Structure Formation From Cosmic Domain Wall Collapses

Clara Winckler, Pedro Avelino, Lara Sousa

Instituto de Astrofisica e Ciências do Espaço/ Universidade do Porto

clara.winckler@astro.up.pt

How many non-linear objects observable today may have been seeded by cosmic domain wall collapses?

Networks of sheet-like topological defects known as domain walls may have formed during discrete symmetry-breaking phase transitions in the early universe. These walls are expected to rapidly collapse as soon as they enter the Hubble horizon, causing a perturbation in the matter-density, which could potentially leave observable signatures in present-day large-scale structures. We show that although the contribution from stable domain walls is subdominant, biased domain wall networks can provide a significant contribution to structure formation, and, in particular, an observed mass excess recently suggested by JWST data.

Background

It was shown that standard stable domain walls would eventually dominate the cosmic energy budget, since their energy density dilutes more slowly than that of the background, leading to strong constraints on their tension. The walls would therefore either have to be very light, with a maximal tension $\sigma_{\rm Zel} = (1{\rm MeV})^3$ derived from the Zel'dovich bound, or have been part of a network that has fully decayed at some time before the present day. Although this severely restricts possible creation scenarios, many are still viable and the observational imprints of their presence and decay could provide interesting insights into the evolution of the early universe.

Biased Wall Networks

The above only considers standard stable networks which survive until the present day. Biased domain wall networks, however, are created due to a slight asymmetry in the underlying potential, causing them to fully collapse at some time before the current day. Since these walls are not present anymore, they are much less constrained by signatures in the cosmic microwave background, allowing for significantly larger tensions and seed energies (such that we can now have that $\varepsilon \geq 1$). We can thus calculate the maximal masses attained by walls collapsing in such networks for a range of network collapse redshifts $z_{\rm bias}$, showing that they can contribute to the high-mass range for a large range of wall collapse redshifts z_*.

Contribution from biased networks

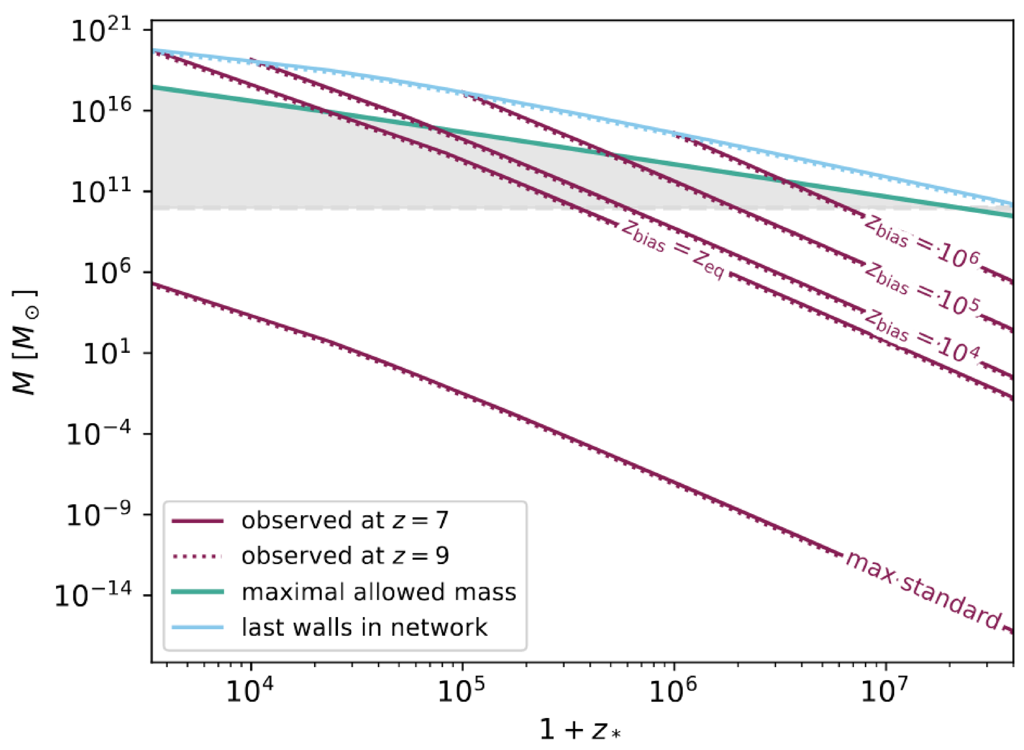

Figure 5: *Maximal masses of non-linear objects generated by biased networks decaying at different $z_{\rm bias}$, observed at $z=9$ (solid line) and $z=7$ (dotted line). The allowed parameter space for a contribution of $M \geq 10^{10} M_\odot$ is shown underlined in grey.*

Modelling a DW network

The parameter-free version of the velocity-dependent one-scale model [1] provides a description of the network collapse process based on a statistical approach. This allows us to calculate the energies associated to a single domain wall collapse,

Decay energies

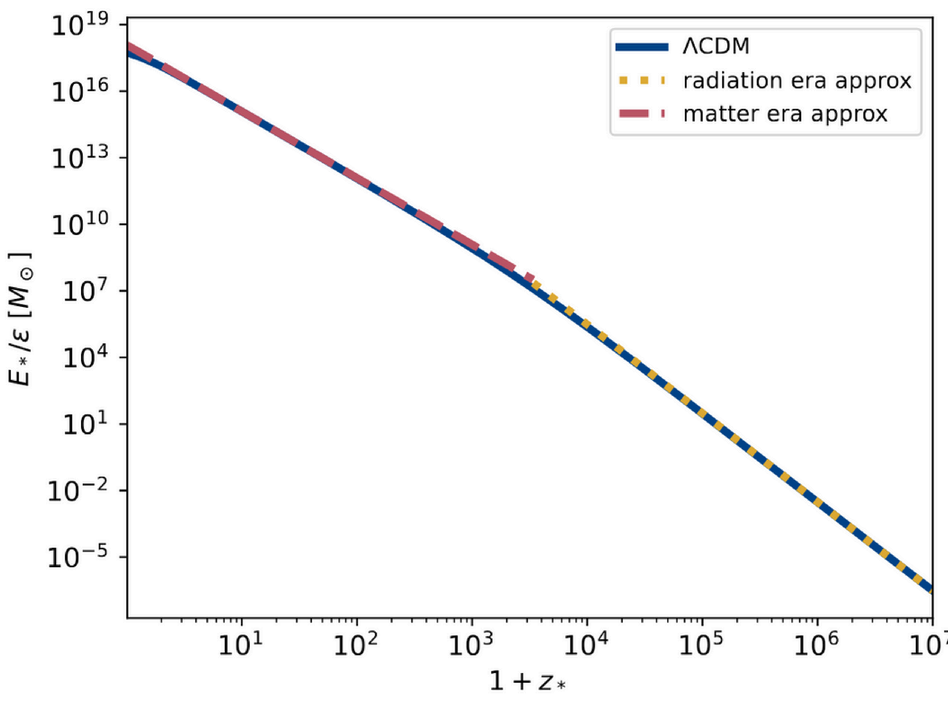

Figure 1: *Decay energies of individual walls collapsing at a redshift $z = z_*$.*

as well as the distribution of relevant collapse events within the physical particle horizon, where $\varepsilon = \sigma_{\rm w}/\sigma_{\rm Zel}$ denotes the wall tension rescaled by the Zel'dovich bound.

Collapse Events

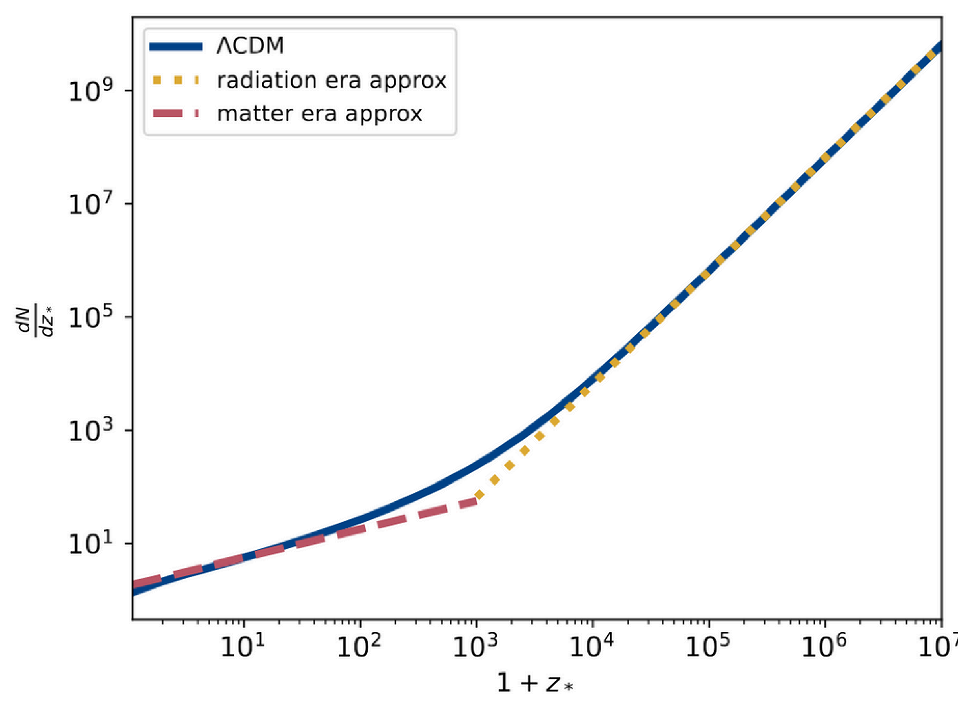

Figure 2: *Distribution of collapse events within the physical particle horizon, potentially contributing to observational signatures.*

Considering the evolution of the comoving displacement associated to the perturbation through a linear relation given by the Zel'dovich approximation, we calculate the masses of the resulting non-linear objects as they appear today.

Accreted Masses

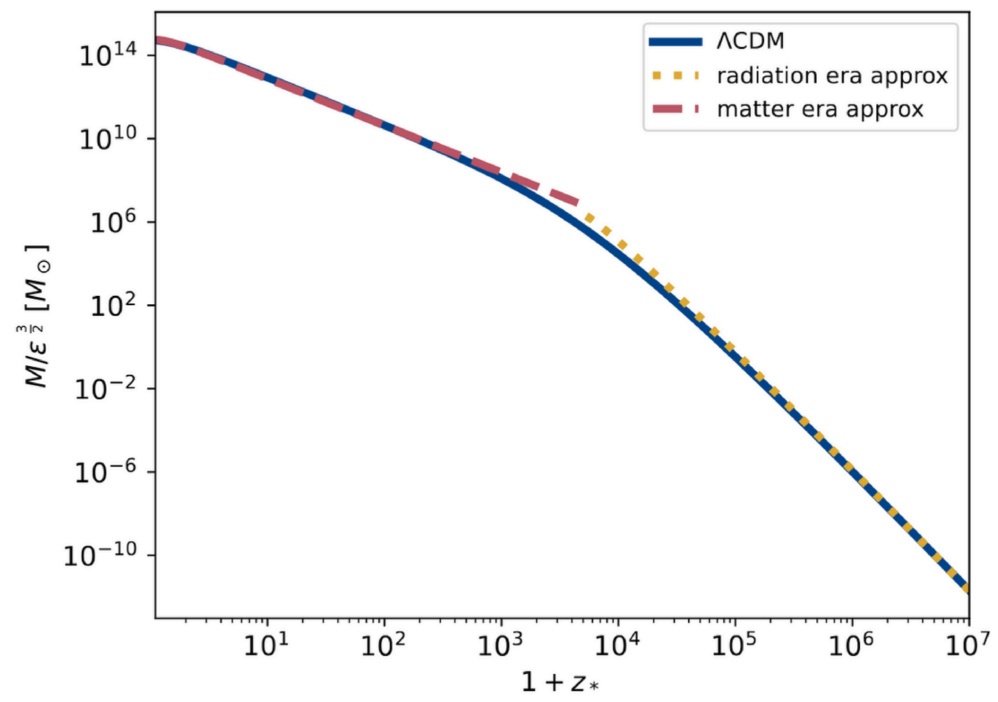

Figure 3: *Masses of non-linear objects seeded by a DW collapse at $z = z_*$ in units of solar masses.*

To estimate the potential contribution of this domain wall seeded structure formation, we calculate the associated halo mass function, defined as the number of objects per unit mass per unit volume.

Halo Mass Function

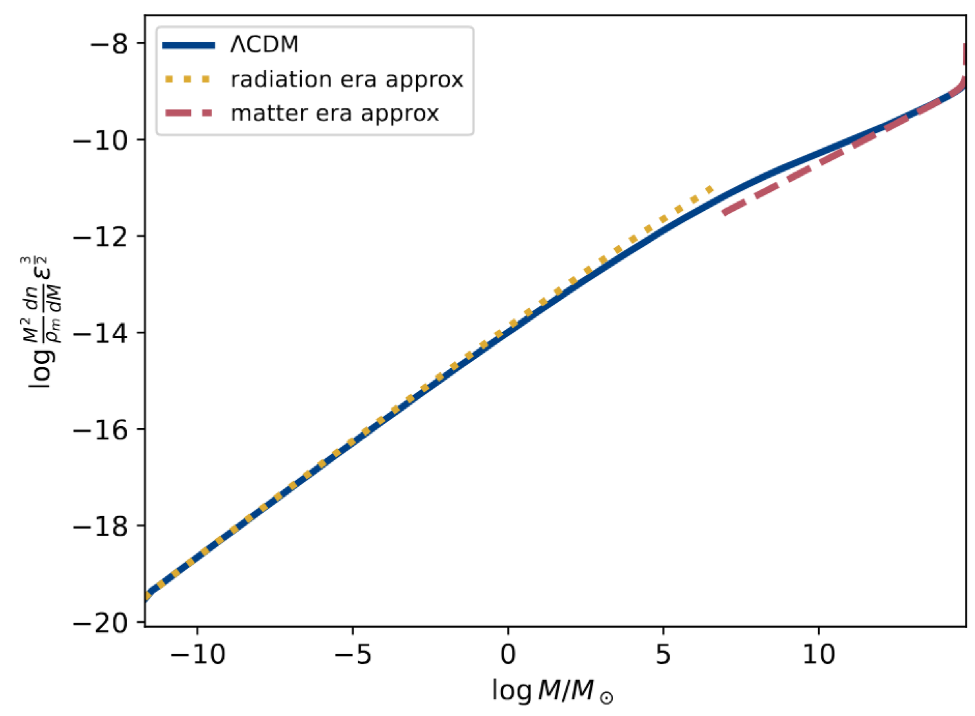

Figure 4: *Halo mass function of objects seeded by walls collapsing within standard stable wall networks.*

Comparing with the observed values as given by [2], domain wall seeded structures could make up a maximal fraction of about $\sim 10^{-9}$ of objects with masses of the order of $10^{10} M_\odot$ and $\sim 10^{-6}$ of objects with large masses of the order of $10^{15} M_\odot$, providing a clearly subdominant contribution to structure formation.

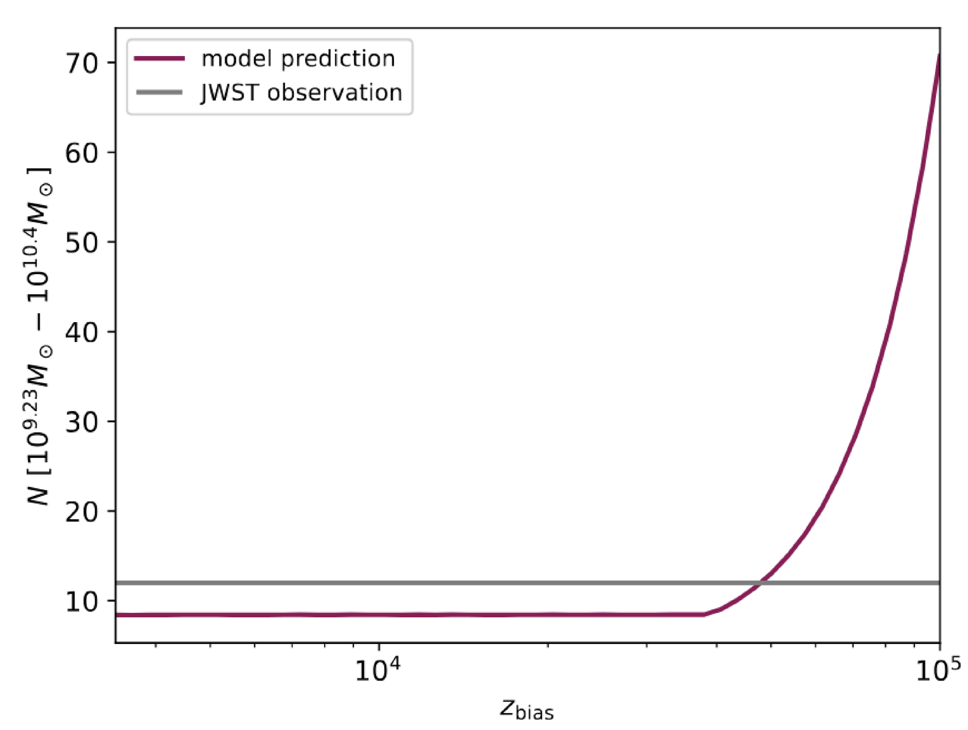

Figure 6: *Number of objects in the $[10^{9.23}, 10^{10.4}]M_\odot$ mass bin depending on the network collapse redshift $z_{\rm bias}$, as predicted by our model (purple) and observed by JWST (grey).*

Mass Excess in JWST Observations

Labbé et al.[3] observe a mass excess in objects with $M \geq 10^{10} M_\odot$ at high redshifts of $7 \leq z \leq 9$ within an observed field of $38\ {\rm arcsec}^2$ with one single object at $10^{10.89} M_\odot$ and 12 futher objects in the $[10^{9.23}, 10^{10.4}]M_\odot$ range. Normalising to one object within the highest mass range of $[10^{10.5}, 10^{11}]M_\odot$, we can predict the number of objects within this observed mass bin based on our model. Our results fit very well with the observed values for a range of $z_{\rm bias}$ of $[z_{\rm eq}, \sim 3\times 10^4]$. Assuming that biased domain walls are responsible for this observation, we can therefore restrict the network collapse redshift to this range.

Conclusions

Although standard stable DWs can only provide a subdominant contribution to the formation of non-linear objects, we have shown that:

- Biased DW networks can potentially provide a significant contribution to the formation of structures
- Could provide an explanation of the observational signature suggested by JWST data

These networks should therefore be seriously considered, not only in the context of this measured mass excess, but also when comparing with future observations.

References

[1] P. Avelino, Parameter-free velocity-dependent one-scale model for domain walls, Phys Review D 101, 023514 (2020).
[2] J. Tinker et al., Toward a Halo Mass Function for Precision Cosmology: The Limits of Universality, Astrophys. J. 688, 709 (2008).
[3] I. Labbé et al., A population of red candidate massive galaxies 600 myr after the big bang, Nature 616, 266–269 (2023).

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