The Origin of Intergalactic Metals

Christopher J. R. Rowe
3rd Year PhD student at LJMU
Primary Supervisor: Prof. Rob Crain

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Session:
The ultimate fate of multi-phase gas in galaxies: from giant molecular clouds to the virial radius

IGM Enrichment and The EAGLE Simulations

Absorption lines from metal ions appear in QSO spectra and an be matched to the Lyman α forest in order to demonstrate the low-density universe is enriched with small amounts of metals.

Simulations enrich the IGM in cosmological hydrodynamical simulations which allows them to be traced to their source.

The EAGLE simulations (with some adjustments – see right) may be used to reproduce the observed enrichment profile of the observed universe (M. Turner et al. 2016).

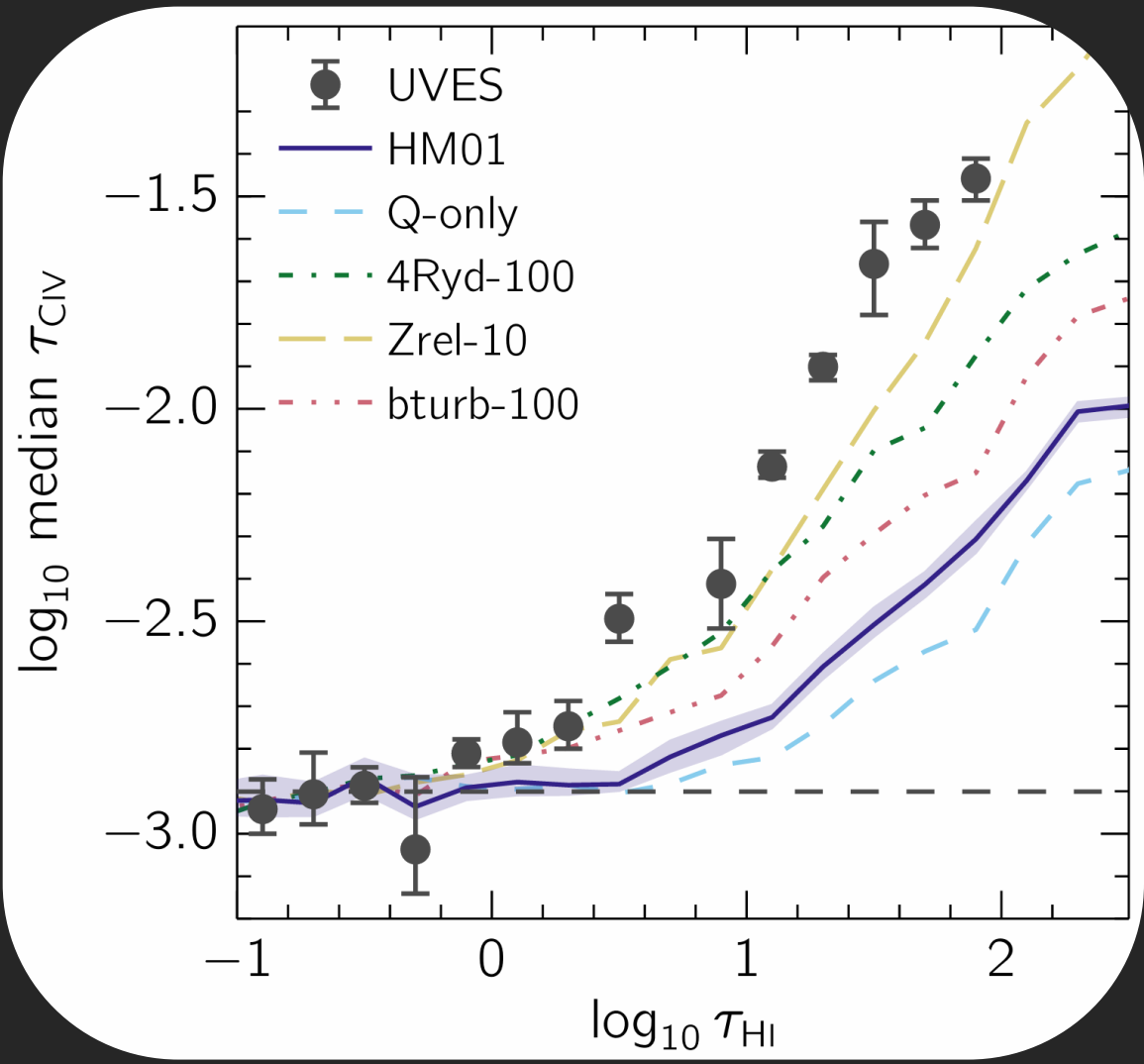
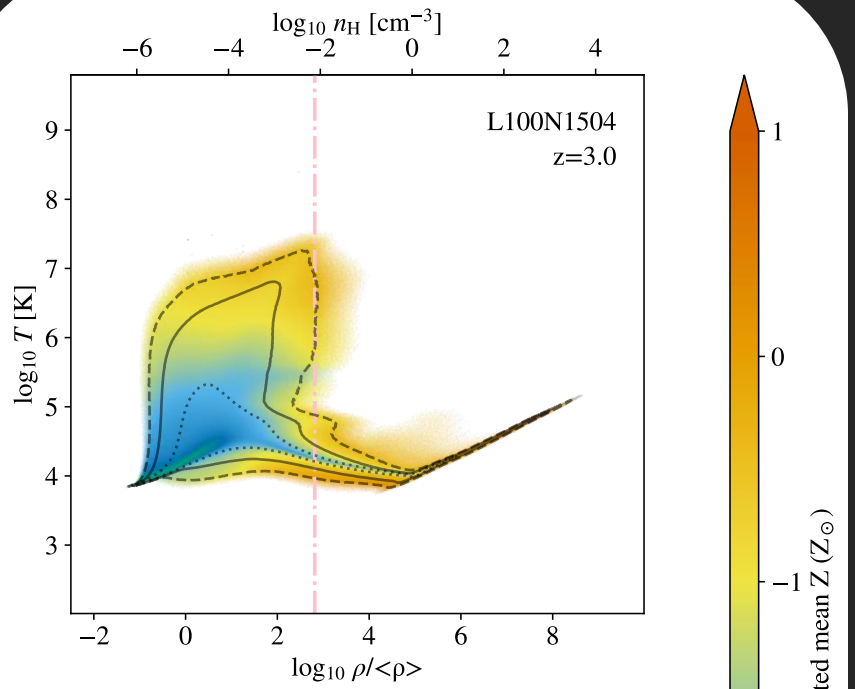


Image Credit: The EAGLE Project

M. Turner et al. (2016) fig. 3

Gas Enrichment Distribution



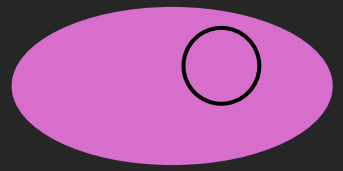
Plotting the Temperature (Y) vs. Density (X) of particles separates the gas by physical environment. This highlights how simulated gas properties are distributed throughout the volume.

In EAGLE the low-density regions of the universe are enriched. This enriched gas *must* have been ejected from galaxies; the question remains which mass range(s) are the dominant source of enrichment in these regions.

Particle Tracking

Particle Tracking

1.) Gas particle receives metal enrichment from host galaxy.



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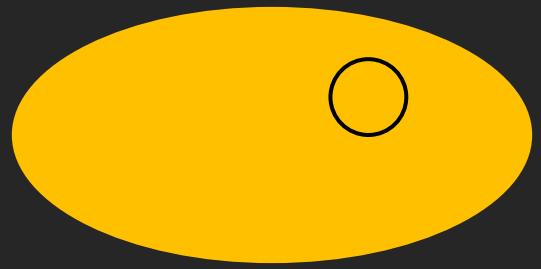
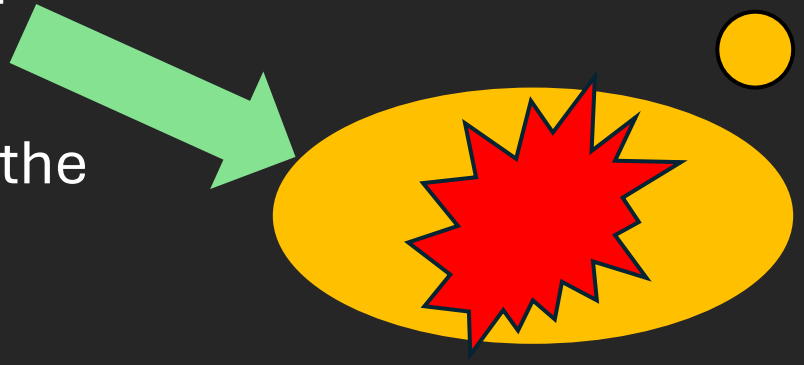


2.) Galaxy
continues to grow.

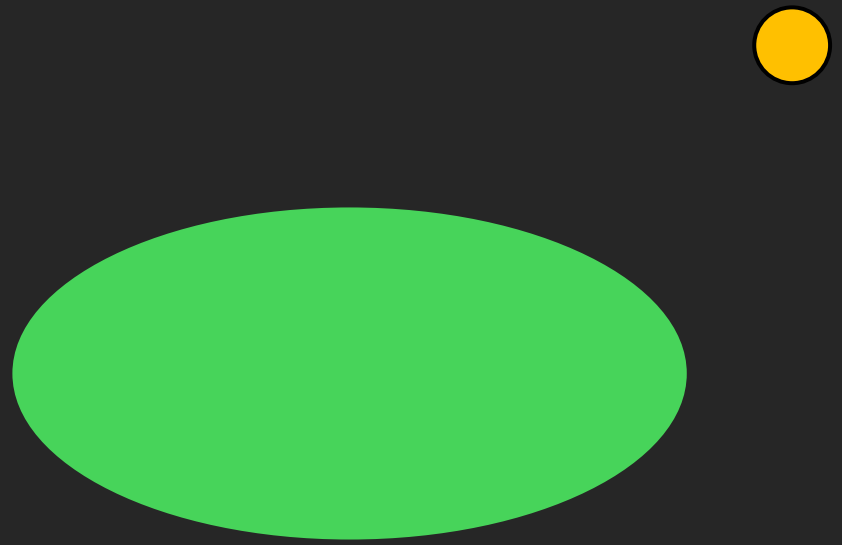
Particle Tracking

Supernova & AGN feedback heat and/or kick gas and drive outflows/winds from the galaxy.



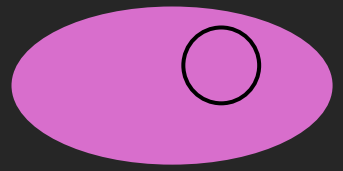
3.) Gas particle is ejected through feedback processes.

Particle Tracking



4.) Galaxy continues to grow, but the gas particle’s tagged values remain unaltered.

Particle Tracking



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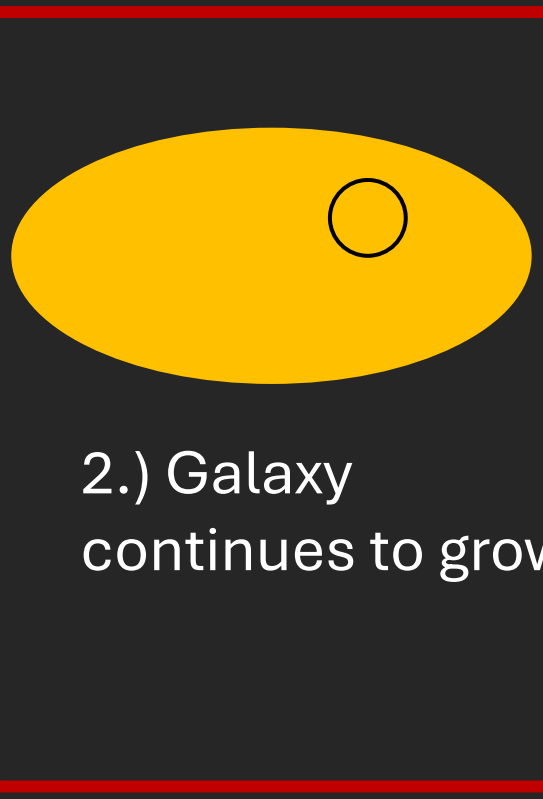

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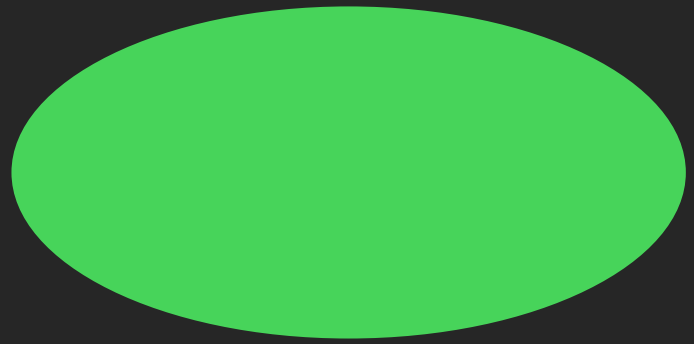
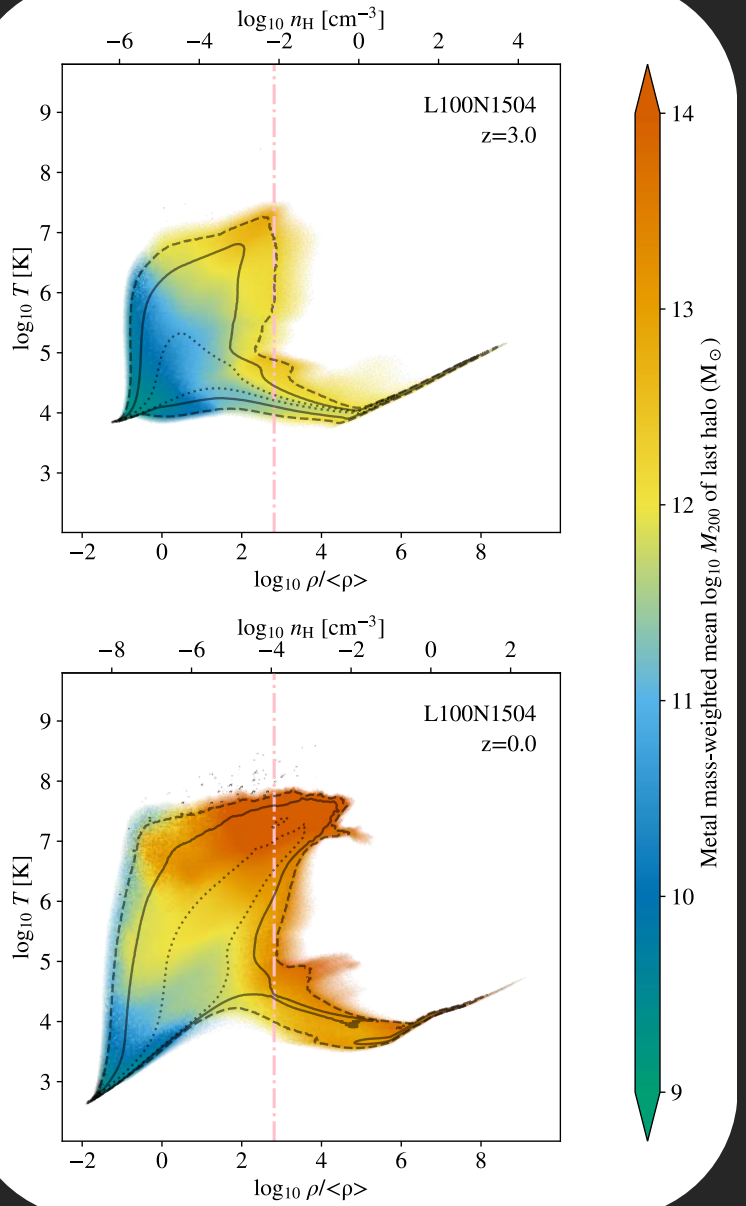


Last Halo's Mass & Ejection Time

M_{200} of last halo

z of last halo membership

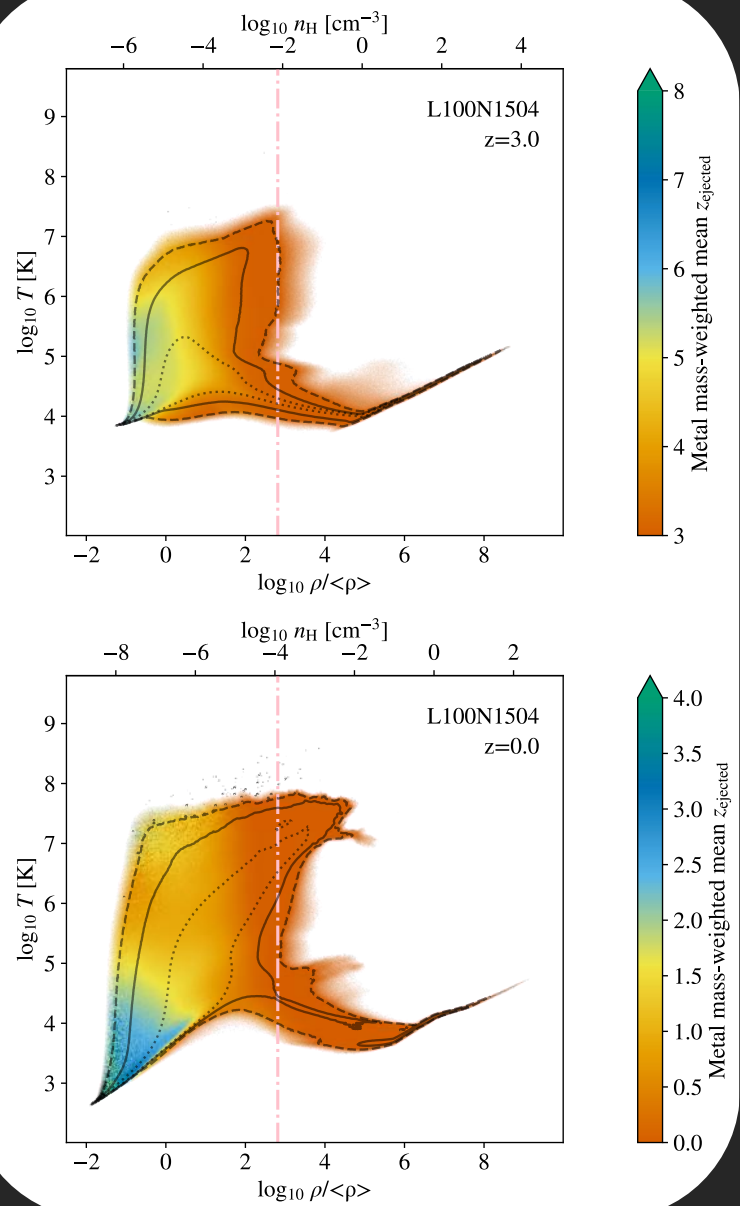


M_{200} and redshift of the last time a particle was in a halo, weighted by the metal-mass of each contributing particle.

Large haloes dominate the ICM and ISM where particles are still within haloes (more total metal mass).

The low-density regions are influenced by a range of halo masses.

The very coldest and low-density gas is dominated by the smallest haloes.



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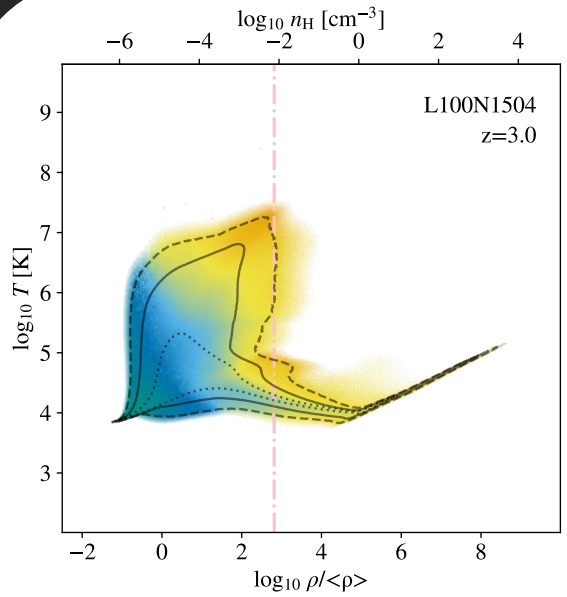

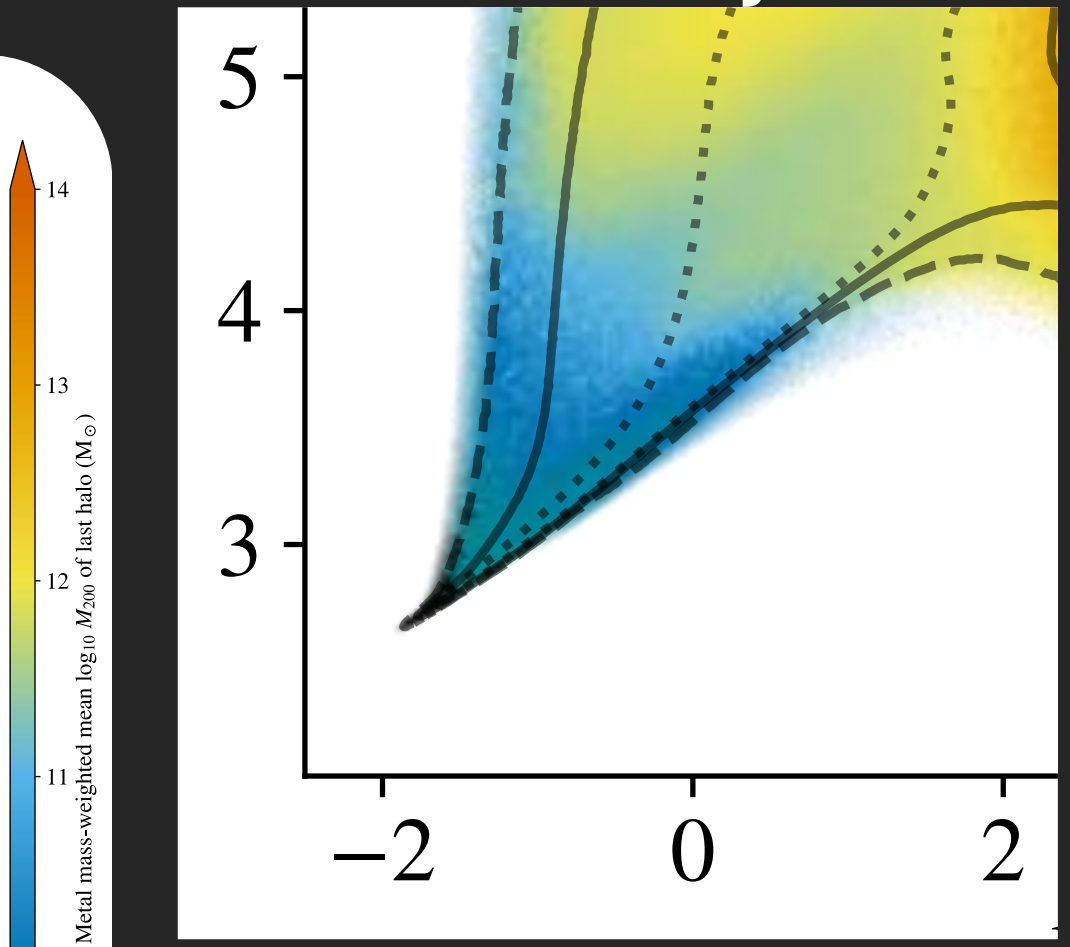

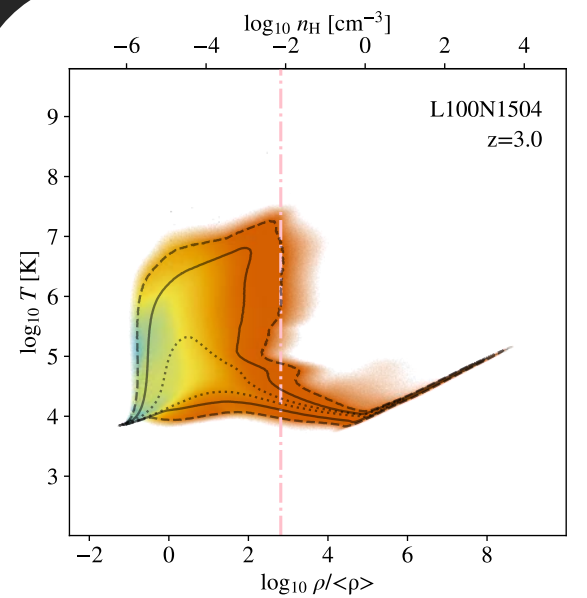

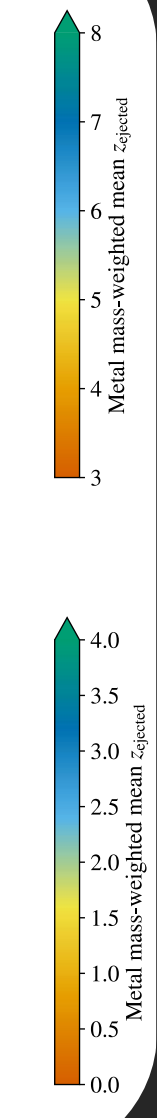

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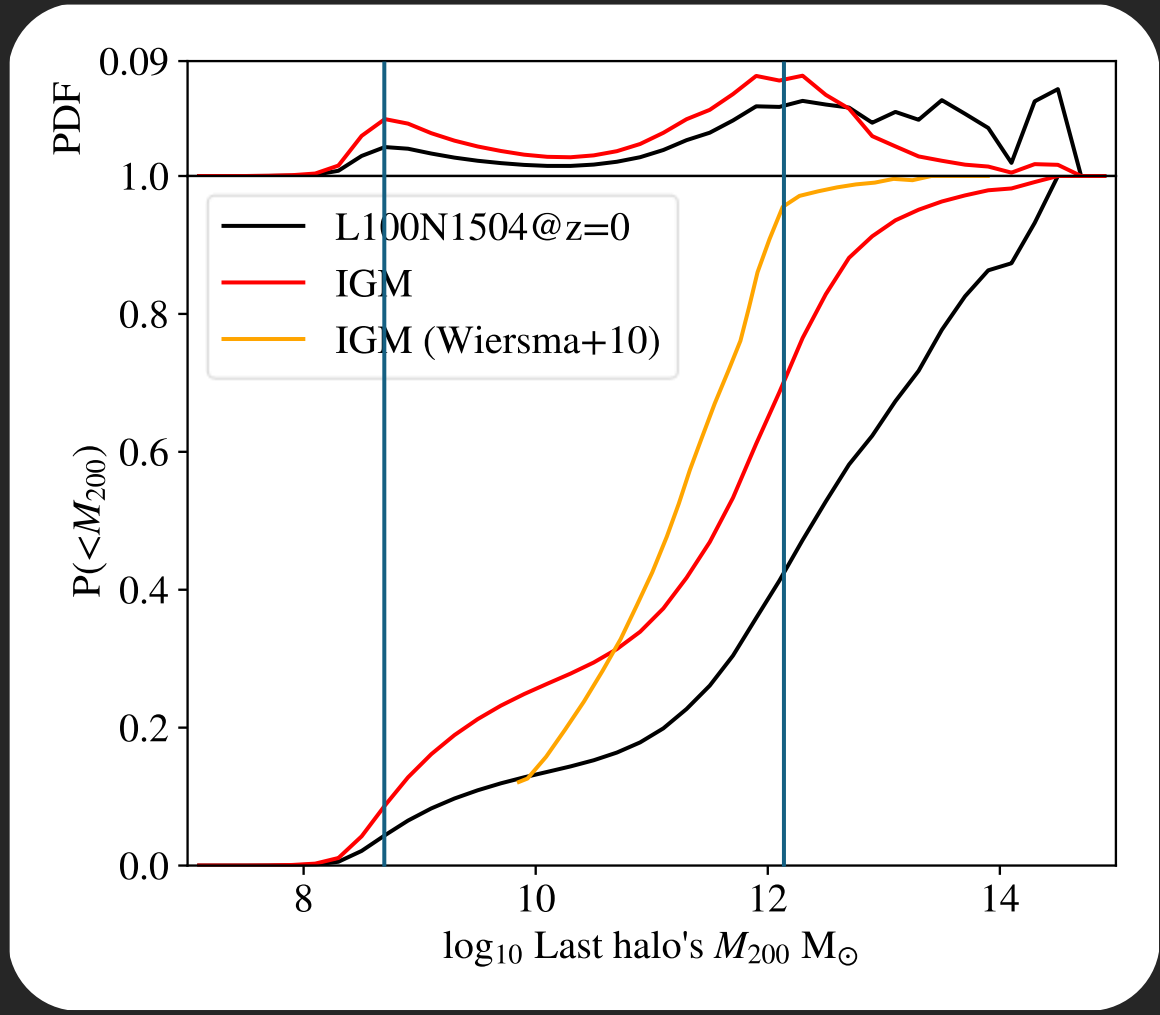
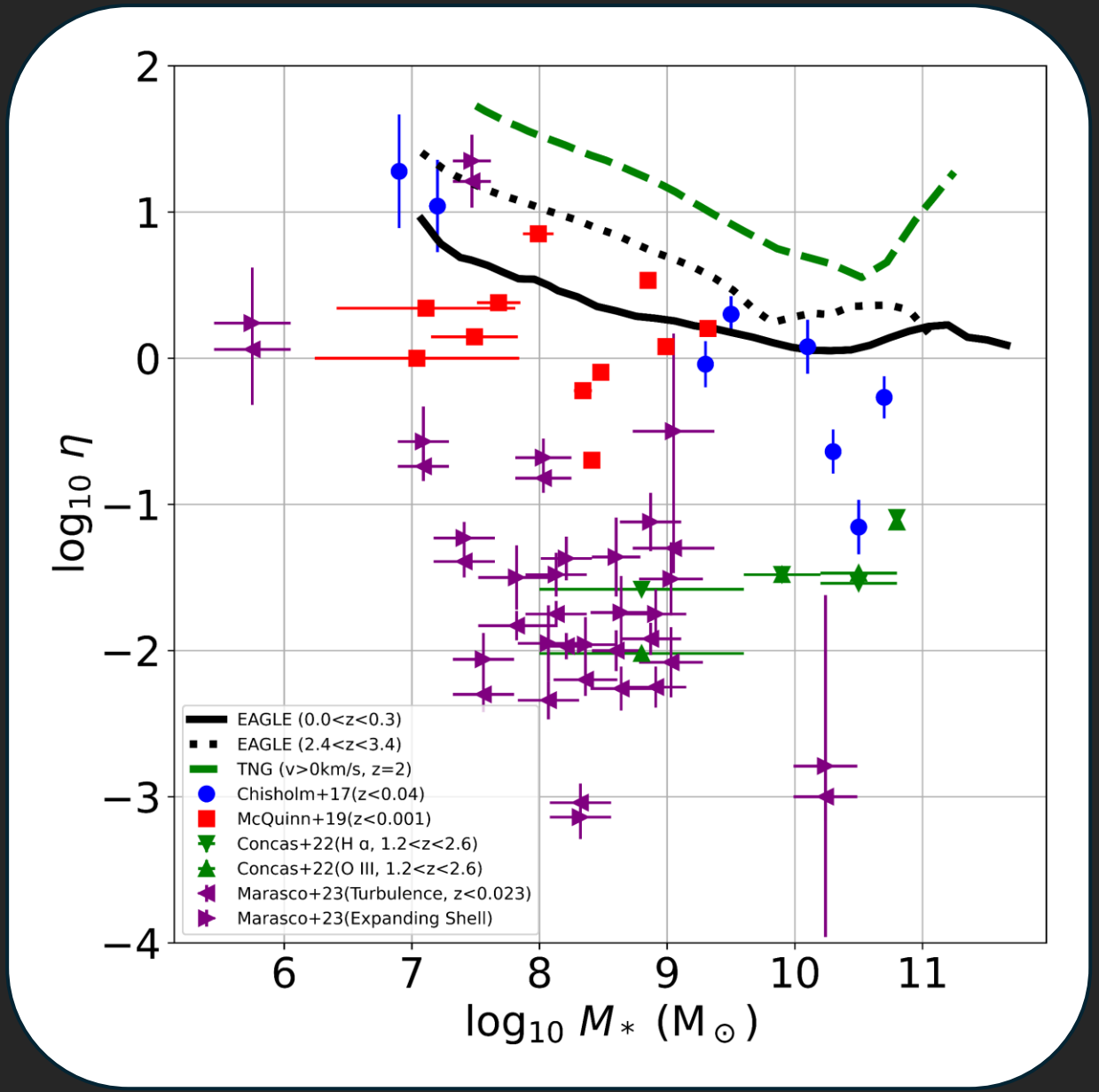
Last Halo Mass

Cumulative distribution of last halo's M_{200}, weighted by particle metal mass.

By limiting the selection to only IGM particles, we see that haloes with masses below 10^{12} $M_\odot$ contribute ~65% of all metal mass, with ~20% contributed by halo masses below 10^9 $M_\odot$



$$\eta = \frac{\dot{M}_{out}}{SFR}$$



Simulations ([EAGLE] & [TNG]) predict that outflows from low mass galaxies should have large mass loading factors between around 10 and 100.

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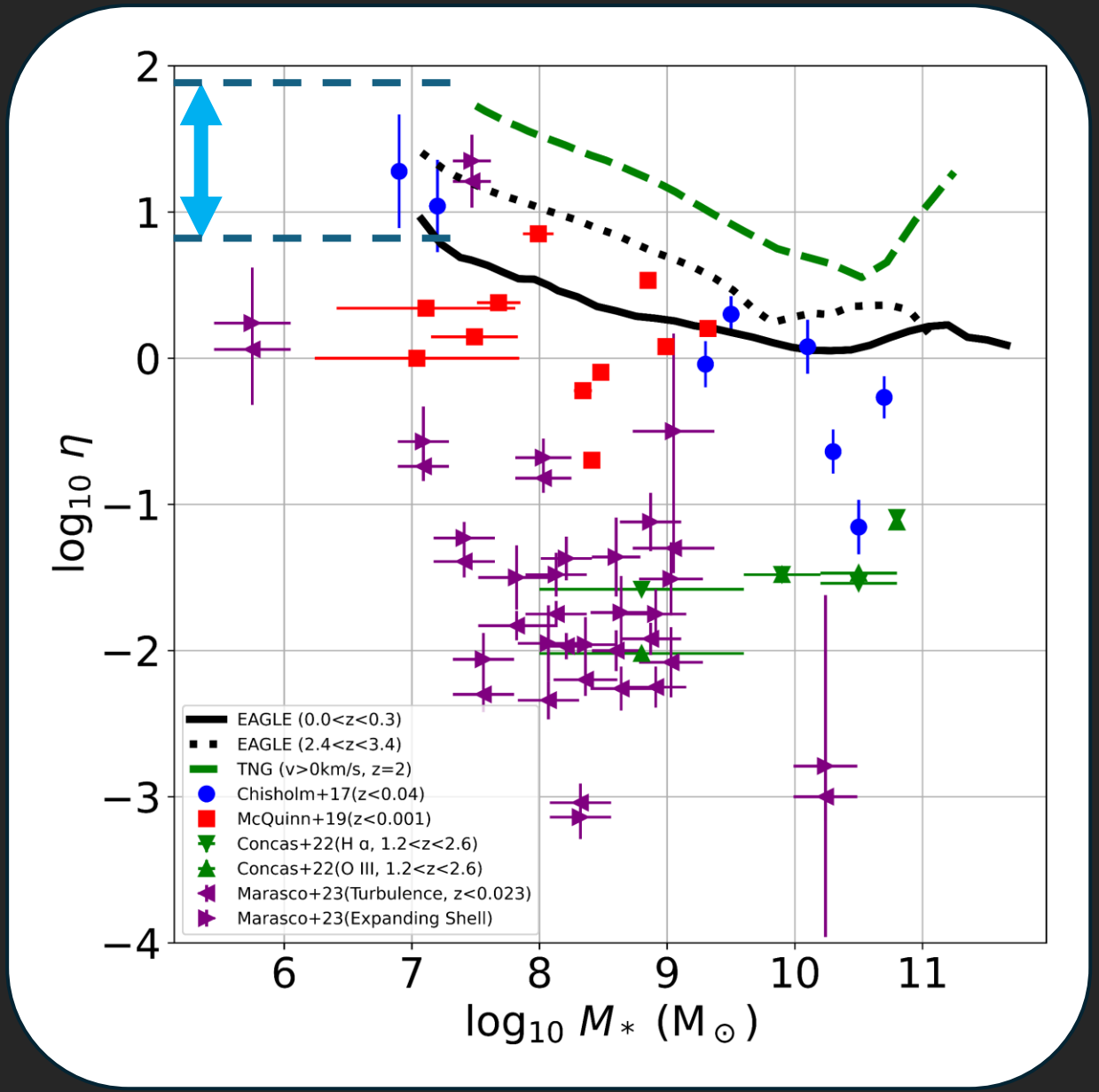

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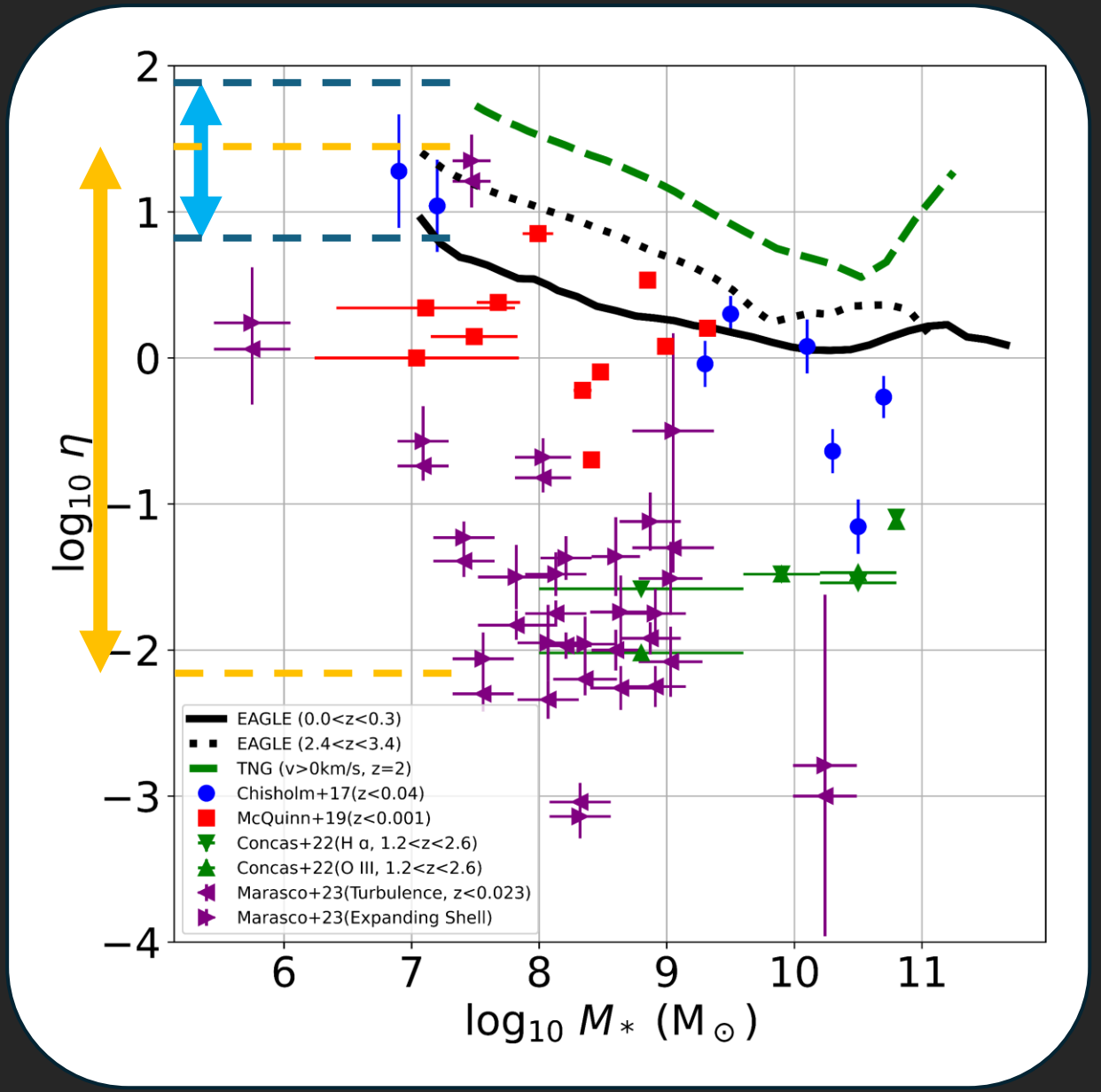
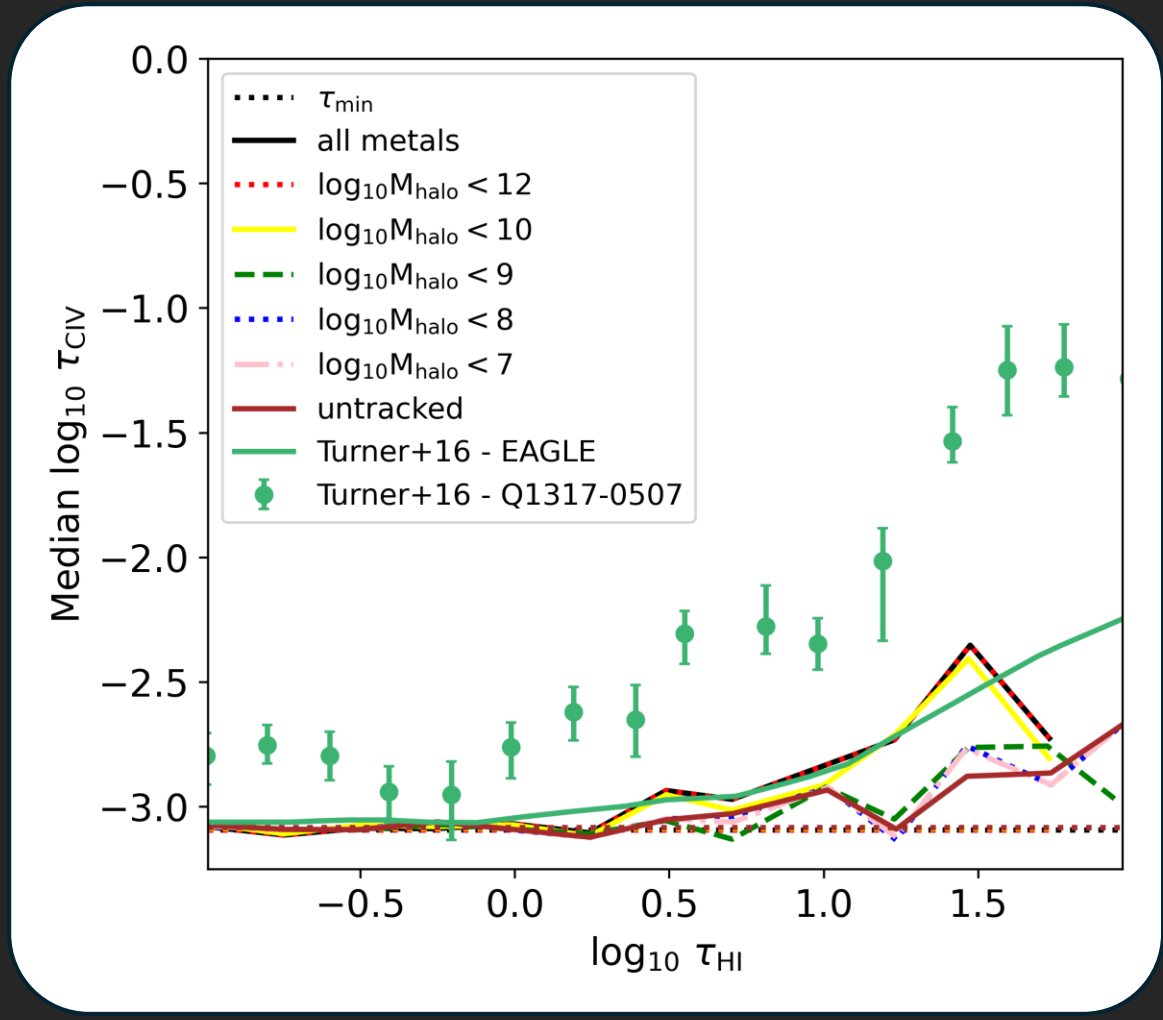


Marasco et al. (2023) find the bulk of outflows in low mass galaxies exhibit low mass loading factors between 0.1 and 0.01.

The observational literature reports significant scatter across ~4 orders of magnitude; there is an **absence of consensus** on the scale of these winds.

SpecWizard and Simulations with Z Diffusion

- Future work:
  - Produce mock observable QSO spectra to analyse how the observed enrichment profile of the universe would be altered without contributions from low-mass galaxy winds.
  - Metal diffusion prevents the same post-processing analysis used for EAGLE. To do this, haloes need to be identified on-the-fly, so that the halo properties may be diffused along with metals.



Summary

- IGM gas in EAGLE is enriched and can be used to probe the galaxy mass range(s) that contribute most.

- Galaxies in low-mass haloes are essential contributors to IGM enrichment, supporting the need for highly mass-loaded winds.
  - $10^9\ \mathrm{M}_\odot$ and below EAGLE haloes are responsible for ~20% of IGM metals.
  - $10^{12}\ \mathrm{M}_\odot$ and below provide ~65%.

- To utilise the same technique with up-to-date simulations, on-the-fly tagging with halo/galaxy information is required due to metal diffusion between resolution elements.