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there is no missing satellites problem

AND ITS IMPLICATIONS FOR DARK MATTER MODELS

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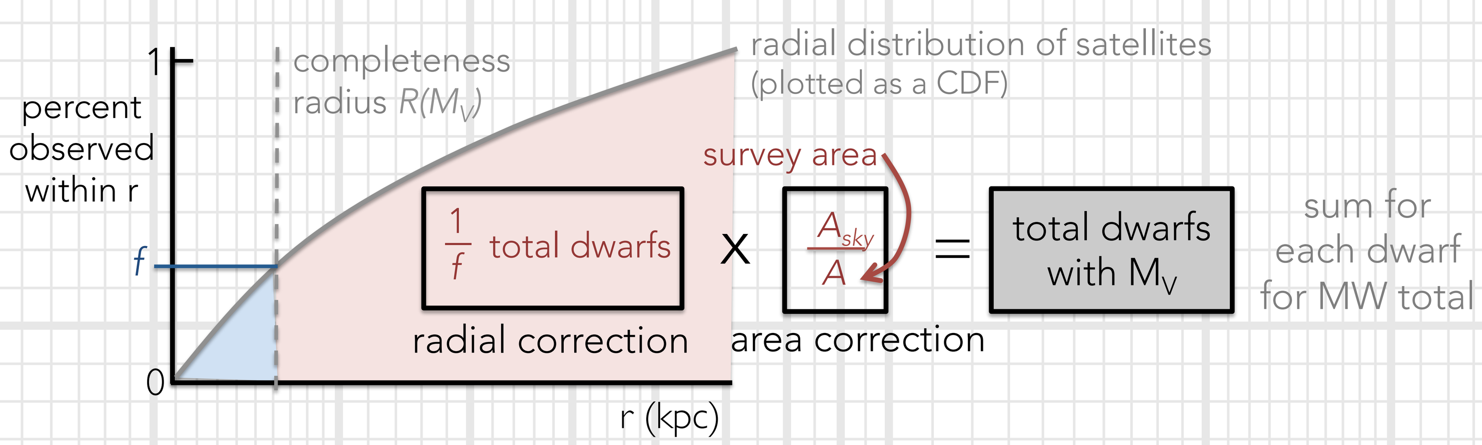
A critical challenge to the cold dark matter paradigm is the missing satellites problem (MSP), a mismatch between the number of satellites observed around the Milky Way (MW) and the number predicted by simulations of dark matter substructure. We revisit the problem and show that accounting for the sensitivity of current surveys and the suppression of star formation by reionization resolves the MSP down to halo masses of 10^8 $M_\odot$. We illustrate how this places stringent new constraints on dark matter models. Importantly, the total number of MW satellites depends sensitively on the spatial distribution of satellites, possibly leading to a "too many satellites" problem. Measurements of dark halos below 10^8 $M_\odot$, achievable with substructure lensing and stellar stream perturbations, are the next frontier for tests of CDM.

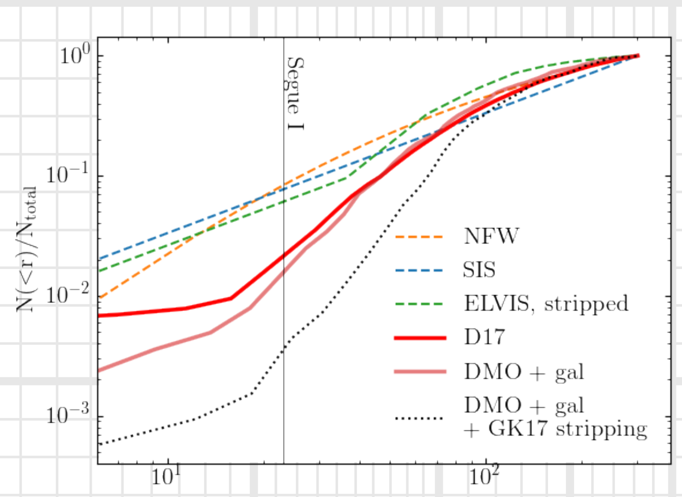
1 revisiting the observations

Since the MSP was first identified, deeper, more sensitive surveys such as the Sloan Digital Sky Survey (SDSS) and the Dark Energy Survey have pushed the satellite count up to ~50. While this partially alleviates the MSP, the question still remains: how many more satellites remain to be found, and do their numbers solve the MSP?

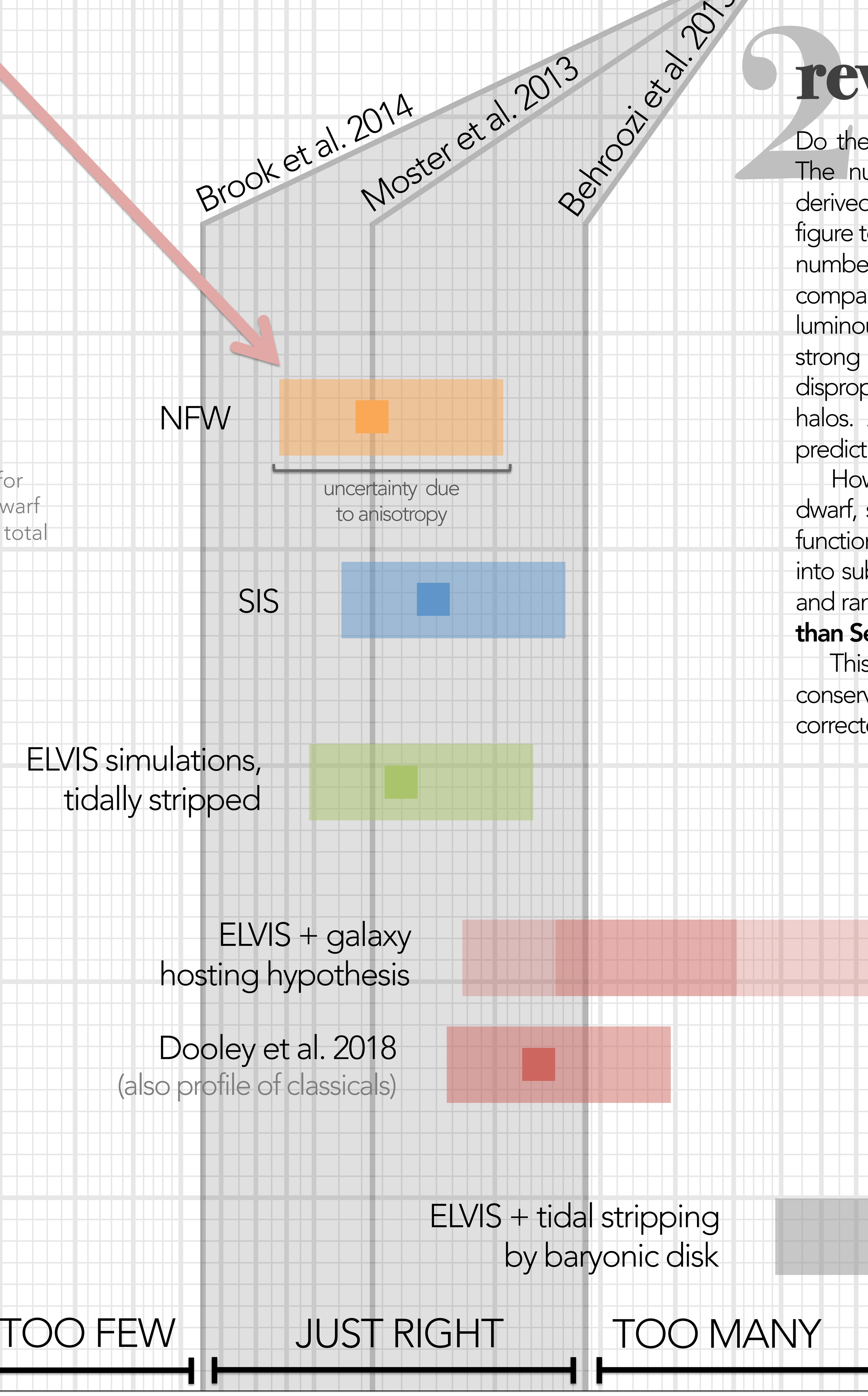
We predict the total number of MW satellites based on the MW dwarf galaxies found by SDSS, correcting for its detection efficiency, as shown below.



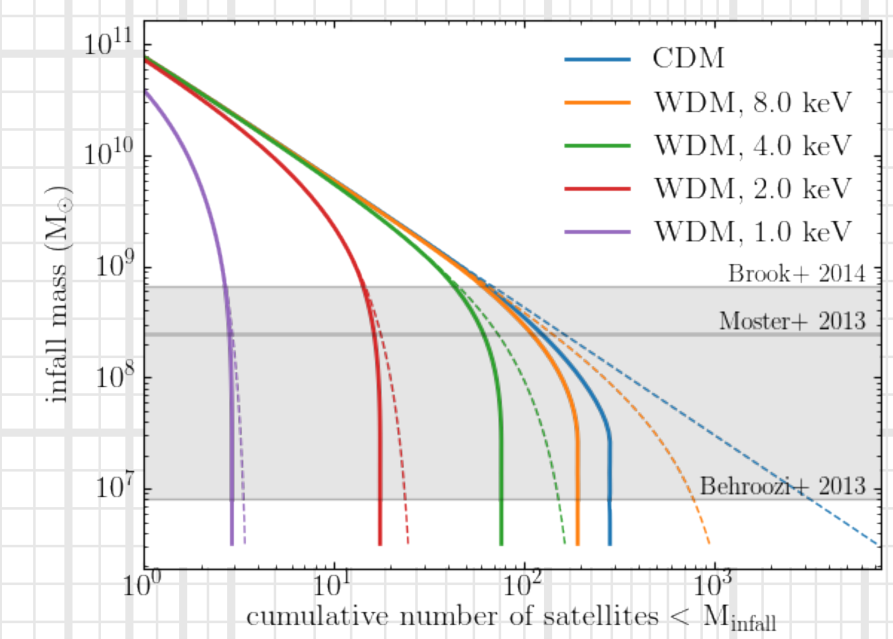
For simplicity, we assume that the satellite distribution is isotropic, but account for uncertainties due to anisotropy. **The correction depends sensitively on the radial distribution of satellites**, which is highly uncertain. We thus compute the correction for well-motivated distributions that span the range of uncertainty on tidal stripping and on which subhalos host galaxies (see figure below). These include the NFW and singular isothermal sphere (SIS) profiles, (i.e. the satellites follow the dark matter, dashed lines), a representative profile derived from ELVIS, a dark matter only (DMO) simulation, paired with assumptions on which subhalos host galaxies (red line), and a profile that includes the effect of tidal stripping by the MW's baryonic disk ("GK17," dotted black line).



The resultant corrections are shown to the right by colored bars. **From the completeness corrections, we infer there exists at least 120 MW dwarf galaxies brighter than Segue I.** The strong dependence on the radial profile is clear: we infer over an order of magnitude more if disk stripping is included.



2 revisiting the theory



Do the corrected counts imply that the MSP is solved? The number of subhalos predicted by CDM can be derived from the CDM mass function (dashed blue line in figure to the right). The completeness correction gives the number of *luminous* satellites, however, and thus for comparison we must determine which subhalos are luminous in CDM. The fraction of luminous subhalos is a strong function of the redshift of reionization, which disproportionately suppressed star formation in low mass halos. Assuming reionization occurred at z = 9.3, we predict the reduced counts shown by the solid blue line.

How far down the mass function do the SDSS dwarfs probe? Assuming that Segue I, the faintest SDSS dwarf, sets the lower bound, we derive its stellar mass from its luminosity assuming a Kroupa initial mass function. We then use empirical scaling relations (i.e. stellar mass halo mass, or SMHM, relations) to convert it into subhalo mass. The masses derived from three SMHM relations are denoted with gray horizontal lines, and range from ~10^7 to 10^9 $M_\odot$. We can now determine that **the number of luminous satellites brighter than Segue I predicted by CDM is about 60 - 280**. This range is denoted at left by the gray band.

This theoretical prediction matches the completeness-corrected counts almost exactly, even for the most conservative radial profiles—there are no missing satellites. In some cases (e.g. with disk stripping), the corrected count exceeds the predictions, what we call the **"too many satellites" problem.**

3 implications for dark matter

The resolution of the MSP down to 10^8 $M_\odot$ places stringent constraints on dark matter models with reduced power spectra, which *must* reproduce the completeness-corrected MW satellite count. As an example, we briefly sketch the implied constraints for warm dark matter (WDM). What follows is not meant to be a rigorous derivation but an illustration of how the limits tighten.

One can repeat the exercise above to derive the number of luminous satellites expected for WDM thermal relics given the corresponding mass function and luminous fraction function. The resultant number counts are shown in the figure above. Assuming that the MW has ~150 satellites, **thermal relics with masses less than 4 keV are likely ruled out**. In addition, the 1-2 keV thermal relic mass functions are close to that of the **7 keV sterile neutrino, which is highly likely to be ruled out**. Measurements of dark halos below 10^8 $M_\odot$, e.g. with substructure lensing and stellar stream perturbations, are the next frontier for tests of CDM.