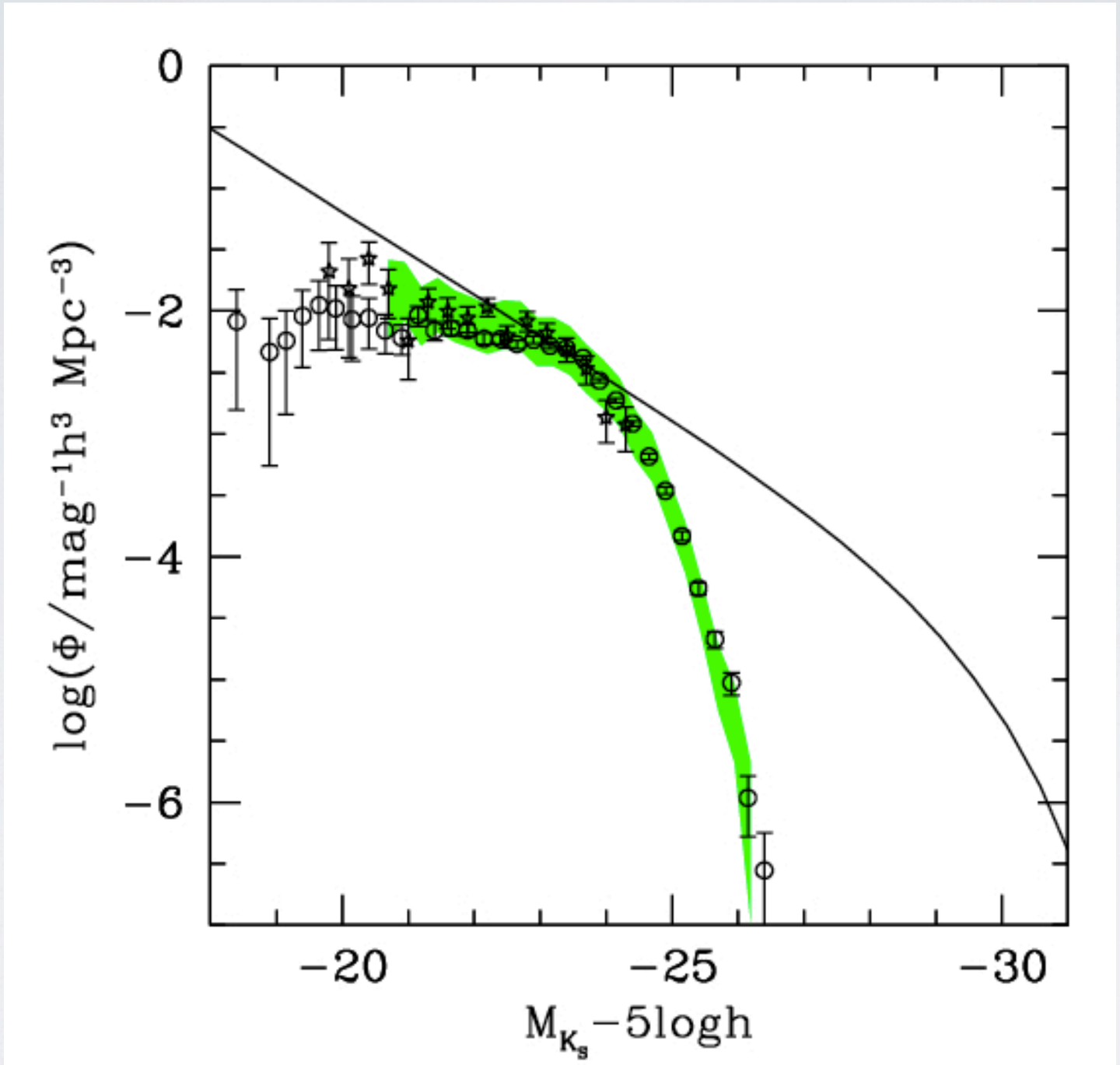
The **Fi**rst **B**illion **Y**ears Simulation

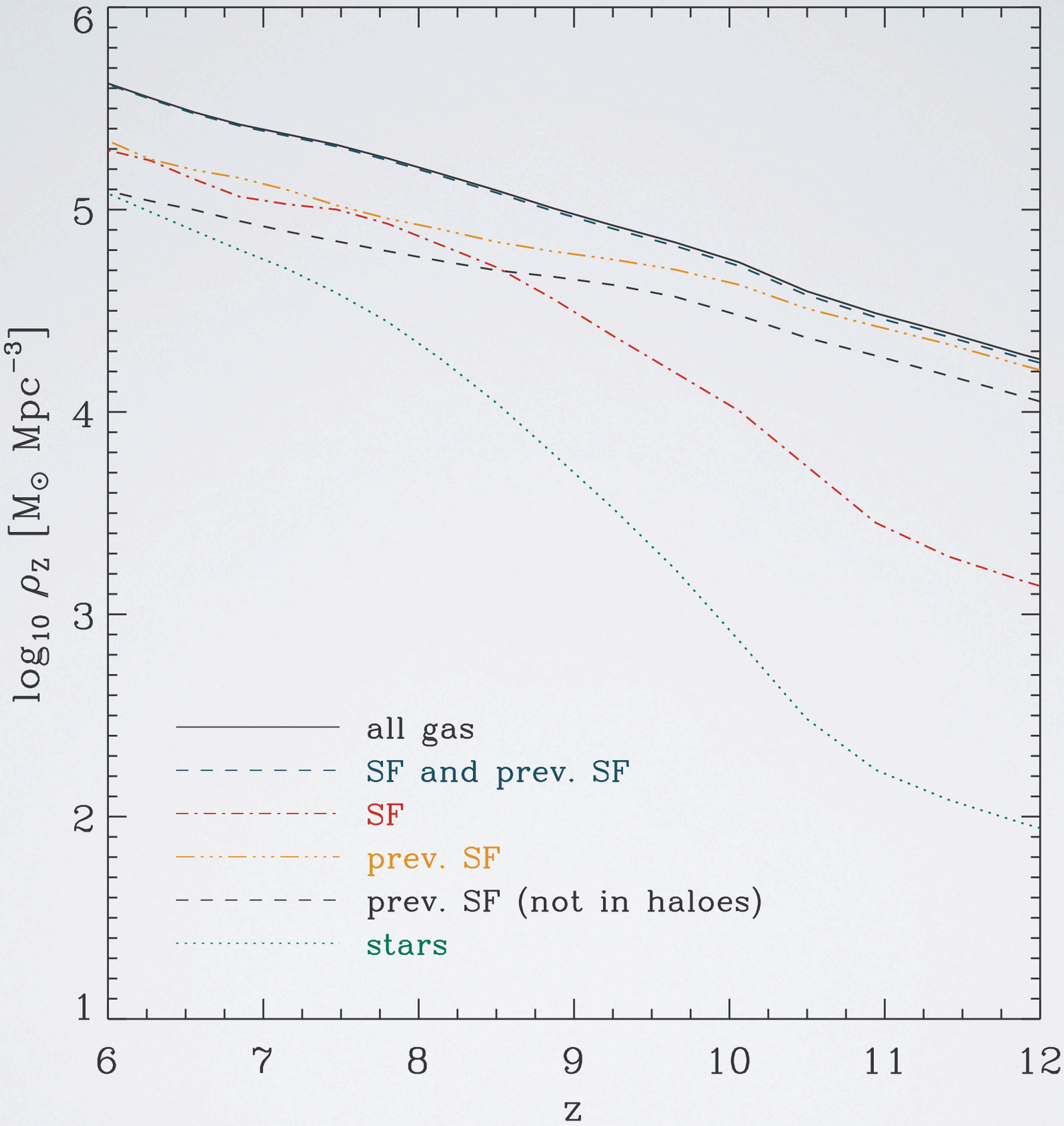
SN FEEDBACK AND METAL ENRICHMENT

Claudio Dalla Vecchia

Sadegh Khochfar, Jarrett Johnson, Jan-Pieter Paardekooper

Andrew Davis, Bhaskar Agarwal


0
−2
−4
−6
log(Φ/mag⁻¹h³ Mpc⁻³)
−20
−25
−30
M_Ks − 5logh

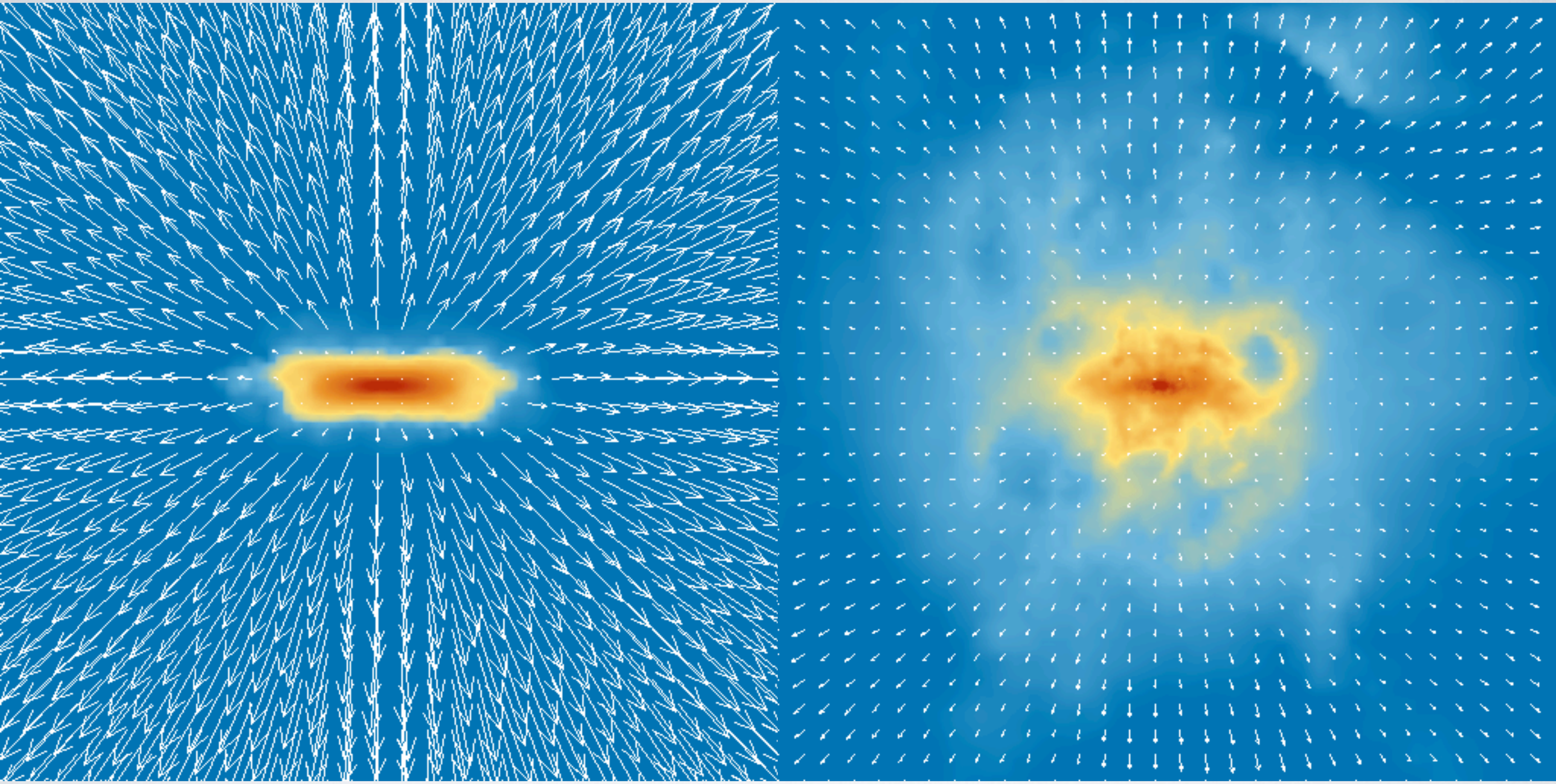

6
5
4
3
2
1
6
7
8
9
10
11
12
z
log10 ρz [M⊙ Mpc−3]
all gas
SF and prev. SF
SF
prev. SF
prev. SF (not in haloes)
stars

Martin et al., 2005

Murray et al., 2005

Springel & Hernquist, 2003

Dalla Vecchia & Schaye, 2008



The **Fi**rst **B**illion **Y**ears Simulation

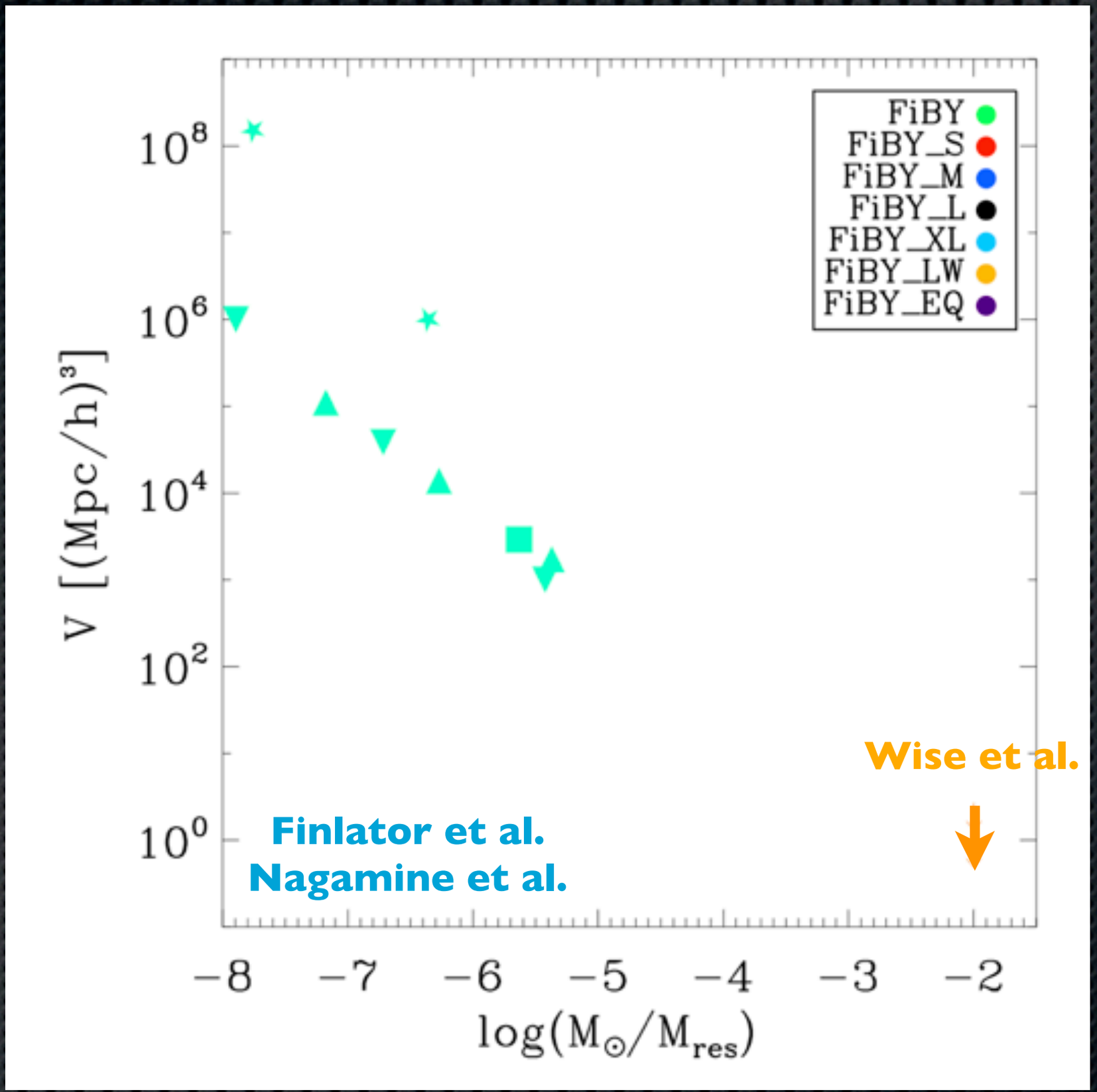
formation of the first mini-haloes via molecular cooling
transition from pop-III to pop-II star formation
formation of the first galaxies and their contribution to reionization
early enrichment of the universe

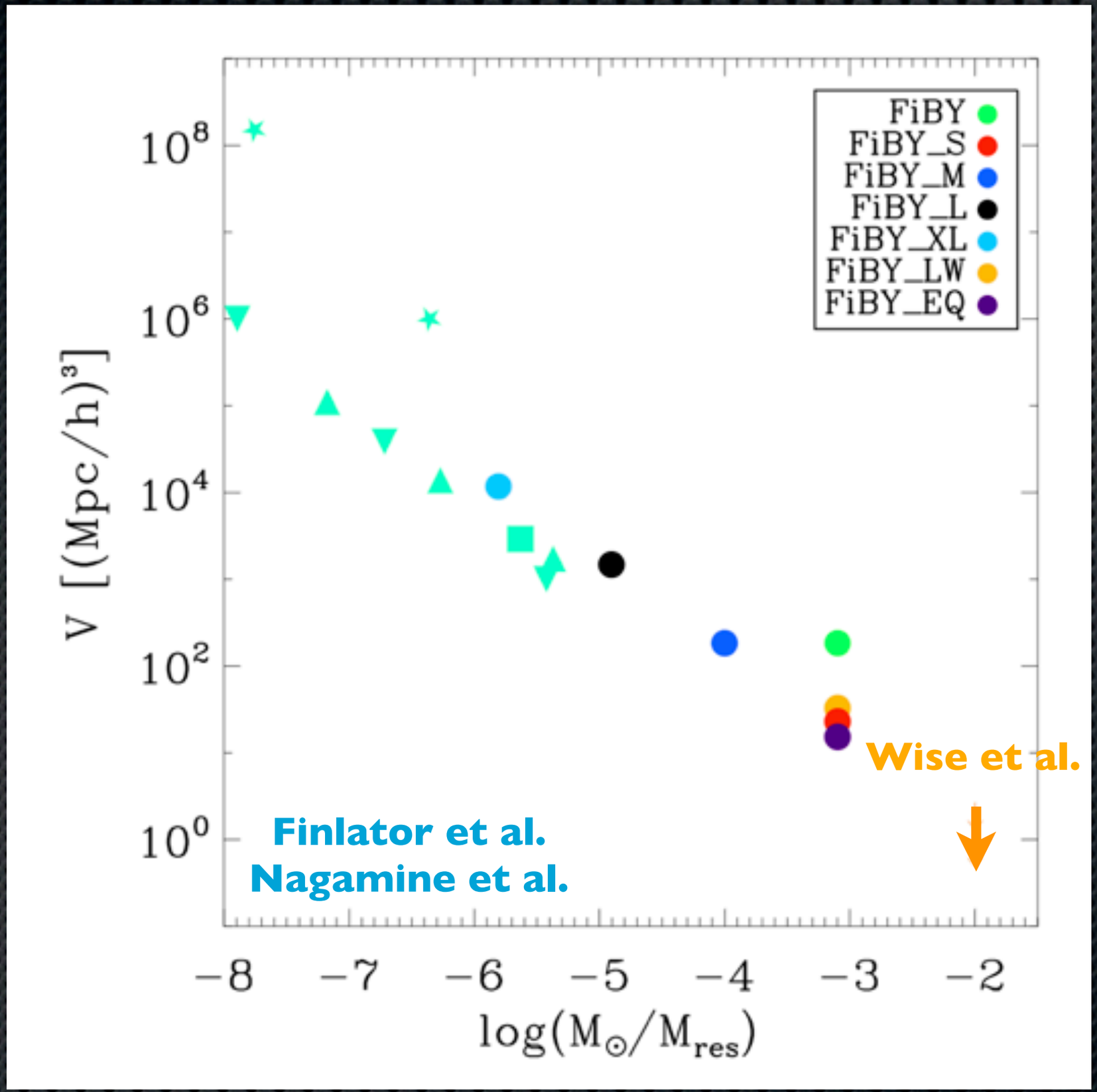
SIMULATIONS

	L [Mpc]	$(N_{GAS})^{1/3}$	$(N_{DM})^{1/3}$
FiBY	8	1368	1368
FiBY-S	4	684	684
FiBY-M	8	684	684
FiBY-X	16	684	684
FiBY-XL	32	684	684
FiBY-LW	4	684	684
FiBY-EQ	4	684	1521

SIMULATIONS

	L [Mpc]		
FiBY	8	$m_{\rm gas}$	$2h$
FiBY-S	**4**	1.25×10^3 $\mathrm{M}_\odot$	4.7×10^1 pc
FiBY-M	**8**	1.00×10^4 $\mathrm{M}_\odot$	9.4×10^1 pc
FiBY-X	**16**	8.02×10^4 $\mathrm{M}_\odot$	1.9×10^2 pc
FiBY-XL	**32**	6.42×10^5 $\mathrm{M}_\odot$	3.7×10^2 pc
FiBY-LW	4		
FiBY-EQ	4		


FiBY
FiBY_S
FiBY_M
FiBY_L
FiBY_XL
FiBY_LW
FiBY_EQ
10^8
10^6
10^4
10^2
10^0
ν [(Mpc/h)^3]
Finlator et al.
Nagamine et al.
Wise et al.
−8
−7
−6
−5
−4
−3
−2
$\log(M_\odot/M_{res})$


FiBY
FiBY_S
FiBY_M
FiBY_L
FiBY_XL
FiBY_LW
FiBY_EQ
10^8
10^6
10^4
10^2
10^0
ν [(Mpc/h)^3]
Finlator et al.
Nagamine et al.
Wise et al.
−8
−7
−6
−5
−4
−3
−2
$\log(M_\odot/M_{res})$

S. Khochfar

SIMULATION CODE

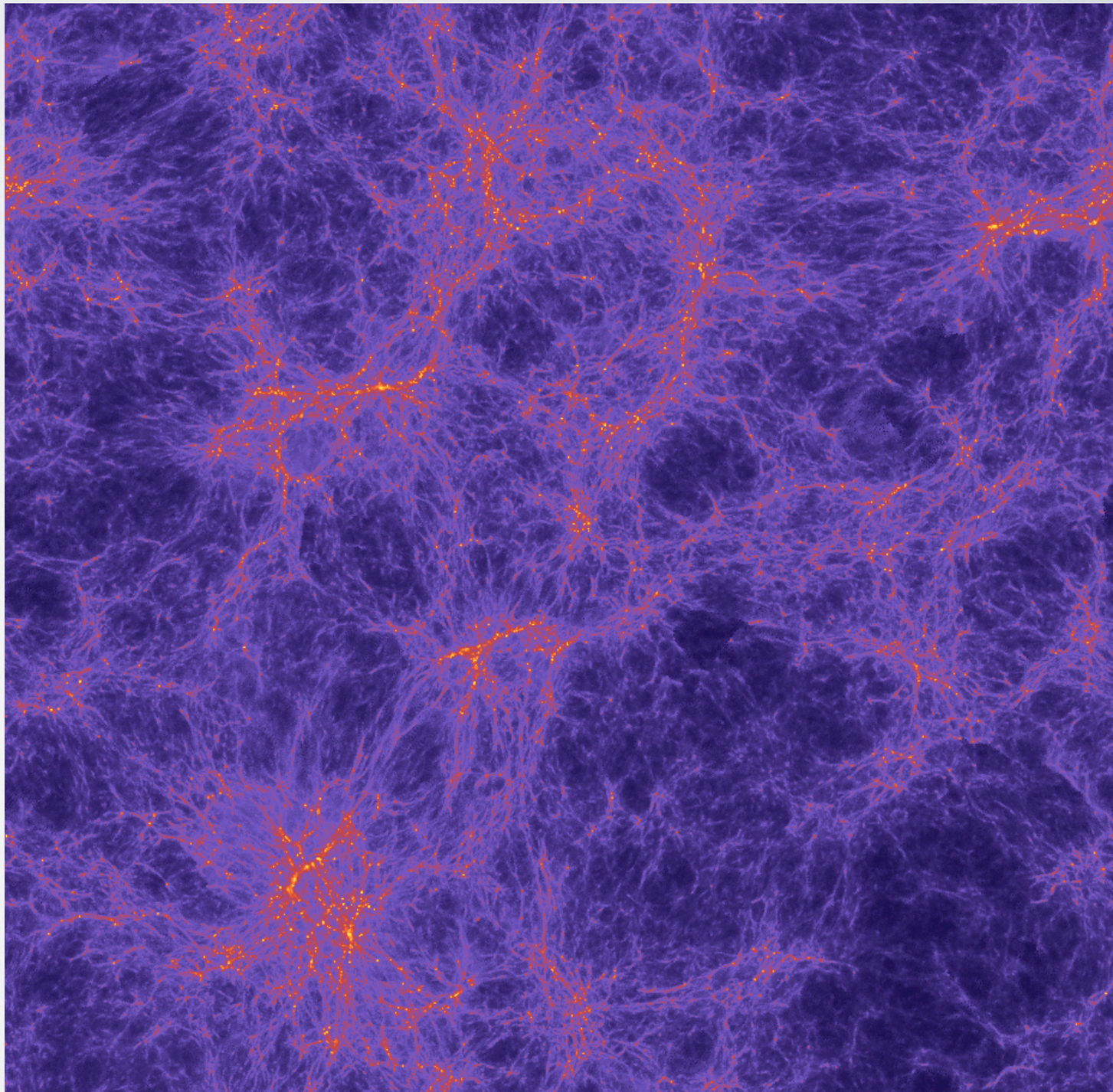
Gadget-2, OWLS/GIMIC
(Schaye et al, 2010)

pressure dependent SFR
(Schaye & Dalla Vecchia, 2008)

enrichment by SN Ia, SN II, AGB
(Wiersma et al, 2009)

metal line cooling
(Wiersma, Schaye & Smith, 2009)

kinetic SN II feedback
(Dalla Vecchia & Schaye, 2008)



SIMULATION CODE

H_2/HD formations and cooling

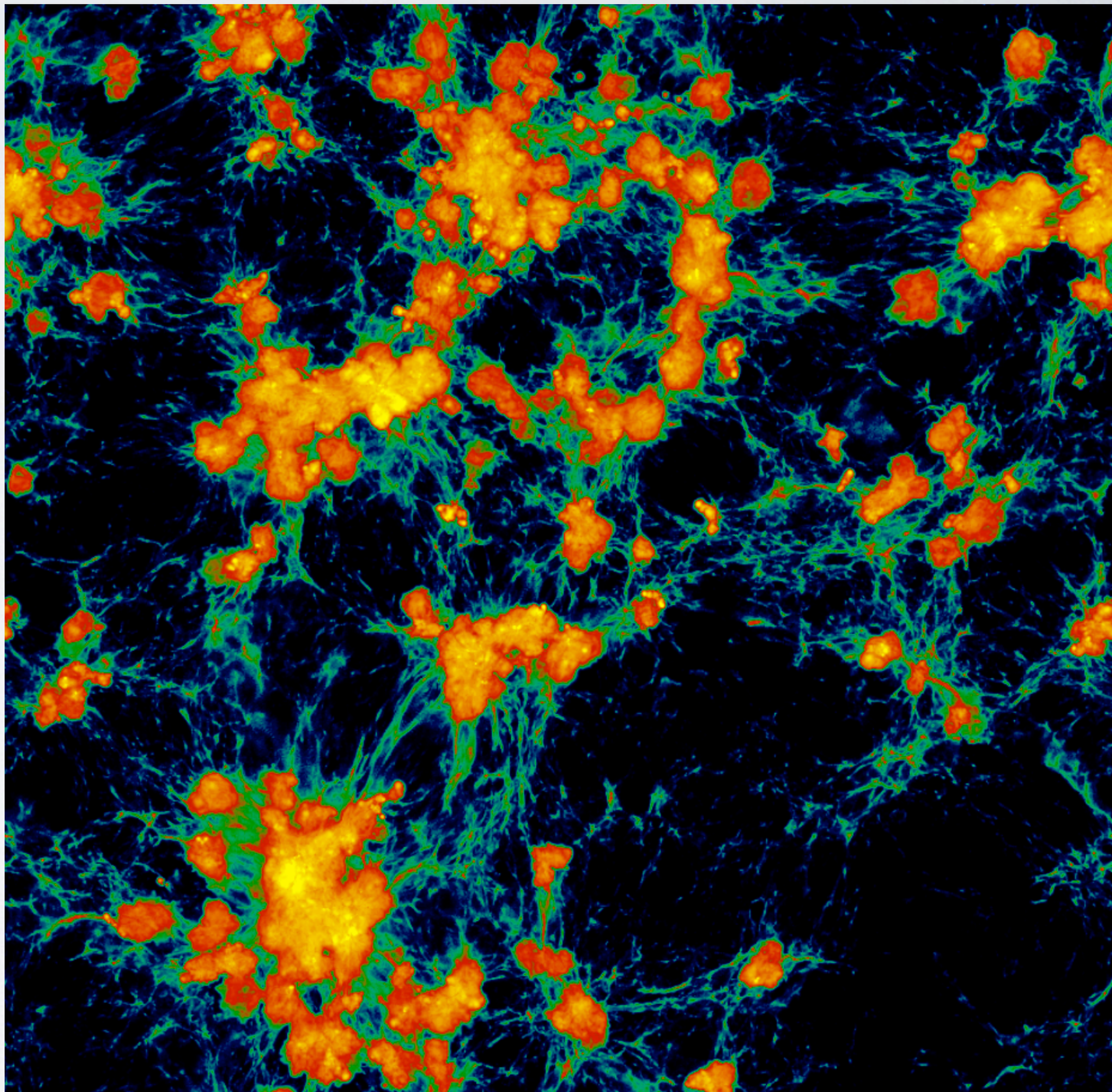
self-shielding

pop-III star formation, yields

thermal PISN/SN II feedback
(Dalla Vecchia & Schaye, 2012)

dust yields, sputtering

pop-III BH remnants



THERMAL PISN/SN II FEEDBACK

Total SN II energy from a SSP

$$\epsilon_{\mathrm{SNII}} = 8.73 \times 10^{15}\ \mathrm{erg\ g^{-1}} \left(\frac{n_{\mathrm{SNII}}}{1.736 \times 10^{-2}\ \mathrm{M_\odot^{-1}}} \right) E_{51} \qquad (6 < M_{\mathrm{SNII}}/\mathrm{M_\odot} < 100)$$

$$\Delta T = 4.23 \times 10^{7}\ \mathrm{K} \left(\frac{n_{\mathrm{SNII}}}{1.736 \times 10^{-2}\ \mathrm{M_\odot^{-1}}} \right) \left(\frac{\mu}{0.6} \right) E_{51} \frac{m_*}{m_{\mathrm{g,heat}}}$$

(Dalla Vecchia & Schaye, 2012)

THERMAL PISN/SN II FEEDBACK

Total SN II energy from a SSP

$$\epsilon_{\rm SNII} = 8.73 \times 10^{15}\ {\rm erg\ g^{-1}} \left(\frac{n_{\rm SNII}}{1.736 \times 10^{-2}\ {\rm M_\odot^{-1}}} \right) E_{51} \qquad (6 < M_{\rm SNII}/{\rm M_\odot} < 100)$$

$$\boxed{\Delta T} = 4.23 \times 10^{7}\ {\rm K} \left(\frac{n_{\rm SNII}}{1.736 \times 10^{-2}\ {\rm M_\odot^{-1}}} \right) \left(\frac{\mu}{0.6} \right) E_{51} \frac{m_*}{m_{\rm g,heat}}$$

only parameter in the model

(Dalla Vecchia & Schaye, 2012)

THERMAL PISN/SN II FEEDBACK

Avoiding over-cooling

$$\frac{t_{\rm cool}}{t_{\rm sound}} = 4.5 \times 10^2 \, F(\mu, N_{\rm ngb}, X_{\rm H}) \left(\frac{n_{\rm H}}{0.1 \ {\rm cm}^{-3}}\right)^{-2/3} \left(\frac{T}{10^{7.5} \ {\rm K}}\right) \left(\frac{\langle m \rangle}{7 \times 10^4 \ {\rm M}_\odot}\right)^{-1/3}$$

$$n_{\rm H}(t_{\rm cool} = t_{\rm sound}) = 9.7 \times 10^2 \, [F(\mu, N_{\rm ngb}, X_{\rm H})]^{3/2} \left(\frac{T}{10^{7.5} \ {\rm K}}\right)^{3/2} \left(\frac{\langle m \rangle}{7 \times 10^4 \ {\rm M}_\odot}\right)^{-1/2}$$

(Dalla Vecchia & Schaye, 2012)

THERMAL PISN/SN II FEEDBACK

Avoiding over-cooling

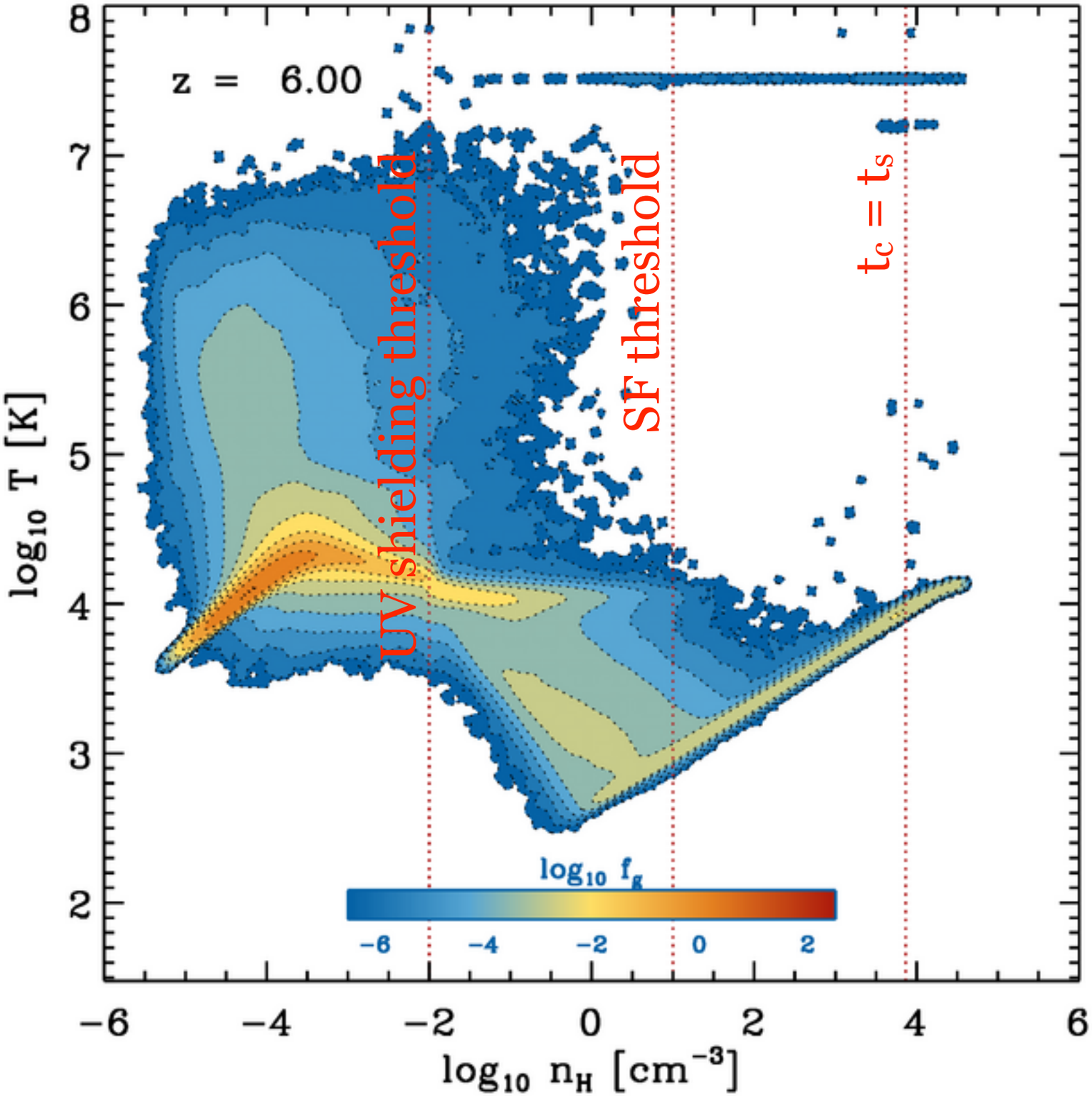
$$\frac{t_{\rm cool}}{t_{\rm sound}} = 4.5 \times 10^2 \, F(\mu, N_{\rm ngb}, X_{\rm H}) \left(\frac{n_{\rm H}}{0.1 \ {\rm cm}^{-3}}\right)^{-2/3} \left(\frac{T}{10^{7.5} \ {\rm K}}\right) \left(\frac{\langle m \rangle}{7 \times 10^4 \ {\rm M}_\odot}\right)^{-1/3}$$

$$n_{\rm H}(t_{\rm cool} = t_{\rm sound}) = 9.7 \times 10^2 \, [F(\mu, N_{\rm ngb}, X_{\rm H})]^{3/2} \left(\frac{T}{10^{7.5} \ {\rm K}}\right)^{3/2} \left(\frac{\langle m \rangle}{7 \times 10^4 \ {\rm M}_\odot}\right)^{-1/2}$$

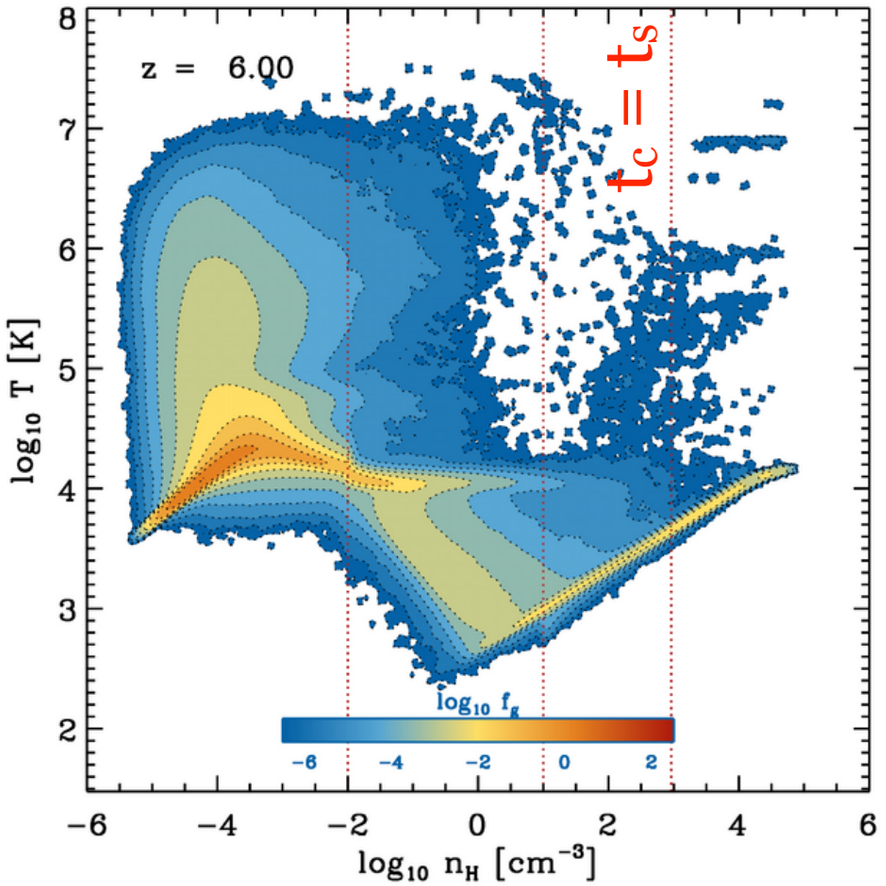
density criterion

(Dalla Vecchia & Schaye, 2012)

L = 4 Mpc



L = 16 Mpc

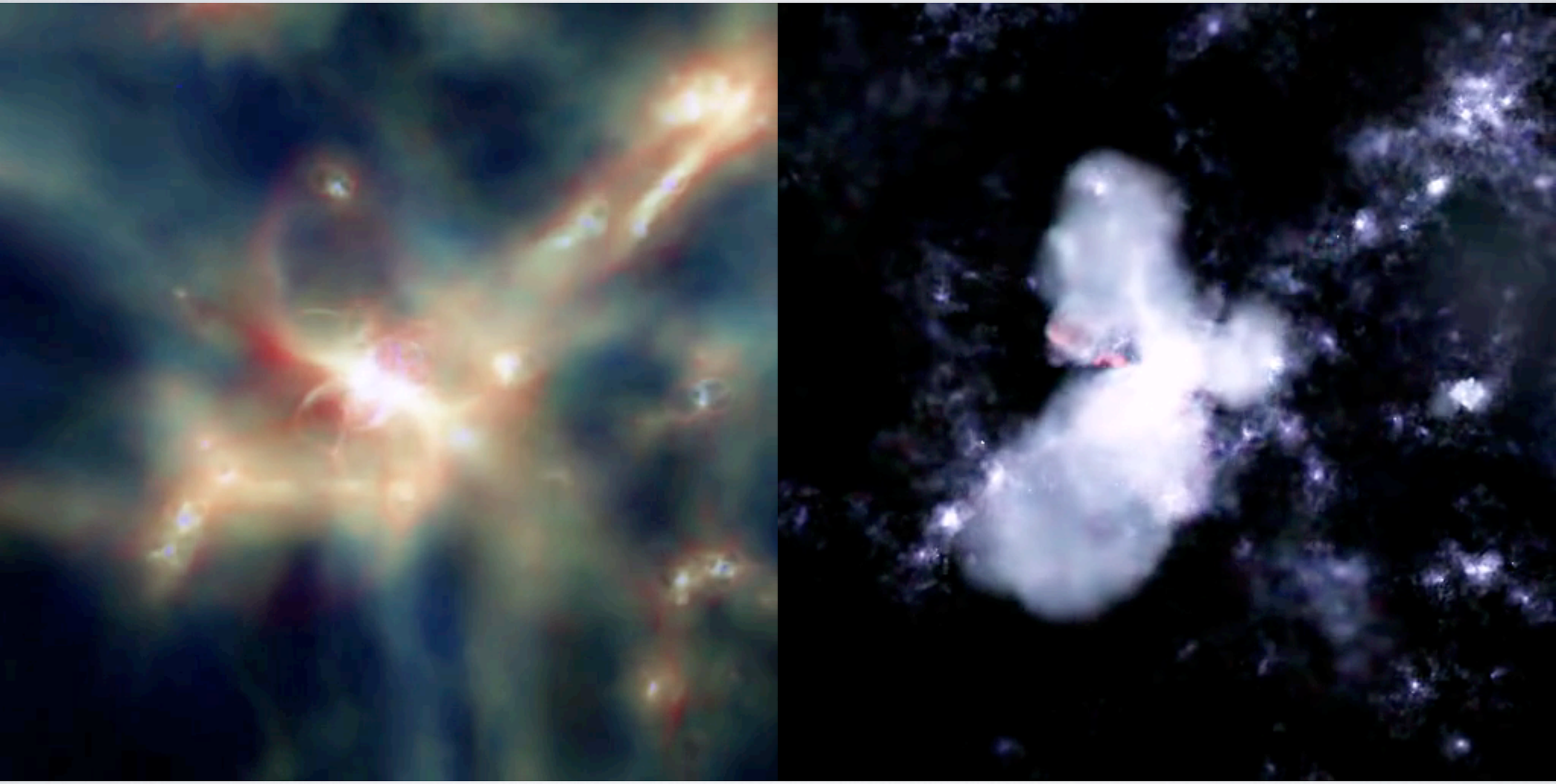


more details in
Creasey, Theuns et al. (2011)

$$n_{\rm H}(t_{\rm cool} = t_{\rm sound}) = 9.7 \times 10^2 \left[F(\mu, N_{\rm ngb}, X_{\rm H})\right]^{3/2} \left(\frac{T}{10^{7.5}\ {\rm K}}\right)^{3/2} \left(\frac{\langle m \rangle}{7 \times 10^4\ {\rm M}_\odot}\right)^{-1/2}$$

gas mass density

metal mass density

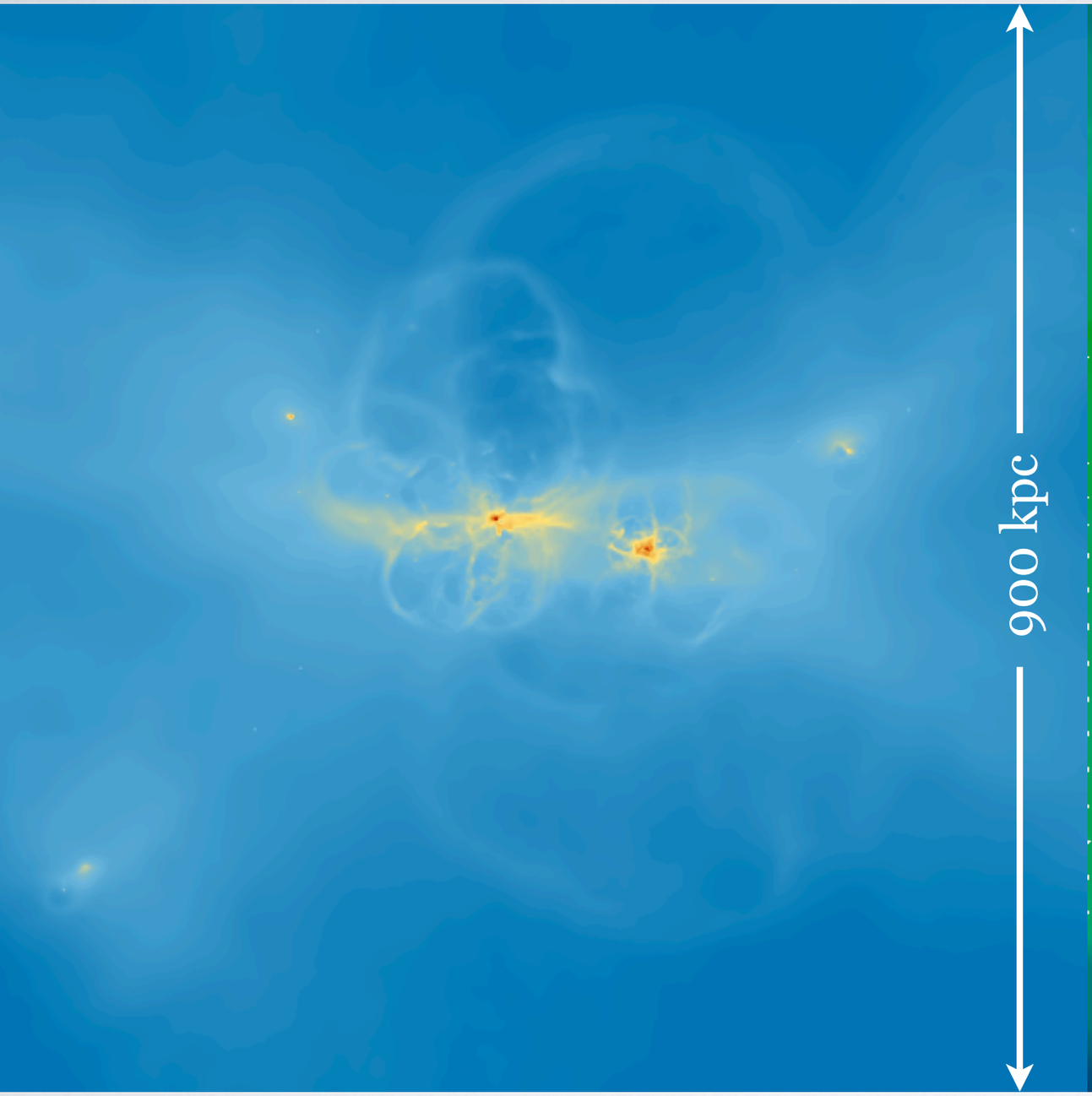


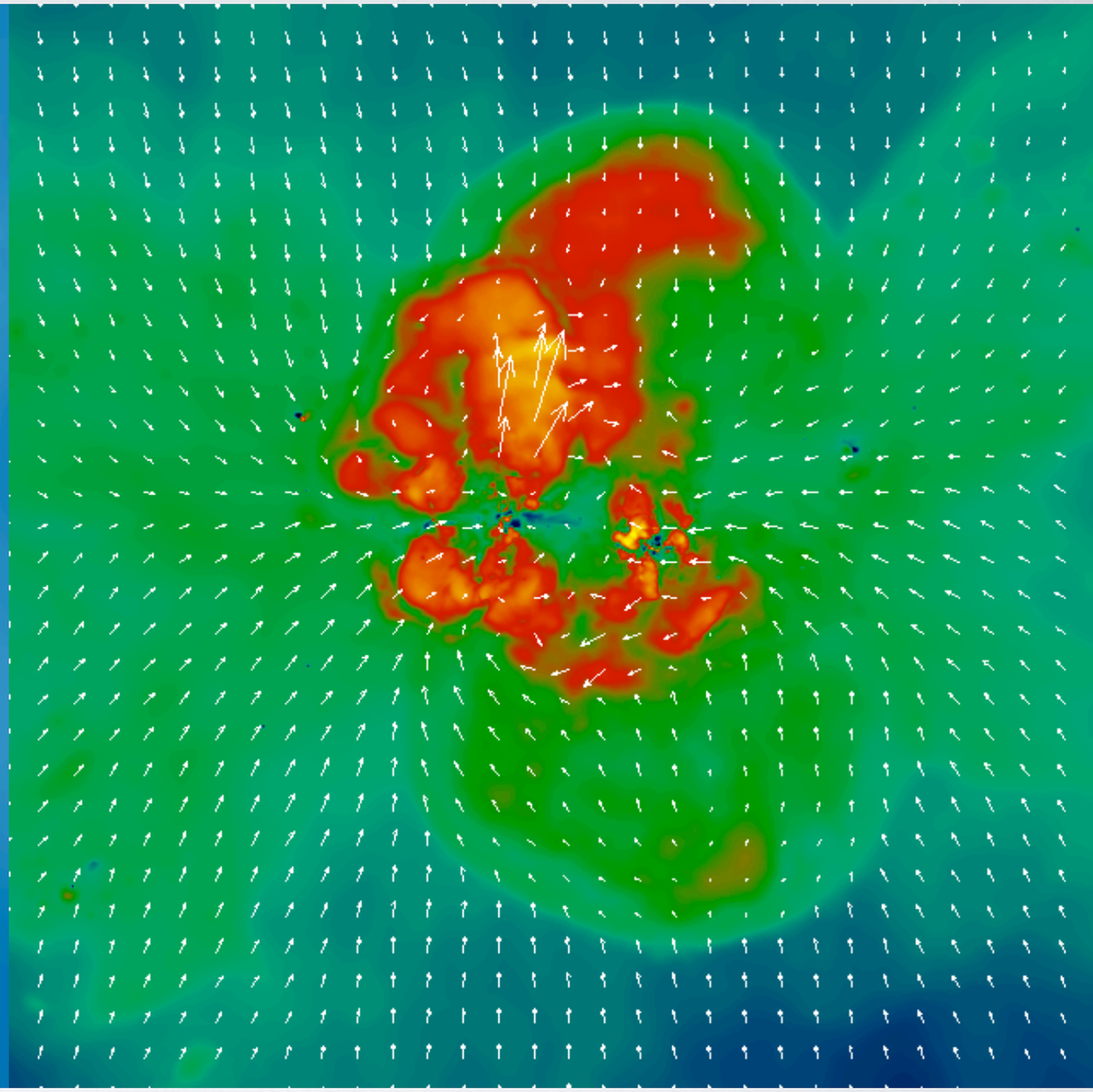
region centred on the most massive galaxy, evolved from z~30 to z=6

z =6

gas density

gas temperature and velocity field

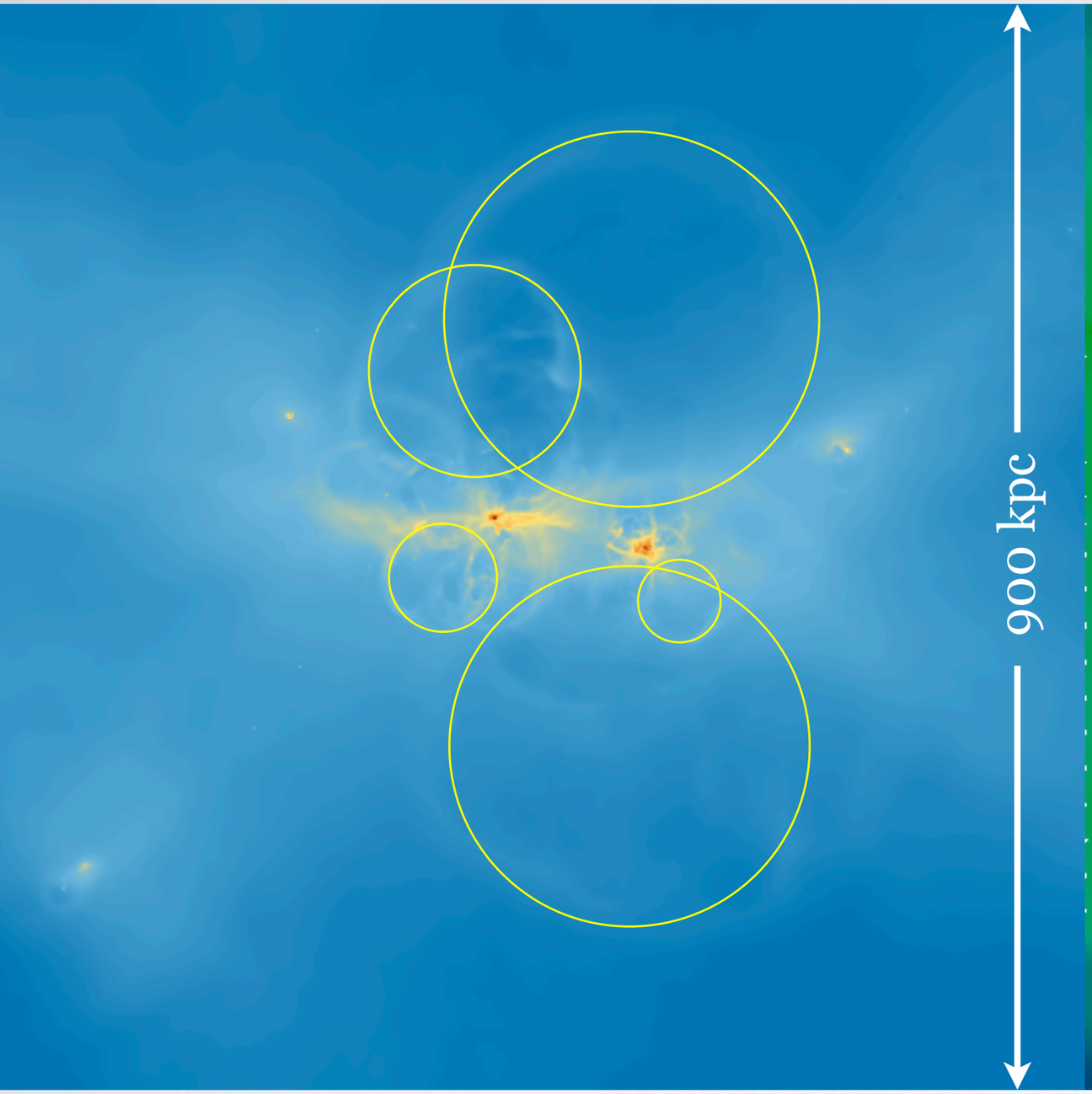


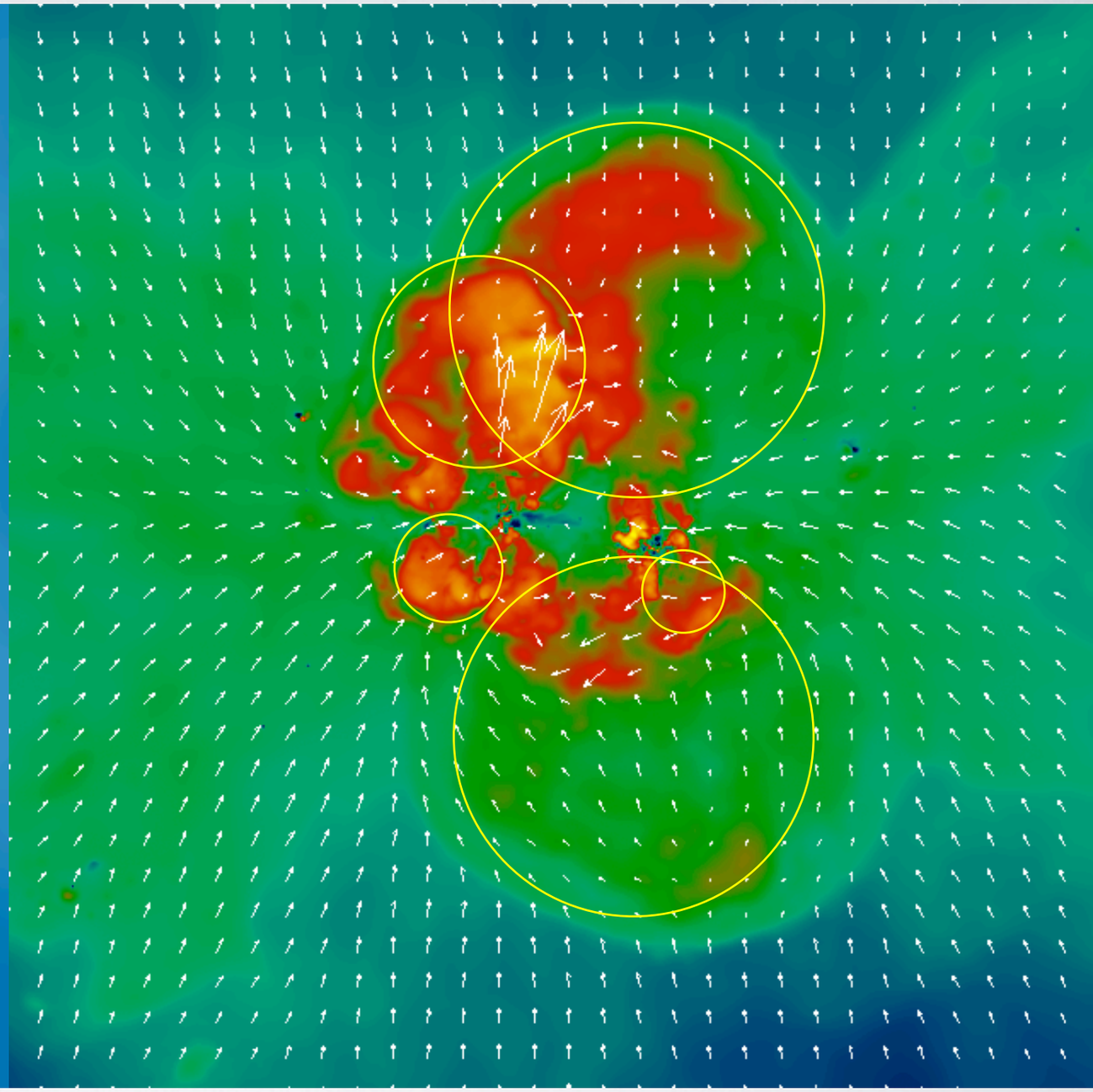


z =6

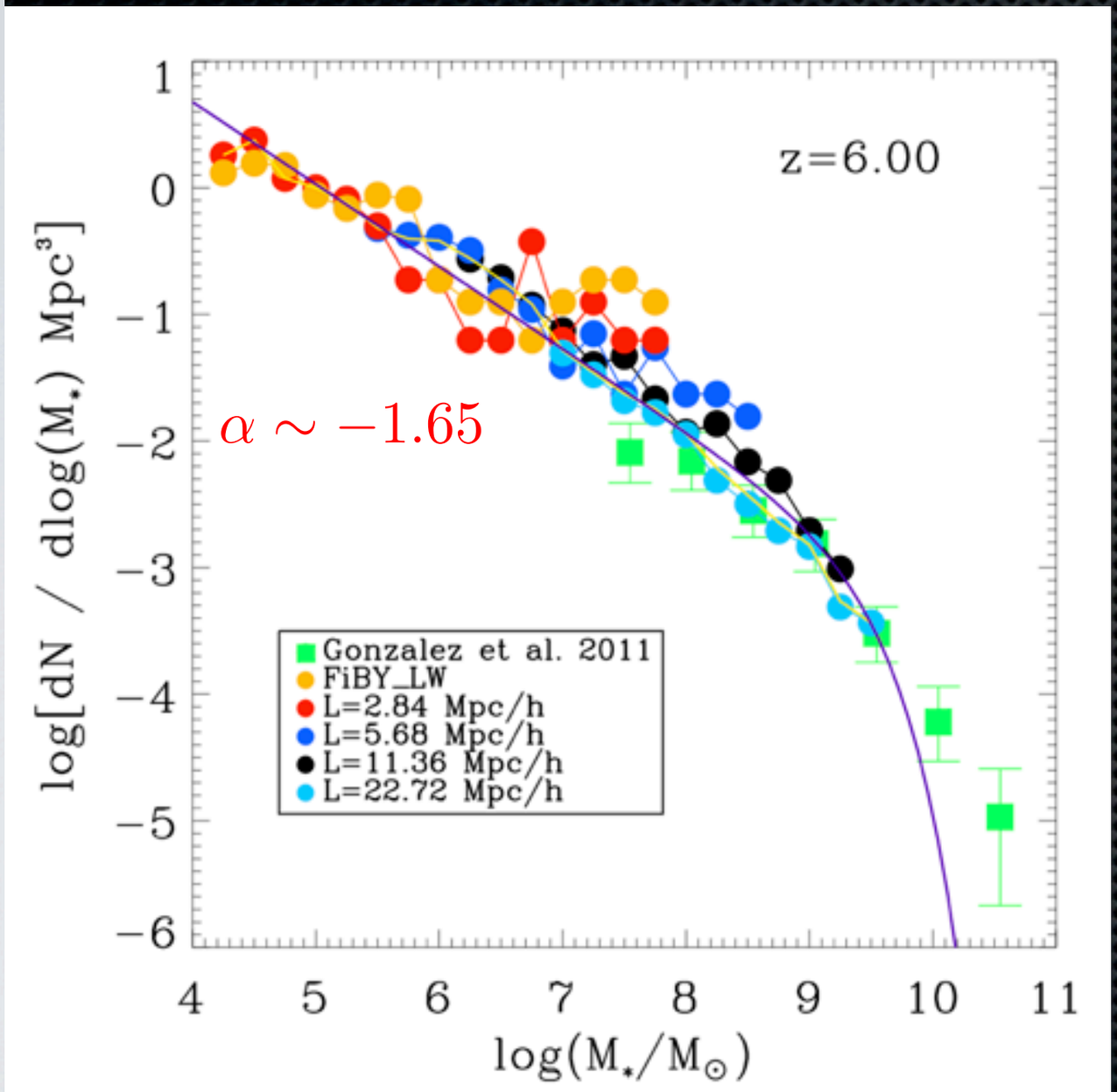
gas density

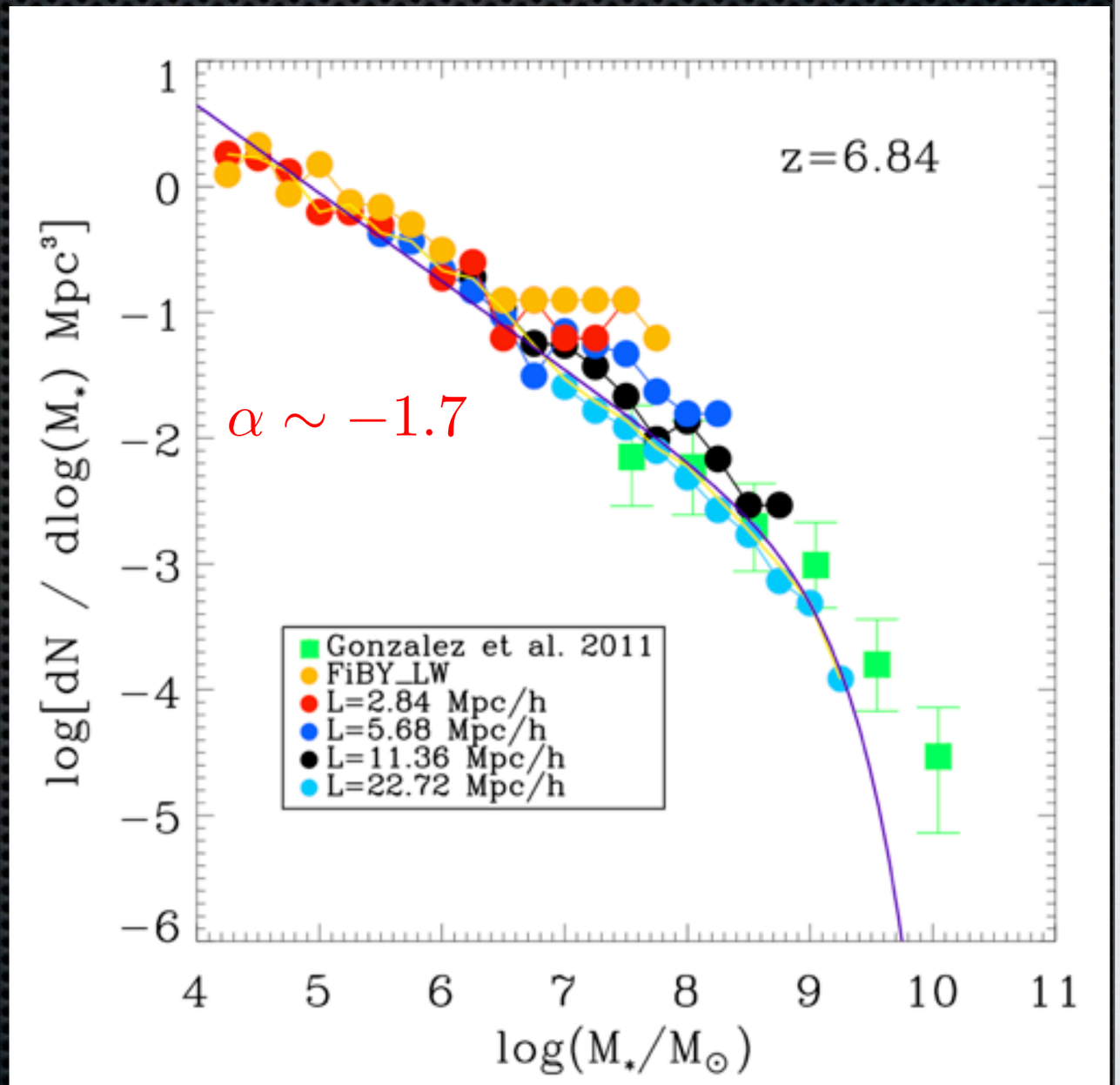
gas temperature and velocity field



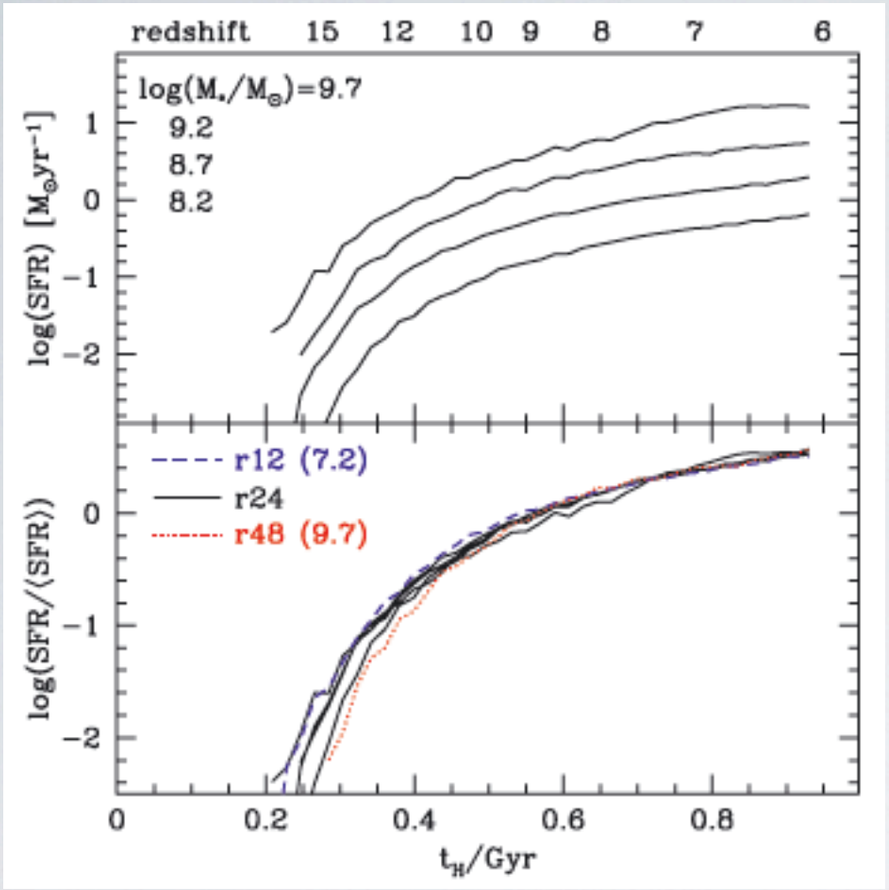


Stellar Mass Function

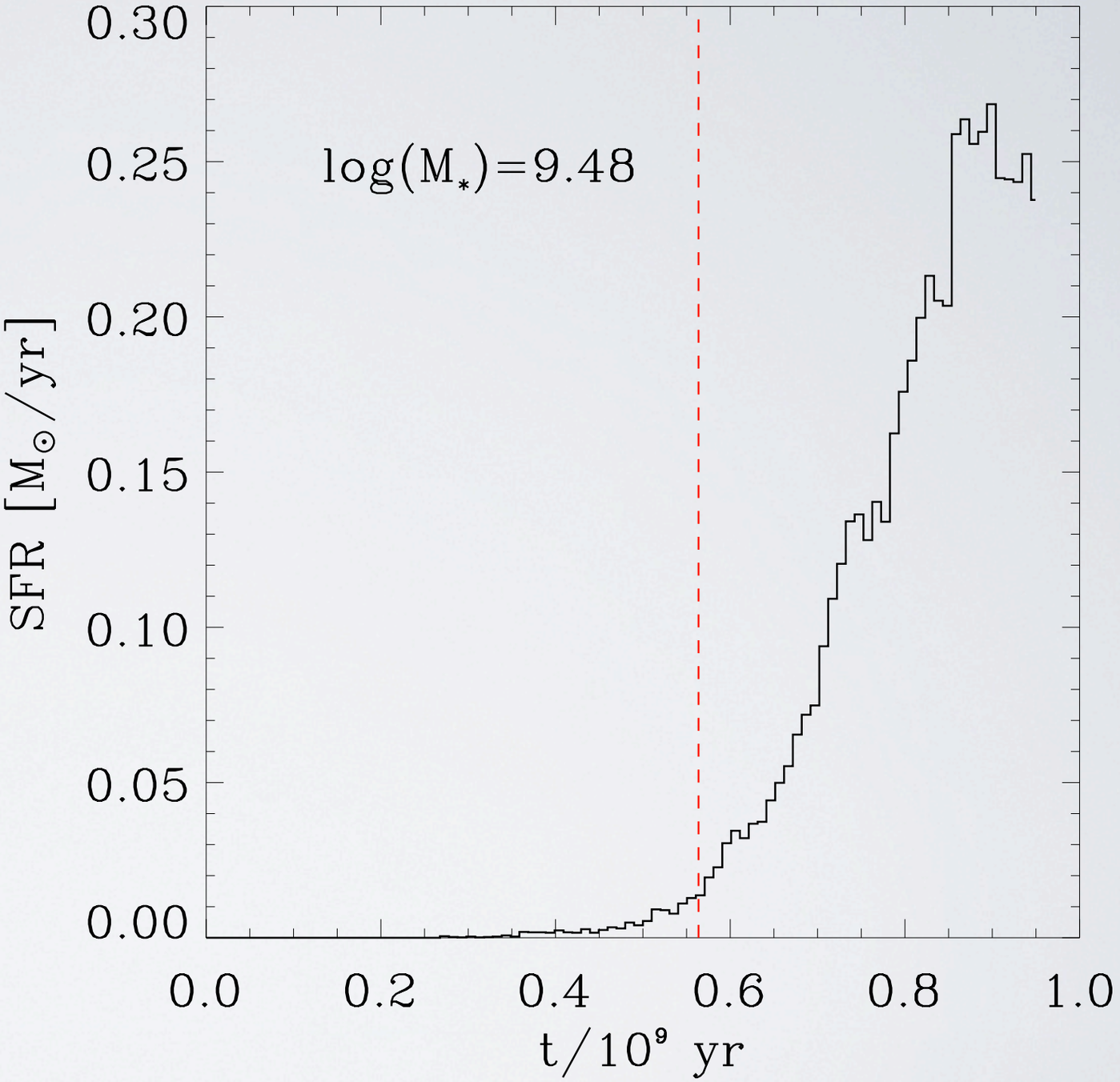


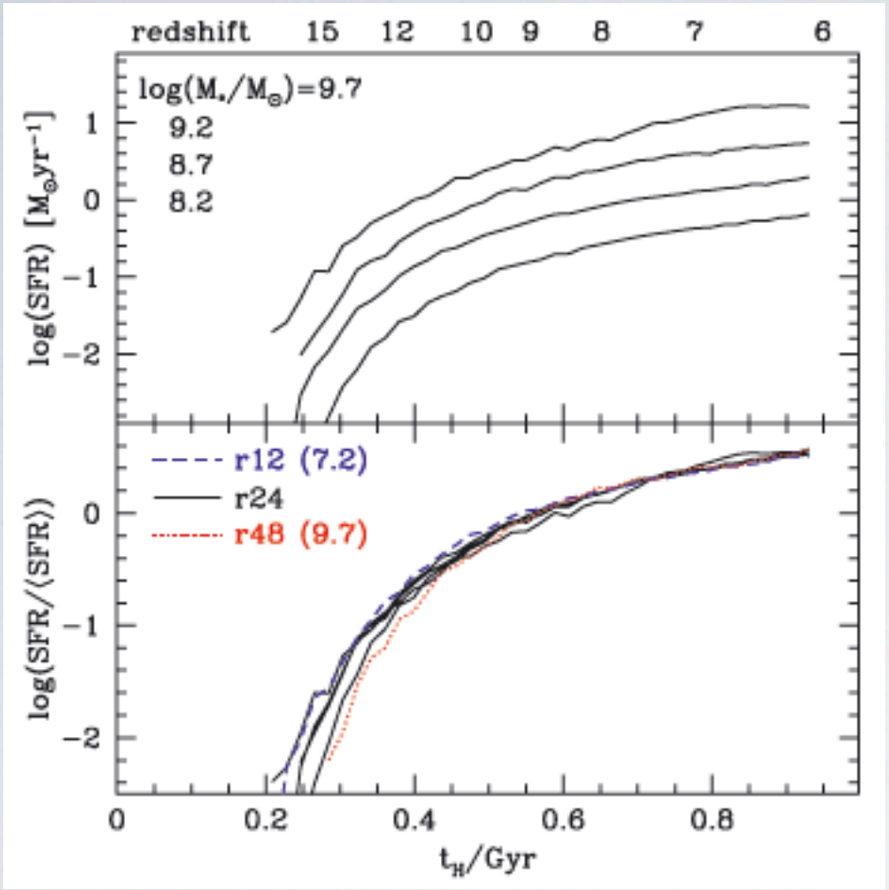


Khochfar et al 2013

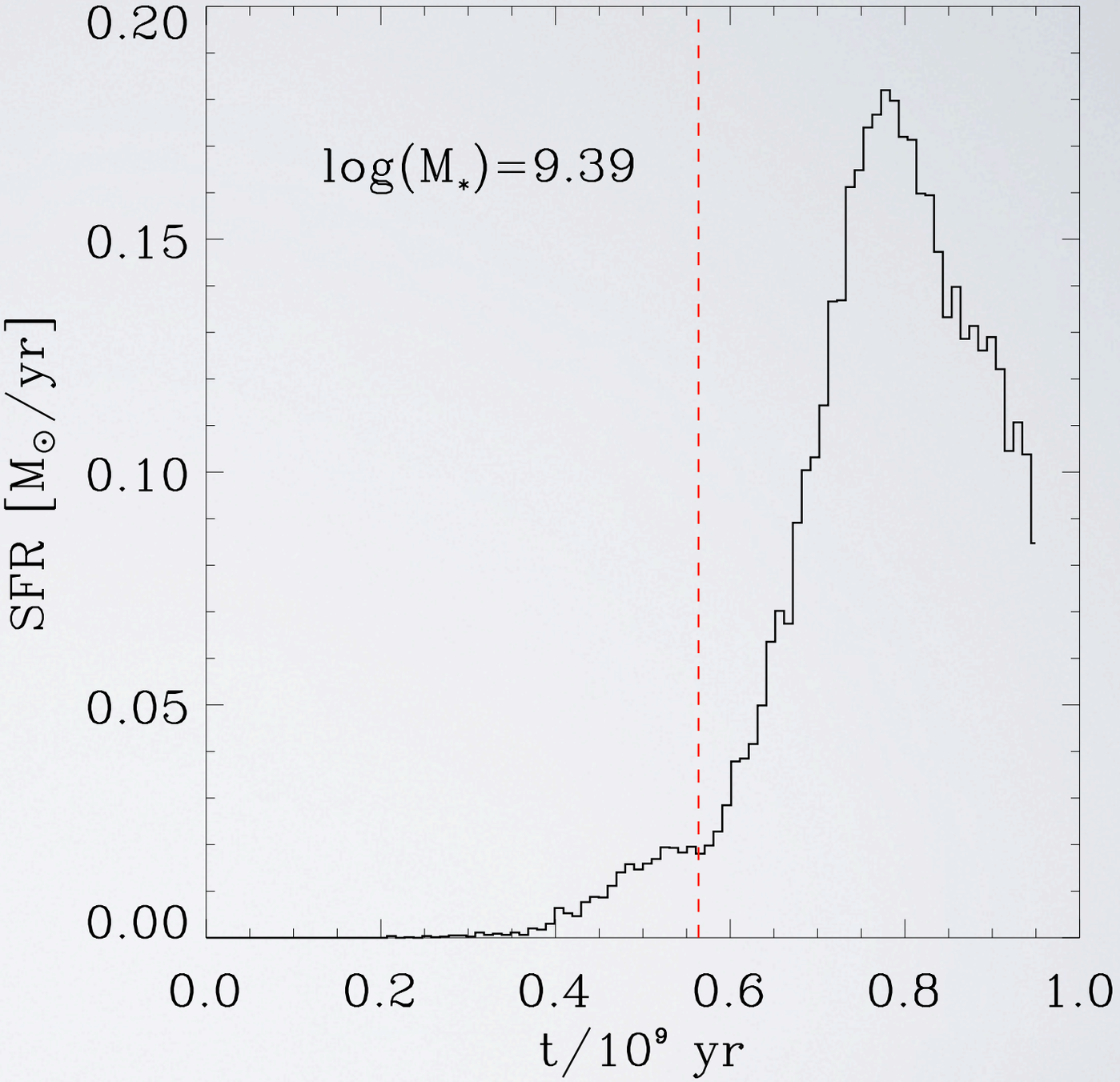


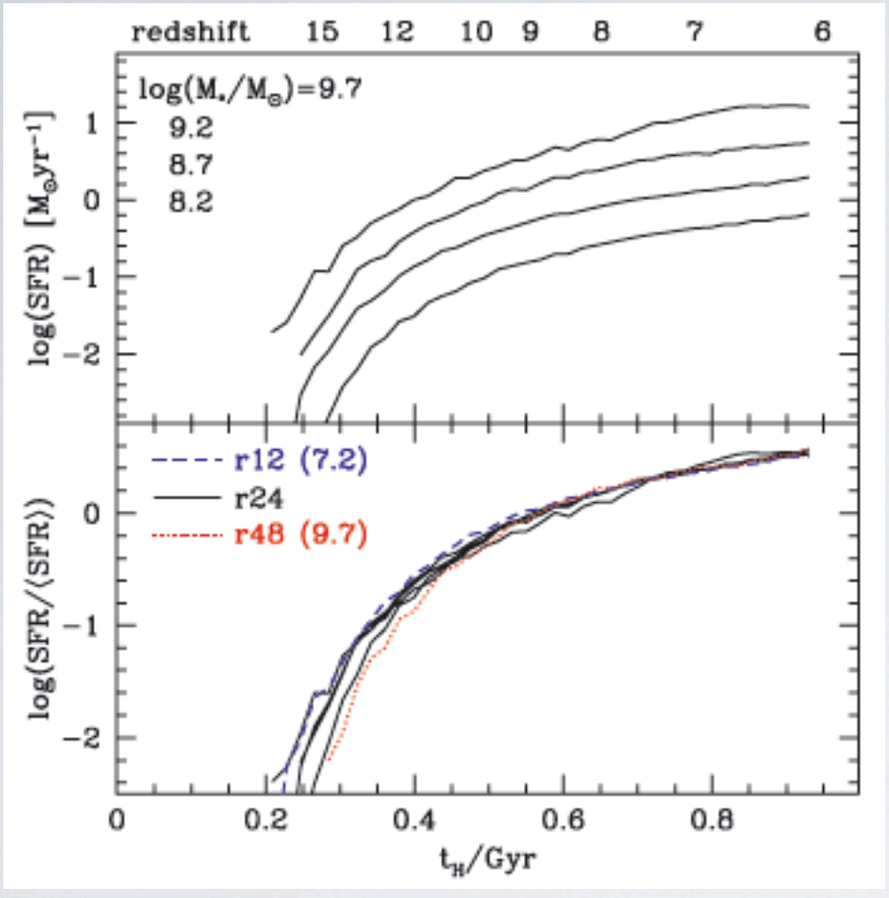
(Finlator et al., 2011)



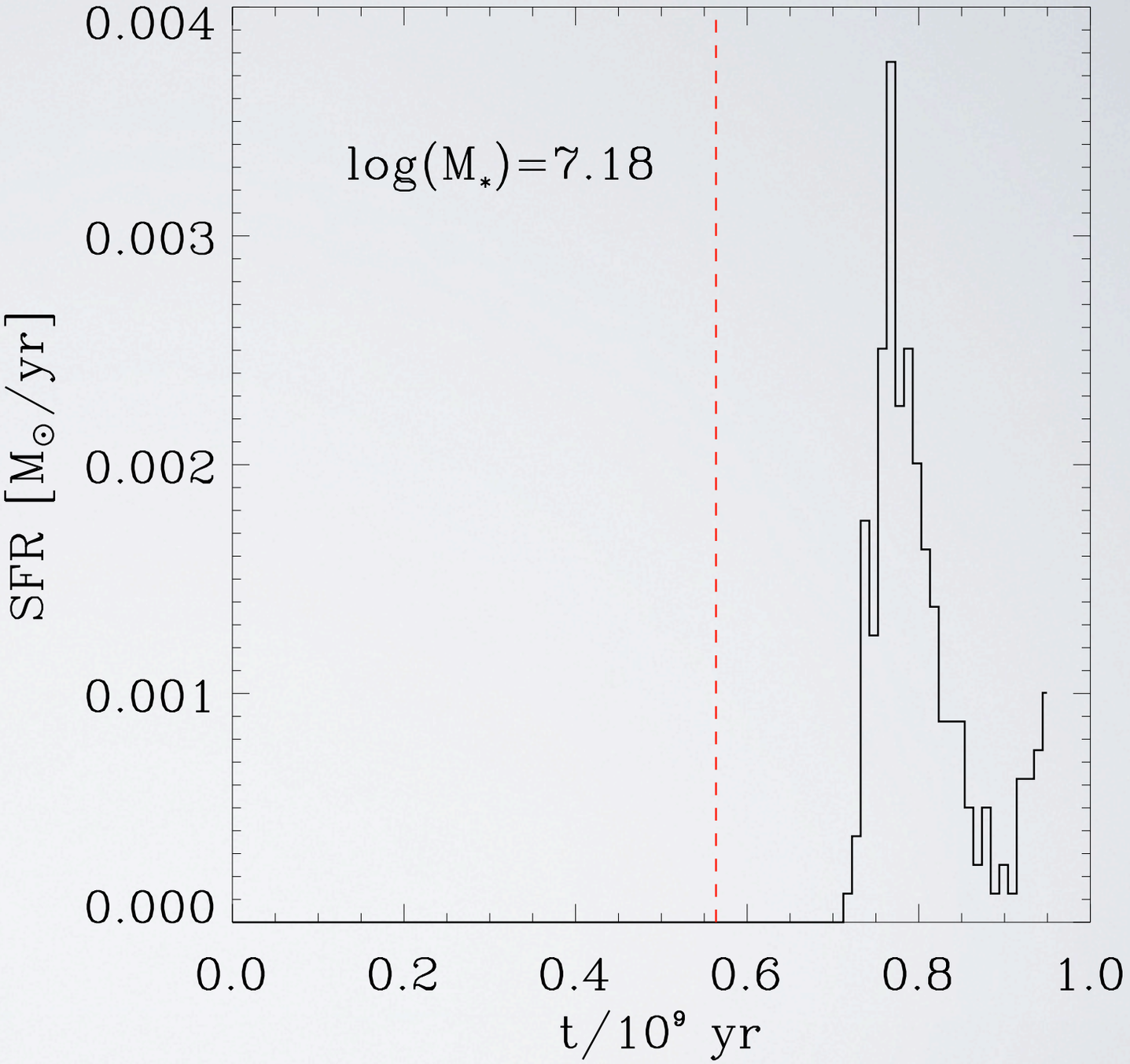


(Finlator et al., 2011)





(Finlator et al., 2011)

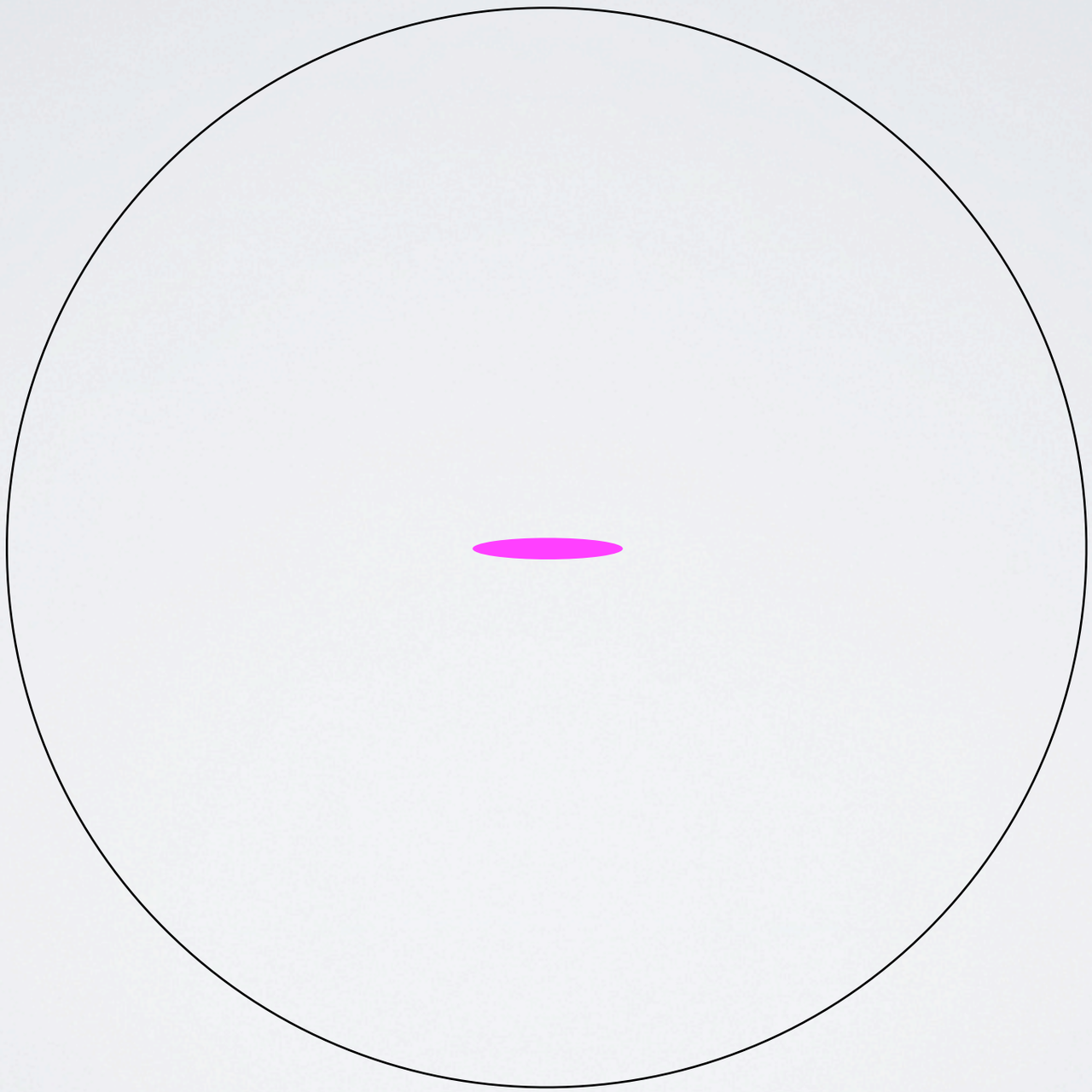


$$\dot{M}_{\rm gas} = \dot{M}_{\rm acc} - \dot{M}_{*} + \dot{M}_{*,\rm yield} - \dot{M}_{\rm out}$$

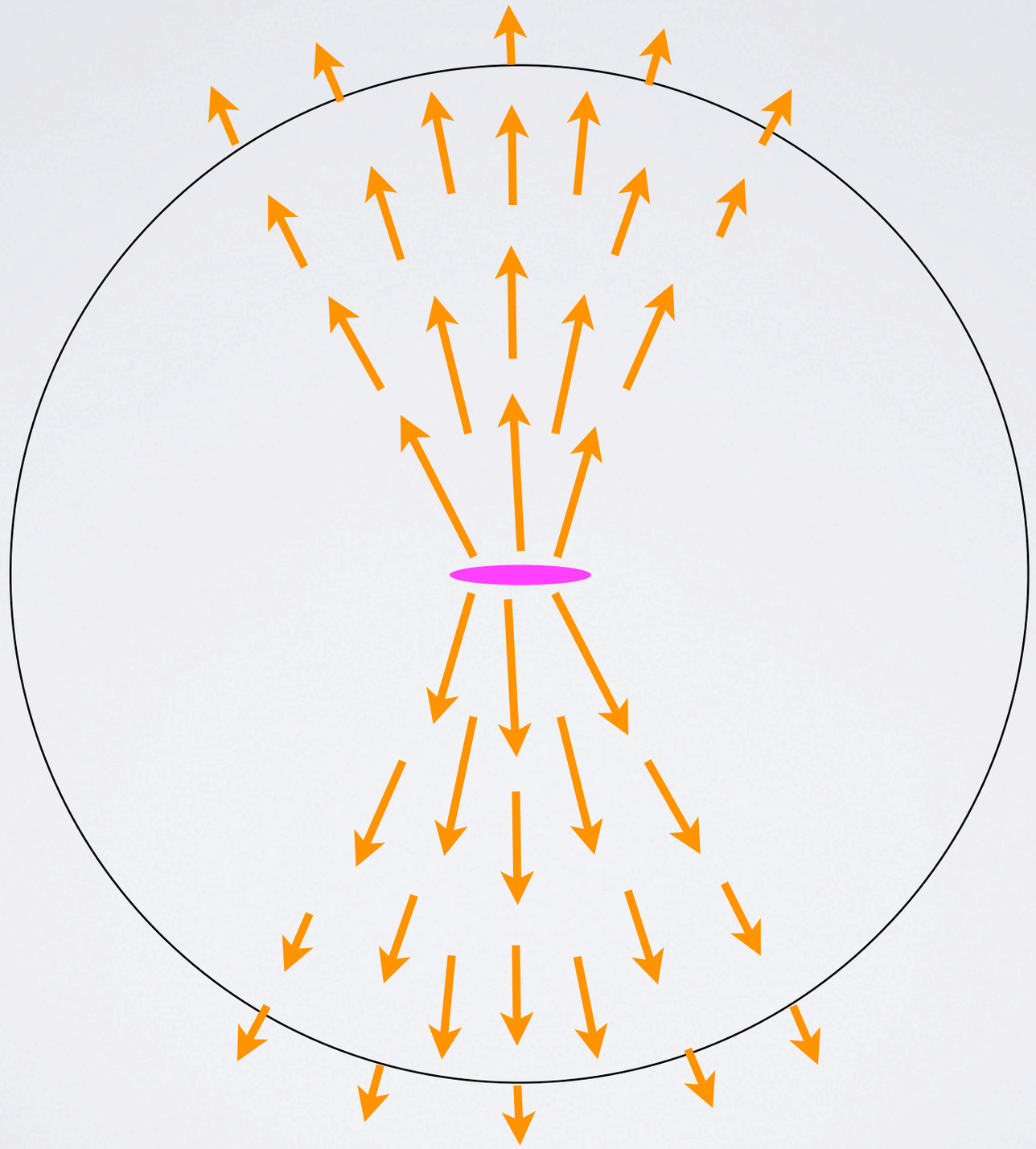
$$\eta = \frac{\dot{M}_{\rm out}}{\dot{M}_{*}}$$

$$\dot{M}_{\rm Z,gas} = \dot{M}_{\rm Z,acc} - \dot{M}_{\rm Z*,lock} + \dot{M}_{\rm Z*,prod} - \dot{M}_{\rm Z,out}$$

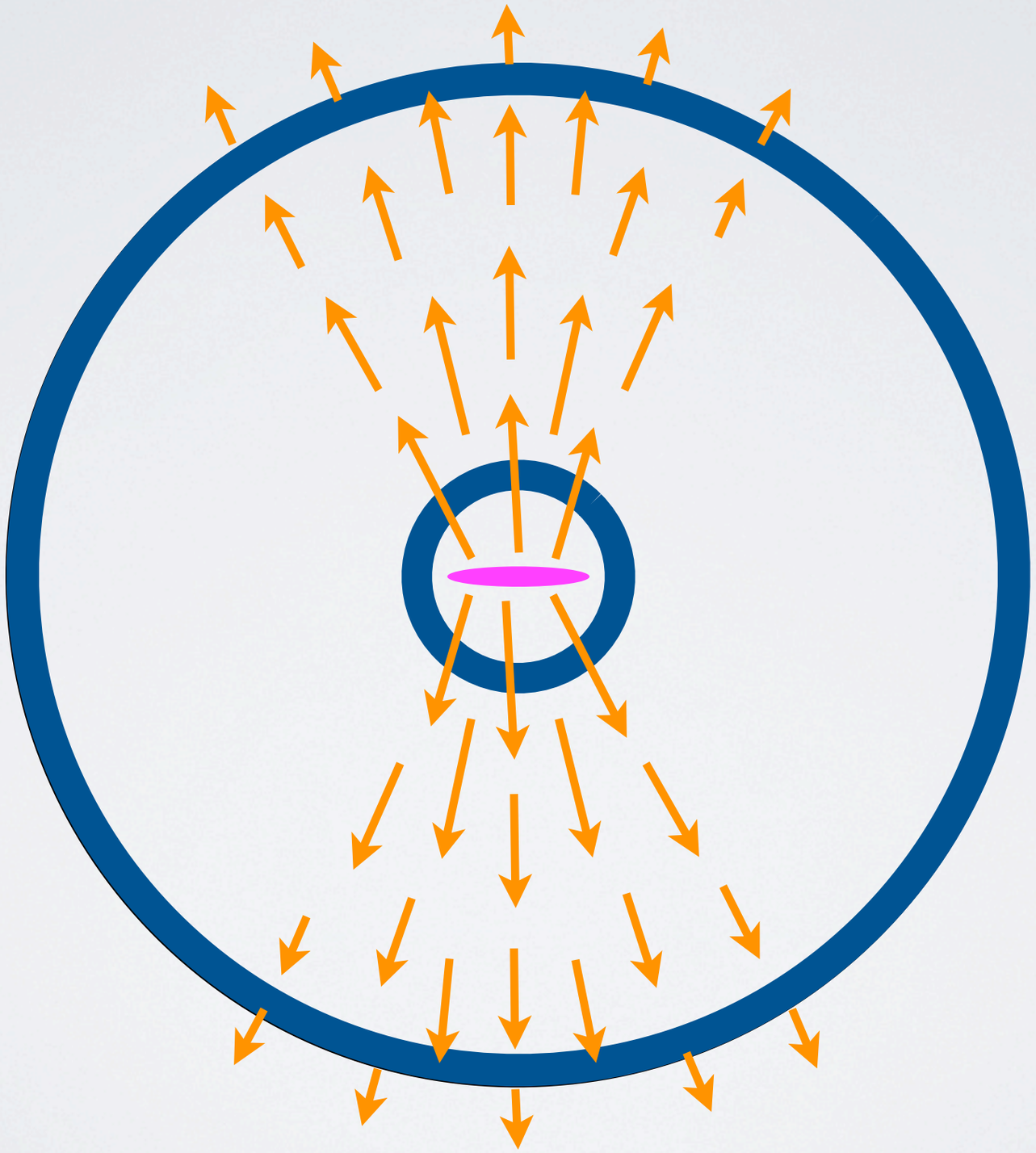
GALACTIC OUTFLOWS



GALACTIC OUTFLOWS

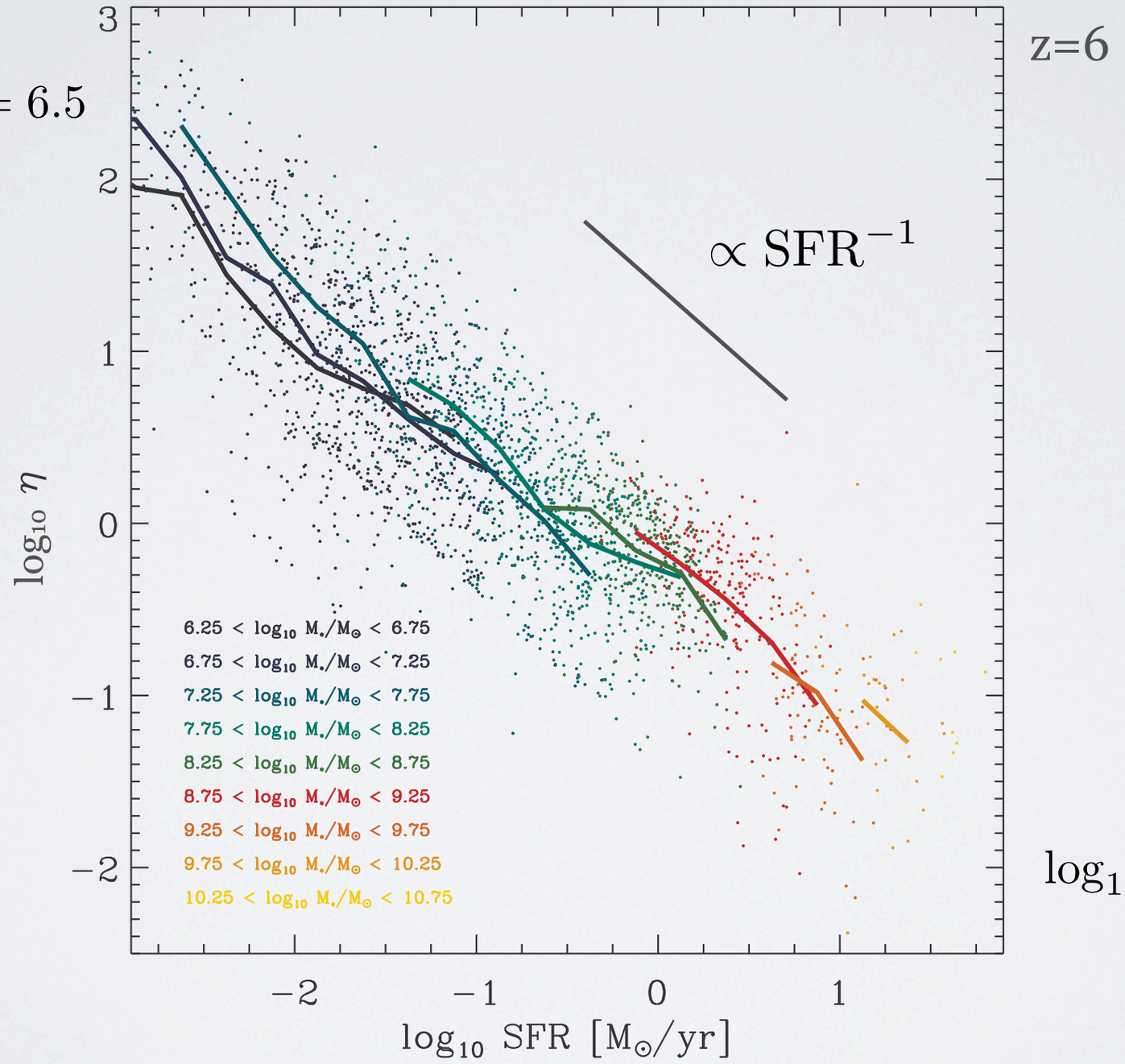


GALACTIC OUTFLOWS



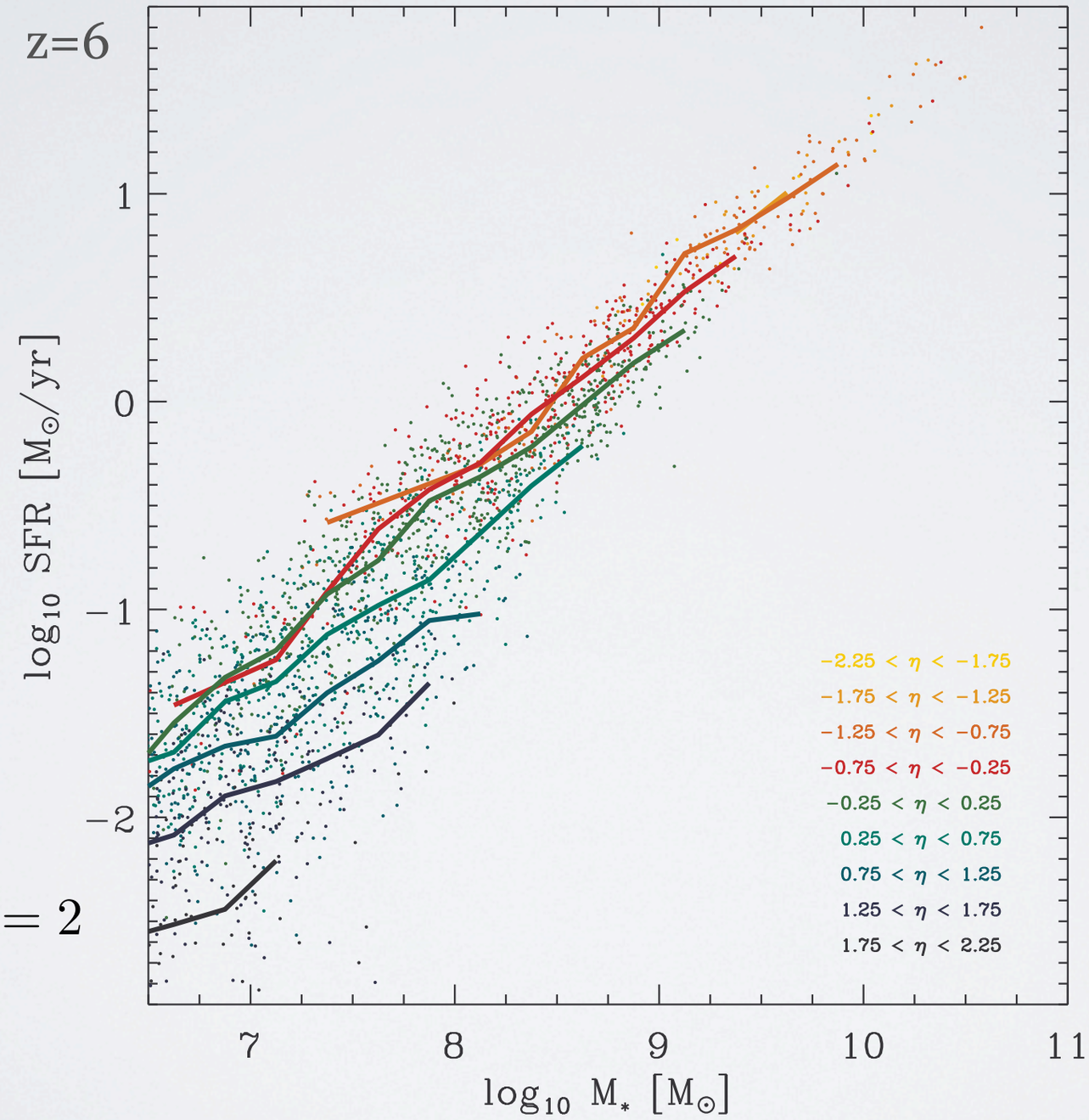
GALACTIC OUTFLOWS

$\log_{10}(M_*/\mathrm{M}_\odot) = 6.5$



$\log_{10}(M_*/\mathrm{M}_\odot) = 10.5$

GALACTIC OUTFLOWS

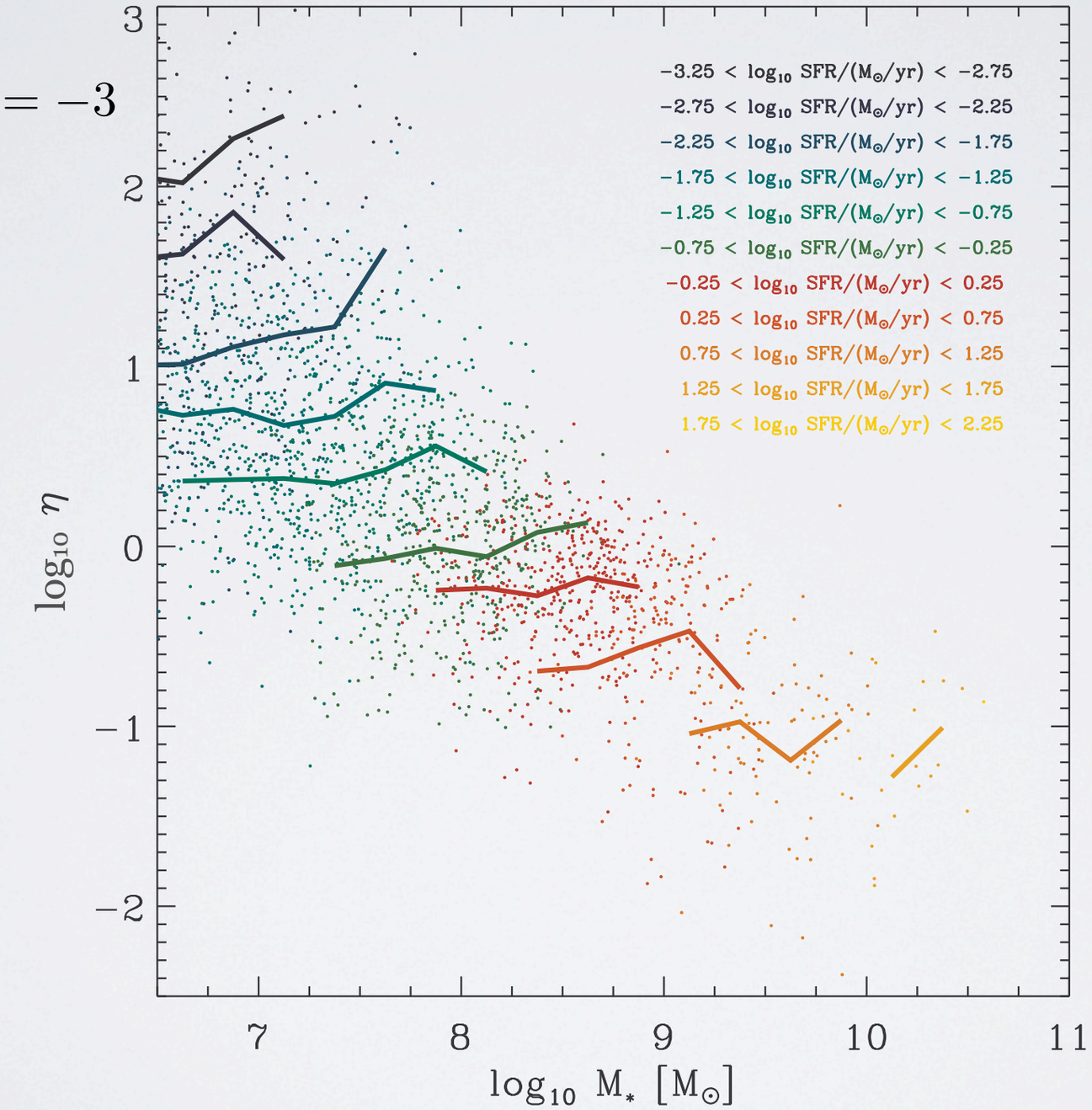


$\log_{10}\eta = -2$

$\log_{10}\eta = 2$

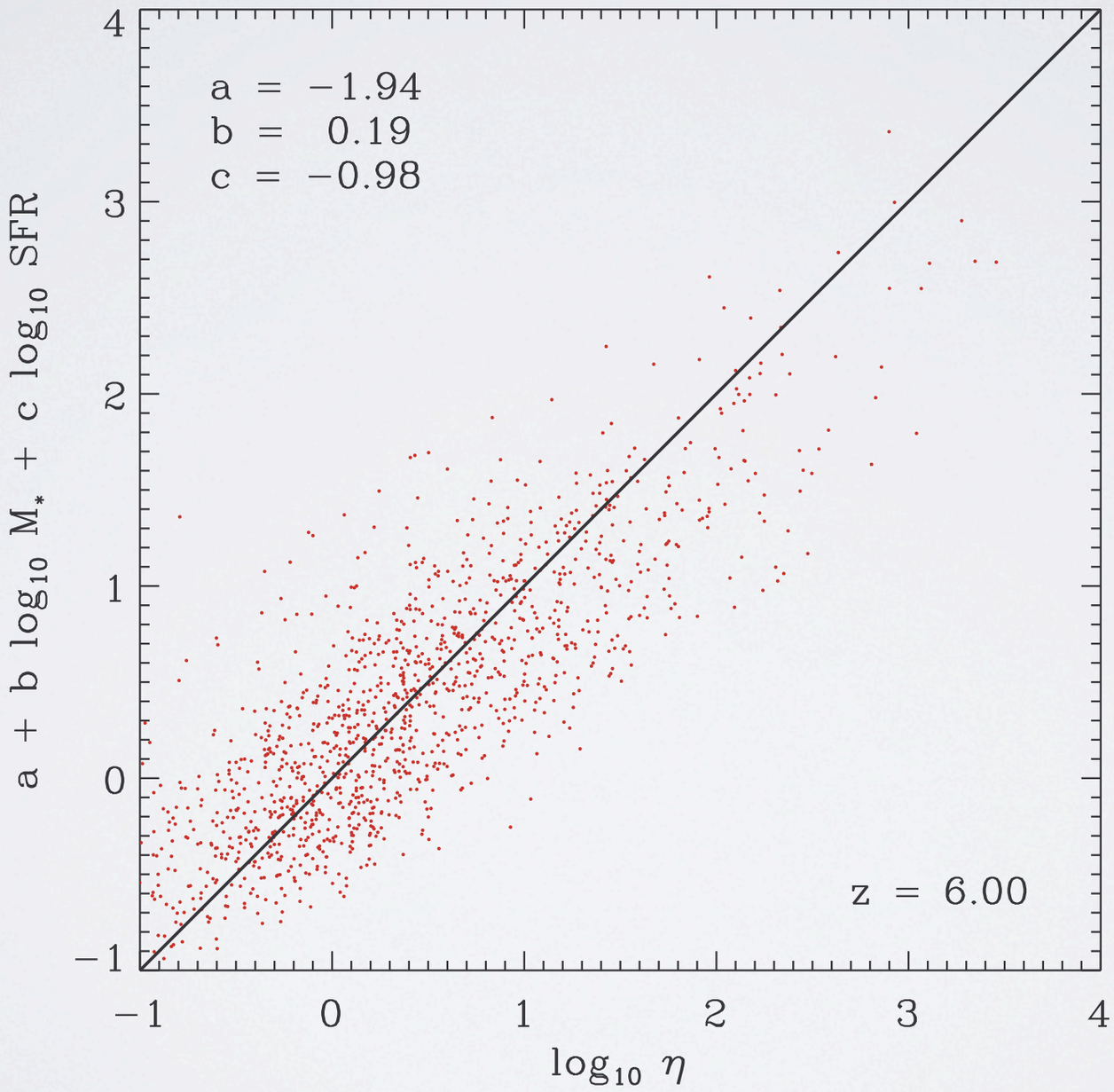
GALACTIC OUTFLOWS

$\log_{10} \mathrm{SFR}/(\mathrm{M}_\odot/yr) = -3$

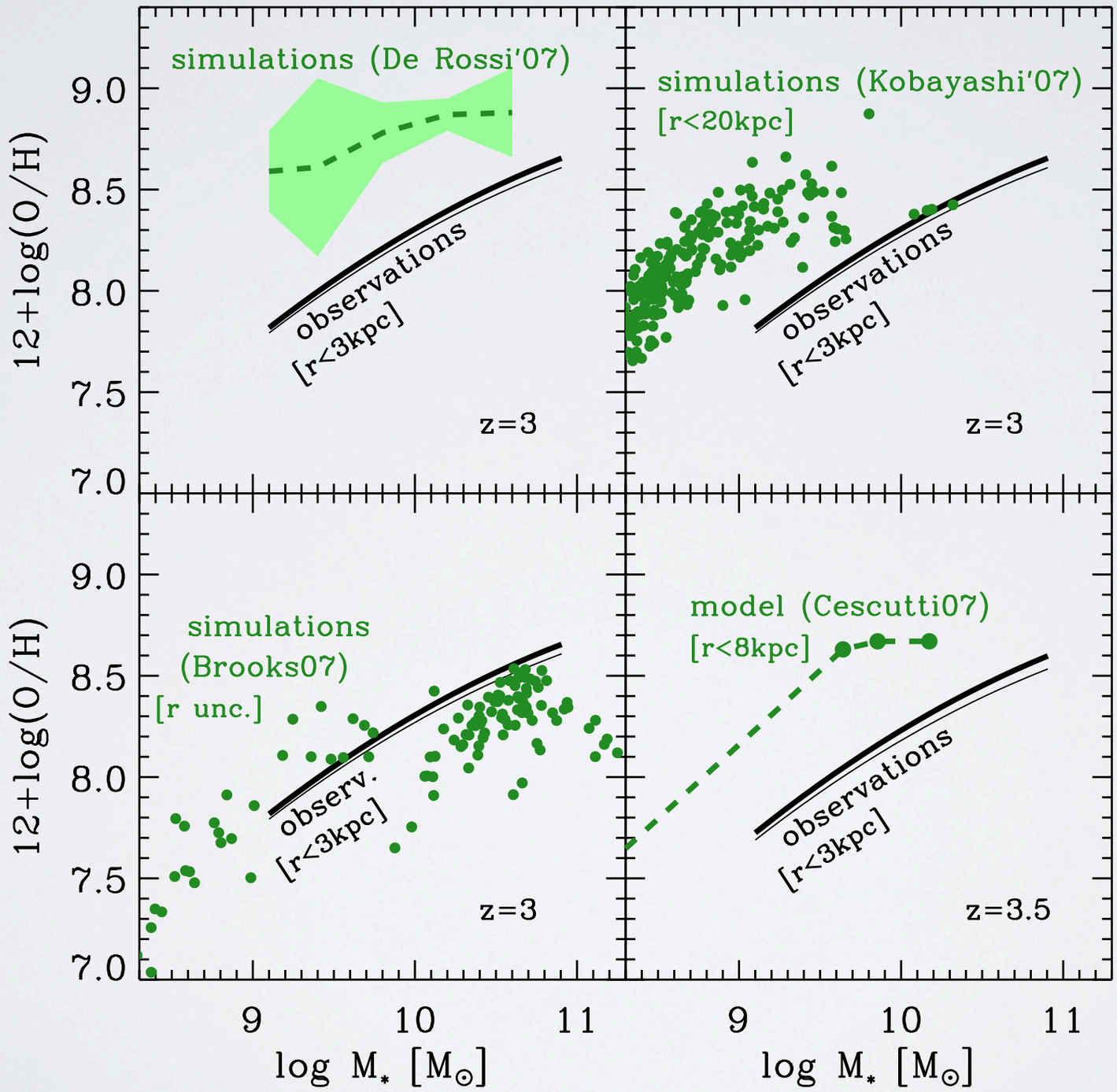


$\log_{10} \mathrm{SFR}/(\mathrm{M}_\odot/yr) = 2$

FUNDAMENTAL PLANE (?)



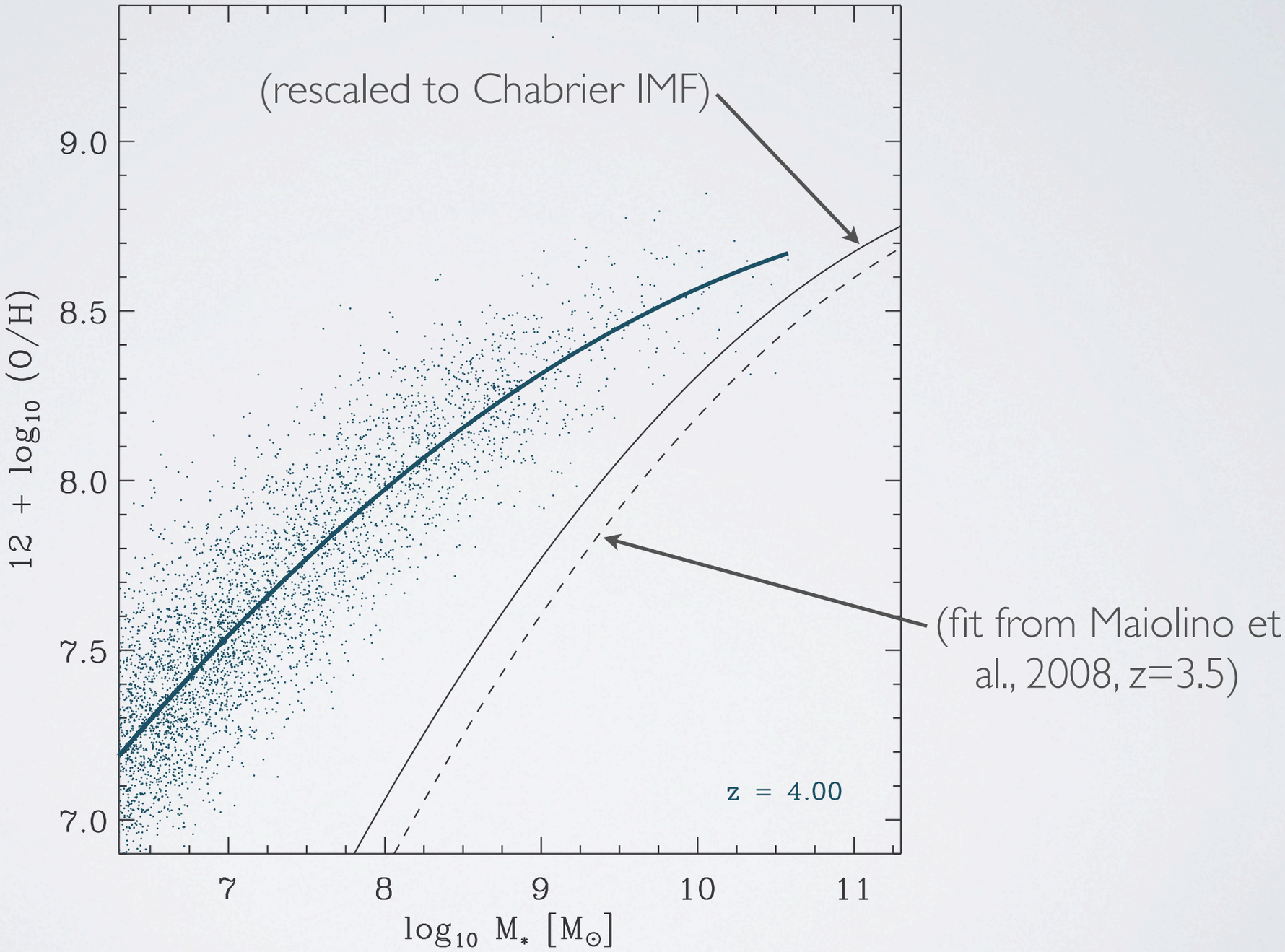
METALLICITY-MASS RELATION



(Maiolino et al., 2008)

(Savaglio et al., 2005)

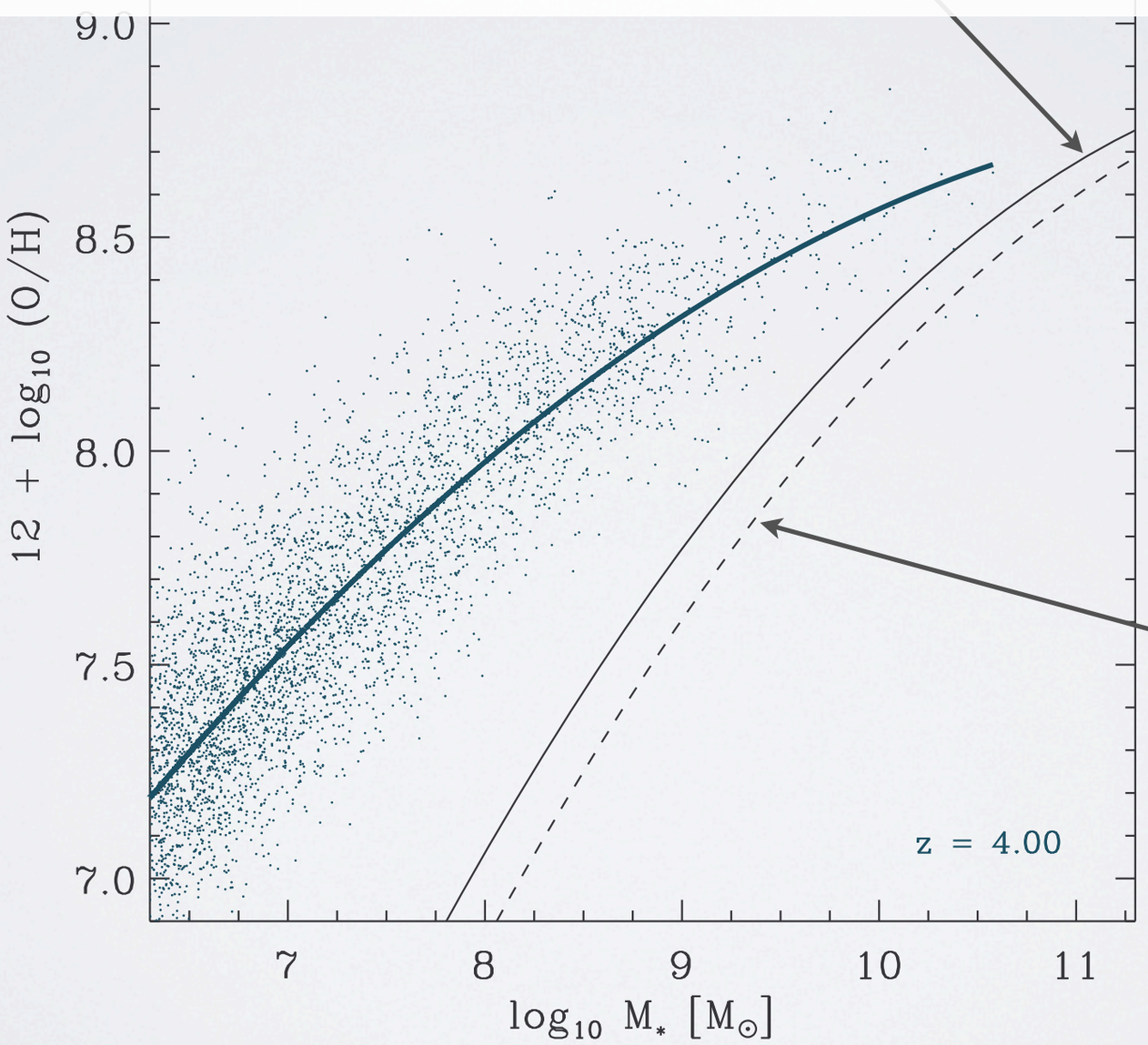
METALLICITY-MASS RELATION



METALLICITY-MASS RELATION

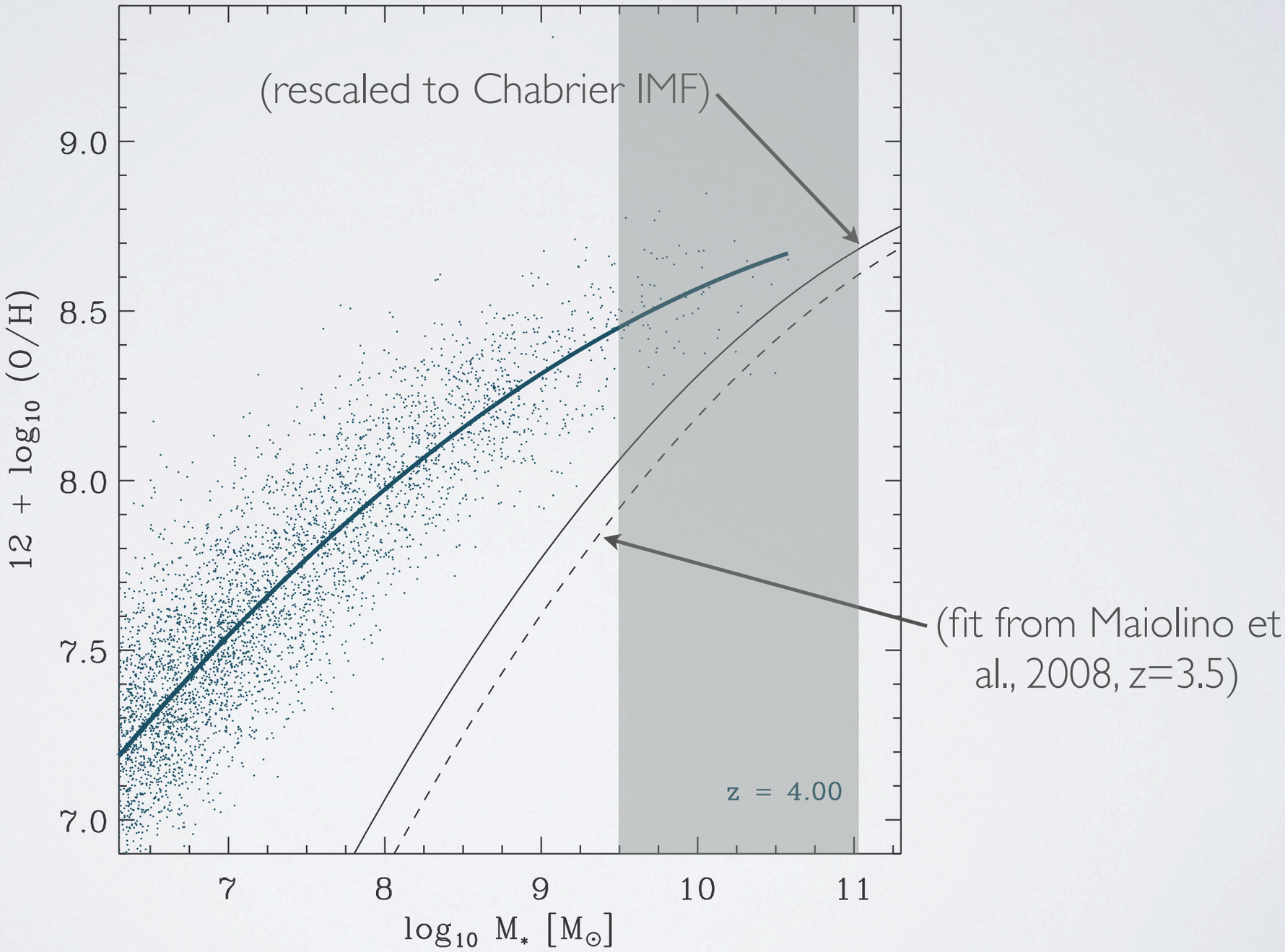
$$12 + \log(\mathrm{O/H}) = A_0(\log M_* - \log M_0)^2 + K_0$$

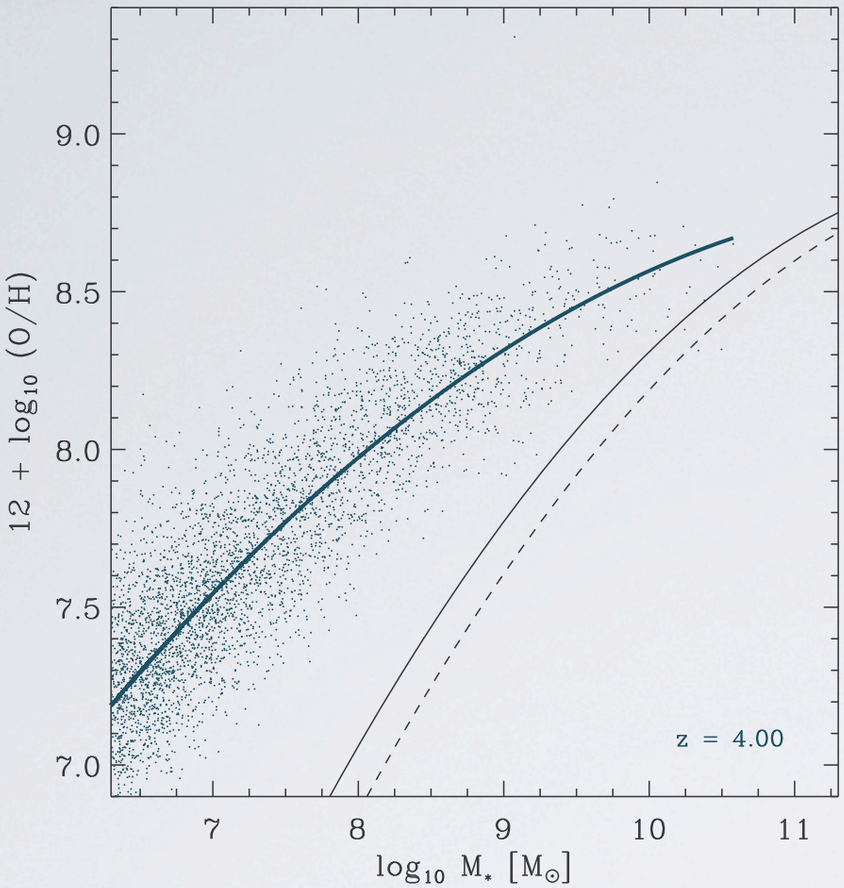
(rescaled to Chabrier IMF)

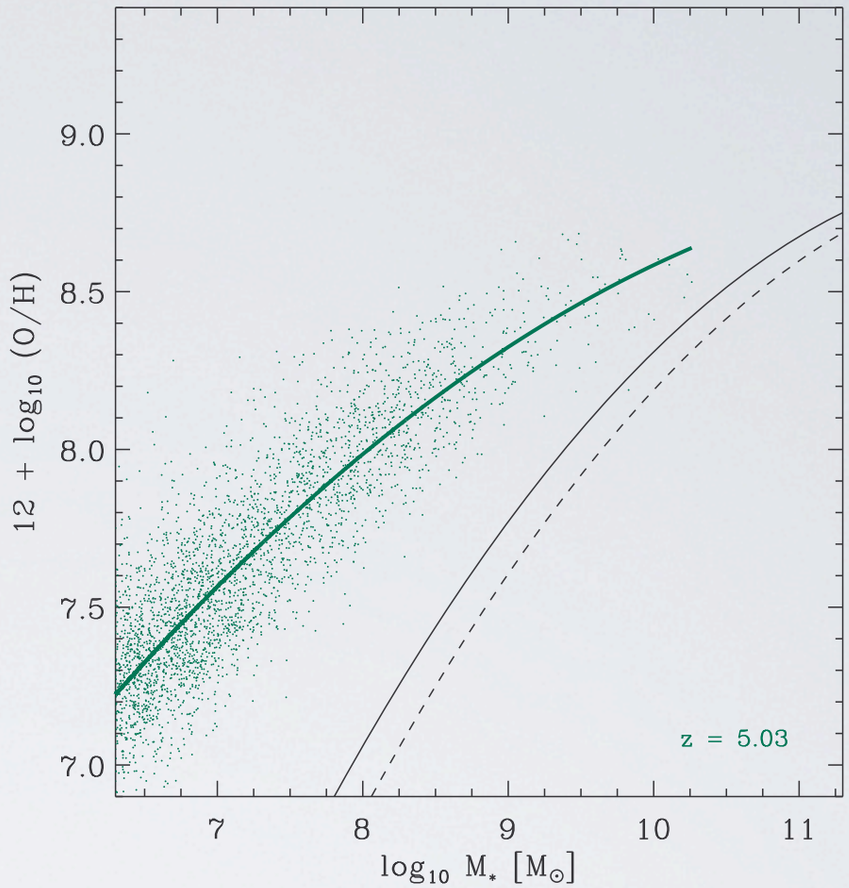


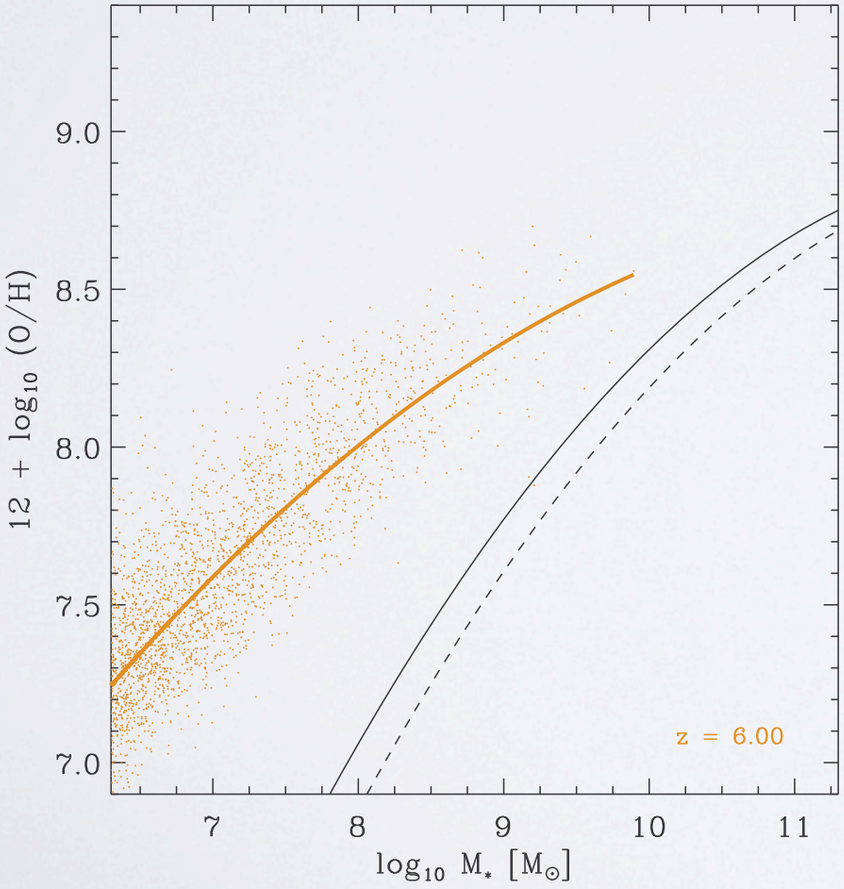
(fit from Maiolino et al., 2008, z=3.5)

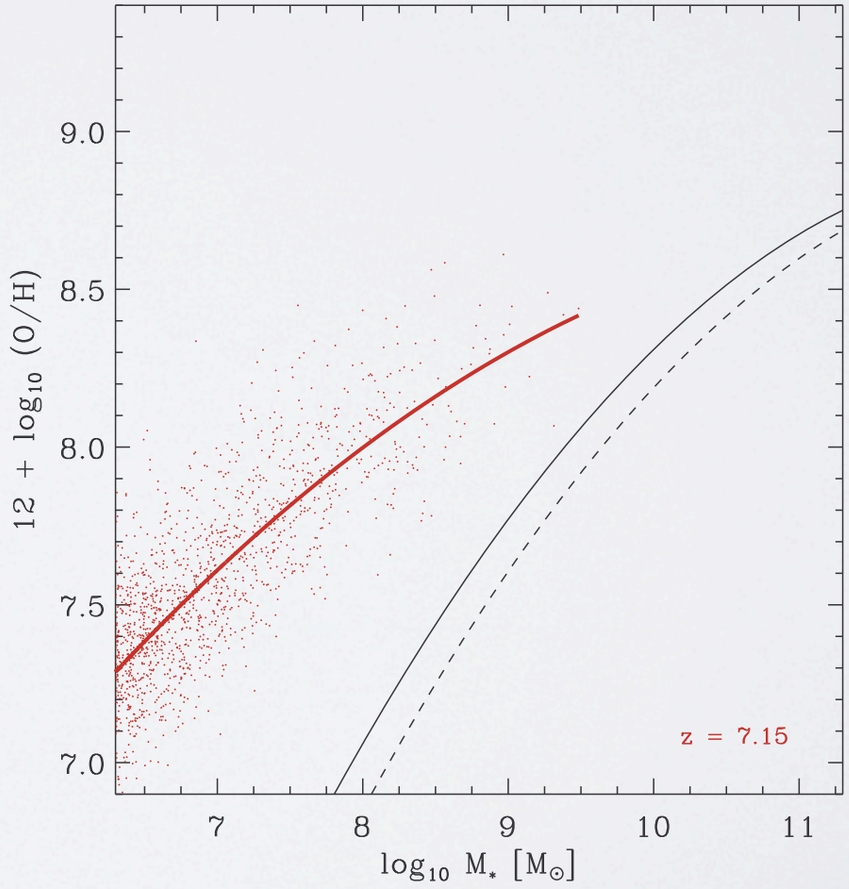
METALLICITY-MASS RELATION




9.0
8.5
8.0
7.5
7.0
12 + log10 (O/H)
7
8
9
10
11
log10 M* [M⊙]
z = 4.00


9.0
8.5
8.0
7.5
7.0
12 + log10 (O/H)
7
8
9
10
11
log10 M* [M⊙]
z = 5.03

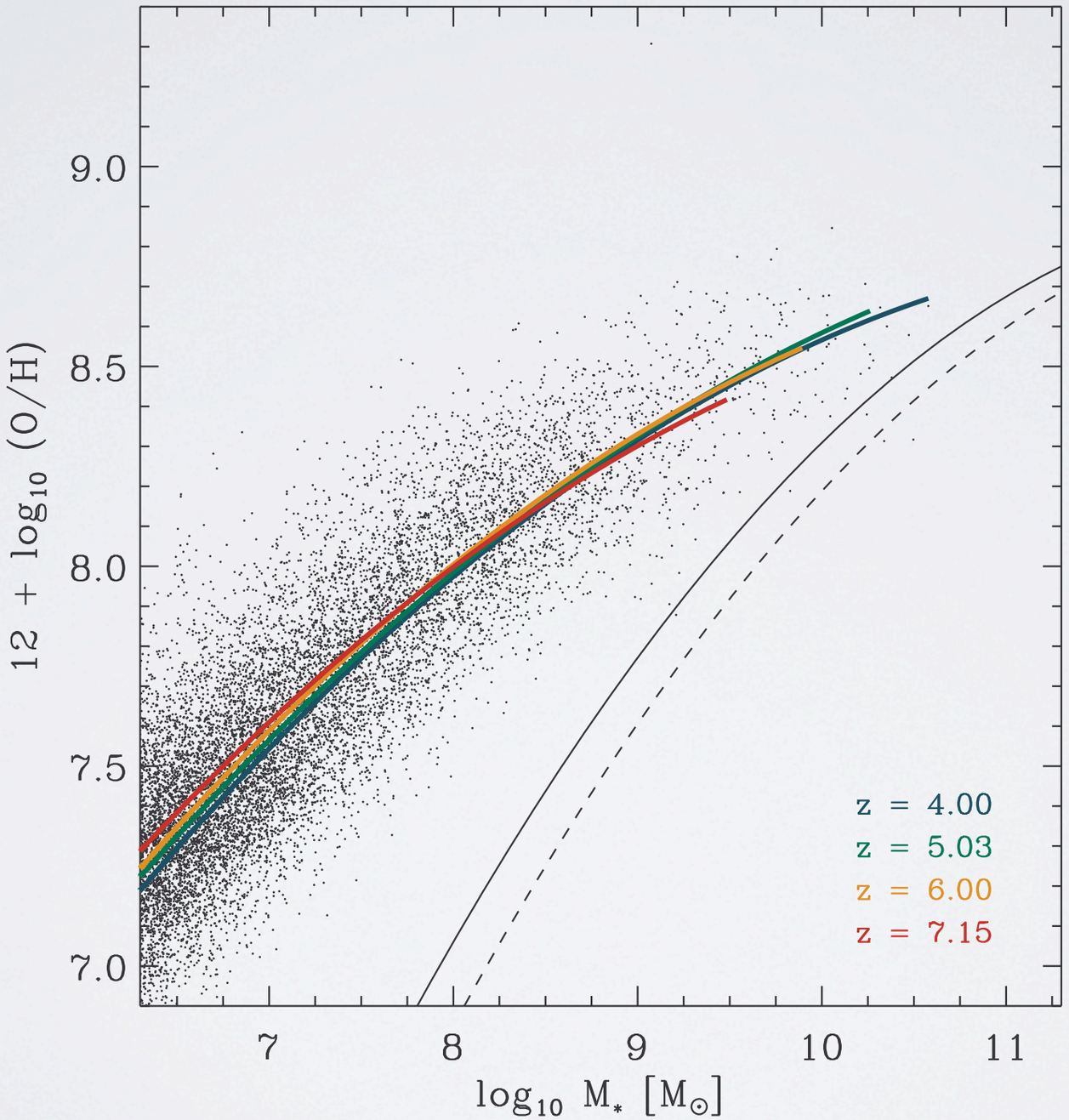

9.0
8.5
8.0
7.5
7.0
12 + log10 (O/H)
7
8
9
10
11
log10 M* [M⊙]
z = 6.00


9.0
8.5
8.0
7.5
7.0
12 + log10 (O/H)
7
8
9
10
11
log10 M* [M⊙]
z = 7.15

FiBY

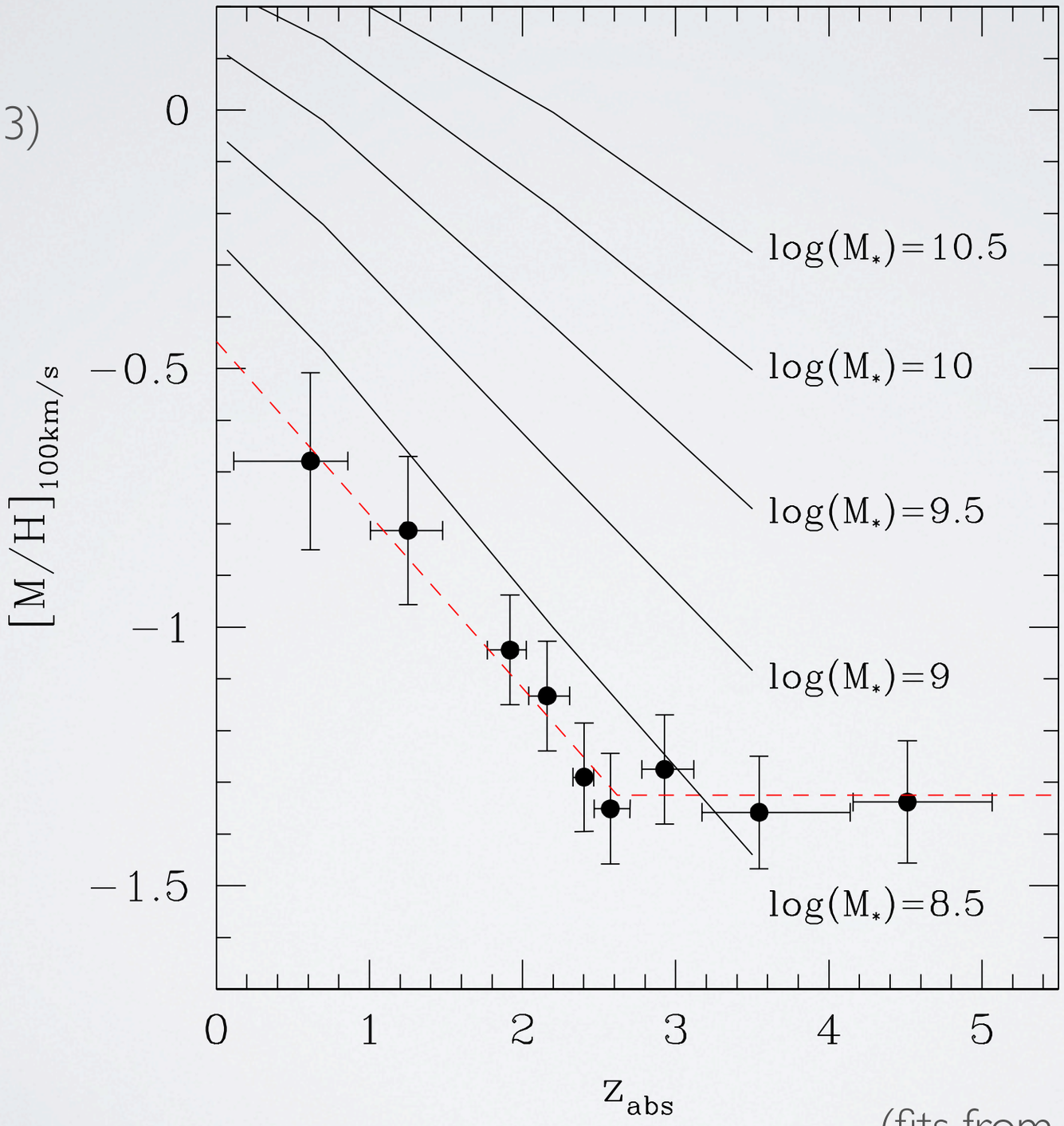
MPE

METALLICITY-MASS RELATION



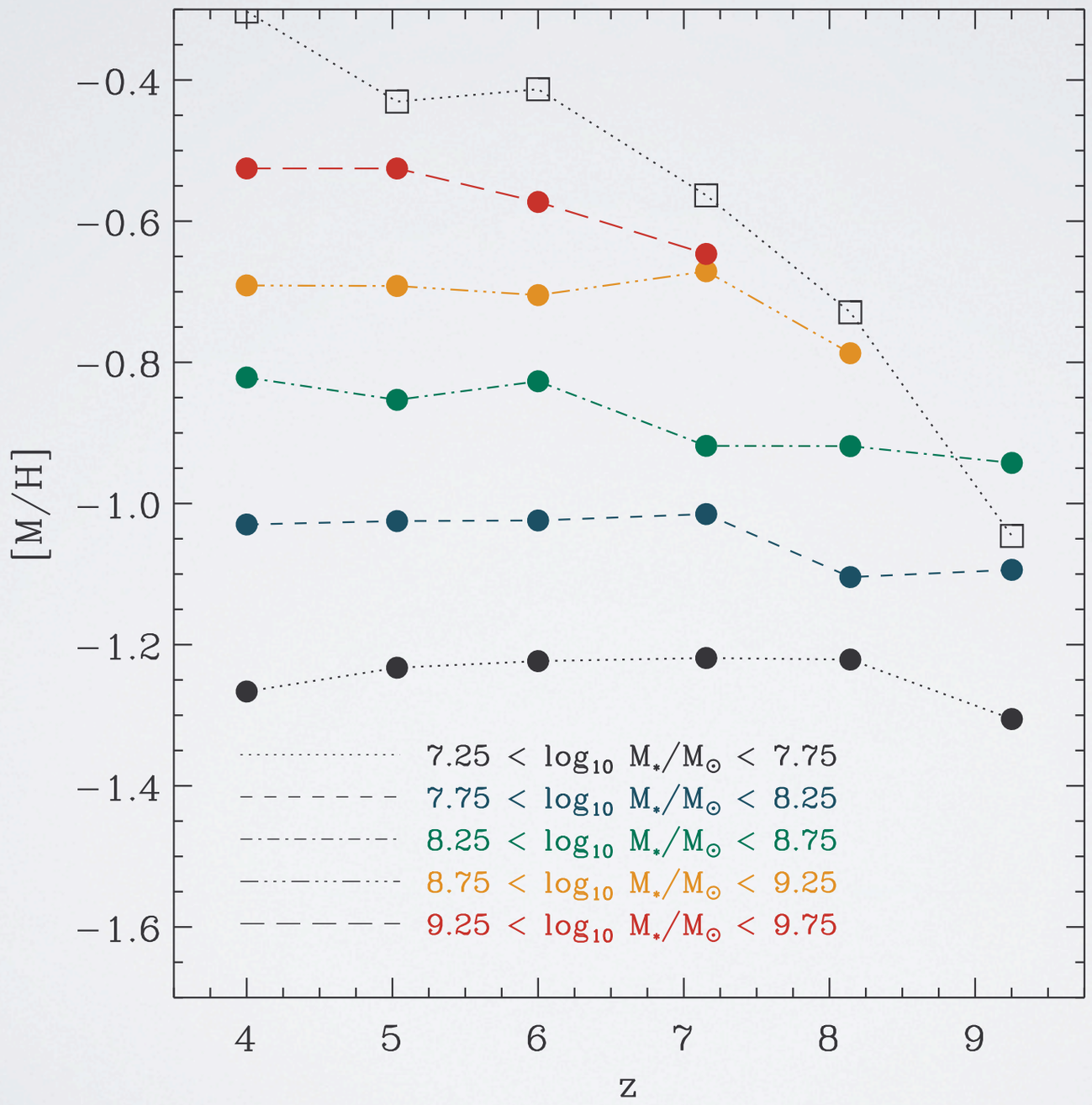
METALLICITY EVOLUTION

(Møller et al., 2013)



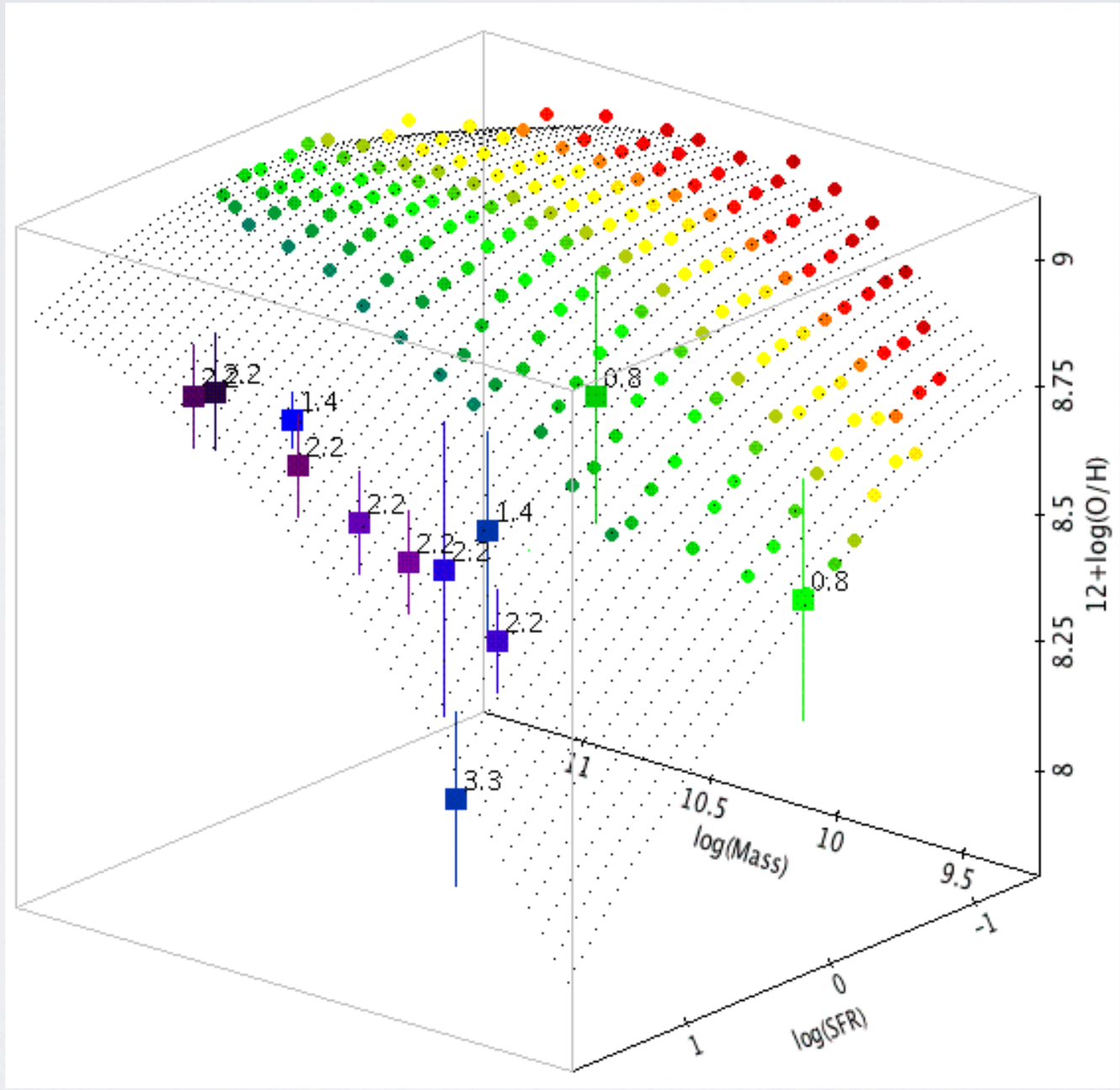
(fits from Maiolino et al., 2008)

METALLICITY EVOLUTION



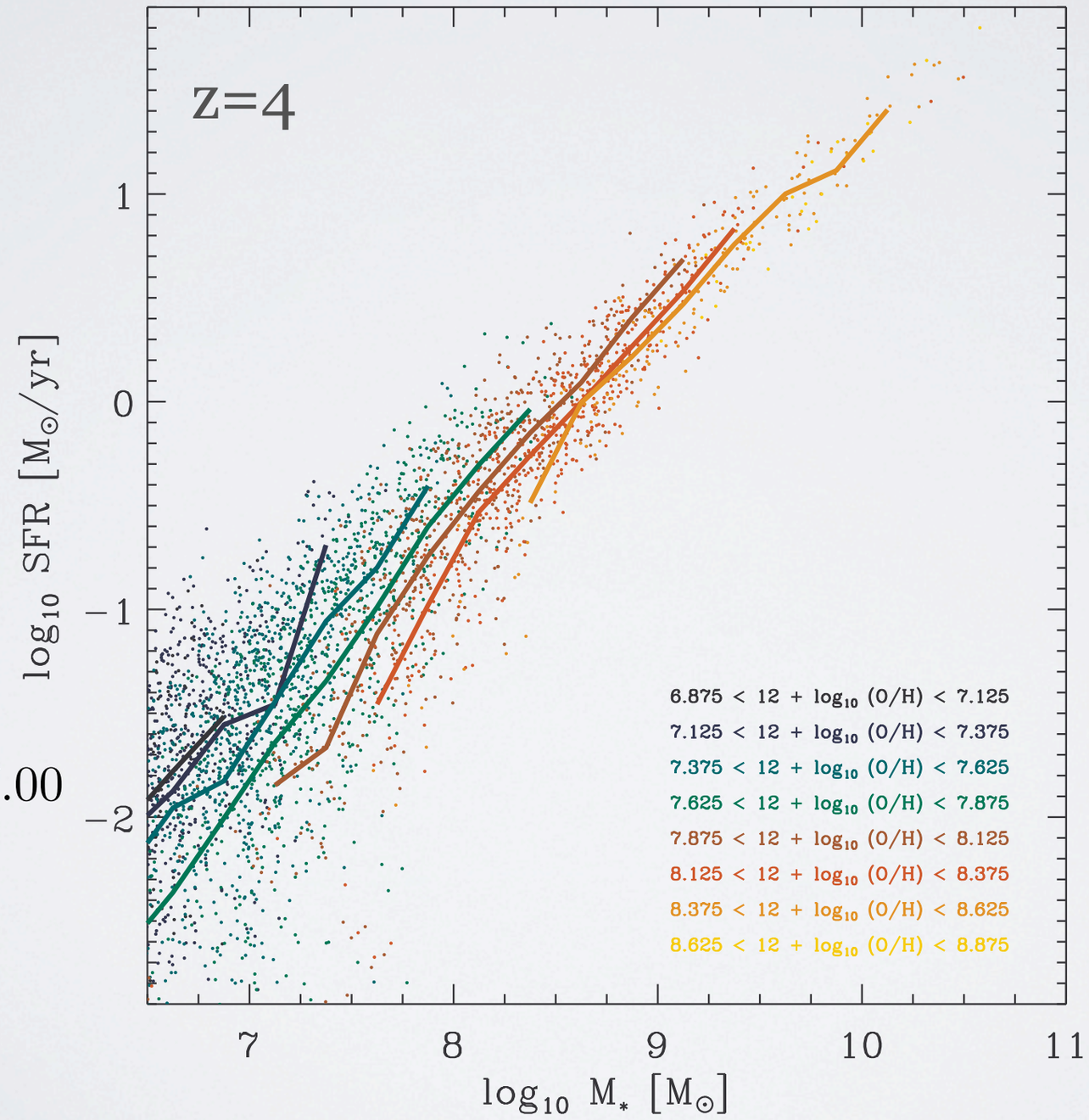
FUNDAMENTAL METALLICITY RELATION

(Mannucci et al., 2010)



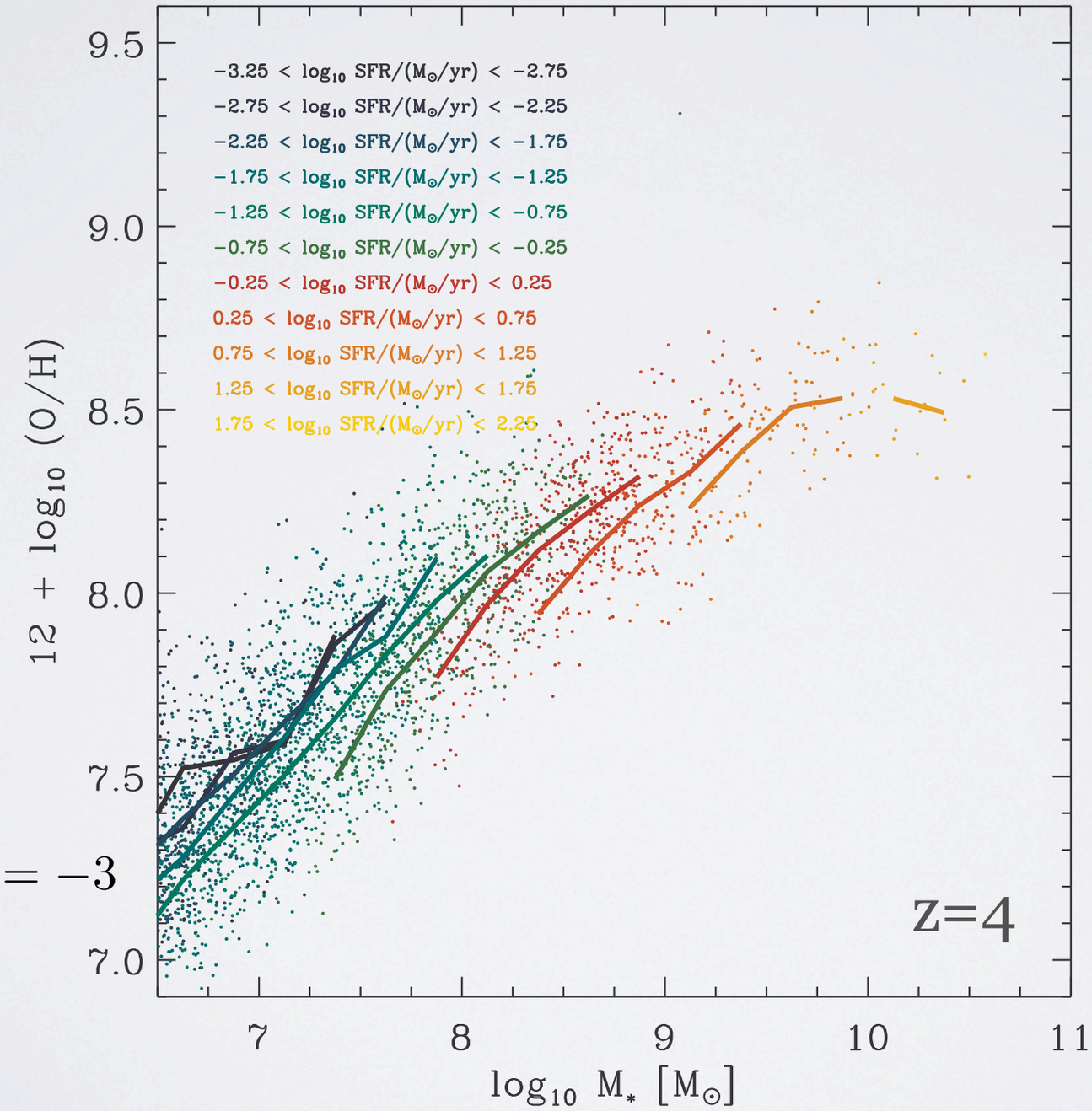
FUNDAMENTAL METALLICITY RELATION

$12 + \log(\mathrm{O/H}) = 8.75$



$12 + \log(\mathrm{O/H}) = 7.00$

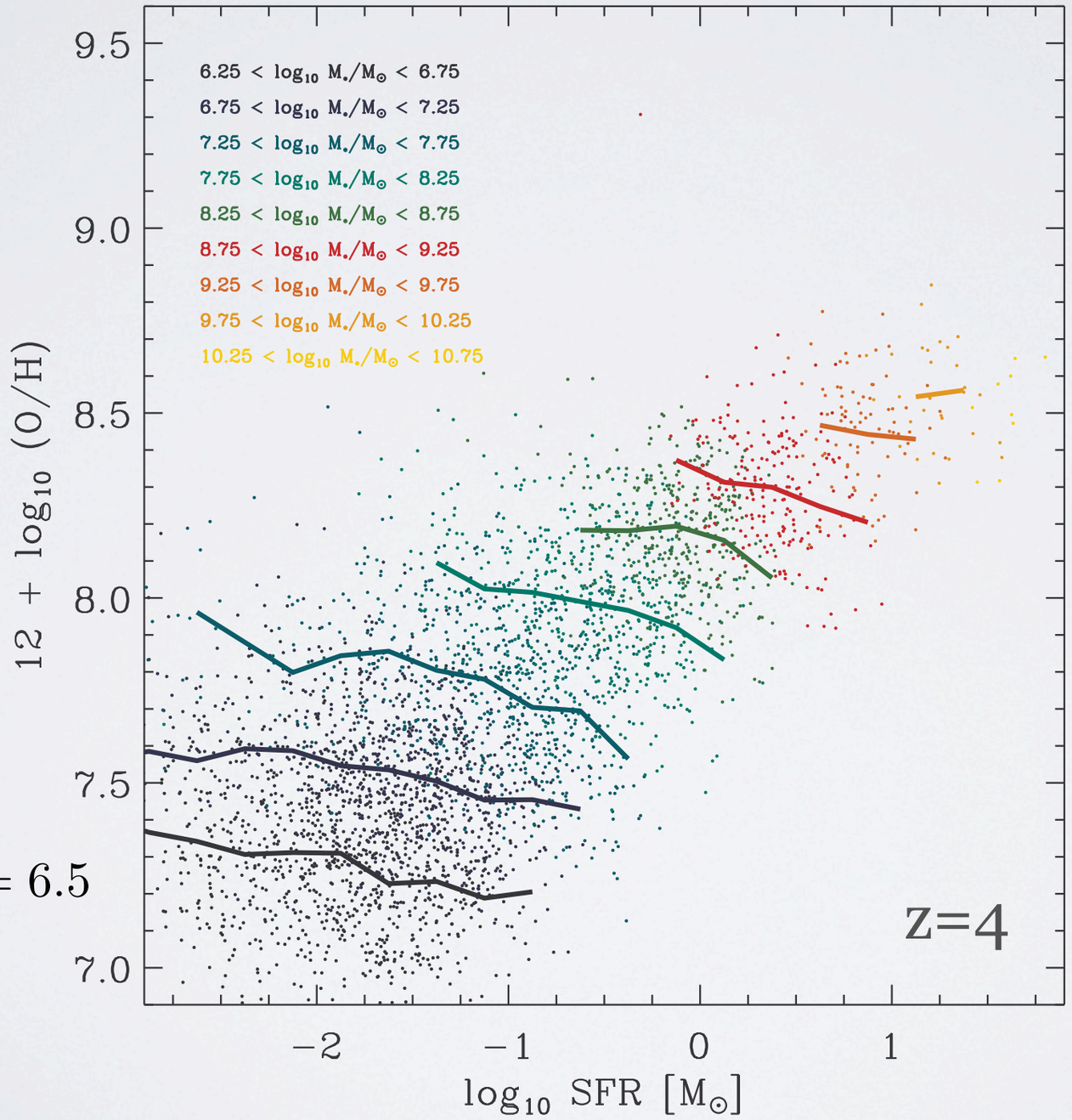
FUNDAMENTAL METALLICITY RELATION



$\log_{10} \mathrm{SFR}/(\mathrm{M}_\odot/yr) = 2$

$\log_{10} \mathrm{SFR}/(\mathrm{M}_\odot/yr) = -3$

FUNDAMENTAL METALLICITY RELATION



$\log_{10}(M_*/\mathrm{M}_\odot) = 10.5$

$\log_{10}(M_*/\mathrm{M}_\odot) = 6.5$

SUMMARY

Feedback model is parameter-free

Hint of a feedback fundamental plane

No evolution of the metallicity-mass relation

FMR is established at z>4