Warm or Cold Dark Matter? A Love-Heat Relationship

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1. SciCom Statement

SciCo Let's Talk Sc

90% of the matter in the universe is comprised of **dark matter**, and it is **undetectable** through modern technology. But it *does* interact with regular visible matter through **gravity**! Large clusters of dark matter are responsible for causing gas and dust clouds to collapse in on themselves to create the first galaxies and stars. However, depending on the **temperature of dark matter**, these first clusters of dark matter could have begun forming at drastically different times. Using a series of simulations for the first billion years of the Universe, we will make predictions for whether **NASA's new James Webb Space Telescope can tell us the temperature of dark matter.**

2. Introduction

Dark Matter (DM) is hypothesized to be an exotic particle that is **invisible** to human observation. But thankfully, its existence is proven through its gravitational interaction with luminous matter (such as stars and galaxies), and it is **responsible for the formation of the humongous structures across our universe.**

The leading interpretation of DM is what we call **Cold Dark Matter** (CDM), where the DM particles have relatively low velocities. This causes **structures to form quite quickly** and easily in the early universe. While CDM can explain many observed properties of the universe, it is not without its flaws, specifically on the scale of low-mass dwarf galaxies. The hypothesis of **Warm Dark Matter (WDM) poses a viable solution to the shortcomings of CDM**. In WDM, the DM particles have higher velocities. This would cause the formation of the first gravitationally bound structures in the Universe to be **delayed and more massive when compared to CDM**.

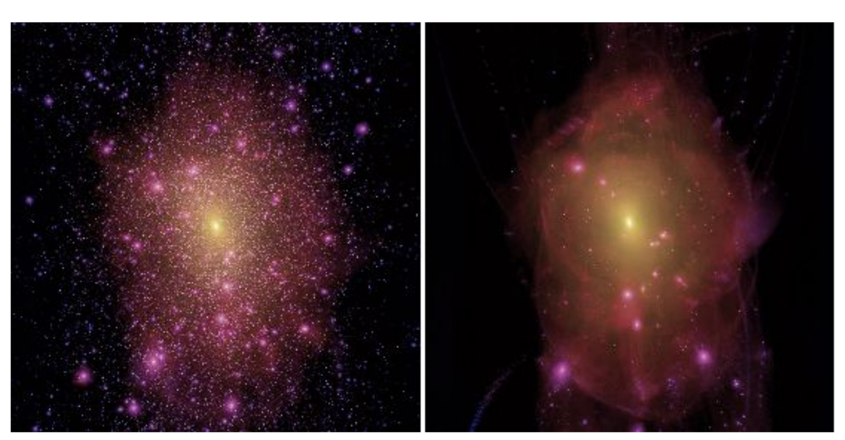

Figure 1: A CDM simulation of a galaxy cluster (left) versus a WDM simulation of the same galaxy cluster (right). Notice the stark differences between the amount of clustering occurring (Image Credit: CERN).

3. Data & Methodology

DM halos cannot be directly detected, instead we observe the stars and gas they contain. The formation of the first stars, is dependent on the **ability of primordial gas to cool**. H_2 molecules absorb radiation/photons through their rotational and vibrational modes. At large enough masses, and with enough H_2, these 'clumps' of cool gas will become gravitationally unstable, collapse, and form the first stars. However, underlying the baryonic physics, the temperature of DM dictates when the dark matter halos in which this gas cools and collapses will form.

Using a computer model for the formation of the first stars, we approximate the implications of WDM during the first billion years (z>6) by introducing a **minimum mass threshold** for dark matter halos to form stars.

We ask the question: Can the detection of the first stars be used to discern the temperature of DM? If so, how can we **optimize observations** with JWST to differentiate between warm and cold dark matter (Fig 6)? Will this be possible through **gravitational lensing** (see Fig. 7)?

Figure 7: Gravitational lensing occurs when massive foreground objects bend and warp the fabric of space itself. The more distant light of incredibly old structures traveling toward us reaches this warped space, which then acts as a lens, bending and magnifying the light. Using this lensing, we hope to see the very first stars of our universe [Image Credit: NASA].

4. Results

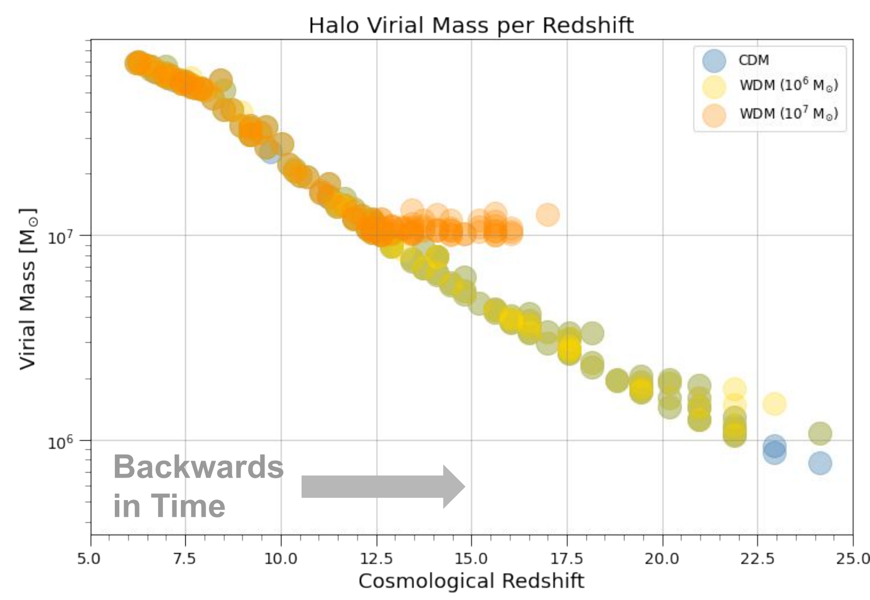

Figure 2: The mass of DM halos as a function of cosmological redshift (z). The blue indicates CDM halos, yellow is WDM halos with a minimum mass threshold of $M_{Halo}>10^6\ M_{Sun}$, and orange is WDM halos with a minimum mass threshold of $M_{Halo}>10^7\ M_{Sun}$. Notice how the masses of the halos never go below the minimum mass threshold that is identified with them. WDM $10^6\ M_{Sun}$ and CDM are very closely aligned, whereas CDM and WDM $10^7\ M_{Sun}$ is drastically different, with the halo formation not occurring until *much* later (z ~ 16).

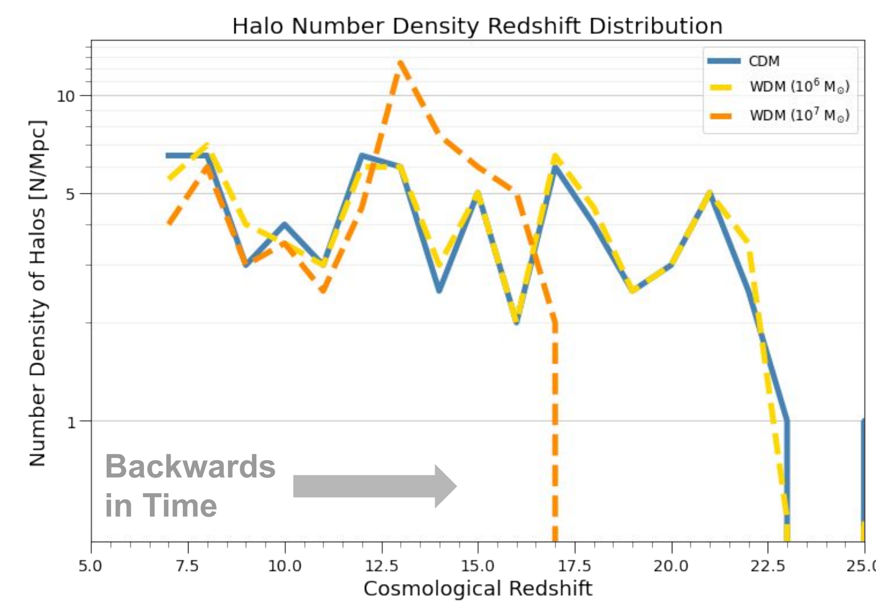

Figure 3: The number density of DM halos as a function of cosmological redshift (z). The colors are notated in the legend above, and as notated in the caption for Fig. 1. Again, WDM $10^6\ M_{Sun}$ and CDM are very closely aligned, and the formation of WDM $10^7\ M_{Sun}$ is delayed. However, there is sharp peak of halo formation (z ~ 12.5) that is significantly above that of the other types of DM.

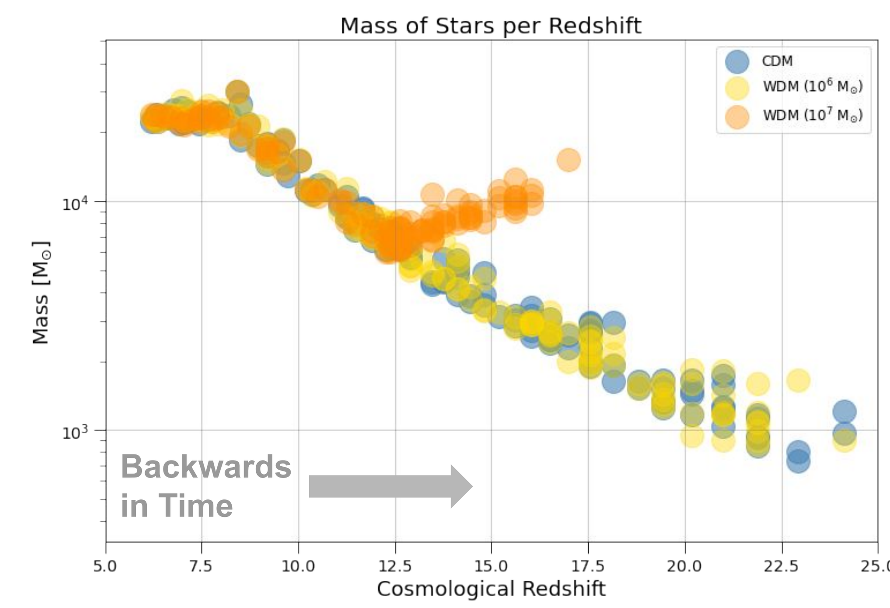

Figure 4: The mass of early universe stars in DM halos as a function of cosmological redshift (z). The colors are notated in the legend above, and as notated in the caption for Fig. 1. Again, WDM $10^6\ M_{Sun}$ and CDM have similar trends to each other, as the mass of the stars increases over time. The formation of WDM $10^7\ M_{Sun}$ is delayed, as seen previously. However, there is a critical point where the mass of the stars in the halos are at a minimum, but then increase past their initial masses (z ~ 12.5).

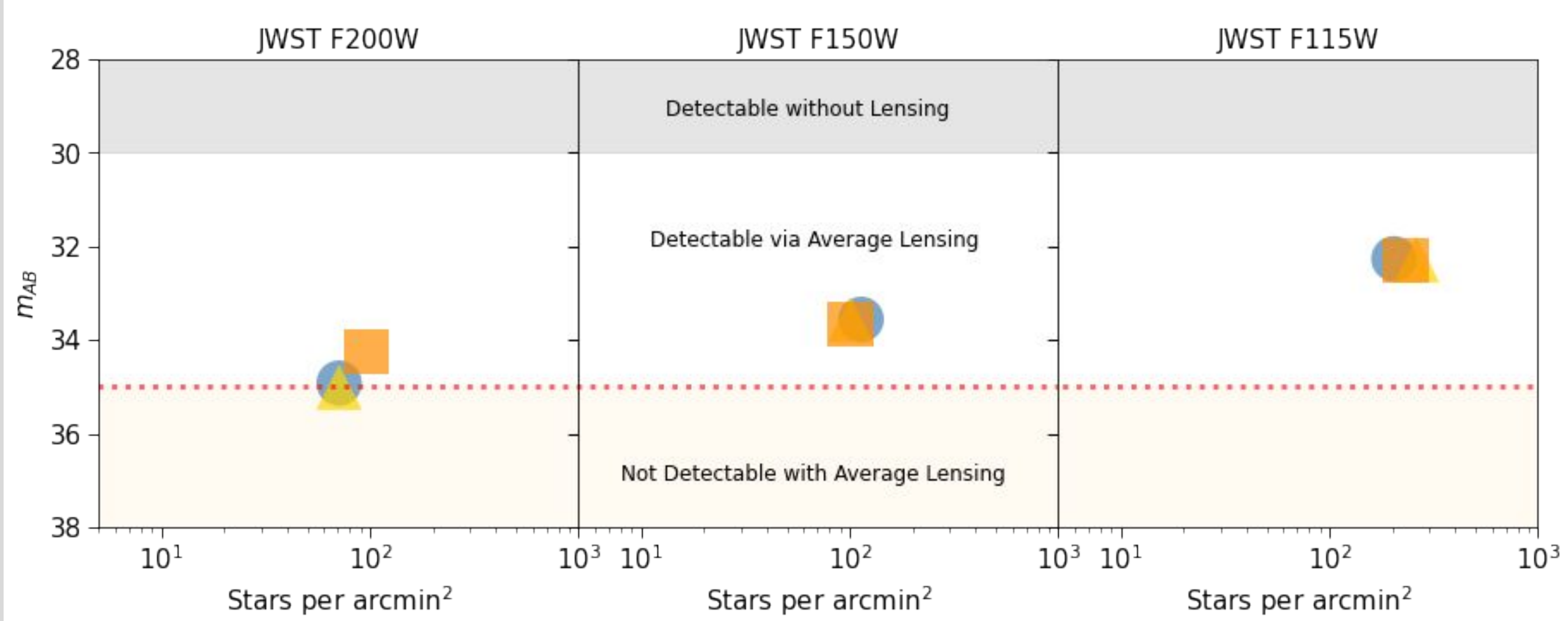

Figure 5: Apparent magnitude for JWST filters versus the number of stars per arcsec^2. From left to right we have the different filters of interest for JWST, namely F200W, F150W, and F115W. The gray shaded region indicates where stars are bright enough to be visible without the aid of gravitational lensing, and the orange shaded region is where stars would be too faint to see without the help of *average* levels of gravitational lensing. The white region is where stars are too faint to be seen without lensing, but bright enough to be seen with an *average* magnification level due to lensing. The colors of the data points are the same as above, where the blue circle is CDM, yellow triangle is WDM $10^6\ M_{Sun}$, and orange square is WDM $10^7\ M_{Sun}$.

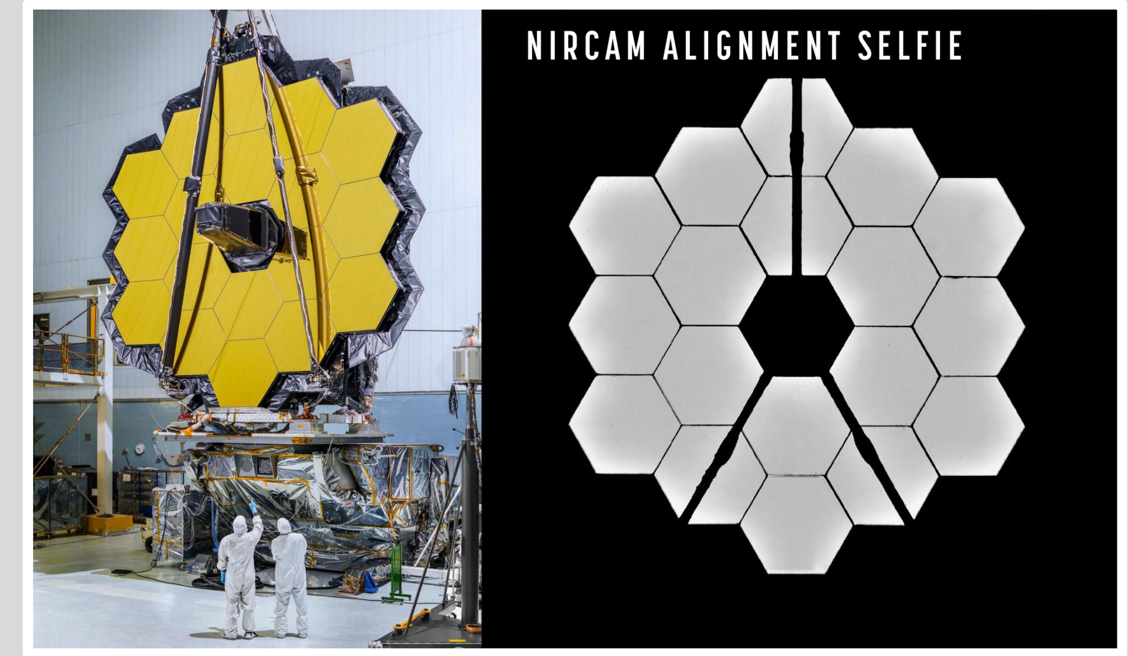

Figure 6: NASA's James Webb Space Telescope (JWST) launched on Christmas Morning of 2021 on an ESA Ariane 5 rocket from Kourou, French Guiana. As of April 2022, JWST is undergoing testing and alignment. Once operational, expected in May 2022, JWST is intended to succeed the Hubble Space Telescope as NASA's flagship mission in astrophysics [Image Credit: NASA].

5. Conclusions & Future Work

CDM v. WDM Conclusions

Concerning the results associated with CDM and WDM $10^6\ M_{Sun}$, we have found that there is no significant discernible difference between these two types of DM (Figs. 2-5). This is due to a cooling threshold that is consistent between the two types of DM. However, when compared to WDM $10^7\ M_{Sun}$, there is a stark contrast. Firstly, there is a dramatic delay in star formation until a cosmological redshift of z ~ 16, as we expected from the minimum mass threshold that was set in our model. However, we have more halos forming all at once when we get to z ~ 12.5 (see Fig. 3), whereas it is more consistent for CDM and WDM $10^6\ M_{Sun}$. Finally, Fig. 4 shows a critical point for stellar masses for WDM $10^7\ M_{Sun}$, which is caused by the decreased efficiency in the fragmentation for halos at z ~ 12.5.

JWST Detectability Conclusions

Fig. 5 details the possible detectability of stars in varying types of DM. We have found that in the F200W filter (the reddest filter pictured, which probes deeper and farther back in time), we expect to see the greatest indicator as to what the temperature is for DM. However, this does show that we must examine regions that have high amounts of gravitational lensing (high magnification factors), as many of these stars may be too faint to observe with average levels of lensing. There doesn't seem to be a observable difference in either the F150W or F115W filter.

Future Work

With a newly-installed computer cluster, we aim to run models that are specified for these types of DM, and to statistically confirm our findings with higher resolution data. A publication is expected in early 2023.