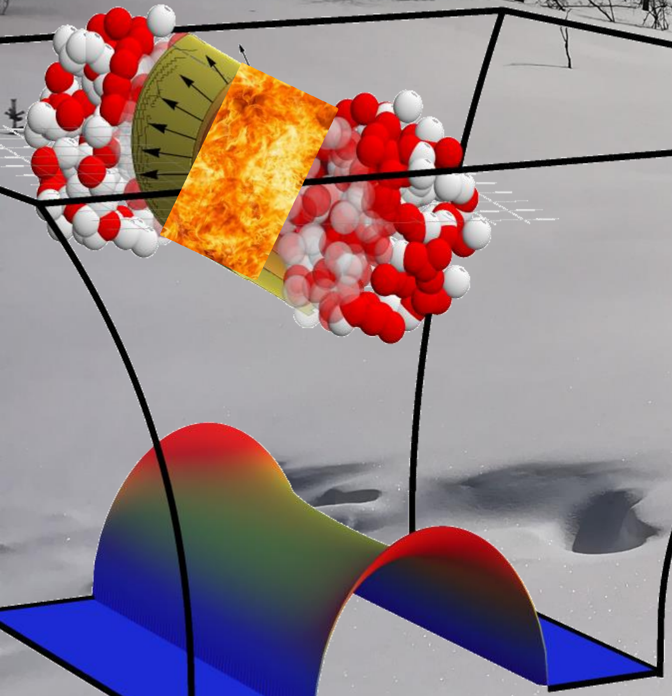
Universiteit Utrecht

HOLOGRAPHIC THERMALISATION: CONSERVED CHARGE & GAUSS-BONNET GRAVITY

TOWARDS DENSER HOLOGRAPHIC HEAVY ION COLLISIONS?

Based on work with David Mateos, Jorge Casalderrey-Solana, Miquel Triana and Saso Grozdanov
References: 1607.05273, 1610.08976 (PRL).



Wilke van der Schee
Fire and ice: Hot QCD meets cold and dense matter
Saariselkä, 5 April 2018

OUTLINE

Short introduction: Holography and QCD/Heavy ions

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

Two simple models

- Colliding lumps of energy including a conserved charge
  - Obtain early hydrodynamics + rapidity distribution
  - Remarkable: 41% of charge `bounces’
- Including finite coupling corrections (Gauss-Bonnet in this case)

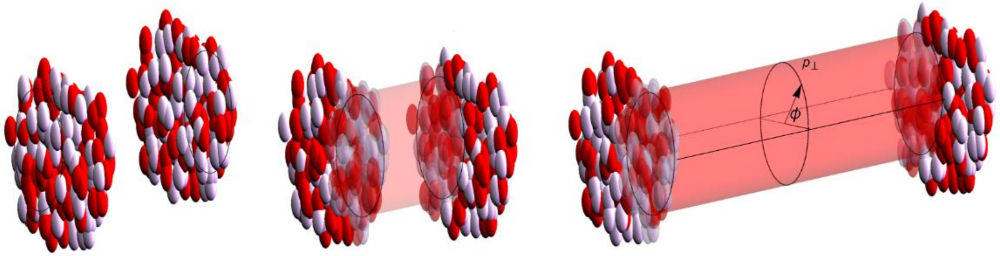
An outlook

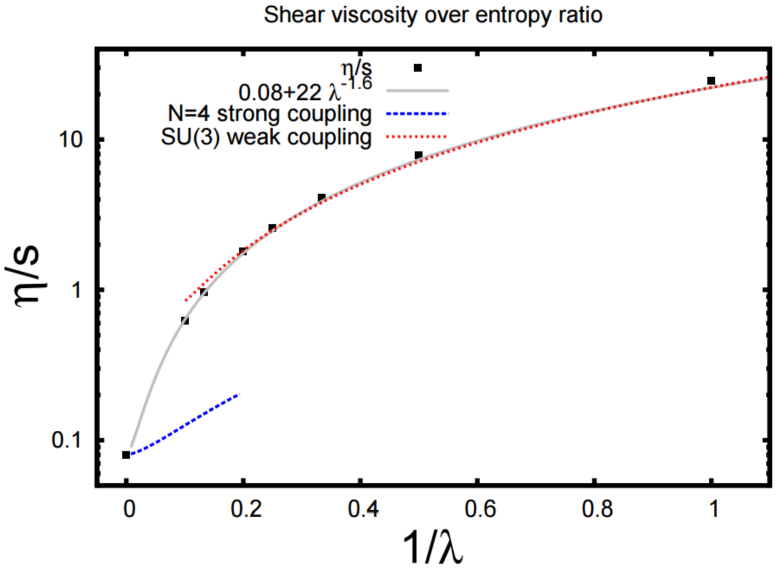
- Try to convince that much more can be done
- Combination of above, magnetic field, CME, high density (?)

STANDARD MODEL OF HEAVY ION COLLISIONS

Initial stage goes from weak to strong coupling

- *Hydrodynamisation*: the process of far-from-equilibrium → hydro
- Rapid longitudinal expansion means much *later isotropisation*
- Much progress on timescale: weak (kinetic) and at finite coupling
- Also important: resulting temperature profile and pre-flow
- Also interesting: chemical potential





L. Keegan, A. Kurkela, P. Romatschke, WS and Y. Zhu, Weak and strong coupling equilibration in nonabelian gauge theories (2015)

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

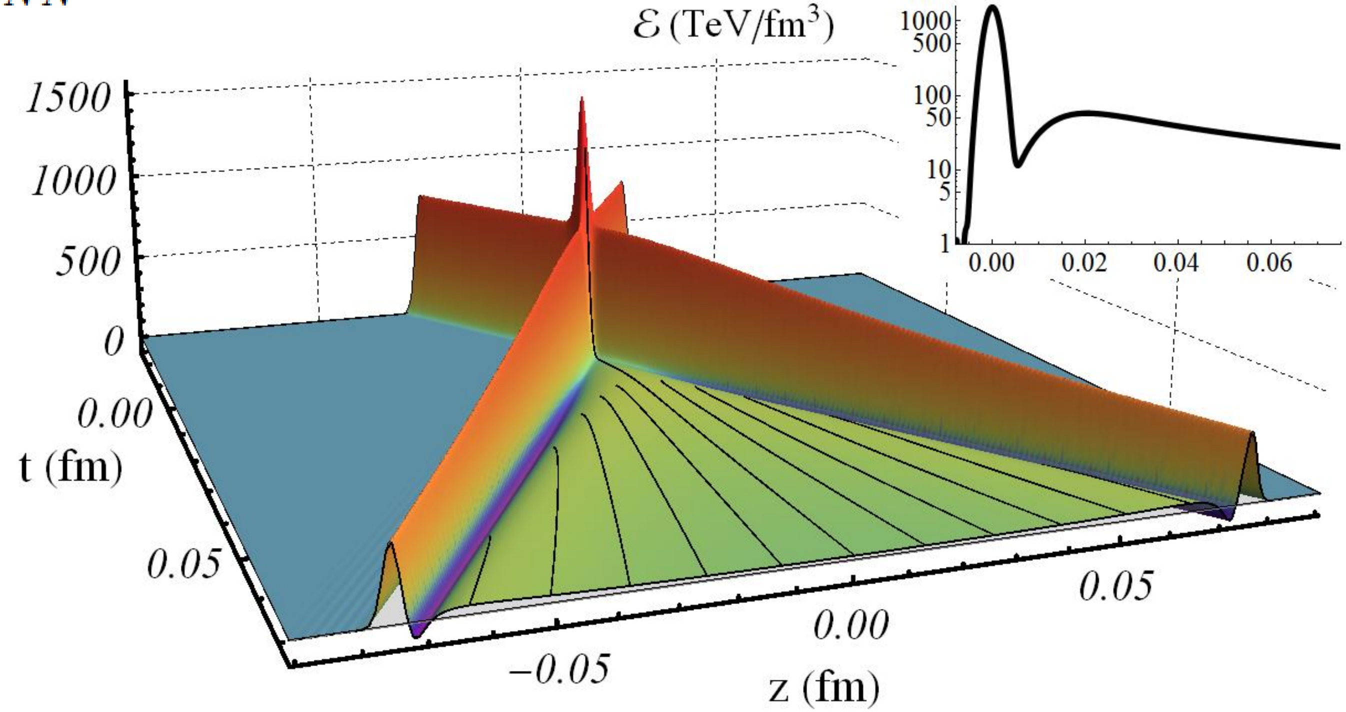
Viscosity is good example: $\eta/s = \frac{1}{4\pi}$

- Canonical theory gives benchmark value
- Qualitative insight: viscosity scales as entropy
- Possible to compute corrections: $\eta/s = \frac{1}{4\pi}\left(1 + \frac{15}{\lambda^{3/2}}\zeta(3) + \frac{5}{16}\frac{\lambda^{1/2}}{N_c^2}\right)$
  - Expected range: 0.08 – 0.12, link with weak coupling result?

COLLISIONS AT INFINITELY STRONG COUPLING

- Match longitudinal profile of energy density to nuclei
- Approximately homogeneous in transverse plane

$\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$

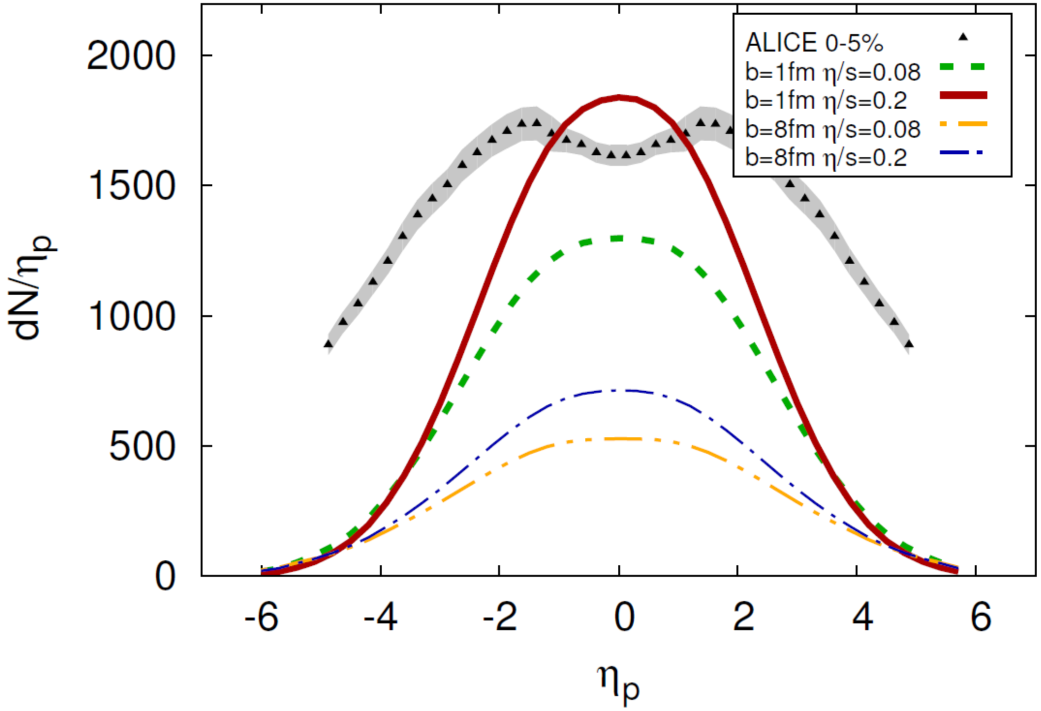


Benchmark: $T_{\mathrm{max}} = 2.6\ \mathrm{GeV}$

J. Casalderrey-Solana, M.P. Heller, D. Mateos and WS, From full stopping to transparency in a holographic model of heavy ion collisions (2013)

RAPIDITY PROFILE + MUSIC

Particle spectra in longitudinal direction:



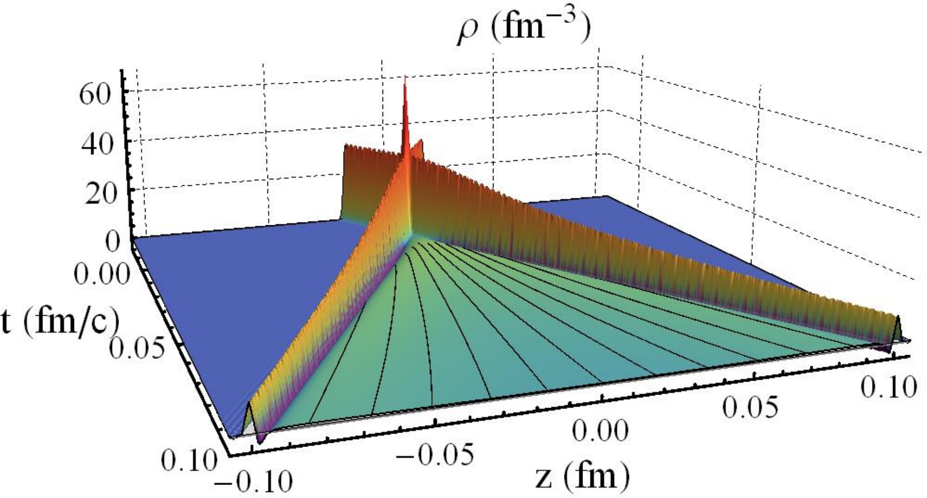
- **Rescaled initial energy density by factor 20**
- **Profile is about 30% too narrow**

WS and B. Schenke, Rapidity dependence in holographic heavy ion collisions (2015)
ALICE, Bulk Properties of Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV measured by ALICE (2011)

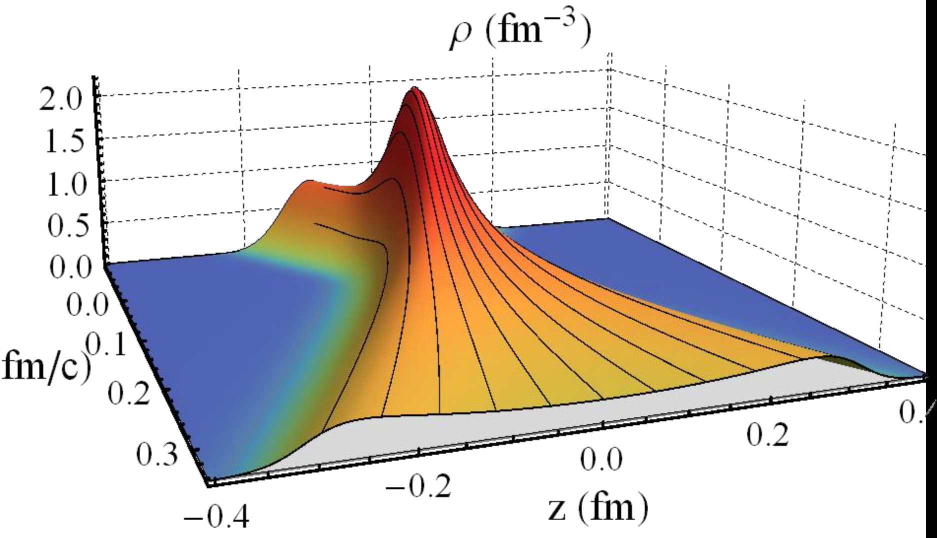
INCLUDING A CONSERVED CHARGE

- Same set-up, but include Maxwell field
- Can be thought of as R-charge,
  not necessarily as quarks carrying baryon number

$\sqrt{s_{NN}} = 2.76\ \text{TeV}$



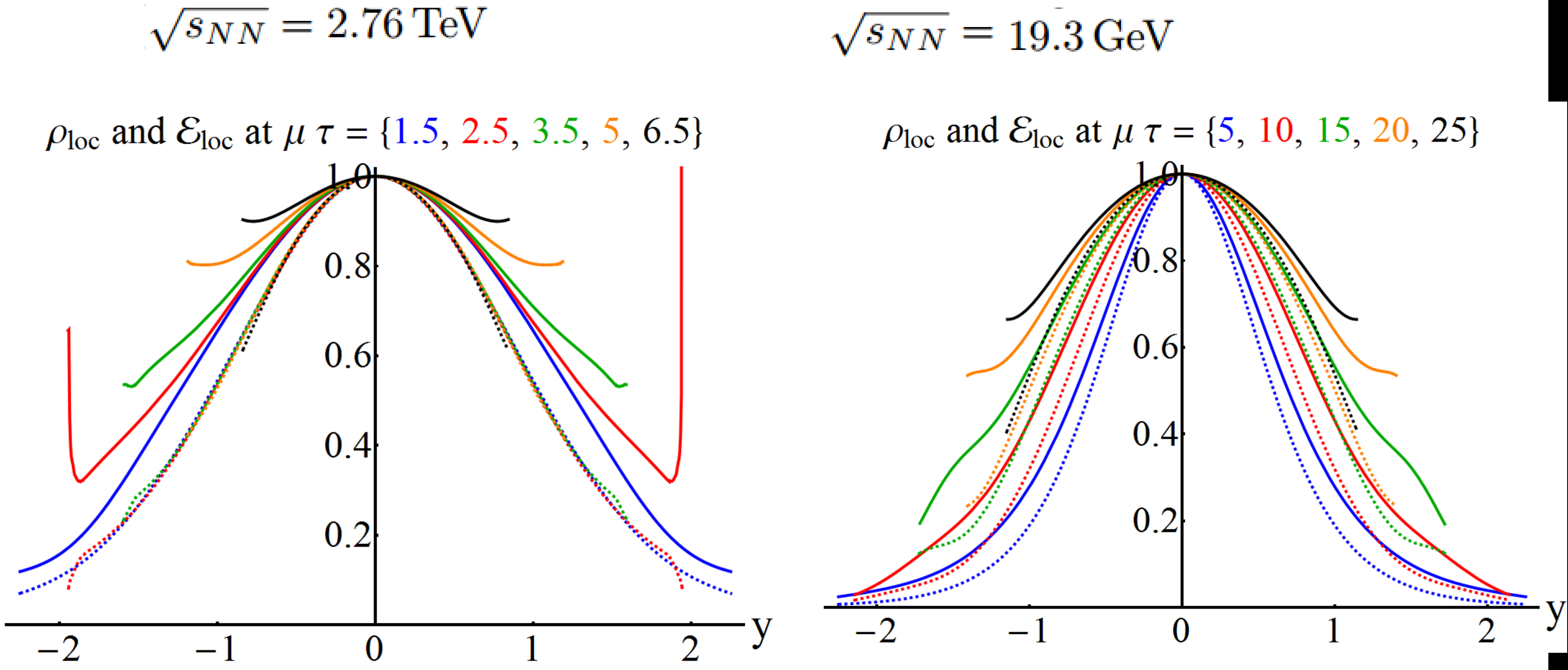
$\sqrt{s_{NN}} = 19.3\ \text{GeV}$



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

CHARGE RAPIDITY PROFILE

- Wider than energy density (dashed), more dynamical



$\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$

ρ_{loc} and $\mathcal{E}_{\mathrm{loc}}$ at $\mu\,\tau = \{1.5, 2.5, 3.5, 5, 6.5\}$

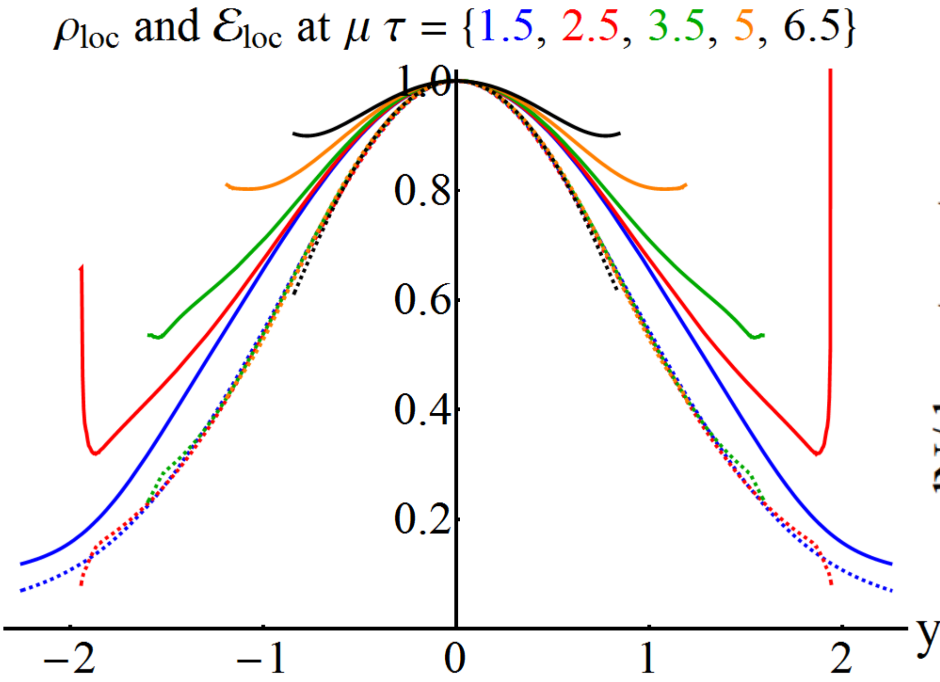
$\sqrt{s_{NN}} = 19.3\,\mathrm{GeV}$

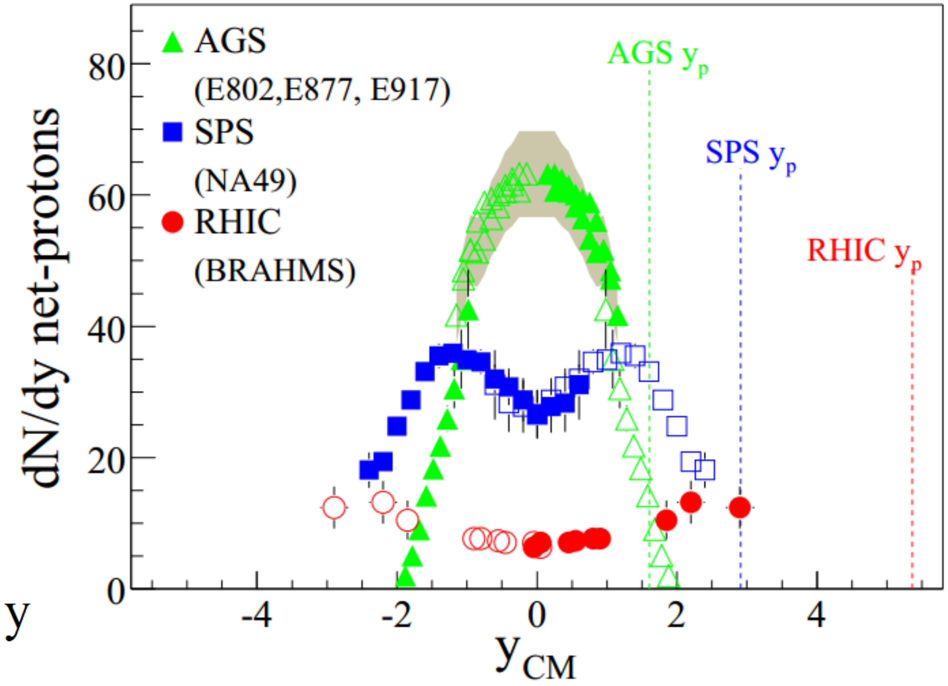
ρ_{loc} and $\mathcal{E}_{\mathrm{loc}}$ at $\mu\,\tau = \{5, 10, 15, 20, 25\}$

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

RIGHT BALL-PARK EXPERIMENTALLY?

- Baryon transparency?





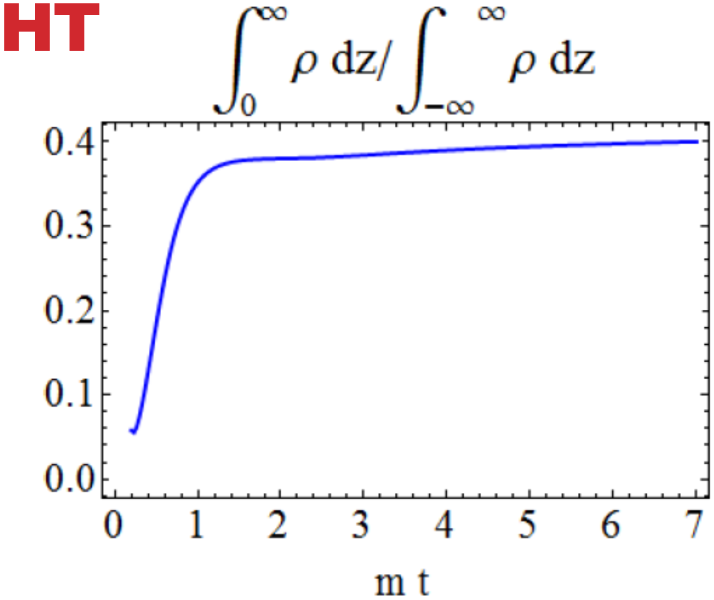
- Many caveats: hydro evolution, freeze-out, space vs momentum rapidity, transverse profiles, *simple AdS model*
- Preliminary: perhaps not so bad at ~ AGS, SPS, difficult for RHIC + LHC

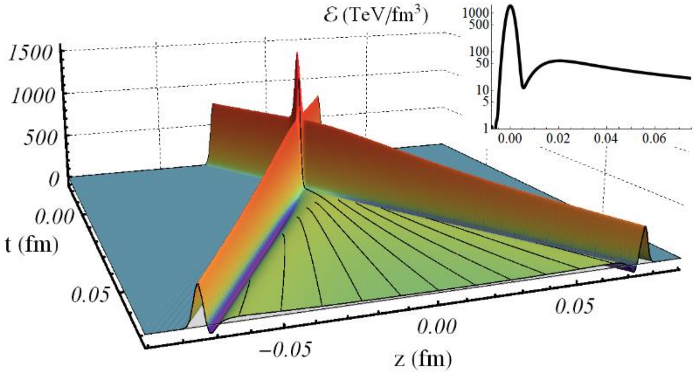
BRAHMS, Nuclear Stopping in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV(2003)

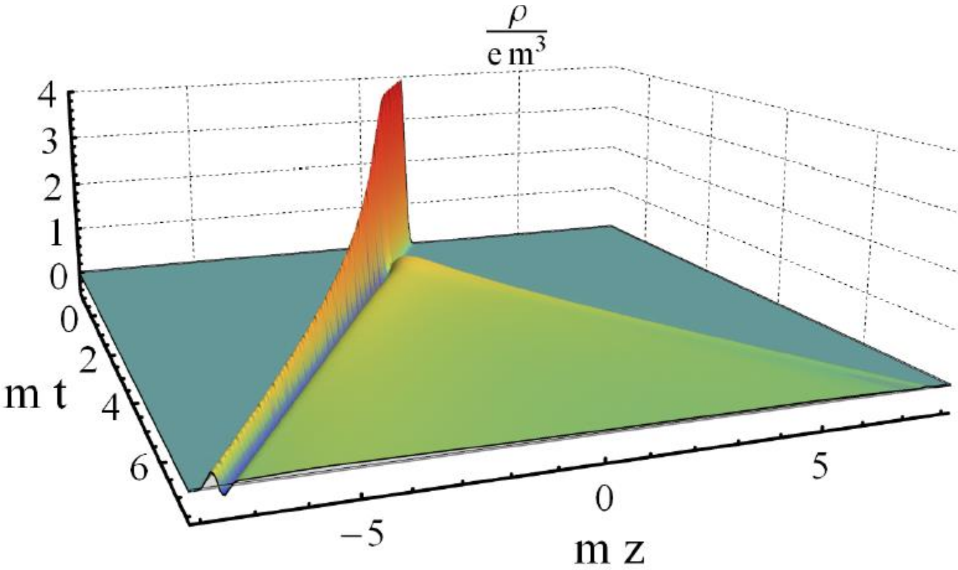
A NEW QUANTITATIVE INSIGHT

- Collide shocks with energy and charge
- Now collide neutral with charged shock
- 41% of charge changes direction

  → strong interactions







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

COLLISIONS AT FINITE COUPLING

Leading order correction: small curvature squared

- Not for N=4 SYM theory (but that’s also not what we want…)
- Einstein-Gauss-Bonnet theory:

$$S_{GB} = \frac{1}{2\kappa_5^2}\int d^5x\sqrt{-g}\left[R - 2\Lambda + \frac{\lambda_{GB}}{2}L^2\left(R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}\right)\right]$$

- Reproduces weak-coupling expectations, i.e. $\eta/s = \frac{1}{4\pi}\left(1 - 4\lambda_{GB}\right)$

Evolution is just as simple as original ☺

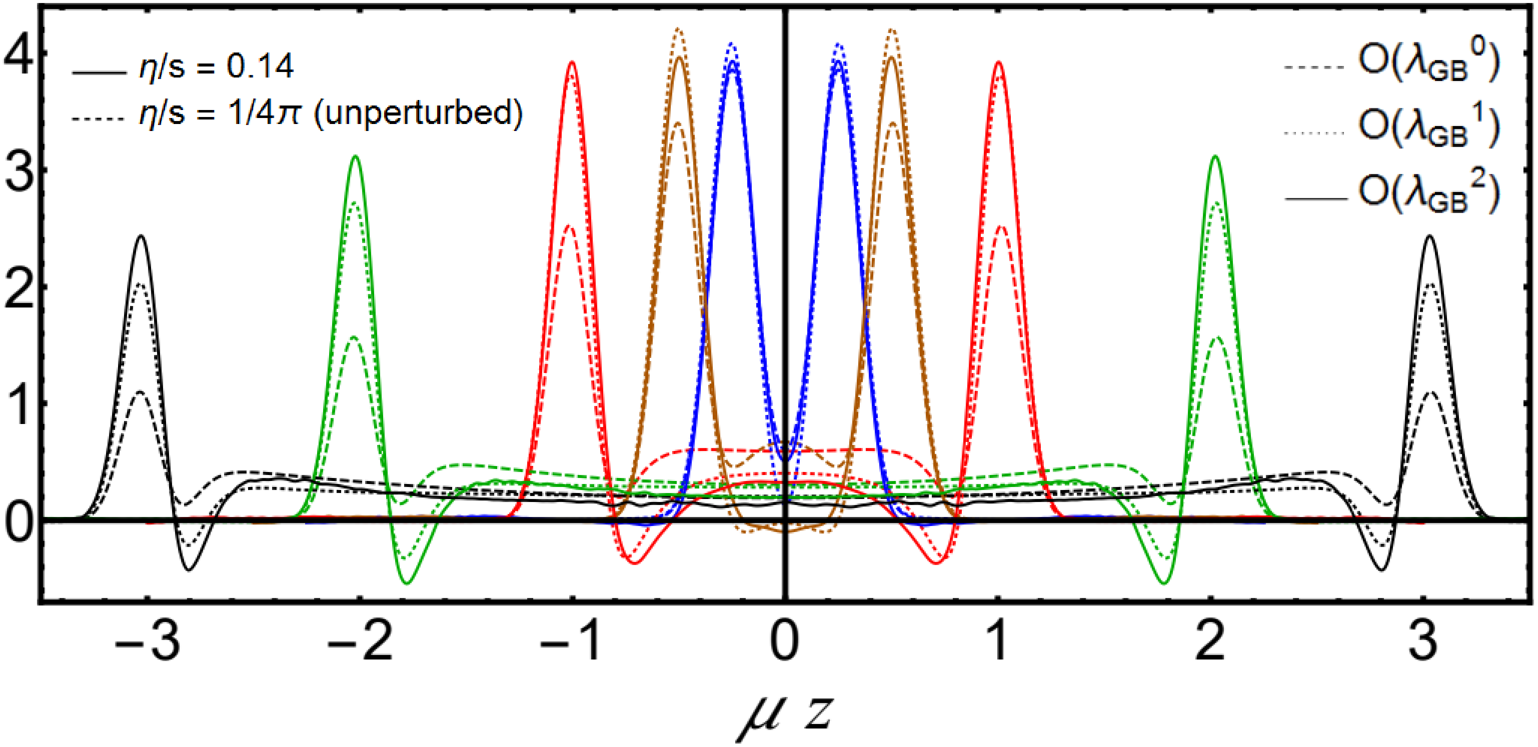
- Initial condition remains exact solution of EOM (for some L)
- Nested scheme survives completely (with source terms)
- Equations get longer… (3.5 MB C-code in current form)

Yevgeny Kats and Pavel Petrov, Effect of curvature squared corrections in AdS on the viscosity of the dual gauge theory (2007)
Sašo Grozdanov, Nikolaos Kaplis and Andrei Starinets, From strong to weak coupling in holographic models of thermalization (2016)
Tomas Andrade, Jorge Casalderrey-Solana and Andrej Ficnar, Holographic Isotropisation in Gauss-Bonnet Gravity (2016)

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

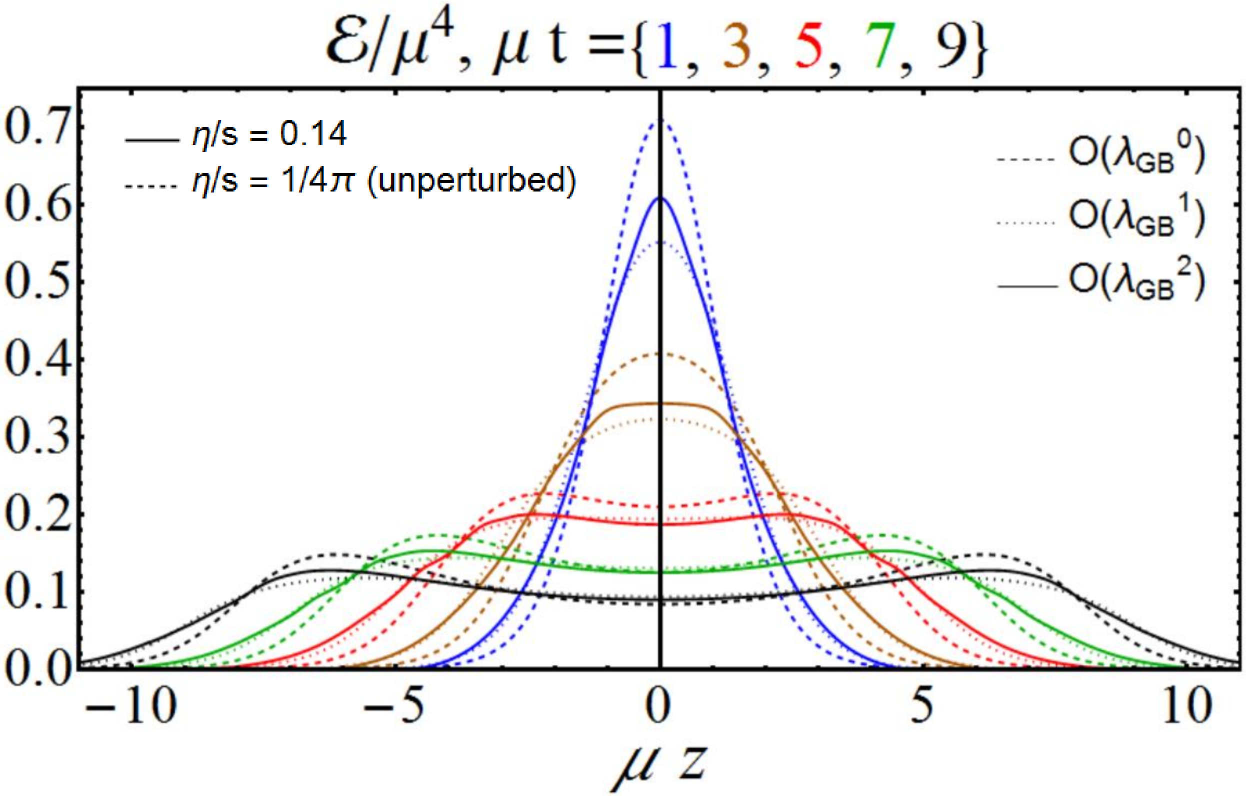
$\mathcal{E}/\mu^4$, μ t ={0.25, 0.5, 1, 2, 3}



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

COLLISIONS AT FINITE COUPLING - WIDE

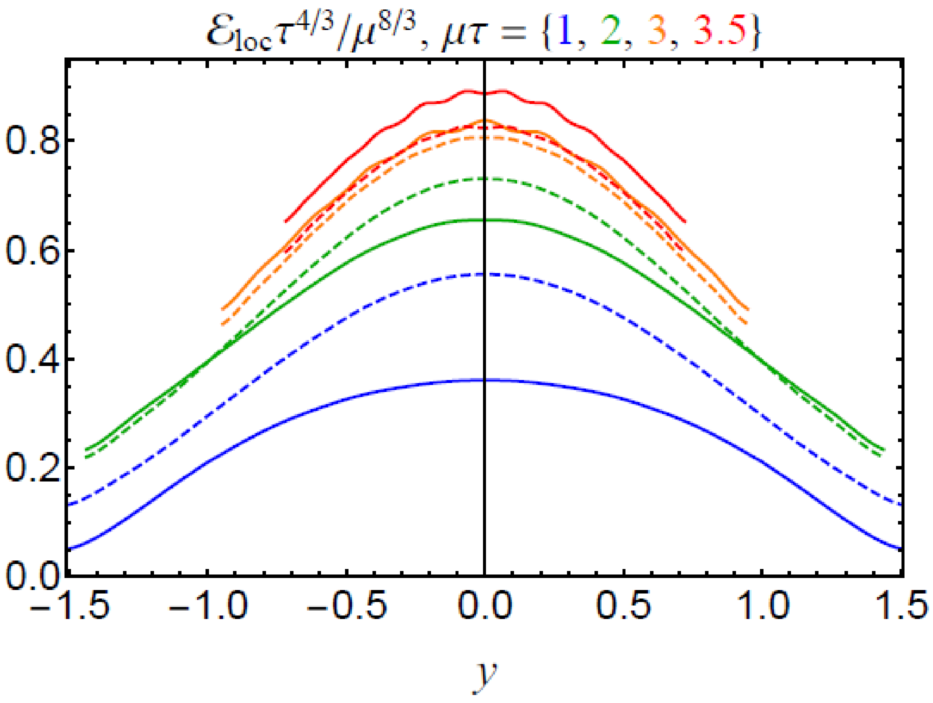
- Results presented for, $\lambda_{GB} = -0.2$ i.e $\eta/s = 1.8/4\pi$
- Initial condition constructed such that energy is the same



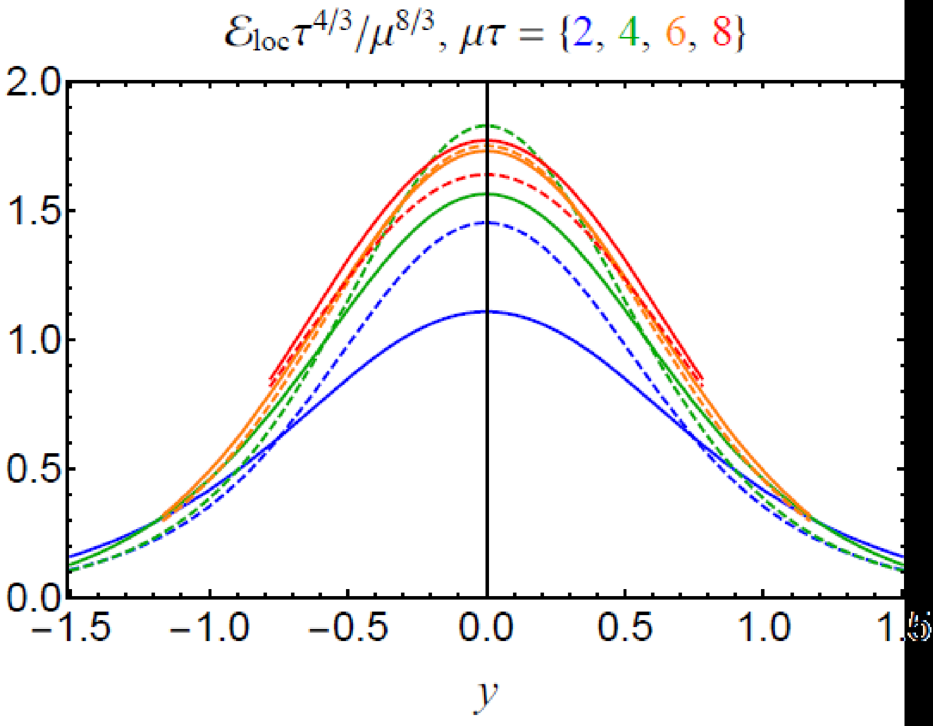
- Energy does not `pile up', i.e. maximum 217% instead of 271%
- Also includes $\lambda_{GB}{}^2$ corrections (small opposite contribution)

COLLISIONS AT FINITE COUPLING - RAPIDITY

- Initial rapidity shape differs from Gaussian



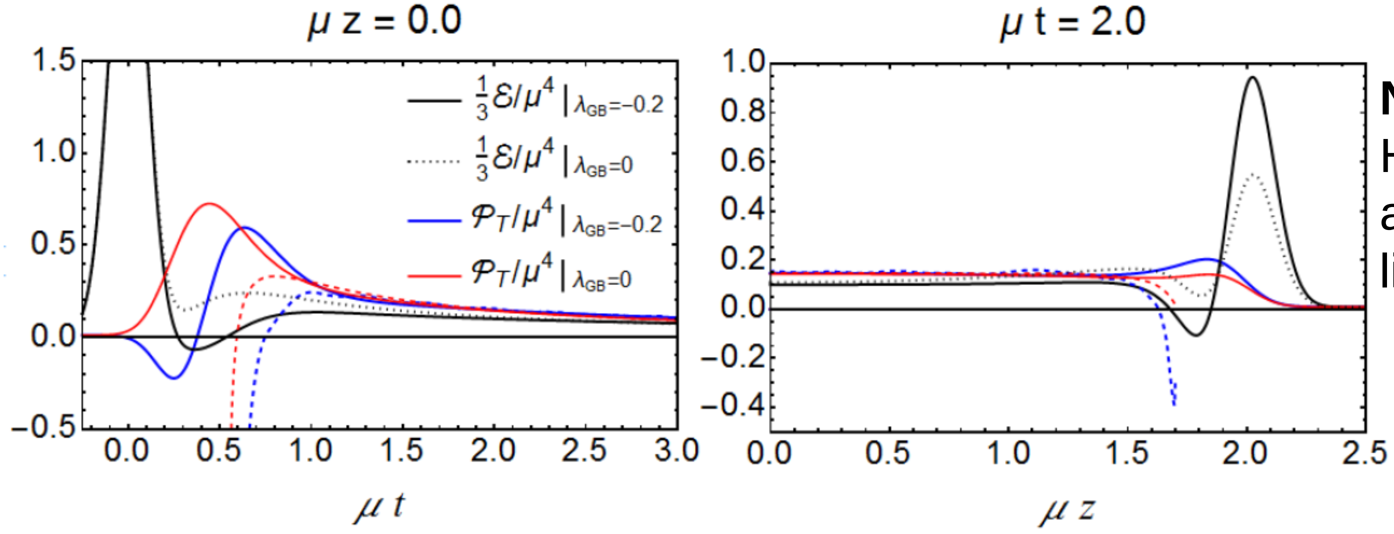
Narrow
Wider and lower initially (energy on lightcone not shown)
Later similar (time 3), then more entropy, similar width



Wide
Almost entirely by hydro + less pile-up:
First lower energies + wider
Viscosity: lower transverse pressure, more entropy

COLLISIONS AT FINITE COUPLING - HYDRO

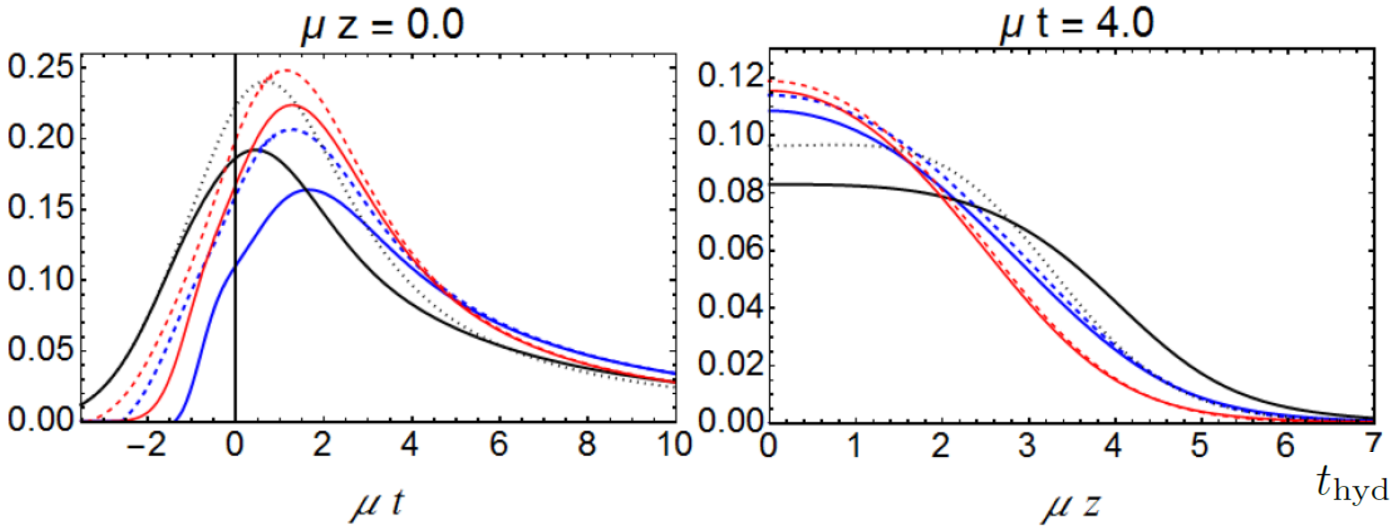
- Hydro applies about 25% later for narrow shocks (subtler for wide)
  - Only transverse pressure: longitudinal from conformal symmetry
- Can be seen as either non-trivial check on viscosity or numerics…



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

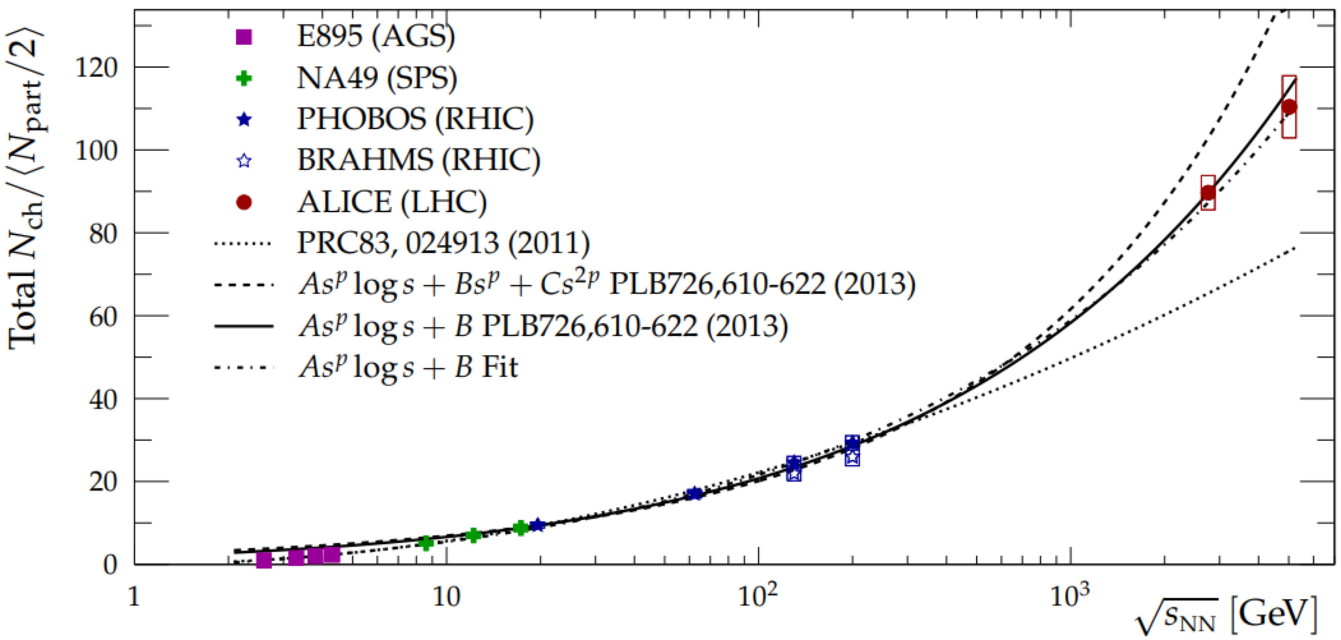
$$t_{\text{hyd}}T_{\text{hyd}} = 0.43 - 6.3\lambda_{GB}$$

ON MULTIPLICITY IN SCALE INVARIANT THEORIES

Final multiplicity is proportional to final entropy

- Little entropy generated in hydro or cascade (low viscosity)
- Entropy is produced early on in initial stage

→ Total N_{ch} good probe for initial entropy production (dN/dy a bit less)



— $0.512\, s_{NN}^{0.15} \log s_{NN} + 1.962$ or $3.62\, s_{NN}^{0.21} - 3.07$

Different power from conformal theory: would have $s_{NN}^{1/3}$

ALICE, Centrality dependence of the pseudorapidity density distribution for charged particles in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02TeV (2016)

$$S_{GB} = \frac{1}{2\kappa_5^2}\int d^5x\sqrt{-g}\left[R - 2\Lambda + \frac{\lambda_{GB}}{2}L^2\left(R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}\right)\right]$$

OUTLOOK

Combination of models could give much richer view

- Scalar potential:
  break conformal symmetry, more realistic dynamics around T_{QCD}
- Maxwell field:
  follow conserved charge
- Higher-derivative gravity:
  more realistic coupling constant; vary with scale?

First idea: how is `bouncing' charge affected by weaker coupling?

$$\mathcal{L} = \frac{1}{2\kappa^2}\left[R - \frac{f(\phi)}{4}F_{\mu\nu}^2 - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$$

$$V(\phi) = -\frac{1}{L^2}\left(8e^{\frac{\phi}{\sqrt{6}}} + 4e^{-\sqrt{\frac{2}{3}}\phi}\right), \quad f(\phi) = e^{-2\sqrt{\frac{2}{3}}\phi}.$$

Oliver DeWolfe, Steven S. Gubser and Christopher Rosen, Dynamic critical phenomena at a holographic critical point (2011)

DISCUSSION

Holography and heavy ion collisions

- AdS/CFT essential tool for insights in strongly coupled matter
- Complementary with weak coupling modelling

Qualitative lessons and quantitative modelling

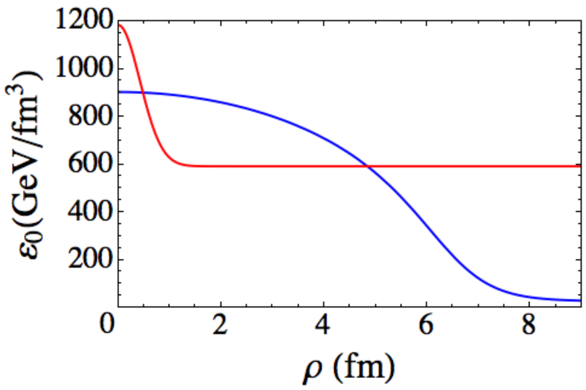
- Most of energy stopped at moderate rapidity, Gaussian shape
- Similar Gaussian shape baryon number, but growing wider
- *Less stopping and broader rapidity profile at finite coupling*

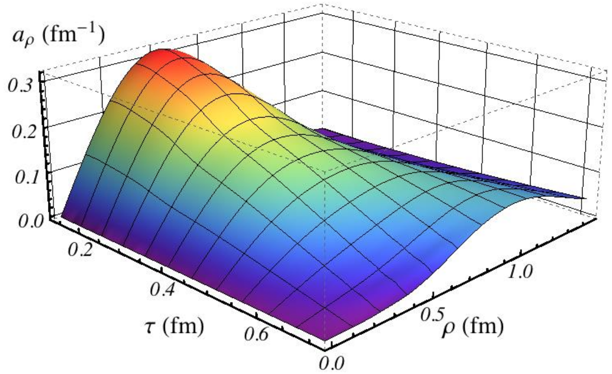
Outlook

- More quantitative comparisons with experiment, perhaps fitting width rapidity spectrum etc
- Improved models closer to QCD, include running coupling

TWO COMPUTATIONS FOR SMALL SYSTEMS

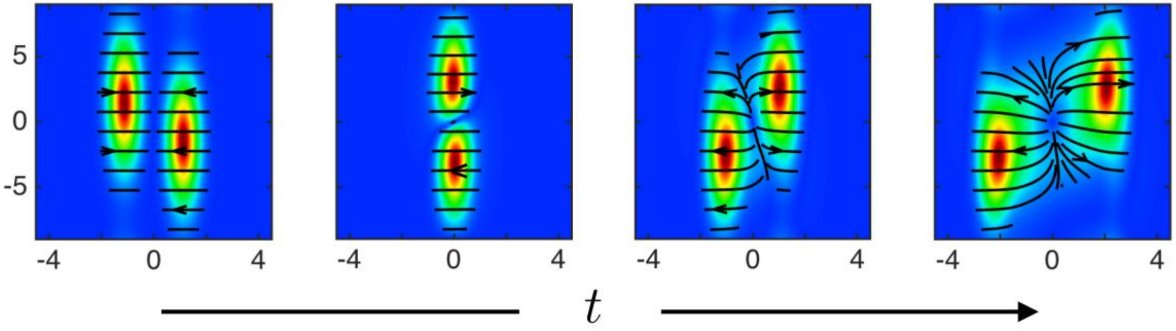
A fluctuation in a thermal bath:





- Hydro works within 0.2 fm/c, for system of size 0.5 fm.

A full-blown off-center `p-p collision':



- Hydro found to work in a system with R ~ 1/T

WS, Holographic thermalization with radial flow (2012)
Paul Chesler, How big are the smallest drops of quark-gluon plasma? (2016)

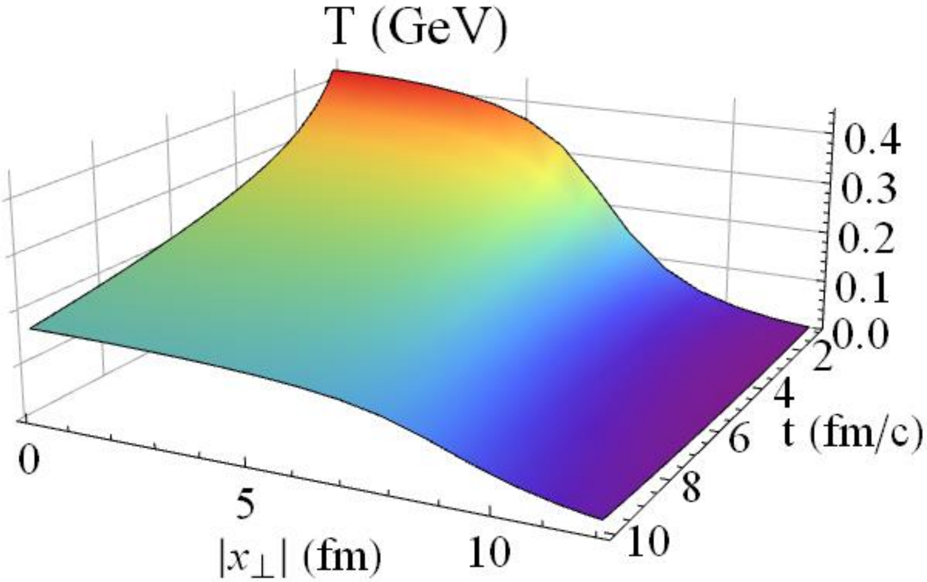
AN ESTIMATE

For p-Pb and p-p collisions only few particles produced

- Naïve estimate: $s \approx 16T^3$ gives $N_{ch} \approx Vs/7.5 \approx 2.1VT^3$
- Volume per rapidity: $R^2 \tau_{ini}$
- When $R > 1/T$ (and $\tau_{ini}T > 1$) then dN_{ch}/dy > 4
- Note that R increases faster than $1/T$ (τ versus $\tau^{1/3}$)
    - Hydro works better at later times
    - Flow requires time to develop, i.e. 4 is `optimistic' estimate

MORE SIMPLIFICATIONS

Simple semi-analytic hydrodynamic temperature profile:



$$T(\tau,\vec{x}_\perp) = b\left[\frac{dN_{\rm ch}}{dy}\frac{1}{N_{\rm part}}\frac{\rho_{\rm part}(\vec{x}_\perp/r_{\rm bl}(\tau))}{\tau\, r_{\rm bl}(\tau)^2}\right]^{1/3},$$

$$r_{\rm bl}(\tau) \equiv \sqrt{1+(v_T\tau/R)^2}$$

(*b* measures N_{ch} per S, given EOS)

Neglect initial dynamics (1 fm/c) + hadronization + confinement

Start string at single point at boundary

- Distribute according to binary scaling and $(E_{\rm jet}^{\rm init})^{-6}$
- Free parameter *b*: to get reasonably energy loss ((coupling) $\mathcal{N}=4\neq{\rm QCD}$)

A. Ficnar, S.S. Gubser and M. Gyulassy, Shooting String Holography of Jet Quenching at RHIC and LHC (2013)