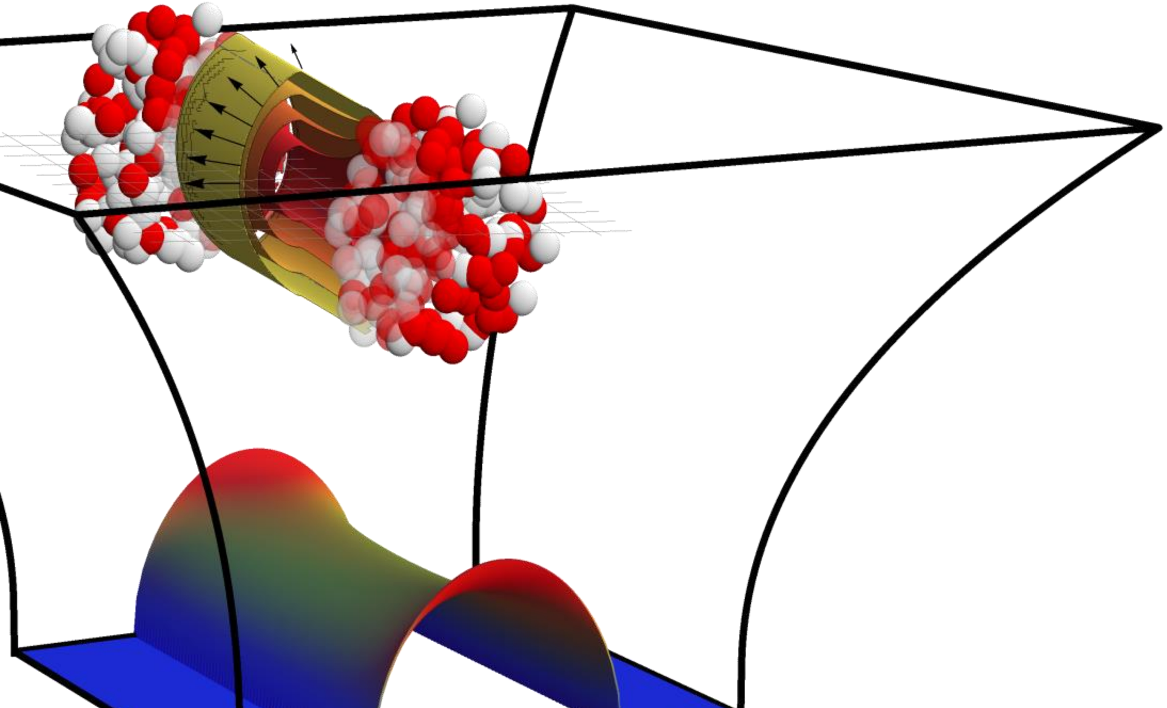
Universiteit Utrecht

EQUILIBRATION AND HYDRODYNAMICS AT STRONG AND WEAK COUPLING

FROM COLLISIONS TO QUARK-GLUON PLASMA

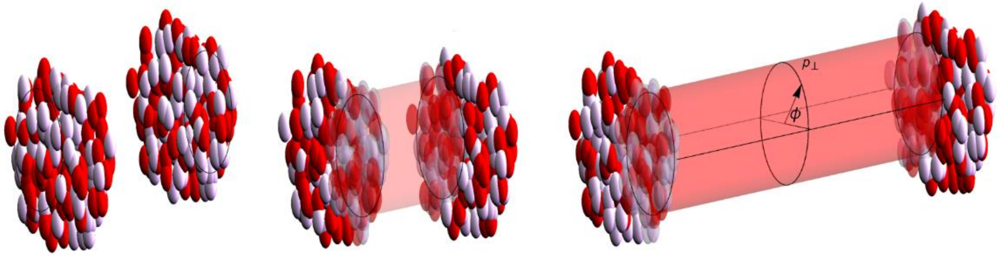


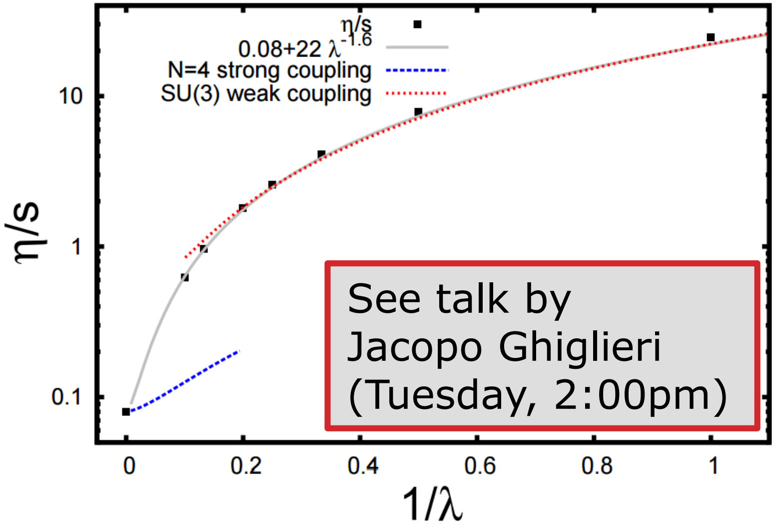
Wilke van der Schee
Quark Matter 2017
6 February 2017

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




Shear viscosity over entropy ratio

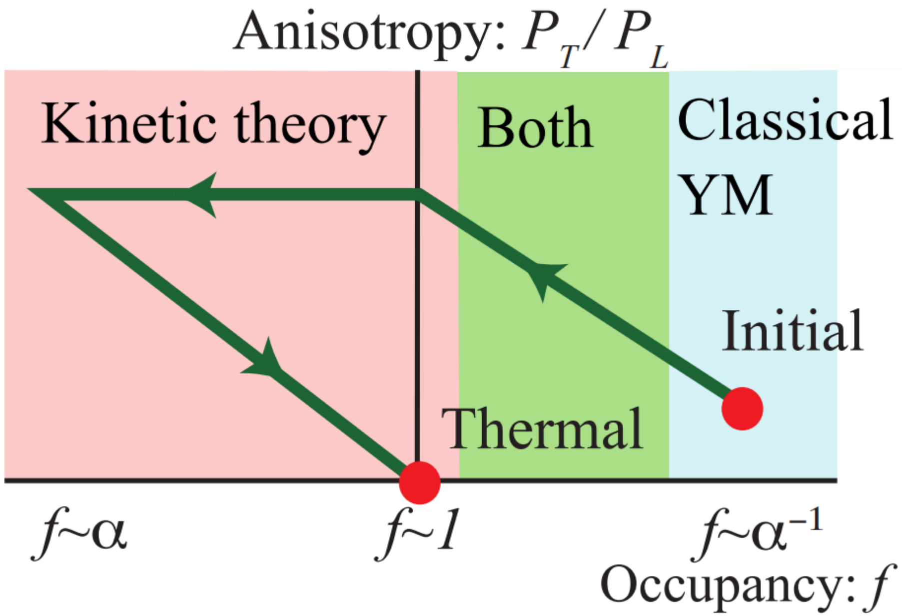
See talk by Jacopo Ghiglieri (Tuesday, 2:00pm)

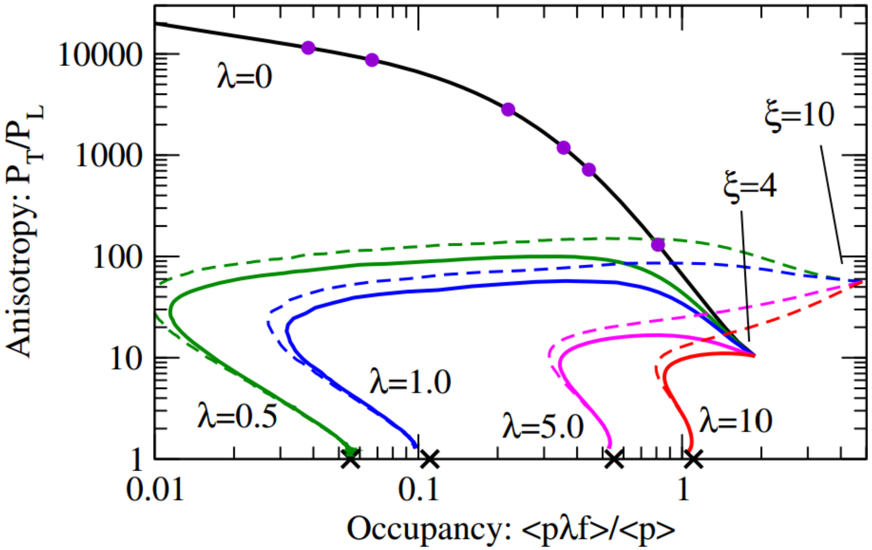
L. Keegan, A. Kurkela, P. Romatschke, WS and Y. Zhu, Weak and strong coupling equilibration in nonabelian gauge theories (2015)

INITIAL STAGE – WEAK COUPLING

Typical process of thermalisation:

- Over-occupied coherent gluons, no quasi-particle but classical Yang-Mills
- Far-from-equilibrium universal scaling in Yang-Mills
- Kinetic theory towards thermal equilibrium, expansion versus equilibration





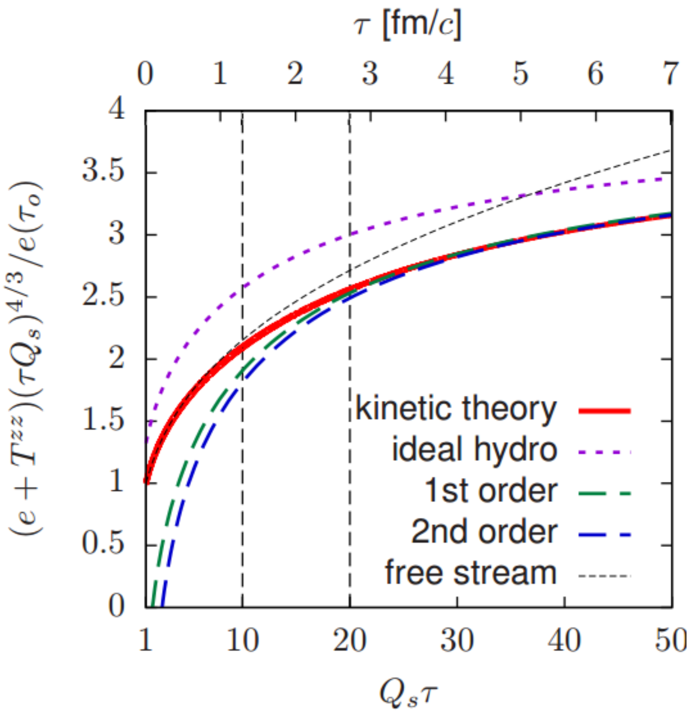
Aleksi Kurkela and Yan Zhu, Isotropization and Hydrodynamization in Weakly Coupled Heavy-Ion Collisions (2015)

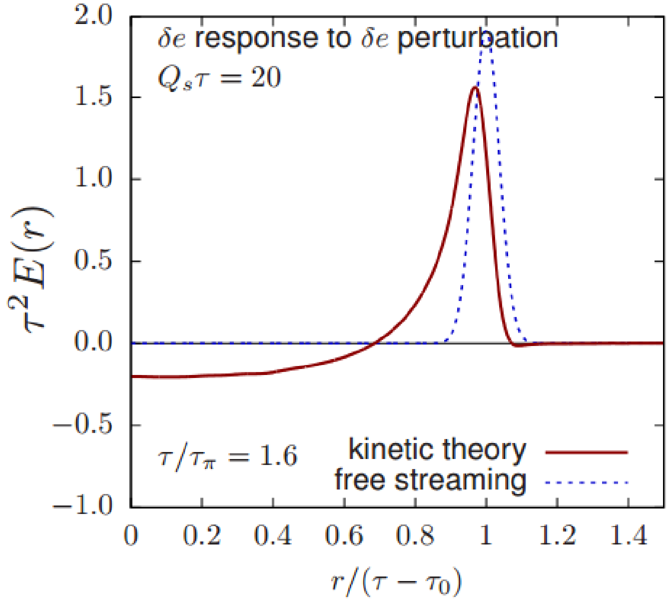
THE APPROACH TO HYDRO

All details in talk by
Aleksas Mazeliauskas
(Tuesday, 11:00am)

Interesting interplay between kinetic, hydro, free streaming

- Hydro gives good (10%) description of $e+P_L$ at 1.4 fm/c
- Green function for perturbations (not yet hydrodynamised)





$$\lambda = 10\ (\alpha_s \approx 0.26),\ \eta/s \approx 0.62$$

L. Keegan, A. Kurkela, A. Mazeliauskas and D. Teaney, Initial conditions for hydrodynamics from weakly coupled pre-equilibrium evolution (2016)

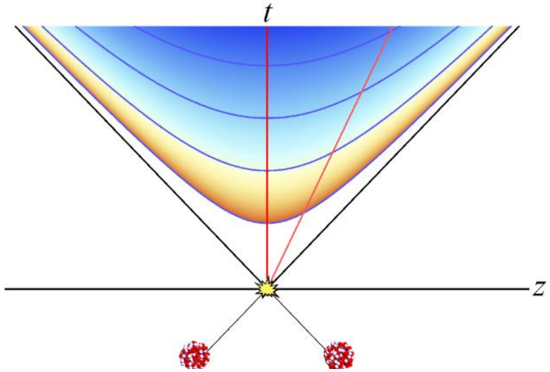
ANISOTROPY IN WEAK VS STRONG

In a locally boost invariant conformal system, energy fixes pressures:

$$T_\mu^\nu = \mathrm{diag}\{\epsilon(\tau),\, -\epsilon(\tau) - \tau\,\epsilon'(\tau),\, \epsilon(\tau) + \tfrac{1}{2}\tau\,\epsilon'(\tau),\, \epsilon(\tau) + \tfrac{1}{2}\tau\,\epsilon'(\tau)\}$$

Leading order at early times:

- Free streaming: $\epsilon(\tau) \sim 1/\tau \rightarrow P_L = 0, \quad P_\perp = \epsilon(\tau)/2$
- Glasma: $\epsilon(\tau) \sim 1 \rightarrow P_L = -\epsilon(\tau), \quad P_\perp = \epsilon(\tau)$
- Strong coupling: $\epsilon(\tau) \sim \tau^2 \rightarrow P_L = -3\epsilon(\tau), \quad P_\perp = 2\epsilon(\tau)$
- Ideal hydro: $\epsilon(\tau) \sim 1/\tau^{4/3} \rightarrow P_L = \epsilon(\tau)/3, \quad P_\perp = \epsilon(\tau)/3$



Daniel Grumiller and Paul Romatschke, On the collision of two shock waves in AdS$_5$ (2008)

THE ROLE OF PRE-FLOW

A formula for pre-flow from gradient and pressure $v_\perp = -\frac{\tau}{2}\frac{\nabla_\perp e}{e+P_\perp}$

- Follows for any conformal theory (SE-conservation)
- Many works studying this question, now conclusive (?) answer
- Relevant question: what is typical transverse pressure?

Weak coupling: pressure starts at $e/2$, does not change much

Strong coupling: starts at $2e$, decreases very fast, same result:

$$v_\perp = -\frac{\tau}{2}\frac{\nabla_\perp e}{e+P_\perp} \approx -0.33\tau\frac{\nabla_\perp e}{e}$$

Note that we still need hydrodynamisation to get collective flow

Joshua Vredevoogd and Scott Pratt, Universal Flow in the First Stage of Relativistic Heavy Ion Collisions (2008)
WS, Holographic thermalization with radial flow (2012)
M. Habich, J. Nagle and P. Romatschke, Particle spectra and HBT radii for simulated central nuclear collisions … (2014)
L. Keegan, A. Kurkela, A. Mazeliauskas and D. Teaney, Initial conditions for hydrodynamics from weakly coupled pre-equilibrium evolution (2016)

FINITE COUPLING CORRECTIONS

Compute corrections to infinitely strongly coupled results:

- In N=4 SYM theory computed for viscosity and relaxation:

$$\eta/s = \frac{1}{4\pi}\left(1 + 18\,\lambda^{-3/2} + \mathcal{O}(\lambda^2)\right) \approx 0.08 + 0.045|_{\lambda=10}$$

$$\tau_{\rm rel} T = 0.73\left(1 + 138\,\lambda^{-3/2} + \mathcal{O}(\lambda^2)\right) \qquad (\tau_{\rm rel} \equiv 2\pi/\mathcal{I}(\omega))$$

puzzling: corrections of 50% and 440% (and more for higher modes)

- Recent new insights from `partially resummed' theory

$\gamma = \lambda^{-3/2}\zeta(3)/8$

$$S_{IIB} = \frac{1}{2\kappa_{10}^2}\int d^{10}x\sqrt{-g}\left(R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{4\cdot 5!}F_5^2 + \gamma e^{-\frac{3}{2}\phi}\mathcal{W} + \ldots\right)$$

Idea: treat theory without '…' as consistent theory, compute non-linear terms

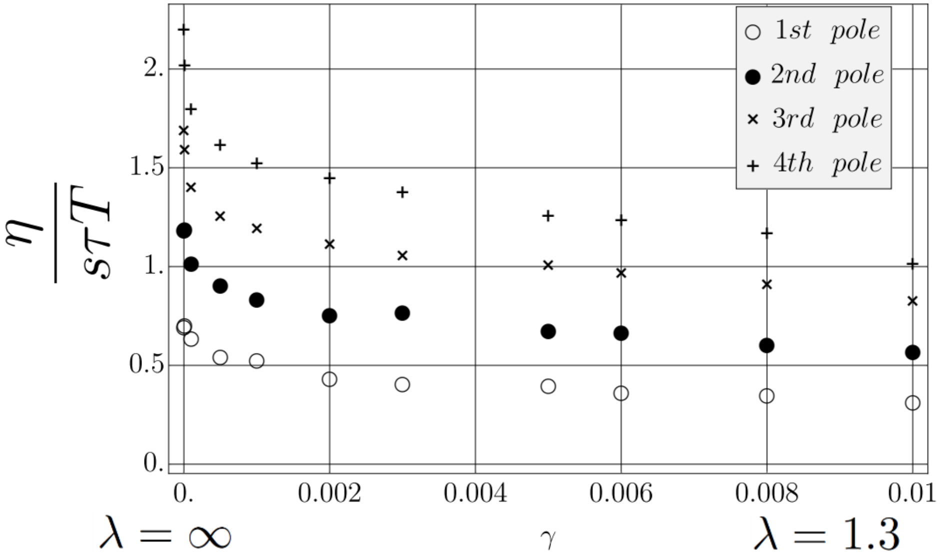
  - Relaxation, as well as higher modes, behave qualitatively similar to viscosity

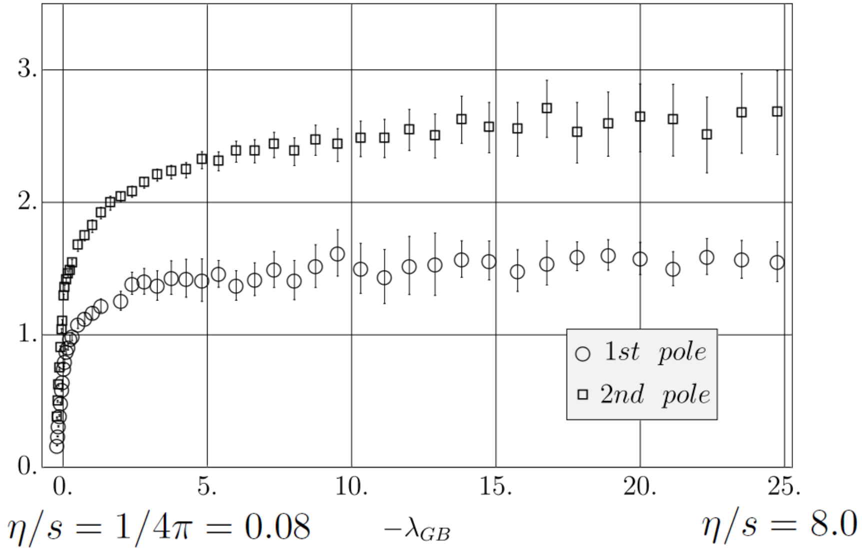
Alex Buchel, Resolving disagreement for η/s in a CFT plasma at finite coupling (2008)
Stefan Stricker, Holographic thermalization in N=4 Super Yang-Mills theory at finite coupling (2013)
Sebastian Waeber, Andreas Schafer, Aleksi Vuorinen and Laurence Yaffe, Finite coupling corrections to holographic predictions for hot QCD (2015)

FINITE COUPLING CORRECTIONS

Beyond pure perturbative treatment:

- Insightful to plot ratio viscosity and relaxation time
- Ratios ~0.5 – 1.5: steep at origin (previous slides), but quickly flattens





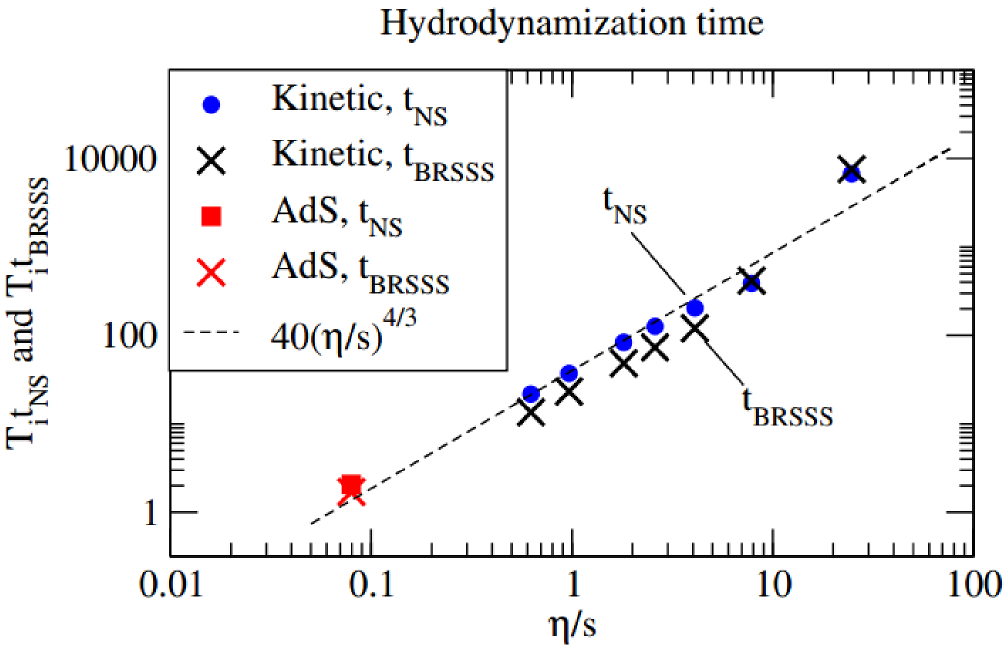
Also for Gauss-Bonnet gravity (right):

- *Leading order correction* (curvature squared, as opposed to R^4)
- Not N=4 SYM: Holographic dual not known explicitly (as with QCD)
  Seen to reproduce expectations of weaker coupling, i.e. larger viscosity

Sašo Grozdanov, Nikolaos Kaplis and Andrei Starinets, From strong to weak coupling in holographic models of thermalization (2016)

STRONG AND WEAK COUPLING TOGETHER

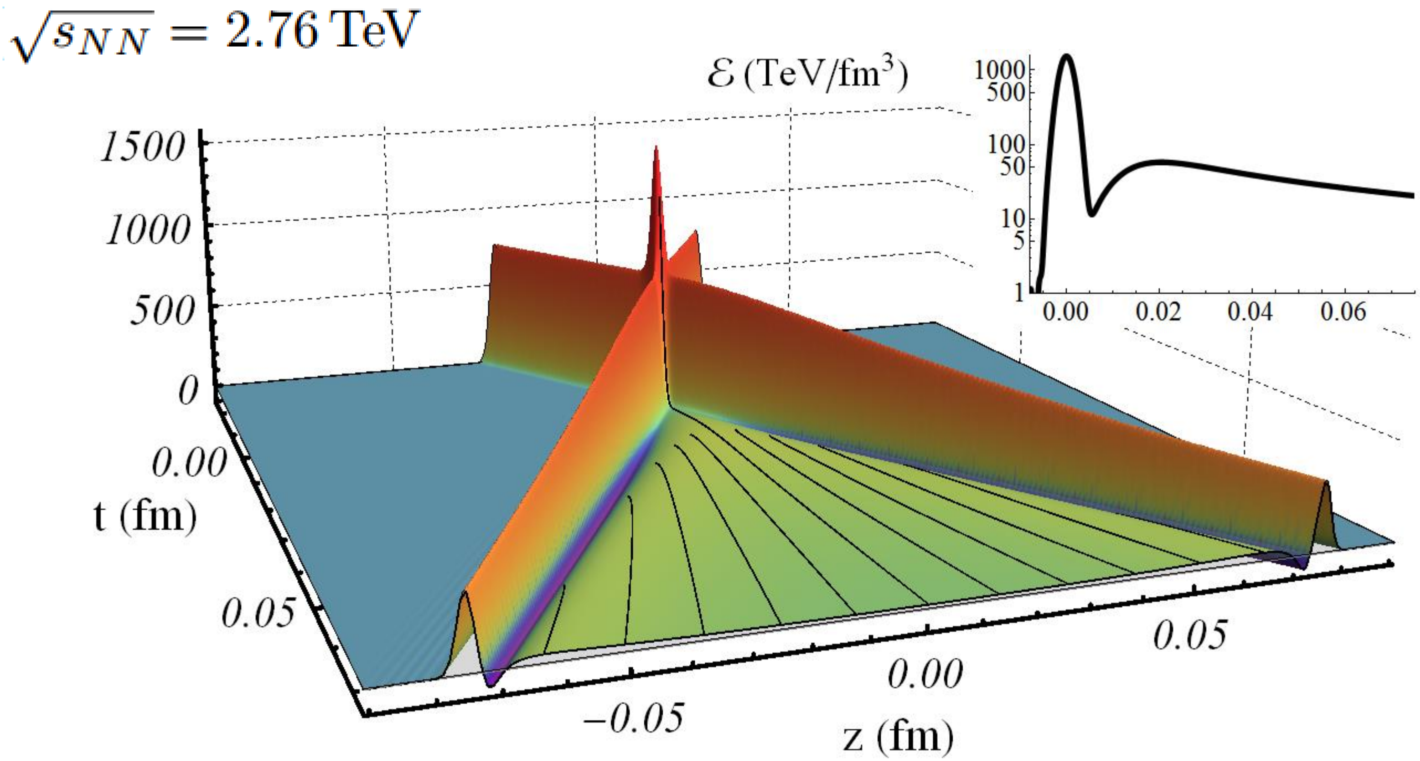
- An apple-to-apple comparison of energy density at various couplings
  - Start in thermal state, quench, and compare relaxation
  - Approximately linear in $(\eta/s)^{4/3}$



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

COLLISIONS AT INFINITELY STRONG COUPLING

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

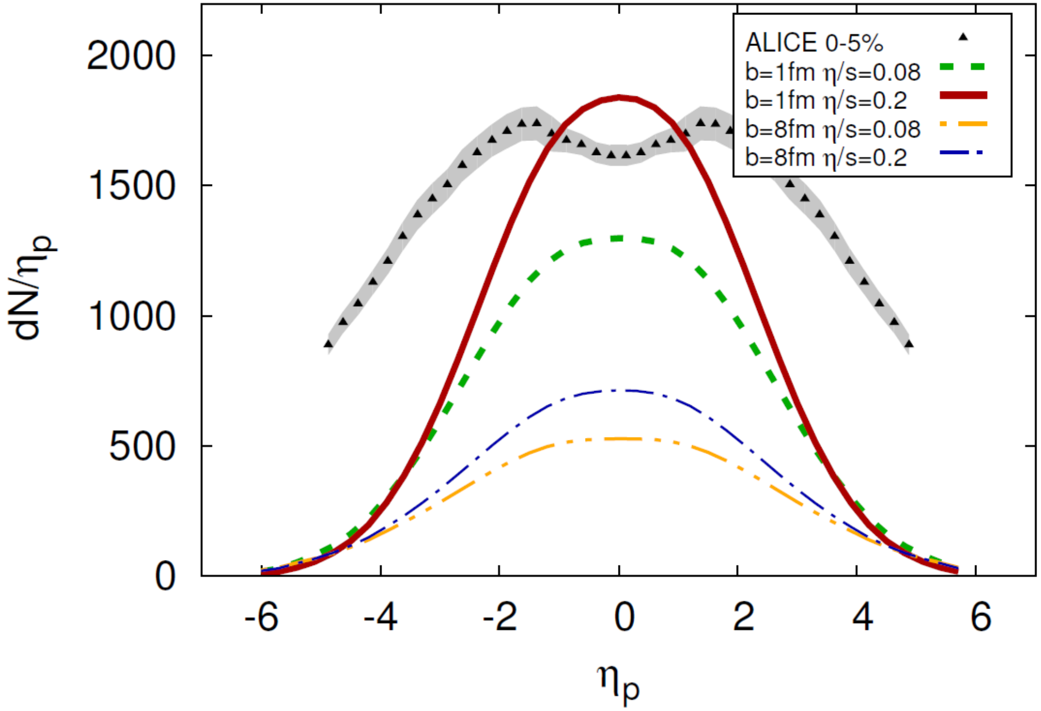


Benchmark at infinite coupling: $t_{\text{hyd}} \approx 0.04\ \text{fm/c}$

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:



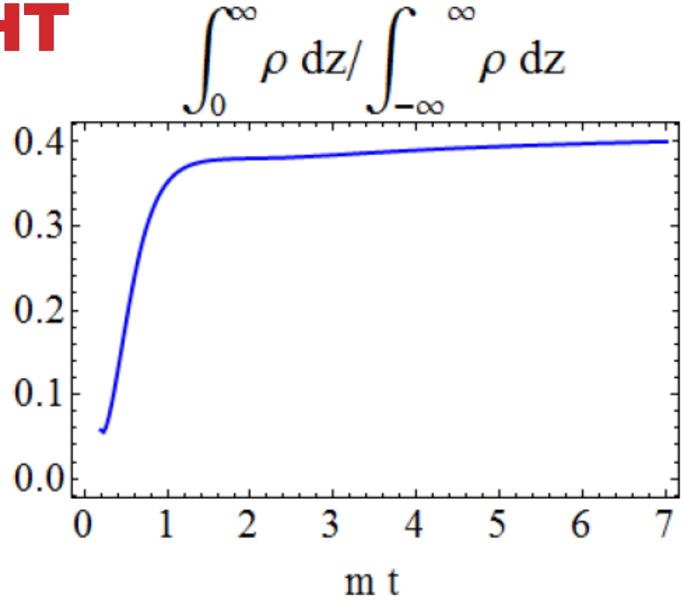
- **Rescaled initial energy density by factor 20**
- **Profile is roughly 30% too narrow**

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)

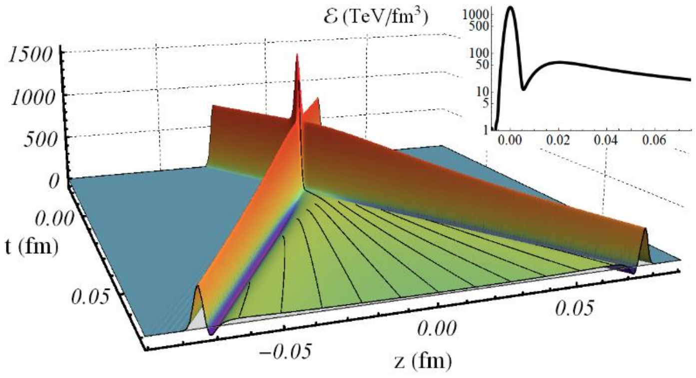
A NEW QUANTITATIVE INSIGHT

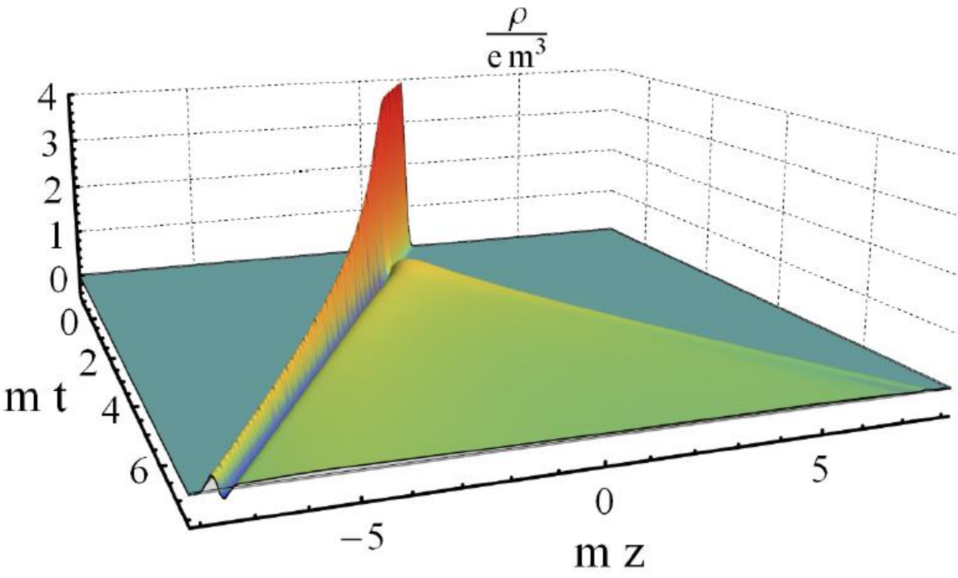
- Collide shocks with energy and charge
- Now collide **neutral** with **charged** shock
- 41% of charge changes direction (c.o.m.)

  → strong interactions



$$\int_0^\infty \rho\,dz \Big/ \int_{-\infty}^{\infty} \rho\,dz$$



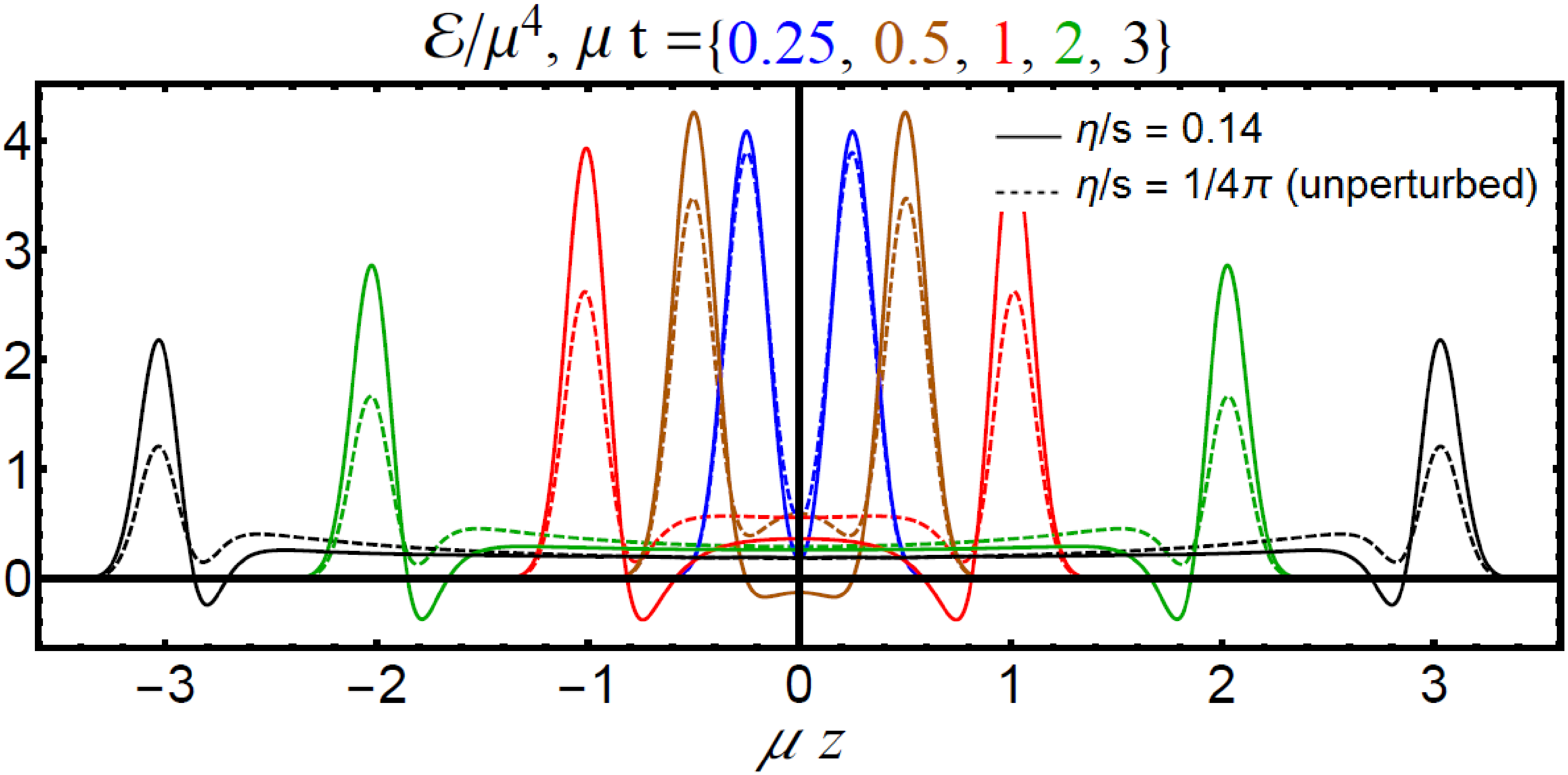


(m is typical energy scale)

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

COLLISIONS AT FINITE COUPLING

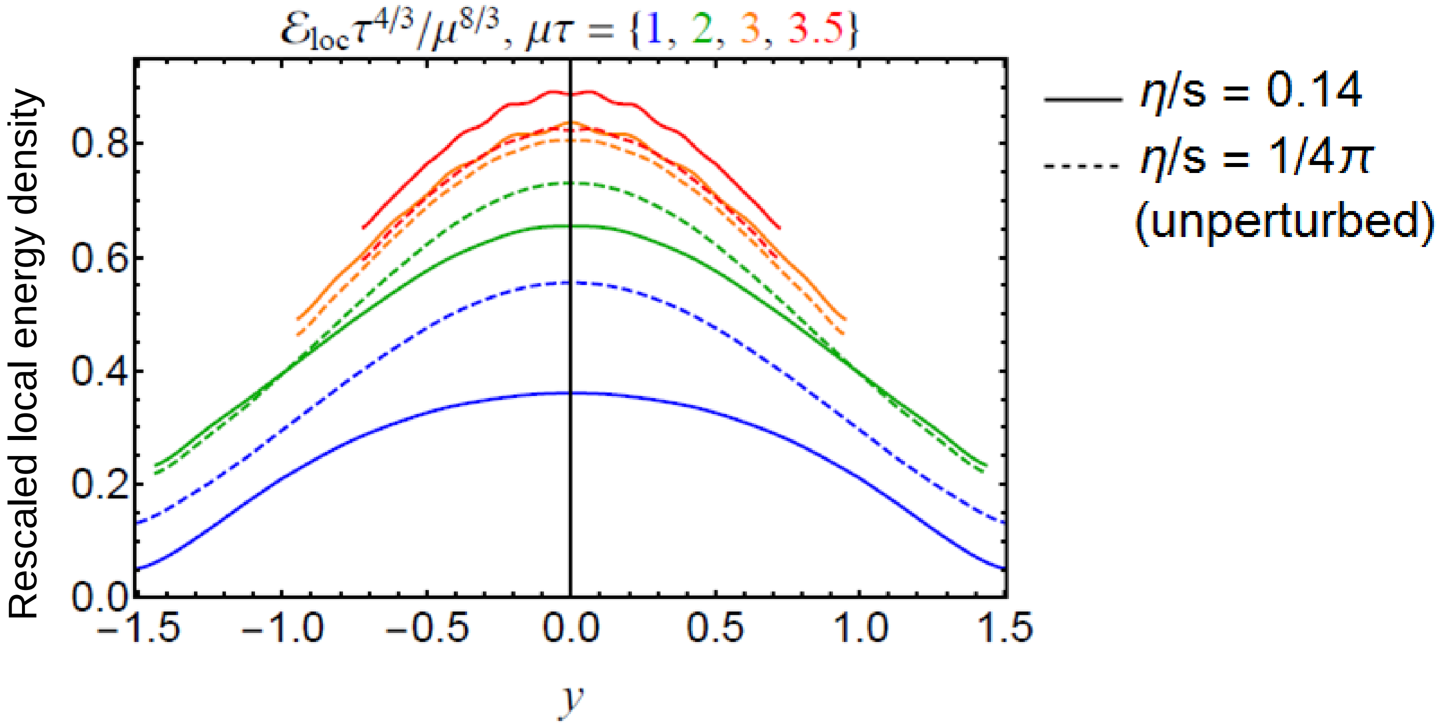
- Results presented for $\lambda_{GB} = -0.2$ i.e. $\eta/s = 1.8/4\pi$ (solid)
- Initial condition constructed such that energy is the same



- Much more energy on light cone (more transparent, less stopping)
- Energy in plasma flatter (will get to rapidity)

COLLISIONS AT FINITE COUPLING - RAPIDITY

- Initial rapidity shape differs from Gaussian



Profile is initially wider and lower than unperturbed case
(energy on light cone not shown)

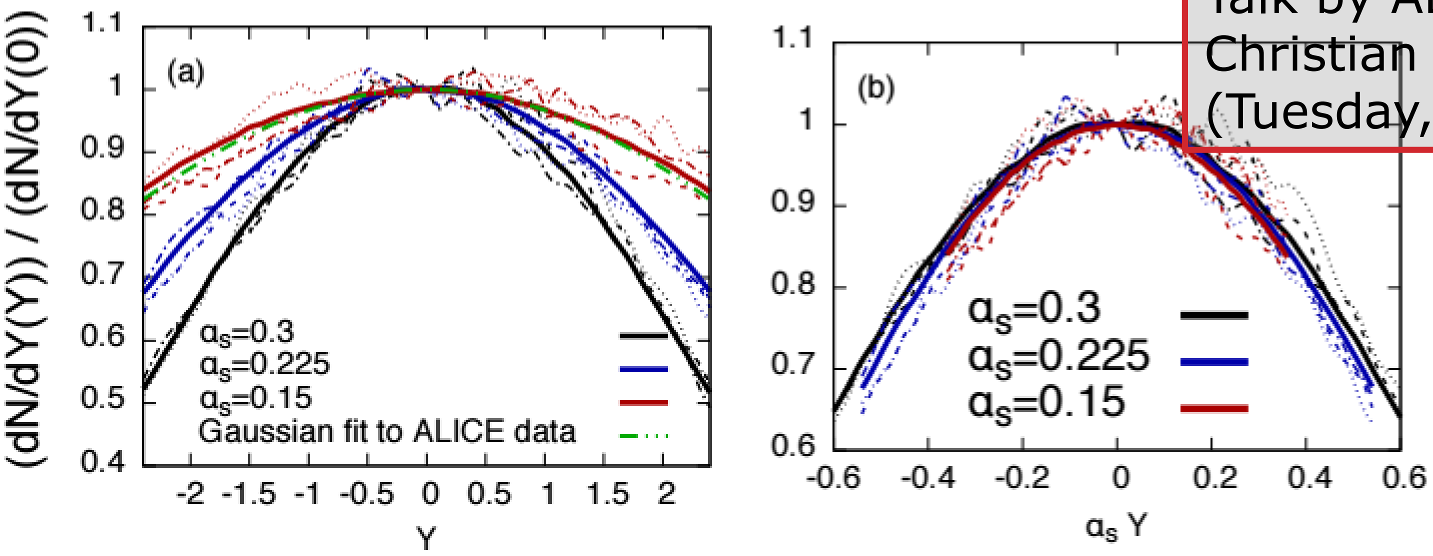
Higher viscosity → smaller longitudinal pressure → more entropy/less wide later

RAPIDITY PROFILE IN GLASMA

Possible to obtain rapidity profile
using JIMWLK evolution

All details in talk by
Sören Schlichting
(Tuesday, 9:50am)

Talk by ALICE:
Christian Christensen
(Tuesday, 12:00am)



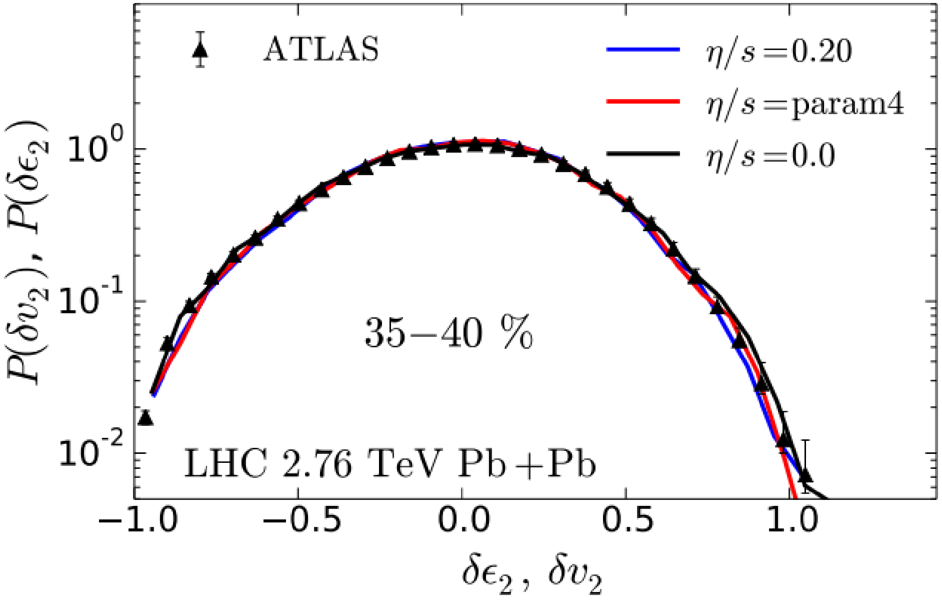
- Shape looks Gaussian, width proportional to $1/\alpha_s$
- Good fit with ALICE 2.76 TeV data for $\alpha_s = 0.15\text{-}0.20$
- Many other correlators computed (see talk)

Björn Schenke and Sören Schlichting, 3-D Glasma initial state for relativistic heavy ion collisions (2016)

INITIAL STAGE FROM EXPERIMENT

How to link initial stage description with experiment?

- E-by-E anisotropy distribution (EKRT does well)
- Very little sensitivity to hydro/freeze-out
- Tells us something about initial stage (see also Bayesian approach)



See also talks by
Kari Eskola
(Wednesday, 09:30am)
Jonah Bernhard
(Tuesday, 11:20am)
Scott McDonald
(Wednesday, 9:50am)
Igor Kozlov
(Wednesday, 10:40am)

H. Niemi, K. Eskolaa and R. Paatelainen, Event-by-event fluctuations in perturbative QCD + saturation + hydro model: pinning down QCD matter shear viscosity in ultrarelativistic heavy-ion collisions (2015)

DISCUSSION

New developments at weak coupling

- Kinetic theory simulations, pre-flow similar to strong coupling
- Small x JIMWLK evolution to get rapidity profile

New developments at strong coupling

- Results on finite coupling corrections
    - Somewhat slower hydrodynamization, somewhat wider rapidity profile
- Collisions with conserved charge: strong bounce

A developing coherent framework

- Convincing initial stage models can provide hydrodynamic initial state
    - What is the initial condition for the initial stage?
    - Do we get a framework valid for all energies and systems?
    - **Small systems** put differences weak and strong to test
- Evolution going from weak to strong coupling: where is cross-over?

Wilke van der Schee, MIT/Utrecht

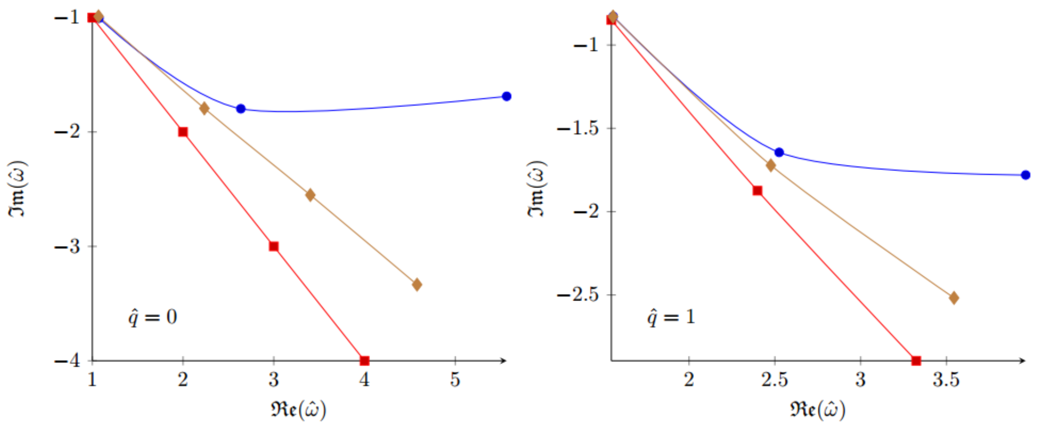
AN APOLOGY TO THOSE WHO CANNOT ATTEND

BACK-UP

FINITE COUPLING CORRECTIONS

Beyond pure perturbative treatment:

- Linearise around non-perturbative background, for $\lambda = 1000$:



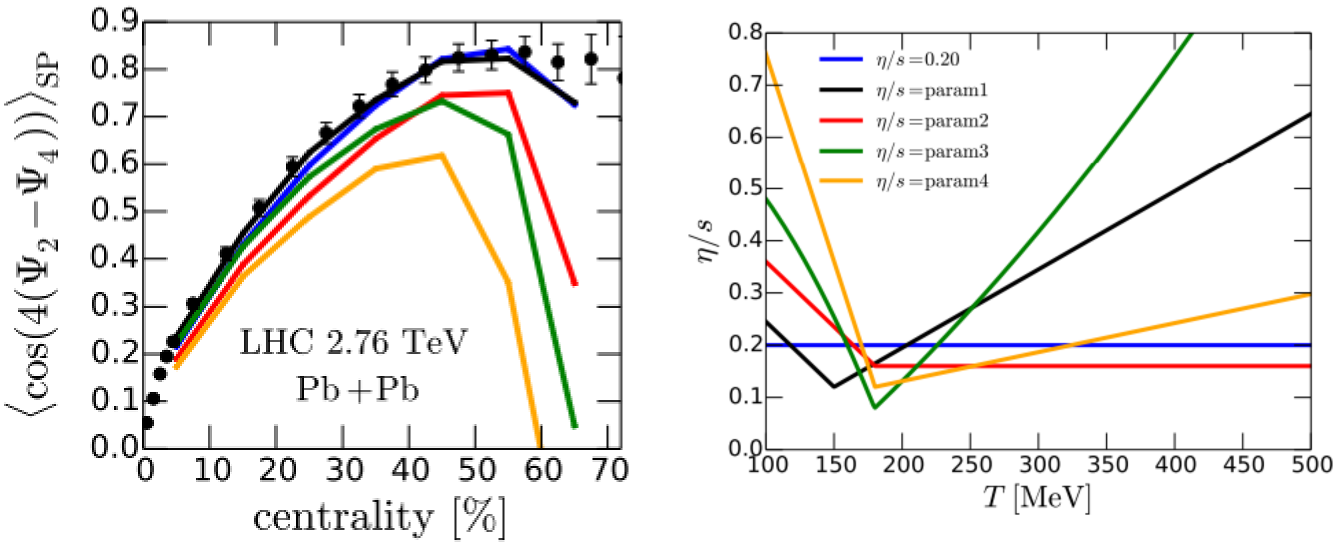
- Especially nice for higher modes: modes move towards real axis together

Sebastian Waeber, Andreas Schafer, Aleksi Vuorinen and Laurence Yaffe, Finite coupling corrections to holographic predictions for hot QCD (2015)

INITIAL STAGE FROM EXPERIMENT

Chose wise set of observables for quantity of interest

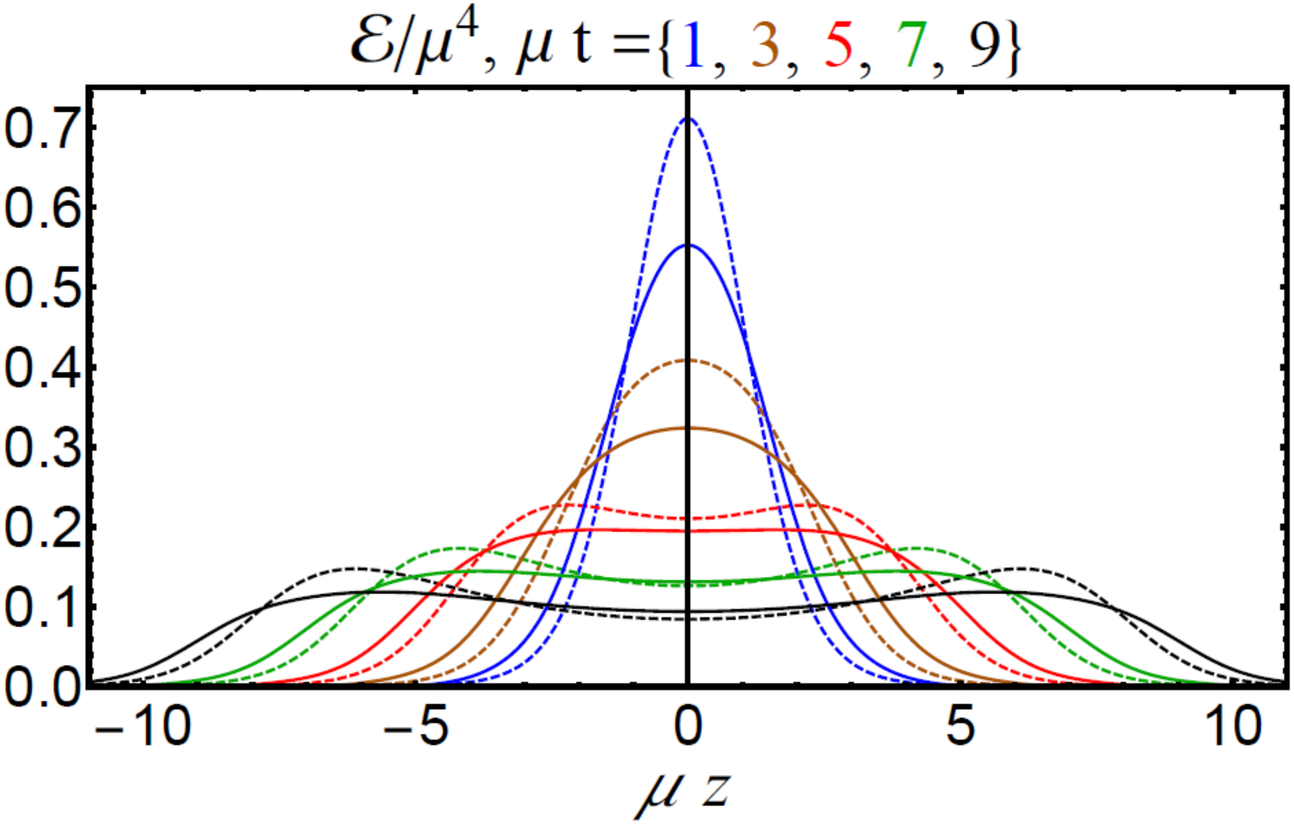
- Event plane correlation very sensitive to viscosity
- Not very suitable for initial stage



H. Niemi, K. Eskolaa and R. Paatelainen, Event-by-event fluctuations in perturbative QCD + saturation + hydro model: pinning down QCD matter shear viscosity in ultrarelativistic heavy-ion collisions (2015)

COLLISIONS AT FINITE COUPLING - WIDE

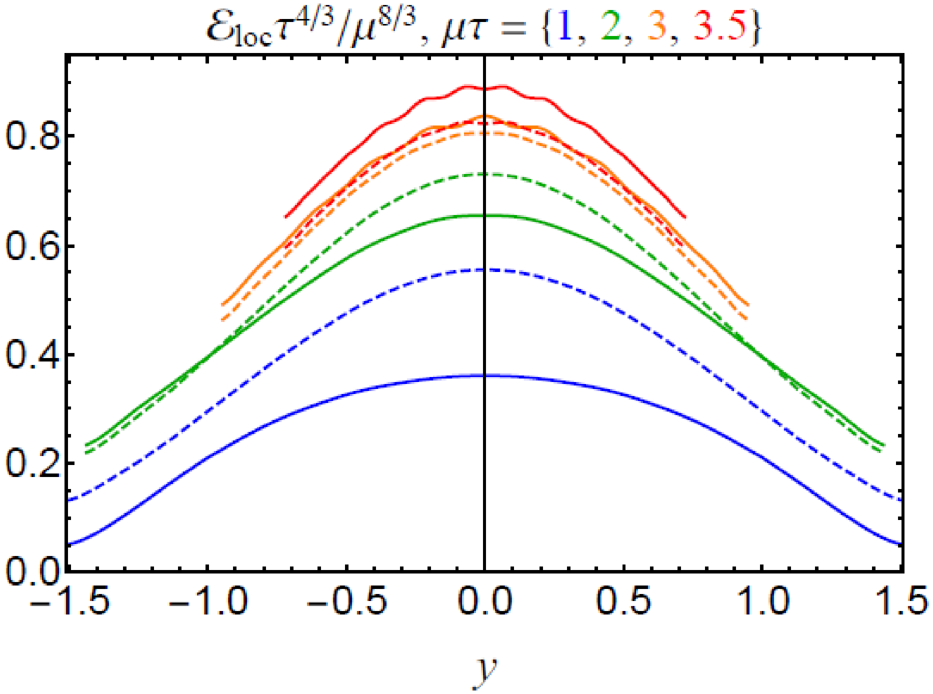
- Results presented for, $\lambda_{GB} = -0.2$ i.e $\eta/s = 1.8/4\pi$
- Initial condition constructed such that energy is the same

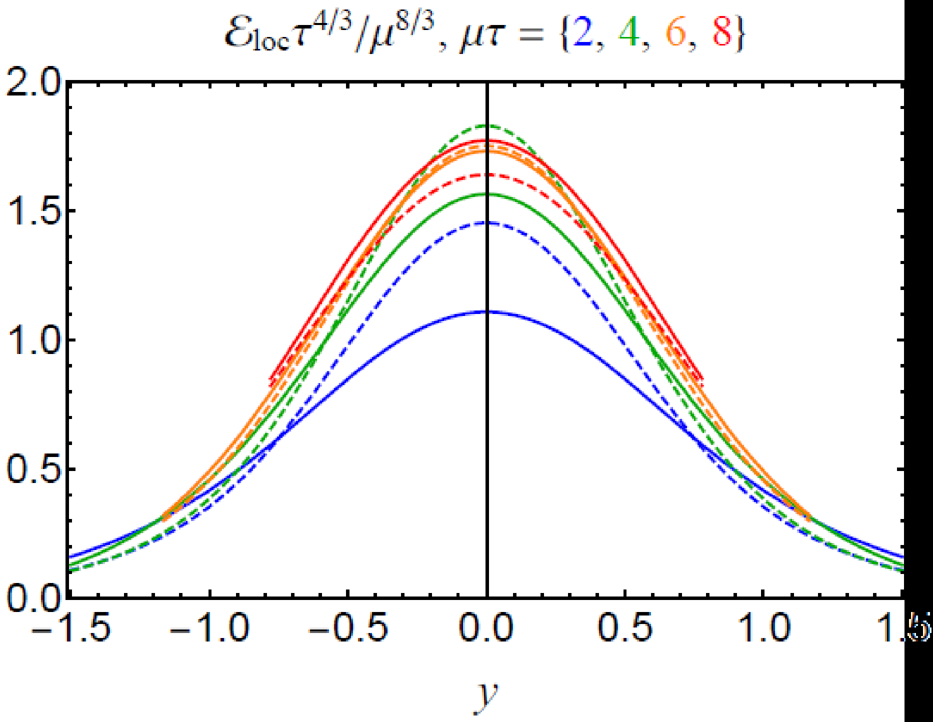


- Energy does not `pile up’, i.e. maximum 217% instead of 271%

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

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. $\eta/s = \frac{1}{4\pi}\left(1 - 4\lambda_{GB}\right)$

Funny thing: evolution is just as simple as original ☺

- Initial condition remains exact solution of EOM (for some L)
- Nested scheme survives completely (with source terms)

Yevgeny Kats and Pavel Petrov, Effect of curvature squared corrections in AdS on the viscosity of the dual gauge theory (2007)