Fast thermalization and almost perfect liquidity of the QGP at RHIC† – fact or fiction?

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*Work supported by the U.S. Department of Energy (DOE)

†RHIC = Renaissance Heavy-Ion Collider
The QCD Phase Diagram and Heavy-Ion Collisions

Particle Physics ↔ Heavy-Ion Physics ↔ Atomic Physics ↔ Condensed Matter Physics
The QCD equation of state (EOS) at zero baryon density

F. Karsch and E. Laermann, hep-lat/0305025, in “Quark-Gluon Plasma 3”

- Critical temperature: \( T_{cr} = 173 \pm 15 \text{ MeV} \) \( (\approx 100 000 \times T_{\text{center of sun}}) \)

- Critical energy density: \( \varepsilon_{cr} \approx 0.7 \text{ GeV/fm}^3 \)

- \( \varepsilon \approx 0.8 \varepsilon_{SB} \) for \( T \gtrsim 1.3 T_{cr} \), \( \varepsilon \approx 3 p \) for \( T \gtrsim 2 T_{cr} \)

\[ \implies \text{Weakly coupled QGP? NO!} \]
Collective flow tests the Equation of State:

Hydrodynamic equations, ideal fluid limit:

\( \dot{f} = \text{time derivative in local rest frame}, \ \partial \cdot u = \text{local expansion rate} \)

\[
\begin{align*}
\dot{n}_B &= -n_B (\partial \cdot u) \\
\dot{\varepsilon} &= -(\varepsilon + p) (\partial \cdot u) \\
\ddot{u}^\mu &= \frac{\nabla^\mu p}{\varepsilon + p} = \frac{c_s^2}{1 + c_s^2} \frac{\nabla^\mu \varepsilon}{\varepsilon}
\end{align*}
\]

- flow driven by pressure gradients \( \nabla^\mu p \)
- acceleration \( \frac{\nabla^\mu p}{\varepsilon + p} \) closely related to speed of sound \( c_s^2 = \frac{\partial p}{\partial \varepsilon} \)

Karsch+Laermann, hep-lat/0305025

Chojnacki et al., nucl-th/0410036

"Softest point" near \( T = T_{cr} \).
Ideal Fluid Dynamics

Relativistic Hydrodynamics: Conservation of energy, momentum and baryon number

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

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
\[ j^\mu(x) = n(x) u^\mu(x) \]

Equation of state:

- EOS I: ultrarelativistic ideal gas, \( p = \frac{1}{3} e \)
- EOS H: hadron resonance gas, \( p \sim 0.15 e \)
- EOS Q: Maxwell construction between EOS I and EOS H

critical temperature \( T_{\text{crit}} = 0.164 \text{ GeV} \)
\[ \Rightarrow \text{ bag constant } B^{1/4} = 0.23 \text{ GeV} \]
latent heat \( \Delta e = 1.15 \text{ GeV/fm}^3 \)

Implement exact longitudinal boost invariance for simplicity (\( Y \approx 0 \) only)
What is fitted, what is predicted?

\textbf{Au+Au @ 130 A GeV:}

\[ \tau_{\text{eq}} = 0.6 \text{ fm}/c, \quad e_{\text{max}}(b=0) = 24.6 \text{ GeV}/\text{fm}^3, \quad \langle e \rangle (\tau=1 \text{ fm}/c) = 5.4 \text{ GeV}/\text{fm}^3 \]

\[ T_{\text{max}}(b=0) = 340 \text{ MeV}, \quad T_{\text{chem}} = T_{\text{had}} = 165 \text{ MeV}, \quad T_{\text{dec}} = 130 \text{ MeV} \]

All fit parameters are fixed in central \((b=0)\) collisions:

- Glauber model \(\Rightarrow\) shape of initial transverse entropy and baryon density profiles \(s(r, \tau_{\text{eq}}), n_B(r, \tau_{\text{eq}})\)
  \(\Rightarrow\) free parameters \(s_0(\tau_{\text{eq}}), n_0(\tau_{\text{eq}}), \text{soft/hard fraction}\)
- Measured \(p/\pi\) ratio \(\Rightarrow\) fixes \(n_0/s_0\)
- Total charged multiplicity \(dN_{\text{ch}}/dy\) \(\Rightarrow\) fixes product \(\tau_{\text{eq}} \cdot s_0(\tau_{\text{eq}})\)
- \text{soft/hard fraction} \(\Rightarrow\) fixed through centrality dependence of \(dN_{\text{ch}}/dy\)
- Shape of \(\pi, p\) spectra \(\Rightarrow\) fixes decoupling temperature \(T_{\text{dec}}\) and radial flow \(\langle v_\perp \rangle\)
- Final radial flow \(\langle v_\perp \rangle\) \(\Rightarrow\) “fixes” \(\tau_{\text{eq}}\) [upper limit] (flow needs time and pressure to develop)
- Equation of State \(\Rightarrow\) compute \(e_0 = e_{\text{max}}(b=0), T_{\text{max}}(b=0)\) from \(s_0, n_0\)

**Predictions (no additional parameters!):**

- All hadron spectra other than \(p, \pi\) in \(b=0\) collisions
- All hadron spectra and elliptic flow coefficients for non-central collisions at any impact parameter

**Shortcomings of early hydro calculations (repaired in later versions):**

- EOS assumes chemical equilibrium all the way down to \(T_{\text{dec}}\)
- No transverse dynamics before \(\tau_{\text{eq}}\)
Successes of hydrodynamics at RHIC:

Single particle spectra from central and peripheral Au+Au @ 130 A GeV (STAR, PHENIX):

Centrality and momentum dependence of elliptic flow $v_2$

(STAR, PHENIX, PHOBOS):

Model parameters fixed with $\pi$, $\bar{p}$ spectra at $b = 0$; all other spectra predicted (UH & P.Kolb, hep-ph/0204061).

Final radial flow $\langle v_\perp \rangle > 0.5 \, c \implies$ bang!
Rest mass dependence of differential elliptic flow (the “fine structure”)


Data follow the hydrodynamically predicted rest mass dependence of $v_2(p_\perp)$ out to $p_\perp \sim 1.5$ GeV for mesons and out to $p_\perp \sim 2.3$ GeV for baryons

$\longrightarrow$ bulk of matter (> 99% of all particles) behaves hydrodynamically!

Note: mass-splitting of $v_2$ (“fine structure”) sensitive to EOS!
so hydro works –
why? what does this mean?
Elliptic collective flow of strongly coupled atoms at $T = 10^{-6}$ K:

Interaction strength can be tuned (Feshbach resonance):

**Strong interaction:** elliptic collective flow

**Weak interaction:** ballistic expansion with aspect ratio $\rightarrow 1$
Breakdown of hydrodynamics at high $p_{\perp}$: upper limits for the QGP viscosity

D. Molnár and M. Gyulassy, NPA 697 (2002) 495

D. Teaney, PRC 68 (2003) 034913

- For sufficiently (very) large $\sigma_{el}$, $v_2(p_{\perp})$ from covariant parton transport model MPC follows hydrodynamic curve at low $p_{\perp}$ and reproduces observed saturation at high $p_{\perp}$
- Similar pattern is seen in viscous hydrodynamics: viscous corrections increase $\sim p_{\perp}^2$
- $v_2$ data suggest $\frac{\Gamma_s}{\tau_0} < 0.1$, close to minimum viscosity $\frac{\eta}{s} = \frac{\hbar}{4\pi}$ (Son et al. 2002)

QGP seems to be the most perfect (real) fluid ever observed!

More quantitative constraints on $\eta$ require viscous hydrodynamics code.
QGP – the most ideal fluid ever observed!

adS/CFT universal lower viscosity bound conjecture: \( \frac{\eta}{s} \gtrsim \frac{\hbar}{4\pi} \)

Kovtun, Son, Starinets, hep-th/0405231

Upper limit for QGP viscosity from Teaney’s estimate is close to this bound!

More quantitative constraints on \( \eta \) require viscous hydrodynamics code.
How quantitatively does ideal hydro work at RHIC?
Where and how does it begin to break down?
Interlude: Chemical Freeze-out at $T_{\text{had}} \sim 170$ MeV

Central Au+Au @ 130 A GeV
(STAR Coll., G. van Buren, QM2002)

Abundance ratios of stable hadrons decouple in maximum entropy state of “apparent chemical equilibrium” with $T_{\text{chem}} \sim T_{\text{had}} \sim 170$ MeV

Need non-equilibrium chemical potentials $\mu_i(T)$ for hadrons $i$ to keep abundance ratios constant at $T < T_{\text{chem}}$.

(R. Rapp, PRC 66 (2002) 017901
T. Hirano, PRC 66 (2002) 054905
D. Teaney, nucl-th/0204023)
Expansion with non-equilibrium chemical potentials:

- Non-equilibrium hadronic potentials do not alter the equation of state $p(e)$
  - unchanged time evolution of energy density $e(\tau)$
- They do, however, change $e(T)$
  - same energy density corresponds to lower temperature
  - system cools faster
- Freeze-out at fixed energy density
  - same time, same flow, but lower temperature

T. Hirano, PRC 66 (2002) 054905
Hydro parameters: \( \tau_{eq} = 0.6 \text{ fm/c}, \ s_0 \equiv s_{\text{max}}(b=0) = 110 \text{ fm}^{-3}, \ s_0/n_0 = 250 \)

\( T_{\text{chem}} = T_{\text{crit}} = 165 \text{ MeV}, \quad T_{\text{dec}} = 100 \text{ MeV} \)

**Note:** • Hydro does not create enough radial flow already at \( T_c \) to describe baryon spectra
  • Multistrange baryons seem to fully participate in continued radial flow build-up during late hadronic phase!
The fine print on hydrodynamics:

PHENIX White Paper, NPA 757 (2005) 184

All theory curves use the same hydrodynamics and EOS in QGP phase!
How we deal with the hadron phase makes all the difference . . .
Redistribution of momentum anisotropy in the HG phase

\[ \varepsilon_x = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \]  
spatial anisotropy

\[ \varepsilon_p = \frac{\langle T_{xx} - T_{yy} \rangle}{\langle T_{xx} + T_{yy} \rangle} \]  
momentum anisotropy

- Momentum anisotropy saturates \( \approx \) when spatial eccentricity passes through zero.
- At sufficiently high energies, this happens before hadronization is complete.
- However, redistribution of momentum anisotropy in HG phase over \( p_T \) for different hadronic species reflects intricate interplay between thermal motion and radial flow and depends on chemical composition, viscosity and EOS of HG, \( T_{\text{dec}} \), . . .
Quantitative interpretation of $v_2$ data requires detailed understanding of viscous hadronic dynamics!

To extract early EOS signature (e.g. $c_s^2$ of QGP), reconstruct total momentum anisotropy ($p_T^2$-weighted elliptic flow) from hadron spectra:

$$
\epsilon_p = \frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle} = \frac{\sum_{i \in \text{hadrons}} \int p_T^2 \cos(2\phi_p) \frac{dN_i}{dy p_T dp_T d\phi_p} d^2p_T}{\sum_{i \in \text{hadrons}} \int p_T^2 \frac{dN_i}{dy p_T dp_T d\phi_p} d^2p_T}
$$

May have to correct this for resonance decays.
So ideal hydro “kind of works” (better than anywhere else in nuclear physics before), but it doesn’t really describe the RHIC data quantitatively!

What (or who?) causes the deviations?
Is there order in this chaos?
What about our ability to extract the QGP EOS??

Let’s look at some more evidence . . .
Limits of ideal fluid dynamics: smaller, less dense systems

STAR, PRC 66 ('02) 034904; NA49, PRC 68 ('03) 034903

3d hydro:
T. Hirano, PRC 65 ('02) 011901; 66 ('02) 054905

\[
\frac{v_2}{\varepsilon} \begin{cases} 
\text{HYDRO limits} & \text{HYDRO limits} \\
0 & 0.05 \end{cases}
\]

\[
\begin{array}{c}
\text{HYDRO limits} \\
0 \quad 0.05 \\
\end{array}
\]

\[
\begin{array}{c}
v_2^\text{hydro} / v_2^\text{measured} \\
0 \quad 1 \end{array}
\]

- $v_2^\text{hydro} / v_2^\text{measured}$ scales with $\frac{1}{S} \frac{dN_{ch}}{dy} \propto s_{\text{init}}$

- $e_{\text{init}} > 10 \text{ GeV/fm}^3$ needed for $v_2$ to saturate before hadronization and exhaust ideal hydro limit!

- Hydrodynamics predicts non-monotonic $v_2 / \varepsilon$: between AGS and RHIC it decreases, due to softening of EOS by quark-hadron transition (Kolb, Sollfrank, UH, PRC 62 (2000) 054909)

- Data show instead monotonous increase of $v_2 / \varepsilon$ with $\sqrt{s}$!? What’s going on??
Breakdown of ideal hydro: the viscous hadron fluid

Excitation function of elliptic flow:

Ideal hydro

P. Kolb, J. Sollfrank, U.H., PRC 62 ('00) 054909

Hydro + RQMD

D. Teaney, J. Lauret, E. Shuryak, nucl-th/0110037

Hadron resonance gas is very viscous and does not respond strongly to spatial eccentricity $\Rightarrow$ non-monotonic behaviour of $v_2$ resulting from dip in $c_s^2$ near phase-transition is erased!

$\Rightarrow$ The inability of the viscous hadronic phase to build elliptic flow kills the phase transition signature!
Is hadronic dissipation enough to explain deviations from perfect fluidity?

(T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, nucl-th/0511046)

3D Hydro+Cascade Model: Ideal fluid dynamics for QGP above $T_c$, hadronic cascade with realistic cross sections (JAM) below $T_c$ (similar to Bass & Dumitru (1D), Teaney & Shuryak (2D))

---

- Not enough elliptic flow from perfect QGP fluid – hadronic contribution to $v_2$ is required
- Treating hadronic stage as ideal fluid overpredicts $v_2$ in peripheral collisions and at forward rapidities
- Dissipation in hadronic cascade brings theory in line with data (except for small $b$ – excess in data due to event-by-event geometry fluctuations? (Miller & Snellings, PHOBOS))
CGC initial conditions give larger elliptic flow – is the QGP 'imperfect' after all?

(T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, nucl-th/0511046)

- **Color Glass Condensate (CGC) model** (McLerran & Venugopalan 1994; Kharzeev, Levin, Nardi 2001) produces steeper edge of initial distribution, resulting in larger eccentricities $\epsilon$ than in Glauber model
- Ideal hydrodynamics turns larger spatial eccentricity $\epsilon$ into larger elliptic flow $v_2$
- Hadronic dissipation insufficient to reduce the calculated $v_2$ enough to agree with data $\implies$ additional QGP viscosity needed!?

$\implies$ Need better control over initial conditions!
In peripheral collisions, CGC initial conditions give too much elliptic flow at all rapidities, even for pure hydro with $T_{\text{dec}}=170$ MeV (i.e. no hadronic rescattering at all)!

\[ \text{CGC initial conditions require QGP viscosity!} \]

- Ideal hydro with Glauber initial conditions and chemical freeze-out at $T_{\text{dec}}=170$ MeV significantly overpredicts $v_2(p_T)$;
- hadronic dissipation brings $v_2(p_T)$ down to agree with data;
- CGC initial conditions again raise $v_2(p_T)$ far above the data.
Glauber vs. CGC initial conditions: $v_2(p_T)$ at midrapidity

(T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, to be published)

- Glauber initial conditions + hadronic dissipation give correct $v_2(p_T)$ for $\pi$, $K$, and $p$ at midrapidity

- CGC initial conditions overpredict slope of $v_2(p_T)$ for all hadrons at midrapidity
How to deal with QGP viscosity?
How to extract it from data quantitatively?
IMHO, quark-gluon cascade is not an option . . .

⇒ Viscous relativistic hydrodynamics!
Viscous relativistic hydrodynamics (Israel & Stewart 1979)

Include shear viscosity $\eta$, neglect bulk viscosity (massless partons) and heat conduction ($\mu_B \approx 0$); solve

$$\partial_\mu T^{\mu\nu} = 0$$

with modified energy momentum tensor

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

$\pi^{\mu\nu} = \text{traceless viscous pressure tensor}$ which relaxes locally to $2\eta$ times the shear tensor $\nabla_\mu \langle u^\nu \rangle$ on a microscopic kinetic time scale $\tau_\pi$:

$$D\pi^{\mu\nu} = -\frac{1}{\tau_\pi} \left( \pi^{\mu\nu} - 2\eta \nabla_\mu \langle u^\nu \rangle \right) - \left( u^{\mu \pi \nu \lambda} + u^{\nu \pi \mu \lambda} \right) Du^\lambda$$

where $D \equiv u^\mu \partial_\mu$ is the time derivative in the local rest frame.

Kinetic theory relates $\eta$ and $\tau_\pi$, but for a strongly coupled QGP neither $\eta$ nor this relation are known $\implies$ treat $\eta$ and $\tau_\pi$ as independent phenomenological parameters. For consistency: $\tau_\pi \theta \ll 1$ ($\theta = \partial^\mu u_\mu = \text{local expansion rate}$).
Azimuthally symmetric transverse dynamics with long. boost invariance:
Use \((\tau, r, \phi, \eta)\) coordinates and solve

- **hydrodynamic equations** for
  \[ T^{\tau\tau} = (e + \mathcal{P})\gamma_r^2 - \mathcal{P}, \quad T^{\tau r} = (e + \mathcal{P})\gamma_r^2 v_r \]
  (with "effective pressure" \(\mathcal{P} = p - r^2 \pi^{\phi\phi} - r^2 \pi^{\eta\eta}\)) together with

- **kinetic relaxation equations** for \(\pi^{\phi\phi}, \pi^{\eta\eta}\):

\[
\begin{align*}
\frac{1}{\tau} \partial_\tau (\tau T^{\tau\tau}) + \frac{1}{r} \partial_r \left( r (T^{\tau\tau} + \mathcal{P}) v_r \right) &= - \frac{p + \tau^2 \pi^{\eta\eta}}{\tau}, \\
\frac{1}{\tau} \partial_\tau (\tau T^{\tau r}) + \frac{1}{r} \partial_r \left( r (T^{\tau r} v_r + \mathcal{P}) \right) &= + \frac{p + r^2 \pi^{\phi\phi}}{r}, \\
(\partial_\tau + v_r \partial_r) \pi^{\eta\eta} &= - \frac{1}{\gamma_r \tau^2} \left[ \pi^{\eta\eta} - \frac{2\eta}{\tau^2} \left( \frac{\theta}{3} - \frac{\gamma_r}{\tau} \right) \right], \\
(\partial_\tau + v_r \partial_r) \pi^{\phi\phi} &= - \frac{1}{\gamma_r \tau^2} \left[ \pi^{\phi\phi} - \frac{2\eta}{r^2} \left( \frac{\theta}{3} - \frac{\gamma_r v_r}{r} \right) \right].
\end{align*}
\]

Close equations with EOS \(p(e)\) where \(e = T^{\tau\tau} - v_r T^{\tau r}\) and \(v_r = T^{\tau r} / (T^{\tau\tau} + \mathcal{P})\).
(1+1)-d viscous hydrodynamics: first results (I)

(Chaudhuri & Heinz, nucl-th/0504022)

Viscosity effects on freeze-out surface ($\tau_\pi = \frac{3\eta}{2p}$, $\pi_{ini}^{rr} = \frac{2\eta}{3\tau_i}$):

- Both sets of initial conditions have similar initial total entropy.
- Viscosity slows down cooling and gives more time for transverse expansion.
- Viscous effects are larger for smaller $\tau_i$, due to faster initial expansion rate.
Sensitivity to initial $\pi^{rr}$, $\frac{\eta}{s}$, and relaxation time $\tau_\pi$ ($T_\pi = 160$ MeV):

- Larger initial viscous pressures create larger overall viscous effects ("memory effect")
- Significant viscous effects for $\frac{\eta}{s} > \frac{\eta}{4\pi}$
- At fixed $\frac{\eta}{s}$, viscous effects increase with increasing relaxation time $\tau_\pi$
Viscous shear pressure reduces longitudinal work, but increases transverse flow.

$$\eta/s = 0.08$$

$$\eta/s = 0.135$$

same initial conditions yield flatter transverse momentum spectra than for ideal fluid dynamics.
If the QGP viscosity is confirmed to be small, does this kill the perturbative QGP?

Does small viscosity really require strong interactions?

Or:

Can plasma instabilities save the wQGP, by causing momentum isotropization (resulting in an ideal fluid form of $T_{\mu\nu}$) without thermalization?

Or:

Can plasma instabilities generate directly anomalously small viscosities?
Anomalous viscosity and energy loss from color chaos

• Viscosity in an expanding fluid $\Rightarrow$ local momentum anisotropies $\sim \eta$
  (Heiselberg, Wang 1996; Teaney 2003)

• Anisotropic momentum distributions $\Rightarrow$ plasma instabilities (Weibel 1959,

• Plasma instabilities $\Rightarrow$ turbulent (color) magnetic fields
  $\Rightarrow$ anomalous viscosity and energy loss of (color)
  charged particles, $\eta_B \sim 1/\langle B^2 \rangle \sim 1/\eta$

$\Rightarrow$ large viscosity leads to small anomalous viscosity $\Rightarrow$ self-regulating!

Collisional and turbulent mean-field scattering rates add
$\Rightarrow$ total viscosity $\eta^{-1} = \eta^{-1}_{\text{coll}} + \eta^{-1}_B$

For $g \ll 1$ Asakawa et al. find $\eta_B \sim \frac{s}{g^{3/2}}$ while $\eta_{\text{coll}} \sim \frac{s}{g^4 \ln g}$.

So at early times (high $T$, small $g$) anomalous viscosity $\eta_B$ may dominate
and render $\eta$ anomalously small!
Conclusions

Collective flow patterns observed at RHIC provide

- **Strong evidence for thermalization** at $\tau_{\text{therm}} < 1 \, \text{fm}/c, \ e > 10 \, \text{GeV}/\text{fm}^3$ $\implies$ matter initially in QGP state.
- **Strong evidence** that QGP is strongly coupled plasma and behaves like an almost ideal fluid with low viscosity

Ideal fluid dynamics $\approx$ works at RHIC because QGP is created!

So far no clear evidence for significant QGP viscosity (initial conditions?), but high viscosity in late hadron gas phase must be taken into account.

The long road towards determining QGP viscosity and EOS requires

- more systematic studies ($\tau_{\text{therm}},$ initial density & velocity profiles, EOS)
- more hydro+cascade simulations to better describe late hadronic stage
- viscous hydrodynamics to constrain transport coefficients of QGP directly from data
- a better understanding of non-equilibrium plasma physics...
Supplements
Chemical Freeze-out at $T_{\text{had}} \approx 170$ MeV

Central Au+Au @ 130 A GeV
(STAR Coll., G. van Buren, QM2002)

Abundance ratios of stable hadrons decouple in maximum entropy state of "apparent chemical equilibrium" with $T_{\text{chem}} \approx T_{\text{had}} \approx 170$ MeV.

$T_{\text{chem}}$ insensitive to expansion rate:


Note: Hadron abundances are in statistical, not in kinetic chemical equilibrium! Requires pre-hadronic phase with large strangeness correlation volume.
CGC initial conditions give larger elliptic flow – is the QGP 'imperfect' after all?

(T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, nucl-th/0511046)

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$\Rightarrow$ Need better control over initial conditions!
Mach cones from quenching jets?
Jet quenching in central Au+Au collisions:

- trigger particle for near-side jet has $4 < p_T < 6$ GeV
- away-side jet ($p_T > 2$ GeV) visible in p+p and d+Au, but fully quenched in central Au+Au
- energy of quenched jet appears as additional multiplicity of low-$p_T$ particles opposite to trigger particle
- $\Longrightarrow$ “thermalization” of intermediate-$p_T$ jets!
Evidence for a “sonic boom”?! 

Shuryak et al., hep-ph/0411315

Away-side jet creates Mach cone at \( \cos \theta_M = \frac{c_s}{c} \)

\[ \theta_M \approx 63^\circ \approx 1.1 \text{ rad} \]
Hydrodynamic simulation of sonic boom

A. Chaudhuri and U.H., nucl-th/0503028(v3)

Energy density contours:

\[ \frac{dE}{dx}|_0 = 14 \text{ GeV/fm} \]

\[ \frac{dE}{dx}|_0 = 140 \text{ GeV/fm} \]

(a) \( \tau = 4.6 \text{ fm}, X_{\text{jet}} = 2.4 \text{ fm} \)

(d) \( \tau = 4.6 \text{ fm}, X_{\text{jet}} = 2.4 \text{ fm} \)

(b) \( \tau = 8.6 \text{ fm}, X_{\text{jet}} = -1.6 \text{ fm} \)

(e) \( \tau = 8.6 \text{ fm}, X_{\text{jet}} = -1.6 \text{ fm} \)

(c) \( \tau = 12.6 \text{ fm}, X_{\text{jet}} = -5.6 \text{ fm} \)

(f) \( \tau = 12.6 \text{ fm}, X_{\text{jet}} = -5.6 \text{ fm} \)

\( \frac{dN}{d\phi} \) for thermal photons:

\( \frac{dN}{d\phi} \) for thermal photons:

(Away-side jet travels to the left)

Note: Mach cone angle sensitive to the speed of sound \( c_s^2 \)!

But: Mach cone not visible in \( dN/d\phi \)!