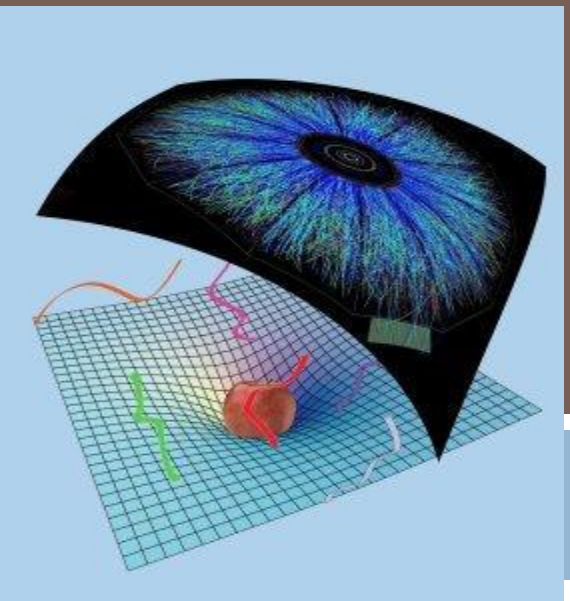
COLLISIONS IN ADS AND THE THERMALISATION OF HEAVY IONS

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



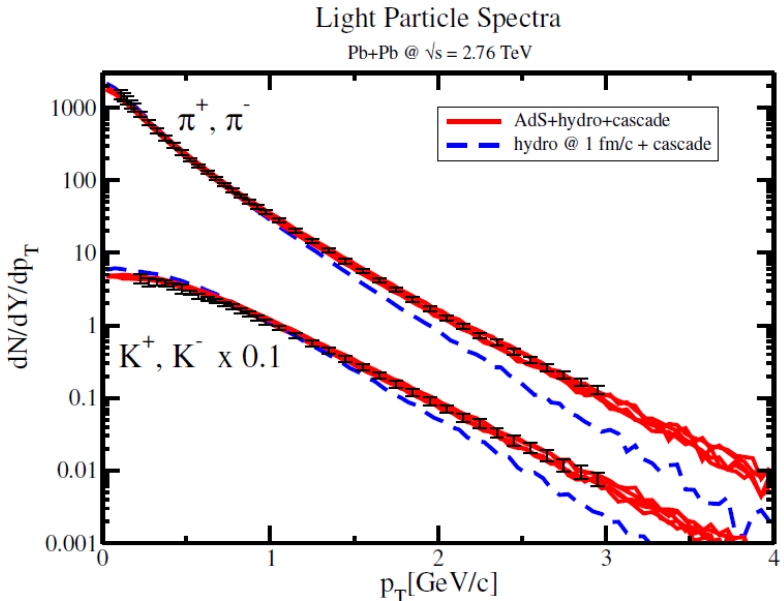
Wilke van der Schee

Supervisors: Gleb Arutyunov,
Thomas Peitzmann and Raimond Snellings

Holographic QCD – progress and challenges, IPMU Tokyo
26September, 2013

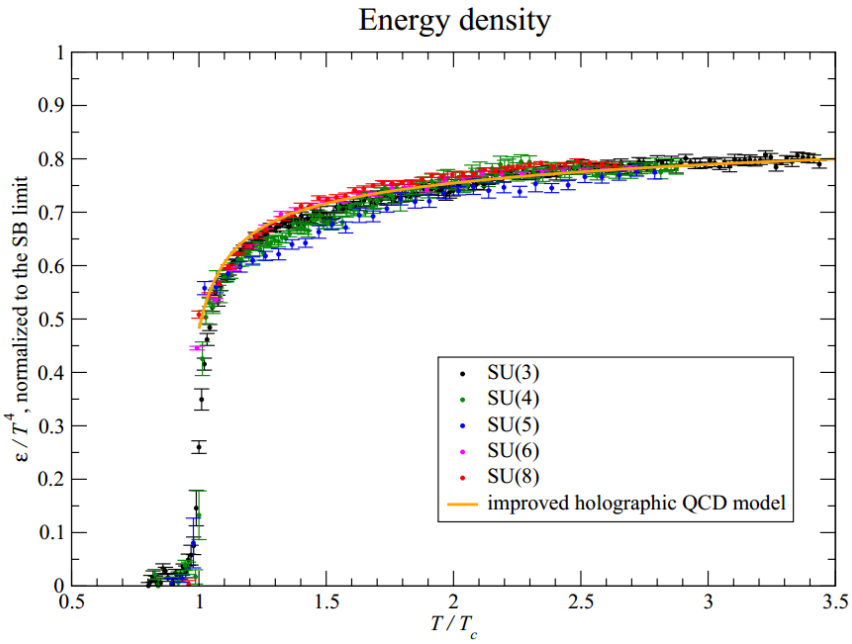
Outline

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



Are we perhaps not cheating with $\mathcal{N}=4$ SYM?

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

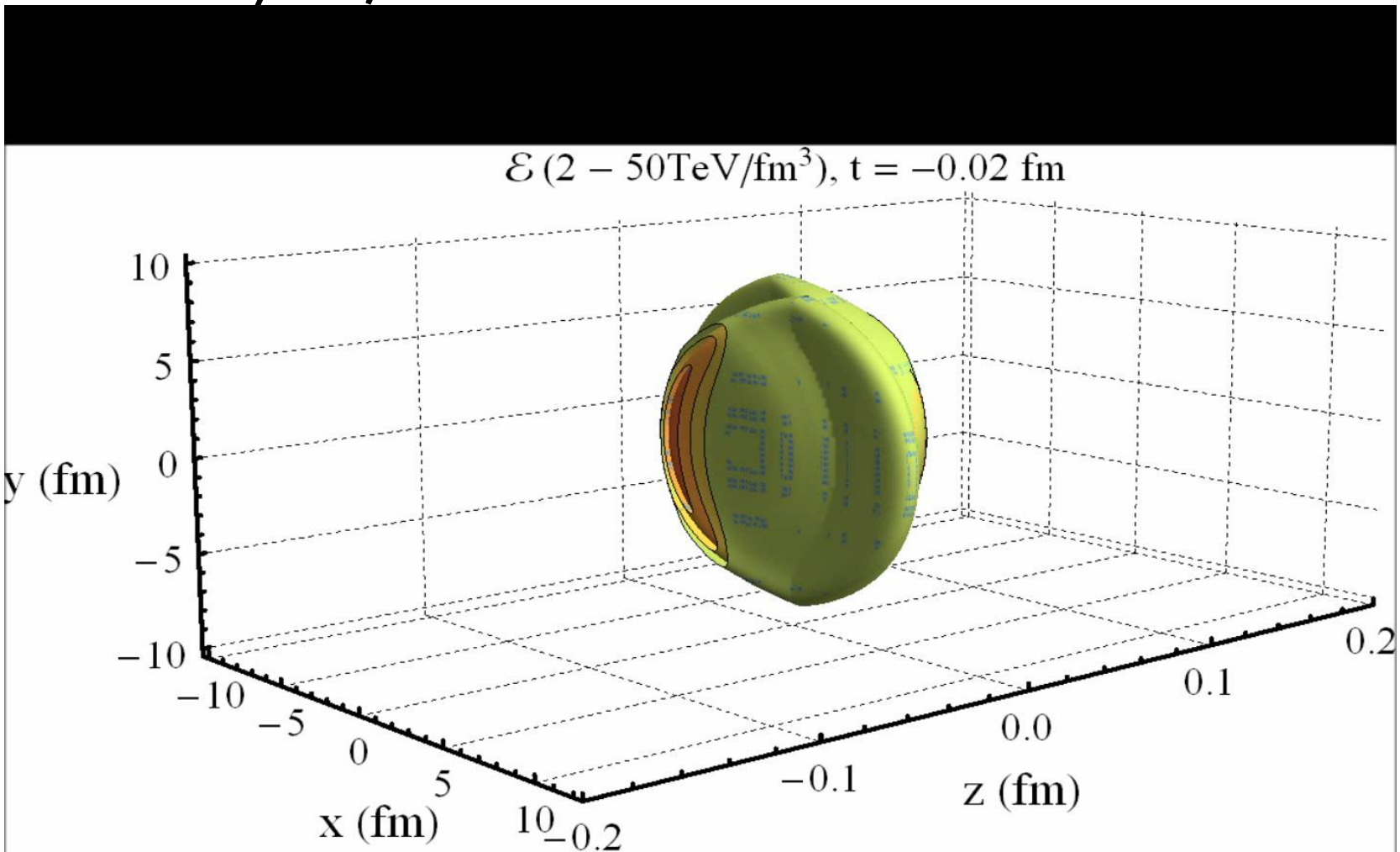


- Infinite coupling strength?
  - But coupling runs only logarithmically…
- So maybe not too bad; and with room for improvement ☺

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

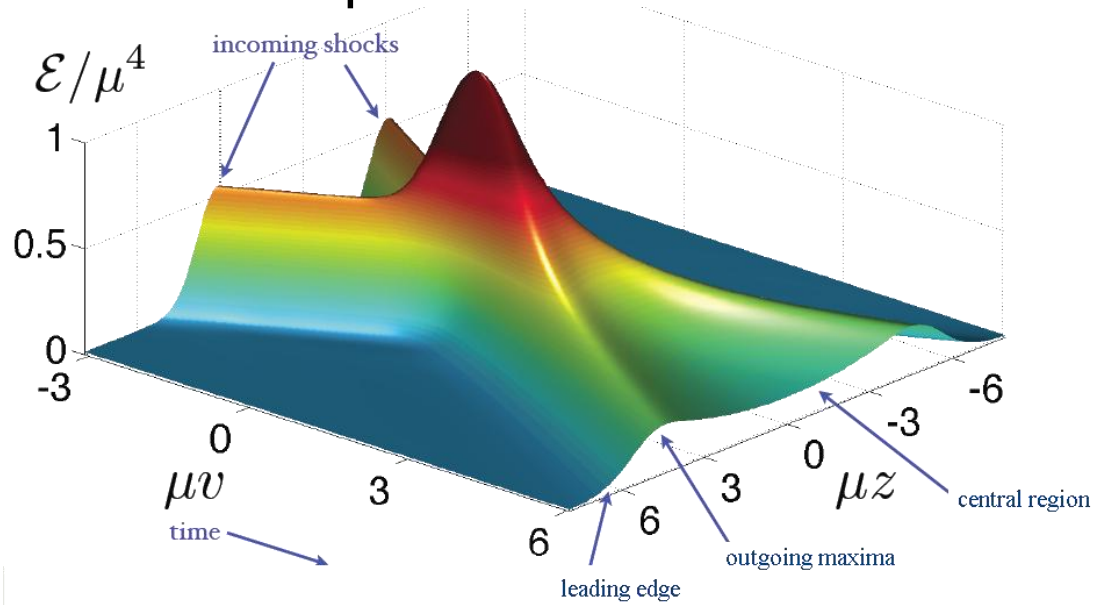
Prospects: colliding nuclei

- Need hydro, freeze-out etc..



Shock waves – initial conditions

- Famous example:



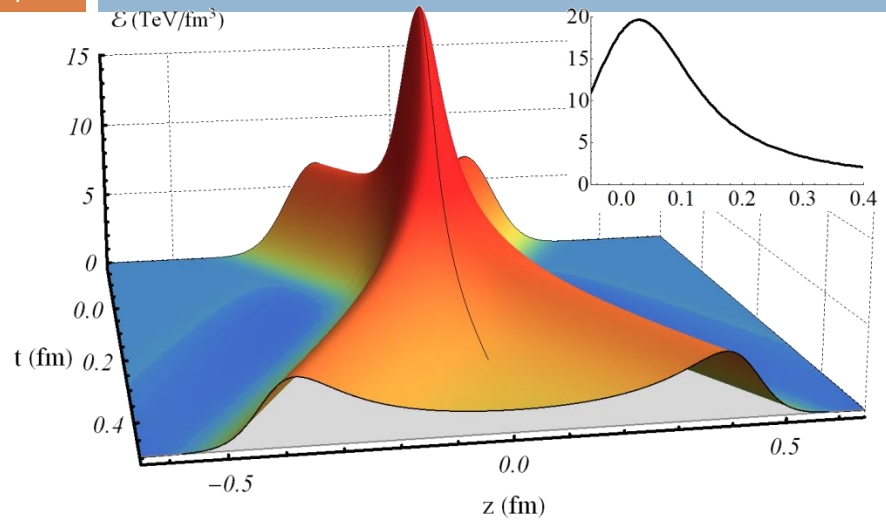
Extra AdS direction

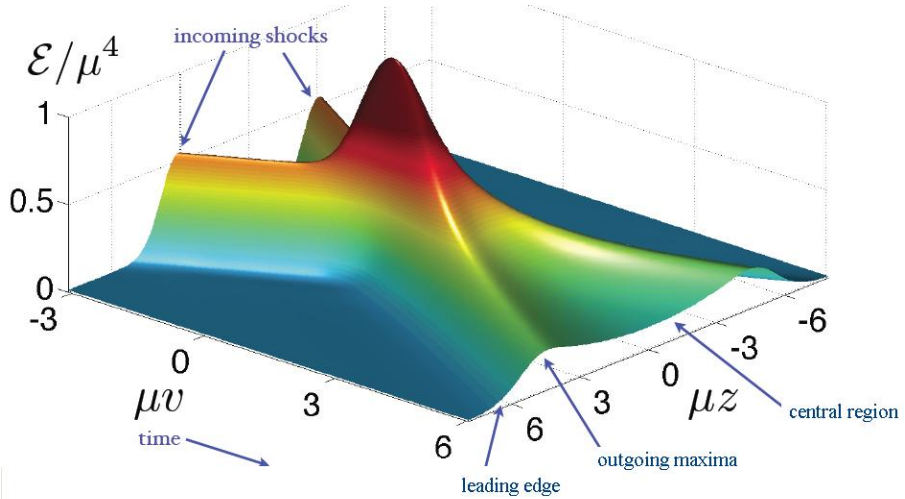
- Homogeneous in transverse plane ('infinite nucleus')
- Energy density moving at speed of light: initial conditions fixed
  - Two scales: width + total energy
- Only gravity: dominant force at high energy

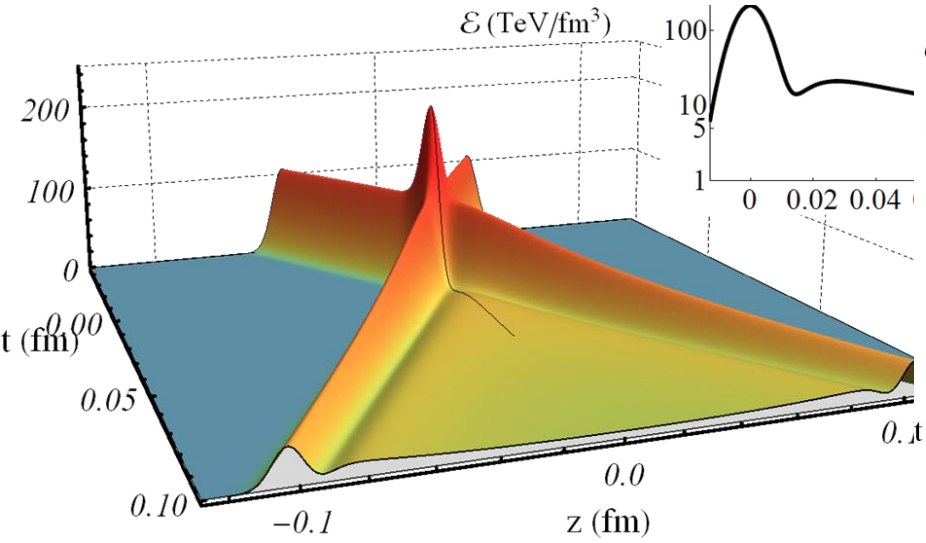
P.M. Chesler and L.G. Yaffe, Holography and colliding gravitational shock waves in asymptotically AdS_5 spacetime (2010)

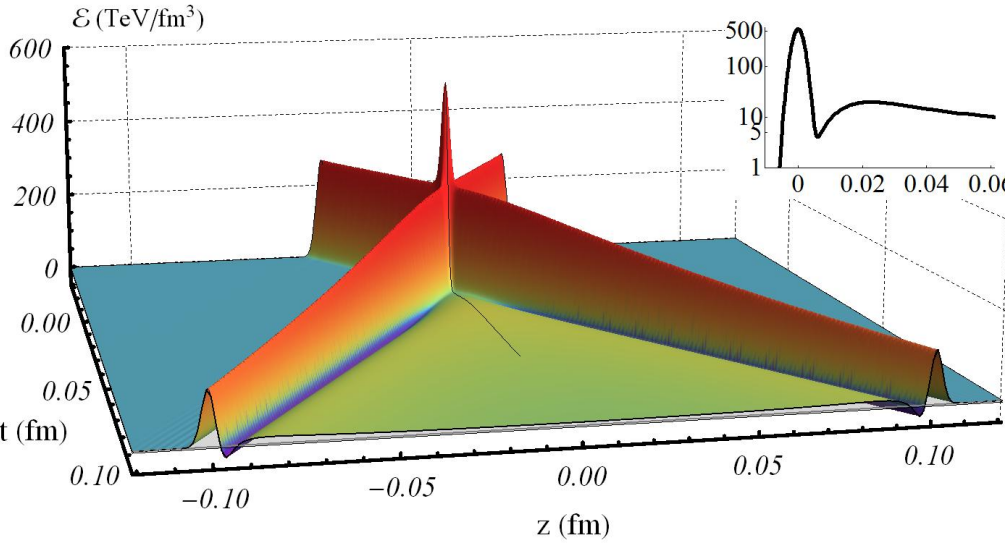
Shock waves – varying the width

Wilke van der Schee, Utrecht



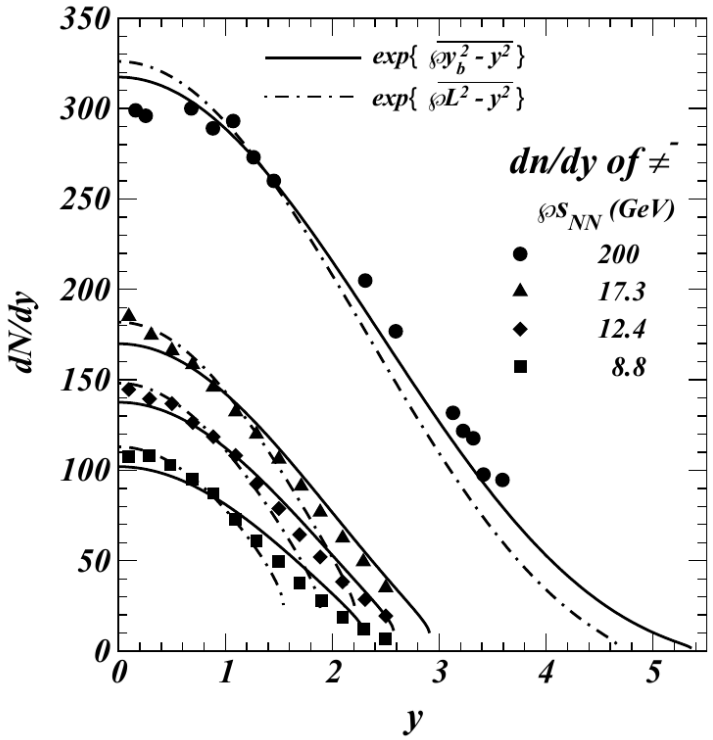


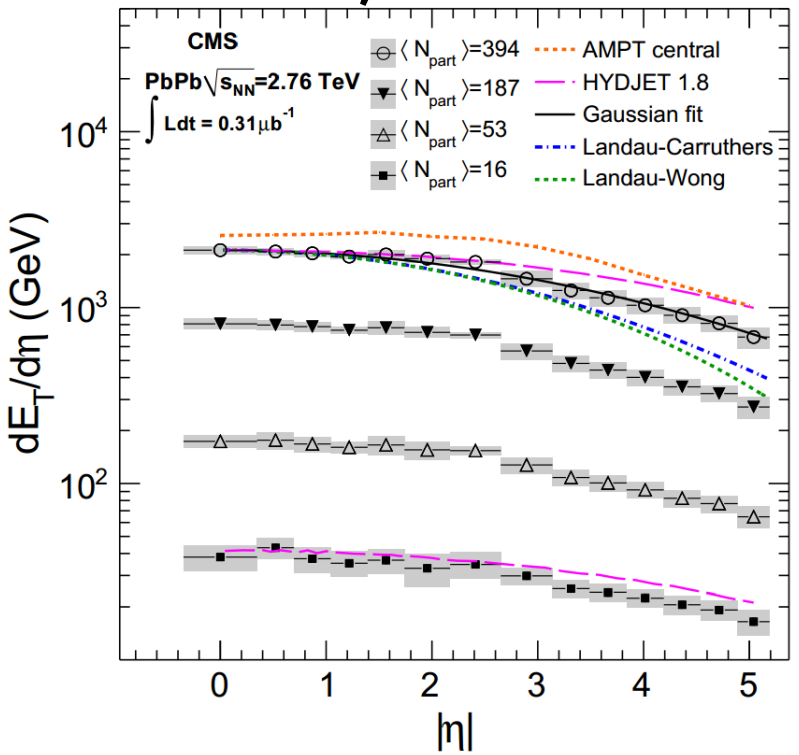




Landau model

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

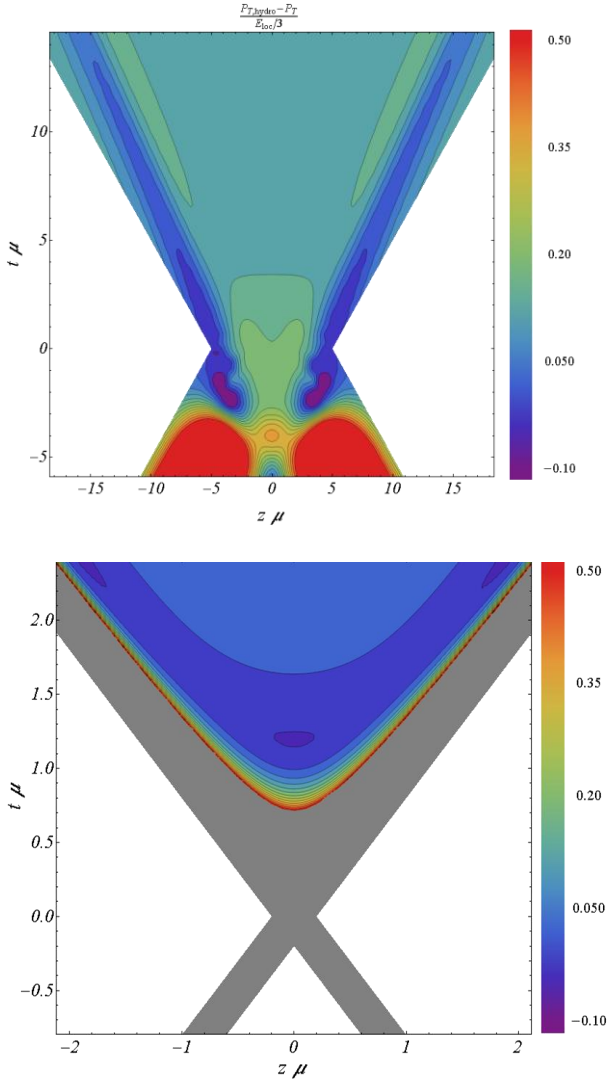




L. D. Landau, Izv. Akad. Nauk Ser. Fiz. 17 (1953)

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



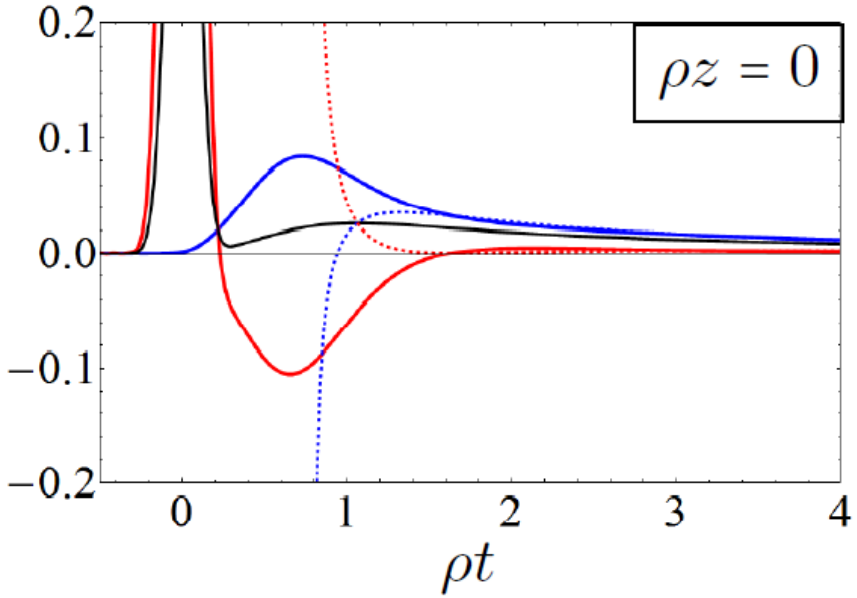
Pressure anisotropy

- Pressure, energy starts at zero, grows

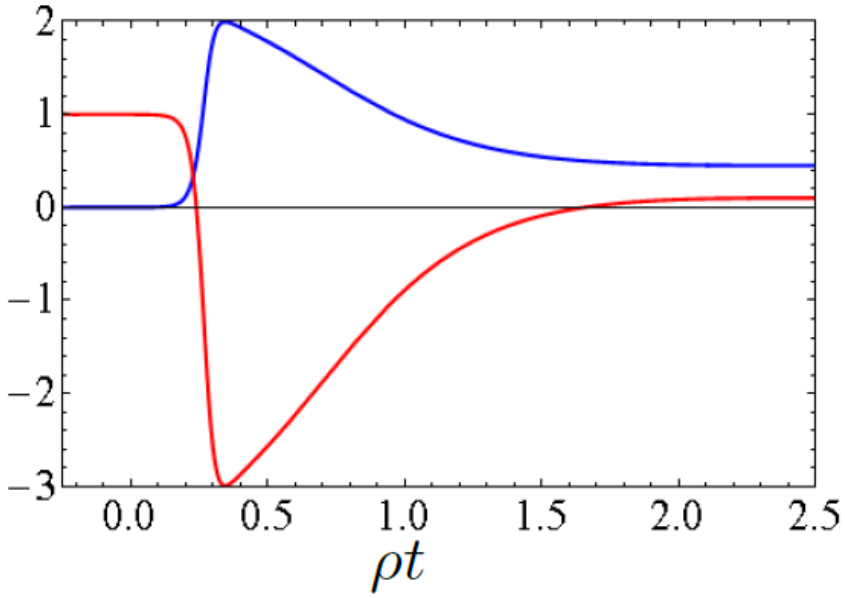
$$T^{\nu}_{\mu} = \mathrm{diag}\{\epsilon(\tau),\, -\epsilon(\tau) - \tau\,\epsilon'(\tau),\, \epsilon(\tau) + \tfrac{1}{2}\tau\,\epsilon'(\tau),\, \epsilon(\tau) + \tfrac{1}{2}\tau\,\epsilon'(\tau)\}$$

- 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)

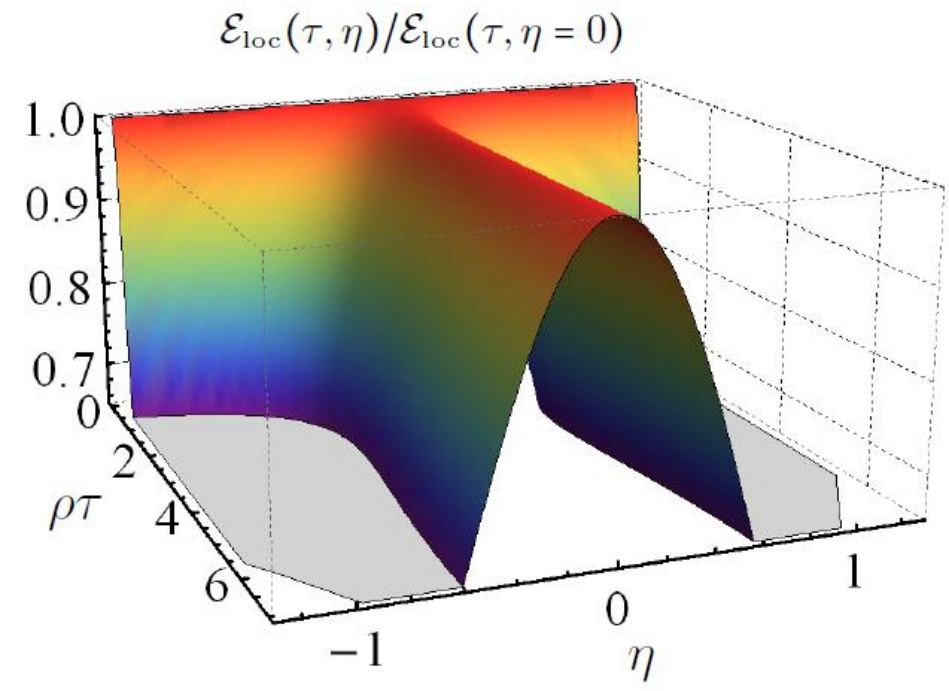


Shock waves – boost-invariance

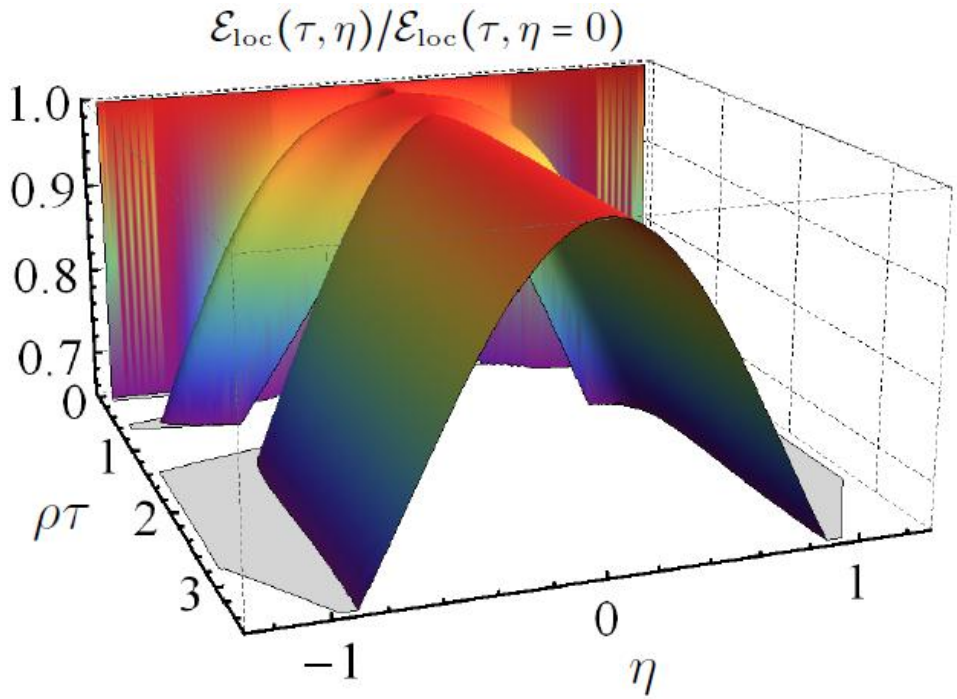
Wilke van der Schee, Utrecht

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

Low energy:

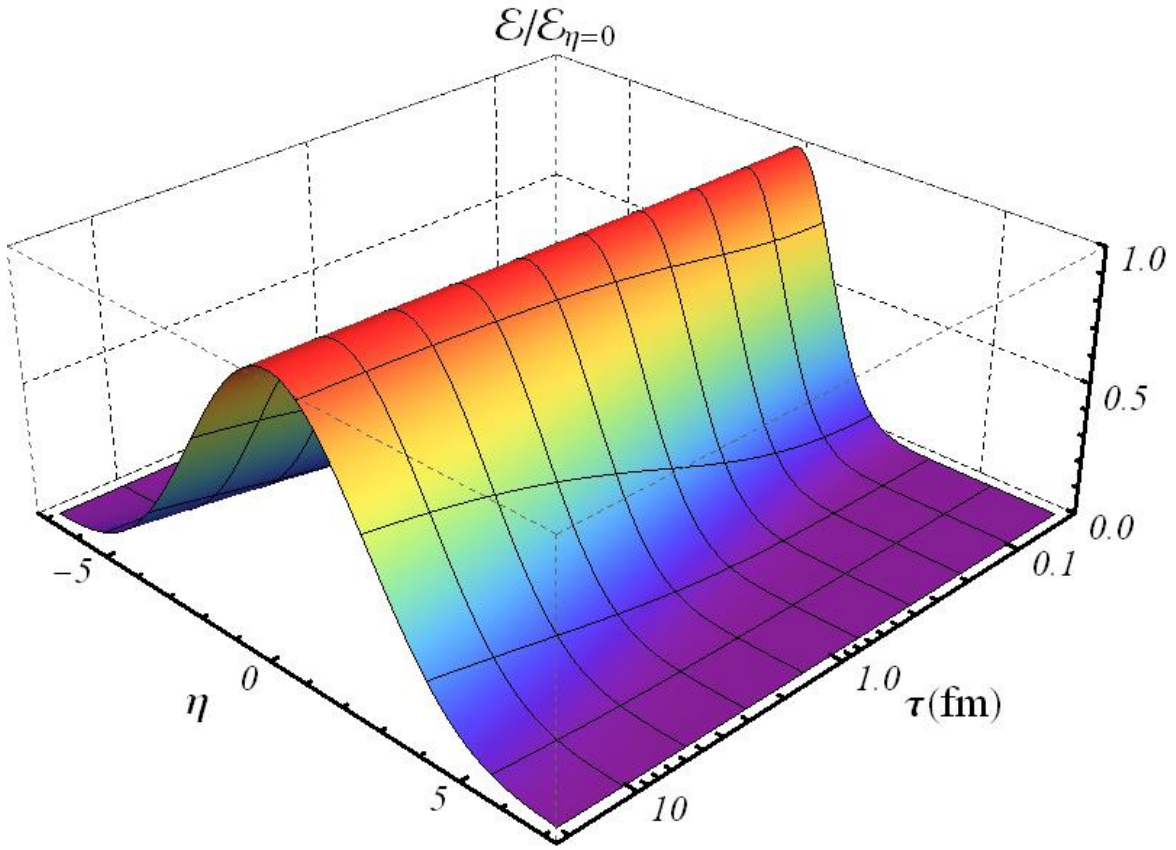


High energy:



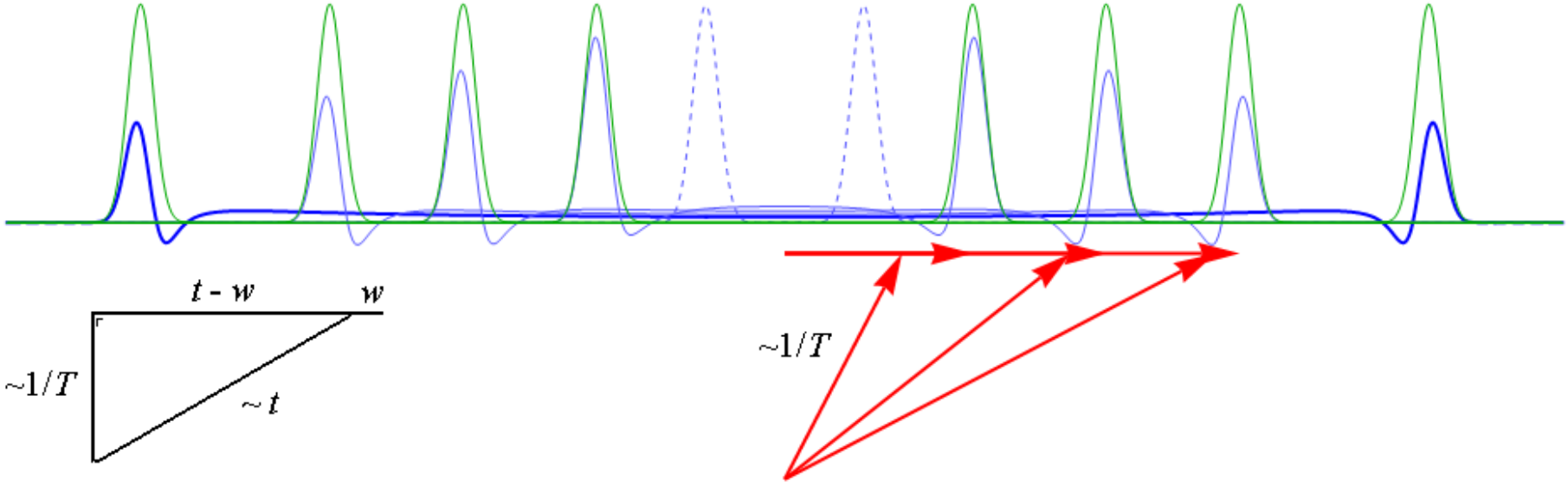
Time evolution of rapidity profile

- Back-of-the-envelope:
  - Plug into EOM of ideal hydro



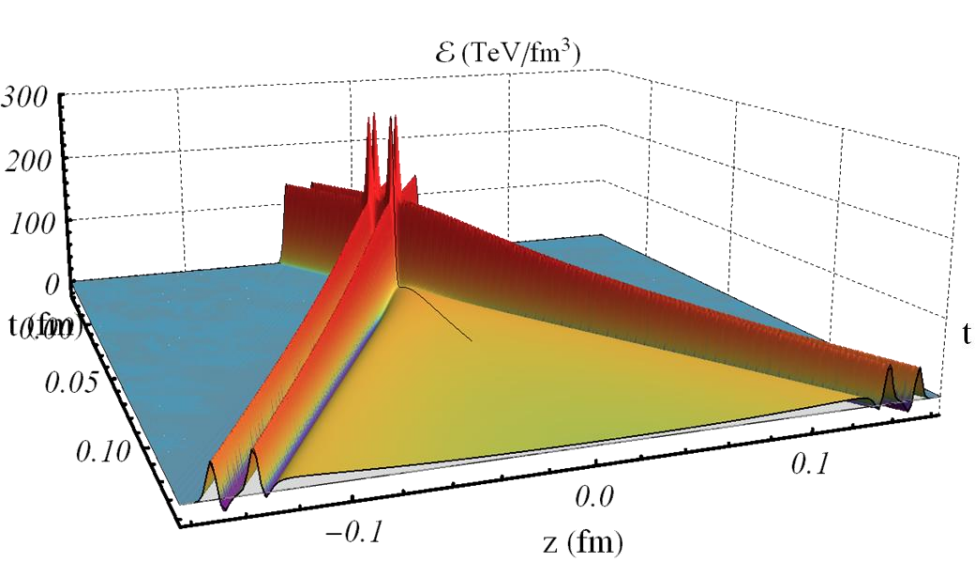
Shock waves from the bulk

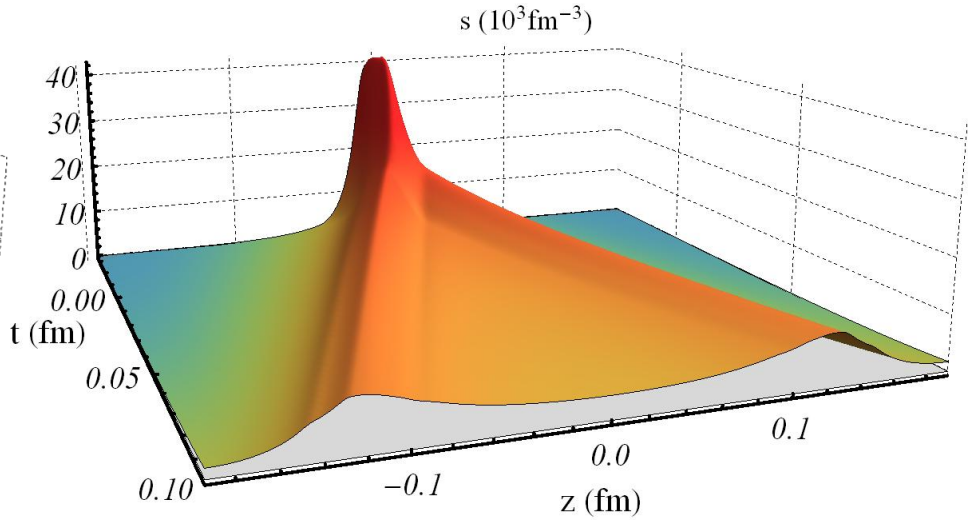
- Interesting interplay between temperature & width:
  - Non-linearity roughly comes from horizon
  - Touches front-end latest: by causality!



Newer results

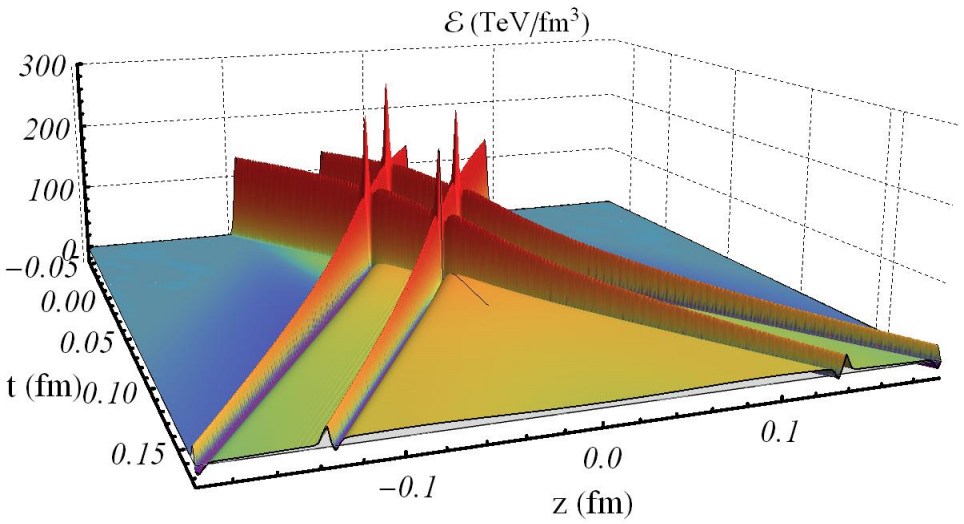
- UV structure is washed out in IR
  - Compare energy density with area apparent horizon
- No longitudinal initial state fluctuations (cf. Stephanov)

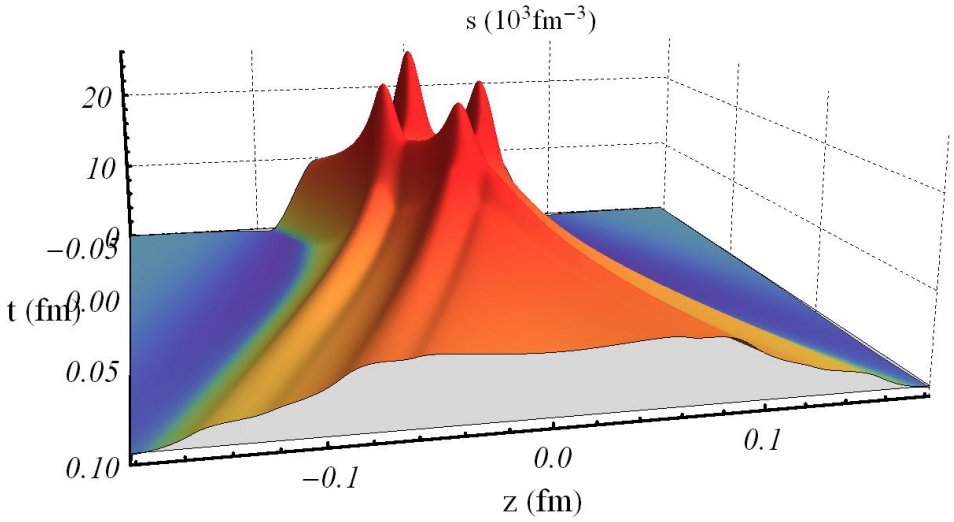




Newer results

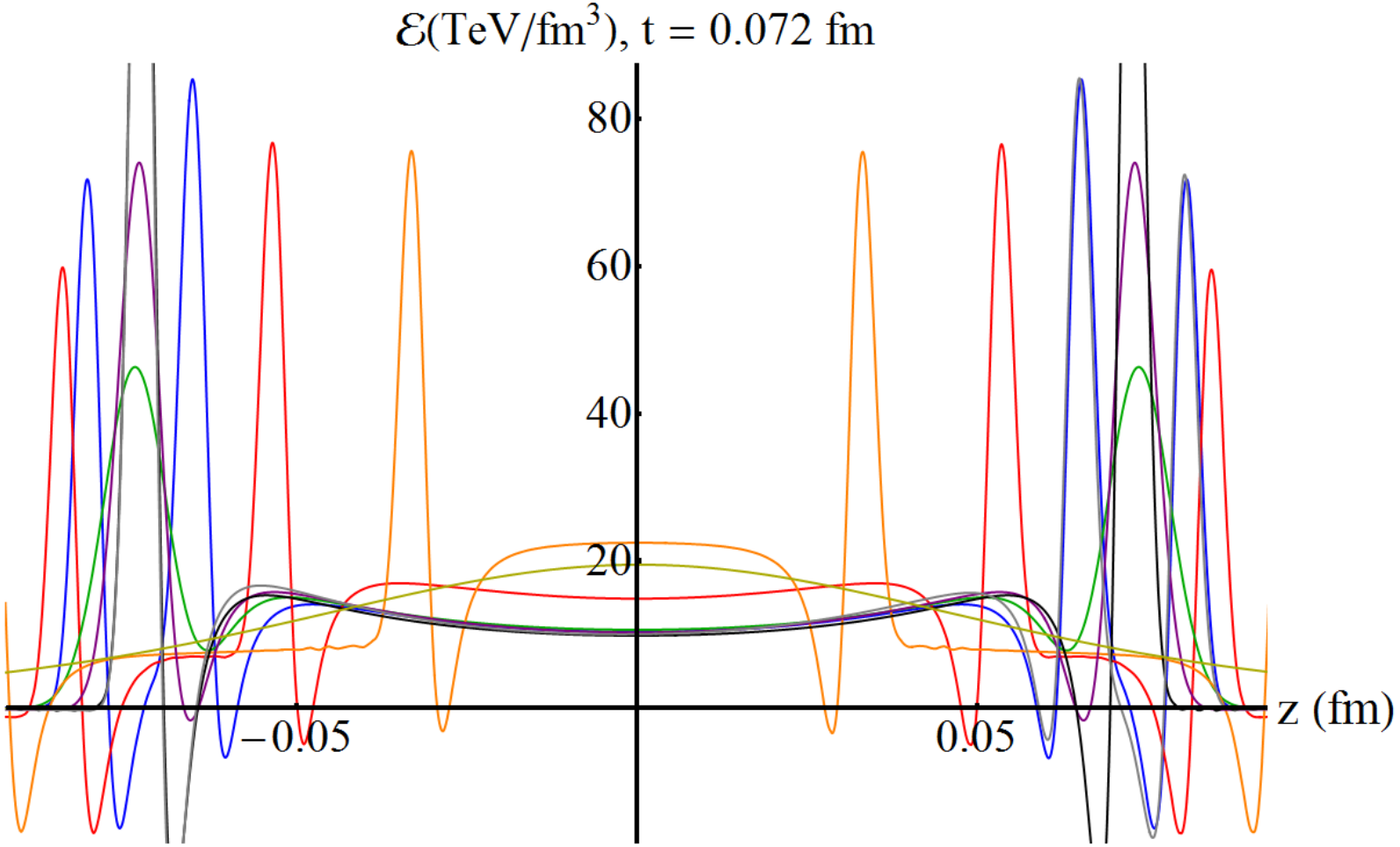
- UV structure is washed out in IR
  - Compare scale with 1/Temperature:



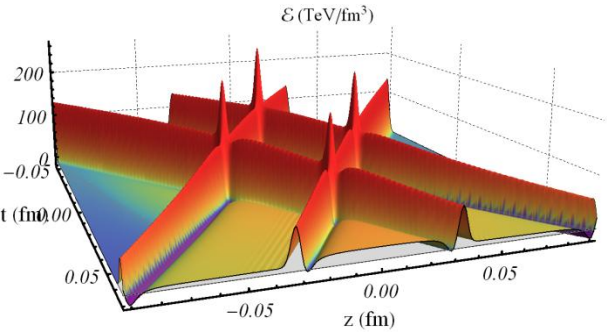


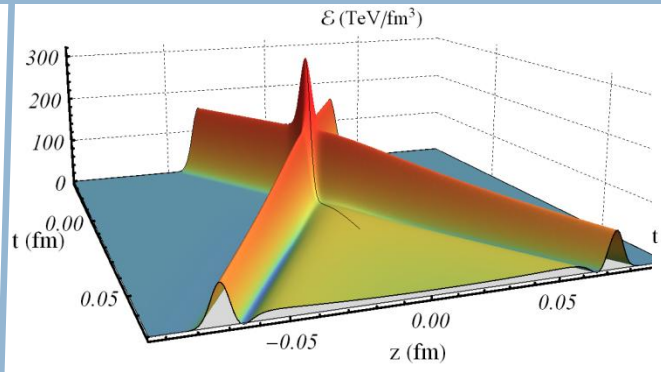
Newer results – a prediction for p-Pb

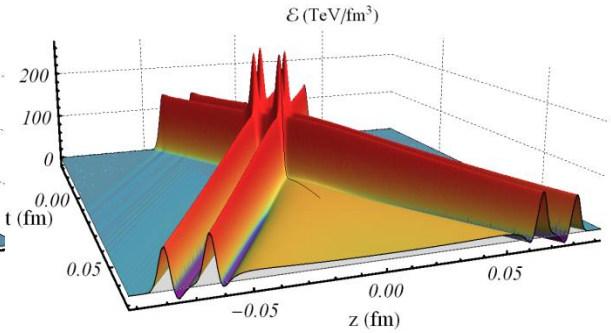
- Comparable c.o.m. late time results for narrow shocks:

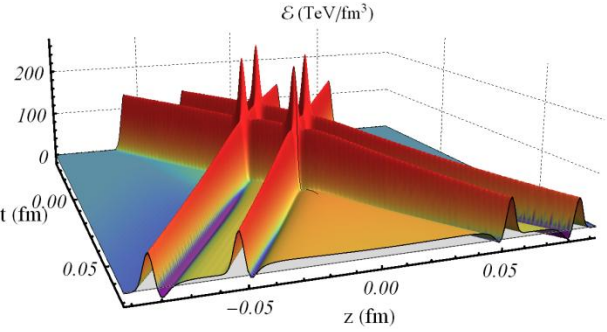


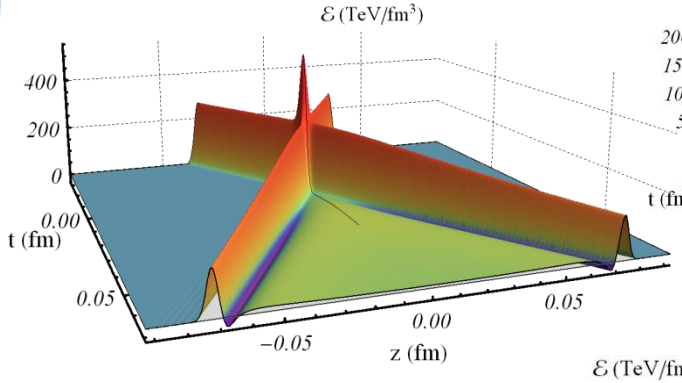
Shocks included in previous plot

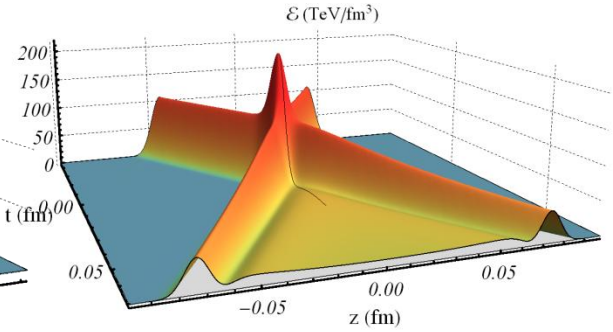


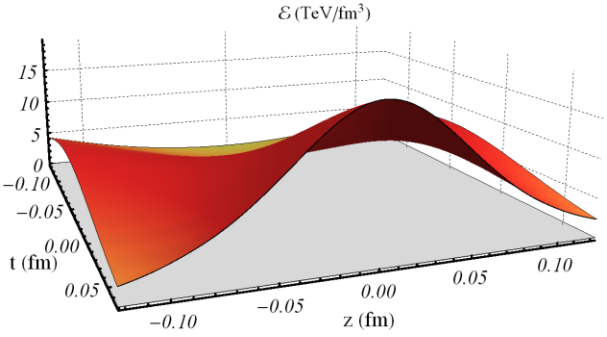


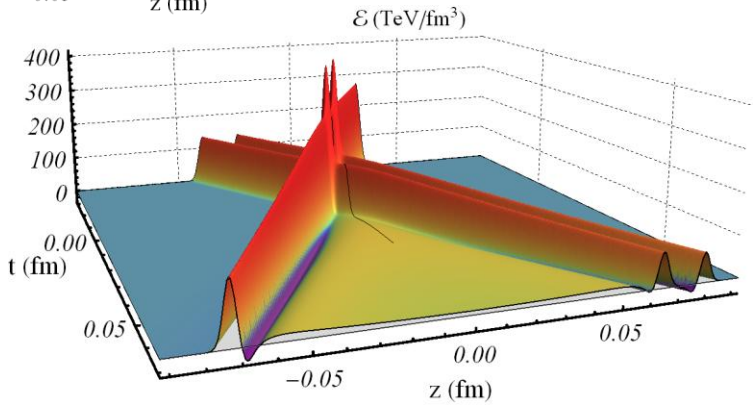






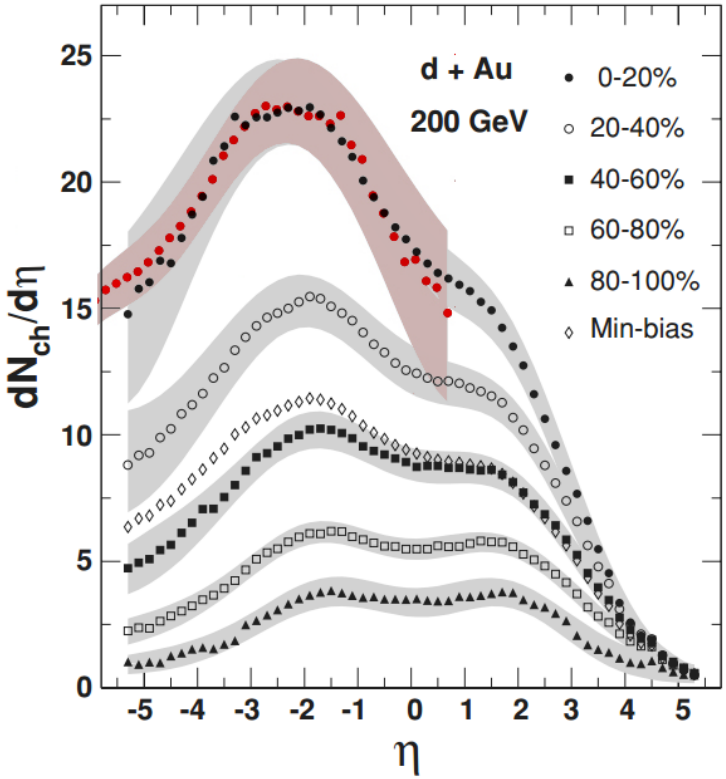


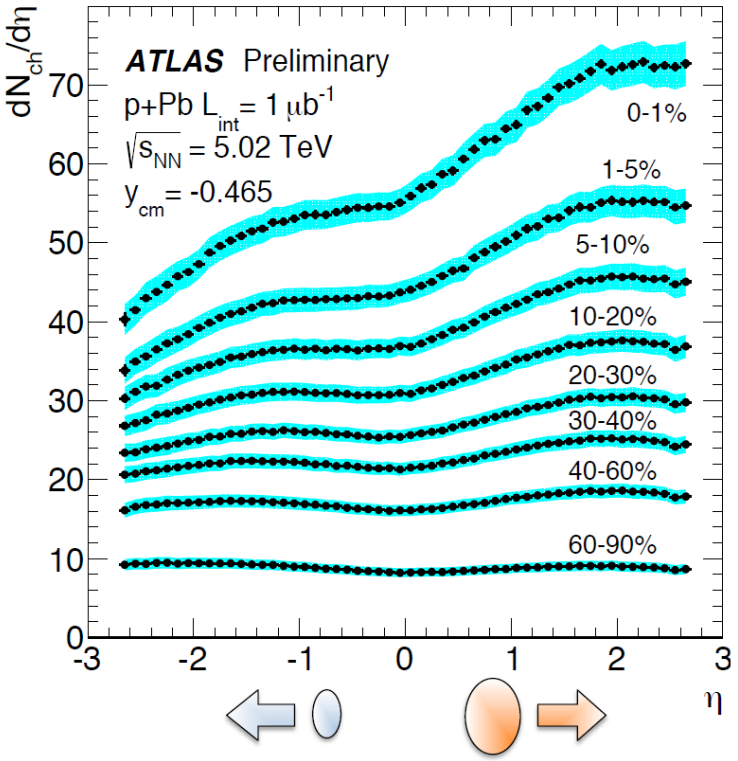




p-Pb symmetry, is it true?

- No indications otherwise; CMS?
- Also results from glasma, but not completely trivial





A fully dynamical model of a HIC

Work with Paul Romatschke and Scott Pratt

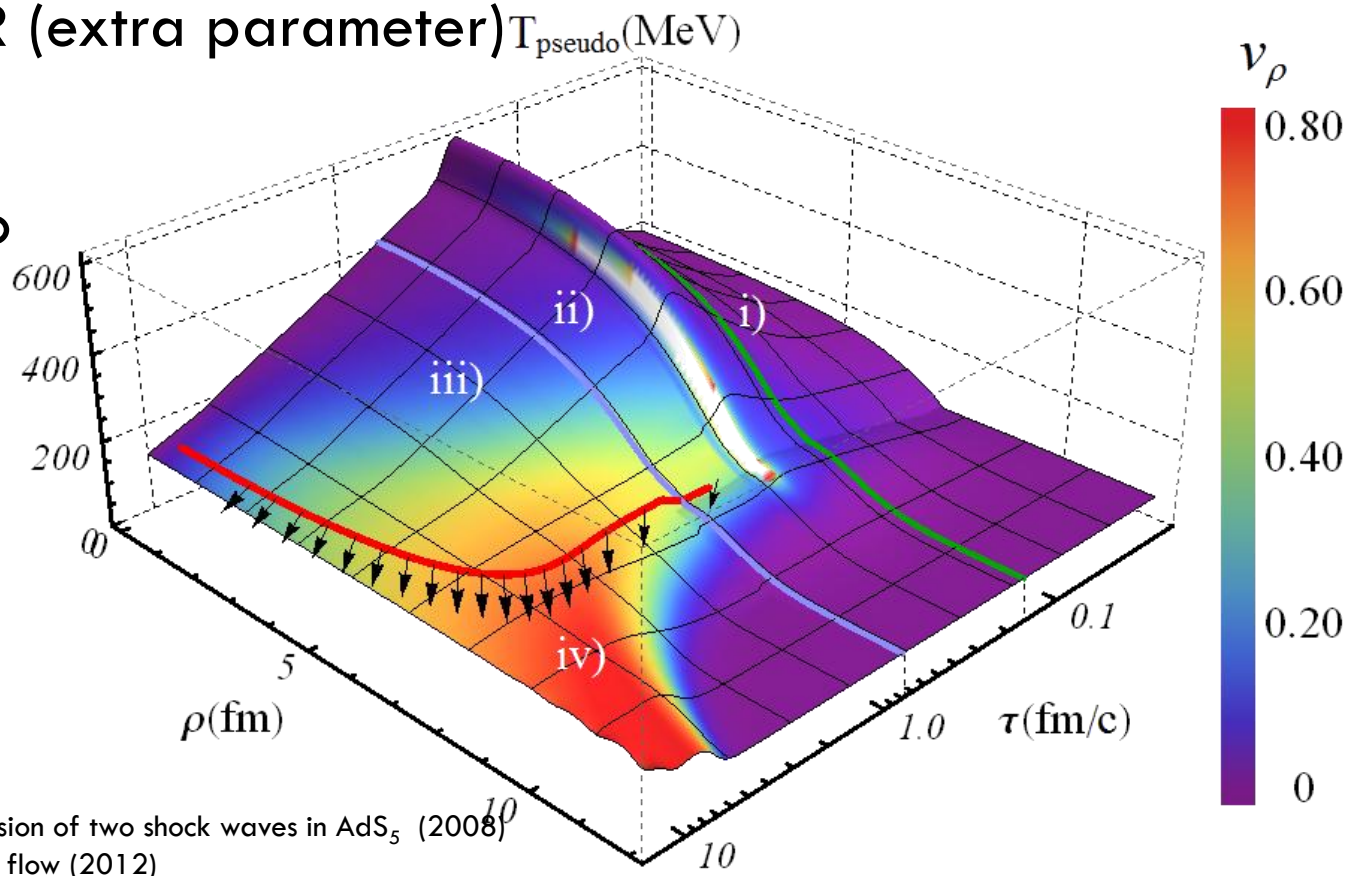
Wilke van der Schee, Utrecht

i) Small time expansion of colliding shocks (central)

ii) Numerical GR (extra parameter)

iii) Viscous hydro

iv) Hadronic cascade

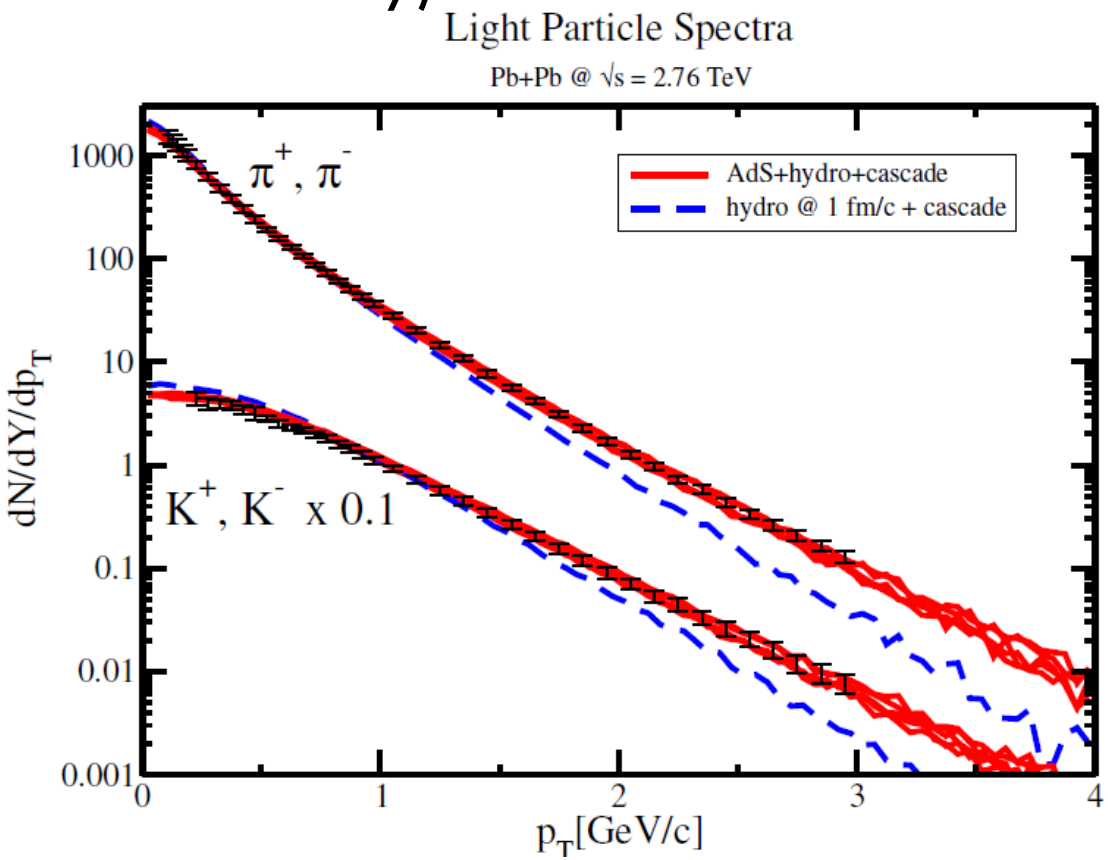


Boost-invariant

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 ☺ (fitted normalization only)
- Approach to hydro
- Approx universal velocity at 1 fm
- Hybrid:
  - Ads collision
  - hydro (QCD EoS)
  - cascade (weakly coupled hadron gas)



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