Crete, Frontiers in Physics June 2012

The sounds of the Big and the Little Bangs (the second act of hydro)

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plan

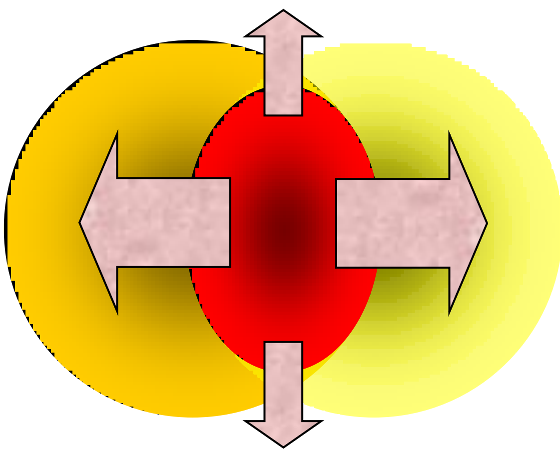
- Reminder of the radial and elliptic flows
- Sound perturbations in the Big Bang
- Sounds in the Little Bang: comparison
- The second act of hydro

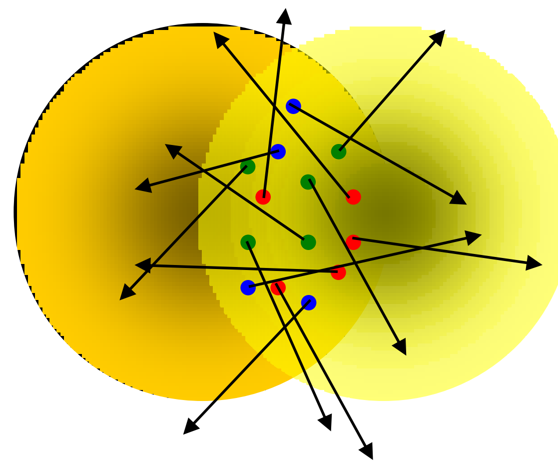
The second approximations: Newton and Einstein

- Comparison with RHIC/LHC data
- Sounds from jets: Mach cones revisited

Contrary to expectations of most, hydrodynamics does work at RHIC!

$$1 + \sum 2v_n cos(n\phi)$$





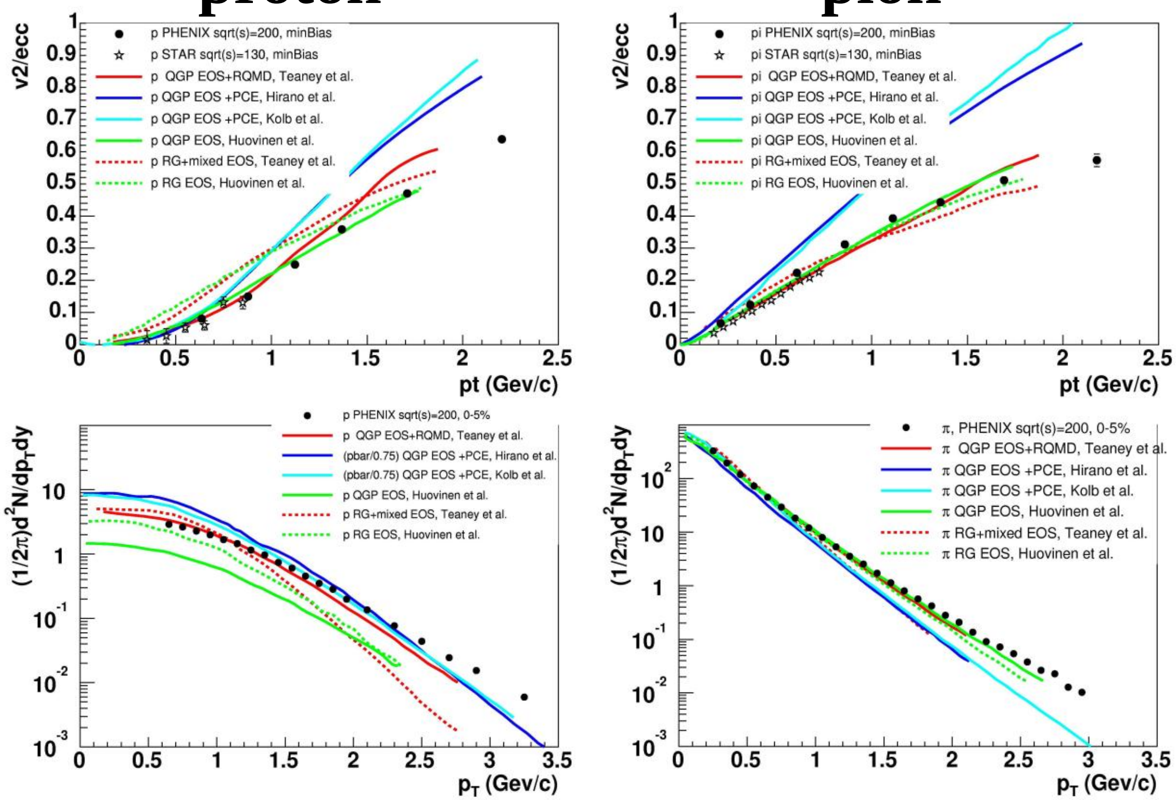
How does the system respond to initial spatial anisotropy? => Hydrodynamics converts it into final anisotropy of the momenta of secondaries

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)

While our experimental friends had made their detectors during 2000-2010, the theorists debated the following question:

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?**

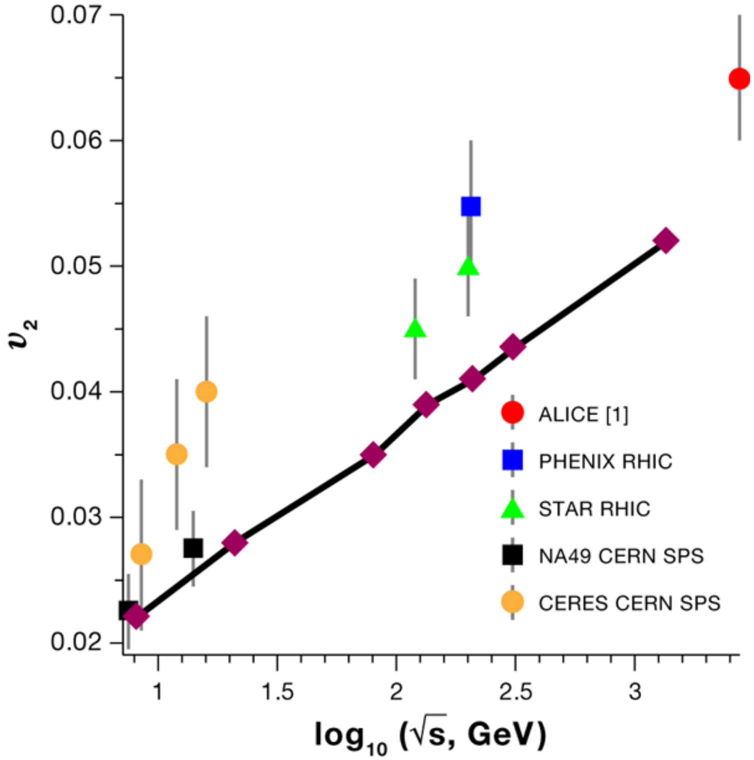


FIG. 1: The ALICE experiment suggests that the quark-gluon plasma remains a strongly coupled liquid, even at temperatures that are 30% greater than what was available at RHIC. The plot shows the "elliptic flow parameter" v_2 (a measure of the coupling in the plasma) at different heavy-ion collision energies,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

The growth with energy happens because QGP is stiffer (has the pressure/e.density higher) than hadronic matter, and larger fraction of the time is spent in QGP at LHC However when E=> infinity and p=(1/3)epslon, V_2 => constant

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

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

Fate of the initial state perturbations in heavy ion collisions

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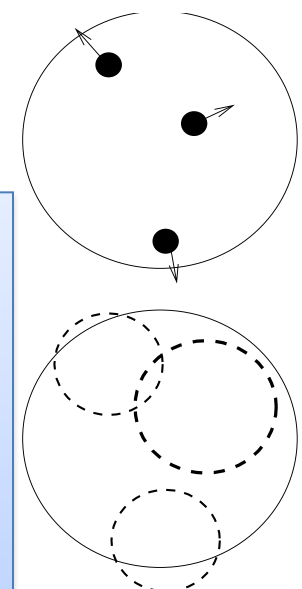
(Received 20 July 2009; revised manuscript received 14 October 2009; published 13 November 2009)

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

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



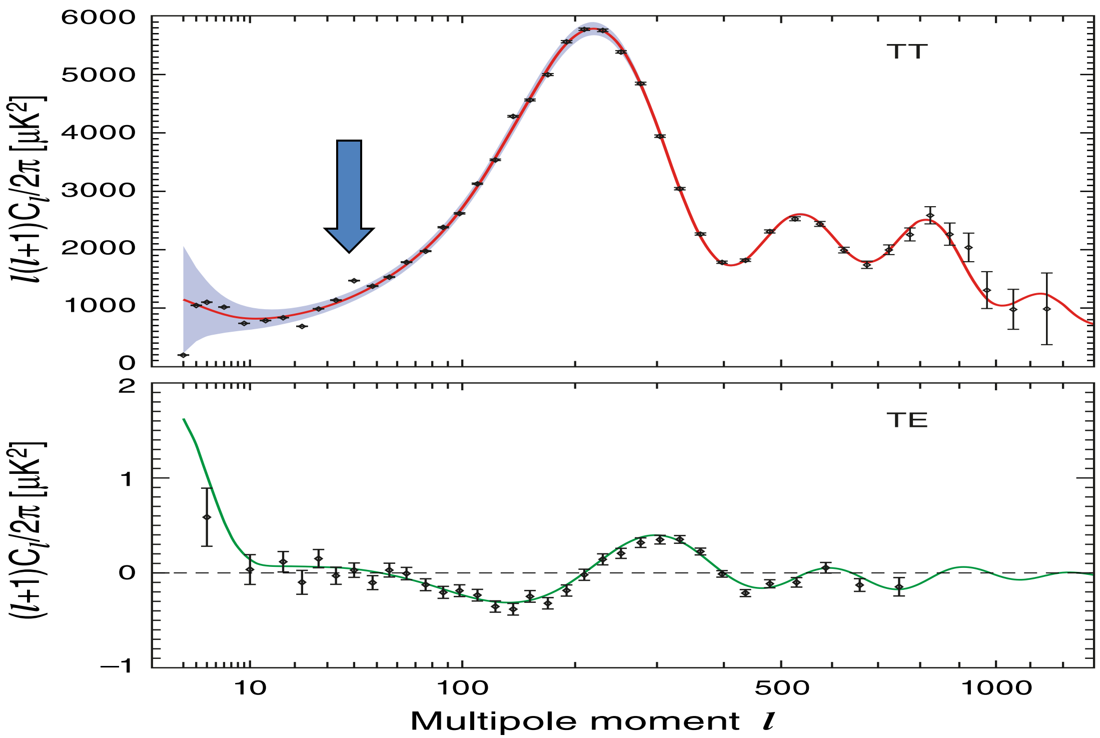
Freezeout time about 12 fm/c
Radius of the circle about 6 fm,
Comparable to the fireball size

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

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]



Note that some unexplained phenomena at small Harmonics remain

current space mission, PLANK, will provide much better data this year (stay tuned)

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 $\sigma_8 = 0.809 \pm 0.024$.

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

(P.Staig,ES,2010)

1.The sound horizon: radius of about 6 fm

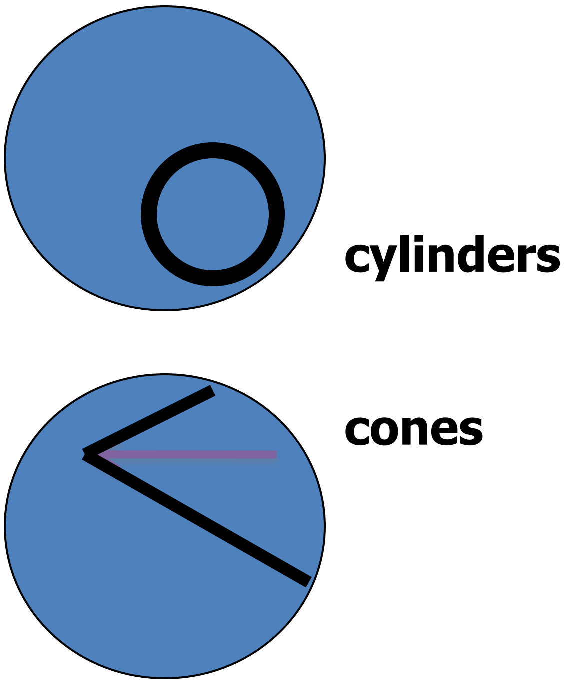
$$H_s = \int_0^{\tau_f} d\tau c_s(\tau)$$

For the Big Bang it is about 150 Mps today

2.The viscous horizon: The width of the circle

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

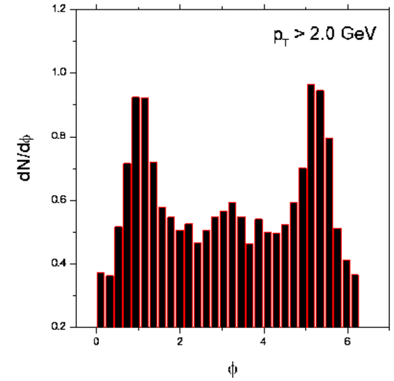
$$k_v = \frac{2\pi}{R_v} = \sqrt{\frac{3Ts}{2\tau_f \eta}} \sim 200MeV$$

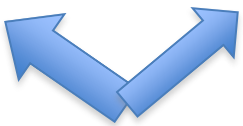


The peaks are at the same angles +- 1 rad (as I got) relative to the perturbation angle, but **+-2 rad in correlations**

One tube model

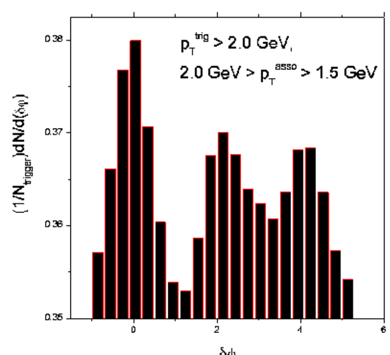
MAIN RESULT: single particle angular distribution has TWO PEAKS separated by Δ *phi* □ 2





CONSEQUENCE: two particle angular distribution has three peaks

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



It is like correlating two ocean waves in Alaska and Chili to find a 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

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

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

Analytic version Of hydro-1 explosion

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

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

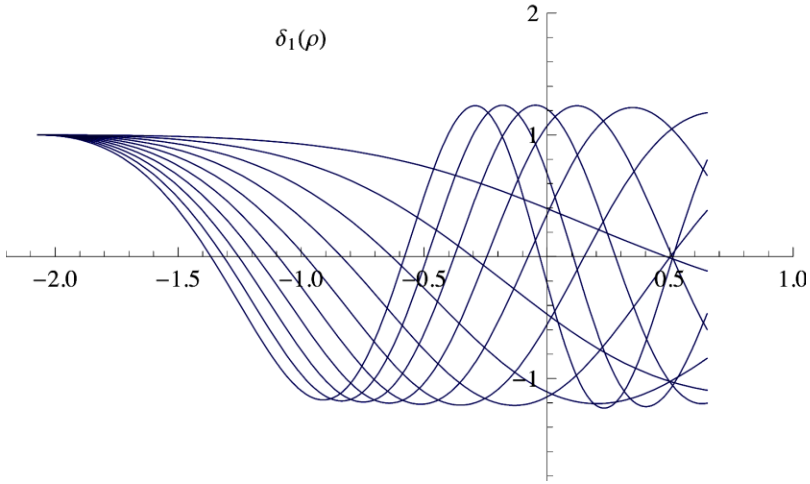
$$\frac{\partial^2\delta}{\partial\rho^2} - \frac{1}{3\cosh^2\rho}\left(\frac{\partial^2\delta}{\partial\theta^2} + \frac{1}{\tan\theta}\frac{\partial\delta}{\partial\theta} + \frac{1}{\sin^2\theta}\frac{\partial^2\delta}{\partial\phi^2}\right) + \frac{4}{3}\tanh\rho\frac{\partial\delta}{\partial\rho}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

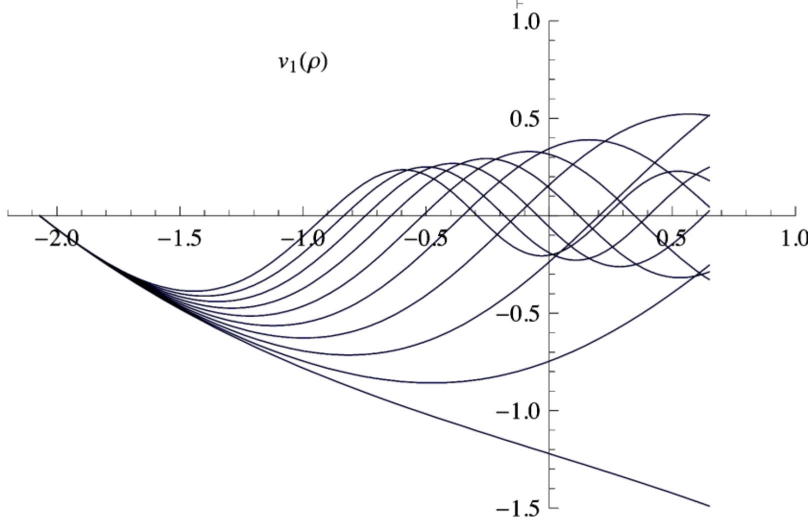
We have seen that in the short wavelength approximation we found a wave-like solution to equation 3.16, but now we would like to look for the exact solution, which can be found by using variable separation such that $\delta(\rho,\theta,\phi) = R(\rho)\Theta(\theta)\Phi(\theta)$, then

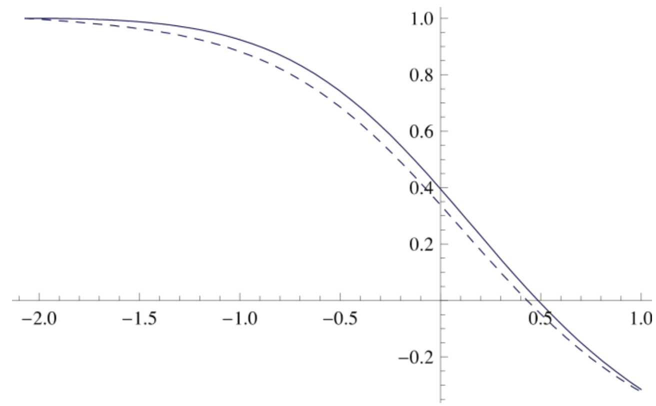
$$R(\rho) = \frac{C_1 P^{2/3}_{-\frac{1}{2}+\frac{1}{6}\sqrt{12\lambda+1}}(\tanh\rho) + C_2 Q^{2/3}_{-\frac{1}{2}+\frac{1}{6}\sqrt{12\lambda+1}}(\tanh\rho)}{(\cosh\rho)^{2/3}}$$
$$\Theta(\theta) = C_3 P_l^m(\cos\theta) + C_4 Q_l^m(\cos\theta)$$
$$\Phi(\phi) = C_5 e^{im\phi} + C_6 e^{-im\phi} \quad (3.26)$$

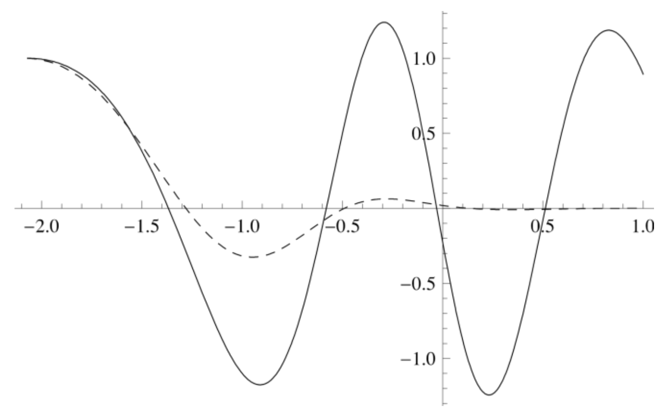
where $\lambda = l(l+1)$ and P and Q are associated Legendre polynomials. The part of the solution depending on θ and ϕ can be combined in order to form spherical harmonics $Y_{lm}(\theta,\phi)$, such that $\delta(\rho,\theta,\phi) \propto R_l(\rho)Y_{lm}(\theta,\phi)$.

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





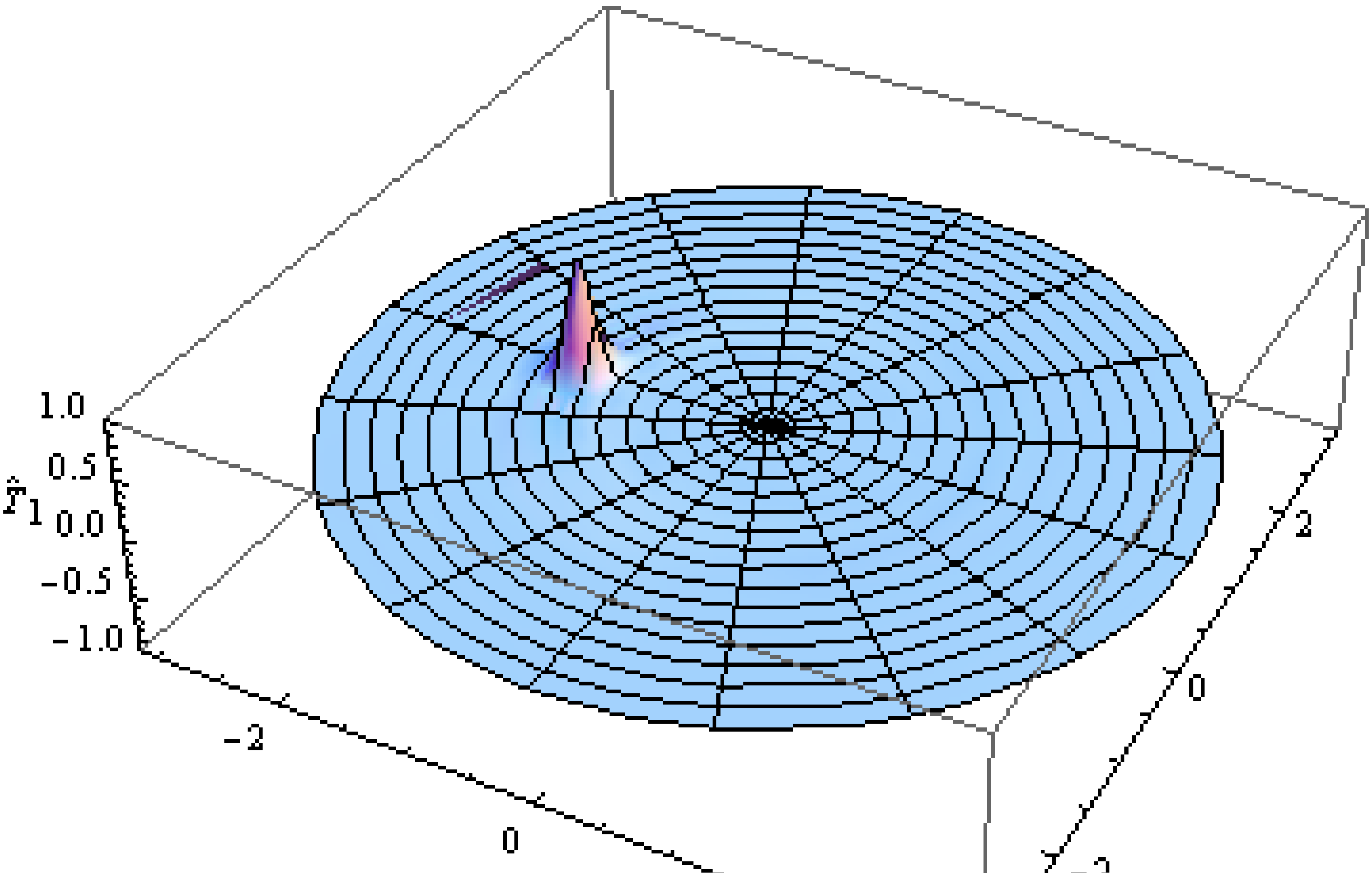


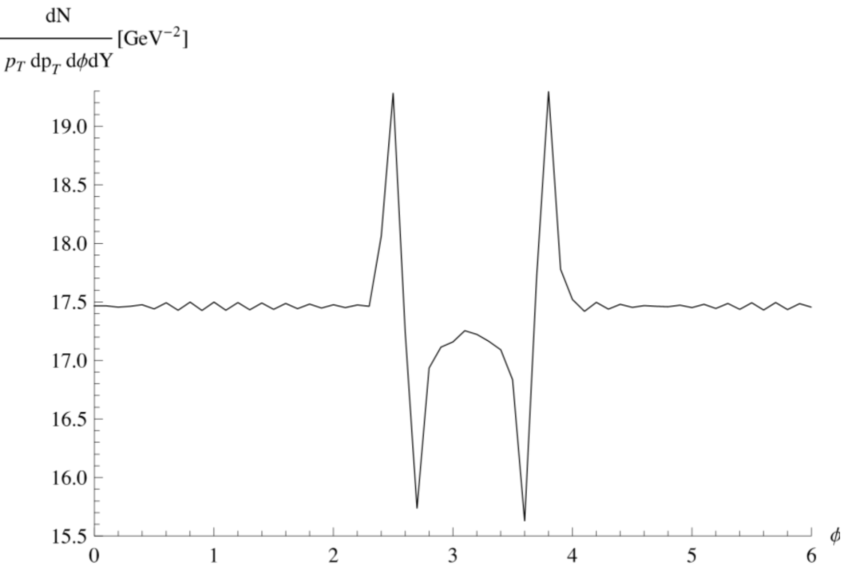


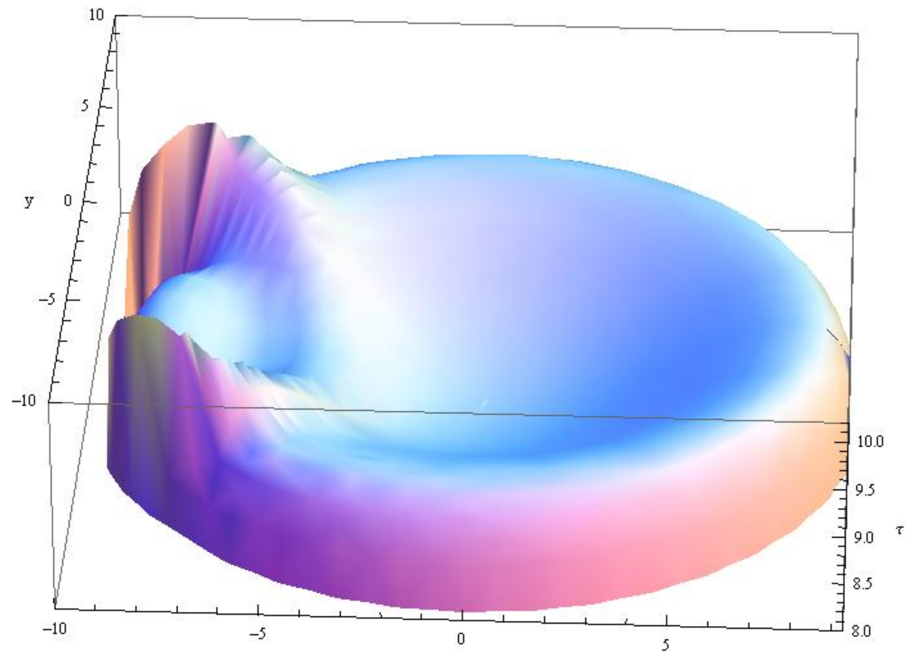
Viscosity (dashed) hardly affect The 1st harmonic, but nearly kills the 10th!

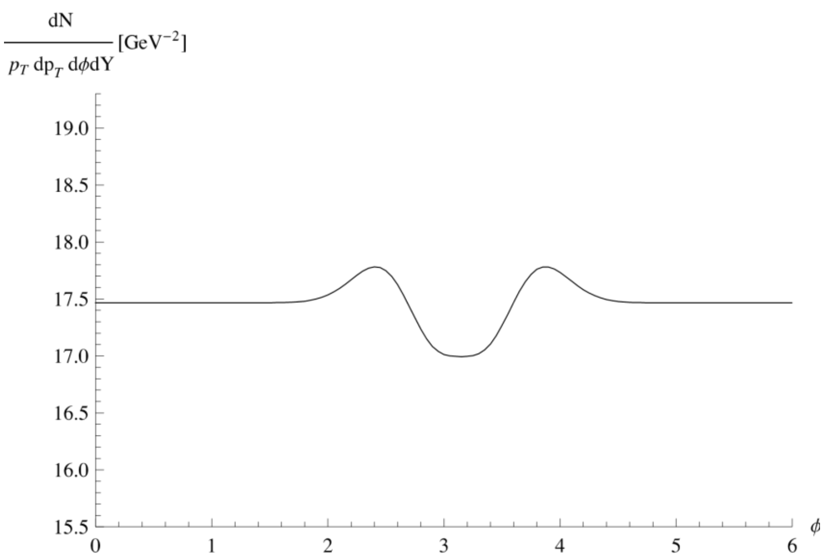
lhs (rho=-2) is initiation time and FO time is around zero

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

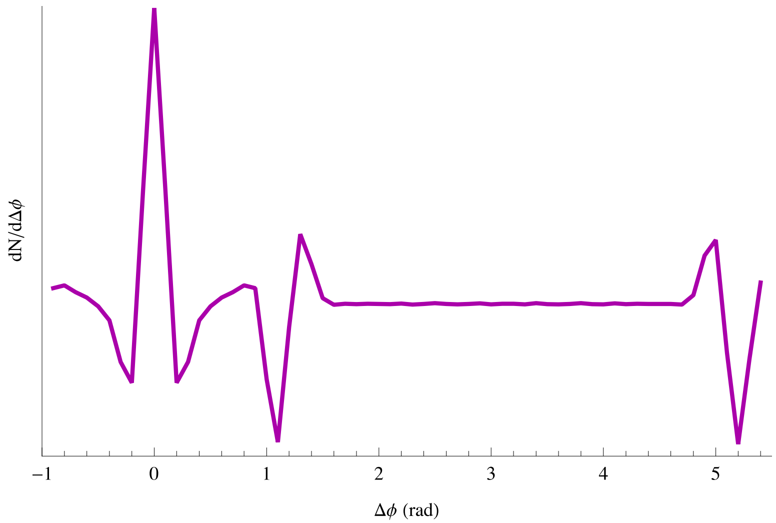








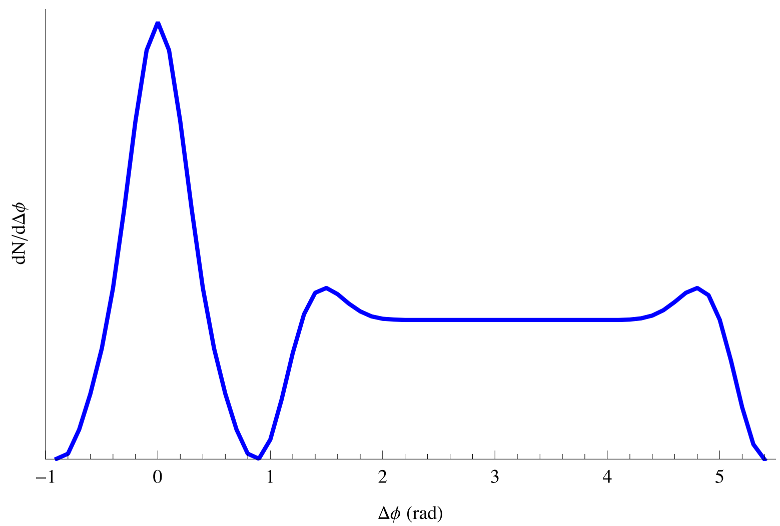
The modified freezeout
Surface (right) leads to
A modified angular distribution
Of particles, with and without viscosity
(left)

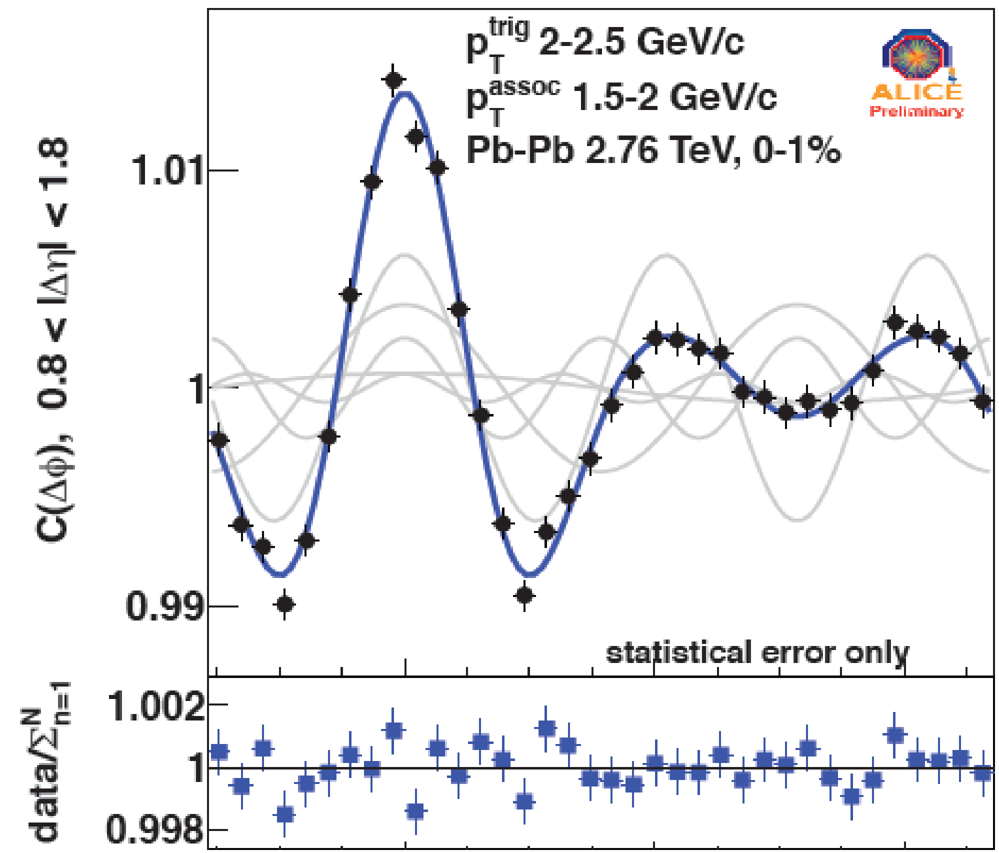


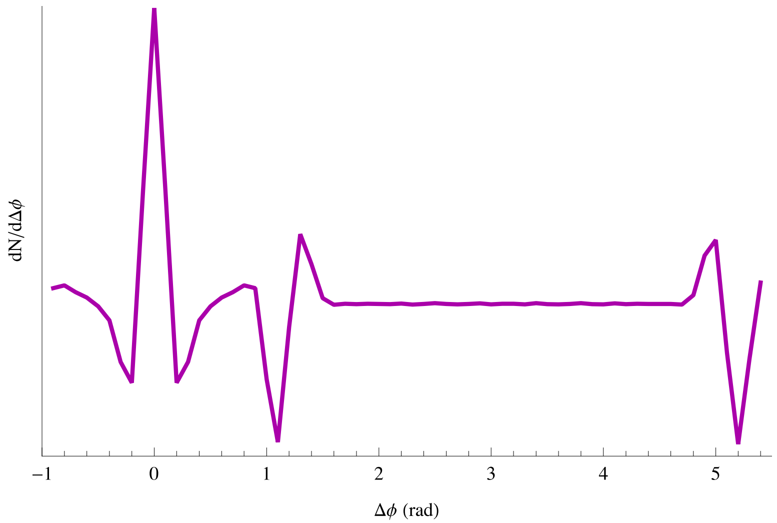
Left:4 pi eta/s=0, 2
Note shape change

The shape was observed by PHENIX first at RHIC

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

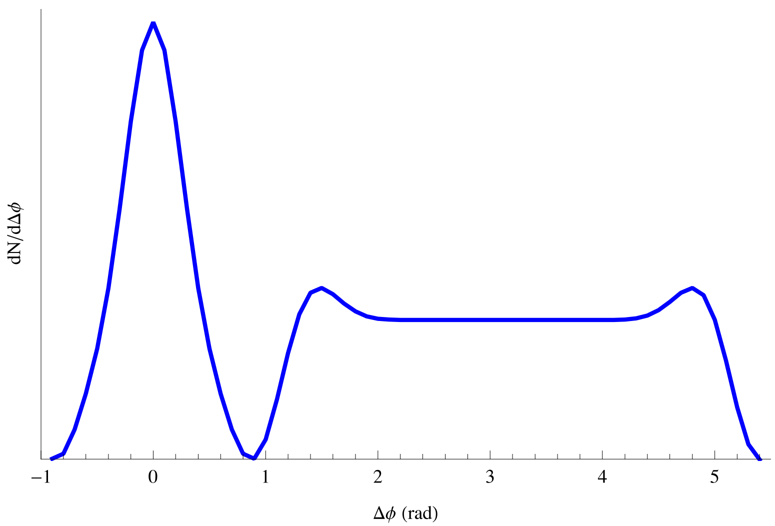


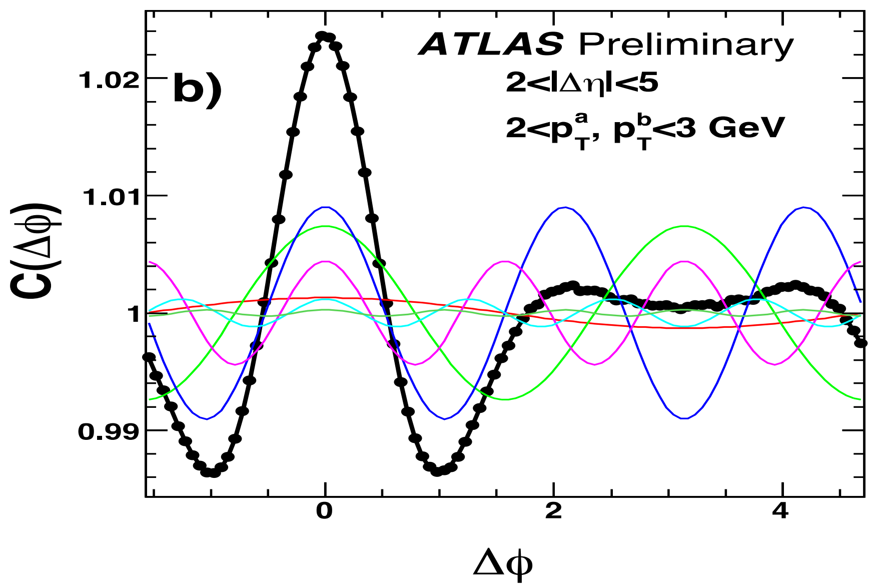




Left:4 pi eta/s=0, 2
Note shape change

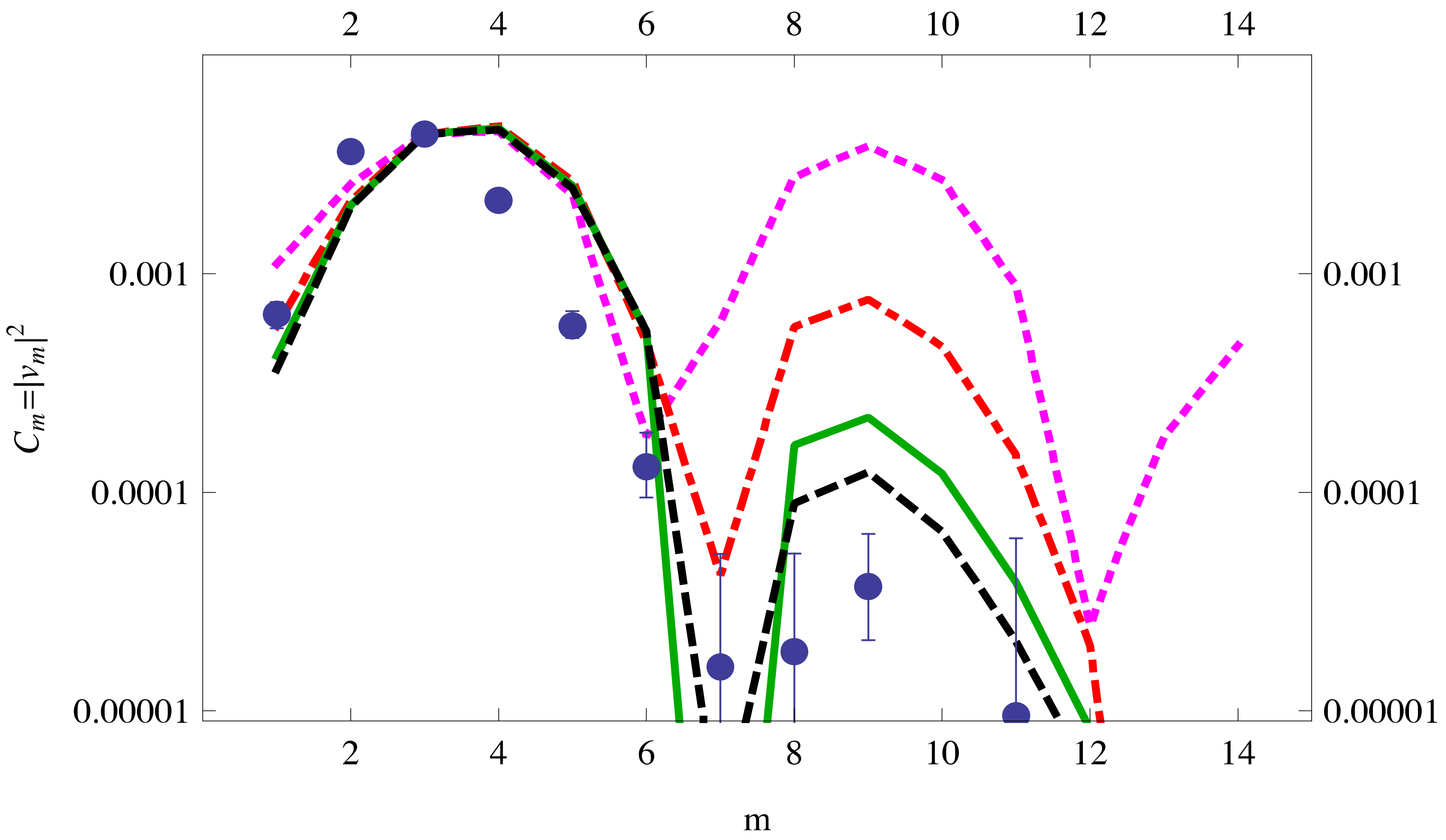
ATLAS central 1% correlators
Note shape agreement
No parameters, just Green
Function from a delta function





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

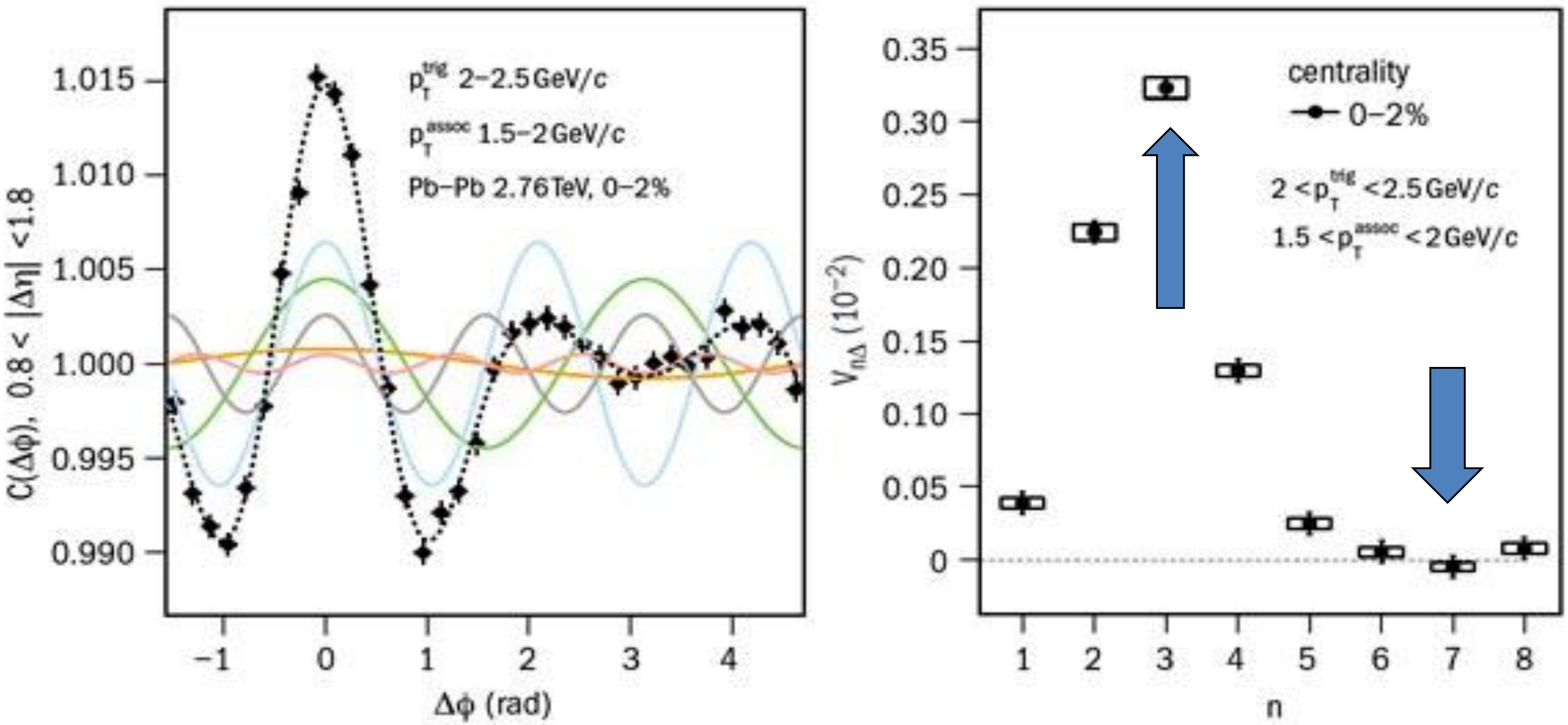
perturbation initial size is 0.7 fm, viscosity eta/s=0,0.08,0.13,0.16



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?**

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 coherence/ non-gaussianity is yet to be observed!

The "maximal coherence" model:

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

Evidences for that From the Glauber model

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

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

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

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

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

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

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

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

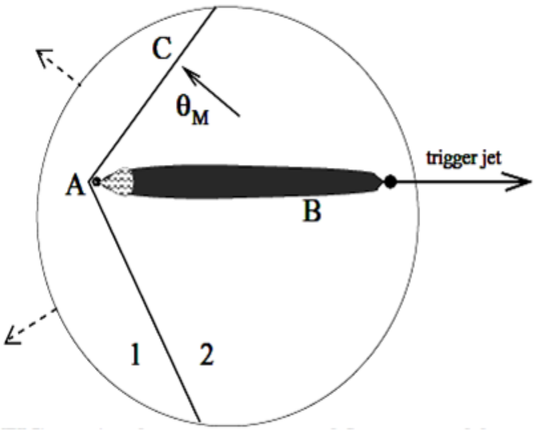
The first 3-body combinations Has been reported by ATLAS At Hard Probes 2 weeks ago

Sonic boom from quenched jets

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

- **the energy deposited by jets into liquid-like strongly coupled QGP must go into conical shock/sound waves**
- **We solved relativistic hydrodynamics and got the flow picture**

Wake effect or "sonic boom"



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

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

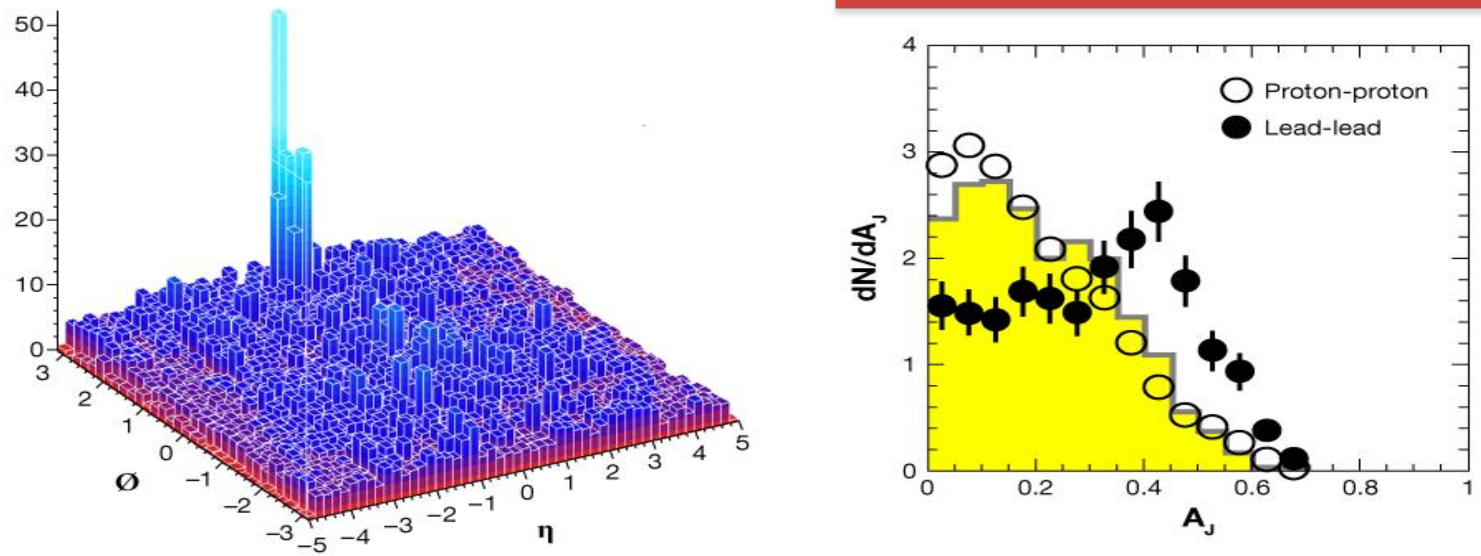


FIG. 2: (Left) Example of a jet without a visible partner. (Right) Asymmetric jets (where one jet loses most of its energy) are rare in proton-proton collisions, but the ATLAS measurements showed such events occur with a high probability in lead-lead collisions. The asymmetry A_j for two jets with energy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

The Wake of a Heavy Quark in Non-Abelian Plasmas : Comparing Kinetic Theory and the AdS/CFT Correspondence

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Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, United States

Paul M. Chesler

Kinetic theory =
Boltzmann eqn=
Weak coupling

AdS/CFT =dual gravity
=strong coupling

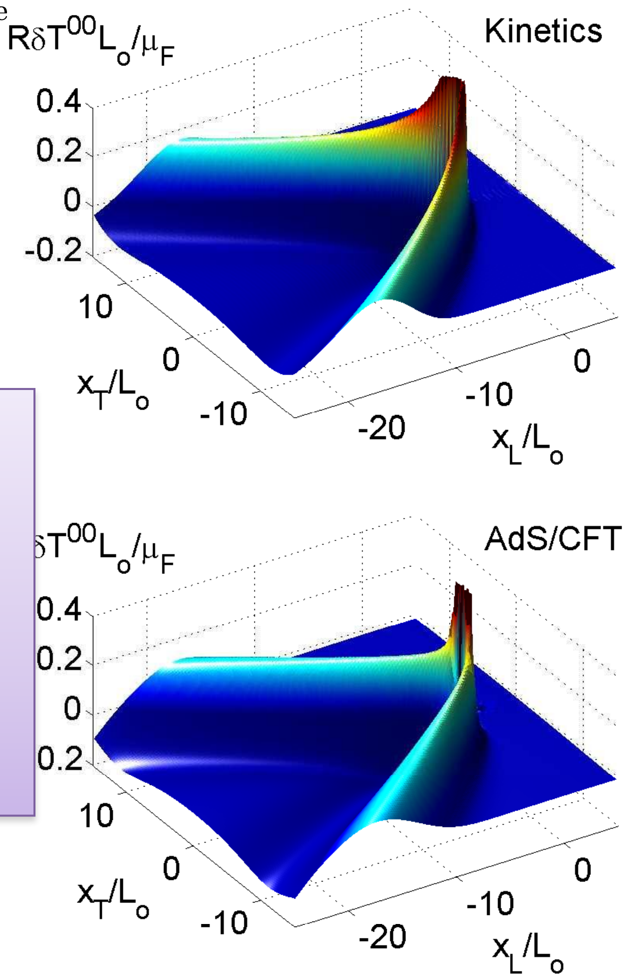
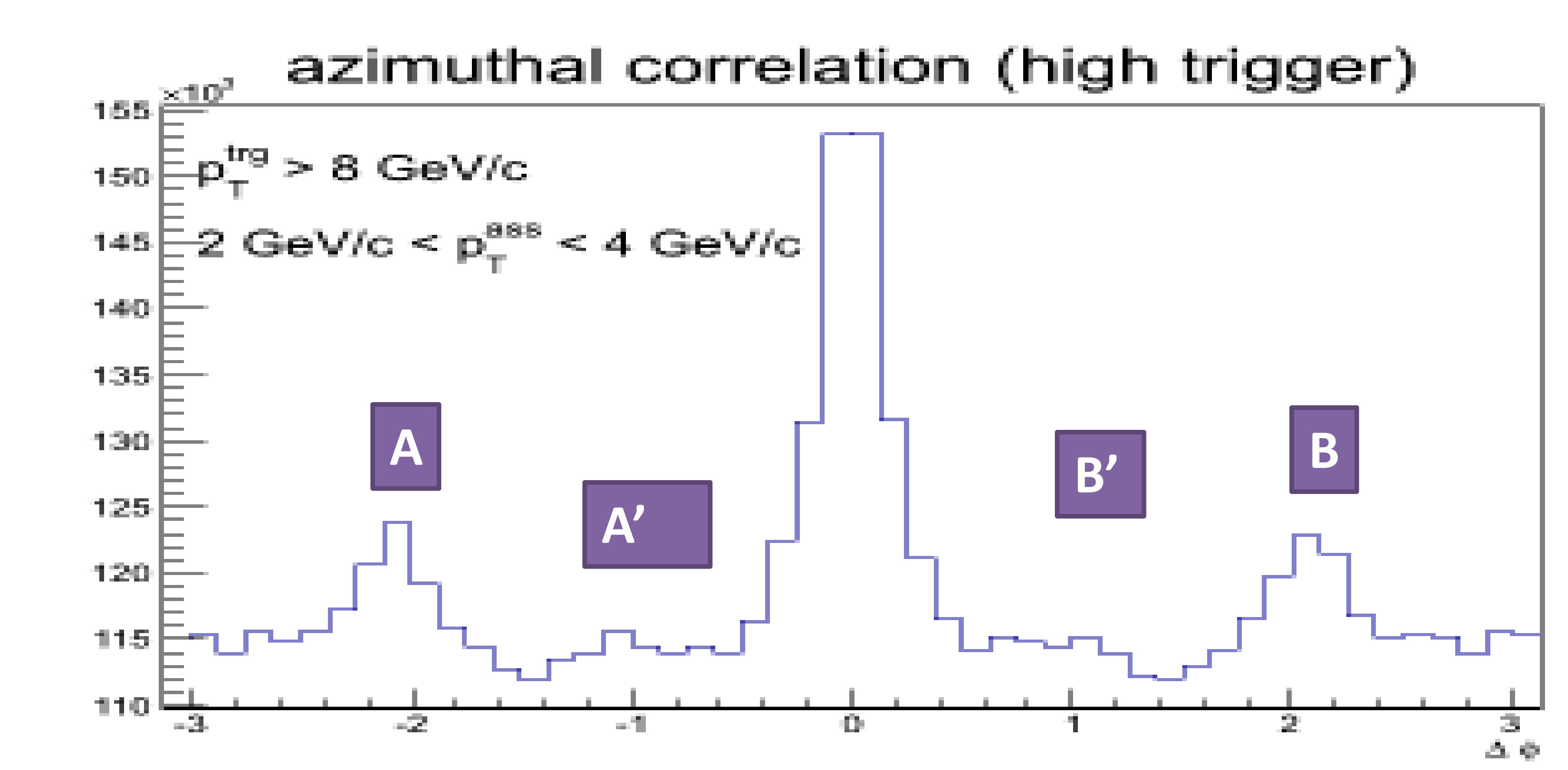
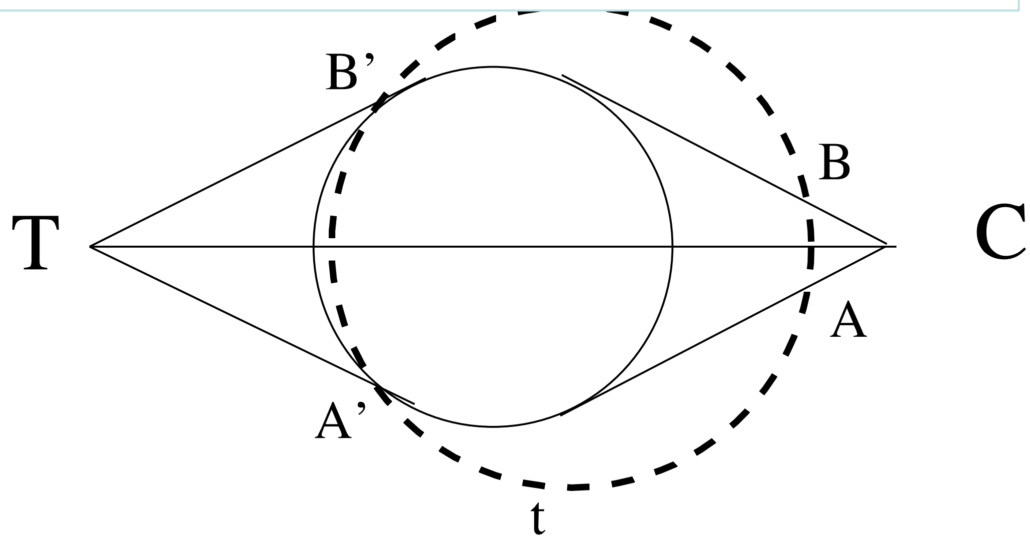


FIG. 1. The energy density (in scaled units) times $R = \sqrt{x_T^2 + x_L^2}$ that is induced by a heavy quark probe in (a) weakly coupled QCD and (b) strongly coupled $\mathcal{N} = 4$ SYM. Here L_o is the shear length and the $\mu_F(v)$ is the drag coefficient for each case (see text).

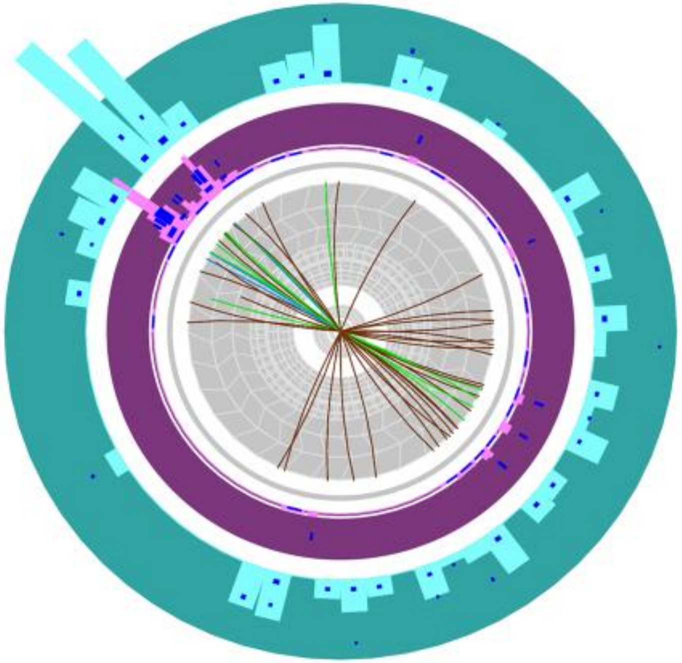


ALICE: very preliminary: peaks perhaps due to 4 points (A-B,A'B') are there



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"?**

Summary

$$\frac{4\pi\eta}{\hbar s} \approx 2$$

- **LHC/ALICE sees 30% larger elliptic (and radial) flows, exactly as Hydro 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 reproduces the correlators beautifully, best with viscosity**

So,we see the sound traversing the Little Bang

- **Coherence: Phases of higher harmonics are being measured in 3-particle correlators!**
- **Large energy deposition to matter from jets creates sound/shocks, makes the inside of the Mach cone a bit hotter**

extras

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 1º but few times larger!

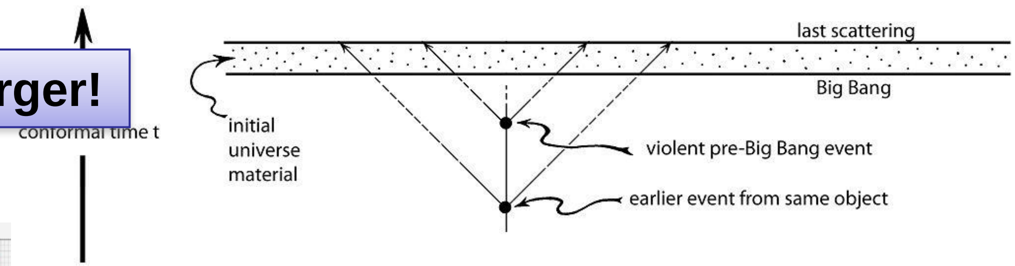


Figure 1.Conformal di... ...ly a galactic clu...

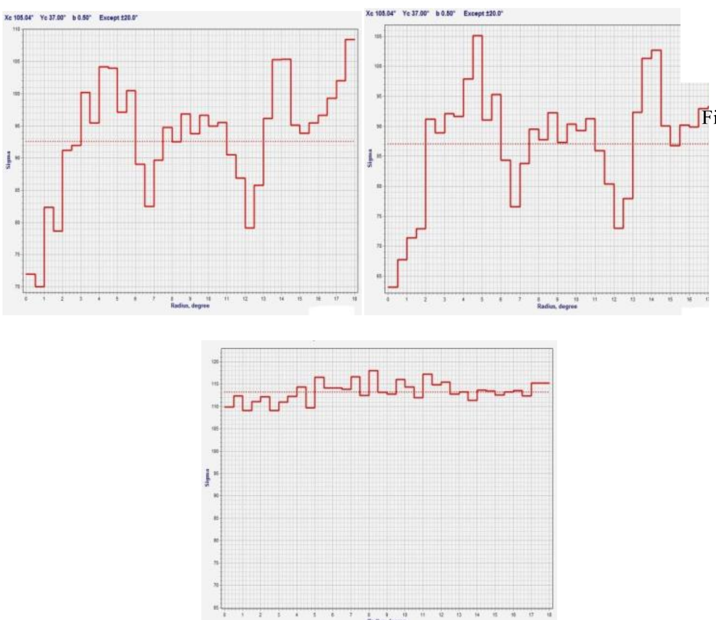
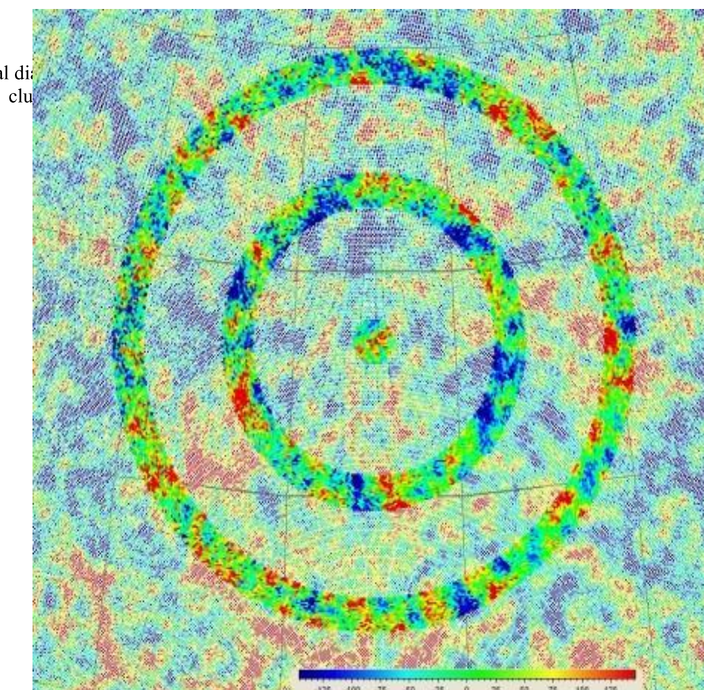
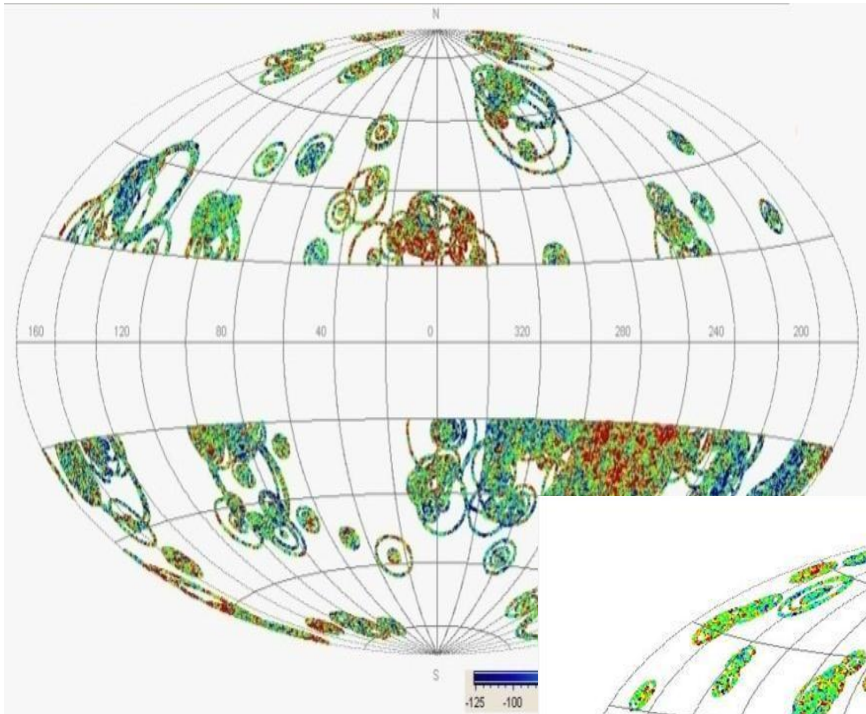


Figure 2. The temperature variance ring structures in WMAP W (a) and V (b) band maps. The Gaussian ma… simulated for WMAP W parameters is shown as well (c).





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

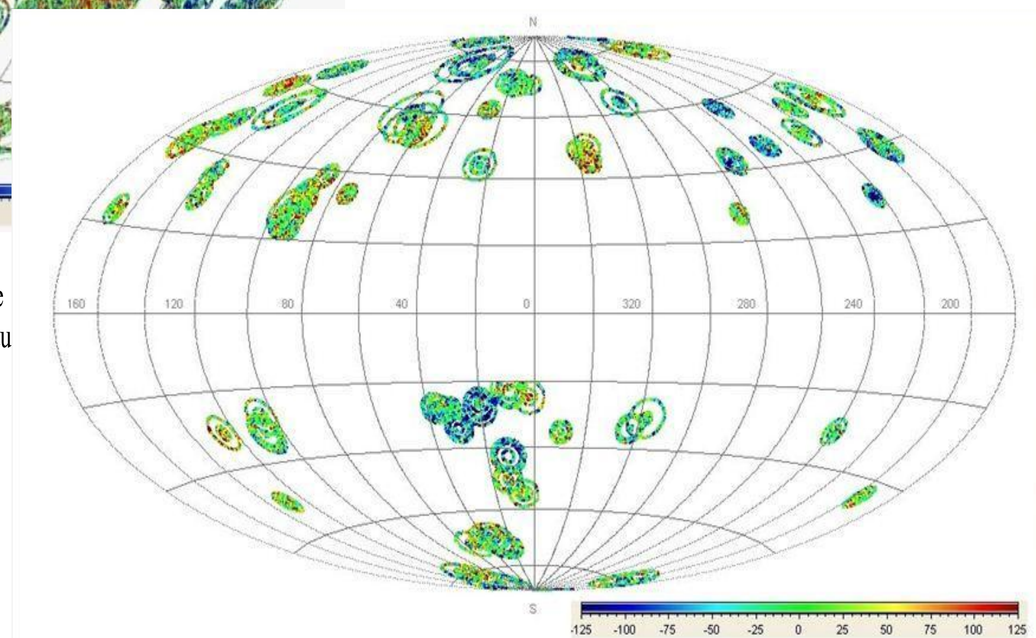


Figure 5. The corresponding maps to those of Figure 4, but where a simulated CMB sky is used incorporating WMAP's *l*-spectrum with randomized *m*-values. The differences are striking, notably the many fewer concentric sets, the absence of significant inhomogeneities and of large circles, and the much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