Vol. 9 (2016) *Acta Physica Polonica B Proceedings Supplement* No 2

ANISOTROPIC HYDRODYNAMICS*

Leonardo Tinti

Institute of Physics, Jan Kochanowski University in Kielce
25-406 Kielce, Poland

(Received June 14, 2016)

We present the latest results on the leading order of the anisotropic hydrodynamic expansion. Anisotropic hydrodynamics has already been shown to be consistent with the second order viscous hydrodynamics in the one-dimensional (Bjorken flow), two-dimensional (radial expansion), and the general (3+1)-dimensional case. It provides a striking agreement with the exact solutions of the Boltzmann equation already at the leading order. In particular, the latest prescription improves both qualitatively and quantitatively the reproduction of the anisotropy and bulk viscosity evolution, providing the best approximation of the exact solution without relying on a next-to-leading order treatment.

DOI:10.5506/APhysPolBSupp.9.333

1. Introduction

Relativistic hydrodynamics is an important tool for the description of collective behavior in relativistic heavy-ion collisions, see, for instance, Refs. [1–6]. Nowadays, viscous hydrodynamics is preferred to the perfect fluid dynamics used in early calculations. Viscous corrections, apart from providing a better description of the data, are expected to never vanish because of general arguments. The latter stems both from quantum mechanical considerations [7] as well as from the AdS/CFT correspondence [8]. Despite its obvious success, there are still fundamental issues with the ordinary hydrodynamic expansion. In the second order viscous hydrodynamics, momentum anisotropies and pressure corrections are treated like small perturbations, however, in heavy-ion collision conditions, they are often very large.

A new approach called *anisotropic hydrodynamics* (aHydro) [9–13] avoids this fundamental issue by treating the large momentum anisotropies, and hence, large pressure corrections, in a non-perturbative way. Since the equa-

* Presented at WPCF 2015: XI Workshop on Particle Correlations and Femtoscopy, Warszawa, Poland, November 3–7, 2015.

tions are consistent with the second order viscous hydrodynamics, it is possible to check if the close to equilibrium behavior is consistent with other models. For instance, see Ref. [14] for the inclusion of a non-ideal equation of state within the anisotropic hydrodynamics framework.

2. The anisotropic hydrodynamic expansion

The working hypothesis of the standard hydrodynamic expansion is that the particle distribution function $f(x,p)$ is very close to local equilibrium. If we ignore conserved charges and consider the Boltzmann limit, the local equilibrium distribution reads

$$f(x,p) = f_{\rm eq}(x,p) + \delta f(x,p)\,, \qquad f_{\rm eq}(x,p) = k \exp\left[-\frac{p\cdot U(x)}{T(x)}\right]\,, \tag{1}$$

with T and U^μ being the effective temperature and the fluid four velocity, respectively. The leading order in expansion (1), $f_{\rm eq}$ represents the perfect fluid, while the viscous correction depends only on δf. The large gradients we expect in the case of (almost) boost invariant flow will produce large pressure corrections, in opposition to the starting hypothesis of the traditional hydrodynamic expansion. The main feature of anisotropic hydrodynamics is to treat the large momentum anisotropy in a non-perturbative way starting from the leading order

$$f(x,p) = f_{\rm aniso}(x,p) + \delta\tilde{f}(x,p)\,. \tag{2}$$

The deviation $\delta\tilde{f}$ from the (non-isotropic and dissipative) background $f_{\rm aniso}$ can be thus expected to be small enough to justify a perturbative treatment. The first formulation of aHydro used the point-dependent version of the Romatschke–Strickland form (presented in [15]) for the leading order of the expansion, and it has a very good agreement with the exact solution of the Boltzmann equation (see Ref. [16]). In order to take into account non-trivial transverse dynamics already at the leading order, in Ref. [17], we extended the formalism of anisotropic hydrodynamics to the (1+1)-dimensional case. The new set of equations reproduces the results of the Boltzmann equation better than the original prescription [18]. The next step is to extend the leading order to the most general (3+1)-dimensional expansion [19], unfortunately, this further generalization does not improve significantly the agreement between aHydro and kinetic theory [20]. However, in Ref. [21], we introduced a better set of dynamical equation for the anisotropic hydrodynamic expansion around the generalized Romatschke–

Strickland form[1]

$$f_{\mathrm{aniso}}(x,p) = k \exp\left[-\frac{1}{\lambda}\sqrt{p_\mu \left(U^\mu U^\nu + \phi\, g^{\mu\nu} + \xi^{\mu\nu}\right) p_\nu}\,\right] . \tag{3}$$

Instead of using the moments of the Boltzmann equations, the evolution of $\xi^{\mu\nu}$ and ϕ is extracted from the exact evolution of the pressure corrections. As shown in Fig. 1, the new prescription (anisotropic matching) removes the unphysical kink for initial stages of the bulk evolution, and at the same time, improves even further the description of anisotropy.

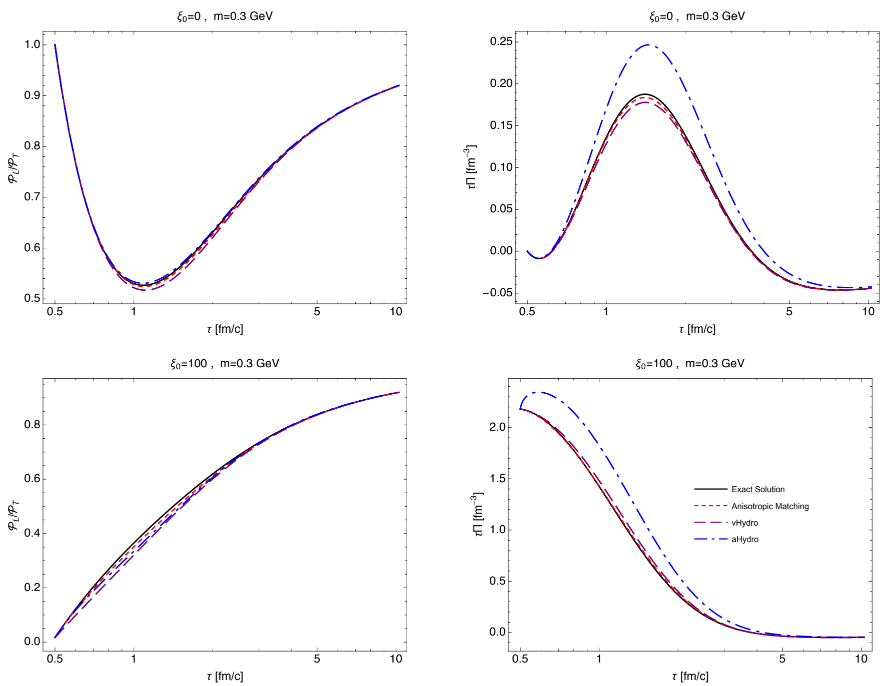

Fig. 1. Time evolution of the pressure anisotropy $\mathcal{P}_{\mathrm{L}}/\mathcal{P}_{\mathrm{T}}$ (left) and the bulk corrections times the proper time $\tau\Pi$ (right), presented in Ref. [21].

3. Conclusions

Anisotropic hydrodynamics is a reorganization of the hydrodynamic expansion around a non-isotropic background. The leading order already provides large longitudinal pressure corrections, justifying the perturbative treatment of the next-to-leading order in heavy-ion collisions.

[1] The anisotropy tensor $\xi^{\mu\nu}$ is space-like and traceless, it is responsible for the anisotropy and it is the higher dimensional version of the anisotropy parameter. The scalar ϕ is taking into account the bulk dynamics, and λ and U are still, respectively, the momentum scale and the four-velocity.

The latest prescription provides the best agreement with the exact solution of the Boltzmann equation, compared to the previous most successful leading order prescription of aHydro and to the most successful prescription for the second order viscous hydrodynamics. All of that without simplifying symmetry assumptions or a next to leading treatment.

This work has been supported by the Polish National Science Center grant No. DEC-2012/06/A/ST2/00390.

REFERENCES

[1] A. Muronga, *Phys. Rev. C* **69**, 034903 (2004).

[2] M. Luzum, P. Romatschke, *Phys. Rev. C* **78**, 034915 (2008) [*Erratum ibid.* **79**, 039903 (2009)].

[3] B. Schenke, S. Jeon, C. Gale, *Phys. Lett. B* **702**, 59 (2011).

[4] C. Shen, U. Heinz, P. Huovinen, H. Song, *Phys. Rev. C* **84**, 044903 (2011).

[5] P. Bożek, I. Wyskiel-Piekarska, *Phys. Rev. C* **85**, 064915 (2012).

[6] G.S. Denicol, H. Niemi, E. Molnar, D.H. Rischke, *Phys. Rev. D* **85**, 114047 (2012).

[7] P. Danielewicz, M. Gyulassy, *Phys. Rev. D* **31**, 53 (1985).

[8] P. Kovtun, D.T. Son, A.O. Starinets, *Phys. Rev. Lett.* **94**, 111601 (2005).

[9] M. Martinez, R. Ryblewski, M. Strickland, *Phys. Rev. C* **85**, 064913 (2012).

[10] R. Ryblewski, W. Florkowski, *Phys. Rev. C* **85**, 064901 (2012).

[11] R. Ryblewski, *J. Phys. G* **40**, 093101 (2013).

[12] W. Florkowski, R. Ryblewski, M. Strickland, *Phys. Rev. D* **86**, 085023 (2012).

[13] M. Nopoush, R. Ryblewski, M. Strickland, *Phys. Rev. C* **90**, 014908 (2014).

[14] M. Alqahtani, M. Nopoush, M. Strickland, *Phys. Rev. C* **92**, 054910 (2015).

[15] P. Romatschke, M. Strickland, *Phys. Rev. D* **68**, 036004 (2003).

[16] W. Florkowski, R. Ryblewski, M. Strickland, *Phys. Rev. C* **88**, 024903 (2013).

[17] L. Tinti, W. Florkowski, *Phys. Rev. C* **89**, 034907 (2014).

[18] W. Florkowski, R. Ryblewski, M. Strickland, L. Tinti, *Phys. Rev. C* **89**, 054909 (2014).

[19] L. Tinti, *Phys. Rev. C* **92**, 014908 (2015).

[20] L. Tinti, R. Ryblewski, W. Florkowski, M. Strickland, *Nucl. Phys. A* **946**, 29 (2016).

[21] L. Tinti, `arXiv:1506.07164 [hep-ph]`.