Shocks in sQGP

Edward Shuryak
(Stony Brook)

plan

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- strong shocks as an out-of-equilibrium but stationary problem in AdS/CFT. **(Does small viscosity imply rapid equilibraion? yes)**

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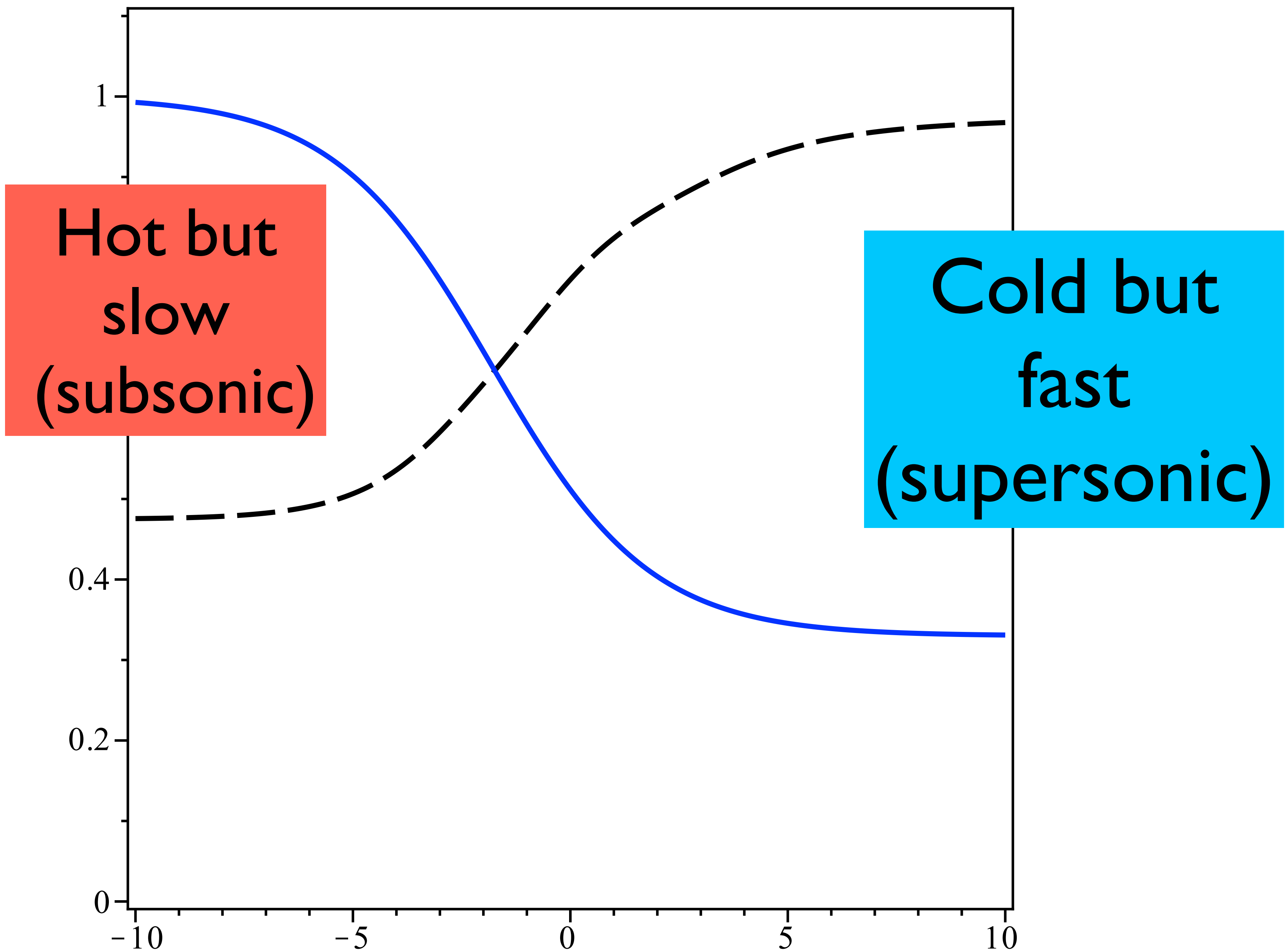
- strong shocks as an out-of-equilibrium but stationary problem in AdS/CFT. **(Does small viscosity imply rapid equilibraion? yes)**
- shocks generated by Rayleigh collapse of the QGP bubbles at the end of ``mixed phase" (Is there enough time till freezout? looks like we have a signal)
- shocks and sounds generated by jets **(Do we see a Mach cone now? yes)**

example of a strong shock

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

Numerical example which is a solution of the NS Equations (without small parameters or expansion)

(Is it justified? What about other terms in the 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

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

T and rapidity are in h and y

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' \\
& -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}
\end{aligned}
\tag{5.4}
$$

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

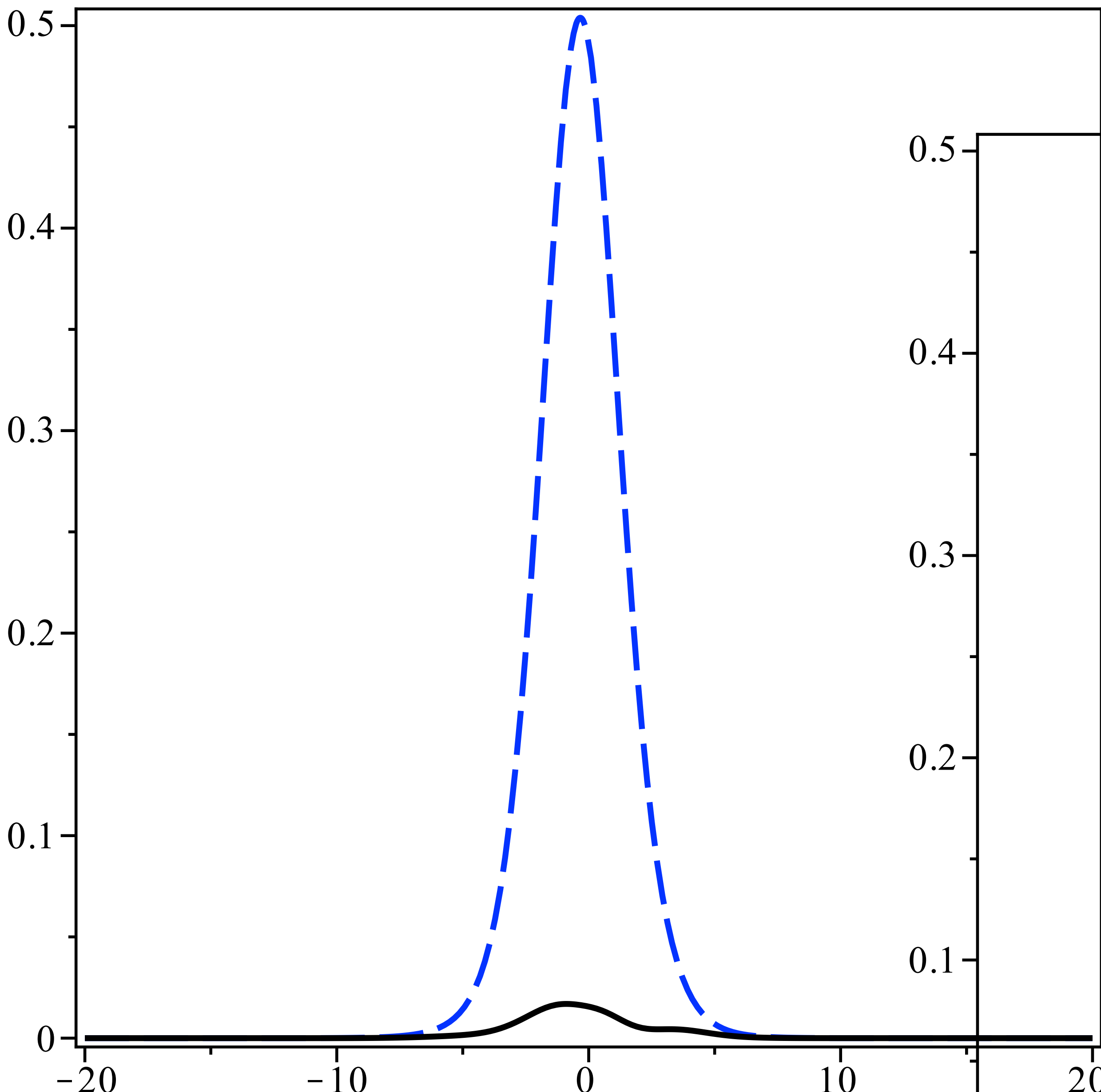
$$\bar{E}^2 = \bar{E}_{mn}\bar{E}^{mn}, \quad \bar{E}_{mn} = E_{mn} + 6g_{mn} \tag{5.6}$$

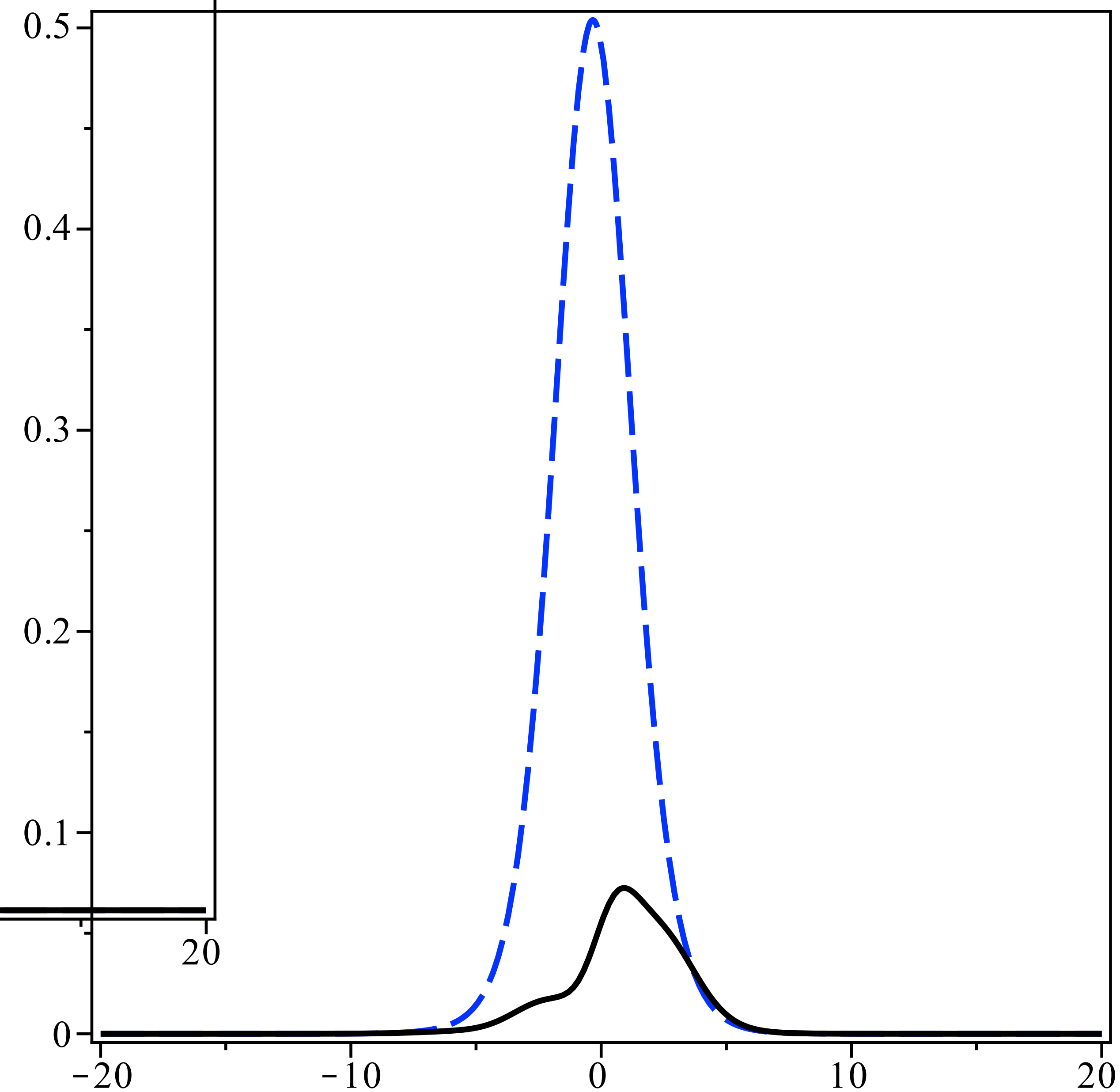
which combines all the Einstein equations (in the AdS/CFT setting) into one (covariant scalar) combina-

or the usual sum of squares

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

Variational result: one function only $A(x,r)=0$

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

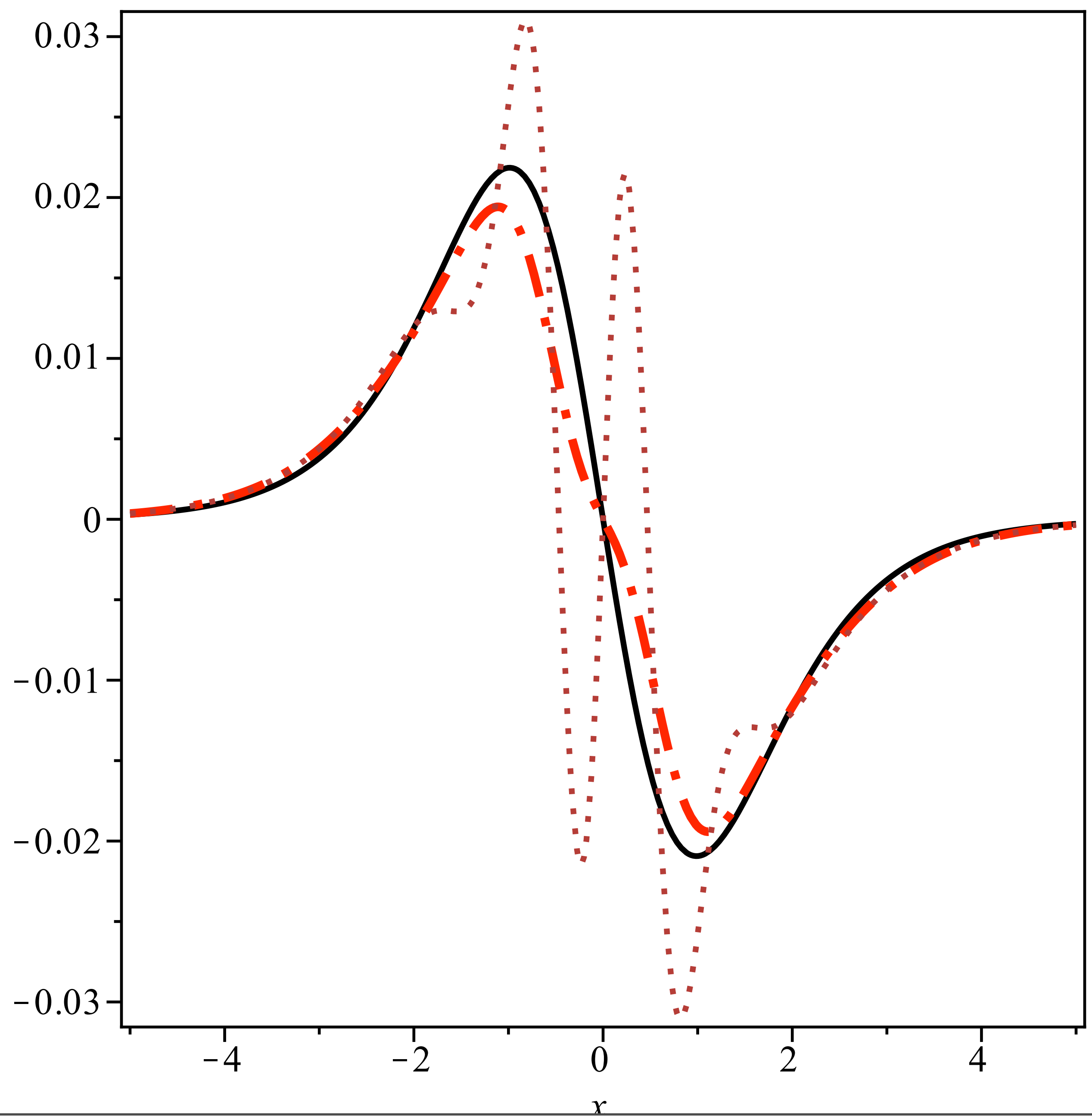
The physical meaning of B is correction to the g_{xx}

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!

LS=Lublinsky-Shuryak

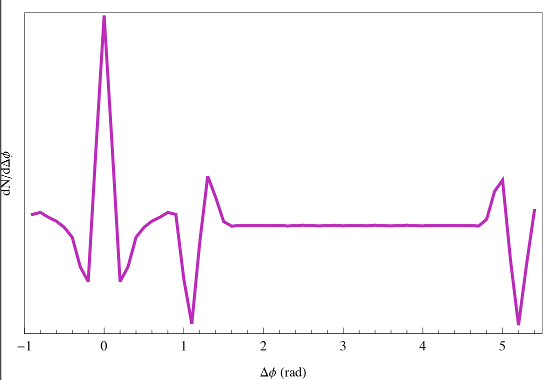
Expansion in gradients (colored) vs the LS resummation (black)

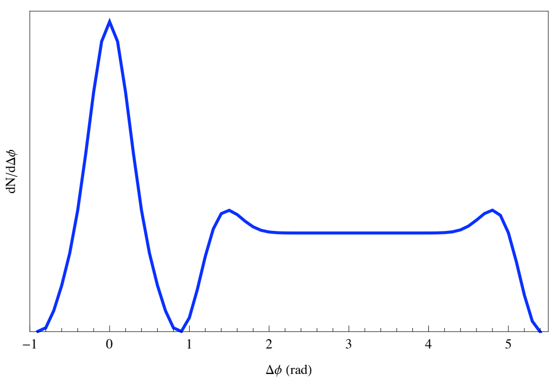


Red dash-dotted line includes all up to 8 derivatives, brown dotted up to 12 derivatives

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

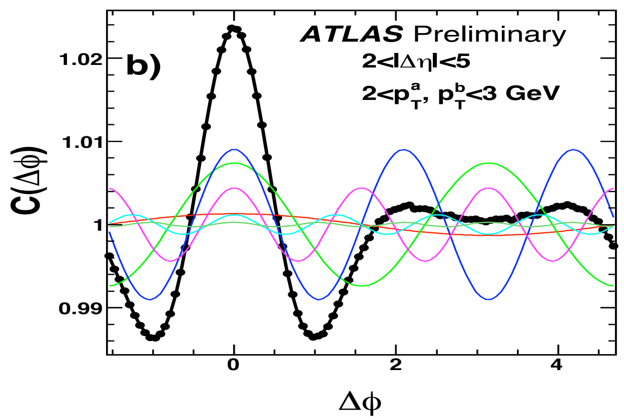
The sound from the initial state perturbations (ES,Staig: QM2011)

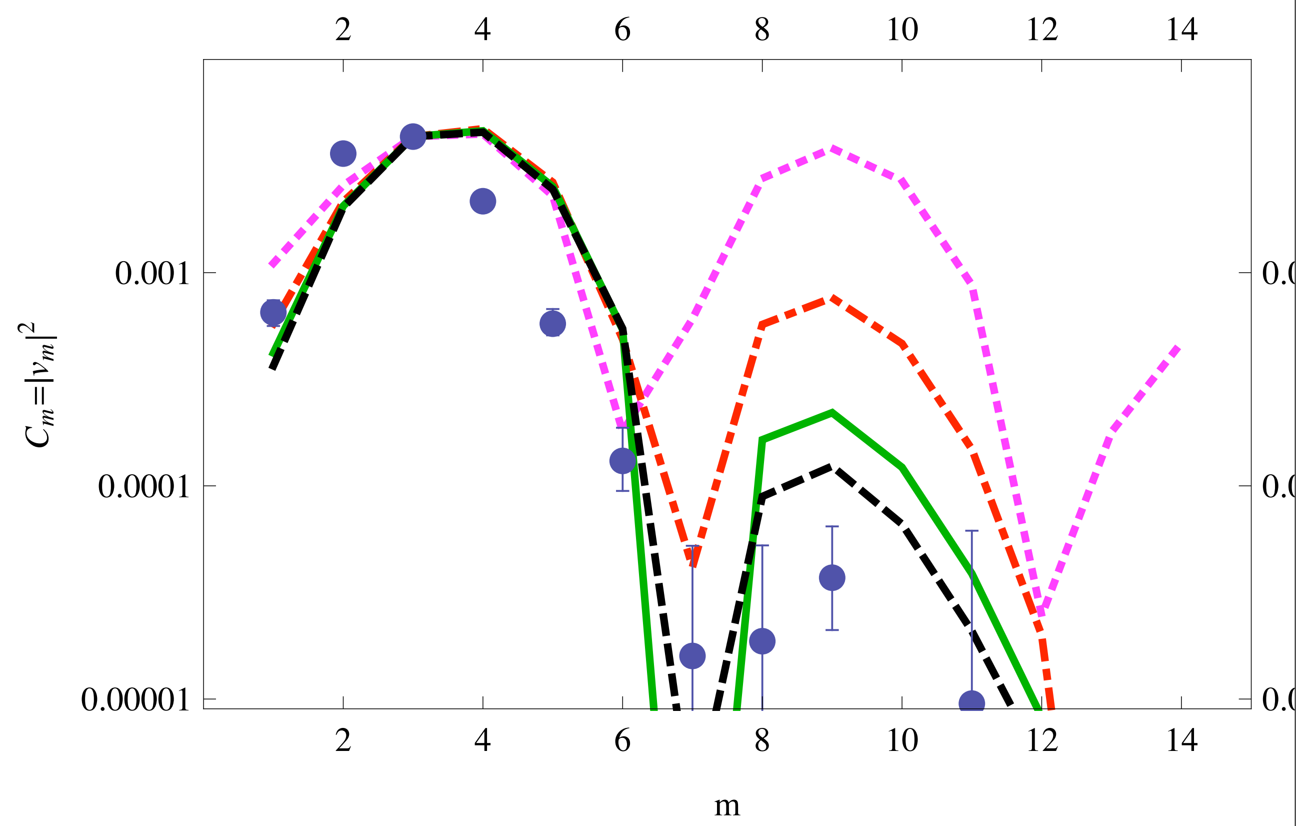




Left:4 pi eta/s=0, 2
Note shape change

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





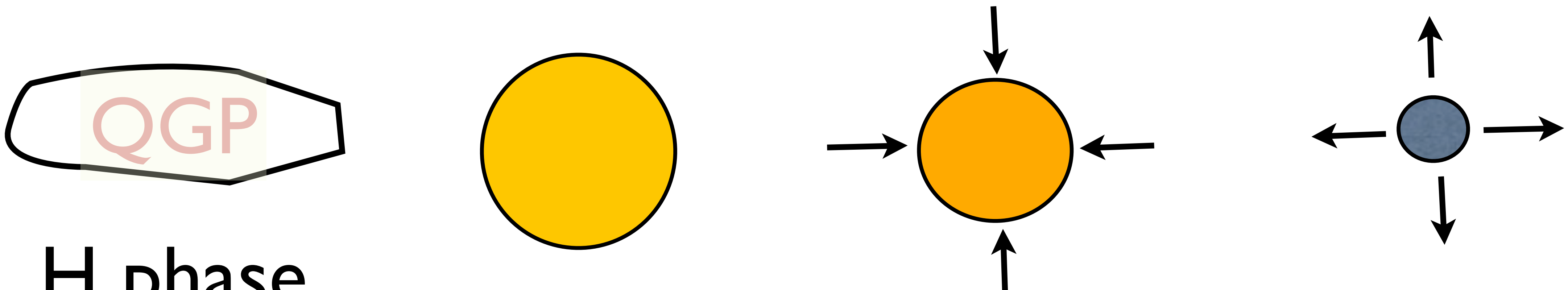
several harmonics is enough to draw quite complex pictures: **sonograms** of the fireball can be made

(Long propagation time till freezout => large circles)

The "Mini-Bangs" as Signals of the QCD Phase Transition

Edward Shuryak and Pilar Staig[1]

New idea: shocks/sounds from Rayleigh collapse of the QGP bubbles



H phase

phase sparation in the ``mixed phase"

=> surface tension makes bubbles spherical

=> as T<Tc the QGP pressure is less than p_H =>

Rayleigh collapse => energy of the bubble goes into the outgoing shock

Rayleigh collapse result in emission of a shock

$$u_r = \partial_r \phi = \dot{R} \quad (5)$$

where a dot means time derivative. It leads to a solution

$$\phi = -\frac{\dot{R}R^2}{r} + const_2(t) \quad (6)$$

and putting it back into Euler equation in the form (3) one finds at $r = R$ the equation for $R(t)$

$$\rho(\ddot{R}R + (2 - 1/2)\dot{R}^2) = p(r = \infty, t) \quad (7)$$

where the (1/2) comes from the second term of (3) and the r.h.s. is the driving pressure.

When the r.h.s. is positive the system is stable, but as it crosses into negative the collapse takes place. What was discovered by Rayleigh, even if the r.h.s. is put to zero, the equation admits simple analytic solution known as "the Rayleigh collapse"

$$R(t) \sim (t_* - t)^{2/5} \quad (8)$$

corresponding to the infinite velocity $\dot{R} \sim (t_* - t)^{-3/5}$

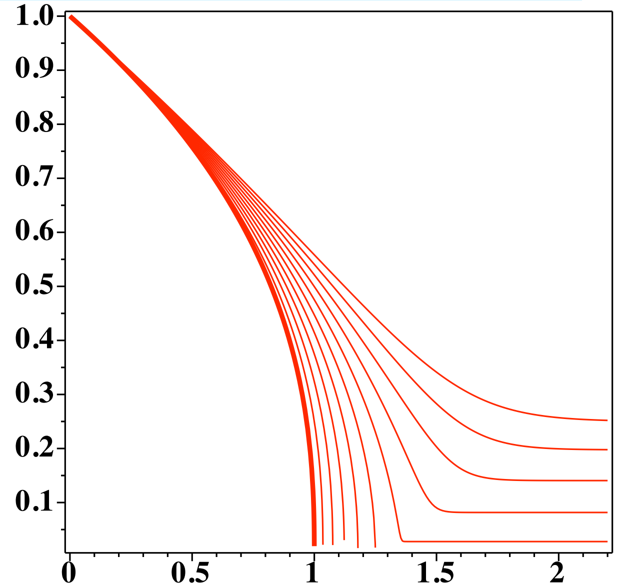


FIG. 1: The time evolution of the drop radius $R(t)$, for the values of $\eta/\rho = 0.01..0.1$ with the 0.01 step.

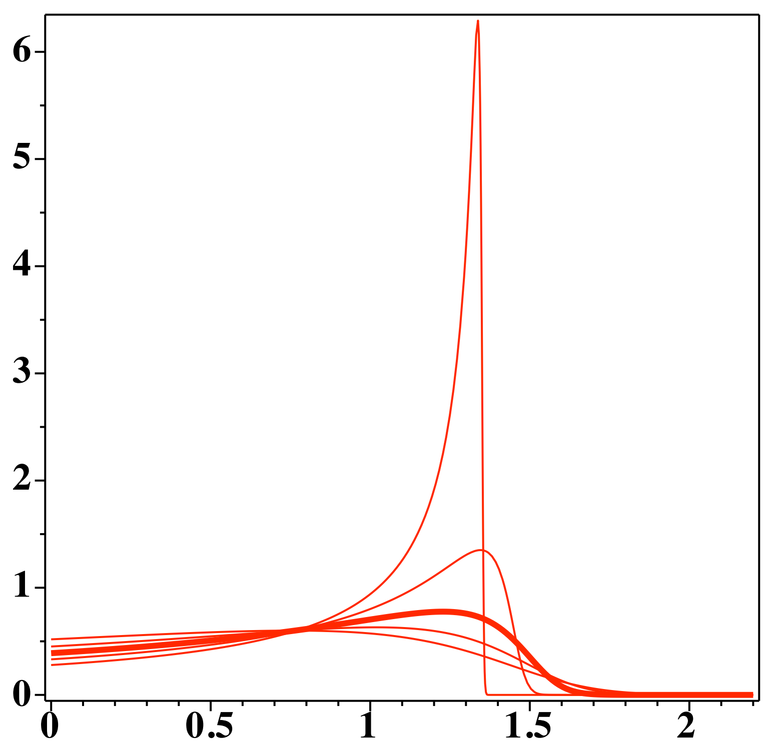


FIG. 2: The time evolution of the quantity $|\ddot{V}(t)|^2$, entering the sound radiation intensity, for the values of $\eta/\rho = 0.06, 0.07, 0.08, 0.09, 0.1$.

Rayleigh collapse result in emission of a shock

sonoluminescence exprts

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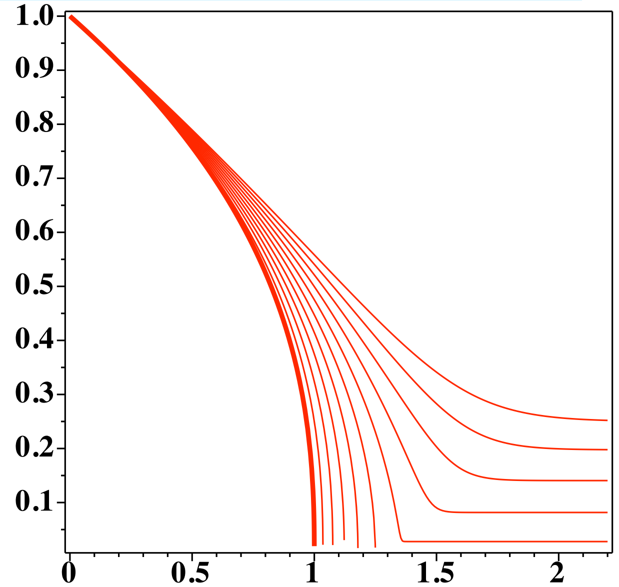

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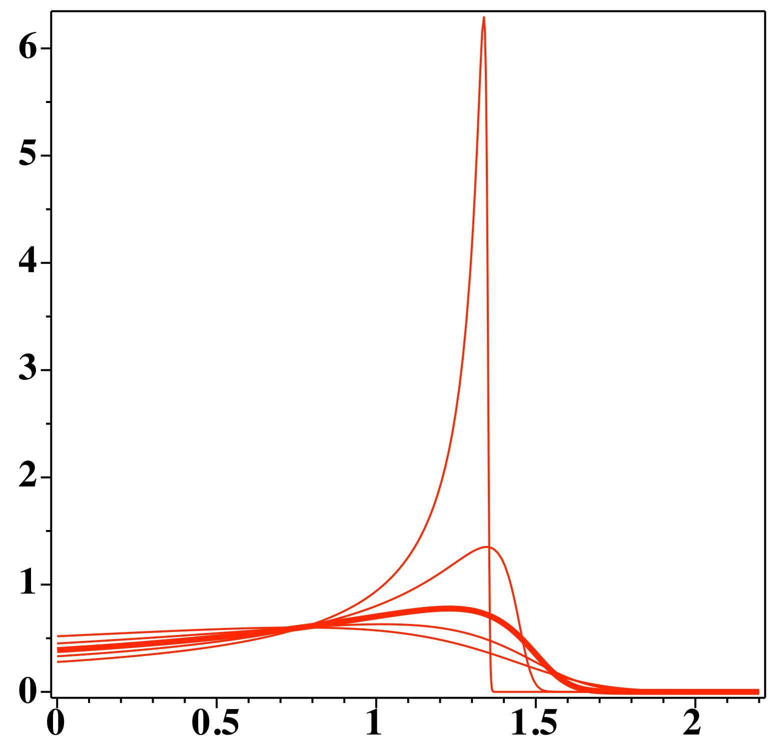

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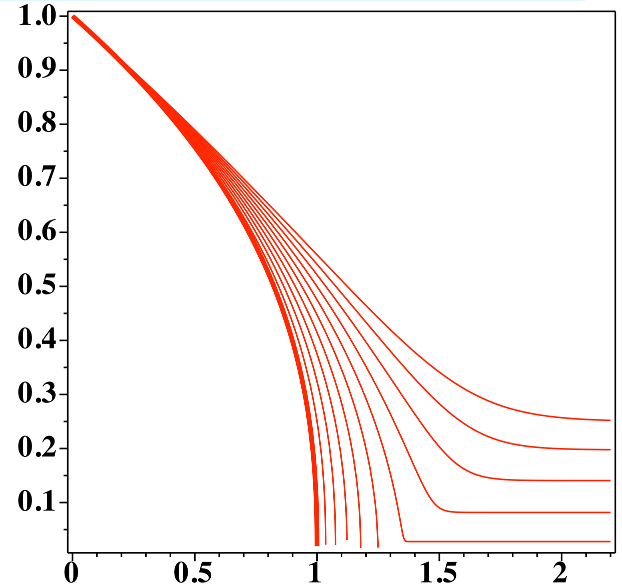

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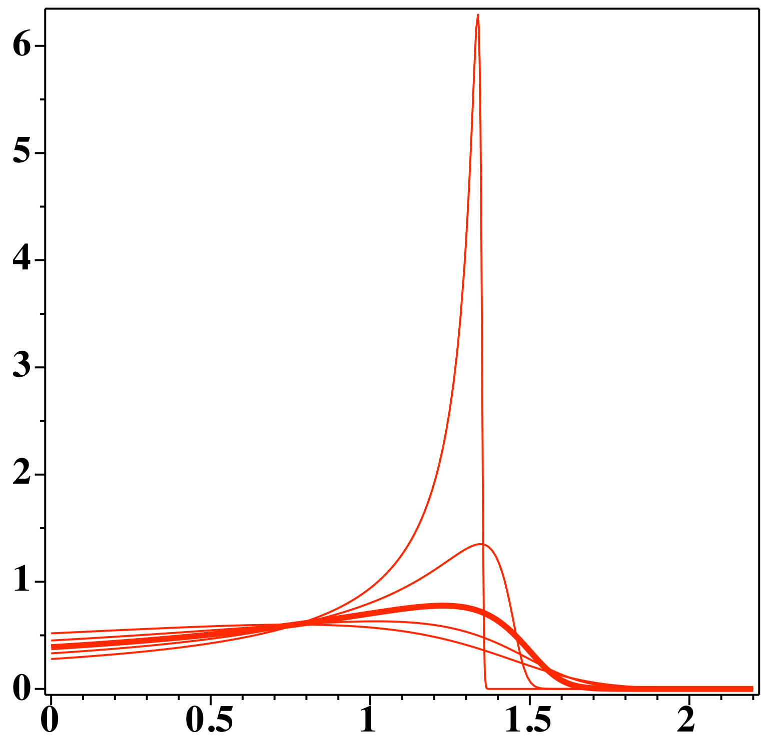

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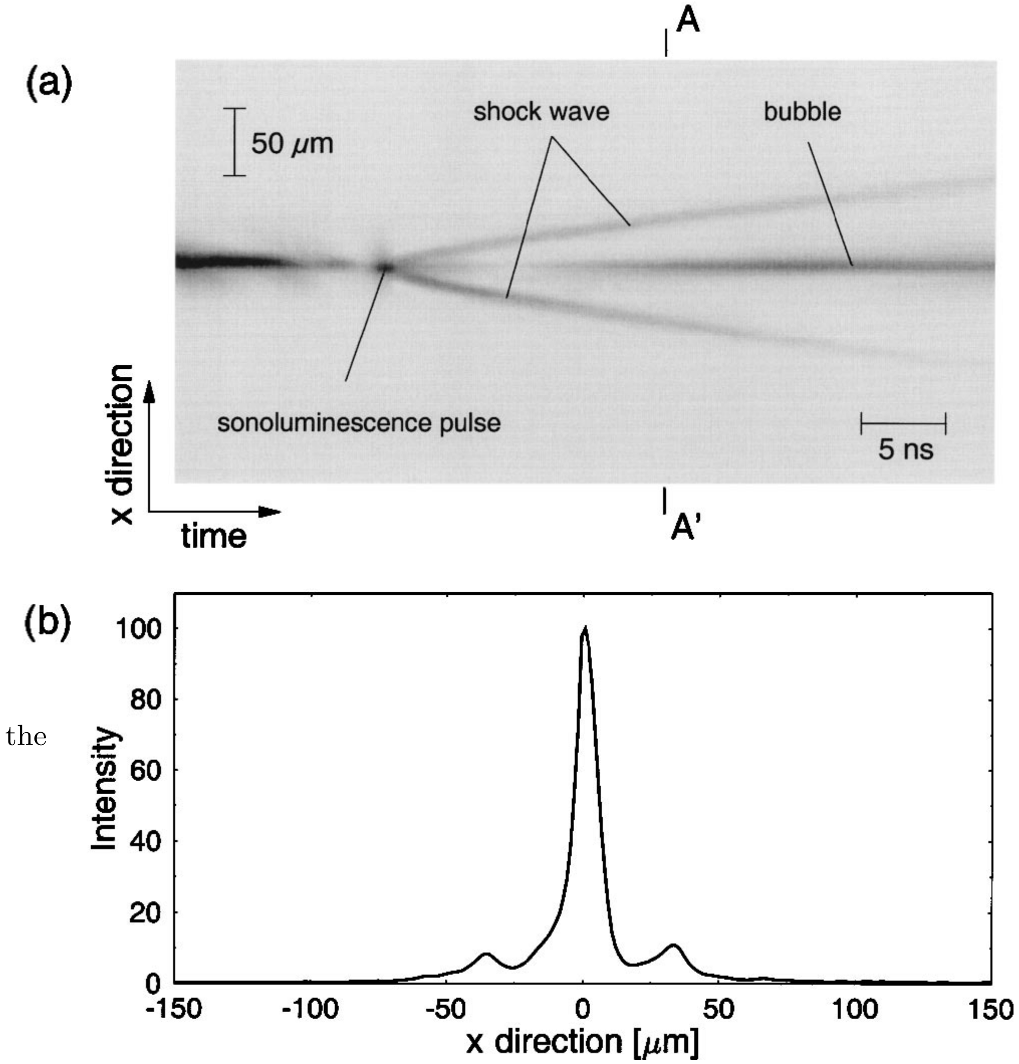

FIG. 22. Outgoing shock wave from a collapsing bubble: (a) Streak image of the emitted outgoing shock wave from the collapsing bubble and (b) an intensity cross section along the line AA'. From Pecha and Gompf (2000).

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$$R(t) \sim (t_* - t)^{2/5} \qquad (8)$$

corresponding to the infinite velocity $\dot{R} \sim (t_* - t)^{-3/5}$

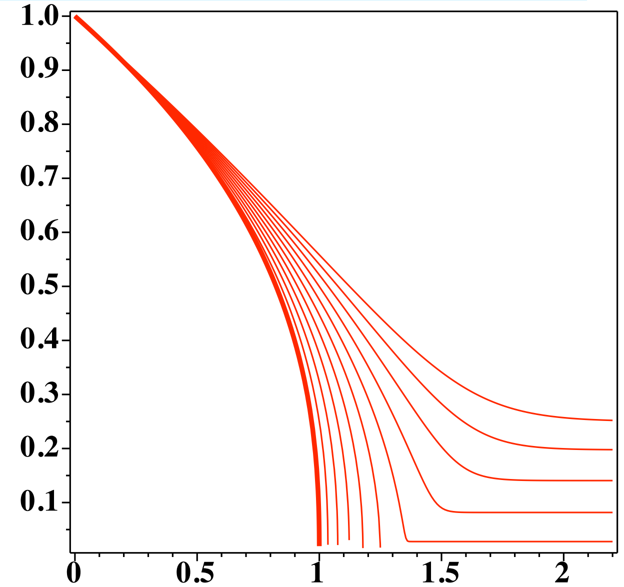


FIG. 1: The time evolution of the drop radius $R(t)$, for the values of $\eta/\rho = 0.01..0.1$ with the 0.01 step.

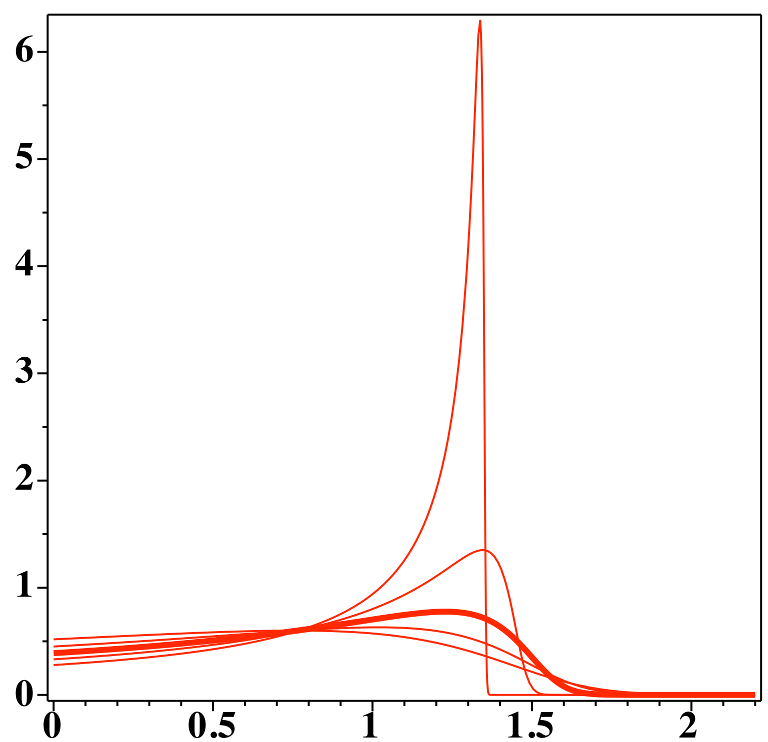


FIG. 2: The time evolution of the quantity $|\ddot{V}(t)|^2$, entering the sound radiation intensity, for the values of $\eta/\rho = 0.06, 0.07, 0.08, 0.09, 0.1$.

sonoluminescence exprts

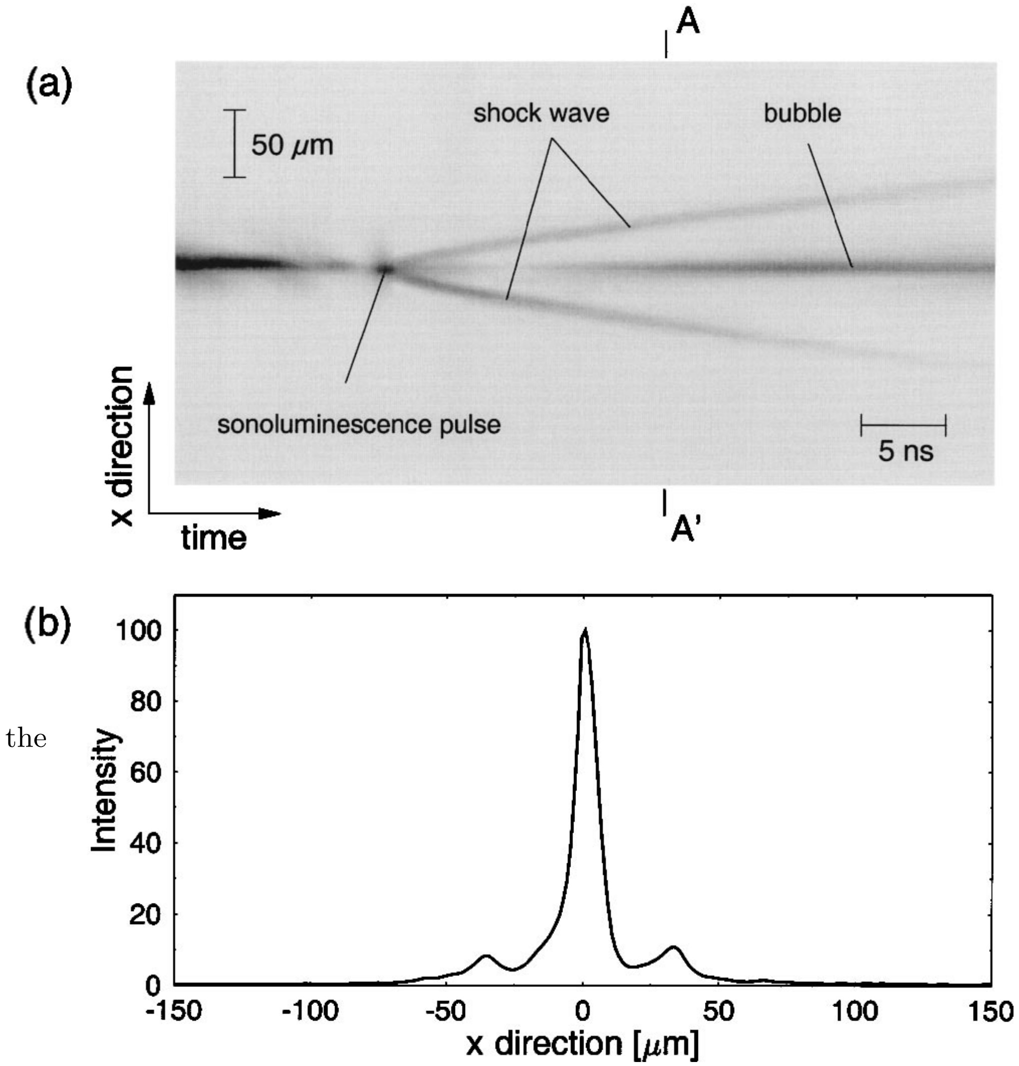


FIG. 22. Outgoing shock wave from a collapsing bubble: (a) Streak image of the emitted outgoing shock wave from the collapsing bubble and (b) an intensity cross section along the line AA'. From Pecha and Gompf (2000).

V_{shock}=4km/s

C_{sound}=1.4km/s

p=40-60 kbar

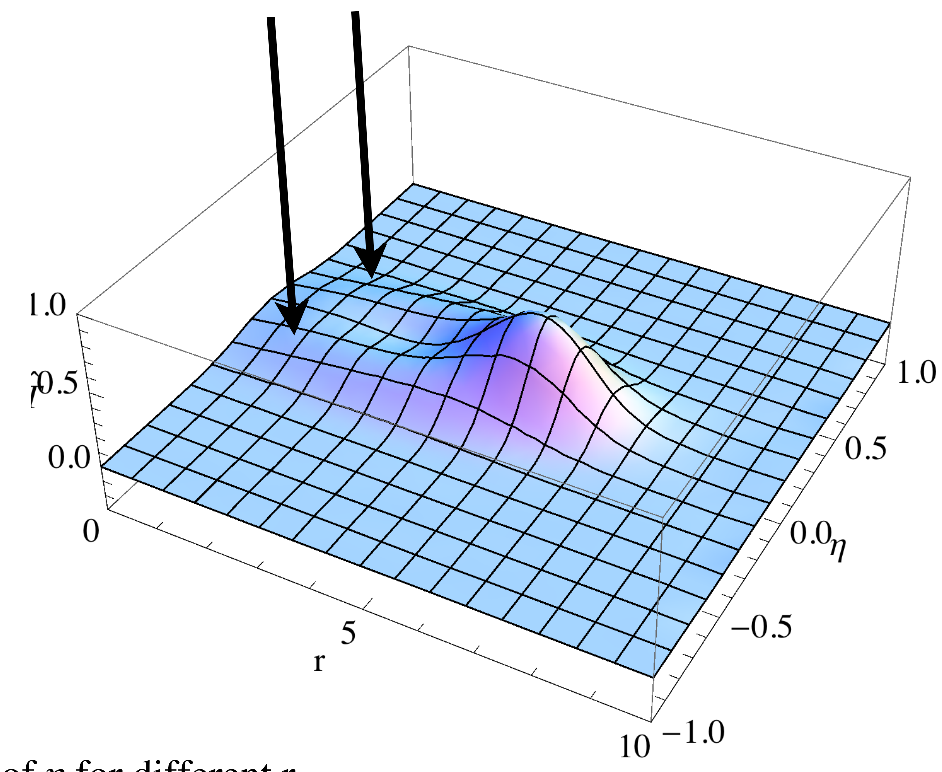
T =1 ev !

Sound propagating in rapidity direction

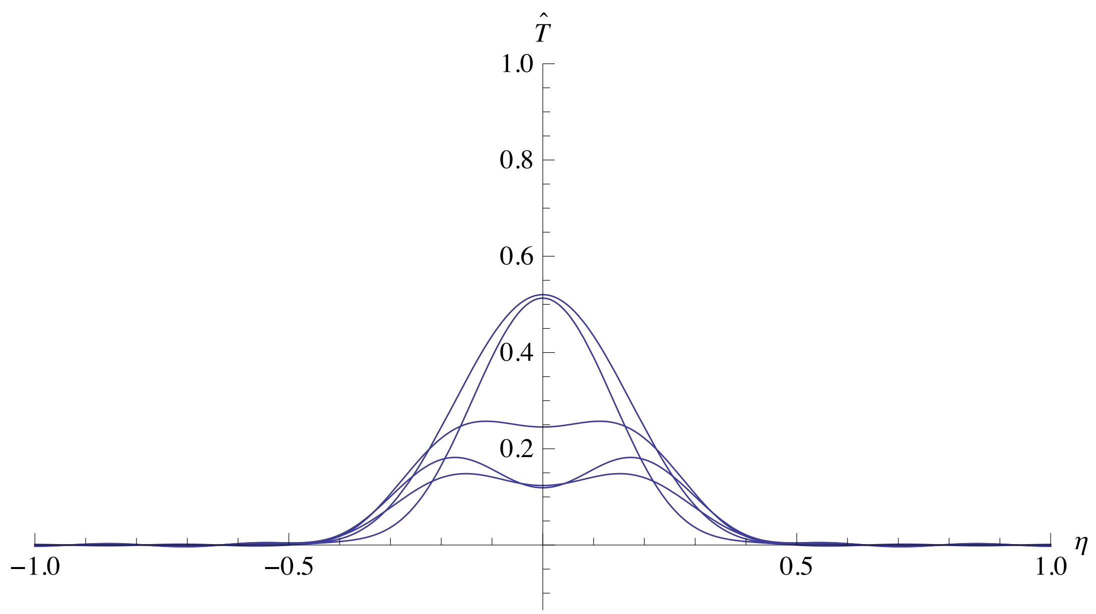
$$\frac{\partial \delta(\rho)}{\partial \rho} = \frac{l\,(l+1)\,v_s(\rho)}{3\cosh^2(\rho)} - \frac{1}{3}\,i\,k\,v_\eta(\rho)$$

$$\frac{\partial v_s(\rho)}{\partial \rho} = \frac{2}{3}\tanh(\rho)\,v_s(\rho) - \delta(\rho)$$

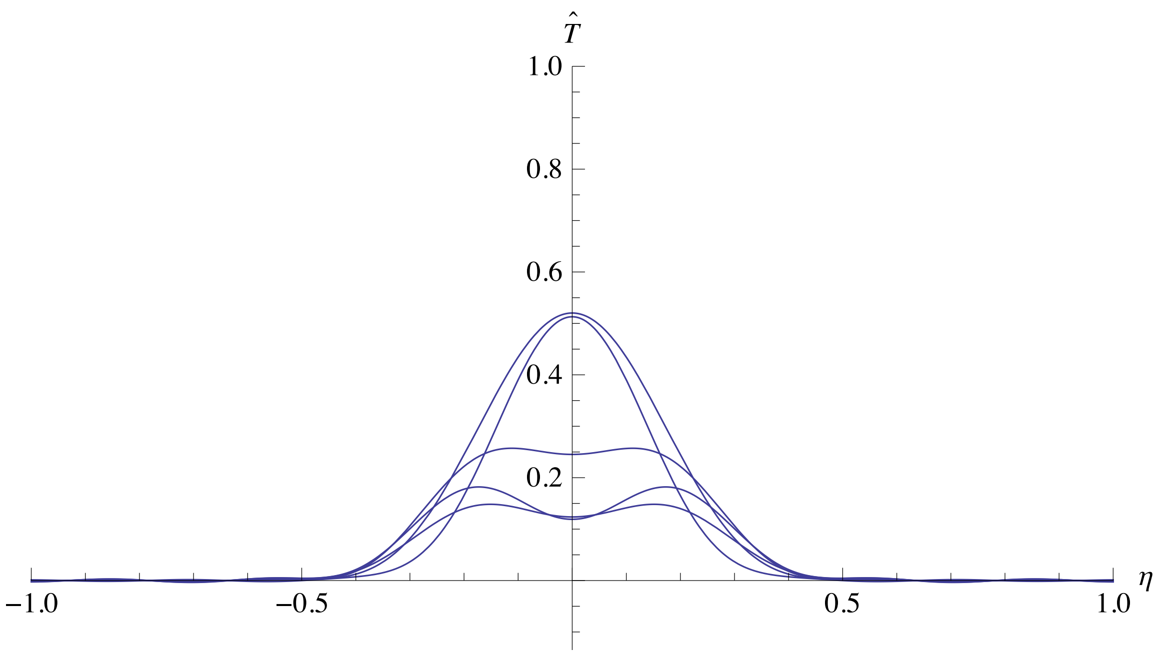
$$\frac{\partial v_\eta(\rho)}{\partial \rho} = \frac{2}{3}\tanh(\rho)\,v_\eta(\rho) - i\,k\,\delta(\rho)$$



The temperature perturbation at freeze-out as a function of η for different r.

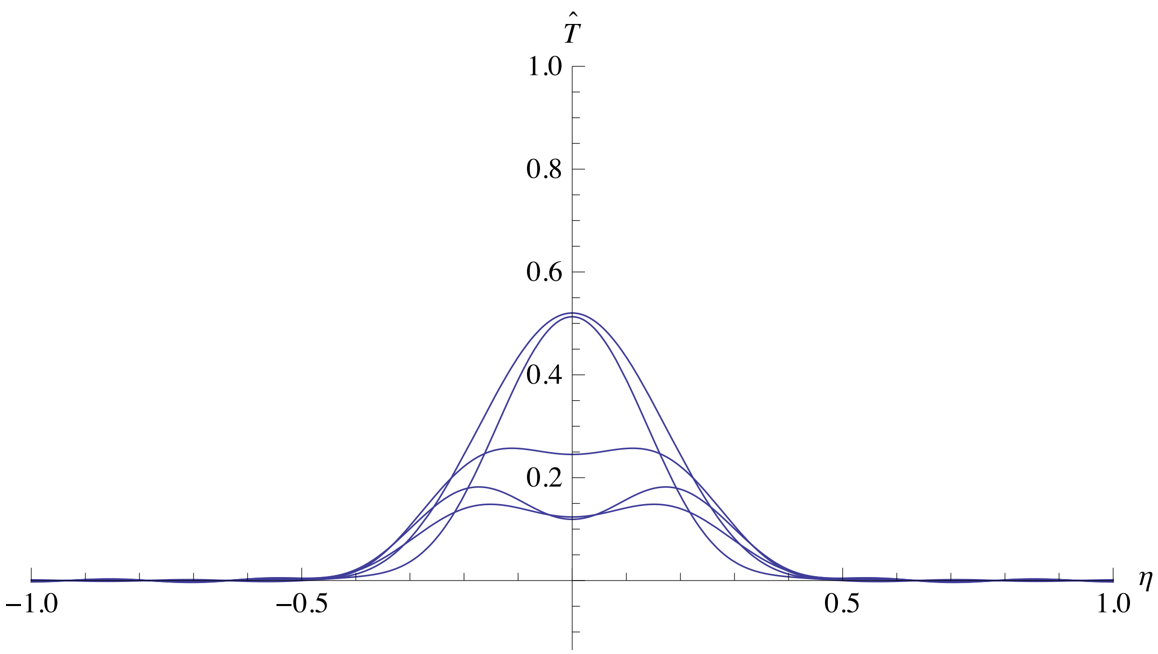


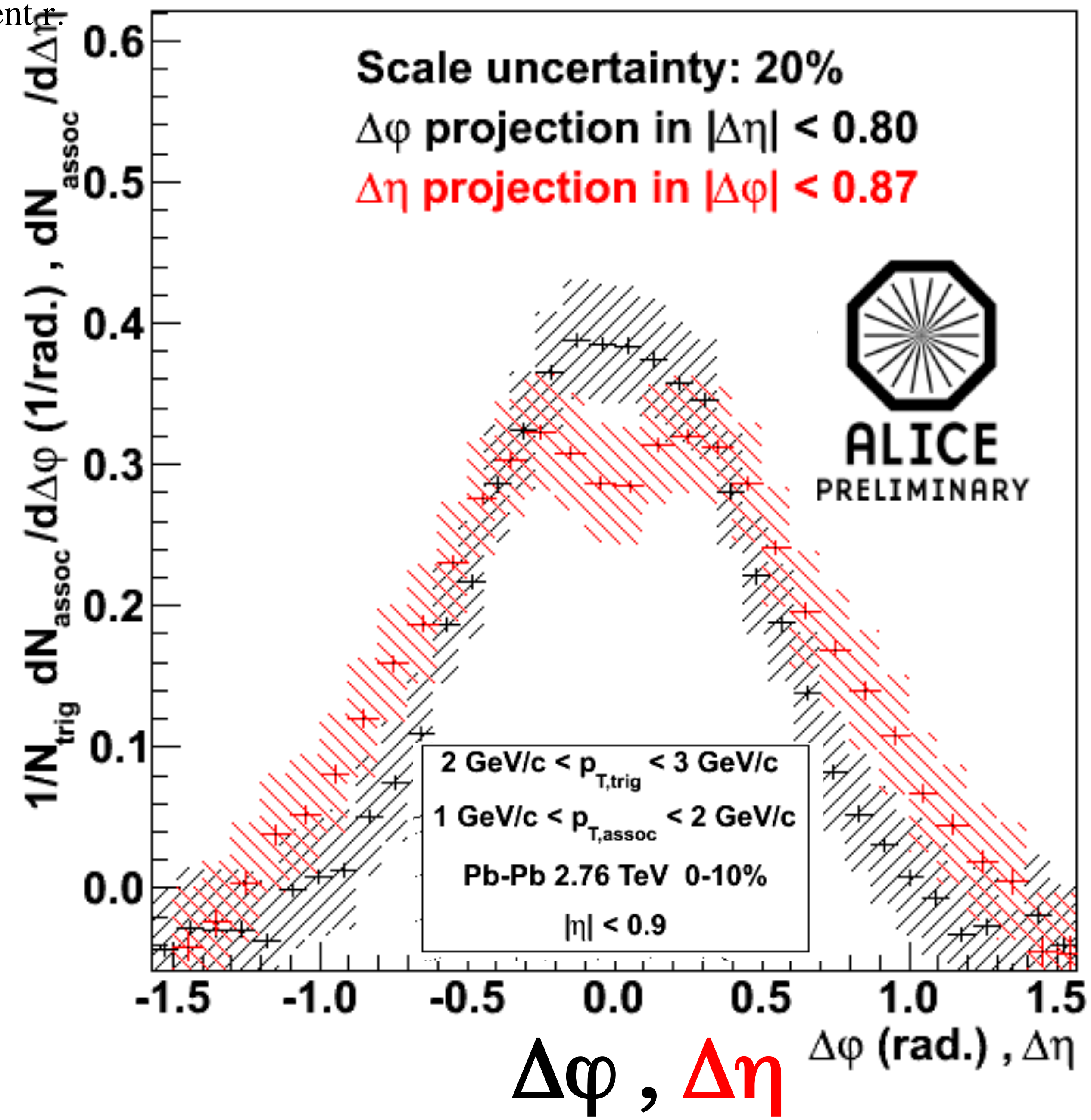
The temperature perturbation at freeze-out as a function of η for different r.



Summing up those curves one gets a double-hump distribution

The temperature perturbation at freeze-out as a function of η for different r.

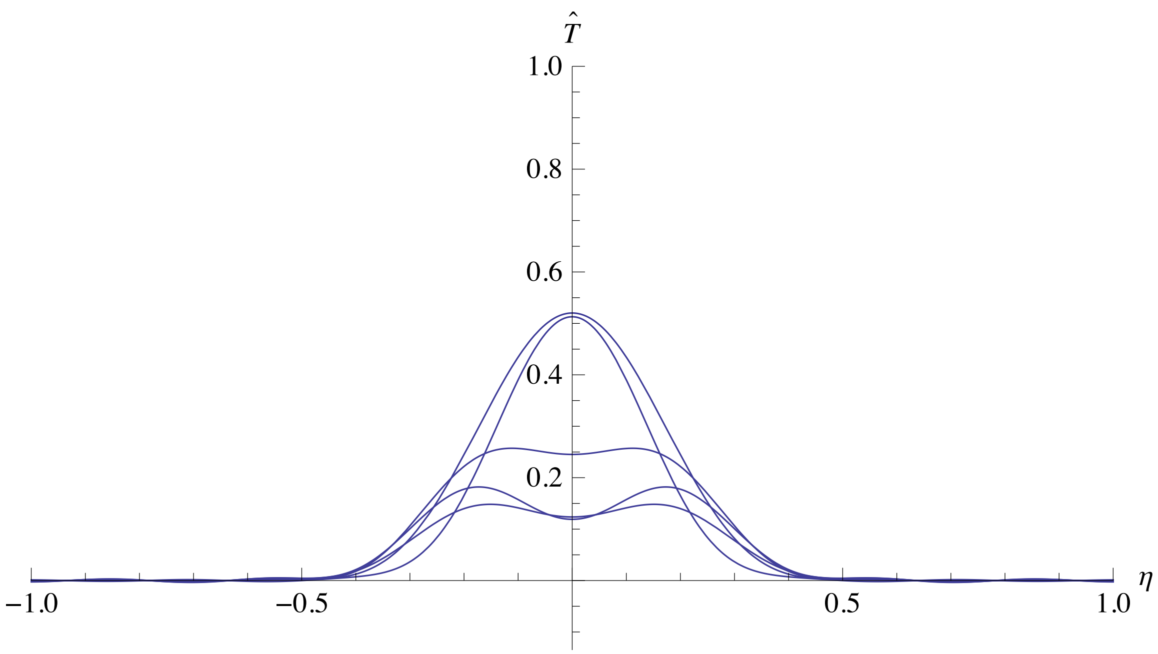




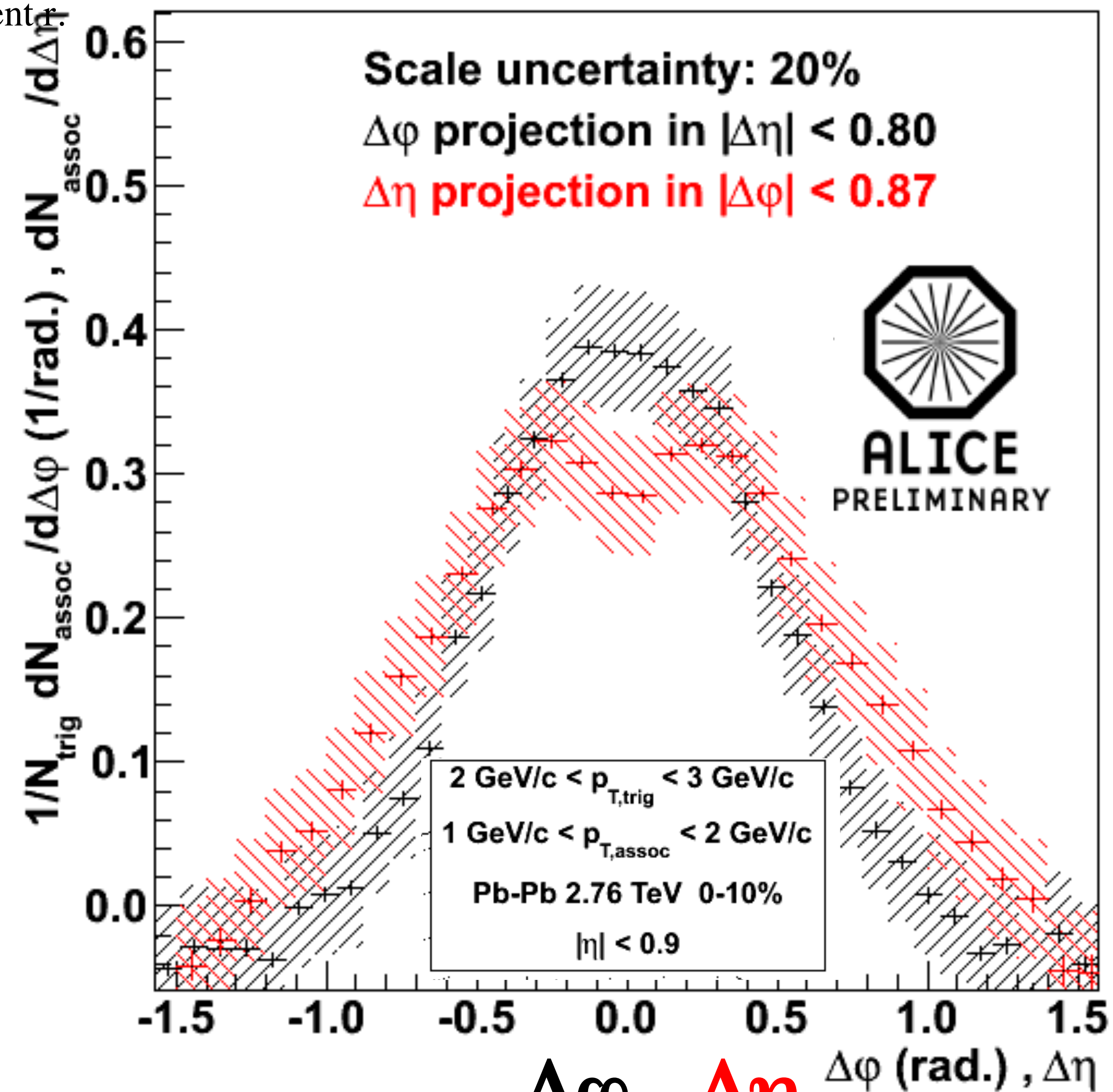
Summing up those curves one gets a double-hump distribution

clusters in rapidity at LHC: first evidences for "mini-bangs"?

The temperature perturbation at freeze-out as a function of η for different r.



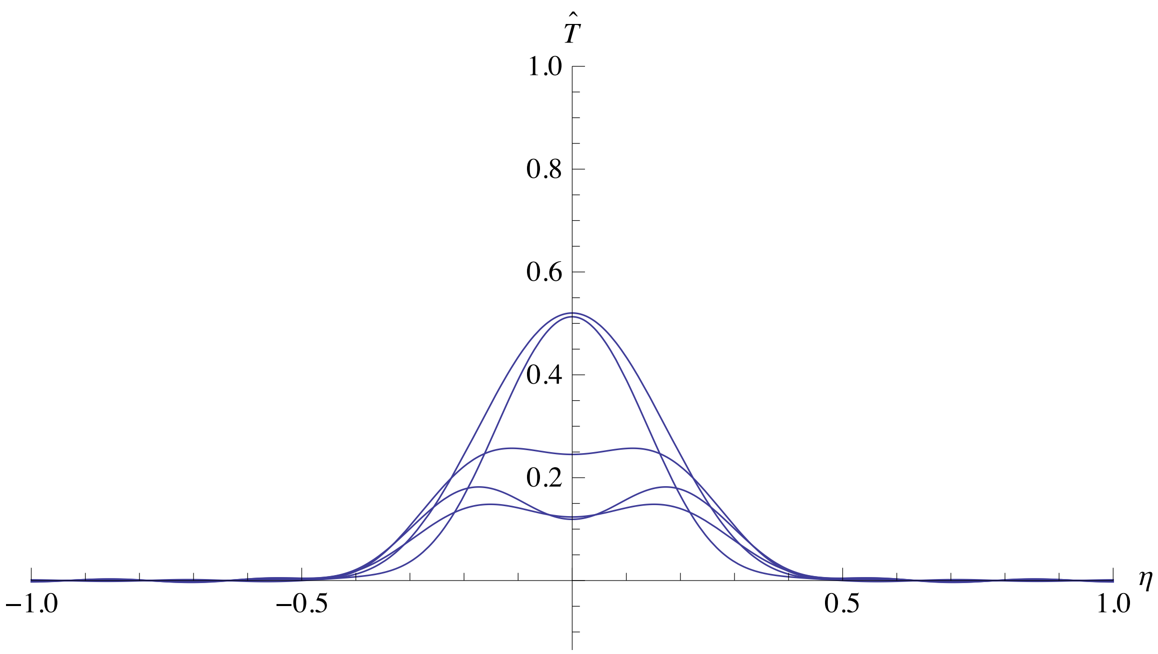
Summing up those curves one gets a double-hump distribution

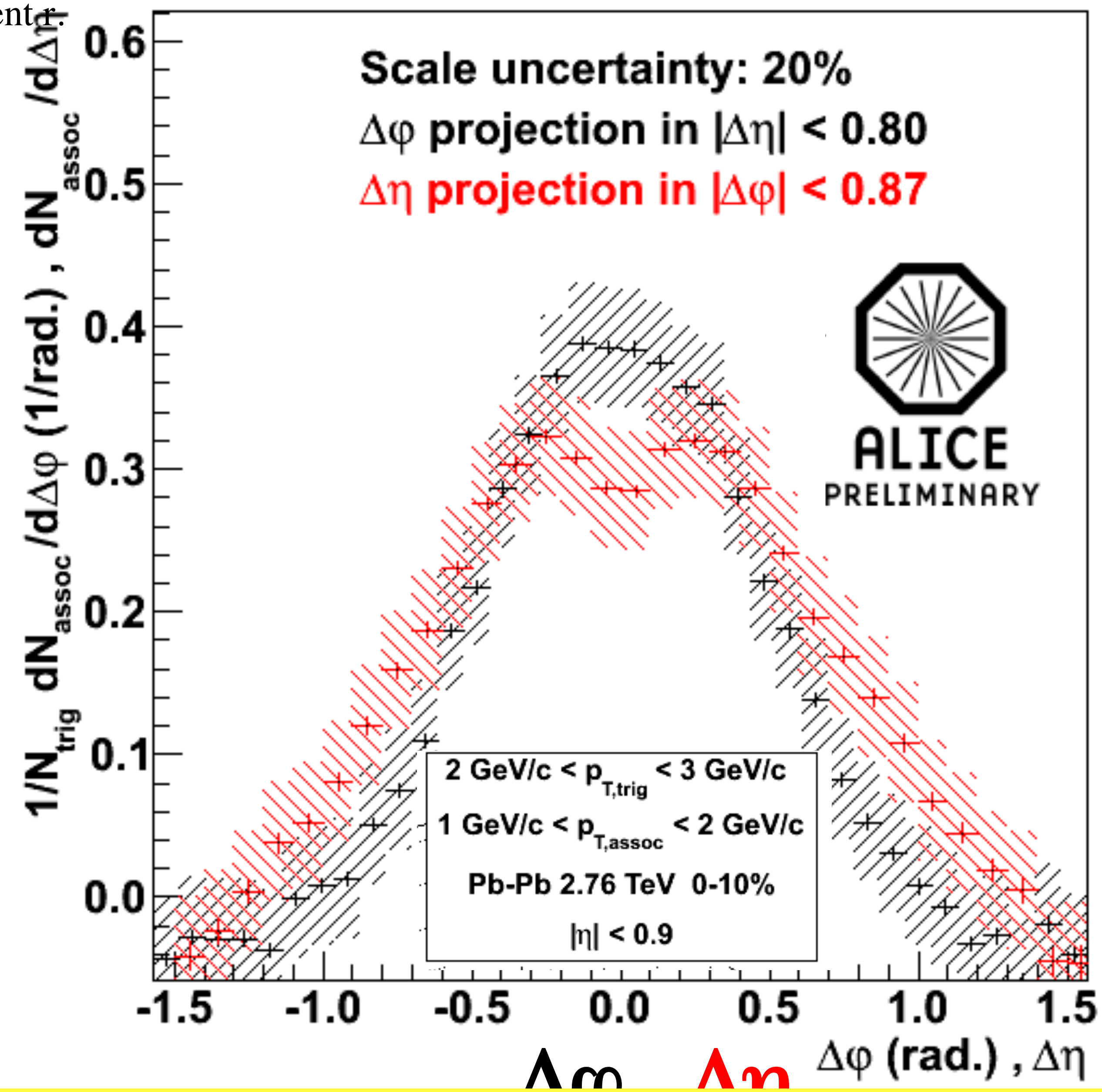


$\Delta\varphi$, $\Delta\eta$

clusters in rapidity at LHC: first evidences for "mini-bangs"?

The temperature perturbation at freeze-out as a function of η for different r.

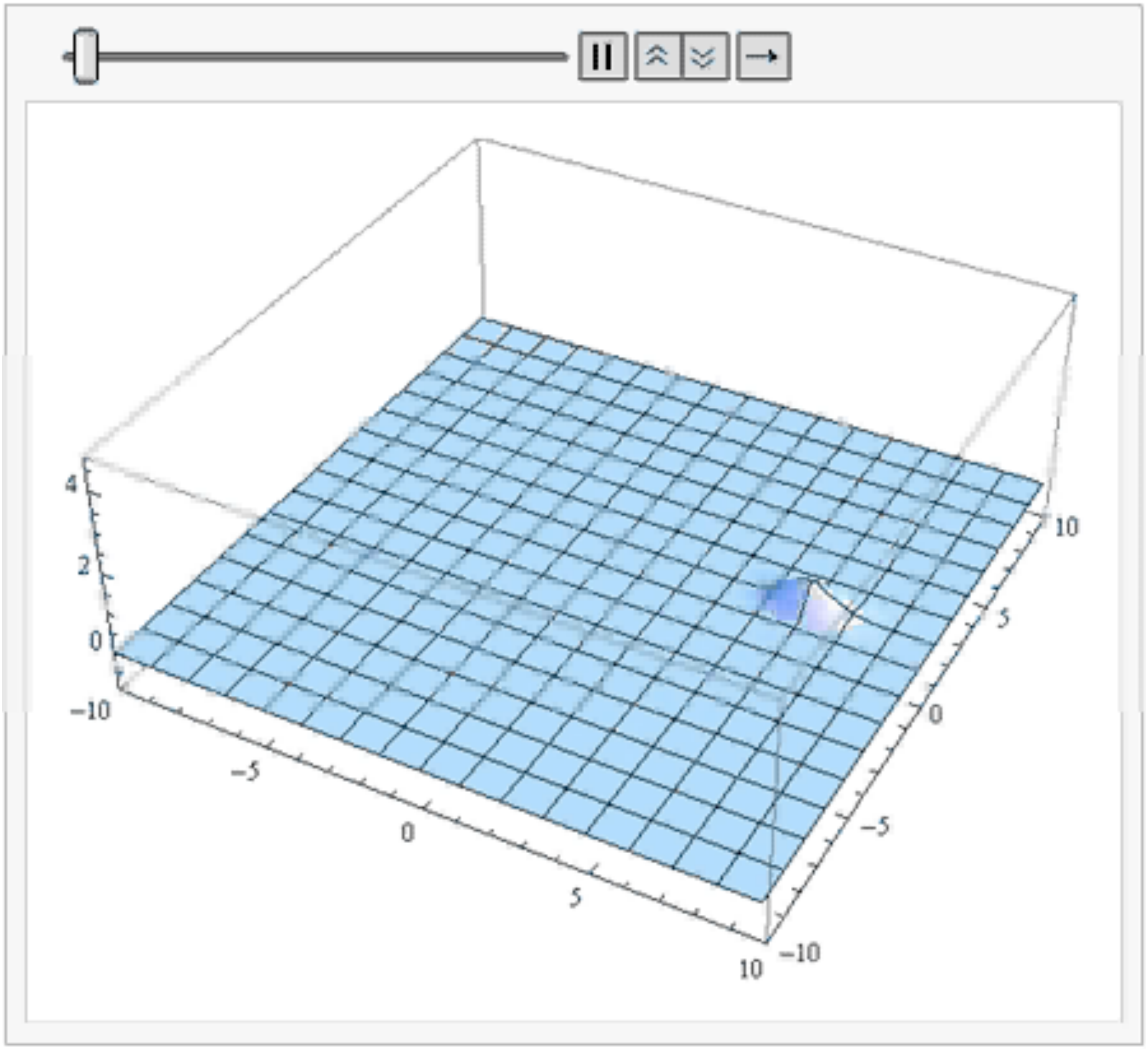


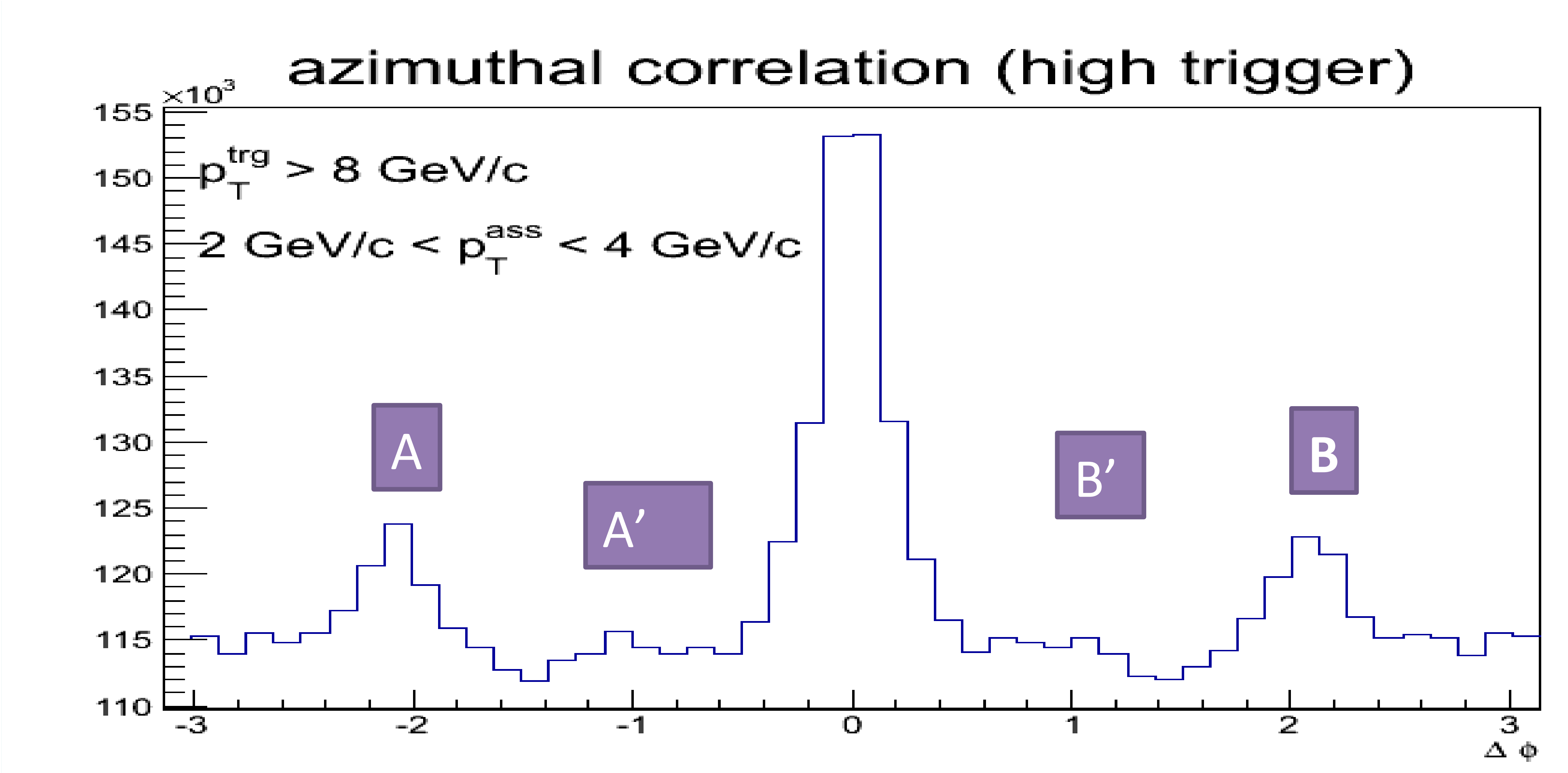


Summing up those curves one gets a double-hump distribution

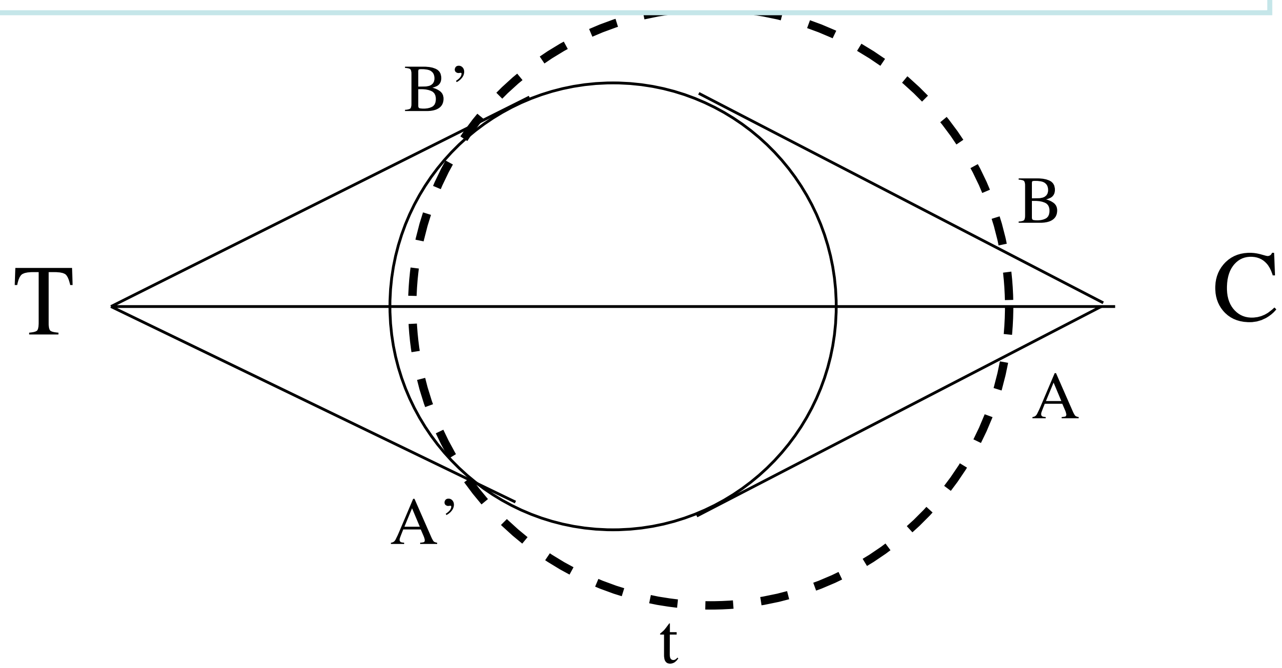
hump separation corresponds to propagation duration of about 2 fm/c (to freezeout): makes sense at LHC

sound from a jet on top of expanding fireball (Gubser flow): the old Mach cone





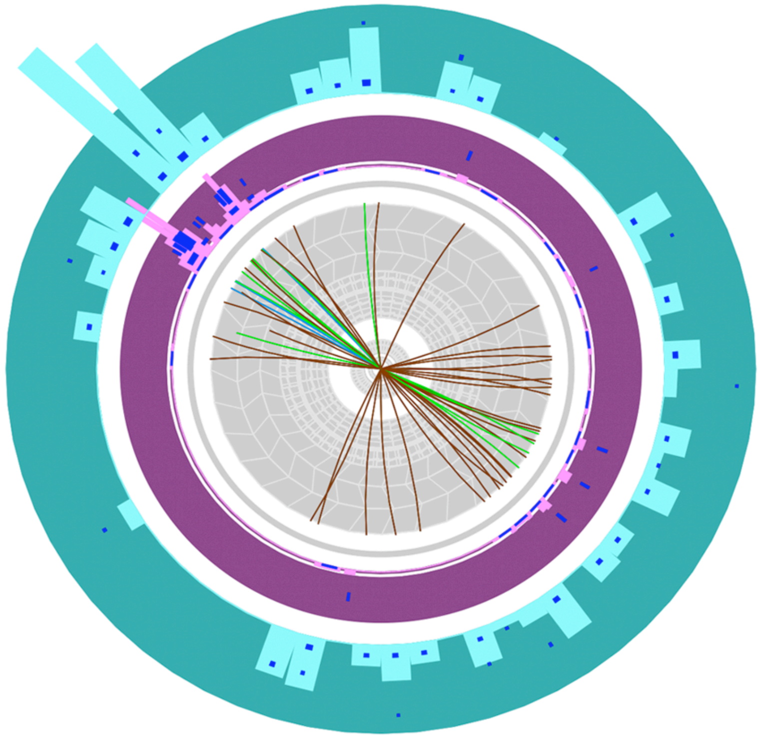
ALICE: very preliminary:
peaks perhaps due to 4 points (A-B,A’B’) are there

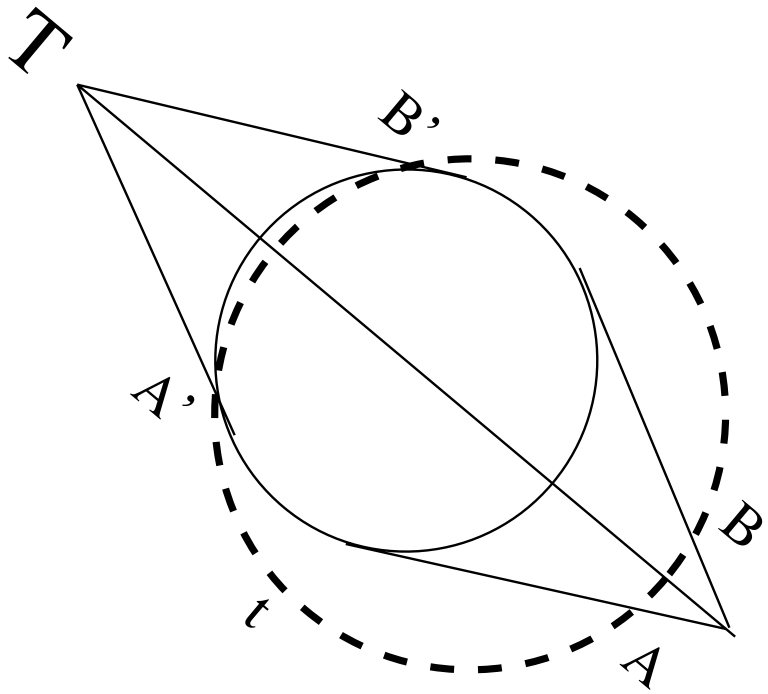


summary

- strong shocks: out-of-equilibrium but stationary problem. LS hydro and ADS/CFT confirm small corrections to Navier-Stokes
- sounds from initial perturbations have many harmonics => sonogramms possible
- shocks and Mach cones from jets are becoming observable
- Rayleigh collapse of the QGP bubble: the sound of the QGP phase transition ?

The angular edge of the jets: matter inside is few % HOTTER => SHOULD BE SEEN at tuned pt





- ATLAS very high energy event, in which there is no identifiable jet
- Tracks pt>2.6 GeV, cal. E>1GeV/cell
- Note the sharp edge of the away-side perturbation! **Is it a "frozen sound"?**

Large O(100 GeV) energy deposition into the medium should create strong shocks, and thus a different (larger) propagation distance