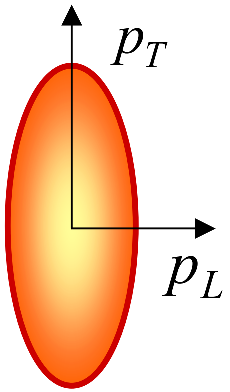
SU(2) Hard Loop Dynamics

1+1 dimensions

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

Scaled field energy density

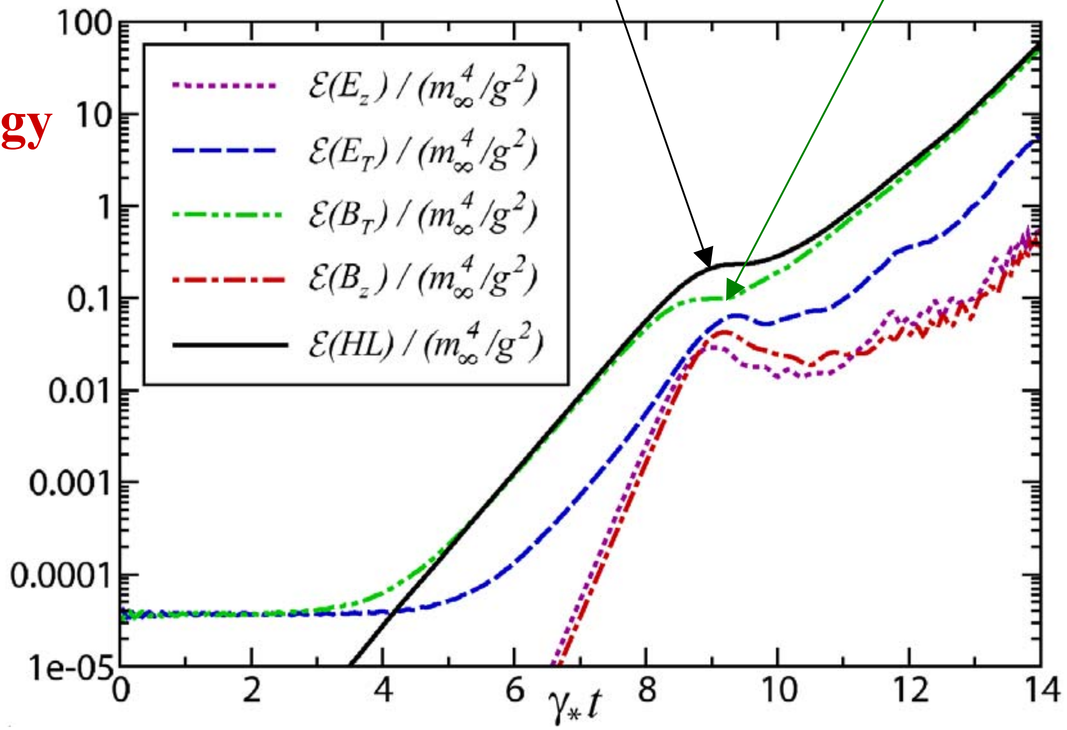
Anisotropic particle's momentum distribution



oblate

total

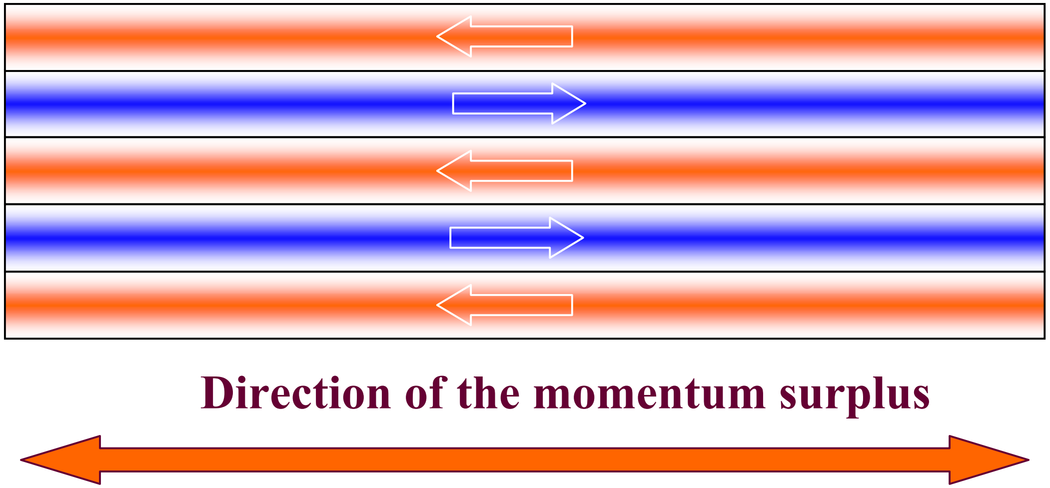
transverse magnetic



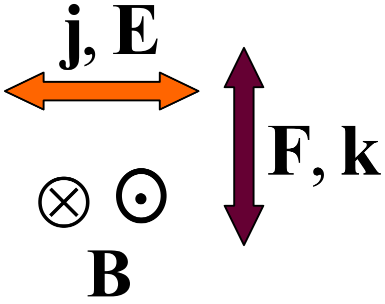
γ_* - maximal growth rate

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

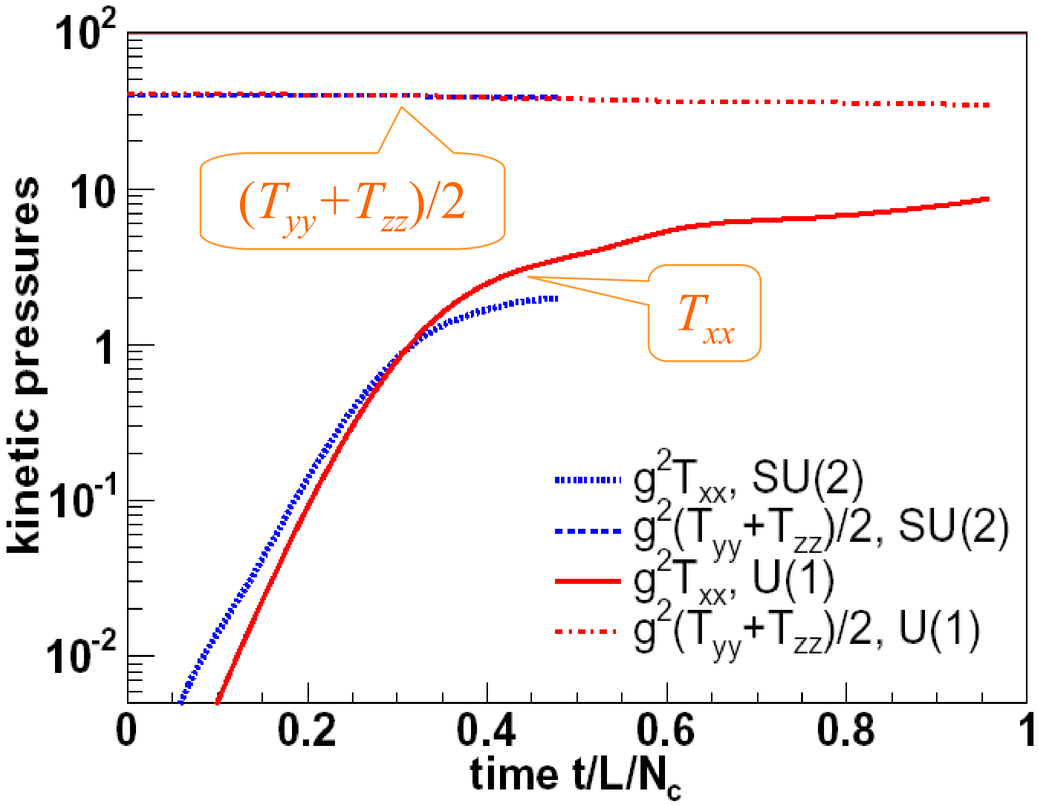
$$T_{ij} = \int \frac{d^3 p}{(2\pi)^3} \frac{p_i p_j}{E} f(\mathbf{p})$$

Initial anisotropy:

$$T_{xx} = 0$$

Isotropy:

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



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

Role of instabilities

Chromomagnetic instabilities efficiently speed up equilibration of weakly coupled plasma

Viscosity of turbulent QGP

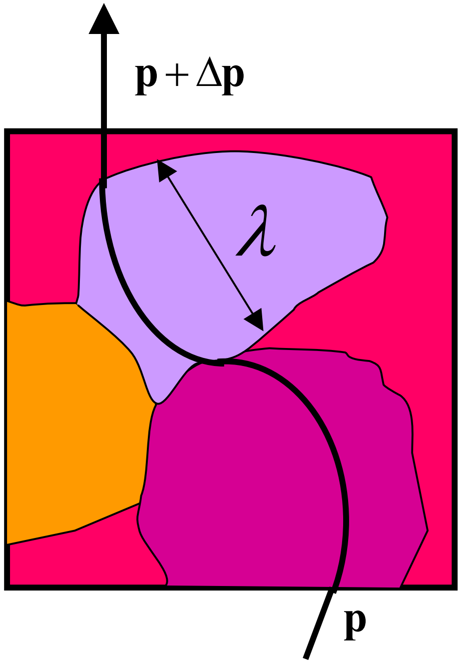
Magnetized turbulent QGP

collisional viscosity: $\eta_C \sim \dfrac{T^3}{\alpha_s^2 \ln(1/\alpha_s)}$

anomalous viscosity: $\eta_A \sim \dfrac{1}{g^2 \langle \mathbf{B}^2 \rangle \lambda}$

λ - size of magnetic domain

$$\frac{1}{\eta} = \frac{1}{\eta_A} + \frac{1}{\eta_C}$$



Viscosity of magnetized turbulent QGP is small

M. Asakawa, S.A. Bass and B. Müller, Prog. Theor. Phys. **116**, 725 (2007)

My personal opinion

Weakly coupled magnetized turbulent QGP can behave as strongly coupled plasma