MSc Detailed Summary

Motivation and Goals

With the successful launch of the James Webb Space Telescope (JWST), a population of surprisingly massive galaxy candidates has been discovered at high redshifts.
These systems provide a convenient way to test a fundamental property of the ΛCDM model: the stellar content of dark matter halos should not exceed the available baryonic material in those halos. It is found that such early formation of massive galaxies is very difficult to reconcile with the ΛCDM model, demanding a high star formation efficiency, which is never seen in the low-redshift universe. In fact, only if all available baryons in all halos with enough baryons to form those galaxies are converted into stars, rather unrealistically, can the JWST data be explained [1].
Possible explanations for these objects could either be simply a high star formation efficiency, or the fact that the massive objects' properties, like photometric redshift and stellar mass, are still subject to several sources of observational uncertainty. If neither of these explanations hold up, these massive galaxies will pose a serious challenge to the ΛCDM cosmological model. In order to show the situation clearly, consider the candidates found in [2] (L22 hereafter). The data consists of 13 objects with photometric redshifts $6.5 < z < 9.1$, of which 6 have fiducial masses $> 10^{10} M_\odot$ with redshifts $7.4 < z < 9.1$. The brightest galaxy in the sample is at $z = 7.5$ and may have a mass that's as high as $M_\star \approx 10^{11} M_\odot$, more massive than present-day Milky Way.
The masses derived for the samples are intriguing if placed in the context of previous studies, since no candidate galaxies with $M_\star > 10^{10.5} M_\odot$ had been found beyond $z \sim 7$, and no candidates with $M_\star > 10^{10} M_\odot$ beyond $z \sim 8$.
Analysis of the L22 data shows a clear contrast with the ΛCDM fits for the cumulative stellar mass density:

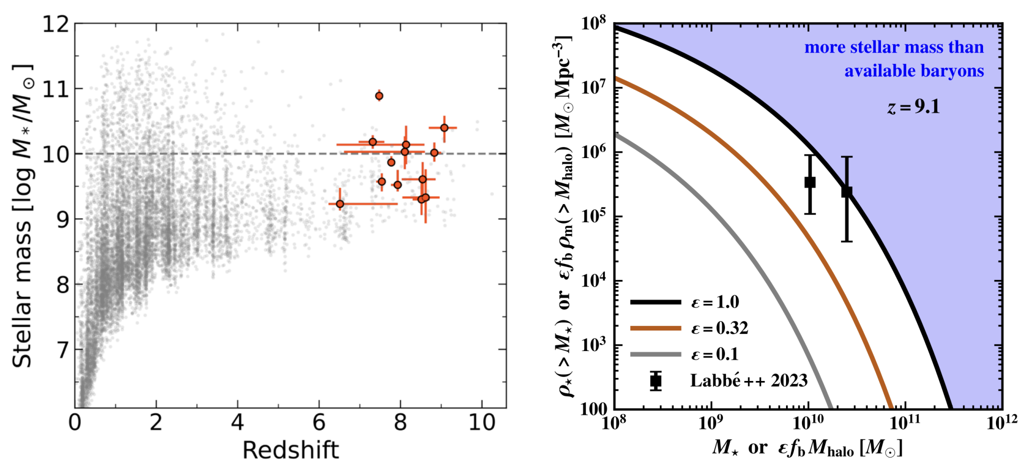

Figure 1: *Left*: The L22 data points are shown in red; it is clear that some the galaxies are very massive given their age. Figure taken from [2]. *Right*: The cumulative stellar mass density deduced from the new high-redshift galaxies compared to the ΛCDM model predictions. The data points are compatible with ΛCDM only if all the baryons are converted into stars, i.e. $\epsilon \sim 1$. Figure taken from [1]

We can see that the L22 objects lie at the extreme of the ΛCDM expectations, implying unrealistic values of stellar formation efficiency $\epsilon(z = 9.1) \approx 0.99$. Even when considering the 1σ error, the data become consistent with an already high SFE $\epsilon(z \approx 9) \geq 0.57$. Assuming more realistic values like $\epsilon = 0.1$ or $\epsilon = 0.32$ yields far more obvious discrepancies at these redshifts.

In this work, we aim to study a possible extension of ΛCDM. In this scenario a fraction of dark matter is composed of a population of primordial black holes (PBHs) that, if added to the standard cosmological background, would provide the necessary aid in the formation of high redshift large scale structures.
In order to explore the implications of these black holes we consider the two ways in which they influence structure formation, the "Poisson effect" and the "seed effect".

Results - The Poisson Effect

Firstly, we study the Poisson effect, where the PBHs number count fluctuations induce an additional white noise to the matter power spectrum, as is shown below:

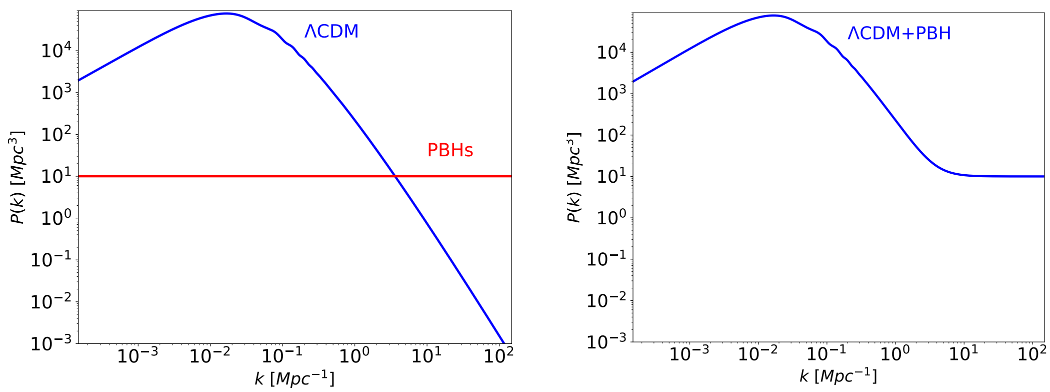

Figure 2: The contribution of primordial black holes to the matter power spectrum.

We use a monochromatic mass function for PBHs, so that our model is specified completely by the fraction $f_{\rm PBH}$ of dark matter in the form of PBHs and their mass $m_{\rm PBH}$. Treating these quantities as parameters, we extend the work done by the authors in [3]. They calculate the cumulative stellar mass density using a Press-Schechter argument:

$$\rho_\star(>M_\star, z) = \epsilon f_b \int_{M_{\rm halo}}^{\infty} M \frac{dn(M, z, f_{\rm PBH}, m_{\rm PBH})}{dM} dM \tag{1.1}$$

Comparing this with the results from L22, they find that relatively massive PBHs with $m_{\rm PBH} \gtrsim 10^5 M_\odot$ are needed. Since the Poisson effect requires that $f_{\rm PBH} \sim 1$, this result is problematic, because this parameter region is highly constrained by observations.
My contribution consists in extending equation (1.1). This equation, in fact, assumes that the population of halos seen by JWST at $z \simeq 10$ formed near that same redshift, given how the Press-Schechter theory is formulated. Clearly, this reasoning fails to incorporate a whole population of halos which, via the accretion of dark matter throughout their evolution, reached the mass of those high-redshift galaxies. Therefore, a term needs to be added to the cumulative stellar mass density, calculated with excursion set theory:

$$\begin{aligned}
\rho_\star(>M_\star, z) &= \rho_{\star,\rm PS}(>M_\star, z) + \rho_{\star,\rm EX}(>M_\star, z) \\
\rho_{\star,\rm PS}(>M_\star, z) &= \epsilon f_b \int_{M_{\rm halo}}^{\infty} M \frac{dn(M,z)}{dM} dM \\
\rho_{\star,\rm EX}(>M_\star, z) &= \epsilon f_b \int_{M_{\rm halo}}^{\infty} dM_f \int_0^{<M_f} dM_i\, M_i \frac{dn(M_i, z_i)}{dM_i} P(M_i \to M_f, z_i \to z)
\end{aligned} \tag{1.2}$$

where $P(M_i \to M_f, z_i \to z)$ is the probability for a dark matter halo to transition from M_i to M_f in a time frame $\Delta z = z_i - z_f$.
The results are that, for fixed PBHs parameters, the extra term ("EX") is negligible compared to the first

one ("PS"). For this reason, the PBHs parameter space necessary to explain the JWST galaxies remains that found by the said paper.

Results - The Seed Effect

We also study a model in which heavy and scarce PBHs with a peaked mass function can work as seeds for the formation of galaxies, which would be created via accretion of the sorrounding dark matter. In this sense, given an initial PBH, the mass of the halo formed around it at a certain redshift is given by [4]:

$$m_H(z) = 3\left(\frac{1000}{1+z}\right) m_{\rm PBH} \tag{2.3}$$

To be clear, in this model all the PBHs in the Universe are isolated and accrete dark matter independently, generating a halo mass function of similar form of that of the PBHs:

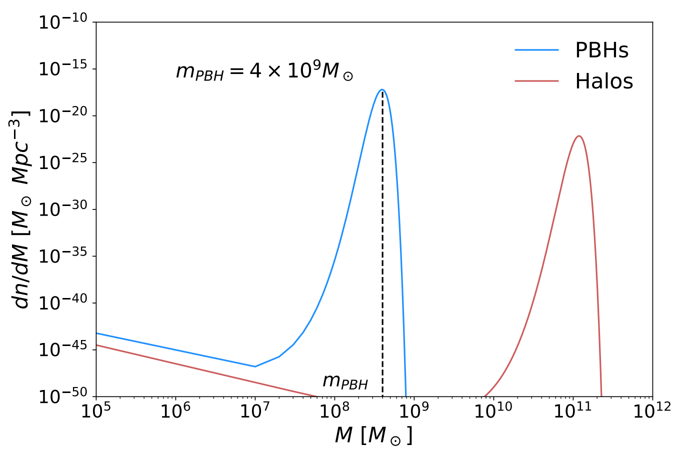

Figure 3: The PBHs mass function at $z \sim 10$ peaked at $m_{\rm PBH} = 4 \times 10^9 M_\odot$ in blue and the resulting halo mass function from dark matter accretion, peaked at $m_H(z)$.

Plugging the halo mass function into the equation for the cumulative stellar mass density (1.1) and comparing it to the results in L22, we found that $f_{\rm PBH} \sim 10^{-4}$ and $m_{\rm PBH} \sim 10^8 M_\odot$ can match the stellar mass density given a high SFE $\epsilon = 1$, whereas we would need $m_{\rm PBH} \sim 10^9 M_\odot$ if $\epsilon = 0.1$.

References

[1] M. Boylan-Kolchin, “Stress testing ΛCDM with high-redshift galaxy candidates,” *Nature Astronomy*, vol. 7, pp. 731–735, Apr 2023.

[2] I. Labbé *et al.*, “A population of red candidate massive galaxies ∼600 Myr after the Big Bang,” *Nature*, vol. 616, pp. 266–269, Feb 2023.

[3] B. Liu and V. Bromm, “Accelerating Early Massive Galaxy Formation with Primordial Black Holes,” *Astrophys. J. Lett.*, vol. 937, p. L30, Aug 2022.

[4] K. J. Mack, J. P. Ostriker, and M. Ricotti, “Growth of structure seeded by primordial black holes,” *The Astrophysical Journal*, vol. 665, pp. 1277–1287, Aug 2007.