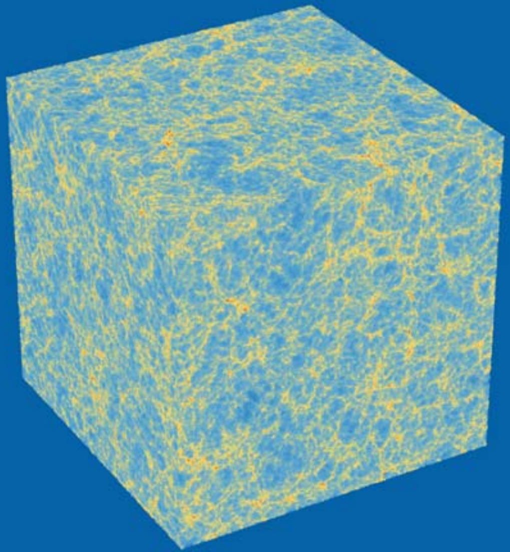
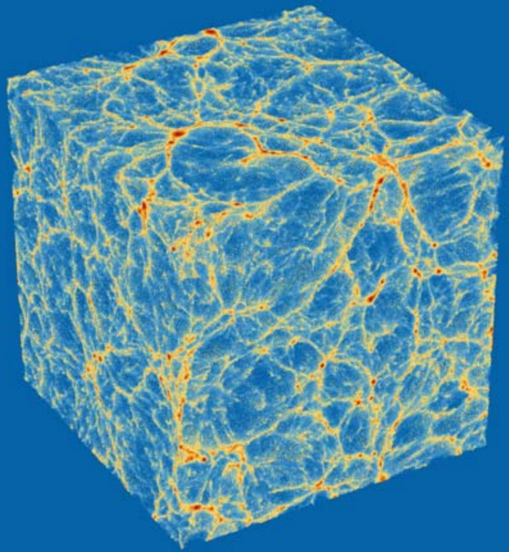
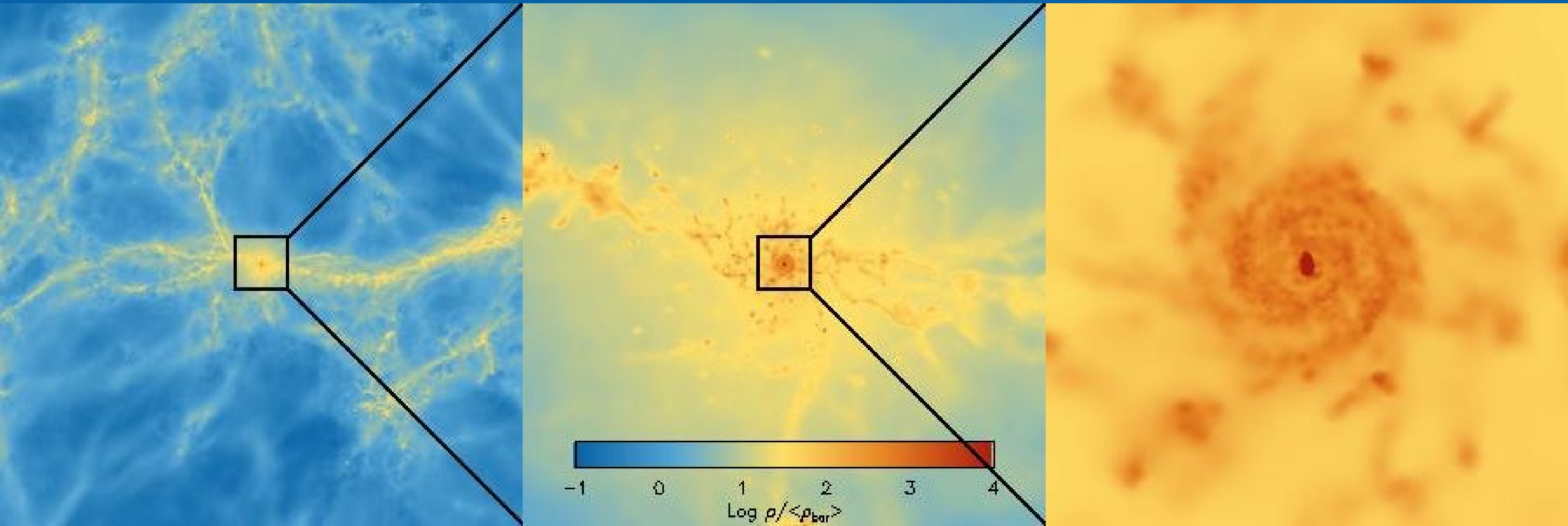
Dark matter haloes, central BHs, and the effect of baryons on clustering

Joop Schaye et al. (Leiden)







Warm dark matter would

- Decrease small-scale clustering
- Reduce the number density of low-mass objects
- Decrease halo concentrations
- Increase disk sizes?

Problem:
How can we rule out baryonic effects?

Outline

- OWLS
- Properties of CDM haloes
- Importance of DM haloes for supermassive black hole growth
- Effect of feedback on
  - Halo DM profiles and concentrations
  - Matter power spectrum
  - Disk sizes
  - Formation of low-mass galaxies

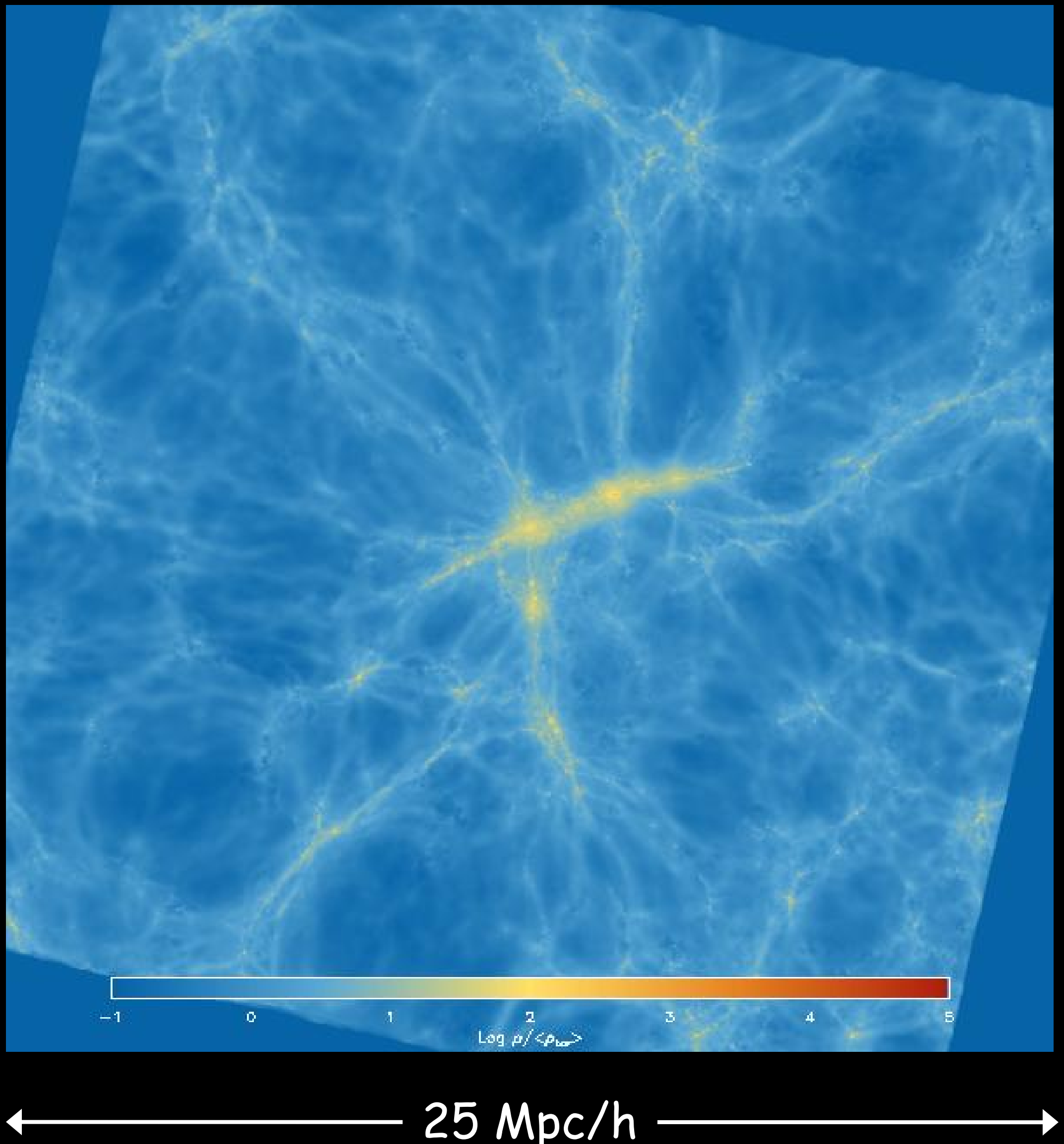
OverWhelmingly Large Simulations (OWLS)

- Cosmological, hydro (SPH,gadget)
- New baryonic physics modules:
  - star formation (JS & Dalla Vecchia 2008)
  - SN feedback (Dalla Vecchia & JS 2008, 2010)
  - chemodynamics (Wiersma et al. 2009b)
  - radiative cooling (Wiersma et al. 2009a)
  - AGN (Booth & JS 2009; Springel et al. 2001)
- $2\text{x}N^3$ particles, N = 512 for most runs

  Two box sizes:
  - L = 25 Mpc/h to z=2
  - L = 100 Mpc/h to z=0
- Runs repeated many (>50) times with varying physics/numerics

JS, Dalla Vecchia, Booth, Wiersma, Theuns, Haas, et al. (2010)

Zooming into a massive galaxy at z=2: Gas density



25 Mpc/h

Depth: 2 Mpc/h

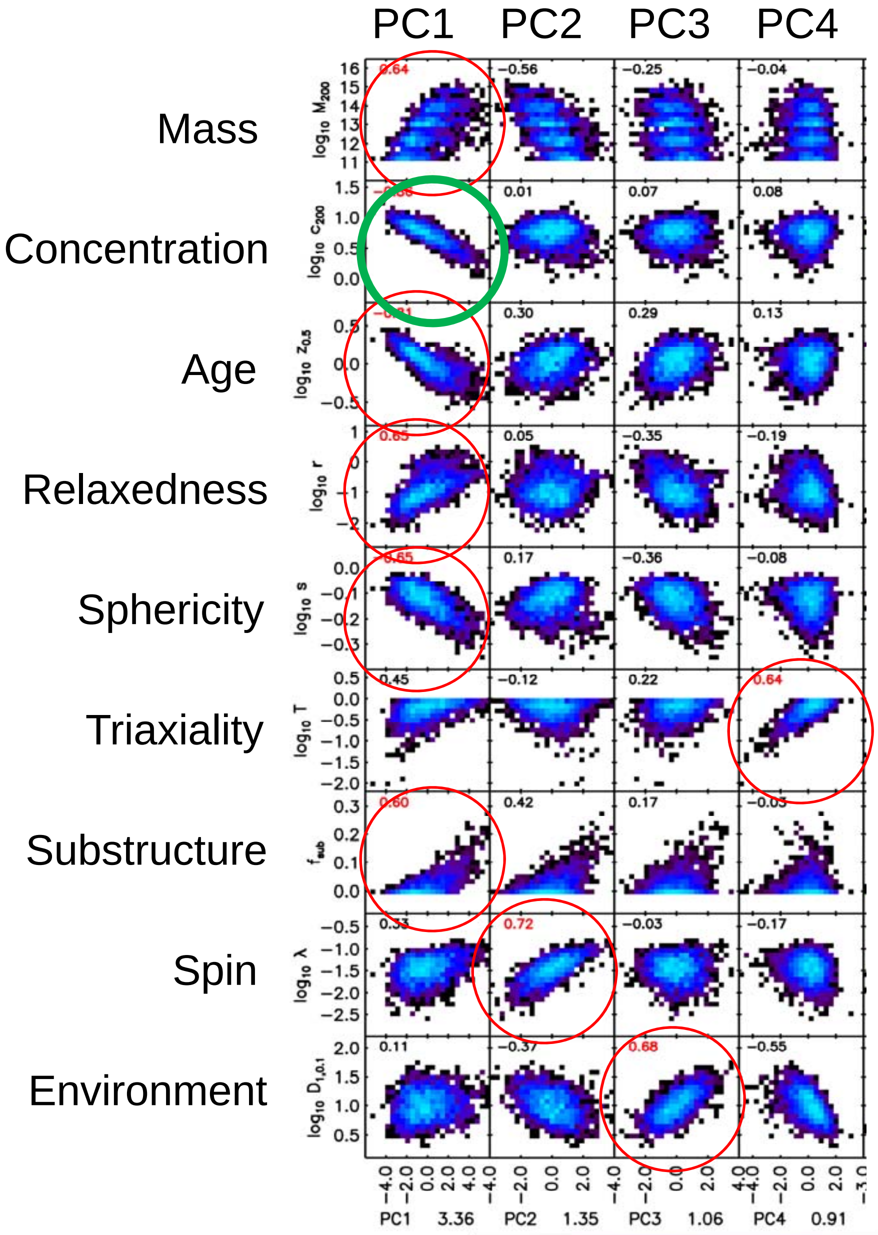
Log M = 12.6
Log M* = 11.5

Simulation:
REF
L025
N512

CDM halo properties

- How many parameters are required to characterize a halo?
- Which parameter is most fundamental? Mass?

Jeeson-Daniel et al. (2011) used a suite of large N-body simulations and carried out a rank correlation and PCA analysis for a set of 9 parameters (see also Skibba & Maccio 2011).



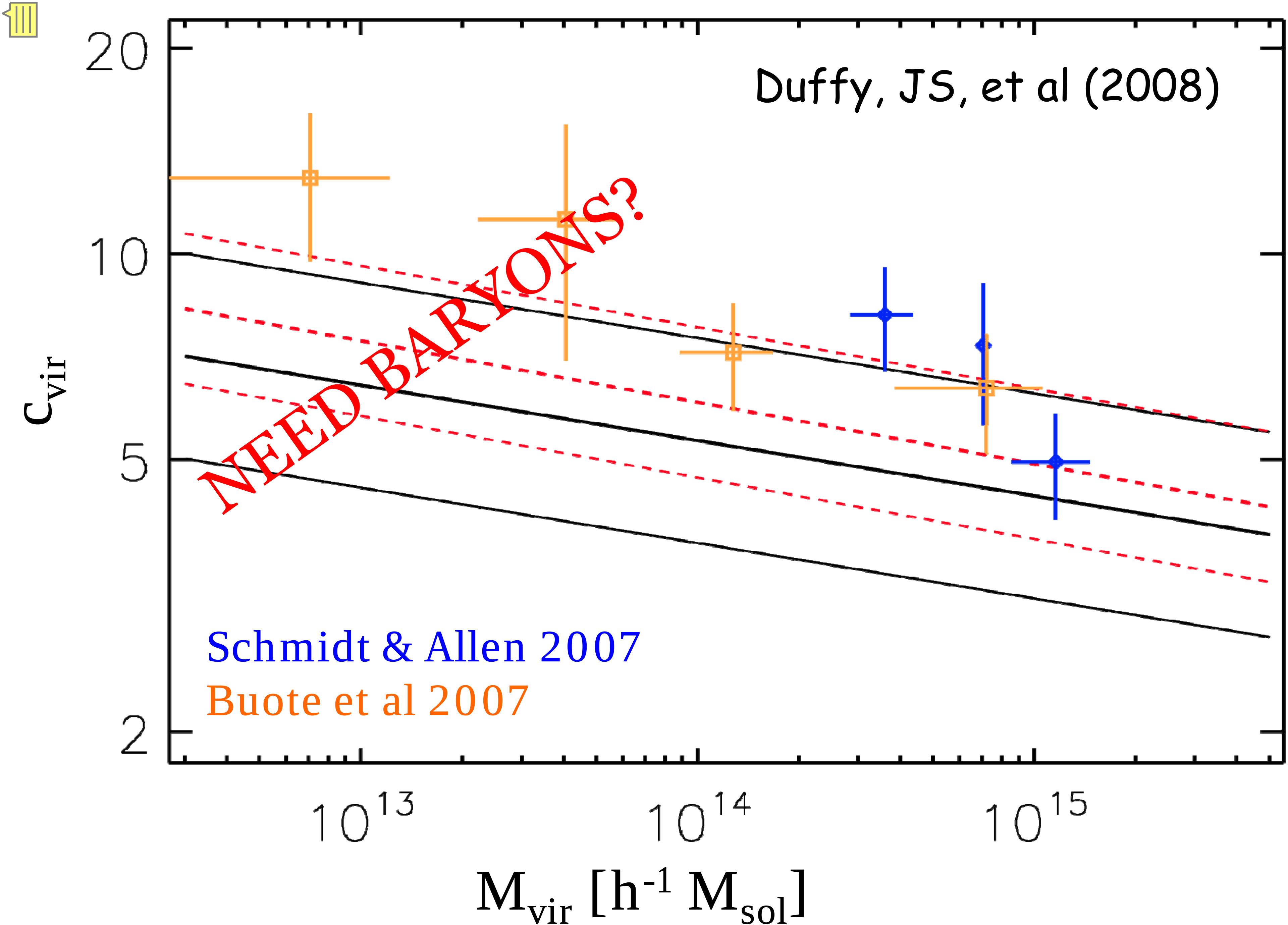
PCA of dark matter halo properties

- Concentration (not mass) is fundamental → WDM would be important!
- Spin, environment, and triaxiality largely independent
- The rest is part of the "concentration" family

Jeeson-Daniel et al. (2011)

CDM halo concentrations

- X-ray/lensing observations of groups and clusters: predicted concentrations too low
- Low-mass galaxies: predicted concentrations too high (indirect)



NFW concentration at z=0.1

Cold streams in hot haloes: varying the physics

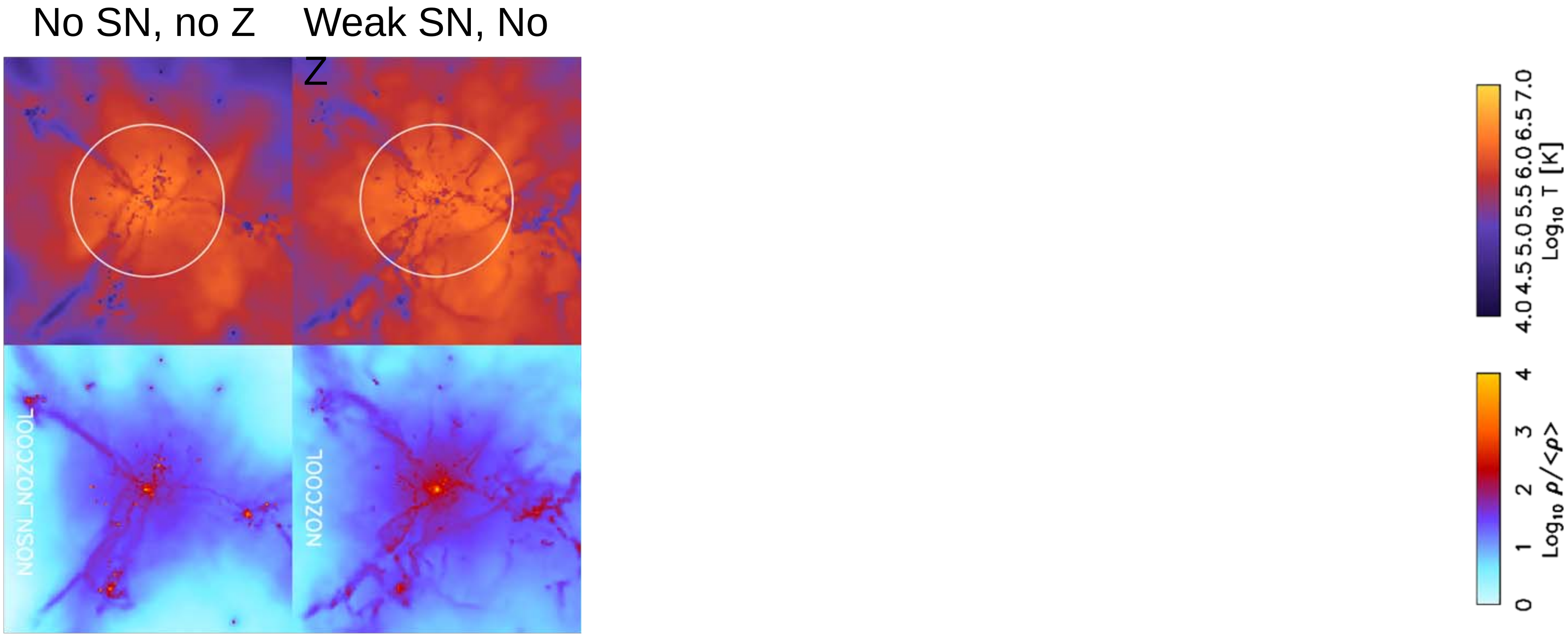
No SN, no Z

$$M_{\text{halo}} = 10^{12}\ \mathrm{M}_{\odot}$$

$$z = 2$$

Van de Voort, JS, et al. (2011a)

Cold streams in hot haloes: varying the physics


No SN, no Z

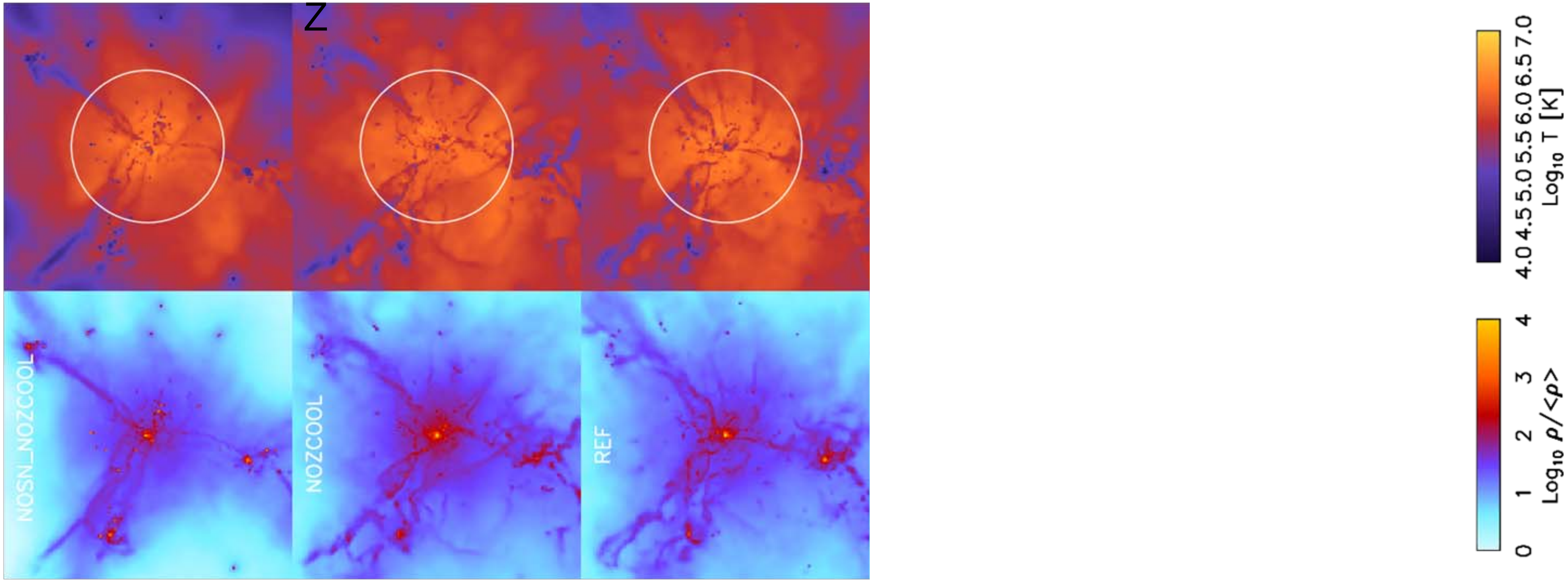
Weak SN, No Z

$$M_{\text{halo}} = 10^{12}\ \mathrm{M}_\odot$$

$$z = 2$$

Van de Voort, JS, et al. (2011a)

Cold streams in hot haloes: varying the physics



No SN, no Z

Weak SN, No Z

Weak SN

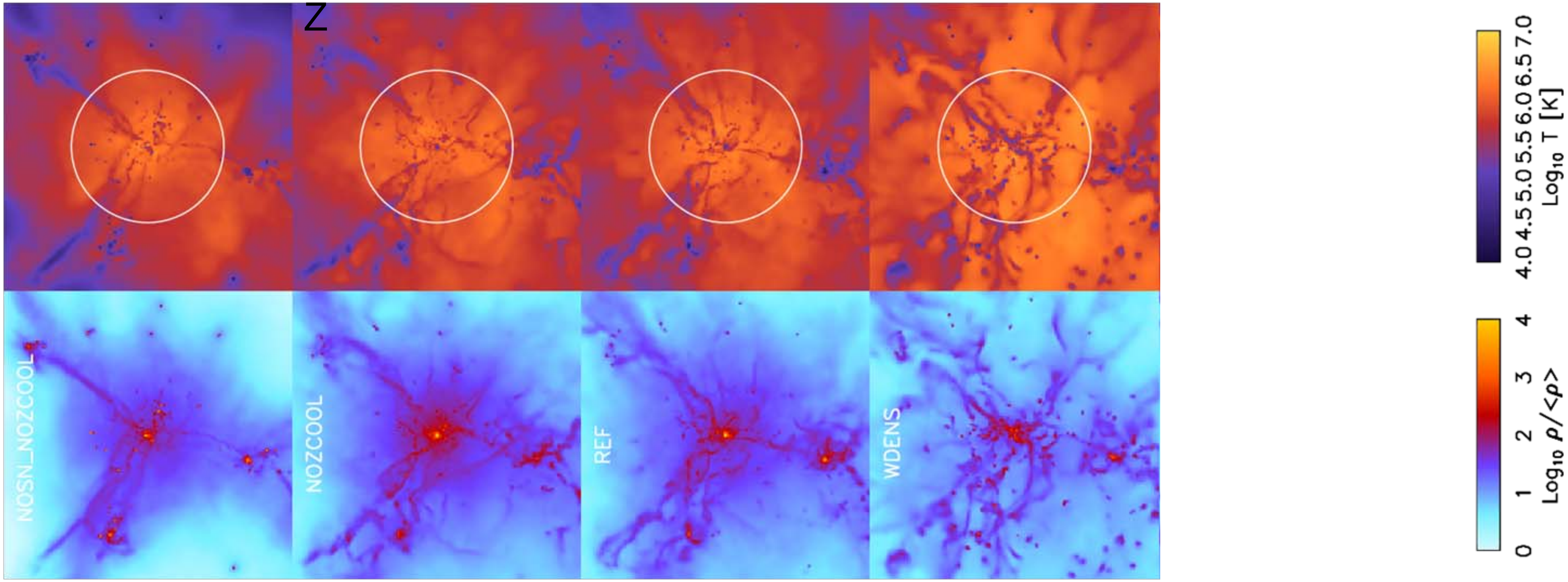
$$M_{\rm halo} = 10^{12}\ \mathrm{M}_\odot$$

$$z = 2$$

Van de Voort, JS, et al. (2011a)

Cold streams in hot haloes: varying the physics

No SN, no Z | Weak SN, No Z | Weak SN | Strong SN



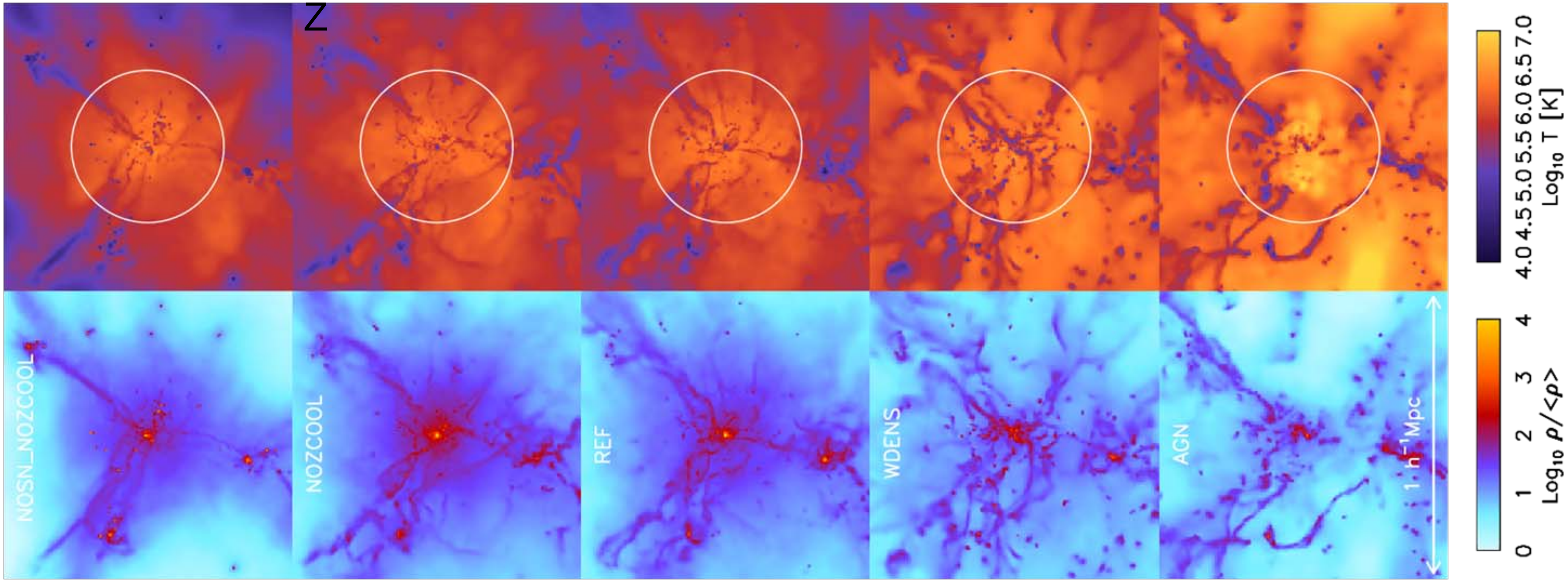
$$M_{\rm halo} = 10^{12}\ {\rm M}_{\odot}$$

$$z = 2$$

Van de Voort, JS, et al. (2011a)

Cold streams in hot haloes: varying the physics

No SN, no Z | Weak SN, No Z | Weak SN | Strong SN | AGN

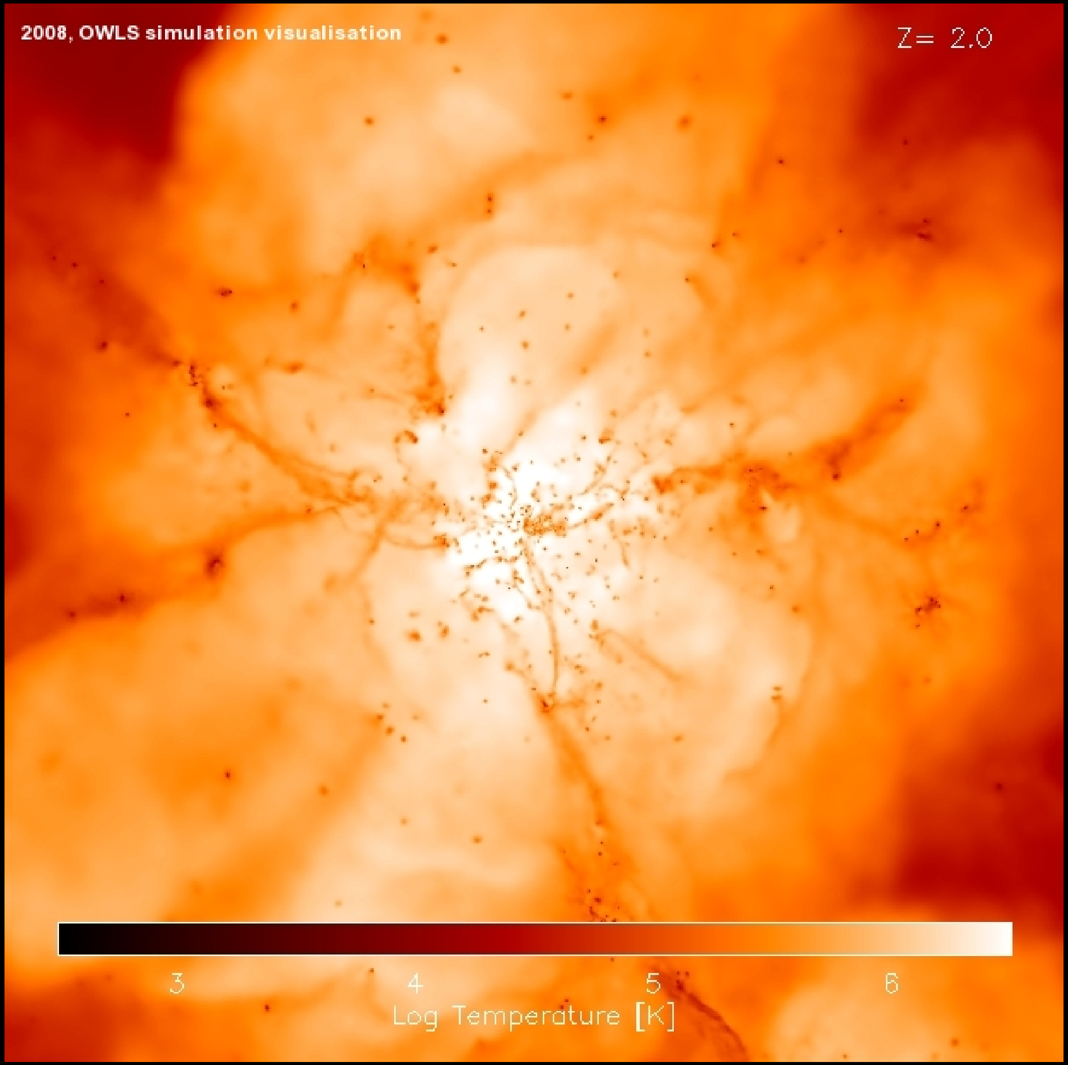


$$M_{\rm halo} = 10^{12}\ {\rm M}_{\odot}$$

$$z = 2$$

Van de Voort, JS, et al. (2011a)

Evolution of a massive galaxy down to z=2



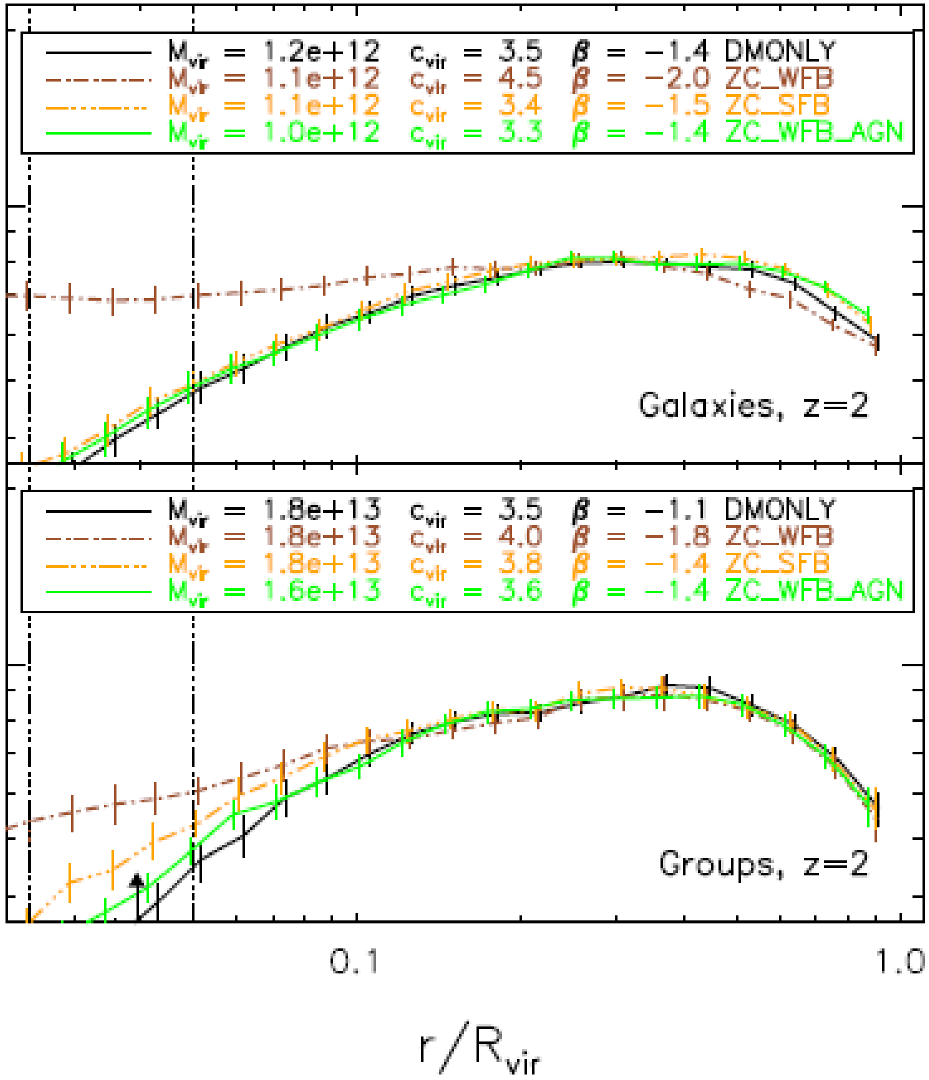
3 Mpc/h

At z = 2:
Log M = 12.3
Log M* = 10.6

Simulation:
WVCIRC
L025
N512

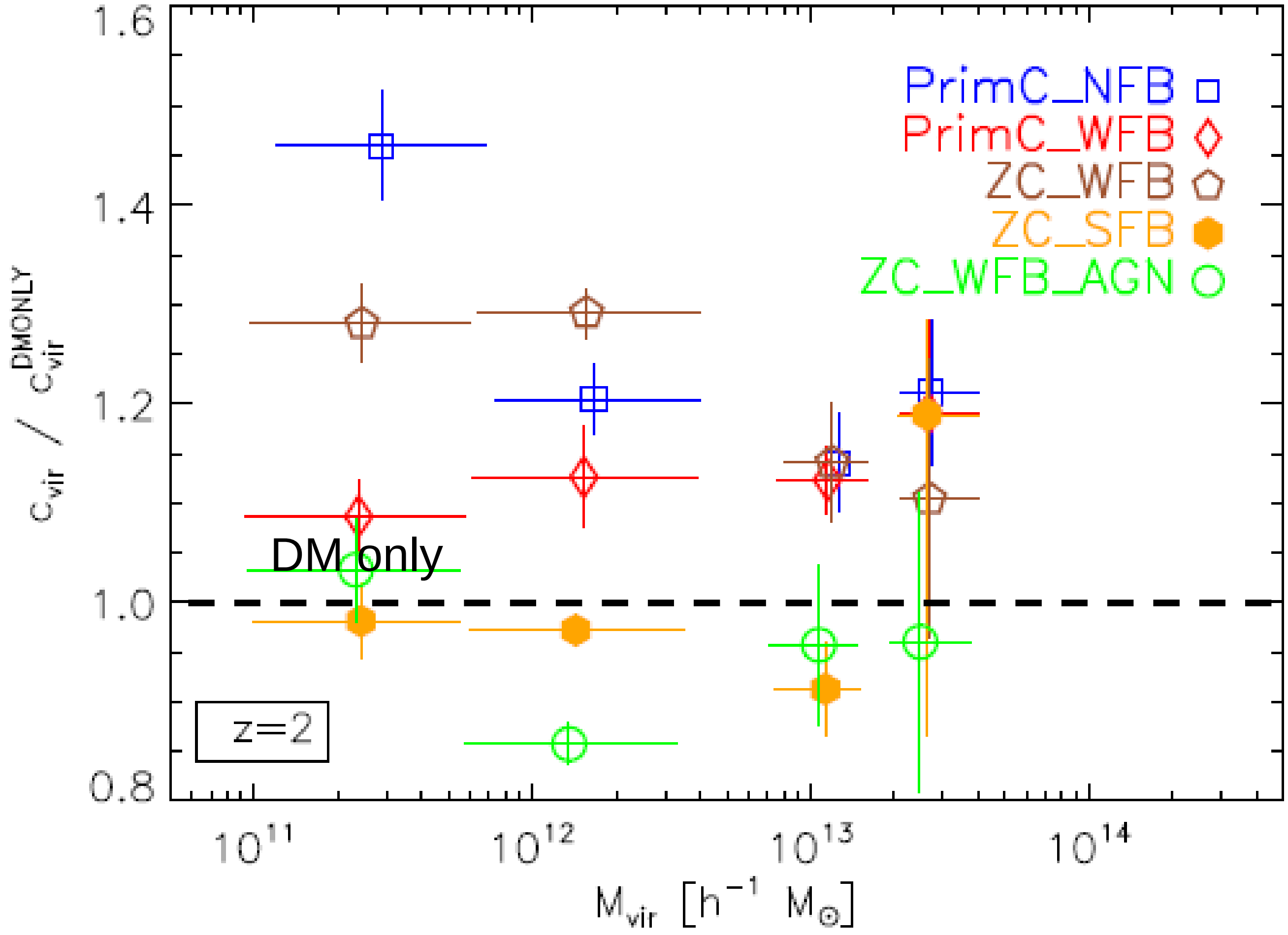
DM density profiles

$$\propto \rho_{\mathrm{DM}}\, r^2$$



Duffy, JS, Kay, et al. (2010)

NFW DM concentrations



Duffy, JS, Kay, et al. (2010)

Halo concentrations

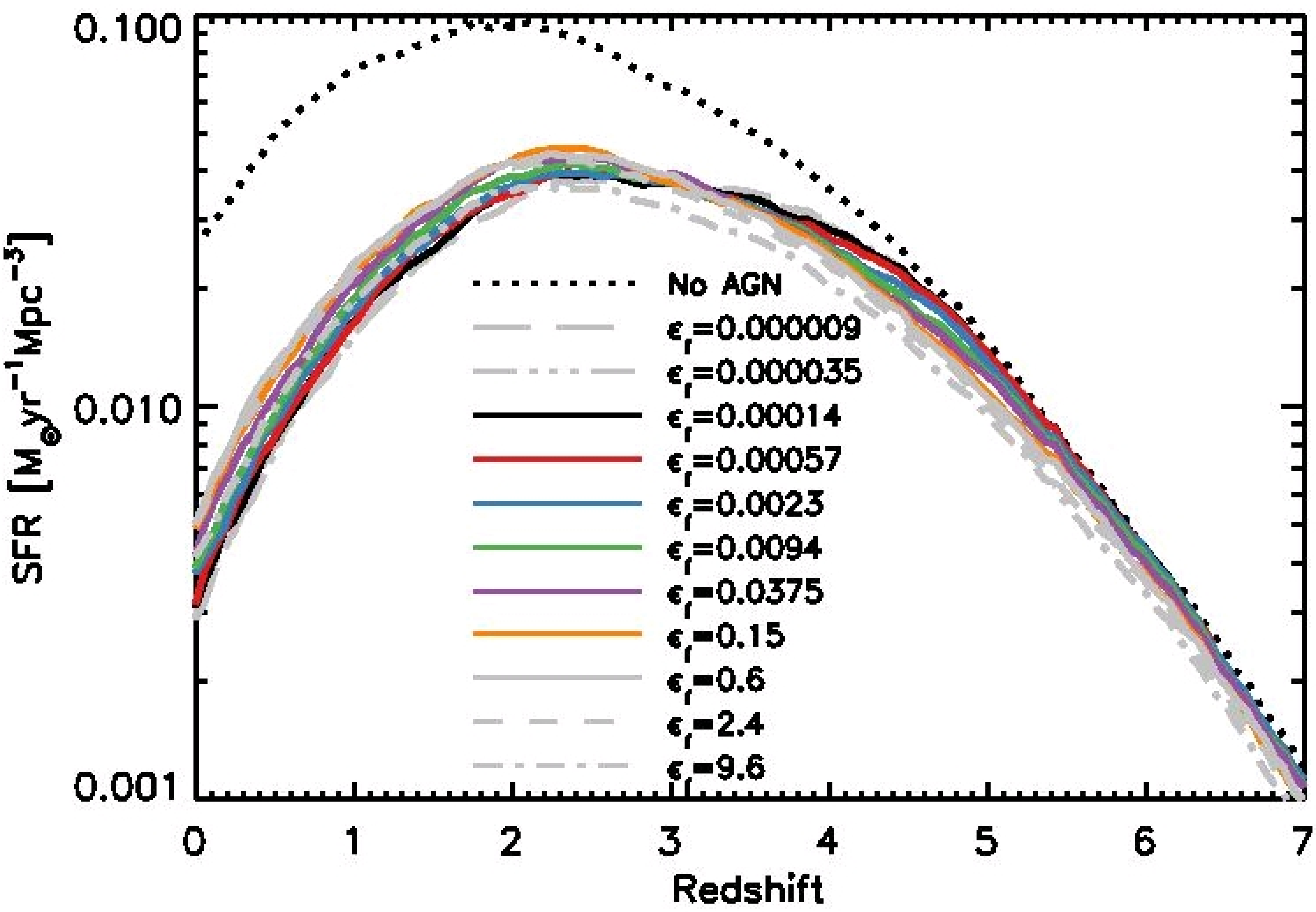
- Without strong feedback baryons cause:
  - DM NFW concentration to increase by few per cent
  - Total concentration to increase by ~ 10%
- With strong feedback (as required by obs):
  - DM NFW concentration unchanged for clusters and galaxies, decrease of 10-20% for groups
  - Total concentration unchanged (decreases by few per cent)
- Adiabatic contraction models inadequate

Duffy, JS, Kay, et al. (2008), MNRAS, 390, L64
Duffy, JS, Kay, et al. (2010), MNRAS, 405, 2161

Self-regulated galaxy formation

- Feedback too weak compared to accretion
  - Gas density increases
  - Star formation /BH growth rate increases
  - Feedback increases
- Feedback too strong compared to accretion
  - Gas density decreases
  - Star formation/BH growth rate decreases
  - Feedback decreases
- There exists a critical rate of energy/momentum injection that depends on halo mass and redshift

Varying the efficiency of AGN feedback



Booth & JS (2009)

AGN self-regulation

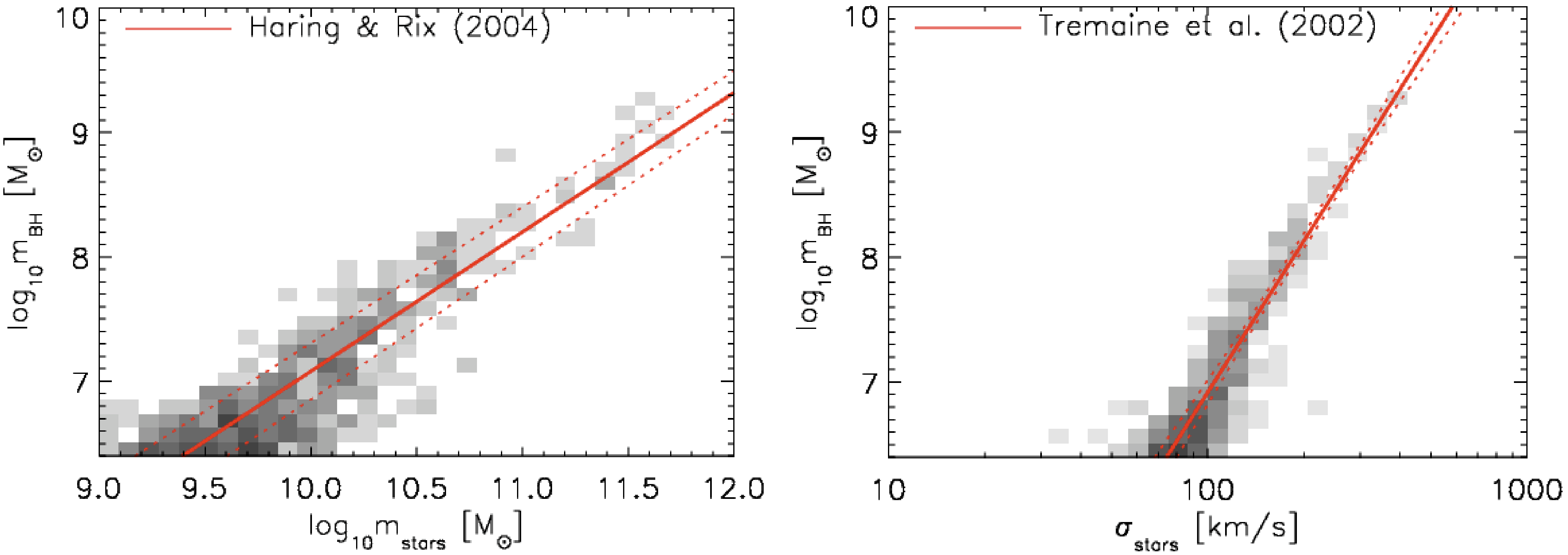
Balance between accretion onto galaxies and AGN feedback

→ BH accretion rate (i.e. black hole mass) adjusted so as to keep rate of energy injection fixed

→ Energy injection rate independent of AGN efficiency

→ SFR independent of the AGN efficiency

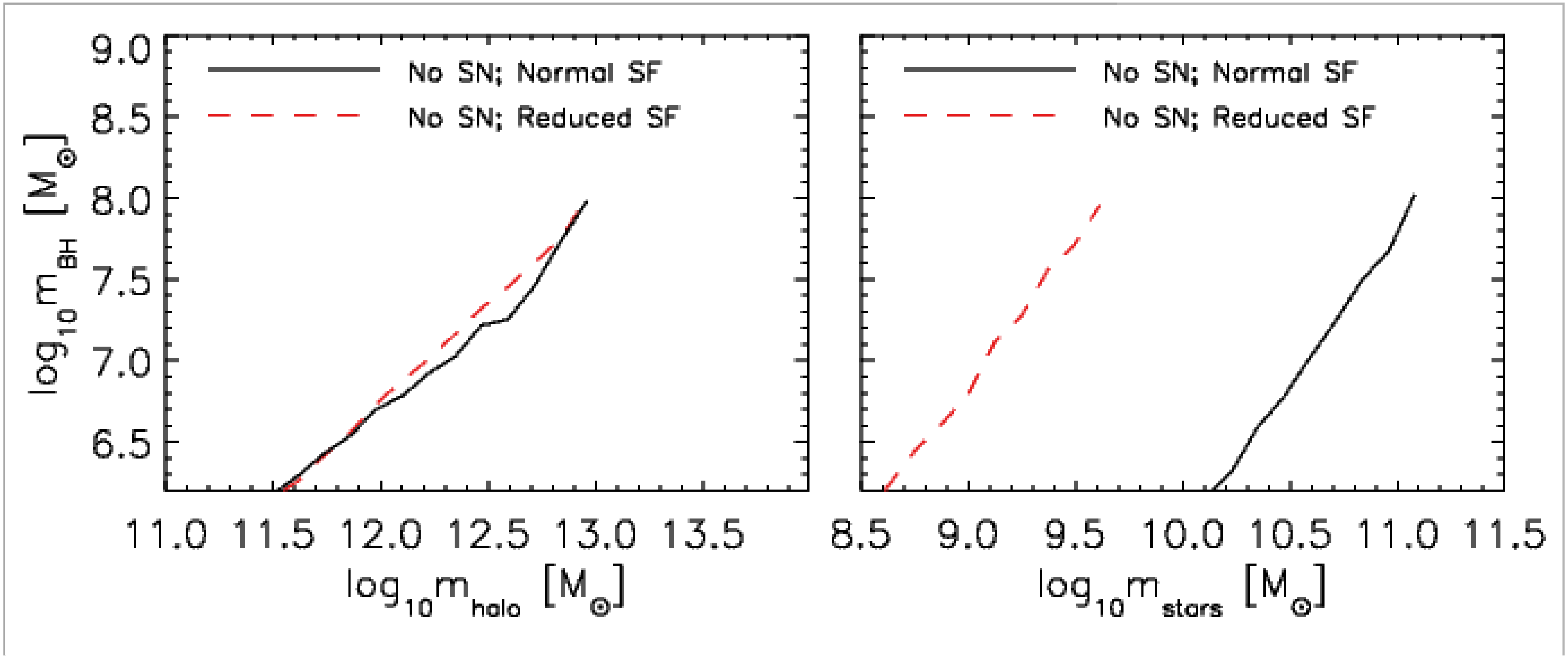
BH scaling relations



Feedback efficiency: 1.5%

Booth & JS (2009)

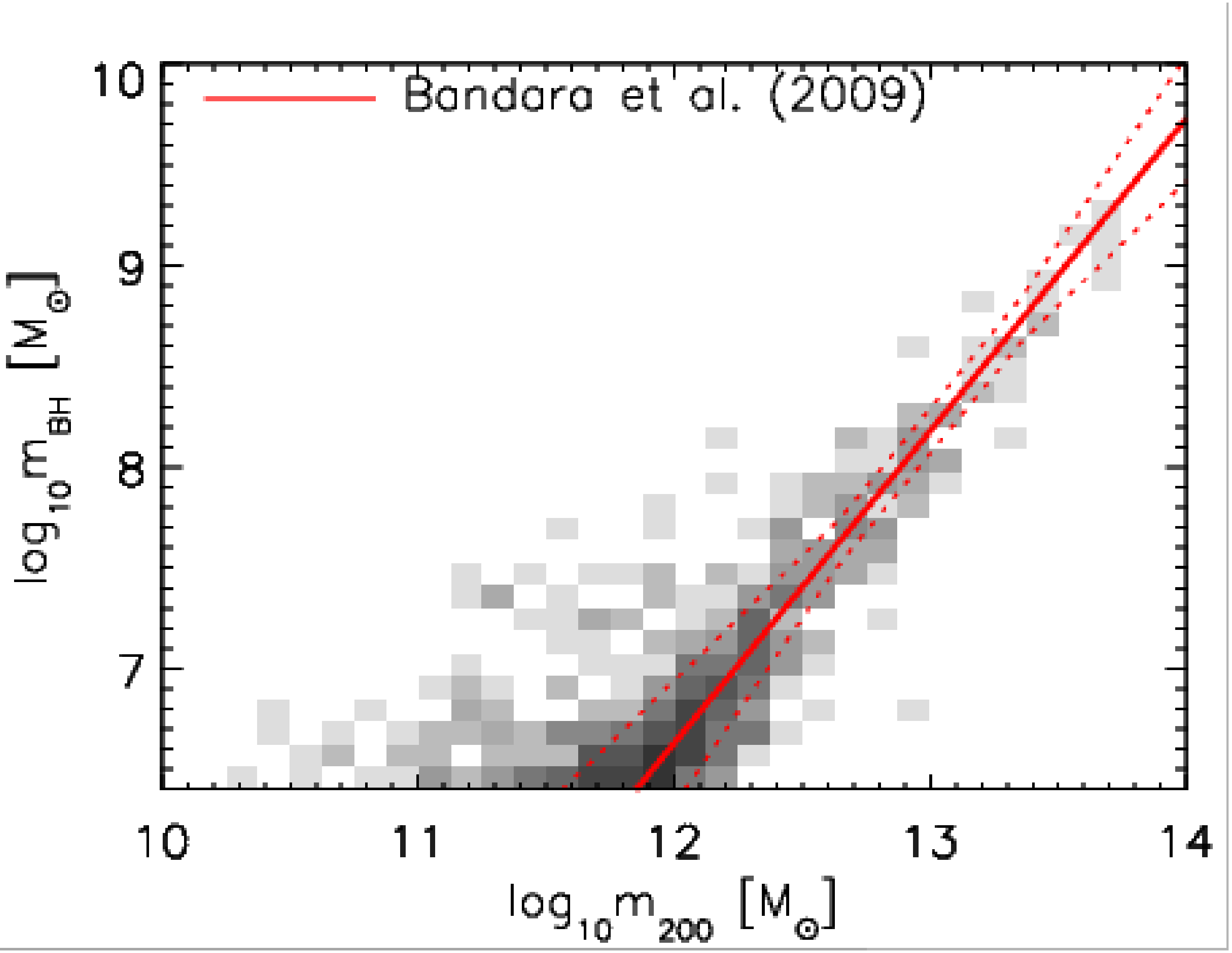
Does the stellar mass set the BH mass?



Booth & JS (2010)

BH self-regulation occurs on a mass scale that is large compared to the stellar mass

The BH - halo mass relation



Booth & JS (2010)

The BH - halo mass relation

- Observed slope: 1.55 +/- 0.31
- Simulated slope: 1.55 +/- 0.05
- Analytic prediction:
  - BH mass scales with dark matter halo binding energy
  - NFW density profile
  - Concentration – mass relation

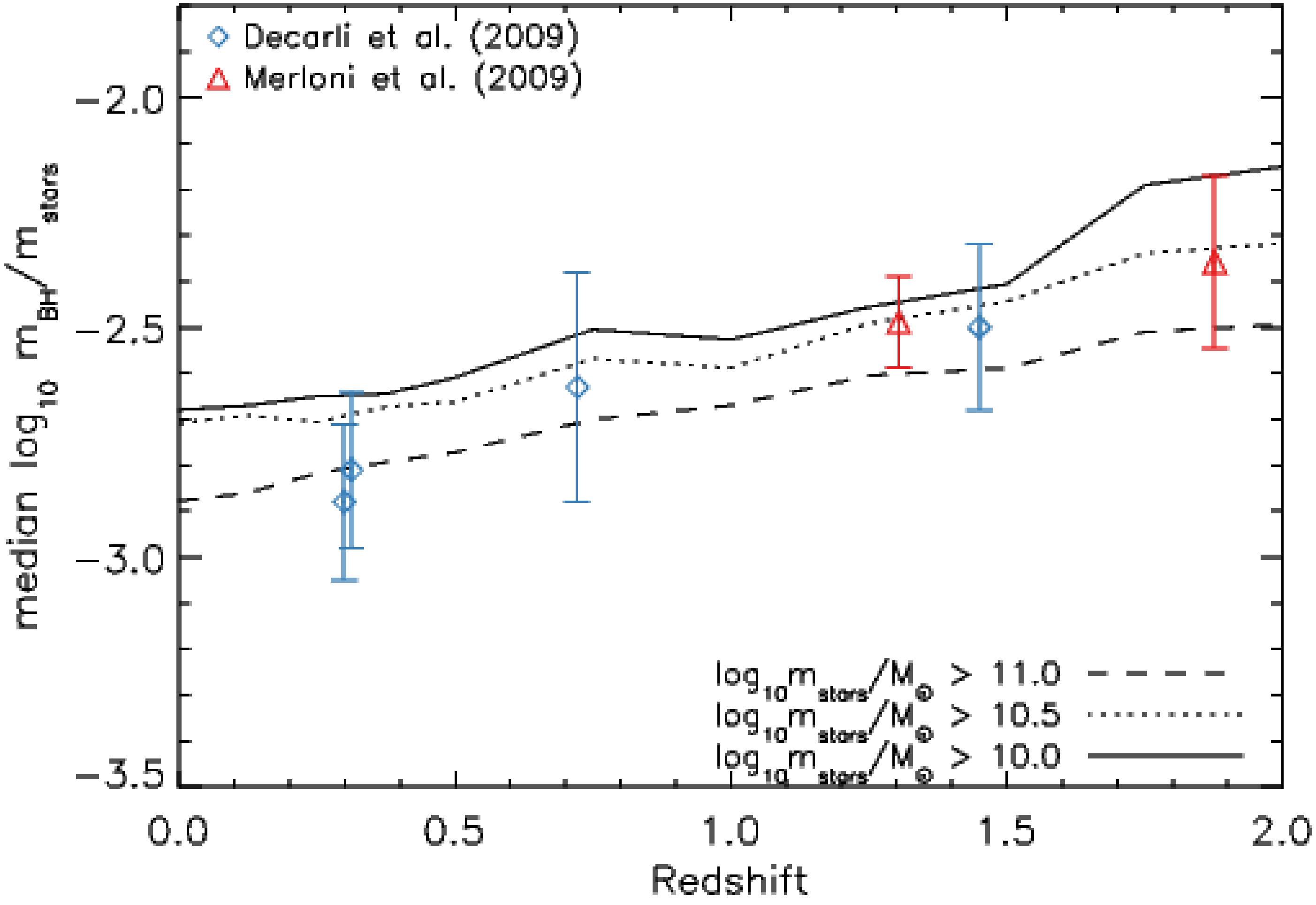
→ Slope: 1.50 – 1.61 for $\frac{r}{r_{\mathrm{vir}}} = 0.1 - 1.0$

AGN self-regulation

- BHs self-regulate on the scale of dark matter haloes
- Rate of energy injection (BH mass) scales with halo binding energy
- BH-bulge relations are not fundamental (bulge properties are also set by the haloes)
- Scatter in BH-halo mass relation partly reflects scatter in the c-M relation
- Higher concentrations (i.e. earlier types) result in larger BH masses → WDM would be important!

Booth & JS 2010, MNRAS, 405, L1

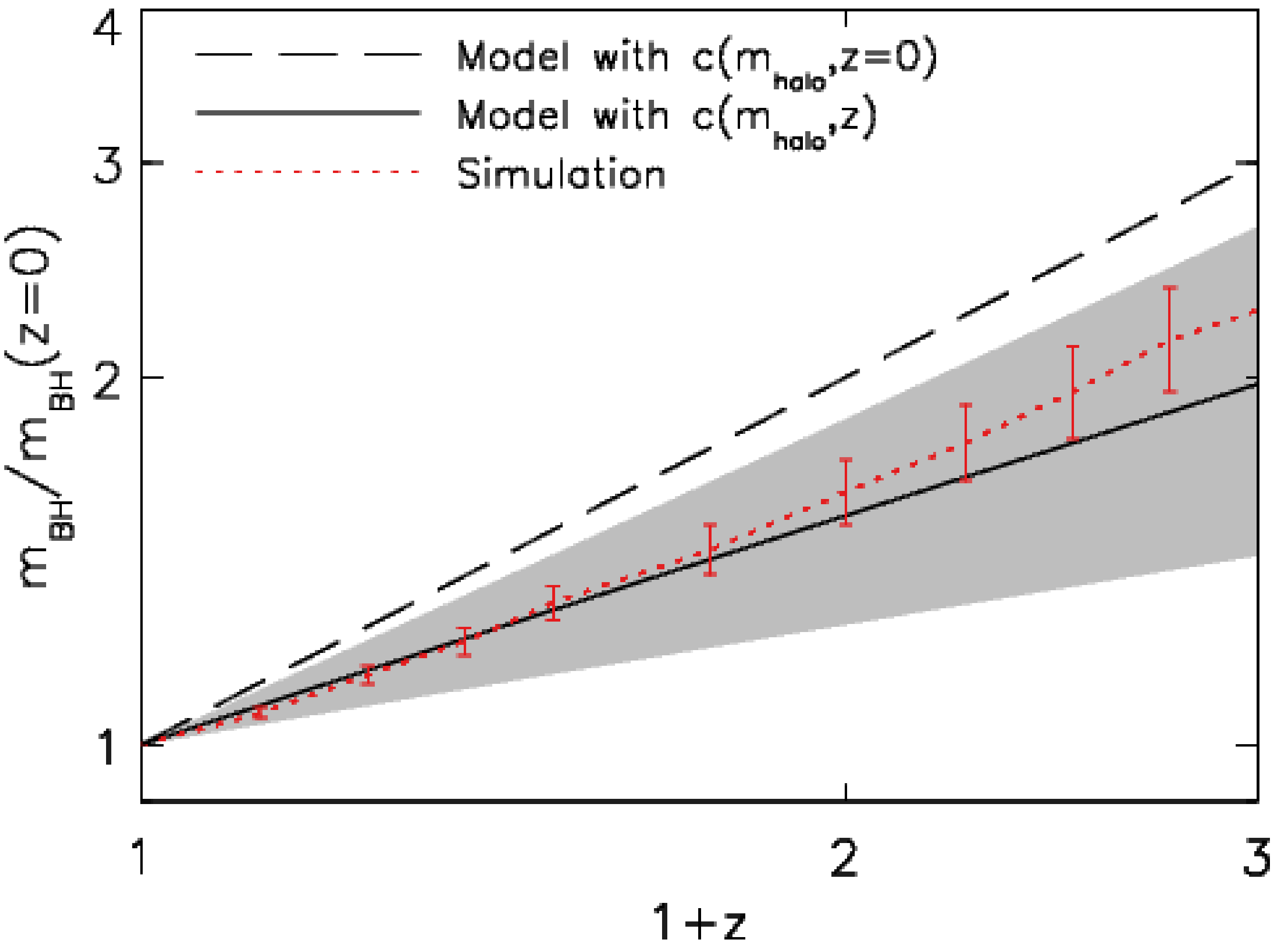
Evolution of the Magorrian relation



Galaxies with $M_* \simeq 10^{11}\ \mathrm{M}_\odot$

Booth & JS (2011)

Evolution of the BH - halo mass relation



Booth & JS (2011)

Evolution of BH scalings

- BHs overly massive at high z, because haloes are more bound
- Analytic model in which BH mass is determined by halo binding energy can reproduce the evolution in halo relations
- Evolution in relations with stellar properties explained if massive galaxies grow mostly through dry mergers

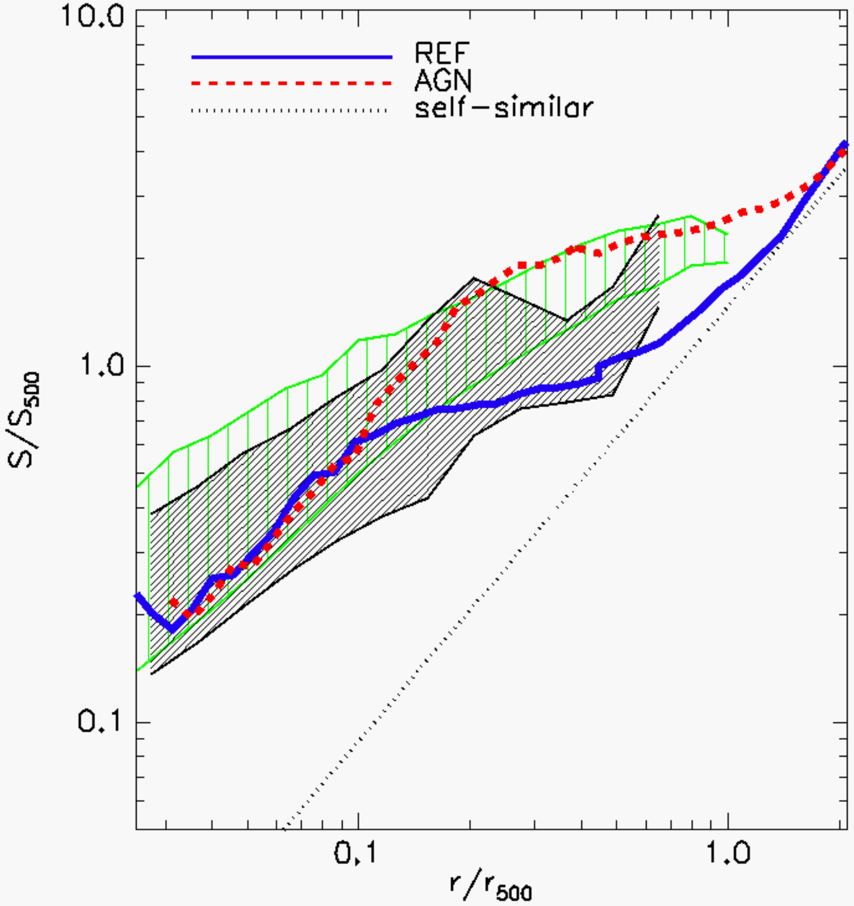
Booth & JS 2011, MNRAS, 413, 1158

AGN feedback

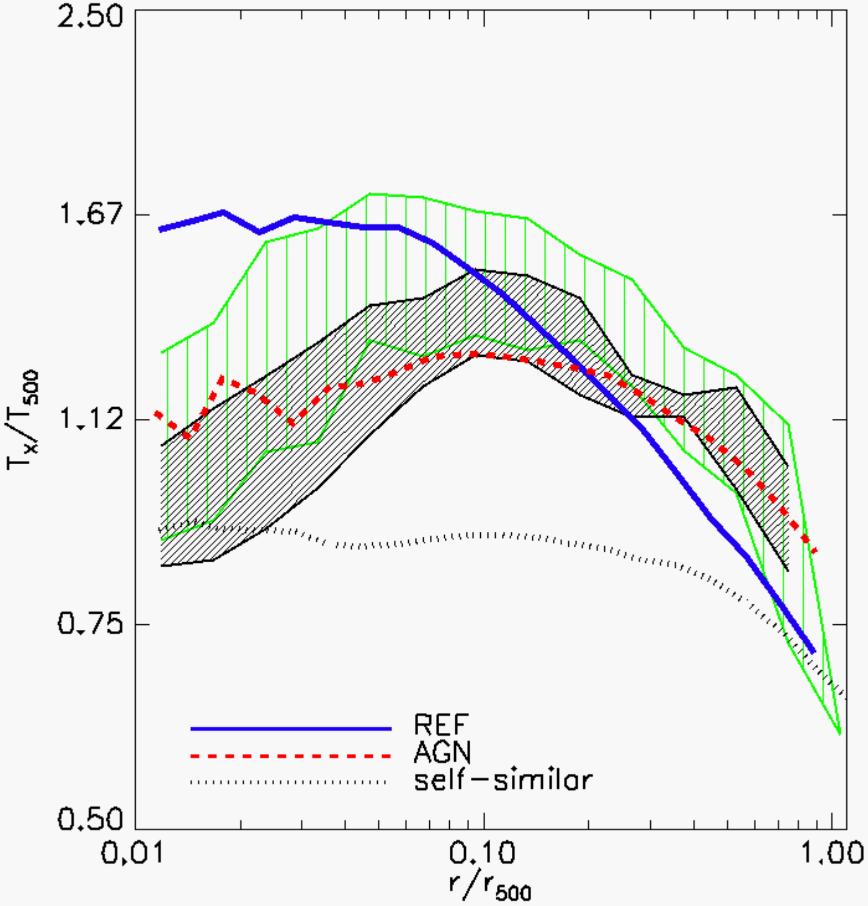
- AGN feedback reproduces the observed BH scaling relations
- In the simulations the AGN feedback regulates BH growth on large scales
- But is such large-scale feedback realistic?

Gas profiles in groups

Entropy $S \propto T / n^{2/3}$



Temperature

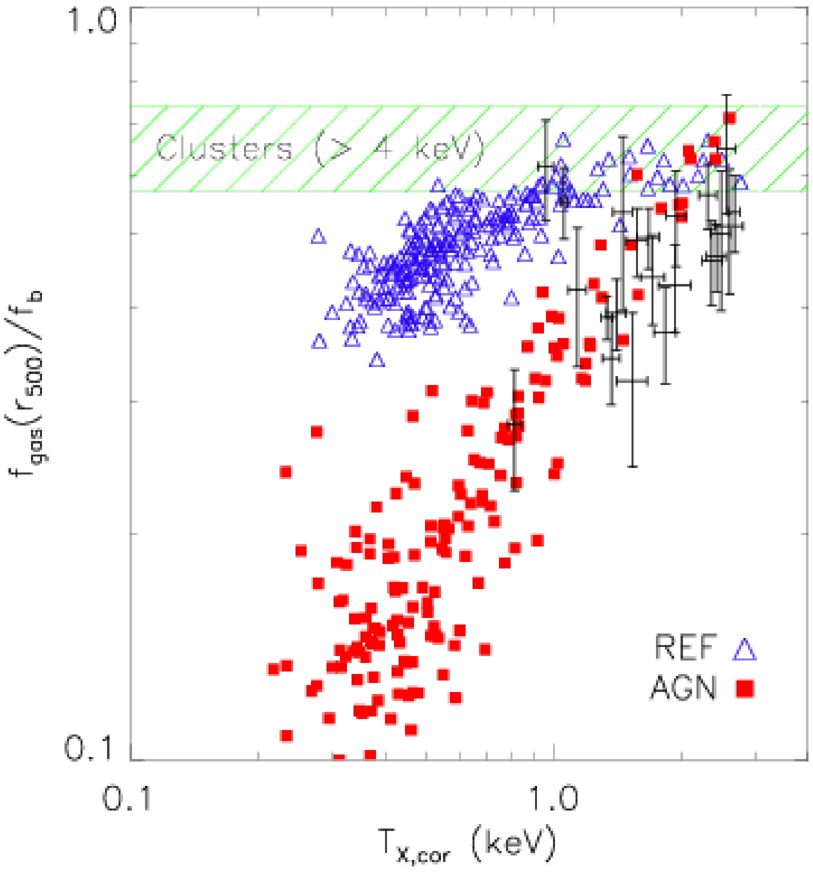


Observations:
Sun et al. (2009), Johnson et al. (2009)
Sun et al. (2009), Rasmussen & Ponman (2009)

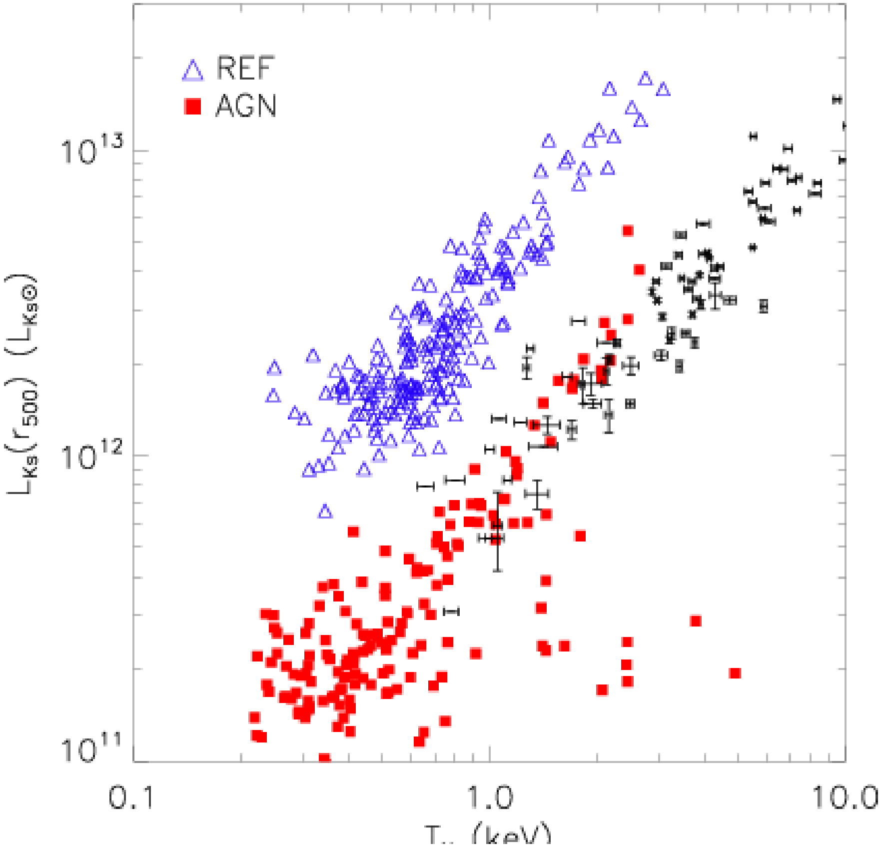
McCarthy, JS, Ponman, et al. (2010)

Gas and stellar contents

Gas fraction



K-band luminosity



Observations: Lin & Mohr 2004, Horner 2001,
Rasmussen & Ponman (2009)

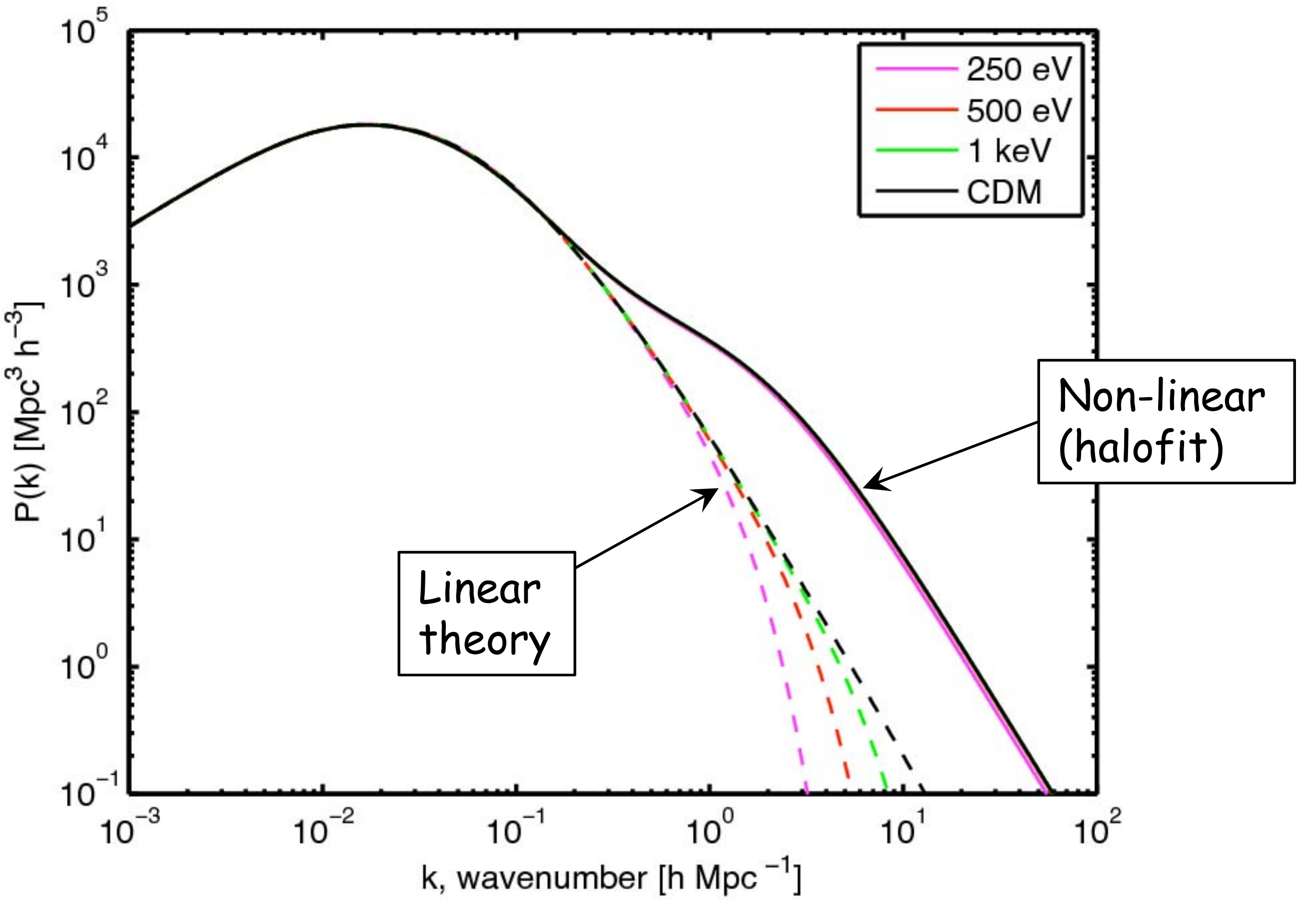
McCarthy, JS, Ponman, et al. (2010)

AGN feedback in groups

- AGN feedback enables us to reproduce both X-ray and optical properties:
  - X-ray derived profiles (entropy, temp, density, metallicity)
  - X-ray scaling relations (L-T, L-M)
  - Optical properties (stellar masses, ages)
- AGN feedback operates by ejecting low-entropy gas from progenitors at high redshift, when the black holes were growing rapidly

McCarthy, JS, Ponman, et al. (2010), MNRAS, 406, 822
McCarthy, JS, Bower, et al. (2011), MNRAS, 412, 1965

WDM and the power spectrum



Non-linear (halofit)

Linear theory

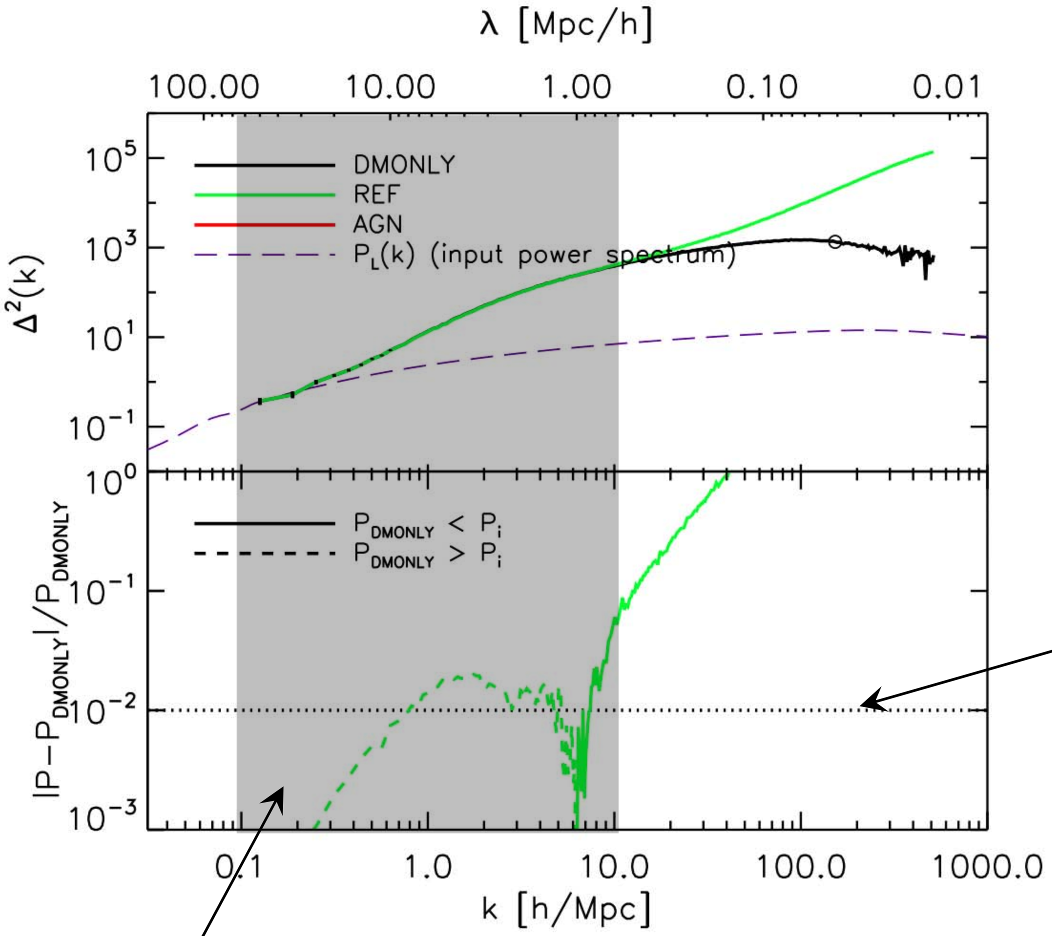
Can we separate the non-linear WDM effects from baryonic effects?

Markovic et al. (2010)

The matter power spectrum

- Baryons change the large-scale distribution of matter. This is important for cosmology.
- Previous work (e.g. Jing et al. 2006; Rudd et al. 2008; Guillet et al. 2009; Cassarini et al. 2010) suffered from overcooling, as is the case for our REF model.
- Overcooling was thought to be conservative: effect of baryons too strong.

Baryons and the matter power spectrum

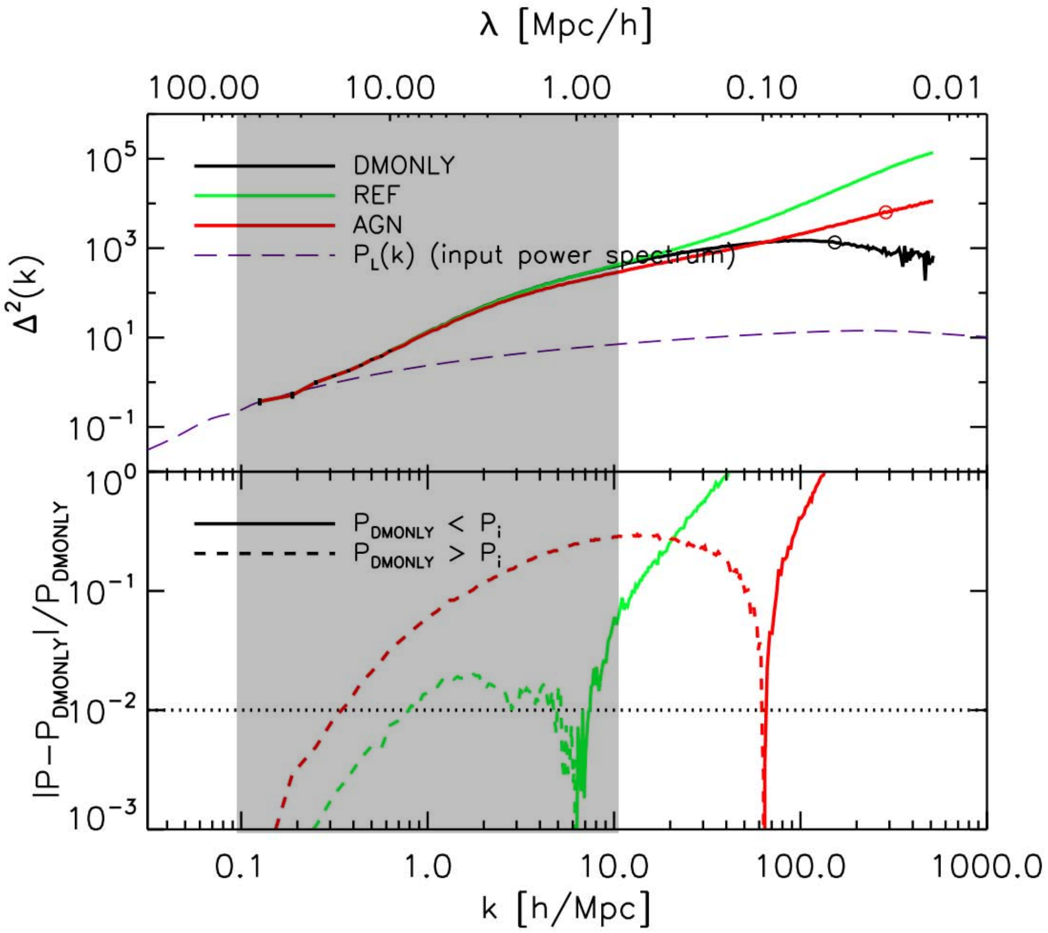


1% difference wrt dark matter only

Range of interest for cosmic shear

Van Daalen, JS, et al. (2011)

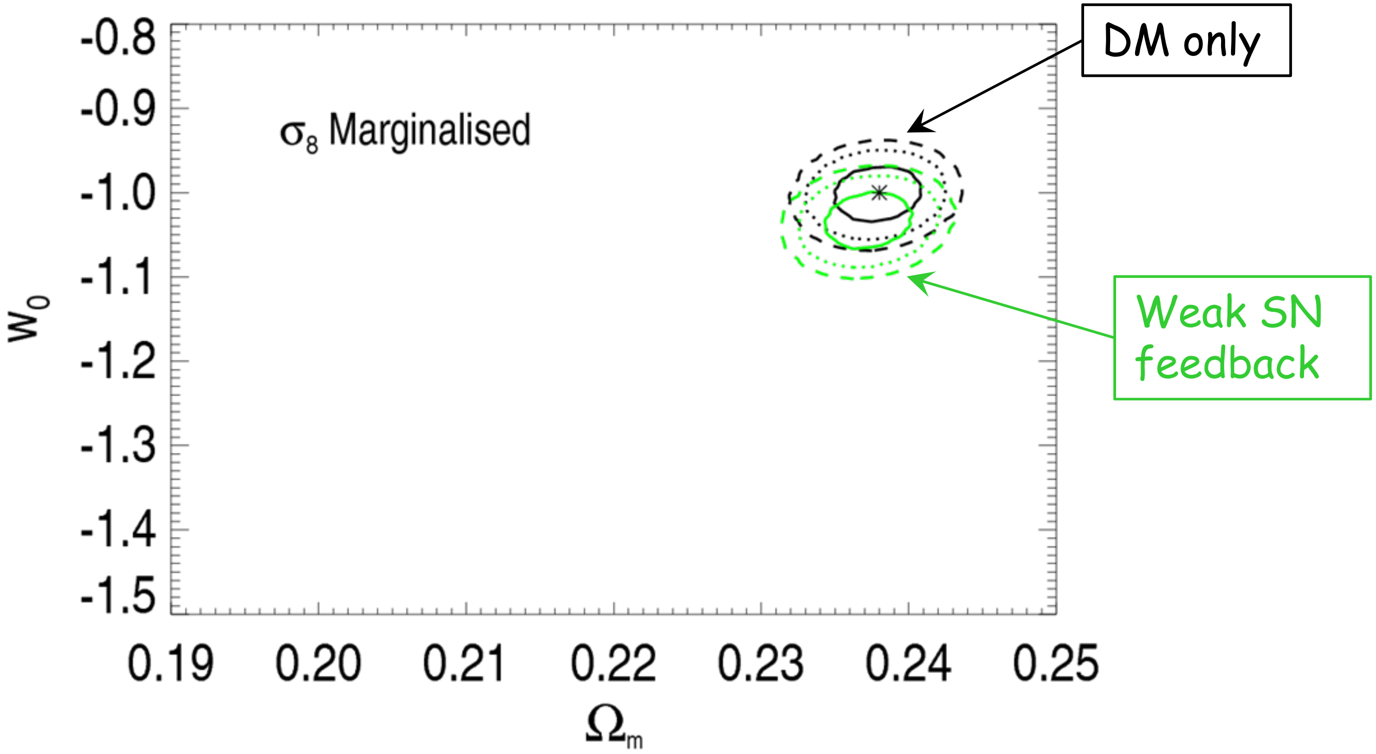
Baryons and the matter power spectrum



The feedback required to solve the overcooling problem suppresses power on large scales

Van Daalen, JS, et al. (2011)

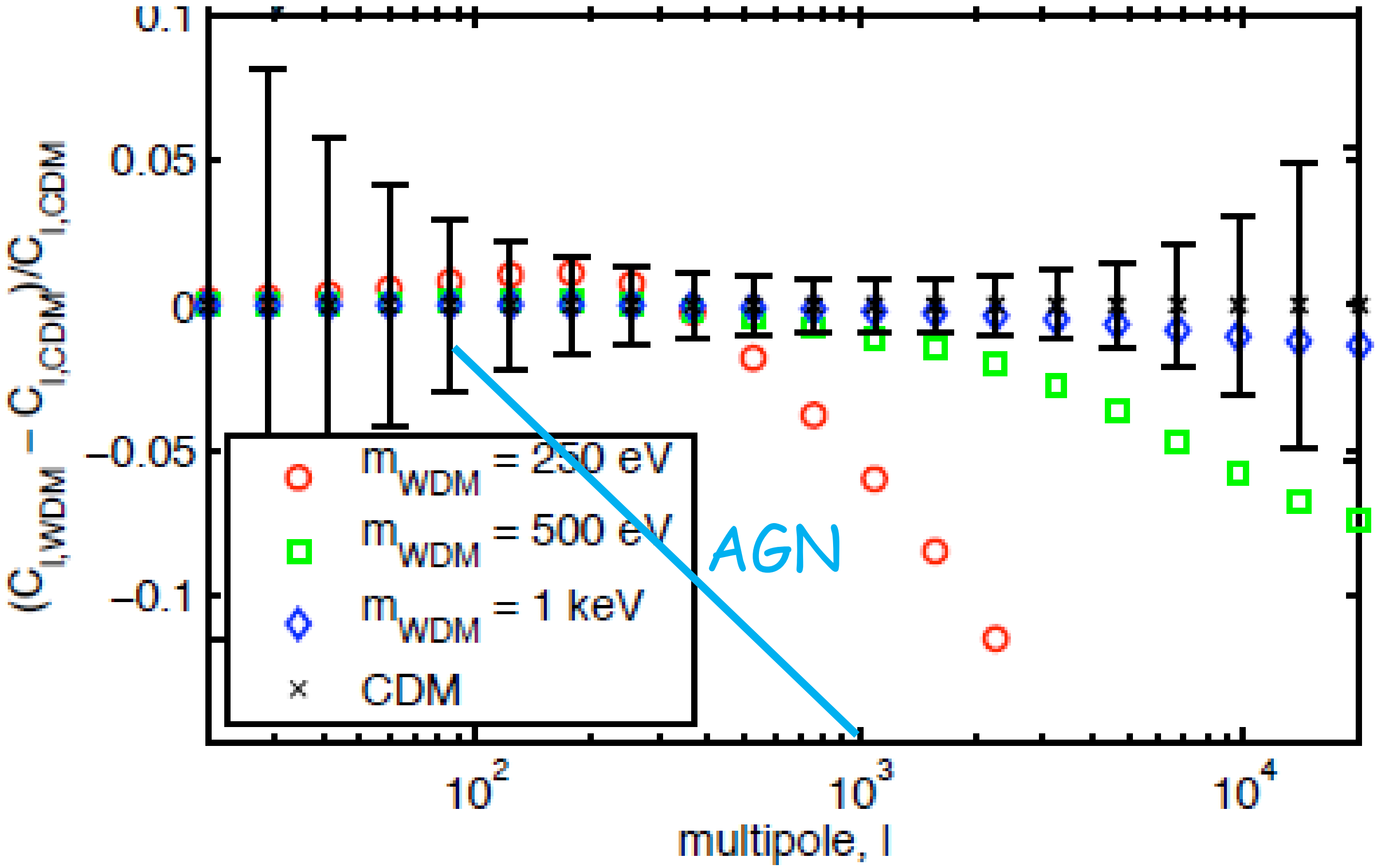
Biases due to galaxy formation for a Euclid-like weak lensing survey



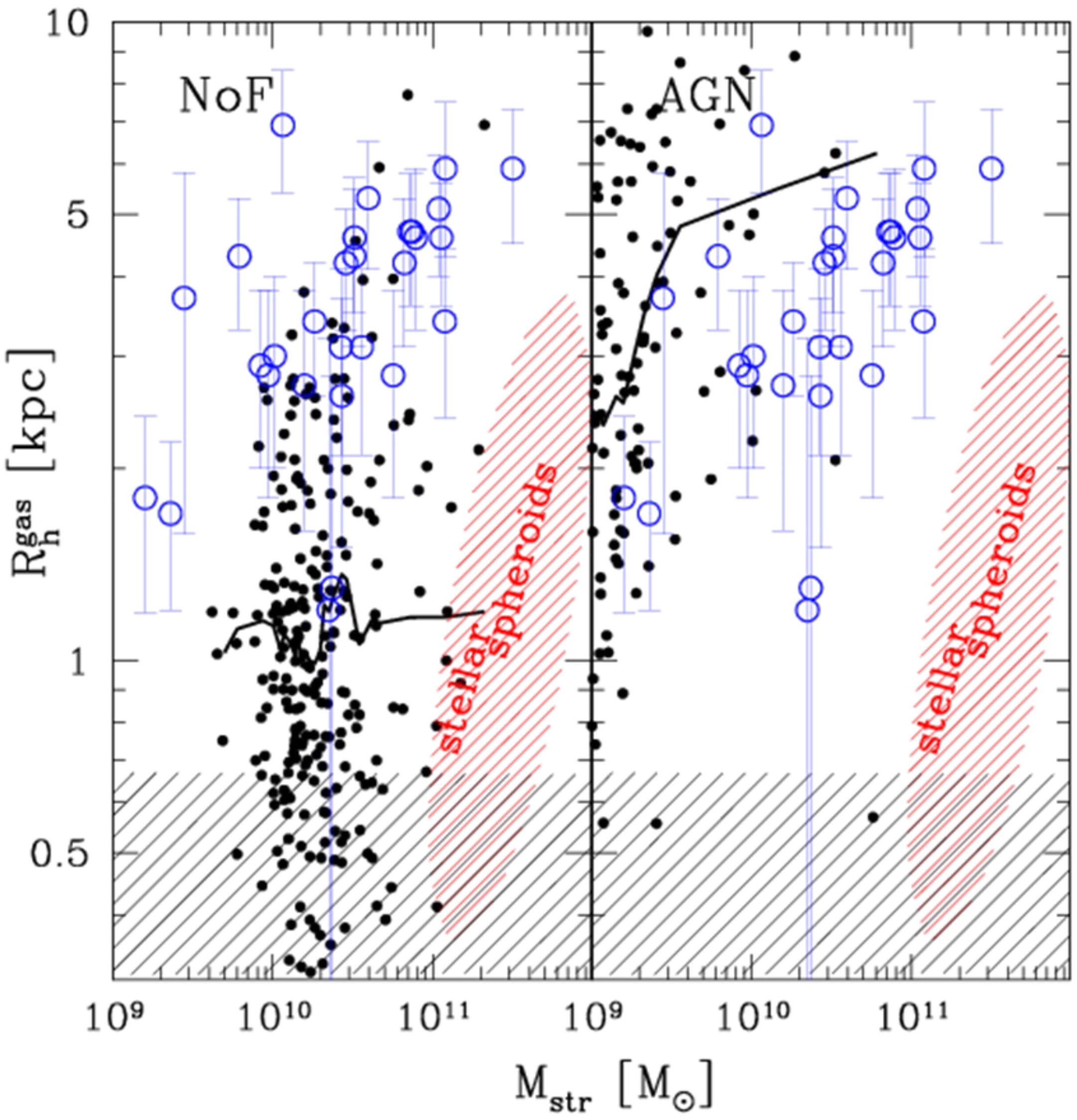
Galaxy formation provides a challenge (target?)
for weak lensing

Semboloni, Hoekstra, JS, et al. (2011)

Effect of WDM swamped by feedback

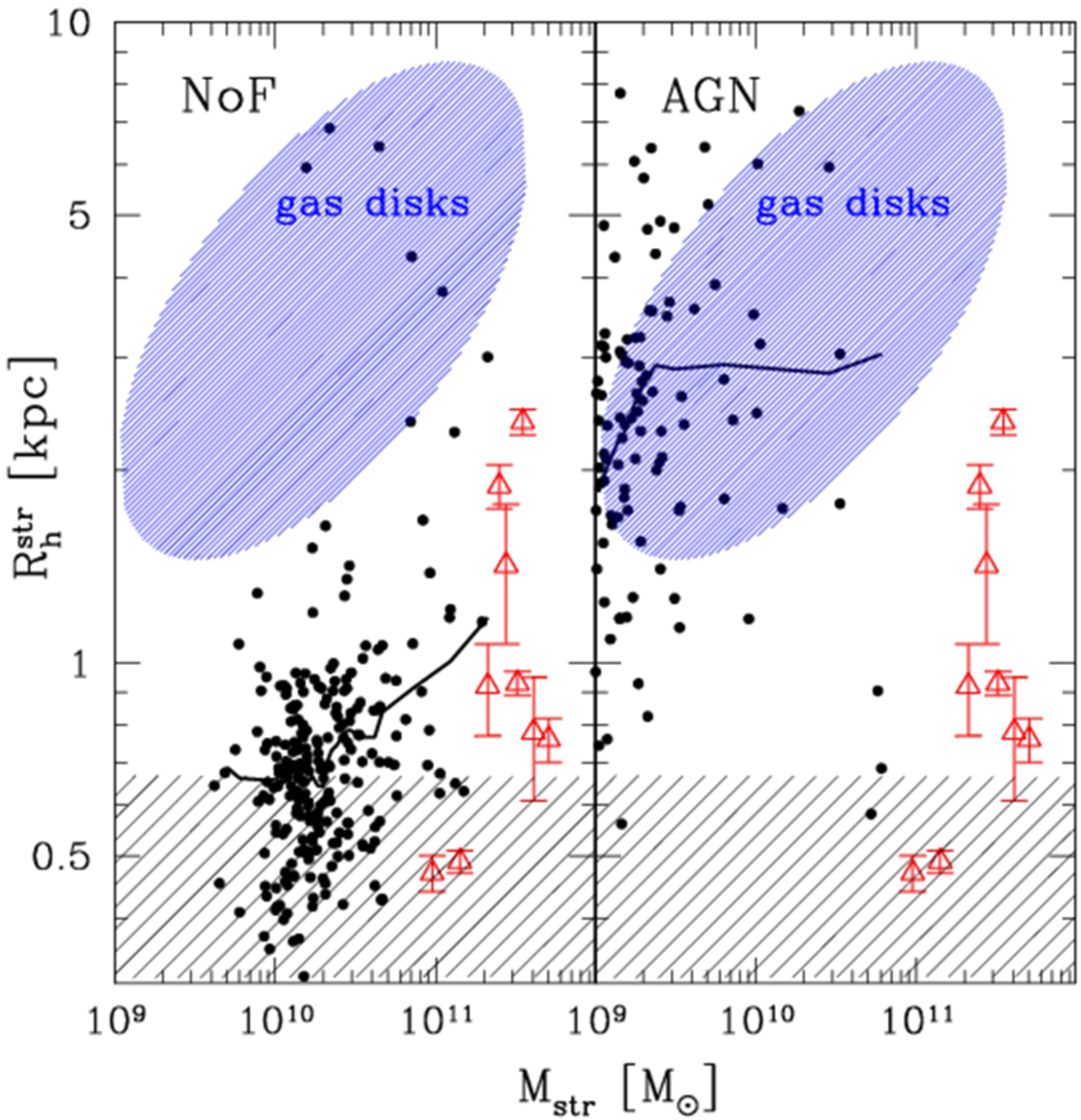


Galaxy sizes at z~2: Gas



Sales, Navarro, JS, et al. (2010)

Galaxy sizes at z~2: Stars

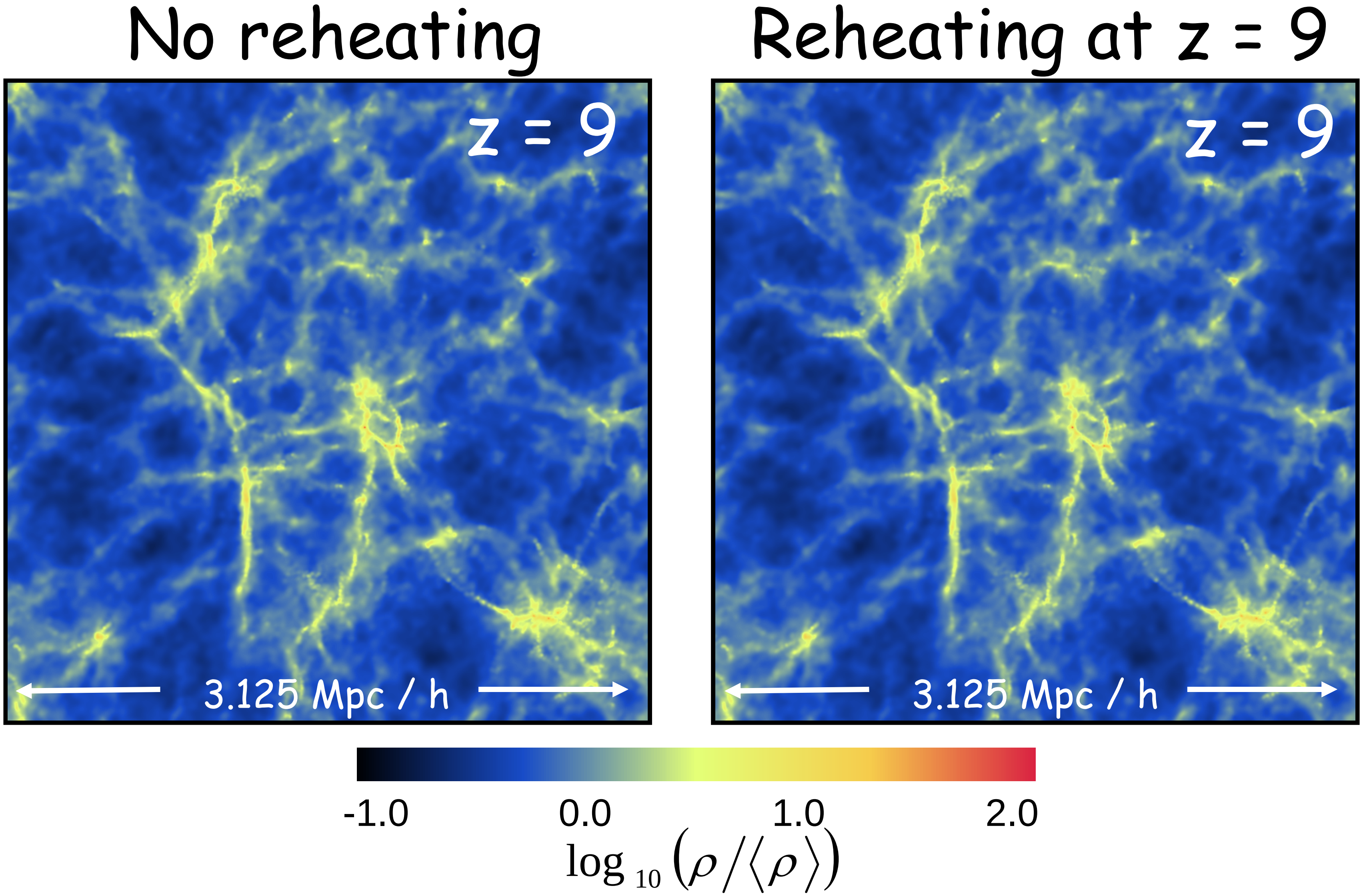


Sales, Navarro, JS, et al. (2010)

Galaxy sizes at z~2

- Weak feedback:
  - High stellar masses (in conflict with z~0 statistics → feedback must become efficient)
  - Small sizes
- Strong feedback (e.g. AGN):
  - Low stellar masses
  - Large sizes (low angular momentum material is preferentially ejected and larger haloes for fixed stellar mass)
- Needed: unbiased samples

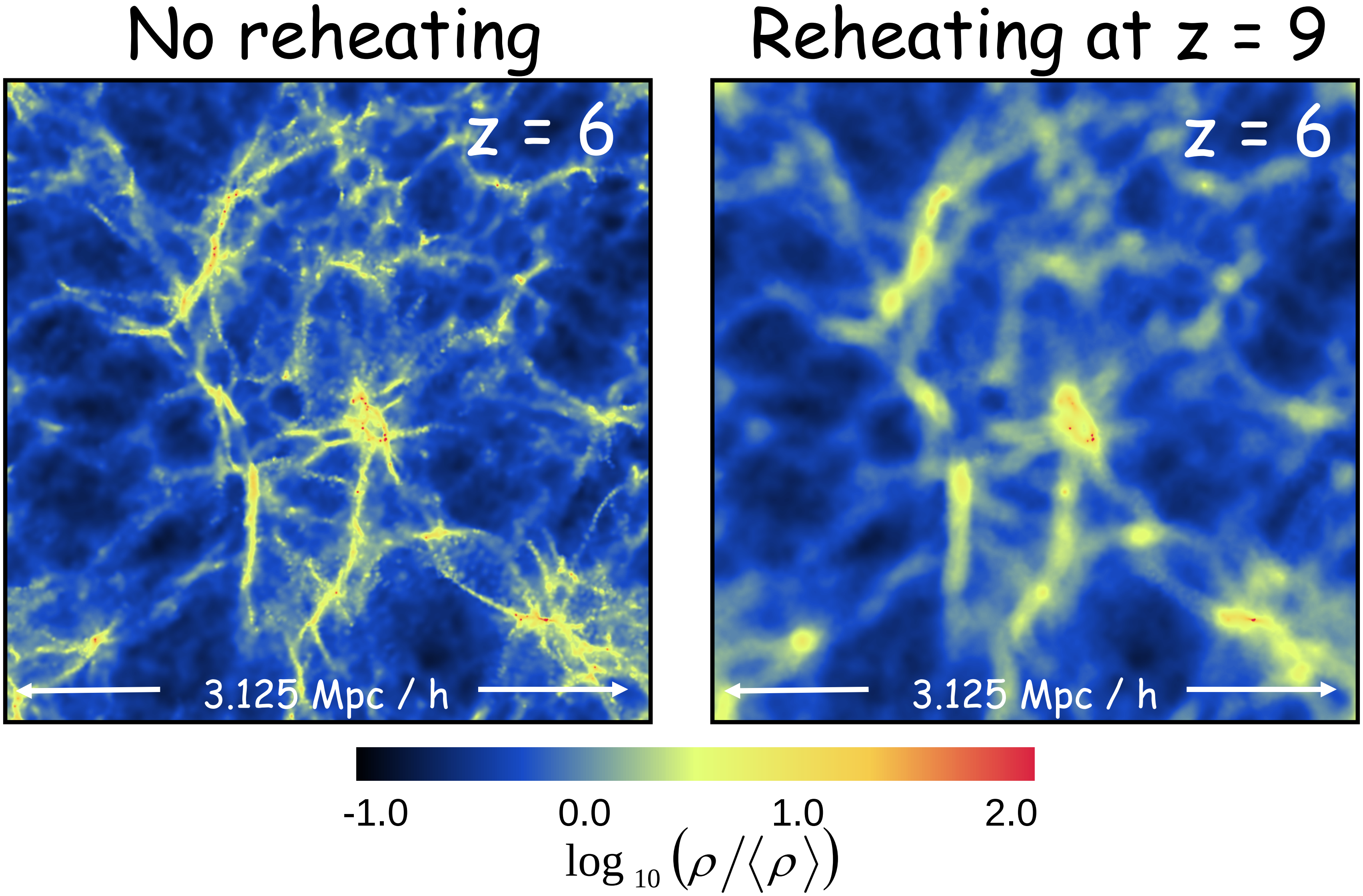
Sales, Navarro, JS, et al. (2010), MNRAS, 409, 1541



No reheating

Reheating at z = 9

Pawlik, JS & van Scherpenzeel (2009)

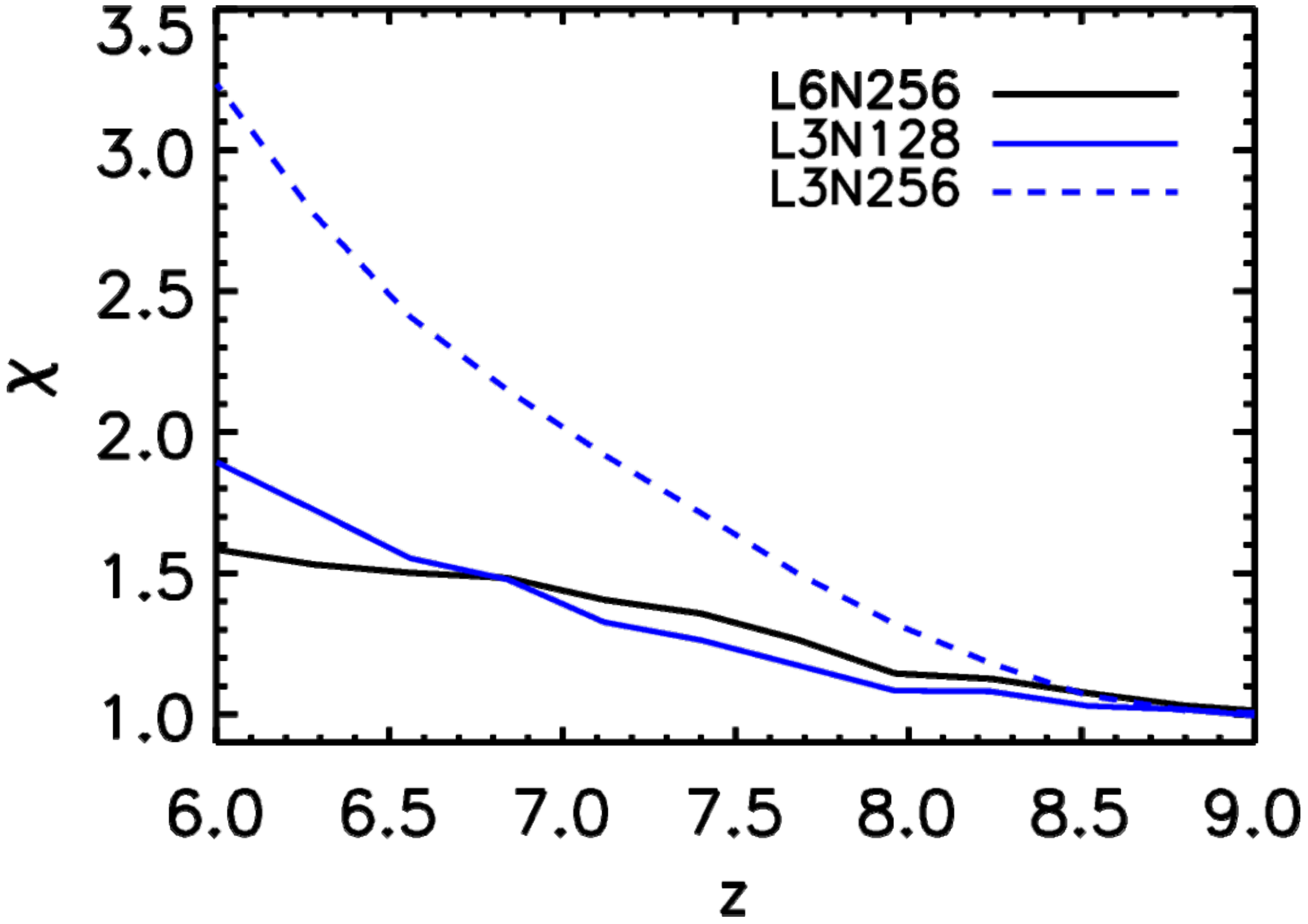


No reheating

Reheating at $z = 9$

Pawlik, JS & van Scherpenzeel (2009)

Photo-heating and galactic winds amplify each other's effect on the SFR



Pawlik & JS (2009)

Suppression of high-z star formation

- Both reheating and supernova feedback reduce the SFR -> negative feedback
- Reheating and supernova feedback mutually strengthen each other
- Current semi-analytic models assume reheating and supernova feedback to be independent and hence strongly underestimate their effect

Pawlik & JS (2009), MNRAS, 396, L46

Conclusion

- Feedback processes in galaxy formation are very strong
- It will be a challenge to distinguish them from WDM
- But:
  - Ly-alpha forest power spectrum relatively immune to feedback