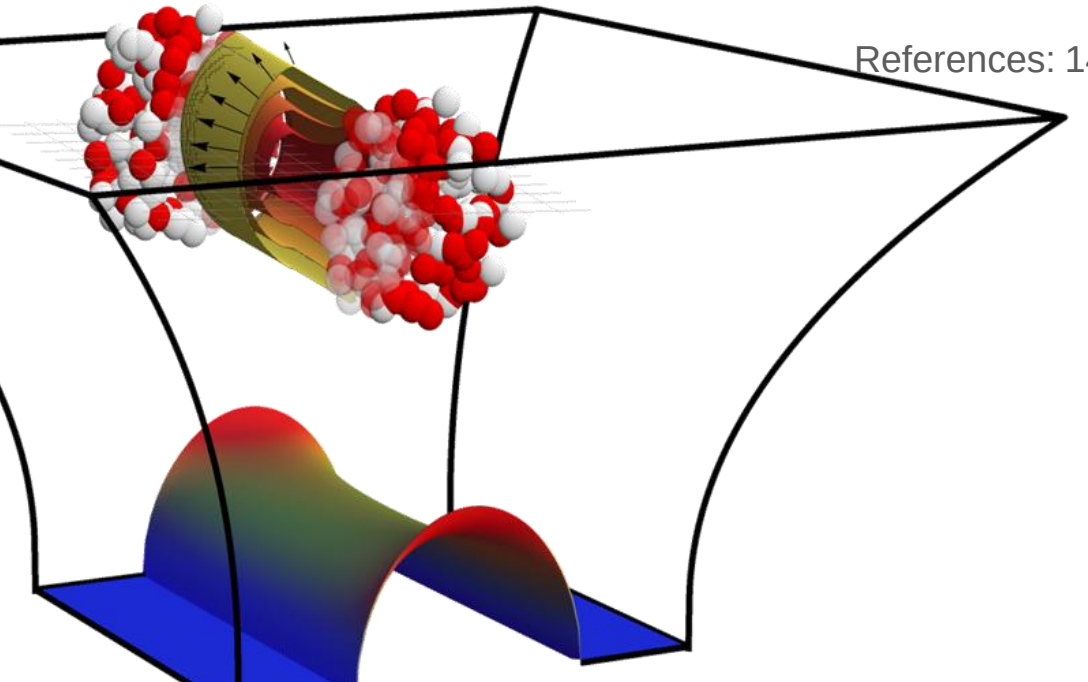
# DIRECTED FLOW IN HOLOGRAPHIC HEAVY ION COLLISIONS

## TOWARDS MORE REALISTIC MODELS OF QGP FORMATION

Based on work with Michał Heller, David Mateos, Jorge Casalderrey, Miquel Triana, Paul Romatschke, Scott Pratt, Peter Arnold, Paul Chesler and Steve Gubser,

New work with Björn Schenke

References: 1407.1849 (Thesis), 1507.02548, 1507.06789



**Wilke van der Schee**

Thermalization workshop INT
Seattle, 13 August 2015

# SOME PHILOSOPHY

**AdS/CFT: very successful for learning qualitative lessons:**

- Small viscosity over entropy density
- Fast applicability of viscous hydrodynamics

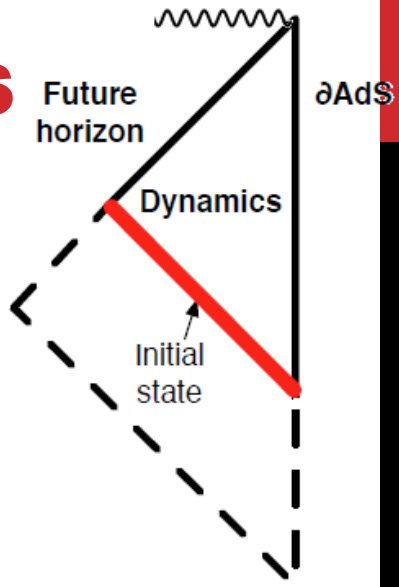
**Not necessarily close to QCD (uncontrolled approximation)**

- Different field content: perhaps not so bad in thermal phase?
- Initial stage at high energy, i.e. weak or intermediate coupling

**Goal: use AdS/CFT in quantitative models for quark-gluon plasma**

- First to leading order, i.e. *infinite coupling benchmark*
- A lot of room for improvement
  (baryon charge, confinement, intermediate coupling, etc)

# SHOCK WAVES – INITIAL CONDITIONS

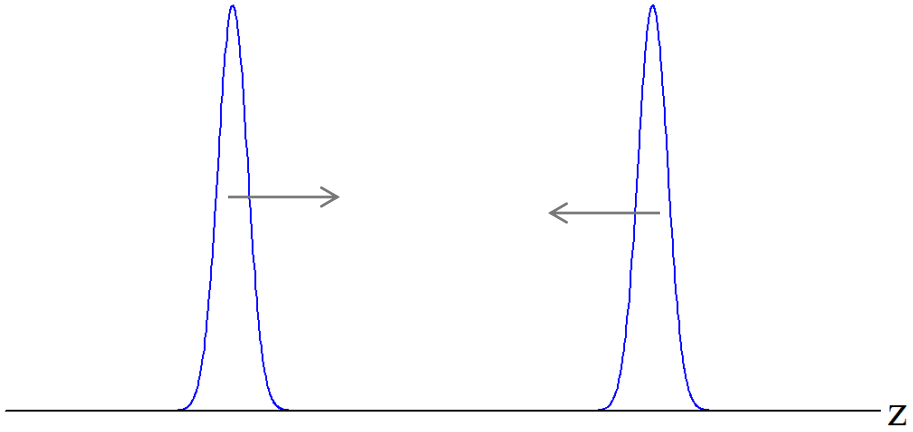



## Field theory interpretation:

- 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

- But applies to general collisions if transverse gradients are small

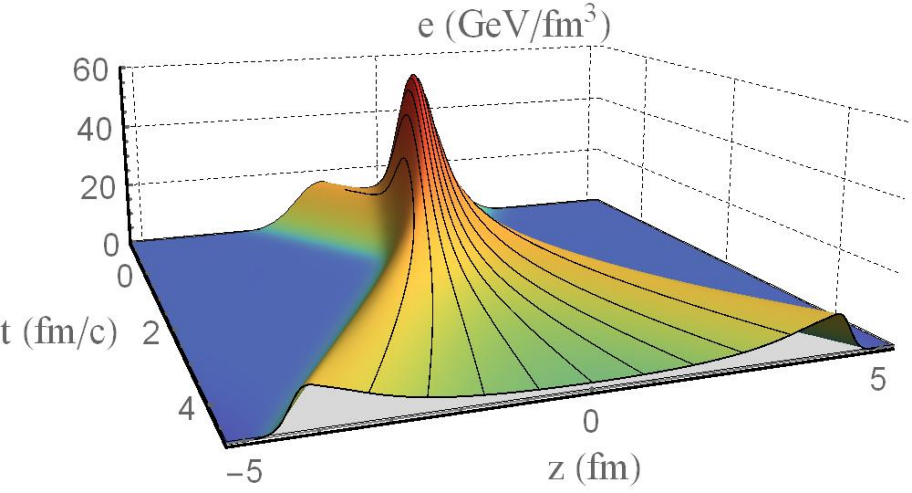



P.M. Chesler and L.G. Yaffe, Holography and colliding gravitational shock waves in asymptotically $AdS_5$ spacetime (2010)

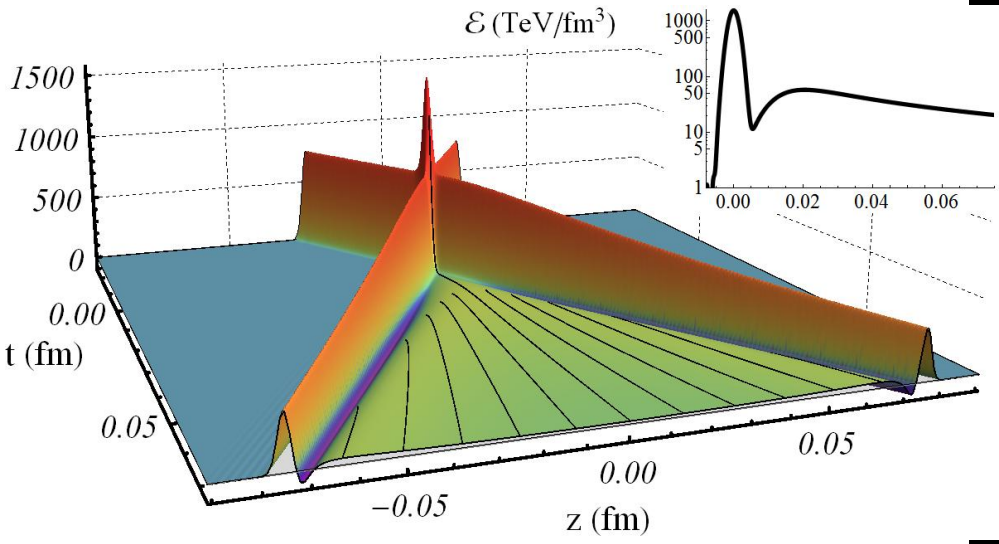
# SHOCK WAVES – A DYNAMICAL CROSS-OVER

Colliding lumps of energy at infinite coupling, neglecting transverse dynamics

$\sqrt{s_{NN}} = 19.3\,\mathrm{GeV}$




$\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$




Benchmarks: $T_{\max} = 440\ \mathrm{MeV}$ $T_{\max} = 2.6\ \mathrm{GeV}$

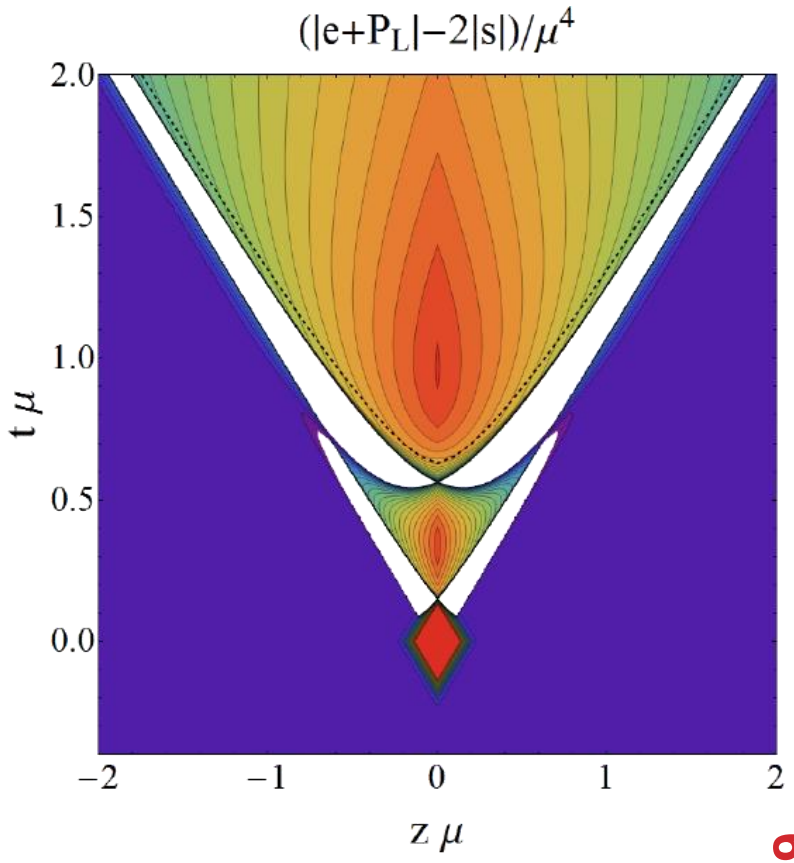


J. Casalderrey-Solana, M.P. Heller, D. Mateos and WS, From full stopping to transparency in a holographic model of heavy ion collisions (2013)

# REGIONS WITHOUT A REST FRAME (THIN SHOCKS)

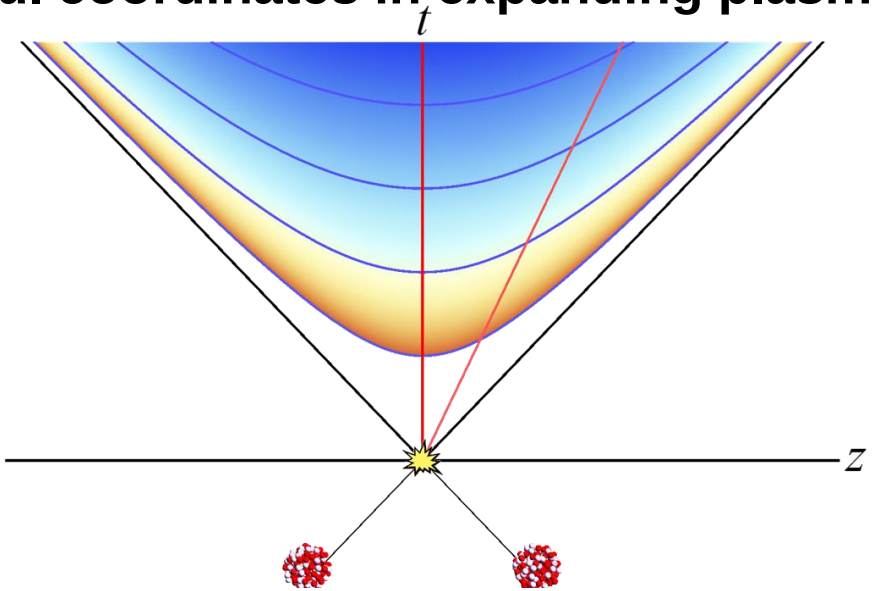
Work with Paul Romatschke and Peter Arnold (1408.2518)

- **Regions 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??!)



# RAPIDITIES AND *INITIAL STATE* BI

**Useful coordinates in expanding plasmas:**




$$t = \tau \cosh y$$

$$z = \tau \sinh y$$

**Weak coupling: interactions follow charge**

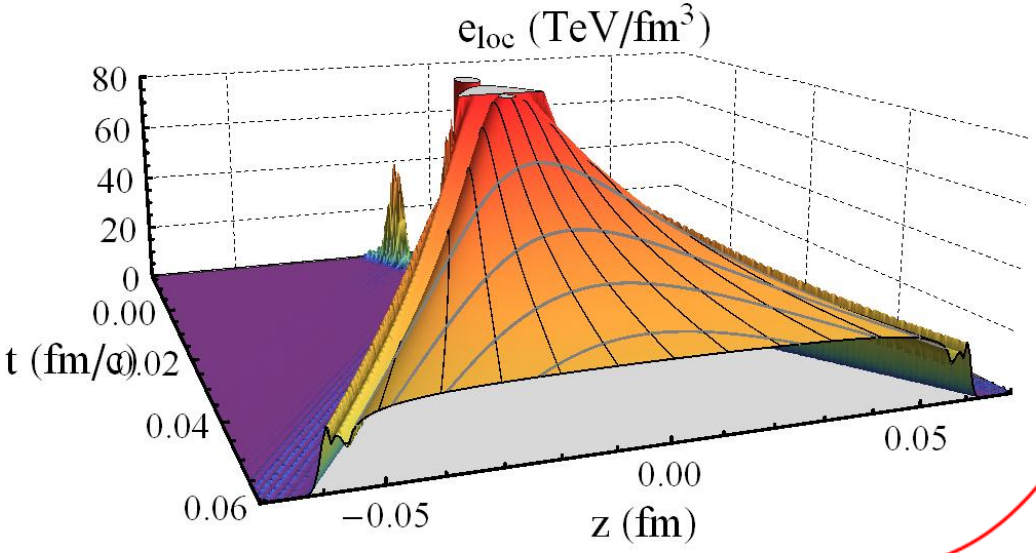
- Boost-invariant if moving on light-cone

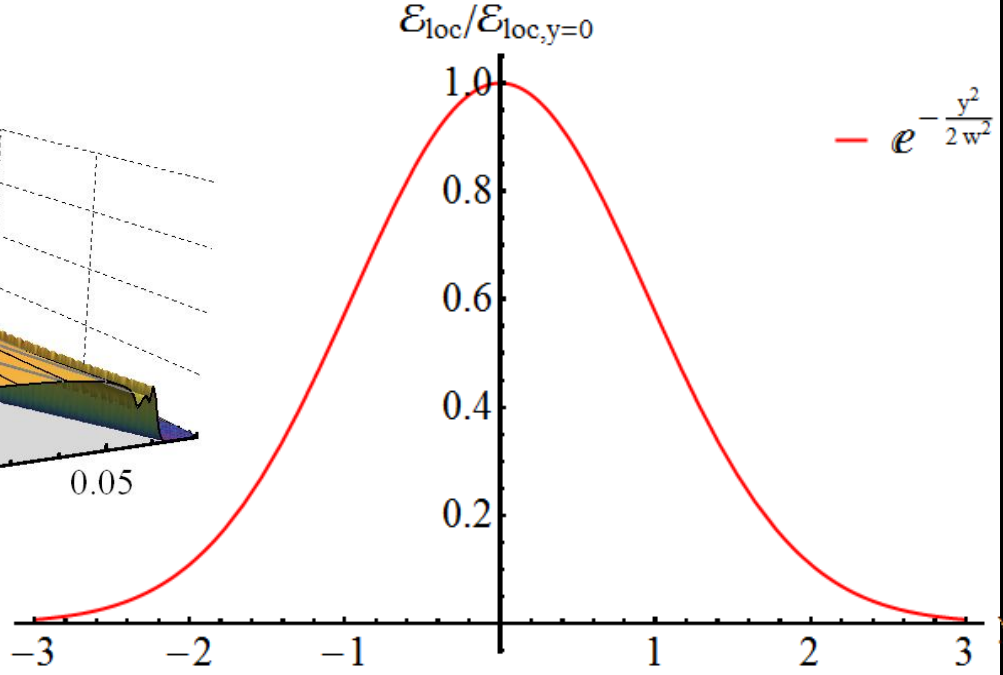
**Strong coupling: interactions follow energy**

- Receives $\gamma$-factor on boosting, even if v ≈ c

# A UNIVERSAL RAPIDITY PROFILE

## Local energy density, flat in *z*, Gaussian-like in rapidity




## Universal profile at high energies (compare with pQCD)

J. Casalderrey-Solana, M.P. Heller, D. Mateos and WS, Longitudinal coherence in a holographic model of asymmetric collisions (2013)
P.M. Chesler, N. Kilbertus and WS, Universal hydrodynamic flow in holographic planar shock collisions (2015)

# DIMENSIONAL ANALYSIS 1.0

$\sqrt{e_L(x_\perp)e_R(x_\perp)}$

**Only one scale in problem:** $\mu^3 \sim e_\perp(\mathrm{GeV/fm}^2) \sim \sqrt{s_{NN}}$

$e_\perp(r=0) \approx 2.5\ \mathrm{TeV/fm}^2 = (0.04\ \mathrm{fm})^{-3} = (4.6\ \mathrm{GeV})^3$

- **Idea: during thermalisation no (local) transverse scale either!**
  - I.e. thermalisation time << 0.1 fm, transverse scale >> 0.1 fm
  - No QCD scale is assumption
  - Event-by-event fluctuations can complicate this picture

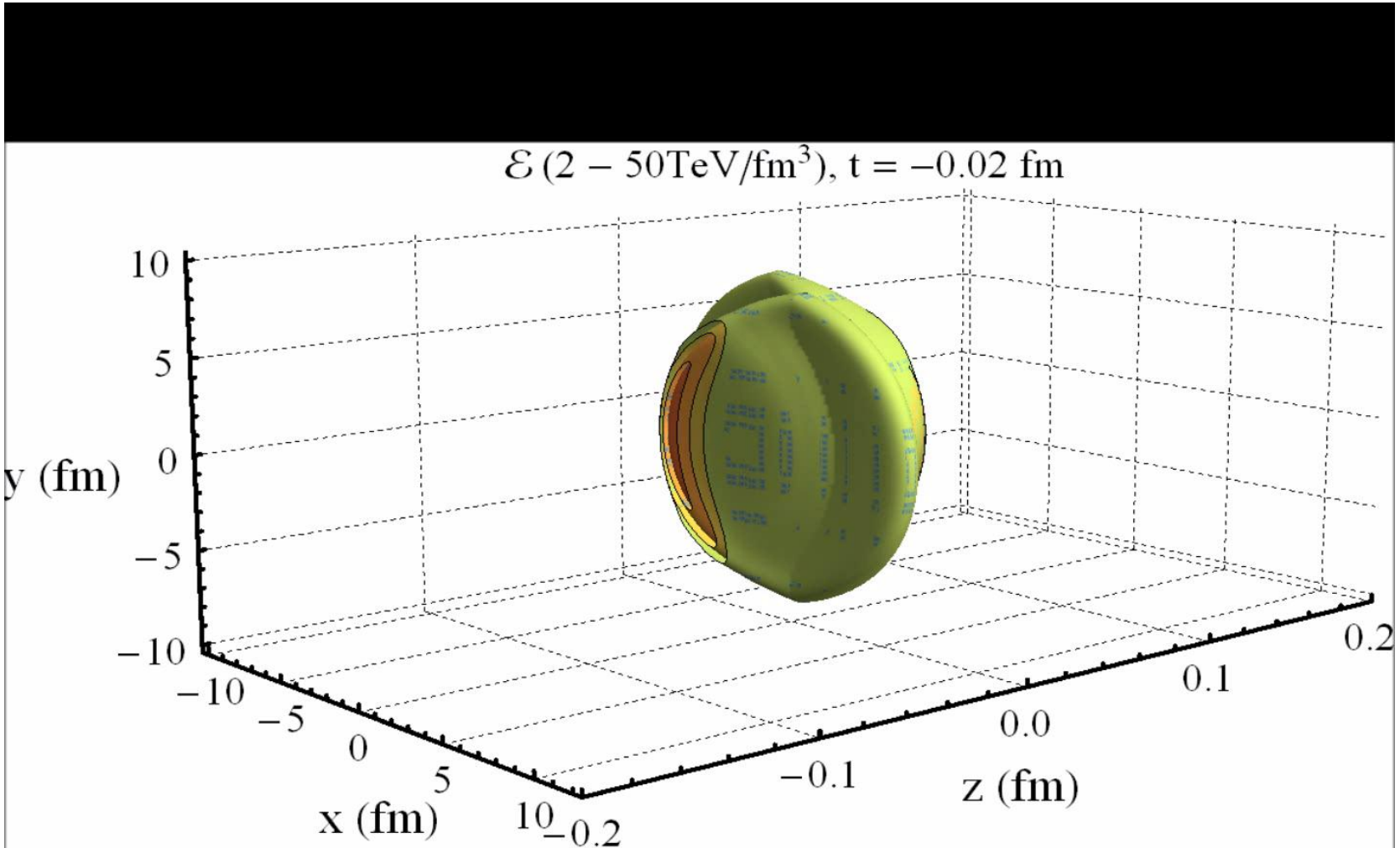
**More non-trivial:**

- **rapidity profile + Bjorken velocity (shift to c.o.m.!)**
- **fast thermalisation → decoupling of transverse dynamics**

# COLLIDING TWO NUCLEI:

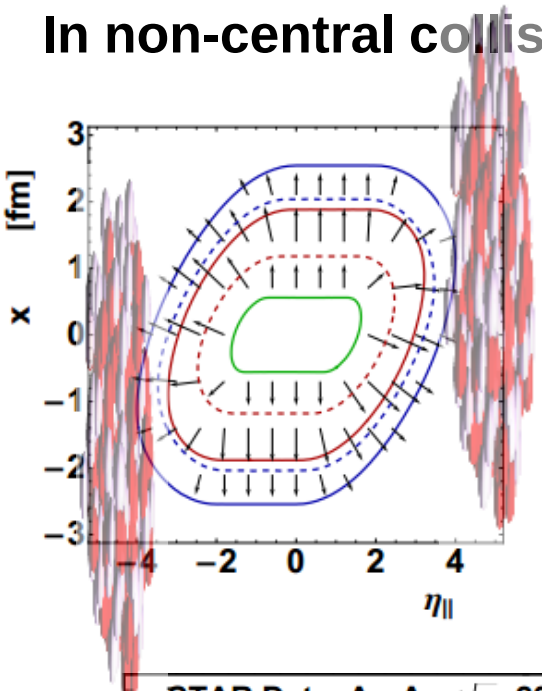
**Locally in transverse plane: use shock waves (i.e. Gaussian rapidity)**

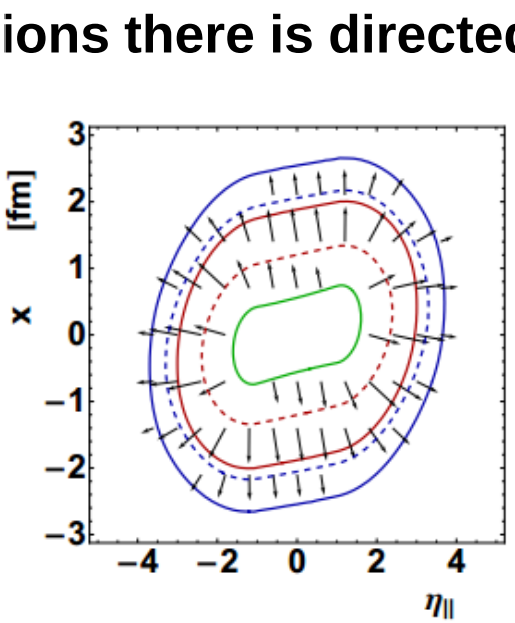
**→ Go and run hydro (MUSIC) and get particle spectra ☺**

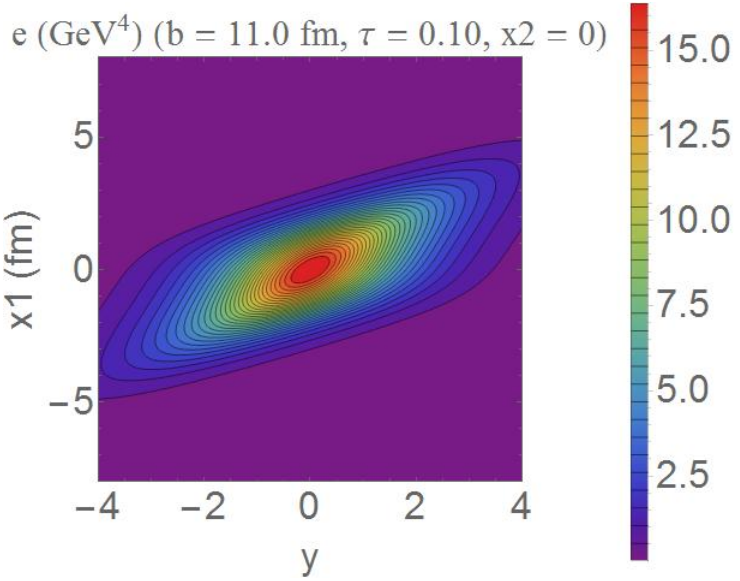


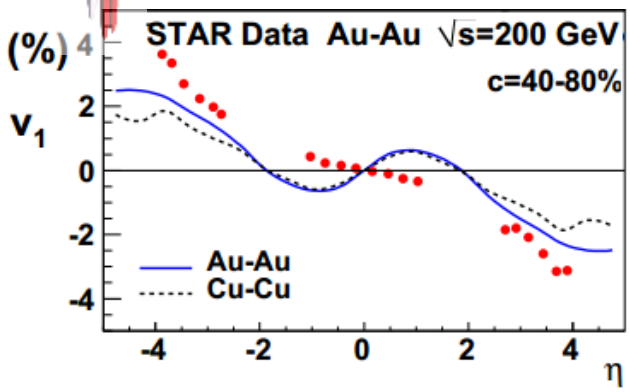
# DIRECTED FLOW AND LONGITUDINAL DYNAMICS

**In non-central collisions there is directed flow:**



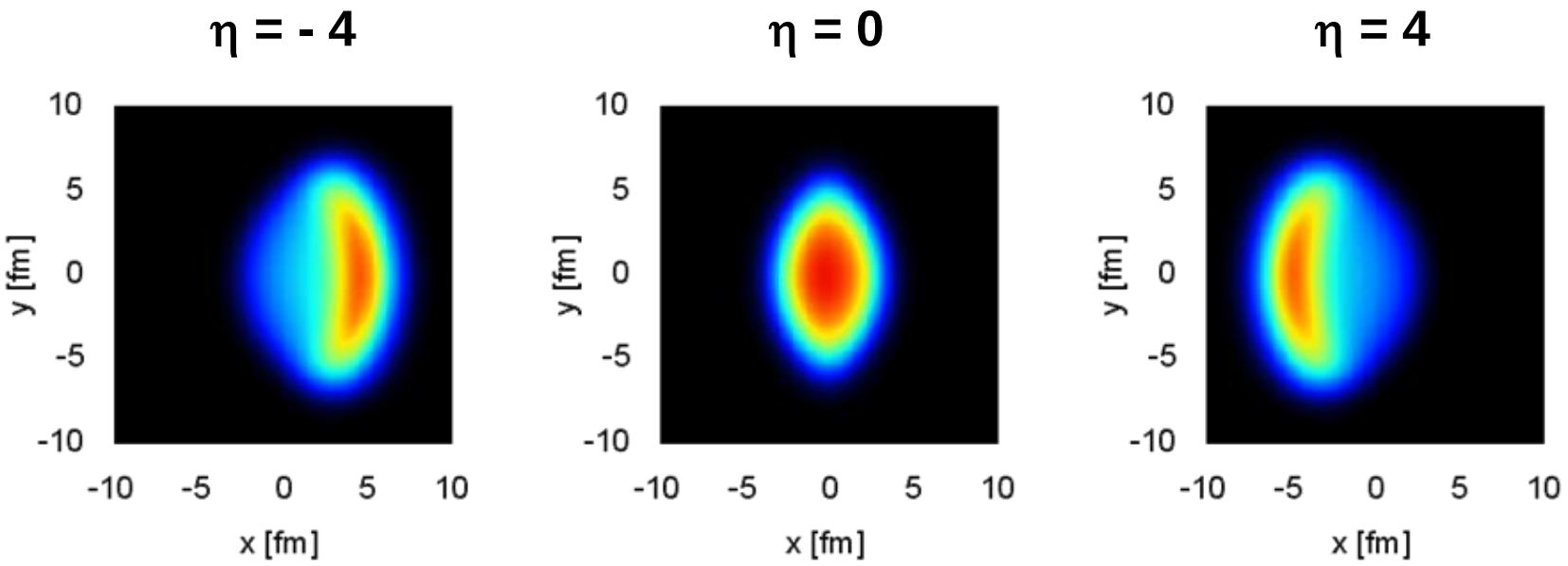




- ‘Standard’ boost-invariant coherent model conflicts with experiment
  - Either tilt,
  - Or use narrow rapidity profile

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

With Björn Schenke (to appear soon)

# MUSIC RESULTS




**Impact parameter 8 fm, time 0.1 fm/c to 10 fm/c**

**Initial flow in transverse plane by `universal pre-flow':** $v_i = -\frac{1}{3}\tau\,\partial_i e/e$

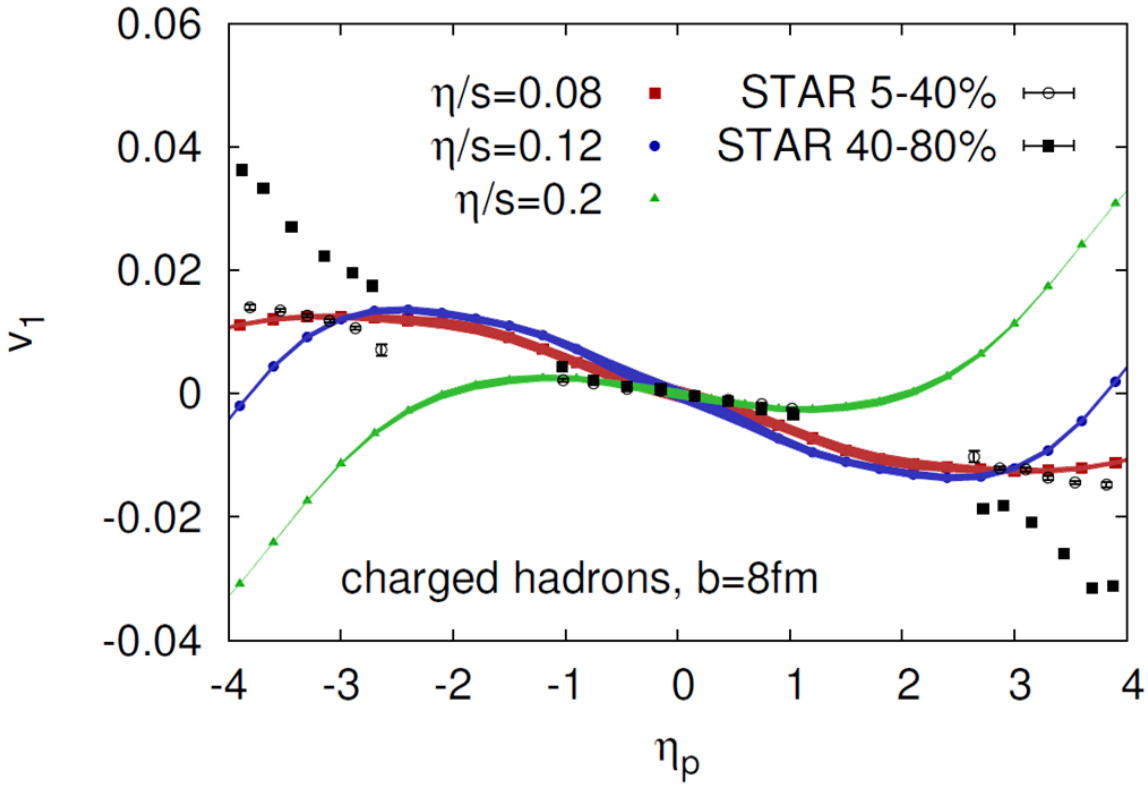


J. Vredevoogd and S. Pratt, Universal flow in the first stage of relativistic heavy ion collisions (2009)
WS, P. Romatschke and S. Pratt, Fully Dynamical Simulation of Central Nuclear Collisions (2013)

With Björn Schenke (to appear soon)

# MUSIC RESULTS, RHIC

**Directed flow: right ball-park values**



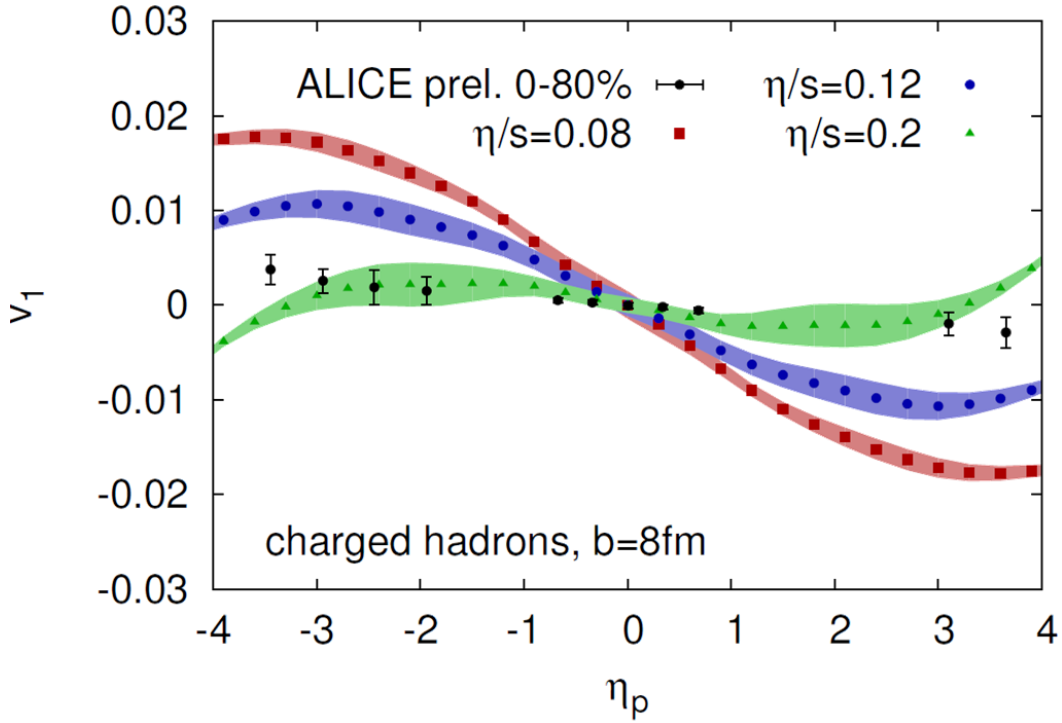

**Note: somewhat subtle to measure; event-plane etc**

***Could be very sensitive to viscosity***

With Björn Schenke (to appear soon)

# MUSIC RESULTS, LHC

**Directed flow: right ball-park values**




**Note: somewhat subtle to measure; event-plane etc**

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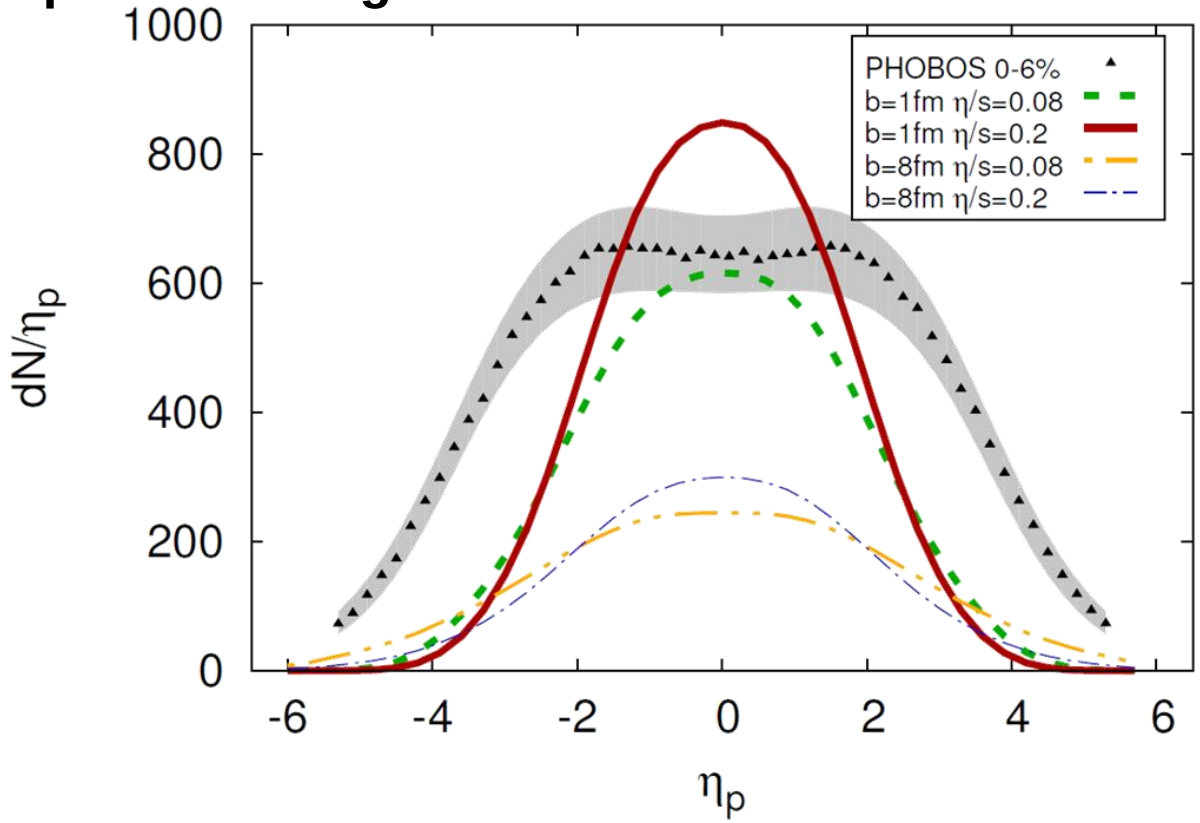
ALICE, Directed flow of charged particles at mid-rapidity relative to the spectator plane in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (2013)

With Björn Schenke (to appear soon)

# MUSIC RESULTS, RHIC

**Particle spectra in longitudinal direction:**



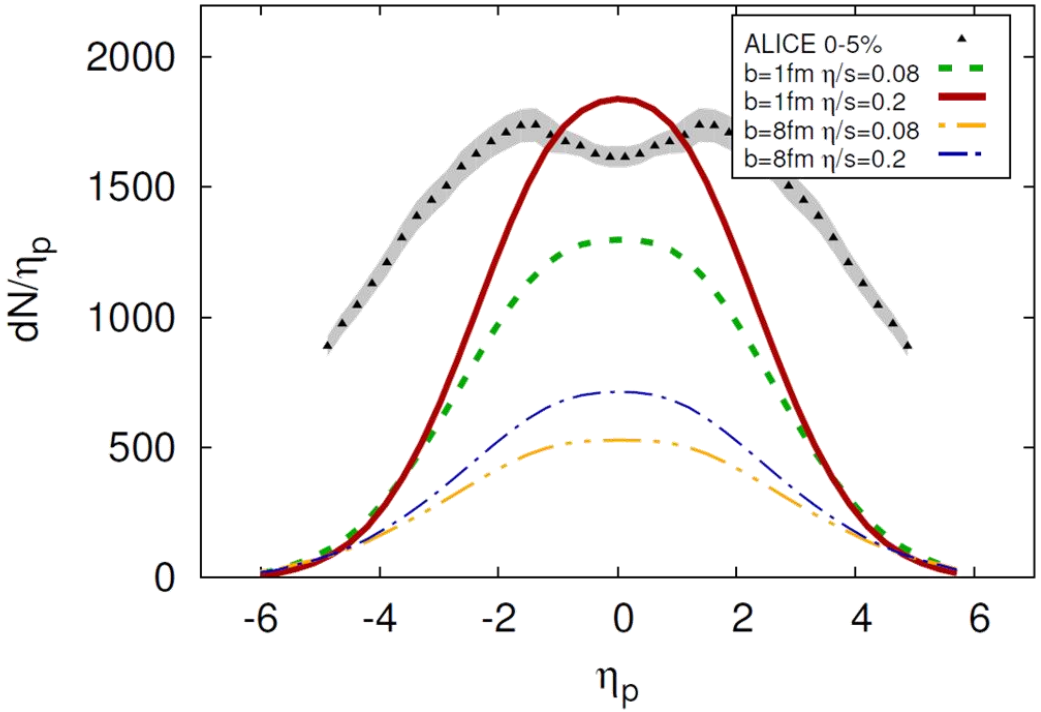

**Width comes out too narrow, rescaled initial energy by factor 6**

**Includes `dynamical cross-over' (i.e. non-universal rapidity)**

With Björn Schenke (to appear soon)

# MUSIC RESULTS, LHC

**Particle spectra in longitudinal direction:**



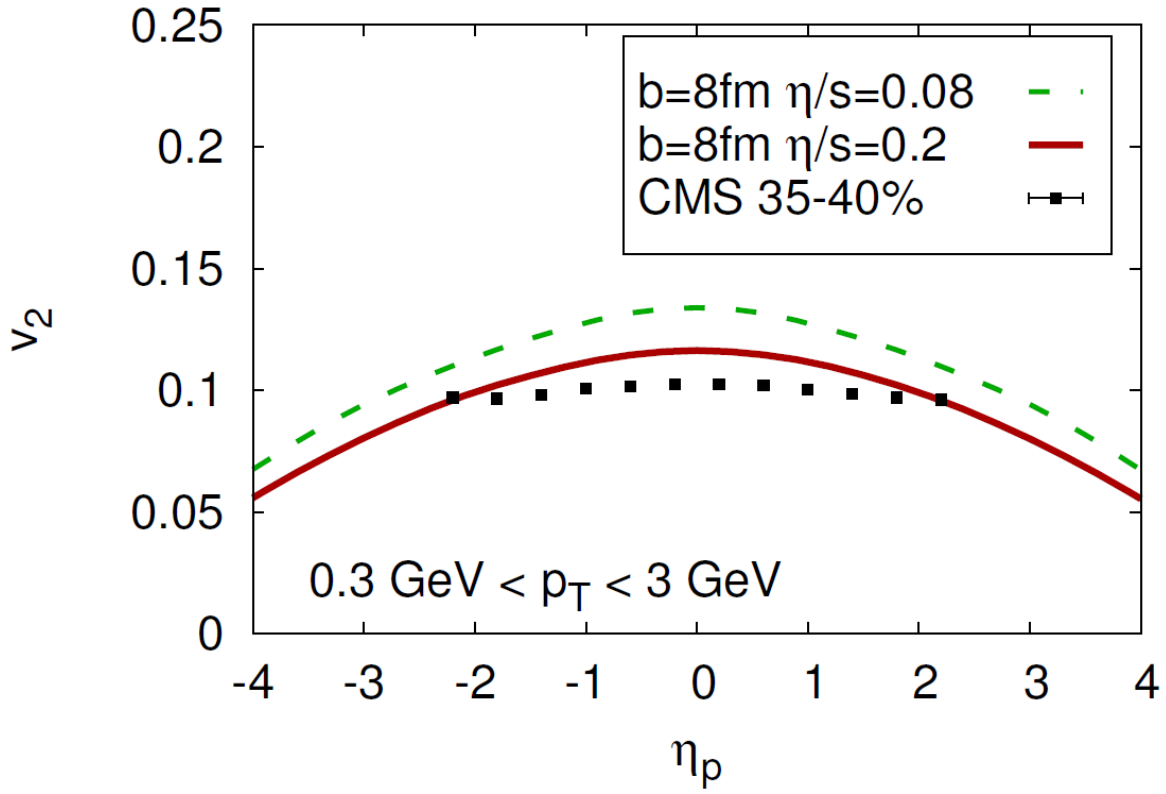

- **Rescaled initial energy density by factor 20 (fit total N)**
- **Profile is significantly too narrow**
- **Fluctuations will change profile**

ALICE, Bulk Properties of Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV measured by ALICE (2011)

With Björn Schenke (to appear soon)

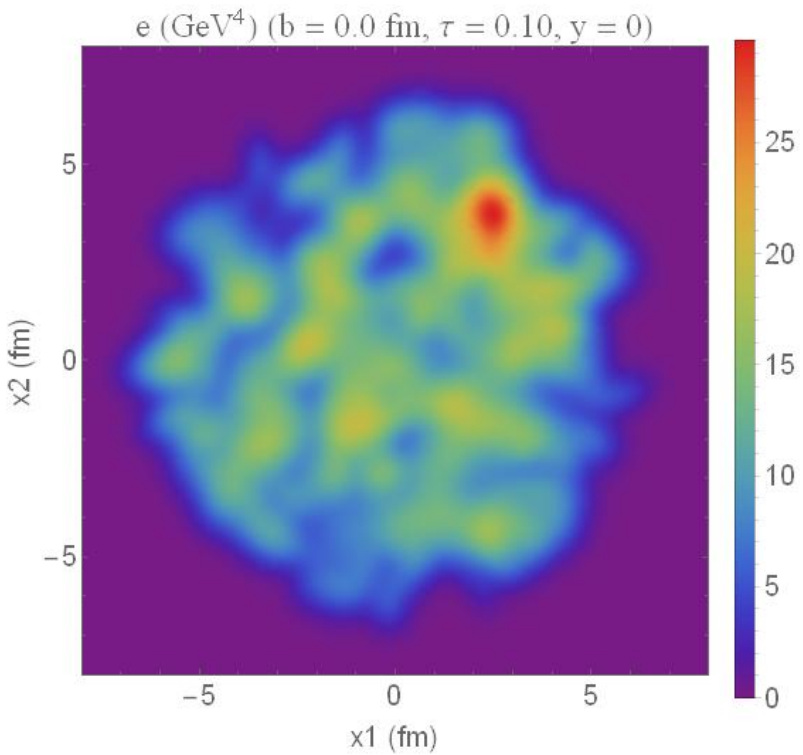
# MUSIC RESULTS, ELLIPTIC FLOW

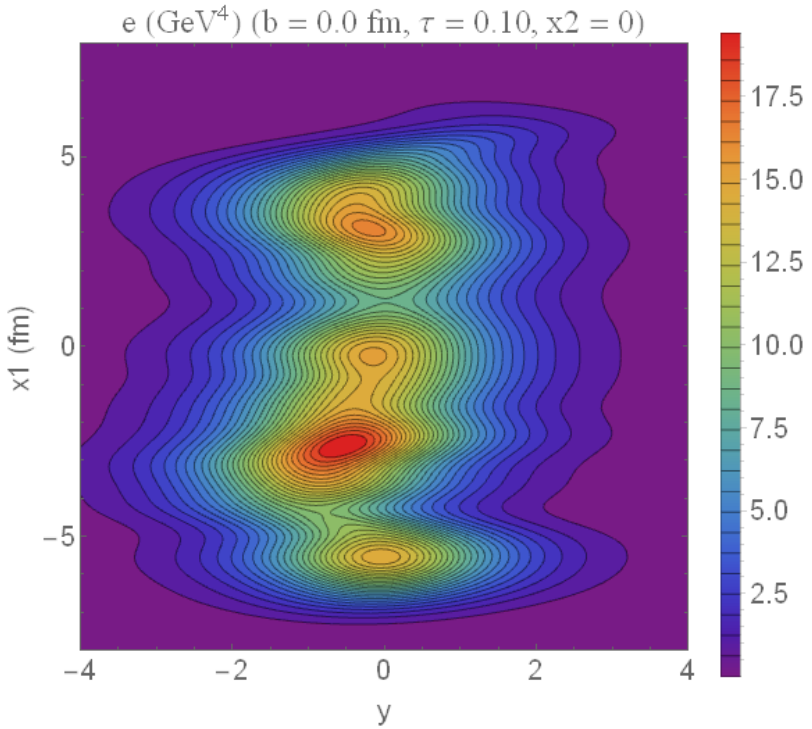
**Elliptic flow: also right order of magnitude, but a bit too narrow**



# EVENT-BY-EVENT

## Single nuclei are not smooth spheres: large fluctuations



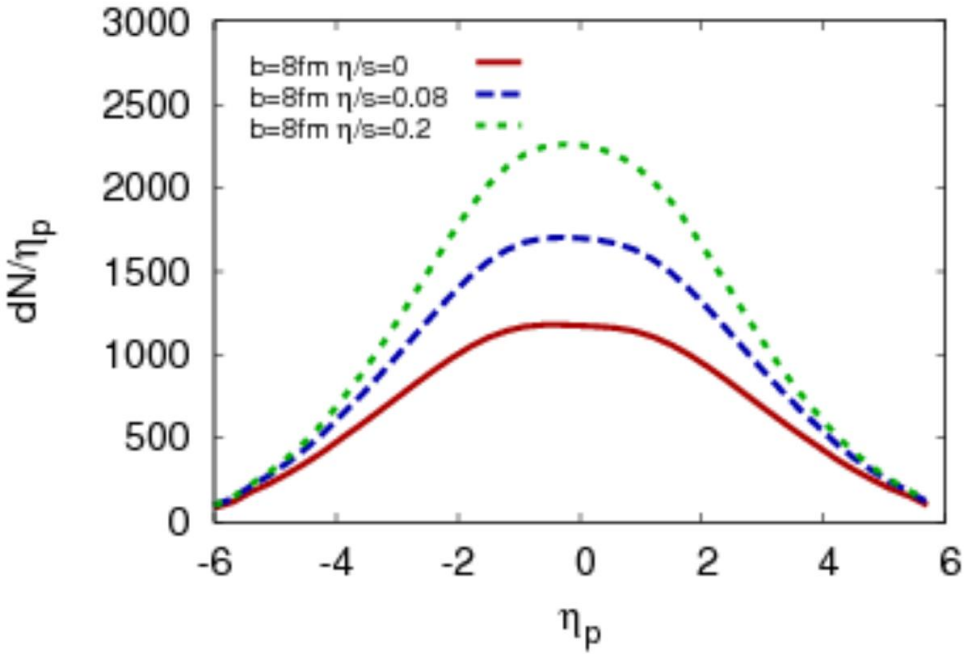




## More non-trivial:

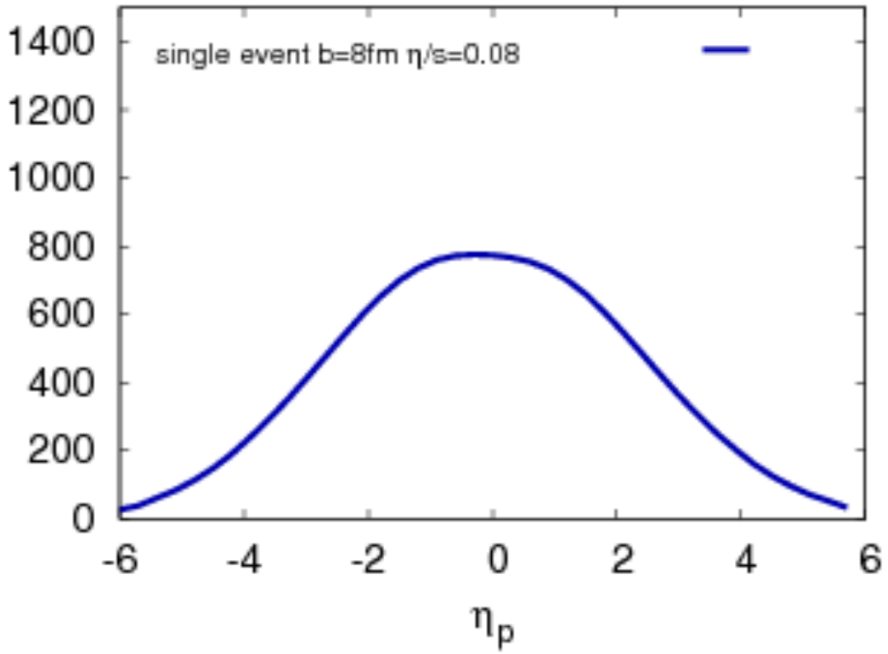
- **rapidity distribution widens**
- **average energy density goes down**

# EVENT-BY-EVENT

## Without fluctuation:




## With fluctuation:




## Big decrease in total multiplicity

- relates back to old computations by Gubser/Pufu/Yarom/Lin/Shuryak
- i.e. dN/dη very sensitive to energy distribution of a nucleon

# DISCUSSION

**A universal rapidity profile**

- Initial state: universal rapidity profile, with Bjorken velocity
- AdS/CFT: simple and strong predictions: fits some data??
- Current model only fitted overall energy density, very constrained

**AdS/CFT plus MUSIC 3+1 hydro exciting: stay tuned ☺**

- Directed flow as function of rapidity
- Test different transverse plane models? p-Pb collisions? Fluctuations?
- Rapidity dependence perhaps not studied enough?

**Future is open: *correct for infinite coupling approximation*, finite baryon density, non-conformal theories, confining theories……**