Probing the Diffuse Baryons in the CGM and IGM using Cosmological Hydrodynamical Simulations

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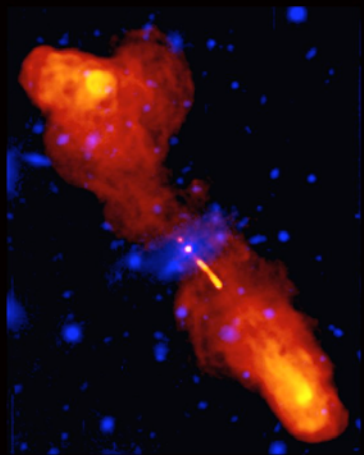
Astro @ TS, Trieste

9 June 2014

Baryons observed to be distributed in various forms at different scales in the Universe: Galaxy, Cluster, Large-scale structures



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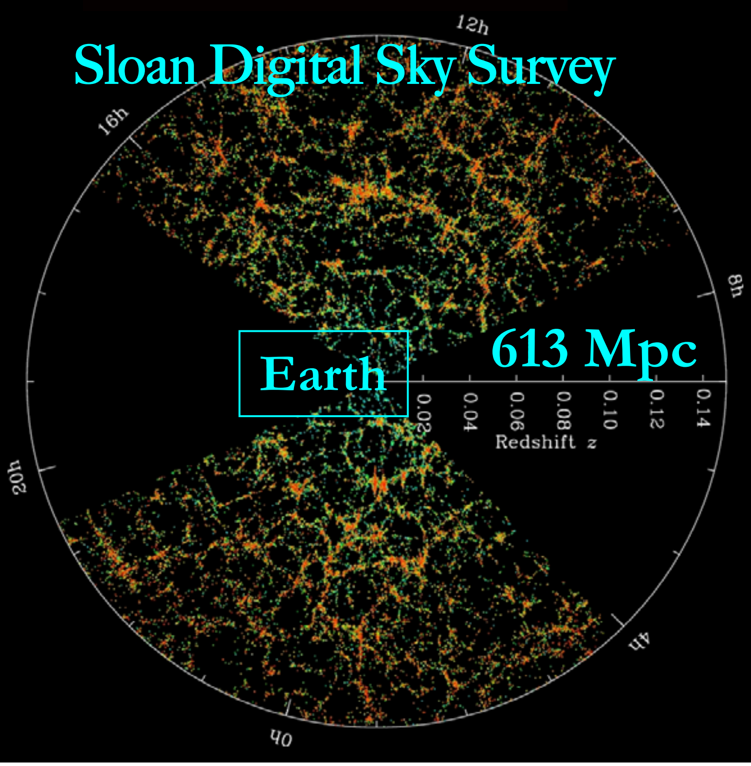
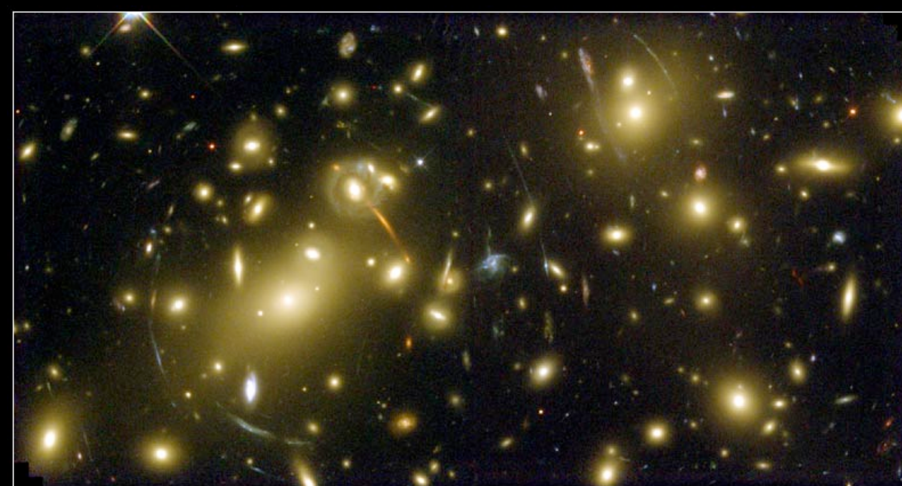
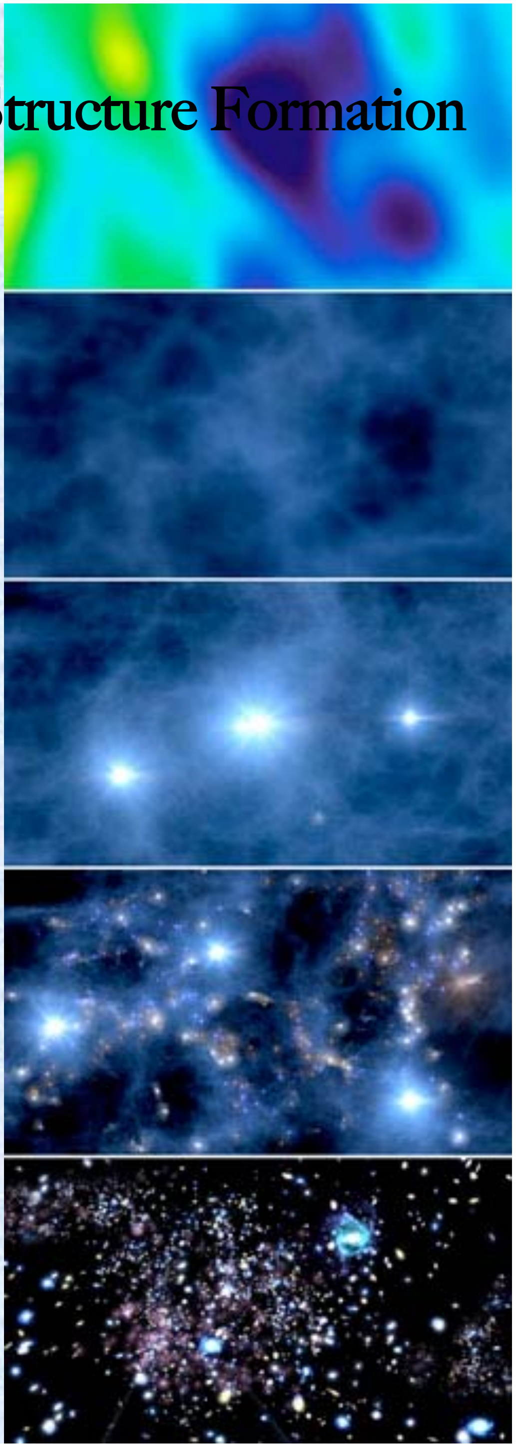




Galaxy Cluster Abell 2218 **HST** • WFPC2

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

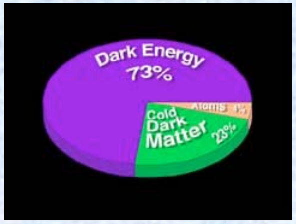
The Universe in a Box:
Cosmological Hydrodynamic Simulations of Galaxy & Structure Formation



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

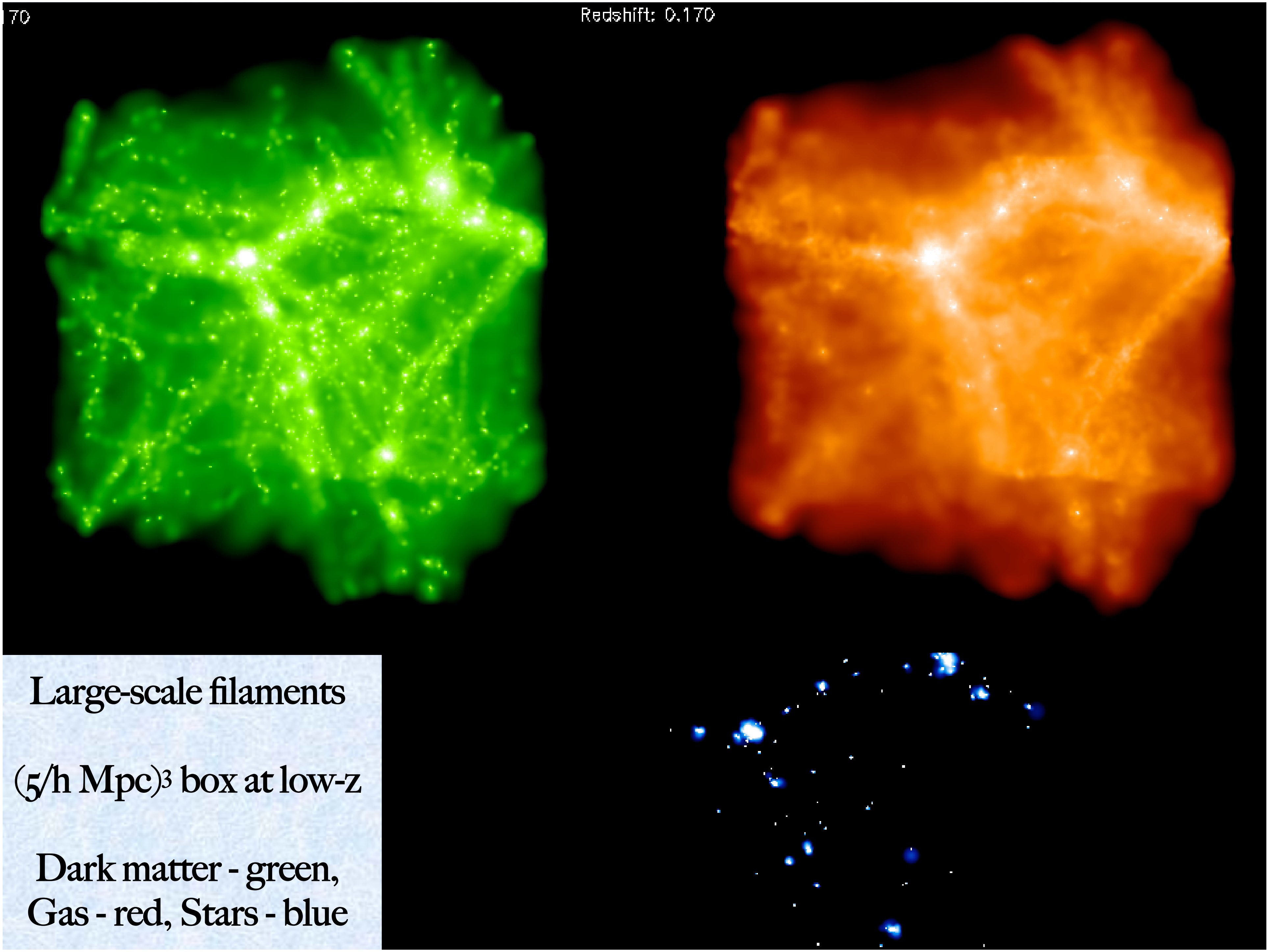
- Model LSS in terms of massive elements each of mass 10^6 - 10^7 $M_\odot$

<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

- Run on supercomputers
  - High speed & processing power, days to weeks of time



Large-scale filaments

(5/h Mpc)^3 box at low-z

Dark matter - green,
Gas - red, Stars - blue

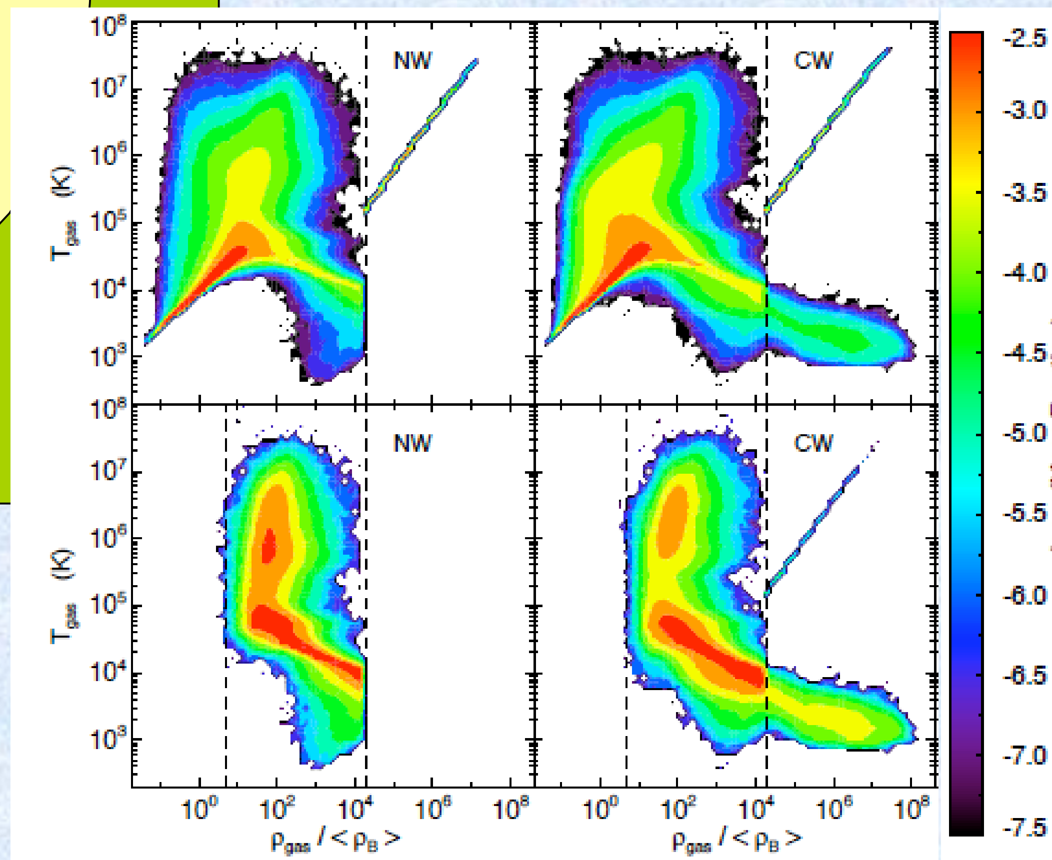
IGM (Intergalactic medium) =
diffuse gas between galaxies

of galaxies. The IGM and "circumgalactic medium" (CGM; by which we mean the gas-phase structures found within $\lesssim$300 kpc (physical) of galaxies) together present a laboratory in which the

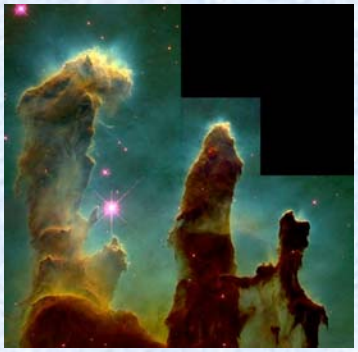
Steidel et al. (2010, ApJ, 717, 289)

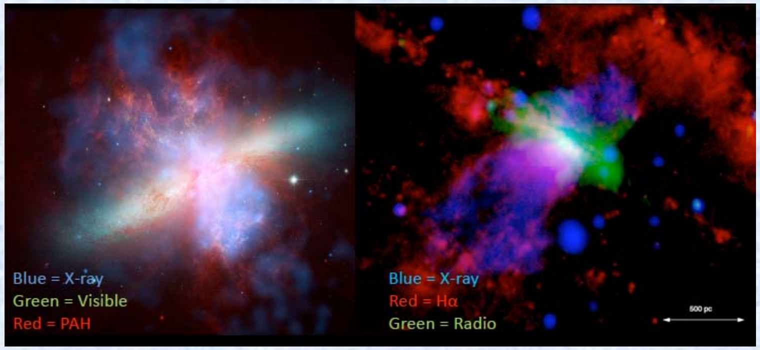
CGM (Circumgalactic medium)
= diffuse gas around galaxy
(R_{galaxy} to R_{virial})

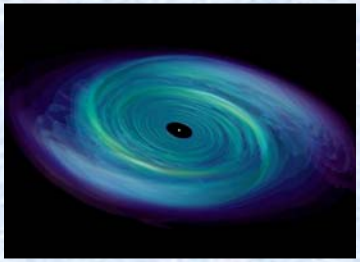
Galaxy =
stars + gas + dust + …

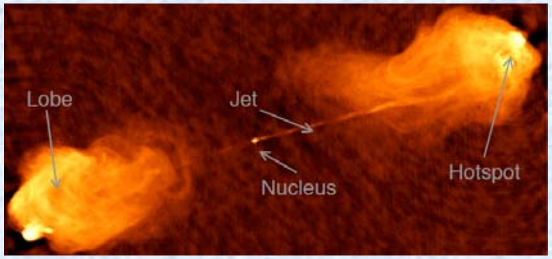


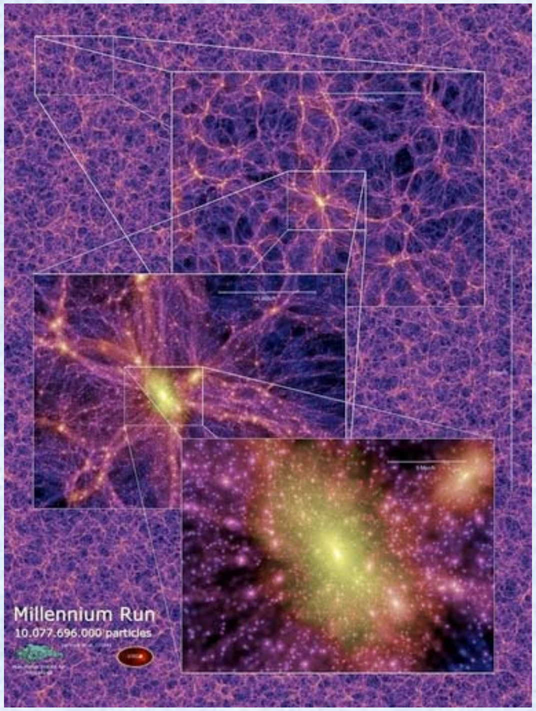
The case for sub-resolution (sub-grid) models











Physics of baryons

- Radiative cooling and (photo + collisional) ionization heating of gas
- Fragmentation, clumping, multiphase ISM
- Star formation
- Metal production & chemical enrichment
- SNe feedback, galactic wind
- AGN accretion + feedback
- …

In cosmological hydrodynamical simulations

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

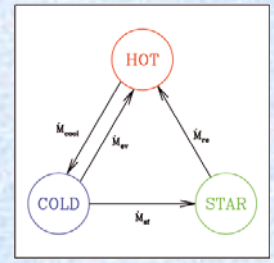
- Crucial ingredient
- Implemented as sub-resolution models

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)

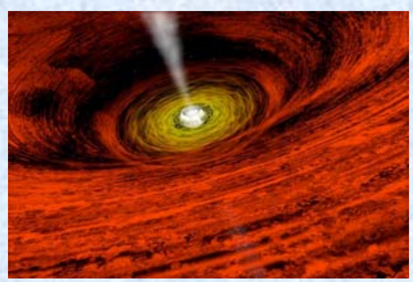
- Star Formation



- 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; stellar age, mass & yield; different IMF; mass & metal loss from starburst

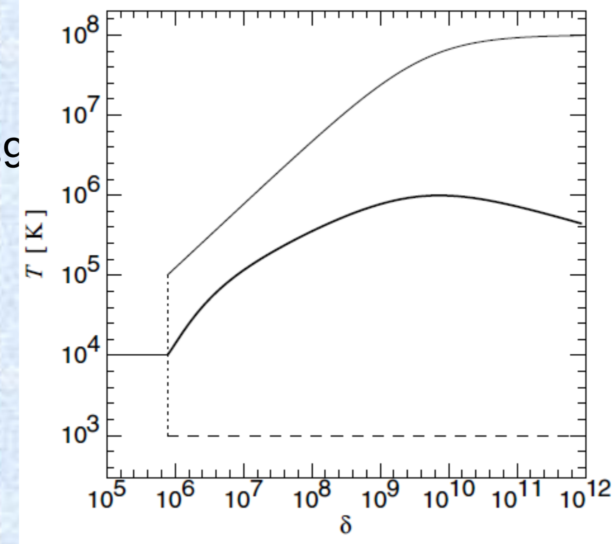
- SNe Feedback
  - Thermal feedback (↑ T) : inefficient, energy radiated away quickly
  - ∴ Kinetic feedback (↑ v)

- AGN accretion + feedback



Star-formation in Multiphase ISM

- High-density SPH particle represents a part of ISM $\rho > \rho_{SF,th}$
  - Composed of 2 gas phases: Cold clouds + Hot ambient, & Stars

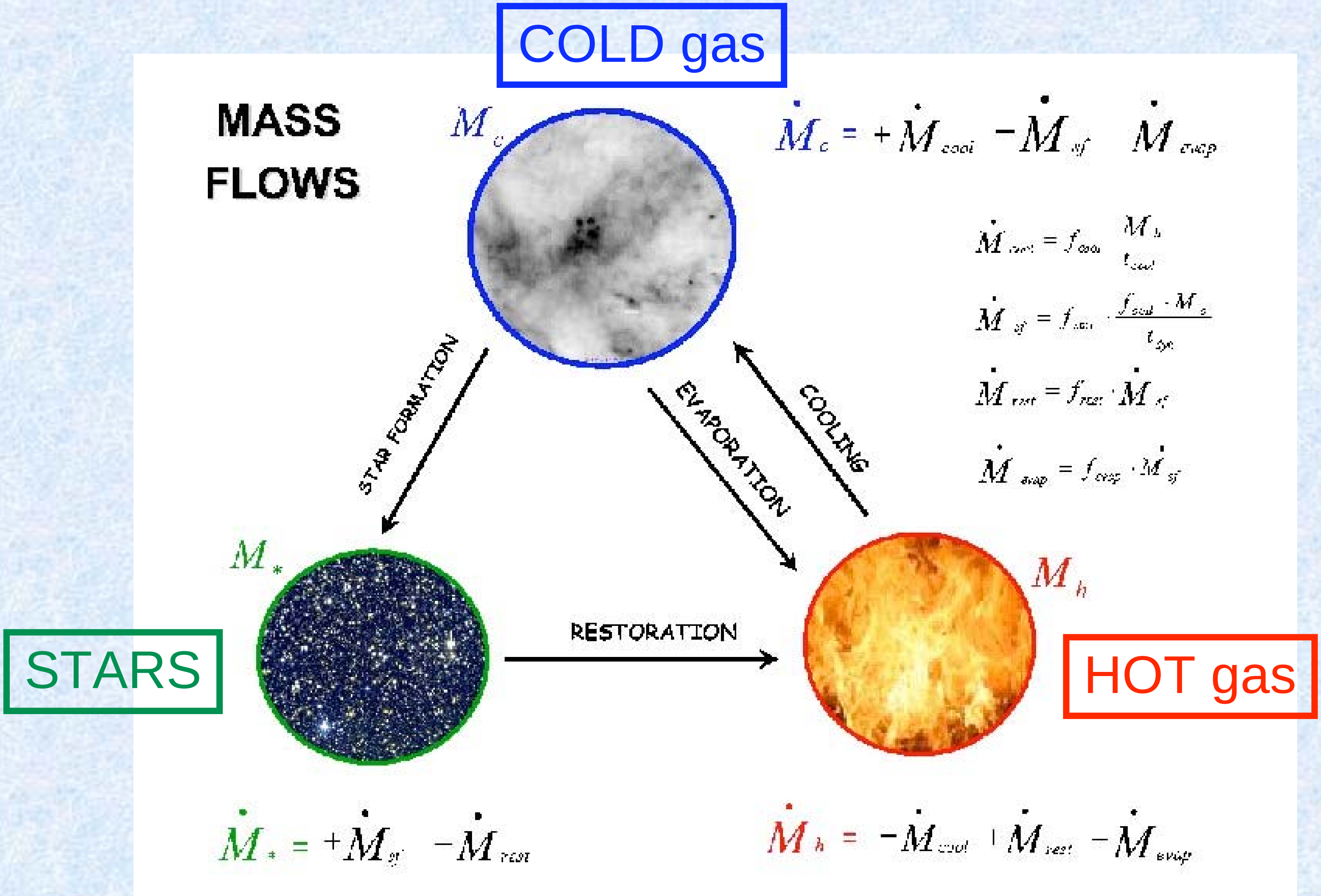


- Effective model (Springel & Hernquist 2003, MNRAS, 339
  - Equilibrium solution
  - Self-regulated SF: constant effective pressure

- MUPPI = MUlti-Phase Particle Integrator

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

MUPPI star-formation algorithm



SNe-driven Kinetic Feedback (Springel & Hernquist 2003)

- Mass-loss rate ∝ SFR

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

- Energy-driven wind :

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

- 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

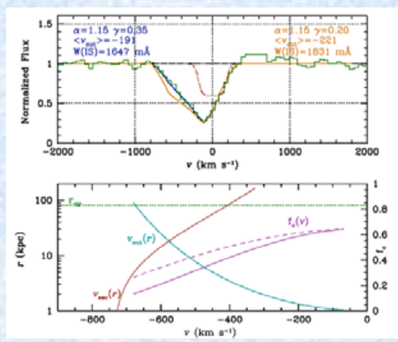
$$\rho_{dec} = 0.25 \rho_{SF} = 0.25 \times 0.1 \text{ cm}^{-3}$$

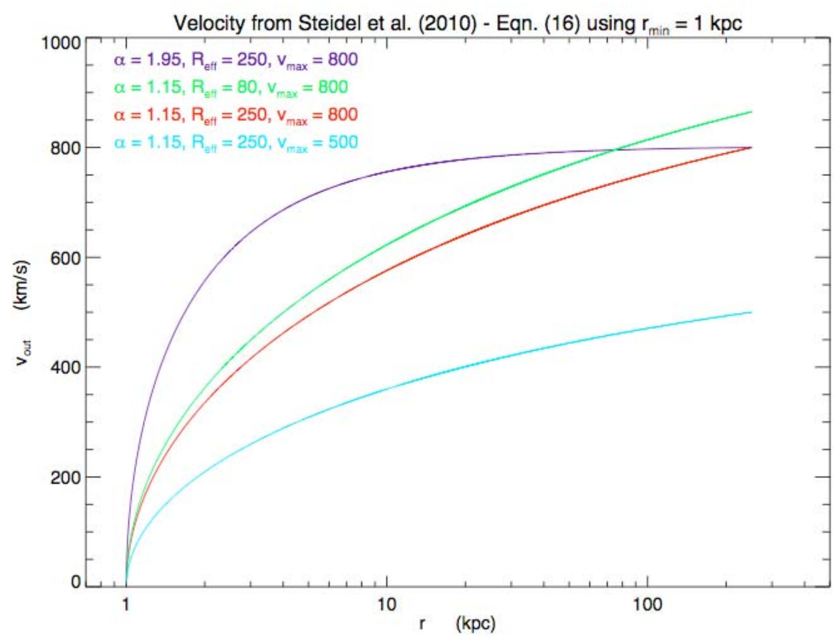
Models of Galactic Wind

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

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

- 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



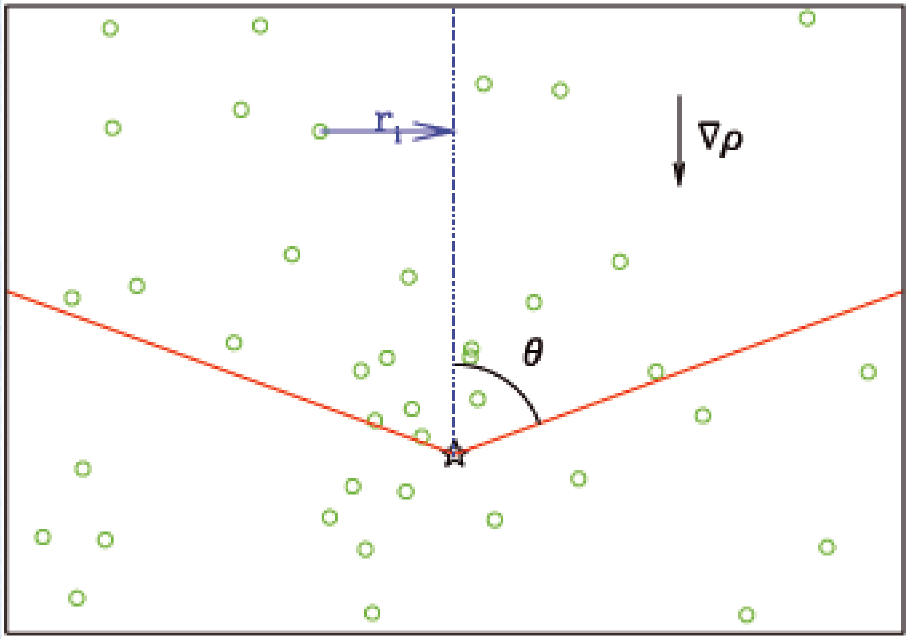


$$a(r) \propto r^{-\alpha} = v\frac{dv}{dr}$$

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

SNe energy feedback in MUPPI

- Energy imparted to gas particles along path of least resistance
  - Negative density gradient



- Direct distribution of
  - Thermal energy
    - Efficiency fraction
  - Kinetic energy
    - Efficiency fraction, Probability

- No direct input expression of wind velocity & outflow mass loading

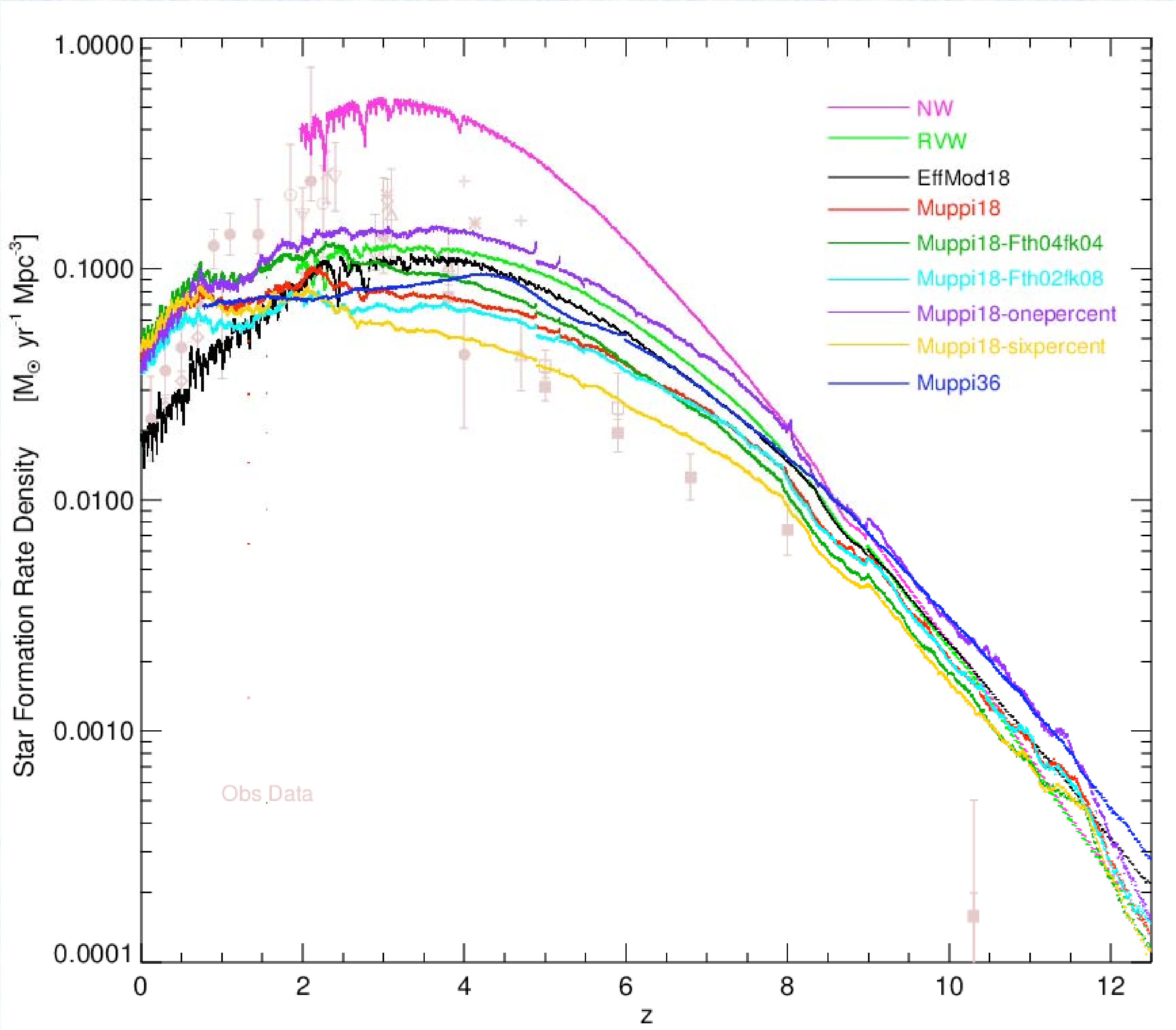
- Wind particles are hydrodynamically decoupled

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 Name	$L_{\rm box}$ $[h^{-1}$ Mpc$]$	$N_{\rm part}$	$m_{\rm gas}$ $[h^{-1} M_{\odot}]$	$L_{\rm soft}$ $[h^{-1}$ kpc$]$	SF & SNe feedback subgrid physics: 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

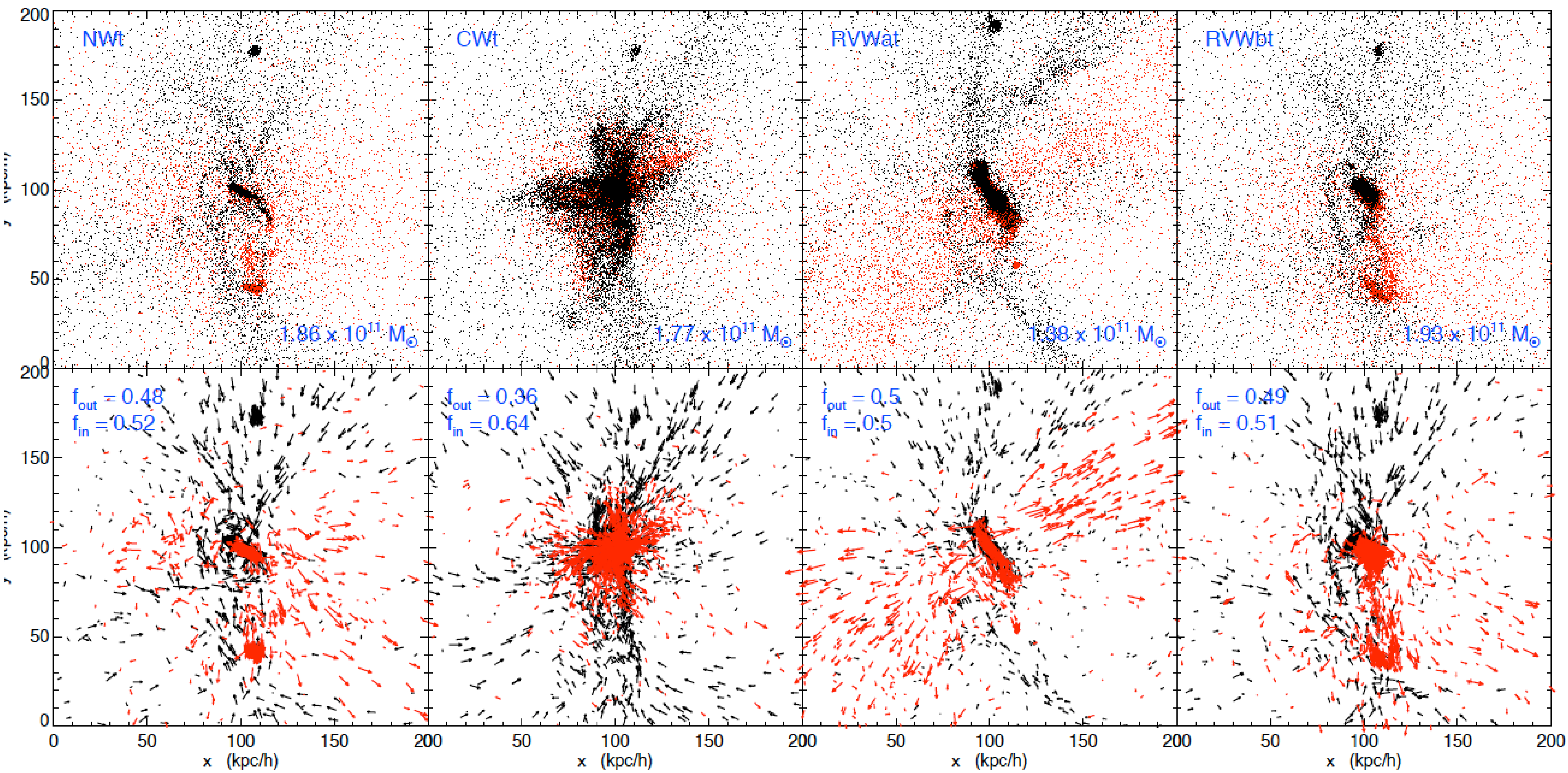
Star Formation Rate Density Evolution



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.

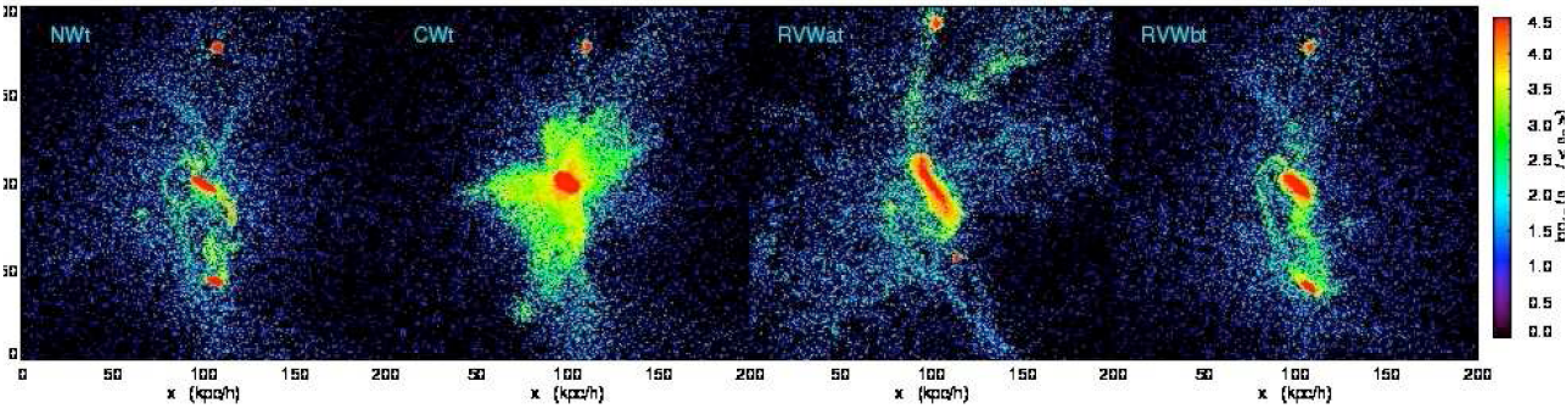
Particle positions

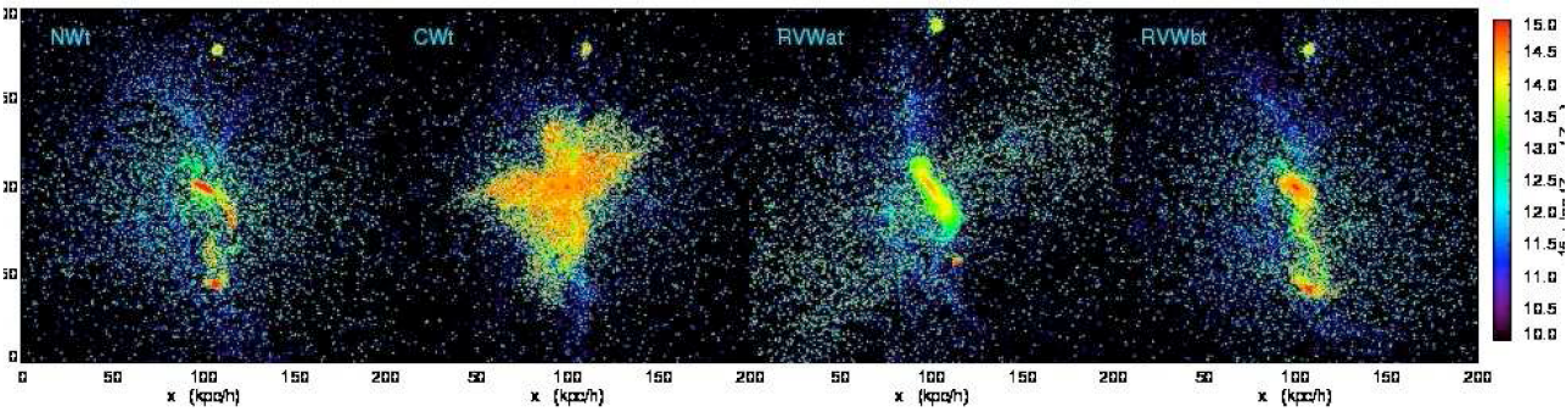


Velocity vectors

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

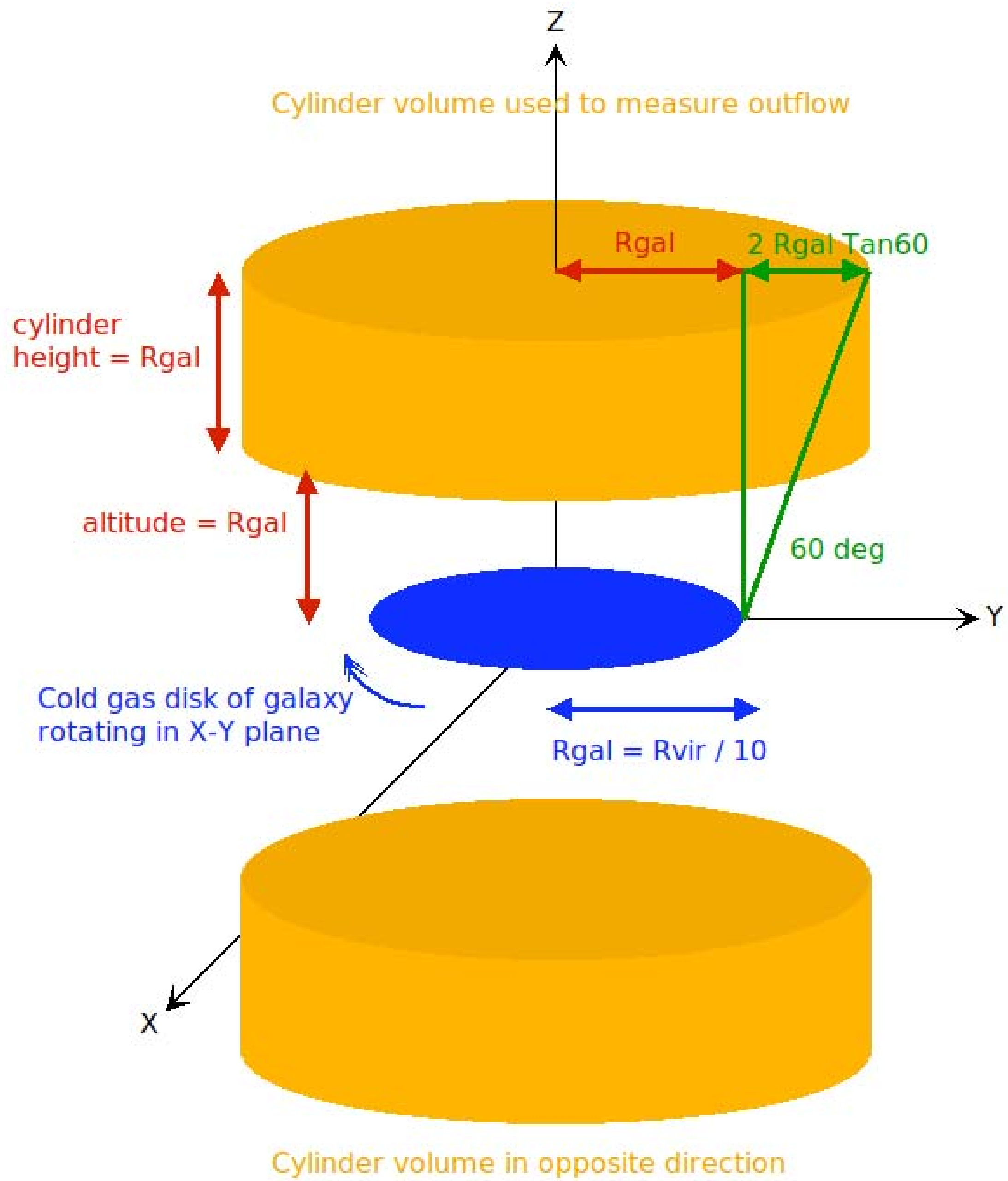
Density





Carbon metallicity

Outflow measurement technique (modified from Antonio Ragagnin 2013, Master thesis)

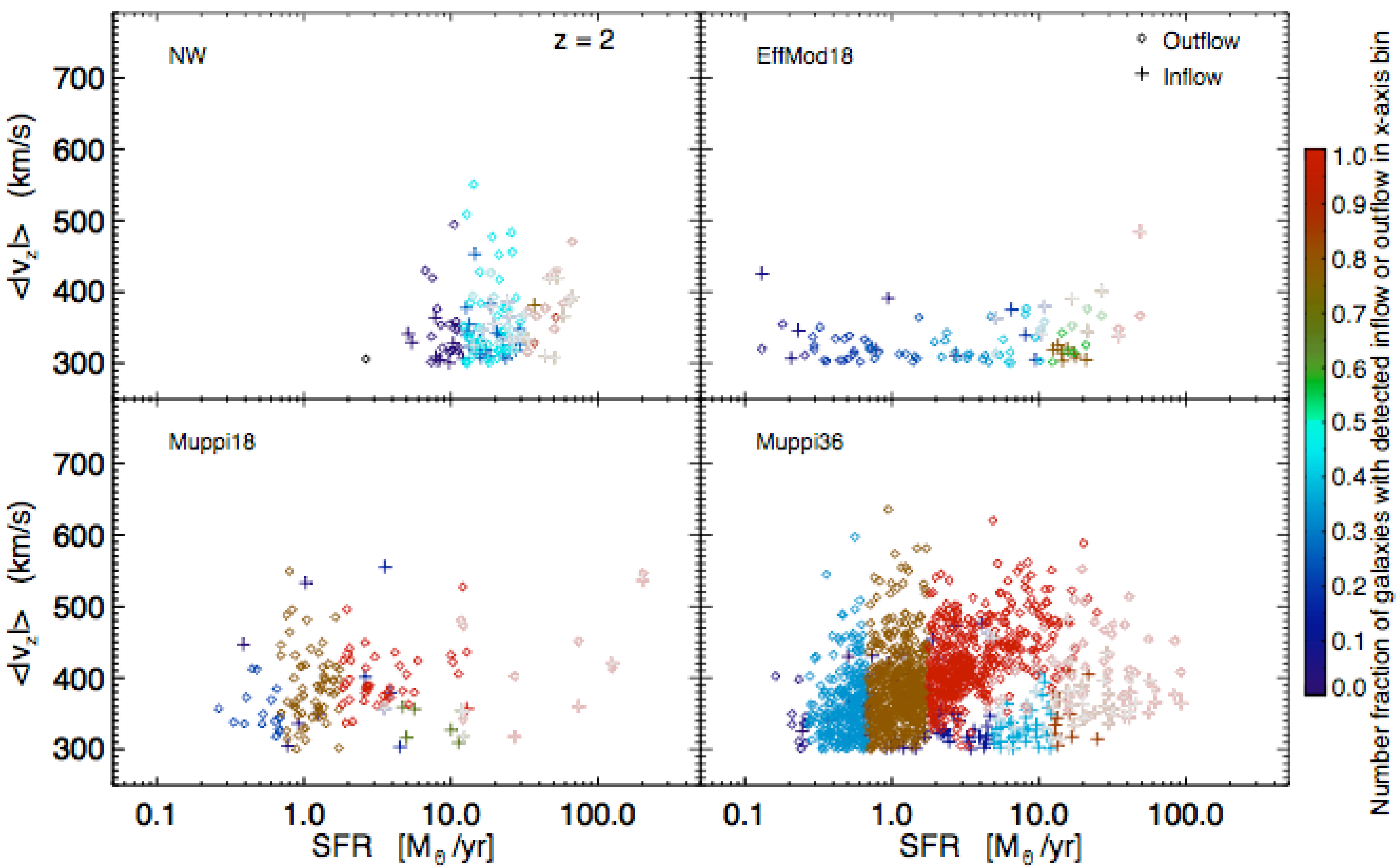


- ➢ Transform galaxy coordinates s.t. cold gas disk is rotating in X-Y plane

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

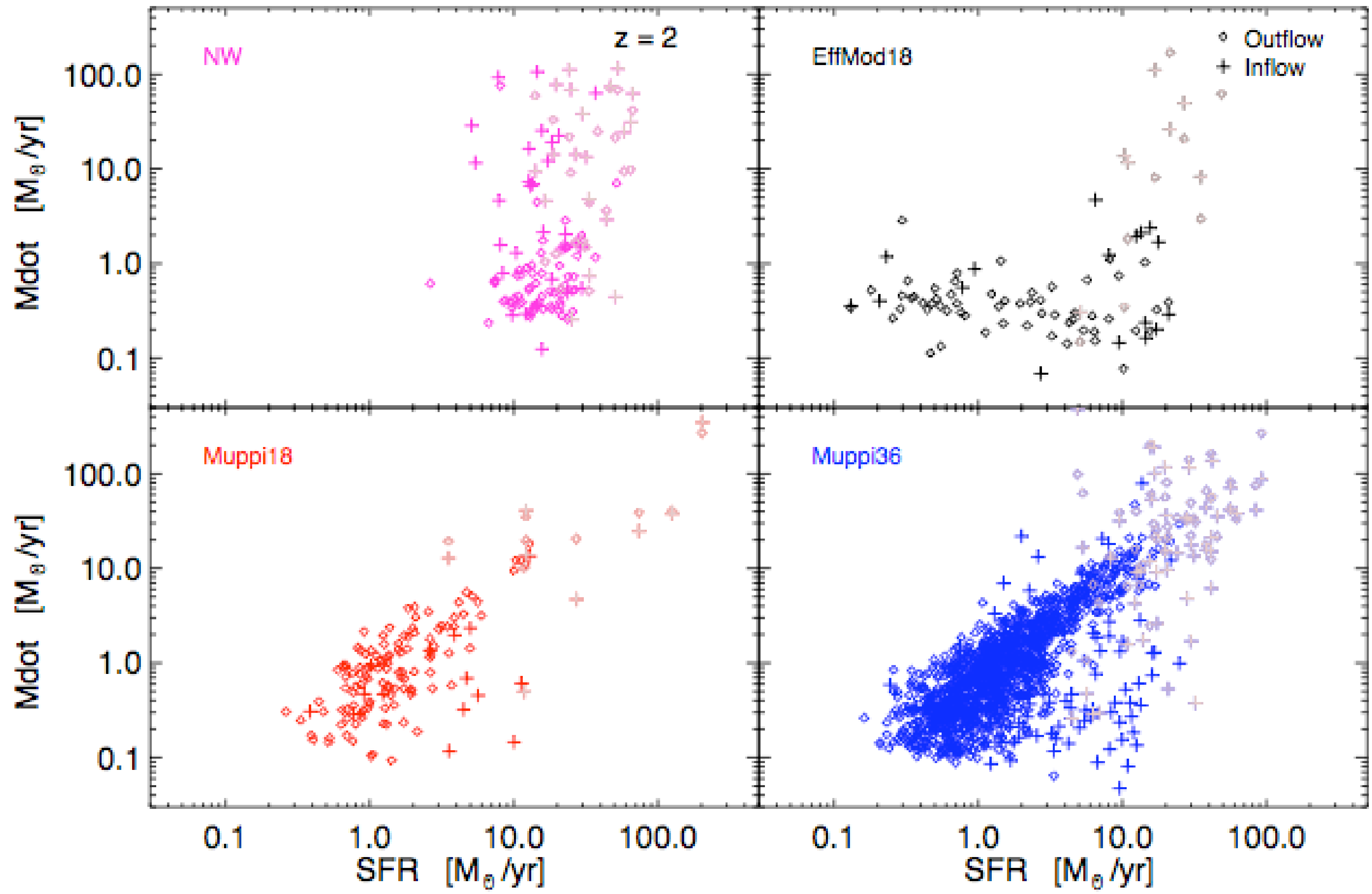
- ▪ if $(z^*v_z > 0) \Rightarrow$ Outflow
- ▪ if $(z^*v_z < 0) \Rightarrow$ Inflow

Outflow velocity vs. galaxy SFR

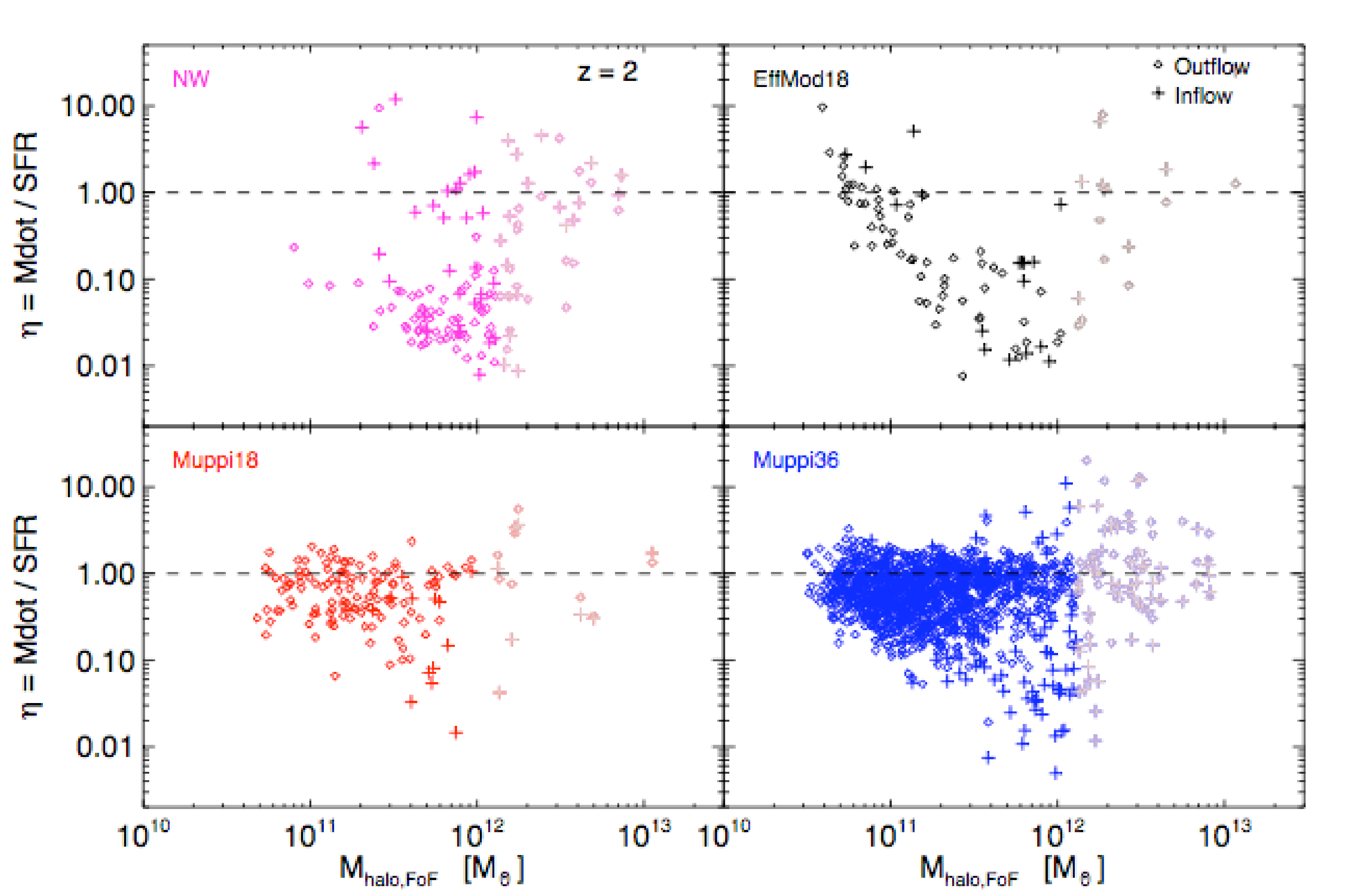


Observation : Martin (2005) - positive correlation of outflow speed with galaxy mass.

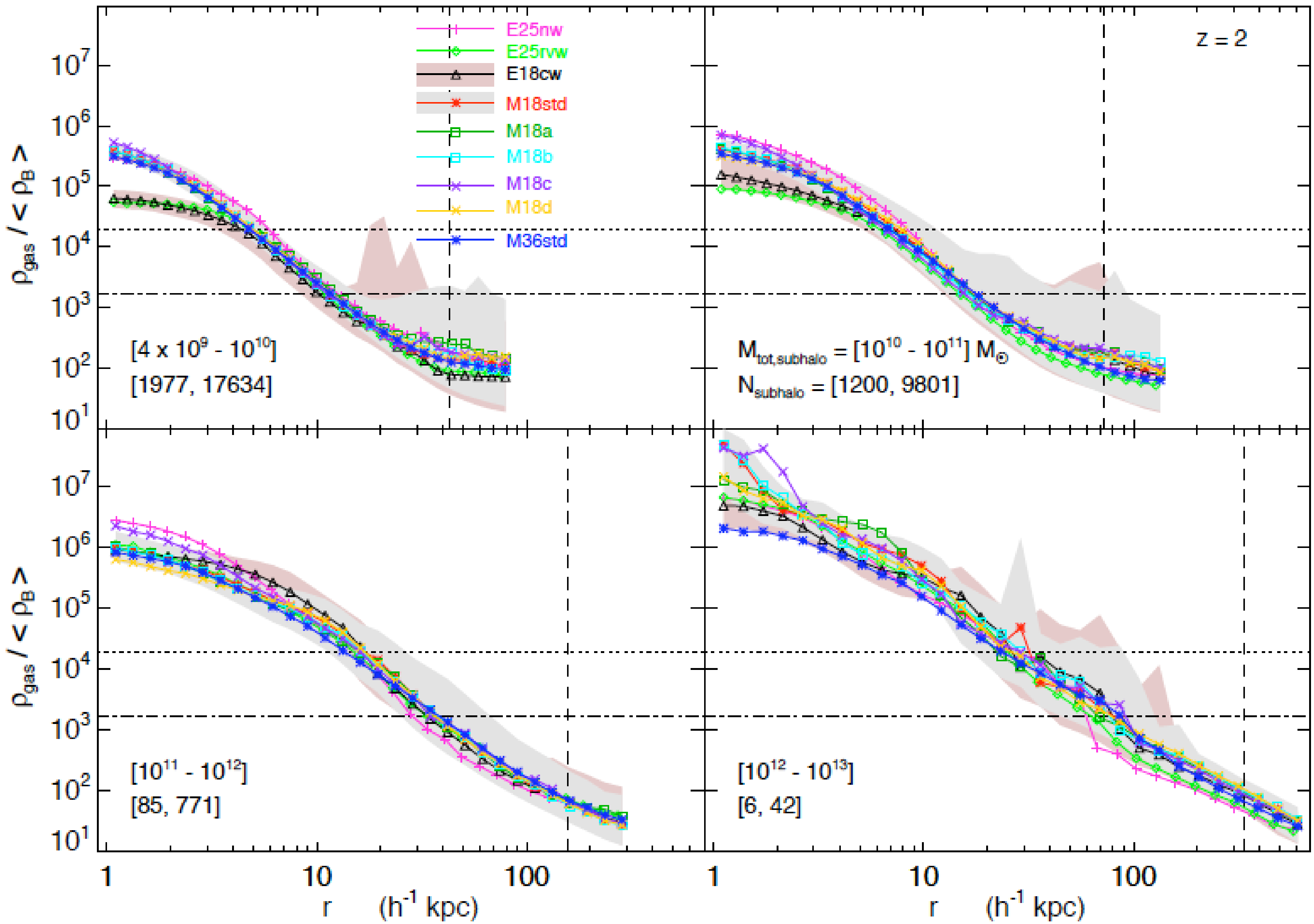
Mass outflow rate vs. galaxy SFR



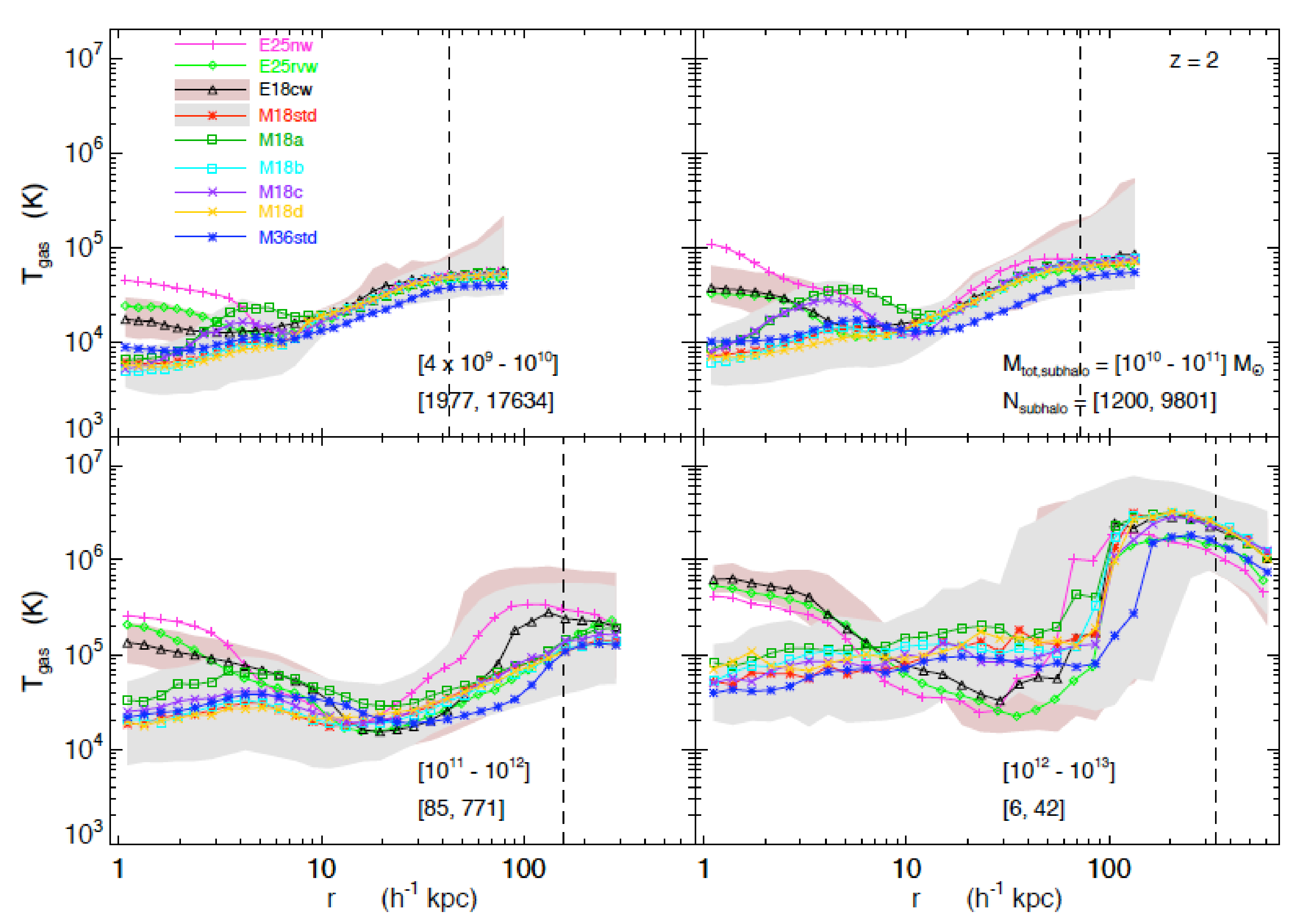
Mass loading factor (η = Mass outflow rate / SFR) vs. halo mass



Gas Density radial profile at z = 2

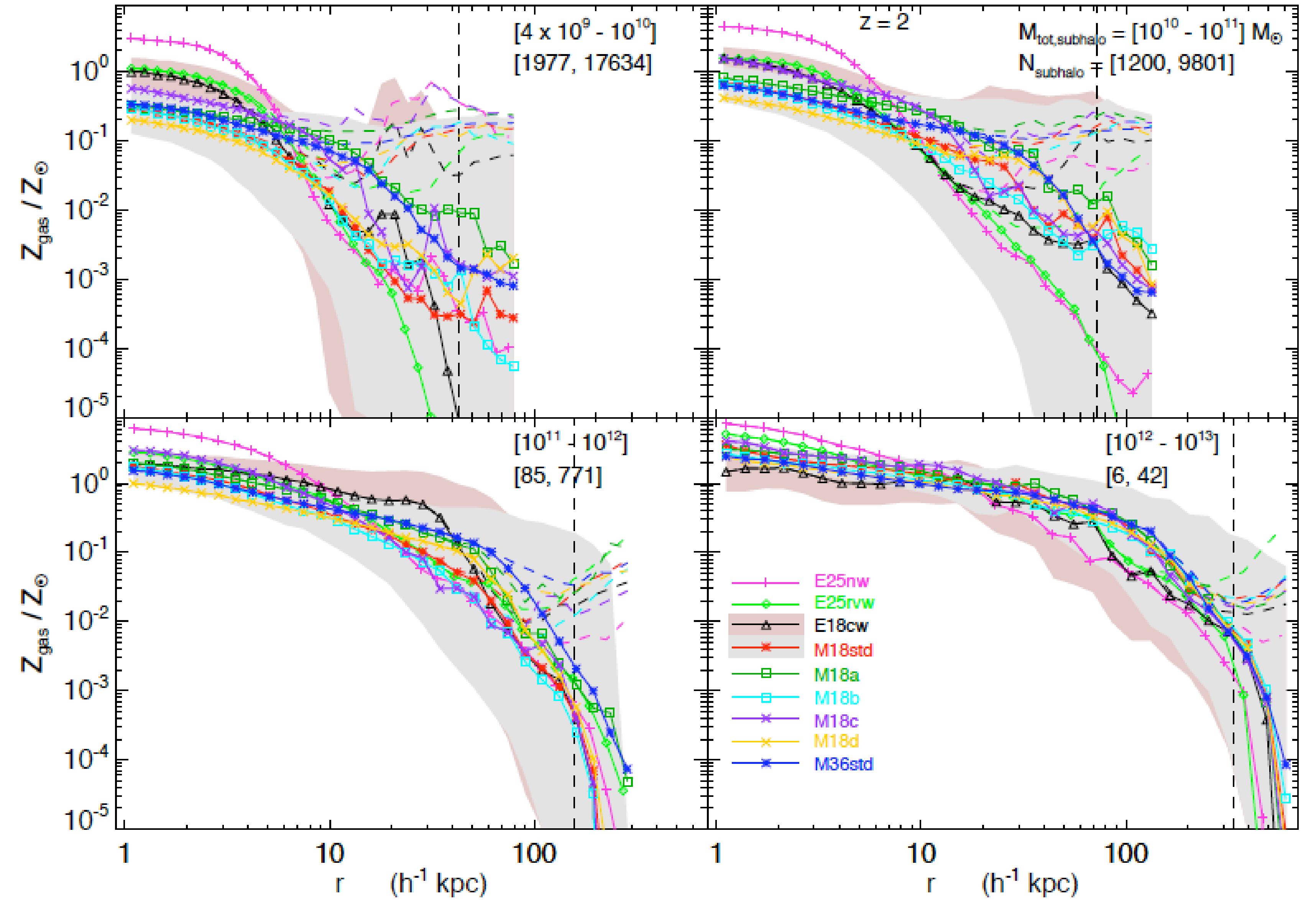


Gas Temperature radial profile at z=2



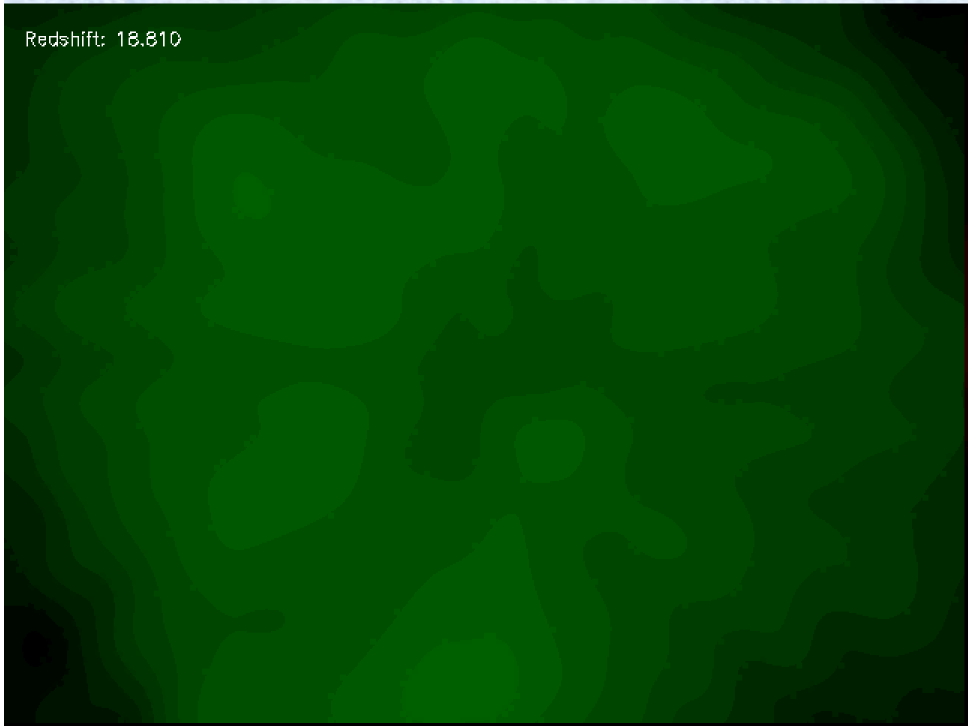
Muppi model produces colder galaxy central regions than effective model.

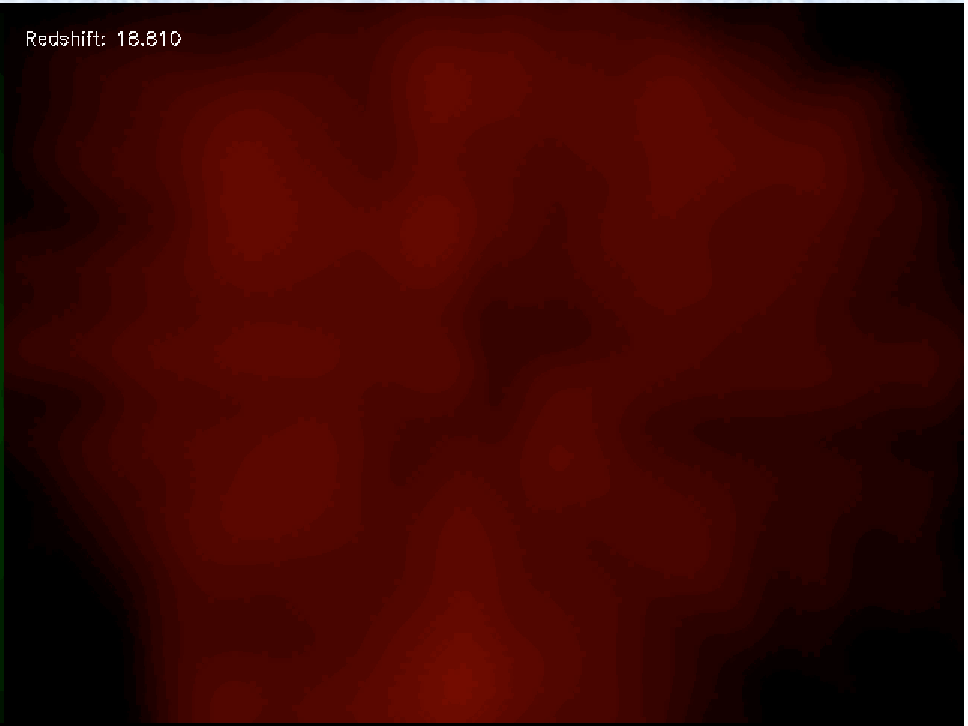
Gas Total Metallicity radial profile at z=2



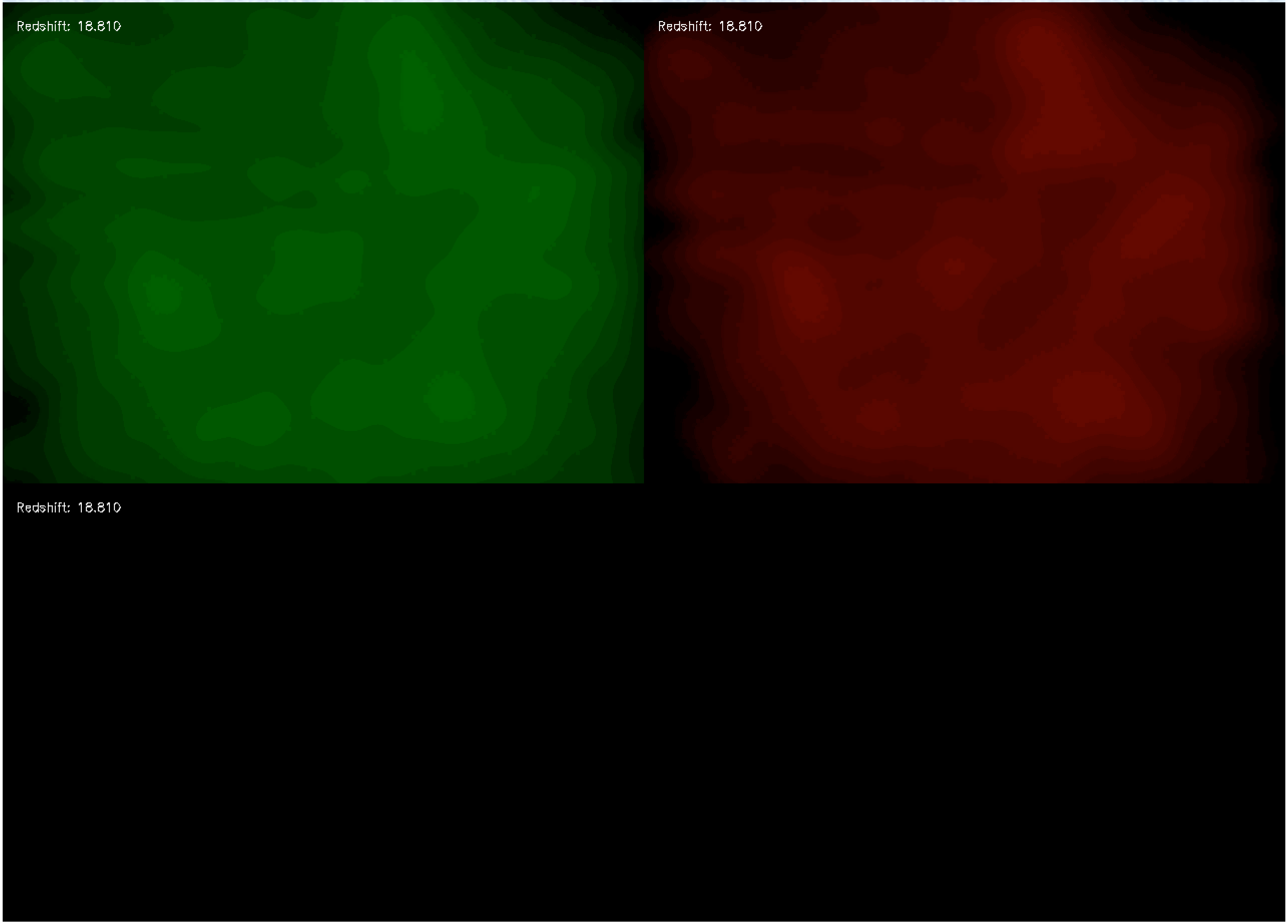
Muppi model produces flatter metallicity gradients than effective model.

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.



Summary

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

SNe kinetic feedback:

- 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