AGN feedback in hydro-dynamical numerical simulations : consequences for the formation of massive galaxies

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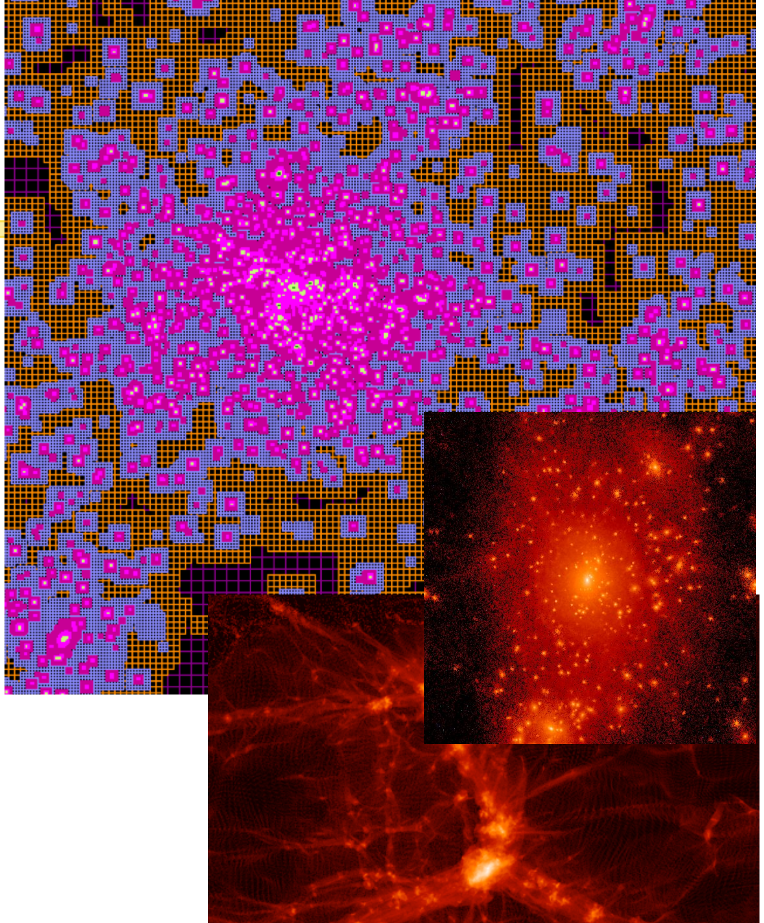
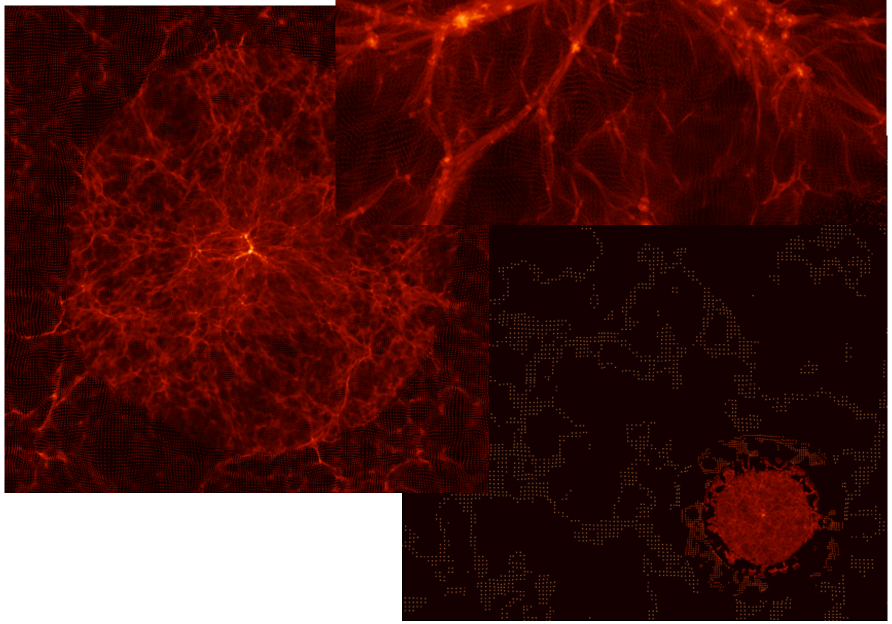
RAMSES : an Adaptive Mesh Refinement (AMR) code

- Language :
  - Fortran 90
  - MPI parallelization
- Method : adaptive grid refinement
- Equations :
  - Hydrodynamics
  - Magneto-hydrodynamics
  - Gravity
  - Atomic/Metal cooling + UV-heating
  - Radiative transfer
- Sub-grid physics :
  - Star formation
  - Supernovae
  - Active Galactic Nuclei (AGN)
- Cosmology

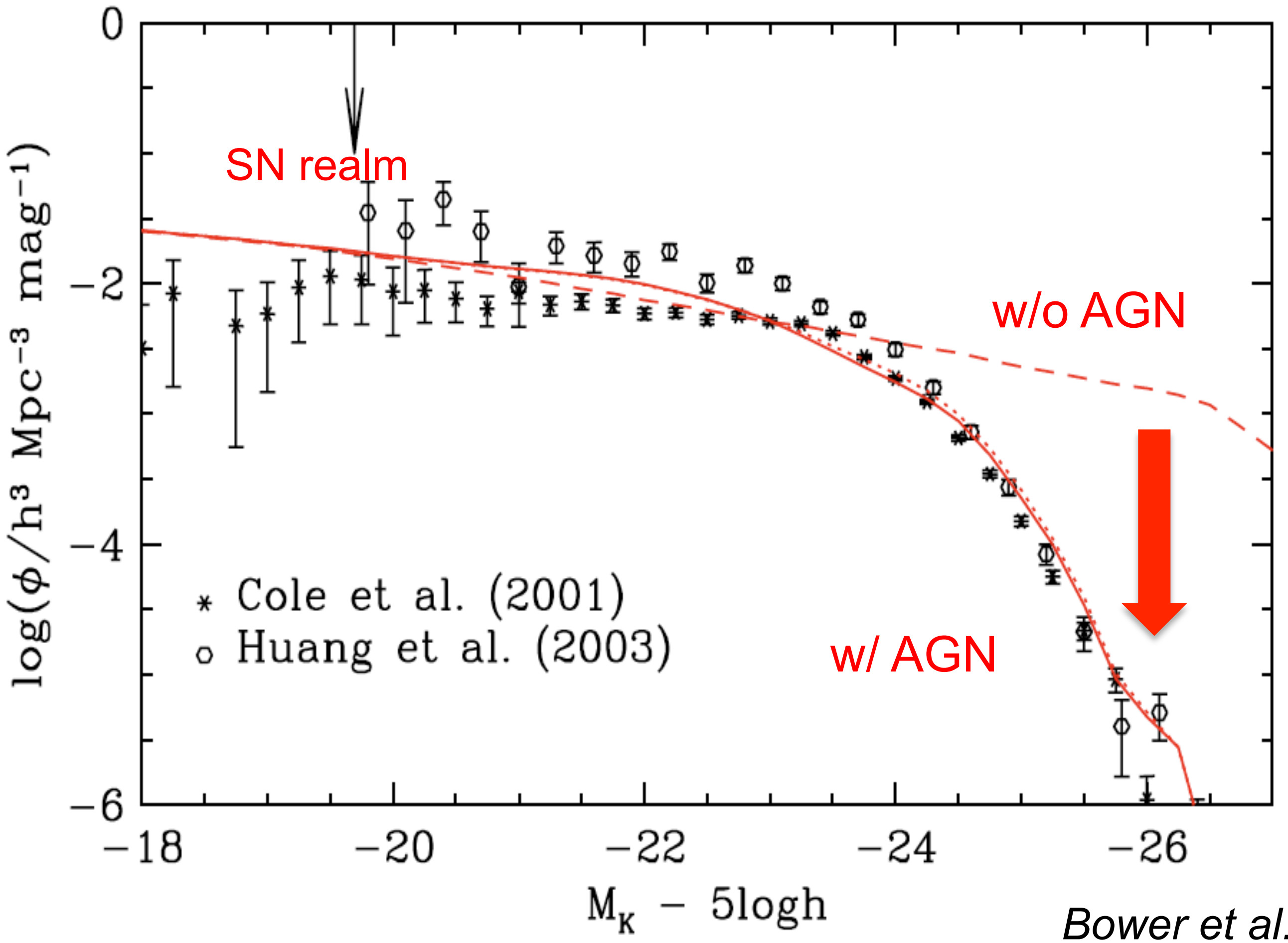
See Teyssier, 2002





Motivation for AGN feedback

Galaxy luminosity (~mass) function
Semi-analytic models



Bower et al., 2006

AGN in cosmological simulations

First AMR simulations of self-consistent AGN feedback in a cosmological context

- Mimic the formation of black holes (where and when)

In the centre of galaxies in high gas and stellar-density regions

$$M_{\rm seed} = 10^5\,{\rm M}_\odot$$

AGN in cosmological simulations

First AMR simulations of self-consistent AGN feedback in a cosmological context

- Mimic the formation of black holes (where and when)
- Mimic the gas accretion onto black holes

In the centre of galaxies in high gas and stellar-density regions

$$M_{\rm seed} = 10^5 \, {\rm M}_\odot$$

Bondi accretion rate

$$\dot{M}_{\rm BH} \propto \rho \frac{M_{\rm BH}^2}{c_{\rm s}^3}$$

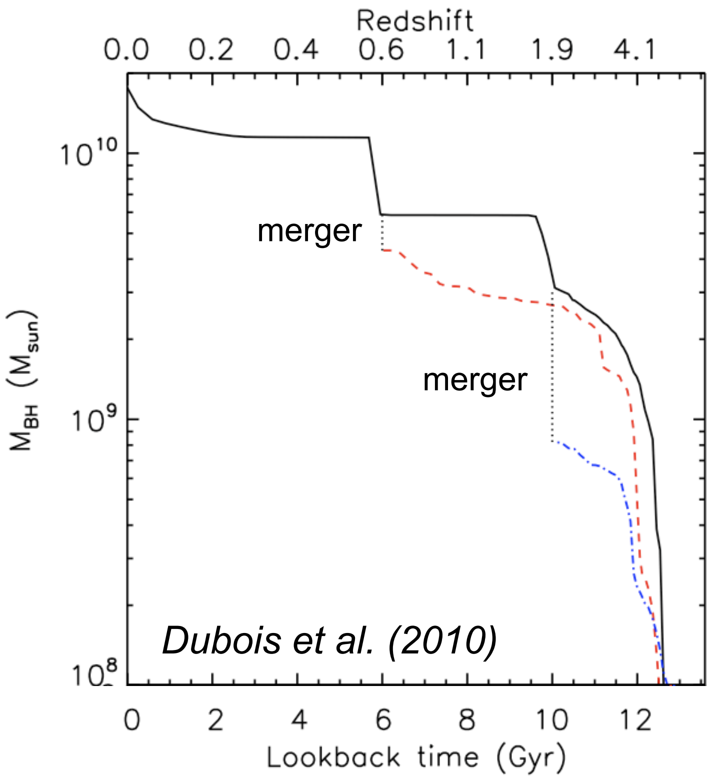
Fast accretion in dense and cold regions

AGN in cosmological simulations

<u>First</u> AMR simulations of self-consistent AGN feedback in a cosmological context

- Mimic the formation of black holes (where and when)
- Mimic the gas accretion onto black holes
- Mimic the mergers between black holes (Friend-of-friend algorithm)

sink particles (Bate et al., 1995, Krumholz et al., 2004)

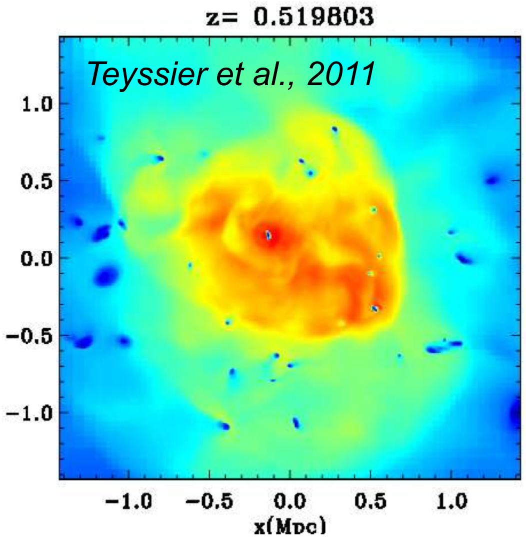


AGN in cosmological simulations

First AMR simulations of self-consistent AGN feedback in a cosmological context

- Mimic the formation of black holes (where and when)
- Mimic the gas accretion onto black holes
- Mimic the mergers between black holes (Friend-of-friend algorithm)
- Mimic the feedback from black holes (AGN)

With thermal input (Teyssier et al., 2011)
(see Sijacki, Di Matteo et al. papers, and Booth & Schaye papers)



Modification of the internal energy

-> increase the gas temperature

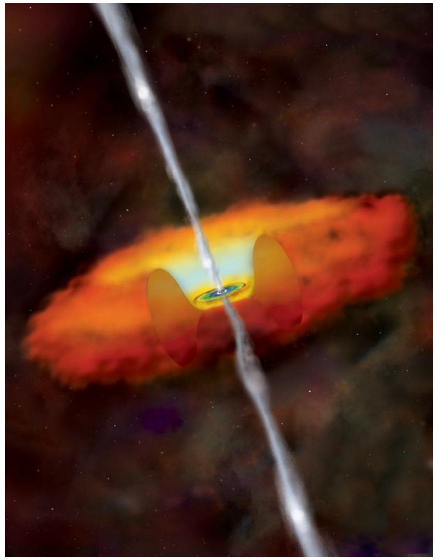
AGN in cosmological simulations

First AMR simulations of self-consistent AGN feedback in a cosmological context

- Mimic the formation of black holes (where and when)
- Mimic the gas accretion onto black holes
- Mimic the mergers between black holes (Friend-of-friend algorithm)
- Mimic the feedback from black holes (AGN)

With thermal input (Teyssier et al., 2011)
or with jets (Dubois et al., 2010, 2011)

$$L_{\rm AGN} = \epsilon_f \epsilon_r \dot{M}_{\rm BH} c^2$$



Compute gas angular momentum around the black hole
-> jet axis

Kinetic energy with bipolar outflow

Mass ejected with velocity 10 000 km/s

(jet-model based on Omma et al. 2004)

AGN in cosmological simulations

First AMR simulations of self-consistent AGN feedback in a cosmological context

- Mimic the formation of black holes (where and when)
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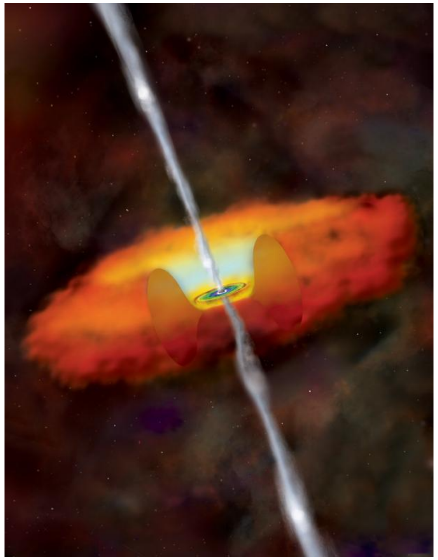
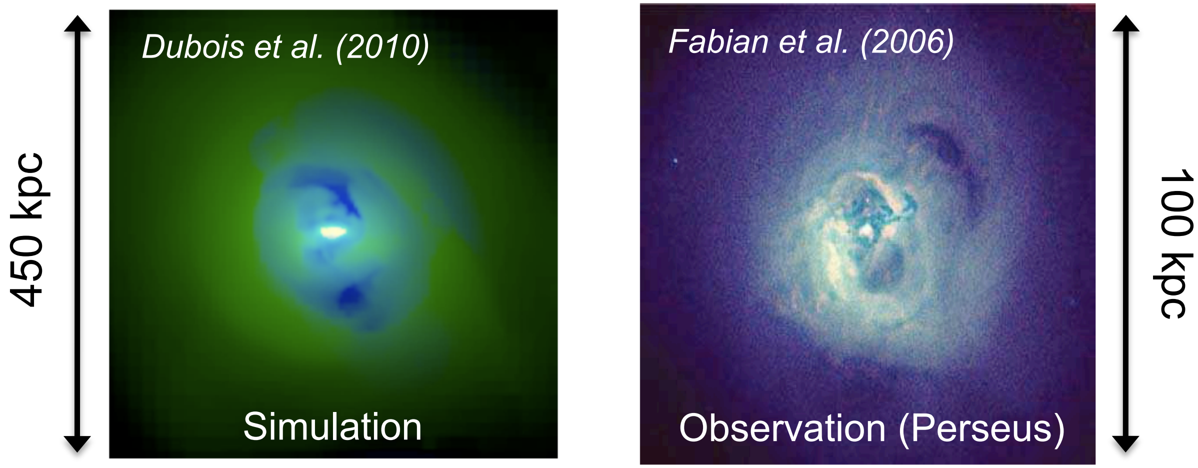
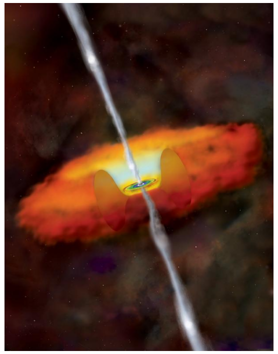


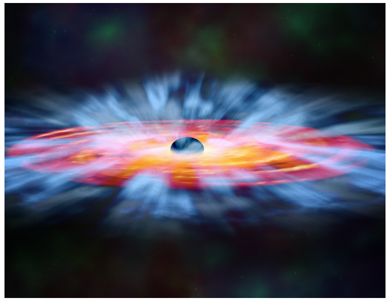


X-ray (3 bands)

Two modes for AGN feedback

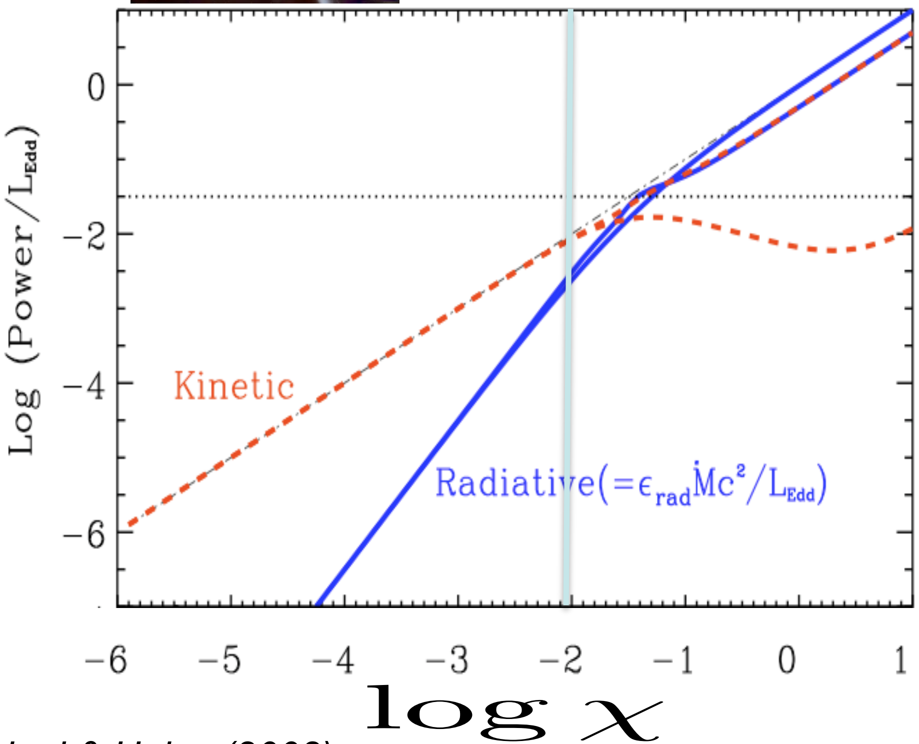


or



Eddington ratio of the accretion rate

$$\chi = \frac{\dot{M}_{\rm BH} c^2}{L_{\rm Edd}}$$



Merloni & Heinz (2008)

Radio mode (kinetic jet) when

$$\chi \leq 0.01$$

$$L_{\rm radio} = 0.1 \dot{M}_{\rm BH} c^2$$

Quasar mode (heating) when

$$\chi > 0.01$$

$$L_{\rm quasar} = 0.015 \dot{M}_{\rm BH} c^2$$

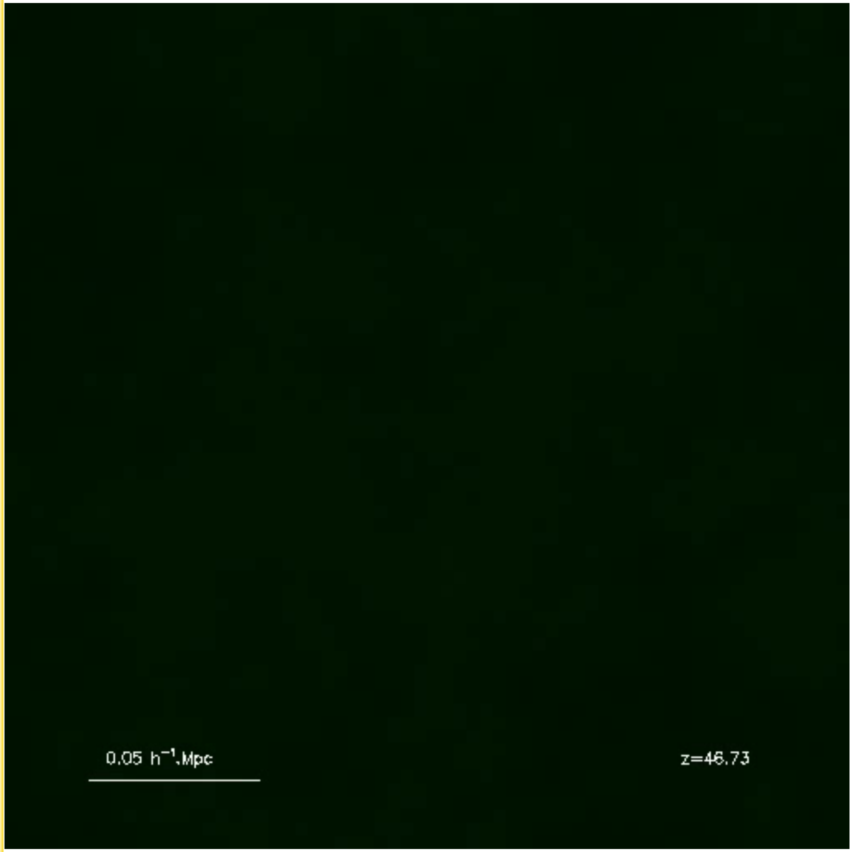
Heuristic efficiencies calibrated from simulations

$L_{\rm box} = 12.5\,{\rm Mpc/h}$
$\Delta x_{\rm min} = 0.38\,{\rm kpc/h}$

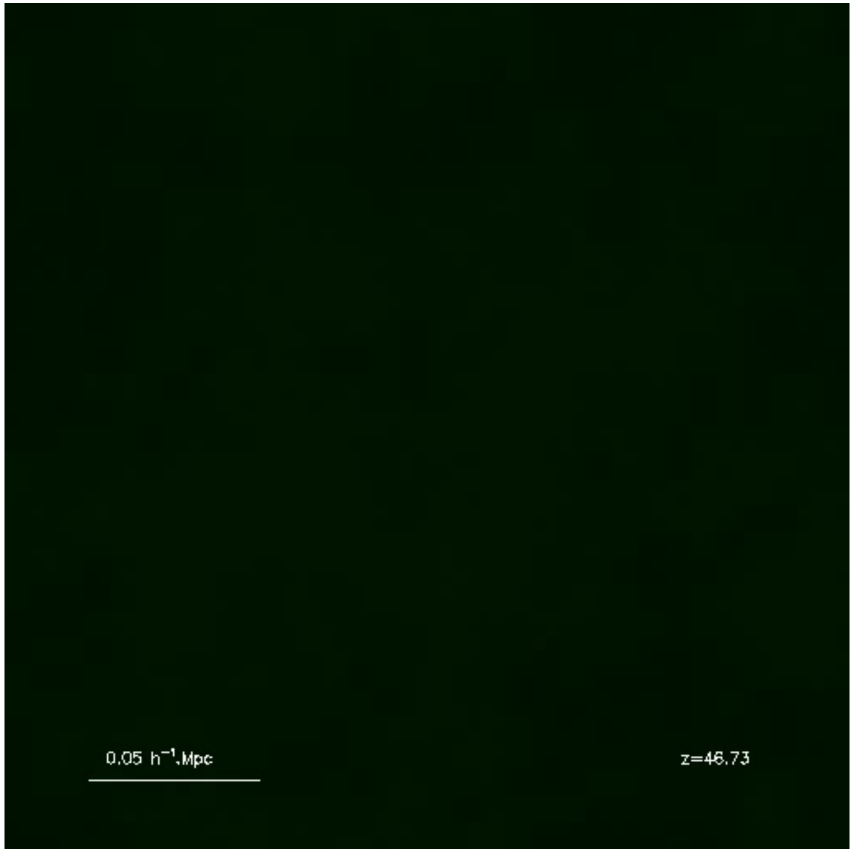
WMAP 5-year cosmology

17.10^6 DM particles
$M_{\rm DM} = 6.9\,10^6\,{\rm M_\odot/h}$

Red = gas temperature / Green = gas density / Blue = gas metallicity



No AGN



AGN

Testing the model: parameters and resolution

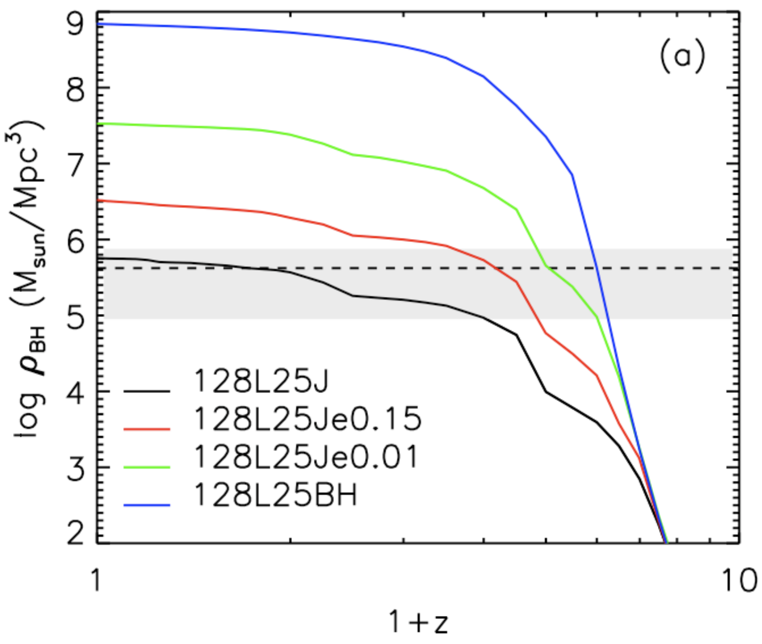
Table 1. Simulations performed with different sub-grid galactic models, different parameters for the AGN feedback mode, and different resolutions. (a) Name of the simulation. (b) Number of DM particles. (c) Mass resolution of a DM particle. (d) Size of the simulation box. (e) Minimum resolution reached at $z = 0$. (f) Presence of feedback from SNe. (g) Presence of AGN feedback: "BH" stands for the formation and growth of BHs without AGN feedback, "Jet" stands for the radio mode only, "Heat" stands for the quasar mode only, and "JET/HEAT" stands for the quasar and radio mode both triggered in the same simulation (see text for details). (h) AGN feedback efficiency. (i) AGN energy delay. (j) Maximum relative velocity of the gas to the BH. (k) Mass loading factor of the jet. (l) Initial BH mass. (m) Size of the AGN energy input.

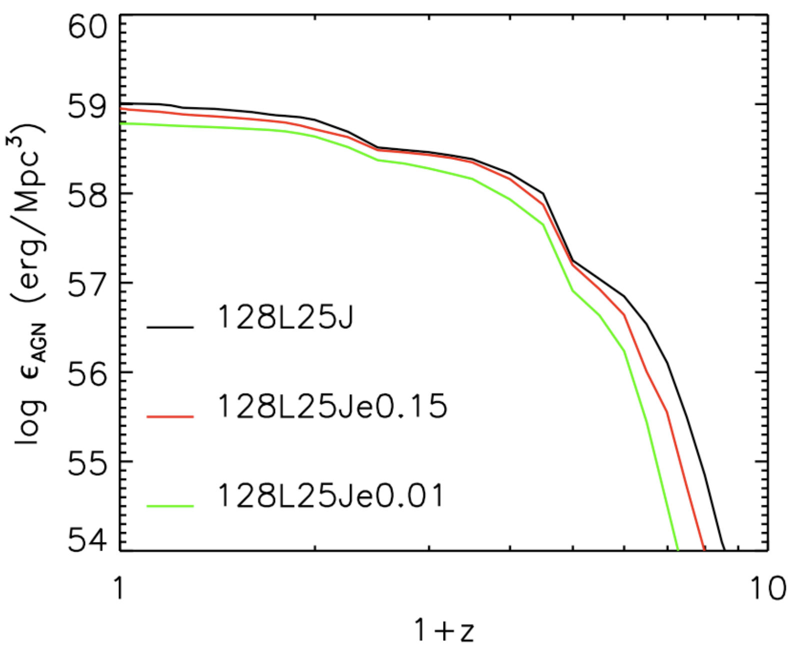
Name	$N_{\rm DM}$	$M_{\rm DM}$ ($M_\odot$/h)	$L_{\rm box}$ (Mpc/h)	Δx (kpc/h)	SN	AGN	ϵ_f	$\Delta M_{\rm d}$ %	$u_{\rm max}$ (km/s)	η	$M_{\rm seed}$ ($M_\odot$)	$r_{\rm AGN}$
256L12noAGN	256^3	$6.9\,10^6$	12.5	0.38	Yes	No	–	–	–	–	–	–
256L12JH	256^3	$6.9\,10^6$	12.5	0.38	Yes	Jet/Heat	1/0.15	0/–	10	100/–	10^5	Δx
64L25JH	64^3	$3.5\,10^9$	25	3.04	Yes	Jet/Heat	1/0.15	0/–	10	100/–	10^5	Δx
128L25BH	128^3	$4.4\,10^8$	25	1.52	Yes	BH	–	–	10	–	10^5	–
128L25J	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	10	100	10^5	Δx
128L25Je0.15	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	0.15	0	10	100	10^5	Δx
128L25Je0.01	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	0.01	0	10	100	10^5	Δx
128L25Jm1	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	1	10	100	10^5	Δx
128L25Jm10	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	10	10	100	10^5	Δx
128L25Jv100	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	100	100	10^5	Δx
128L25Jv1000	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	1000	100	10^5	Δx
128L25Jη10	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	10	10	10^5	Δx
128L25Jη1000	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	10	1000	10^5	Δx
128L25Js0.1	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	10	100	10^4	Δx
128L25Js10	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	10	100	10^6	Δx
128L25J2dx	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	10	100	10^5	$2\Delta x$
128L25J4dx	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	10	100	10^5	$4\Delta x$
128L25H	128^3	$4.4\,10^8$	25	1.52	Yes	Heat	0.15	–	10	–	10^5	Δx
128L25H2dx	128^3	$4.4\,10^8$	25	1.52	Yes	Heat	0.15	–	10	–	10^5	$2\Delta x$
128L25H4dx	128^3	$4.4\,10^8$	25	1.52	Yes	Heat	0.15	–	10	–	10^5	$4\Delta x$
128L25JH	128^3	$4.4\,10^8$	25	1.52	Yes	Jet/Heat	1/0.15	0/–	10	100/–	10^5	Δx
256L25noSNAGN	256^3	$5.5\,10^7$	25	0.76	No	No	–	–	–	–	–	–
256L25noAGN	256^3	$5.5\,10^7$	25	0.76	Yes	No	–	–	–	–	–	–
256L25JH	256^3	$5.5\,10^7$	25	0.76	Yes	Jet/Heat	1/0.15	0/–	10	100/–	10^5	Δx
128L50noAGN	128^3	$3.5\,10^9$	50	3.04	Yes	No	–	–	–	–	–	–
128L50JH	128^3	$3.5\,10^9$	50	3.04	Yes	Jet/Heat	1/0.15	0/–	10	100/–	10^5	Δx
256L50noAGN	256^3	$4.4\,10^8$	50	1.52	Yes	No	–	–	–	–	–	–
256L50JH	256^3	$4.4\,10^8$	50	1.52	Yes	Jet/Heat	1/0.15	0/–	10	100/–	10^5	Δx

Dubois et al., 2012

Parameter test: the efficiency

$$L_{\mathrm{AGN}} = \epsilon_f \epsilon_r \dot{M}_{\mathrm{BH}} c^2$$

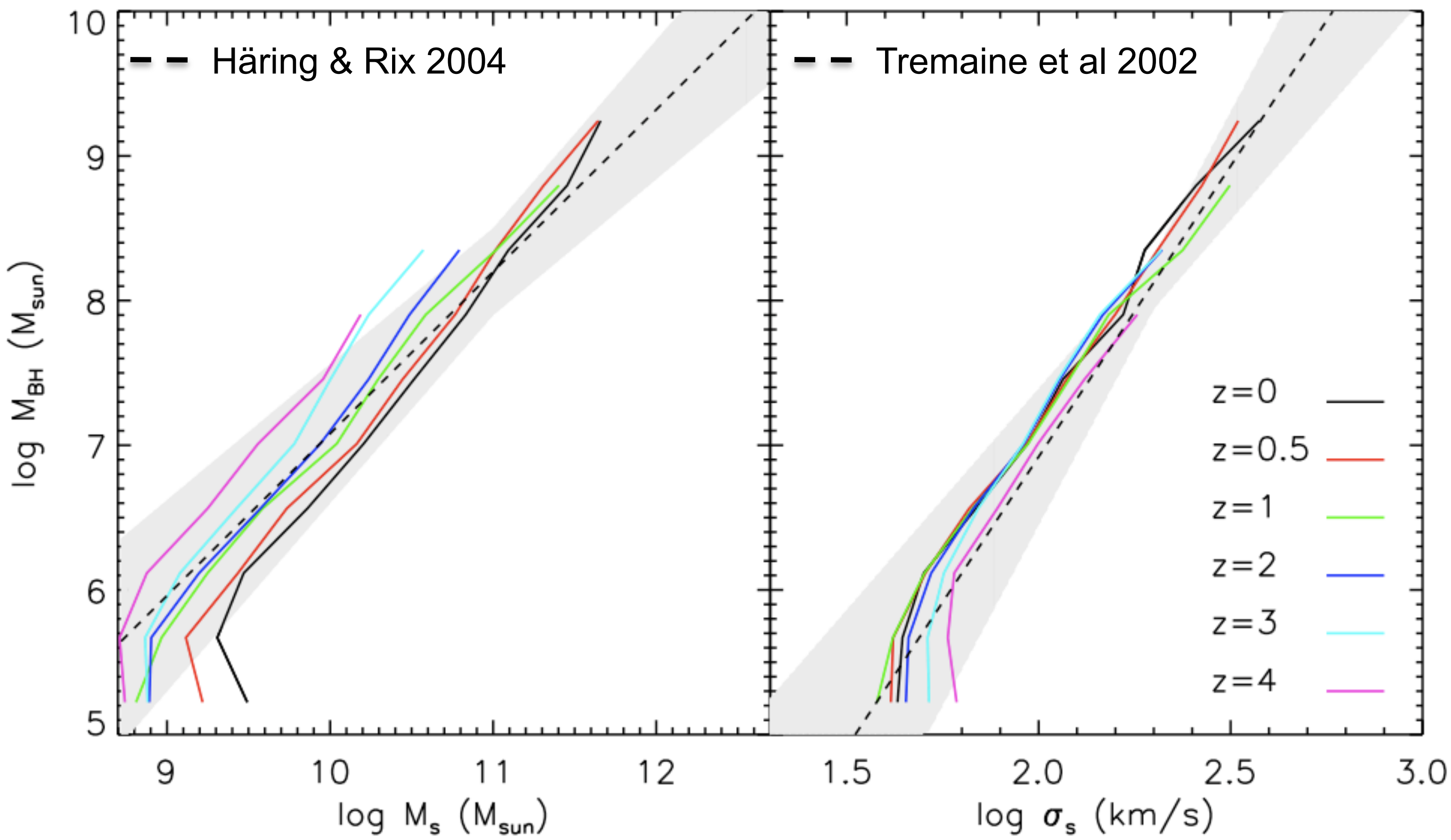




BHs deposit the same energy / independant of the AGN efficiency

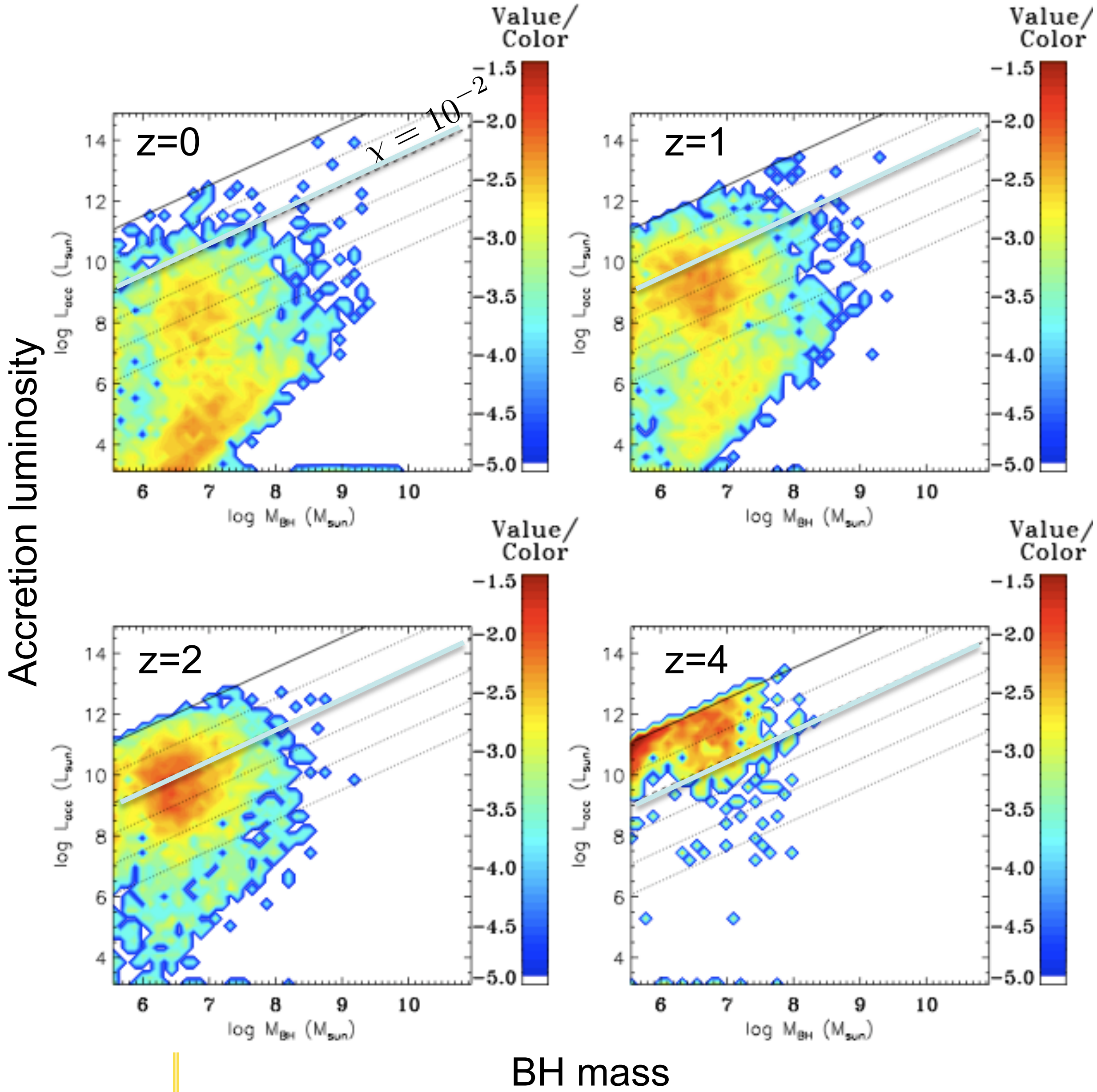
Dubois et al., 2012

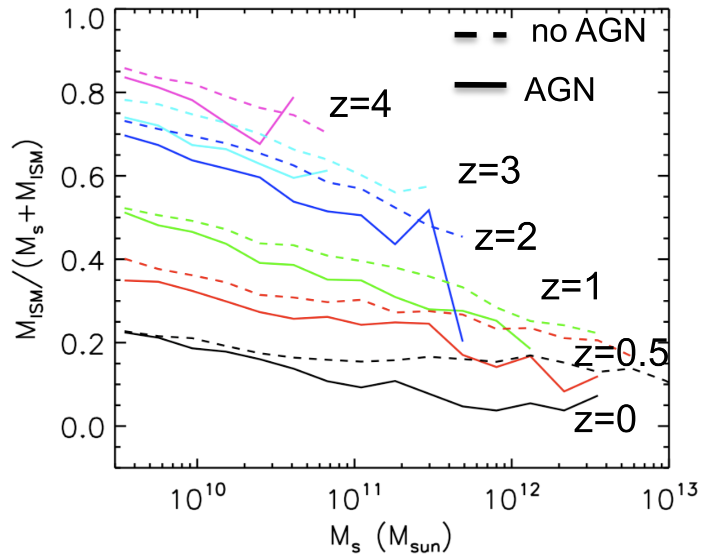
Fitting observationnal M_{BH}-M_* / M_{BH}-σ_* laws



Dubois et al., 2012

Radio mode or quasar mode ?



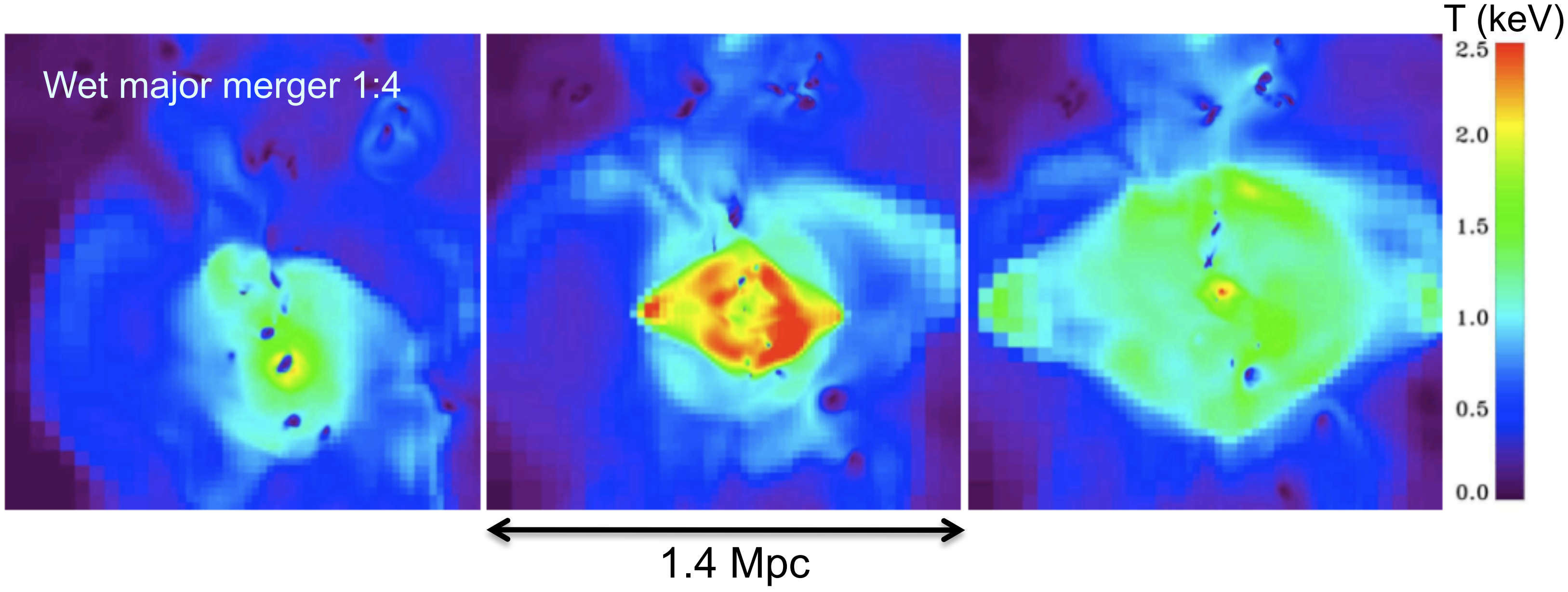


Galaxies are gas-rich at high-redshift
Star formation and feedback removes cold gas efficiently

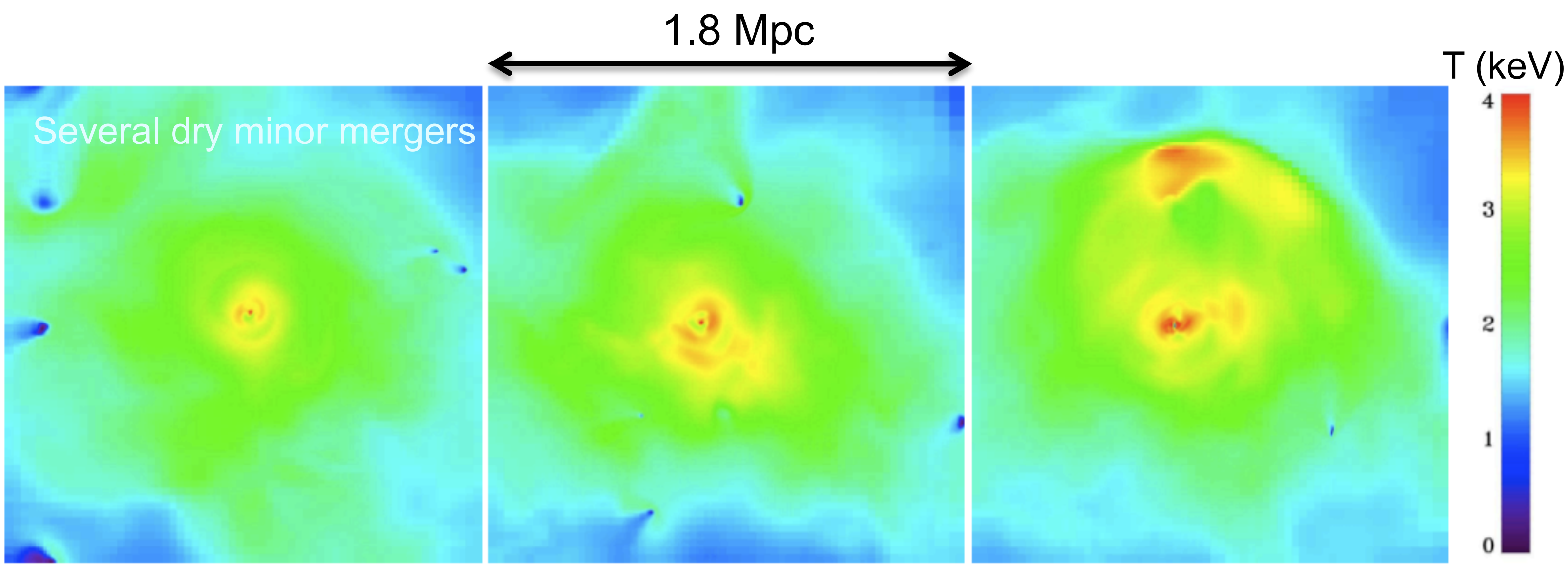
Dubois et al., 2012

Quasar mode versus radio mode

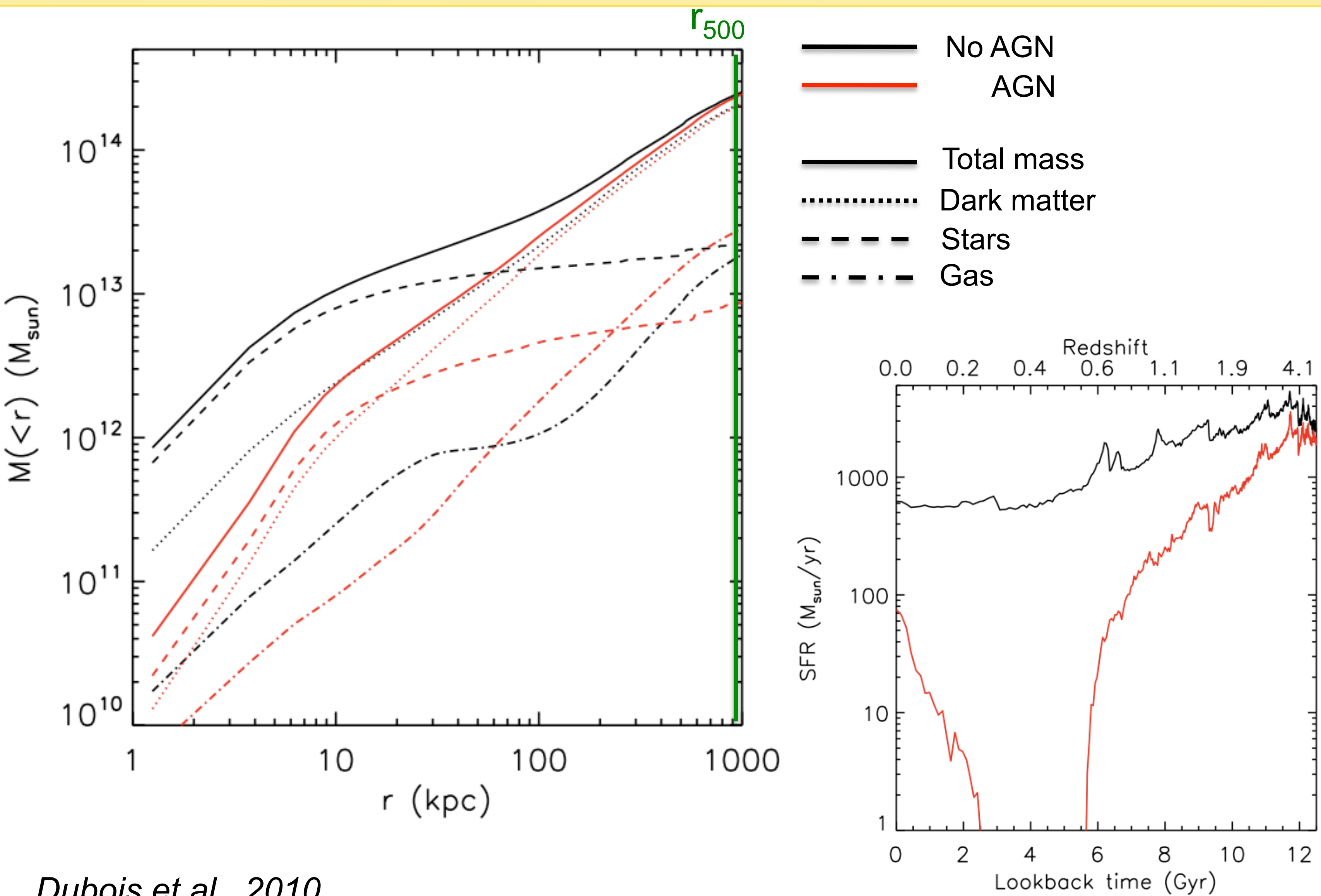
z=1.5
Quasar
mode



z=0
Radio
mode



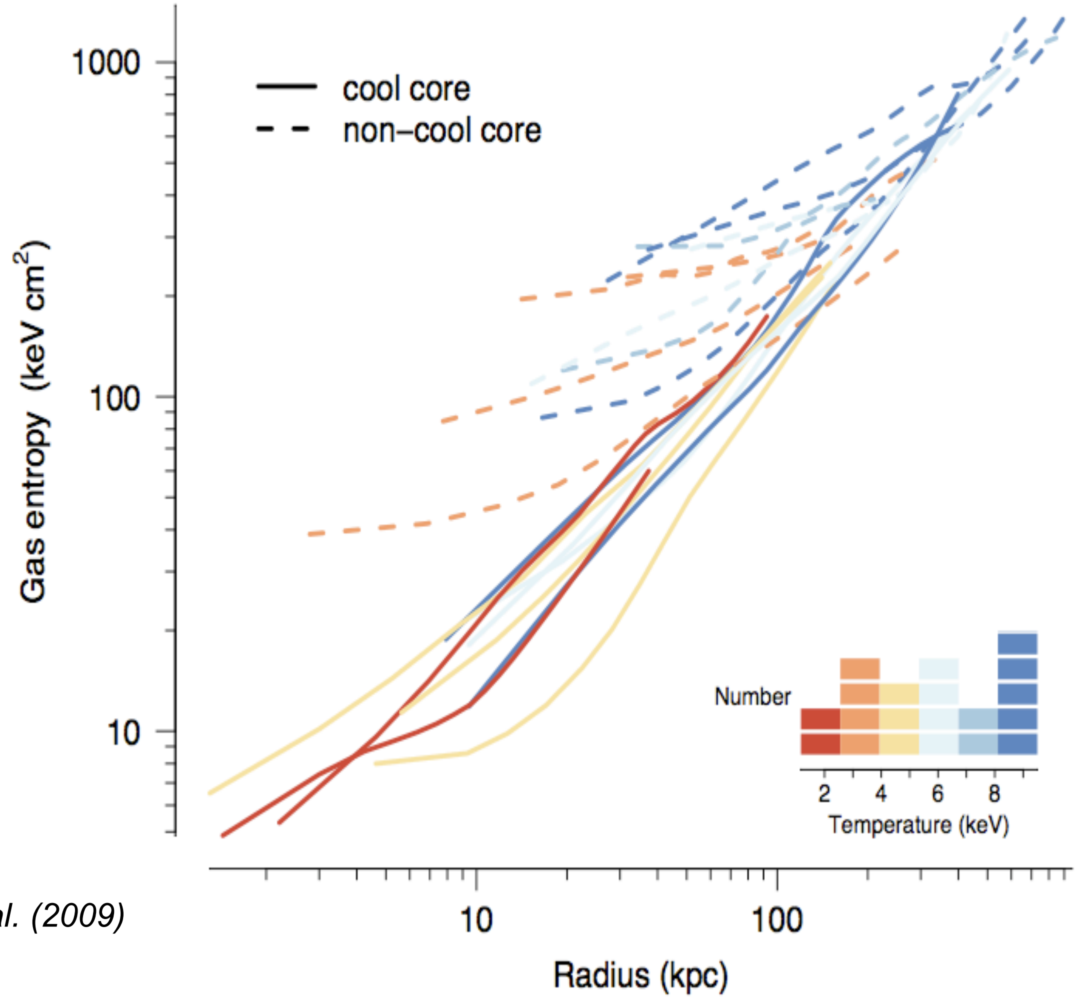
Mass distribution in a cluster of galaxies



Dubois et al., 2010

« Bimodality » in cluster cores

Chandra X-ray observations

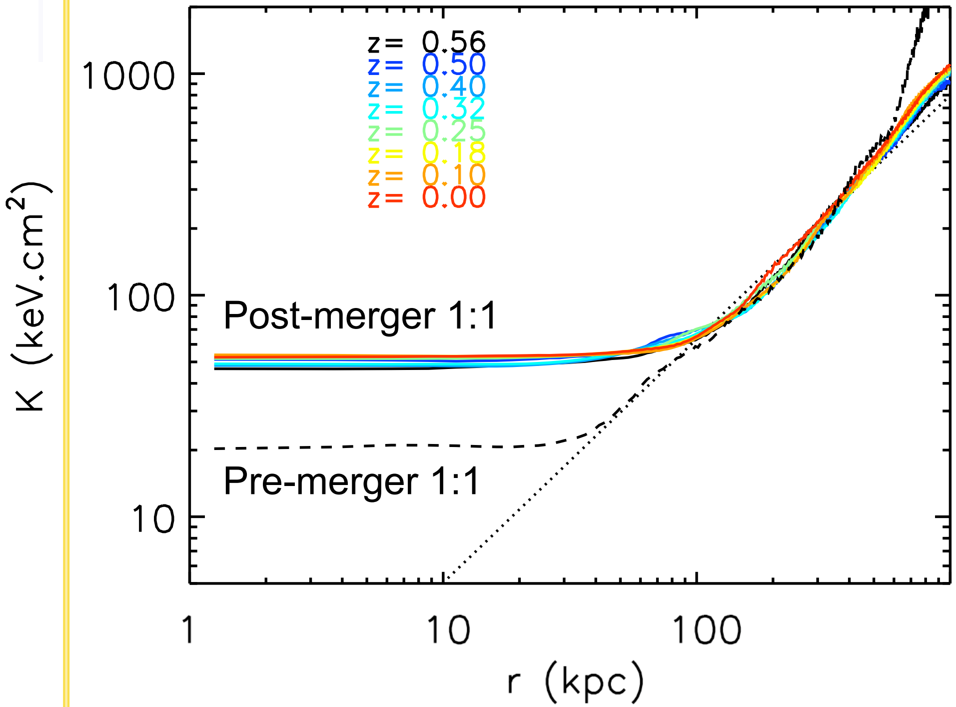


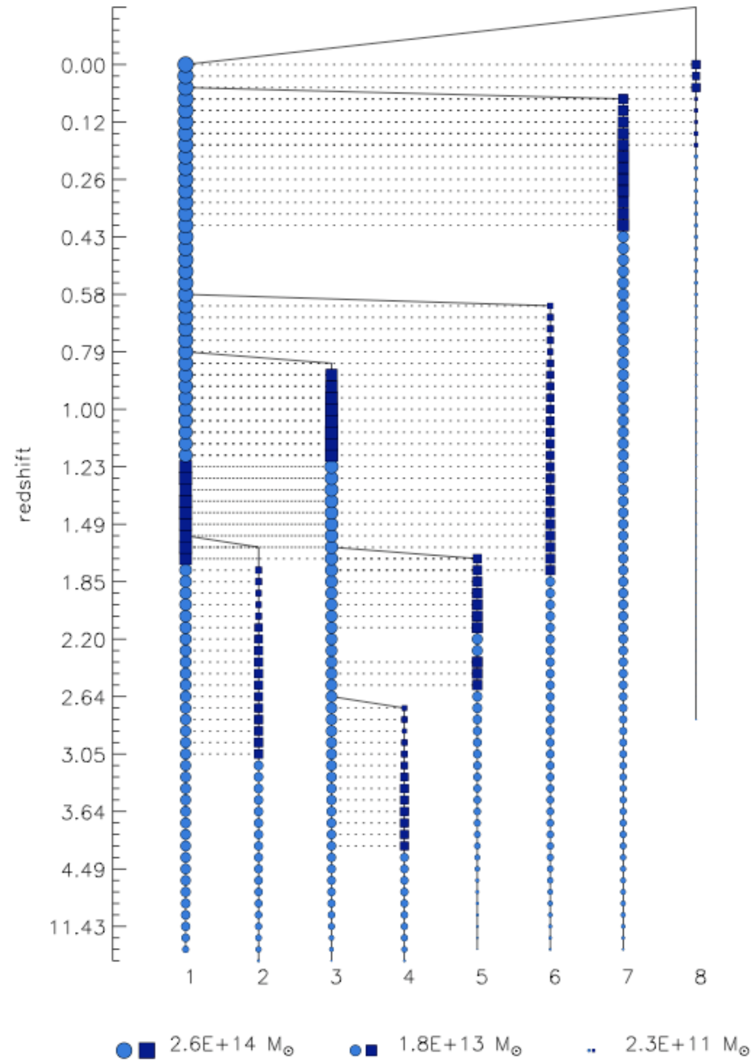
Sanderson et al. (2009)

What physics drives the entropy profiles ?

Some hints on the origin of entropy cores

No gas cooling



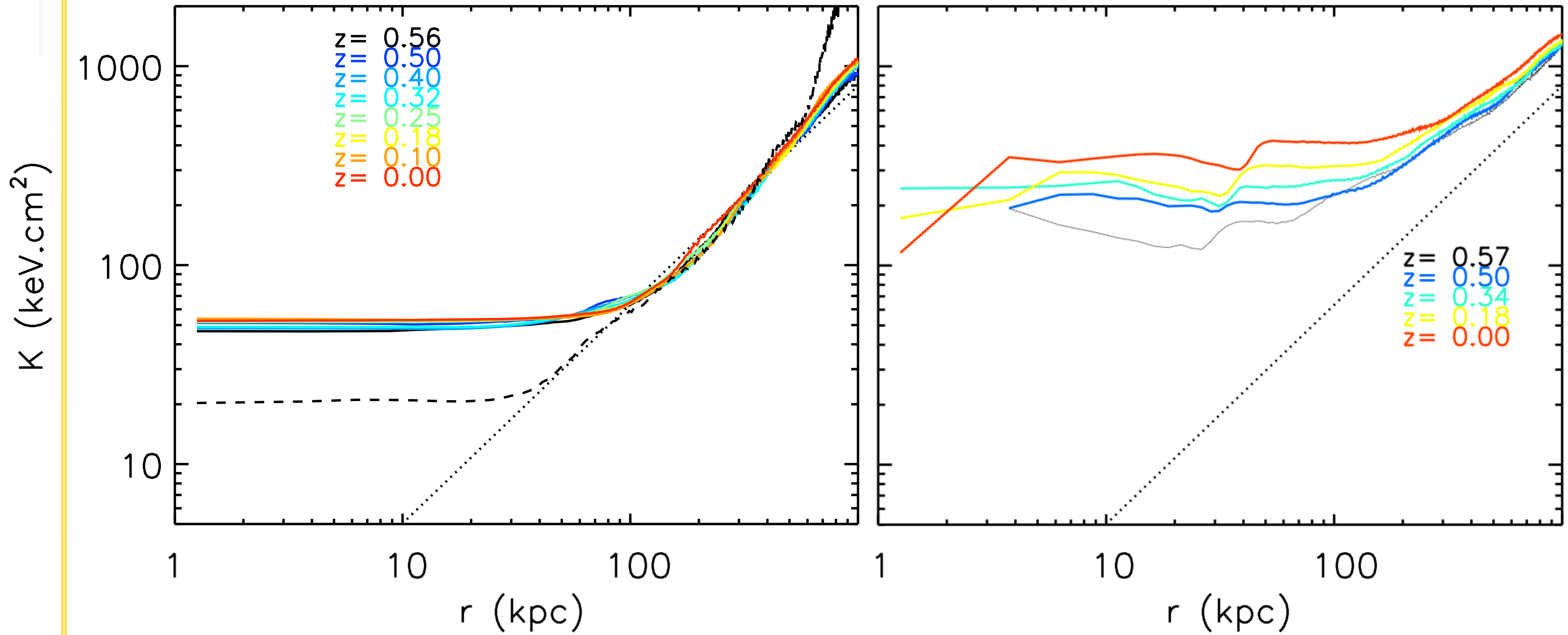


Dubois et al., 2011

Some hints on the origin of entropy cores

No gas cooling

Primordial gas cooling + SF

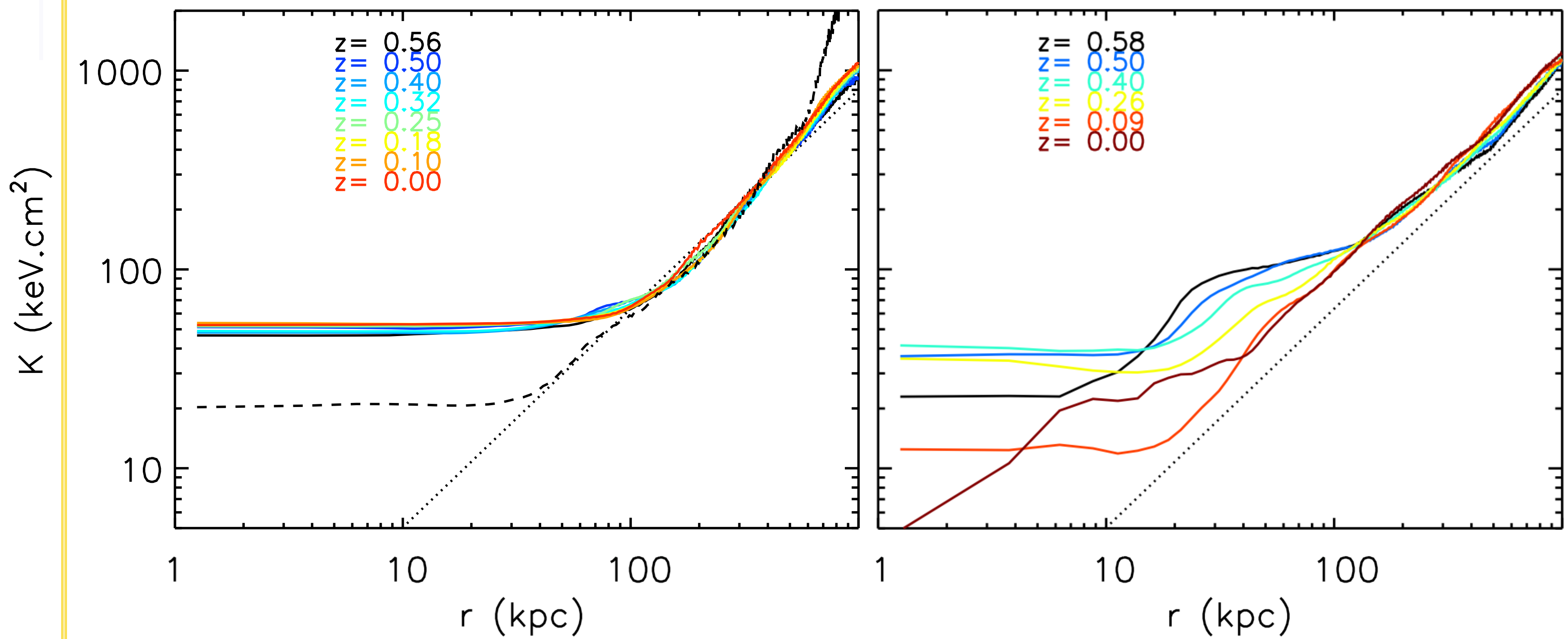


Dubois et al., 2011

Some hints on the origin of entropy cores

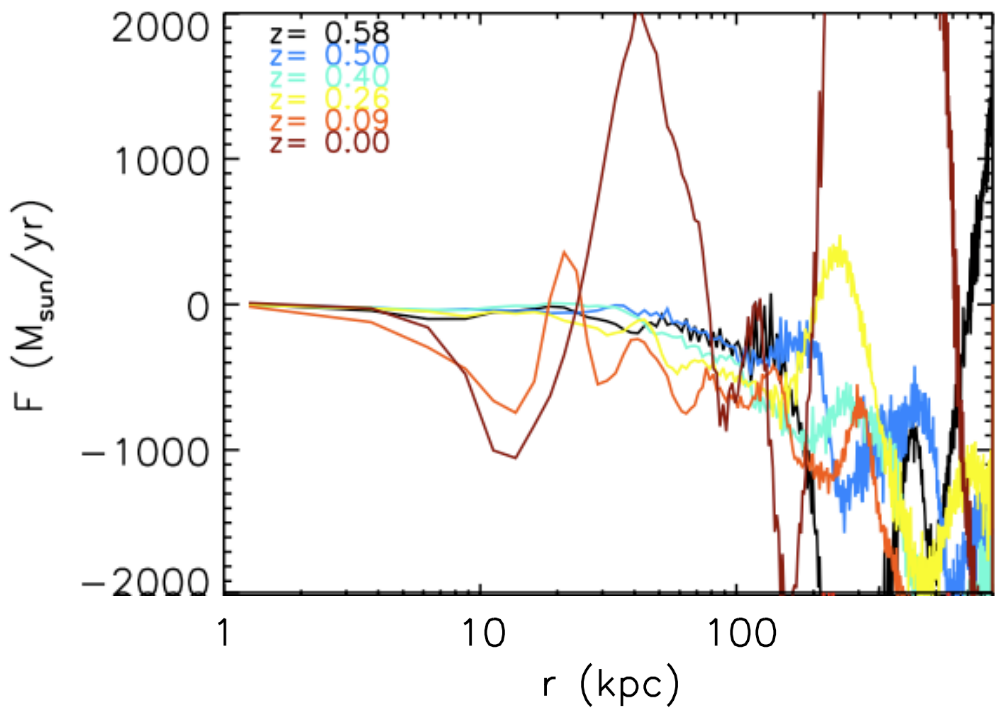
No gas cooling

Primordial gas cooling + SF + AGN feedback



Dubois et al., 2011

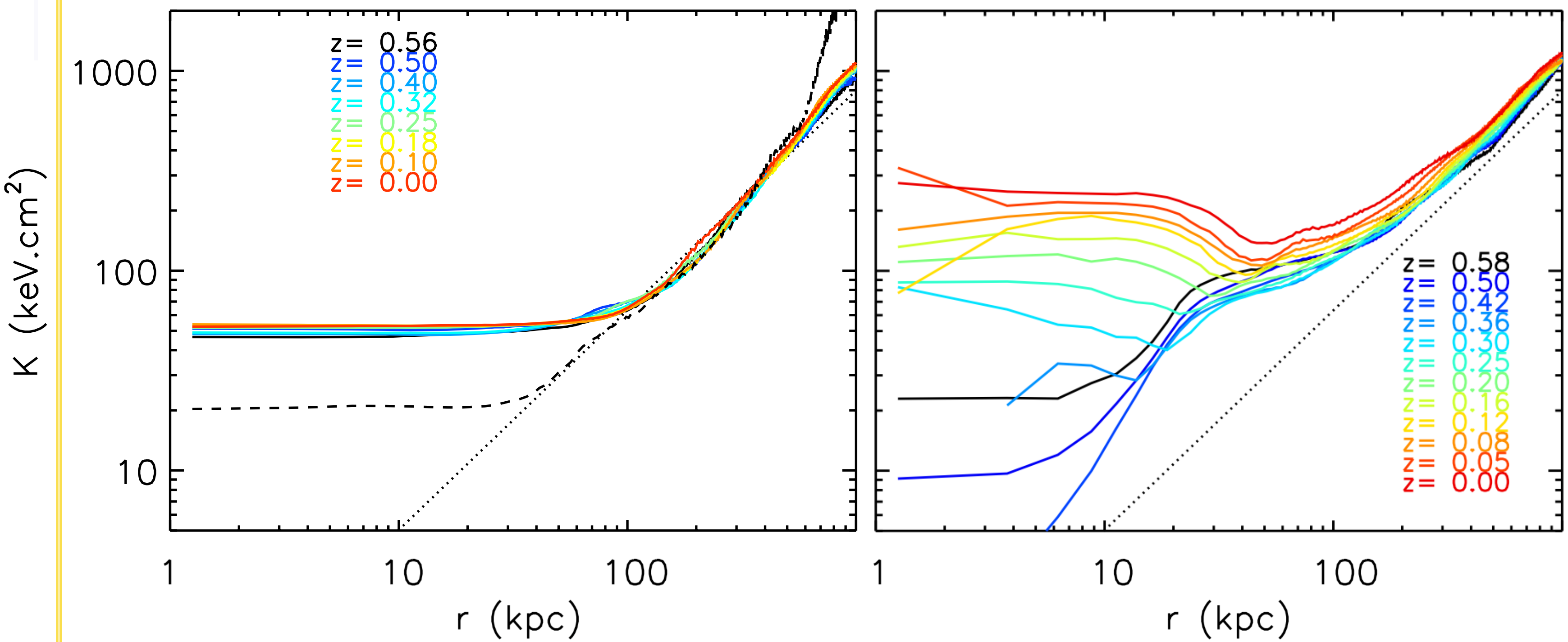
Primordial gas cooling + SF + AGN feedback



Dubois et al., 2011

No gas cooling

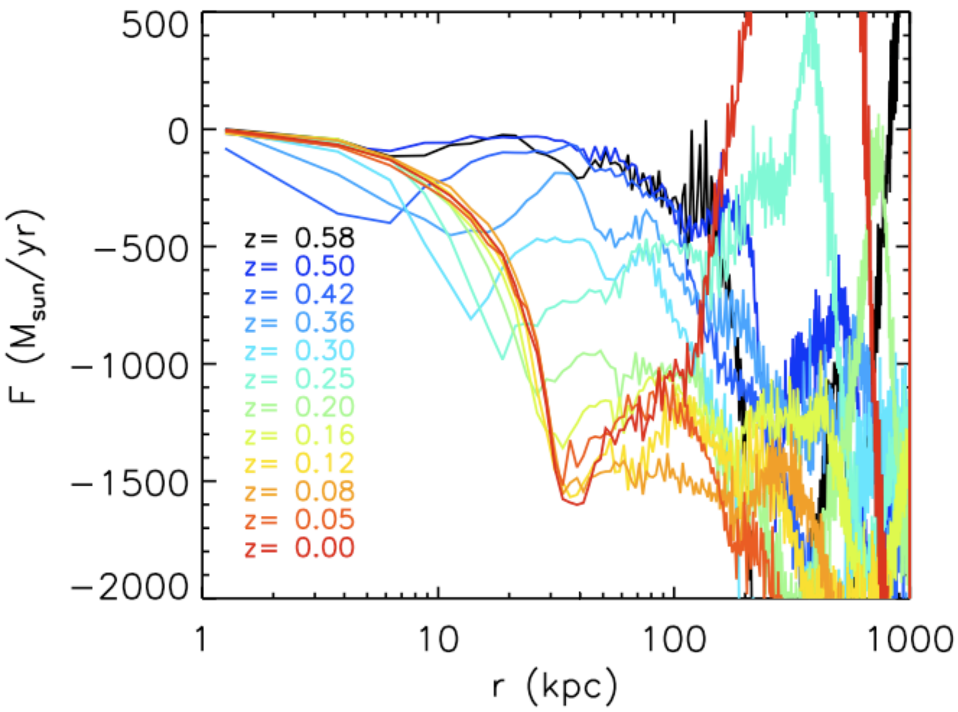
Primordial gas cooling + SF
+ stop AGN feedback @ z=0.6



Cooling catastrophe!

Dubois et al., 2011

Primordial gas cooling + SF
+ stop AGN feedback @ z=0.6



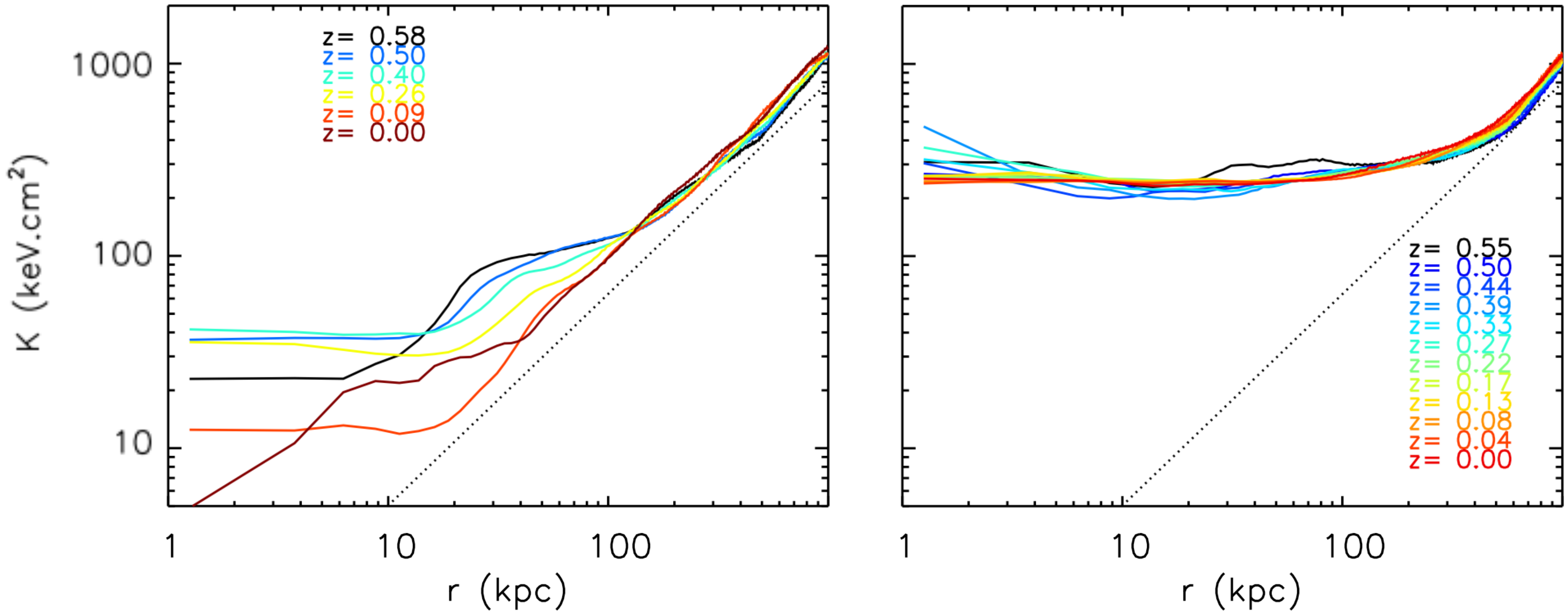
Cooling catastrophe !

Dubois et al., 2011

Some hints on the origin of entropy cores

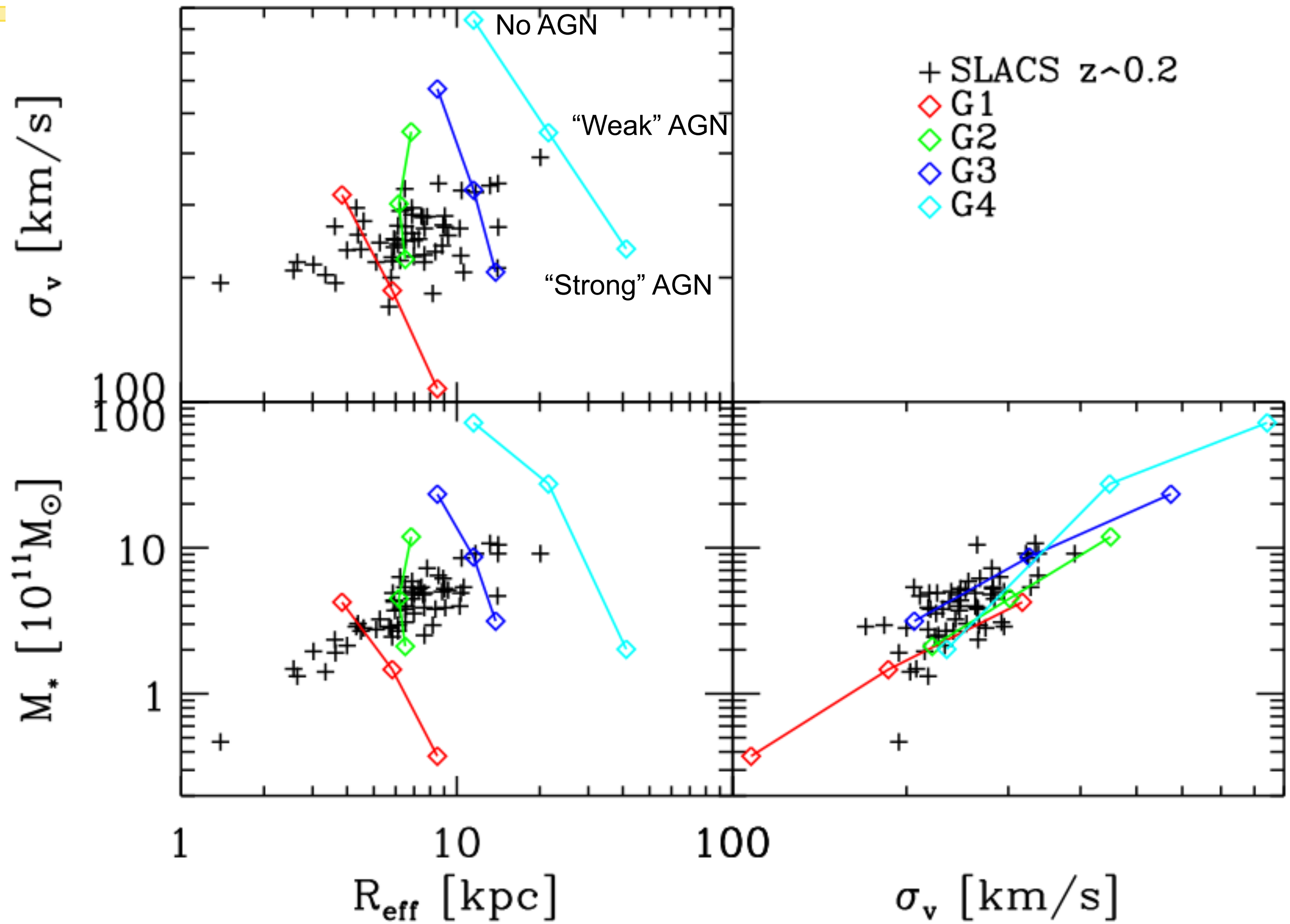
Primordial gas cooling + SF + AGN feedback

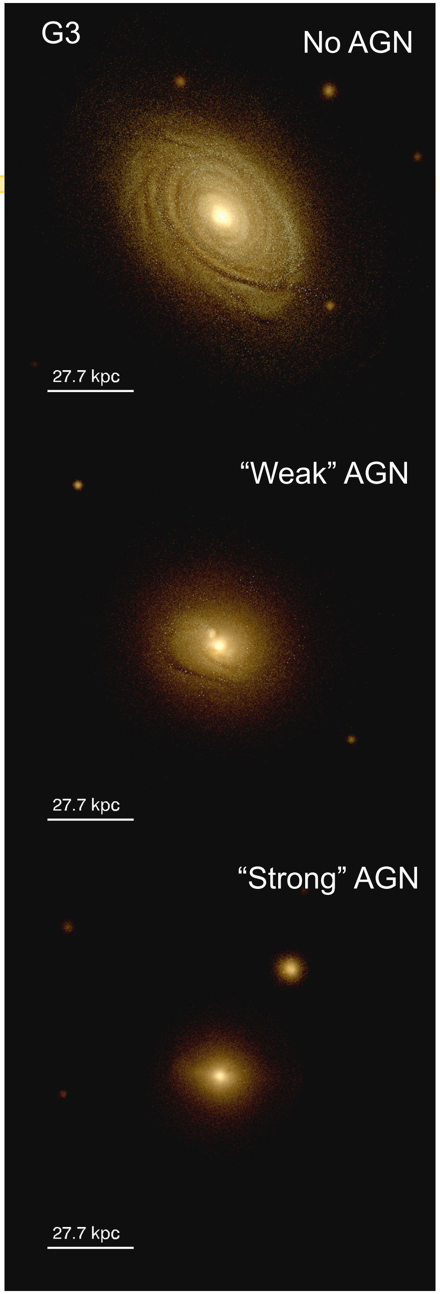
Primordial gas cooling + SF + AGN feedback + metal cooling

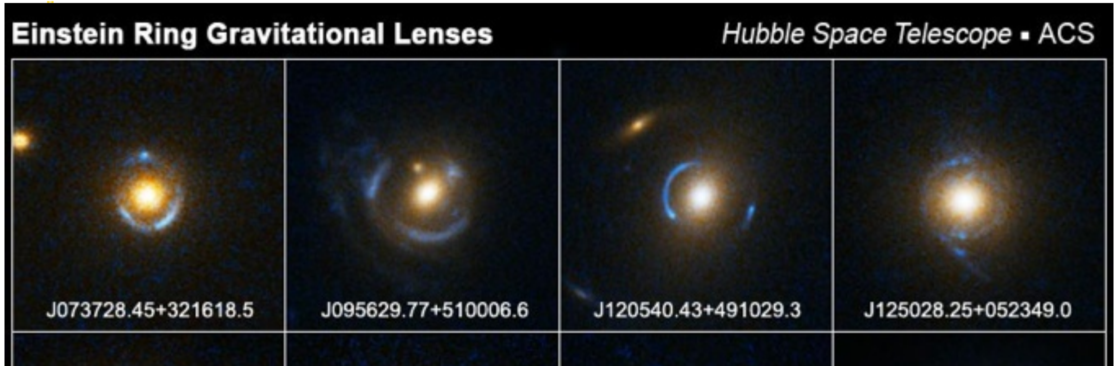


Dubois et al., 2011

Do we match stellar dynamics in groups/clusters ?

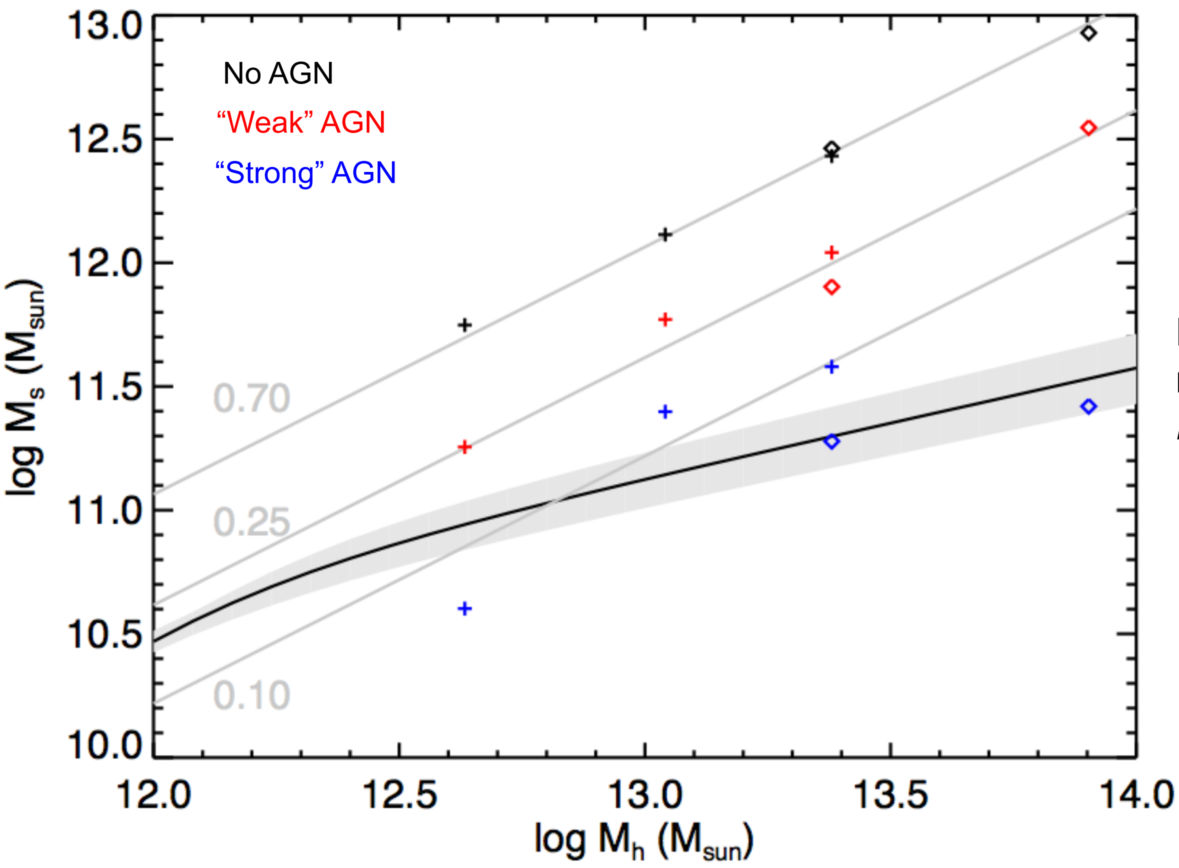






Dubois, Gavazzi, Peirani, in prep.

Is the stellar content in groups/clusters consistent with stellar dynamics ?



Data from abundance matching
Moster et al., 2010

Dubois, Gavazzi, Peirani, in prep.

Summary on AGN feedback

- AGN can reheat the core of massive halos and prevent cooling catastrophe
  - Efficiently suppresses star formation
  - Prevents high concentration of material
  - Change the thermodynamical properties of the intra-cluster gas
  - Powerful quasar modes are preferentially triggered at high redshift in gas rich systems (cold flows & wet mergers)
  - Quiescent radio modes are predominant at low redshift in massive structures (little cold material)

<u>Some issues</u>:

- Is the Bondi accretion the right definition ? Need to resolve the BH sphere of influence $R_{BH}=GM_{BH}/\sigma_*^2$ (< pc scale in most cases)
- Does the AGN feedback from early BH growth can totally unbind the gas of compact bulges ?
- Do we need super-Eddington accretion to get very massive BHs @ high-z?
- What is the importance of the AGN mode: isotropic energy release versus collimated winds


Thank you for your attention