HOLOGRAPHIC COLLISIONS WITH BARYON NUMBER AT INTERMEDIATE COUPLING

HOLOGRAPHY BEYOND $\eta/s=1/4\pi$

Based on work Åsmund Folkestad, Sašo Grozdanov and Krishna Rajagopal
References: 1501.04952, 1507.08195, 1610.08976 (PRL), 1907.13134

Wilke van der Schee
OUTLINE

Holography to model QCD

• AdS/CFT: first principle non-perturbative QFT computations
• Limitations: QCD(-like) theory with intermediate coupling is hard

Baryon number is interesting: collision transparent?

• Not so at infinite coupling: baryon charge follows energy

Finite coupling corrections, including baryon number

• Extra terms in the AdS Lagrangian
• Following baryon charge for thick and thin holographic collisions
  • Depending on extra parameter $\beta$: much more transparency
FOLLOWING BARYON NUMBER

Input: ~400 baryons, conserved: more protons than anti-protons

- Picture: transparent baryon flow, energy created at mid-rapidity
- Depending on beam rapidity ($y_b$) baryons lose $1 - 2.5$ units of rapidity ($\delta y$)

![Graph showing rapidity loss and net-protons vs. CM rapidity](image)

(5, 17, 200) GeV

BRAHMS, Nuclear stopping and rapidity loss in Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV (2009)
BRAHMS, Nuclear Stopping in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV
RAPIDITY PROFILE AT INFINITE COUPLING

- Collide shocks with energy and charge (=general conserved current)
- Charge rapidity (solid) similar to energy (dashed), but grows in time
A QUANTITATIVE INSIGHT

- Collide shocks with energy and charge
- Now collide neutral with charged shock
- 41% of charge changes direction
  → strong interactions
**ADS/CFT AND HOLOGRAPHY**

Heavy ion physics: a weak/strong coupling interplay?

- A ‘hybrid’ approach: make a model inspired by strong and weak models
- Bolder approach: strong coupling entirely
  - Qualitative/quantitative trends can inspire better modelling
  - In either approach some amount of fitting is required

Here: try to bridge gap by including (important) corrections in AdS:

\[
S = \frac{1}{2\kappa_5^2} \int d^5x \sqrt{-g} \left[ R + \frac{12}{L^2} - \frac{\epsilon^2 L^2}{4} F_{\mu \nu} F^{\mu \nu} + \frac{\lambda_{GB} L^2}{2} \left( R^2 - 4 R_{\mu \nu} R^{\mu \nu} + R_{\mu \nu \rho \sigma} R^{\mu \nu \rho \sigma} \right) \right. \\
+ \left. \beta \epsilon^2 L^4 \left( RF_{\mu \nu} F^{\mu \nu} - 4 R^{\mu \nu} F_{\mu \rho} F_{\nu \rho} + R^{\mu \nu \rho \sigma} F_{\mu \nu} F_{\rho \sigma} \right) \right]
\]

- With \( R \) Riemann tensor, \( F \) Maxwell field; two new couplings: \( \lambda_{GB} , \beta \)
- Bottom-up: field theory interpretation only known qualitatively
Here: try to bridge gap by including (important) corrections in AdS:

\[
S = \frac{1}{2\kappa_5^2} \int d^5 x \sqrt{-g} \left[ R + \frac{12}{L^2} F_{\mu\nu} F^{\mu\nu} + \frac{\lambda_{GB} L^2}{2} \left( R^2 - 4 R_{\mu\nu} R^{\mu\nu} + R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma} \right) \right] \\
+ \beta \varepsilon^2 L^4 \left( RF_{\mu\nu} F^{\mu\nu} - 4 R^{\mu\nu} F_{\mu\rho} F_{\nu}^{\rho} + R^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma} \right)
\]

- Effect on i.e. transport coefficients and charge susceptibility:

\[
\frac{\eta}{s} = \frac{1}{4\pi} \left[ 1 - 4\lambda_{GB} + O\left(\lambda_{GB}^2\right) + \frac{2}{3\pi^2} \frac{\mu^2}{T^2} \left(\lambda_{GB} + 3\beta\right) + \ldots \right]
\]

\[
\chi = \frac{\partial \rho}{\partial \mu} \bigg|_{\mu=0} = \frac{1}{2\pi T^2} \left[ 1 + 3\lambda_{GB} + 16\beta \right]
\]

- `Reasonable' values are \( \lambda_{GB} = -0.2 \) and \( \beta \in [0.08, 0.09] \)
  - \( \eta/s = 1.8/4\pi \) and \( \frac{\chi}{\chi_0} \big|_{QCD} \in [0.8, 0.9] \)
  - But all computations done perturbatively in \( \lambda_{GB} \) and \( \beta \)
COLLISIONS AT FINITE COUPLING - NARROW

- Results presented for, $\lambda_{GB} = -0.2$ i.e $\eta/s = 1.8/4\pi$ (solid)
- Initial condition constructed such that energy is the same

$\mathcal{E}/\mu^4, \mu t = \{0.25, 0.5, 1, 2, 3\}$

- Much more energy on lightcone (more transparent, less stopping)
- Energy in plasma flatter

Sašo Grozdanov and WS, Coupling Constant Corrections in a Holographic Model of Heavy Ion Collisions (2017)
**BARYON CHARGE COLLISIONS**

- Results presented for, $\lambda_{GB} = -0.2$ i.e $\eta/s = 1.8/4\pi$ (solid)
- Result strongly depends on $\beta$, especially on light-cone
  
  \[(\rho + \lambda_{GB} \delta \rho)/\mu^3 e, \mu t = \{1, 2, 3, 4, 5\}\]

- Much more baryon charge on light-cone (more transparent)
BOUNCING CHARGE

- With finite coupling corrections considerably less charge `bounces'
COLLISIONS AT FINITE COUPLING - RAPIDITY

- Initial rapidity shape differs from Gaussian

\[ \frac{\mathcal{E}_{\text{loc}}}{\mu^8} \text{ with } \mu T = \{1, 2, 3, 3.5\} \]

Narrow
Wider and lower initially (energy on lightcone not shown)
Around time 3 similar
Later more entropy, similar width
CHARGE - RAPIDITY

- Rapidity shape similar at $\beta = 0$:

\[ \beta = 0, \tau \rho_{\text{loc}}/\mu^2 \text{ at } \mu \tau = \{1.5, 2.5, 3.5, 4\} \]

Narrow
Wider and lower initially, similar at $\mu \tau = 3.5$
CHARGE - RAPIDITY

- Rapidity shape at non-zero $\beta$ considerably lower and perhaps wider:

$$\beta = 0.05, \tau \rho_{loc}/\mu^2 \text{ at } \mu \tau = \{1.5, 2.5, 3.5, 4\}$$

Narrow
Always lower, more baryon charge on the light-cone (total conserved)
WIDE SHOCK COLLISIONS

- Landau-like: hydrodynamic explosion

\[ \overline{\rho}/m^3, m t = \{1, 4, 7, 10, 13\} \]

- Here larger \( \beta \) needed for similar effects as compared to narrow
  - Effects of \( \beta = 0.1 \) at edge of perturbative window
DISCUSSION

Holography and heavy ion collisions

- AdS/CFT essential tool for insights in strongly coupled matter
- Can we get closer to ‘realistic’ baryon number transparency?

Holographic collisions at finite coupling

- New parameter $\beta$: ‘coupling between stress and (baryon) charge’
- Charge on light-cone: crucial dependence on $\beta$
- Rapidity spectrum charge plasma initially: wider and more transparent

Outlook

- Improved models closer to QCD, include coupling changing with time
COLLISIONS AT FINITE COUPLING - HYDRO

- Hydro applies about 25% later for narrow shocks (subtler for wide)
  - Only transverse pressure: longitudinal from conformal symmetry
  - Can be seen as either non-trivial check on viscosity or numerics...

\[
\mu z = 0.0
\]

\[
\mu t = 2.0
\]

Narrow
Hydro later (blue), and further from lightcone

\[
t_{\text{hyd}} T_{\text{hyd}} = 0.41 - 0.52 \lambda_{GB}
\]

Wide
Hydro later (blue), and further from lightcone, smaller transverse pressure early on, bigger later

\[
t_{\text{hyd}} T_{\text{hyd}} = 0.43 - 6.3 \lambda_{GB}
\]
A PUZZLE: DECAY CHARGE ON LIGHT-CONE:

Charge (solid) and energy (dashed) decay exactly the same way

- Non-trivial from equations
- Charge distribution flatter in plasma

\[ \frac{\rho}{em^3} \text{ and } \frac{E}{m^4}, \quad m_t = \{0.5, 1.5, 2.5, 3.5\} \]
COLLISIONS AT FINITE COUPLING - WIDE

• Results presented for, $\lambda_{GB} = -0.2$ i.e $\eta/s = 1.8/4\pi$
• Initial condition constructed such that energy is the same

![Graph showing energy distribution](image)

• Energy does not `pile up', i.e. maximum 217% instead of 271%
• Also includes $\lambda_{GB}^2$ corrections (small opposite contribution)
RAPIDITY PROFILE + MUSIC

Particle spectra in longitudinal direction:

- Rescaled initial energy density by factor 20
- Profile is about 30% too narrow
DECAY CHARGE ON LIGHT-CONE:

Baryon charge (solid) and energy (dashed) decay differently

- $\beta = 0$: much more energy on light-cone, a bit more charge

\[
\beta = 0.00, \quad \rho/\text{em}^3 \text{ and } \varepsilon/m^4, \quad m \tau = \{0.5, 1.5, 2.5, 3.5\}
\]
DECAY CHARGE ON LIGHT-CONE:

Baryon charge (solid) and energy (dashed) decay differently

- $\beta = 0.05$: much more charge on light-cone

$\beta = 0.05$, $\rho/\varepsilon m^3$ and $\varepsilon/m^4$, $m t = \{0.5, 1.5, 2.5, 3.5\}$

J. Casalderrey-Solana, D. Mateos, WS and M. Triana, Holographic heavy ion collisions with baryon charge (2016)