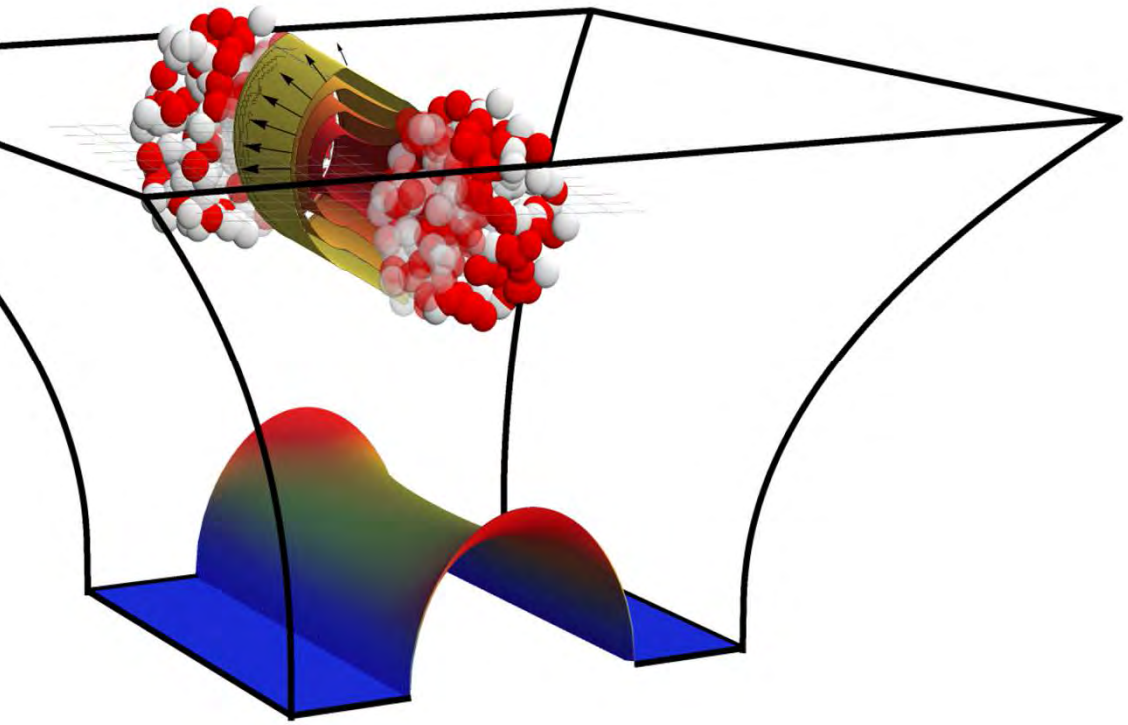
GRAVITATIONAL COLLISIONS AND THE QUARK-GLUON PLASMA

TOWARDS MORE REALISTIC MODELS OF THE QGP THERMALISATION

Work with Michał Heller, David Mateos, Jorge Casalderrey, Paul Romatschke, Scott Pratt and Peter Arnold
References: 1305.4919 (PRL), 1307.253 (PRL), 1312.2956 (PRL), 1407.1849 (Thesis) and 1408.2518



Wilke van der Schee

1 September 2014, Kolimbari

OUTLINE

Heavy-ion primer

AdS/CFT: initial state @ strong coupling

- Only approximate to QCD at intermediate coupling; simplified setting
- Starting to get useful conclusions for HIC

Gravitational shock waves in AdS

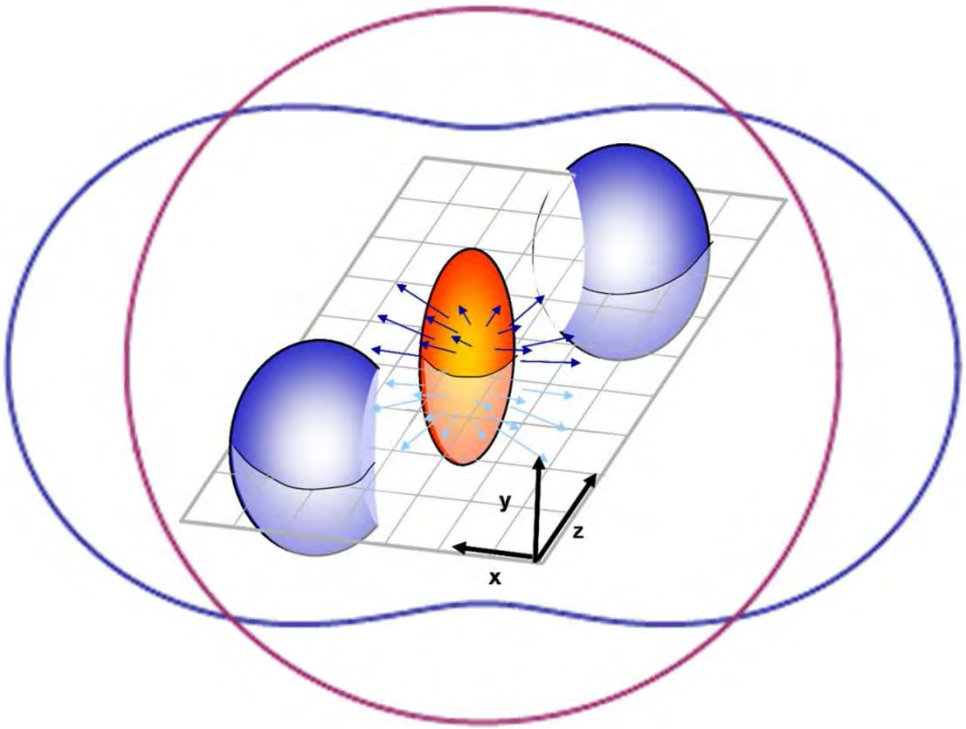
- From Landau to Bjorken (but not quite)
- Coherence and a *universal rapidity profile*

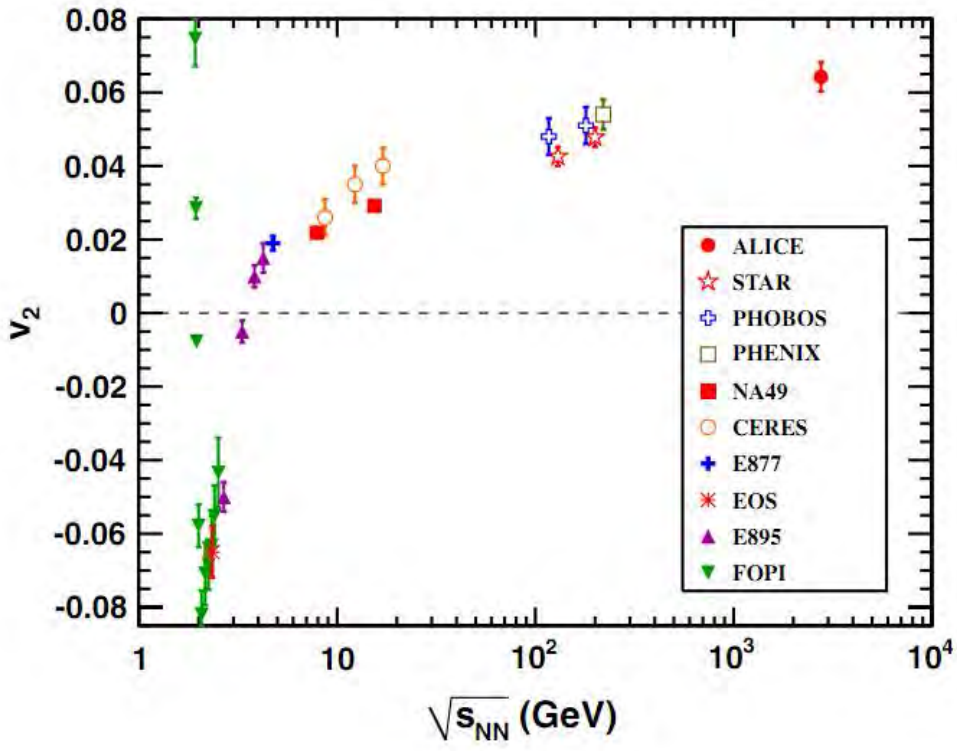
Dynamical thermalisation with radial flow and spectra

ELLIPTIC FLOW: v_2, QGP IS INTERESTING

How anisotropic is the final state?

- Ideal gas/weak coupling
- Perfect fluid/strong coupling





K. Aamodt et al, Elliptic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}}$=2.76 TeV (2010)

KEY HEAVY ION PHYSICS:

Surprising (?): quark-gluon plasma is a fluid!

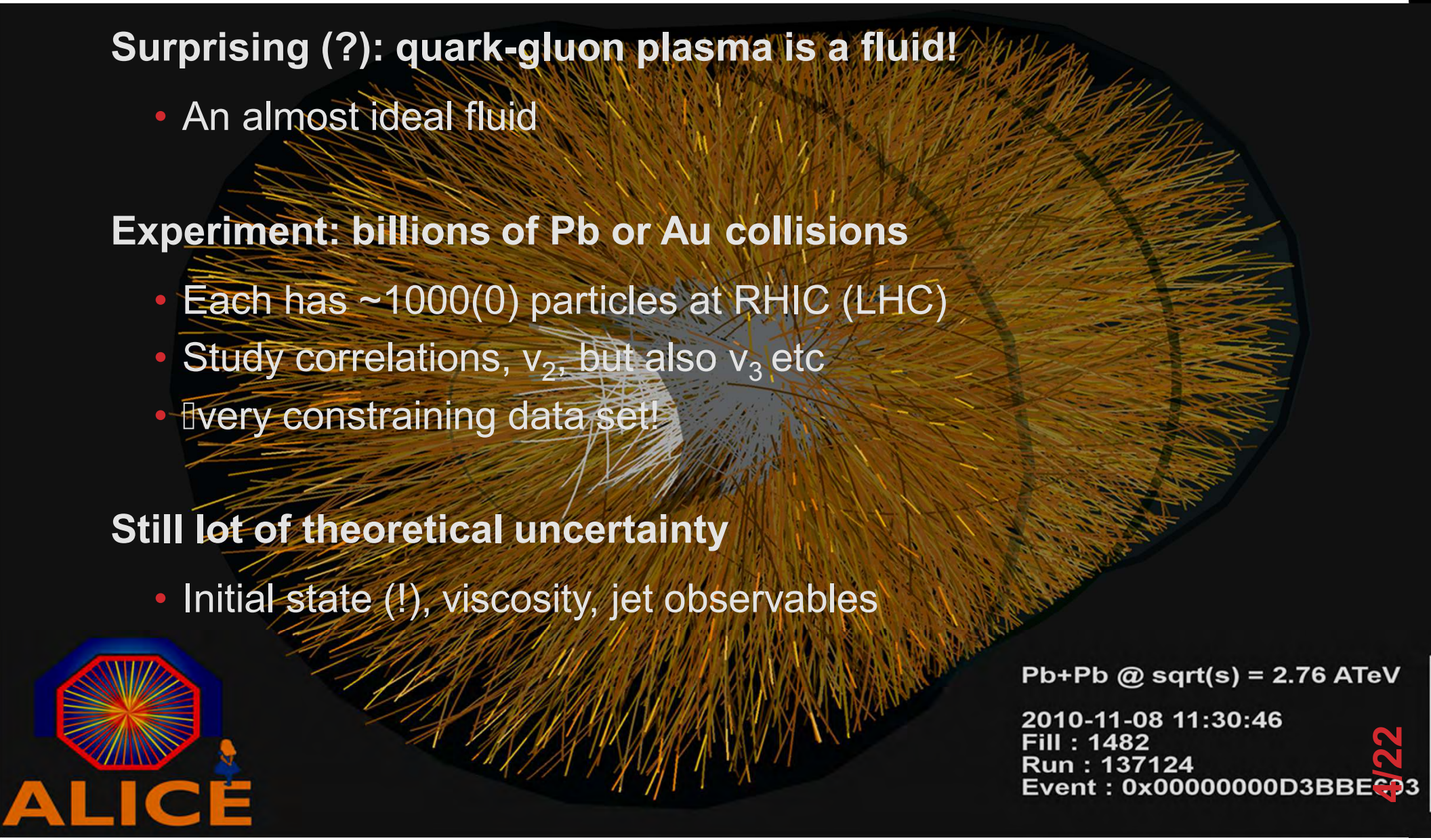
- An almost ideal fluid

Experiment: billions of Pb or Au collisions

- Each has ~1000(0) particles at RHIC (LHC)
- Study correlations, v_2, but also v_3 etc
- very constraining data set!

Still lot of theoretical uncertainty

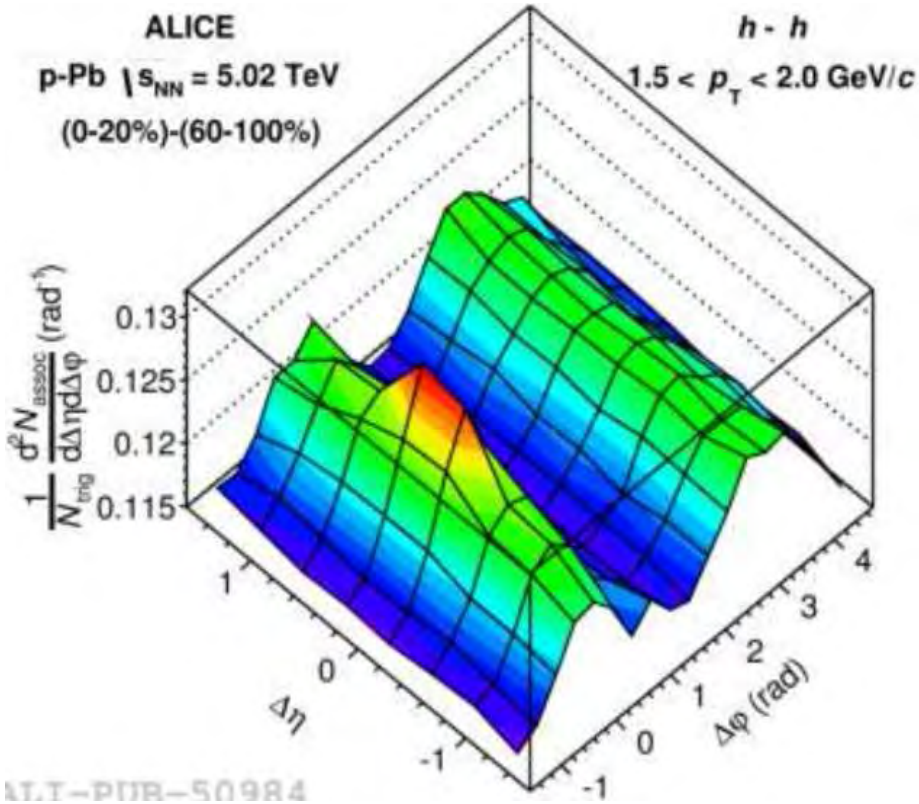
- Initial state (!), viscosity, jet observables

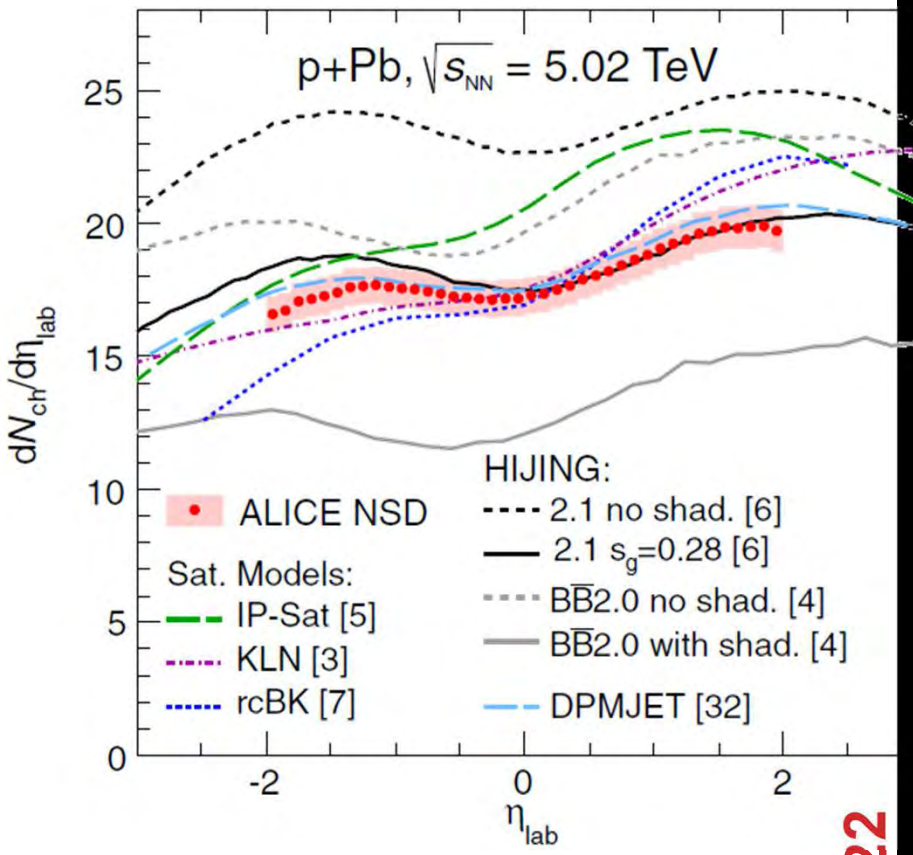


HEAVY IONS - RECENT EXCITEMENT

Double ridge observed in p-Pb

Mass ordering of v_2 similar to hydro models



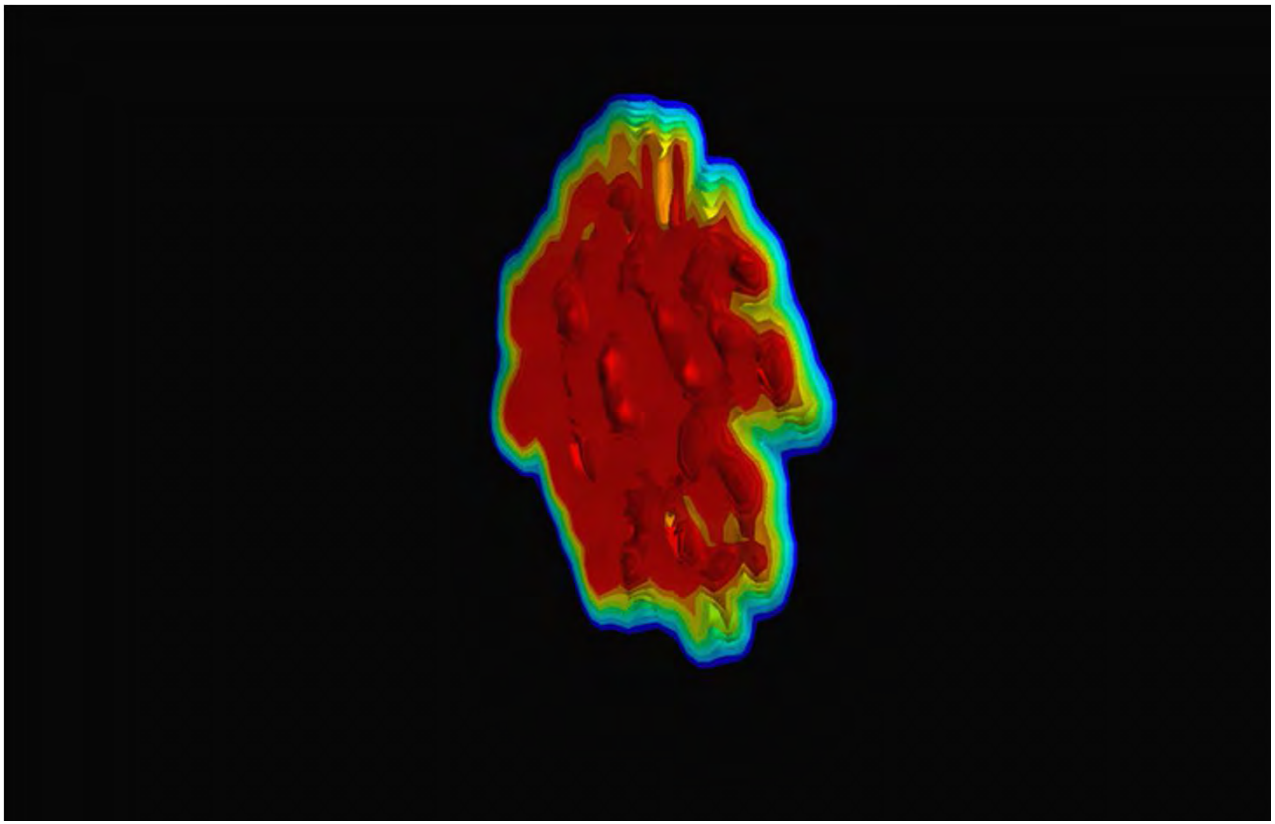


ALICE, Long-range angular correlations on the near and away side in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
ALICE, Pseudorapidity Density of Charged Particles in p-Pb Collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

HEAVY ION STATE-OF-THE-ART (BJORN SCHENKE)

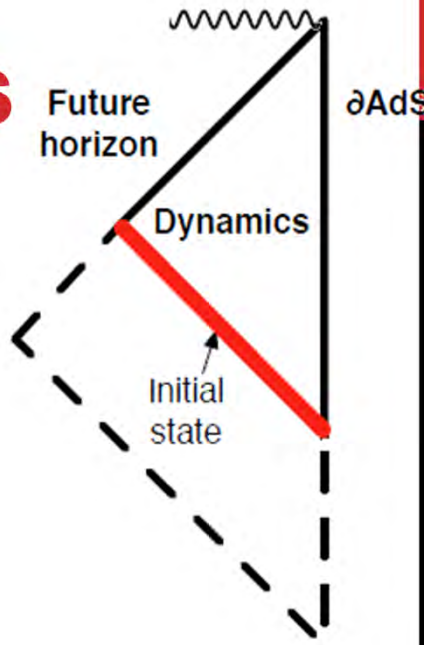
Start with energy density from Wood-Saxon profile

- Profile in rapidity largely put in by hand (BI+cut-off)
- □ hydrodynamics has uncertainty in initial state!



Glossed over: subtleties in applying AdS/CFT
(in particular: infinite coupling)

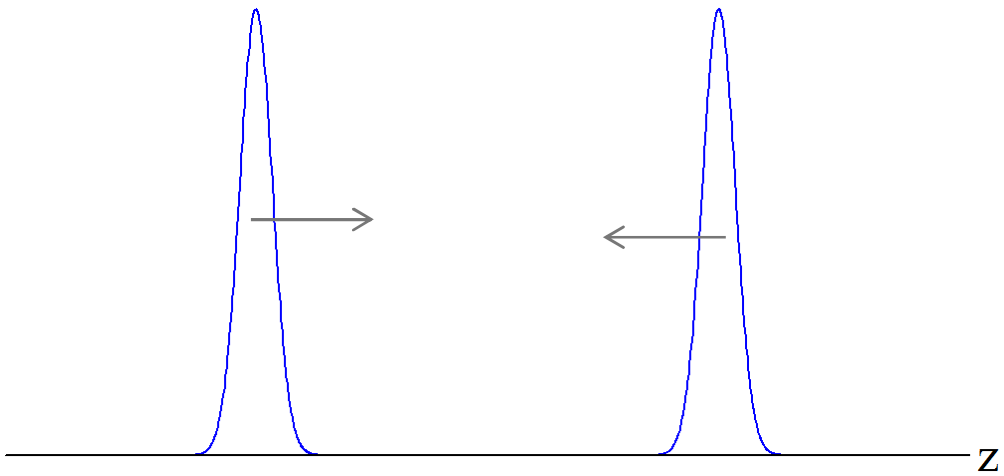
SHOCK WAVES – INITIAL CONDITIONS



Field theory interpretation:

- Start with energy as function of space
- Demand that it moves with speed of light
- ⇒ quantum state/AdS geometry is completely fixed

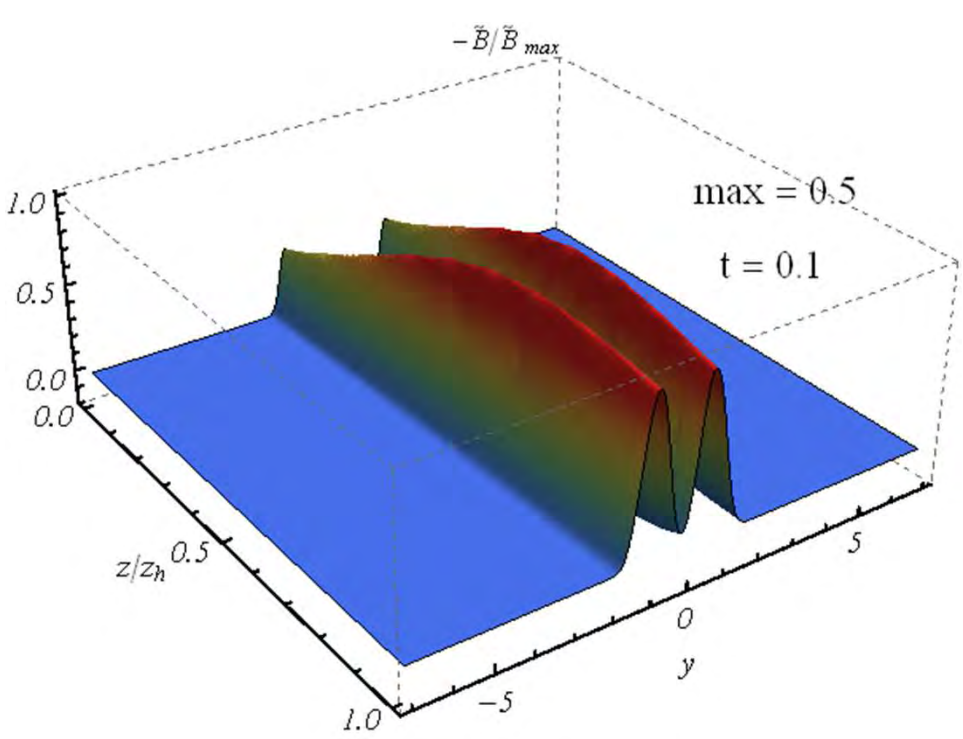
Homogeneous in transverse plane ('infinite nucleus')

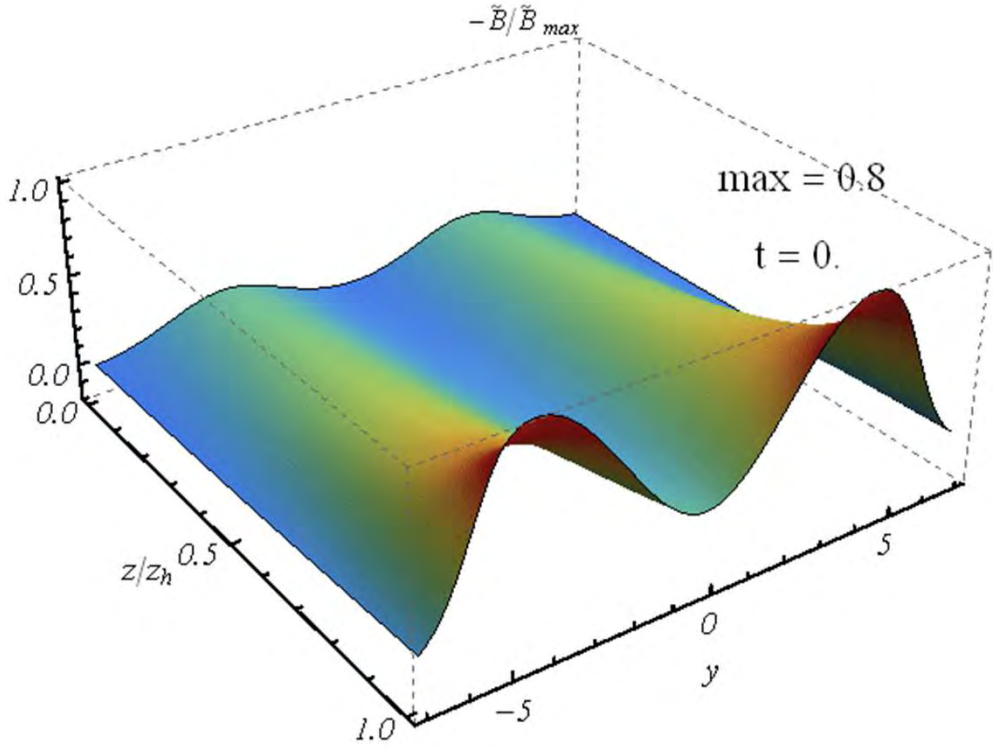


P.M. Chesler and L.G. Yaffe, Holography and colliding gravitational shock waves in asymptotically AdS_5 spacetime (2010)

SHOCK WAVES – EVOLUTION

$$ds^2 = dt(2dr - Adt + 2Fdz) + S^2(e^B d\mathbf{x}_\perp^2 + e^{-2B} dy^2)$$

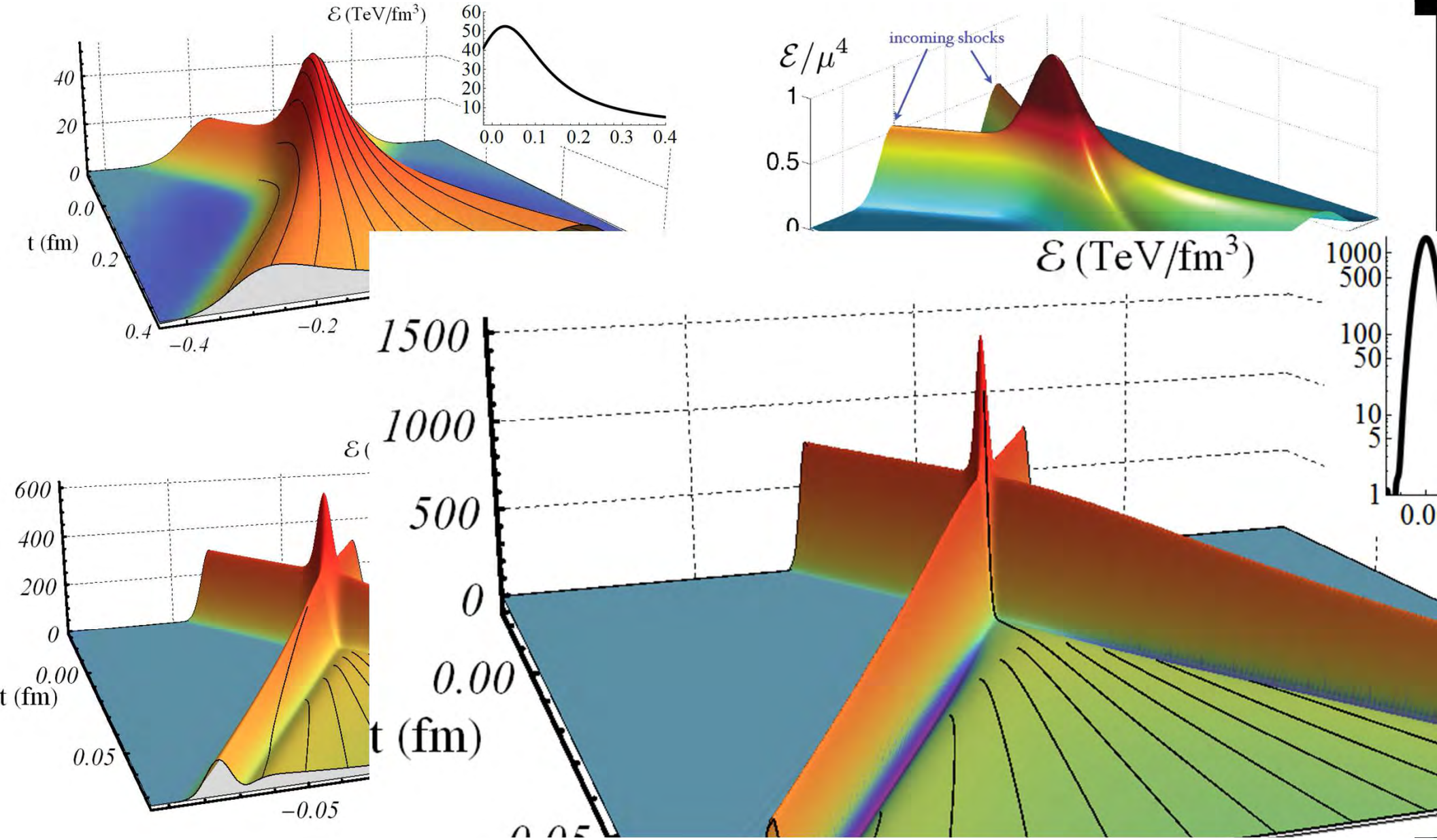




- Details in PhD thesis

All units are fixed by total energy per transverse area at centre of central LHC-collisions

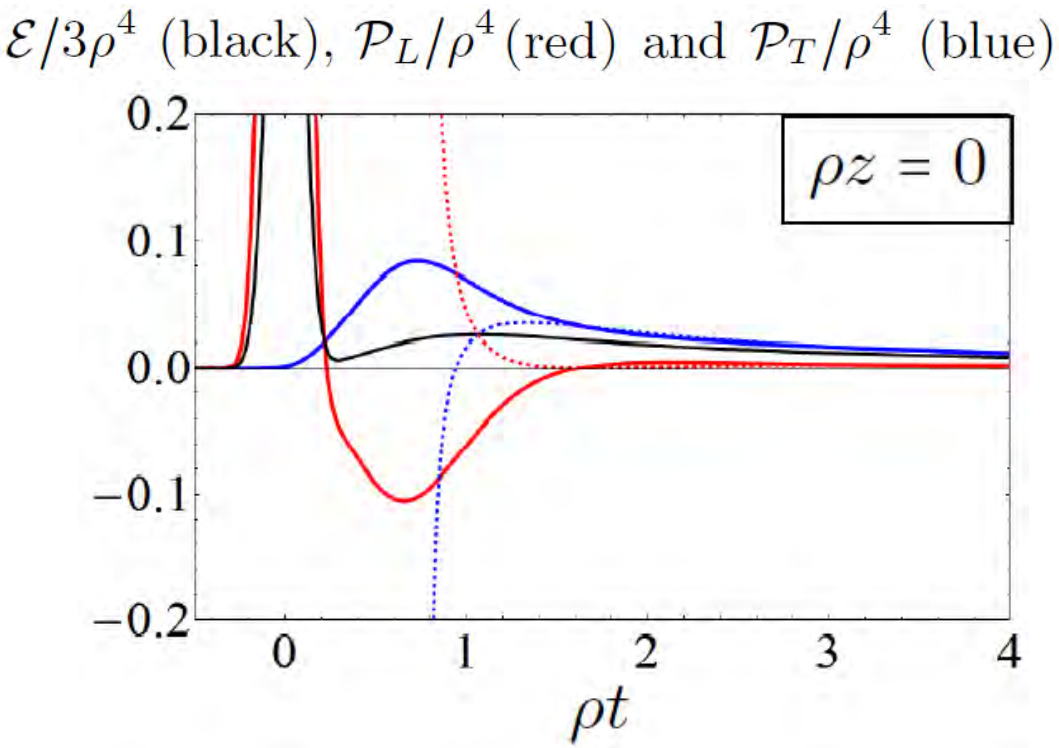
SHOCK WAVES – A DYNAMICAL CROSS-OVER

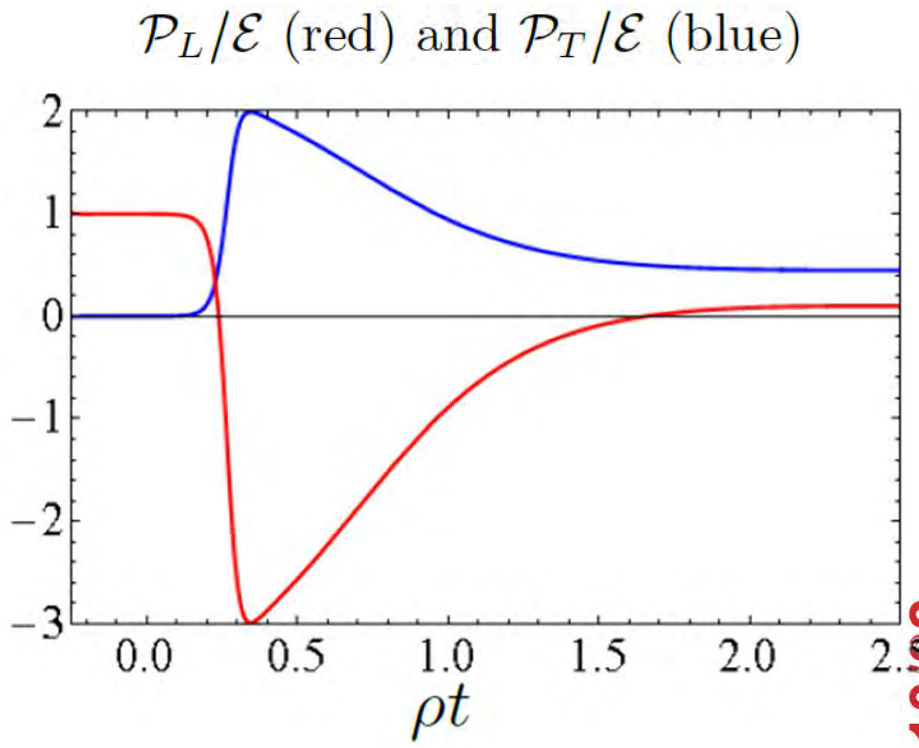


PRESSURE ANISOTROPY

Pressure, energy starts at zero, grows

Can give large negative longitudinal pressure:





A DYNAMICAL CROSS-OVER

Low energy:

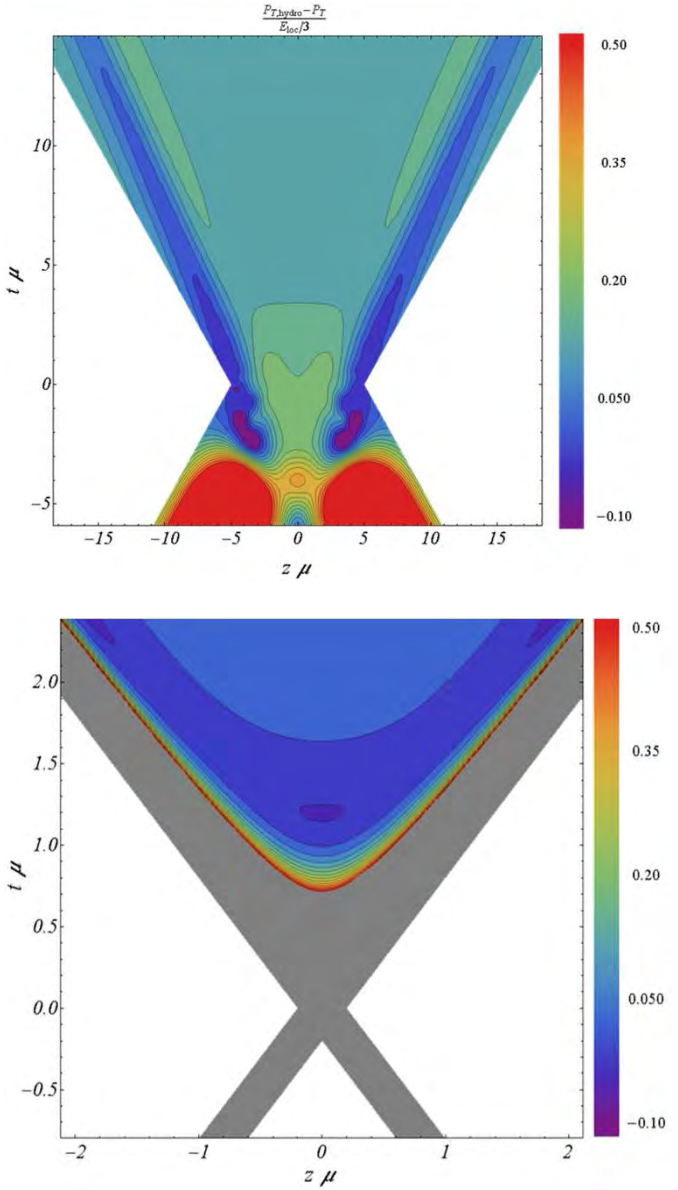
- Stopping, piling up of energy
- Expansion by hydro
- Compressed Landau model

RHIC energy

- Landau model
- entropy ~ $(\sqrt{s_{NN}})^{1/2}$

High energy:

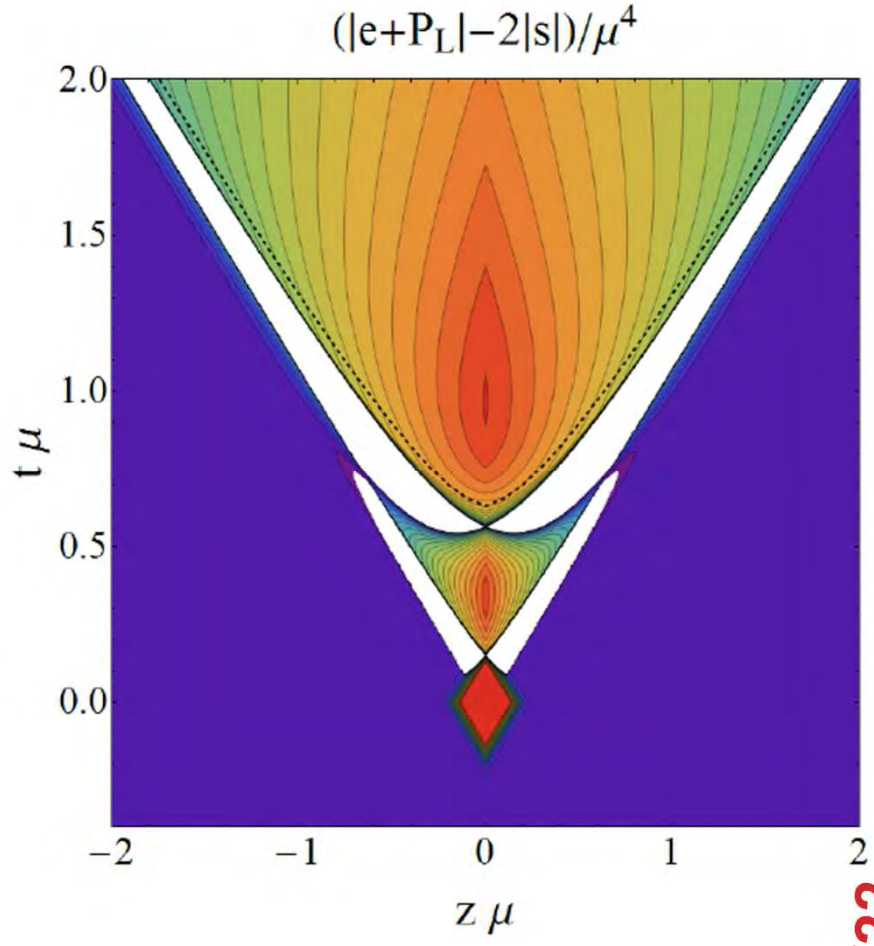
- no stopping
- plasma forms slowly
- transient negative energy
- entropy ~ $(\sqrt{s_{NN}})^{2/3}$



REGIONS WITHOUT A REST FRAME (THIN SHOCKS)

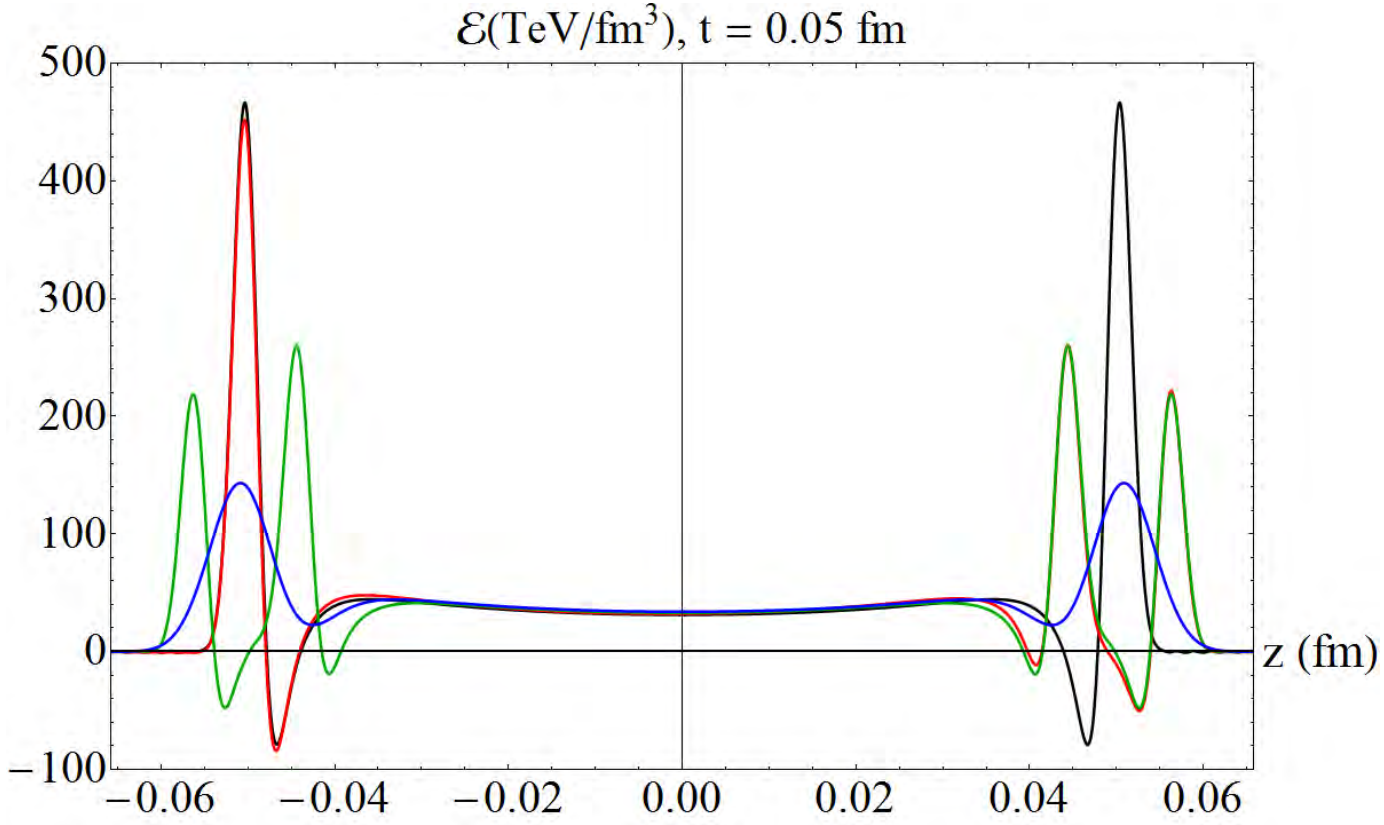
Work with Paul Romatschke and Peter Arnold (1408.2518)

- **Regios with negative energy density**
- **Regions where no Lorentz boost can diagonalise stress tensor!**
  - Also found in other systems
- **But no pathologies: well-defined quantum phenomenon**
  - Still curious: possibly present in HIC! (consequences??!)



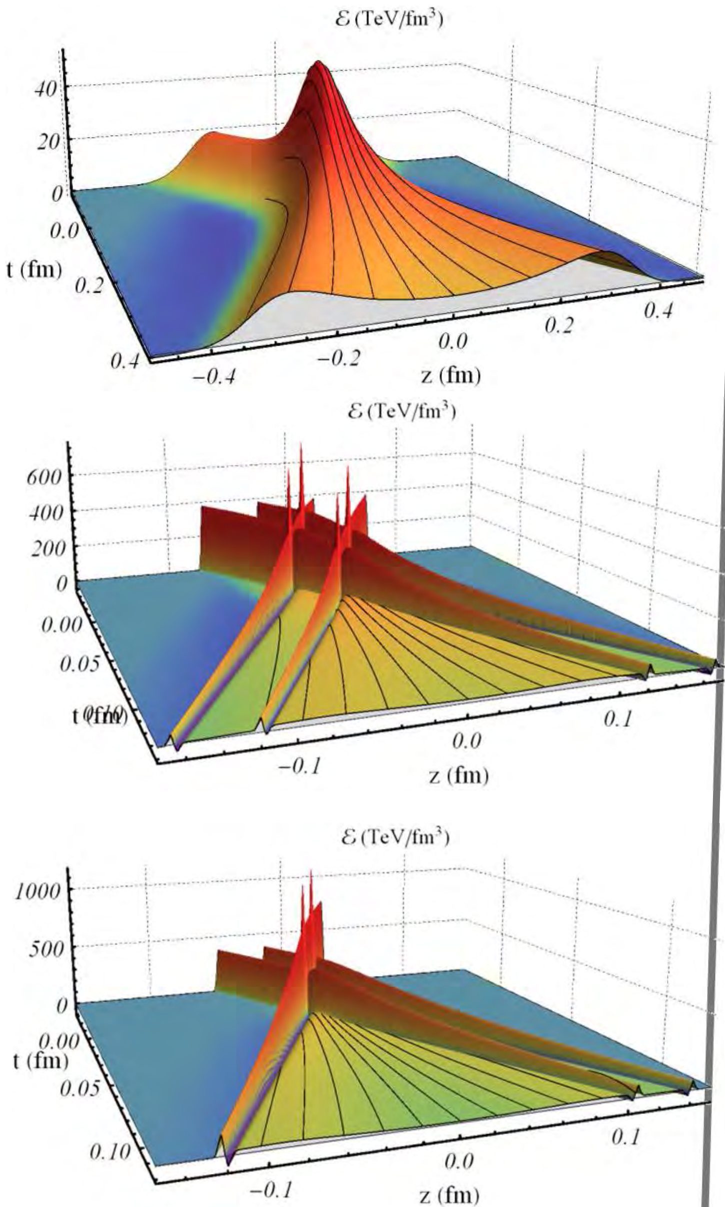
LONGITUDINAL COHERENCE

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



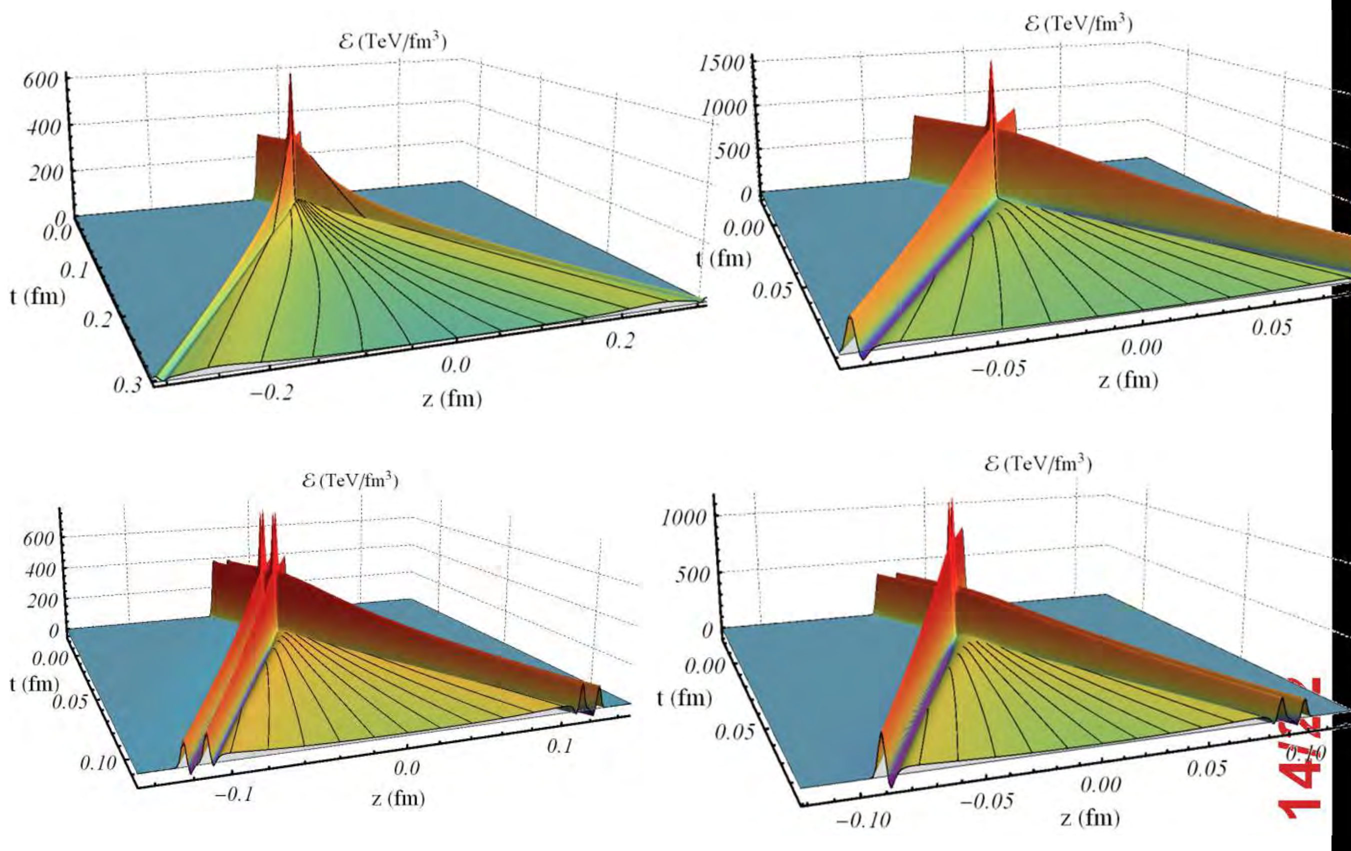
So narrow shocks approximate `delta-limit'

IMPORTANT CONCLUSION



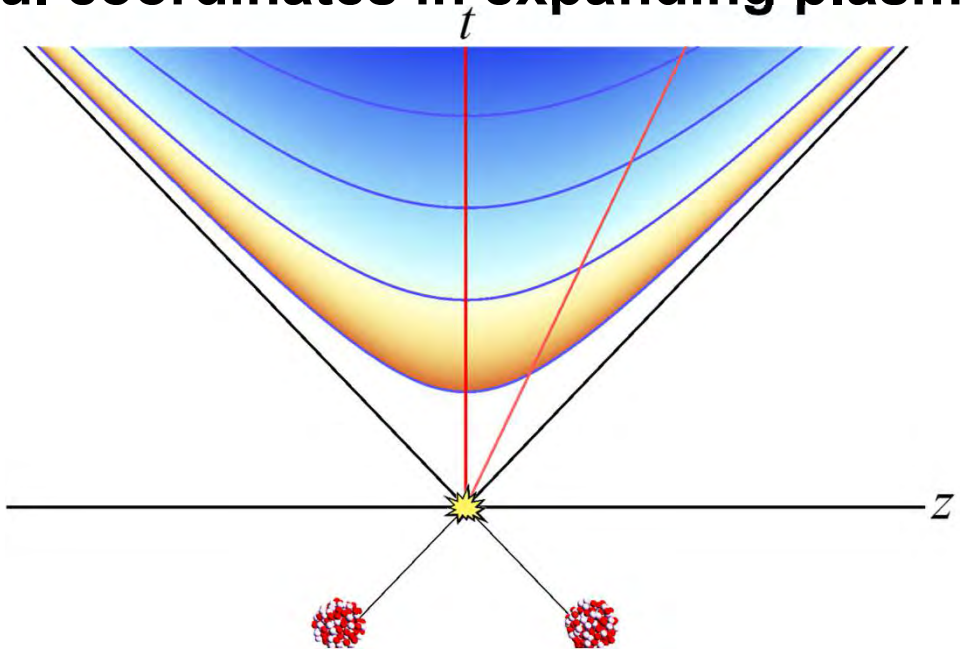
Longitudinal dynamics takes place in c.o.m. of participating nucleons

In particular, it is symmetric around mid-rapidity



RAPIDITIES AND *INITIAL STATE* BI

Useful coordinates in expanding plasmas:



$$t = \tau \cosh y$$

$$z = \tau \sinh y$$

Weak coupling: interactions follow charge

- Boost-invariant if moving on light-cone

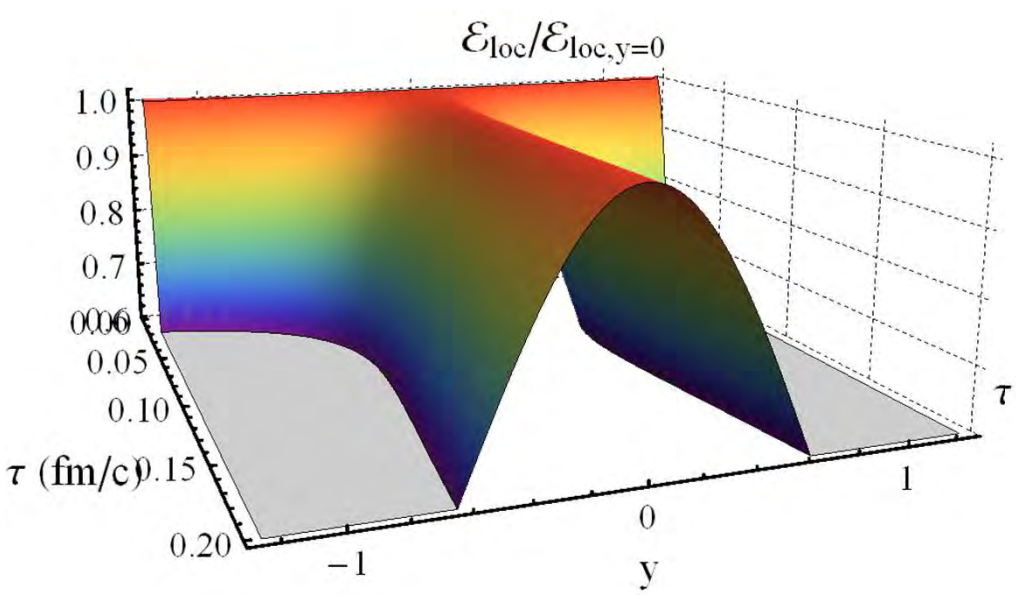
Strong coupling: interactions follow energy

- Receives γ-factor on boosting, even if v ≈ c

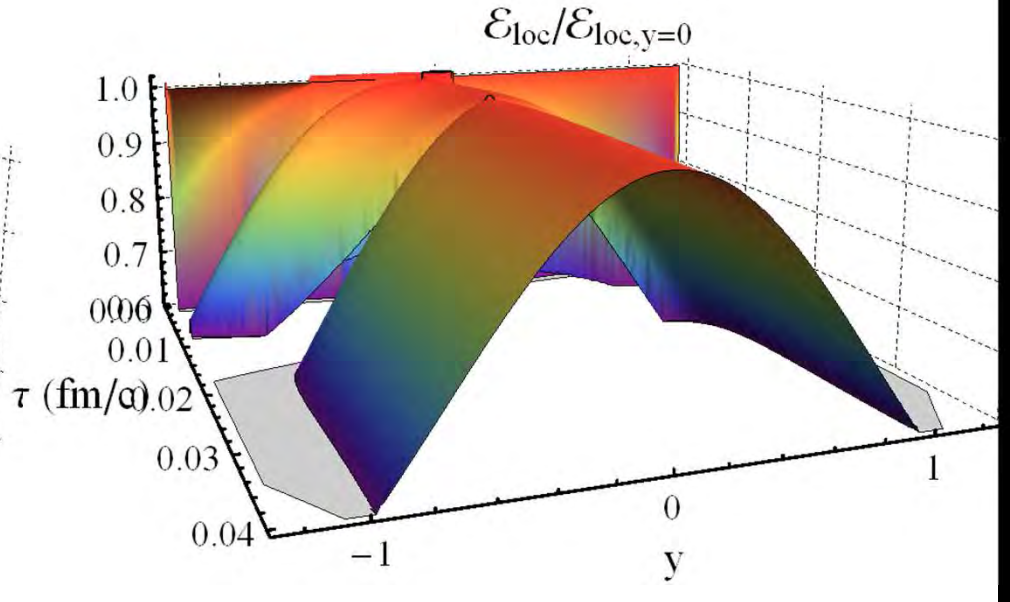
A UNIVERSAL RAPIDITY PROFILE

How is plasma energy distributed in longitudinal direction?

Low energy:



High energy:



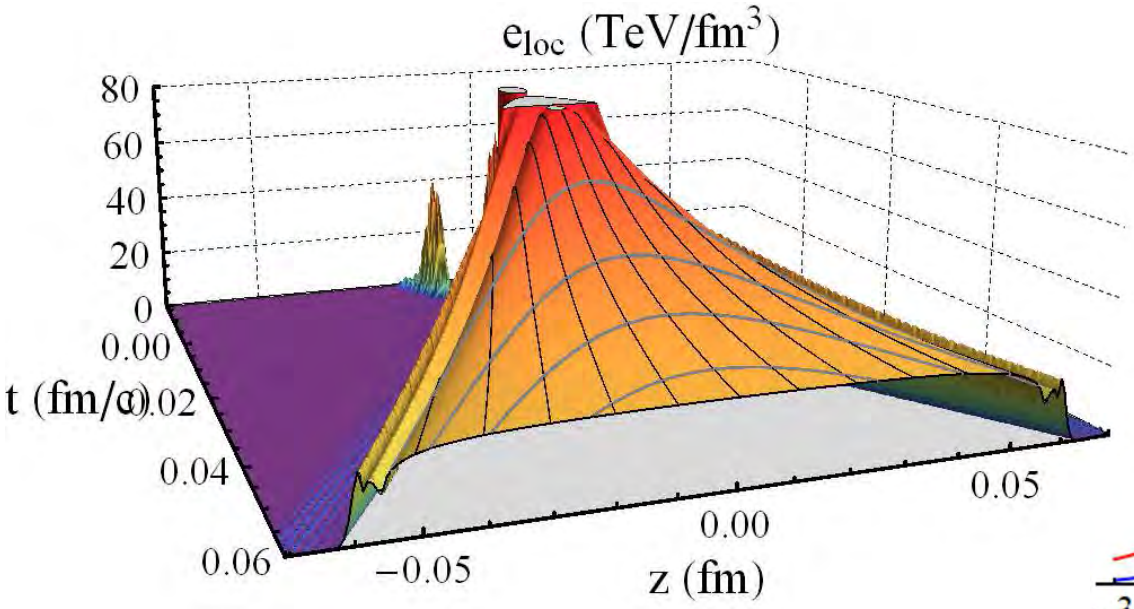
Coherence: high energy profile is universal!

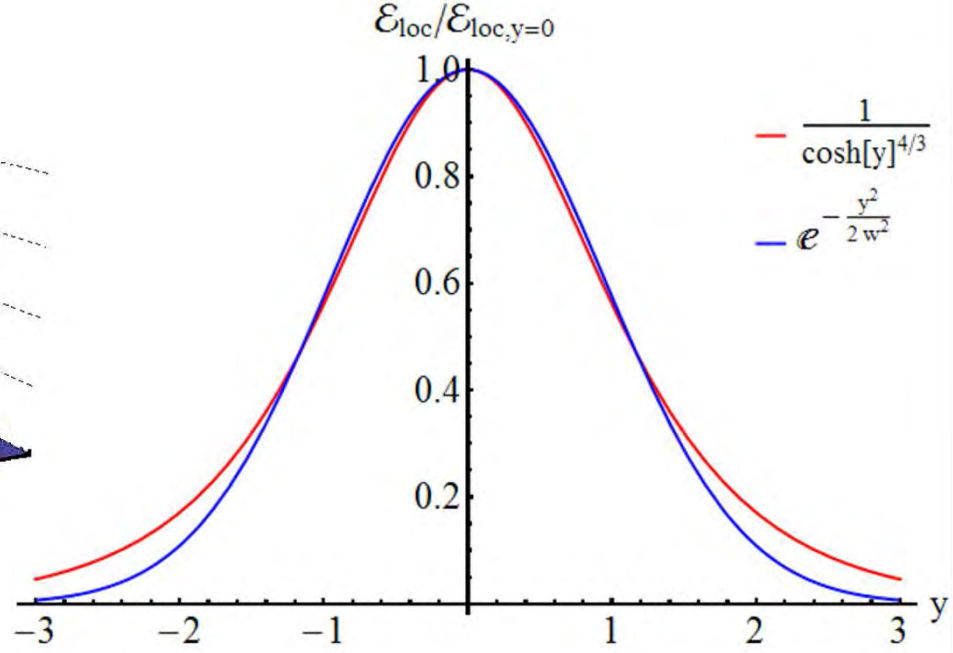
EVEN CLEARER IN REAL SPACE-TIME

Local energy density, flat in *z*

Approximation: decay in time $\mathcal{E}_{\rm loc} \sim t^{-4/3} = (\tau \cosh(y))^{-4/3}$

- Rapidity Gaussian, or perhaps $\cosh(y)^{-4/3}$

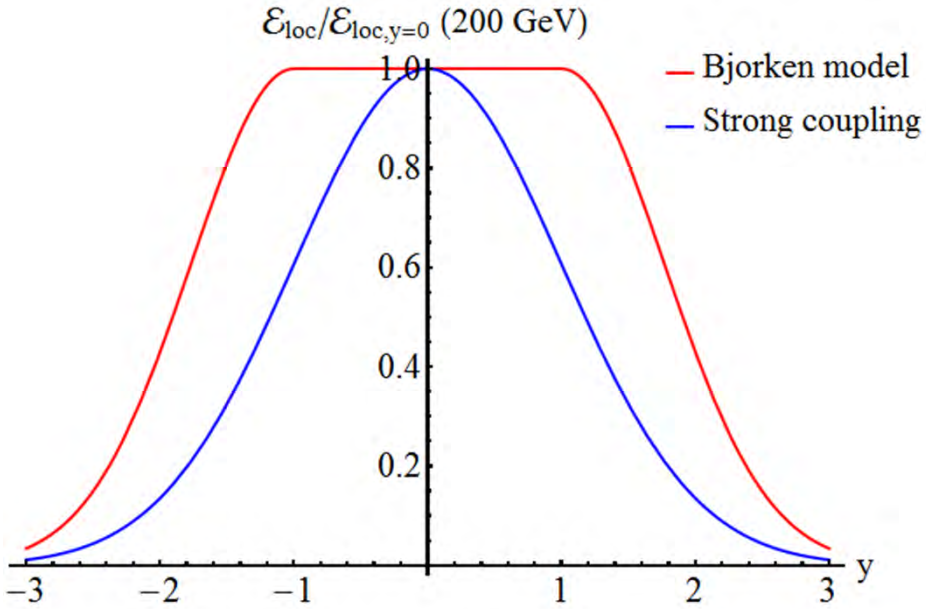


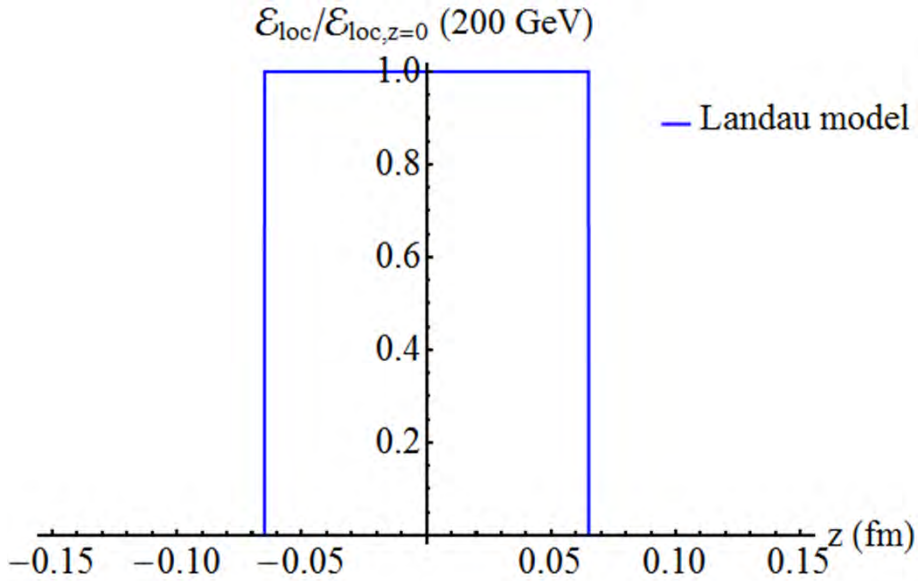


Why flat? Don't know, but robust computation.

LONGITUDINAL HIC PHYSICS: LANDAU VS BJORKEN

- **Bjorken: boost-invariant at high energies and mid-rapidity**
- **Landau: completely equilibrated at moment of overlap**
- **Strong coupling: universal profile,** $\cosh(y)^{-4/3}$



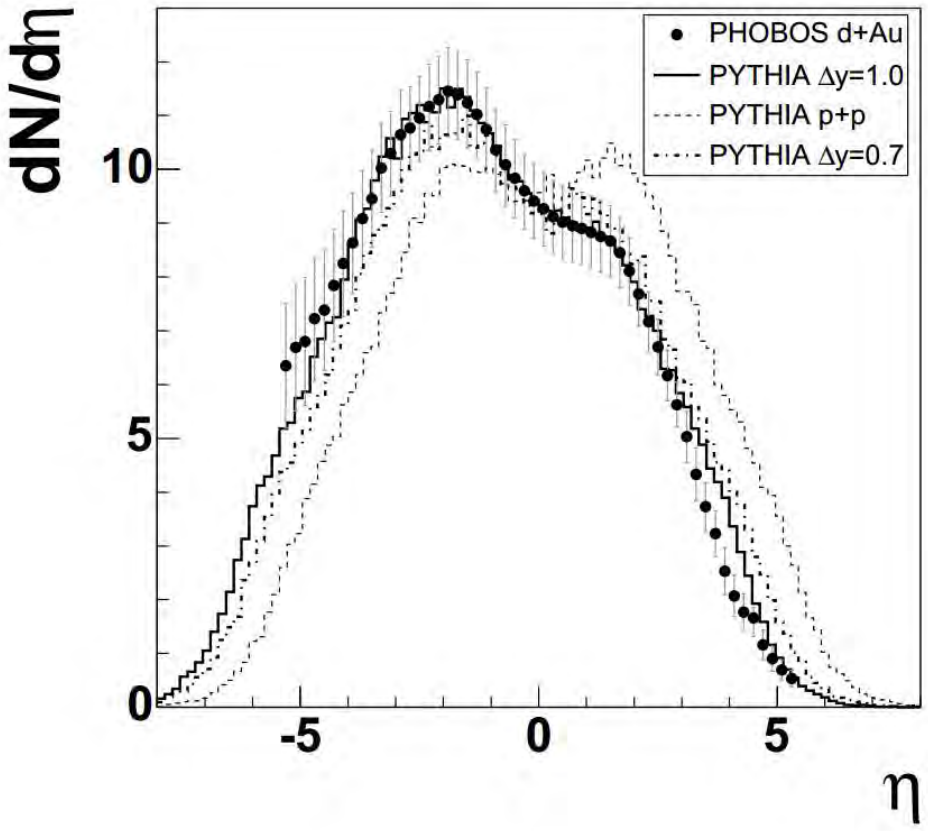


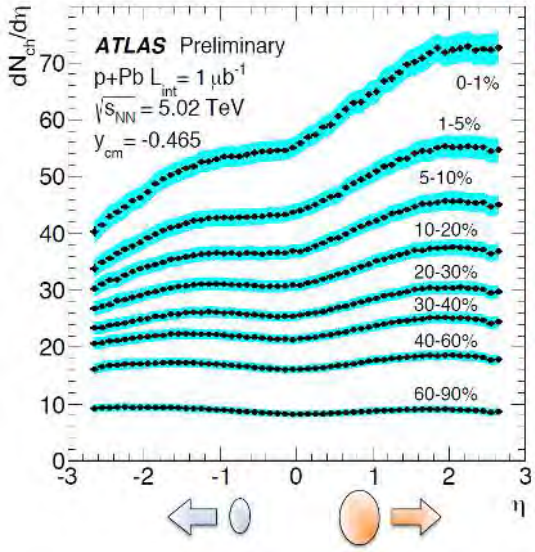
P. Bozek, I. Wyskiel, Directed flow in ultrarelativistic heavy-ion collisions (2010)

p-Pb SYMMETRY, A PREDICTION?

Subtlety converting rapidity pseudo-rapidity

- Many interesting articles by Peter Steinberg





P. Steinberg, Inclusive Pseudorapidity Distributions in p(d)+A Collisions Modeled With Shifted Rapidity Distributions (2007)
ATLAS presentation

A FULLY DYNAMICAL MODEL OF A HIC

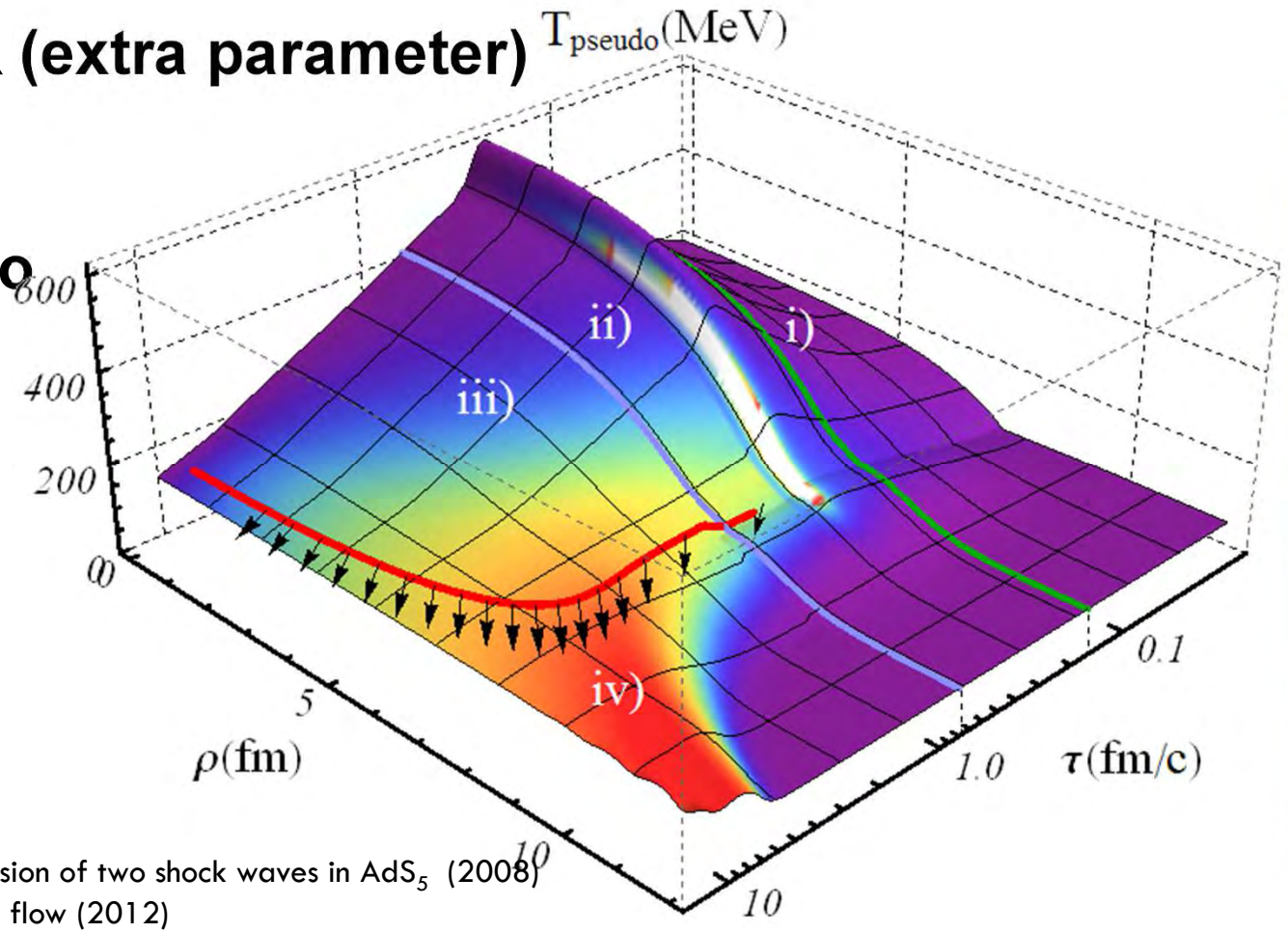
Work with Paul Romatschke and Scott Pratt

i) Small time expansion of colliding shocks (central)

ii) Numerical GR (extra parameter)

iii) Viscous hydro

iv) Hadronic cascade

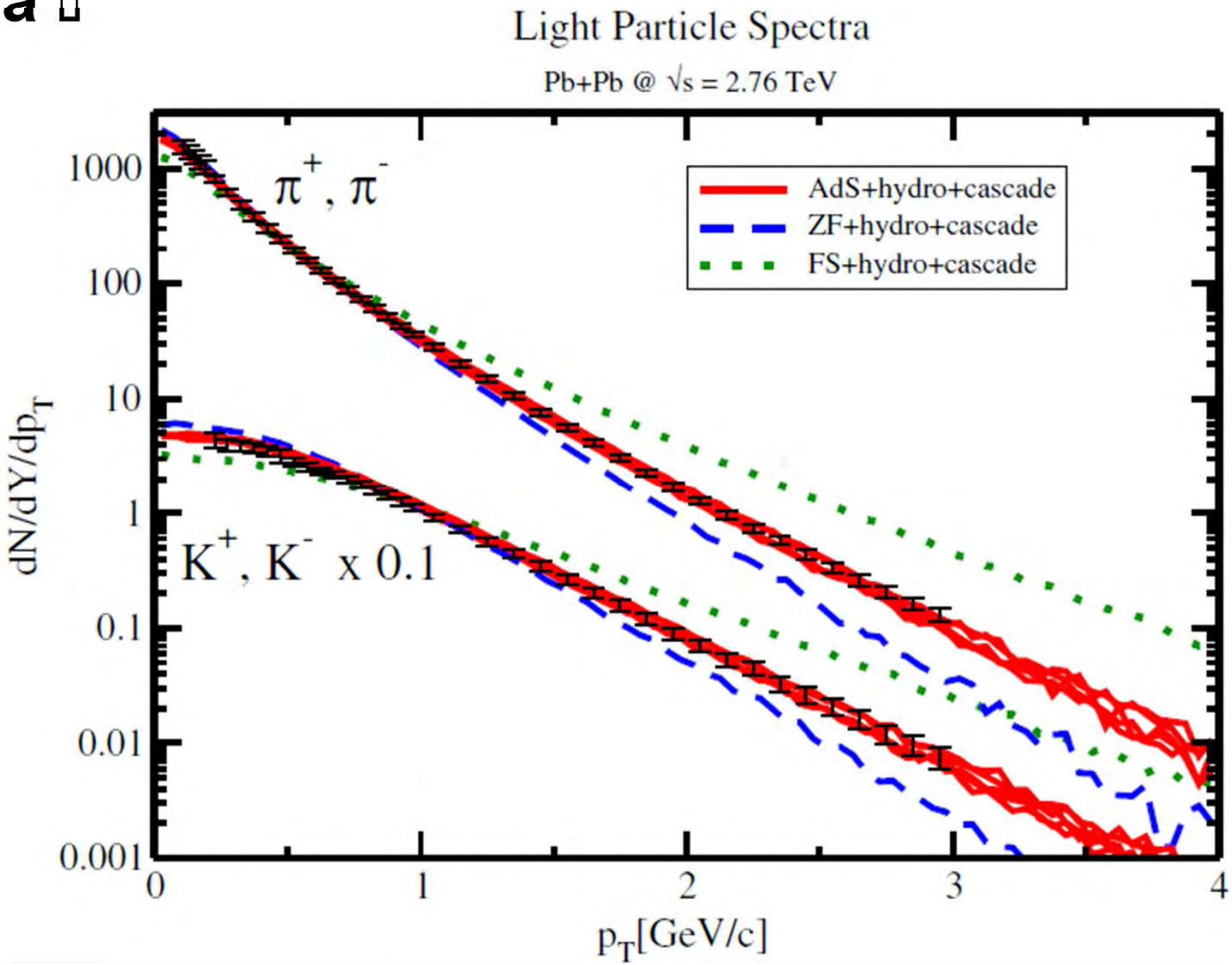


Boost-invariant

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

BOOST-INVARIANT RADIAL FLOW

Spectra



DISCUSSION

Lessons at infinite coupling

- Strong coupling ≠ full stopping
- Evolution thermalises dynamically

A universal rapidity profile

- Initial state: constant temperature at fixed time, with Bjorken velocity
- Longitudinal coherence: p-Pb symmetry

Left out: total multiplicity plots (too much entropy/stopping)

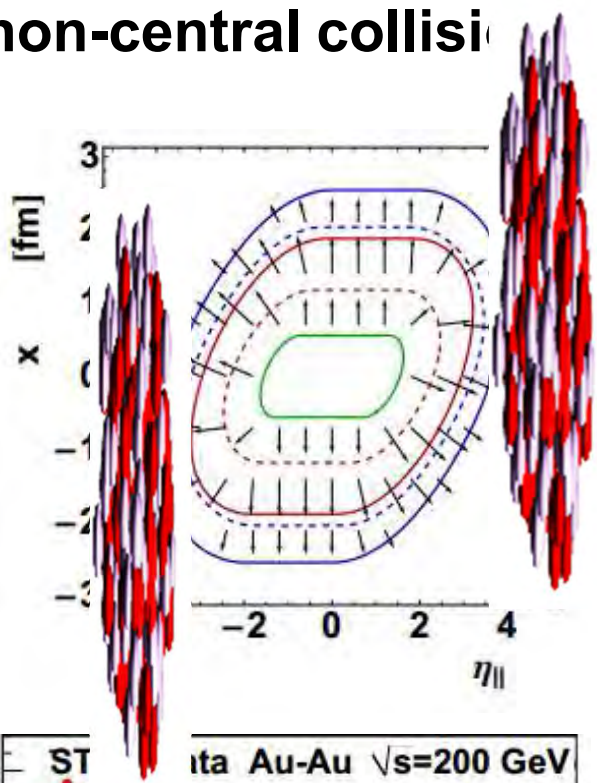
Left out: suggestive initial profile for direct flow

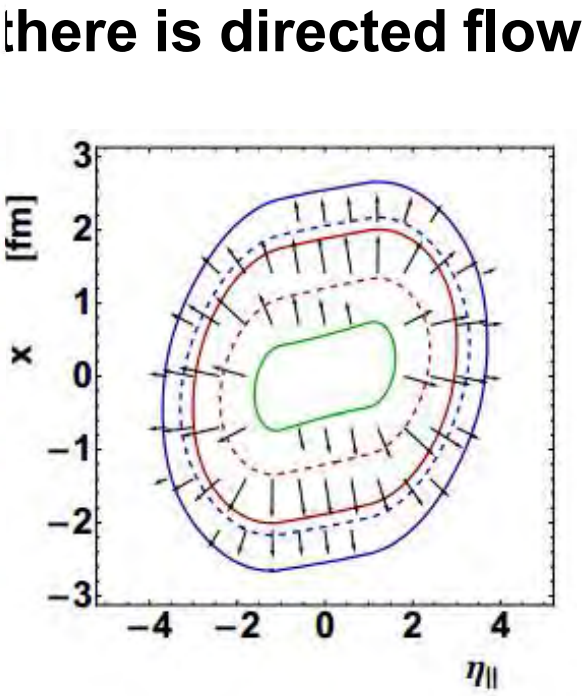
Left out: shock evolution with a conserved charge

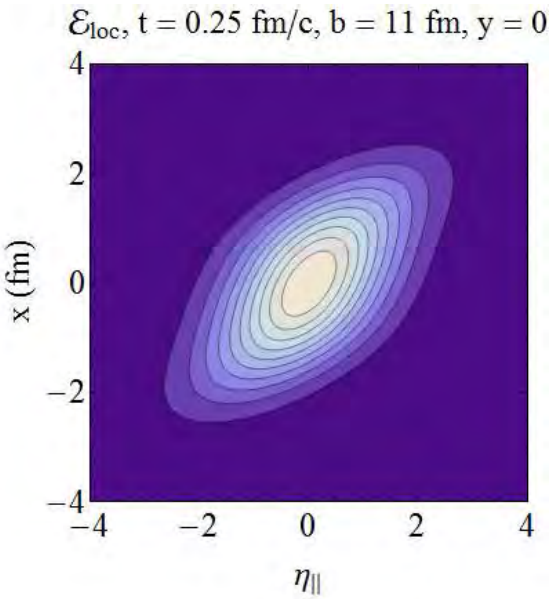
Future: correct for infinite coupling approximation

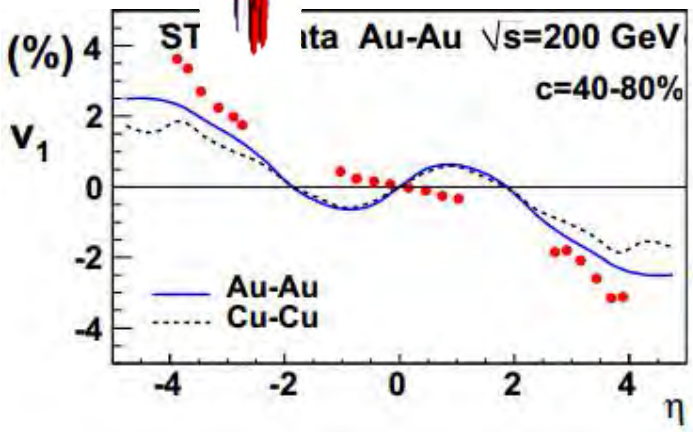
A CONSEQUENCE: DIRECTED FLOW

In non-central collisi there is directed flow:









- ‘Standard’ boost-invariant coherent model conflicts with experiment
  - Either tilt,
  - Or use narrow Gaussian rapidity profile

P. Bozek, I. Wyskiel, Directed flow in ultrarelativistic heavy-ion collisions (2010)

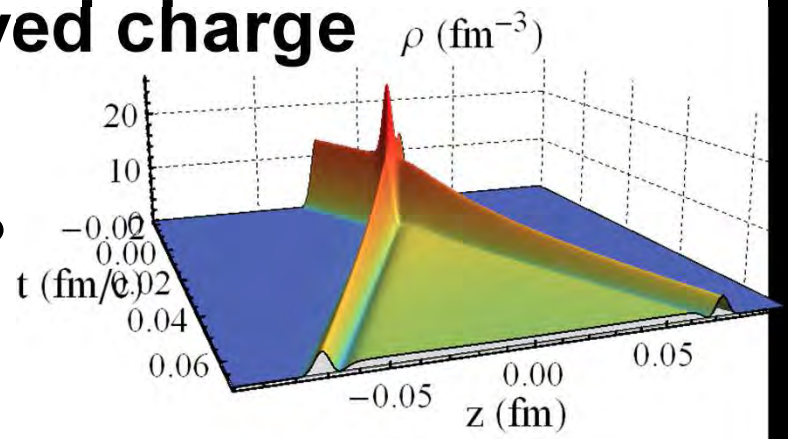
BARYON NUMBER AND CONSERVED CHARGE

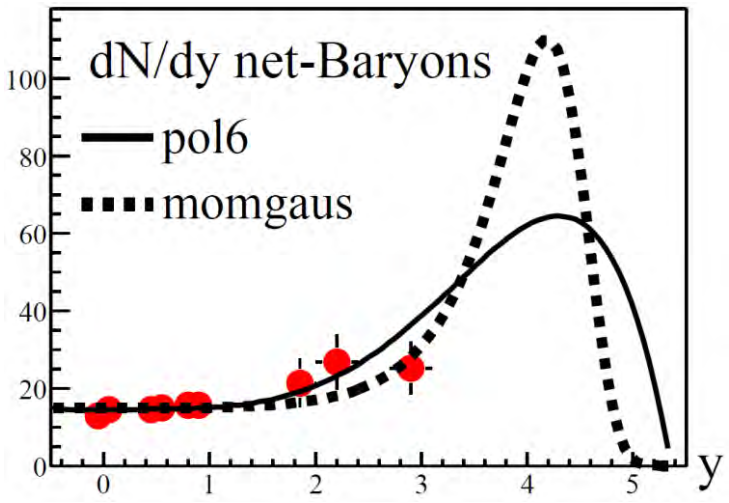
Pure gravity doesn't have conserved charge

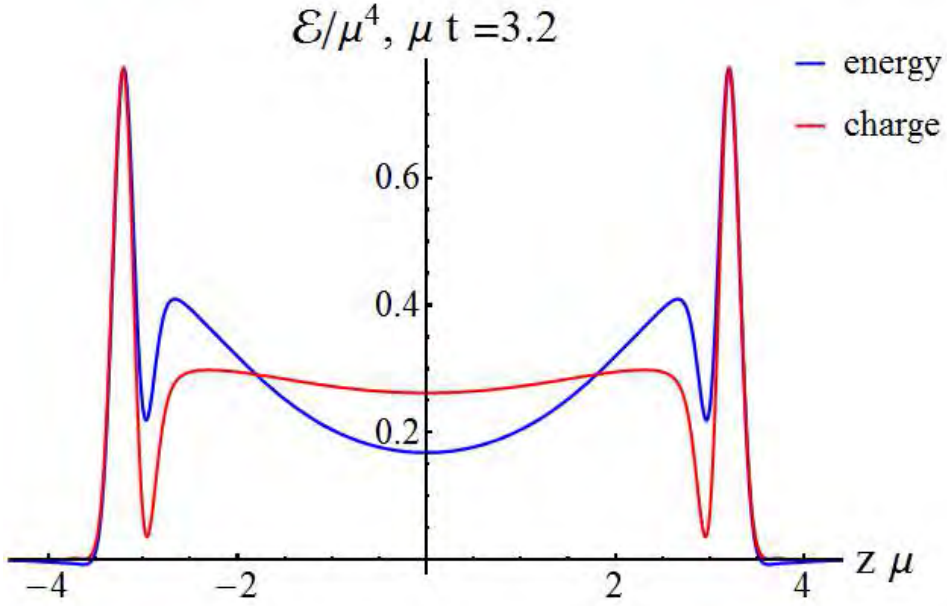
- Add vector field

Does net charge end up at high y?

- Preliminary: no or maybe...







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

PERTURBATIVE QCD

Coherence: trivial and/or experimentally disfavoured?

Perturbative QCD: interaction crucially depends on charge

- c.om.: same energy, but not the same charge!

$$Q_s^2(A, y + \frac{Y}{2}) = Q_{s_0}^2(A) \left(\frac{\sqrt{s}}{\sqrt{s_0}}\right)^{\lambda_s} \exp\left[\lambda_s y\right]$$

Particle production ~ saturation

$$Q_s(A_1, -y + \frac{Y}{2})^2 = Q_s(A_2, y + \frac{Y}{2})^2$$

$$Q_0(A_1)^2 \left(\frac{\sqrt{s_1}}{\sqrt{s_0}}\right)^{\lambda_s} \exp\left[-\lambda_s y\right] = Q_0(A_2)^2 \left(\frac{\sqrt{s_2}}{\sqrt{s_0}}\right)^{\lambda_s} \exp\left[\lambda_s y\right]$$

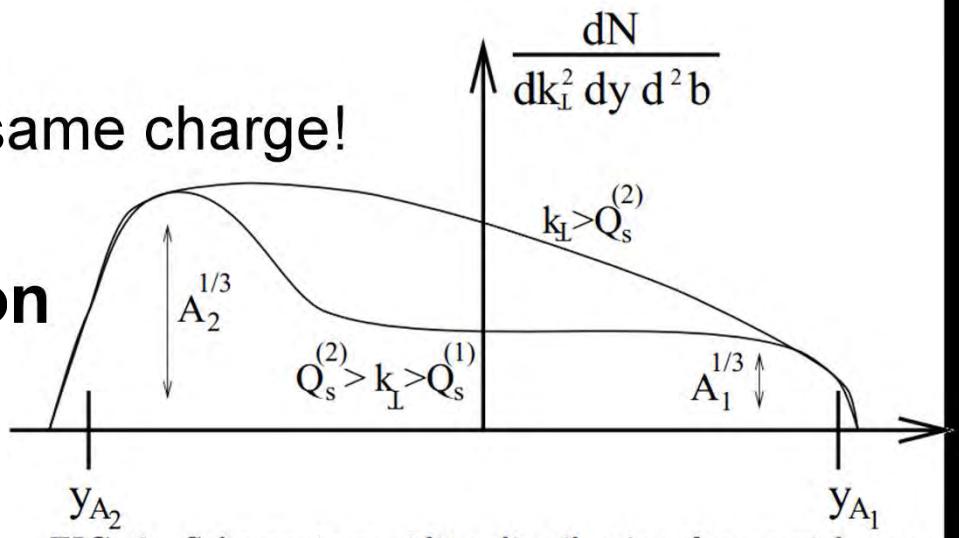


FIG. 3. Schematic rapidity distribution for particles produced in high-energy $p + A$ collisions.

A. Dumitru and L. McLerran, How Protons Shatter Colored Glass (2001)

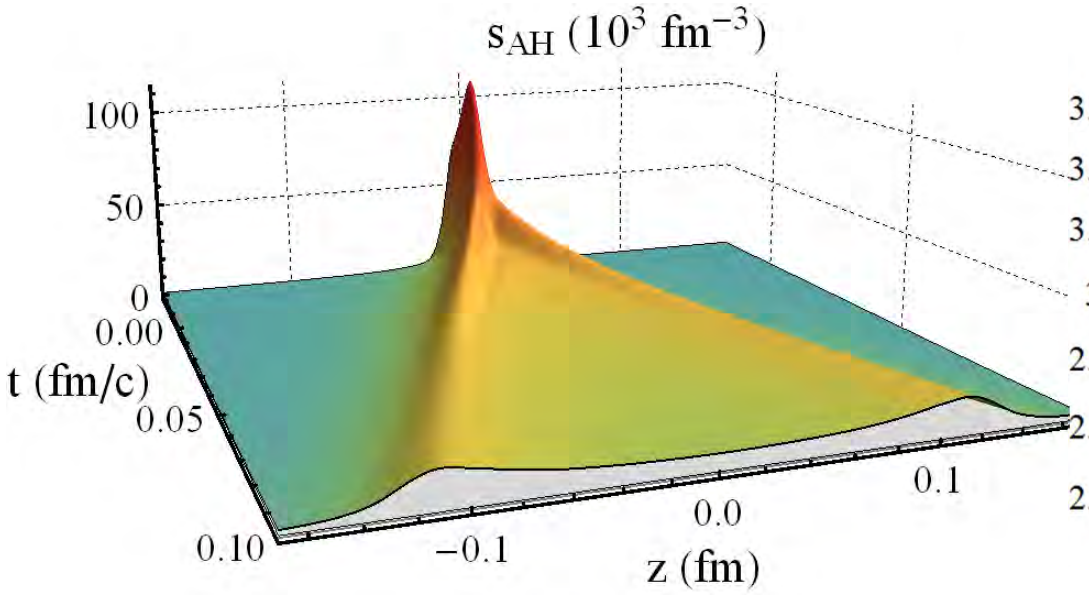
B. Xiao, Multiplicity and transverse energy of produced gluon in relativistic heavy ion collision (2005)

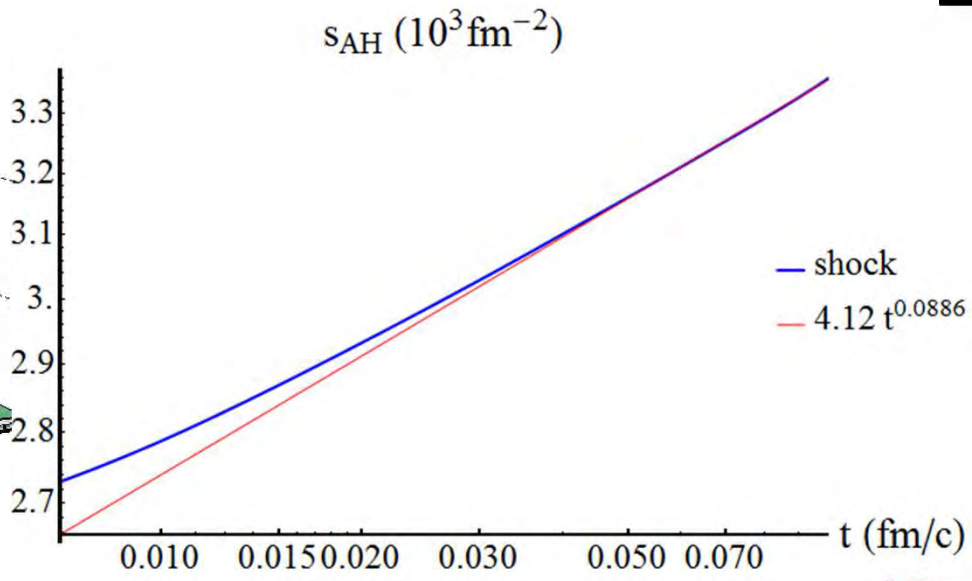
ENTROPIES AND MULTIPLICITIES

Plasma hadronises around T~170MeV

# of particles ~ local energy or entropy (~E/T)

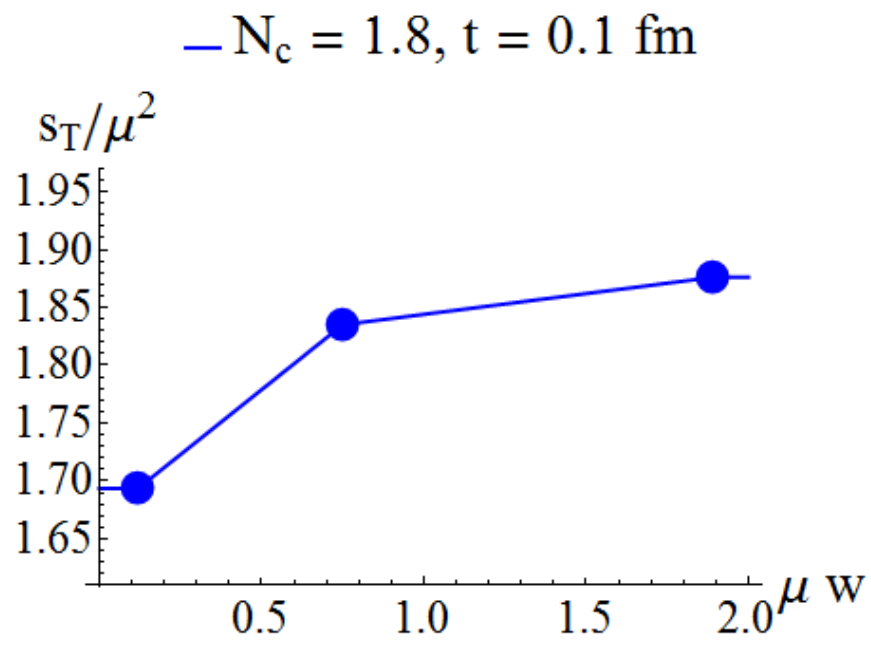
Entropy is approximately conserved (η small)

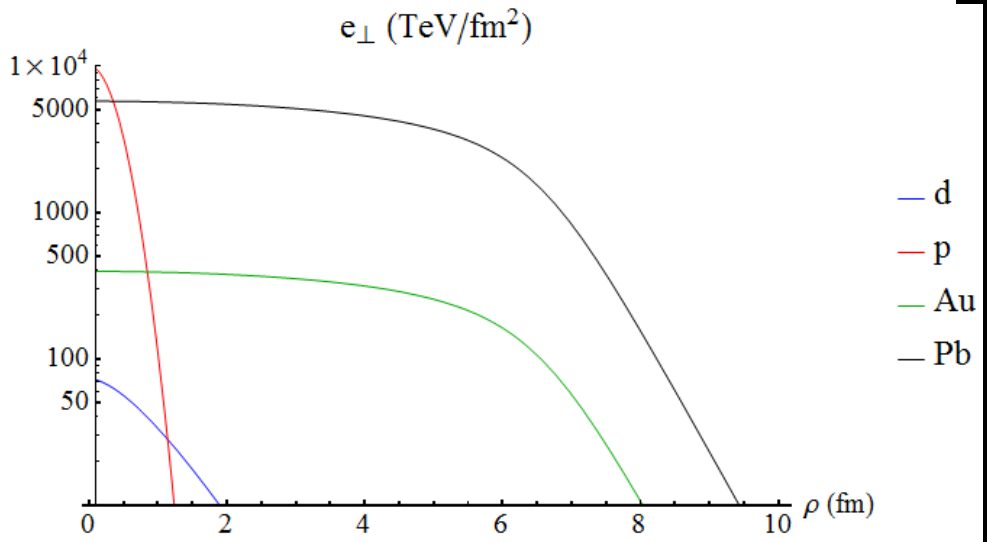




APPARENT HORIZON

Total entropy (per transverse area) mildly depends on *w*

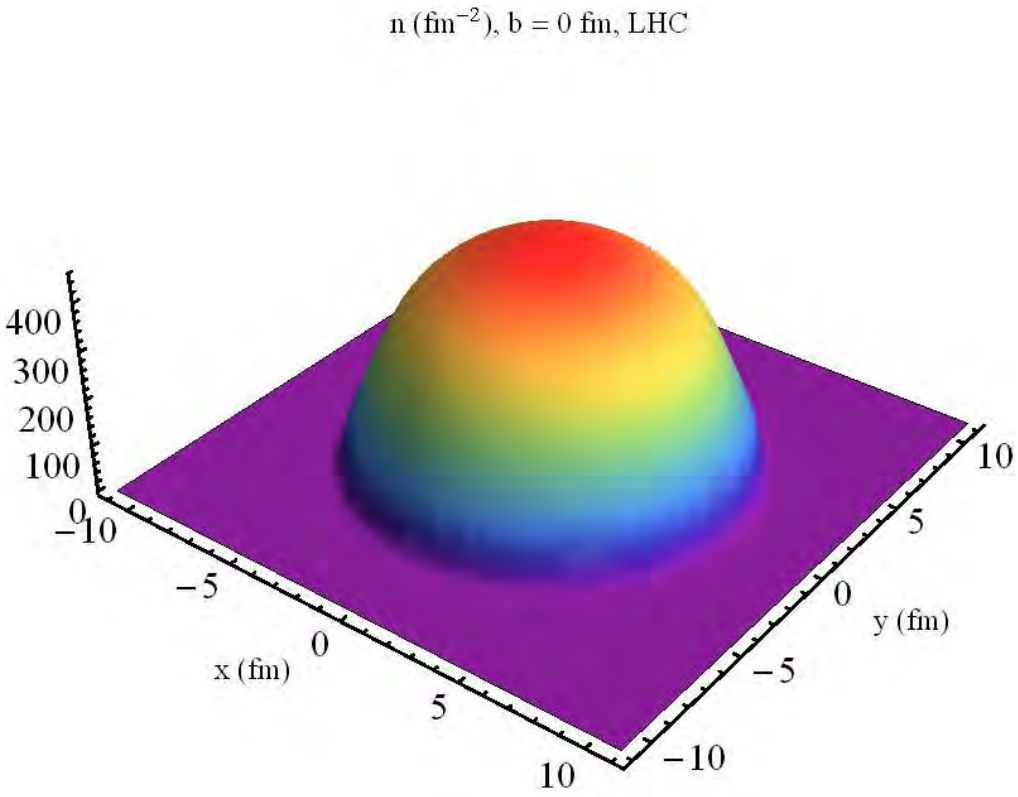


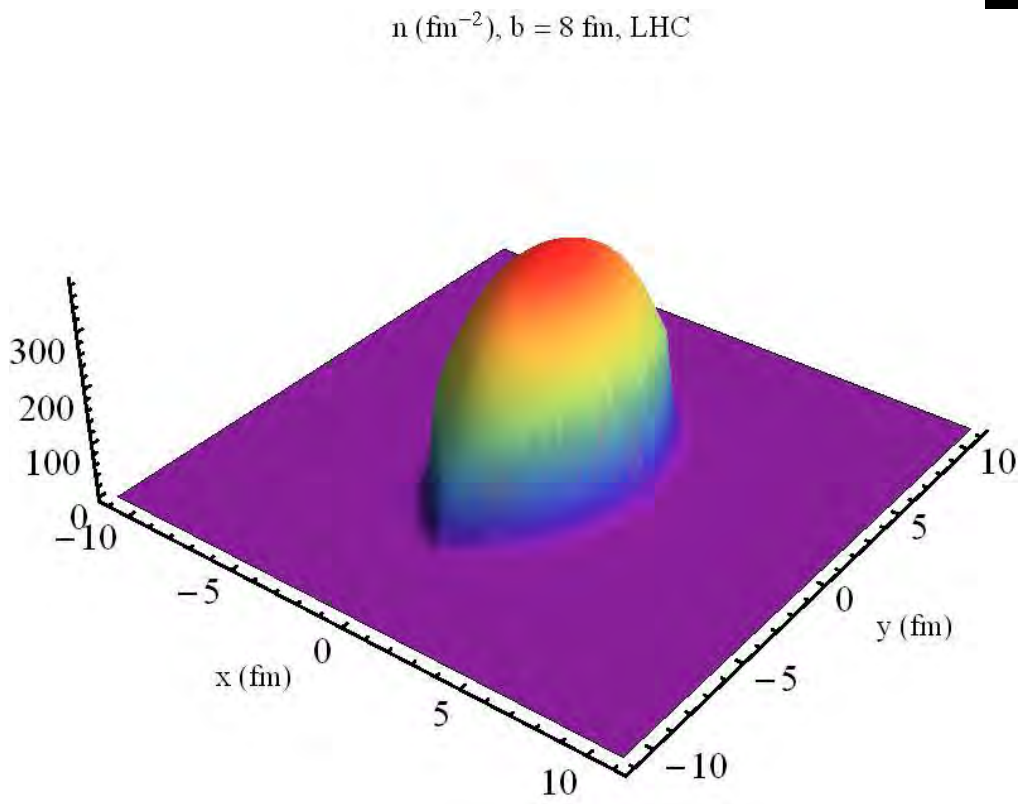


Step: assume small gradients in transverse plane

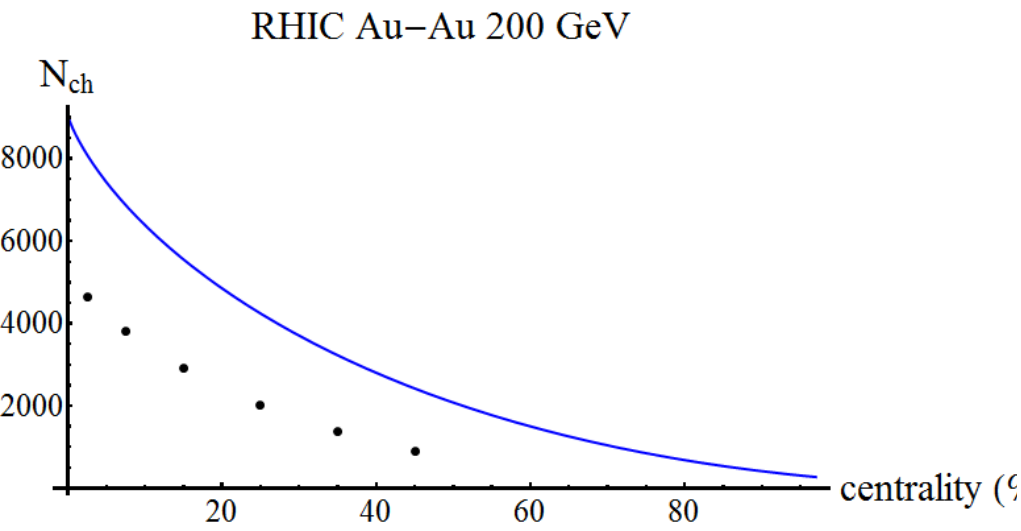
EXAMPLE MULTIPLICITIES

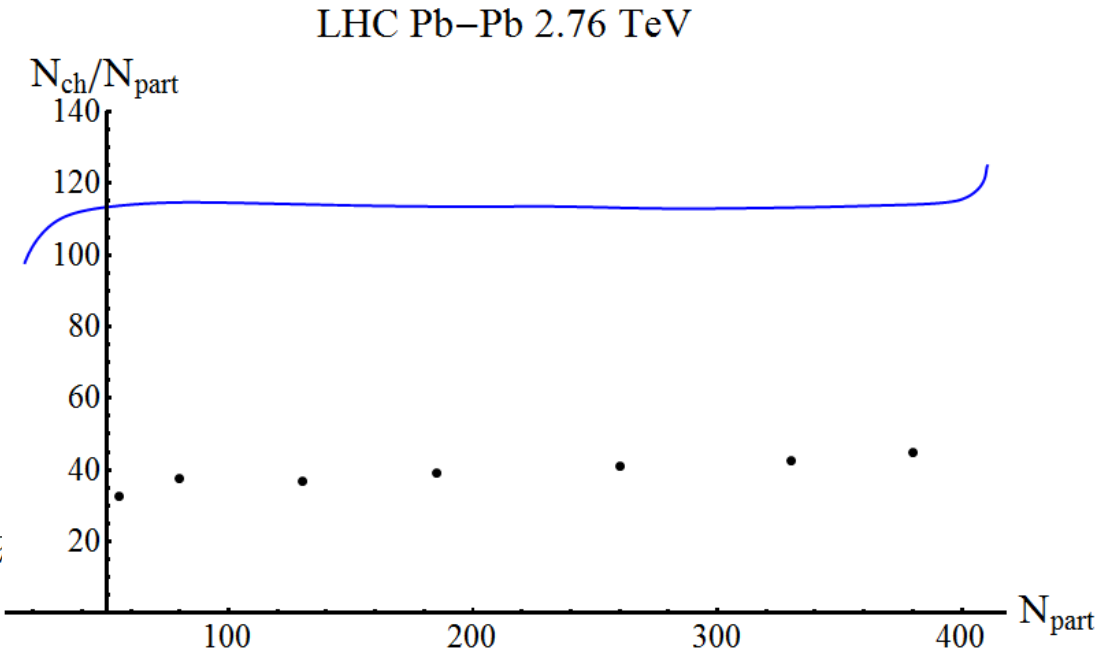
Two examples of entropy per transverse area

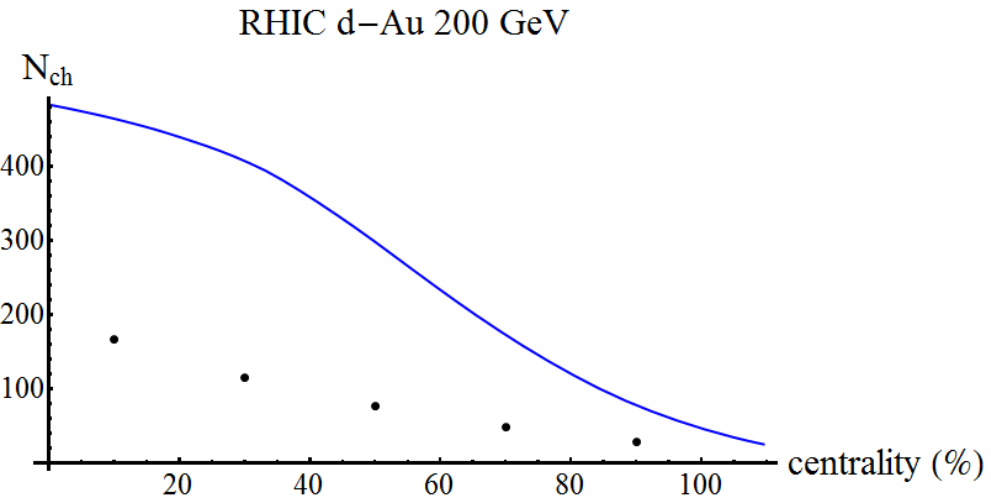




MULTIPLICITY PLOTS







Several corrections:

- No spectators (-15%)
- Event-by-event fluctuations
- More viscous effects?
- Shape deuteron? N_{part}?
- **Weak coupling effects**

THERMALISATION/HYDRO IN SMALL SYSTEMS?

When is hydro applicable?

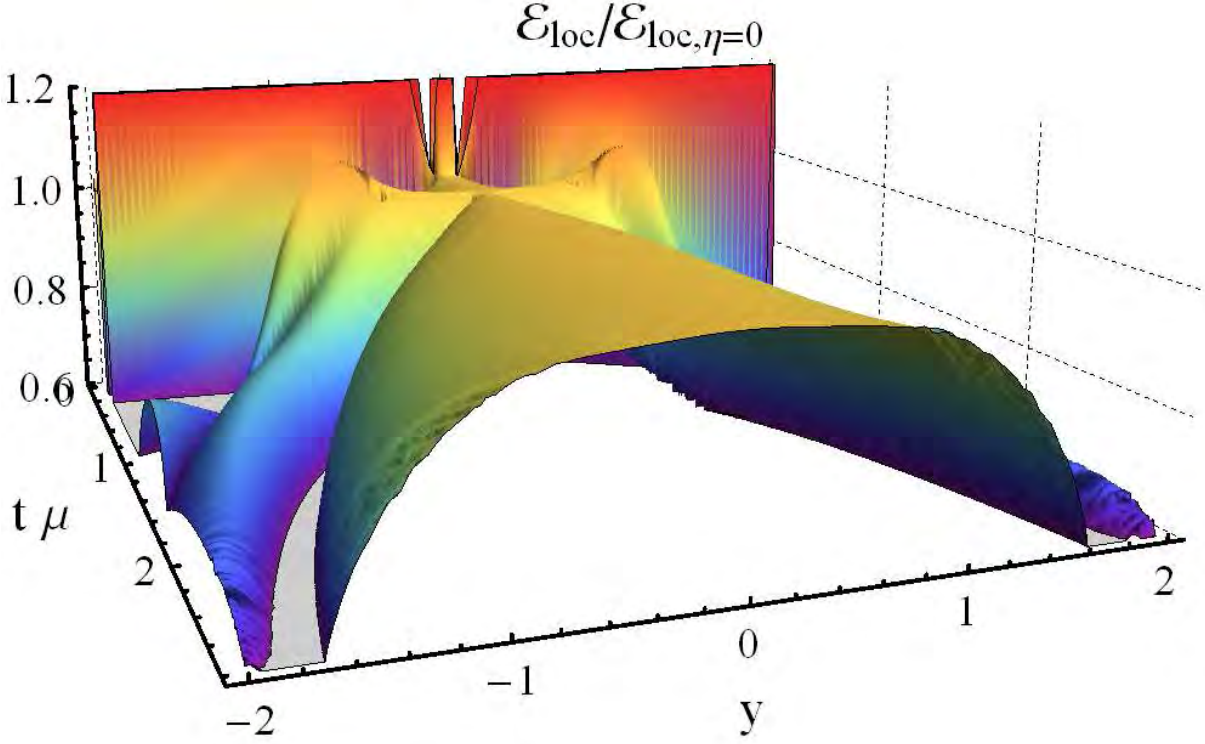
- Not far-from-equilibrium (shock,
- Not when pressure is negative (unstable)
  - But **viscous/anisotropic hydro** can apply if pressure ~ 0 (!!)
- Not in confining state
- Not in small system $L \gg 1/T$ (perhaps $L \gg 1/\pi T$ $VT^3 \gg 1$
- Turbulence? (HIC typically too short?)
- Shocks: **hydro applies within** $0.3/T$

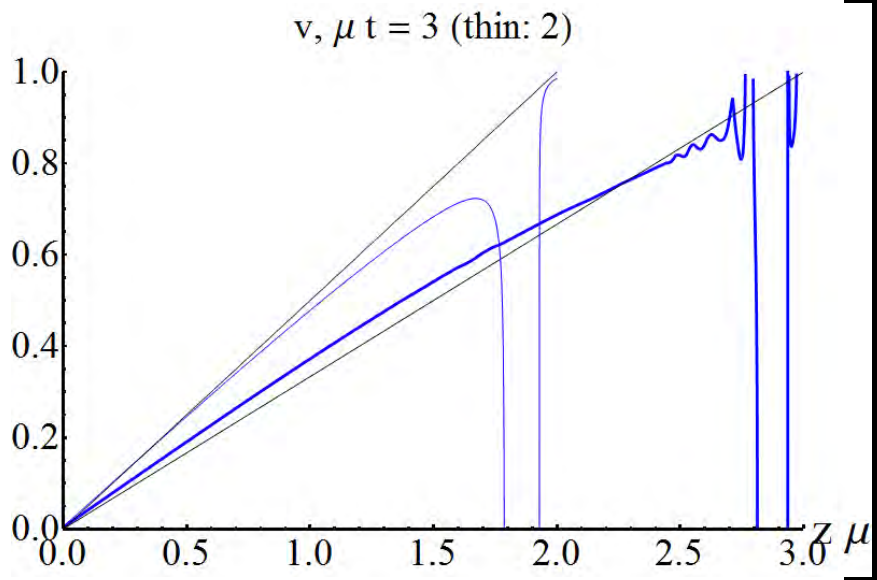
For p-Pb and p-p collisions only few particles produced

- Naïve estimate: $s \approx 16T^3$ gives $N_{ch} \approx Vs/7.5 \approx 2.1VT^3$
- So it all depends on the π's…
- AdS/CFT: hydro in small systems definitely possible

LOCAL ENERGY DENSITY FLATTER IN REAL TIME!

Instead of proper time, try real time local energy density:





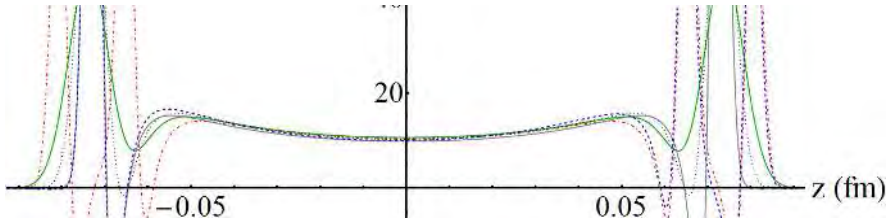
Numerically hard at high rapidities

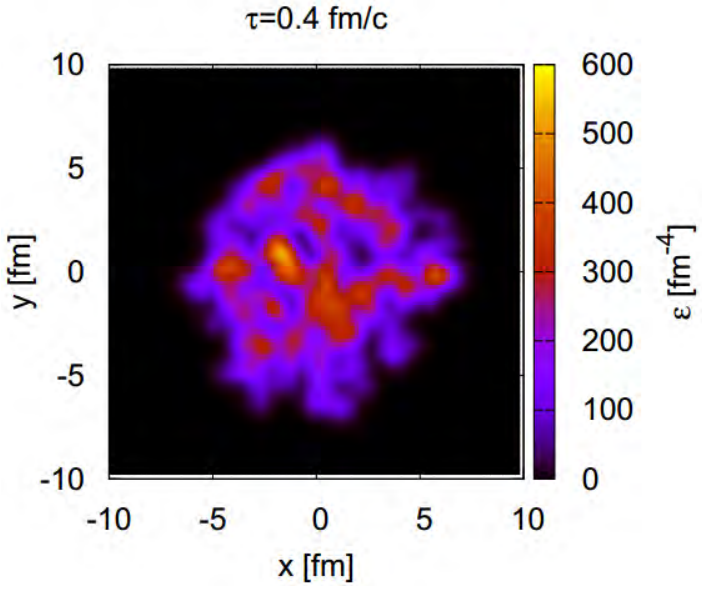
- Perhaps constant local energy density in real time?
- Velocity seems close to boost-invariant: $v = z/t$ (but changes?)

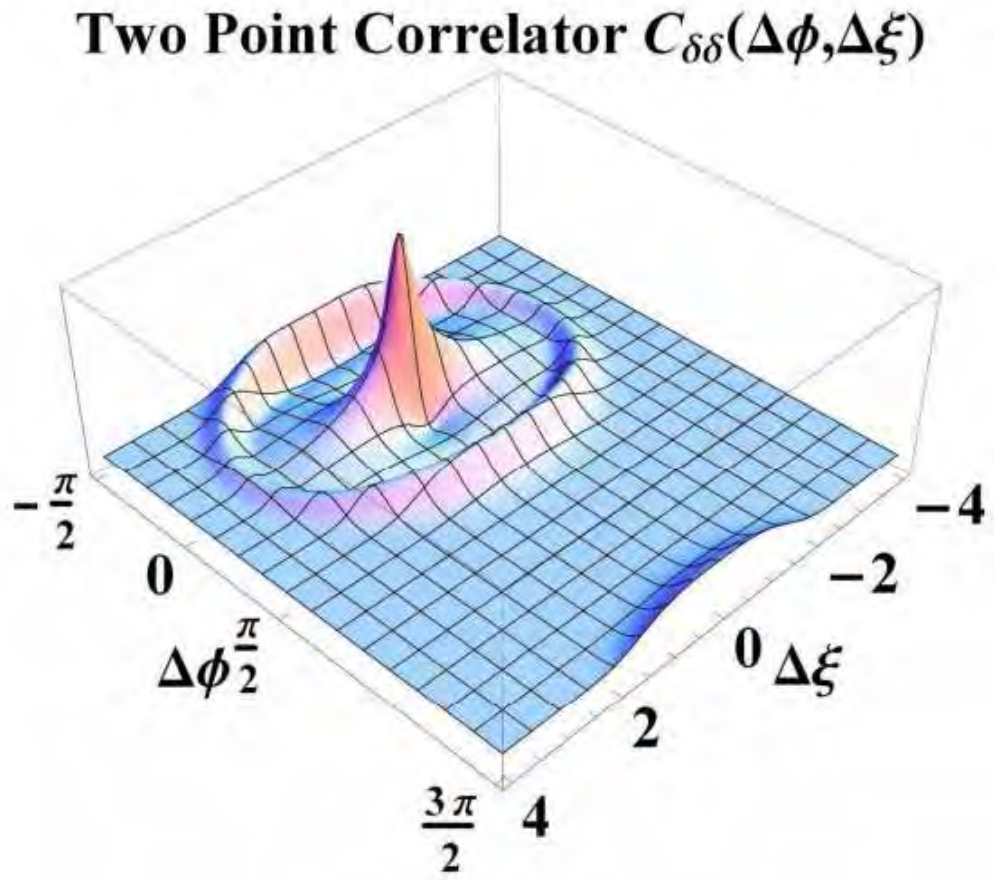
INITIAL STATE VERSUS THERMAL FLUCTUATIONS

Result: little longitudinal initial state fluctuations

- As opposed to transverse fluctuations!







T. Springer and M. Stephanov, Hydrodynamic fluctuations and two-point correlations (2012)

SHOCK WAVES FROM THE BULK

Interesting interplay between temperature & width:

- Non-linearity roughly comes from horizon
- Touches front-end latest: by causality!