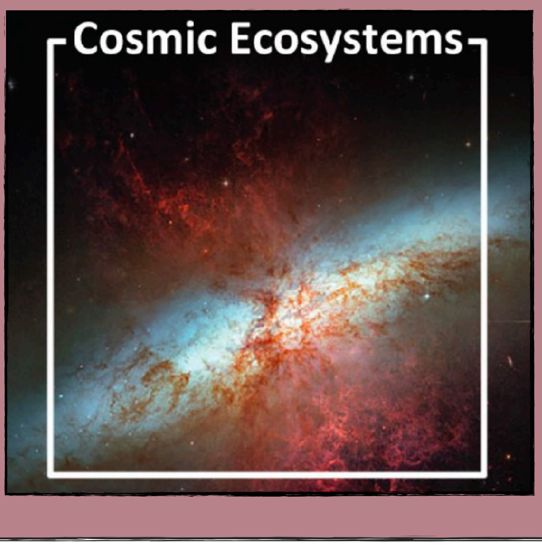

The Circumgalactic Medium of Low-Mass Galaxies

Upper Limits on the Cool Gas Mass

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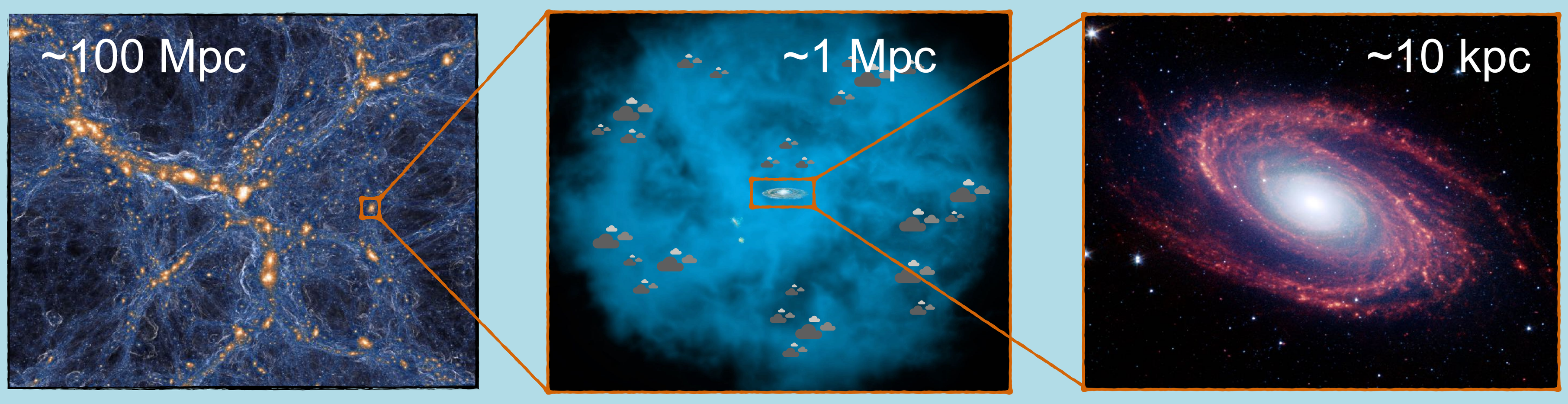
Motivation

The circumgalactic medium (CGM) connects the large-scale structure with the galaxies that reside at the nodes of the cosmic web. Gas accreted from the intergalactic medium (IGM) and stripped from satellite galaxies is deposited into the CGM, which can then fuel star formation and the growth of supermassive black holes. Galactic processes, such as stellar and active galactic nuclei feedback, shape the CGM by heating it, enriching it with metals, and even ejecting gas into the IGM.

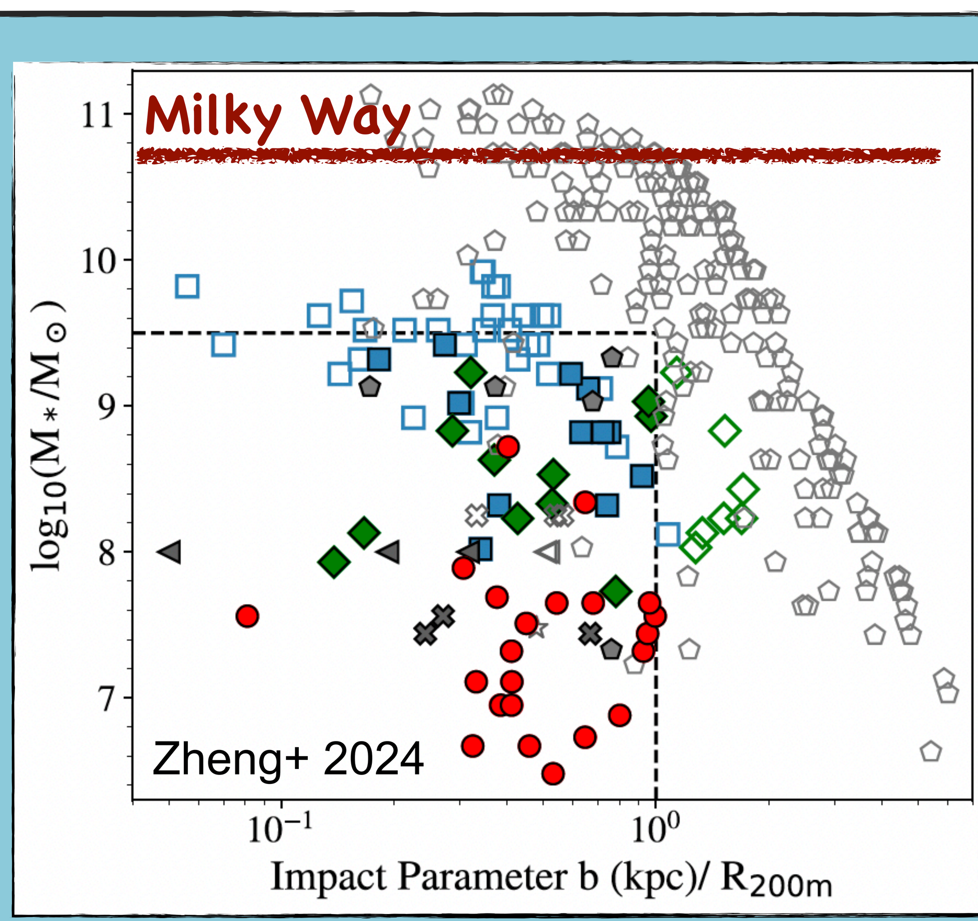
The last decades saw significant progress in multi-wavelength observations, revealing that the CGM is an extended, dynamic, and multiphase structure. However, many questions are still open - **how much gas is out there, what are its thermal properties, spatial distribution, and morphology?** These are all linked to the properties of gas accretion onto galaxies, feedback processes, and gas microphysics, and are crucial to our understanding of how cosmic ecosystems form and evolve.



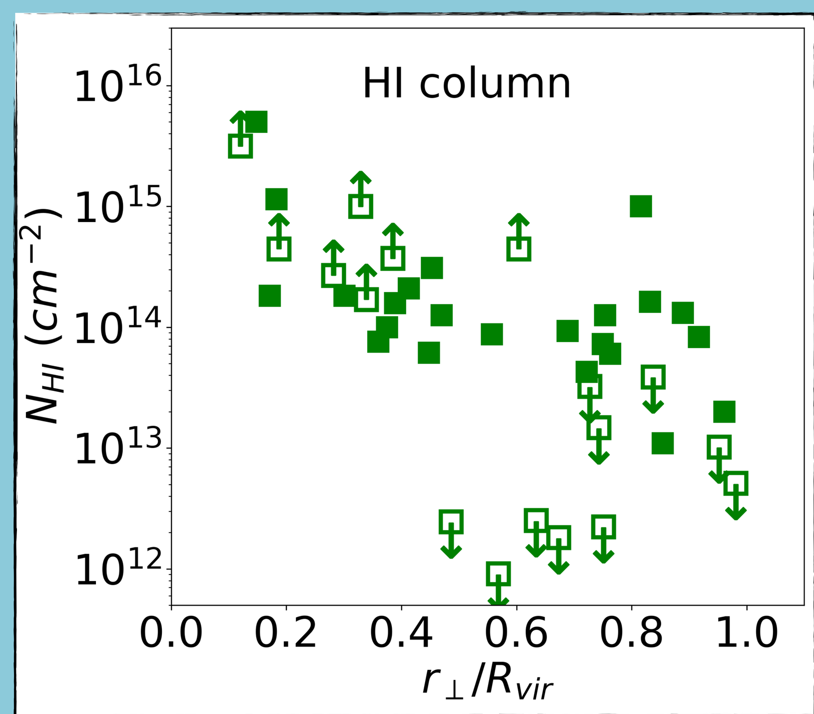
Dwarf galaxies are great laboratories for understanding star formation and feedback processes, and the role of the CGM in these. Previous empirical theoretical studies of the CGM largely focused on more massive galaxies, relating observables to the underlying gas properties. In this work we construct a model for the CGM of dwarf galaxies, apply it to observations, and provide limits on the cool ($T \approx 10^4$ K) gas mass.

Data set

We study low-redshift (z<0.3) isolated dwarf galaxies. Our sample consists of 40 galaxy-QSO pairs reported and analyzed by Zheng+ 2024 and Mishra+ 2024. The galactic stellar masses are $M_* \sim 10^{6.5} - 10^{9.5}\ M_\odot$. We convert these to halo masses using the Universe Machine (Behroozi+ 2019) and Colossus (Diemer 2018) toolkits and obtain $M_{\rm vir} \sim 10^{10} - 10^{11.5}\ M_\odot$.



Background QSOs probe the galaxies' CGMs at impact parameters up to the viral radius, and HST/COS UV spectra show absorption from neutral hydrogen (HI) and metal species (CII, CIV, SiII, SiIII, SiIV, OVI). **In this work we focus on HI absorption**, tracing cool photoionized gas. The figure shows the HI column densities versus impact parameters normalized to the halo viral radii. The data show a mix of measurements, lower limits due to line saturation, and non-detections.



Empirical Model

$f_{\rm HI}$ - HI fraction
L - path length
f_V - volume filling fraction

Gas mass upper limit

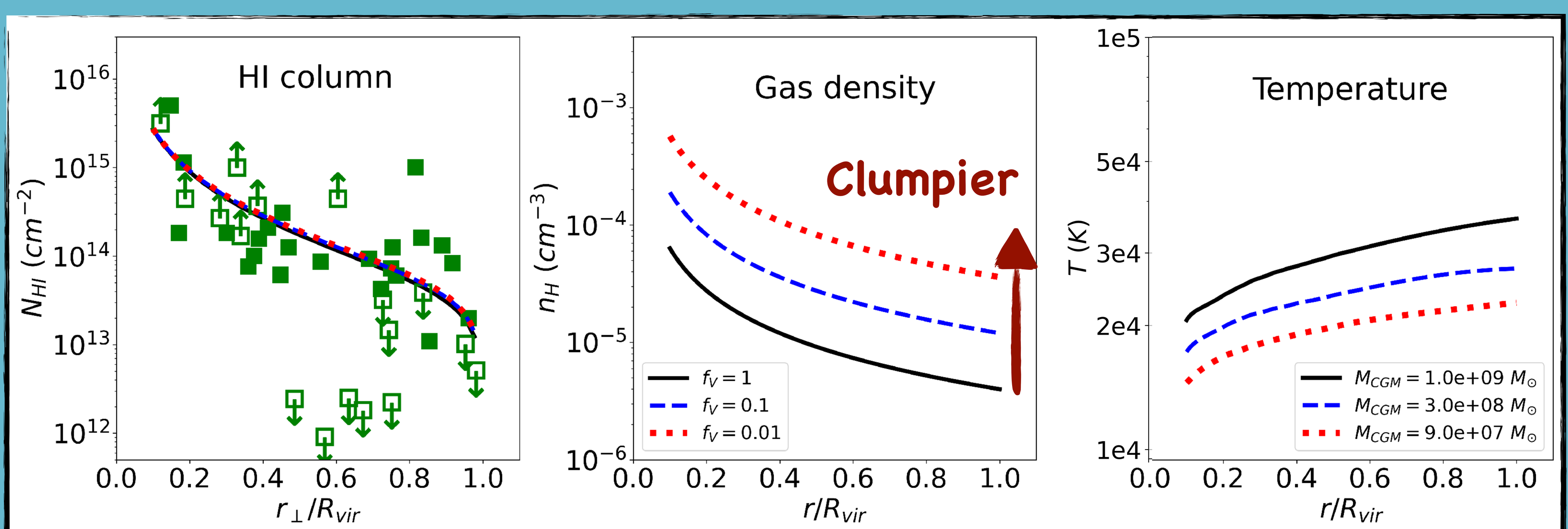
For constant density gas, the neutral hydrogen column is $N_{\rm HI} = f_{\rm HI} n_{\rm H} L f_V$

In photoionized gas at low densities, the hydrogen is mostly ionized and the neutral fraction is proportional to the gas density ($f_{\rm HI} \propto n_{\rm H}$). Then $N_{\rm HI} \propto n_{\rm H}^2 f_V$, and the cool gas mass associated with a measured HI column is $M_{cool} \propto n_{\rm H} f_V \propto f_V^{1/2}$

Since $f_V \leq 1$, the volume-filling scenario gives an upper limit on the mass.

Gas spatial distribution

We assume a power-law volume density profile $n_{\rm H}(r) = n_{\rm H,0}\left(r/R_{vir}\right)^{-a_n}$ and $f_V = const$, and that gas is at a heating/cooling equilibrium and photoionization equilibrium (PIE). Equilibrium temperatures and ion fractions are calculated with Cloudy (Ferland+ 2017) assuming the Khaire & Srianand (2019) $z = 0$ UV background (UVB) radiation field.



All three models shown here produce the same HI column density profile (left) with different gas volume densities (middle) and volume filling factors, ranging from $f_V = 1$ (volume filling) to $f_V = 0.01$ (clumpy). The gas mass in these models differs by a factor of ≈ 10. The gas temperature (right), set by the UVB, varies weakly with density.

References and Acknowledgements

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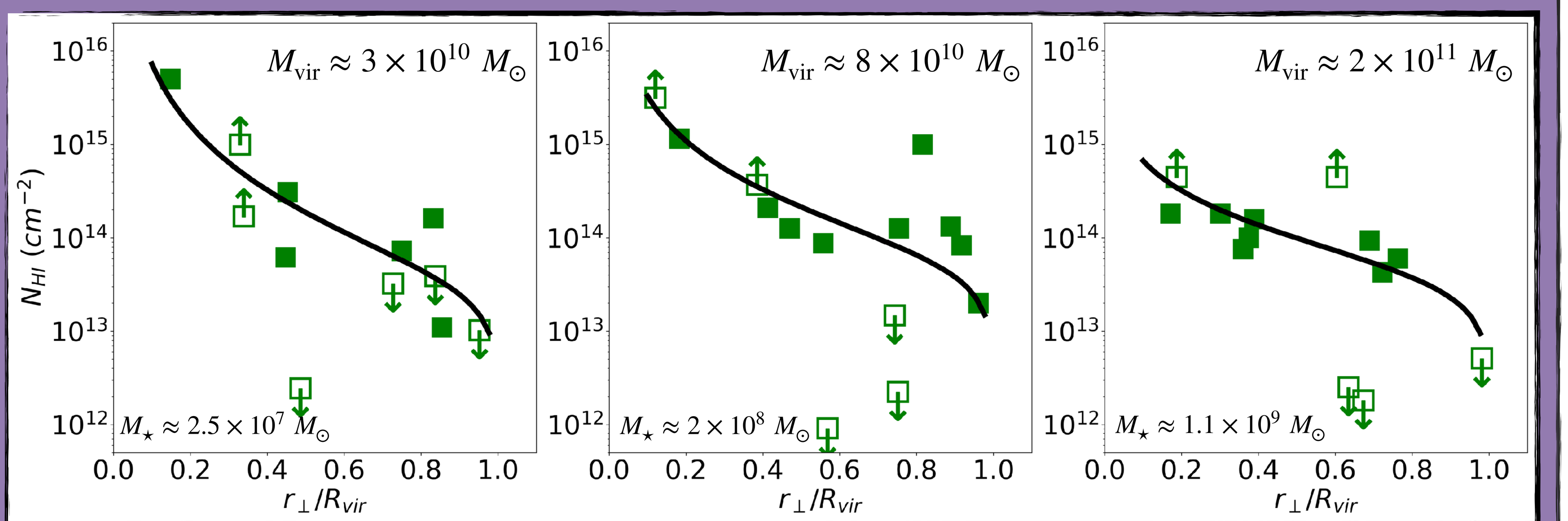
Dwarf galaxies

MW-mass galaxies

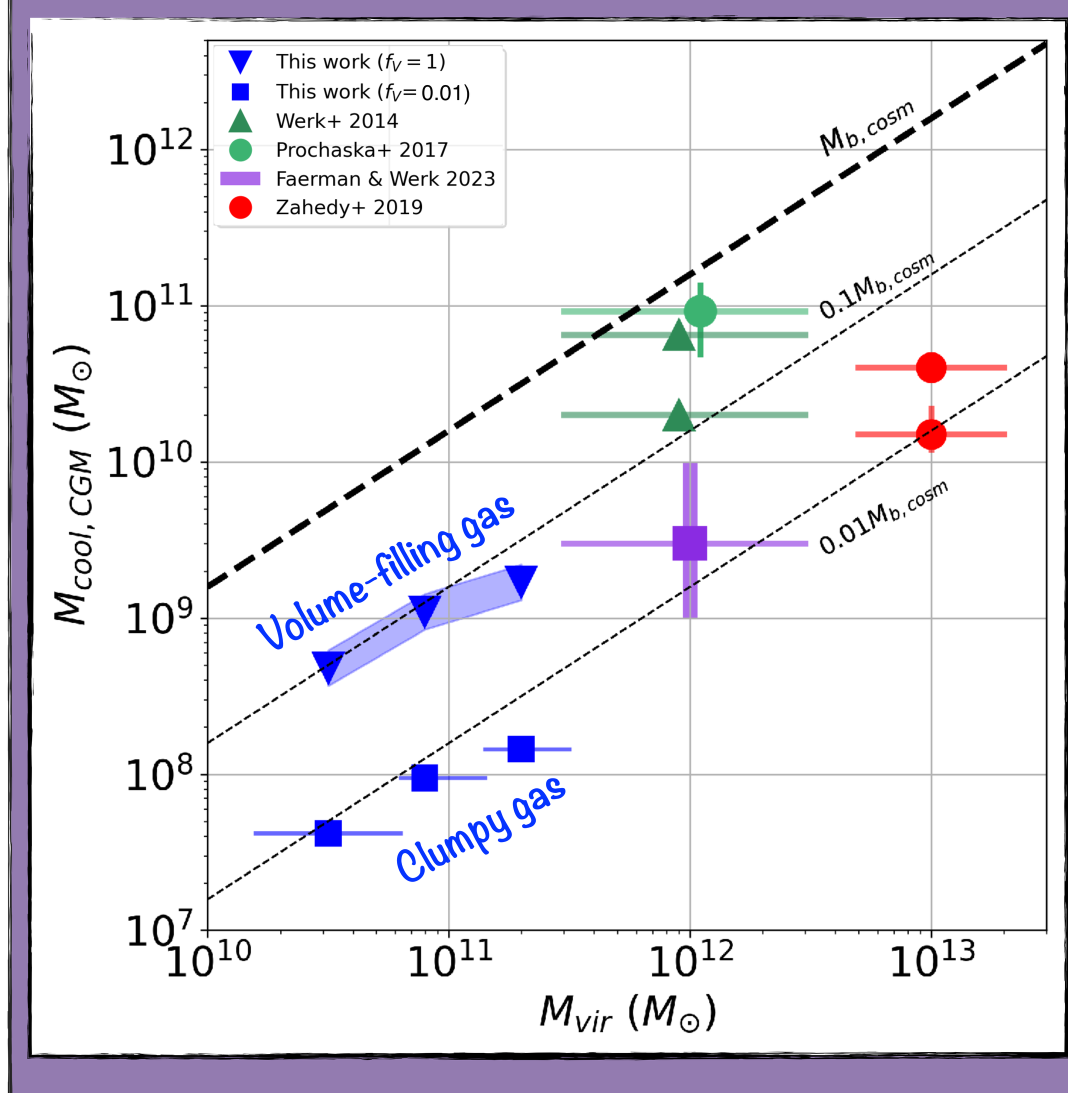
Y.F. is supported by NASA award 19-ATP19-0023 and NSF award AST-2007012. This work was partially performed at the Aspen Center for Physics, supported by NSF grant PHY-2210452. Y.F. thanks the astronomy department at Tel Aviv University for their hospitality, and the organizers of this conference for support.

Results

We bin our sample by halo mass and apply our empirical model to the observations. We vary the volume density profile slope (a_n) and normalization ($n_{\rm H,0}$) to fit the measured column densities, resulting in an average CGM profile for each halo mass. The figure shows the best-fit models (curves) compared to HI observations (markers).



We address two morphological scenarios: (i) volume-filling gas ($f_V = 1$), providing an upper limit on the gas mass, and (ii) clumpy gas with $f_V = 0.01$, motivated by studies of MW-mass galaxies CGM (Faerman & Werk 2023). We integrate over the best-fit gas density profiles to obtain the cool CGM masses ($M_{\rm cool}$) and plot them versus $M_{\rm vir}$.



The dashed diagonals show fractions of the cosmological halo baryonic mass budget. **Our results show that the cool CGM constitutes <10% of the halo baryon budget.** With the stellar masses included, this leaves >85% of the halo baryons unaccounted for. Do these reside in warm/hot gas or were they ejected from the halos by feedback?

We compare our results to $M_{\rm cool}$ estimates in more massive halos from other studies. While results for MW-mass galaxies vary, Zahedy+ 2019 infer similar fractions (<5%) in luminous red galaxies (LRGs, red).

Our estimates assume the measured HI column density forms entirely in the cool CGM. Some fraction of the measured columns may originate in warm/hot CGM or in the IGM, further strengthening our limits. Uncertainties in the background radiation intensity or the (unknown) gas metallicity have a <30% effect on the inferred $M_{\rm cool}$.

In **future work** we will explore our model predictions for metal ions and gas accretion rates onto the galaxy. We also plan extending our models to include additional CGM phases and model CGM-galaxy evolution, including accretion and outflows.