34th International Nuclear Physics School, Erice 2012

Sounds of the Big and Little Bangs

Edward Shuryak
(Stony Brook)

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we need to learn how to use
the **sonogram** of the fireball,
as sound is the only propagating mode...

Outline

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- Fluctuations and higher harmonics, in Big and Little Bang

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- Multiparticle correlators, nonlinearities, coherence, number of sources

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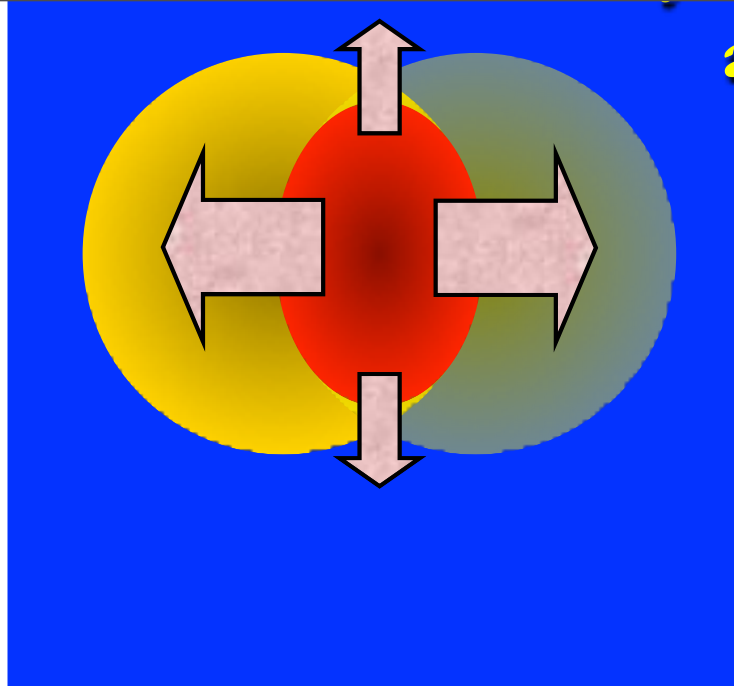
- Multiparticle correlators, nonlinearities, coherence, number of sources
- sounds/shocks generated by Rayleigh collapse of the QGP bubbles at the end of ``mixed phase'' (Is there enough time till freezout? looks like we have a signal)
- shocks and sounds generated by jets **(Do we see a Mach cone now? yes)**



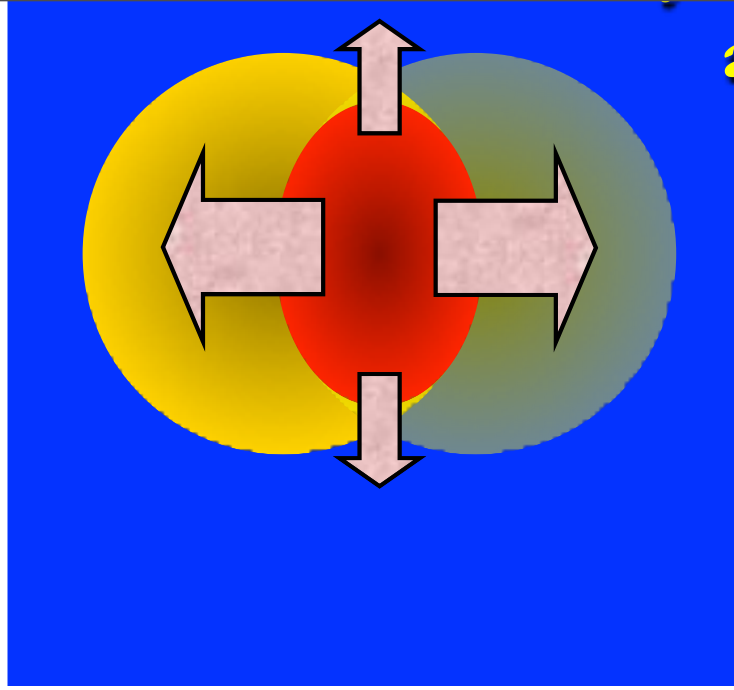
Viewpoint

A "Little Bang" arrives at the LHC

Edward Shuryak
Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA

Published December 13, 2010

1% of PRL's get a special treatment



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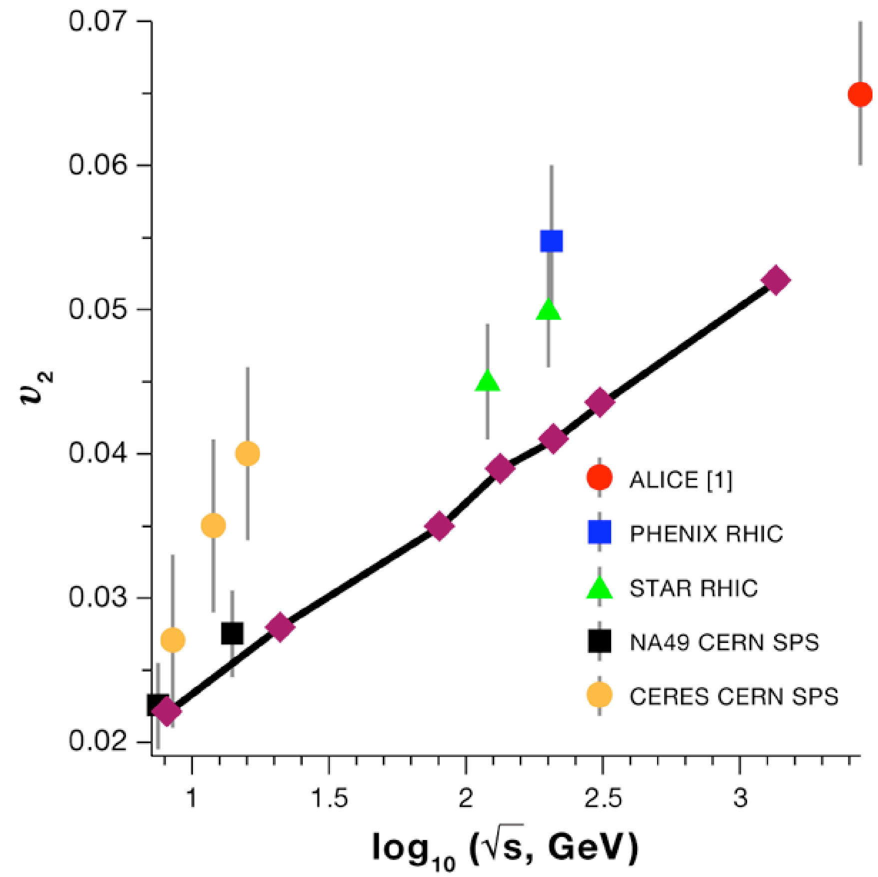
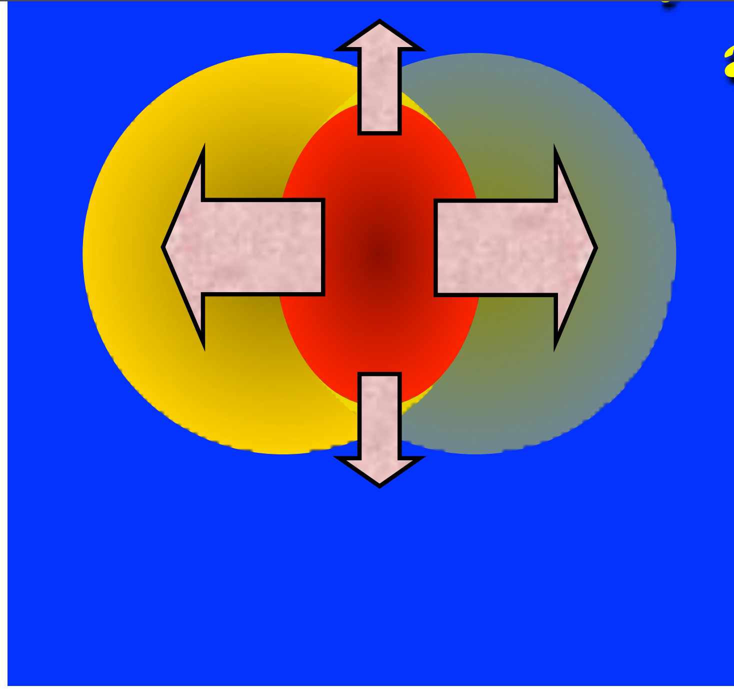


FIG. 1: The ALICE experiment suggests that the quark-gluon plasma remains a strongly coupled liquid, even at temperatures that are 30% greater than what was available at RHIC. The plot shows the "elliptic flow parameter" v_2 (a measure of the coupling in the plasma) at different heavy-ion collision energies, based on several experiments (including the new data from ALICE [1]). (Note the energy scale is plotted on a logarithmic scale and spans three orders of magnitude.) The trend is consistent with theoretical predictions (pink diamonds) for an ideal liquid [4].



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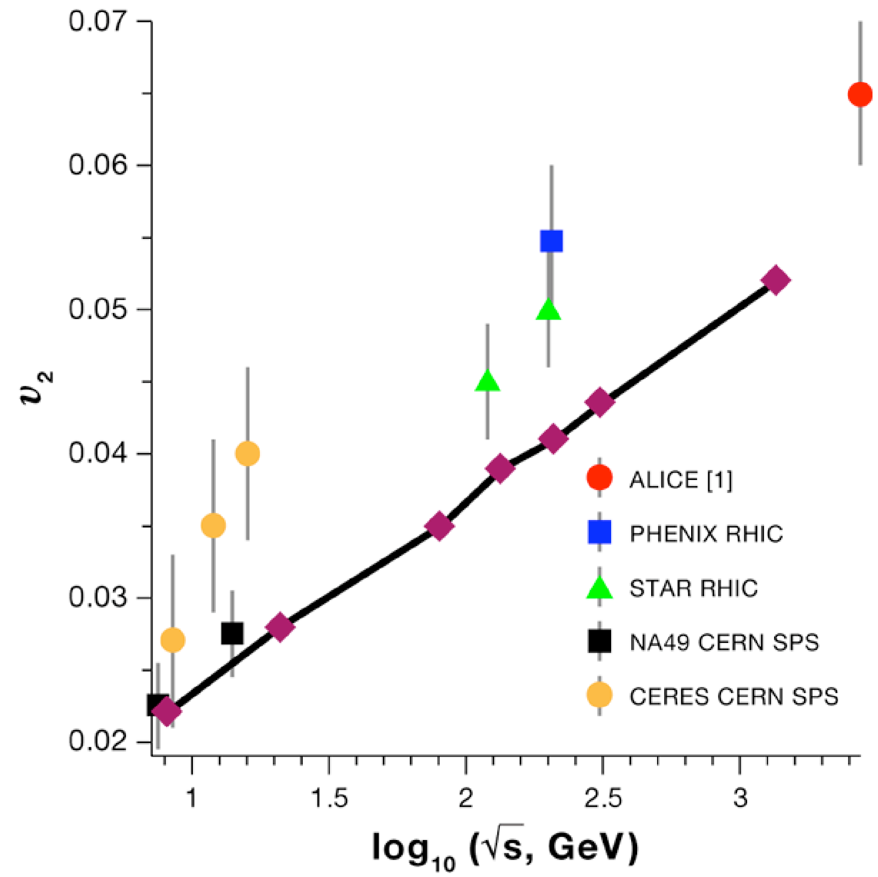

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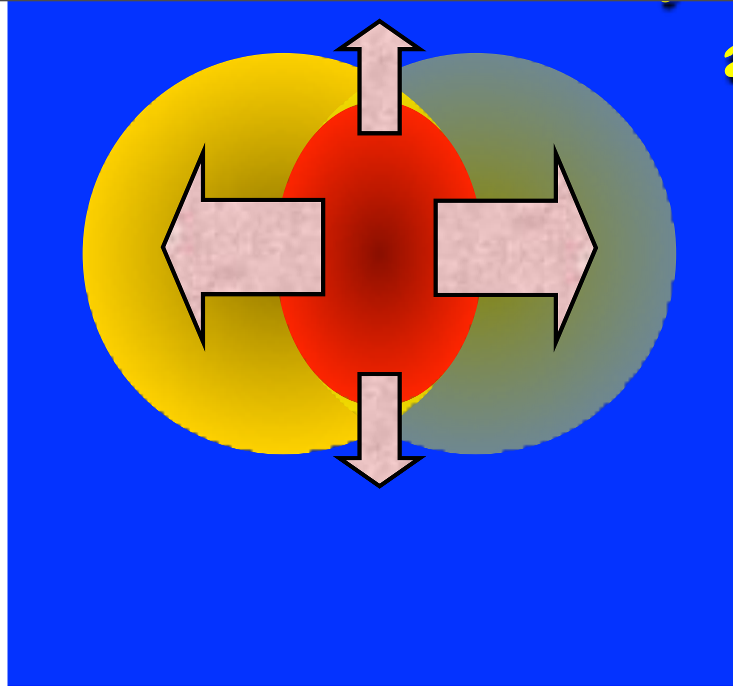
look at the slope,
the points and curve
do not match because of
somewhat different centrality



it works at LHC perfectly!

look at the slope,
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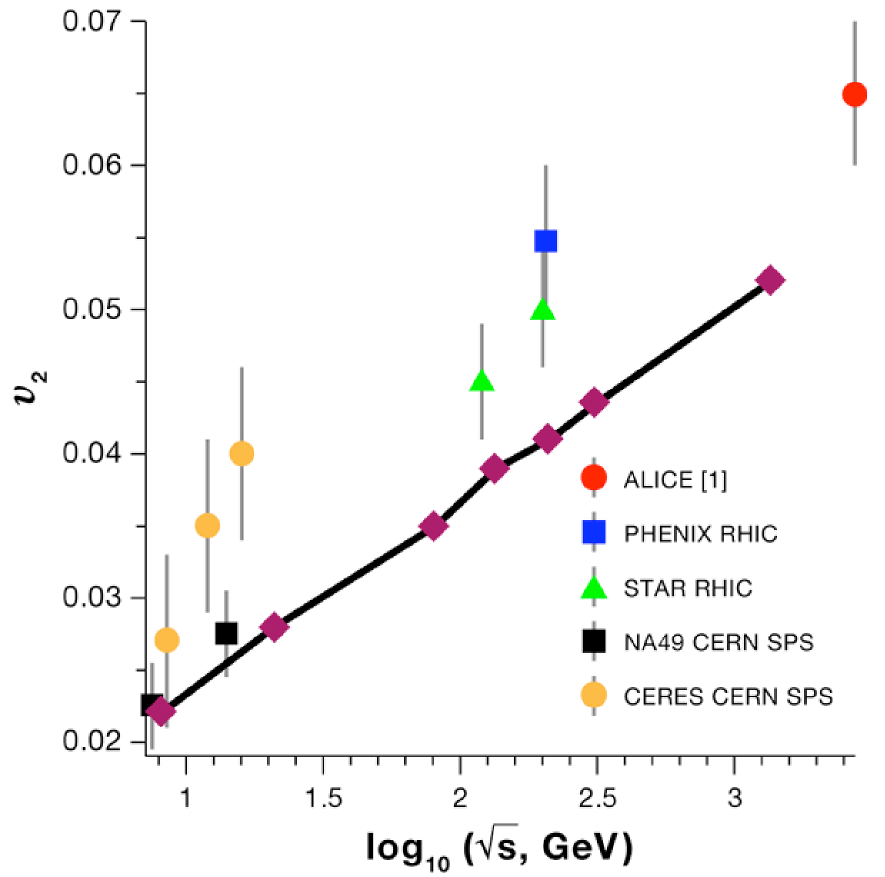

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Two fundamental scales, describing perturbations **at freezeout**

(P.Staig,ES,2010)

1. The sound horizon: radius of about 6fm

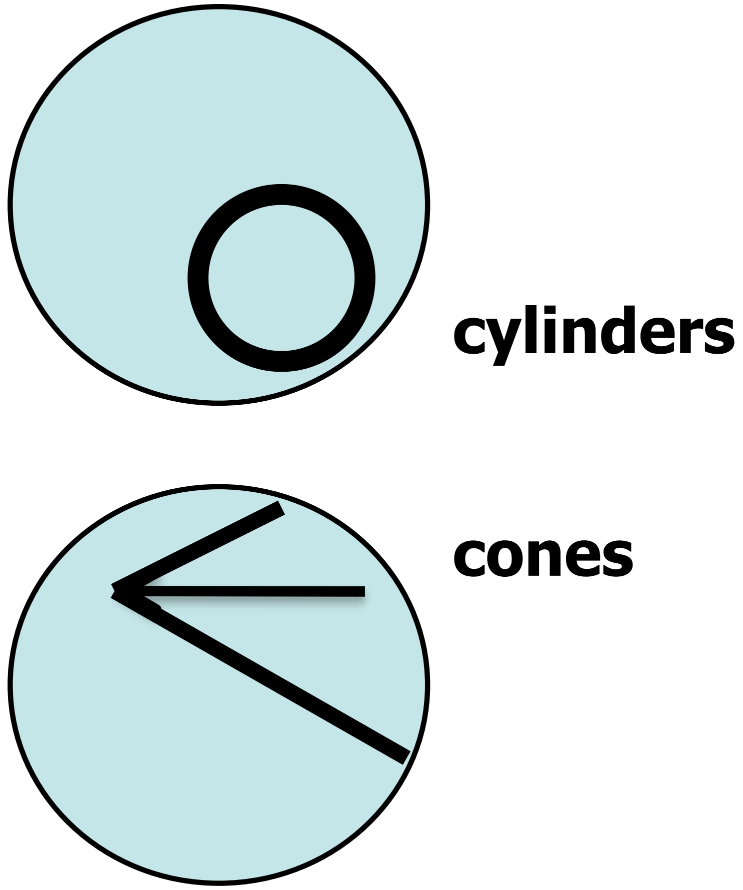
$$H_s = \int_0^{\tau_f} d\tau c_s(\tau)$$

For the Big Bang it is about 150 Mps

2.The viscous horizon: The width of the circle

$$\delta T_{\mu\nu}(t) = exp\left(-\frac{2}{3}\frac{\eta}{s}\frac{k^2 t}{3T}\right)\delta T_{\mu\nu}(0)$$

$$k_v = \frac{2\pi}{R_v} = \sqrt{\frac{3Ts}{2\tau_f\eta}} \sim 200MeV$$



Perturbations of the Big and the Little Bangs

Frozen sound (from the era long gone) is seen on the sky, both in CMB and in distribution of Galaxies

$$\frac{\Delta T}{T} \sim 10^{-5}$$

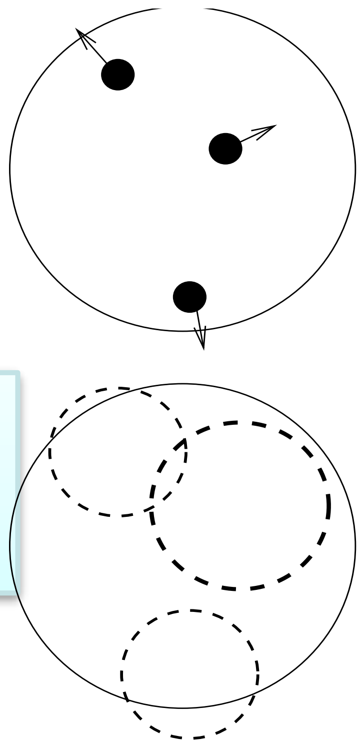
$$l_{maximum} \approx 210$$

$$\delta\phi \sim 2\pi/l_{maximum} \sim 1^o$$

They are remnants of the sound circles on the sky, around the primordial density perturbations
Freezeout time O(100000) years

Initial state fluctuations
in the positions of participant nucleons
lead to perturbations of the Little Bang also

$$\frac{\Delta T}{T} \sim 10^{-2}$$



Freezeout time about 12 fm/c
Radius of the circle about 6 fm,
Comparable to the fireball size

PHYSICAL REVIEW C **80**, 054908 (2009)

Fate of the initial state perturbations in heavy ion collisions

Edward Shuryak
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(Received 20 July 2009; revised manuscript received 14 October 2009; published 13 November 2009)

the sound horizon scale is seen both in microwave radiation and in galaxy distribution

Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP[1]) Observations: Sky Maps, Systematic Errors, and Basic Results

N. Jarosik[2], C. L. Bennett[3], J. Dunkley[4], B. Gold[3], M. R. Greason[5], M. Halpern[6], R. S. Hill[5], G. Hinshaw[7], A. Kogut[7], E. Komatsu[8], D. Larson[3], M. Limon[9], S. S. Meyer[10], M. R. Nolta[11], N. Odegard[5], L. Page[2], K. M. Smith[12], D. N. Spergel[12,13], G. S. Tucker[14], J. L. Weiland[5], E. Wollack[7], E. L. Wright[15]

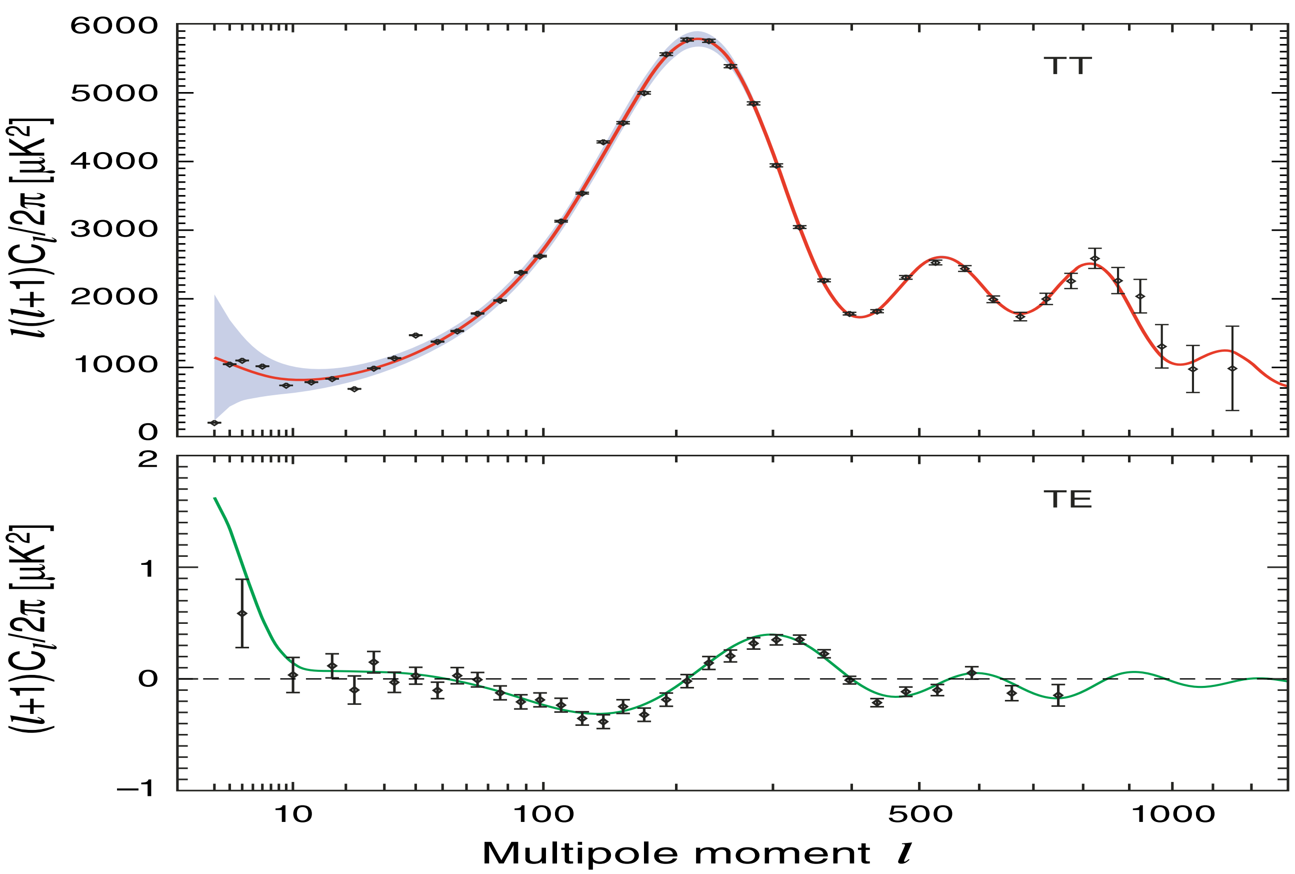

Fig. 9.— The temperature (TT) and temperature-polarization(TE) power spectra for the seven-year *WMAP* data set. The solid lines show the predicted spectrum for the best-fit flat ΛCDM model. The error bars on the data points represent measurement errors while the shaded region indicates the uncertainty in the model spectrum arising from cosmic variance.

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Seven-Year Wilkinsor

Sky Maps, Sys

N. Jarosik[2], C. L. Bennett[3], J.
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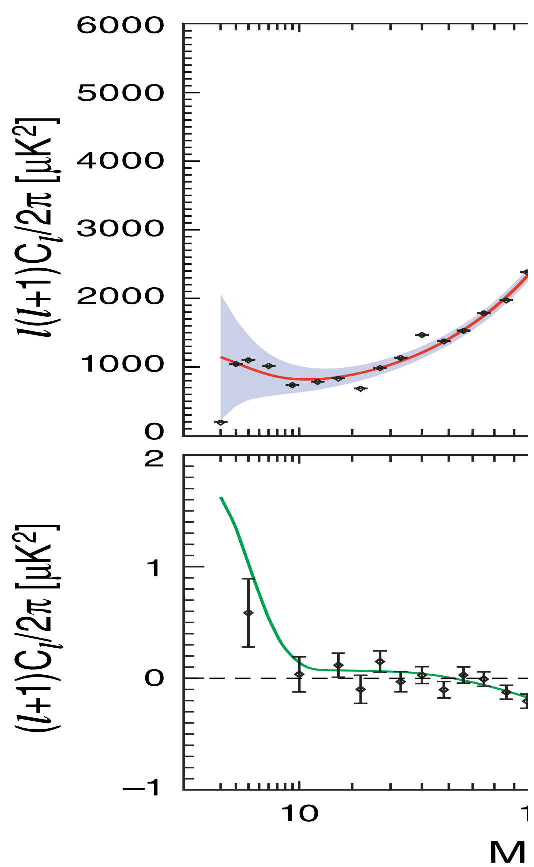

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DETECTION OF THE BARYON ACOUSTIC PEAK IN THE LARGE-SCALE CORRELATION FUNCTION OF SDSS LUMINOUS RED GALAXIES

Daniel J. Eisenstein[1,2], Idit Zehavi[1], David W. Hogg[3], Roman Scoccimarro[3], Michael R. Blanton[3], Robert C. Nichol[4], Ryan Scranton[5], Hee-Jong Seo[1], Max Tegmark[6,7], Zheng Zheng[8], Scott F. Anderson[9], Jim Annis[10], Neta Bahcall[11], Jon Brinkmann[12], Scott Burles[7], Francisco J. Castander[13], Andrew Connolly[5], Istvan Csabai[14], Mamoru Doi[15], Masataka Fukugita[16], Joshua A. Frieman[10,17], Karl Glazebrook[18], James E. Gunn[11], John S. Hendry[10], Gregory Hennessy[19], Zeljko Ivezić[9], Stephen Kent[10], Gillian R. Knapp[11], Huan Lin[10], Yeong-Shang Loh[20], Robert H. Lupton[11], Bruce Margon[21], Timothy A. McKay[22], Avery Meiksin[23], Jeffery A. Munn[19], Adrian Pope[18], Michael W. Richmond[24], David Schlegel[25], Donald P. Schneider[26], Kazuhiro Shimasaku[27], Christopher Stoughton[10], Michael A. Strauss[11], Mark SubbaRao[17,28], Alexander S. Szalay[18], István Szapudi[29], Douglas L. Tucker[10], Brian Yanny[10], & Donald G. York[17]

Submitted to The Astrophysical Journal 12/31/2004

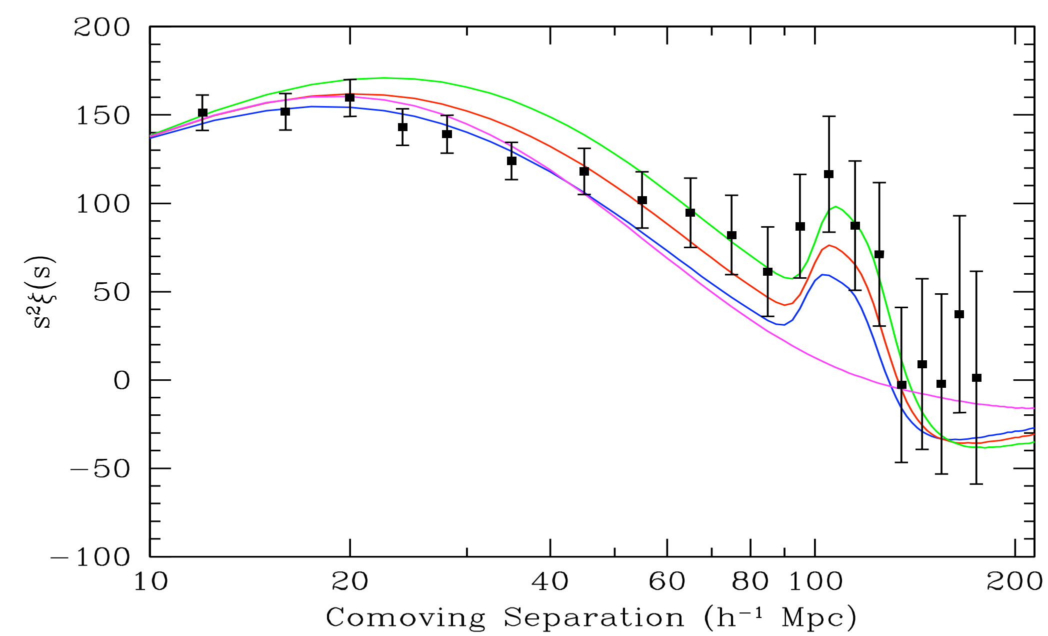
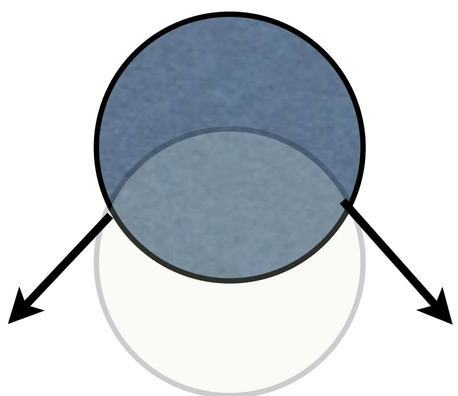


Fig. 3.— As Figure 2, but plotting the correlation function times s^2. This shows the variation of the peak at $20h^{-1}$ Mpc scales that is controlled by the redshift of equality (and hence by $\Omega_m h^2$). Varying $\Omega_m h^2$ alters the amount of large-to-small scale correlation, but boosting the large-scale correlations too much causes an inconsistency at $30h^{-1}$ Mpc. The pure CDM model (magenta) is actually close to the best-fit due to the data points on intermediate scales.

Radial flow enhances the fireball surface: spectra are blue shifted toward detection with v about 0.8 c
So we should see two “horns”

The peaks are at the same angles +- 1 rad (as I got) relative to the perturbation angle, but **+-2 rad in correlations**

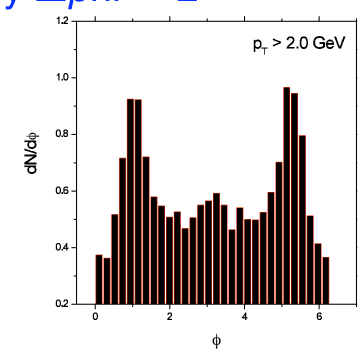


sound horizon

$t_f\, c_s$ =6 fm

One tube model

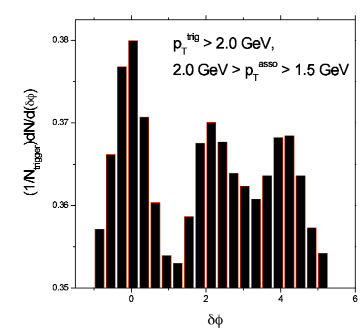
MAIN RESULT: single particle angular distribution has TWO PEAKS separated by $\Delta phi \sim 2$



Pictures due to F.Grassi et al

CONSEQUENCE: two particle angular distribution has three peaks

Correlators and statistics:
10^9 events
10^6 pairs/event



It is like correlating Two waves in US and Chili to observe tsunami In Japan

S.Gubser, arXiv:1006.0006

found nice solution for nonlinear relativistic axially symmetric explosion of conformal matter

Working in the (τ, η, r, ϕ) coordinates with the metric

$$ds^2 = -d\tau^2 + \tau^2 d\eta^2 + dr^2 + r^2 d\phi^2, \qquad (3.2)$$

and assuming no dependence on the rapidity η and azimuthal angle ϕ, the 4-velocity can be parameterized by only one function

$$u_\mu = (-\cosh\kappa(\tau, r), 0, \sinh\kappa(\tau, r), 0) \qquad (3.3)$$

Omitting the details from [14], the solution for the velocity and the energy density is

$$v_\perp = \tanh\kappa(\tau, r) = \left(\frac{2q^2\tau r}{1 + q^2\tau^2 + q^2 r^2}\right) \qquad (3.4)$$

$$\epsilon = \frac{\hat{\epsilon}_0 (2q)^{8/3}}{\tau^{4/3}\left(1 + 2q^2(\tau^2 + r^2) + q^4(\tau^2 - r^2)^2\right)^{4/3}} \qquad (3.5)$$

Kappa is the transverse rapidity

q is a parameter fixing the overall size

Comoving coordinates with Gubser flow:

Gubser and Yarom, arXiv:1012.1314

$$\delta = \delta T/T$$

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

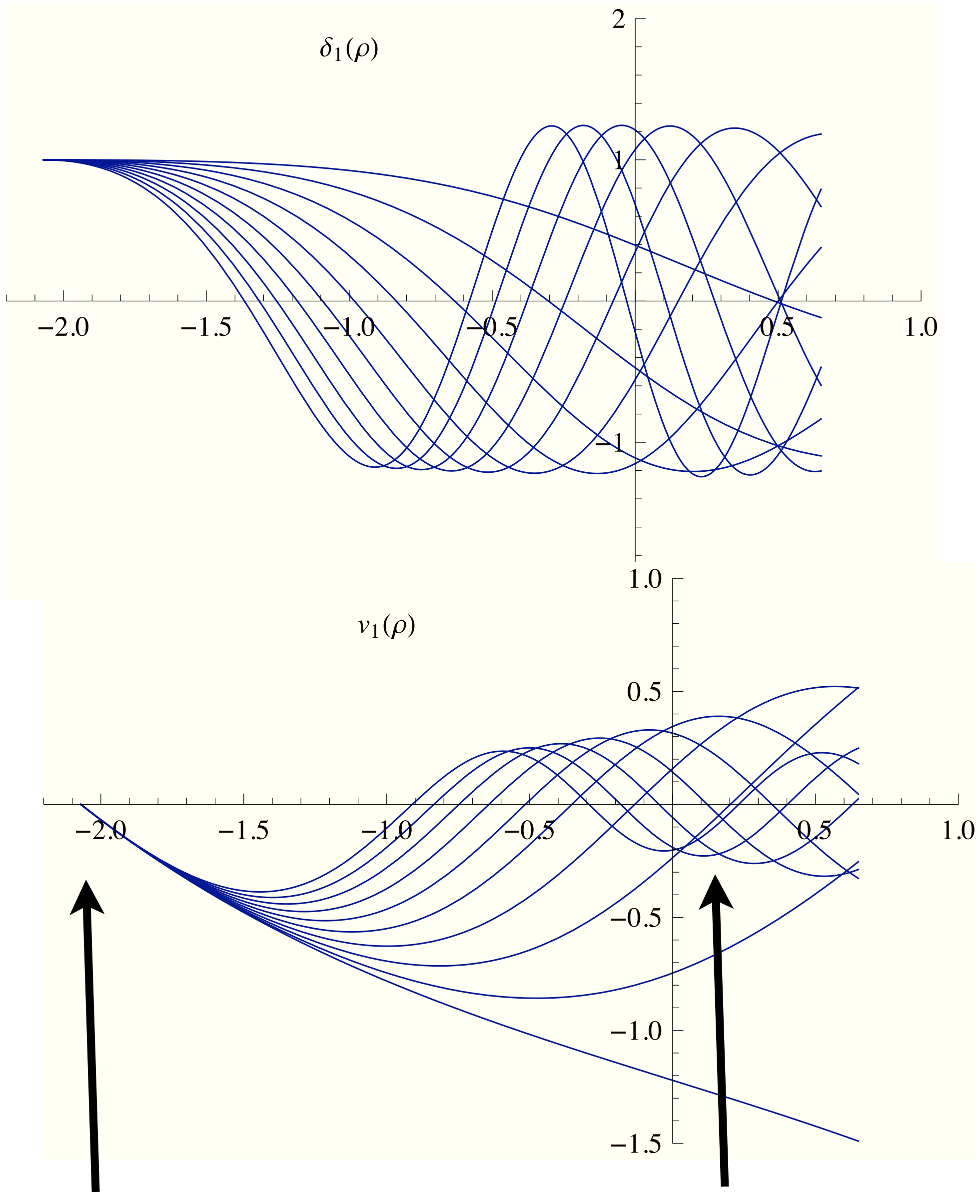
$$\frac{\partial^2\delta}{\partial\rho^2} - \frac{1}{3\cosh^2\rho}\left(\frac{\partial^2\delta}{\partial\theta^2} + \frac{1}{\tan\theta}\frac{\partial\delta}{\partial\theta} + \frac{1}{\sin^2\theta}\frac{\partial^2\delta}{\partial\phi^2}\right) + \frac{4}{3}\tanh\rho\frac{\partial\delta}{\partial\rho}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

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

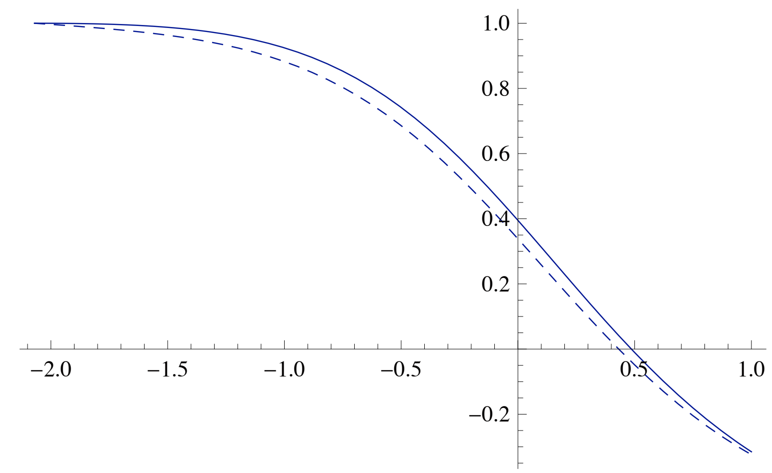
$$\begin{aligned} R(\rho) &= \frac{C_1 P^{2/3}_{-\frac{1}{2}+\frac{1}{6}\sqrt{12\lambda+1}}(\tanh\rho) + C_2 Q^{2/3}_{-\frac{1}{2}+\frac{1}{6}\sqrt{12\lambda+1}}(\tanh\rho)}{(\cosh\rho)^{2/3}} \\ \Theta(\theta) &= C_3 P_l^m(\cos\theta) + C_4 Q_l^m(\cos\theta) \\ \Phi(\phi) &= C_5 e^{im\phi} + C_6 e^{-im\phi}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

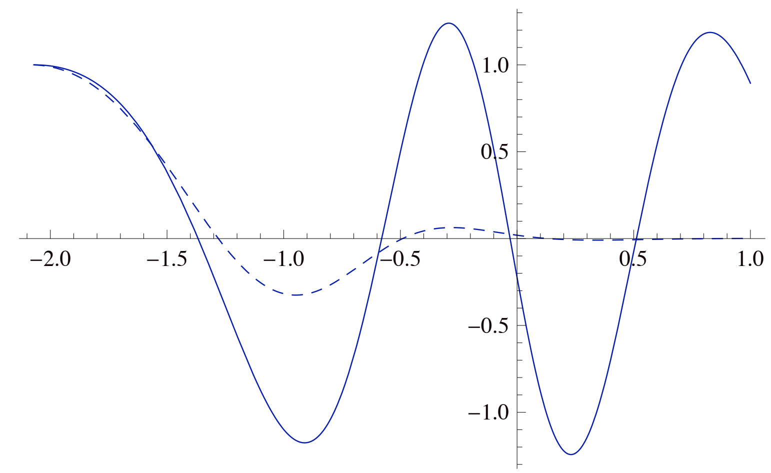
where $\lambda = l(l+1)$ and P and Q are associated Legendre polynomials. The part of the solution depending on θ and ϕ can be combined in order to form spherical harmonics $Y_{lm}(\theta,\phi)$, such that $\delta(\rho,\theta,\phi) \propto R_l(\rho)Y_{lm}(\theta,\phi)$.

harmonics l=1..10, Temperature perturbation and velocity

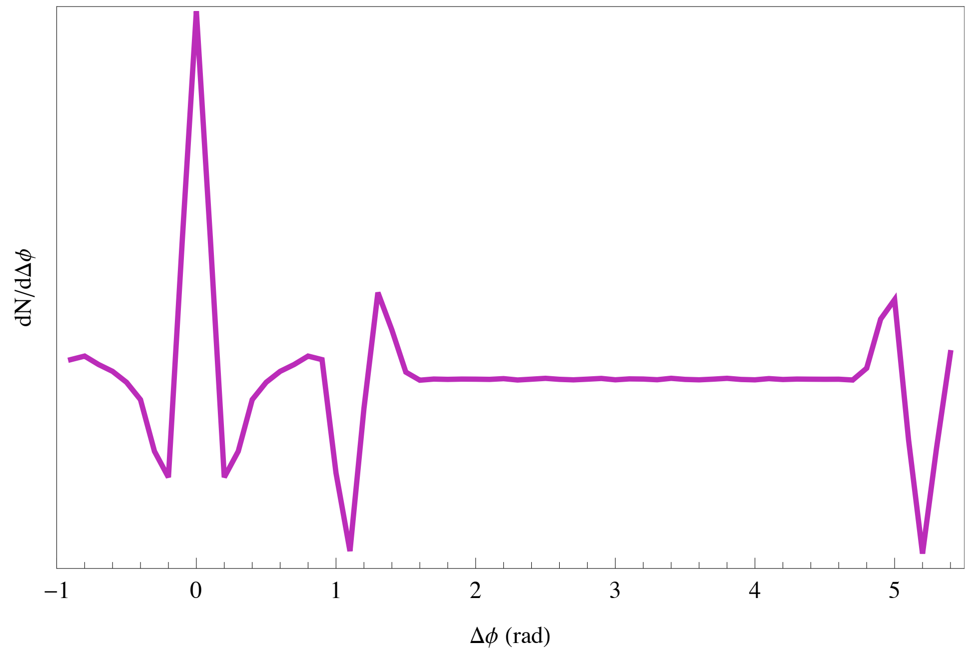


lhs (rho=-2) is initiation time and FO time is around zero



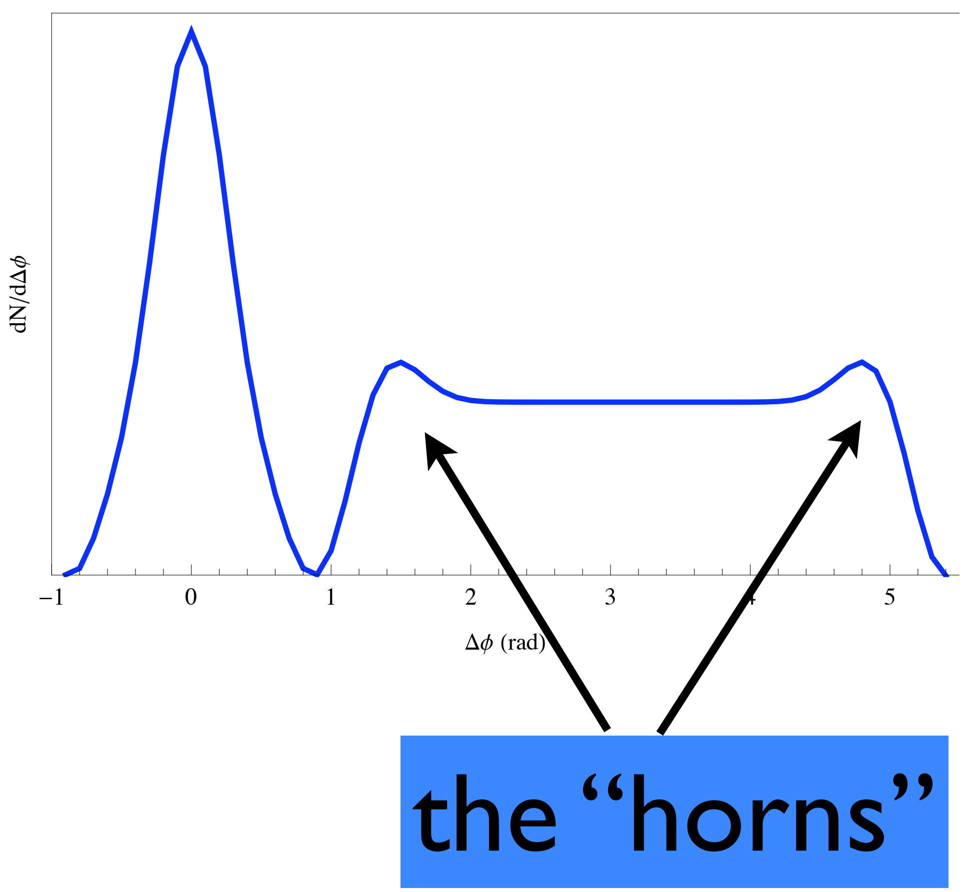


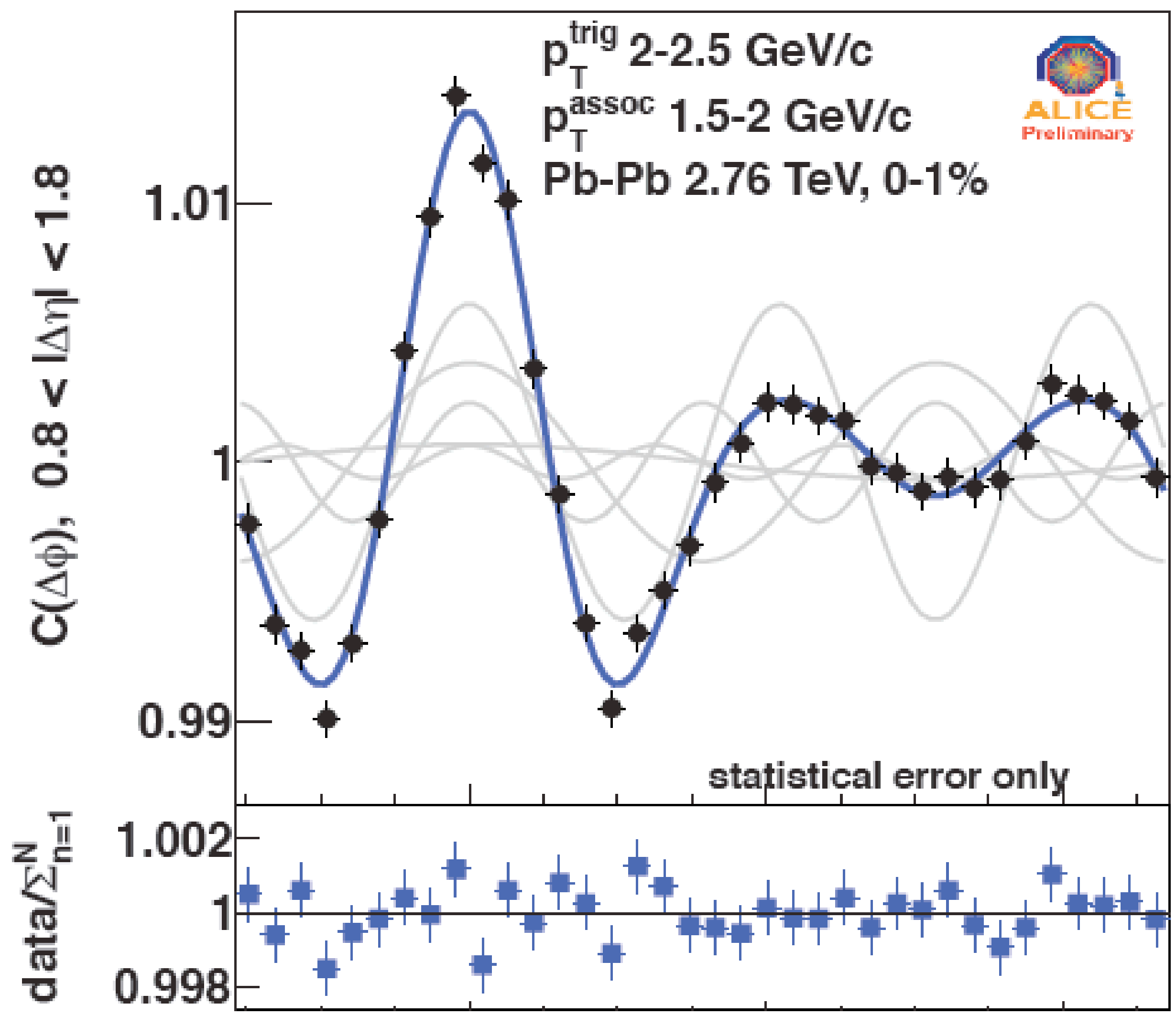
Viscosity (dashed) hardly affect The 1st harmonic, but nearly kills the 10th!



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

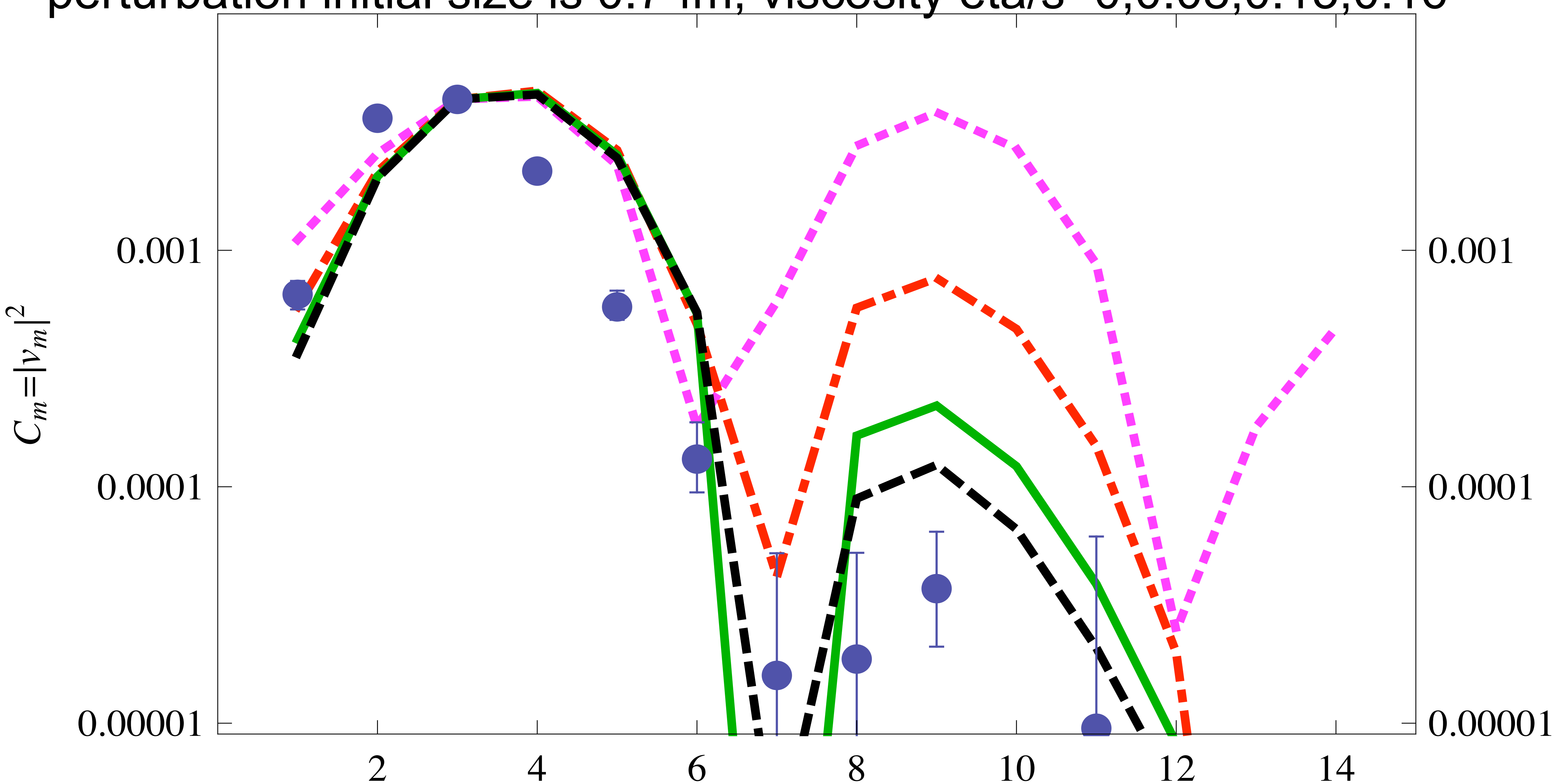
ALICE central 1% correlators
Note shape agreement
No parameters, just Green
Function from a delta function





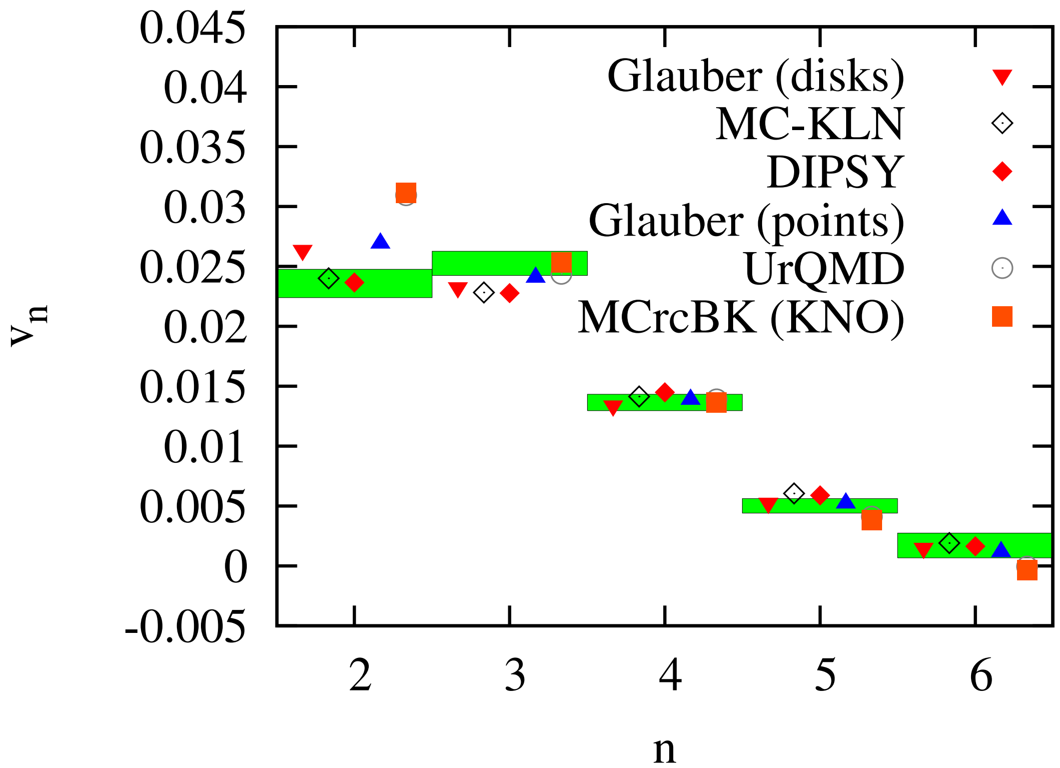
The power spectrum is very sensitive to viscosity, and it has acoustic minima/ maxima (at m=7,12 and m=9)

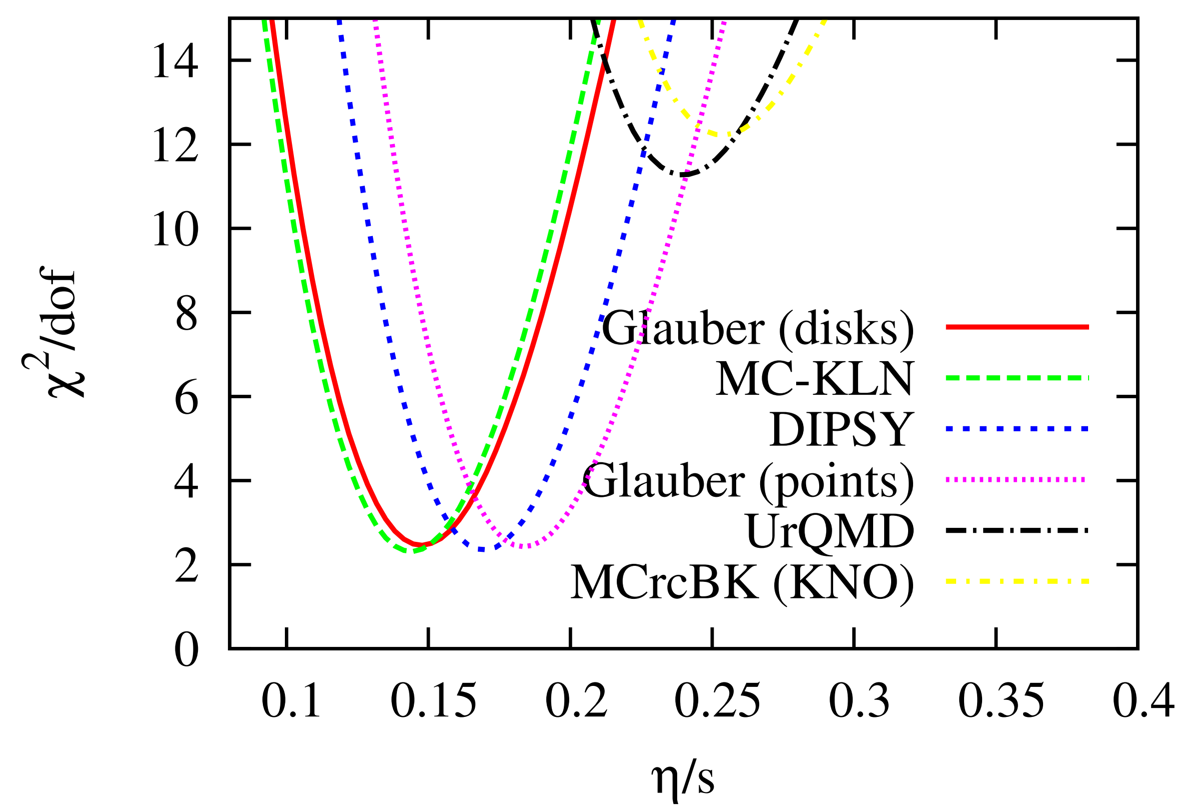
perturbation initial size is 0.7 fm, viscosity eta/s=0,0.08,0.13,0.16



The summary of e-by-e hydro:

Luzum: QM2012





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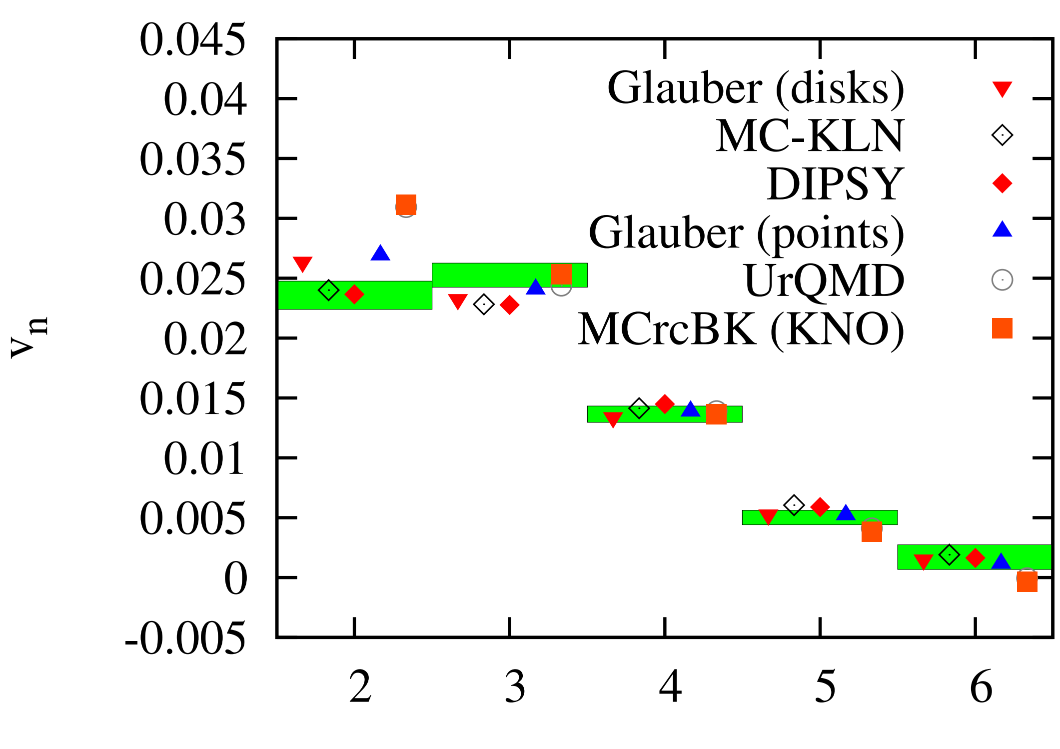
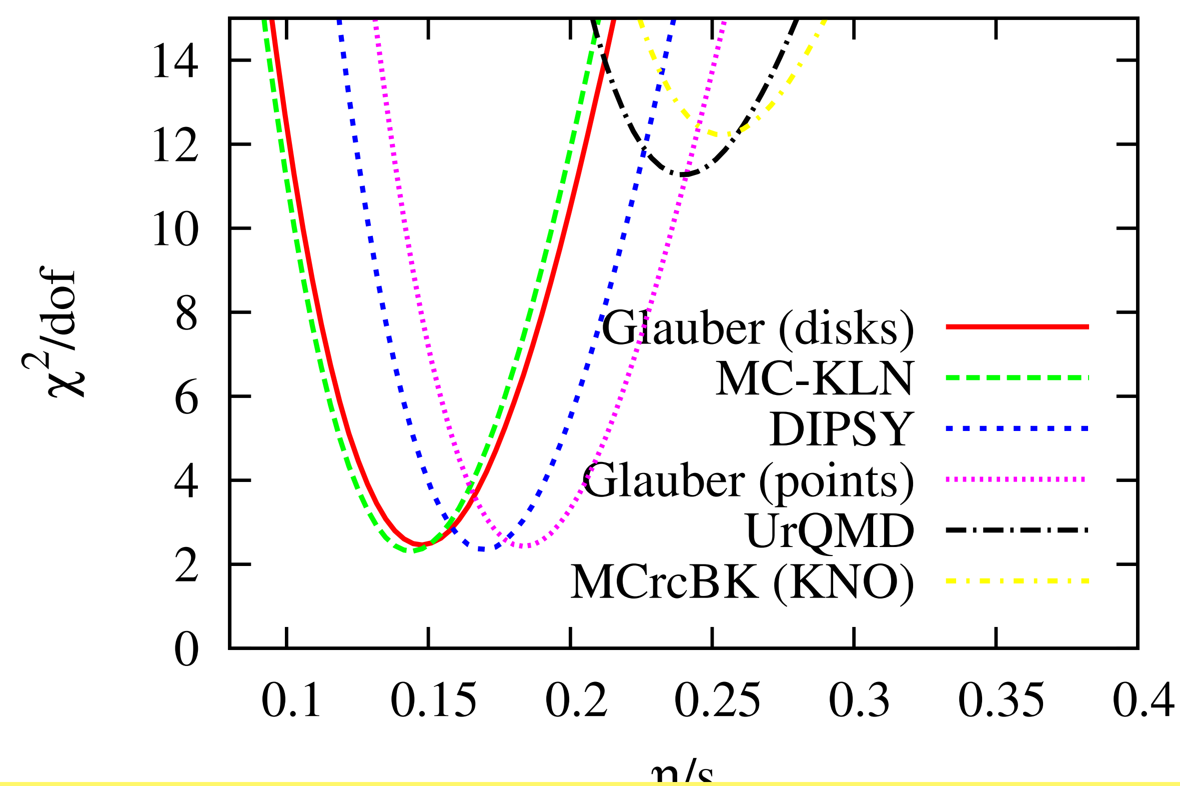




note that eta/s fit 0.15 is the same as we got a year ago

none of the models produce correct shape of the angular correlator, no peak at the 3ed harmonic

all of those are sum of many O(10) sources => small perturbations, e-by-e hydro hardly justified

So what? Why is hydro's success for the Little Bang so 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 still have 10^20 molecules...**

- **Little Bang has about 10^3 particles (per unit rapidity) or 10 of them per dimension. So the first application of hydro was surprising: only astonishingly small viscosity saved it...**

- **And now we speak about the 10th harmonics! How a volume cell with O(1) particles can act as a liquid?**

coherence and nonlinearities

Many-particle correlations reveal phases!

- 2-body correlation function gives $|v_n|^2$,so no phase information
- k-body terms are preserved in averaging provided a **resonance condition** is fulfilled with some integers n_i

$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum v_n exp(in\phi - in\Psi_n) + cc$$

in an event

$$\sum_{i=1}^{k} n_i = 0$$

$$<< cos(\sum_{i=1}^{k} n_i \phi_i) >>=$$

k particles, all events

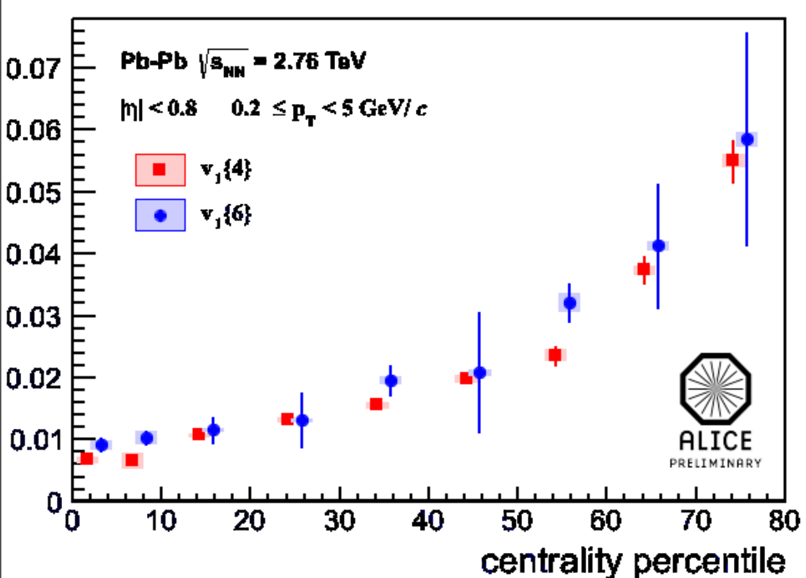
$$< v_1..v_k cos(\sum_{i=1}^{k} n_i \Psi_{n_i}) >$$

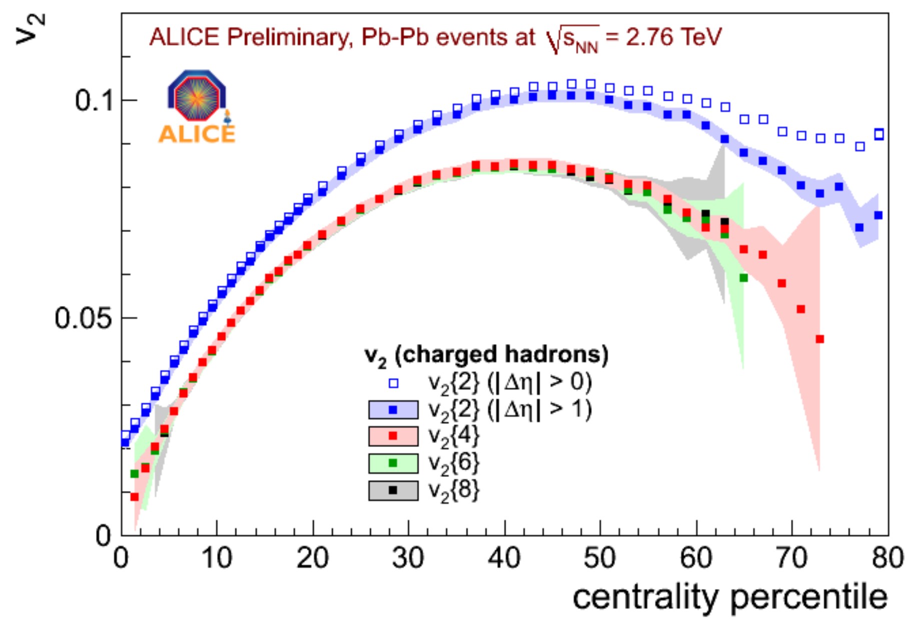
events

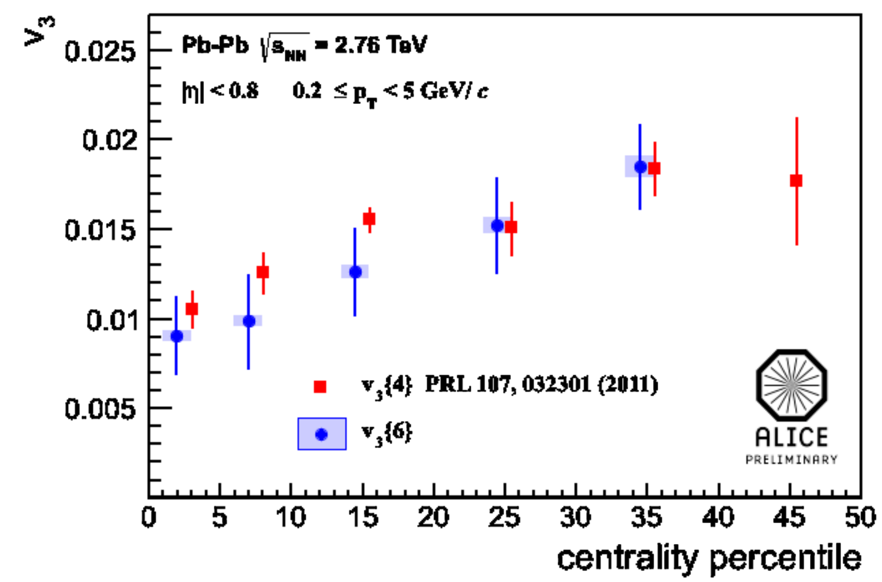
P.Staig, ES arXiv:1008.3139
Bhalerao, Luzum, Ollitrault PRC 84 034910 (2011)
Teaney, Yan PRC 83, 064904 (2011)

non-central collisions (ALICE data,QM12)

v_n(b) and 1+2=3 and some 5-particle examples







Out of these 3 ingredients
one can make many combinations
Even v2 is small, and it has a
characteristic b-dependence

$$v_1, v_3 \sim 0.01;$$
$$v_2 \sim 0.1$$

nonlinearity at large pt from Cooper-Fry

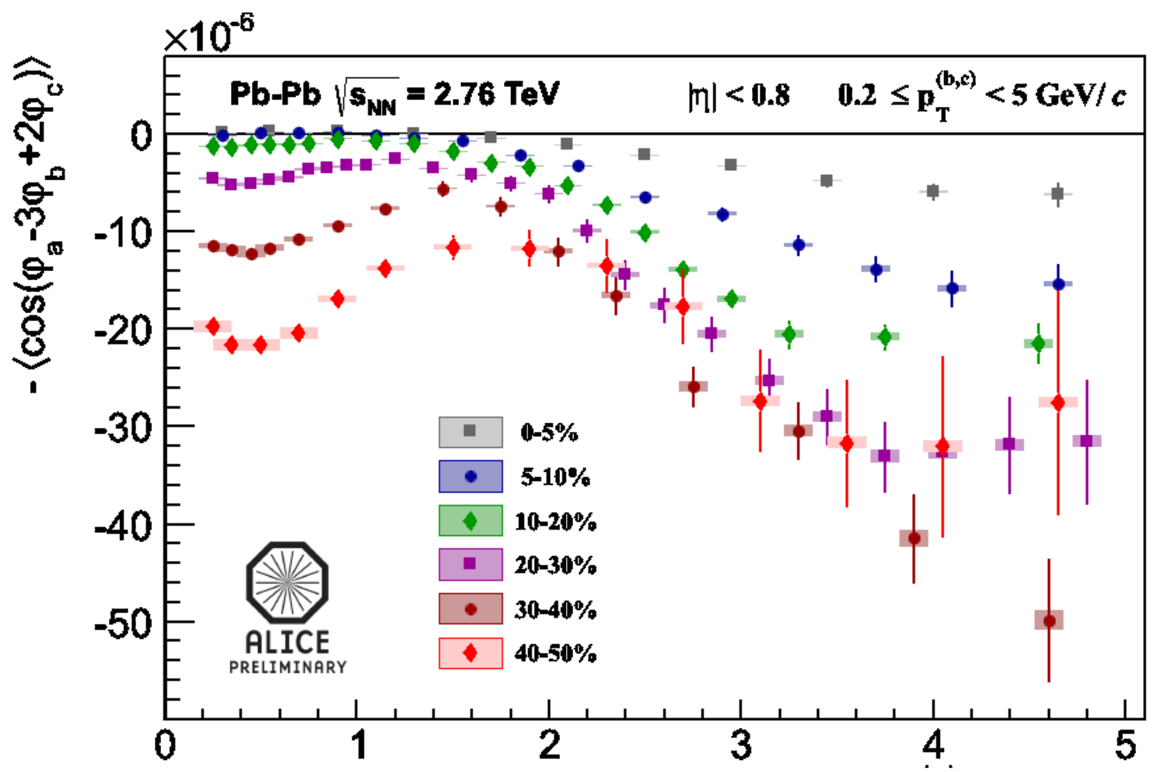
The crucial (but well known by now) observation is that the smallness of $v_2 \sim 0.1 \ll 1$ can be compensated by large factor $p_t/T_f \gg 1$. While in the examples of the previous section, integrated over momenta, we have seen that higher powers of v_2 are suppressed but still observable, at "high" p_t the terms with higher powers of their product $(v_2 p_4/T_f)^k$ are not suppressed at all.

Example K_3 (slide 11 of [7]) or simply the v_1 in which the transverse momentum of p_a is large. In the exponent

$$exp\left[-(1/T_f)p_\mu u_\mu\right] \quad (8)$$

the velocity is a sum of all harmonics such as $u_\mu = u^0_\mu + u^1_\mu + u^2_\mu + u^3_\mu$. Thus there is the direct first harmonics and the nonlinear terms with the same ϕ-dependence

$$v_1 = O(\epsilon_1 p_t) + O(\epsilon_2 \epsilon_3 p_t^2) \quad (9)$$



$$3 - 2 = 1$$

$$(p_t = 3GeV/T_f \approx 120\, MeV) \sim 25 \gg 1$$

ALICE data: $v_n(b)$ and 1+2=3 and some 5-particle examples

Irreducable and reducable sums: example 3 particles $K_3 =< cos(3\phi_a - 2\phi_b - \phi_c) >$ is irreducable. But a correlation of 5 particles called a,b,c,d,e of the type $K_5 =< cos(3\phi_a + 2\phi_b - 2\phi_c - 2\phi_d - 1\phi_e) >$ is reducable because it can contain the previous one and simple elliptic flow correlation from two other particles.

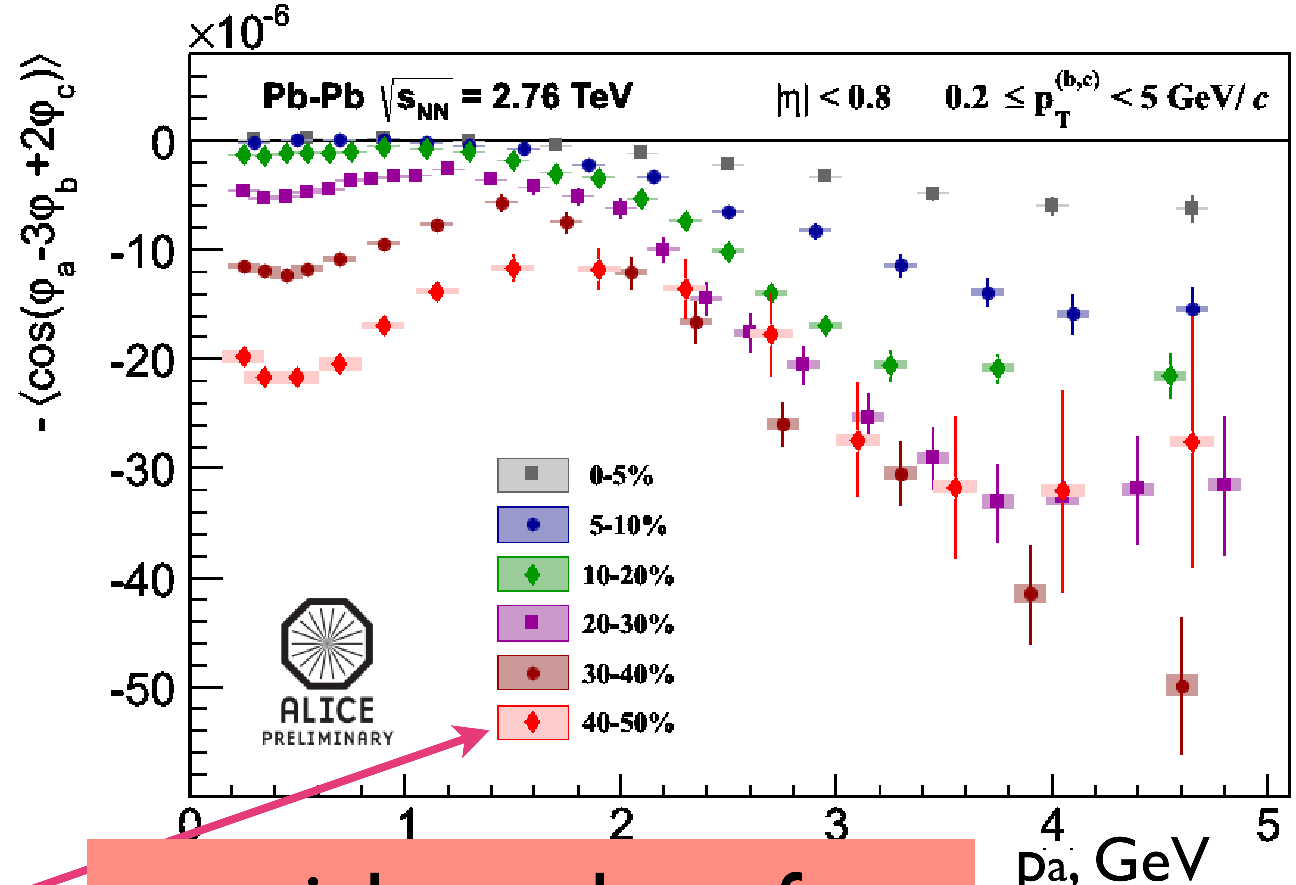
$$< cos(3\phi_a + 2\phi_b - 2\phi_c - 2\phi_d - 1\phi_e) > |_c$$
$$= cos(3\phi_a + 2\phi_b - 2\phi_c - 2\phi_d - 1\phi_e) >$$
$$-2 < cos(3\phi_a - 2\phi_b - \phi_c) >< cos(2\phi_d - 2\phi_e) > \quad (5)$$

3-2-1=0,2-2=0

Crude estimate can be made by using measured v_n in the place of ϵ_n (this assumes that hydro-determined ratios $v_n/\epsilon_n = O(1)$: one can do better, especially in respect to the signs.) As an example, one can do order-of-magnitude estimate of those two examples at a particular centrality, say 50%. The measured values are $v_1 = 210^{-2}, v_2 = 0.1, v_3 = 1.710^{-2}$. Using those one get

$$K_3 \sim v_1 v_2 v_3 \sim 3.410^{-5} \quad (6)$$

$$K_5 \sim v_1 v_2^3 v_3 = v_2^2 K_3 \sim 3.410^{-7} \quad (7)$$



right order of magnitude and correct b- and pt dependence:

Teaney, Yan

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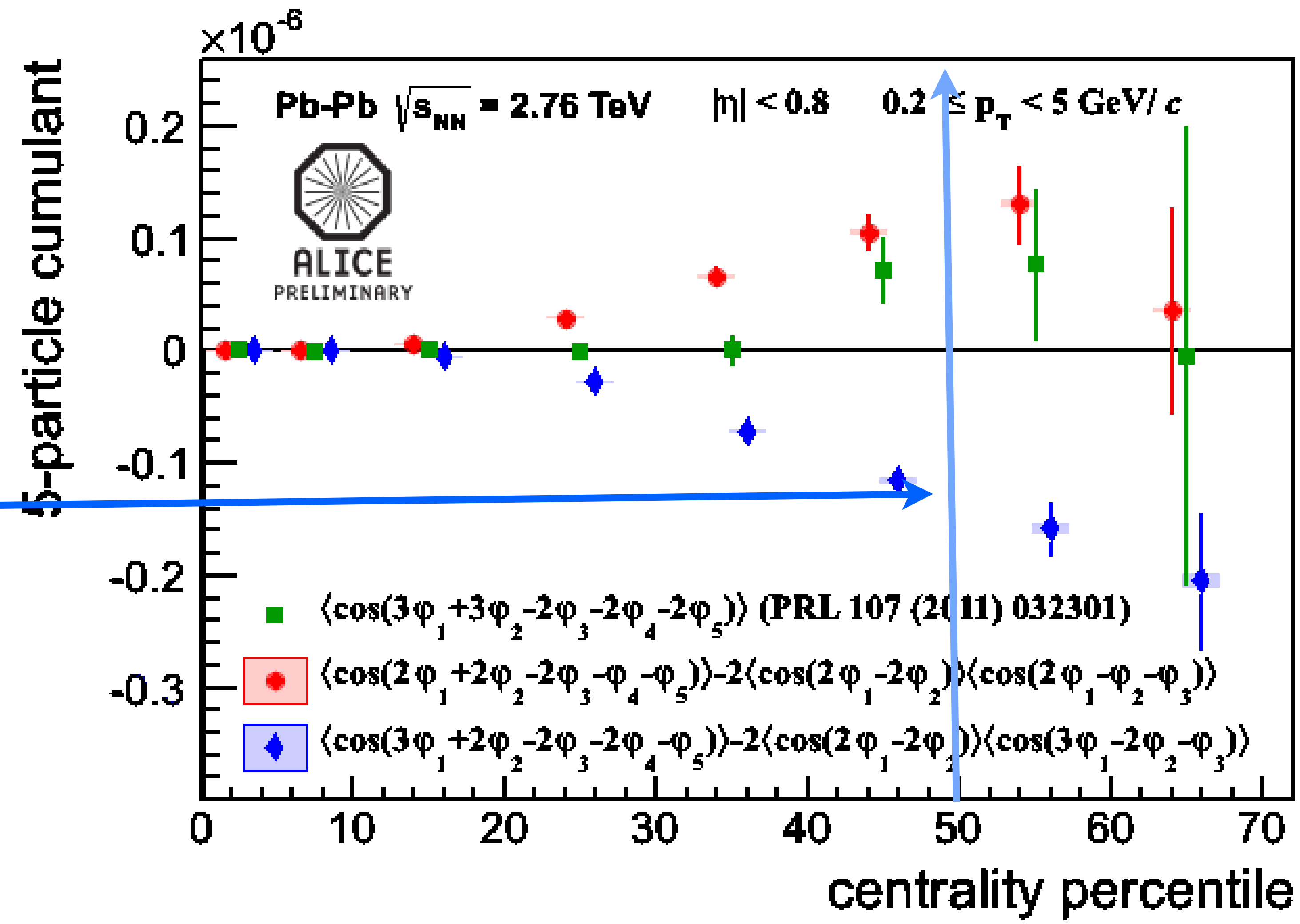


the negative signs have been explained already in Staig, ES arXiv:1008.3139 where phase correlation has been noticed in Glauber

$$\xi_1 - 3\xi_3 \approx \pi, \qquad 2\xi_2 \approx \pi$$

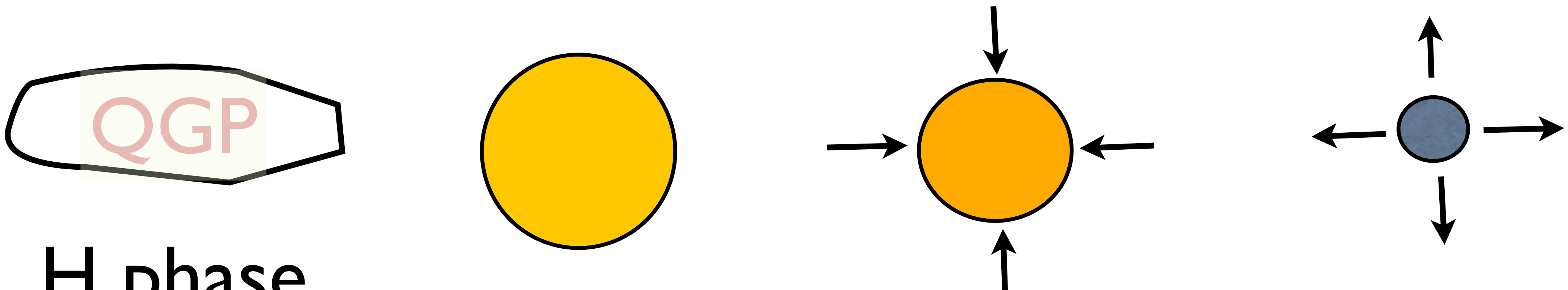
$$\rightarrow < cos(\xi_1 - 3\xi_3 - 2\xi_2) > \approx 1, > 0$$

like a boiling coffe pot,the fireball may “sing” before hadronization

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 $T<T_c$ the QGP pressure is less than p_H =>

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

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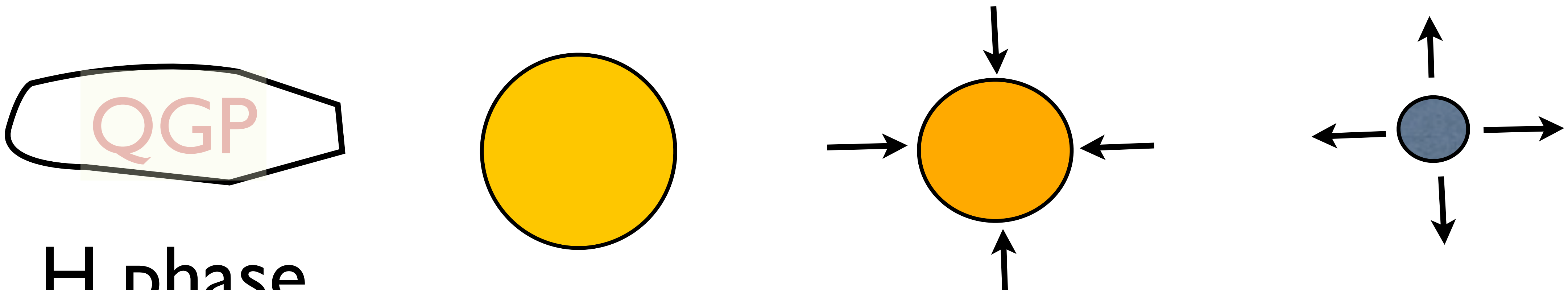

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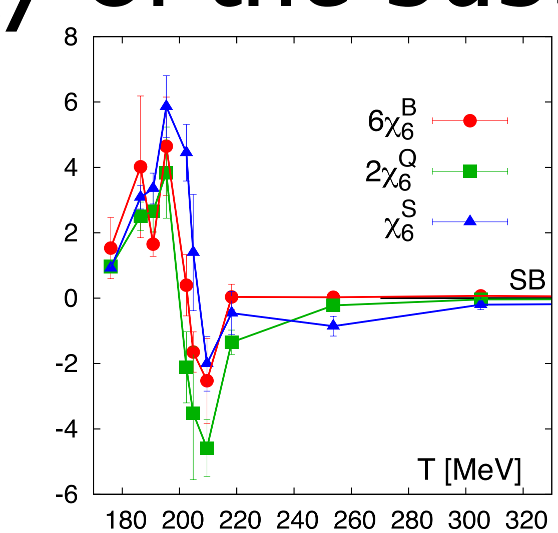

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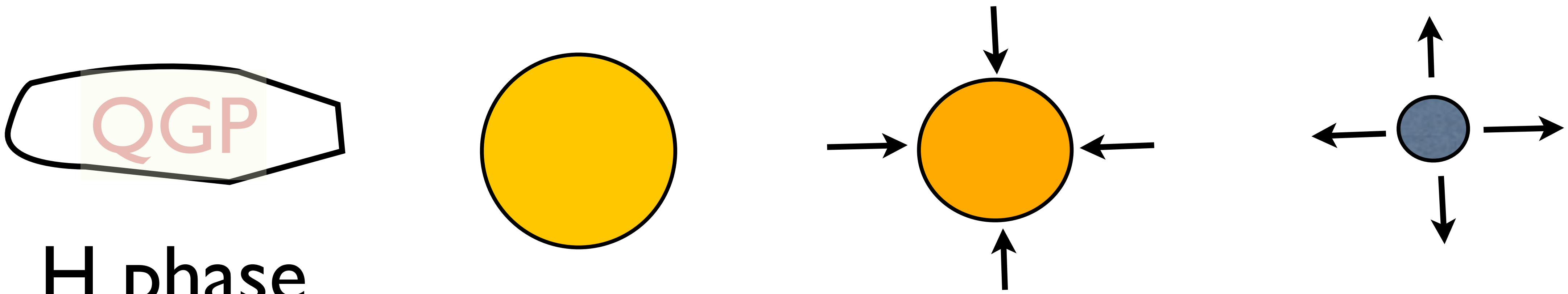

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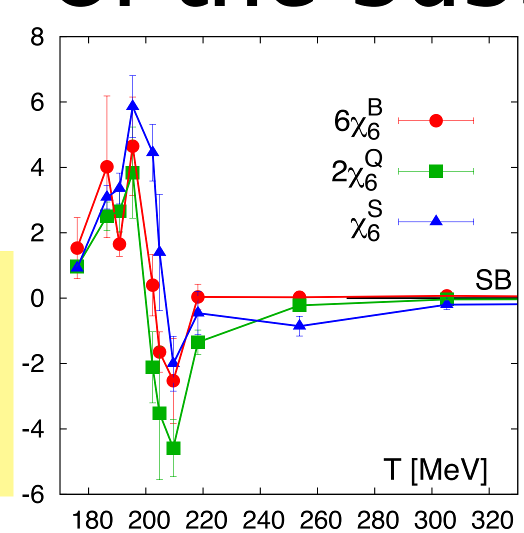
microscopic view:
Redlich-Karsch results higher cumulants,
which like 6-clusters just above Tc
but dislike it just below Tc



Rayleigh collapse result in emission of a shock

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

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

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

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

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

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"

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

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

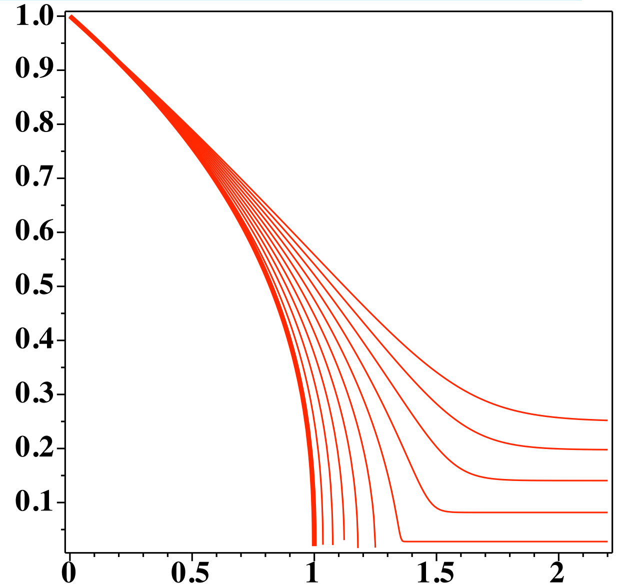


FIG. 1: The time evolution of the drop radius $R(t)$, for the values of $\eta/\rho = 0.01..0.1$ with the 0.01 step.

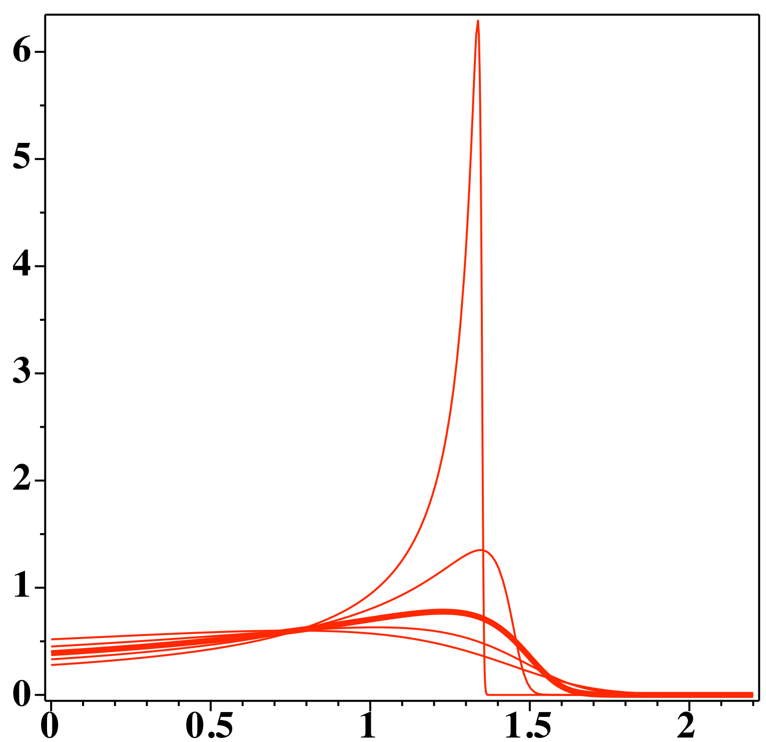


FIG. 2: The time evolution of the quantity $|\ddot{V}(t)|^2$, entering the sound radiation intensity, for the values of $\eta/\rho = 0.06, 0.07, 0.08, 0.09, 0.1$.

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sonoluminescence exprts

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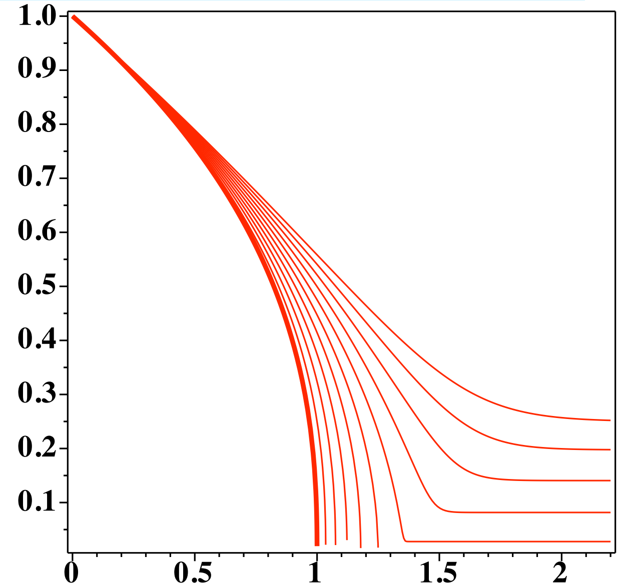

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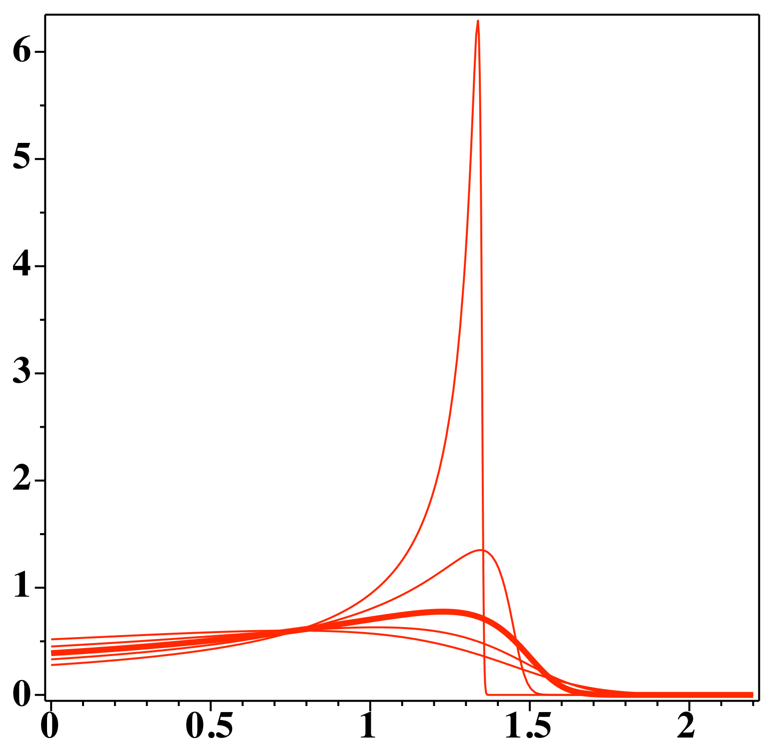

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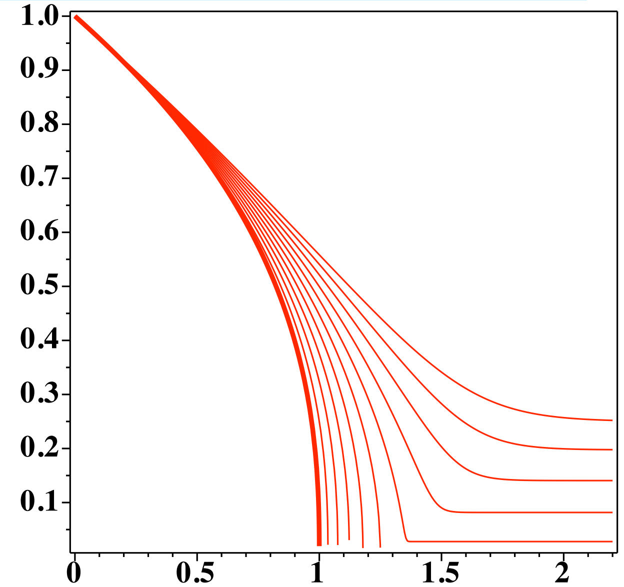

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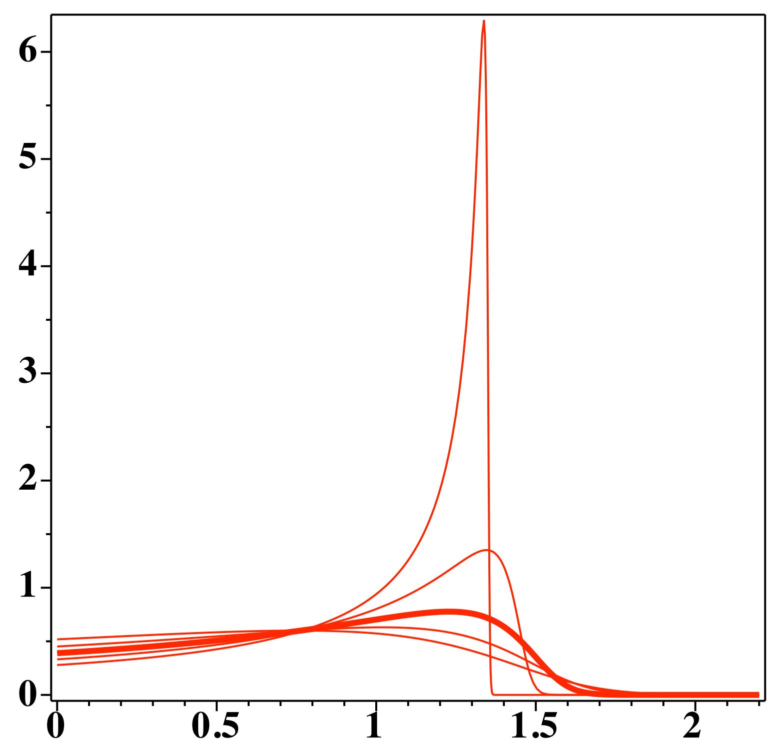

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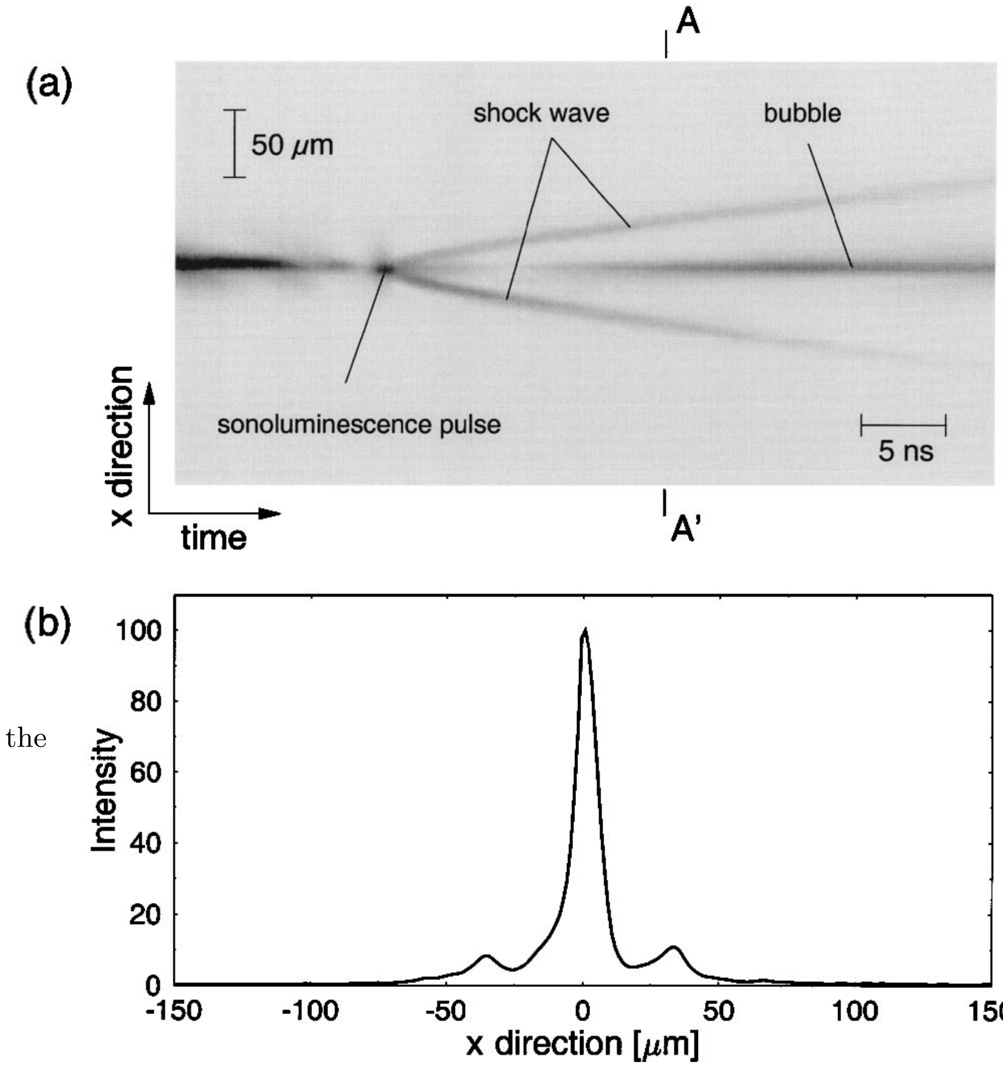

FIG. 22. Outgoing shock wave from a collapsing bubble: (a) Streak image of the emitted outgoing shock wave from the collapsing bubble and (b) an intensity cross section along the line AA'. From Pecha and Gompf (2000).

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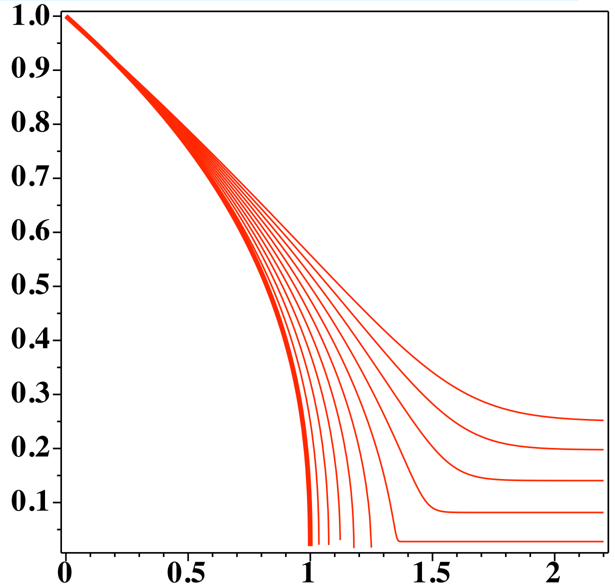

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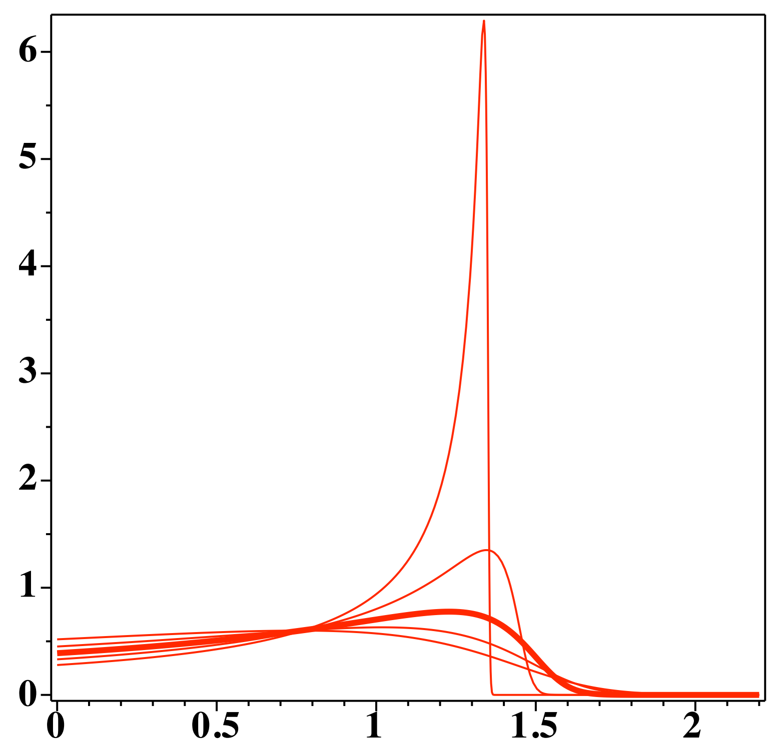

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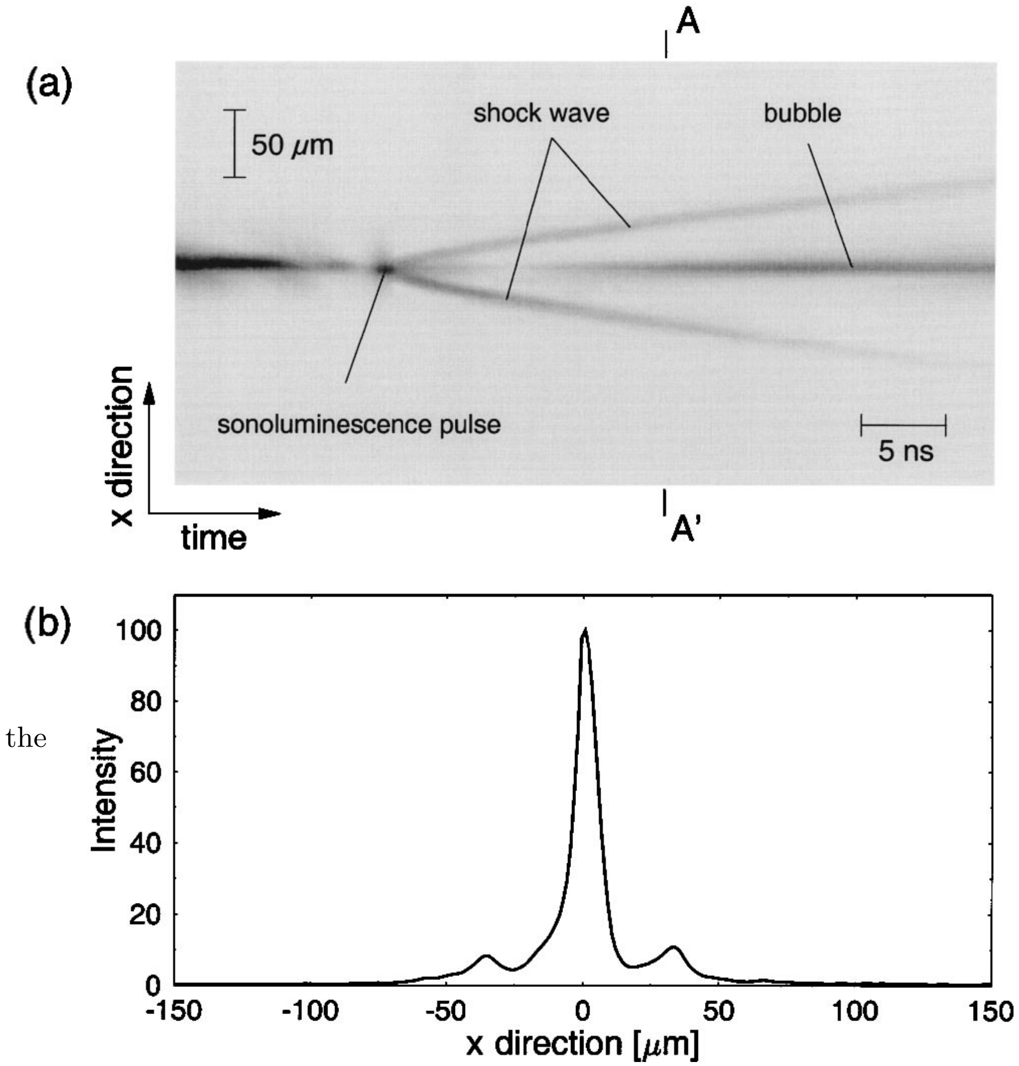

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V_{shock}=4km/s

C_{sound}=1.4km/s

p=40-60 kbar

T =1 ev !

Sound propagating in rapidity direction

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

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

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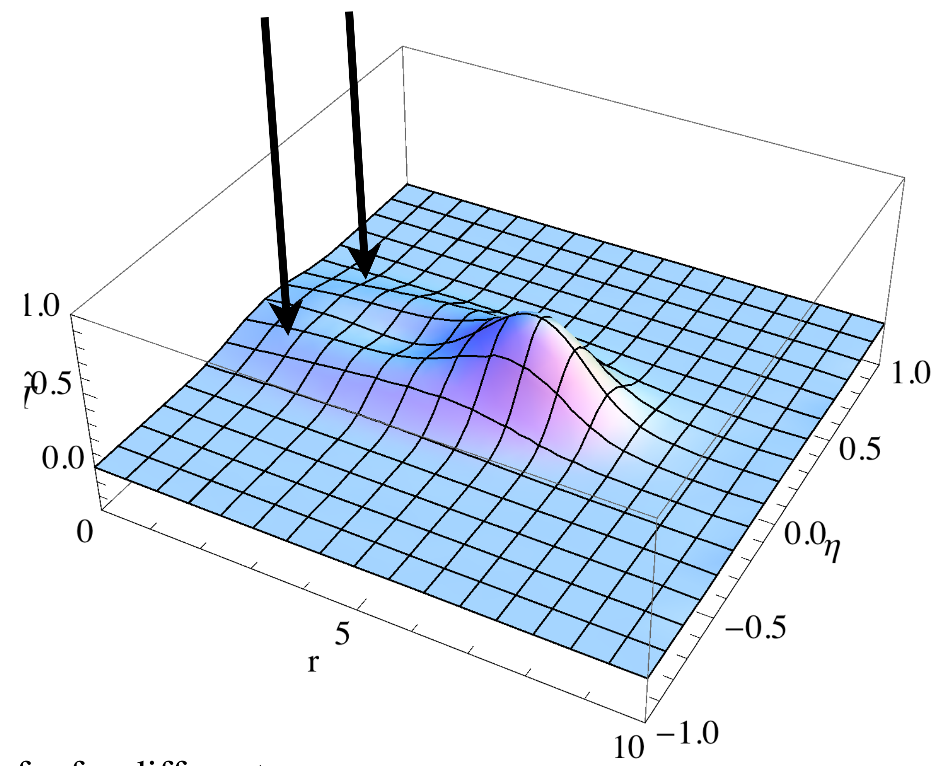
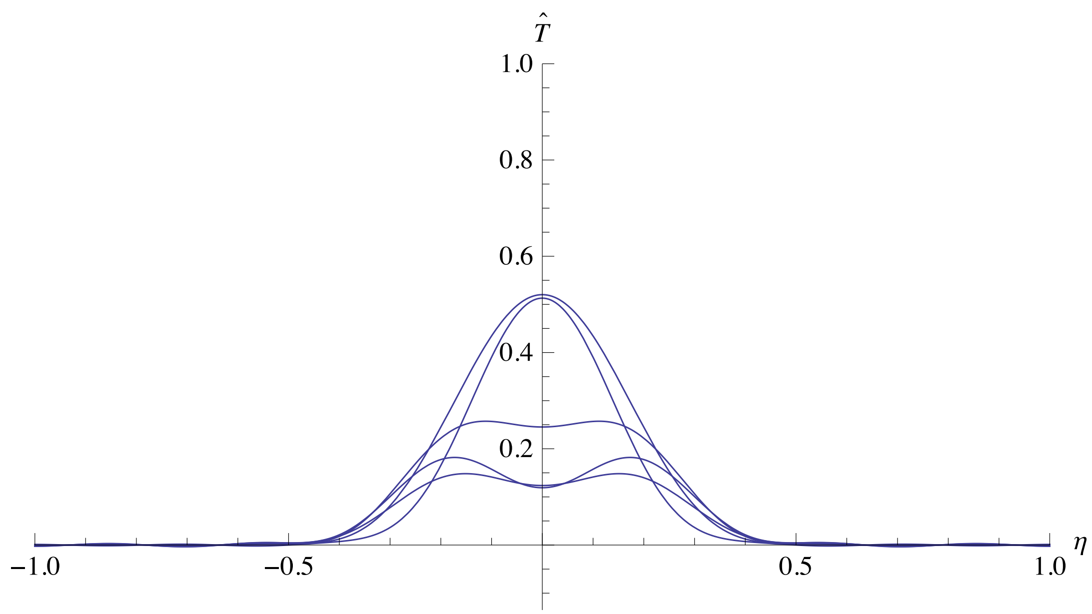


The temperature perturbation at freeze-out as a function of η for different r.



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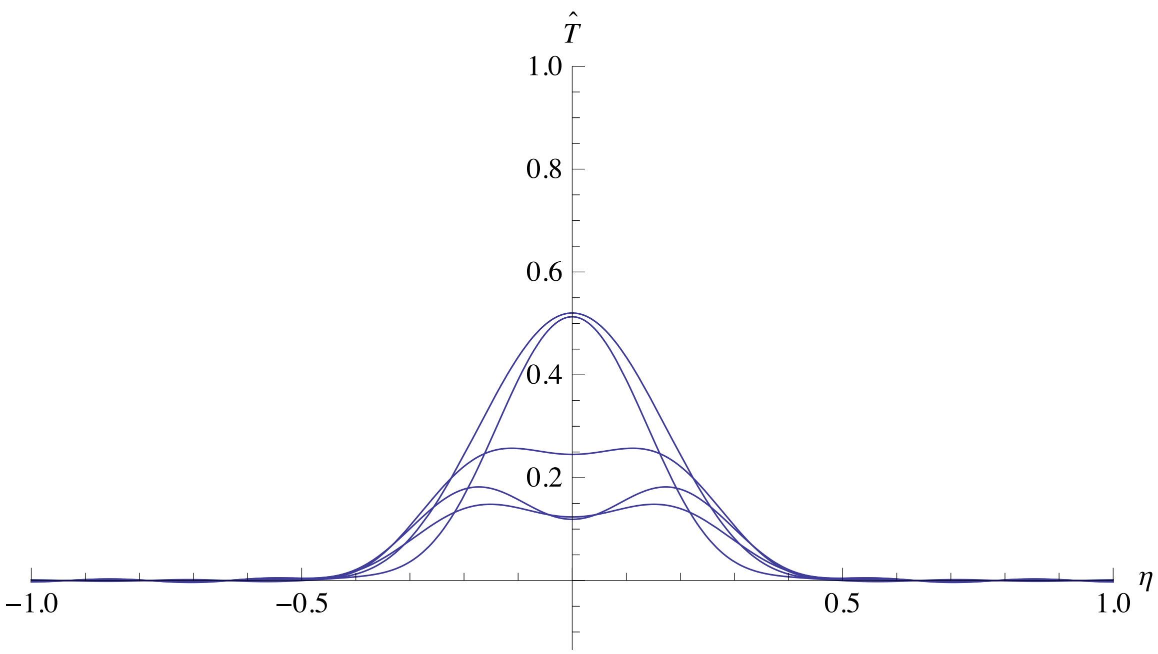

Summing up those curves one gets a double-hump distribution

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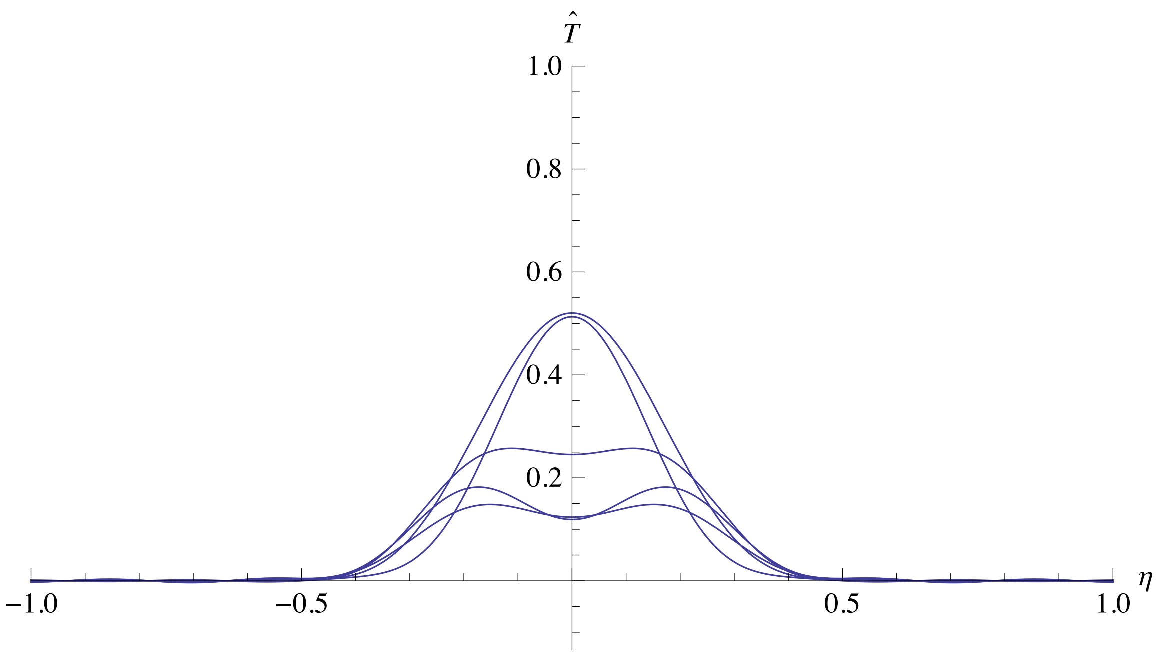

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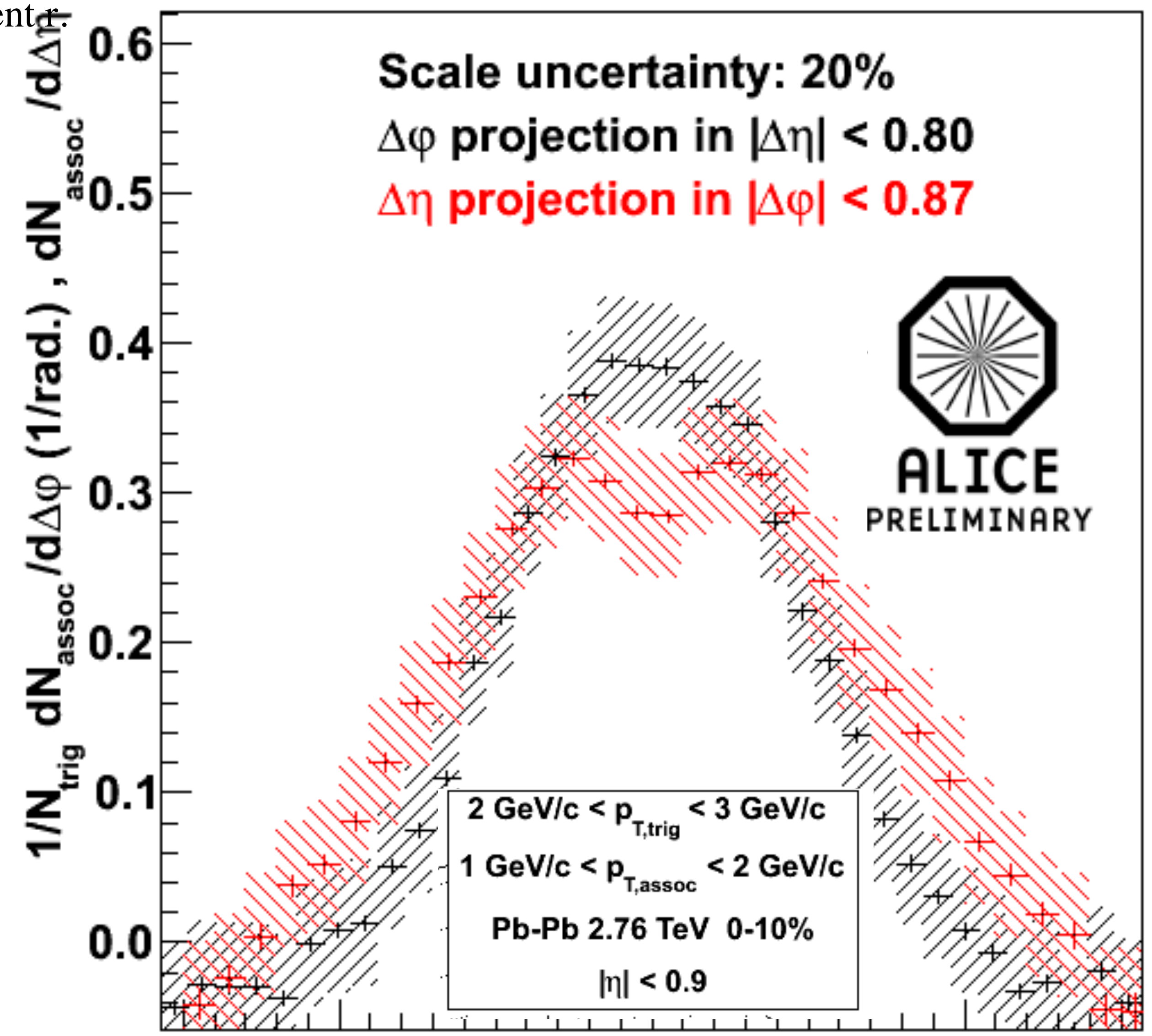

Δφ , Δη

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

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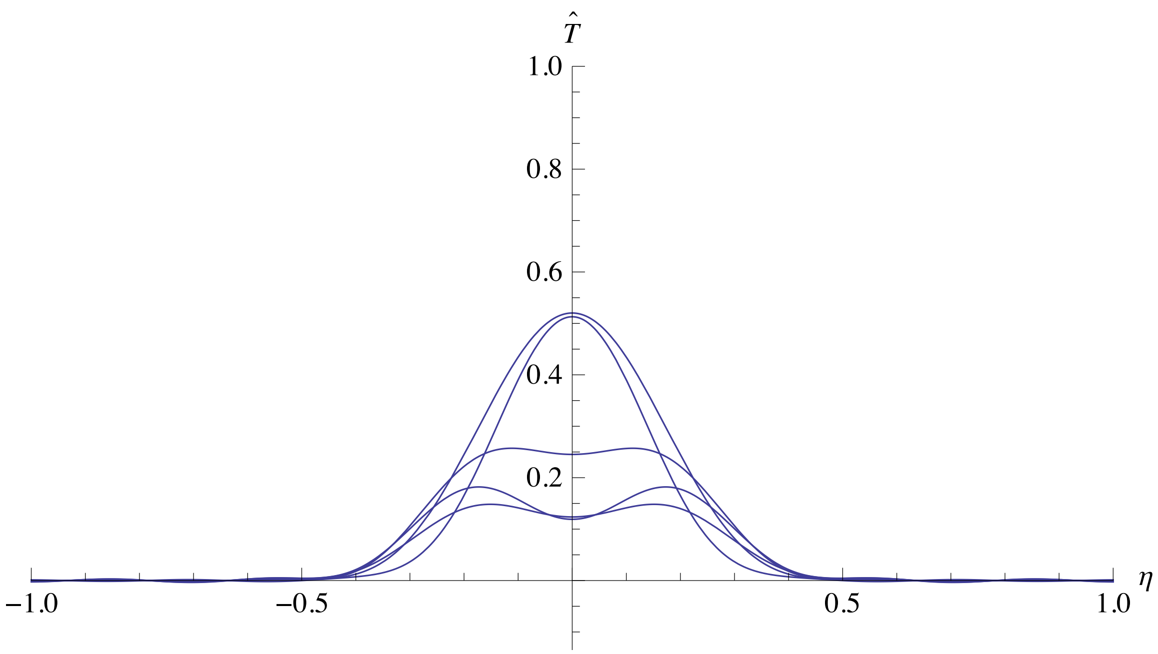

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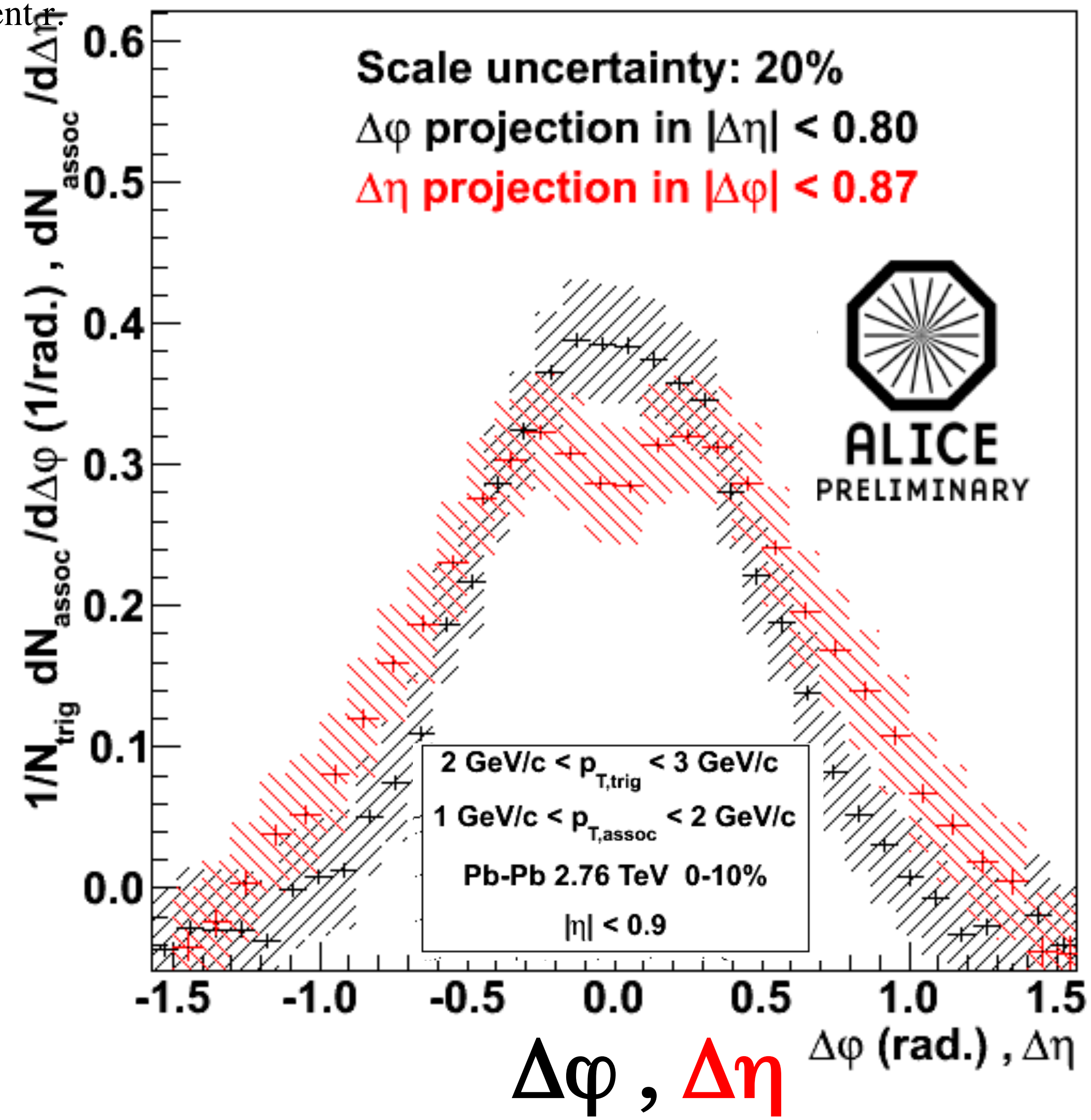

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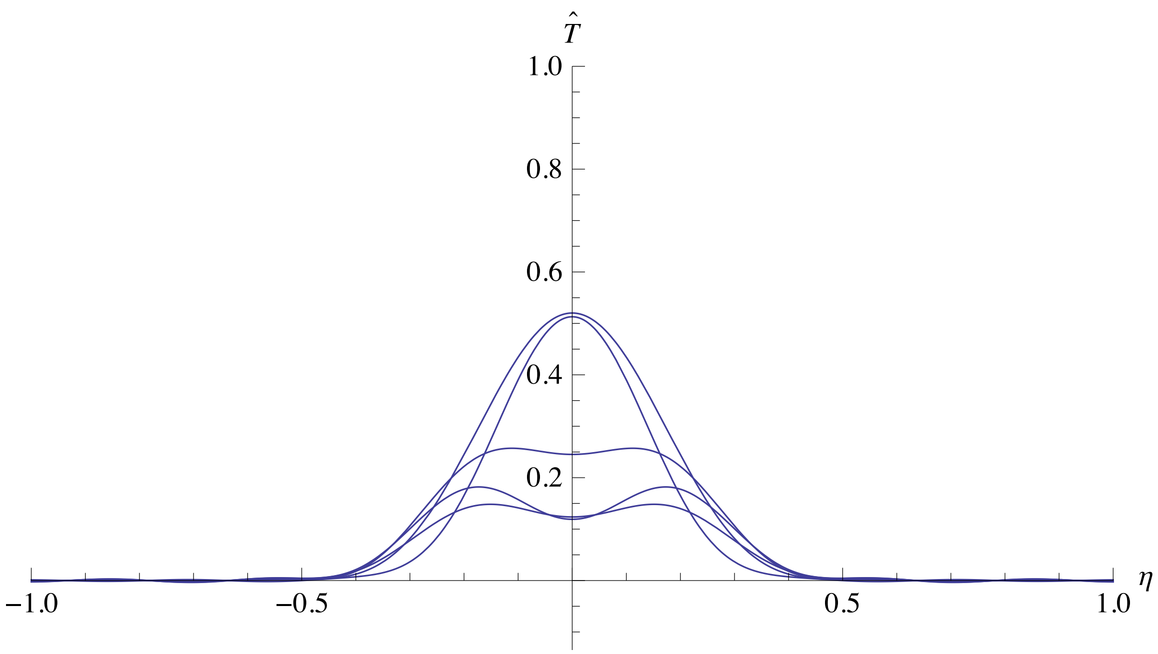

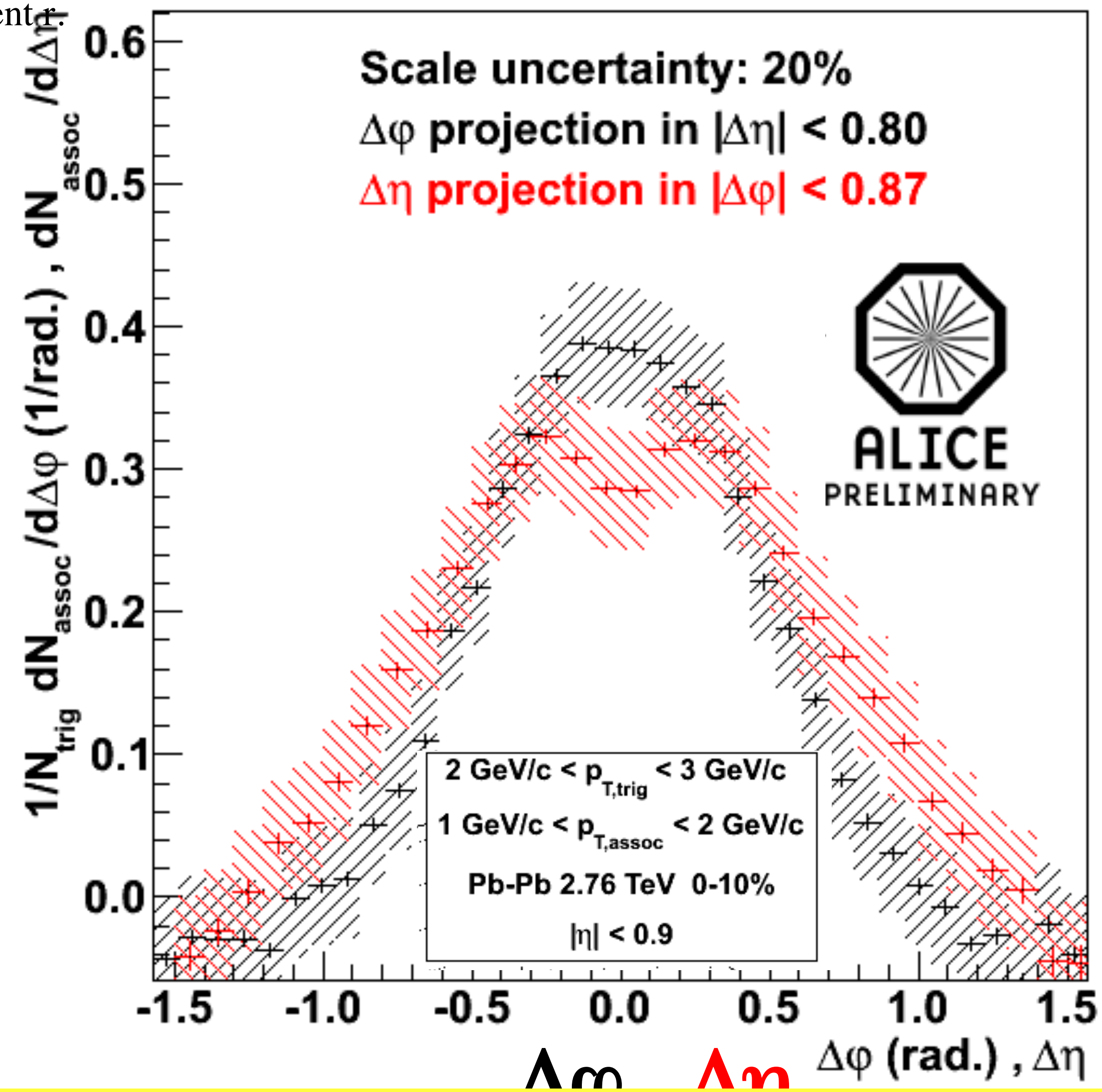

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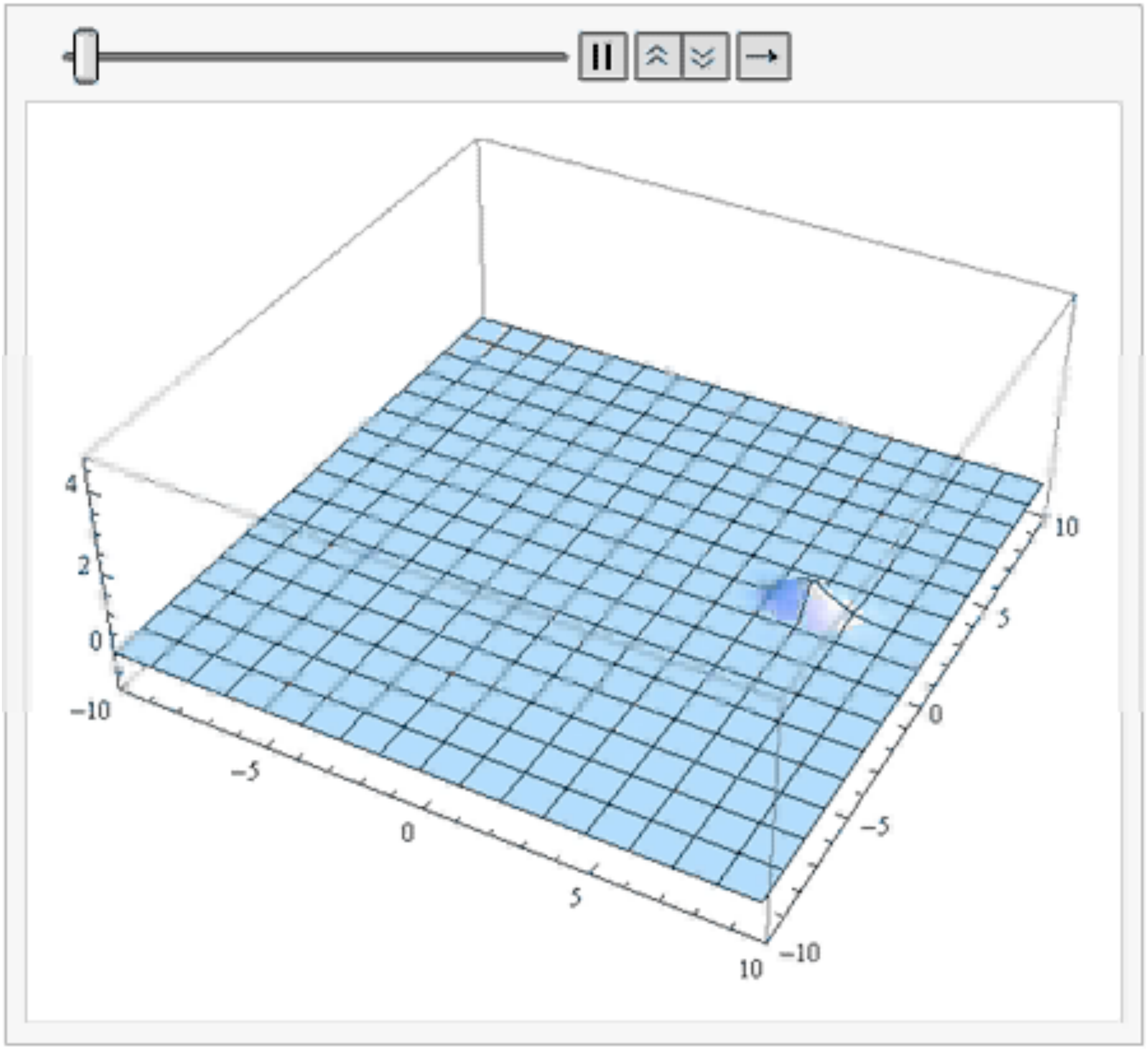
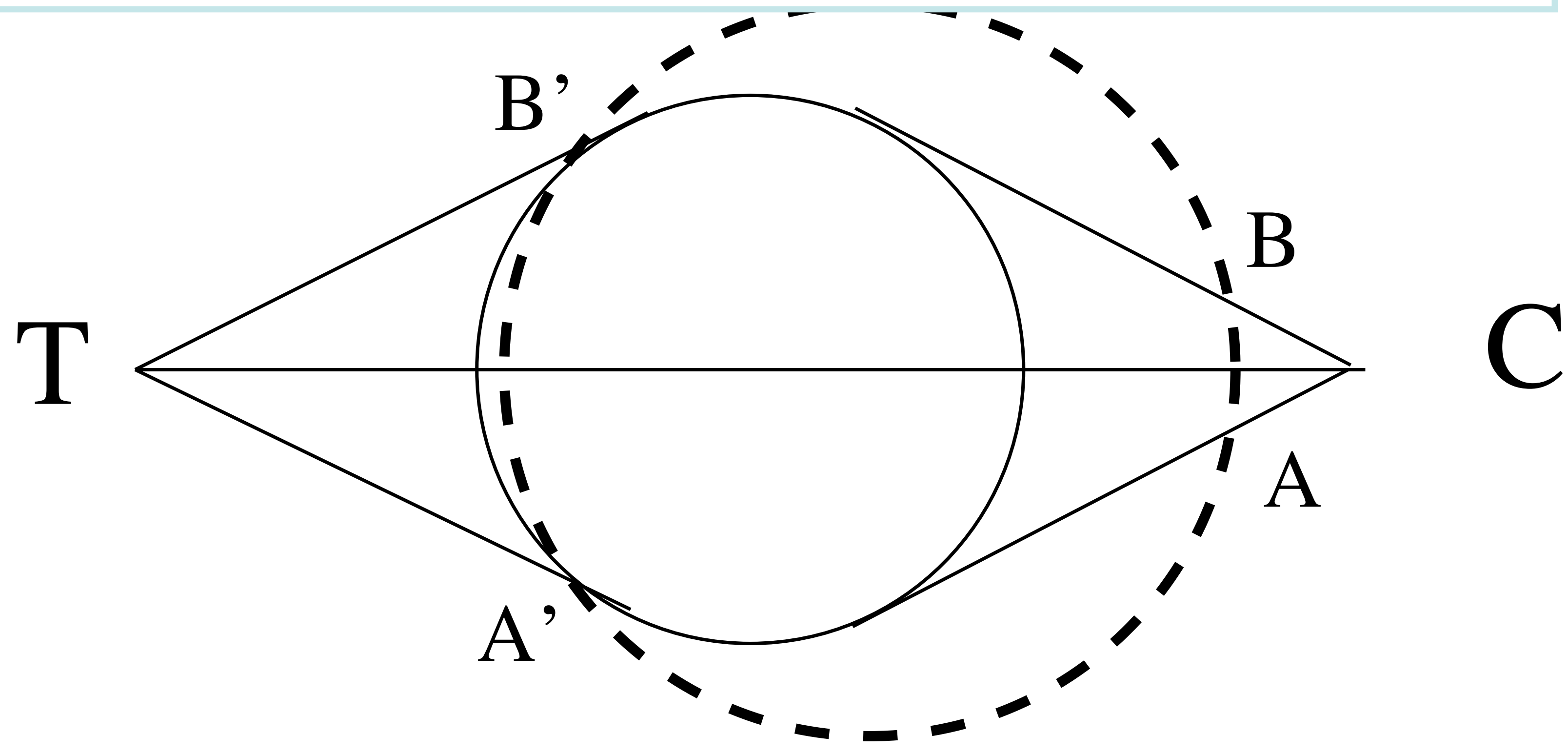
hump separation corresponds to propagation duration of about 2 fm/c (to freezeout): makes sense at LHC

sounds from quenched jets

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

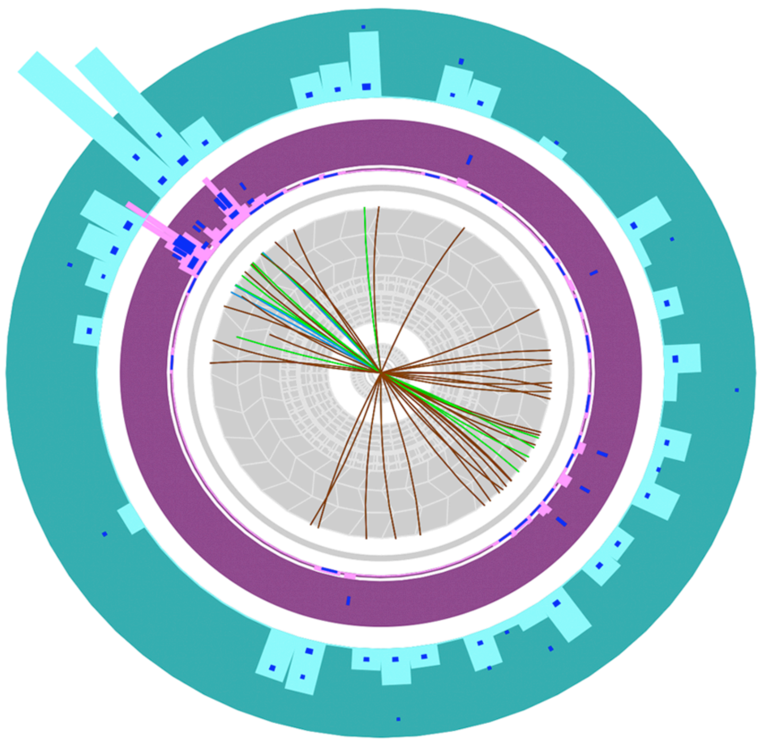


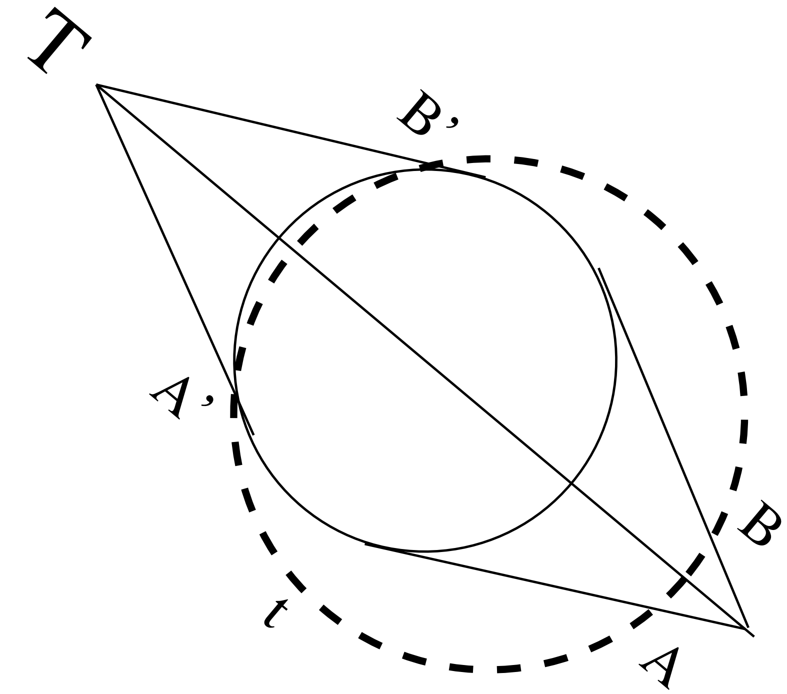
perturbed and unperturbed regions



The dashed line is that of maximal transverse flow: 4 points are to be visible at pt=2-4 GeV

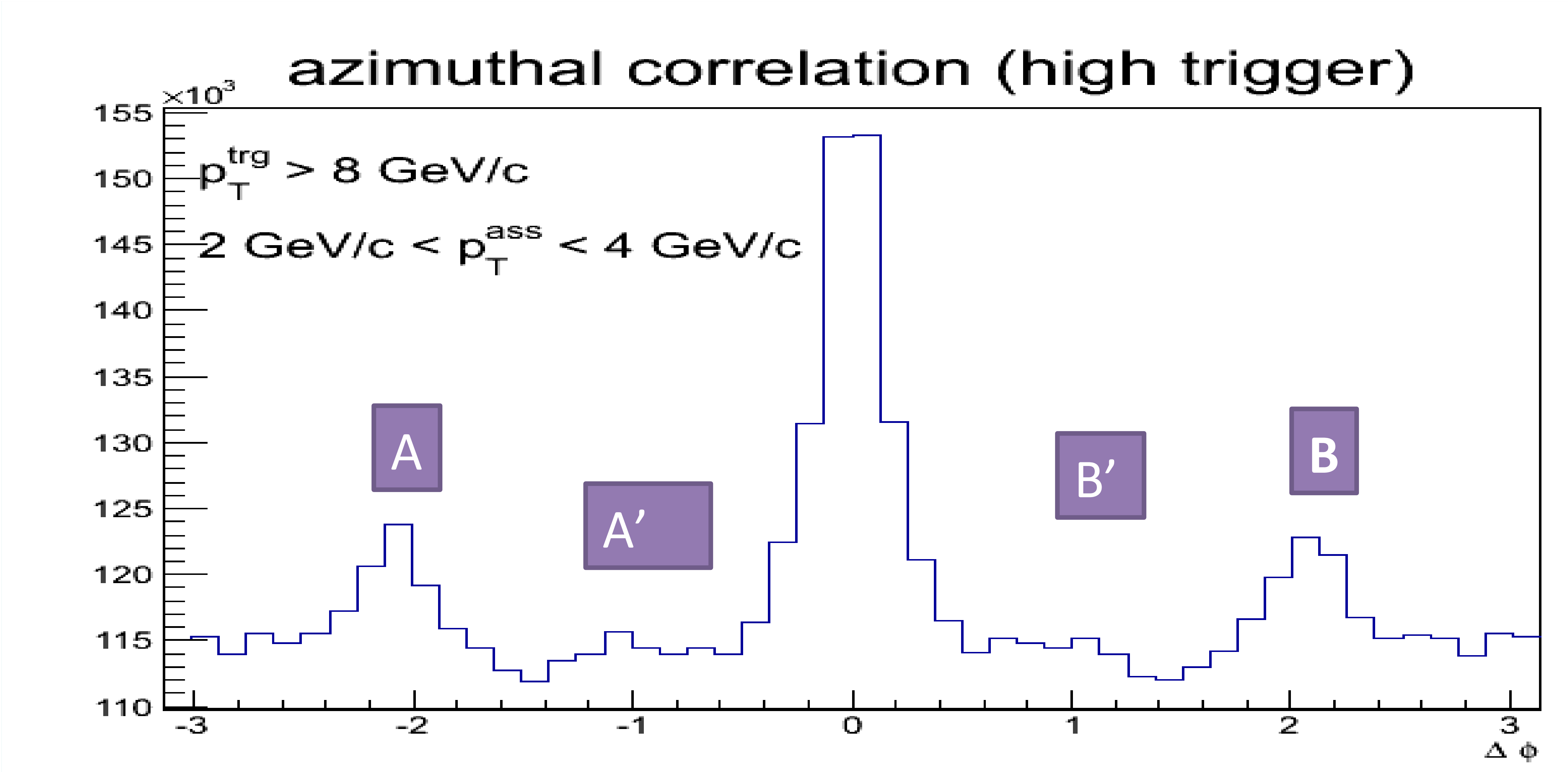
The angular edge of the jets: matter inside is few % HOTTER =>
SHOULD BE SEEN
at tuned pt



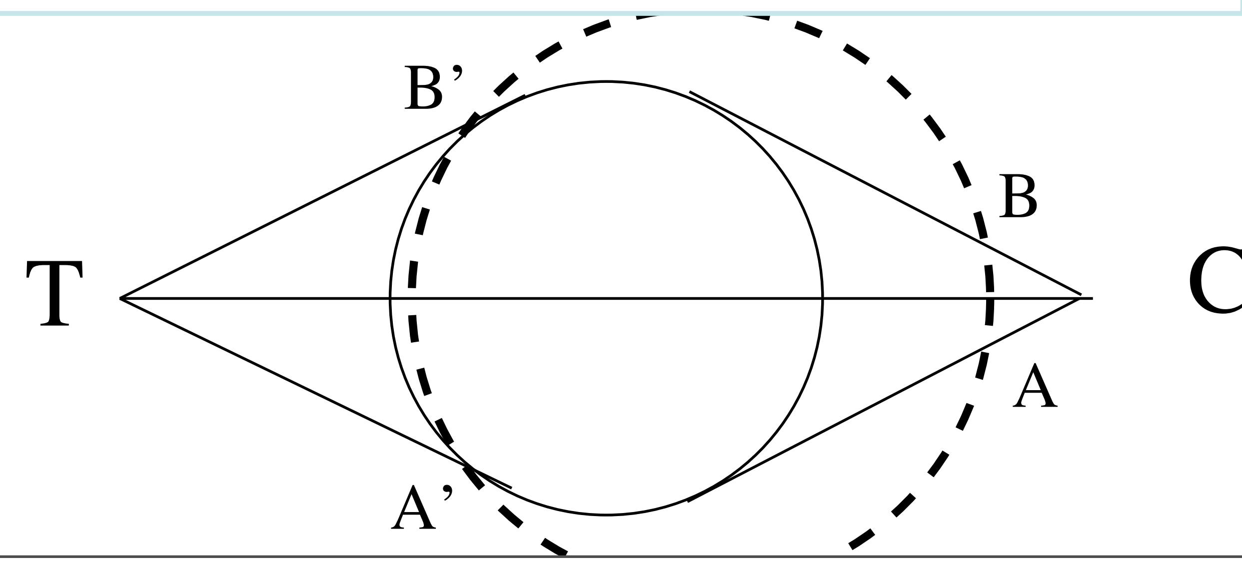


- ATLAS very high energy event, in which there is no identifiable jet
- Tracks pt>2.6 GeV, cal. E>1GeV/cell
- Note the sharp edge of the away-side perturbation! **Is it a "frozen sound"?**

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



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



summary

- sounds from initial perturbations have many harmonics => **sonograms possible**.freezeout, eta/s
- Many observable many-hadron correlators => number of sources, nonlinearities
- Rayleigh collapse of the QGP bubble: the sound of the QGP phase transition, possibly seen already at LHC (RHIC does not have long enough hadronic phase lifetime)
- Mach cones from jets ? at pt=2-3 GeV **jet edges** are becoming observable, perhaps on e-by-e basis