APH N.S., Heavy Ion Physics 17/2–4 (2003) 261–270

HEAVY ION PHYSICS

Why Is the Null HBT Result at RHIC So Interesting?

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Received 10 May 2002

Abstract. Pion interferometry (HBT of A+A) data have posed a thorn in the theoretical interpretation of AA collisions at RHIC ($\sqrt{s}$ = 130 AGeV). How can $R_{\rm out} \approx R_{\rm side} \approx R_{\rm long}$ and remain so between AGS and RHIC? Where is the QGP Stall? Can elephants hide along the x_0^+ dimension? We rummage old hydrodynamic scenarios and uncover some previously ignored NULL solutions.

Keywords: pion interferometry, ultra-relativistic nuclear collisions
PACS: 25.75.-q, 24.85.p

1. NULL Effects at RHIC

The verdict from the RHIC jury is out: ET went home without a time-delay. STAR [1] and PHENIX [2] collaborations have splashed the cold water of experimental facts on a number of theoretical speculations. Figure 1 shows that HBT (small relative momentum $\pi\pi$ correlations) at RHIC hardly differ from HBT data at SPS and even AGS. The QGP, if formed, therefore shows no evidence for a sought after "Stall" [3–7]. All the projected radii are comparable and vary similarly with transverse mass over a huge energy range. Figure 2 from PHENIX [8] further shows that while the total transverse energy per participant (and hence initial energy density) increases by ∼40% from SPS to RHIC and reveals a modest nonlinearity with centrality expected due to copious mini jet production at RHIC, the E_T/N_{ch} is virtually independent of beam energy as well as of centrality! This second major NULL result precludes for example the direct observation of possible gluon saturation $E_T/N_{ch} \propto Q_s(E,A)$ (see talk of Krasnitz [9]).

Compared to the other striking RHIC discoveries, 1) jet quenching [10, 11], 2) large azimuthal asymmetries [12,13] out to $p_T \sim 6$ GeV, as well as the unexpected 3) high p_T baryon and hyperon excess to mesons [14], the HBT and ET global

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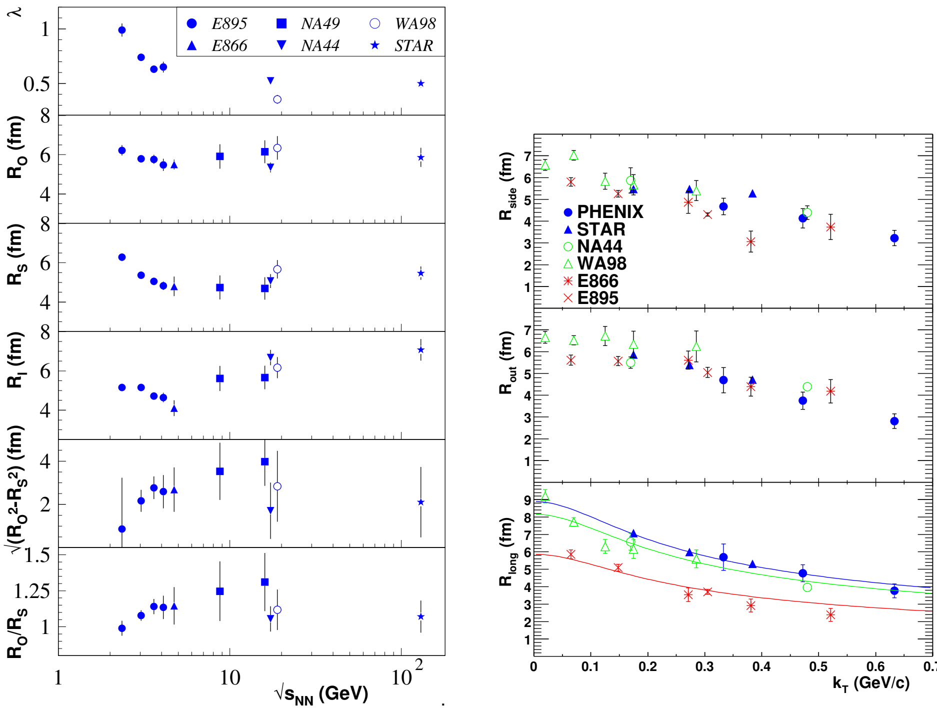

Fig. 1. Left: Energy systematics of HBT radii in nuclear collisions from STAR [1]. Right: Transverse mass dependence of HBT radii from PHENIX [2].

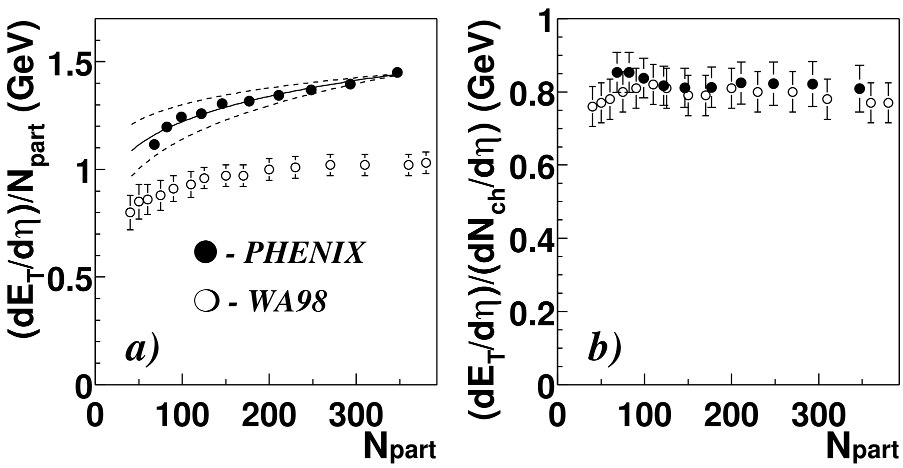

Fig. 2. Transverse energy systematics at RHIC from PHENIX [8]

(low p_T) data appear at first sight to be extremely dull. However, the aim in this talk is to show that these null data are in fact extremely interesting and challenge some of the core ideas and assumptions about the physics and interpretation of data on ultra-relativistic nuclear collisions.

In the semiclassical transport theory picture of QGP evolution and hadronization, the thousands of produced pions undergo final state interactions and eventually decouple when the density becomes sufficiently low. Their decoupling space-time and momentum space distribution, $\rho(x,k)$, is a 7 dimensional (on-shell) phase space density. Single inclusive pion spectra measure $\int d^4x\rho(x,k)$ and hence project the 7 dimensional density onto a 3D plane. In the absence of dynamical multi-body correlations, the multi-pion distribution simply factorizes $\rho(x_1,k_1)\cdots\rho(x_2,k_n)$. This is the one of the central assumption (together with local equilibration) in the application of hydrodynamics to A+A.

However, the observable n-pion inclusive distributions do not factor because Bose symmetrization induces an interference between pion amplitudes [15,16]:

$$P_n(\mathbf{k}_1,\cdots,\mathbf{k}_n) \propto \left\langle \sum_\sigma \prod_{j=1}^{n} e^{i(k_j-k_{\sigma_j})\cdot x_j}\delta_\Delta(k_j,k_{\sigma_j},p_j)\right\rangle , \tag{1}$$

with the smoothed delta function given by

$$\delta_\Delta(k,k',p) = (2\pi\Delta p^2)^{-3/2}\exp\left(\tfrac{1}{2}\left[p-\tfrac{1}{2}(k+k')\right]^2/\Delta p^2 + \tfrac{1}{2}(k-k')^2\Delta x^2\right) . \tag{2}$$

The brackets $\langle\cdots\rangle$ denotes the ensemble average over the $7n$ pion *freeze-out* space coordinates $\{x_1,p_1,\cdots,x_n,p_n\}$. The smoothed delta function arises if Gaussian wavepackets are assumed. The widths Δx and Δp depend on details of the pion production mechanism which are unimportant only *if* the semiclassical HBT limit applies. It is of course not at all obvious that this limit applies in ultra-relativistic nuclear collisions, but this is one of the current working hypotheses as is for example approximate Bjorken boost invariance. Indirect evidence that such assumptions *may* apply comes from the considerable success of hydrodynamic [17,18] and transport models [19,20] to reproduce the bulk of the single inclusive spectra at RHIC including the dramatic high p_T collective azimuthal flow v_2 [13].

Pion interferometry tries to invert the two pion correlation function, $C_2(\mathbf{q},\mathbf{K})$, where $\mathbf{q}=\mathbf{k}_1-\mathbf{k}_2$ and $\mathbf{K}=(\mathbf{k}_1+\mathbf{k}_2)/2$ to infer constraints on the decoupling x^μ distribution [21–23]. However, there is a catch: one of the 7 dimensions, namely near the light cone $x_0^+=\beta_\mathbf{K}\cdot\mathbf{r}+t$ where $\beta_\mathbf{K}=\mathbf{K}/\sqrt{(\mathbf{K}^2+m^2)}$ is completely invisible as shown in Fig. 3 because of the on-shell constraint $q^0=\sqrt{(\mathbf{K}+\mathbf{q}/2)^2+m^2}-\sqrt{(\mathbf{K}-\mathbf{q}/2)^2+m^2}\approx\beta_\mathbf{K}\cdot\mathbf{q}$. Thus for $q\ll K$ the correlation function,

$$C(\mathbf{k}_1,\mathbf{k}_2) = C_2(\mathbf{q},\mathbf{K}) = 1+ \lambda\frac{\langle\cos(\mathbf{q}\cdot(\beta_\mathbf{K}(t_1-t_2)-(\mathbf{r}_1-\mathbf{r}_2))e^{-\mathbf{q}^2\Delta x^2}\delta^3_{\Delta p}(\mathbf{K}-\mathbf{p}_1)\delta^3_{\Delta p}(\mathbf{K}-\mathbf{p}_2)\rangle}{\langle\delta^3_{\Delta p}(\mathbf{k}_1-\mathbf{p}_1)\rangle\langle\delta^3_{\Delta p}(\mathbf{k}_2-\mathbf{p}_2)\rangle} , \tag{3}$$

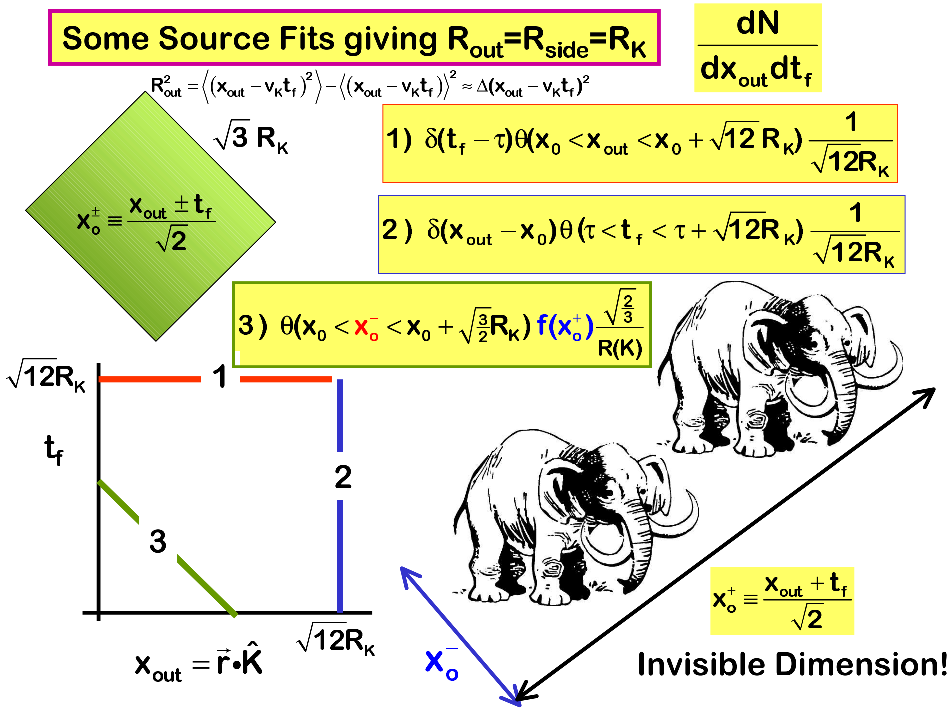

Fig. 3. The invisble HBT $x_0^+ \propto \mathbf{v_T} \cdot \mathbf{r} + t$ dimension! Beware of elephant herds.

for fixed $\mathbf{K}$ really only determines the rms correlations between the *relative three* vectors $\mathbf{r} - \beta_{\mathbf{K}} t$. For $\mathbf{K}_z = 0$ (the longitudinal comoving frame), the direction $\mathbf{K}$ is perpendicular to the beam "z" and defines the "out" direction $\mathbf{x}_{\rm out}$. The "side" direction is then perpendicular to both the beam and out directions. For relativistic pairs, it is therefore clear that only the rms negative light cone transverse coordinate $x_0^- \propto x_{\rm out} - \beta_K t$ can be determined. The four space-time distribution $\rho(x_0^-, x_s, x_z, x_0^+, \mathbf{K})$ is thus projected down to a three space time hypersurface as shown in Fig. 3. C_2 is completely blind to the x_0^+ direction and all distributions ranging from 1) time-like shocks, 2) space-like surface emission, 3) rapid surface burn, 4) tilted box, to 5) elephant herds all lead to the *same* out and side widths!

In the hydrodynamic pictures the freeze-out space time hypersurfaces depend on the initial conditions, equation of state, and freeze-out prescriptions [24–27] employed. Figure 4 shows illustrative results from [7] for three EOS: 1) strong first order, 2) infinite order with $\Delta T/T_c = 0.1$ and 3) ideal gas. A uniform sharp edge cylinder with energy denity 20 GeV/fm^3 was assumed and the evolution in Bjorken boost invariant dynamics was computed. Different isotherms are shown as a function of the transverse radius and time. The strong first order transition leads to a very slow deflagration front [3] that slowly transform the QGP cylinder into hadronic ashes on a long time scale $t \sim 6R$. This is the "QGP Stall" expected under these most favorable conditions [3]. The robustness of the time-delay of hadronization is evident even if only a smooth cross over transition is realized in Nature. Note that even the ideal gas EOS leads to a $t \sim 2R$ elongation along the time axis relatively independent of the freeze-out temperature. Detailed hydrodynamic calculations of

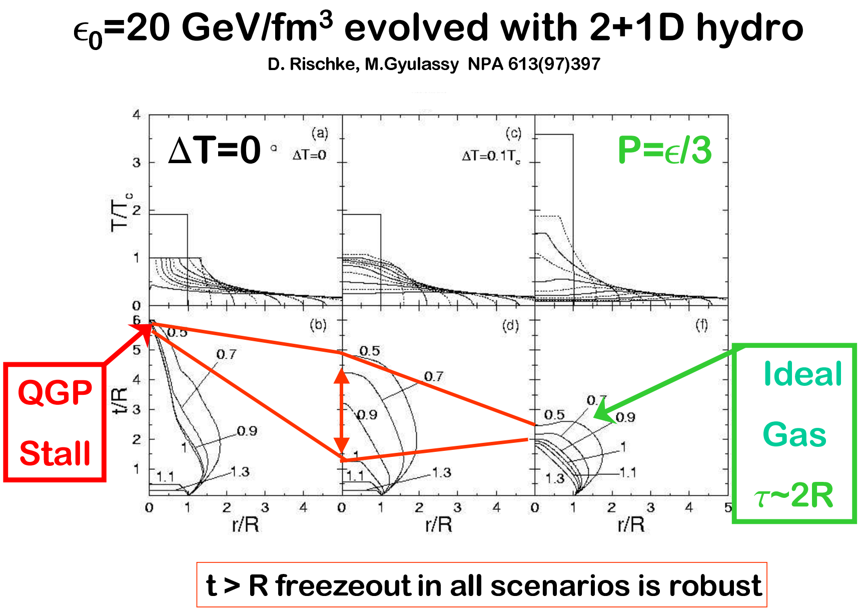

Fig. 4. $R_{\rm out} > R_{\rm side}$ is robust to changes in the QCD equation of state in Bjorken hydrodynamic evolution [7]. A strong first order transition leads to a slowly burning "Stalled" QGP log. A smooth cross over ($\Delta T/T = 0.1$) transition burns a bit faster, but even an ideal $p = \epsilon/3$ equation of state leads to $t/R \sim 2$.

[17] in Fig. 5 show that the side radius is predicted to be too small while the longitudinal radius is too large. The inclusion of realistic dissipative effects in Fig. 6 in order to decouple pion dynamically using the UrQMD model [20] also fails to reproduce the NULL $R_{\rm out}/R_{\rm side} = 1$ data.

Searching for at least some (weird) scenario that could account dynamically for the observed effect, note in Fig. 7 that for a rapid cross over transition and an early freeze-out at $T = T_c$ (long-dashed), $R_{\rm out}/R_{\rm side} \approx 1.0-1.2$ over a very wide range of initial densities. The thin curves for an ideal gas EOS lie *above* this scenario for all T_f. The "conventional" $T = 0.7T_c$ isotherm (thick solid) leads to the expected stall for RHIC initial conditions.

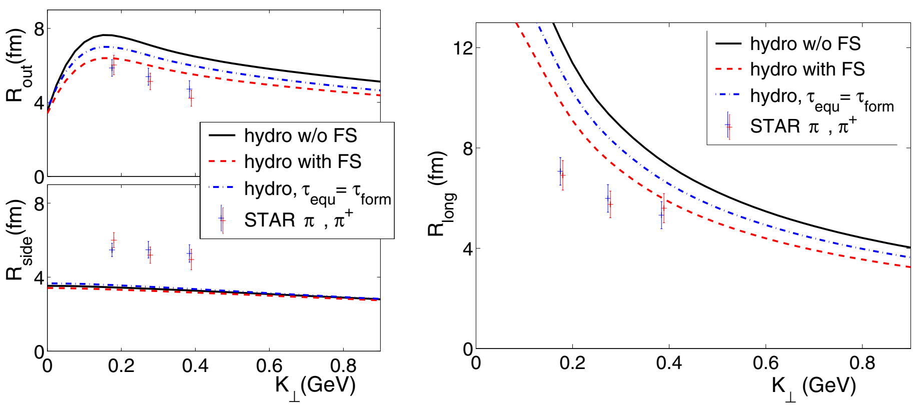

Fig. 5. Hydrodynamic HBT radii as a function of transverse momentum from Heinz and Kolb [17] are compared to RHIC data. $R_{\rm out}/R_{\rm side}$ is too big as is the longitudinal radius.

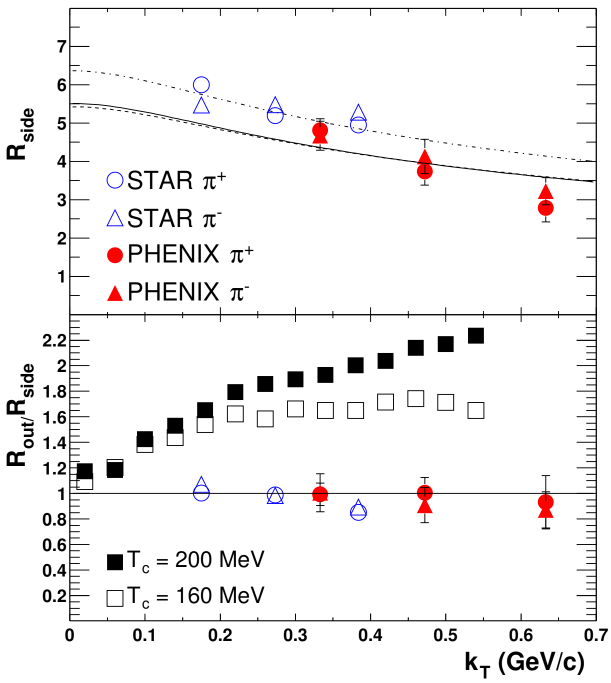

Fig. 6. K_T dependence of HBT radii from [2] compared predictions (squares) of hydrodynamics decoupled with UrQMD [20]

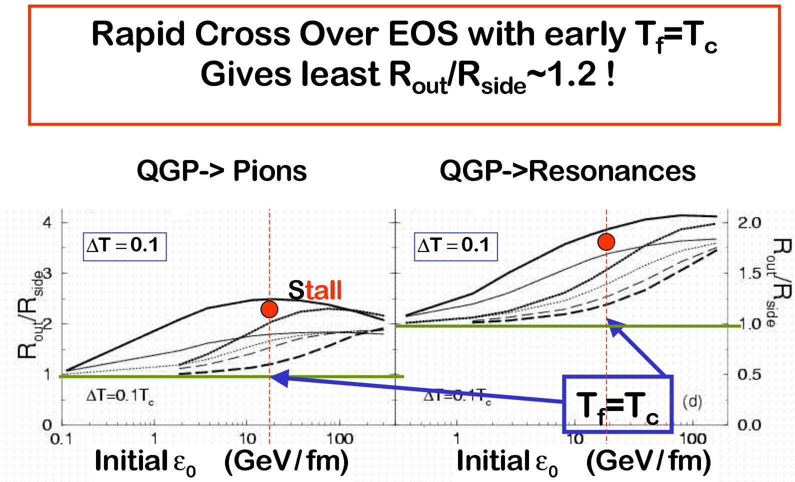

Fig. 7. Null ($R_{\rm out}/R_{\rm side} \approx 1$) hydro solutions for a wide range of initial energy densities do exist from Fig. 18 [7], but they correspond to early freeze-out $T_f = T_c$! In contrast a QGP stall is predicted with $T_f = 0.7T_c$ in either case of a transition to pion or resonance matter.

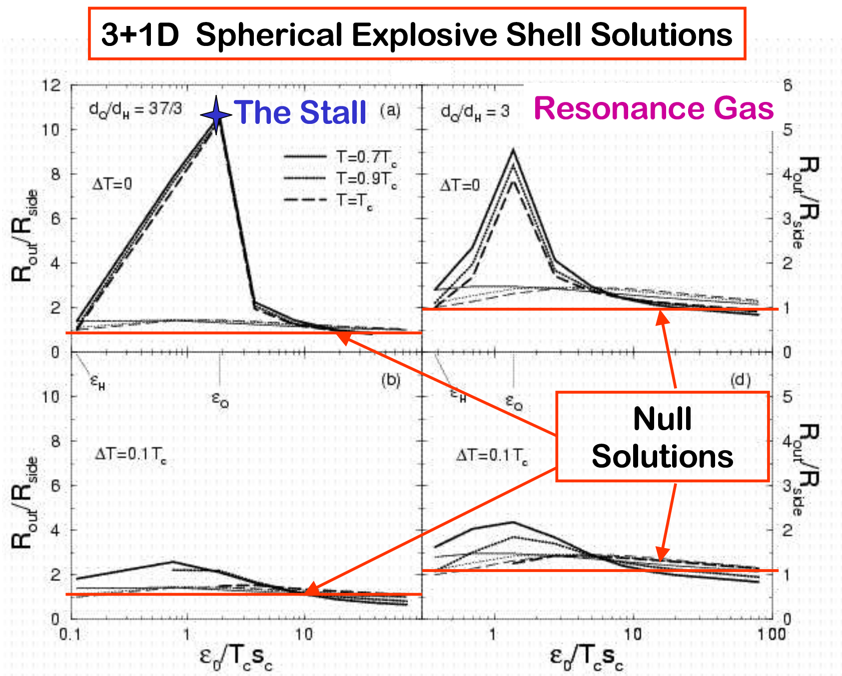

Fig. 8. 3D Null hydro solutions also exist [7], but they are even weirder!

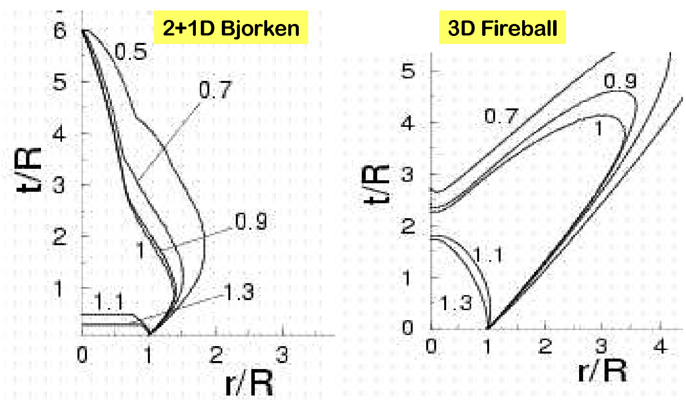

Fig. 9. Compare 2+1D Bjorken cylinder and 3D fireball space-time freeze-out surfaces. They both involve times $t \sim 5R$, yet the projection onto the x_0^- axis leads to HBT $R_{\rm out}/R_{\rm side} \gg 1$ in the first case while $\sim$1 in the second.

In Fig. 8, other even more extreme solutions are shown. These arise from 3D isotropically expanding fireballs with rather high initial density $\epsilon_0 > 20$ GeV/fm^3 above the maximum stall point. In 3D the maximum stall is up to a factor of ten larger than the radius. Yet for high enough initial densities the plasma explodes along the positive transverse light cone and the actual very long decoupling surface becomes invisible due to the on-shell projection of the whole 4 space-time onto the negative transverse light cone hypersurface as shown in Fig. 4 and Fig. 9! For these geometries it is possible to drive $R_{\rm out}/R_{\rm side} < 1$ due to the explosive expansion. These results illustrate well the extremely different space-time dynamics that can lead to apparent NULL results in HBT analysis. See [27] for further discussion of the decoupling problem at RHIC.

2. Conclusions?

The null HBT data at RHIC remain a major interesting puzzle as do the null E_T/N_{ch} data. While clever parameterizations [30] of $\rho(x,k)$ have been constructed to fit the data, the puzzle is simply shifted to why such parameterizations are created in AA collisions. What clearly does not work is the transport evolution of a large class of "conventional" initial conditions characterized by no initial radial flow. The fits that reproduce data postulate initial state radial flow. However, another possible source of the discrepancies may be traced to the HBT theory itself [29] as well as to distortions of the actual space-time decoupling density arising from the experimental Gaussian fits to 3D correlation functions [28]. As emphasized in [16, 29] quantum wavepacket distortions of the HBT lenses are likely to be large especially in the transverse directions. Such distortions are amplified in the inside-outside Bjorken geometries under consideration. Lin et al. [28] proposed that the experimental fits themselves to non-Gaussian correlation patterns can induce up to a factor of 3 distortion of the HBT radii and have obtained plausible fits varying only the effective gluon–gluon elastic cross sections for ideal gas equation of state. It is too early to judge now which if any of the above ideas will survive further scrutiny. In any case the null HBT results are a major thorn in the otherwise successful hydrodynamic picture of RHIC reactions. Such thorns are important clues that are worth pursuing until a satisfactory explanation can be found.

Acknowledgements

We celebrate in this conference the over two centuries of combined creative theoretical work of the Hungarian (MTA) academicians J. Zimányi, J. Németh and I. Lovas. They built up a thriving nuclear theory school in Hungary that produced much insight and remains in the forefront of research in the field of ultra-relativistic heavy ion physics [30–38]. We are also thankful to T. Csörgő for many years critical debates on the topic of HBT and to P. Lévai on the topics jet quenching and QAP vs. QGP models of AA dynamics.

This work was supported by the Director, Office of Science, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, of the U.S. Department of Energy under Contract No. DE-FG02-93ER40764 and by the U.S. NSF under INT-0000211 and OTKA No. T032796.

References

1. C. Adler et al. (STAR Collaboration), *Phys. Rev. Lett.* **87** (2001) 082301 [nucl-ex/0107008].
2. K. Adcox et al. (PHENIX Collaboration), *Phys. Rev. Lett.* **88** (2002) 192302 [nucl-ex/0201008].
3. L. Van Hove, *Z. Phys.* **C21** (1983) 93; M. Gyulassy, K. Kajantie, H. Kurki-Suonio and L. McLerran, *Nucl. Phys.* **B237** (1984) 477.
4. S. Pratt, *Phys. Rev. D* **33** (1986) 1314; *Phys. Rev. C* **49** (1994) 2722.
5. G. Bertsch, M. Gong and M. Tohyama, *Phys. Rev. C* **37** (1988) 1896; G. Bertsch, *Nucl. Phys.* **A498** (1989) 173c; G. Bertsch and G.E. Brown, *Phys. Rev. C* **40** (1989) 1830.
6. M. Gyulassy and S.S. Padula, *Phys. Lett. B* **217** (1989) 181; *Phys. Rev. C* **41** (1990) 21.
7. D.H. Rischke and M. Gyulassy, *Nucl. Phys.* **A608** (1996) 479.
8. K. Adcox et al. (PHENIX Collaboration), *Phys. Rev. Lett.* **87** (2001) 052301 [nucl-ex/0104015].
9. A. Krasnitz, *Heavy Ion Phys.* **17** (2002) 249.
10. K. Adcox et al., *Phys. Rev. Lett.* **88** (2002) 022301; G. David et al., *Nucl. Phys.* **A698** (2002) 227.

11. I. Vitev, M. Gyulassy and P. Lévai, *Heavy Ion Phys.* **17** (2002) 237 [nucl-th/0204019]; M. Gyulassy, P. Lévai and I. Vitev, *Phys. Lett.* **B538** (2002) 282 [nucl-th/0112071].
12. K.H. Ackermann et al., *Phys. Rev. Lett.* **86** (2001) 402; C. Adler et al., *Phys. Rev. Lett.* **87** (2001) 182301.
13. D. Molnár and M. Gyulassy, *Nucl. Phys.* **A697** (2002) 495 [nucl-th/0104073].
14. K. Adcox et al. (PHENIX Collaboration), *Phys. Rev. Lett.* **88** (2002) 242301 [nucl-ex/0112006]; *Phys. Rev. Lett.* in press; nucl-ex/0204007.
15. M. Gyulassy, S.K. Kauffmann and L.W. Wilson, *Phys. Rev. C* **20** (1979) 2267.
16. S.S. Padula, M. Gyulassy and S. Gavin, *Nucl. Phys.* **B329** (1990) 357.
17. U.W. Heinz and P.F. Kolb, *Nucl. Phys.* **A702** (2002) 269 [hep-ph/0111075]; hep-ph/0204061.
18. D. Teaney, J. Lauret and E.V. Shuryak, nucl-th/0110037.
19. Z. Lin, S. Pal, C.M. Ko, B.A. Li and B. Zhang, *Phys. Rev. C* **64** (2001) 011902 [nucl-th/0011059]; *Nucl. Phys.* **A698** (2002) 375 [nucl-th/0105044].
20. S. Soff, S. Bass and A. Dumitru, *Phys. Rev. Lett.* **86** (2001) 3981.
21. T. Csörgő, hep-ph/0001233.
22. R.M. Weiner, *Phys. Rep.* **327** (2000) 249 [hep-ph/9904389].
23. S.A. Bass, M. Gyulassy, H. Stöcker and W. Greiner, *J. Phys. G* **25** (1999) R1 [hep-ph/9810281].
24. S. Pratt, T. Csörgő and J. Zimányi, *Phys. Rev. C* **42** (1990) 2646.
25. A.N. Makhlin and Y.M. Sinyukov, *Z. Phys.* **C39** (1988) 69; Yu.M. Sinyukov, *Z. Phys.* **C43** (1989) 401.
26. F. Cooper and G. Frye, *Phys. Rev. D* **10** (1974) 186; F. Cooper, G. Frye and E. Schonberg, *Phys. Rev. D* **11** (1975) 192.
27. D. Molnár and M. Gyulassy, *Heavy Ion Phys.* **18** (2003) in print [nucl-th/0204062].
28. Z. Lin, C.M. Ko and S. Pal, nucl-th/0204054.
29. F. Gastineau and J. Aichelin, *Phys. Rev. C* **65** (2002) 014901.
30. T. Csörgő and A. Ster, hep-ph/0112006.
31. T. Csörgő and A. Ster, *Heavy Ion Phys.* **17** (2003) 295 [hep-ph/0112064].
32. T. Csörgő, J. Zimányi, J. Bondorf, H. Heiselberg and S. Pratt, *Phys. Lett. B* **241** (1990) 301.
33. T. Csörgő and J. Zimányi, *Phys. Rev. Lett.* **80** (1998) 916 [hep-ph/9705433].
34. J. Zimányi and T. Csörgő, *Heavy Ion Phys.* **9** (1999) 241 [hep-ph/9705432].
35. T. Csörgő, B. Lorstad and J. Zimányi, *Z. Phys. C* **71** (1996) 491 [hep-ph/9411307].
36. A. Ster, T. Csörgő and B. Lorstad, *Nucl. Phys.* **A661** (1999) 419 [hep-ph/9907338].
37. I. Lovas, J. Németh and K. Sailer, *Phys. Lett. B* **135** (1984) 258.
38. I. Lovas, K. Sailer and Z. Trócsányi, *J. Phys. G* **15** (1989) 1709.