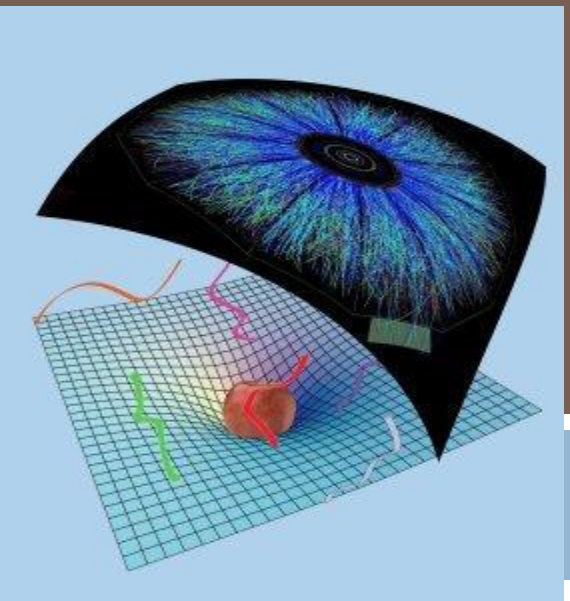
FROM FULL STOPPING TO TRANSPARENCY IN HOLOGRAPHY

Towards more realistic models of the QGP thermalisation

Work with Michał Heller, David Mateos, Jorge Casalderrey, Paul Romatschke and Scott Pratt
References: 1305.4919, 1307.2539



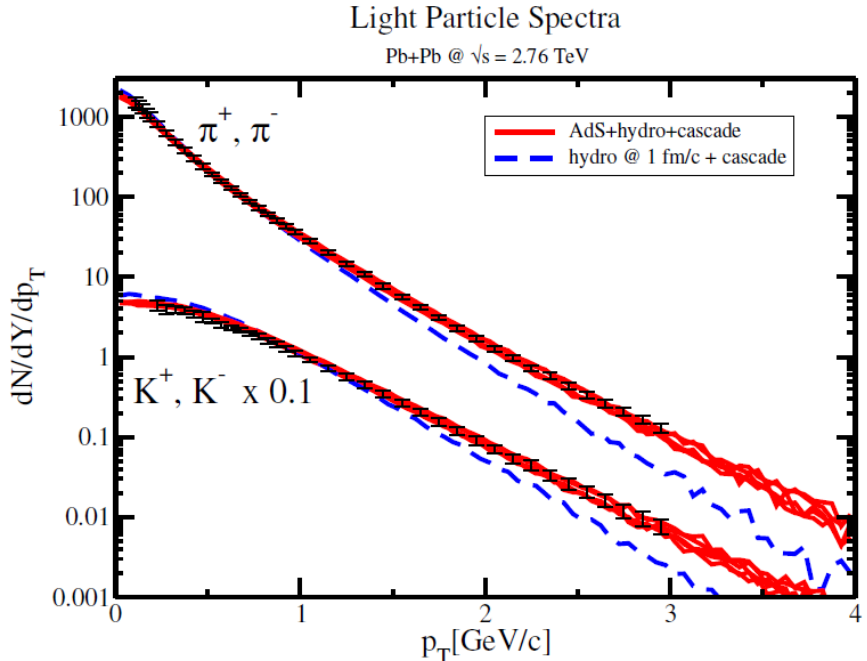
Wilke van der Schee

Supervisors: Gleb Arutyunov,
Thomas Peitzmann and Raimond Snellings

Holography: From Gravity to Quantum Matter, Cambridge, UK
17 September, 2013

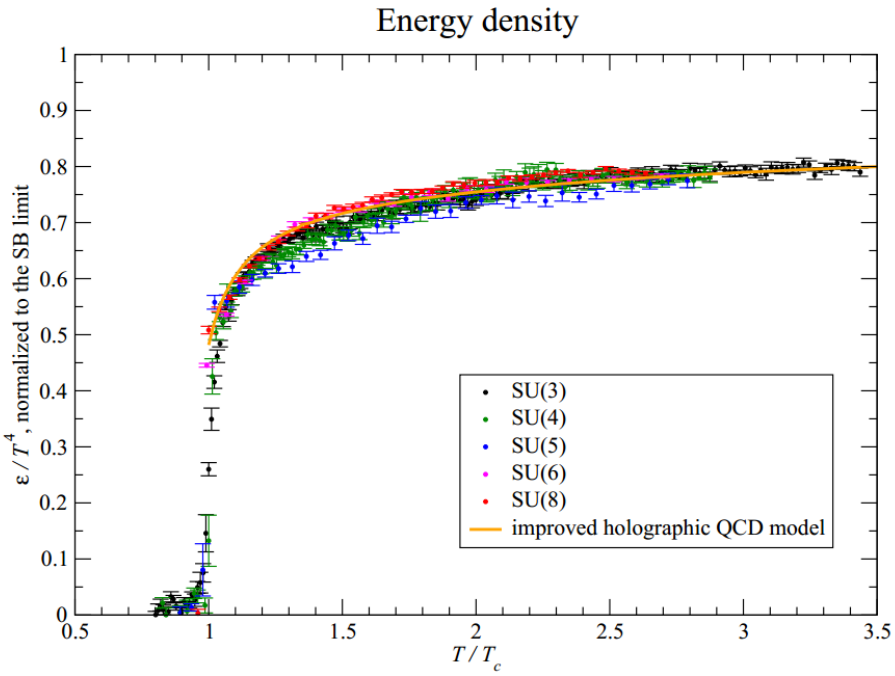
Outline

- Motivation: AdS/CFT
- Gravitational shock waves in AdS
- Towards experiments: boost-invariant radial flow
  - Combination of AdS/CFT+viscous hydro+cascade



Are we cheating with $\mathcal{N}$=4 SYM?

- SU(N): 3 ≈ ∞?
  - Good for thermal
- SUSY?
  - Supressed with temperature
- Quarks?
  - Replaced by (dominant) gluons



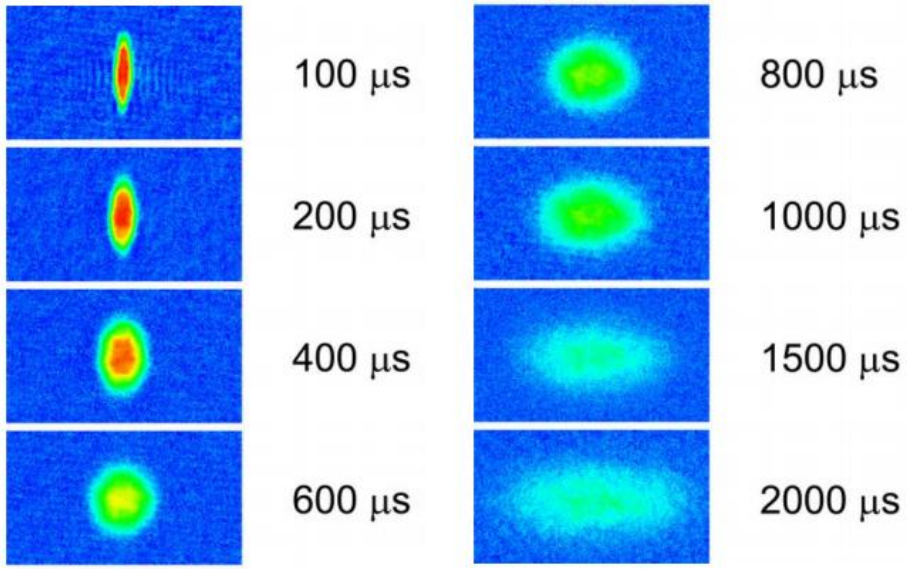
- Infinite coupling strength?
  - But coupling runs only logarithmically…
- So maybe not too bad; and with room for improvement ☺

M. Panero, Thermodynamics of the QCD plasma and the large-N limit (2009)

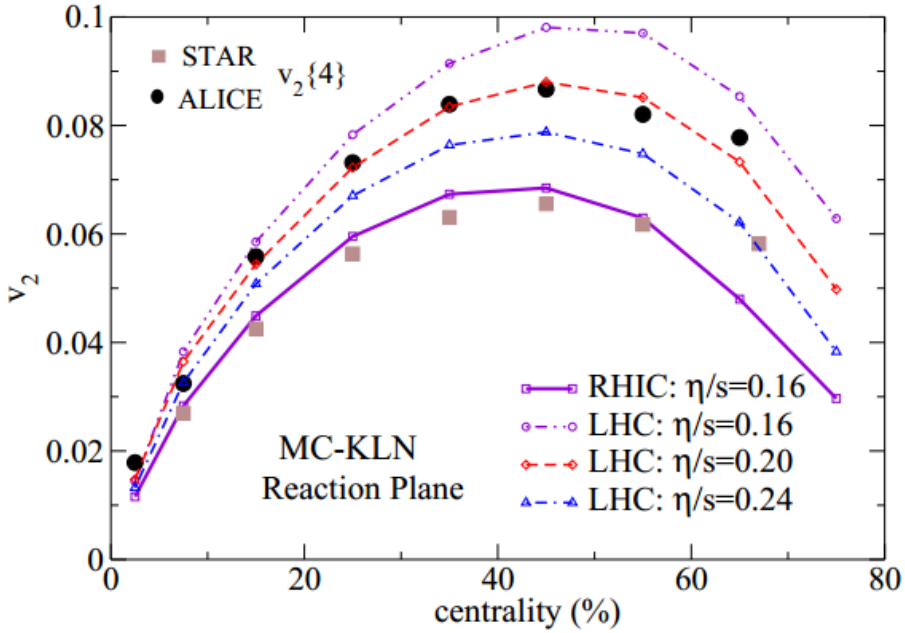
The most perfect liquid?

- Famous viscosity: $\frac{\eta}{s} = \frac{1}{4\pi} \approx 0.08$

Fermions at unitarity



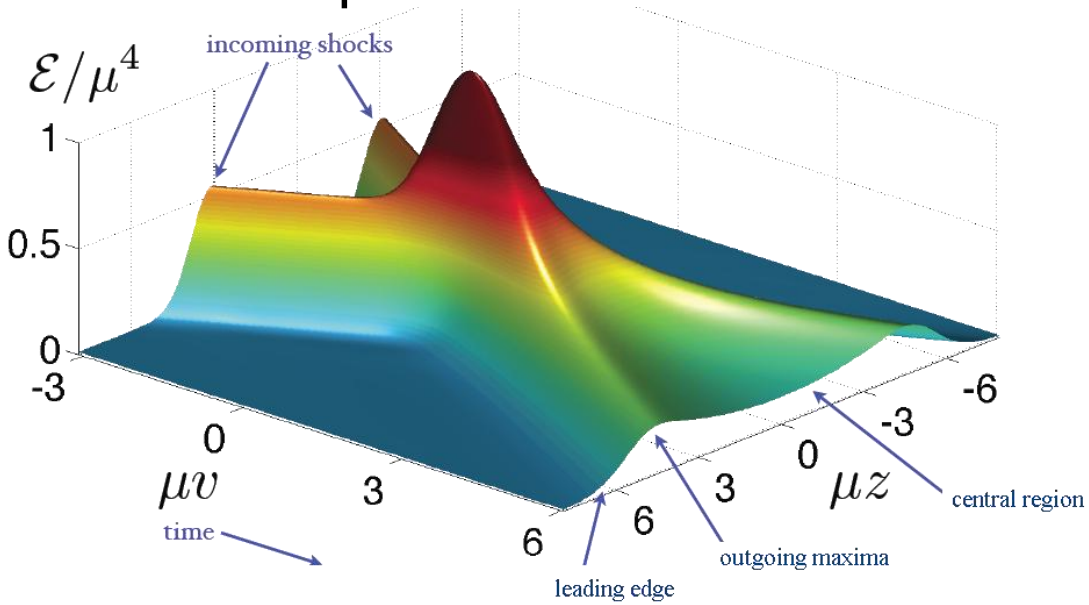
Quark-gluon plasma



K. O'Hara, S. Hemmer, M. Gehm, S. Granade and J. Thomas, Observation of a Strongly-Interacting Degenerate Fermi Gas of Atoms, 2002
U. Heinz, C. Shen and H. Song, The Viscosity of Quark-Gluon Plasma at RHIC and the LHC, 2011

Shock waves – initial conditions

- Famous example:

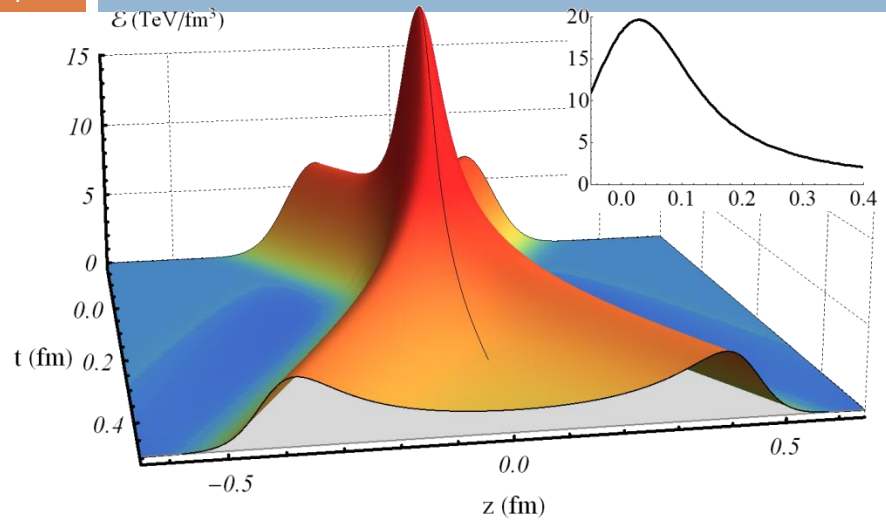


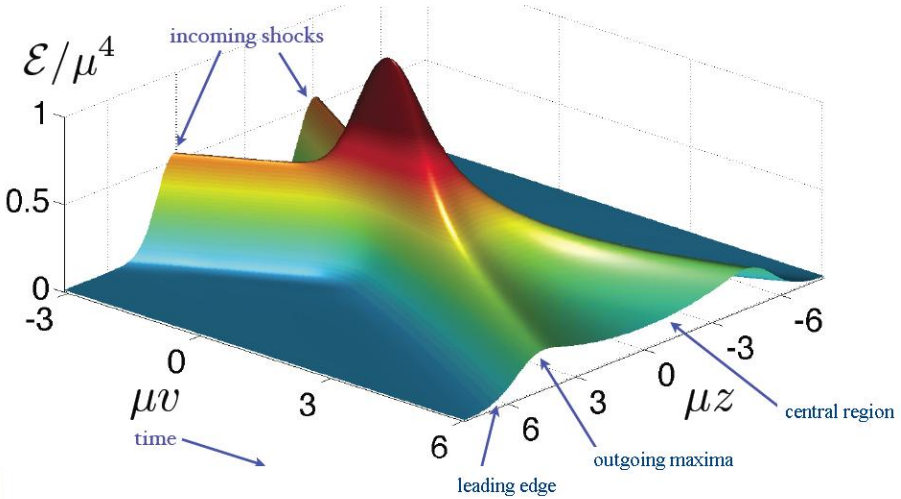
Extra AdS direction

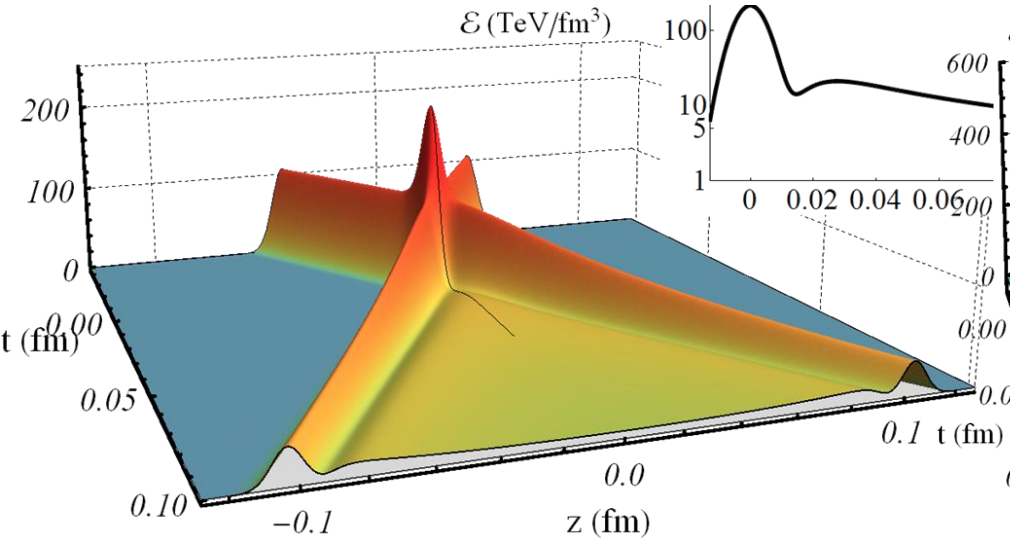
- Homogeneous in transverse plane ('infinite nucleus')
- Energy density moving at speed of light: initial conditions fixed
  - Two scales: width + total energy
- Only gravity: dominant force at high energy

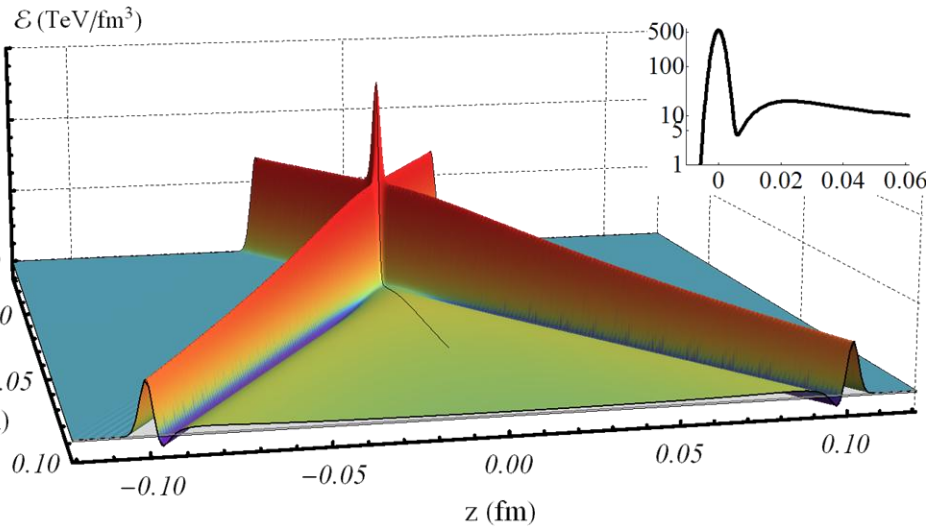
P.M. Chesler and L.G. Yaffe, Holography and colliding gravitational shock waves in asymptotically AdS_5 spacetime (2010)

Shock waves – varying the width



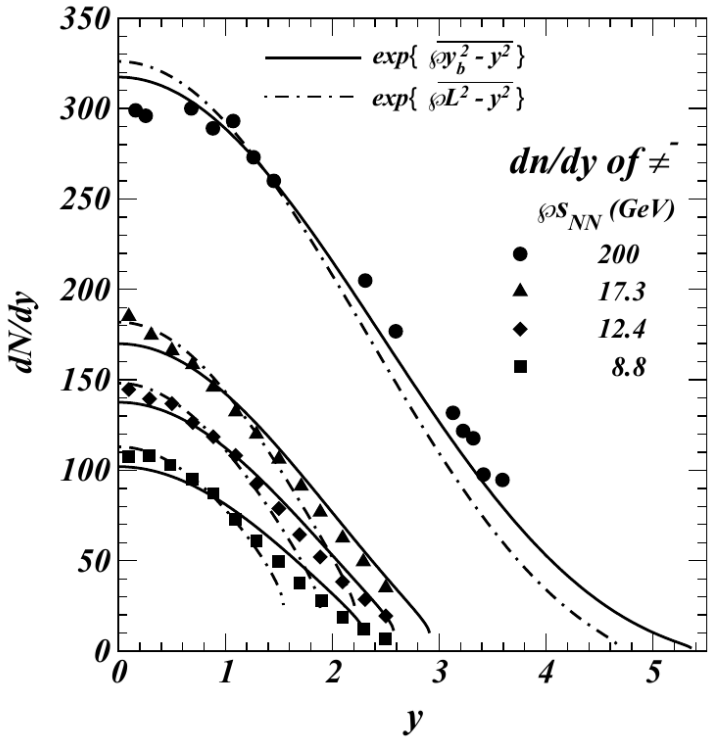


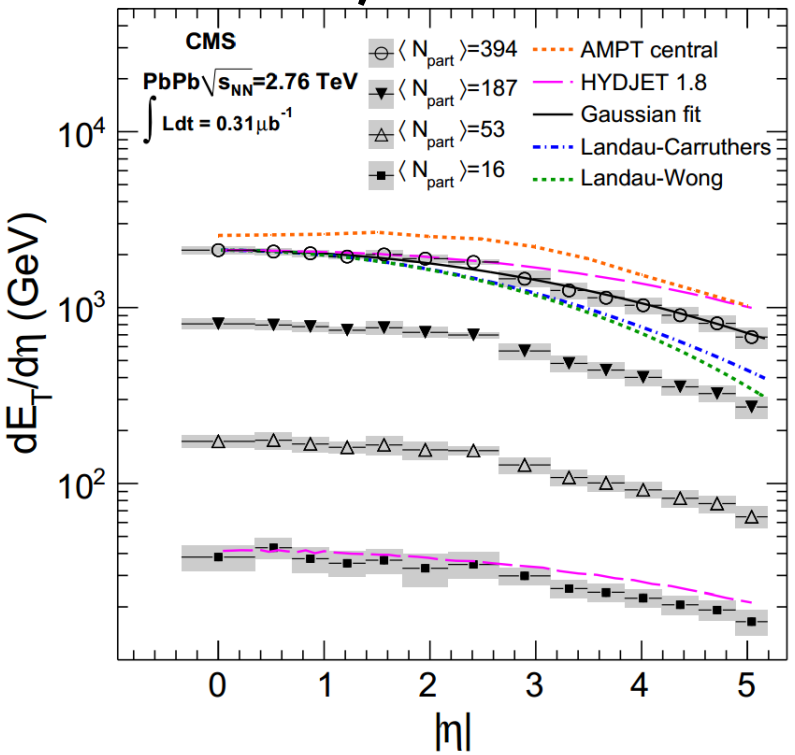




Landau model

- Assume: shocks are thermalised at time of overlap
- Can be approximated analytically
- Fits multiplicity/rapidity well at RHIC, not at LHC

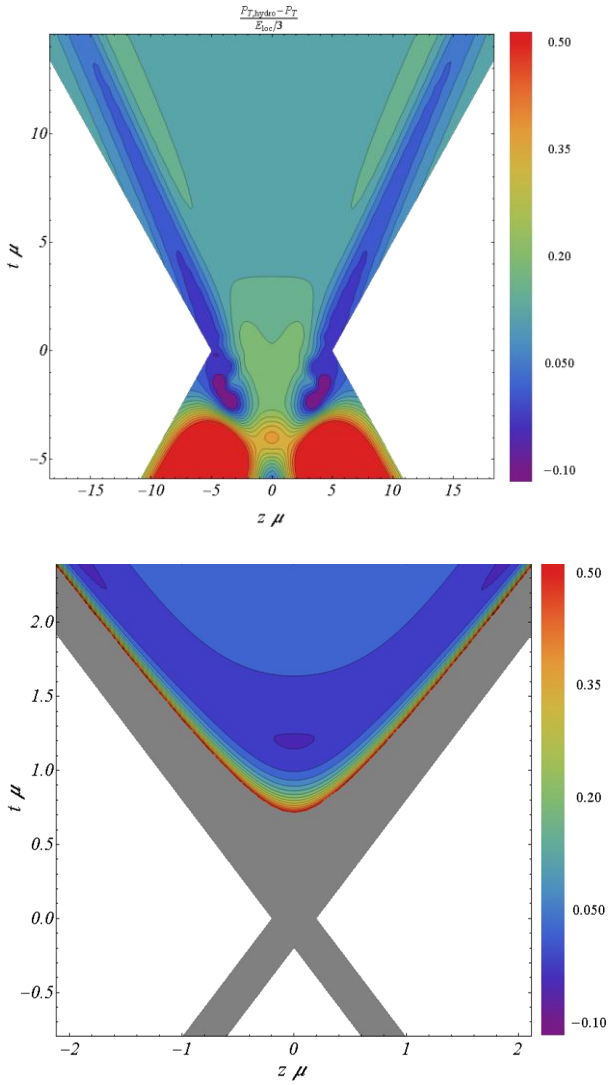




L. D. Landau, Izv. Akad. Nauk Ser. Fiz. 17 (1953)

A dynamical cross-over

- Low energy:
  - Stopping, piling up of energy
  - Expansion by hydro
  - Compressed Landau model
- RHIC energy
  - Landau model
- High energy:
  - no stopping
  - plasma forms slowly
  - negative energy



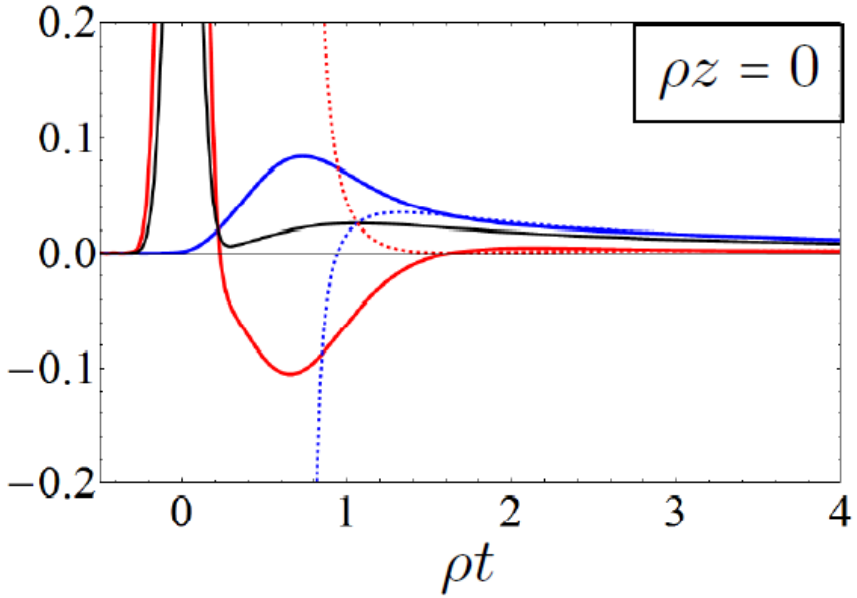
Pressure anisotropy

- Pressure, energy starts at zero, grows

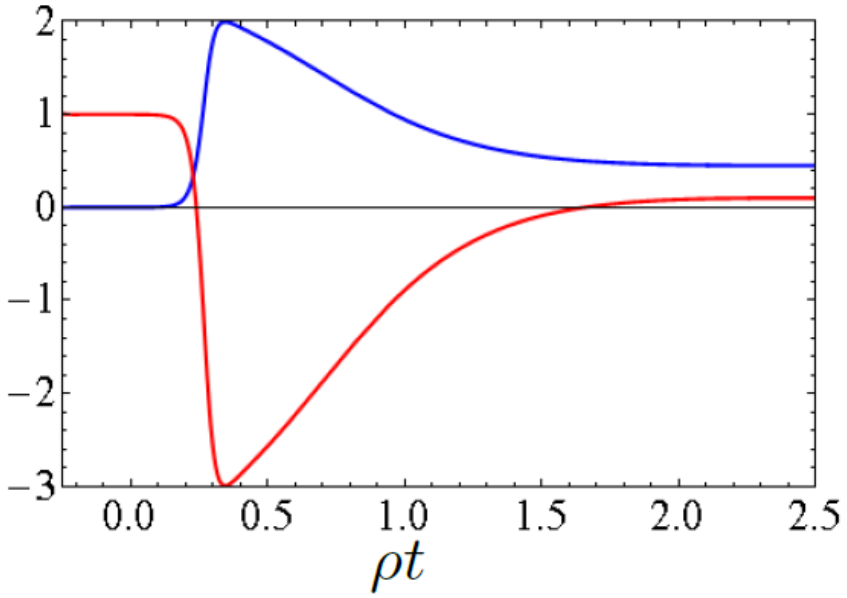
$$T^{\nu}_{\mu} = \mathrm{diag}\{\epsilon(\tau),\, -\epsilon(\tau) - \tau\,\epsilon'(\tau),\, \epsilon(\tau) + \tfrac{1}{2}\tau\,\epsilon'(\tau),\, \epsilon(\tau) + \tfrac{1}{2}\tau\,\epsilon'(\tau)\}$$

- Can give large negative longitudinal pressure:

$\mathcal{E}/3\rho^4$ (black), $\mathcal{P}_L/\rho^4$ (red) and $\mathcal{P}_T/\rho^4$ (blue)



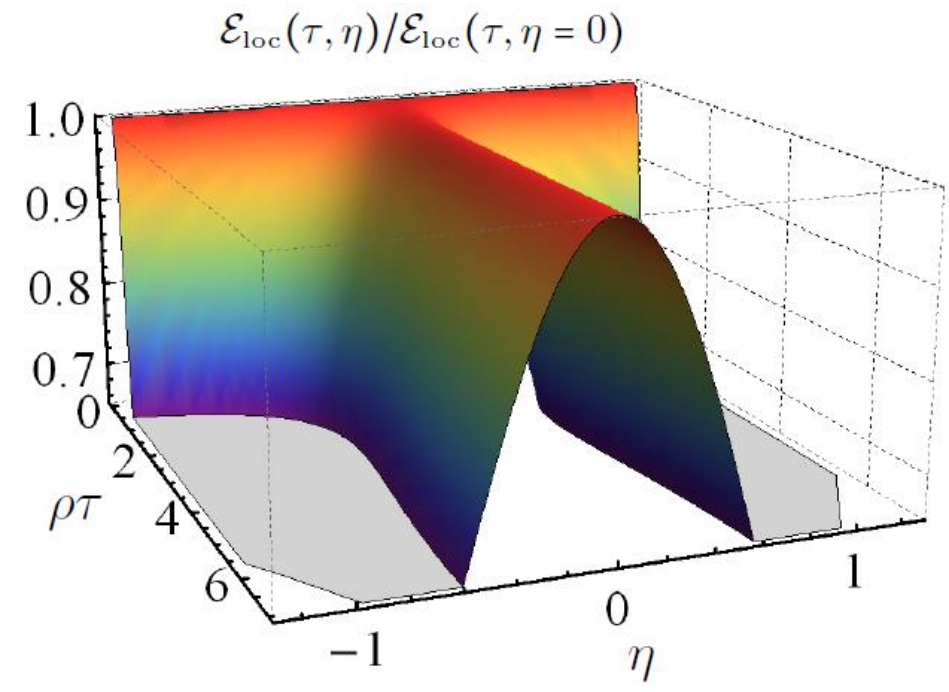
$\mathcal{P}_L/\mathcal{E}$ (red) and $\mathcal{P}_T/\mathcal{E}$ (blue)



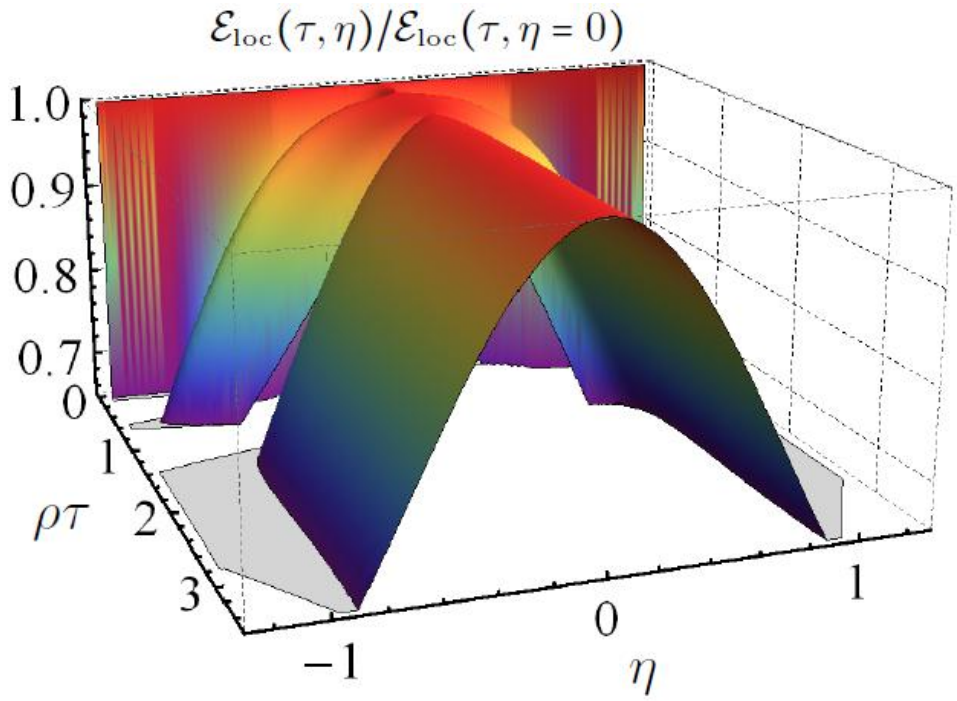
Shock waves – boost-invariance

- No boost-invariance
  - Profile approx gaussian with slightly increasing width

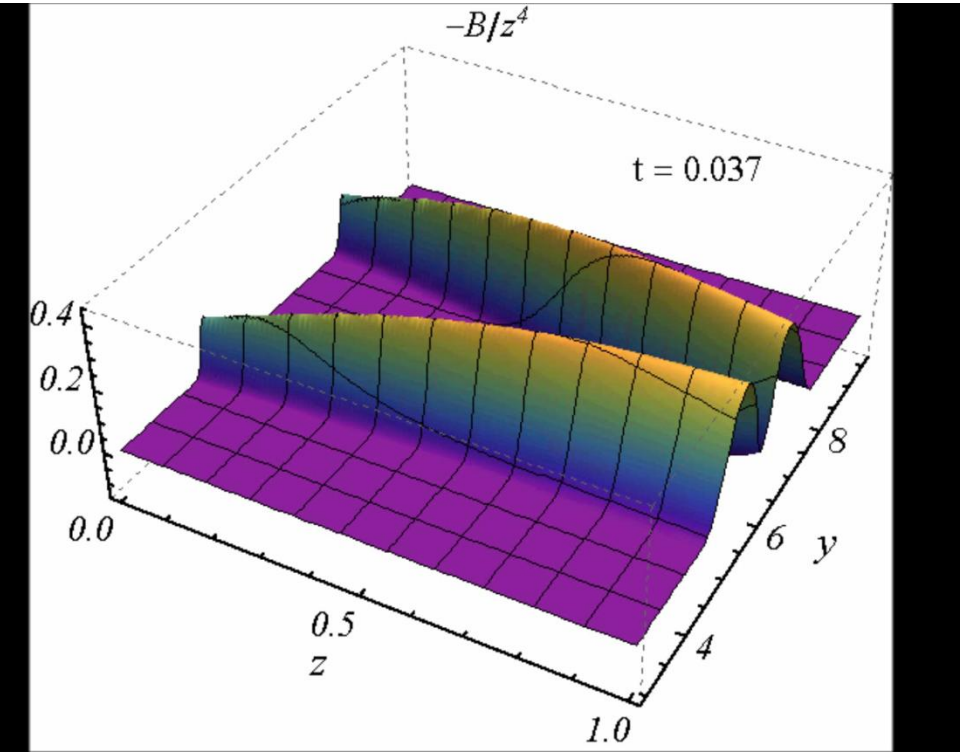
Low energy:

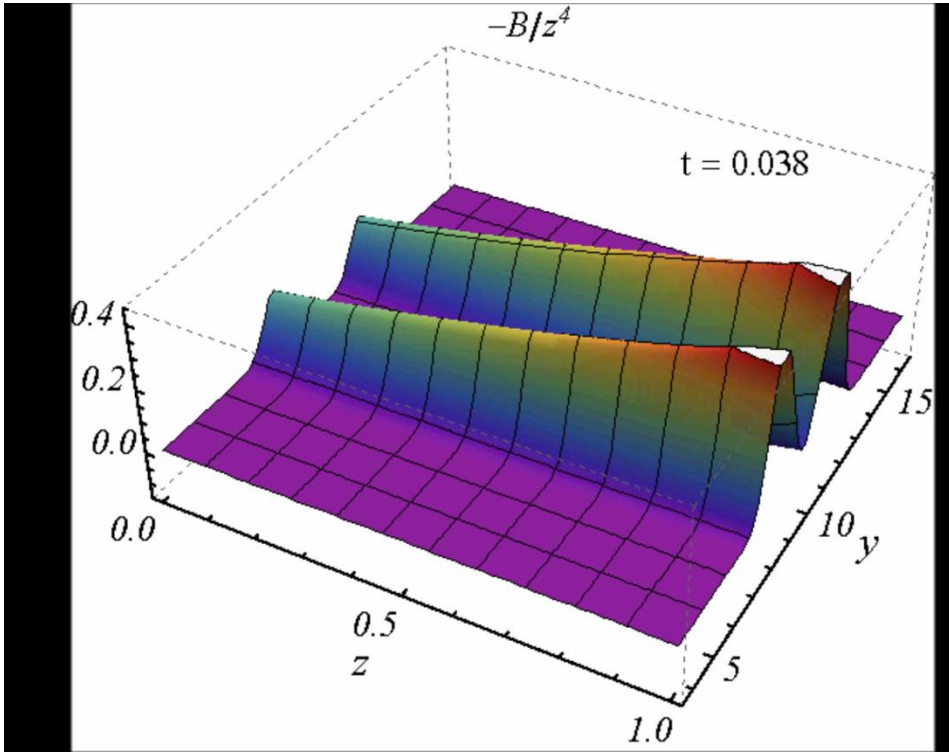


High energy:



Dynamics in AdS – in movies

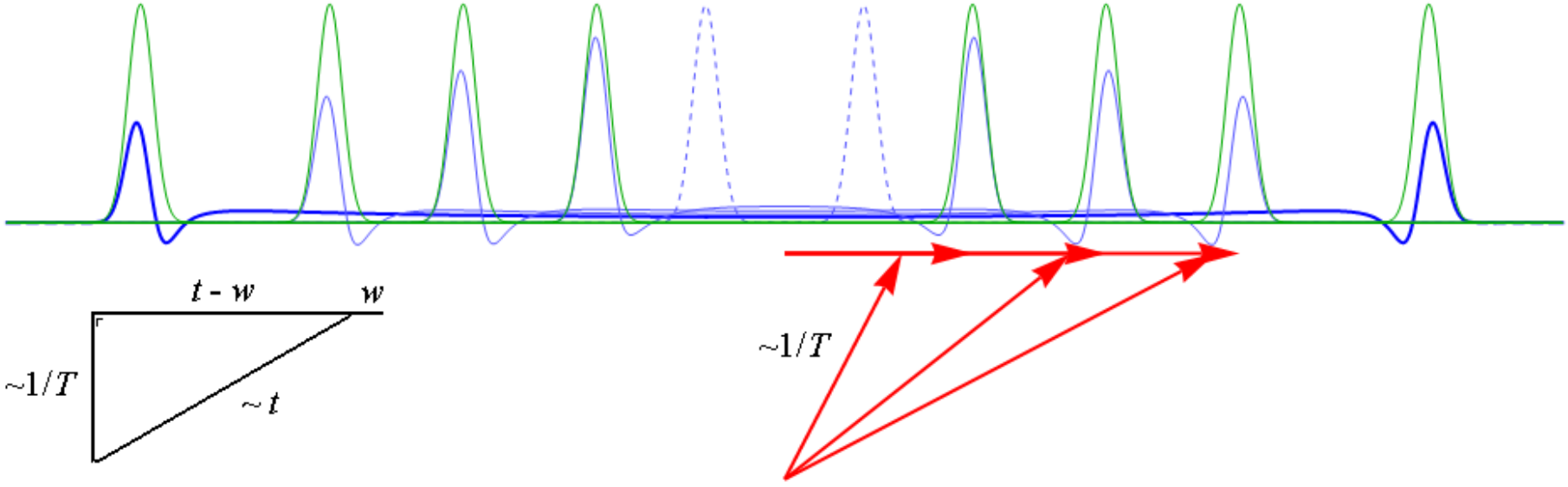




- Intuition: compare scales 1/Temperature and width
  - Perhaps pancake at RHIC is not so thin?

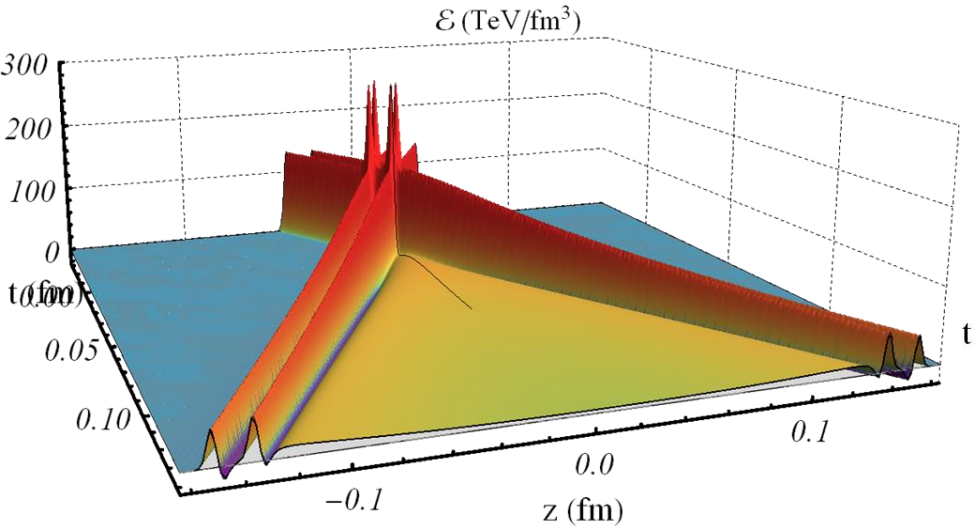
Shock waves from the bulk

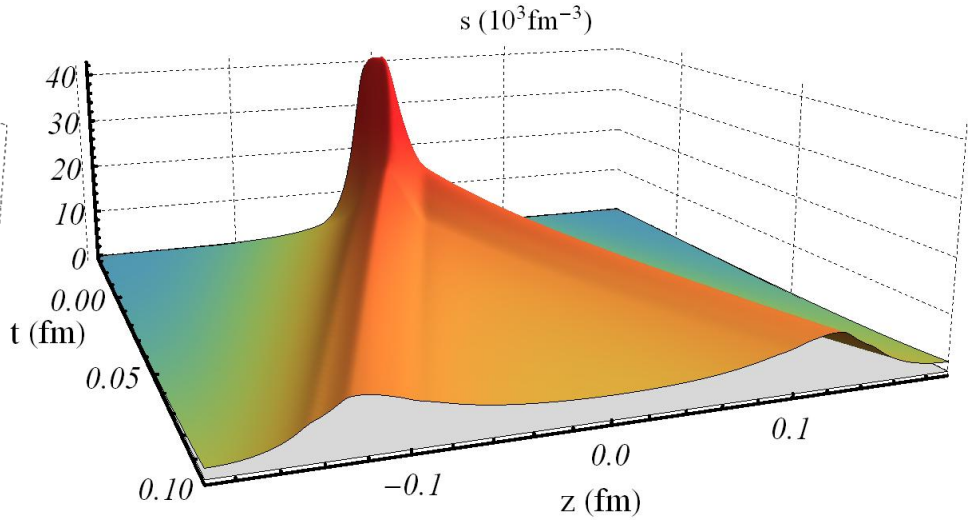
- Interesting interplay between temperature & width:
  - Non-linearity roughly comes from horizon
  - Touches front-end latest: by causality!



Newer results

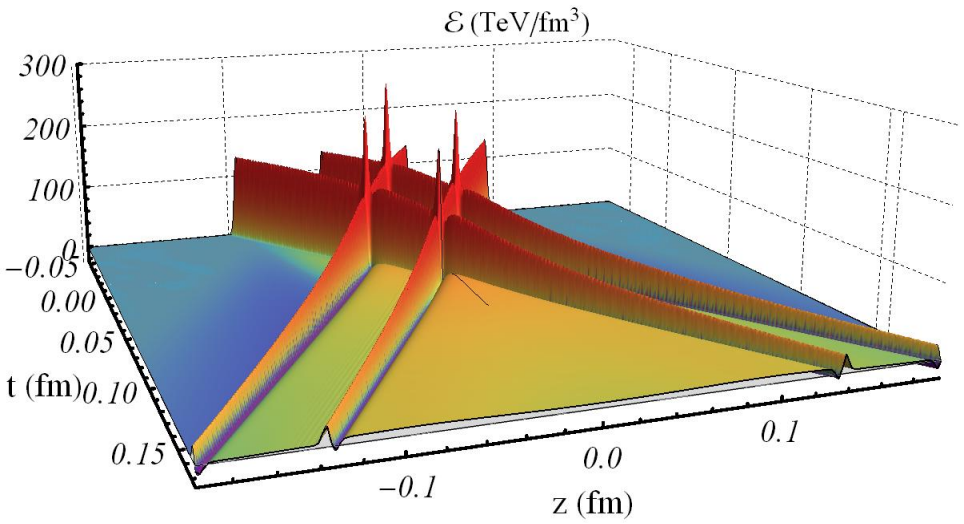
- UV structure is washed out in IR
  - Compare energy density with area apparent horizon

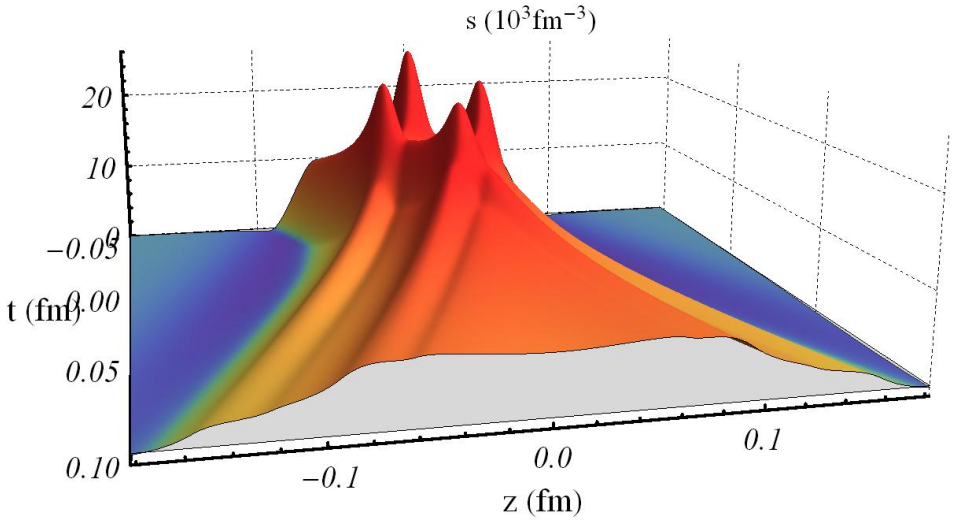




Newer results

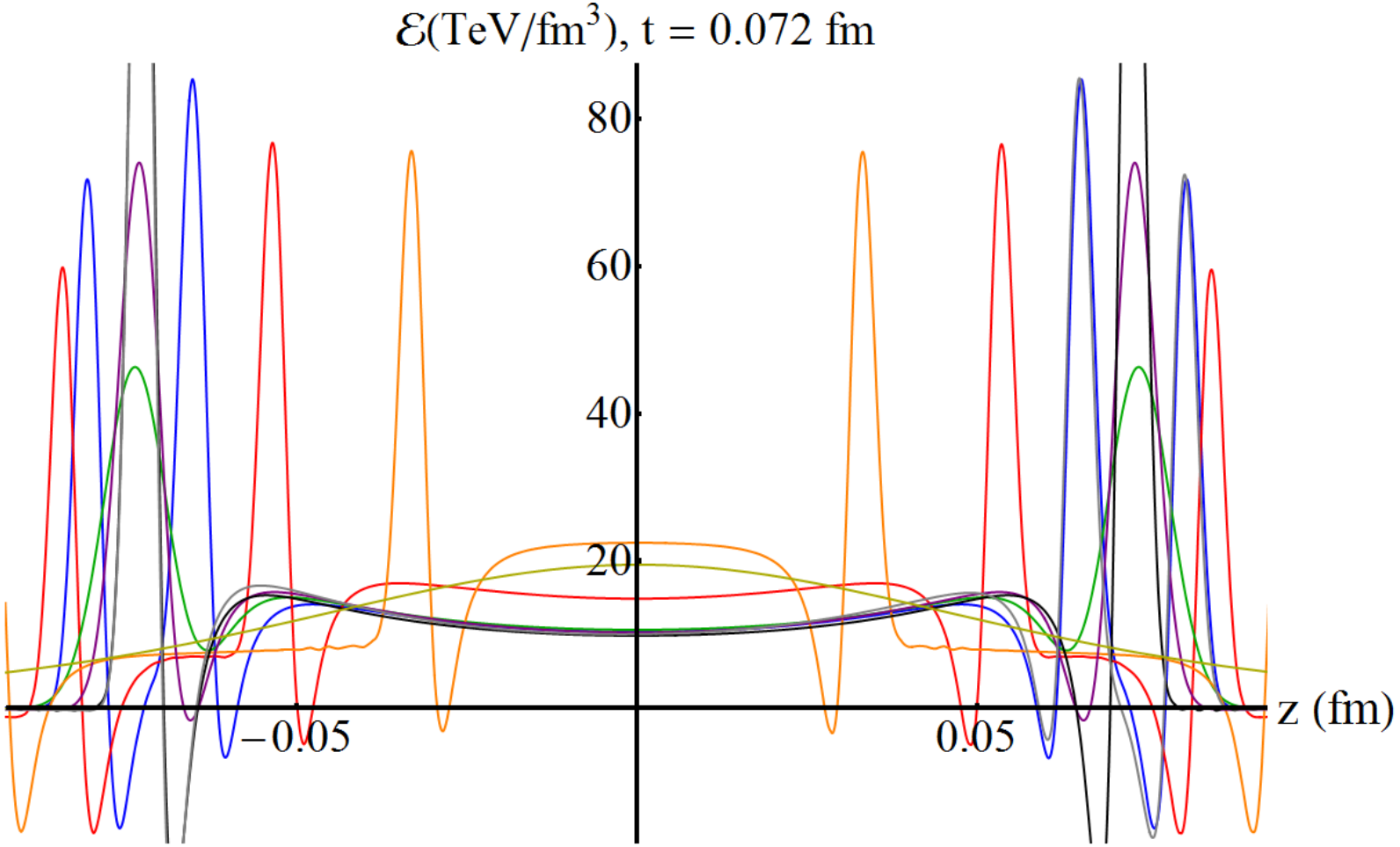
- UV structure is washed out in IR
  - Compare scale with 1/Temperature:



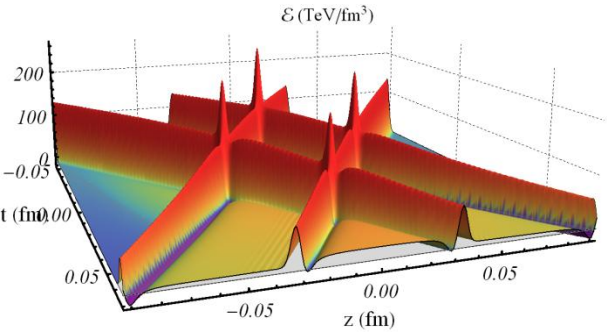


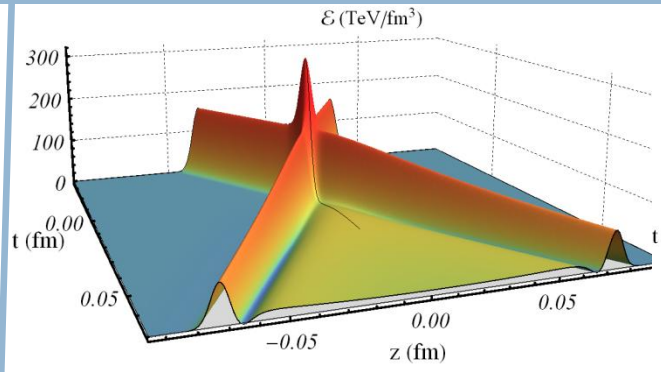
Newer results – a prediction for p-Pb

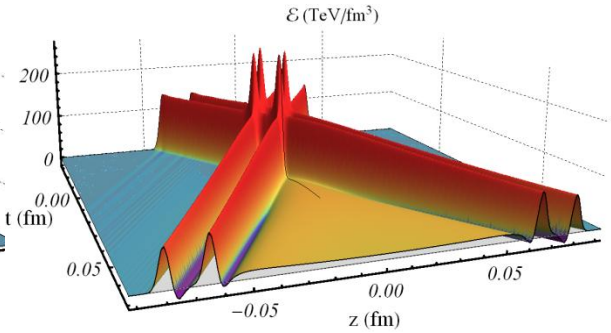
- Comparable c.o.m. late time results for narrow shocks:

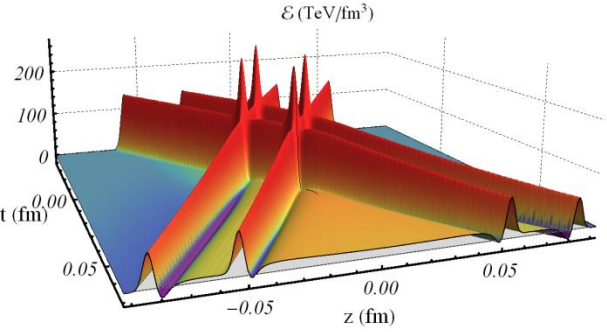


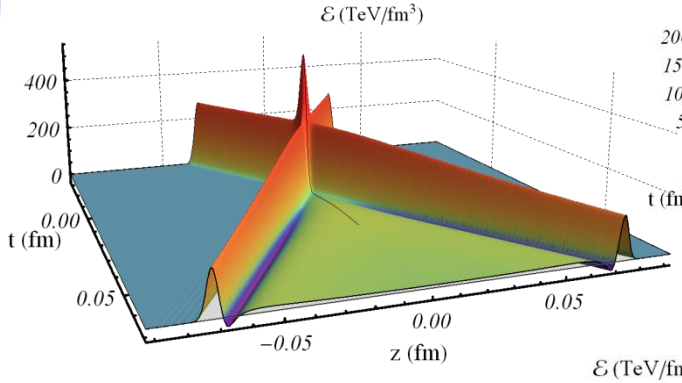
Shocks included in previous plot

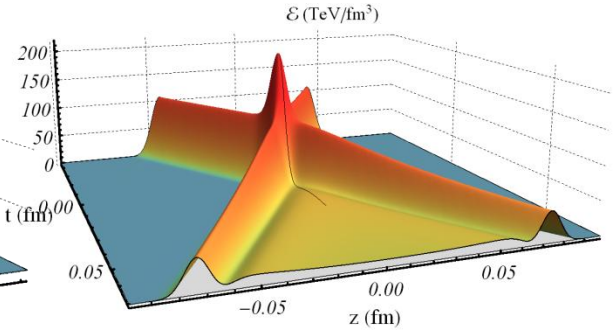


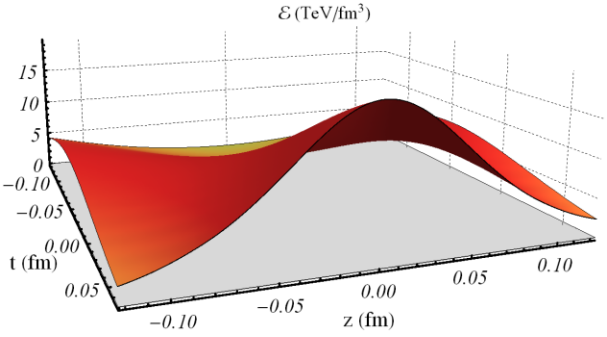


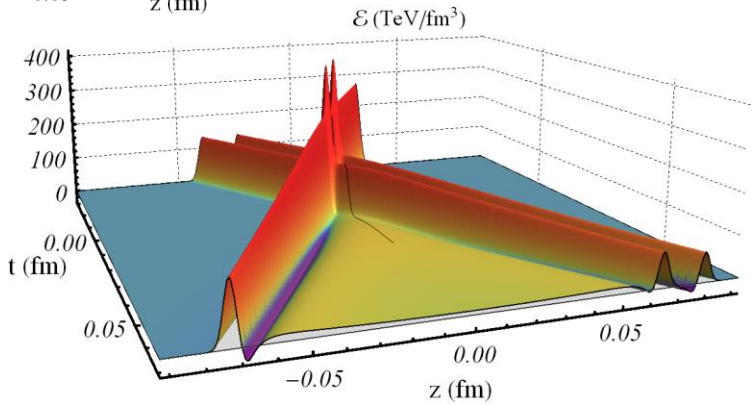










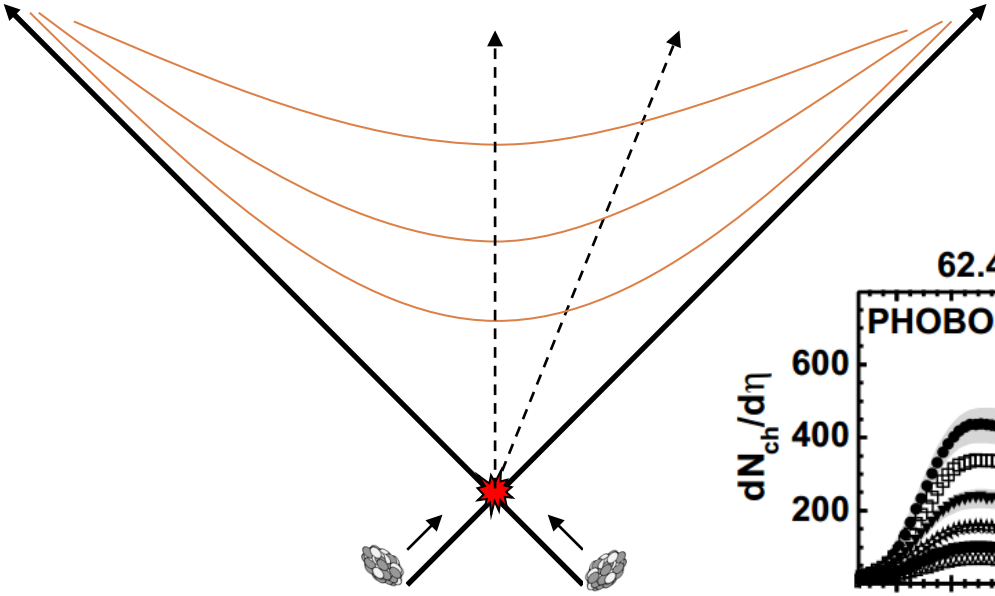


Boost-invariant radial flow

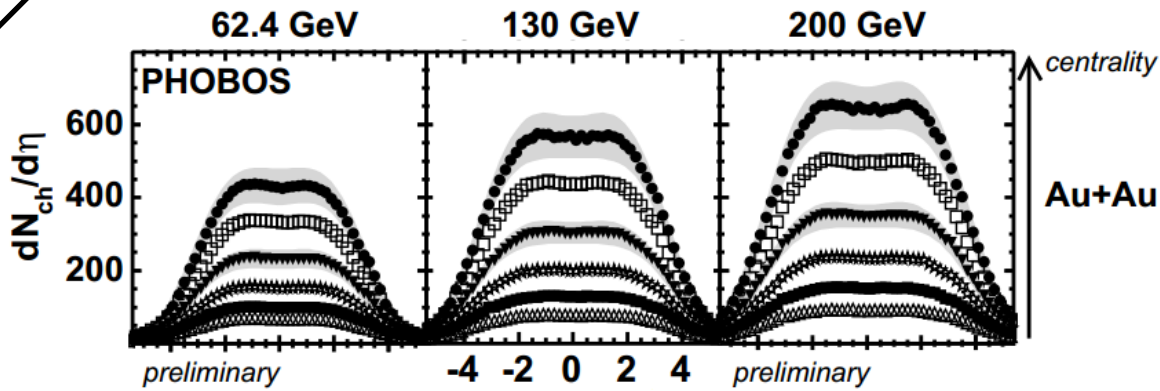
Work with Paul Romatschke and Scott Pratt

Wilke van der Schee, Utrecht

- simple 'realistic' model of expanding plasma:



$$t = \tau \cosh \eta \text{ and } y = \tau \sinh \eta$$



- Real collisions probably not boost-invariant
  - Perhaps good model at mid-rapidity? (perhaps not!)

R.P. Feynman, Very High-Energy Collisions of Hadrons (1969)
J.D. Bjorken, Highly relativistic nucleus-nucleus collisions: the central rapidity region (1983)
PHOBOS collaboration, New results from the PHOBOS experiment (2005)

A fully dynamical model of a HIC

Work with Paul Romatschke and Scott Pratt

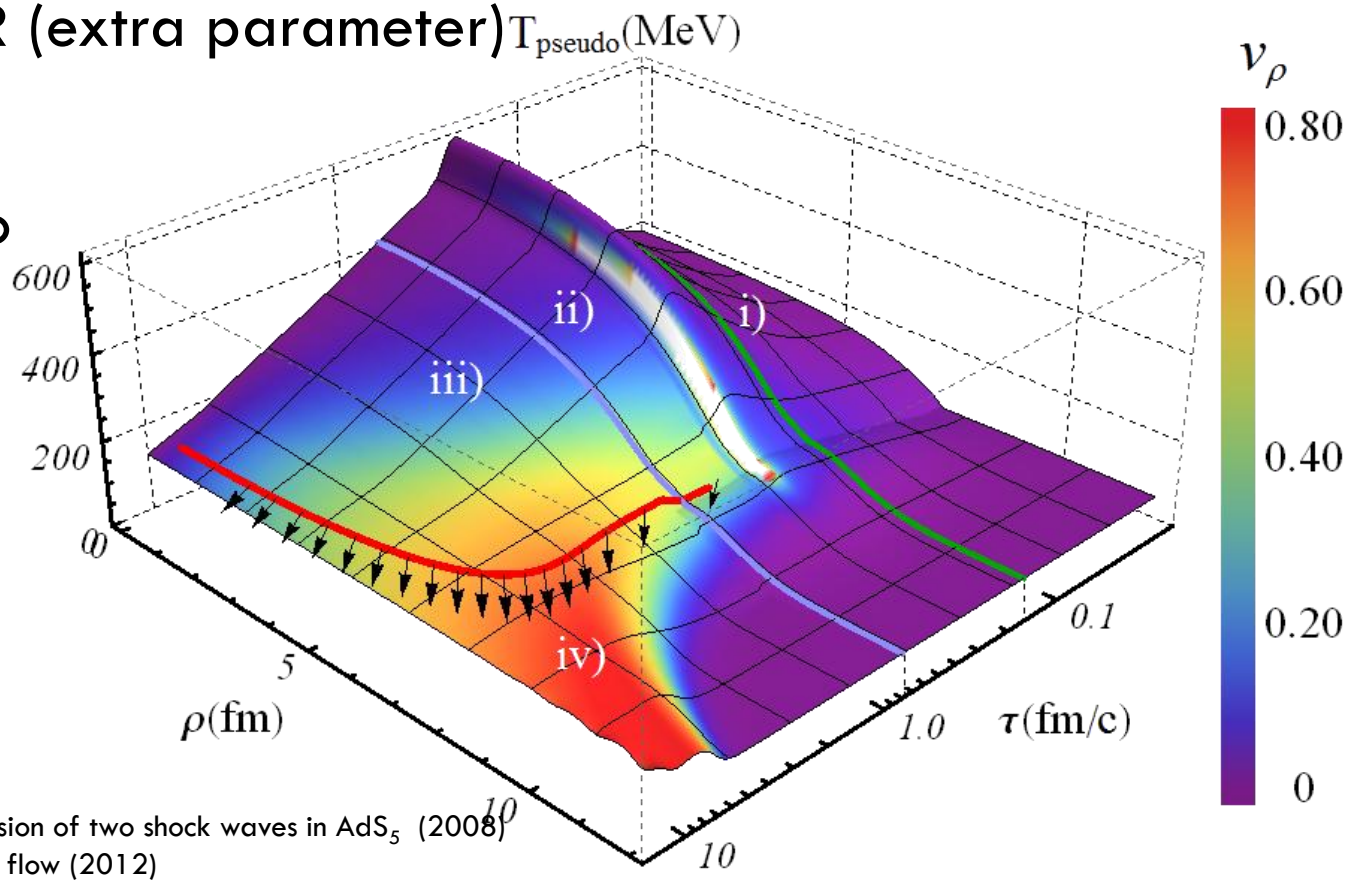
Wilke van der Schee, Utrecht

i) Small time expansion of colliding shocks (central)

ii) Numerical GR (extra parameter)

iii) Viscous hydro

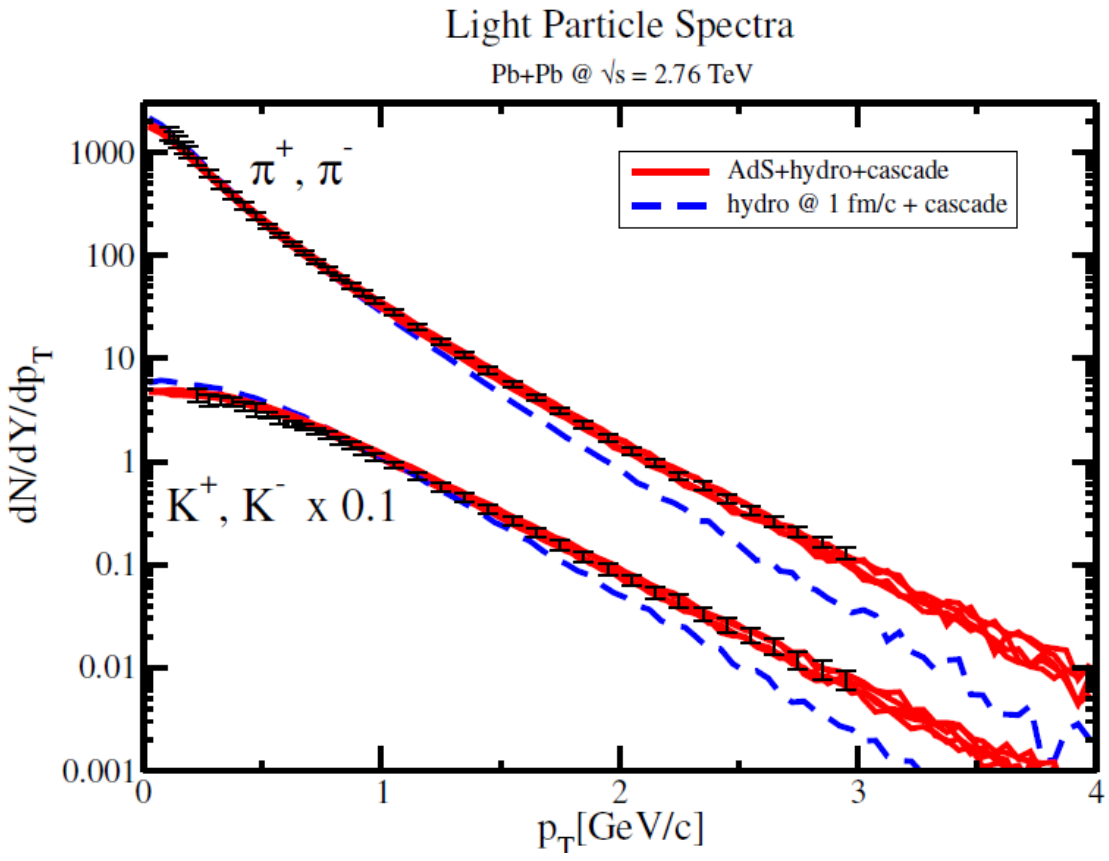
iv) Hadronic cascade



P. Romatschke and D. Grumiller, On the collision of two shock waves in AdS_5 (2008)
WS, Holographic thermalization with radial flow (2012)

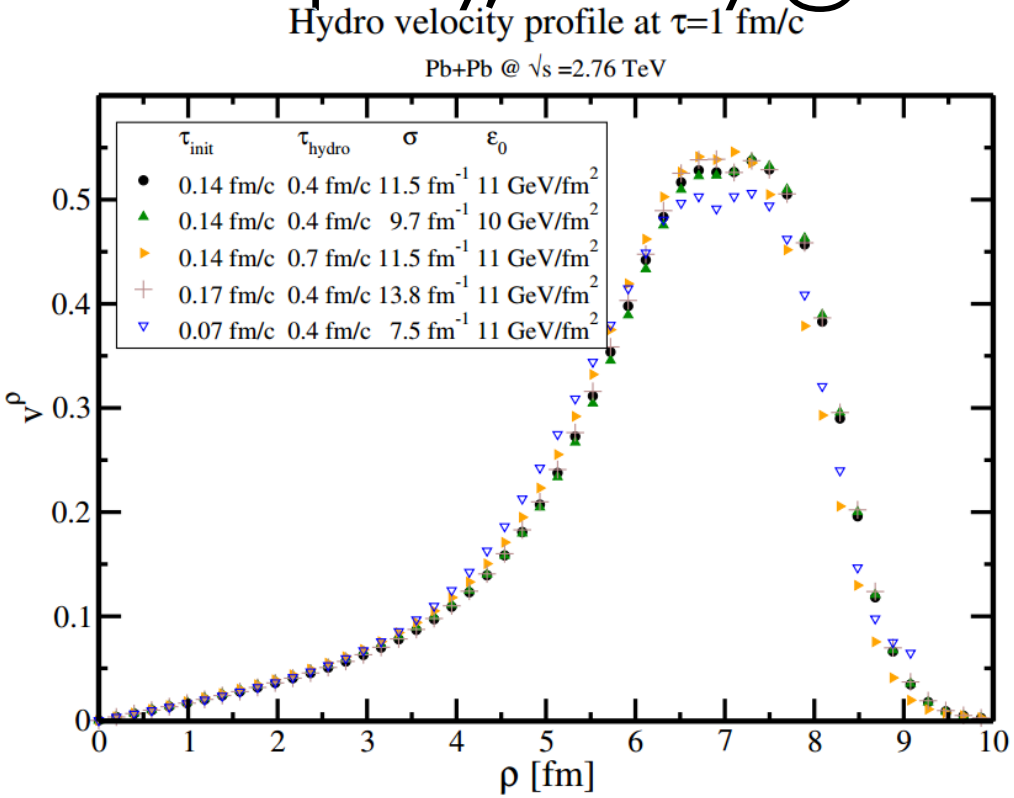
Radial flow – initial conditions

- Spectra ☺



Results – approach to hydro

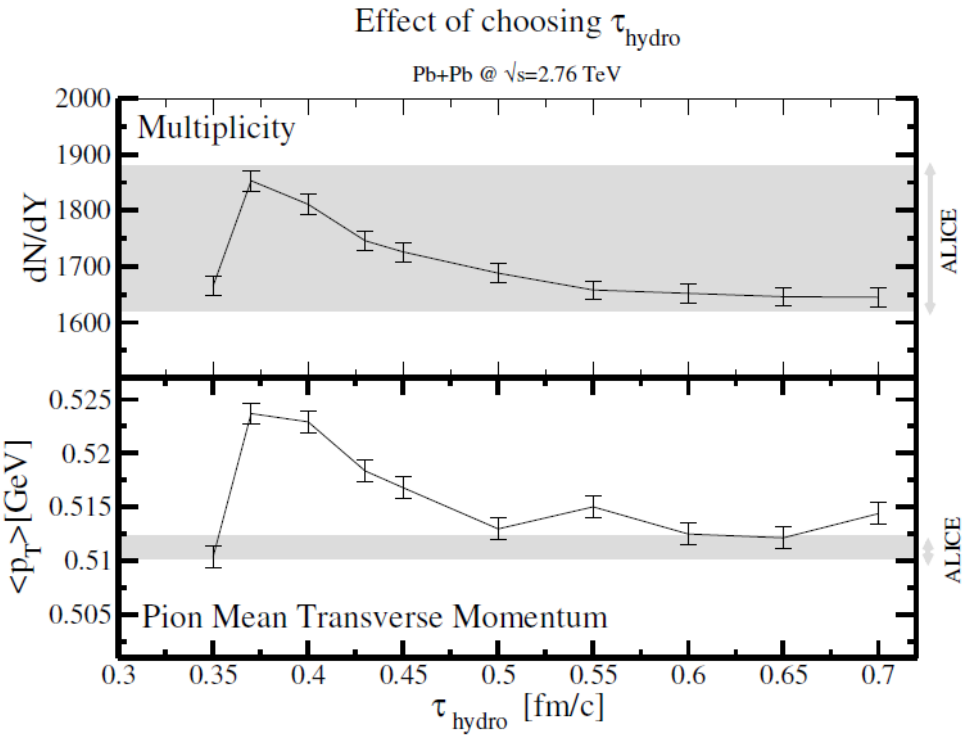
- Fixing total multiplicity, velocity @ 1 fm/c:



- Velocity profile approx universal; little depedence on initial AdS time, extra AdS parameter

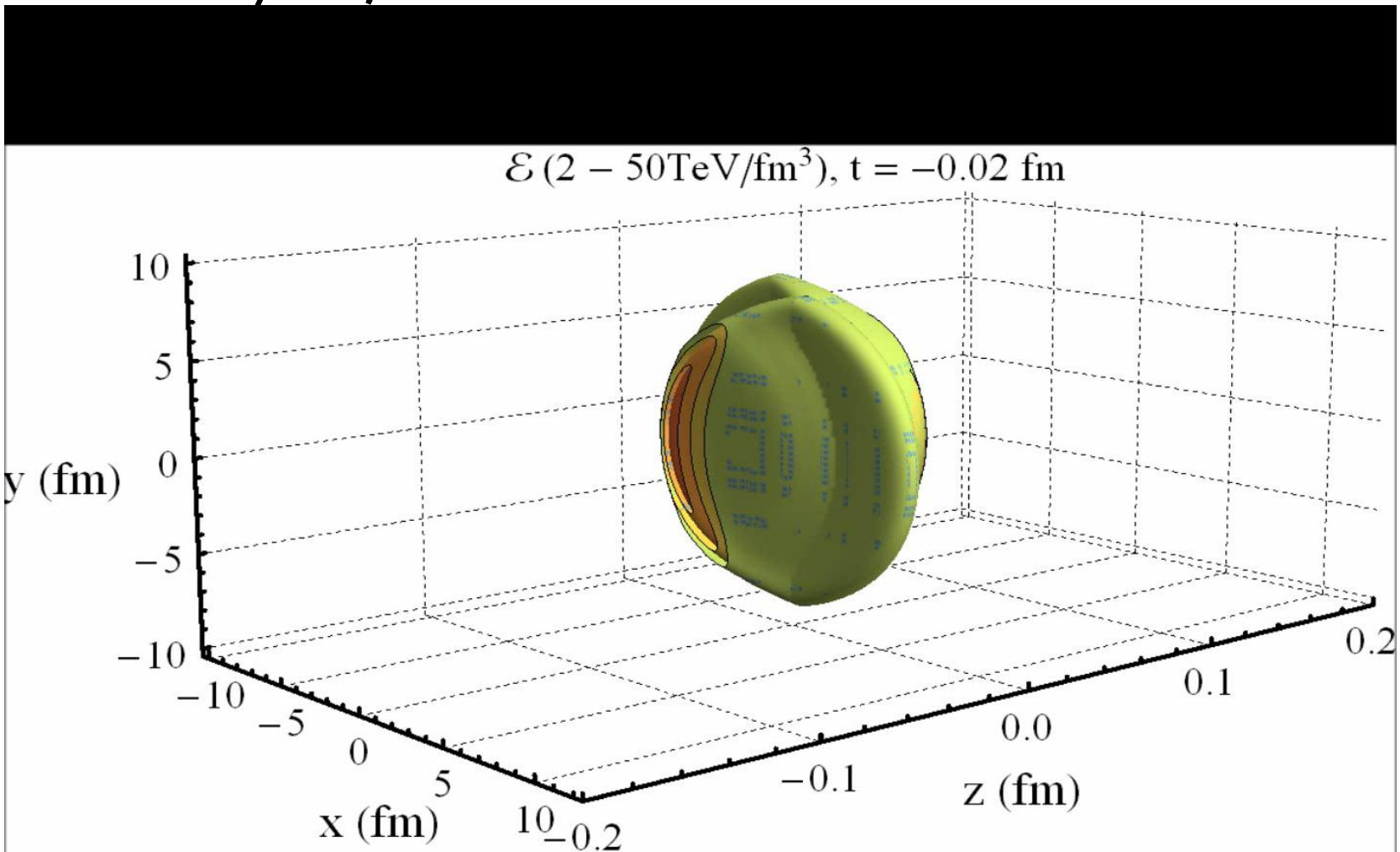
Results – approach to hydro

- Not too early: far-from-equilibrium
  - Rest frame does not even exist!
- Not too late: AdS = conformal ≠ QCD
  - In practice: 15% discontinuity in pressure



Prospects: a combination

- Need hydro, freeze-out etc..



Discussion

Speculative

- Disclaimer
  - Modeling at infinite N and infinite coupling, at all scales
  - Colliding 'blobs of plasma' = nuclei?
- Shock waves: Strong coupling ≠ full stopping
  - Working hypothesis: shocks provide good model for HIC
- Lessons towards experiments
  - Pre-flow can be produced dynamically
  - Perhaps much higher temperatures (1.8 TeV/fm^3 @ t=0.25 fm?)
  - Perhaps much faster thermalisation (1/T~0.05 fm)
  - Energy density grows initially?
  - p-Pb should be symmetric in c.o.m. frame
- Curious: shocks give Landau model precisely at RHIC!

Fancy plots: microstructure, p-Pb, longer runs