NBI,Copenhagen
Nov.2011

Higher harmonics of sound perturbations at RHIC/LHC heavy ion collisions

Edward Shuryak

Department of Physics and Astronomy

Stony Brook

Plan

- The Little Bang comes to LHC
- Sound perturbations in Big and Little Bang: the circles
- The second act of hydro: solving for all harmonics
- 2-pion correlators and power spectrum vs experiment
- Coherence? Big Bang detour and a homework for expermts
- Sound from jets
- Is quenching the gravitational radiation in BH AdS? What is its dependence on jet energy?

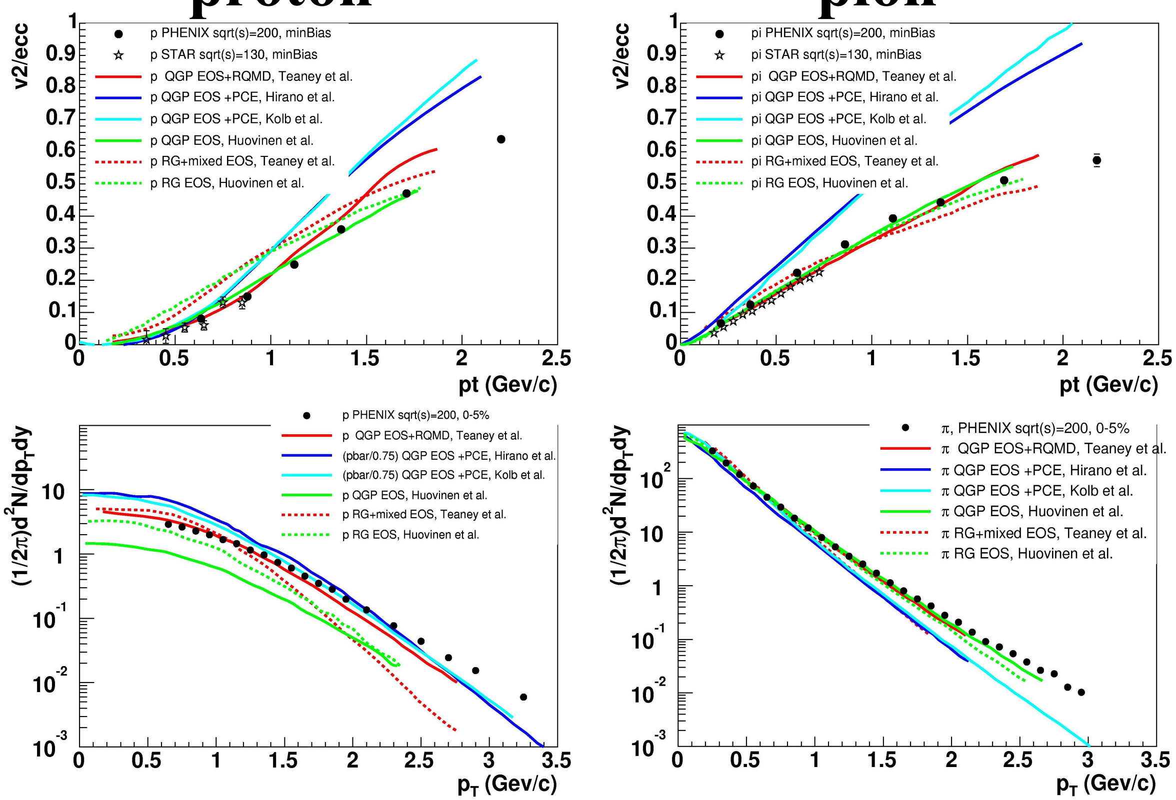
2001-2005: hydro describes radial and elliptic flows for all secondaries , pt<2GeV, centralities, rapidities, A (Cu,Au)…

Experimentalists were very sceptical but were convinced and ``near-perfect liquid" is now official,

=>AIP declared this to be discovery #1 of 2005 in physics

v_2=<cos(2 phi)>

proton **pion**



PHENIX,
Nucl-ex/0410003

red lines are for ES+Lauret+Teaney
done before RHIC data, never changed or fitted, describes SPS data as well! It does so because of the correct hadronic matter /freezout via (RQMD)

Few general commments about hydrodynamics

- Field theory development was helped by hydro in the 19th century (Stokes-> Maxwell…)
- Fermi…Landau in 1950's
- But when I was dreaming about it in 1970's most theorists said it is ridiculously simplistic to describe anything and that it obviously contradicts both quantum mechanics and QCD
- Not anymore: now theorists using AdS/CFT correspondence had derived it from Einstein equations of GR, a hot topic for string theorists these days
- (Hydro has dissipation/equilibration and Einstein's eqns are t-even: how can it be true? Well, boundary conditions on the black hole horizon are NOT, as everything falls into it but nothing comes out…)

While our experimental friends had made their detectors, the theorists debated

Will it be like that at LHC?

- Energy is up by about factor 20
- Initial T changes from 2Tc -> 3 Tc

(Tc about 170 MeV)

- Multiplicity is up by 2.2
- Will QGP change from strongly to weakly coupled regime?**=> v2 goes up or down?**

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

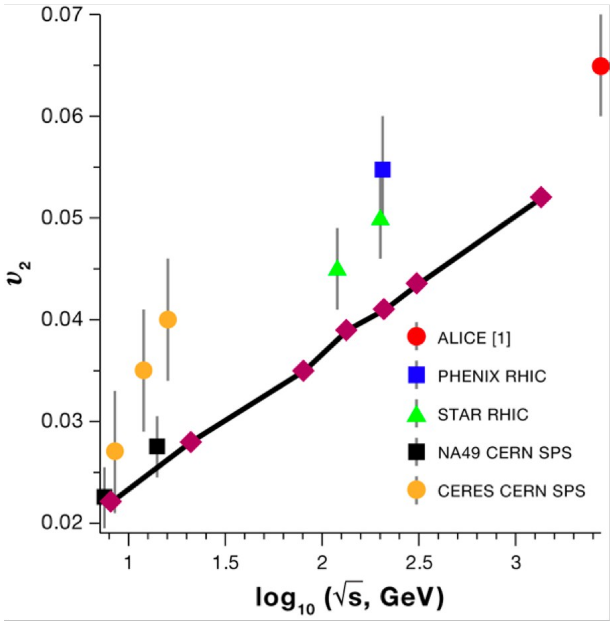


FIG. 1: The ALICE experiment suggests that the quark-gluon plasma remains a strongly coupled liquid, even at temperatures that are 30% greater than what was available at RHIC. The plot shows the "elliptic flow parameter" v_2 (a measure of the coupling in the plasma) at different heavy-ion collision energies, 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].

Increased elliptic and radial flows, as well as increased HBT radii/volume are all supporting "Hydro1", the "Little Bang"

What do these results tell us about the quark-gluon plasma? The mean free path for particles in the plasma can be conveniently expressed via a dimensionless ratio ($\eta/s\hbar$), where η is the shear viscosity, s is the entropy density and $\hbar$ is Planck's constant. In a weakly coupled quark-gluon plasma, the mean free path should be large ($\eta/s\hbar \gg 1$), while it should be small in a strongly coupled plasma. RHIC data analysis has shown it to be extremely small, close to the theoretically conjectured lower limit $\eta/s\hbar = 1/4\pi$ for infinitely strong coupling [5]. That this strong-coupling picture holds for the QGP seen at the LHC seems now likely. Naively, one might

Perturbations of the Big Bang

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

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

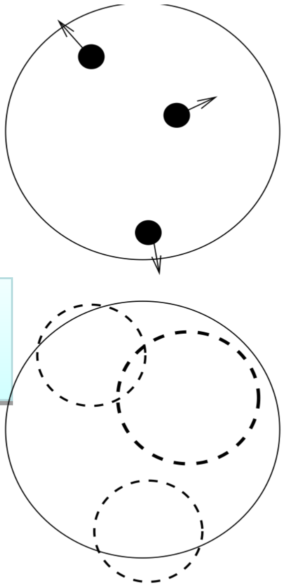
$$l_{maximum} \approx 210$$

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

They are remnants of the sound circles on the sky, around the primordial density perturbations
Freezeout time 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

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

Fate of the initial state perturbations in heavy ion collisions

Edward Shuryak
Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794, USA
(Received 20 July 2009; revised manuscript received 14 October 2009; published 13 November 2009)

ACOUSTIC SIGNATURES IN THE COSMIC MICROWAVE BACKGROUND

Wayne Hu
Institute for Advanced Study
School of Natural Sciences
Princeton, NJ 08540

and

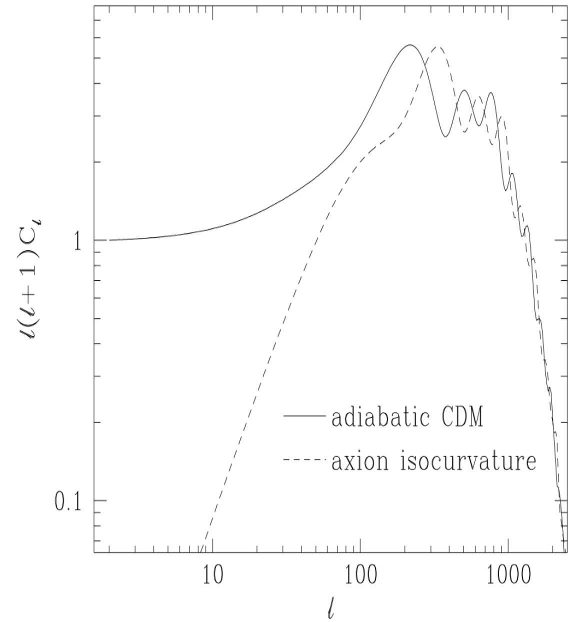
Martin White
Enrico Fermi Institute
University of Chicago
Chicago, IL 60637

ABSTRACT

We study the uniqueness and robustness of acoustic signatures in the cosmic microwave background by allowing for the possibility that they are generated by some as yet unknown source of gravitational perturbations. The acoustic *pattern* of peak locations and relative heights predicted by the standard inflationary cold dark matter model is essentially unique and its confirmation would have deep implications for the causal structure of the early universe. A generic pattern for isocurvature initial conditions arises due to backreaction effects but is not robust to exotic source behavior inside the horizon. If present, the acoustic pattern contains unambiguous information on the curvature of the universe even in the general case. By classifying the behavior of the unknown source, we determine the minimal observations necessary for robust constraints on the curvature. The diffusion damping scale provides an entirely model independent cornerstone upon which to build such a measurement. The peak spacing, if regular, supplies a precision test.

Subject headings: cosmology:theory – cosmic microwave background

Acoustic peaks



Dissipative cutoff

Fig. 6.— Diffusion damping.

Although adiabatic and isocurvature models predict acoustic oscillations in different positions, they both suffer diffusion damping in the same way. The damping length is fixed by background assumptions, here $\Omega_0 = 1$, $h = 0.5$, $\Omega_b = 0.05$ and standard recombination. These calculations were performed using a full numerical integration of the Boltzmann equation with the code of Sugiyama (1995) as were results in Figs. 7,8,10,11.

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]

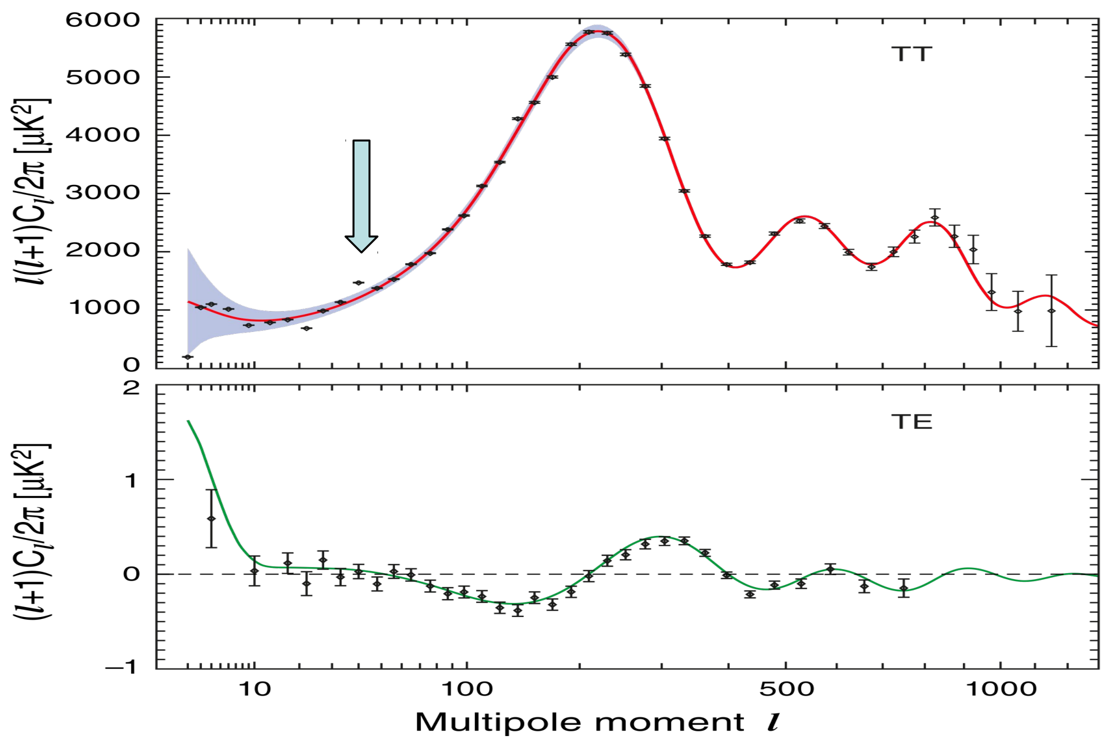


Fig. 9.— The temperature (TT) and temperature-polarization(TE) power spectra for the seven-year *WMAP* data set. The solid lines show the predicted spectrum for the best-fit flat ΛCDM model. The error bars on the data points represent measurement errors while the shaded region indicates the uncertainty in the model spectrum arising from cosmic variance. The model parameters are: $\Omega_b h^2 = 0.02260 \pm 0.00053$, $\Omega_c h^2 = 0.1123 \pm 0.0035$, $\Omega_\Lambda = 0.728^{+0.015}_{-0.016}$, $n_s = 0.963 \pm 0.012$, $\tau = 0.087 \pm 0.014$ and $\sigma_8 = 0.809 \pm 0.024$.

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

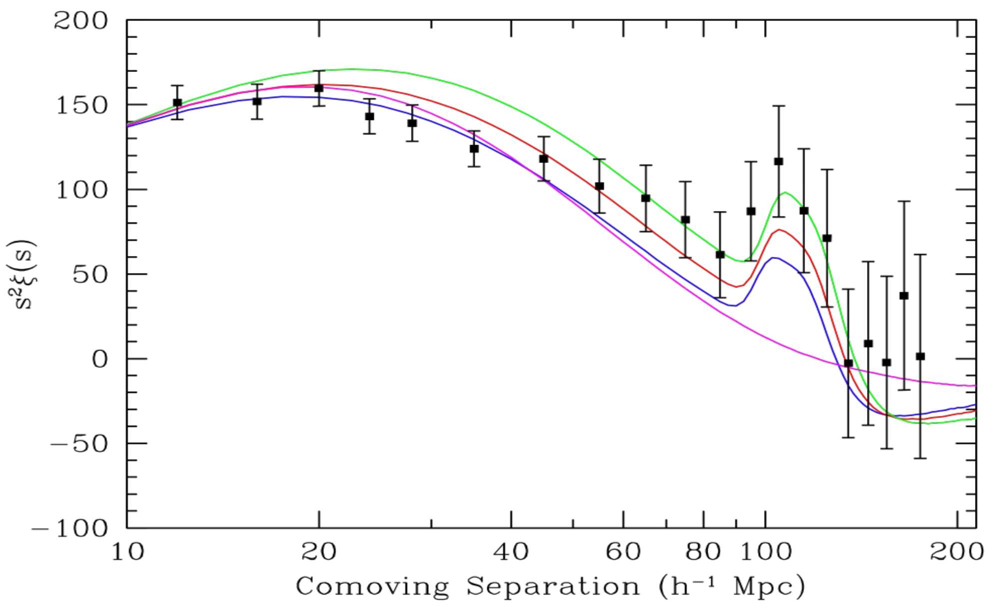


Fig. 3.— As Figure 2, but plotting the correlation function times s^2. This shows the variation of the peak at $20h^{-1}$ Mpc scales that is controlled by the redshift of equality (and hence by $\Omega_m h^2$). Varying $\Omega_m h^2$ alters the amount of large-to-small scale correlation, but boosting 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.

Back to the Little Bang

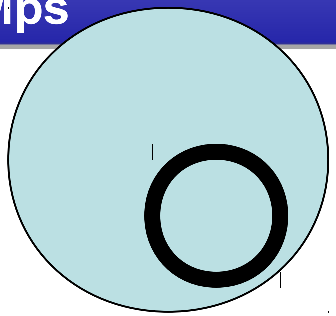
Two fundamental scales, describing perturbations **at freezeout**

(P.Staig,ES,2010)

1.The sound horizon: radius of about 6fm

For the Big Bang it was introduced by Sunyaev-Zeldovich about 40 years ago, was observed in CMB and galaxy correlations, it is about 150 Mps

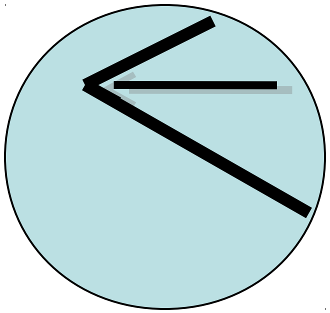
$$H_s = \int_0^{\tau_f} d\tau c_s(\tau)$$



cylinders

2.The viscous horizon:
The width of the circle

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



cones

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

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

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

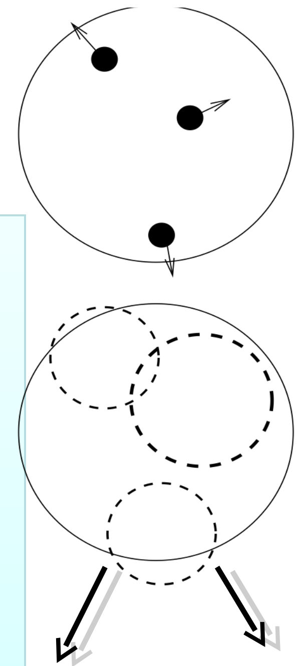
$$l_{maximum} \approx 210$$

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

They are literally circles on the sky, around primordial density perturbations

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

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



Cylindrical (extended in z) at FO surface tau_f=2R and sound velocity is ½ => radius is about R =>

Radial flow enhances the fireball surface: move toward detection with v about 0.8 c So we should see two "horns"

Azimutal harmonics m=O(1) Angle about 1 radian

Visible shape of the sound (at freezeout, boosted by radial flow)

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

Fate of the initial state perturbations in heavy ion collisions

Edward Shuryak
Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794, USA

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

Peak at +- 1 rad, 60°?

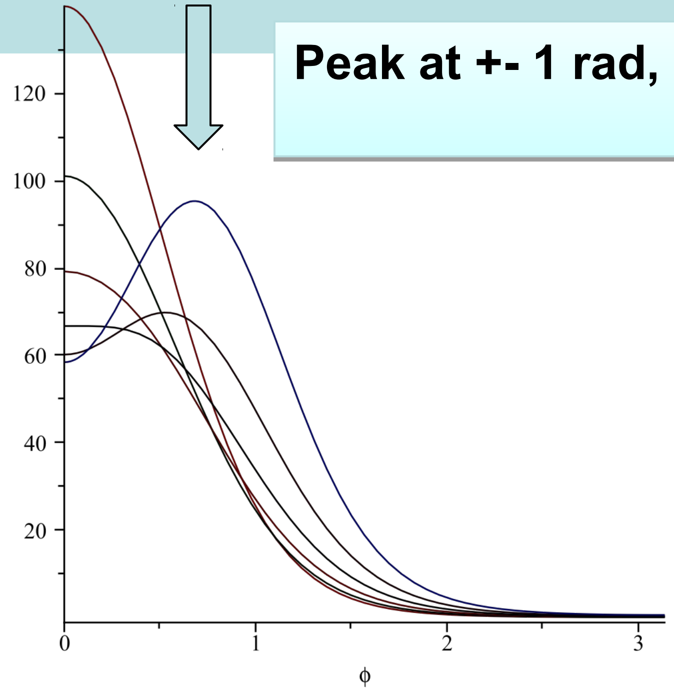
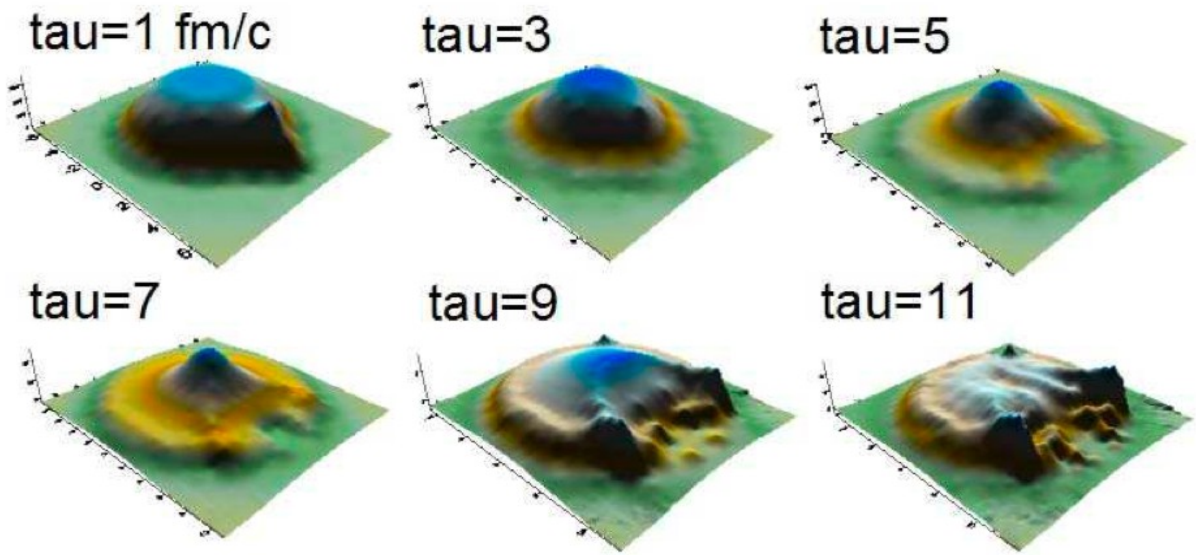


FIG. 5. (Color online) Dependence of the visible distribution in the azimuthal angle on the width of the (semi)circle at the time of freeze-out. Six curves, from the most narrow to the widest ones, correspond to the radius of the circle of 1, 2, 3, 4, 5, and 6 fm, respectively. The original spot position is selected to be at the edge of the nuclei. The distribution is calculated for a particle of $p_t = 1$ GeV and fixed freeze-out $T_f = 165$ MeV.

- The blue line is how asimuthal distribution would look like **for sound cylinders, double peak because of two points where the circle crosses the FO surface**
- **The circles were found and studied by Hama,Grassi et al in event-by-event hydro**

The sound cylinders and two peaks are also seen by Brazilian group (Andrade, Grassi et al)

Origin of the two peaks
Tube "sinks" and matter around "rises" forming a hole+two horns

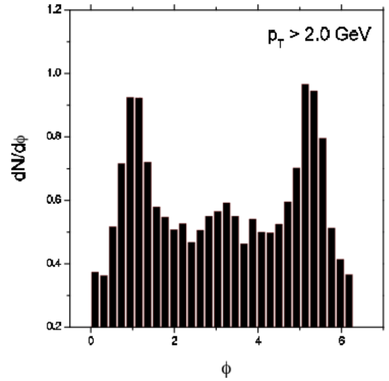


Temporal evolution of energy density for the one tube model.

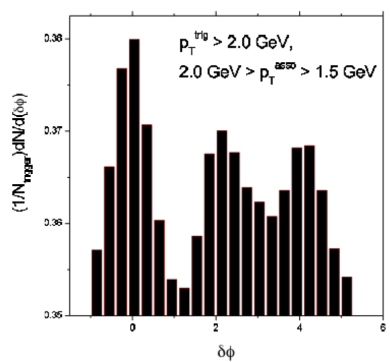
The peaks are at the same angles +- 1 rad (as I got) from perturbation but **+-2 rad in correlations**

One tube model

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



CONSEQUENCE: two particle angular distribution has three peaks



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

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

Pilar Staig and Edward Shuryak

Comoving coordinates with Gubser flow: Gubser and Yarom, arXiv:1012.1314

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

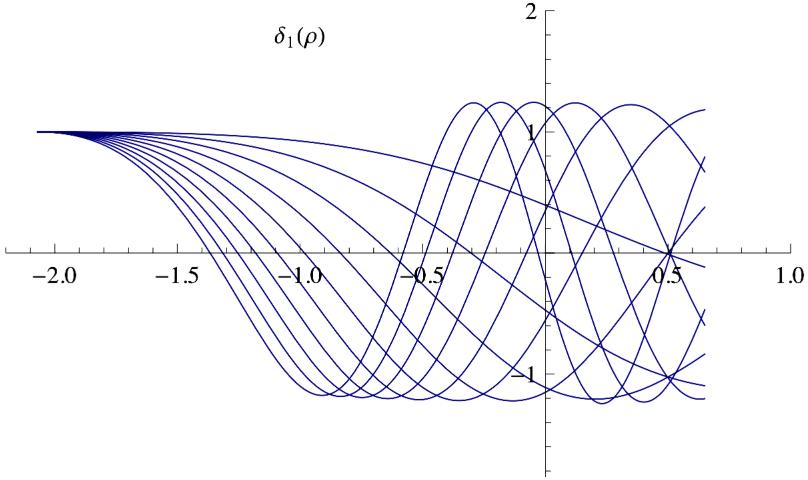
$$\frac{\partial^2\delta}{\partial\rho^2} - \frac{1}{3\cosh^2\rho}\left(\frac{\partial^2\delta}{\partial\theta^2} + \frac{1}{\tan\theta}\frac{\partial\delta}{\partial\theta} + \frac{1}{\sin^2\theta}\frac{\partial^2\delta}{\partial\phi^2}\right) + \frac{4}{3}\tanh\rho\frac{\partial\delta}{\partial\rho}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

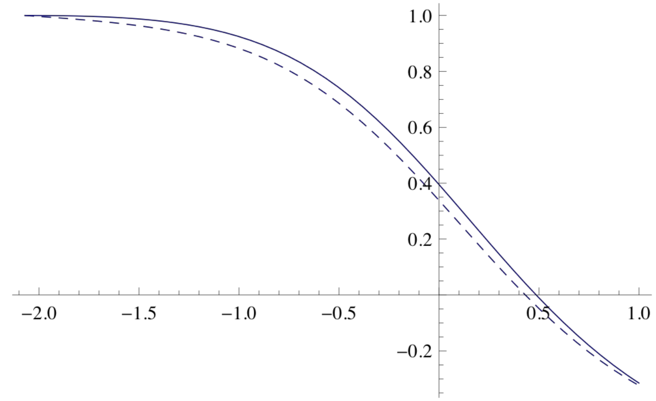
We have seen that in the short wavelength approximation we found a wave-like solution to equation 3.16, but now we would like to look for the exact solution, which can be found by using variable separation such that $\delta(\rho,\theta,\phi) = R(\rho)\Theta(\theta)\Phi(\theta)$, then

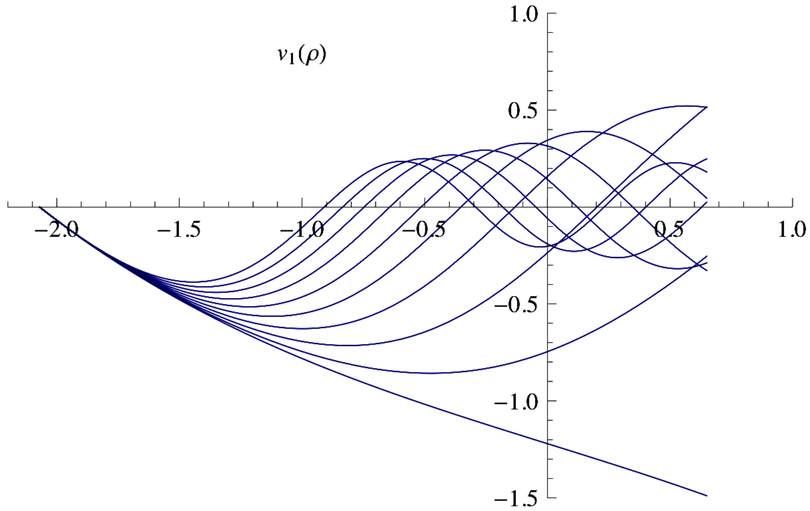
$$R(\rho) = \frac{C_1 P^{2/3}_{-\frac{1}{2}+\frac{1}{6}\sqrt{12\lambda+1}}(\tanh\rho) + C_2 Q^{2/3}_{-\frac{1}{2}+\frac{1}{6}\sqrt{12\lambda+1}}(\tanh\rho)}{(\cosh\rho)^{2/3}}$$
$$\Theta(\theta) = C_3 P_l^m(\cos\theta) + C_4 Q_l^m(\cos\theta)$$
$$\Phi(\phi) = C_5 e^{im\phi} + C_6 e^{-im\phi} \quad (3.26)$$

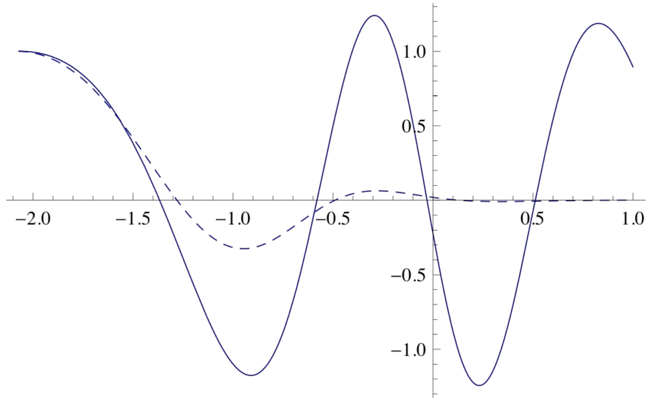
where $\lambda = l(l+1)$ and P and Q are associated Legendre polynomials. The part of the solution depending on θ and ϕ can be combined in order to form spherical harmonics $Y_{lm}(\theta,\phi)$, such that $\delta(\rho,\theta,\phi) \propto R_l(\rho)Y_{lm}(\theta,\phi)$.

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





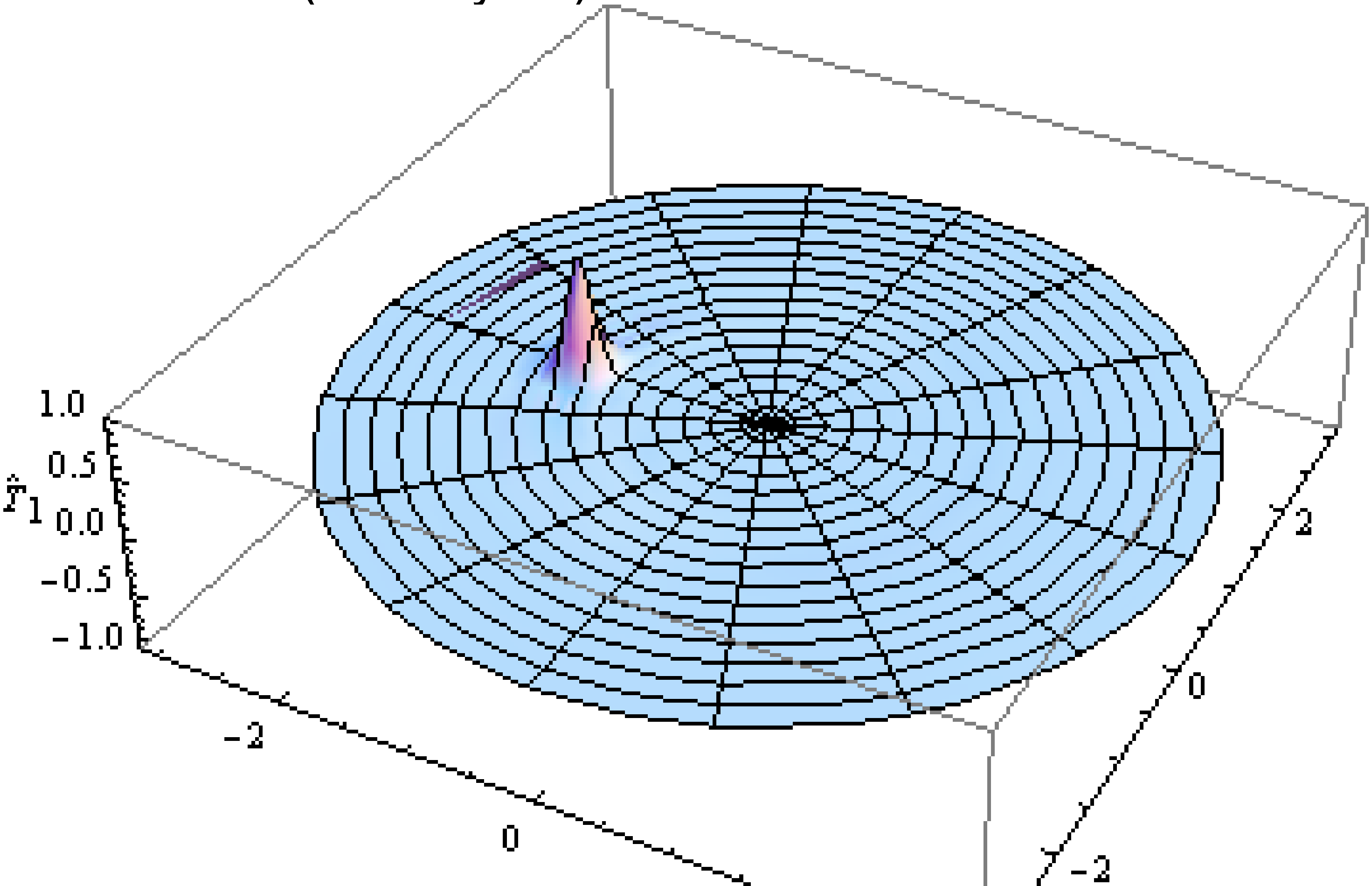


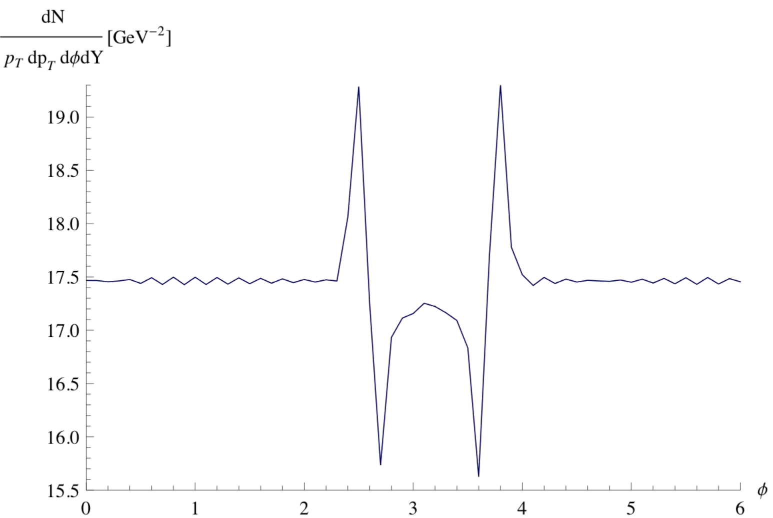


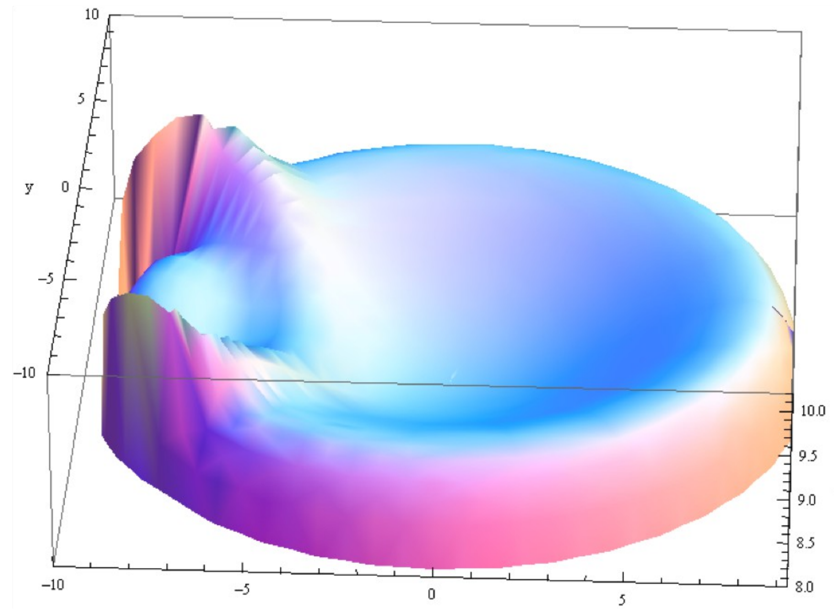
lhs (rho=-2) is initiation time and FO time is around zero

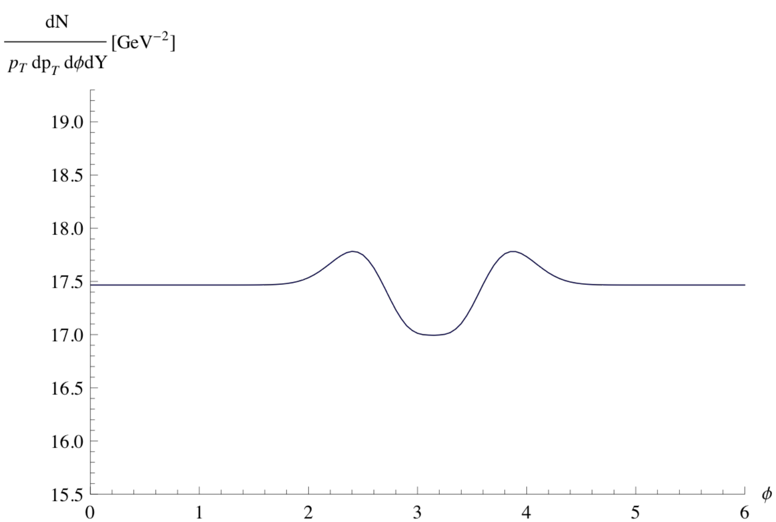
Viscosity (dashed) hardly affect The 1st harmonic, but nearly kills the 10th!

HERE IS THE SUM OF **all** (actually 30) HARMONICS





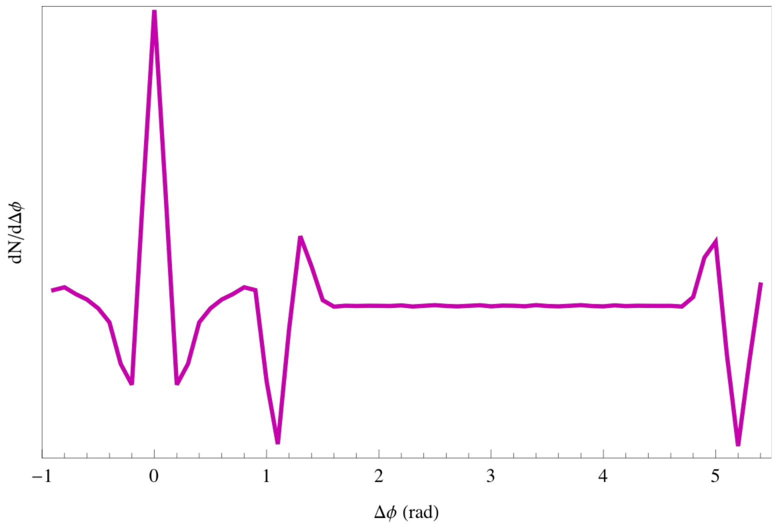


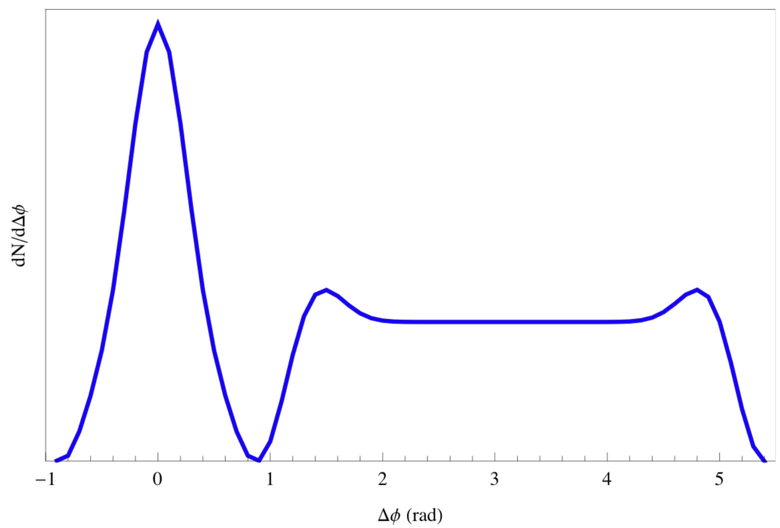


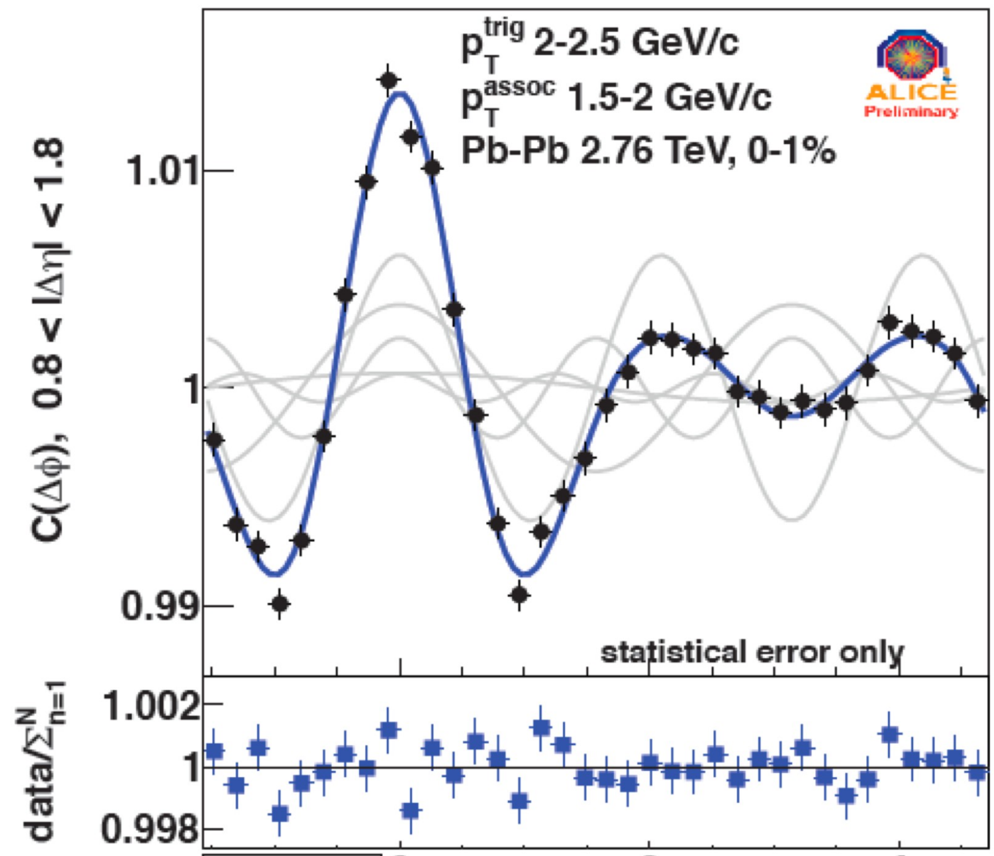
The modified freezeout
Surface (right) leads to
A modified angular distribution
Of particles, with and without viscosity
(left)

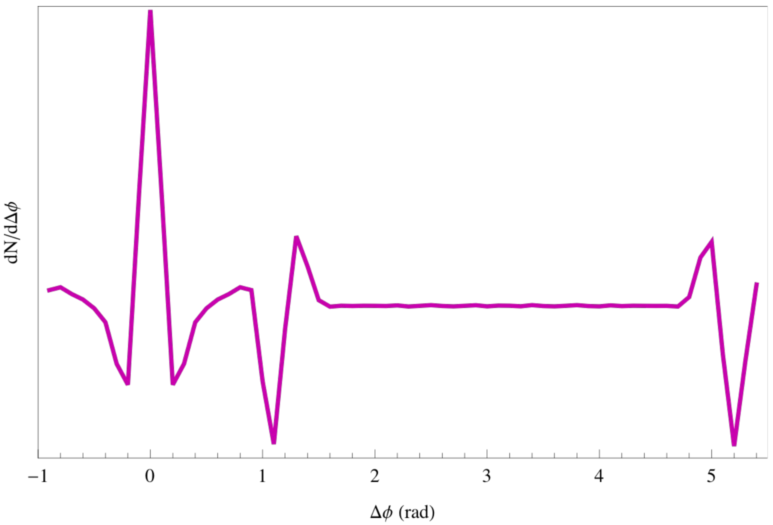
Left:4 pi eta/s=0, 2
Note shape change

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



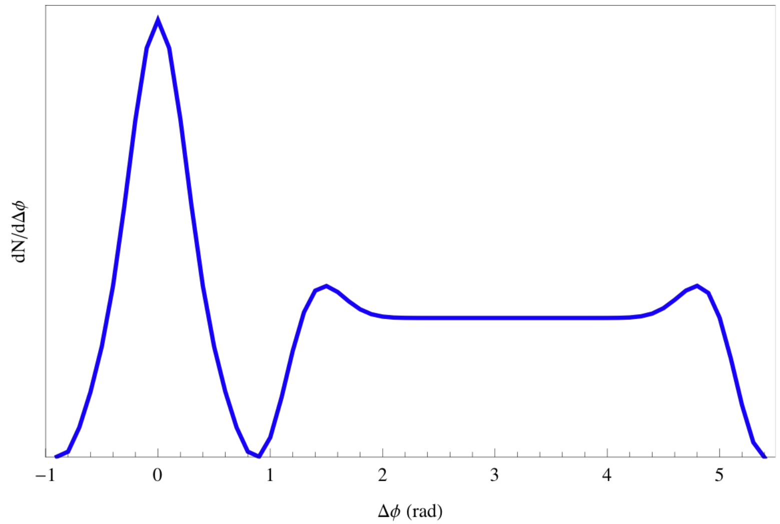


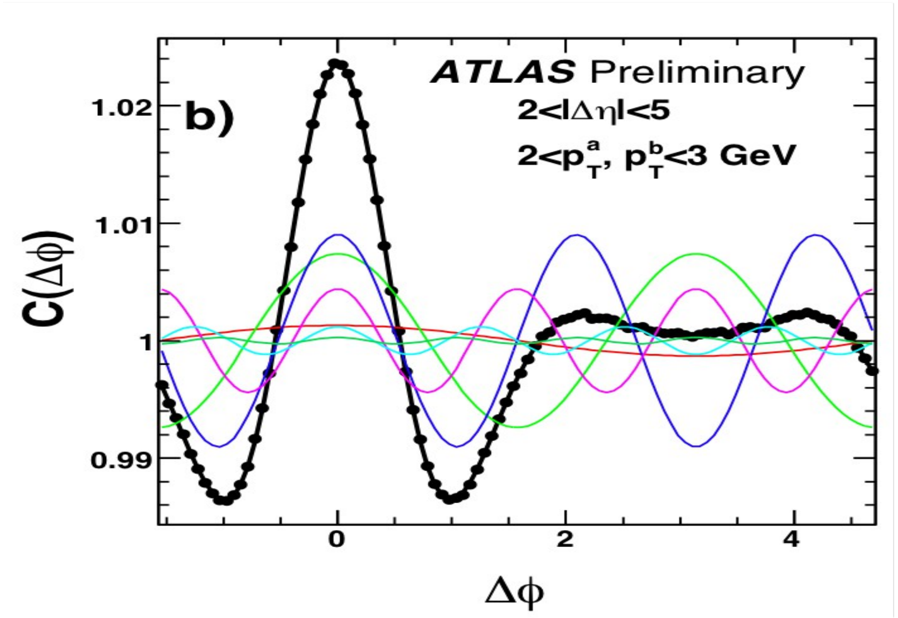




Left:4 pi eta/s=0, 2
Note shape change

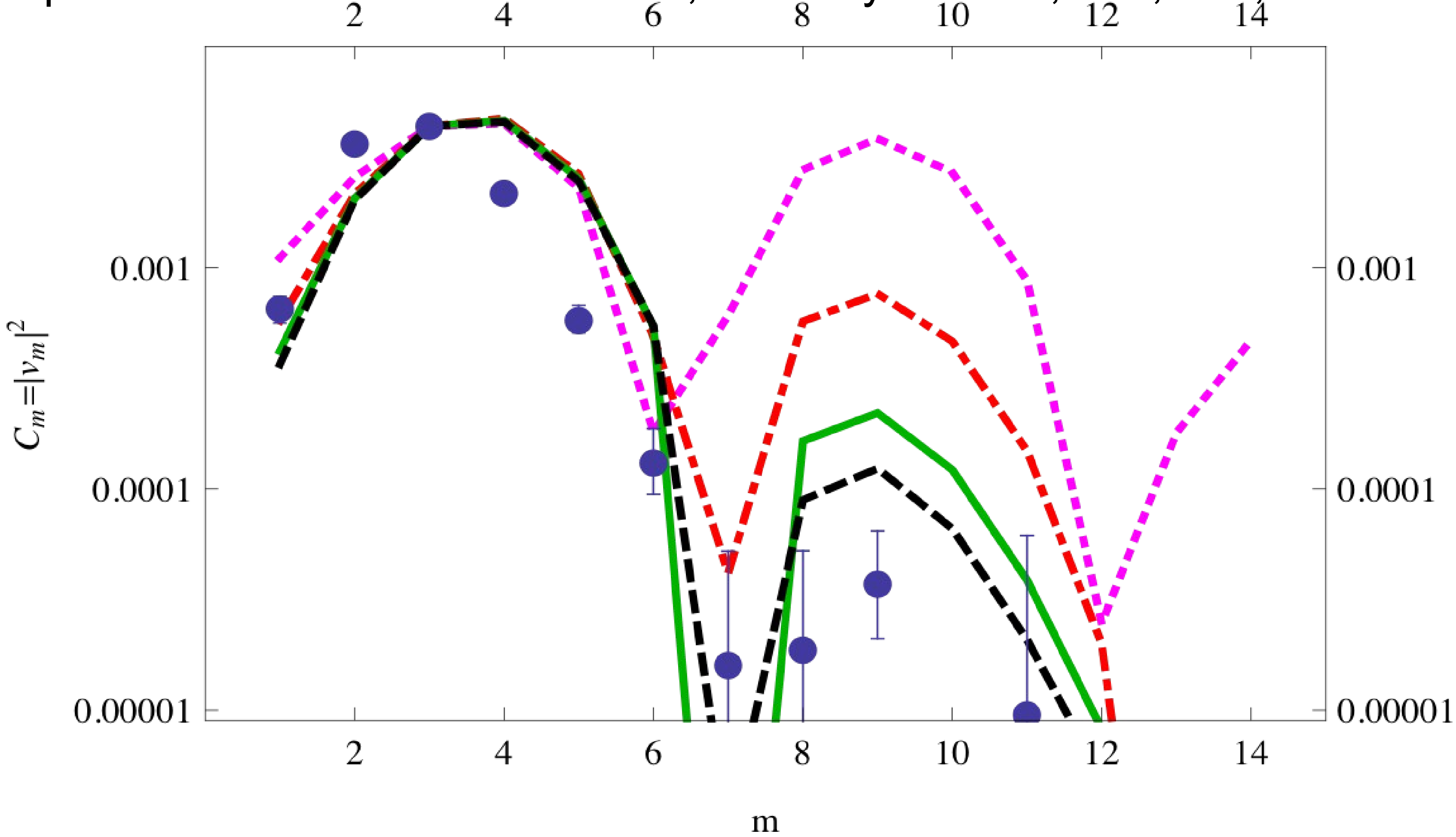
ATLAS central 1% correlators
Note shape agreement
No parameters, just Green
Function from a delta function





The power spectrum has acoustic minima/maxima (at m=7,12 and m=9)

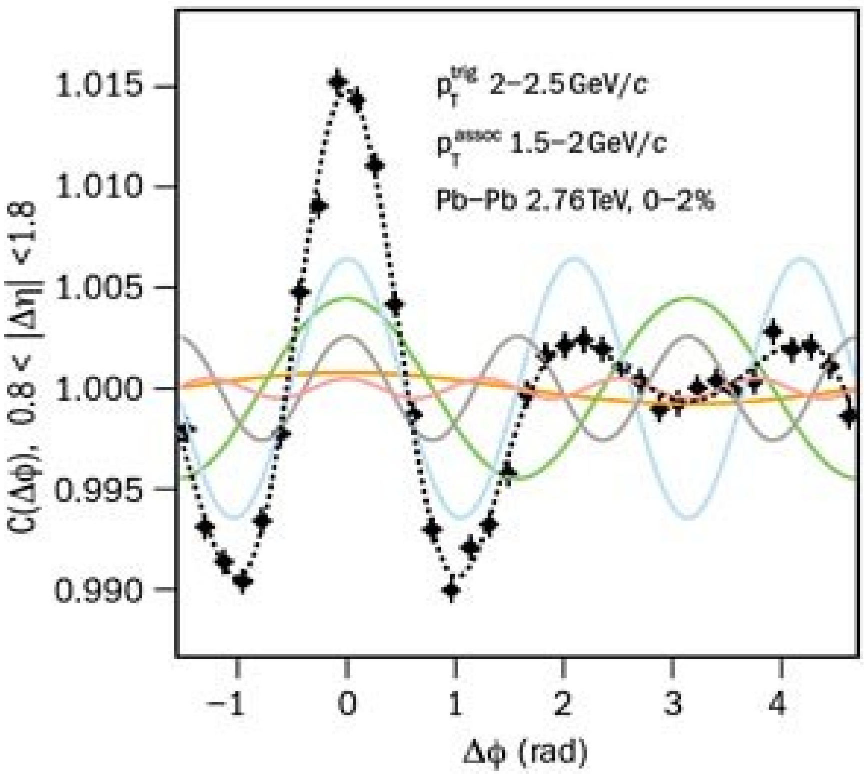
perturbation initial size is 0.7 fm, viscosity eta/s=0,0.08,0.13,0.16

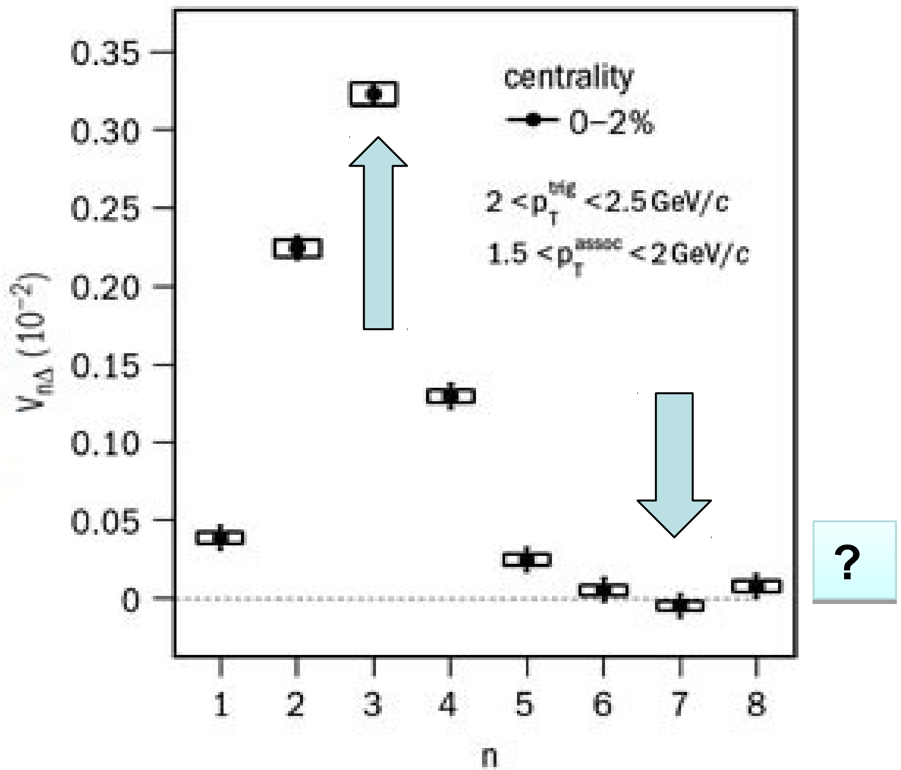


From october CERN Courier, the ALICE power spectrum:

do we see a minimum at n=7?

Maximum at 3 due to 120 degrees peak





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?**

What needs to be done

Are various harmonics coherent?

- **Minimal Gaussian model <=**
- **No coherence, the power plot P(<v_m^2>) is all we can possibly know about them**

Both for the Big and Little bangs the degree of coherence/ non-gaussianity is yet to be determined!

The “maximal coherence” model:

All harmonics come from the same local perturbation and are thus coherent

Evidences for that
From the Glauber model

Concentric circles in WMAP data may provide evidence of violent pre-Big-Bang activity

By V. G. Gurzadyan[1] and R. Penrose[2]

1.Yerevan Physics Institute and Yerevan State University, Yerevan, 0036, Armenia
2. Mathematical Institute,24-29 St Giles', Oxford OX1 3LB, U.K.

Note: not 1° but few times larger!

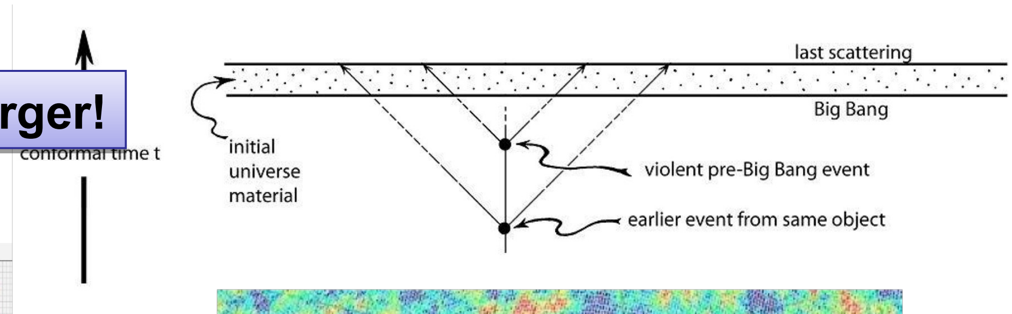


Figure 1.Conformal dia… …ly a galactic
clu…

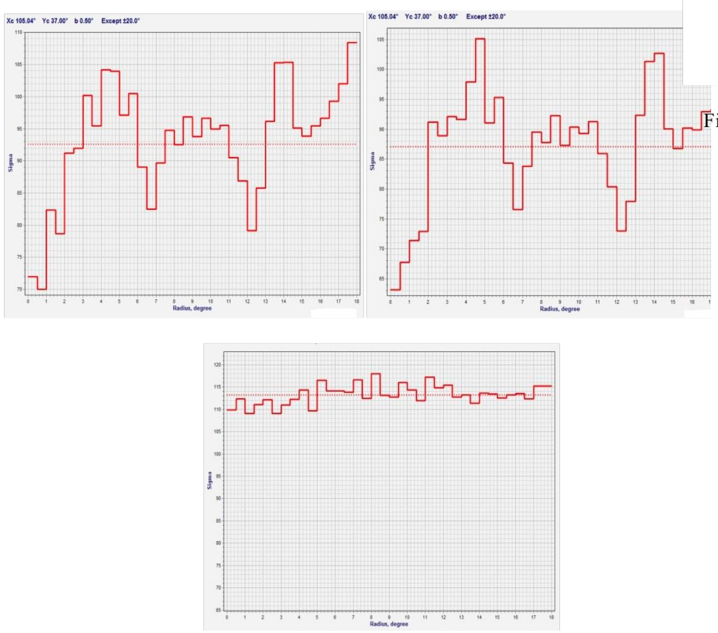
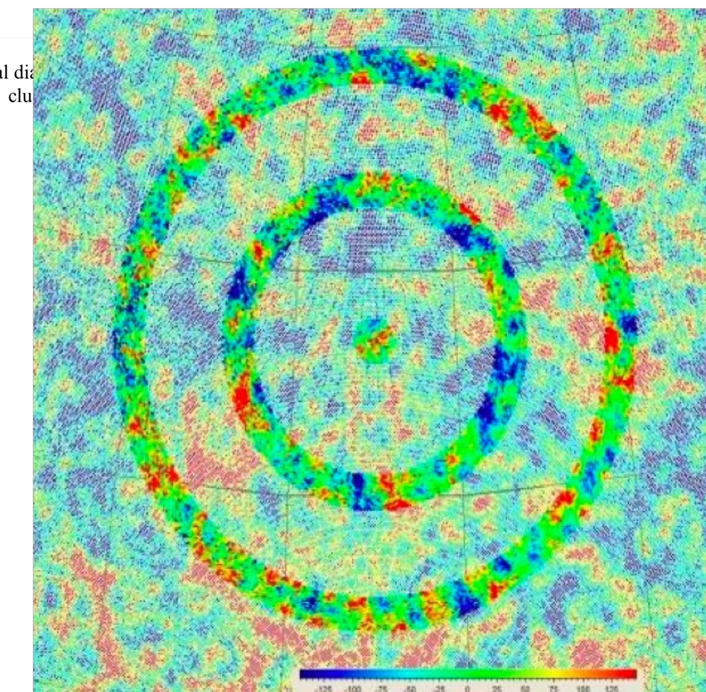
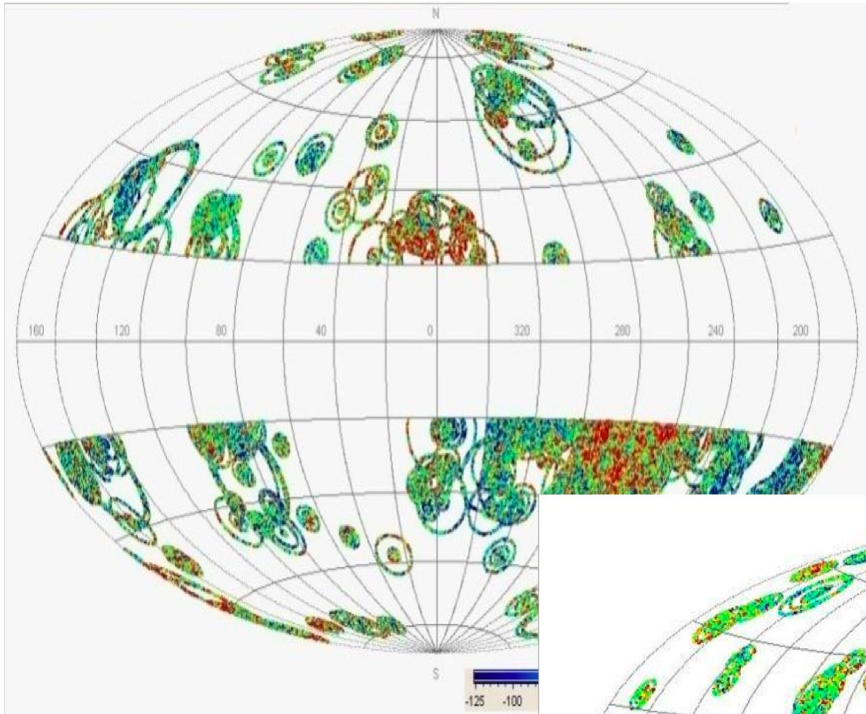


Figure 2. The temperature variance ring structures in WMAP W (a) and V (b) band maps. The Gaussian ma… simulated for WMAP W parameters is shown as well (c).





e 4. The sky distribution of concentric sets containing three
ates the positions of the centres, the lower one exhibits the actu

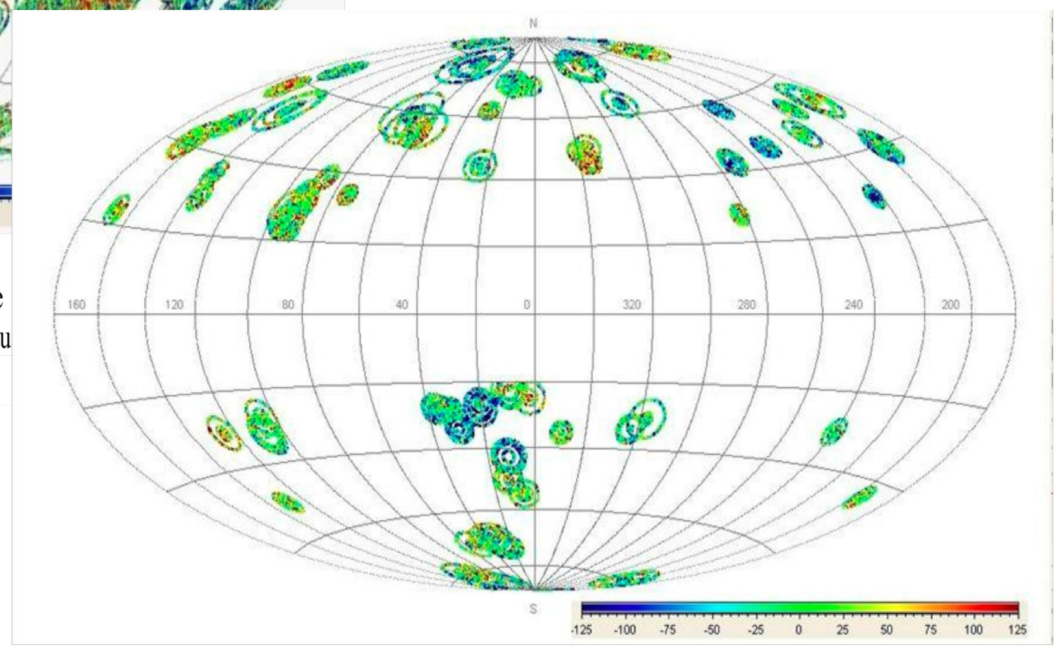


Figure 5. The corresponding maps to those of Figure 4, but where a simulated CMB sky is used incorporating WMAP's l-spectrum with randomized m-values. The differences are striking, notably the many fewer concentric sets, the absence of significant inhomogeneities and of large circles, and the much smaller departures from the average CMB temperatures.

How to do phase-sensitive measurements?

- Central collisions: 2 vs 3 particles

This is of course all well known , and usually written as the 2-body correlator

$$C_2(\Delta\phi) =< \frac{d^2N}{d\phi_1 d\phi_2} > |_{\psi_p} \quad (4.4)$$

decomposed into harmonics of its argument, which can be easily computed

$$c_{n\Delta} = \frac{\int d(\Delta\phi) C_2(\Delta\phi) cos(n\Delta\phi)}{\int d(\Delta\phi) C_2} =< v_n^2 > \quad (4.5)$$

Note that this correlation function provides the *squared* amplitudes of the original harmonics, *averaged* over the events. (As we assumed the exactly central collisions, none of the harmonics have average values, $< \epsilon_n >=< v_n >= 0$: thus all effects actually come from the root-mean-square fluctuations of ϵ_n.) This is e.g. how Alver and Roland [12] and others have obtained their estimates for the "triangular" flow. Note again, that the phases of the harmonics *disappear* in this function, and thus remain undetermined.

However, the situation is different for *three* (or more) body correlation functions: the phases survive and thus can be found. Indeed, now the single-body distribution (4.2) is cubed (or raised into higher power), so one finds a *triple* sum in which the random perturbation direction appears as $exp[i(n_1+n_2+n_3)\psi_p]$. Averaging over it, one finds the condition

$$n_1 + n_2 + n_3 = 0 \quad (4.6)$$

One then can e.g. eliminate n_3 and find the double sum

$$\sum_{n_1,n_2} \epsilon_{n_1}\epsilon_{n_2}\epsilon_{n_1+n_2} exp\{i[n_1(\phi_1-\phi_3)+n_2(\phi_2-\phi_3) \\ -n_1(\tilde{\psi}_{n_1}-\tilde{\psi}_{n_1+n_2})-n_2(\tilde{\psi}_{n_1}-\tilde{\psi}_{n_1+n_2})]\}$$

Staig+ES, summer 2010
And also the same idea was
Known in cosmology

Glauber fluctuations up to 6th are all comparable

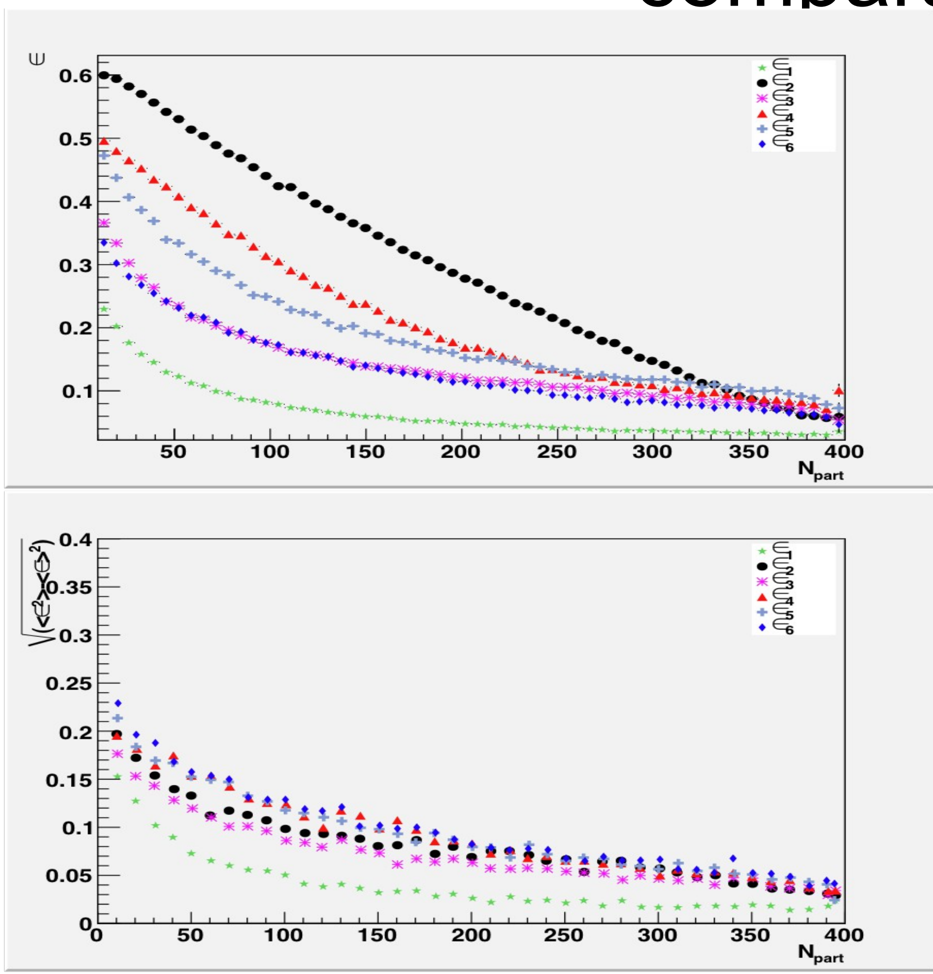


FIG. 5: Average anisotropies (upper plot) and their variations (lower), as a function of centrality expressed via the number of participants N_{part}

$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \cos(n\phi)\rangle^2}}{\langle r^n \rangle}$$

$$\epsilon_1 = \frac{\sqrt{\langle r^3 \cos(\phi)\rangle^2 + \langle r^3 \cos(\phi)\rangle^2}}{\langle r^3 \rangle}$$

The angles ψ_n are defined by:

$$\tan(n\psi_n) = \frac{\langle r^n \sin(n\phi)\rangle}{\langle r^n \cos(n\phi)\rangle}$$

and to calculate ψ_1 we use:

$$\tan(\psi_1) = \frac{\langle r^3 \sin(\phi)\rangle}{\langle r^3 \cos(\phi)\rangle}$$

•The odds are **all** correlated!
There are “tips” and ”waist” peaks
geometry tells us that peripheral events
should be both 2- and 3-peaks

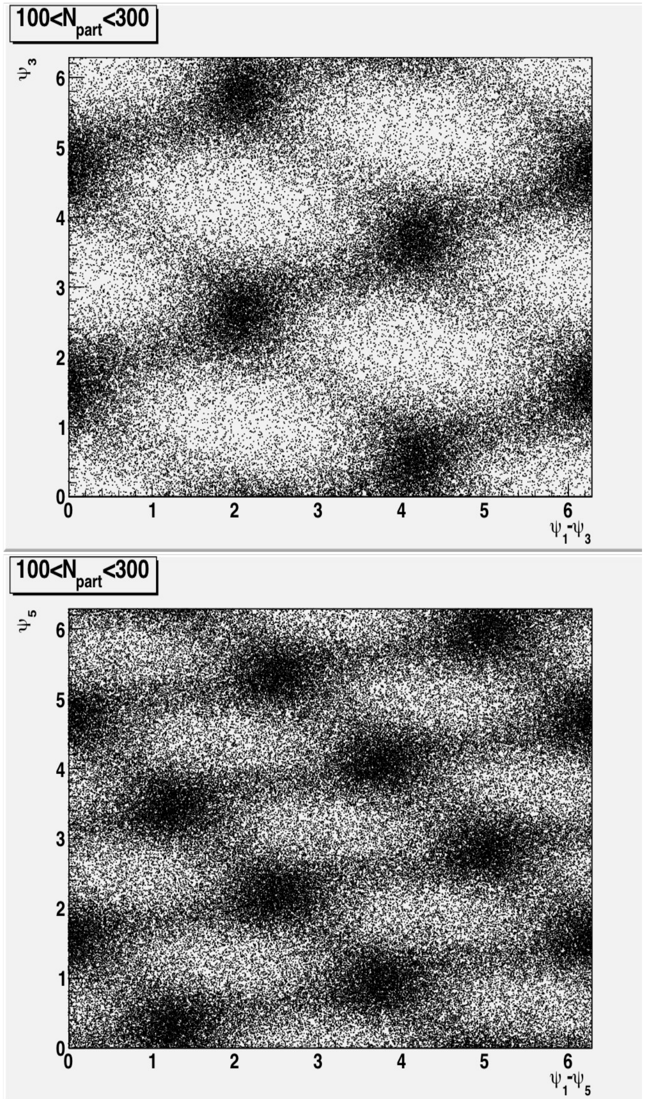


FIG. 8: Scatter plot of the ψ_3 vs $\psi_3 - \psi_1$ (above), and of the ψ_5 vs $\psi_5 - \psi_1$ (below), the same centrality

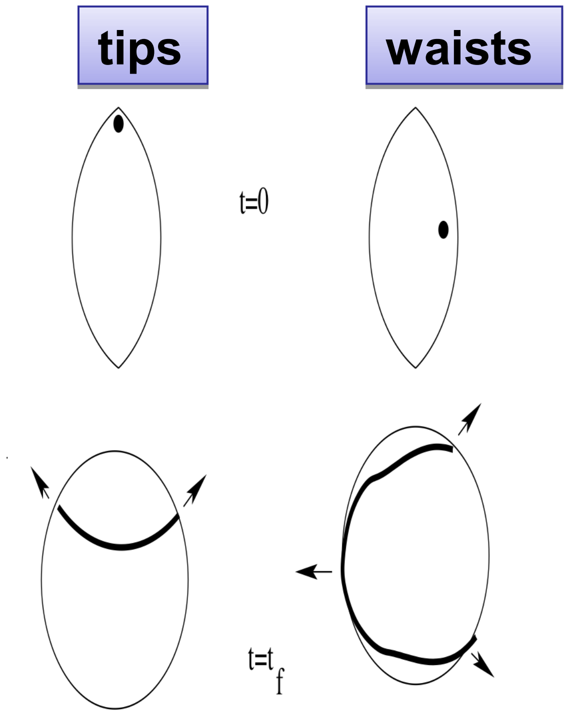


FIG. 4: Two upper picture correspond to initial time $t = 0$: the system has almond shape and contains perturbations (black spots). Two lower pictures show schematically location and diffuseness of the sound fronts at the freezeout time t_f. The arrows indicate the angular direction of the maxima in the angular distributions, 2 and 3 respectively.

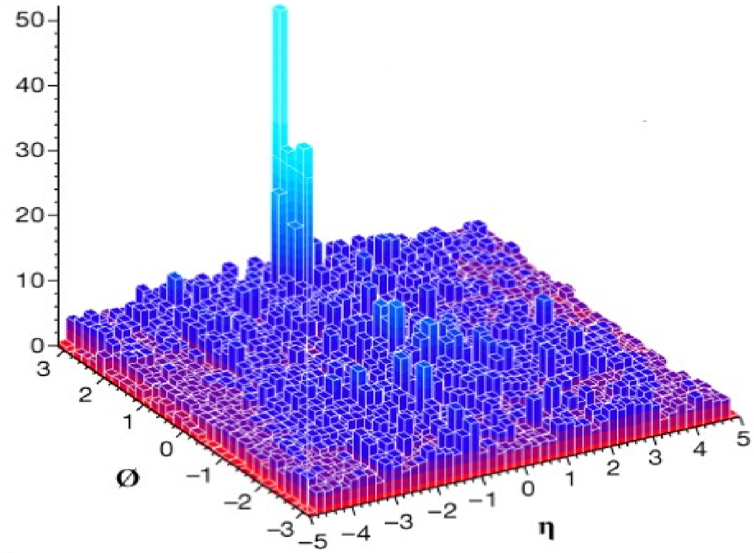
2- or 3-peak events? can be separated by the relative phase of the 3ed and other Harmonics!

For central collisions theory prediction are very clear: 2 horns!

LHC jets as sources of sounds/shocks

Much more energetic jets and stronger quenching is found at LHC!

ATLAS, 1st PRL on heavy ions, Accepted in one (Thanksgiving!) day



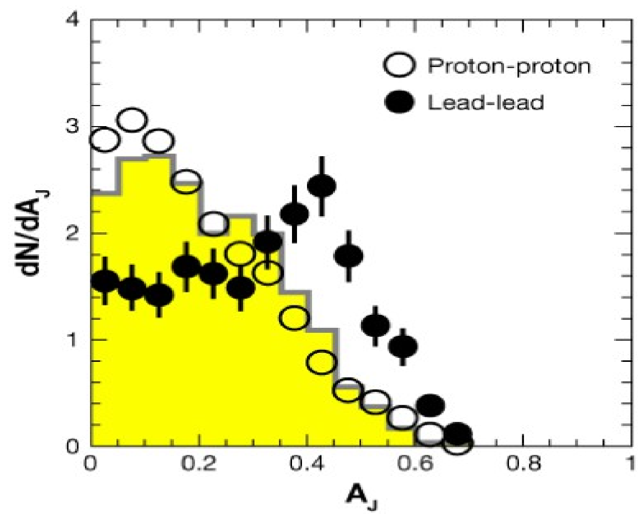


FIG. 2: (Left) Example of a jet without a visible partner. (Right) Asymmetric jets (where one jet loses most of its energy) are rare in proton-proton collisions, but the ATLAS measurements showed such events occur with a high probability in lead-lead collisions. The asymmetry A_j for two jets with energy E_1 and E_2 is defined as $A_j = (E_1 - E_2)/(E_1 + E_2)$. (Credit: G. Aad *et al.*, [2])

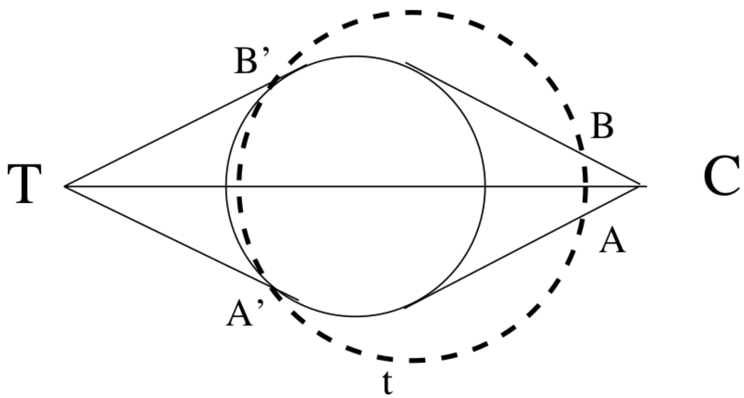
Jet/Fireball Edge should be observable!

Edward Shuryak

Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794

(Dated: January 26, 2011)

Shock/sound propagation from the quenched jets have well-defined front, separating the fireball into regions which are and are not affected. While even for the most robust jet quenching observed this increases local temperature and flow of ambient matter by only few percent at most, strong radial flow increases the contrast between the two regions so that the difference should be well seen in particle spectra at some p_t, perhaps even on event-by-event basis. We further show that the effect comes mostly from certain ellipse-shaped 1-d curve, the intercept of three 3-d surfaces, the Mach cone history, the timelike and spacelike freezeout surfaces. We further suggest that this "edge" is already seen in an event released by ATLAS collaboration.



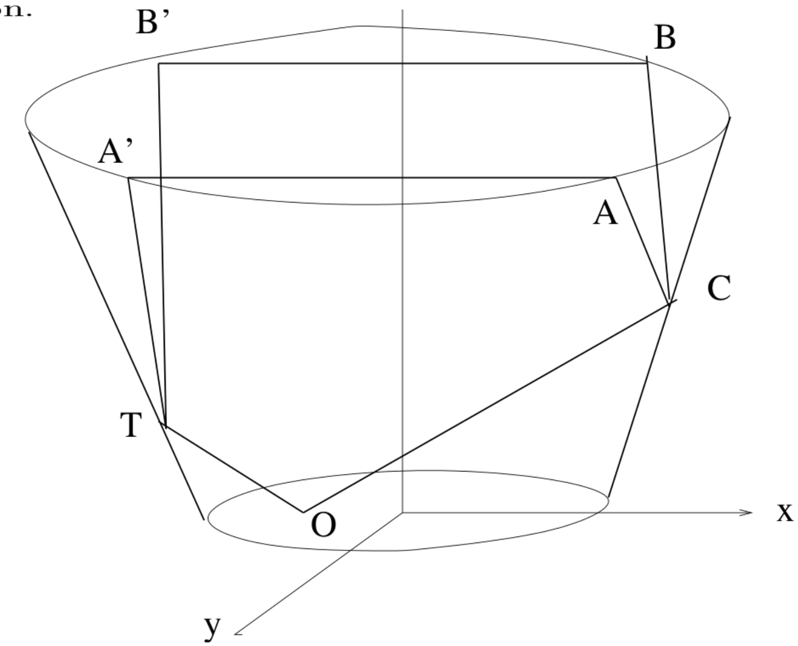
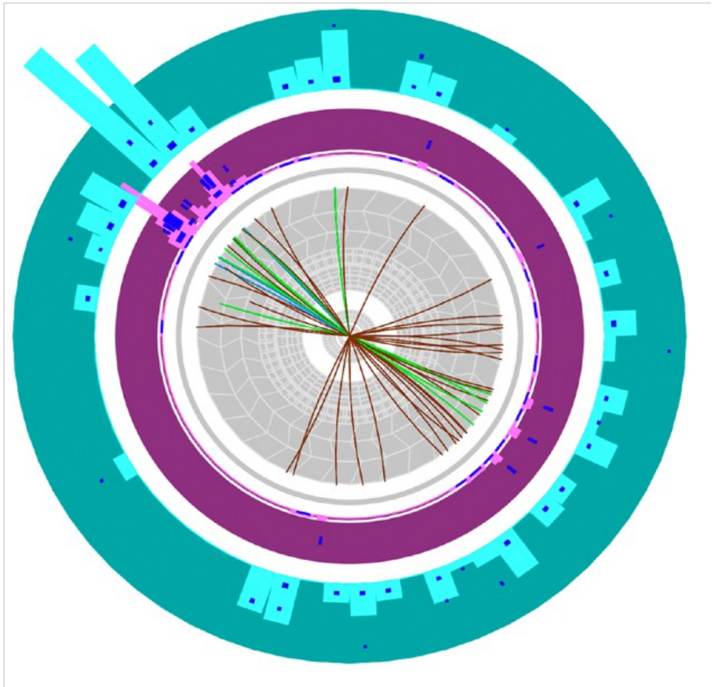


FIG. 1: Schematic shape of the Mach surface in the transverse x, y plane at $z = 0$ and fixed time (upper plot), as well as its shape in 3d including the (proper longitudinal) time (lower plot). Mach surface σ_M is made of two parts, $OCAA'T$ and $OCBB'T$. For more explanations see text.

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

$$\Delta\phi = \pm\frac{H s(t,t_f)}{R}$$



- ATLAS 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“?**

Geometric acoustics can describe modification of shapes by flow

$$\frac{d\vec{r}}{dt} = \frac{\partial \omega(\vec{k},\vec{r})}{\partial \vec{k}}\,,$$
$$\frac{d\vec{k}}{dt} = -\frac{\partial \omega(\vec{k},\vec{r})}{\partial \vec{r}}\,,$$

In this case the dispersion relation is obtained from that in the fluid at rest by a local Galilean transformation, so that

$$\omega(\vec{k},\vec{r}) = c_s k + \vec{k}\vec{u}\,. \qquad (4.3)$$

In the simplest case of constant flow vector $\vec{u} = const(r)$ the first of these eqn just obtains an additive correction by flow

$$\frac{d\vec{r}}{dt} = c_s \vec{n}_{\vec{k}} + \vec{u}\,, \qquad (4.4)$$

where $\vec{n}_{\vec{k}} = \vec{k}/k$ is the unit vector in the direction of the momentum. The second eqn gives $\frac{d\vec{k}}{dt} = 0$ as there is no

a (generalized) Hubble-like flow

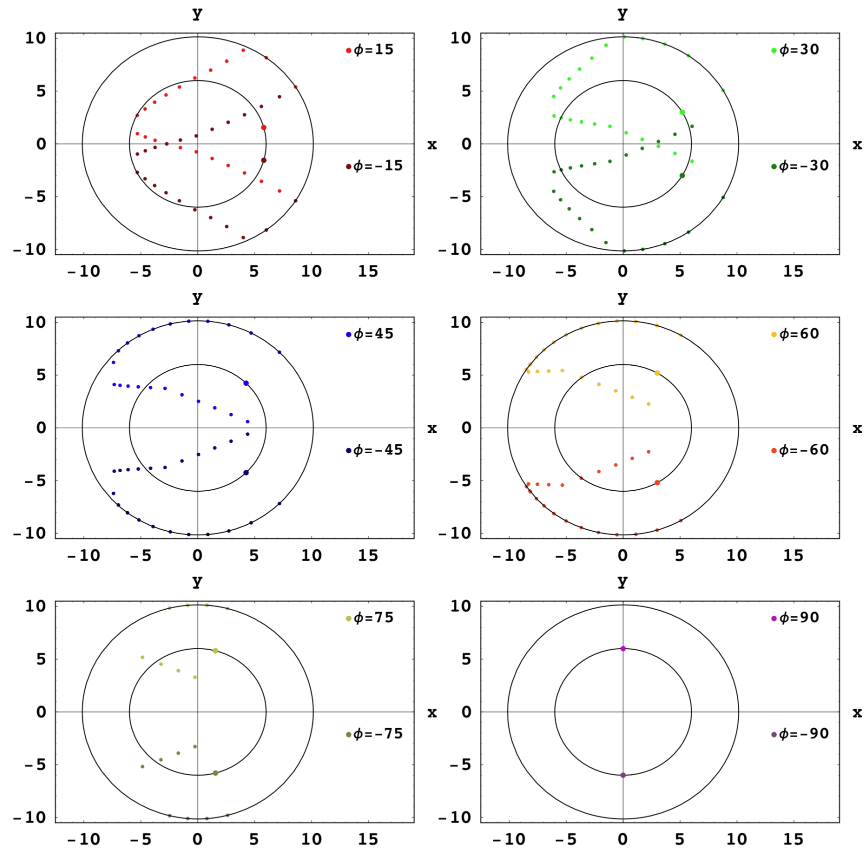
$$u_i(r) = H_{ij} r_j\,, \qquad (4.5)$$

with some time and coordinate independent Hubble tensor. The eqn (4.2) now reads

$$\frac{dk_i}{dt} = -H_{ij} k_j\,, \qquad (4.6)$$

$k_i(t) = exp(-H_i t) k_i(0)$. $\quad \vec{r}(t) = t c_s \vec{n}_{\vec{k}} + \vec{r}(0) exp(+Ht)\,.$

Relativistic flow brings in Lorentz factor, easily solvable numerically: e.g.



Sound Waves from Quenched Jets

Vladimir Khachatryan and Edward Shuryak

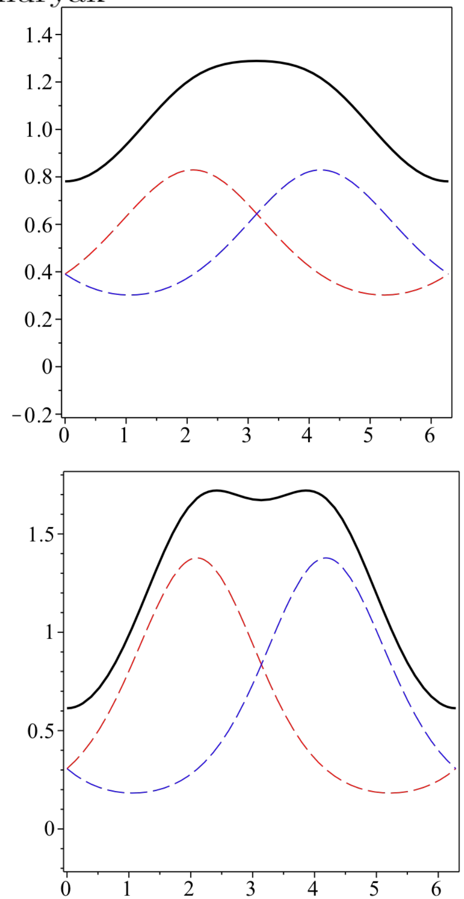


FIG. 10: (Color online) The spectrum vs ϕ_p at $p_t = 1\,GeV$ and $2\,GeV$, for $dE/dx = 1\,GeV/fm$. The contribution to the spectrum mostly comes from a phonon at the "cross" in Fig.2. The red and blue dashed lines show contributions of the jets in the upper ($\alpha > 0$) and lower ($\alpha < 0$) half plane in Fig.1.

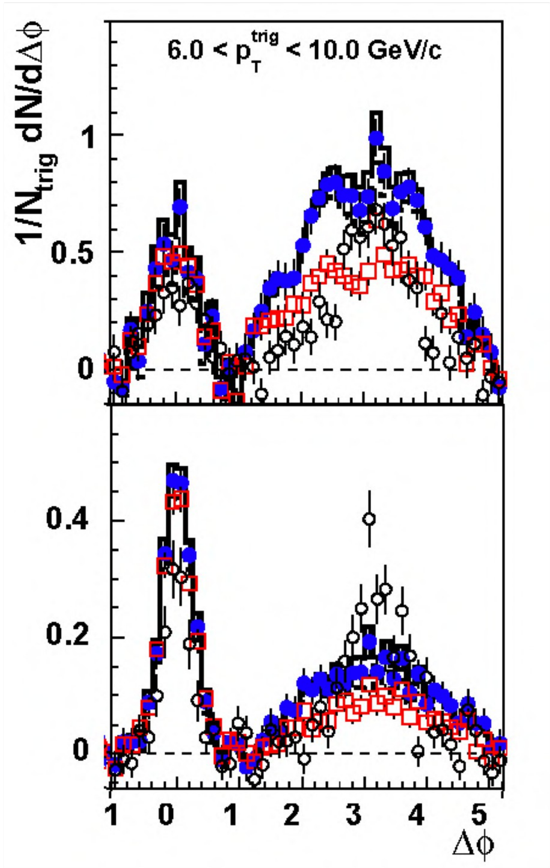


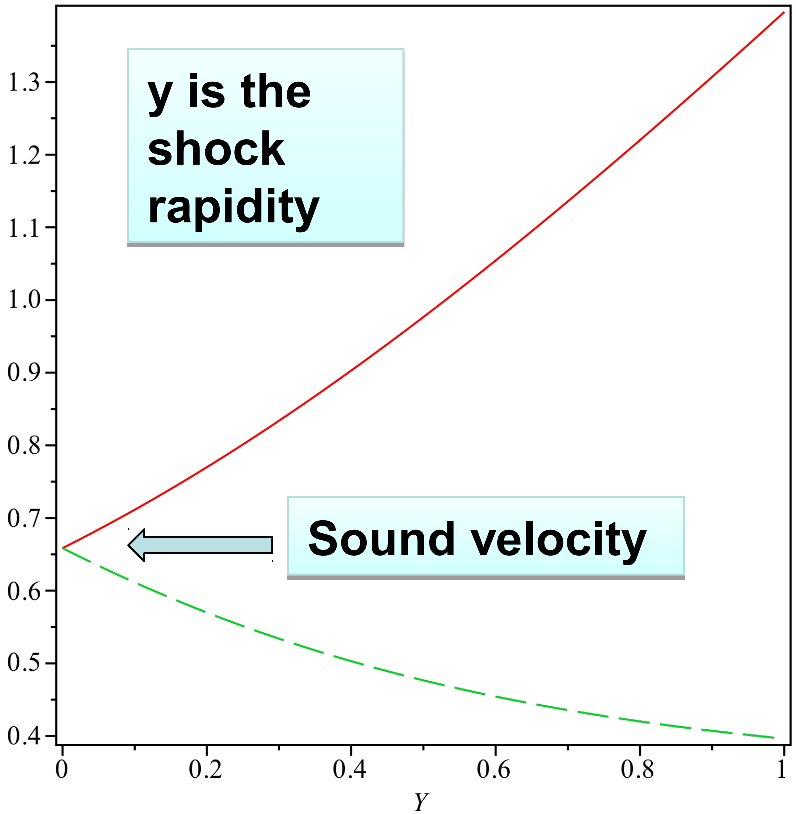
FIG. 11: (Color online) From [33]. Background-subtracted azimuthal angle difference distributions for near-central collisions (fraction of the total cross section 0-12%). The associated particles have the range of p_T between $0.5 - 1\,GeV/c$ (upper figure), between $1.5 - 2.5\,GeV/c$ (lower figure), and the trigger particles have p_T ranging from 6.0 to $10.0\,GeV/c$. The data for Au+Au collisions are shown by the solid circles and for d+Au by the open circles. The rapidity range is $|\eta| < 1$ and as a result the rapidity difference is $|\Delta\eta| < 2$. Open red squares show results for a restricted acceptance of $|\Delta\eta| < 0.7$. The solid and dashed histograms show the upper and lower range of the systematic uncertainty due to the v_2 modulation subtracted.

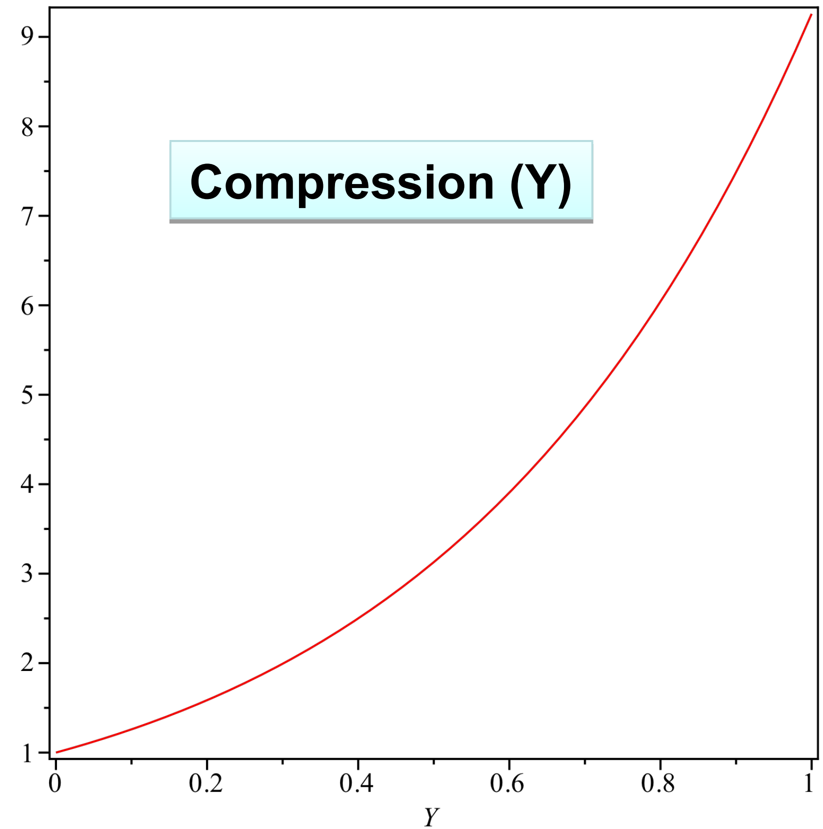
but in average together with another half-plane it creates a plateau-like sum. As p_t grows, it starts develop a double-hump structure reminiscent of the original Mach

If the deposited energy is large, we have shocks rather than sounds, and this will increase angles

$$-4\,p\_f\cosh(Y-y)\sinh(Y-y) = 4\,p\_i\cosh(y)\sinh(y)$$

$$3\,p\_f\sinh(Y-y)^2 + p\_f\cosh(Y-y)^2 = 3\,p\_i\sinh(y)^2 + p\_i\cosh(y)^2$$





Comments on jet quenching

- Is it due to charge or energy?
- Is it pQCD, radiation of gluons, or AdS/CFT, radiation of gravitons (sounds)?
- (transverse quantum kicks vs longitudinal classical breaking force)

Jet Quenching via Gravitational Radiation in Thermal AdS

Edward Shuryak, Ho-Ung Yee, and Ismail Zahed

Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794

(Dated: October 4, 2011)

We argue that classical bulk gravitational radiation effects in AdS/CFT, previously ignored because of their subleading nature in the $1/N_c$-expansion, are magnified by powers of large Lorentz factors γ for ultrarelativistic jets, thereby dominating other forms of jet energy loss in holography at finite temperature. We make use of the induced gravitational self-force in thermal AdS_5 to estimate its effects. In a thermal medium, relativistic jets may loose most of their energy through longitudinal drag caused by the energy accumulated in their nearby field as they zip through the strongly coupled plasma.

D. Cyclotron versus gravitational radiation

The first step toward relating two very different motivations mentioned in the earlier part of introduction has been done by one of us (with Khriplovich) nearly 40 years ago [17], applying the same method to 4 problems: cyclotron electromagnetic/gravitational radiations in flat or curved 3+1 dimensional spaces in the ultrarelativistic regime $\gamma \gg 1$. The results for the radiation intensity are

$$\mathbf{I}^{\text{flat}}_{\text{e.m.}} \approx e^2\gamma^4/R^2, \qquad \mathbf{I}^{\text{flat}}_{\text{grav}} \approx G_4 m^2\gamma^4/R^2,$$
$$\mathbf{I}^{\text{curv}}_{\text{e.m.}} \approx e^2\gamma^2/R^2, \qquad \mathbf{I}^{\text{curv}}_{\text{grav}} \approx G_4 m^2\gamma^2/R^2, \quad (1.6)$$

But calculate gravitational radiation from ultrarelativistic body is hard!

Can we calculate the Self-force?

II. SELF-FORCE IN GENERAL RELATIVITY

The local self-force in 3+1 gravity with zero cosmological constant was derived originally by Mino, Sasaki and Tanaka and also Queen and Wald [2, 3]. As we noted in the introduction and now we repeat for completeness,

$$m\ddot{x}^a = G_5 m^2 \dot{x}^b \dot{x}^c \int_{-\infty}^{\tau_-} d\tau' \left(\frac{1}{2}\nabla^a \mathbf{G}^-_{bca'b'} - \nabla_b \mathbf{G}^{-a}_{c\ \ a'b'} - \frac{1}{2}\dot{x}^a\dot{x}^d\nabla_d\,\mathbf{G}^-_{bca'b'}\right)\dot{x'}^{a}\dot{x'}^{b}, \quad (2.1)$$

But does it actually work?
It is zero in flat 3+1 dimensions!

Self-force

$$2+1: \quad (m\ddot{x}^a)_L \approx -\frac{2e^2}{\sqrt{3}}\frac{\ddot{x}\cdot\ddot{x}}{\sqrt{\ddot{x}\cdot\ddot{x}}}\,\dot{x}^a,$$

$$4+1: \quad (m\ddot{x}^a)_L \approx -\frac{e^2}{10\sqrt{3}}\frac{\dddot{x}\cdot\dddot{x}}{\sqrt{\ddot{x}\cdot\ddot{x}}}\,\dot{x}^a,$$

- We defined/calculated it in flat 2+1 and 4+1 dimensions, in the former one it matches exactly the radiation intensity
- Grav.radiation in thermal (B.H.) AdS5

$$m\ddot{x}^a \approx -\frac{G_5 m^2}{30\pi}\left(\frac{4}{\sqrt{6\,\dddot{x}\cdot\dddot{x}}}\right)\mathbf{R}^m{}_e{}^n{}_b\mathbf{R}_{mcnd}\;\dot{x}^e\dot{x}^b\dot{x}^c\dot{x}^d\;\dot{x}^a,$$

Finally, we note that the longitudinal covariant force following from a dragging colored string is of the order of $\gamma\sqrt{\lambda}T^2$ [14, 15]. The ratio of the longitudinal drag from gravitational radiation (or selfforce) to color is

$$\frac{\text{gravity}-\text{radiation}-\text{drag}}{\text{color}-\text{drag}} \approx \frac{\gamma^2}{N_c^2\sqrt{\lambda}} \approx \frac{10^{2..4}}{10\times 5}, \quad (3.21)$$

not small, for typical jets at RHIC and LHC with $\gamma = 10-100$. Of course, the derivation given is perturbative, without back reaction explicitly included. (It means it is only formally valid for N_c, λ exceeding the realistic values of $N_c = 3$ and $\lambda \approx 25$.)

Subleading in Nc but maybe not small !

: Summary

- **LHC/ALICE sees large (30% larger) elliptic (and radial) flows, exactly as Hydro 1 predicted already 10 years ago!**
  => QGP @ LHC remains a very good liquid !

- **Hydro 2: Quantitative analytic theory in the linear approximation => Green function from a point perturbation (for Gubser flow)**
  Reproduces the correlators beautifully, best with viscosity $\frac{4\pi\eta}{\hbar s} \approx 2$
  So,we see the sound traversing the Little Bang, perhaps Even the second maximum…

- **Homework: Phases of higher harmonics can/should be measured in 3-particle correlators!**

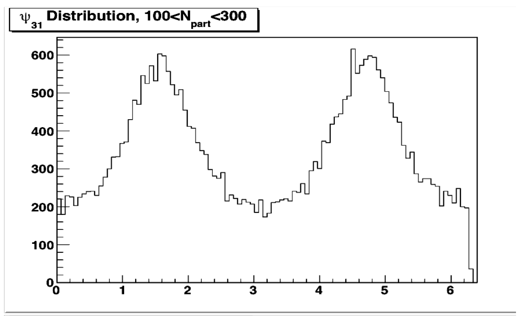
- **Large energy deposition to matter from jets creates sound/shocks, and also make the inside of the Mach cone**

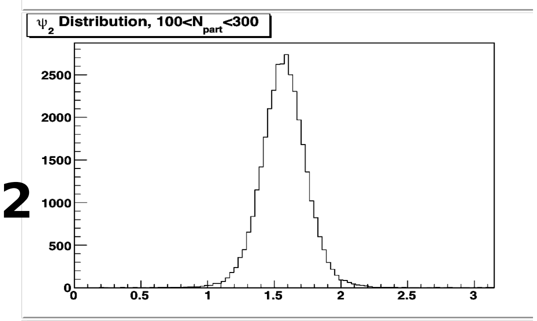
extras

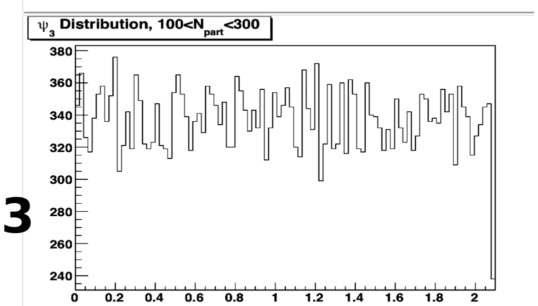
"While throwing stones into the pond, watch carefully the circles they make, or else this occupation is meaningless" K.Prutkov

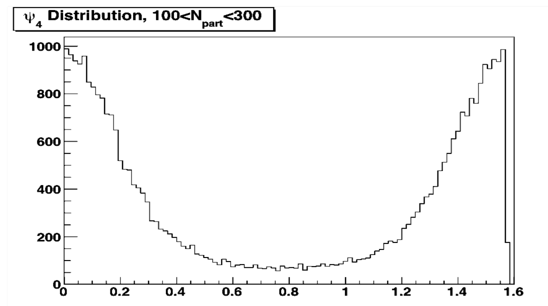
1. Hydro1: sQGP remains a good liquid at LHC
2. Hydro2: perturbations. Initial "hot spots" => "circles" => are observed in correlations
3. Sounds from the "Tiny Bangs" are solved analytically (on top of "Gubser flow), even with viscosity
4. Mach cones separate (slightly) hotter matter from the unperturbed one: the "edge" should be observable in events with large O(100 GeV) deposition, and is perhaps already seen at LHC!)

Distribution of the angles

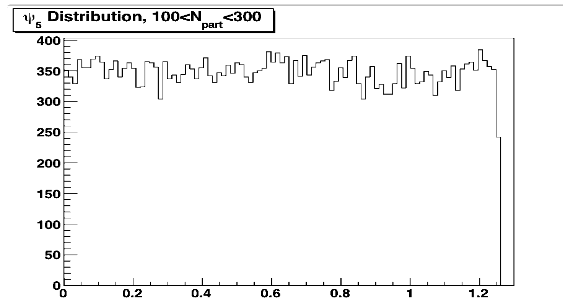
1


2


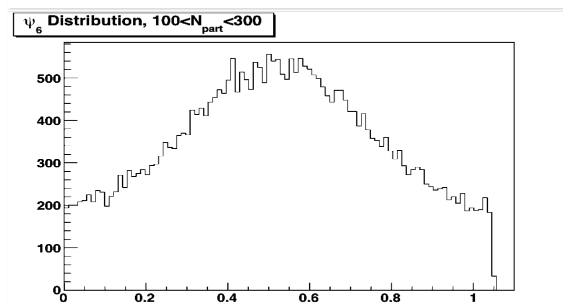
3




4

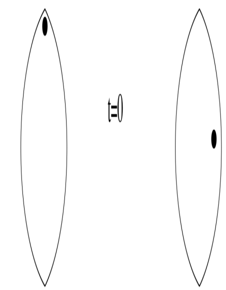


5



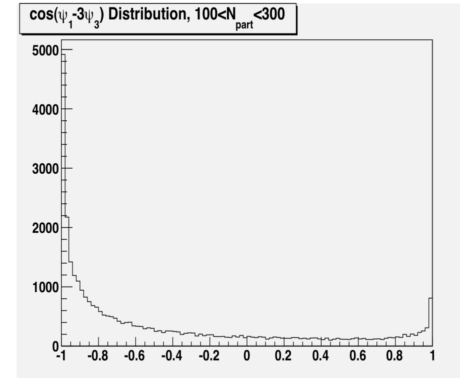
6

1st : tips and waist



3ed and 5th Uncorrelated?

Non-central collisions, no integral => n1+2=n2, such as 1+2=3,3+2=5



"tips" => all angles are about 90^o

Let us present some details about this case, which will illustrate a general case. Let us make a simplification, writing only the second harmonics in the weight and ignoring small fluctuations in the magnitude and the angle ψ_2 around $\pi/2$ (see Fig.6b)

$$W(\psi_p) = 1 + 2W_2 cos(2(\psi_p - \pi/2)) + ... \qquad (4.10)$$

where $W_2 \approx 0.95$.One can then calculate any moments of the 2-body distribution, for example the one corresponding to 1+2=3 term

experiment

$$\int \frac{d\phi_1}{2\pi}\frac{d\phi_2}{2\pi} cos\,(\phi_1 - 3\phi_2) < \frac{d^2N}{d\phi_1 d\phi_2} > |_W$$

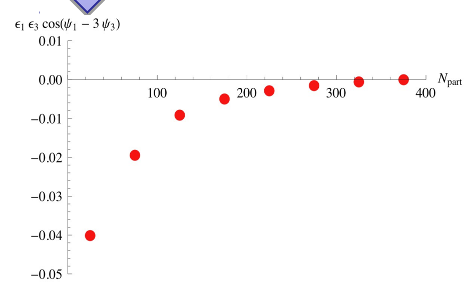
$$\approx -W_2(\frac{v_1}{\epsilon_1})(\frac{v_3}{\epsilon_3}) < \epsilon_1\epsilon_3 cos(3\psi_3 - \psi_1) >$$

Glauber

(or other initial state model)

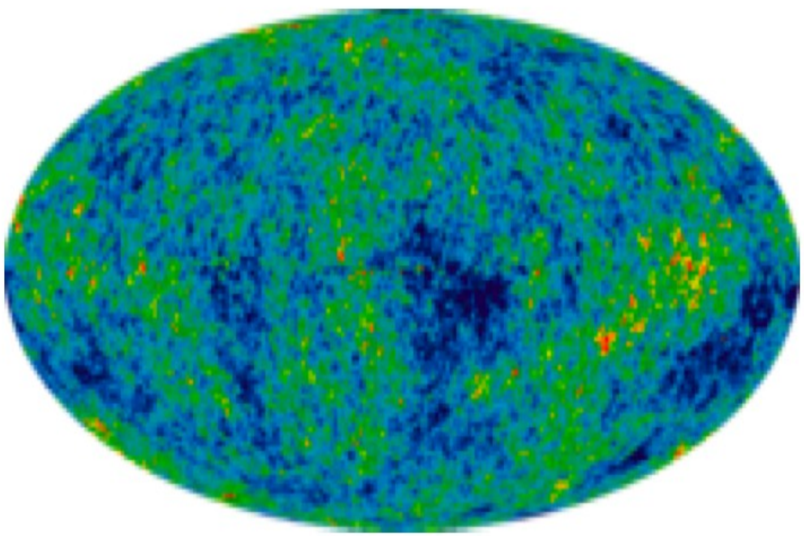
hydro

Here we have separated the ratios $v_1/\epsilon_1, v_3/\epsilon_3$ (which are calculable by hydrodynamics) from the subsequent angular bracket containing the initial state deformations and their phases: those are to be averaged over the ensemble of initial conditions. For example, calculated in the Glauber model as explained at the beginning of the paper we obtain



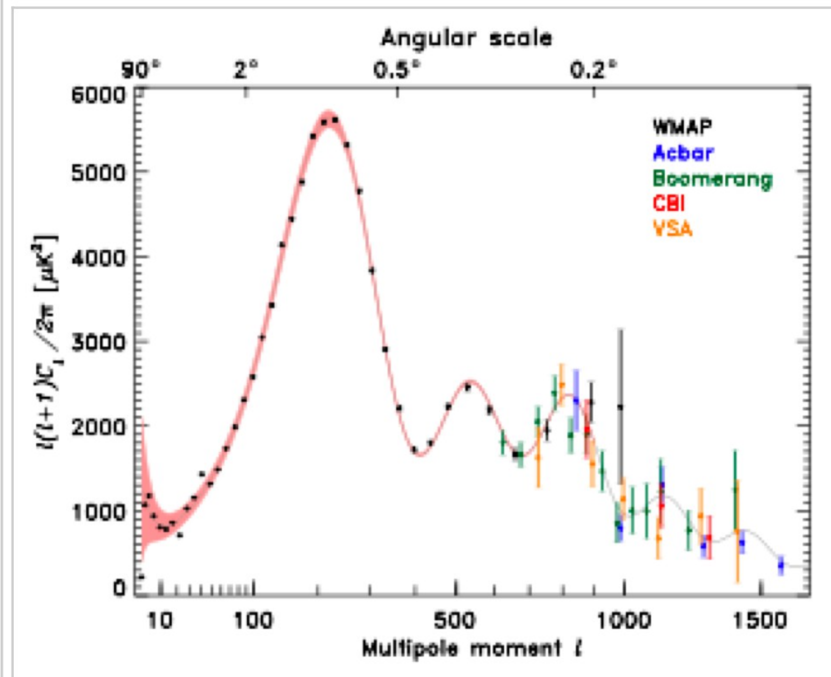
More about CMB fluctuations

41. ^ Zeldovich, Y. B. (1972). "A hypothesis, unifying the structure and the entropy of the Universe". *Monthly Notices of the Royal Astronomical Society* **160**: 1P–4P. doi:10.1016/S0026-0576(07)80178-4 (http://dx.doi.org/10.1016%2FS0026-0576%2807%2980178-4) .
42. ^ Doroshkevich, A. G.; Zel'Dovich, Y. B.; Syunyaev, R. A. (12–16 September 1977). "Fluctuations of the microwave background radiation in the adiabatic and entropic theories of galaxy formation". In Longair, M. S. and Einasto, J.. *The large scale structure of the universe; Proceedings of the Symposium*. Tallinn, Estonian SSR: Dordrecht, D. Reidel Publishing Co.. pp. 393–404. Bibcode: 1978IAUS...79..393S (http://adsabs.harvard.edu/abs/1978IAUS...79..393S) . While this is the first paper to discuss the detailed observational imprint of density inhomogeneities as anisotropies in the cosmic microwave background, some of the groundwork was laid in Peebles and Yu, above.

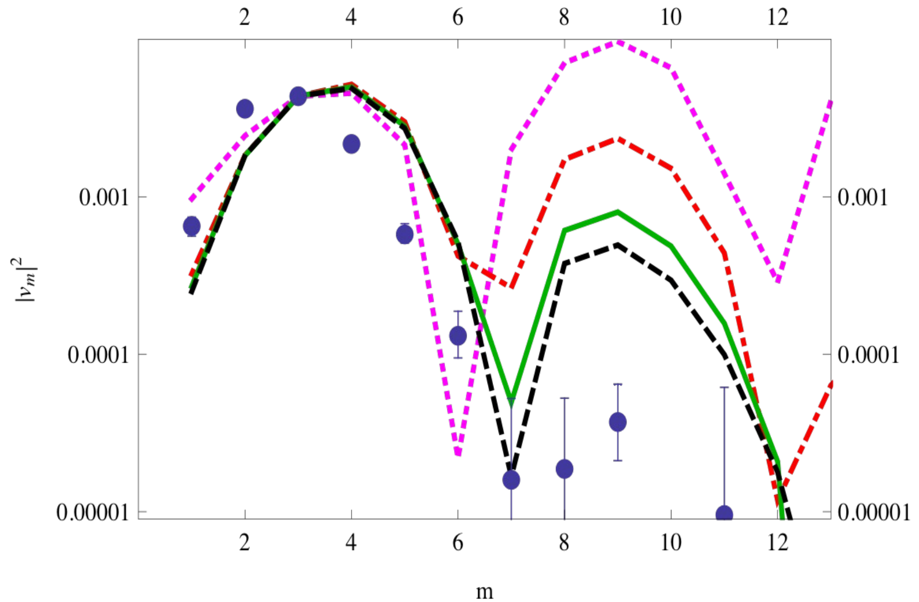


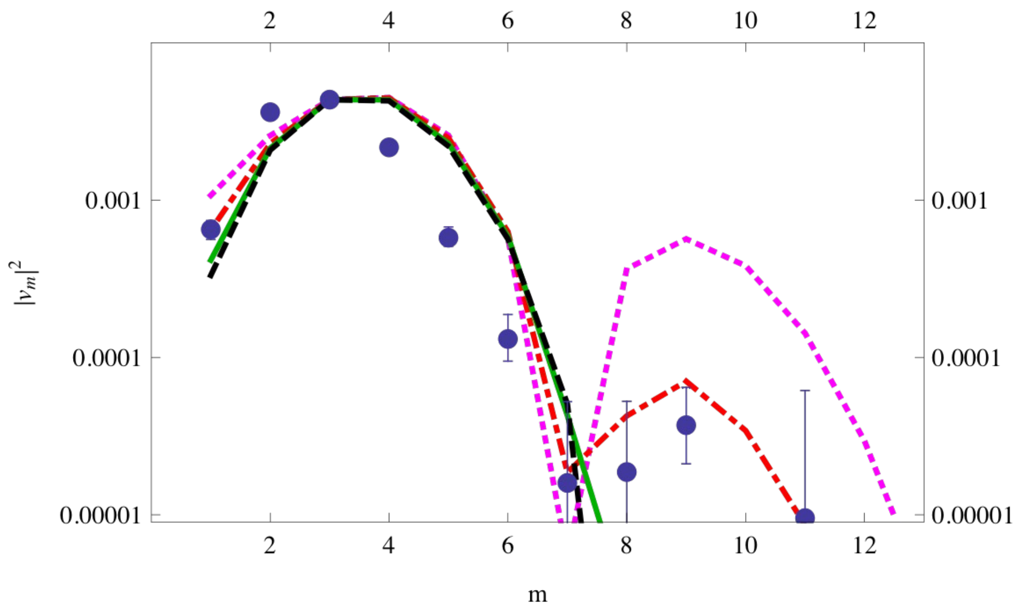
The same scale is seen in CMB and correlations of the galaxies:

All correspond to Sound Horizon,
The distance sound travel before neutralization



The power spectrum of the cosmic microwave background radiation temperature anisotropy in





The power spectrum

Points – ATLAS preliminary

upper plot: small size perturbation, various viscosities
Lower plot: about 1 fm size

A dip around m=7 and maximum around 9 have The same acoustic origin as in the Big Bang => zero amplitude of the ``observable combination" at freezeout