# *Cosmological Simulations with Galactic Wind Feedback*


**Paramita Barai**

(INAF - Osservatorio Astronomico di Trieste)

Collaborators : Matteo Viel,
Luca Tornatore, Stefano Borgani, Pierluigi Monaco,
Giuseppe Murante,
Klaus Dolag (univ. Munich)



**Galactic Winds of Change - Sesto Workshop**

20th July, 2012

# Outline

- Introduction to Cosmological Hydrodynamic Simulation
- Galactic Wind subgrid physics in GADGET code
- Simulations
- Preliminary Results
  - Impact of winds on galaxy properties
- Conclusions
- <u>Question:</u> What (aspects) of galactic winds can be studied in cosmol sims?

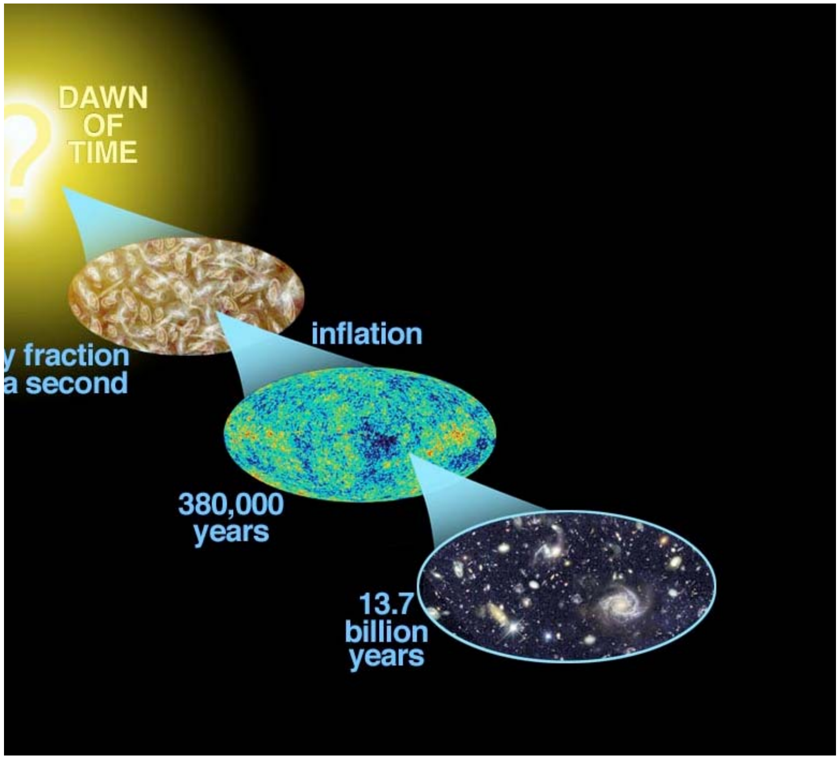
*Galaxy Formation Modeling*

*---*

*Cosmological Hydrodynamic Simulations*

*---*

*What is done? How?*

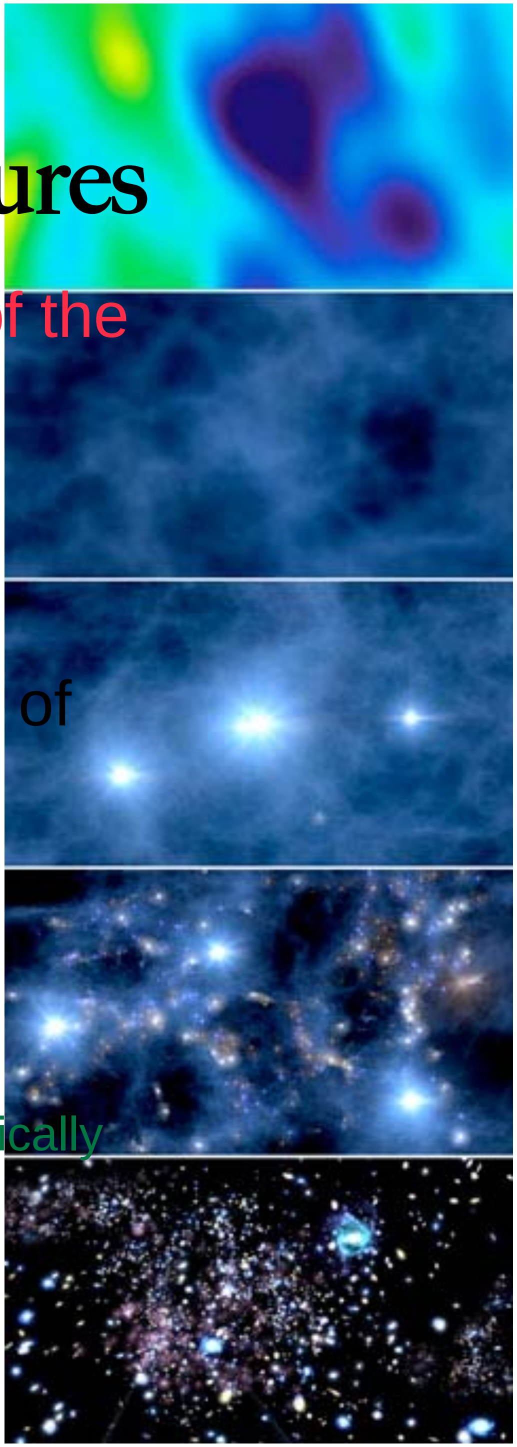



# Large Scale Structure Formation

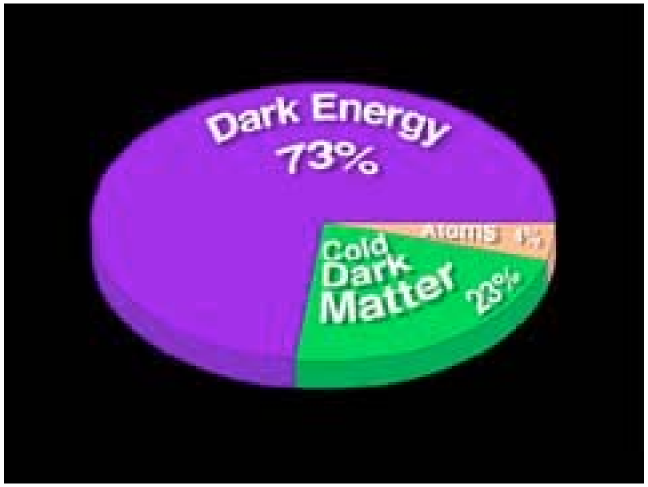
- Quantum fluctuations shortly after the Big Bang ⇒ Primordial density perturbations
- Inflation expands the perturbations

- Gravitational clumping of matter from these density fluctuations ⇒ Structures grow
- Main forces driving evolution
  - Gravity : affects dark matter and baryons
  - Gas dynamics : only baryons

# The Universe in a Box: Simulations of Large Scale Structures



- Computational box ⇔ representative volume of the Universe
- Resolution elements (particles or grid) in box ⇔ matter
- Model LSS in terms of massive elements each of mass $10^6$ - $10^7$ $M_\odot$
- 2 steps:
  - Generate the initial condition
  - Evolve IC using dynamical equations
    - Follow the non-linear evolution of density fields numerically
- Goal: get the final distribution consistent with observations of the Universe

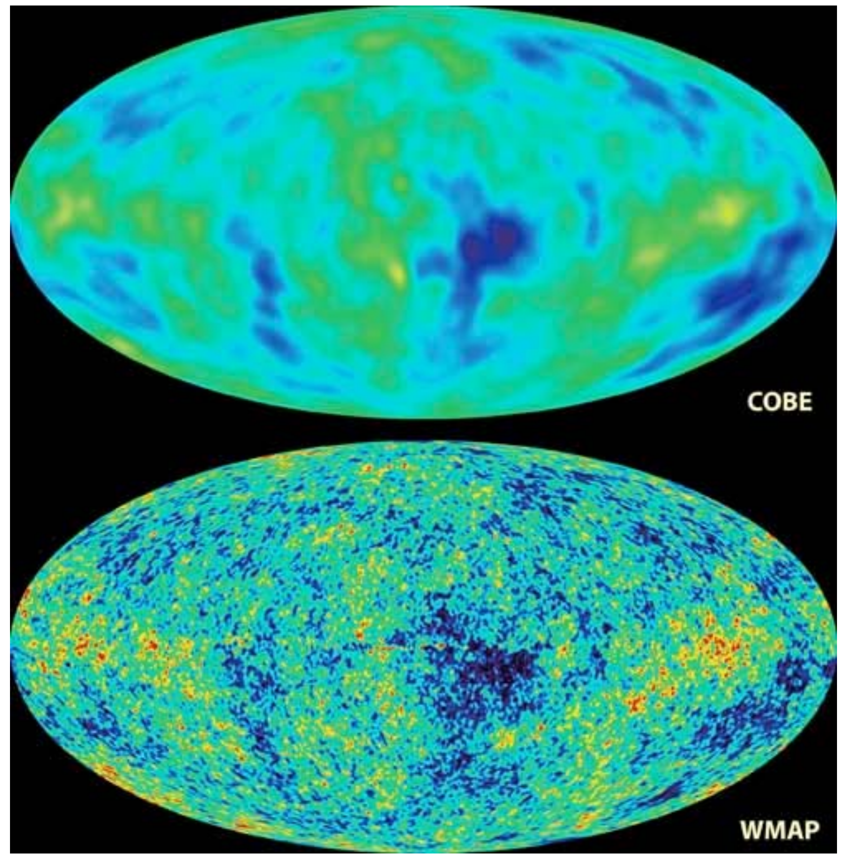



# Initial Condition

- Cosmological model well constrained by observations
  - CMBR (WMAP), SN, Galaxy clusters, Gravitational lensing

$\Lambda$CDM model $\Rightarrow$ dark energy + cold dark matter, Flat

- Primordial density fluctuations
  - Gaussian
- Cosmological sim
  - Start with gaussian $\Delta\rho$ at CMB epoch (0.38 Myr after Big Bang, z~1100)
- Isolated galaxy, or, galaxy merger sim
  - Start with well formed galaxies



# Physics

- Dark matter (dissipation-less, collision-less)
  - Gravity-only
  - Particle N-body method

$$\frac{d\vec{v}}{dt} = -\nabla\Phi$$

$$\nabla^2\Phi = 4\pi G\rho$$

- Baryon / Gas evolution
  - Gravity + Hydrodynamics

$$\frac{\partial\rho}{\partial t} + \vec{\nabla}\cdot(\rho\vec{v}) = 0$$

$$\frac{\partial\vec{v}}{\partial t} + (\vec{v}\cdot\vec{\nabla})\vec{v} = -\vec{\nabla}\Phi - \frac{\vec{\nabla}P}{\rho}$$

$$\frac{\partial E}{\partial t} + \vec{\nabla}\cdot\left[(E+P)\vec{v}\right] = -\rho\vec{v}\cdot\vec{\nabla}\Phi$$

$$P = K\rho^{\gamma}$$

$$\varepsilon = \frac{1}{(\gamma-1)}\frac{P}{\rho}$$

- Comoving coordinates

$$H(z) = H_0\left[\Omega_\Lambda + \frac{\Omega_m}{(1+z)^3} + \frac{\Omega_r}{(1+z)^4} - \frac{(\Omega-1)}{(1+z)^2}\right]^{1/2}$$

- Add source & sink terms / sub-grid physics
  - Radiative cooling and heating of gas
  - Star formation + stellar & SNe feedback
  - AGN accretion + feedback
  - Galactic Wind

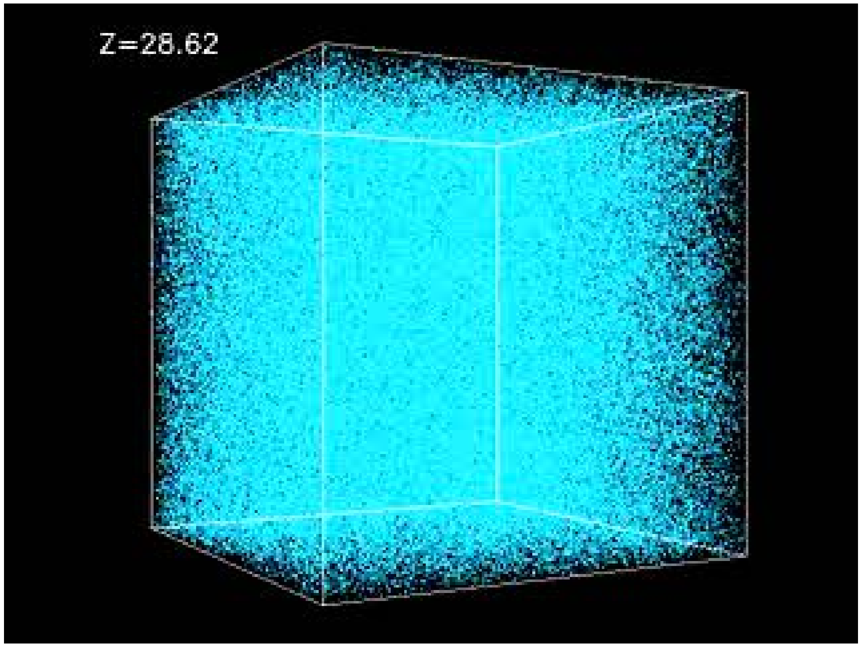
# Successful Results

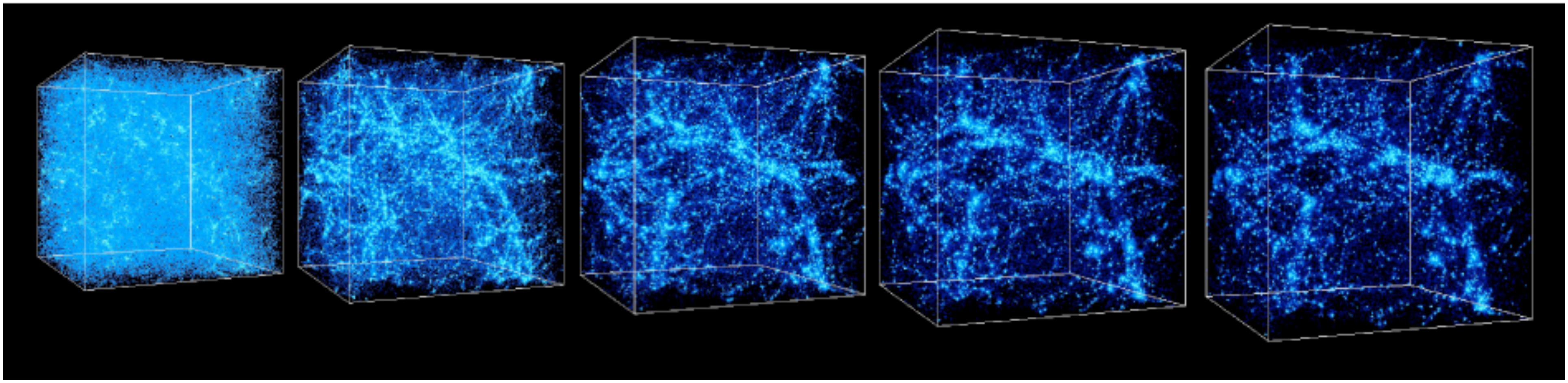
- Hierarchical Structure Formation
  - Can reproduce the distribution and structure of galaxies in very large scales as seen in observations
- Distribution of matter in the Universe
  - Collapse via gravitational forces into filaments. Galaxies form in these filaments
- Clustering of galaxies at all z (z~0, z~1, z~4-5) observed in large scale surveys is well reproduced
- Galaxy cluster scaling relations
- Mass and luminosity functions of galaxies

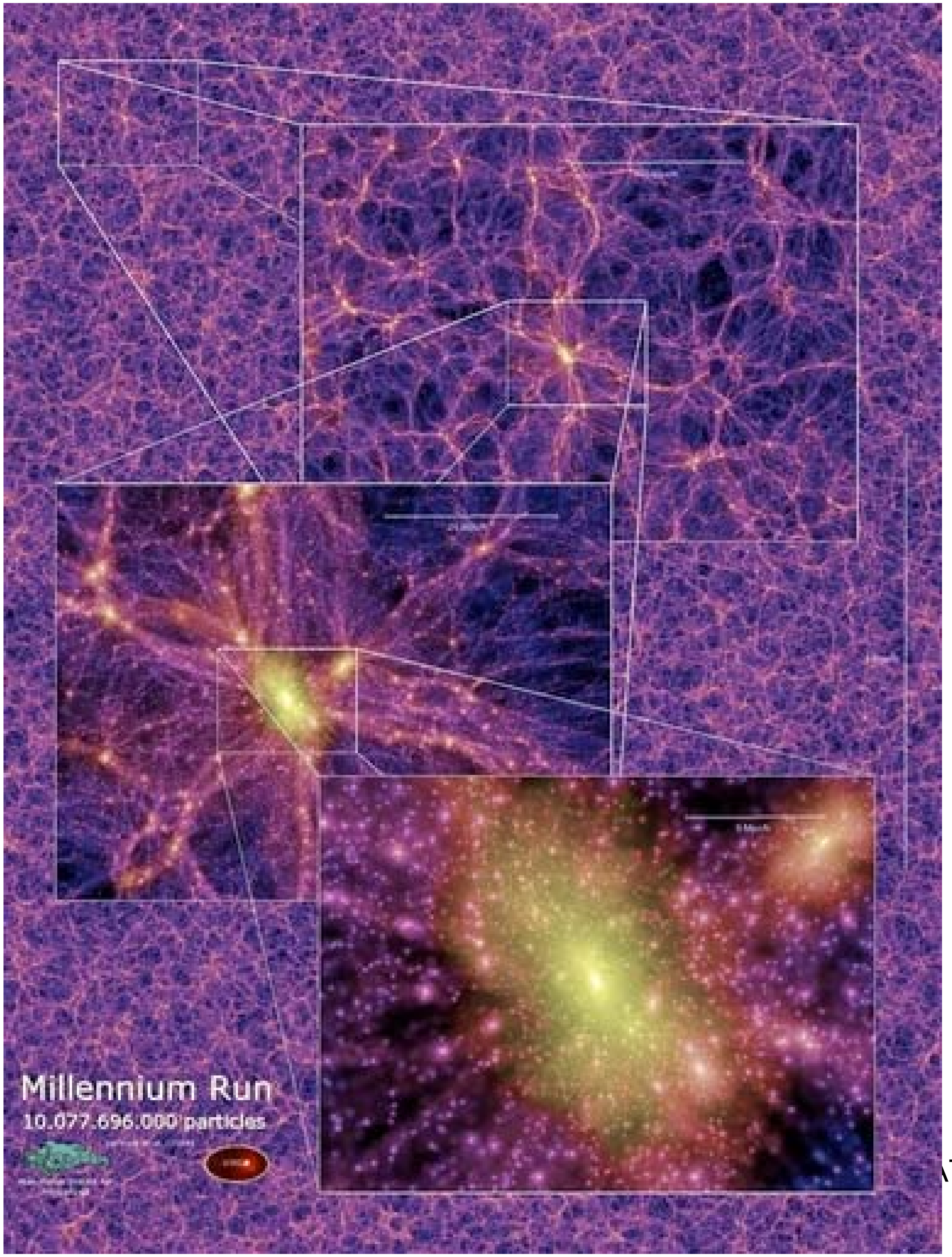
# Large-Scale Filaments

- A (43 Mpc)$^3$ box
- From z = 30 to z = 0

- Frames below show structure forming from z = 10 to the present



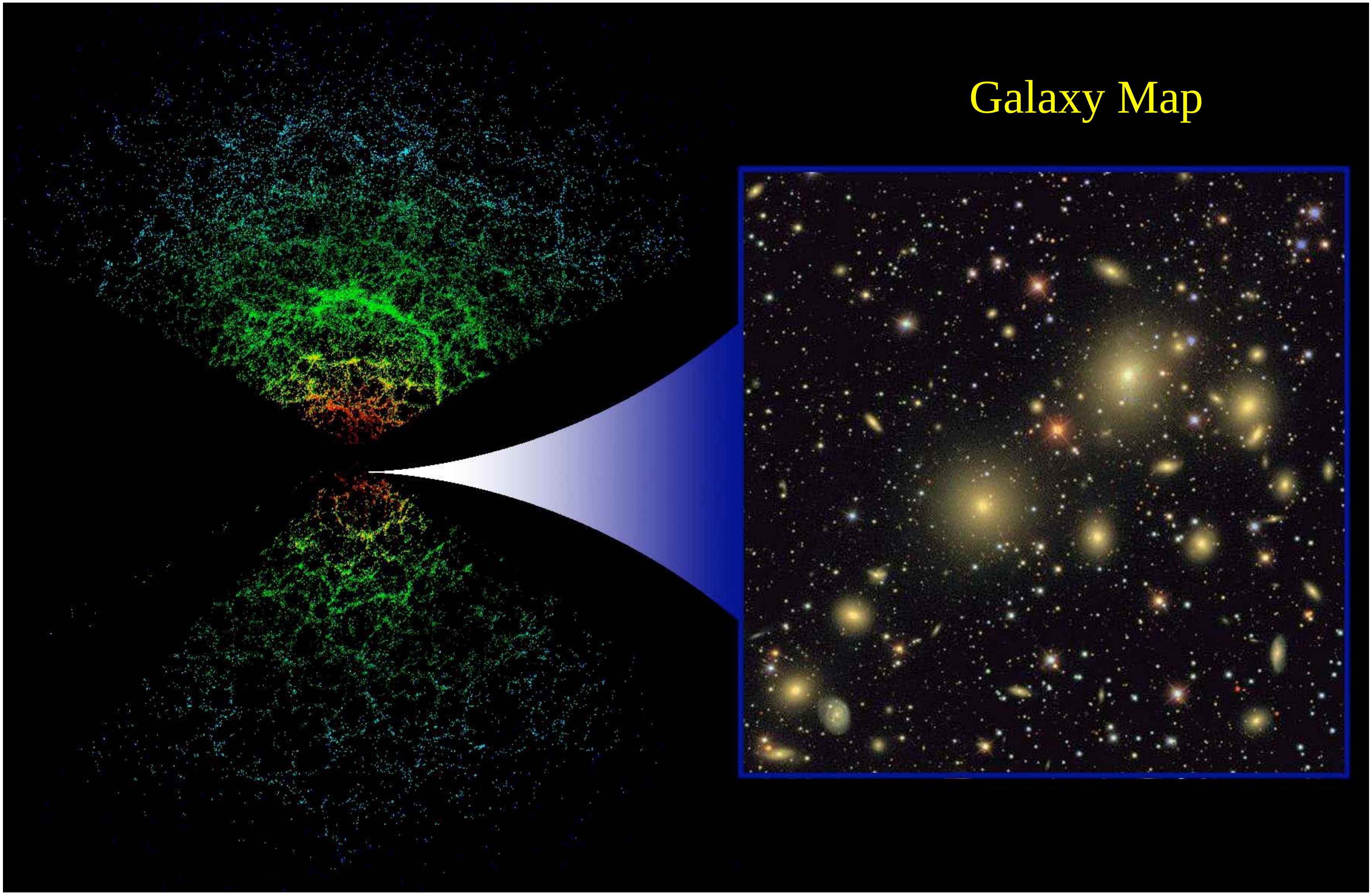






# Millennium Simulation

- Cosmol N-body run
- Box size = 500 $h^{-1}$ Mpc
- $2160^3 \sim 10^{10}$ particles
- Particle mass = 8.6 x $10^8$ $h^{-1} M_{\odot}$
- Comoving softening length, $\varepsilon = 5\ h^{-1}$ kpc
- A projected density field for a 15 Mpc/h thick slice of the $z$=0 output
- The overlaid panels zoom in by factors of 4 in each case

# Sloan Digital Sky Survey



# GADGET Code (Springel 2005, MNRAS, 364, 1105)

- Gravity : Tree + PM
- Hydro : SPH
  - Entropy-conserving formulation (Springel & Hernquist 2002, MNRAS, 333, 649)
- Adaptive time-stepping for particles
- Heating from UV photoionizing background (Haardt & Madau 1996, ApJ, 461, 20)
- Radiative cooling , zero-metallicity (Katz, Weinberg & Hernquist 1996, ApJS, 105, 19
- Sub-resolution model of SF in multiphase ISM (Springel & Hernquist 2003, MNRAS, 339, 289)
  - Hybrid model : each SPH particle has cold + hot phases, hydrodynamics is only followed for hot-phase
  - SN-driven kinetic feedback
- Checmical enrichment from SNII using Salpeter IMF (Salpeter 1955, ApJ, 121 161) with IRA

# LT-GADGET3 code: Sub-Grid Galaxy Physics Incorporated

- Metal-line cooling (Wiersma et al. 2009, MNRAS, 399, 574)
- Star Formation (Springel & Hernquist 2003, MNRAS, 339, 289)
- Chemical Evolution (Tornatore et al. 2007, MNRAS, 382, 1050)
  - Metal (C, O, Fe, Si, Mg, S) release from SN Type-II, Type-Ia, & AGB stars; consider stellar age, mass & yield; different IMF; mass & metal loss from starburst
- Thermal feedback from SN --- inefficient, energy is radiated away
- ∴ Kinetic feedback implemented
- Recent work: (Dalla Vecchia & Schaye 2012 arXiv: 1203.5667)
  - Min. heating T required for the injected thermal energy to be efficiently converted into kinetic energy

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

- Mass-loss rate ∝ SFR

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

- Energy-driven wind :

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

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

$$\eta = 2$$
$$\chi = 0.25$$
$$\varepsilon_{SN} = 4 \times 10^{48} \mathrm{erg} / M_{sun,SF}$$
$$v_w = 224.17 \text{ km/s}$$

- Probabilistic method for kicking star-forming gas particles

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

- 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 (in GADGET code)

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

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

- Momentum-driven
  - Murray, Quataert & Thompson 2005
    - Momentum injection by SN & radiation pressure of photons
  - 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

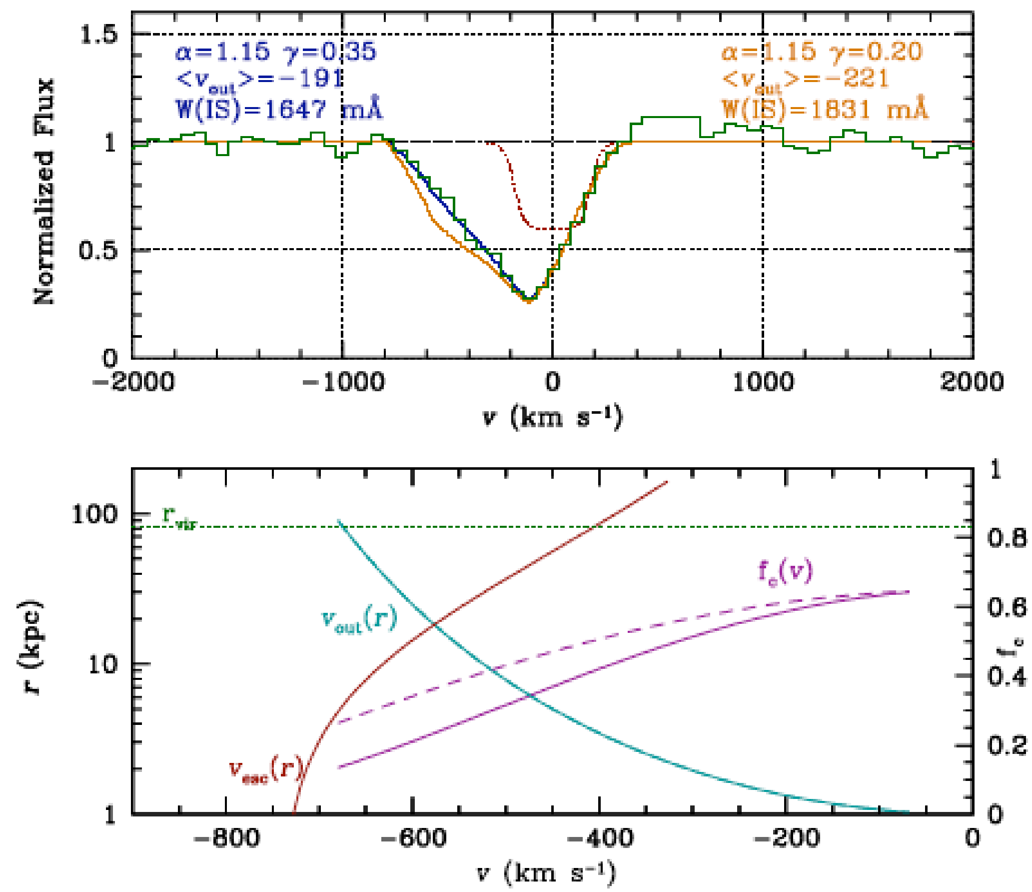
- Observations by Steidel et al. (2010, ApJ, 717, 289)
  - Spectroscopic data fitted by simple model

- Quantities are function of galactocentric distance, *r*

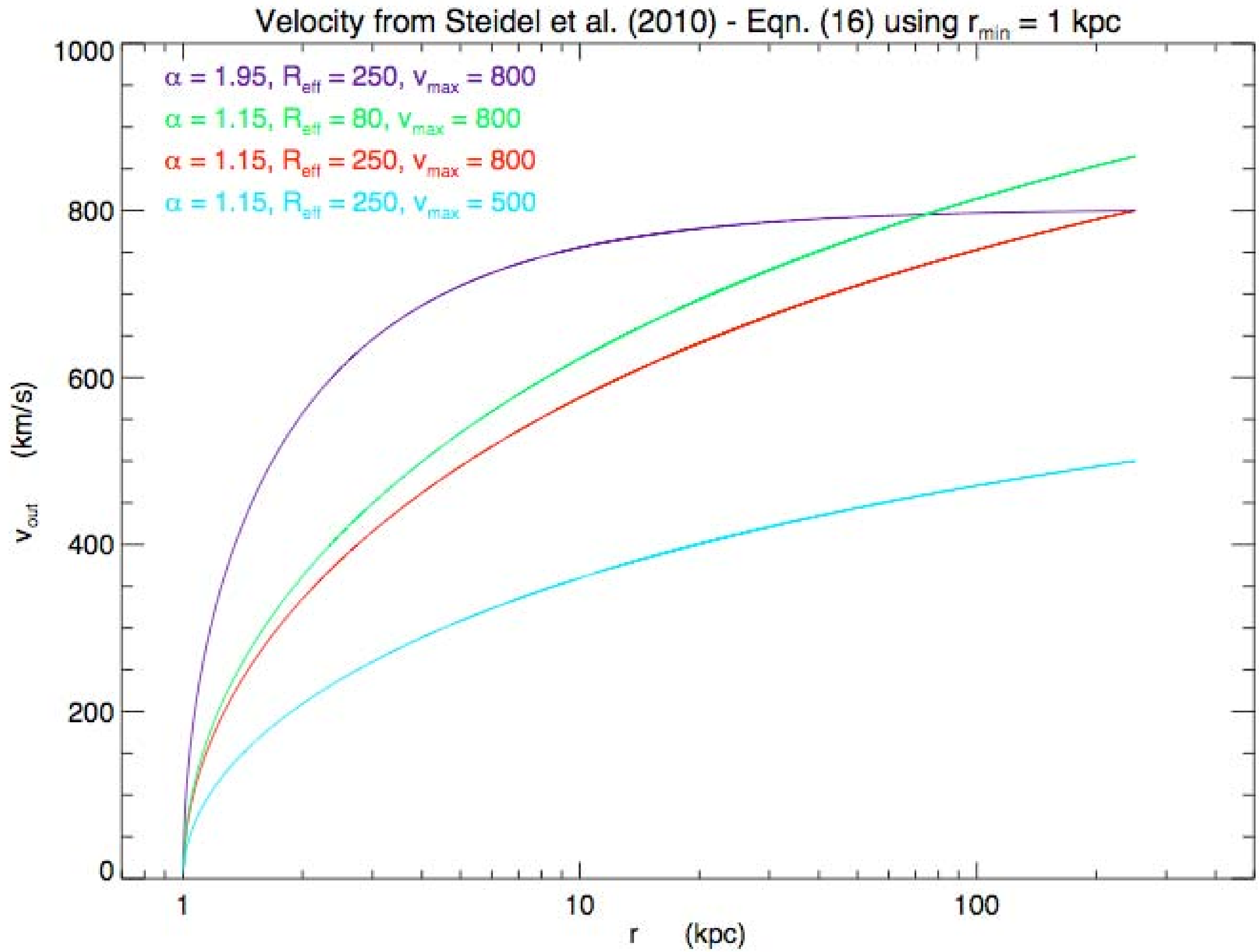
- Acceleration & Velocity :

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

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



# Our Modification in GADGET3: Radial Gradient of Outflow Velocity



# Simulations

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

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

$v_w = 400$ 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)

Table 1. Simulations Parameters [a]

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

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

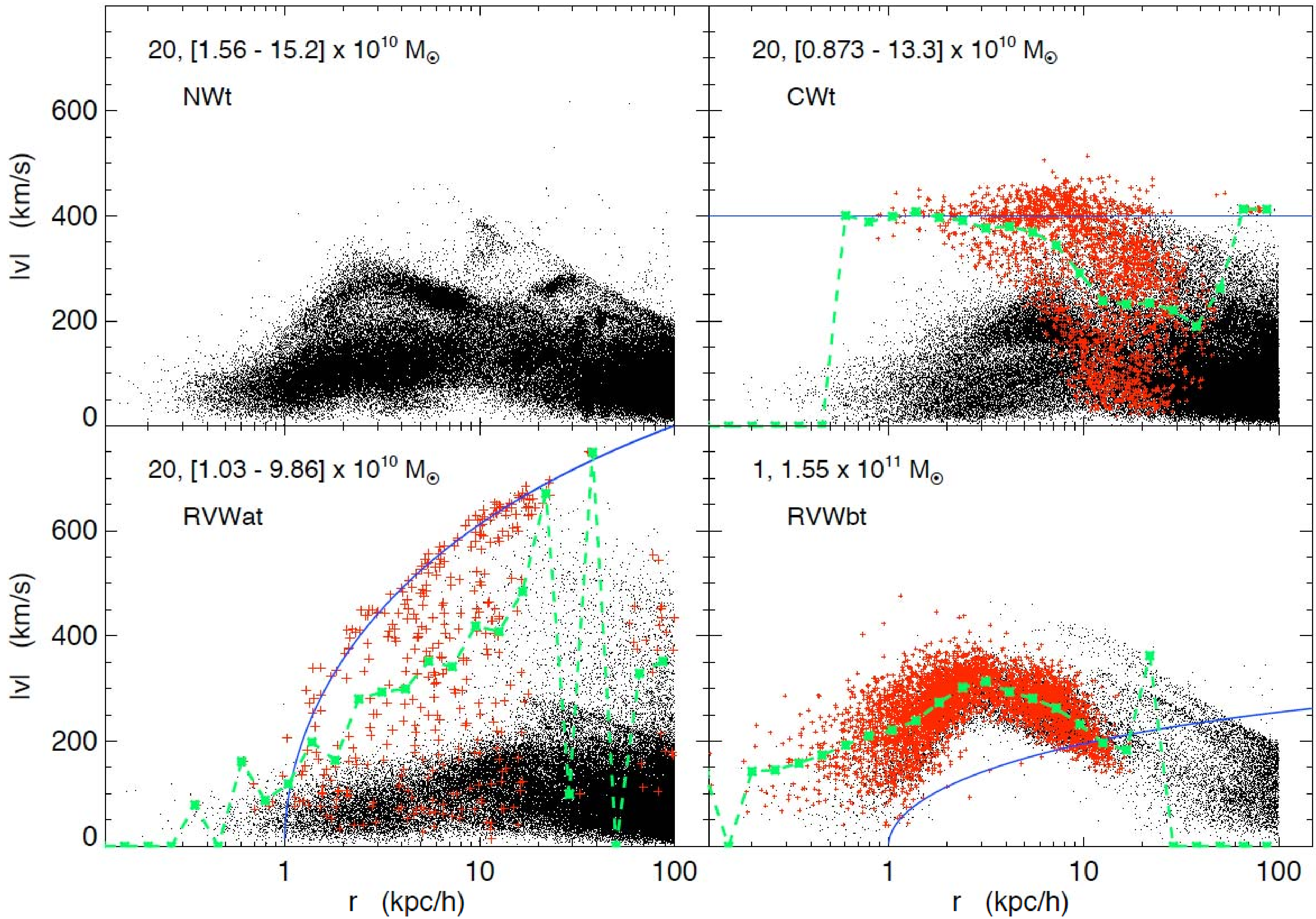
[d] $m_{gas}$ = Mass of gas particle (which has not undergone any star-formation).

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

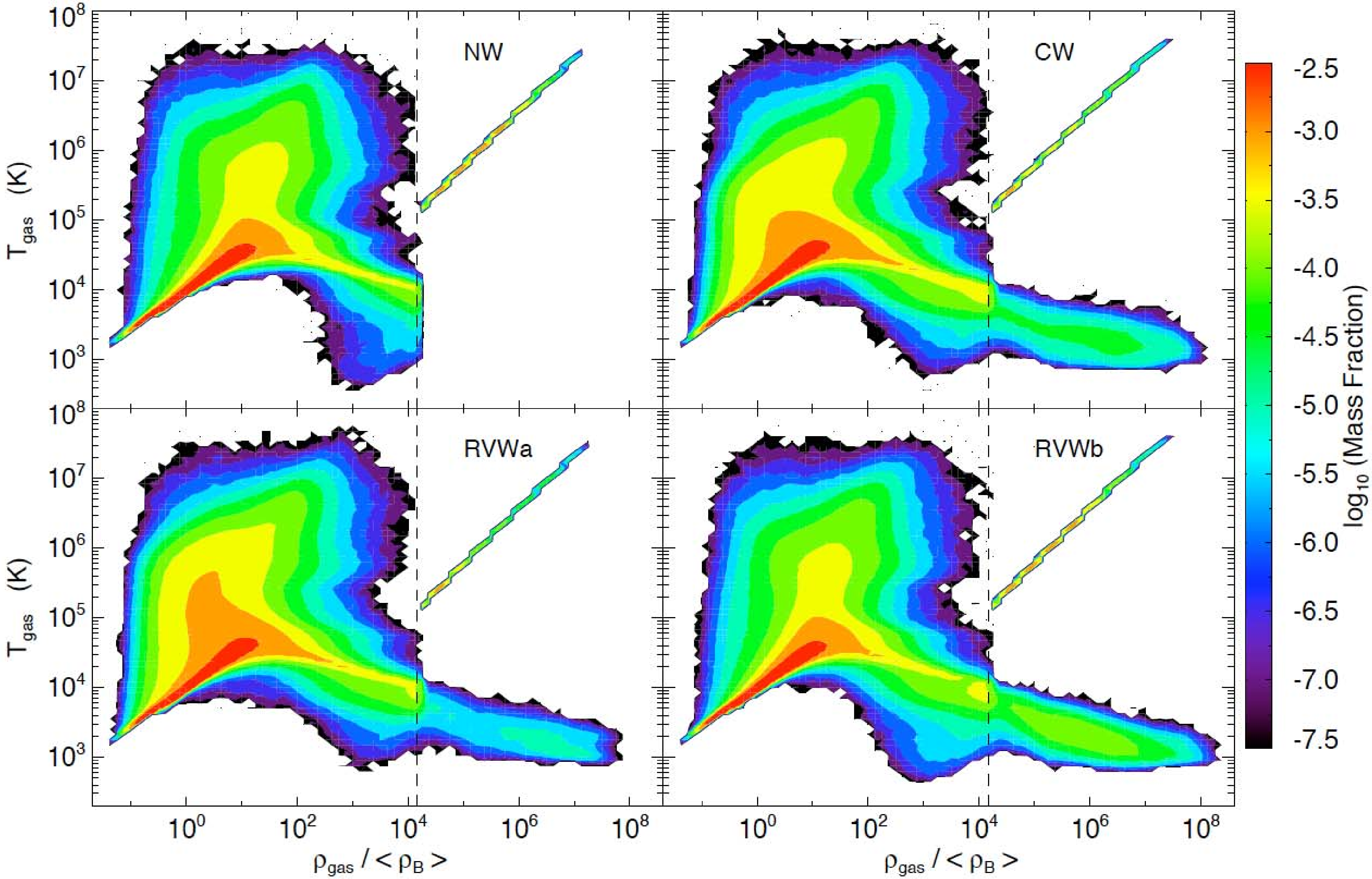
[f] Run names ending with "t" are smaller boxsize runs for test purposes, done up to $z \sim 3$.

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

# Different Wind Models

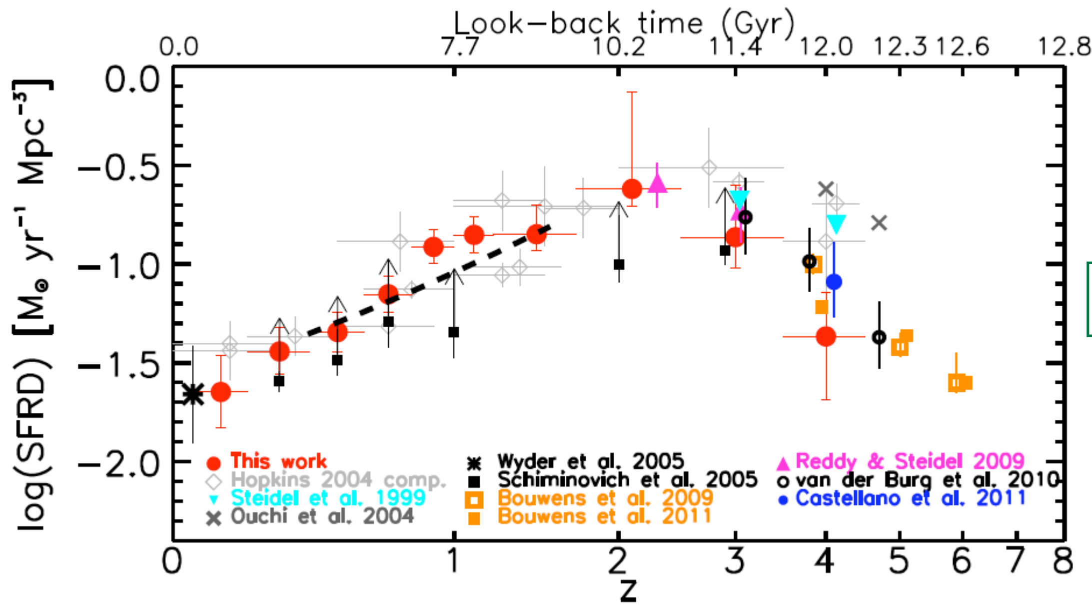


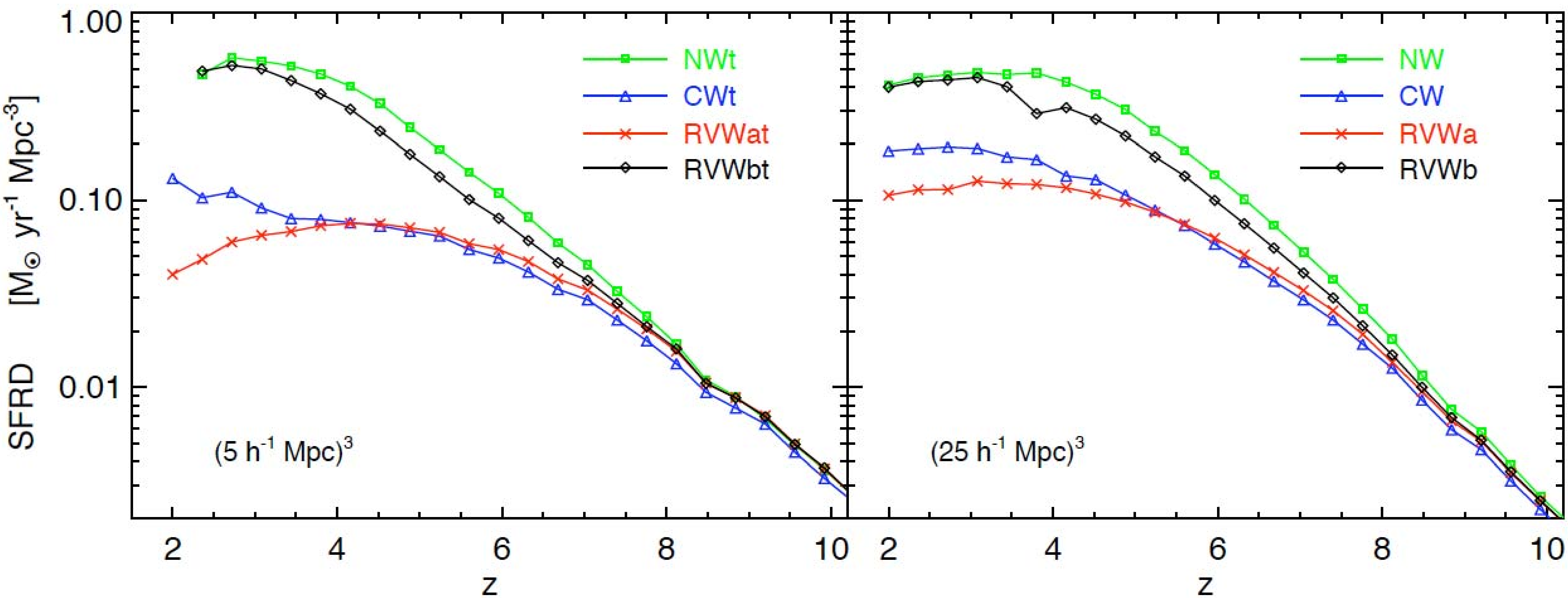
# Phase Diagram at z=1.98



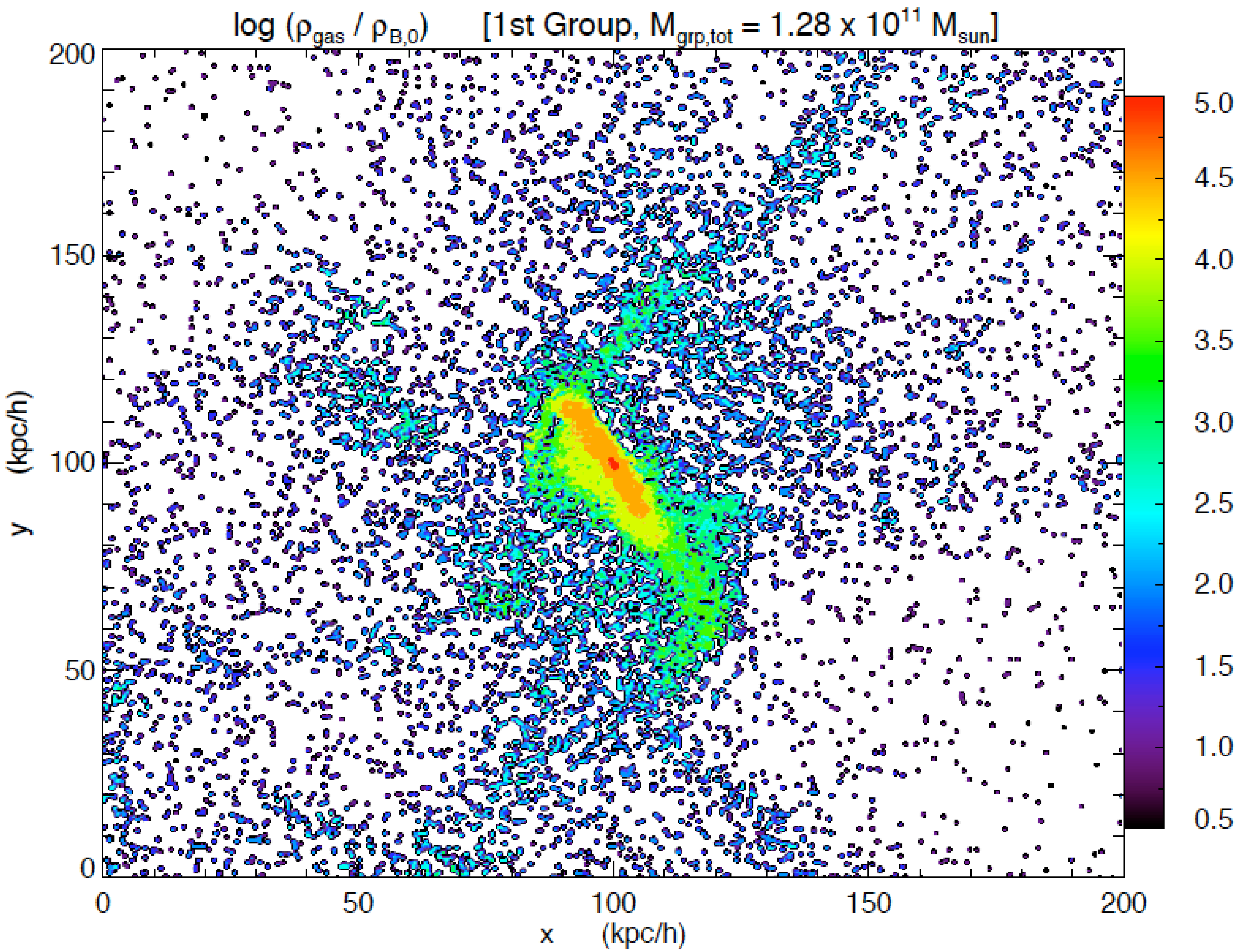
# nsity Evolution

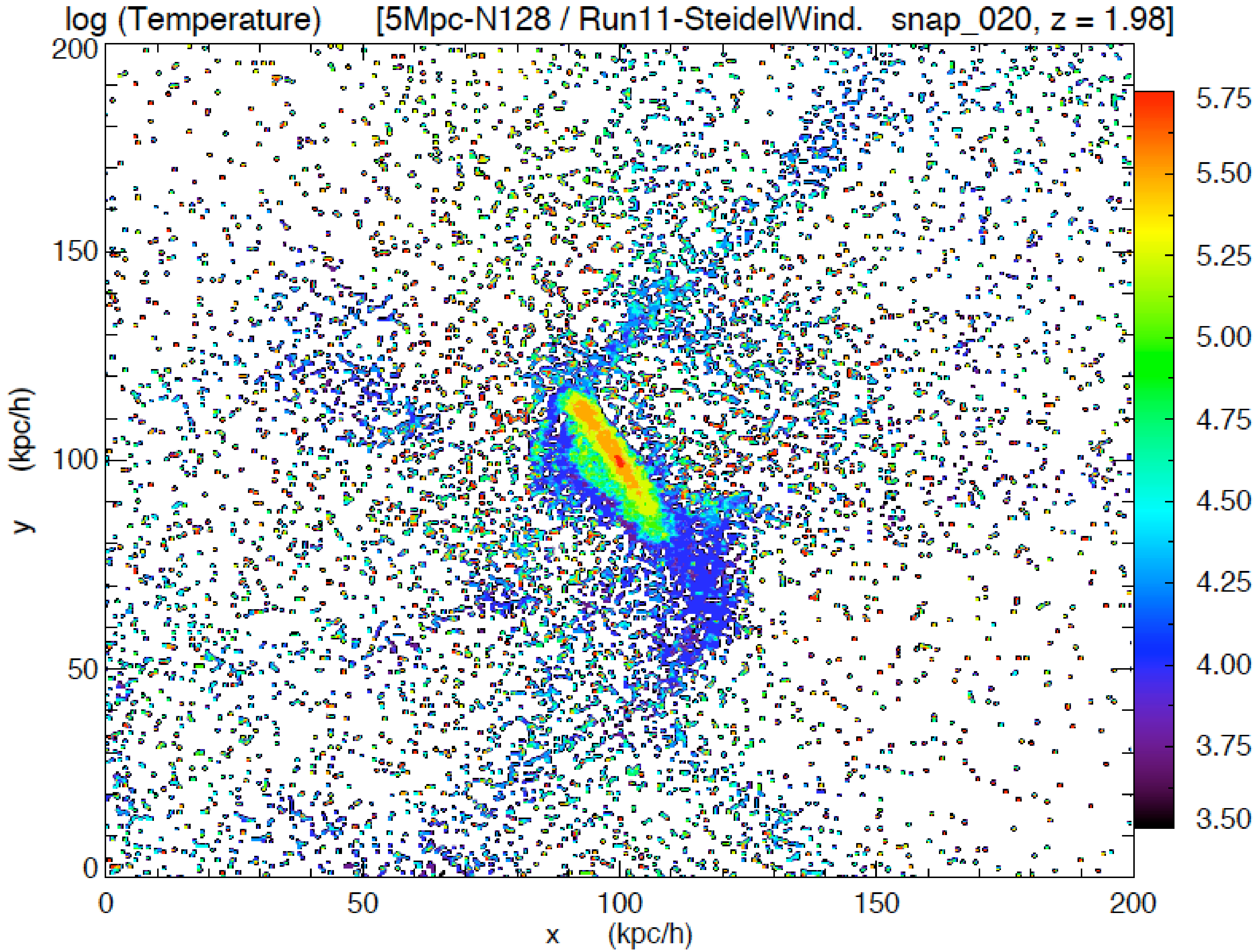
Cucciati et al. 2012, A&A, 539A, 31 (VVDS)

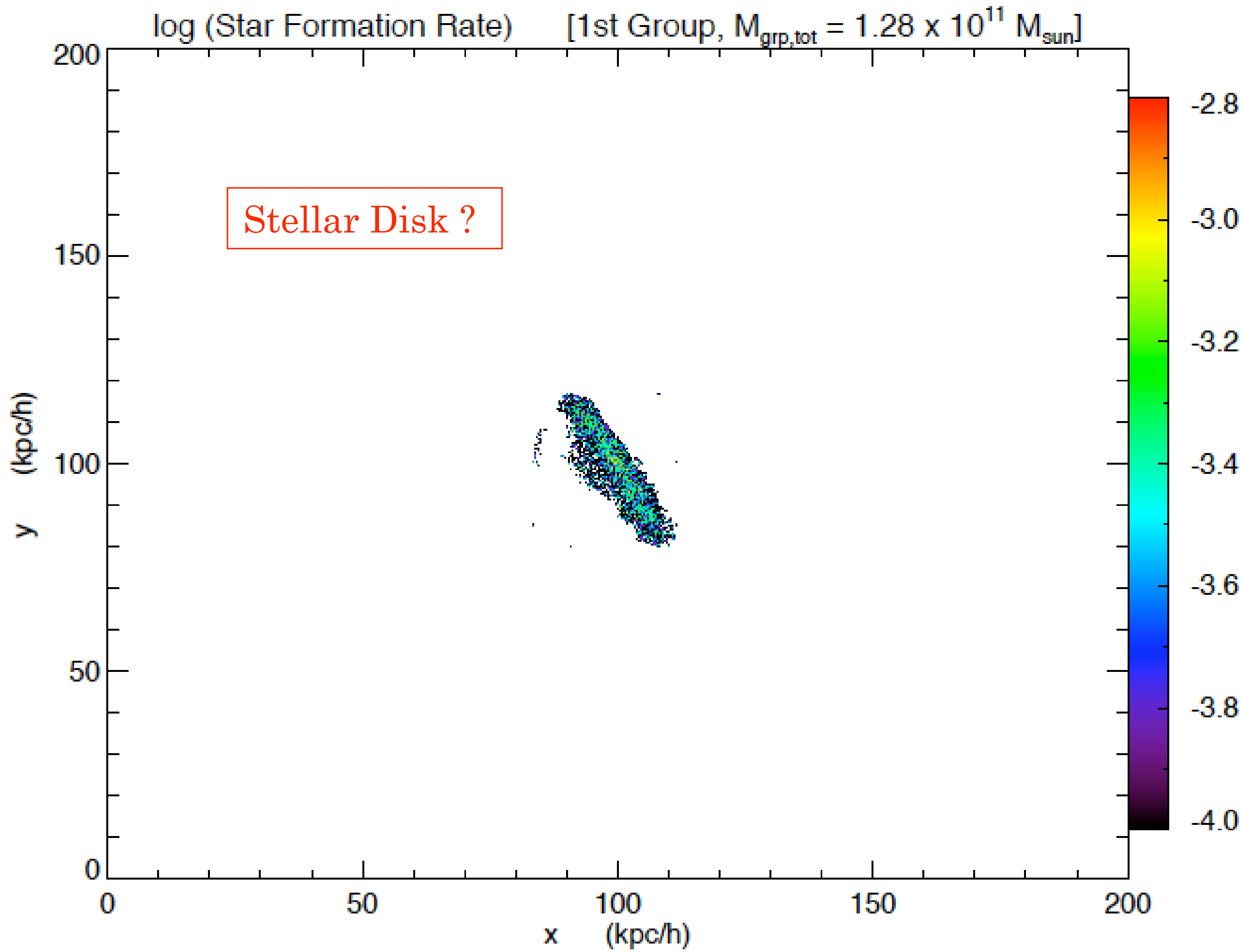


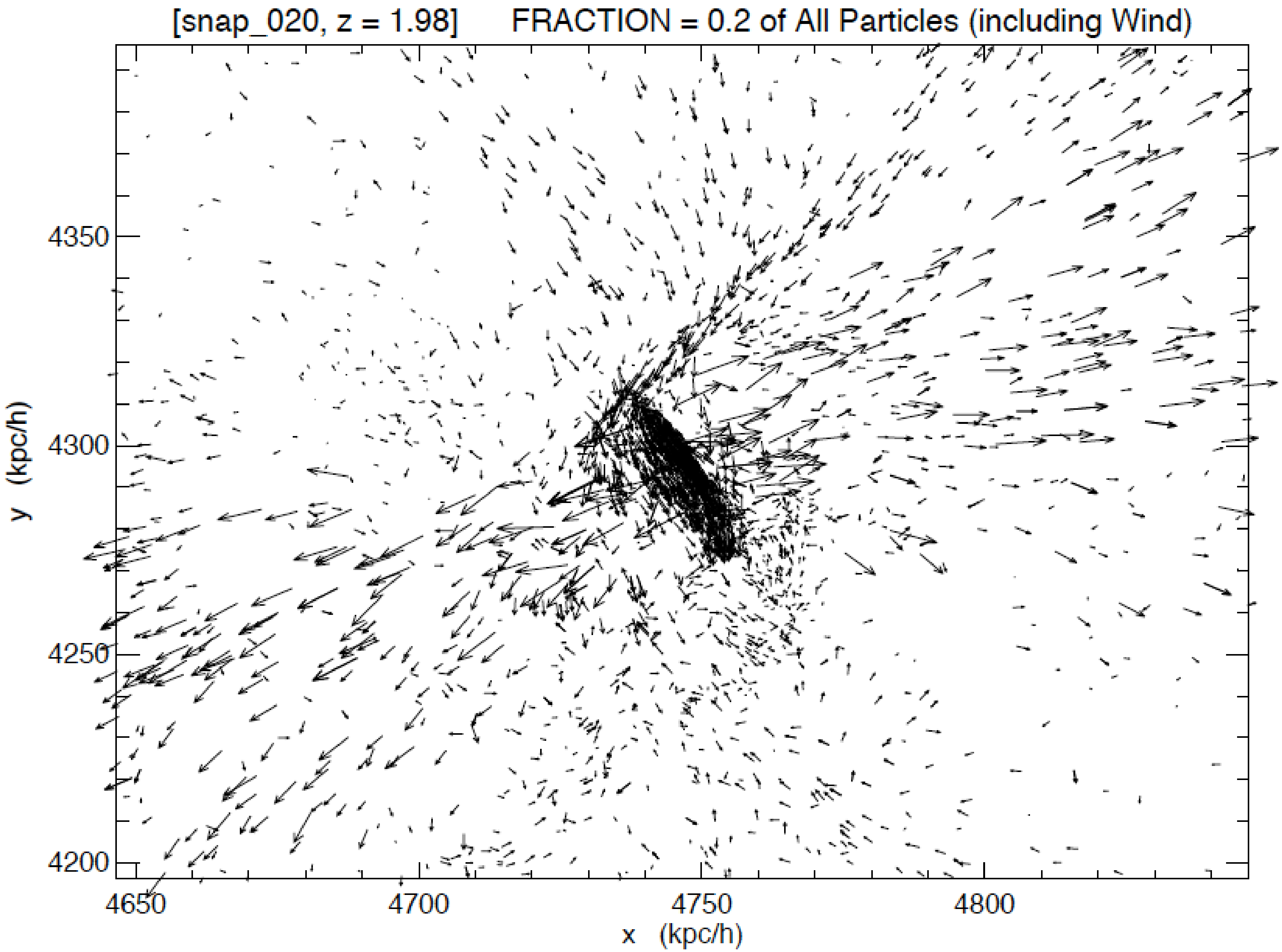
Projection of $(200/h\ kpc)^3$ volume around a massive galaxy center (run RVWat) showing Gas properties



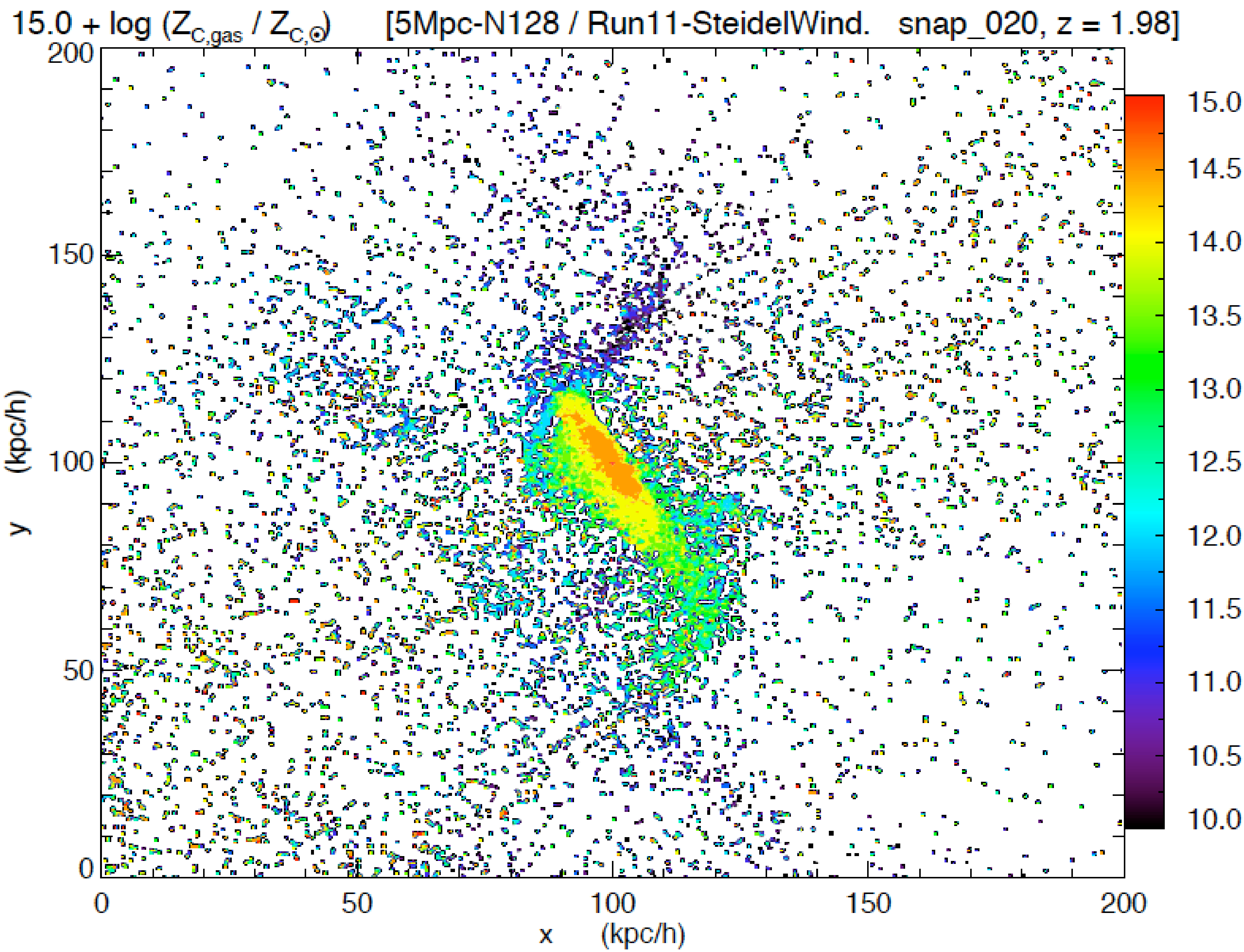

log (Temperature) [5Mpc-N128 / Run11-SteidelWind. snap_020, z = 1.98]
y (kpc/h)
x (kpc/h)
0
50
100
150
200
3.50
3.75
4.00
4.25
4.50
4.75
5.00
5.25
5.50
5.75



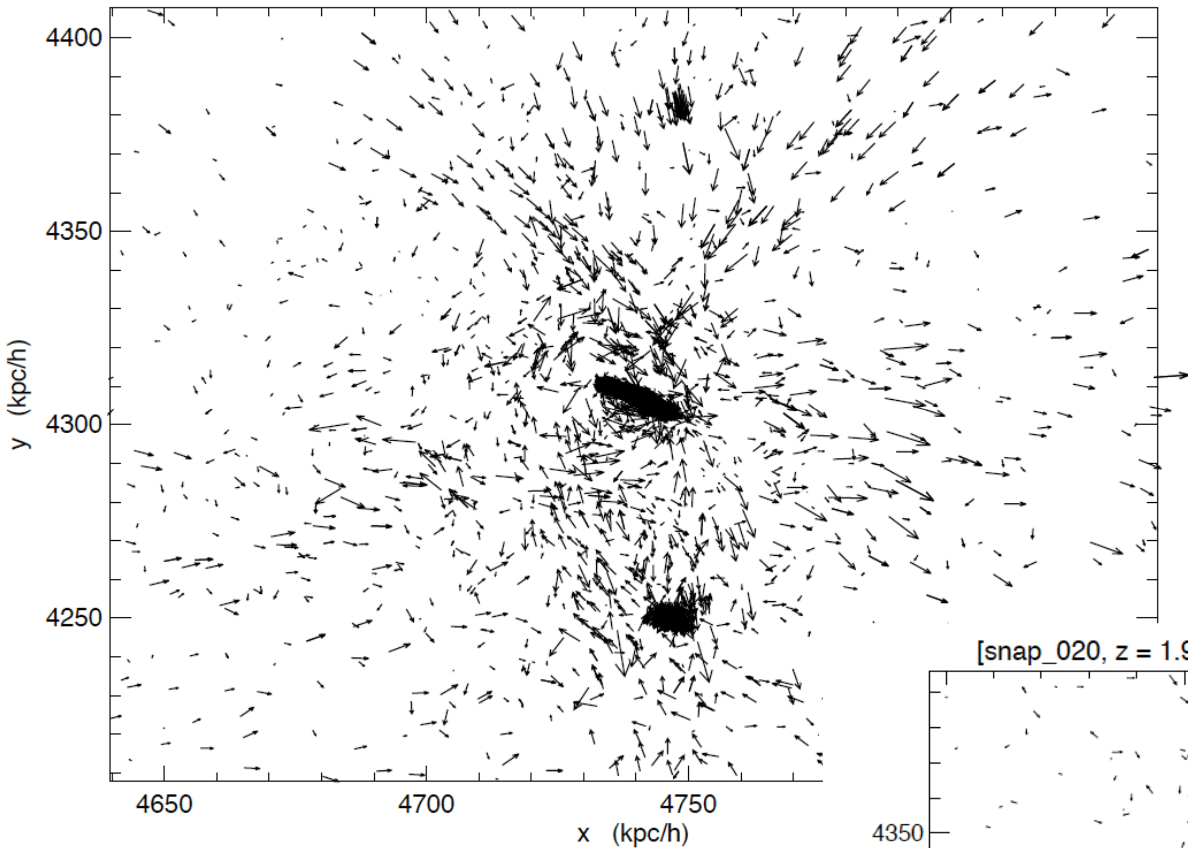
log (Star Formation Rate) [1st Group, $M_{grp,tot} = 1.28 \times 10^{11} M_{sun}$]
Stellar Disk ?
200
150
100
50
0
y (kpc/h)
0
50
100
150
200
x (kpc/h)
-2.8
-3.0
-3.2
-3.4
-3.6
-3.8
-4.0



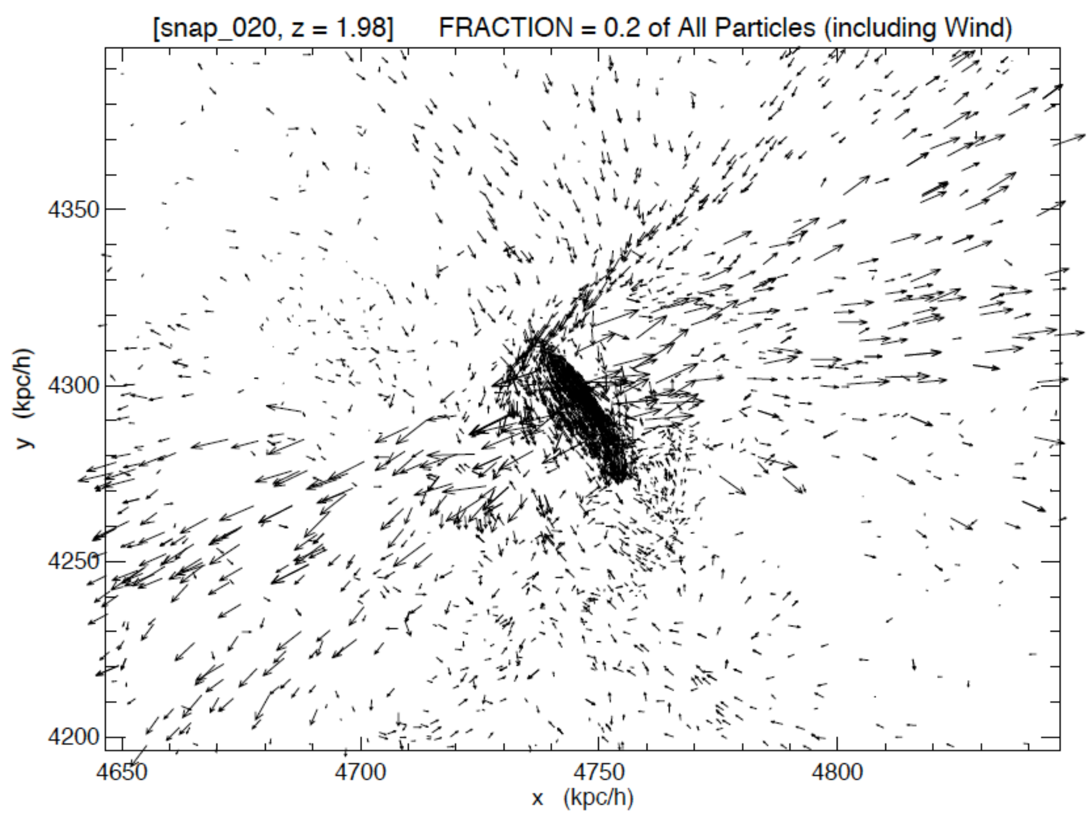
[snap_020, z = 1.98]      FRACTION = 0.2 of All Particles (including Wind)
4350
4300
4250
4200
y (kpc/h)
4650
4700
4750
4800
x (kpc/h)



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

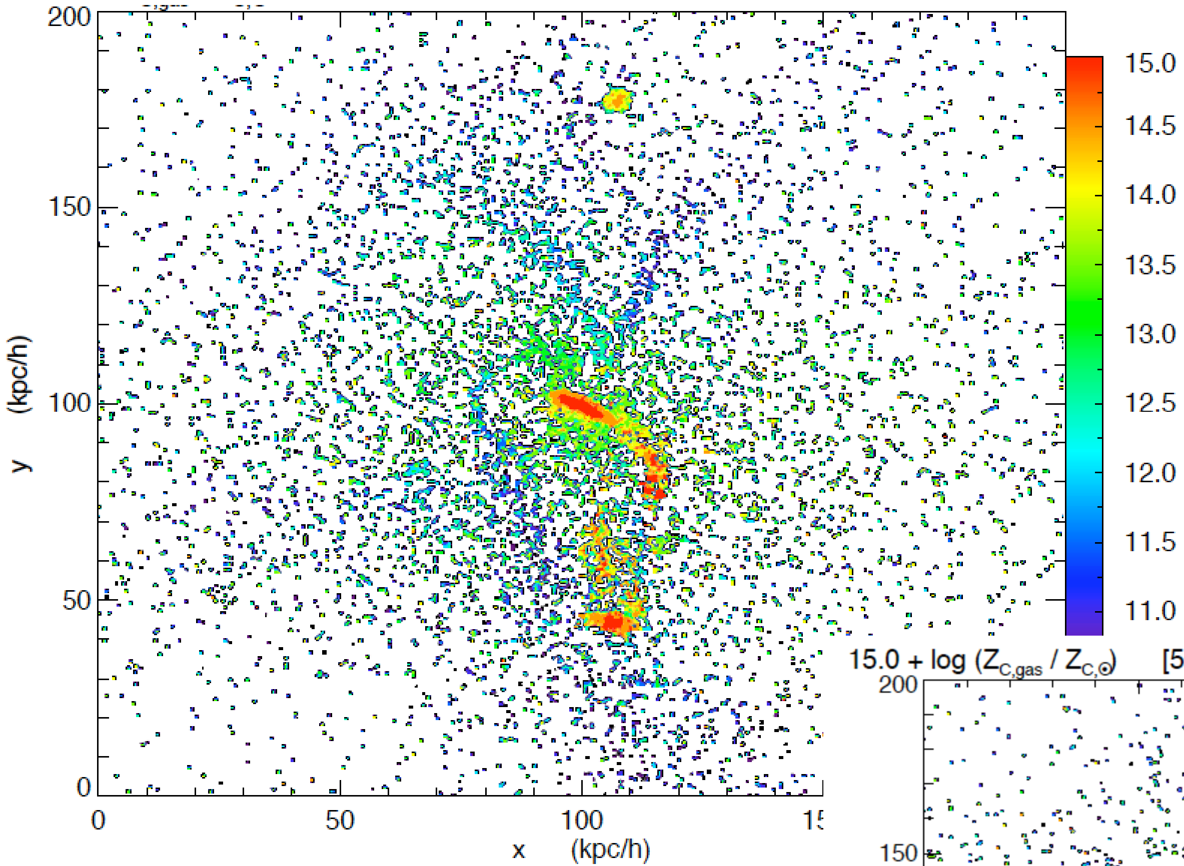



NWt

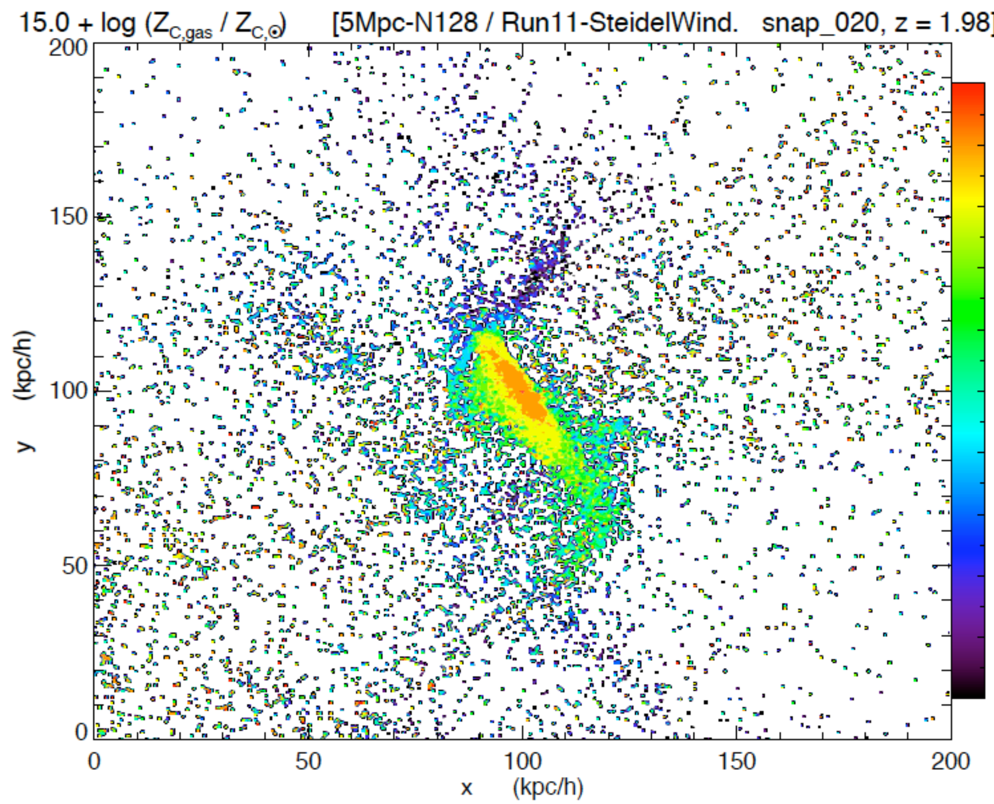



RVWat

20-juil-12



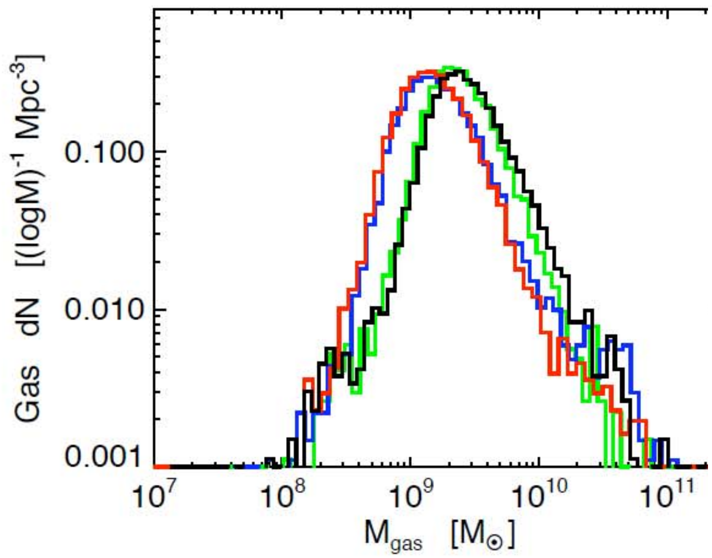

NWt

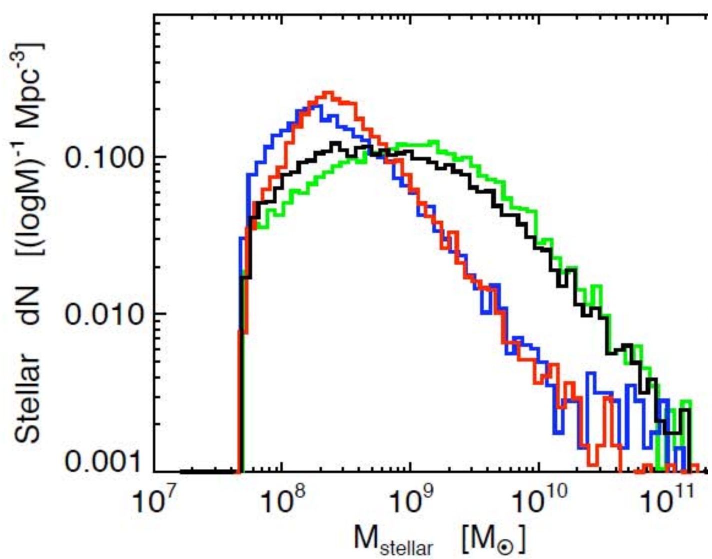


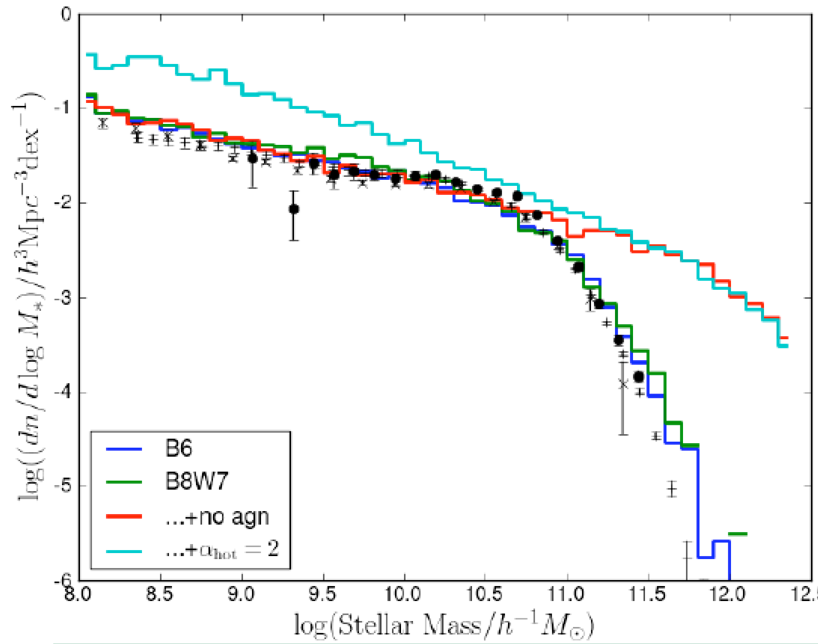

RVWat

20-juil-12

# Mass-Function and Mass-Fraction of Galaxies at z = 2.23



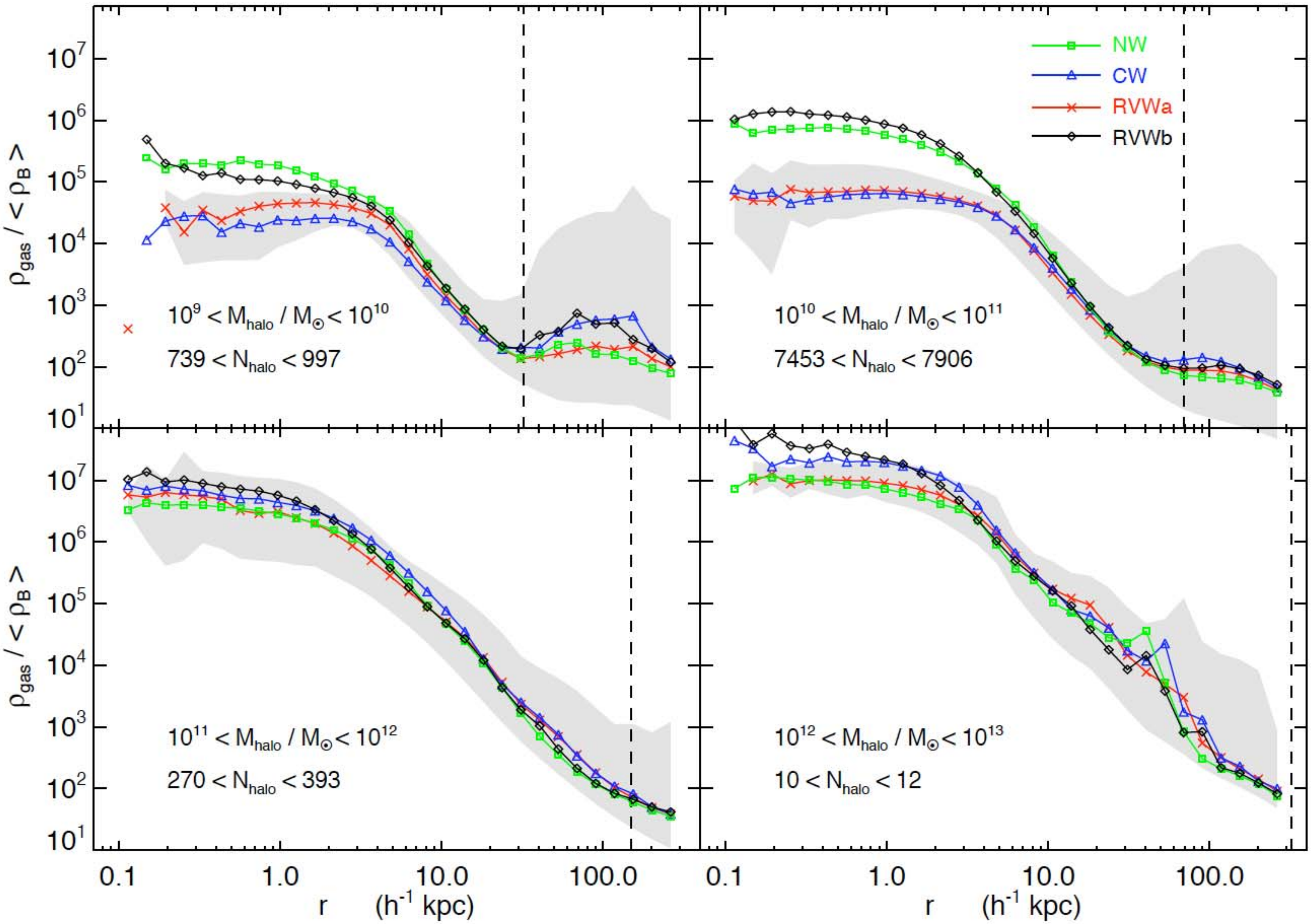



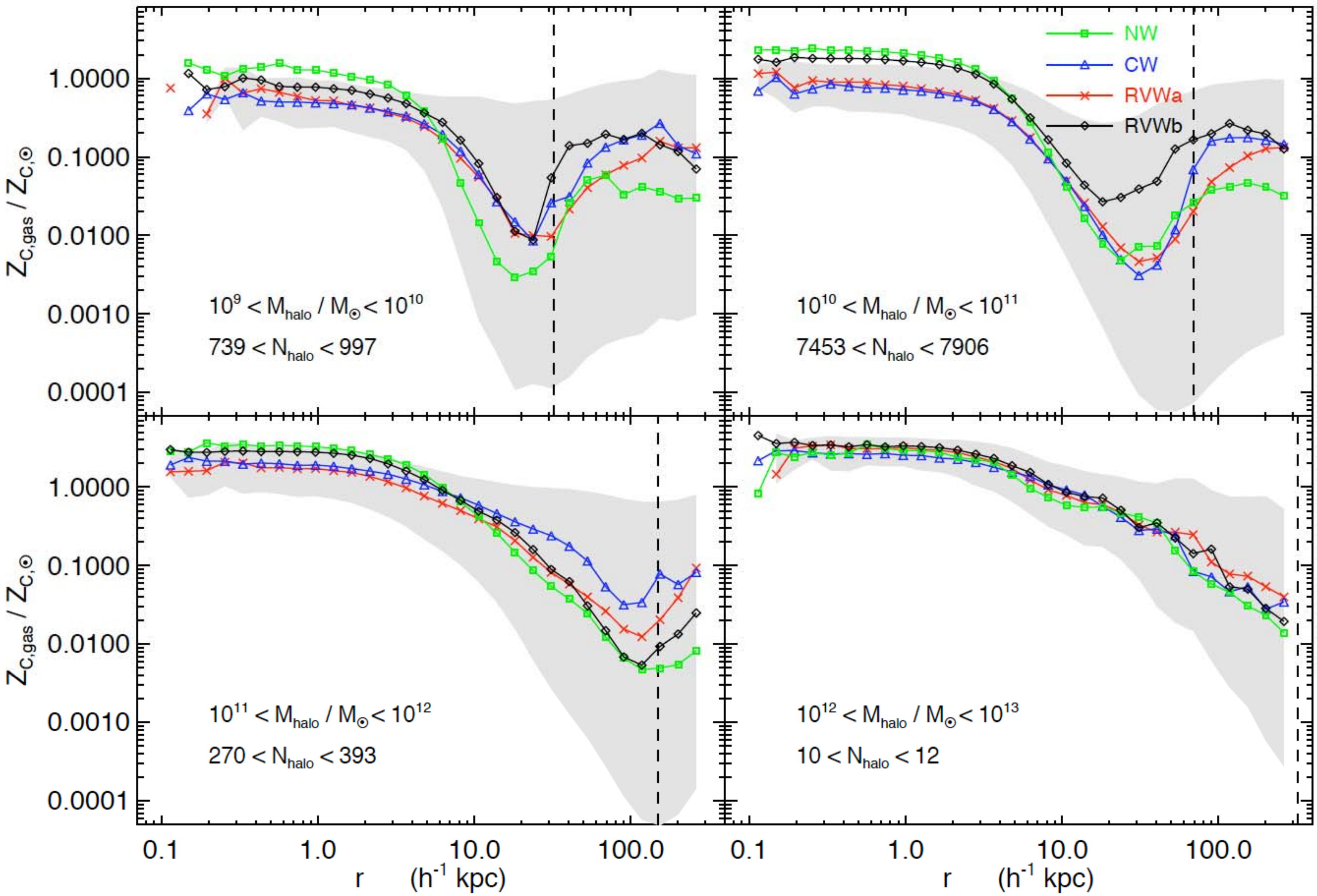

Bower, Benson & Crain 2012, MNRAS, 422, 2816

**Figure 1.** Comparison of the stellar mass function of the Bow06 model (blue line) with the base-line B8W7 model used in this paper (green line). This is based on the WMAP7 cosmology and includes AGN "hot halo" feedback following Bower et al. 2008. The two models are almost indistinguishable. To illustrate the importance of AGN feedback, we show the effect of turning off the AGN feedback (red line). We also show the effect of then adopting the $\alpha_{hot} = -2$ (cyan line). For comparison, observational data are shown as black points with error bars. The data is taken from Bell et al. (2003) (circles) and Li & White (2009) (crosses).

# Gas Density - Radial Profile at z=1.98



# (Gas) Carbon Metallicity - Radial Profile at z=1.98



# Conclusions

## What aspects of galactic winds can be studied in cosmol sims?

- Can study impact of galactic winds on larger-scales galaxy & IGM properties
  - Still far away from self-consistently driving these winds in such sims
  - Need subgrid prescription
  - How does larger-scale environments & mergers affect wind?

- Galactic winds can:
  - Reduce cosmic SFR density, quench SF in galaxies
  - Affect density profile of galaxy halos
  - Enrich the CGM and IGM with metals

- Galaxy merger simulations (resolving length scales lower than purely cosmol sims) $\Rightarrow$ study wind driving

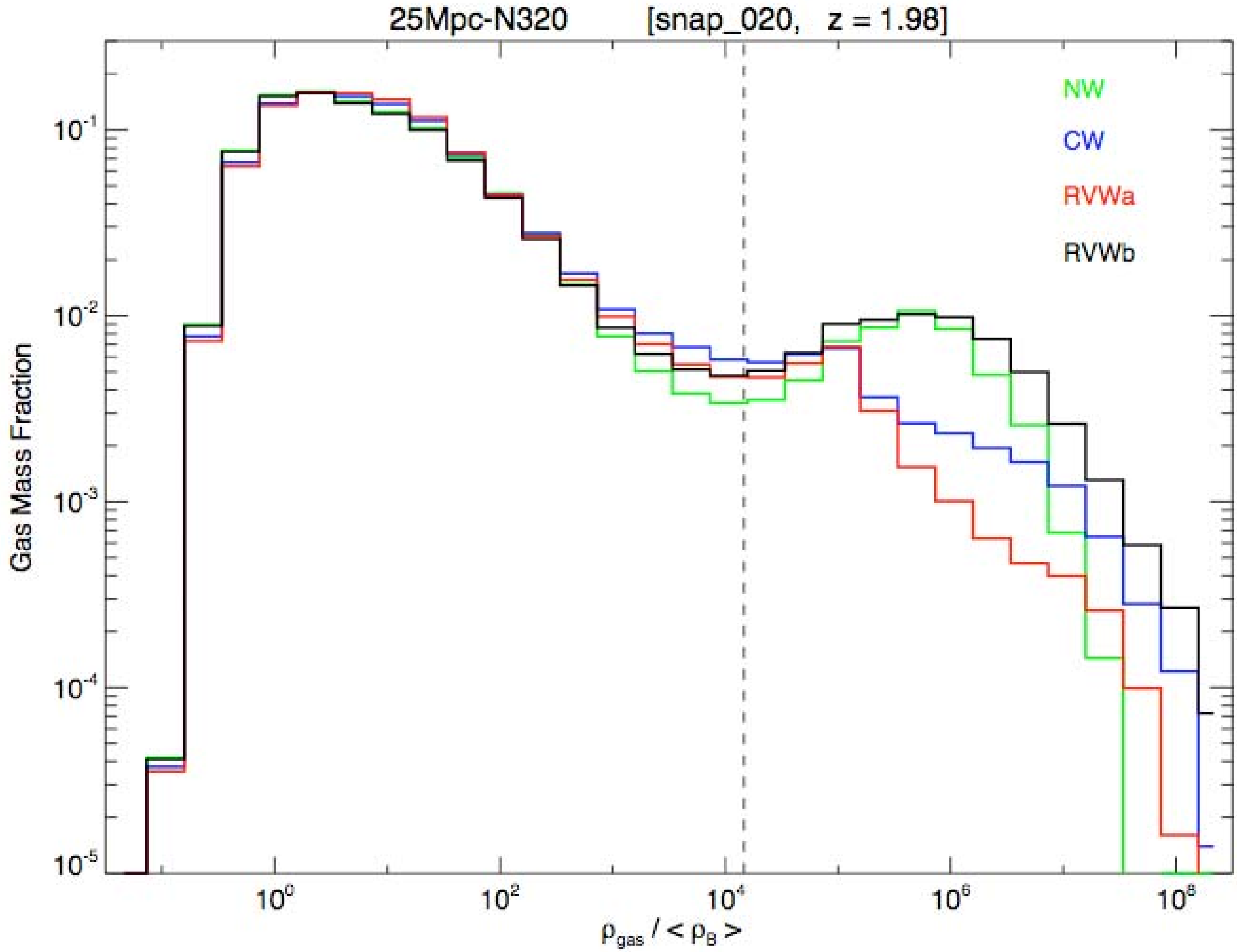
- Can prescriptions from pc-scale sims be incorporated into cosmol sims?

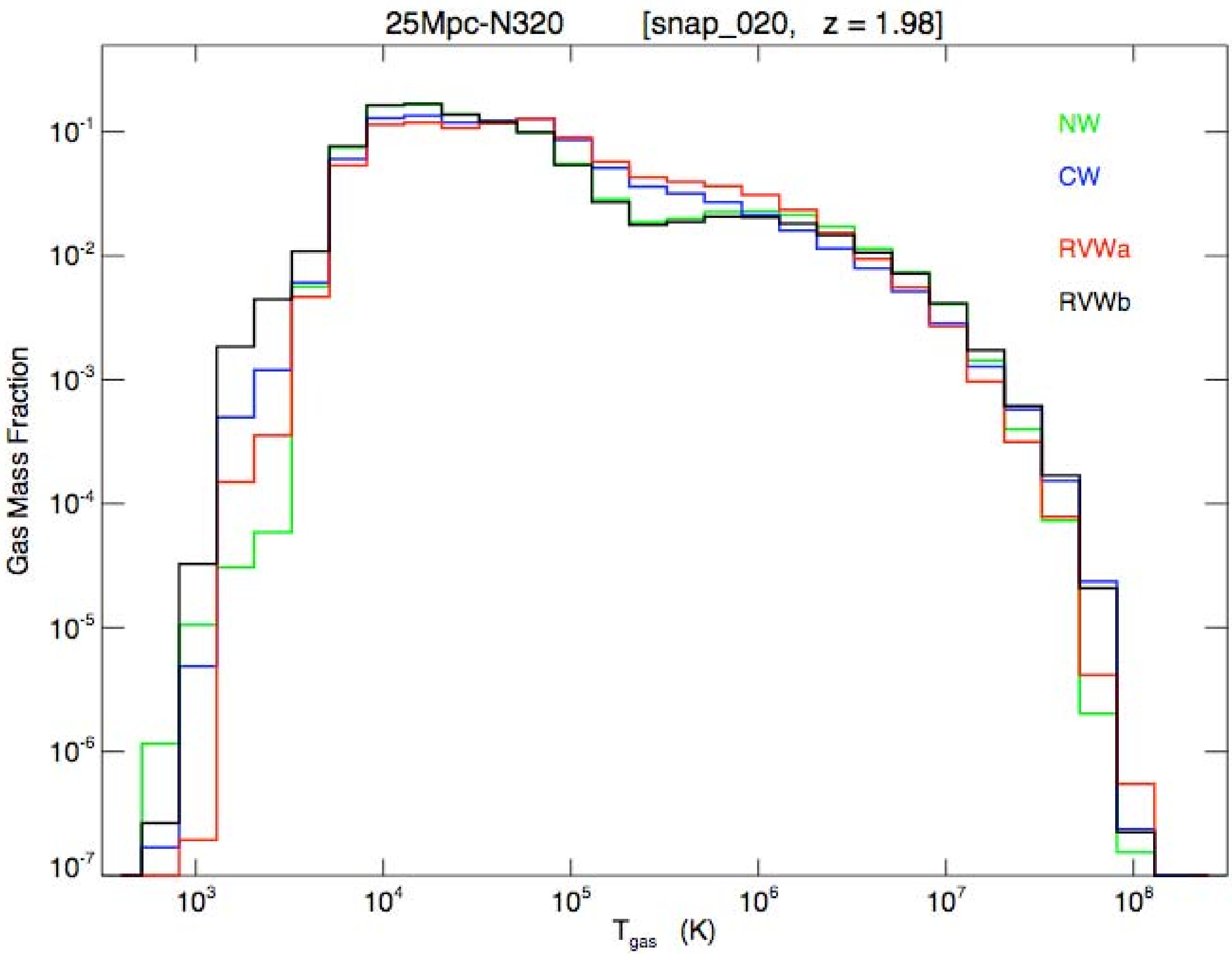
# Extra Slides

# Simulation Volume

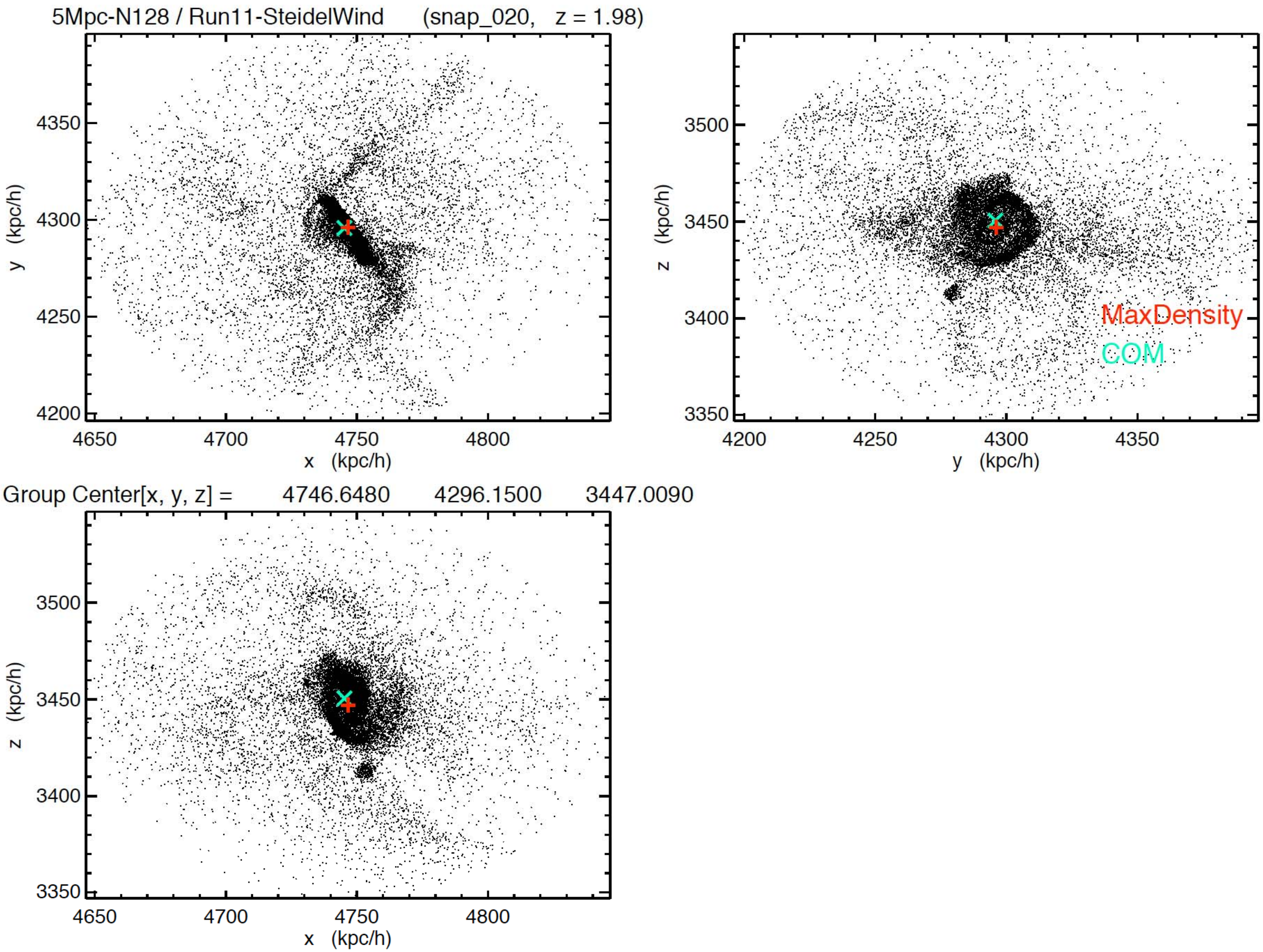
- The computational box has Hubble expansion just like the real Universe
  - Always encompasses the same mass

- The expansion is taken out from computations, s.t. the box appears static
- Coordinate system that expands (or co-moves) with the Universe (the comoving coordinates) is used

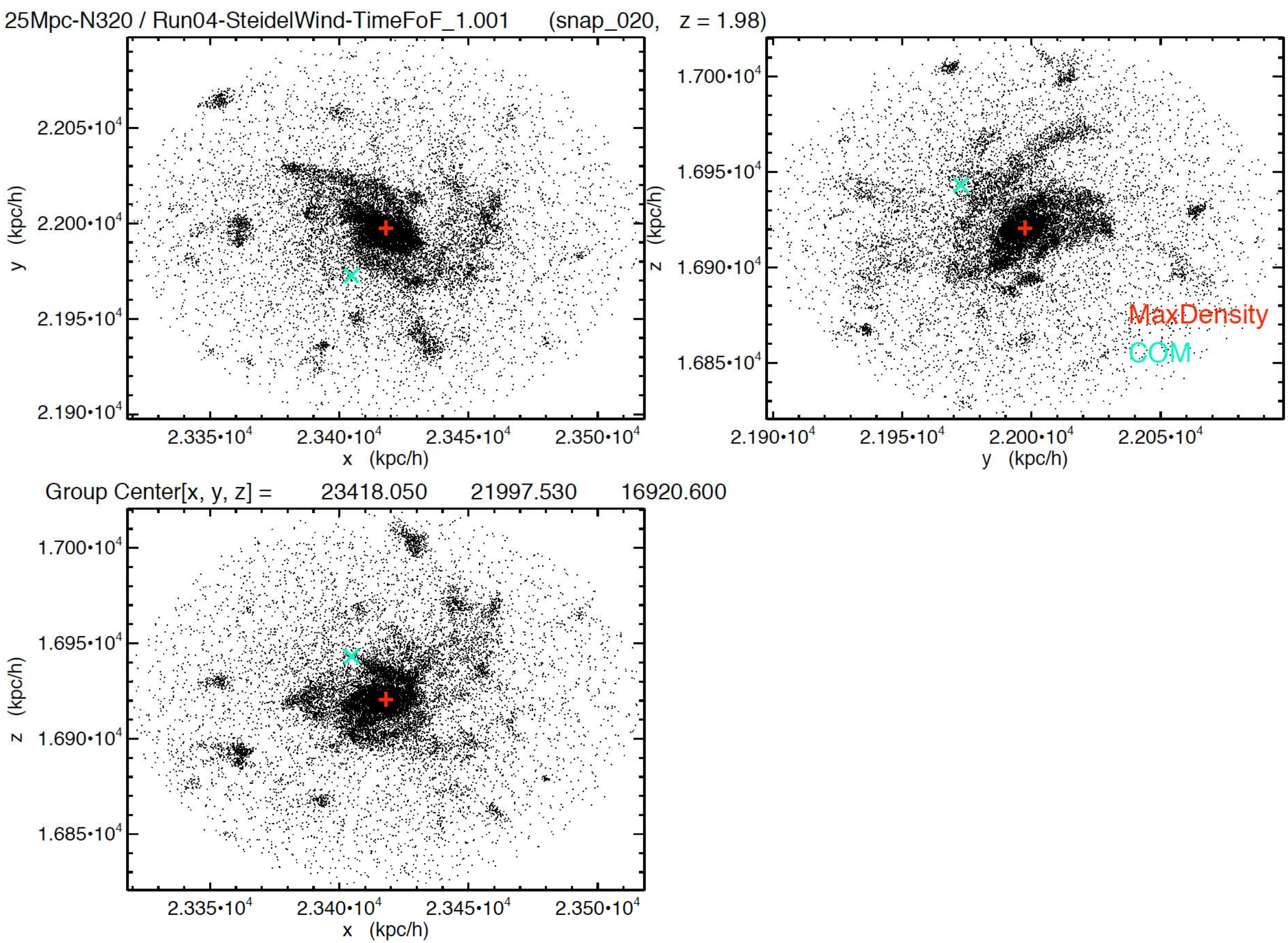

25Mpc-N320 [snap_020, z = 1.98]
NW
CW
RVWa
RVWb
Gas Mass Fraction
$\rho_{gas} / < \rho_B >$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^0$
$10^2$
$10^4$
$10^6$
$10^8$



25Mpc-N320 [snap_020, z = 1.98]
NW
CW
RVWa
RVWb
Gas Mass Fraction
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{3}$
$10^{4}$
$10^{5}$
$10^{6}$
$10^{7}$
$10^{8}$
$T_{gas}$ (K)

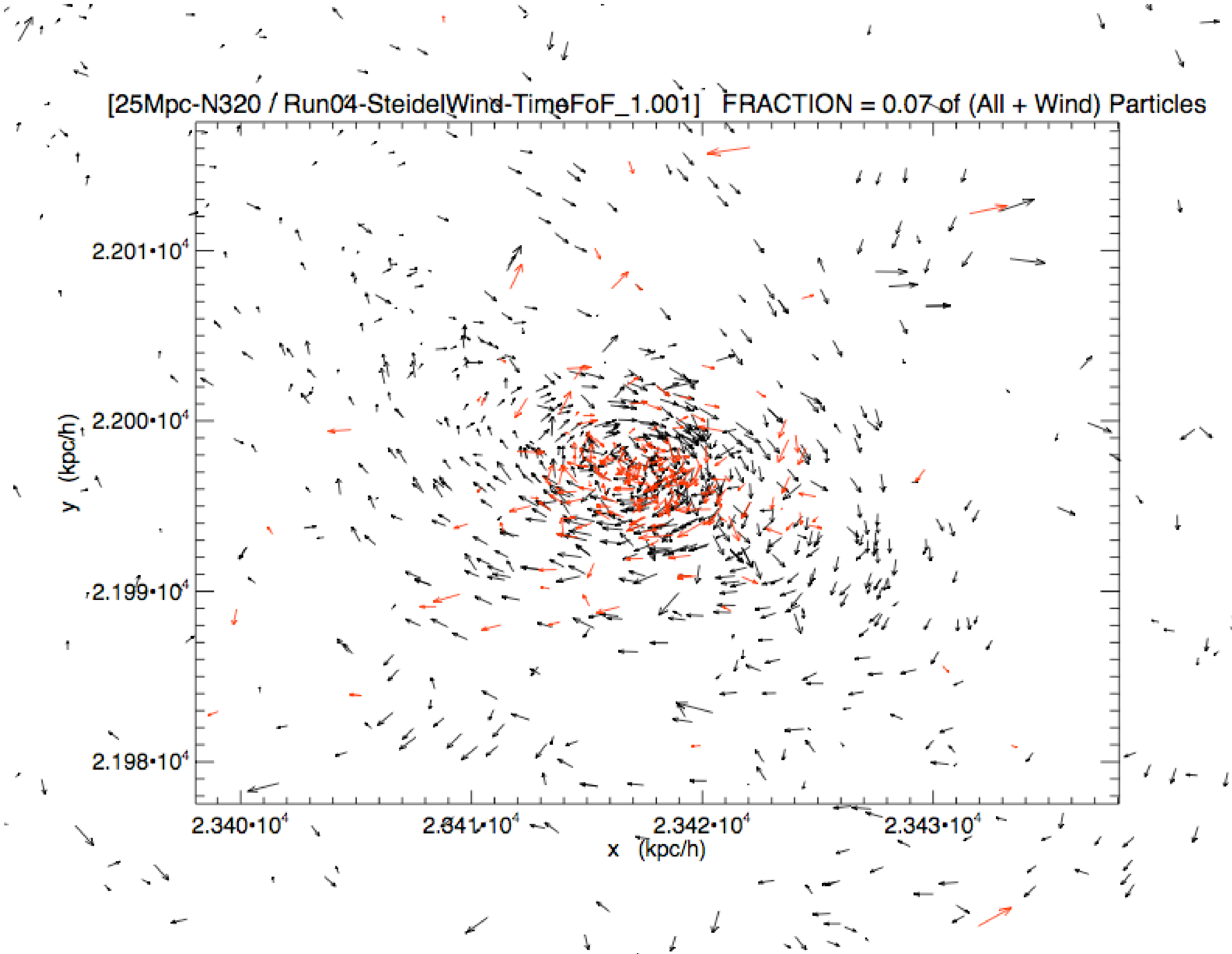


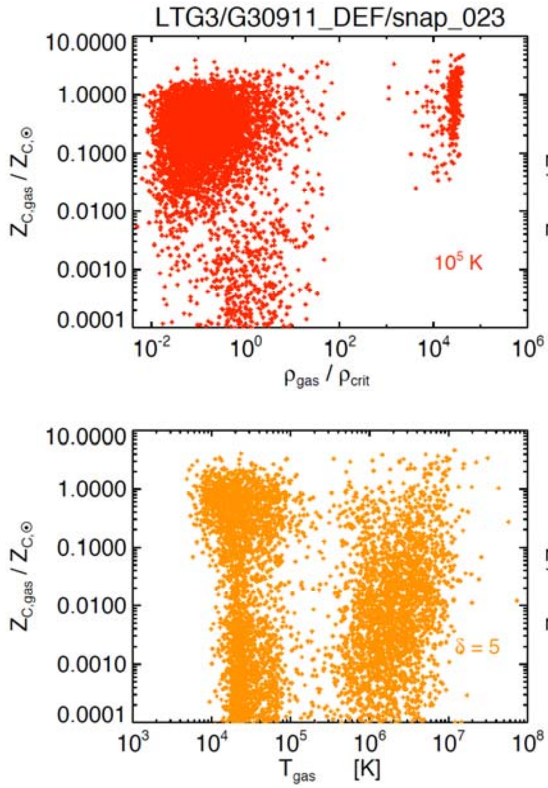
5Mpc-N128 / Run11-SteidelWind (snap_020, z = 1.98)
y (kpc/h)
x (kpc/h)
4200
4250
4300
4350
4650
4700
4750
4800
z (kpc/h)
y (kpc/h)
3350
3400
3450
3500
4200
4250
4300
4350
MaxDensity
COM
Group Center[x, y, z] = 4746.6480 4296.1500 3447.0090
z (kpc/h)
x (kpc/h)
3350
3400
3450
3500
4650
4700
4750
4800



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

# Velocity Field of Gas Particles in run RVWa






- Range roughly consistent with Tornatore et al. (2010, MNRAS, 402, 1911)

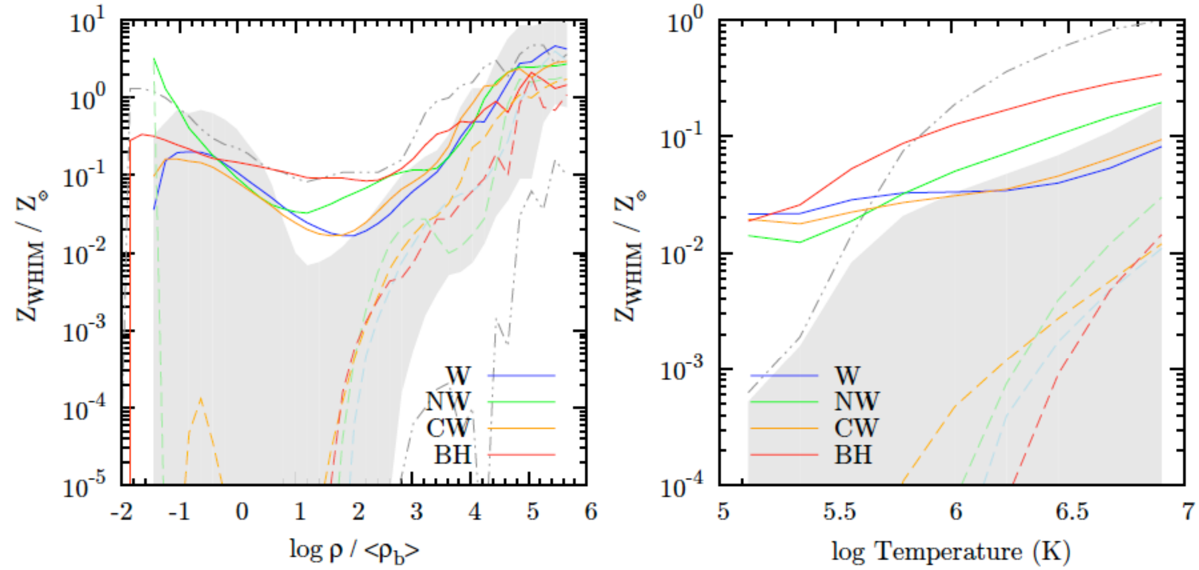
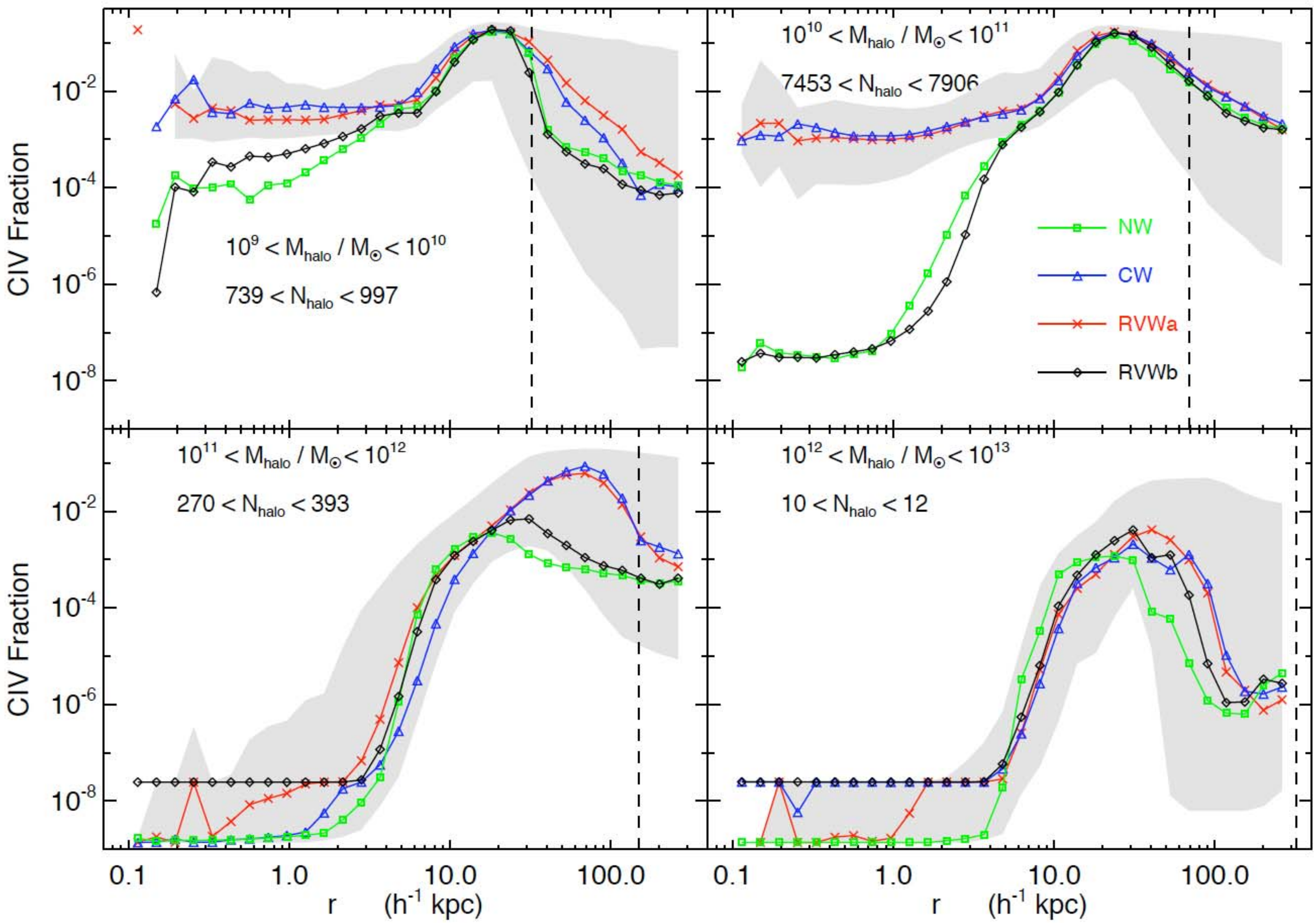



**Figure 9.** Total metallicity of the WHIM (gas particles at temperatures $10^5 - 10^7$ K) in solar units at $z = 0$, as a function of gas density (in units of the cosmic mean baryon density $\langle \rho_b \rangle$, left panel) and temperature (right panel). In each panel, the grey shaded area encompasses the 10 and 90 percentiles of the W run, while the dot–dot–dashed lines show the same percentiles for BH the run. Thick coloured lines show the average metallicities while thin dashed lines show the median metallicities.

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



# (Gas) Temperature - Radial Profile at z=1.98