Cosmological Hydrodynamical Simulations of Large Scale Structures

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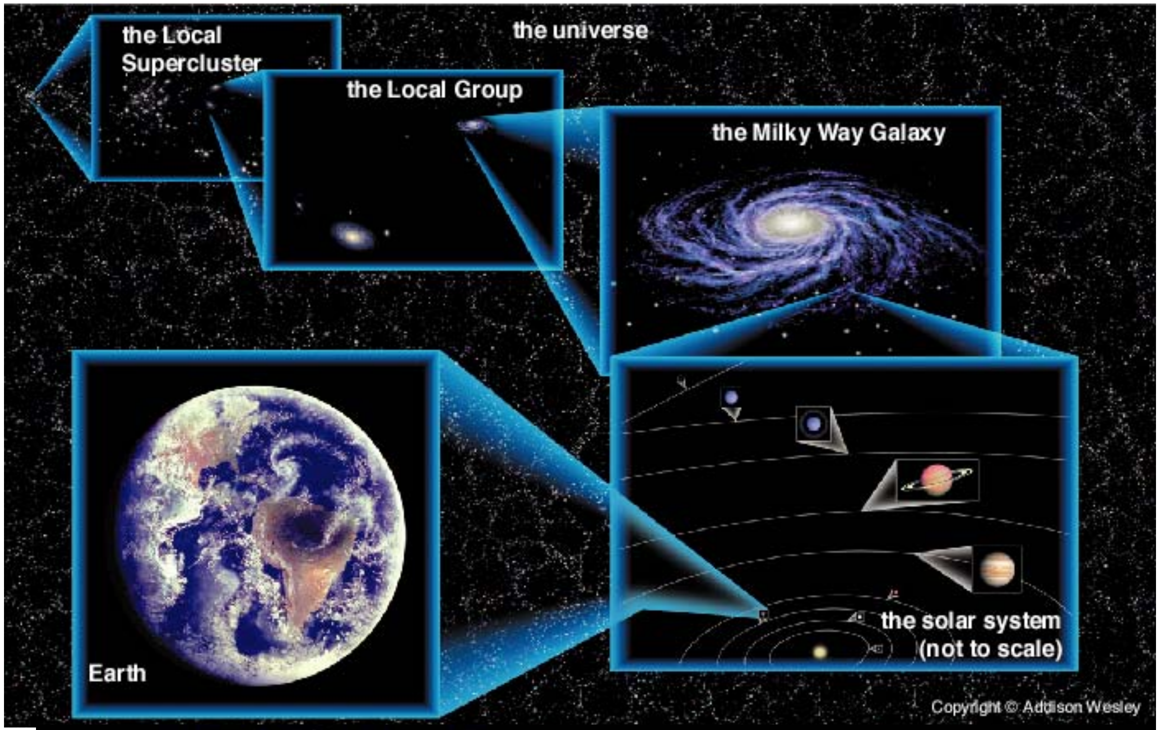
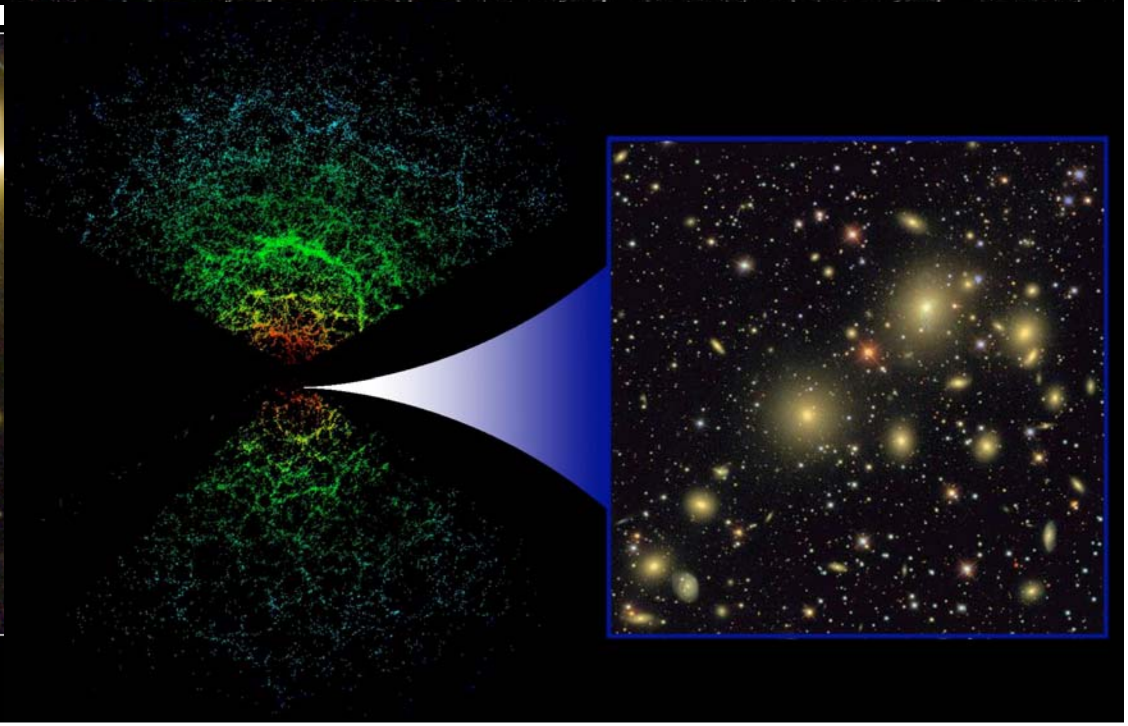
Outline

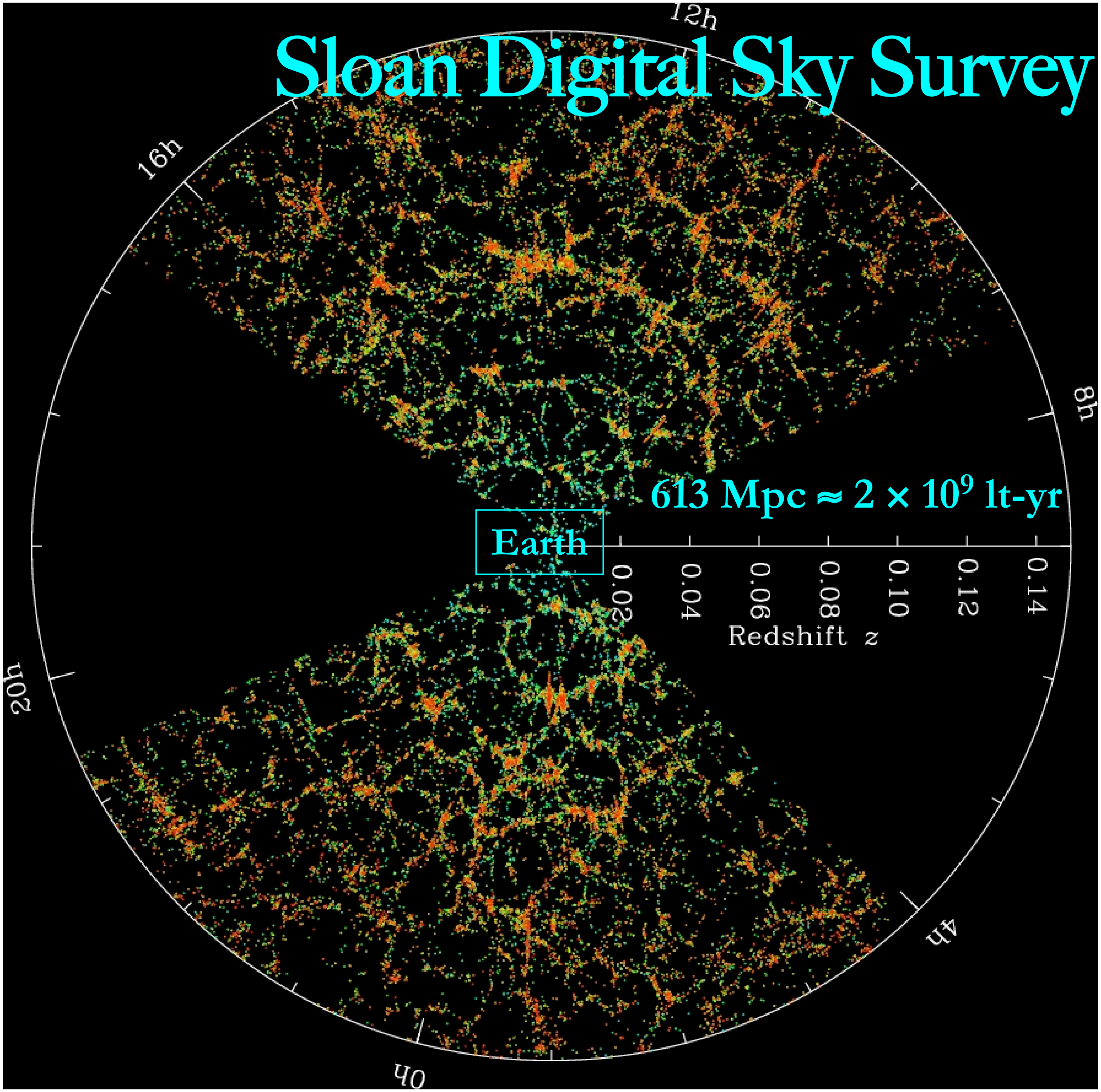
- Introduction to cosmology
  - Galaxies & large-scale structures
  - Observations
  - Modeling in hydrodynamical simulations
- My research : Galactic wind feedback
  - Methodology : Subgrid physics in GADGET code
  - Simulations
  - Preliminary Results
    - Impact of winds on galaxy and IGM properties
- Conclusions

From Earth to LSS





Sloan Digital Sky Survey



- Credit:
  M. Blanton & SDSS team

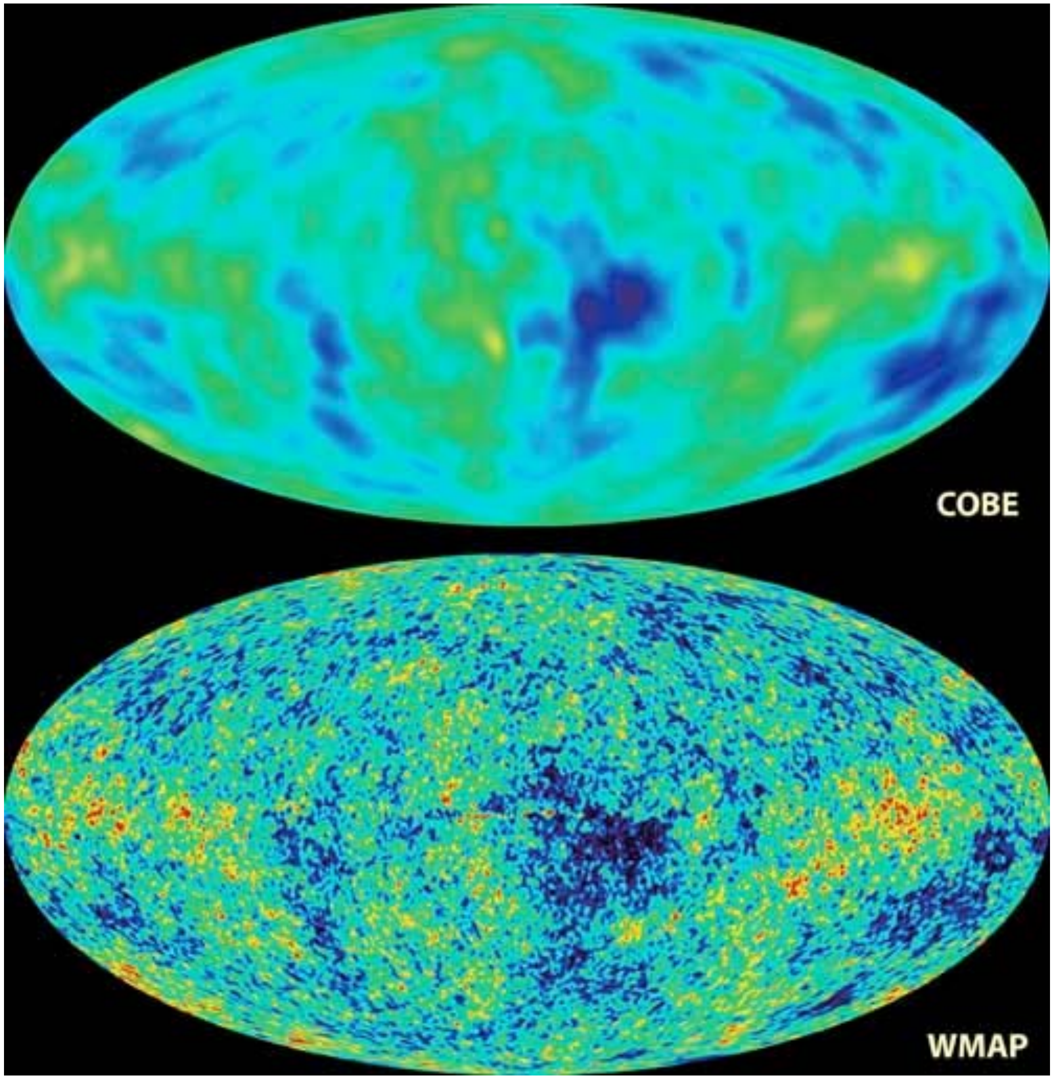
- 1 pc (parsec)
  = 3.26 light-years
  = 3.09 x 10^{18} cm

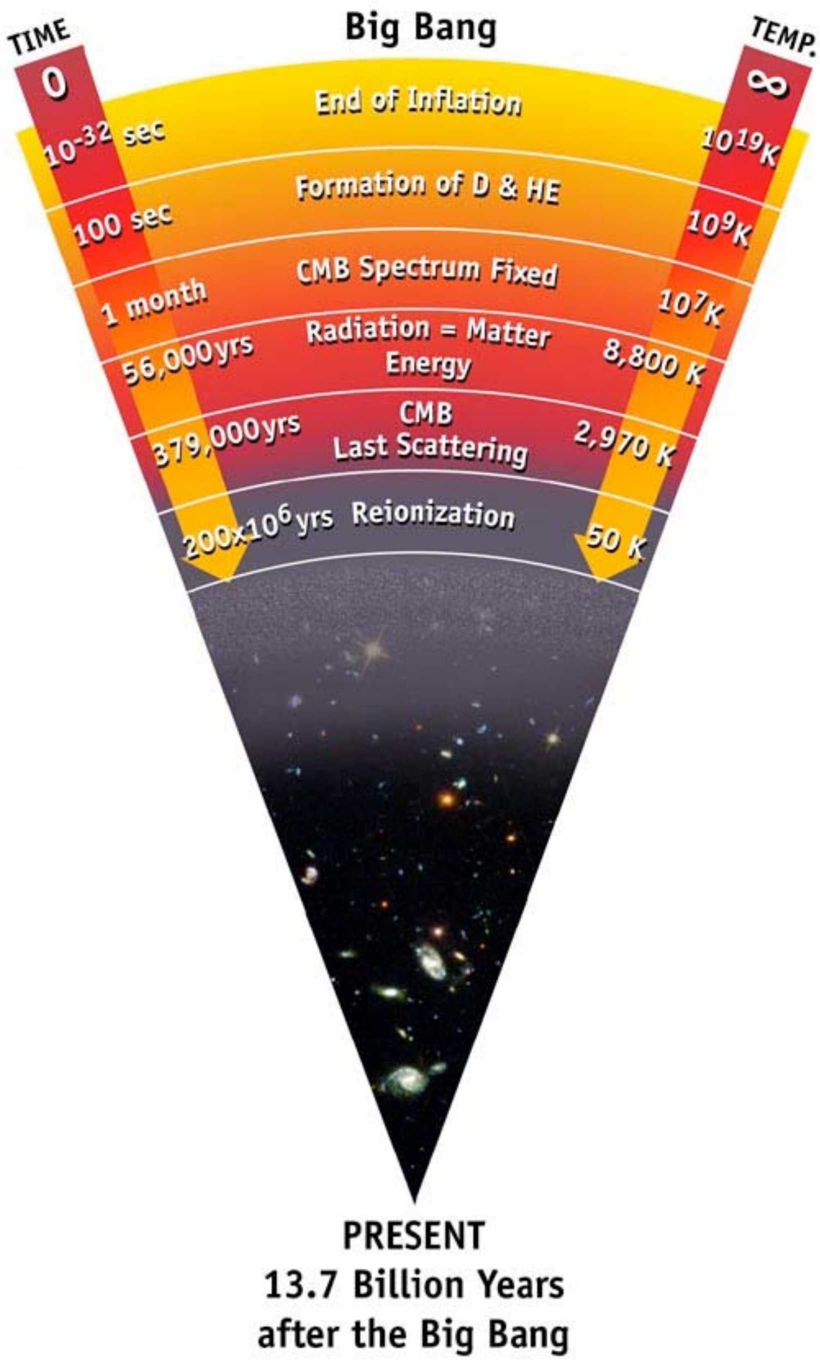
Current Cosmological Scenario

- Cosmological principle
  - Homogeneous and isotropic on large scales (> 50 - 100 Mpc)
  - Laws of science are universal
- Structure formation in small scales (< 50 -100 Mpc) by gravitational self organization
- Our observable Universe
  - Started from a very dense, hot initial state (Big Bang)
  - Had an early period of Inflation
  - Cold dark matter dominated
  - Having accelerated expansion now due to dark energy
- Such a model has been conclusively verified by observations (CMBR, Supernovae, Galaxy clusters, Gravitational lensing)
  $\Rightarrow$ the era of **Precision Cosmology**

Cosmic Microwave Background Radiation (CMBR)

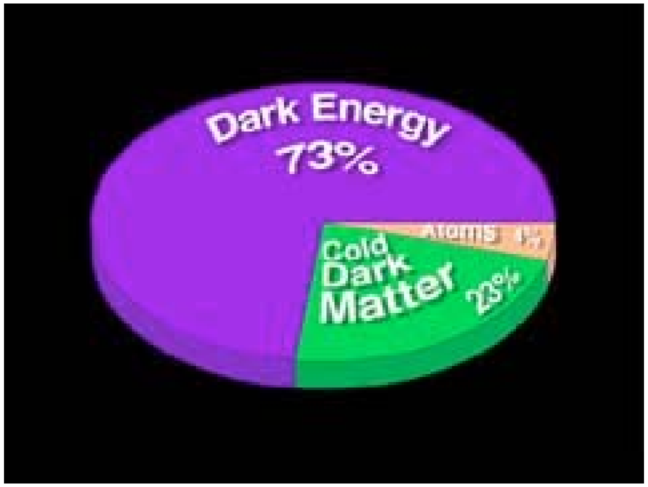
- Penzias & Wilson 1965
- Uniform faint background of microwaves throughout space
- Radiation left over from early hot epoch
  - 380,000 years after the Big Bang
- Blackbody: 2.725 °K
- Anisotropies (10^{-5} - 10^{-4}) in the CMBR give us the nature of initial density fluctuations





- Age of our Universe, from the Big Bang ≈13.7 Gyrs
- $t_{decoupling} \approx 379$ kyr
- $t_{reionization} \approx 180$ Myr
- $H_0 = 70.4$ km/s/Mpc

Cosmological Mass-Energy Budget



ΛCDM model $\Rightarrow$

dark energy + cold dark matter, Flat

- Density parameter
  $\Omega_{TOT} = \rho / \rho_C = 1$

Critical density for flat universe:

$$\rho_C = \frac{3H_0^2}{8\pi G}$$

- $\Omega_\Lambda = 0.732 \pm 0.018$
- $\Omega_M = 0.268 \pm 0.018 = \rho_M / \rho_C$
- $\Omega_{Baryon} = 0.0441$
  - n_b (baryon density) = 2×10^{-7} cm^{-3}

Hubble Expansion

- Galaxies moving away from us, further galaxies move away faster

→ The Universe (space itself) is expanding

- Hubble's Law
  - *H(t)* = Hubble parameter
  - *a(t)* = Normalized scale factor

$$\vec{v} = H(t)\,\vec{r}$$

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

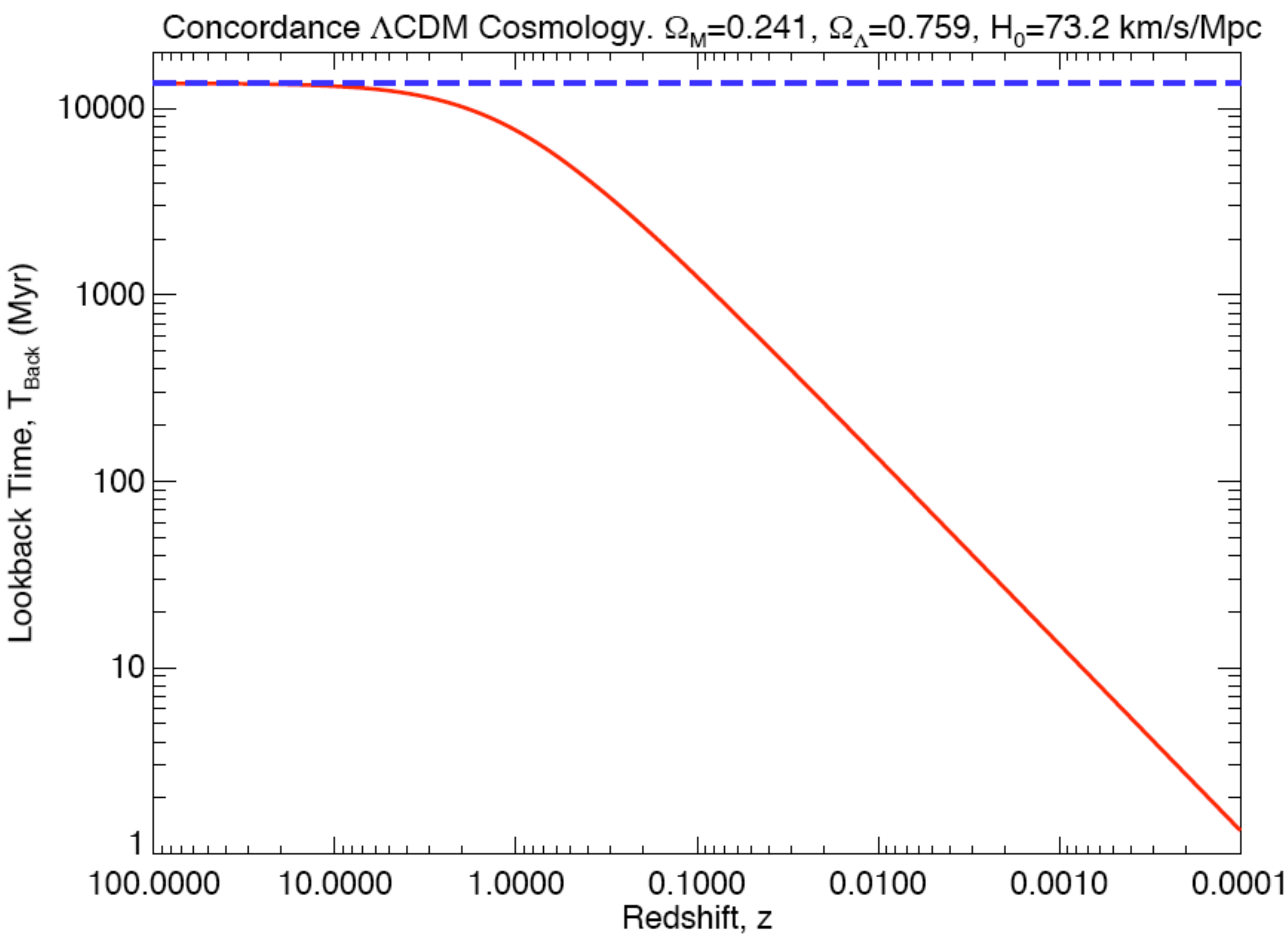
- This recession affects the light emitted by the distant galaxies, stretching the wavelengths of emitted photons

Cosmological Redshift

- Stretching of light waves traveling through space
- Caused by expansion of the Universe

$$z = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}$$

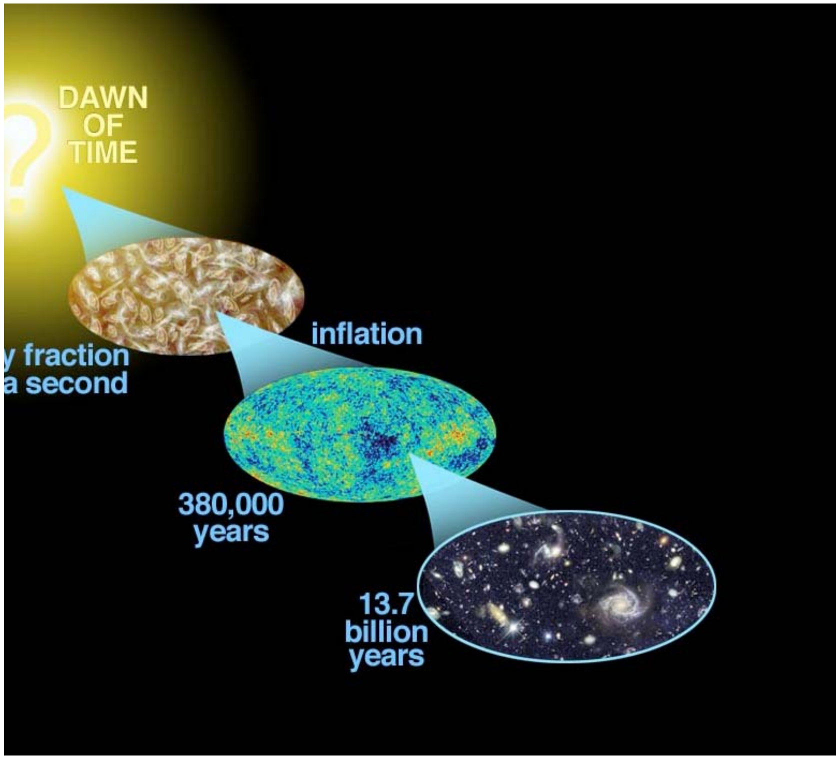
$$1 + z = \frac{1}{a(t)}$$



Galaxy Formation Modeling

Cosmological Hydrodynamic Simulations

What is done? How?



Large Scale Structure Formation

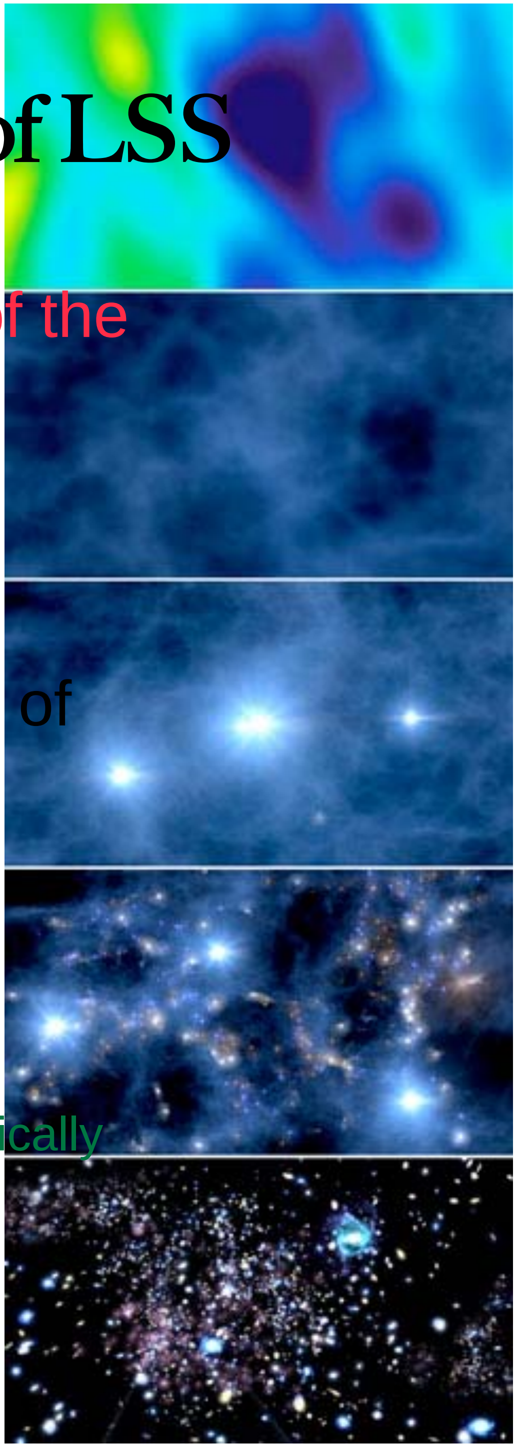
- Quantum fluctuations shortly after the Big Bang ⇒ Primordial density perturbations

- 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

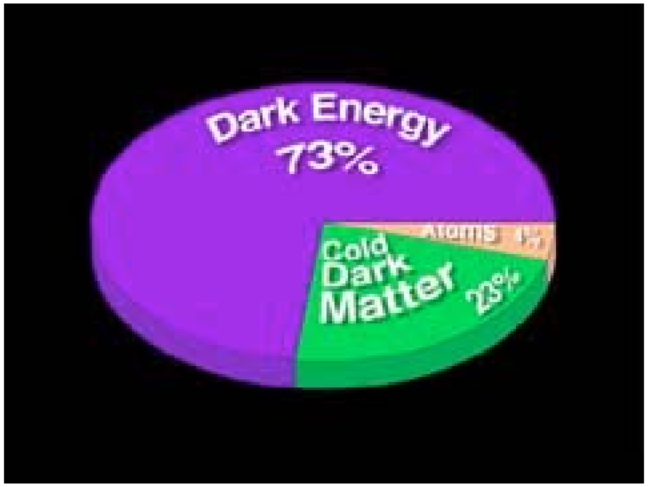


- Computational box ⇔ representative volume of the Universe
- Resolution elements (particles or grid) in box ⇔ matter

- 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

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

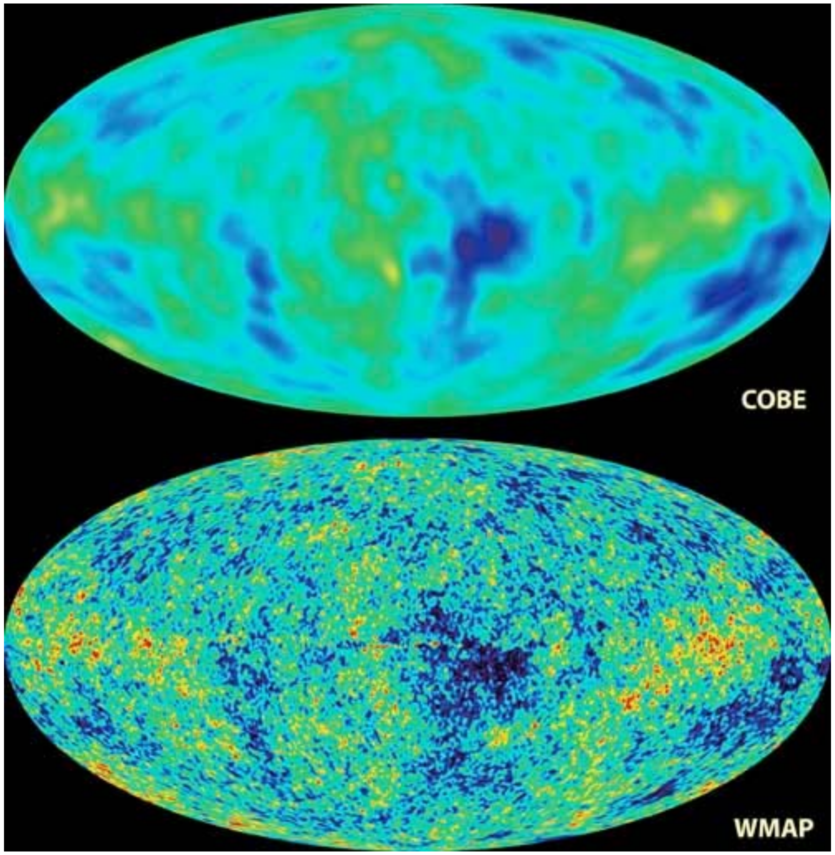


Initial Condition

- 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

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

$$\delta \equiv \frac{\rho}{\overline{\rho}} - 1$$

- Inflation ⇒ near homogeneous initial particle distribution
  - Small perturbations

- Linear regime
  - Λ dominated
  - EdS/Matter dominated

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

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

- 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

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

- Numerically integrate dynamical equations in Comoving Coordinates

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

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

Volume Expansion

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

$$L_{box}(z)_{before} = \frac{L_{box}(z=0)_{now}}{1+z}$$

- The expansion is taken out from computations, s.t. the box appears static

- Use coordinate system that expands (or co-moves) with the Universe

- Comoving Coordinate, *x(t)*
  - Distance between 2 points measured now, at z = 0

$$x(t) = \frac{r(t)}{a(t)} \qquad r = \int_{t_{emit}}^{t_{now}} \frac{c\,dt'}{a(t')}$$

  - *r(t)* = Proper Distance

N-body (Collision-less)

- Dark matter + Baryons
- Gravitational interactions only
  - No thermal velocities, no other interactions
- Equations of particle motion

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

- Poisson's equation $\nabla^2\Phi = 4\pi G\rho$
- Non-relativistic velocities $\Rightarrow$ 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

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

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

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

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

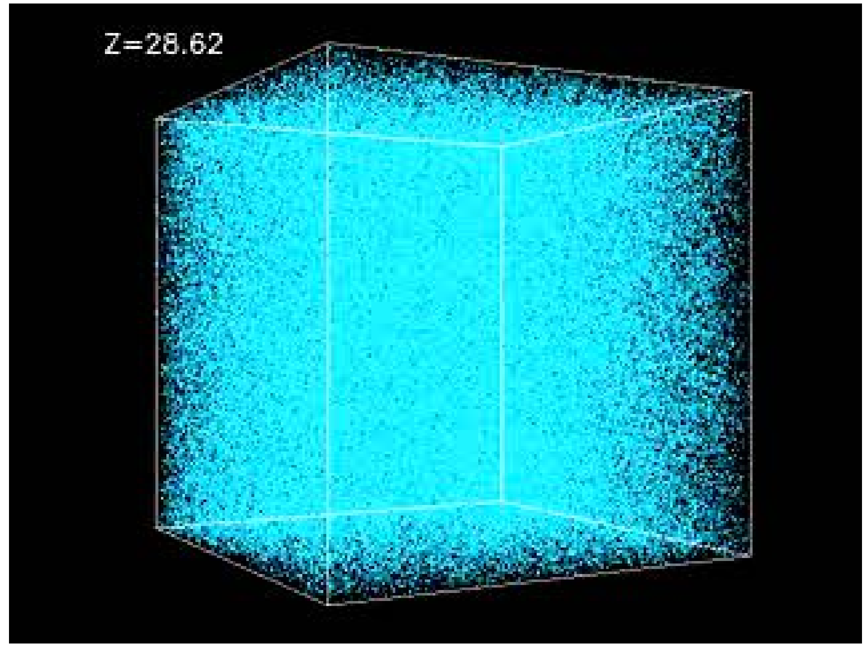
Successful Results

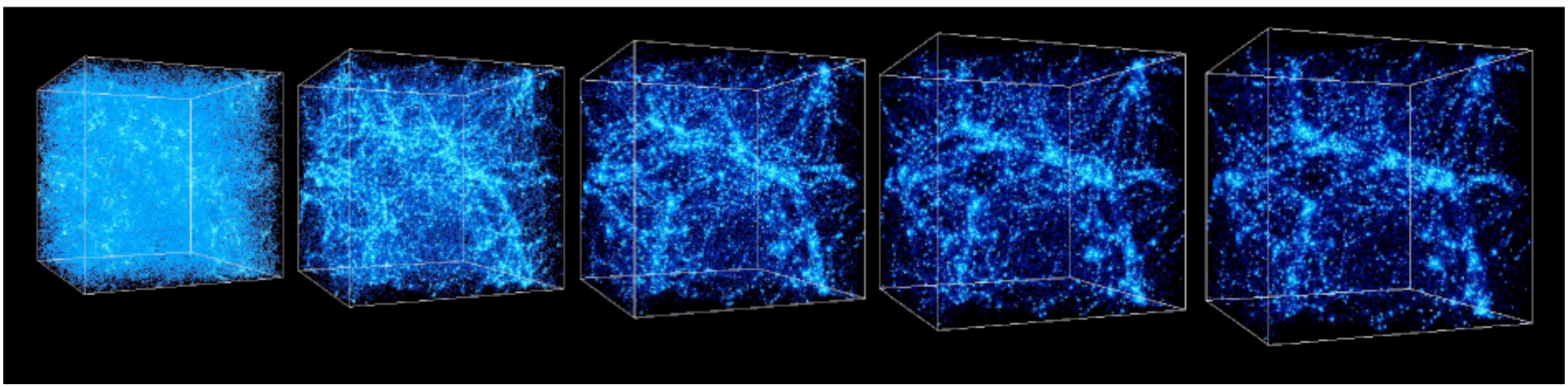
- Hierarchical Structure Formation
  – Can reproduce the distribution and structure of galaxies in very large scales as seen in observations
- Distribution of matter in the Universe
  – Collapse via gravitational forces into filaments. Galaxies form in these filaments
- Clustering of galaxies at all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

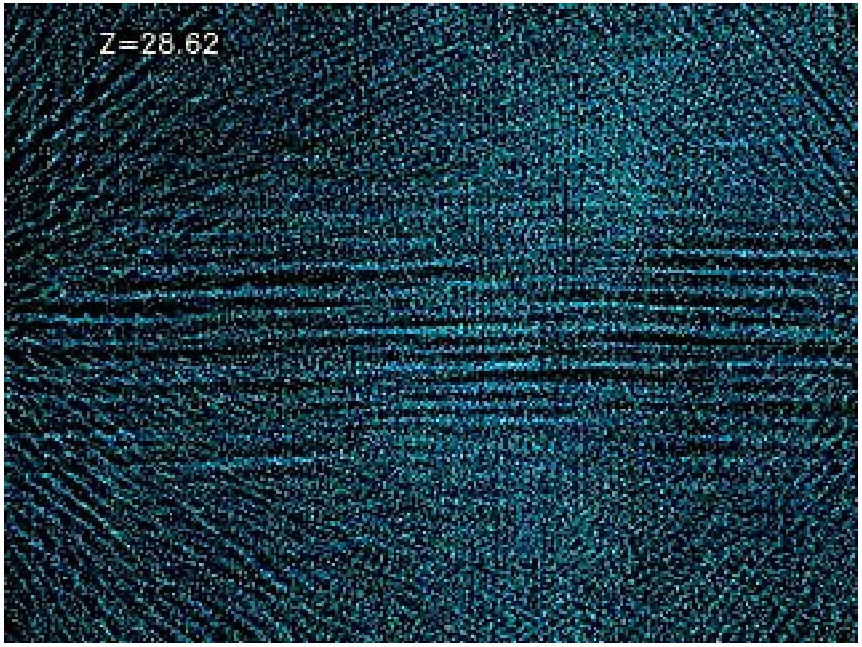
- A (43 Mpc)^3 box
- From z = 30 to z = 0

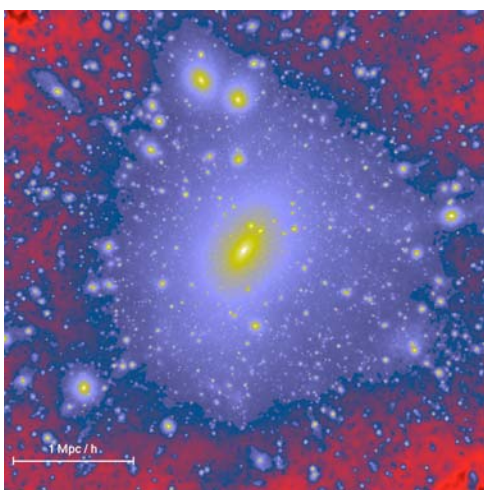
- Frames below show structure forming from z = 10 to the present





Formation of a Galaxy Cluster





- 4.3 Mpc region of box
- The formation of a cluster proceeds hierarchically
  - Small-mass objects form first at z > 5
  - Quickly grow in size by accretion & violently merge with each other, creating increasingly larger system
- Accretion & mergers continues up to z = 0

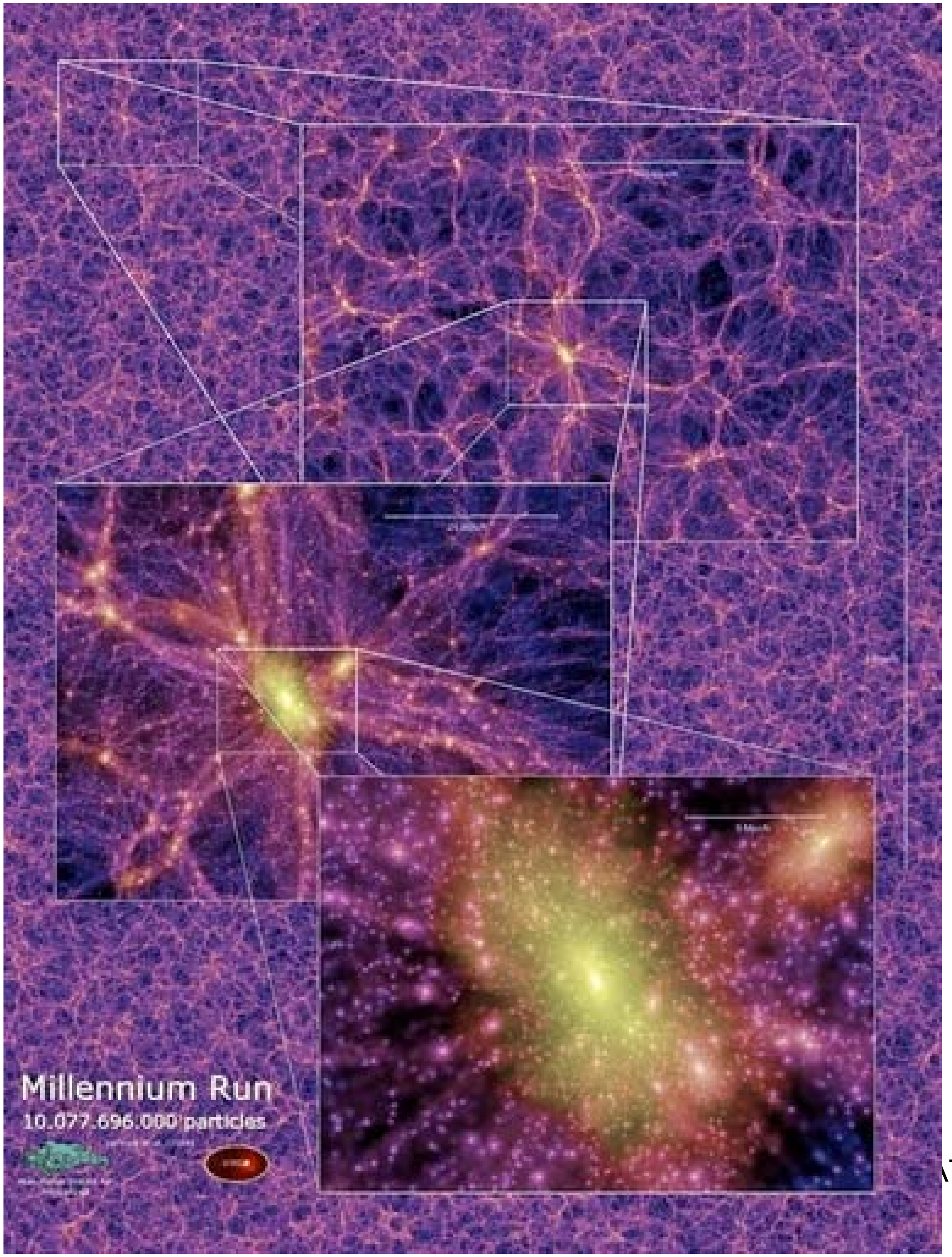
The Millennium Simulation

- One of the largest cosmological N-body sim
  - Dark matter sim
  - Gravity only, no hydrodynamics

- Done by the Virgo Consortium
  - Springel et al. 2005, Nature, 435, 629

- Box comoving side = 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

- From $z = 127$ to $z = 0$
- Took 28 days on 512 CPUs



- 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, enlarging the regions indicated by the white squares

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My research : Galactic wind feedback

- Wind observed in many galaxies
- Carry gas mass and metals out from galaxy into the IGM

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
- Energy-driven wind :

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

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

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

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

- 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

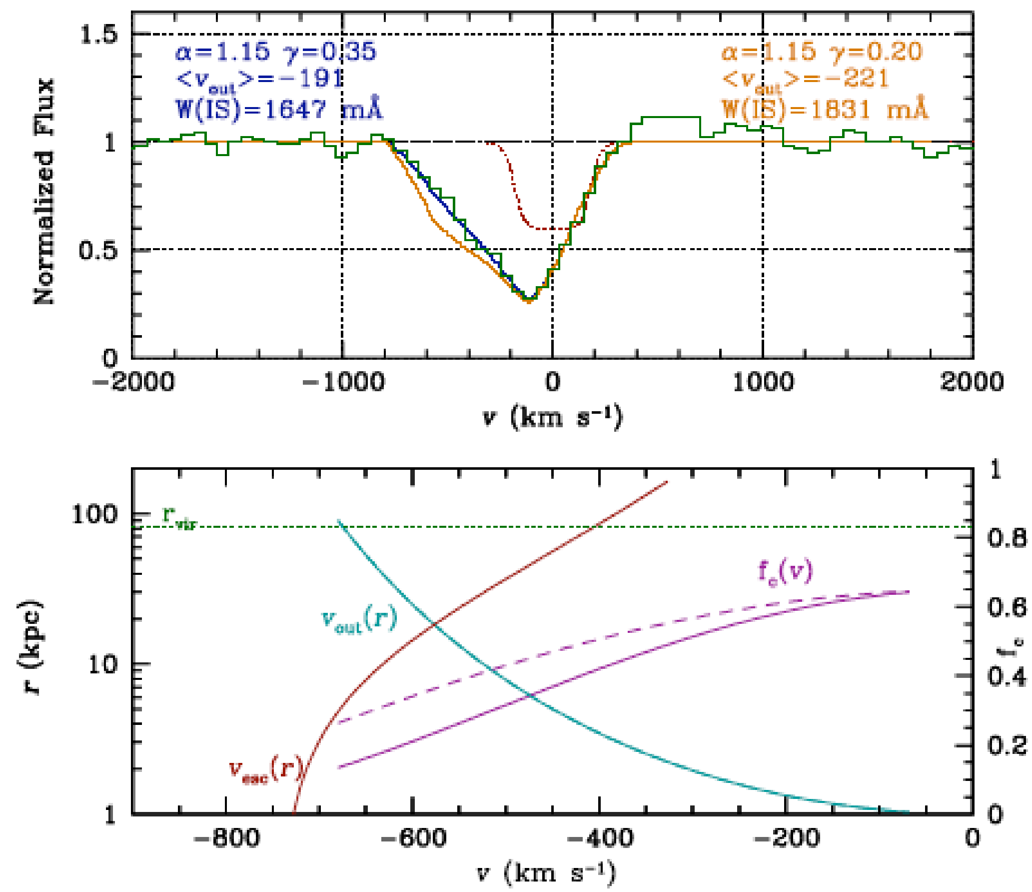
- Observations by Steidel et al. (2010, ApJ, 717, 289)
  - Spectroscopic data fitted by simple model

- Quantities are function of galactocentric distance, *r*

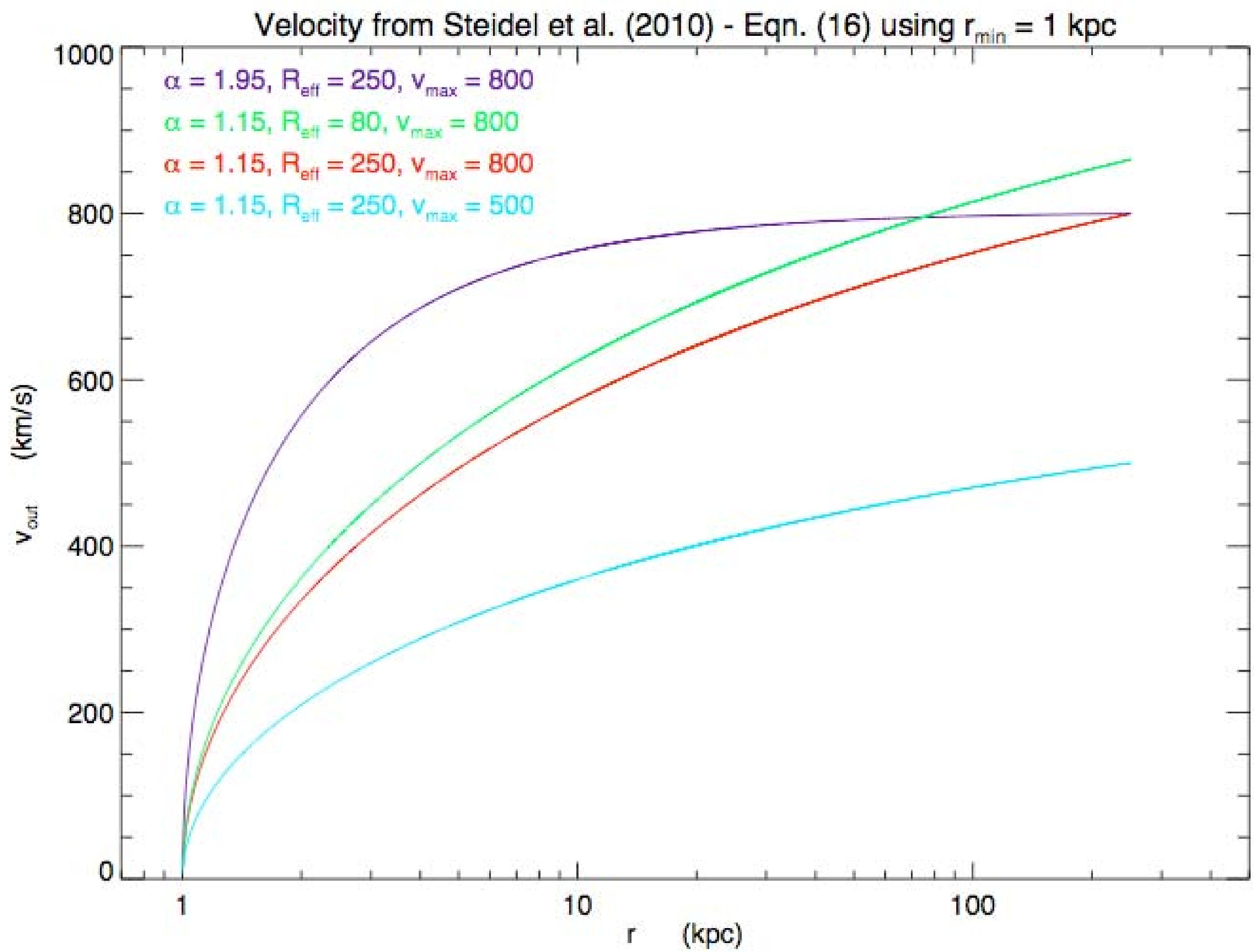
- Acceleration & Velocity :

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

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



Our Modification in GADGET3: Radial Gradient of Outflow Velocity



Simulations

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

$$5\ h^{-1}\ \mathrm{Mpc},\ N = 2\times128^3.$$
$$25\ h^{-1}\ \mathrm{Mpc},\ N = 2\times320^3.$$
$$\text{upto } z\sim 2.$$

- 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)

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.

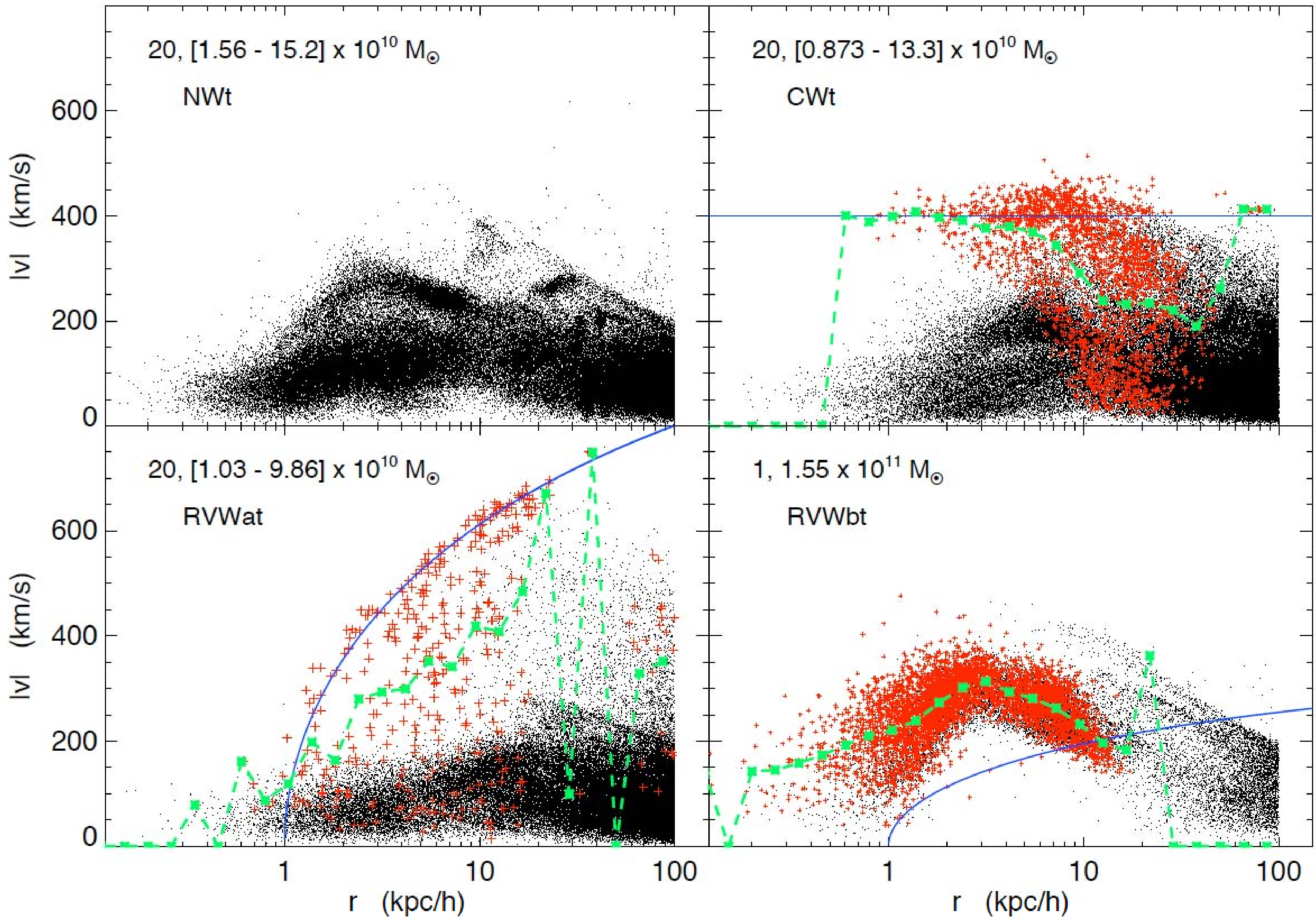
[d] $m_{\rm gas}$ = Mass of gas particle (which has not undergone any star-formation).

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

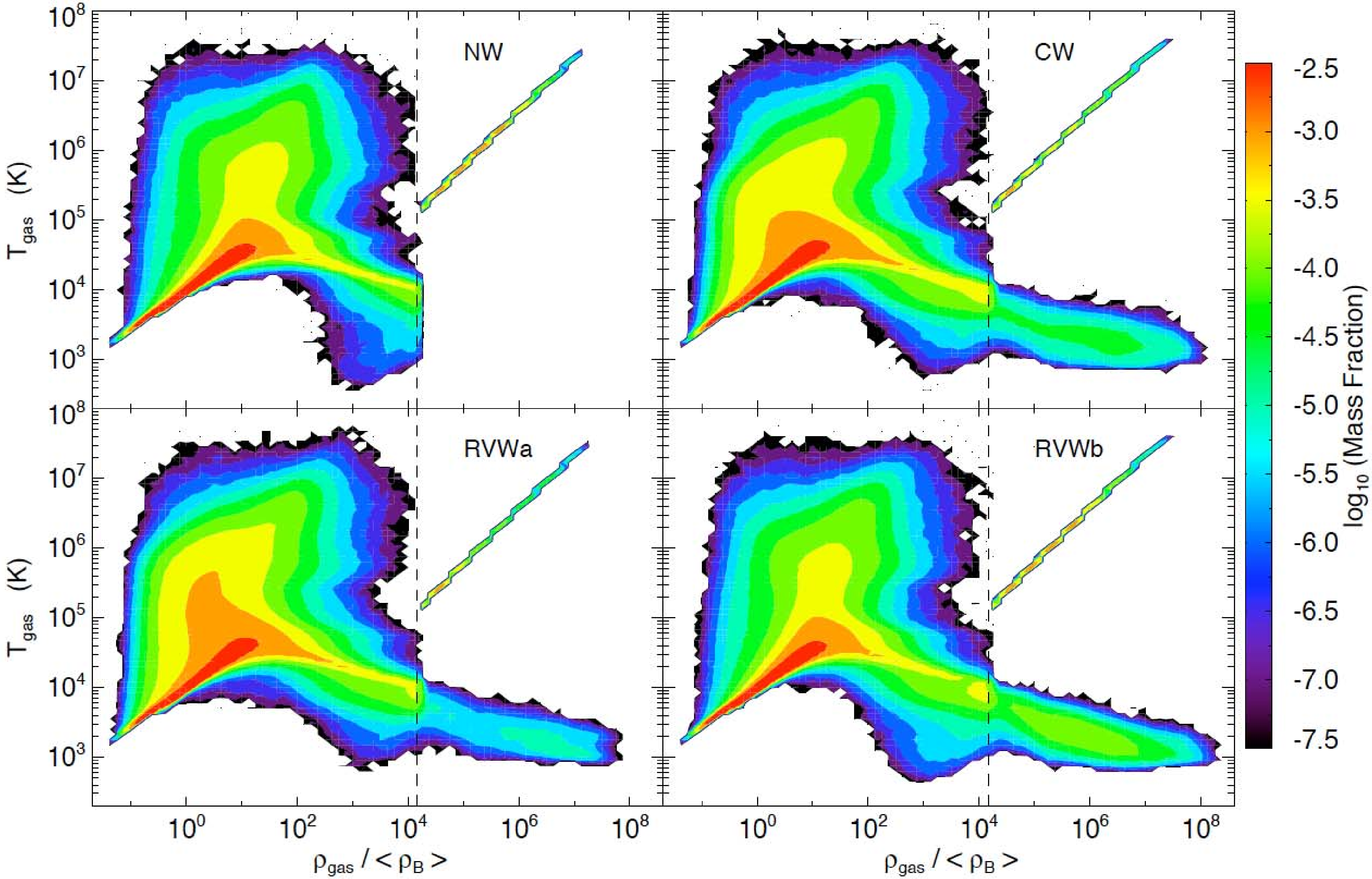
[f] Run names ending with "t" are smaller boxsize runs for test purposes, done up to $z \sim 3$.

[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, $\alpha = 1.15$.

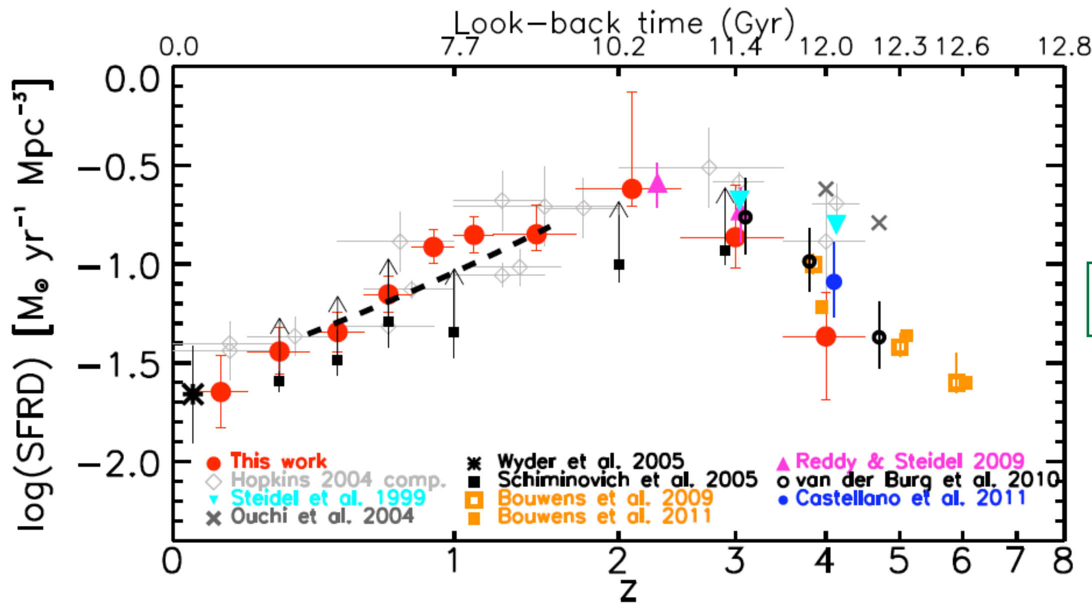
Different Wind Models



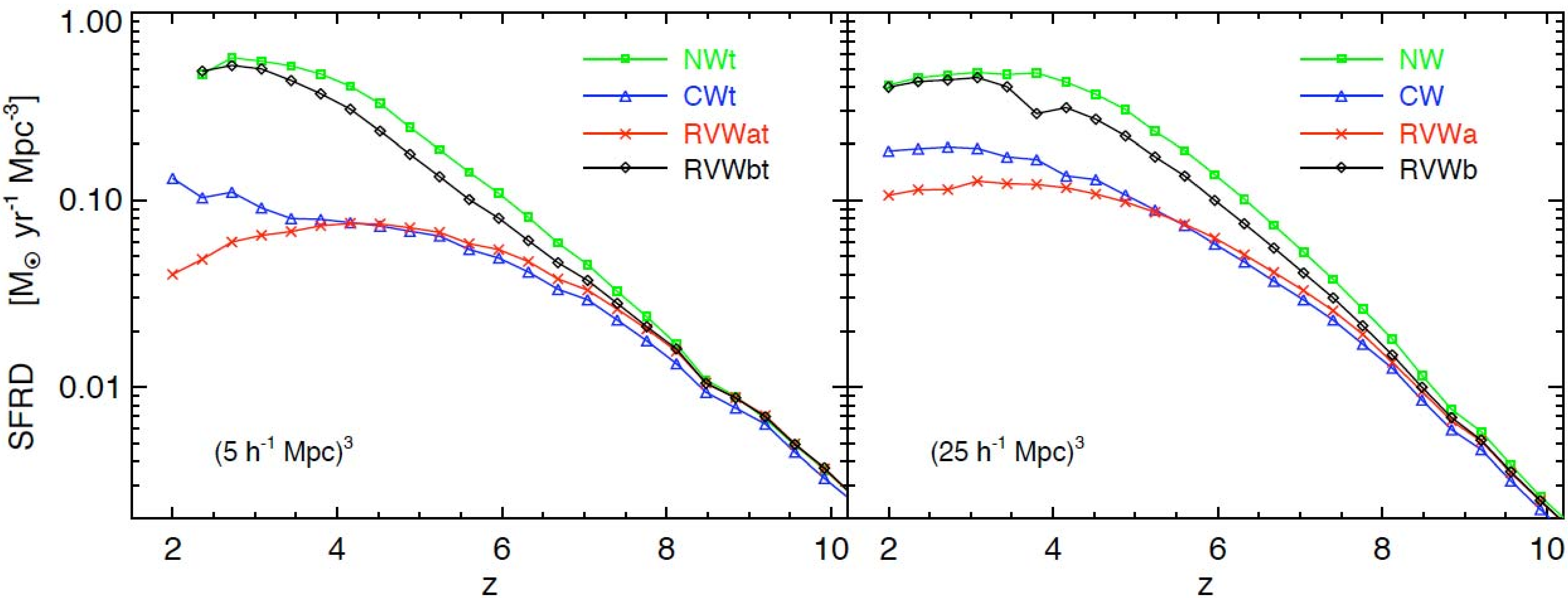
Phase Diagram at z=1.98



nsity Evolution



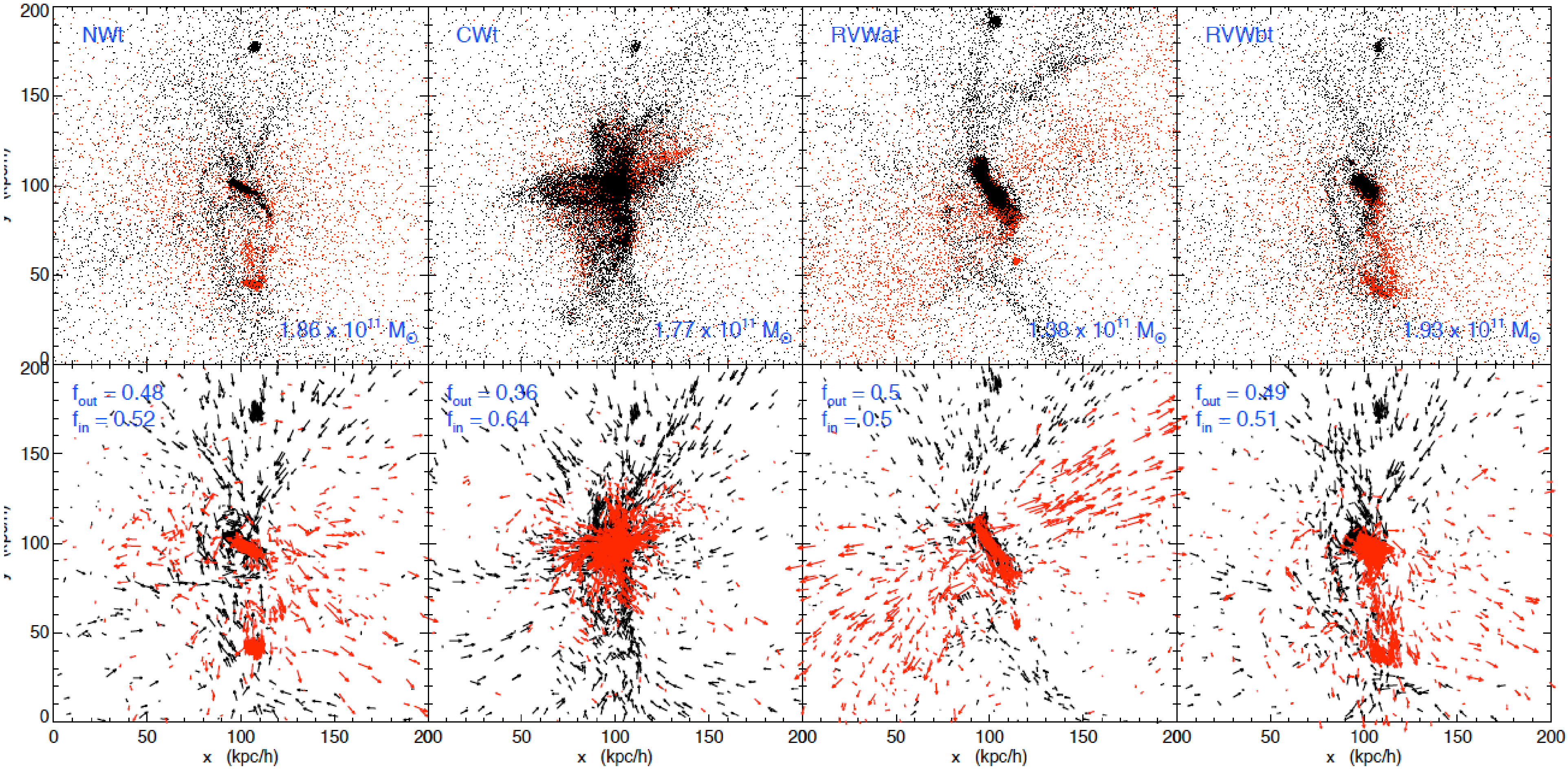
Cucciati et al. 2012, A&A, 539A, 31 (VVDS)



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

Red - Outflowing, Black - Inflowing.

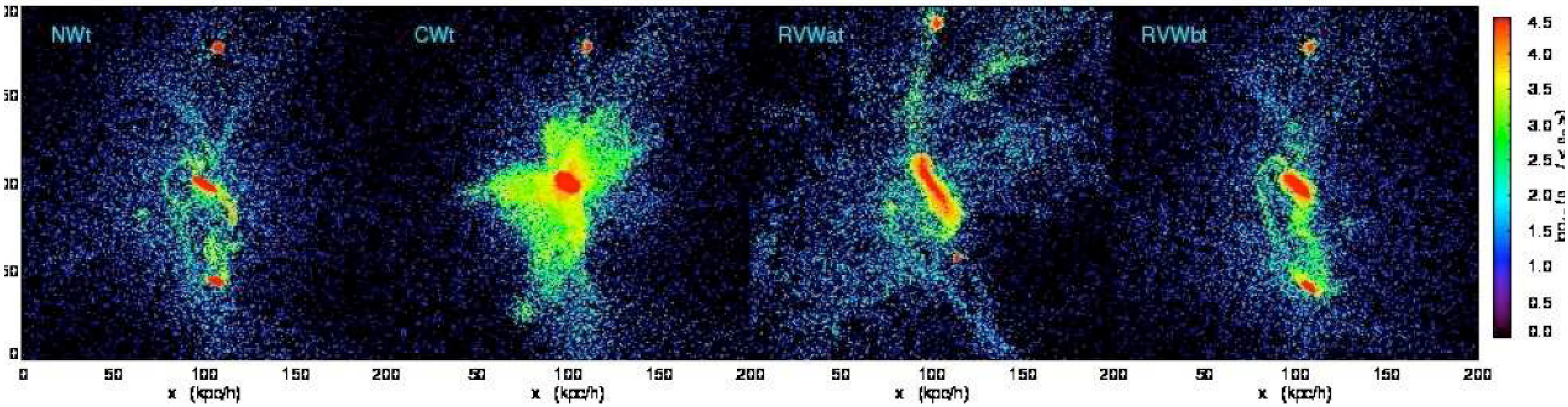
Particle positions

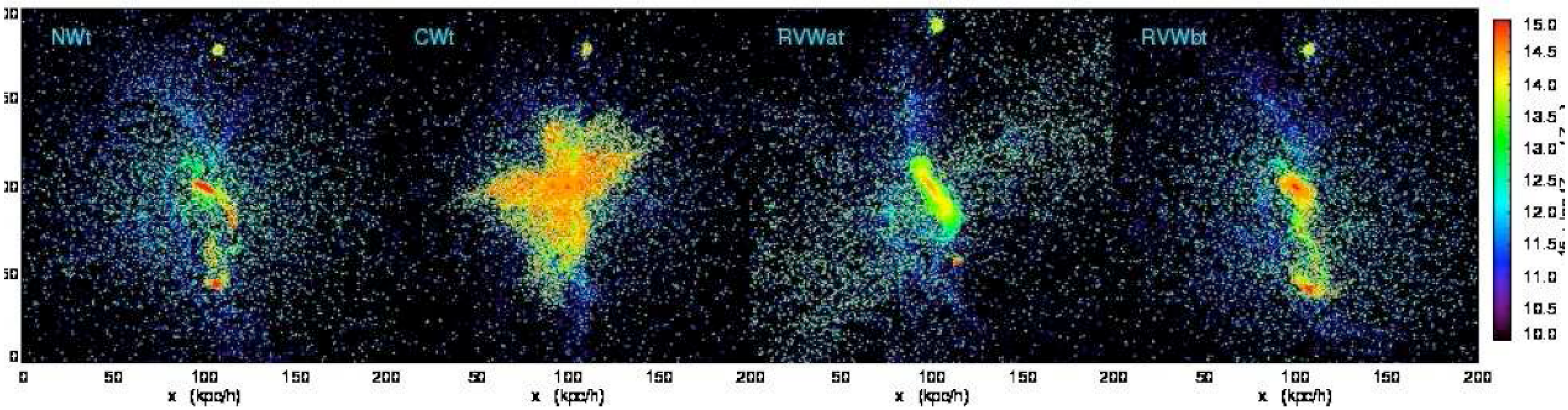


Velocity vectors

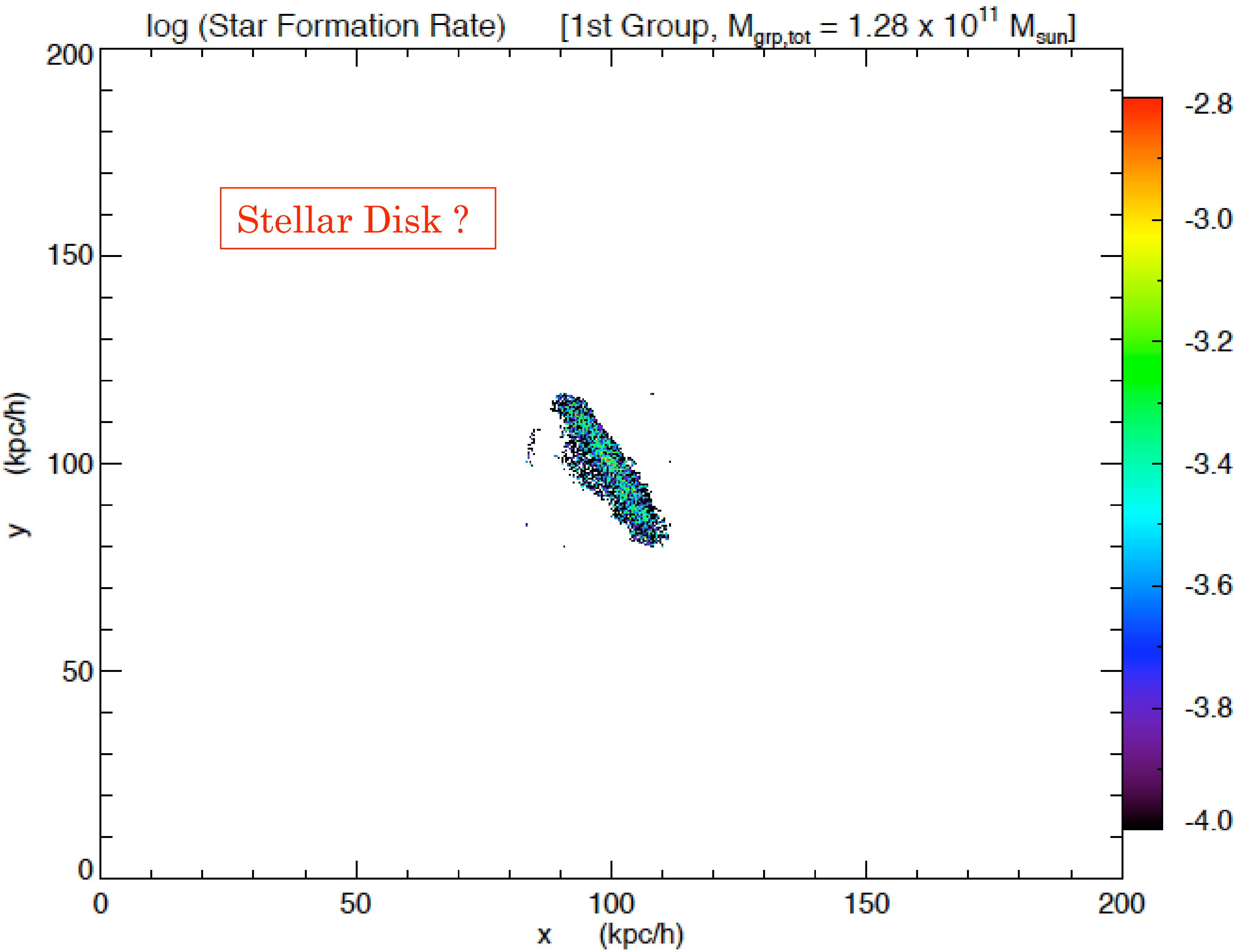
Projection of (200/h kpc)^3 volume around most-massive galaxy center at z = 2.12, showing gas properties in 4 runs.

Density

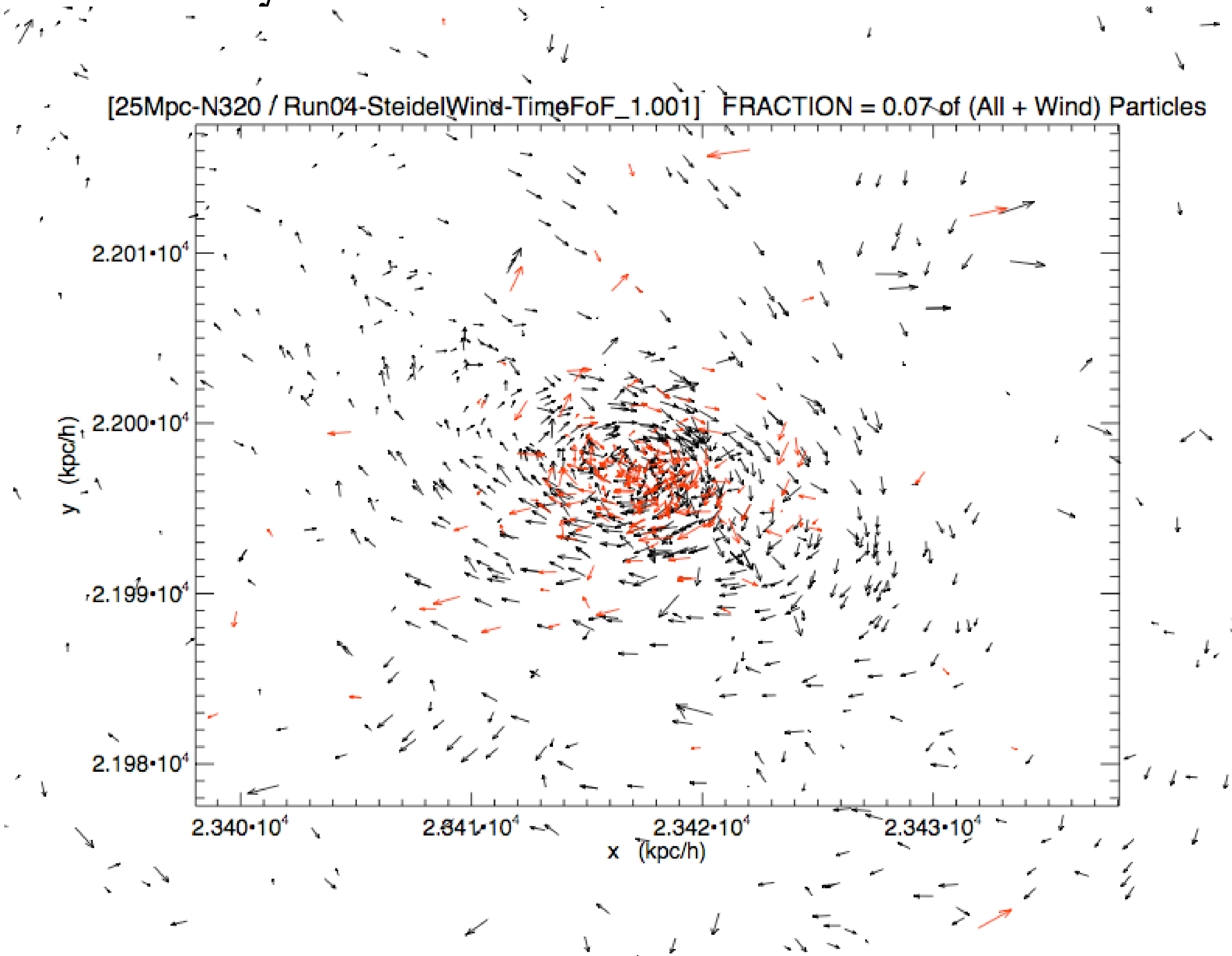




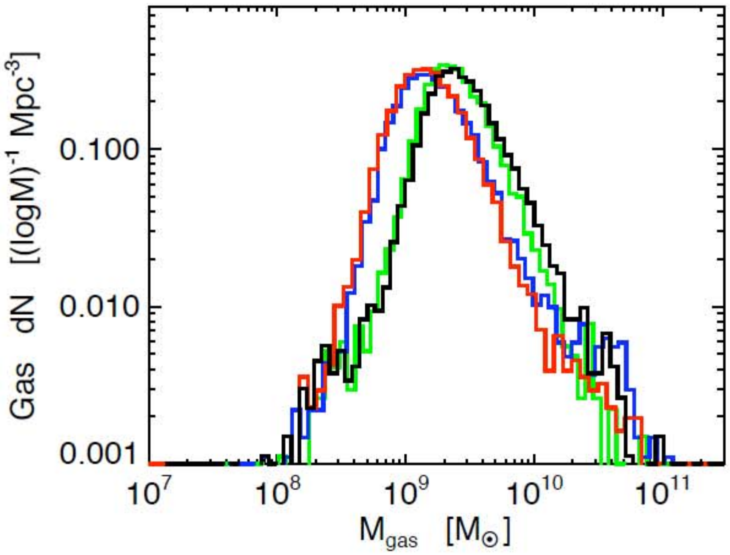
Carbon metallicity

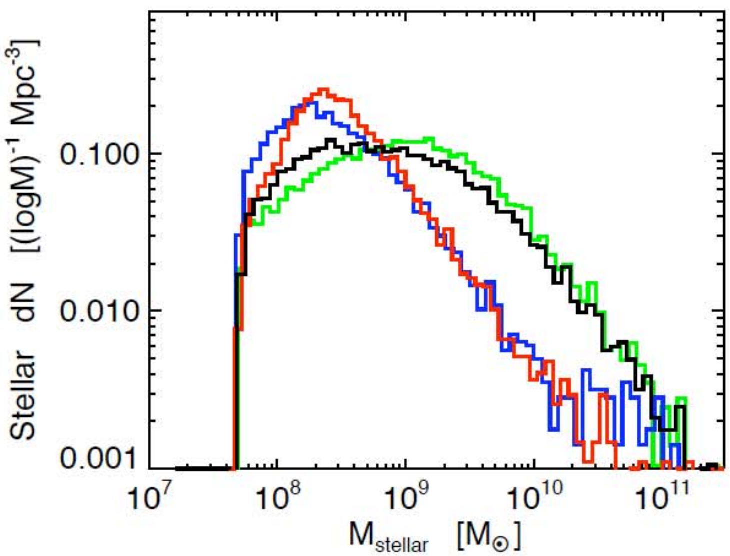

log (Star Formation Rate) [1st Group, M$_{grp,tot}$ = 1.28 x 10^{11} M$_{sun}$]
Stellar Disk ?
y (kpc/h)
x (kpc/h)
0
50
100
150
200
-2.8
-3.0
-3.2
-3.4
-3.6
-3.8
-4.0

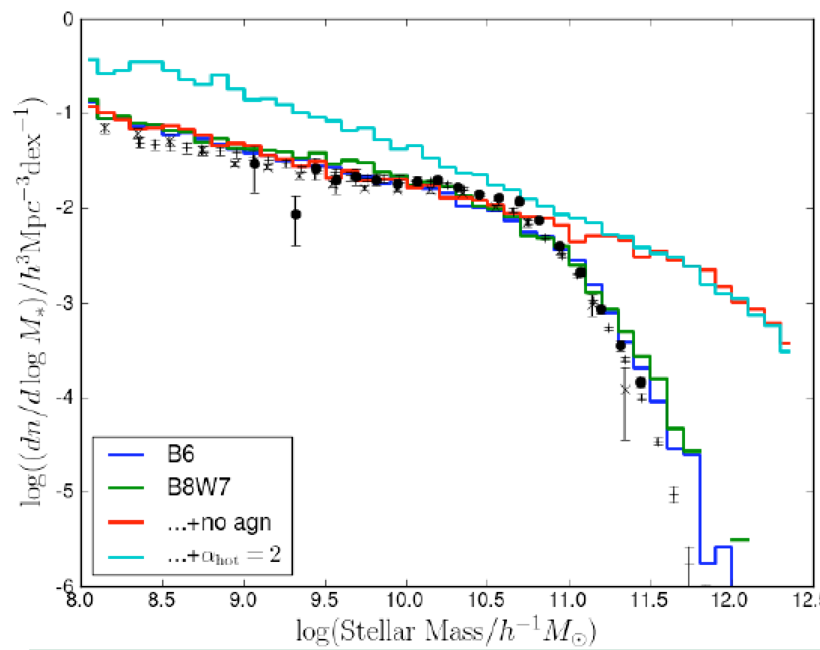
Velocity Field of Gas Particles in run RVWa



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



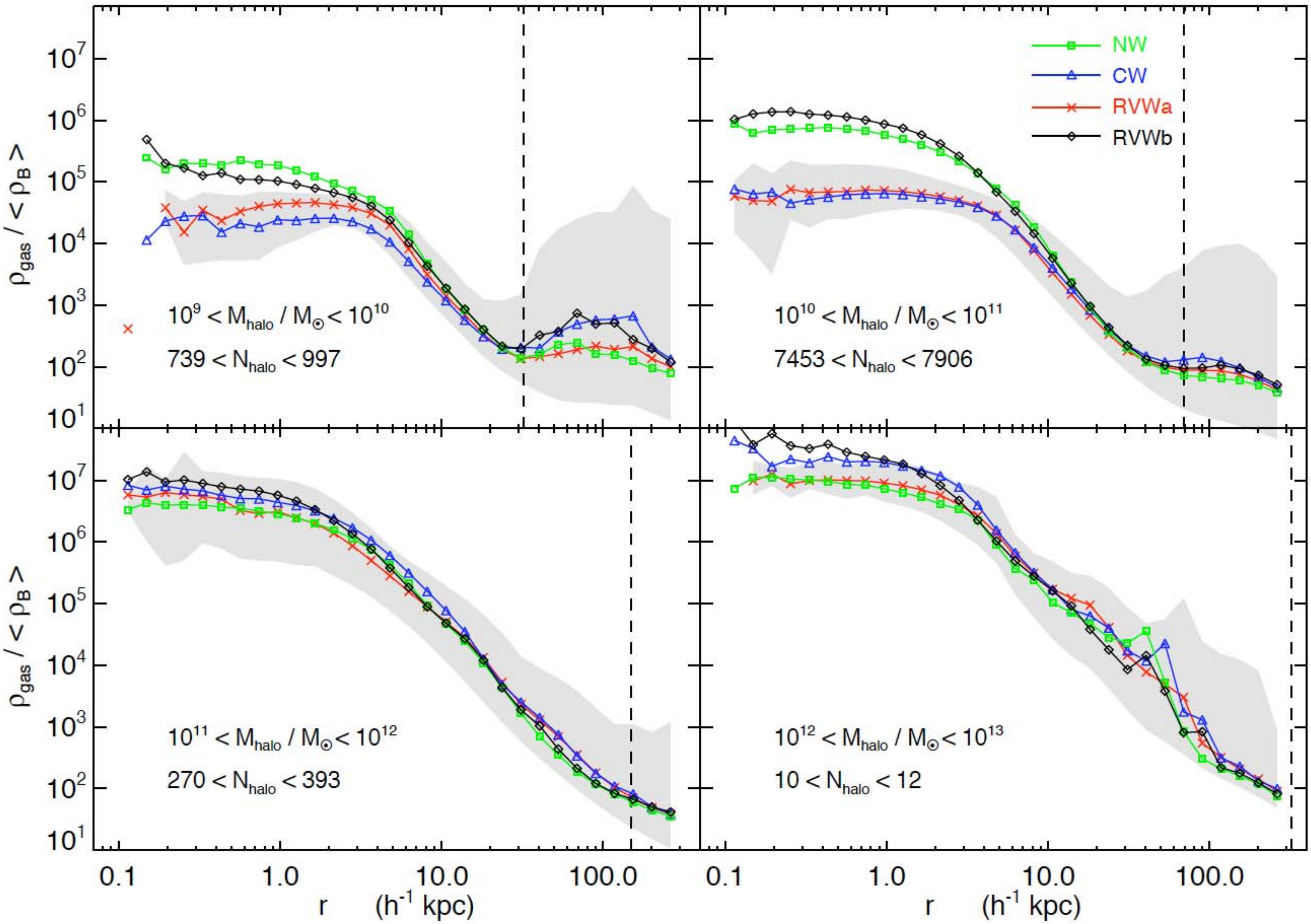




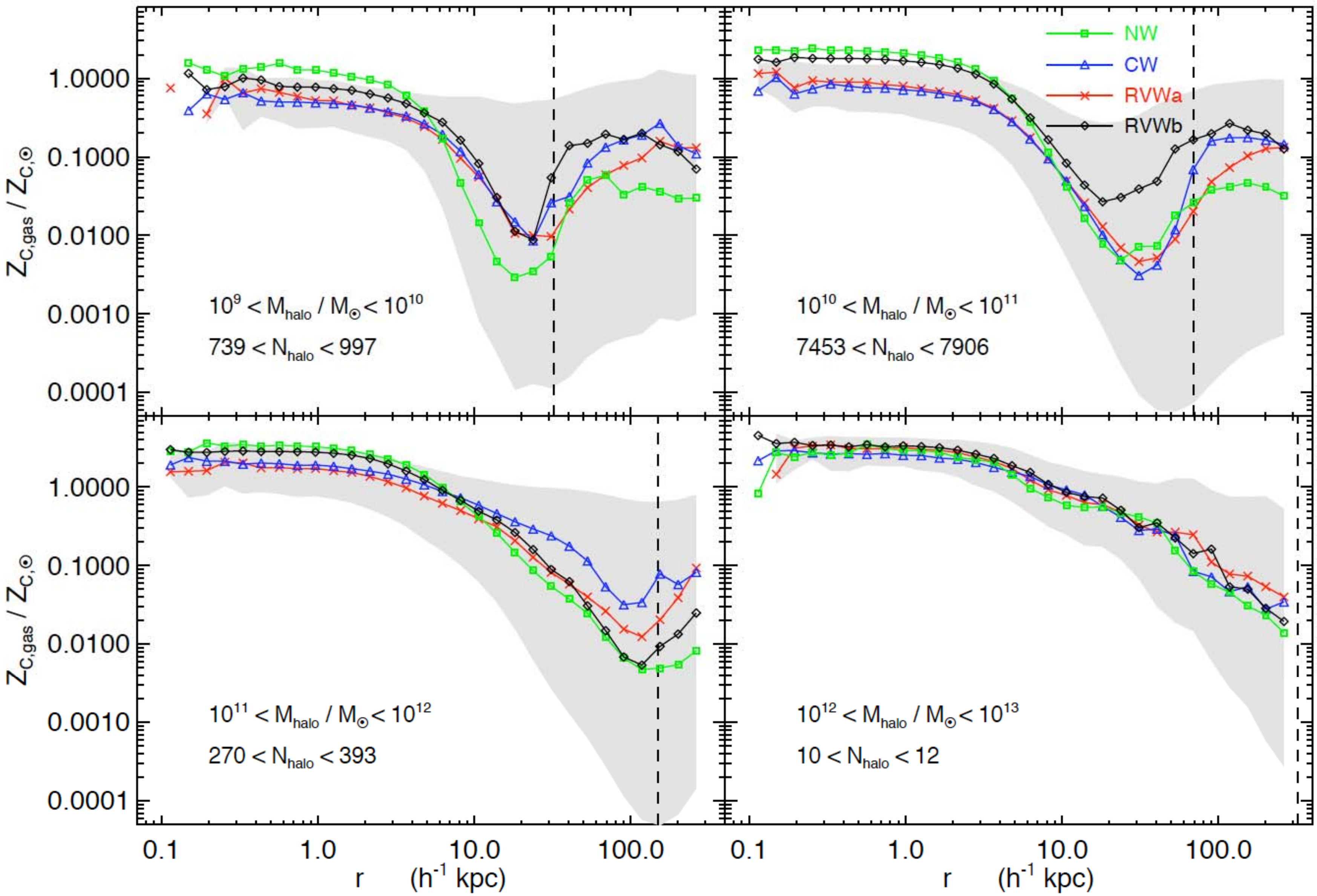
Bower, Benson & Crain 2012, MNRAS, 422, 2816

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).

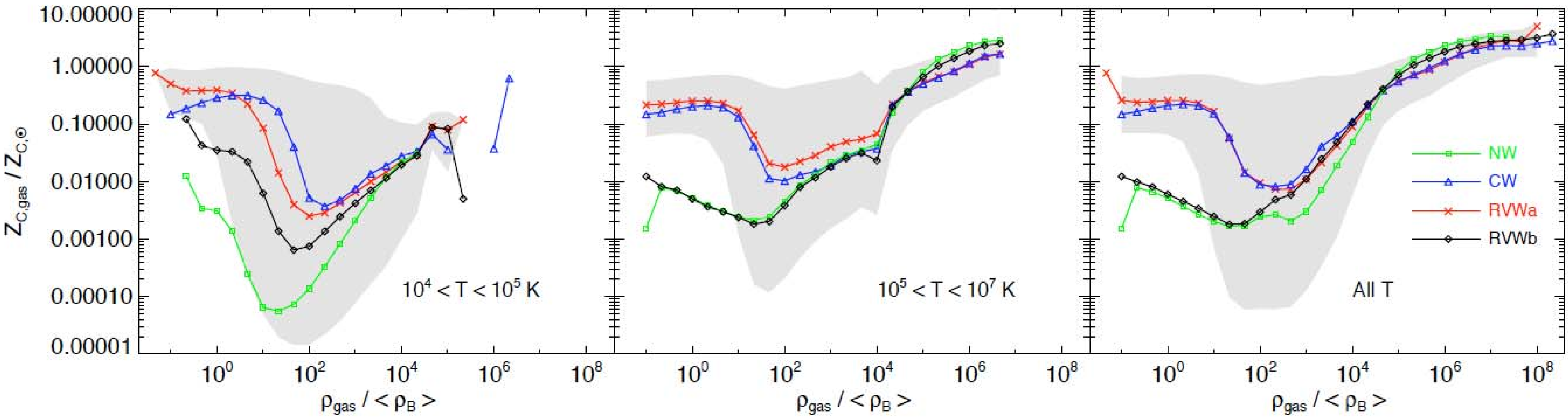
Gas Density - Radial Profile at z=1.98



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



(Gas) Carbon Metallicity vs. Overdensity at z=1.98, in T-bins



Conclusions

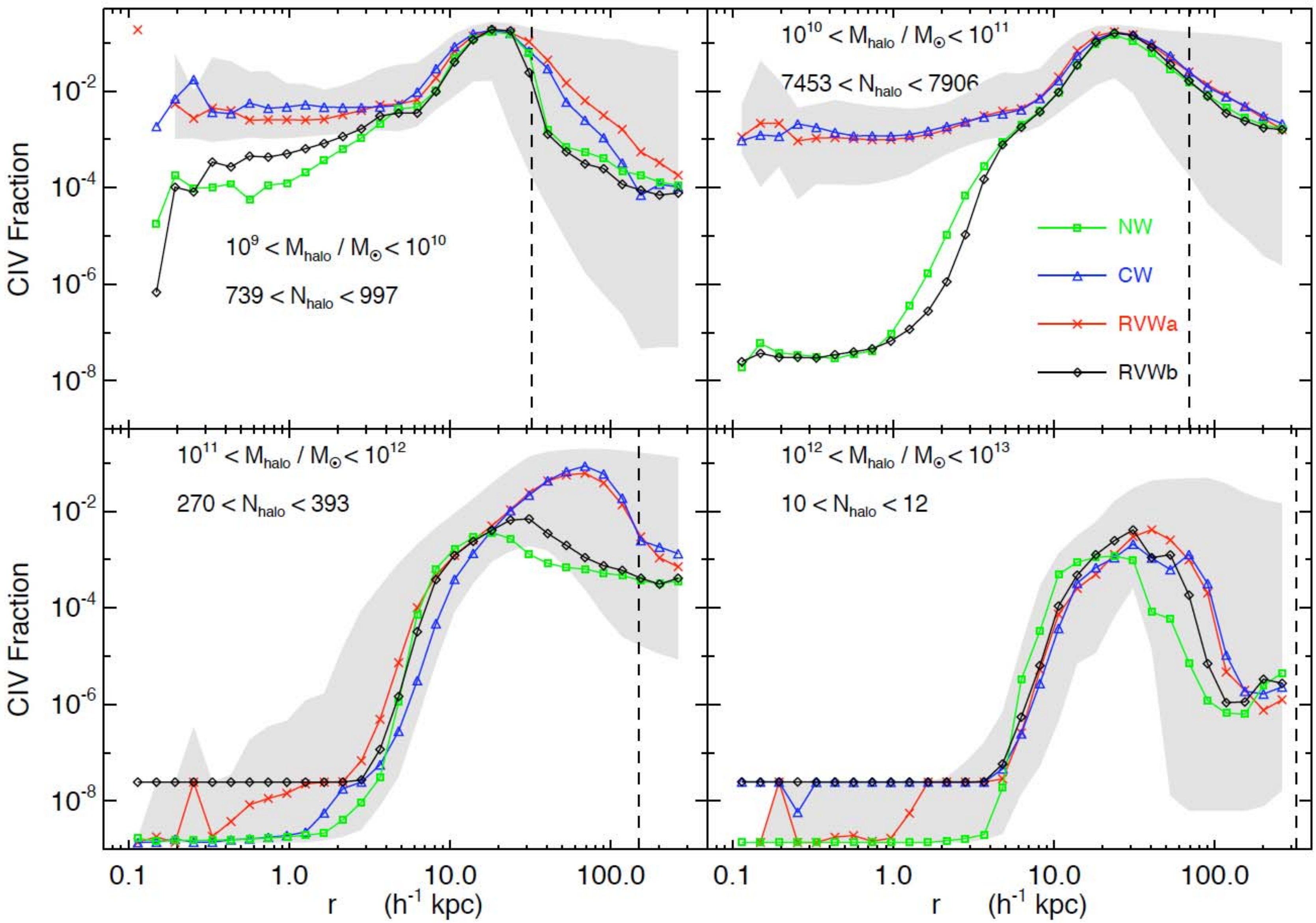
- Cosmological Hydrodynamic Simulations are powerful tool
  - Reproduce the observed large-scale structures
  - Study origin & evolution of galaxies over Hubble time
  - Bridge gap between observations of early epochs
    - CMBR: radiation from $3x10^5$ yrs, vs, Oldest stars: 10^9 yrs after
  - Are like experiments
    - Can run many experiments over cosmic ages in practical times

Specific 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

Extra Slides

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



(Gas) Temperature - Radial Profile at z=1.98