Gas and Stellar Properties of Galaxies at z>=2 in Cosmological Hydrodynamical Simulations

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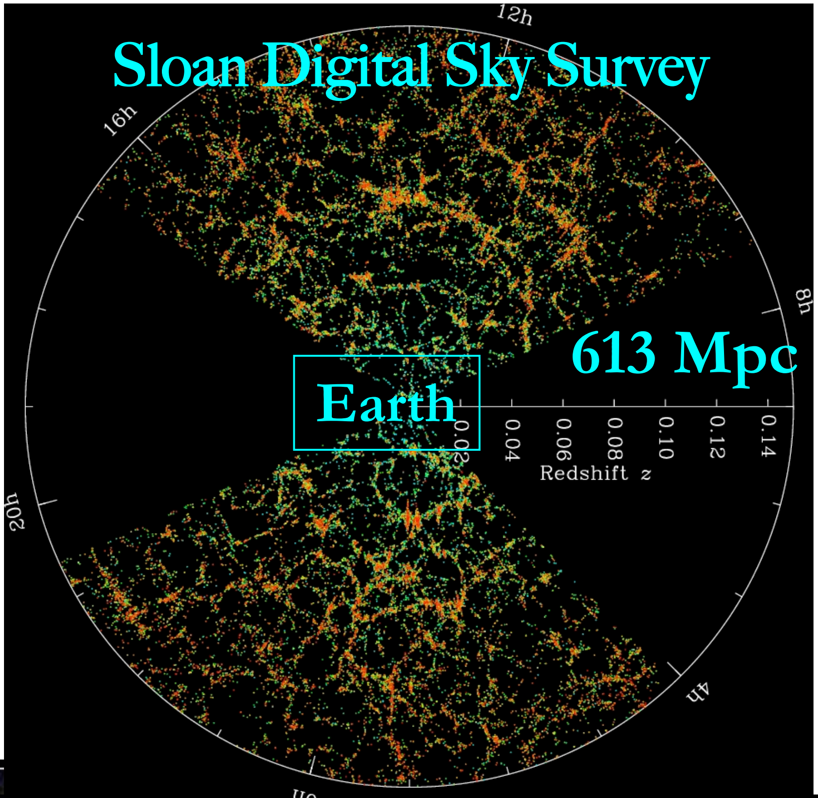
Outline

- Introduction
  - Galaxies & large-scale structures
  - Modeling in hydrodynamical simulations

- My research : SNe-driven kinetic feedback
  - Methodology : subgrid physics in GADGET3 code
  - Simulations
  - Results

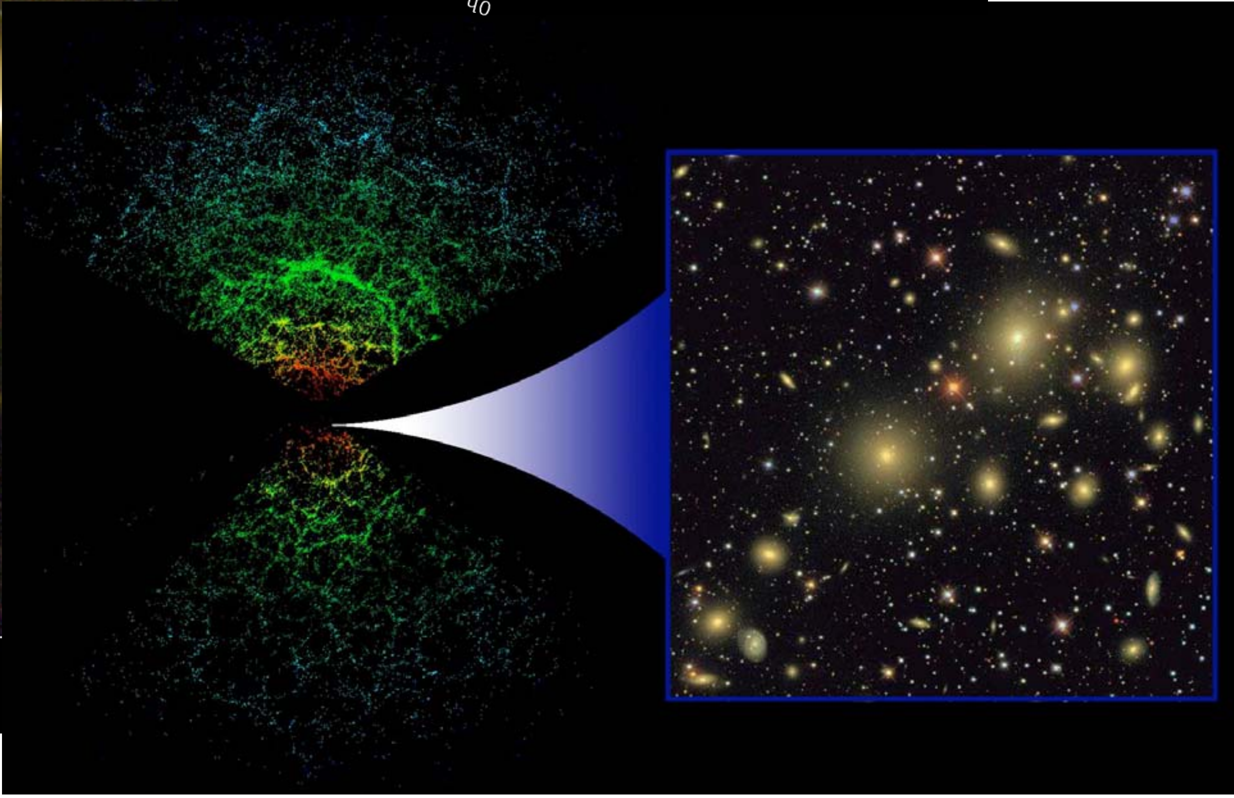
- Conclusions

Baryon distribution at different scales



Galaxy Cluster Abell 2218

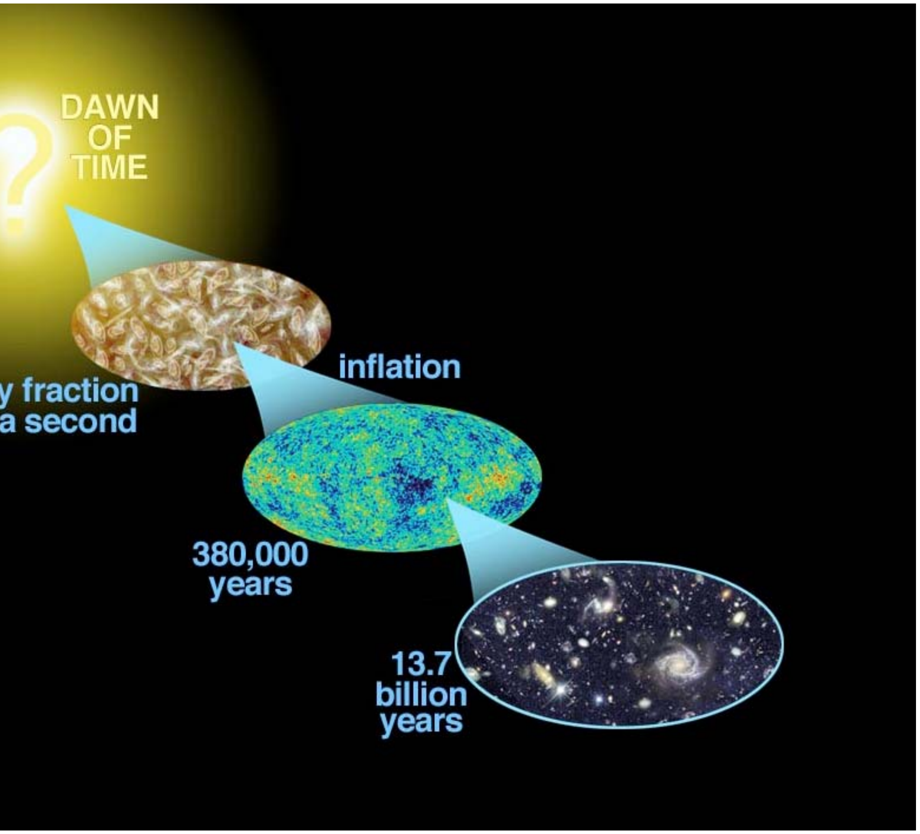
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08



Galaxy Formation Modeling

Cosmological Hydrodynamic Simulations

What is done? How?



Large Scale Structure Formation

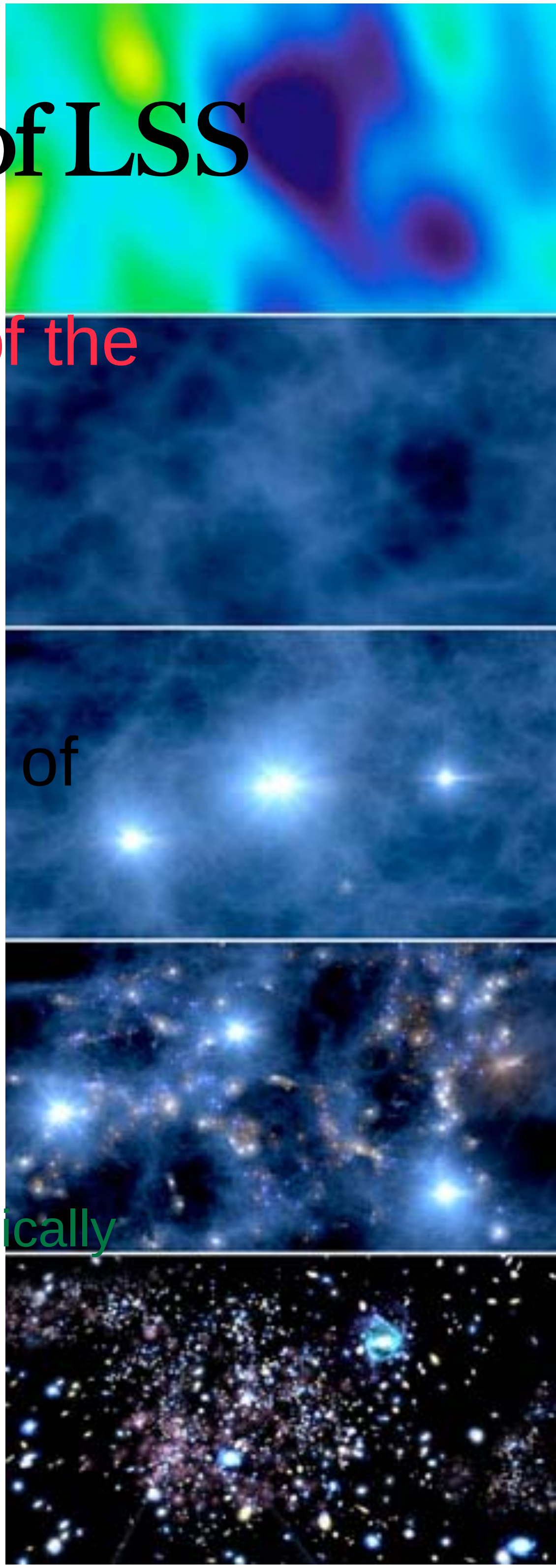
- Quantum fluctuations shortly after the Big Bang ⇒ Primordial density perturbations

- 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 LSS

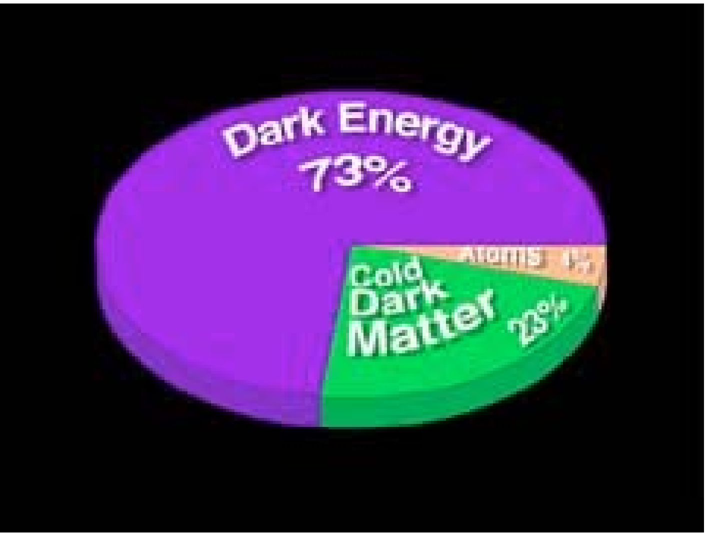


- Computational box ⇔ representative volume of the Universe
- Resolution elements (particles or grid) in box ⇔ matter

- 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

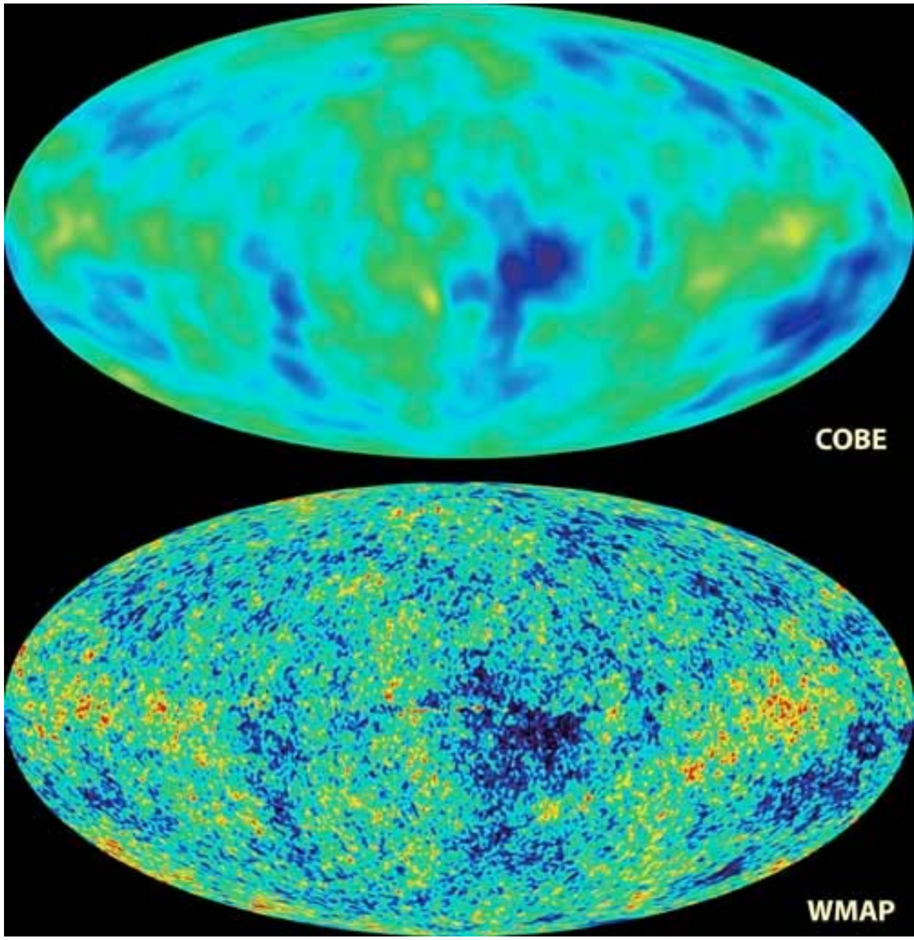


Initial Condition

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

ΛCDM universe

- 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



Tracking Gravitational Collapse

$$\boxed{\# = \%1}$$

- Overdensity, δ
- When δ << 1 : linear regime
  - Use Zeldovich approximation (Zeldovich 1970, A&A, 5, 84)
- In galaxies, δ >> 1 : linear approx. breaks down

- Inflation ⇒ near homogeneous initial particle distribution
  - Small perturbations

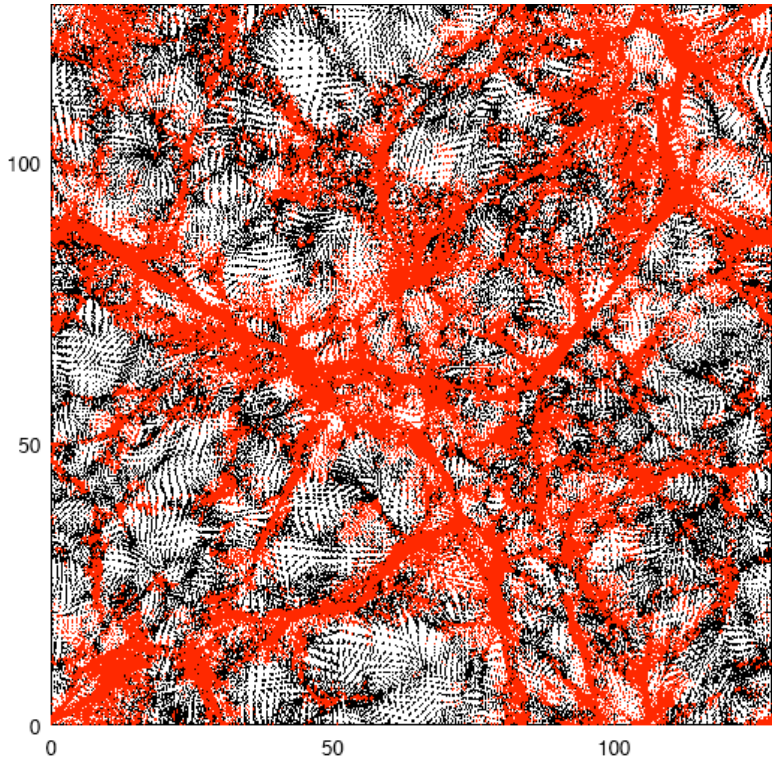
- Linear regime
  - Λ dominated
  - EdS/Matter dominated

$$\boxed{\delta_k(t) = A + Be^{-2Ht}}$$

$$\boxed{\delta_k(t) = At^{\frac{2}{3}} + Bt^{-1}}$$

- Need supercomputer simulations to track non-linear evolution

Galaxy Simulation Physics



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

- Baryon / Gas evolution
  - Gravity + Hydrodynamics

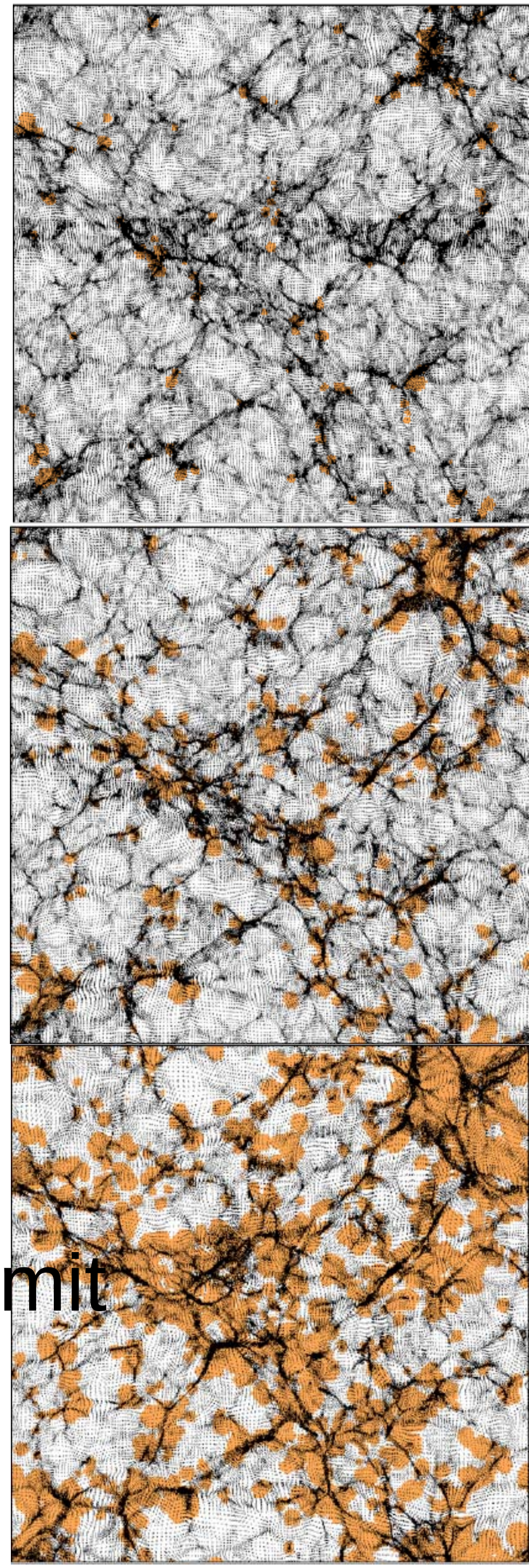
- Numerically integrate dynamical equations in Comoving Coordinates

$$\boxed{H(z)}$$

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

- Evolve box from z = 100 up to z = 0
  - From after Big Bang (t → 0) to present (t = 13.7 Gyr)

N-body (Collision-less)

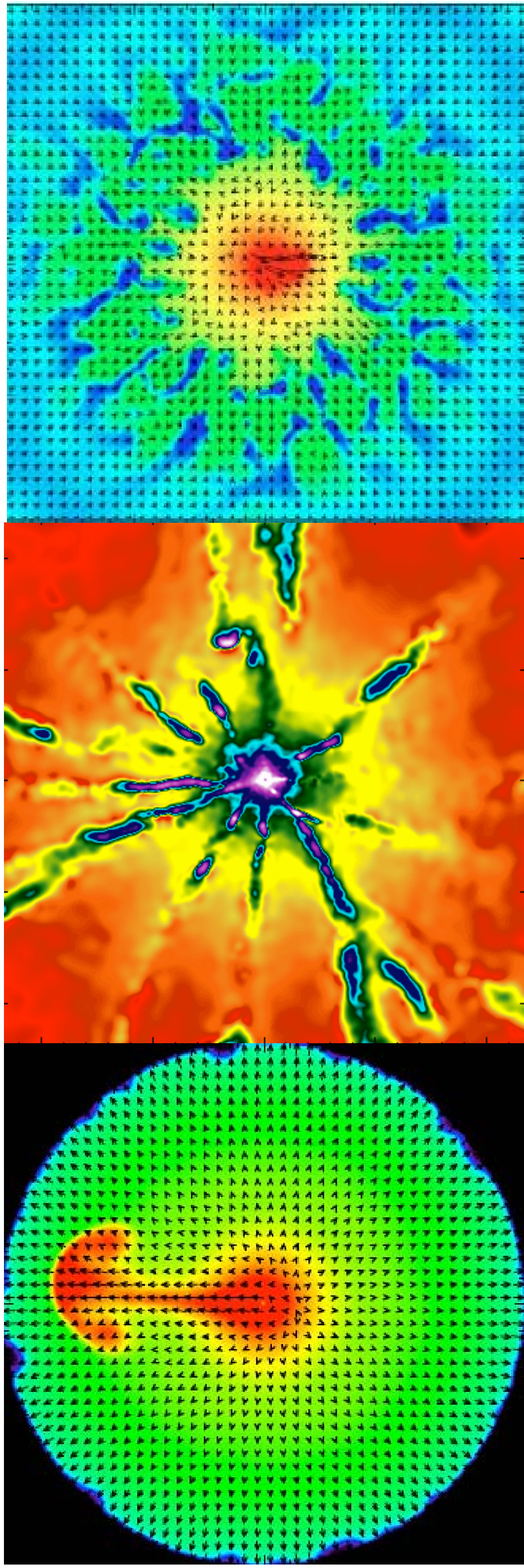


- Dark matter + Baryons
- Gravitational interactions only
- Equations of particle motion

$$\boxed{\frac{d\vec{x}}{dt} = \vec{u}} \qquad \boxed{\frac{d\vec{u}}{dt} = -\nabla\Phi}$$

- Poisson's equation $\boxed{\nabla^2\Phi = 4\pi G\rho}$
- Non-relativistic velocities ⇒ Newtonian limit

Hydrodynamics (Baryons)



- Collisional particles with ideal gas properties
- Mass

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

- Momentum

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

- Energy

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

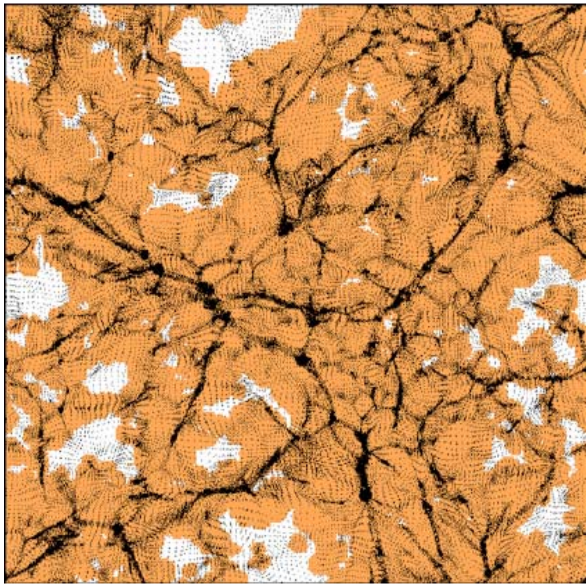
$$\varepsilon = \frac{1}{\left(\gamma - 1 \right)} \frac{P}{\rho}$$

- Equation of state, $\varepsilon = f(\rho, P)$
  - Ideal gas
  - Polytropic

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

Successful Results

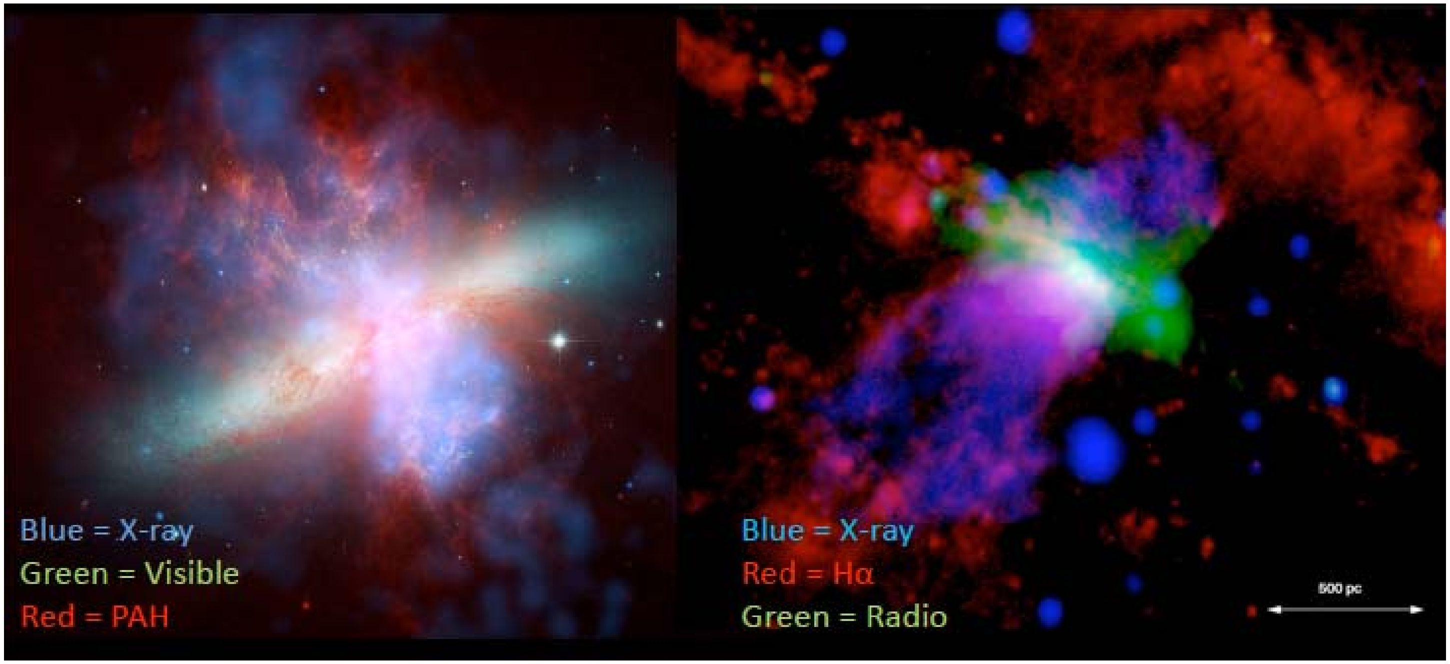
- Hierarchical Structure Formation
  - Can reproduce the distribution and structure of galaxies in very large scales as seen in observations
- Distribution of matter in the Universe
  - Collapse via gravitational forces into filaments. Galaxies form in these filaments
- Clustering of galaxies at all 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

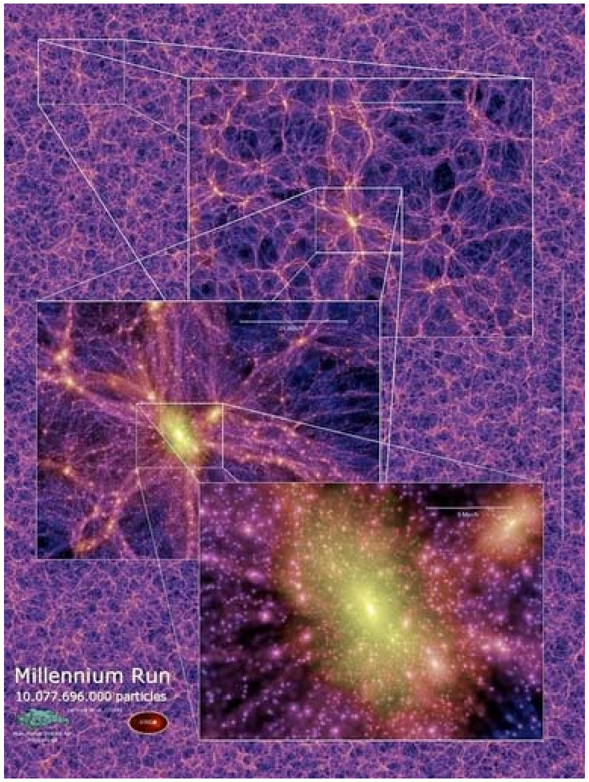


Large-Scale Filaments. (5/h Mpc)^3 box at low-z

Movie-WholeBox/Last-Snap-Rotation/DM_Gas_Star.gif

The case for sub-resolution (sub-grid) models





e.g. Galactic Wind Feedback

- Outflowing gas observed
- 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

$$\boxed{\text{(few - 10's Mpc) box : Resolution} \sim 10^6 M_{Sun}, \text{ 1 kpc}}$$

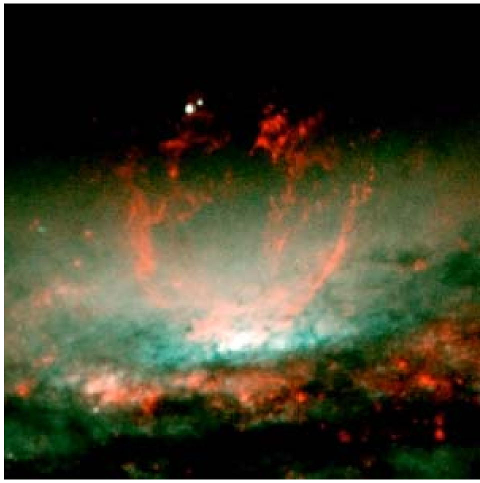
- Crucial ingredient
- Implemented as sub-resolution models

Modified-GADGET3 code: numerical sub-grid physics

- GADGET : TreePM (gravity) - SPH (hydro) (Springel 2005, MNRAS, 364, 1105)
- Metal-line cooling & radiative heating (Wiersma et al. 2009, MNRAS, 399, 574) in the presence of UV photoionizing background (Haardt & Madau 2001)
- Star Formation
- 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

<u>SNe Feedback</u>

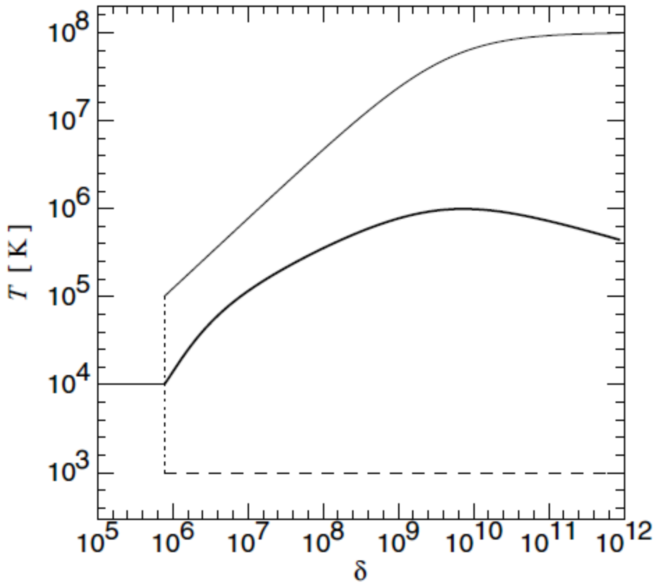
- Thermal feedback (↑ T) : inefficient, energy radiated away quickly
  - Recent (Dalla Vecchia & Schaye 2012, MNRAS, 426, 140) : Min. heating T
- ∴ Kinetic feedback (↑ v)
- Alternative : Blastwave model (Stinson et al.)
  - Switch off cooling manually



Star-formation in multiphase ISM

$\boxed{\rho > \rho_{SF,th}}$

- High-density SPH particle represents a part of ISM
  - Composed of 2 gas phases: Cold clouds + Hot ambient, & Stars
  - In pressure equilibrium
  - Mass & energy exchange between components
  - Hydrodynamics done on the hot-phase



- Effective model (Springel & Hernquist 2003, MNRAS, 339, 289)
  - Internal energy eqn. integrated for hot-phase only
  - Fixed $T_c = 1000\ \mathrm{K}$
  - Equilibrium solution
  - Self-regulated SF: constant effective pressure

$\boxed{\rho_{SF,th} = 0.1\ \mathrm{cm}^{-3}}$

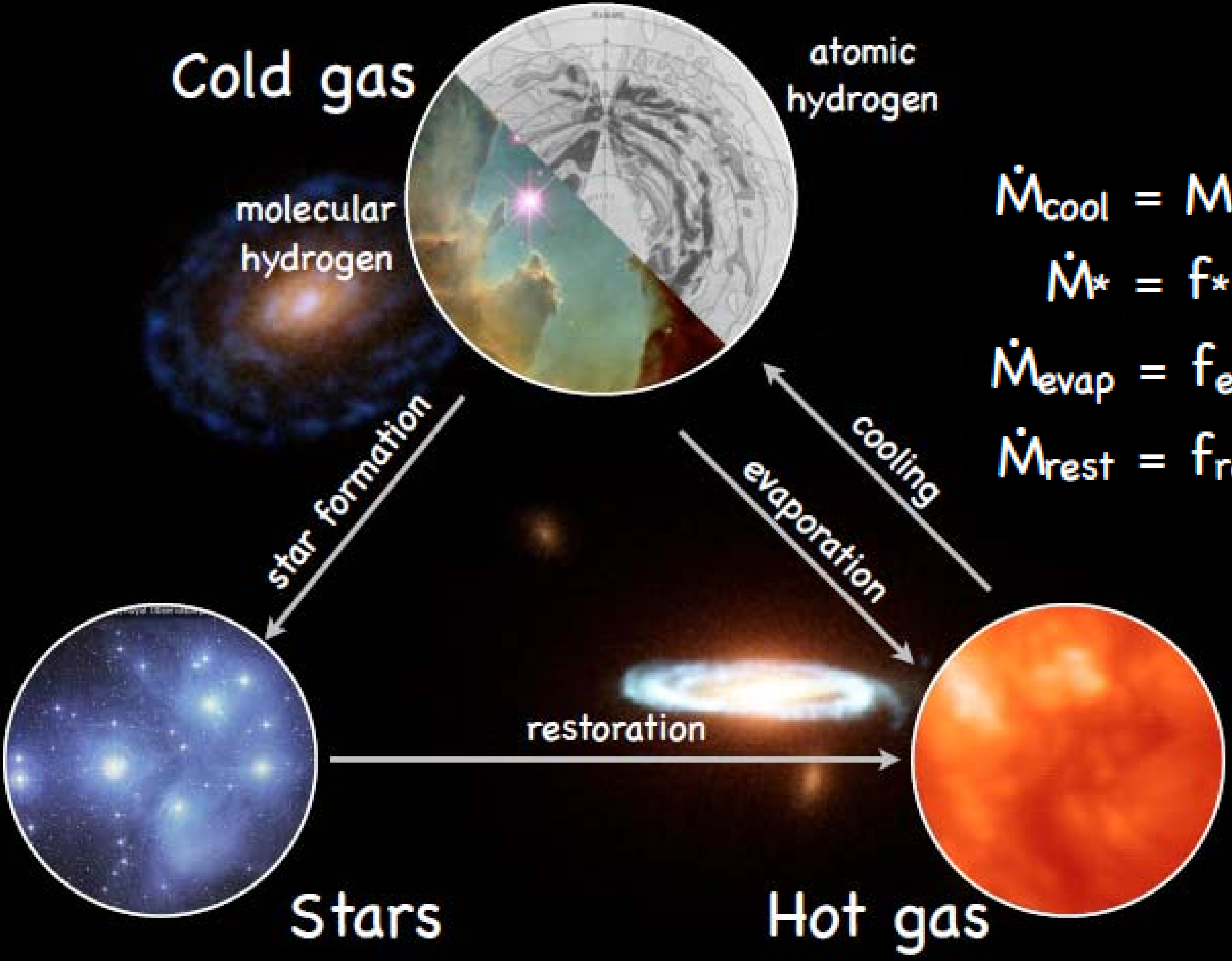
- MUPPI = MUlti-Phase Particle Integrator

  (Monaco, 2004, MNRAS, 352, 181; Murante et al. 2010, MNRAS 405, 1491)
  - Molecular fraction of gas ∝ Pressure
  - System of ordinary differential equations, which are numerically integrated within the SPH time-step

$\boxed{\rho_{SF,th} = 0.01\ \mathrm{cm}^{-3}}$

MUPPI algorithm

$\dot{M}_{cold} = \dot{M}_{cool} - \dot{M}_* - \dot{M}_{evap}$



computed on cold phase

$\dot{M}_{cool} = M_{hot}/t_{cool}$

$\dot{M}_* = f_* \, f_{mol} \, M_{cold}/t_{dyn}$

$\dot{M}_{evap} = f_{evap} \, \dot{M}_*$

$\dot{M}_{rest} = f_{rest} \, \dot{M}_*$

computed on hot phase

$\dot{M}_{star} = \dot{M}_* - \dot{M}_{rest}$

$\dot{M}_{hot} = -\dot{M}_{cool} + \dot{M}_{rest} + \dot{M}_{evap}$

SNe-driven Kinetic Feedback (Springel & Hernquist 2003)

- Mass-loss rate ∝ SFR

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

- Energy-driven wind :

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

- Probabilistic method for kicking star-forming gas particles

- New particle velocity
  - Along rotation axis

$$\boxed{\begin{array}{l} v_{new} = v_{old} + v_w \hat{n} \\ \hat{n} \rightarrow \vec{v} \times \vec{\nabla}\phi \end{array}}$$

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

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

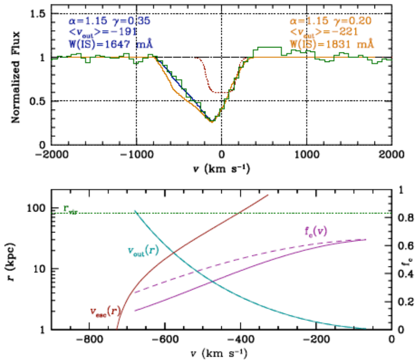
$$\boxed{\rho_{dec} = 0.25 \rho_{SF} = 0.25 \times 0.1 \text{ cm}^{-3}}$$

Models of Galactic Wind

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

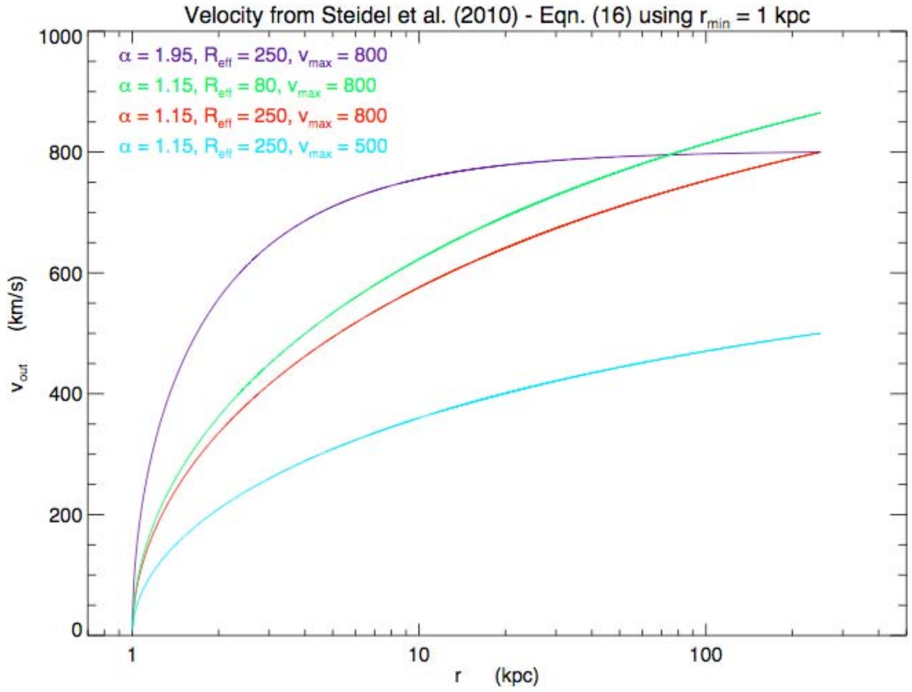
$$\boxed{v_w, \eta = \text{constant}}$$

- Radially Varying Outflow Velocity - Our Modification in GADGET3
  - Observations by Steidel et al. (2010, ApJ, 717, 289)
    - Spectroscopic data fitted by simple model
  - Quantities are function of galactocentric distance, r



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

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



Distribution of SN energy in MUPPI

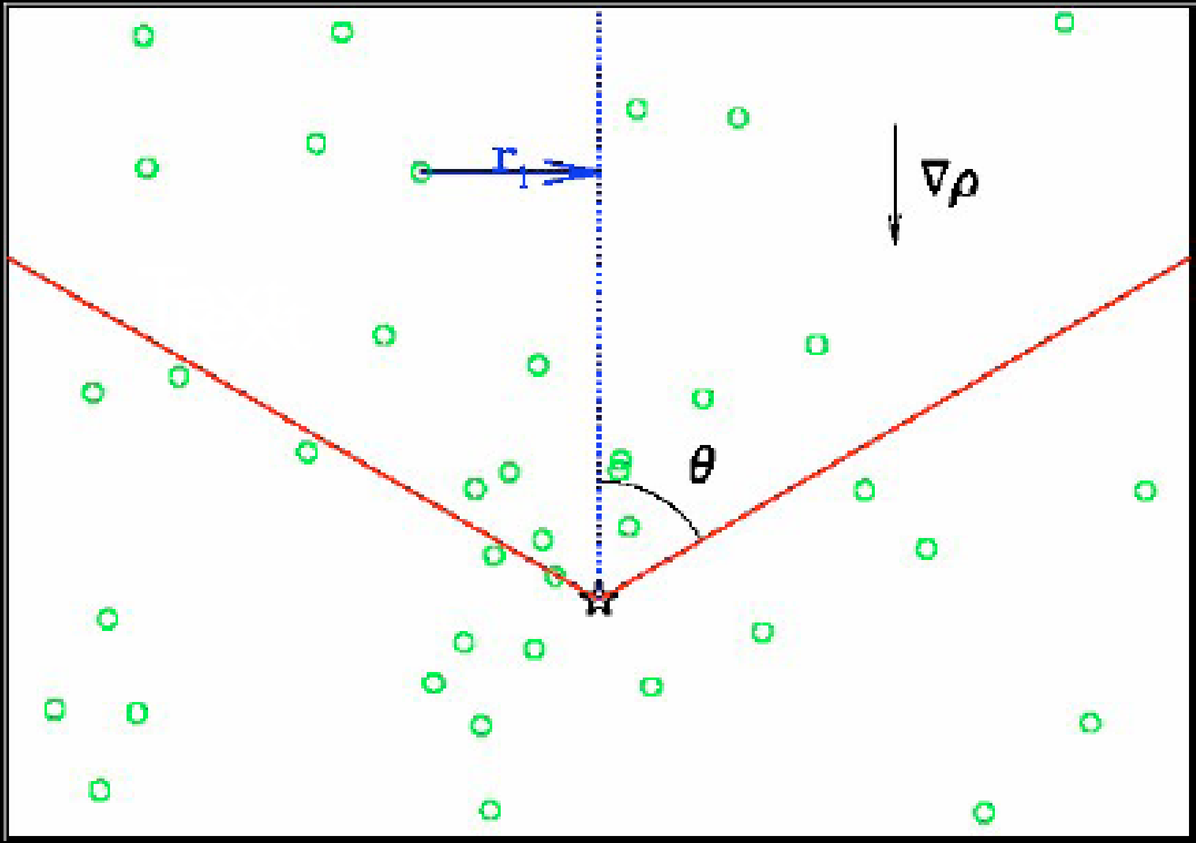
Only a small part (2%) of SN energy is given to the local hot phase, the rest is distributed to neighbours.

The energy given to neighbours is assigned along the "least resistence path", i.e. along (minus) the density gradient

Thermal energy (20-30% of 10^{51} erg per SN) is weighted by distance from cone axis

Kinetic energy (40-60% of 10^{51} erg per SN) is weighted in the same way, but it is given only to 3% of particles that exit a multi-phase cycle

Wind particles are decoupled



Wind speed and mass loading are determined by energy fraction and probability

Simulations

- Modified-G3 code

$$\boxed{\begin{array}{l}(5\ h^{-1}\ \mathrm{Mpc})^3,\ N = 2\times 128^3,\ \mathrm{m}_{gas} = 7.66\times 10^5 h^{-1} M_{Sun},\ L_{soft} = 0.98 h^{-1}\mathrm{kpc}.\\ (25\ h^{-1}\ \mathrm{Mpc})^3,\ N = 2\times 320^3,\ \mathrm{m}_{gas} = 6.13\times 10^6 h^{-1} M_{Sun},\ L_{soft} = 1.95 h^{-1}\mathrm{kpc}.\\ \text{From } z = 100 \ \rightarrow\ \text{upto } z = 2.\end{array}}$$

- NW : no-wind (cooling + SF + chemical evolution)
- CW : Energy-driven constant-velocity $\boxed{v_w = 400\ \mathrm{km/s}}$

Outflow with radial velocity gradient, motivated by observations

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

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

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

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

Different Wind Models (Barai et al. 2013)

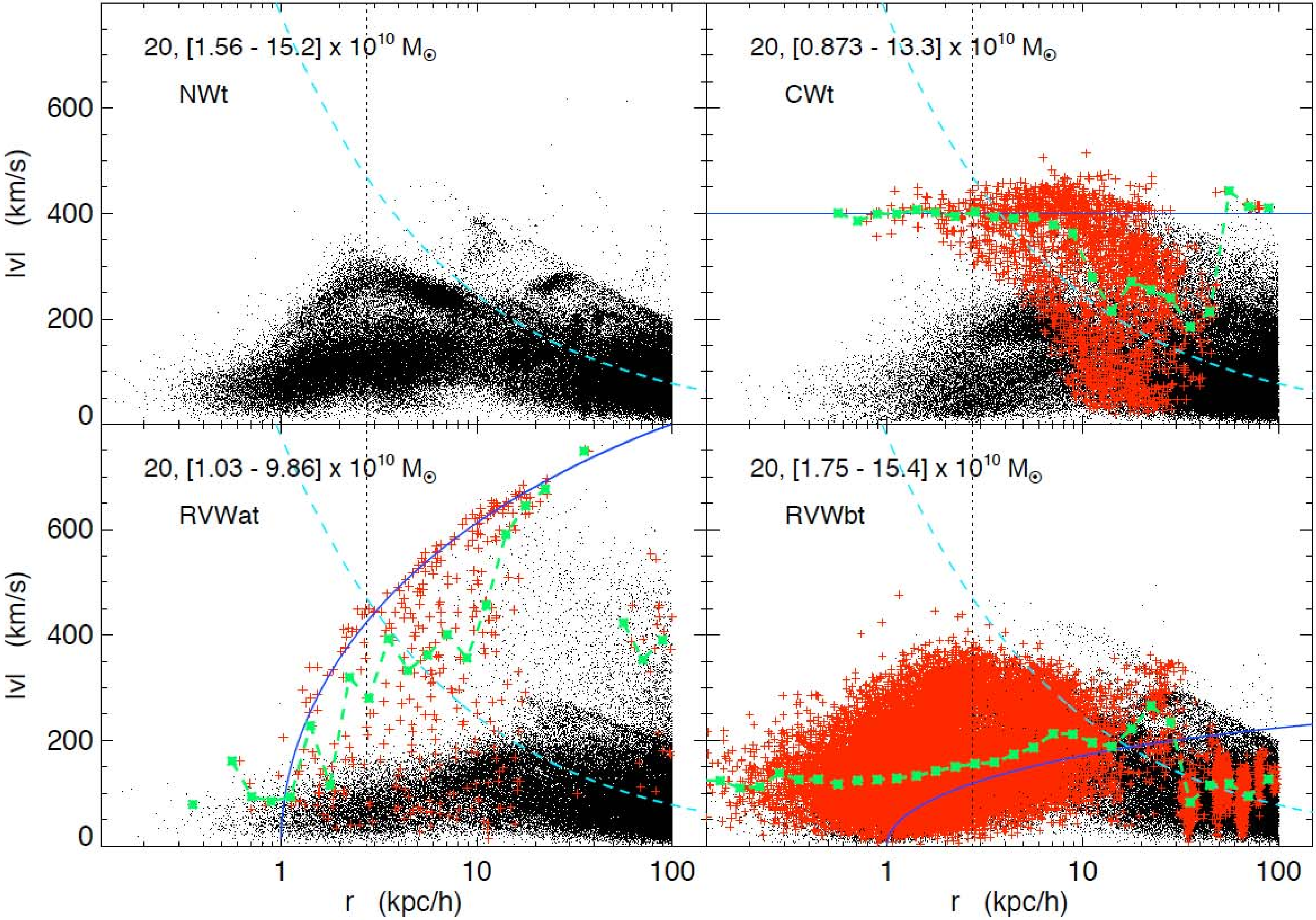
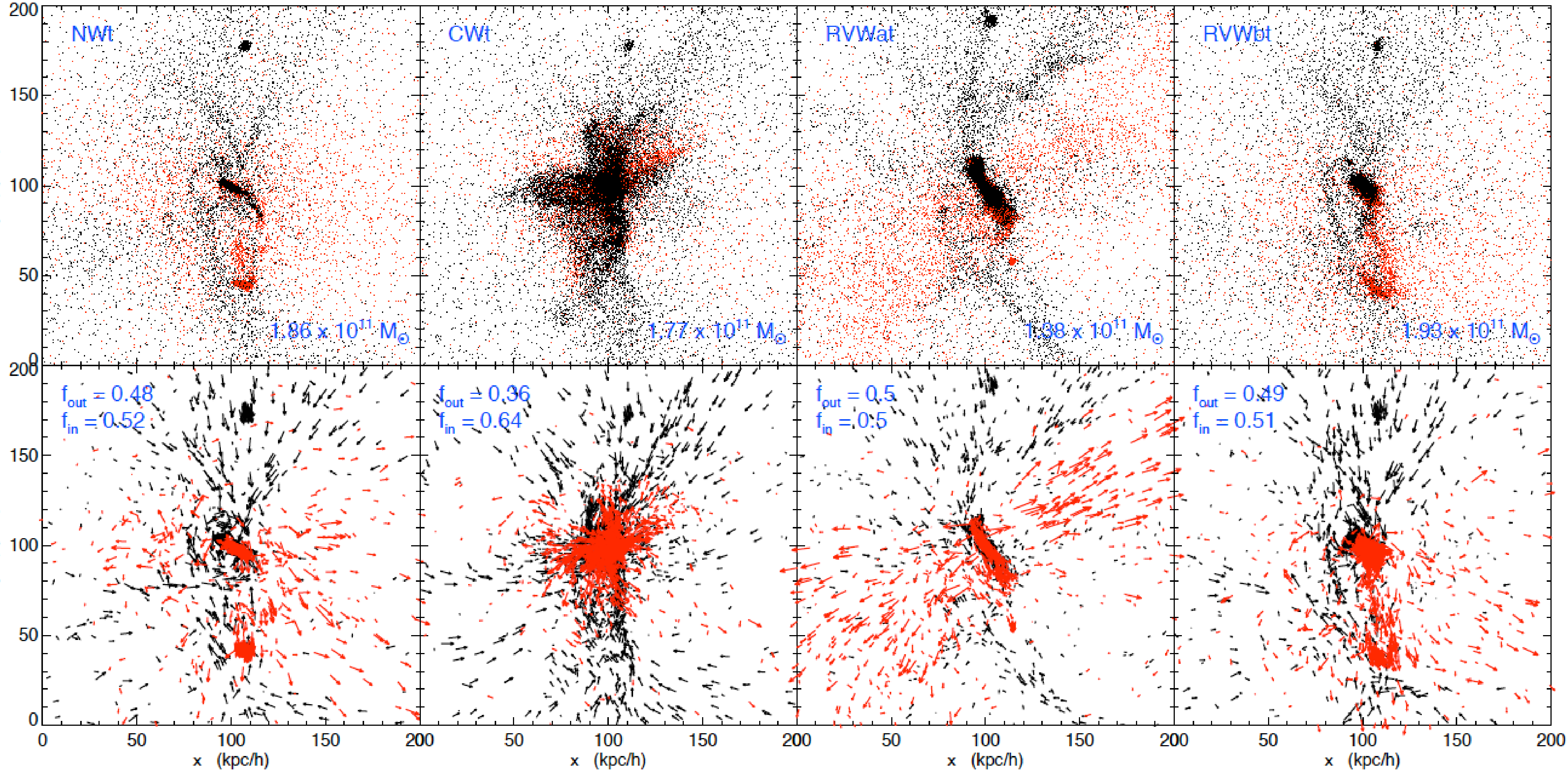


Figure 2. Velocity magnitude of the gas as a function of distance from galaxy center at $z = 2.44$ in the SB runs with different win
models: no wind (top-left), energy-driven constant-velocity wind (top-right), radially varying wind with fixed parameters (bottom-left)
and radially varying wind with parameters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

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.

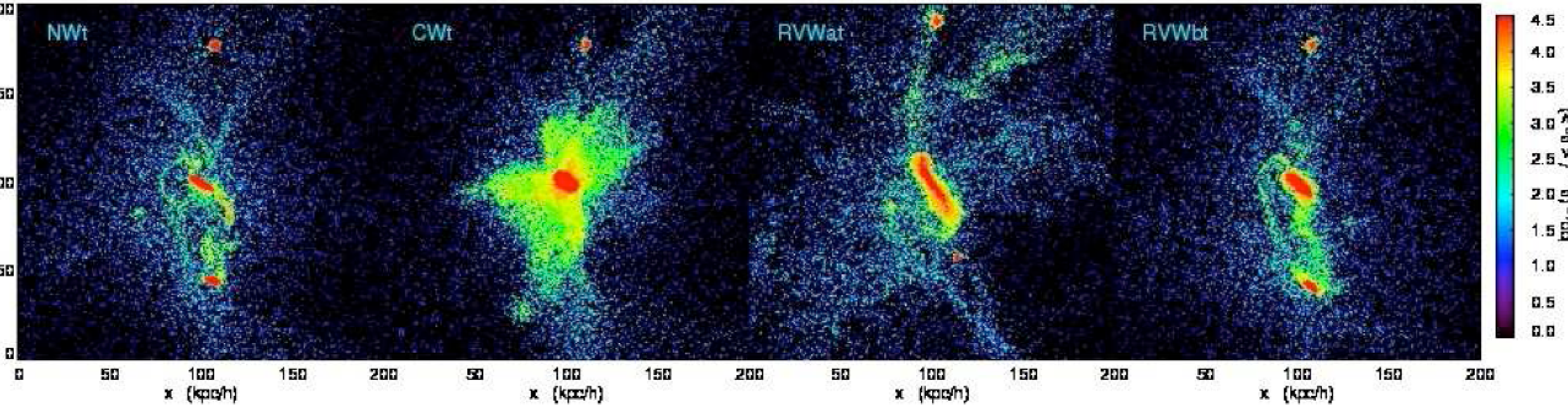
Particle positions

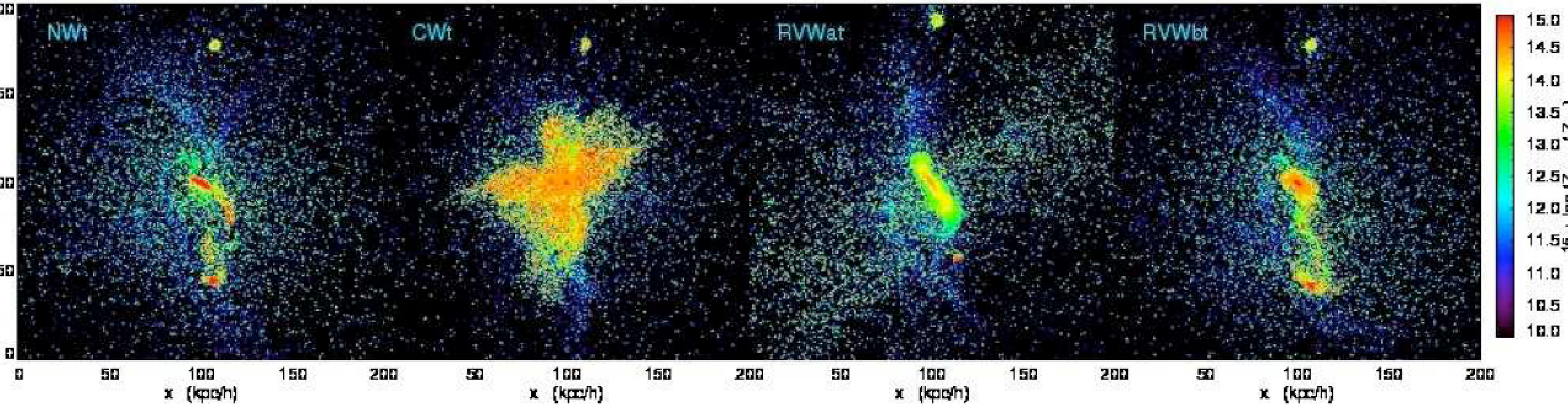


Velocity vectors

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

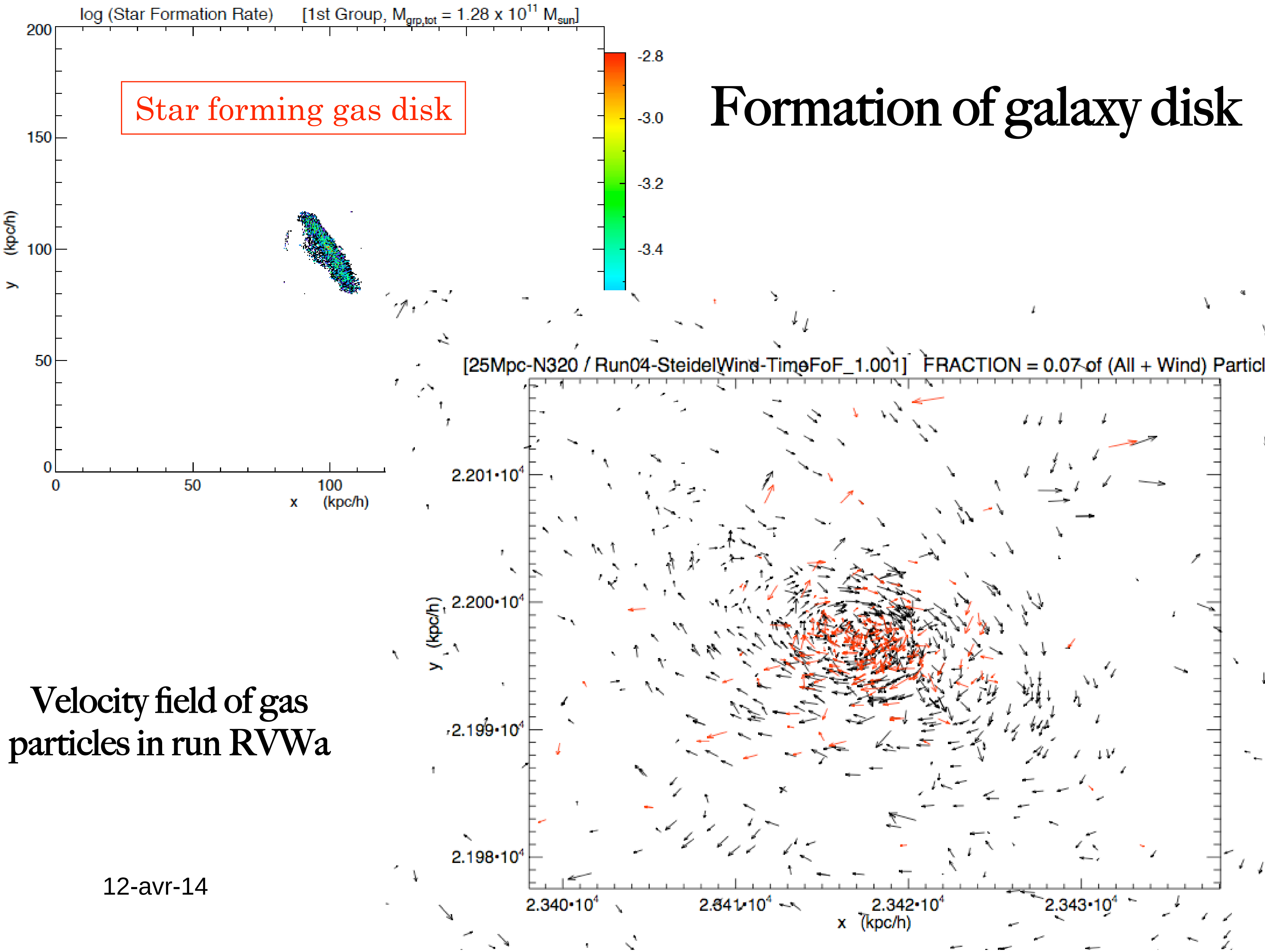
Density





Carbon metallicity

Formation of galaxy disk



Velocity field of gas particles in run RVWa

Simulation runs (Barai et al. in prep)

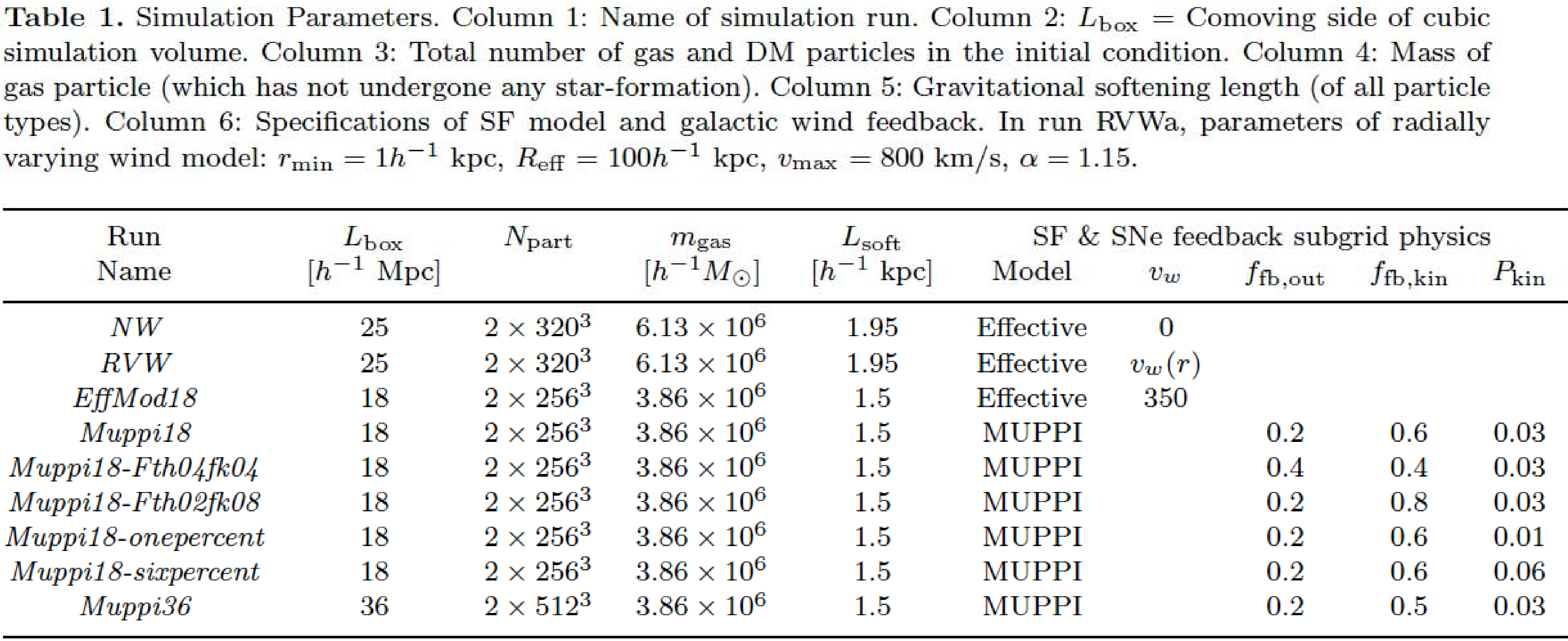
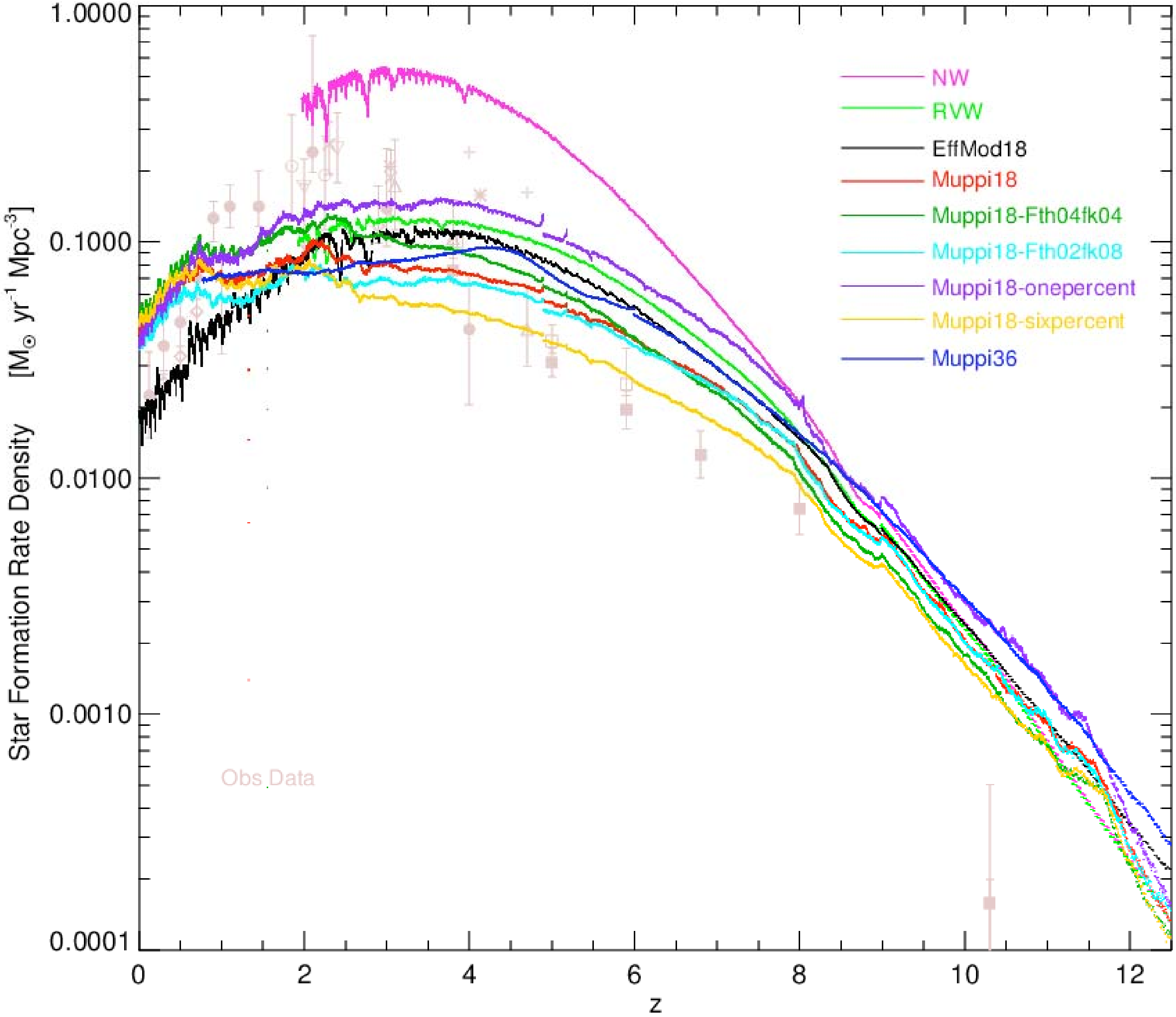
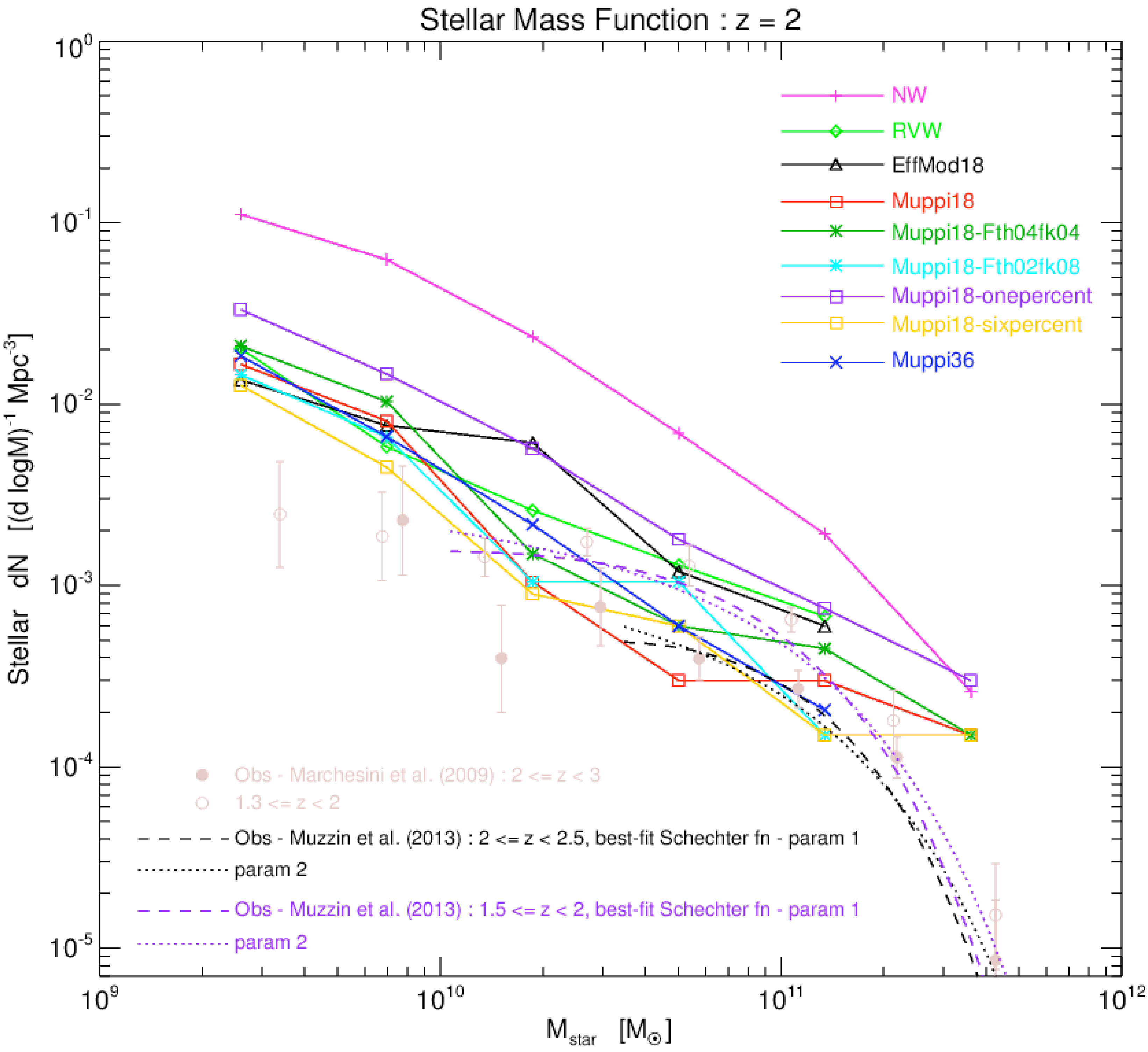


Table 1. Simulation Parameters. Column 1: Name of simulation run. Column 2: $L_{\rm box}$ = Comoving side of cubic simulation volume. Column 3: Total number of gas and DM particles in the initial condition. Column 4: Mass of gas particle (which has not undergone any star-formation). Column 5: Gravitational softening length (of all particle types). Column 6: Specifications of SF model and galactic wind feedback. In run RVWa, parameters of radially varying wind model: $r_{\rm min} = 1 h^{-1}$ kpc, $R_{\rm eff} = 100 h^{-1}$ kpc, $v_{\rm max} = 800$ km/s, $\alpha = 1.15$.

Run	$L_{\rm box}$	$N_{\rm part}$	$m_{\rm gas}$	$L_{\rm soft}$	SF & SNe feedback subgrid physics				
Name	$[h^{-1}$ Mpc$]$		$[h^{-1} M_{\odot}]$	$[h^{-1}$ kpc$]$	Model	v_w	$f_{\rm fb,out}$	$f_{\rm fb,kin}$	$P_{\rm kin}$
NW	25	2×320^3	6.13×10^6	1.95	Effective	0			
RVW	25	2×320^3	6.13×10^6	1.95	Effective	$v_w(r)$			
EffMod18	18	2×256^3	3.86×10^6	1.5	Effective	350			
Muppi18	18	2×256^3	3.86×10^6	1.5	MUPPI		0.2	0.6	0.03
Muppi18-Fth04fk04	18	2×256^3	3.86×10^6	1.5	MUPPI		0.4	0.4	0.03
Muppi18-Fth02fk08	18	2×256^3	3.86×10^6	1.5	MUPPI		0.2	0.8	0.03
Muppi18-onepercent	18	2×256^3	3.86×10^6	1.5	MUPPI		0.2	0.6	0.01
Muppi18-sixpercent	18	2×256^3	3.86×10^6	1.5	MUPPI		0.2	0.6	0.06
Muppi36	36	2×512^3	3.86×10^6	1.5	MUPPI		0.2	0.5	0.03

Star Formation Rate Density Evolution




Stellar Mass Function : z = 2
NW
RVW
EffMod18
Muppi18
Muppi18-Fth04fk04
Muppi18-Fth02fk08
Muppi18-onepercent
Muppi18-sixpercent
Muppi36
Obs - Marchesini et al. (2009) : 2 <= z < 3
1.3 <= z < 2
Obs - Muzzin et al. (2013) : 2 <= z < 2.5, best-fit Schechter fn - param 1
param 2
Obs - Muzzin et al. (2013) : 1.5 <= z < 2, best-fit Schechter fn - param 1
param 2
Stellar dN [(d logM)$^{-1}$ Mpc^{-3}]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^9
10^{10}
10^{11}
10^{12}
M_{star} [$M_\odot$]

Galaxy stellar properties at z=0 (Antonio Ragagnin et al. 2014, in prep.)

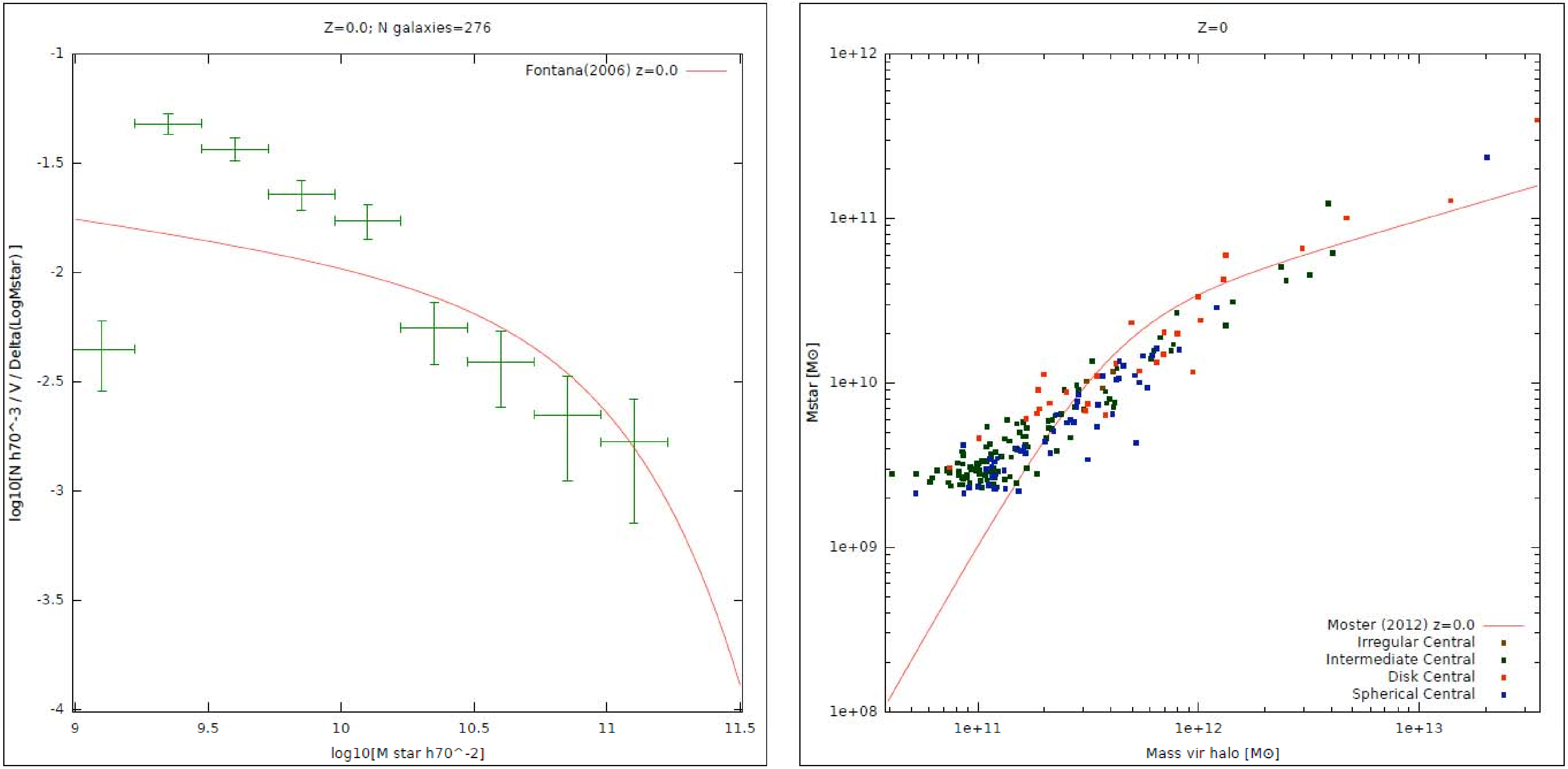
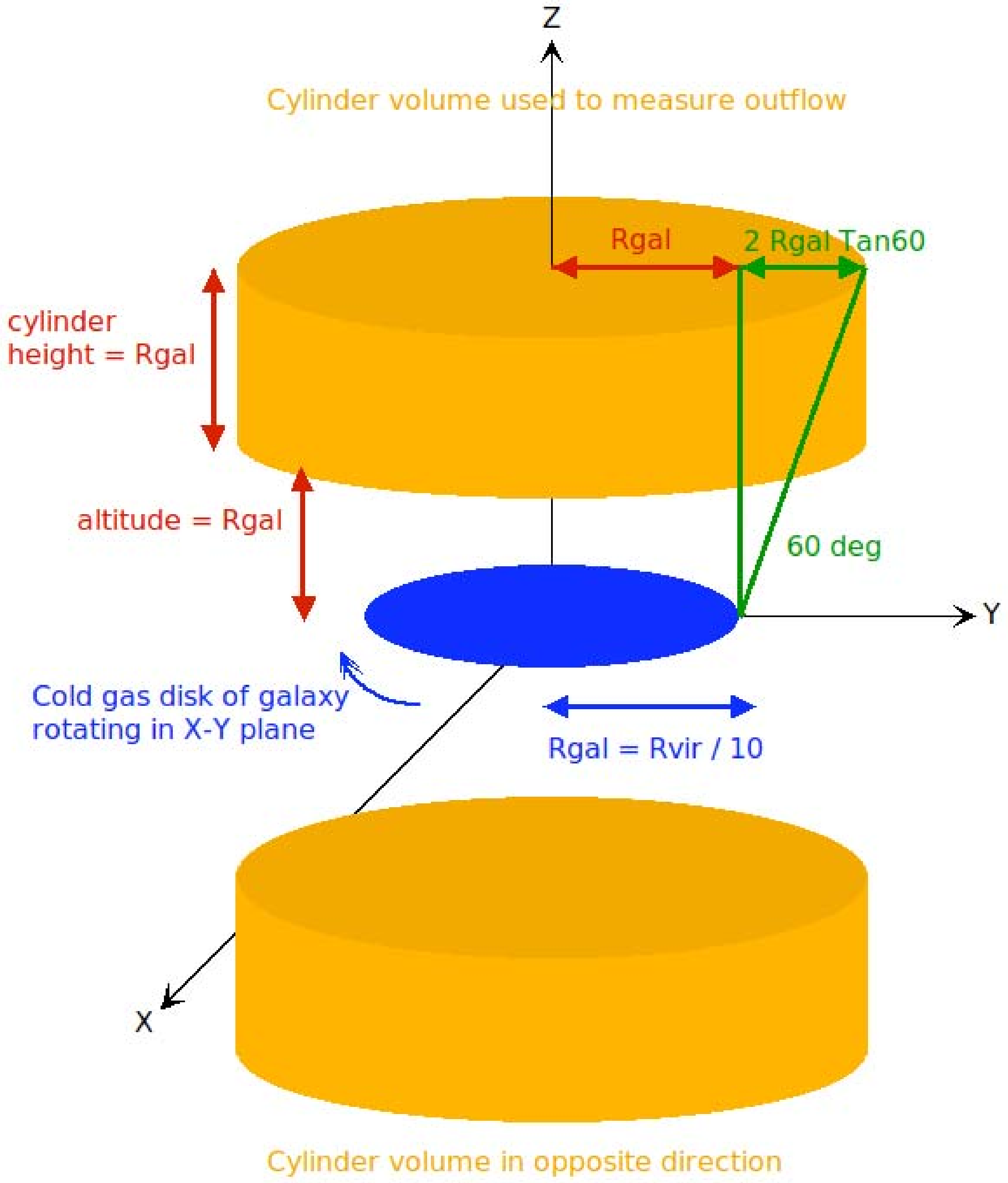


Figure 2.21: Left panel contains the stellar mass function for the sample of galaxies in the 18 Mpc/h simulation extracted by SubFind, over-plotted in red there is the observed relation found by Fontana et al. (2006). Right panel contains the stellar mass vs. halo mass, over-plotted there is the predicted relation by Moster et al (2012). In this plots different colors mark different morphologies: disk galaxies are marked in red, spherical galaxies are marked in blue, intermediate galaxies are marked in green and the irregular ones are marked in purple.

Outflow measurement technique



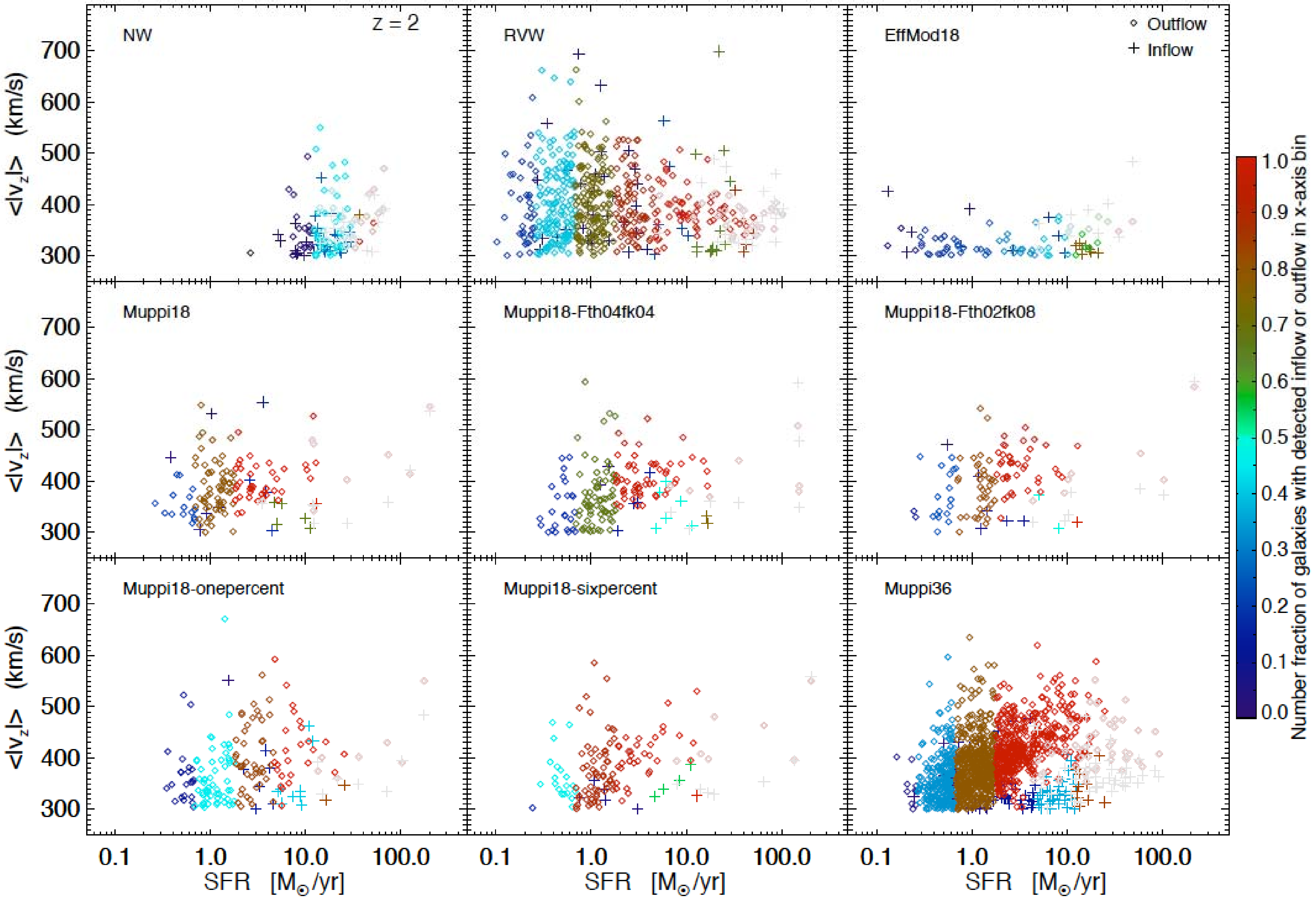
➢ Transform galaxy coordinates s.t. cold gas disk is rotating in X-Y plane

➢ Select gas particles:

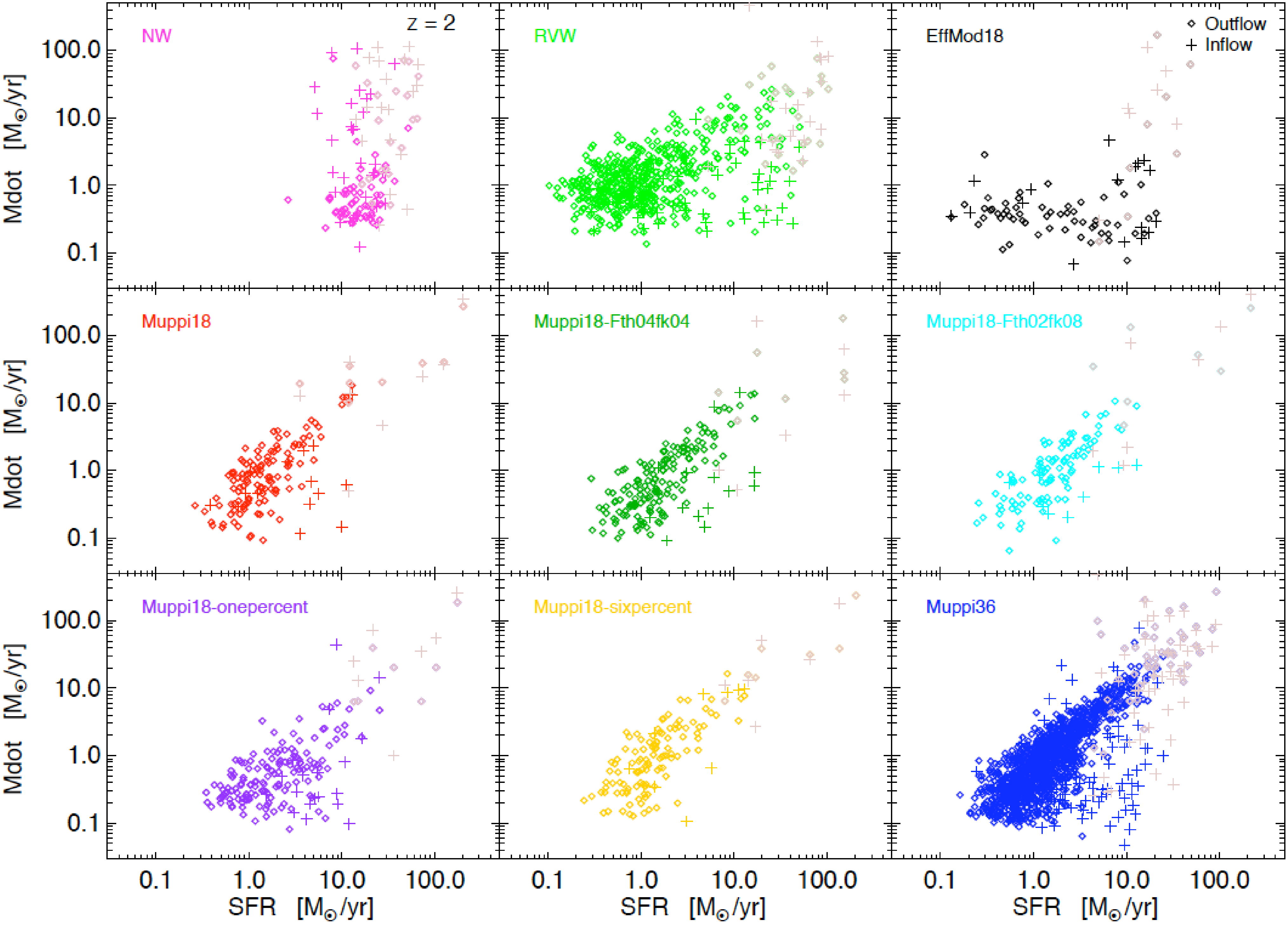
- lying inside either cylinder
- moving at a high-velocity, $|v_z| > V_{limit,outflow}$

- if $(z*v_z > 0) \Rightarrow$ Outflow
- if $(z*v_z < 0) \Rightarrow$ Inflow

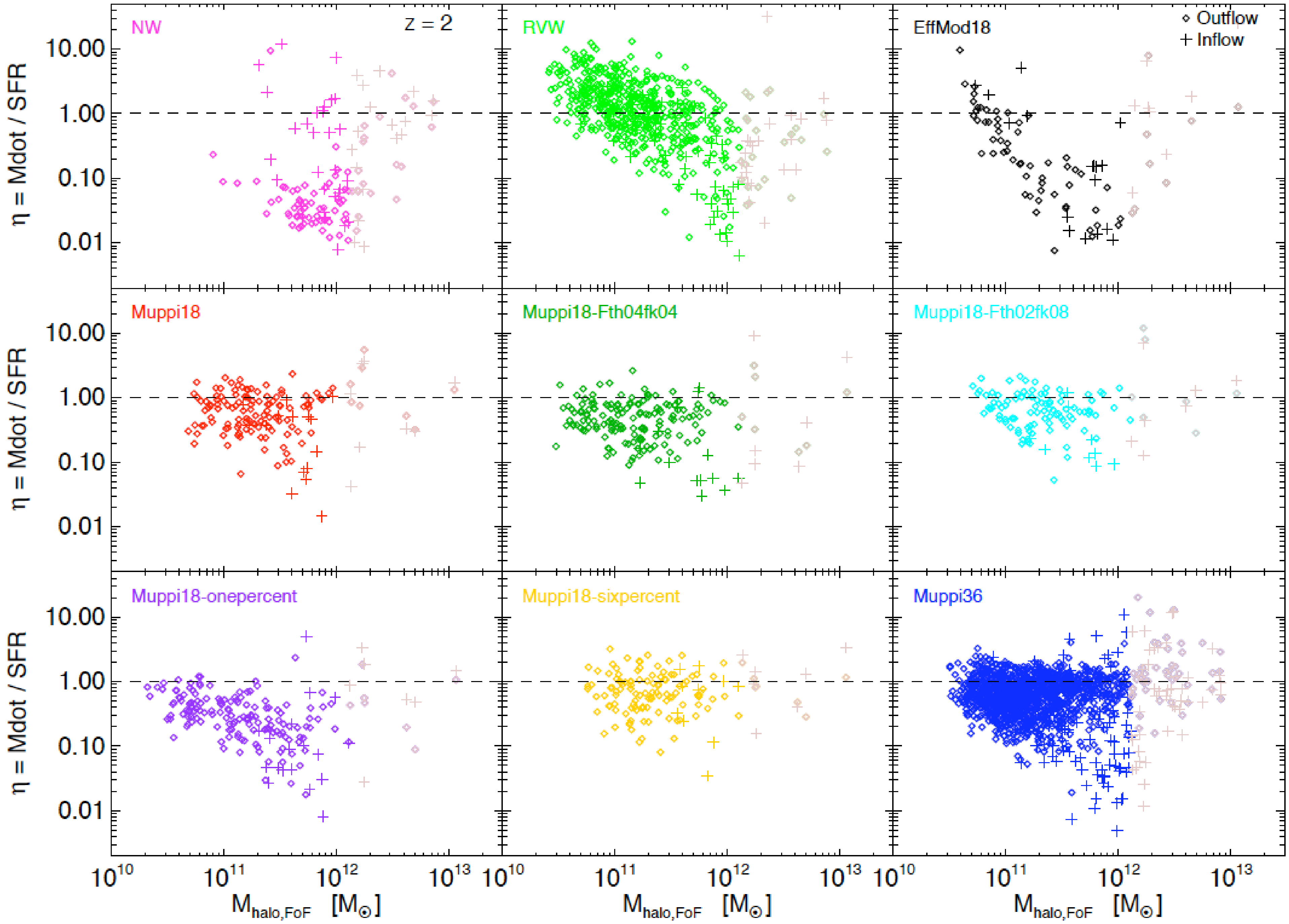
Outflow velocity vs. galaxy SFR



Mass outflow rate vs. galaxy SFR



Mass loading factor (η = Mass outflow rate / SFR) vs. halo mass



Outflow numbers

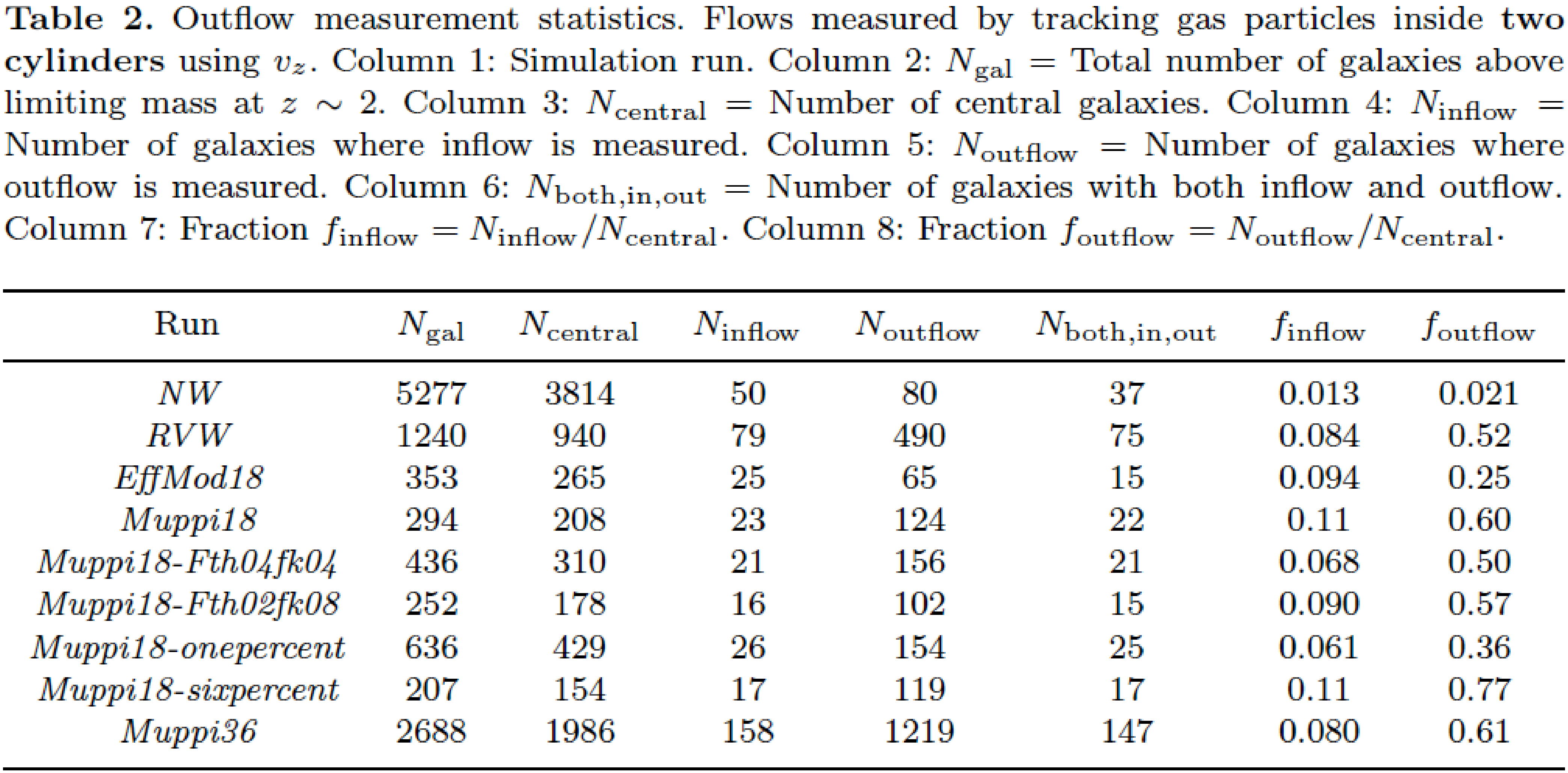


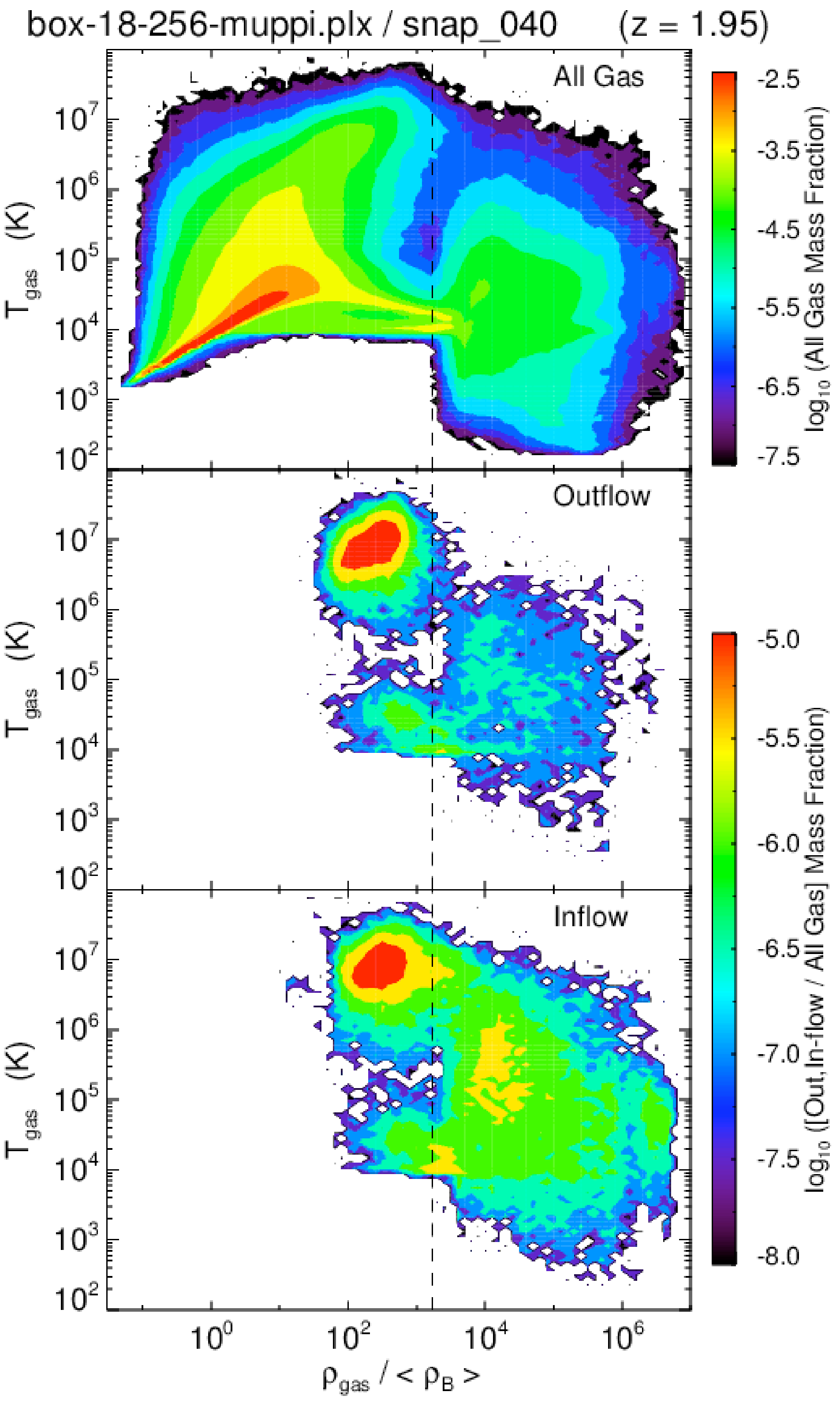
Table 2. Outflow measurement statistics. Flows measured by tracking gas particles inside **two cylinders** using v_z. Column 1: Simulation run. Column 2: $N_{\rm gal}$ = Total number of galaxies above limiting mass at $z \sim 2$. Column 3: $N_{\rm central}$ = Number of central galaxies. Column 4: $N_{\rm inflow}$ = Number of galaxies where inflow is measured. Column 5: $N_{\rm outflow}$ = Number of galaxies where outflow is measured. Column 6: $N_{\rm both,in,out}$ = Number of galaxies with both inflow and outflow. Column 7: Fraction $f_{\rm inflow} = N_{\rm inflow}/N_{\rm central}$. Column 8: Fraction $f_{\rm outflow} = N_{\rm outflow}/N_{\rm central}$.

Run	$N_{\rm gal}$	$N_{\rm central}$	$N_{\rm inflow}$	$N_{\rm outflow}$	$N_{\rm both,in,out}$	$f_{\rm inflow}$	$f_{\rm outflow}$
NW	5277	3814	50	80	37	0.013	0.021
RVW	1240	940	79	490	75	0.084	0.52
EffMod18	353	265	25	65	15	0.094	0.25
Muppi18	294	208	23	124	22	0.11	0.60
Muppi18-Fth04fk04	436	310	21	156	21	0.068	0.50
Muppi18-Fth02fk08	252	178	16	102	15	0.090	0.57
Muppi18-onepercent	636	429	26	154	25	0.061	0.36
Muppi18-sixpercent	207	154	17	119	17	0.11	0.77
Muppi36	2688	1986	158	1219	147	0.080	0.61

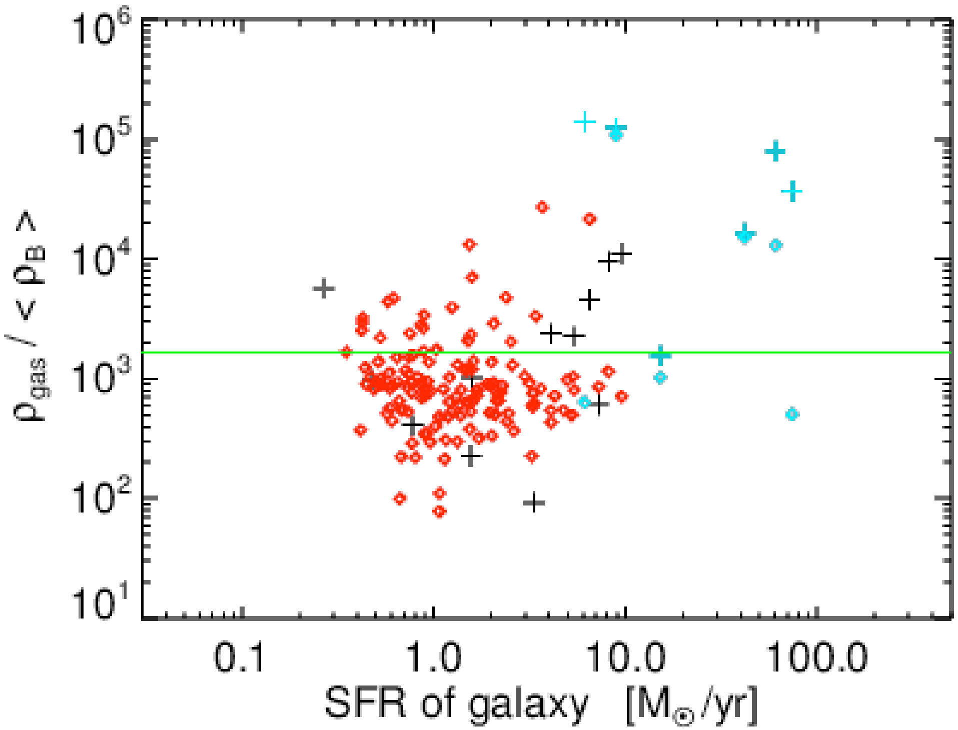
Physical state of the outflowing gas

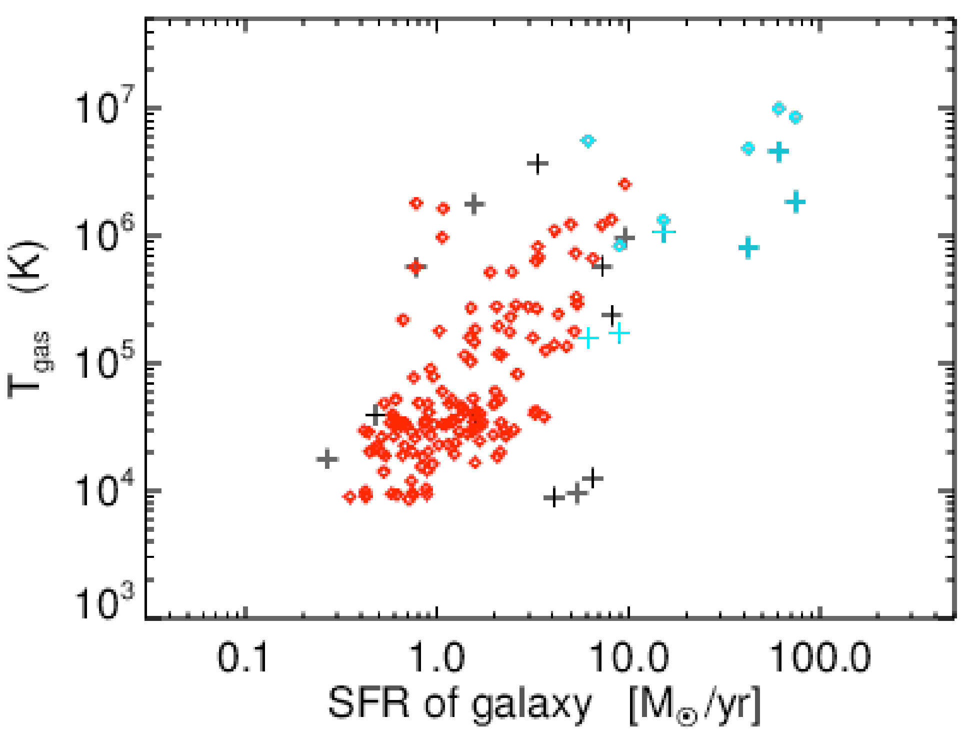
-

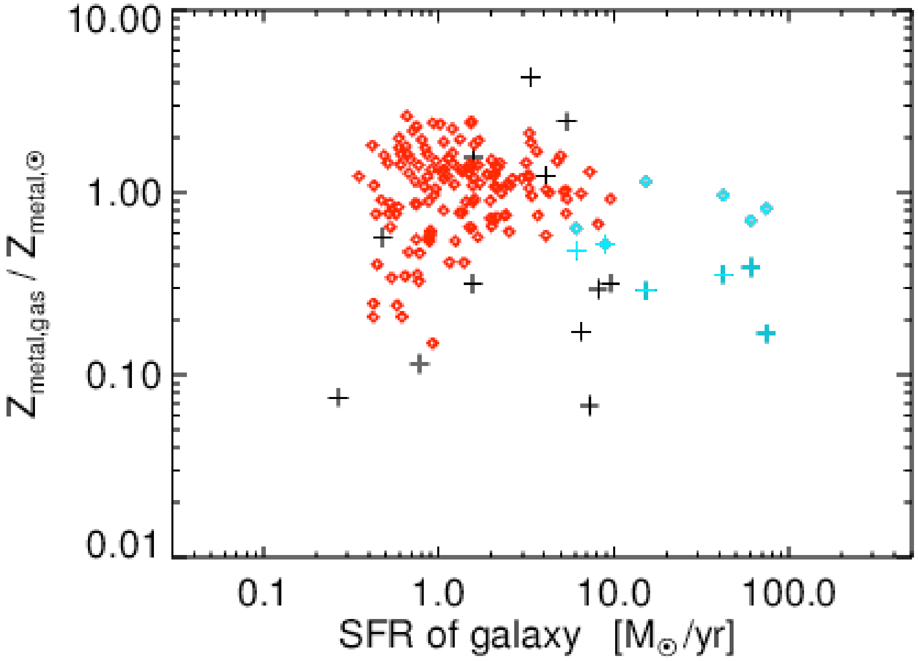
[ρ - T] phase diagram of gas particles counted in outflow (or, inflow)



Physical state : mass weighted average density, temperature, & total metallicity







- Temperature shows a positive correlation with galaxy mass (halo, gas & stellar components), and SFR

Formation of a disk galaxy at z = 2. Dark matter, gas, stars. Edge-on view.

When bigger is not better. Simulating realistic disk galaxies at moderate resolution.

(to be submitted)

zoomed-in initial conditions

Giuseppe Murante[1], Pierluigi Monaco[2,3], Stefano Borgani[3,2,4], Luca Tornatore[3,2], Klaus Dolag
Felix Stoehr

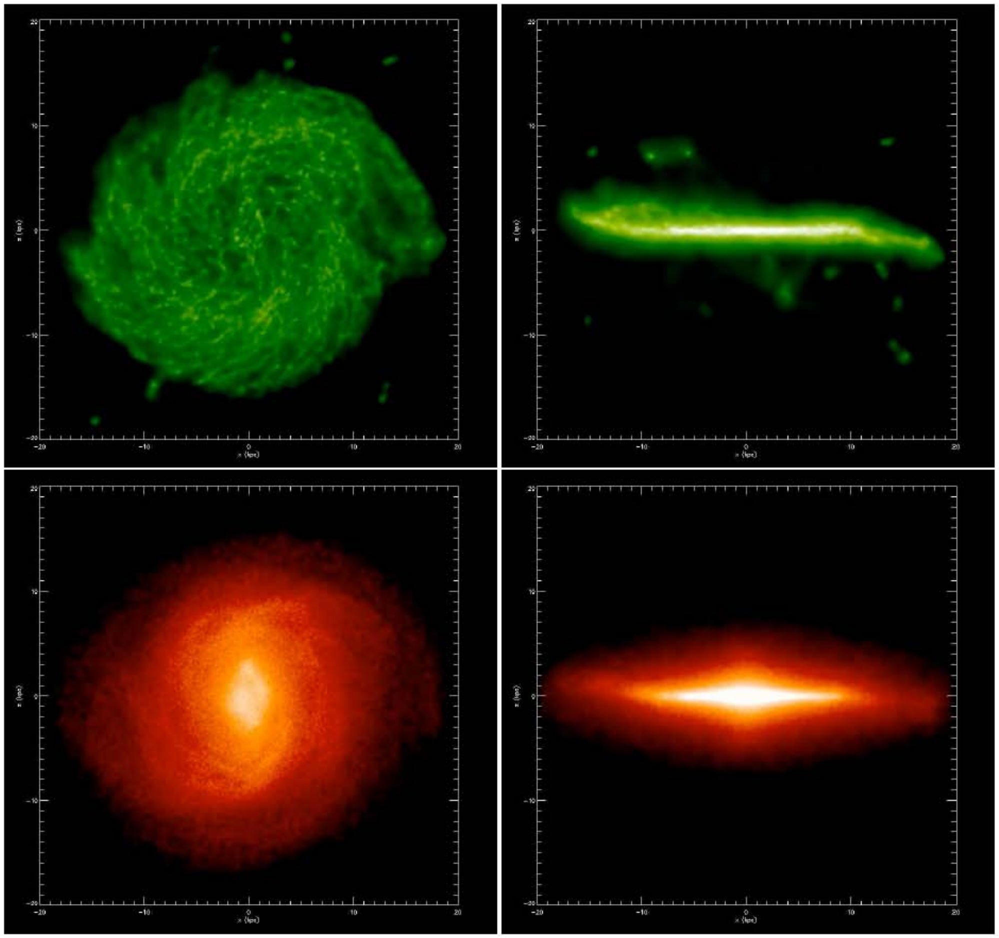
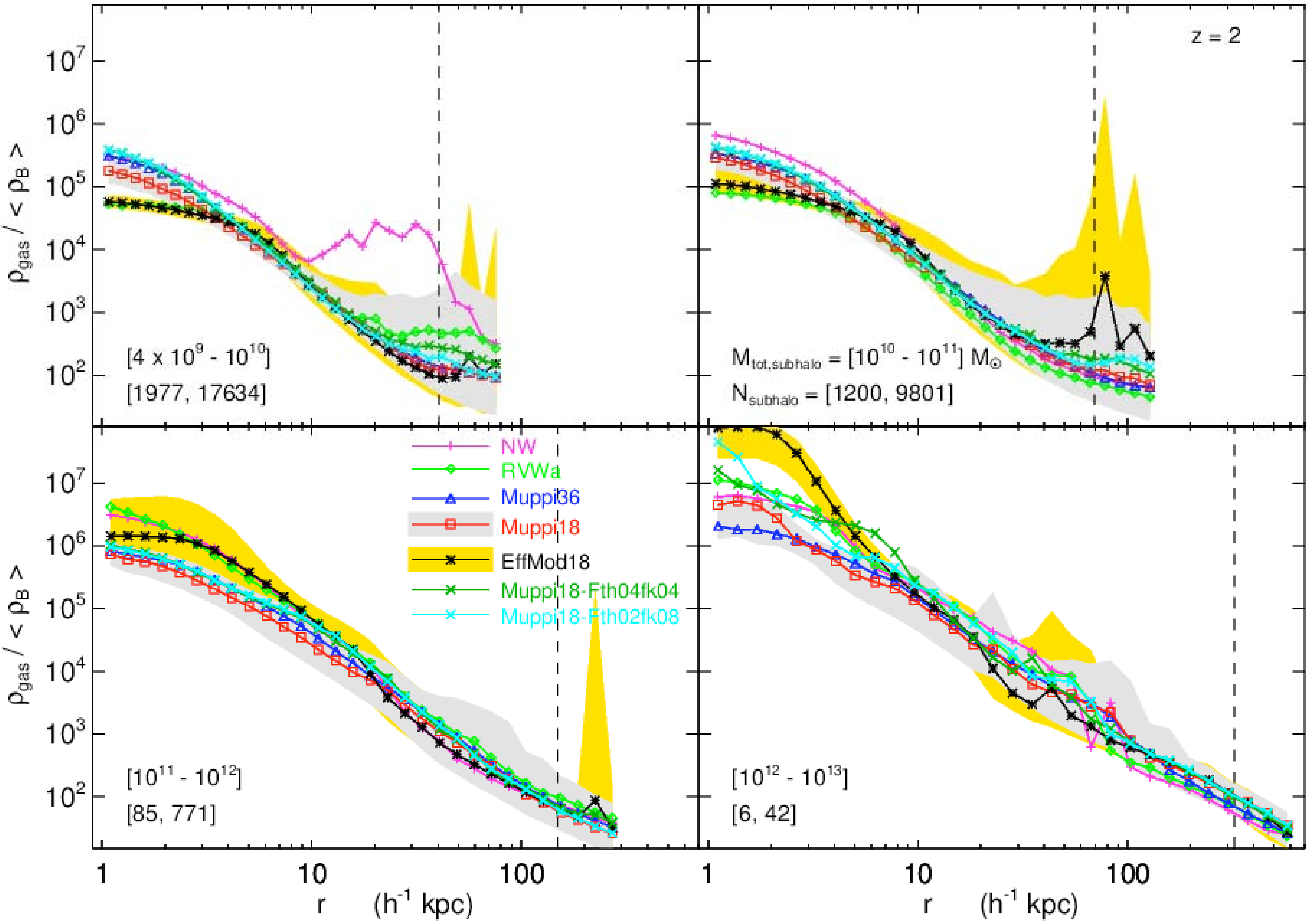


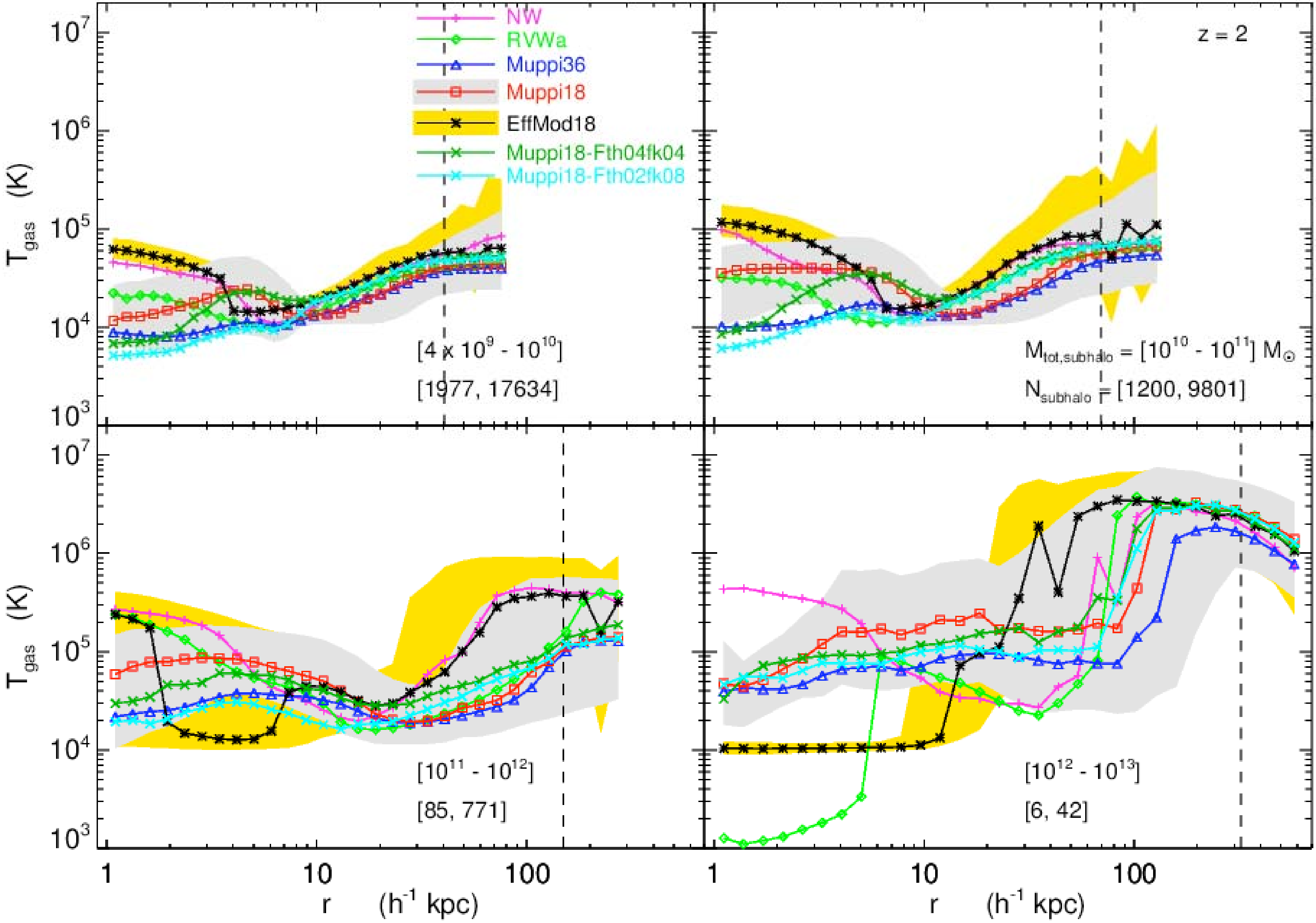
Figure 1. Projected gas (upper row) and stellar (lower row) density for the simulation GA2. The z-axis of the coordinate system is aligned with the angular momentum vector of the gas enclosed in the inner 8 kpc. Left column show face-on densities, right column shows edge-on densities. Box size is 57 kpc.

resolution levels. In all cases we obtain spiral galaxies with small bulge over total stellar mass ratio ($B/T \sim 0.15$), extended stellar and gas disks, flat rotation curves and realistic values of stellar masses with respect to host halo masses. Gas profiles are relatively flat, molecular gas

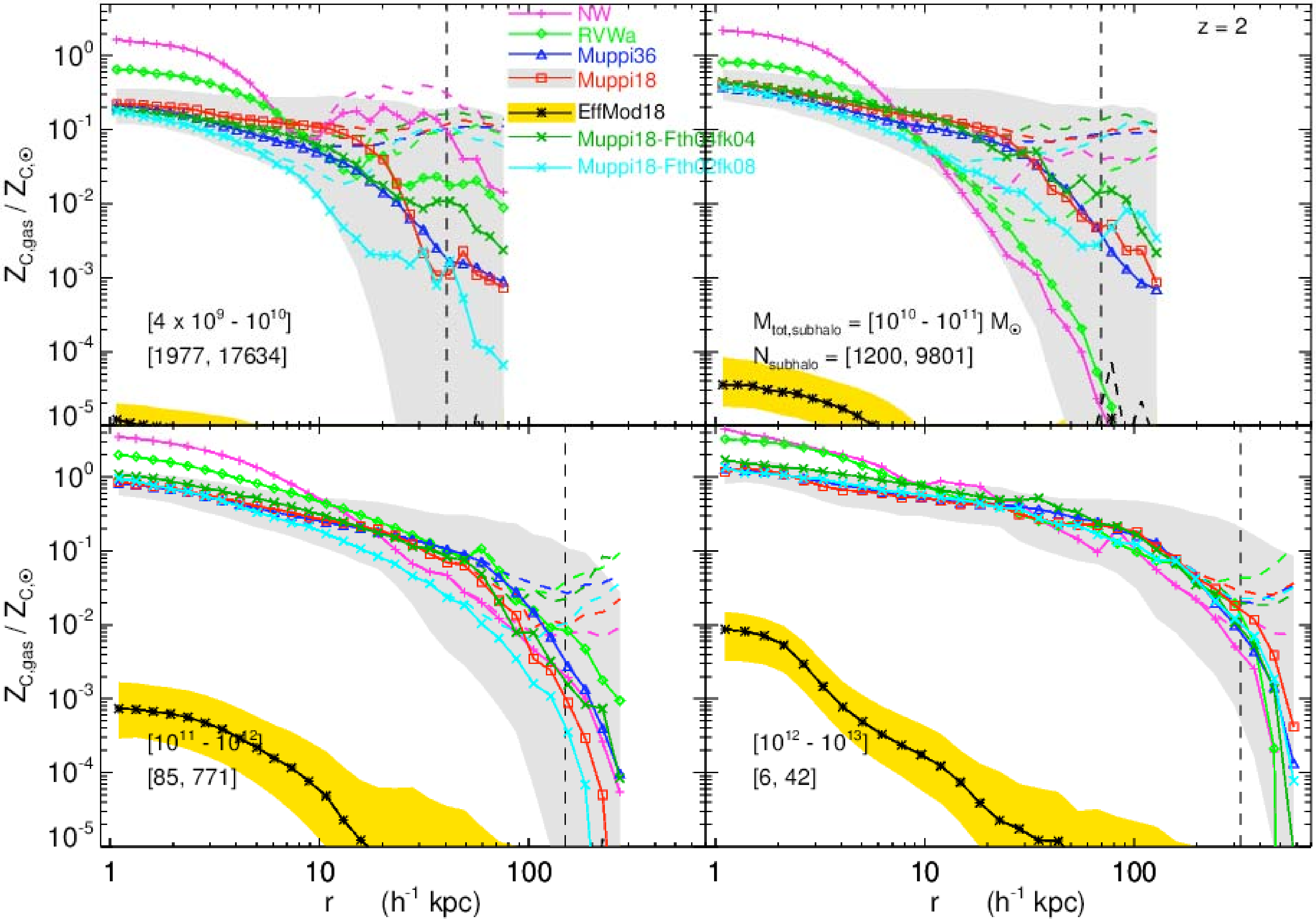
Gas Density radial profile at z = 2



Gas Temperature radial profile at z=2



Gas Carbon Metallicity radial profile at z = 2



Conclusions

- Cosmological Hydrodynamic Simulations are powerful tool
  - Reproduce the observed large-scale structures
  - Study origin & evolution of galaxies over Hubble time

My research:

- Can study impact of galactic winds on galaxy & IGM properties
  - Still far away from self-consistently driving these winds in such sims
  - Need subgrid prescription

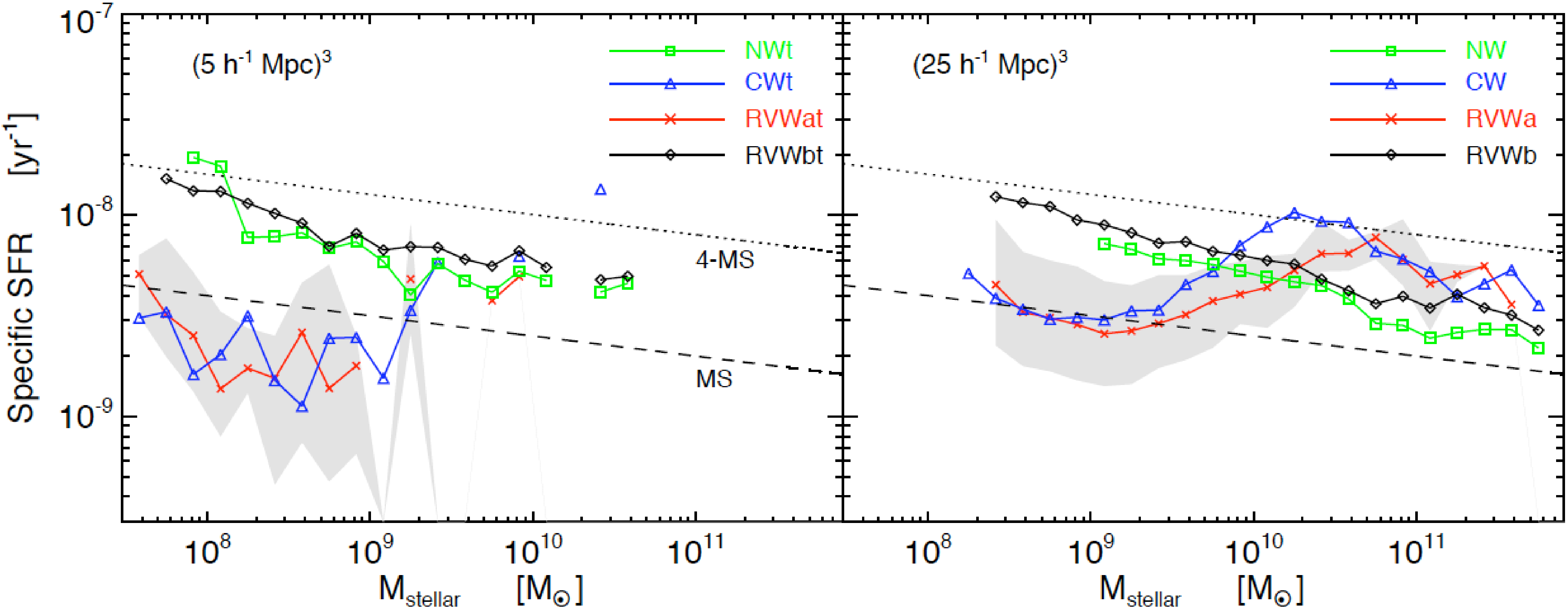
- Galactic winds can:
  - Reduce cosmic SFR density, quench SF in galaxies
  - Affect density profile of galaxy halos
  - Enrich the CGM and IGM with metals

- MUPPI is better sub-grid model than SH03
  - Realistic disk galaxies, outflows.

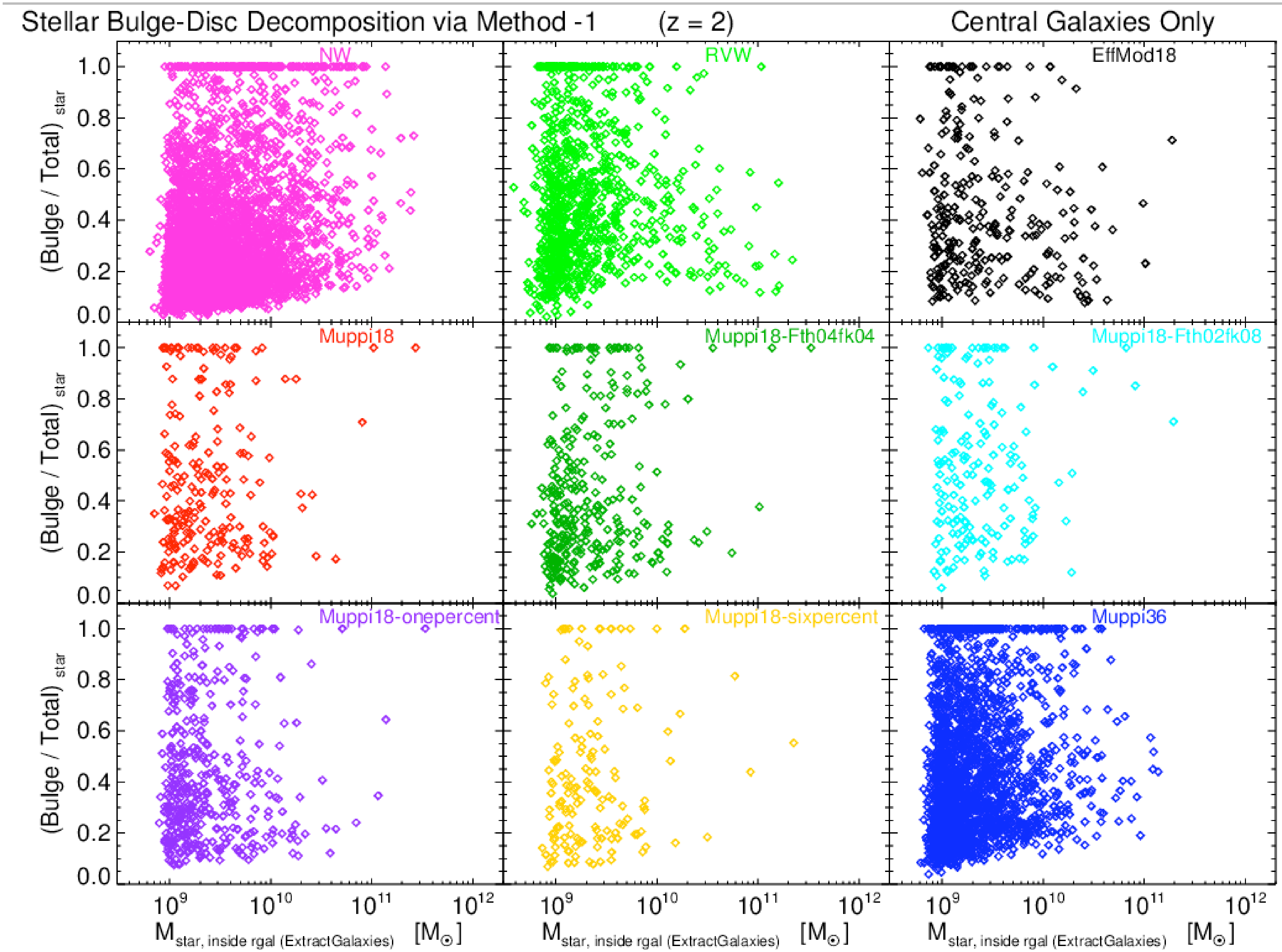
Extra Slides

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
in 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, $\mathrm{SFR} = 200 \left(\frac{M_{\rm stellar}}{10^{11} M_\odot}\right)^{0.9} M_\odot\ \mathrm{yr}^{-1}$. The black dotted line marks the loci 4 times above t
gion between MS and 4-MS encompass a majority fraction of observed galaxies from Rodighiero et al. (2011).


Stellar Bulge-Disc Decomposition via Method -1
(z = 2)
Central Galaxies Only
NW
RVW
EffMod18
Muppi18
Muppi18-Fth04fk04
Muppi18-Fth02fk08
Muppi18-onepercent
Muppi18-sixpercent
Muppi36
(Bulge / Total) star
0.0
0.2
0.4
0.6
0.8
1.0
10^9
10^{10}
10^{11}
10^{12}
$M_{\mathrm{star,\ inside\ rgal\ (ExtractGalaxies)}}$ $[M_\odot]$

Temperature of outflow vs. halo mass