Measuring the thermalization time

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Fluid expansion at RHIC

- HBT requires hard EOS

- Early transverse expansion

Have we seen a 3D expanding fireball?
Transverse / Longitudinal Pressure

Non-equilibrium and/or viscosity
Early stage

\[
\tau_{\mu \nu} = \begin{pmatrix}
\epsilon & 0 & 0 & 0 \\
0 & p + \pi/2 & 0 & 0 \\
0 & 0 & p + \pi/2 & 0 \\
0 & 0 & 0 & p - \pi
\end{pmatrix}
\]

\[
\pi = \frac{4 \eta}{3 \tau} \quad \text{Navier-Stokes}
\]

more general \( \pi \) possible - (initial value, dynamics, far off-equilibrium)

What signatures of isotropization?
What measure of thermalization time?
Early dissipation

\[ (P_\perp - P_\parallel) \propto \exp \left( -\frac{\tau}{\tau_{iso}} \right) \]

phenomenological ansatz
thermalization time \( \tau_{iso} \)

Early dissipation

\[ (P_\perp - P_\parallel) \propto \exp \left( -\frac{\tau}{\tau_{iso}} \right) \]

phenomenological ansatz

thermalization time \( \tau_{iso} \)


BUT Universal flow


No sensitivity of transverse flow to early dissipation!
Longitudinal expansion - cooling

Ideal hydro

Viscous hydro $\eta/s = 0.2$


Cannot be observed in final distributions!

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Early thermalization
Standard observables are not sensitive to early dissipation

transverse or longitudinal expansion alone is insufficient
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\[
\text{transverse } + \text{ longitudinal expansion } = \text{ directed flow}
\]
Standard observables are not sensitive to early dissipation

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\[ \text{transverse} + \text{longitudinal} \text{ expansion} = \text{directed flow} \]

and

it happens very early
Directed flow - $v_1$

\[ \frac{dN}{d^2pdy} = \frac{dN}{2\pi pdp} dy \left( 1 + 2v_1 \cos \phi + 2v_2 \cos 2\phi + \ldots \right) \]

- large flow at 200GeV
- anti-flow
- Au-Au similar to Cu-Cu
- Dynamics: early, 3D
Asymmetric emission

Asymmetric emission


\[ \rho(\eta, x, y) \propto f_+(\eta)N_+(x, y) + f_-(\eta)N_-(x, y) \]
Asymmetric emission


\[
\rho(\eta, x, y) \propto f_+(\eta)N_+(x, y) + f_-(\eta)N_-(x, y)
\]

bremsstrahlung (Adil Gyulassy, Phys. Rev. C72, 034907 (2005))
Tilted source

\[ \partial_\tau u_x = -\frac{\partial_x p_\perp}{p + \epsilon} \]

\[ \partial_\tau Y = -\frac{\partial_\eta p_\parallel}{\tau(p + \epsilon)} \]

Tilted source \(\rightarrow\) transverse pressure + longitudinal pressure

Glauber model
Anti-flow explained!
System size dependence
Consistent with asymmetric emission
3+1D expansion with off-equilibrium pressure

\[ T^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p_\perp & 0 & 0 \\ 0 & 0 & p_\perp & 0 \\ 0 & 0 & 0 & p_\parallel \end{pmatrix} \]

\[ \partial_\mu T^{\mu\nu} = 0 \]

in 3+1D

\[ \epsilon, P_\perp, P_\parallel, P_{eq} \]
Central collisions - *spectra*

No sensitivity to off-equilibrium pressure
Central collisions - HBT

No sensitivity to off-equilibrium pressure
Mid-peripheral collisions - \textbf{elliptic flow}

PHENIX Data Au-Au $\sqrt{s}=200$ GeV
Charged particles \( c=20-25\% \)

- $P_L(\tau_0)=0$, $\tau_{\text{iso}}=0.25\text{fm/c}$
- $P_L(\tau_0)=0$, $\tau_{\text{iso}}=0.5\text{fm/c}$ large tilt
- Ideal fluid

No sensitivity to off-equilibrium pressure
Mid-peripheral collisions - directed flow

- Sensitive to off-equilibrium pressure
- RHIC data indicate early thermalization
tilt $\rightarrow$ HYDRO $\rightarrow$ $v_1$
\[ \tilde{t} \rightarrow \text{HYDRO} \rightarrow \nu_1 \]

\[ 0 \leq \tau_{iso} \]

STAR Data  Au-Au  \( \sqrt{s}=200 \text{ GeV} \)  c=5-40\%

\( \rho \sim x \)
Viscosity- minimal pressure anisotropy

\[ \Pi \simeq \frac{4\eta}{3\tau} \]
\[ \frac{\eta}{s} = \frac{1}{4\pi} \]

Pressure anisotropy compatible with small shear viscosity
Directed flow

New observable for early stages

- Directed flow sensitive to longitudinal and transverse pressure
- Directed flow develops early
- Need 3+1D model
Directed flow

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Conclusions

- No room for early pressure anisotropy
- Very fast thermalization

$\tau_{iso} \leq 0.25\text{fm/c}$
Hydro : mass scaling

PID $\nu_1$

Au-Au $\sqrt{s}=200$ GeV  $b=6.7$fm
PID $v_1$

Hydro: mass scaling

Zero baryon flow! (STAR)
Baryon asymmetry!

Fragmenting nucleons

\[ \Delta \gamma_1 \propto \frac{\mu}{T} \frac{N_+ - N_-}{N_+ + N_-} \]

Baryons pushed to \( \gamma_1 > 0 \)
Transverse + Longitudinal Expansion = Directed Flow

longitudinal pressure appears before 1 fm/c
fast isotropization

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Early thermalization
Early collectivity

$\nu_1$ develops before $\nu_2$
$\left< p_\perp \right>$ dependence

deformed source
(Kolb Heinz)

$\left< p_x \right> = 0$
$p_\perp$ dependence

![Graph showing the $v_1$ dependence on $p_T$ with different $\eta_s$ values.](image)

Deformed source
    
(Kolb Heinz)

$\langle p_x \rangle = 0$

3+1D → shift to $v_1 < 0$