The Galaxy-Intergalactic Medium Connection in Simulations with Resolved Stellar Feedback

Claude-André Faucher-Giguère
Northwestern University | CIERA
galaxies.northwestern.edu | fire.northwestern.edu

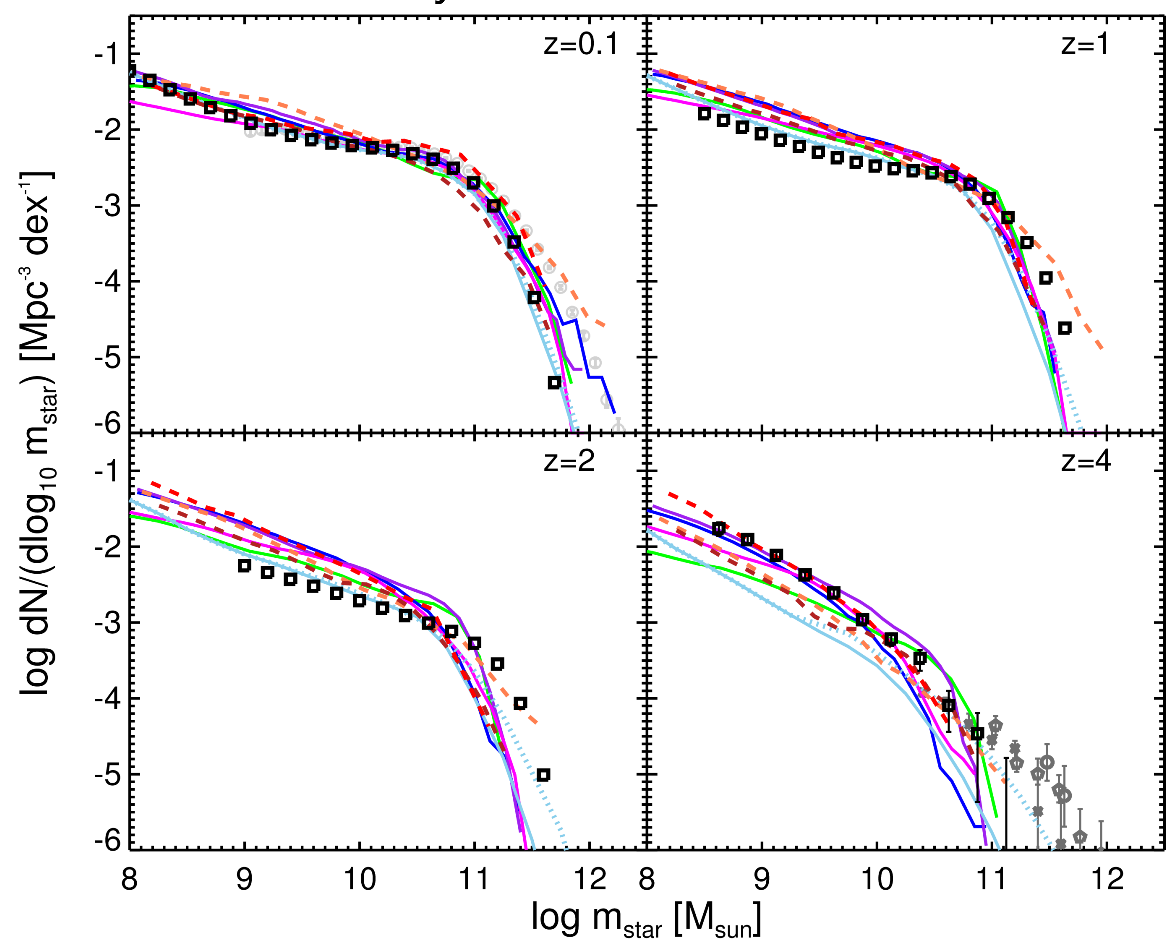
Collaborators: D. Kereš, P. Hopkins, E. Quataert, N. Murray,
A. Muratov, X. Ma, D. Anglés-Alcázar, R. Feldmann, N. Sravan, Z. Hafen

State-of-the-art cosmological models have broadly converged on first-order stellar predictions

- Both cosmo sims and semi-analytic models (SAMs)

- Feedback is key:
  - strong SF-driven winds
  - AGN at massive end

Galaxy stellar mass function



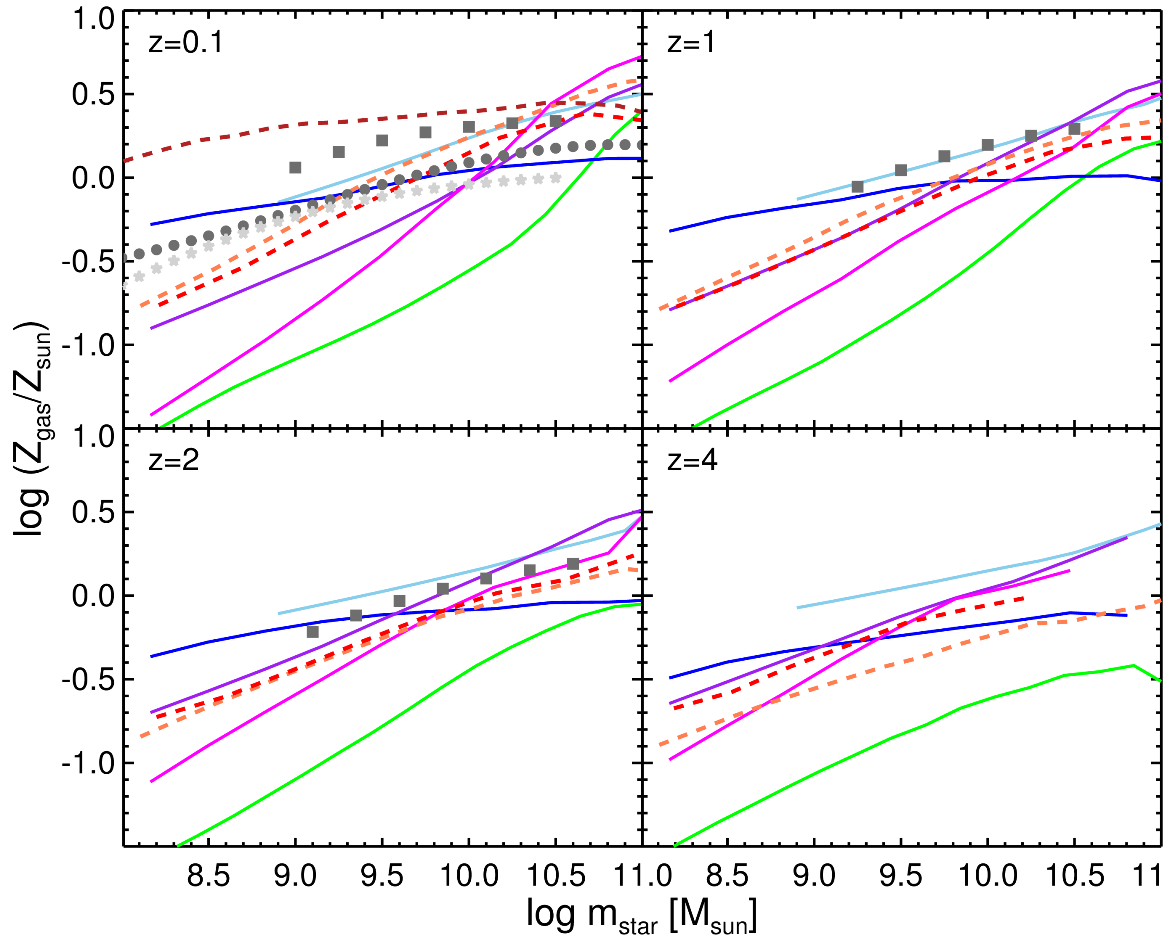
Solid: SAMs
Dashed: cosmo sims (**EAGLE**, **Illustris**, **Davé+**)

Somerville & Davé ARAA review

Models diverge strongly on their predictions for gas properties

- Models that match stellar galaxy properties agree neither with observations nor among themselves!
  - models are degenerate
  - gas can break degeneracies

Mass-metallicity relation

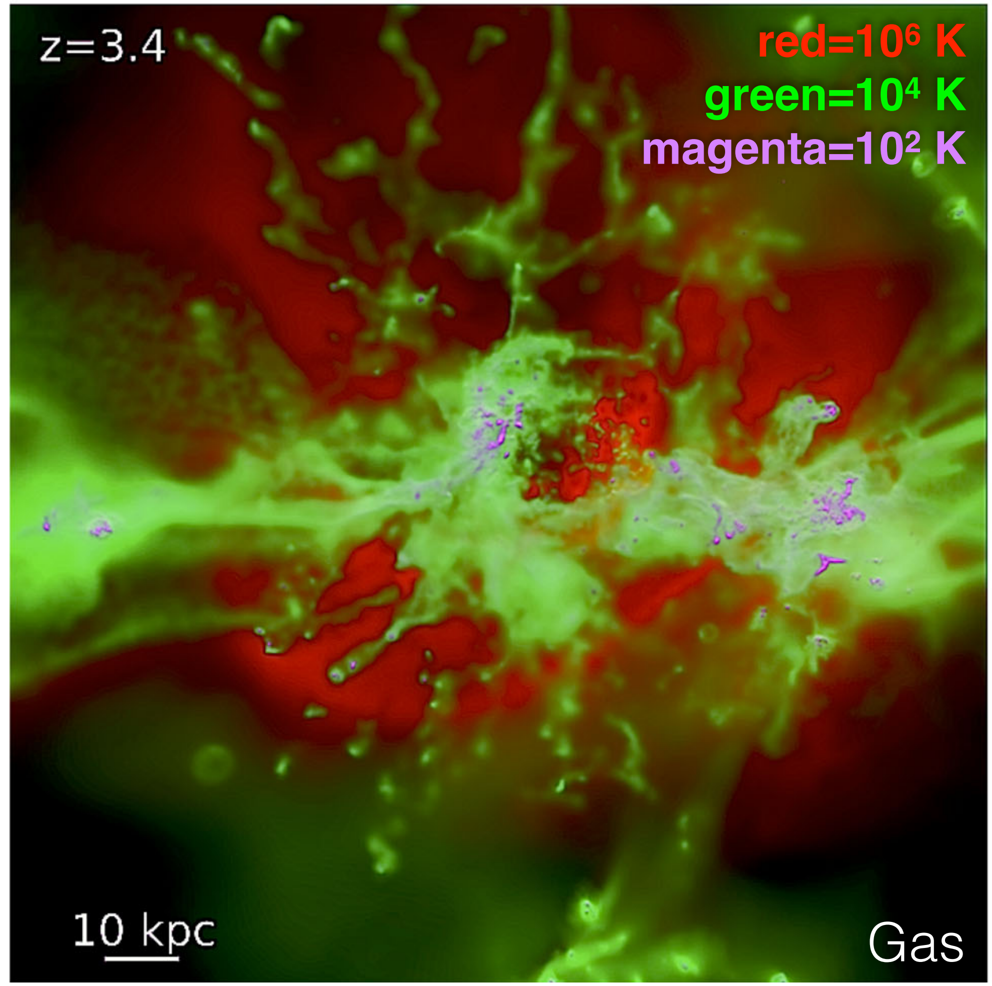


Solid: SAMs
Dashed: cosmo sims (**EAGLE**, **Illustris**, **Davé+**)

Somerville & Davé ARAA review

FIRE: Feedback in Realistic Environments

- Cosmological zoom-ins resolving GMCs
- Metal and molecular cooling to T~10 K; SF in mol., self-grav. gas
- Stellar feedback (SNe, photoion, stellar winds, rad. P) based on SB99
- No parameter tuning
  - K-S law, outflows, etc. emerge

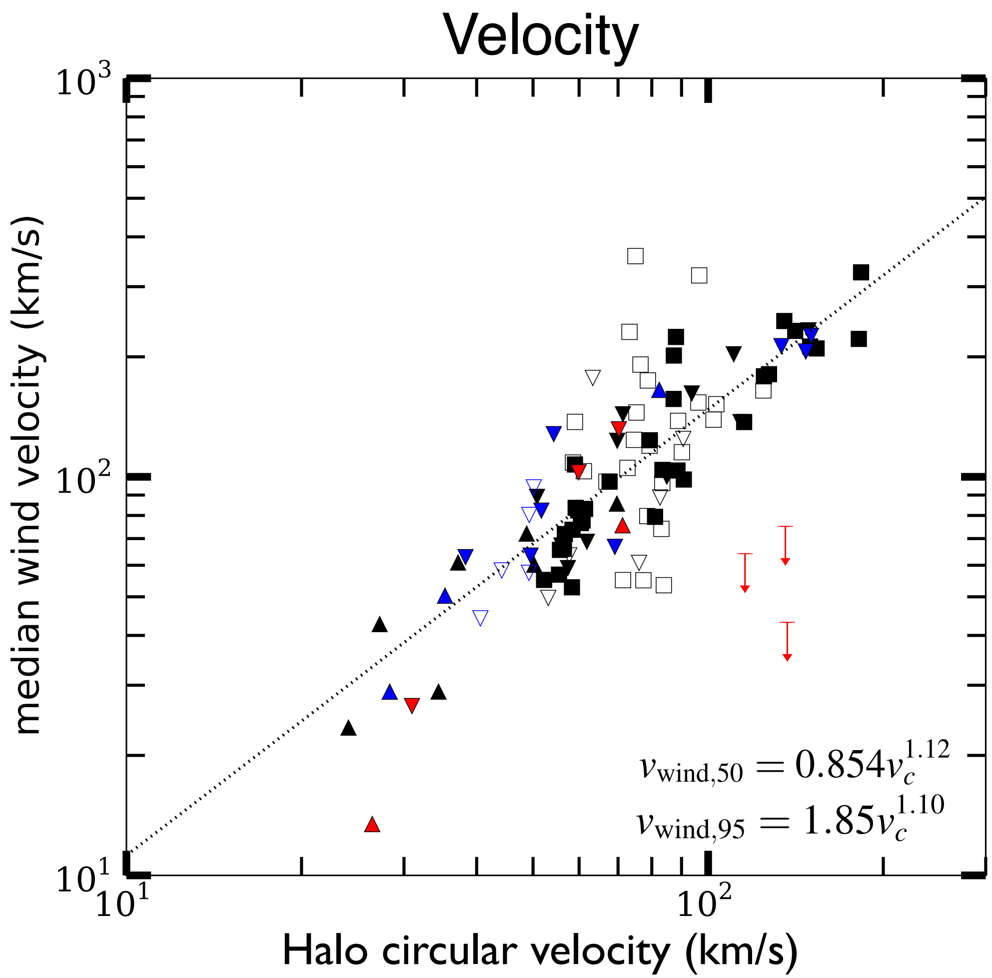


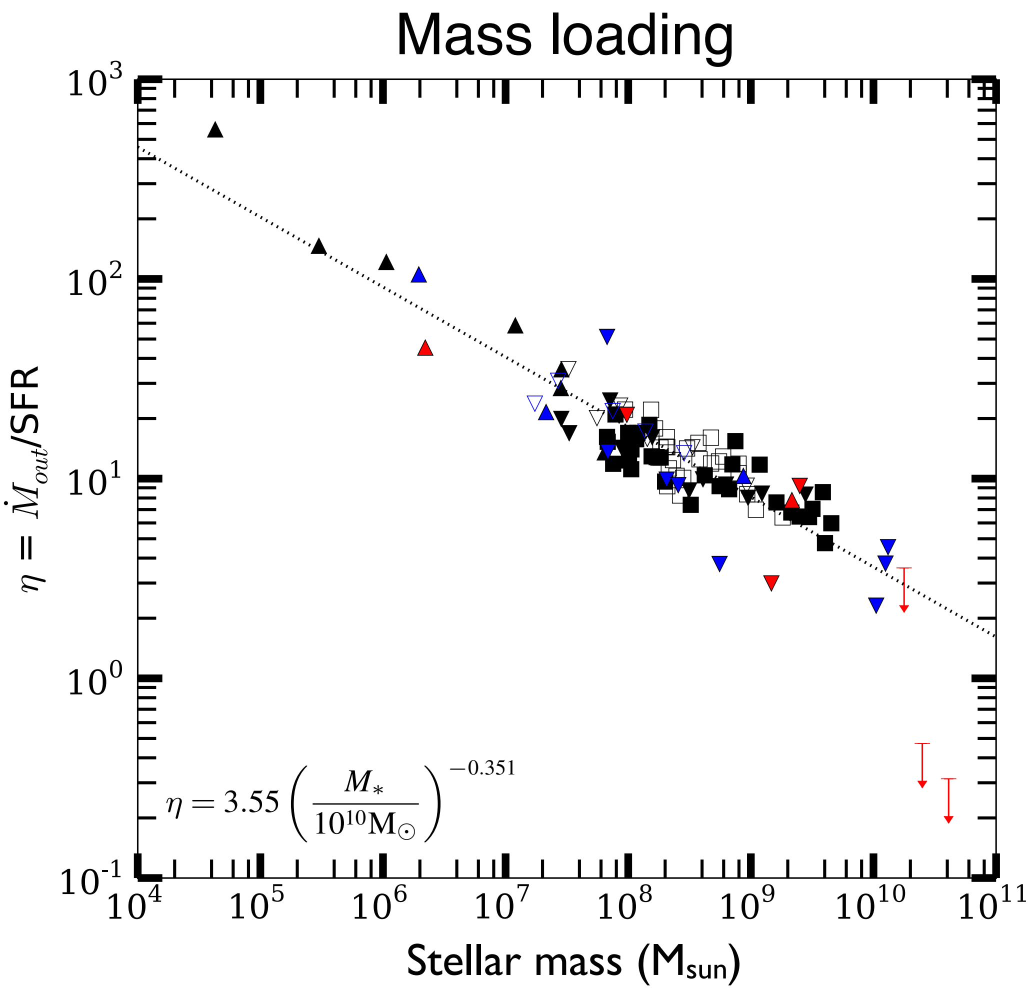
GIZMO P-SPH, $M_h(z=0)=10^{12}$ M_{sun}

$m_{gas}=7\times10^3$ M_{sun}, $\varepsilon_{gas}=10$ pc

w/ Hopkins, Kereš, Quataert + students, p'docs & collaborators

Galactic winds in FIRE

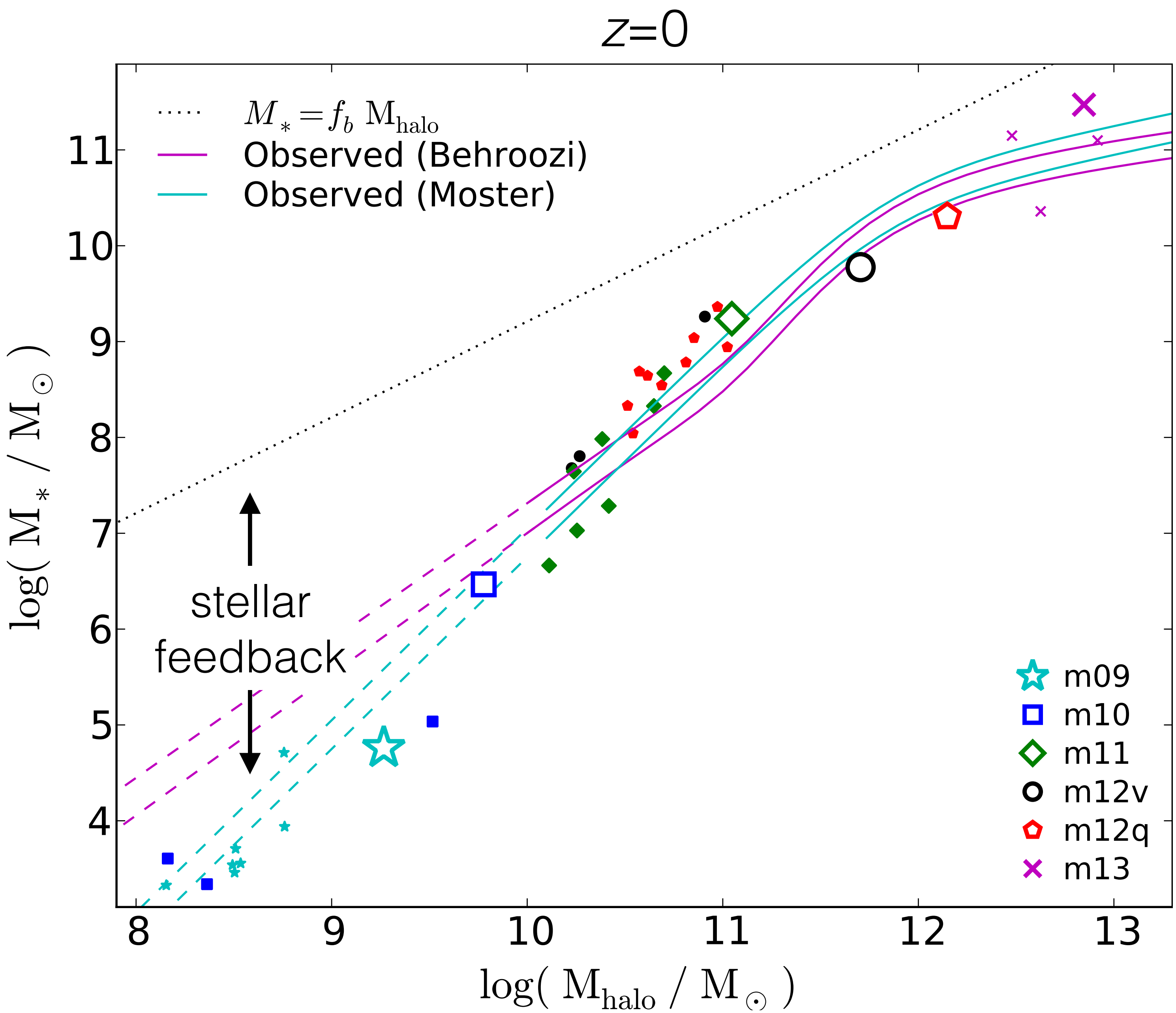




0<z<0.5, 0.5<z<2, 2<z<4

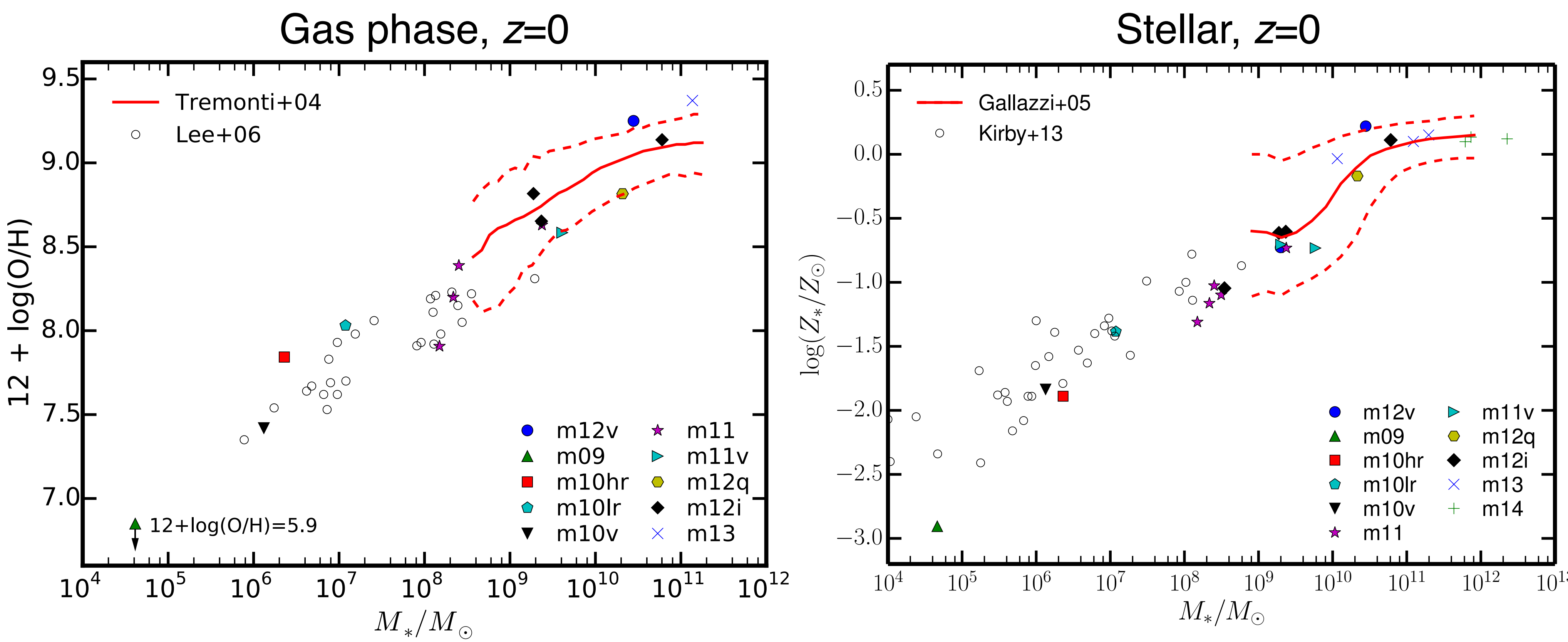
Muratov, Kereš, CAFG+ (arXiv:1501.03155)

Galaxy stellar masses in FIRE



Hopkins, Kereš, Oñorbe, CAFG+14

Mass-metallicity in FIRE



Ma, Hopkins, CAFG+ (arXiv:1504.02097)

Halos are approximately closed boxes

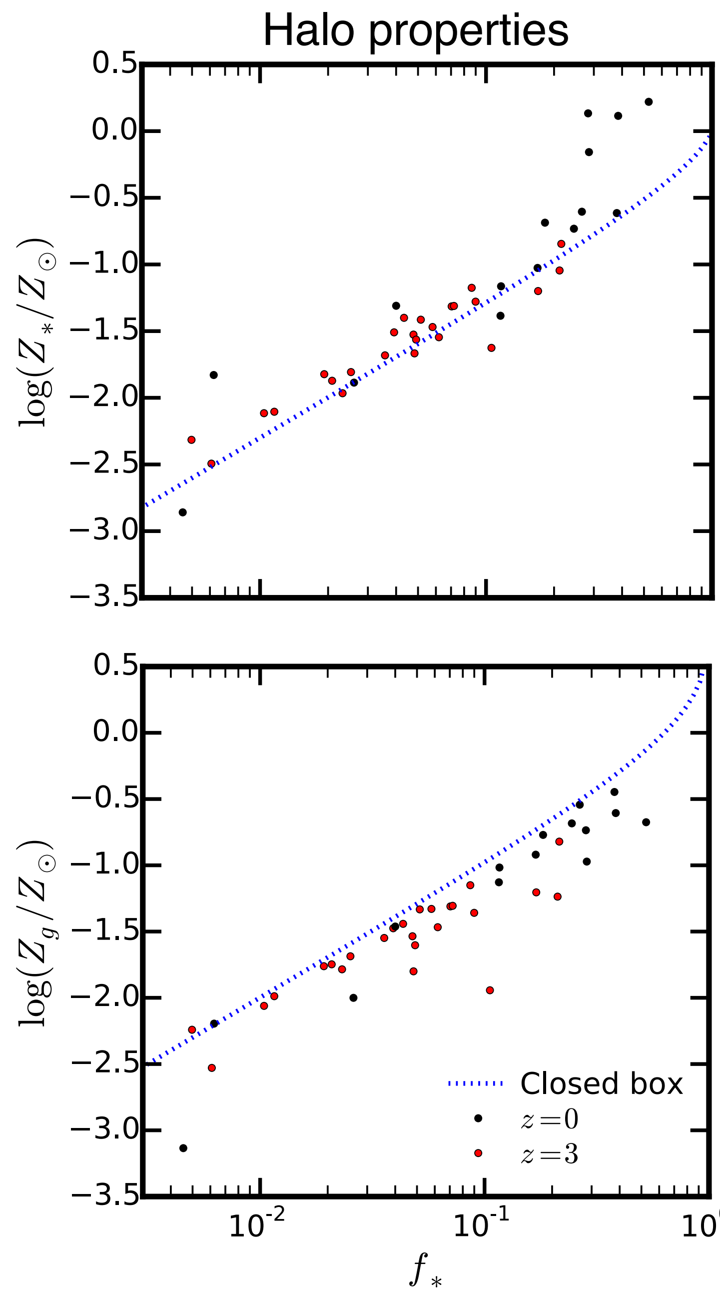
- ***Halo* MZR**:

$$Z_* = y\left[\frac{1-f_*}{f_*}\ln(1-f_*)+1\right]$$
$$Z_g = y\ \ln(1-f_*)$$

y=metal yield

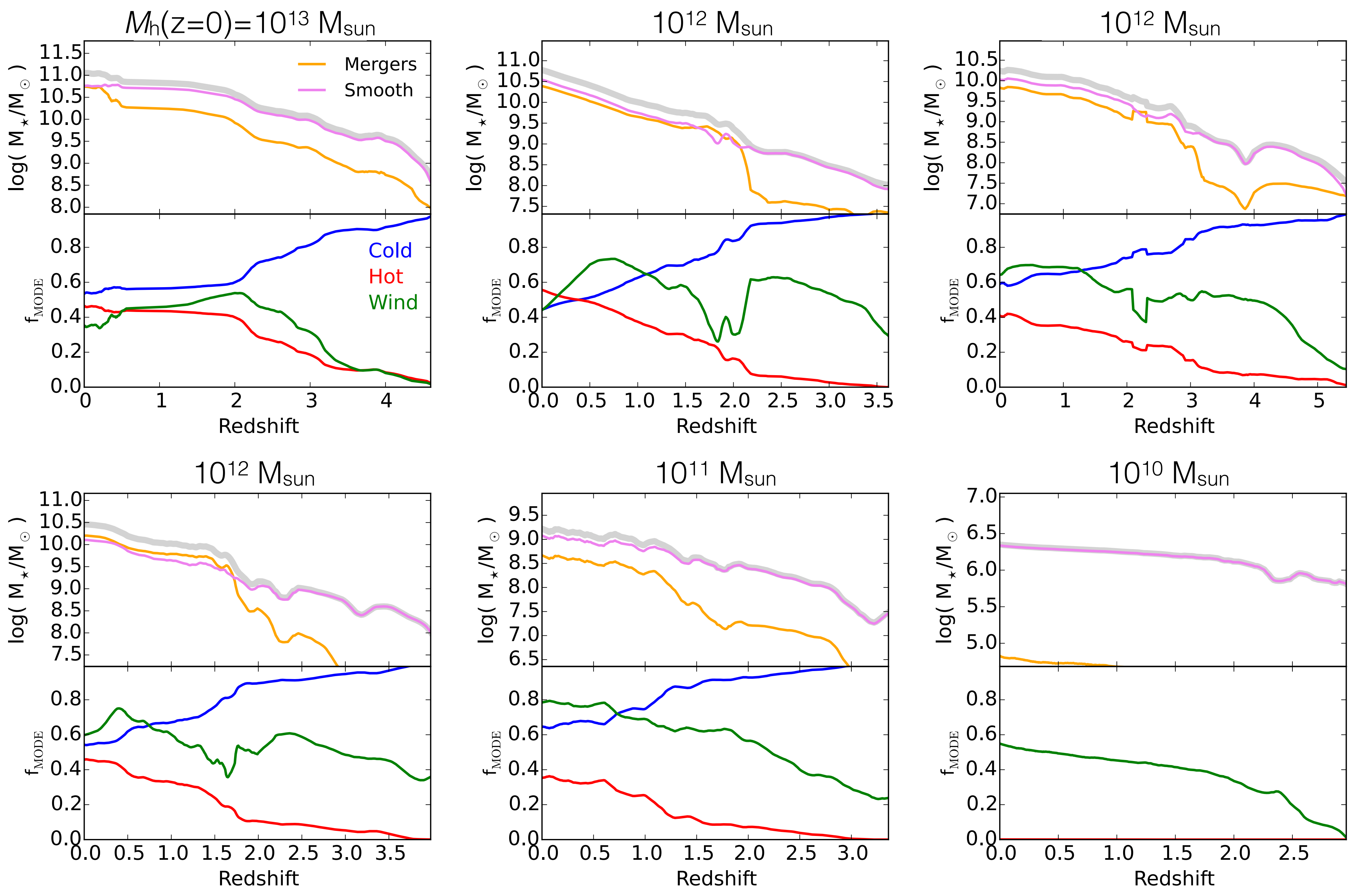
$f_\bigstar = M_\bigstar/(M_\bigstar+M_g)$

- ***Observed* (galaxy) MZR** sensitive to how gas is mixed in ISM and CGM



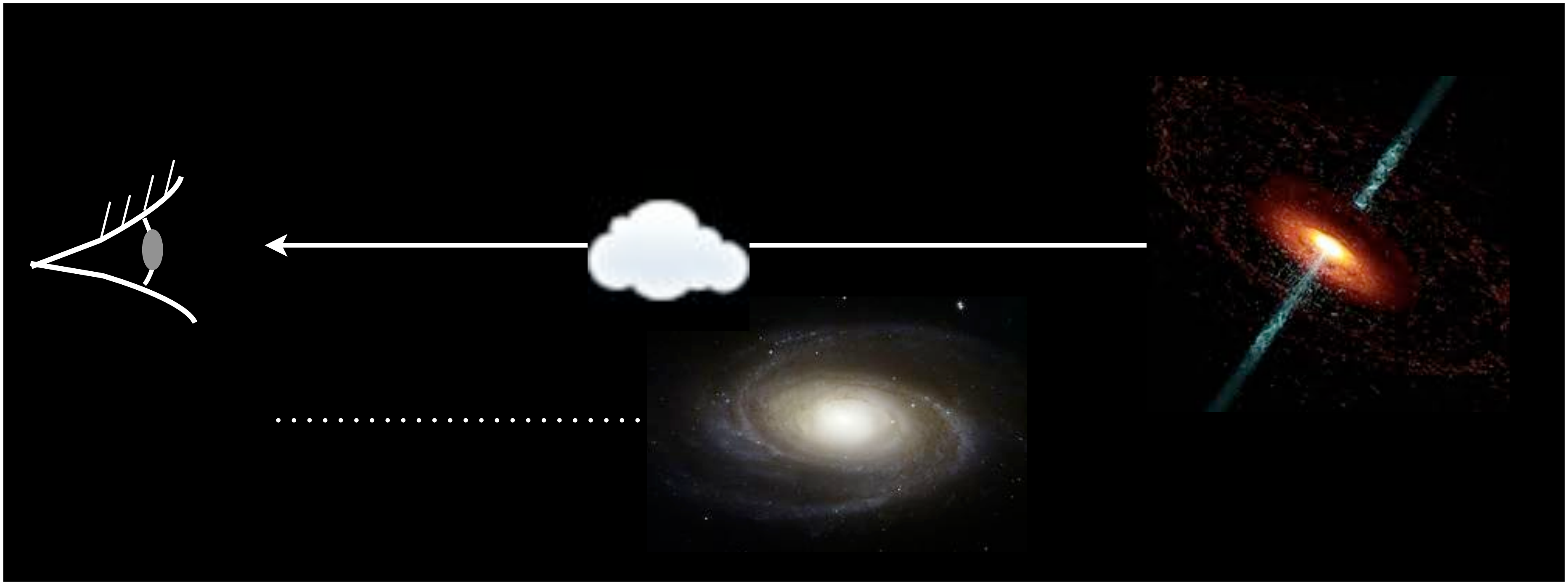
Ma, Hopkins, CAFG+ (arXiv:1504.02097)

Most stars form from smoothy accreted, wind-recycled gas



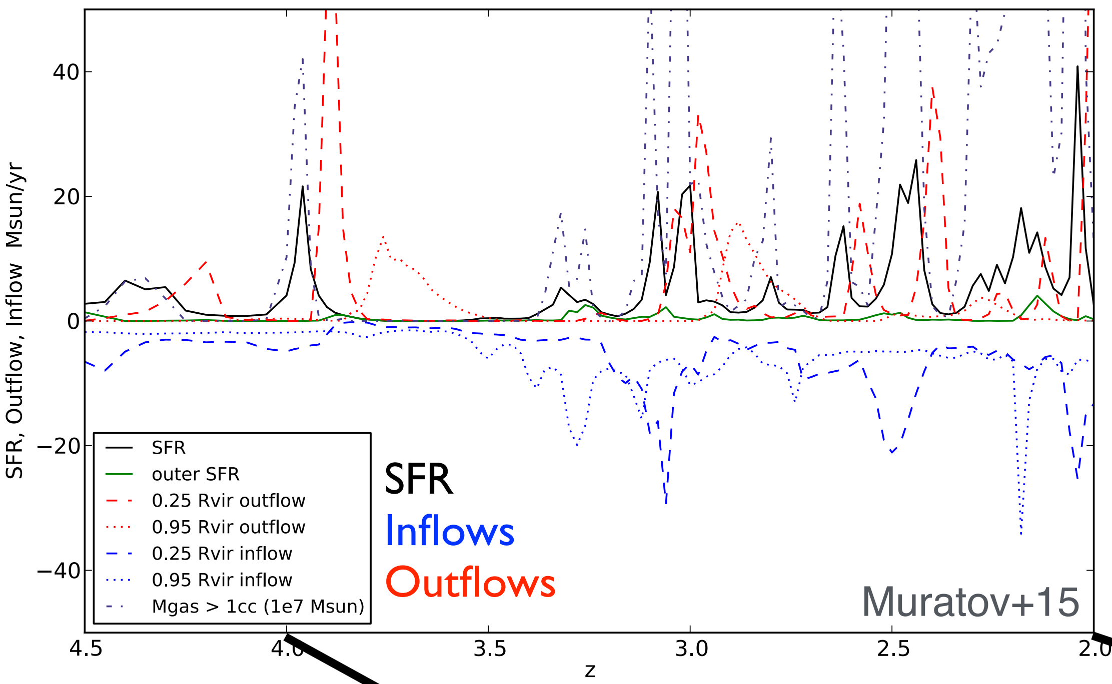
Anglés-Alcázar, CAFG+, in prep. (see also Oppenheimer+10)

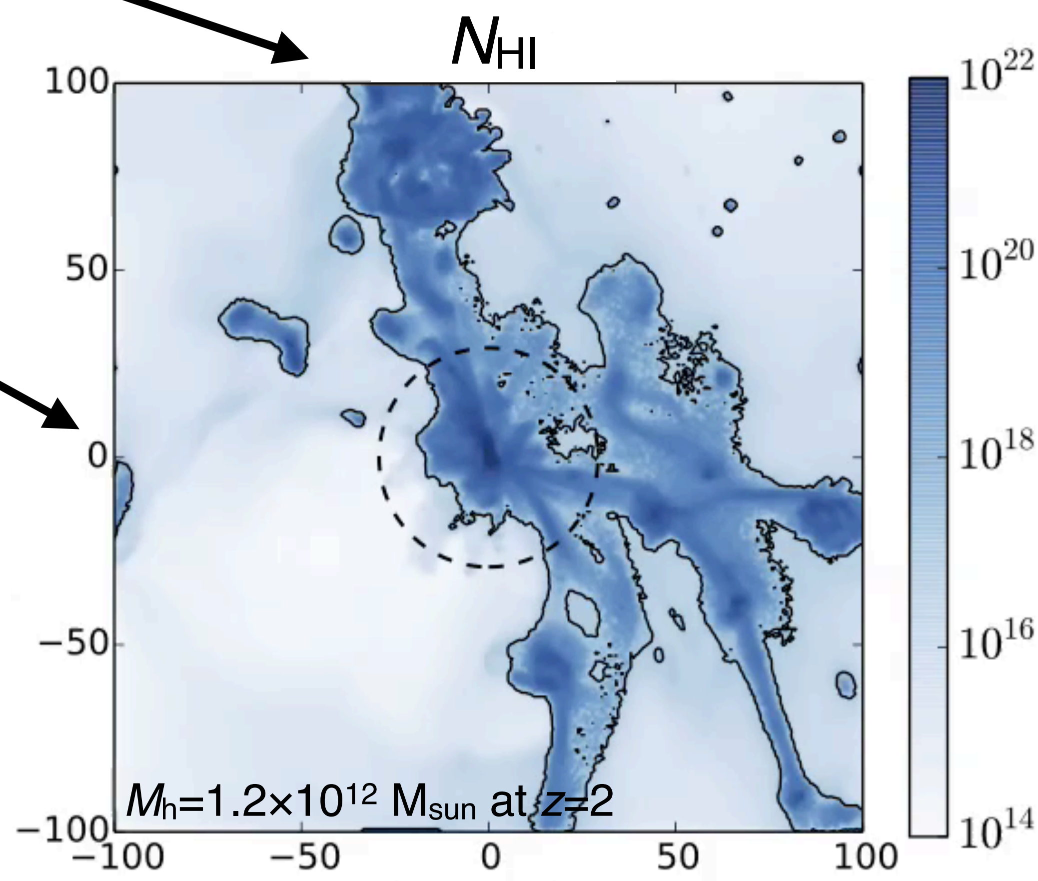
Probing inflows/outflows with absorption lines



- At z~2-3 with ground-based telescopes, z<1 with HST/COS
- Foreground object can be galaxy (e.g., Steidel+, Rudie+, Tumlinson+, Chen+, Bouché+), DLA (e.g., Rubin+), QSO (e.g., Prochaska+), …

Inflow-SF-outflow cycles → time variable CGM





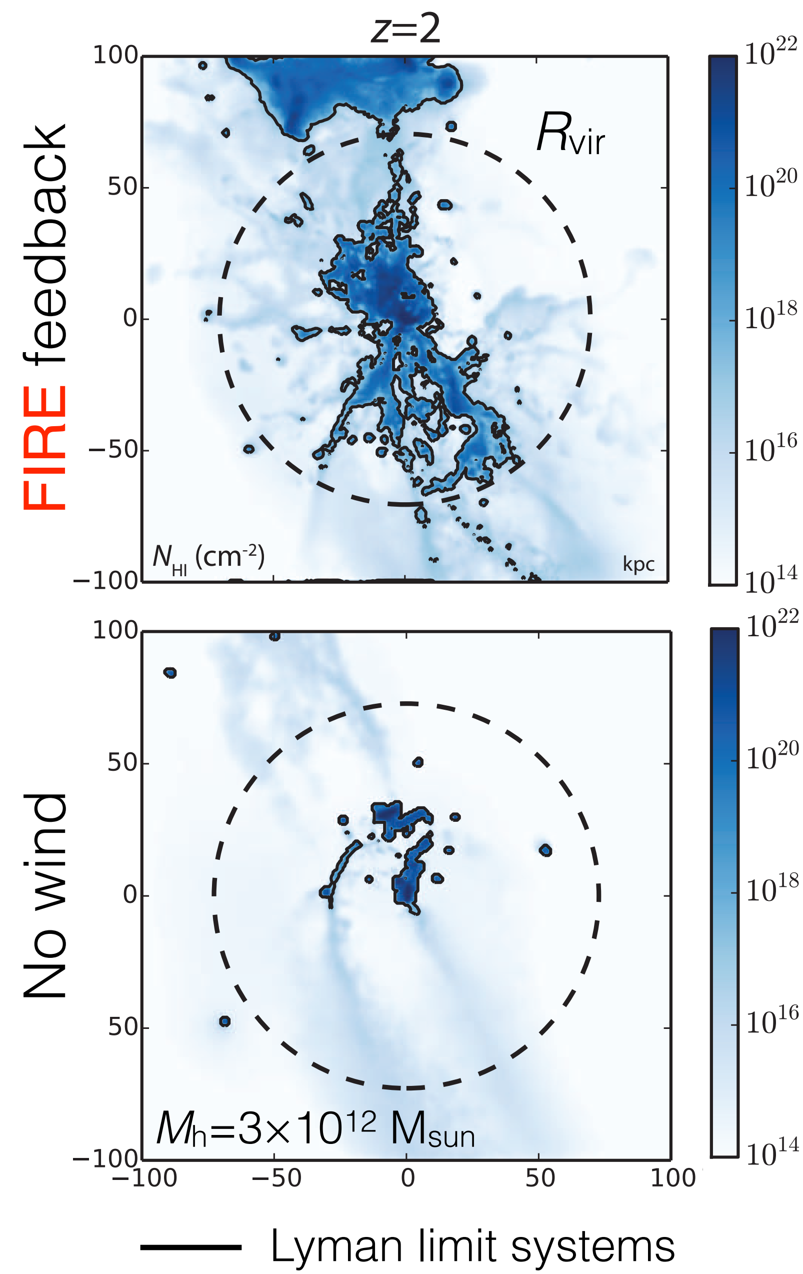
⇒ statistical samples critical for robust comparison

Lyman limit systems (solid contours) trace inflows+outflows

CAFG+15

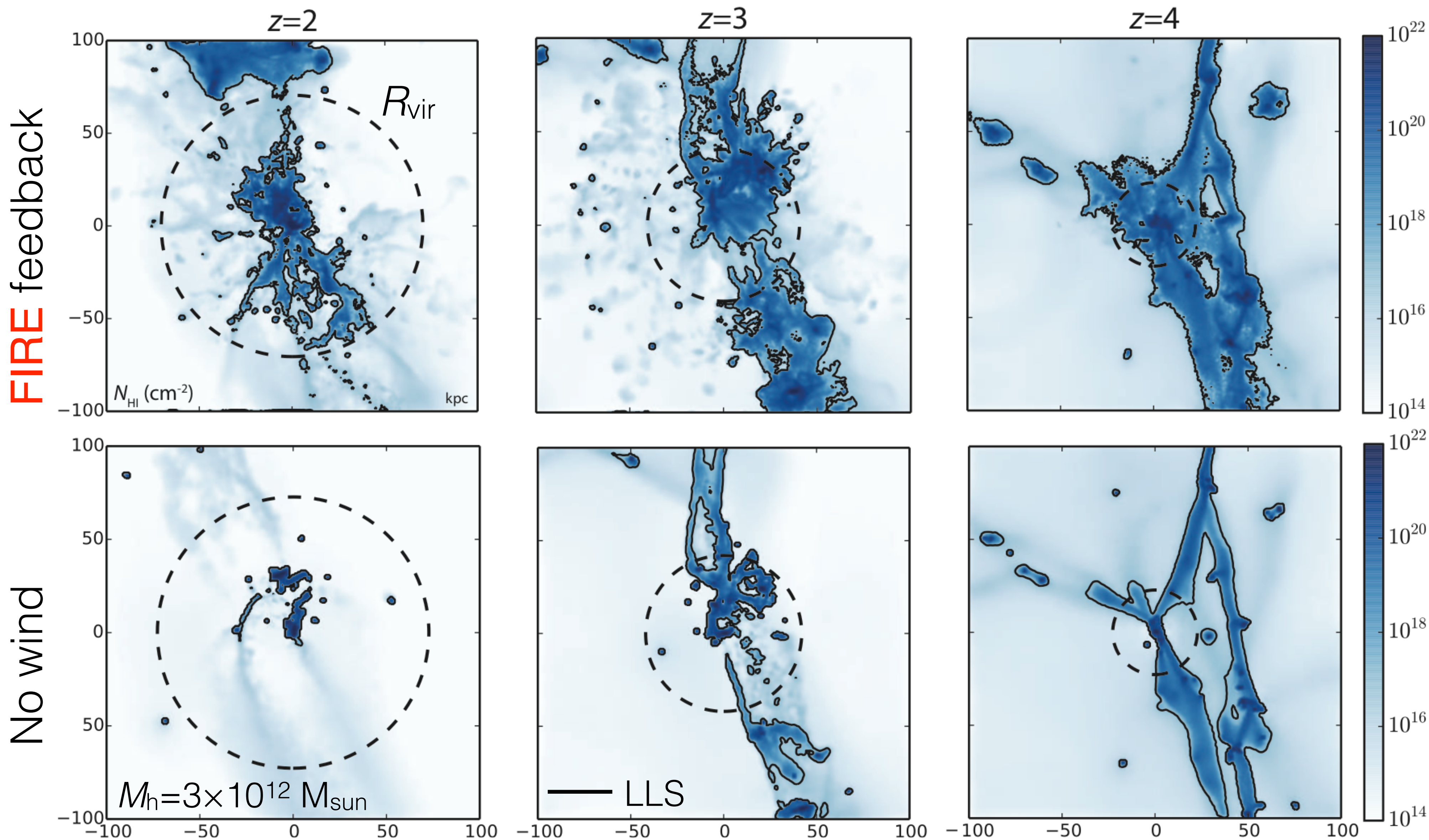
The CGM in FIRE: HI in z=2-4 halos

- 16 $M_h(z=2)\sim10^9$-10^{13} M_{sun} halos
  - 12 LBG halos: $\varepsilon\sim10$ pc, $m_b\sim6\times10^4$ M_{sun}
  - better for lower M_h, worse for highest M_h
  - stellar feedback only
- RT to compute covering fractions within R_{vir}, 100 kpc
- 100 time slices from z=4→2



CAFG+15

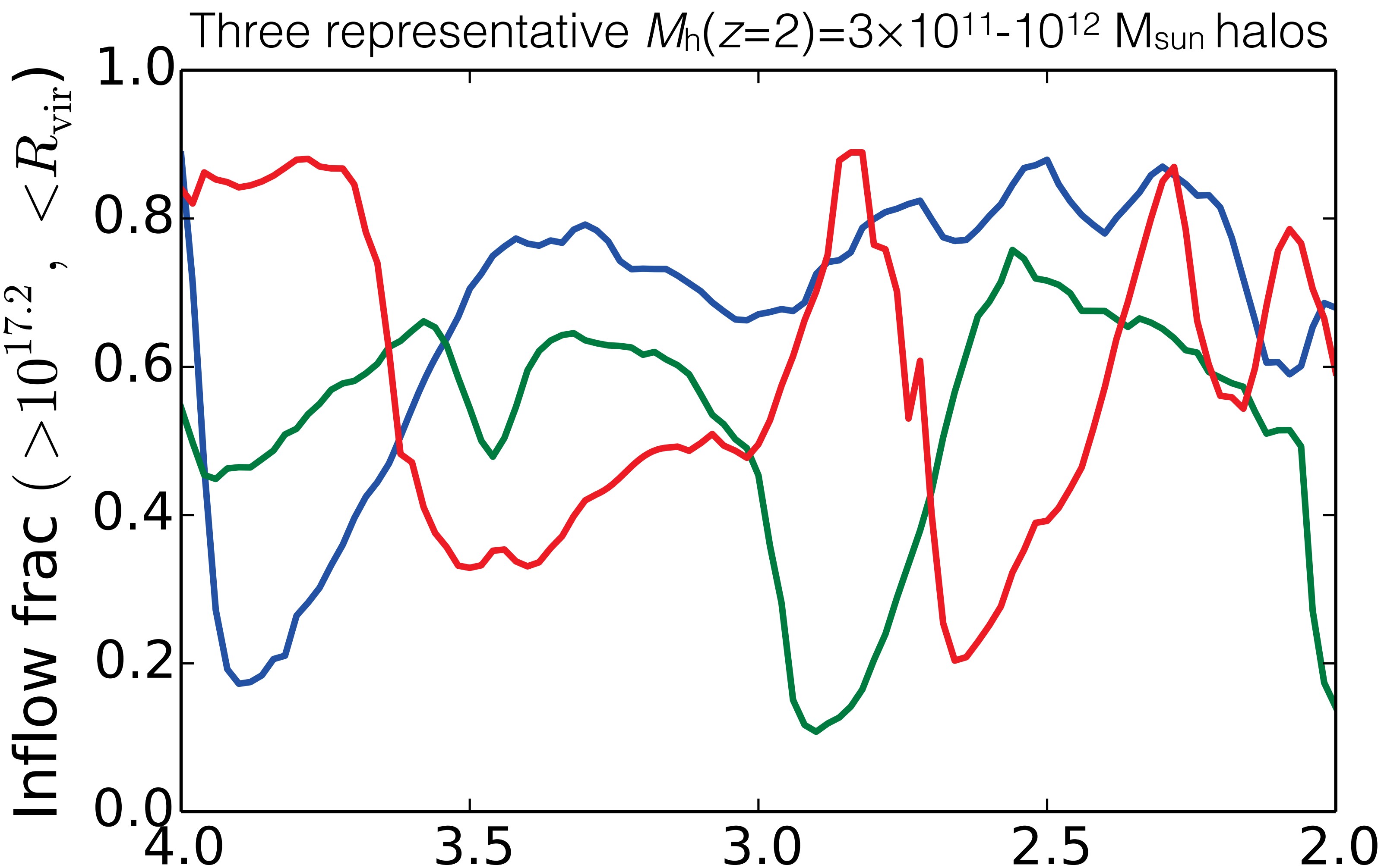
Galactic winds increase cool gas covering fractions



direct cool gas ejection + interaction with infalling filaments

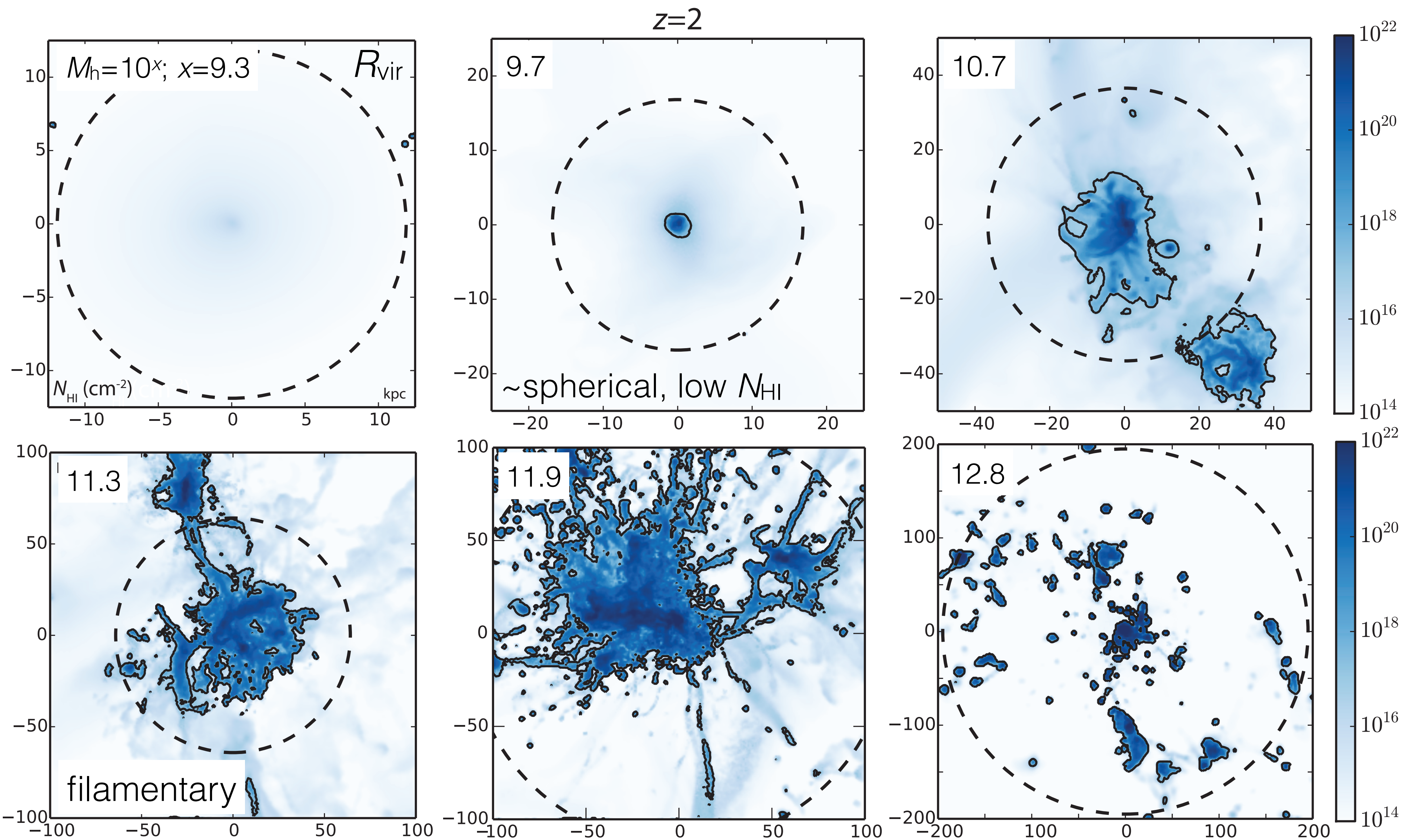
CAFG+15

Strongly time-variable, ~50-50 inflow-outflow contributions to covering fractions



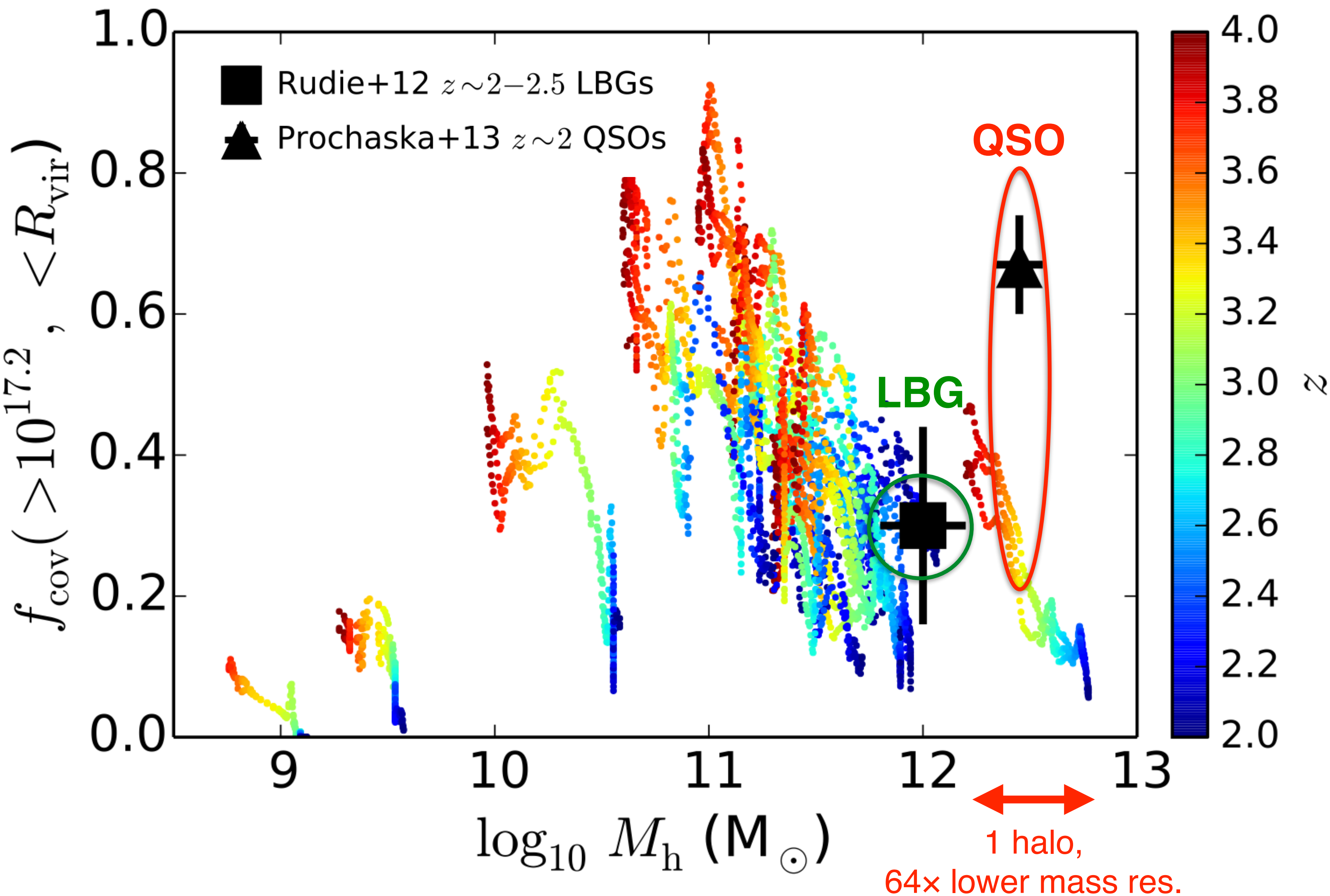
CAFG+15

Lyman limit systems peak in massive halos



CAFG+15

Lyman limit systems vs. halo mass and time

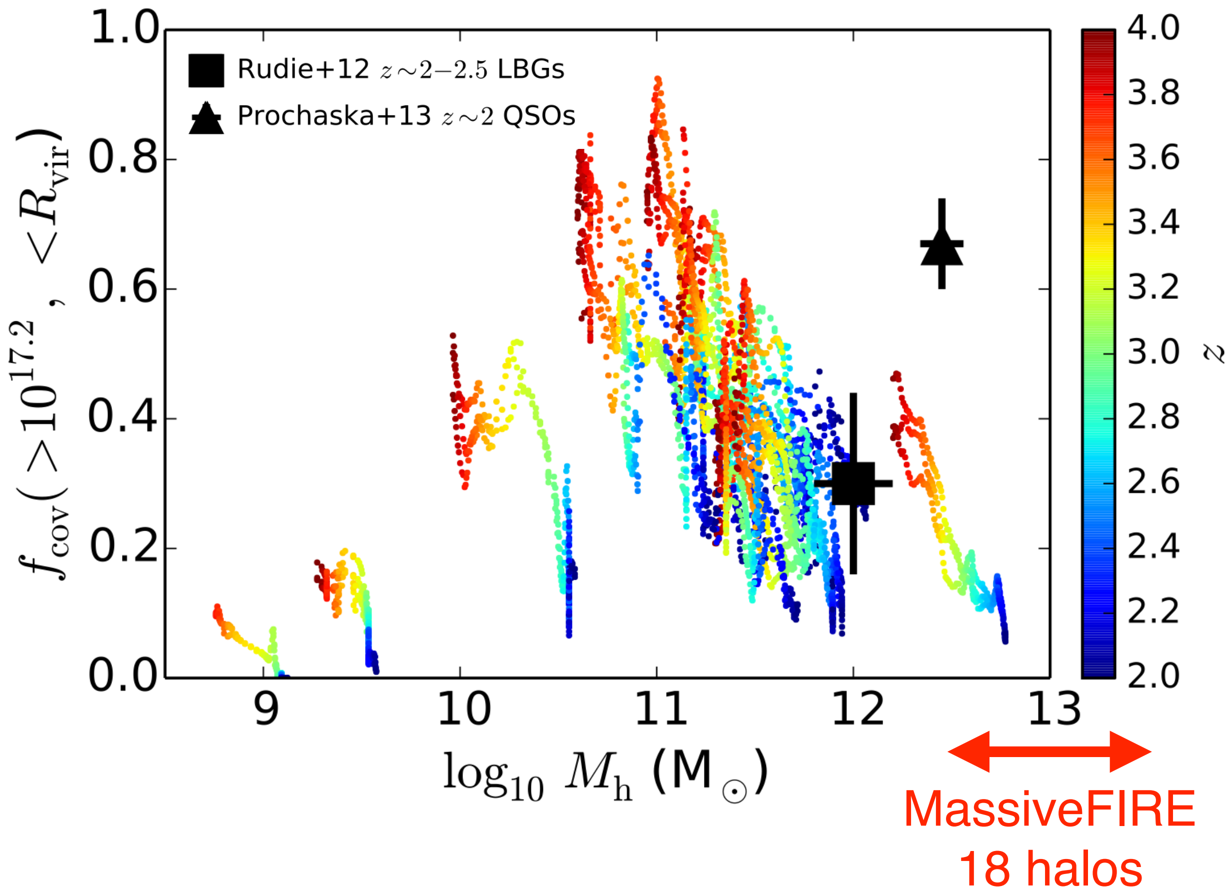


3 orthogonal sky projections for each time slice

CAFG+15 (see also Fumagalli+14, cf. Rahmati+15)

Preliminary results from MassiveFIRE

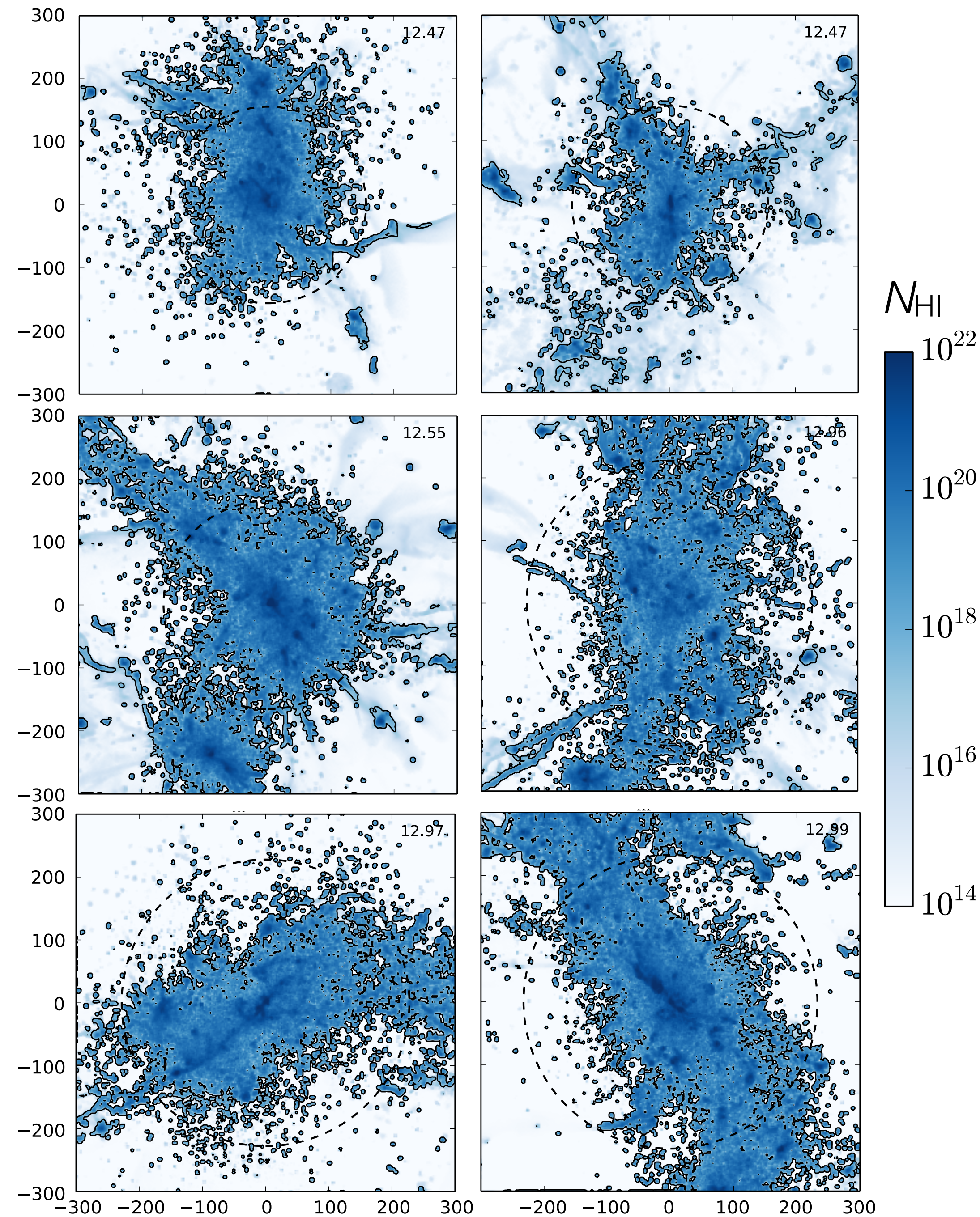
- 18 $M_h(z=2)=2\times10^{12}$-10^{13} M_{sun} halos
  - fiducial res.: ε=10 pc, $m_b=3\times10^4$ M_{sun}
  - statistical, high-res stellar feedback-only comparison sample for QSO halos
  - later: with BHs (Anglés-Alcázar+, in prep.)



Feldmann+, in prep.; CAFG+, in prep.

Large covering fractions in MassiveFIRE halos at high res

- $f_{\rm cov}$(LLS, $<R_{\rm vir}$)=0.5±0.1
  - close to Prochaska+13's $f_{\rm cov}$(LLS, $<R_{\rm vir}$)=$0.64^{+0.06}_{-0.07}$ for QSO halos
- Stellar feedback puffs up inflowing filaments
- In luminous QSOs, wind energetics » SF (e.g., Feruglio+10, Rupke & Veilleux 11, Cicone+14), so QSO feedback could also play a role in QSO halos



Note: Our LBG $f_{\rm cov}$ were convergence tested in CAFG+15.

CAFG+, in prep.

Summary

- The FIRE simulations
  - ➡ generate strong galactic winds from small-scale explicit feedback
  - ➡ explain:
    - $M_\bigstar$-M_h below L^*
    - stellar and gas phase metallicity relations
    - HI in LBG halos
  - ➡ indicate:
    - roughly correct overall stellar feedback efficiency
    - reasonably accurate cosmological gas / metal transport and mixing
- Most z=0 stellar mass forms from wind-recycled smooth IGM accretion
- Most massive halos ($M_\mathrm{h} \gtrsim 10^{12}$ M_sun) appear more sensitive to resolution, likely due to multiphase interactions in hot halos
  - ➡ stellar feedback puffing up inflowing filaments helps explain large LLS coverings in QSO halos