FEEDBACK AND GALAXY FORMATION FROM SMALL SCALES TO LARGE

Insights from Extremely Large Cosmological Simulations

Craig Booth

University of Chicago

&

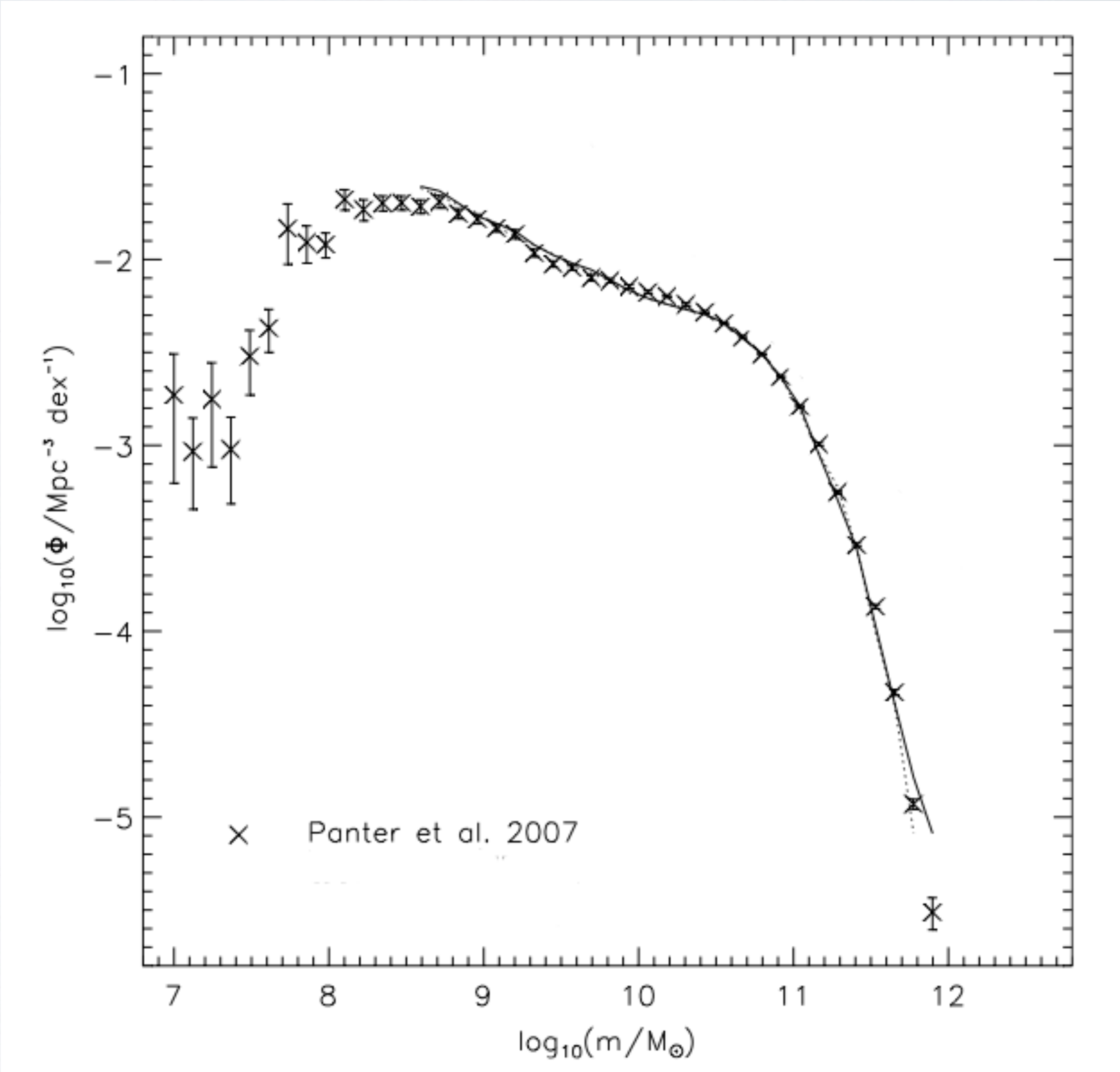
Leiden Observatory

Craig Booth, Fermilab,
March 12th, 2012

WHAT DO WE UNDERSTAND?

About simulating galaxy formation

- Galaxy mass function is well measured
- Structure formation: The mass function and clustering of haloes
- Galaxy formation implies that different physics is operating at different masses.
- Feedback effects. SN? AGN?

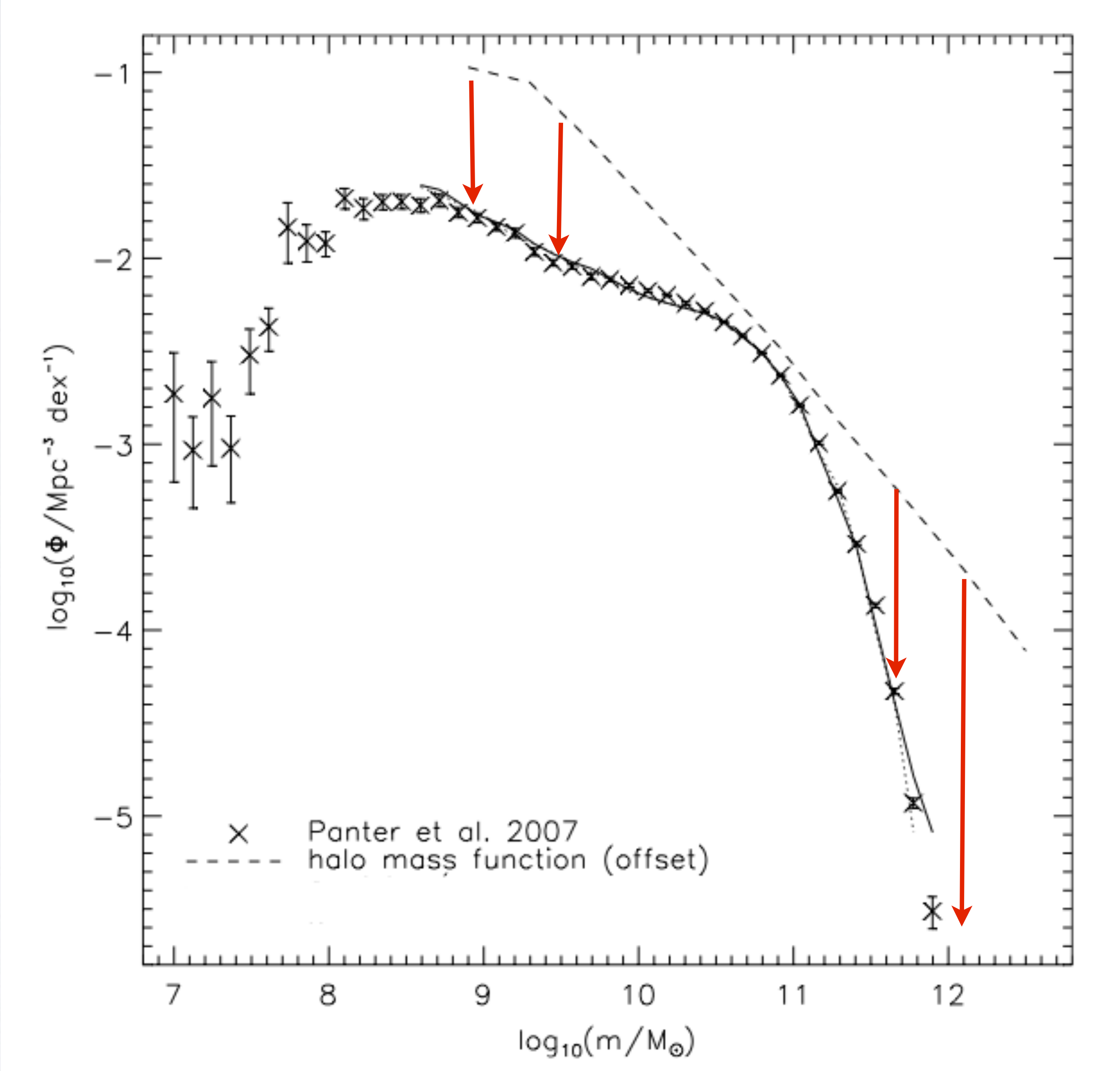


Moster et al. (2010)

WHAT DO WE UNDERSTAND?

About simulating galaxy formation

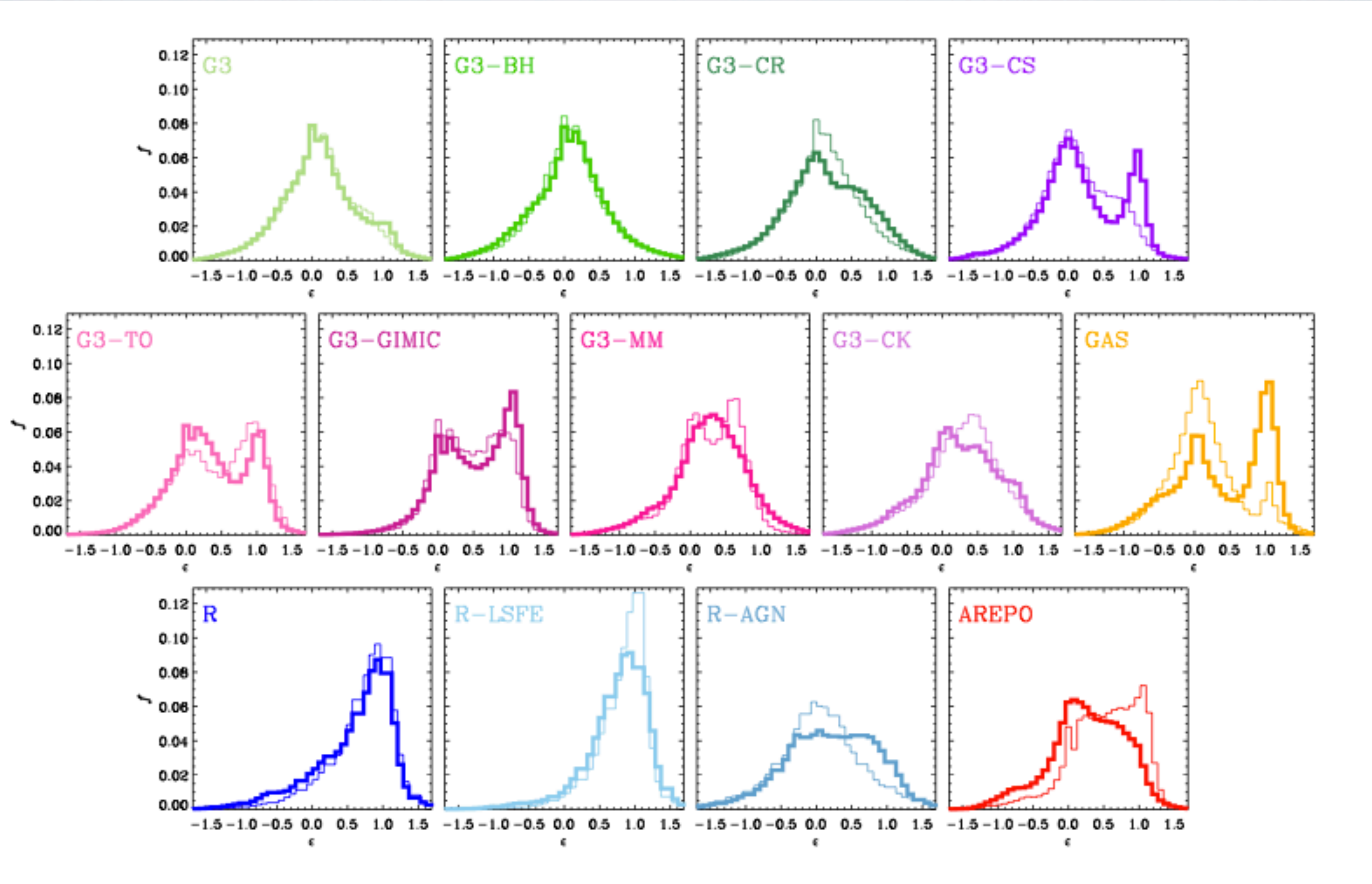
- Galaxy mass function is well measured
- Structure formation: The mass function and clustering of haloes
- Galaxy formation implies that different physics is operating at different masses.
- Feedback effects. SN? AGN?



Moster et al. (2010)

WHAT DO WE *NOT* UNDERSTAND?

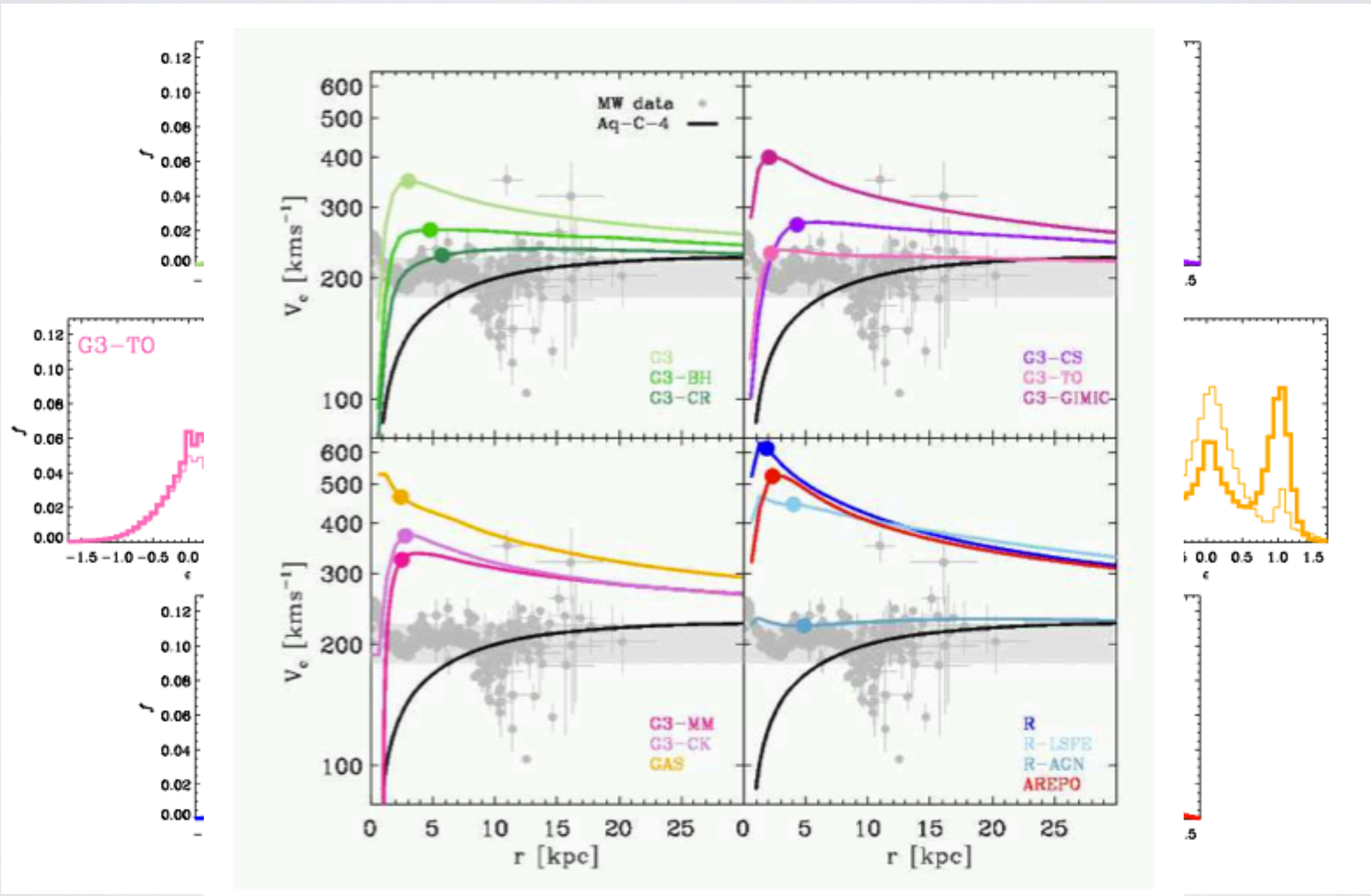
About simulating galaxy formation



Scannapieco+ 2011

WHAT DO WE *NOT* UNDERSTAND?

About simulating galaxy formation



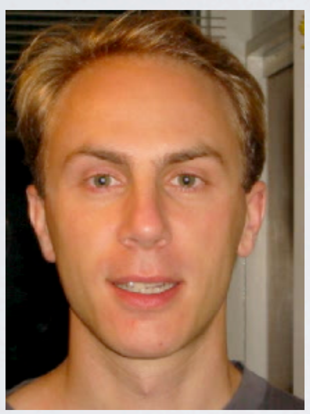
Scannapieco+ 2011

OVERVIEW

- OWLS: OverWhelmingly Large Simulations
- Growing galaxies:
  - PART I: The balance between fueling and feedback
  - PART II: An example. The case of AGN.
- EAGLE: GaLaxies and their Environments

OWLS PEOPLE

A highly incomplete list...



Schaye

Dalla Vecchia

Springel

Theuns

Tornatore

Wiersma

Bertone

Crain

Duffy

Haas

McCarthy

Sales

van de Voort

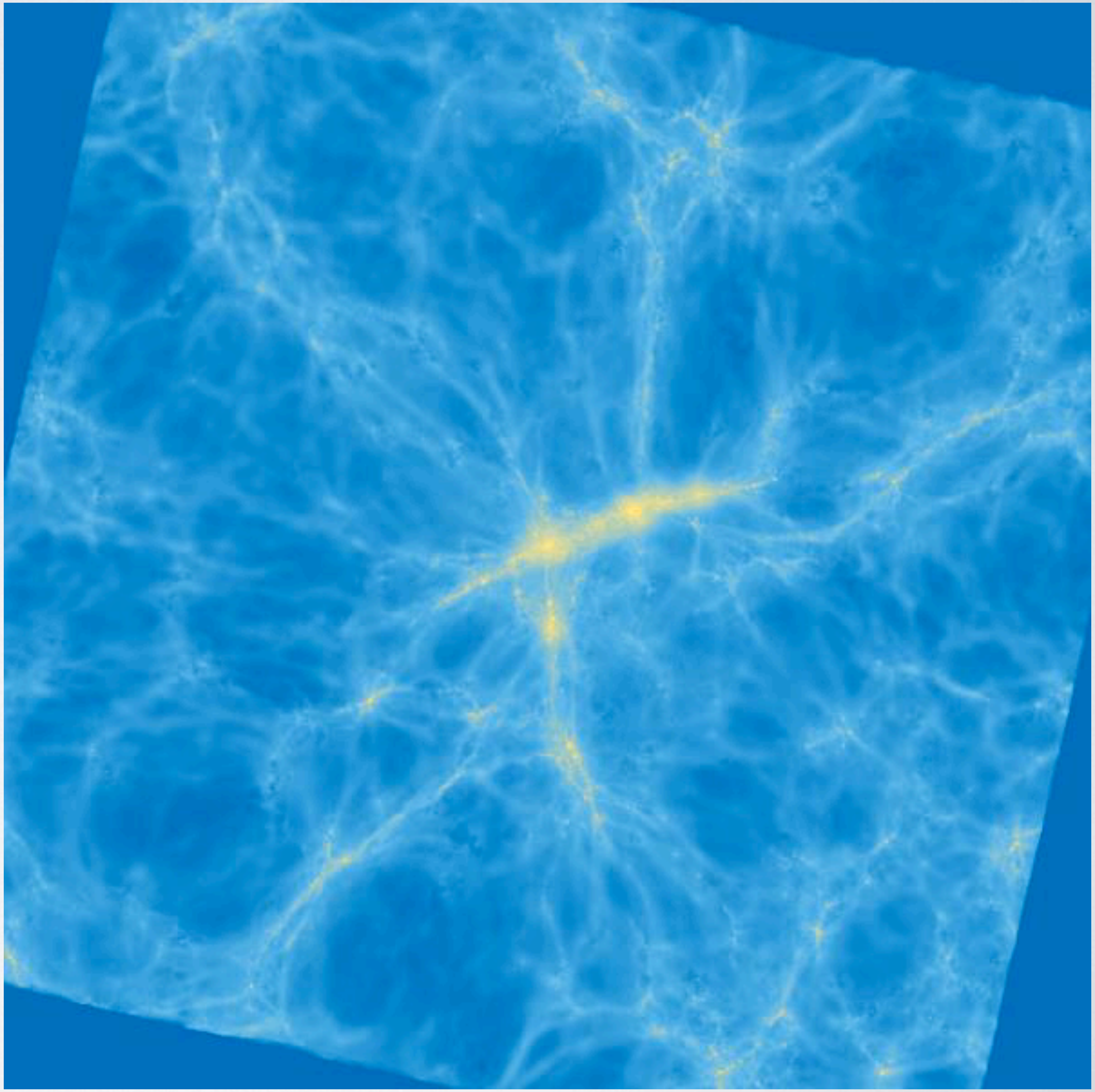
SIMULATIONS

Evolution from z>100 to z~0 of a representative part of the universe

Containing: Gas, DM, Stars (Hydro, SF, Metal enrichment, reionization, feedback, AGN, etc.)

Scales ~ kpc to ~ 100 Mpc

Sub-grid modules are of vital importance...



Simulate what we can -- Use simple subgrid models where necessary

Physics on small scales unresolved →

New Physics Modules:

- Star formation (Schaye & Dalla Vecchia 2008)
- SN Feedback (Dalla Vecchia & Schaye 2008)
- Radiative Cooling (Wiersma, Schaye & Smith 2008)
- Chemodynamics (Wiersma et al. 2009)
- AGN Feedback (Booth & Schaye 2009a)

$m_b = 1\times10^6\ h^{-1}\ M_\odot,\quad \varepsilon \le 0.5\ h^{-1}\ \mathrm{kpc}$

$m_b = 9\times10^7\ h^{-1}\ M_\odot,\quad \varepsilon \le 2\ h^{-1}\ \mathrm{kpc}$

- Cosmological (default: WMAP3)
- Hydrodynamical (SPH)
- Gadget III
- $2xN^3$ particles, N = 512 for most
- Two sets:
  - L = 25 Mpc/h to z=2
  - L = 100 Mpc/h to z=0

← Gravity and hydrodynamics simulated explicitly

THE OWLS PHILOSOPHY 1/2

- Simulate what we can -- Use *simple* subgrid models where necessary
- Physic
  - Pref e
    cool
- Empir
  - Preferred if physics is complex (e.g. SN feedback, star-formation)
- Systematically test uncertainties...

New Physics Modules:

Star formation (Schaye & Dalla Vecchia 2008)

SN Feedback (Dalla Vecchia & Schaye 2008)

Radiative Cooling (Wiersma, Schaye & Smith 2008)

Chemodynamics (Wiersma et al. 2009)

AGN Feedback (Booth & Schaye 2009a)

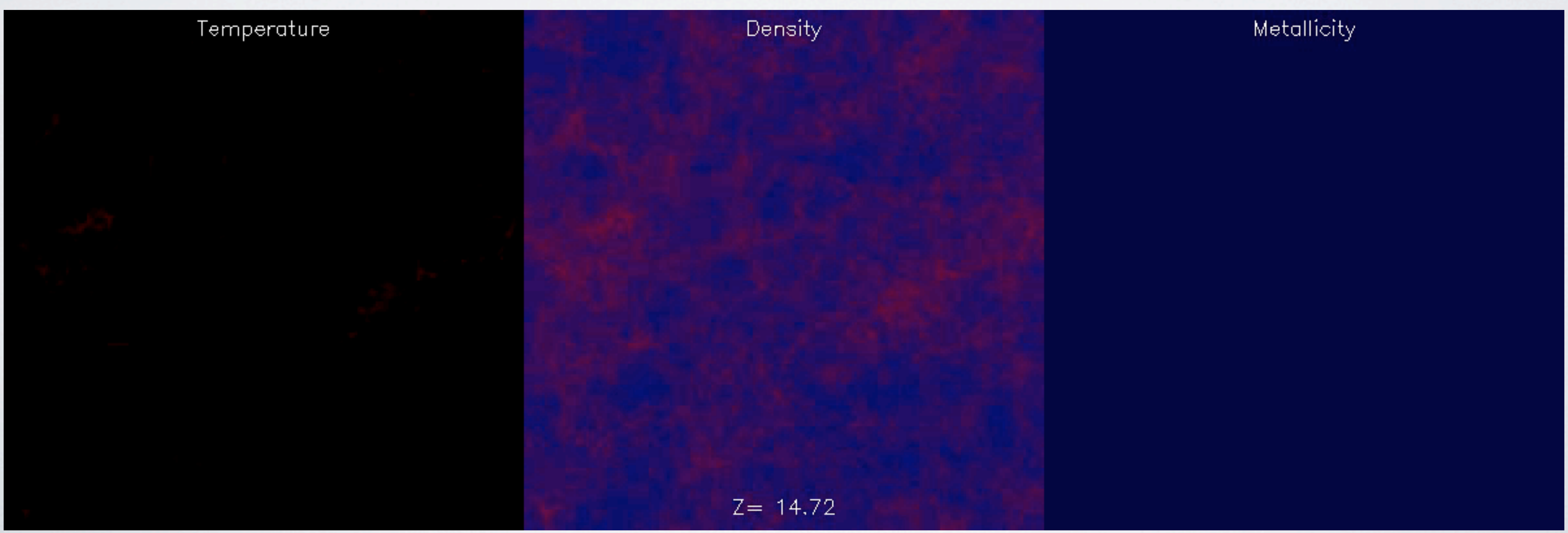
THE OWLS PHILOSOPHY 1/2

- Simulate what we can -- Use *simple* subgrid models where necessary
- Physically motivated recipe
  - Preferred if physics is well understood (radiative cooling, stellar evolution)
- Empirically motivated recipe
  - Preferred if physics is complex (e.g. SN feedback, star-formation)
- Systematically test uncertainties...

OVERWHELMINGLY LARGE SIMULATIONS (OWLS)

- Systematically vary: Box size, mass resolution, feedback prescriptions (SNIa, SNII, AGB), reionization history, Helium reionization, stellar IMF, double IMF, properties of the ISM, star formation law, cosmology, radiative cooling, AGN
- Total of 50+ simulations, 100's of terabytes of data products

Temperature Density Metallicity

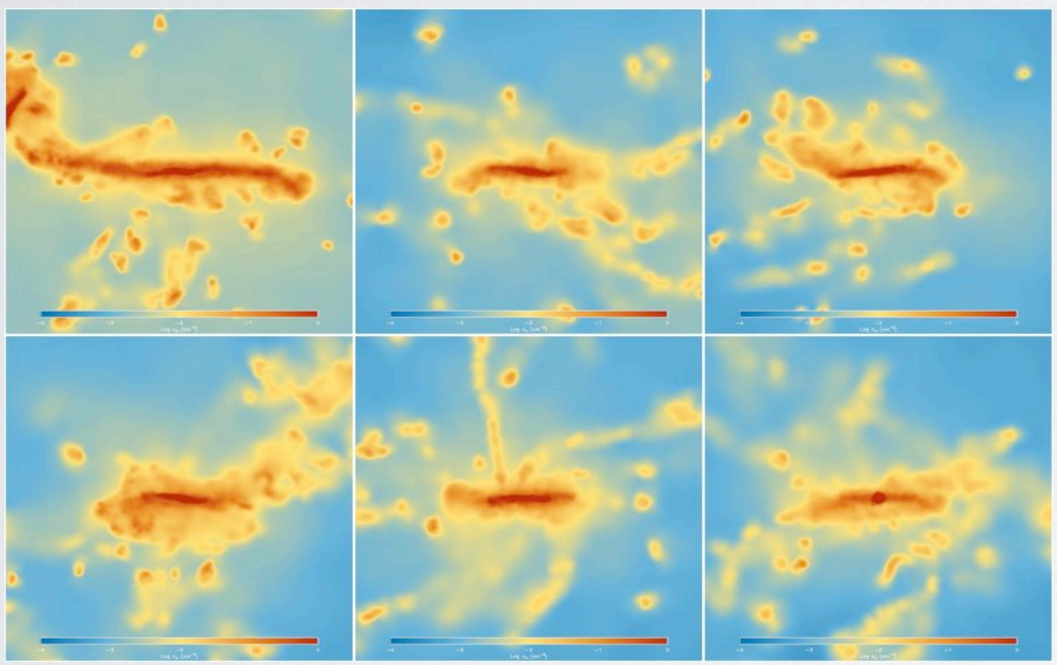


ONE LAST THING...

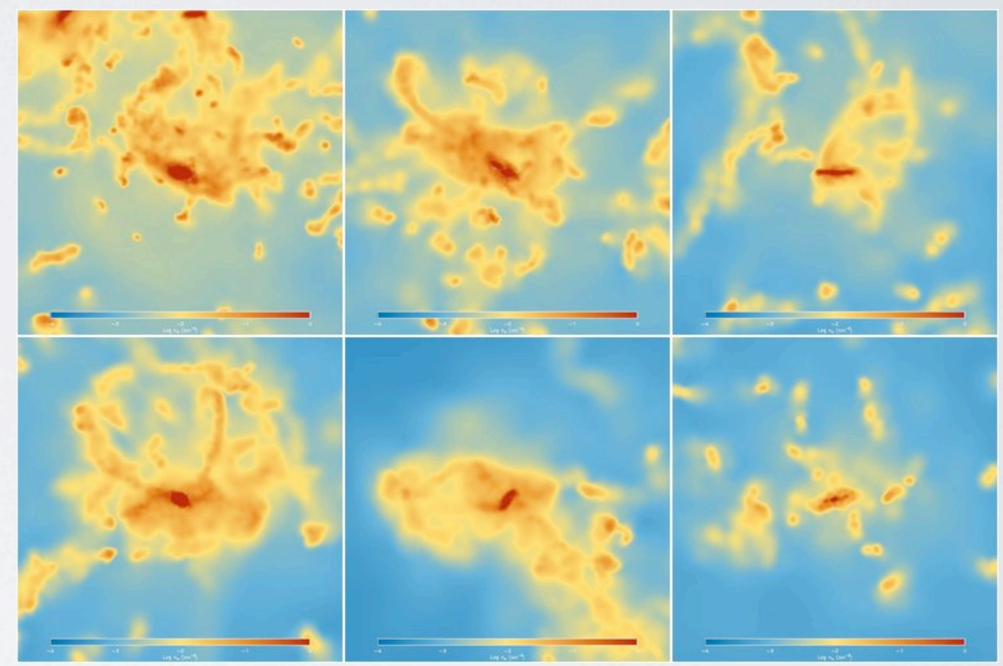
- Some of these simulations look nothing like observation. How could they possibly be useful!?
  - Simulations contain many uncertain numerical parameters. It is important to ascertain what results are robust to these uncertainties
  - By examining what pieces of physics impact certain observables we can begin to 'untangle' the galaxy formation process.

EXAMPLE GALAXIES

Disks

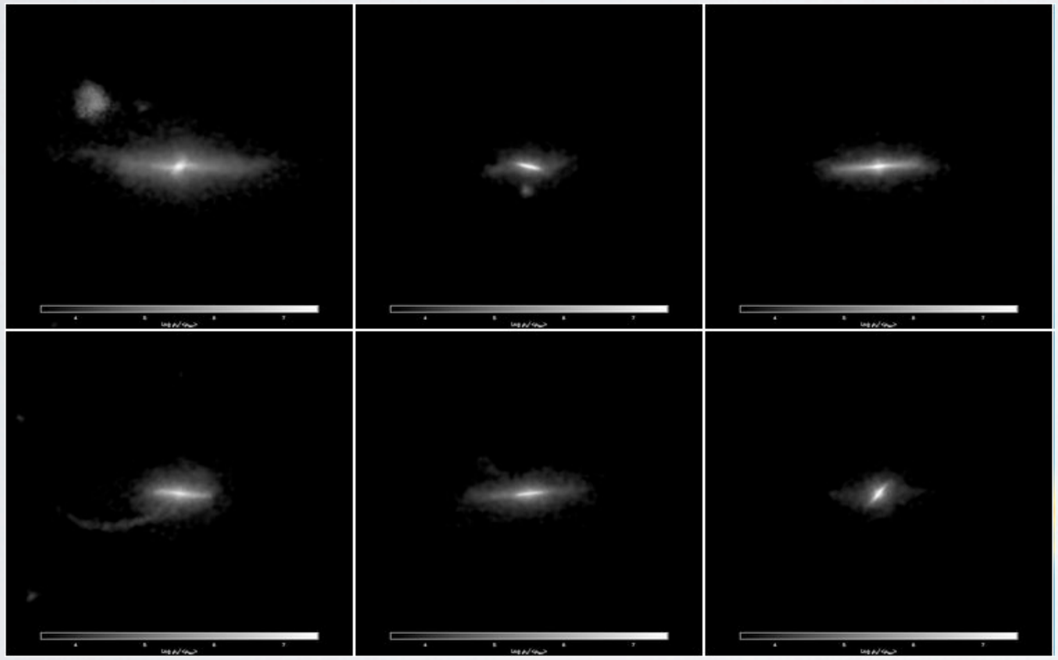


Train wrecks

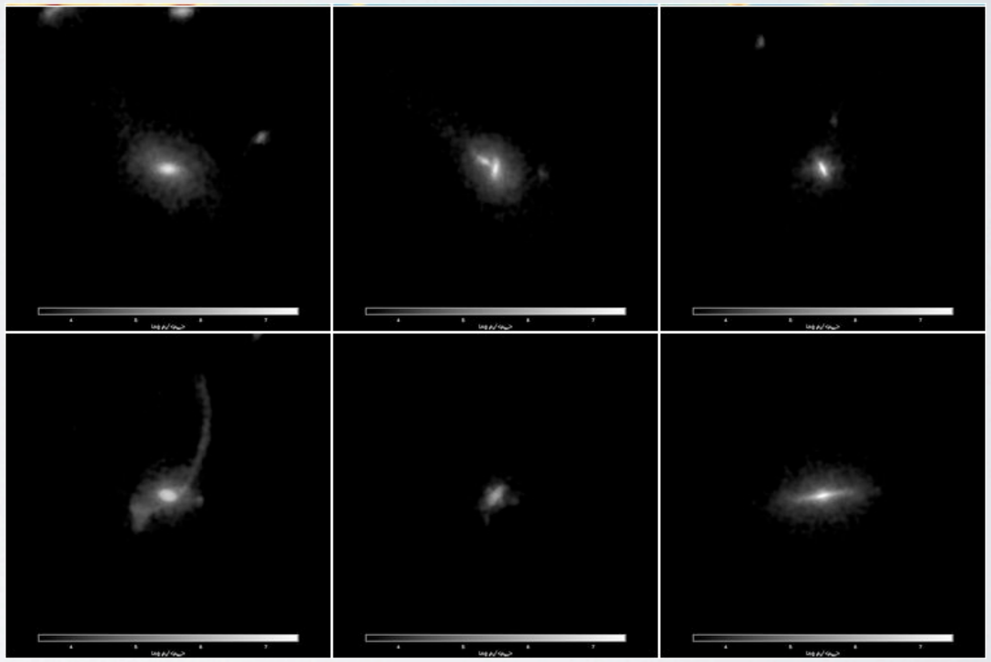


EXAMPLE GALAXIES

Disks



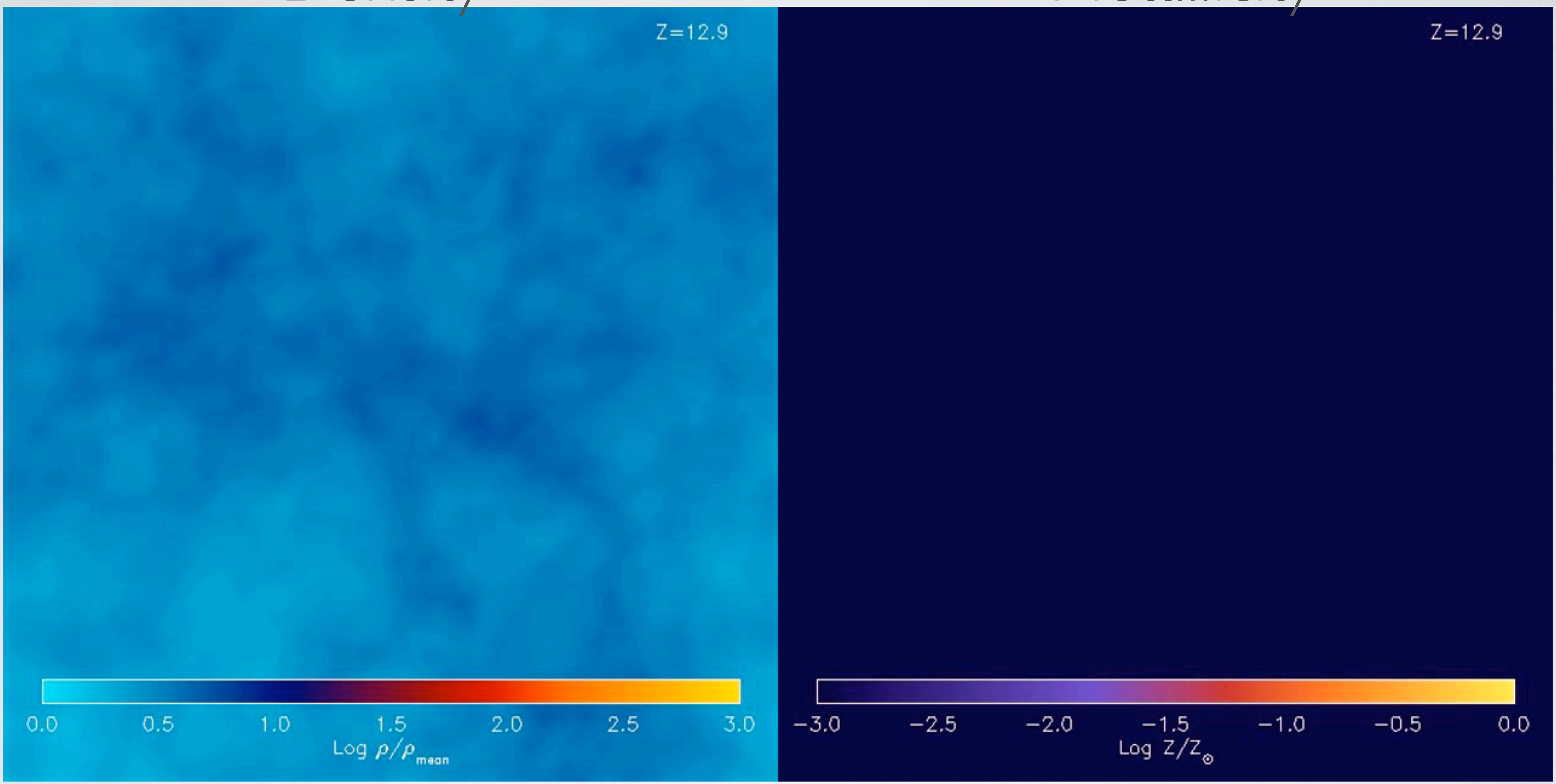
Train wrecks



AND CLUSTERS...

Density

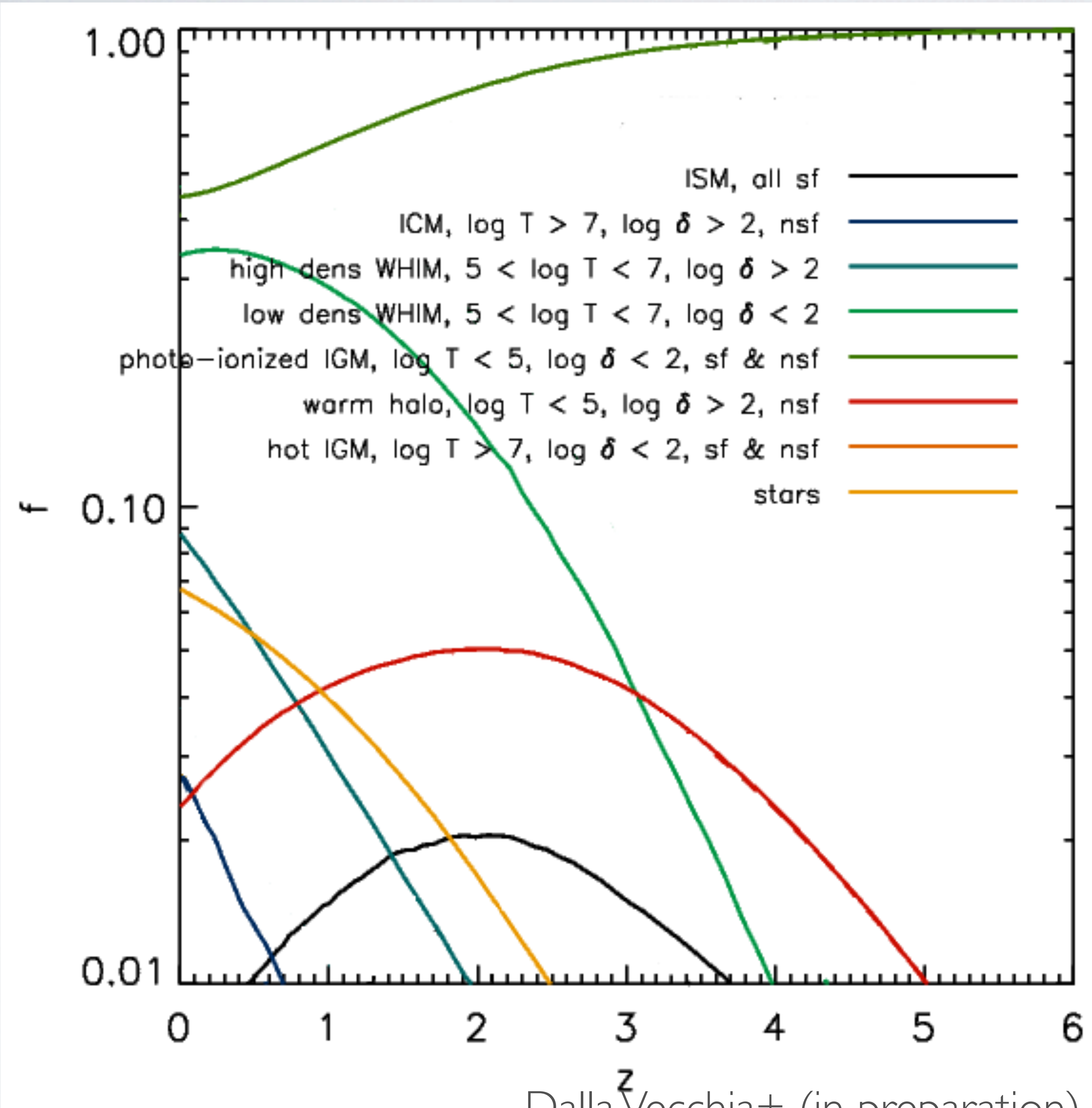
Metallicity



10 Mpc

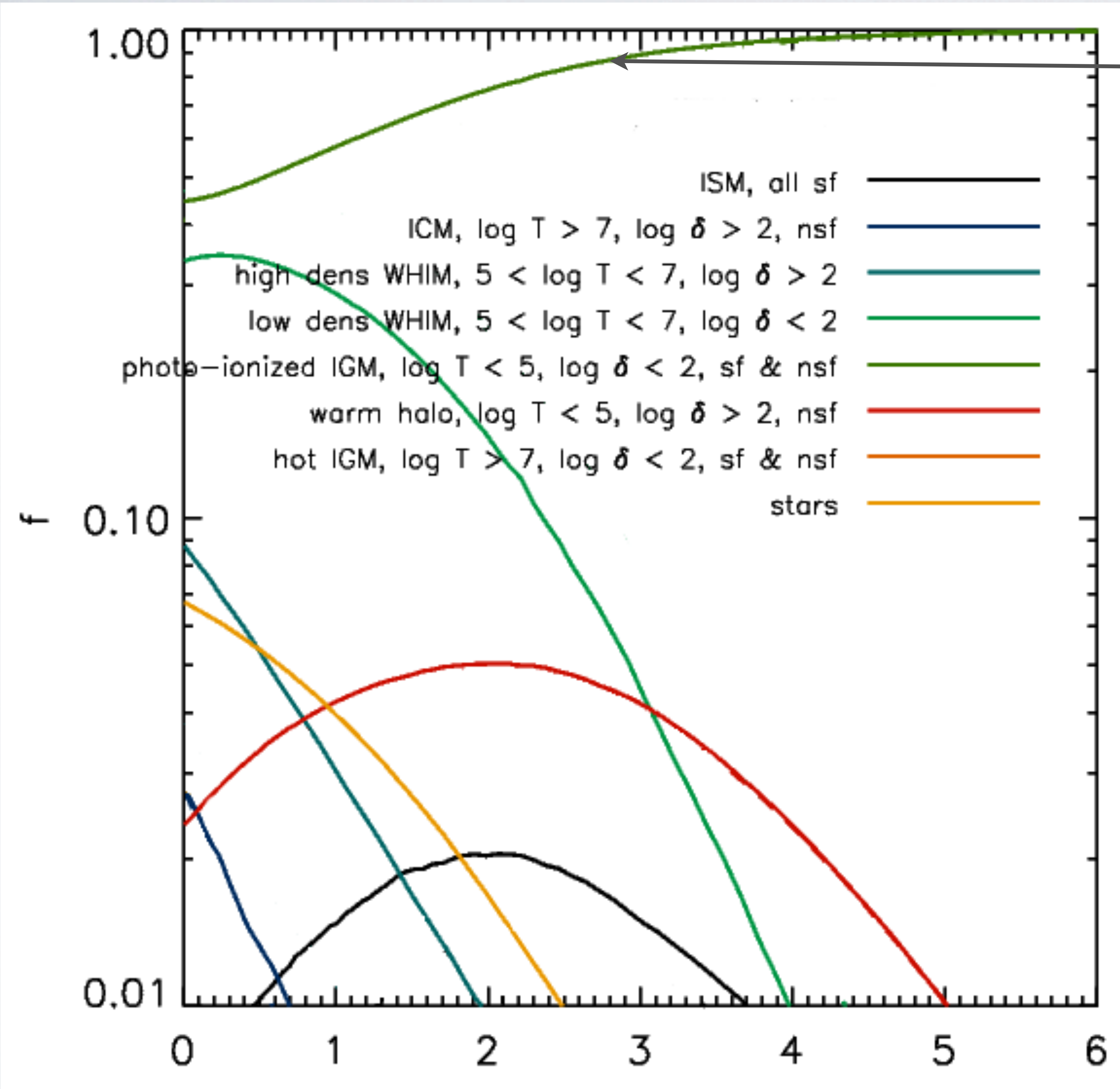
0.1% of the computational volume

WHERE ARE THE BARYONS



Dalla Vecchia+ (in preparation)

WHERE ARE THE BARYONS

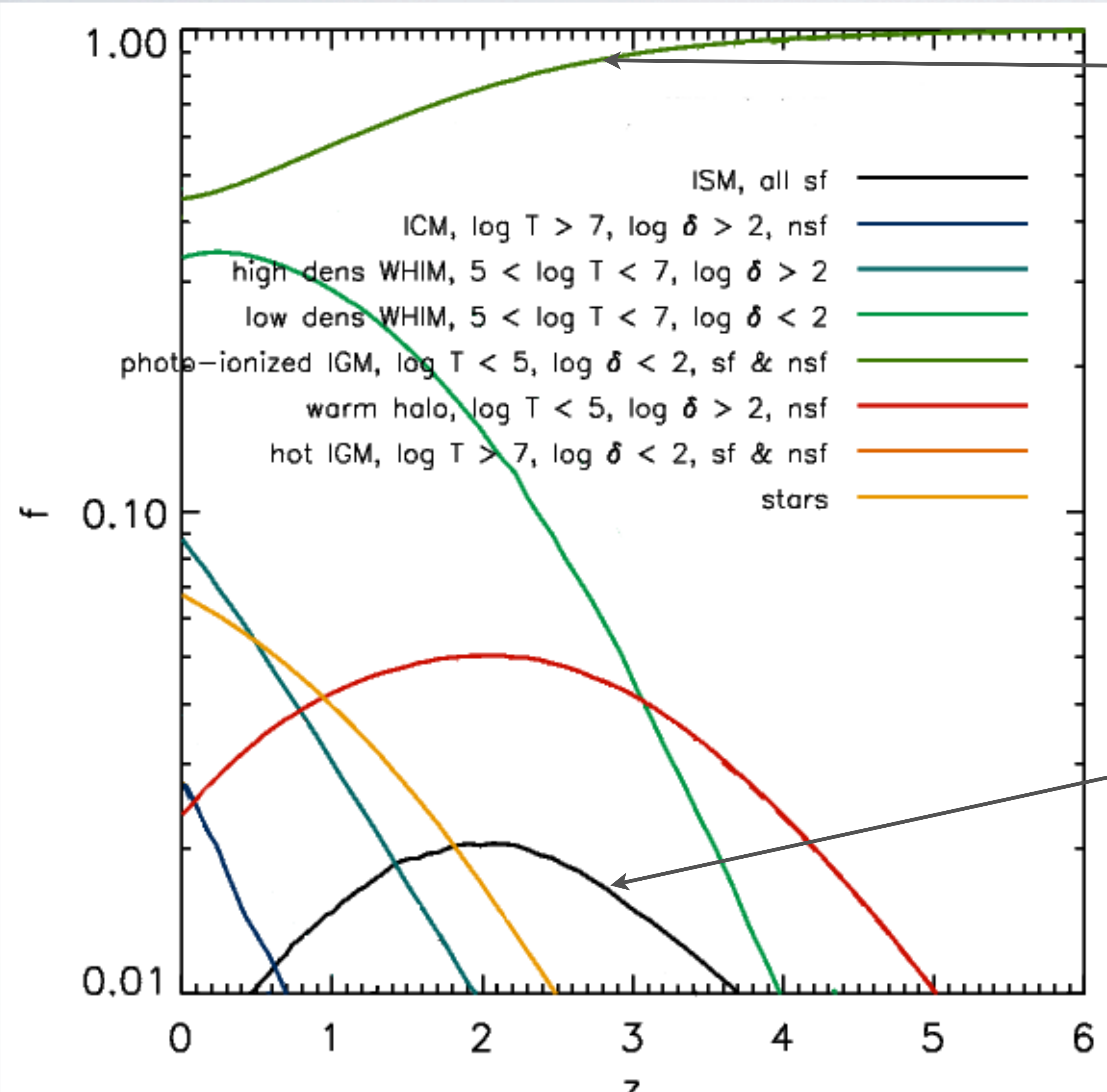


Dalla Vecchia+ (in preparation)

Most gas remains in the IGM

Persic & Salucci 1992, Fukugita et al 1998, Cen & Ostriker 1999

WHERE ARE THE BARYONS



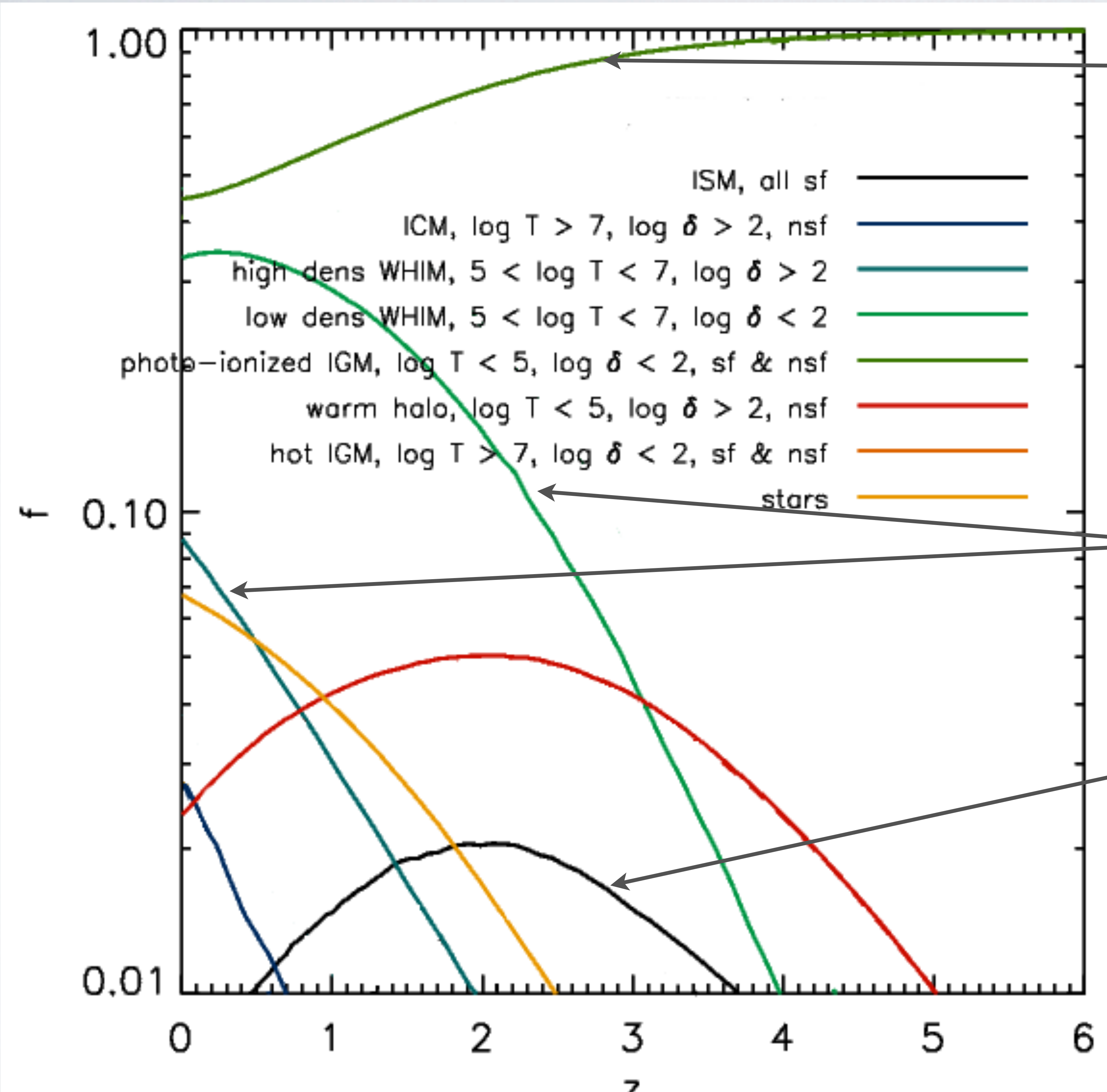
Dalla Vecchia+ (in preparation)

Most gas remains in the IGM

Persic & Salucci 1992, Fukugita et al 1998, Cen & Ostriker 1999

Only A few percent in the ISM

WHERE ARE THE BARYONS



Dalla Vecchia+ (in preparation)

Most gas remains in the IGM

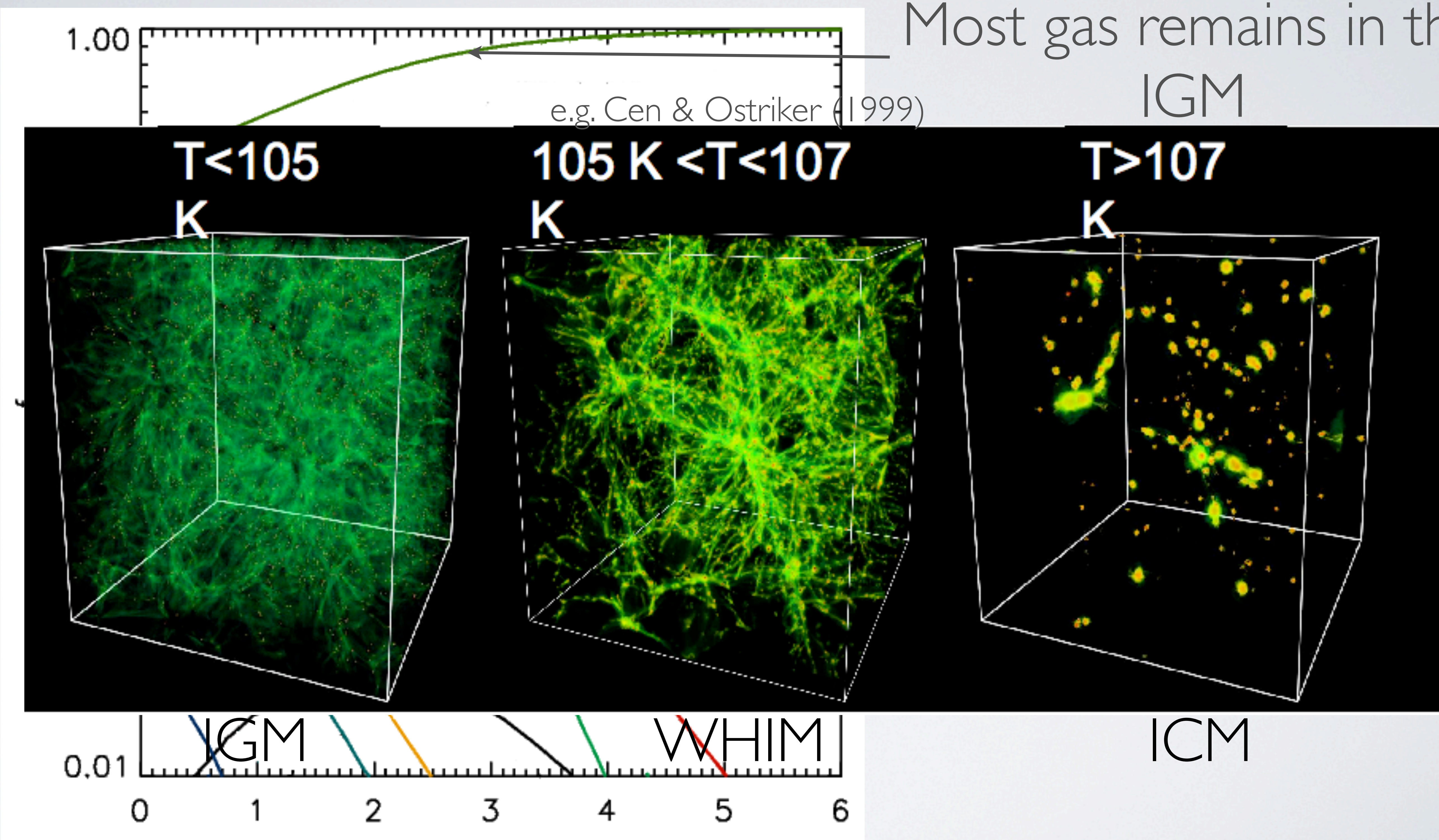
Persic & Salucci 1992, Fukugita et al 1998, Cen & Ostriker 1999

The remainder is mainly in the WHIM

Cen & Ostriker 1999

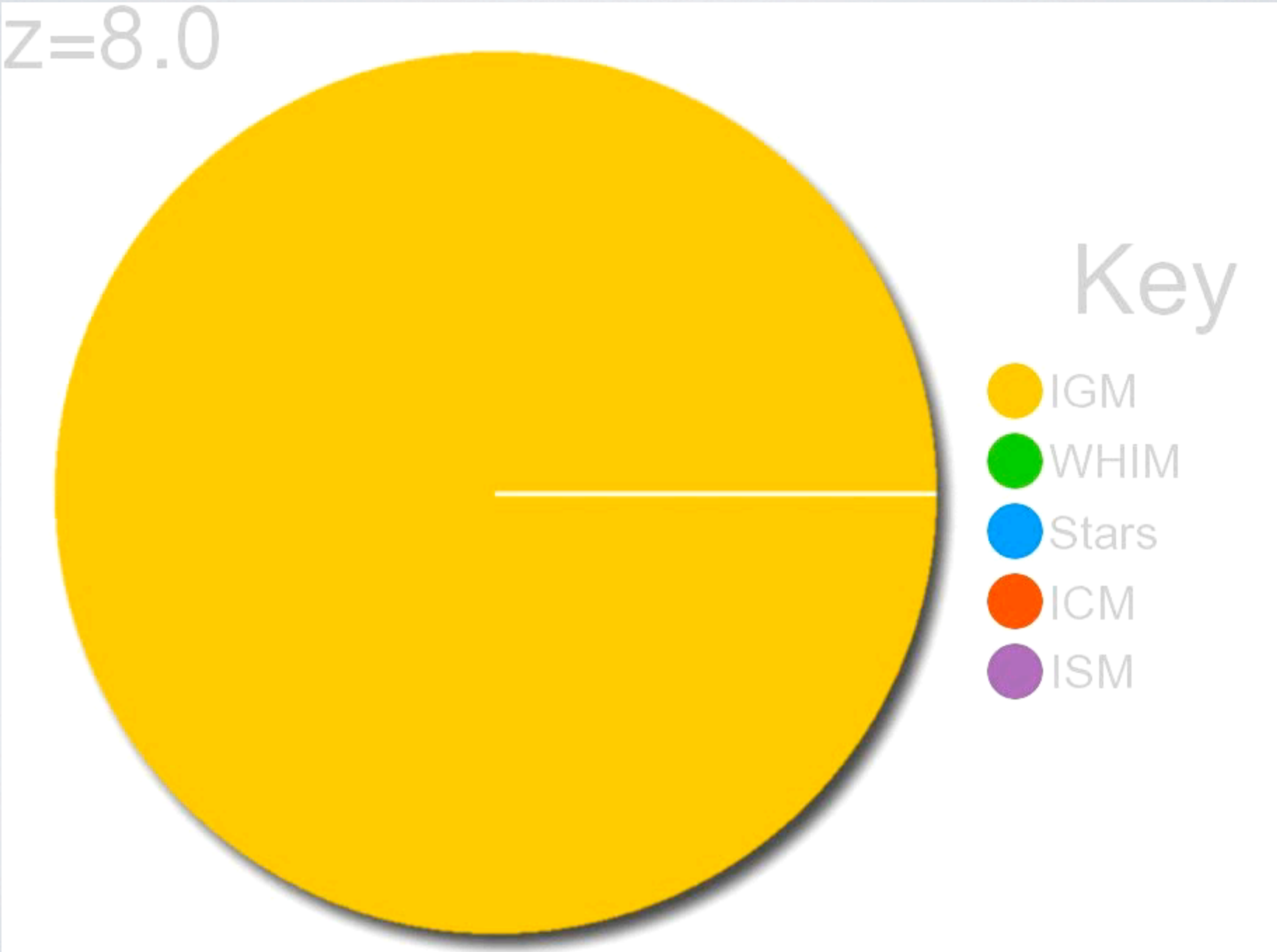
Only A few percent in the ISM

WHERE ARE THE BARYONS



Dalla Vecchia+ (in preparation)

WHERE ARE THE BARYONS



PART I

Growing galaxies: Feeding, self regulation, stars

Three numerical experiments from the OWLS simulations
What sets the masses of galaxies?

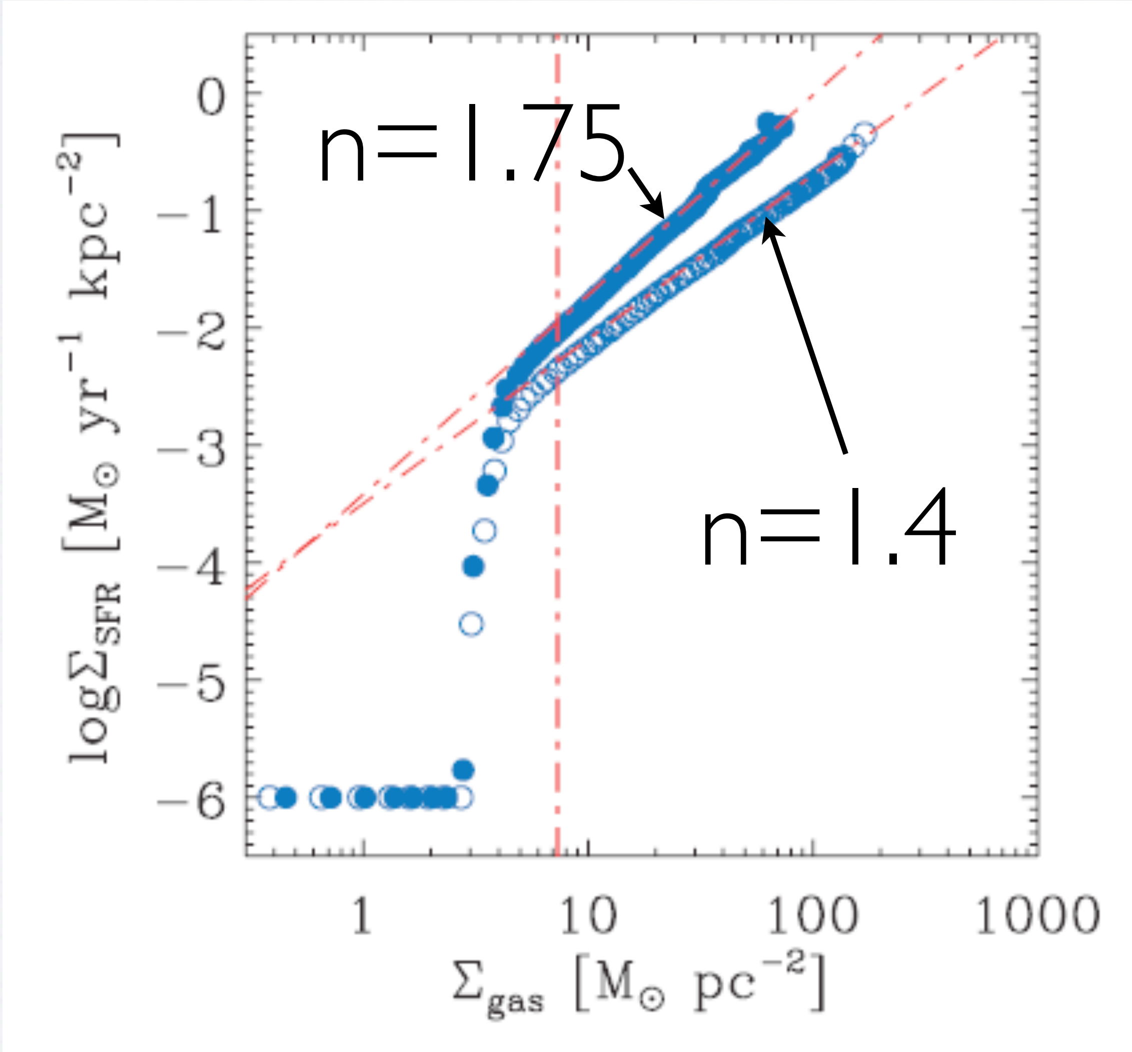
EXPERIMENT 1: CHANGE THE FORM OF THE KS LAW

Kennicutt-Schmidt Law

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm g}^n$$

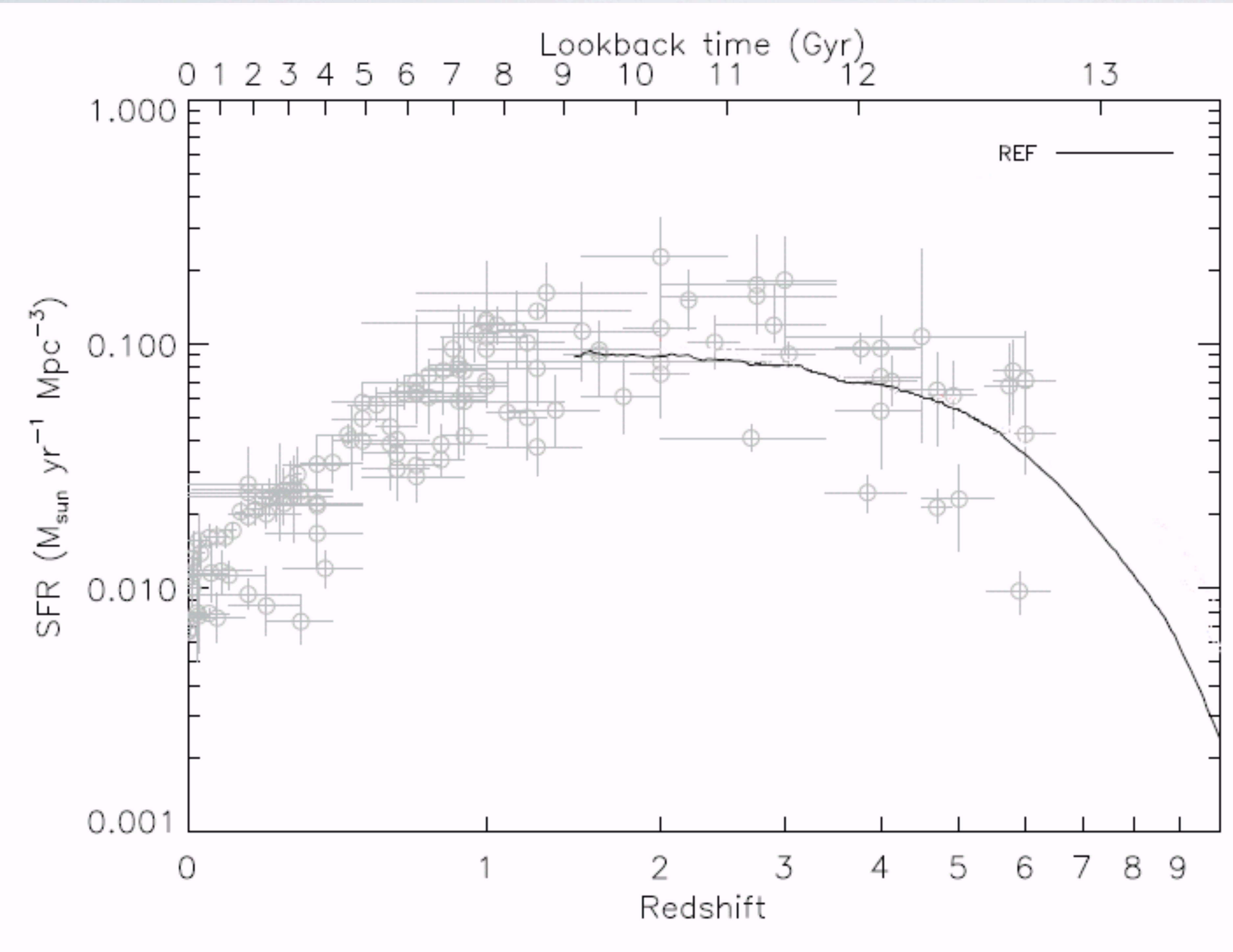
Normalization (x3, x6)

Slope (1.4->1.75)

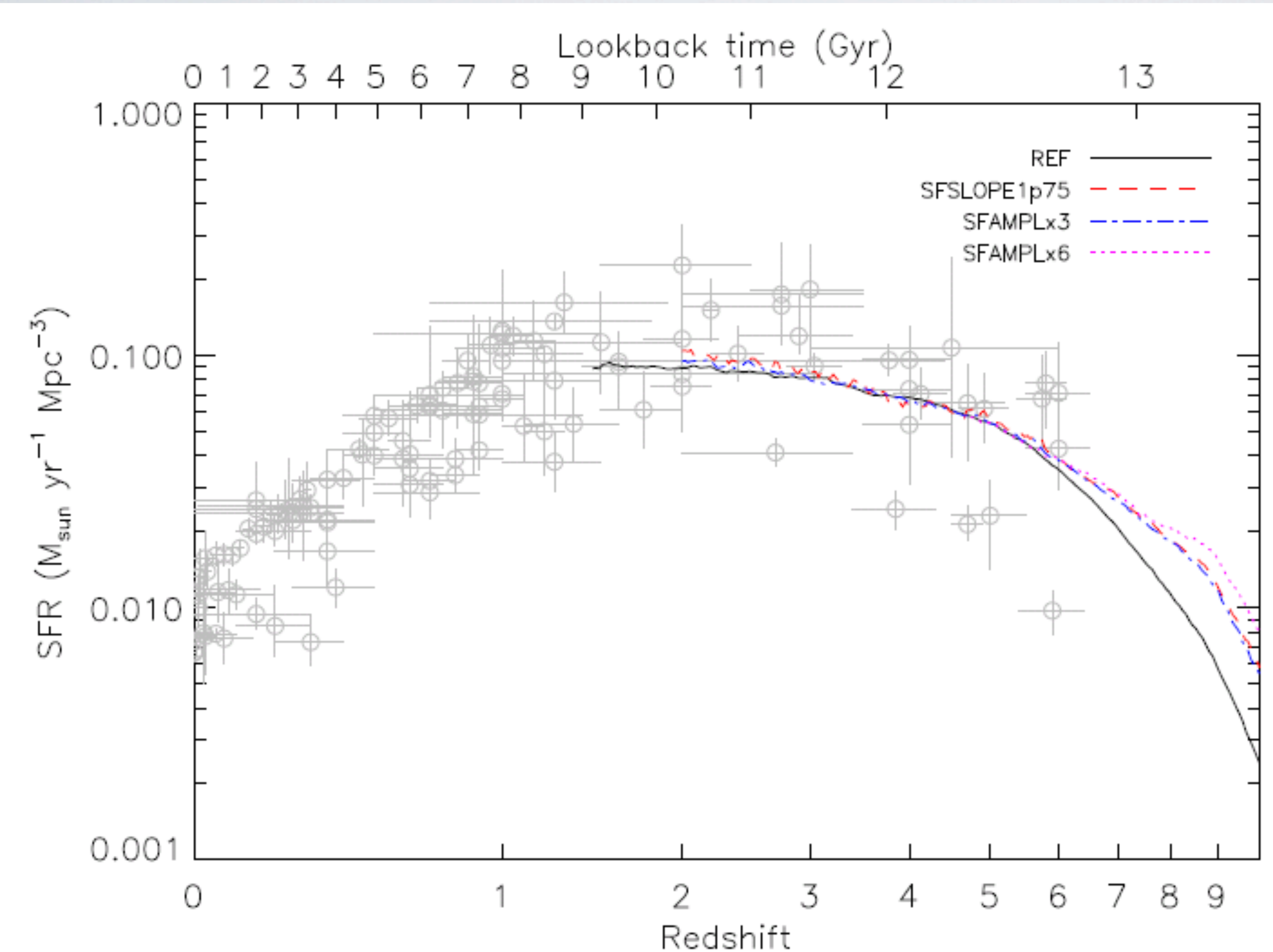


Schaye & Dalla Vecchia (2008)

EXPERIMENT 1: CHANGE THE FORM OF THE KS LAW



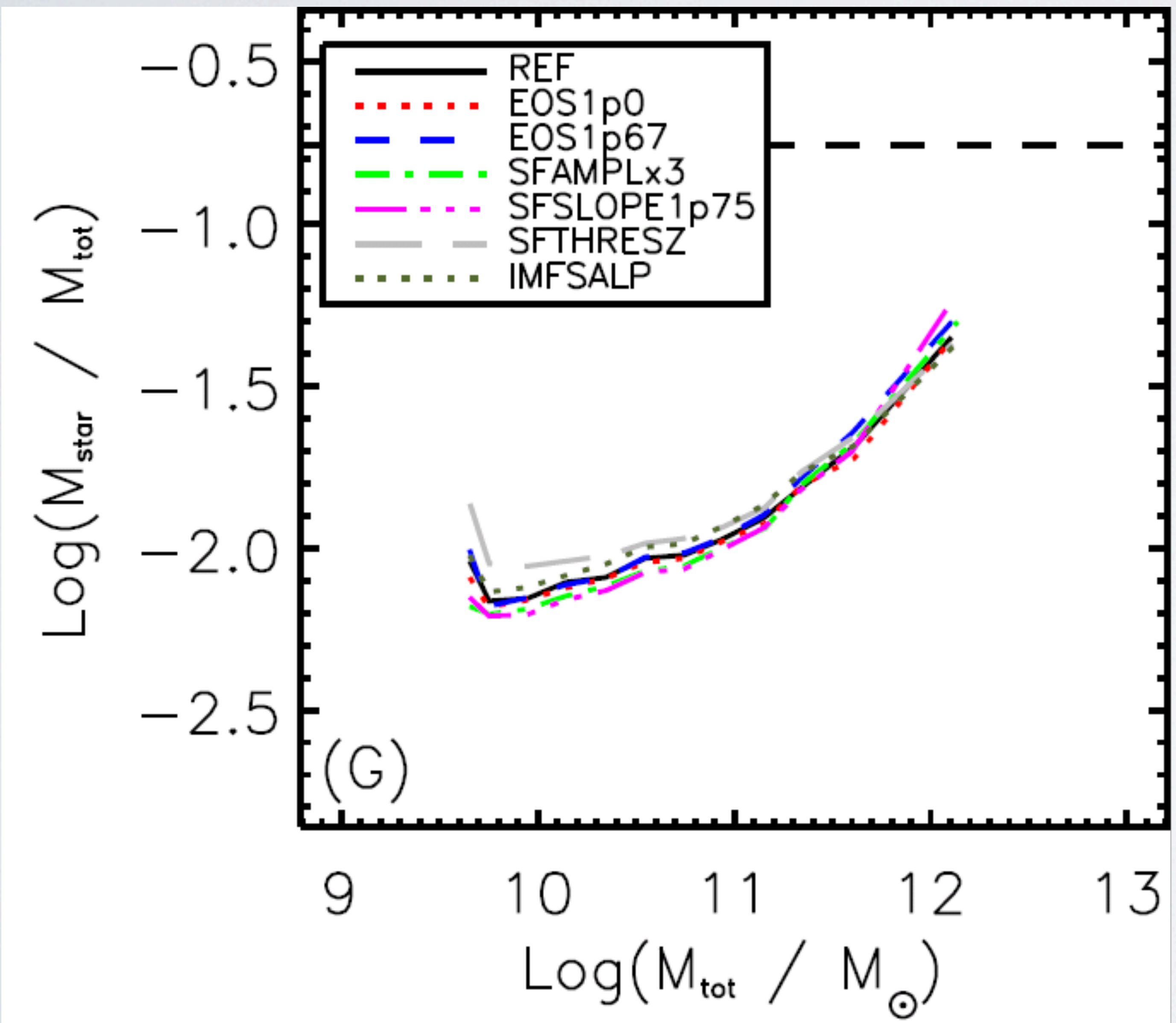
EXPERIMENT 1: CHANGE THE FORM OF THE KS LAW



Schaye et al. (incl. CMB) 2010

- No matter what you do with the star formation law (or the properties of the ISM), star formation rates do not change substantially!

EXPERIMENT 1: CHANGE THE FORM OF THE KS LAW



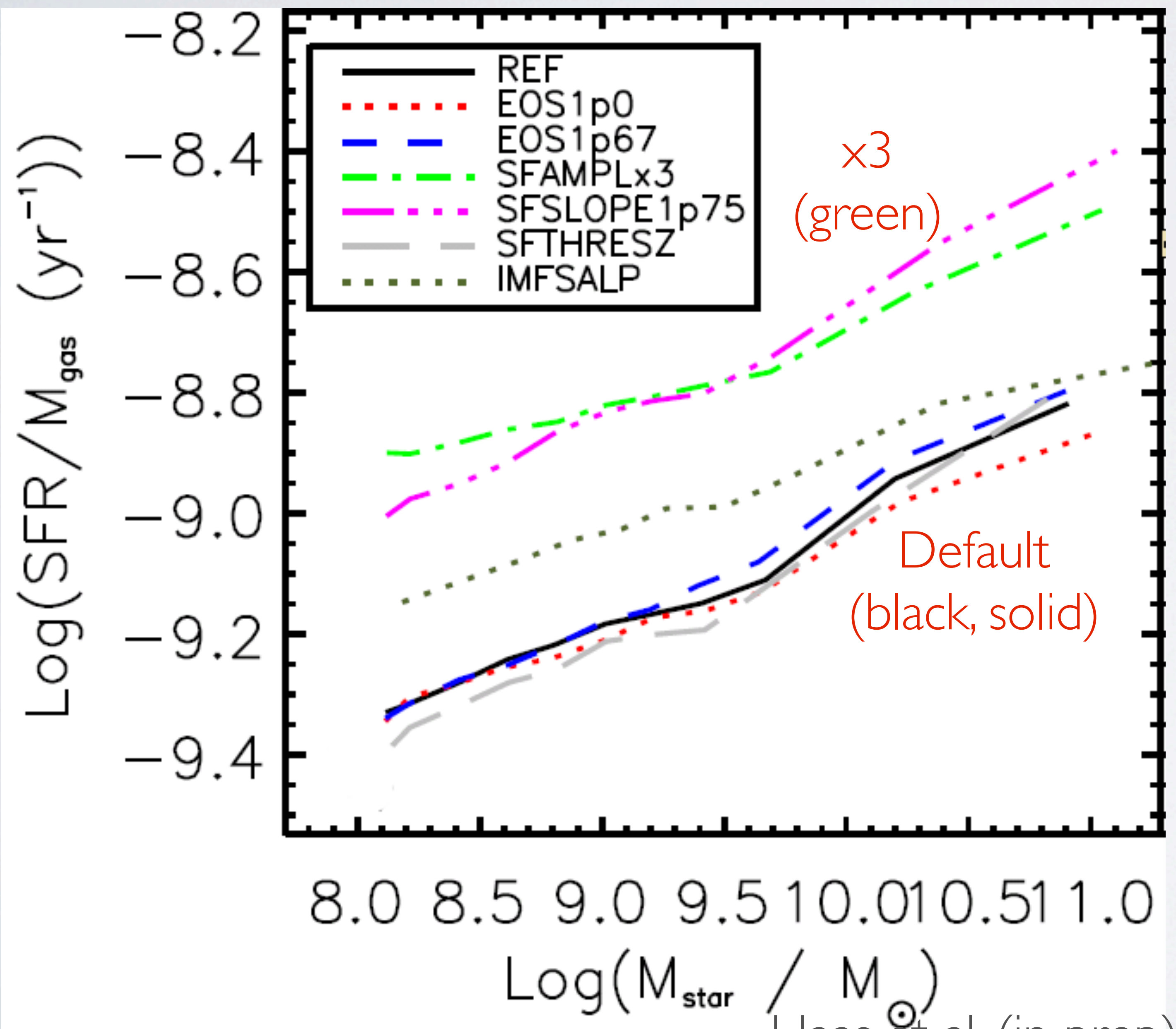
Haas et al. (in prep)

The same is true in individual haloes

Haas

EXPERIMENT I: CHANGE THE FORM OF THE KS LAW

Balance between fuelling and feedback

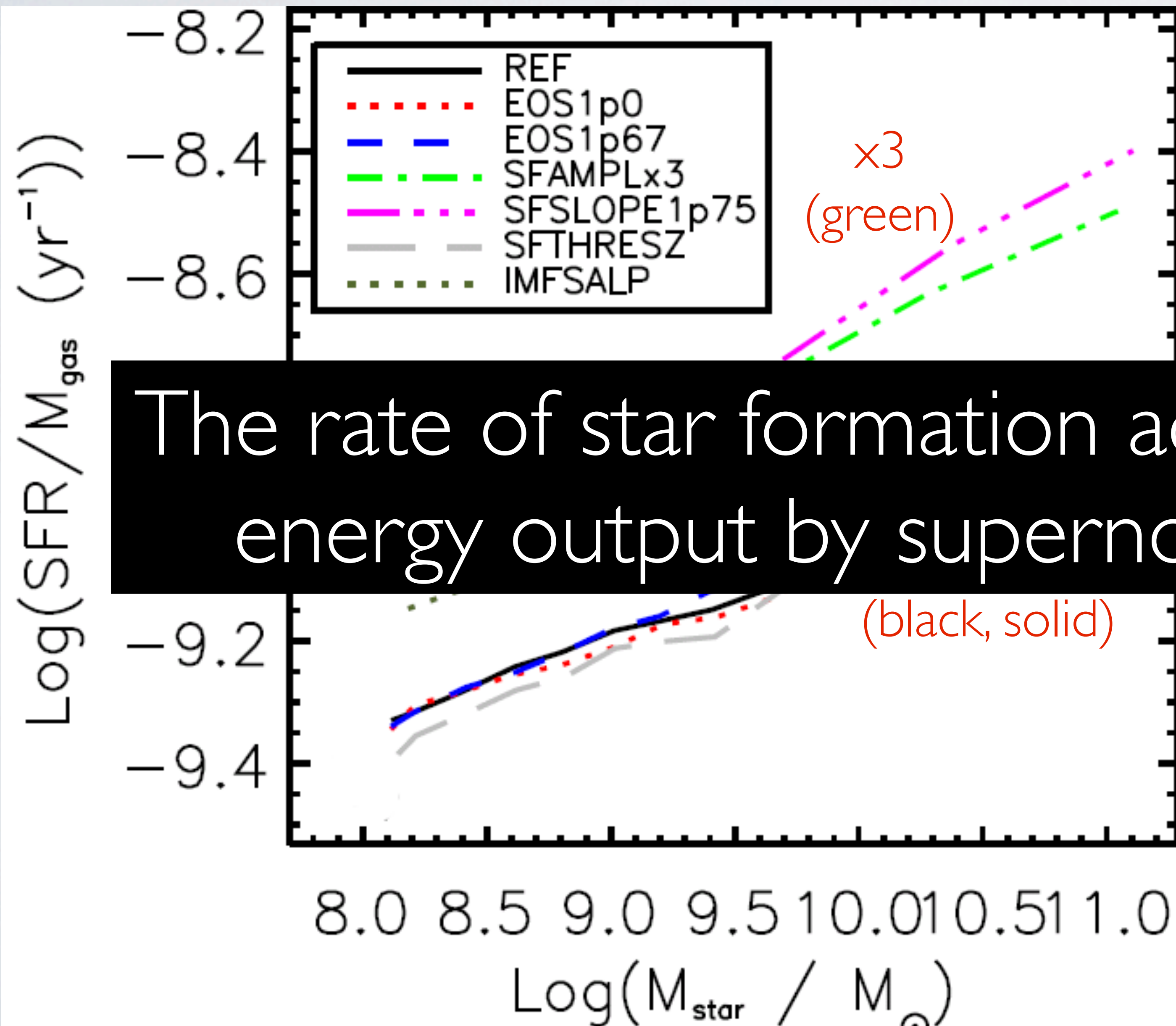


Haas et al. (in prep)

- Gas fraction adjusts to keep SFR fixed
- On large scales the SFR is independent of the SF efficiency

EXPERIMENT 1: CHANGE THE FORM OF THE KS LAW

Balance between fuelling and feedback



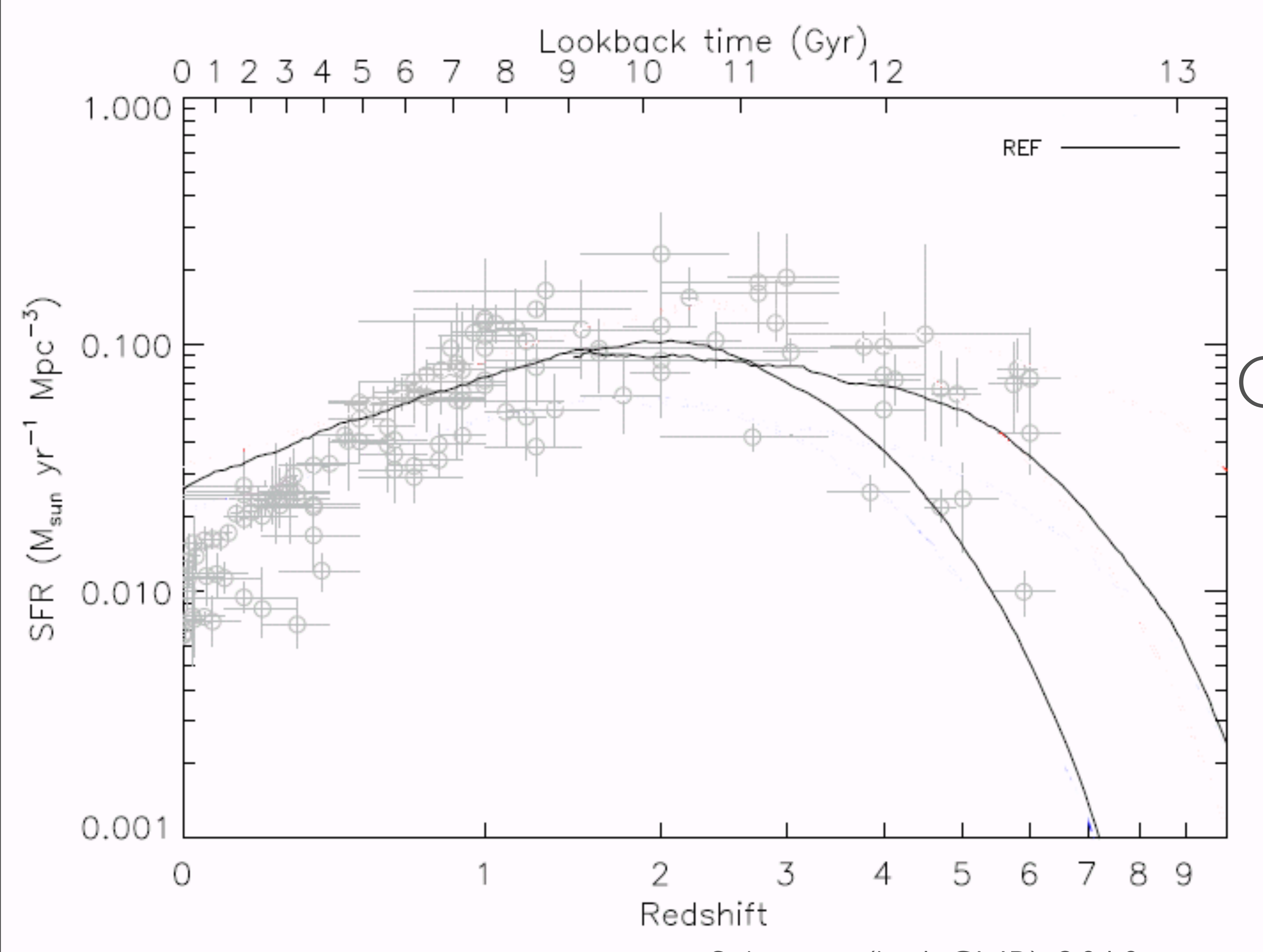
Haas et al. (in prep)

- Gas fraction adjusts to keep SFR fixed

efficiency

The rate of star formation adjusts so that the rate of energy output by supernovae remains constant

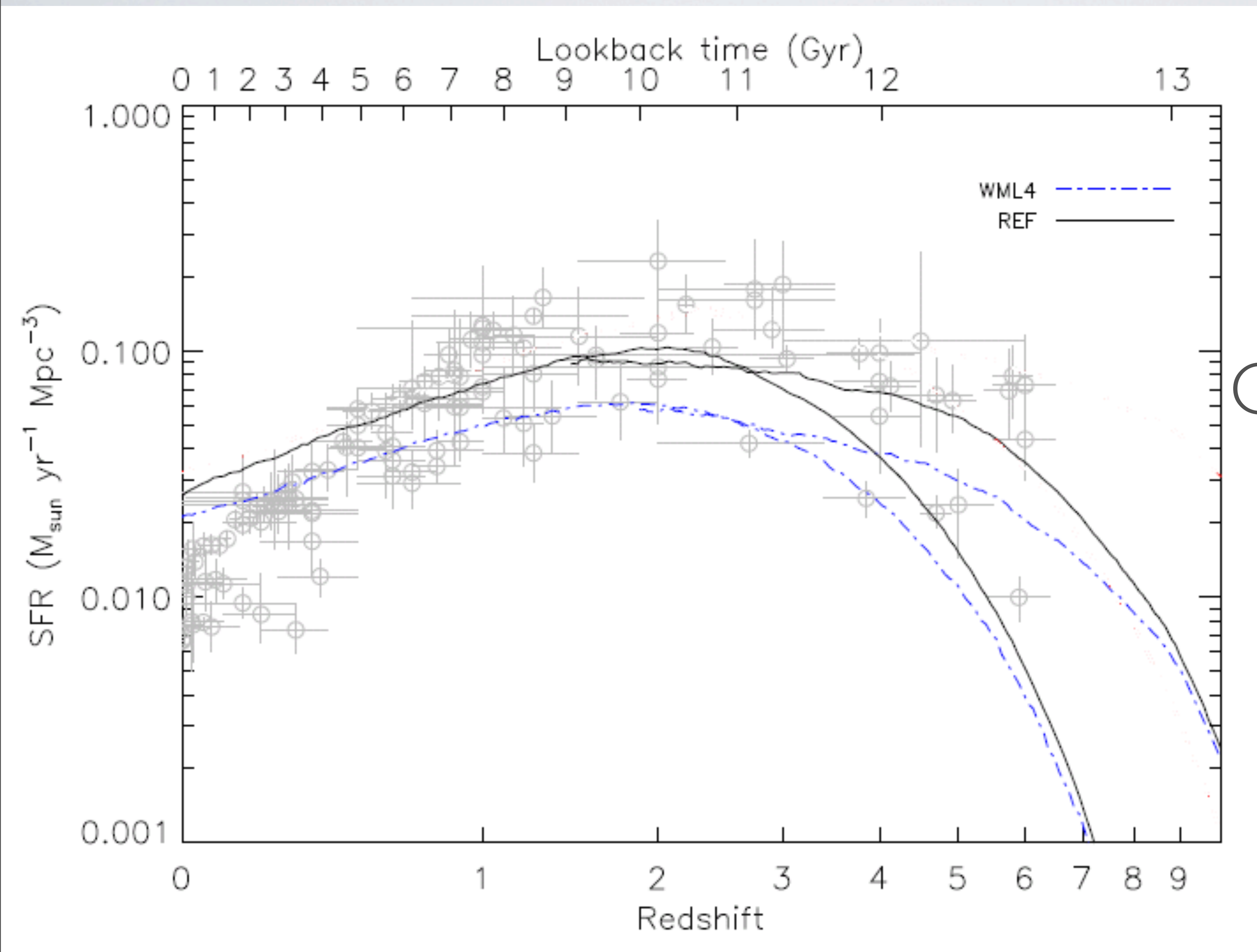
EXPERIMENT II: CHANGE THE SN ENERGY



Schaye+ (incl. CMB) 2010

Comparison against a simulation with double the SN energy

EXPERIMENT II: CHANGE THE SN ENERGY

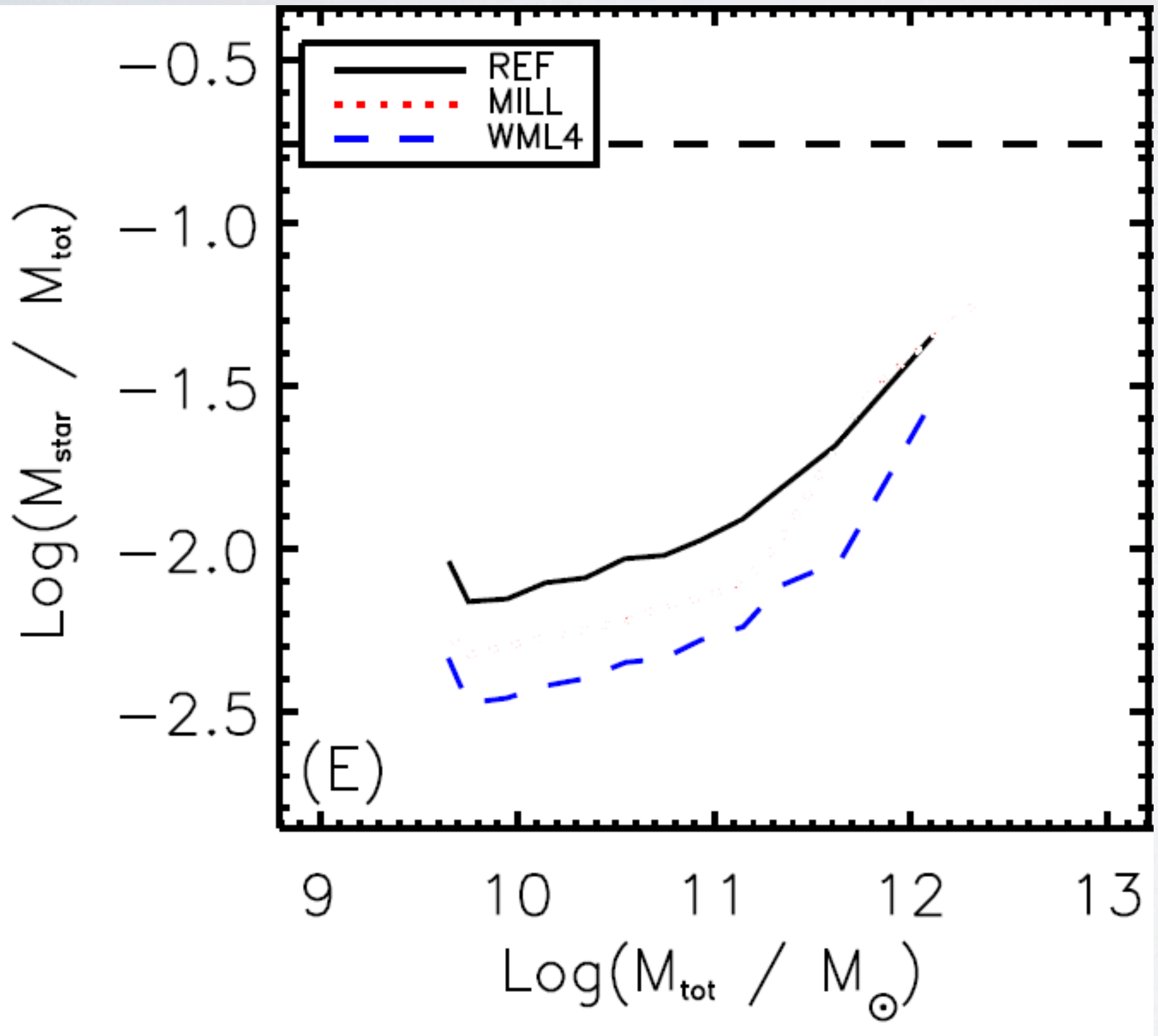


Comparison against a simulation with double the SN energy

Schaye+ (incl. CMB) 2010

EXPERIMENT II: CHANGE THE SN ENERGY

Balance between fueling and feedback



Haas+ (in prep)

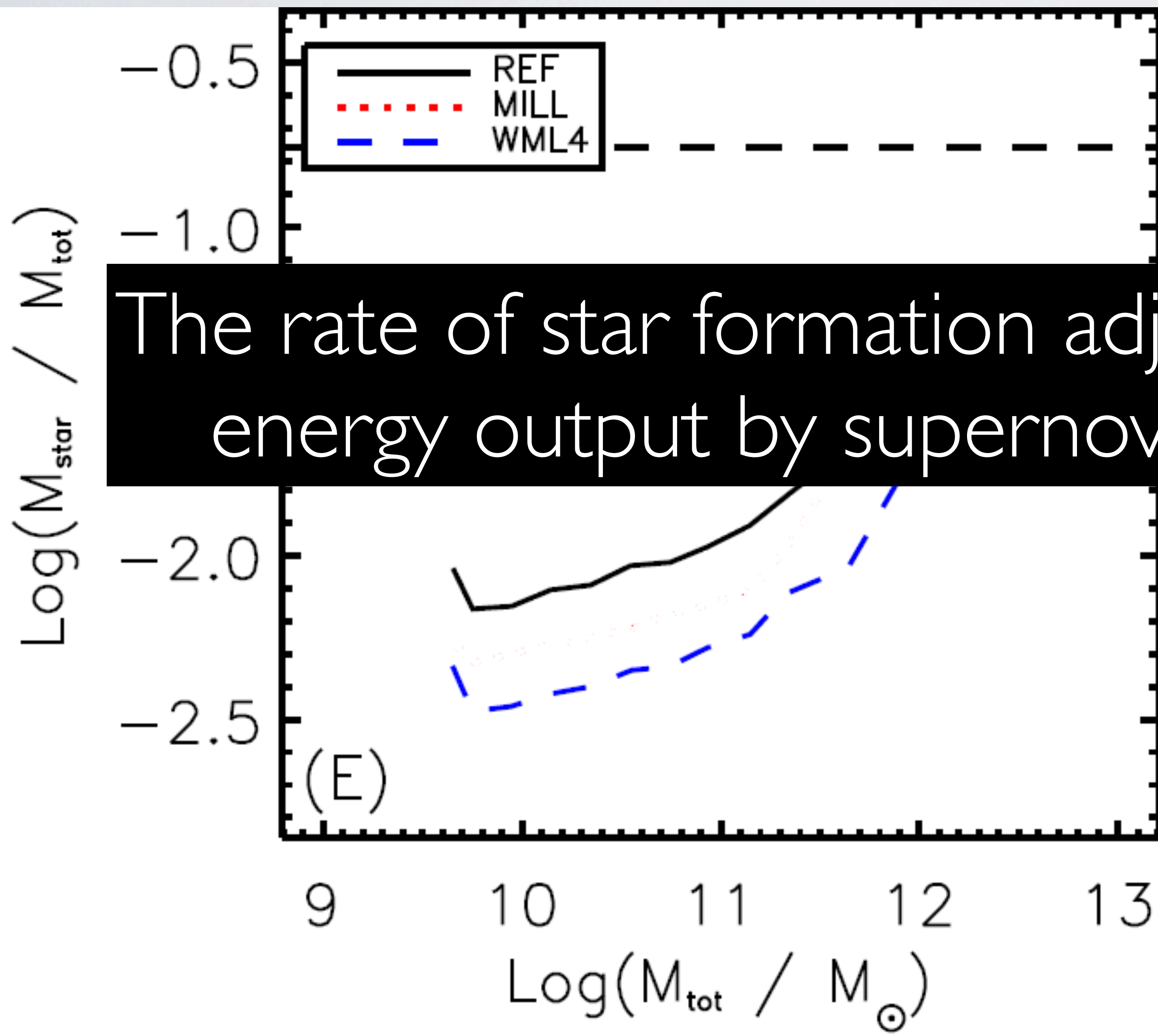
Stellar masses decreased by a factor of two

SFR adjusts to keep E_{out} fixed (through changing gas fractions)

SFR inversely proportional to SN feedback efficiency

EXPERIMENT II: CHANGE THE SN ENERGY

Balance between fueling and feedback



Haas+ (in prep)

Stellar masses decreased by a factor of two

ut

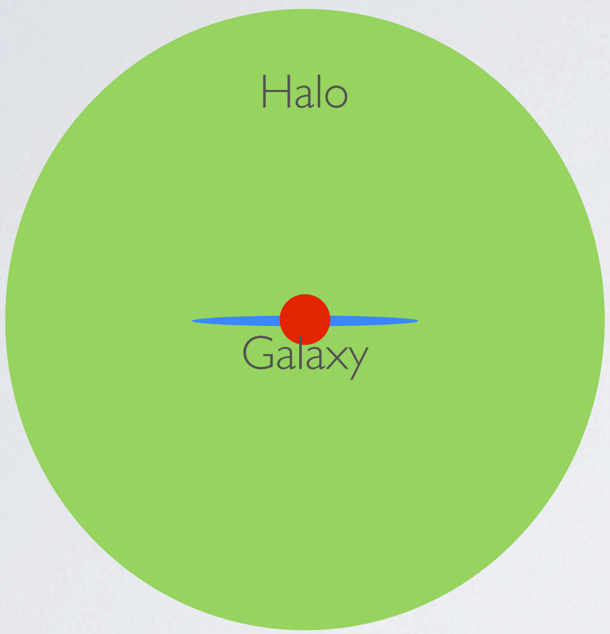
gas

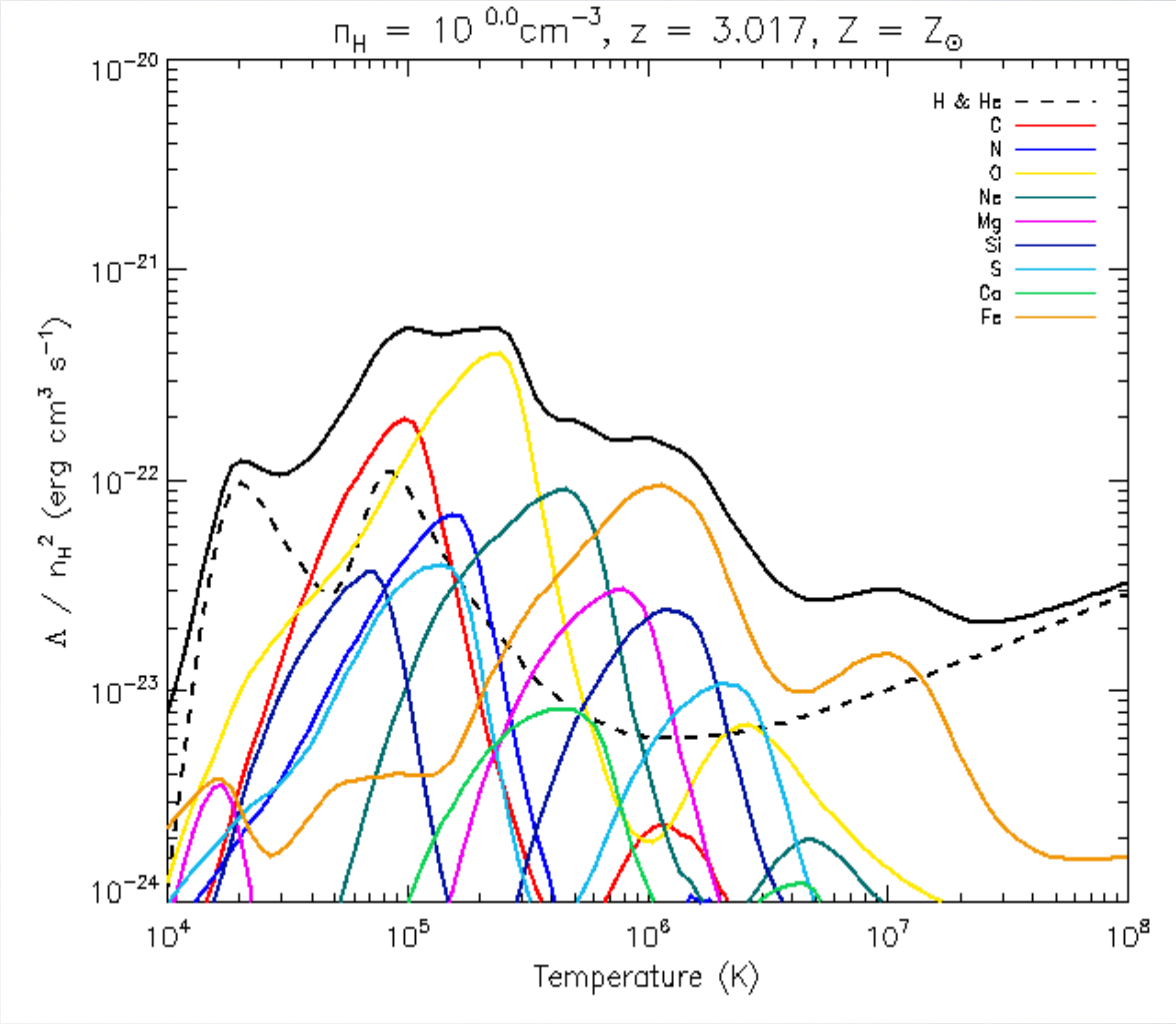
fractions)

SFR inversely proportional to SN feedback efficiency

The rate of star formation adjusts so that the rate of energy output by supernovae remains constant

AN ASIDE: RADIATIVE COOLING

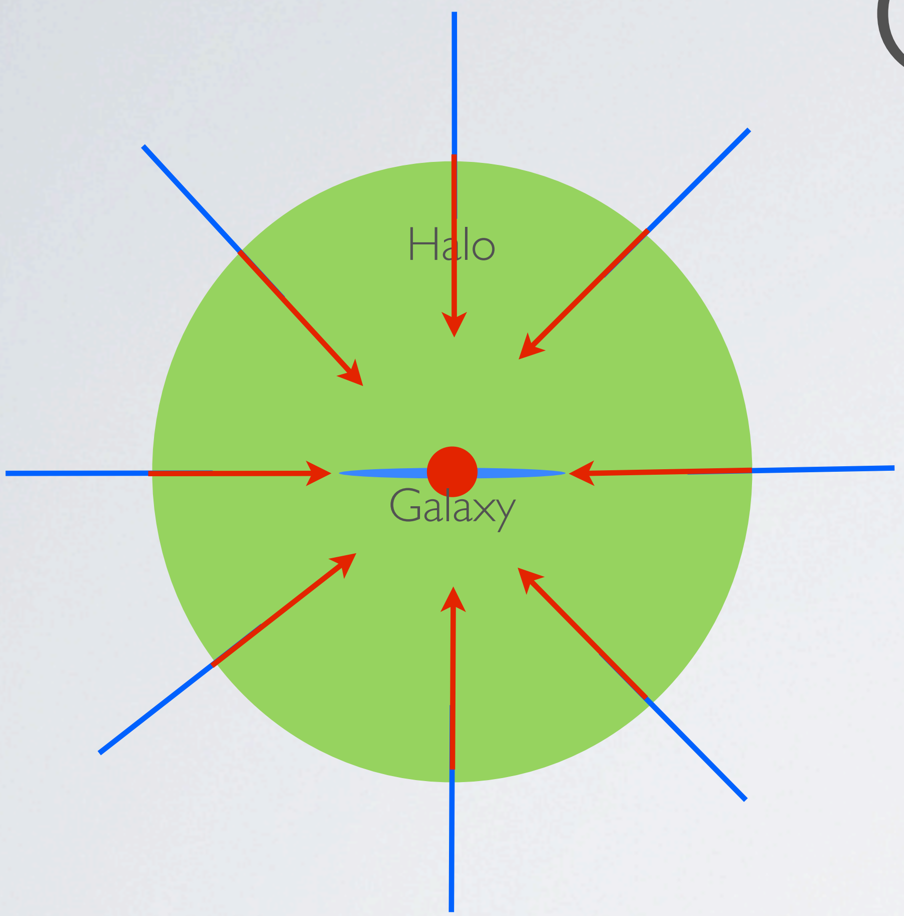


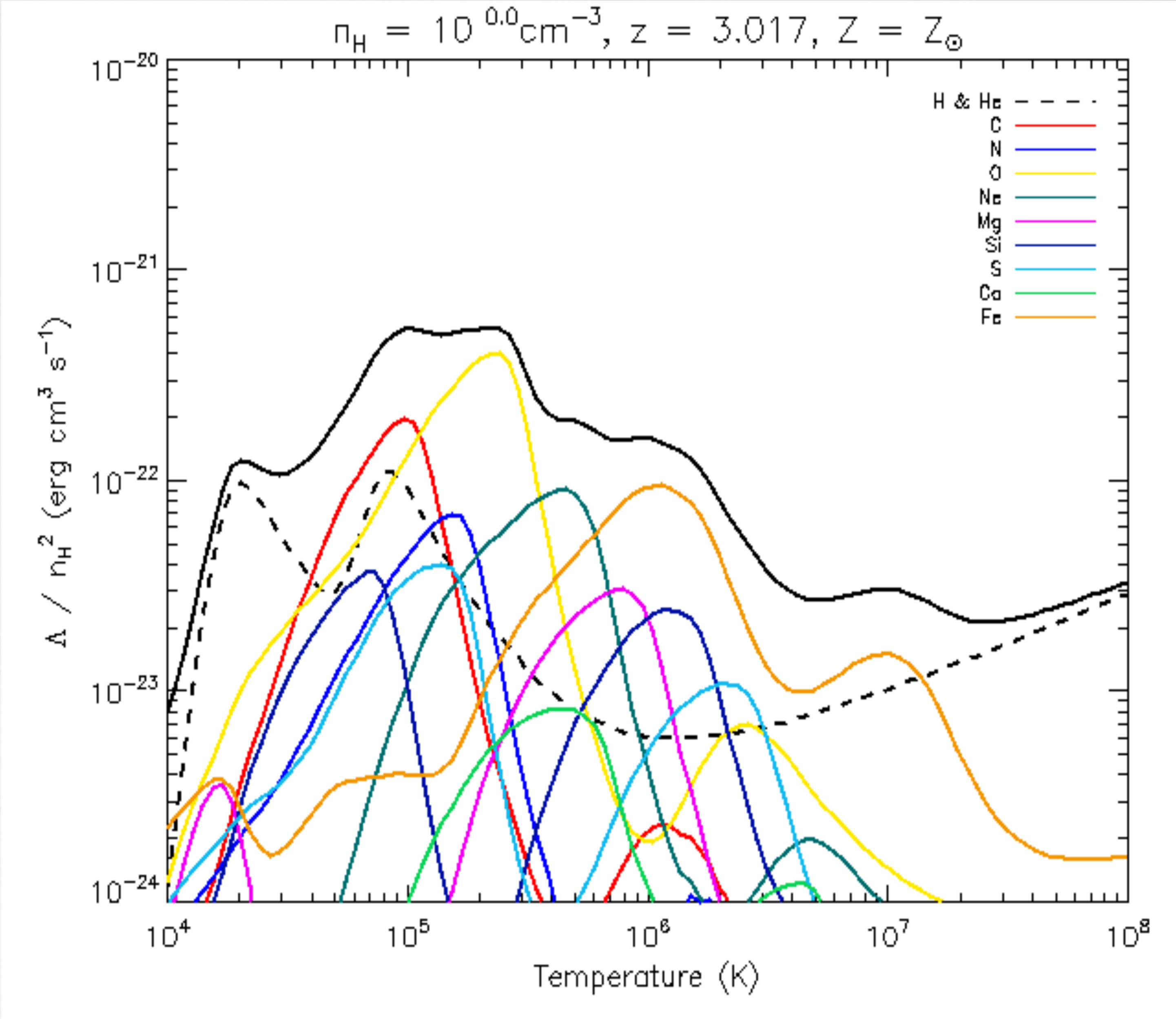


In the basic picture, gas shocks at the virial radius

Wiersma+ (2009)

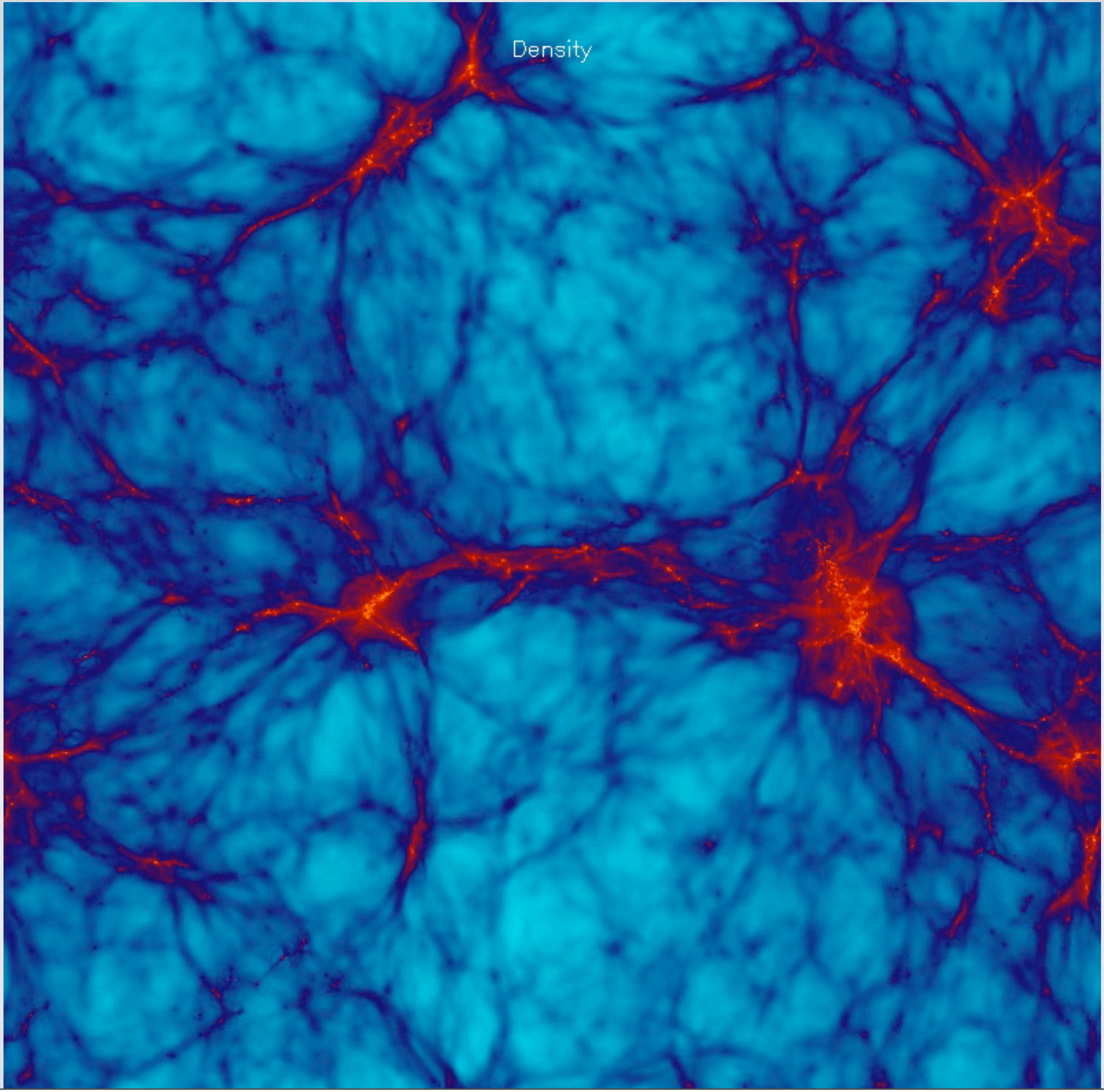
AN ASIDE: RADIATIVE COOLING

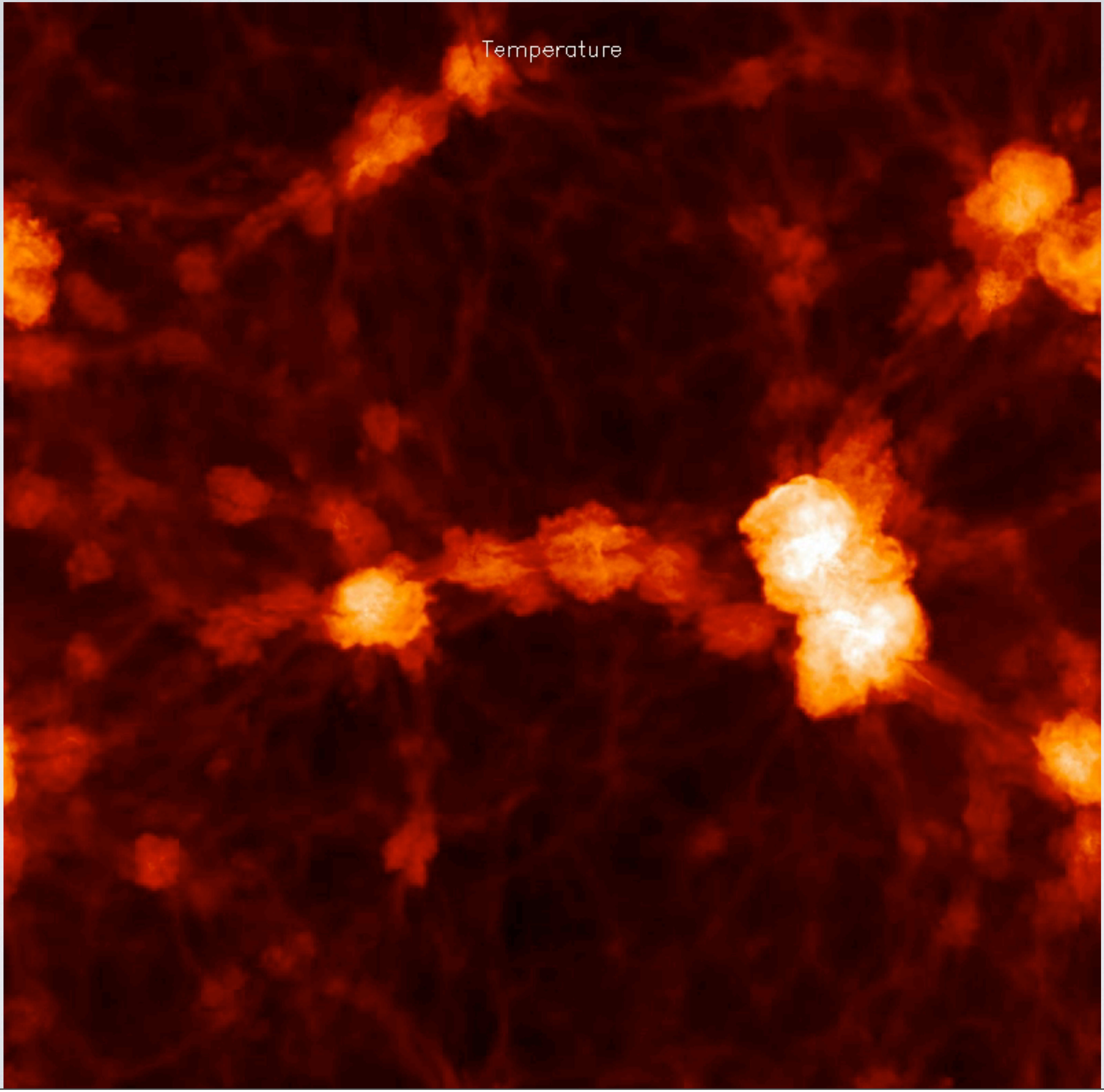




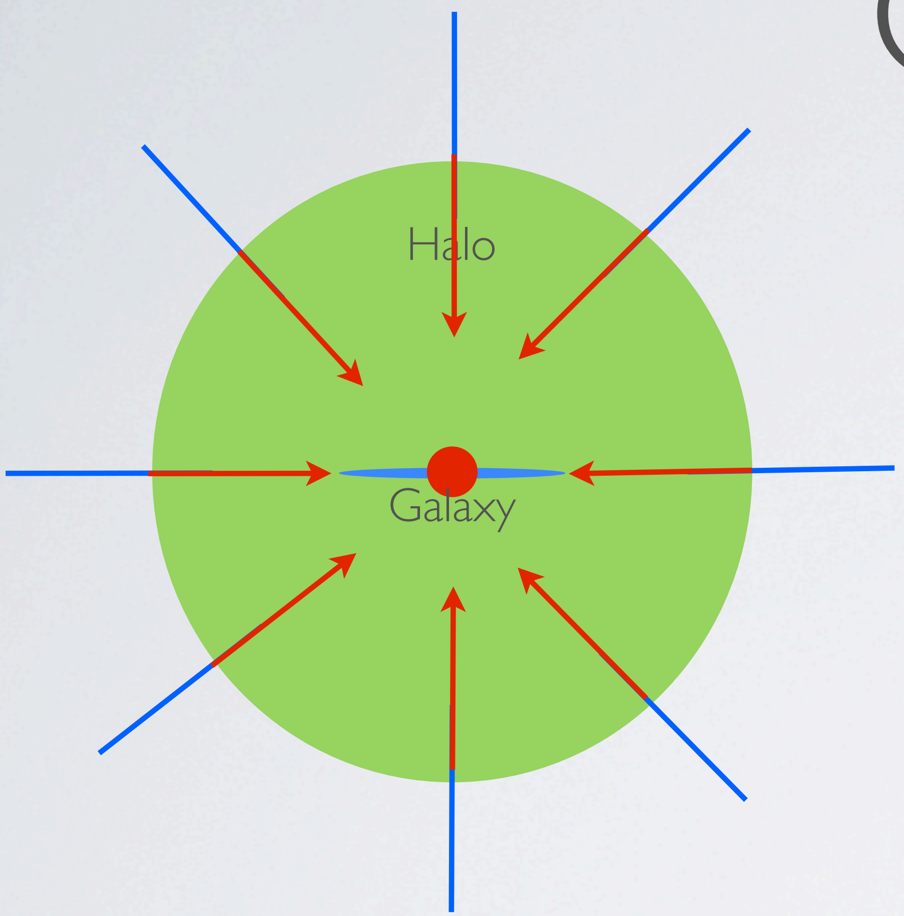
In the basic picture, gas shocks at the virial radius

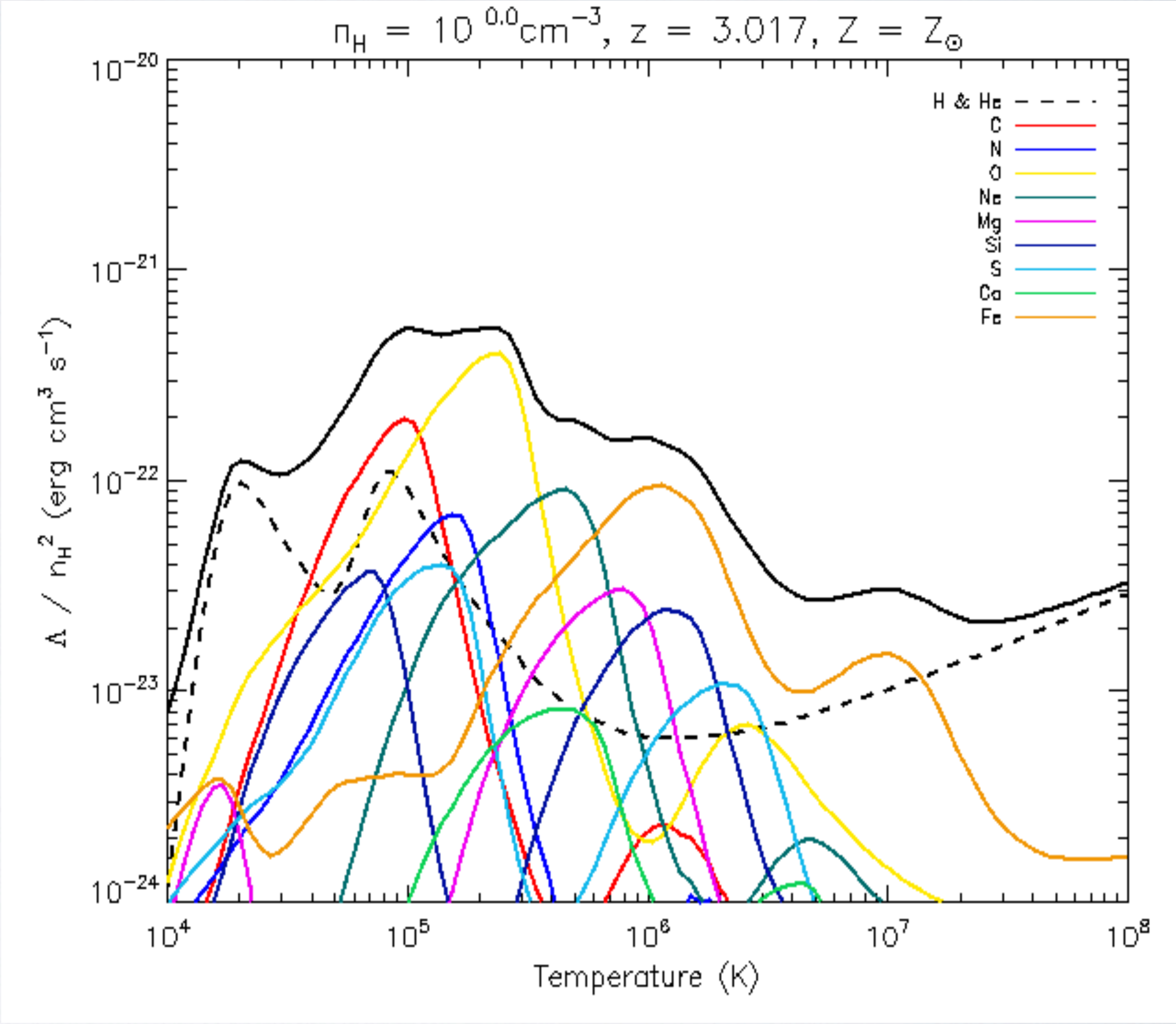
Wiersma+ (2009)


Density


Temperature

AN ASIDE: RADIATIVE COOLING



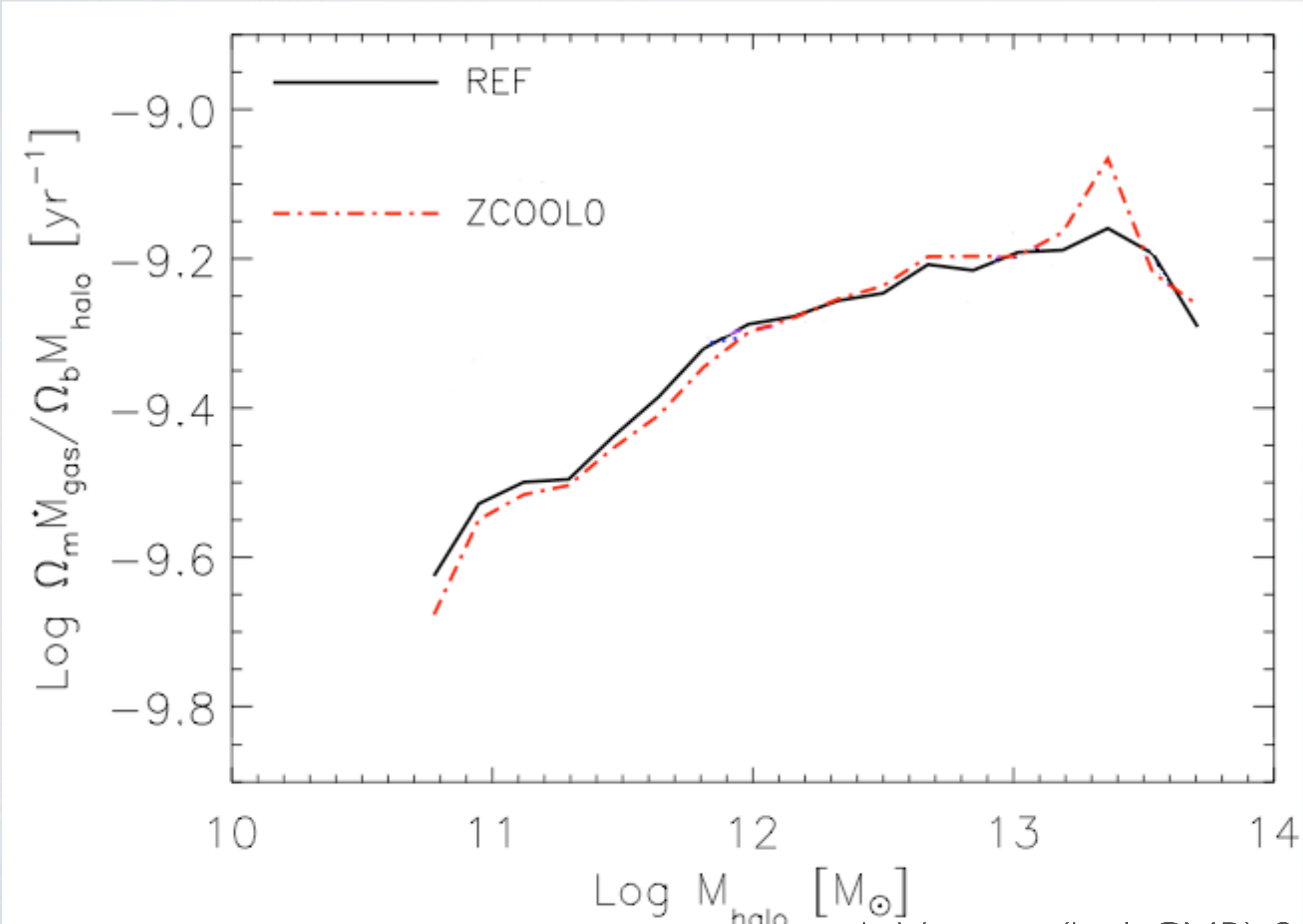


In the basic picture, gas shocks at the virial radius

Wiersma+ (2009)

EXPERIMENT III: SWITCHING OFF METAL LINES

Halo specific accretion rate at z=2

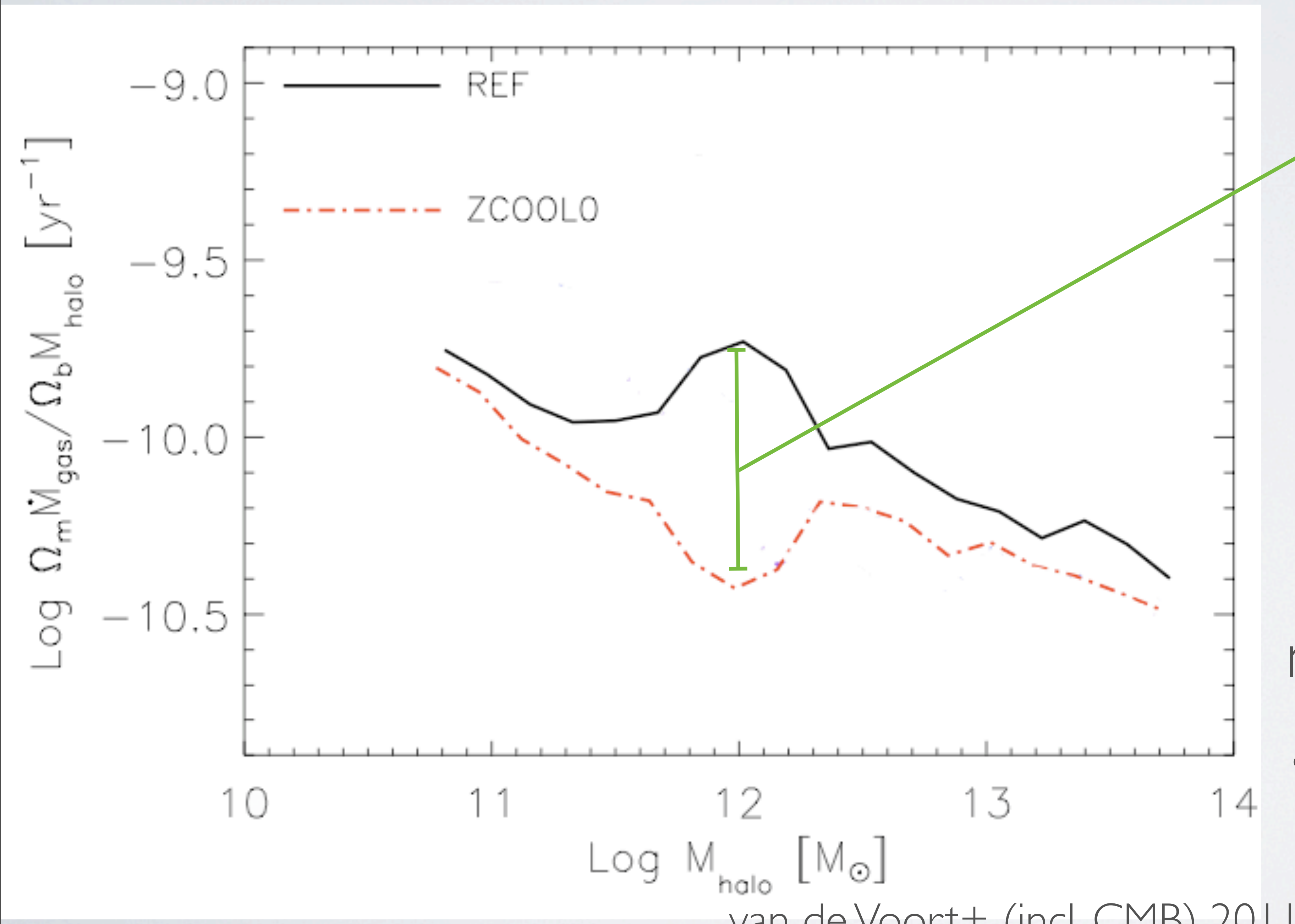


Metal cooling has no effect on accretion onto haloes

van de Voort+ (incl. CMB) 2011

EXPERIMENT III: SWITCHING OFF METAL LINES

Galaxy specific accretion rate at z=2

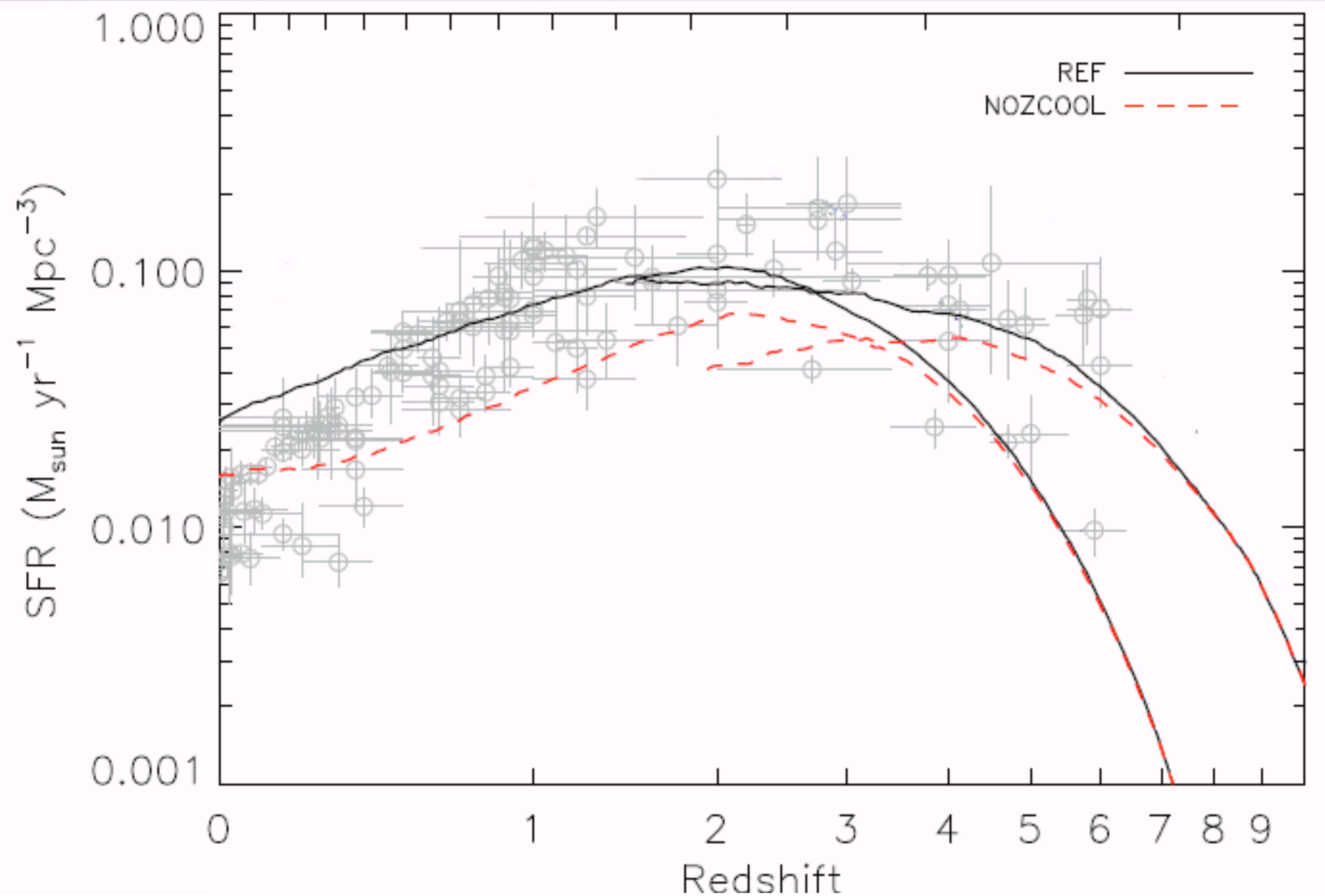


van de Voort+ (incl. CMB) 2011

Metals are the dominant coolants at virial temperatures around this mass

Switching off metal cooling
makes it harder for hot gas to get into galaxies

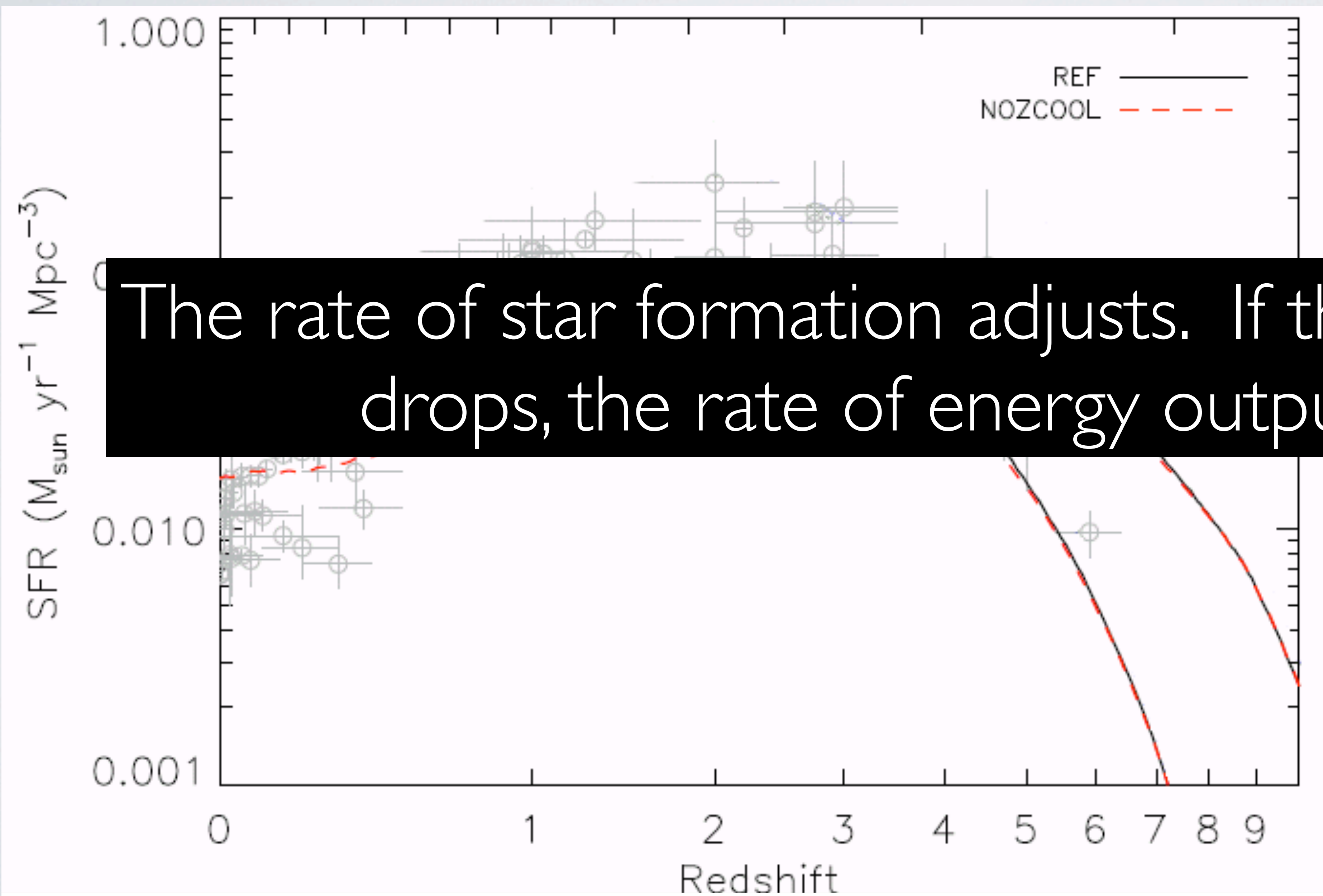
EXPERIMENT III: SWITCHING OFF METAL LINES



Schaye+ (incl. CMB) 2010

- E_{out} is lower in this case
- With less efficient galaxy fuelling a lower E_{out} is sufficient to counteract inflow

EXPERIMENT III: SWITCHING OFF METAL LINES



Schaye+ (incl. CMB) 2010

- E_{out} is lower in this case … efficient galaxy fuelling a lower E_{out} is sufficient to counteract inflow

The rate of star formation adjusts. If the fueling rate drops, the rate of energy output falls.

Monday, March 12, 12

THE STORY SO FAR...

- The SFR is tightly regulated by competition between fueling (cooling) and ejection (feedback)

1. If the SF law is changed. SFRs stay the same, but gas fractions adjust to keep the energy output rate constant

2. If the feedback implementation is changed. SFRs adjust to keep the energy output rate constant

3. If the fueling rate changes then the SFR adjusts to reflect this

- Considering something different can give us insight into what scales self-regulation takes place.
- Let’s consider the AGN population...

CMB & Schaye (2009)
CMB & Schaye (2010)
CMB & Schaye (2011)

THE STORY SO FAR...

- The SFR is tightly regulated by competition between fueling (cooling) and ejection (feedback)

1. If the SF law is changed. SFRs stay the same, but gas

If the fueling rate remains the same
the feedback energy output rate remains the same

2. If the feedback implementation is changed. SFRs adjust to keep the energy output rate constant

If the fueling rate changes,
the feedback energy output rate adjusts accordingly

- Considering something different can give us insight into what scales self-regulation takes place.

- Let's consider the AGN population...

CMB & Schaye (2009)
CMB & Schaye (2010)
CMB & Schaye (2011)

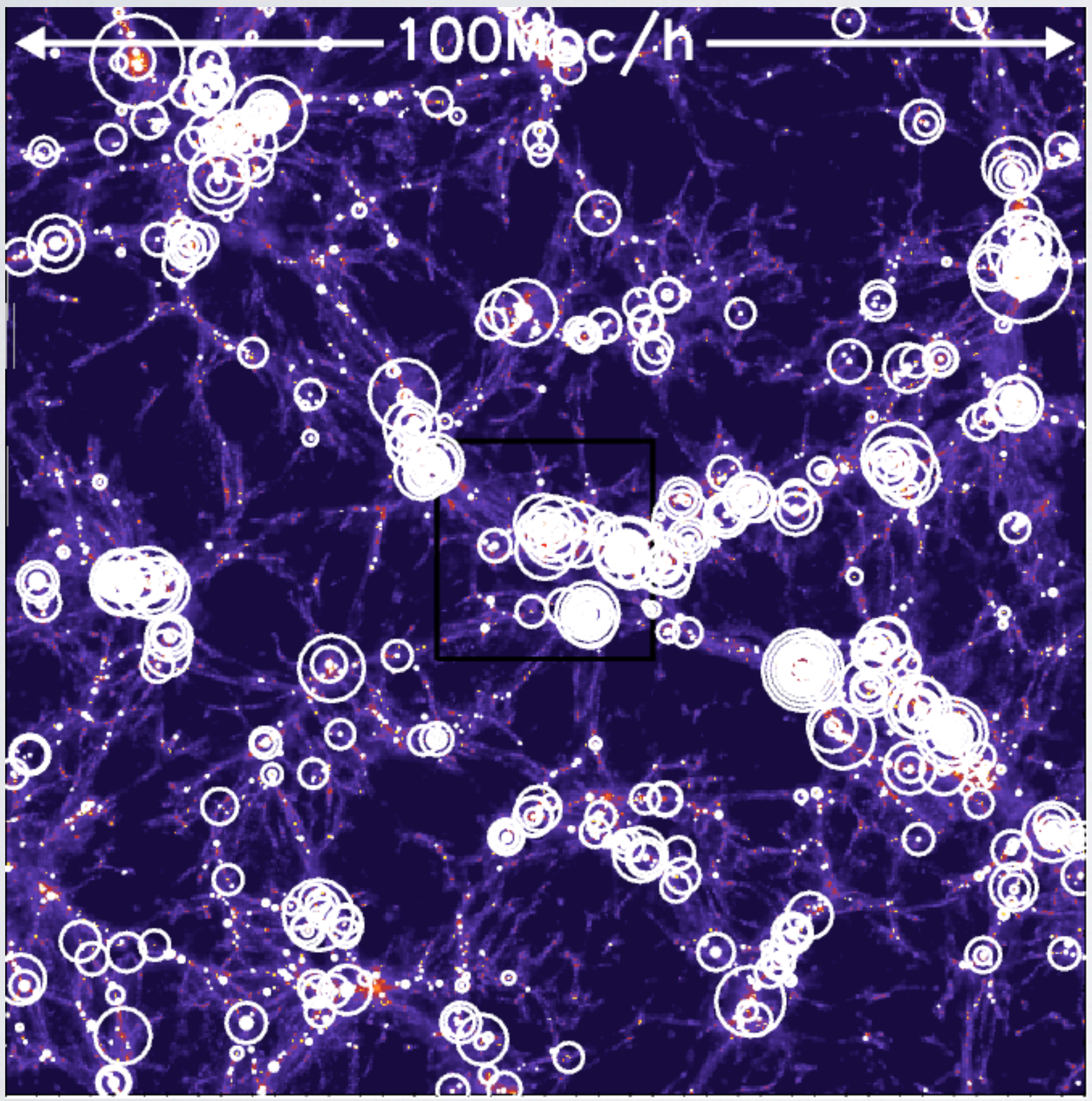
PART II

What sets the masses of supermassive black holes?

WHY AGN

Virtually all galaxies contain BHs

e.g. Magorrian et al. 1998



CMB & Schaye (2009a)

BHs get most of their mass through luminous accretion

Soltan 1982

Various theoretical studies indicate that this energy source is cosmologically important

Silk & Rees 1998, Springel et al. 2005; Bower et al. 2006; Somerville et al. 2008

I. AGN MODEL

Variant on Springel et al. 2005, Di Matteo et al. 2008

The model is simple and consists of three processes...

- Black hole formation

→ m_{seed} $m_{halo,crit}$

- Black hole growth (mergers and gas accretion)

→ β

- AGN feedback

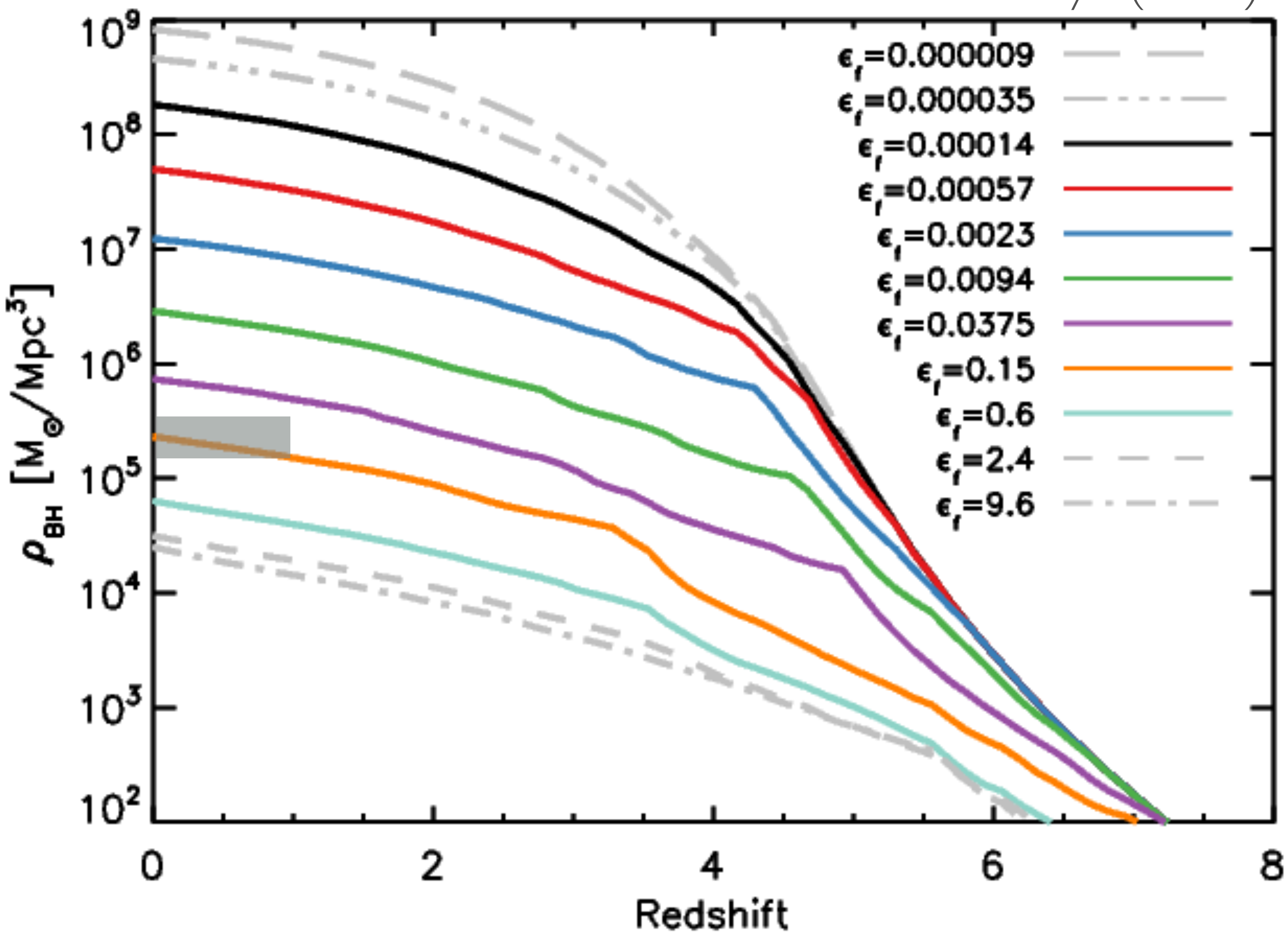
$$E_{\rm feed} = \epsilon_{\rm f}\epsilon_{\rm r}\dot{m}_{\rm BH}c^2\Delta t$$

→ ε_f

Feedback efficiency is the major factor that controls the masses of BHs

2. AGN MODEL

Booth & Schaye (2010)



Observations: Shankar et al. (2004)

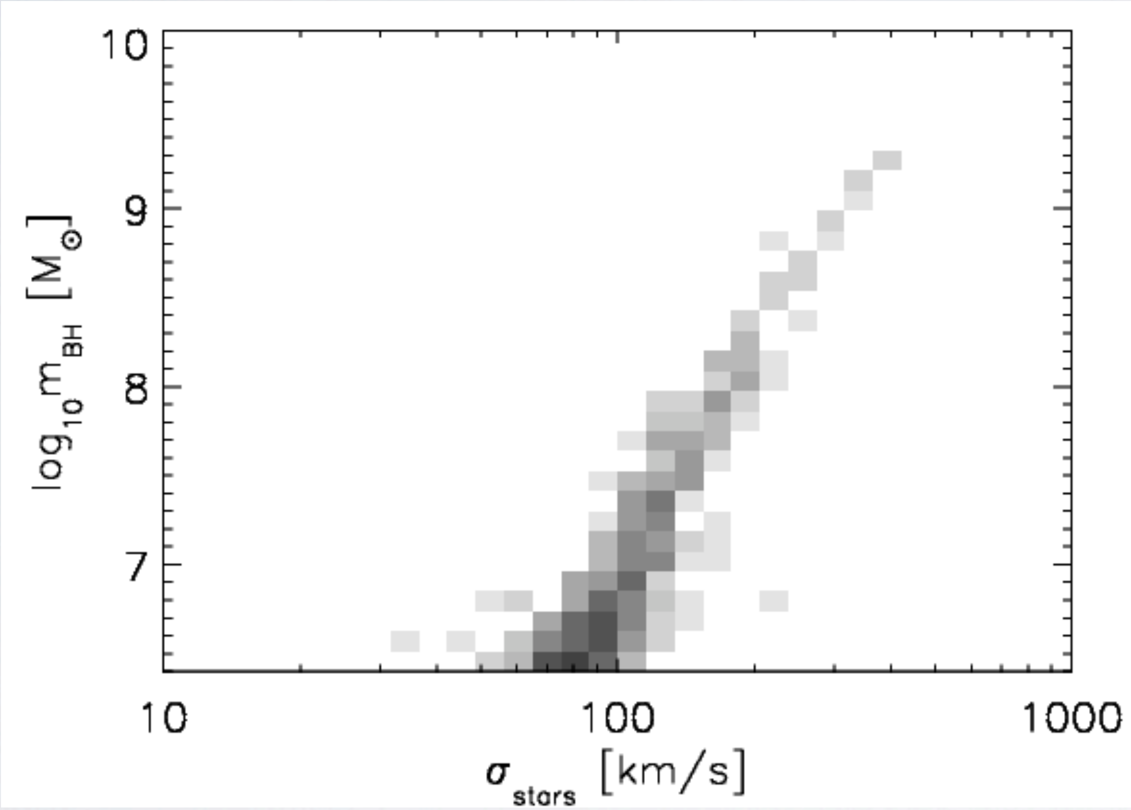
- The free parameter ϵ_f controls the total mass in BHs
- 0.15 reproduces observations.

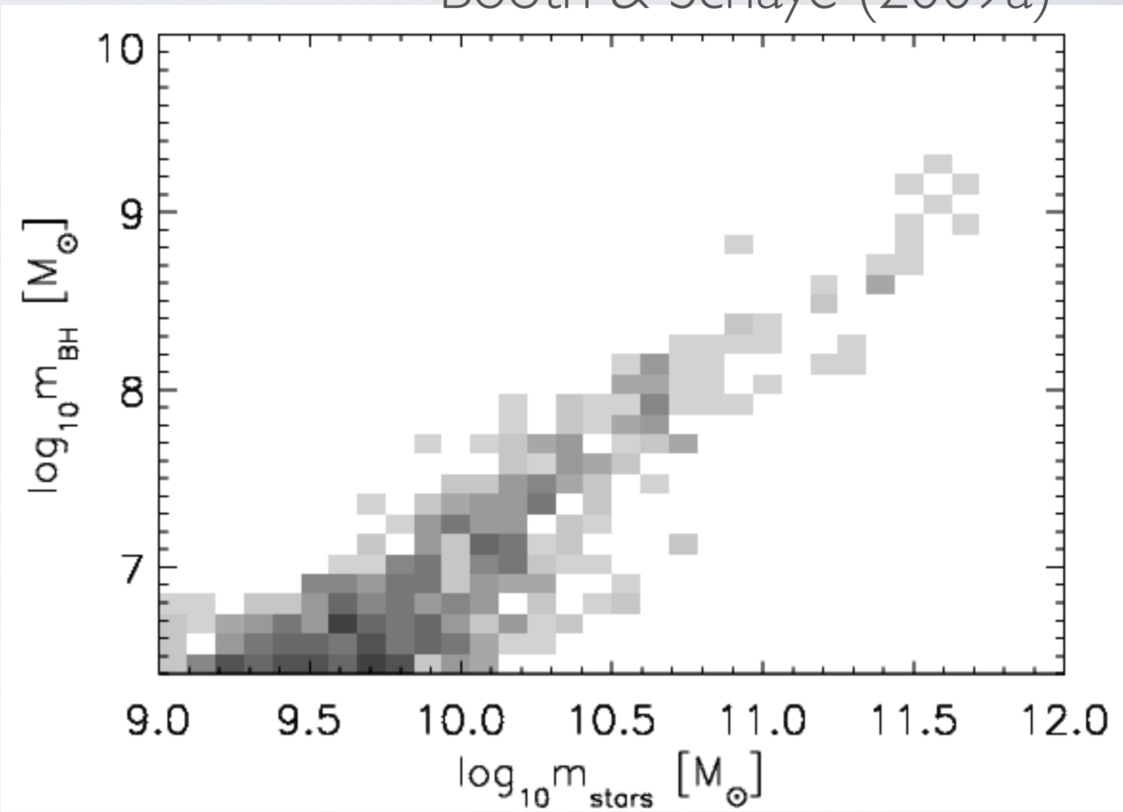
$$E_{\mathrm{feed}} = \epsilon_{\mathrm{f}} \epsilon_{\mathrm{r}} \dot{m}_{\mathrm{BH}} c^2 \Delta t$$

So what does this simple model predict?

3. BH SCALING RELATIONS

Booth & Schaye (2009a)





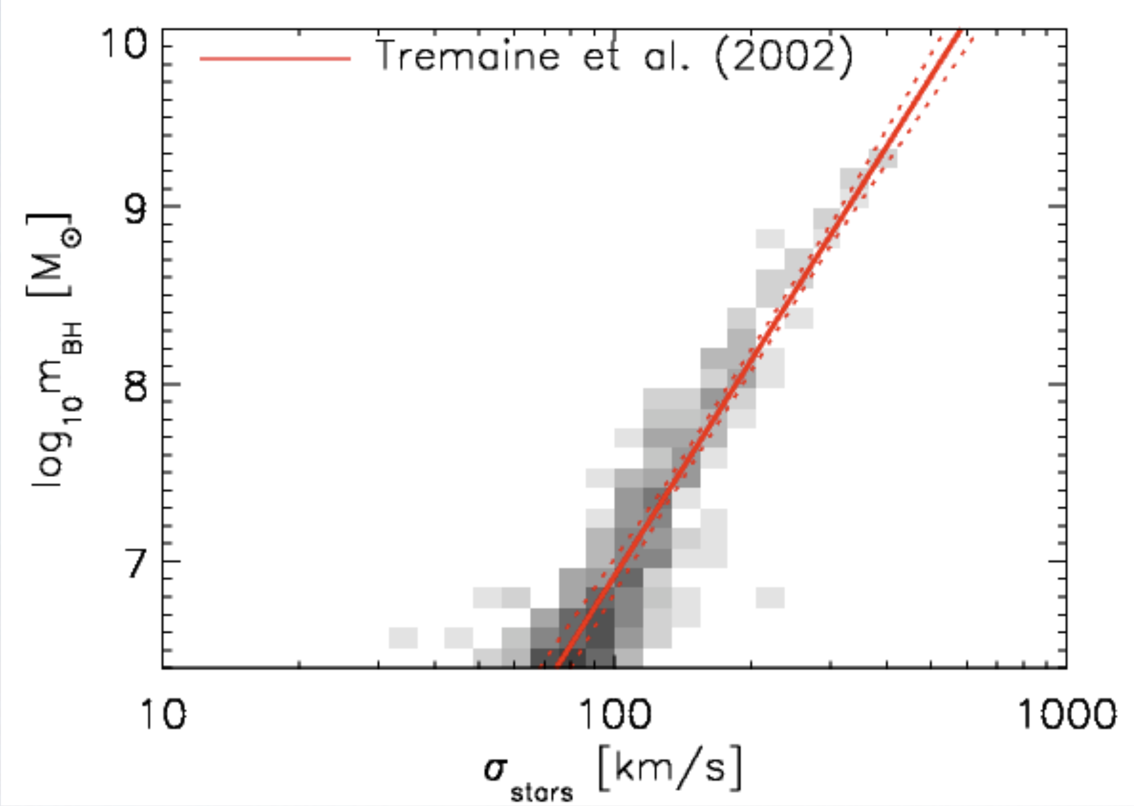
BH mass vs stellar velocity dispersion

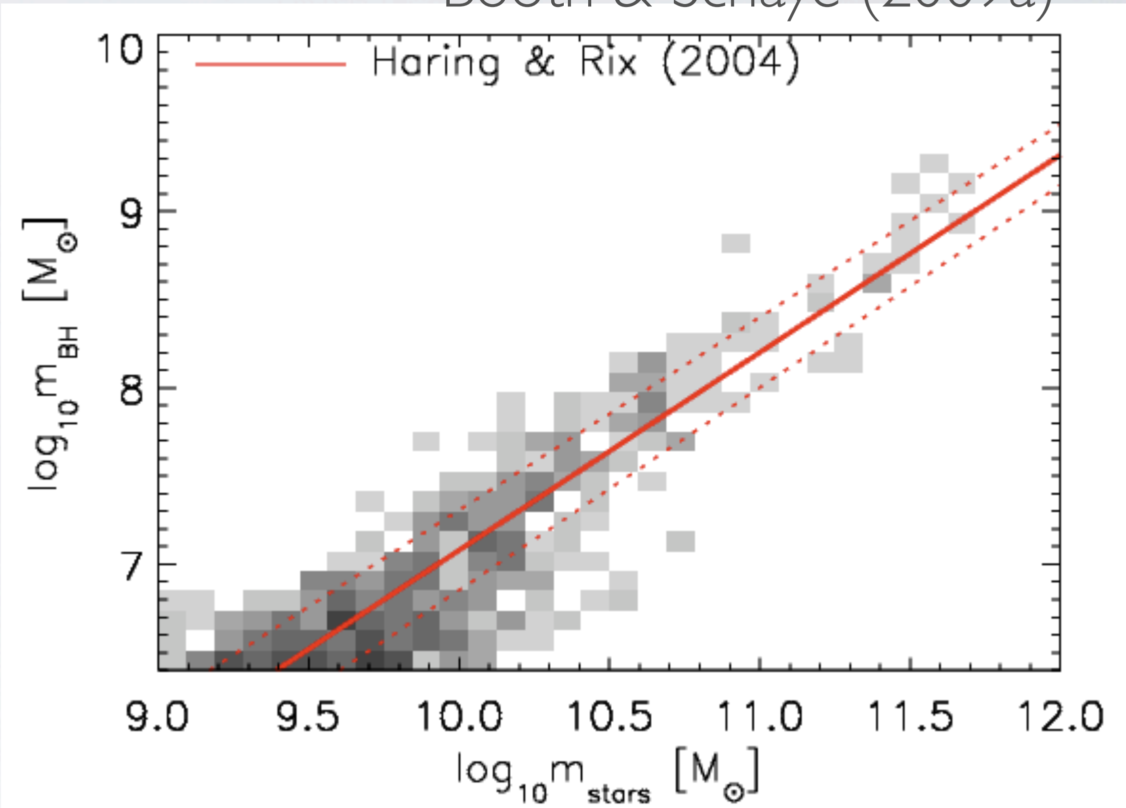
BH mass vs stellar mass

The existence of tight stellar - BH correlations implies that BHs and galaxies evolve together

3. BH SCALING RELATIONS

Booth & Schaye (2009a)



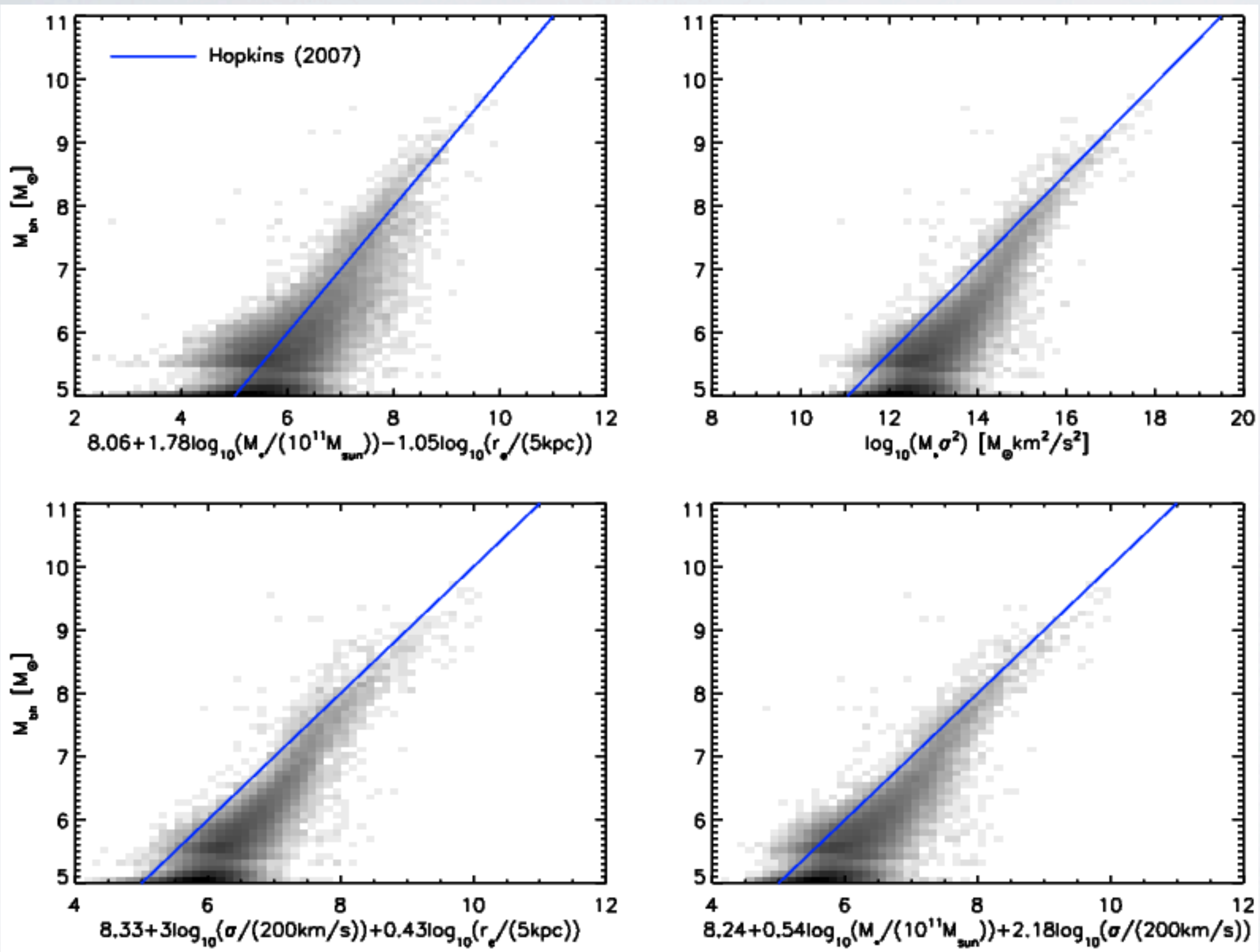


BH mass vs stellar velocity dispersion

BH mass vs stellar mass

The existence of tight stellar - BH correlations implies that BHs and galaxies evolve together

3. BH SCALING RELATIONS



Black hole 'fundamental plane'

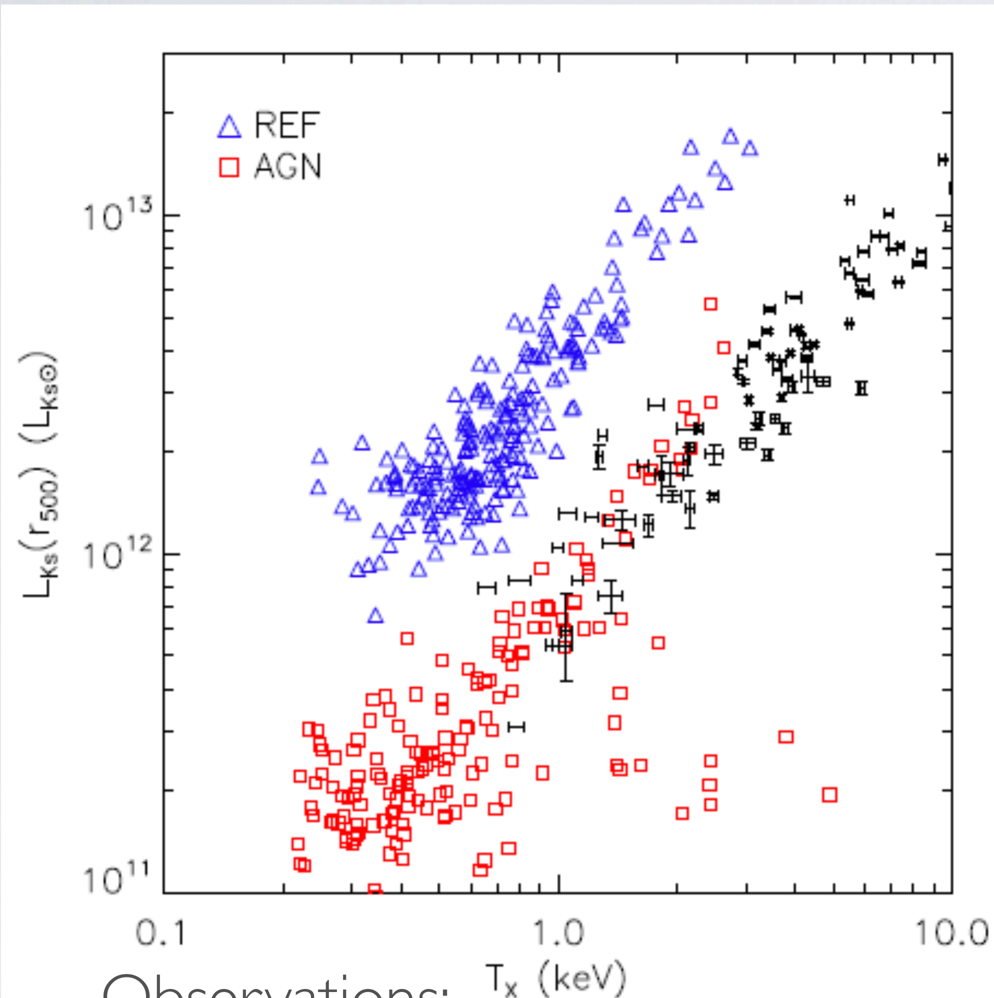
↓

Predicted BH demographics consistent with observation

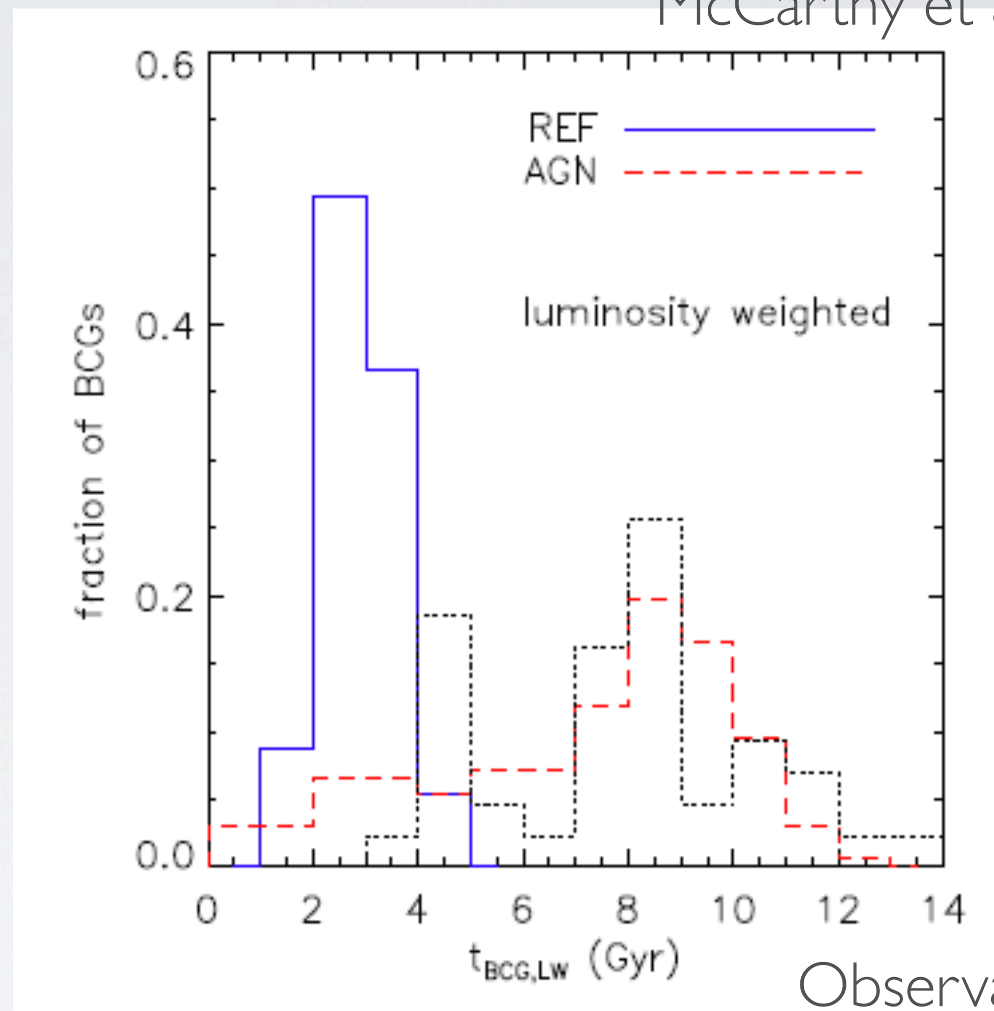
What about groups/clusters?

3. PROPERTIES OF THE BCG

McCarthy et al. (2009)



Observations:
Lin & Mohr (2004), Horner (2001)



Observations:
Loubser et al. (2009)

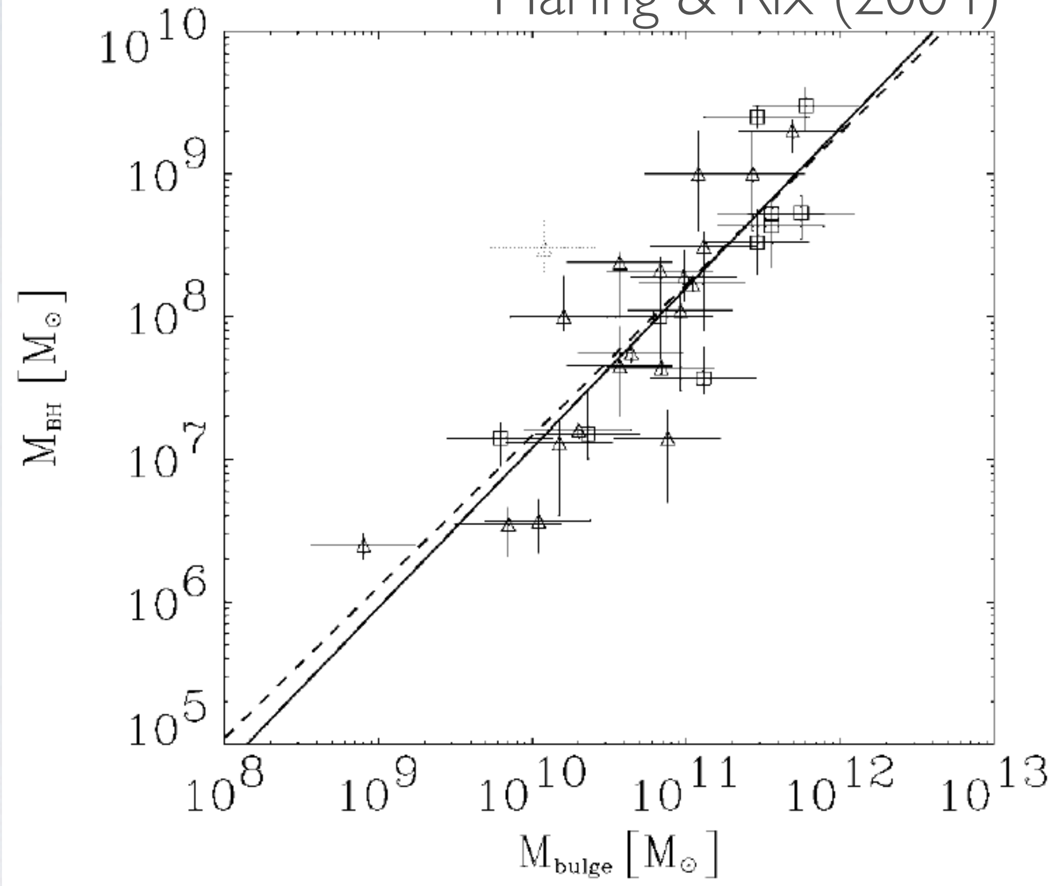
Simulations without AGN feedback form far too many stars and they are too young --> SN feedback cannot prevent catastrophic cooling of gas in clusters

3. THE EFFECT OF AGN

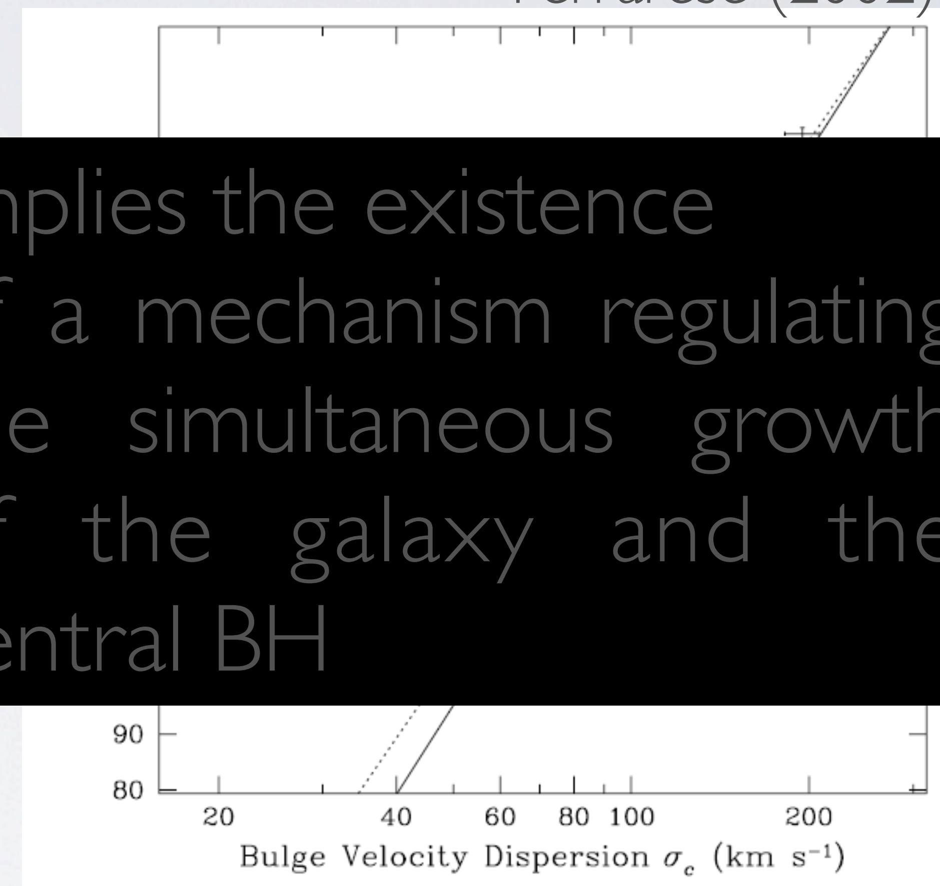
- Note, these simulations were tuned *only* to match the amount of BHs, but still reproduce
  - BH-galaxy connection.
  - Thermodynamic properties of groups and clusters
  - Properties of central galaxies.
  - The drop in the global SFR below z~2
- What can we now learn from these simulations?

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

Haring & Rix (2004)



Ferrarese (2002)



Implies the existence of a mechanism regulating the simultaneous growth of the galaxy and the central BH

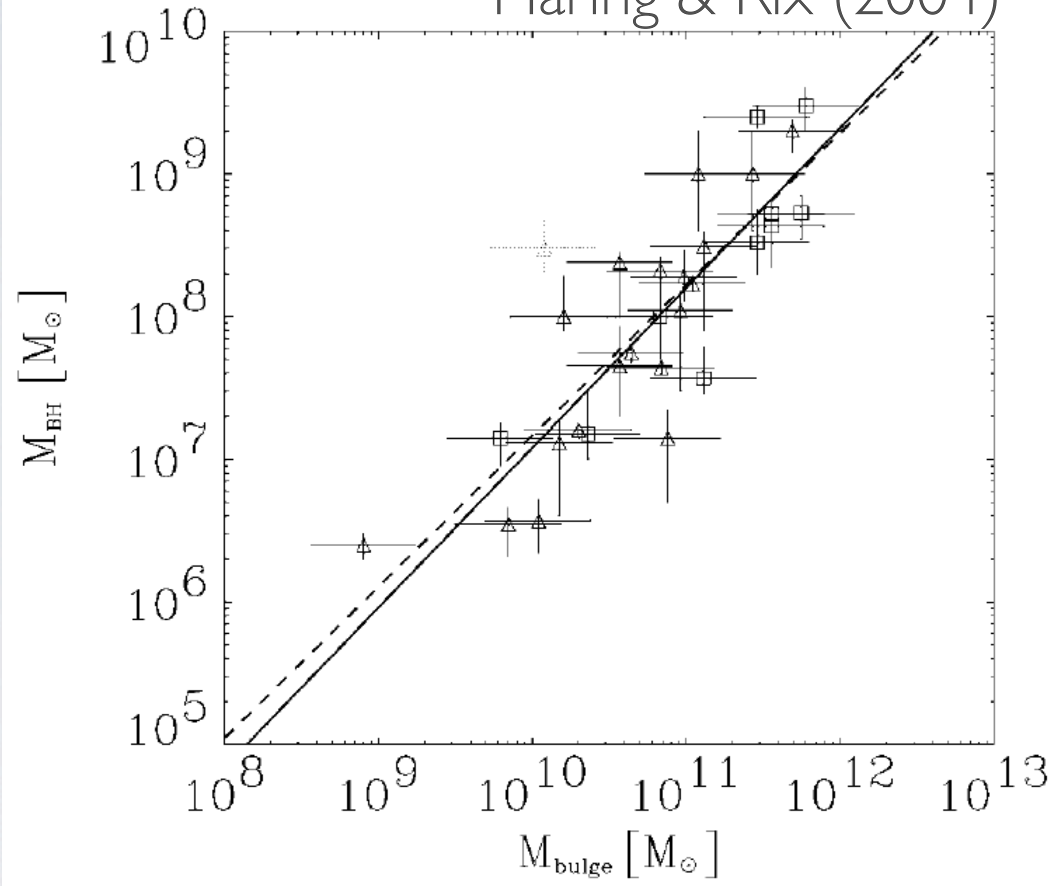
Observations link BH to galaxy.

Various theoretical models use stellar bulge. BH scale. Halo.

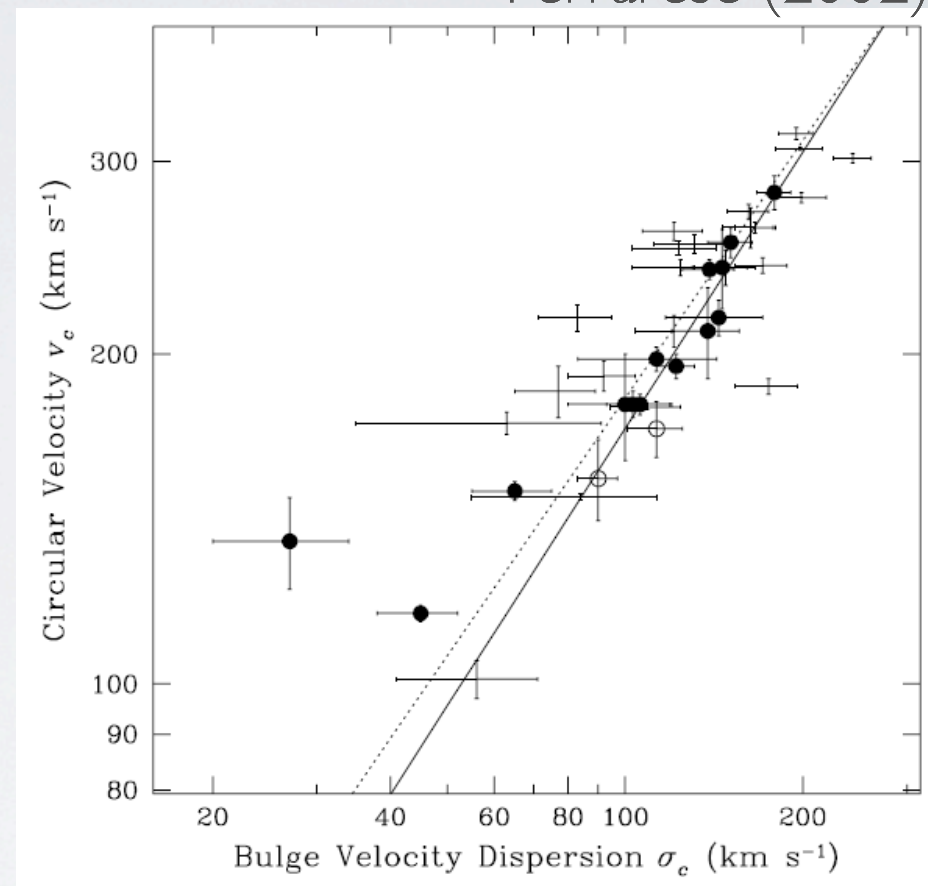
Our simulations get the BH demographics right. What sets the masses of SMBHs?

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

Haring & Rix (2004)



Ferrarese (2002)



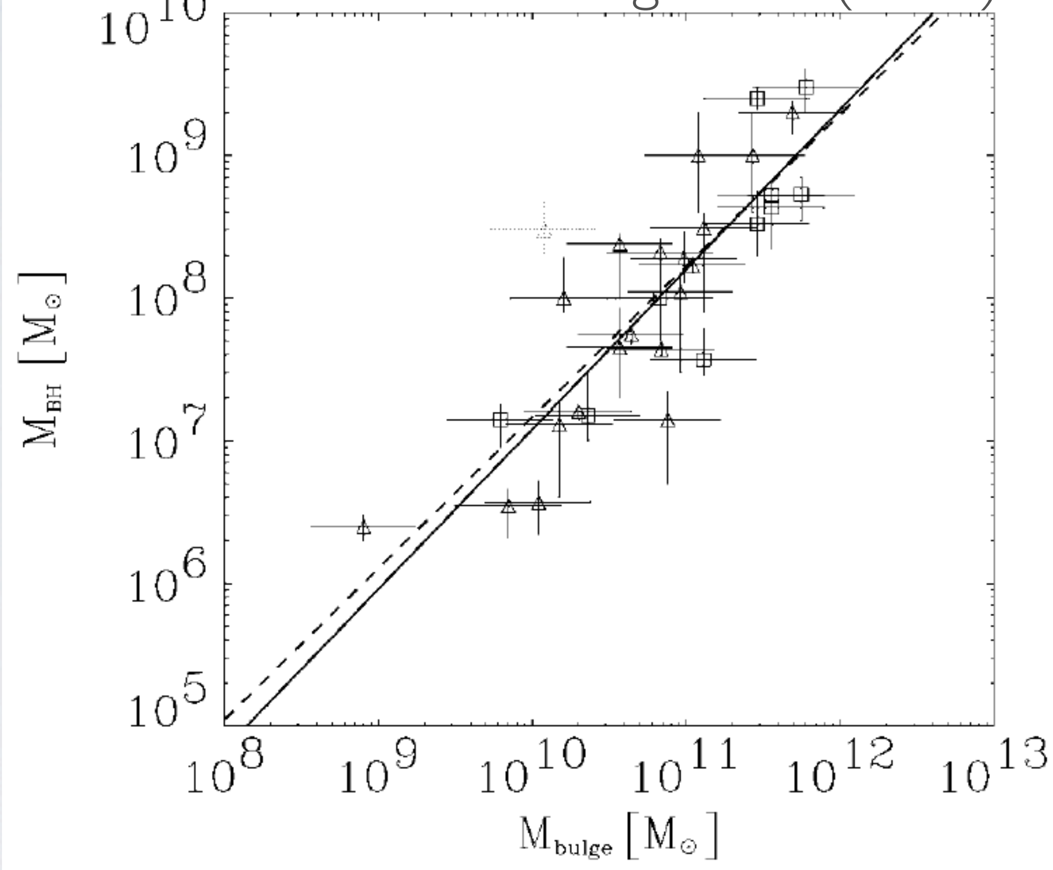
Observations link BH to galaxy.

Various theoretical models use stellar bulge. BH scale. Halo.

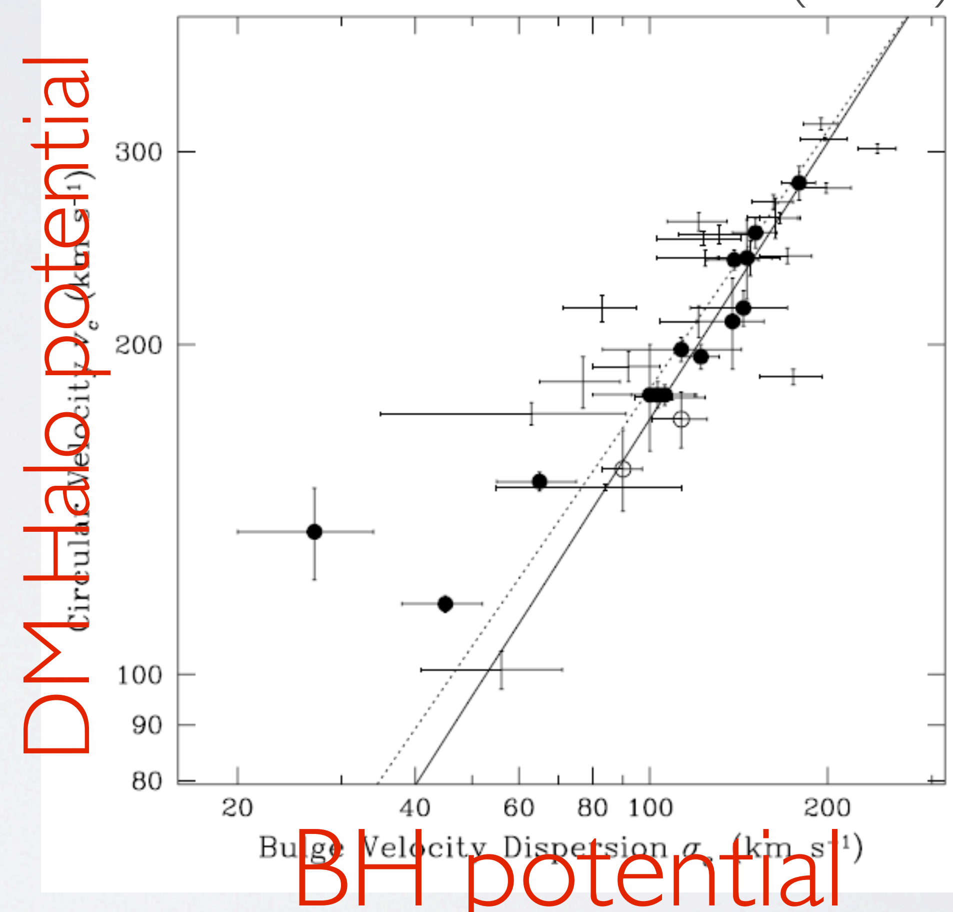
Our simulations get the BH demographics right. What sets the masses of SMBHs?

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

Haring & Rix (2004)



Ferrarese (2002)



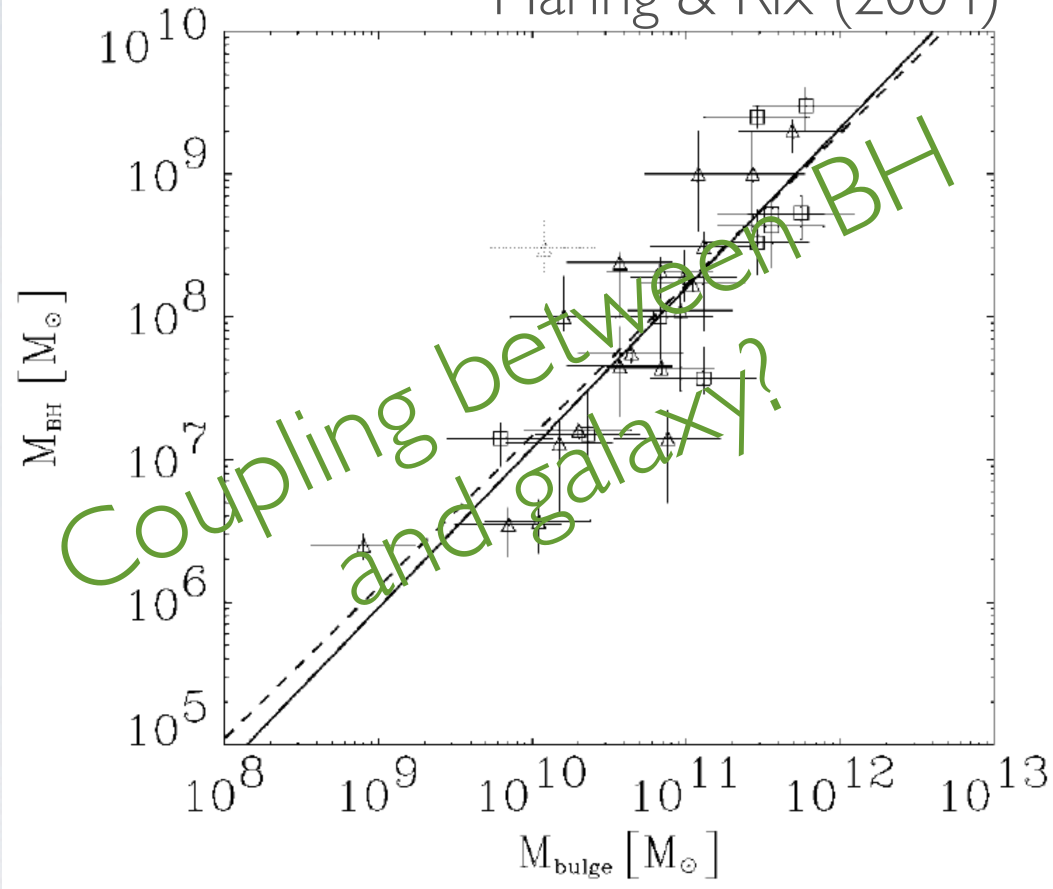
Observations link BH to galaxy.

Various theoretical models use stellar bulge. BH scale. Halo.

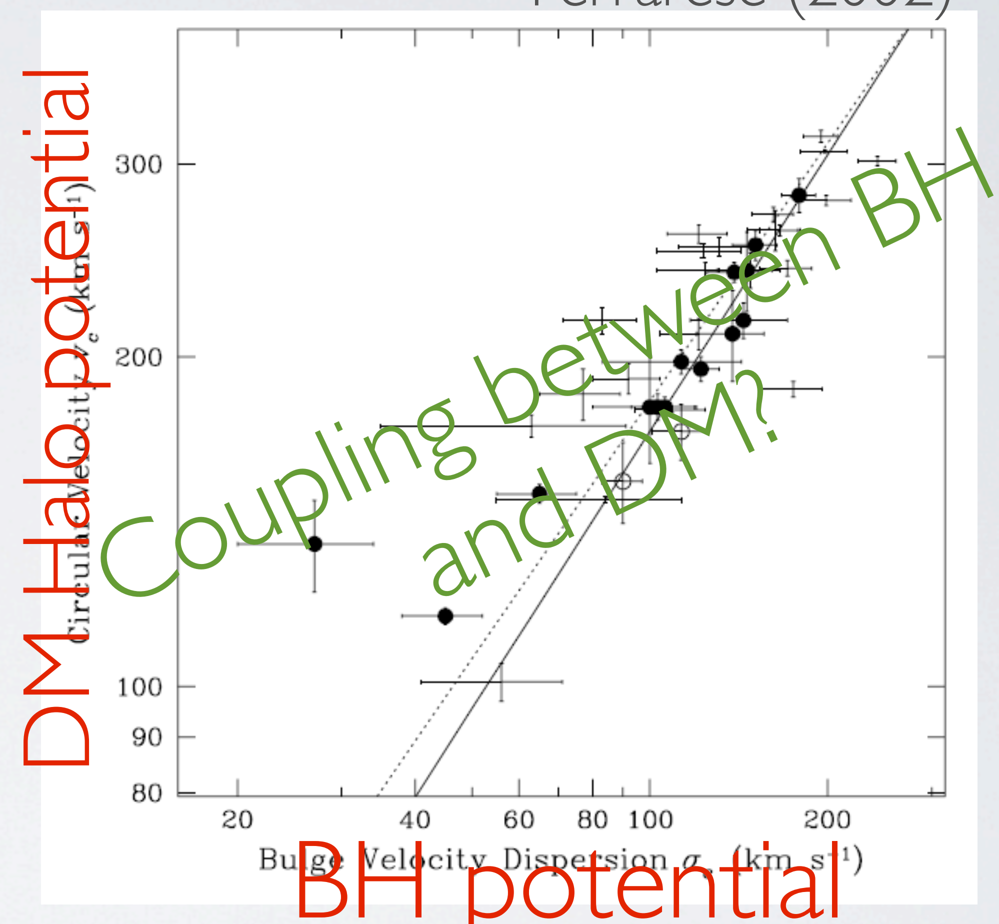
Our simulations get the BH demographics right. What sets the masses of SMBHs?

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

Haring & Rix (2004)



Ferrarese (2002)



Observations link BH to galaxy.

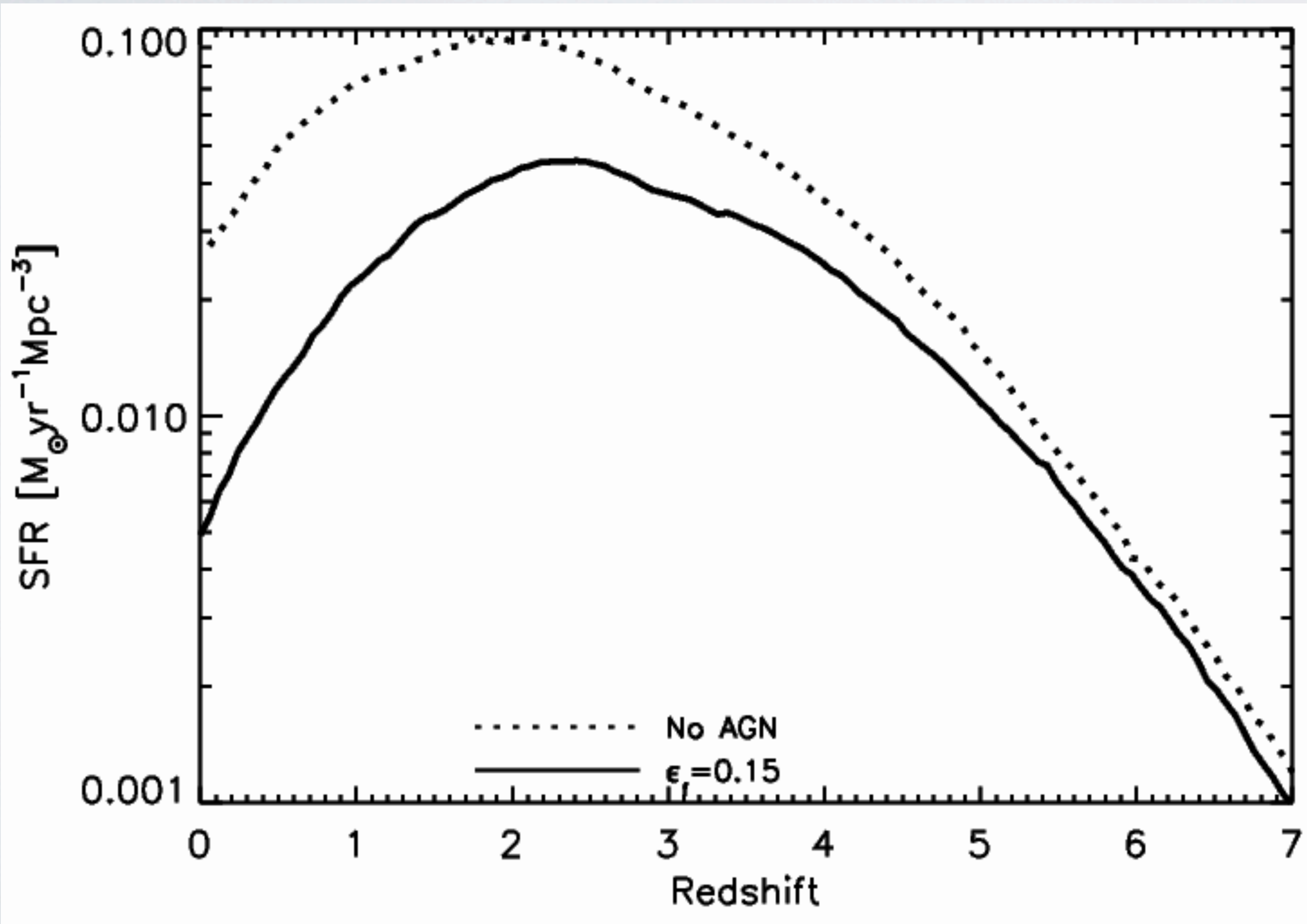
Various theoretical models use stellar bulge. BH scale. Halo.

Our simulations get the BH demographics right. What sets the masses of SMBHs?

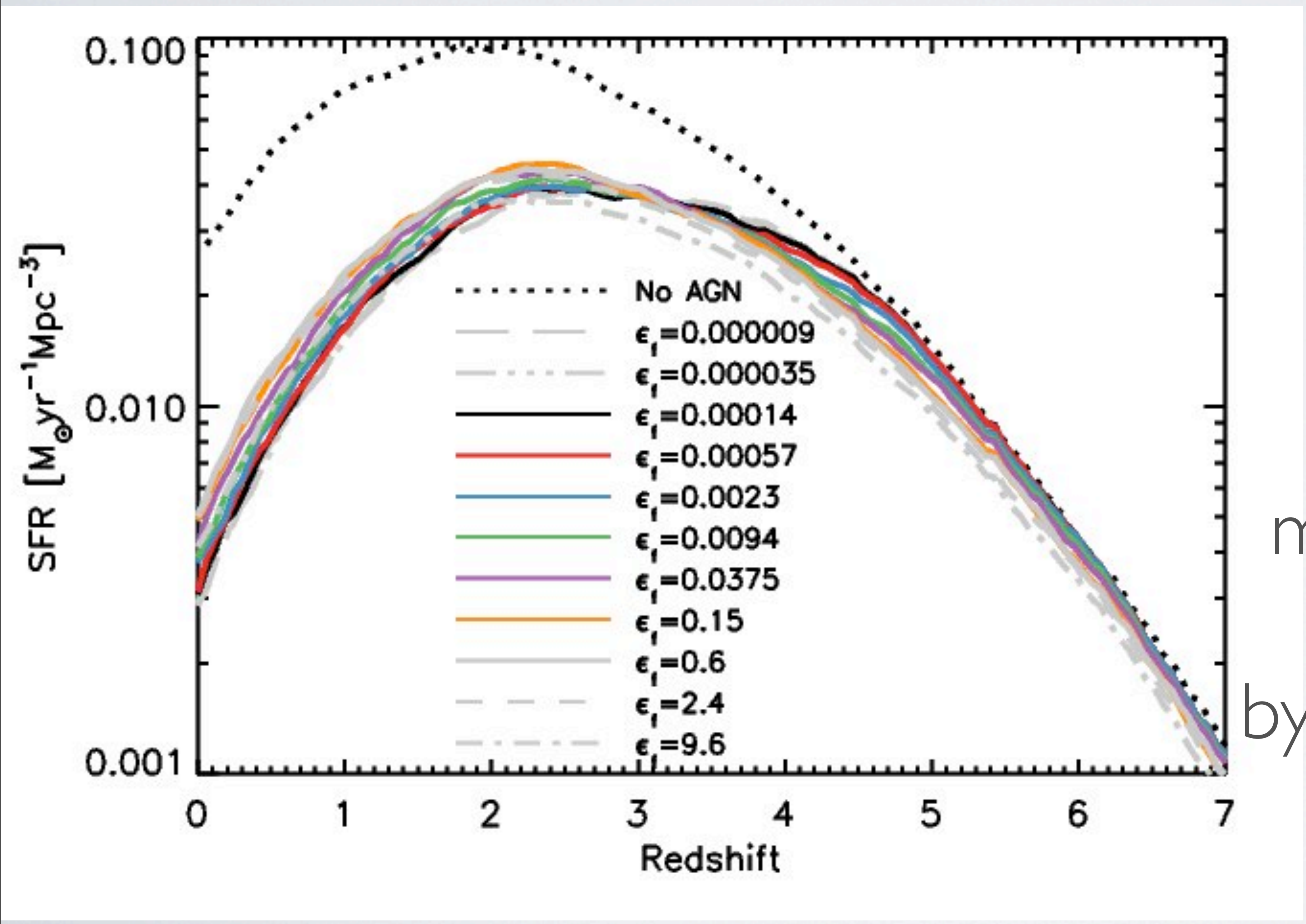
4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

Start with the Madau plot...

...at low z AGN suppress SF



4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

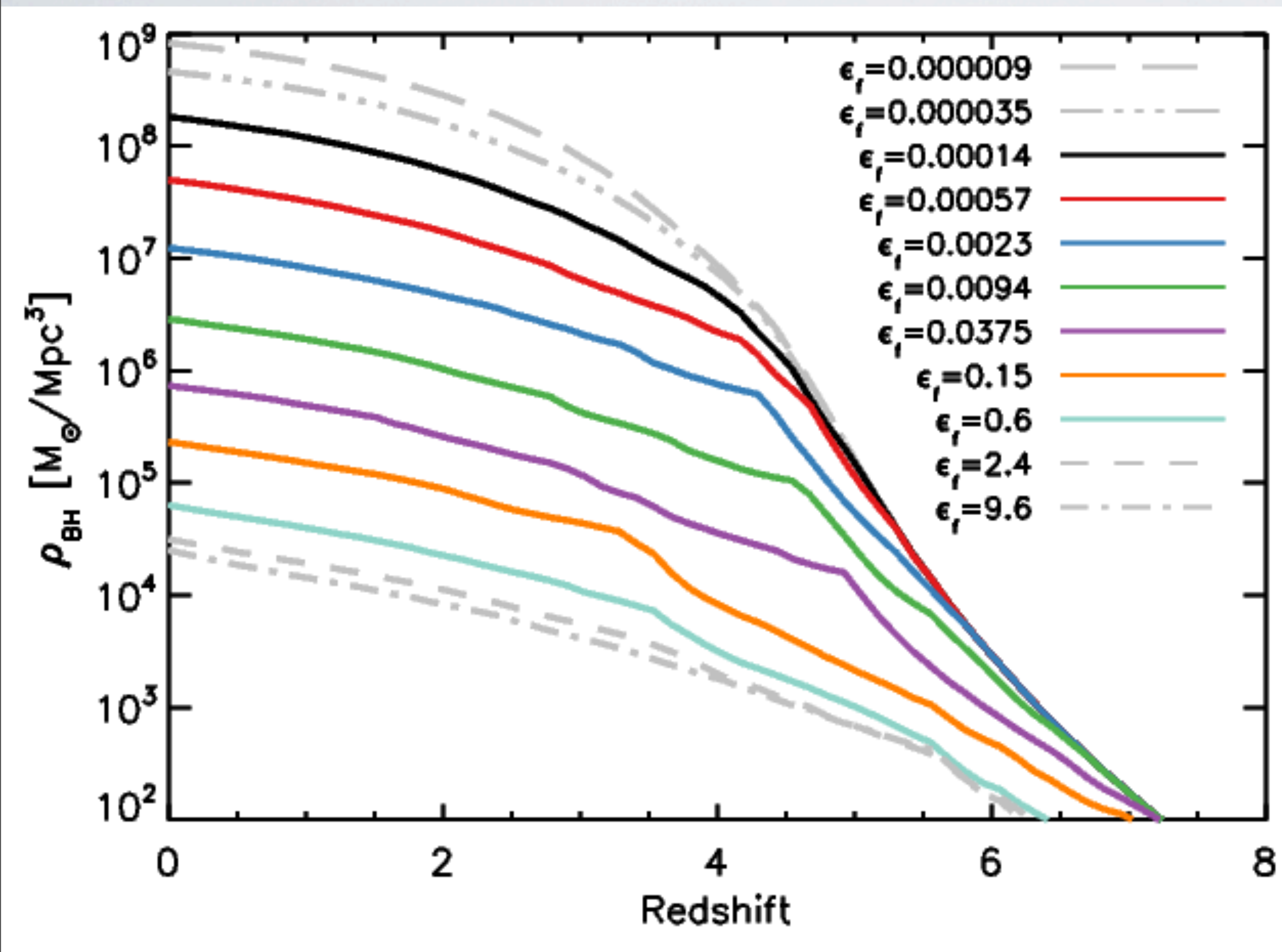


Start with the Madau plot...

...at low z AGN suppress SF

Over 5 orders of magnitude in ε_f, SFR does not change by more than a factor of 2

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

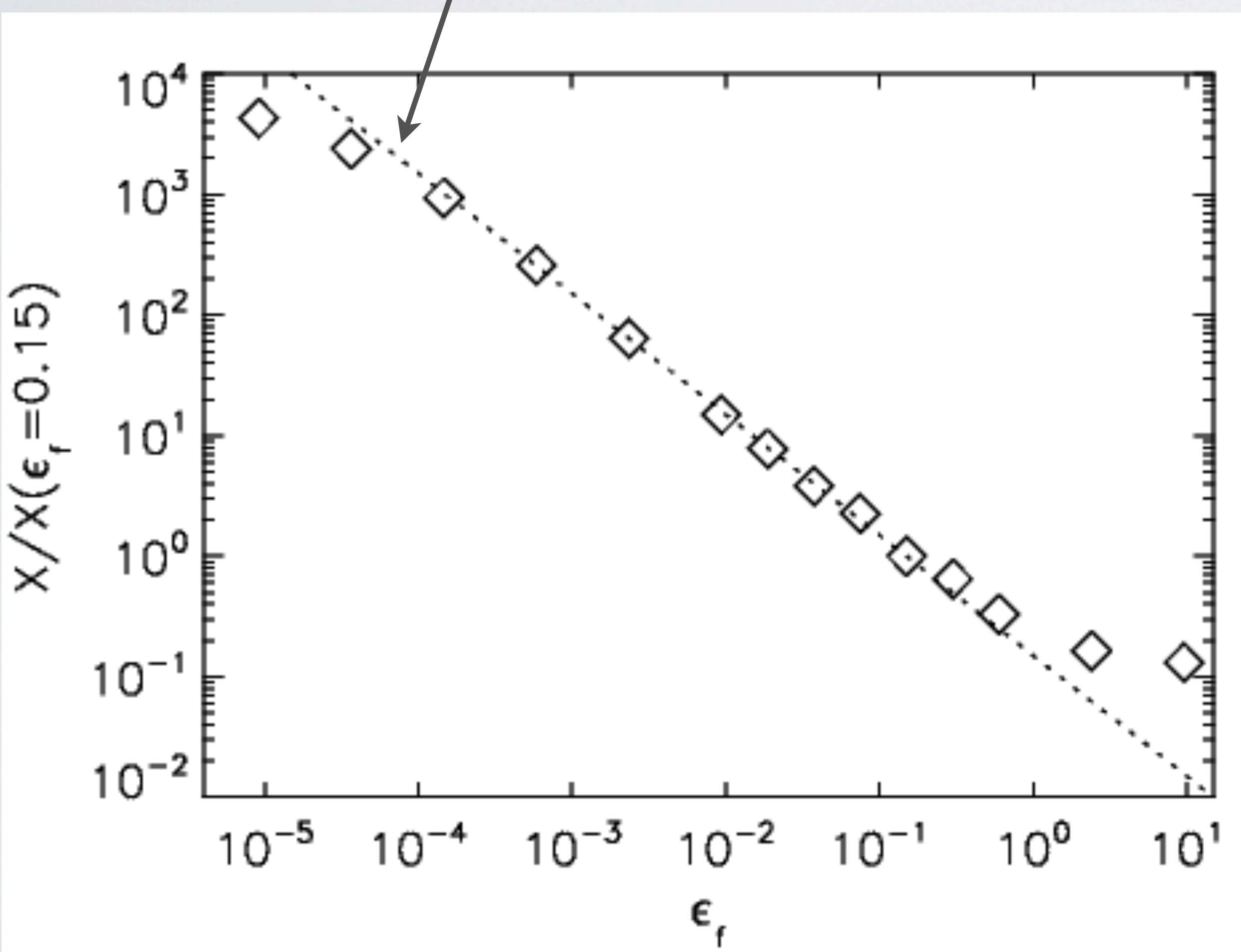


- The free parameter $\boldsymbol{\varepsilon}_f$ controls the total mass in BHs
- 0.15 reproduces observations.

$$E_{\rm feed} = \epsilon_{\rm f}\epsilon_{\rm r}\dot{m}_{\rm BH}c^2\Delta t$$

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

Dashed line shows slope of -1



$m_{BH} \propto \boldsymbol{\varepsilon}_f^{-1}$

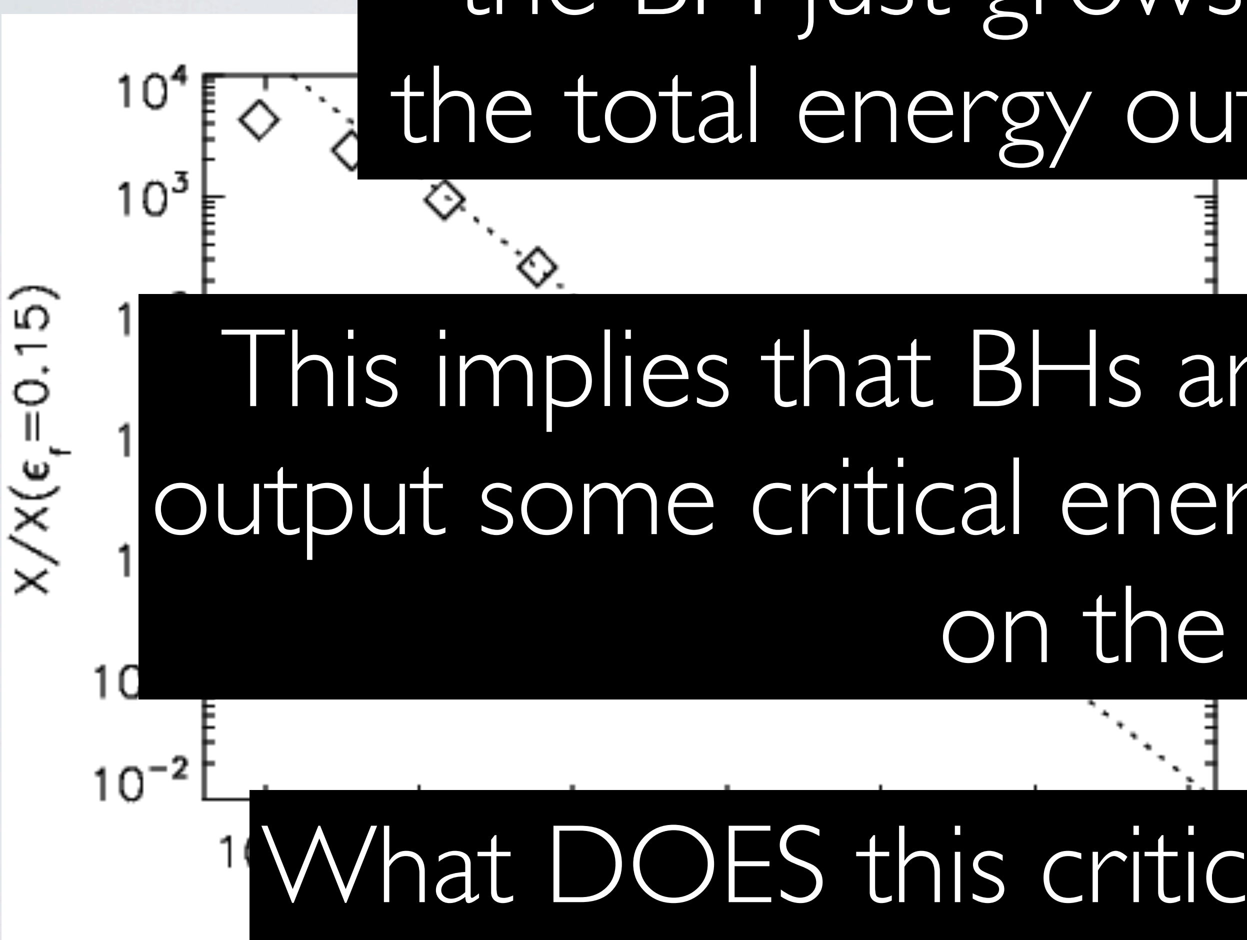
BHs adjust their masses to keep E_{out} constant

E_{out} is "some critical energy" for self-regulation. What does it correspond to?

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

D

If energy feedback is made half as efficient the BH just grows twice as massive so the total energy output remains invariant



BHs adjust their masses to

This implies that BHs are growing until they have output some critical energy, which does not depend on the BH mass

y"

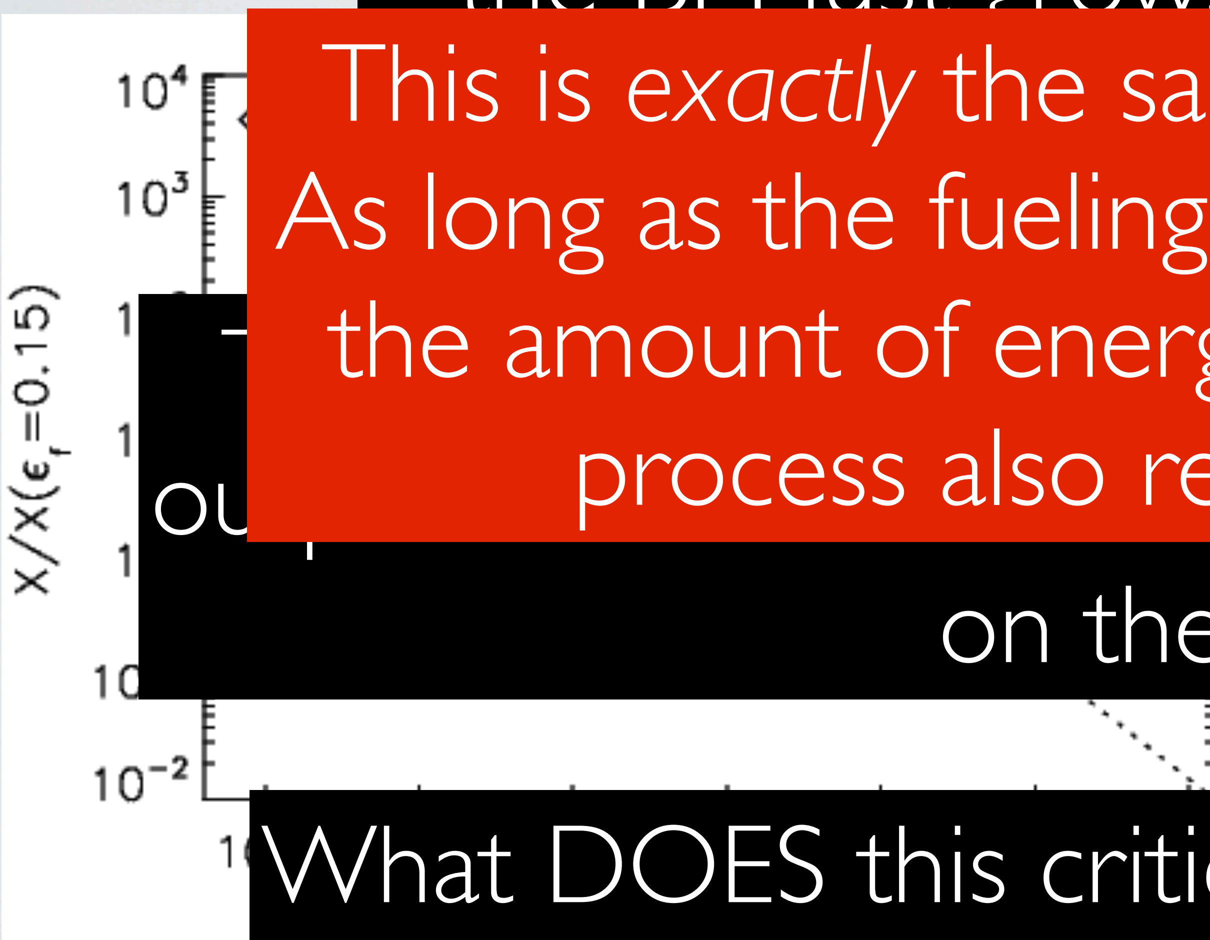
for self-regulation. What

What DOES this critical energy correspond to? Something to do with the galaxy? the halo?

o?

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

D If energy feedback is made half as efficient the BH just grows twice as massive so



This is *exactly* the same argument as before: As long as the fueling rate remains unchanged, the amount of energy output by a feedback process also remains unchanged.

s to

e

ou nd

on the BH mass

y"

for self-regulation. What

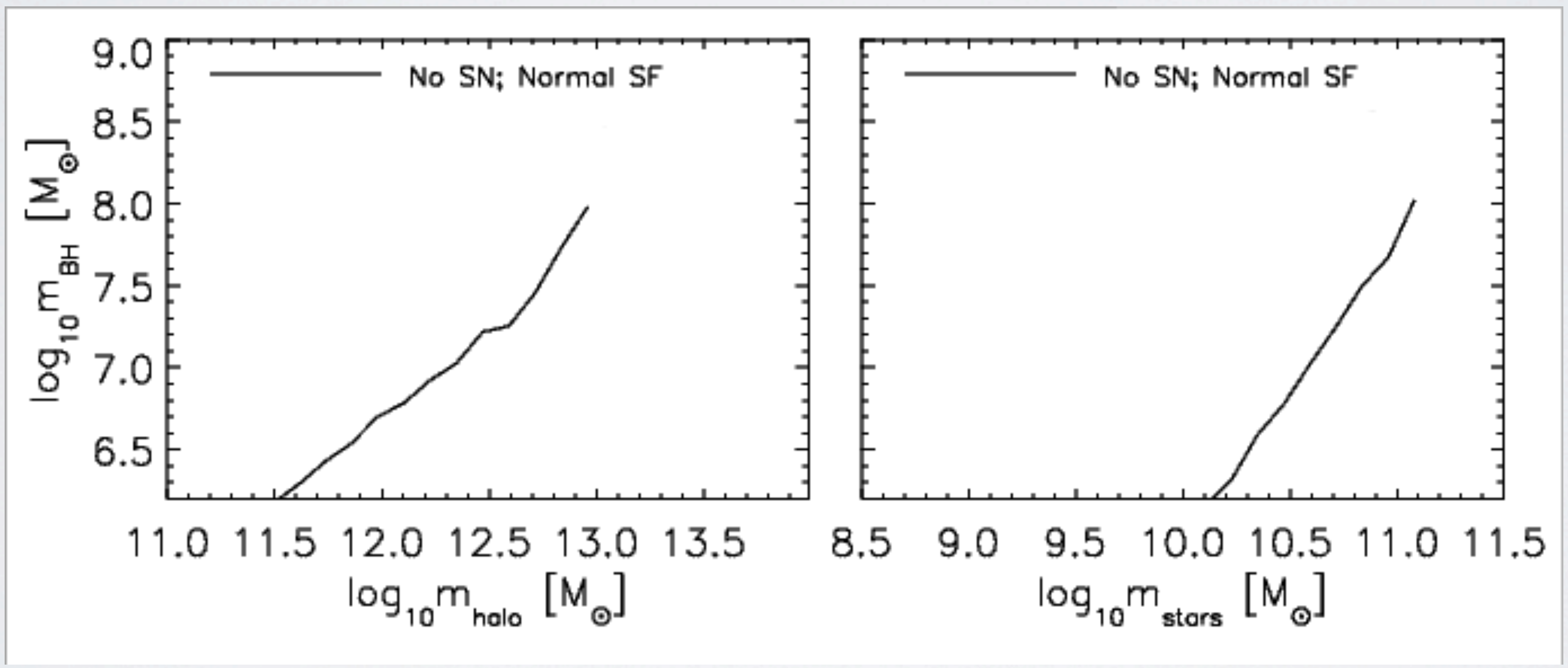
o?

What DOES this critical energy correspond to? Something to do with the galaxy? the halo?

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

At the galactic centre the gravitational potential is dominated by baryons.

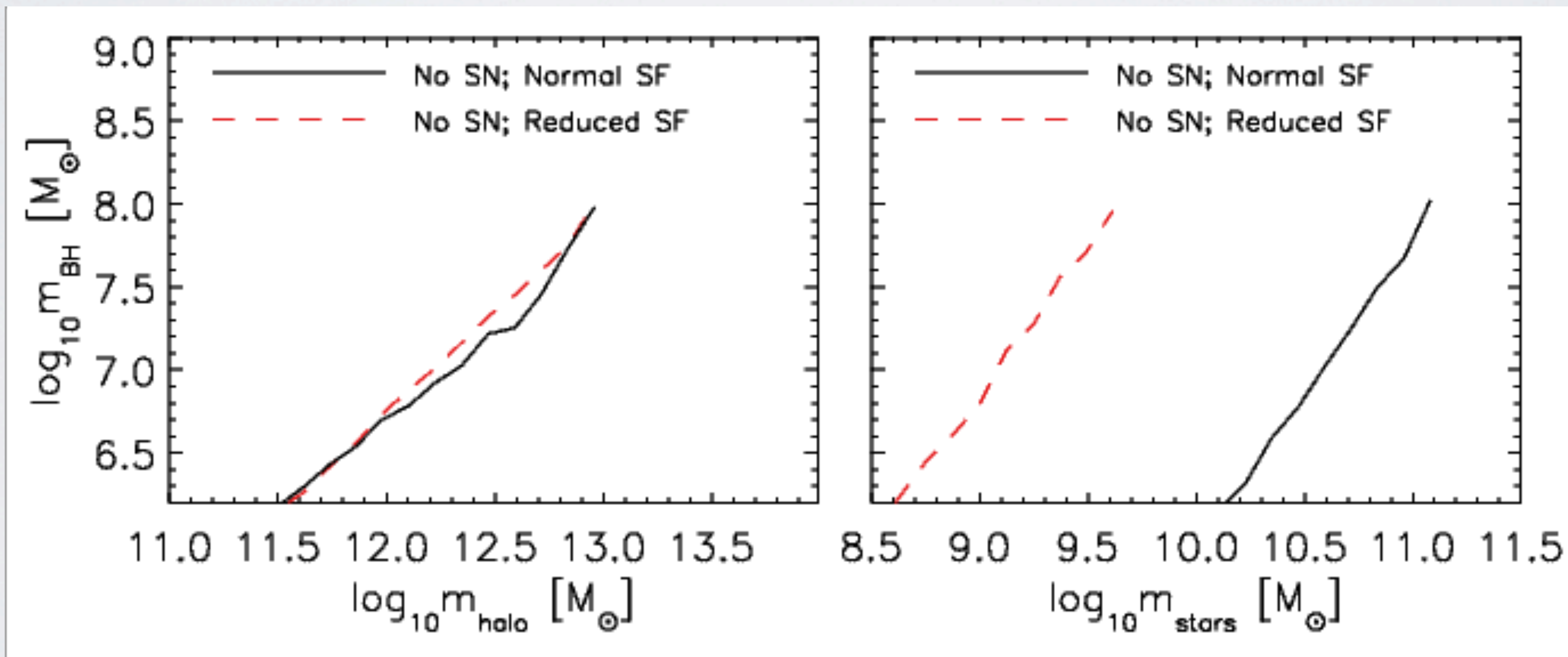
What happens if they are removed?



4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

At the galactic centre the gravitational potential is dominated by baryons.

What happens if they are removed?

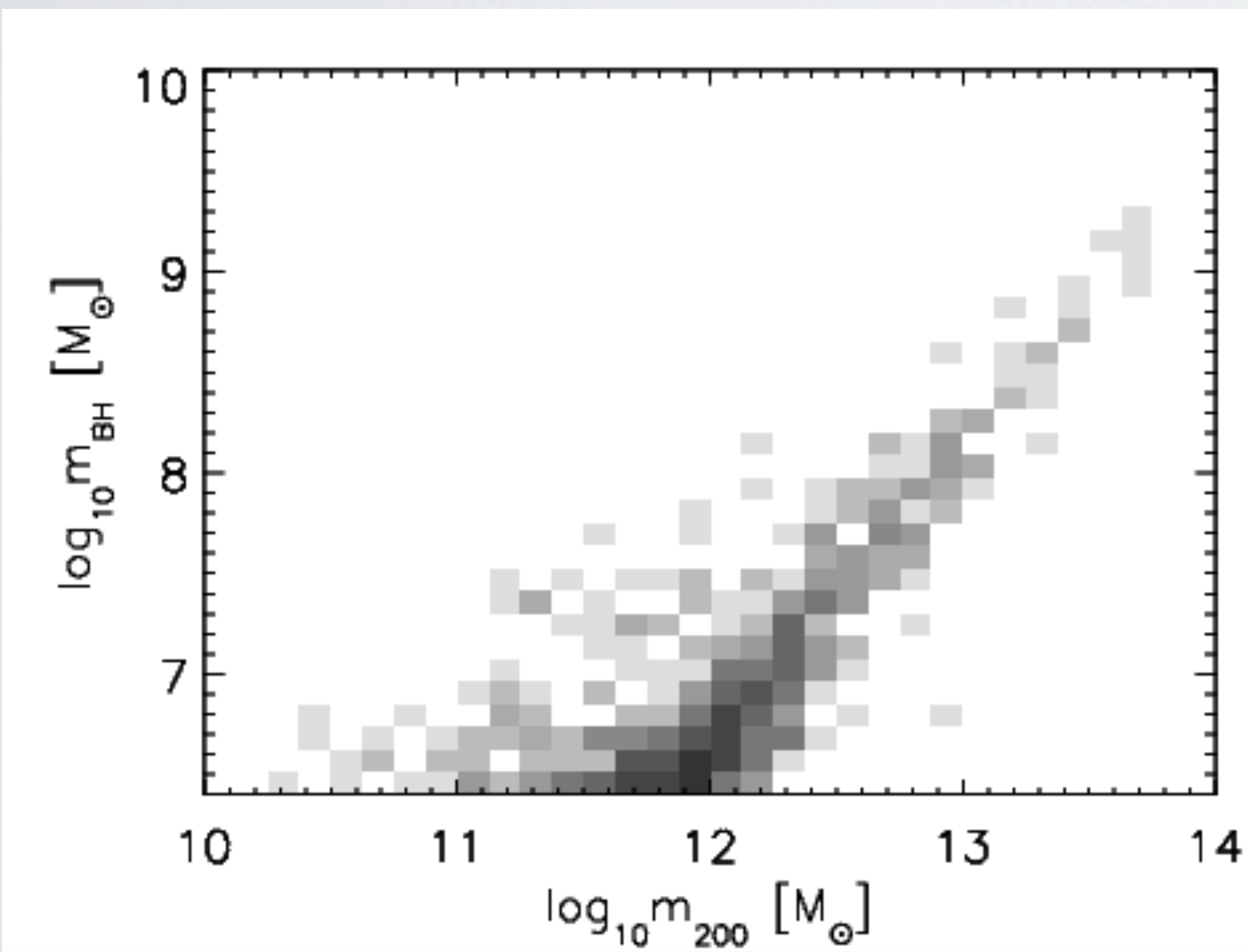


The BHs do not care about the matter distribution on small scales

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

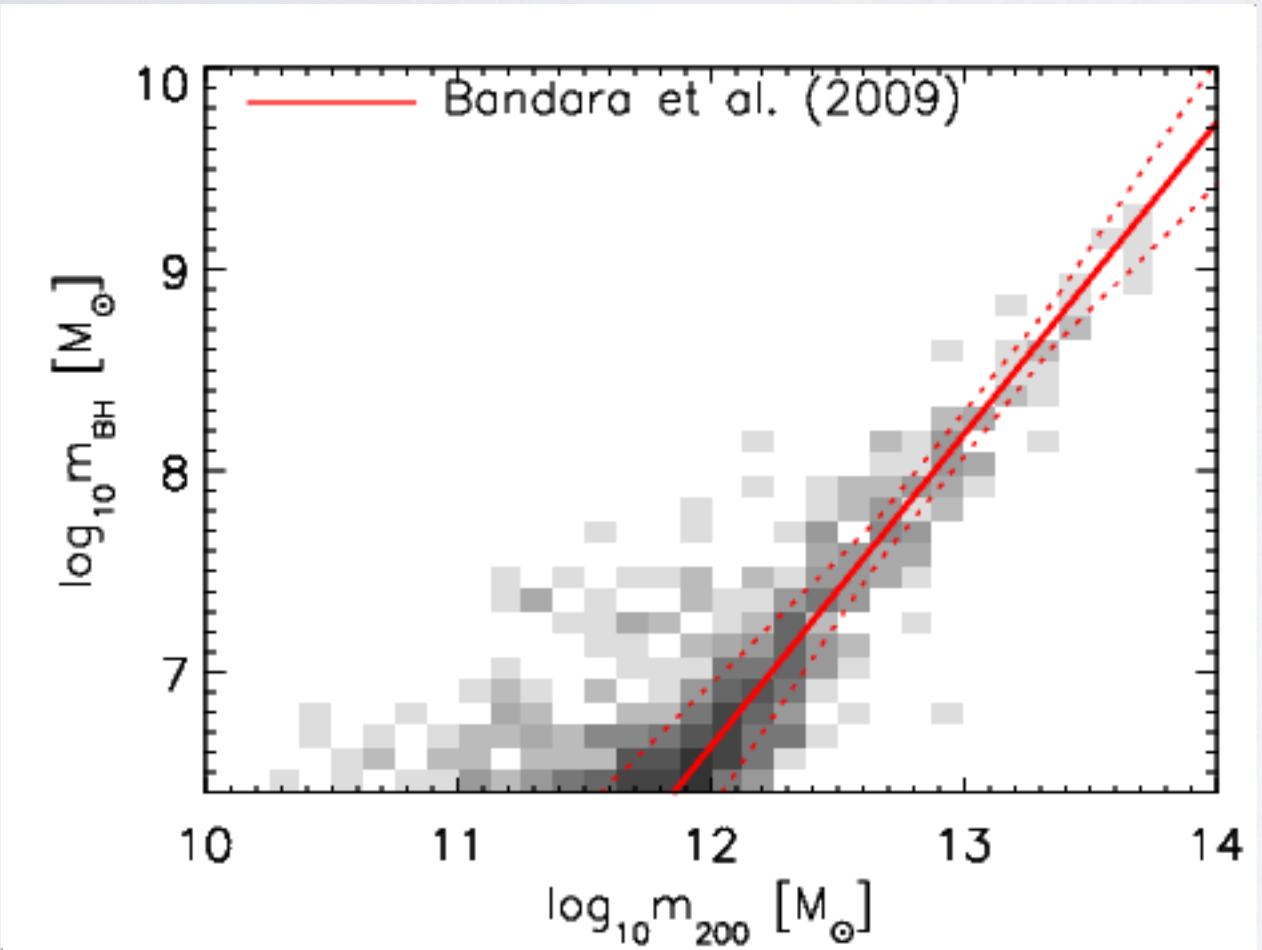
Self regulation occurs on scales > the galaxy

- Simulated slope: 1.55±0.03



4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

Self regulation occurs on scales > the galaxy



- Simulated slope: 1.55±0.03
- Observed slope: 1.55±0.31

Again, note that the only thing we tuned here was the total mass in BHs

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

Booth & Schaye 2010

- Comparing energy output by a BH to halo gravitational binding energy:

$$E_{\rm feed} = \epsilon_{\rm f}\epsilon_{\rm r}\dot{m}_{\rm BH}c^2\Delta t$$

$$m_{\rm BH} \propto U \propto \frac{GM_{\rm halo}^2}{r_{\rm halo}} \propto m_{\rm halo}^{5/3}$$

(e.g. Silk & Rees 1998)

- For the case of an NFW halo with concentration, c

$$m_{\rm BH} \propto \left(\frac{c}{\left(\ln(1+c) - c/(1+c)\right)^2}\right)\left(1 - \frac{1}{(1+c\frac{r_{\rm ej}}{r_{\rm v}})^2} - \frac{2\ln(1+c\frac{r_{\rm ej}}{r_{\rm v}})}{1+c\frac{r_{\rm ej}}{r_{\rm v}}}\right)m_{\rm v}^{5/3}$$

-

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

Booth & Schaye 2010

- Comparing energy output by a BH to halo gravitational binding energy:

$$E_{\rm feed} = \epsilon_{\rm f}\epsilon_{\rm r}\dot{m}_{\rm BH}c^2\Delta t$$

$$m_{\rm BH} \propto U \propto \frac{GM_{\rm halo}^2}{r_{\rm halo}} \propto m_{\rm halo}^{5/3}$$

(e.g. Silk & Rees 1998)

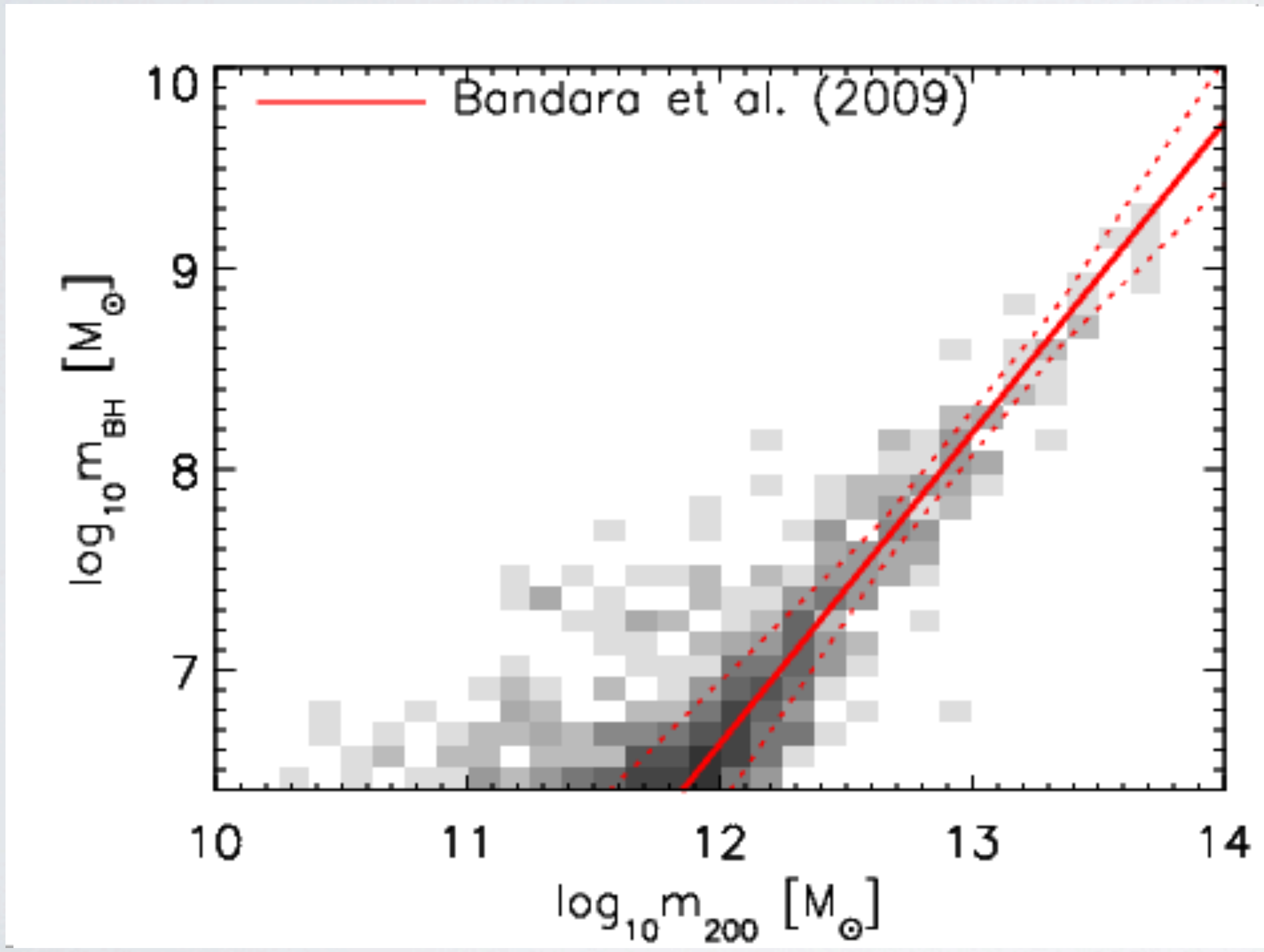
- For the case of an NFW halo with concentration, c

$$m_{\rm BH} \propto \left(\frac{c}{(\ln(1+c) - c/(1+c))^2}\right)\left(1 - \frac{1}{(1+c\frac{r_{\rm ej}}{r_{\rm v}})^2} - \frac{2\ln(1+c\frac{r_{\rm ej}}{r_{\rm v}})}{1+c\frac{r_{\rm ej}}{r_{\rm v}}}\right)m_{\rm v}^{5/3}$$

$c \sim m^{-0.1}$ (e.g. Neto et al. 2007)

-

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?



- Simulated slope: 1.55±0.03
- Observed slope: 1.55±0.31
- Theoretical slope: 1.56±0.05

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

- Comparing energy output by a BH to halo gravitational binding energy:

$$E_{\rm feed} = \epsilon_{\rm f}\epsilon_{\rm r}\dot{m}_{\rm BH}c^2\Delta t$$

$$m_{\rm BH} \propto U \propto \frac{GM_{\rm halo}^2}{r_{\rm halo}} \propto m_{\rm halo}^{5/3}$$

(e.g. Silk & Rees 1998)

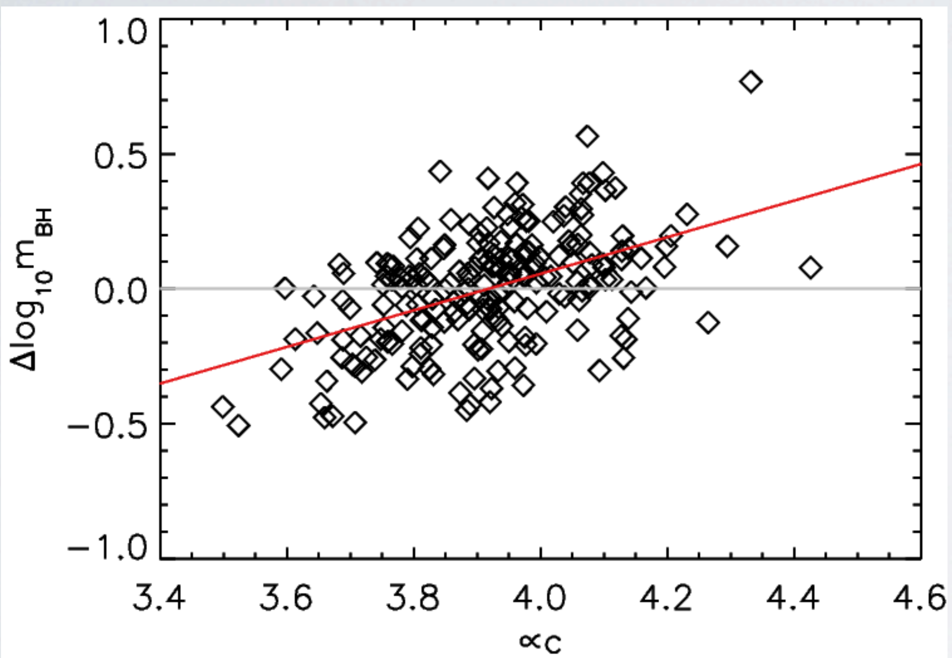
- For the case of an NFW halo with concentration, c

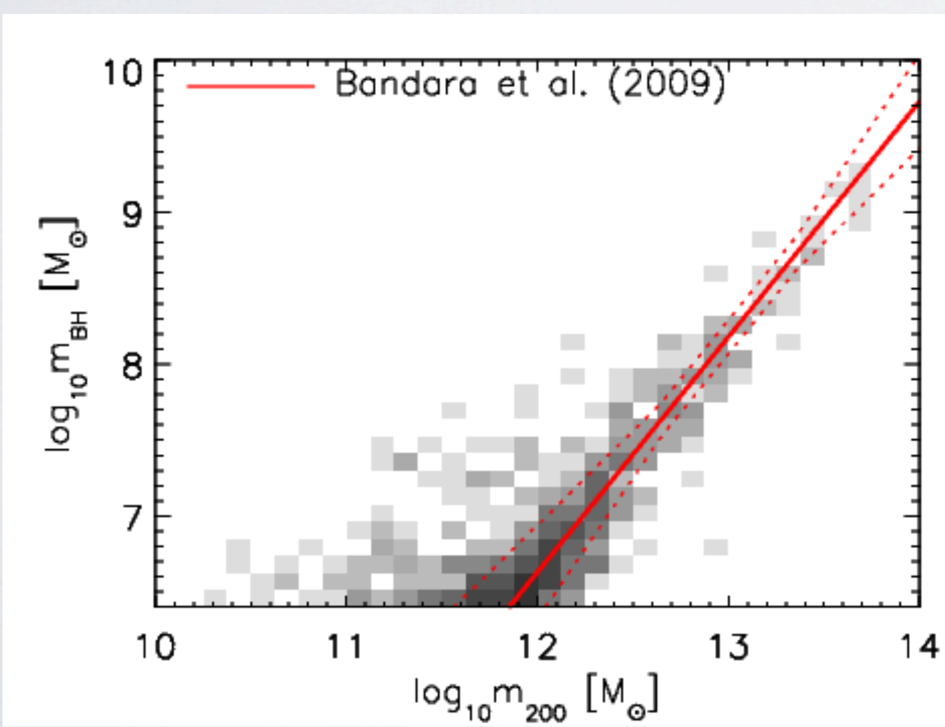
$$m_{\rm BH} \propto \left(\frac{c}{\left(\ln(1+c) - c/(1+c)\right)^2}\right)\left(1 - \frac{1}{(1+c\frac{r_{\rm ej}}{r_{\rm v}})^2} - \frac{2\ln(1+c\frac{r_{\rm ej}}{r_{\rm v}})}{1+c\frac{r_{\rm ej}}{r_{\rm v}}}\right)m_{\rm v}^{5/3}$$

$c \sim m^{-0.1}$ (e.g. Neto et al. 2007)

- **Prediction:** If BH mass is determined by DM halo binding energy there should be a relation between residual in the m_{BH}-m_{halo} relation and halo concentration

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

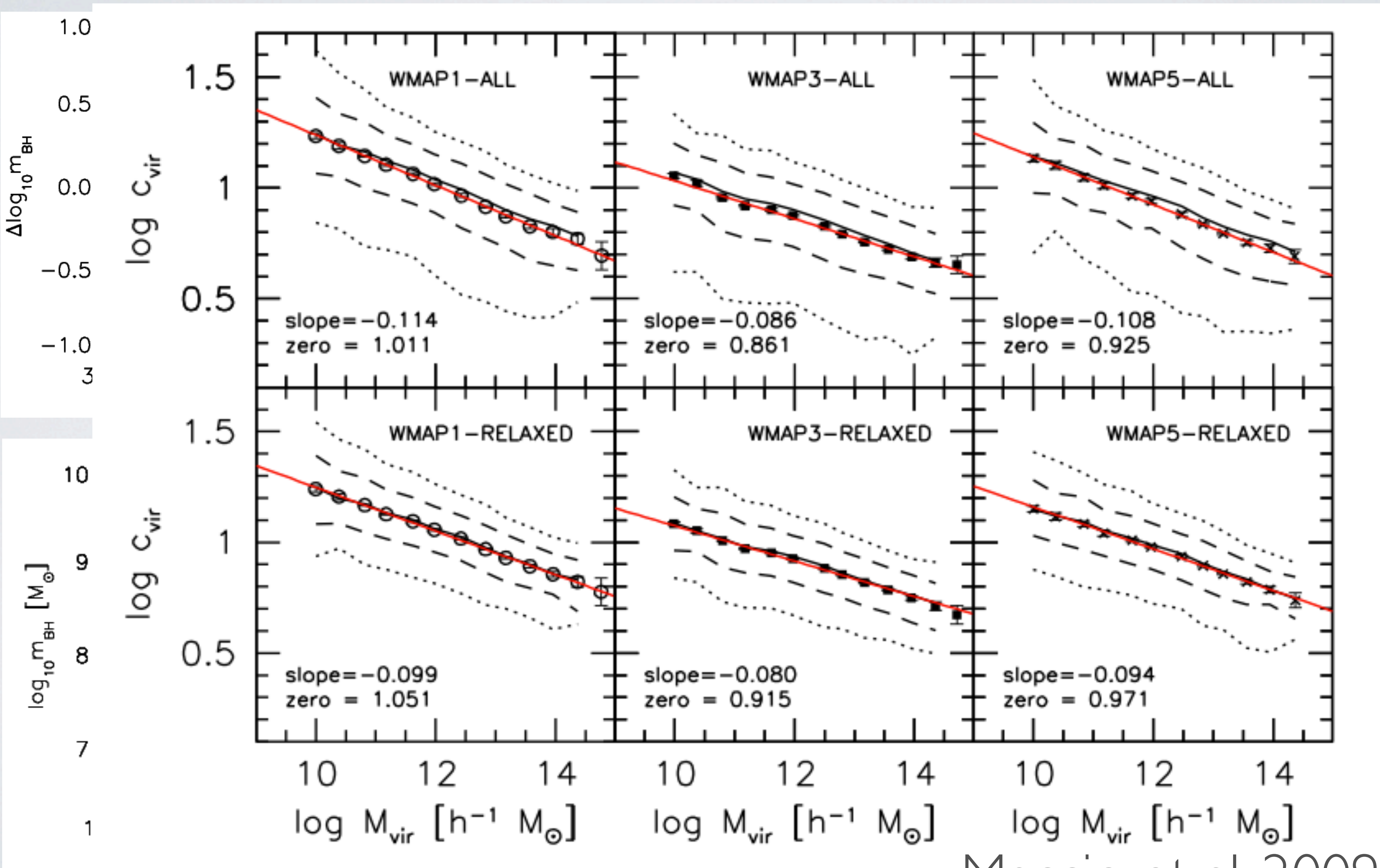




- Simulated slope: 1.55±0.03
- Observed slope: 1.55±0.31
- Theoretical slope: 1.56±0.05

Correlation between Δm_{BH} and *c*?

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?



.03

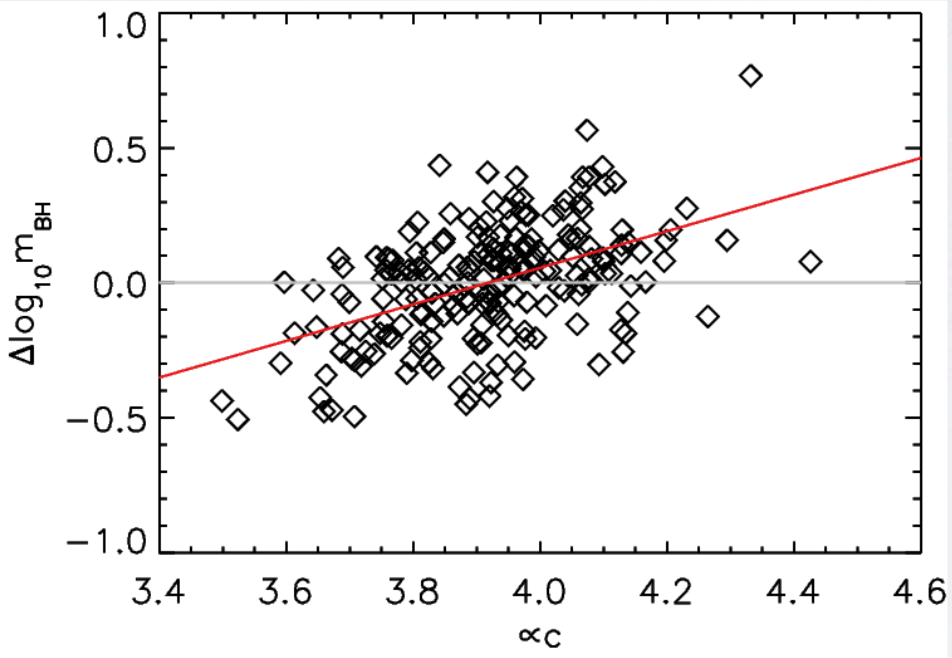
.31

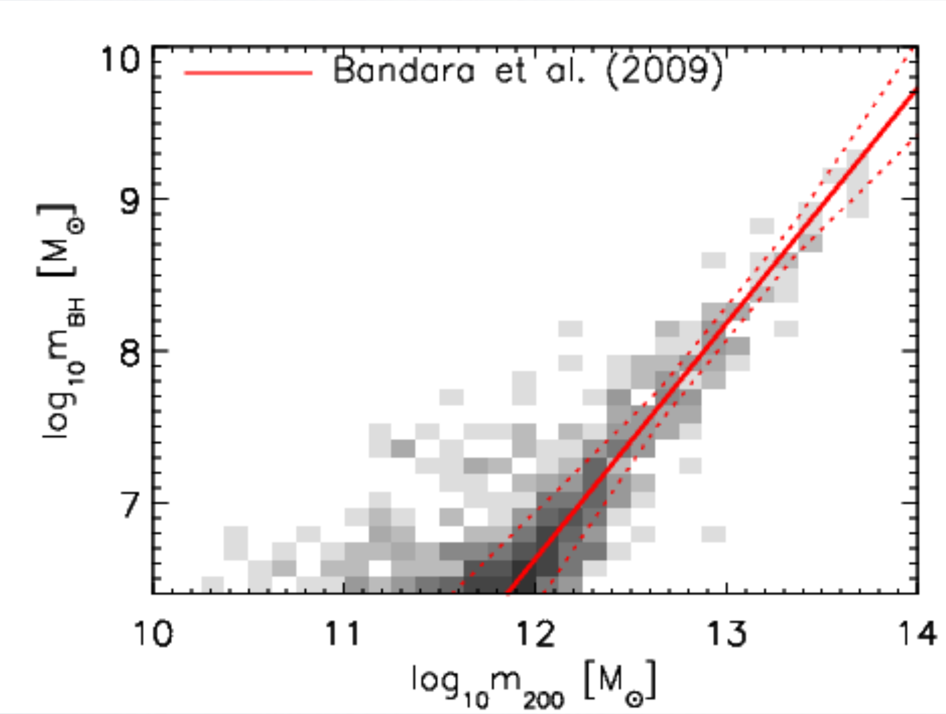
±0.05

m_{BH}

Maccio et al. 2009

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?

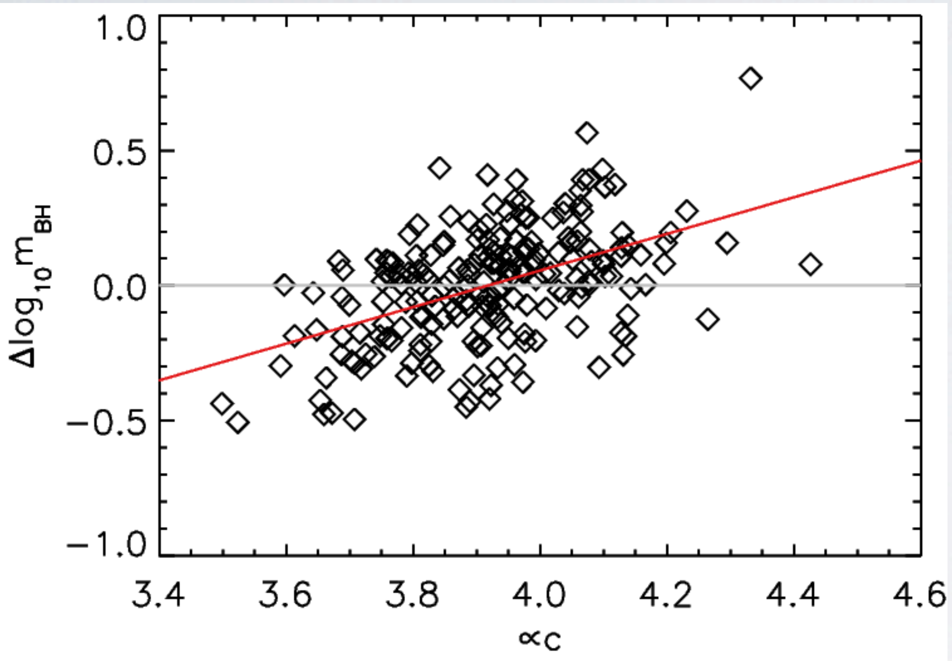


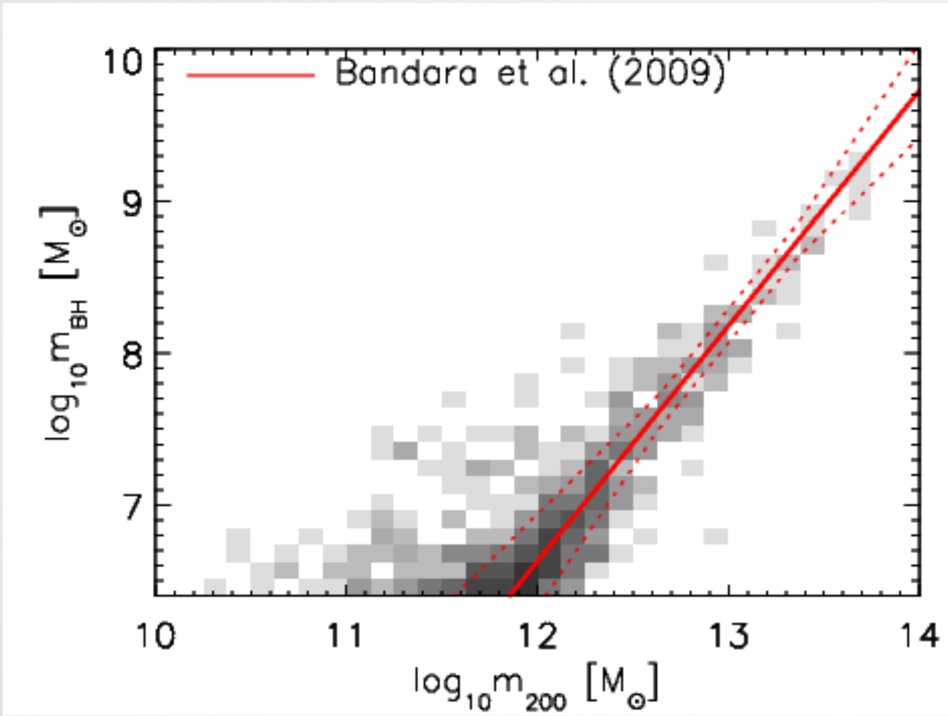


- Simulated slope: 1.55±0.03
- Observed slope: 1.55±0.31
- Theoretical slope: 1.56±0.05

Correction between Δm_{BH} and c?

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE BLACK HOLES?





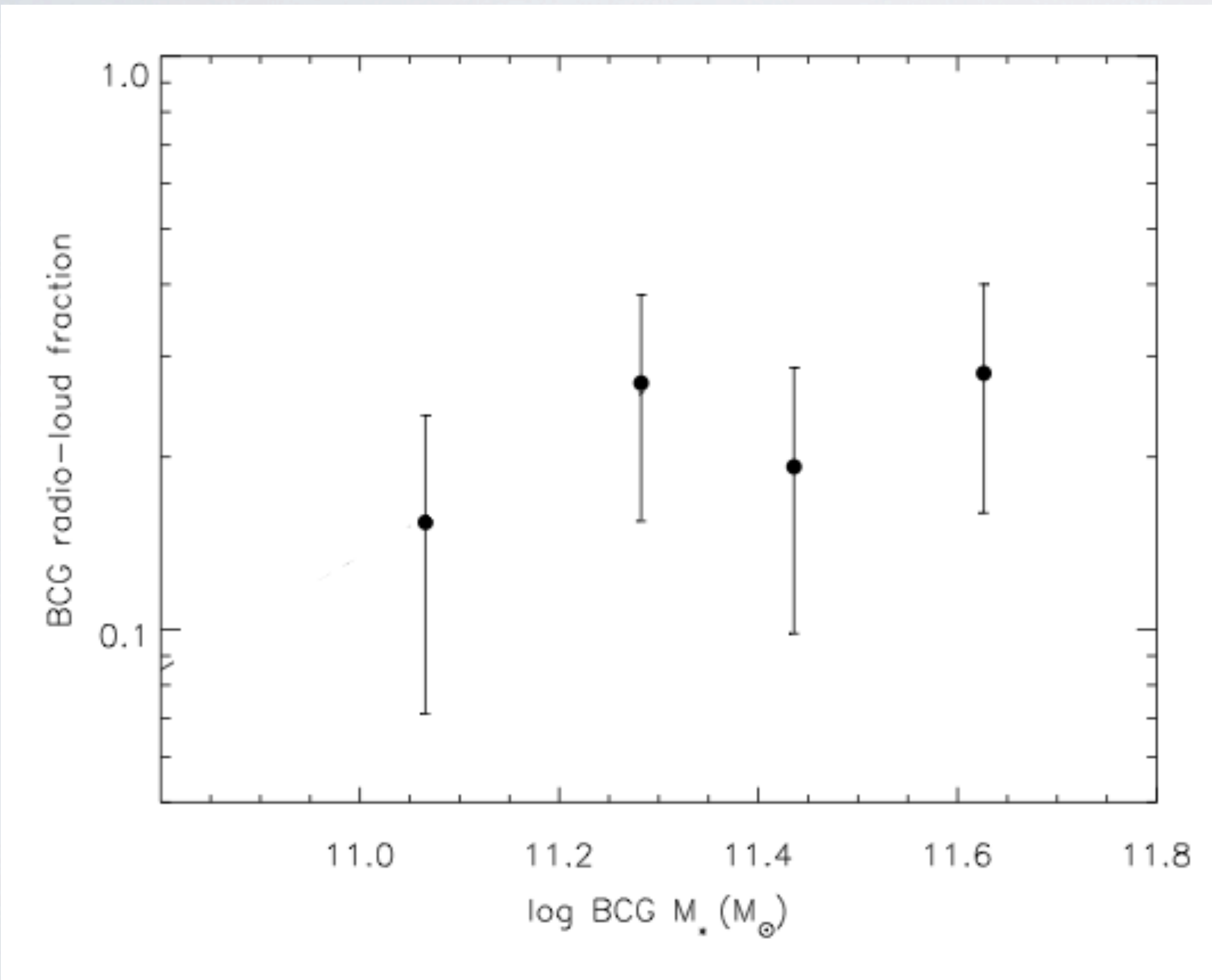
- Simulated slope: 1.55±0.03
- Observed slope: 1.55±0.31
- Theoretical slope: 1.56±0.05

Correlation between Δm_{BH} and *c*?

ρ=0.29 ; P=0.9998

Strong and positive!

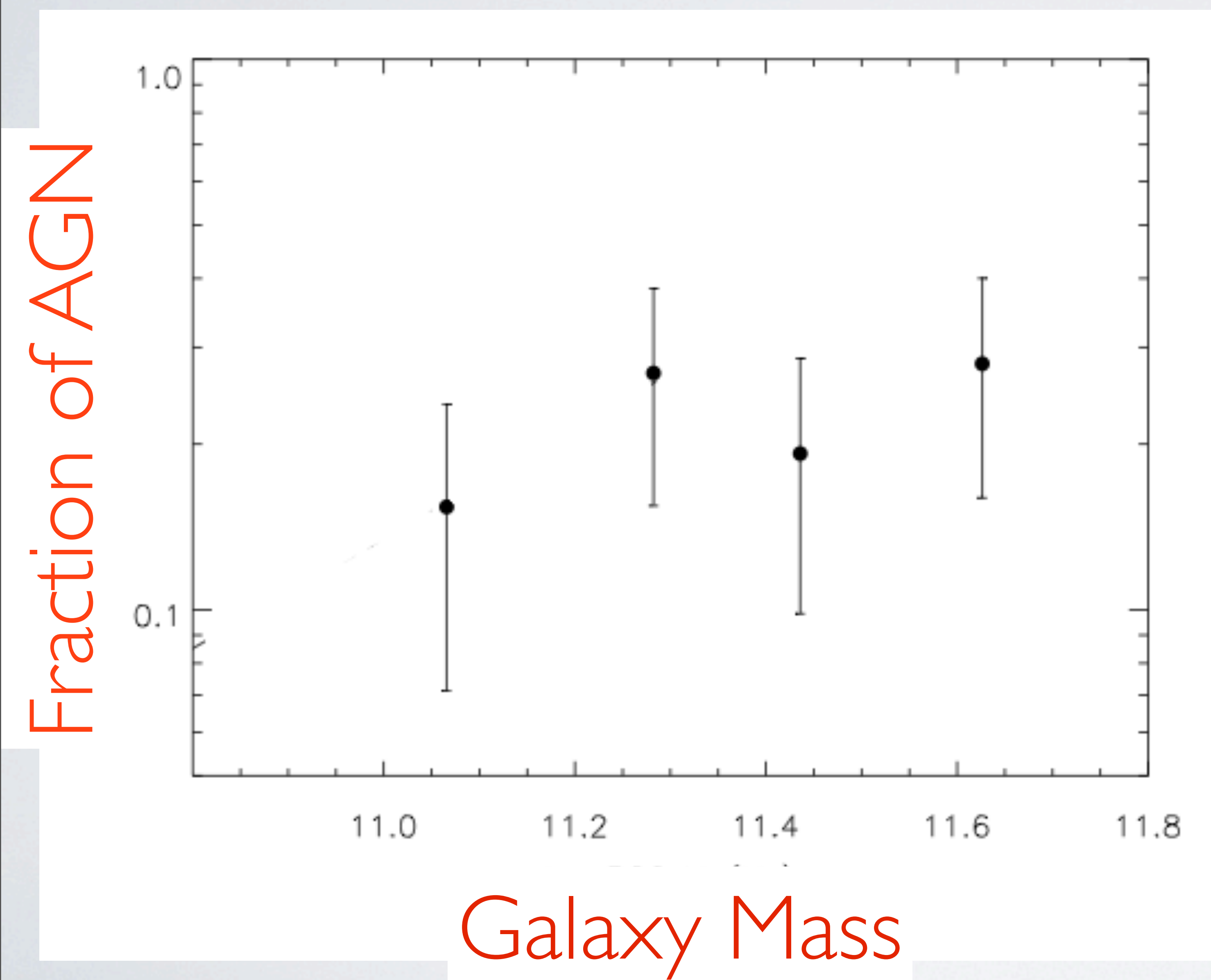
OBSERVATIONAL EVIDENCE?



- Sample of clusters from XMM
- Central galaxies from SDSS
- The AGN fraction does *not* know about galaxy mass

Stott et al. (incl CMB) 2012

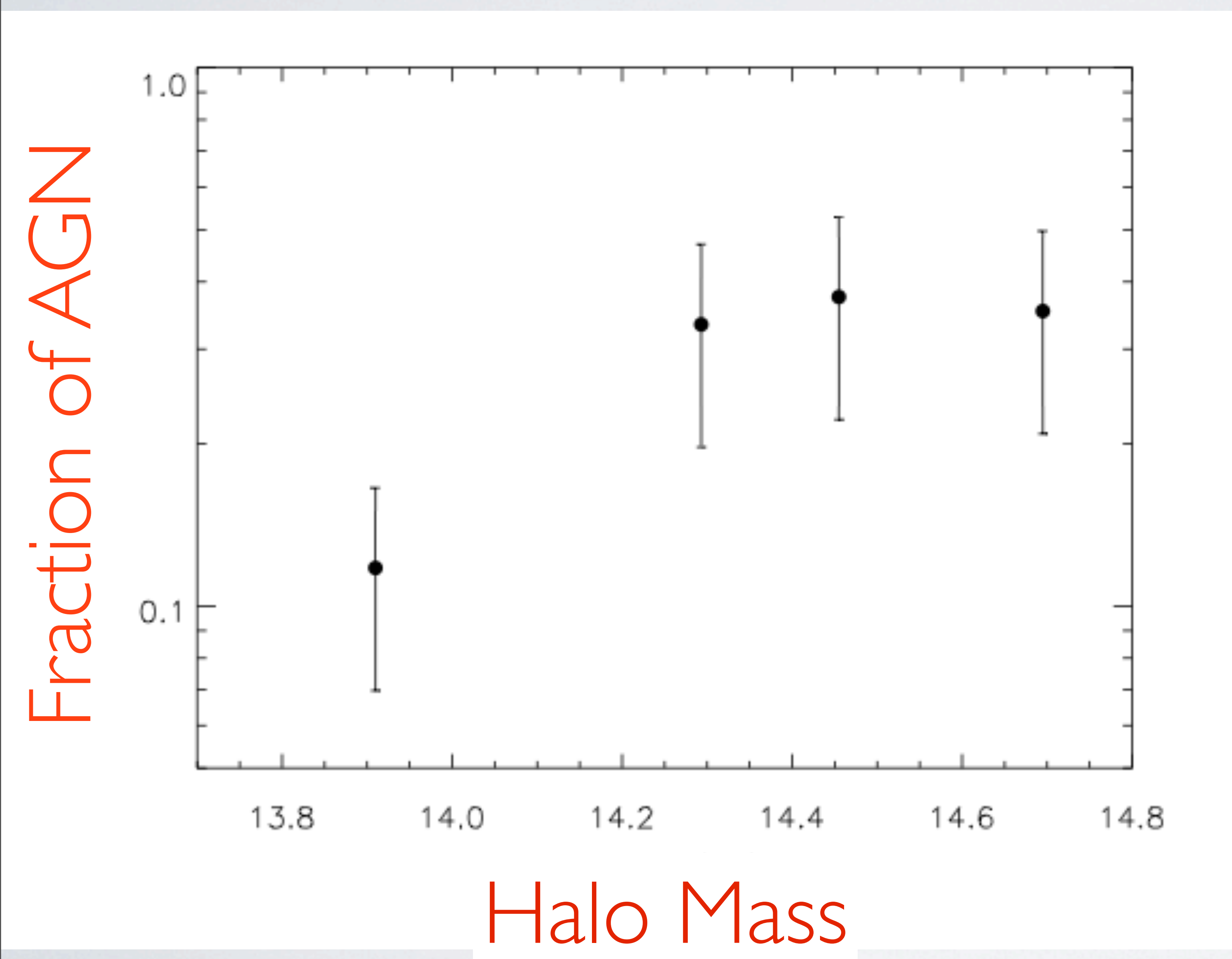
OBSERVATIONAL EVIDENCE?



Stott et al. (incl CMB) 2012

- Sample of clusters from XMM
- Central galaxies from SDSS
- The AGN fraction does *not* know about galaxy mass

OBSERVATIONAL EVIDENCE?



- It does, however, know about halo mass.

From the above relations between AGN fraction and both galaxy and cluster properties it seems that the key parameters that govern the presence of AGN in BCGs are primarily the cluster mass/T_X/L_X and to a lesser extent the BCG offset from the cluster X-ray centroid, but not BCG mass. A picture is therefore emerging that the supermassive black holes at the centres of BCGs in cluster cores know more about their host cluster than they do about their host galaxy. While this is consistent with some simulations

Stott et al. (incl CMB) 2012

OBSERVATIONAL EVIDENCE?

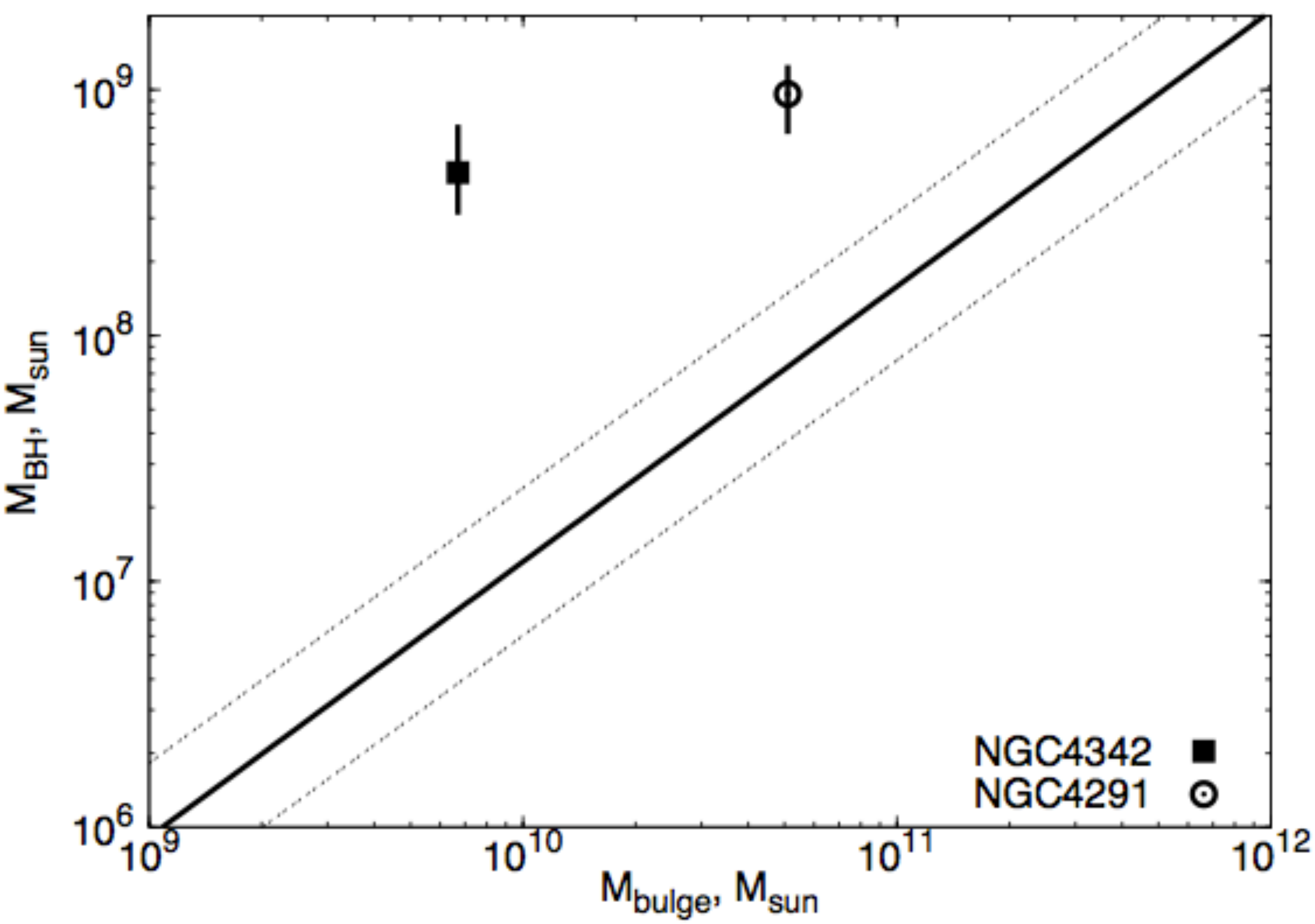


FIG. 3.— Black hole mass as a function of bulge mass. Thick solid line shows the mean $M_\bullet - M_{\rm bulge}$ relation from Häring & Rix (2004), whereas the thin dashed line represent the intrinsic scatter of the relation. Both NGC4342 and NGC4291 are highly significant outliers from the trend.

A major result of this paper is that both NGC4342 and NGC4291 reside in massive dark matter halos. In fact, both the black hole masses and the observed dark matter halos are typical of galaxies having stellar masses that are $\sim 10 - 40$ times greater, hence the characteristics of the dark matter halos are consistent with those expected for the black holes. Therefore the only truly anomalous property of NGC4342 and NGC4291 are their low stellar masses. Since the black hole mass correlates well with the halo mass, it suggests that dark matter halos may play a fundamental role in governing the black hole growth.

Bogdan et al. (2012)

OBSERVATIONAL EVIDENCE?

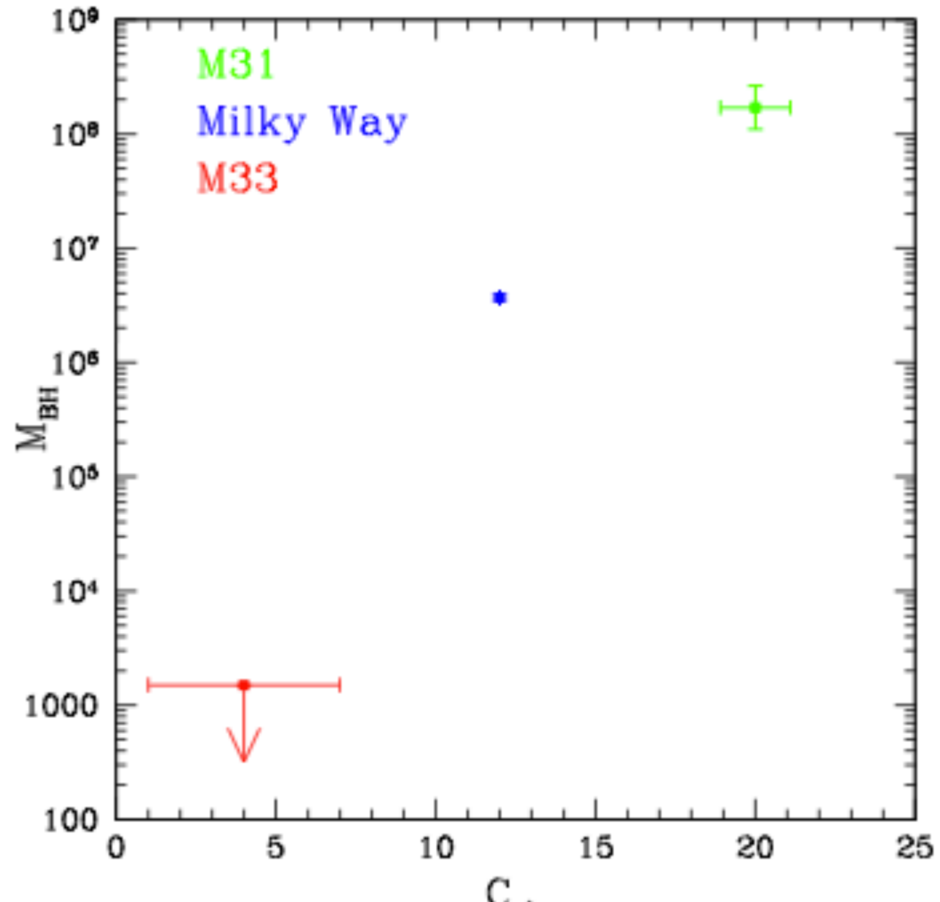


Figure 5: Central supermassive black hole mass versus NFW concentration parameter, showing a correlation. The green point represents data for M31, the blue point for the Milky Way and the red point shows the data for M33.

Seigar (2011)

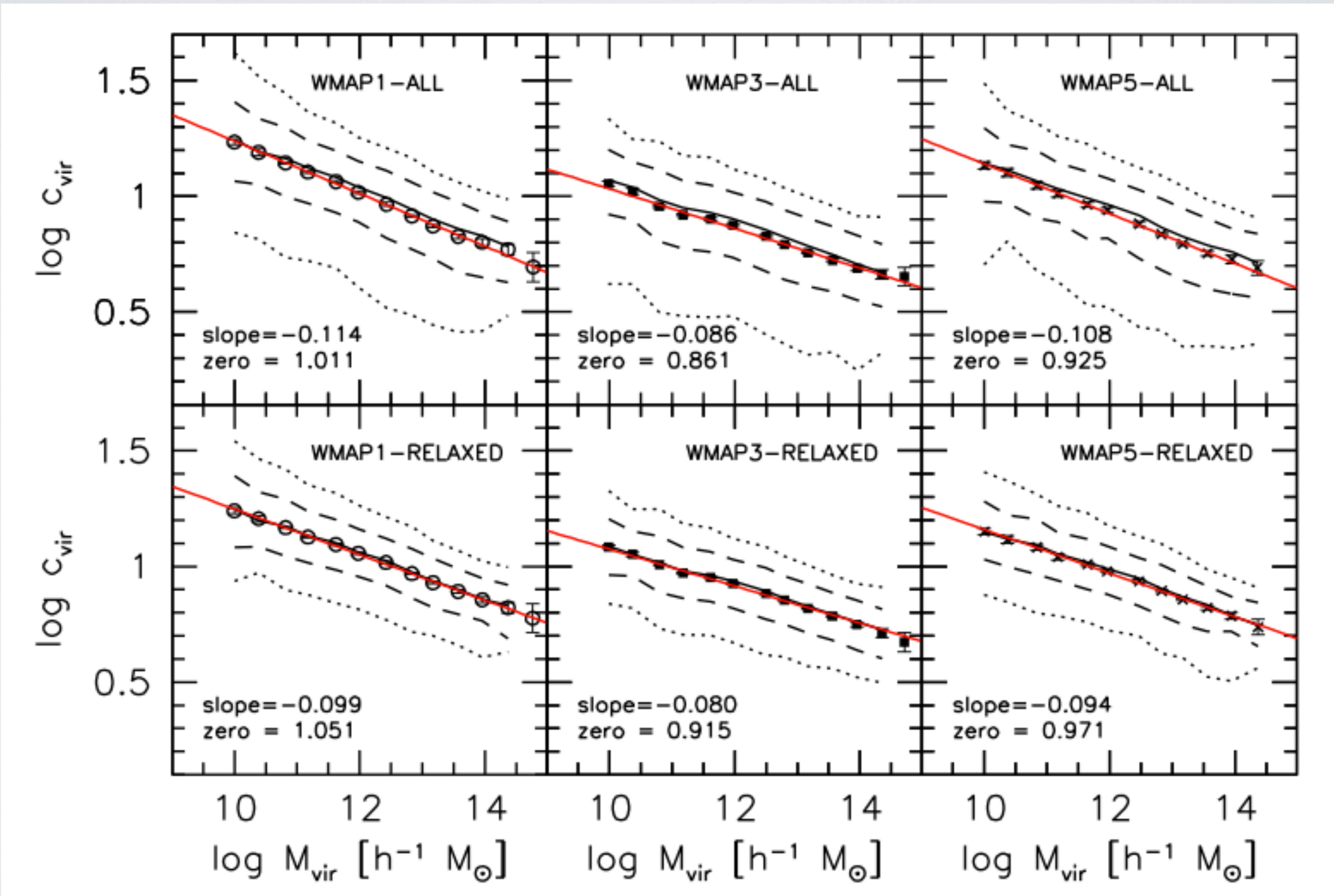
- Can estimate DM halo profiles from the stellar rotation curve
- This is difficult to do accurately, so results only exist for a few objects
- Same correlation as predicted earlier

CONCLUSIONS

- Star formation is tightly regulated by the interplay between:
  - The amount of available fuel (cooling and cosmology)
  - The efficiency of feedback processes
- Galaxies simply adjust their properties so that the rate of energy output is the same
- BH mass is set by the DM halo mass with a secondary dependence on halo concentration, as would be expected if BH mass were dependent upon DM halo binding energy.

WHERE NEXT?

- OWLS weakness: it is great for exploring what physics is important; some key observables are not reproduced
- EAGLE: Use what we learned while doing OWLS
  - The intersection of simulations and semi-analytics



Maccio et al. 2009