Cosmic Gas, Galaxy Formation, Feedback & Cosmological Hydro Simulation

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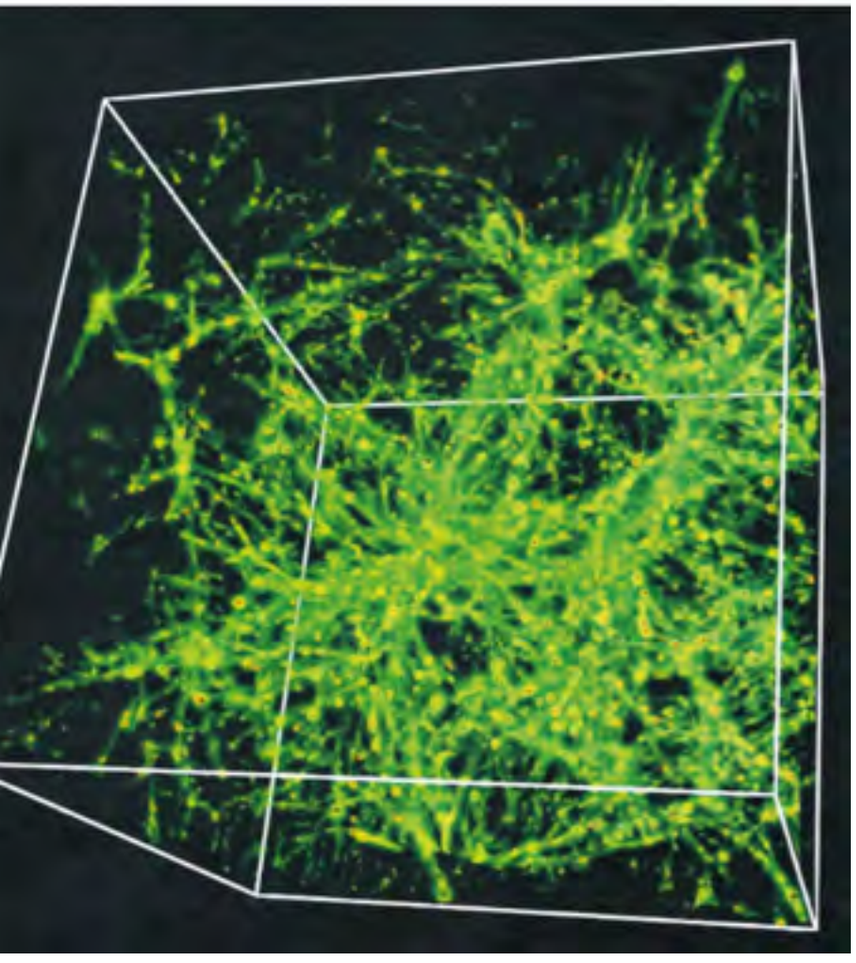
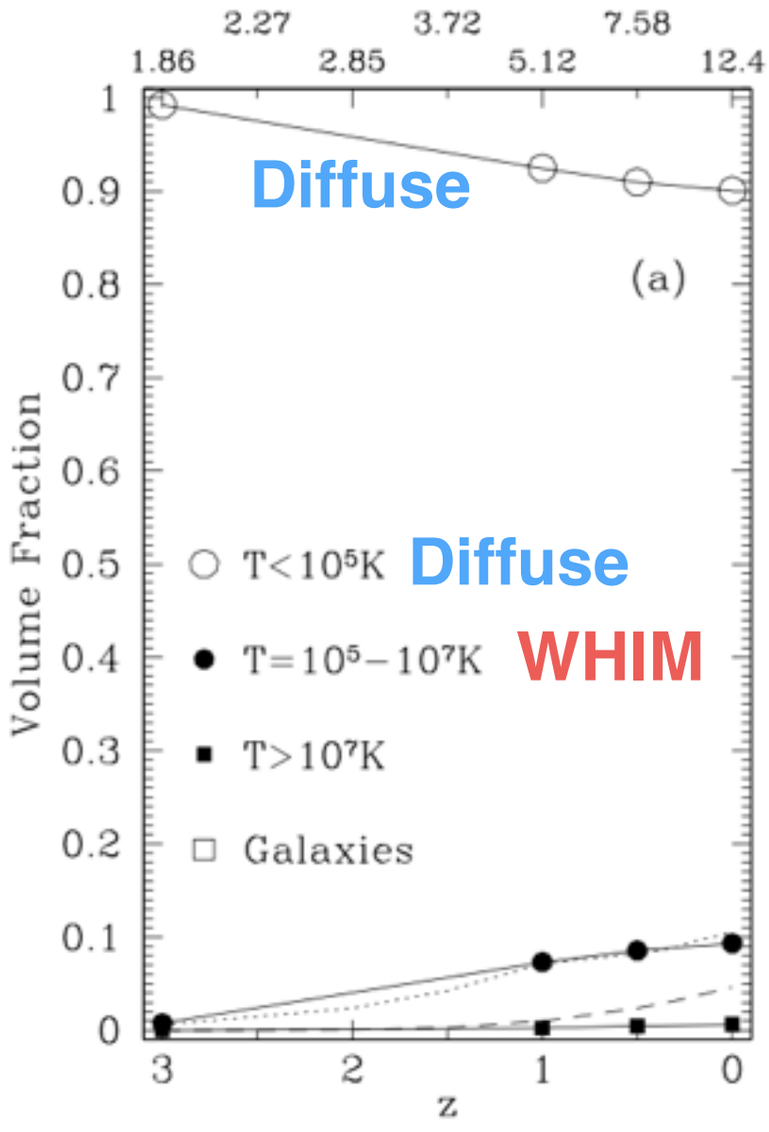
Contents

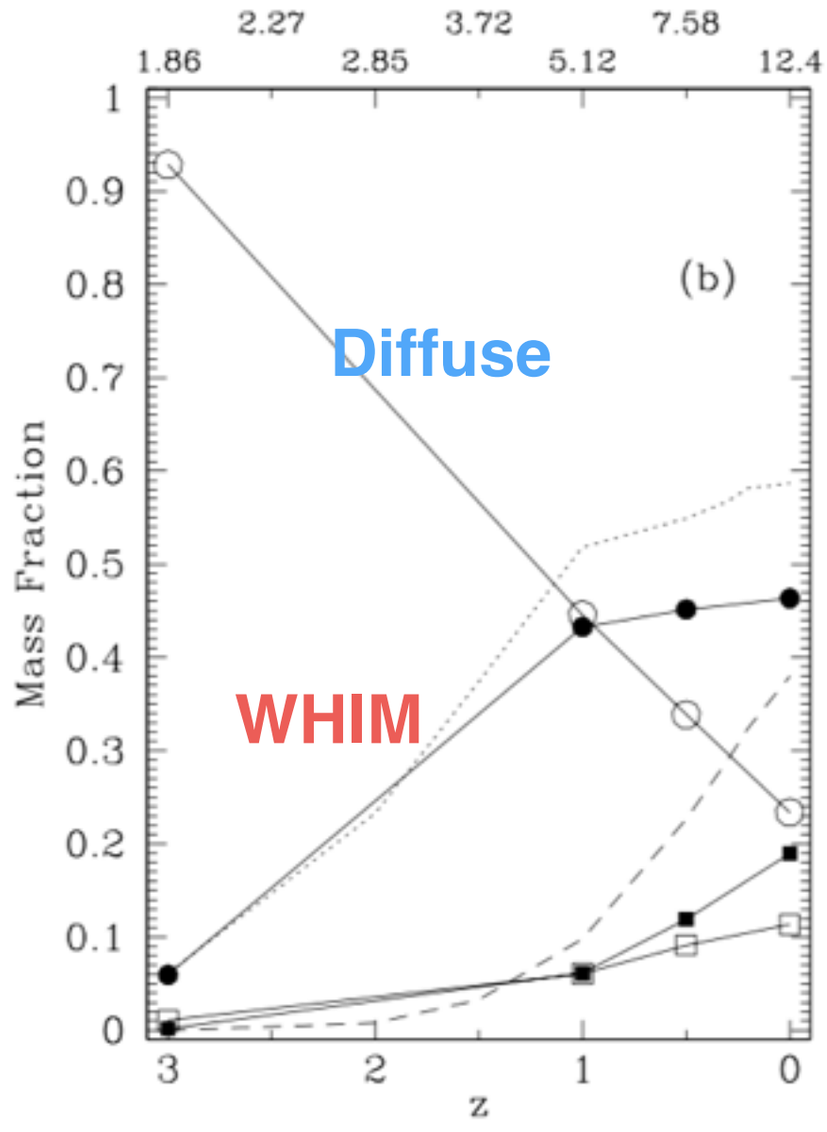
- **Intro**: **Distribution** of **Cosmic Gas** — phase diagram, Lyα forest
- **Metals** — **Feedback** from galaxies into **CGM, IGM**
- **Galactic Wind — SN feedback**
- Beyond 2-pt corr. fcn. — (now IGM tomography @~3Mpc resol.)
- **Non-linear scales (≲ 2Mpc/h) with PFS?**

WHERE ARE THE BARYONS?



Cen & Ostriker ‘99

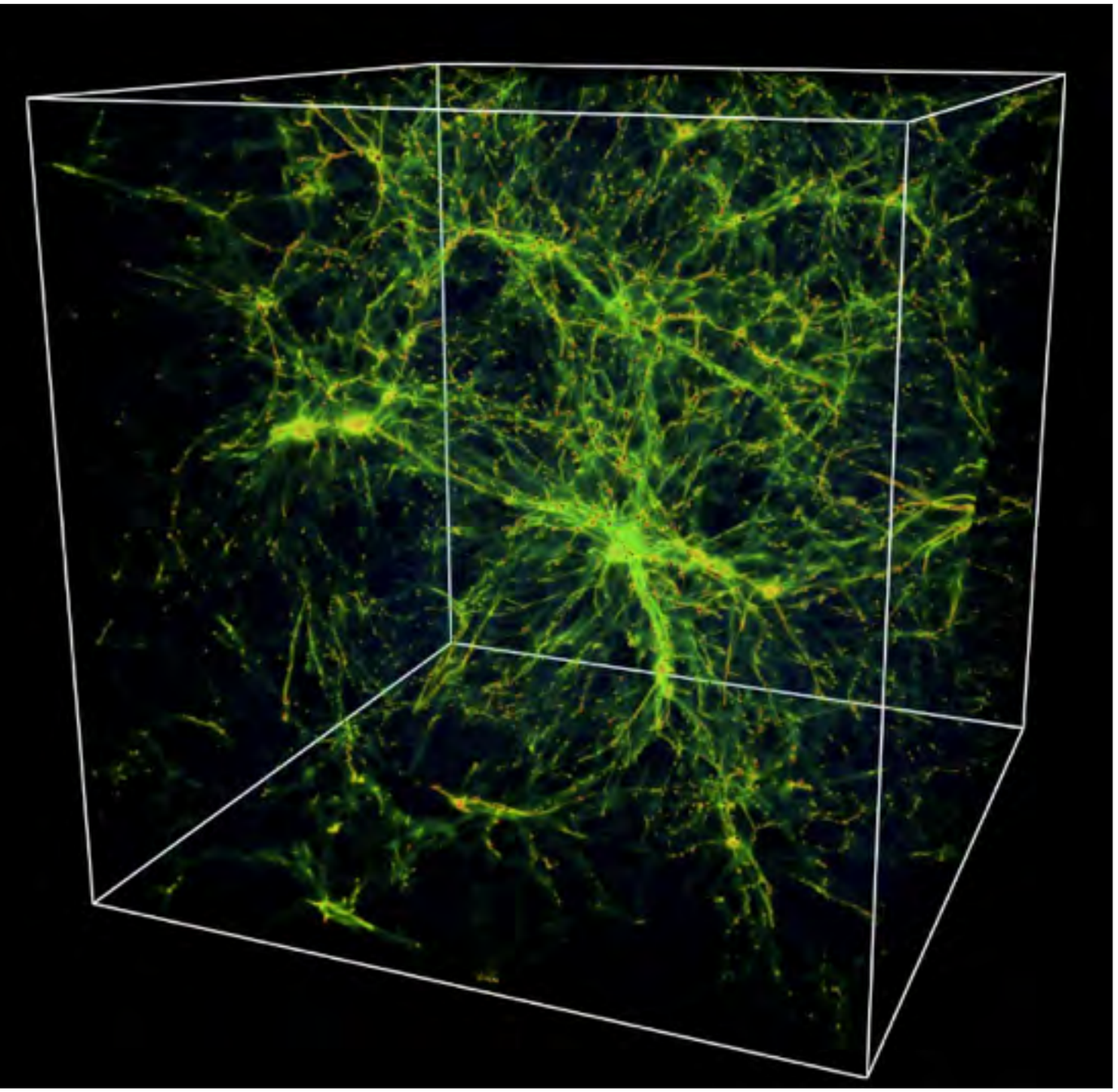




Most of the baryons at the present time has T=10^5-10^7 K.

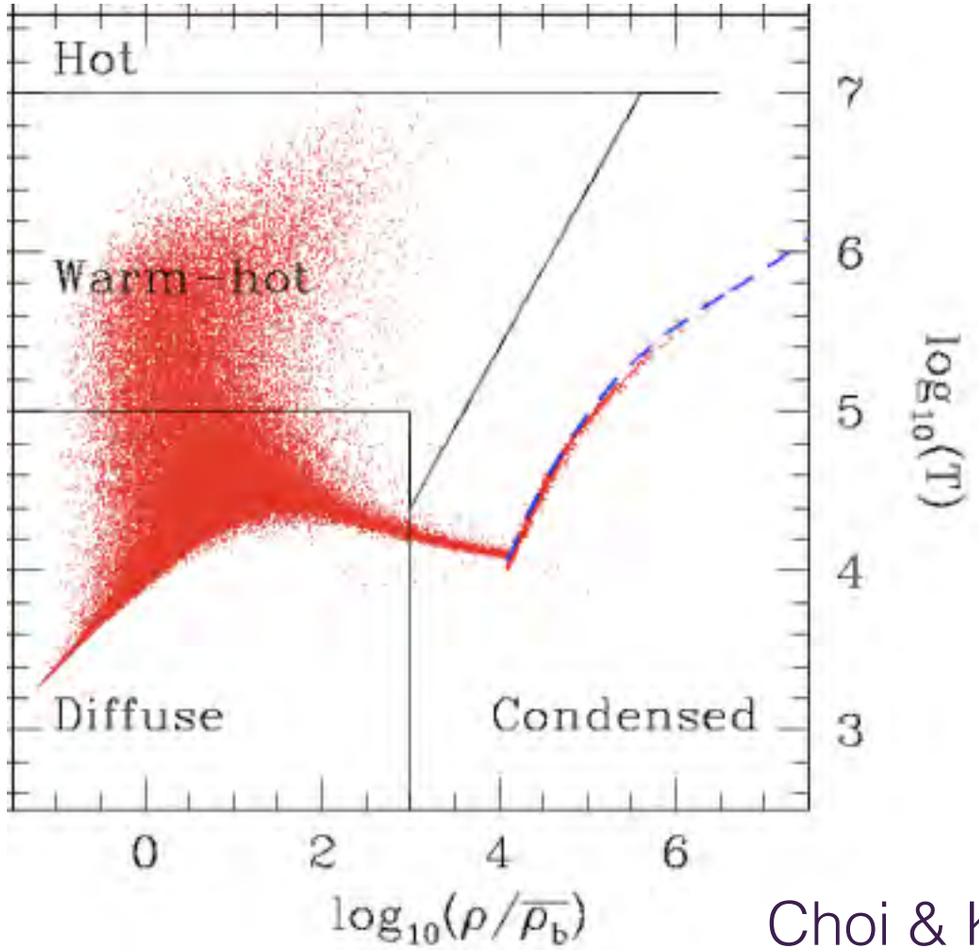
(~50%) Warm-Hot Intergalactic Medium (WHIM)

The Cosmic Gas

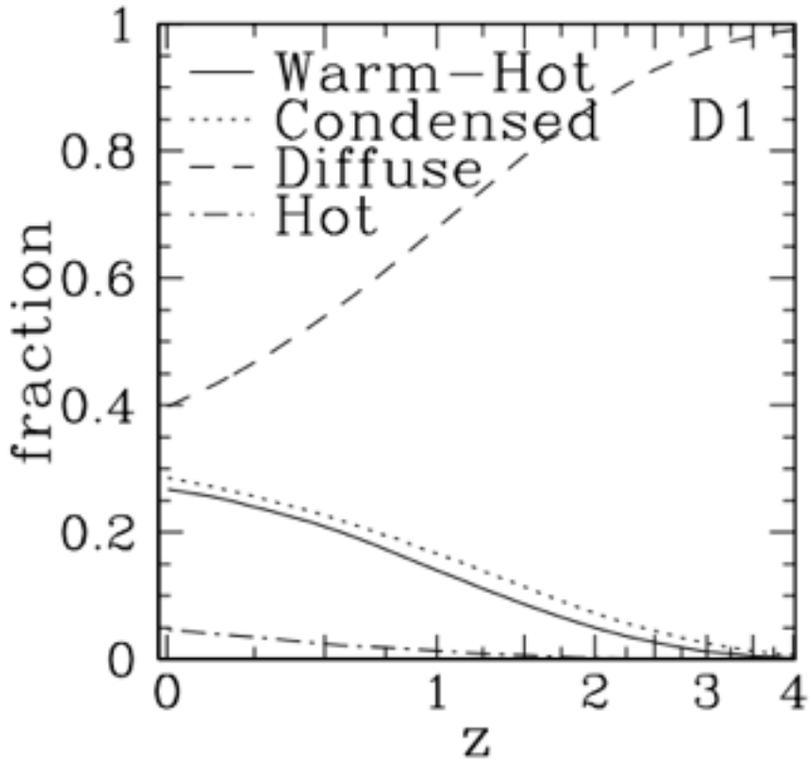


total gas density (z=3)

Cen & Ostriker ’99



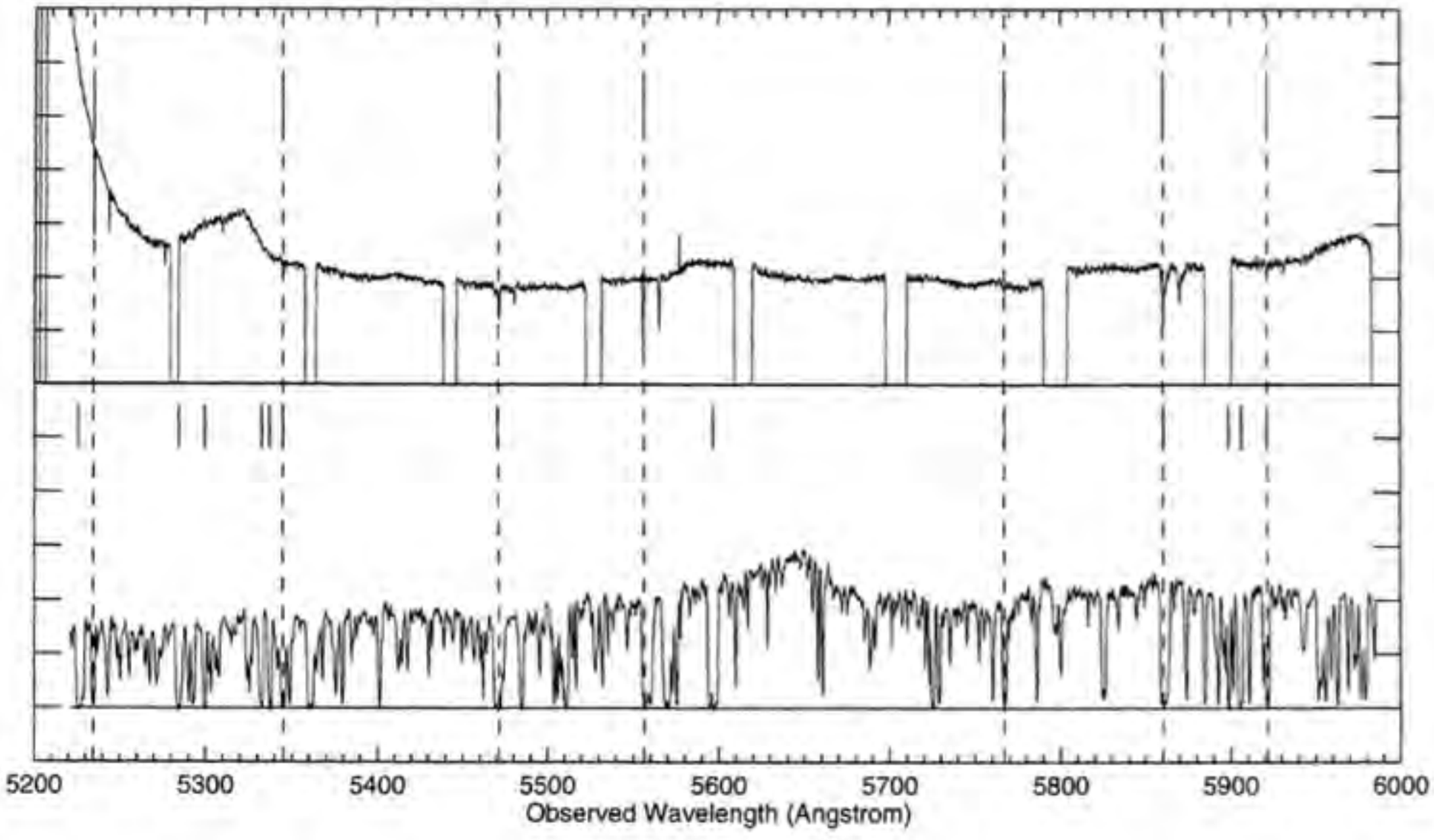
Choi & KN



Dave+’01

Metals exist in Lyα clouds

QSO0302-003 Keck HIRES spectrum



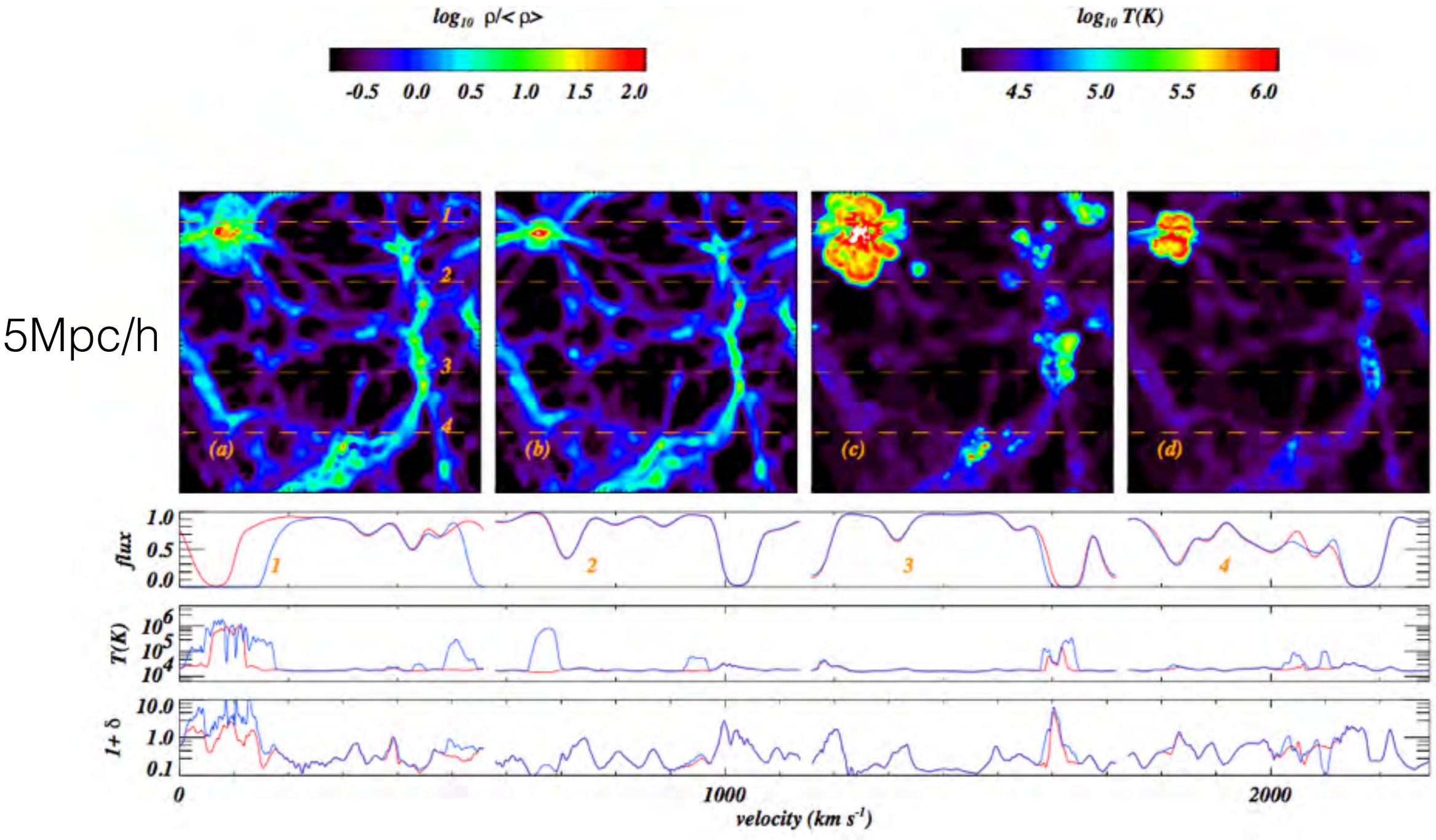
Nc_{iv}/N_{HI} ~ 2e-3

$Z/Z_{\odot}$ ~10^{-2}

~1/2 of $N_{HI} \gtrapprox 3e14$ cm^{-2} clouds are enriched by Civ w/ $Nc_{vi} \sim 10^{12}$ cm^{-2}

Cowie+'95

Impact of SN Feedback on Ly-α forest



Galactic wind carries metals into IGM without disturbing filaments (H_I) too much.

Theuns+'02

Cen, KN, Ostriker '05

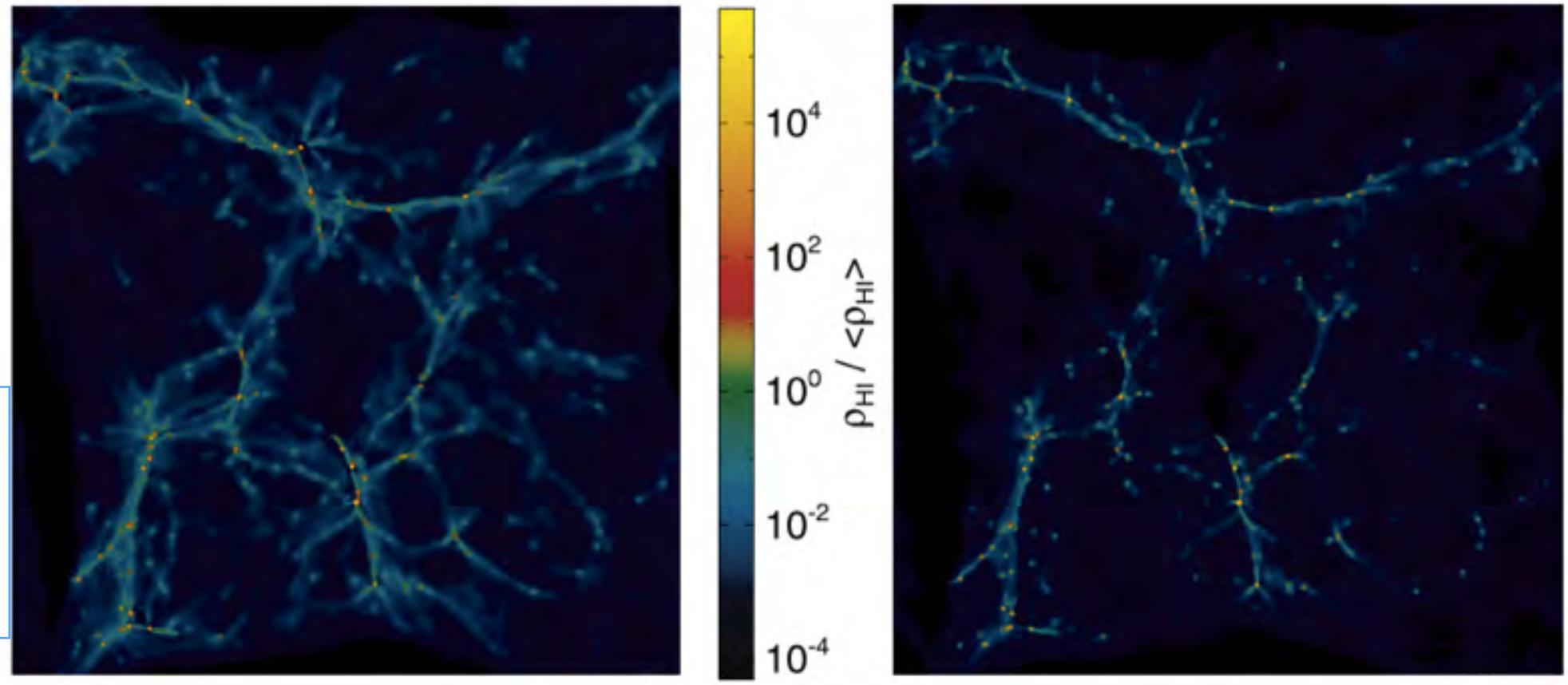
w/ feedback

11 Mpc/h

w/out feedback

Ly-α forest PDF not affected so much.

Winds emanate mostly perpendicular to the filaments.

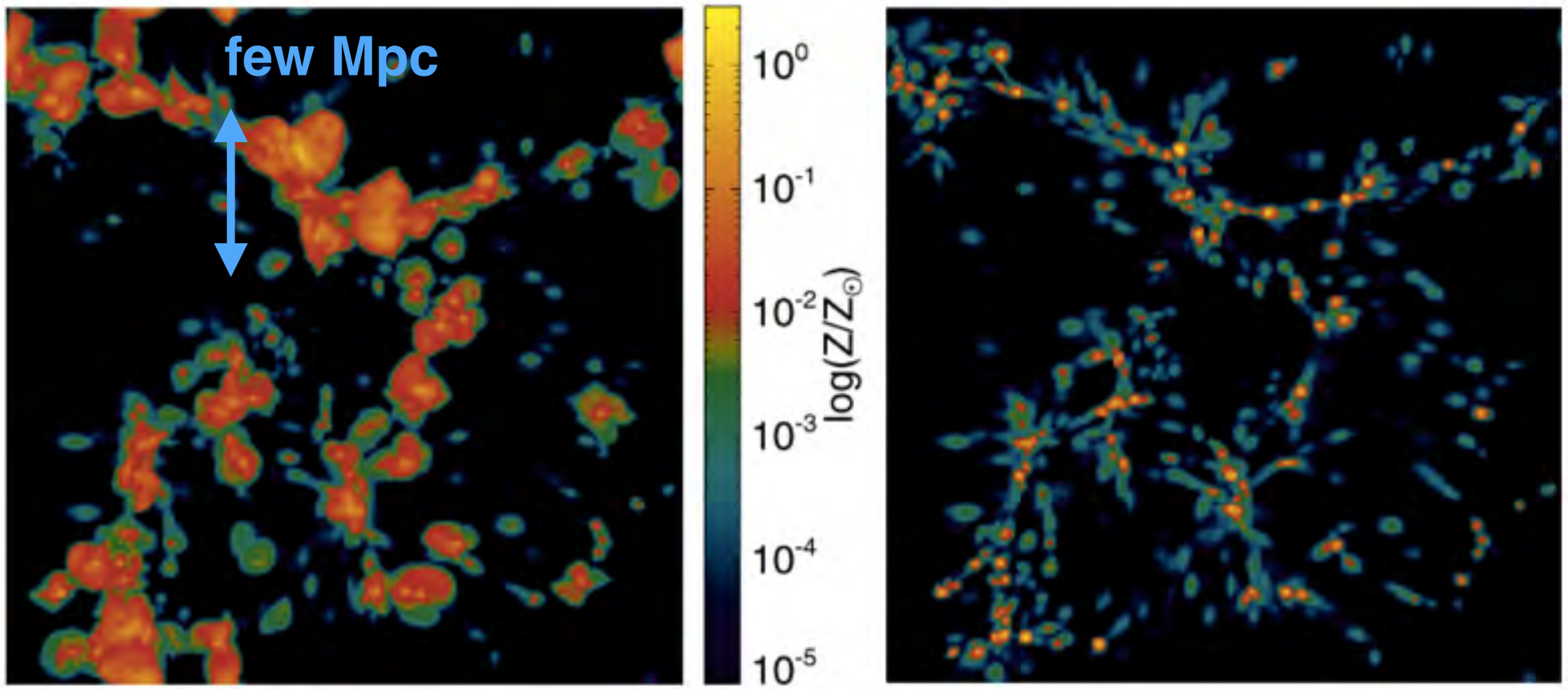


volume filling factor

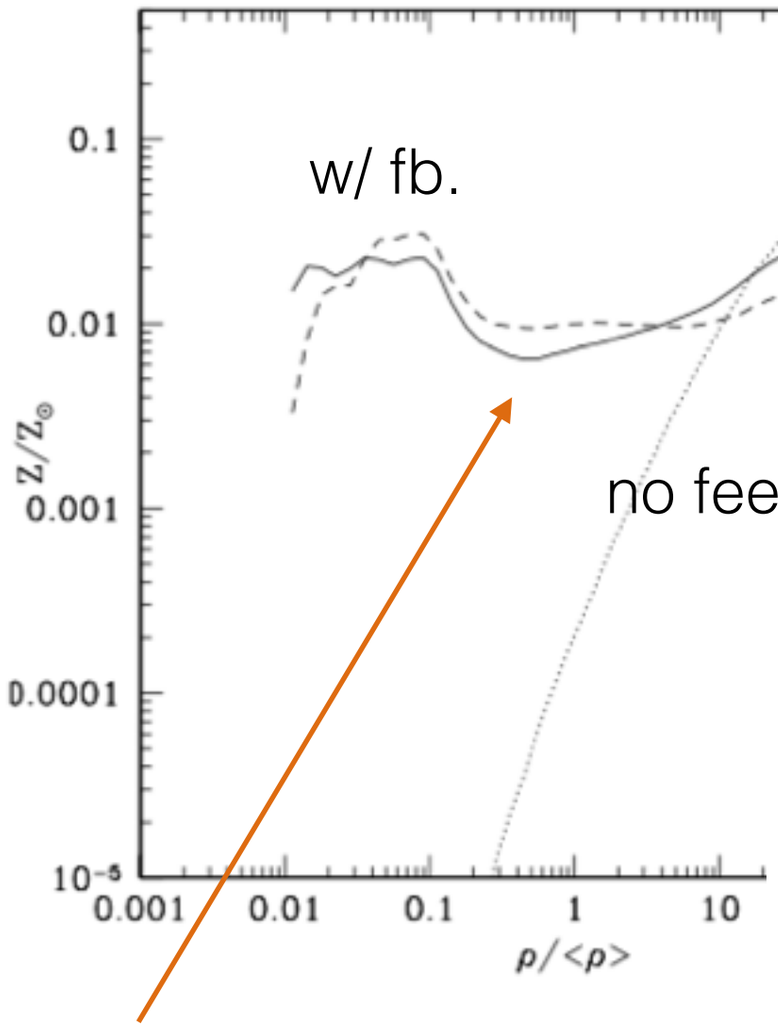
$Z > 10^{-3}$ Zsun : ~6%,

$Z > 10^{-2}$ Zsun : ~4%,

$Z > 10^{-1}$ Z_{sun} : ~2%



GW feedback efficiency



$\delta \lesssim 5$ can be enriched by GW

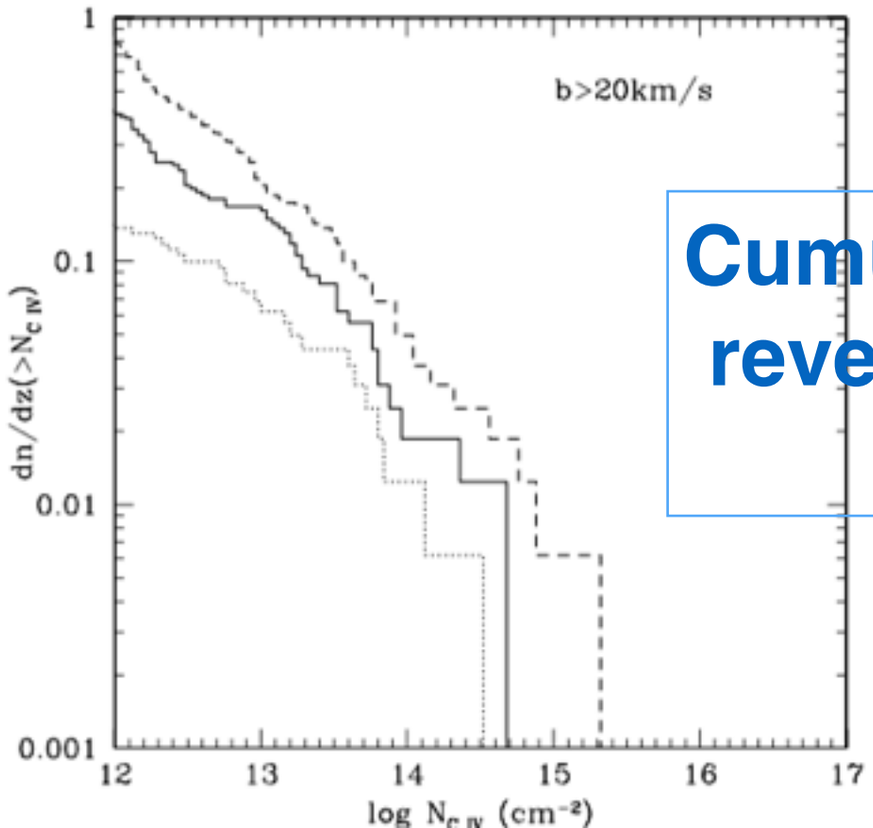
$$\dot{E}_{GW} = \epsilon_W \dot{M}_\star c^2$$

$$\epsilon_W \sim 3 \times 10^{-6}$$

$$\dot{M}_W = \eta \dot{M}_\star$$

$$\eta = 0.25$$

These params would depend on detailed ISM geometry.



Cumulative N-dist. can reveal the strength of gal. wind.

Cen, KN, Ostriker ‘05

Galactic Wind (Kinetic) Feedback

Need to specify $\dot{M}_w$ **and** V_w

"Energy-driven" vs. "Momentum-driven"

$$\dot{M}_W = \eta \dot{M}_\star,$$

η : mass-loading factor

Energy-driven: $\frac{1}{2}\dot{M}_W V_W^2 \sim \dot{E}_{\rm SN} \sim SFR$

$$\eta = \left(\frac{\sigma_0}{\sigma_{\rm gal}}\right)^2$$

$$V_W \sim V_{\rm esc} \sim \sigma_{\rm gal}$$

$$\sigma_0 \approx 300 \text{ km s}^{-1}$$

Momentum-driven: $\dot{M}_W V_W \sim \dot{P}_{\rm rad} \sim SFR$

$$\eta = \frac{\sigma_0}{\sigma_{\rm gal}}$$

Radiation pressure from massive stars and SNe is applied to the dust particles, which entrains the wind

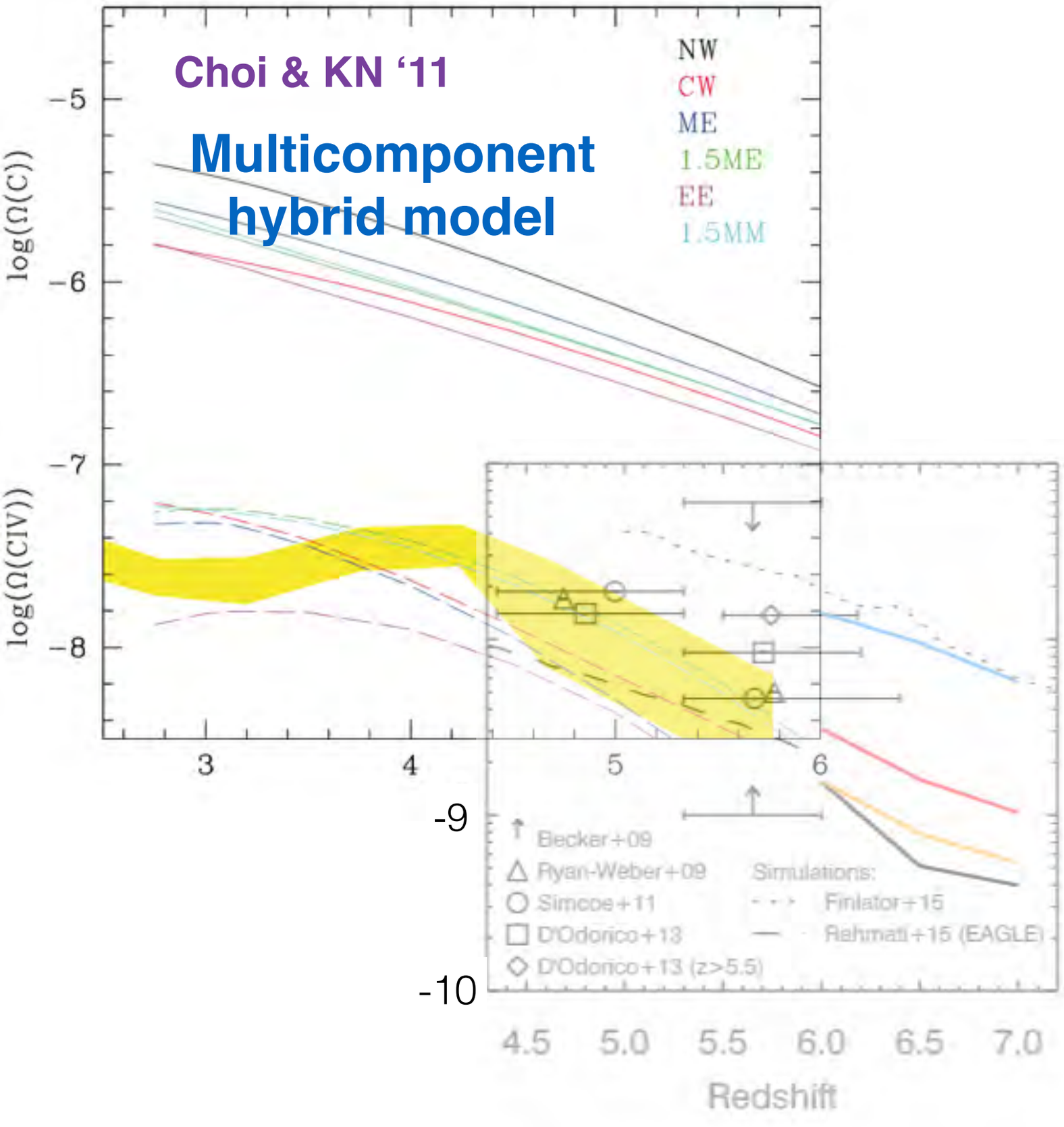
Murray+ '05

Higher mass-loading factor for lower mass galaxies.

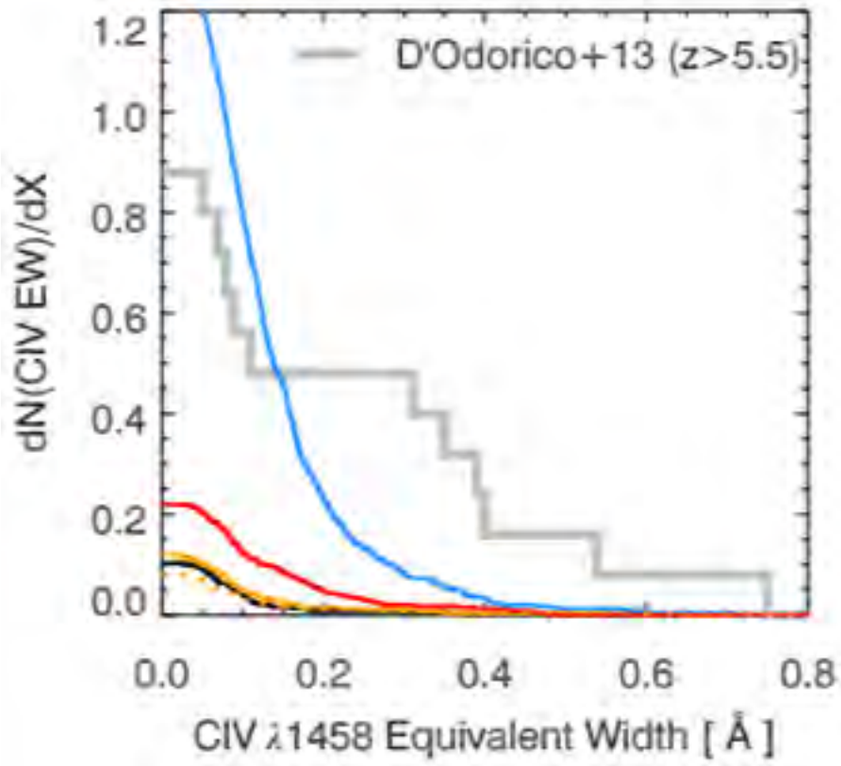
C_{IV} evolution

Choi & KN ‘11

Multicomponent hybrid model



another Gadget-3 (Sherwood sim)

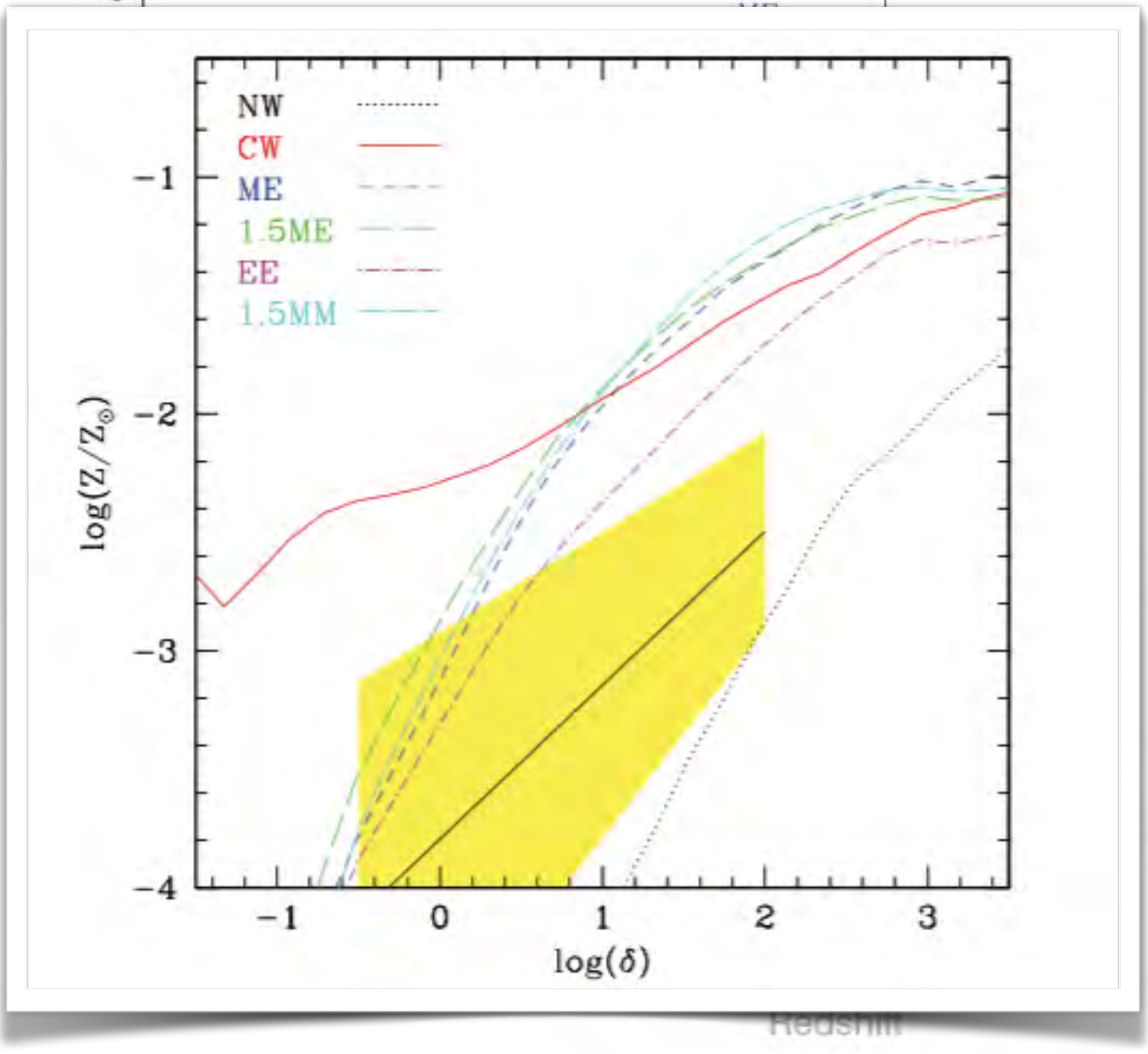


Metals not distributed widely enough for high-EW Civ?

Keating+’16

Ovi (hotter phase) is ok.

C_{IV} evolution



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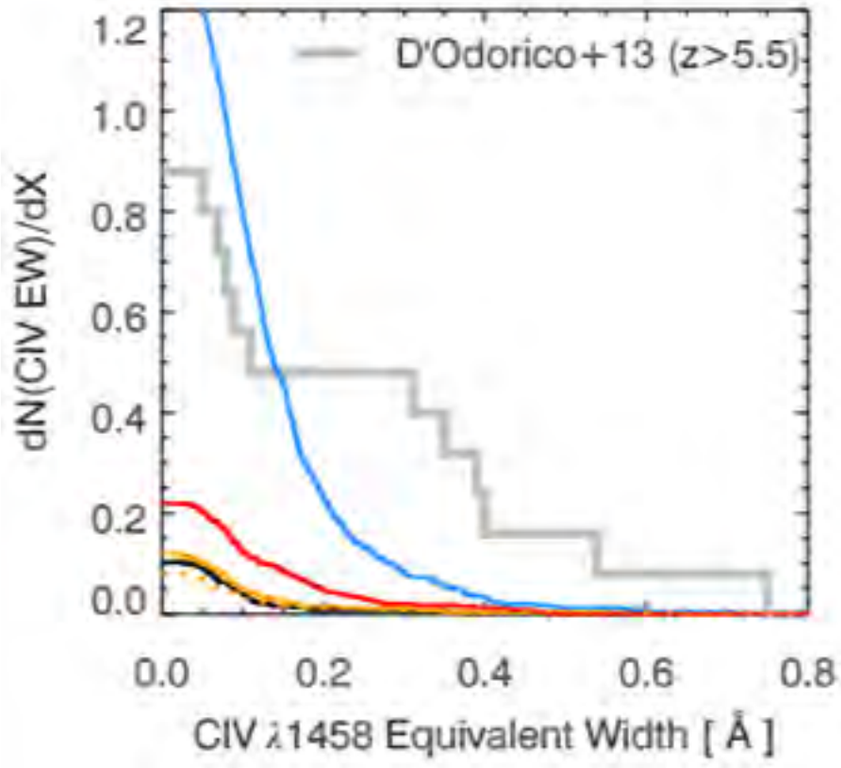


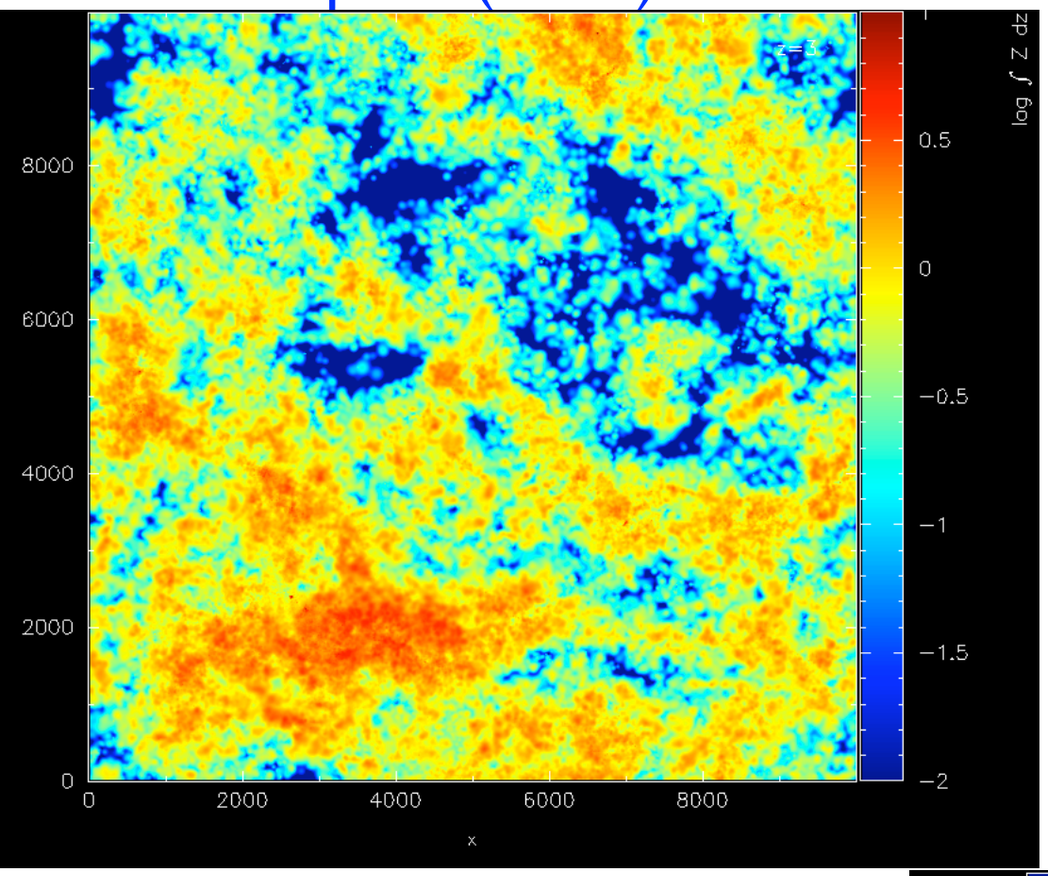
Metals not distributed widely enough for high-EW Civ?

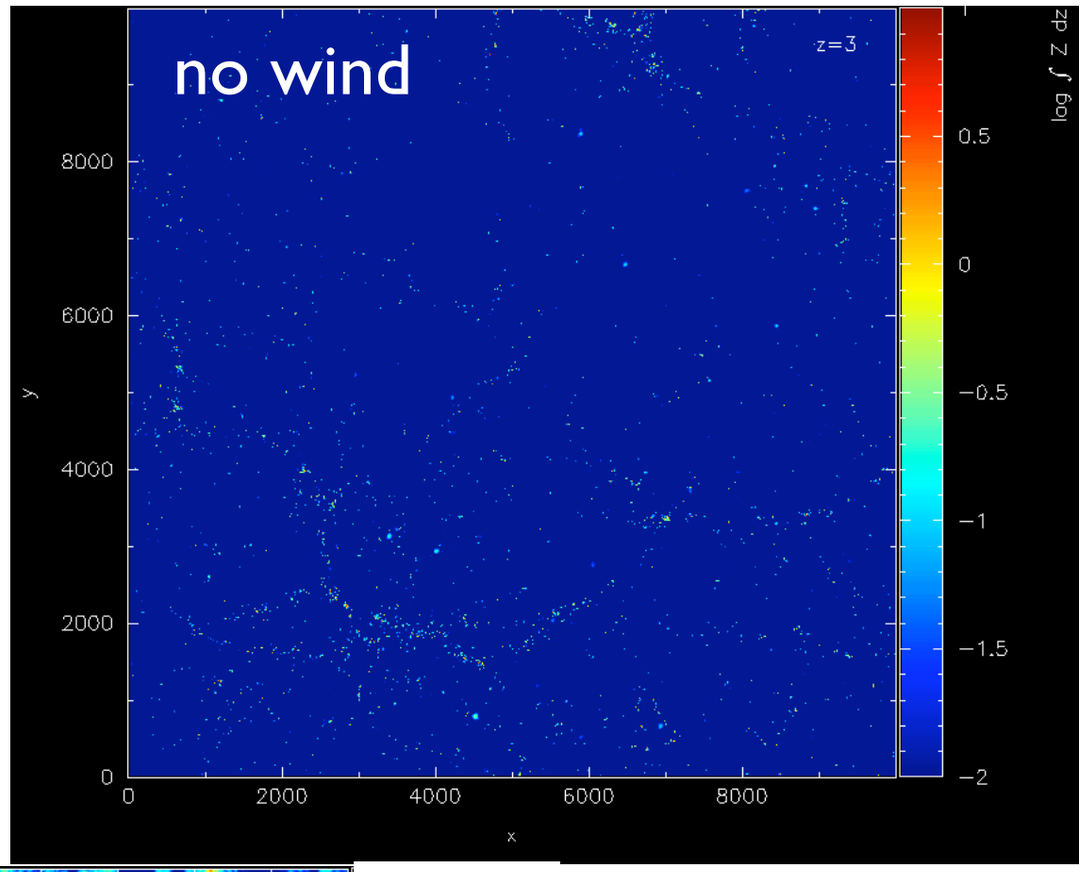
Keating+'16

Ovi (hotter phase) is ok.

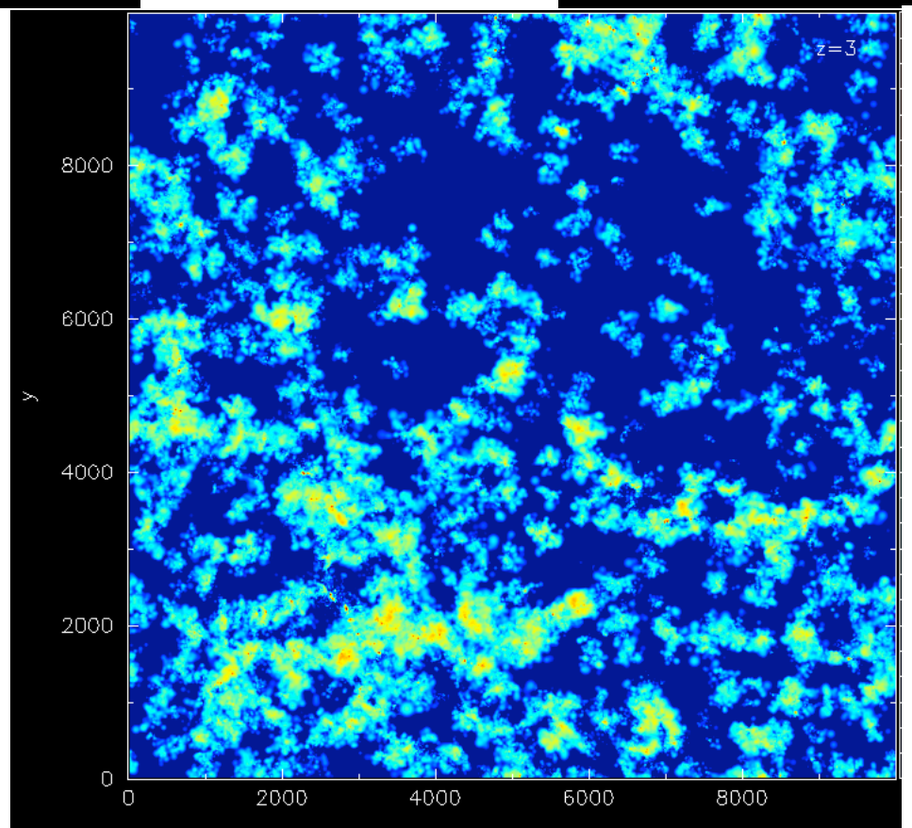
SN feedback & IGM Enrichment

constant speed (SH03)





Multicomponent variable velocity (MVV) wind model (based on momentum-driven wind)

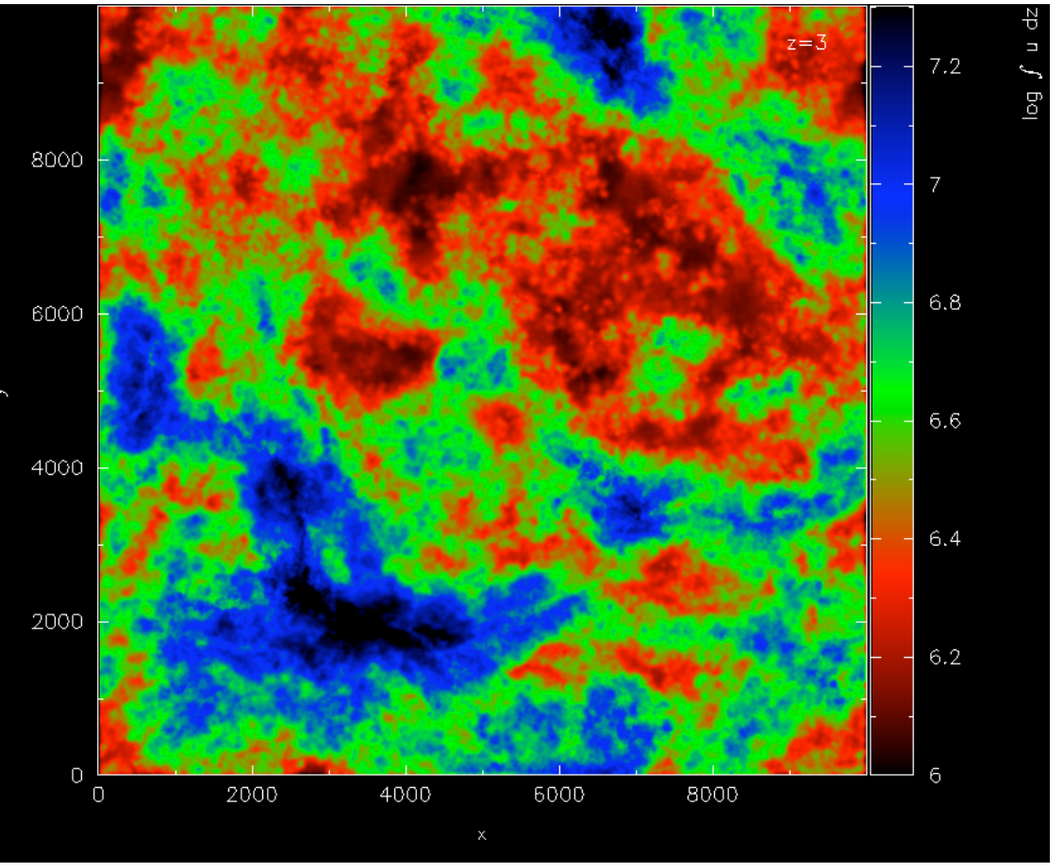


Projected metallicity distribution

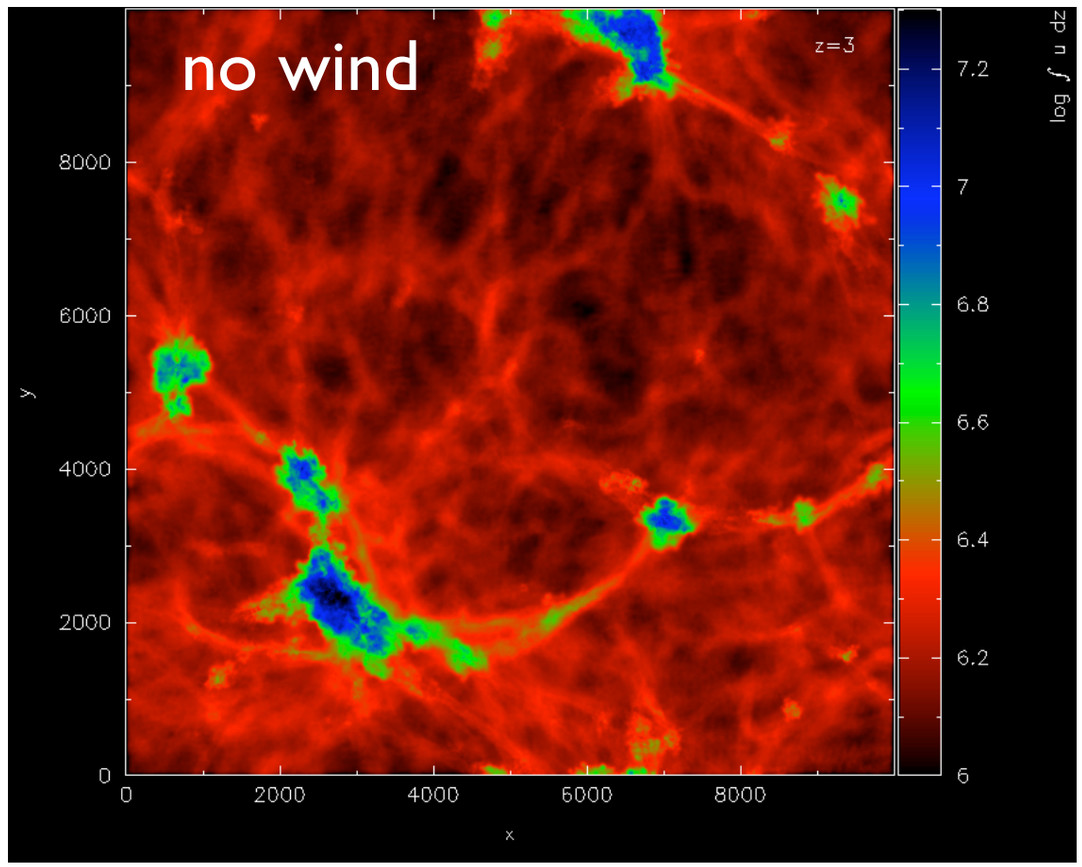
Choi & KN '10

SN feedback & Wind model

constant speed (SH03)



10 Mpc/h
across



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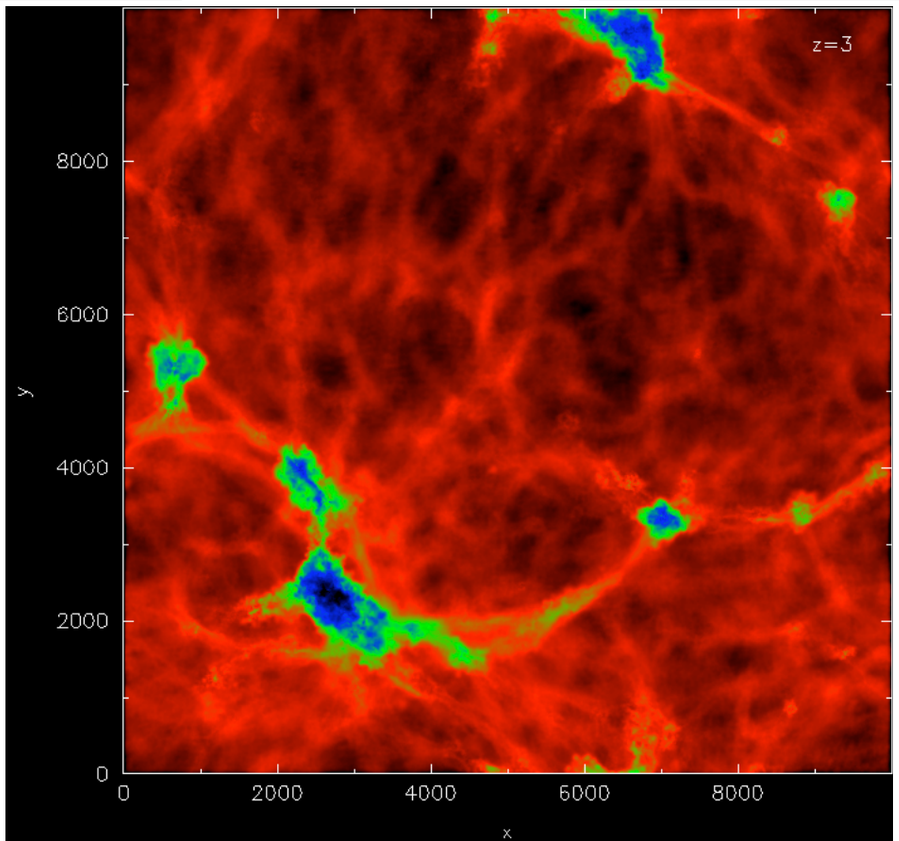
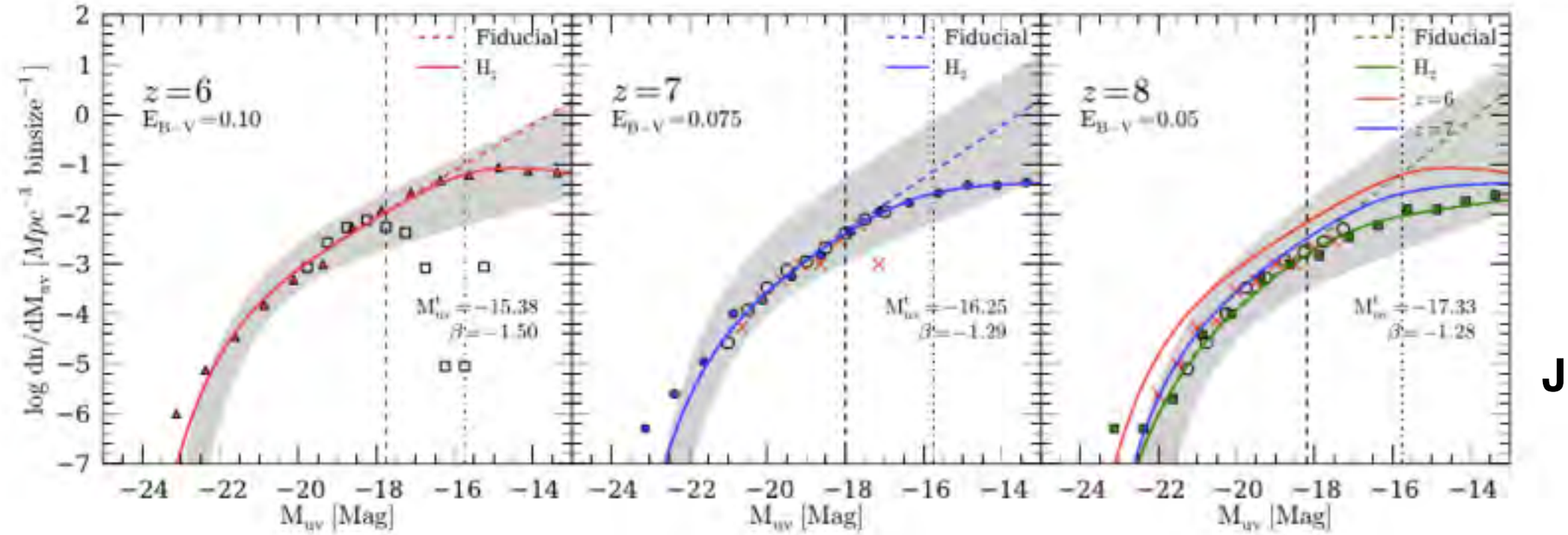


Projected internal energy (~temperature) distribution

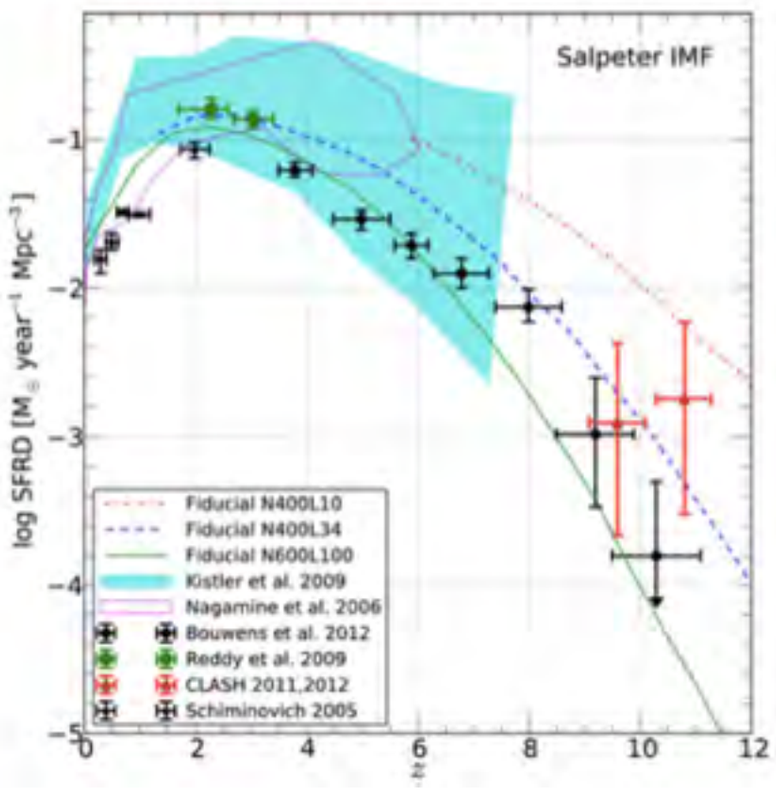
Choi & KN '10

Galaxy Stellar Mass Functions & SFRD

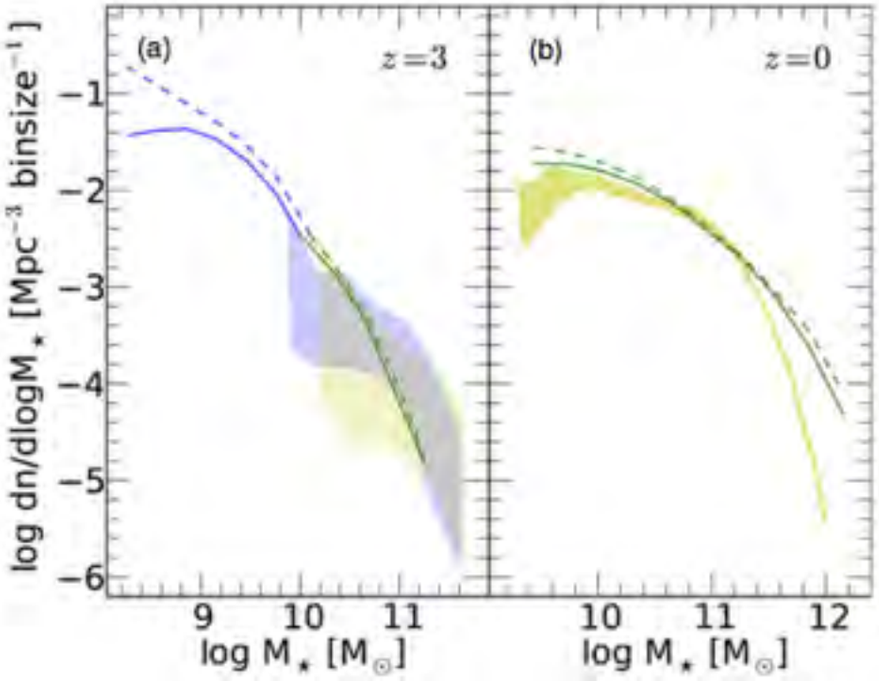
Under some control…..

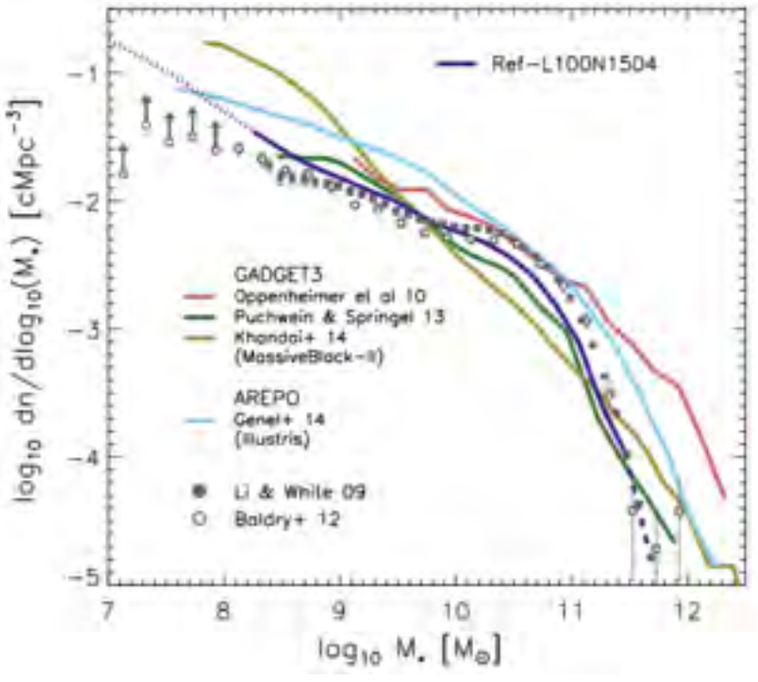


Jaacks+'13



Thompson+'14





Schaye+'15 EAGLE sim.

Stellar Feedback in Zoom-in Cosmo Sim

$$\dot{M}_W = \eta \dot{M}_\star,$$

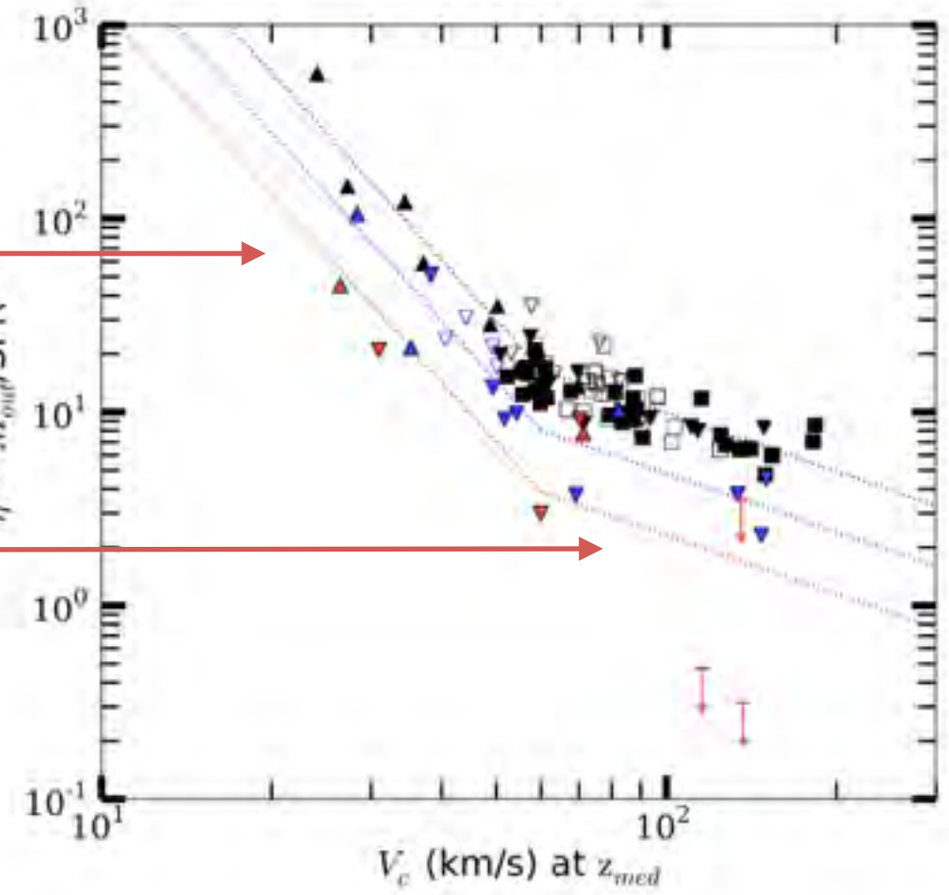
Mass Loading Factor : η

$$\eta = 2.91(1+z)^{1.25}\left(\frac{v_c}{60\mathrm{km/s}}\right)^{-3.22}$$

(steeper than Energy-driven)

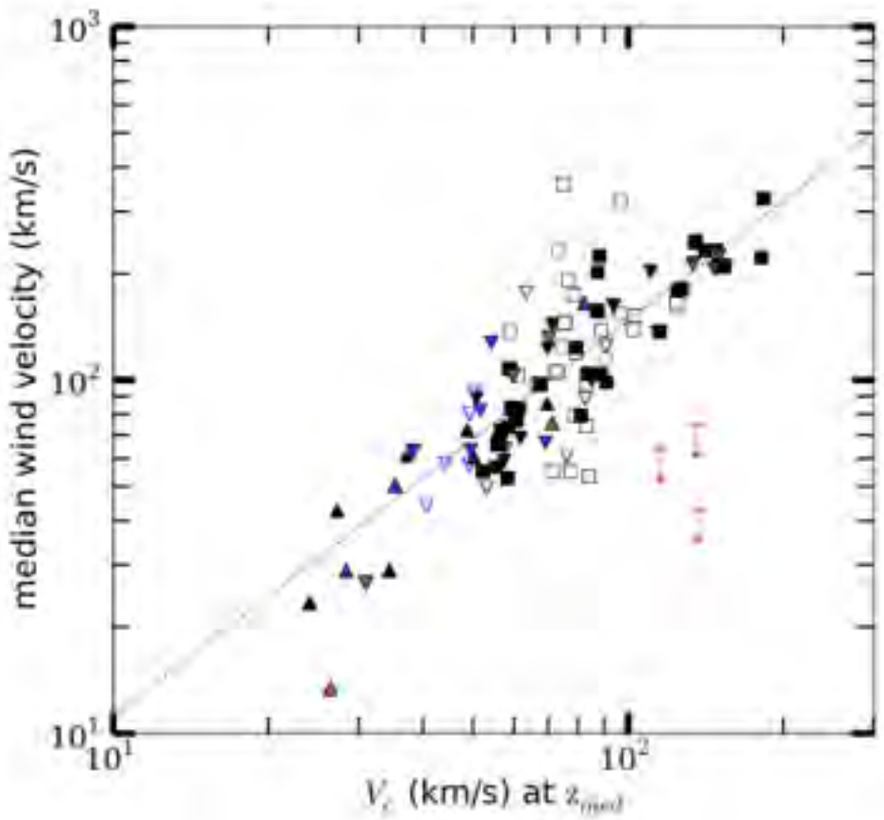
$$\eta = 2.91(1+z)^{1.25}\left(\frac{v_c}{60\mathrm{km/s}}\right)^{-1.00}$$

(≈ Momentum-driven)



(Hopkins+'13; Muratov+ '14)

res. 1-10pc

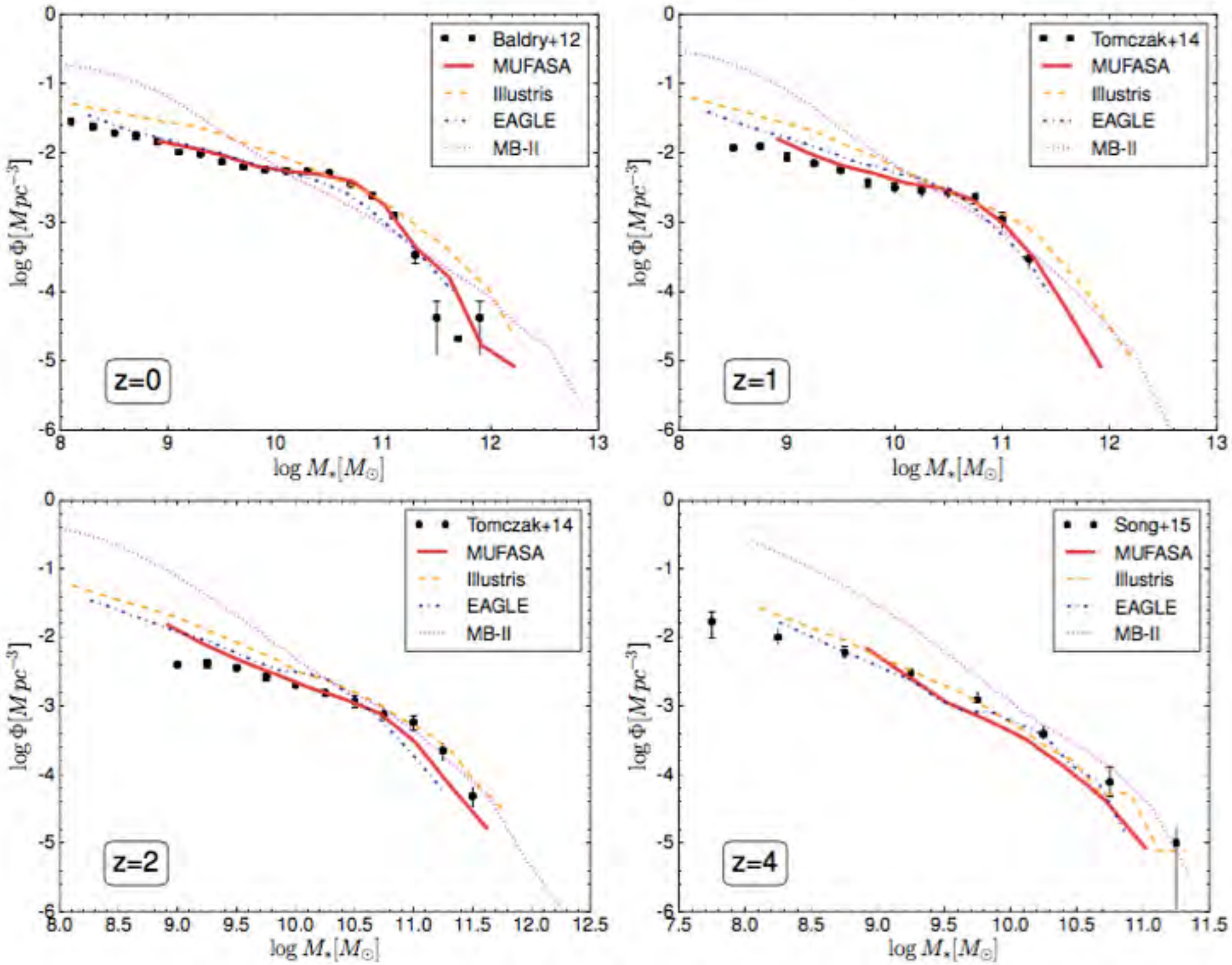


Wind Velocity

$V_w \sim V_c \sim M_h^{1/3} \sim SFR^{1/3}$

(Choi & KN '10)

SPH systematic effect subdominant compared to feedback



Gizmo SPH, 50 Mpc/h box, 512^2 ptcls

MFM (meshless finite volume) method

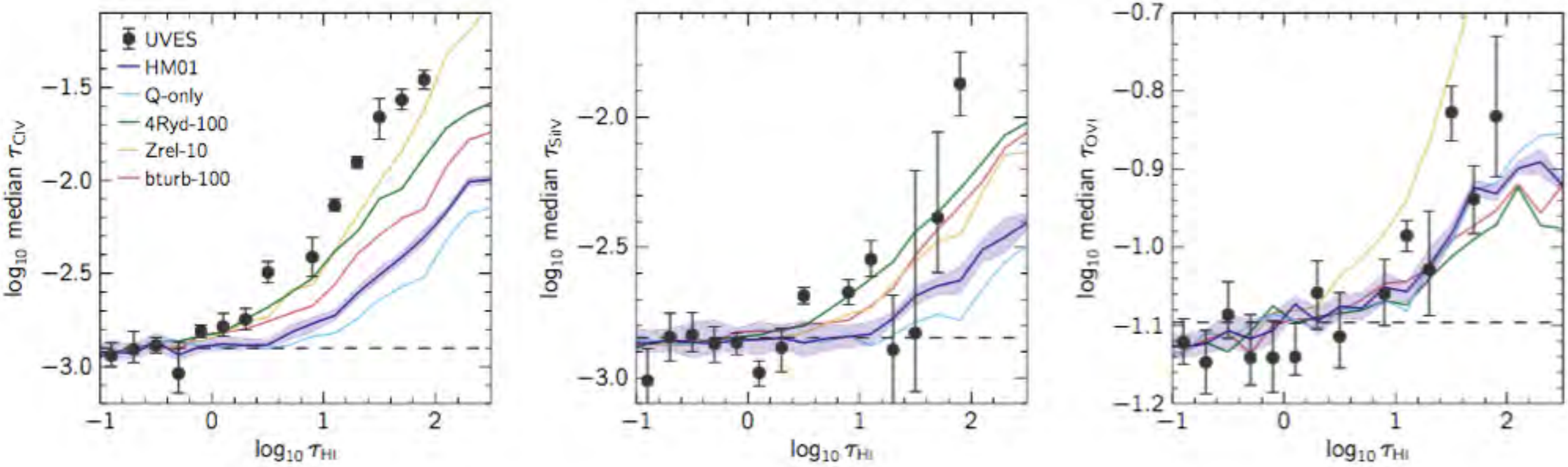
Dave+'16
(MUFASA sim.)

Sim. underpredicts $\tau_{CIV}(\tau_{HI})$ significantly.

8 QSOs, <z>~3.75

(comparison btw obs. & EAGLE sim.)

(but O_{IV}, better agreement)



Possible solutions:

(a) different models for the ionizing background radiation;

(b) simulations run at a higher resolution;

(c) inclusion of additional line broadening due to unresolved turbulence;

(d) increased elemental abundances.

Outflows need to entrain more cold gas w/ metals?

Turner+'15

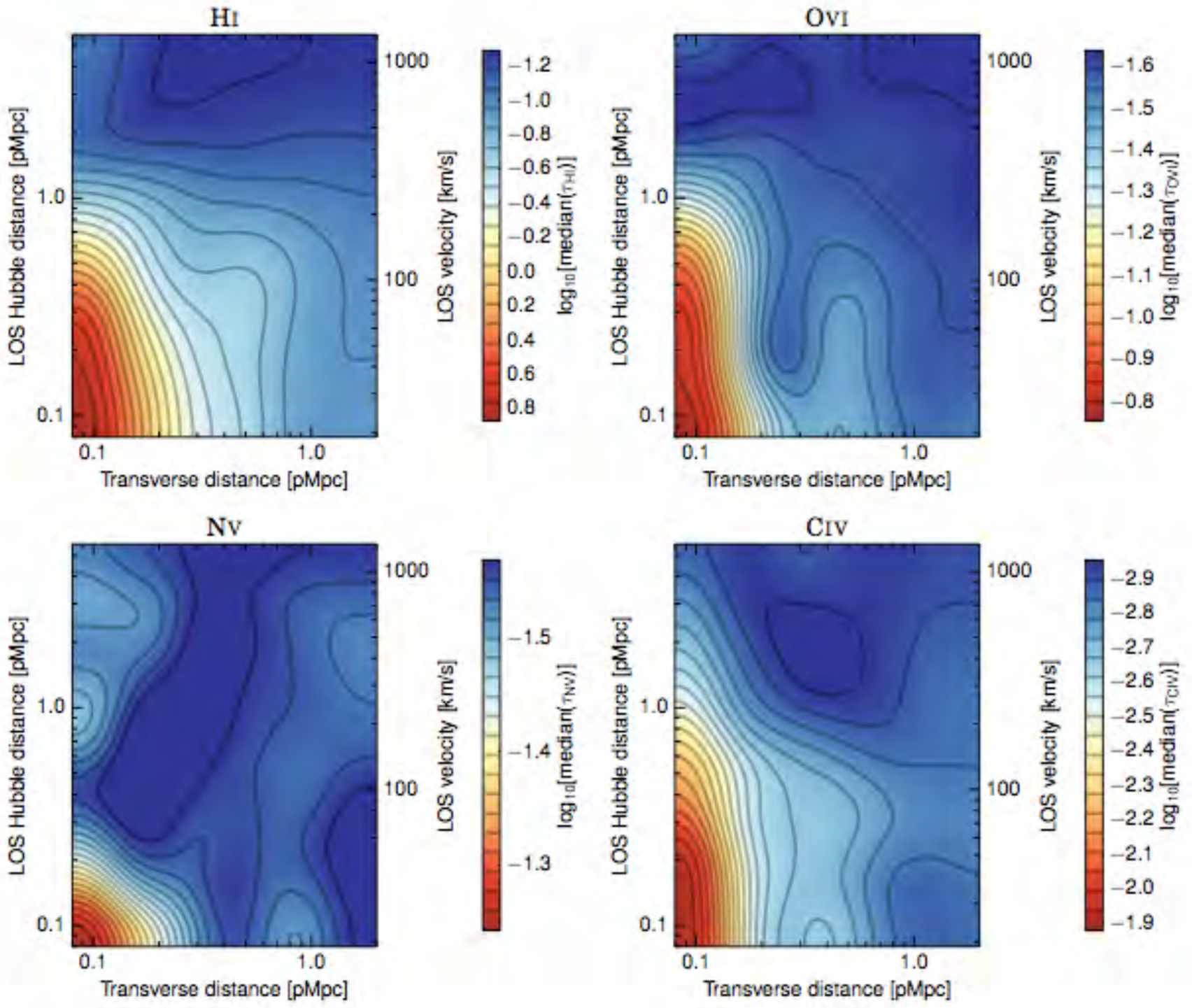
Pixel Optical Depth method: Galaxy-centered 2D maps

Metals detected up to ~1Mpc LOS and ~200 kpc transverse

elongation towards LOS

↓

inflow, outflow, virial motion



Turner+'15 (update of Rakic+'12)

PFS spec & Cosmo Sim.

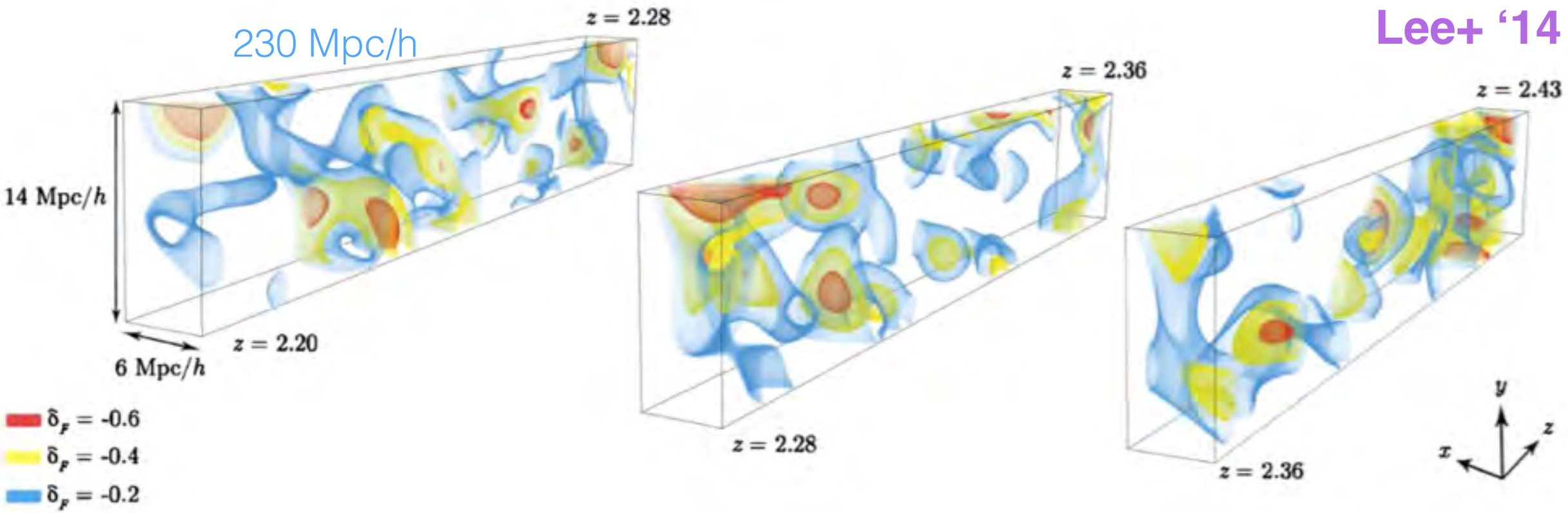
- FoV ~ 1.3 deg^2
- (Om, Ol)~(0.3, 0.7): 1 deg ~ **100 cMpc** (z=2-3)
- min. fiber separation ~ 30” ~ **1 cMpc**

- **1 cMpc** is easily resolved, but need proper models of **gal. formation & chemical enrichment**

Run Name	Box Size (h^{-1} Mpc)	Particle Count DM and Gas	m_{dm} ($h^{-1}\ M_\odot$)	m_{gas} ($h^{-1}\ M_\odot$)	ϵ (h^{-1} kpc)	z_{end} H_2
N400L10	10.00	2×400^3	9.37×10^5	1.91×10^5	1.00	6.00
N400L34	33.75	2×400^3	3.60×10^7	7.34×10^6	3.38	3.00
N600L100	100.00	2×600^3	2.78×10^8	5.65×10^7	4.30	0.00

Tomographic Reconstruction of 3D Lyα forest absorption

24 star-forming gals (SFGs) @ z~ 2.3 - 2.8



Lee+ '14

CLAMATO survey
(COSMOS Lyα mapping and tomography observations)

$z \sim 2.3$

$g \gtrsim 23$ star-forming gal.

eventually 1 deg^2
~1000 SFGs

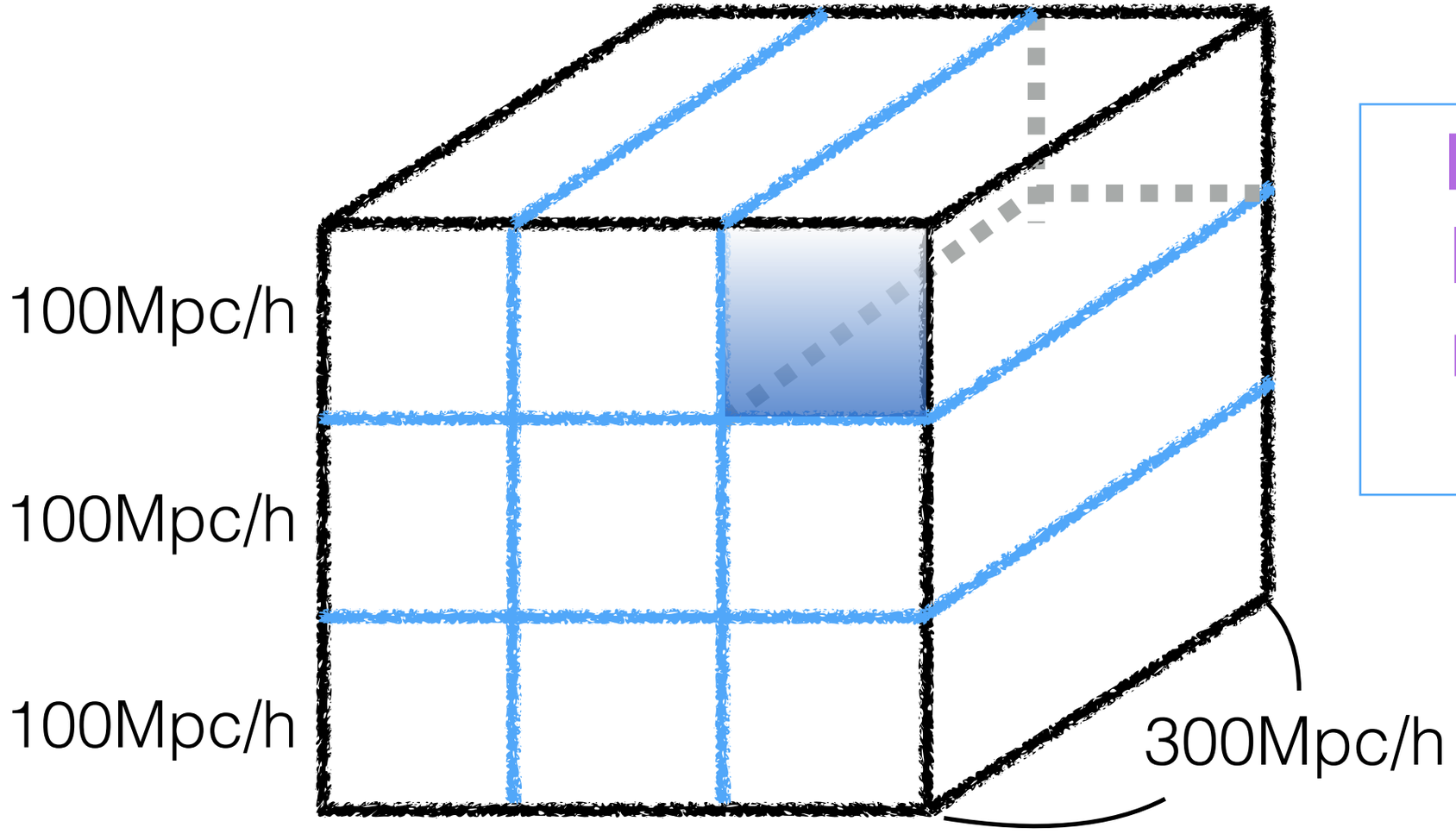
moderate spec res. $R \equiv \frac{\lambda}{\Delta\lambda} \sim 1000$

$\epsilon_{\rm 3D} \sim 2 - 5\ {\rm Mpc}/h$

(60Mpc/h)^2 x 300Mpc/h

Difficulty of simulating large-scale IGM and Galaxy Formation at the same time….

Run Name	Box Size (h^{-1} Mpc)	Particle Count DM and Gas	$m_{\rm dm}$ ($h^{-1}\,M_\odot$)	$m_{\rm gas}$ ($h^{-1}\,M_\odot$)	ϵ (h^{-1} kpc)
N600L300	**300**	**2×600^3**	**7.5×10^9**	**1.5×10^9**	**~20**
N1000L300	**300**	**2×1000^3**	**1.6×10^9**	**3.3×10^8**	**~12**
N1500L300	**300**	**2×1500^3**	**4.8×10^8**	**9.8×10^7**	**~8**
N2000L300	**300**	**2×2000^3**	**2.0×10^8**	**4.1×10^7**	**~6**



Dilemma btw box size and mass/spatial resolution

Summary

- Overall dist. of Cosmic Gas: relatively good understanding — hot, WHIM, diffuse, condensed.
- ***Metals observed around gals in CGM & IGM, up to ~1Mpc***
- *Feedback* , galactic wind *is the issue.*
- ***Mass-loading; Hot vs. Cold outflow***
- ***Background radiation models***
- ***Radiation Transfer***
- ***Difficulty of simulating large-scale IGM (~100Mpc), and the sources (galaxies) and feedback at <1kpc simultaneously w/ high-resolution.***
- ***Towards "Precision Structure Formation"!***