Bubble Wall Velocity at Strong Coupling

UNIVERSITÀ DEGLI STUDI FIRENZE

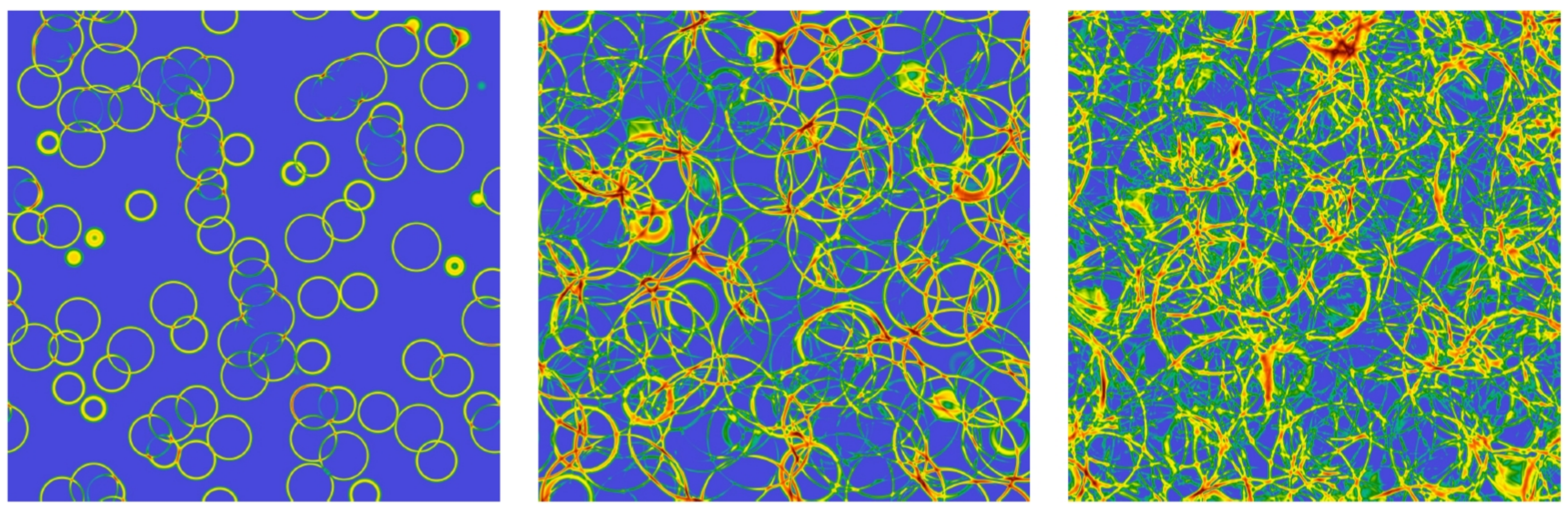
F. Bigazzi, A. Caddeo, **T. Canneti**, A. L. Cotrone, J. High Energ. Phys. 2021, 90 (2021) [arXiv:2104.12817 [hep-ph]]

Abstract

Using the holographic correspondence as a tool, we determine the steady-state velocity of expanding vacuum bubbles nucleated within finite temperature first-order phase transitions occurring in strongly-coupled large N QCD-like models having a gravity dual. We deal with general setups of different dimensions. Then, we briefly compare our results, obtained within a fully non-perturbative framework, to other estimates of the bubble velocity in the literature.

Motivations

In nature, first-order phase transitions (FOPTs) proceed through the nucleation of bubbles of the energetically favored phase within the non-favored one. These transitions could have taken place in the early Universe [1]. The resulting bubbles expand due to the pressure gradient, collide and transfer energy to the surrounding plasma. Such processes may be the source of detectable stochastic gravitational (GW) backgrounds [2-3].



From [4]

The Standard Model (SM) does not predict any cosmological FOPTs [5-6]. Therefore, a GW signal like that would represent a signal of new physics. It is thus necessary to compute the GW spectrum as accurately as possible.
These expressions contain parameters such as the bubble wall velocity v. Nevertheless, computations of v are rare and often perturbative.

The model

Holographically, the phase transitions we consider are related to changes in the embedding of N_f Dq-$\overline{\text{Dq}}$ flavor branes probing the black hole background sourced by a stack of N Dp-branes and placed at a distance L along x_p [7].

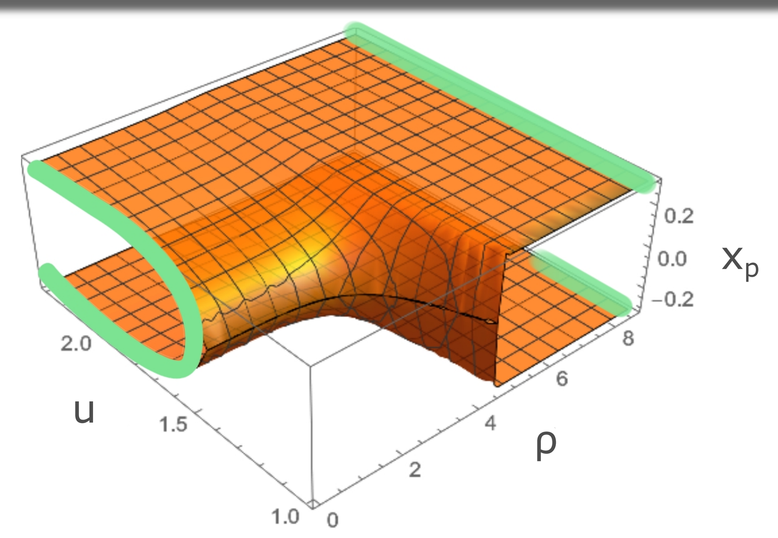
	t	x^1	…	x^d	x^{d+1}	…	x^p	u	Ω_n	Y_{8-p-n}
Dp:	x	x	…	x	x	…	x			
Dq:	x	x	…	x				x	x	

The low-energy dynamics of the probes ($N \ll N_f$) is described by the DBI action. The equation of motion admits two configurations: the disconnected (connected) one is preferred above (below) a certain critical temperature T_c.

The bubble

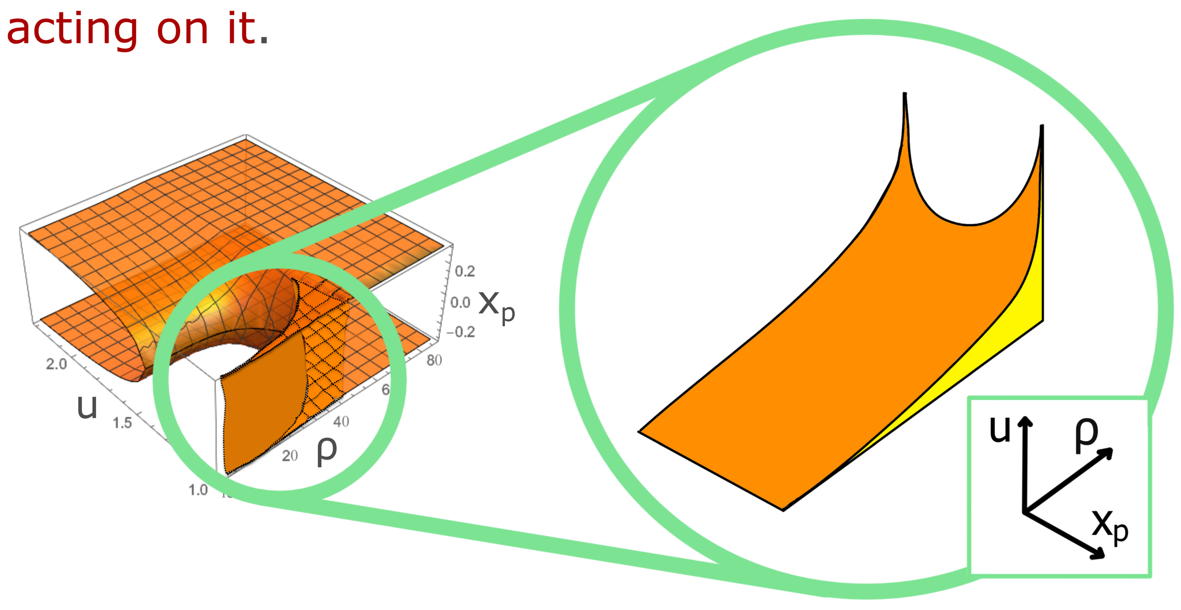
The bubble corresponds to a space-dependent O(d)-symmetric solution of the Euclidean DBI Euler-Lagrange equations.

It interpolates between the true vacuum at the center of the bubble at $\rho=0$ and the false vacuum at $\rho\to\infty$ [8-9].



The trailing wall

The nucleated bubble reaches a steady state after a transient period of acceleration. The profile of the brane dual to the bubble gets distorted by the forces acting on it.



At late time, the bubble radius can be assumed to be much larger than its thickness and a planar approximation can be taken. The DBI action for the Dq-brane profile ξ describing the bubble wall reduces to

$$S_w = -\frac{k}{L}\int dt\, du\, dx_p \left(\frac{u}{R}\right)^{\frac{7-p}{4}(3+d-p-n)} u^n \sqrt{1+(\partial_{x_p}\xi)^2+\left(\frac{u}{R}\right)^{7-p} f\,(\partial_u\xi)^2 - f^{-1}v^2},$$

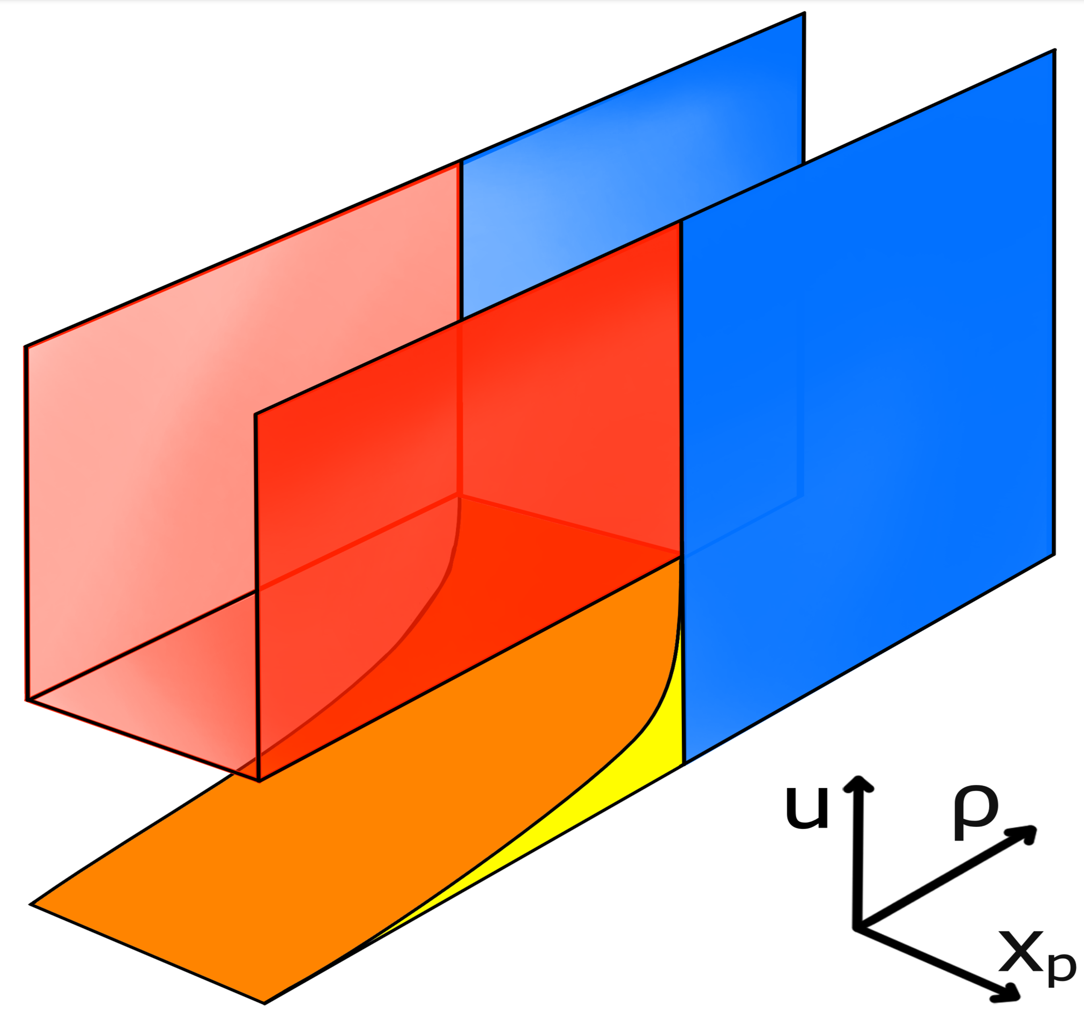
where $k = T_q\, A\, L\, V(S^n)$, $A=\int dx^1 \ldots dx^{d-1}$, $f = 1-\left(\frac{u_T}{u}\right)^{7-p}$, $T=\frac{7-p}{4\pi R}\left(\frac{u_T}{R}\right)^{(5-p)/2}$.

The complete steady-state configuration

The complete brane configuration can be described by a total action coming from the sum of the actions of the components.

We assume that the simplified configuration showed in figure is sufficient to catch the fundamental aspects of the physics of the true configuration.

This represents the limit of our construction, but allows us to approach the problem analytically.



The bubble wall velocity

Taking the variation of the total action w.r.t. the trailing wall profile and its boundary values, we get some relations which allow to rewrite the zero force condition defining the steady state as

$$\frac{F}{A} = C_d \frac{T_{boost}}{T_c} w_f(T_{boost})\, v + p_f(T_{boost}) - p_f(T) = p_t(T) - p_f(T) = \Delta p,$$

from which

$$\boxed{v = C_d^{-1} \frac{T_c}{T_{boost}} \frac{p_t(T) - p_f(T_{boost})}{w_f(T_{boost})}},$$

where F is the friction force due to the plasma, p_t (p_f) is the pressure of the true (false) vacuum and

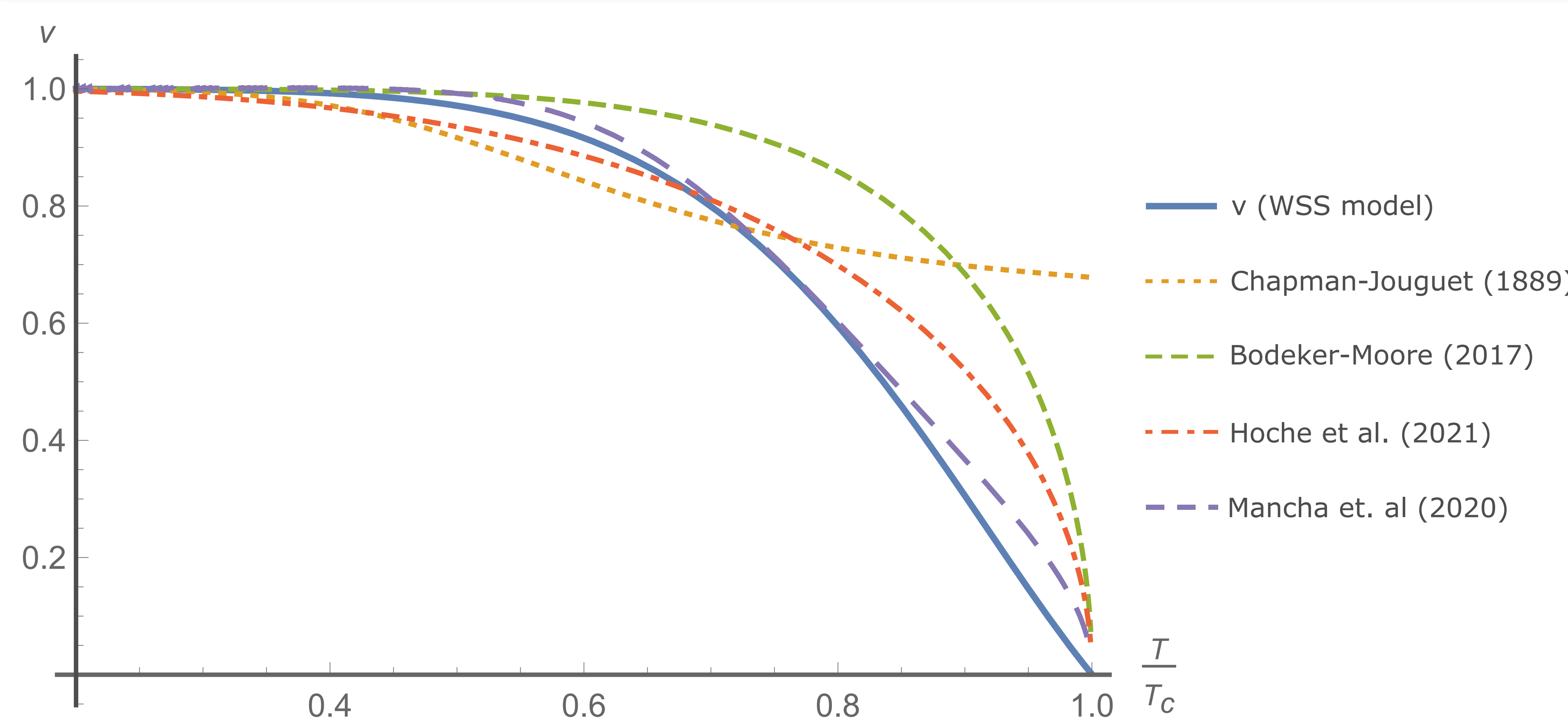
$$C_d = \frac{\pi(5-p)}{7-p}\kappa_c = 2\pi \frac{c^2_{s,glue}}{(1+c^2_{s,glue})}\kappa_c, \quad \kappa_c = L\, T_c,$$

$$w_f(T) = T\frac{\partial}{\partial T} p_f(T), \quad T_{boost}(v) = \frac{T}{(1-v^2)^{\frac{5-p}{2(7-p)}}}.$$

Notice that the drag coeffcient C_d carries information about the gluonic part of the plasma and all the model dependence of the formula is contained in κ_c=0.15÷0.30.

An interesting feature is the linear relation between v and the ratio of $\Delta p = p_t(T) - p_f(T)$ over the energy density of the false vacuum near T_c.

Comparison



The Chapman-Jouguet formula gives a common benchmark value for v and it comes from the study of the wavefront propagation of explosions within gases.

From a perturbative analysis, Bodeker-Moore and Hoche respectively found a linear and quadratic dependence of the friction effects of the plasma on the Lorentz factor.

Mancha et. al found an expression for v by modeling the plasma as an ideal fluid and exploiting the conservation of the energy-impulse-stress tensor.

References

[1] C. Caprini et al., JCAP 04 (2016) 001, arXiv:1512.06239 [astro-ph.CO].
[2] C. Caprini et al., JCAP 03, 024 (2020) [arXiv:1910.13125 [astro-ph.CO]].
[3] M. Hindmarsh et al., SciPost Phys. Lect. Notes 24, 1 (2021), [arXiv:2008.09136 [astro-ph.CO]].
[4] M. Hindmarsh et al., PoS LATTICE2015 (2016), 233, [arXiv:1511.04527 [hep-lat]].
[5] Y. Aoki et al., Nature 443 (2006) 675–678, arXiv:hep-lat/0611014.
[6] K. Kajantie et al., Phys. Rev. Lett. 77 (1996) 2887–2890, arXiv:hep-ph/9605288.
[7] Aharony et al., Annals Phys. 322, 1420-1443 (2007), arXiv:hep-th/0604161.
[8] F. Bigazzi et al., JHEP 12, 200 (2020) [arXiv:2008.02579 [hep-th]].
[9] F. Bigazzi et al., JHEP 04,094 (2021) [arXiv:2011.08757 [hep-ph]].