Resolving the Turbulent Circumgalactic Medium

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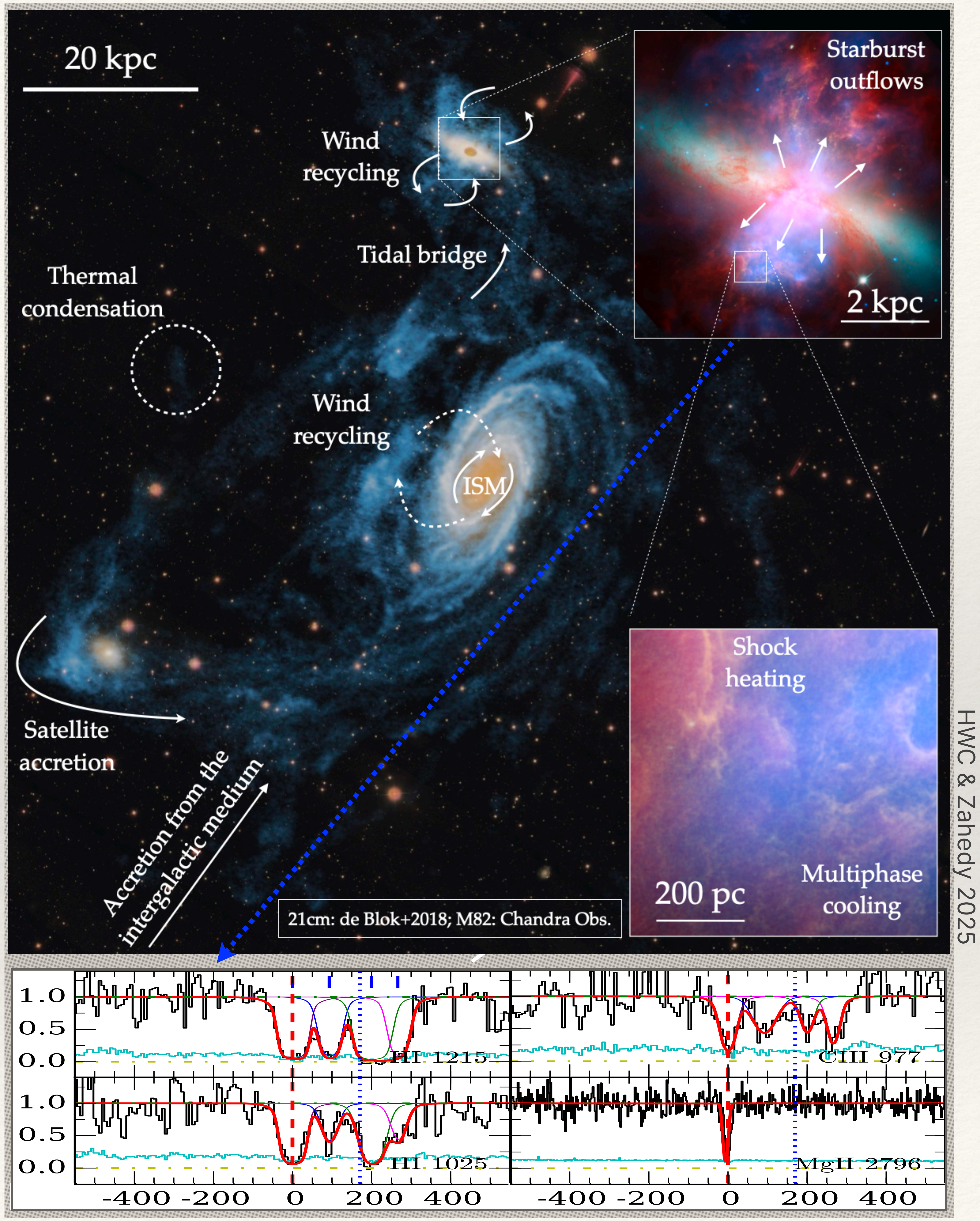
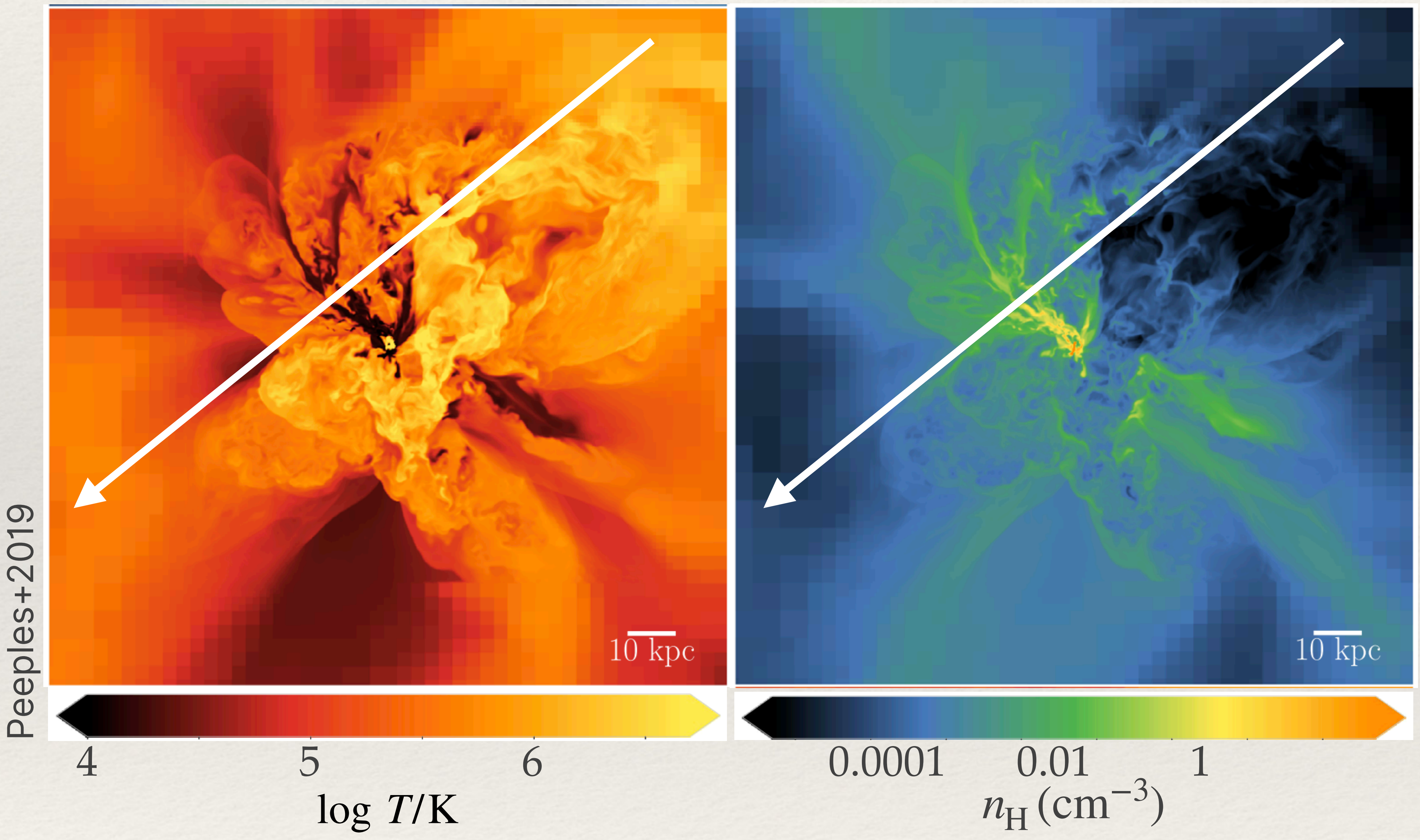


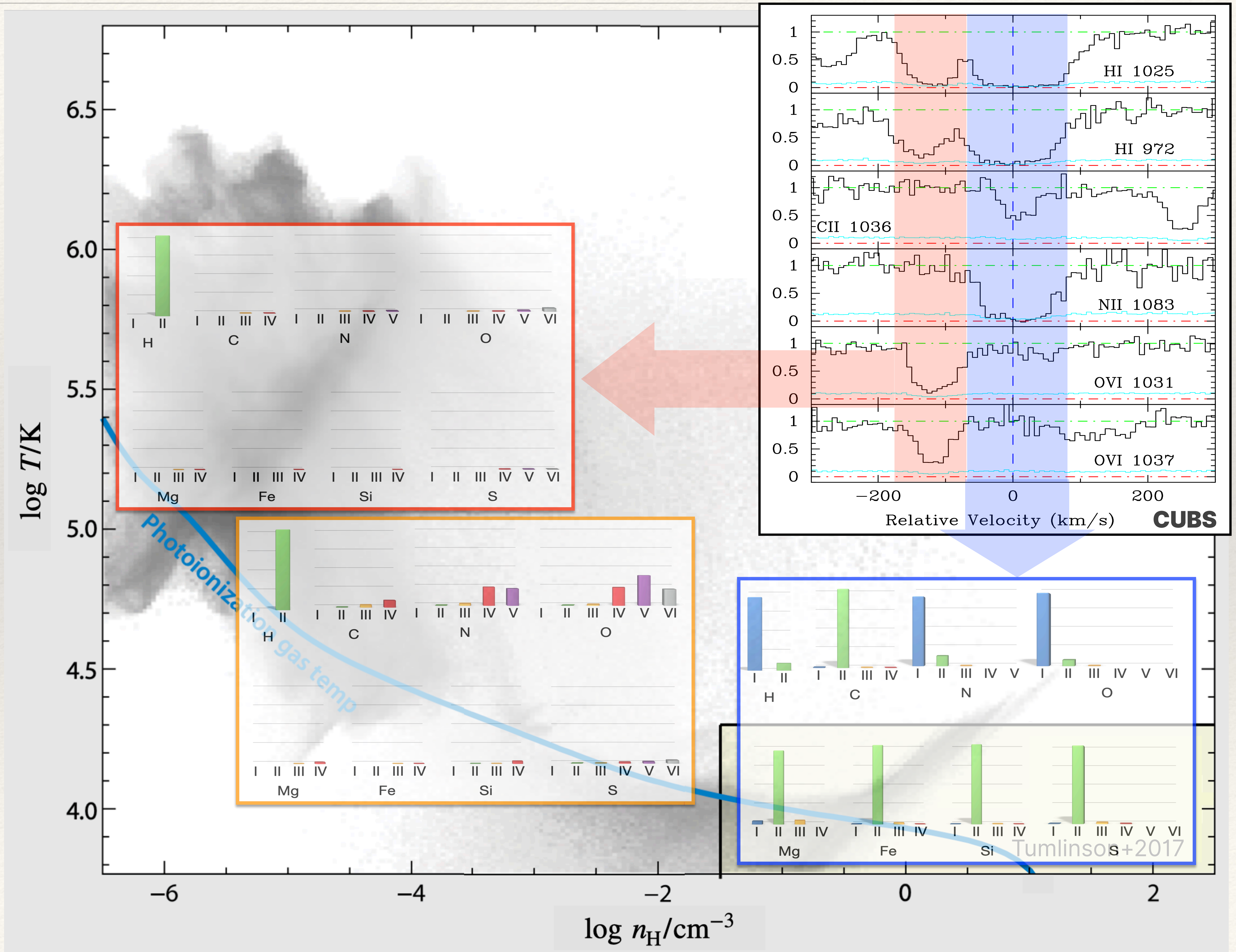
HWC & Zahedy 2025

Outline

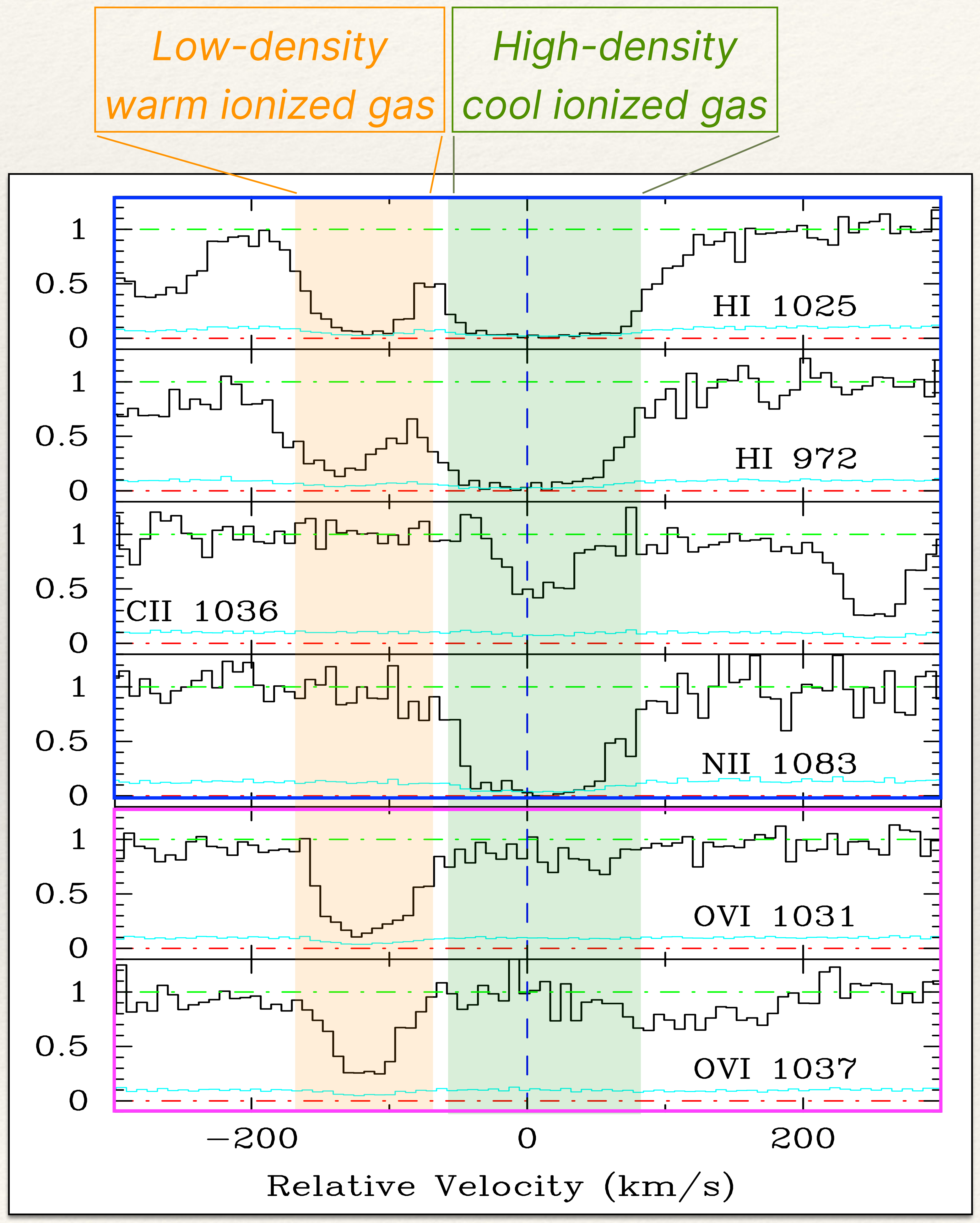
- Resolving the density, chemical enrichment, and thermodynamics in gaseous halos using absorption spectroscopy
- The turbulent velocity-size relation of the cool circumgalactic medium
- Constraining multi-scale turbulence in the CGM by combining emission and absorption measurements

Probing the multiphase CGM using absorption spectroscopy

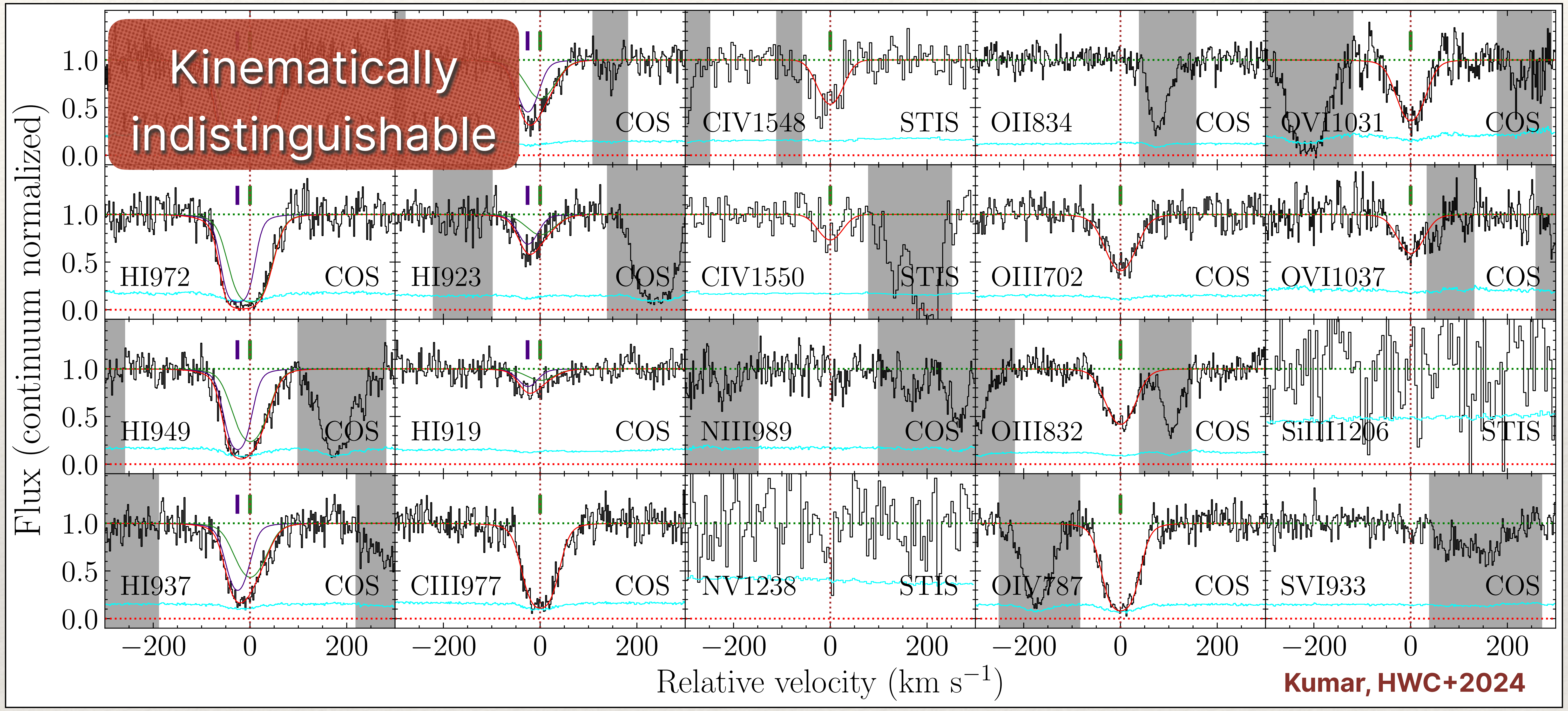


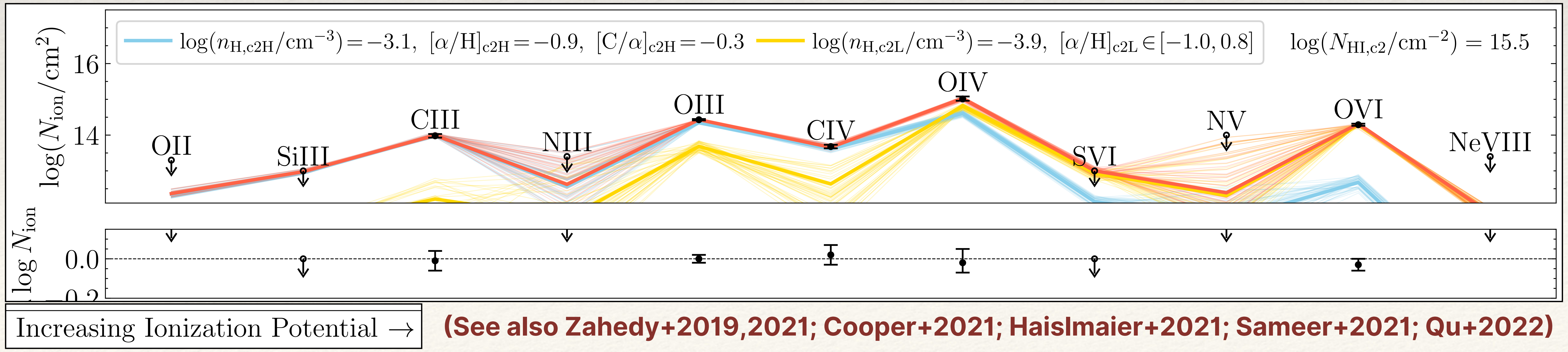


Probing the multiphase CGM using absorption spectroscopy



Kinematically distinct





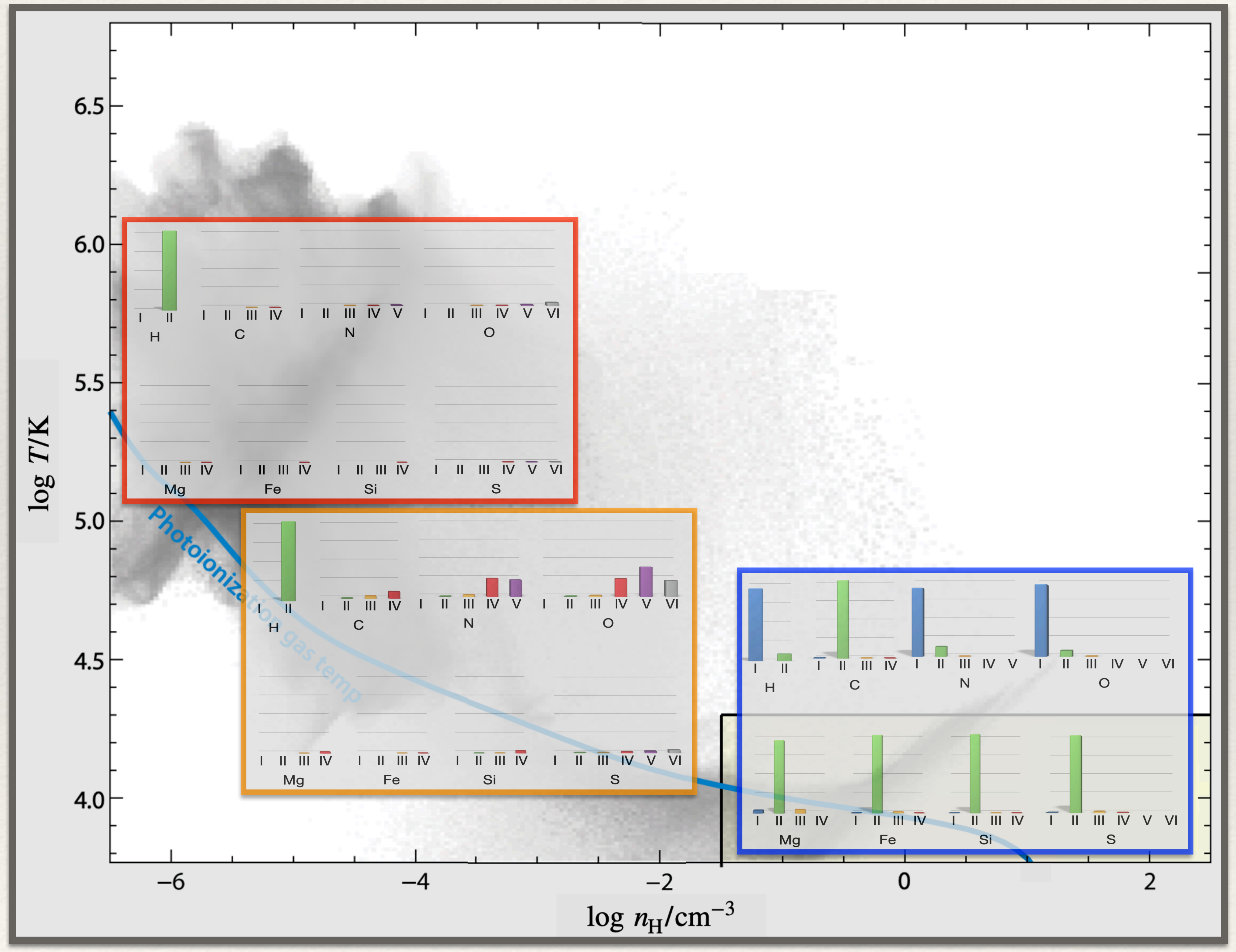
(See also Zahedy+2019,2021; Cooper+2021; Haislmaier+2021; Sameer+2021; Qu+2022)

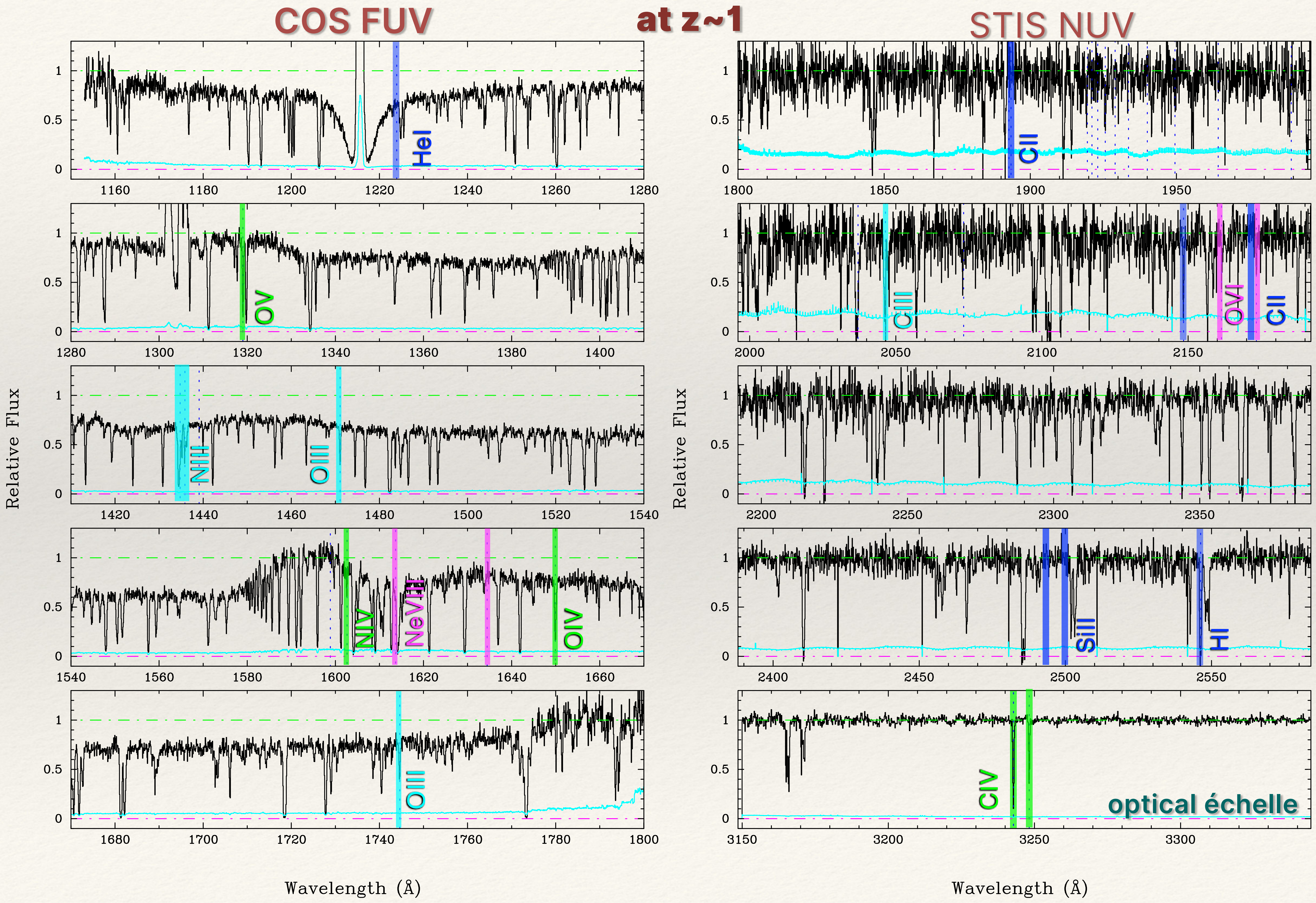
The Cosmic Ultraviolet Baryon Survey

Circumgalactic Observations of Nuv-shifted Transitions Across Cosmic Time

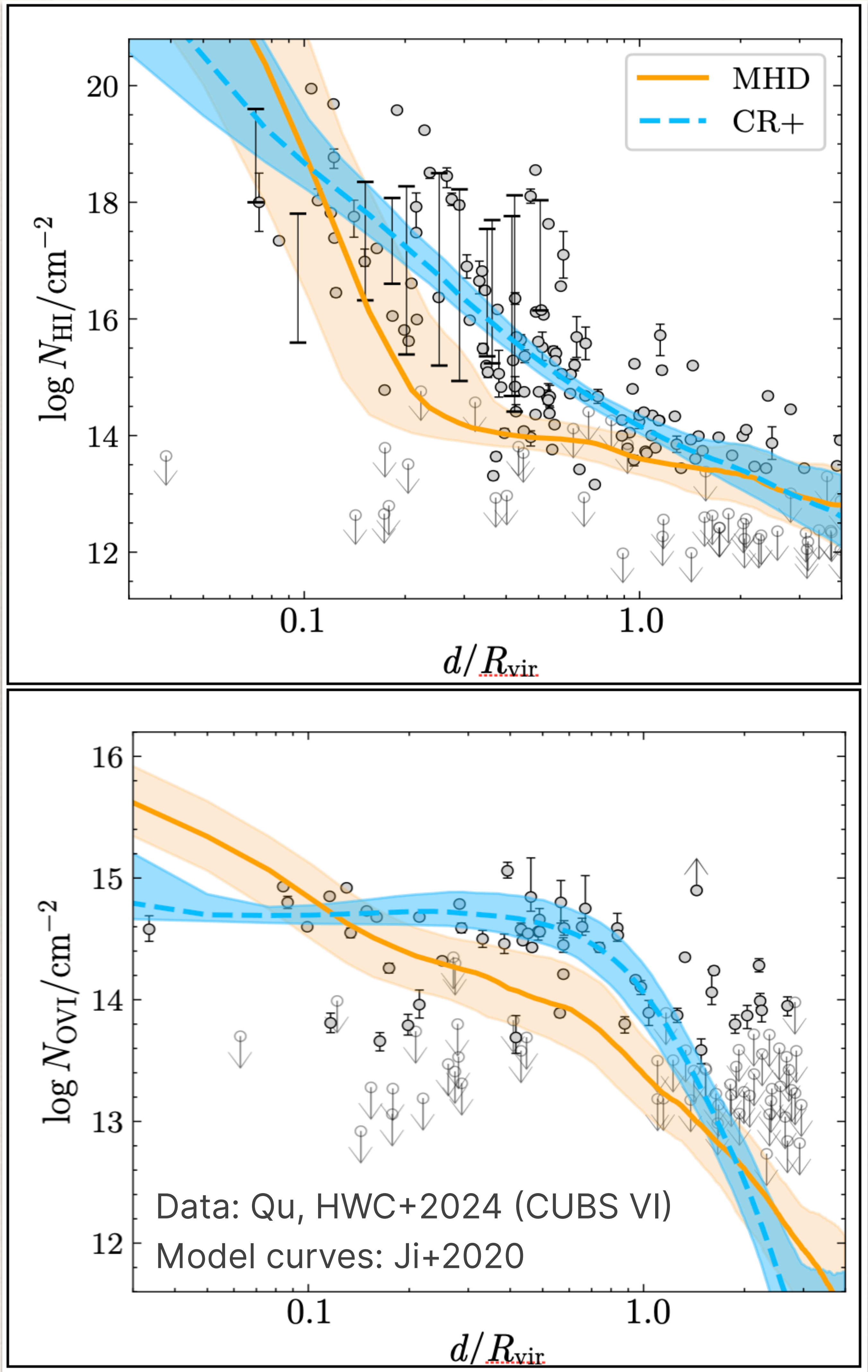
https://cubs.uchicago.edu

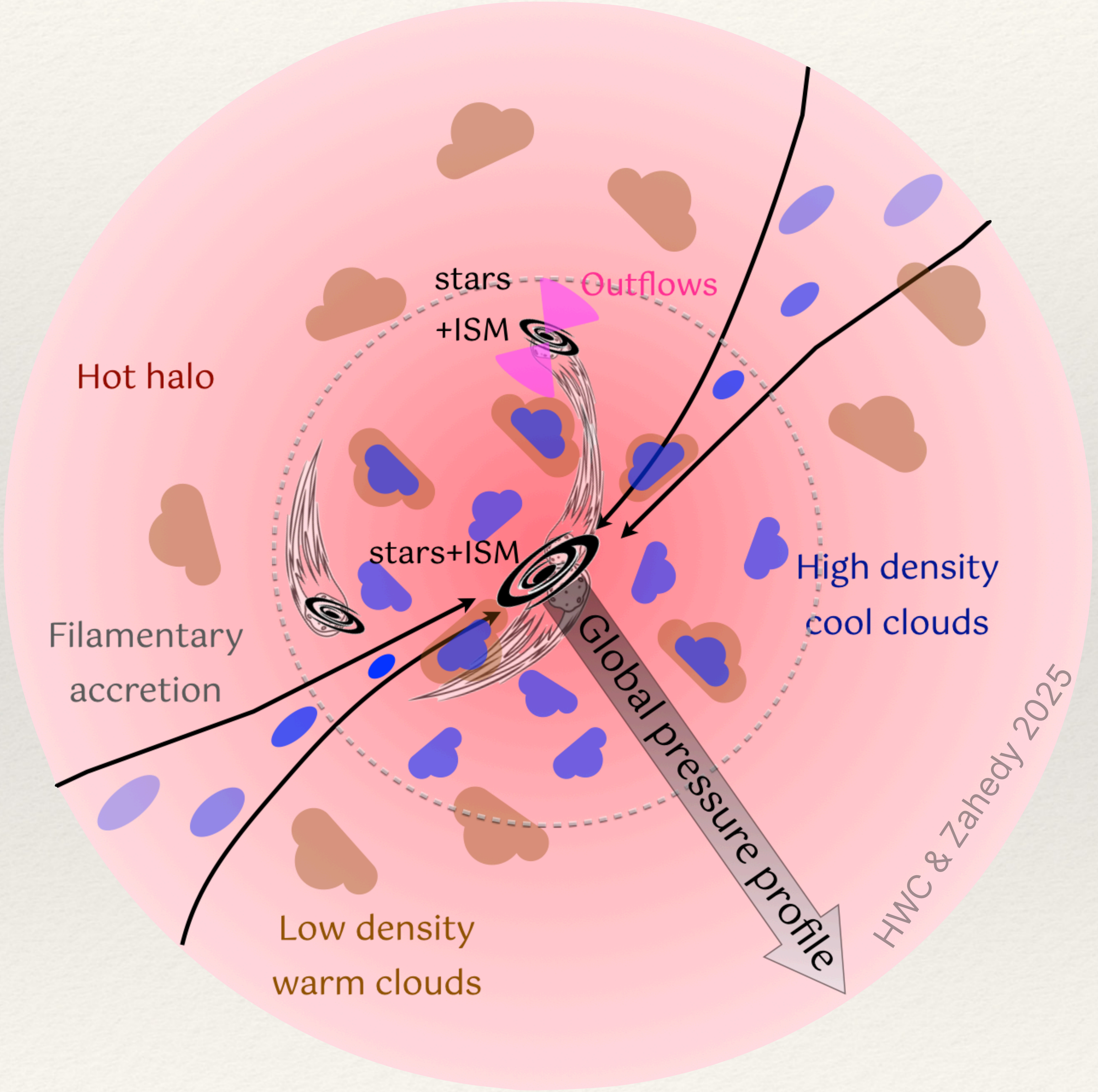
Broad spectral coverage to resolve multiphase gas



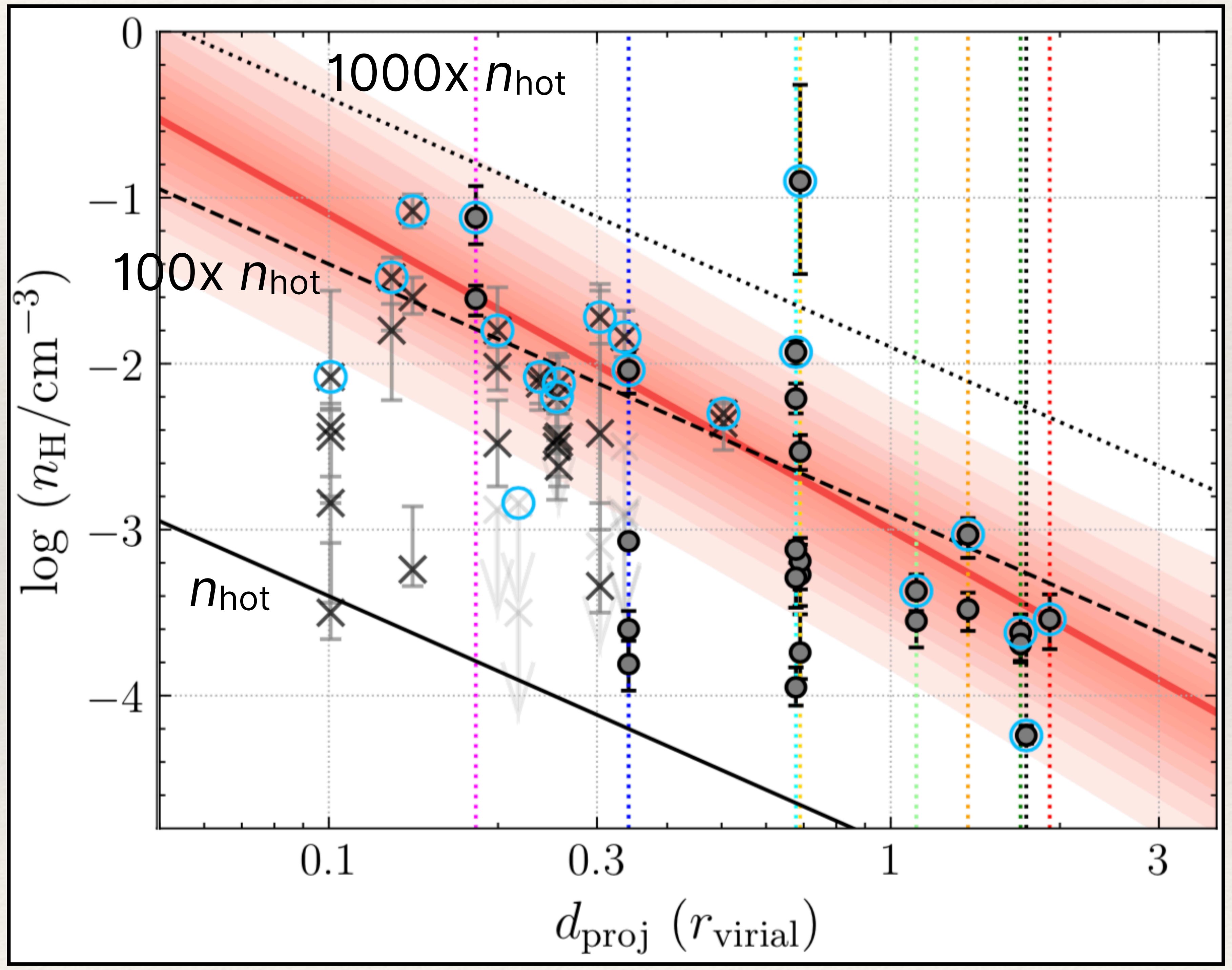


From cross-section to resolved density structures





Resolved density/pressure profile

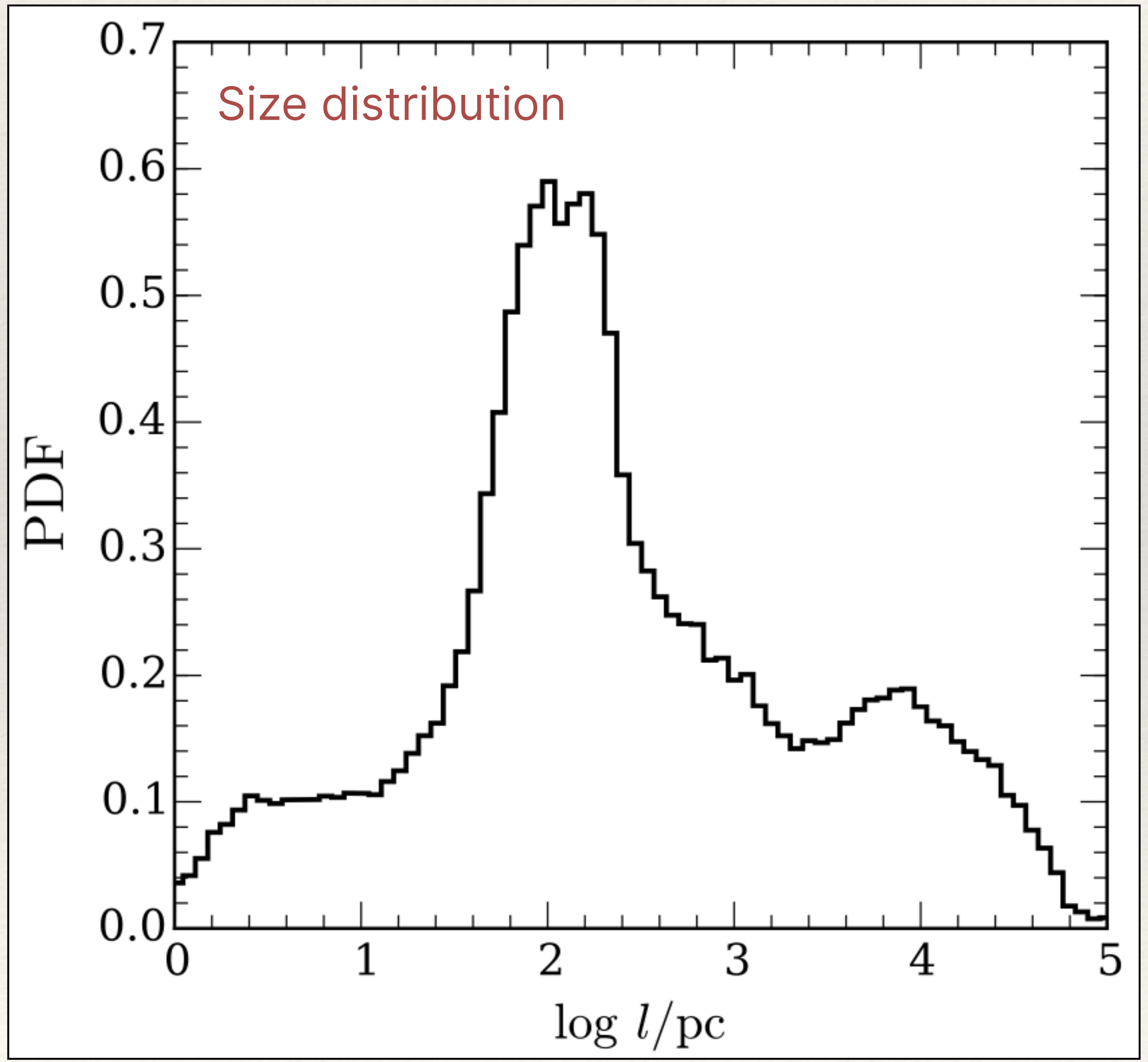


Qu, HWC+2022 (CUBS V);
see also Zahedy, HWC+2019

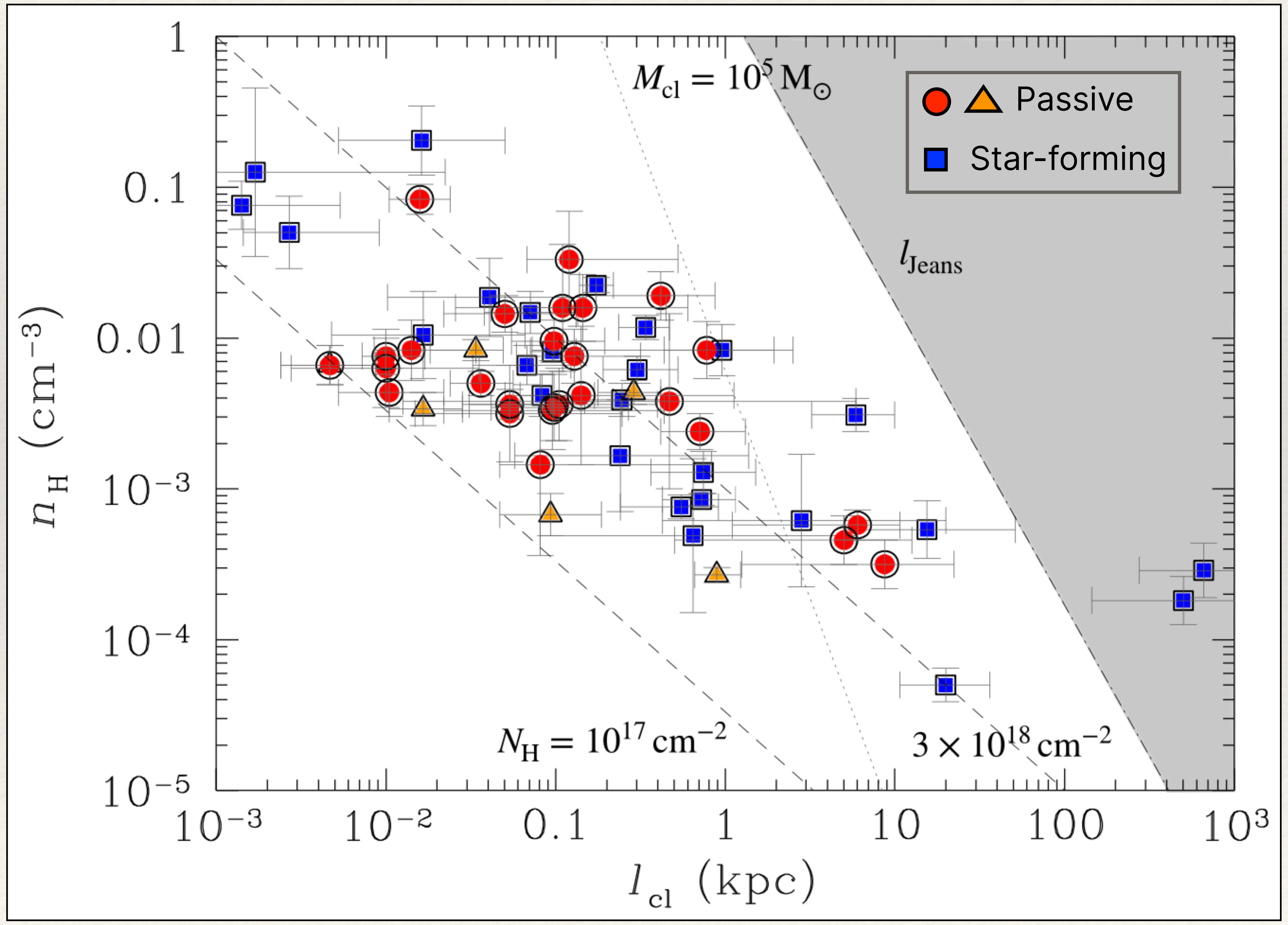
From cross-section to resolved density structures

Constraints on clump size: $l_c = N_{HI}/(f_{HI}\, n_H)$, ~ 100 pc

Resolved clumps have characteristic N_H from $\sim 10^{17}$ to $\sim 10^{19}\,\mathrm{cm}^{-2}$, implications for survival length scales (see e.g., Gronke & Oh 2018)



Zahedy, HWC+2021 (CUBS III)

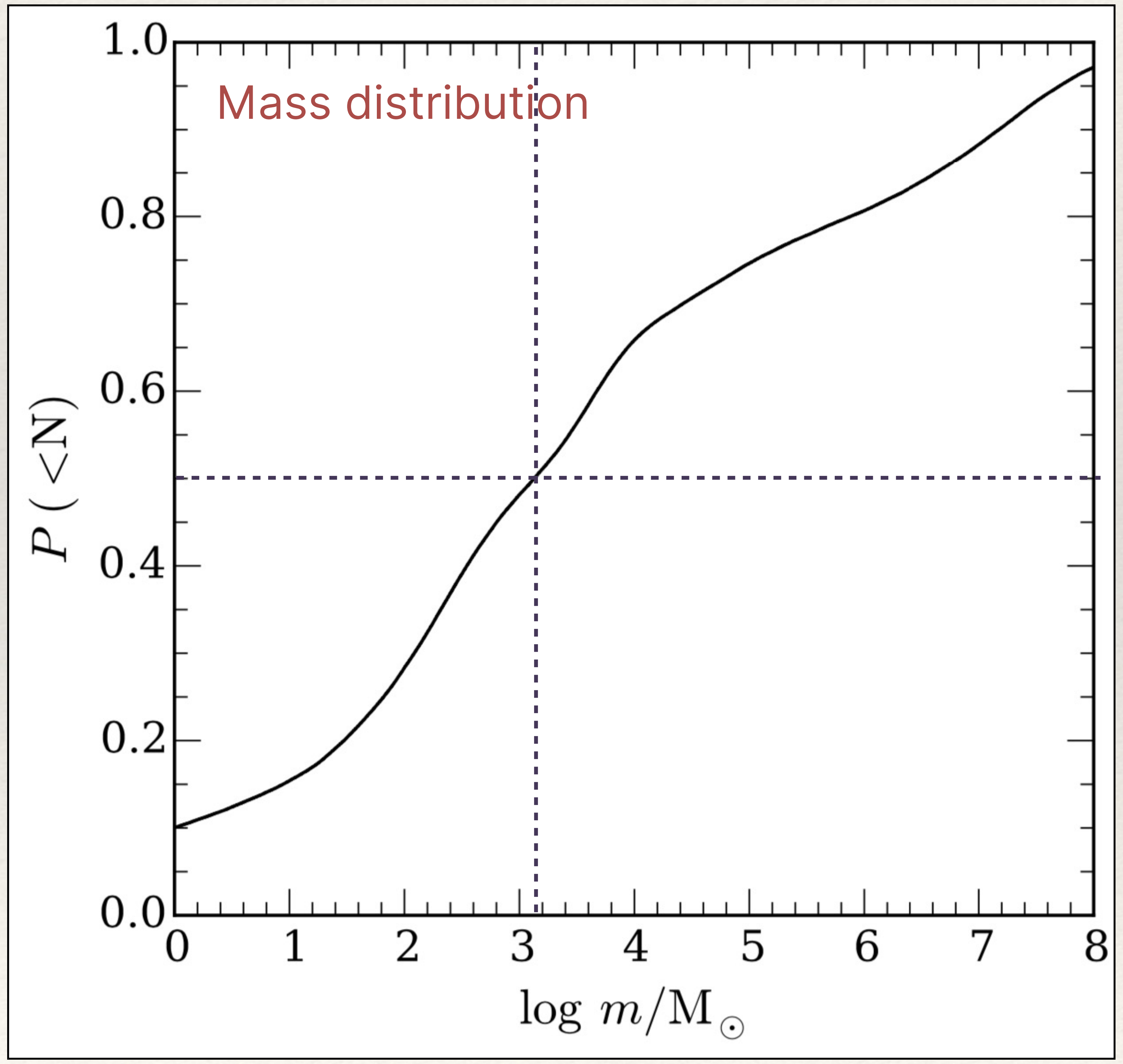


HWC+2023

From cross-section to resolved density structures

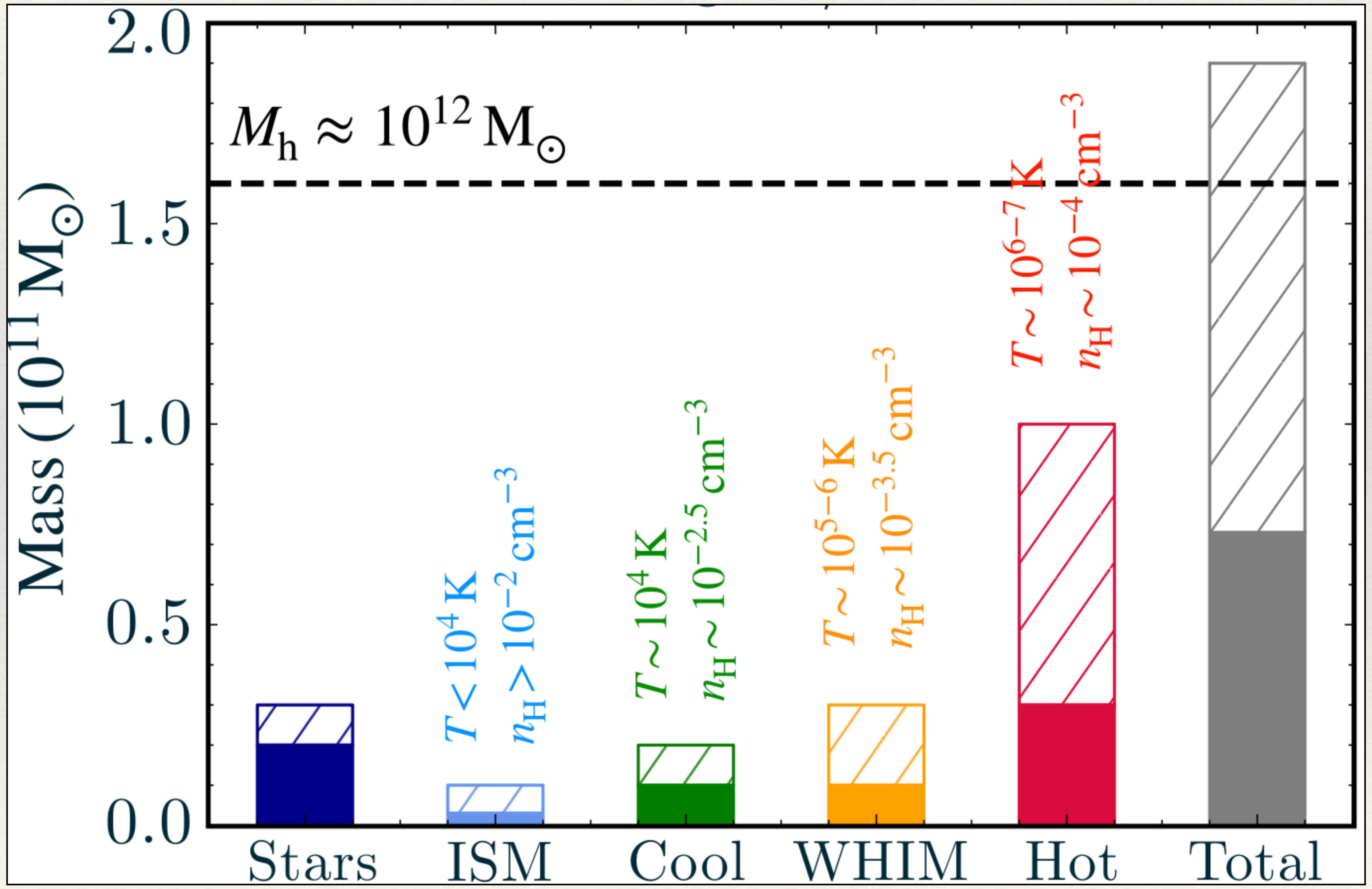
Constraints on clump mass

$m_c = (\pi/6)\,\mu\, m_p\, n_{\rm H}\, l_c^3 \sim 1000\,{\rm M}_\odot$



Zahedy, HWC+2021 (CUBS III)

Baryon mass budget in difference phases for L_*-like halos

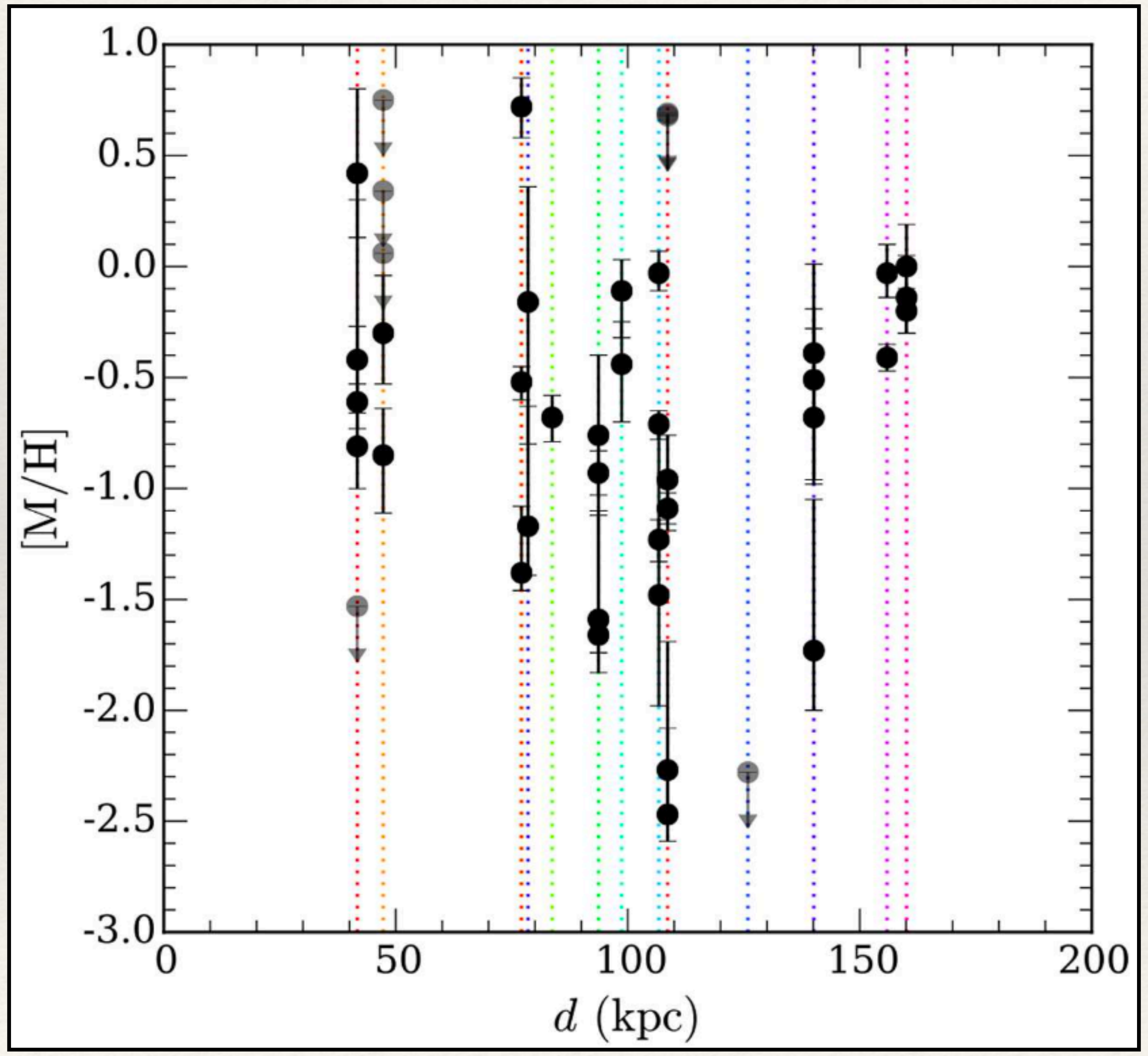


Chen & Zahedy (2025)

From cross-section to resolved chemical enrichment

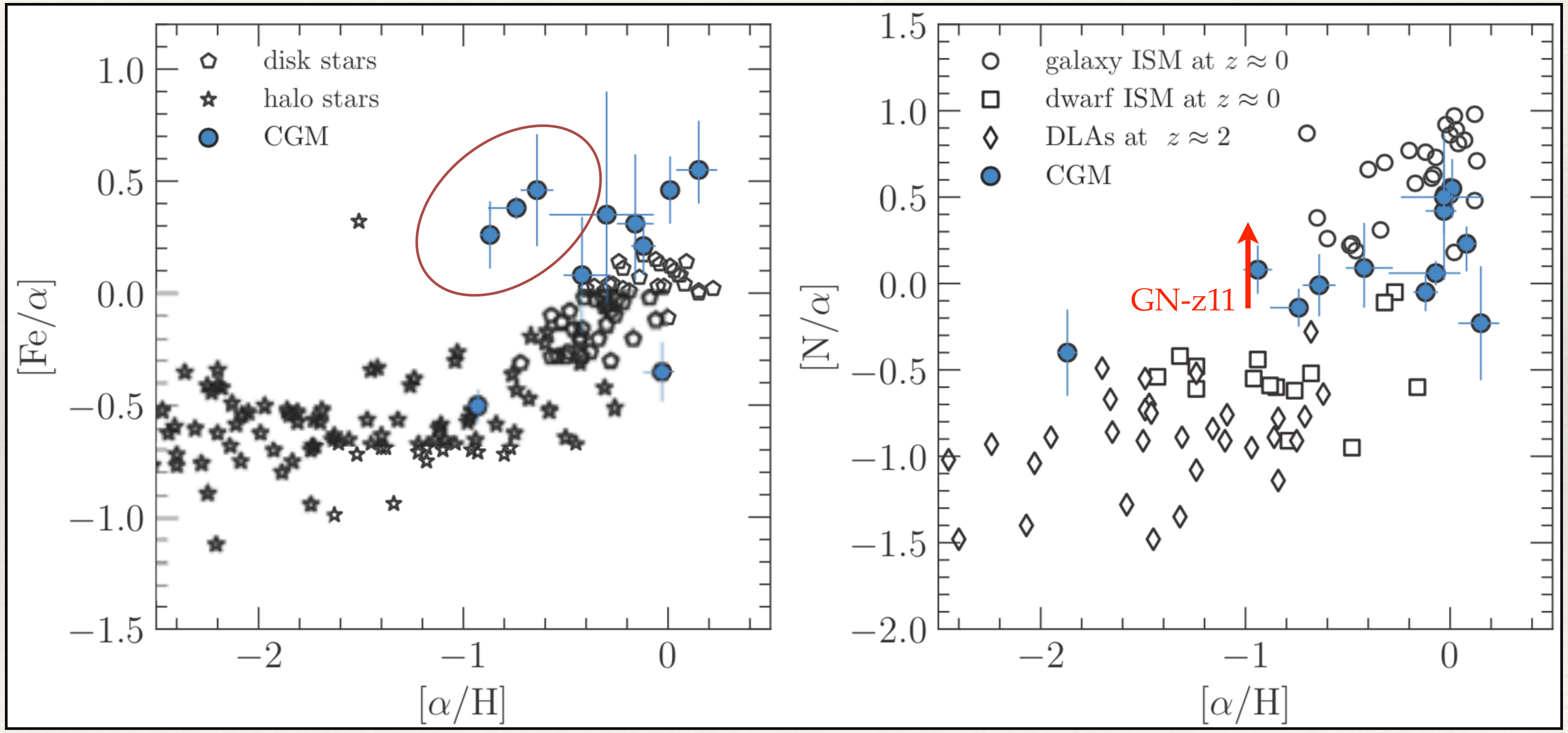
Inhomogeneous chemical enrichment in the CGM and its connection to star formation history

Metallicity



Zahedy+2019, 2021; HWC+2020; Cooper+2021; Kumar+2024

Elemental abundance pattern

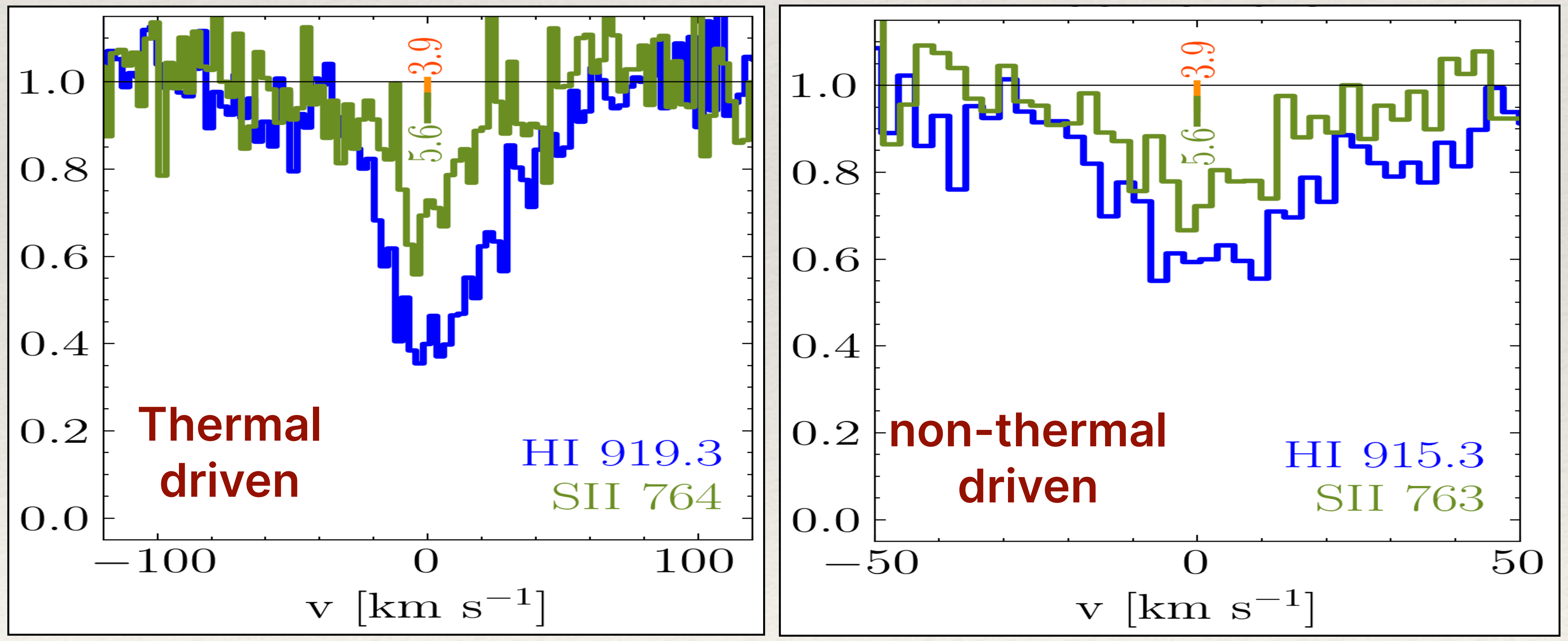


Chemically evolved material in low-metallicity gas, evidence of dilution.

From cross-section to resolved thermodynamics

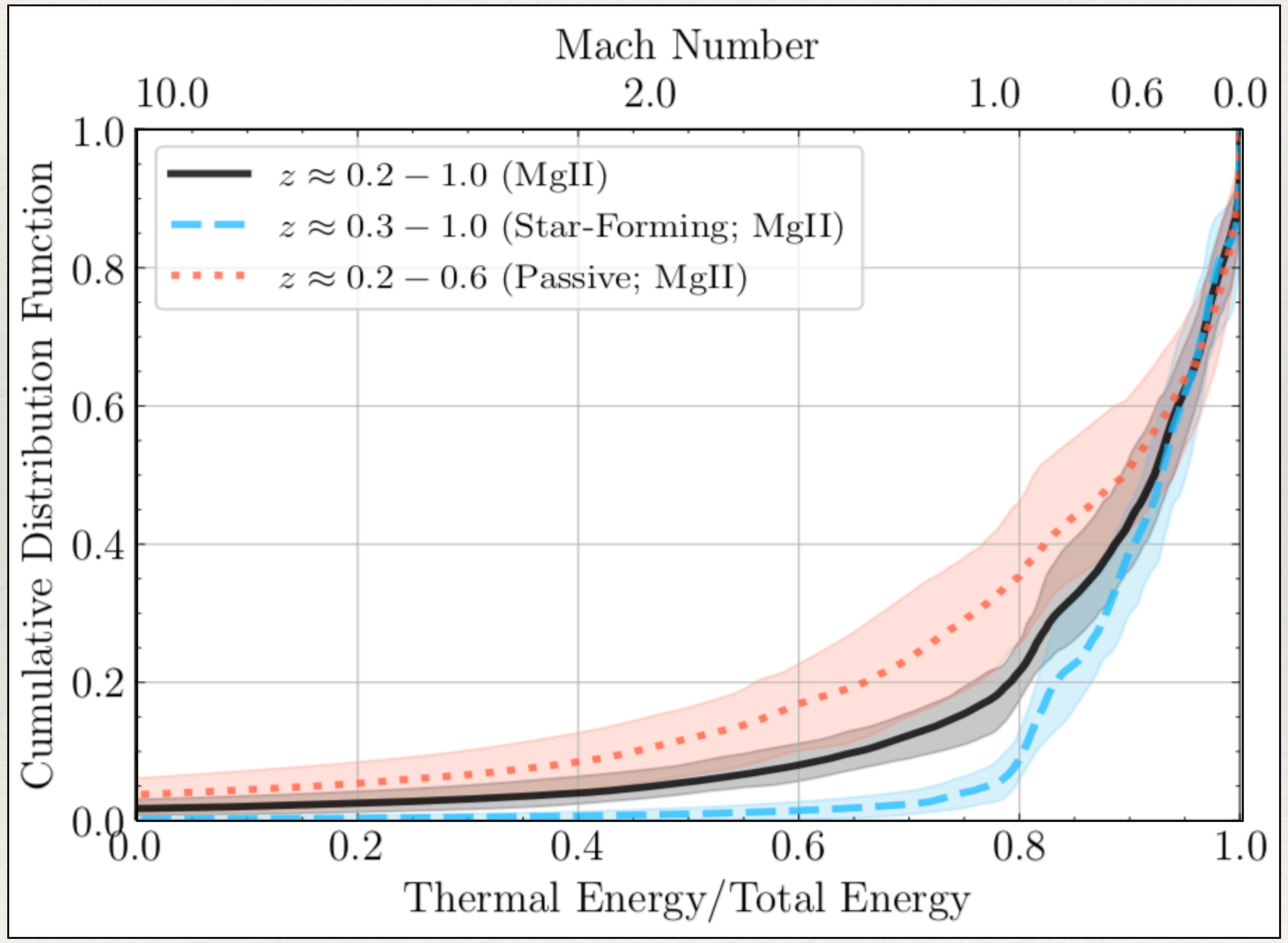
Empirical constraints on the gas temperature and turbulence by comparing the observed line widths of different elements, independent of the ionization models.

$$b_I^2 = \frac{2k_BT}{m_I} + b_{non-thermal}^2$$



See also Rauch+1996; Rudie+2019

Thermal energy fraction: $\frac{E_{\text{thermal}}}{E_{\text{total}}} = \frac{1}{1 + \frac{\gamma(\gamma-1)}{2}\mathcal{M}^2}$



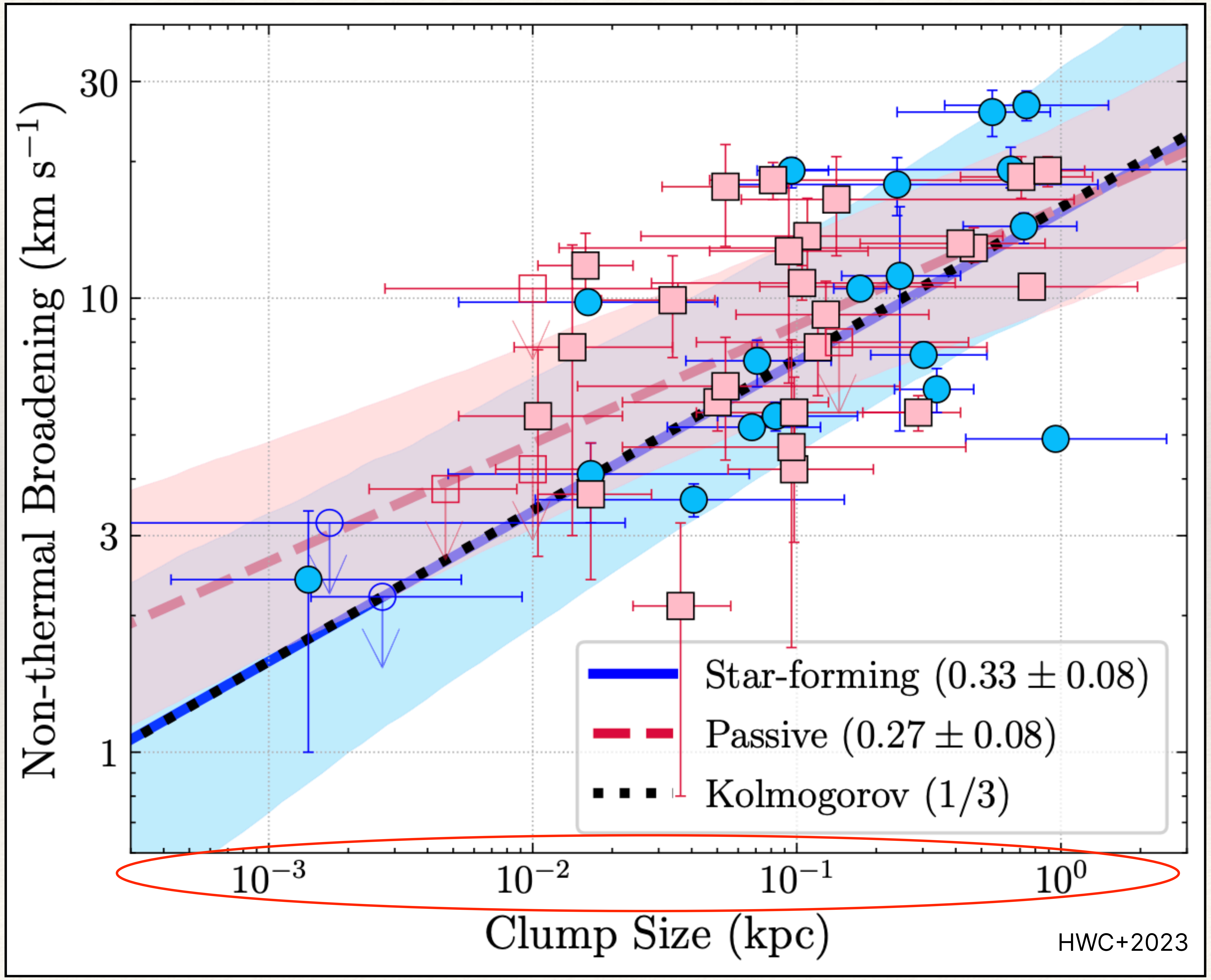
Qu, HWC+2022 (CUBS V)

From cross-section to resolved thermodynamics

CGM Larson's law: velocity-size relation

Resolved turbulence down to pc scales with roughly constant energy transfer rate of $\epsilon \approx 0.003\,\mathrm{cm}^2\,\mathrm{s}^{-3}$ per unit mass and dissipation time scale of < 100 Myr.

No distinction can be found between passive and star-forming halos, but the scatters are large.



HWC+2023

Probing the turbulent CGM in emission

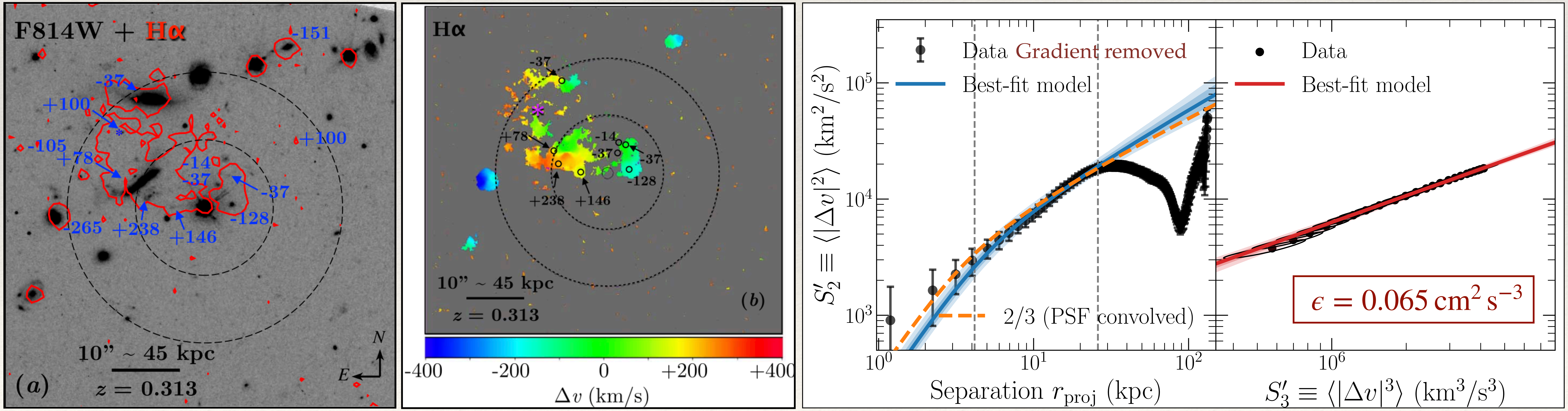
See Mandy Chen's talk on Friday!

The velocity structure functions (VSFs), $S_p(r) = \langle |v(\mathbf{x}) - v(\mathbf{x}+\mathbf{r})|^p \rangle \propto r^{\zeta(p)}$

The Kolmogorov theory predicts that $\zeta(p) = p/3$ for homogeneous, isotropic, and incompressible fluids

The energy transfer rate is $\epsilon = \frac{5}{4}\frac{|\delta v|^2}{\frac{r}{\delta v}} = \frac{5}{4}\frac{|\delta v|^3}{r} = \frac{5}{4}\frac{S_3(r)}{r}$

non-AGN host halo



HWC+2019

Hirn, HWC, Chen+2025

Summary

- By extending beyond cross-section studies, high-resolution absorption spectroscopy covering low-, intermediate-, and high-ionization species, enables direct connections to galaxy star formation histories based on resolved density, thermodynamics, and chemical enrichment structures of the multi-phase CGM.

- Cool clumps exhibit a $v_{\rm NT} \propto l^{0.3}$ velocity-size relation from ~ 1 pc to ~ 1 kpc, regardless of galaxy star formation history, consistent with subsonic turbulence driven by a global halo origin with dissipation time scales shorter than 100 Myr

- Combining spatially resolved 2D velocity maps from IFS emission-line observations with absorption spectroscopy provides critical insights into the origins of the clumps, through identifications of turbulence drivers, the energy injection scale and transfer rate based on the observed scale-dependent velocity variance over more than four decades in spatial scales.