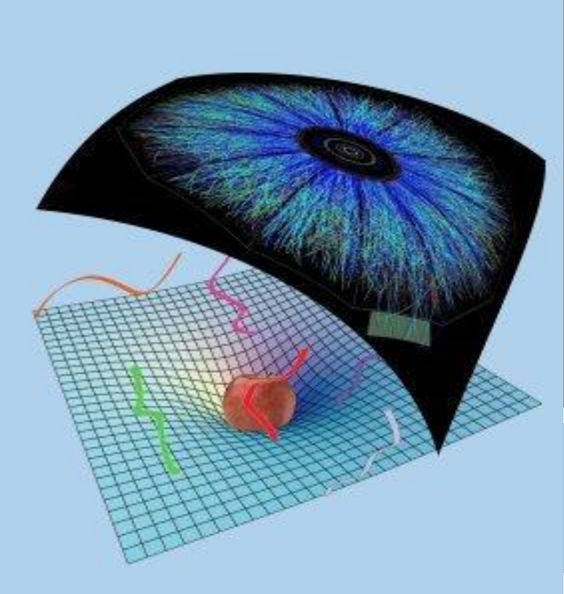
COLLISIONS IN ADS AND THE THERMALISATION OF HEAVY IONS

Towards more realistic models of the QGP thermalisation

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



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Supervisors: Gleb Arutyunov,
Thomas Peitzmann and Raimond Snellings

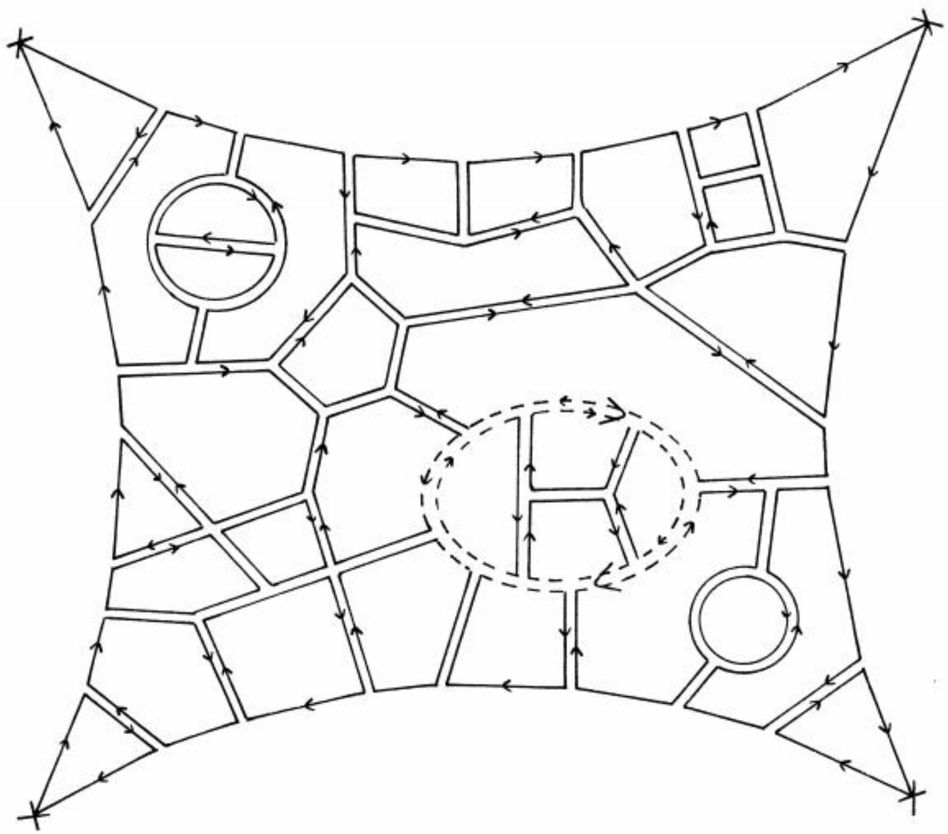
Seminar CERN
8 October, 2013

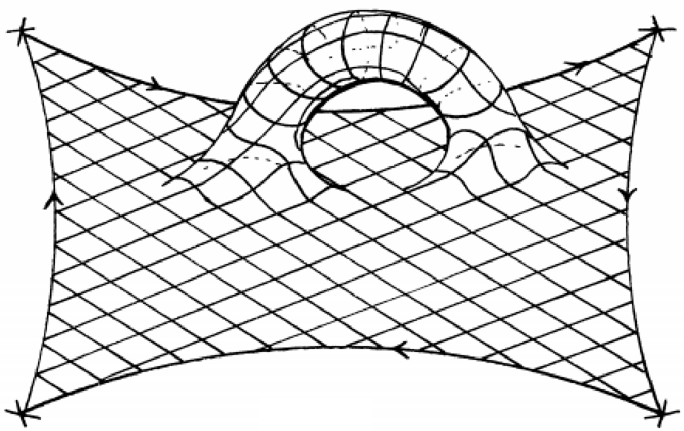
Outline

- Motivation: AdS/CFT
- A first try: boost-invariant radial flow
  - Hydrodynamics+cascade → spectra
- Gravitational shock waves in AdS
  - Low/high energy behaviour: stopping/transparency
  - Boost-invariance?
  - New: Influence of microstructure: a prediction for p-Pb
  - New: total multiplicities from entropy (unfinished)

Large N gauge theories

- At strong coupling we can get GR





Planar limit:

$\lambda = g^2 N$ fixed

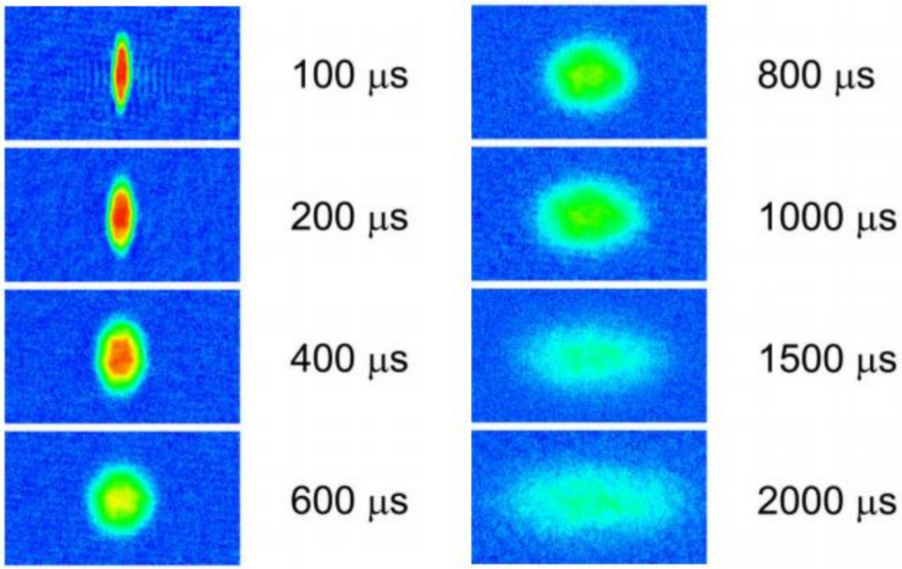
$N \to \infty$

G. 't Hooft, A planar diagram theory for strong interactions (1974)

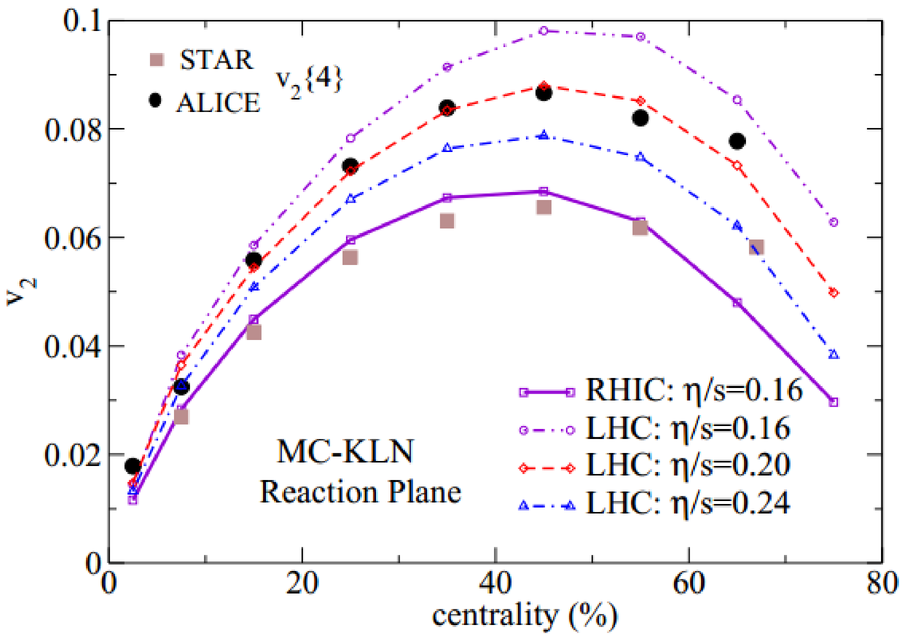
The most perfect liquid?

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

Fermions at unitarity



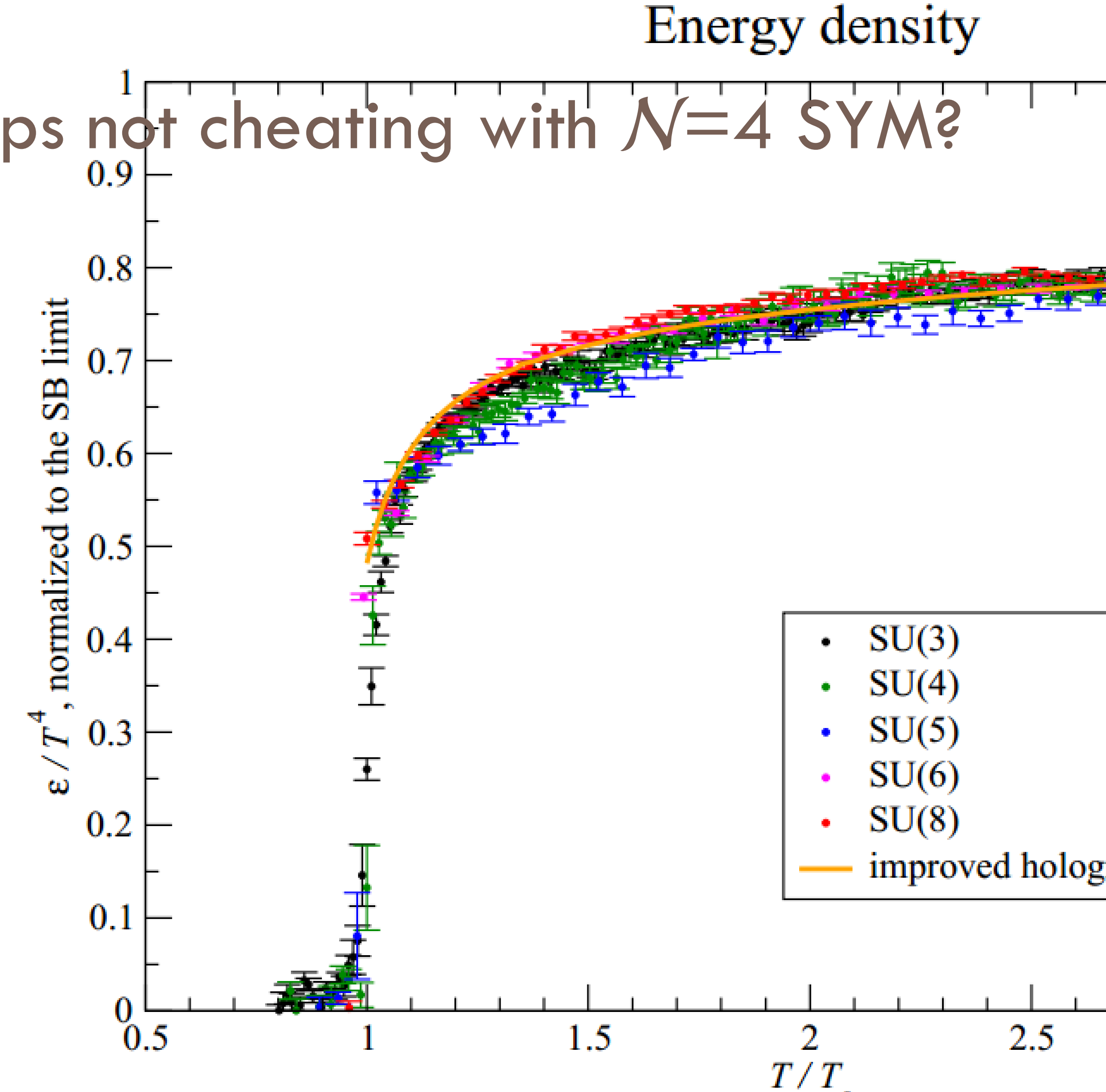
Quark-gluon plasma



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

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

- SU(N): 3 ≈ ∞?
  - Good for therr
- SUSY?
  - Supressed with
- Quarks?
  - Replaced by (c
- Infinite coupling
  - But coupling ru

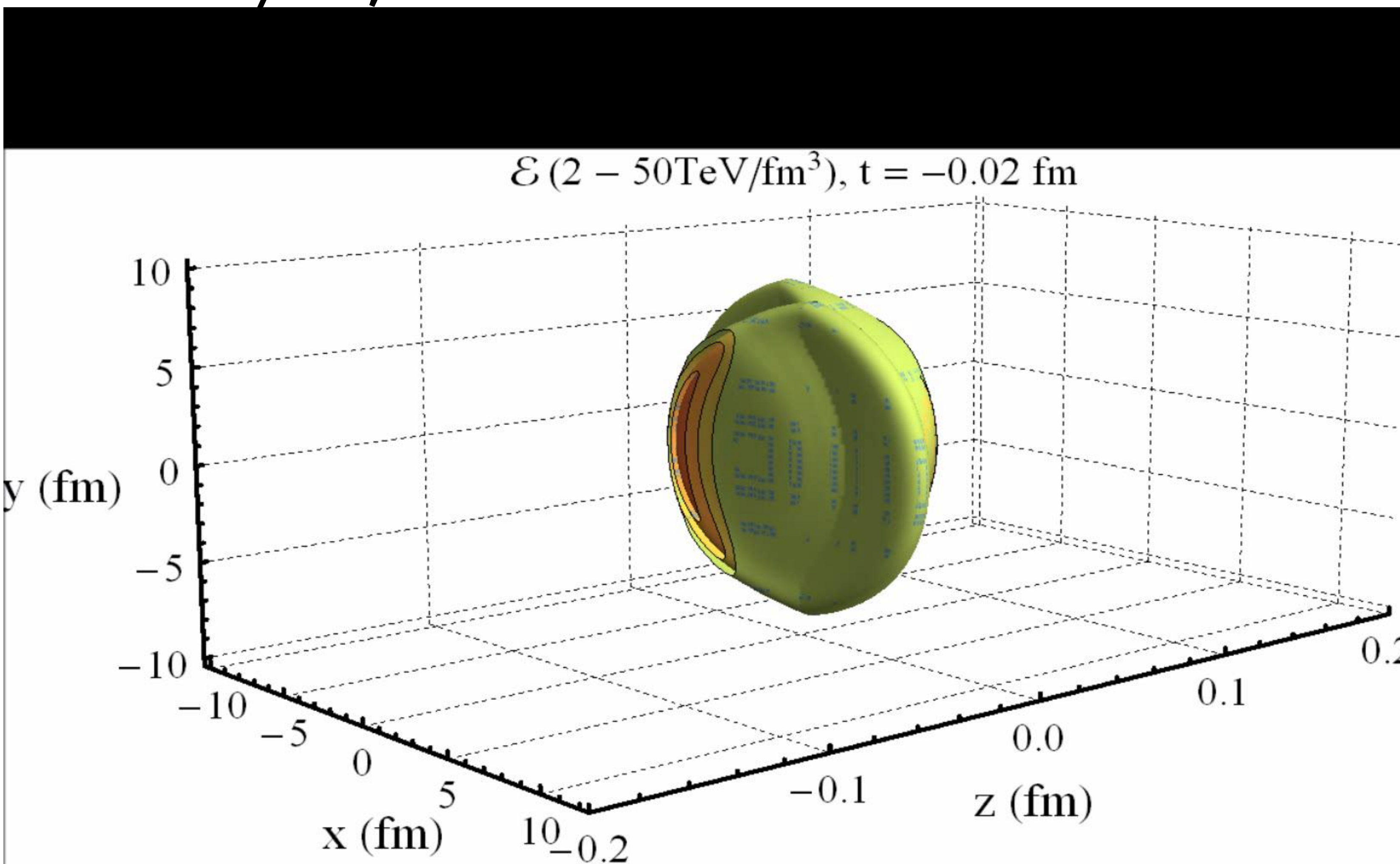


- So maybe not t

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

Prospects: colliding nuclei

- Need hydro, freeze-out etc..



The set-up: characteristic formulation

- Very old trick:
  - Use null coordinates
  - Split out determinant spatial part metric
  - Write time derivatives along geodesics: $\dot{h} \equiv \partial_t h + \frac{1}{2} A \, \partial_r h$

$$ds^2 = -Adt^2 + \Sigma^2 (e^{-B-C} dy^2 + e^B d\rho^2 + e^C d\theta^2) + 2drdt + 2F d\rho dt$$

$$ds_B^2 = -d\tau^2 + d\rho^2 + \rho^2 d\theta^2 + \tau^2 dy^2$$

- The real trick (plus some complications…):

```
In[32]:= eq = 0 == # & /@ Flatten[RicciTensor + 4 metric /. funct_^(ddr_,1,ddρ_)[r, t, ρ] → D[funct^(0,1,0)[r, t, ρ] - 1/2 A[r, t, ρ] funct^(1,0,0)[r, t, ρ], {r, ddr}, {ρ, ddρ}], 1];

In[35]:= Solve[eq, {S^(2,0,0)[r, t, ρ], F^(2,0,0)[r, t, ρ], S^(1,1,0)[r, t, ρ], C^(1,1,0)[r, t, ρ], B^(1,1,0)[r, t, ρ], A^(2,0,0)[r, t, ρ], F^(1,1,0)[r, t, ρ], S^(0,2,0)[r, t, ρ]}] // Simplify

Out[35]= {{S^(2,0,0)[r, t, ρ] → -1/6 S[r, t, ρ] (B^(1,0,0)[r, t, ρ]^2 + B^(1,0,0)[r, t, ρ] C^(1,0,0)[r, t, ρ] + C^(1,0,0)[r, t, ρ]^2),
    F^(2,0,0)[r, t, ρ] → 1/(6 S[r, t, ρ]^2) (24 S^(1,0,0)[r, t, ρ] (-S^(0,0,1)[r, t, ρ] + F[r, t, ρ] S^(1,0,0)[r, t, ρ]) -
      6 S[r, t, ρ] (3 S^(0,0,1)[r, t, ρ] B^(1,0,0)[r, t, ρ] - 3 F[r, t, ρ] B^(1,0,0)[r, t, ρ] S^(1,0,0)[r, t, ρ] + F^(1,0,0)[r, t, ρ] S^(1,0,0)[r, t, ρ] - 4 S^(1,0,1)[r, t, ρ]) +
      S[r, t, ρ]^2 (3 B^(0,0,1)[r, t, ρ] (2 B^(1,0,0)[r, t, ρ] + C^(1,0,0)[r, t, ρ]) + 3 C^(0,0,1)[r, t, ρ] (B^(1,0,0)[r, t, ρ] + 2 C^(1,0,0)[r, t, ρ]) -
```

H. Bondi, Gravitational Waves in General Relativity (1960)
P.M. Chesler and L.G. Yaffe, Numerical solution of gravitational dynamics in asymptotically anti-de Sitter spacetimes (2013)

A fully dynamical model of a HIC

Work with Paul Romatschke and Scott Pratt

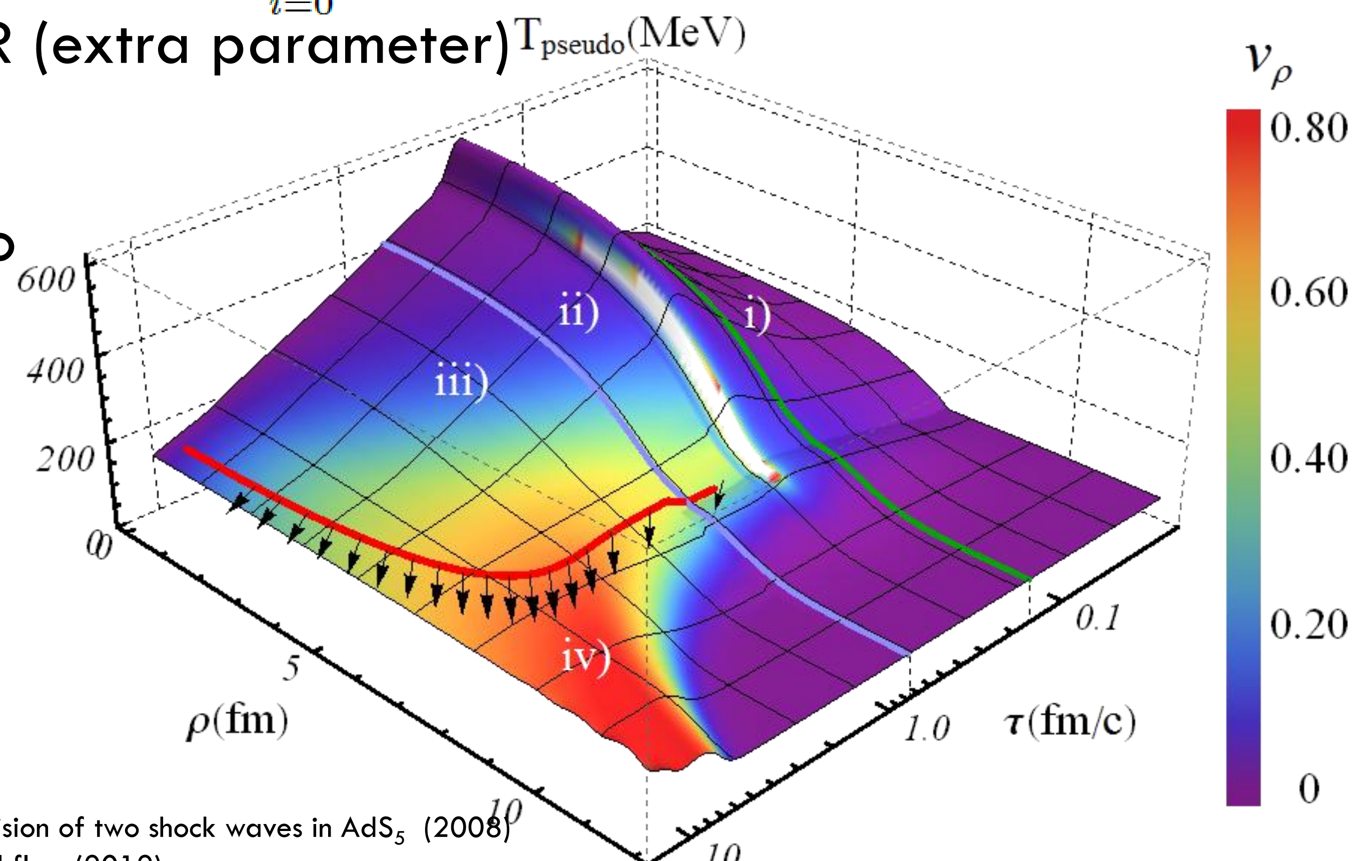
i) Small time expansion of colliding shocks (central)

$$B(r,\tau,\rho) \to B_0(r,\tau,\rho) + \sum_{i=0}^{6} \frac{b_i(\tau,\rho) r^{-i}}{1+\sigma^7 r^{-7}},$$

ii) Numerical GR (extra parameter)

iii) Viscous hydro

iv) Hadronic cascade

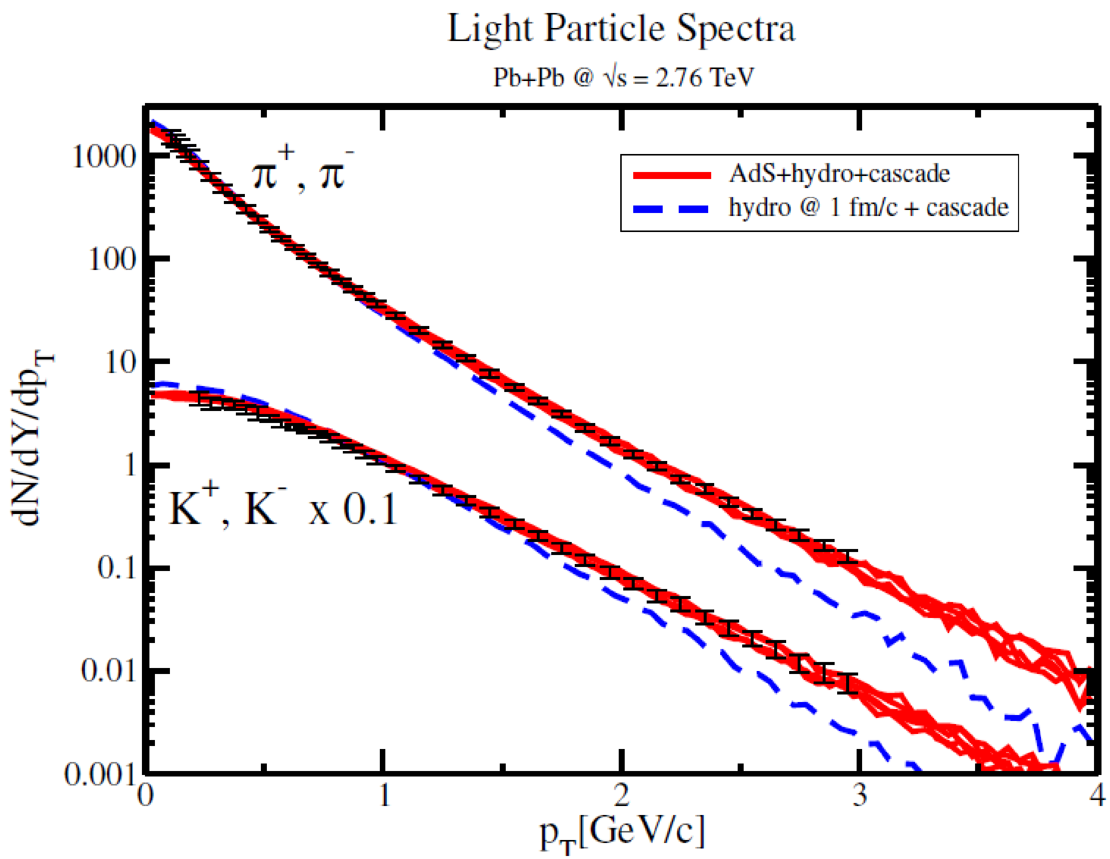


Boost-invariant

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

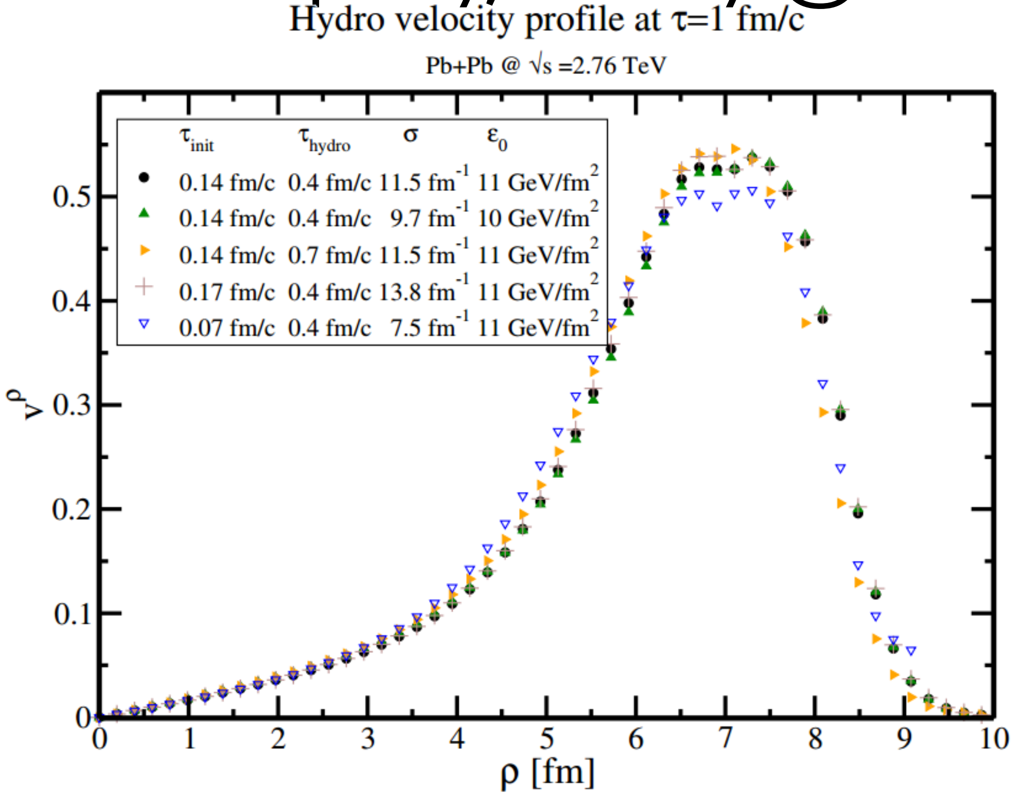
Boost-invariant radial flow

- Spectra ☺



Results – approach to hydro

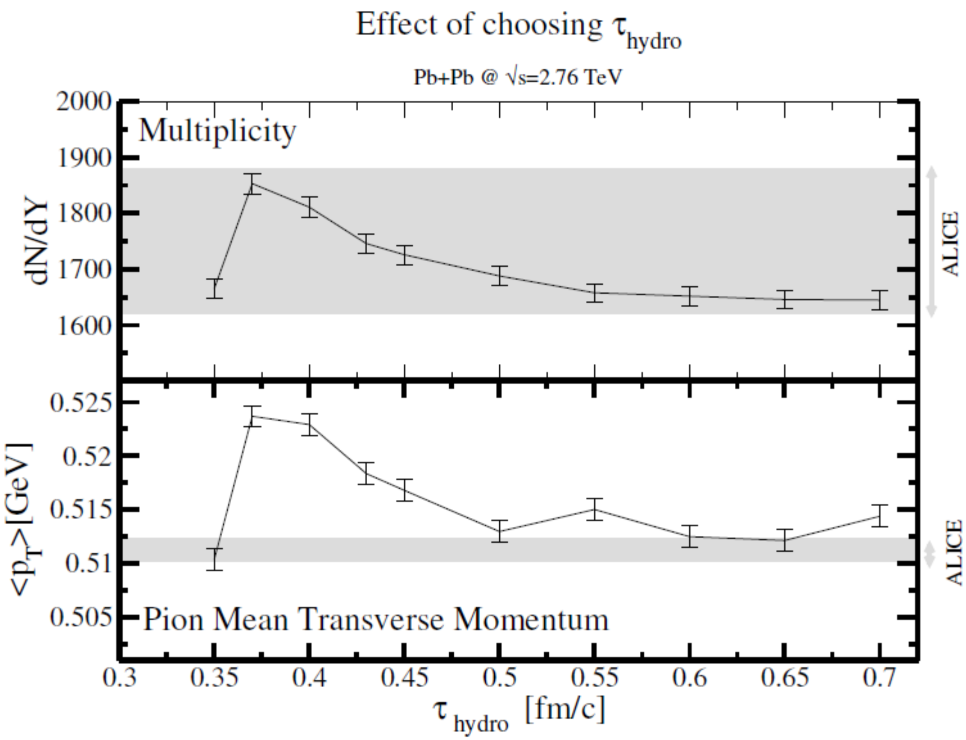
- Fixing total multiplicity, velocity @ 1 fm/c:



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

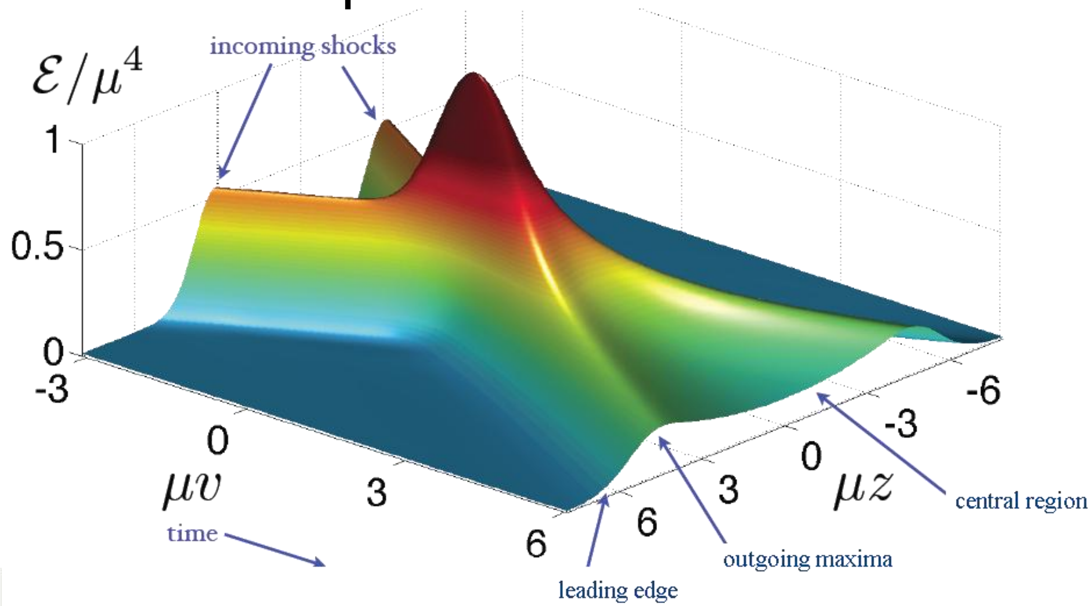
Results – approach to hydro

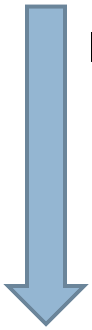
- Not too early: far-from-equilibrium
  - Rest frame does not even exist!
- Not too late: AdS = conformal ≠ QCD
  - In practice: 15% discontinuity in pressure



Shock waves – initial conditions

- Famous example:



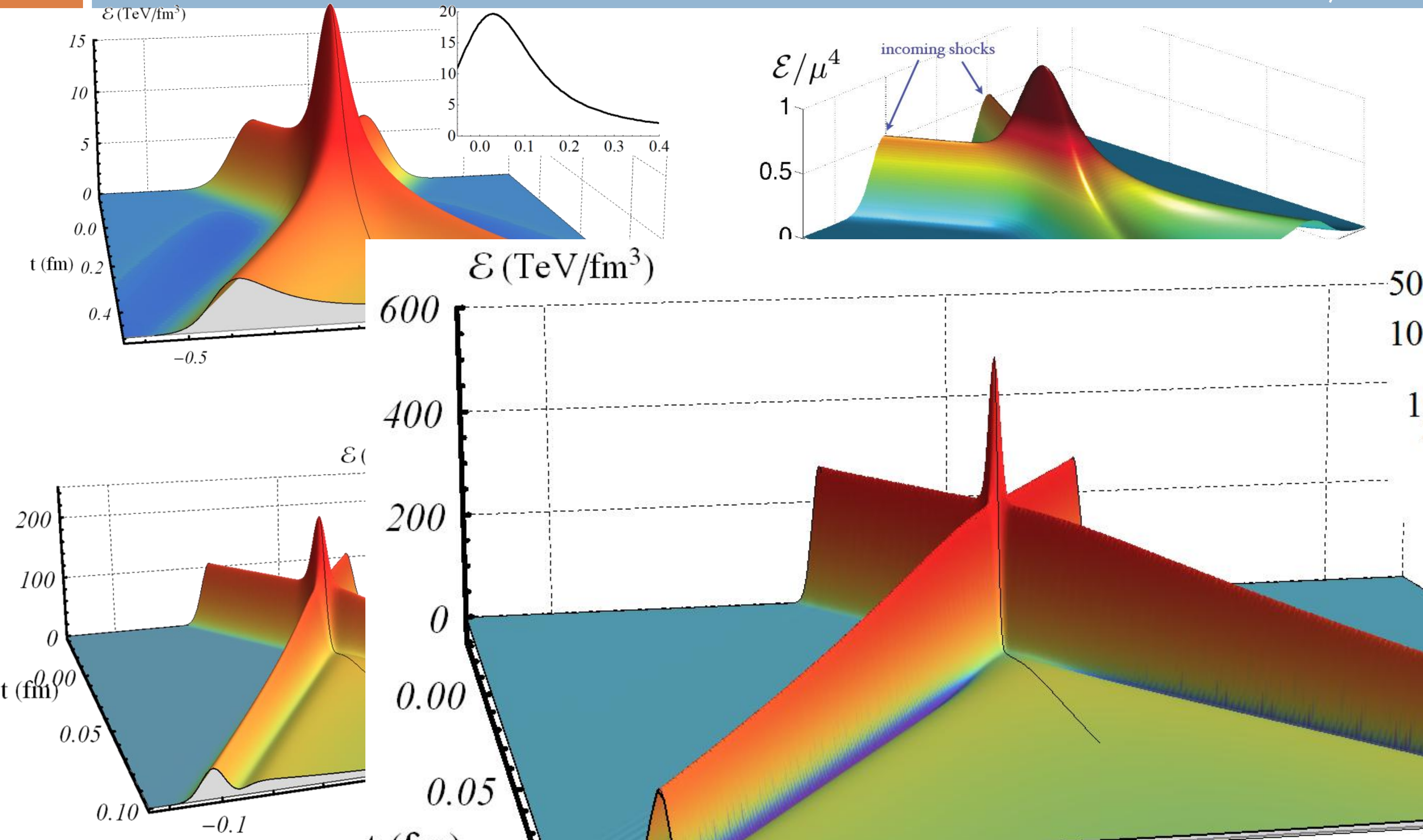


- Homogeneous in transverse plane ('infinite nucleus')
- Energy density moving at speed of light: initial conditions fixed
  - Two scales: width + total energy
- Only gravity: dominant force at high energy

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

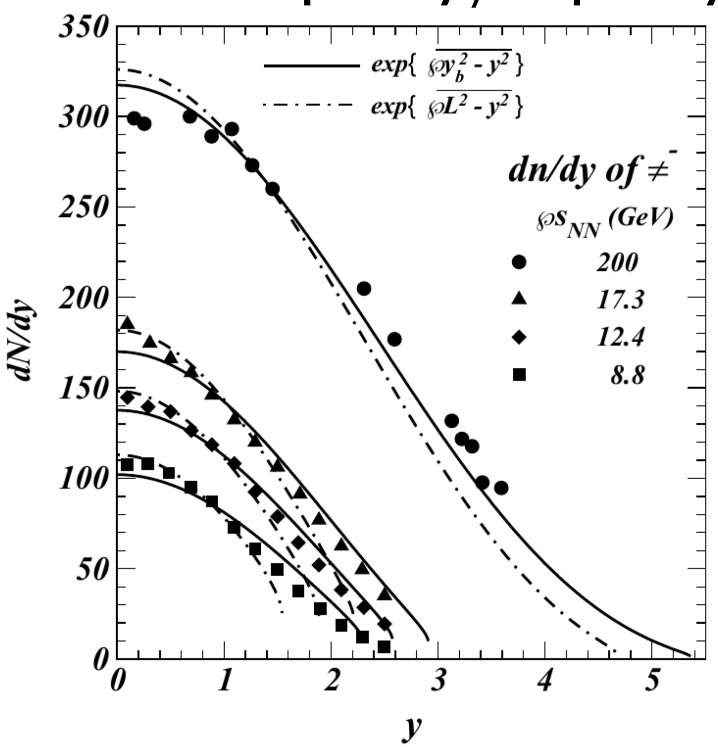
Shock waves – varying the width

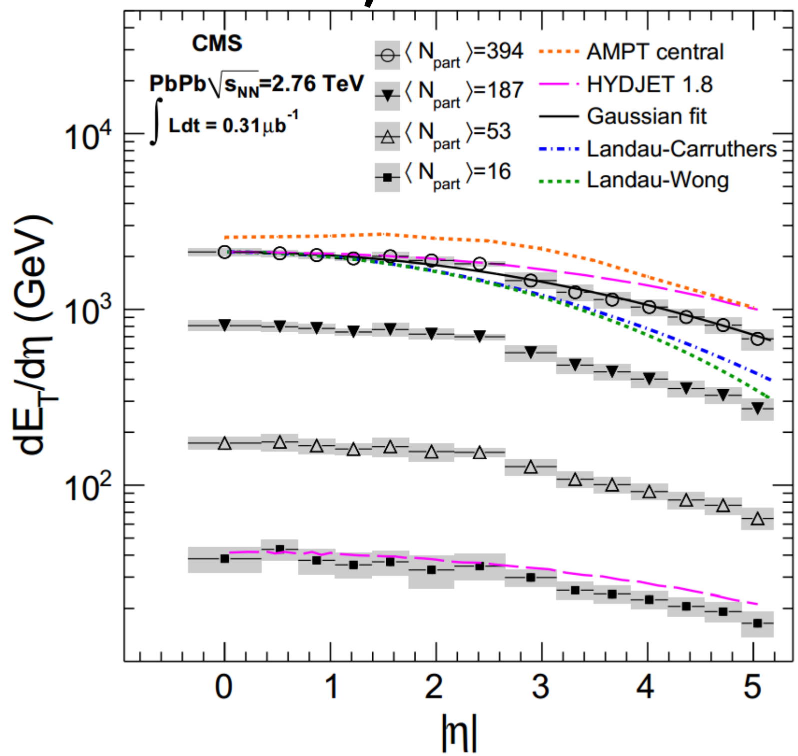
Wilke van der Schee, Utrecht



Landau model

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

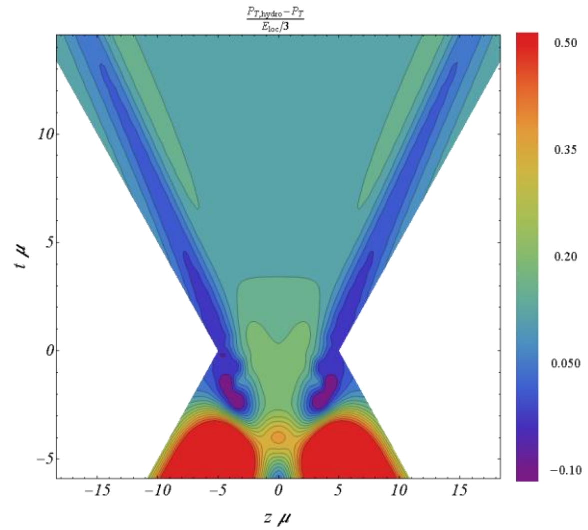


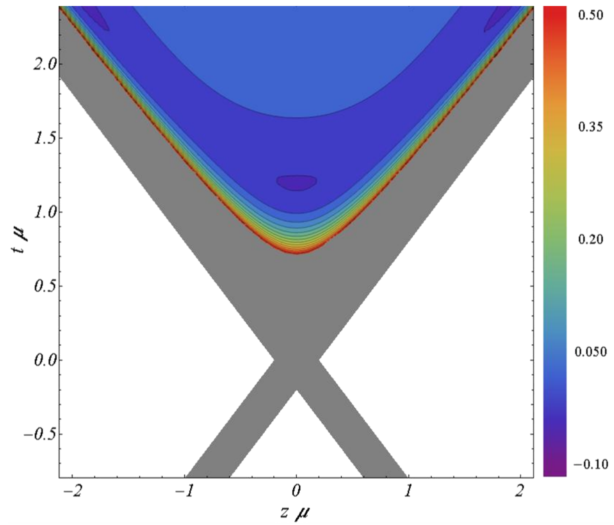


L. D. Landau, Izv. Akad. Nauk Ser. Fiz. 17 (1953)

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

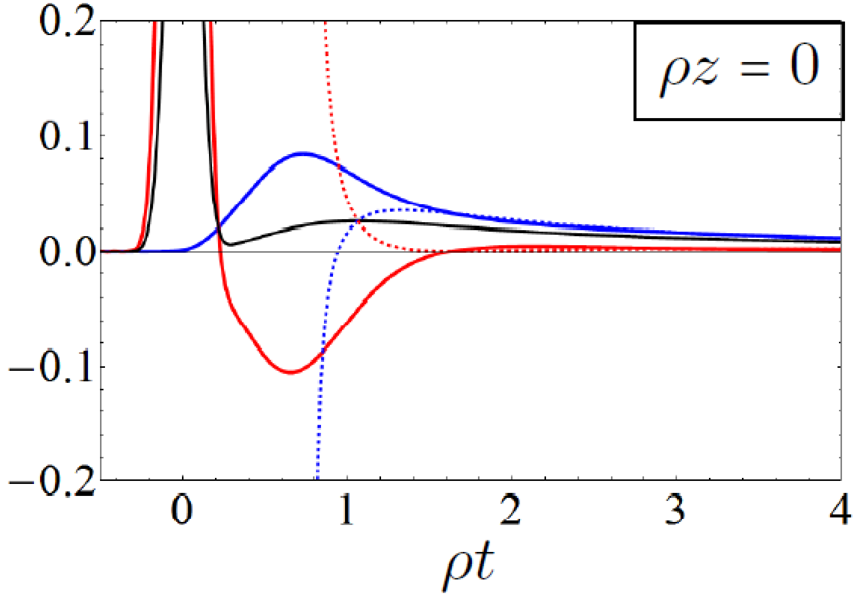
Wilke van der Schee, Utrecht

- Pressure, energy starts at zero, grows

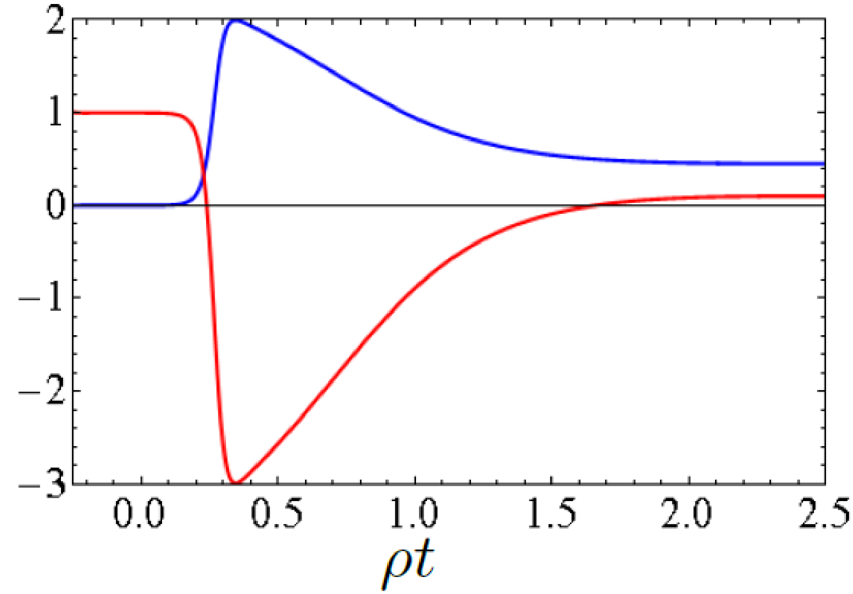
$$T_\mu^\nu = \text{diag}\{\epsilon(\tau),\, -\epsilon(\tau) - \tau\,\epsilon'(\tau),\, \epsilon(\tau) + \tfrac{1}{2}\tau\,\epsilon'(\tau),\, \epsilon(\tau) + \tfrac{1}{2}\tau\,\epsilon'(\tau)\}$$

- 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)



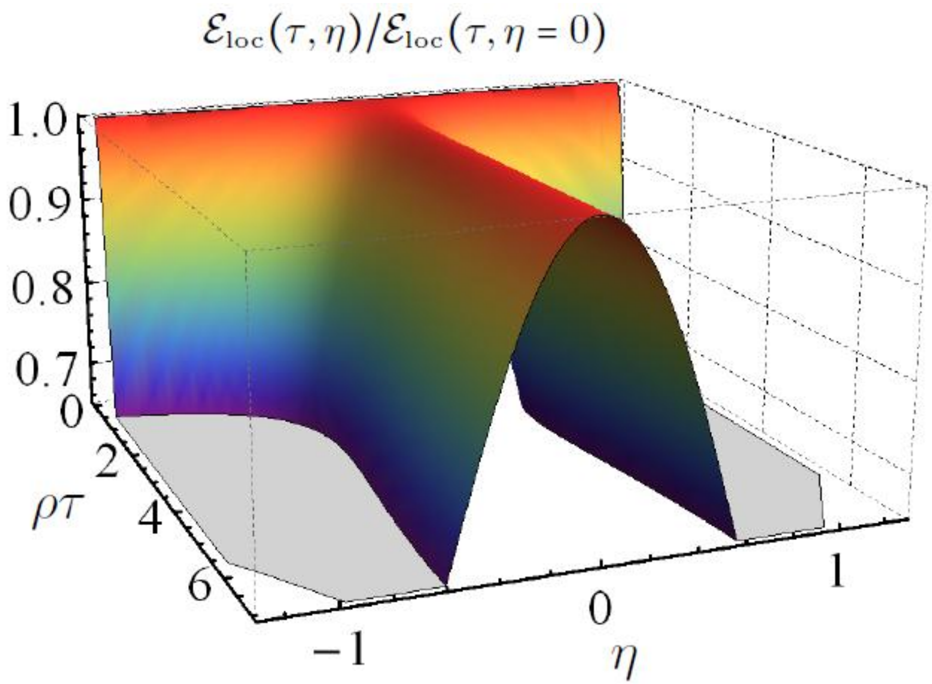
$\mathcal{P}_L/\mathcal{E}$ (red) and $\mathcal{P}_T/\mathcal{E}$ (blue)



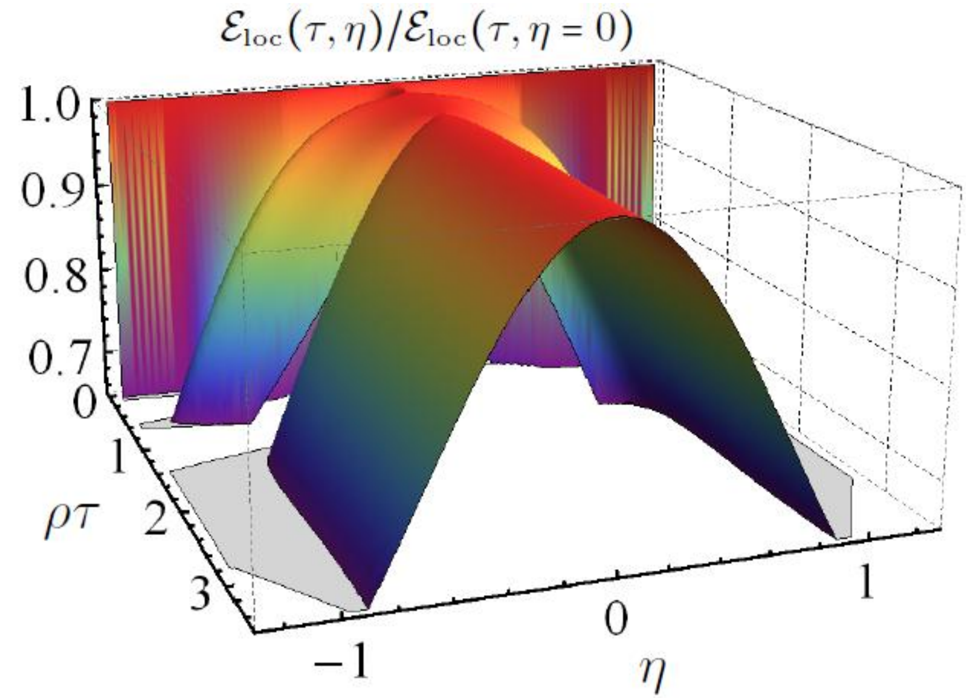
Shock waves – boost-invariance

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

Low energy:

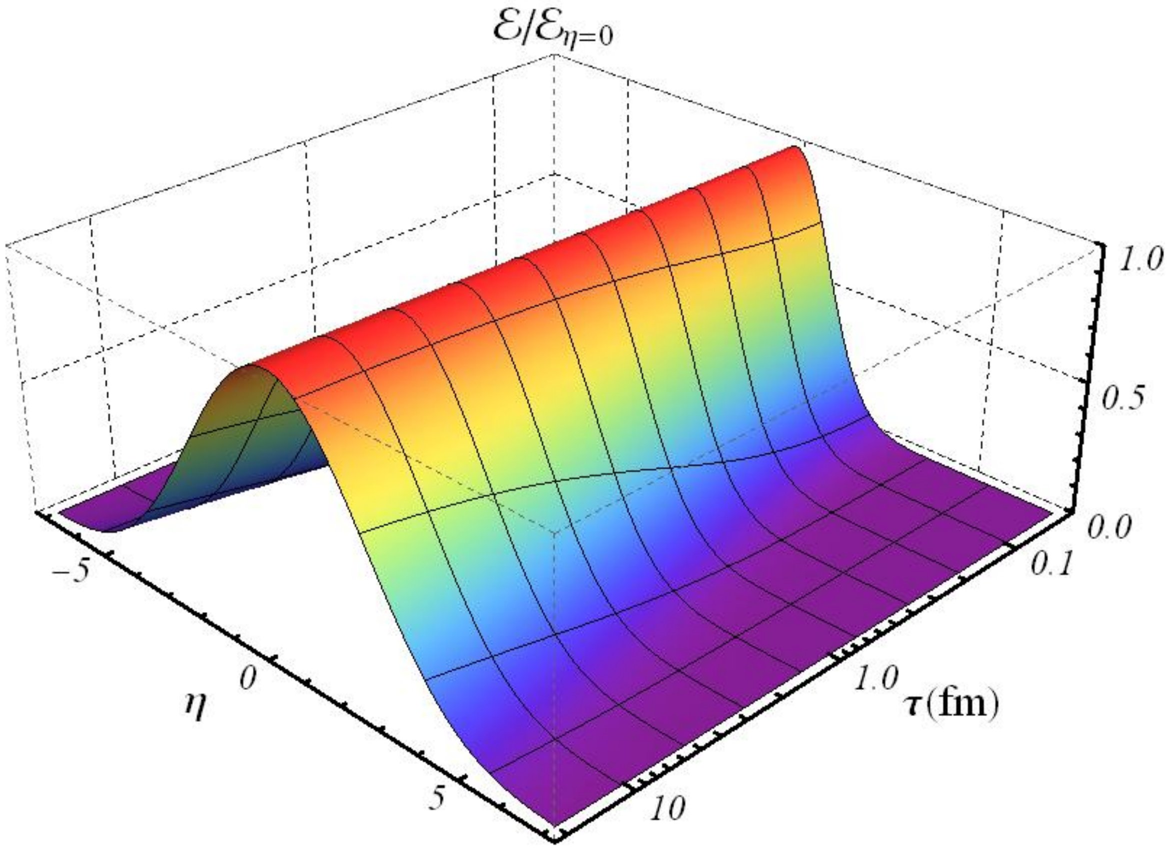


High energy:



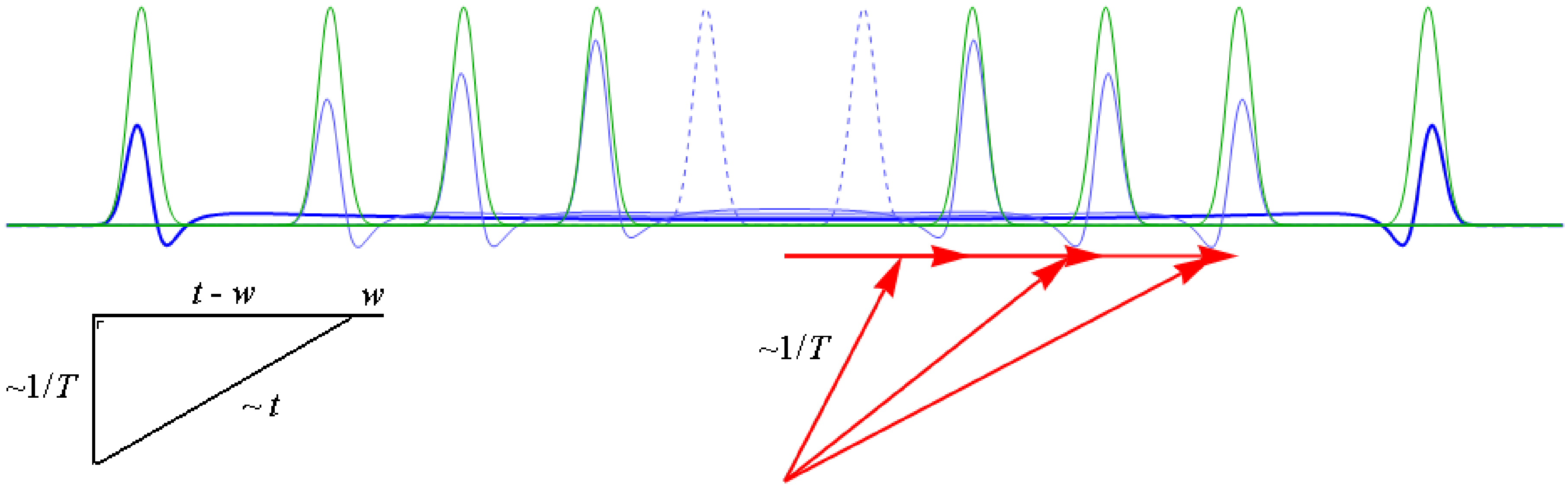
Time evolution of rapidity profile

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



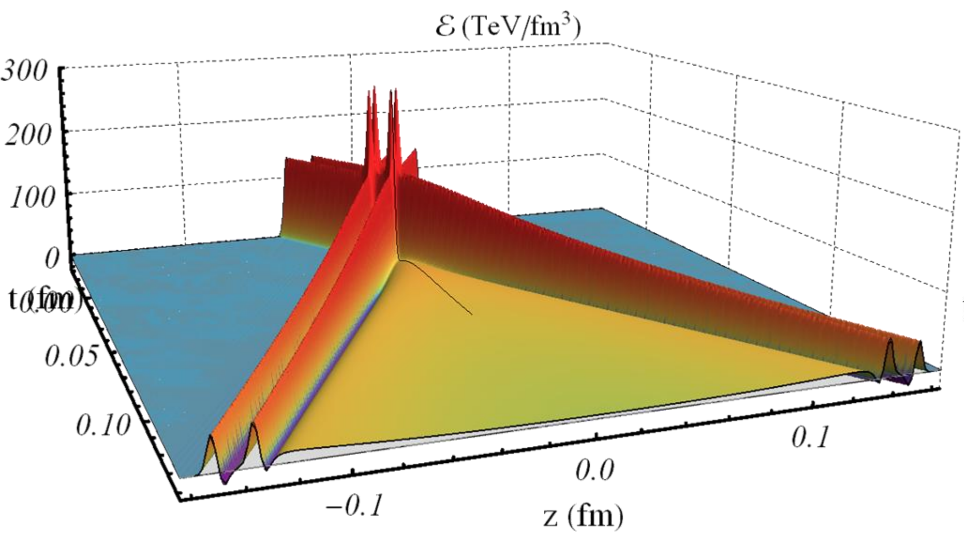
Shock waves from the bulk

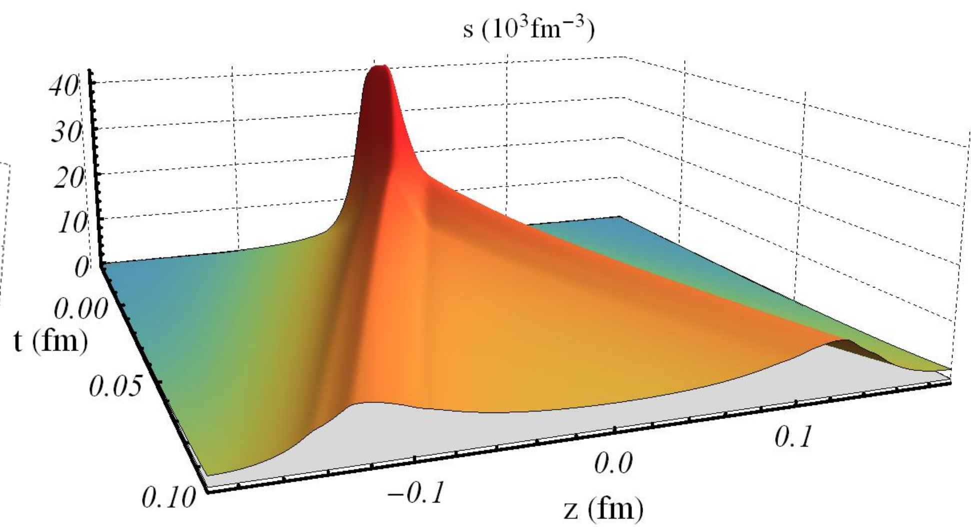
- Interesting interplay between temperature & width:
  - Non-linearity roughly comes from horizon
  - Touches front-end latest: by causality!



Newer results

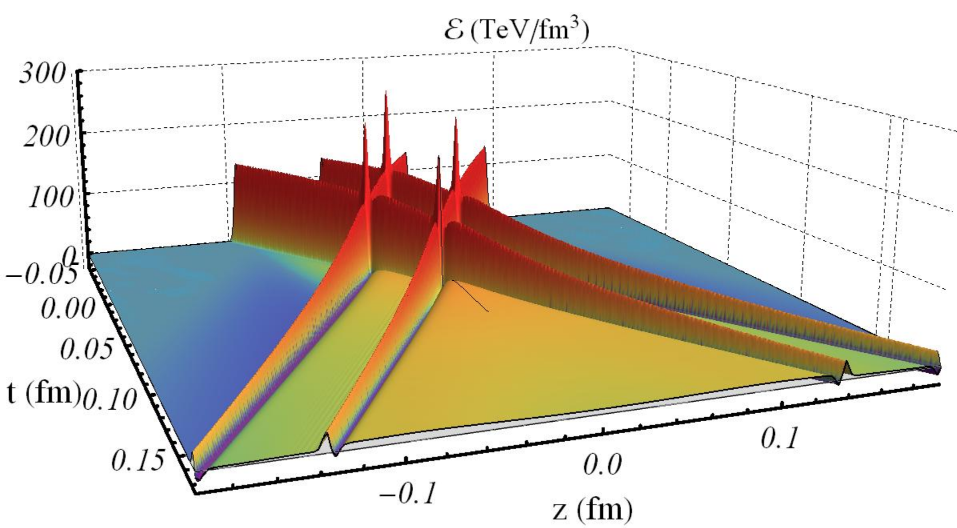
- UV structure is washed out in IR
  - Compare energy density with area apparent horizon
- No longitudinal initial state fluctuations (but thermal ones)

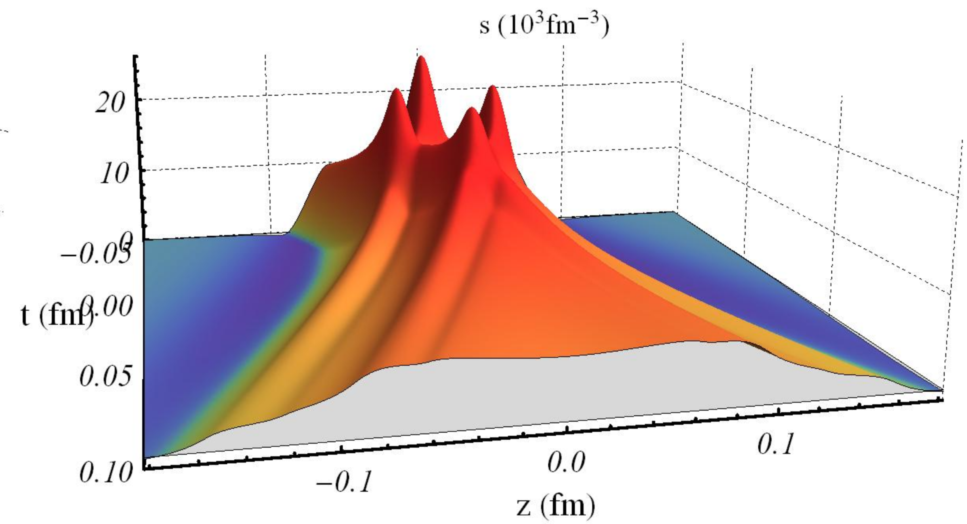




Newer results

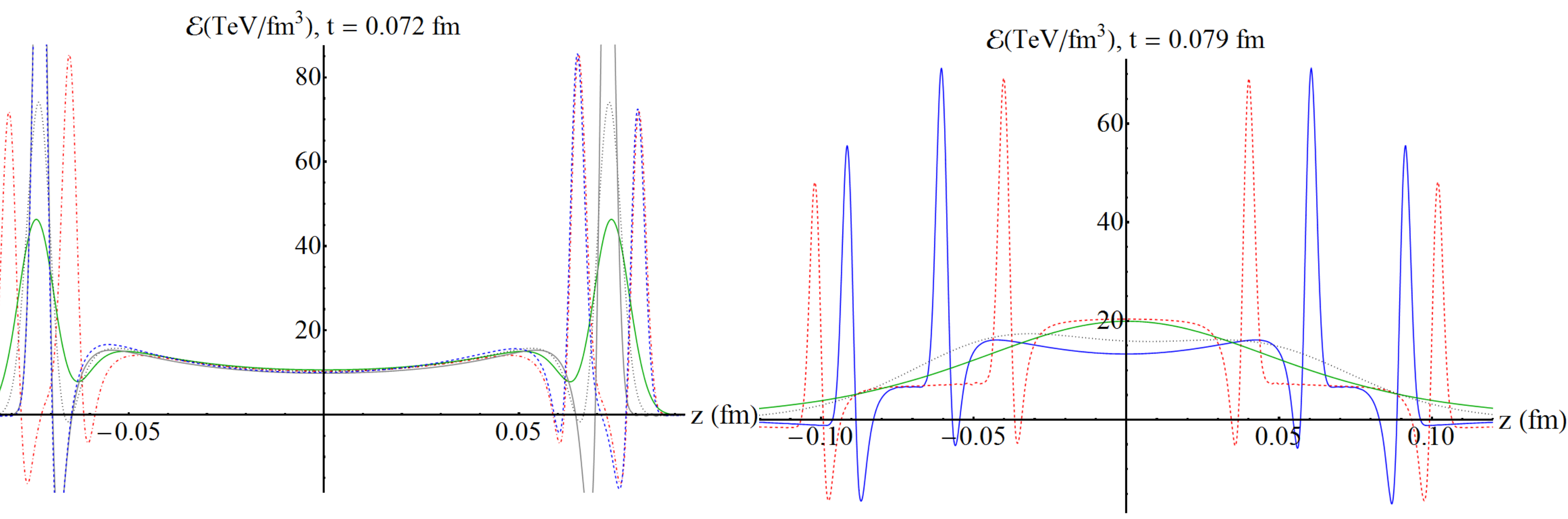
- UV structure is washed out in IR
  - Compare scale structure with 1/πTemperature:





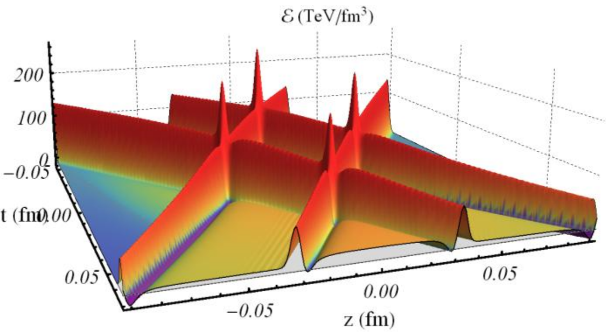
Newer results – longitudinal coherence

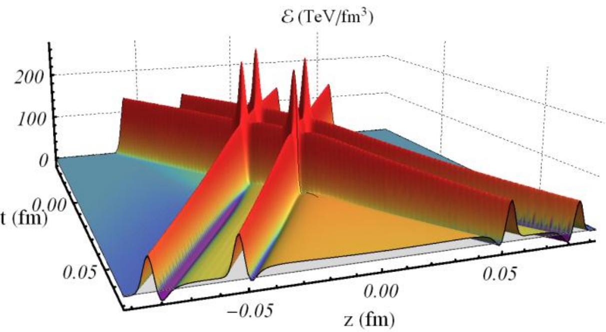
- Comparable c.o.m. late time results for narrow shocks:

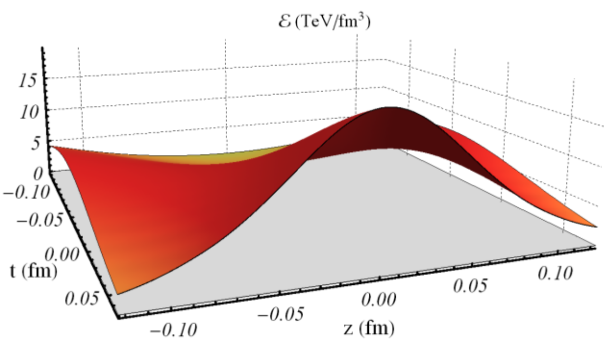


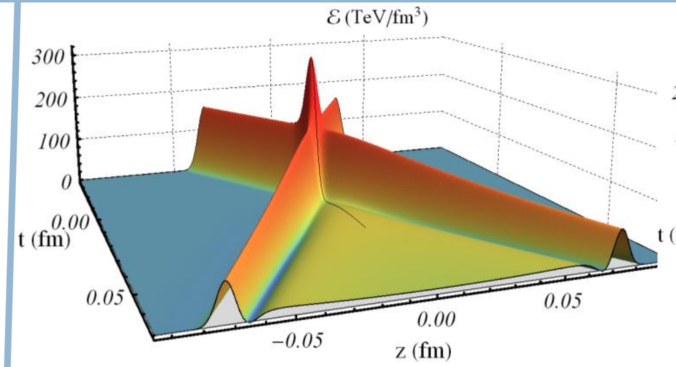
- Depending on characteristic size of longitudinal structure

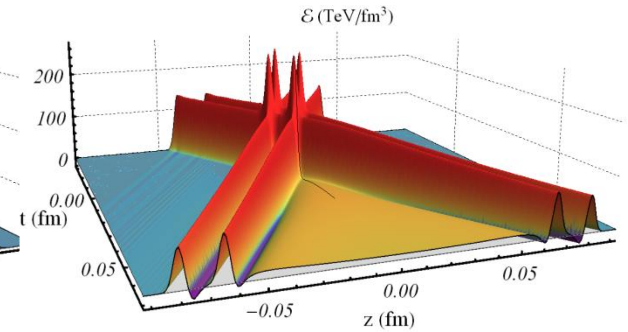
Shocks included in previous plot

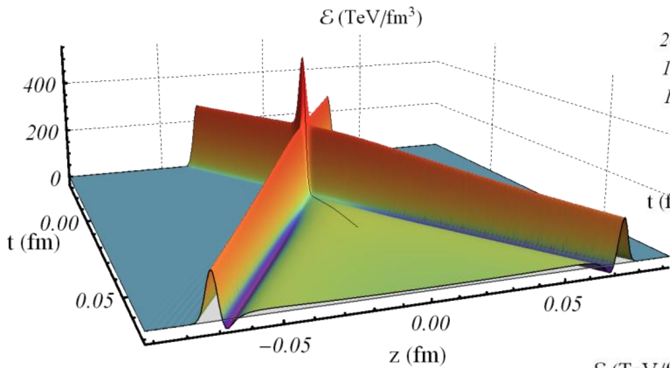


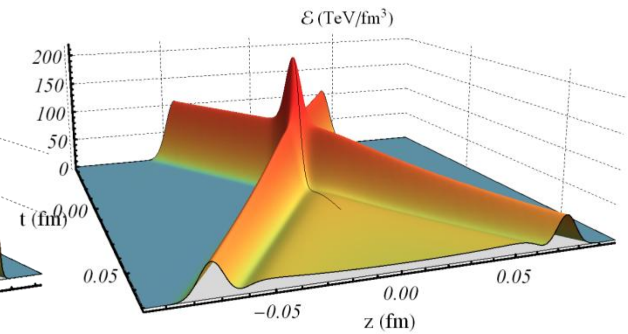


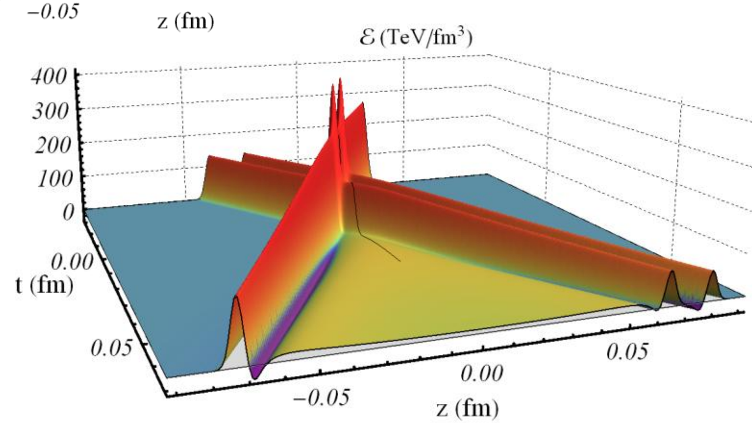






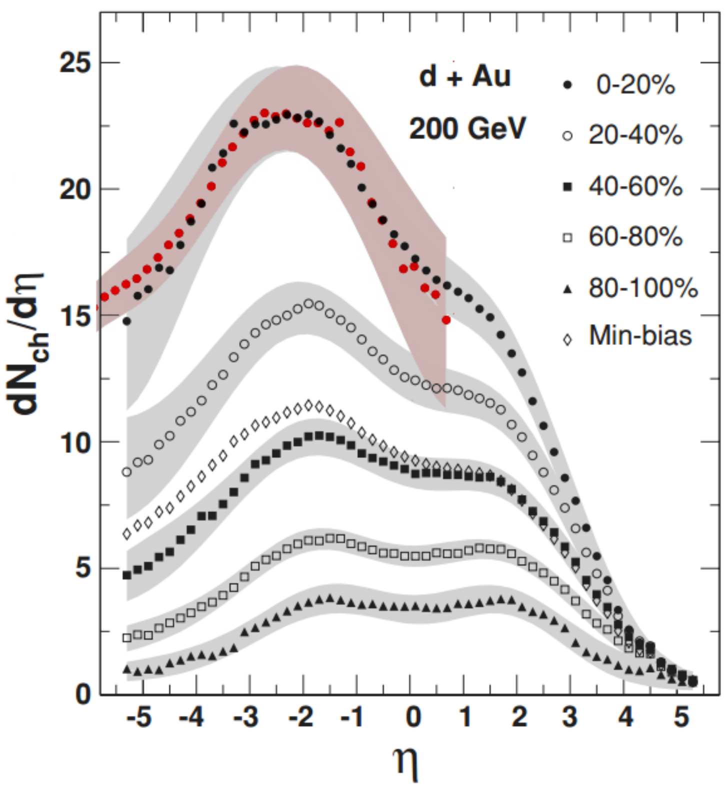


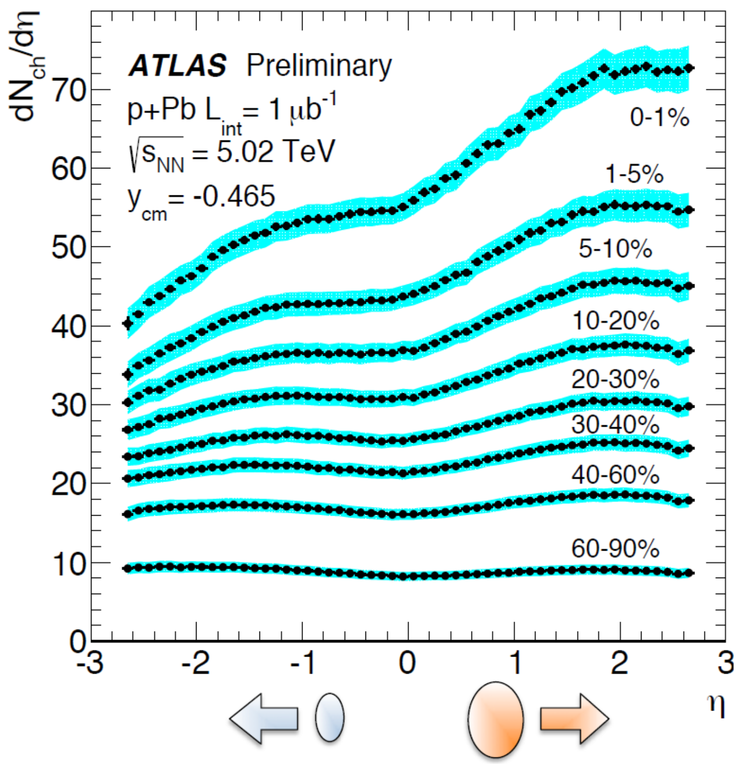




p-Pb symmetry, a prediction?

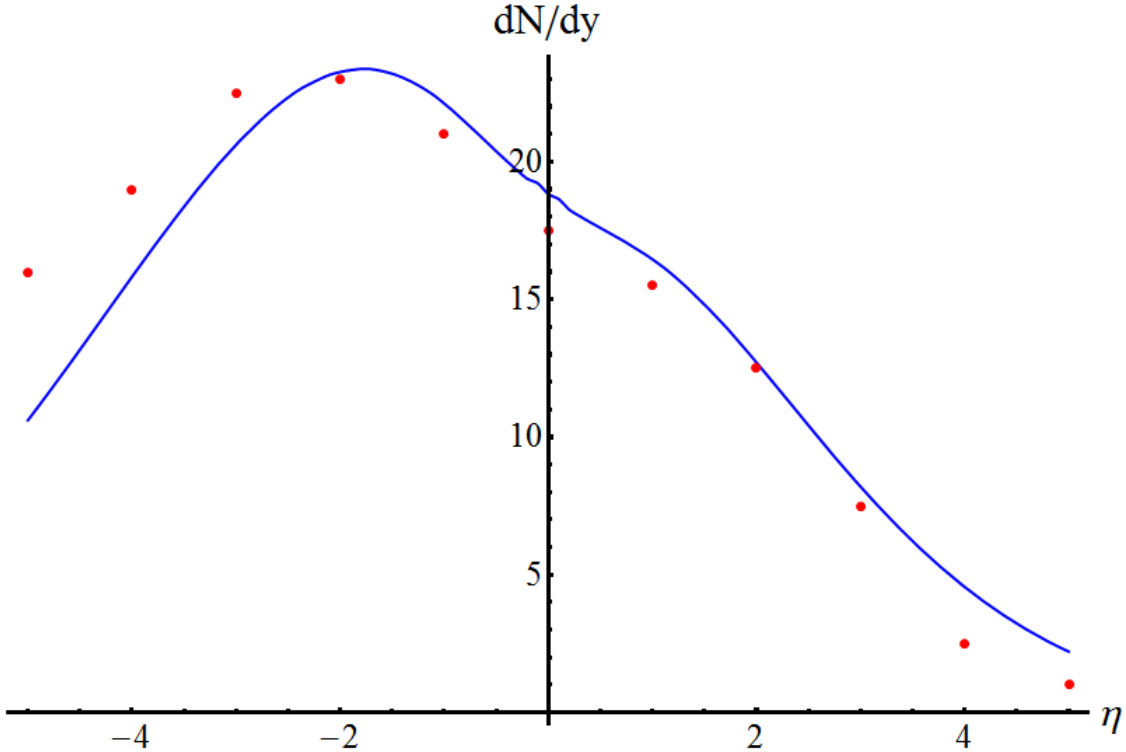
- No indications otherwise; CMS?
- pQCD gives dependence on saturation scales





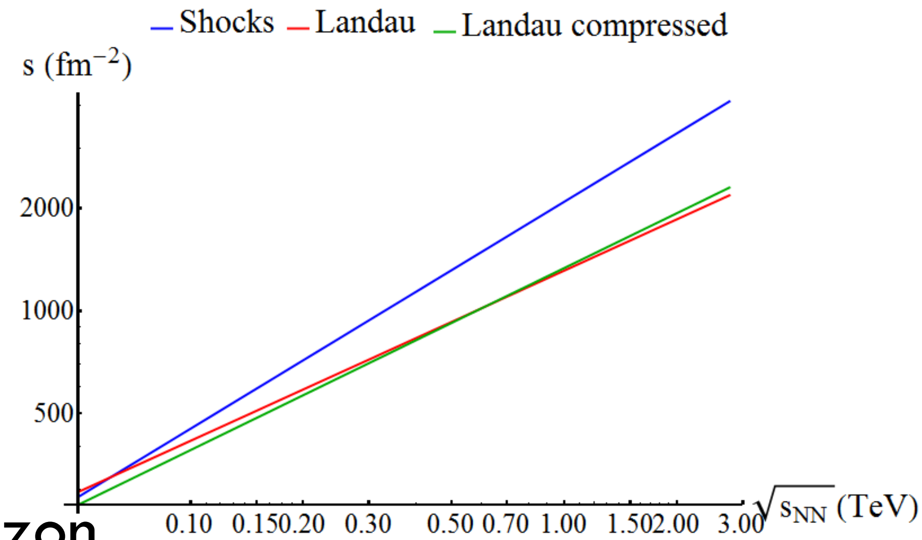
Rapidity vs pseudo-rapidity subtlety

- Jacobian effect, depending on mass, transverse p…
- Gaussian (shift 1.25, width 2.75) input
- Reasonable fit, given simplicity:



Multiplicities (work in progress)

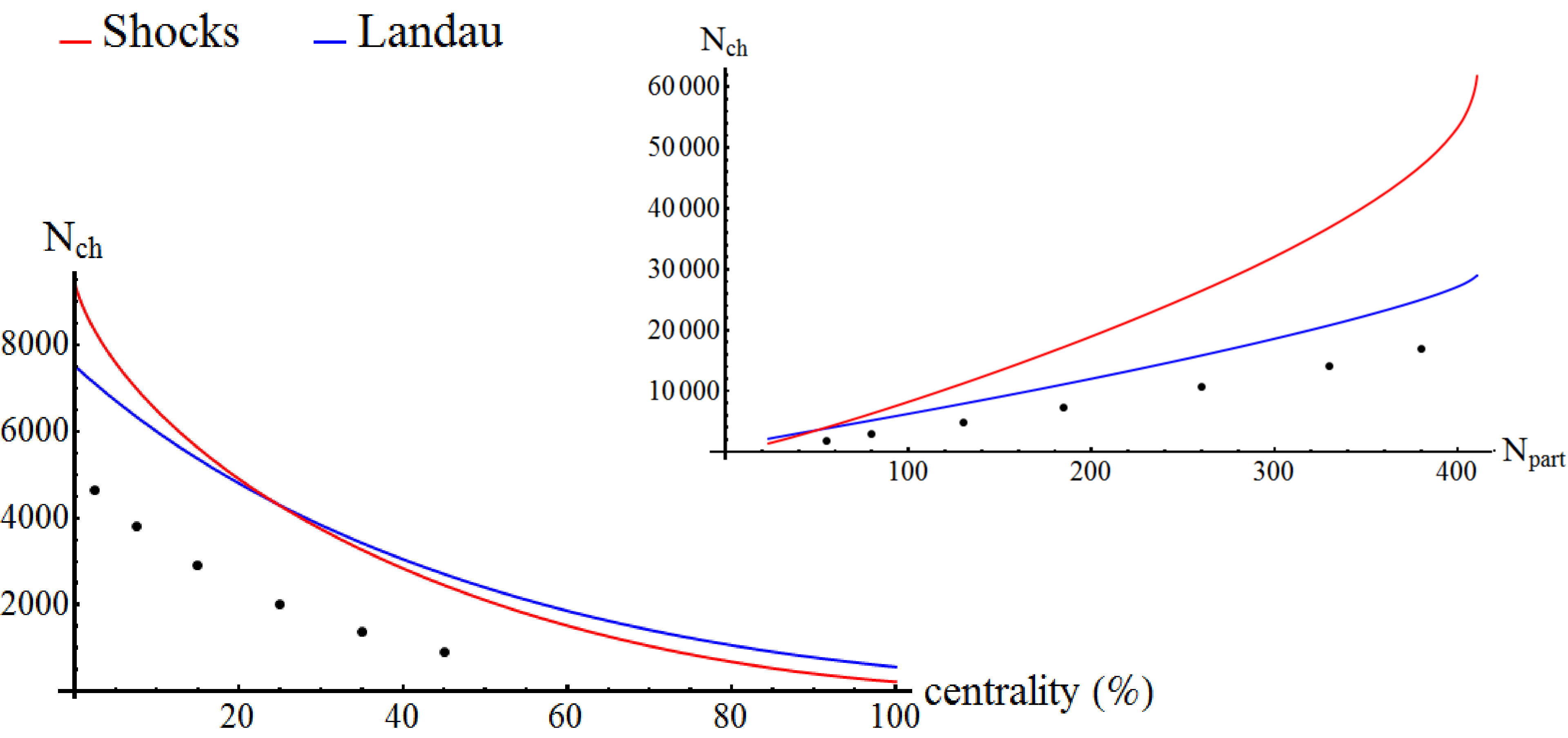
- Cooper-Frye: particles follow from phase space
  - Heuristic: $n \sim e / < E > \sim T^4 / T \sim s$
  - Calculation: $S/N_{\text{charged}} = 7.7$
- Ideal hydro conserves S
- Estimate initial entropy:
  - Compressed Landau
  - Landau model
  - Shocks with apparent horizon



- What multiplication factor to use?? (right now N_c=3)

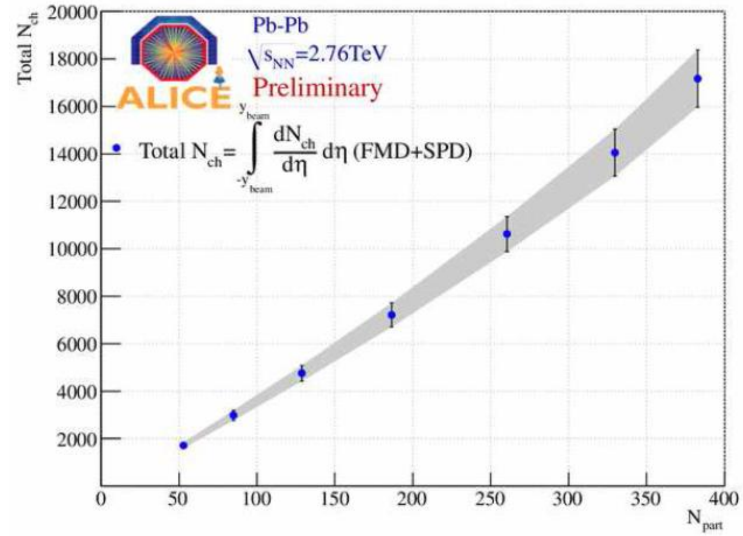
Preliminary plots

- pPb central (no fluctuations): $N_{ch} = 690$



Compare with experiments

- Normalisation tricky, but rest can be done!
- All kind of approximation,
  - To be continued
  - Errors also in N_{part}, N_{col}
- No fitting for now ☺



Cent. (%)	$\langle N_{\rm part}^{\rm Au}\rangle$	$\langle N_{\rm part}^{d}\rangle$	$\langle N_{\rm coll}\rangle$	$N_{\vert\eta\vert\leqslant 5.4}^{\rm ch}$	$N_{\rm Tot}^{\rm ch}$
0–20	13.5 ± 1.0	2.0 ± 0.1	14.7 ± 0.9	157 ± 10	167^{+14}_{-11}
20–40	8.9 ± 0.7	1.9 ± 0.1	9.8 ± 0.7	109 ± 7	115^{+10}_{-8}
40–60	5.4 ± 0.6	1.7 ± 0.2	5.9 ± 0.6	74 ± 5	77^{+7}_{-5}
60–80	2.9 ± 0.5	1.4 ± 0.2	3.1 ± 0.6	46 ± 3	48^{+3}_{-3}
80–100	1.6 ± 0.4	1.1 ± 0.2	1.7 ± 0.5	28 ± 3	29^{+3}_{-3}
Min-Bias	6.6 ± 0.5	1.7 ± 0.1	7.1 ± 0.5	82 ± 6	87^{+7}_{-6}
50–70	3.9 ± 0.6	1.6 ± 0.2	4.2 ± 0.6	59 ± 4	62^{+5}_{-4}

Centrality	$\eta = 0$	$\eta = 3.0$	$\eta = 4.5$	N_{ch}	$\langle N_{coll}\rangle$	$\langle N_{part}\rangle$
0-5	625±55	470±44	181 ±22	4630±370	1000±125	357±8
5-10	501±44	397±37	156±18	3810±300	785±115	306±11
10-20	377±33	309±28	125±14	2920±230	552±100	239±10
20-30	257±23	216±17	90 ±10	2020±160	335±58	168±9
30-40	174±16	149±14	64 ±7	1380±110	192±43	114±9
40-50	110±10	95±9	43 ±5	890±70	103±31	73±8

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 (3.7 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, longitudinal coherence
- Curious: shocks give Landau model precisely at RHIC!

Fancy plots: microstructure, p-Pb, longer runs