Bubble wall velocities in local thermal equilibrium

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In collaboration with:
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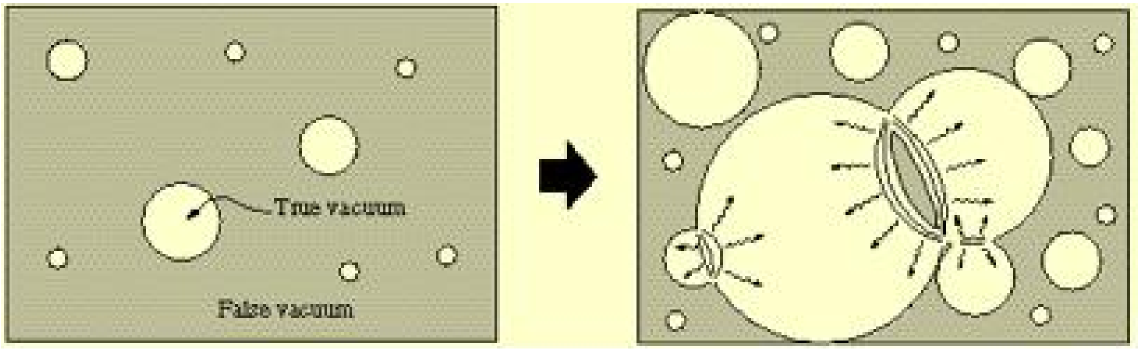
Cosmological first-order phase transitions

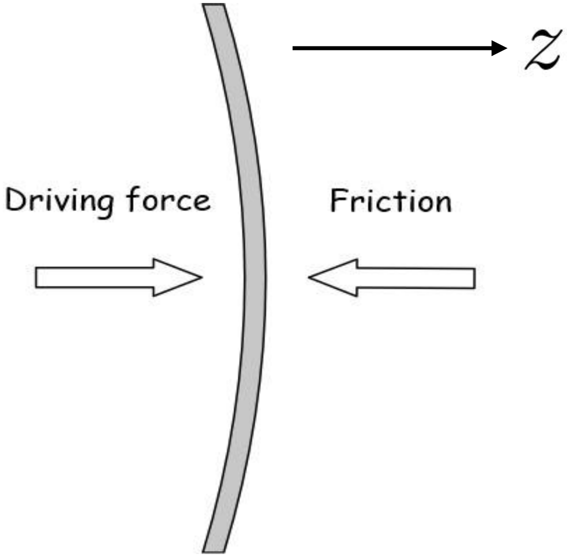
In many BSM models, the cosmological phase transition of electroweak symmetry breaking is of first order



Possible phenomenological consequences:
electroweak baryogenesis, GW production

Experiment projects : LISA, BBO, DECIGO, Taiji, and Tianqin…

In both the above phenomena, the bubble wall velocity is an important parameter



Backreaction force in local equilibrium

Recently, Mancha, Prokopec & Swiezewska, JHEP 01 (2021) 070 proposed that in local thermal equilibriuim

$$\frac{F_{\rm back}}{A} = (\gamma_w^2 - 1) T \Delta s$$

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How to derive?

The energy-momentum tensors read

$$T_\phi^{\mu\nu} = (\partial^\mu \phi)\partial^\nu \phi - g^{\mu\nu} \left(\frac{1}{2} (\partial \phi)^2 - V(\phi) \right)$$

$$T_f^{\mu\nu} = (\rho_f + p_f) u^\mu u^\nu - p_f g^{\mu\nu}$$

Then from $\nabla_\mu T^{\mu 0} = 0$ and $\nabla_\mu T^{\mu 3} = 0$, one obtains

$$\omega \gamma^2 v = \text{const}$$

$$\omega \gamma^2 v^2 + \frac{1}{2} \left(\partial_z \phi(z) \right)^2 + p = \text{const}$$

where $\omega = \rho_f + p_f, \; p = p_f - V(\phi)$

Backreaction force in local equilibrium

This leads the following two well-known matching conditions

$$\omega_+\gamma_+^2 v_+ = \omega_-\gamma_-^2 v_-$$

$$\omega_+\gamma_+^2 v_+^2 + p_+ = \omega_-\gamma_-^2 v_-^2 + p_-$$

From the second condition, one can identify (recall $\omega = Ts$) Balaji, Spannowsky & Tamarit, 2021

$$\frac{F_{\text{pressure}}}{A} \equiv -\Delta p\,, \qquad \boxed{\frac{F_{\text{back}}}{A} = \Delta\{(\gamma^2 - 1)Ts\}}$$

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In local equilibrium, we have Review: Hindmarsh, Lüben, Lumma & Pauly 2020

$$\partial_\mu S^\mu \equiv \partial_\mu(su^\mu) = 0 \quad \Rightarrow \quad s(z)\gamma(z)v(z) = \text{const}$$

Together with $\gamma^2 - 1 = \gamma^2 v^2$, one obtains

$$\frac{F_{\rm back}}{A} = \text{const} \times \Delta\{\gamma v T\}$$

Further, divide the first condition by the above new condition, we have

$$\gamma(z)T(z) = \text{const}$$

A new matching condition in local equilibrium

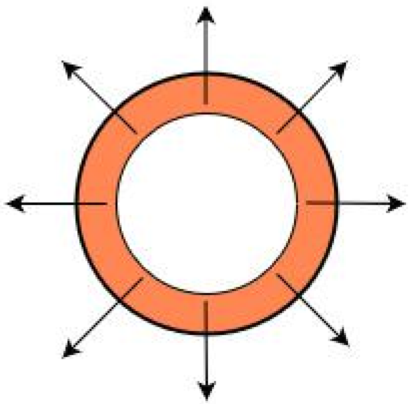
Therefore, non-constant plasma temperature is necessary!

Moore & Prokopec, 1995
Kurki-Suonio & Laine, 1996
Espinosa, Konstandin, No & Servant, 2010
Konstandin & No, 2011

In local equilibrium, there is a new matching condition

$$\gamma_+ T_+ = \gamma_- T_-$$

Detonation:



$v_w > c_s$

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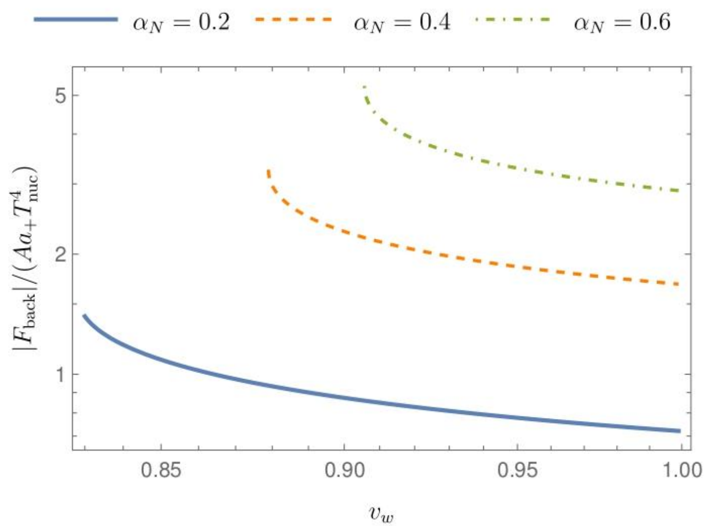
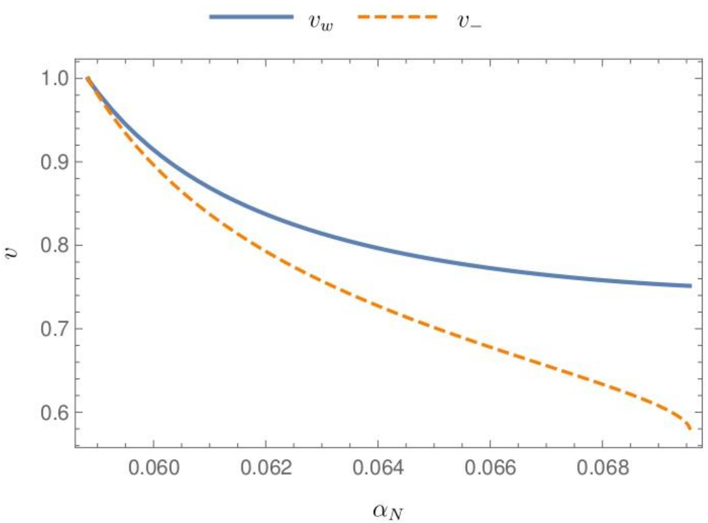


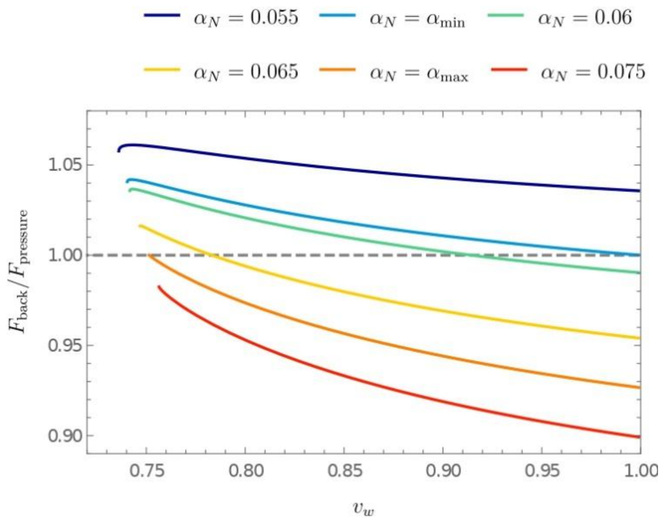


$$\alpha_N = \frac{\Delta\epsilon}{a(T_{\rm nuc})T_{\rm nuc}^4}, \quad a(T) = \frac{\pi^2}{30} g_{\rm eff}(T)$$

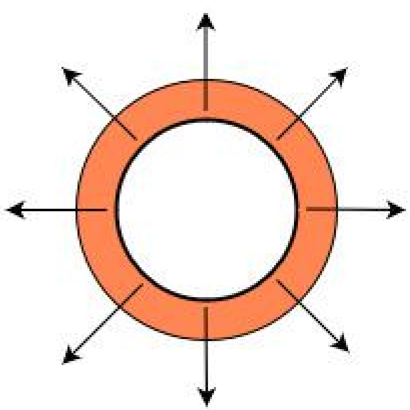
$$[\alpha_{\min} \approx 0.059, \alpha_{\max} \approx 0.07]$$

Bubble wall velocity in local equilibrium

Balance of the forces:



Deflagration:



$v_w < c_s$

- ❑ Need to relate T_+, α_+ to $T_{\rm nuc}$ and α_N
- ❑ For simplicity, we used the planar-wall approximation

Bubble wall velocity in local equilibrium

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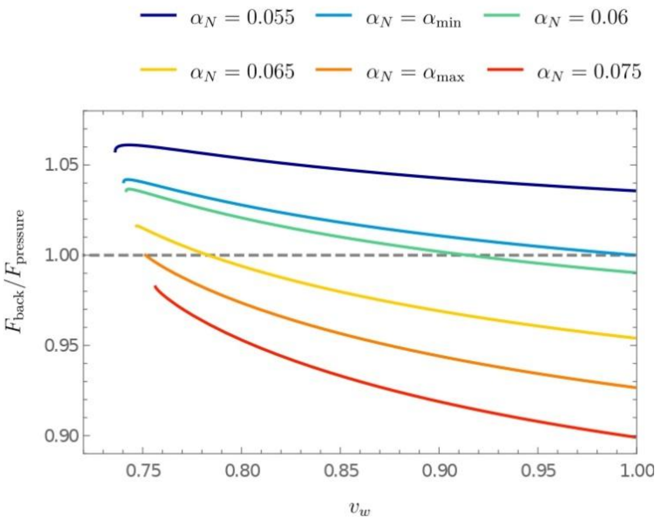

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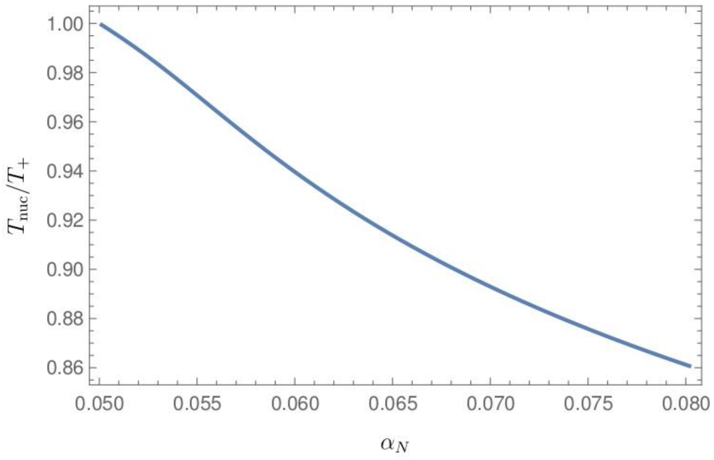

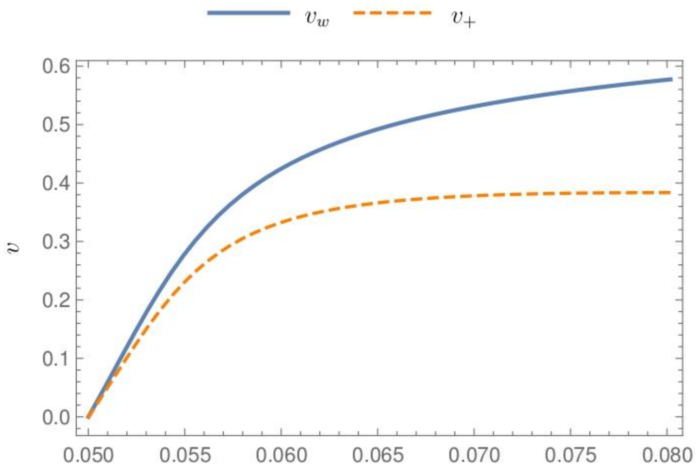

$\alpha'_{\rm max} \approx 0.08$

Conclusions

- There can be an effective friction in local thermal equilibrium, but non-constant plasma temperature across the bubble wall is a necessary condition
- We proposed a new matching condition for the plasma hydrodynamic quantities in local equilibrium $\gamma_+ T_+ = \gamma_- T_-$
- The backreaction force in local equilibrium decreases in the detonation regime as the bubble wall velocity increases
- In local thermal equilibrium, there is a critical phase transition strength $\alpha_{\rm crit} = \alpha'_{\rm max}$, below which the bubble wall does not run away while above which the bubble wall does run away

Thank you!