Galactic Wind Model with Radial Velocity Gradient

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(cosmo-IGM project)

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

- Mass-loss rate ∝ SFR

$$\dot{M}_w = \eta \dot{M}_*$$

- Energy-driven wind :

$$\frac{1}{2}\dot{M}_w v_w^2 = E_{SN}\dot{M}_{\#}$$

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

- Probabilistic method for kicking star-forming gas particles

$$p = 1 - \exp\left(-\frac{\eta \dot{m}_* \Delta t}{m_{part}}\right)$$

- 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

Existing Models

- Energy-driven

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

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

- Momentum-driven
  - Oppenheimer & Dave 2006
  - Tescari et al. 2009, 2011

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

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

- Multicomponent & variable velocity outflow
  - Choi & Nagamine 2011

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

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

- Variable energy-driven
  - Puchwein & Springel 2012

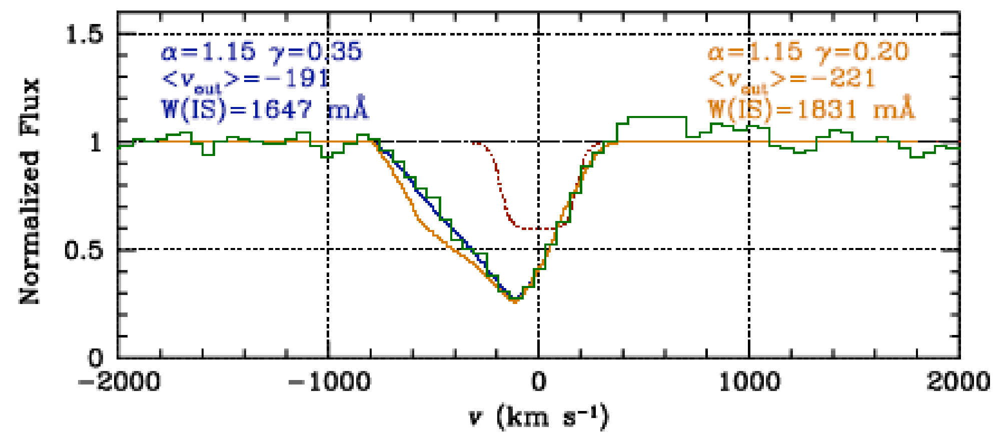
$$v_w, \eta \propto M_{halo}$$

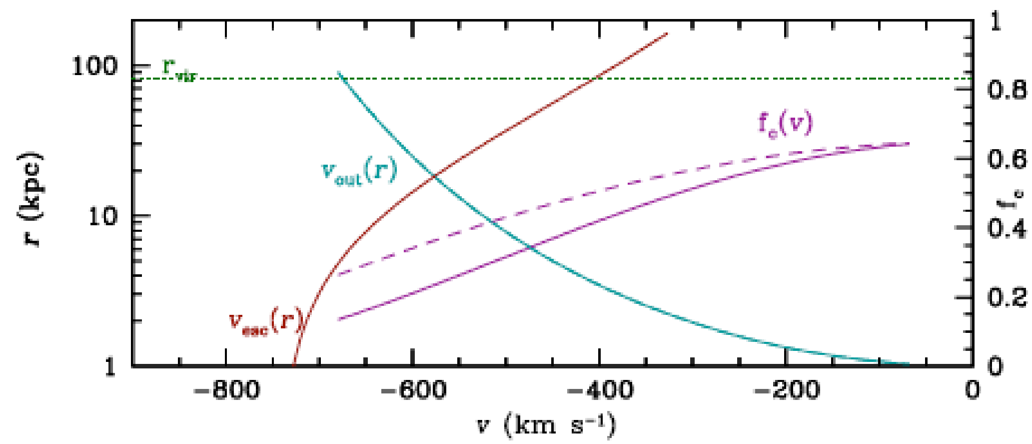
Radially Varying Wind Velocity

- Observations by Steidel et al. 2010
  - Spectroscopic data fitted by simple model
- Quantities are function of galactocentric distance, *r*
- Acceleration & Velocity

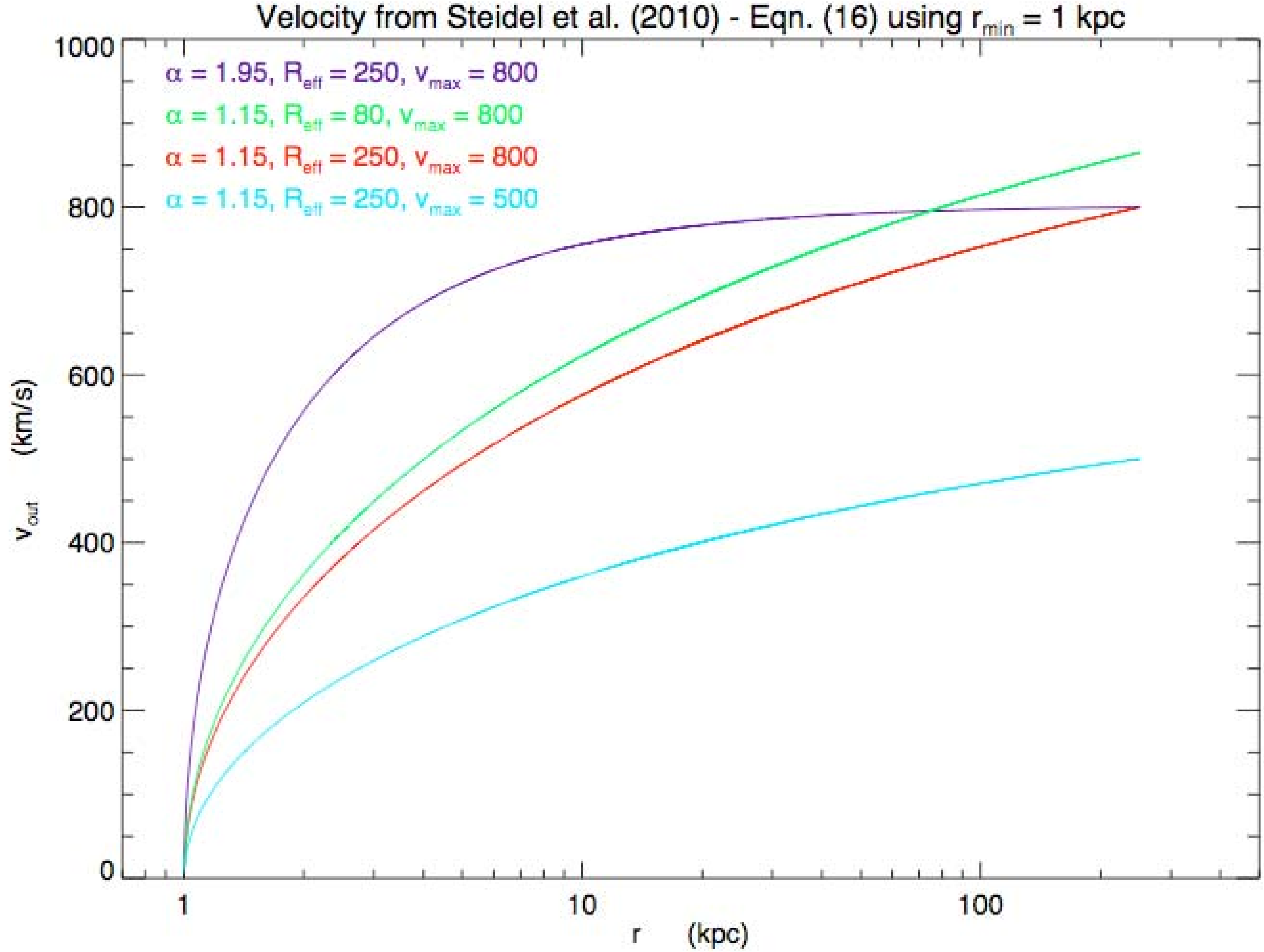
$$a(r) \propto r^{-\alpha} = v\frac{dv}{dr}$$

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





Our Modification in G3: Radial Gradient of Outflow Velocity

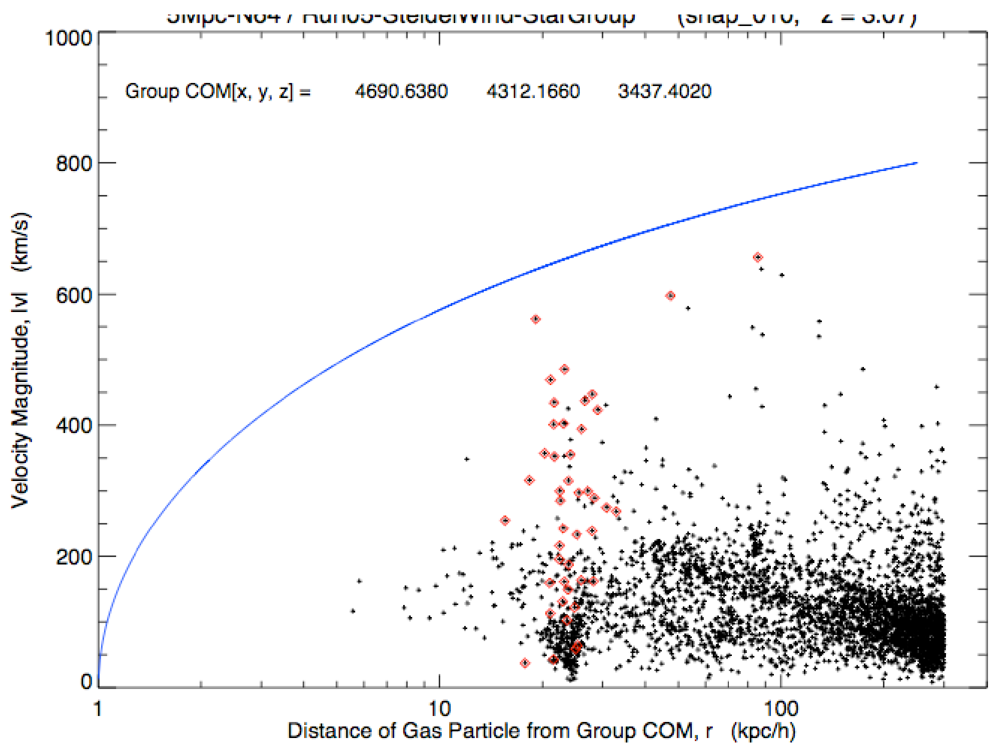


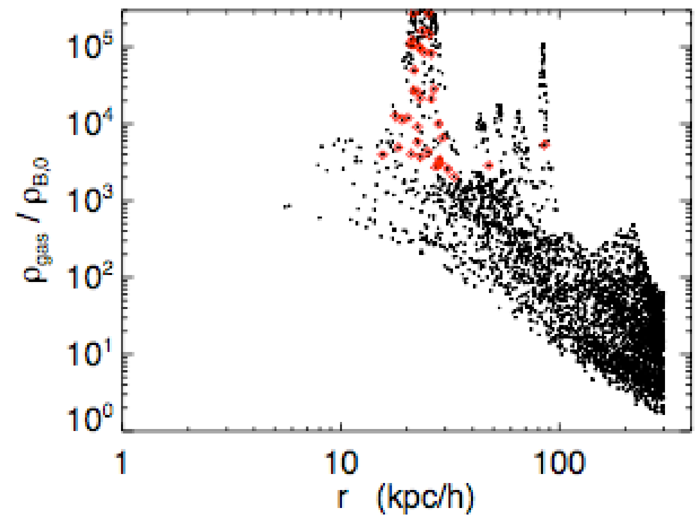
Criticalities

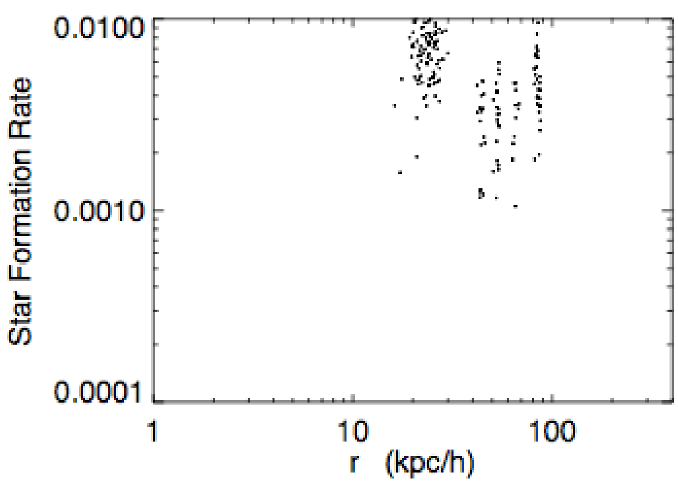
- Find the halo to which each gas particle belong to, and the halo center
- Distance of particle from center = r
- Use on-the-fly FoF group finder in G3

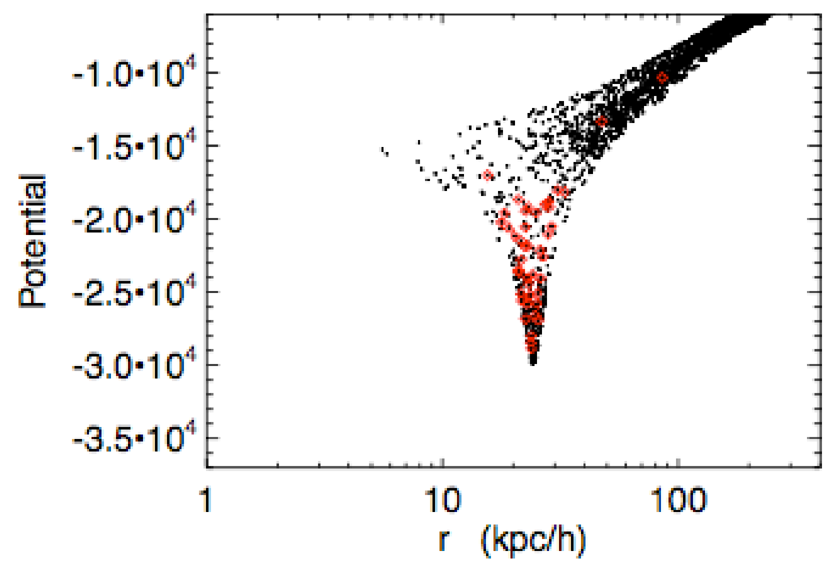
- 1st Attempts
  - Default particle types for linking FoF groups
  - Group COM

- Modify energy-driven wind formalism (lt_sfr.c)
  - $v_w = v_w(r)$


Group COM[x, y, z] = 4690.6380 4312.1660 3437.4020
Velocity Magnitude, |v| (km/s)
Distance of Gas Particle from Group COM, r (kpc/h)


$\rho_{gas} / \rho_{B,0}$
r (kpc/h)


Star Formation Rate
r (kpc/h)


Potential
r (kpc/h)

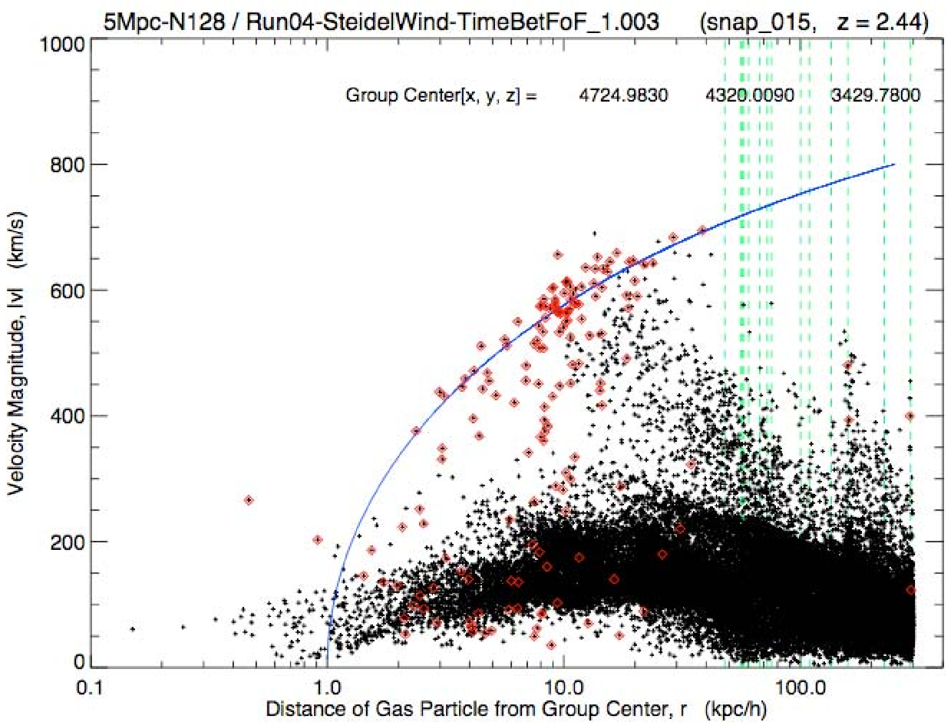
Modifications in Group-Finder (fof.c)

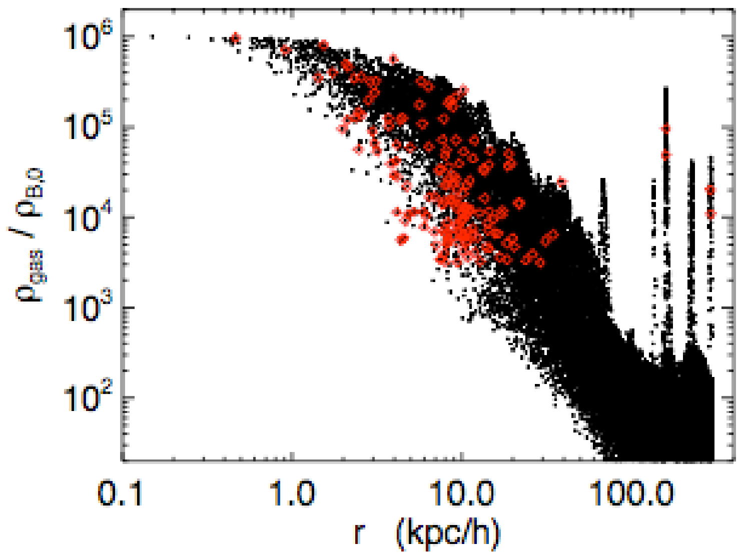
- Stellar components of FoF groups are more stable

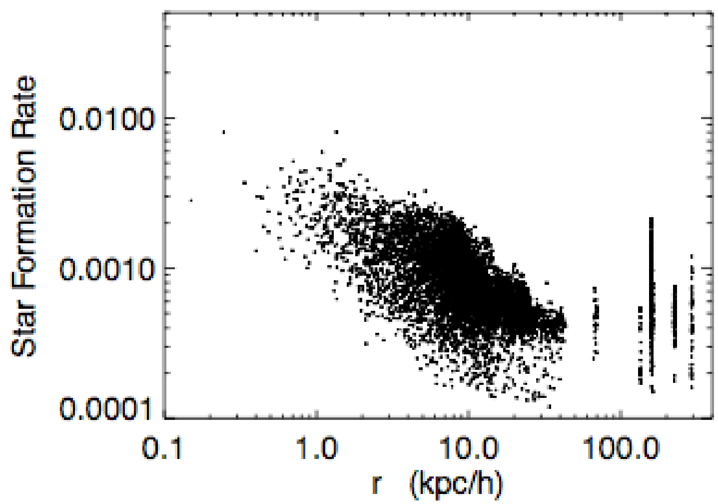
- Obtain stellar groups by linking over
  - Primary particle type: Star
  - Secondary particle type: Gas + DM
  - Group minimum length = 32

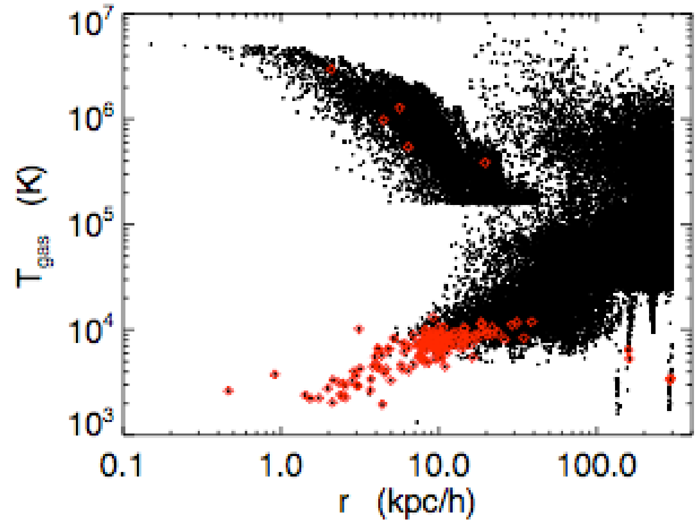
- Find position of member gas particle w/ Maximum Density → Group center

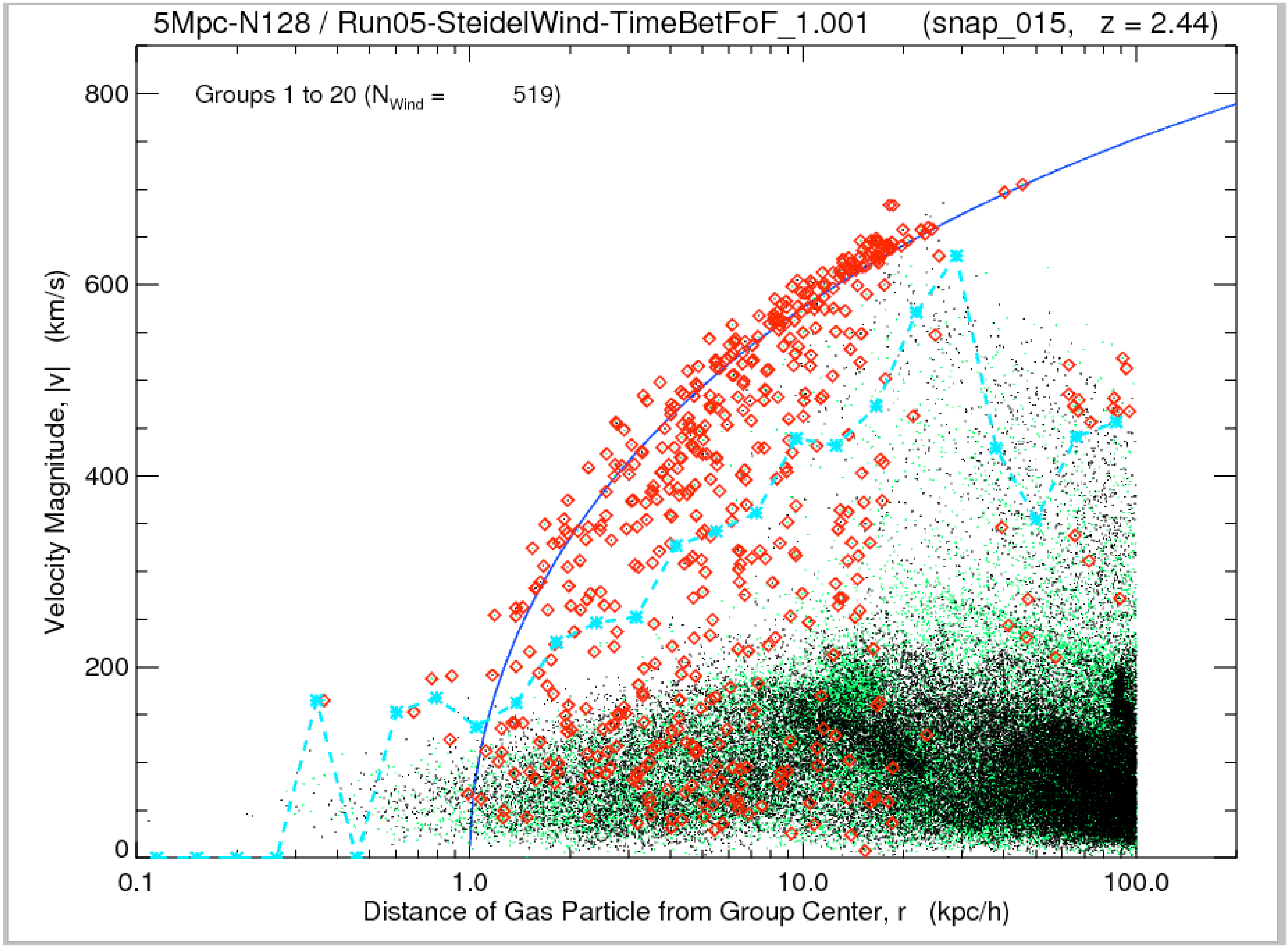
- Run FoF more frequently on-the-fly $\frac{a_{next}}{a_{prev}} = 1.001$


5Mpc-N128 / Run04-SteidelWind-TimeBetFoF_1.003 (snap_015, z = 2.44)
Group Center[x, y, z] = 4724.9830 4320.0090 3429.7800
Velocity Magnitude, |v| (km/s)
Distance of Gas Particle from Group Center, r (kpc/h)


$\rho_{gas} / \rho_{B,0}$
r (kpc/h)


Star Formation Rate
r (kpc/h)


T_{gas} (K)
r (kpc/h)


5Mpc-N128 / Run05-SteidelWind-TimeBetFoF_1.001 (snap_015, z = 2.44)
Groups 1 to 20 (N_{Wind} = 519)
Velocity Magnitude, |v| (km/s)
800
600
400
200
0
0.1
1.0
10.0
100.0
Distance of Gas Particle from Group Center, r (kpc/h)

Simulations

- With LTG3 code + modifications
  - Run on *cosmos@Cambridge*

$$5\ h^{-1}\ \mathrm{Mpc},\ N = 2\times 128^3.$$
$$25\ h^{-1}\ \mathrm{Mpc},\ N = 2\times 320^3.$$
$$\text{upto } z \sim 2.$$

- NW : no-wind (cooling + SF + chemical evolution)
  - Wiersma et al. 2009, Springel & Hernquist 2003, Tornatore et al. 2007
- CW : Energy-driven constant-velocity

$$v_w = 400\ \mathrm{km/s}$$

Recent implementations in G3 - Outflow with radial velocity gradient, motivated by observations

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

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

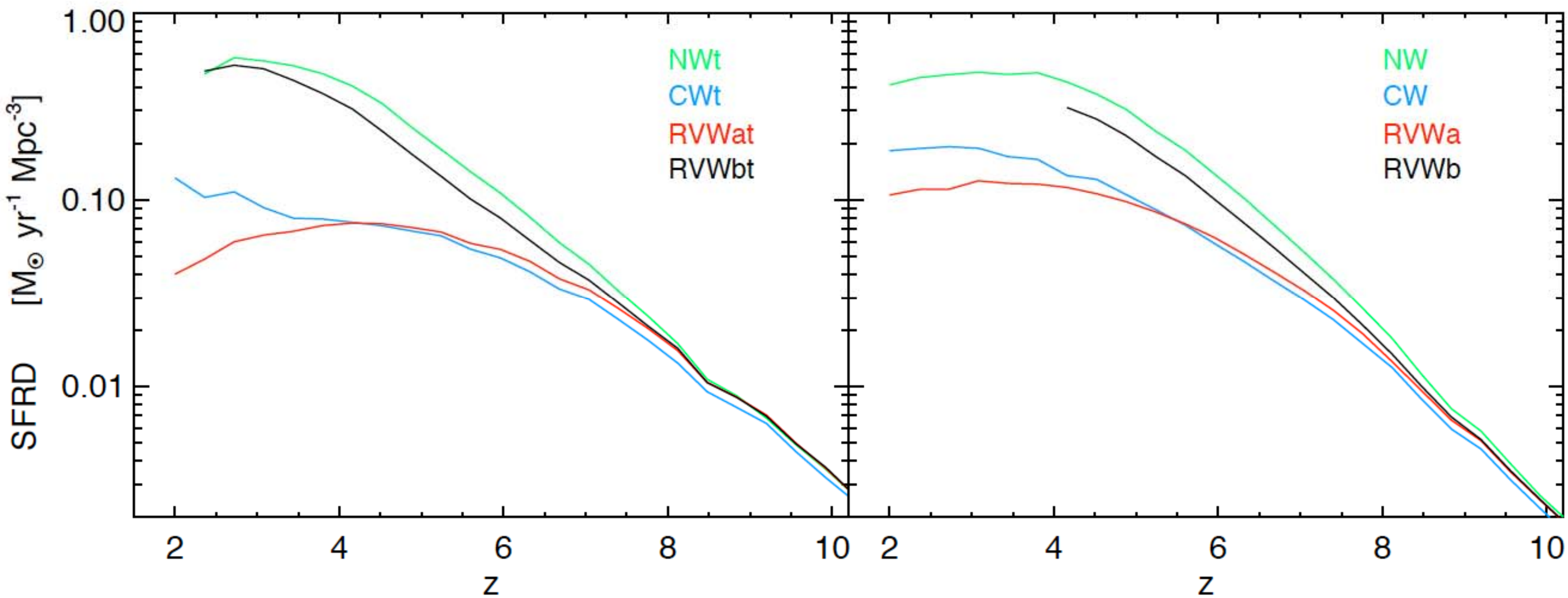
$$R_{eff} = R_{200}(M_{halo}, z)$$
$$v_{\max} = 2v_{circ} = 2\sqrt{GM_{halo}/R_{200}}$$

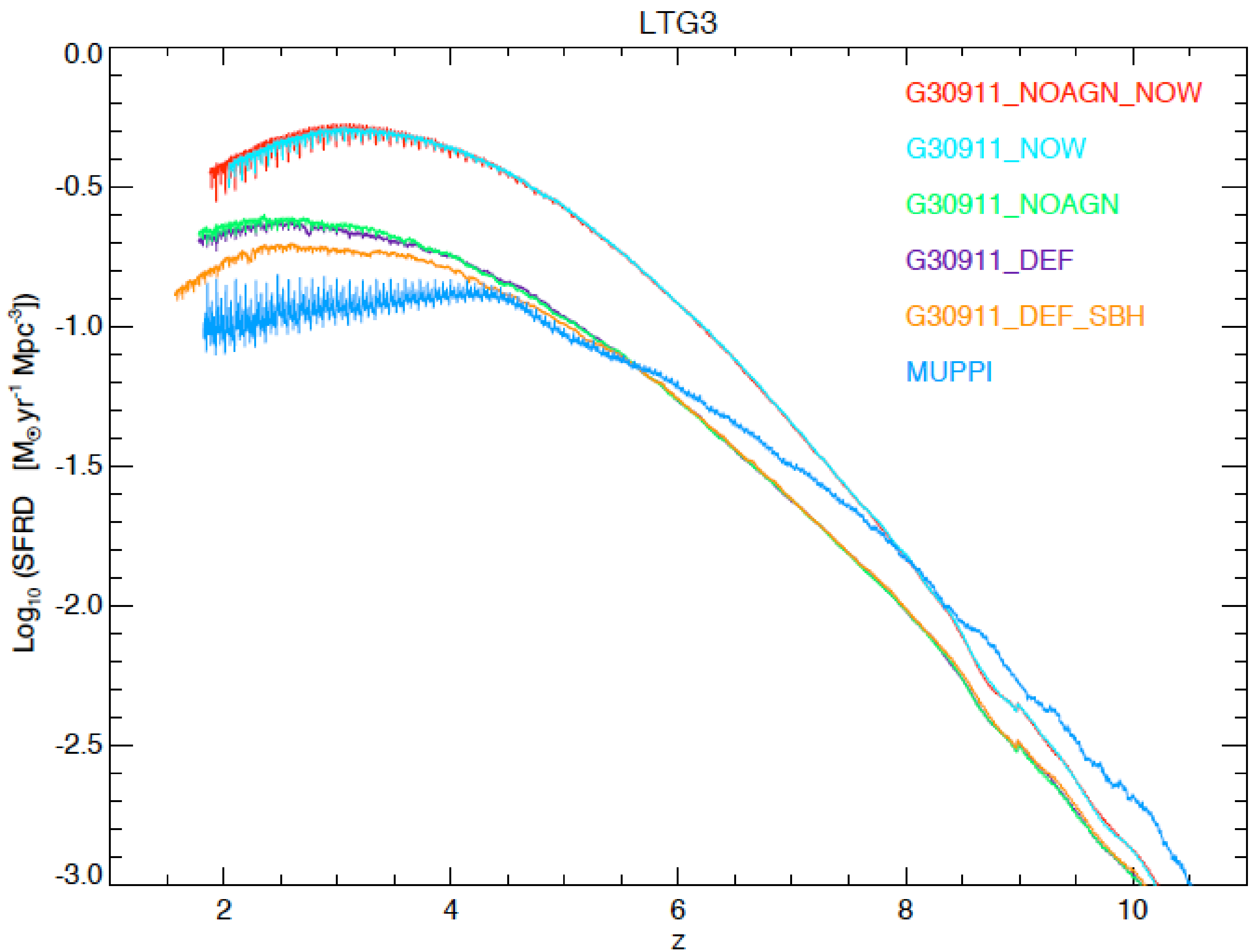
- RVWb : Parameters dependent on halo mass (Martin 2005)

Star Formation Rate Density Evolution

$5\ h^{-1}$ Mpc, $N = 2 \times 128^3$

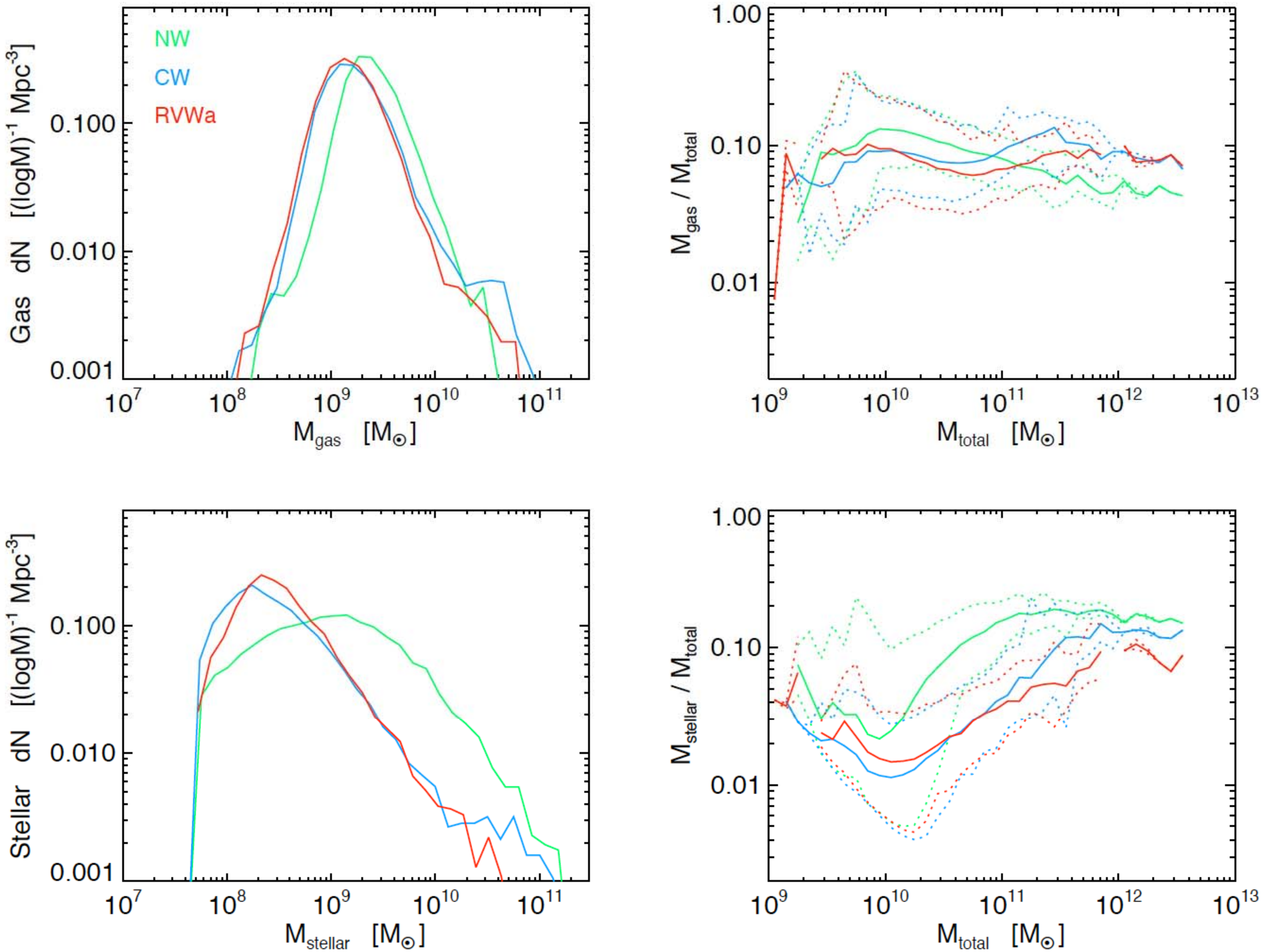
$25\ h^{-1}$ Mpc, $N = 2 \times 320^3$



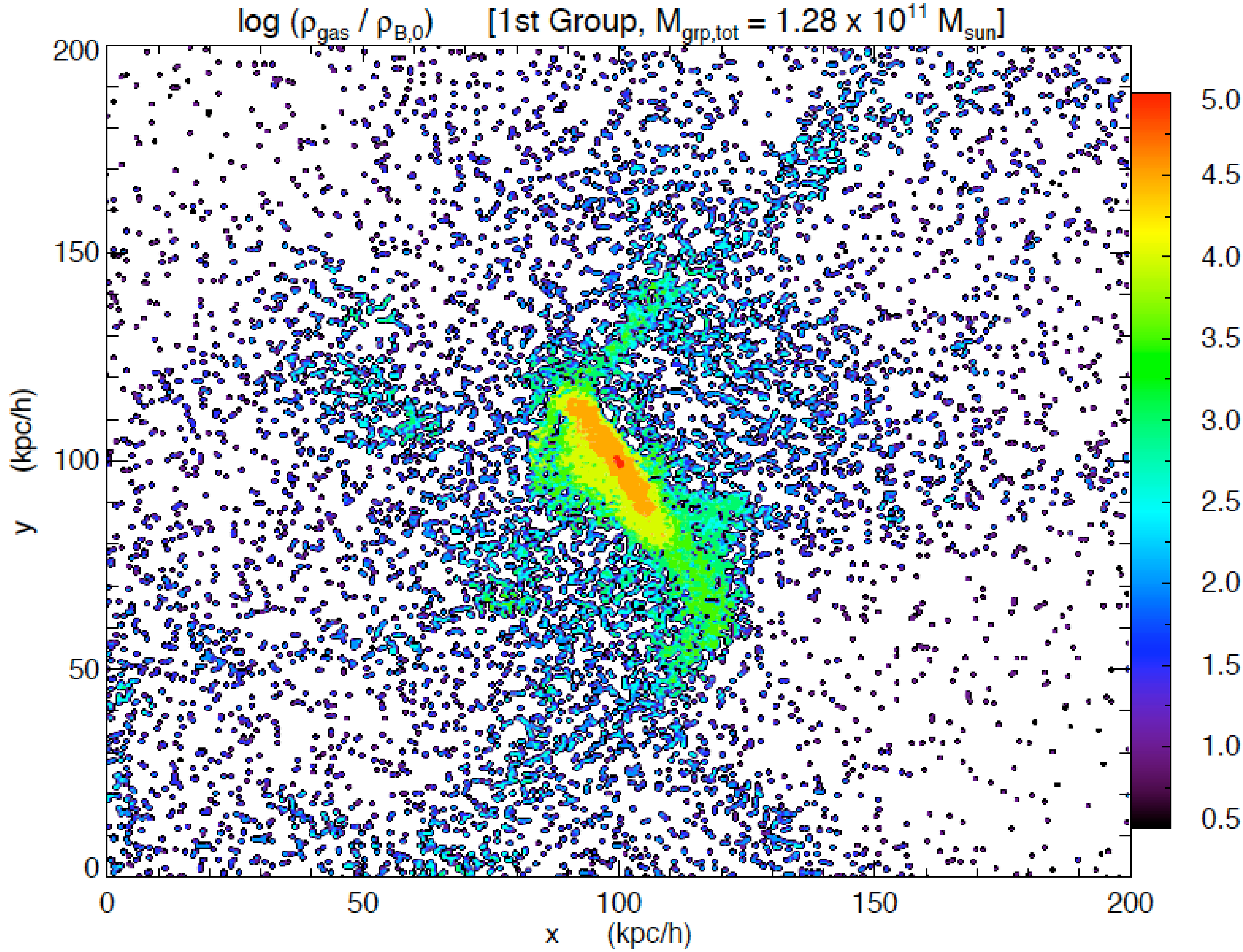


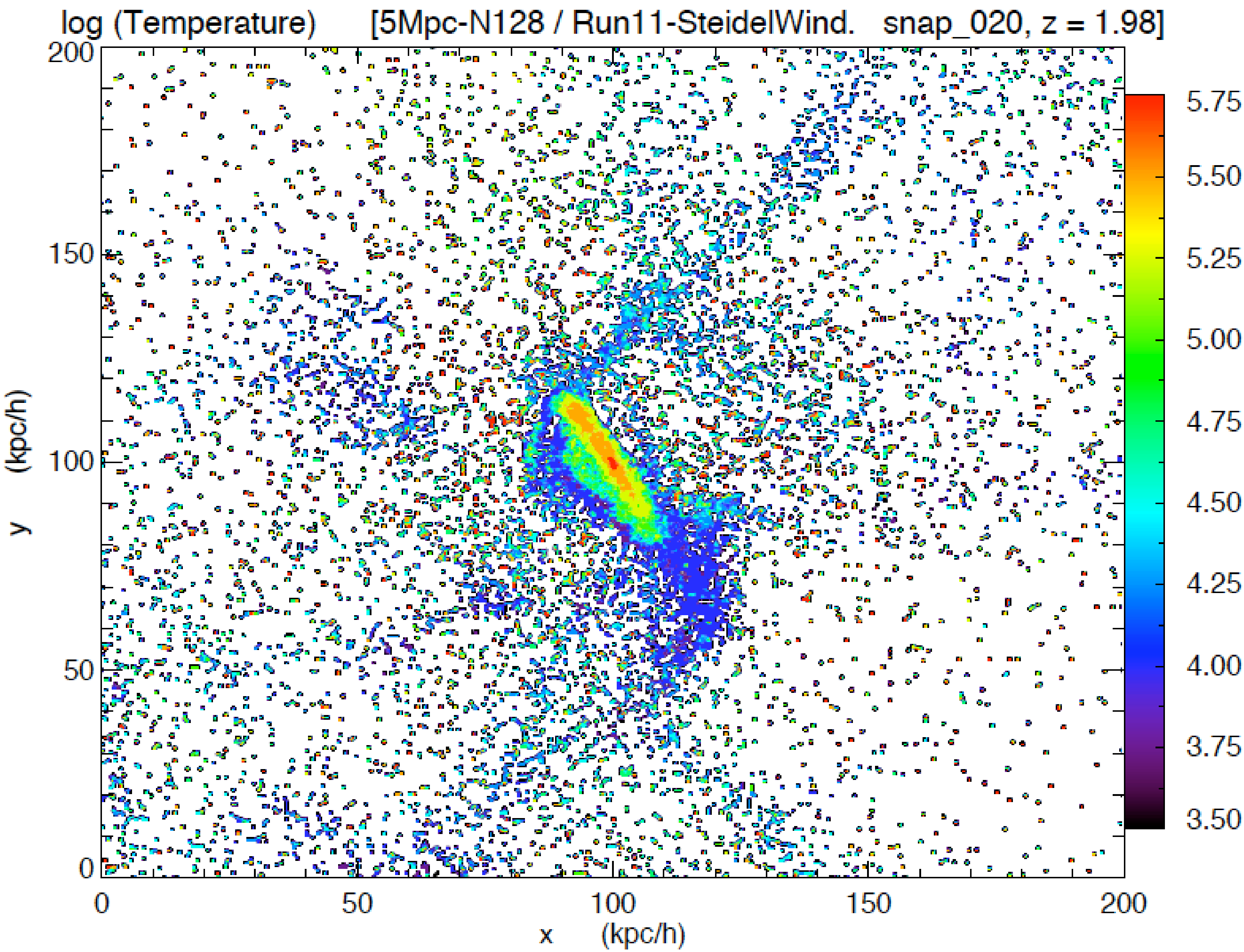
LTG3
G30911_NOAGN_NOW
G30911_NOW
G30911_NOAGN
G30911_DEF
G30911_DEF_SBH
MUPPI
Log10 (SFRD [M⊙ yr-1 Mpc-3])
z
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
2
4
6
8
10

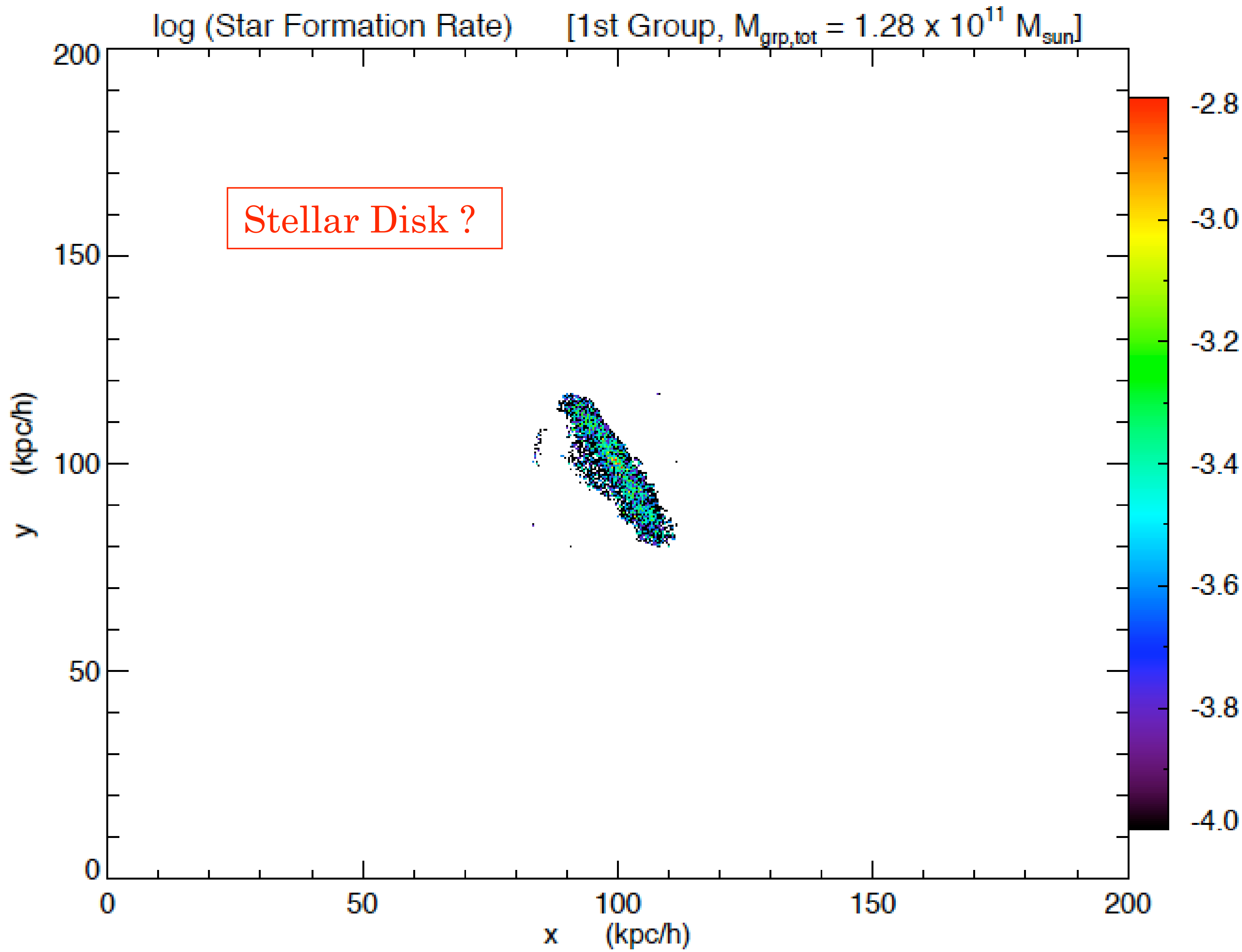
Mass-Function & Mass-Fractions in Groups, at z = 2.23



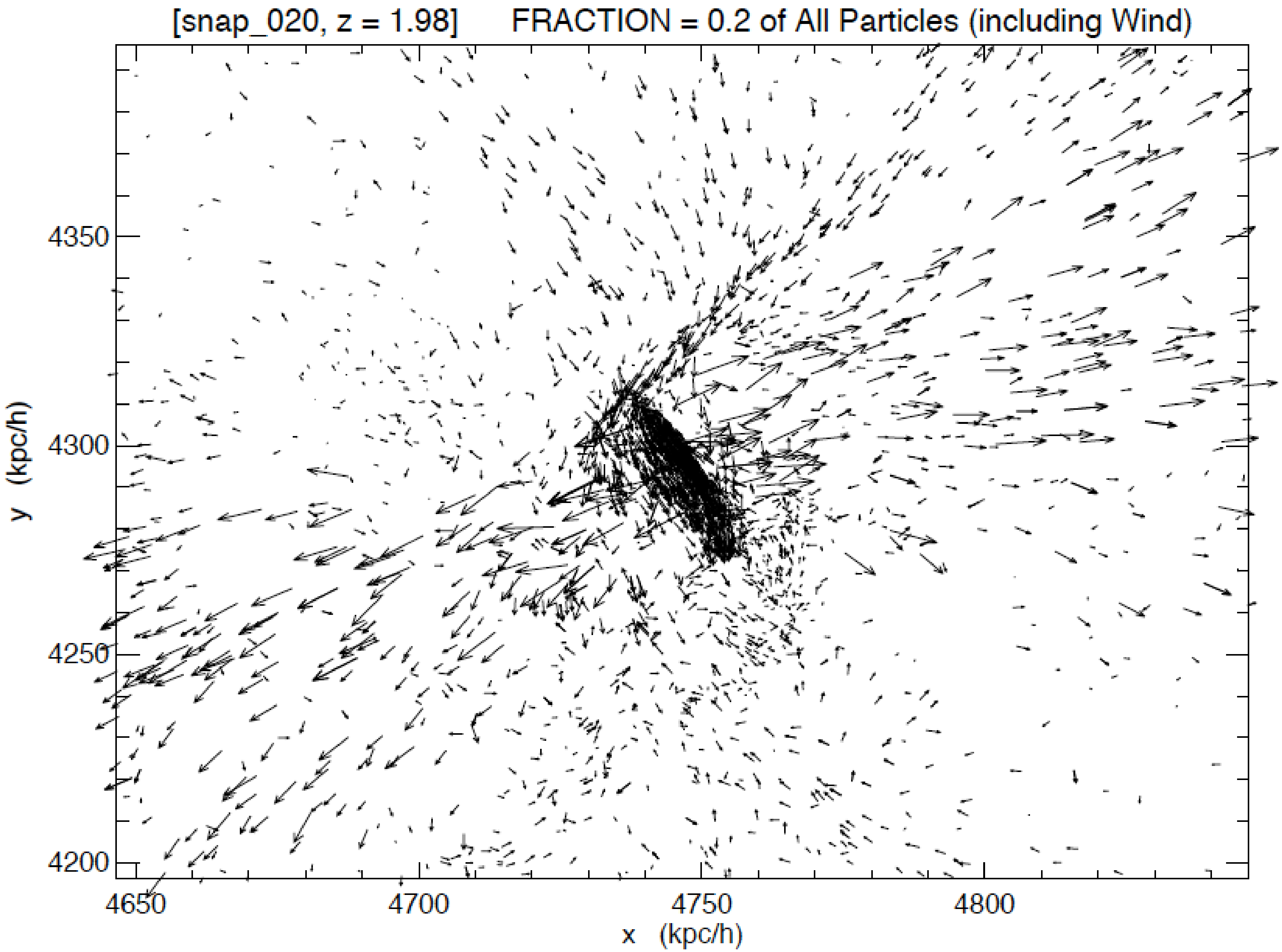
Projection of (200/h kpc)^3 volume around a massive group center (run RVWat) showing Gas properties

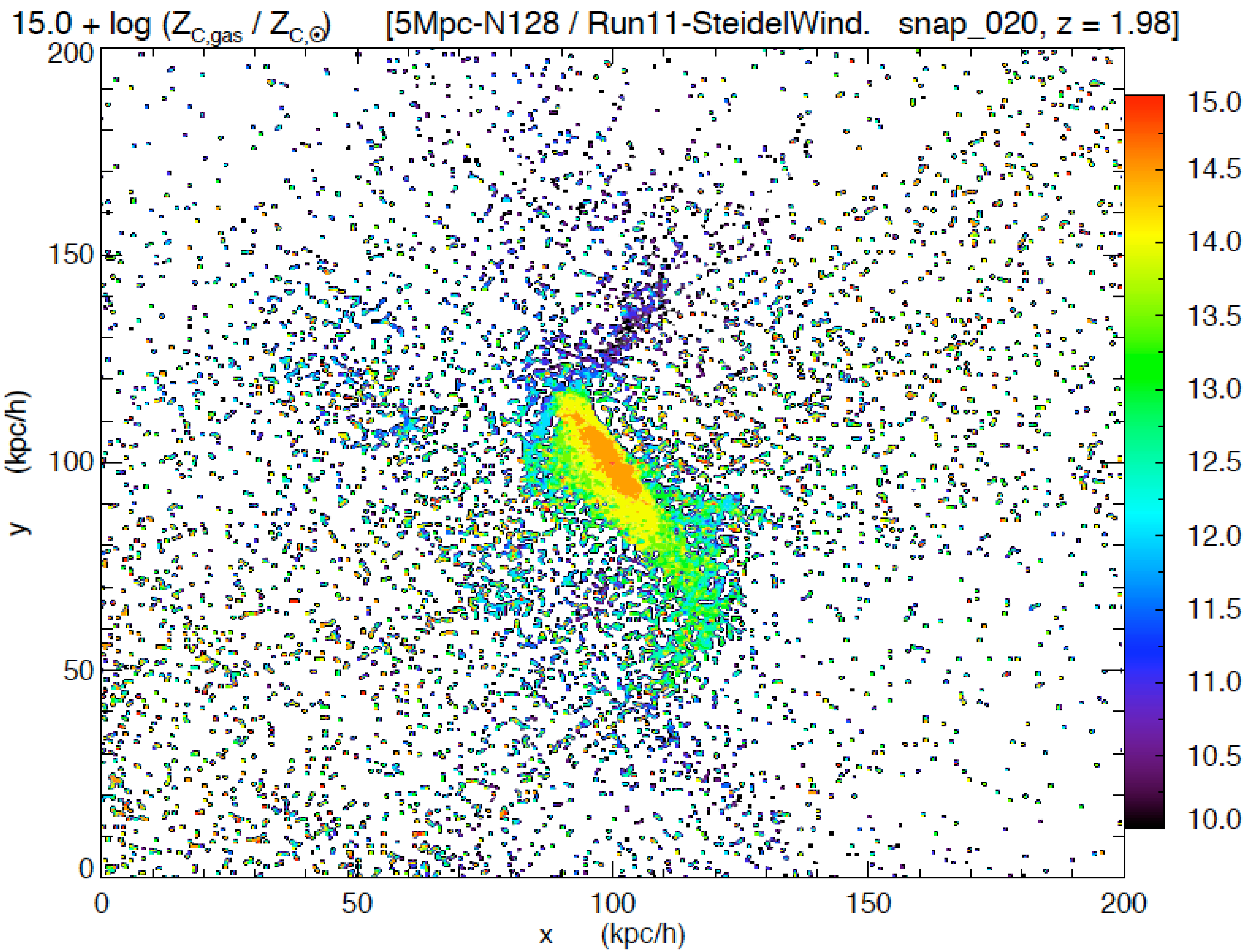


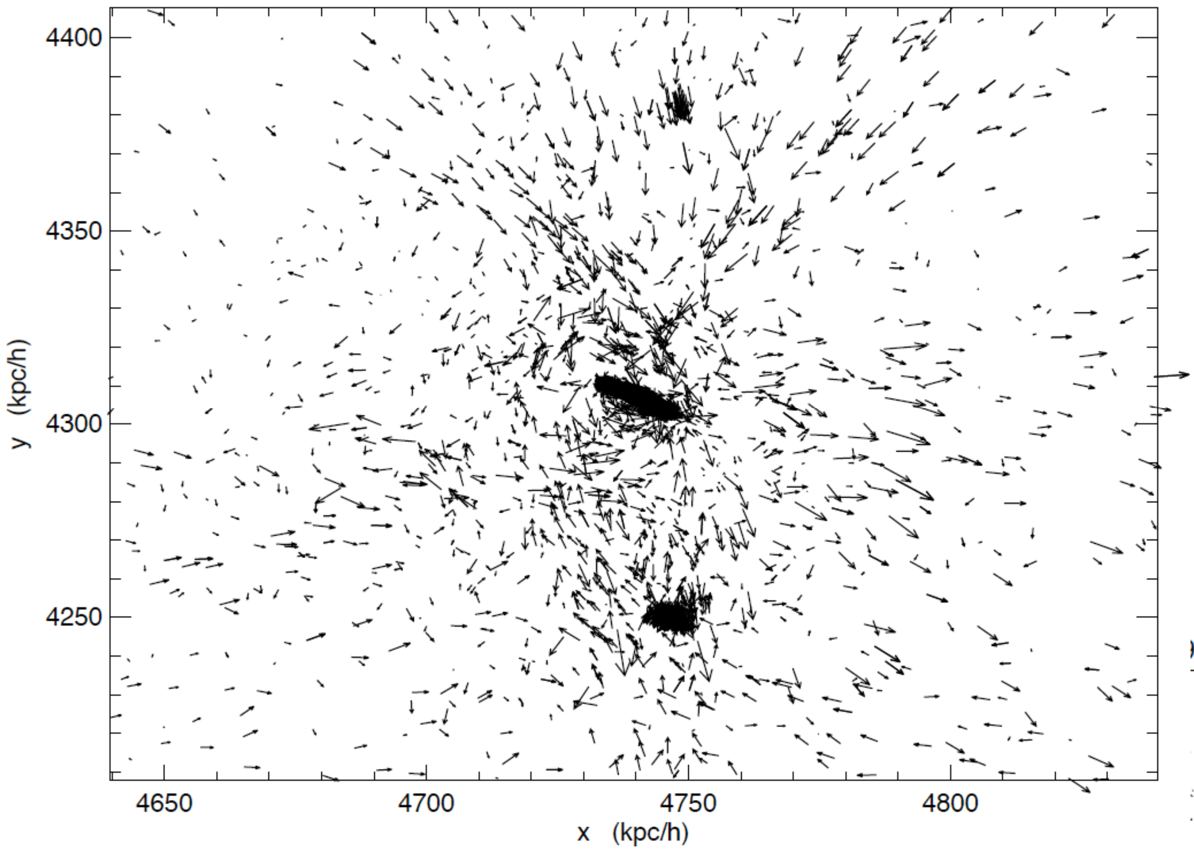

log (Temperature)
[5Mpc-N128 / Run11-SteidelWind. snap_020, z = 1.98]
y (kpc/h)
x (kpc/h)
0
50
100
150
200
0
50
100
150
200
5.75
5.50
5.25
5.00
4.75
4.50
4.25
4.00
3.75
3.50



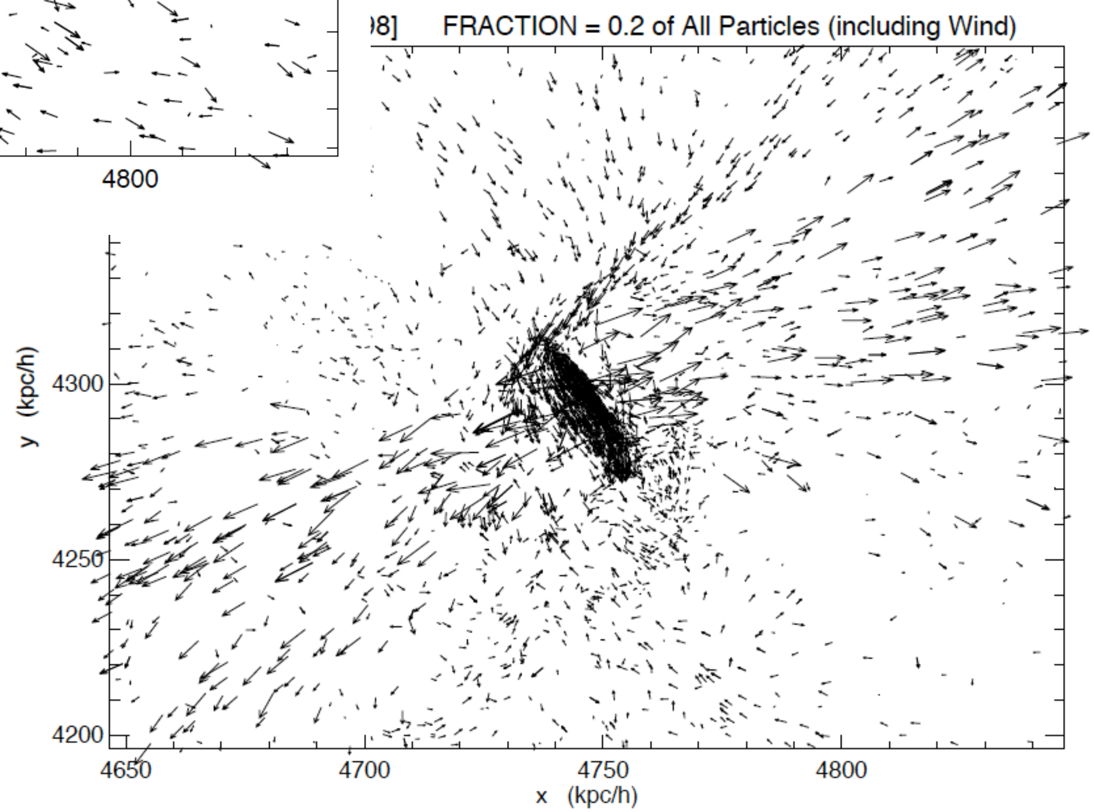
log (Star Formation Rate) [1st Group, $M_{grp,tot} = 1.28 \times 10^{11}$ M_{sun}]
Stellar Disk ?
y (kpc/h)
x (kpc/h)
0
50
100
150
200
-2.8
-3.0
-3.2
-3.4
-3.6
-3.8
-4.0


[snap_020, z = 1.98] FRACTION = 0.2 of All Particles (including Wind)
4350
4300
4250
4200
y (kpc/h)
4650
4700
4750
4800
x (kpc/h)


15.0 + log (Z_C,gas / Z_C,⊙)
[5Mpc-N128 / Run11-SteidelWind.   snap_020, z = 1.98]
200
150
100
50
0
y (kpc/h)
0
50
100
150
200
x (kpc/h)
15.0
14.5
14.0
13.5
13.0
12.5
12.0
11.5
11.0
10.5
10.0

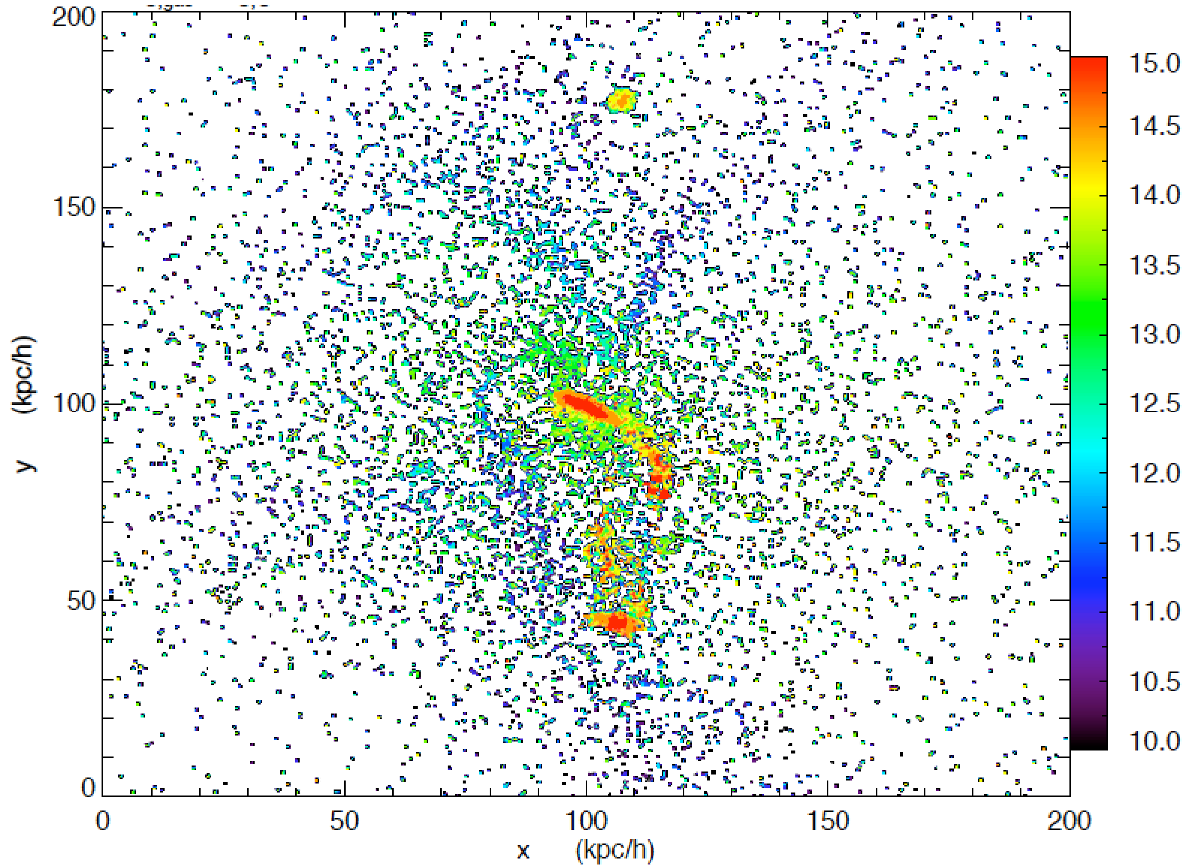


NWt

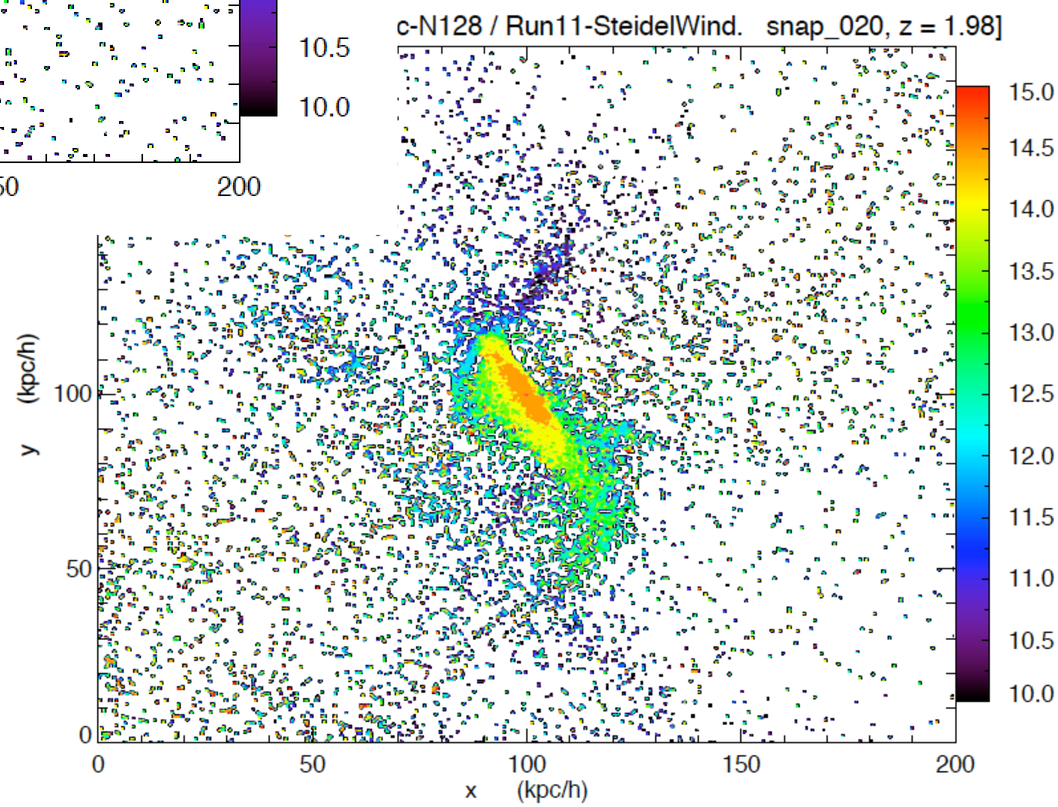


RVWat

13-juin-12



NWt



RVWat

13-juin-12

Summary / Future

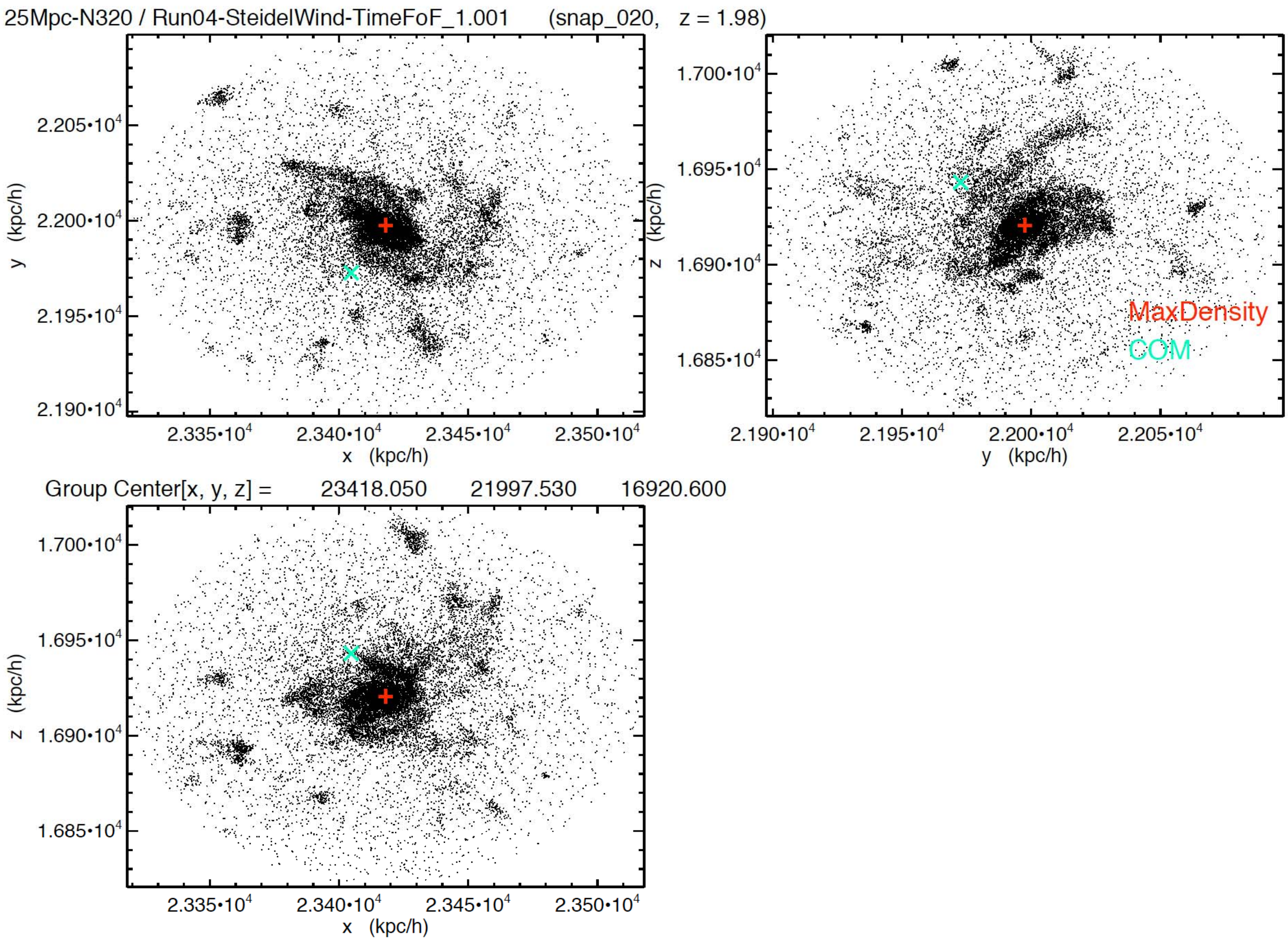
- Have implemented a new observationally-motivated wind model in G3
  - Do quantitative comparison of RVW with other wind models

- Study low-z IGM properties by running sims up to z = 0

- MUPPI comparison

- Other sub-grid physics:
  - Pressure-driven wind model (Sharma & Nath 2011, arXiv: 1112.3447)
  - AGN feedback
    - Improve SMBH accretion prescription
    - Include kinetic feedback from AGN winds

Extra Slides


25Mpc-N320 / Run04-SteidelWind-TimeFoF_1.001 (snap_020, z = 1.98)
y (kpc/h)
x (kpc/h)
2.205•10^4
2.200•10^4
2.195•10^4
2.190•10^4
2.335•10^4
2.340•10^4
2.345•10^4
2.350•10^4
z (kpc/h)
y (kpc/h)
1.700•10^4
1.695•10^4
1.690•10^4
1.685•10^4
2.190•10^4
2.195•10^4
2.200•10^4
2.205•10^4
MaxDensity
COM
Group Center[x, y, z] = 23418.050 21997.530 16920.600
z (kpc/h)
x (kpc/h)

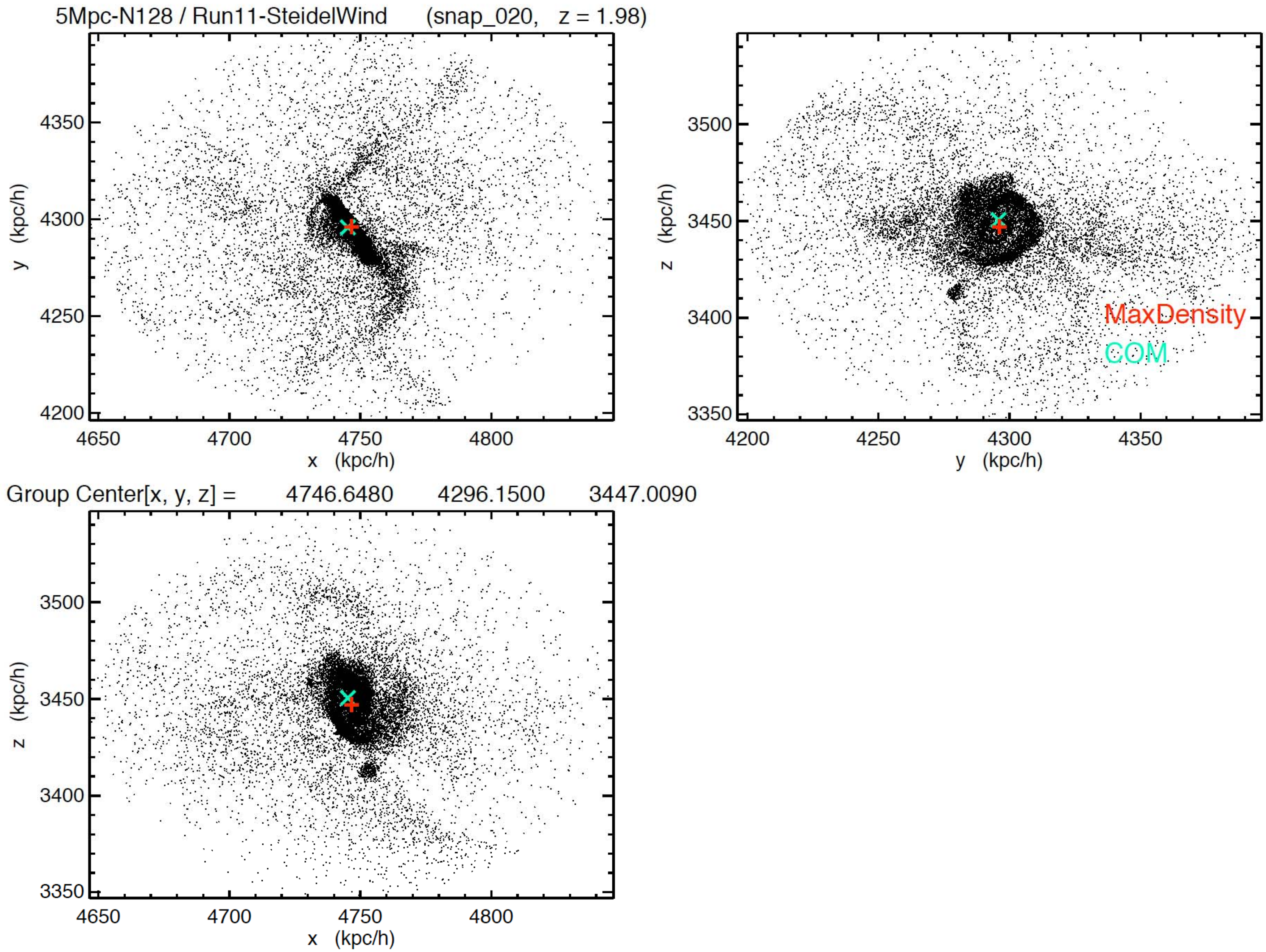

5Mpc-N128 / Run11-SteidelWind (snap_020, z = 1.98)
y (kpc/h)
x (kpc/h)
z (kpc/h)
y (kpc/h)
MaxDensity
COM
Group Center[x, y, z] = 4746.6480 4296.1500 3447.0090
z (kpc/h)
x (kpc/h)

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, $\alpha = 1.15$.

[h][illegible]