What aspects of initial stages will NOT be tractable
(or will, but without sufficient precision)
with current or foreseeable theoretical tools?

Derek Teaney
Stony Brook University

What aspects of initial stages are ALMOST tractable with current theoretical tools?

Derek Teaney
Stony Brook University

Spatial scales for initial stages in A+A

Many scales are the same:

$$R \gg c\tau_{\text{init}} \sim R_p \sim \ell_{\text{mfp}} \gg \frac{1}{Q_s}$$

Need kinetics!
Spatial scales for initial stages in A+A

Many scales are the same:

\[ R \gg c\tau_{\text{init}} \sim R_p \sim \ell_{\text{mfp}} \gg \frac{1}{Q_s} \]

Need kinetics!
Many scales are the same:

\[ R \gg c\tau_{\text{init}} \sim R_p \sim \ell_{\text{mfp}} \gg \frac{1}{Q_s} \]

Need kinetics!
Momentum scales and “bottom-up” thermalization

Classical Production

Longitudinal Squeeze

Soft Stabilization

Mini-jet parton shower

Plasma instabilities dominate screening?

Reach a thermal state in $\tau_{\text{init}} \sim 1/(\alpha_s^{2.6}Q_s)$
Recent progress on the first phase of “bottom-up”

- Scaling solution for phase space distribution
  \[ f(\tau, p_z, p_T) = \frac{(Q\tau)^{1/3}}{\tau} f_o(p_z(Q\tau)^{1/3}, p_T) \]
- Need to compare classical and kinetics in detail
- Instabilities do not seem to play a significant role

Reach the end of the first phase at \( \tau \sim 1/(\alpha_s^{3/2} Q_s) \)

Berges, Boguslavski, Schlichting, Venugopalan
Momentum scales and “bottom-up” thermalization

Classical Production

Longitudinal Squeeze

Soft Stabilization

Mini-jet parton shower

Plasma instabilities dominate screening?

Reach a thermal state in $\tau_{\text{init}} \sim 1/(\alpha_s^{2.6} Q_s)$
The kinetic phase of “bottom-Up” in 2015

- Compare the longitudinal pressure $T_{zz}$ with hydro prediction to calibrate equilibration

For realistic coupling three stages still “exists” and

$$
\tau_{\text{init}} \simeq \frac{10}{Q_s \left( \frac{0.3}{\alpha_s} \right)^{2.6}} 
$$

constitutive relations satisfied to 10%
Equilibration, transverse dynamics, and green functions

\[ \int d^2 \mathbf{x}' \frac{\delta e(\tau_0, \mathbf{x}')}{e(\tau_0)} \frac{\mathbf{\nabla} e(\tau_0, \mathbf{x}')}{e(\tau_0)} \times \frac{E(|\mathbf{x} - \mathbf{x}'|; \tau, \tau_0)}{e(\tau)} = \frac{\delta e(\tau, \mathbf{x})}{e(\tau)} \frac{\mathbf{g}(\tau, \mathbf{x})}{e(\tau)} \]

\text{ip-glasma} \quad \text{Green fcn} \quad \text{hydro}

1. Assumes that \( \tau_{\text{init}} \ll R \)

2. Matches the early glasma kinetics, to an effective theory of hydro initial states

\[ \langle e(\mathbf{x}) \rangle \langle e(\mathbf{x}) e(\mathbf{y}) \rangle = A \langle e(\mathbf{x}) \rangle \delta^2(\mathbf{x} - \mathbf{y}) \]

3. Include momentum into the hydro initial state effective theory at first order in \( \tau_{\text{init}}/R \)

When the pre-equilibrium response is in, the hydro results will (hopefully) not depend on \( \tau_{\text{init}} \).
Can we measure this?

Need control parameters – system size, $p_T$, rapidity, . . .
Can we measure this?

Need control parameters – system size, $p_T$, rapidity, . . .
Sören Schlichting’s dream plot

Exploring pre-equilibrium dynamics in small systems?

Sensitive to non-equilibrium

-> Small systems provide a unique laboratory to probe early time dynamics.

(SS arXiv:1601.01177)

Let’s put some numbers on the $x$ axis . . .
When do you see initial state correlations?

1. To see the initial state correlations we require

\[ R \ll \tau_{\text{init}} \quad \text{or} \quad \frac{R}{\tau_{\text{init}}} \ll 1 \]

2. Now we reach a thermal state in:

\[ \tau_{\text{init}} \sim \frac{10}{Q_s} \left( \frac{0.3}{\alpha_s} \right)^{2.6} \]

and

\[ Q_s^2 = \alpha_s \frac{dN/dy}{\pi R^2} \]

Exploring pre-equilibrium dynamics in small systems?

- Sensitive to non-equilibrium
- Small systems provide a unique laboratory to probe early time dynamics.

\[ \frac{R}{\tau_{\text{init}}} = 0.2 \left( \frac{\alpha_s}{0.3} \right)^{3.1} \left( \frac{dN/dy}{12} \right)^{1/2} \]
Remarks on \textit{pp}:

1. Gradual transition from low to high mult.

2. Is $v_2$ at small multiplicity is important?
   - See CMS data on $v_2\{4\}$, $v_2\{6\}$, …

3. The $v_2$ correlation does not decrease with multiplicity, and factorizes

4. How are minijets modified in $p_T$?

The last stage of thermalization is minijet-quenching
Can we measure this?

Need control parameters – system size, $p_T$, rapidity, . . .
1. An effective theory for hydro initial states must specify

\[ \left\langle \frac{d e(x)}{d \eta} \right\rangle \quad \text{and} \quad \left\langle \frac{d e(x)}{d \eta_1} \frac{d e(y)}{d \eta_2} \right\rangle_{\text{conn}} = A(\eta_1, \eta_2) \left\langle e(x) \right\rangle \delta(x - y) \]
Rapidity correlations

\[ \frac{de}{d\eta} \equiv \sum_{\phi} \frac{de}{d\eta} e^{i2\phi} \]

A model for rapidity fluctuations that doesn’t work:

Teaney & Bzdak

Then

\[ \frac{de}{d\eta} = C_0 (N_F + N_B) + C_1 \eta (N_F - N_B) \]

and

\[ \left\langle \frac{de}{d\eta_1} \frac{de}{d\eta_2} \right\rangle = C_0^2 \left\langle (N_F + N_B)^2 \right\rangle + C_1^2 \eta_1 \eta_2 \left\langle (N_F - N_B)^2 \right\rangle \]

measurable rapidity odd correlations
1. In $pA$ events the number of forward backward participants doesn’t fluctuate much. Fluctuations reflect the correlations in the tube, not the participants.

2. But, significant (rapidity-odd) longitudinal fluctuations of $v_2$ are seen.

   Successful string-like models incorporate the $dx/x$ parts of the splitting function into the rapidity corelation function $\langle e(\eta_1)e(\eta_2) \rangle$.

3. Opportunity to predict the functional form in CGC or EKRT model of

\[
\left\langle \frac{de}{d\eta_1} \frac{de}{d\eta_2} \right\rangle_{\text{conn}}
\]
Rapidity odd v2 fluctuations

p+Pb@5.02TeV

Without internal rapidity correlations

Model with internal rapidity correlations

CMS, 120 < N_{trk}^{offline} < 150

torque model, c=0-3.4%

model w/ no length fluct.
From the almost to truly intractable . . .

1. A path to document theoretically and experimentally the path to hydro

   - System size, $p_T$ mini-jet quenching, rapidity

2. Going beyond weak coupling:

   - Non-perturbatively calculate screening?

   - Is the temperature scale perturbative?

Thank you!