Holographic heavy ion collisions with baryon charge

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based in arXiv:1606.XXXXX [hep-th]

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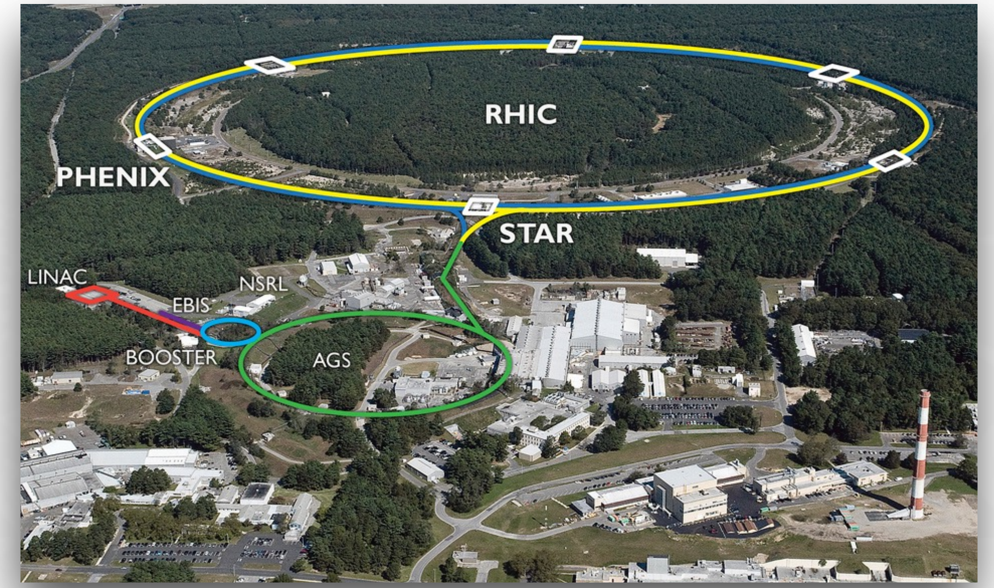
Outline

- **Introduction**
    - Heavy ion collisions and holographic shock-waves (very brief!)
- **Adding baryon charge** to the shock-wave collisions
    - **The model**: Einstein-Maxwell
    - **Shock wave collisions**: far from equilibrium full dynamic evolutions
    - **Results**: interpretation and comparison
- **Summary**

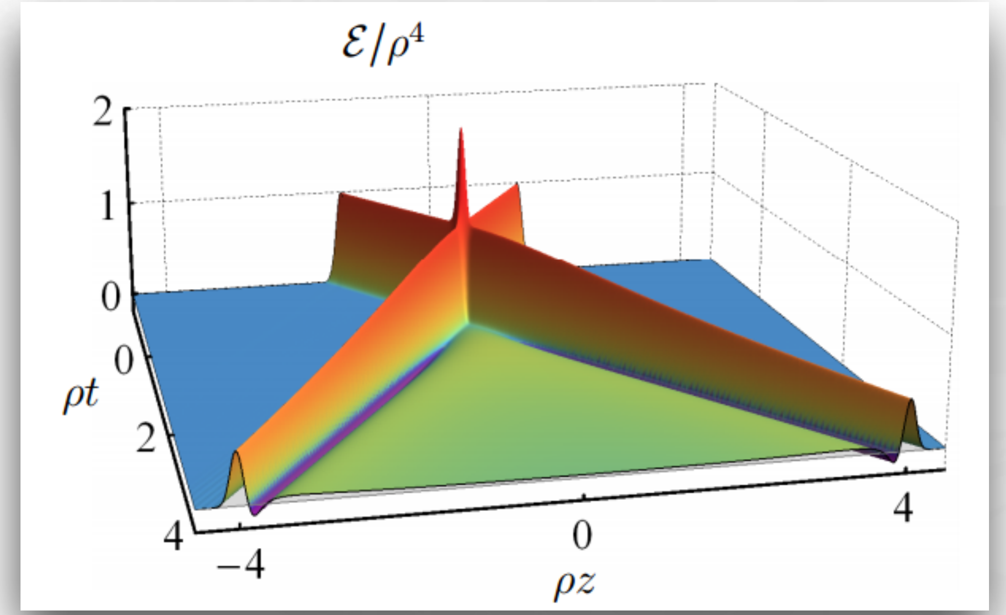
Introduction — Holographic shock-wave collisions

Heavy ion collisions



- Out of equilibrium quark-gluon plasma is created. Dynamic properties and collective behavior are studied.
- Striking observations: small shear viscosity and **fast hydrodynamization.**

Holographic shock-wave collisions



- Simple holographic toy models for collisions (**pure gravity** at first) **assuming very strong coupling**
- Very remarkable feature: reproduce **fast hydrodynamization!**
- Can we reproduce/predict more features (**baryon charge**)?

Introduction — Holographic shock-wave collisions

Simplest setup:
Pure gravity in 5d
corresponding to a 4d gauge theory

$$L = R + \frac{12}{L^2}$$

Lagrangian

$$R_{mn} + \frac{4}{L^2} g_{mn} = 0$$

Einstein's equations

The **metric** is dual to the **stress-energy tensor** operator of the gauge theory (not enough to capture baryon distribution!)

$$g_{mn} \longleftrightarrow T_{ij}$$

If we know the **evolution of the metric** we know the dynamics of the plasma's pressures, energy density, fluxes. **We want more details: baryon current!**

Adding baryon charge — The model

Modified setup:
Einstein-Maxwell theory in 5d corresponding to a 4d gauge theory with a conserved **U(1) current**

$$L = R + \frac{12}{L^2} - \frac{1}{4} e^2 F_{mn} F^{mn}$$

Lagrangian

$$R_{mn} + \frac{4}{L^2} g_{mn} = e^2 L^2 T_{mn}$$

Einstein's equations

$$\partial_m \left(\sqrt{-g} F^{mn} \right) = 0$$

Maxwell's equations

The **metric** is dual to the **stress-energy tensor** operator of the gauge theory

$$g_{mn} \longleftrightarrow T_{ij}$$

The **electromagnetic tensor** is dual to the conserved **U(1) current** (that can be interpreted as baryon current)

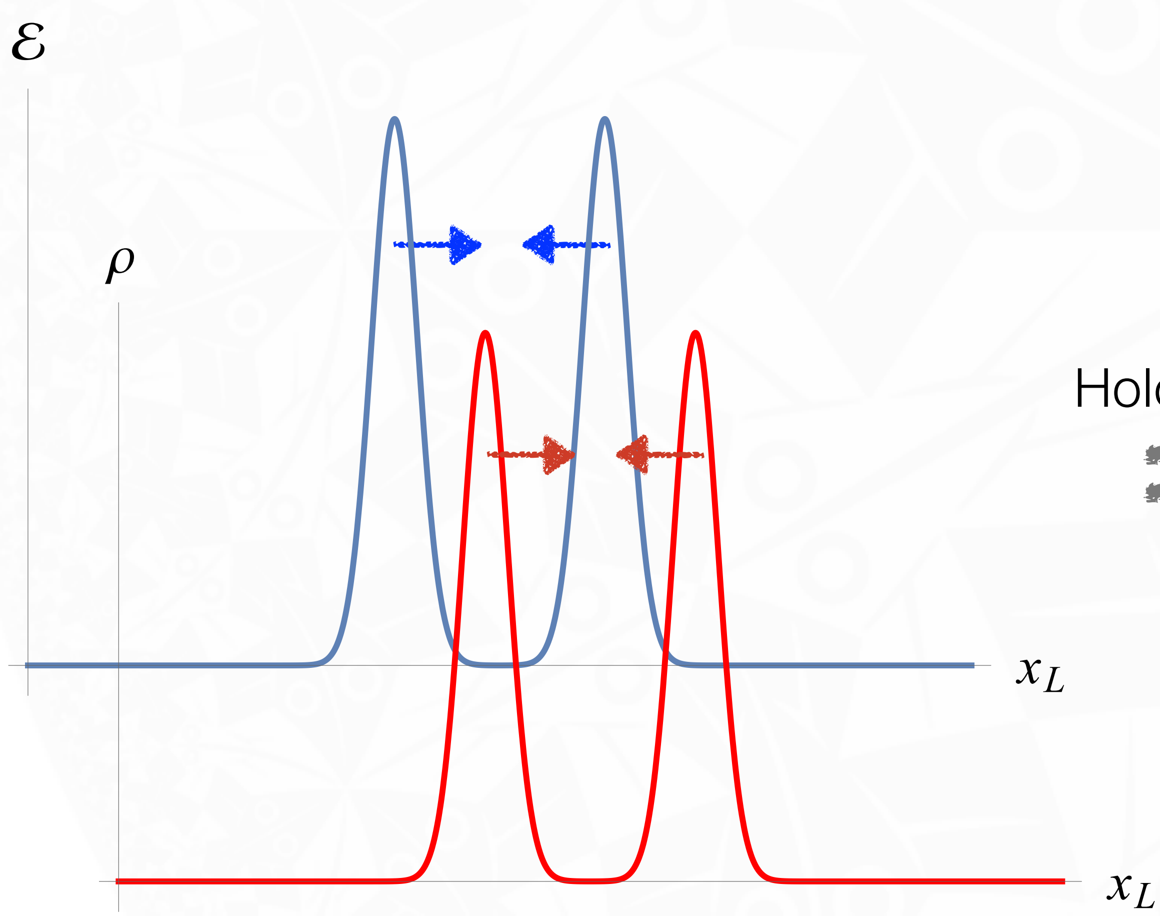
$$F_{mn} \longleftrightarrow J_i$$

If we know the **evolution of the electromagnetic tensor** we now know the evolution and the distribution of **the "baryon" current**

Adding baryon charge — Shock-wave collisions

…One only needs an **initial state/geometry!**

Two infinite sheets of energy (and **"baryon" charge**!) colliding at the speed of light **(dynamics in 1 + 1 dimensions)**



Holography

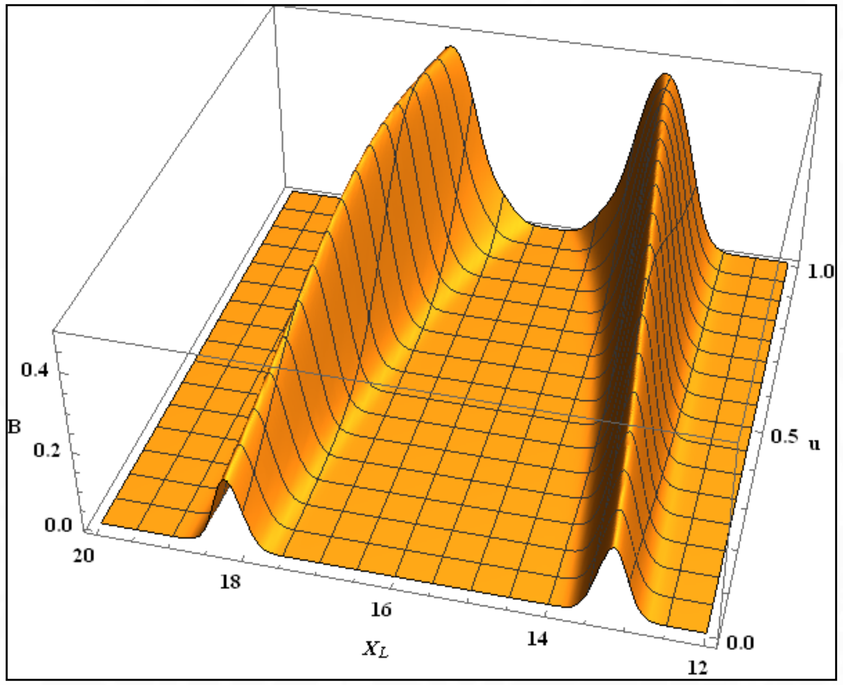
=

Traveling **"gravity-electromagnetic" waves** (**dynamics in 2 + 1 dimensions**, holographic coordinate "u" and longitudinal "X_L")

$$ds^2 = \frac{L^2}{u^2}\Big(-dx_+dx_- + d\mathbf{x}^2 + \\ + \Big[u^4 h(x_+) - \frac{1}{3}e^2u^6 a(x_+)^2\Big]\, dx_+^2 + du^2\Big)$$

In Feffferman-Graham coordinates

$$A = \frac{u^2}{L^2}a(x_+)dx_+$$



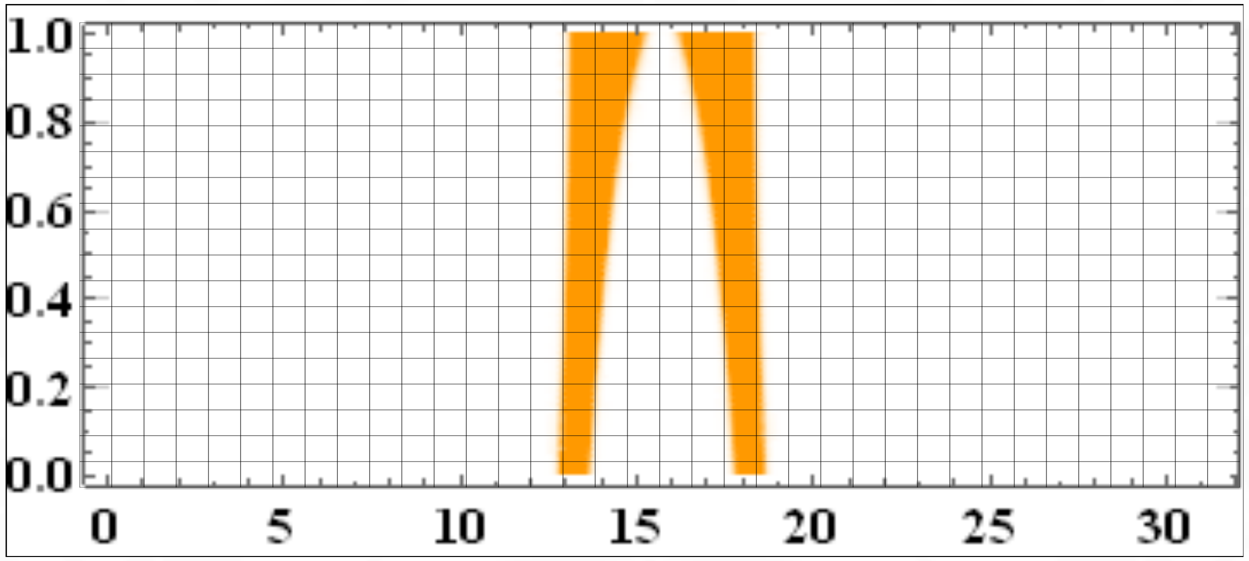
In Eddington-Finkelstein coordinates

Adding baryon charge — Shock-wave collisions

<u>Numeric implementation</u>:

- Ingoing coordinates (Eddington-Finkelstein), **characteristic formulation**
- **Ultra-local in X_L longitudinal direction**: only needed to solve 1d ODEs in the “u” direction for each X_L point.
- Set of nested equations (Only first non-linear, some other linearly are coupled)

Example of a metric coefficient (B[u, x_L, t])



Horizon

~40 points in **u** direction

Boundary

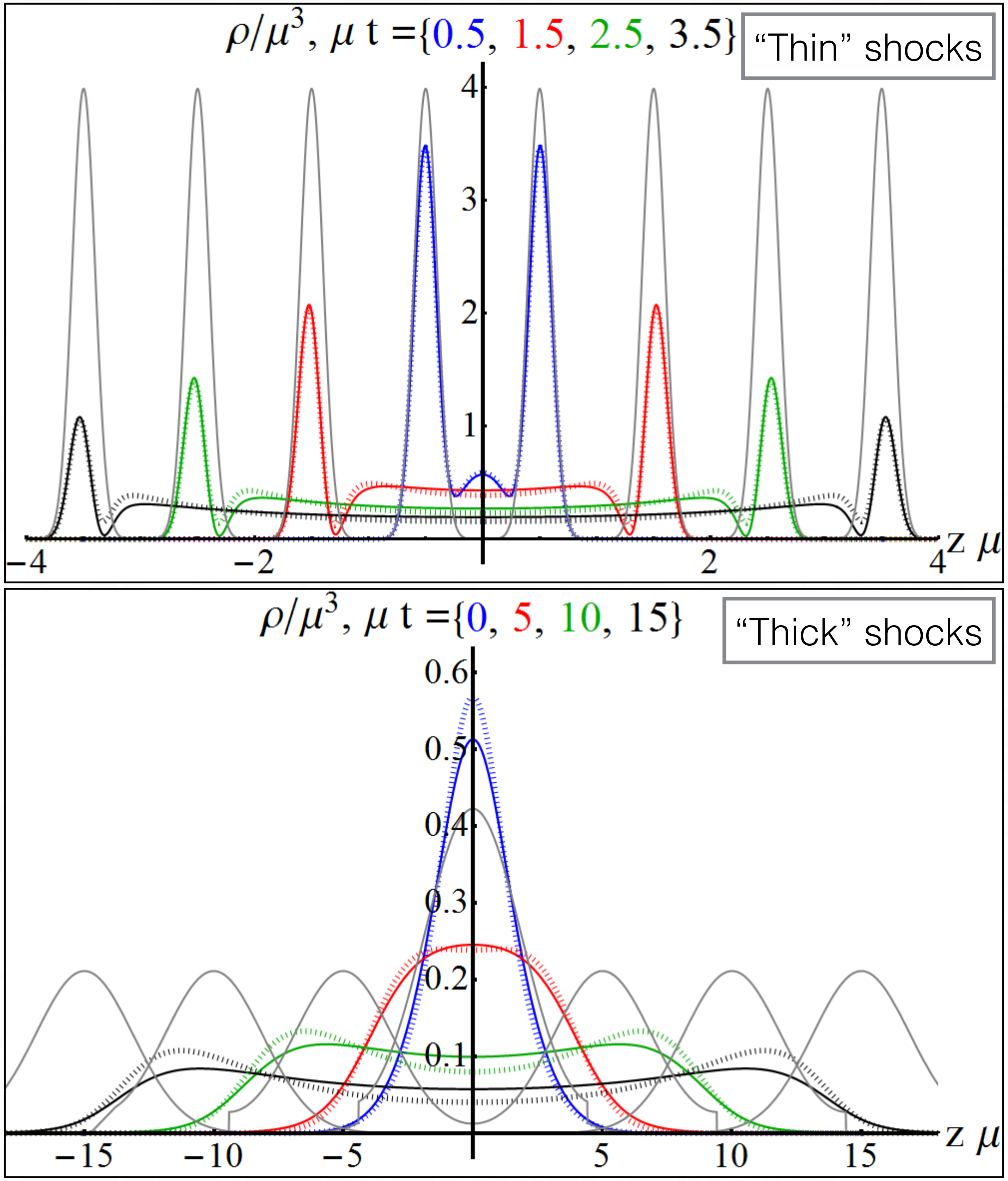
~500-1000 points in **X_L** direction (periodic)

Adding baryon charge — Results

Outcome

First we set **e = 0 (no backreaction)**: energy remains the same as in pure grav.
We check "baryon" distribution.

- Behavior sensitive to initial width of the shock-waves (as pure grav.)
- Charge follows energy on the light-cone but does not at mid rapidities
- Lab frame does not show all the information (Lorentz effects)

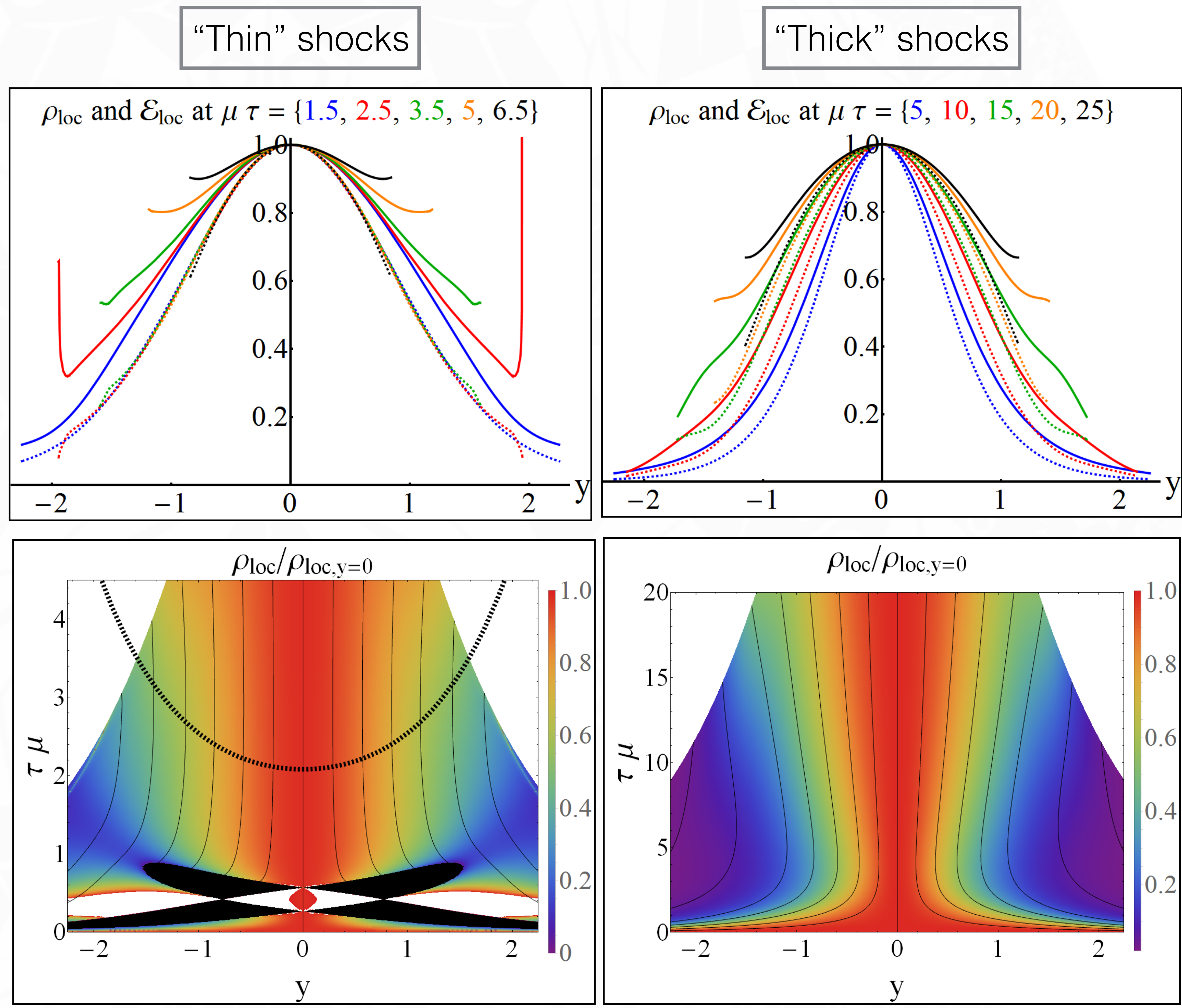


Adding baryon charge — Results

Outcome

We check the **local rest frame** distributions **at constant proper time** (more relevant for freeze-out)

- Baryon content in plasma grows with proper time (non-boost inv.)
- Baryon charge distribution widens with proper time
- Hydrodynamic expansion pushes baryon charge towards large rapidities

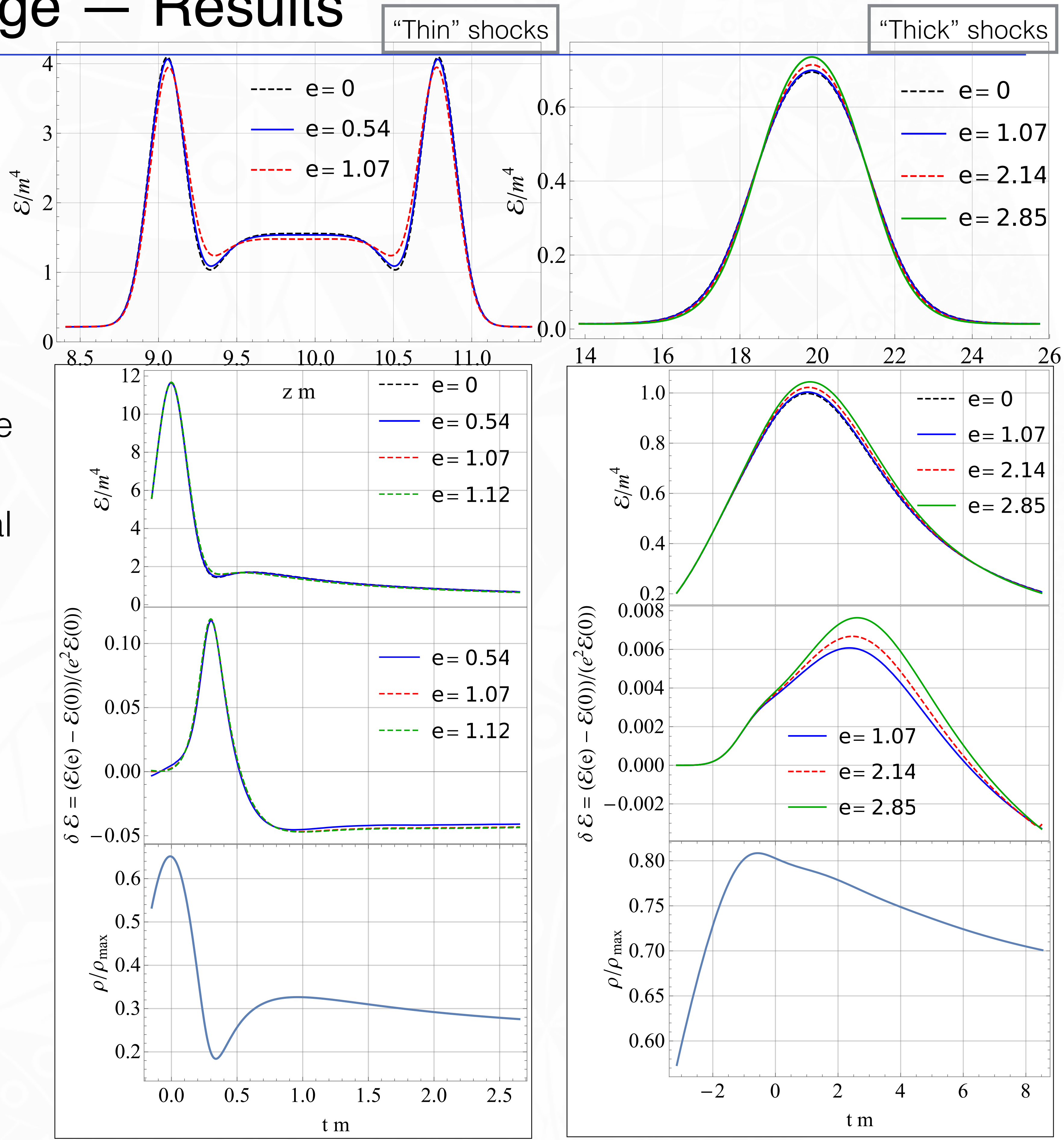


Adding baryon charge — Results

Outcome

Adding backreaction e > 0: energy distribution is affected by the baryon charge

- Effects of back-reaction moderate all the way up to maximum charge simulated (close to critical ratio?)
- Hydro time gets modified by a ~3-5%
- Existence of two regimes: linear in e^2 ,and non-linear



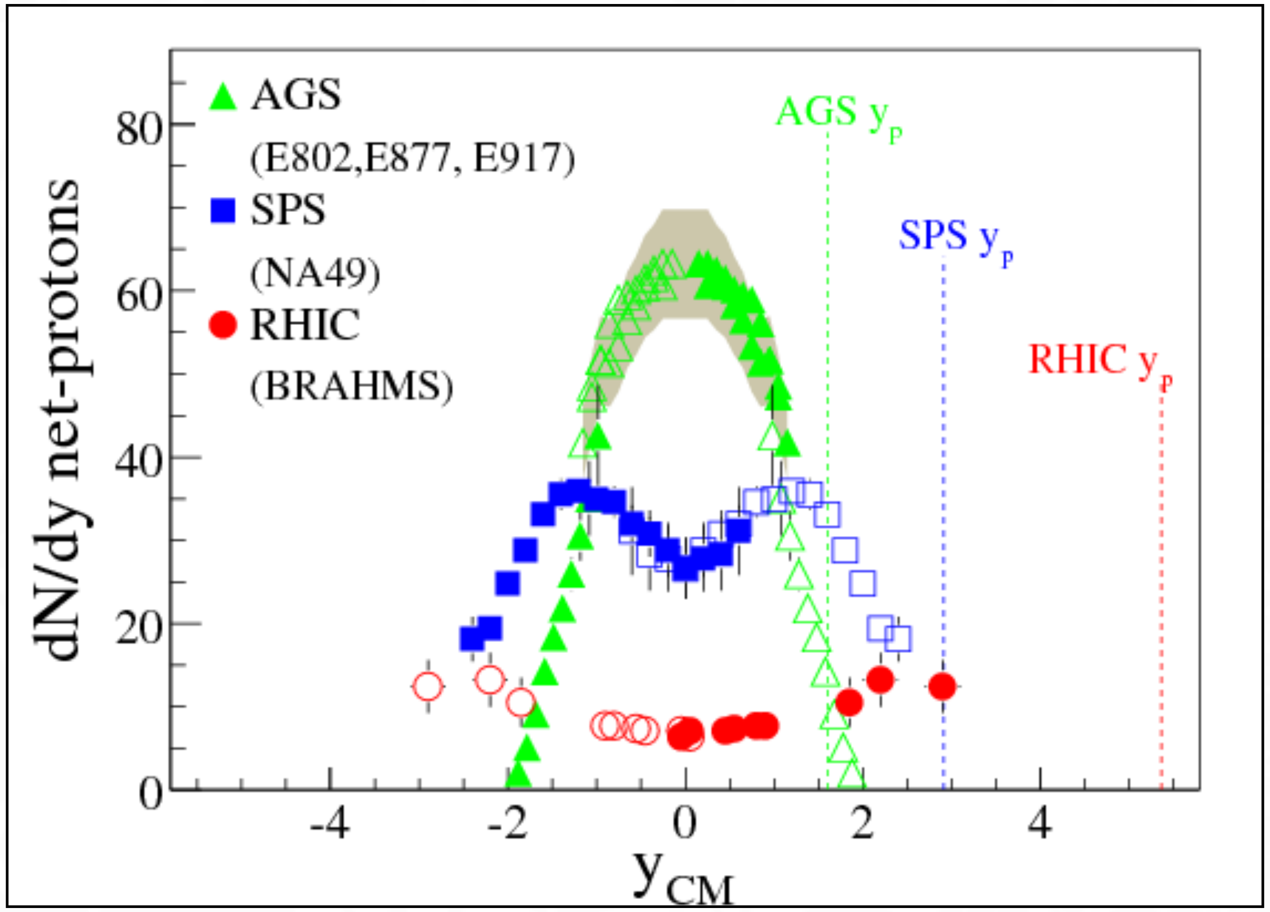
Adding baryon charge — Results

Outcome…How does compare to experiments?

Disclaimer: a proper comparison would require much longer run times and a proper freeze-out simulation.

Results seem to catch qualitative trend of low energy experiments (**AGS** or **SPS**)…

…However do not agree with high energy collisions at **RHIC** or **LHC** , as the fraction and not-so-high rapidities is small.



Plot from nucl-ex/0312023, BRAHMS Collaboration

Conclusion: our simple set-up is unable capture the weakly coupled physics at very high energies, nor the fine structure of the initial state involved in the dynamics of the collision.

Summary

- Plasma becomes more baryon rich with proper time time. **Baryon charge is pushed towards higher rapidities** at later proper times.

- **Effects of back-reaction are small** all the way up to the maximum “e” values simulated. Two regimes: linear and non-linear.

- Simulations capture low energy experiments behavior but do not agree with the high energy ones. Limitations of setup and/or strong coupling?

Extra slides

Equation of state