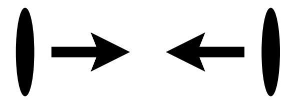
QCD at High Temperature

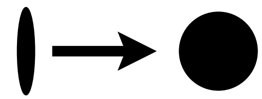
(Experiment)

Kinematics

CMS: $s = (p_1 + p_2)^2 = 4E_{CM}^2$



Lab: $p_1 = (m, 0)$ $p_2 = (E_L, p_z) = (E_L, \sqrt{E_L^2 - m^2})$



$s = (m + E_L)^2 - (E_L^2 - m^2) = 2m(E_L + m)$ $\qquad E_{CM} = \sqrt{mE_L/2}$

$$\begin{array}{llll} \text{SPS}: & 200 \text{ GeV (LAB)} & E_{CM} = 10 \text{ GeV} & \gamma = 10 \\ \text{RHIC}: & 100 \text{ GeV (CMS)} & E_{CM} = 100 \text{ GeV} & \gamma = 100 \\ \text{LHC}: & 2.75 \text{ TeV (CMS)} & E_{CM} = 2.75 \text{ TeV} & \gamma = 2750 \end{array}$$

Rapidity:

$$y = \frac{1}{2} \log \left(\frac{E + p_z}{E - p_z} \right)$$

$$\text{SPS}: \ \Delta y = 6 \qquad \text{RHIC}: \ \Delta y = 10.6 \qquad \text{LHC}: \ \Delta y = 17.3$$

Bjorken Expansion

Experimental observation: At high energy ($\Delta y \to \infty$) rapidity distributions of produced particles (in both pp and AA) are "flat"

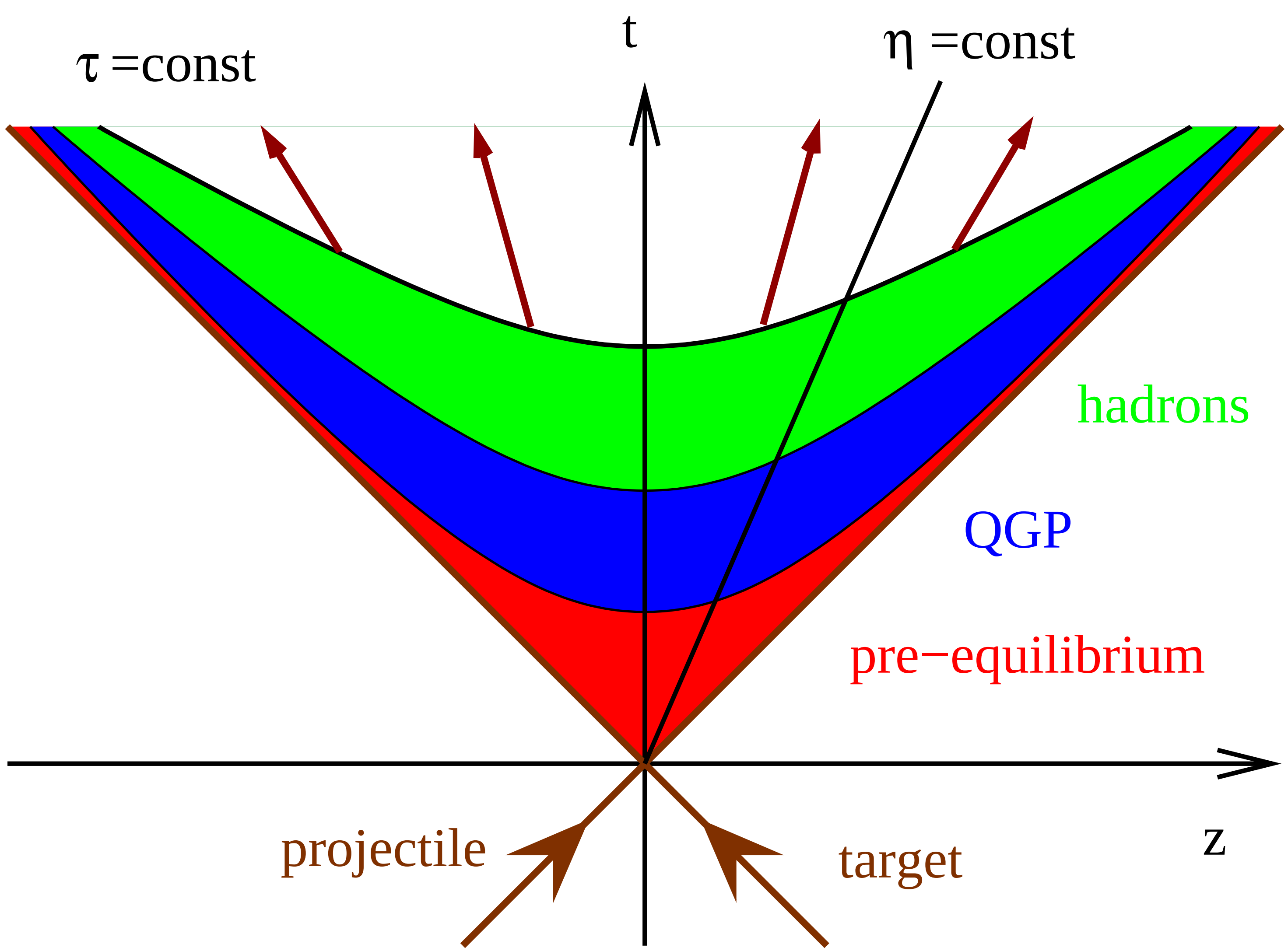
$$\frac{dN}{dy} \simeq const$$

Physics depends on proper time $\tau = \sqrt{t^2 - z^2}$, not on y

All comoving ($v = z/t$) observers are equivalent

Analogous to Hubble expansion

Bjorken Expansion



Bjorken Expansion: Hydrodynamics

Consider perfect relativistic fluid; 4-velocity $u_\mu = (1, \vec{v})\gamma$

$$T_{\mu\nu} = (\epsilon + P)u_\mu u_\nu - P g_{\mu\nu}$$

Hydro = Conservation Laws ($\partial^\mu T_{\mu\nu}$=0) + Equ. of State ($P = P(\epsilon)$)

$$\partial^\mu T_{\mu\nu} = (\partial^\mu \epsilon + \partial^\mu P)u_\mu u_\nu + (\epsilon + P)((\partial^\mu u_\mu)u_\nu + u_\mu \partial^\mu u_\nu) - \partial_\nu P = 0$$

Contract with u_ν, use $u^2 = 1$

$$(\partial^\mu \epsilon + \partial^\mu P)u_\mu + (\epsilon + P)\partial^\mu u_\mu - u^\nu \partial_\nu P = 0$$

$$u_\mu \partial^\mu \epsilon + (\epsilon + P)\partial^\mu u_\mu = 0$$

Thermodynamic relations

$$d\epsilon = T ds \qquad \epsilon + P = Ts$$

Hydrodynamic equations

$$u^\mu (T\partial_\mu s) + (Ts)\partial^\mu u_\mu = 0$$

$$\boxed{\partial_\mu \left(s u^\mu\right) = 0} \qquad \text{isentropic expansion}$$

Variables: $t = \tau \cosh\alpha, \;\; z = \tau \sinh\alpha. \;\Rightarrow u_\mu = (\cosh\alpha, 0, 0, \sinh\alpha)$

$$\partial^\mu (s u_\mu) = 0 \qquad \Rightarrow \qquad \frac{d}{d\tau}\left[\tau s(\tau)\right] = 0$$

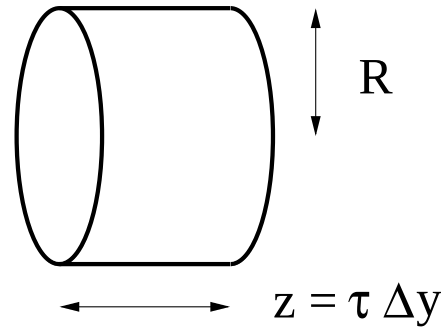
Solution for ideal Bj hydrodynamics

$$\boxed{s(\tau) = \frac{s_0 \tau_0}{\tau}} \qquad T = \frac{const}{\tau^{1/3}}$$

Exact boost invariance, no transverse expansion, no dissipation, ...

Numerical Estimates

Total entropy in rapidity interval $[y, y + \Delta y]$



$$S = s\pi R^2 z = s\pi R^2 \tau \Delta y = (s_0 \tau_0) \pi R^2 \Delta y$$

$$s_0 \tau_0 = \frac{1}{\pi R^2} \frac{S}{\Delta y}$$

Use $S/N \simeq 3.6$

$$s_0 = \frac{3.6}{\pi R^2 \tau_0} \left(\frac{dN}{dy} \right) \qquad \text{Bj estimate}$$

$$\epsilon_0 = \frac{1}{\pi R^2 \tau_0} \left(\frac{dE_T}{dy} \right)$$

Depends on initial time τ_0

RHIC: Au-Au collisions ($\sqrt{s} = 200$ GeV)

$$\frac{dN}{dy} \simeq 998 \qquad \tau_0 = 1 \text{ fm} \qquad s_0 \simeq 33 \text{ fm}^{-3}$$

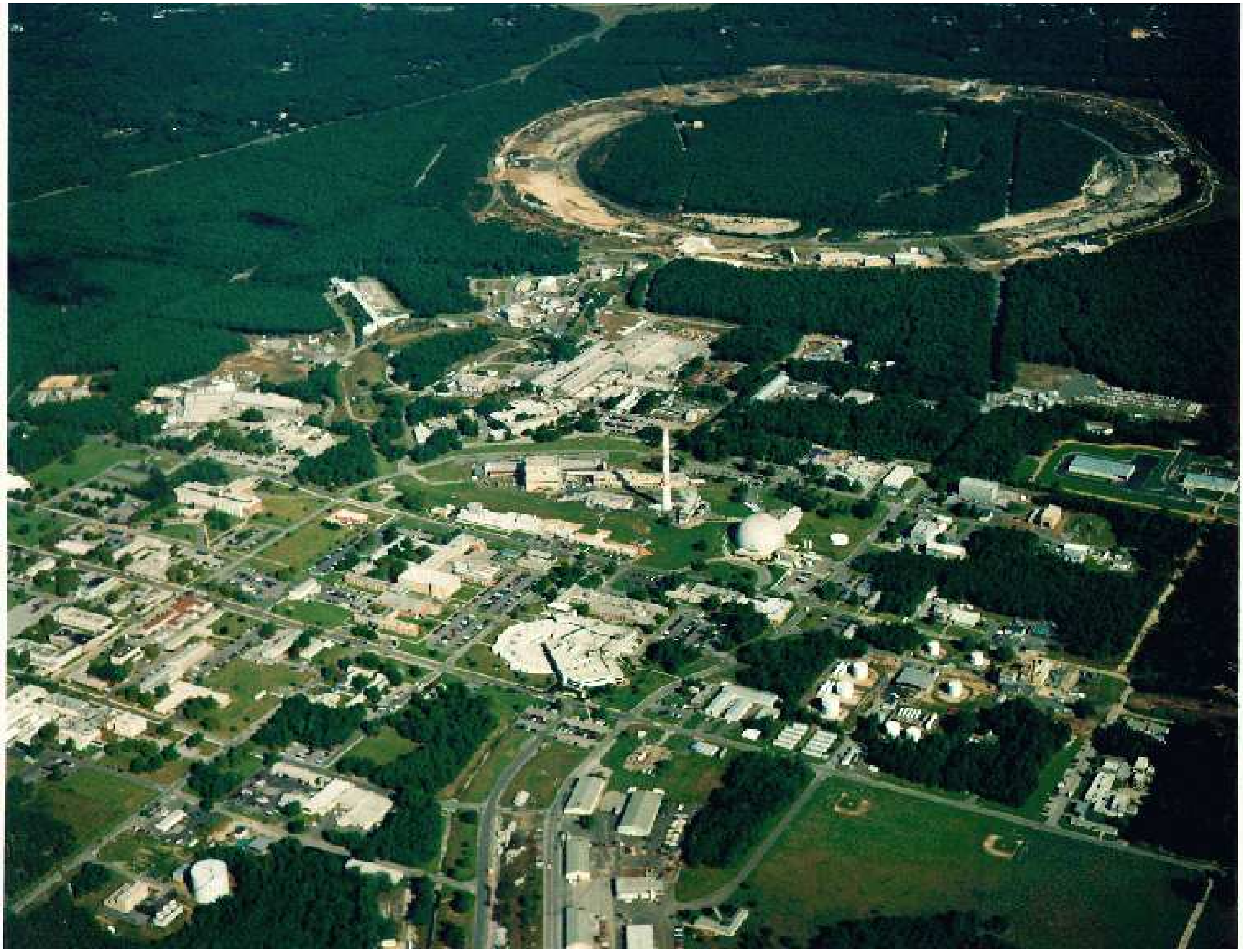
Use QGP equation of state $s = 2g\pi^2 T^3/45$

$$T_0 \simeq 240 \text{ MeV} \qquad \epsilon_0 \simeq (5-6)\text{GeV}/\text{fm}^3$$

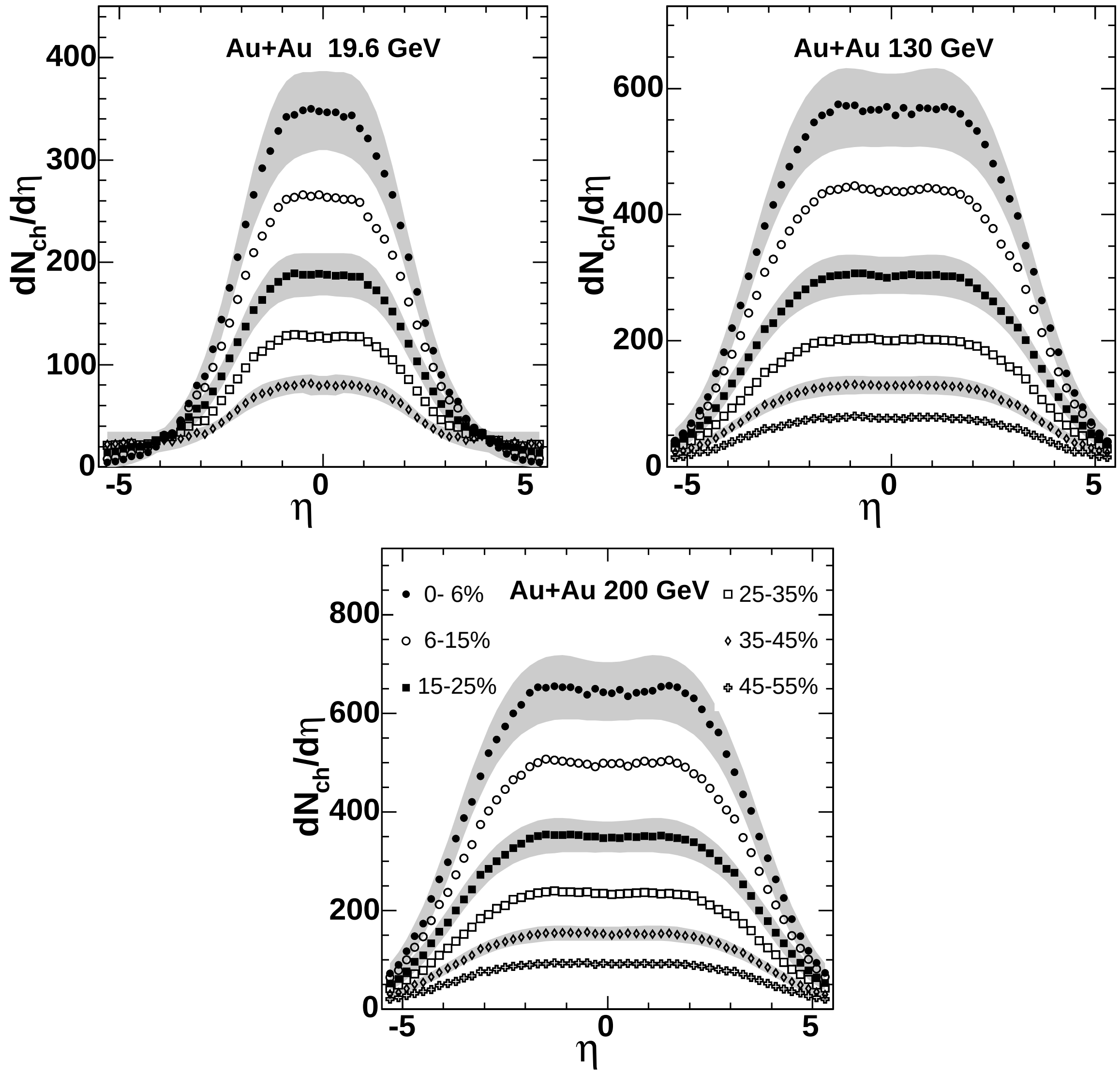
LHC: Factor ~ 2 in multiplicity

$$T_0 \simeq 300 \text{ MeV} \qquad \epsilon_0 \simeq 15\text{GeV}/\text{fm}^3$$

BNL and RHIC

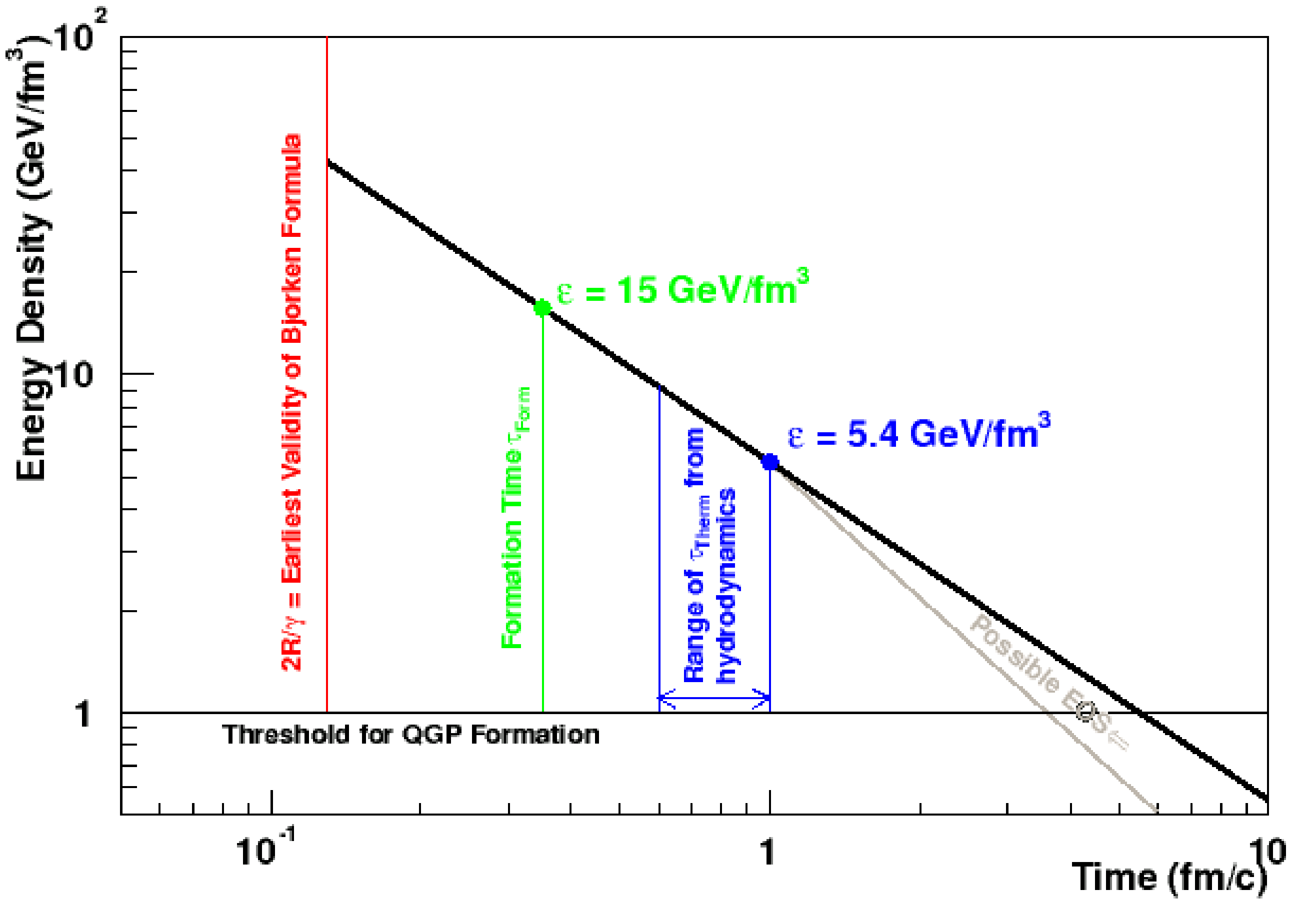


Multiplicities



Phobos White Paper (2005)

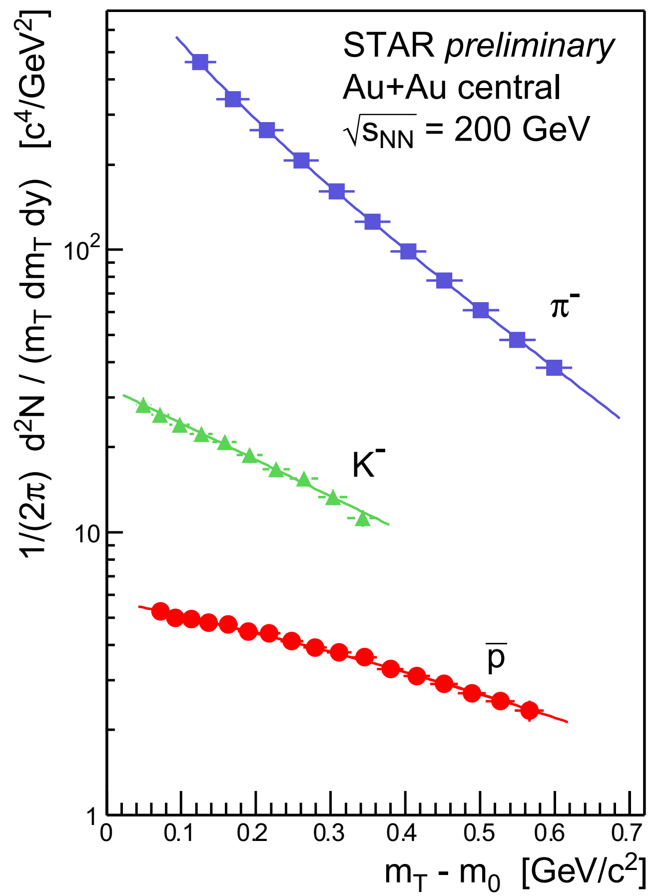
Bjorken Expansion



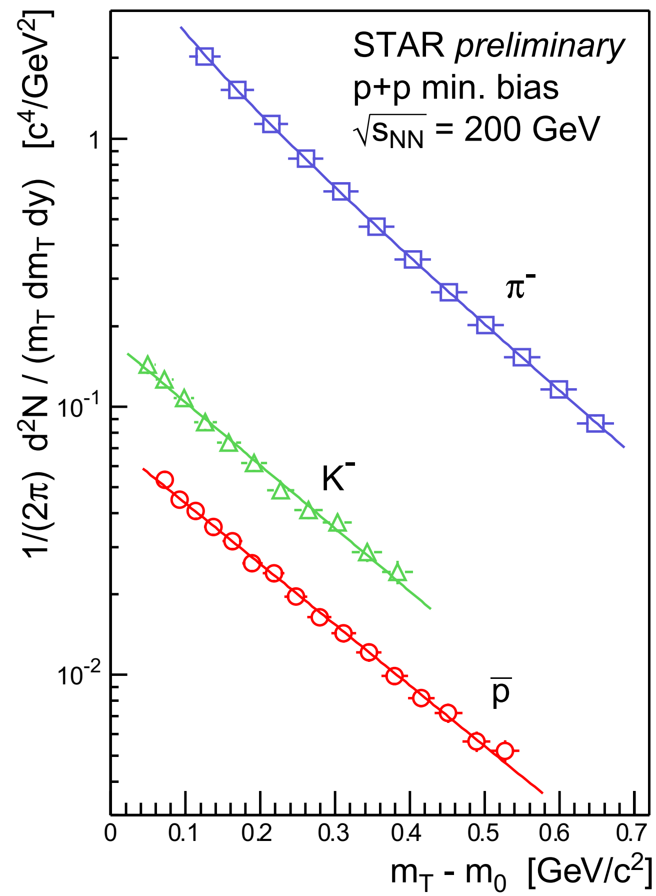
Collective Behavior: Radial Flow

Radial expansion leads to blue-shifted spectra in Au+Au

Au+Au



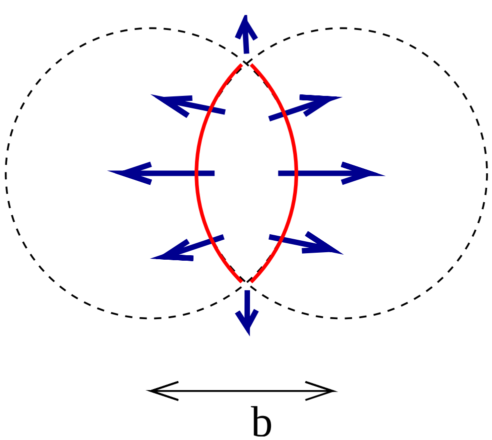
p+p

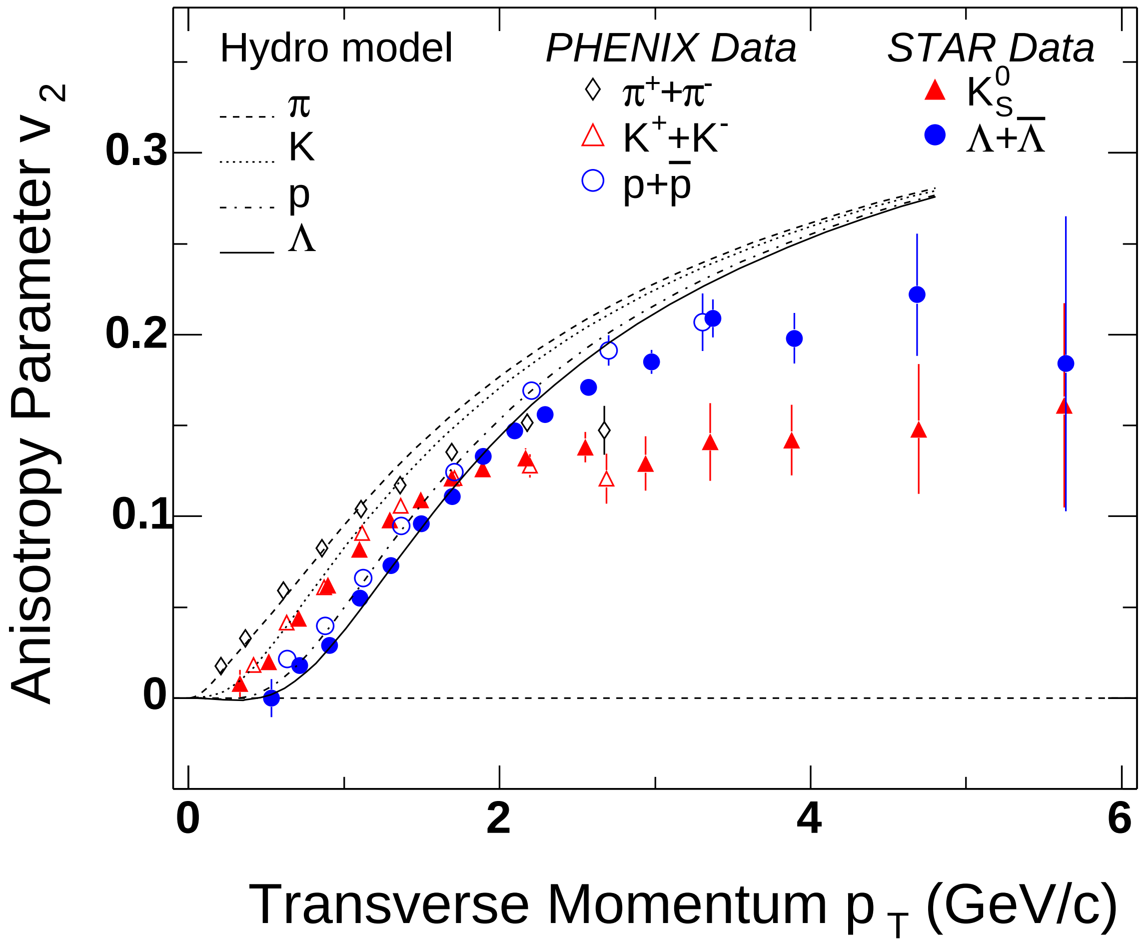


$v_T \sim 0.6c!$ $m_T = \sqrt{p_T^2 + m^2}$

Elliptic Flow

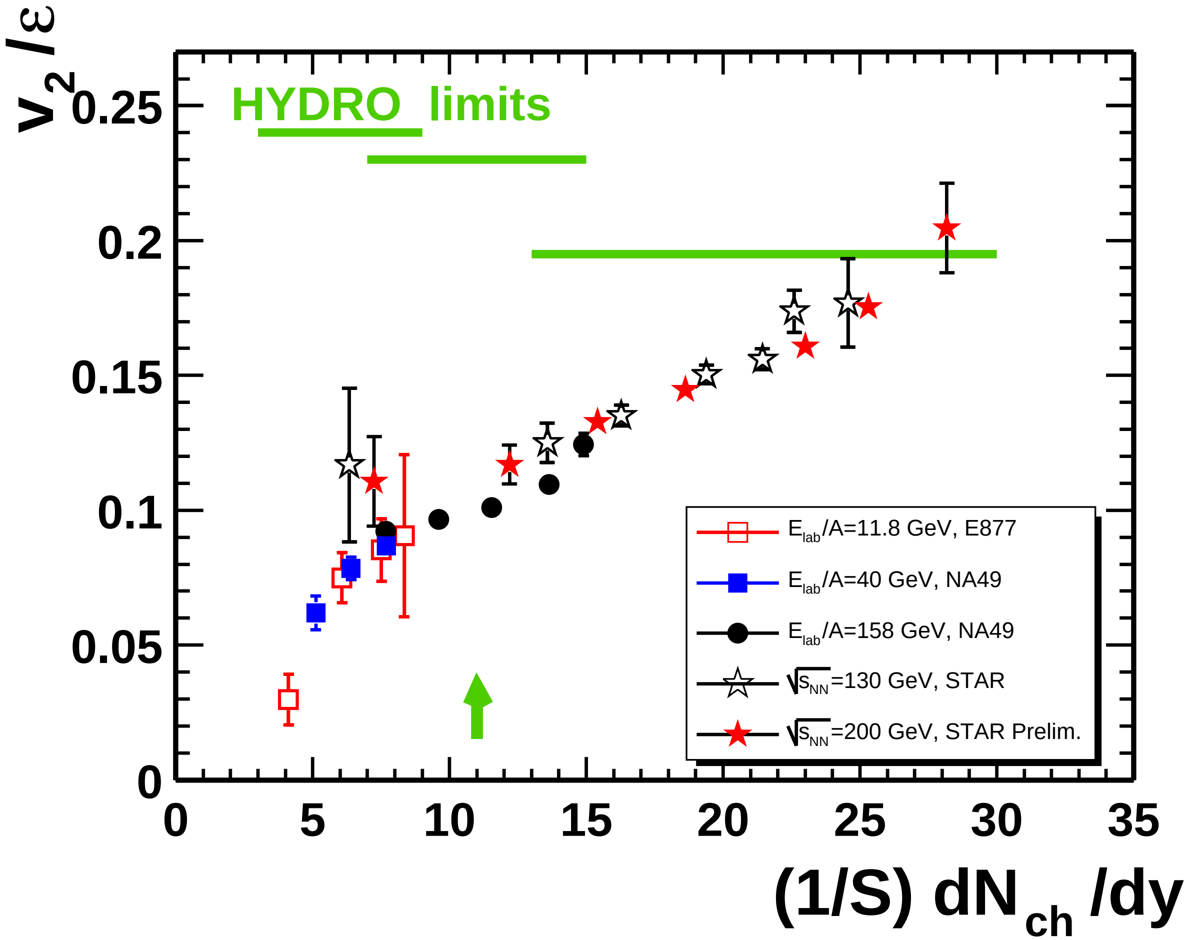
Hydrodynamic expansion converts coordinate space anisotropy to momentum space anisotropy





source: U. Heinz (2005)

Elliptic Flow II



source: U. Heinz (2005)

Elliptic Flow III: Viscosity

$$T_{\mu\nu} \to T_{\mu\nu} + \eta(\nabla_\mu u_\nu + \nabla_\nu u_\mu - trace)$$

perturbative QCD

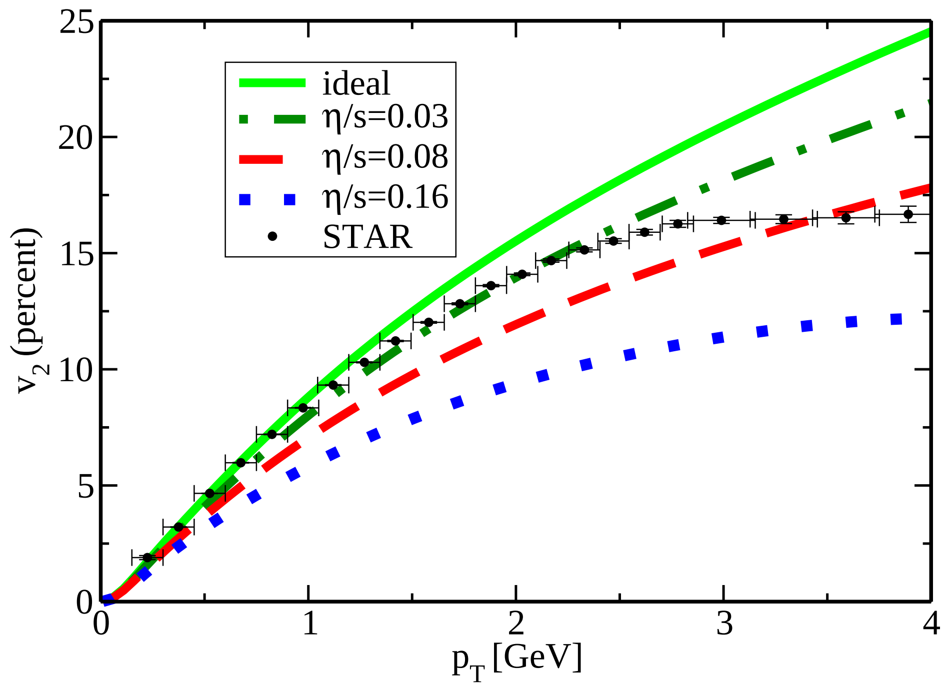
$$\frac{\eta}{s} = \frac{5.12}{g^4 \log(g^{-1}))} \sim 1$$

Arnold, Moore, Yaffe

universal bound?

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

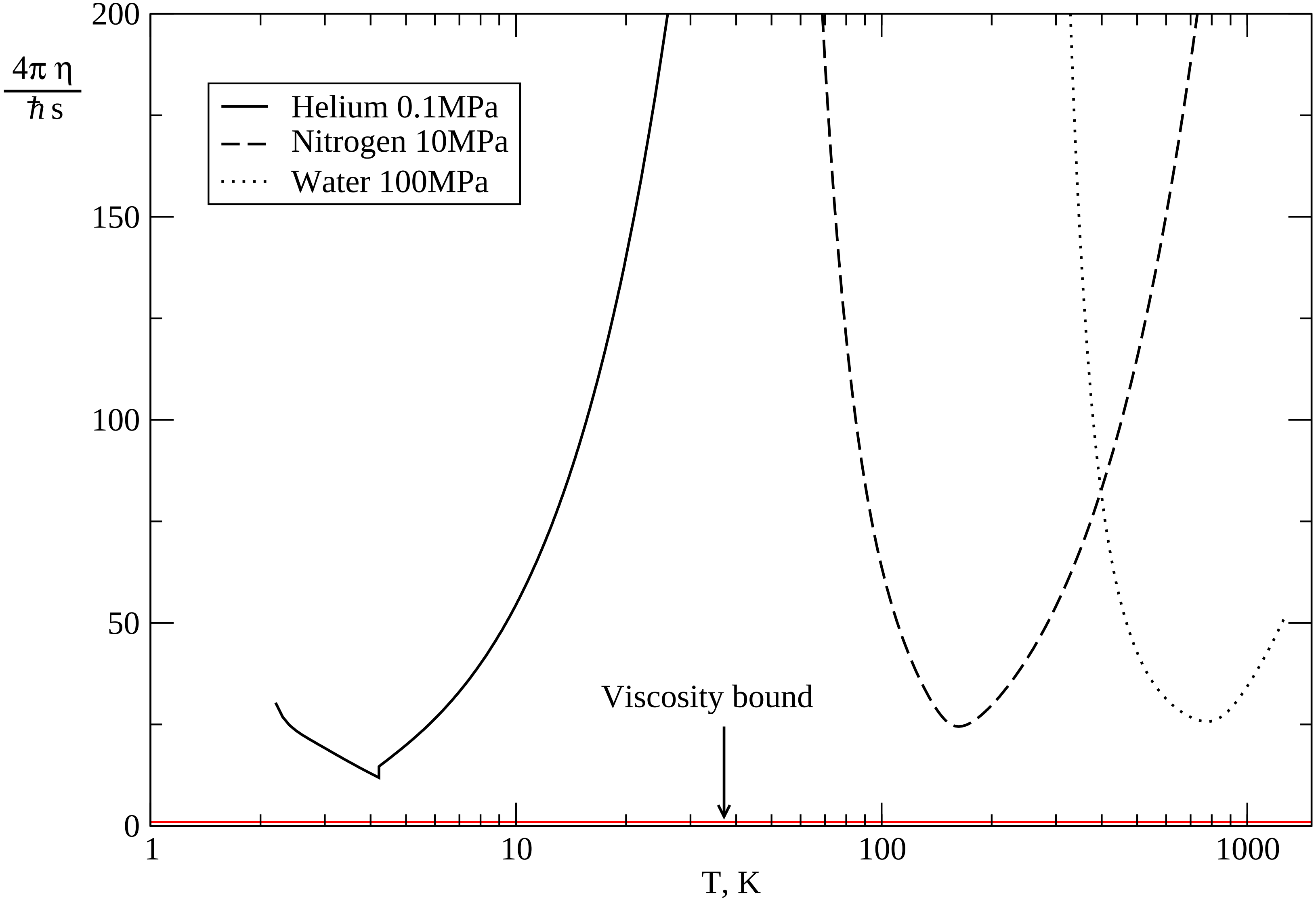
Son, Starinets



Romatschke (2007), Teaney (2003)

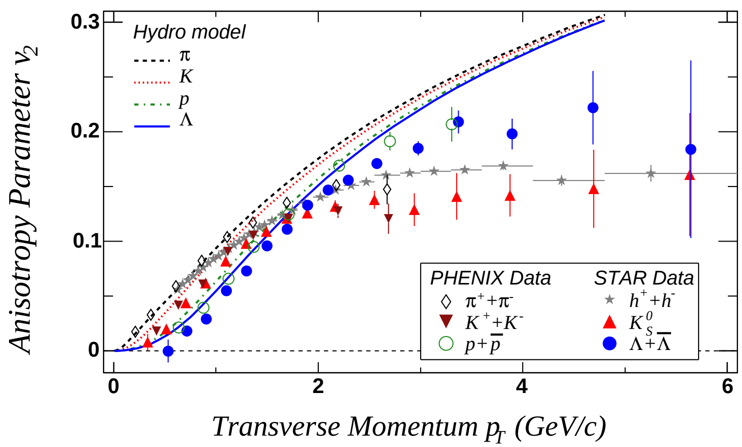
A (Most) Perfect Fluid?

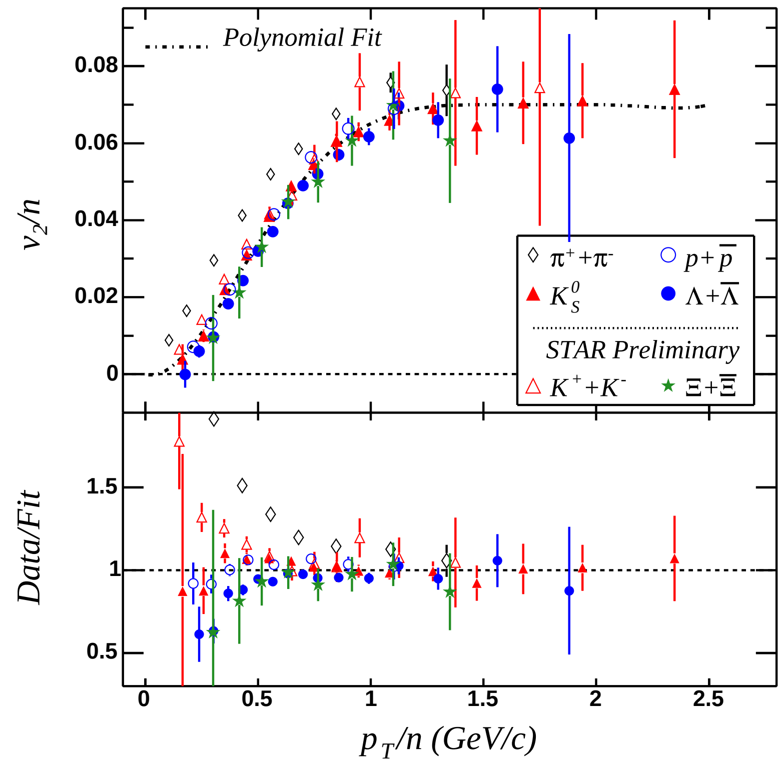
A (Most) Perfect Fluid?

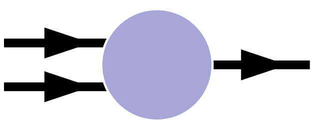


Elliptic Flow IV: Recombination

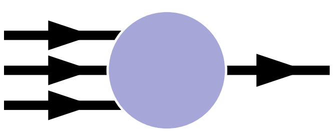
"quark number" scaling of elliptic flow







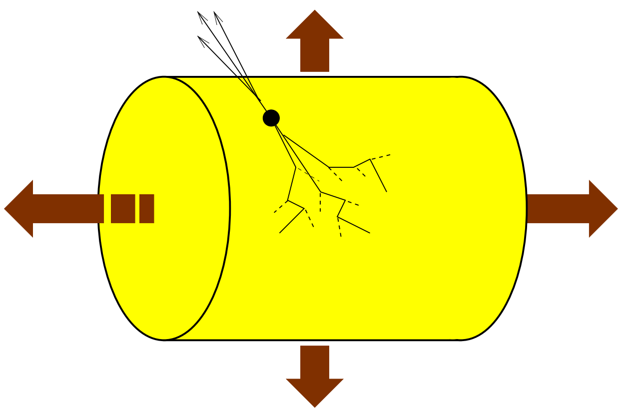
(q$\bar{\text{q}}$) (mes) $p_\perp^{mes} = 2p_\perp^{qu}$

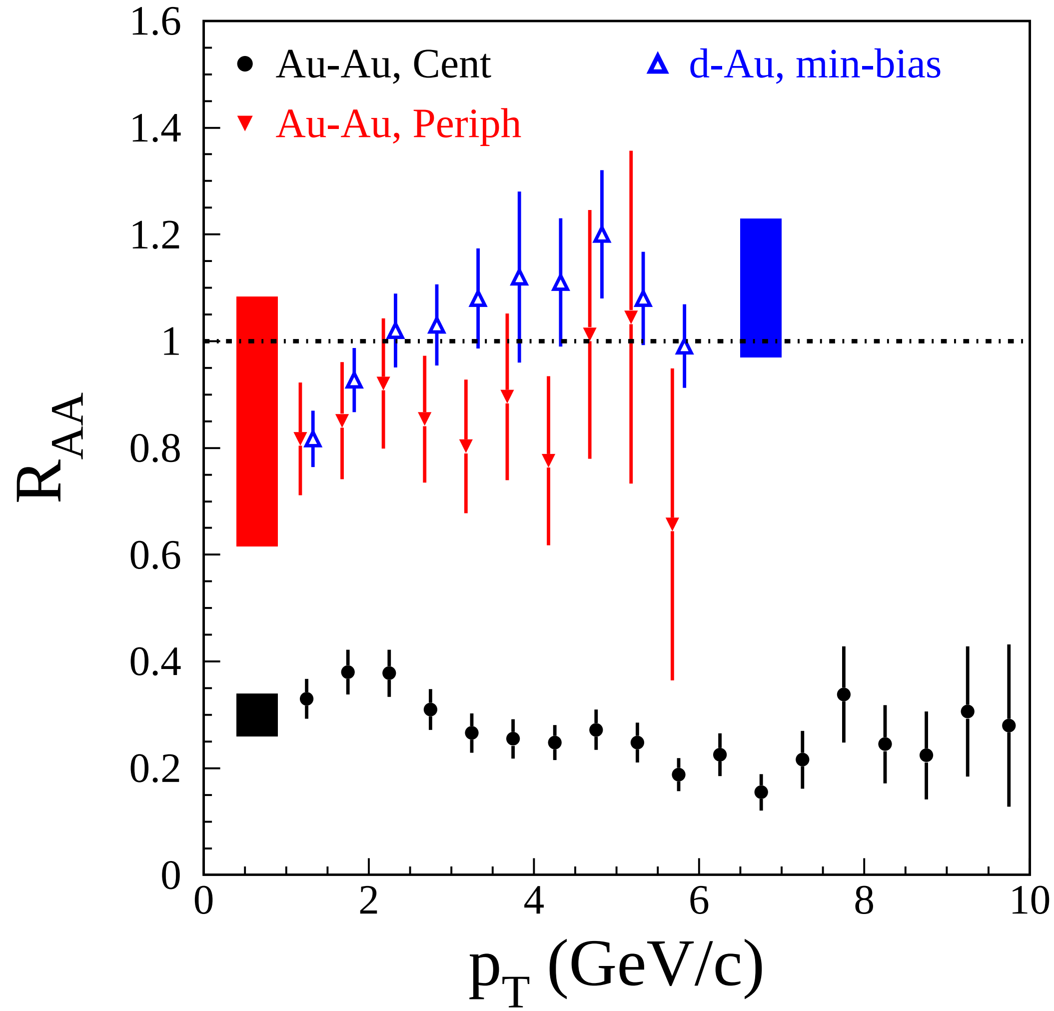


(qqq) (bar) $p_\perp^{bar} = 3p_\perp^{qu}$

Jet Quenching

$$R_{AA} = \frac{n_{AA}}{N_{coll} n_{pp}}$$

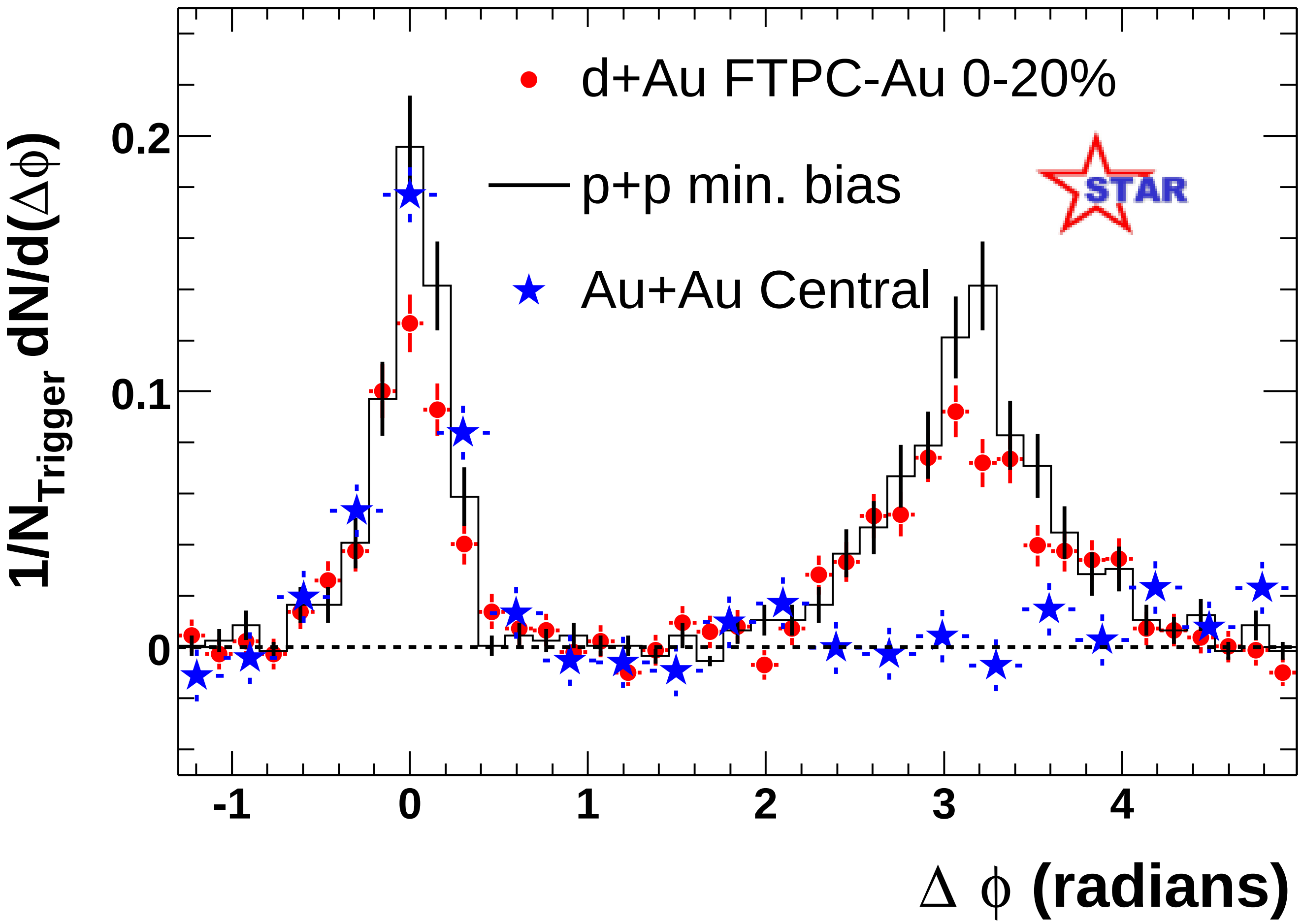




source: Phenix White Paper (2005)

Jet Quenching II

Disappearance of away-side jet



source: Star White Paper (2005)

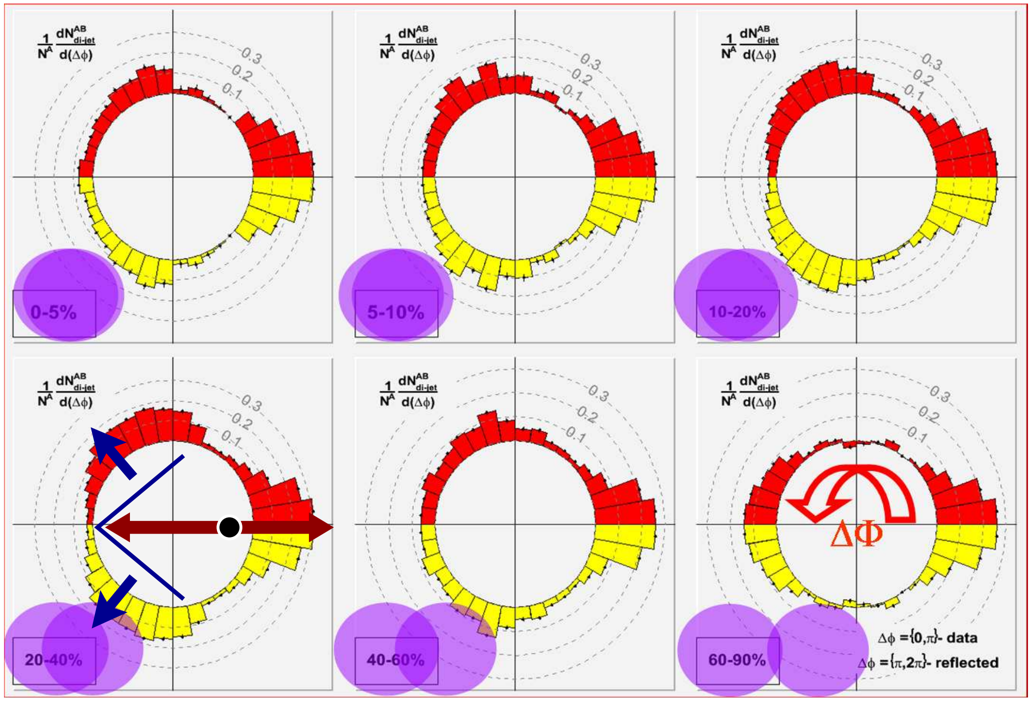
Jet Quenching III: The Mach Cone

azimuthal multiplicity $dN/d\phi$

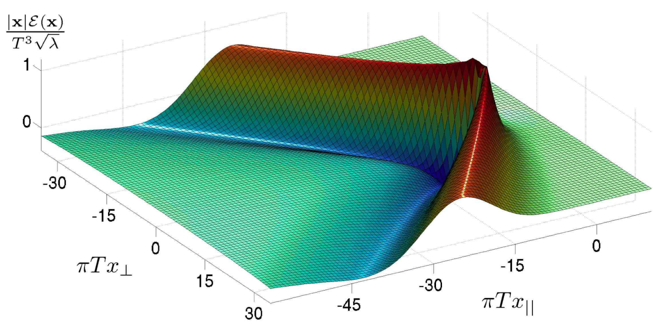
(high energy trigger particle at $\phi = 0$)

wake of a fast quark

in $\mathcal{N} = 4$ plasma



source: Phenix (PRL, 2006), W. Zajc (2007)

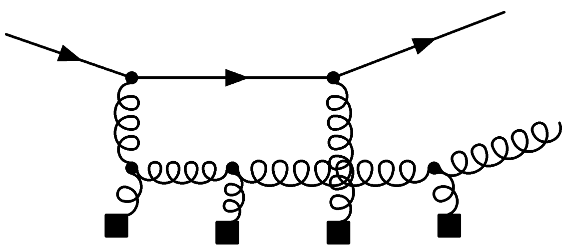


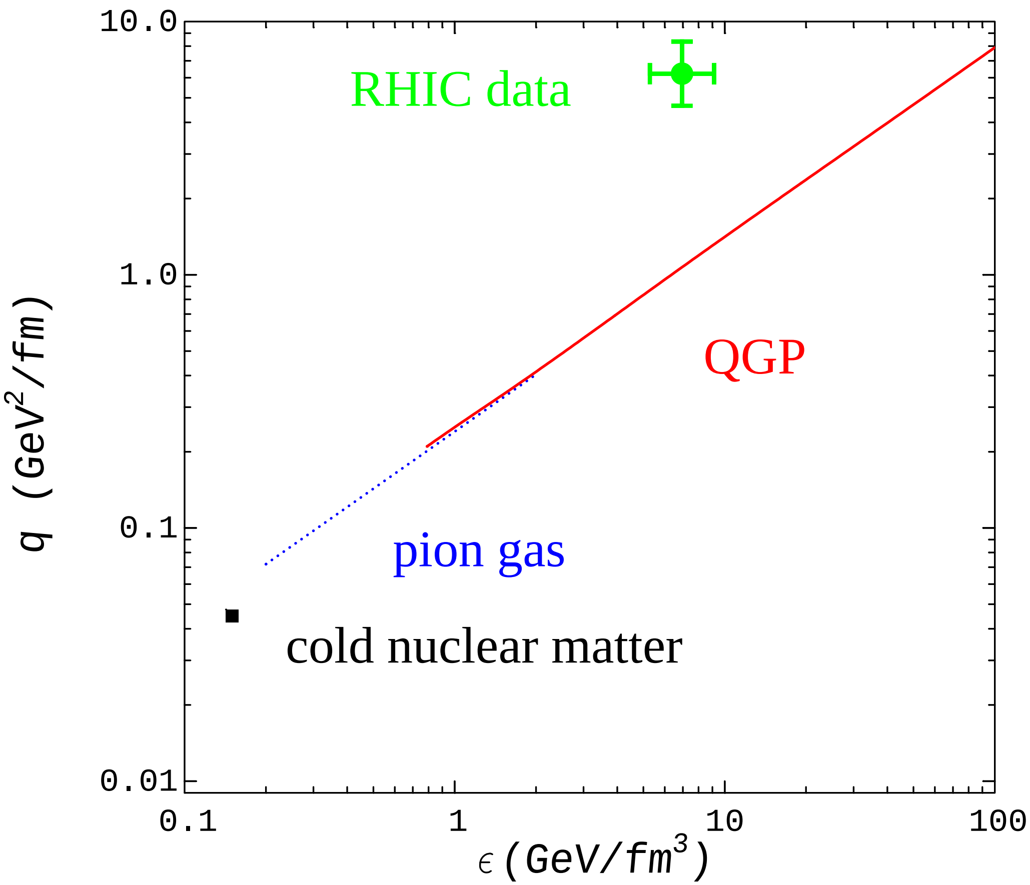
Chesler and Yaffe (2007)

Jet Quenching: Theory

energy loss governed by

$$\hat{q} = \rho \int q_\perp^2 \, dq_\perp^2 \, \frac{d\sigma}{dq_\perp^2}$$



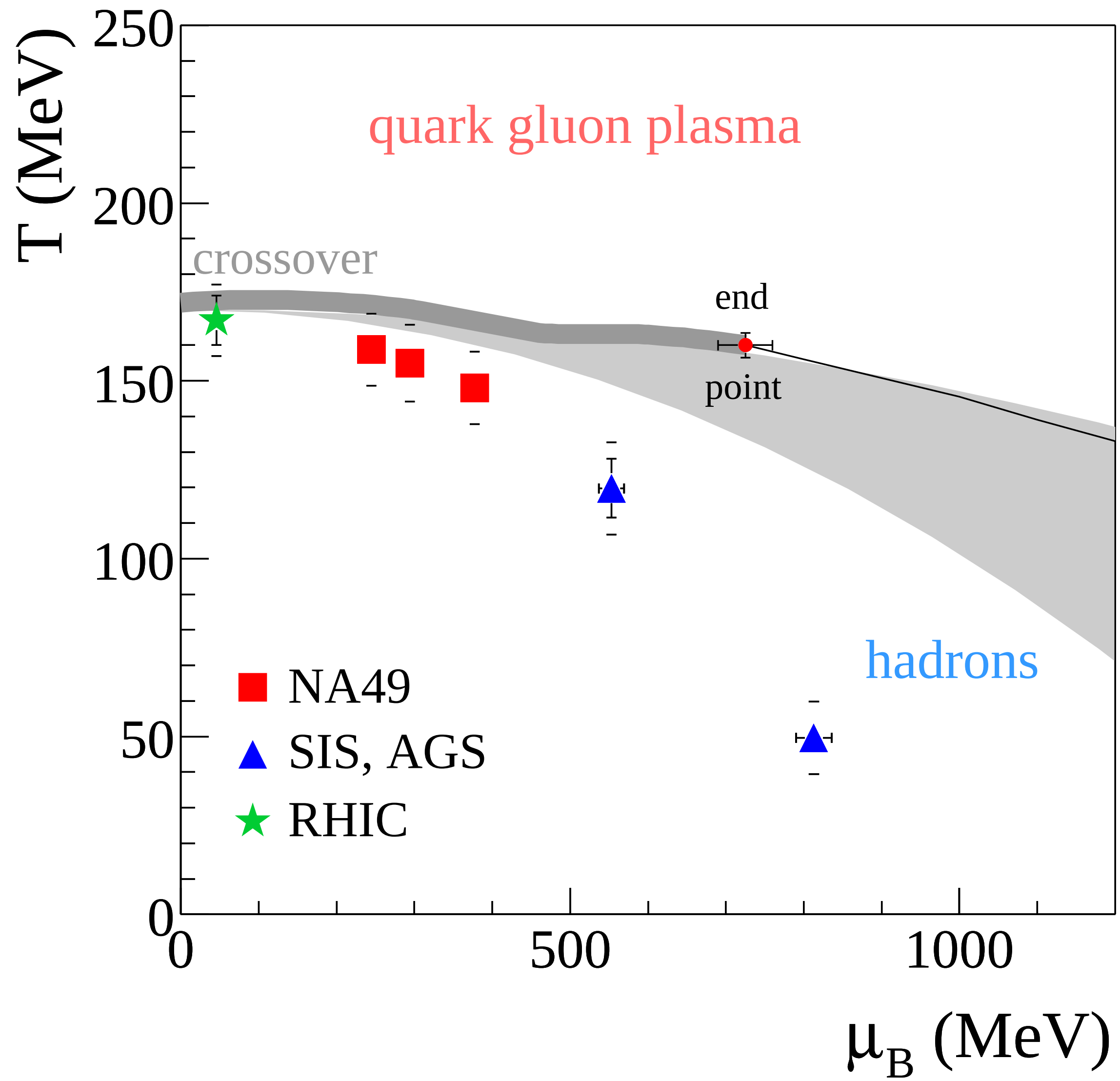


larger than pQCD predicts?

also: large energy loss of heavy quarks

[some recent doubts about $\hat{q}$, see P. Stankus seminar], source: R. Baier (2004)

Phase Diagram: Freezeout



Summary (Experiment)

Matter equilibrates quickly and behaves collectively

Little Bang, not little fizzle

Initial energy density in excess of 10 GeV$/\mathrm{fm}^3$

Conditions for Plasma achieved

Evidence for strongly interacting Plasma ("sQGP")

Fast equilibration $\tau_0 \ll 1$ fm

Large elliptic flow, "perfect fluid"

Strong energy loss of leading partons

The Future: LHC