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

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The Unquiet Universe:
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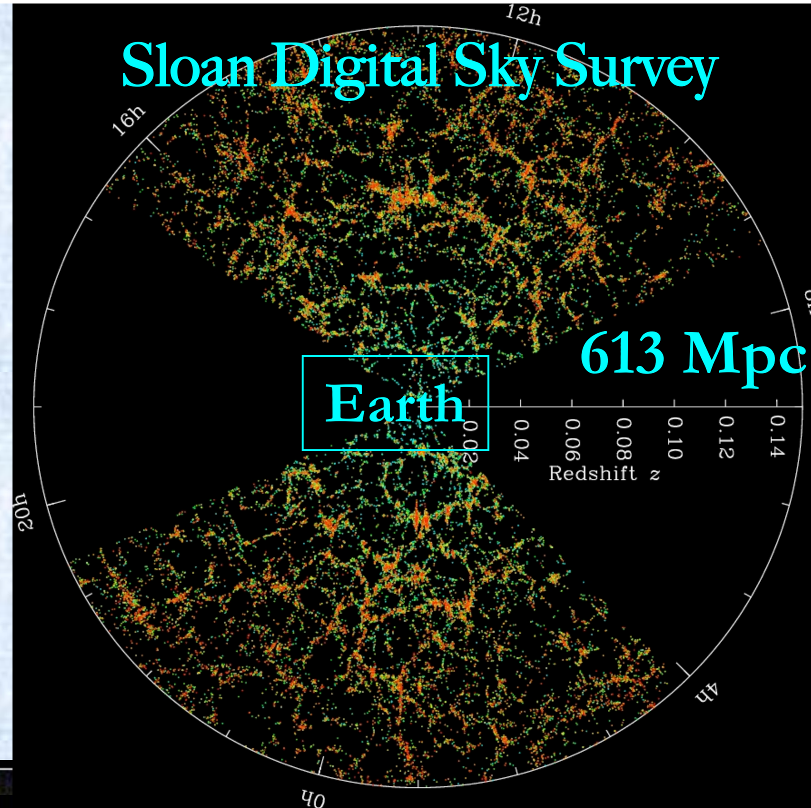
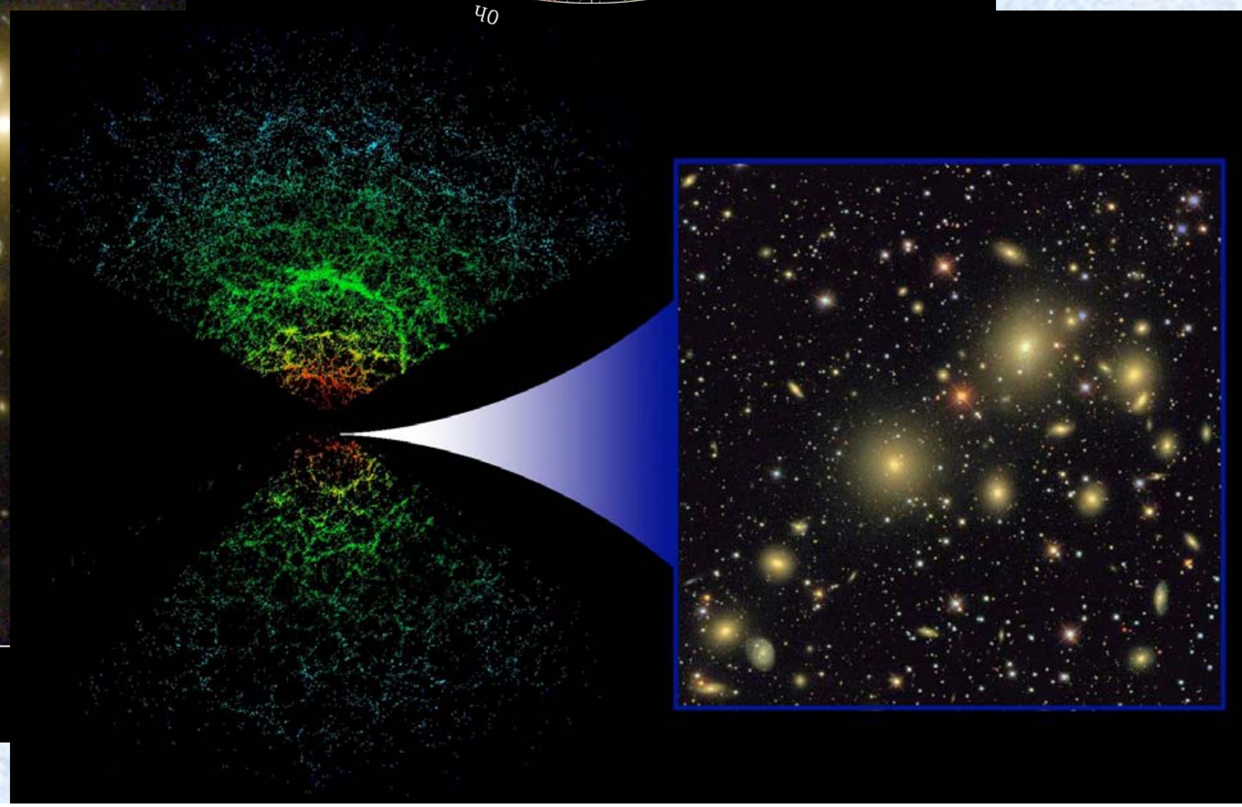
Baryon distribution at different scales



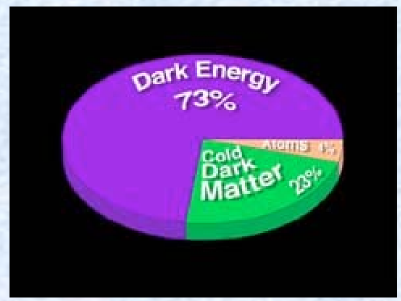
Galaxy Cluster Abell 2218
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08



The Universe in a Box: Simulations of LSS

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

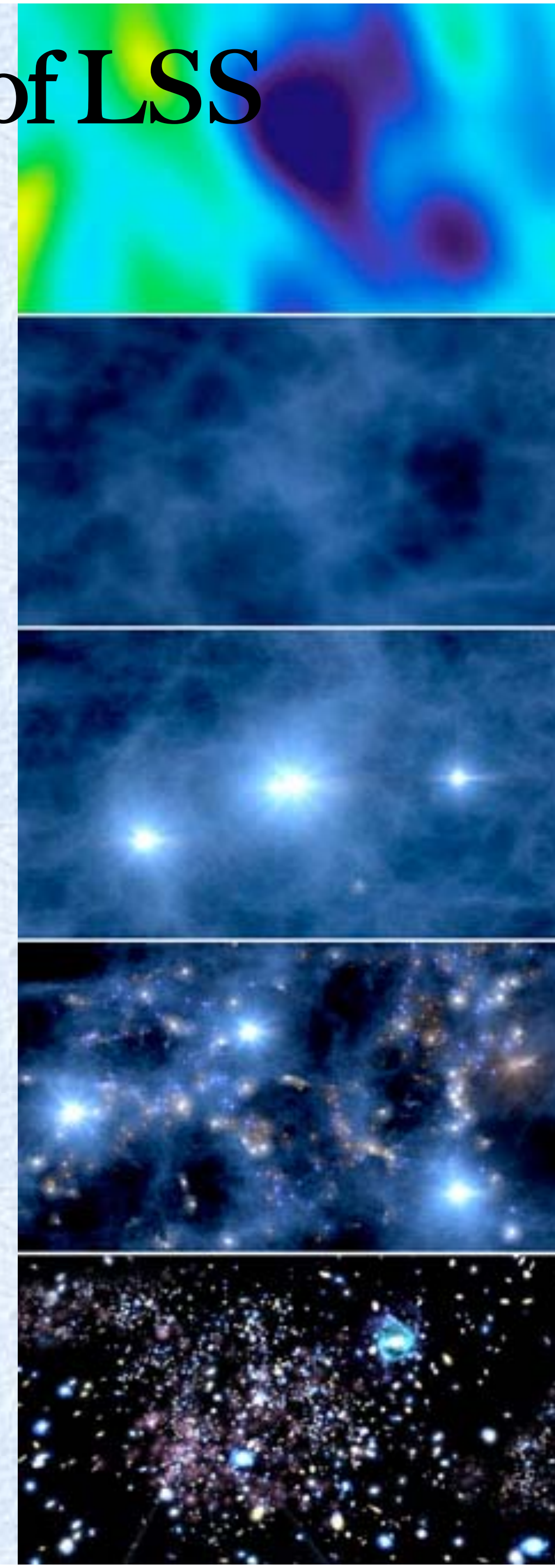
- Model LSS in terms of massive elements each of mass 10^6 - 10^7 $M_\odot$



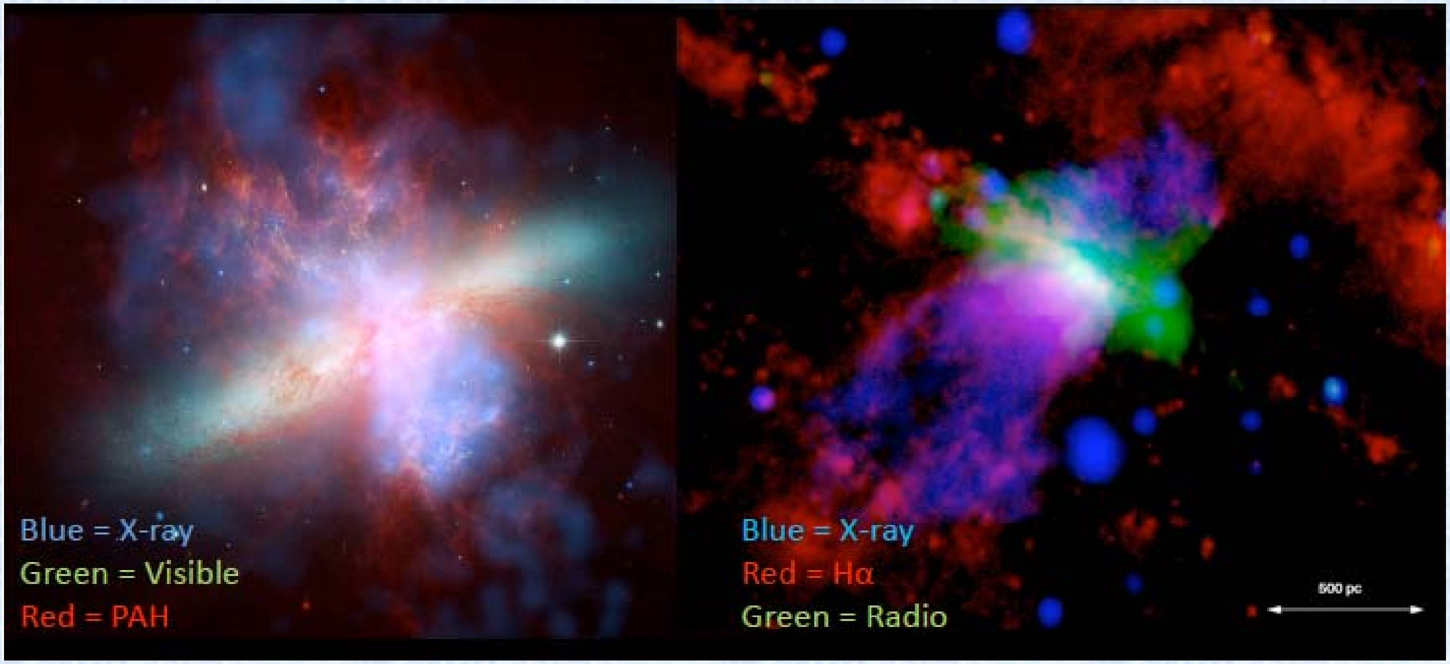
<u>ΛCDM cosmology</u>

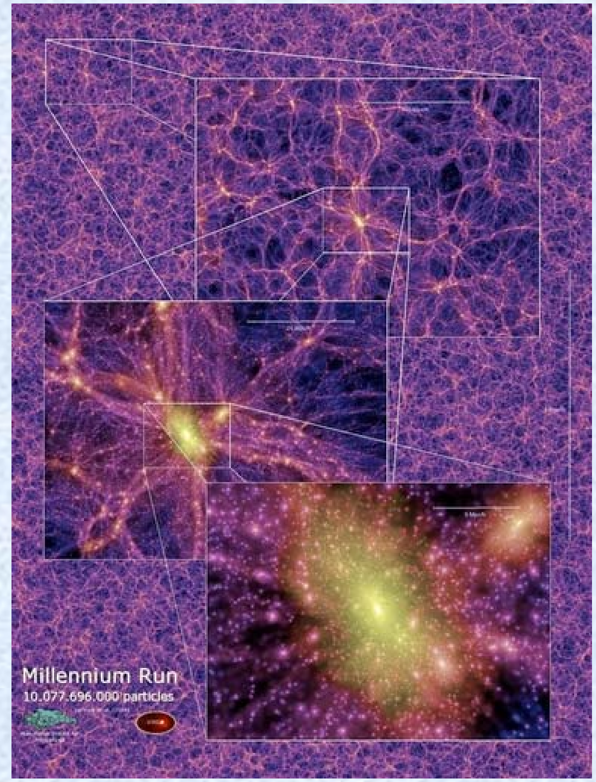
- Steps:
  - Generate the initial condition
    - Primordial density fluctuations (Gaussian) at CMB epoch (z~1100)
  - Follow the non-linear evolution of density fields numerically
  - Identify galaxies, clusters (group finder) at different z

- <u>Goal:</u> get the final galaxy properties consistent with observations of the Universe



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

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

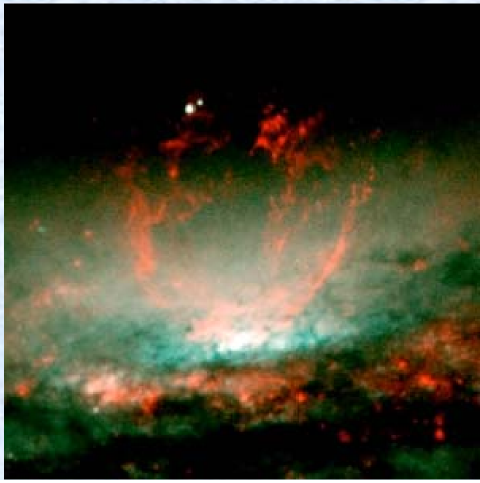
- Crucial ingredient
- Implemented as sub-resolution models

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

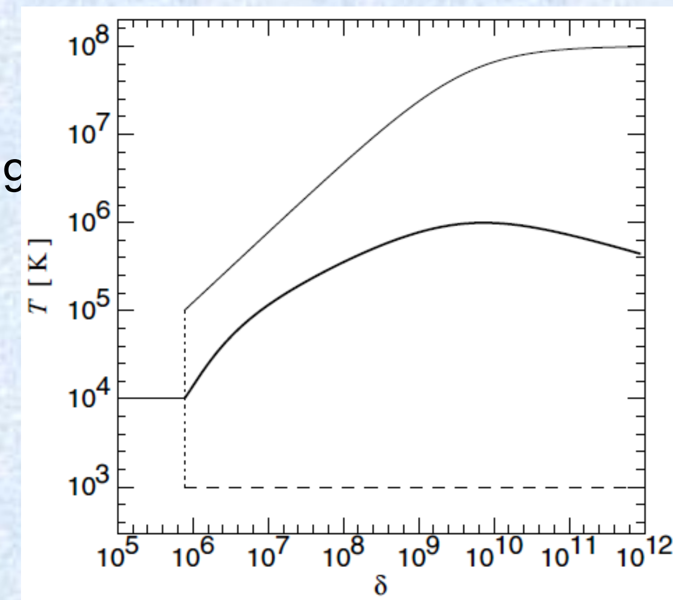


Star-formation in Multiphase ISM

- High-density SPH particle represents a part of ISM
  - Composed of 2 gas phases: Cold clouds + Hot ambient, & Stars

$> {}_{SF,th}$

- Effective model (Springel & Hernquist 2003, MNRAS, 339
  - Equilibrium solution
  - Self-regulated SF: constant effective pressure

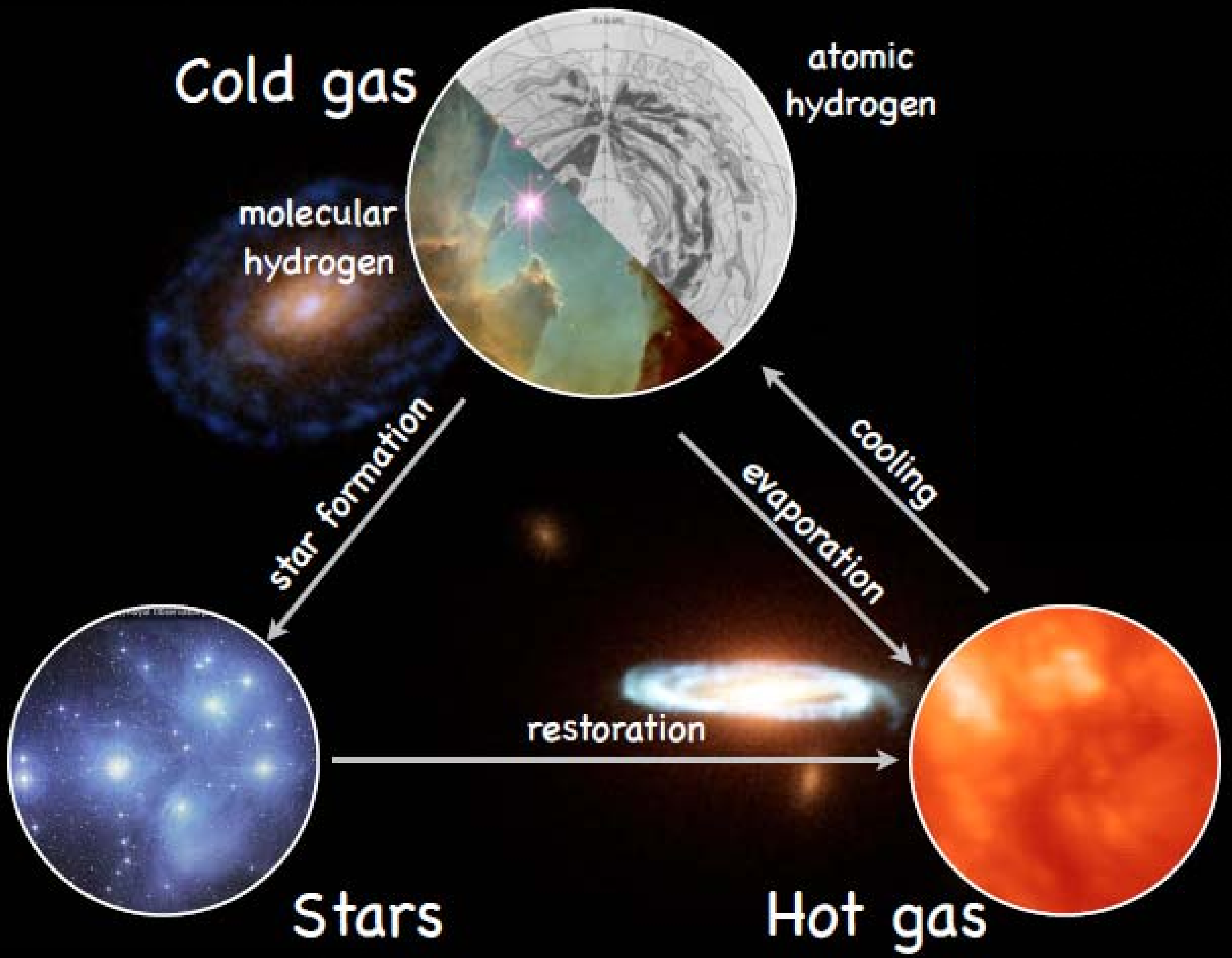


- MUPPI = MUlti-Phase Particle Integrator

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

MUPPI algorithm

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



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

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

SNe-driven Kinetic Feedback (Springel & Hernquist 2003)

- Mass-loss rate ∝ SFR

$$\frac{dM_w}{dt} = \frac{dM_\#}{dt}$$

- Energy-driven wind :

$$\frac{1}{2}\frac{dM_w}{dt}v_w^2 = \#_{SN}\frac{dM}{dt}$$

- New particle velocity
  - Along rotation axis

$$v_{new} = v_{old} + v_w \hat{n}$$

$$\hat{n} \qquad \vec{v} \# \vec{\ } \%$$

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

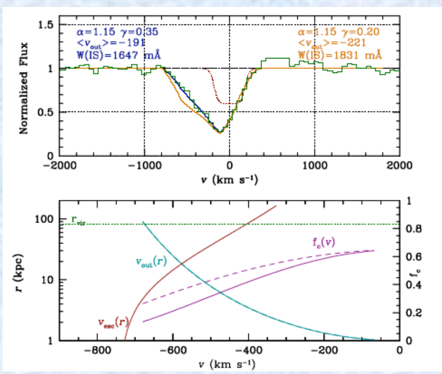
$$_{dec} = 0.25 \qquad _{SF} = 0.25 \# 0.1 \text{ cm}^{3}$$

Models of Galactic Wind

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

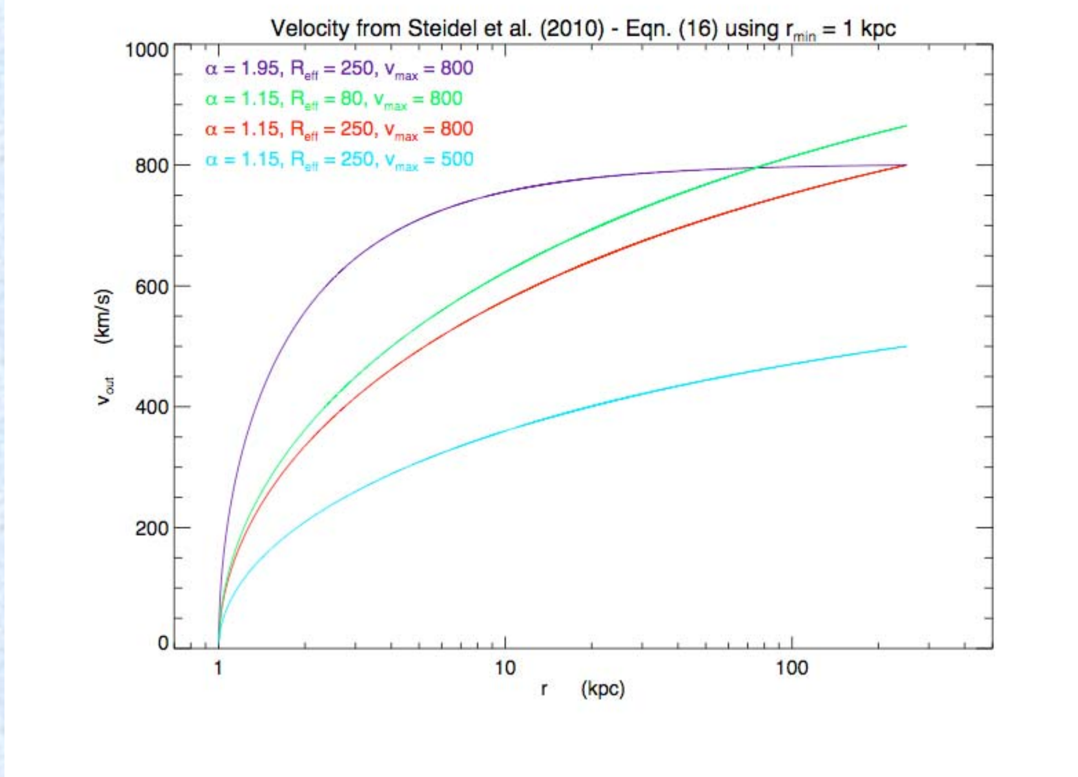
$$v_{w}, \quad = \text{constant}$$

- Radially Varying Outflow Velocity - (Barai et al. 2013)
  - Observations by Steidel et al. (2010, ApJ, 717, 289)
    - Spectroscopic data fitted by simple model
  - Quantities are function of galactocentric distance, r



$$a(r) \quad r^{\#} = v \frac{dv}{dr}$$

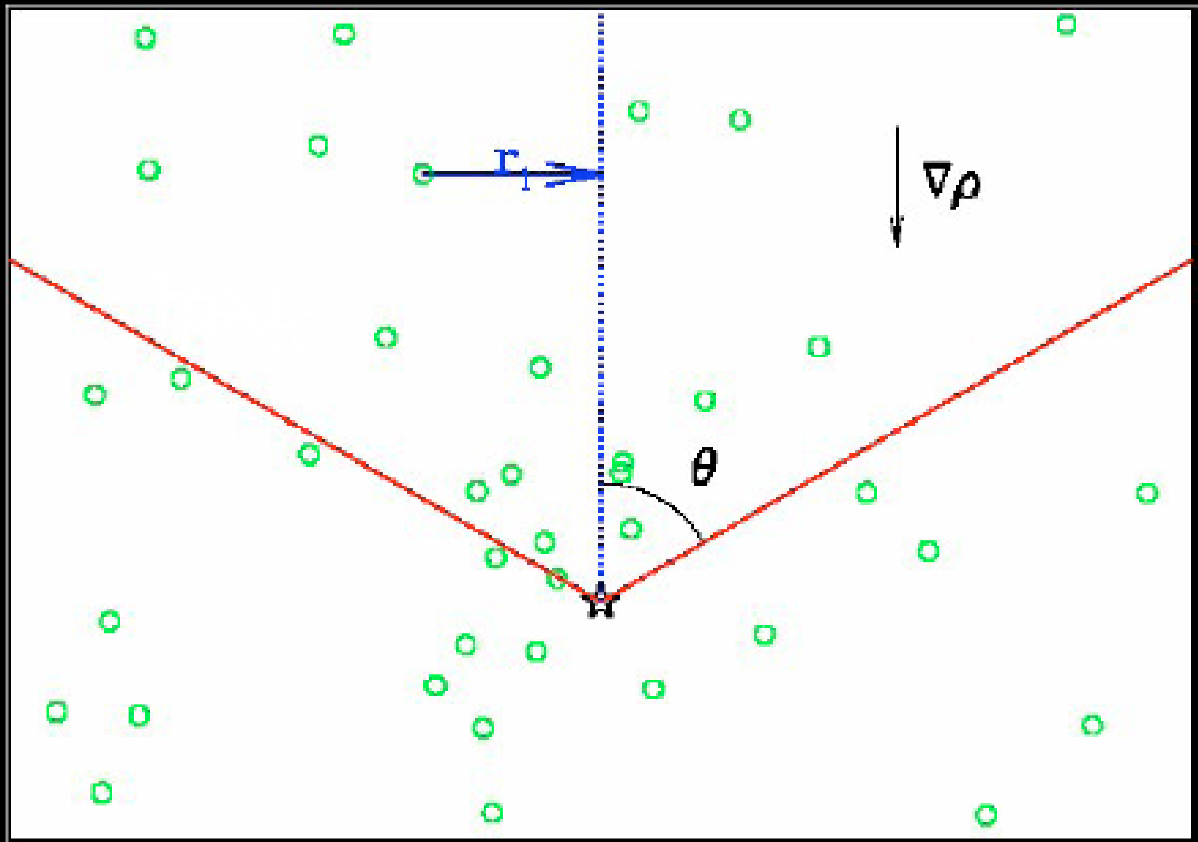
$$v_w(r) = v_{\max} \frac{r_{\min}^{1\#} \; \# \; r^{1\#}}{r_{\min}^{1\#} \; \# \; R_{eff}^{1\#}}^{0.5}$$



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

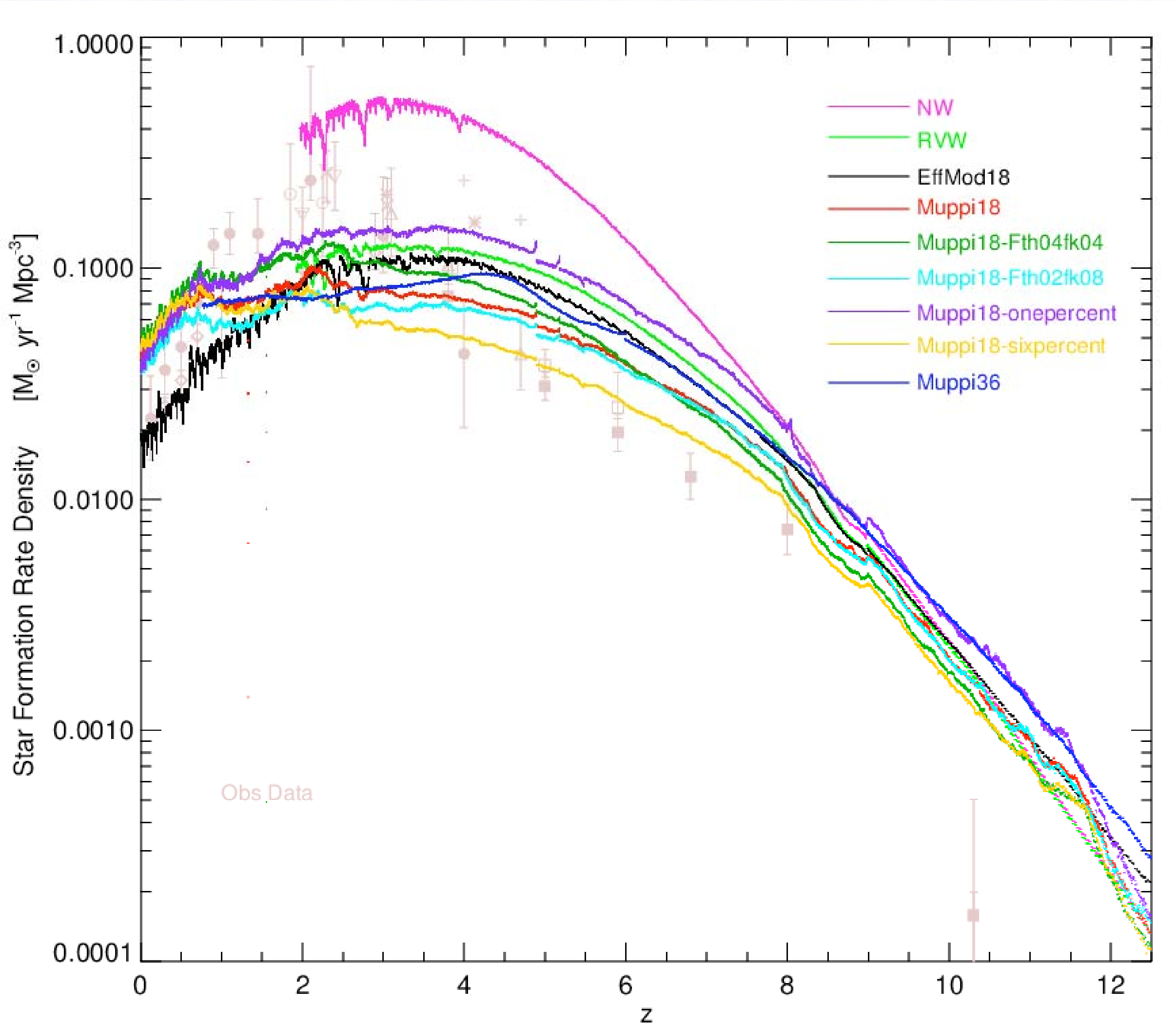
Wind speed and mass loading are determined by energy fraction and probability

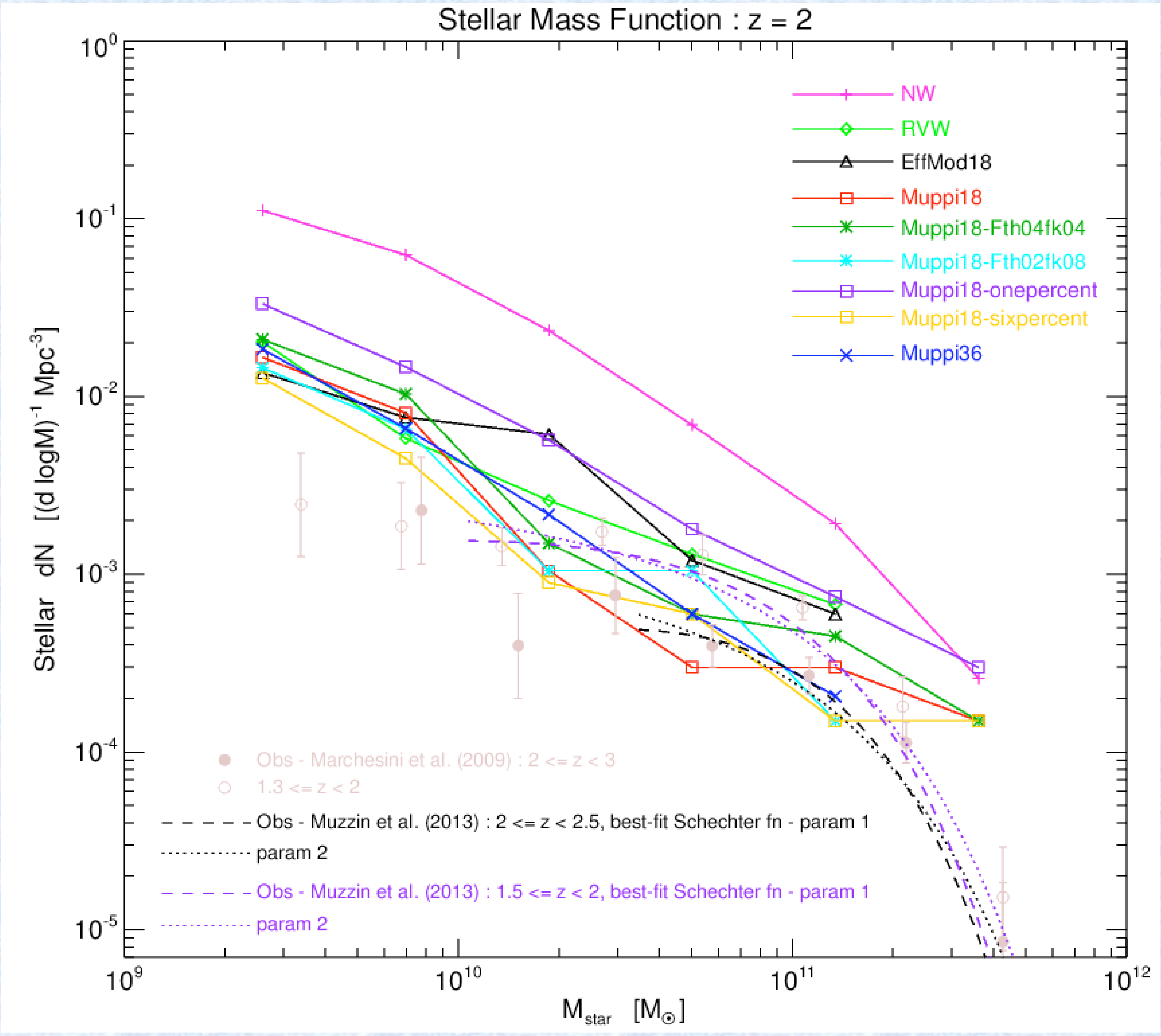
Simulation runs (Barai et al. in prep)

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



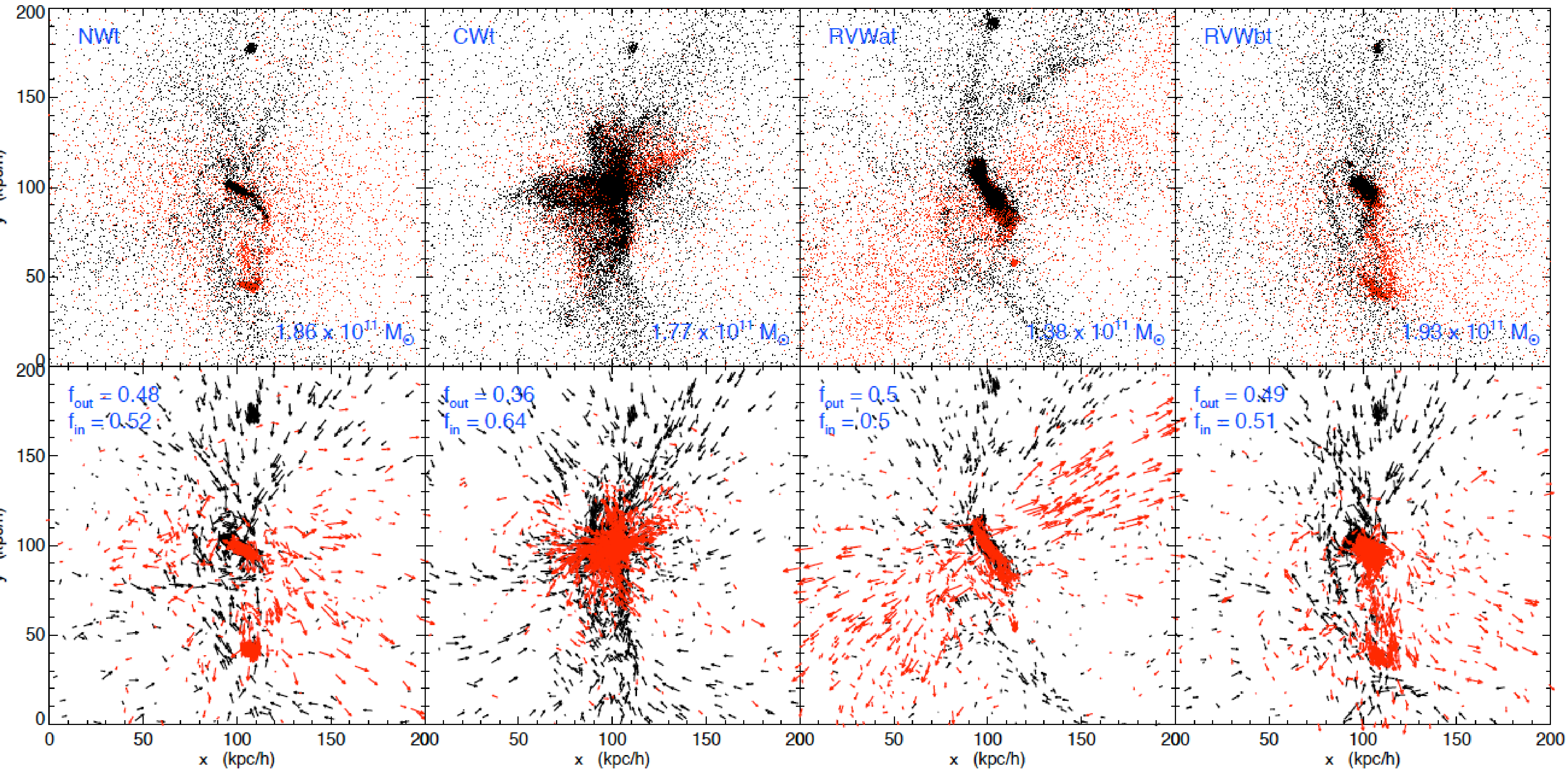


Stellar Mass Function : z = 2
NW
RVW
EffMod18
Muppi18
Muppi18-Fth04fk04
Muppi18-Fth02fk08
Muppi18-onepercent
Muppi18-sixpercent
Muppi36
Obs - Marchesini et al. (2009) : 2 <= z < 3
1.3 <= z < 2
Obs - Muzzin et al. (2013) : 2 <= z < 2.5, best-fit Schechter fn - param 1
param 2
Obs - Muzzin et al. (2013)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

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

Red - Outflowing, Black - Inflowing.

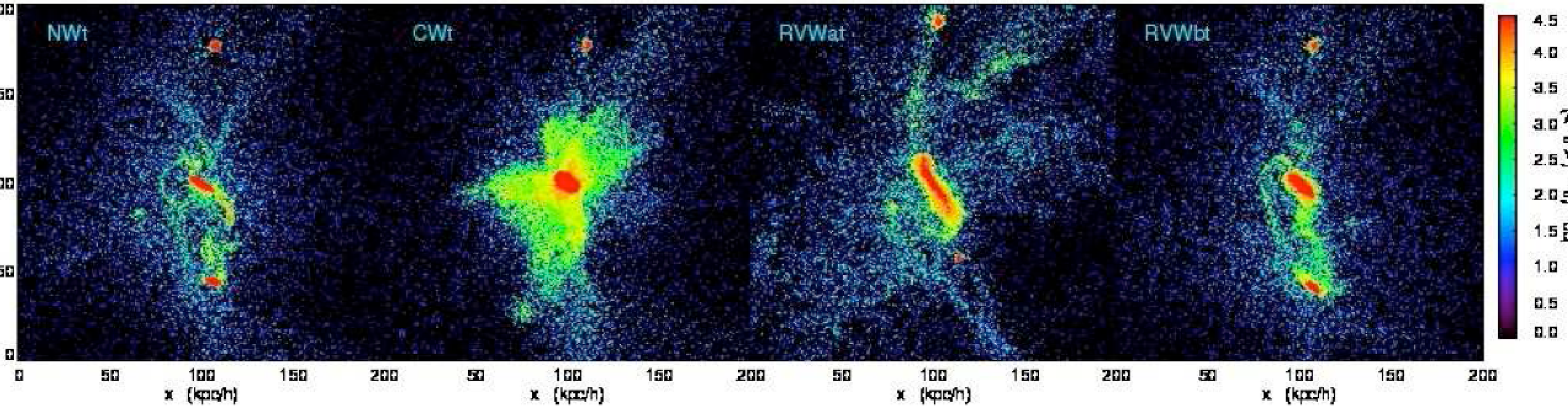
Particle positions

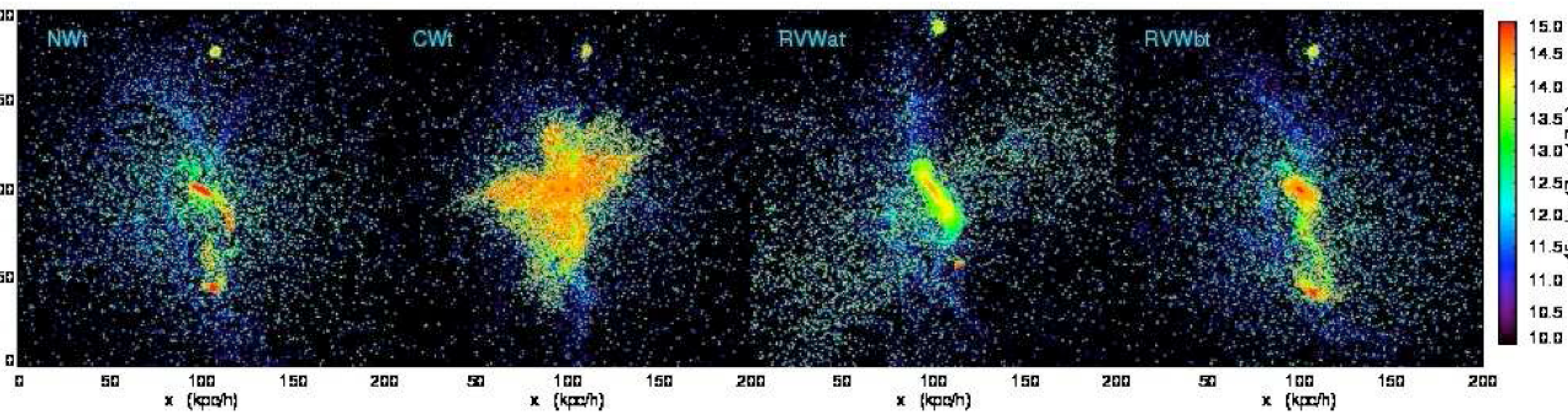


Velocity vectors

Projection of (200/h kpc)^3 volume around most-massive galaxy center at z = 2.12.

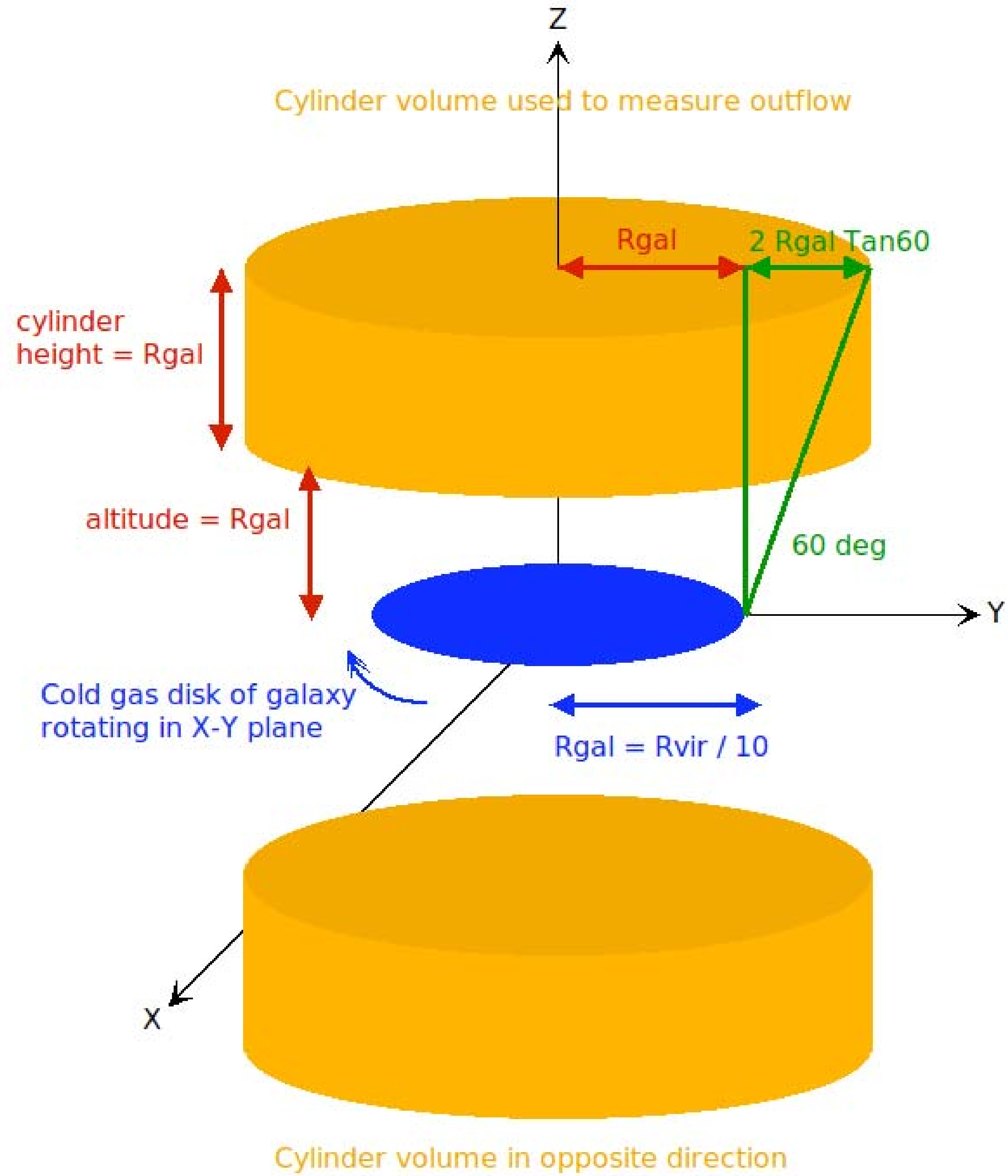
Density





Carbon metallicity

Outflow measurement technique



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

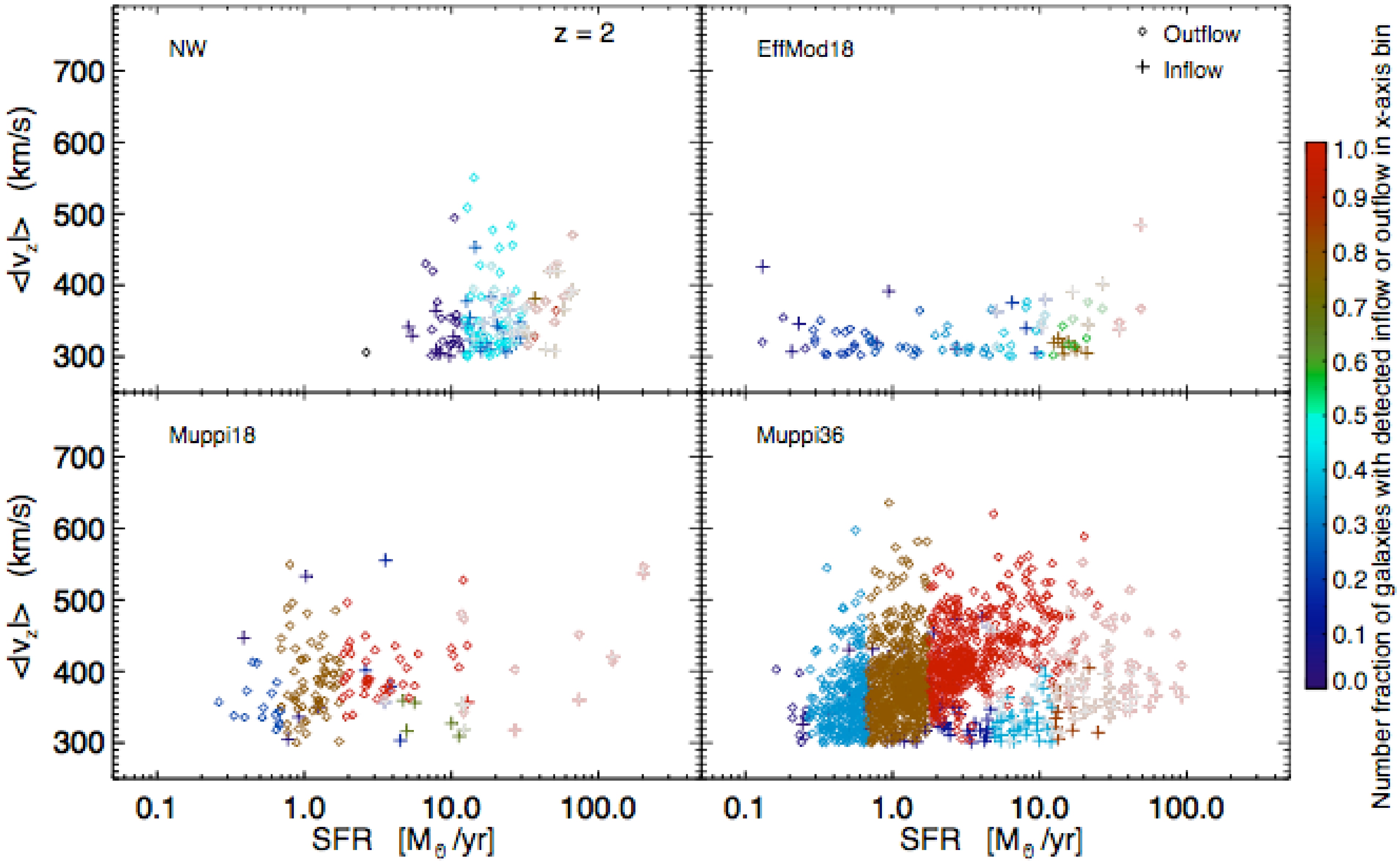
➢ Select gas particles:

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

▪ if $(z*v_z > 0) \Rightarrow$ Outflow

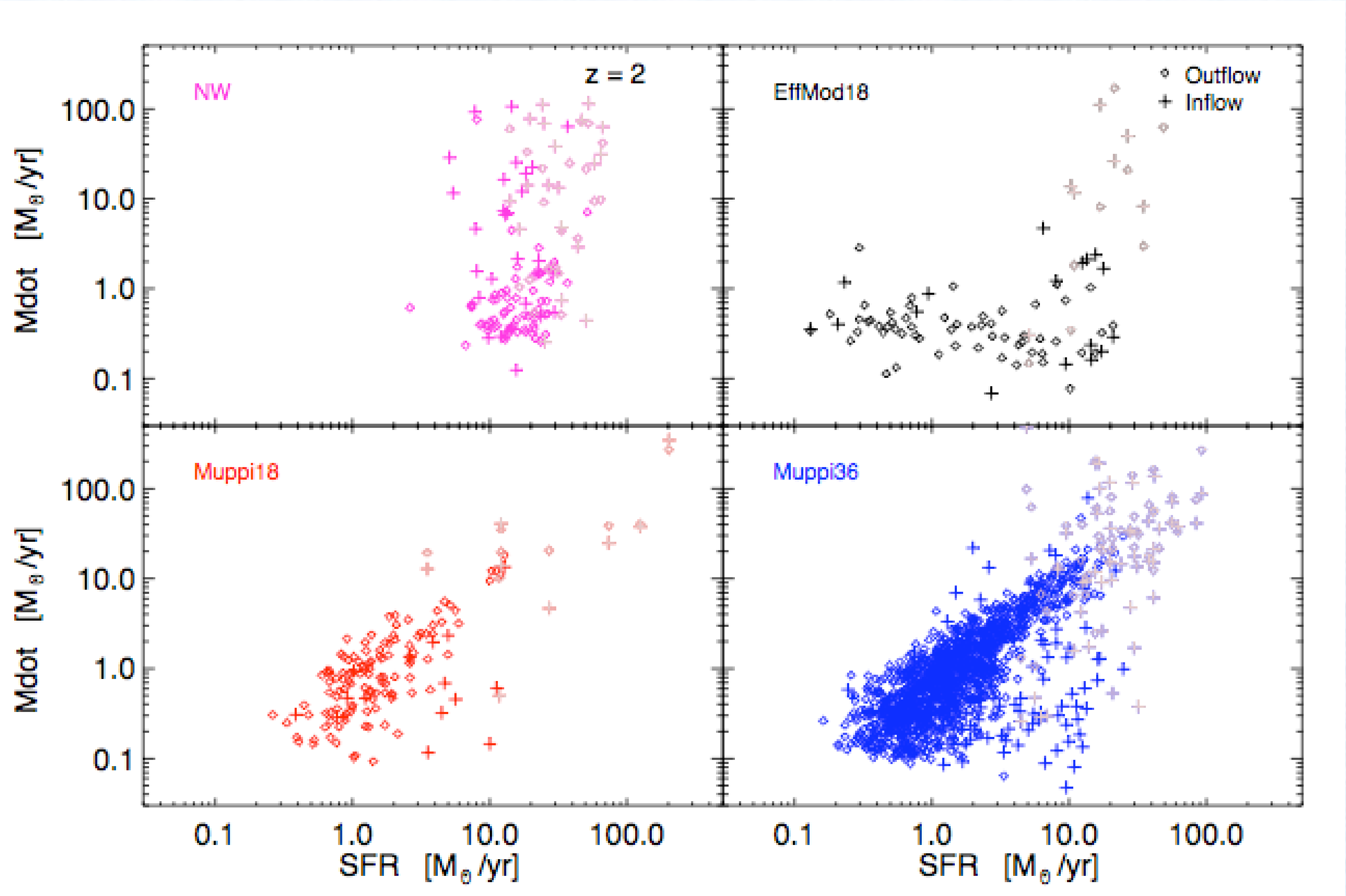
▪ if $(z*v_z < 0) \Rightarrow$ Inflow

Outflow velocity vs. galaxy SFR

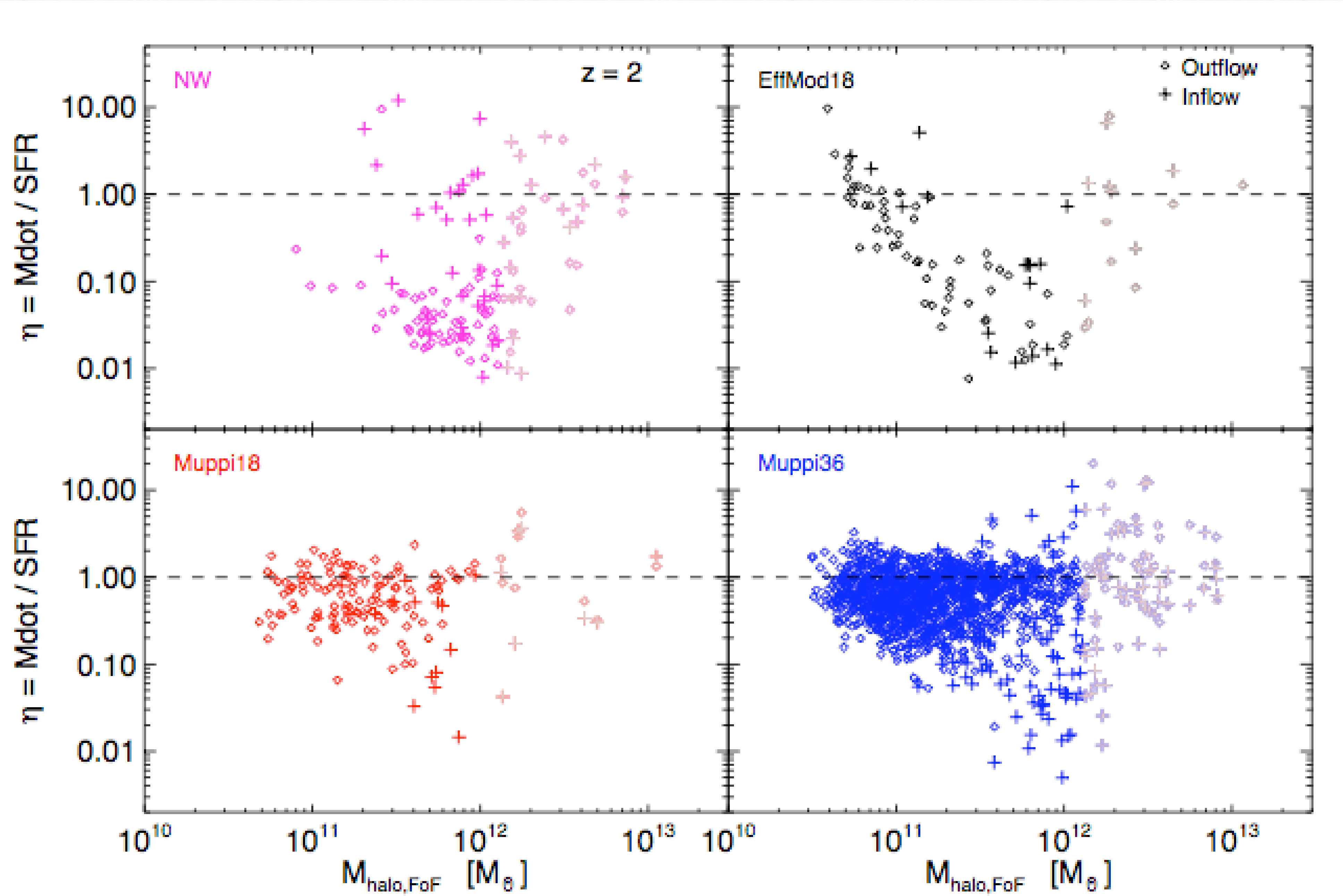


Observation : Martin (2005) - positive correlation of outflow speed with galaxy mass.

Mass outflow rate vs. galaxy SFR



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



Summary

- Cosmological Hydrodynamic Simulations are powerful tool
  - Study origin & evolution of galaxies over Hubble time

<u>SNe kinetic feedback:</u>

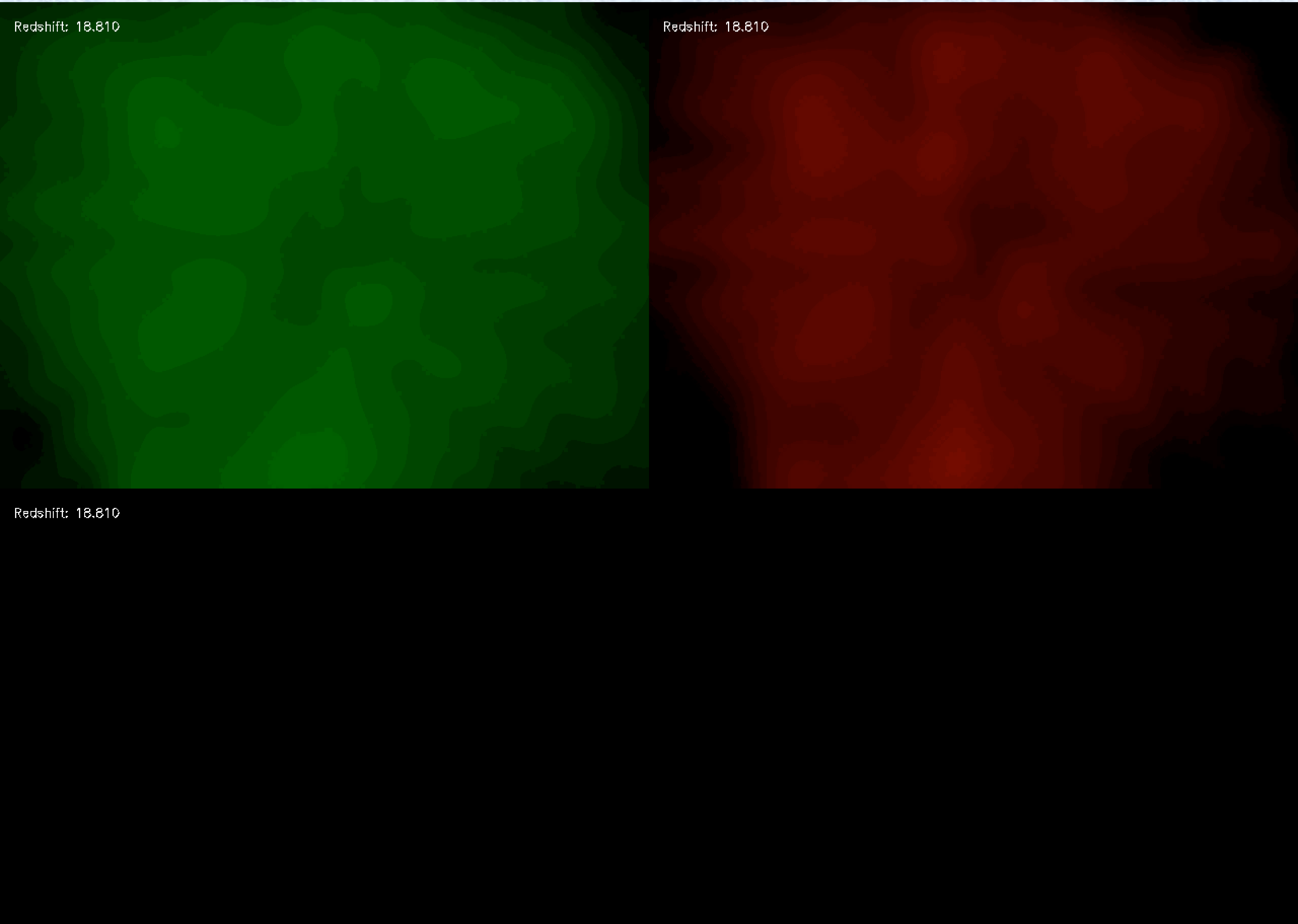
- Can study impact of galactic winds on galaxy & IGM properties
  - Still far away from self-consistently driving these winds in such sims
  - Need subgrid prescription

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

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

- Future :
  - Compute further galaxy & IGM observables from sim
  - More physics : molecular cooling, AGN feedback

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



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