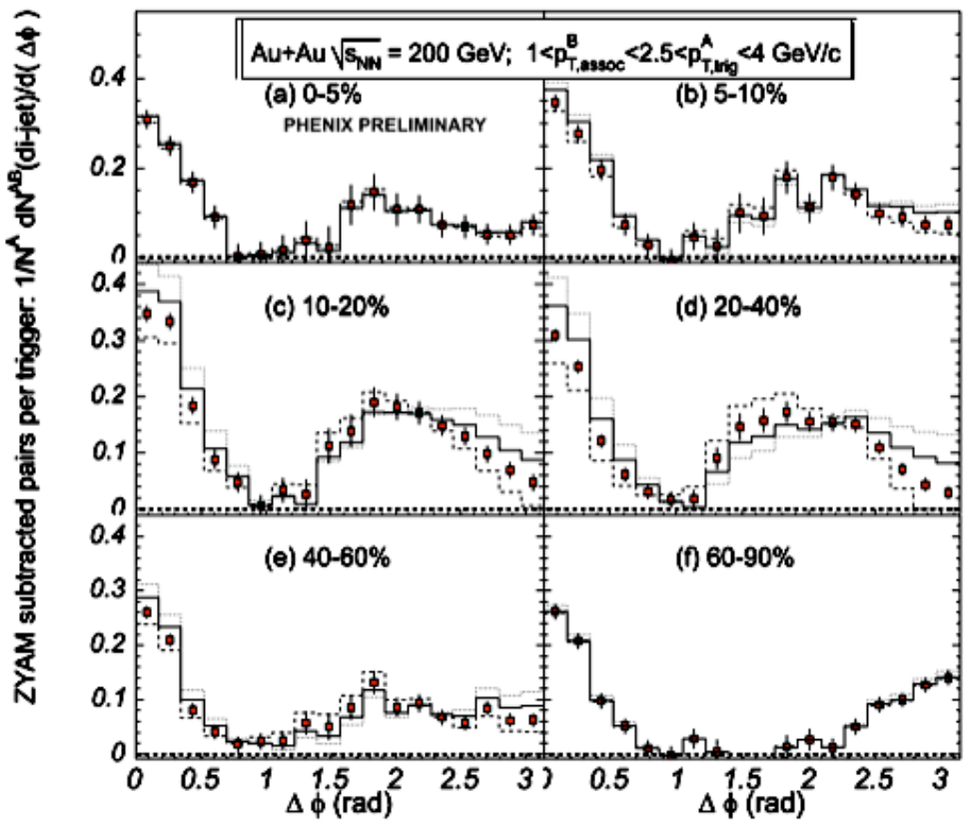
The Sound Edge of the Quenching Jets

Edward Shuryak
Stony Brook

a slide from my talk years ago: suggesting **Mach cone:**



Sonic boom from quenched jets

Casalderrey,ES,Teaney, hep-ph/0410067; H.Stocker…

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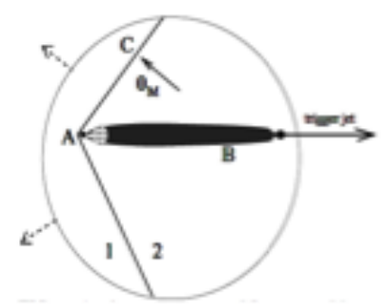
- **We solved relativistic hydrodynamics and got the flow picture**

Wake effect or "sonic boom"



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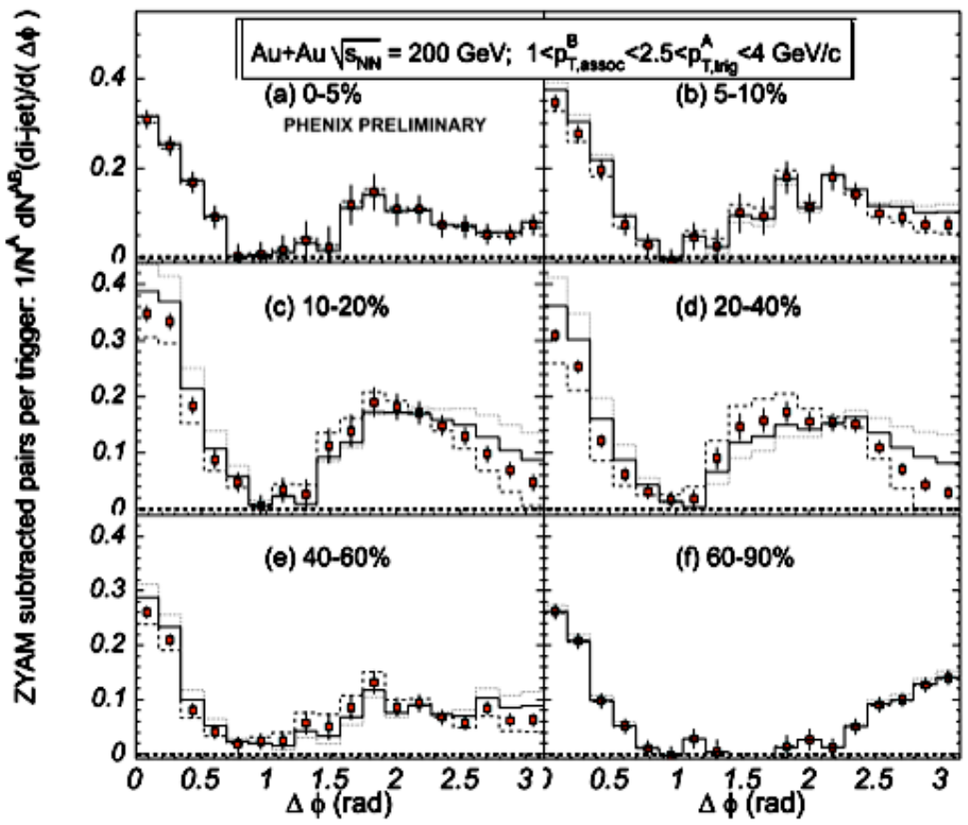

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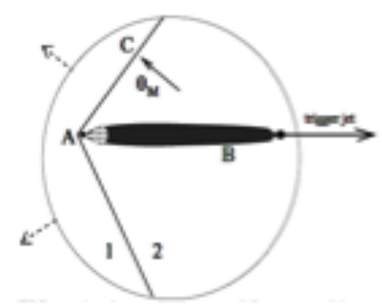


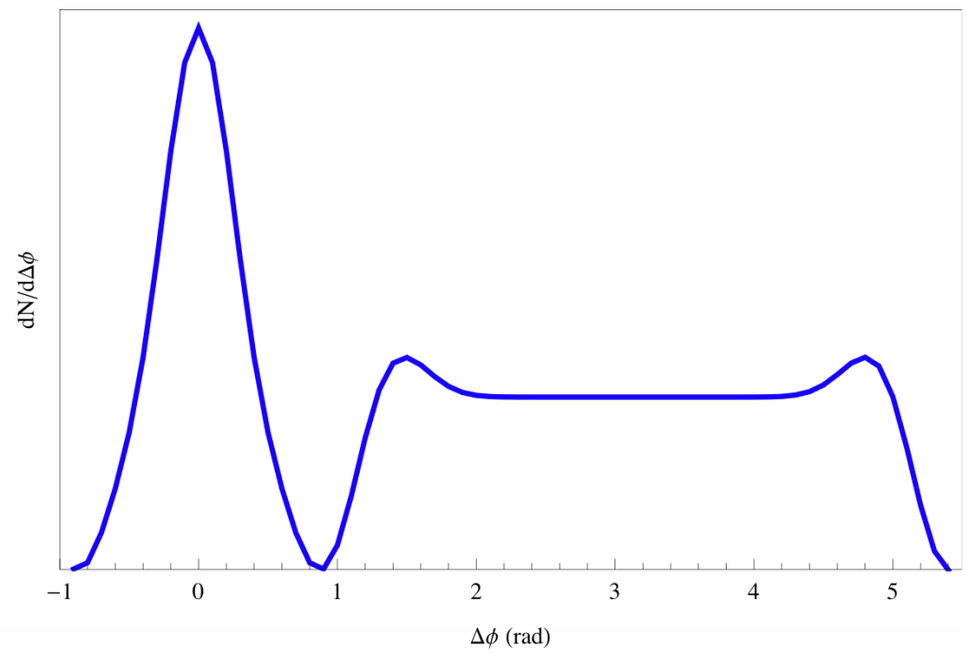
but then the interpretation of correlation function completely changed: what went wrong?

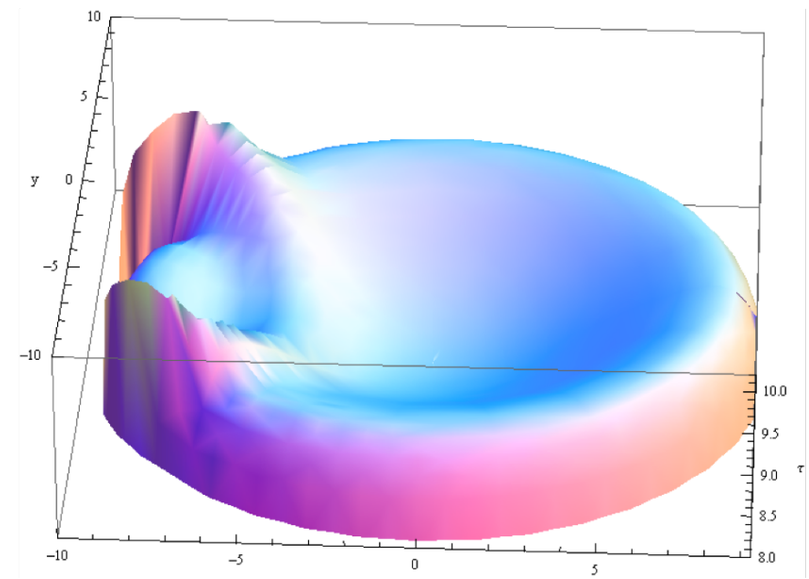
what was wrong with the original Mach cone idea?

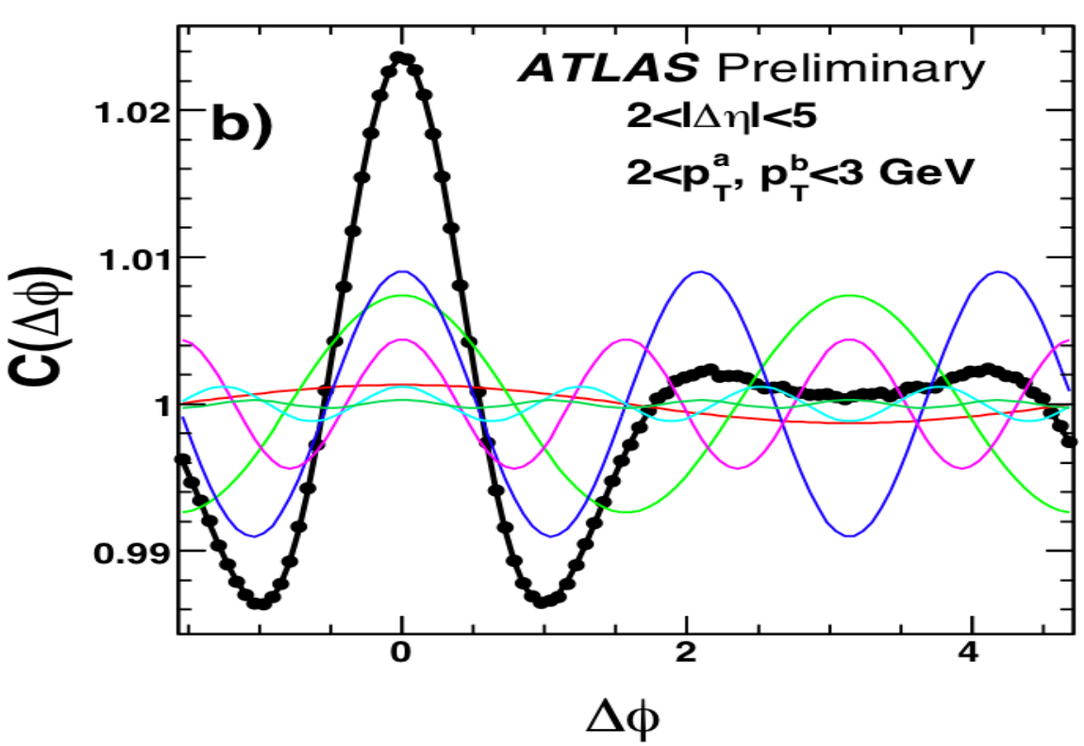
- a decade ago everyone (?) thought that a trigger hadron with 2.5 GeV < pt < 4 GeV **must be** from a jet **(wrong)**
- yet we later learned that high flow harmonics (due to initial state fluctuations) not only reach such pt but in fact are maximal at pt=3..4 GeV.

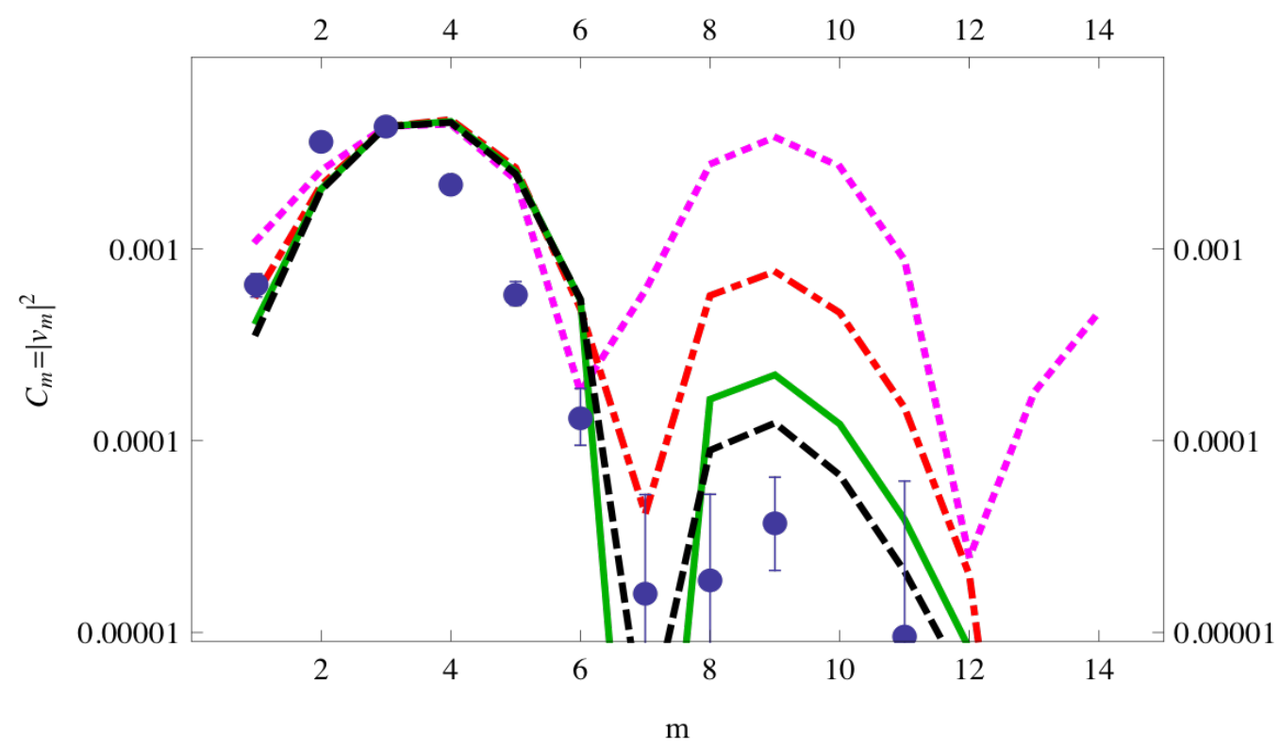
Pilar Staig, Edward Shuryak Phys.Rev. C84 (2011) 044912
arXiv:1105.0676

high harmonics of flow









Hydro, spectra, and **the fireball's rim**

the so called Cooper-Fry formula

$$dN = \frac{d^3p}{(2\pi)^3 E} p^\mu \int_\Sigma d^3\Sigma_\mu exp(p^\mu u_\mu / T_f).$$

Indeed, let us single out one term in the exponent governing the ϕ integral, namely the one containing $\cos(\phi_p - \phi)$. Its coefficient

$$A = \frac{p_\perp}{T_f} sinh(\kappa) \approx 26 \qquad (5)$$

in which we have introduced the transverse rapidity of the flow κ and use $u_r = sinh(\kappa)$ in the r.h.s. , substituted some typical values $p_\perp = 2.4\,GeV$ and $T_f = .12\,GeV$ and the maximal flow $\kappa \approx 1.1$. Since it is in the exponent and $A\cos(\phi_p - \phi) \approx A - ((\phi_p - \phi)^2 A/2$, the angular integral in ϕ is approximately Gaussian. Ignoring for now pre-exponent, one can write those two as well known generic integrals

$$\int_0^{2\pi} \frac{d\phi}{2\pi} exp[Acos(\phi - \phi_p)] = J_0(A) \approx exp(A)\frac{1}{\sqrt{2\pi A}}$$

$$\int_{-\infty}^{\infty} d\eta e^{-Acosh(\eta - y_p)} = 2K_0(A) \approx \sqrt{\frac{2\pi}{A}} exp(-A)$$

where the right expressions are asymptotics at large A. For A in the realistic range the asymptotical expressions work reasonably well. Therefore, the width of the contributing "spot" in ϕ integration is thus indeed small:

$$\sqrt{<(\phi - \phi_p)^2>} = \frac{1}{\sqrt{A}} \approx \frac{1}{5} \qquad (6)$$

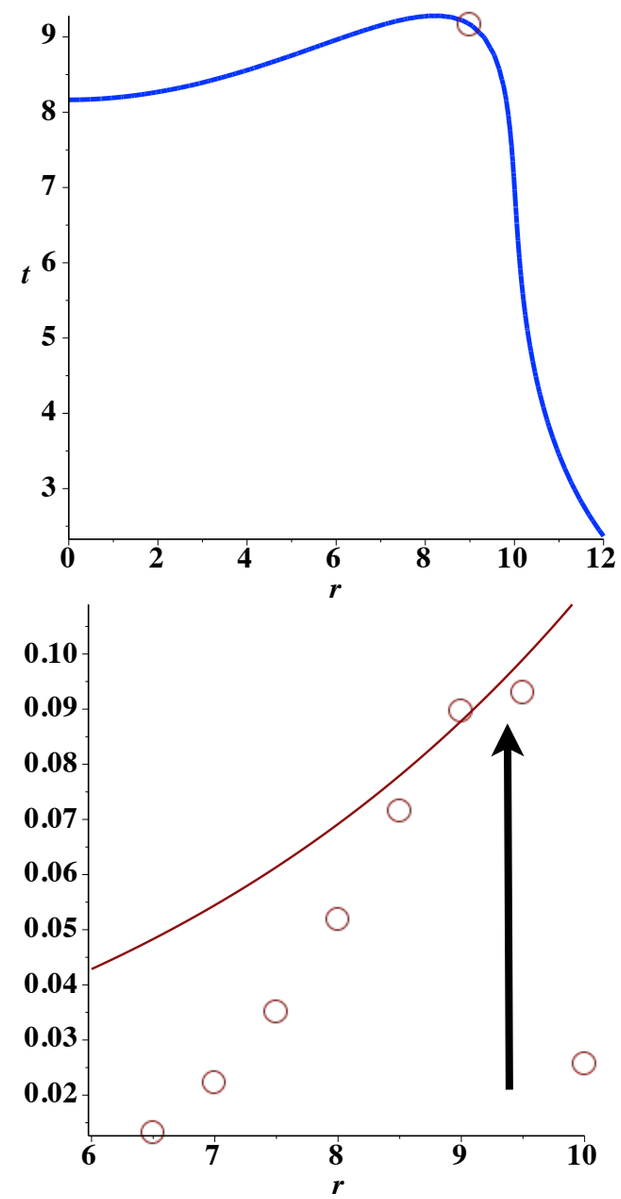


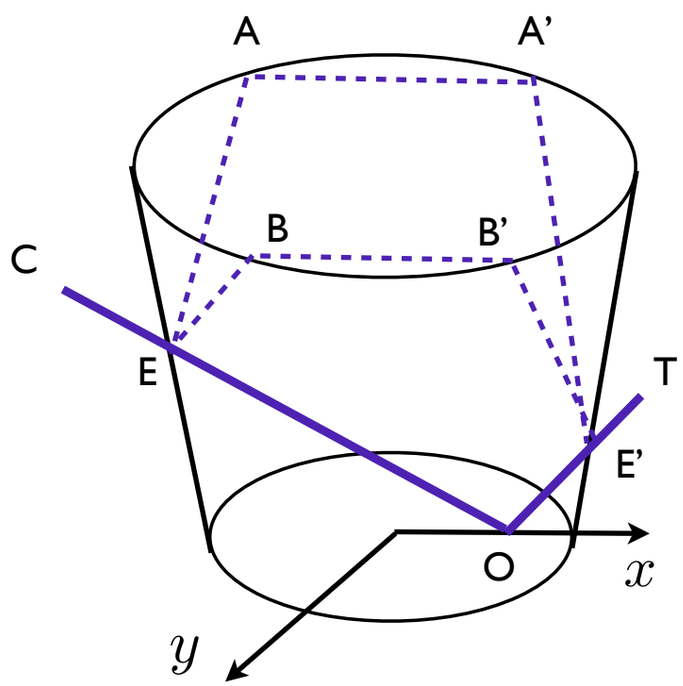
FIG. 3: (Color online) (a) Example of a freezeout surface with $T_f = 120\,MeV$ surface in the r, τ plane (both in fm). The circle on the line indicate a point in which the transverse flow reaches its maximal value $v_\perp = 0.89$. (b) The circles show the radial dependence of the expression (8), the line indicates the exponential approximation discussed in the text.

freezeout surface has maximal flow point, which dominates the r integral

its small perturbations are observable

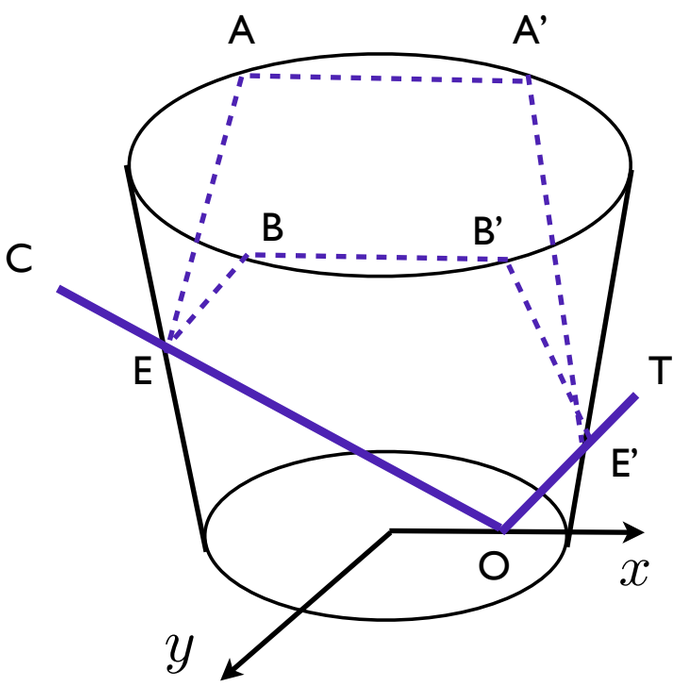
$$r * exp\left(-\frac{p_t}{T_f}\sqrt{\frac{1 - v_\perp}{1 + v_\perp}}\right)$$

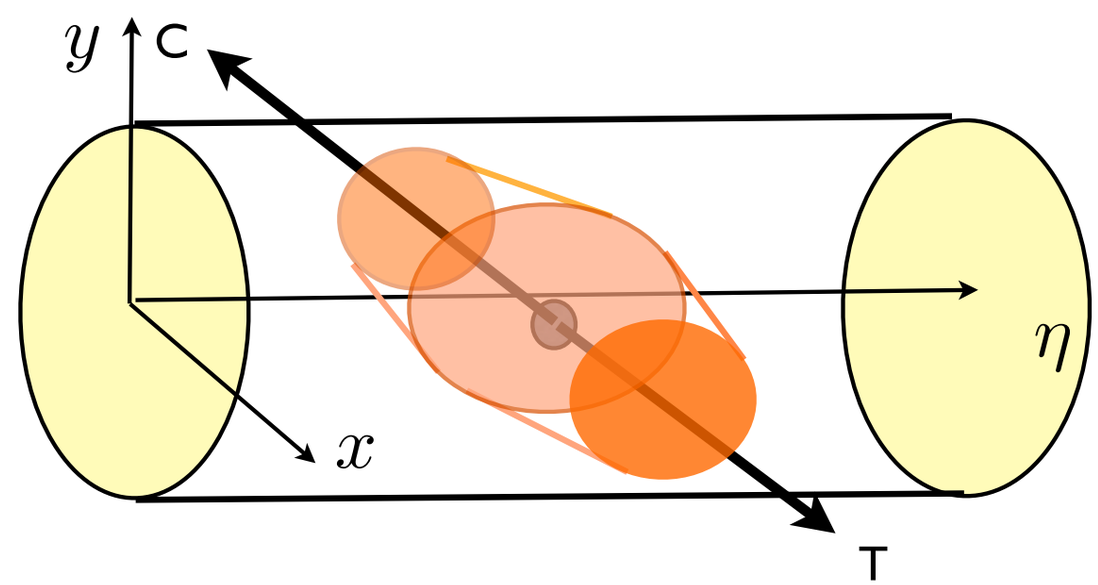
Geometry: the sound surface



(3d) picture including the transverse coordinates x, y and the proper time τ (vertical direction). The lower and upper cir- cles indicate the initial and final surfaces. The jet origination point is called O, the two exit points are E and E'. **The sound surface consists of two parts, OEAA′E′ and OEBB′E′,** in- dicated by the dashed lines. The value b = 0 is chosen for simplicity.

Geometry: the sound surface





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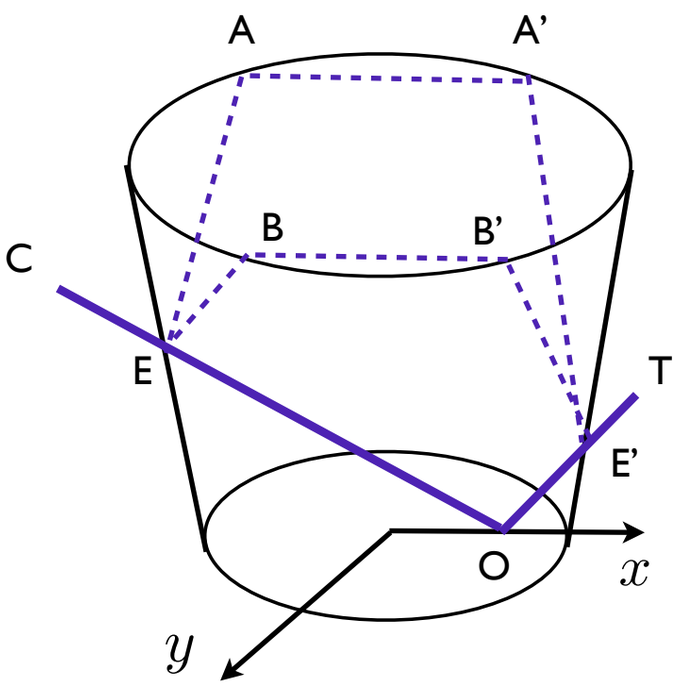

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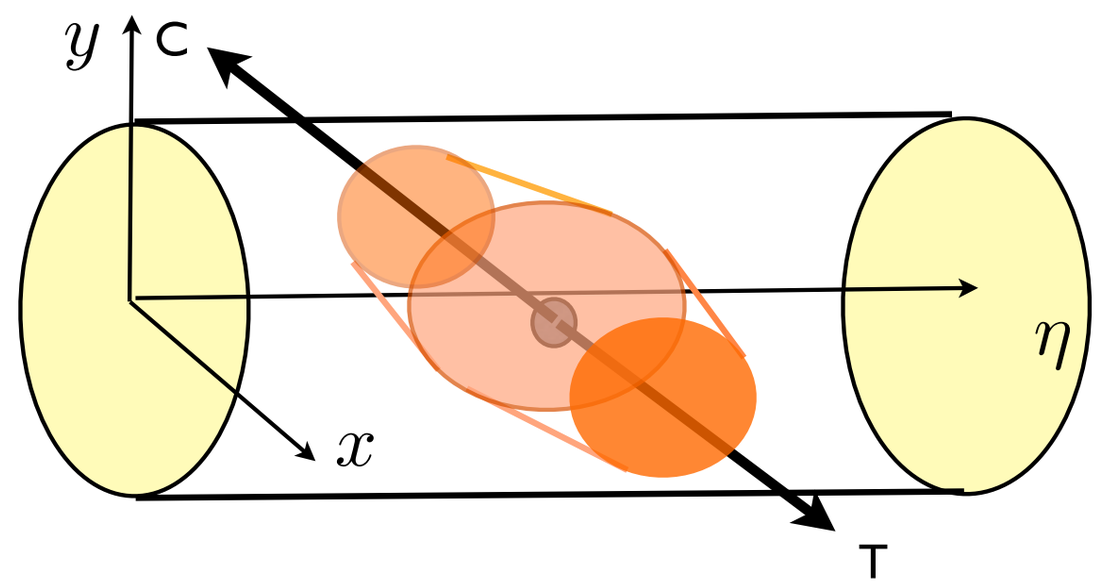


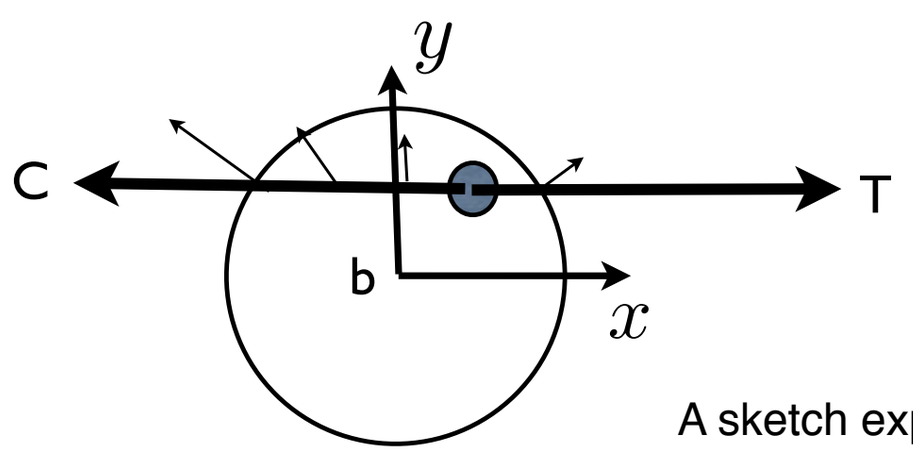
A schematic view of the sound surface in coordinates x, y and (spatial) rapidity η. Trigger and companion jets are chosen to have the same rapidity, for simplicity.

The Sound Edge of the Quenching Jets

Edward Shuryak and Pilar Staig[1]

[1]*Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794, USA.*

When quenching jets deposit certain amount of energy and momentum into ambient matter, part of it propagates in the form of shocks/sounds. The "sound surface", separating disturbed and undisturbed parts of the fireball, makes what we call the sound edge of jets. In this work we semi-analytically study its shape, in various geometries. We further argue that since hadrons with in the kinematical range of $p_\perp \sim 2\,GeV$ originate mostly from the "rim" of the fireball, near the maximum of the radial flow at the freezeout surface, only the intersection of the "sound surface" with this "rim" would be observable. The resulting "jet edge" has a form of extra matter at the elliptic curve, in $\Delta\phi, \Delta\eta$ coordinates, with radius $|\Delta\phi| \sim |\Delta\eta| \sim 1$. In the case of large energy/momentum deposition $\sim 100\,GeV$ we argue that the event should be considered as two sub-events, with interior of the "sound surface" having modified radial and directed flow. We further argue that in the kinematical range of $p_\perp \sim 3\,GeV$ the effect of that can be large enough to be seen on event-by-event basis. If so, this effect has a potential to become a valuable tool to address geometry of jet production and quenching.



A sketch explaining notations: x, y are coordinates in the transverse plane. The trigger jet T is, by definition, emit- ted in x direction, ϕ = 0 and the companion jet C opposite to it, ϕ = π. The jet path has impact parameter b in respect to the fireball center. Thin arrows indicate direction of the radial flow, whose magnitude grows with time approximately linearly.

here is the main idea of the talk:

the intersection of
(i) **the sound surface** and
(ii) **the fireball's rim**
create **"the jet edge"**

we hope to observe it with pt=2-4 GeV hadrons

S. S. Gubser, Phys. Rev. D **82**, 085027 (2010) [arXiv:1006.0006 [hep-th]].
S. S. Gubser and A. Yarom, Nucl. Phys. B **846**, 469 (2011) [arXiv:1012.1314 [hep-th]].

Gubser flow and its perturbations

$$t = q\bar{\tau}, \quad r = q\bar{r}$$

$$v_\perp(t,r) = \frac{2tr}{1+t^2+r^2} \tag{8}$$

$$\frac{\epsilon}{q^4} = \frac{\hat{\epsilon}_0 2^{8/3}}{t^{4/3}\left[1+2(t^2+r^2)+(t^2-r^2)^2\right]^{4/3}}$$

The basic coordinates used are hyperbolic pair τ, η for longitudinal coordinates – already defined above – and the polar coordinates r, ϕ in the transverse plane. However equation of motion for perturbations become separable in different – comoving – coordinates [17] , substituting τ, r by

$$\sinh\rho = -\frac{1-q^2\tau^2+q^2r^2}{2q\tau} \tag{9}$$

$$\tan\theta = \frac{2qr}{1+q^2\tau^2-q^2r^2} \tag{10}$$

The dimensionless temperature (such quantities are denoted by a hat) $T\tau$ is only a function of ρ. In ideal approximation (without viscosity) it is given by especially simple expression

$$T(r,\tau) = \frac{\hat{T}_0}{f_*^{1/4}} \frac{1}{\tau cosh^{2/3}(\rho)} \tag{11}$$

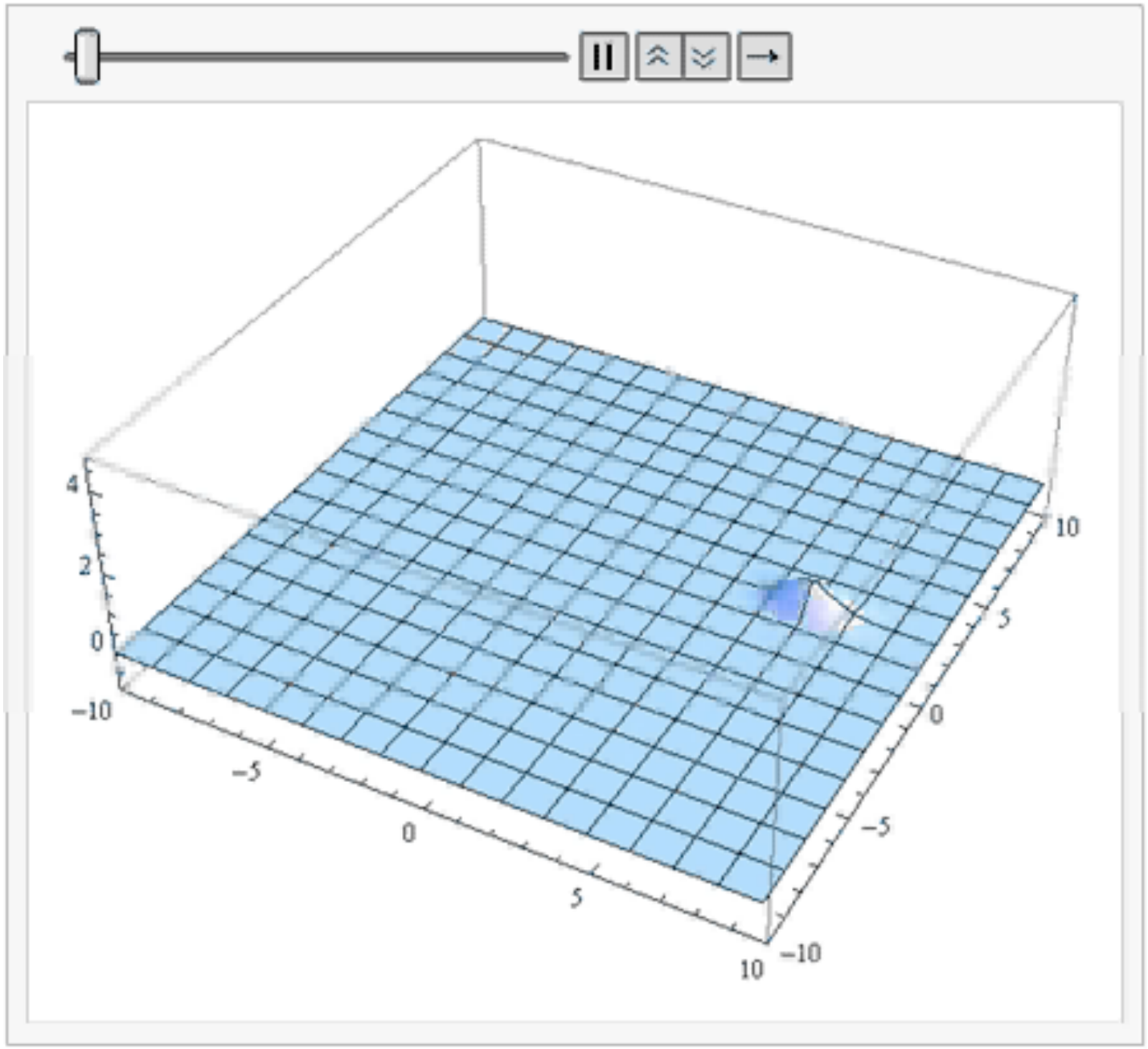
where the parameter $f_* = \frac{\epsilon}{T^4} \approx 11$ according to QGP thermodynamics. For the LHC conditions we had selected in [1] the value $\hat{T}_0 = 10.1$. The freezeout surface we define as the isotherm $T = 120\,MeV$.

$$\frac{\delta T}{T} = \delta(\rho,\theta,\phi,\eta) = \sum_{l,m,k} c_{k,l,m} R_{l,k}(\rho) Y_{l,m}(\theta,\phi) e^{ik\eta} \tag{12}$$

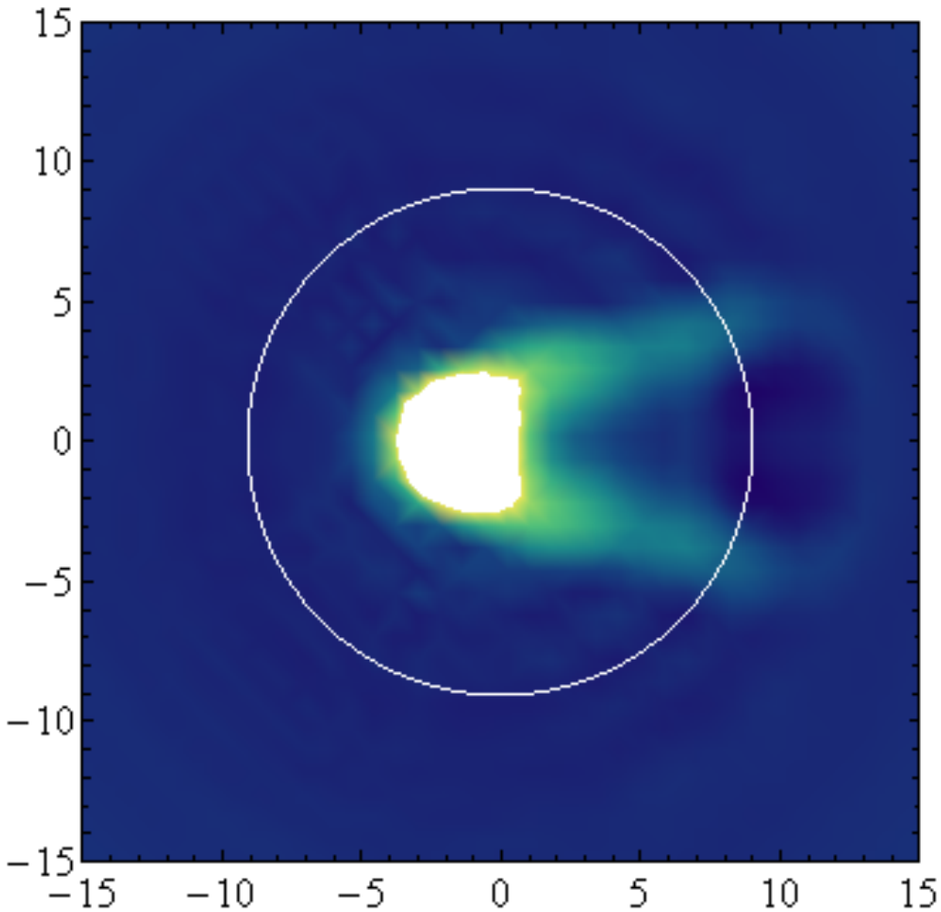
where $Y_{l,m}$ are the usual spherical harmonics. The function R depending on "comoving time" is analytically known for zero viscosity, and is numerically calculated in the non-zero viscosity case, from the corresponding (ordinary) differential equations. We typically discretize the energy deposition into 20 events along the jet path, calculating corresponding coefficients $c(k,l,m)$ as a sum over those events. We also keep 20 values of l and $m = -l..l$, as well as 20 values of discretized k. Those multiple sums are done via fortran program. The results will be typically shown as pictures of δ at fixed τ in the transverse plane x, y.

collecting harmonics we have

perturbation from a jet, on top of exploding fireball

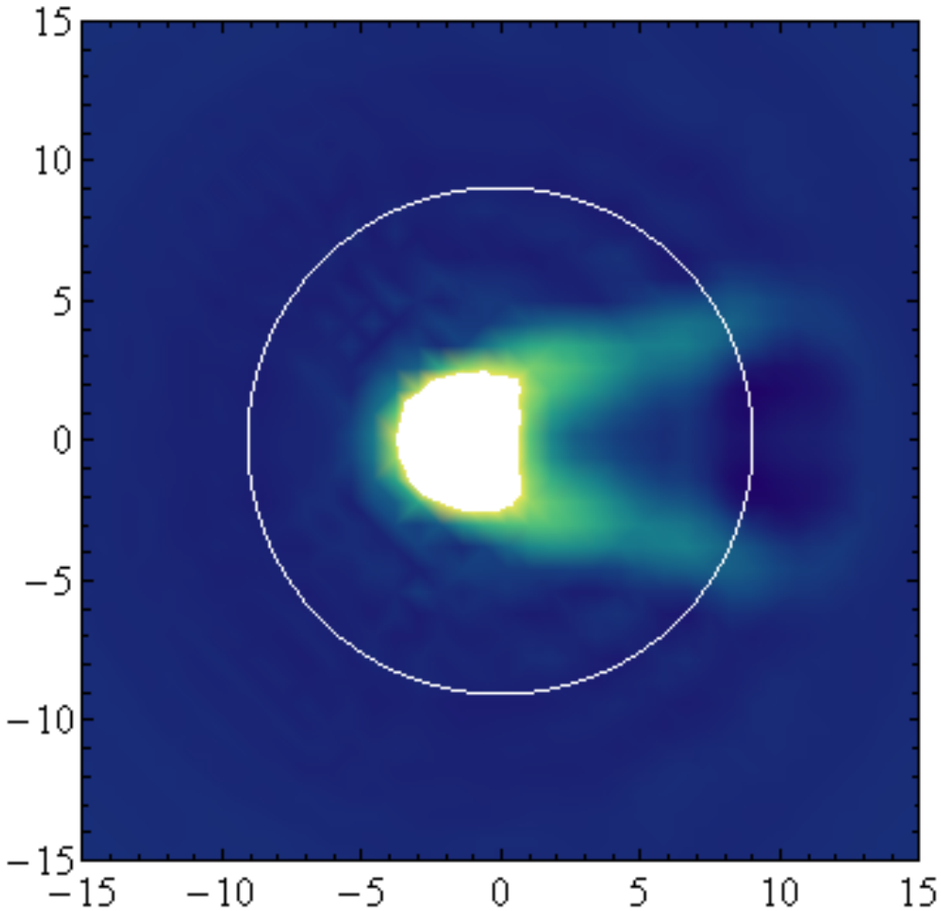


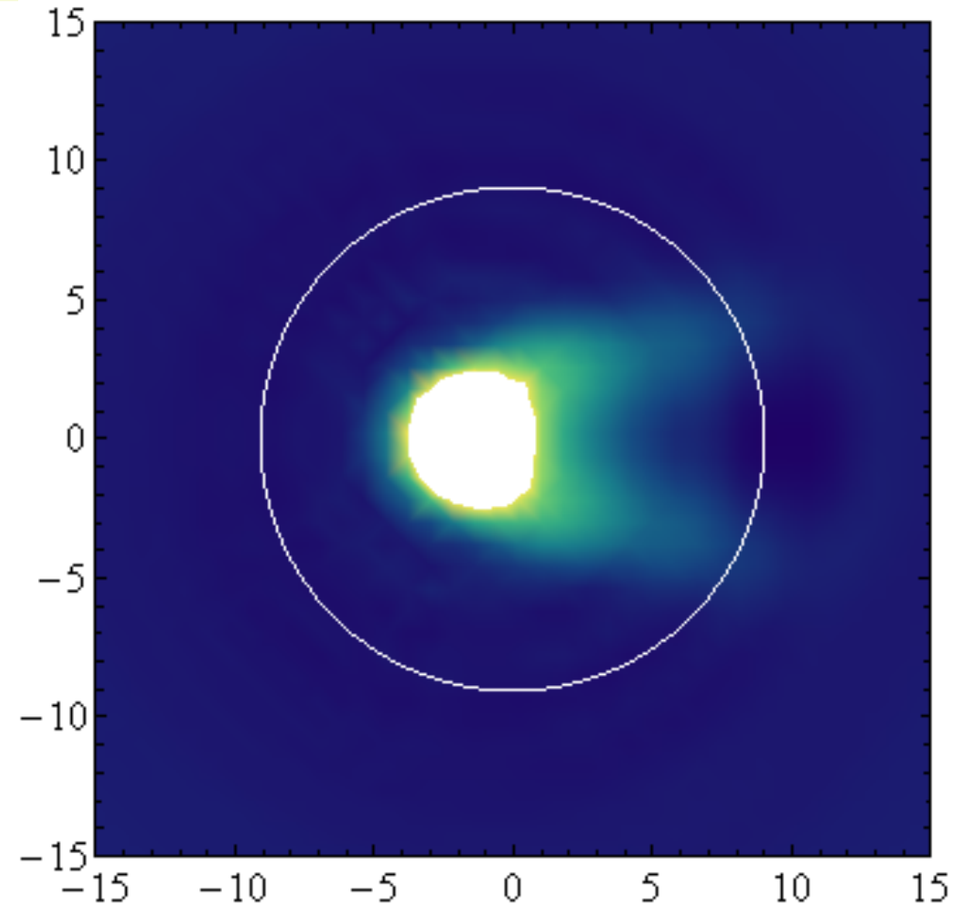
Mach cone, viscosity and an inhomogeneous energy deposition



the Mach cone
in the transverse plane (x,y) (in fm), induced by a jet generated at the point (6.1,0) and moving to the left along the diameter with the speed of light. In the upper plot the energy deposition dE/dx = const and viscosity is put to zero,

Mach cone, viscosity and an inhomogeneous energy deposition





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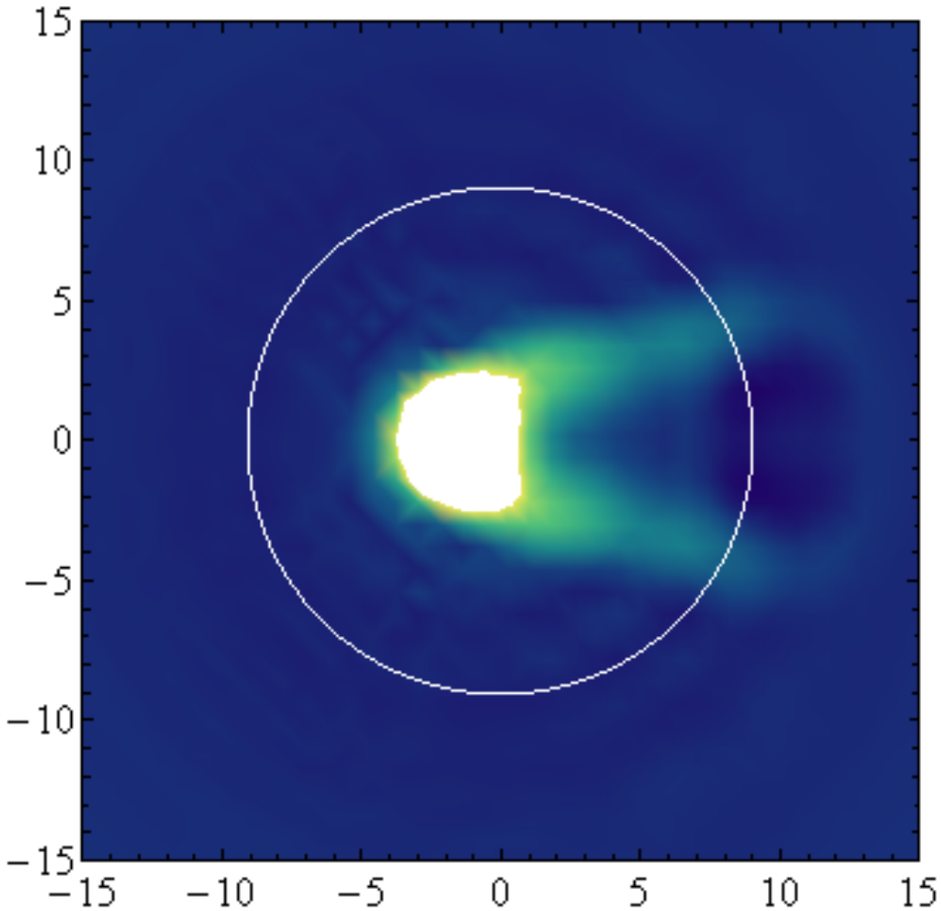

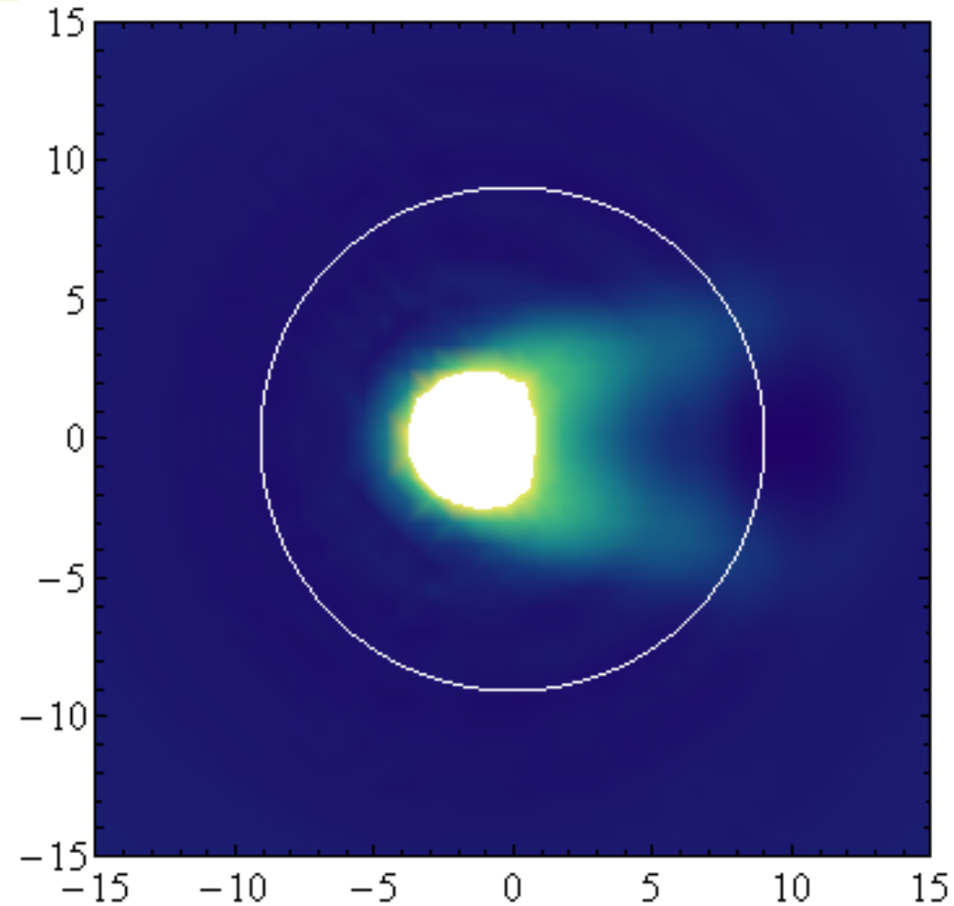

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in this version
dE/dx ~ x and realsitic viscosity-to-entropy combination $4\pi\eta/s = 2$.
the Mach cone is weakened by still seen: yet its overlap with **the fireball rim** (the white circle) is nearly gone!

Jets which die in the middle of fireball
leave only **a very diffuse signal** on the fireball's rim
and can hardly be observed

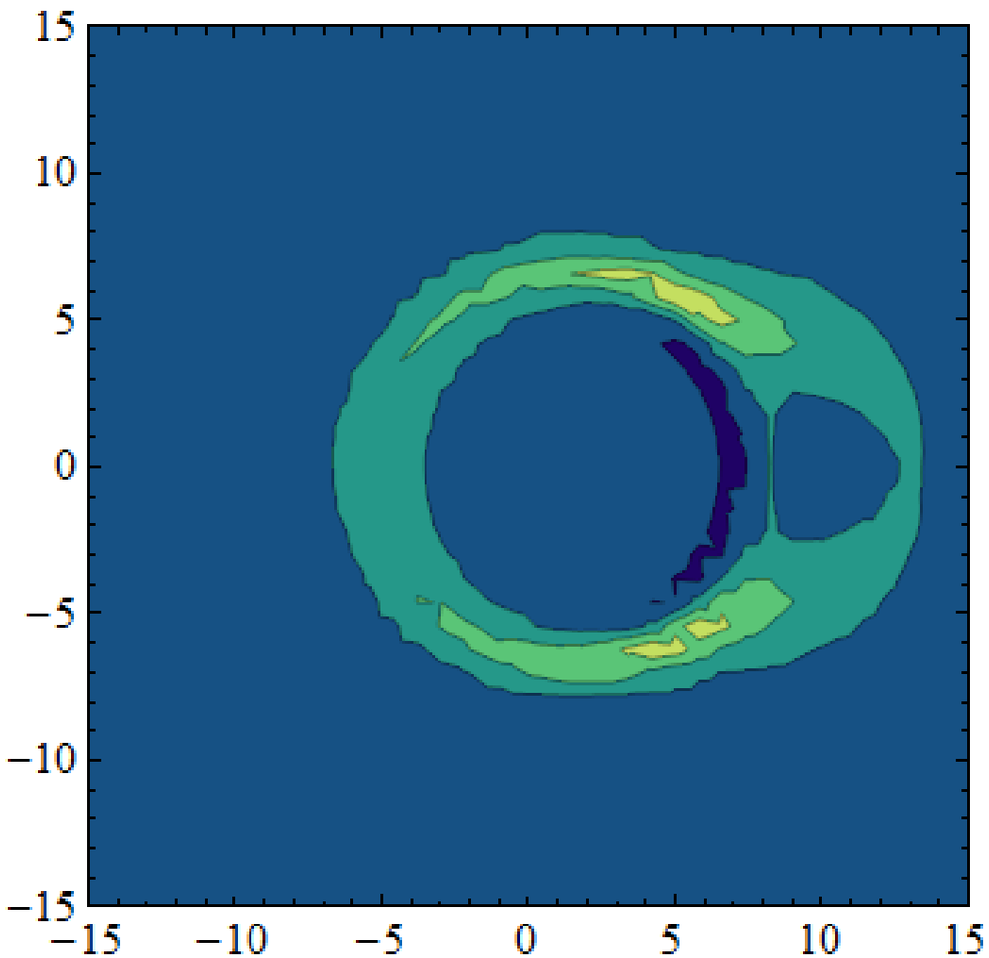


FIG. 5: Perturbation (arbitrary scale) of the temperature in the transverse plane (x,y) (in fm), induced by a jet generated at the point (6,0) and stopped at (0,0).

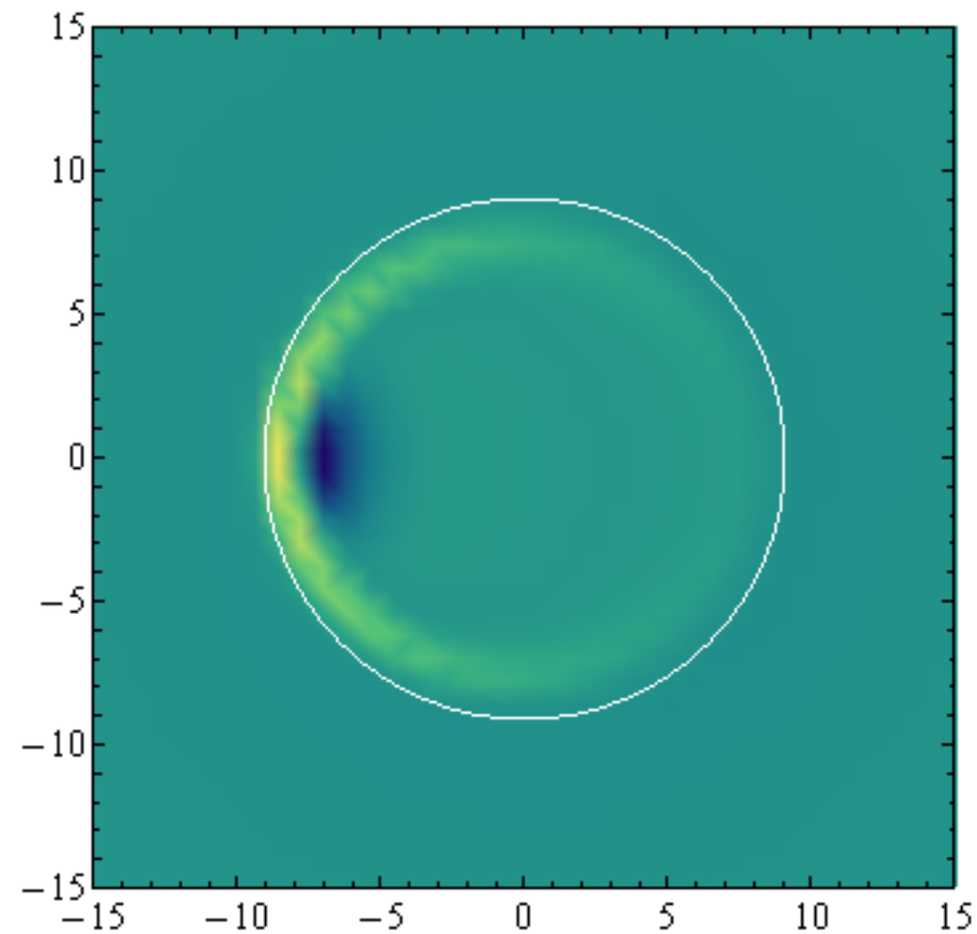


FIG. 6: Perturbation (arbitrary scale) of the temperature in the transverse plane (x,y) (in fm), induced by a jet generated at the point (0,0) and stopped at (-8,0). The fireball rim is indicated by the wide circle.

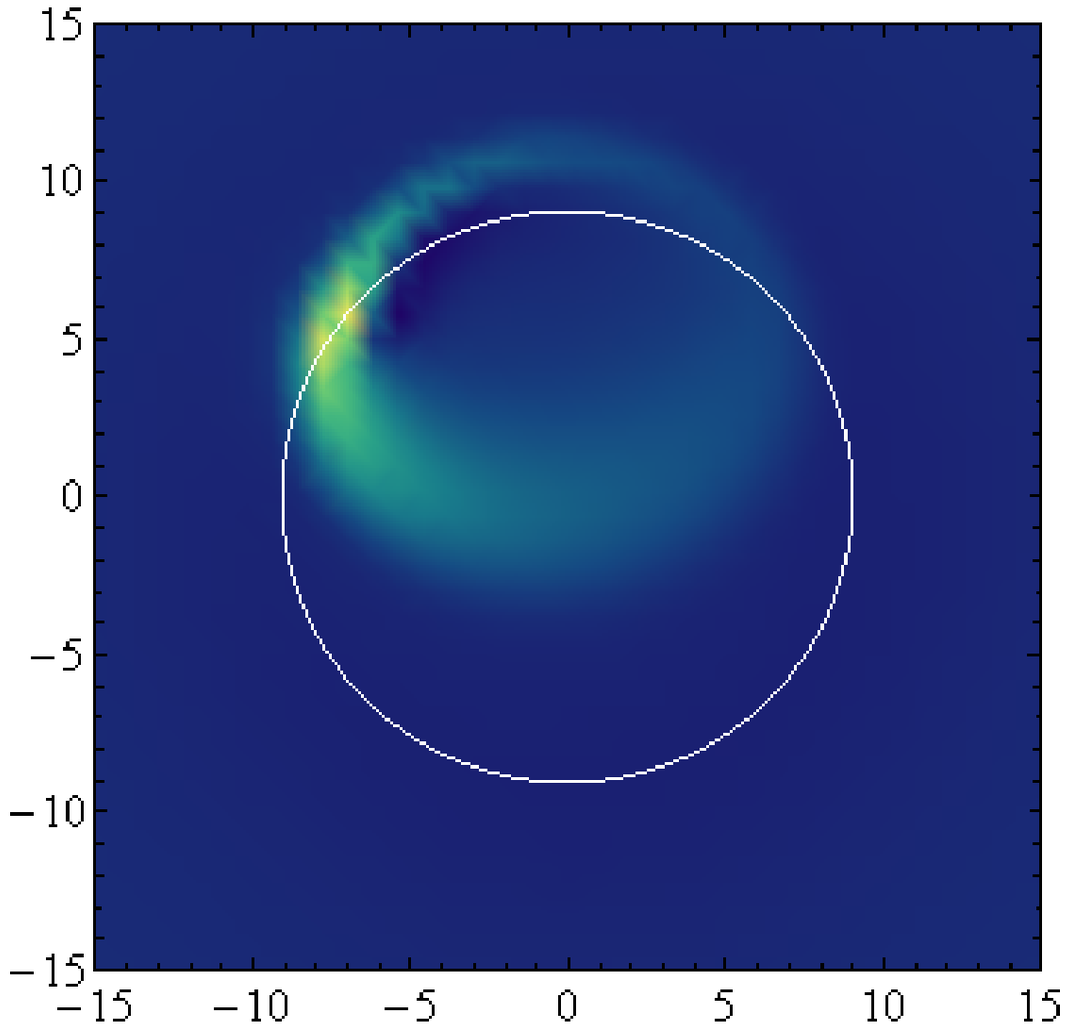


FIG. 7: Temperature perturbation (arbitrary scale) of the temperature in the transverse plane (x,y) (in fm), induced by a jet generated at the point (0,3) and stopped at the point (-5,3).

nonzero impact parameter of a jet and a **“side wind” effect** produce highly separated displaced intersections with the rim

The pictures sliced in rapidity

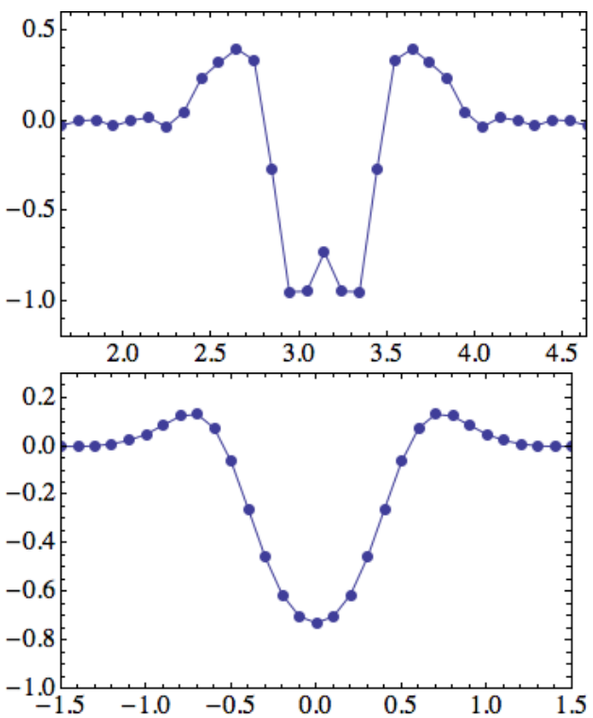


FIG. 10: Distribution over ϕ at $\eta = 0$ (upper plot) and η at $\phi = \pi$ (lower plot), projected on the fireball rim $r = 9.1\, fm$. The same case as in the previous Fig.9 .

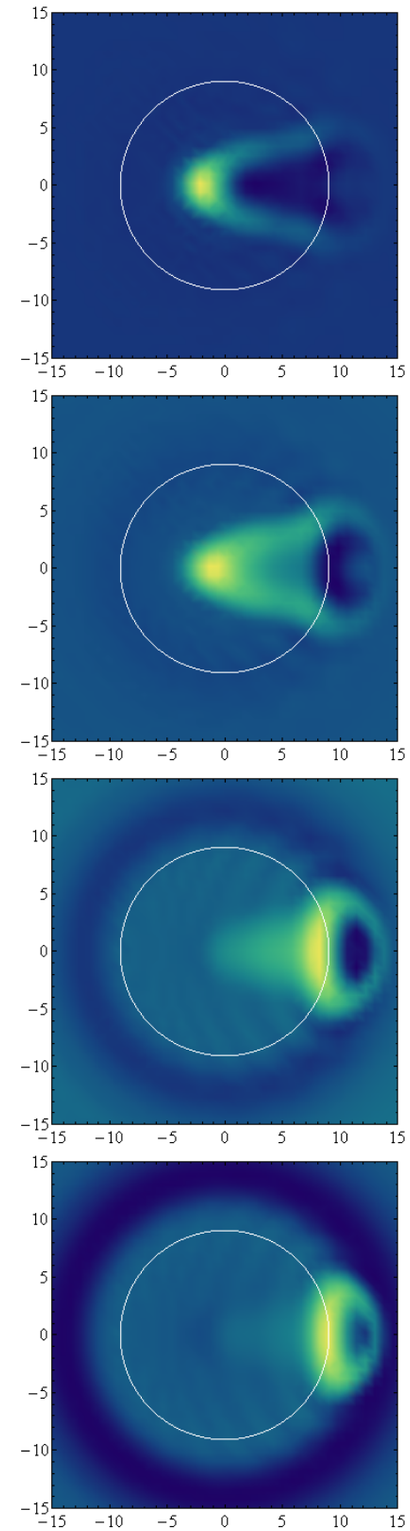


FIG. 8: Perturbation (arbitrary scale) of the temperature in the transverse plane (x,y) (in fm), induced by a jet generated at the point (6.1,0): the same case as in Fig.4 but with the η variable included. Four pictures, top to bottom, are for $\eta = 0, 0.4, 0.8$ and 1 .

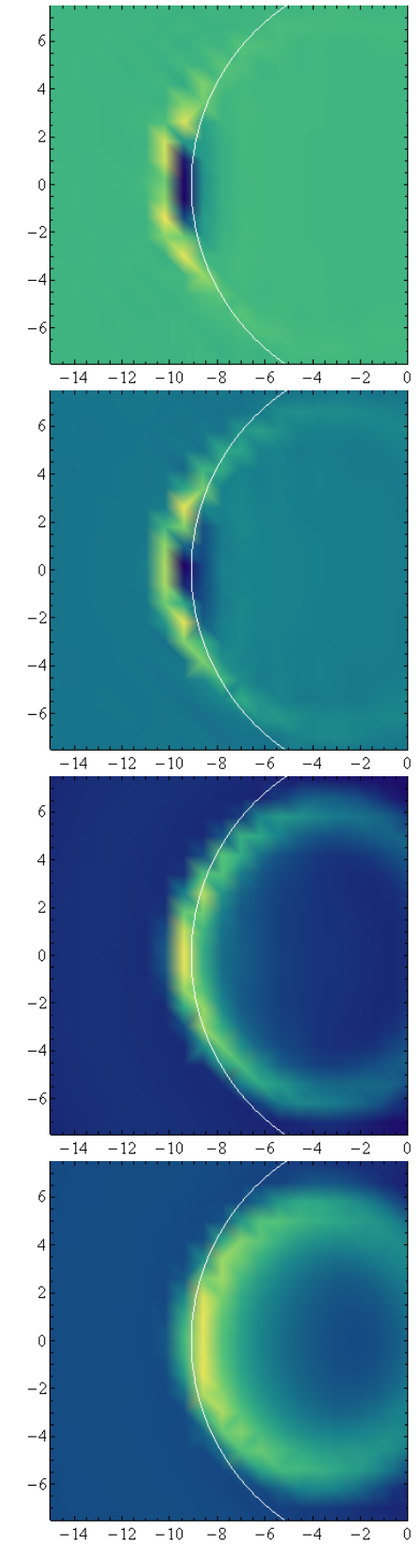
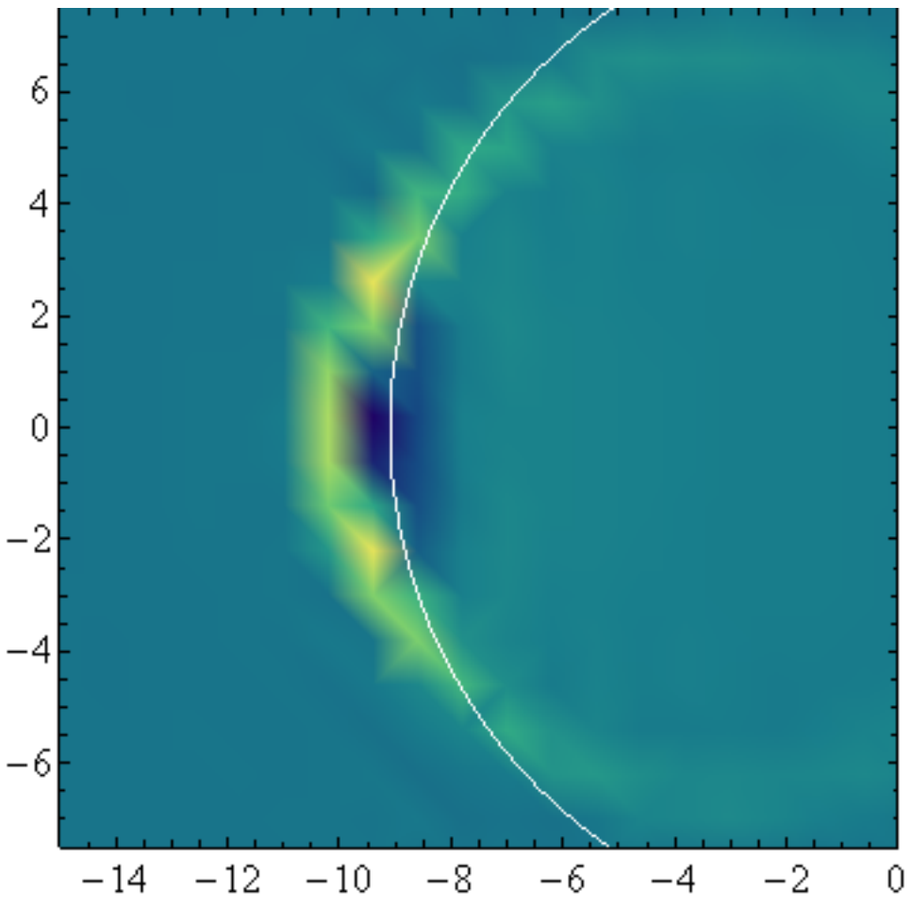


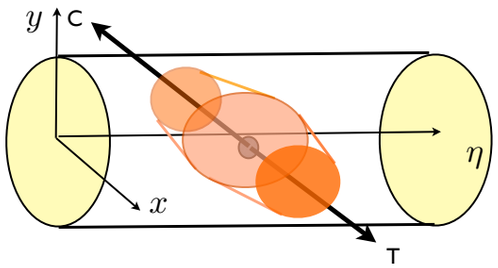
FIG. 9: Perturbation (arbitrary scale) of the temperature in the transverse plane (x,y) (in fm), induced by a jet generated at the point (-2,0) and stopped near the fireball edge. Four pictures, top to bottom, are for $\eta = 0, 0.4, 0.8$ and 1 .

typical punch-through



The jet exiting from the fireball spacelike side perturbs **the fireball's rim** (white circle) in an elliptic curve of width 1/2-1 rad (depending on the time left till freezeout) matter outside it is not affected

Large energy deposition create two **distinct "sub-events"**



At deposited $E_\perp \sim 100$ GeV the number of extra secodaries is about Nextra ~ 200, to be compared to $dN/d\eta \sim 2400$.

The multiplcity increase is about 8%. Since multiplicity scales as T^3, the increase of the temperature (if homogeneous) is about

$\delta T/T \sim 2.7\%$. increasing the freezeout radius by the square root of it, or 4% in our example. The Hubble law of expansion then tell us that it will increase flow velocity linearly with r, or also by 4%.

The boost exponent however can easily increase the contrast to be as large as 100%, for example

$$exp[(\frac{p_\perp u_t}{T_f})\frac{\delta u_t}{u_t}] \sim exp(20 * 0.04) \sim 2.2$$

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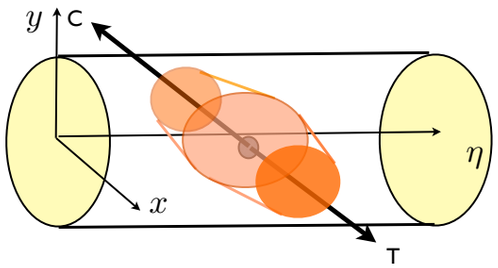

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Another effect stems from the fact that jets deposit not only energy but also equal amount of momentum, which does not get lost by rescatterings. If e.g. it is fully equilibrated, meaning that that matter inside the affected "tube" gets extra directed flow velocity

$$\delta v = \frac{P}{M} \sim 0.1 \qquad (14)$$

where we used $P \sim 100\,GeV$ and the total mass of the affected matter $M \sim 1\,TeV$. This directed flow velocity is to be added to the extra radial flow estimated above. (Unlike enhanced radial flow directed radially outward, this δv is directed along the jet.)

Can this effect be so strong as to be seen even on event-by-event basis?

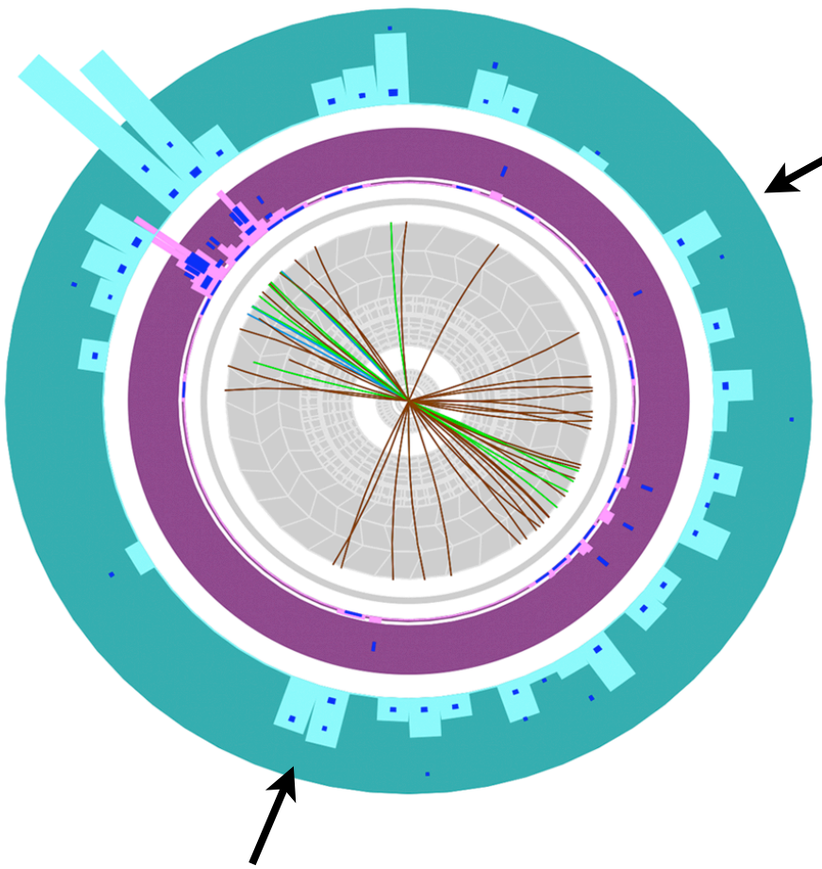

FIG. 11: (color online) Azimuthal distribution of the transverse energy in one event from [21] , the inner part shows tracks with $p_\perp > 2.6\,GeV$, the intermediate (pink) histogram is the electromagnetic calorimeter energy with $E_t > 0.7\,GeV$ threshold, and the outer (blue) histogram is the hadronic calorimeter energy distribution, with thresholds $E > 1\,GeV$ per cell.

The density of the tracks and blue histogramm between two arrows (+- 1 rad, presumably the jet edges) is **higher than outside**

I suggest event-by-event fits of the density-in-a-cone

summary

- strong radial flow makes a very high contrast image of the fireball's rim at pt=2-4 GeV
- quenching jets produce perturbations at the "sound surface"
- **intersection of the two** produces "the jet edge". Geometry variations are large but typically it is +- 1 rad in phi-eta around a jet.
- if energy/momentum deposition is large, the whole interior of the sound surface is affected => new sub-event with different flow. Perhaps can be seen on event-by event basis: if so, a new tool to get jet geometry in each event