Enrichment of the Intergalactic Medium as Evidence of Expulsive Feedback in Low-mass Galaxies

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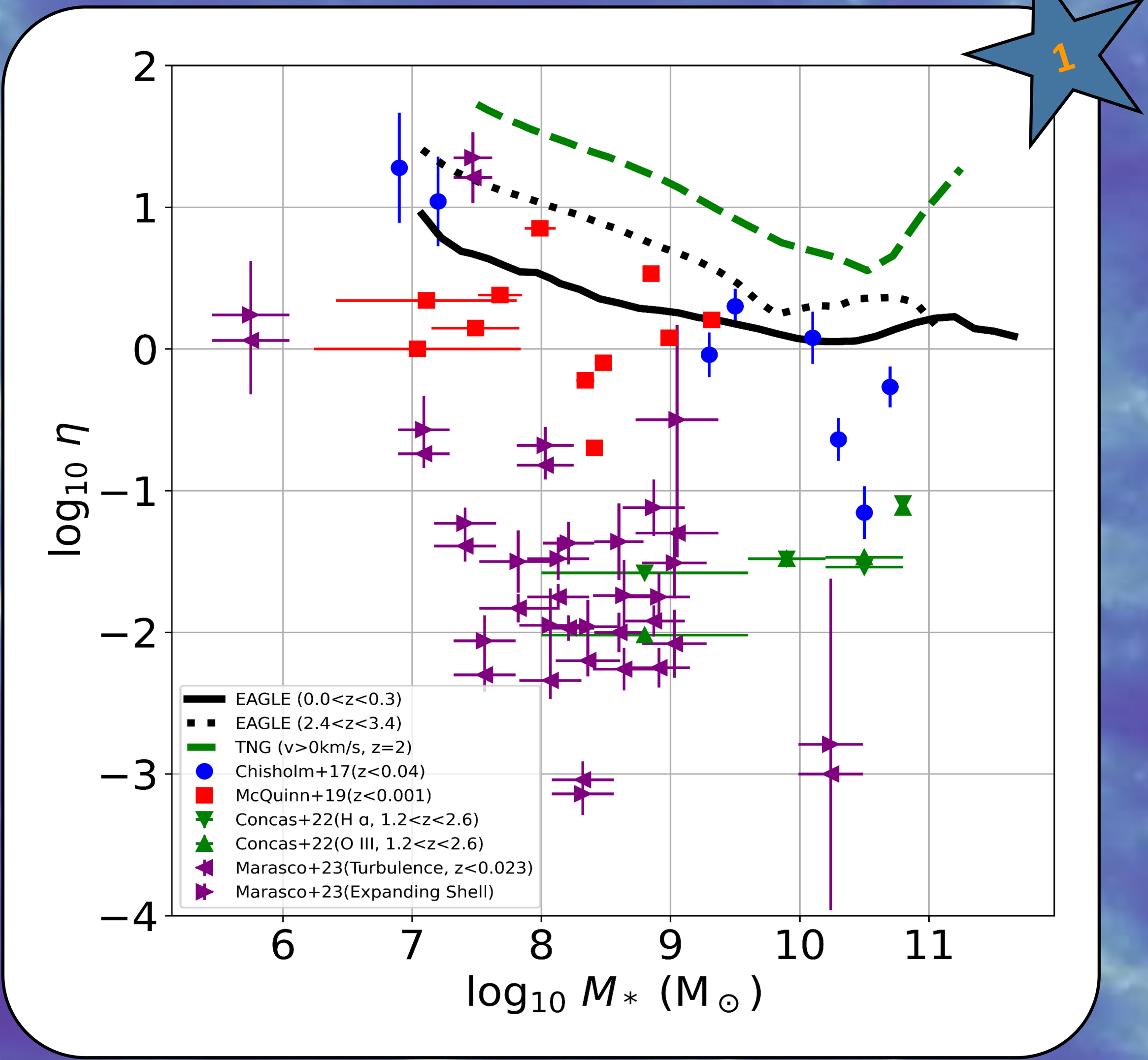
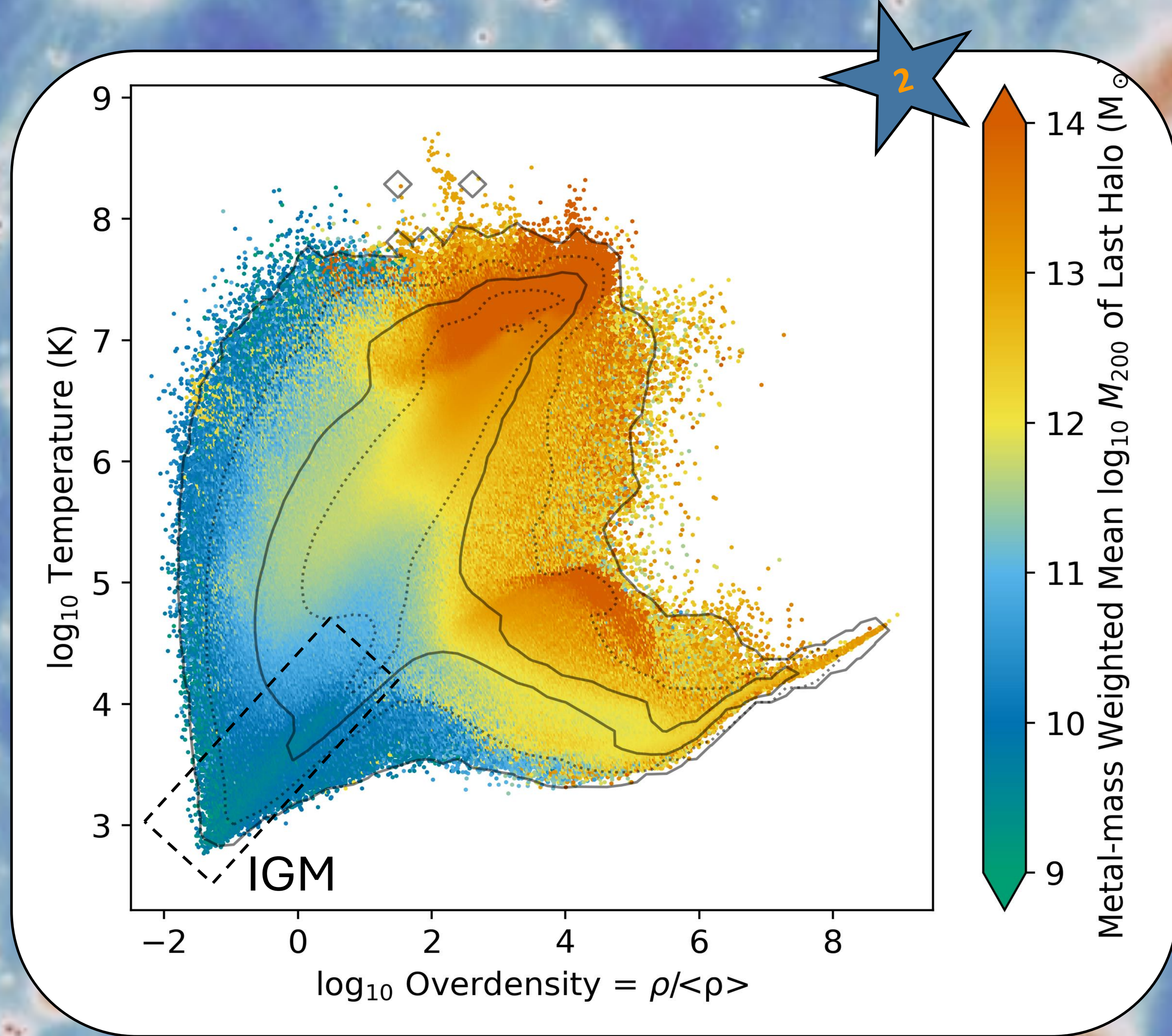


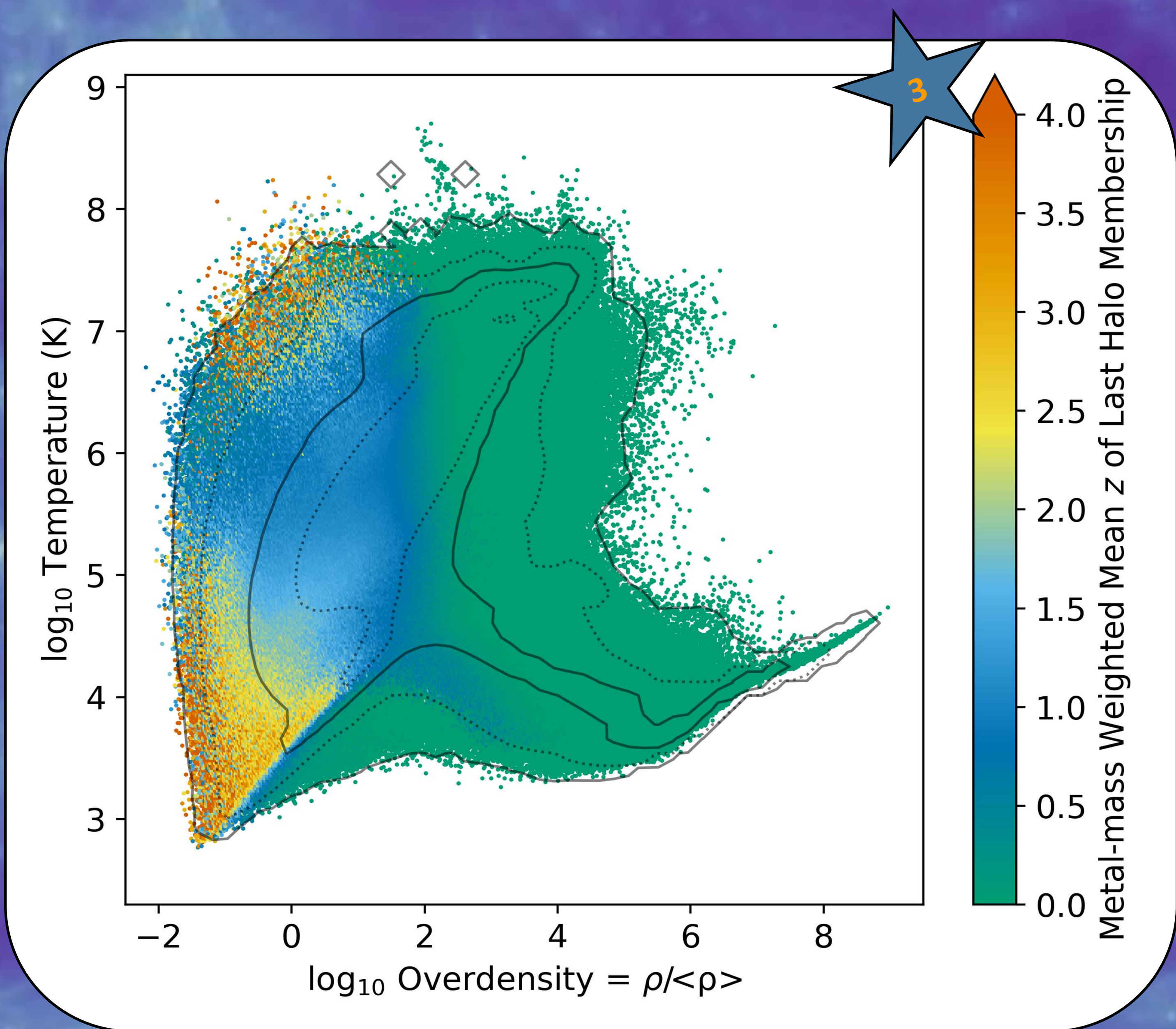
Background:

Supernova and AGN feedback drive outflows of metal-enriched gas that permeate the low-density intergalactic medium (IGM). The mass flux of these outflows can be quantified using the mass loading parameter (η). This is defined as $\eta = \dot{M}_{\rm out}/{\rm SFR}$. There is a consensus amongst state-of-the-art cosmological simulations that reproduction of the present-day galaxy stellar mass function requires that low-mass galaxies drive highly mass-loaded winds. However there is to date scant observational support for this `requirement' of the simulations. Figure 1 illustrates the lack of consensus in the observational literature with measurements of η spanning at least three orders of magnitude. Whilst observational estimates are notoriously difficult to make, this apparent disagreement has been interpreted as signalling a shortcoming of state-of-the-art simulations of the galaxy population. Whilst it is plausible that simulations with more sophisticated treatments of the dense ISM may yield realistic galaxy populations with lower mass loadings, it has been posited that metal-bearing outflows from low-mass galaxies are responsible for enriching the low-density intergalactic medium. We therefore ask how would simulated QSO spectra look in the absence of metals synthesised by dwarf galaxies. We cannot simply 'switch off' winds from dwarf galaxies as this would result in an unrealistic simulated galaxy population. Instead, we identify the metals synthesised by dwarf galaxies and toggle their inclusion when constructing synthetic QSO spectra.

Simulation Data:

To consider the impact of galaxies with different masses on IGM enrichment, we use volumes from the EAGLE simulations. At each snapshot (or snipshot where available) we tag each gas particle in a halo with the associated value of M_{200}, redshift and other relevant properties. By doing this in chronological order and carrying through the tags from the previous snapshot(s), we build up a reference set of particle tags that give us the properties of the last halo of which a given particle was a member at a given snapshot redshift. Figures 2 & 3 use data from the L50N752 REFERENCE run (50^3 Mpc^3 (co-moving) volume and 752^3 DM particles) and Figure 4 uses the L12N188 version. We eventually intend to use the 100^3 Mpc^3 EAGLE box (L100N1504) however the analysis for this is ongoing. In the future, we would like to replace this post-processing approach with an implementation of on-the-fly tagging, involving identifying structure during the simulation. We propose to do this by periodically running the Friends-Of-Friends (FOF) group finder to locate haloes and galaxies.





Environment:

Figures 2 & 3 show the temperature-density distribution of gas particles at present day that have at some point during the simulation been tagged as belonging to a FOF group containing at least one bound substructure. Contours show the gas mass distribution. Figure 2 shows the mean last known halo's M_{200} for all particles within a given 2D hex-bin (weighted by the particle metal mass). Figure 3 is coloured in a similar fashion but showing the redshift a particle was last in a halo – this can be considered approximately the redshift at which a particle is ejected from its host halo for IGM particles (those bins at the very lowest densities and temperatures). In EAGLE we find that the heavy elements in the IGM were, broadly speaking, ejected from haloes of mass $M_{200} \sim 10^{10}\ M_\odot$ at $z \simeq 3.5 - 4$.

Pixel Optical Depth Statistics:

Using the particle tags at each redshift, we use software called SpecWizard (Schaye, Theuns & Booth) to produce synthetic QSO absorption spectra for a handful of different ions, including the Lyman series (hydrogen), C IV, Si IV & OVI to name a few of interest. Using the Pixel Optical Depth technique (see most recently Turner et al. 2016) we construct a statistical relationship between the optical depth of H I (from the Lyman series) and the median optical depth in C IV (see figure 4 for an example of this using the 12.5^3 Mpc^3 box). Turner et al. considered discrepancies between observations and EAGLE data without any additional corrections (both shown in green with the simulation results taken from the 100^3 Mpc^3 EAGLE box).

Modified Metal Contributions:

We show our optical depth relations for the 12.5^3 Mpc^3 run (in black) along with variations with contributions to metallicity from large halos excluded – this is done for increasingly smaller halo masses down to the exclusion of haloes with M_{200} above $10^7\ M_\odot$. Whilst this box is too small for conclusive results, there is still little deviation when excluding halo masses above $10^{10}\ M_\odot$. This suggests that it is low-mass haloes (and therefore the lowest-mass galaxies) that are responsible for the observed IGM metal enrichment, supporting the need for more strongly mass-loaded outflows.