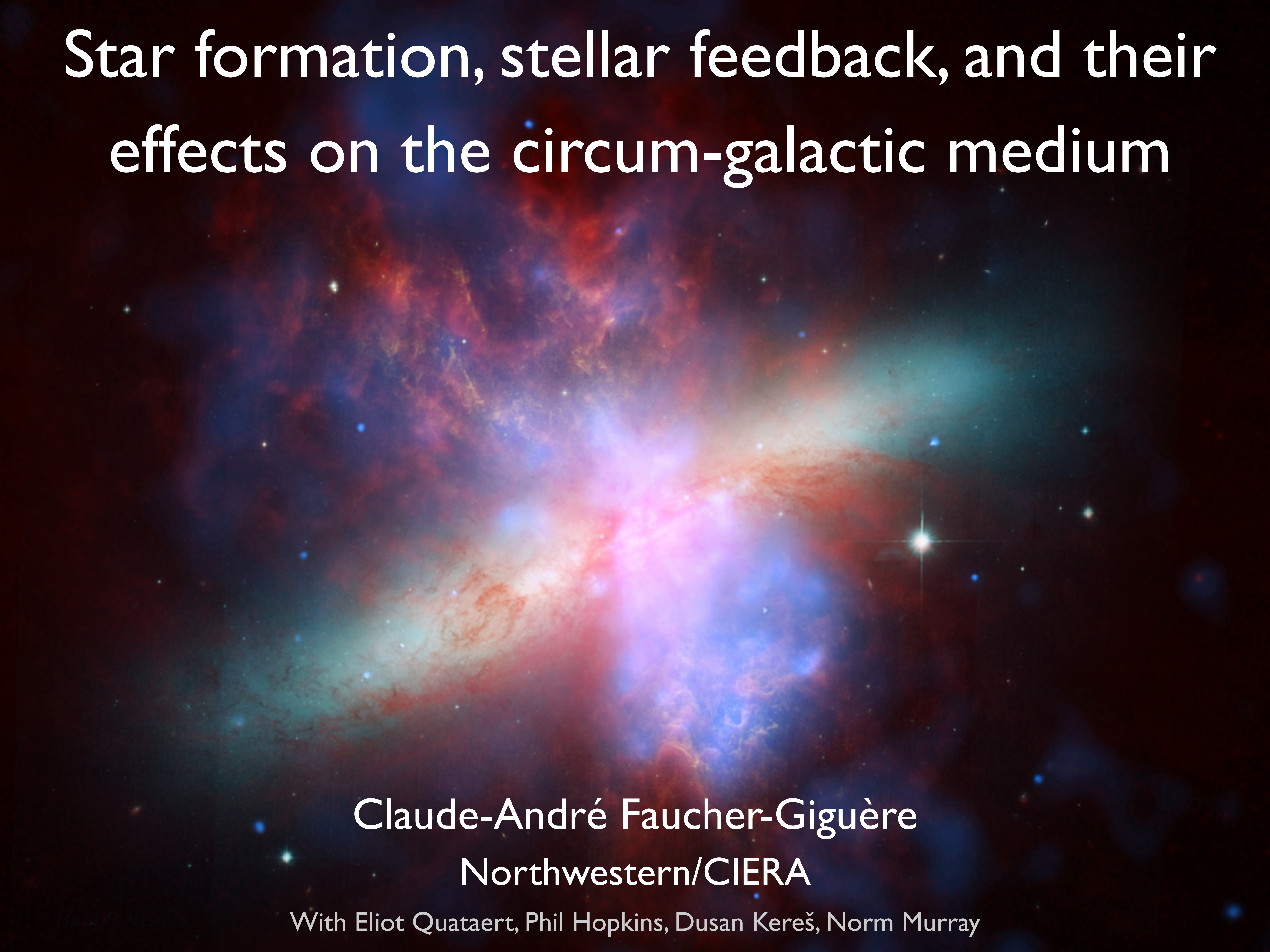

Star formation, stellar feedback, and their effects on the circum-galactic medium

Claude-André Faucher-Giguère
Northwestern/CIERA
With Eliot Quataert, Phil Hopkins, Dusan Kereš, Norm Murray

Outline

- **Regulation of star formation within galaxies**
  - ➡ feedback origin of the galaxy-averaged $\dot{\Sigma}_{\star} - \Sigma_{\rm g}$ relation (K-S law)
  - ➡ test with dependence of SF efficiency on gas mass fraction
  - ➡ GMC formation as rate limiting step
- Circum-galactic medium of FIRE galaxies
  - ➡ HI around z~2-3 Lyman break galaxies
  - ➡ Metallicity bi-modality of Lyman limit systems at z<1

On what scale is SF regulated (inside galaxies)?

Star-forming clouds

"Supersonic turbulence"
universal ϵ_{ff}~0.01 models

Krumholz & McKee 05,
Krumholz, Dekel & McKee 12, Federrath 13, …

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Galaxy-scale balance

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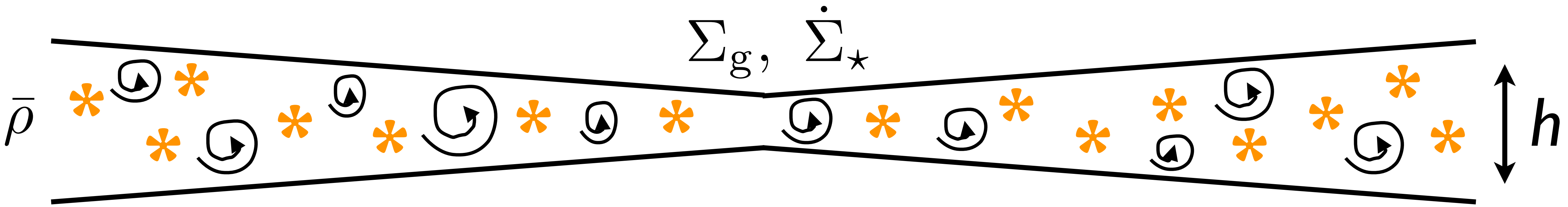
"Feedback-regulated" models

Thompson, Quataert & Murray 05,
Ostriker & Shetty 11,
CAFG, Quataert & Hopkins 13, …

SF regulation via global hydrostatic balance



$P_\star/m_\star = \text{mom./stellar mass}$ $\qquad$ $v_{\rm turb} = \text{turbulent vel.}$

Thompson, Quataert & Murray 2005, Ostriker & Shetty 2011; CAFG, Quataert, & Hopkins 13

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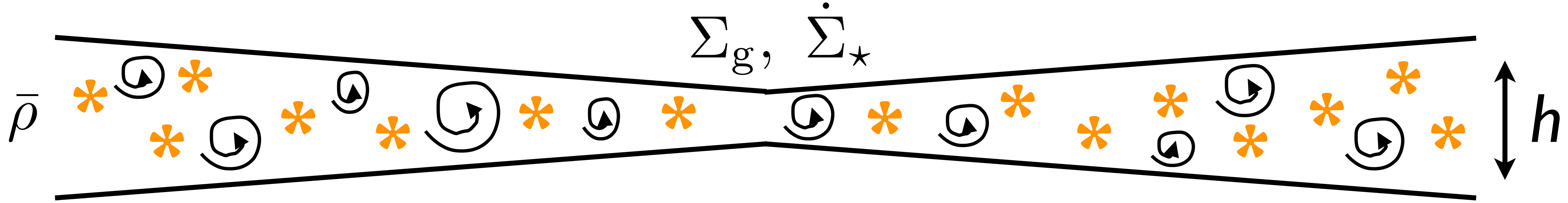

$P_\star/m_\star = \text{mom./stellar mass}$ $\qquad$ $v_{\rm turb} = \text{turbulent vel.}$

$$p_{\rm turb} \approx \bar{\rho} v_{\rm turb}^2 \sim \dot{\Sigma}_\star \left(\frac{P_\star}{m_\star}\right)$$

$$p_{\rm grav} \sim G\Sigma_{\rm g}^2$$

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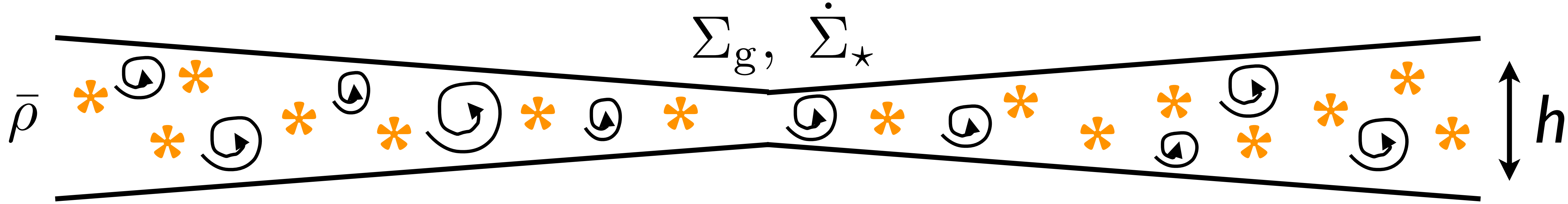

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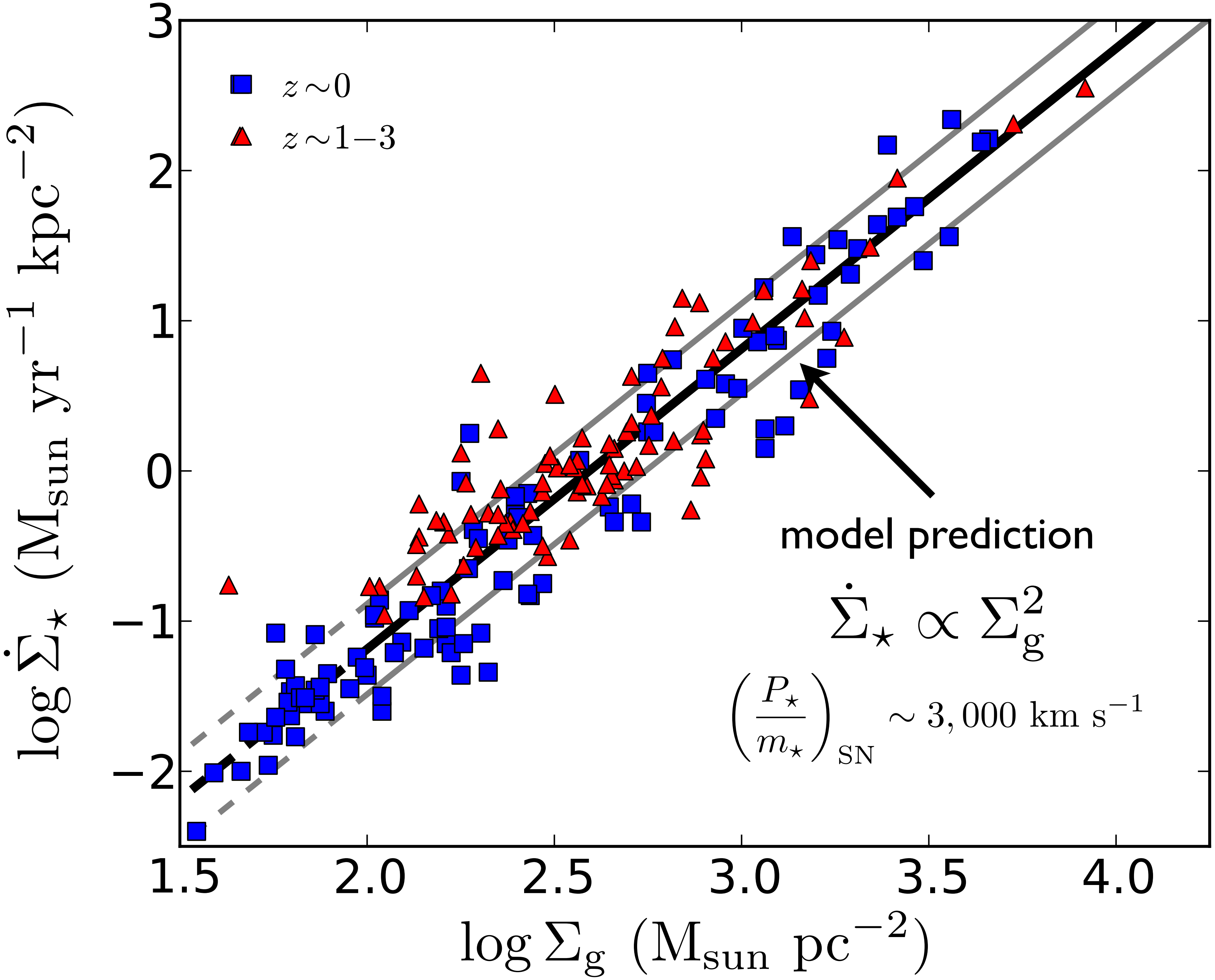
$$p_{\rm turb} = p_{\rm grav} \Rightarrow \boxed{\dot{\Sigma}_\star \sim \frac{G}{P_\star/m_\star}\Sigma_g^2}$$

Thompson, Quataert & Murray 2005, Ostriker & Shetty 2011; CAFG, Quataert, & Hopkins 13

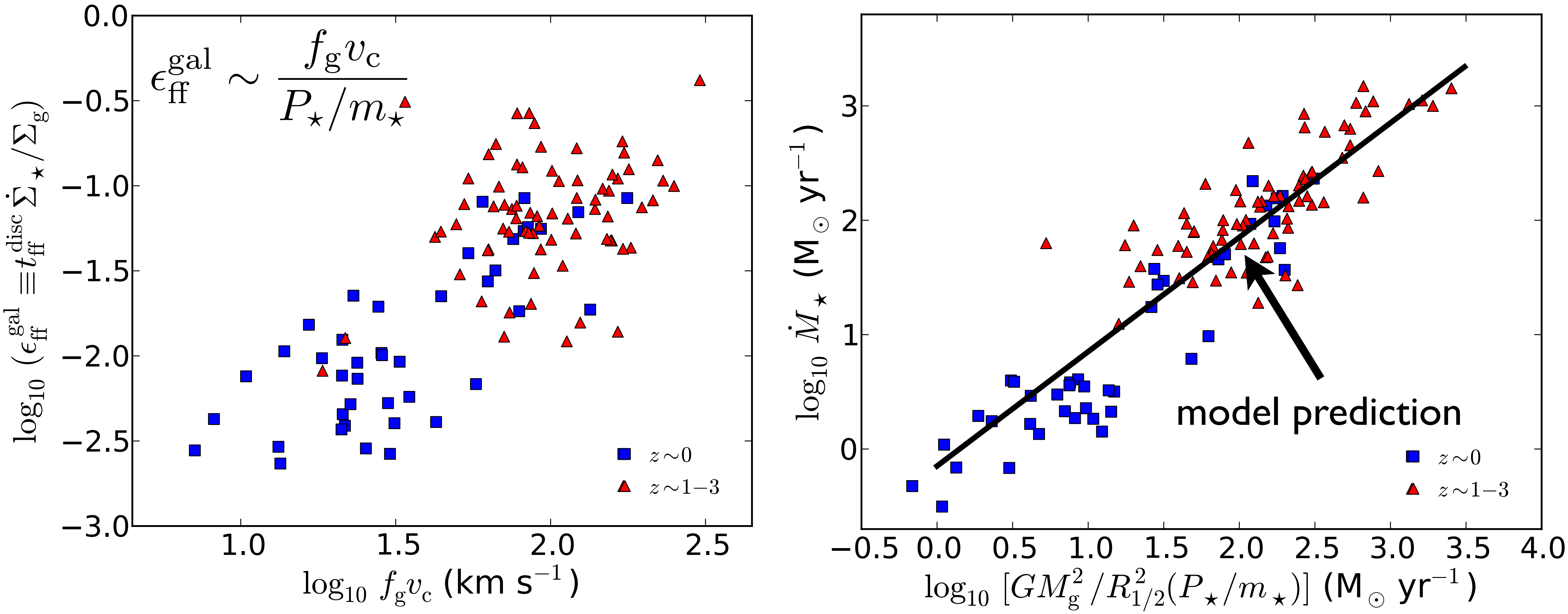
Global hydrostatic balance explains high-Σ_g K-S law



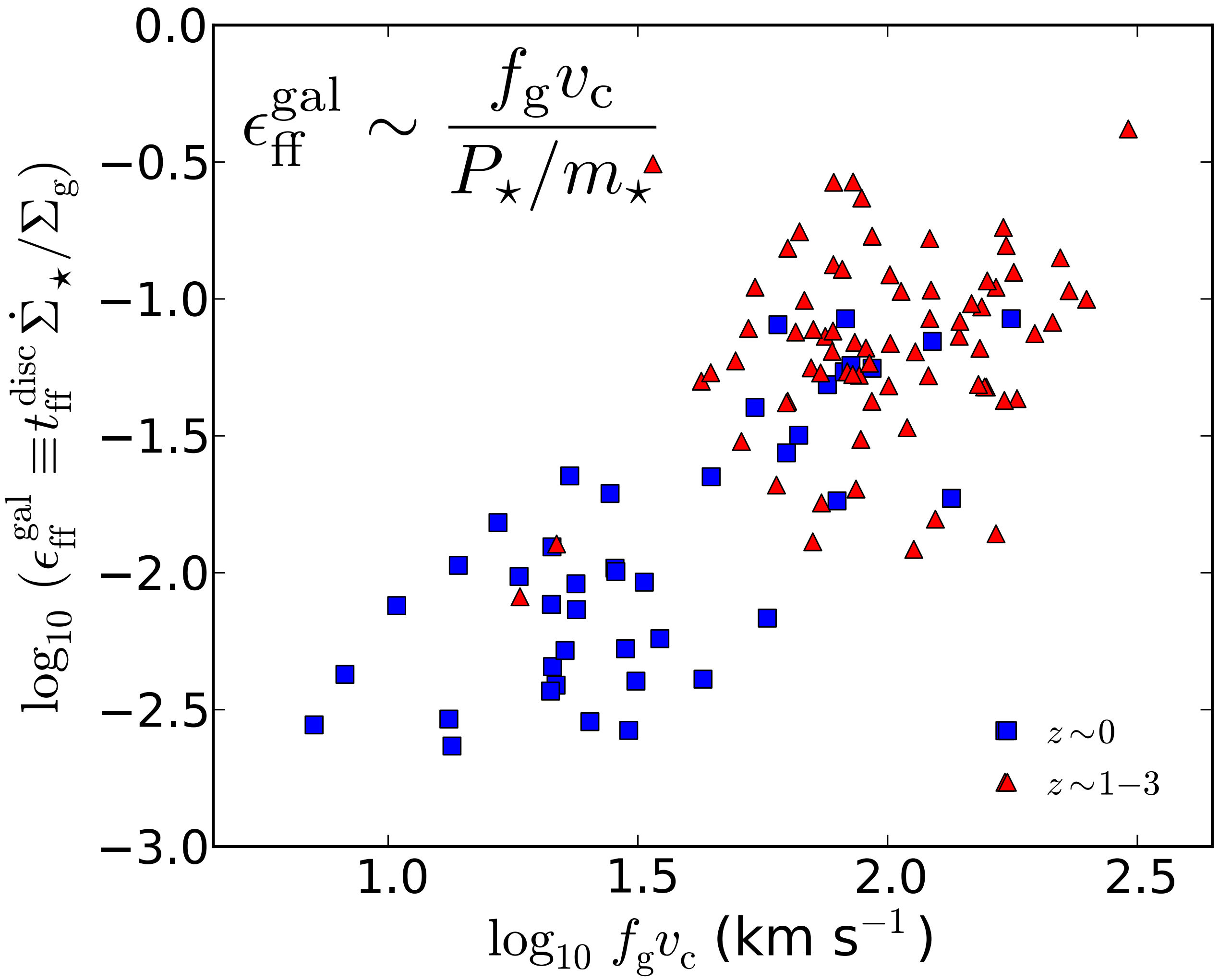
Observations from Genzel+10, Tacconi+13;
Continuous X_{CO} from Ostriker & Shetty 11, Narayanan+12

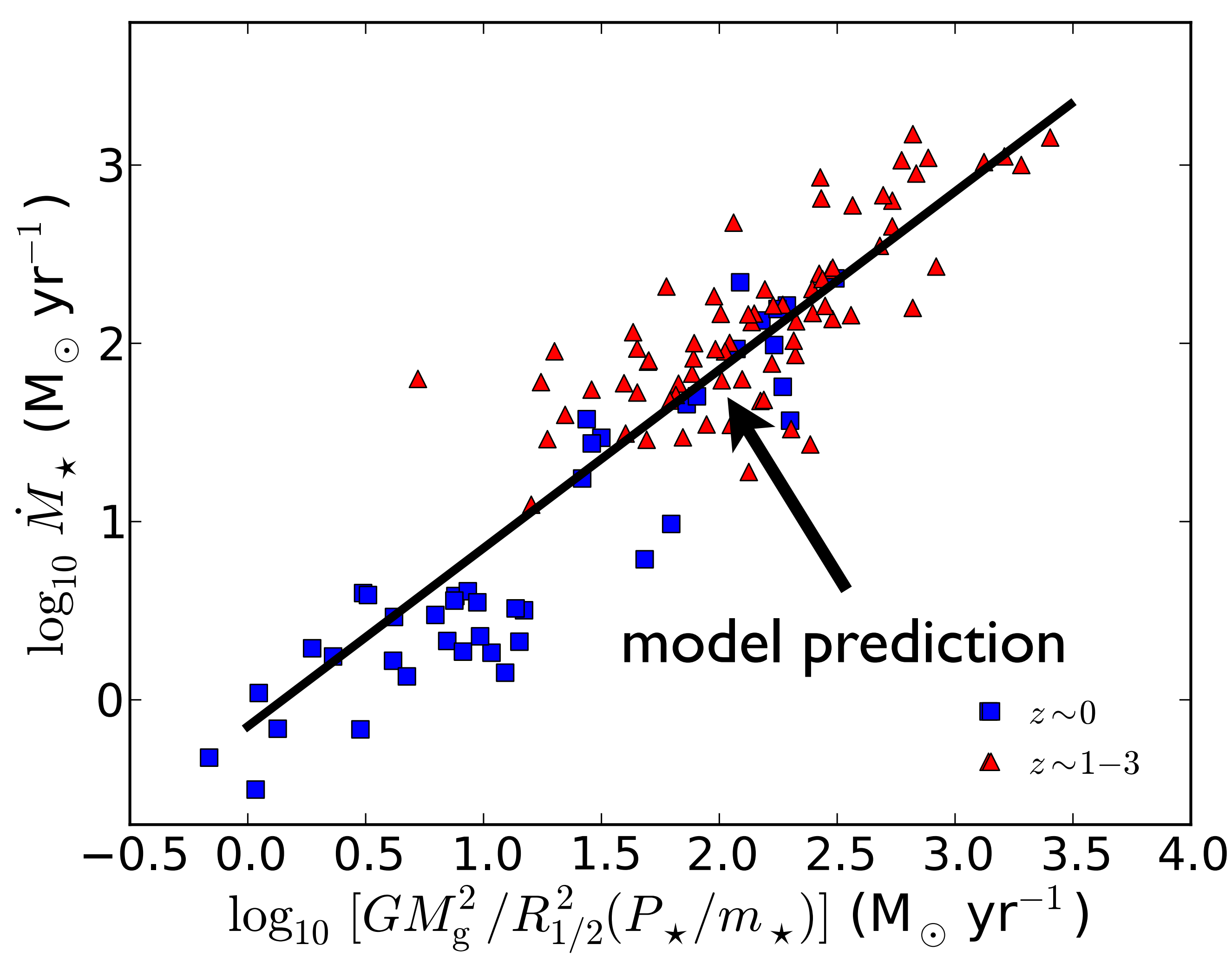
O&S 11; CAFG, Quataert, & Hopkins 13

For Q~1, model predicts that ε_{ff}^{gal} scales with f_g



For $Q\sim1$, model predicts that ϵ_{ff}^{gal} scales with f_g





in tension with "supersonic turbulence"

models that predict universal $\epsilon_{ff}\sim0.01$

CAFG, Quataert, & Hopkins 13

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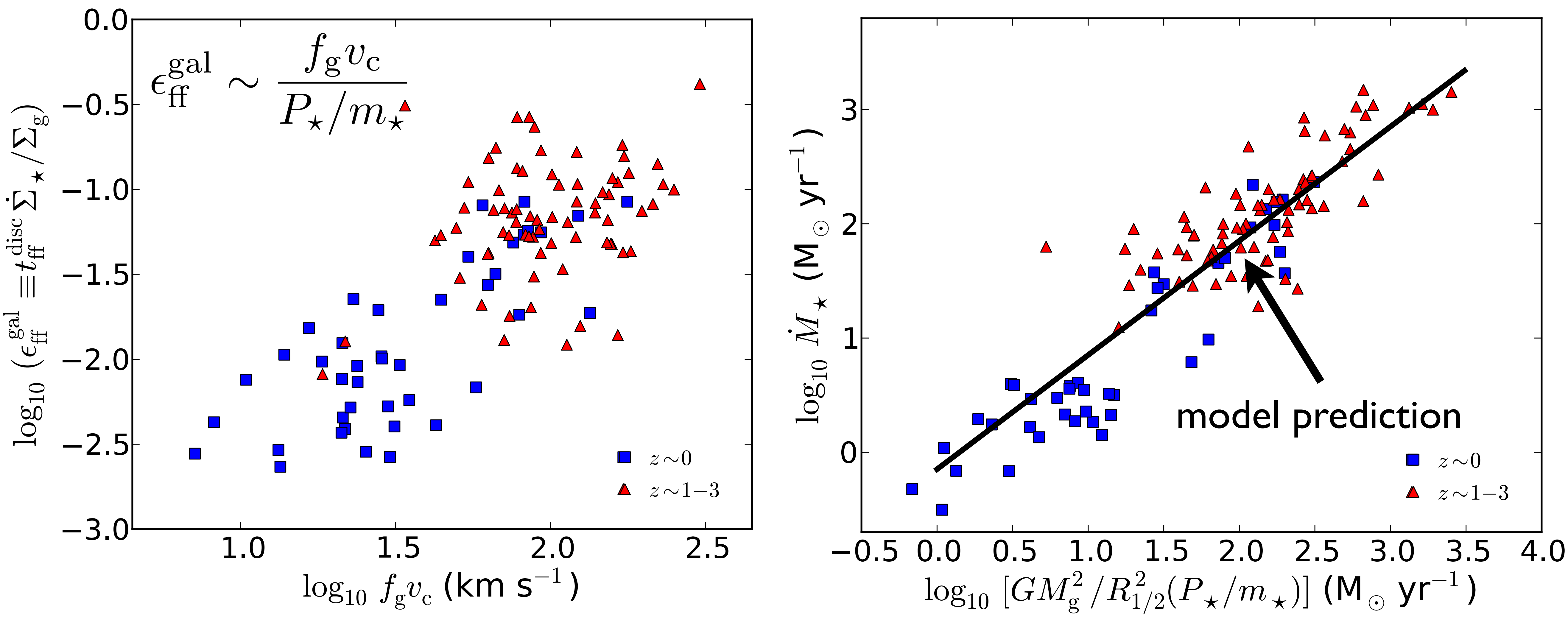

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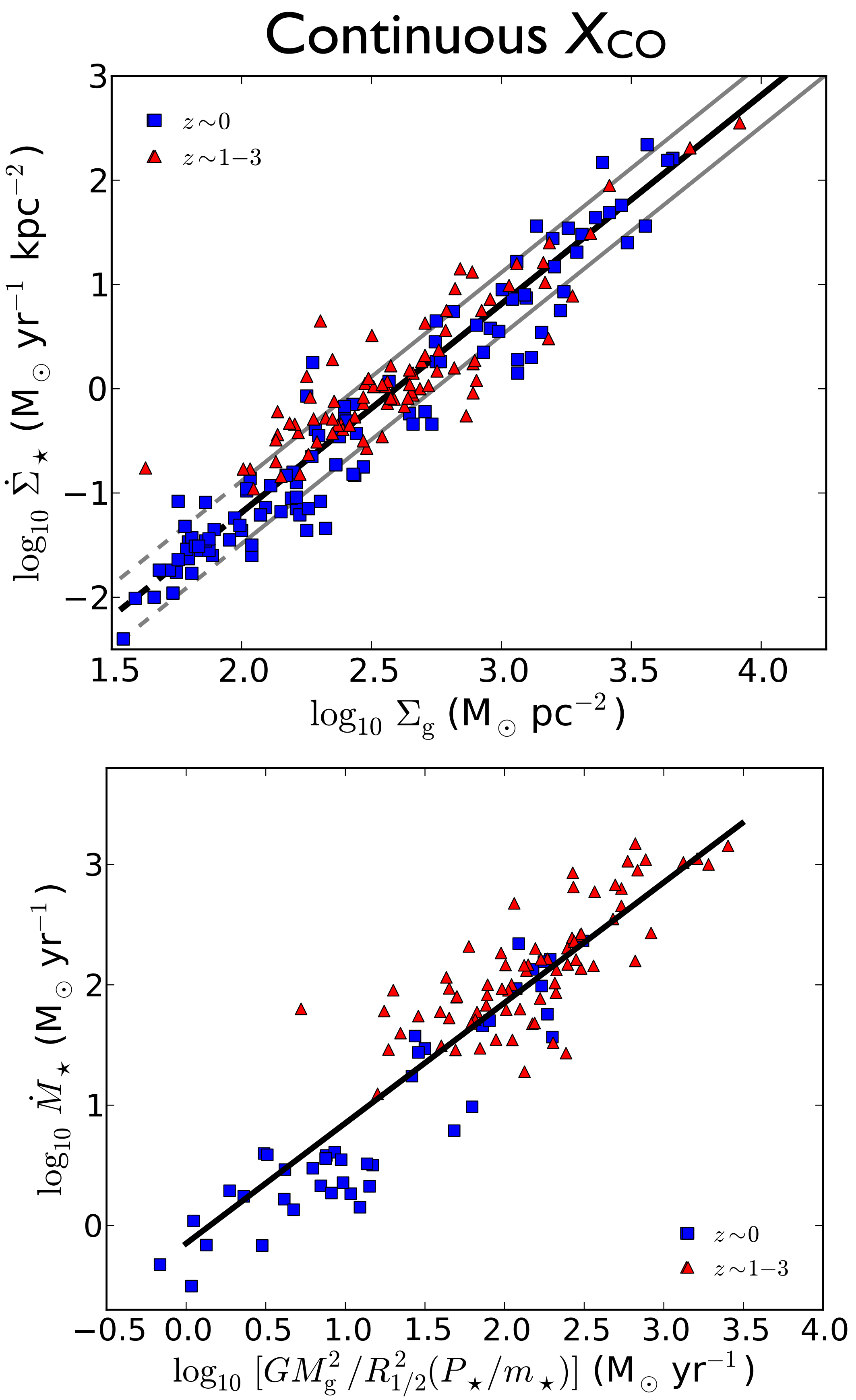
Also: $c_T \sim f_g\ v_c\ /\ 2 \Rightarrow$ high c_T in ULIRGs, high-z SFGs

CAFG, Quataert, & Hopkins 13

X_{CO} uncertain, but continuous reduces scatter



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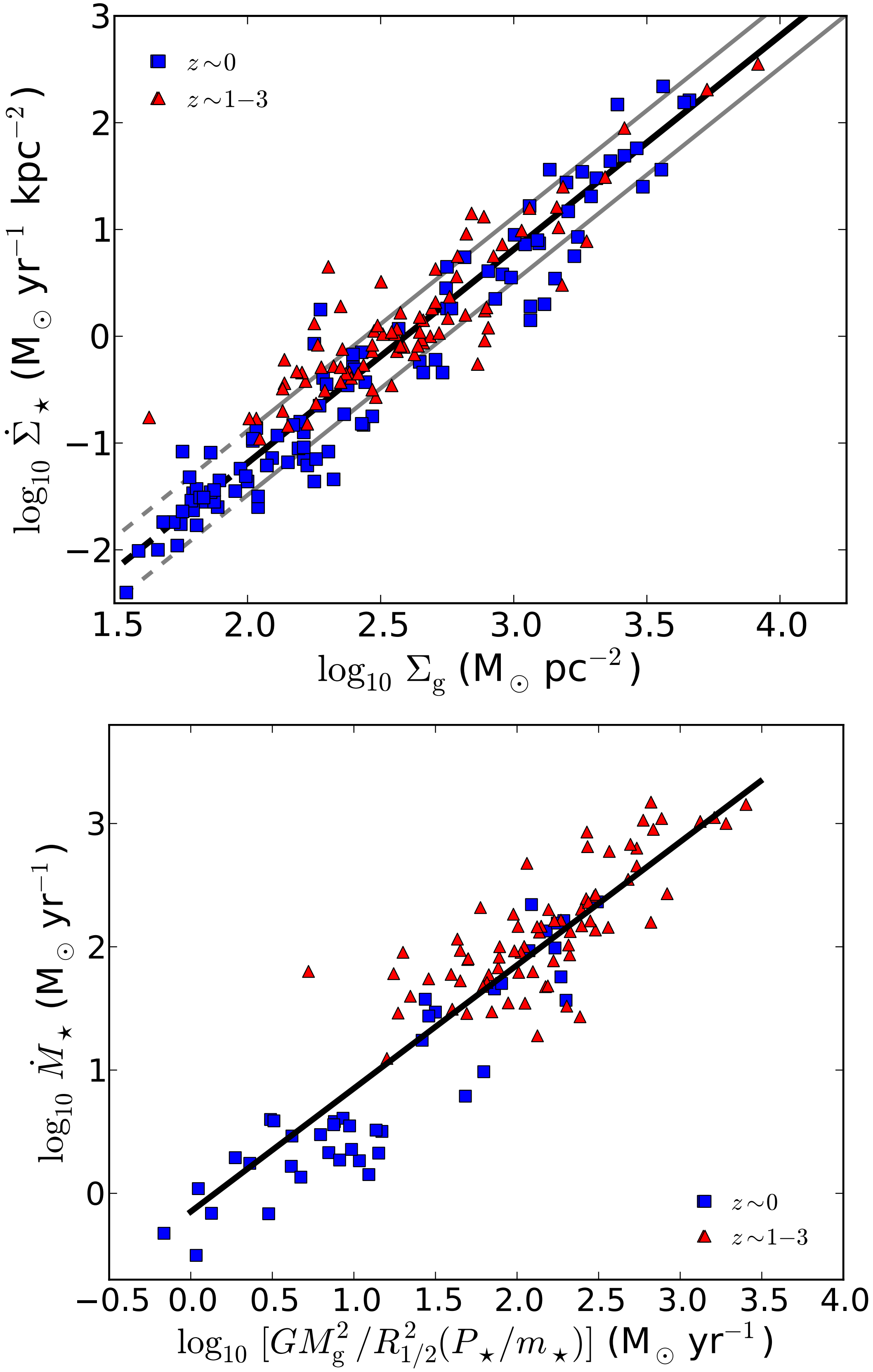
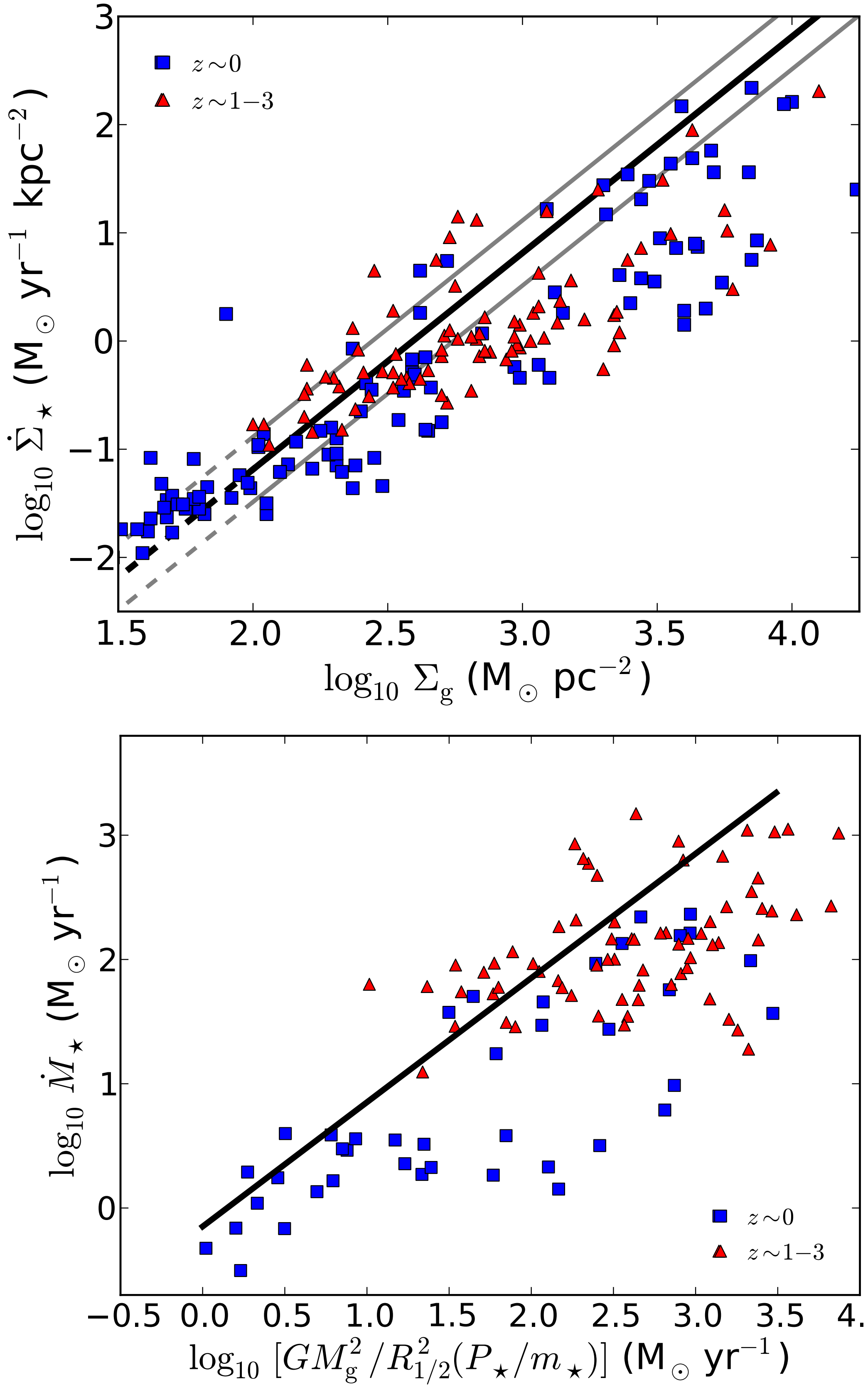
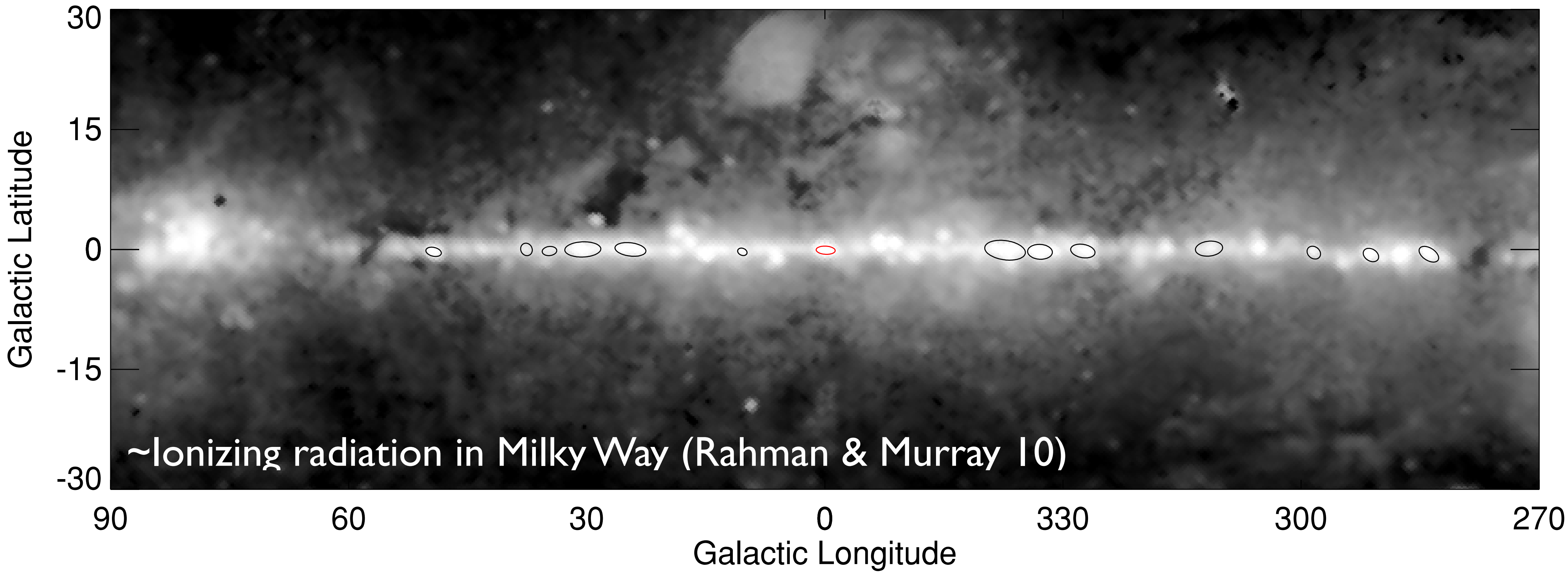


Standard MW-ULIRG bimodal X_{CO}



Stars form in giant molecular clouds

- In Milky Way, 1/3 of current star formation occurs in 33 GMCs



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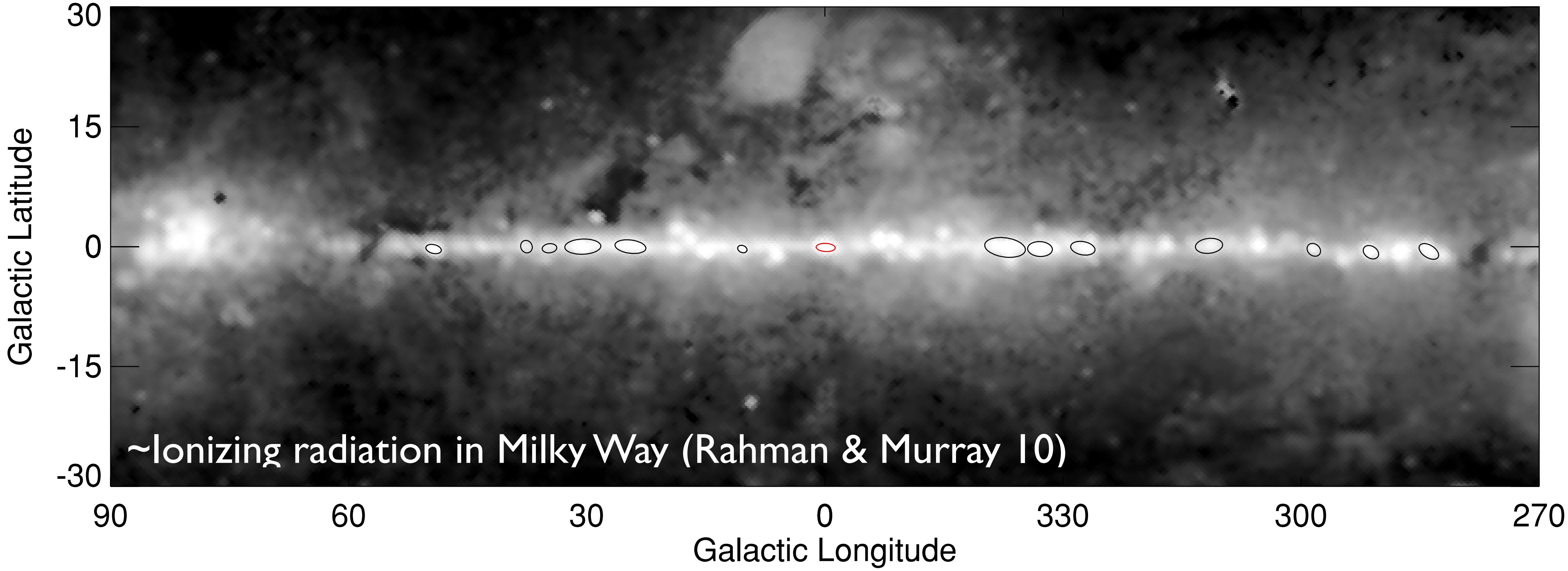


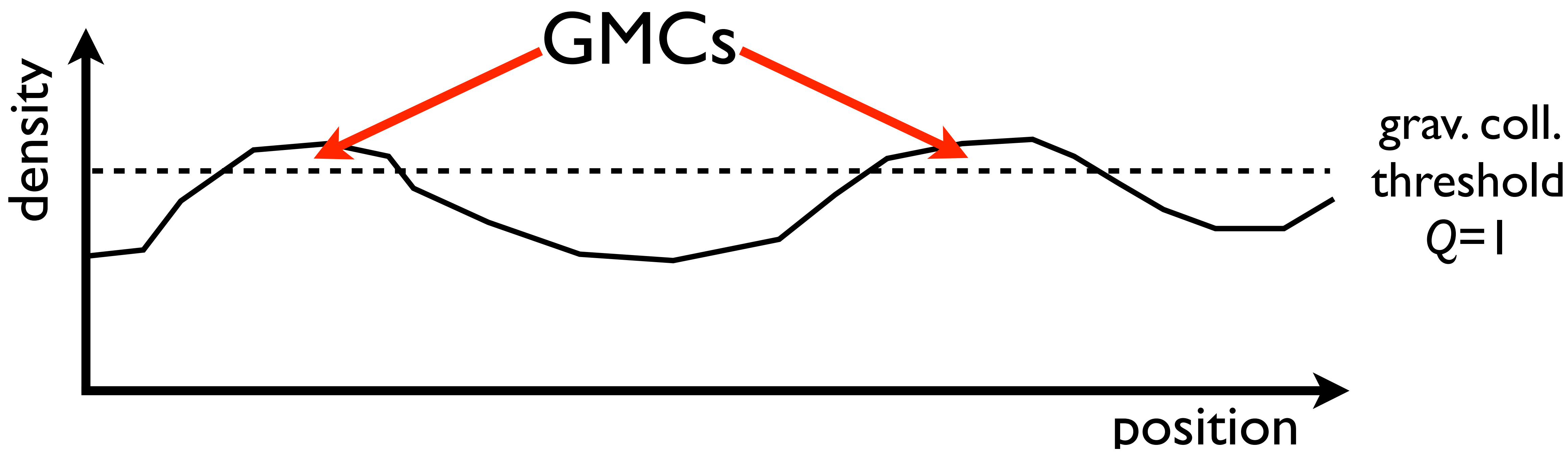
- Gravitational instability forms GMCs and sets their mass $M_T \sim h^2\, \Sigma_g$

  ➡ $\sim 10^6$ M_{sun} in Milky Way

  ➡ $\sim 10^9$ M_{sun} in gas-rich $z \sim 2$ star-forming galaxies (e.g., Genzel+11)

GMC formation is rate limiting step for SF

- Feedback-driven turbulence keeps disk marginally grav. stable, throttles *formation rate of GMCs* and thus galaxy star formation rate



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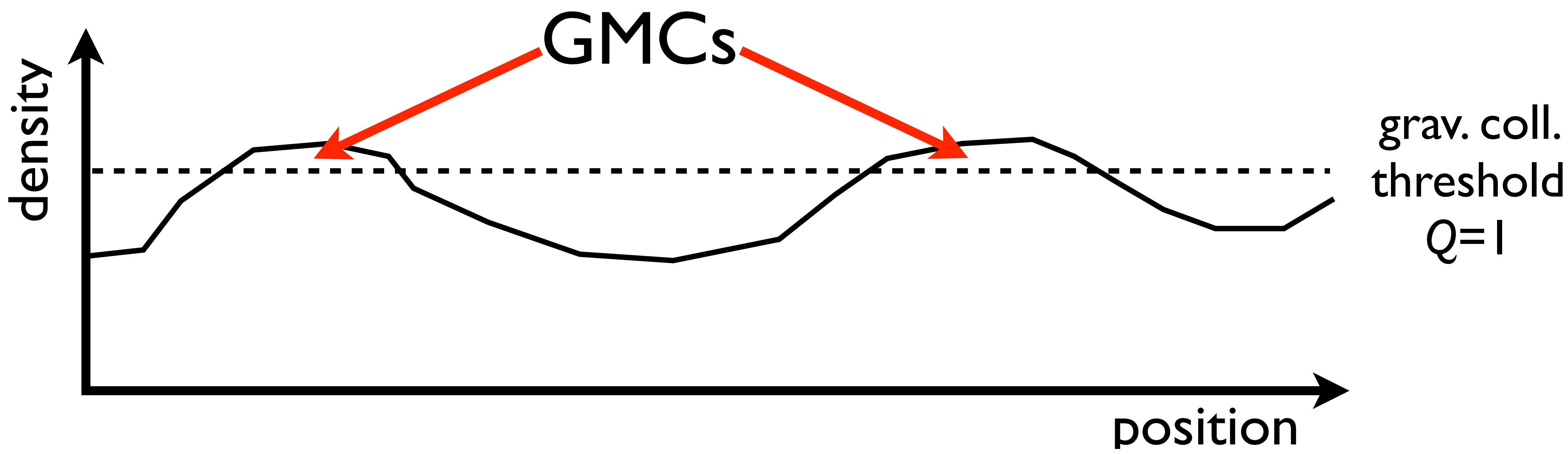

- To capture essential physics of star formation, resolve GMC formation and model stellar feedback

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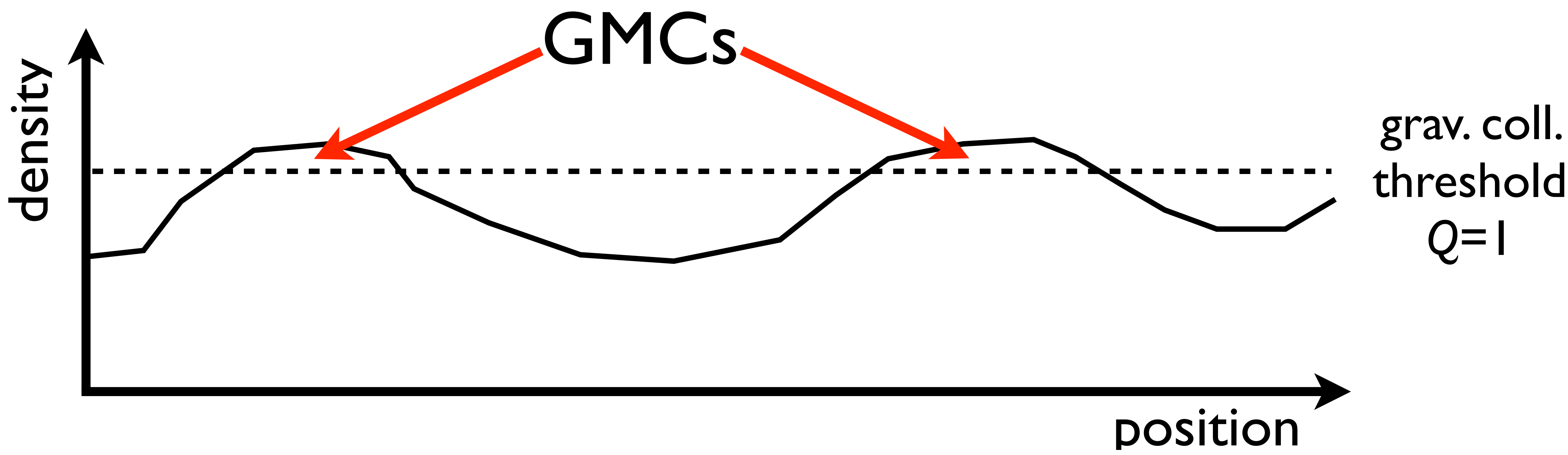

- To capture essential physics of star formation, resolve GMC formation and model stellar feedback

- Galaxy SFR weakly dependent on SF prescription on scales ≪ GMCs

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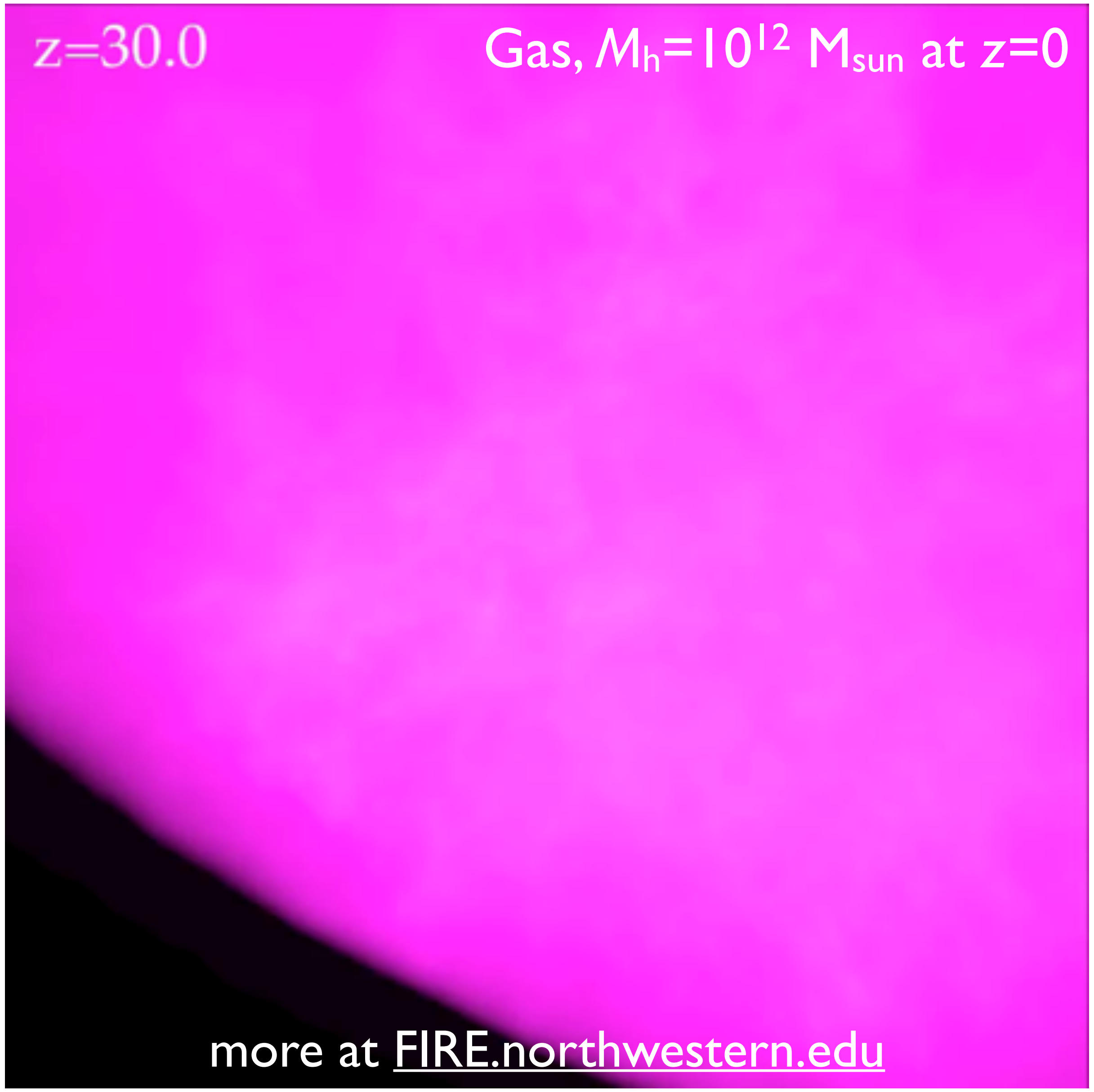
FIRE: Feedback In Realistic Environments

- Cosmological zoom-ins resolving GMCs at all redshifts
- Metal and molecular line 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 from the calculation



w/ Hopkins, Kereš, Quataert, Murray, Muratov…

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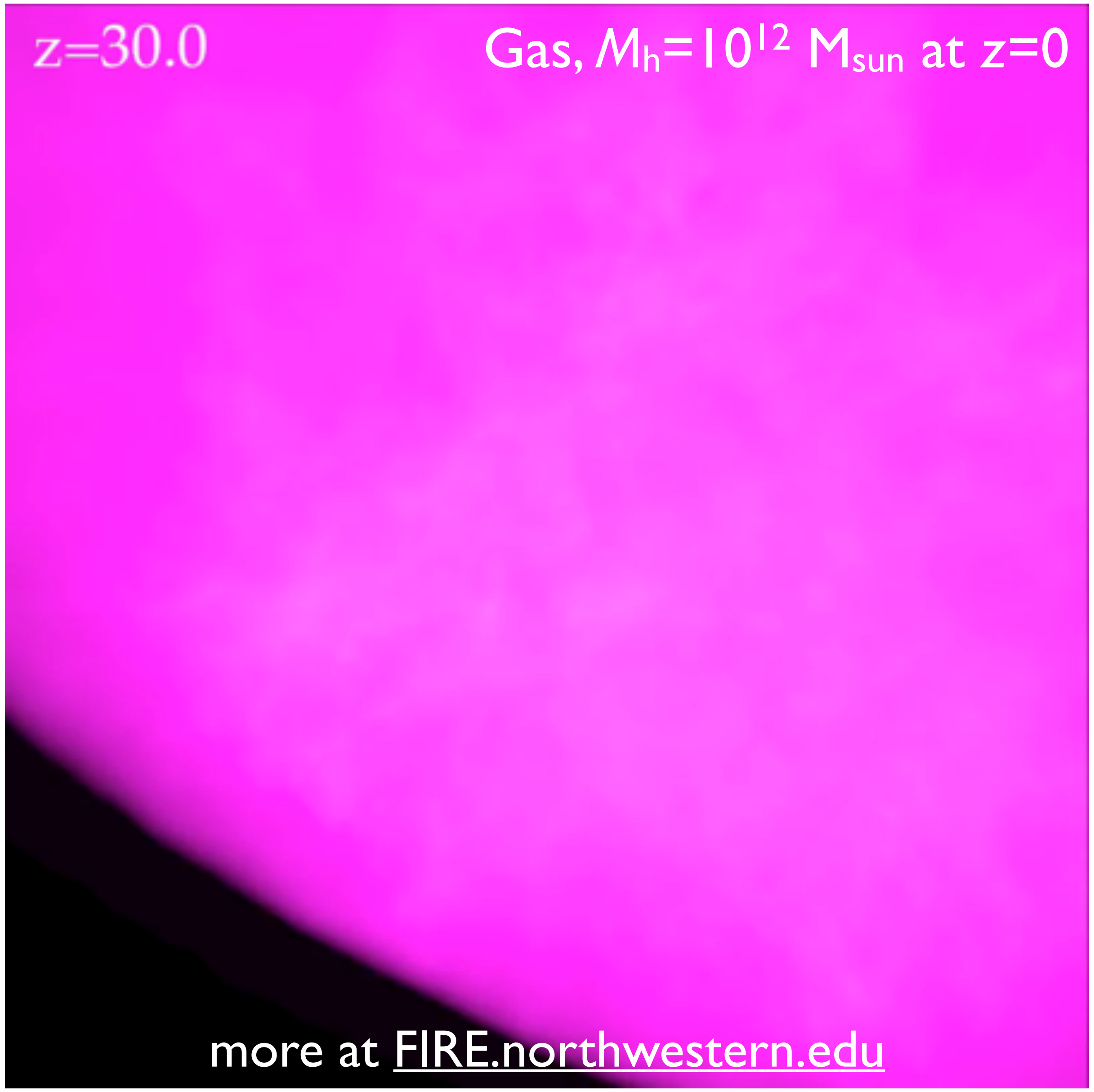
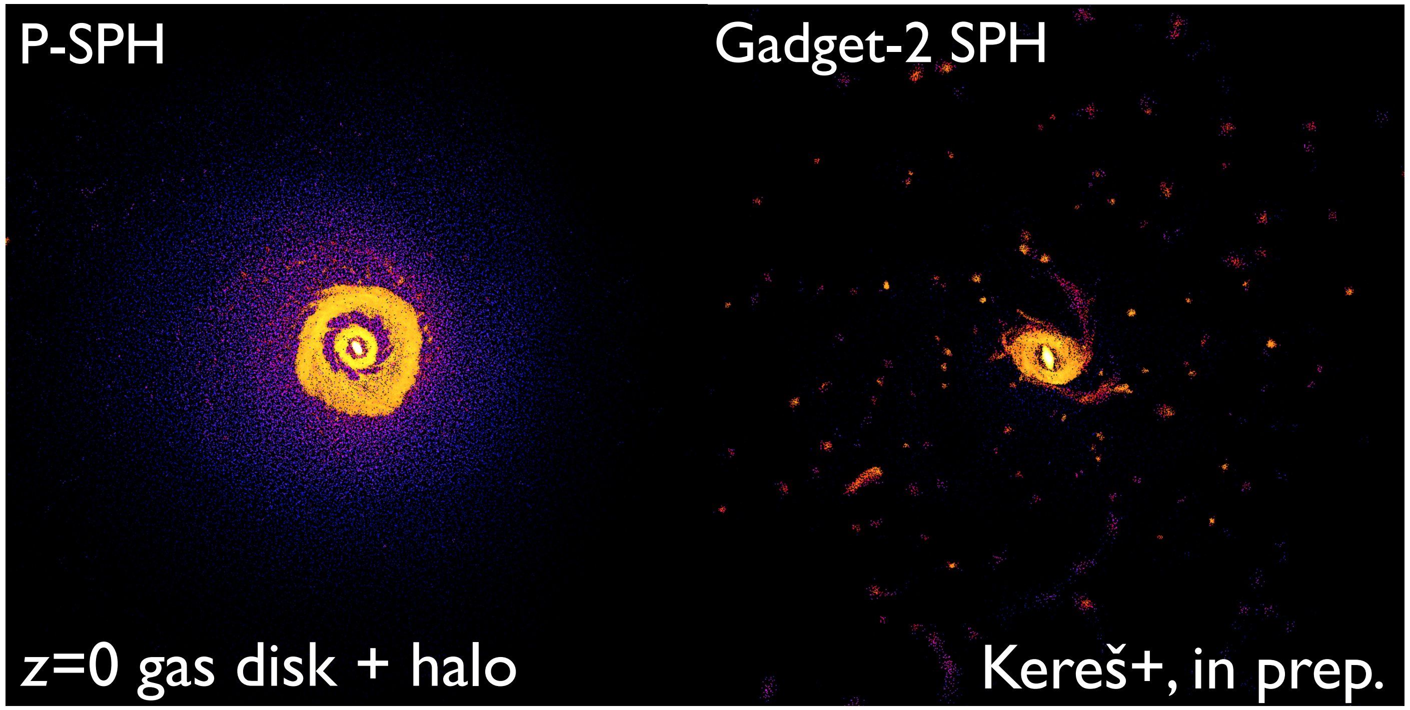
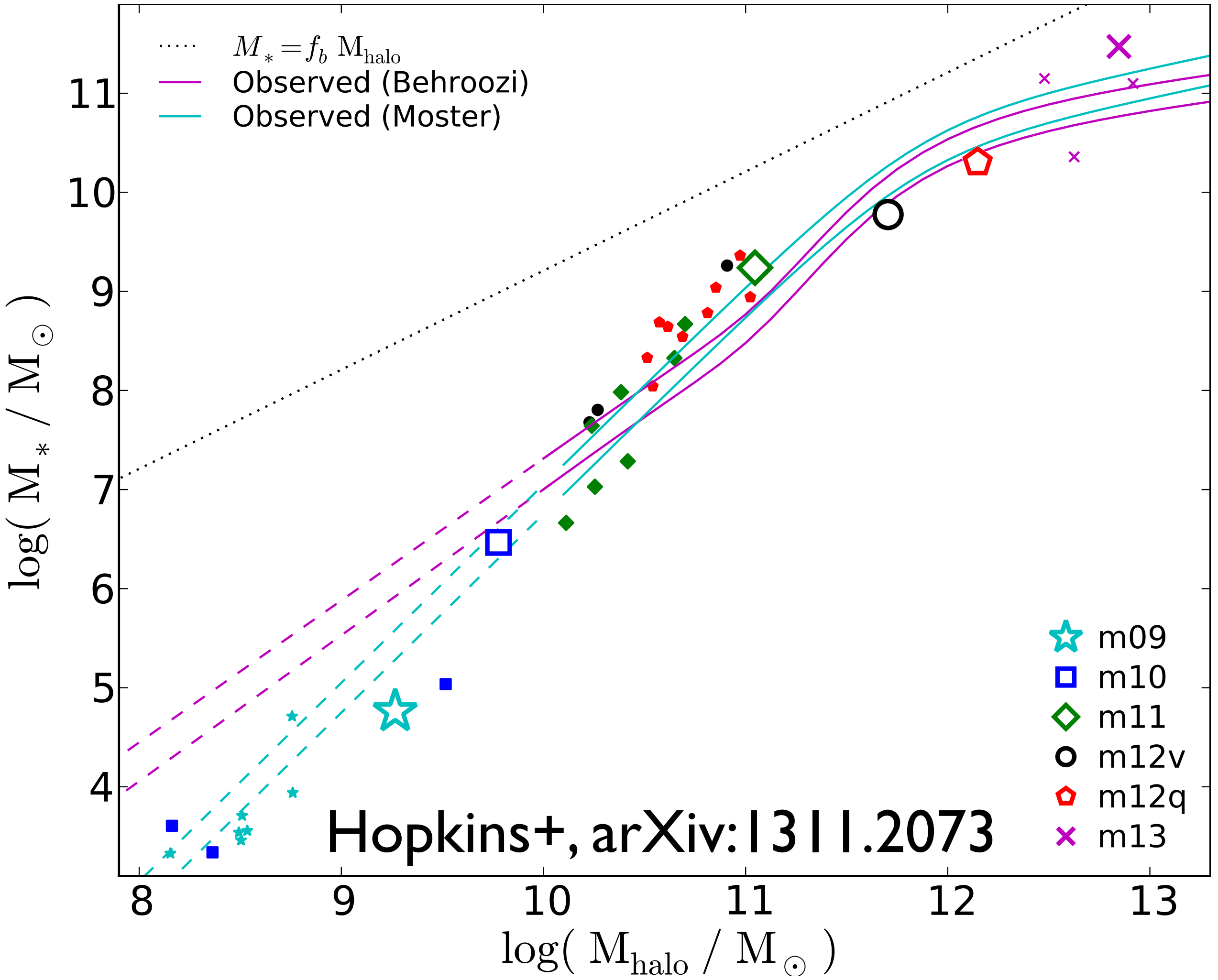


w/ Hopkins, Kereš, Quataert, Murray, Muratov…

Multiphase gas in FIRE

- P-SPH+Gadget-3 gravity
  - ➡ resolves historical discrepancies between SPH and grid-based codes
- No hydro decoupling or gas cooling suppression
- High-res. MW analog sim:
  - ➡ $m_{gas}=5\times10^3$ M_{sun}, $\varepsilon_{gas}=10$ pc
- Track 11 elements+r-process





Probing inflows/outflows in the CGM

- Directly constrain baryon cycle regulating galaxy growth

- A lot of data to compare to:
  - ➡ ground-based telescopes, Cosmic Origins Spectrograph on Hubble

    (Steidel, Prochaska, Hennawi, Martin, Tumlinson, …)
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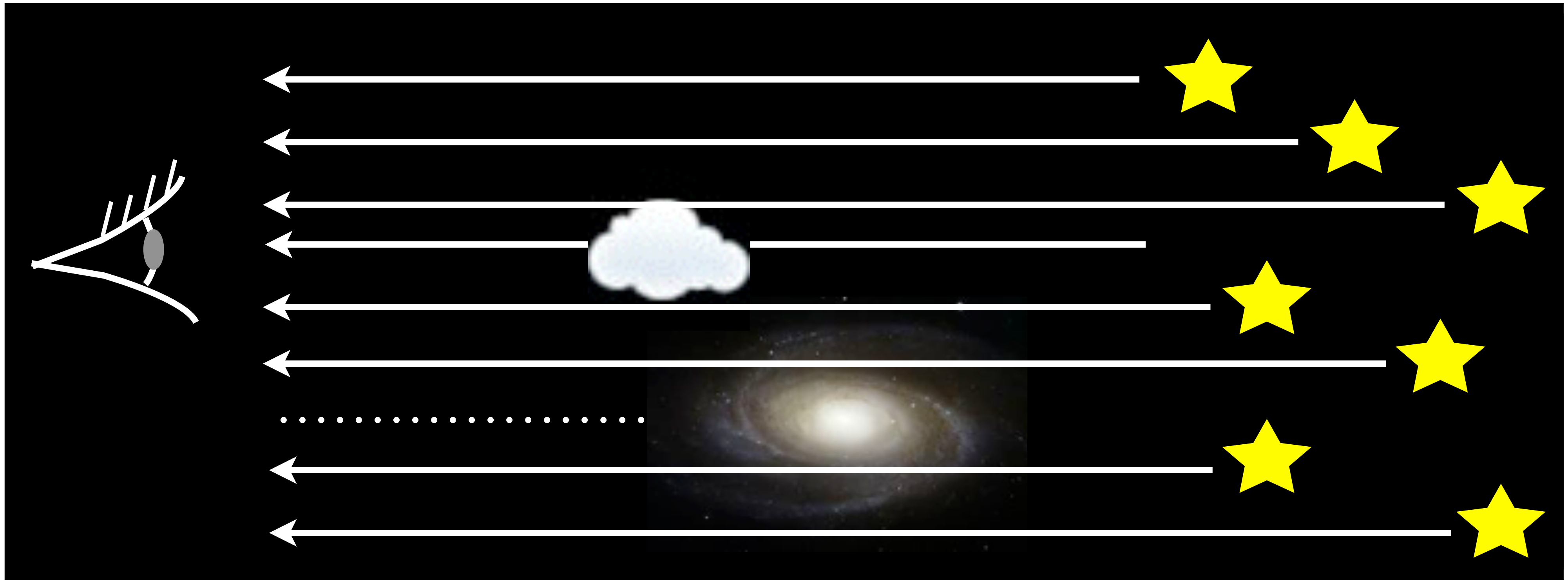

30-m

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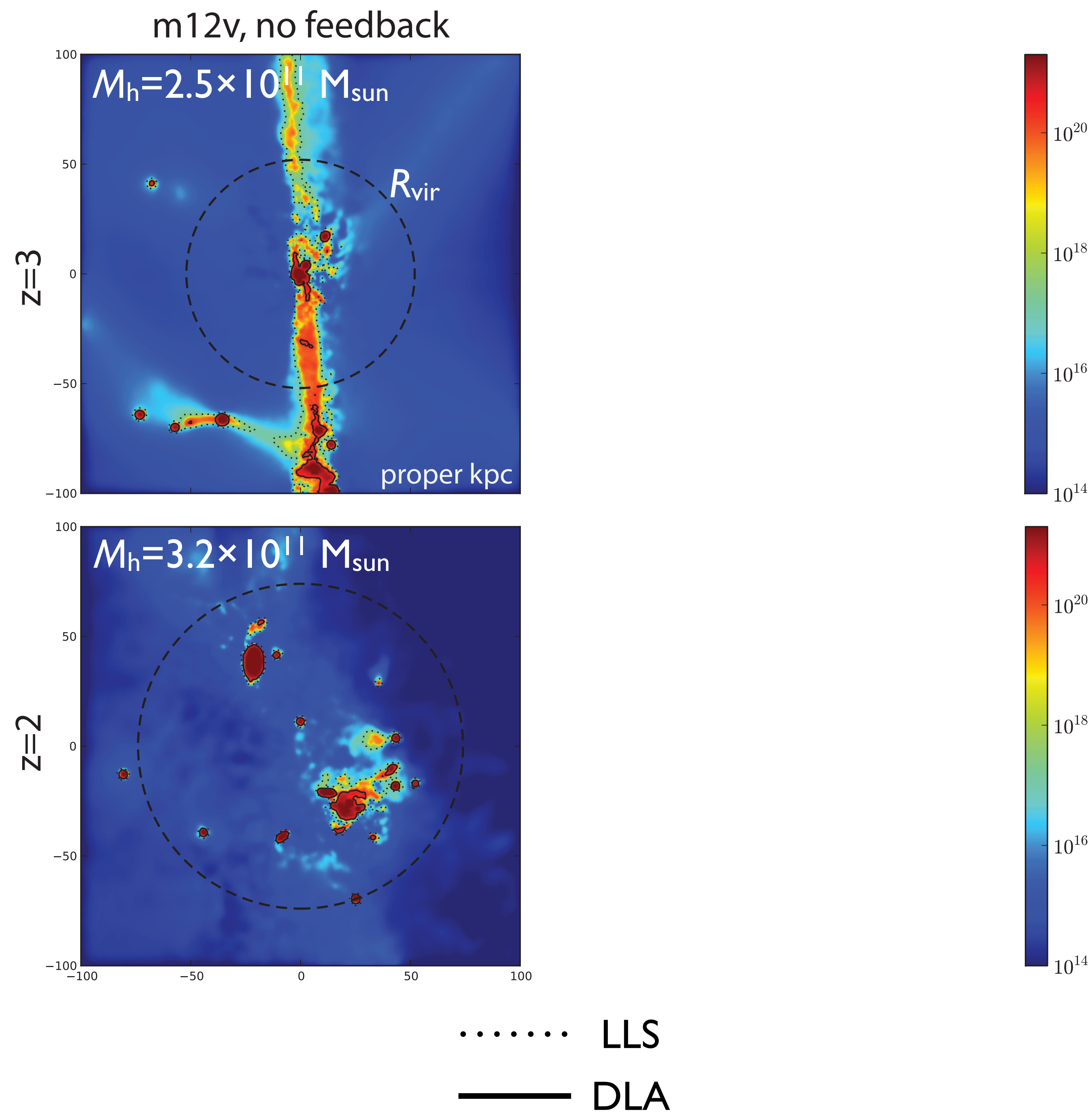
Inflows and outflows in FIRE: HI

- Ionizing RT following CAFG +10, CAFG & Kereš 11
- Winds increase covering fractions of cool gas
- Especially in massive halos otherwise dominated by hot gas



CAFG+, in prep.

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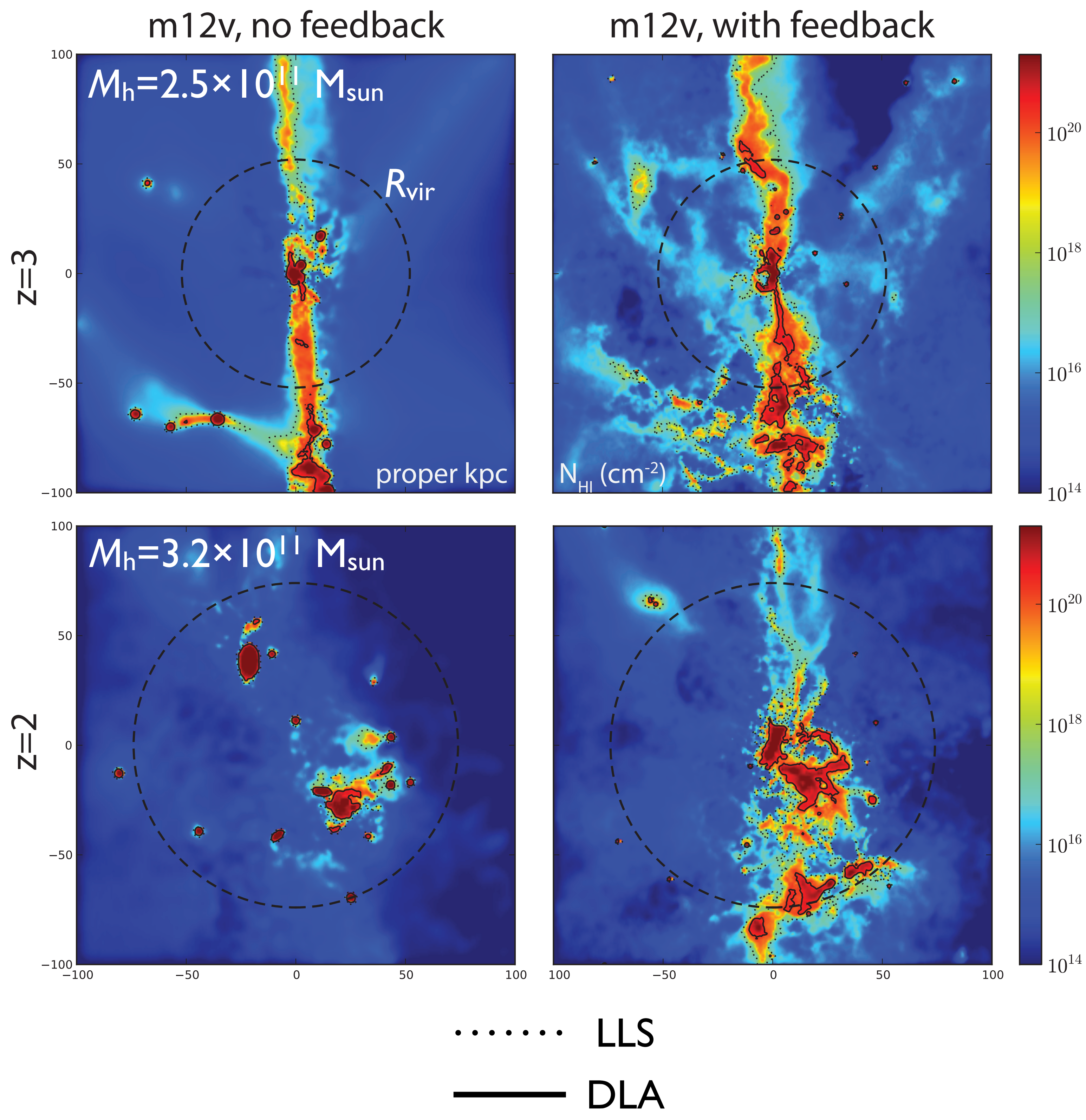
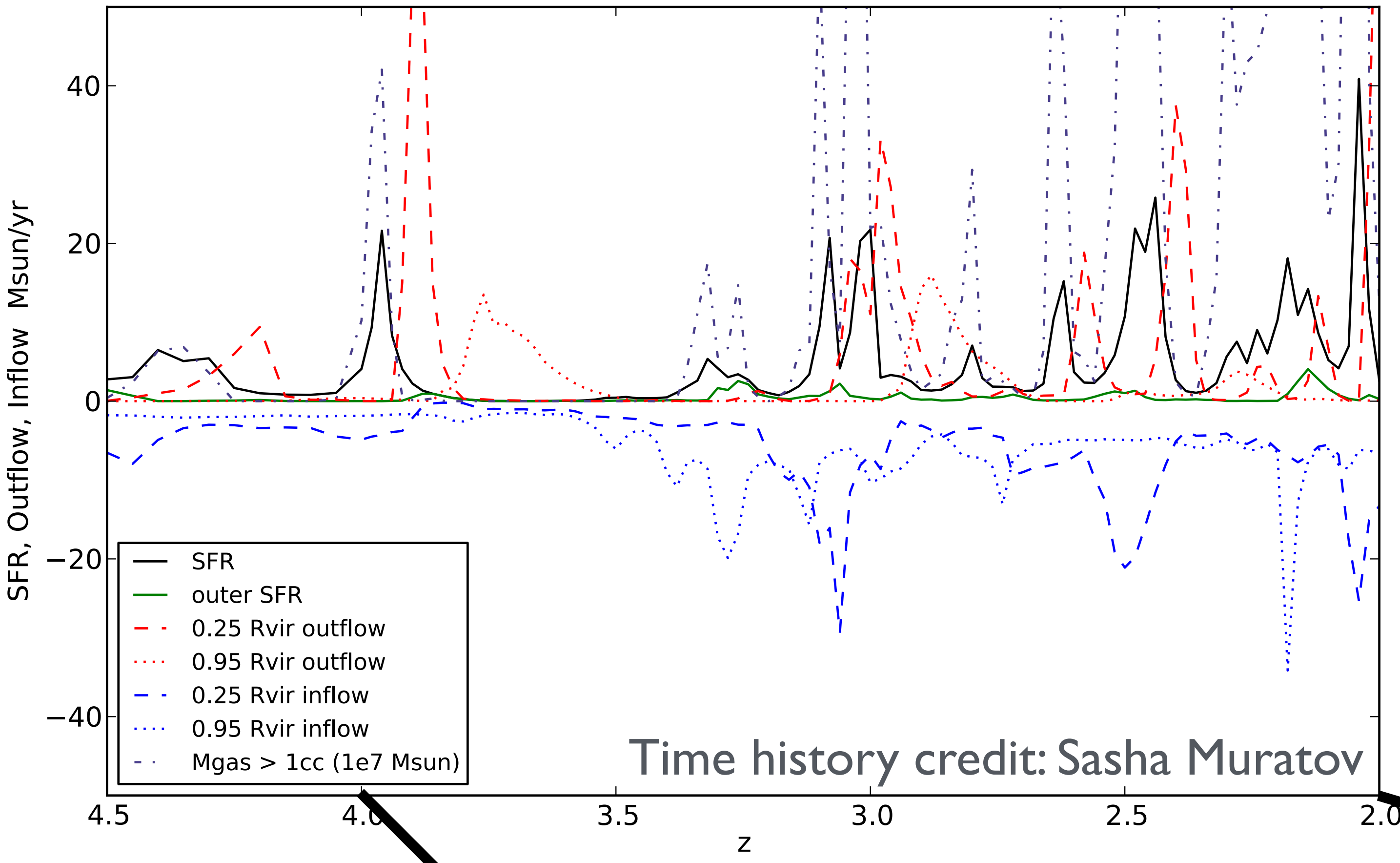
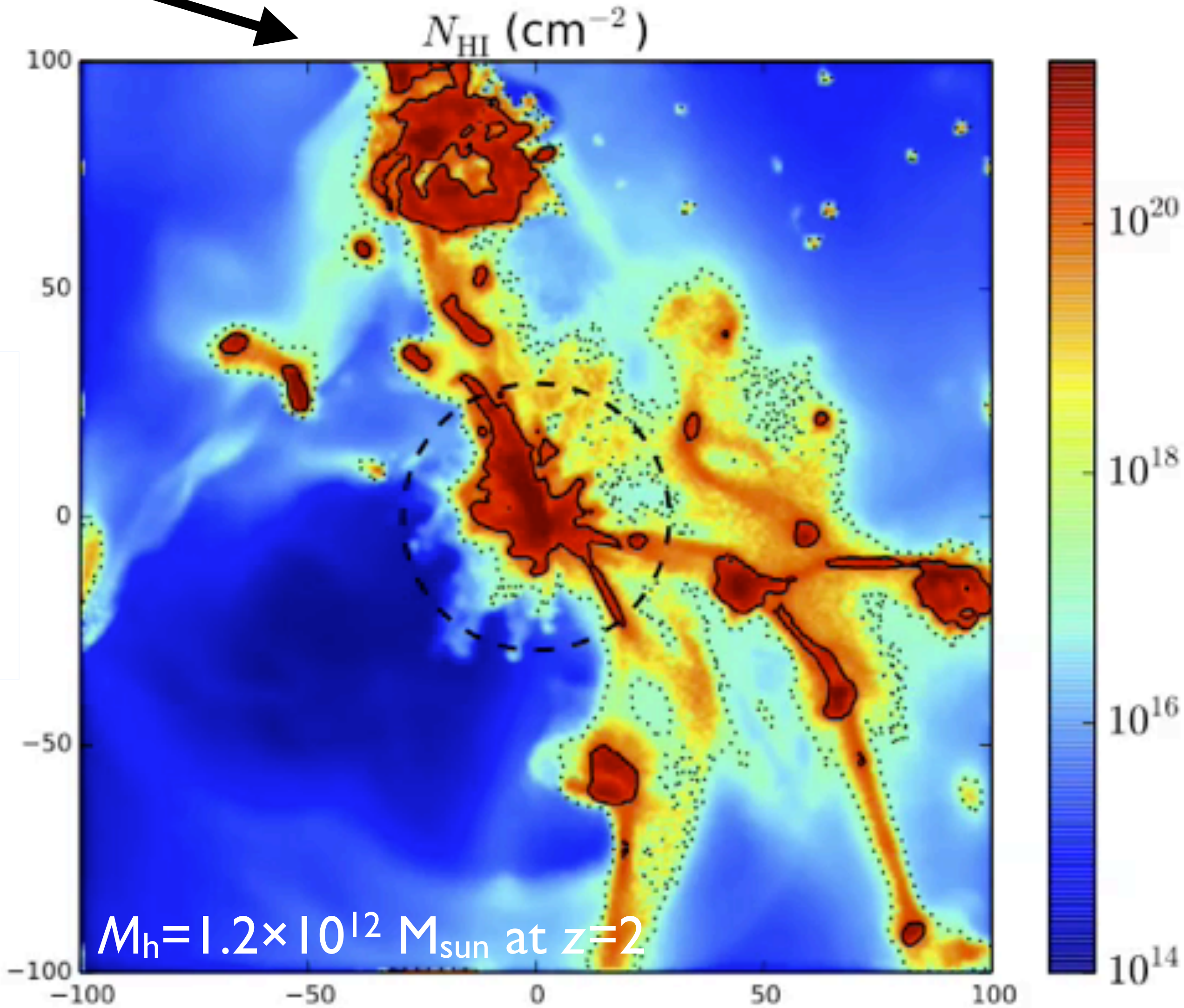


CAFG+, in prep.

SF, outflows, & CGM absorption highly time variable





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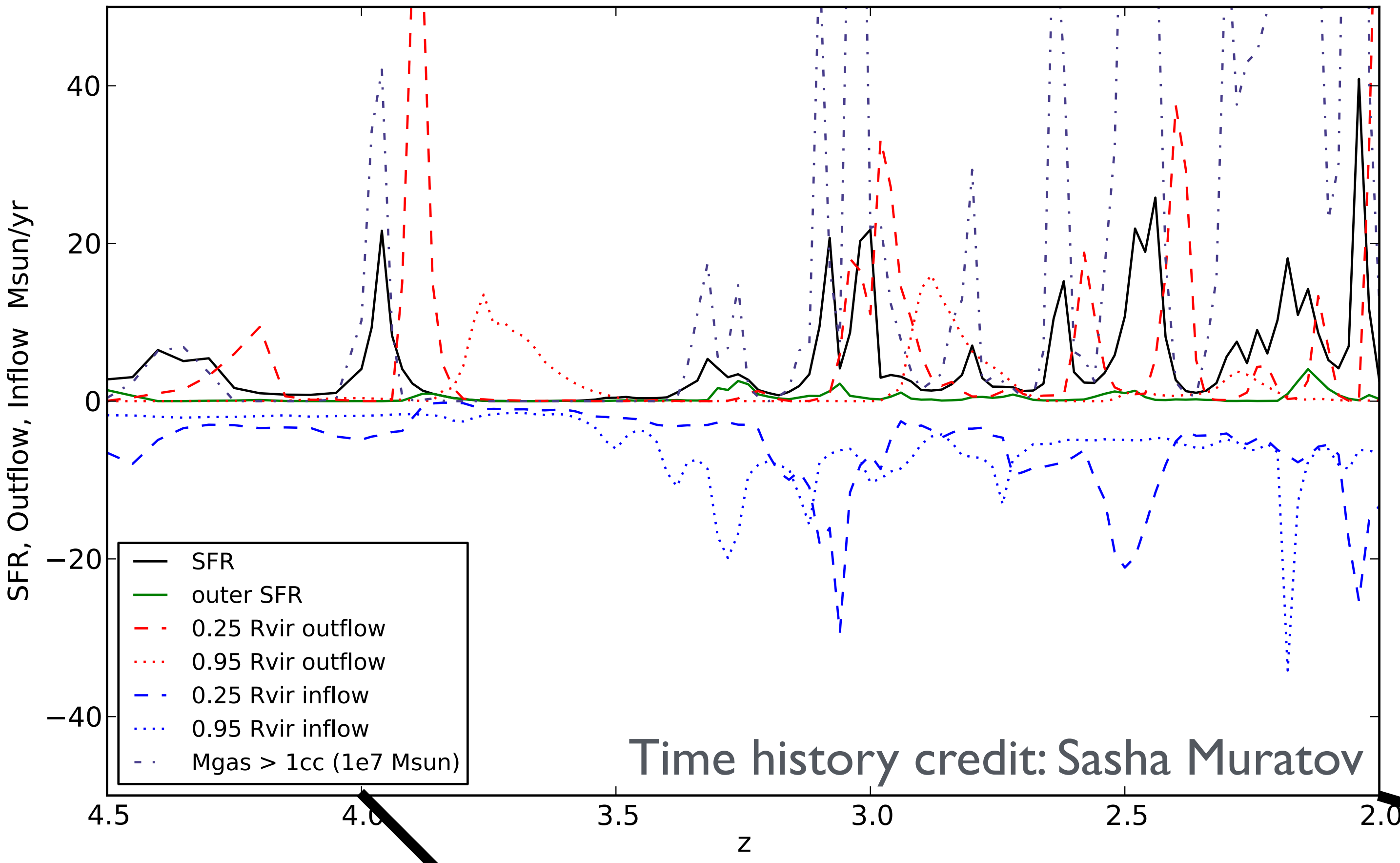

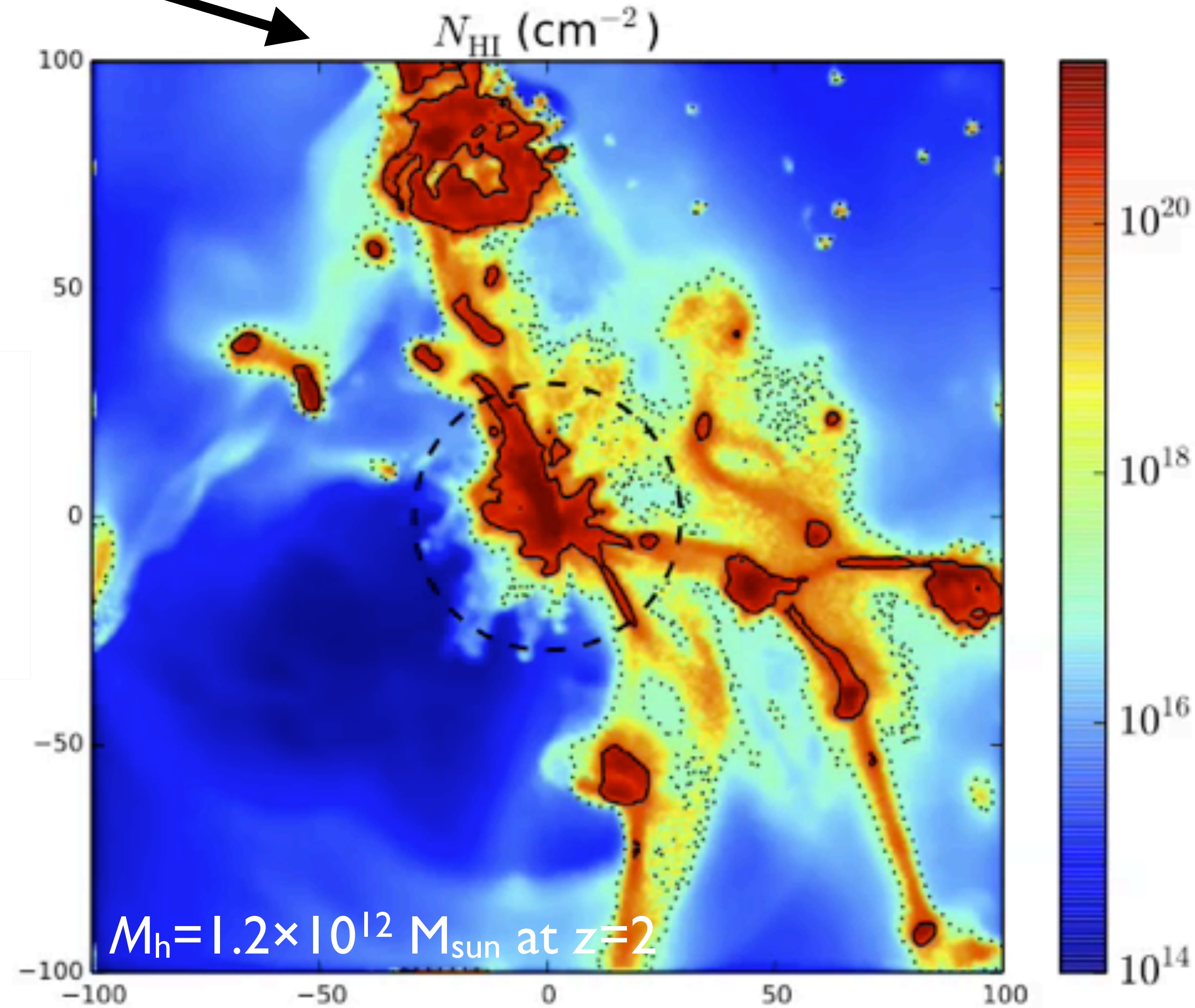

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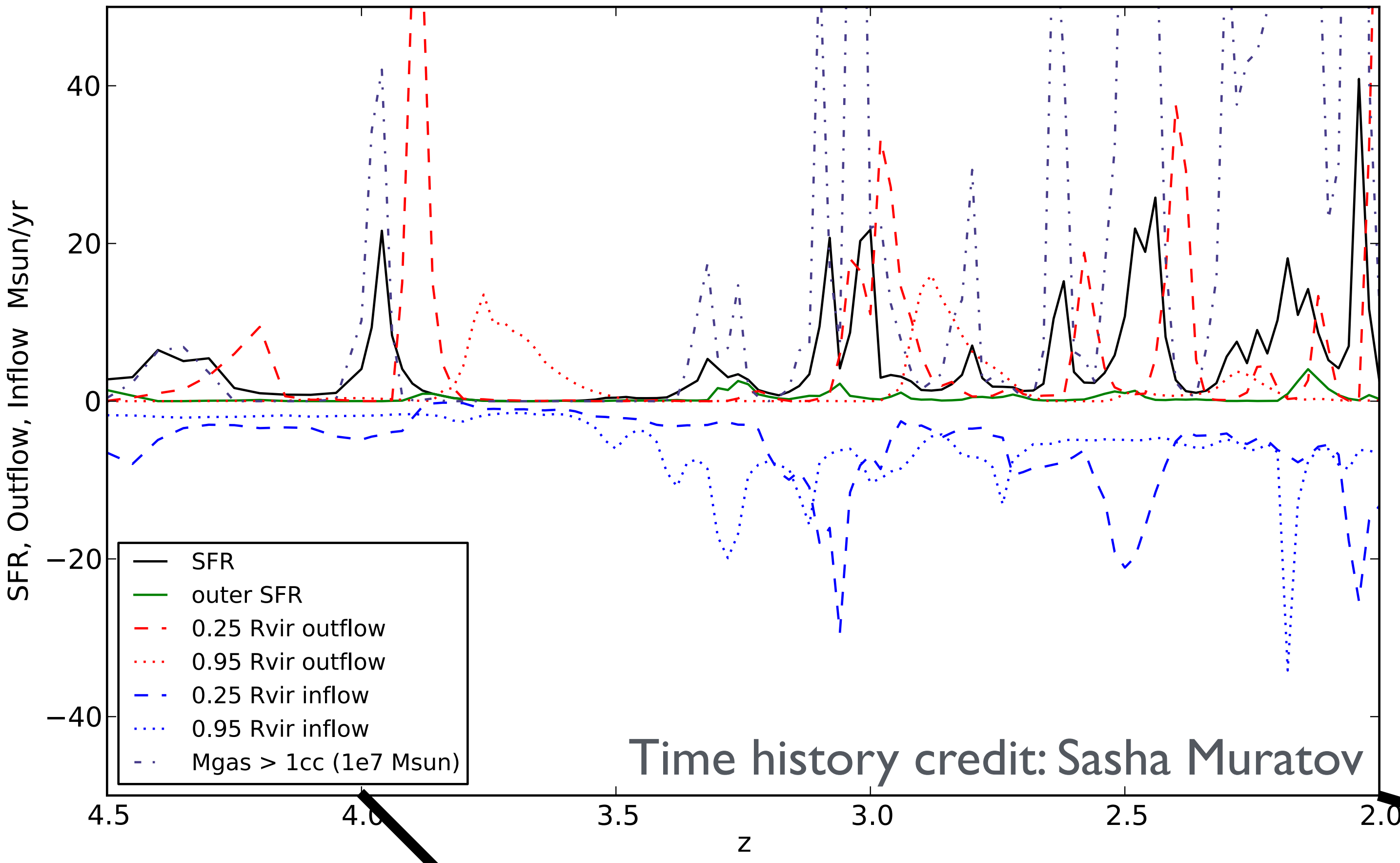
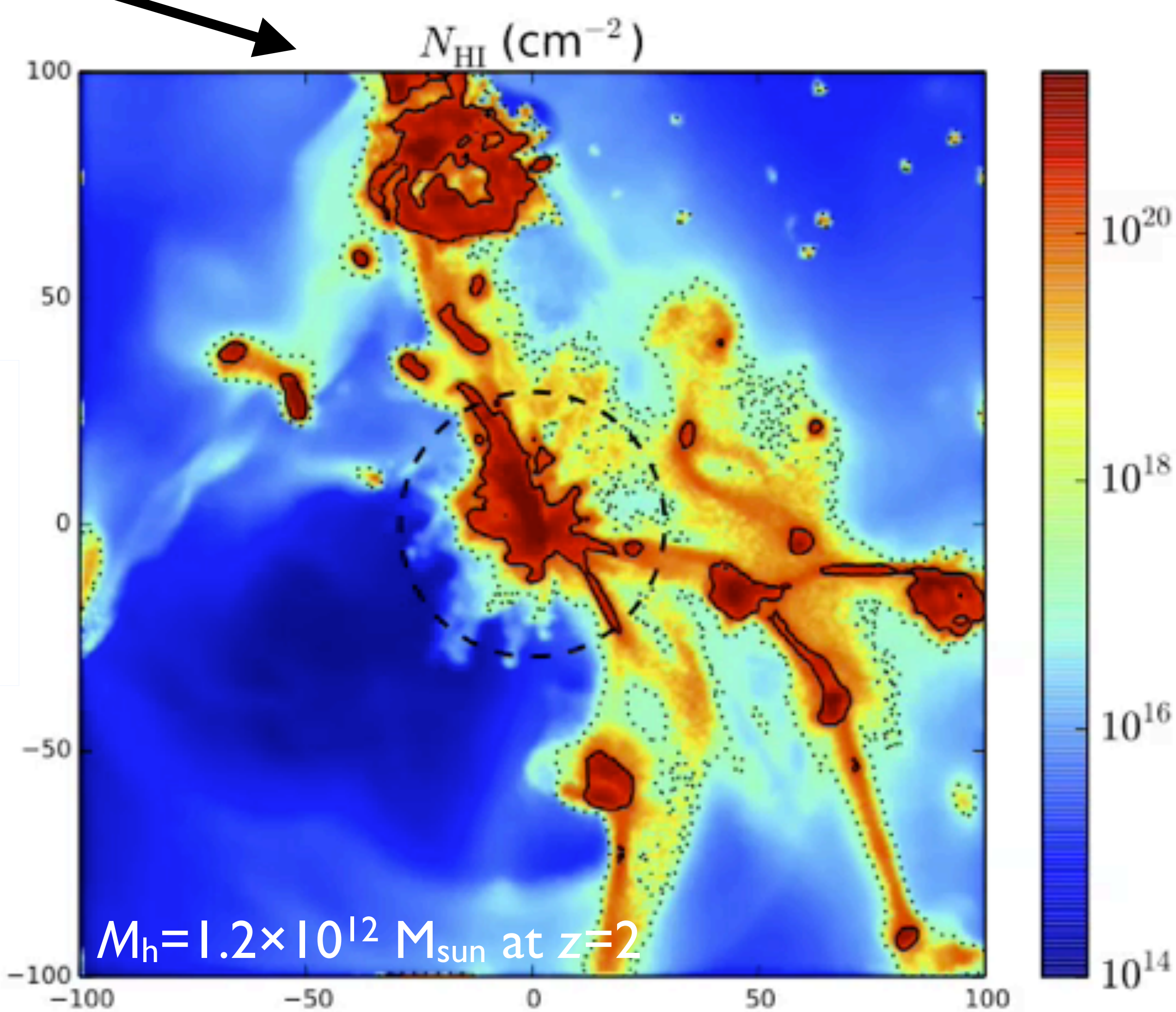
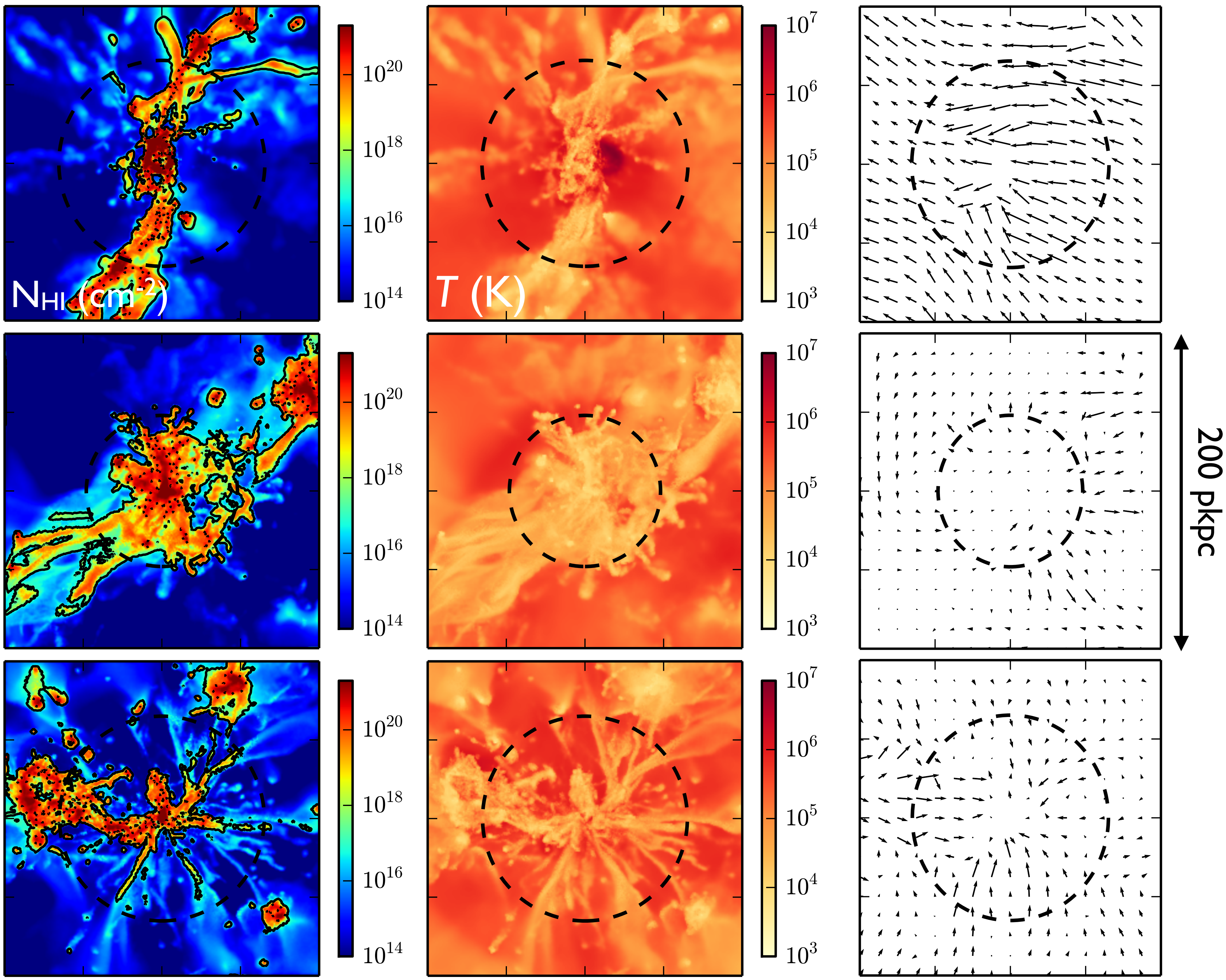




⇒ statistical samples critical

for robust comparison

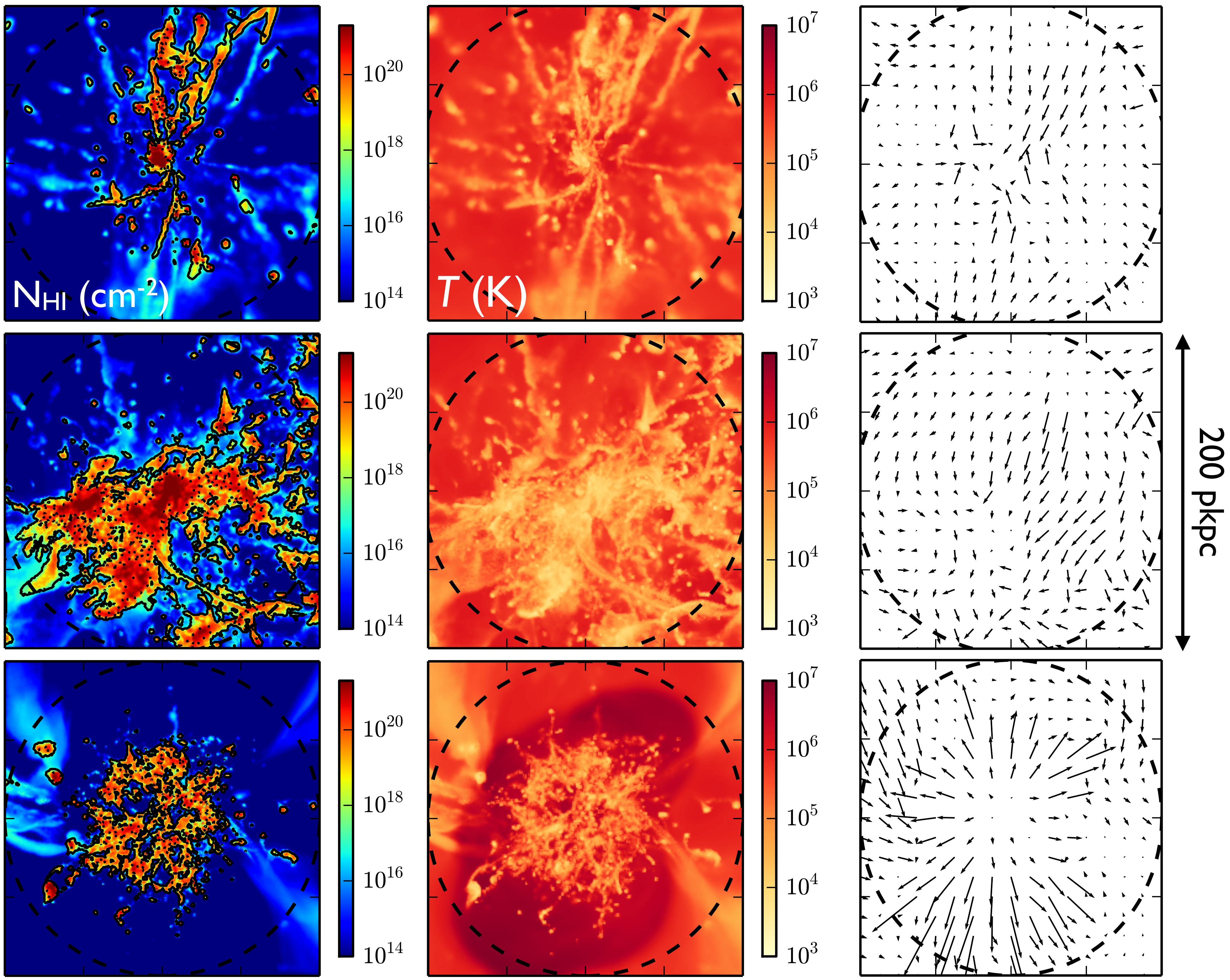
Sample of 12 LBG halos



z=3: M_h=7×10^{10}-5×10^{11} M_{sun}

CAFG+, in prep.

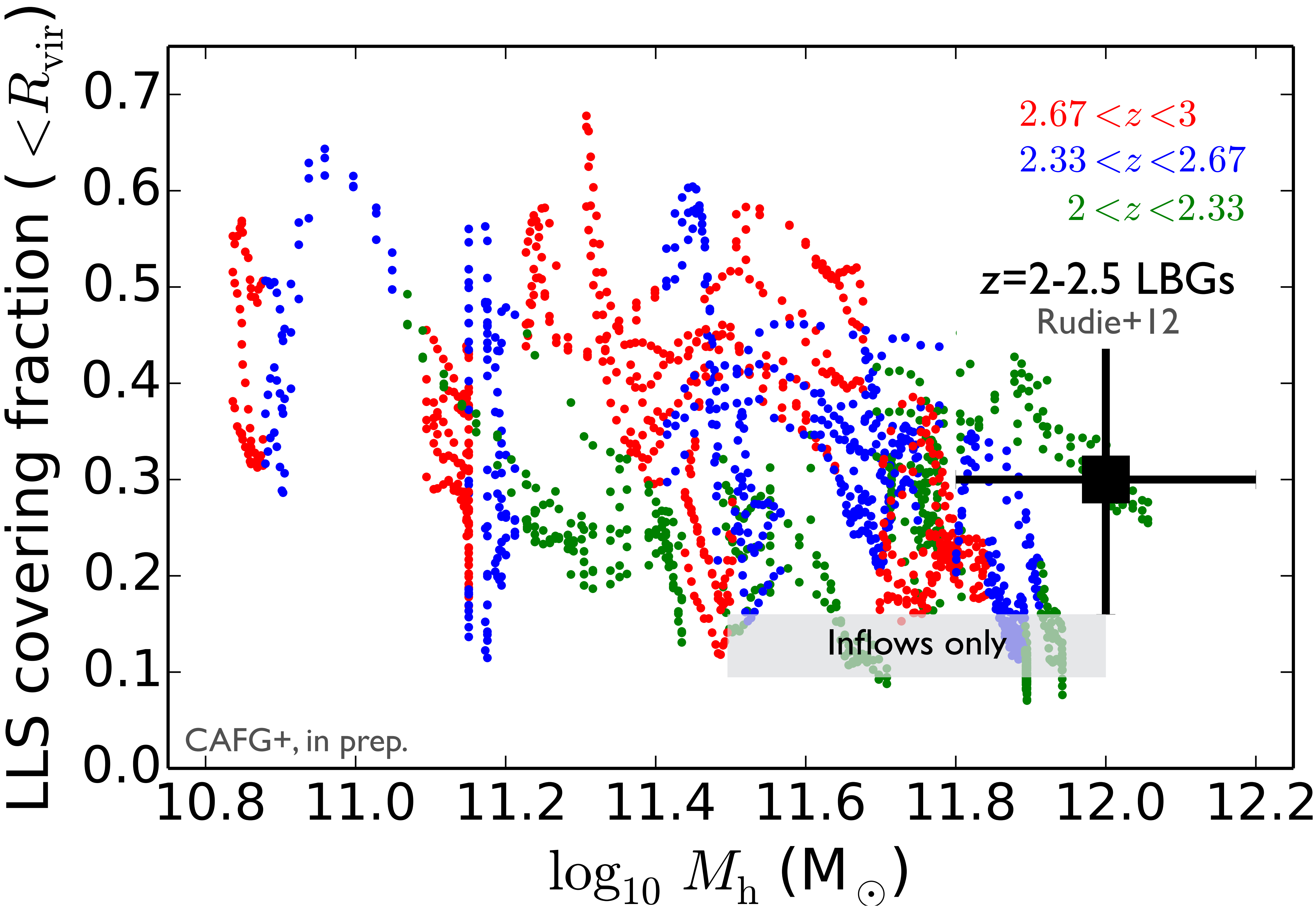
Sample of 12 LBG halos



z=2: M_h=10^{11}-1.5×10^{12} M_{sun}

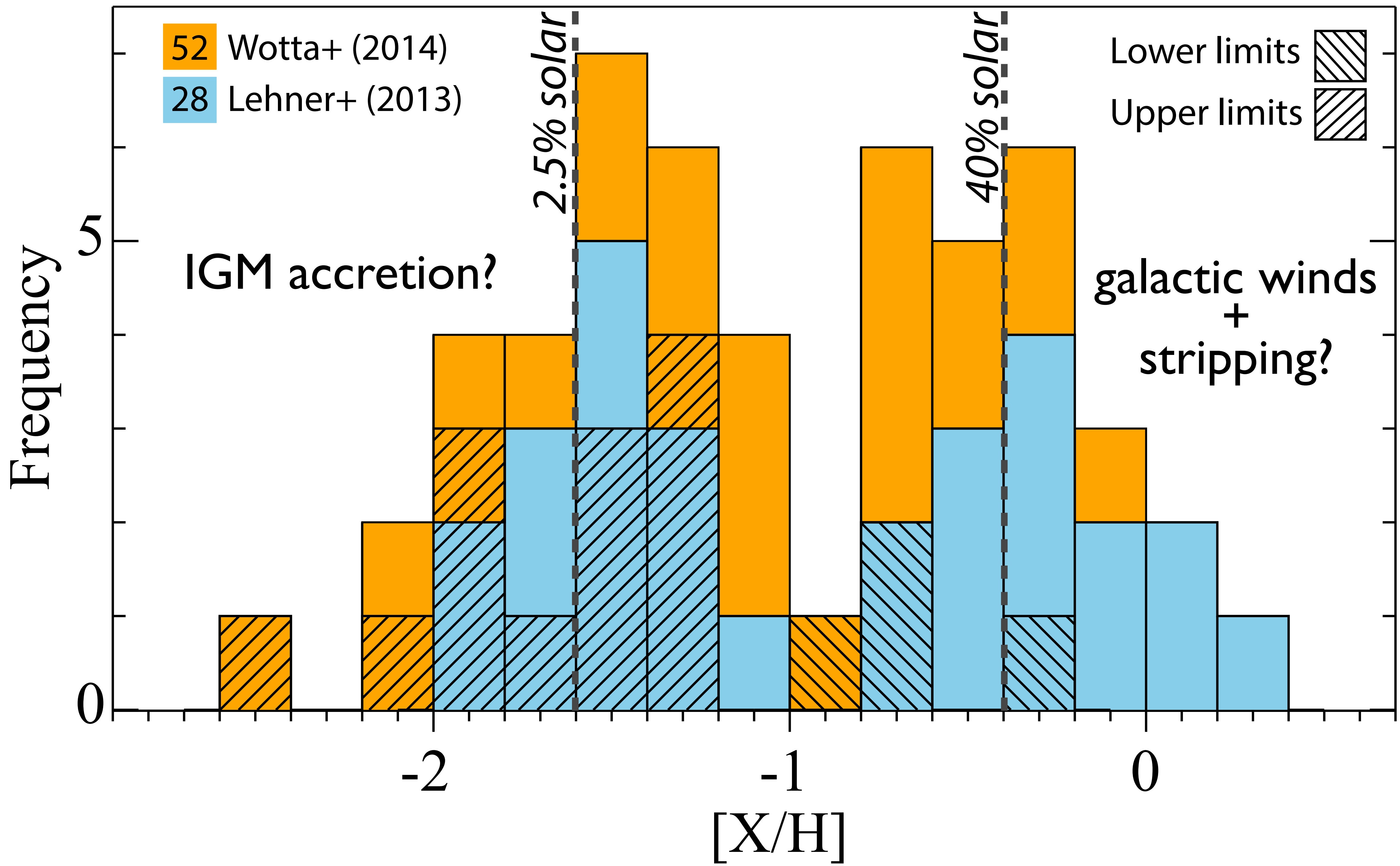
CAFG+, in prep.

z=2-3 HI covering fractions



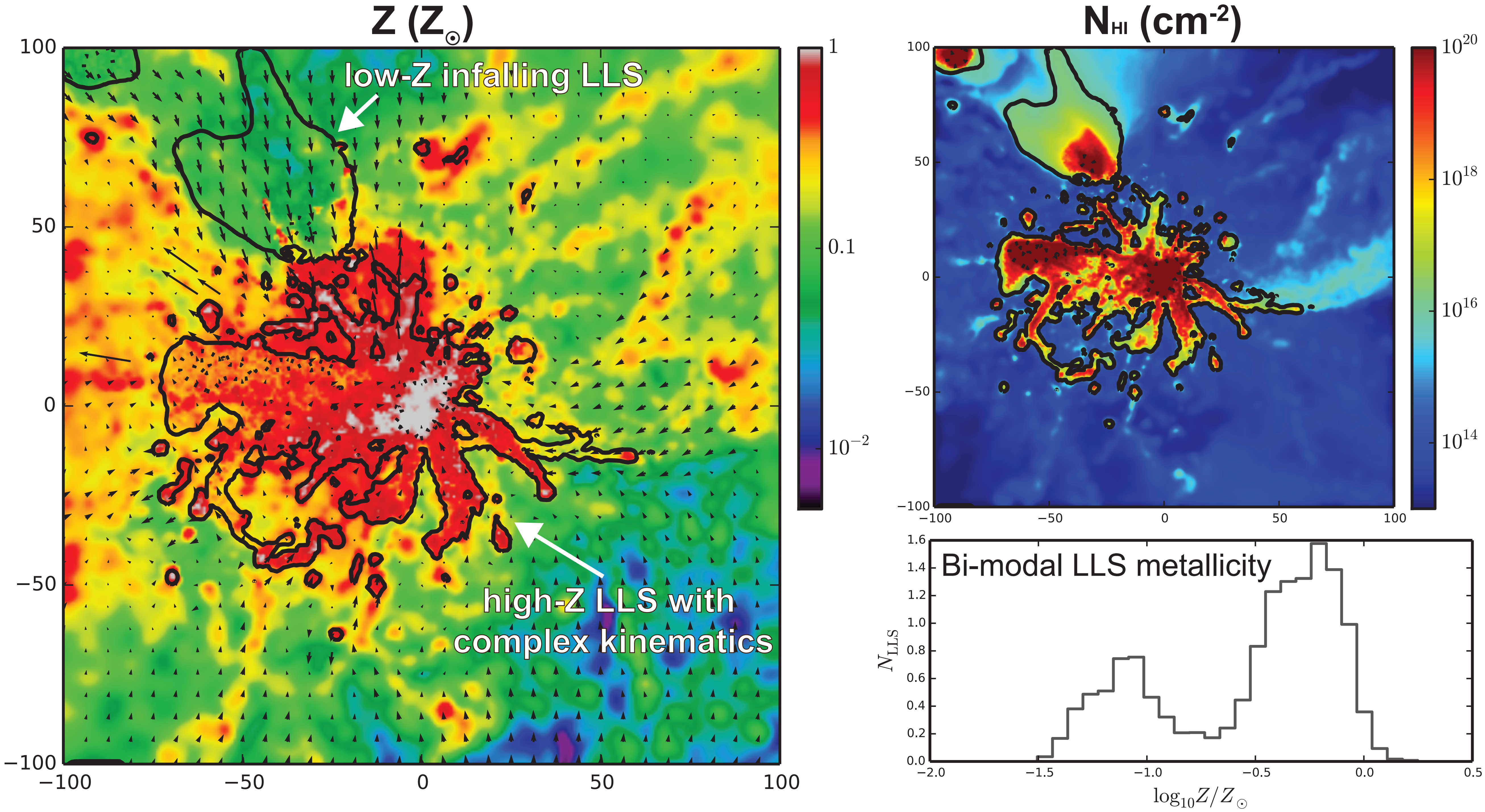
Future: lower-$N_{\rm HI}$ systems, metals, kinematics, …

COS Lyman limit system metallicity bi-modality



Wotta+, in prep.

Low-z Lyman limit systems in FIRE



M_h=5×10^{11} M_{sun} at z=0.5, to be convolved with dn/dM_h

CAFG+, in prep.

Summary

- Global balance between gravity and stellar feedback explains $\dot{\Sigma}_\star - \Sigma_{\rm g}$
- Dependence of SF efficiency on gas fraction can be used to distinguish from local “supersonic turbulence" models
- FIRE: physically-predictive simulations of star formation and stellar feedback in cosmological environments

➡ galactic winds increase HI covering fractions by ~2-3× at *z*~2-3

➡ preliminary: cosmic inflows detected as low-metallicity LLS branch?