SELF REGULATED BLACK HOLE GROWTH

What sets the masses of supermassive black holes?

Craig Booth
Leiden Observatory
with
Joop Schaye & the OWLS team

1. What are we doing?
2. Does it work?
3. What can it tell us?

CMB & Schaye, 2009, MNRAS, 398, 53
CMB & Schaye, 2010a, MNRAS 405, L1
CMB & Schaye, 2010b, MNRAS submitted
McCarthy+ , 2009, MNRAS 406, 822

Durham, July 2010

WHAT ARE WE DOING?

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

Containing: Gas, DM, Stars Scales ~ kpc to ~ 100 Mpc

Contains 1,000's of galaxies

Sub-grid modules are of vital importance...

Treat these like 'toy models'

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)

An example...

AN EXAMPLE:

Density Metallicity

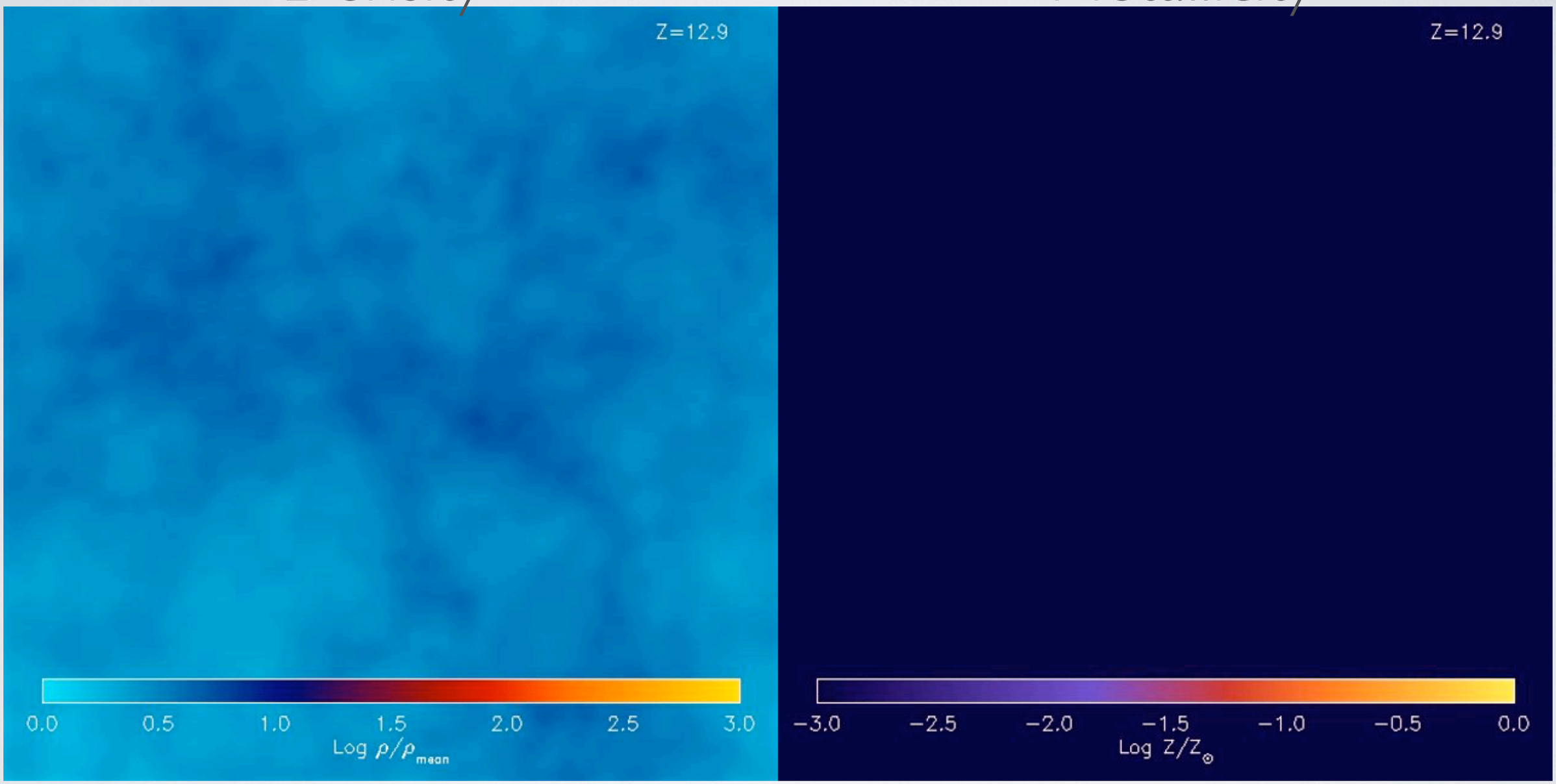
← 10 Mpc →

0.1% of the computational volume

AN EXAMPLE:

Density

Metallicity



10 Mpc

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AGN MODEL

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

The model has three components:

- Black hole formation

==> results robust for 'reasonable' parameter values

- Black hole growth (mergers and gas accretion)

- AGN feedback

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

Feedback efficiency, ϵ_f, is the major factor that controls the mass of BHs

AGN MODEL

Va

The mo

- Black

- Black

- AGN

Fe

By necessity very crude!

"grossly leap over five orders of magnitude"

However!

At this resolution results are robust so long as two criteria are met:

1. Accr. rate increases with density
2. Accr. rate reaches Eddington

Assume gas *can* get into BHs

Posters: Alex Hobbs (4.8) Paramita Barai; Talks: e.g. Chris Power, Phil Hopkins

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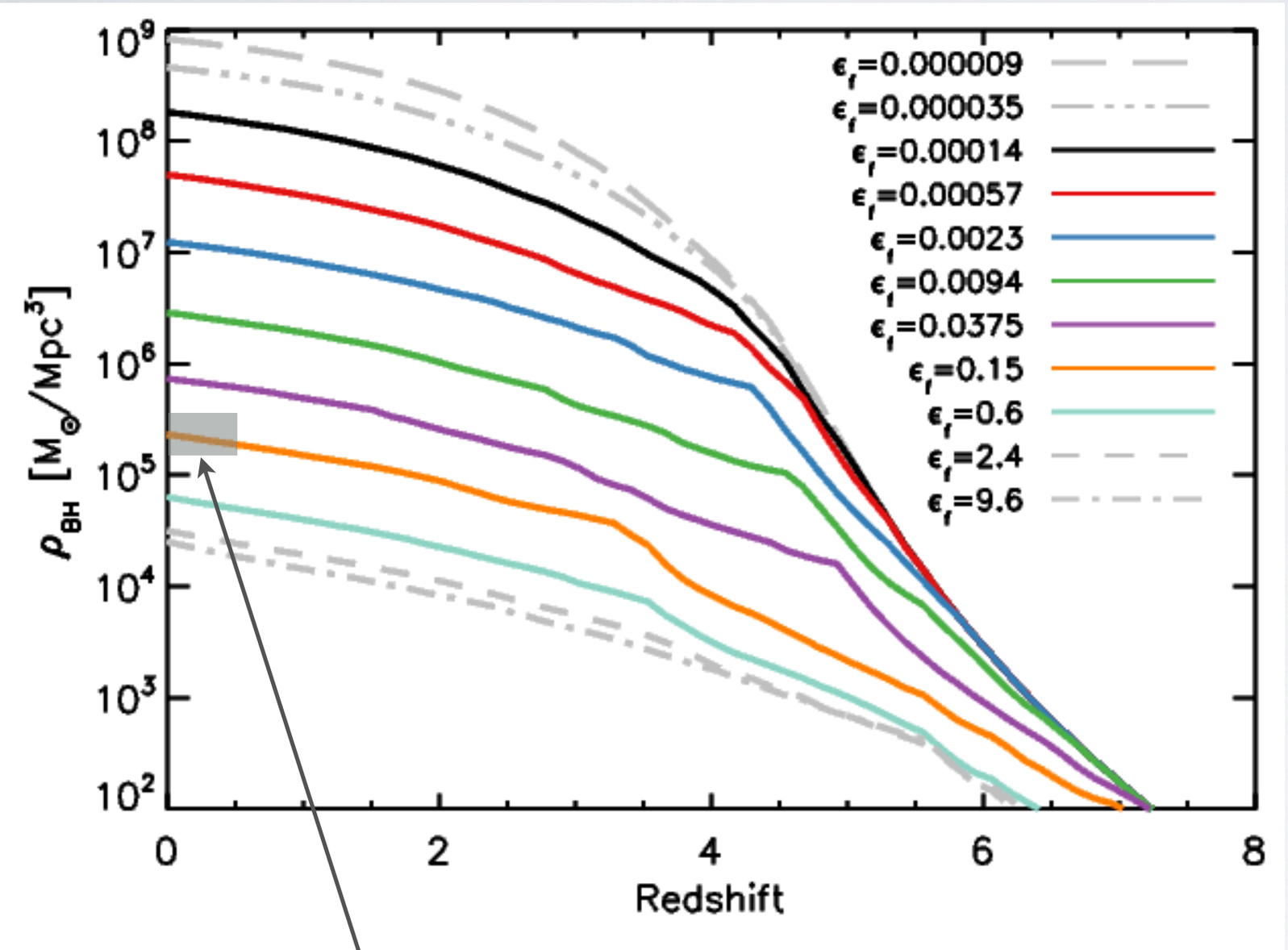
4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE



Shankar et al. (2004)

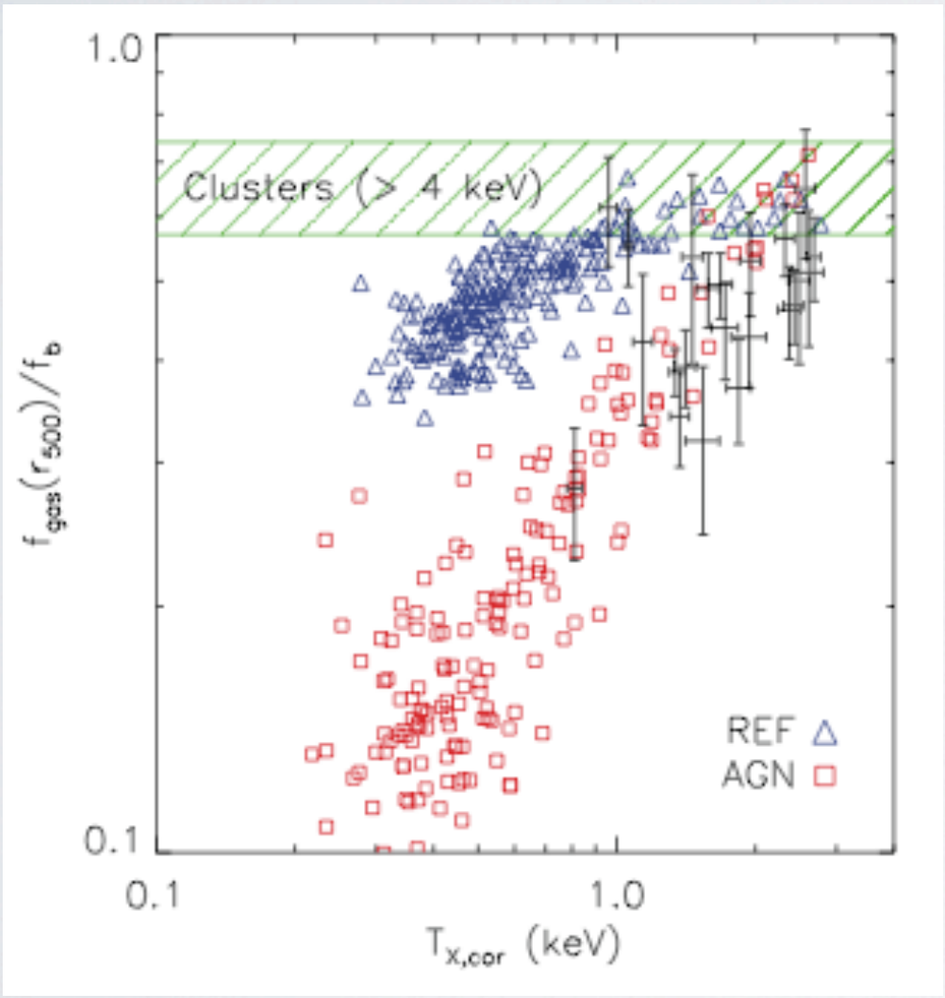
- The free parameter ϵ_f controls the total mass in BHs
- 0.15 reproduces observations.

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

THE EFFECT OF AGN FEEDBACK

McCarthy et al. (2009)

Red=AGN Blue=No AGN



AGN decrease gas fractions in groups

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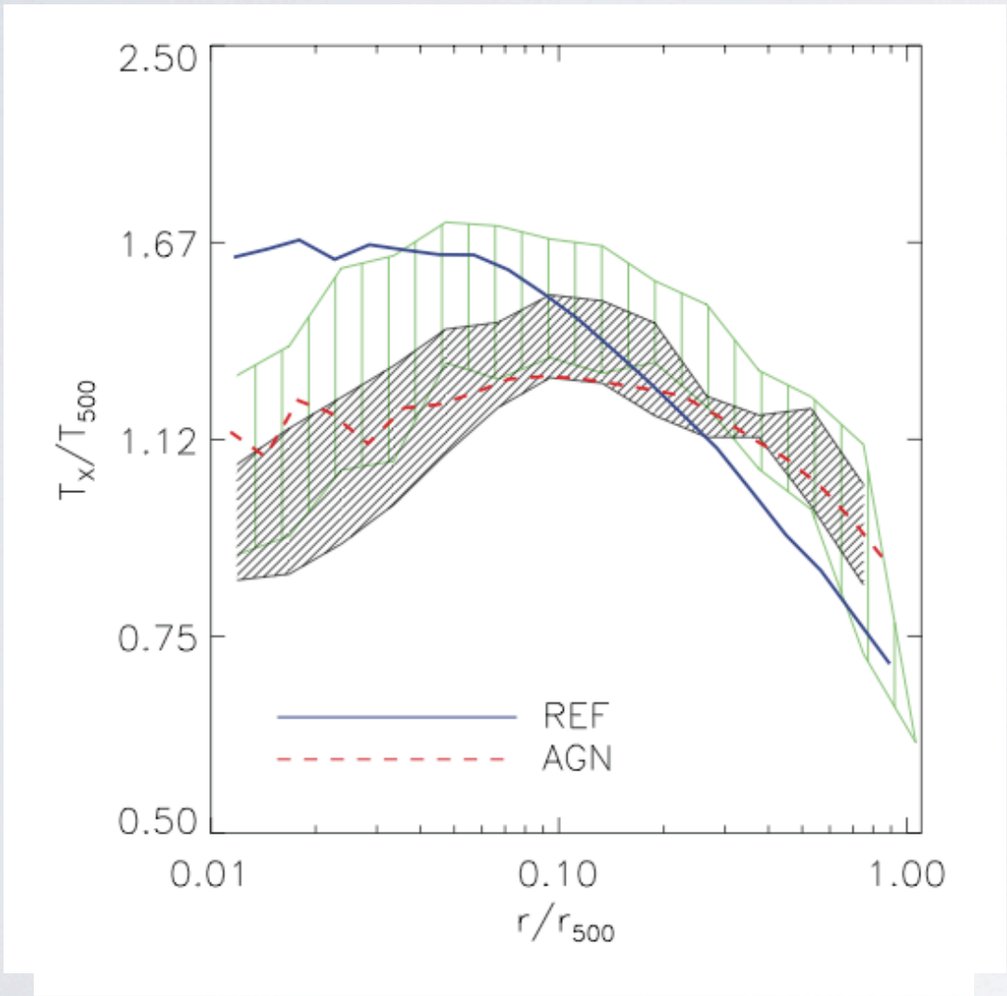

AGN decrease gas fractions in groups

Which prevents excessive accumulation of baryons in the halo centre

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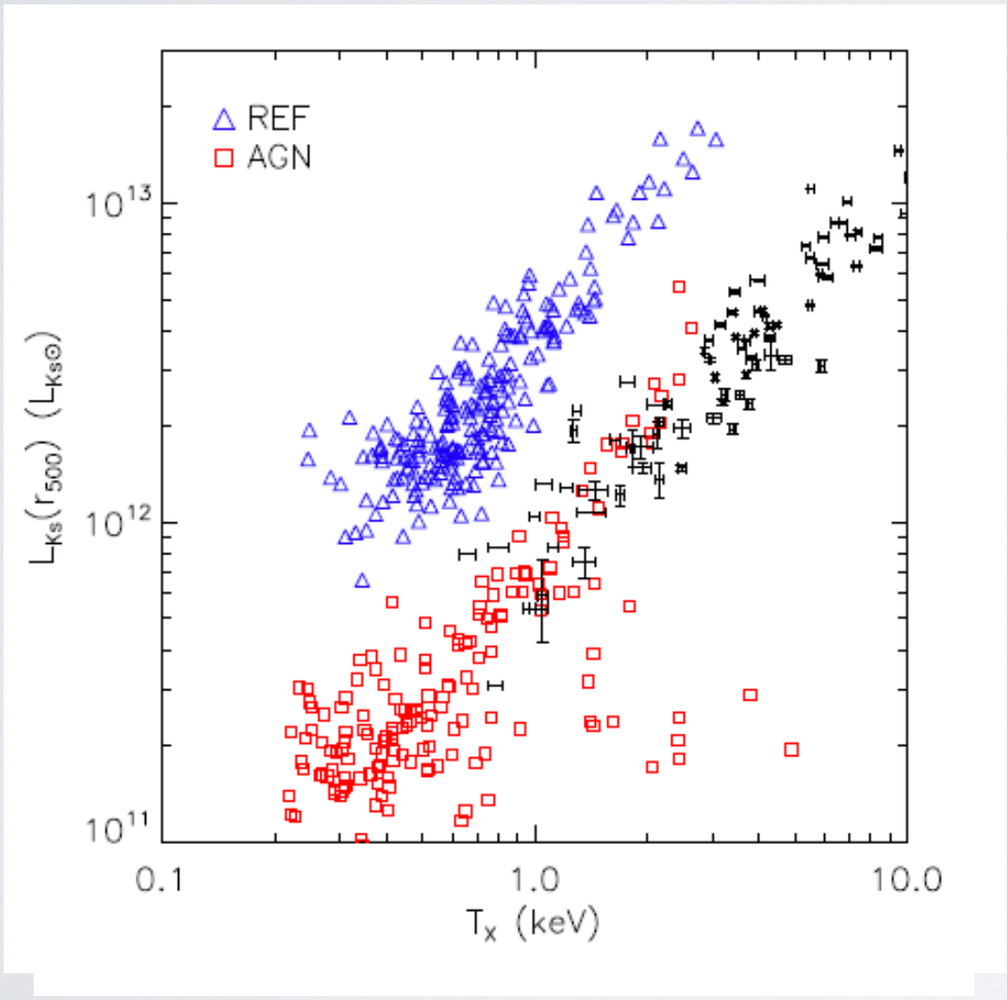


Lin & Mohr (2004), Horner (2001)

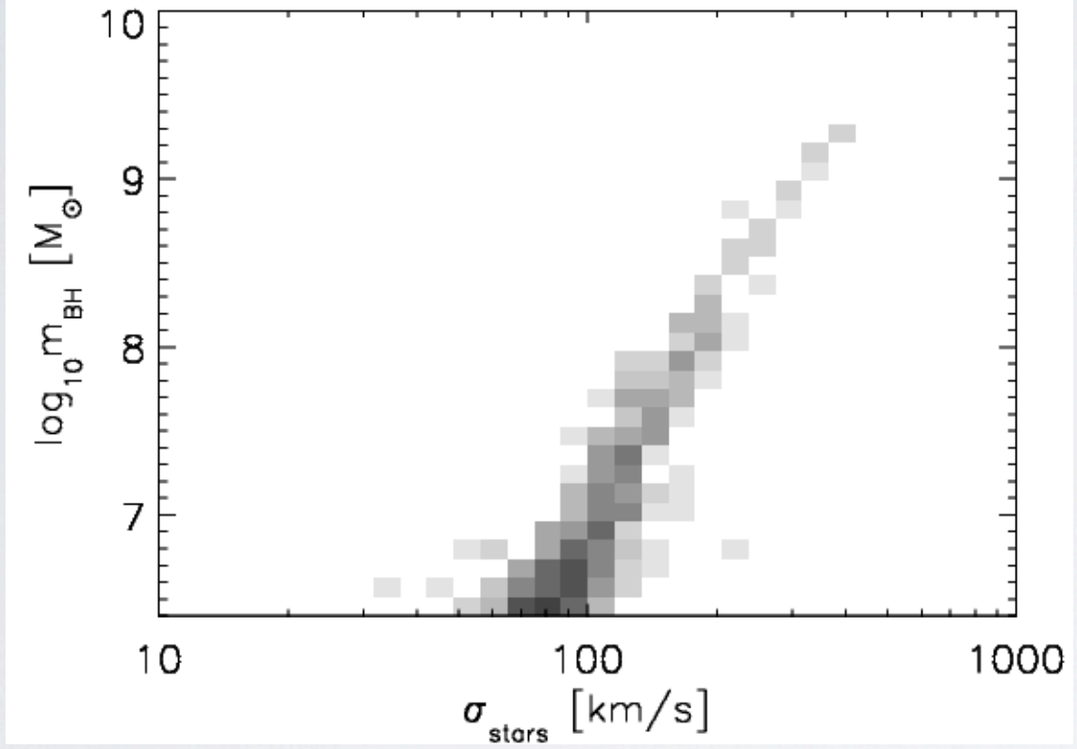
AGN decrease gas fractions in groups

Which prevents excessive accumulation of baryons in the halo centre

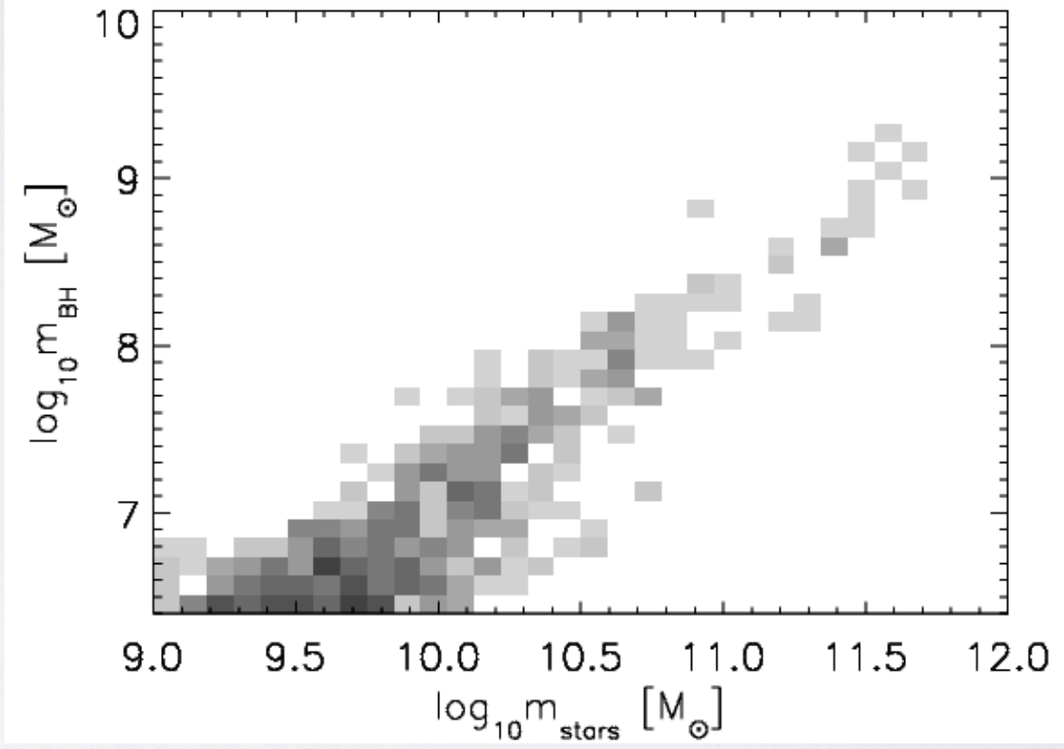
Bringing K-band magnitudes in line with observations

THE BH POPULATION

Booth & Schaye (2009a)



BH mass vs stellar velocity dispersion



BH mass vs stellar mass

see also e.g. Di Matteo et al. (2008)

THE BH POPULATION

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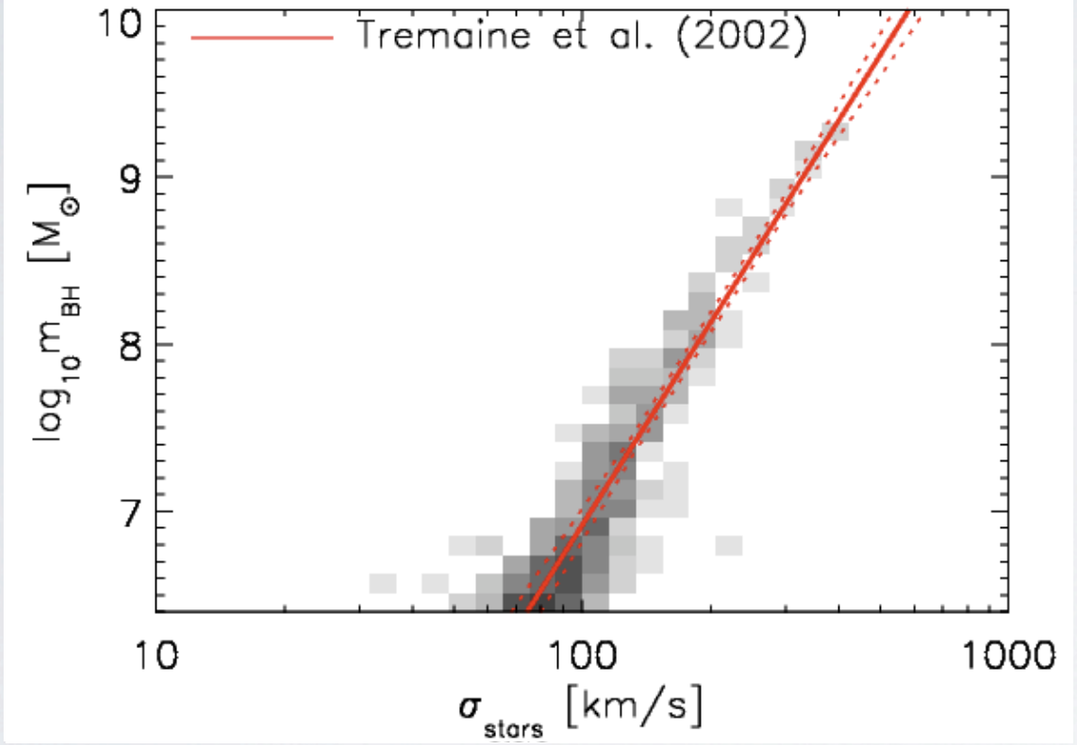

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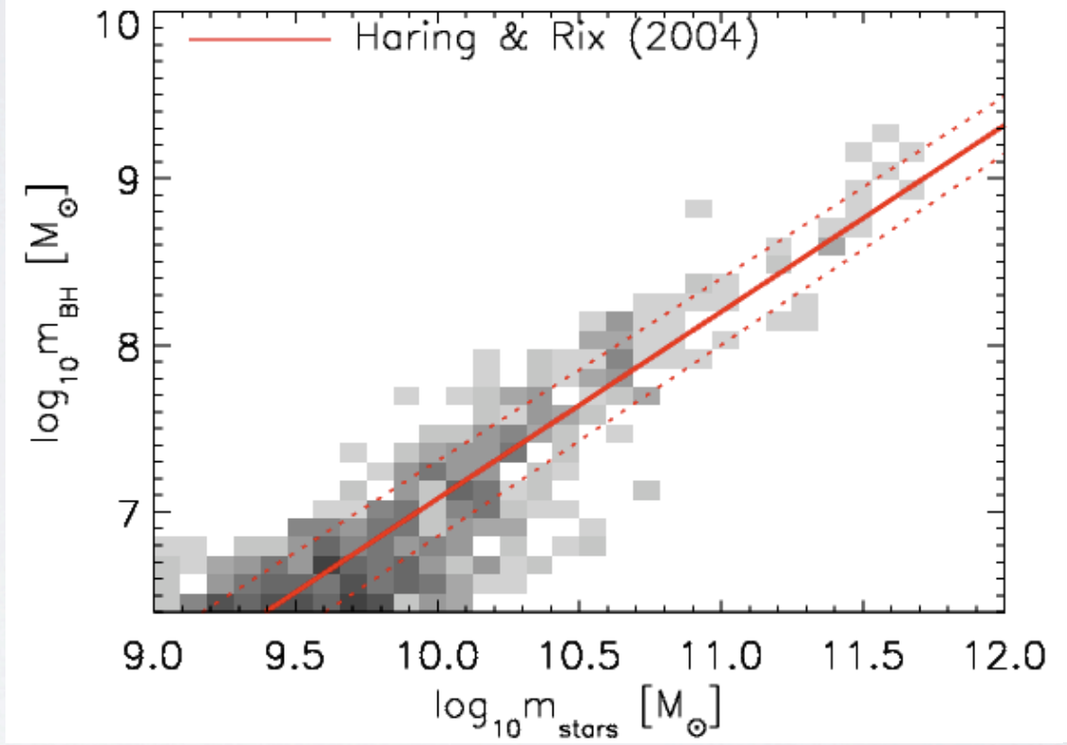

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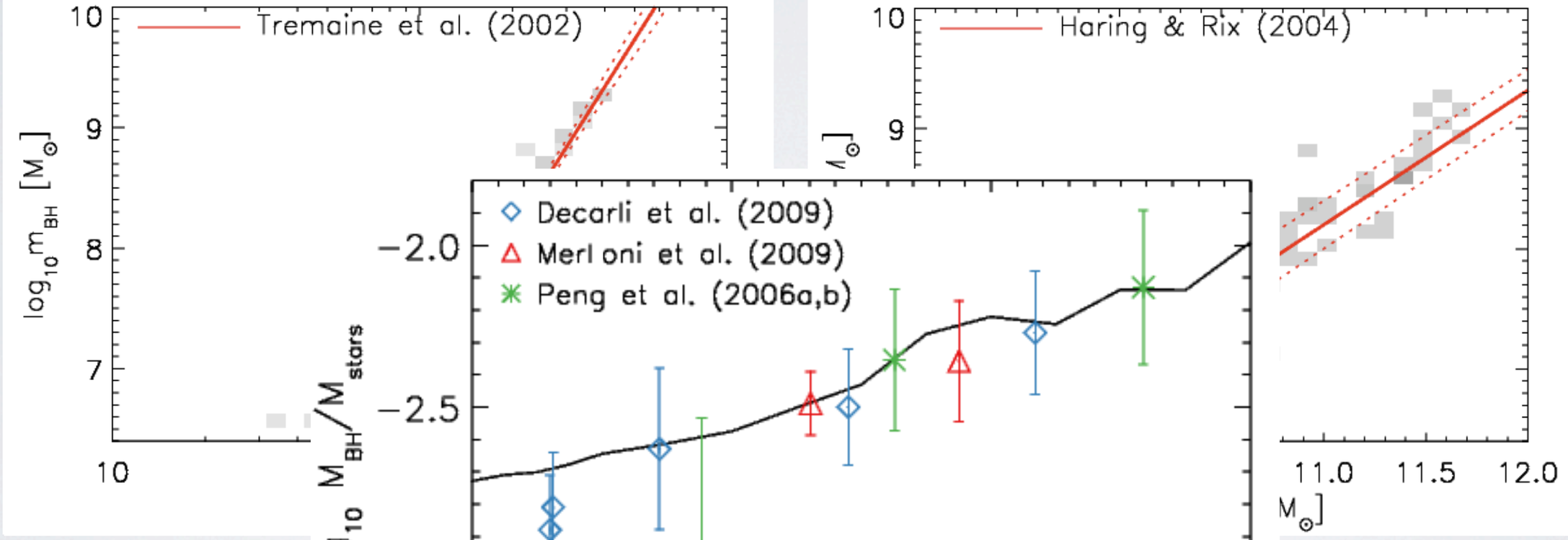


BH r … stellar
veloc …

Di Matteo et al. (2008)

THE EFFECT OF AGN

- Note, these simulations were tuned *only* to match the amount of BHs, but still reproduce
  - BH-galaxy connection.

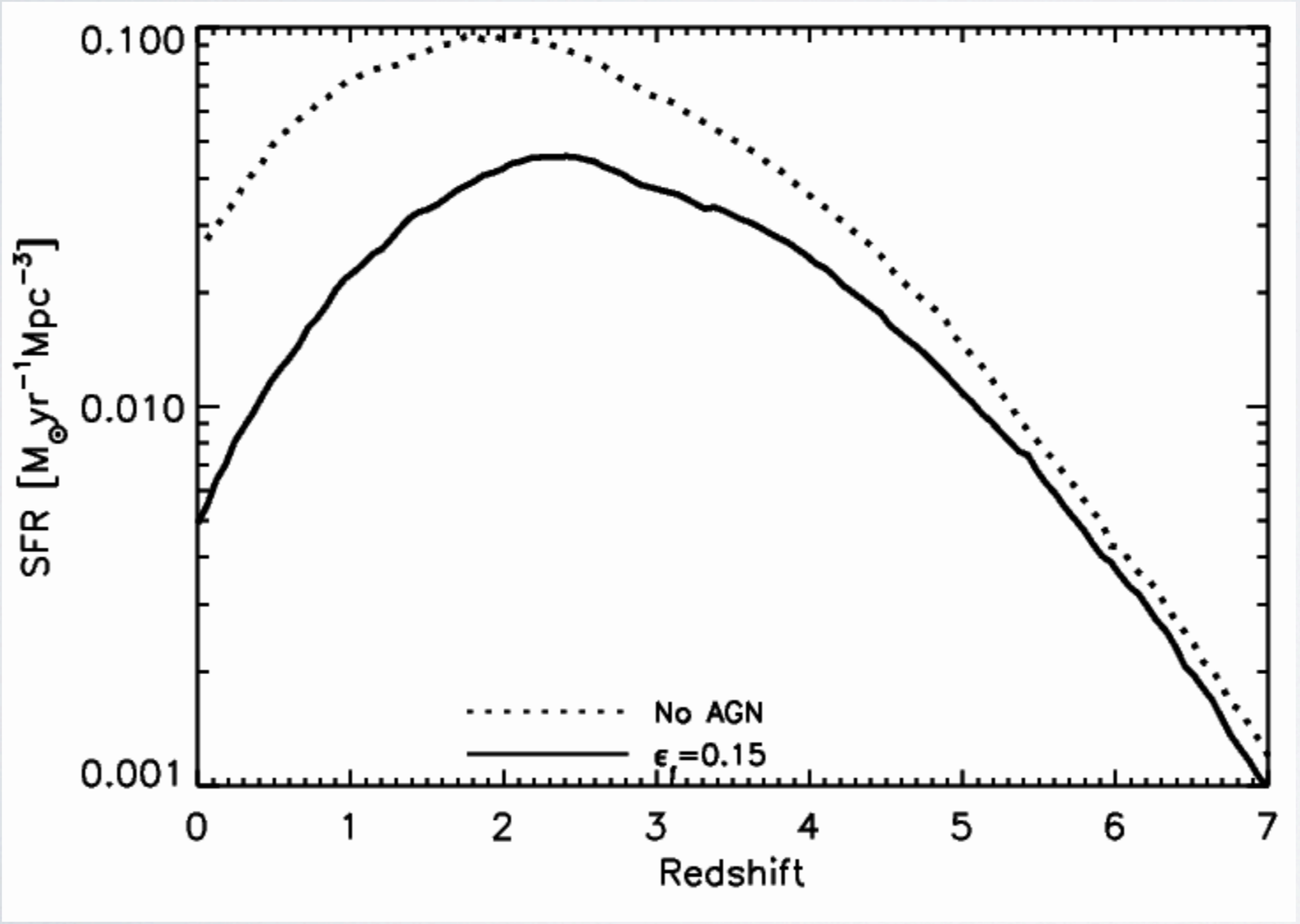
    Also black hole fundamental plane
  - Thermodynamic properties of groups and clusters

    Also entropy profiles, metal profiles, etc.
  - Properties of central galaxies.

    Also distribution of stellar ages, etc.
- What, then, can we learn from these simulations?

WHAT DETERMINES THE MASSES OF SUPERMASSIVE

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



Start with the Madau plot...

...at low z AGN suppress SF

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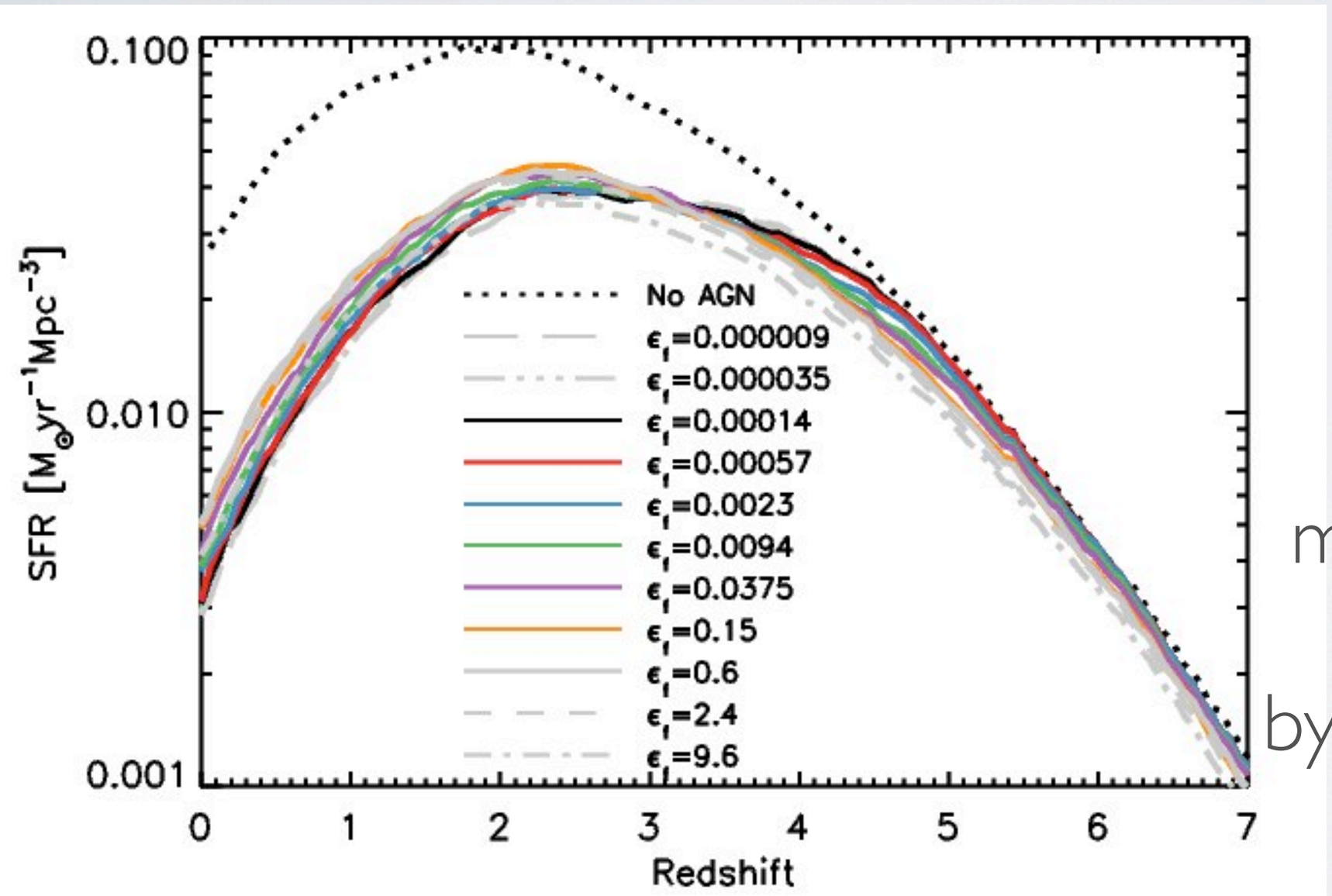

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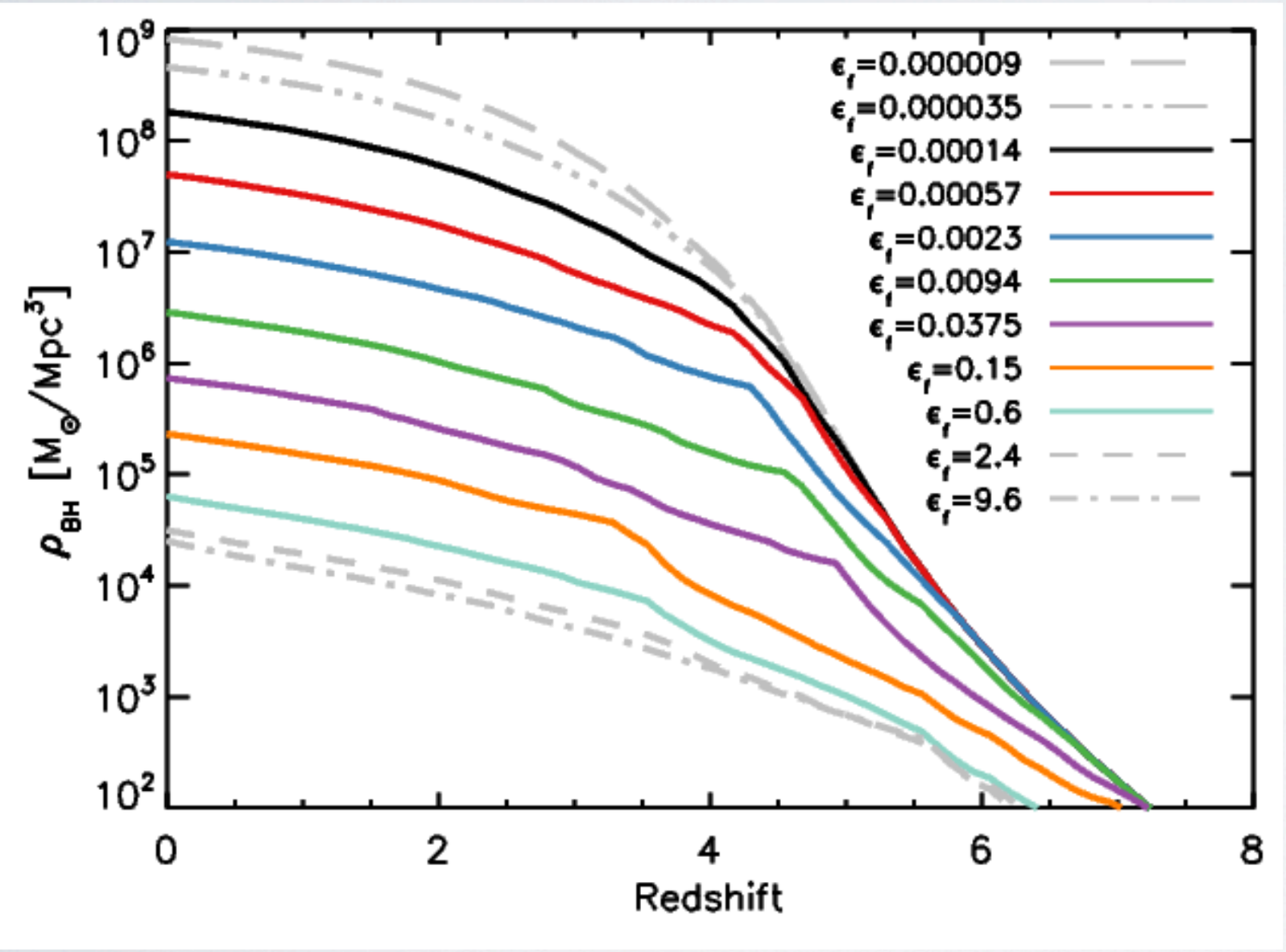
Over 5 orders of magnitude in ϵ_f, SFR does not change by more than a factor of 2

4. WHAT DETERMINES THE MASSES OF SUPERMASSIVE



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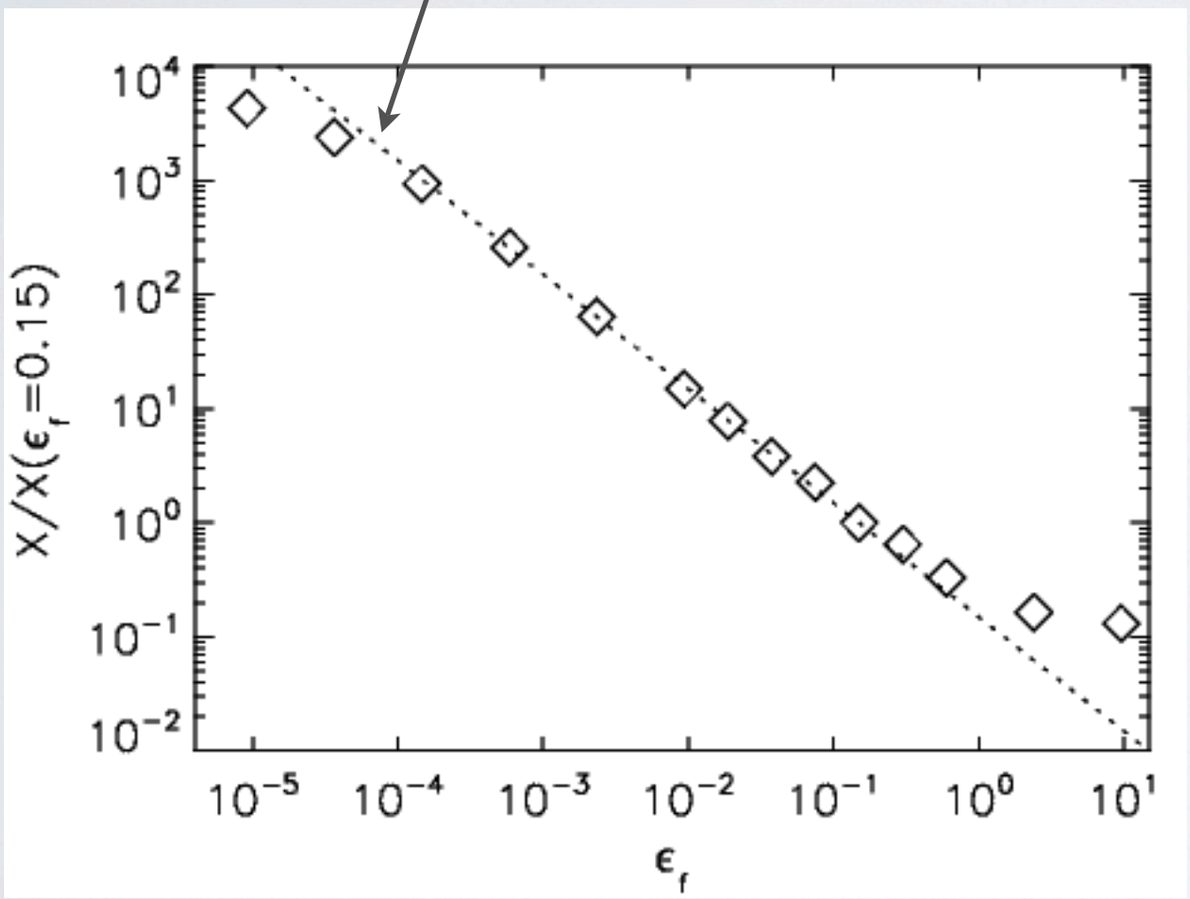
WHAT DETERMINES THE MASSES OF SUPERMASSIVE

Dashed line shows slope of -1



$m_{BH} \propto \epsilon_f^{-1}$

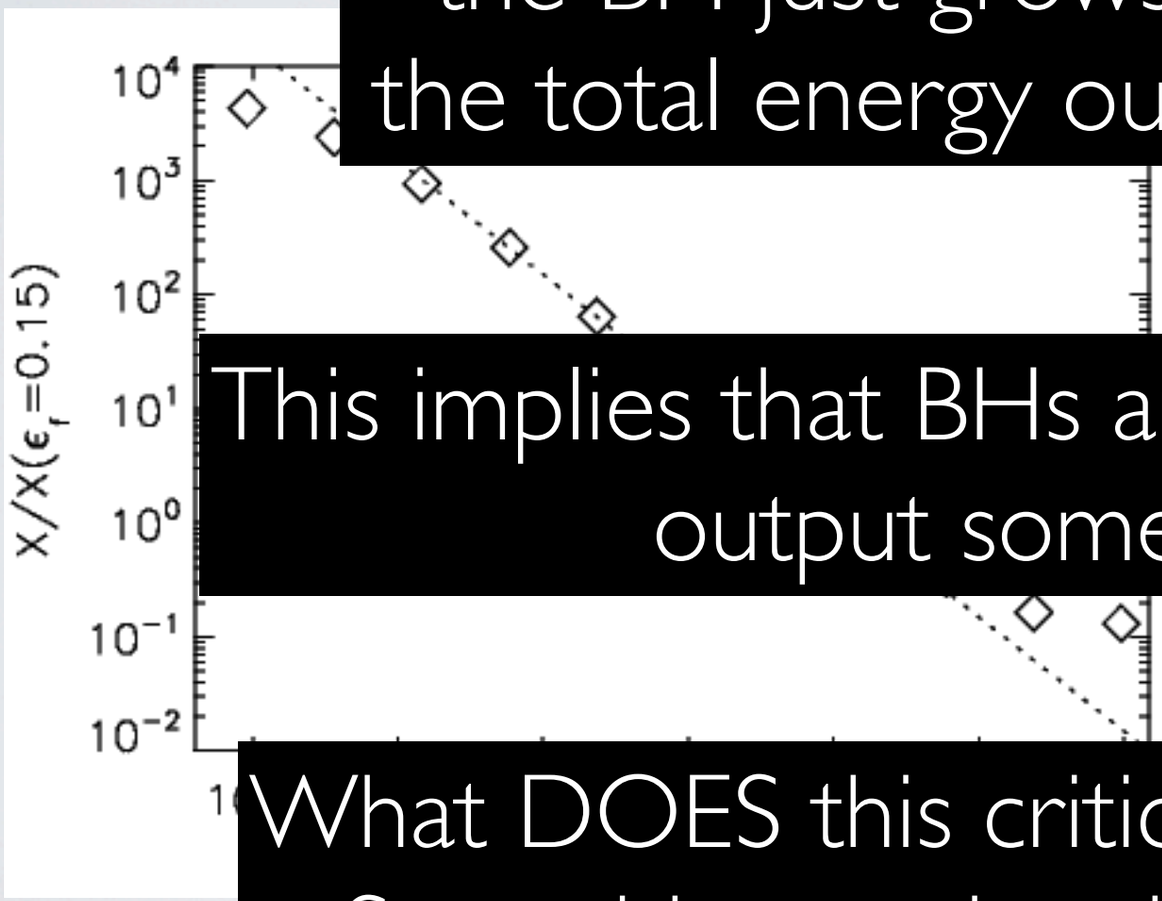
BHs adjust their masses to keep E_{out} constant

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

WHAT DETERMINES THE MASSES OF SUPERMASSIVE

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 keep E_{out} constant

This implies that BHs are growing until they have output some critical energy

...gy"

for self-regulation. What

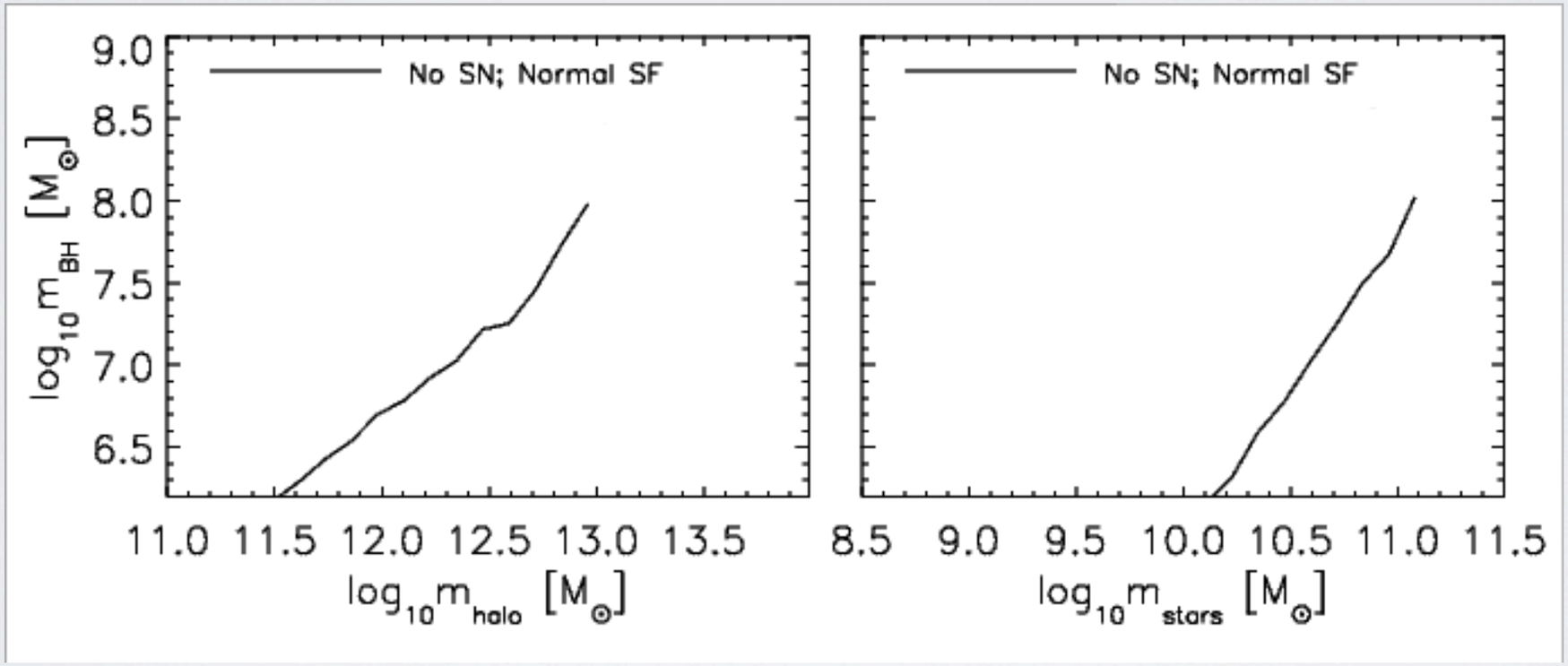
...?

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

WHAT DETERMINES THE MASSES OF SUPERMASSIVE

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

What happens if they are removed?



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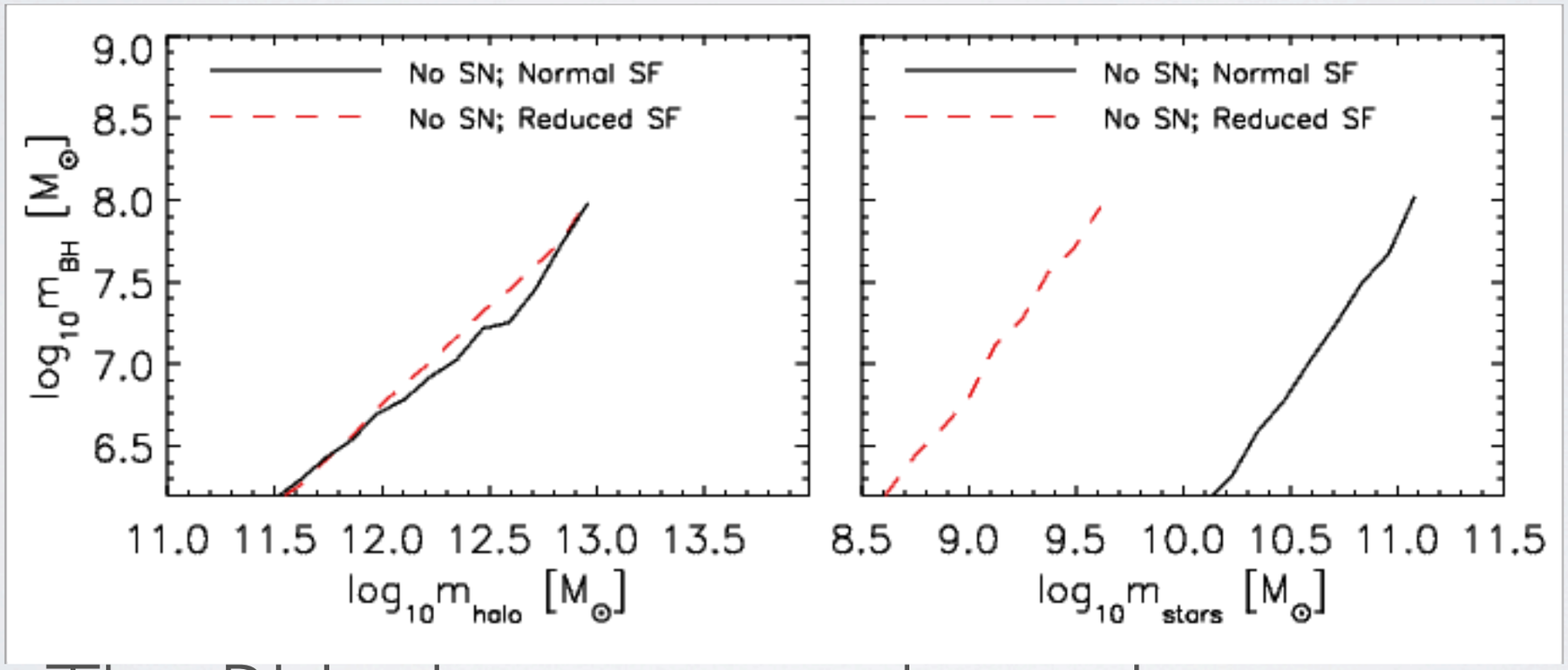
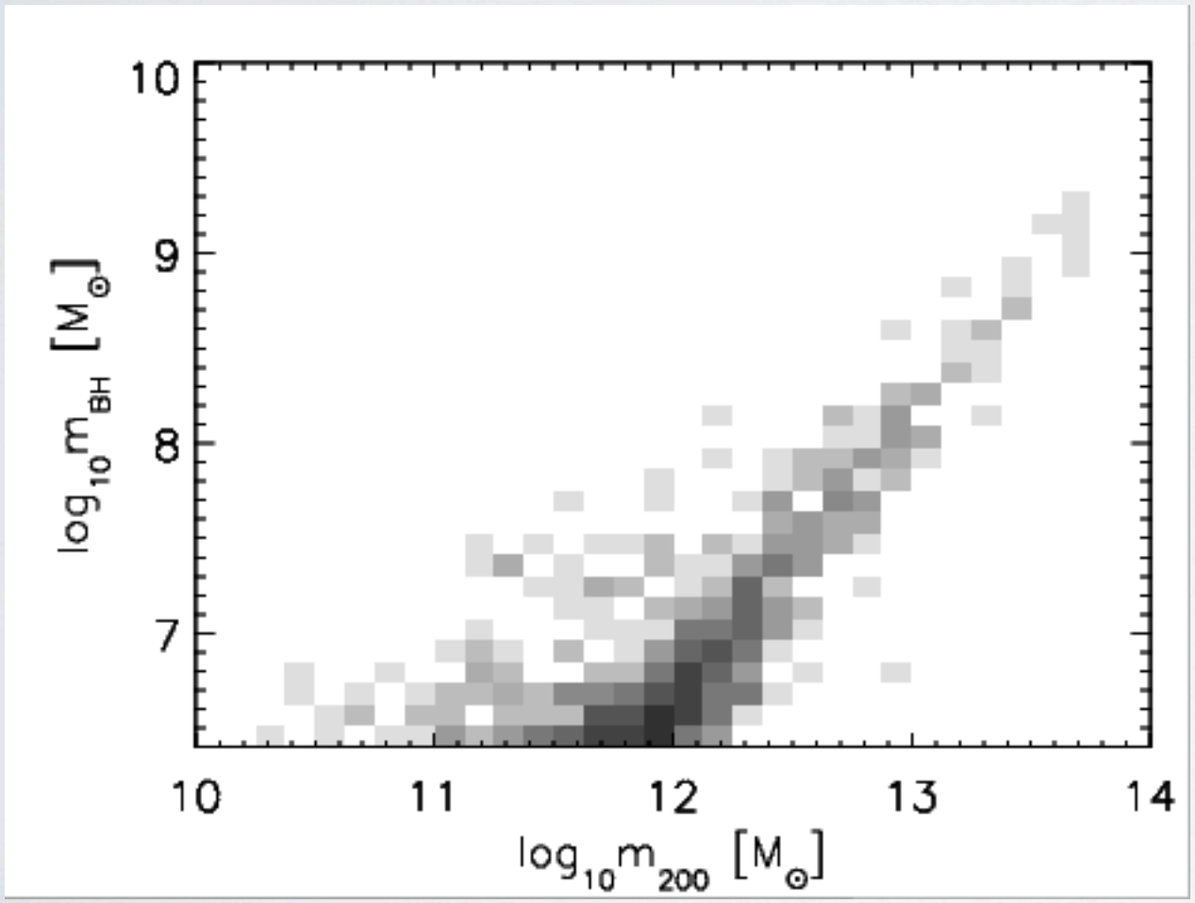


The BHs do not care about the matter distribution on small scales

WHAT DETERMINES THE MASSES OF SUPERMASSIVE

Self regulation occurs on scales > the galaxy

- Simulated slope: 1.55±0.20



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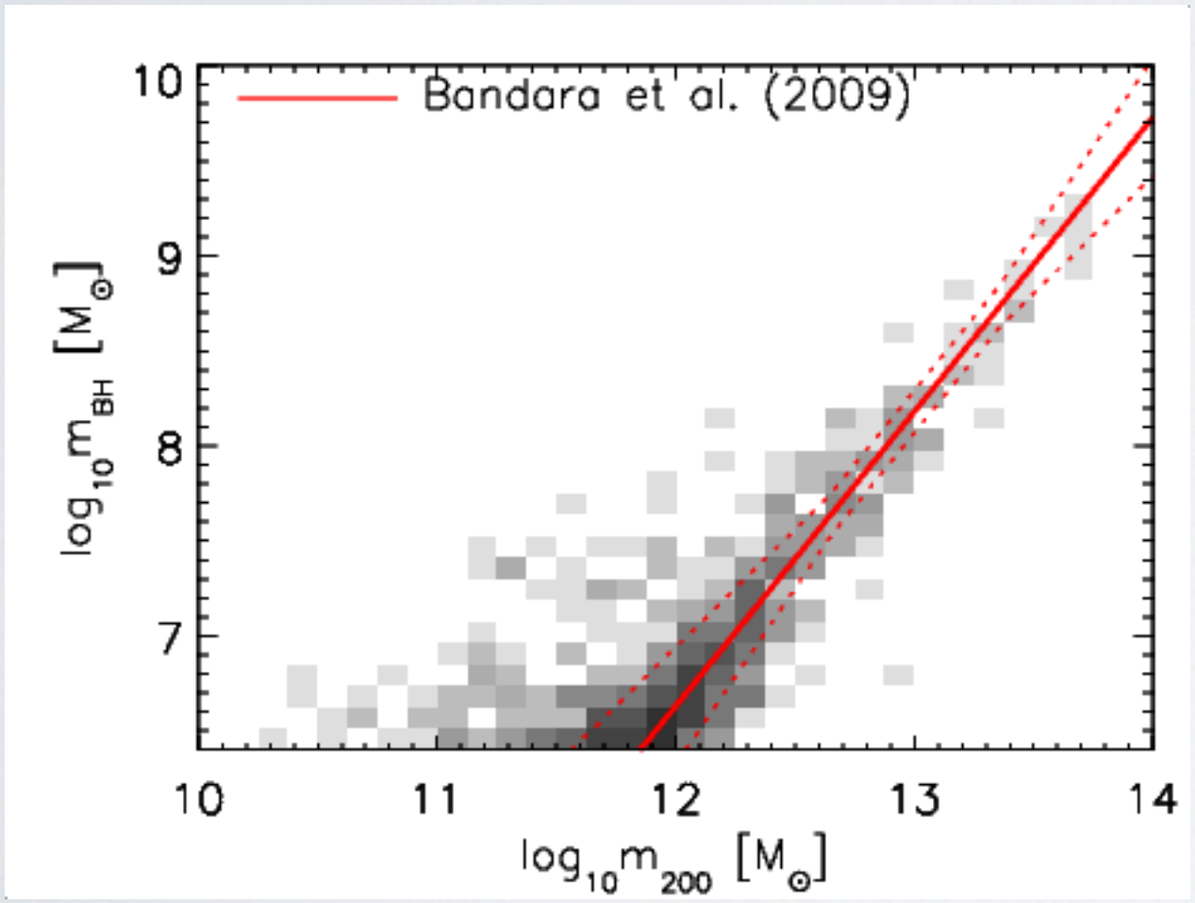

- Simulated slope: 1.55±0.20
- Observed slope: 1.55±0.31

see also Dutton et al. (2010)

WHAT DETERMINES THE MASSES OF SUPERMASSIVE

- 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

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

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

-

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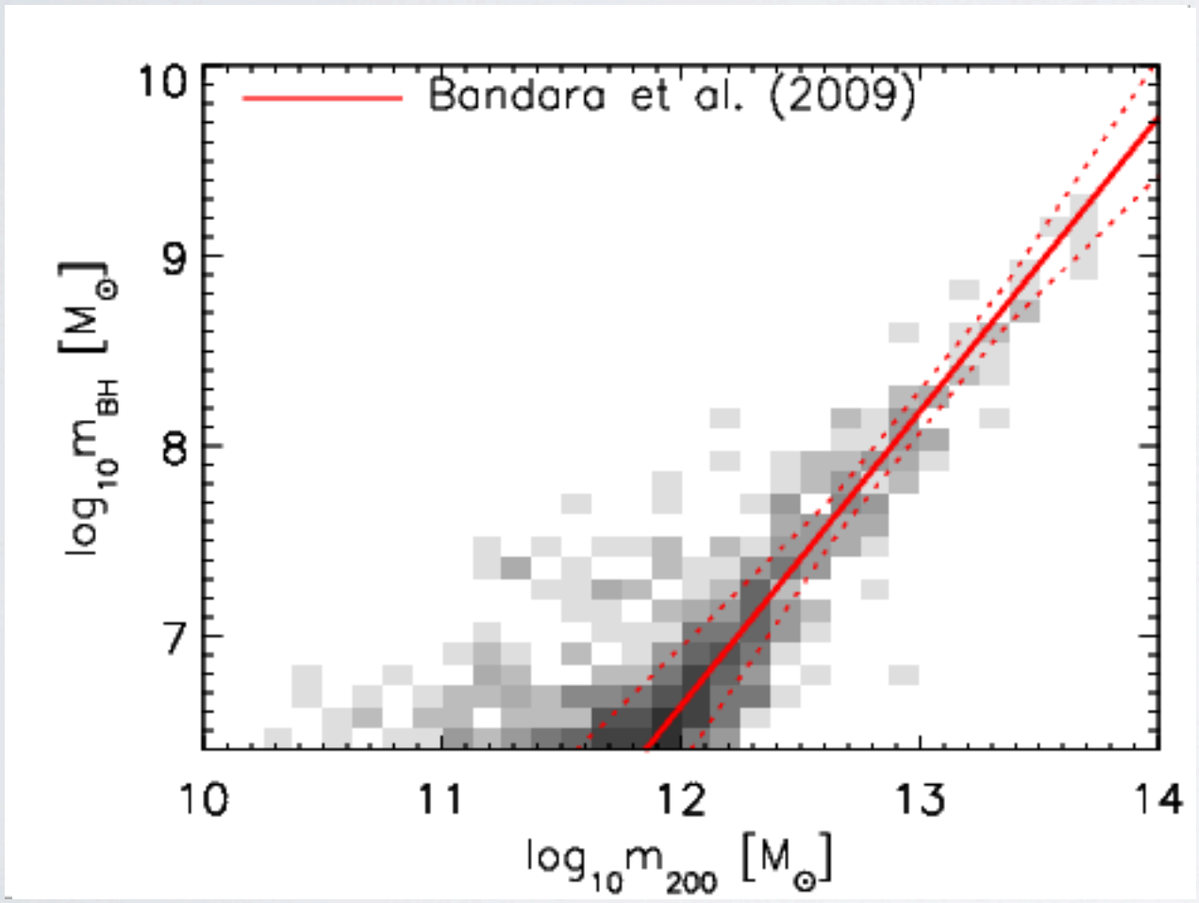

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- Theoretical slope: 1.56±0.05

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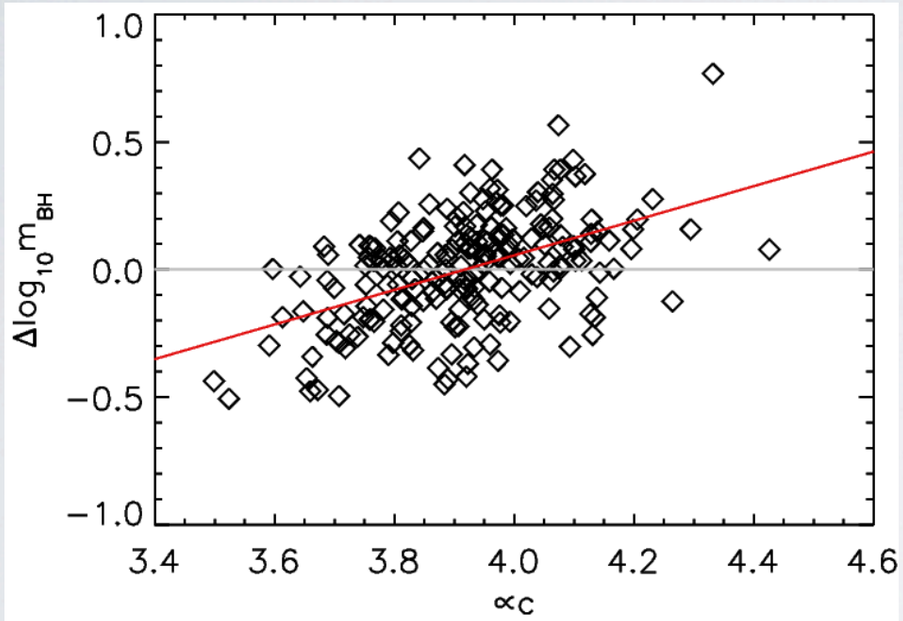
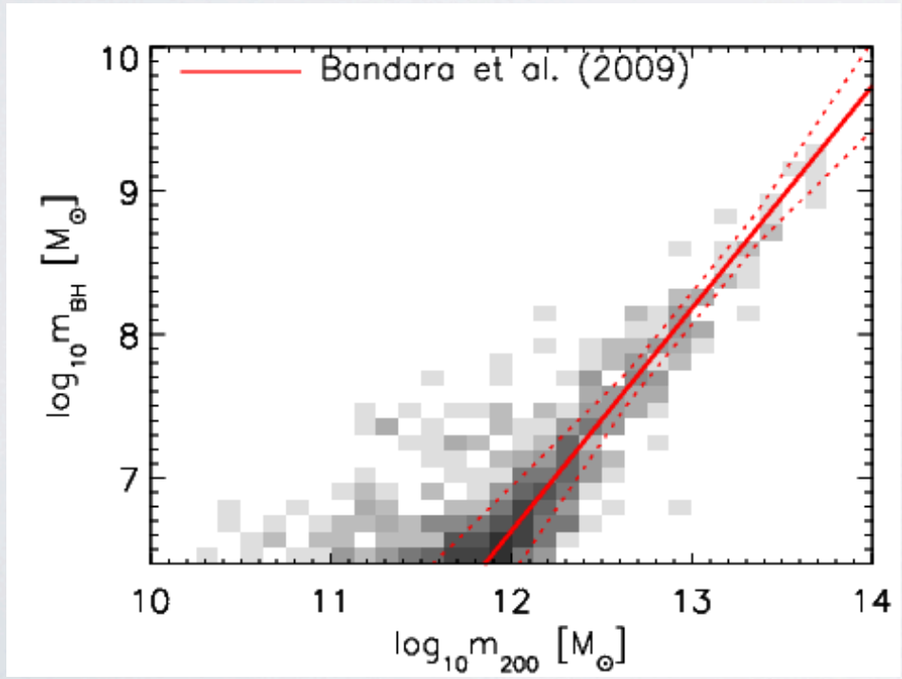
- **Prediction:** If BH mass is determined by DM halo binding energy there should be a relation between residual in the m_{BH}-m_{halo} relation and halo concentration

WHAT DETERMINES THE MASSES OF SUPERMASSIVE





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Correlation between Δm_{BH} and c?

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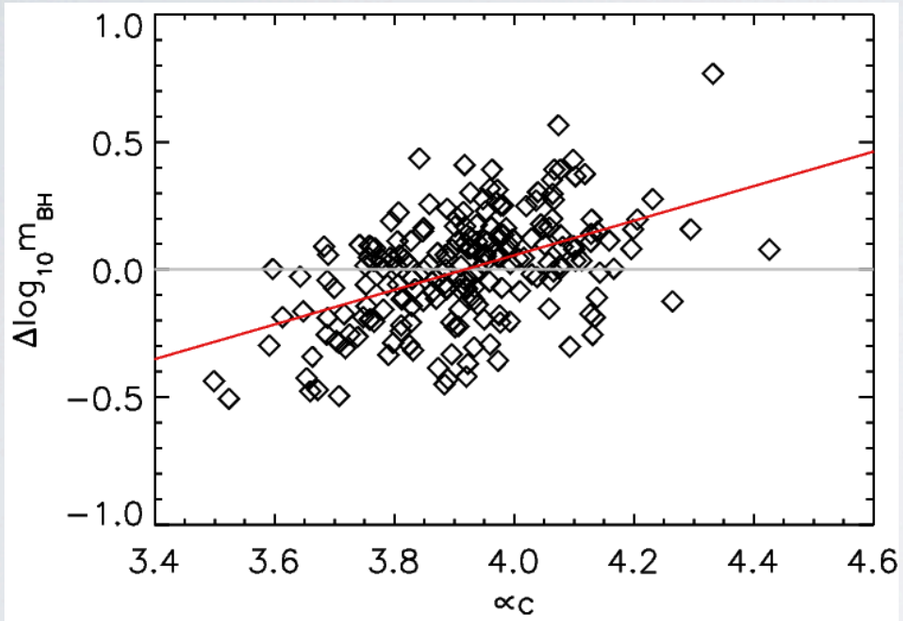

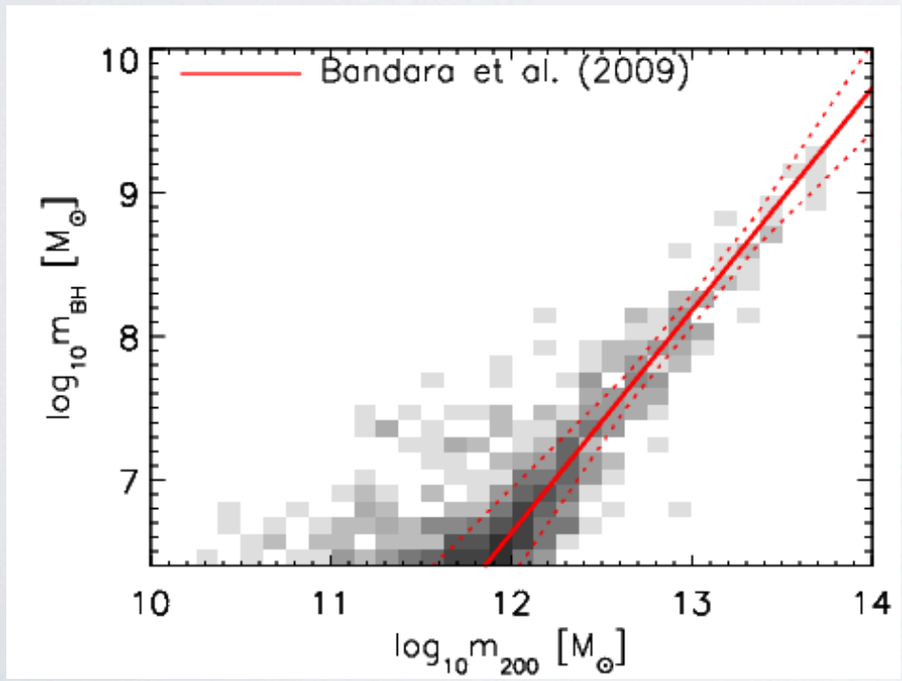

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Correlation between Δm_{BH} and c?

ρ=0.29 ; P=0.9998

Strong and positive!

CONCLUSIONS

- A simple model, tuned to match the density in BHs in the local universe matches both the observed BH demographics and produces realistic massive galaxies, groups and clusters

- BH masses are insensitive to the properties of their host *galaxy*

- ...but are dependent on the properties of their DM haloes, in such a way that BH mass scales with the gravitational binding energy of the *DM halo*.