SNe-driven Galactic Outflow Feedback in Cosmological Simulations of the CGM

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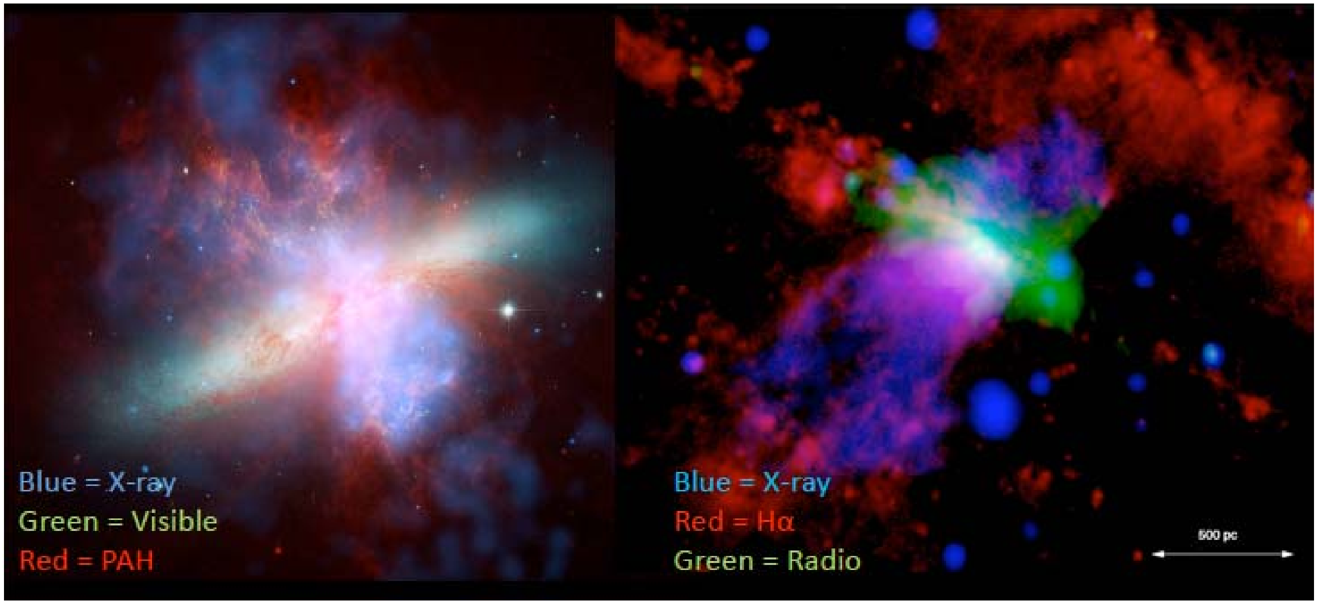
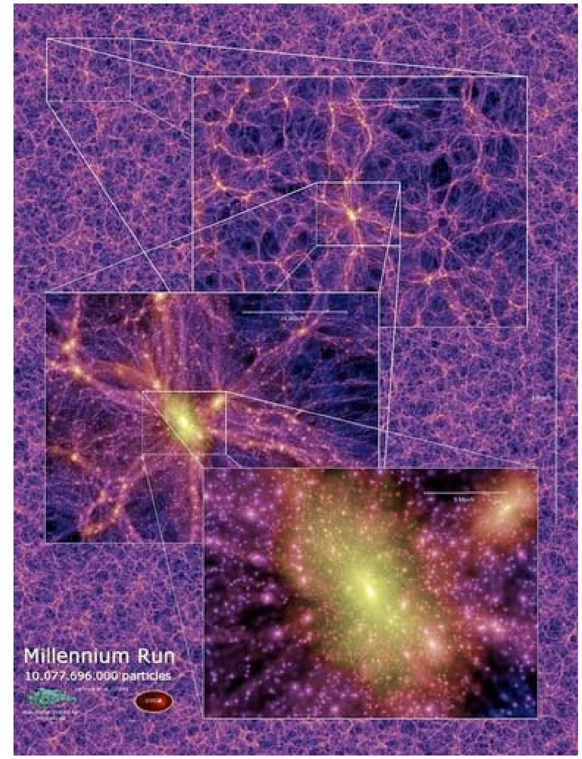
Feeding, Feedback, & Fireworks: Celebrating Our Cosmic Landscape - Hamilton Island, Australia

25 June 2013





Galactic Wind Feedback

- Outflowing gas observed in many galaxies
- Carry gas and metals out from galaxy into the CGM & IGM
- Driven by SNe / AGN
  - From multiphase ISM
  - Thermal, radiation pressure, …

In Cosmological Hydrodynamical Simulations

- Crucial ingredient
- Implemented as subgrid (sub-resolution) physics
- Conference talks (until now) : P.Torrey, R.Somerville, E.Tescari, C.Martin, R.Crain, …

Modified-GADGET3 code: Sub-Grid Physics Incorporated

- Metal-line cooling (Wiersma et al. 2009, MNRAS, 399, 574)
- Star Formation (Springel & Hernquist 2003, MNRAS, 339, 289)
- Stellar & Chemical Evolution (Tornatore et al. 2007, MNRAS, 382, 1050)
  - Metal (C, Ca, O, N, Ne, Mg, S, Si, Fe) release from SN Type-II, Type-Ia, & AGB stars; consider stellar age, mass & yield; different IMF; mass & metal loss from starburst
- Kinetic feedback from SNe
  - Since thermal feedback is inefficient, energy is radiated away quickly
- Same version of GADGET-3 code used for the ANGUS sims by E.Tescari et al.

Kinetic Feedback from SNe-driven Galactic Winds (Springel & Hernquist 2003)

- Mass-loss rate ∝ SFR

$$\frac{dM_w}{dt} = \eta \frac{dM_*}{dt}$$

- Energy-driven wind :

$$\frac{1}{2}\frac{dM_w}{dt} v_w^2 = \chi \varepsilon_{SN} \frac{dM_*}{dt}$$

$$v_w = \sqrt{\frac{2\chi\varepsilon_{SN}}{\eta}}$$

$$\eta = 2$$
$$\varepsilon_{SN(\text{Chabrier 2003})} = 1.1 \times 10^{49} \text{erg} / M_{sun,SF}$$
$$v_w = 400 \text{ km/s}$$
$$\chi = 0.29$$

- Probabilistic method for kicking star-forming gas particles

$$p = 1 - \exp\left(-\frac{\eta x \Delta t}{t_{SFR}}\right)$$

- New particle velocity
  - Along rotation axis

$$v_{new} = v_{old} + v_w \hat{n}$$
$$\hat{n} \rightarrow \vec{v} \times \vec{\nabla}\phi$$

- To enable wind escape from dense, SF phase without directly affecting it → Wind particle decoupled (briefly) from hydro

$$\rho_{dec} = 0.25 \rho_{SF} = 0.25 \times 0.1 \text{ cm}^{-3}$$

Existing Models

- Energy-driven

$$v_w, \eta = \text{constant}$$

  – Springel & Hernquist 2003, Dalla Vecchia & Schaye 2008, Tornatore et al. 2004, 2007, 2010

- Momentum-driven

$$v_w = 3\sigma\sqrt{\frac{L}{L_{crit}} - 1}$$

$$\eta = \frac{\sigma_0}{\sigma}$$

  – Murray, Quataert & Thompson 2005
    - Momentum injection by SN & radiation pressure of photons
  – Oppenheimer & Dave 2006
  – Tescari et al. 2009, 2011

- Multicomponent & variable velocity outflow

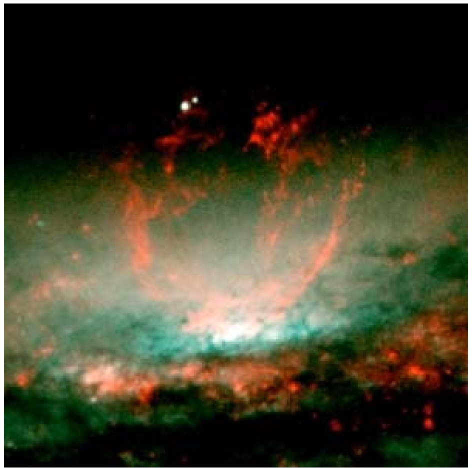
$$v_w = \zeta v_{esc} \propto SFR^{1/3}$$

$$\eta \propto \dot{M}_*$$

  – Choi & Nagamine 2011

- Variable energy-driven
  – Puchwein & Springel 2012

$$v_w, \eta \propto M_{halo}$$



Radially Varying Wind Velocity

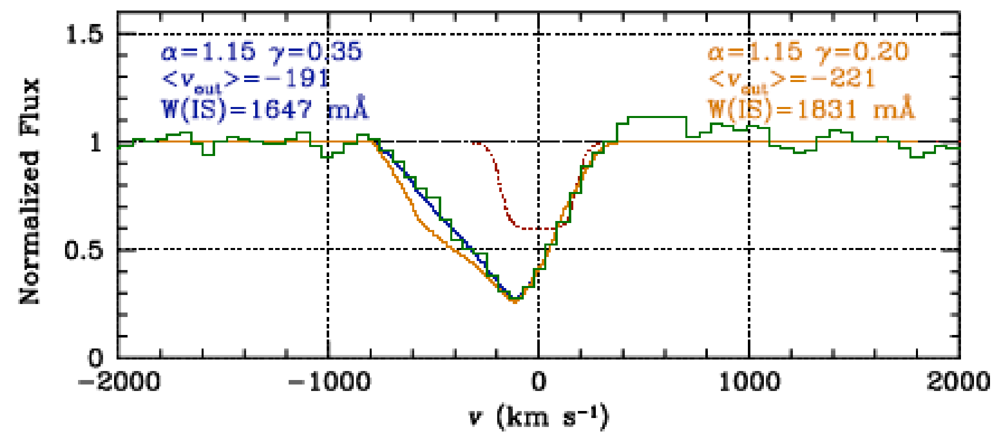
- Observations by Steidel et al. (2010, ApJ, 717, 289)
  - Spectroscopic data fitted by simple model

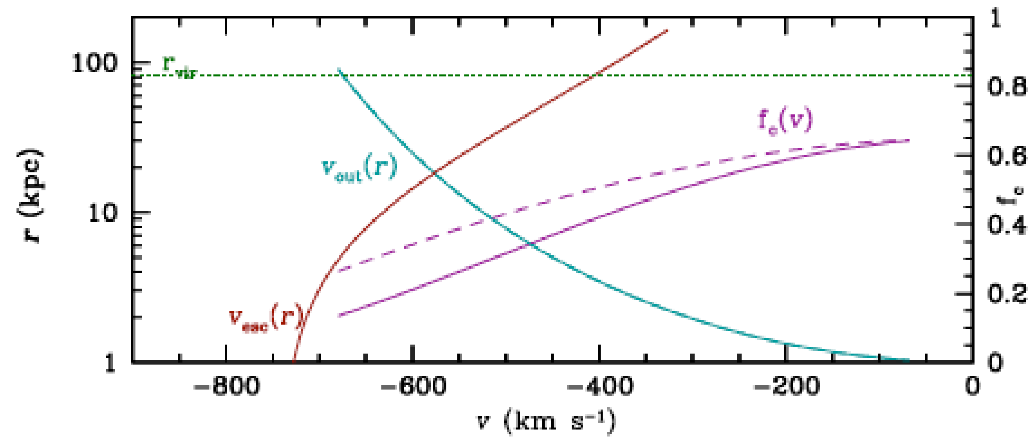
- Quantities are function of galactocentric distance, *r*

- Acceleration & Velocity :

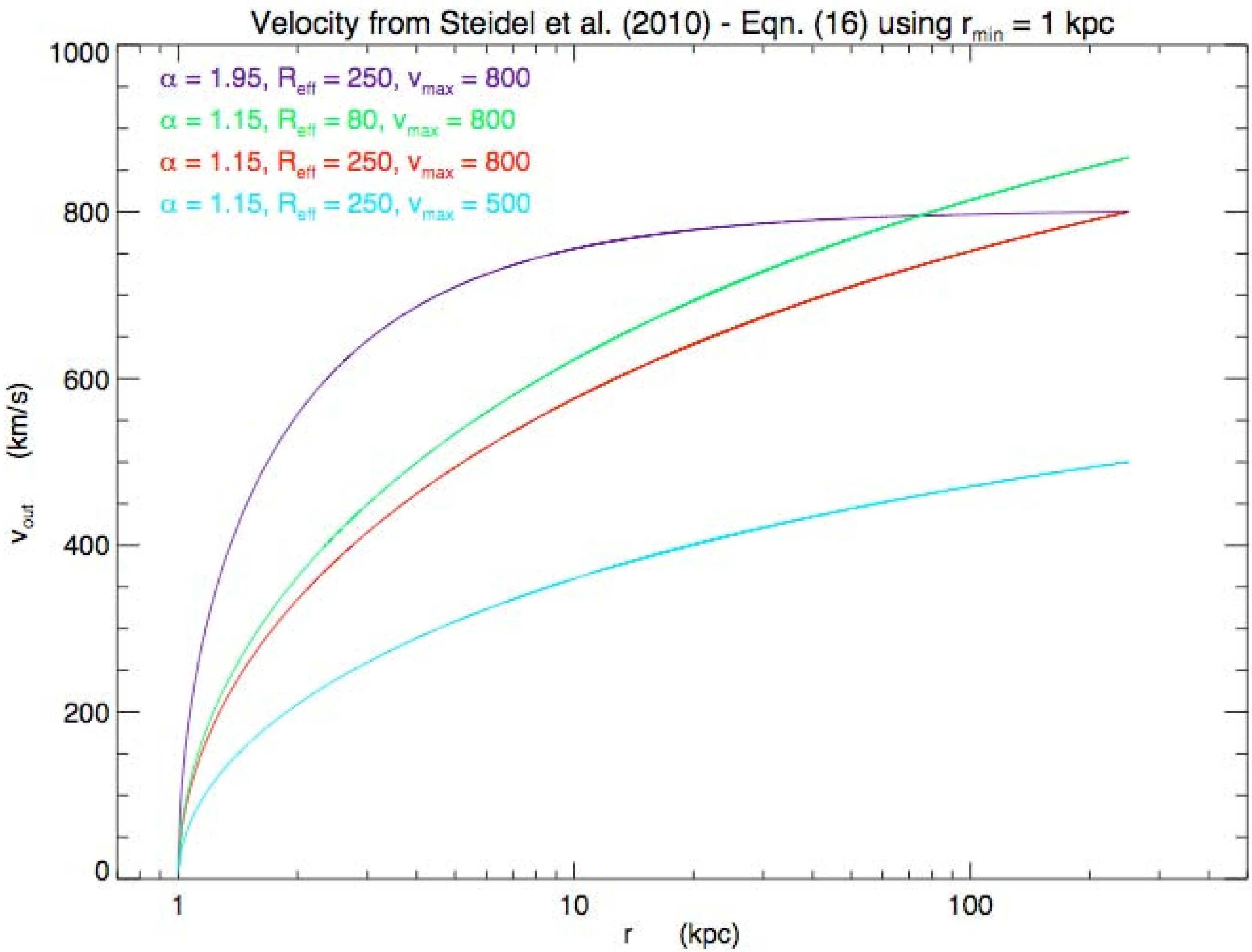
$$a(r) \propto r^{-\alpha} = v\frac{dv}{dr}$$

$$v_w(r) = v_{max}\left(\frac{r_{min}^{1-\alpha} - r^{1-\alpha}}{r_{min}^{1-\alpha} - R_{eff}^{1-\alpha}}\right)^{0.5}$$





Our Modification in GADGET3:
Radial Gradient of Outflow Velocity (Barai et al. 2013, MNRAS, 430, 3213)



Simulations

- Modified-G3 code

$$(5\ h^{-1}\ \mathrm{Mpc})^3,\ N = 2\times128^3,\ \mathrm{m}_{gas} = 7.66\times10^5 h^{-1}M_{Sun},\ L_{soft} = 0.98h^{-1}\mathrm{kpc}.$$
$$(25\ h^{-1}\ \mathrm{Mpc})^3,\ N = 2\times320^3,\ \mathrm{m}_{gas} = 6.13\times10^6 h^{-1}M_{Sun},\ L_{soft} = 1.95h^{-1}\mathrm{kpc}$$
$$\text{upto } z \sim 2.$$

- NW : no-wind (cooling + SF + chemical evolution)

- CW : Energy-driven constant-velocity $v_w = 400\ \mathrm{km/s}$

Outflow with radial velocity gradient, motivated by observations

- RVWa : Radially varying with fixed parameters (Steidel et al. 2010)

$$v_w(r) = v_{\max}\left(\frac{r_{\min}^{1-\alpha} - r^{1-\alpha}}{r_{\min}^{1-\alpha} - R_{eff}^{1-\alpha}}\right)^{0.5}$$

- RVWb : Parameters dependent on halo mass (Martin 2005)

$$R_{eff} = R_{200}\left(M_{halo}, z\right)$$
$$v_{\max} = 2v_{circ} = 2\sqrt{GM_{halo}/R_{200}}$$

Different Wind Models

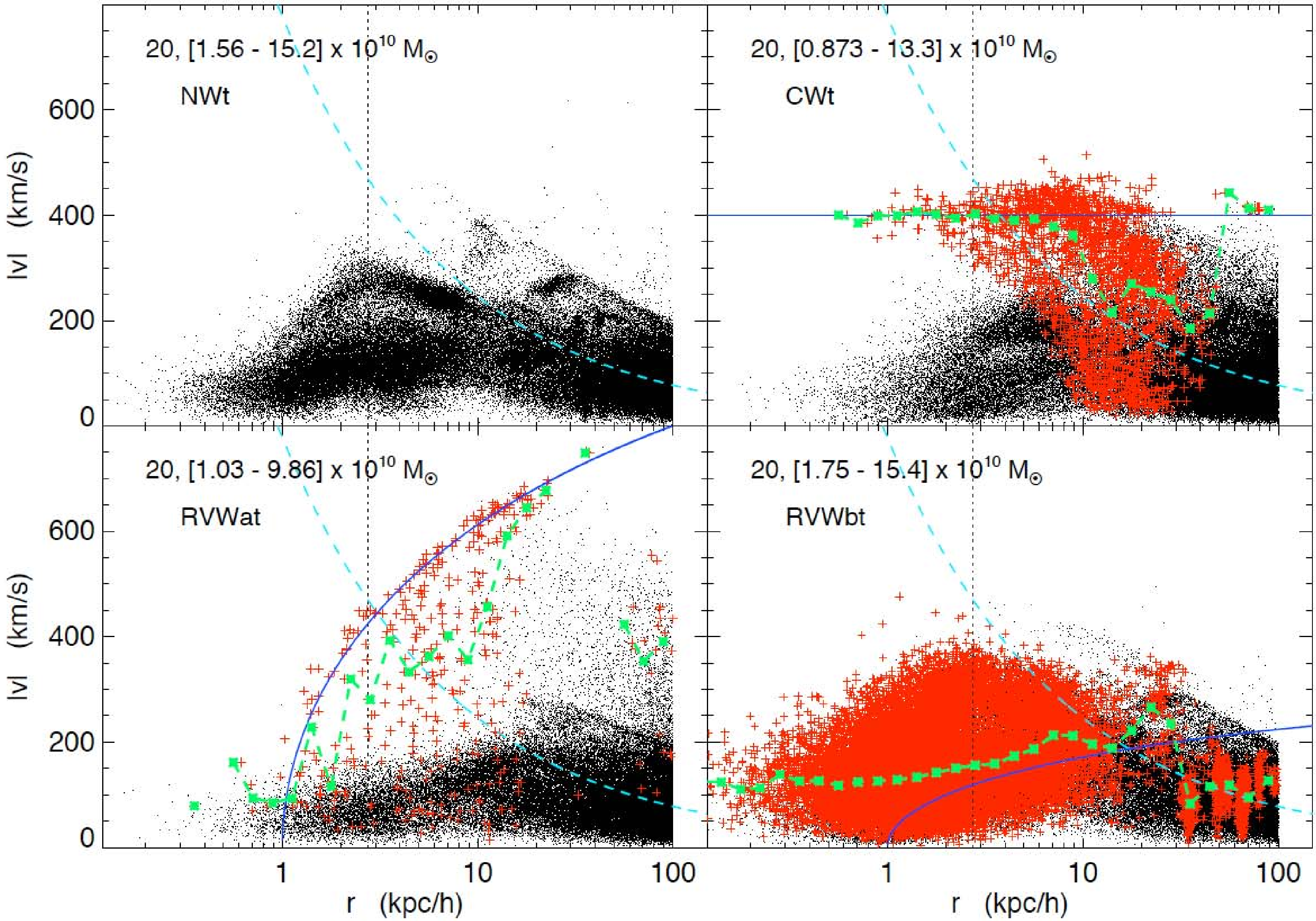
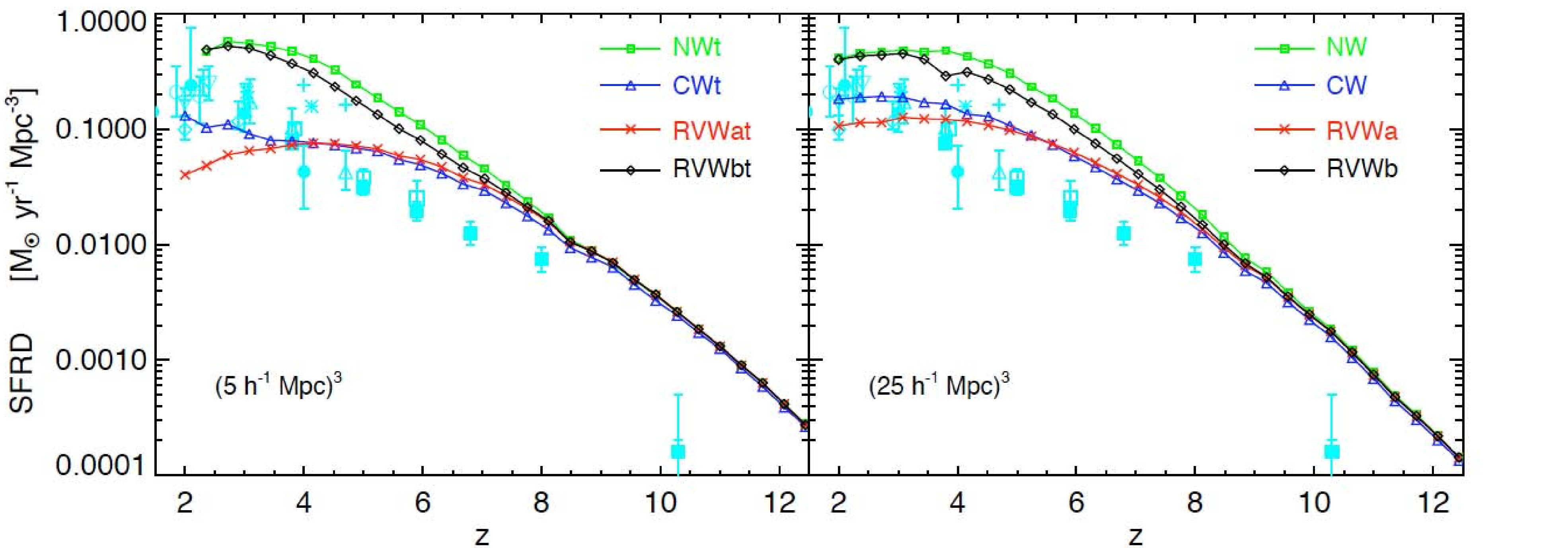


Figure 2. Velocity magnitude of the gas as a function of distance from galaxy center at $z = 2.44$ in the SB runs with different wind models: no wind (top-left), energy-driven constant-velocity wind (top-right), radially varying wind with fixed parameters (bottom-left) and radially varying wind with parameters dependent on halo mass (bottom-right). All the gas particles within $100h^{-1}$ kpc from the

Star Formation Rate Density Evolution

Cucciati et al. 2012, A&A, 539, A31 (VVDS)

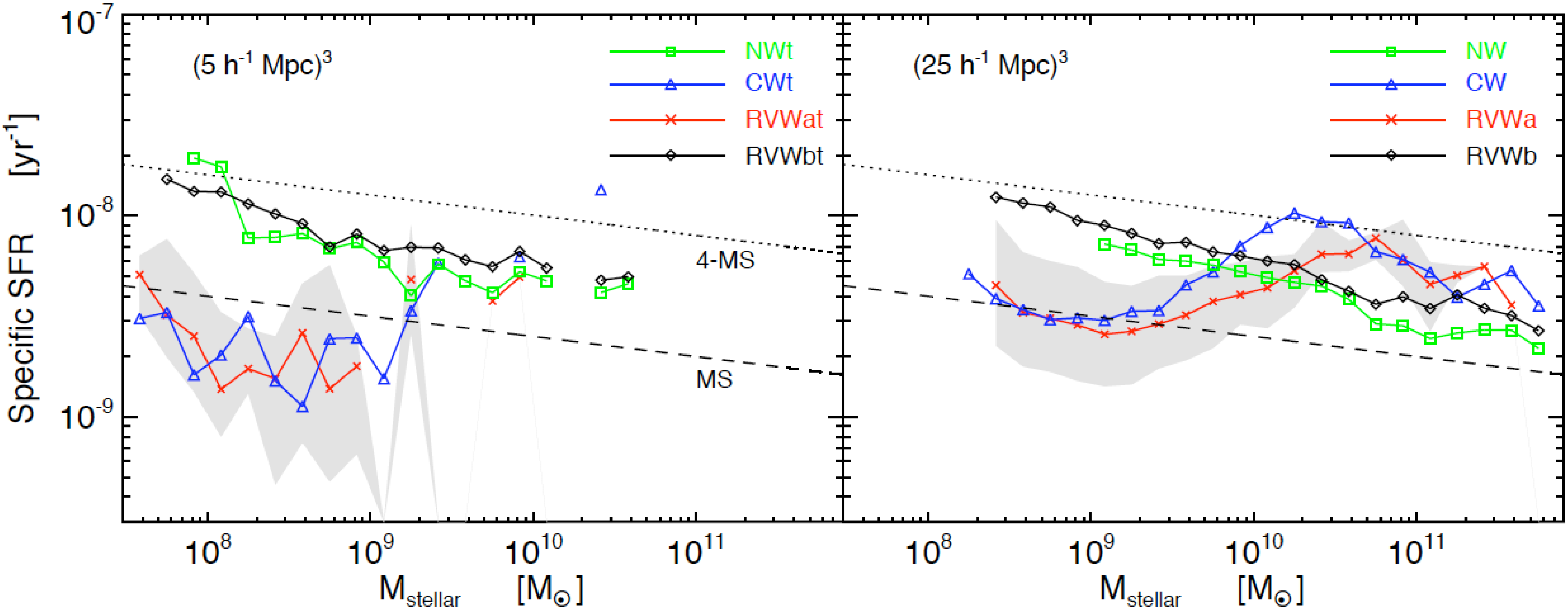
Bouwens et al. 2012, ApJ, 754, 83 (HUDF09+ERS+CANDELS)



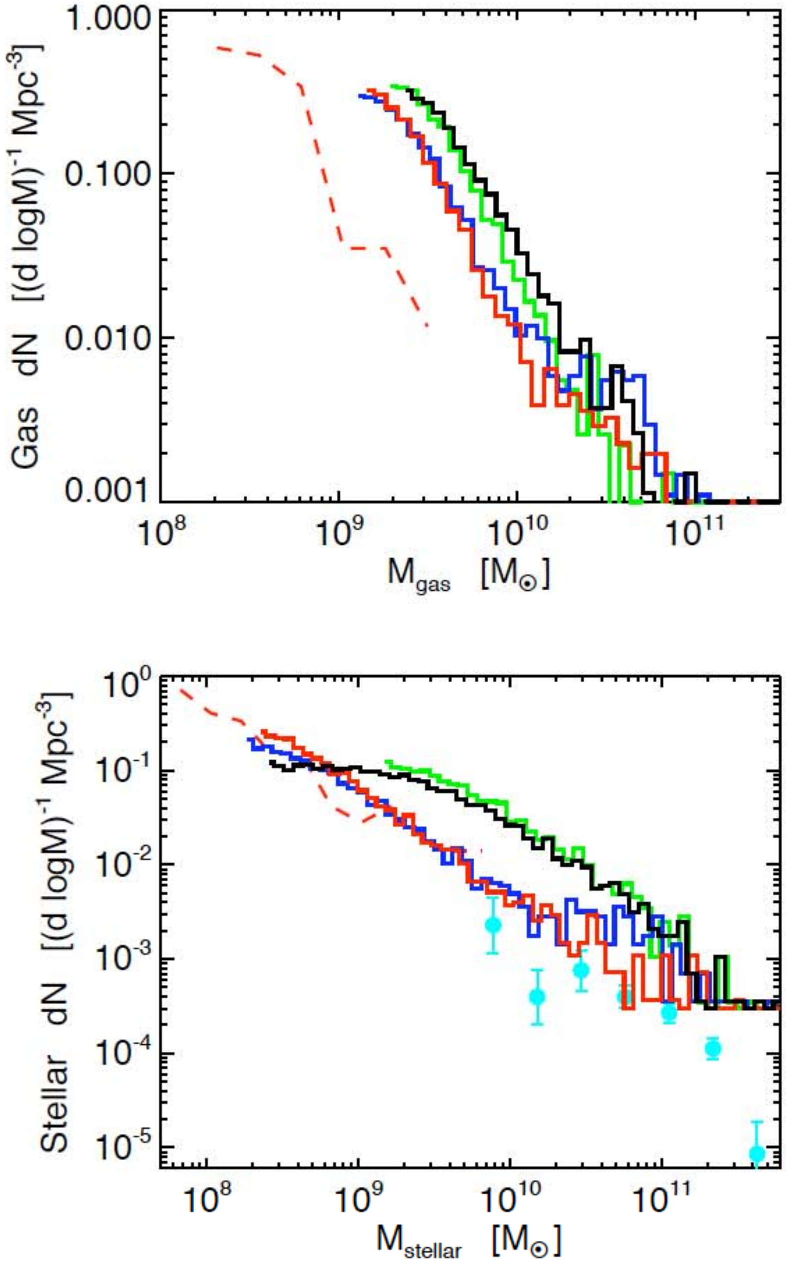
gure 4. Star formation rate density in whole simulation volume as a function of redshift, for the SB runs in the left and LB in the ri nel, with the respective wind models labeled by the color and plotting symbol. The cyan symbols and error bars denote observatio ta from Cucciati et al. (2012) - *filled circles*, and the compilations therein originally from Steidel et al. (1999) - *asterisks*, Ouchi et)04) - *plus signs*, Perez-Gonzalez et al. (2005) - *inverted triangles*, Schiminovich et al. (2005) - *diamonds*, Bouwens et al. (2009) - *o* *uares*, Reddy & Steidel (2009) - *crosses*, Rodighiero et al. (2010) - *open circles*, van der Burg, Hildebrandt & Erben (2010) - *upri* *angles*, Bouwens et al. (2012) - *filled squares*. Detailed comparison is in §3.2.1.

Specific Star Formation Rate

Daddi et al. (2007, ApJ, 670, 156), Rodighiero et al. (2011, ApJ, 739, L40)



e 5. Specific star formation rate as a function of galaxy stellar mass at $z = 1.98$, for the SB runs in the left and LB in th with the respective wind models labeled by the color and plotting symbol. The solid curves denote the median value wi bin for each run, and the grey shaded area enclose the 70 percentiles above and below the median in runs RVWat and RVW) showing the typical scatter. The black dashed line is observational data at $z = 2$ from Daddi et al. (2007), indicating th nce (MS) for star forming galaxies, $\mathrm{SFR} = 200 \left(\frac{M_{\mathrm{stellar}}}{10^{11} M_\odot}\right)^{0.9} M_\odot\ \mathrm{yr}^{-1}$. The black dotted line marks the loci 4 times above tl gion between MS and 4-MS encompass a majority fraction of observed galaxies from Rodighiero et al. (2011).



Gas & Stellar Mass Function of Galaxies at $z = 2.23$

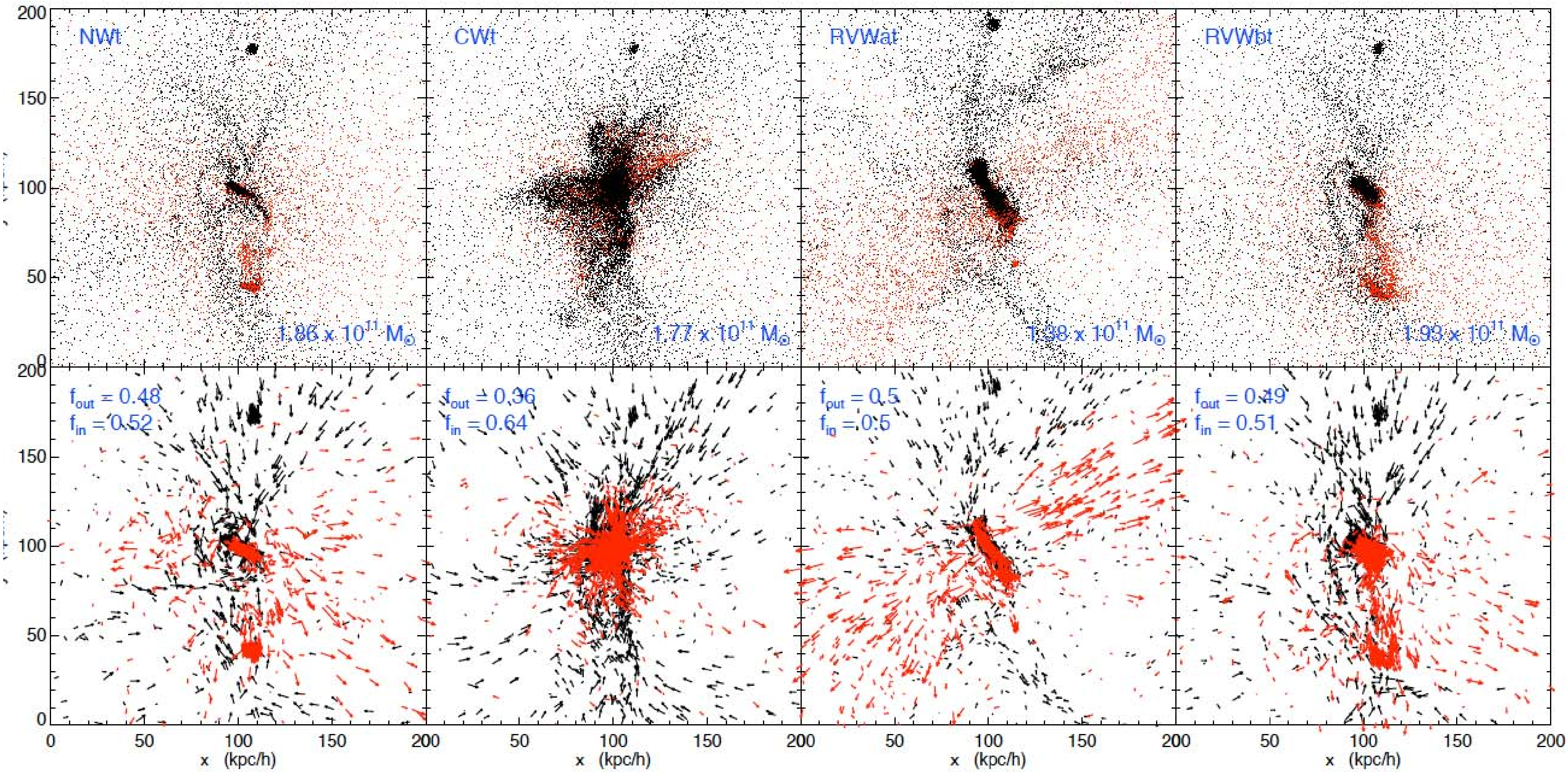
Marchesini et al. 2009, ApJ, 701, 1765

gure 6. Galaxy gas mass function (top-left), stellar mass function (bottom-left), along with gas mass fraction (top-right) and stellar ass fraction (bottom-right) w.r.t. total mass of halos, at $z = 2.23$, of the LB runs shown as the solid curves. In the right panels the solid

Projection of (200/h kpc)^3 volume around most-massive galaxy center at z = 2.12, showing gas properties in 4 runs.

Red - Outflowing, Black - Inflowing.

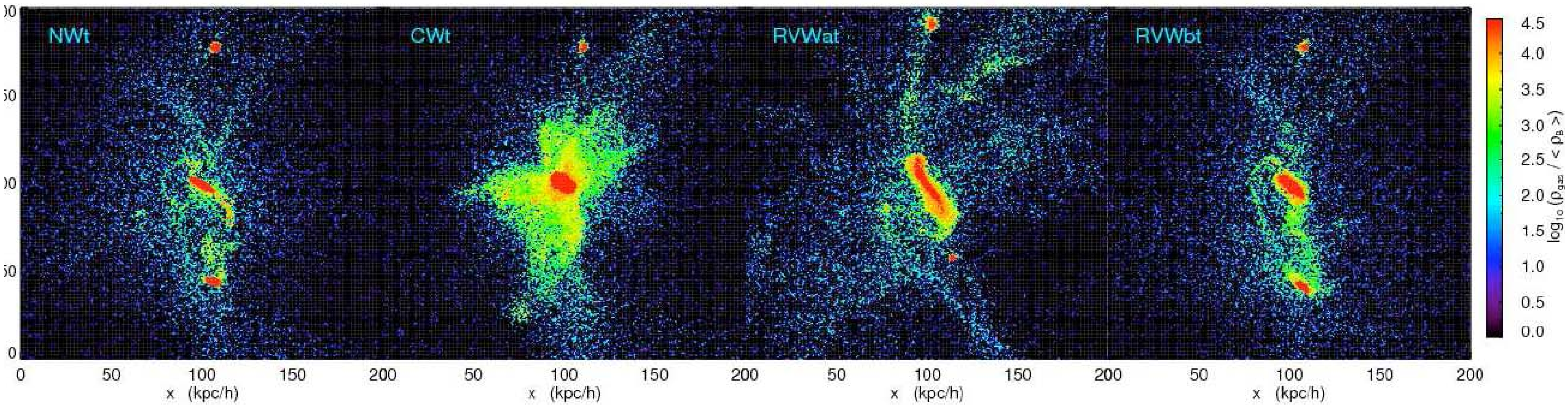
Particle positions

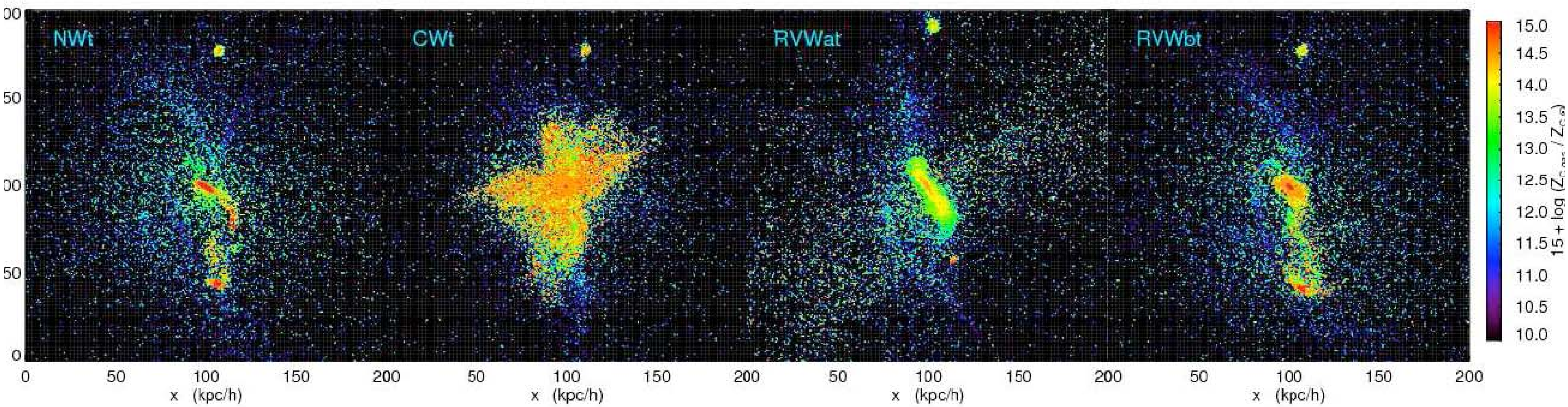


Velocity vectors

Projection of (200/h kpc)^3 volume around most-massive galaxy center at z = 2.12, showing gas properties in 4 runs.

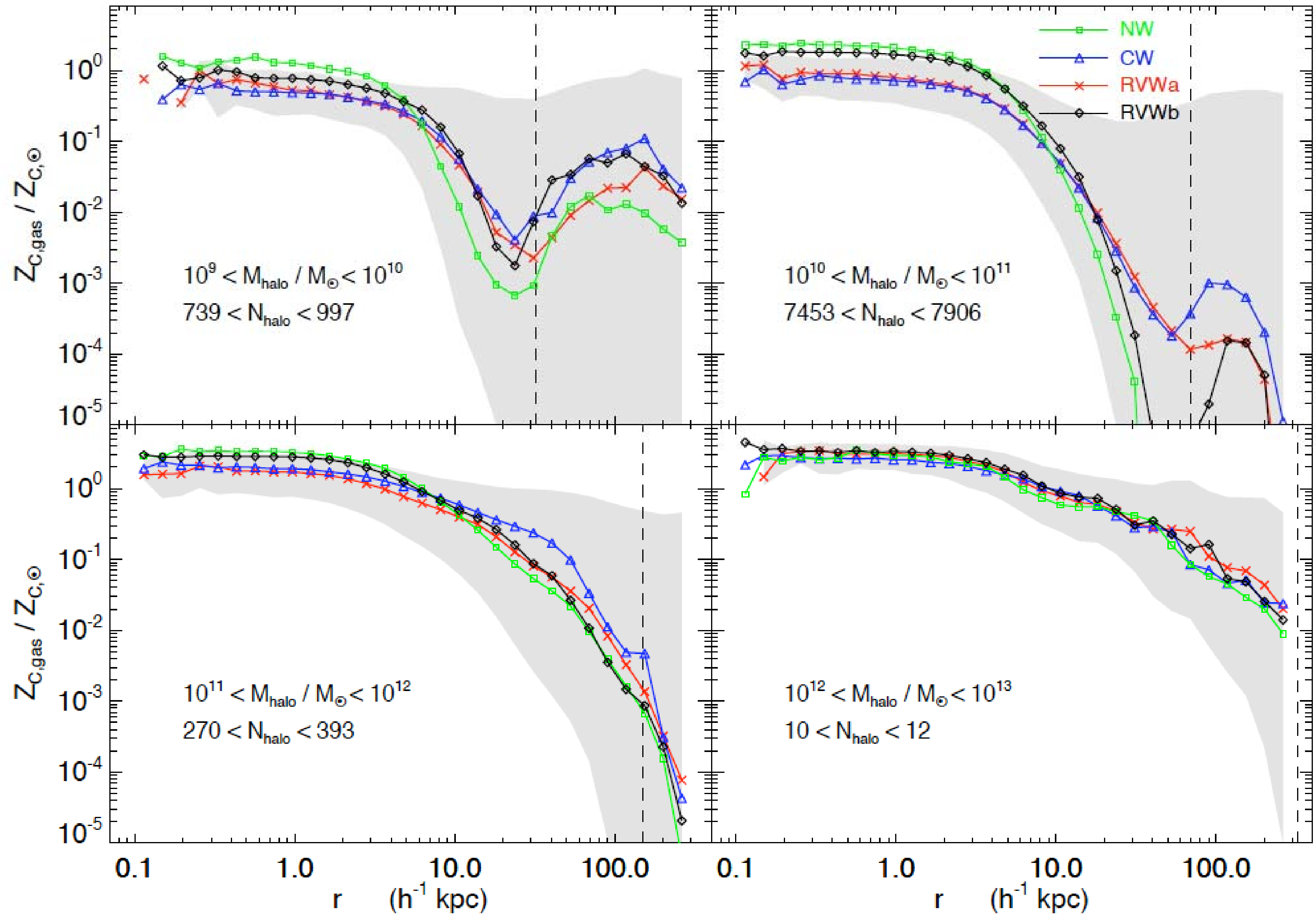
Density





Carbon metallicity

(Gas) Carbon Metallicity - Radial Profile at z=1.98
(Median of All Particles)



Carbon Metallicity vs. Overdensity in T-bins

Schaye et al. 2003, ApJ, 596, 768

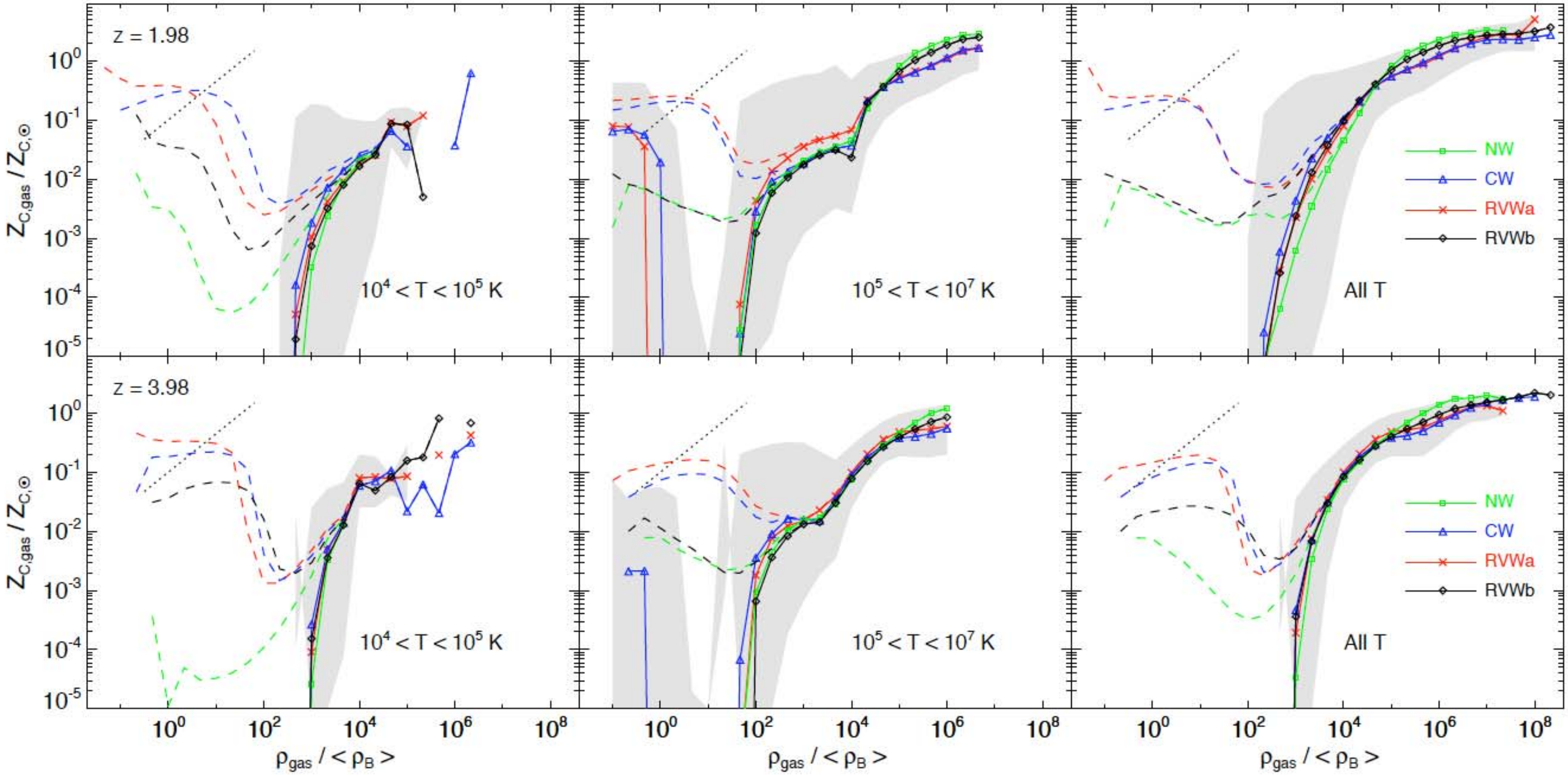


Figure 10. Carbon metallicity versus density contrast of gas at $z = 1.98$ (top row, described in §3.7), and at an earlier epoch $z = 3.98$ (bottom row, discussed in §3.8), for the LB runs labeled by the color and plotting symbol. Gas in three temperature ranges are shown: $10^4 - 10^5$ K (left panels), $10^5 - 10^7$ K (middle), and all the gas (right). The plotted solid curves denote the median value in each density bin. The grey shaded area encloses the 70th percentiles above and below the median in run RVWa (red curve), showing the typical scatter. These medians and percentiles are computed using all (both enriched and non-enriched) gas particles. The dashed curves show the median-Z_C for enriched ($Z_C > 0$) particles only in density bins. The black dotted line in each panel shows the δ-range and $[Z_C - \delta]$ slope obtained from observations by Schaye et al. (2003).

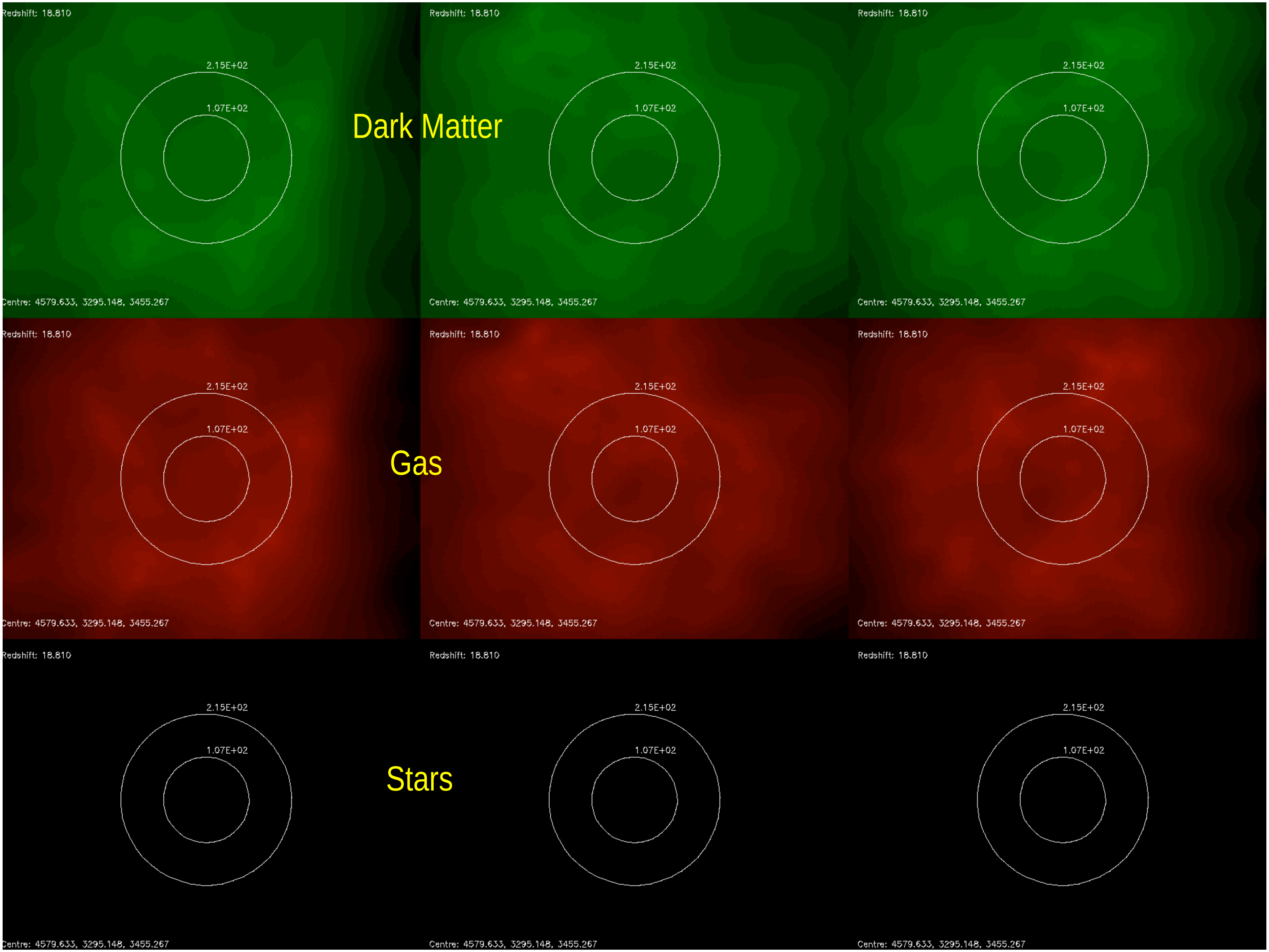
Conclusions

- Can study impact of galactic winds on galaxy & IGM properties
  - Still far away from self-consistently driving winds in cosmol hydro sims
  - Need sub-resolution prescription

- Galactic outflows can:
  - Reduce cosmic SFR density, quench SF in galaxies
  - Enrich the CGM and IGM with metals

- Implementated in G3 a new observationally-motivated model for energy feedback by SNe-driven galactic winds
  - Qualitative same results as constant-*v* outflow
  - RVW gives 2 times lower SFRD than CW
  - Z_C radial profiles : Z_C in RVW is higher than CW inside R_{200} and lower outside
  - Different Z_C - δ slopes in $\delta = 10^{-1.8} – 10^{1.5}$
  - Better galaxy stellar disk?

- <u>Future :</u>
  - Study low-z IGM properties by running sims up to $z = 0$
  - More physics : molecular cooling, AGN feedback


Dark Matter
Gas
Stars
Redshift: 18.810
2.15E+02
1.07E+02
Centre: 4579.633, 3295.148, 3455.267

Extra Slides

Modifications in Code

- Find the galaxy to which each gas particle belong to, & the galaxy center
- Distance of particle from center = r

- Use on-the-fly FOF group finder in G3
- Stellar components of FOF groups = Galaxies

- Obtain stellar groups by linking over
  - Primary particle type: Star
  - Secondary particle type: Gas + DM
  - Linking length = (0.16 $L_{inter\text{-}part}$) / 3
  - Group minimum length = 32

- Find position of member gas particle w/ Maximum Density ⇒ Galaxy Center

- Run FOF more frequently on-the-fly

$$\frac{a_{next}}{a_{prev}} = 1.001$$

- Modify wind velocity

$$v_w = v_w(r)$$

Table 1. Simulations Parameters [a]

Run Name	$L_{\rm box}$ [b] $[h^{-1}$ Mpc$]$	$N_{\rm part}$ [c]	$m_{\rm gas}$ [d] $[h^{-1} M_{\odot}]$	$L_{\rm soft}$ [e] $[h^{-1}$ kpc$]$	Galactic Wind Feedback
			Smaller-Box Runs [f]		
NWt	5	128^3	7.66×10^5	0.98	No Wind
CWt	5	128^3	7.66×10^5	0.98	Energy-driven constant-velocity $v = 400$ km/s
RVWat	5	128^3	7.66×10^5	0.98	Radially varying with parameter set 1 [g]
RVWbt	5	128^3	7.66×10^5	0.98	Radially varying with parameter set 2
			Larger-Box Runs [h]		
NW	25	320^3	6.13×10^6	1.95	No Wind
CW	25	320^3	6.13×10^6	1.95	Energy-driven constant-velocity $v = 400$ km/s
RVWa	25	320^3	6.13×10^6	1.95	Radially varying with parameter set 1 [g]
RVWb	25	320^3	6.13×10^6	1.95	Radially varying with parameter set 2

[a] All simulations have the same physics described in §2, with the wind model varied. There is no AGN feedback.

[b] $L_{\rm box}$ = Comoving side of cubic simulation volume.

[c] $N_{\rm part}$ = Number of particles each of gas and dark matter in the initial condition.

[d] $m_{\rm gas}$ = Mass of gas particle (which has not undergone any star-formation).

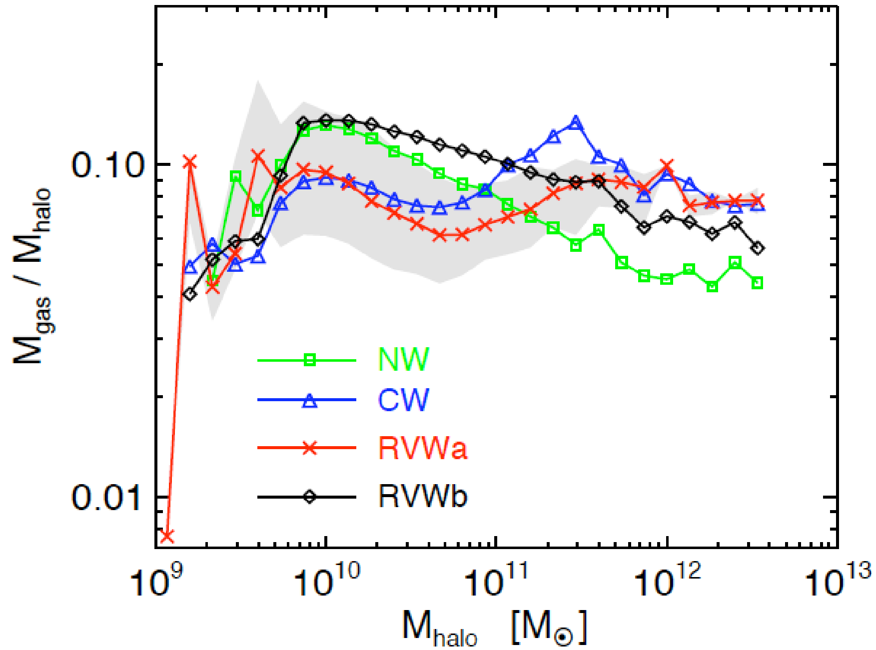
[e] $L_{\rm soft}$ = Gravitational softening length (of all particle types). The minimum gas smoothing length is set to a fraction 0.001 of $L_{\rm soft}$.

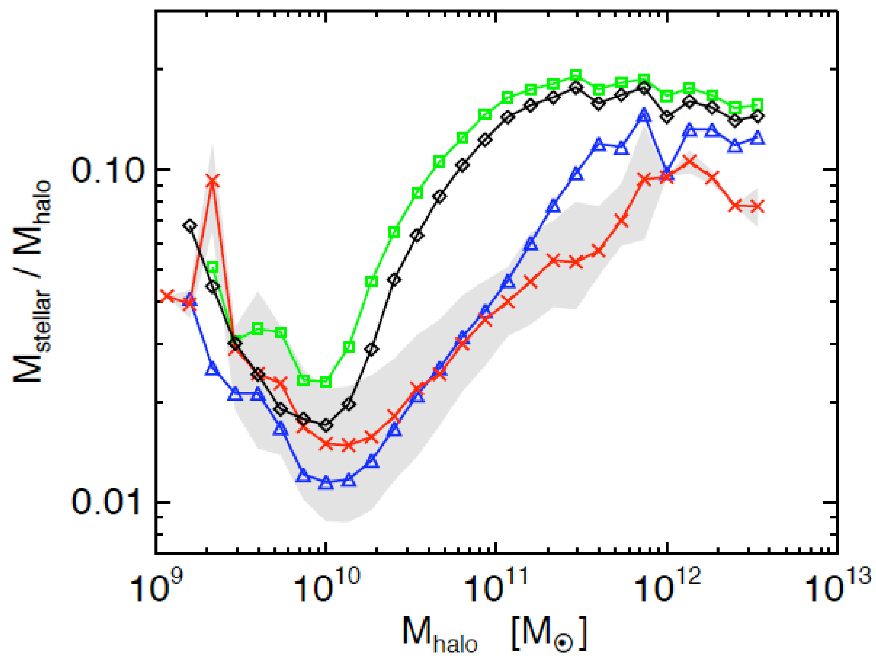
[f] Run names ending with "t" are smaller boxsize runs for test purposes, done up to $z \sim 3$.

[g] Parameters of radially varying wind model (§2.2): $r_{min} = 1 h^{-1}$ kpc, $R_{eff} = 100 h^{-1}$ kpc, $v_{max} = 800$ km/s, $\alpha = 1.15$.

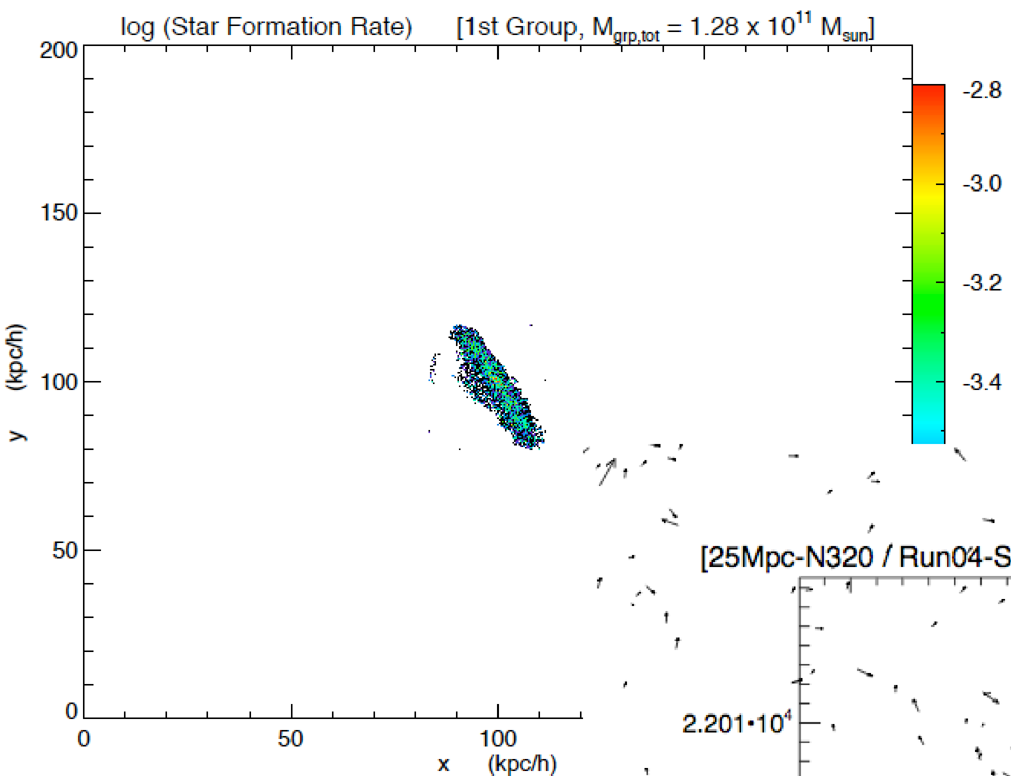
Gas & Stellar Mass Fraction in Galaxies at z = 2.23

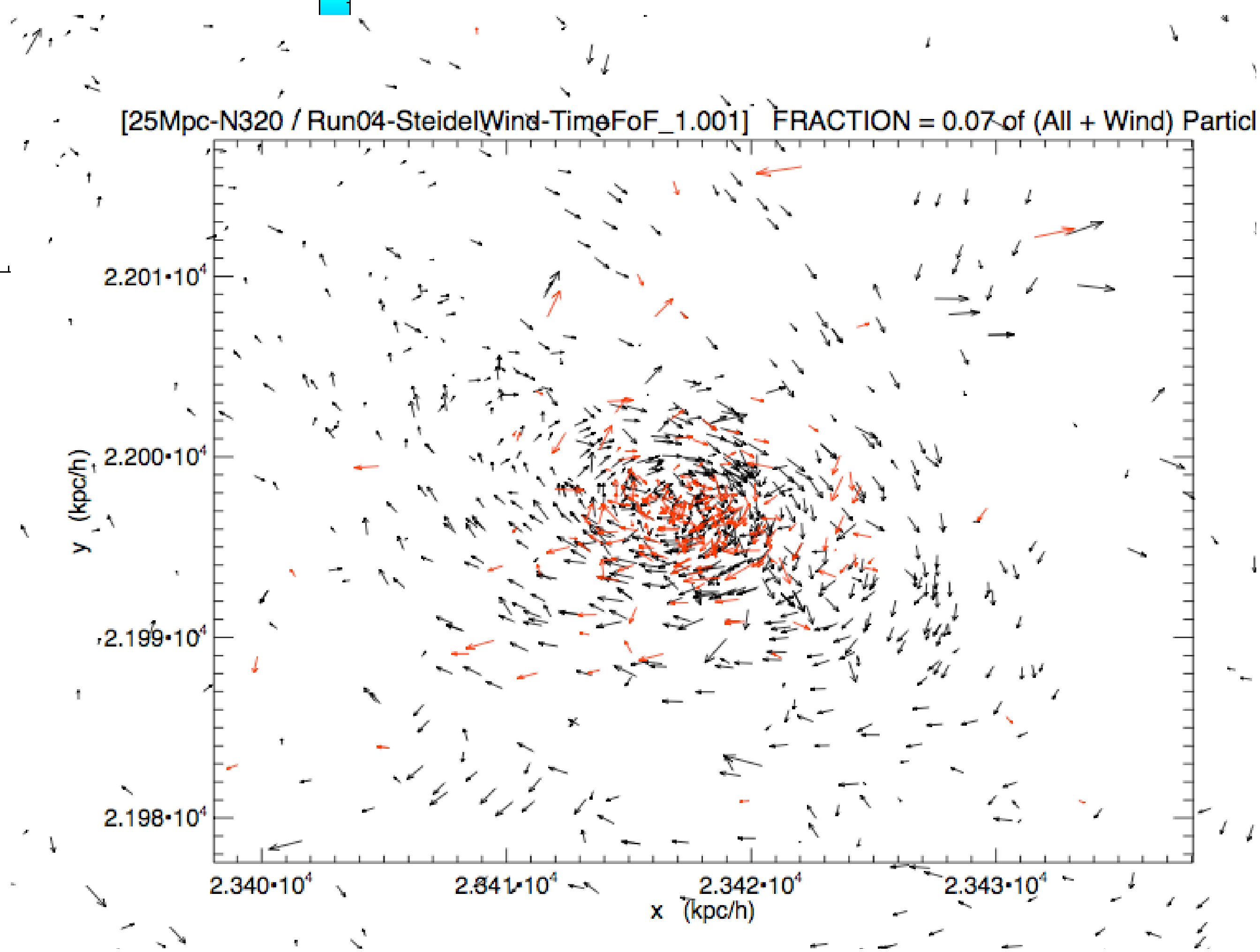
- Gas fractions < $(\Omega_{B,0}/\Omega_{M,0})$
- Consistent with gas mass fraction in *DIANOGA* cluster halos, when extrapolated to $M < 10^{13}\ M_\odot$ halos at $z \sim 2$
  - Talk by S. Planelles





Formation of Galaxy Stellar Disk





Velocity Field of Gas Particles in run RVWa

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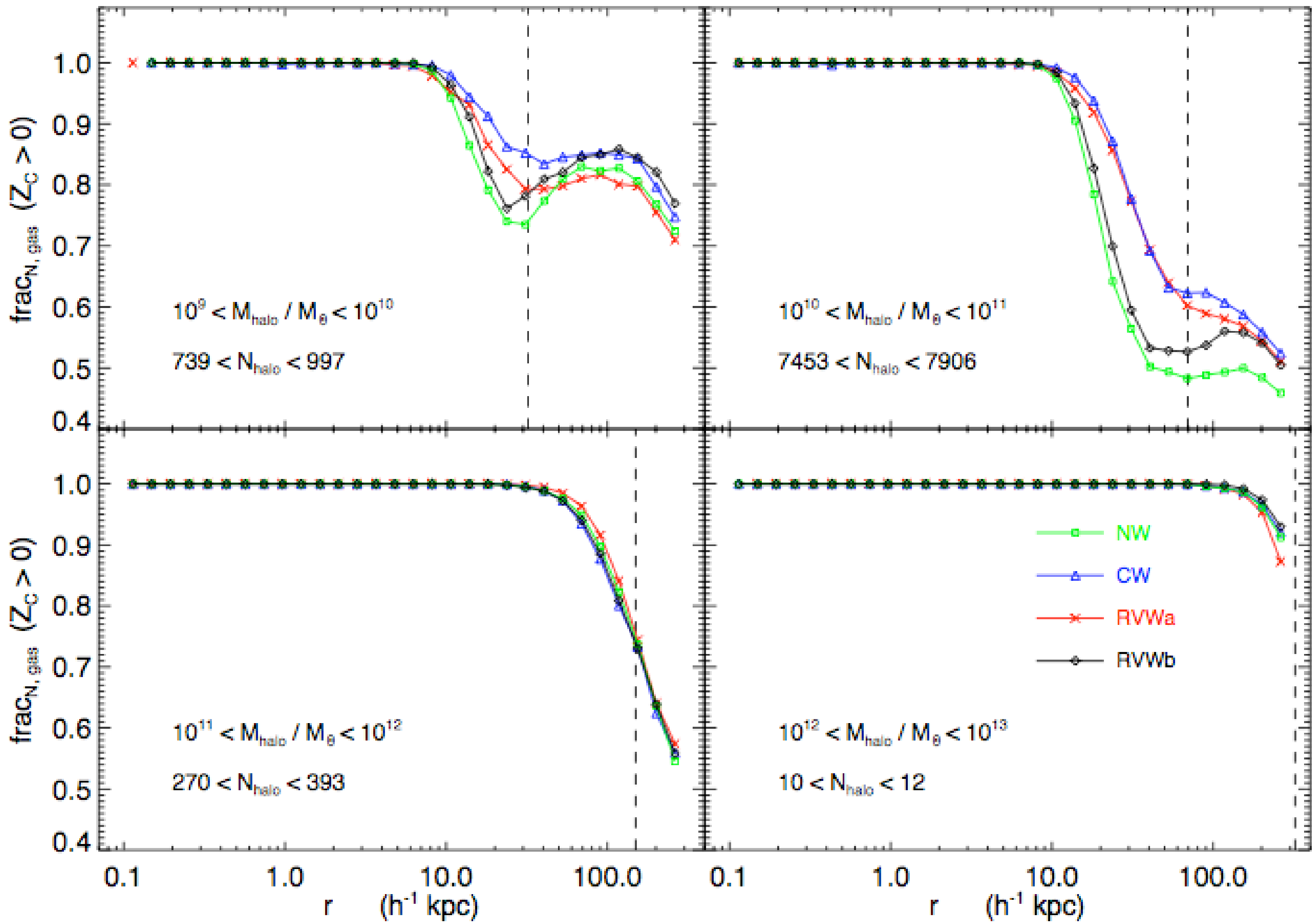
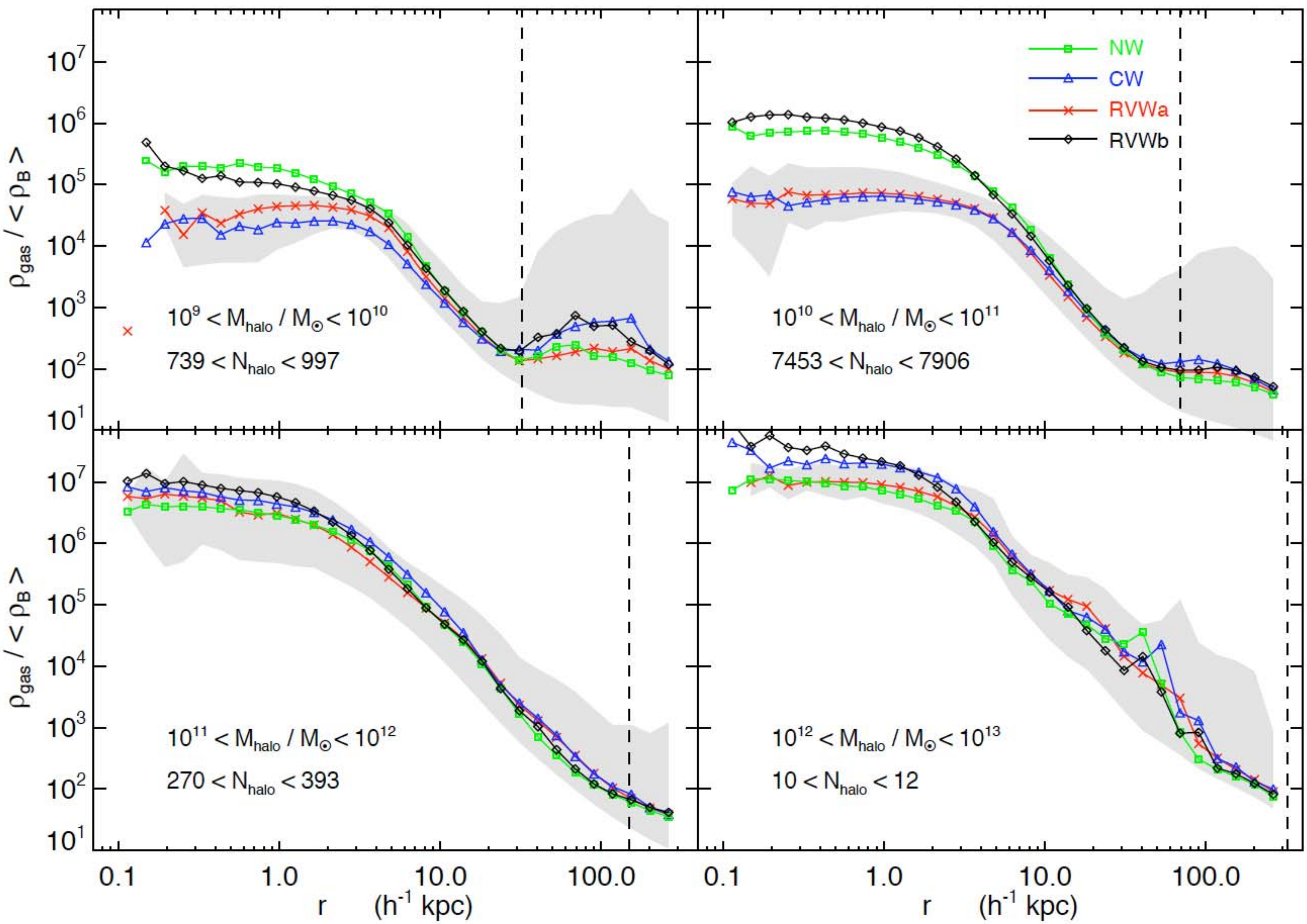
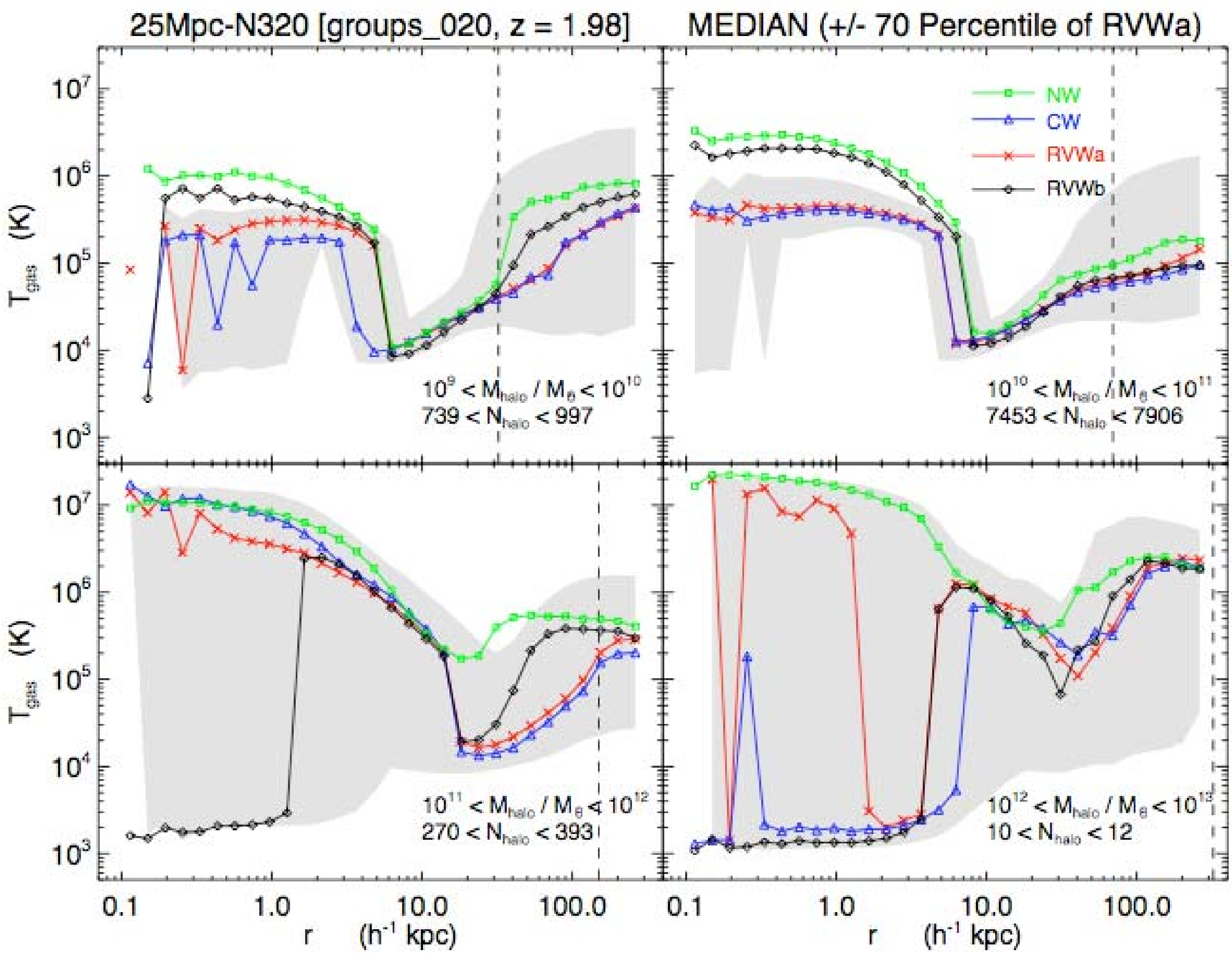
Number Fraction of Gas Particles Enriched at z=1.98



Gas Density - Radial Profile at z=1.98



(Gas) Temperature - Radial Profile at z=1.98



(Gas) CIV Fraction - Radial Profile at z=1.98