Holography and Equilibration

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Hydrodynamics and quantum anomaly SCGP program
May 1st 2014

outline

A falling membrane, dual to
equilibration shock wave in the scale space

strong stationary shock wave

high energy collisions

onset of
various versions
of hydro,
re-summed gradients

News about hydro vs experiments: high harmonics, small systems pA and pp

News on QCD string systems: “spaghetti” and “string balls”

Toward the AdS/CFT Gravity Dual for High Energy Collisions. 3.Gravitationally Collapsing Shell and Quasiequilibrium

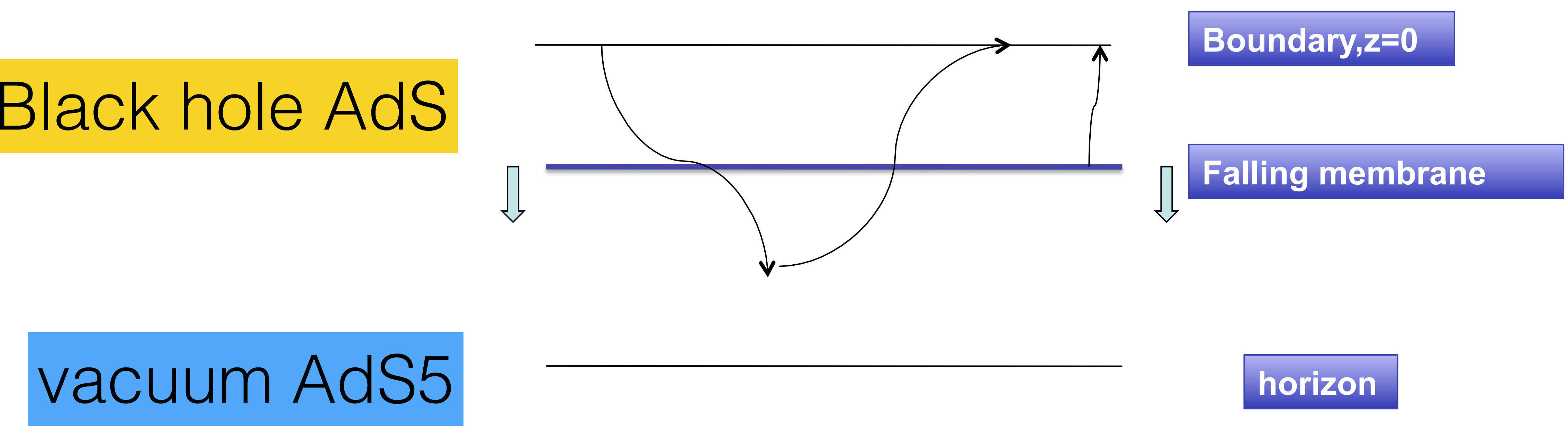
Phys.Rev.D78: 125018,2008.
arXiv:0808.0910

Shu Lin[1], and Edward Shuryak[2]

The main simplification of the paper is that this shell is *flat* - independent on our world 3 spatial coordinates. Therefore the overall solution of Einstein eqns reduces to two separate regions with well known *static* AdS-BH and AdS metrics. The falling of the shell is time dependent, its equation of motion is determined by the Israel junction condition, which we solve and analyzed. We also determined how final temperature (horizon position) depends on initial scale and shell tension.

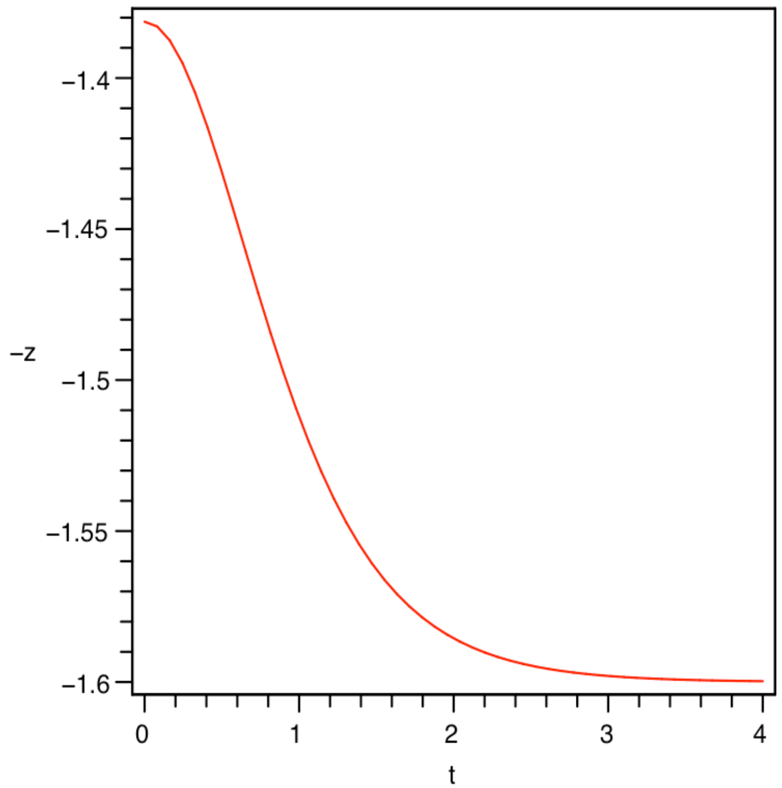
- Falling is dual to

further equilibration UV=>IR



Bottom line: there is no need to solve the Einstein equation
2 known and time-independent solutions combined =>
plus an **equilibration shock** in “scale” space

Israel's junction condition is dual to the equilibration dynamics



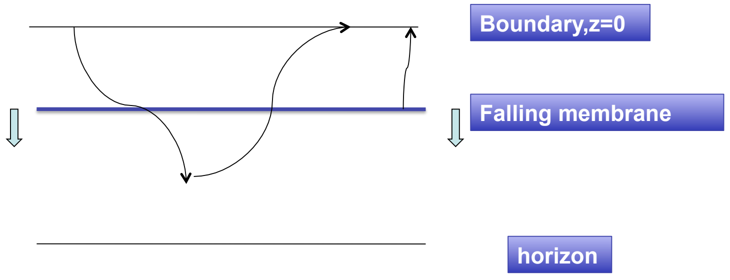
- Thermal AdS above= UV is equilibrated
- Cold AdS5 below= IR is not equilibrated
- The equilibration front moves

$$\frac{dz}{dt} = \frac{\dot{z}}{\dot{t}} = \frac{f\sqrt{(\frac{\kappa_5^2 p}{6})^2 + (\frac{3}{2\kappa_5^2 p})^2(1-f)^2 - \frac{1+f}{2}}}{\frac{\kappa_5^2 p}{6} + \frac{3}{2\kappa_5^2 p}(1-f)}$$

$$f = 1 - (z/z_h)^4$$

Two types of observers

- Single-point observer sees thermal stress tensor with T=const(t)
- Nonlocal 2-point experiments (the stress tensor correlators) send signal into the bulk and finds deviations: equilibration is actually time dependent



Average T_{ij} is thermal but the correlators (the two-point observers) deviate from equilibrium: (depending)

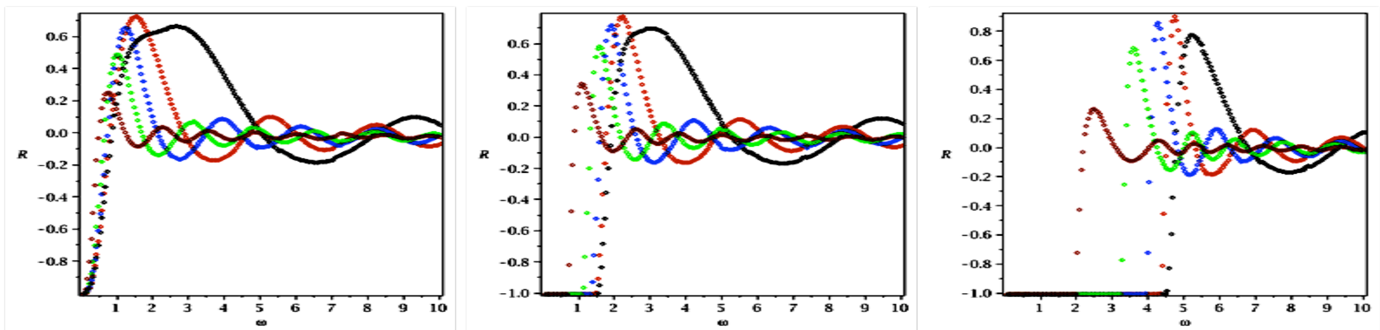


Figure 3: (color online)The relative deviation R at $q = 0$ left, $q = 1.5$ middle and $q = 4.5$ right. Different stages of thermalization are indicated by: black($u_m = 0.1$), red($u_m = 0.3$), blue($u_m = 0.5$), green($u_m = 0.7$), brown($u_m = 0.9$). As u_m approaches 1, i.e. the medium evolves to equilibrium, the oscillation decreases in amplitude and increases in frequency, thus the spectral density relaxes to thermal one

The reason for oscillations in spectral densities is in fact the ``echo" effect, induced by a gravitons scattering from a membrane, Confirmed numerically and semiclassically

Shocks in Quark-Gluon Plasmas

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(Dated: March 30, 2012)

Hydrodynamics is known to describe matter created in high energy heavy ion collisions well. Large deposition of energy by passing jets should create not only the sound waves, already discussed in literature, but also the shocks waves of finite amplitude. This paper is an introduction to relativistic shocks, which go through elementary energy and momentum continuity argument, to weak shocks treated in Navier-Stokes approximation, to out-of-equilibrium setting of AdS/CFT. While we have not yet found numerical solution to corresponding Einstein equations, we have found a variational approximation to the sum of their squares. Our general conclusion is that deviations from LS and NS hydrodynmical shock profiles are surprisingly small, even for strong shocks. We end with a list of open questions which the exact solution should be able to answer.

- The setting and flux equations
- Weak shocks (NS from textbooks)
- Strong shock: NS vs LS
- AdS/CFt shock: variational
- conclusions

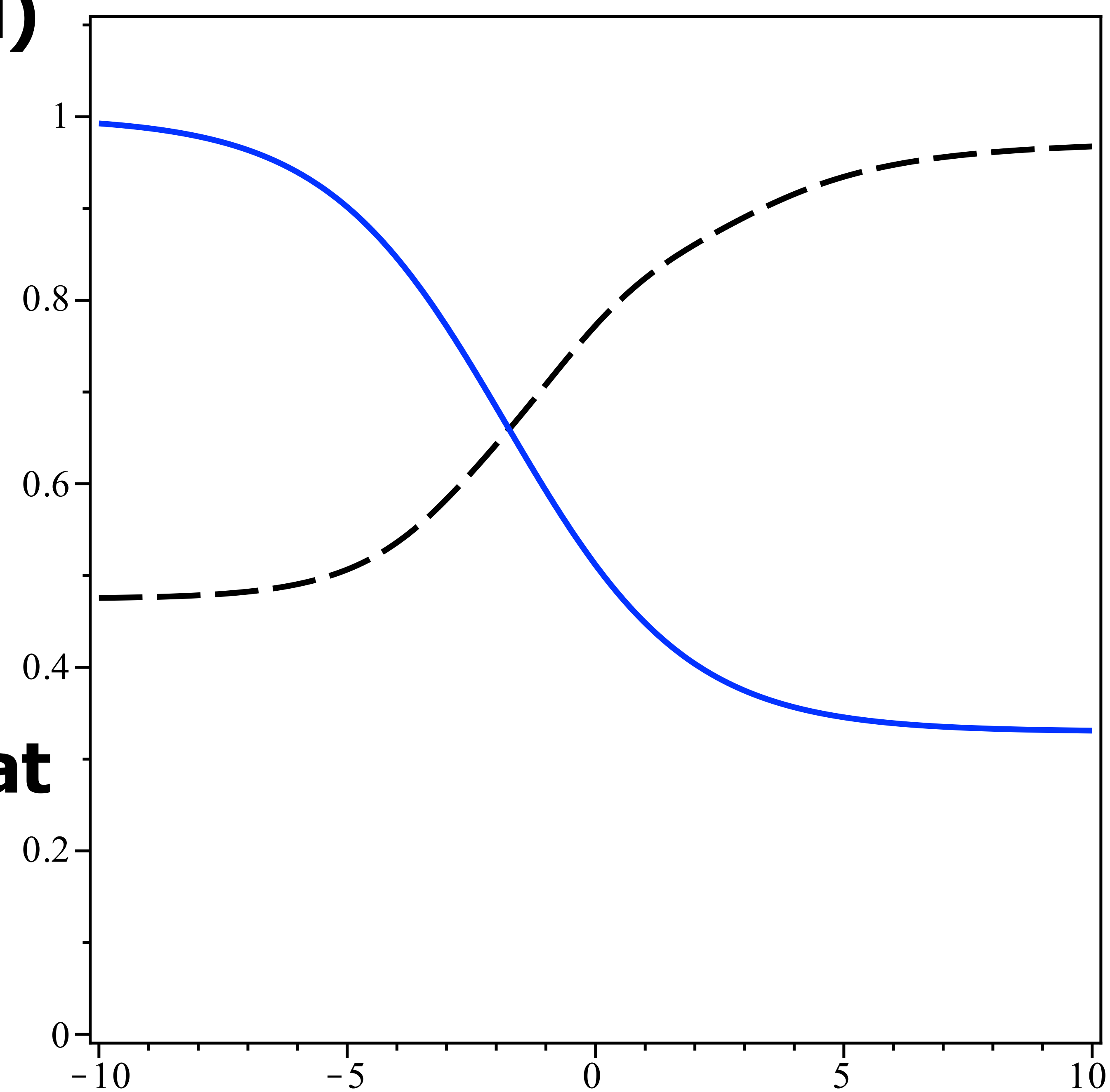
IV. STRONG SHOCKS AND THE RESUMED HYDRODYNAMICS

T01 and T11 balanced

Pressure (solid) jumps down, rapidity (dashed) up

Numerical example which is a solution of the NS Equations without expansion

(but is it justified? What about other Terms in gradient expansion?



AdS/CFT

- Weak shocks are basically hydro, can be done systematically, see 1004.3803 by Khlebnikov,Kruczenski Michalogiorgakis
- So we jump to a strong case
- If y=const, h=const, A=B=0 it is a boosted brane

V. SHOCKS IN THE ADS/CFT

We use coordinates $v, x_1 = x, x_2, x_3, r$ and write the nonzero component of the metric as

$$\begin{aligned}
g_{11} &= -r^2 f c^2 + r^2 s^2; \\
g_{12} &= g_{21} = -r^2 f cs + r^2 cs + A(x_1, r); \\
g_{22} &= -r^2 f s^2 + r^2 c^2 + B(x_1, r); \\
g_{15} &= g_{51} = c; \\
g_{25} &= g_{52} = s; \\
g_{44} &= g_{33} = r^2
\end{aligned} \tag{5.1}$$

where

$$\begin{aligned}
f &= 1 - h(x, r)^4 / r^4; \\
c &= cosh[y(x)]; \; s = sinh[y(x)]
\end{aligned} \tag{5.2}$$

$$
\begin{aligned}
R = & -(-96A h c h r - 96sAh c h r B - 40r \\
& +16scA^2r^4A'' - 12r^6B + 4r^4A^2 - 4AA''r^6 \\
& +16c^6h^4BA''A + 32c^2Br^3h^3(h') \\
& +16c^4B^2h^3(h')r - 12cBsr^5A' \\
& -12B'r^7 + 24c^4B^2h^3h''r^2 \\
& +2c^6h^4B^2B'' - 8AA''r^4c^2B + 4cr^6\dot{A}' \\
& +16r^2sA^2\ddot{y}c^3 - 4r^2c^5B^2s\ddot{y} \\
& +48sA^2cA'r^3 + 52cAB'r^5s + 8scr^3h^4A' \\
& +8c^2r^3sA\dot{A} + 16c^2rh^4AA' - 4c^4rBh^4B' \\
& -16c^4rAA'h^4 - 52AA'r^3c^2B - 64A^2h^3c^2(h')r \\
& +64A^2h^3c^4(h')r + 72sAcBr^4 - 8sAh^4r^2c \\
& -16sAc^3Bh^4 - 2r^8B'' + 3r^6\dot{y}^2 - 3r^6A'^2 \\
& +16A^4c^2 - 16A^4c^4 - 16sc^5h^4A^2A'' \\
& -4sAr^5\dot{y} - 6c^2BA'^2r^4 - 10c^4B\dot{y}^2r^4 \\
& +20c^3Br^5\dot{y} + 2c^2B\dot{y}^2r^4 + 16A^3c^3sB \\
& +24c^6B^3h^2(h')^2 - 4c^6h^4BA'^2 - c^6h^4BB'^2 \\
& +4c^4h^4BA'^2 + 2sr^6\dot{y}A' - r^2c^4h^4B'^2 \\
& +4r^2c^2h^4A'^2 - 16rA^2\dot{A}c^3 + 16r^3c^5B\dot{A} \\
& +16A^2r^3c^5\dot{y} + r^4c^4BB'^2 - 4c^4h^4r^2A'^2 \\
& +4A^2r^2c^2A'^2 + 16A^2r^2c^4\dot{y}^2 \\
& -4A^2r^2c^2\dot{y}^2 - 48rc^4A^3A' + 48rc^2A^3A' - \\
& 4r^2c^4A^2A'^2 - 12r^2c^6A^2\dot{y}^2 + 16c^5rA^2\dot{A} \\
& +8c^5rB^2\dot{A} + 4r^3c^5B^2\dot{y} - 8r^3c^4B^2B' \\
& -3r^2c^6B^2\dot{y}^2 - 3r^2c^4B^2A'^2 \\
& -96r^2c^4BA^2 + 8r^5c^4BB' - r^2c^4B^2\dot{y}^2 \\
& +16r^3c^5A\dot{B} - 56A^2r^3B'c^4 - 4c^4r^4\dot{y}\dot{A} \\
& +4c^2r^4\dot{y}\dot{A} - 2c^3r^4A'\dot{B} \\
& +12c^3B^2\dot{y}r^3 - 32c^2r^5A'A - 8A^2\dot{y}r^3c^3 \\
& -2r^6c^3\dot{y}B' + 2r^6c\dot{y}B' + 32r^5c^4AA' \\
& -32sc^5ABh^3(h')B' - 32r^2sAc^3h^3(h')B' \\
& -32r^2c^3BsA'h^3(h') - 2r^2c^4BAs\dot{y}B' \\
& -288sAh^2c^3(h')^2r^2B + 16c^4r^2Bh^3(h')B' \\
& +64c^4r^2AA'h^3(h') - 64c^2r^2AA'h^3(h') \\
& +4c^2Bs\dot{y}r^4A' - 144sAh^2c(h')^2r^4 \\
& +64sA^2c^3A'h^3(h') - 64c^4BAA'h^3(h') \\
& -64sc^5A^2A'h^3(h') + 4sc^5h^4BA'B' \\
& 144sAc^5B^2h^2(h')^2 + 64c^6BAA'h^3(h') \\
& -16c^5B^2h^3s(h')A' + 4r^4c^4Bs\dot{y}A' \\
& -2r^4c^3BsA'B' + 8r^2c^3BAA'\dot{y} - 24c^4rsA\dot{A}B \\
& +2r^2c^4BAA'B' + 2r^2c^4B^2s\dot{y}A' \\
& +4r^2c^4BsA'\dot{A} + 2r^2c^5Bs\dot{y}\dot{B} \\
& -4r^2c^5BAA'\dot{y} + 4r^4sAc^4\dot{y}B' \\
& -6r^4sAc^2\dot{y}B' - 8r^2sAc^3\dot{y}\dot{A} \\
& -8r^2sA^2c^2A'\dot{y} - 16sr^4h^3c(h')A' \\
& +12sc^5r^2A\dot{y}^2B + 44sc^3r^3ABB' \\
& +4sc^4r^2AA'\dot{B} + 8sc^3r^2ABA'^2 \\
& +8sc^5r^2A\dot{y}\dot{A} - 4sc^3A^2r^2A'B'
\end{aligned}
$$

$$
\begin{aligned}
& -96A^2h^3c^4h''B + 8r^6h^3h'' - 4r^6B''c^2B \\
& -48sAh^3ch''r^4 - 48sAc^5B^2h^3h'' - 8c^5h^4BB''sA \\
& +8c^6h^4A^2B'' + 8r^4c^3BB''sA - 8sc^3h^4BA''r^2 \\
& -16r^2c^4B\ddot{y}A - 16c^2r^2h^4A''A + 96A^2h^3c^4h''r^2 \\
& +16c^4r^4\ddot{y}A - 16c^2r^4\ddot{y}A + 8c^2A^2B''r^4 \\
& +16c^4r^2h^4A''A + 224c^2A^2r^4 - 8c^4h^4A^2B'' \\
& +8c^6B^3h^3h'' - 16sr^5c^3BA' - 16sr^5c^3AB' \\
& +4sr^6\dot{y}A'c^2 + 8r^2Ac^3A'\dot{A} + 4r^2Ac^4\dot{y}\dot{B} \\
& -8r^4c^5AA'\dot{y} + 4r^4c^2sA'\dot{A} + 2r^4c^3s\dot{y}\dot{B} \\
& -8r^2c^5AA'\dot{A} - 4r^2c^6A\dot{y}\dot{B} + 4r^4c^4AA'B' \\
& -2r^4c^3AsB'^2 - 8rc^3A^3B's + 4rc^4A^2B'B \\
& +4r^2c^5A^2\dot{y}B' + 96r^2sAc^3B^2 - 8r^3c^4Bs\dot{B} \\
& -4r^2c^6B\dot{y}\dot{A} - 2r^2c^5BA'\dot{B} + 24r^3c^4BAA' \\
& -16rc^4B^2AA' + 8c^4rA^2\dot{B}s - 4c^5rA\dot{B}B \\
& -12sc^3r^3B^2A' + 8r^4AA'c\dot{y} - 2sr^6cA'B' \\
& +4r^2c^4B\dot{y}\dot{A} - 32r^3sA\dot{A}c^4 - 16A^3rc^2\dot{y}s \\
& +8A^2rc^3\dot{y}B + 224r^4c^3BAs - 2r^4c^5B\dot{y}B' \\
& -4A^2r^2c^3\dot{y}B' + 8r^4c^2h^3(h')B' + 4c^3r^4AA'\dot{y} \\
& -2Ac^2A'r^4B' - 288A^2h^2c^2(h')^2r^2 \\
& +288A^2h^2c^4(h')^2r^2 + 2c^3B\dot{y}r^4B' - 8c^3sh^4AA'^2 \\
& +192A^3h^2c^3(h')^2s - 288A^2h^2c^4(h')^2B + 32c^6A^2h^3(h')B' \\
& +8c^5sh^4AA'^2 + 2c^5sh^4AB'^2 + 288c^6BA^2h^2(h')^2 \\
& +8c^6B^2h^3(h')B' - 8c^6h^4AA'B' - 192sc^5A^3h^2(h')^2 \\
& +8c^4h^4AA'B' - 32A^2h^3c^4(h')B' + 8sAcA'^2r^4 \\
& +20sAc^3\dot{y}^2r^4 - 40sAc^2r^5\dot{y} - 8sAc\dot{y}^2r^4 \\
& +72c^4B^2h^2(h')^2r^2 + 72c^2Bh^2(h')^2r^4 \\
& -64sAc^3Bh^3(h')r + 8sr^6B''cA + 16r^2c^6B\ddot{y}A \\
& +192sAcr^6 + 12cBr^5\dot{y} + 4c^2Bh^4r^2 \\
& -16scr^7A' - 20c^3r^3A\dot{B} - 8c^2r^5s\dot{B} \\
& -20c^2r^5BB' + 60c^2A^2B'r^3 - 4r^3c^2h^4B' \\
& +96A^2r^2c^2B - 64sAr^3h^3(h')c + 8sc^3h^4BA'r \\
& +8c^3sh^4AB'r + 64A^3h^3c^3h''s - 4sc^5h^4B^2A'' \\
& -16c^4h^4BA''A - 7c^2r^6\dot{y}^2 + r^6c^2B'^2 \\
& +24r^6h^2(h')^2 - 8cr^5\dot{A} - 4A^2c^4B^2 \\
& -56r^4c^4B^2 - 24r^2c^4B^3 - 224A^2r^4c^4 \\
& +16r^2c^5A^2\dot{A}' - 8r^4c^4A^2B'' + 16r^2c^2A^3A'' \\
& +4r^2c^5B^2\dot{A}' + 8c^3r^4\dot{A}'B + 4c^4h^4Br^2B'' \\
& +16r^5h^3(h') + 16r^7c\dot{y} + 16c^3r^5\dot{A} \\
& +8c^2r^7B' + 16A^2c^4h^4 - 16A^2c^2h^4 \\
& -12AA'r^5 - 96c^2Br^6 - 36c^2B^2r^4 + 4c^4B^2h^4 \\
& +24c^2Bh^3h''r^4 - 64sc^5A^3h^3h'' - 16r^4c^2s\dot{A}'A \\
& -16sc^4r^2A\dot{A}'B + 96c^6BA^2h^3h'' - 16sc^5r^2A^2\ddot{y} \\
& -4scr^4h^4A'' + 16sc^3A^2r^2A''B - 8c^3sh^4Ar^2B'' \\
& -8r^4c^3s\ddot{y}B + 16sc^3h^4A^2A'' - 4r^2c^4B^2AA'') \\
& \frac{1}{2r^2(r^2 - 2csA + c^2B)^3} \qquad (5.4)
\end{aligned}
$$

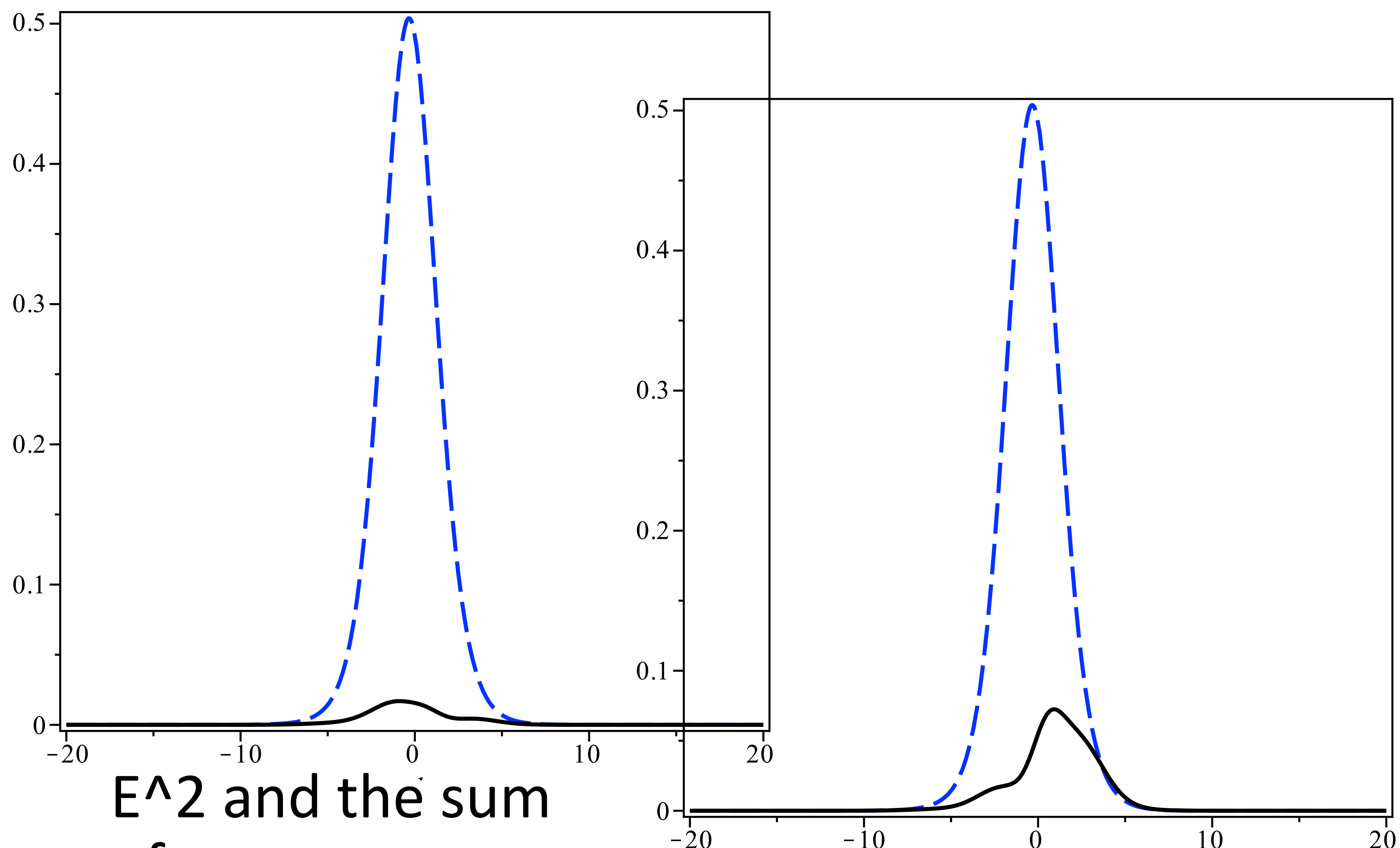
Unfortunately the Einstein-Hilbert action R is not bounded from below and cannot be used for variational studies. The so called conformal gravity, with a squared Weyl tensor in the Lagrangian, should work [22]. What we propose to do is to use the covariantly squared (modified) Einstein tensor

$$
\bar{E}^2 = \bar{E}_{mn}\bar{E}^{mn}, \quad \bar{E}_{mn} = E_{mn} + 6g_{mn} \qquad (5.6)
$$

which combines all the Einstein equations (in the AdS/CFT setting) into one (covariant scalar) combina-

Maple refuses to even display the expression for it, but fortunately it still takes explicit functions and evaluate/plot the results… so one
can play with that

Variational method



E^2 and the sum of squares

Dashed is NS, it already is rather good

Variational result: one function only

$$B(x, r) = -0.052r(1 - 0.3x)\exp[-.1(x + 0.3)^2]$$

The physical meaning of B is correction to the g_{xx}

Its **negative sign** and magnitude imply few percent reduction of the shock width, especially near the horizon

Conclusions: same as from LS resummation, Corrections to NS are quite small!

Improved Hydrodynamics from the AdS/CFT

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Abstract: We generalize (linearized) relativistic hydrodynamics by including all order gradient expansion of the energy momentum tensor, parametrized by four momenta-dependend transport coefficients, one of which is the usual shear viscosity. We then apply the AdS/CFT duality for $\mathcal{N} = 4$ SUSY in order to compute the retarded correlators of the energy-momentum tensor. From these correlators we determine a large set of transport coefficients of third- and fourth-order hydrodynamics. We find that higher order terms have a tendency to reduce the effect of viscosity.

In the near-longwave limit all of the coefficient functions are expandable in power series [8]

$$\eta = \eta_0(1 + i\eta_{0,1}\,\omega + \eta_{2,0}\,k^2 + \eta_{0,2}\,w^2 + i\,\eta_{2,1}\,\omega\,k^2 + i\,\eta_{0,3}\,\omega^3 + \eta_{4,0}\,k^4 + \eta_{2,2}\,\omega^2\,k^2 + \eta_{0,4}\,\omega^4 + \cdots);$$

$$\eta_0 = (\epsilon + P)/2; \qquad \tau \equiv \eta_{0,1} = 2 - \ln 2\,; \qquad \eta_{2,0} = -1/2;$$

$$\eta_{0,2} \simeq -1.379 \pm 0.001 \simeq -\frac{3}{2} + \frac{\ln^2 2}{4}$$

4th order hydro

$$\eta_{2,1} = -2.275 \pm 0.005\,; \qquad \eta_{0,3} = -0.082 \pm 0.003$$

5th order hydro

$$\eta_{4,0} = 0.565 \pm 0.005\,; \qquad \eta_{0,4} = 2.9 \pm 0.1\,; \qquad \eta_{2,2} = 1.1 \pm 0.2\,;$$

Pade resummation of the series

- Model 1 has 3 poles and reproduce 8 coeff. exactly and more approximately

the scalar channel. The second and third poles practically cancel each other. Despite the fact that it does not accurately reproduce the expansion, it turns out to be a very good approximation to retain only one pole, similarly to IS but with three-momentum dependence.

$$\eta_{model\,2} = \frac{\eta_0}{1 - \eta_{2,0}\,k^2 - i\,w\,\eta_{0,1}} \tag{4.3}$$

Note: for stationary (time independent) problem omega=0
And only k^2 term in denominator remains, like in screening resummation

$$-k^2/q^2 \;\rightarrow\; \left(\frac{\partial}{\partial r}\right)^2 + \frac{1}{r}\frac{\partial}{\partial r}$$

$$i\omega/q \;\rightarrow\; \frac{\partial}{\partial t}$$

$$\mathbf{O}_{LS}^{-1}(f) = \quad 1 + \frac{q^2}{2(2\pi T)^2}\left(\frac{\partial^2 f}{\partial r^2} + \frac{1}{r}\frac{\partial f}{\partial r}\right)\frac{1}{f} + (2 - \ln 2)\,\frac{q}{2\pi T}\,\frac{\partial f}{\partial t}\,\frac{1}{f} \tag{31}$$

LS hydrodynamics

Schematically the resummed hydro equations look as

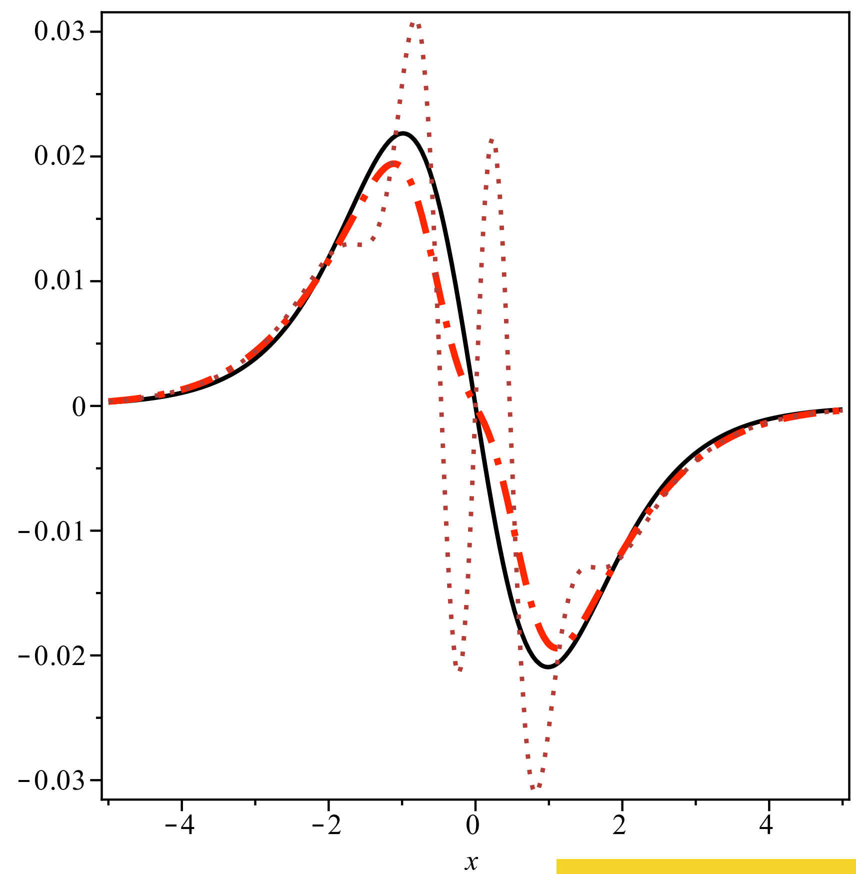
$$(Euler) = \eta \mathbf{O}_{LS}(Navier - Stokes) \tag{32}$$

where $\mathbf{O}_{LS}$ is an integral operator. However, one can act with its inverse on the hydrodynamical equation as a whole, acting on the Euler part but canceling it in the viscous term

$$\mathbf{O}_{LS}^{-1}(Euler) = \eta(Navier - Stokes) \tag{33}$$

These are the equations of the LS hydrodynamics. Obviously they have two extra derivatives and thus need more initial conditions for solution.

Expansion in gradients (colored) vs the LS resummation (black)



Red dash-dotted line includes all up to 8 derivatives, brown dotted up to 12 derivatives

The solid line is the LS factor $$\frac{1}{1-f''/8f}$$

while there is no small parameter (strong shock example) the LS deviations from NS are on the level of a percent

(and thus it is hard to tell if they are closer to Einstein eqn answer as we dont know it that well)

The characteristics of thermalization of boost-invariant plasma from holography

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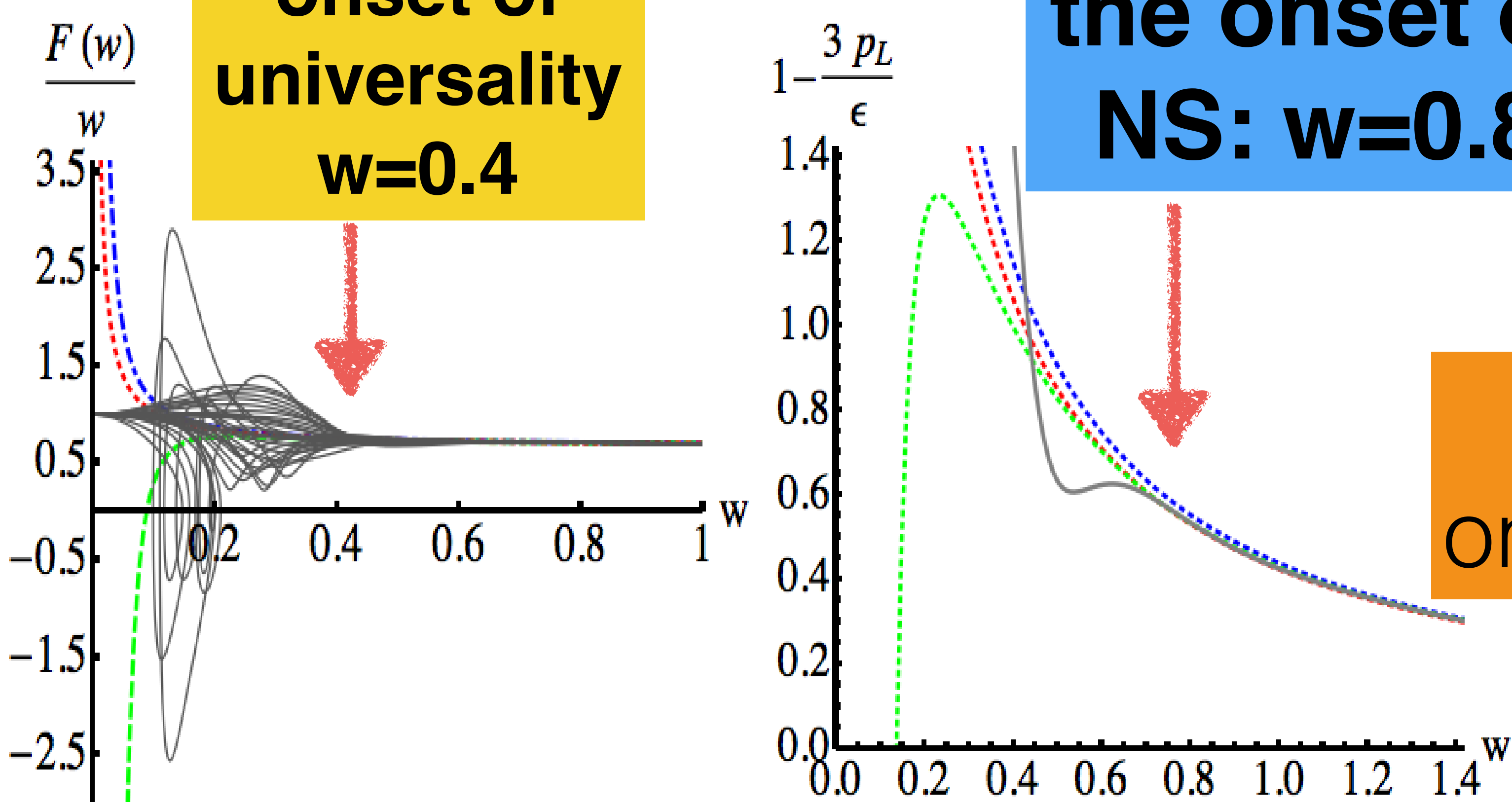
We report on the approach towards the hydrodynamic regime of boost-invariant $\mathcal{N} = 4$ super Yang-Mills plasma at strong coupling starting from various far-from-equilibrium states at $\tau = 0$. The results are obtained through numerical solution of Einstein's equations for the dual geometries, as described in detail in the companion article arXiv:1203.0755. Despite the very rich far-from-equilibrium evolution, we find surprising regularities in the form of clear correlations between initial entropy and total produced entropy, as well as between initial entropy and the temperature at thermalization, understood as the transition to a hydrodynamic description. For 29 different initial conditions that we consider, hydrodynamics turns out to be definitely applicable for proper times larger than 0.7 in units of inverse temperature at thermalization. We observe a sizable anisotropy in the energy-momentum tensor at thermalization, which is nevertheless entirely due to hydrodynamic effects. This suggests that effective thermalization in heavy ion collisions may occur significantly earlier than true thermalization.

onset of universality w=0.4

the onset of NS: w=0.8

$$w = \tau T$$

$$\frac{dw}{d\ln\tau} = F(w)$$



Zero anisotropy onset of ideal hydro

[G. 1. a) $F(w)/w$ versus w for all 29 initial data. b) Pressur
ıisotropy $1 - \frac{3p_L}{\varepsilon}$ for a selected profile. Red, blue and gree
ırves represent 1^{st}, 2^{nd} and 3^{rd} order hydrodynamics fit.

So, its a hint that there may exist a better hydro valid for w>0.4

Universal hydrodynamics and charged hadron multiplicity at the LHC

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Time evolution of a "little bang" created in heavy ion collisions can be divided into two phases, the pre-equilibrium and hydrodynamic. At what moment the evolution becomes hydrodynamic and is there any universality in the hydrodynamic flow? To answer these questions we briefly discuss various versions of hydrodynamics and their applicability conditions. In particular, we elaborate on the idea of "universal" (all-order resumed) hydrodynamics and propose a simple new model for it. The model is motivated by results obtained recently via the AdS/CFT correspondence. Finally, charged hadron multiplicities in heavy ion collisions at the RHIC and LHC are discussed. At the freezout, the multiplicities can be related to total entropy produced in the collision. Assuming the universal hydrodynamics to hold, we calculate the entropy production in the hydro stage of the collision. We end up speculating about a connection between the multiplicity growth and the temperature dependence of the QGP viscosity.

$$F(w)/w = \frac{2}{3} + \frac{1}{3w}\,\bar\eta - \frac{1}{3\,w^2}\frac{\bar\eta\,(\ln 2 - 1)}{3\pi} + \frac{15 - 2\pi^2 - 45ln(2) + 24(ln(2))^2}{972\pi^3\,w^3} + O(1/w^4)\,.$$

$$(3/2)F(w_0)/w_0 = 1 + 0.1326 + 0.0107 - 0.0189$$

$$w_0 \simeq 0.4$$

higher order terms smaller and tend to cancel
also in this problem, although it is not linear

but we do not yet know if LS hydro is
indeed more accurate than NS …

hydro in small systems, pp and pA

- 1953 Landau: hydro model for pp collisions (longitudinal)
- 1979 Shuryak,Zhirov looked for **transverse flow** in pp in ISR data, but found **Mt scaling** instead
- 1990's Bjorken and Minimax experiment in Fermilab found some hints at Tevatron high multiplicity events
- 1995 and on: a lot of flows in AA collisions, since 2000 RHIC,2010 LHC => ``ideal fluid" paradigm, hydro becomes a mainstream
- 2010 CMS ridge in high multiplicity pp => **Hydro in pp?**

The Fate of the Initial State Fluctuations in Heavy Ion Collisic
III The Second Act of Hydrodynamics

Pilar Staig and Edward Shuryak

Co-moving coordinates for the Gubser flow: Gubser and Yarom, arXiv:1012.1314

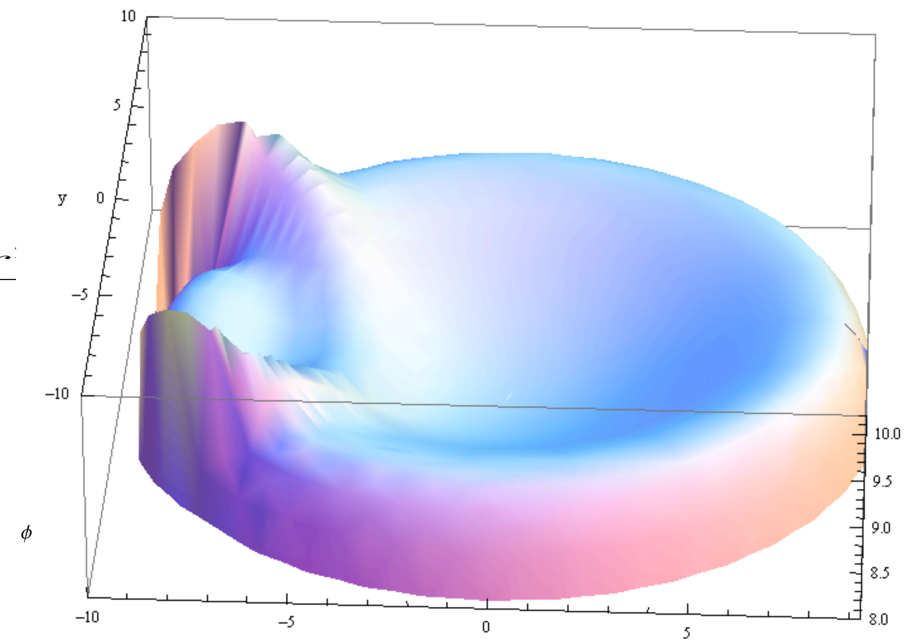
$$\sinh\rho = -\frac{1 - q^2\tau^2 + q^2 r^2}{2q\tau}$$
$$\tan\theta = \frac{2qr}{1 + q^2\tau^2 - q^2 r^2}$$

$$\frac{\partial^2\delta}{\partial\rho^2} - \frac{1}{3\cosh^2\rho}\left(\frac{\partial^2\delta}{\partial\theta^2} + \frac{1}{\tan\theta}\frac{\partial\delta}{\partial\theta} + \frac{1}{\sin^2\theta}\frac{\partial^2\delta}{\partial\phi^2}\right) + \frac{4}{3}\tanh\rho\frac{\partial\delta}{\partial\rho} = 0 \qquad (3.16)$$

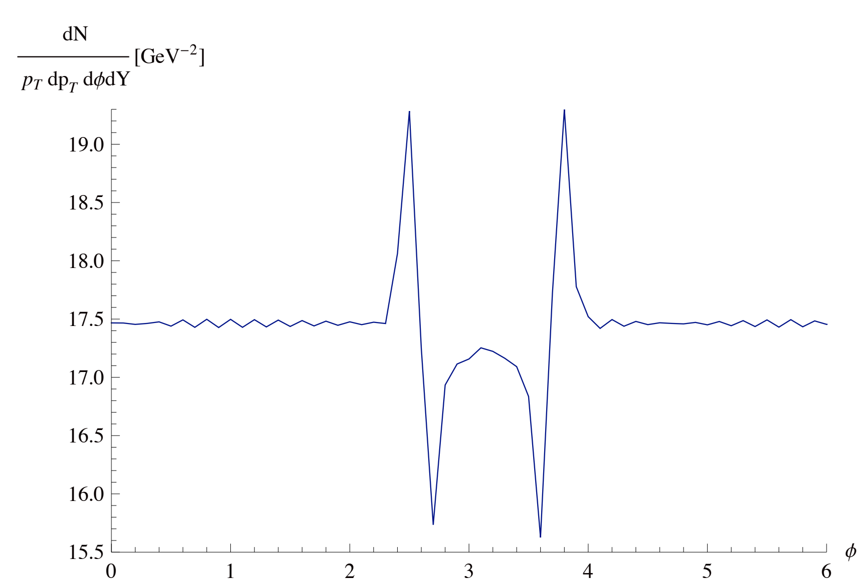
We have seen that in the short wavelength approximation we found a wave-like solution to equation 3.16, but now we would like to look for the exact solution, which can be found by using variable separation such that $\delta(\rho,\theta,\phi) = R(\rho)\Theta(\theta)\Phi(\theta)$, then

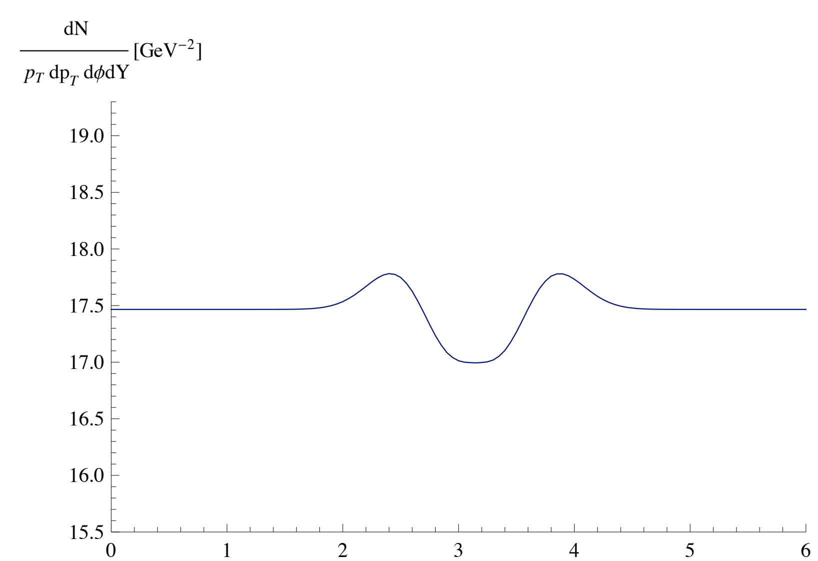
$$R(\rho) = \frac{C_1 P^{2/3}_{-\frac{1}{2}+\frac{1}{6}\sqrt{12\lambda+1}}(\tanh\rho) + C_2 Q^{2/3}_{-\frac{1}{2}+\frac{1}{6}\sqrt{12\lambda+1}}(\tanh\rho)}{(\cosh\rho)^{2/3}}$$
$$\Theta(\theta) = C_3 P_l^m(\cos\theta) + C_4 Q_l^m(\cos\theta)$$
$$\Phi(\phi) = C_5 e^{im\phi} + C_6 e^{-im\phi} \qquad (3.26)$$

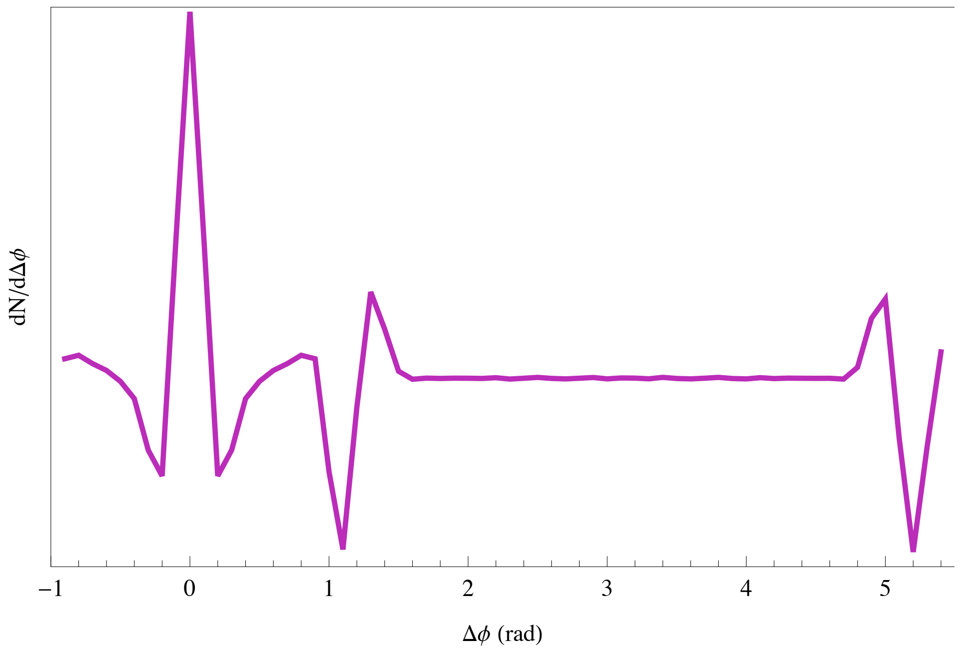
where $\lambda = l(l+1)$ and P and Q are associated Legendre polynomials. The part of the solution depending on θ and ϕ can be combined in order to form spherical harmonics $Y_{lm}(\theta,\phi)$, such that $\delta(\rho,\theta,\phi) \propto R_l(\rho)Y_{lm}(\theta,\phi)$.



The modified freezeout
Surface (right) leads to
A modified angular distribution
Of particles, with and without viscosity
(left)

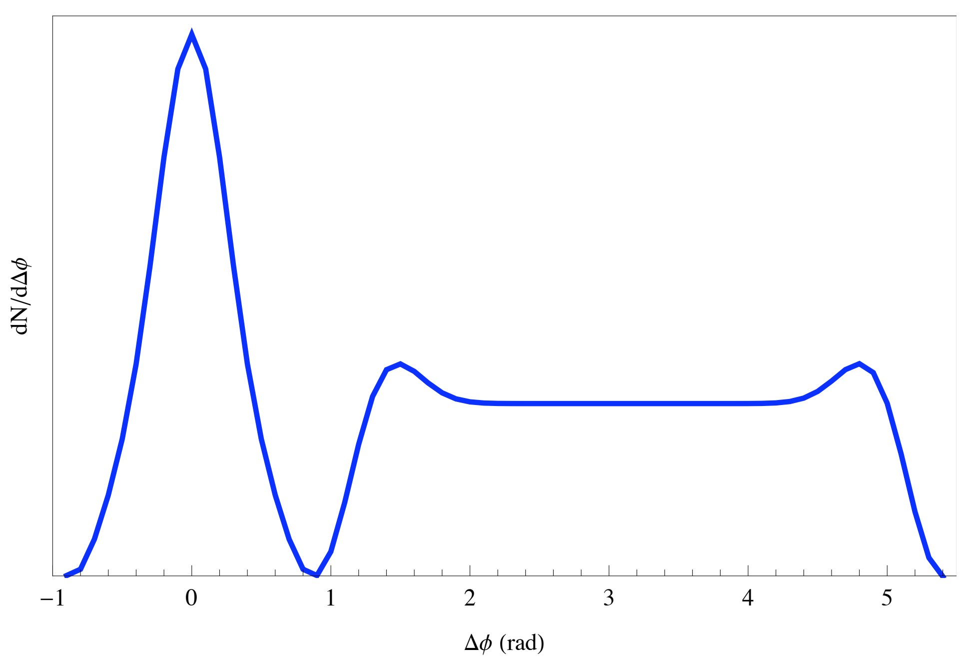


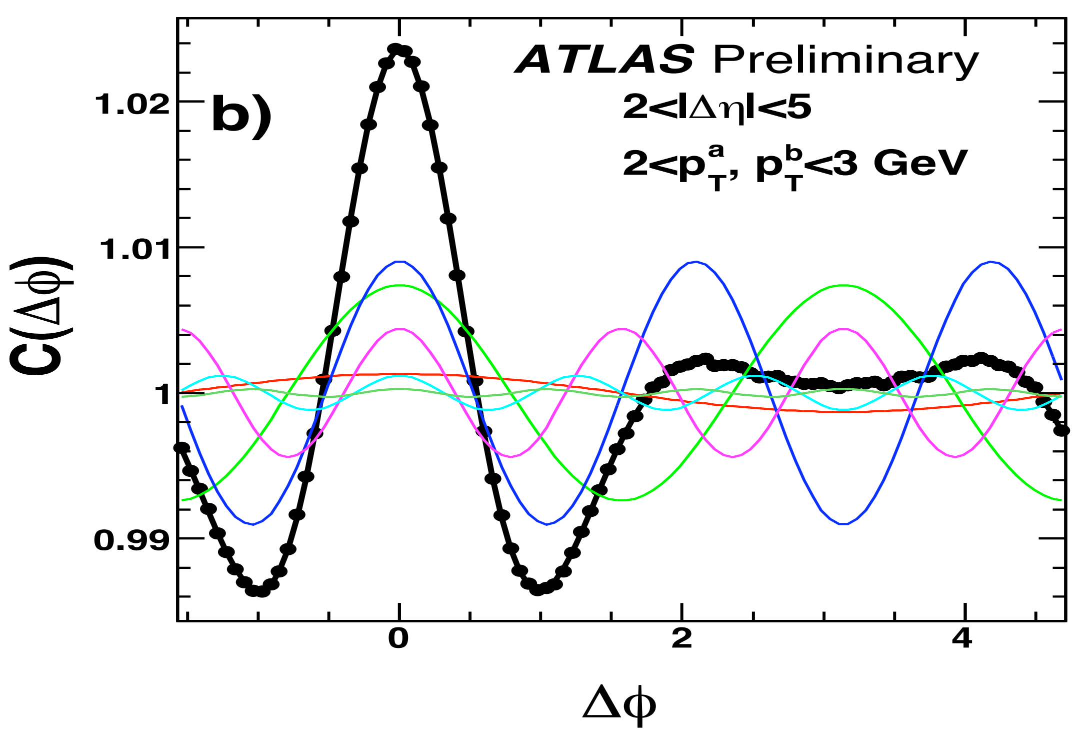




Left:4 pi eta/s=0, 2
Note shape change

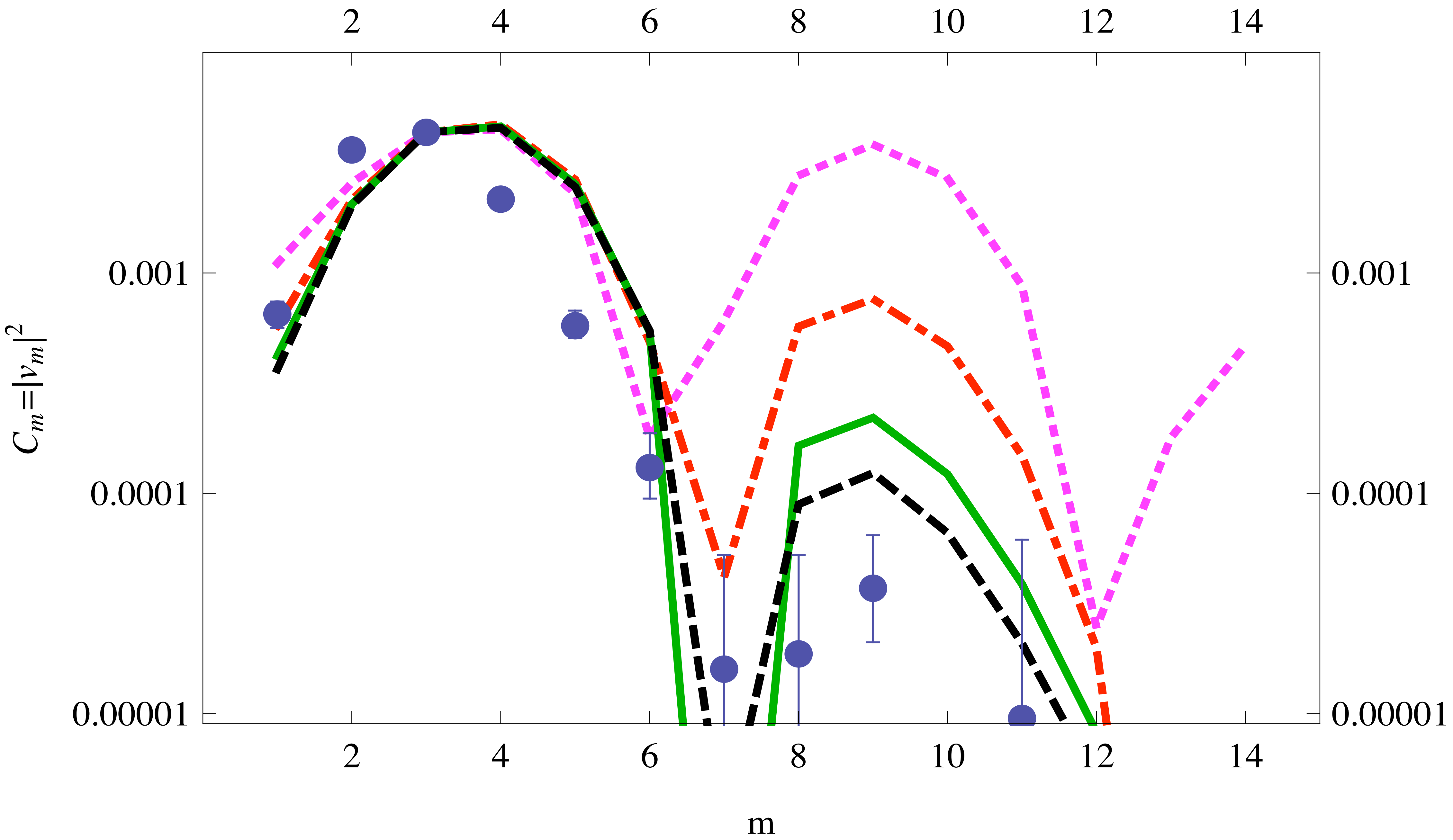
ATLAS central 1% correlators
Note shape agreement
No parameters, just Green
Function from a delta function





The power spectrum is very sensitive to viscosity, and it has acoustic minima/maxima (at m=7,12 and m=9)

perturbation initial size is 0.7 fm, viscosity eta/s=0,0.08,0.13,0.16



So what? Why is hydro's success for the Little Bang interesting/exciting?

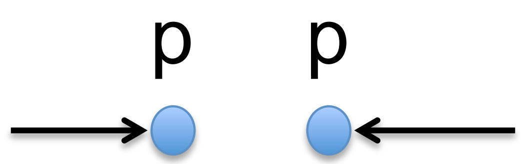
- **True that already in the 19th century sound vibrations in the bulk (as well as of drops and bubbles) have been well developed (Lord Rayleigh, …)**

- **But, those objects are macroscopic, they still have 10^20 molecules…**

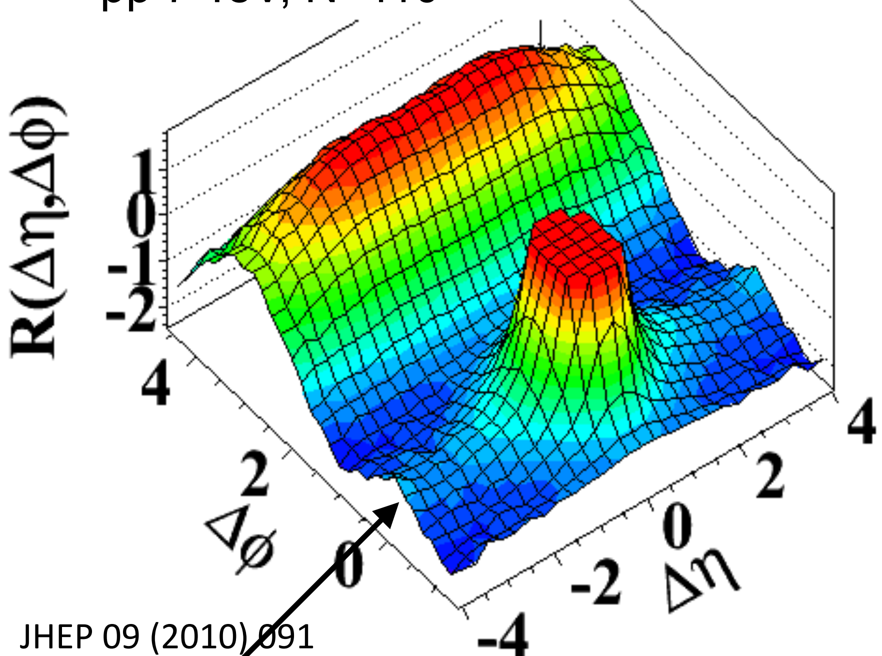
- **Little Bang has about 10^3 particles (per unit rapidity) or 10 per dimension. The radial flow well described was already quite surprising: it worked only due to astonishingly small viscosity …**

- **And now we speak about the 10th harmonics! How a volume cell with O(1) particles can act as a liquid? (well, we look at the surface at freezeout, 2piR about 50 fm, so even 1/10 of it is 5fm…**
- **Comment: so far the agreement is limited not by a hydro failure, but because of limited experimental statistics!**

hydro in small systems, pp and pA



pp 7 TeV, N>110



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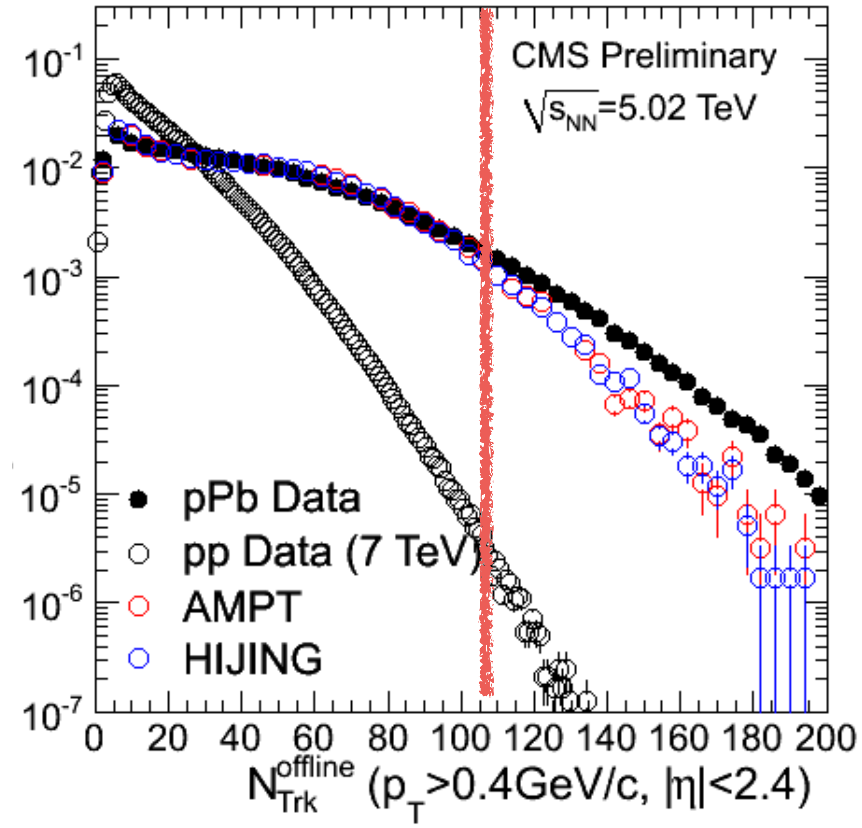
ridge



multiplcity to the right of the line show new — explosive — behavior

each event costs 10^6$ and yet one can measure two particle correlator!

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High-multiplicity *pp* and *pA* collisions: Hydrodynamics at its edge

Edward Shuryak and Ismail Zahed

We predicted the radial flow in pp/pA to be even stronger than in central AA

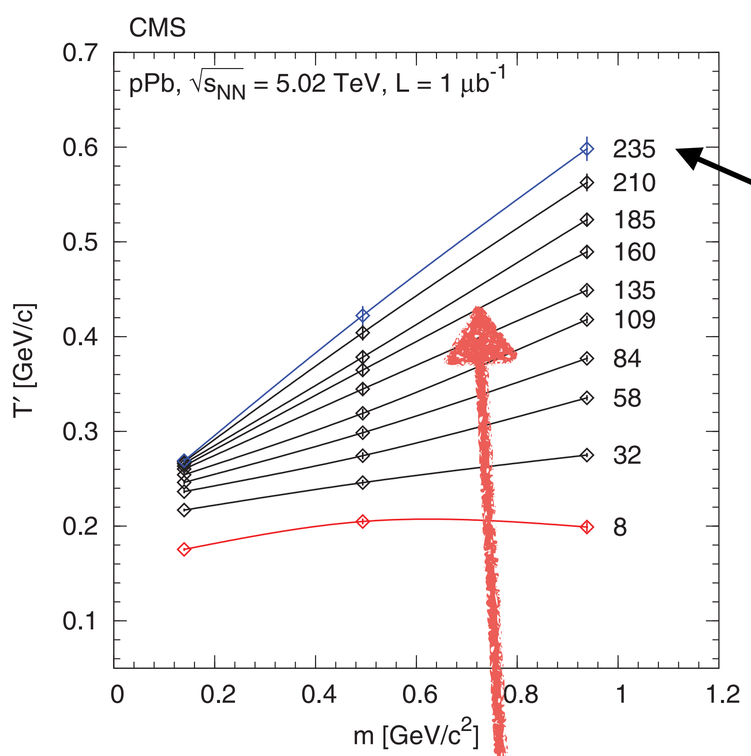


FIG. 8. (Color online) The slopes of the $m_\perp$ distribution T' (GeV) as a function of the particle mass, from [13]. The numbers on the right

Not the Mt scaling at large Ntr => not a large Qs but a collective flow: p=m v

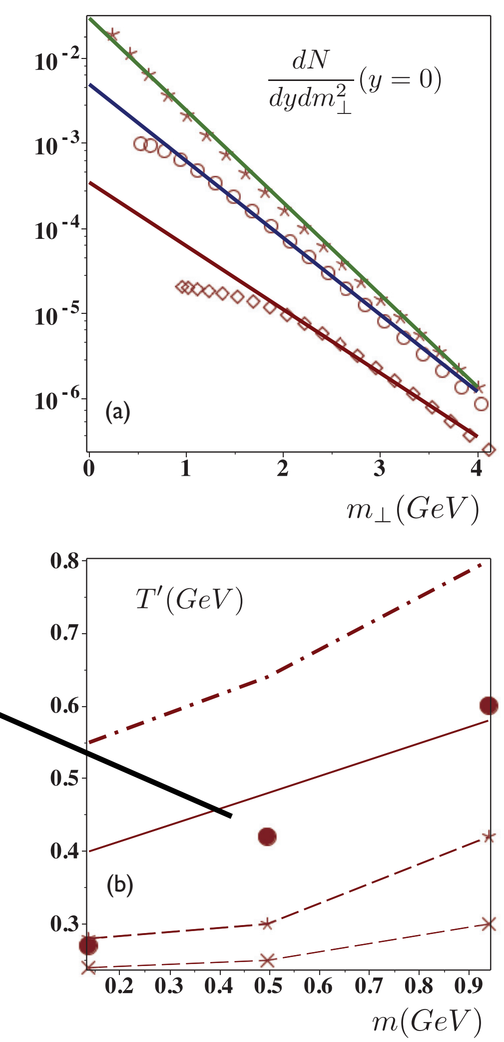


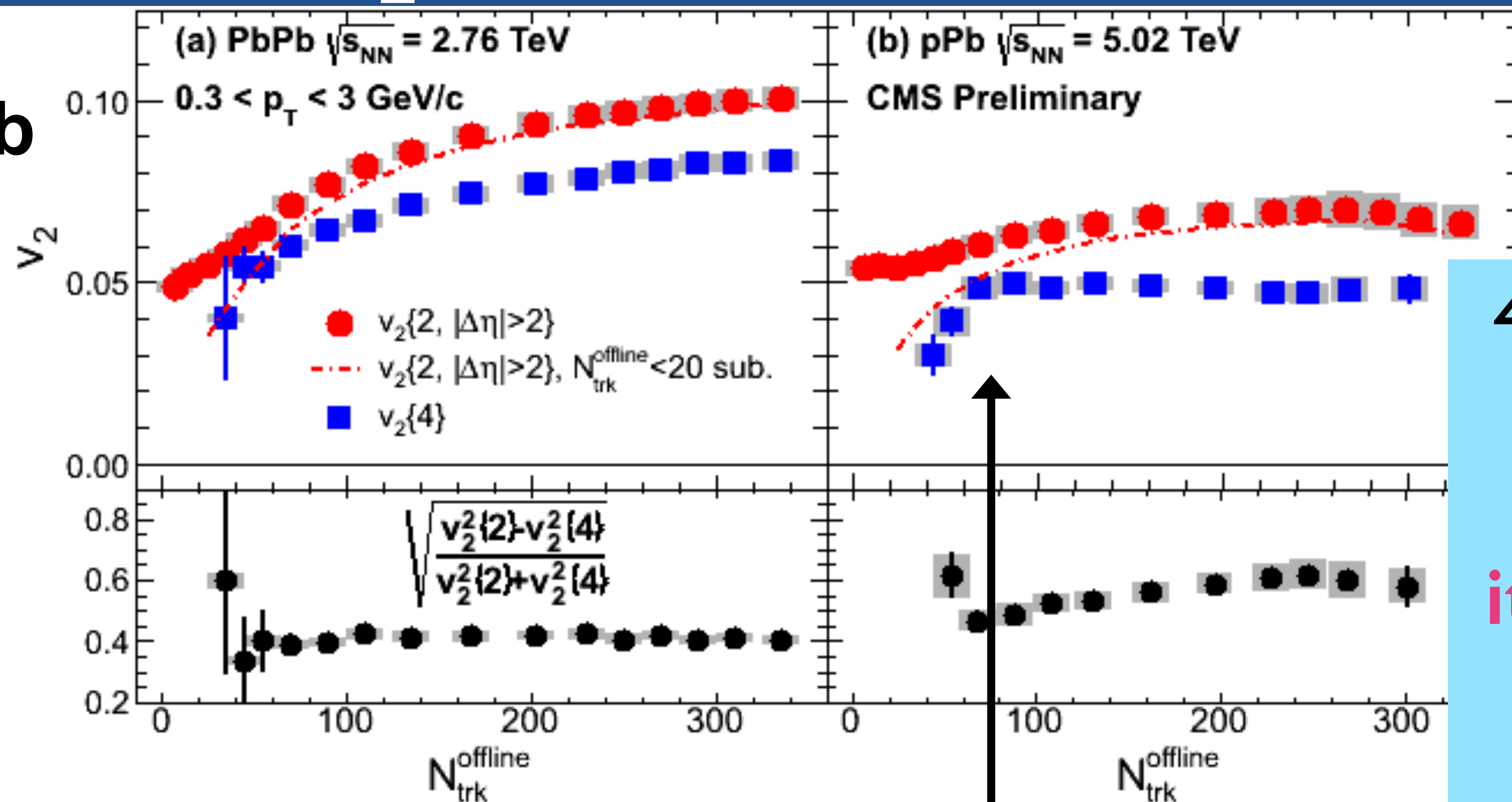
FIG. 9. (Color online) (a) A sample of spectra calculated for π, K, p, top-to-bottom, versus $m_\perp$ (GeV), together with fitted exponents.(b) Comparison of the experimental slopes $T'(m)$ versus the particle mass m (GeV). The solid circles are from the highest multiplicity bin data of Fig. 8, compared to the theoretical predictions. The solid and dash-dotted lines are our calculations for freeze-out temperatures $T_f = 0.17, 0.12$ GeV, respectively. The asterisk-marked dashed lines are for Epos LHC model, diagonal crosses on the dashed line are for AMTP model.

“standard” hydro is **not** enough

CMS pPb: v2 from 2 and 4-particles

v_2 in pPb and PbPb

PbPb



pPb

4 particle one is a clear sign of collectivity

it has clear onset at multiplcity of around 80

in AA fluctuations are too large

v_2 smaller in pPb than PbPb

$v_2\{4\}$ drops at low multiplicity

$$v_2\{2\} = \sqrt{<v_2>^2 + \sigma_{v_2}^2}$$

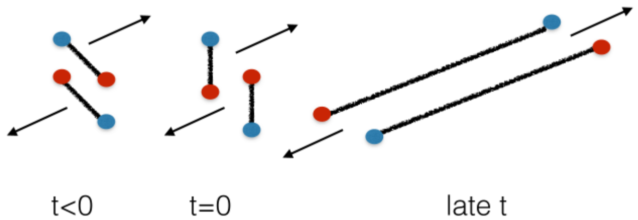
$$v_2\{4\} = \sqrt{<v_2>^2 - \sigma_{v_2}^2},$$

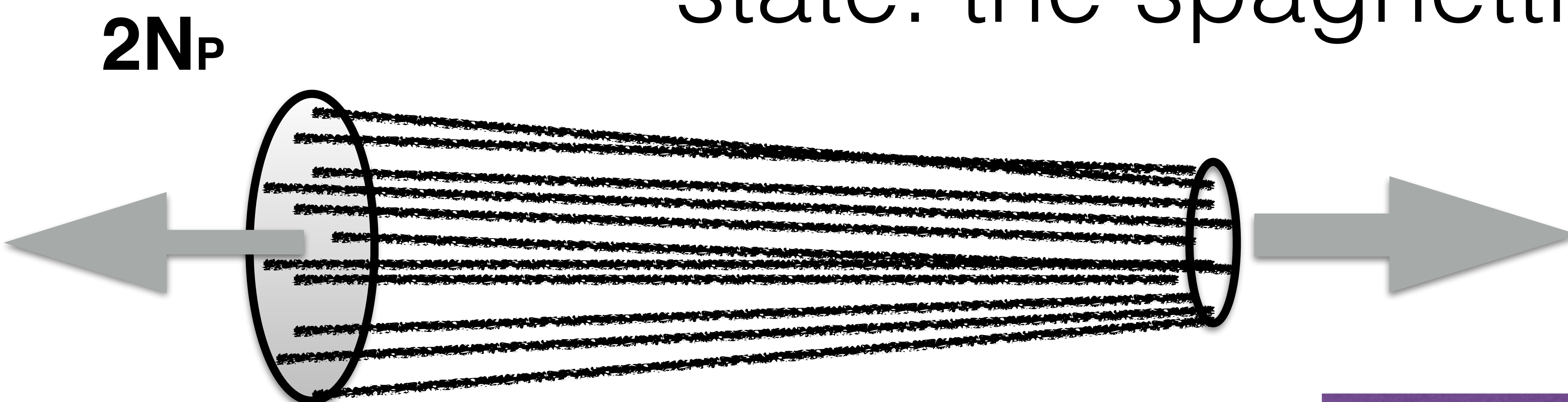
Which is the real end of hydro!

short history of QCD strings

- **1960's: Regge phenomenology, Veneziano amplitude. Strings have exponentially growing density of states N(E)**
- **1970's Polyakov,Susskind => Hagedorn phenomenon near deconfinement**
- **1980's: Lund model (now Pythia,Hijing): string stretching and breaking**
- **1990-now lattice studies. Dual Abrikosov flux tubes. (Very few) papers on string interaction**
- **2013 Zahed et al: holoraphic Pomeron and its regimes**

the simplest multi-string state: the spaghetti





N(strings)=2N(Pomerons)

central pPb
Ns is about 30

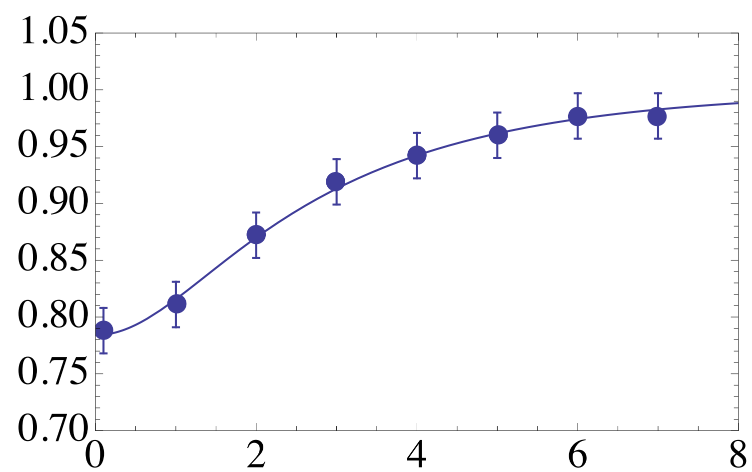
in small multiplicity bins strings are broken independently (the Lund model),

but one should obviously think about their interaction if their number gets large enough!

string interaction via sigma meson exchange

T. Iritani, G. Cossu and S. Hashimoto, arXiv:1311.0218

our fit uses
the sigma mass
600 MeV

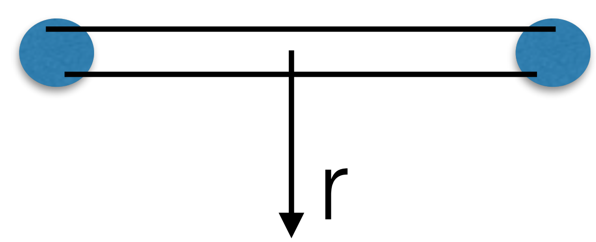


r, in units of a=0.11 fm

$$\frac{\langle\sigma(r_\perp)W\rangle}{\langle W\rangle\langle\sigma\rangle} = 1 - CK_0(m_\sigma \tilde{r}_\perp)$$

FIG. 2. (Color online). Points are lattice data from [12], the curve is expression (8) with $C = 0.26$, $s_{string} = 0.176\,\text{fm}$.

$$\tilde{r}_\perp = \sqrt{r_\perp^2 + s_{string}^2}$$



So the sigma cloud around a string is there!

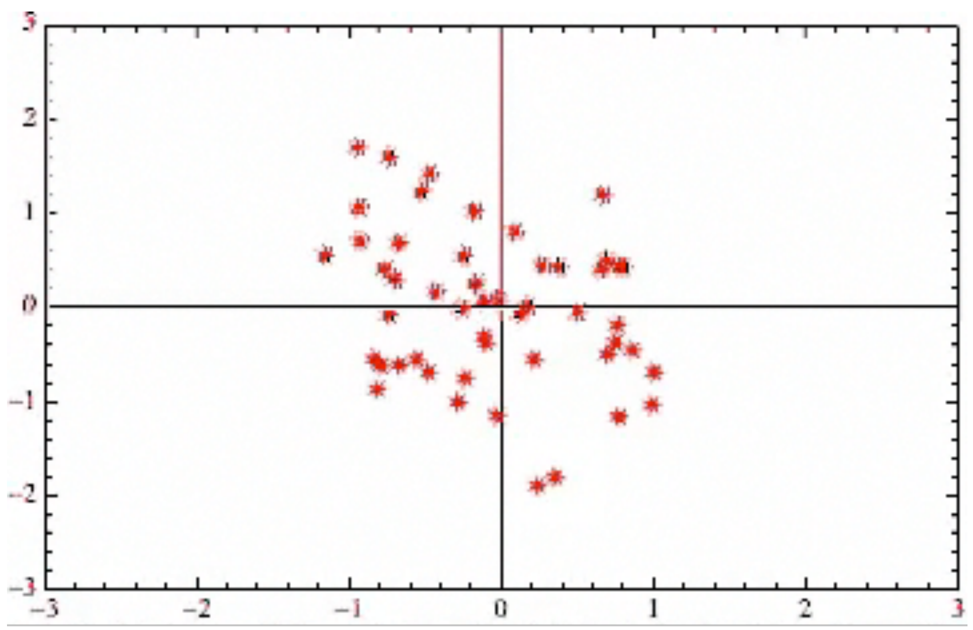
2d spaghetti collapse

Basically strings can be viewed as a 2-d gas of particles with unit mass and forces between them are given by the derivative of the energy (8) , and so

$$\ddot{\vec{r}}_i = \vec{f}_{ij} = \frac{\vec{r}_{ij}}{\tilde{r}_{ij}}(g_N\sigma_T)m_\sigma 2K_1(m_\sigma\tilde{r}_{ij}) \tag{19}$$

with $\vec{r}_{ij} = \vec{r}_i - \vec{r}_j$ and "regularized" $\tilde{r}$ (9).

$$E_{tot} = \sum_i \frac{v_i^2}{2} - 2g_N\sigma_T \sum_{i>j} K_0(m_\sigma r_{ij})$$



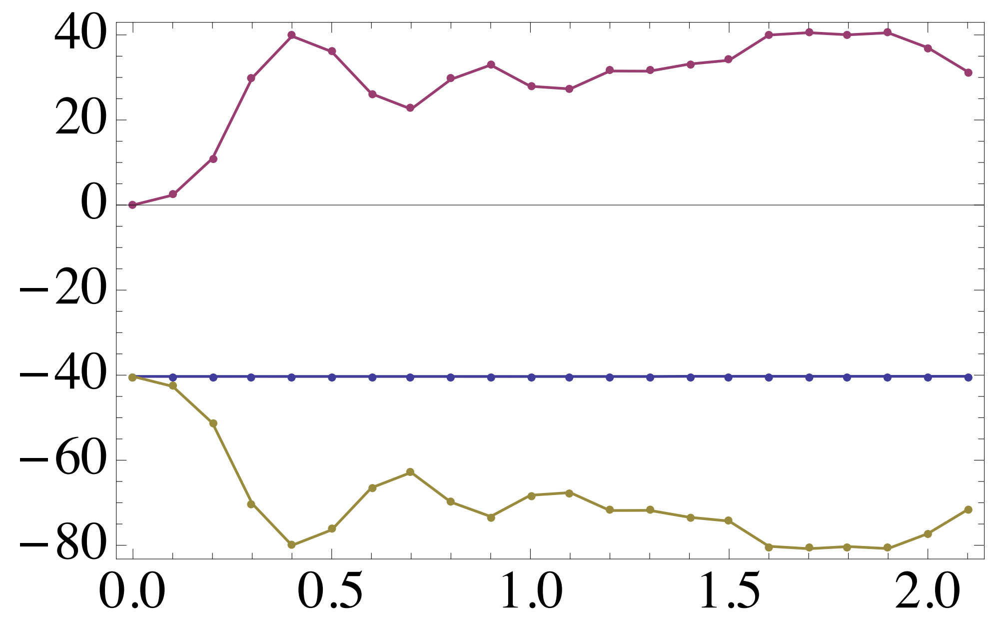
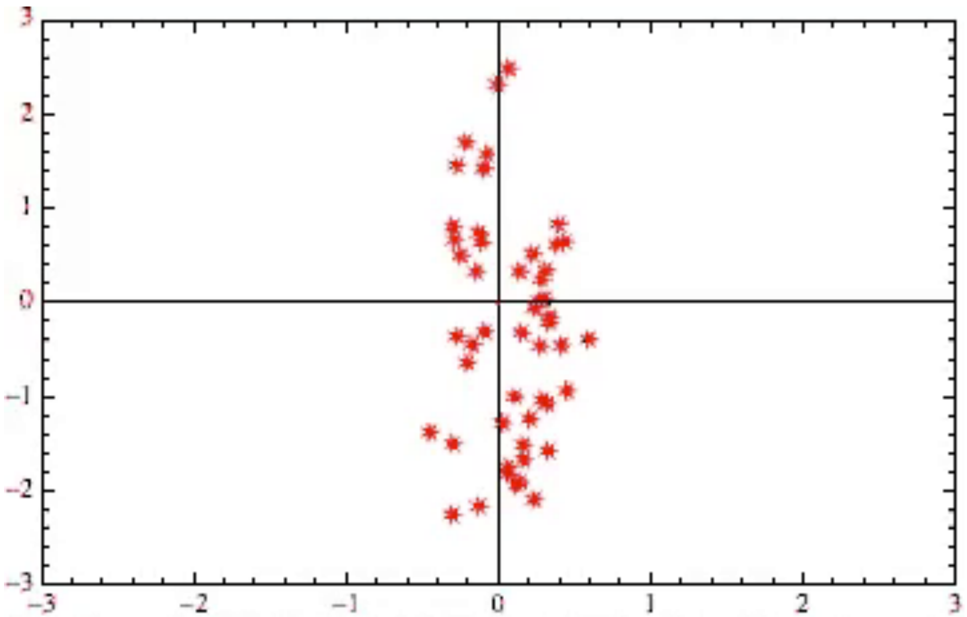
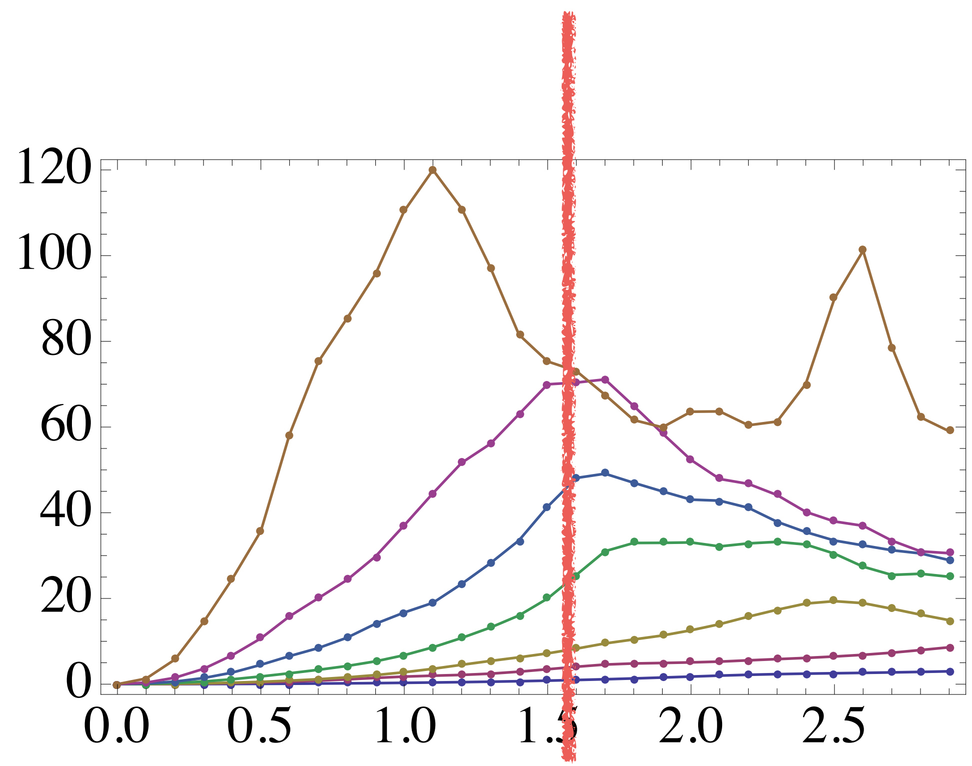


FIG. 4. (Color online) The (dimensionless) kinetic and potential energy of the system (upper and lower curves) for the same example as shown in Fig. 6, as a function of time t(fm). The horizontal line with dots is their sum, namely E_{tot}, which is conserved.



peripheral AA

contraction in x first
(and only: limited time scale)



$g_N \sigma_T$ =0.01,0.02,0.03,0.05,0.08,0.10,0.20.

string stretching - about 1fm/c

1/4 period of yo-yo - another 0.5

so too small coupling does not work

collectivization of field

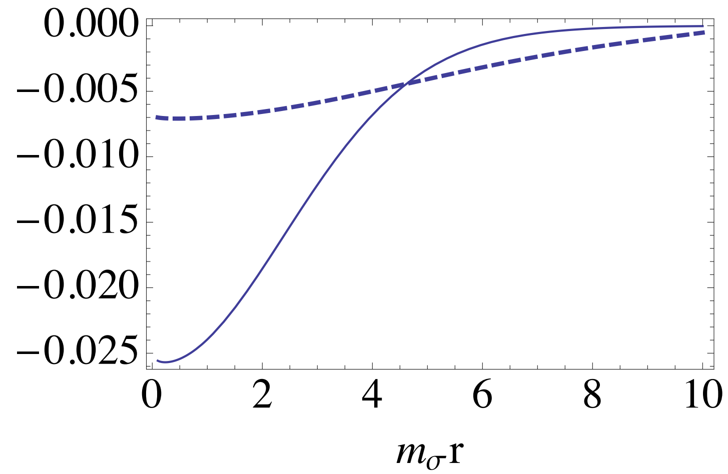


FIG. 4: The mean field (normalized as explained in the text) versus the transverse radius in units of inverse m_σ. The dashed and solid curves correspond to the source radii $R = 1.5$ and 0.7 fm, respectively.

initial and final field

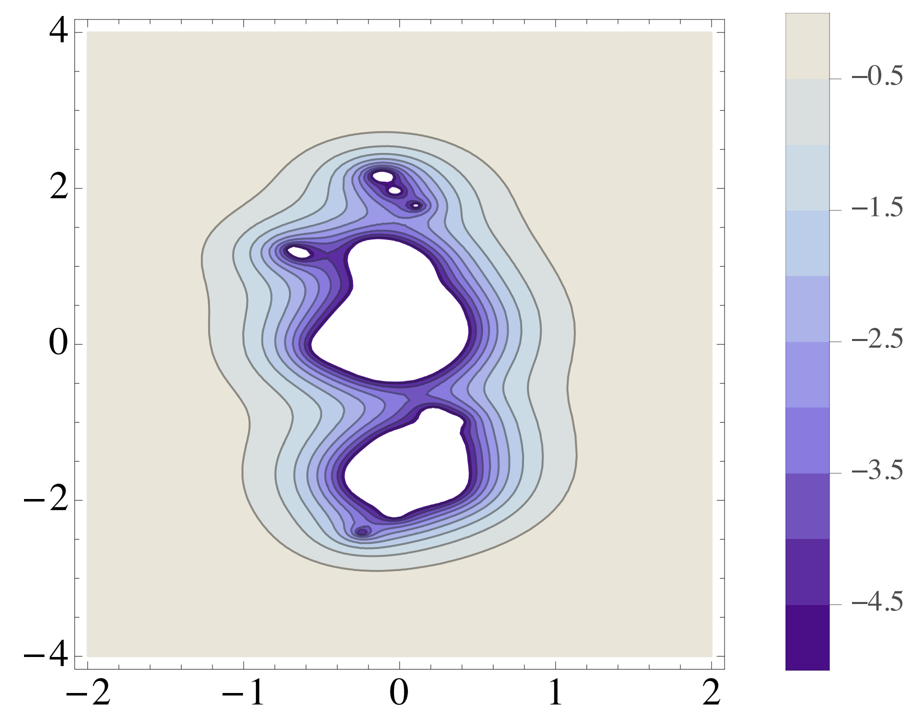


FIG. 10: Instantaneous collective potential in units $2g_N\sigma_T$ for an AA configuration with $b = 11\,\text{fm}$, $g_N\sigma_T = 0.2$, $N_s = 50$ at the moment of time $\tau = 1\,\text{fm}/c$. White regions correspond to the chirally restored phase.

in white regions
chiral symmetry is restored

Gradient of the collective field should create gluon/quark pairs: QCD analog of Hawking radiation

more work on QCD strings

- Holographic Pomeron: semiclassical derivation
- it has 3 regimes
- **Self-interacting high entropy string balls are the way to place holes**
- **holographic AdS/QCD+ quarks (V-QCD)**

summary

- out-of-equilibrium examples solved all indicate early onset of NS which is more accurate than it should be based on next term evaluation
- higher order gradients tend to cancel: LS conjecture for re-summation needs to be checked
- in AA hydro reaches the next level: sounds with few harmonics, all works till pt=3-4 GeV or 99.99% of secondaries
- pp and pA at multiplcities >300 or so show unexpectedly robust explosive behavior
- pA and peripheral AA => spaghetti => QCD string collective implosion and collectivization of their sigma field
- need to work out holographic scenarios for small systems => trapped surfaces? (in progress)

fundamental string balls

A string ball can be naively generated by a "random walk" process, of M/M_s steps, where $M_s \sim 1/\sqrt{\alpha'}$ is the typical mass of a straight string segment. If so, the string entropy scales as the number of segments

$$S_{ball} \sim M/M_s \tag{1}$$

$$\frac{R_{ball,r.w.}}{l_s} \sim \sqrt{M}$$

The Schwarzschild radius of a black hole in d spatial dimensions is

$$R_{BH} \sim (M)^{\frac{1}{(d-2)}} \tag{2}$$

and the Bekenstein entropy

$$S_{BH} \sim Area \sim M^{\frac{d-1}{d-2}} \tag{3}$$

Can be matched for one M only => critical string ball its Hawking T is the Hagedorn T_H

Damour and Veneziano

entropy of a self-interacting string ball of radius R and mass M,

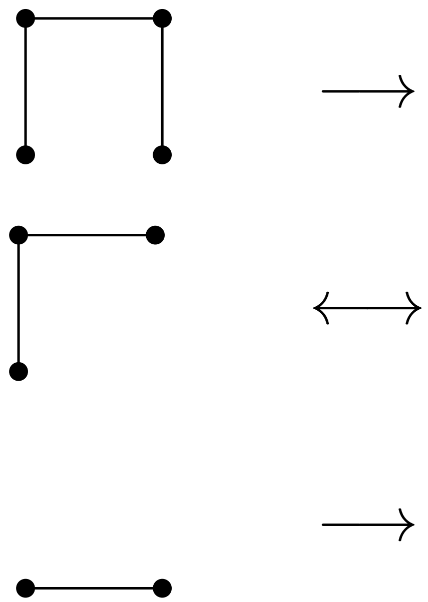
$$S(M,R) \sim M\left(1-\frac{1}{R^2}\right)\left(1-\frac{R^2}{M^2}\right)\left(1+\frac{g^2M}{R^{d-2}}\right) \tag{5}$$

where all numerical constants are for brevity suppressed and all dimensional quantities are in string units given

even for a very small g,

the importance of the last term depends not on g but on g^2M. So, very massive balls can be influenced by a very weak gravity (what, indeed, happens with planets and stars)

Self-interacting string balls



Metropolis algorithm, updates,
T(x) instead of a box
Yukawa self-interaction

we observe a new regime: the

entropy-rich self-balanced string balls

separated by 2 phase transitions

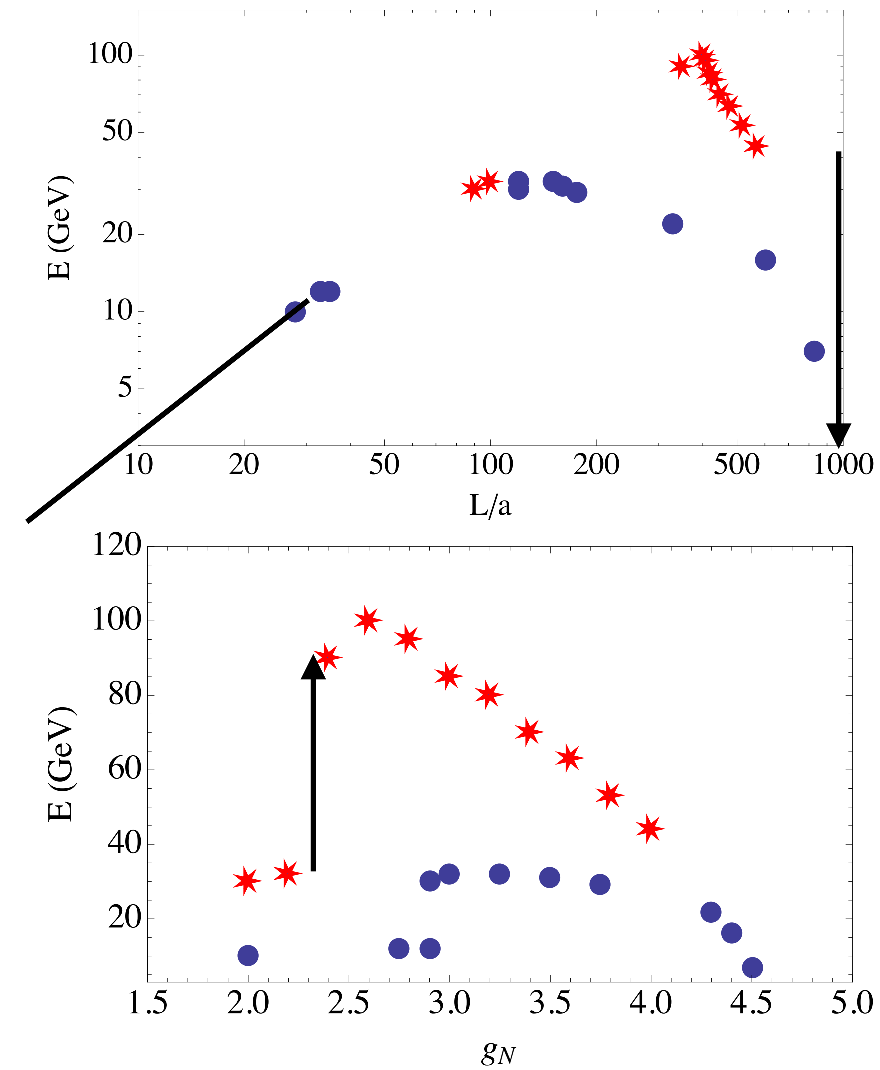


FIG. 7: Upper plot: The energy of the cluster E (GeV) versus the length of the string L/a. Lower plot: The energy of the cluster E (GeV) versus the "Newton coupling" g_N (GeV^{-2}). Points show the results of the simulations in setting $T_0 = 1$ GeV and size of the ball $s_T = 1.5a, 2a$, for circles and stars, respectively.

extreme example

in spite of a very large string length

$L/a \sim 700$, the total energy is only $E \approx 17\text{GeV}$,

as a result of the balancing between

the string tension and self- interaction.