Studying Galaxy Clusters with Hydrodynamical Simulations

Stefano Borgani
Department of Astronomy
Interdept. Centre for Computational Sciences
University of Trieste

(a) Amplification of the ICM entropy and the nature of energy feedback.

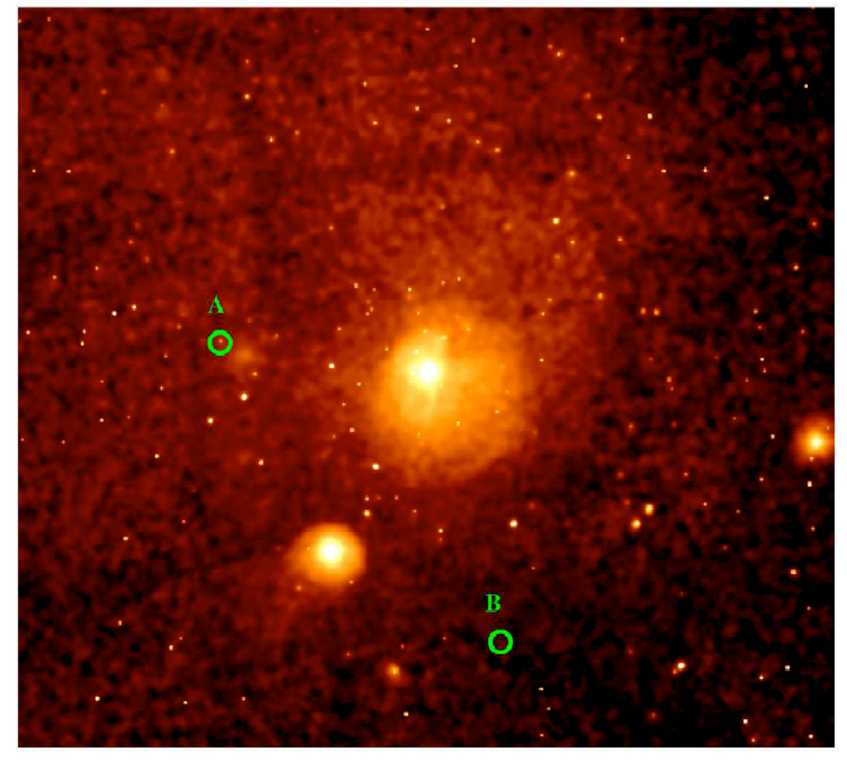
(b) Simulating the chemical enrichment of the ICM (see also poster by L. Tornatore).

(c) Controlling the effects of numerics and physics (see also talk by K. Dolag).

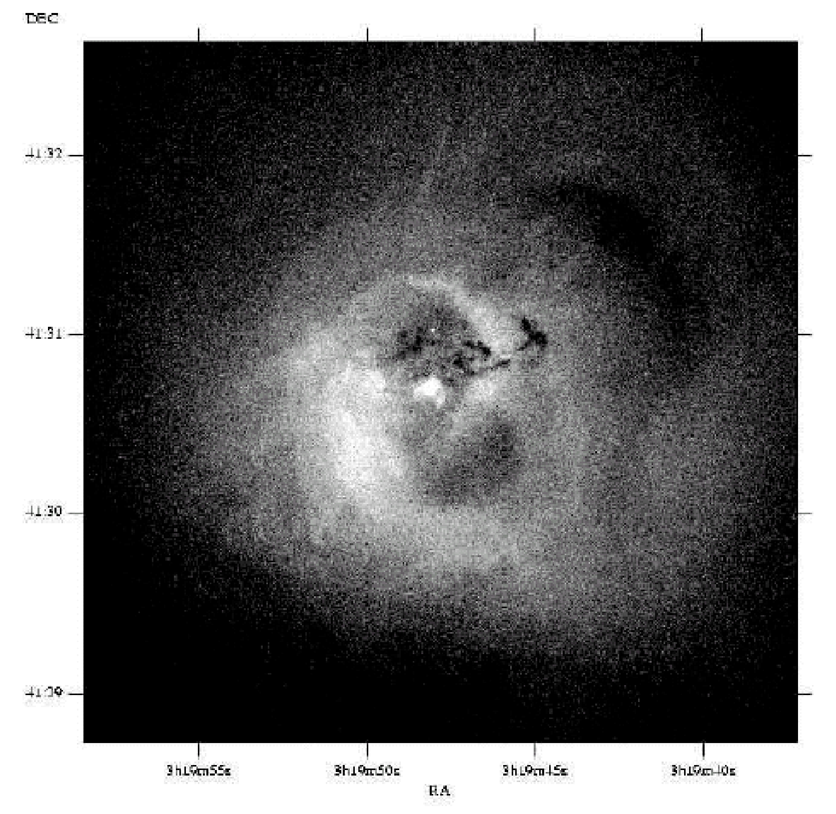
Talk @ Computational Cosmology, Trieste, May 31th – June 4th 2005

Looking deep into the ICM with CHANDRA

Fornax cluster: mosaic of 10 exposures of 50 ks with ACIS-I
Scharf et al. 2004
(100 pc resolved structures)



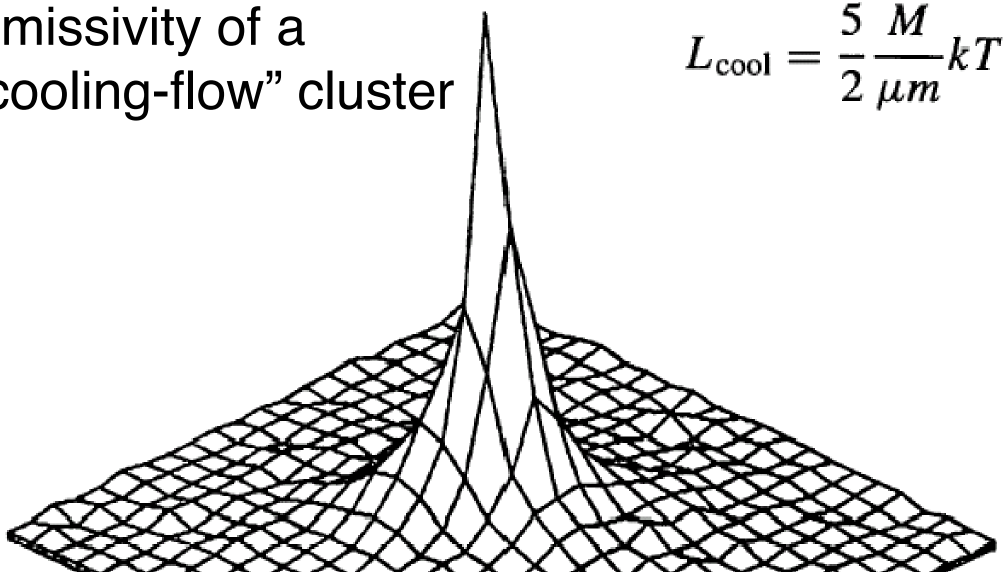
Perseus cluster:
200 ks ACIS-S3 exposure
Fabian et al. 2003
(120 kpc a side)



The puzzle of the cluster cool cores

Emissivity of a
“cooling-flow” cluster

$$L_{\rm cool} = \frac{5}{2}\frac{\dot{M}}{\mu m}kT$$

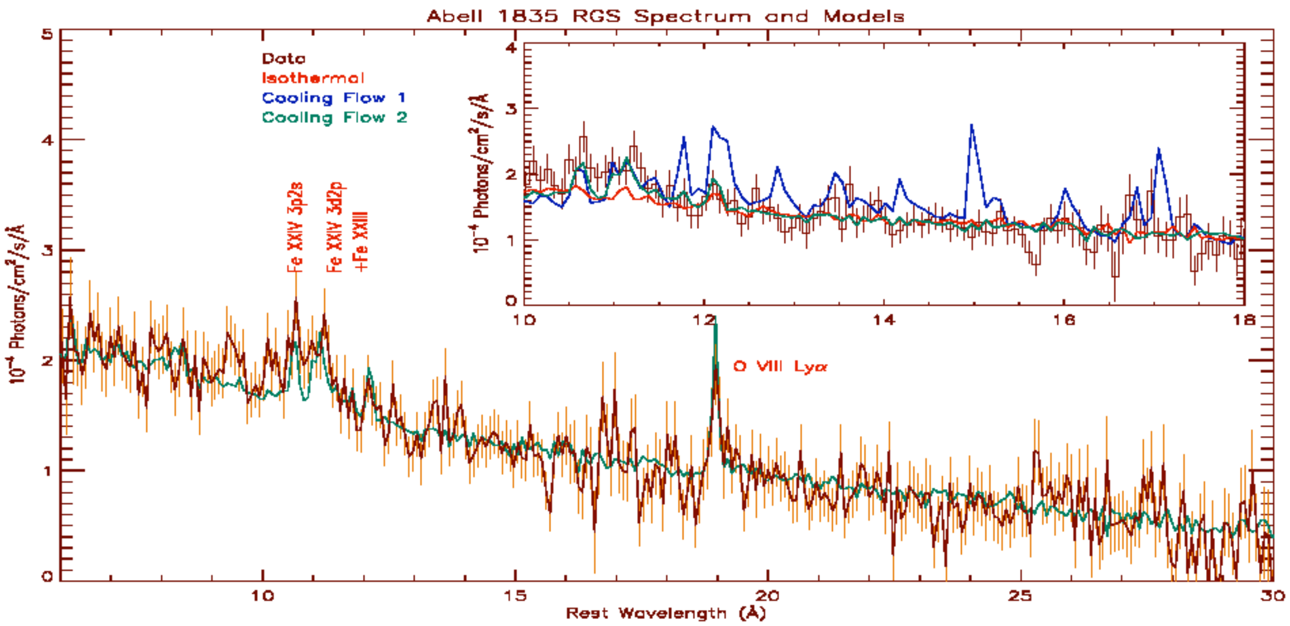


Pre-Chandra/XMM:
High Mass-Deposition
Rates: few 10^2 $M_\odot$ /yr

Spectroscopic MDR:
few 10 $M_\odot$ /yr

No gas detected with
$T<(0.3\text{-}0.5)\ T_{\rm vir}$

How to prevent this
gas from cooling?



Petersen et al. 2001
XMM-Newton spectra

Self-similar ICM: gravity only at work

(Kaiser 1986)

Critical density: $\rho_c(z) \propto \rho_c(0)E^2(z)$

$$E(z) = [\Omega_m(1+z)^3 + (1-\Omega_m-\Omega_\Lambda)(1+z)^2 + \Omega_\Lambda]^{1/2}$$

Cluster mass: $M_{\Delta_c} \propto \rho_c(z)\Delta_c R^3$ **At fixed Δ_c:** $R \propto M^{1/3}E^{-2/3}(z)$

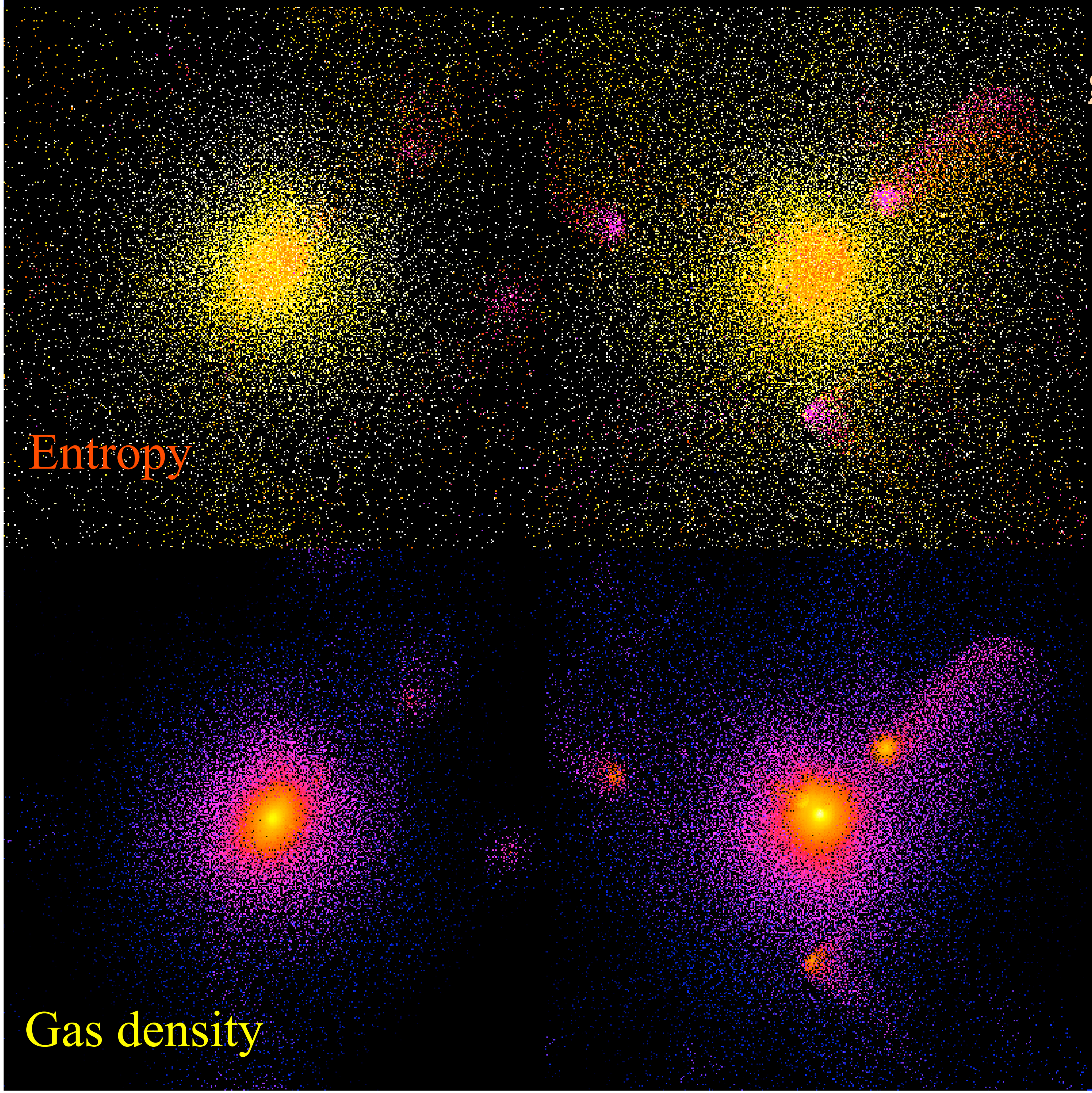
The M-T relation: hydrostatic equilibrium ⇒ $T \propto M^{2/3}E(z)^{-2/3}$

The L_X-T relation: $L_X \propto \int n_e n_H \Lambda(T)\,dV \propto T^2 E(z)$ for $\Lambda(T) \propto T^{1/2}$

Gas entropy: $S = \frac{T}{n_e^{2/3}} \propto TE^{-4/3}(z)$

Thermodynamical def.: $s = c_V \ln(P/\rho^\gamma)$ $\gamma = 5/3$

$P = R\rho T$ ⇒ $S = e^{(s/c_V)}/R$



Self-similar ICM: gravity only at work

(Kaiser 1986)

Hydrostatic eq.

$$T(M,z) \propto M^{2/3}\, E(z)^{2/3}$$

Bremss emiss.:

$$L_X \propto M \rho T^{1/2}$$

$$\Rightarrow$$

$$\boxed{\begin{aligned} L_X &\propto M^{4/3} E(z)^{7/3} \\ &\propto T^2\, E(z) \end{aligned}}$$

$$\boxed{\begin{aligned} S &\propto (T/\rho_g^{2/3}) \\ &\propto T\, E(z)^{-4/3} \end{aligned}}$$

$$S = e^{(s/c_V)}/R$$

$$\boxed{y_0 \propto T^{3/2}\, E(z)}$$

PART I: Entropy amplification from feedback

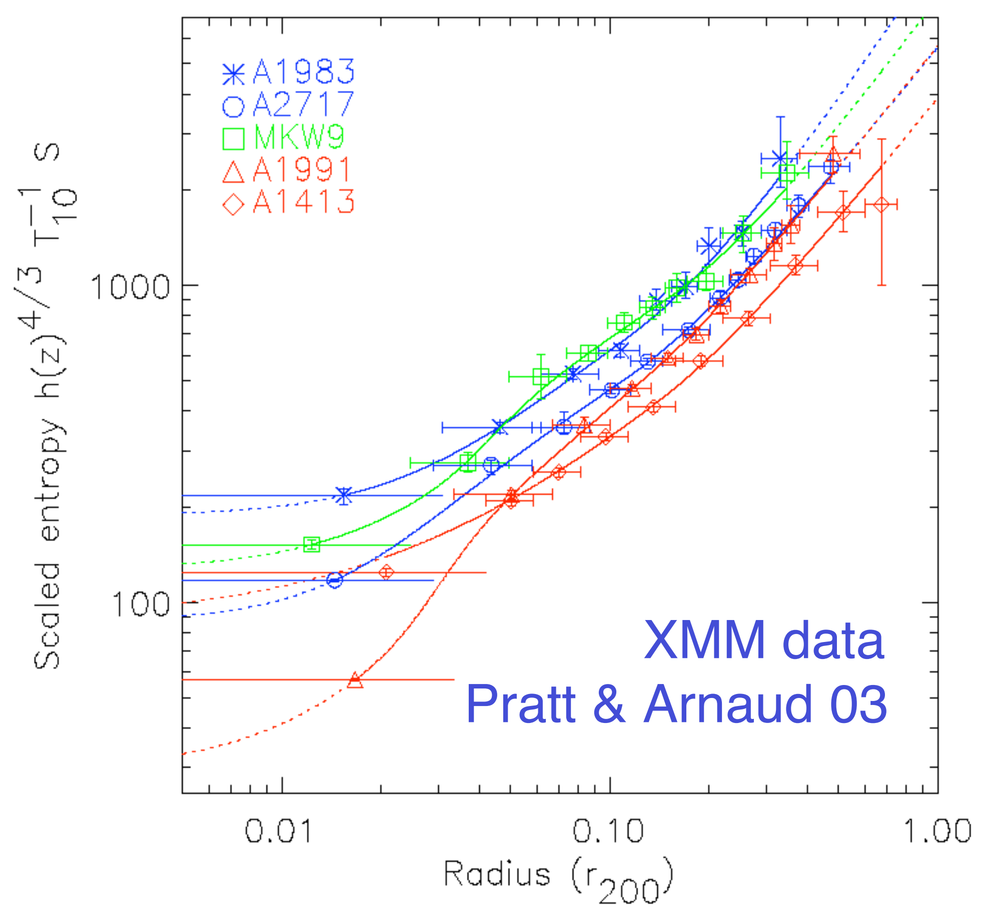
SB, Finoguenov, Kay, Ponman, Springel, Tozzi & Voit 2005

Entropy amplification by diffuse accretion
(Voit et al. ’03; Ponman et al. ’03)

X-ray def: $S=T/n_e^{2/3}$

Expected: $S \propto T$

Observed: $S \propto T^{2/3}$



XMM data
Pratt & Arnaud 03

- Groups accrete from smaller halos relative to clusters.

⇒ With pre-heating, gas clumps accreting in groups are more efficiently diffused wrt those accreting into clusters.

⇒ Transition from clumpy to diffuse accretion.

⇒ More efficient entropy generation at the shocks.

The simulation code

Tree + SPH GADGET2 (Springel et al .'01; Springel '05)

www.MPA-Garching.MPG.DE/gadget

- Explicit entropy conservation (Springel & Hernquist '02)
- Radiative cooling + uniform evolving UV background
- Multiphase model for self-regulated star-formation
- Phenomenological model for galactic winds (Springel & Hernquist '03)
- Chemical enrichment from Sn-Ia and II (Tornatore et al. '04, '05)
- Reduced-viscosity SPH scheme (Dolag et al. '05, in prep.)
- .....

$$v_{\rm w} = \sqrt{\frac{2\beta\chi u_{\rm SN}}{\eta(1-\beta)}}$$

β: fraction of mass in stars $>8M_\odot$ (Salpeter IMF)

χ: SN energy fraction powering winds (=0.5-1)

η: amount of gas in wind, units of dM_* (=2)

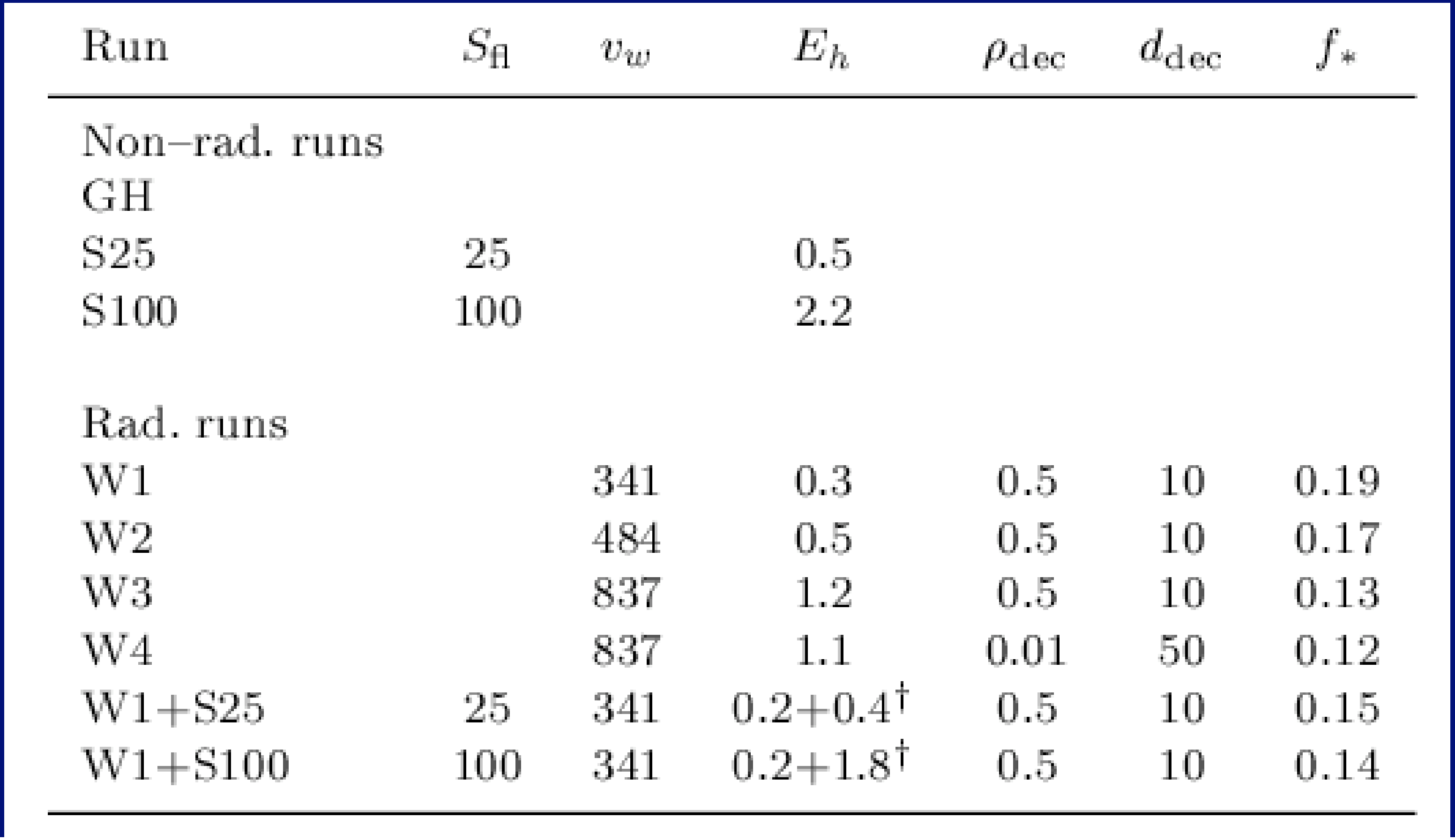
$\Rightarrow v_w \approx (300\text{-}500)\ \mathrm{km\ s^{-1}}$

Entropy amplification from feedback - II

1 Cluster: $M_{vir} = 2.6\ 10^{14}\ h^{-1}\ M_{\odot}$

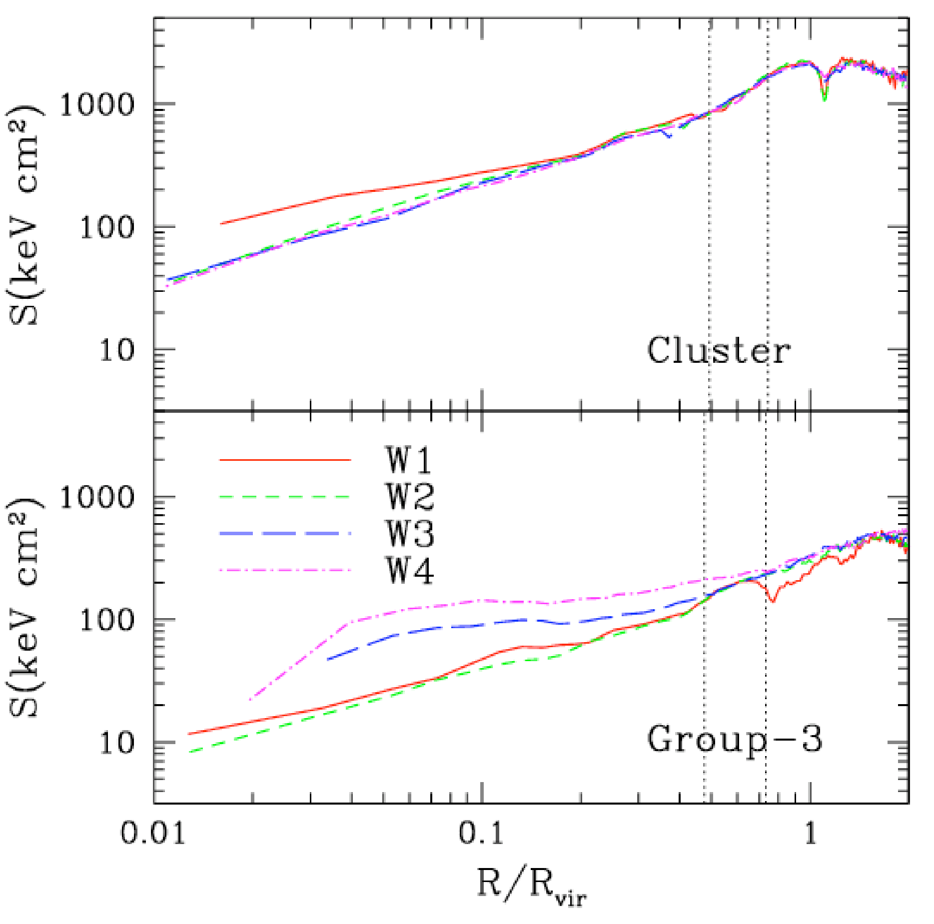
3 Groups: $M_{vir} = (1.6\text{-}4.2)\ 10^{13}\ h^{-1}\ M_{\odot}$

- Galactic winds from SN energy feedback
- Preheating by entropy floor at z_h=3



Run	S_{fl}	v_w	E_h	ρ_{dec}	d_{dec}	f_*
Non–rad. runs						
GH						
S25	25		0.5			
S100	100		2.2			
Rad. runs						
W1		341	0.3	0.5	10	0.19
W2		484	0.5	0.5	10	0.17
W3		837	1.2	0.5	10	0.13
W4		837	1.1	0.01	50	0.12
W1+S25	25	341	$0.2+0.4^{\dagger}$	0.5	10	0.15
W1+S100	100	341	$0.2+1.8^{\dagger}$	0.5	10	0.14

Entropy amplification from feedback - III



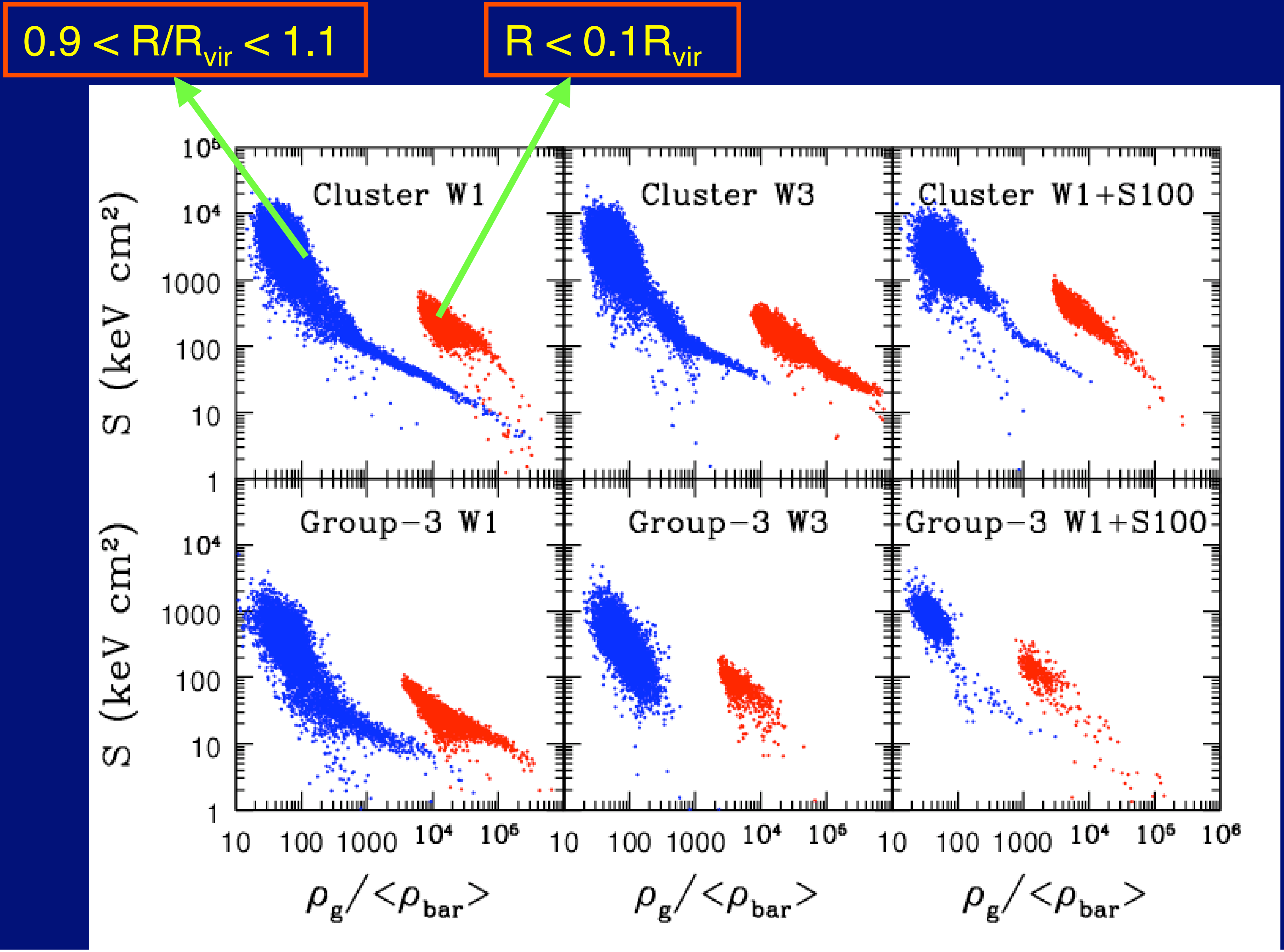
⇒ Large amplification in the non-radiative runs.

⇒ In Group-3 more efficient than in the Cluster.

⇒ Much reduced in the radiative runs.

⇒ Strong winds only effective in the Group-3

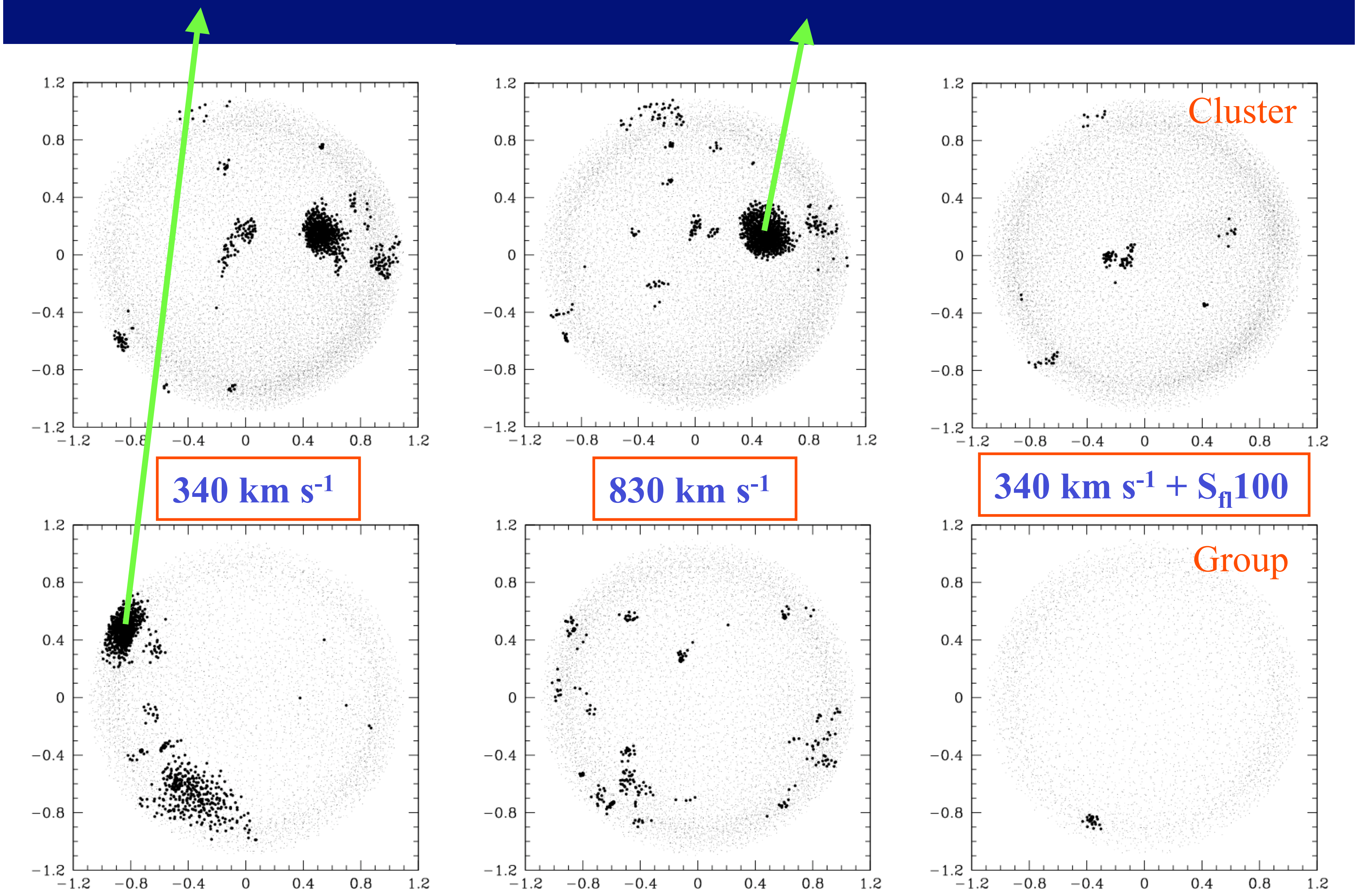
Entropy amplification from feedback - IV


$0.9 < R/R_{vir} < 1.1$

$R < 0.1R_{vir}$

S< 60 kev cm^2

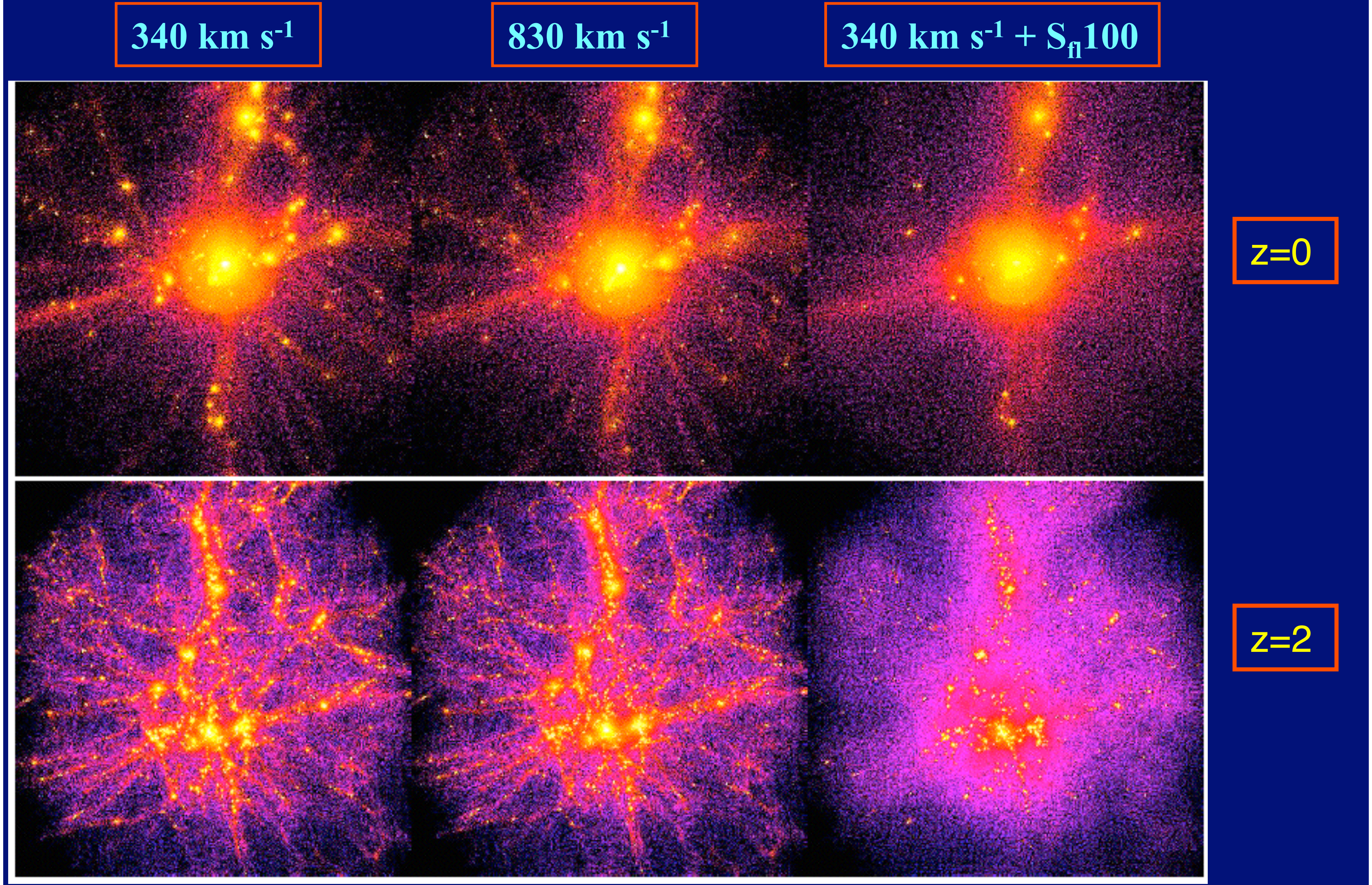
S< 400 kev cm^2



340 km s^{-1}

830 km s^{-1}

340 km s^{-1} + S$_{fl}$100



$340\ \mathrm{km\ s^{-1}}$

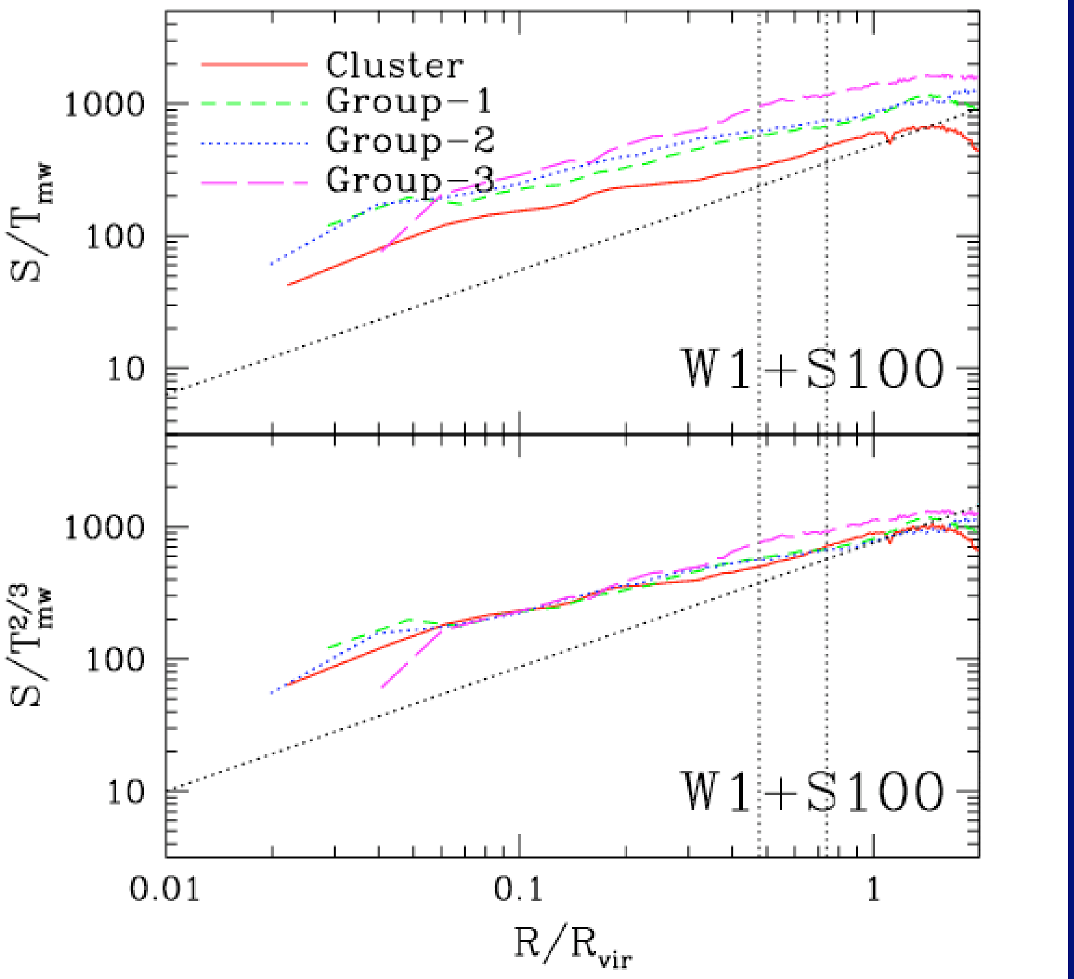
$830\ \mathrm{km\ s^{-1}}$

$340\ \mathrm{km\ s^{-1}} + S_{\mathrm{fl}}100$

$z=0$

$z=2$

Entropy amplification from feedback - V



⇒ Even strong winds don’t break self-similarity in the halo outskirts (although effective in regulating star formation)

⇒ Entropy amplification requires a quite diffuse feedback heating (i.e. not localized around SF regions).

Part II. Following the chemical enrichment of the ICM

Tornatore et al. '04, '05 (collab. K. Dolag, F. Matteucci, C. Chiappini)

See posters by Scannapieco et al. and Kobayashi et al.

Implementation in the SF/feedback model by Springel & Hernquist (2003)

(a) Avoid IRA: Fe contributed by long-lived stars

(b) SSP for each star particle. Ingredients:

- ⇒ Initial mass function
- ⇒ Stellar lifetimes as a function of star mass
- ⇒ Stellar yields

Compute N_{SNIa}, N_{SNII} and N_{PNe} at each time step Δt:
SNII: stars with $M>8M_{\odot}$
SNIa: binary systems with $M=(0.8-8)M_{\odot}$ for each component
PNe: stars with $M=(0.8-8)M_{\odot}$ not turning into SNIa

(c) Modify the effective model by SH03 to account for:

i) extra energy source from stars outside the IRA;
ii) metallicity-dependent cooling function

(d) Metal diffusion: spreading over neighbors using an SPH kernel

Following the chemical enrichment of the ICM

Model parameters:

(a) IMF: $\phi(m) \sim m^{-(1+x)}$ x=1.35: Salpeter IMF

x=0.95: top-heavy (Arimoto-Yoshii) IMF

(b) Stellar lifetimes: Padovani & Matteucci ’93

Maeder& Meynet ‘89

(c) Fraction of binary stars, providing SN-Ia: bf=0.07-1

(d) Velocity of galactic winds: v_w=500 km s^{-1} (normal winds)

v_w=1000 km s^{-1} (strong winds; AY IMF only)

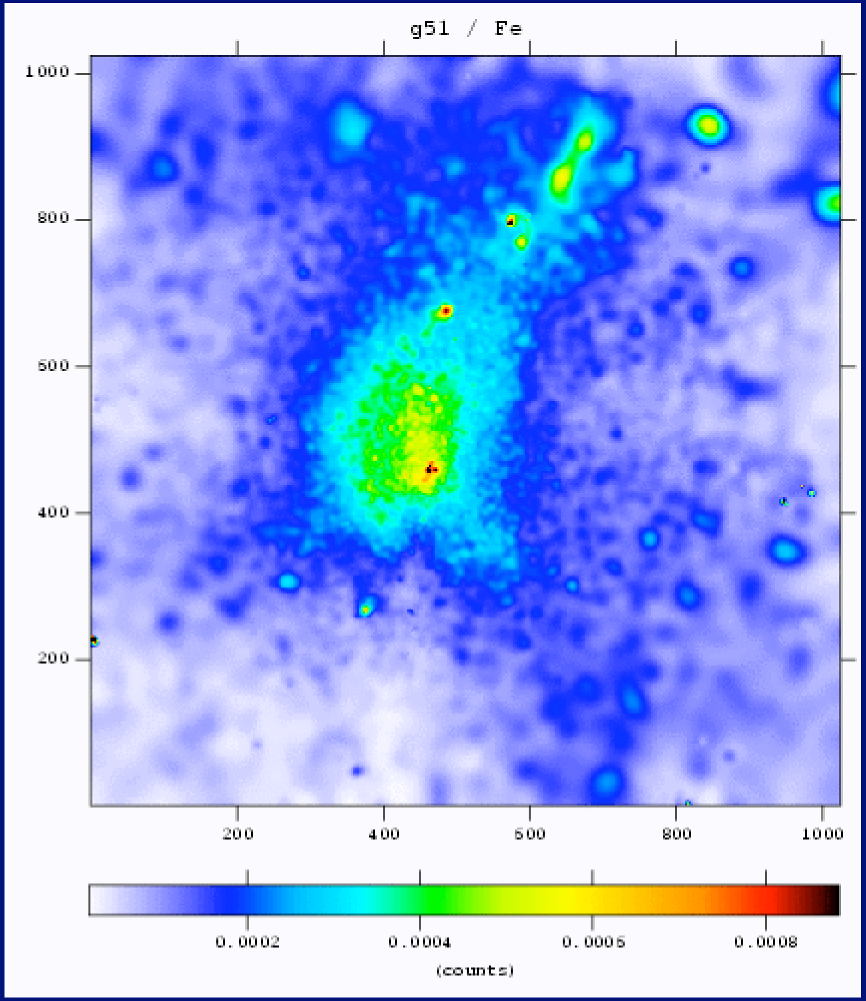
Simulated clusters (as of today):

1. Rich cluster: M_{vir}=1.0 x 10^{15} $h^{-1}M_{sun}$ (three more to be done)

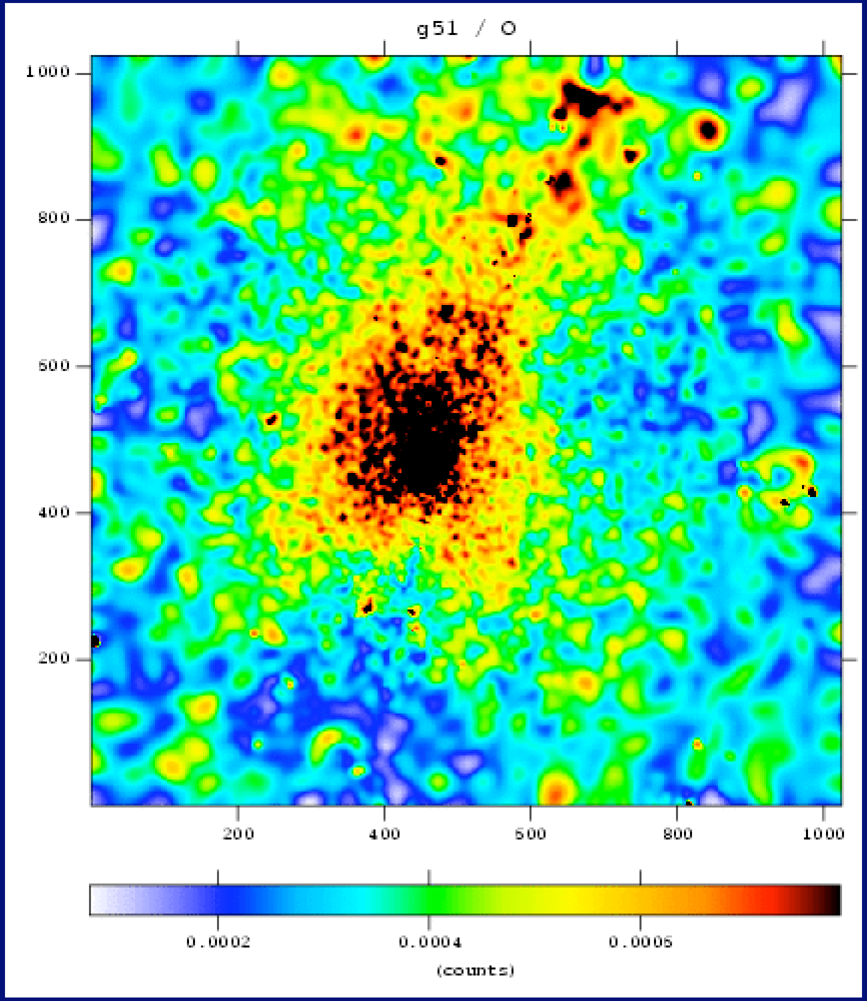
2. Poor cluster: M_{vir}=1.0 x 10^{14} $h^{-1}M_{sun}$ (four more to be done)

Following the chemical enrichment of the ICM

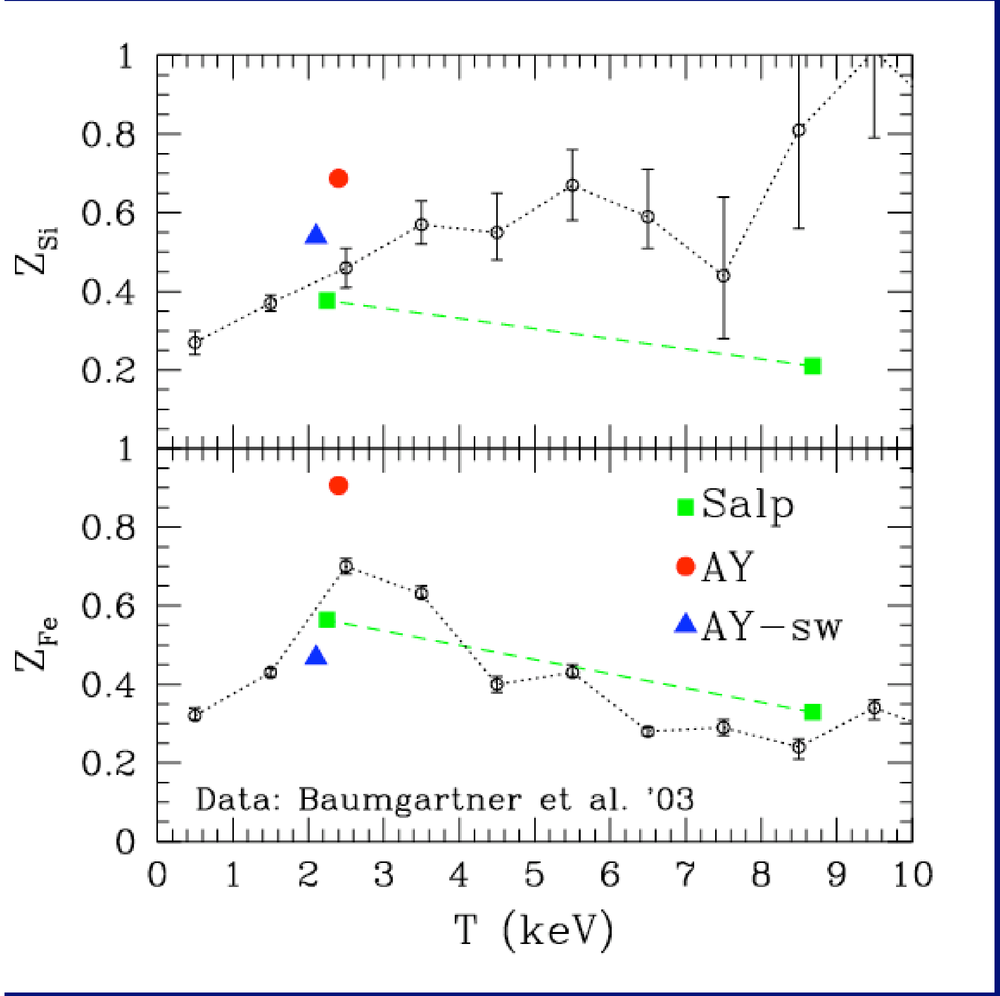
Iron [0.01-0.5] $\mathrm{Fe}_{\odot}$



Oxygen [0.01-0.1] $\mathrm{O}_{\odot}$



Following the chemical enrichment of the ICM



Salpeter IMF

- Z_{Fe} larger for the smaller cluster (similar trend as in observations)
- Too low Z_{Si} for the massive cluster.
- No change in Z_{Si} by increasing the fraction of binary stars (Si not produced by SN-Ia)

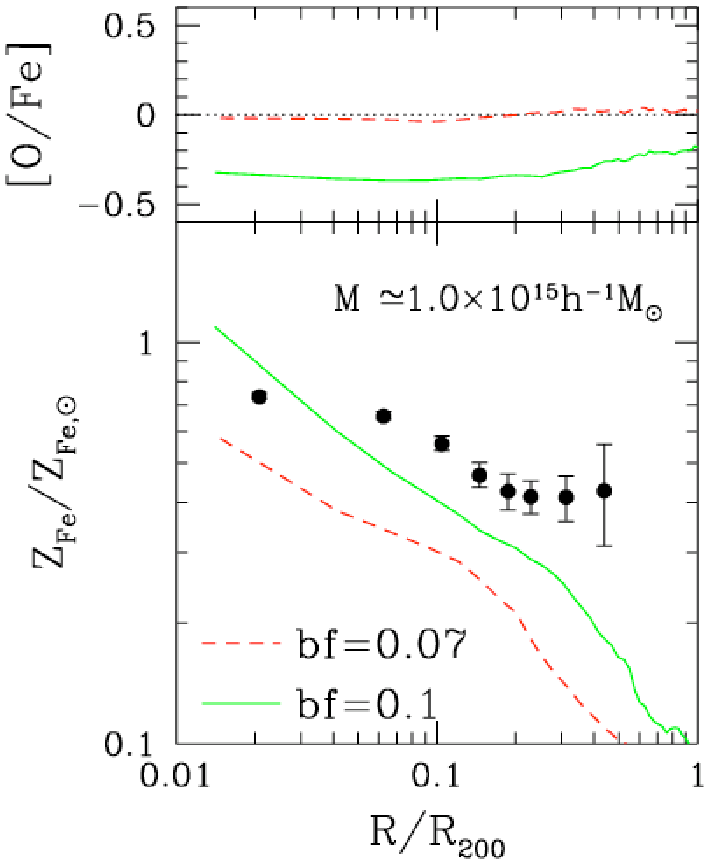
Changing the IMF

- Z_{si} larger for a top-heavier IMF
- Z_{Fe} lower for strong winds due to the suppression of star formation ($f^*=0.12$ vs. $f^*=0.22$)

Following the chemical enrichment of the ICM

Abundance profiles

Data: De Grandi et al. '03



Salpeter IMF

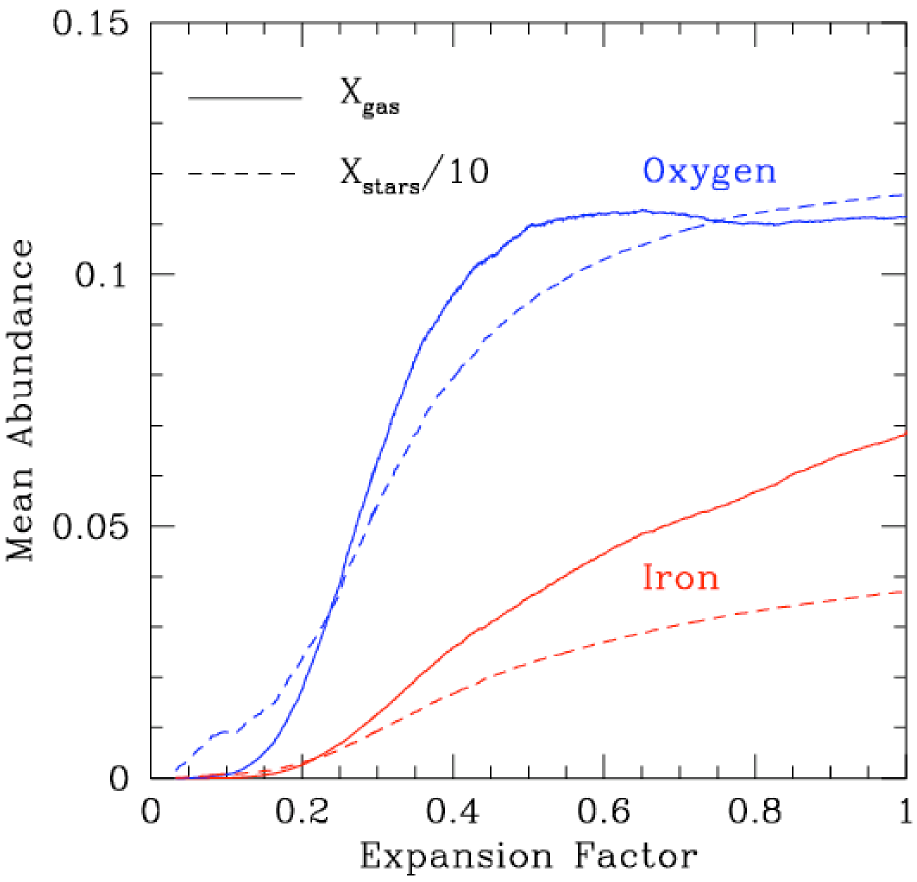
- Fraction of binaries has a sizeable effect on [O/Fe]
- Profiles of Z_{Fe} steeper than observed!

⇒ Lack of metal diffusion (by turbulence?)

⇒ Higher resolution to better treat the stripping of metal-enriched gas in galactic halos?

Following the chemical enrichment of the ICM

Star-formation rates



- SFR peaking at z=2-3
- Changing the IMF at constant wind velocity: marginal effect.
- Increasing the wind speed:
  a. suppress the SFR peak
  b. make SFR flat at z=1.5-3

- SN-II nearly follow the SFR
- SN-Ia rate much flatter to low z

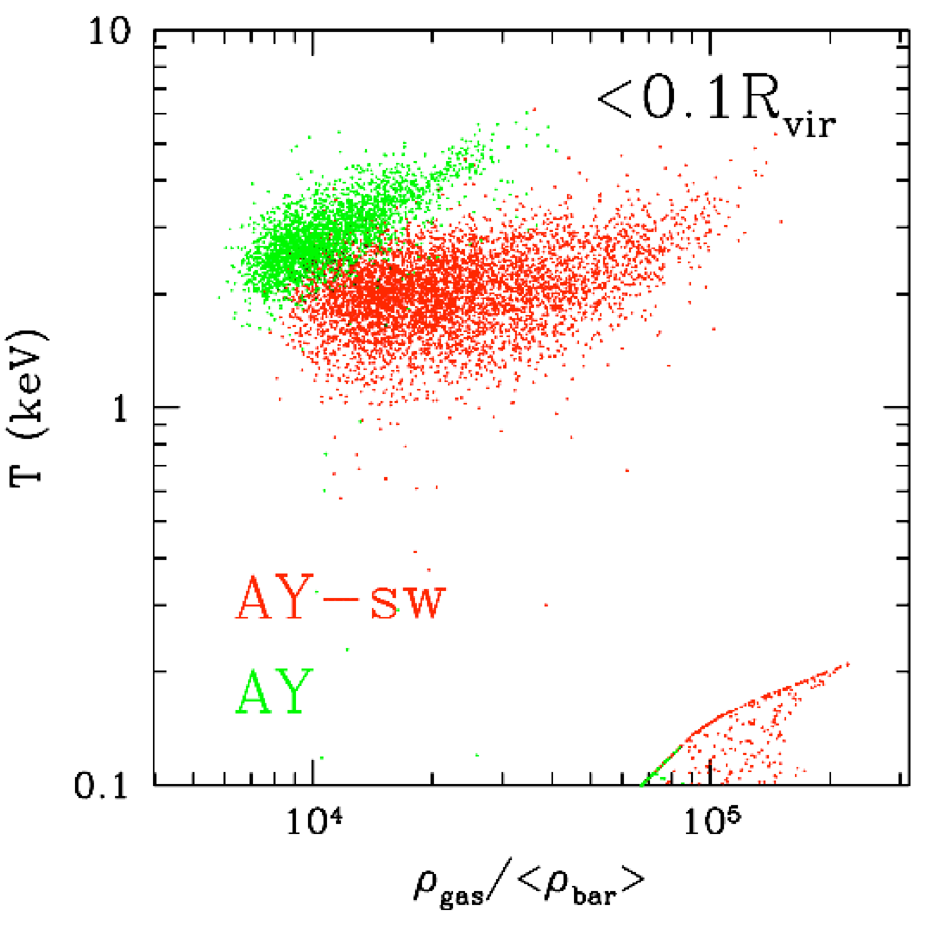
⇒ Important to correctly follow the lifetimes!

a. Iron produced down to low z

b. Oxygen almost unchanged since z=1

Following the chemical enrichment of the ICM

Gas-related profiles



- Entropy profiles:

flatter due to the more efficient cooling of metal-enriched gas.

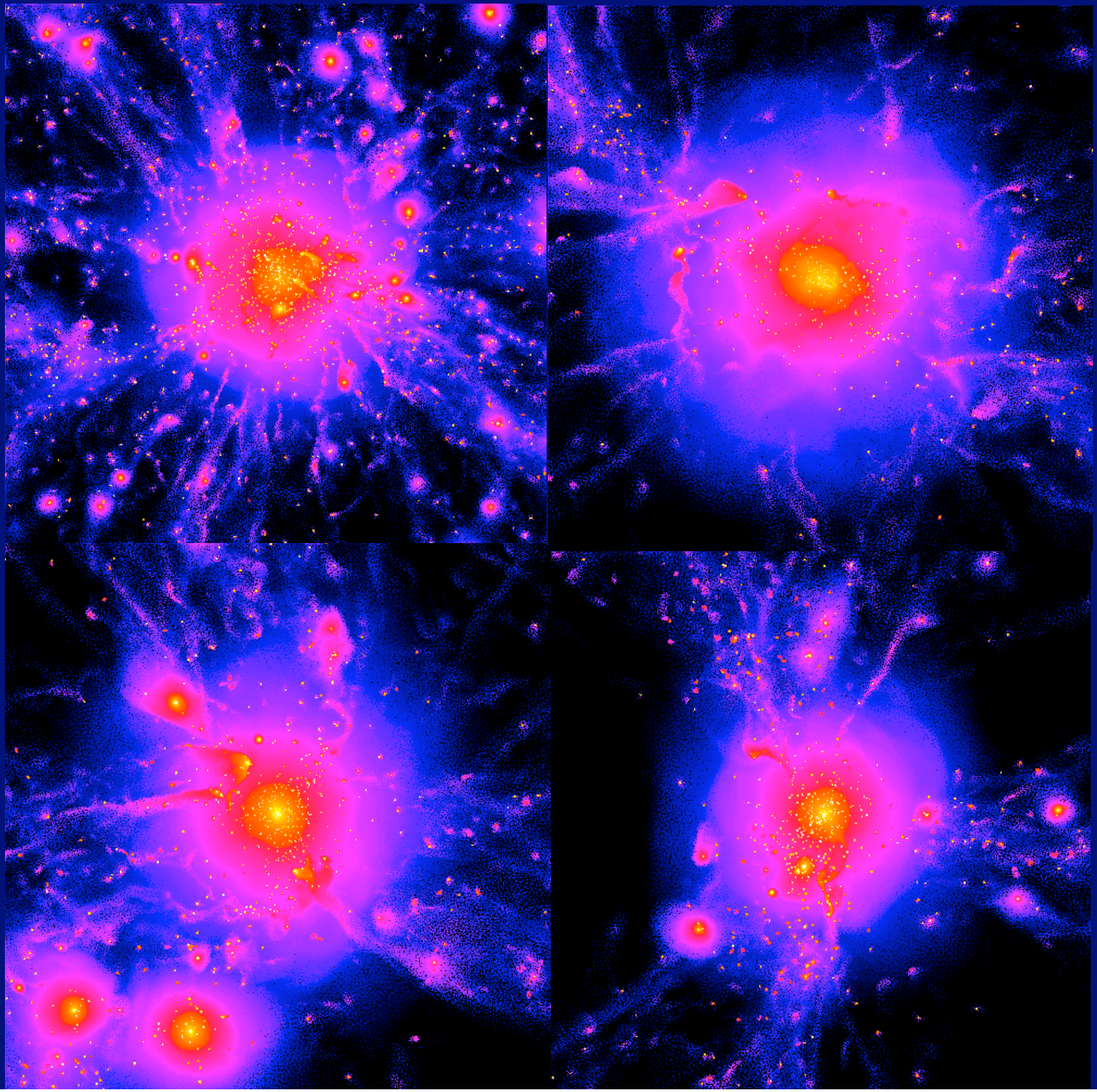
Exception: stronger feedback preventing a population of low-S gas from cooling out of the hot phase.

⇒ IMF dominant in determining the pattern of chemical enrichment.

⇒ Feedback strength dominant in determining the ICM thermodynamics.

PART III: controlling numerics and physics

Maps of gas density



Cl-1

1.4e15 $M_\odot$ /h

m_g=7e7 $M_\odot$ /h

ϵ_{Pl}=3.2 kpc/h

Cl-2

2.9e14 $M_\odot$ /h

m_g=1.5e7 $M_\odot$ /h

ϵ_{Pl}=2.1 kpc/h

Cl-3

2.7e14 $M_\odot$ /h

m_g=1.5e7 $M_\odot$ /h

ϵ_{Pl}=2.1 kpc/h

Cl-4

1.6e14 $M_\odot$ /h

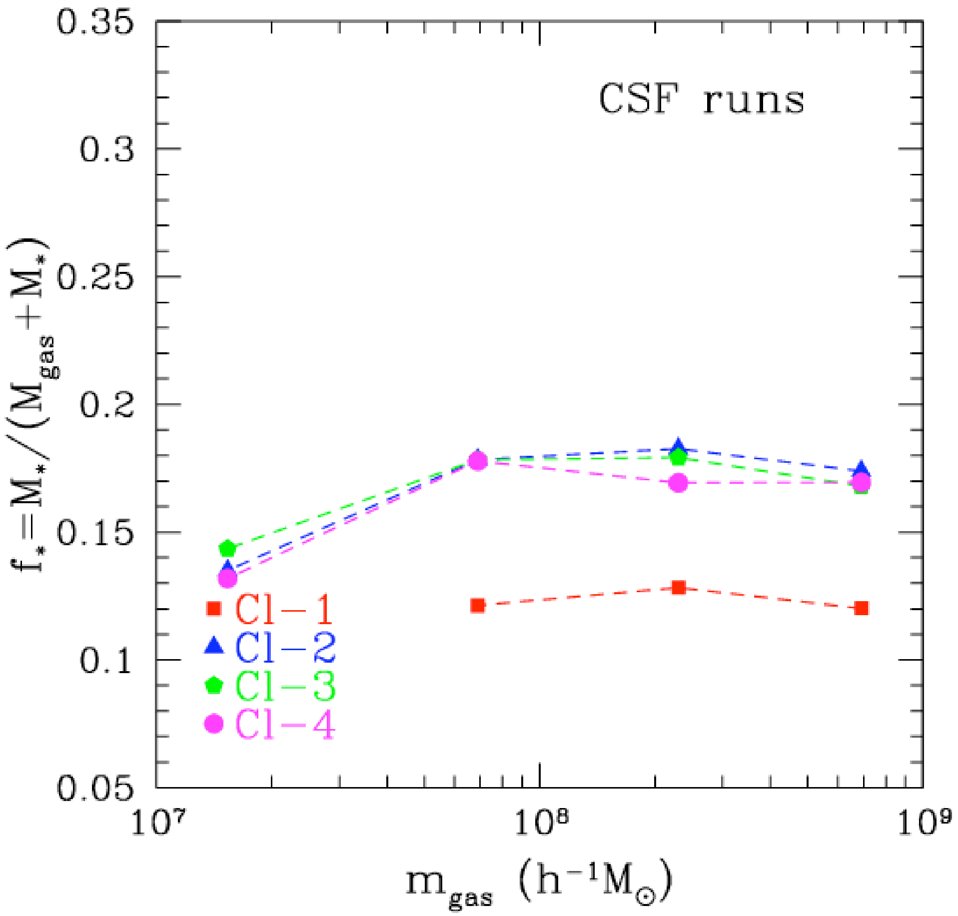
m_g=1.5e7 $M_\odot$ /h

ϵ_{Pl}=2.1 kpc/h

Preventing the cooling catastrophe with feedback

SB, Dolag, Murante, Cheng et al. '05

Star fraction vs. resolution



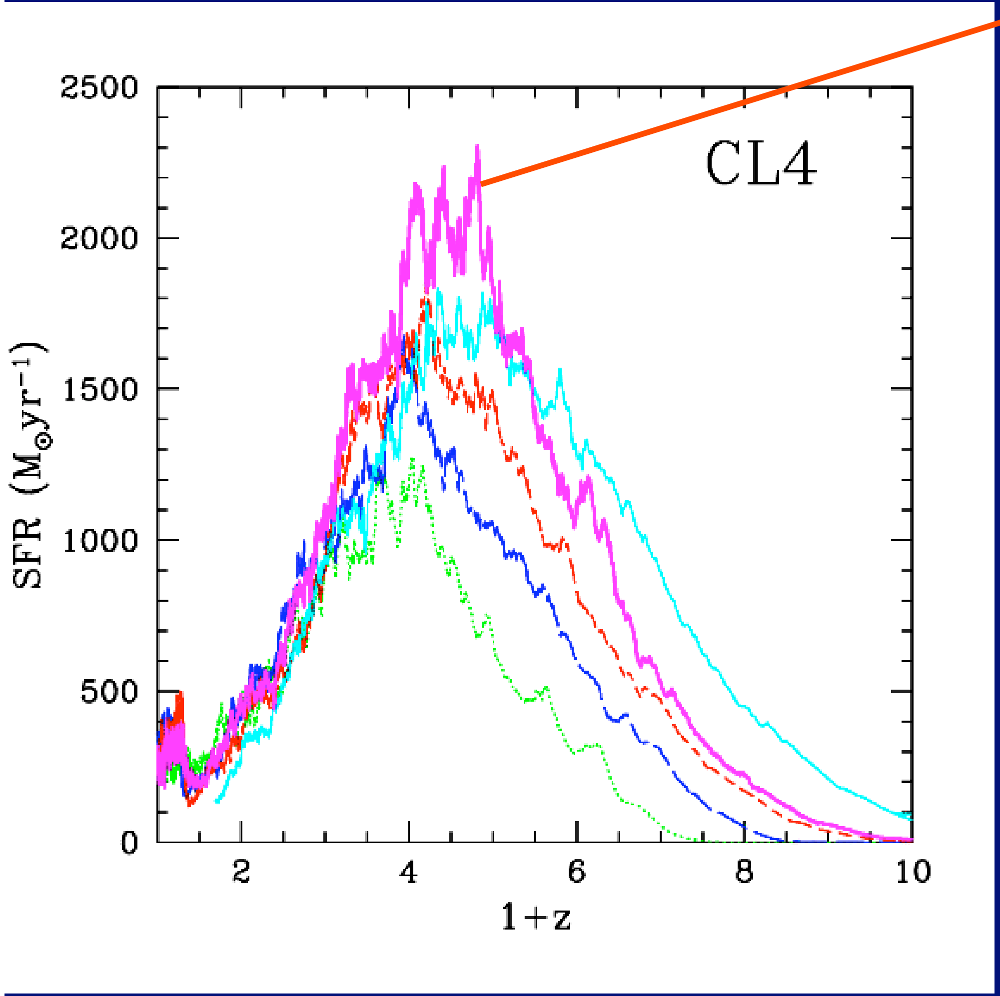
- Feedback with galactic winds prevents the cooling runaway.
- f* even decreasing at the highest resolution.

Effect of pre-heating: earlier winds from smaller halos forming at higher redshift.

Getting closer to the observed f*...

Also, what about diffuse light?

The star-formation history



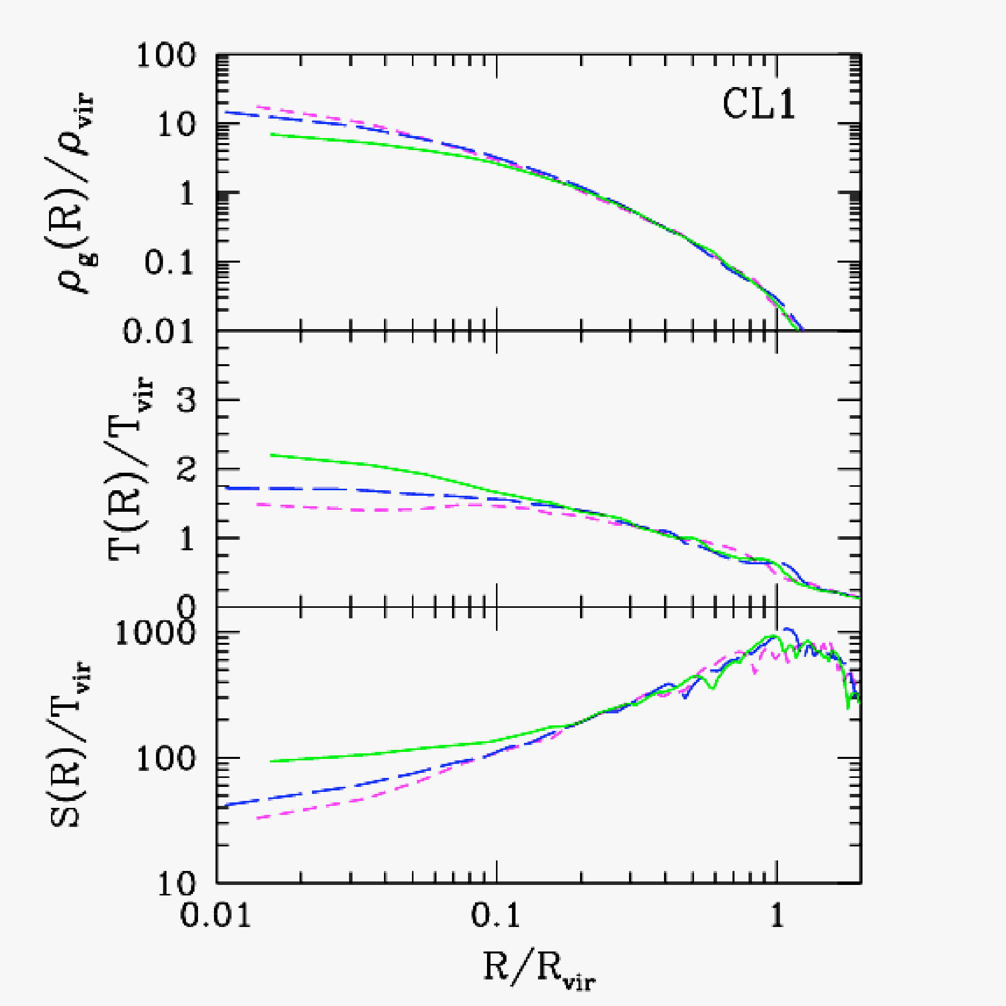
$m_{gas}=m_{DM}$

- Winds suppress SF at z<7.
- Stronger SF at large redshift for higher resolution

⇒ Quite expected…

- Lower f* at high res. due to suppression of SF at z<2

T, S & ρ_{gas} profiles



Effect of increasing resolution:

- Improved description of the gas cooling structure

⇒ Steepening of the central T-profiles.

- Higher central entropy ($R<0.1 R_{vir}$) from more efficient high-redshift feedback.

- Excellent convergence of the outer ($R>0.1R_{vir}$) profiles

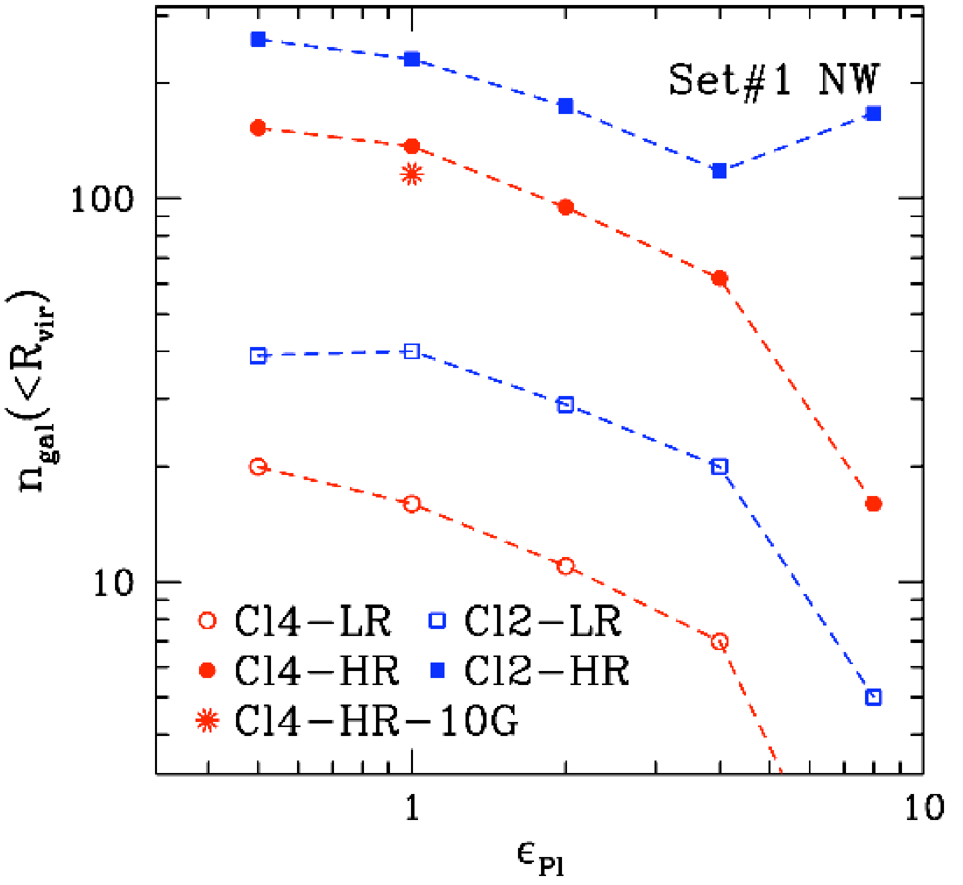
⇒ Isothermal profiles from data would be a nightmare for simulations…..

Controlling numerical heating

SB, Dolag, Murante et al. in prep

Looking for an optimal softening?

$$\varepsilon \propto m_{gas}^{1/3}$$



Star formation suppressed by:

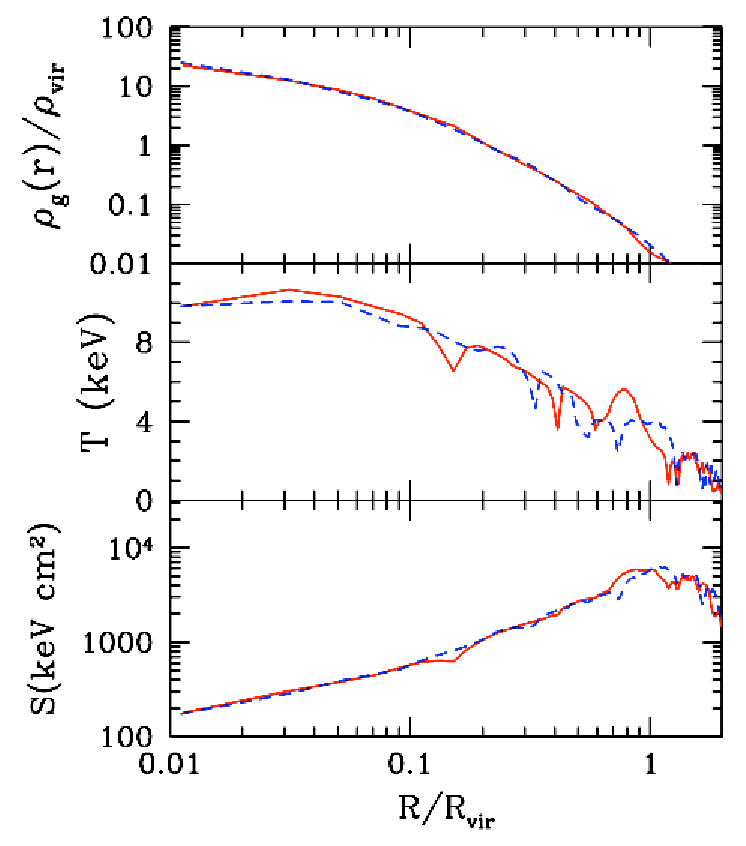
- too small softening:numerical gas heating (Thomas & Couchman '93).
- too large softening: unresolved halos.

Number of resolved galaxies:

- always decreasing with softening

⇒ Compromise between f_* and n_{gal}.

Grid vs. Glass ICs



Glass ICs (White 1994):

- Unperturbed particle positions define an amorphous (glass-like) configuration.
- Obtained by evolving a random particle distribution with negative gravity.

Almost negligible effect on SFR and gas-related profiles

CONCLUSIONS

(a) Entropy amplification in cluster outskirts: not easy to obtain.

⇒ ICM entropy as diagnostic for the high-z feedback.

(b) Chemical enrichment of the ICM:

b.1 Global metal content and relative abundances reproduced by suitable choices of the IMF.

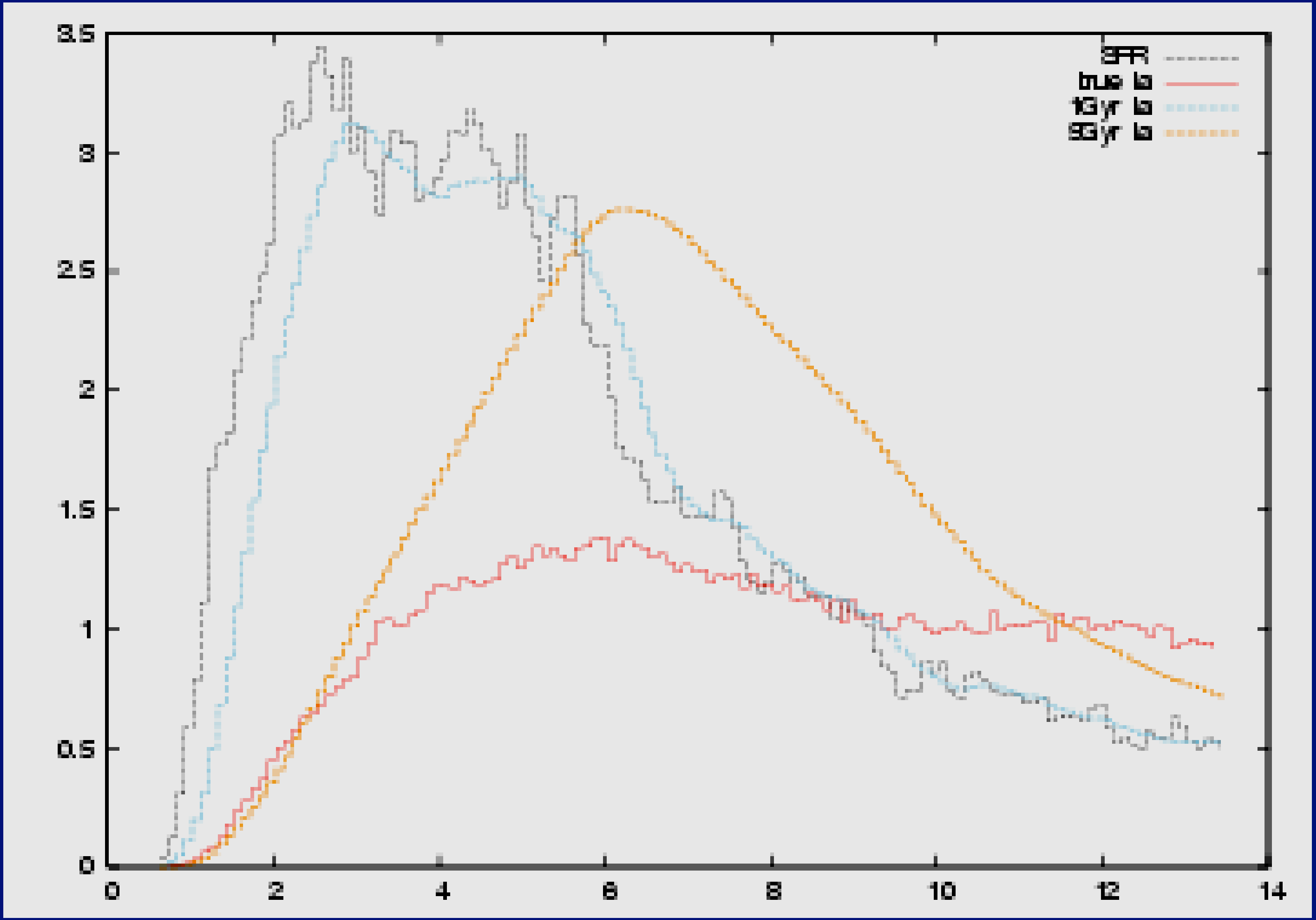
b.2 Profiles of Z_{Fe} steeper than observed: Lack of diffusion?

(c) Feedback quite effective in regulating SF and preventing cooling catastrophy:

Problem: Temperature profiles always too steep in central regions!

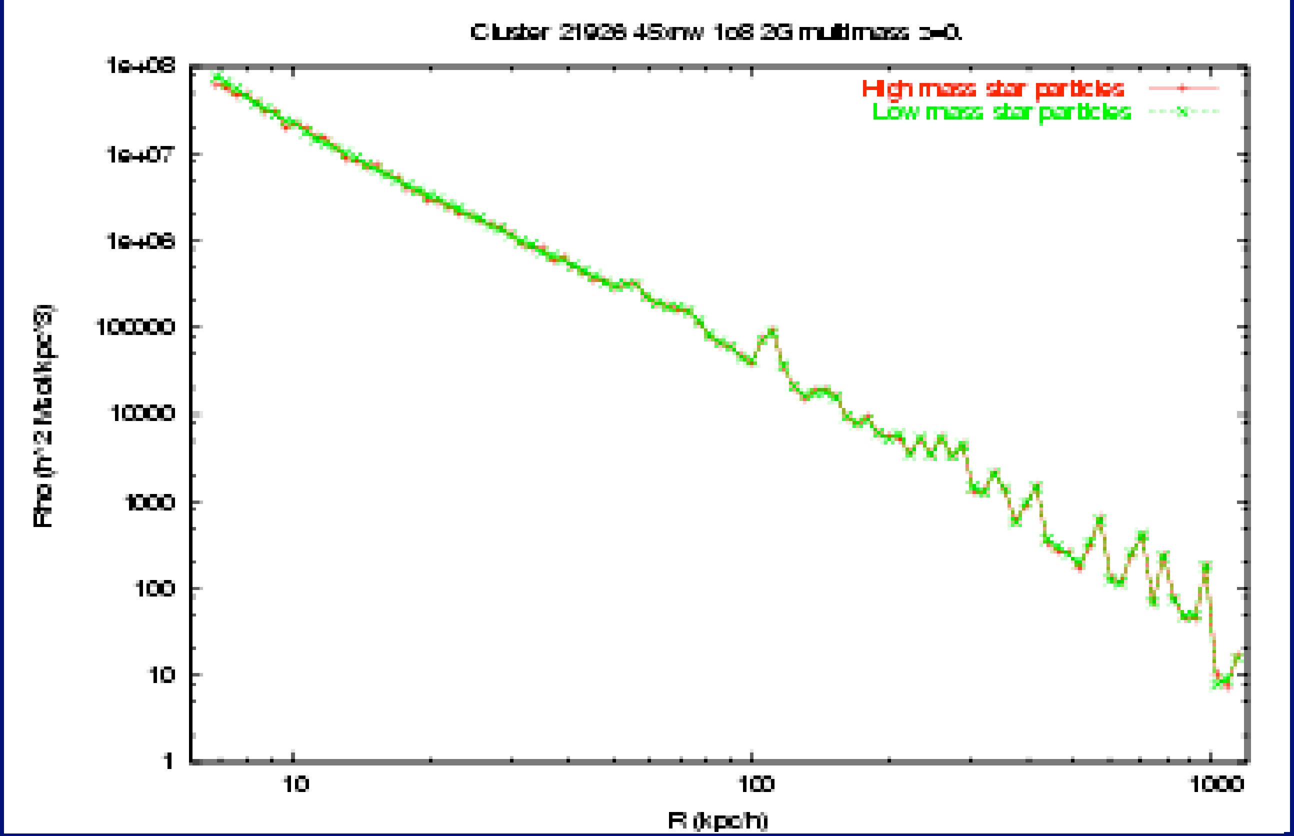
Solution: The same as for the cooling-flow problem (AGN? See poster by D. Sijacki).

- Find a robust way to include observational biases (see poster by E. Rasia)


SFR
true Ia
1Gyr Ia
3Gyr Ia
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14

Checking for mass segregation

Generate stars with masses differing by a factor 10



- No significant difference in the distributions of the 2 star populations
- Virtually identical profiles ⇒ Good news for the ICL study in simulations!