Flow and Early Thermalization at RHIC

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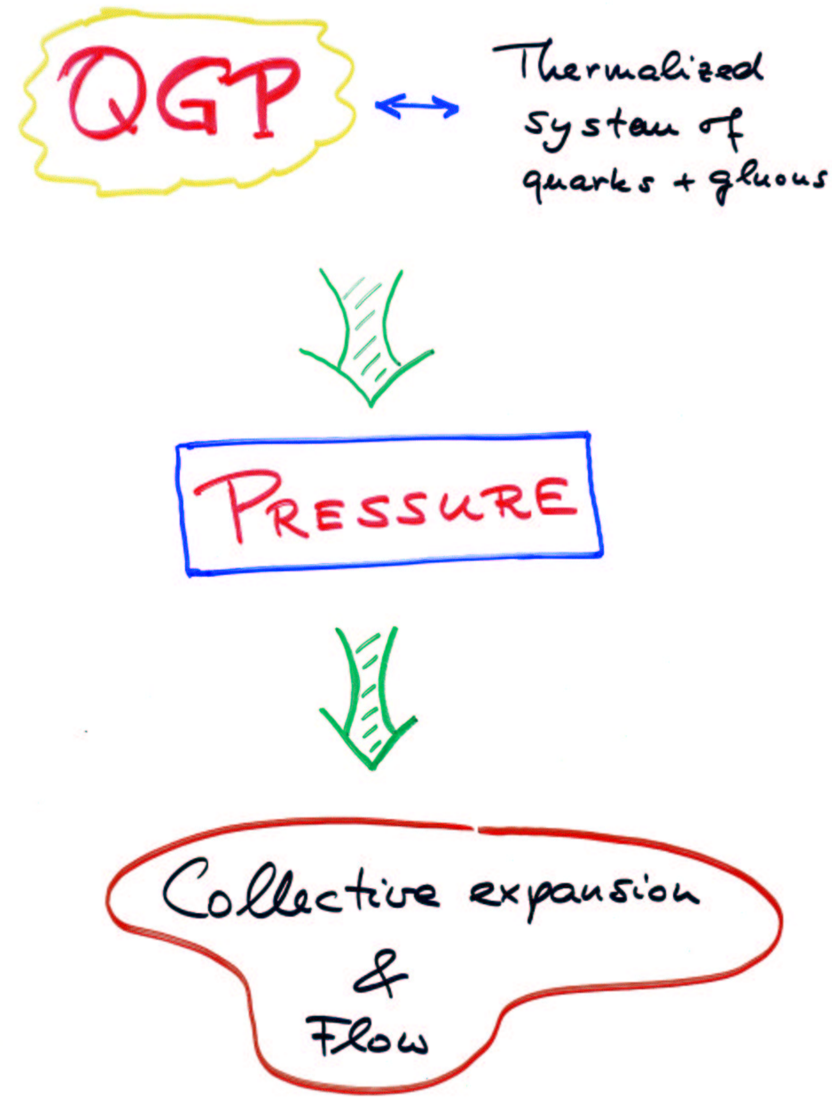
- RHIC spectra vs. hydrodynamics – radial and elliptic flow
- Early thermalization – a challenge for microscopic theories
- The HBT puzzle – how does the system freeze out?

Based on work done in collaboration with P. Kolb

QCD in the RHIC Era, ITP 4/11/02



QGP ⟷ Thermalized system of quarks + gluons

↓

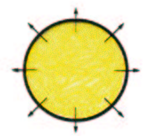
PRESSURE

↓

Collective expansion & Flow

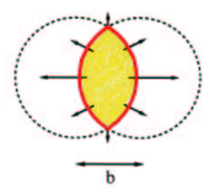
Transverse Flow Patterns

Radial flow:



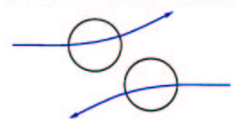
→ Only type of transverse flow in $b = 0$, $A = B$ collisions (Aspherical)
→ Integrates pressure history over complete expansion stage

Anisotropic flow:



→ from deformed initial overlap region
→ peaks at $y = 0$
→ anisotropic flow reduces spatial deformation, → shuts itself off
→ more weigth towards early stage of expansion (H. Sorge)

Directed transverse flow:



→ only in $b \neq 0$ collisions
→ probes the earliest collision stages (pre-equilibrium)

Relativistic Hydrodynamics

Conservation of energy, momentum and baryonnumber

$$\partial_\mu T^{\mu\nu} = 0, \qquad \partial_\mu j^\mu = 0$$

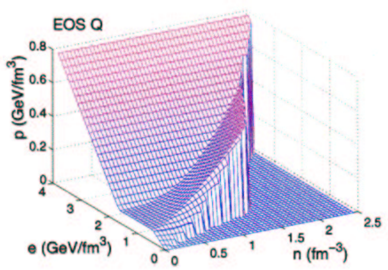
with energy momentum tensor:

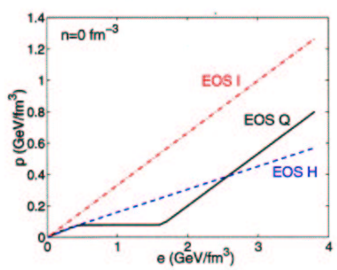
$$T^{\mu\nu}(x) = (e(x) + p(x))\, u^\mu(x) u^\nu(x) - g^{\mu\nu} p(x)$$

and baryon current: $j^\mu(x) = n(x)\, u^\mu(x)$

Equations of state

- EOS I: ultrarelativistic ideal gas, $p = \frac{1}{3} e$
- EOS H: massive, interacting gas of hadrons, $p \sim 0.15\, e$
- EOS Q: Maxwell construction between EOS I and EOS H
  - critical temperature $T_{\text{crit}} = 0.16$ GeV
  - bag constant $B^{1/4} = 0.23$ GeV



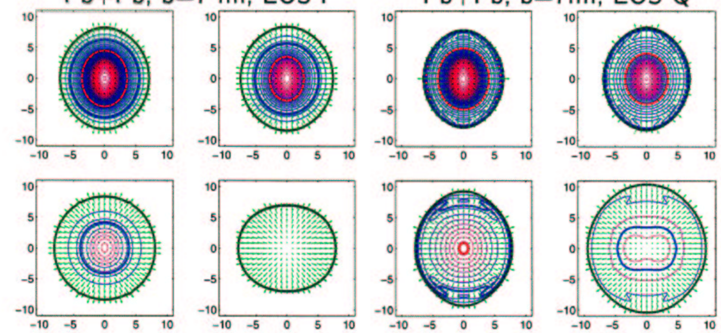


Evolution of energy density,

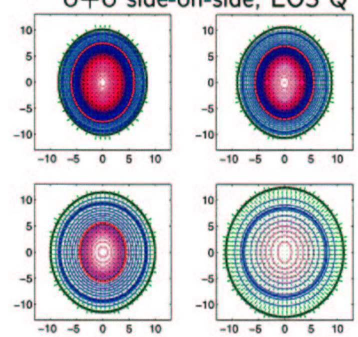
$T_0 \approx 500 MeV$ @ $\tau_{equ} = 0.4$ fm/c

snapshots at τ=3.2, 4.0, 5.6 and 8.0 fm/c after initialization

Pb+Pb, b=7 fm, EOS I   Pb+Pb, b=7fm, EOS Q



U+U side-on-side, EOS Q

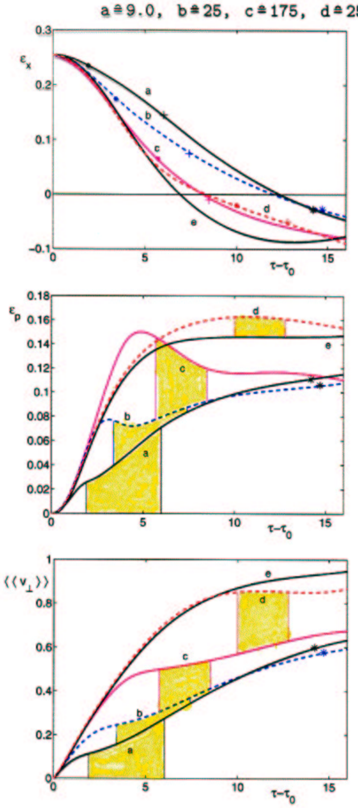


Peter Kolb June 2000

Evolution of Pb+Pb, b=7 fm

for various initial energies

a ≙ 9.0, b ≙ 25, c ≙ 175, d ≙ 25000 GeV/fm^3; e ≙ ideal gas limit



spatial asymmetry

$$\epsilon_x = \frac{\langle\langle y^2 - x^2 \rangle\rangle}{\langle\langle y^2 + x^2 \rangle\rangle}$$

momentum anisotropy

$$\epsilon_p = \frac{\langle\langle T^{xx} - T^{yy} \rangle\rangle}{\langle\langle T^{xx} + T^{yy} \rangle\rangle}$$

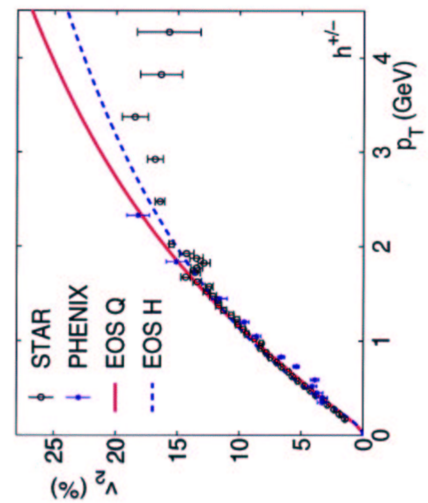
radial flow

$$\langle\langle v_\perp \rangle\rangle = \frac{\left\langle\left\langle \gamma \sqrt{v_x^2 + v_y^2} \right\rangle\right\rangle}{\langle\langle \gamma \rangle\rangle}$$

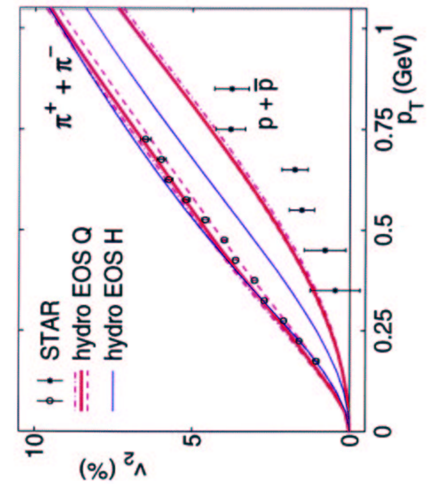
P. Kolb et al., PRC 62, 054909 (2000)

11

above $p_\perp \approx 2$ GeV/c thermalization is incomplete:



heavier hadrons have less elliptic flow at small $p_\perp$:

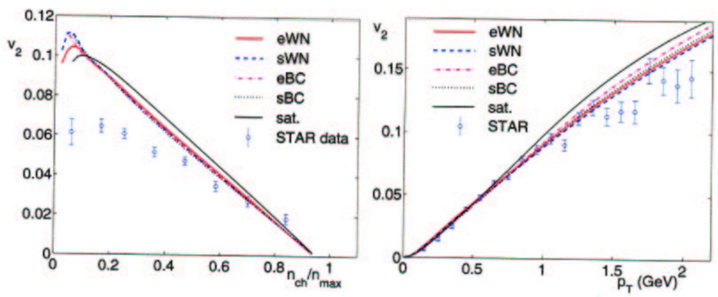


Elliptic flow

STAR-collaboration, K.H. Ackermann et al., Phys. Rev. Lett. 86 (2001) 402

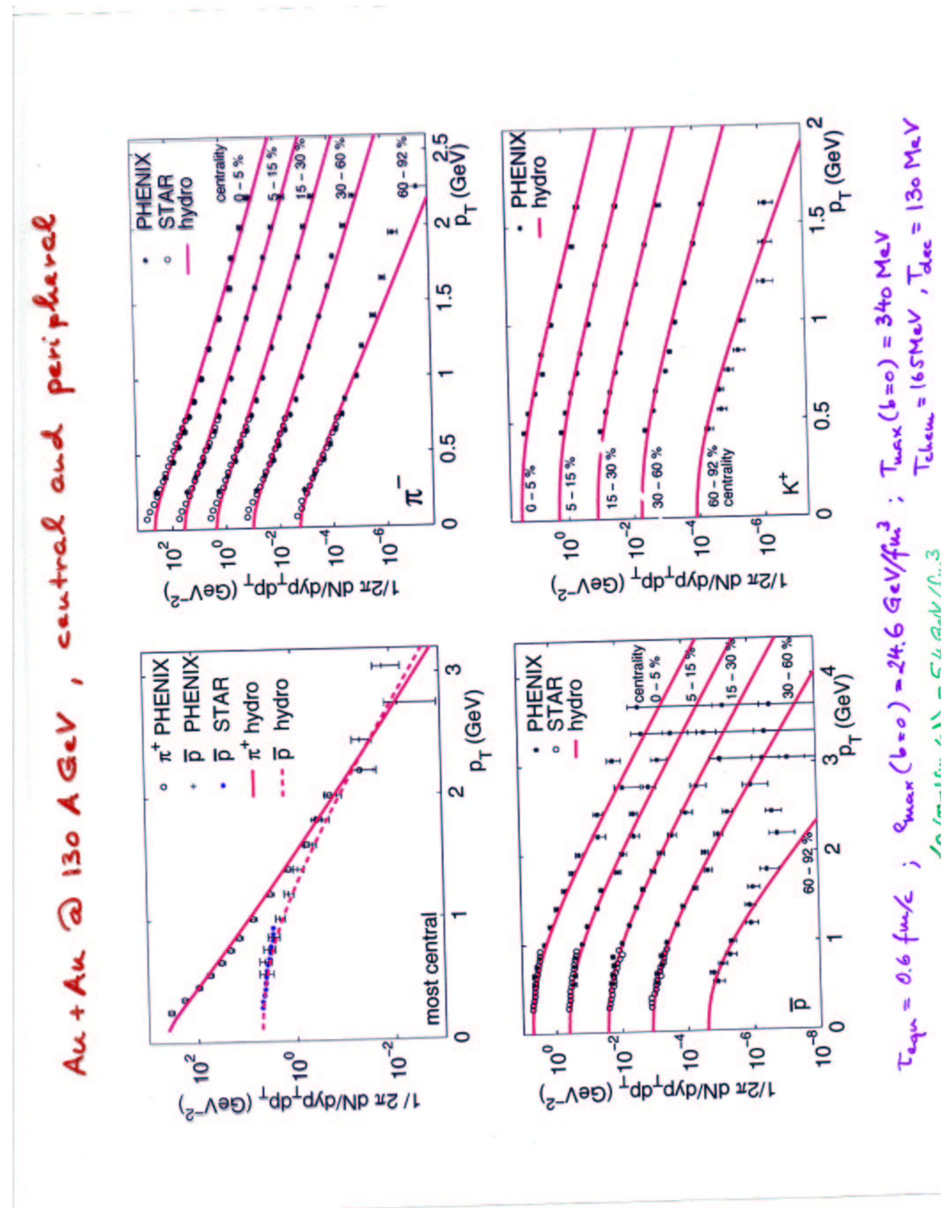
$$v_2(p_t;\, b) = \frac{\int d\phi \cos(2\phi) \frac{dN}{dy\, d\phi\, p_t dp_t}(p_t, \phi; b)}{\int d\phi \frac{dN}{dy\, d\phi\, p_t dp_t}(p_t, \phi; b)}$$

over centrality over momentum



→ hydrodynamics is in good agreement with the data at central and semicentral collisions ($b < 7-8$ fm) and transverse momenta up to $p_T < 1.5 - 2.0$ GeV.

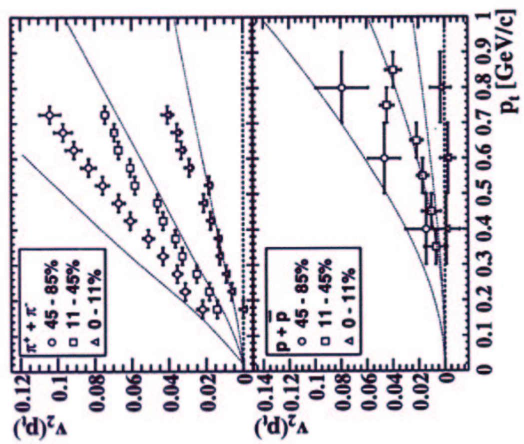
Deviations are due to lack of thermalization in peripheral collisions ('free streaming' → reduction of initial spacial anisotropy) and for high p_T particles (escape without equilibration).



Elliptic flow – mass, centrality and momentum dependence

STAR-collaboration, nucl-ex/0107008

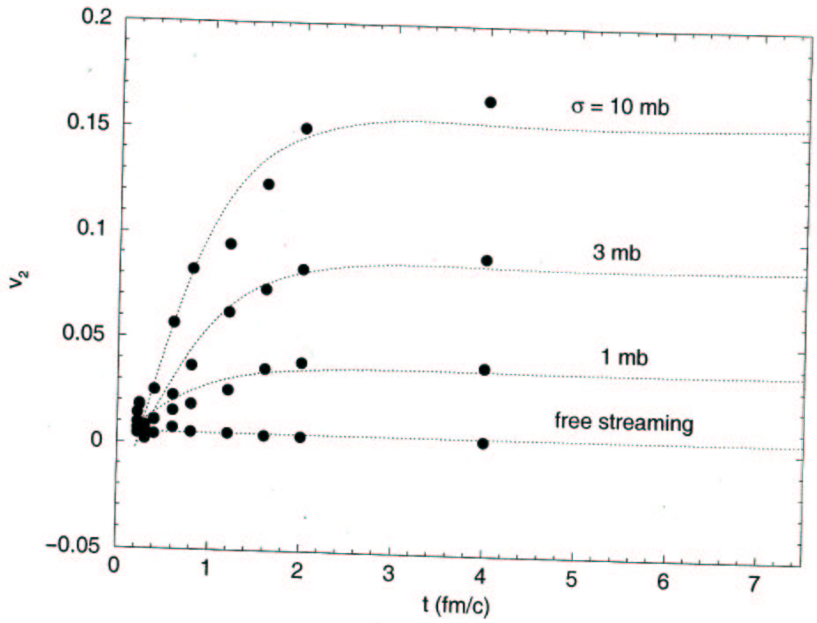
Radial flow shifts particle spectra to higher p_t, producing a plateau at low p_t. The width of the plateau increases with particle mass and thus the difference of particle yields in and out of the reaction plane (i.e. v_2) increases slower with p_t. Observing $v_2(p_t)$ rising more gradually for heavier particles is a *flow* effect! Its magnitude is in quantitative agreement with full hydrodynamic calculations.



Why is this so interesting?

- Initial momentum distribution is locally isotropic
  $\to v_2^{init} = 0$ even if $\langle p_\perp^2\rangle(\vec{r})$ initially anisotropic in $\vec{r}$.
- $\to$ $v_2 \neq 0$ requires "rescattering".
- $v_2 \neq 0$ also requires spatial anisotropy ε_x.
  ε_x is diluted by free-streaming:
  $$\frac{\varepsilon_x(\tau_0+\delta\tau)}{\varepsilon_x(\tau_0)} \approx \frac{1}{1+\frac{(c\,\delta\tau)^2}{R^2(1+\delta^2)}}$$
  In Pb+Pb @ $b = 7$ fm, $\delta\tau = \left\{\begin{matrix}1\text{ fm}/c\\ 2\text{ fm}/c\end{matrix}\right\}$ dilutes ε_x by $\left\{\begin{matrix}10\%\\ 25\%\end{matrix}\right\}$
- $\to$ v_2 must be built up early
- For given ε_x, ideal (non-viscous) hydrodynamics gives largest possible v_2 response. For $b \lesssim 7$ fm and $p_\perp \lesssim 1.5$–2 GeV, RHIC data saturate this upper limit!
- $\to$ data require very strong rescattering and $\approx$ local thermalization ($T^{\mu\nu} \approx T^{\mu\nu}_{\text{ideal fluid}}$) at a very early stage! How??
- elliptic flow is self-quenching
  $\to$ sensitive to EOS before hadronisation.

Elliptic flow requires rescattering:



B. Zhang, M. Gyulassy, C.M. Ko, PLB 455 (1999) 45

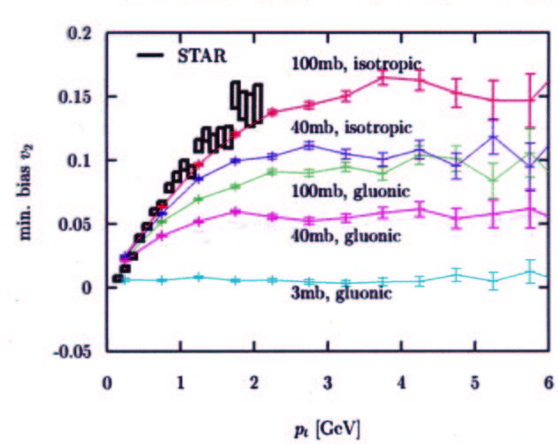
In fact, a lot of rescattering!

Quark Matter, January 15–20, 2001, Dénes Molnár

D. Molnar + M. Gyulassy nucl-th/0104073

Minimum bias v2

MPC Au+Au, $dN/d\eta_{cent} = 210$ (HIJING, 130A GeV)



Simple estimate:

$$v_2^{minbias} = \frac{2\pi}{\pi b_{max}^2} \int_0^{b_{max}} v_2(b)\, b\, db$$

b_{max} **not known → take 12fm**

- v_2 **grows with p_t until $\sim 2 - 3$GeV, then saturates**
- **data supports: HIJING $dN/dy_{cent} = 210$, $\sigma = 100$mb isotropic,** $\gtrsim 30 \times \sigma_{QCD}$!
  or EKRT $dN/dy_{cent} = 1000$, 21mb isotropic $\gtrsim 10$ times σ_{QCD} !
- **also possible with gluonic but needs higher cross sections or densities**
  NOTE: 3mb gluonic requires $dN/dy > 7000$(!)

How the freeze-out surface shines

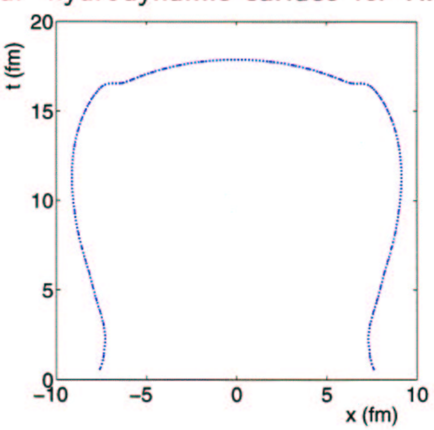
Source function:

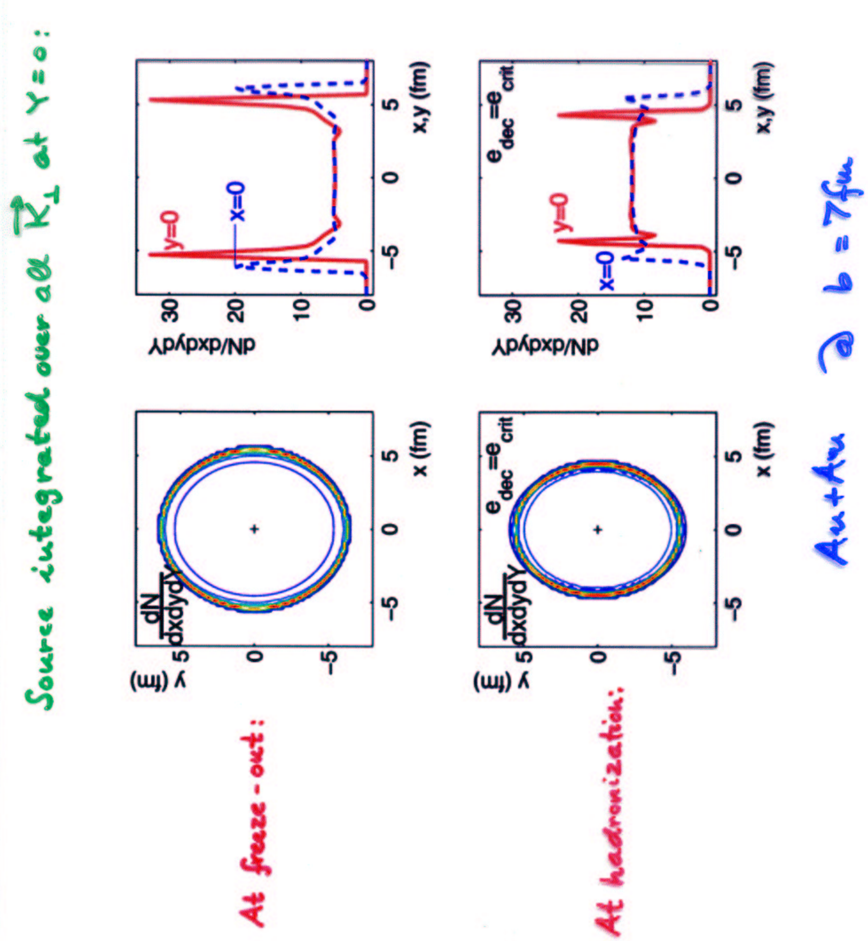
$$S(x,y,\eta,\tau;\,p) = \frac{2s+1}{(2\pi)^3}\int_\Sigma \frac{p^\mu d^3\sigma_\mu(x')\delta^4(x-x')}{\exp\{\beta(x')[p\cdot u(x')-\mu_\alpha(x')]\}\pm 1}$$

$$E\,d^3N/dp^3 = \int d^4x\, S(x,p)$$

Integrate the source function over two coordinates and study contour plots of the emission.

A 'typical' hydrodynamic surface for RHIC energies:





Angular dependence of HBT radii in noncentral collisions

M.A. Lisa, U. Heinz, and U.A. Wiedemann, Phys. Lett. B 489 (2000) 287

evaluate spatial correlation tensor as func. of (K_T, ϕ)

$$S_{\mu\nu} = <\tilde{x}_\mu \tilde{x}_\nu> \text{ with } \tilde{x}_\mu = x_\mu - \bar{x}_\mu$$

for $\beta_{long} = 0$ get

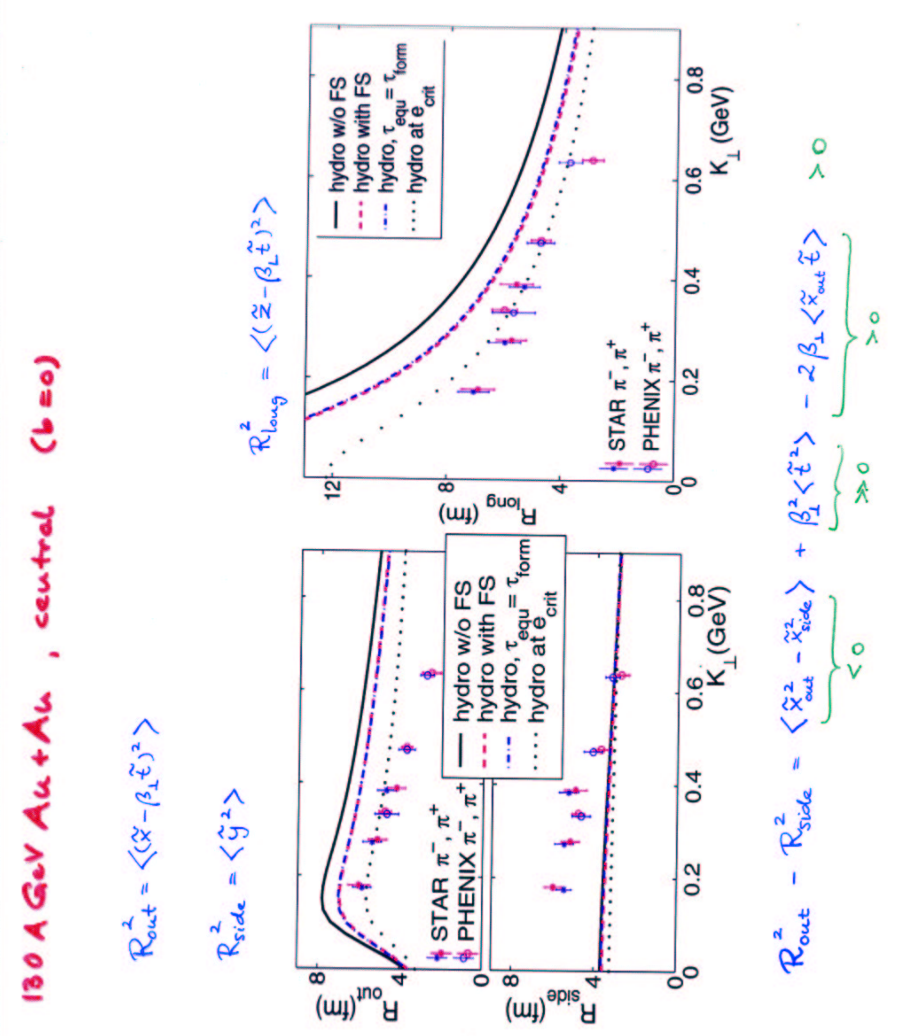
$$R_s^2 = S_{11}\sin^2\phi + S_{22}\cos^2\phi - S_{12}\sin 2\phi$$

$$R_o^2 = S_{11}\cos^2\phi + S_{22}\sin^2\phi + S_{12}\sin 2\phi$$
$$\quad - 2\beta_\perp(S_{01}\cos\phi + S_{02}\sin\phi) + \beta_\perp^2 S_{00}$$

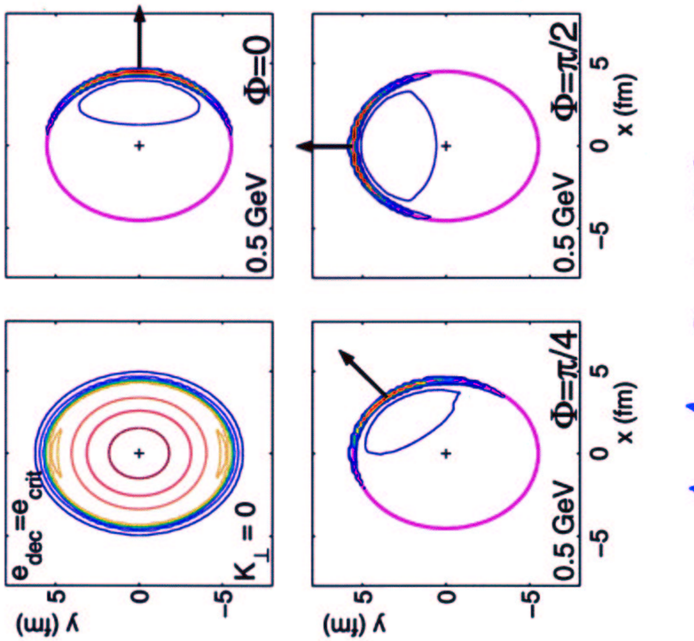
$$R_{os}^2 = S_{12}\cos 2\phi + \tfrac{1}{2}(S_{22} - S_{11})\sin 2\phi$$
$$\quad + \beta_\perp(S_{01}\sin\phi - S_{02}\cos\phi)$$

$$R_l^2 = S_{33}$$

→ Gives more detailed access to the collision geometry

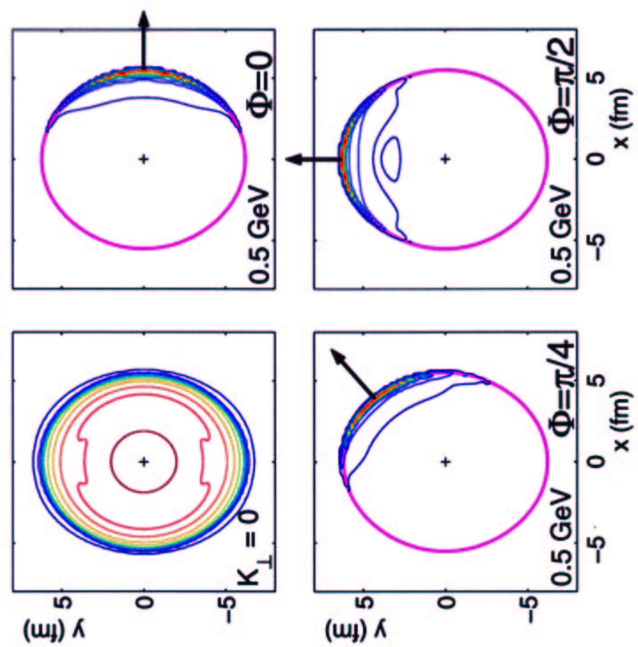


Homogeneity regions at hadronization:
(Y=0)



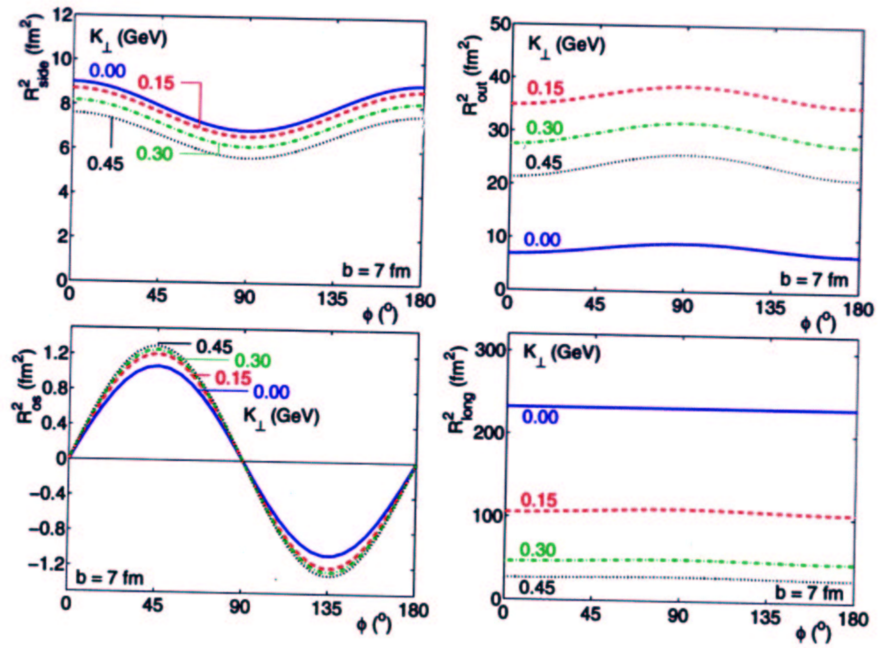
Au+Au @ b = 7fm

Homogeneity regions at freeze-out:
(Y=0)



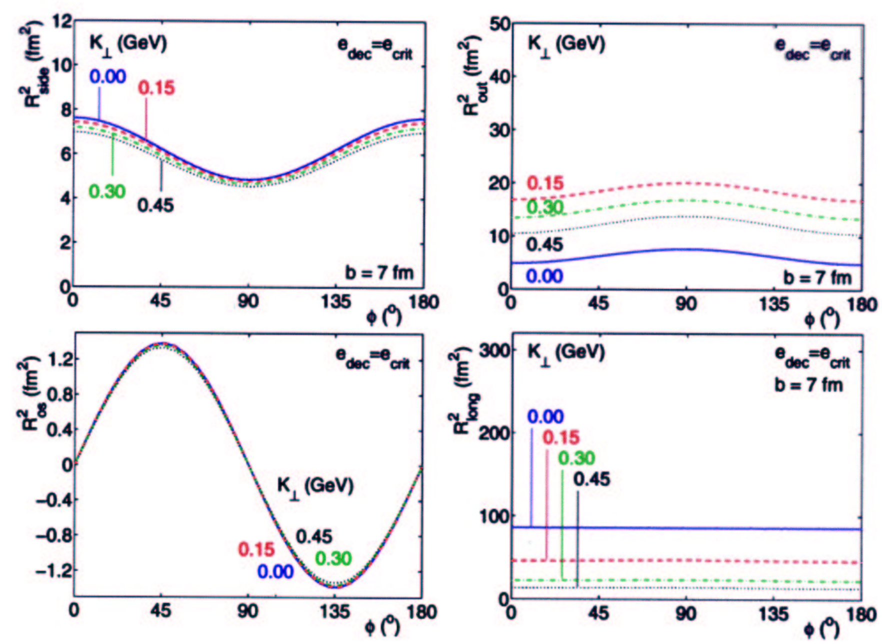
Au+Au @ b = 7fm

Azimuthal oscillations of HBT radii @ freeze-out:



Au+Au @ b = 7fm

Azimuthal oscillations of HBT radii at hadronization:



Au+Au @ b = 7fm

Summary

- In Au+Au at RHIC for $b \leq 7$ fm, and $p_T \leq 1.5 - 2$ GeV/c, the anisotropic flow data reach the upper limit set by infinitely strong rescattering. Such a maximum mapping of the initial spatial anisotropy to final momentum anisotropy requires *rapid thermalization* and *early pressure*, at energy densities well above 1 GeV/fm^3.

At $\sqrt{s_{NN}} = 130$ GeV we seem to have reached the hydrodynamic limit within these parameters.

However:

- Hydrodynamics gives too large values for R_{out} and too small values for R_{side}. The collision fireball seems be shorter lived but larger than the hydrodynamic picture suggests.
- A proper initialization scheme eases, but does not completely resolve this problem. Initial flow from a free-streaming phase has an appreciable effect on the HBT radii and should not be neglected in hydrodynamical studies.
- The microscopic mechanisms for early thermalization are presently unclear and require further study.