WHAT PHYSICS SHAPES THE GALAXY POPULATION?

Insights from the OverWhelmingly Large Simulations project

OWLS PEOPLE

Schaye (PI) Dalla Vecchia Springel Theuns Tornatore Wiersma

Bertone Crain Duffy Haas McCarthy Sales van de Voort

OVERVIEW

- PART I: The gas in and around galaxies --- Where are the metals and how can we see them? How are different gas phases enriched?

- PART II: Growing galaxies --- Self regulation, stars, and black holes

MOTIVATION

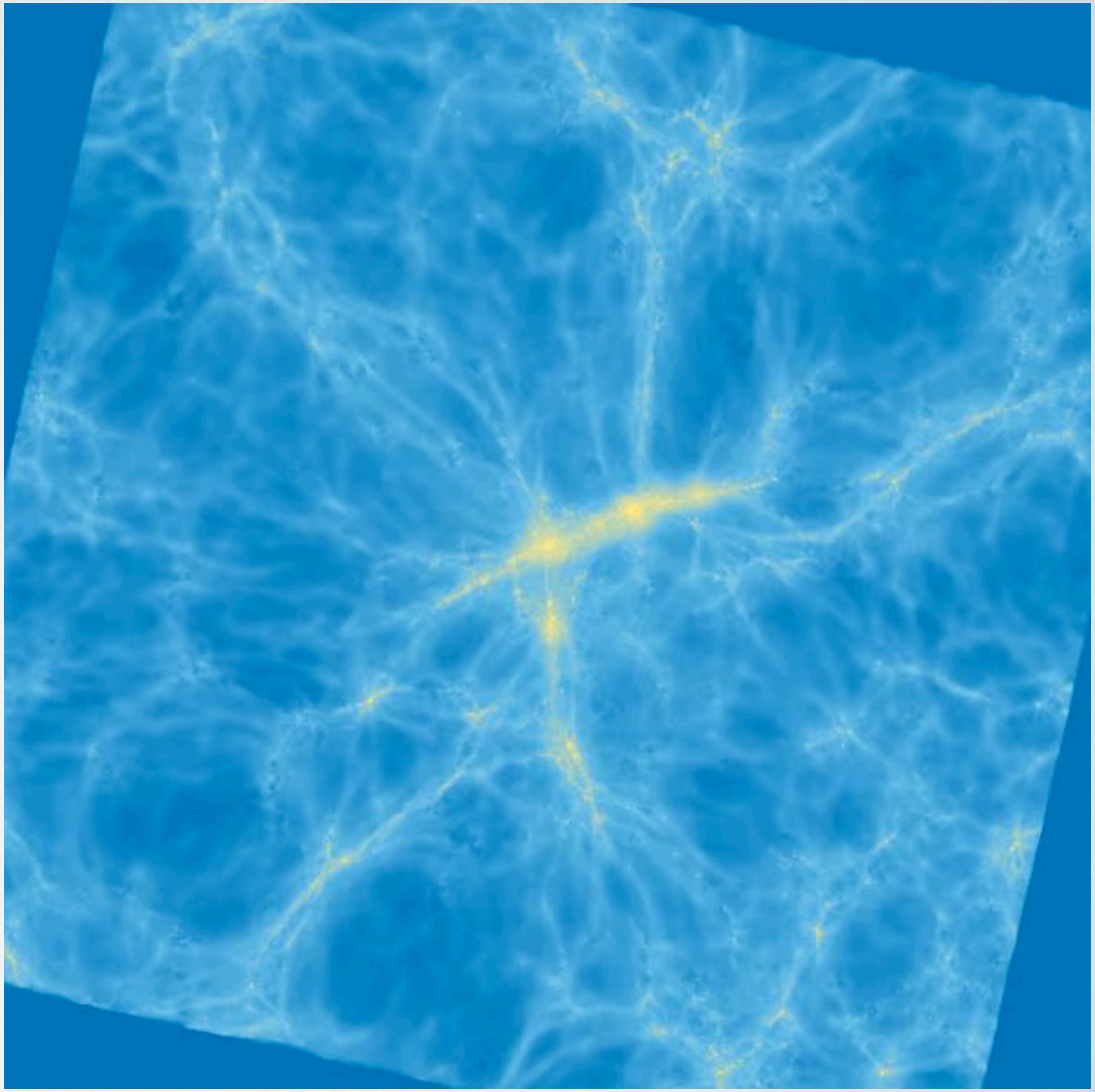
Evolution from $z>100$ to $z\sim0$ of a representative part of the universe

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

Scales ~ kpc to ~ 100 Mpc

Sub-grid modules are of vital importance...

MOTIVATION



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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

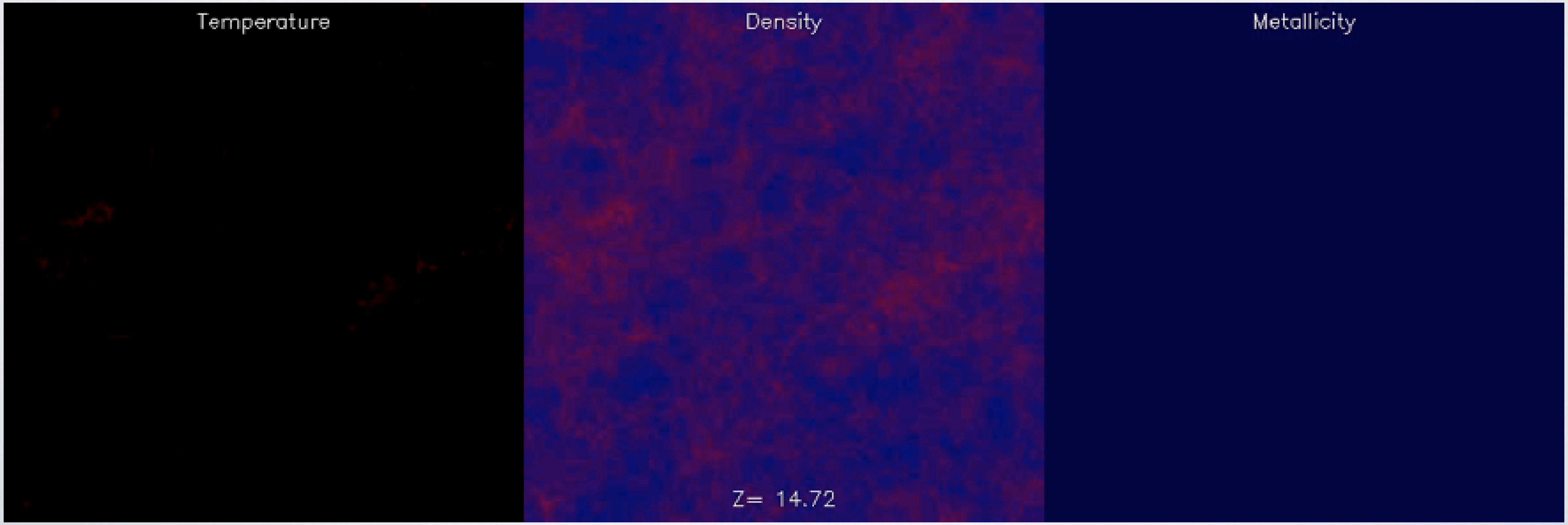
- Simulate what we can -- Use *simple* subgrid models where necessary
- Physically motivated recipe
    - Preferred if physics is well understood (radiative cooling, stellar evolution)
- Empirically motivated recipe
    - Preferred if physics is complex (e.g. SN feedback, star-formation)
- Systematically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

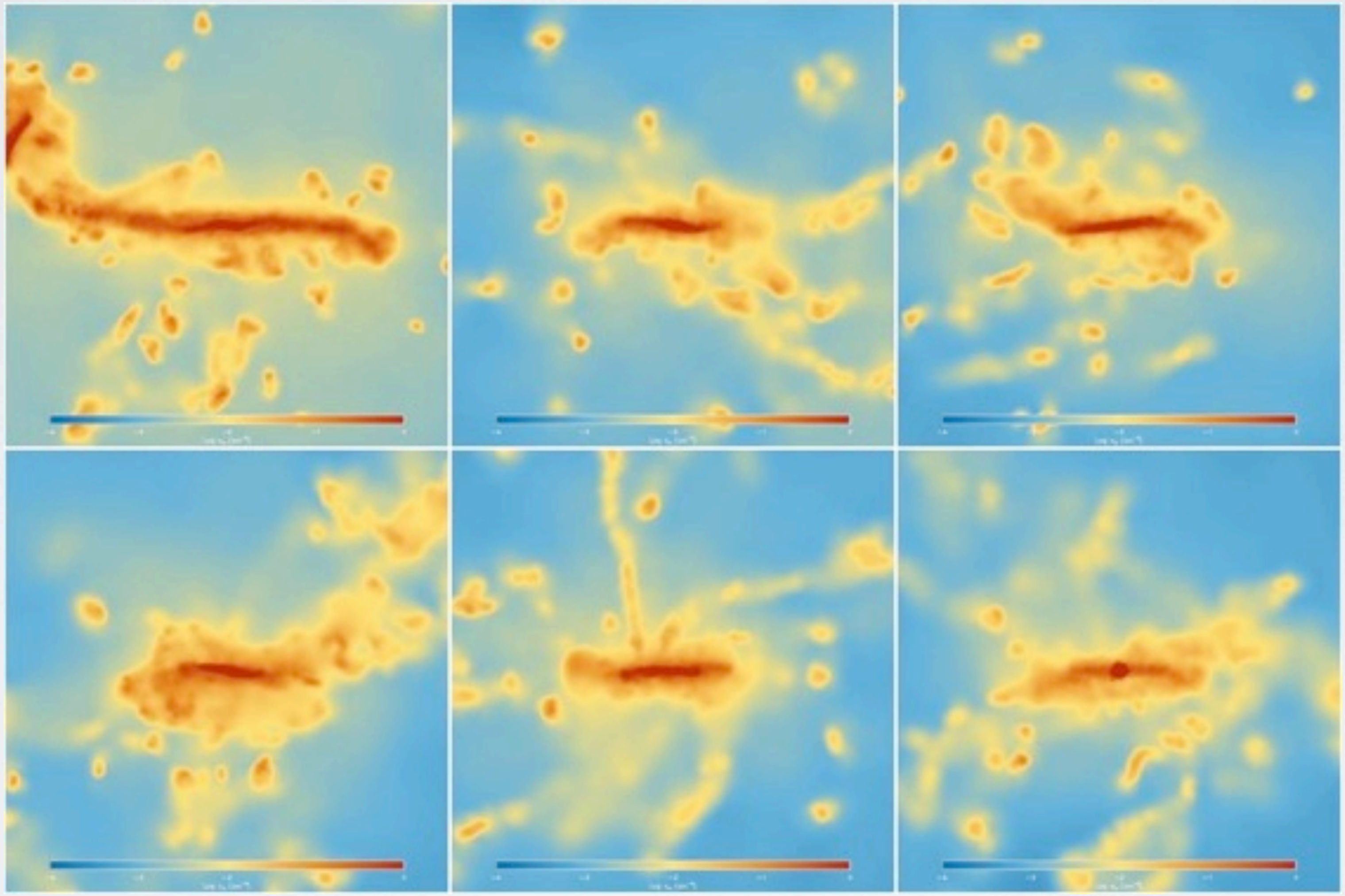
Temperature Density Metallicity



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)



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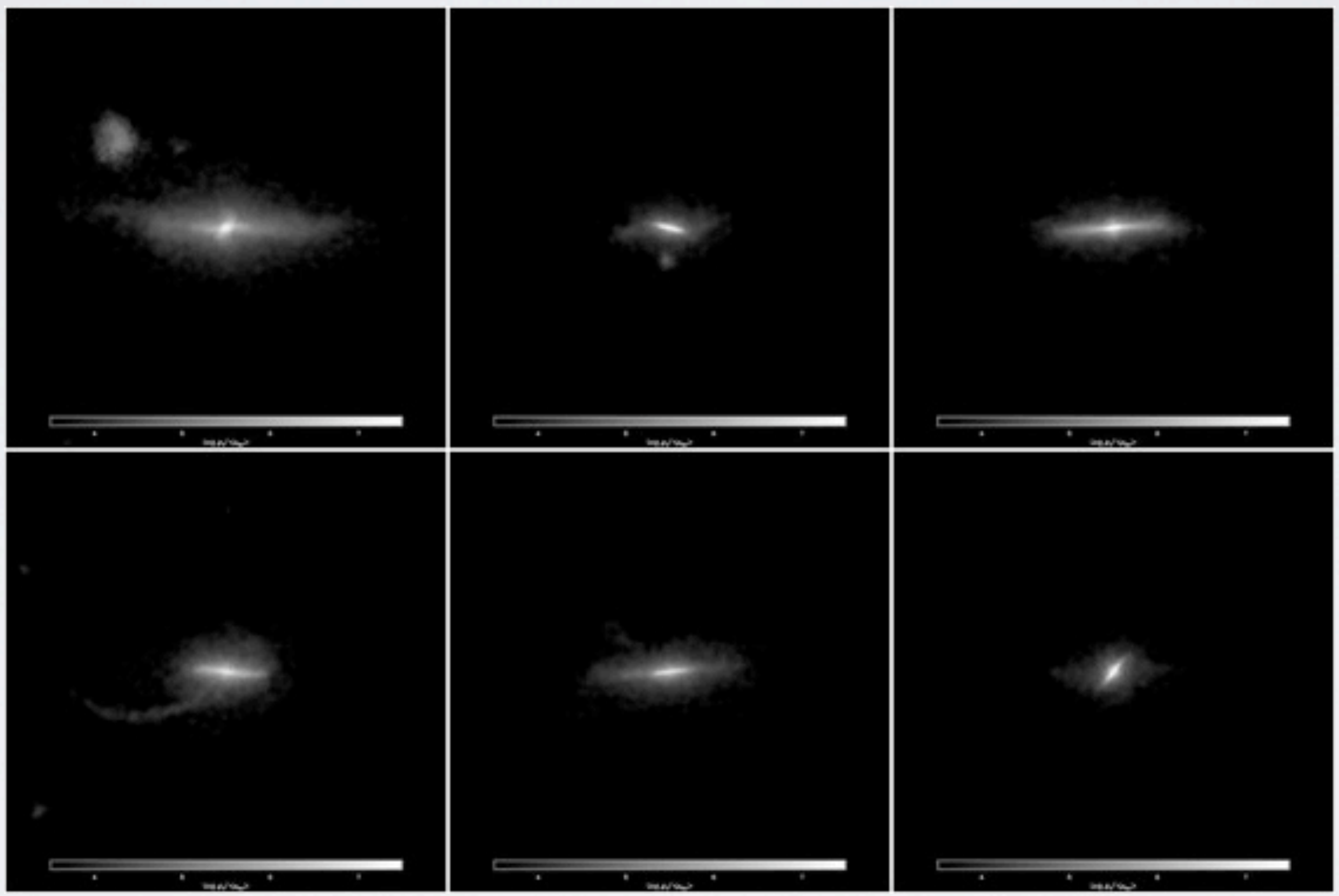

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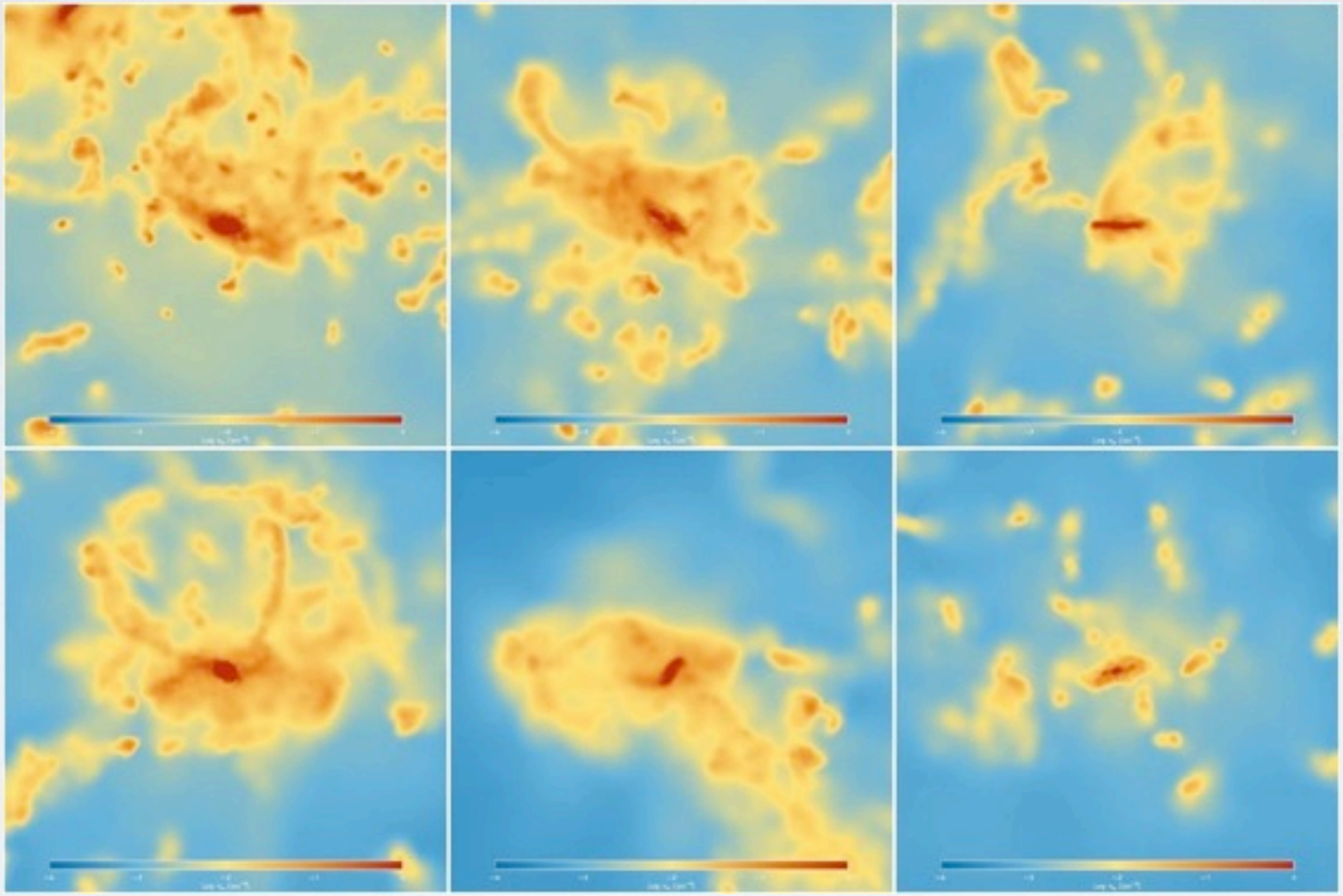

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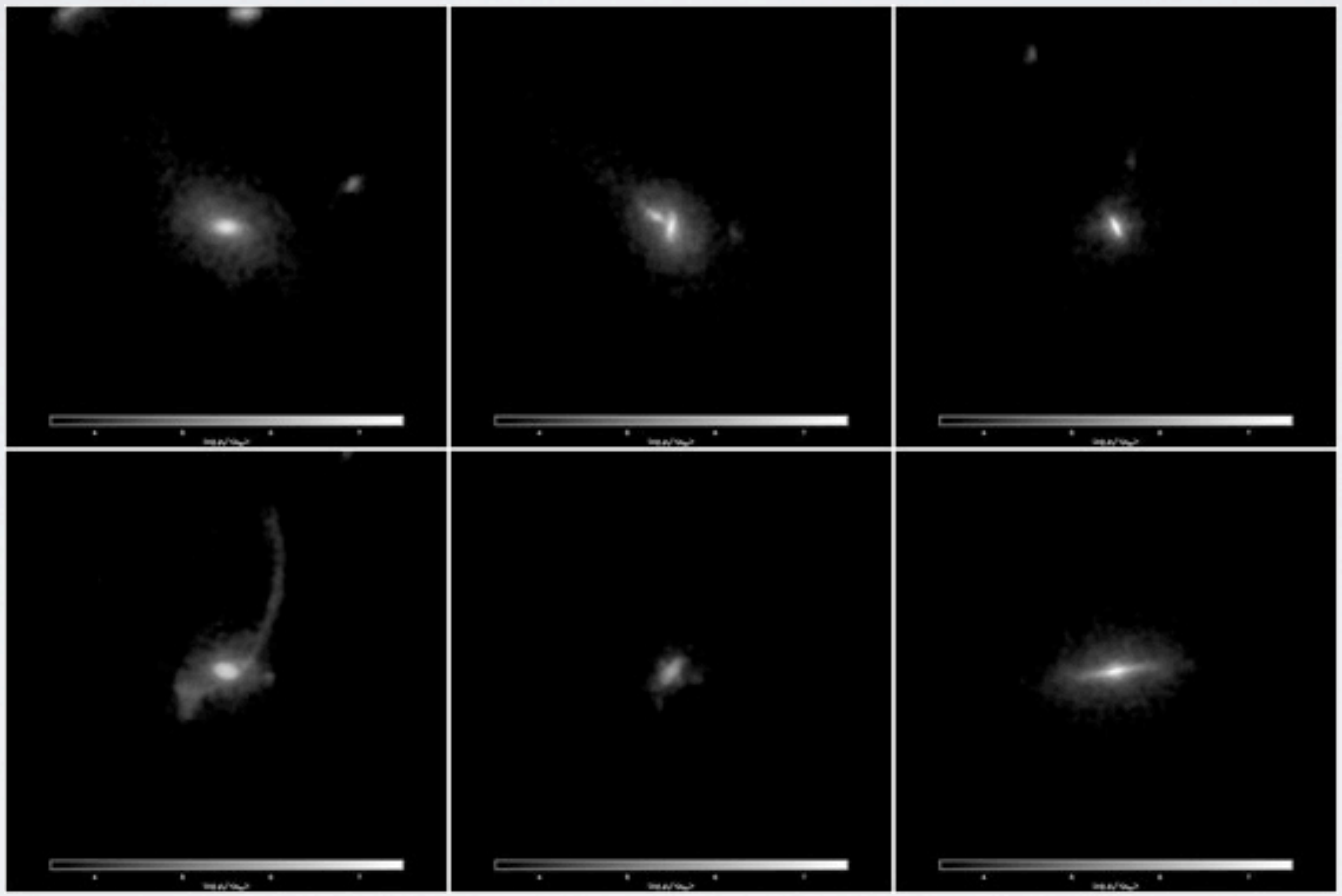
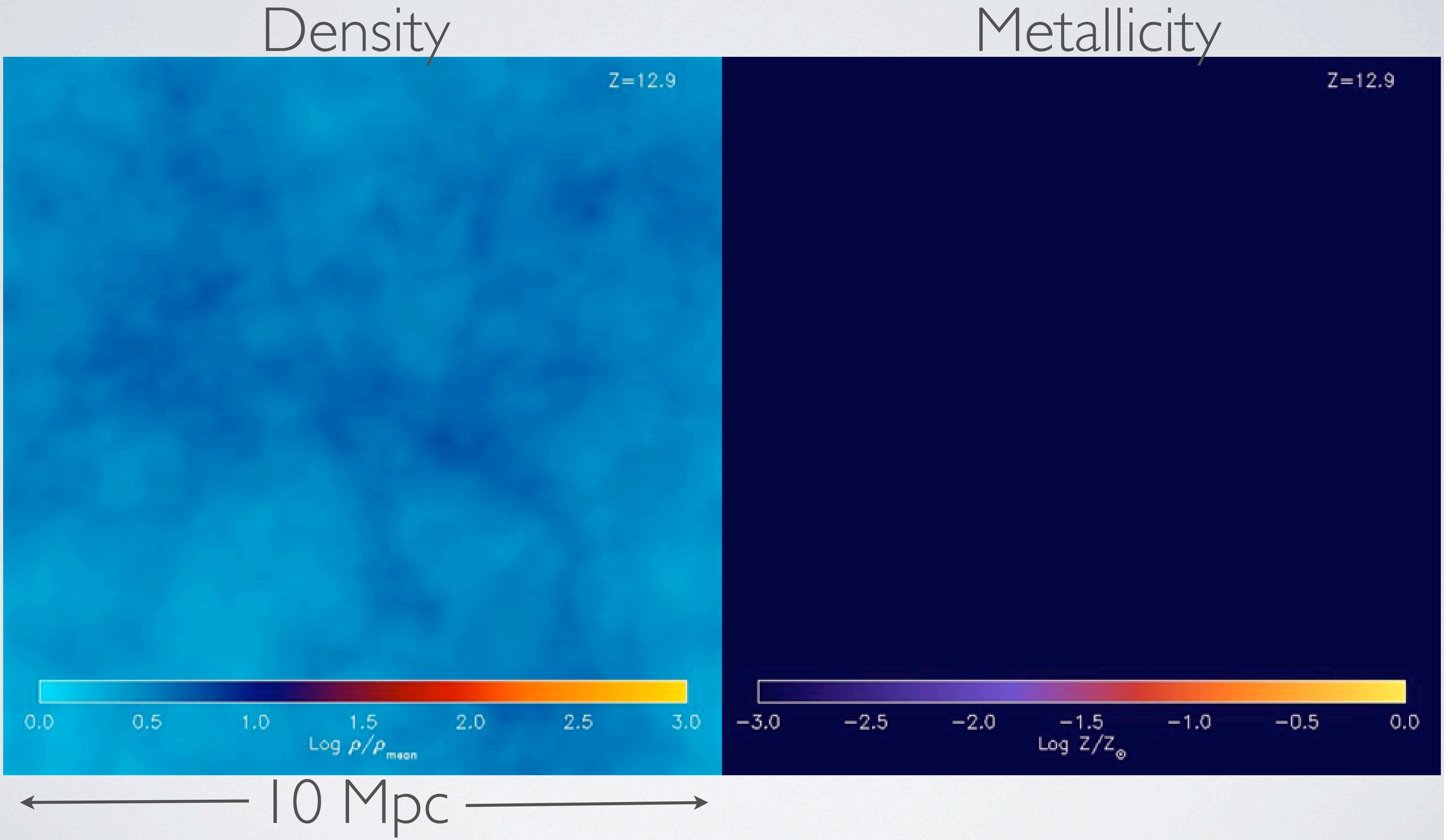


AND CLUSTERS...



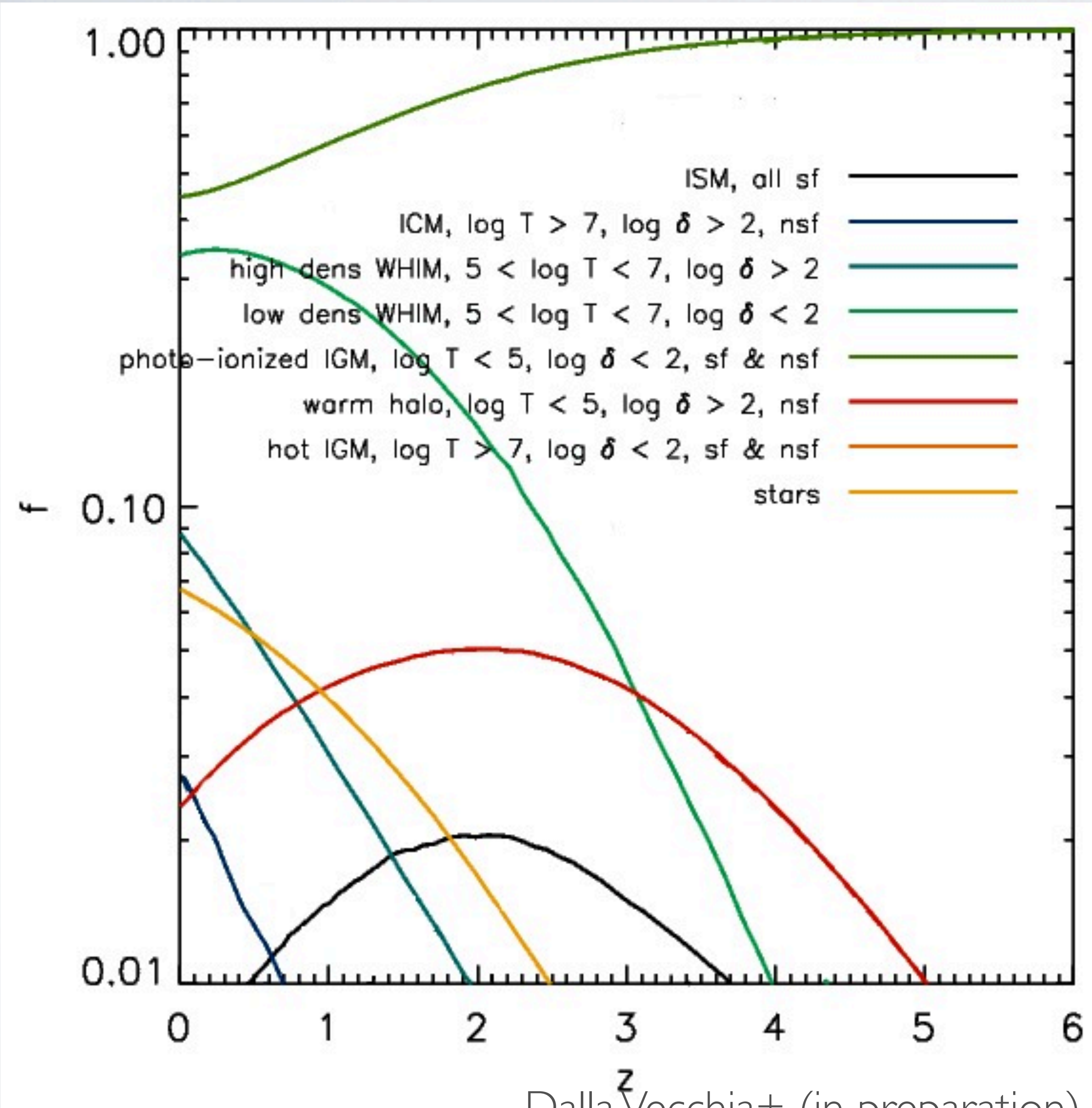
0.1% of the computational volume

PART I

The gas in and around galaxies.

Where is the gas? Where are the metals? How does gas get into galaxies? How do metals escape?

WHERE ARE THE BARYONS



Dalla Vecchia+ (in preparation)

Dalla Vecchia

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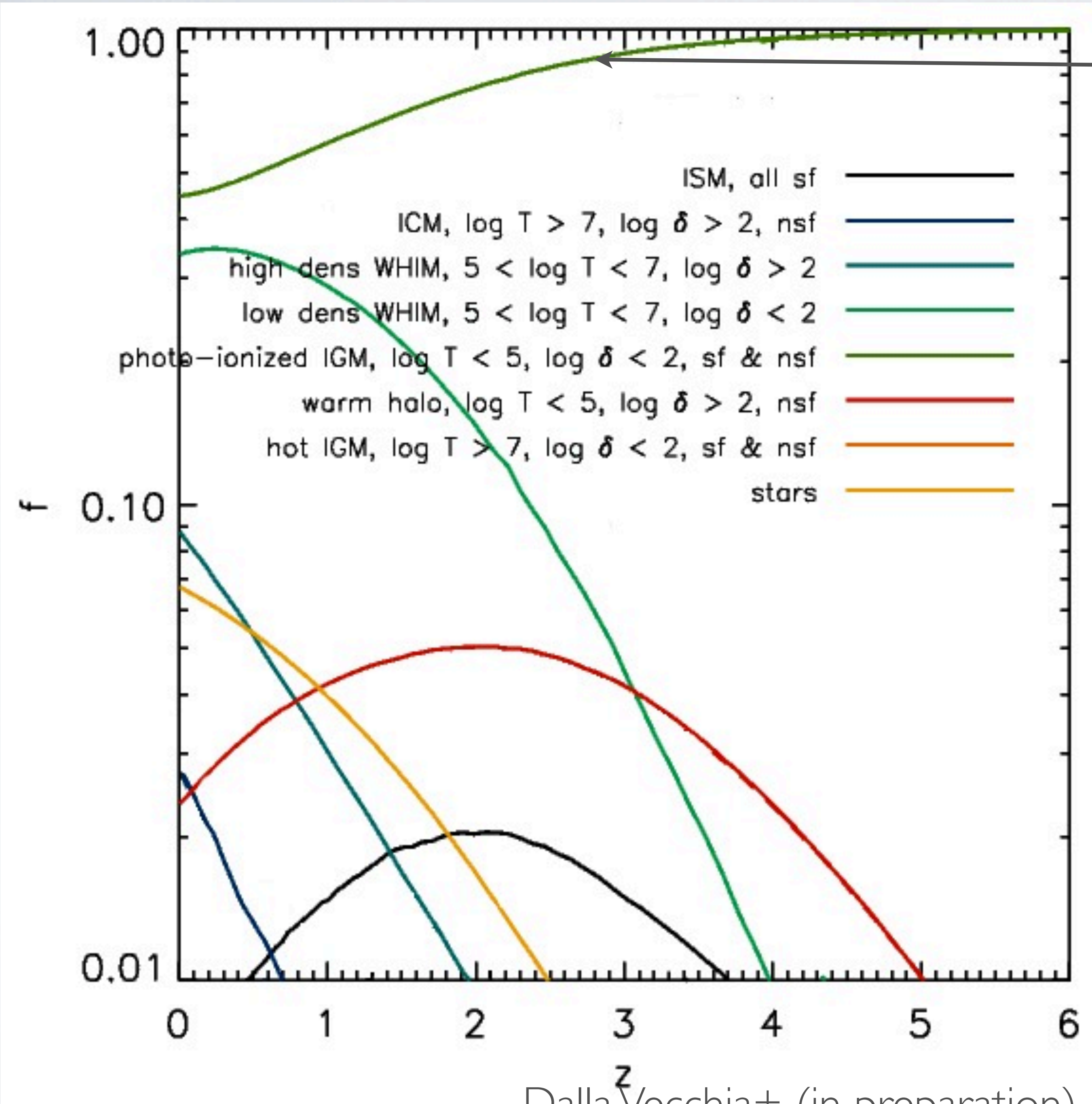

Most gas remains in the IGM

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

Dalla Vecchia+ (in preparation)

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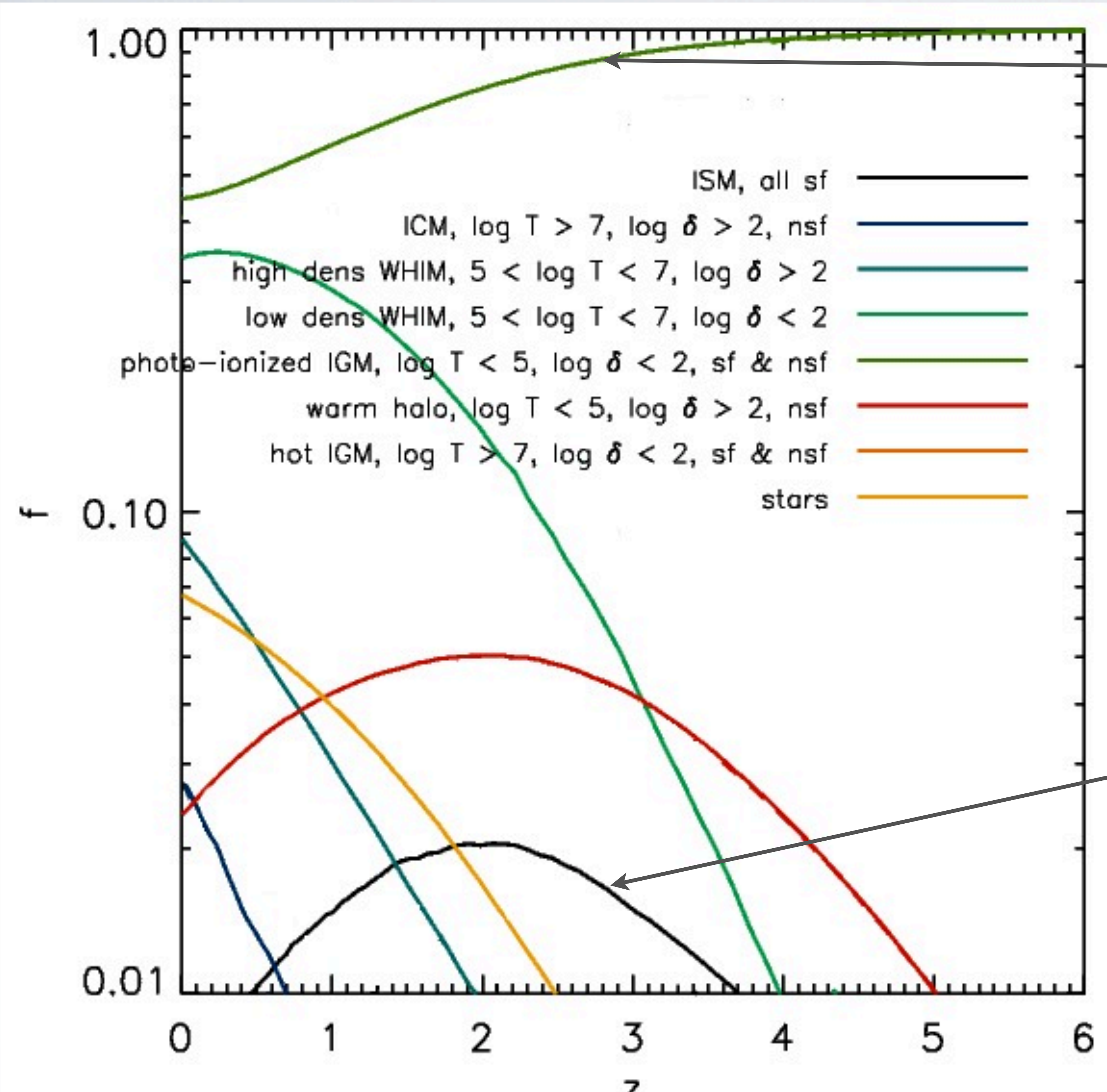

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Only A few percent in the ISM

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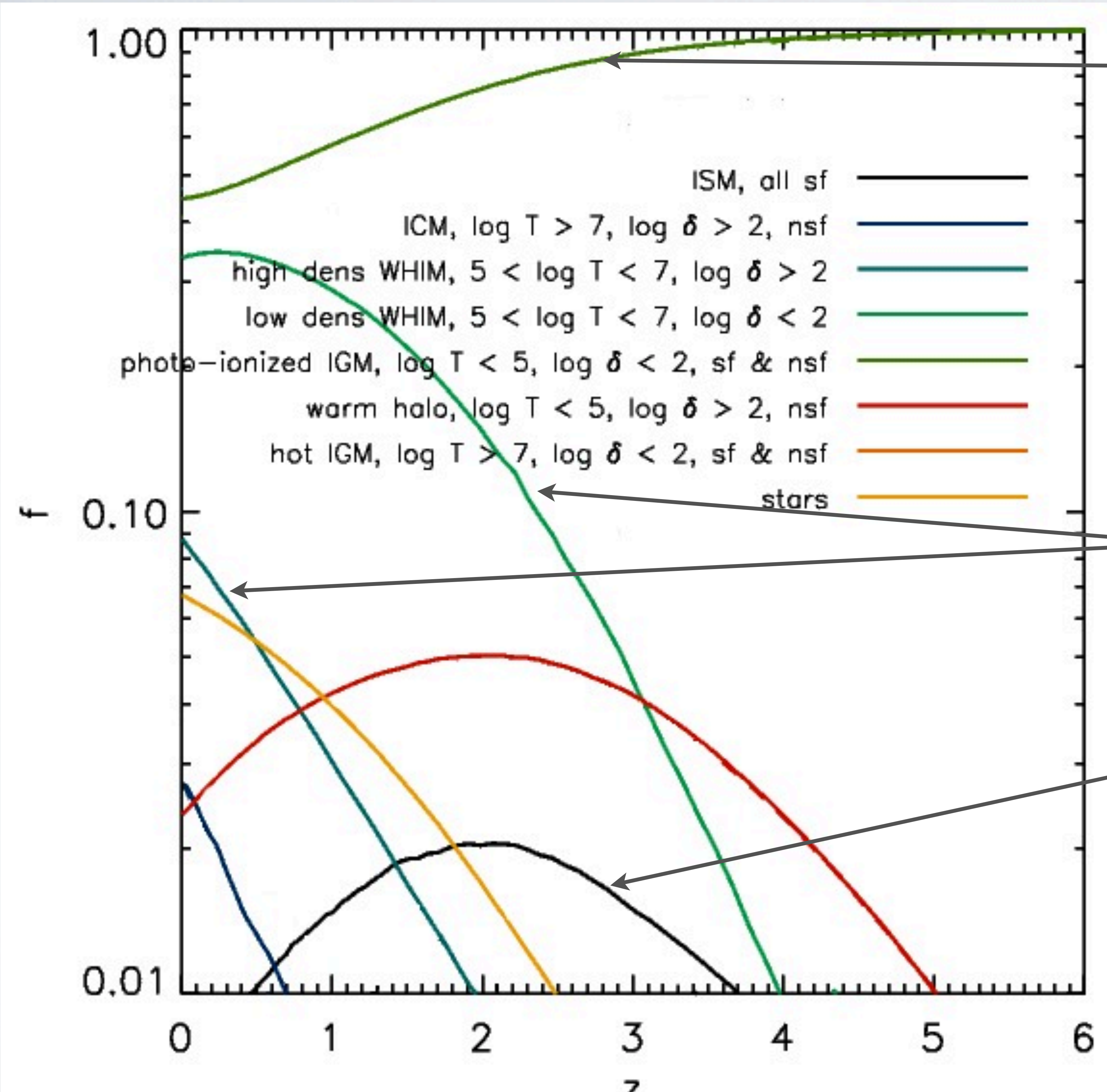

Dalla Vecchia+ (in preparation)

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The remainder is mainly in the WHIM

Cen & Ostriker 1999

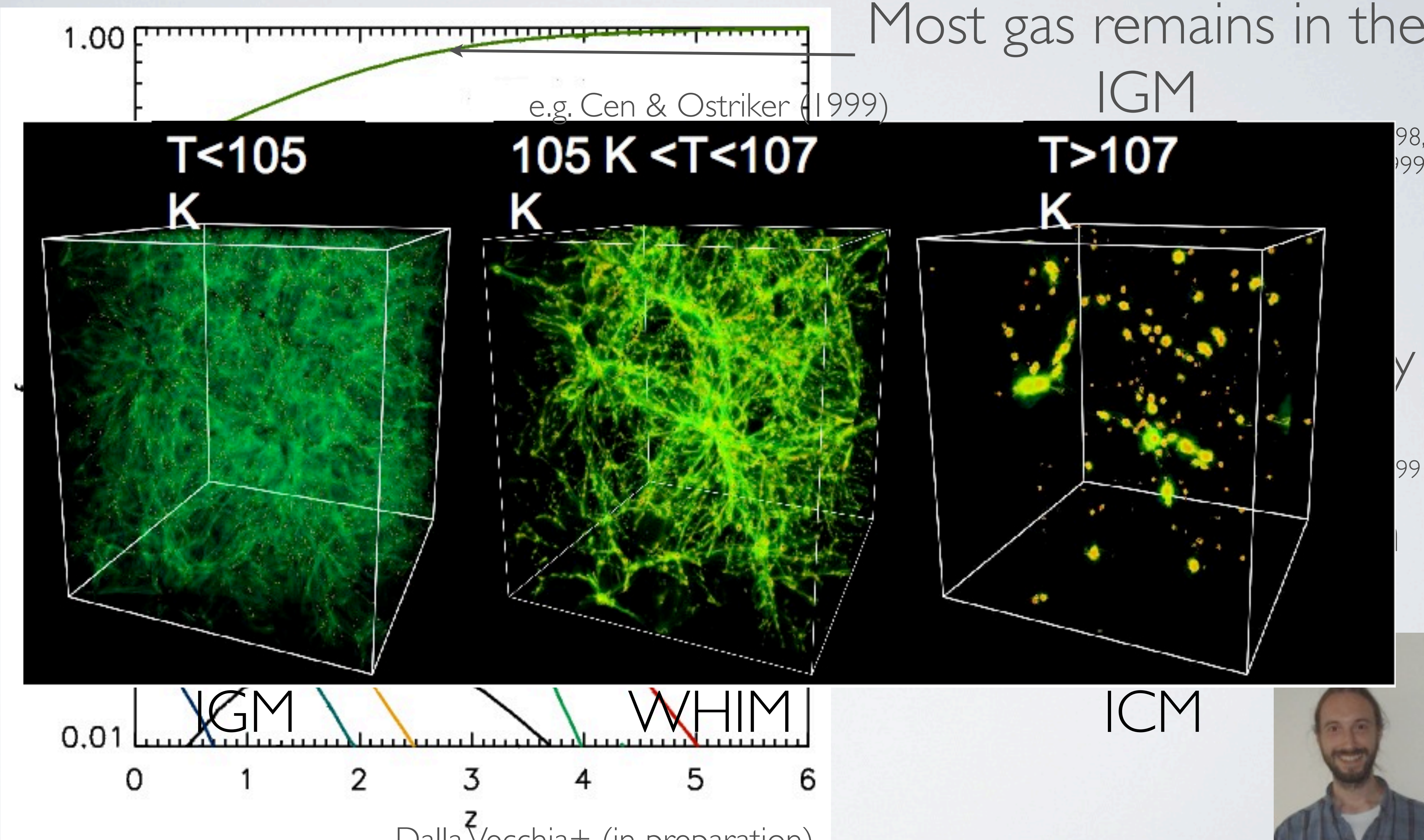
Only A few percent in the ISM

Dalla Vecchia

WHERE ARE THE BARYONS

Most gas remains in the IGM

e.g. Cen & Ostriker (1999)



IGM

WHIM

ICM

Dalla Vecchia+ (in preparation)

Dalla Vecchia

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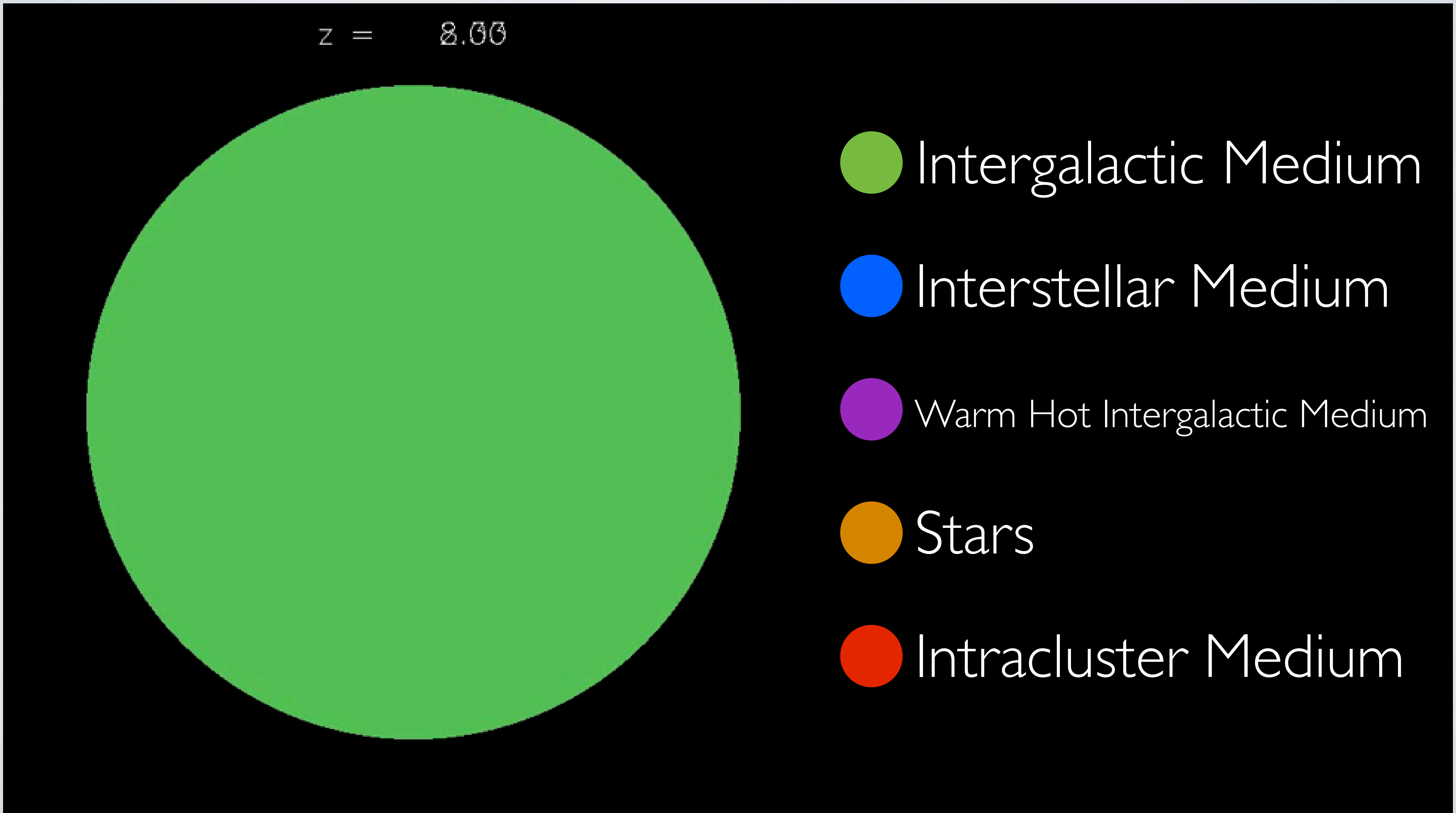
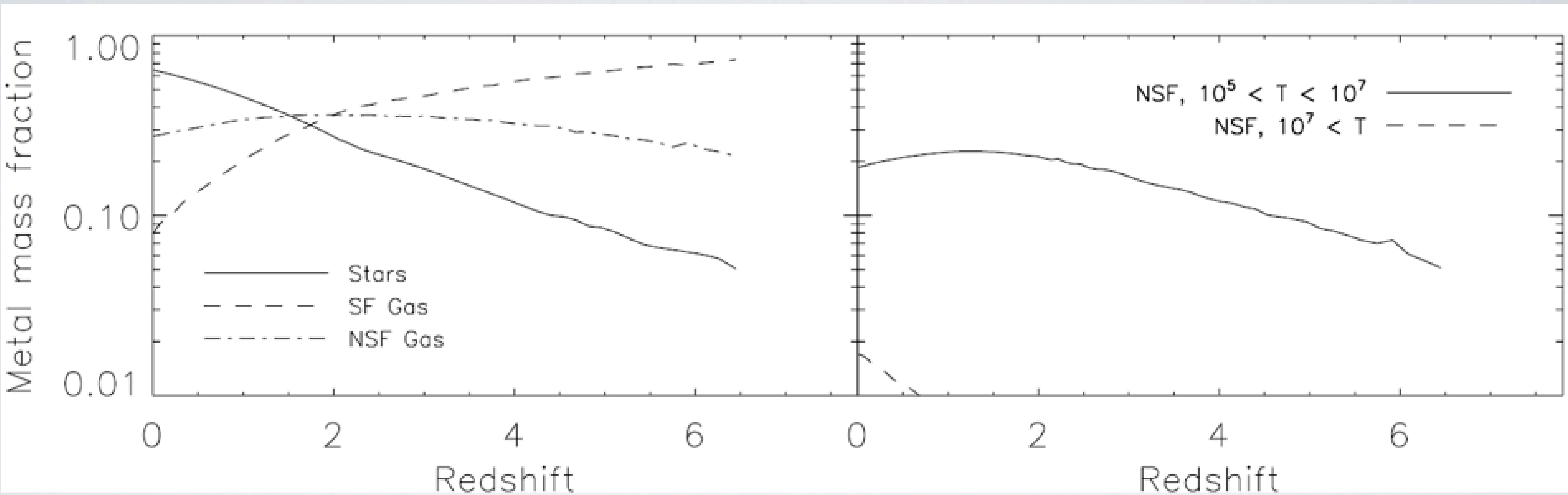


WHERE ARE THE METALS?



Wiersma+ (2009)

At low redshift:

Most (80%) of the metals are in stars

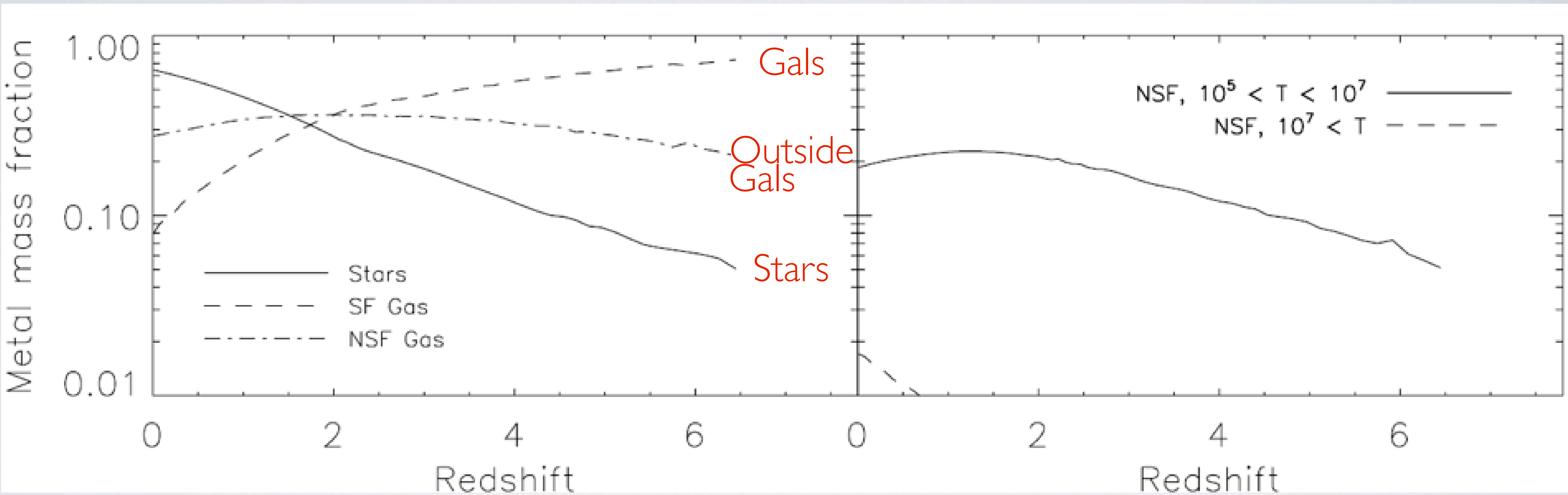
Of the metals that are not locked up in stars:

Most are outside of galaxies

And in the WHIM

Wiersma

WHERE ARE THE METALS?



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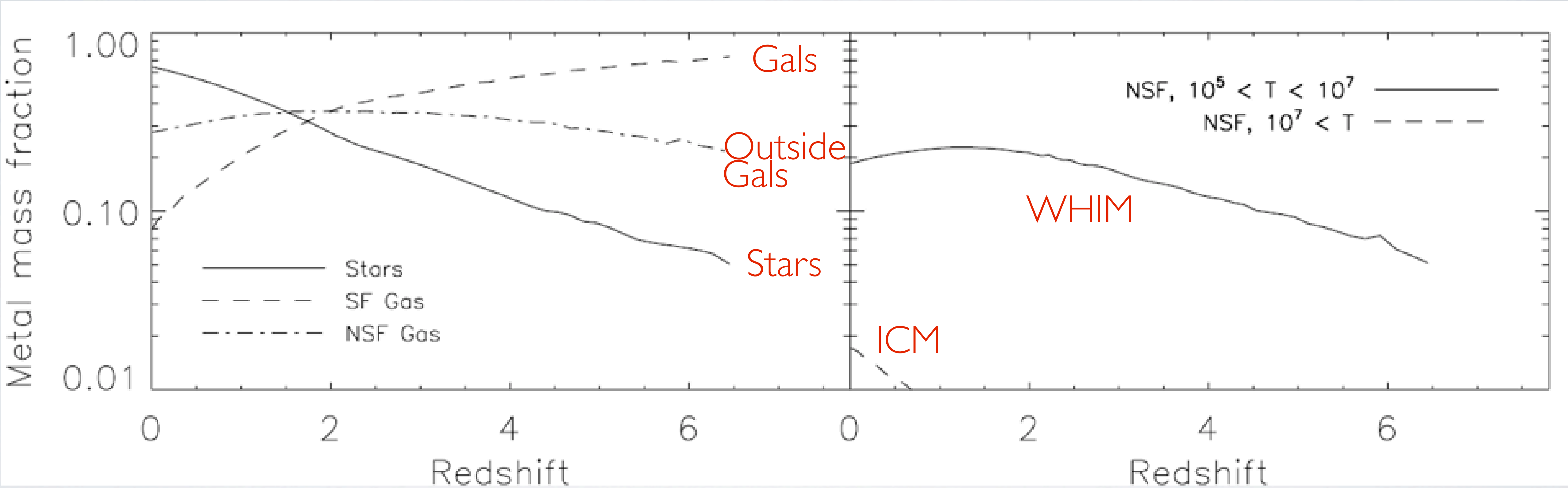

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Thursday, 12 November 2009

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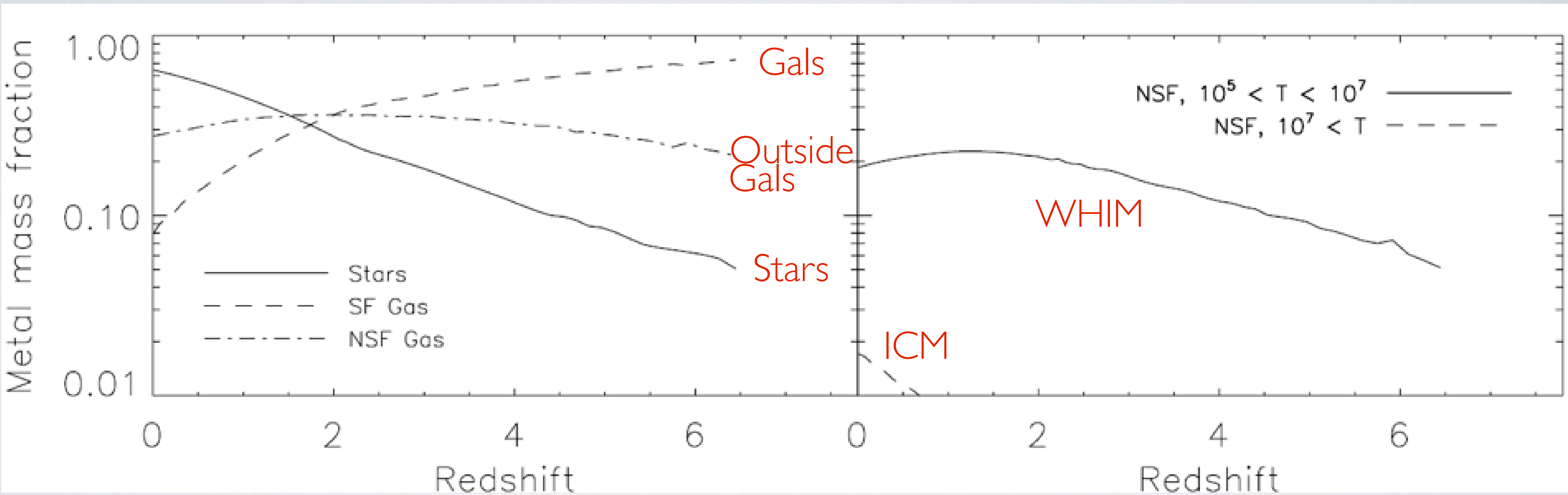

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➔how does gas enter and leave galaxies?

Wiersma

AN ASIDE: RADIATIVE COOLING

- Dissipation of energy by radiative cooling plays a crucial role in galaxy formation
- In the absence of photoionization we have collisional ionization equilibrium
- However, the cosmic UV background can have a large effect on gas cooling e.g. Efstathiou (1992); for primordial abundances

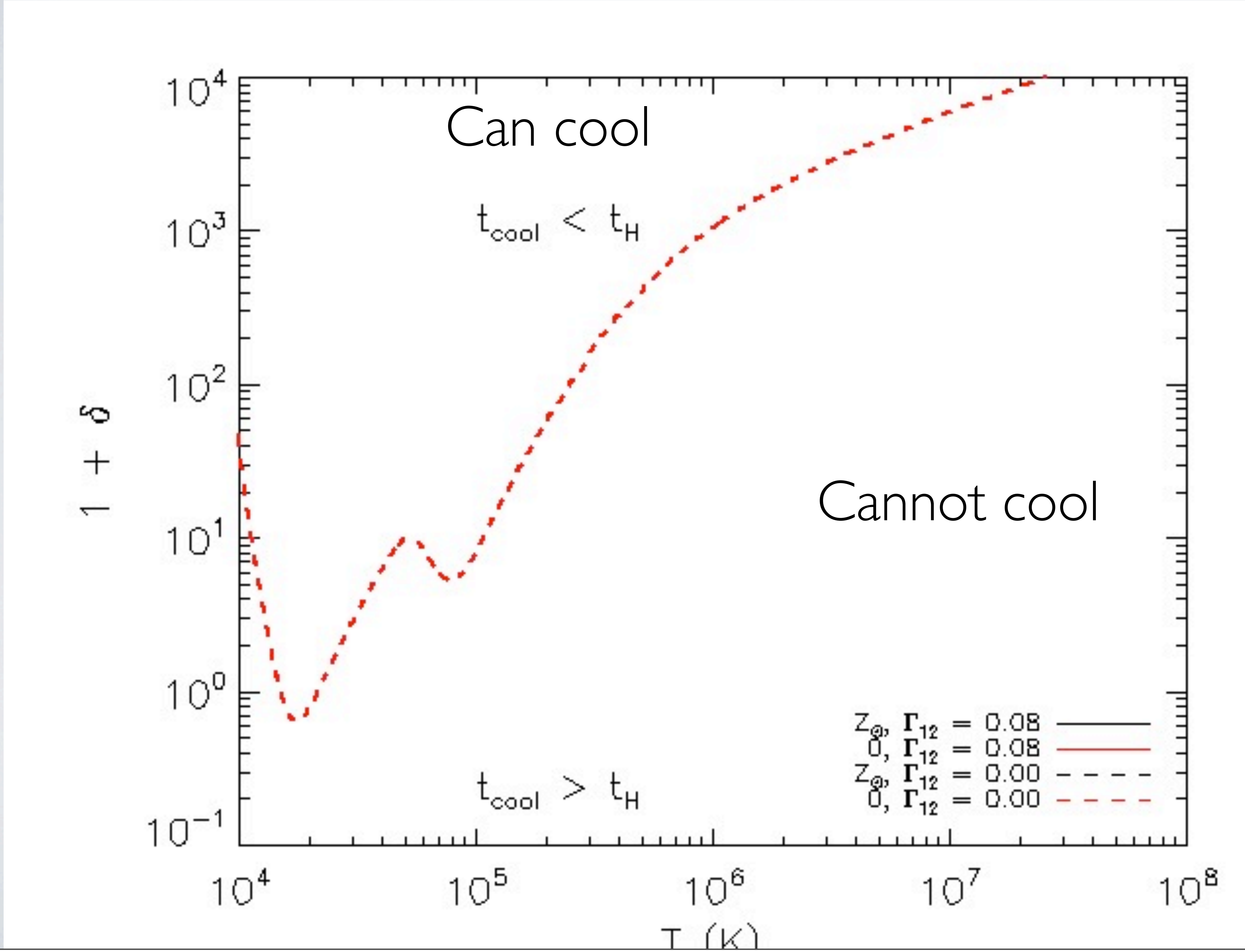
Wiersma

AN ASIDE: RADIATIVE COOLING

- What is typically done:
  - H and He including optically thin photo-ionization
  - Metal cooling ignored or assuming CIE and solar relative abundances
- Is the addition of photoionization on metals important?

Wiersma, Schaye & Smith MNRAS 2009, 393, 99

Wiersma


Can cool
$t_{cool} < t_H$
Cannot cool
$t_{cool} > t_H$
$1 + \delta$
T (K)
$Z_{\odot}$, Γ_{12} = 0.08
0, Γ_{12} = 0.08
$Z_{\odot}$, Γ_{12} = 0.00
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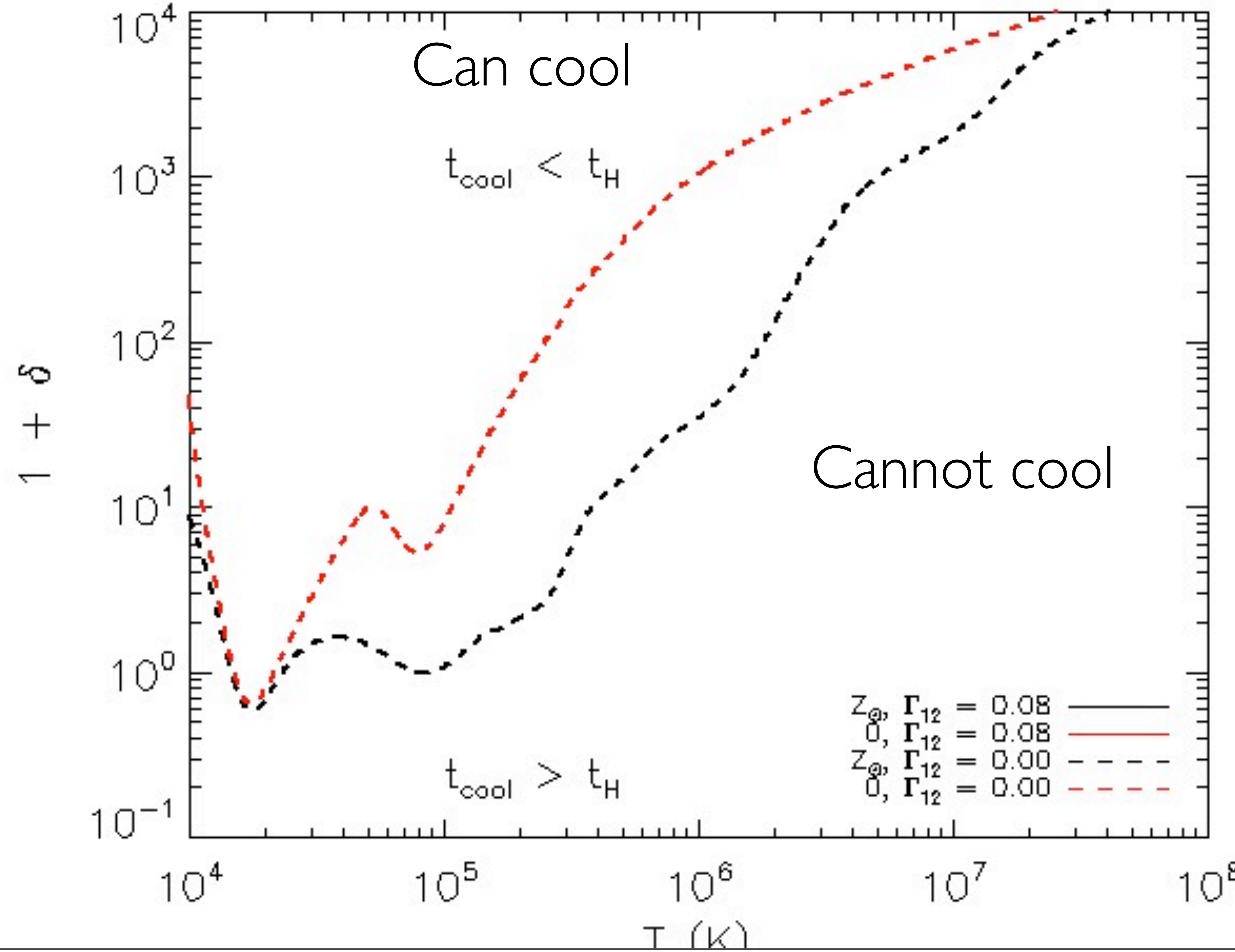
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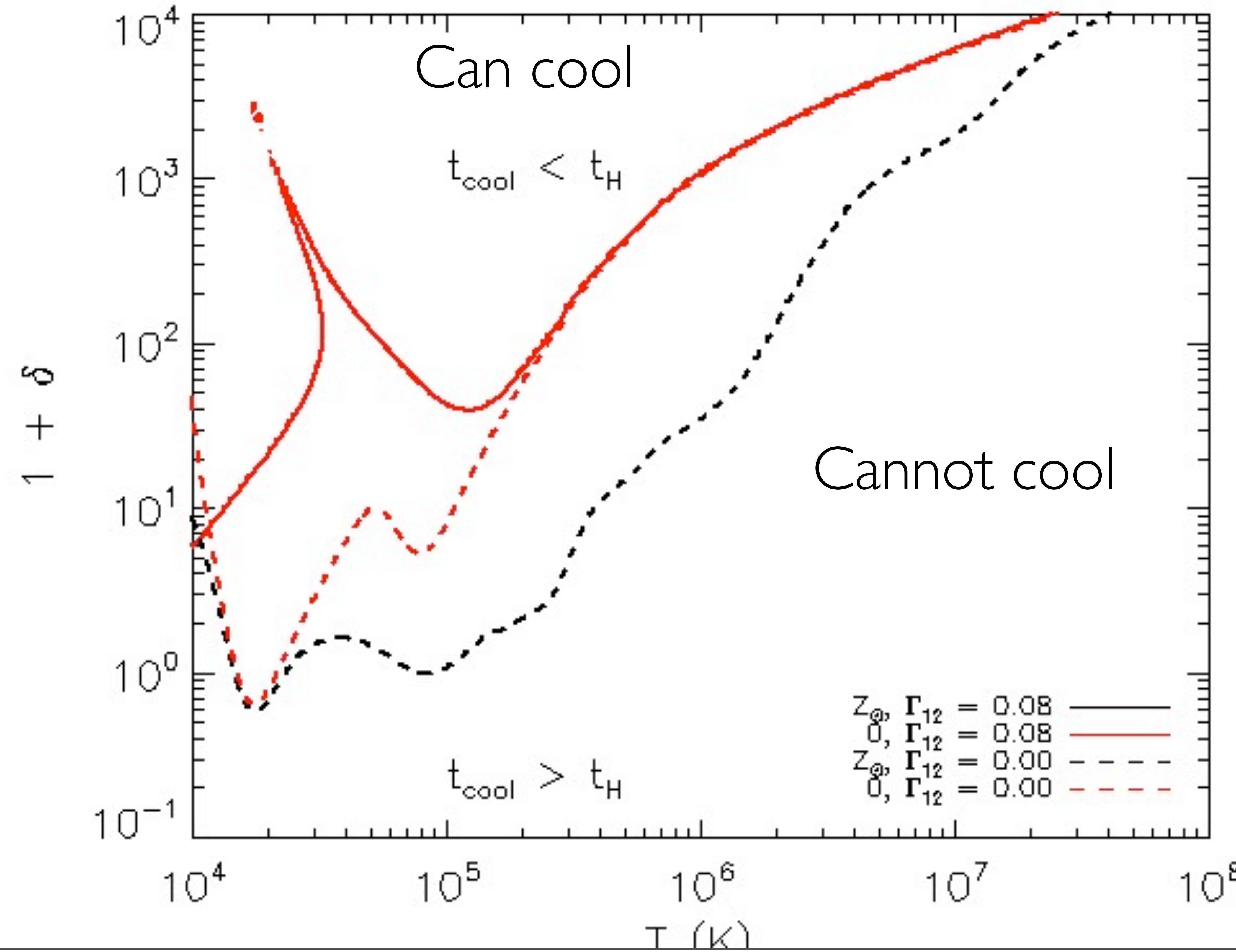
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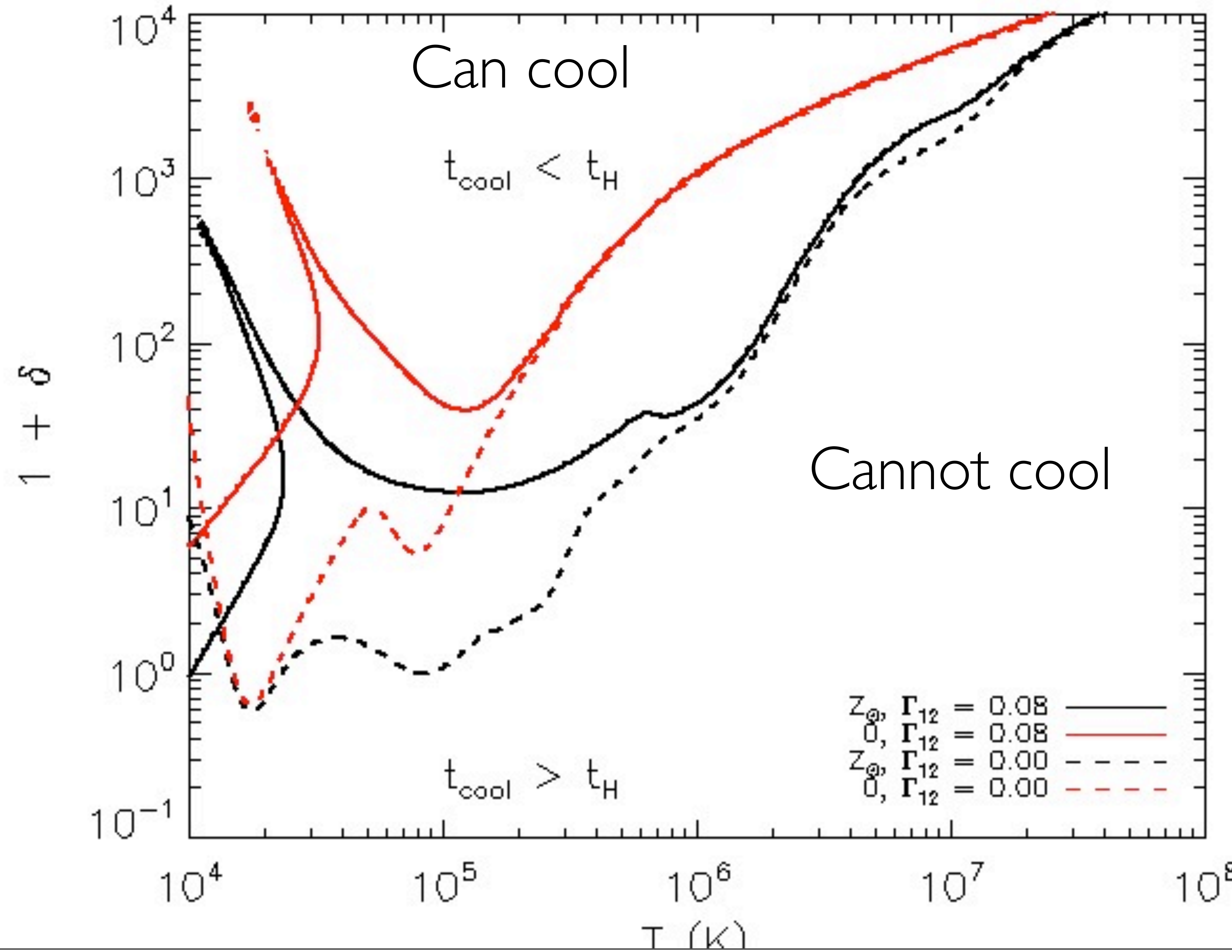

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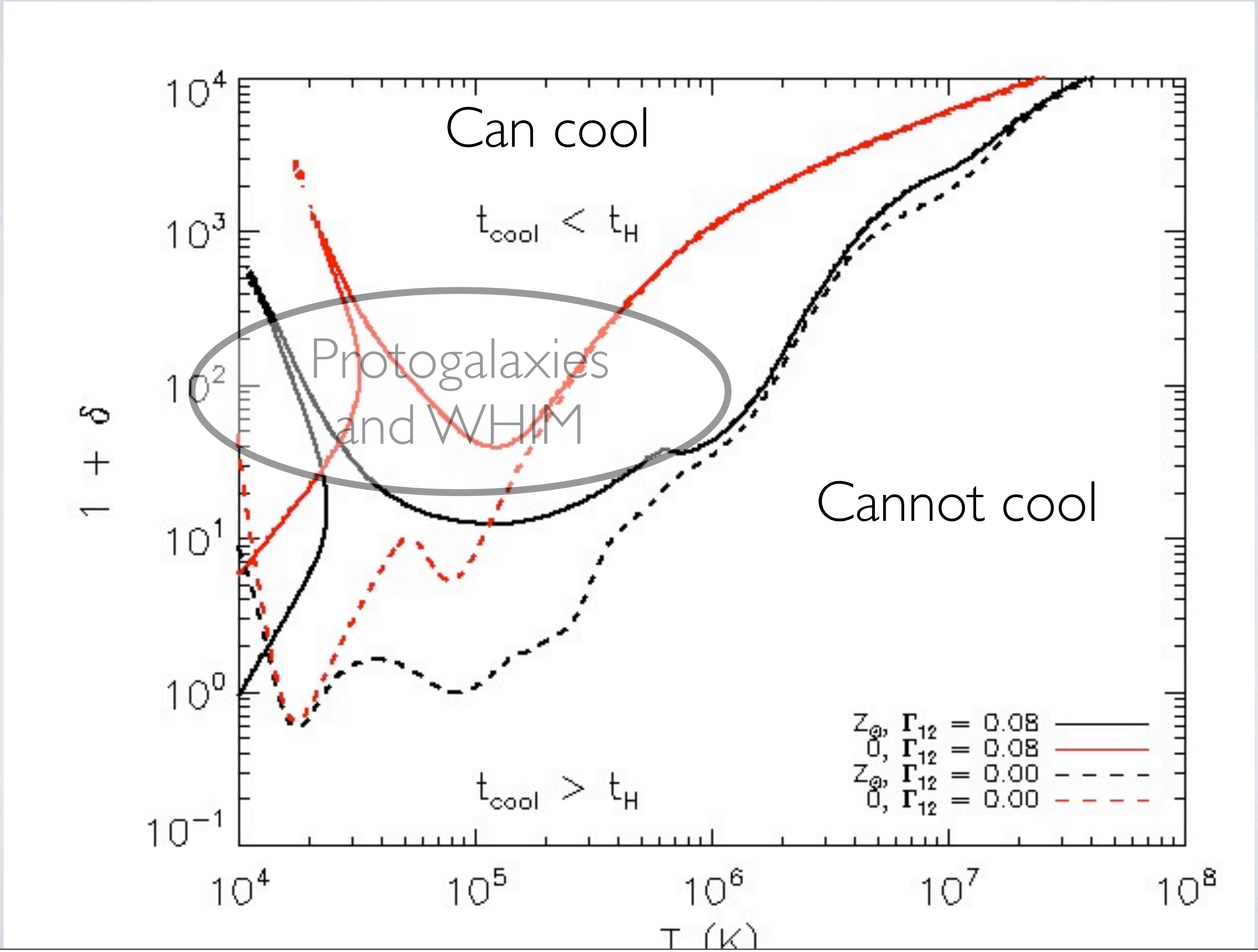
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and WHIM
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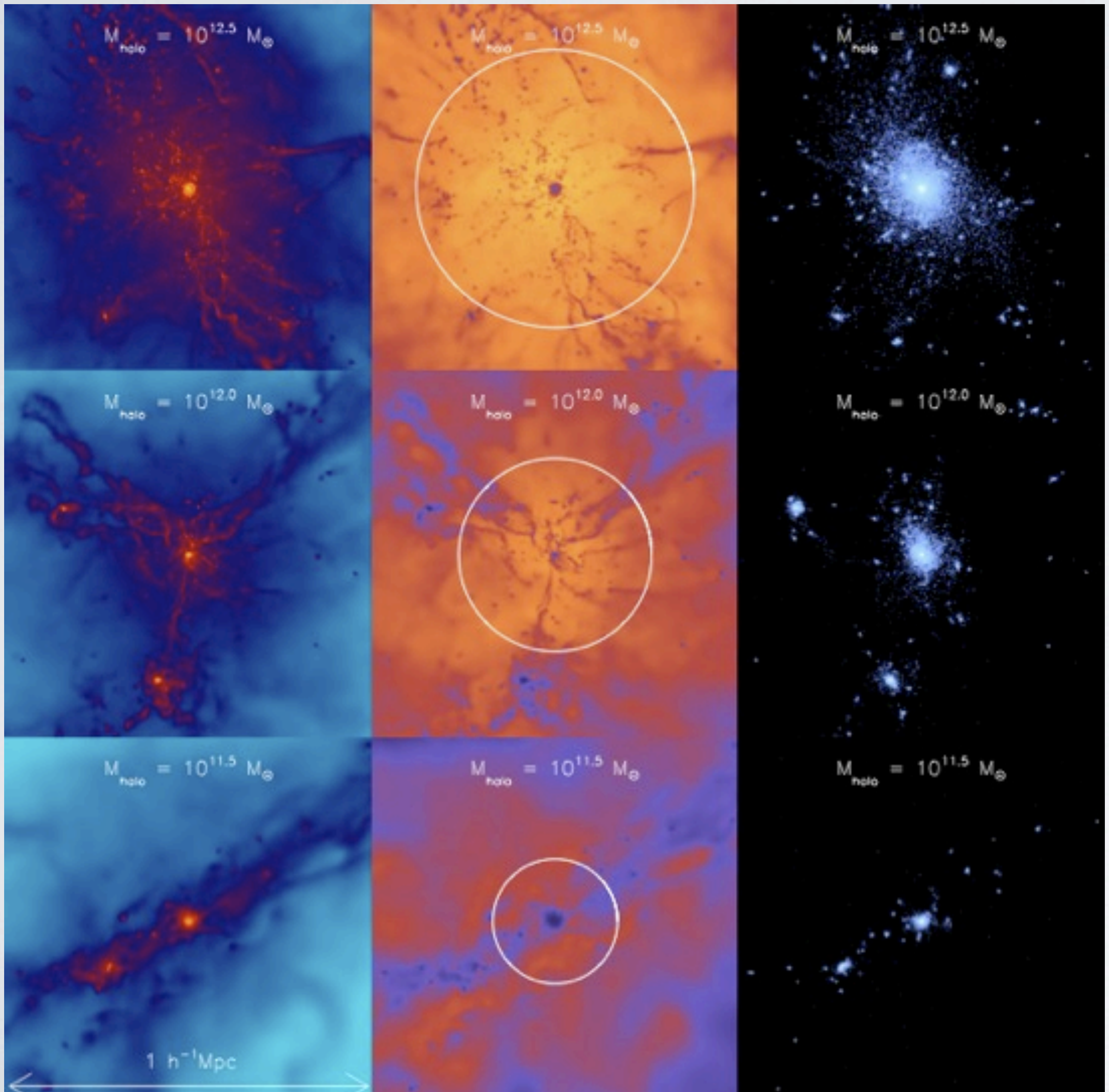
1 + δ
T (K)

HOW DOES GAS GET INTO GALAXIES?



van de Voort+ (in prep)

- In the traditional picture, gas shocks at the virial radius

  White & Rees (1978)

- Then cools radiatively and forms stars

  Fall & Efstathiou (1980)

- Simulations are not spherical... how shocks and cold streams

  Keres+ (2005)
  Ocvirk+ (2008)
  Brooks+ (2009)
  Dekel+ (2009)

van de Voort

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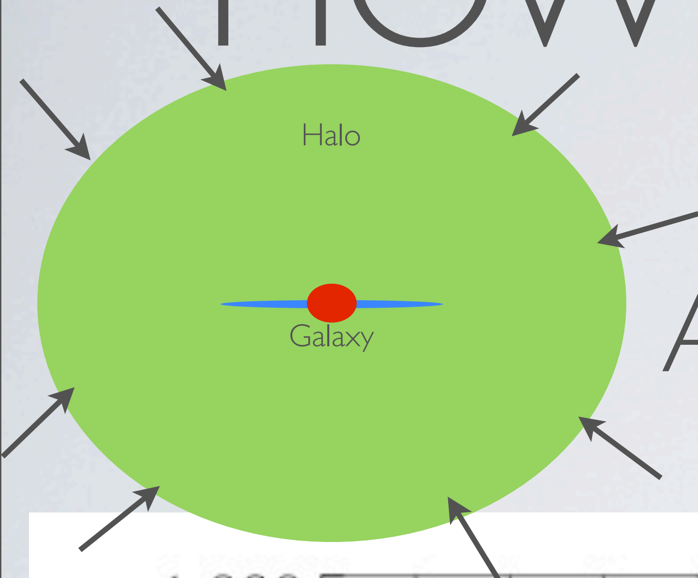
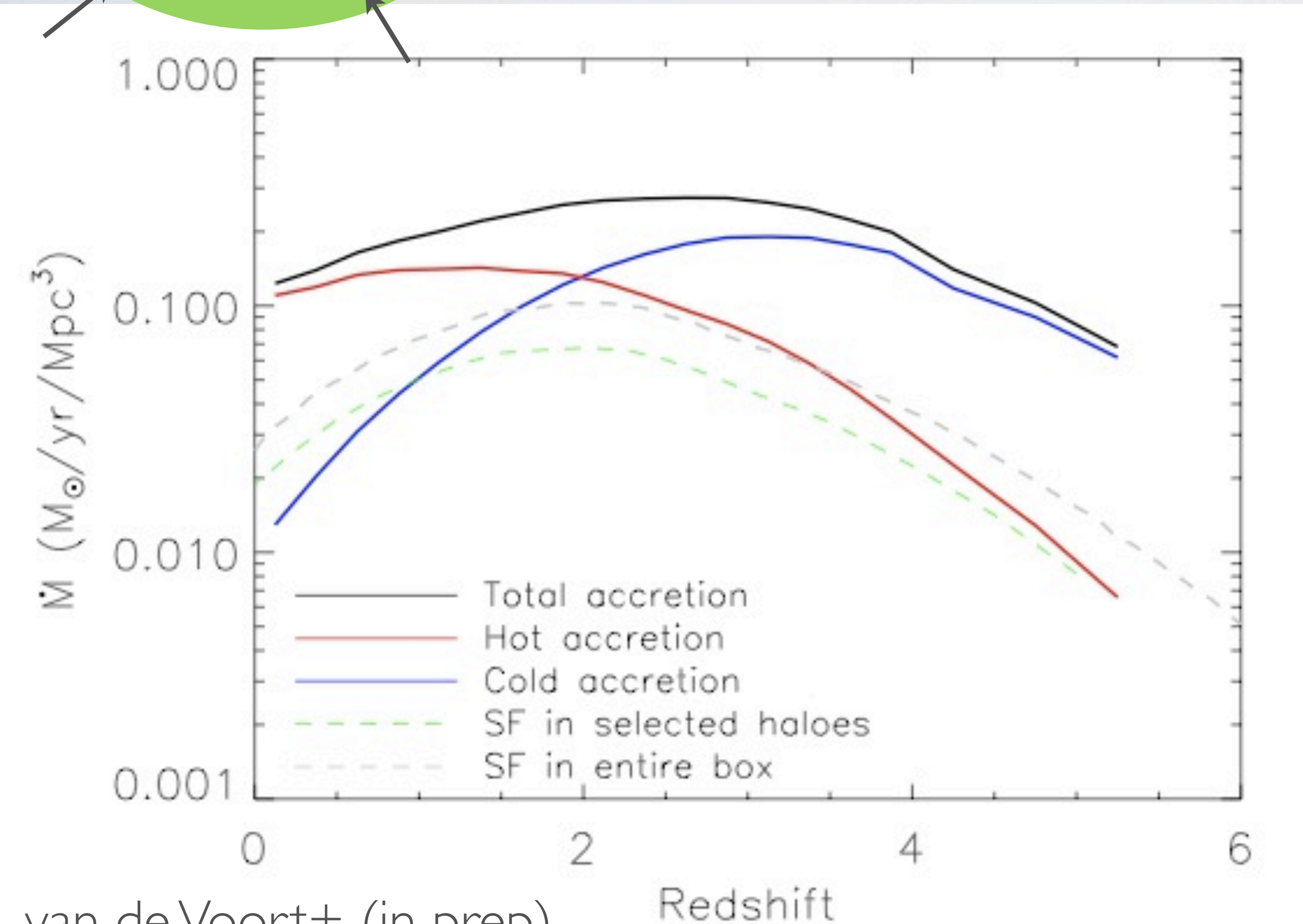


ACCRETION ONTO HALOES



van de Voort+ (in prep)

- Gas that never reaches $T>10^{5.5}$K is 'cold' accretion
- Compare accretion rates to SFR

van de Voort

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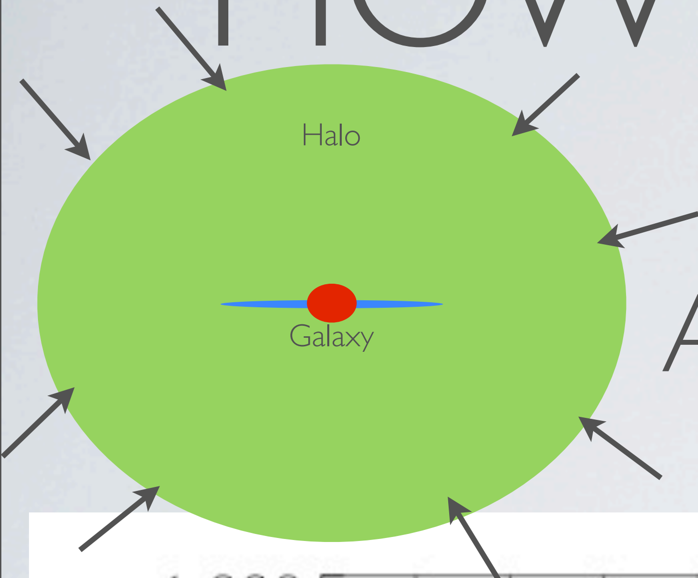

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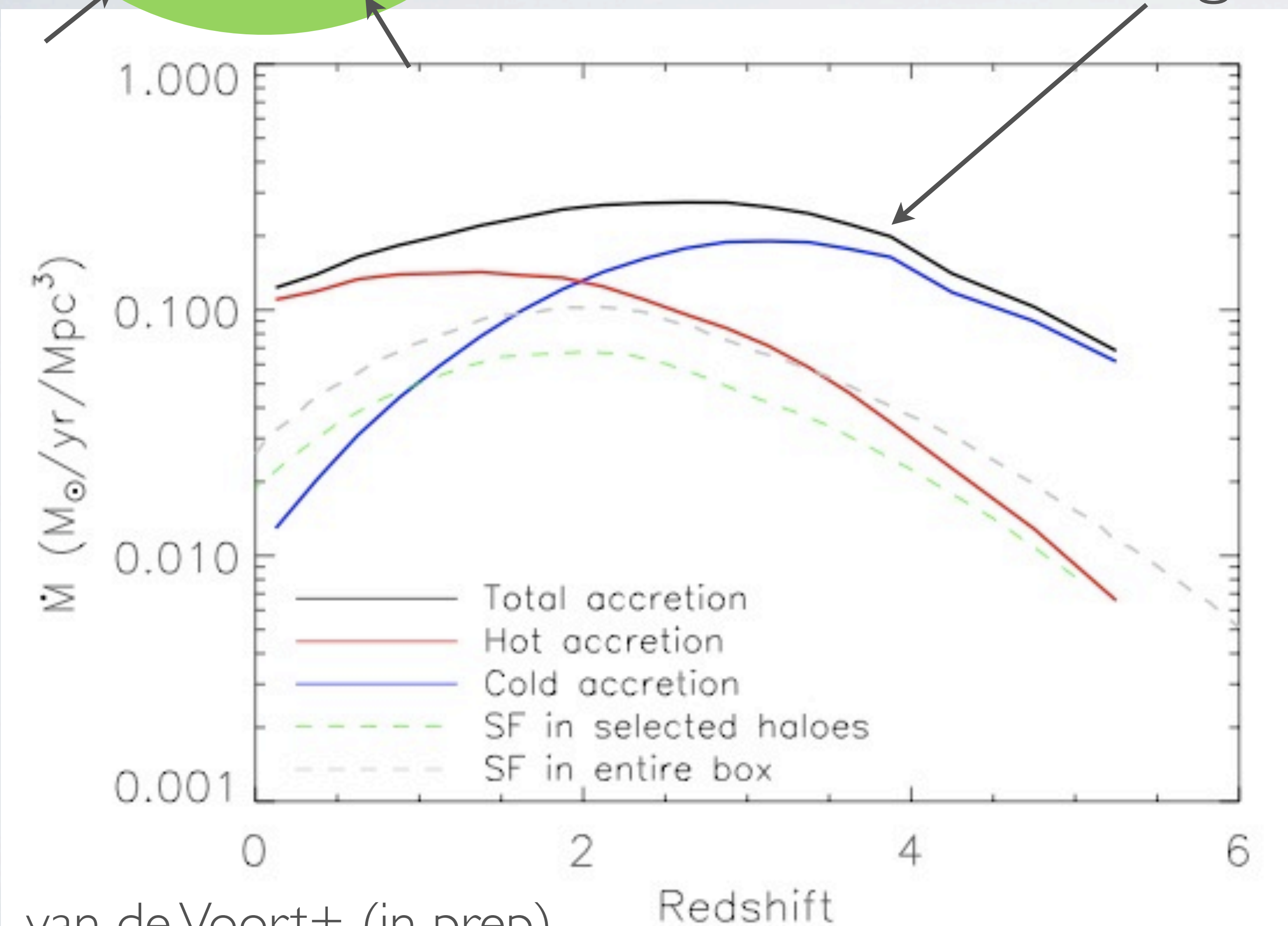
Most accreted gas never forms stars



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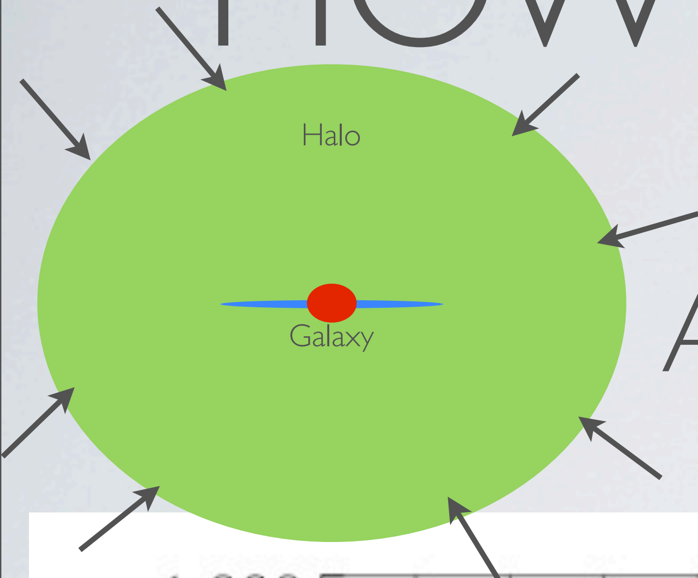

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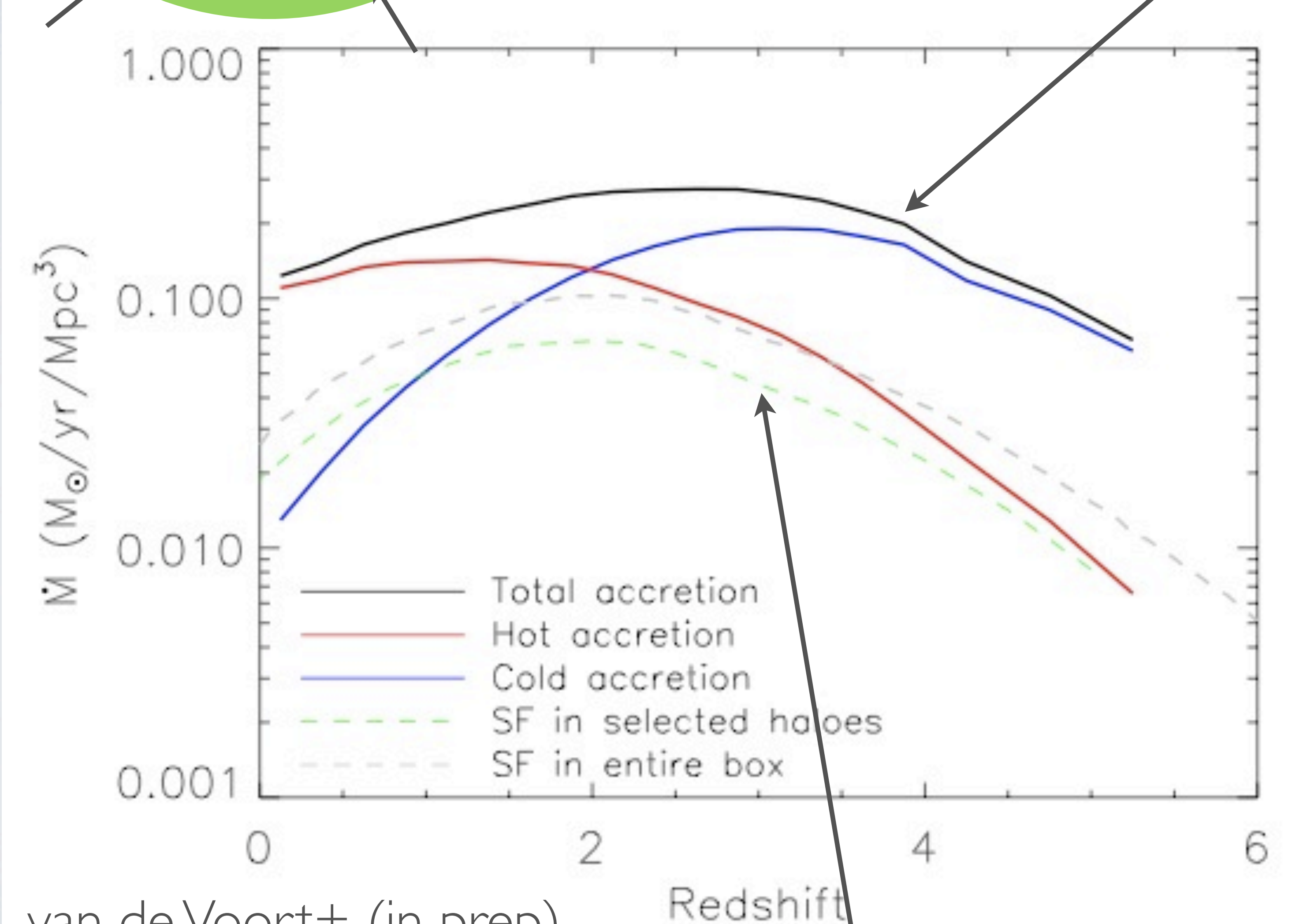

van de Voort+ (in prep)

global SFR decreases after z=2

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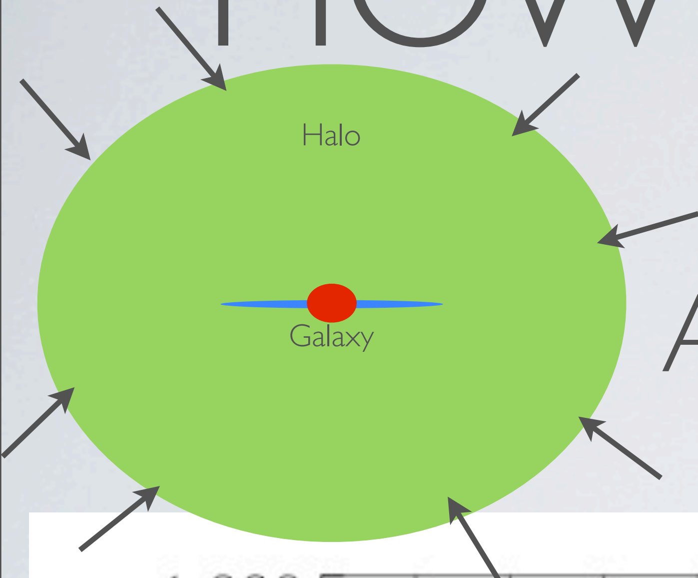

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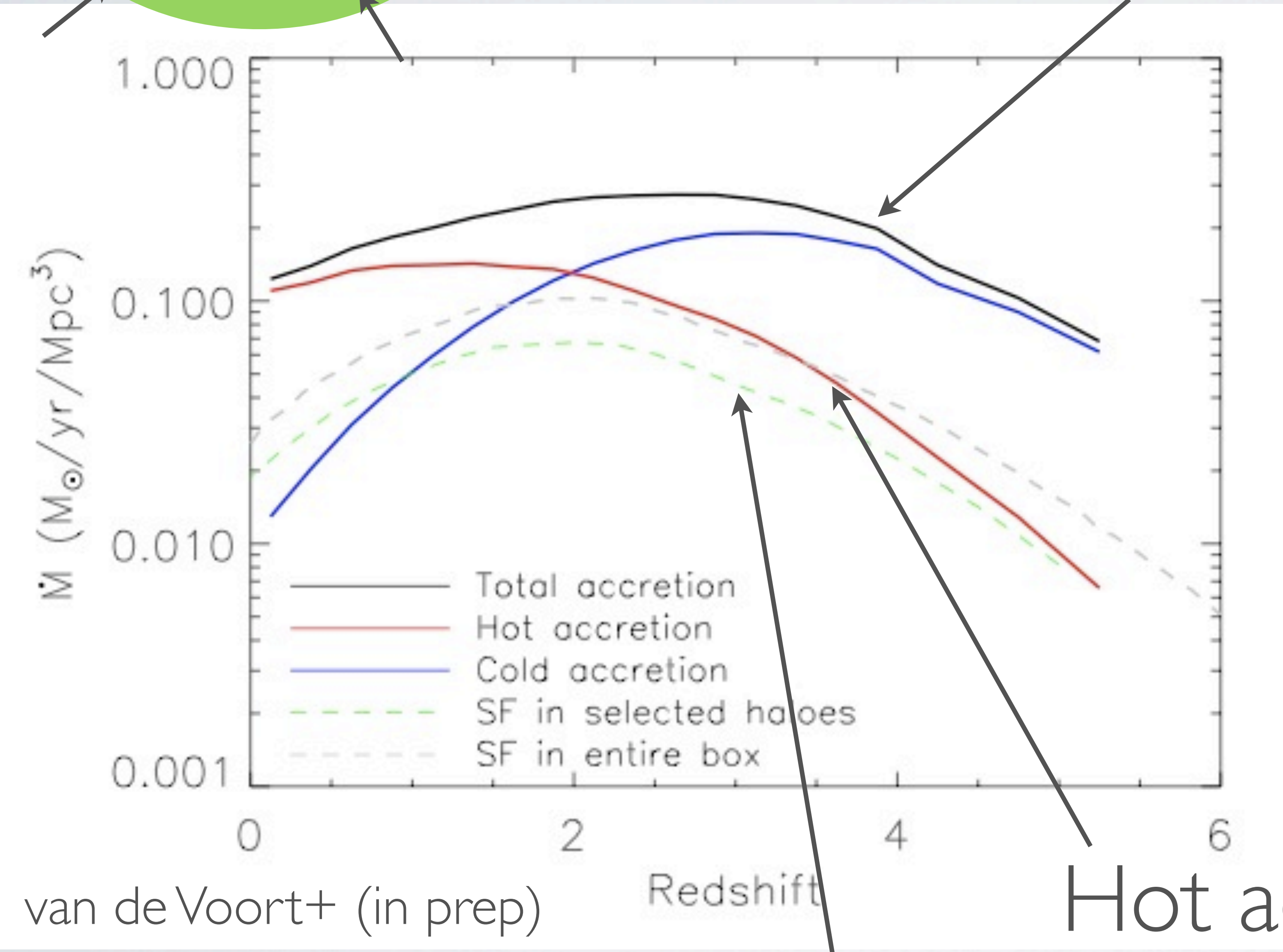

van de Voort+ (in prep)

Hot accr. rate rises

global SFR decreases after z=2

- Gas that never reaches $T>10^{5.5}$K is 'cold' accretion
- Compare accretion rates to SFR

van de Voort

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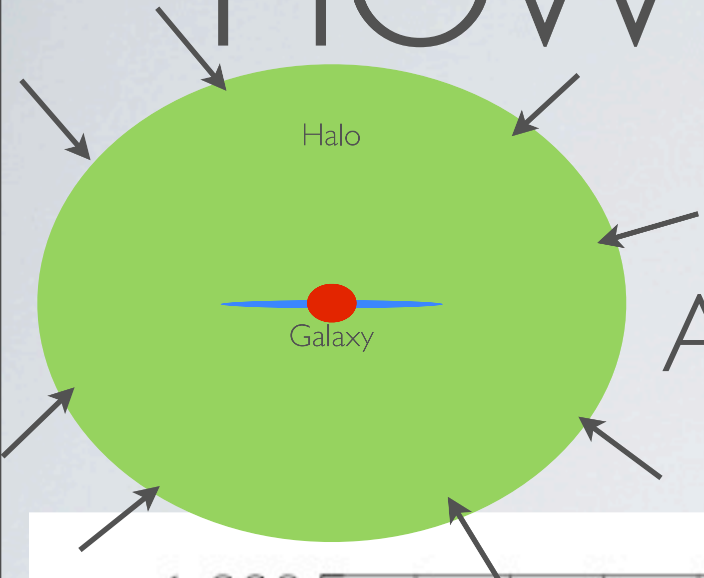

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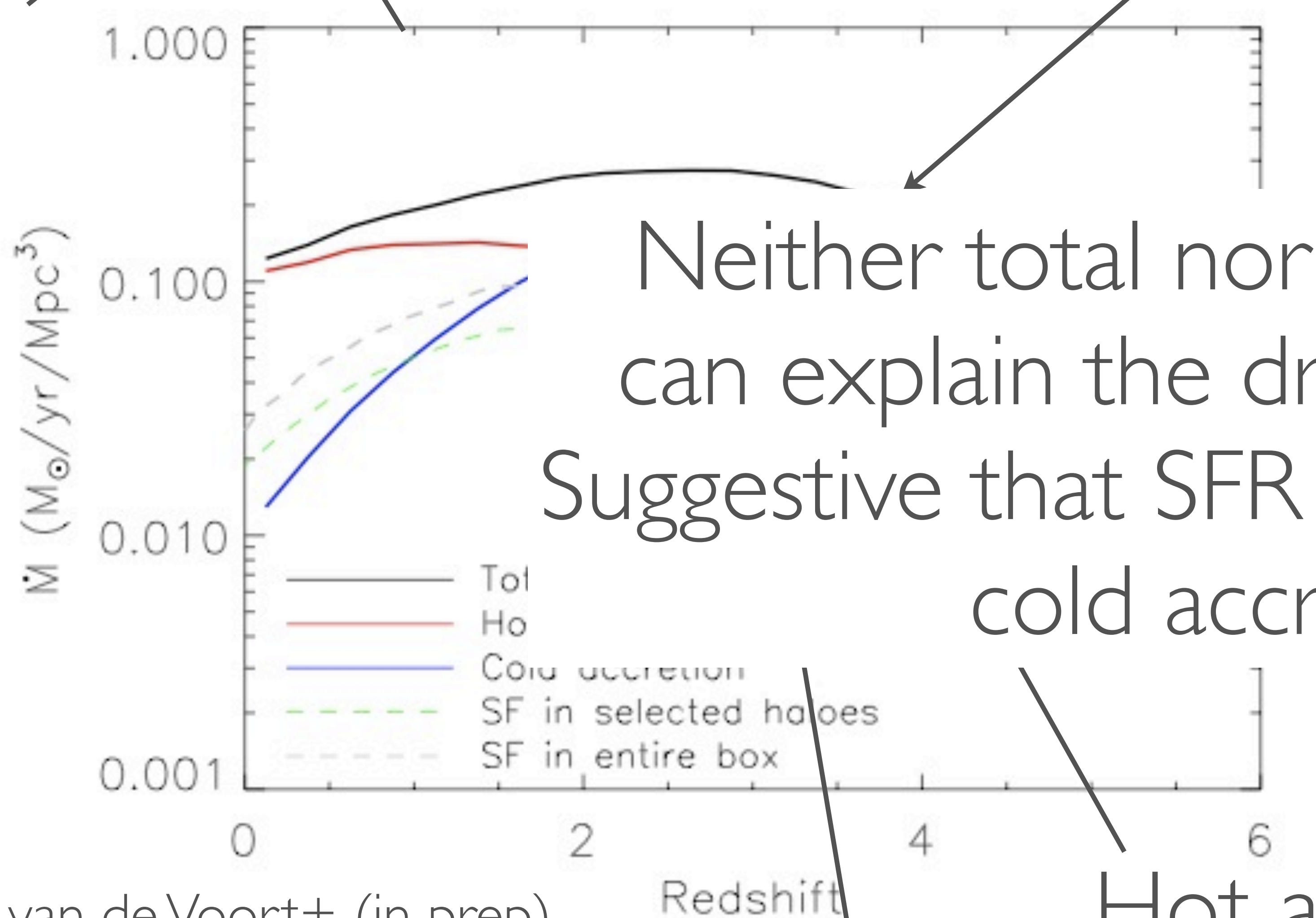


van de Voort+ (in prep)

reaches

d'

tion rates

to SFR

Neither total nor hot accretion can explain the drop in the SFR. Suggestive that SFR is dominated by cold accretion

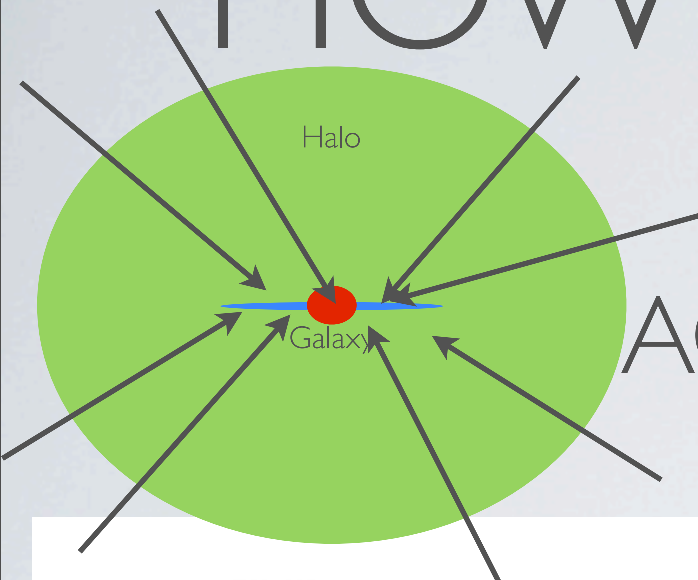
Hot accr. rate rises

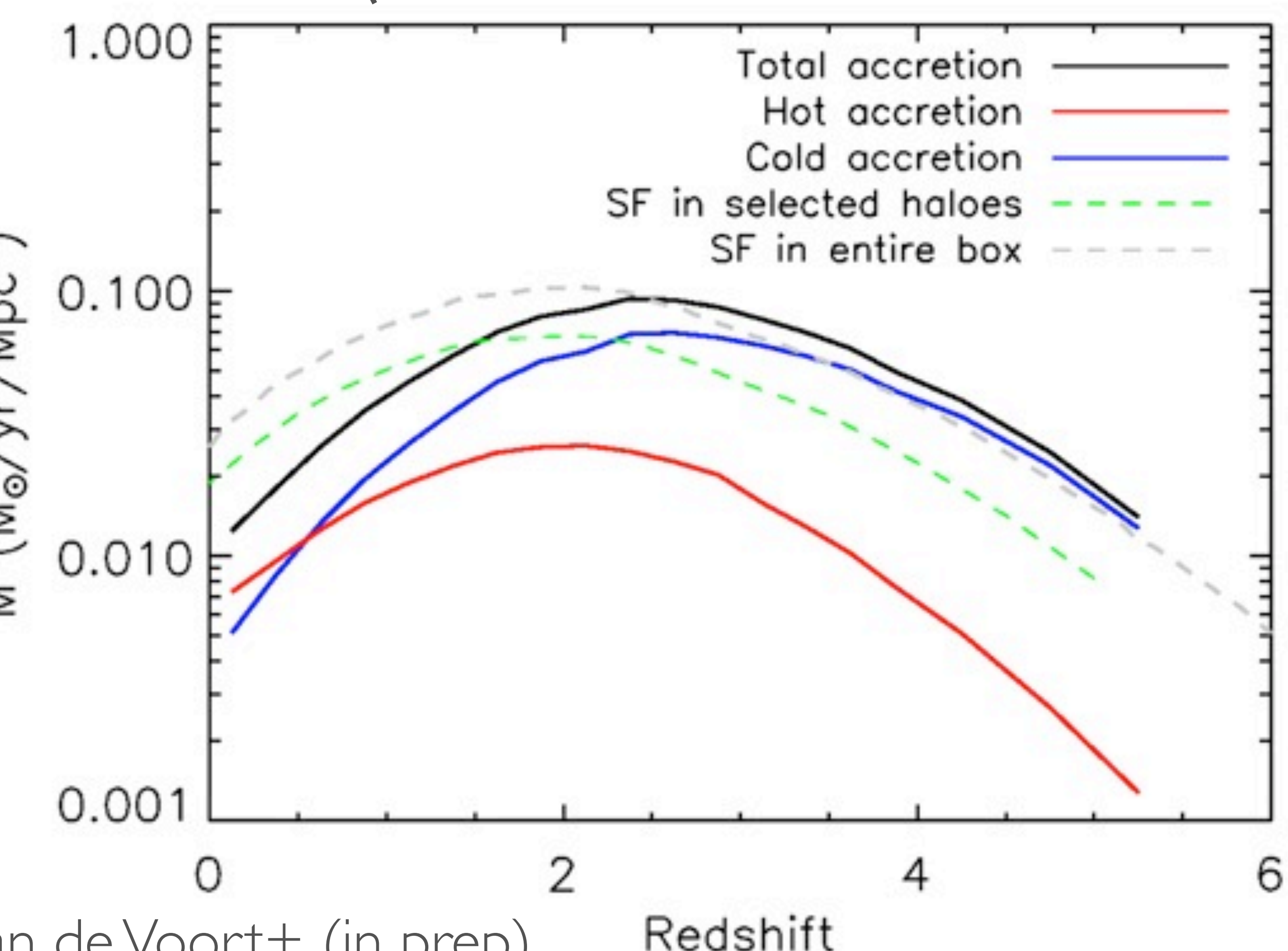
global SFR decreases after z=2

van de Voort

HOW DOES GAS GET INTO GALAXIES?

ACCRETION ONTO GALAXIES





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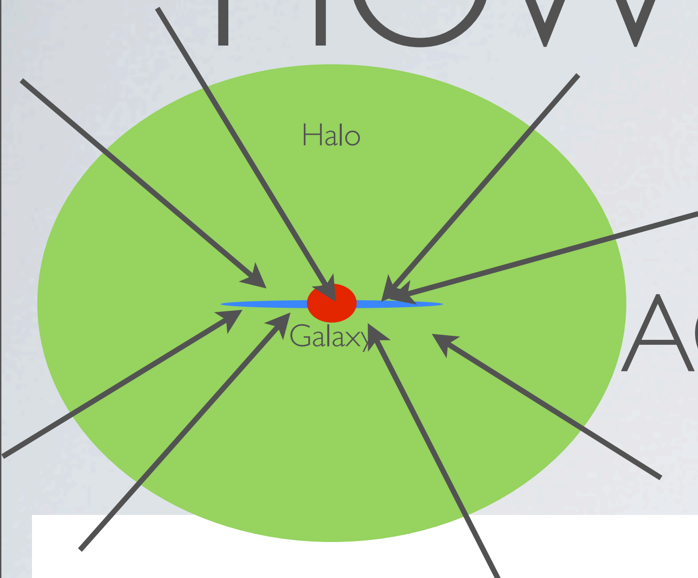
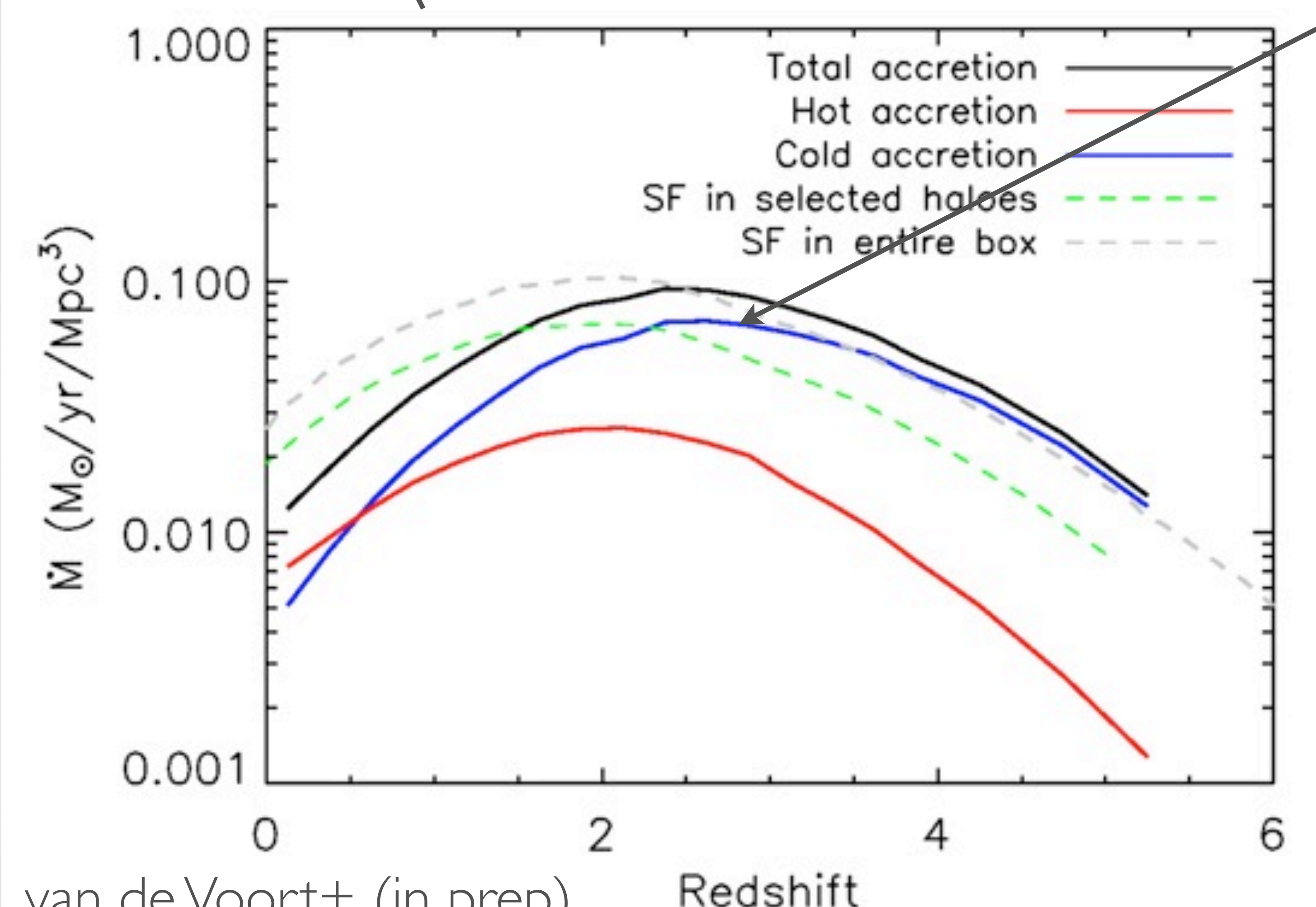


ACCRETION ONTO GALAXIES

Cold accretion dominates growth of GALAXIES



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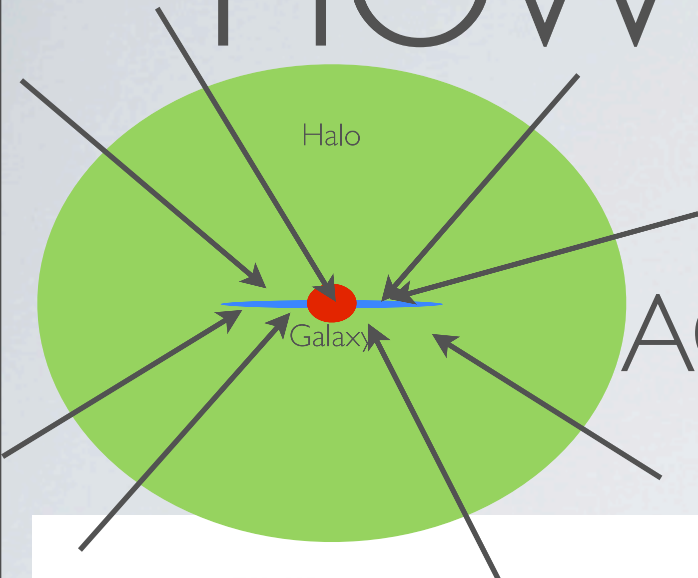

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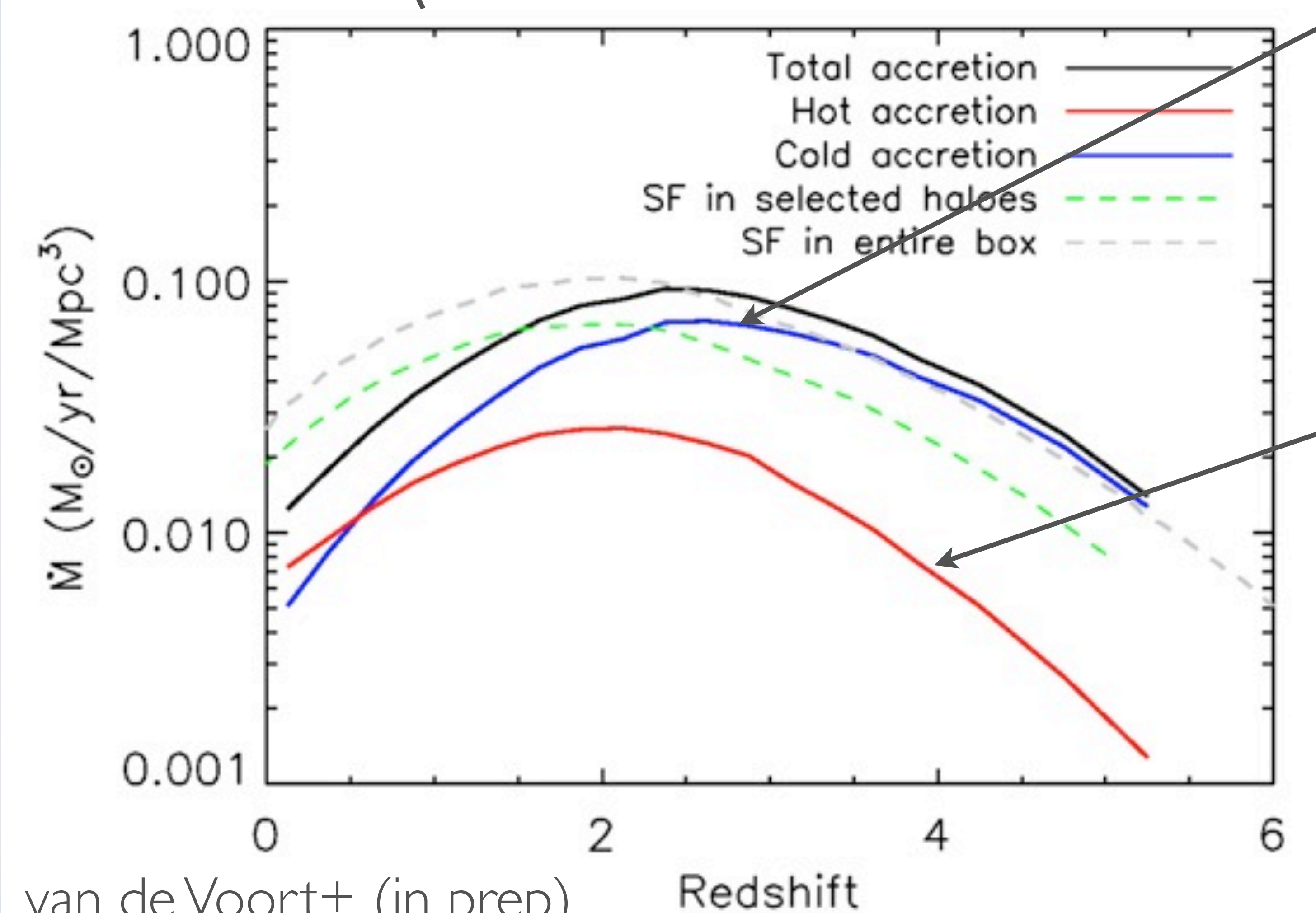


van de Voort+ (in prep)

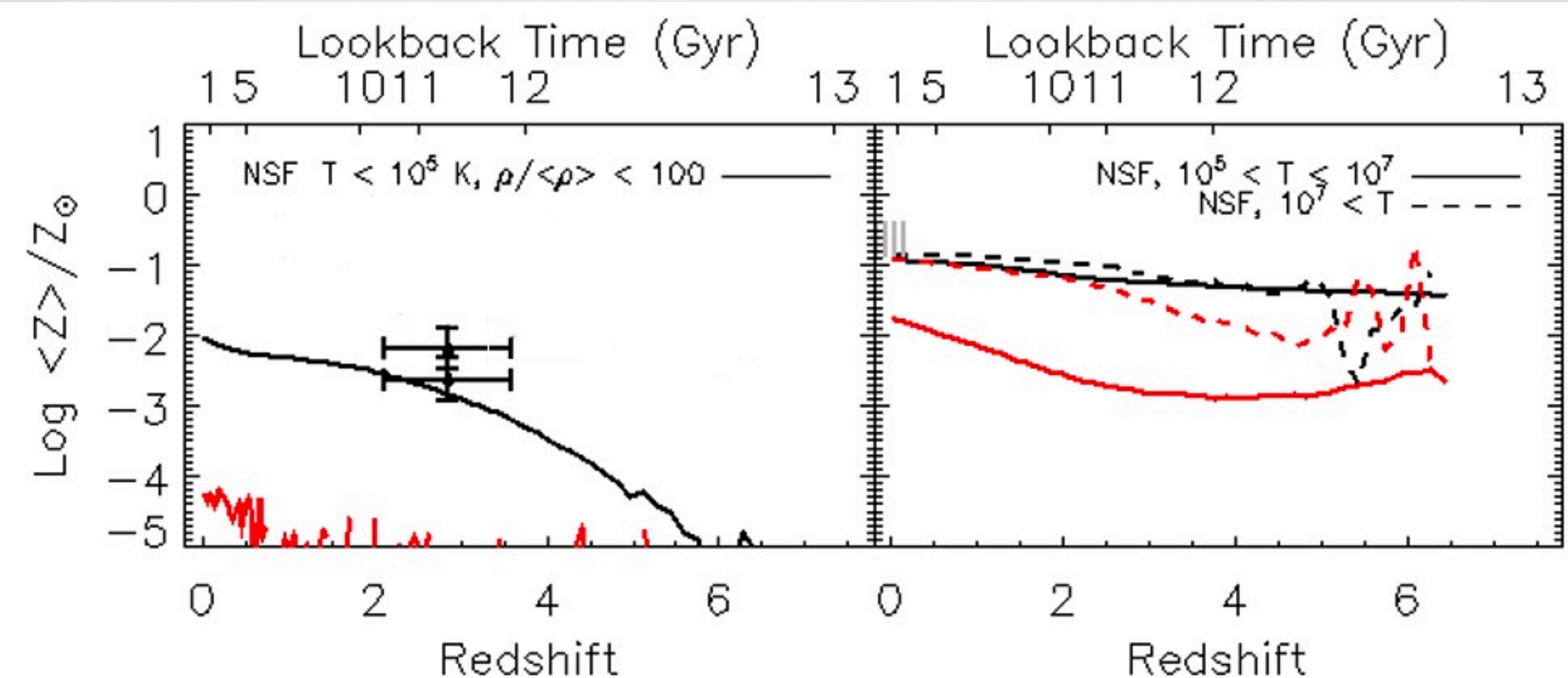
Cold accretion dominates growth of GALAXIES

Hot accretion cannot account for growth of galaxies

van de Voort

HOW DO METALS ESCAPE?

Red: No SN Feedback. Black: SN Feedback



Solid line: IGM

Solid line: WHIM Dashed line: ICM

Aguirre et al. (2008) (upper)
Schaye et al. (2003) (lower)

Simionescu et al. 2009

Danforth & Shull (2005) Z_{WHIM}~-1

Wiersma+ (2009)

CONCLUSIONS (PART I)

- Some gas that falls into galaxies is shocked to the halo virial temperature some is not
- The cold gas in and around galaxies:
  - Gas that accretes cold dominates the global SFR
  - Most gas that accretes onto haloes never forms stars
- The hot gas in and around galaxies:
  - To study hot gas, accurate treatment of the UV background is necessary
  - ICM enriched without galactic winds

PART II

Growing galaxies: Feeding, self regulation, stars, and black holes

What sets the masses of galaxies?

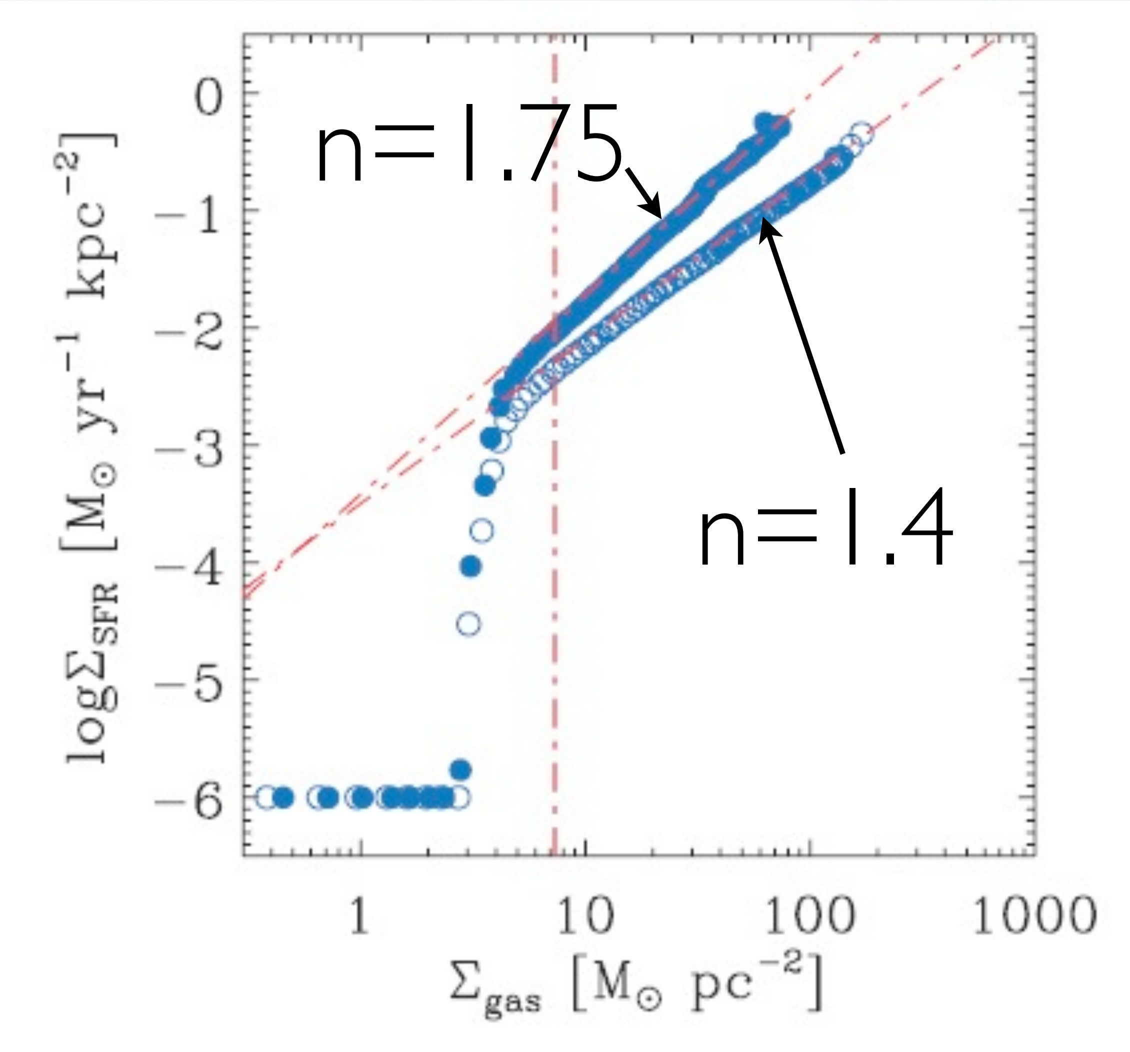
A NUMERICAL EXPERIMENT: CHANGE THE FORM OF THE KS LAW

Kennicutt-Schmidt Law

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

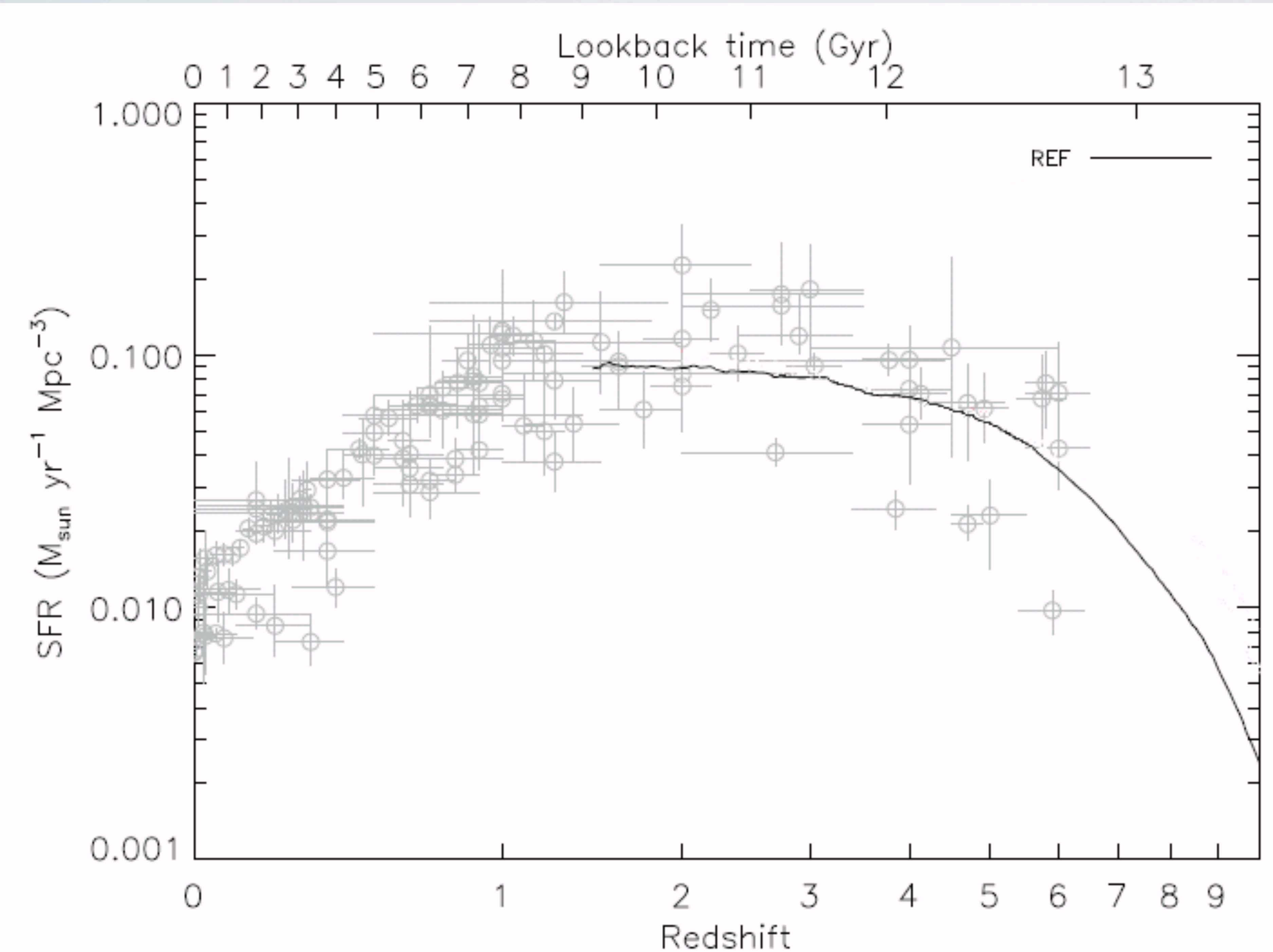
Normalization (x3, x6)

Slope (1.4->1.75)



Schaye & Dalla Vecchia (2008)

A NUMERICAL EXPERIMENT: CHANGE THE FORM OF THE KS LAW



Schaye et al. (MNRAS submitted)

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

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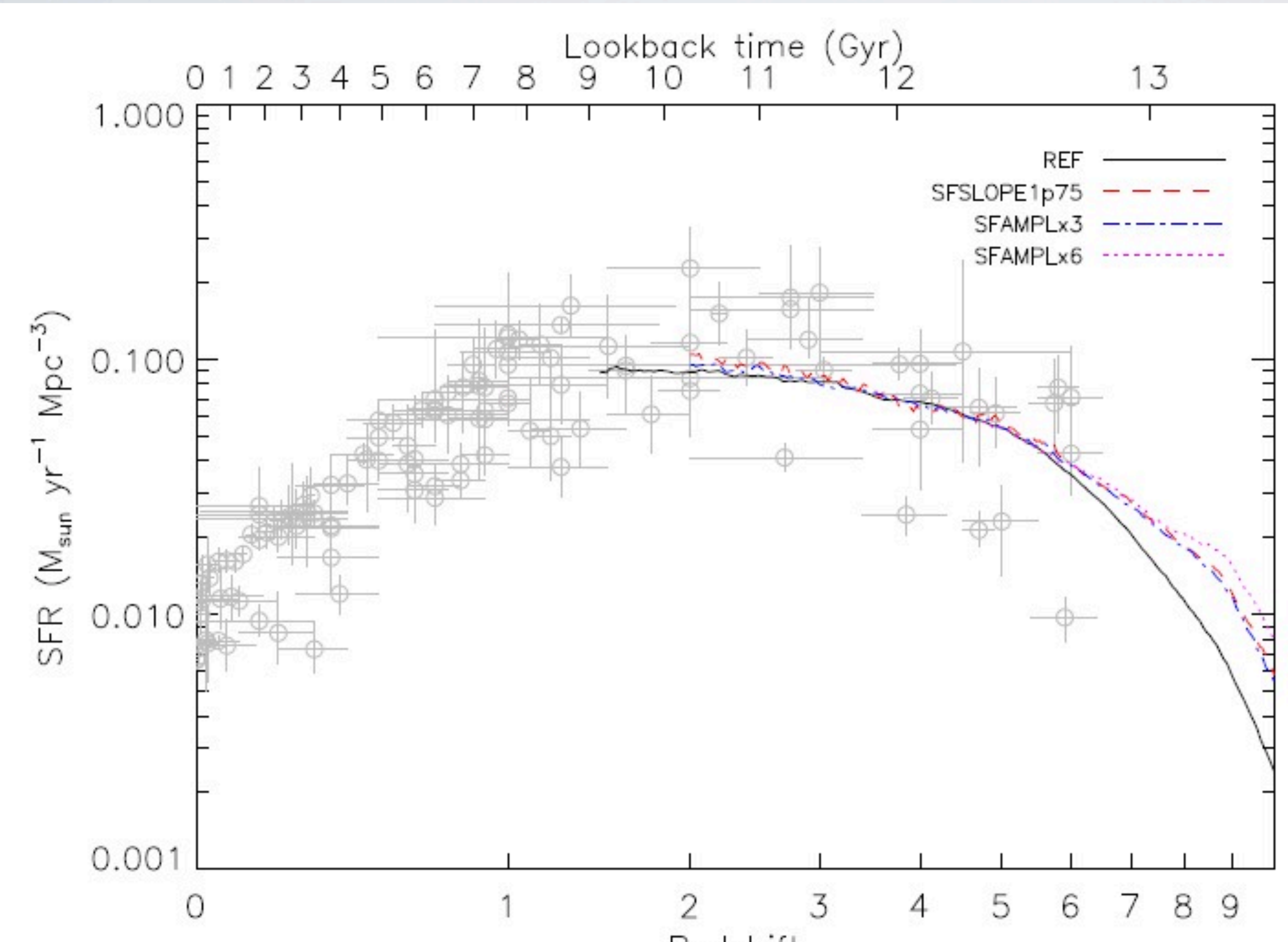

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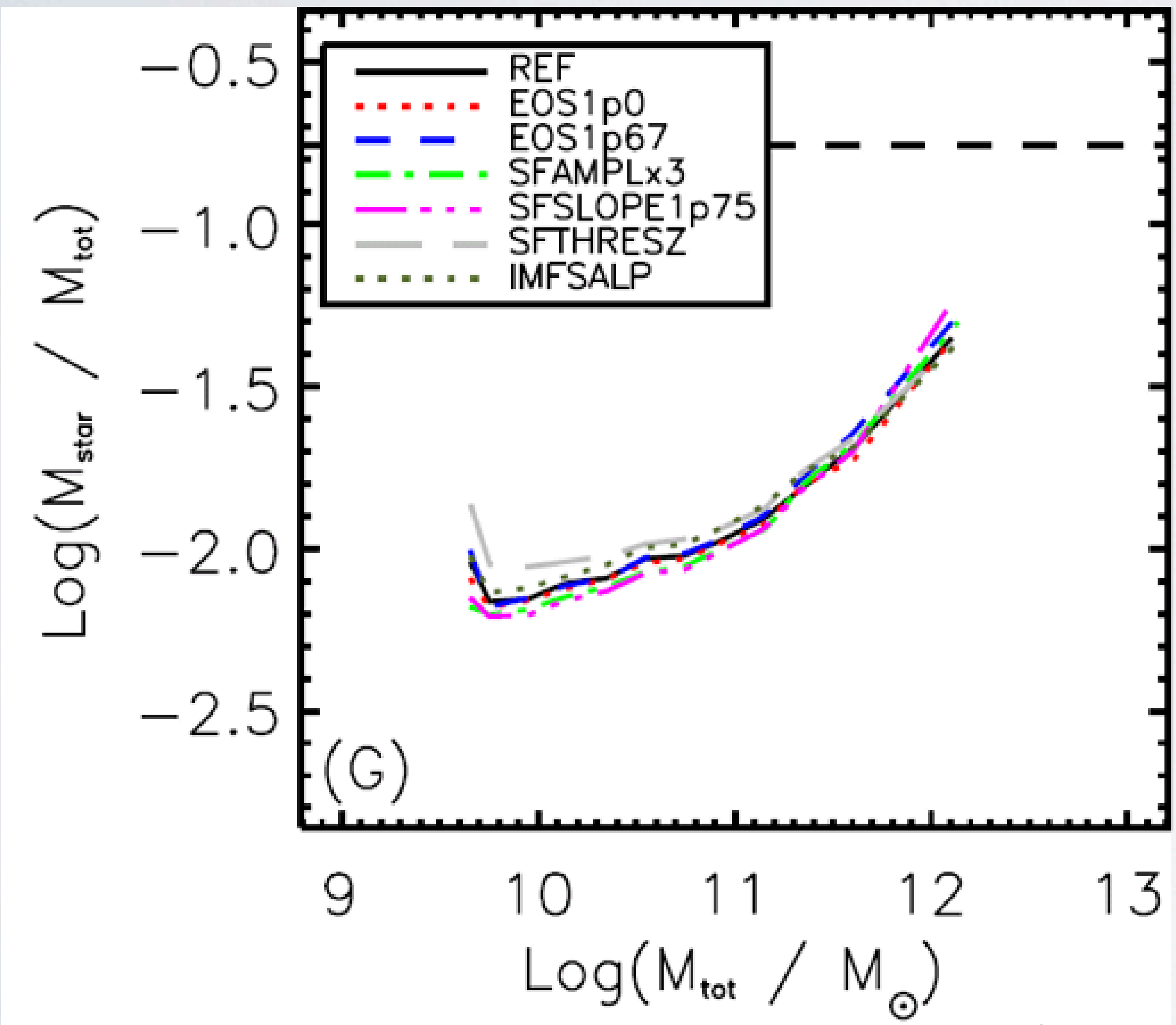


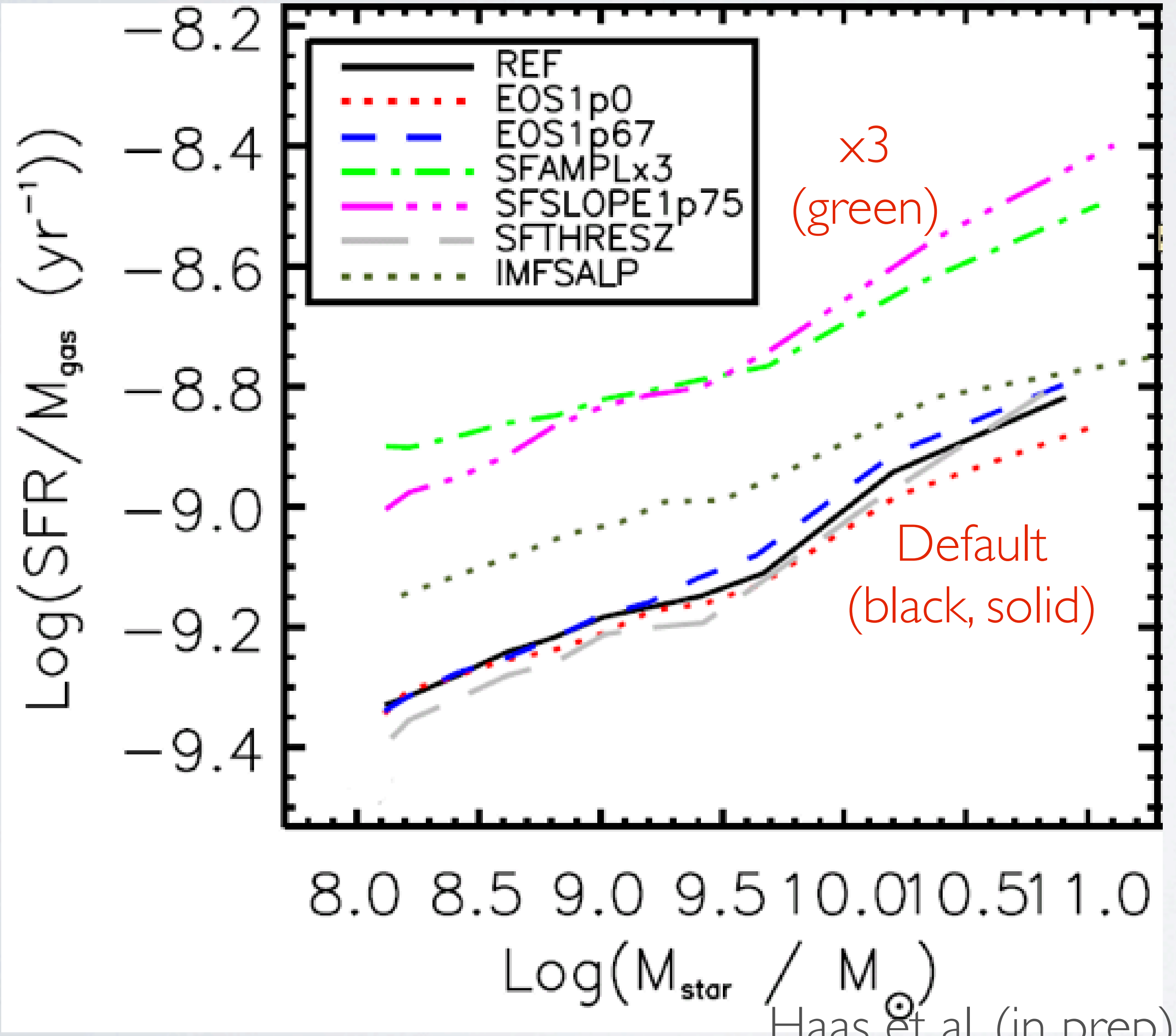
Haas et al. (in prep)

The same is true in individual haloes

Haas

A NUMERICAL EXPERIMENT: CHANGE THE FORM OF THE KS LAW

Balance between fuelling and feedback

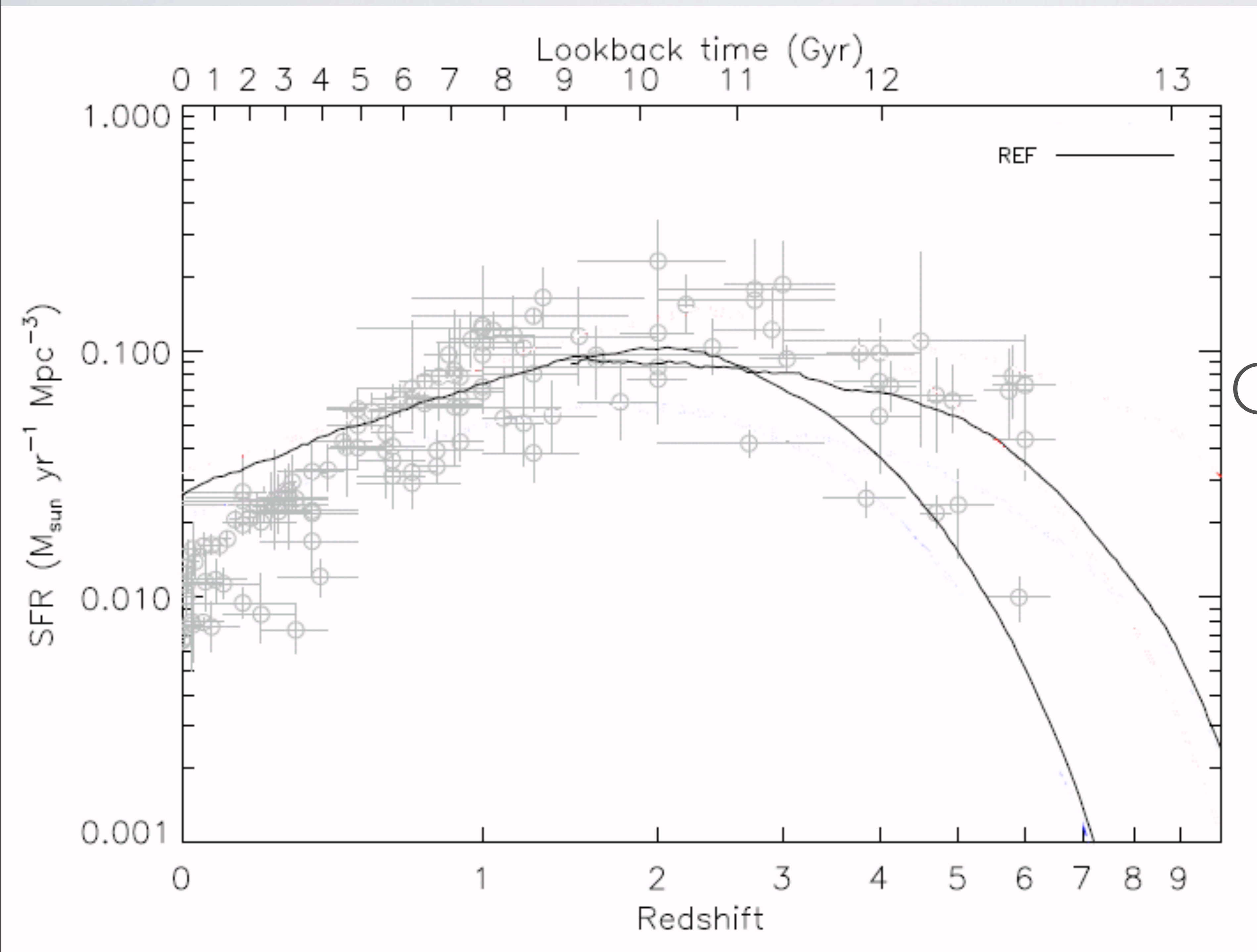


Haas et al. (in prep)

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

Haas

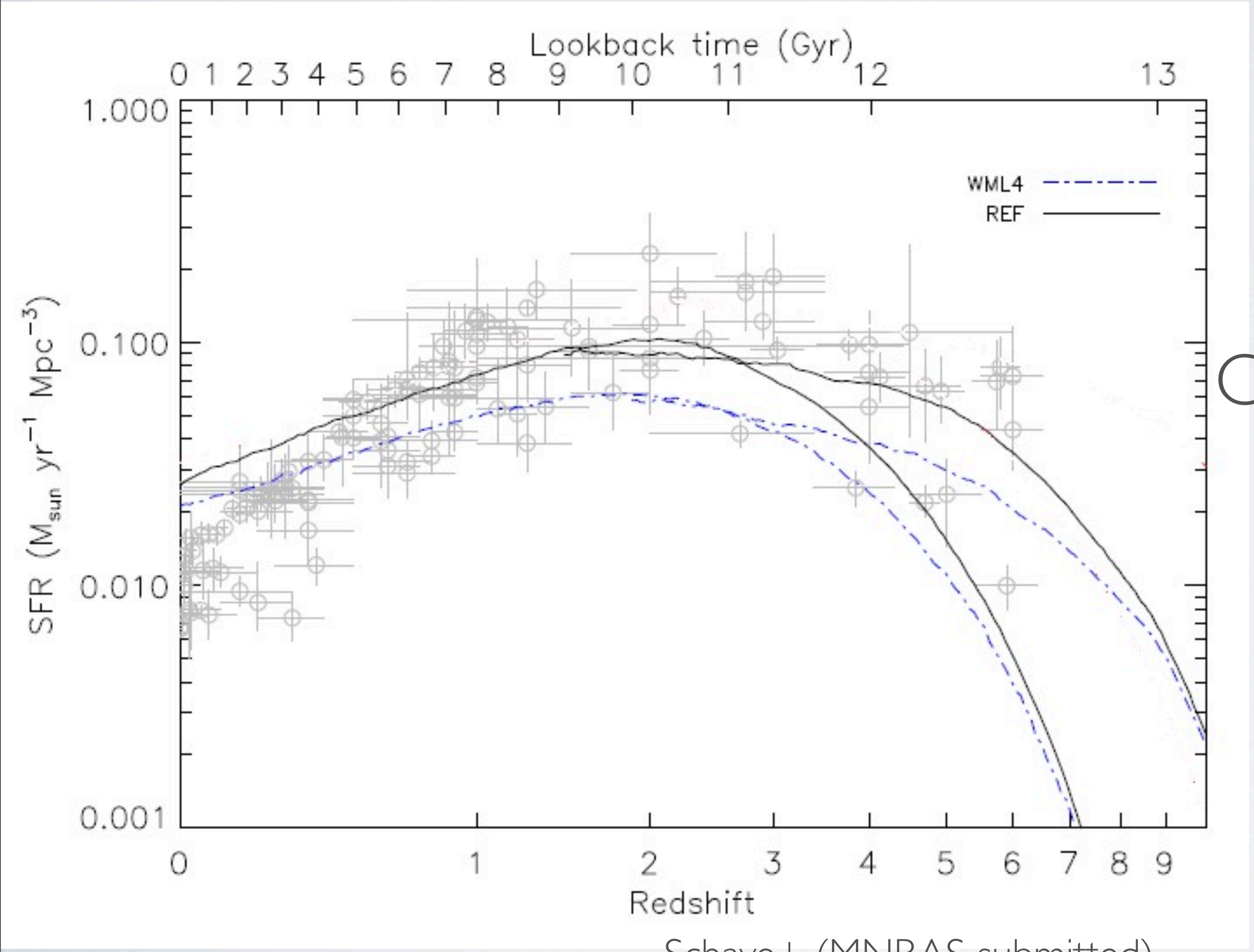
A NUMERICAL EXPERIMENT: CHANGE THE SN ENERGY



Comparison against a simulation with double the SN energy

Schaye+ (MNRAS submitted)

A NUMERICAL EXPERIMENT: CHANGE THE SN ENERGY



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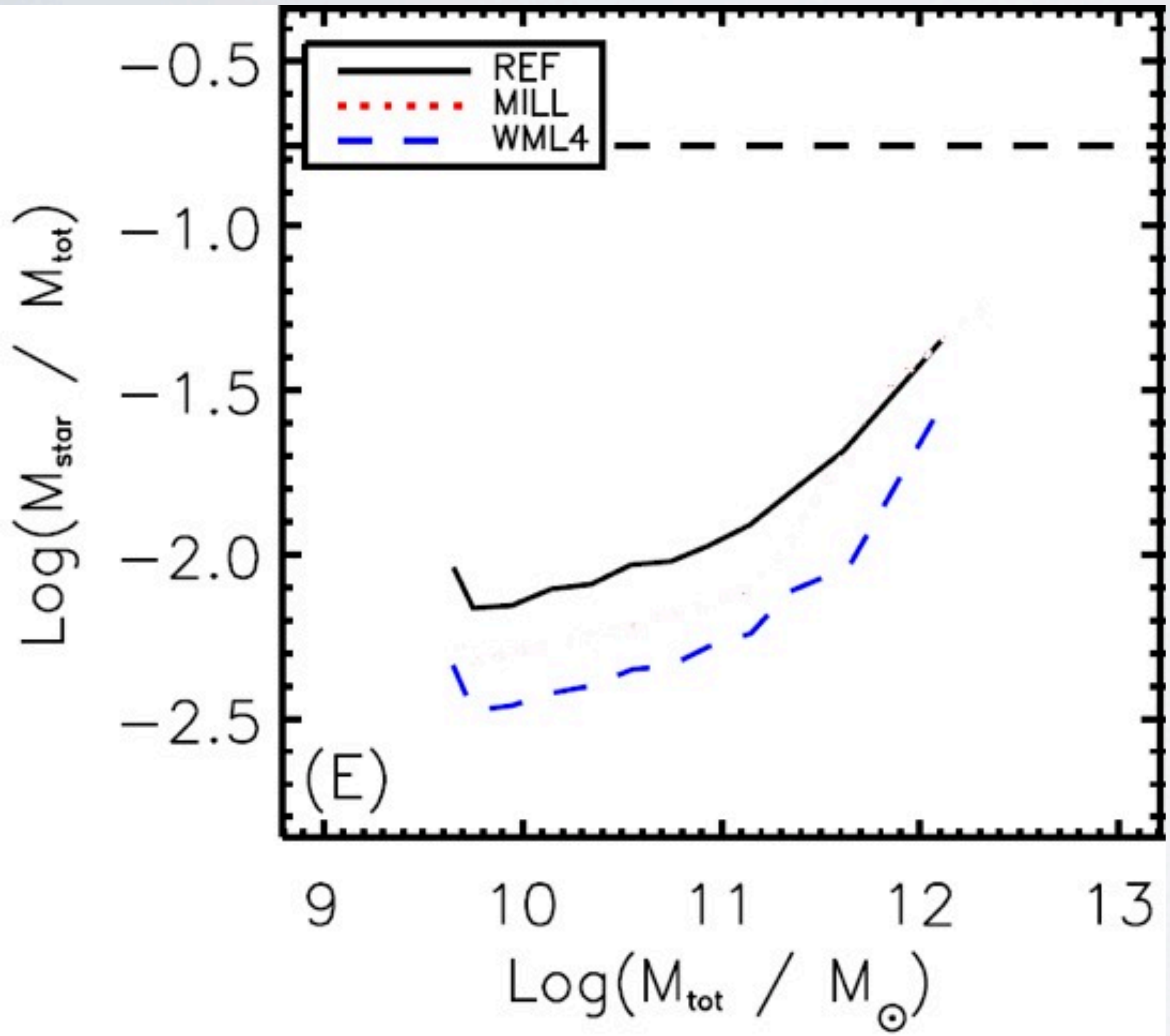
A NUMERICAL EXPERIMENT: CHANGE THE SN ENERGY

Balance between fuelling and feedback



Haas+ (in prep)

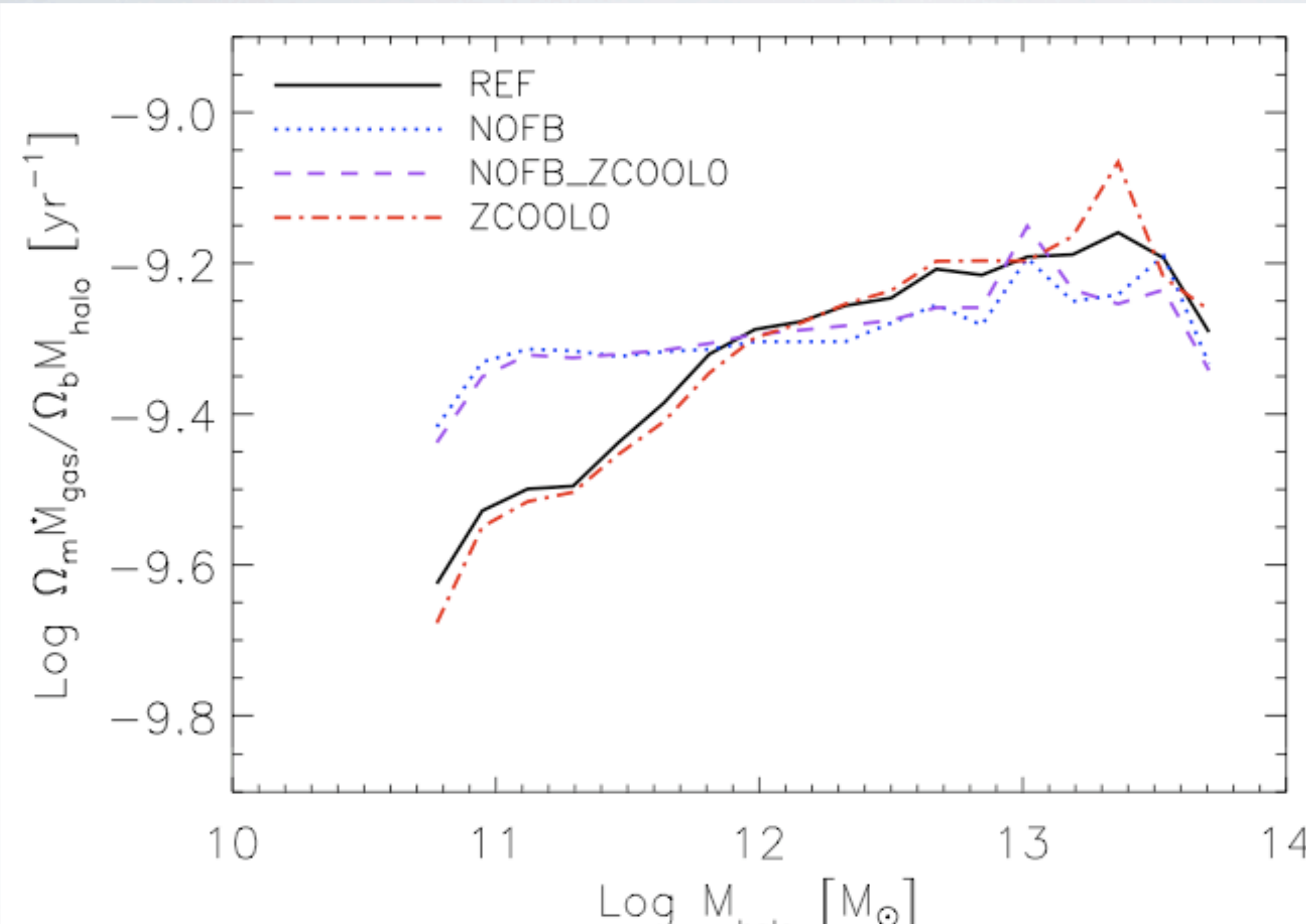
Stellar masses decreased by a factor of two

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

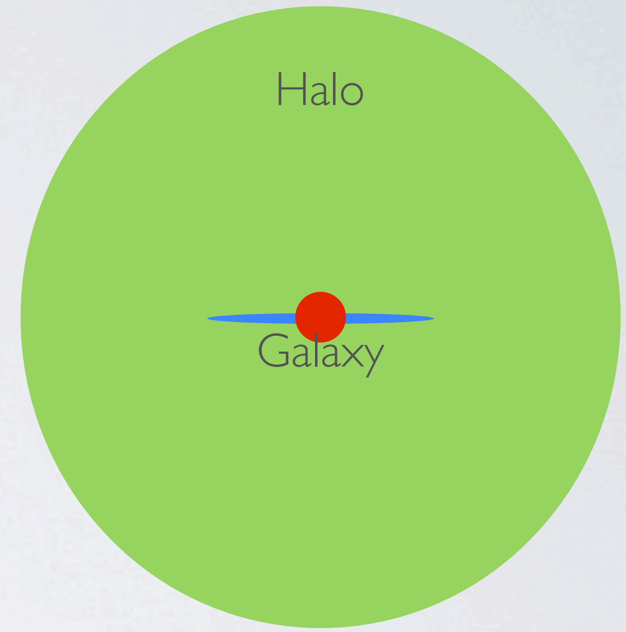
SFR inversely proportional to SN feedback efficiency

A NUMERICAL EXPERIMENT: SWITCHING OFF METAL LINES

Halo specific accretion rate at z=2



van de Voort+ (in prep)

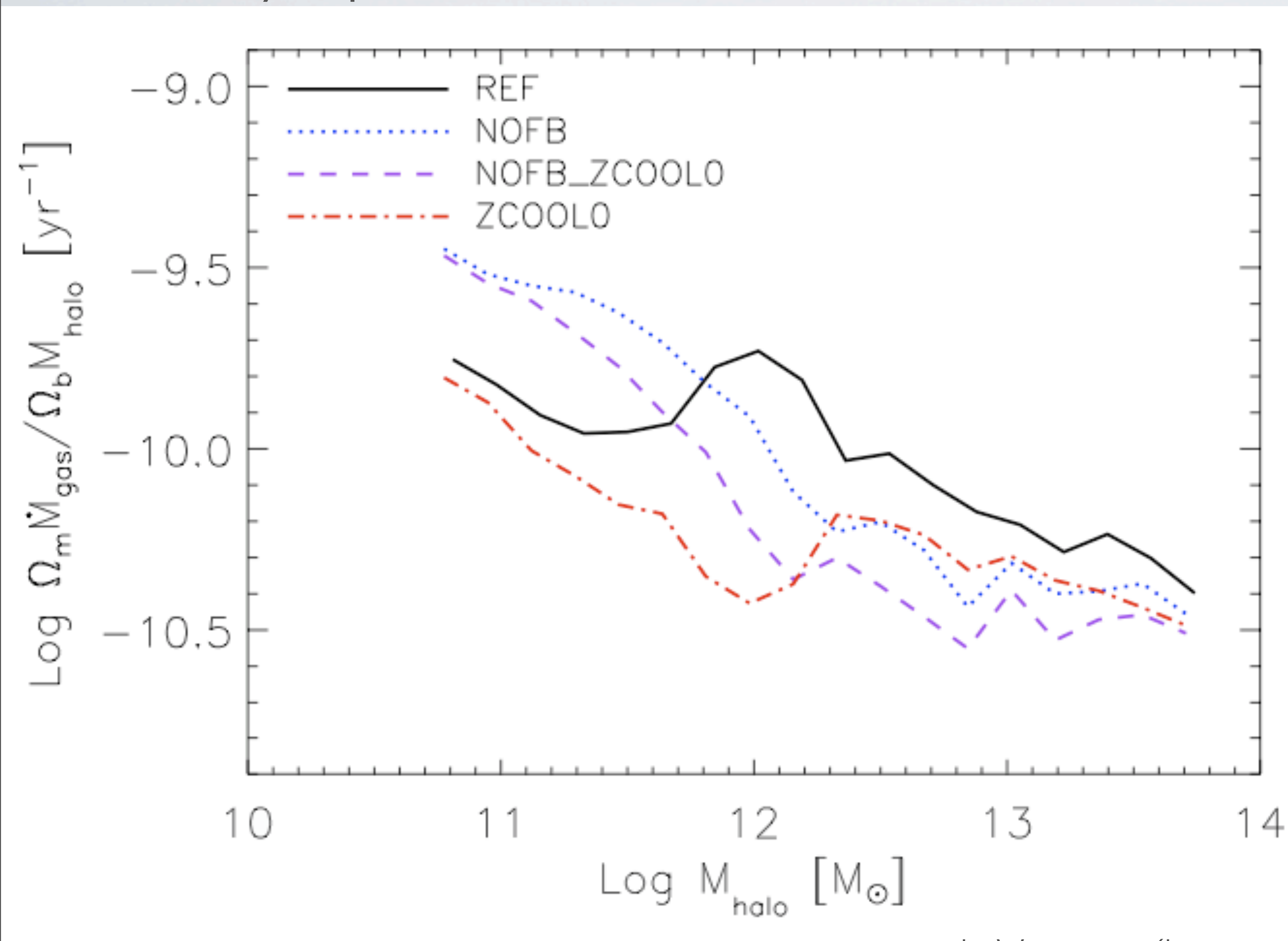


Metal cooling has no effect on accretion onto haloes

van de Voort

A NUMERICAL EXPERIMENT: SWITCHING OFF METAL LINES

Galaxy specific accretion rate at z=2



van de Voort+ (in prep)

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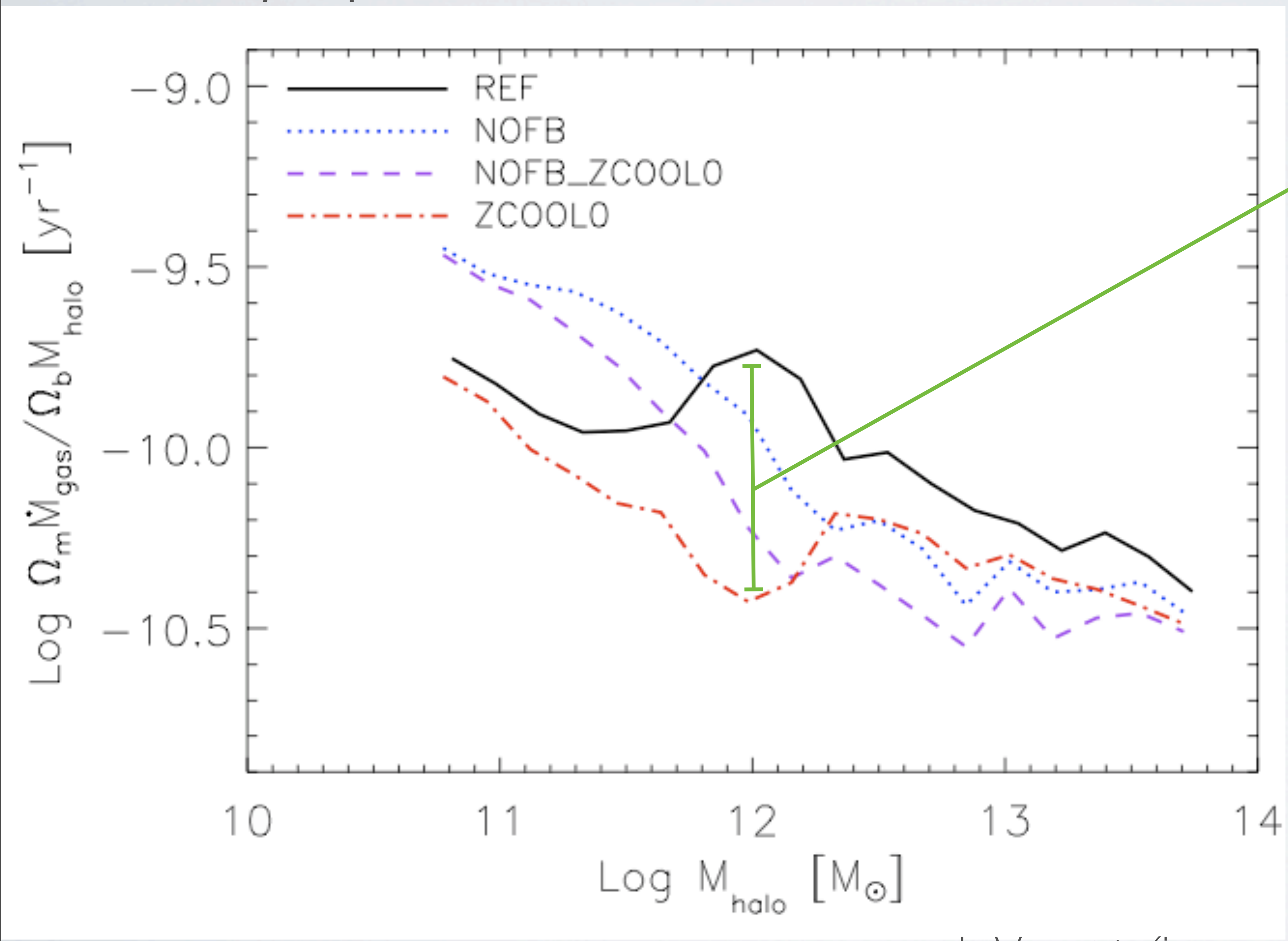


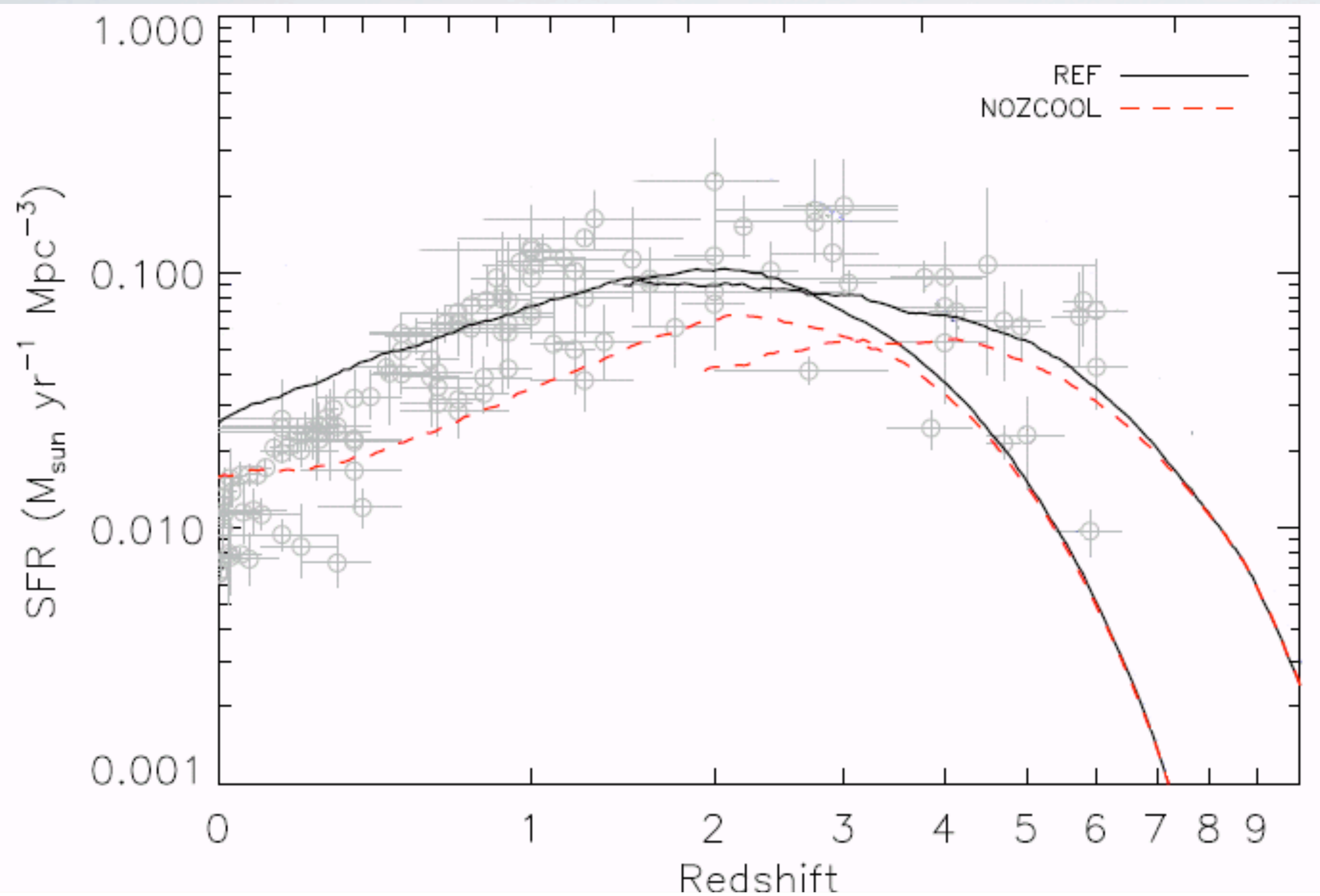
van de Voort+ (in prep)

Lack of metal cooling makes it harder for hot gas to get into galaxies

van de Voort

Thursday, 12 November 2009

A NUMERICAL EXPERIMENT: SWITCHING OFF METAL LINES



Schaye+ (MNRAS submitted)

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

THE STORY SO FAR...

- The SFR is tightly regulated by competition between fuelling (cooling) and ejection (feedback)
    - If you form more stars at a given density, gas densities decrease to keep E_{out} constant.
    - If you output more energy for a given amount of stars, the mass in stars decreases to keep E_{out} constant.
    - If fuelling is less effective, less energy is required to balance gas inflow (see also σ_8)
- Considering something different can give us insight into what scales self-regulation takes place.
- Let's consider the AGN population...

CMB & Schaye (2009a)
CMB & Schaye (2009b)

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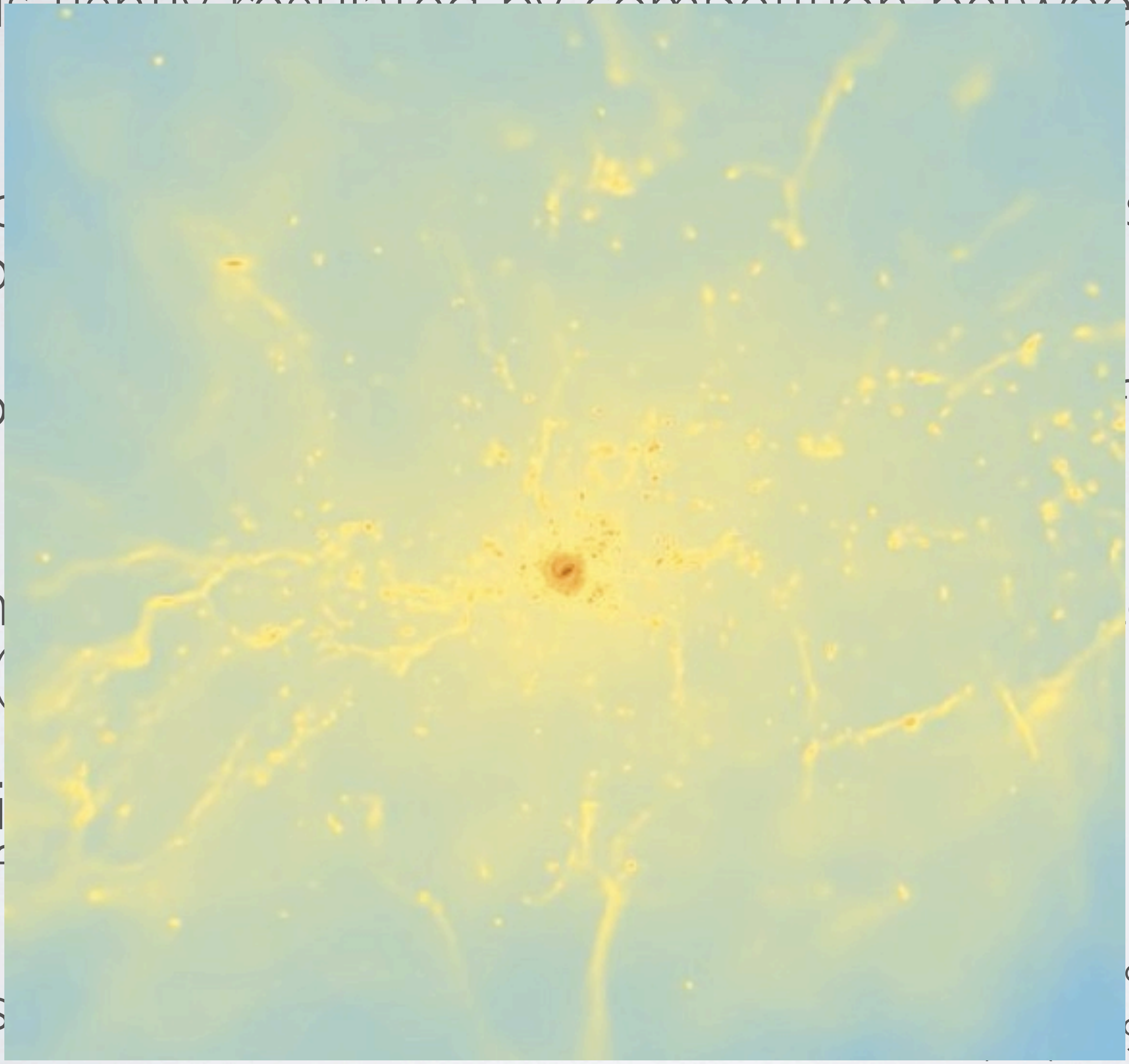

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CMB & Schaye (2009a)
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AGN MODEL

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

The model has three components:

- Black hole formation

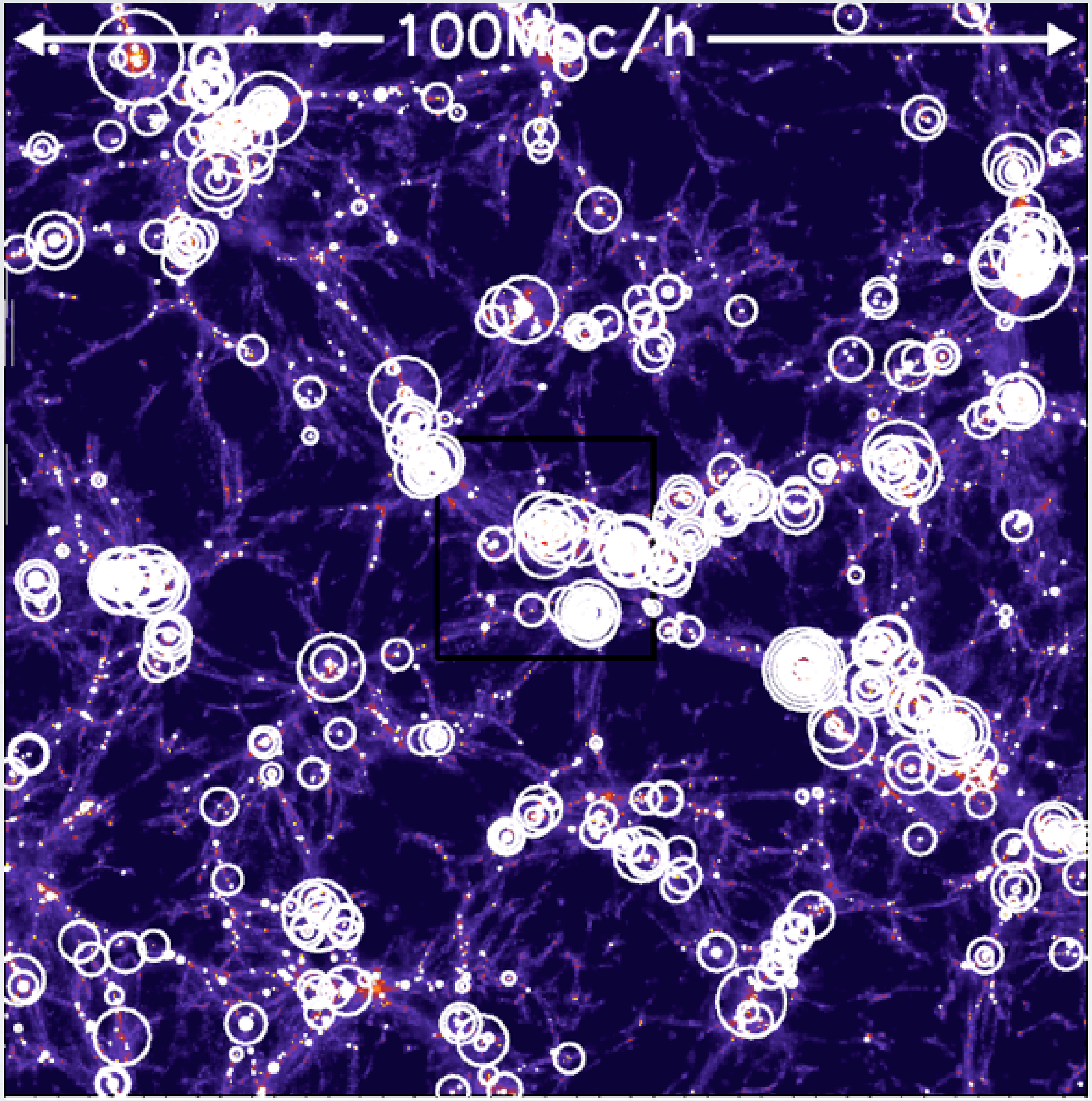
  m_{seed} $m_{halo,crit}$

- 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 is the major factor that controls the amount of BHs



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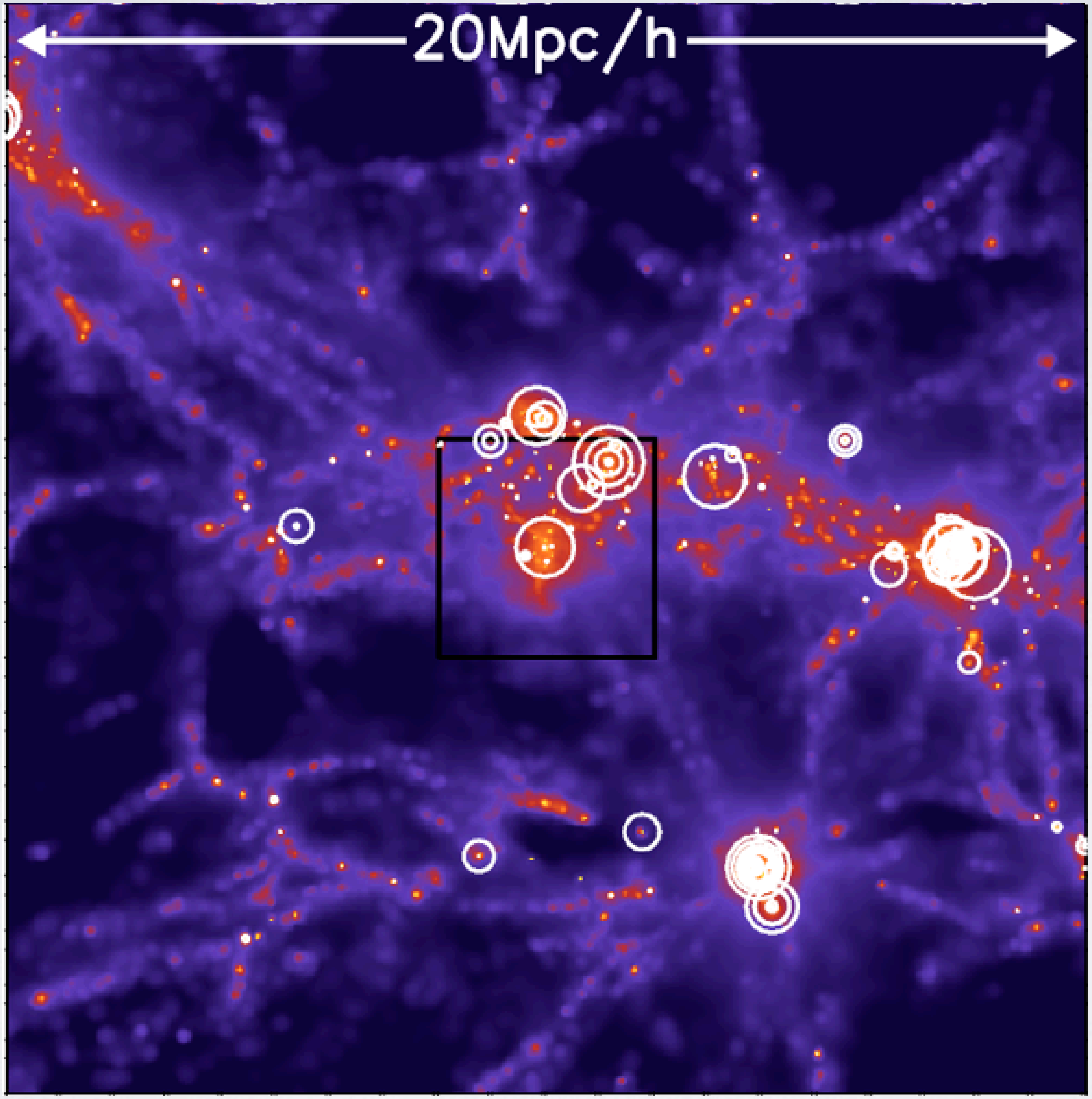

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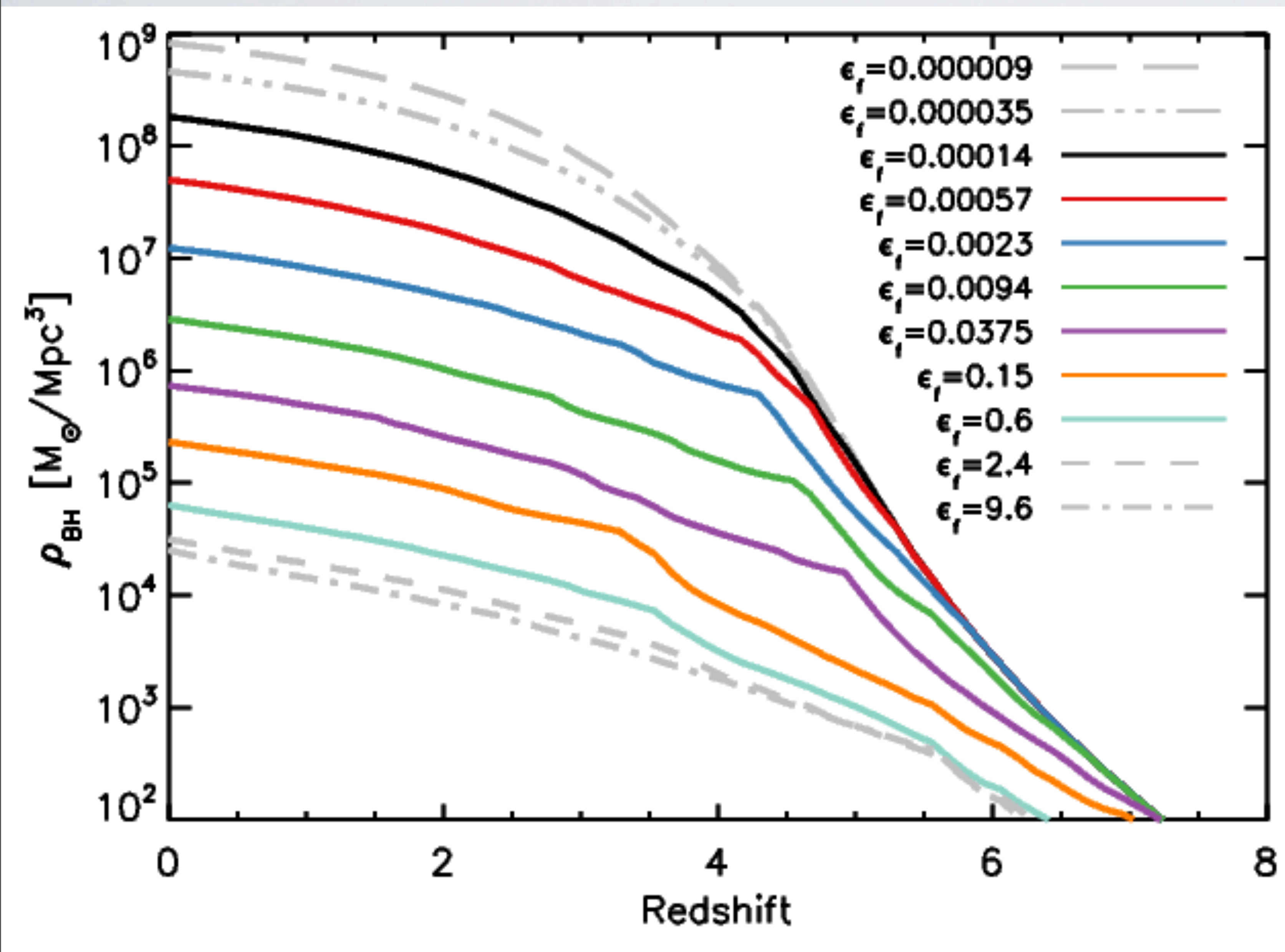
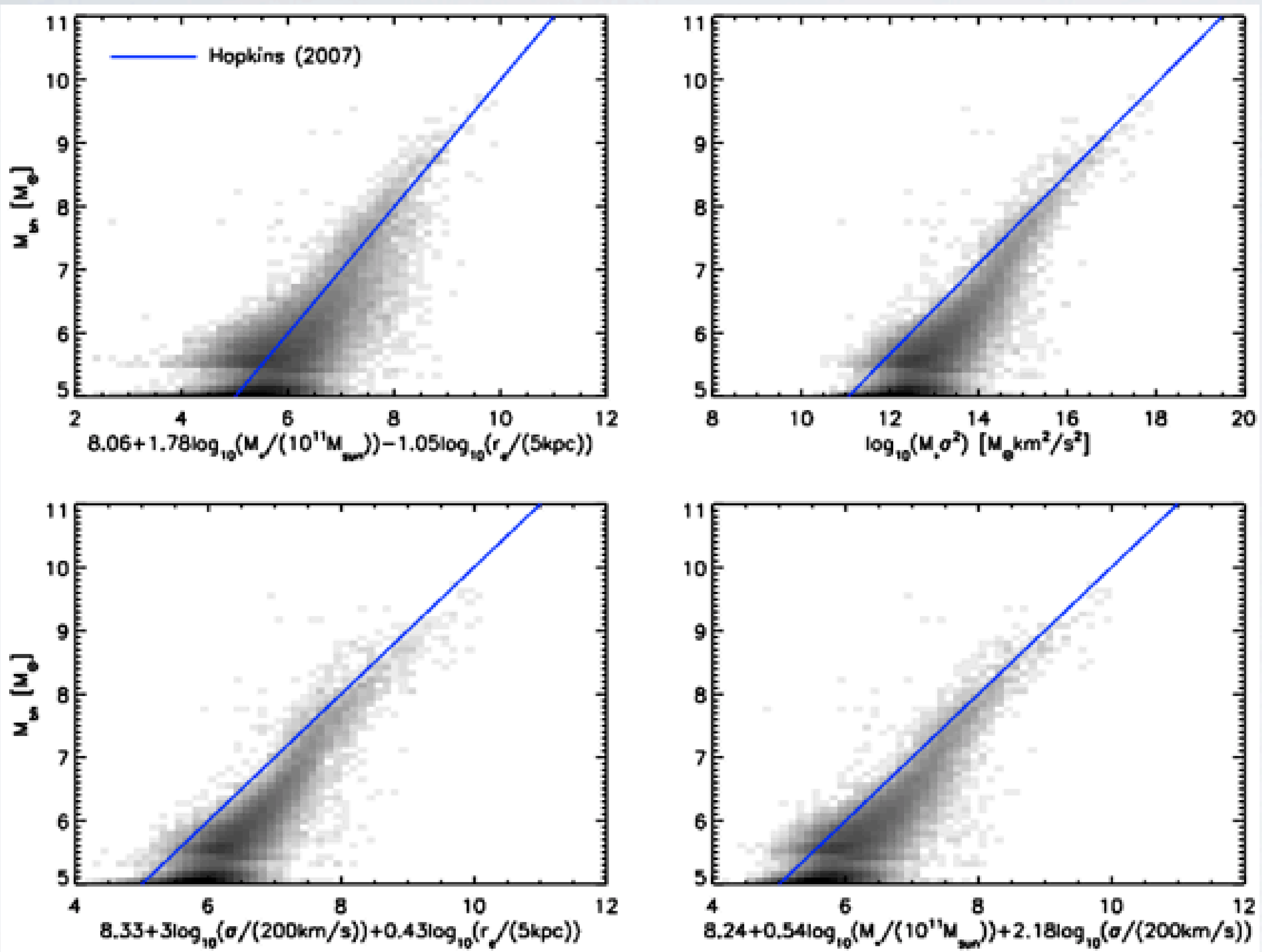
AGN MODEL



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

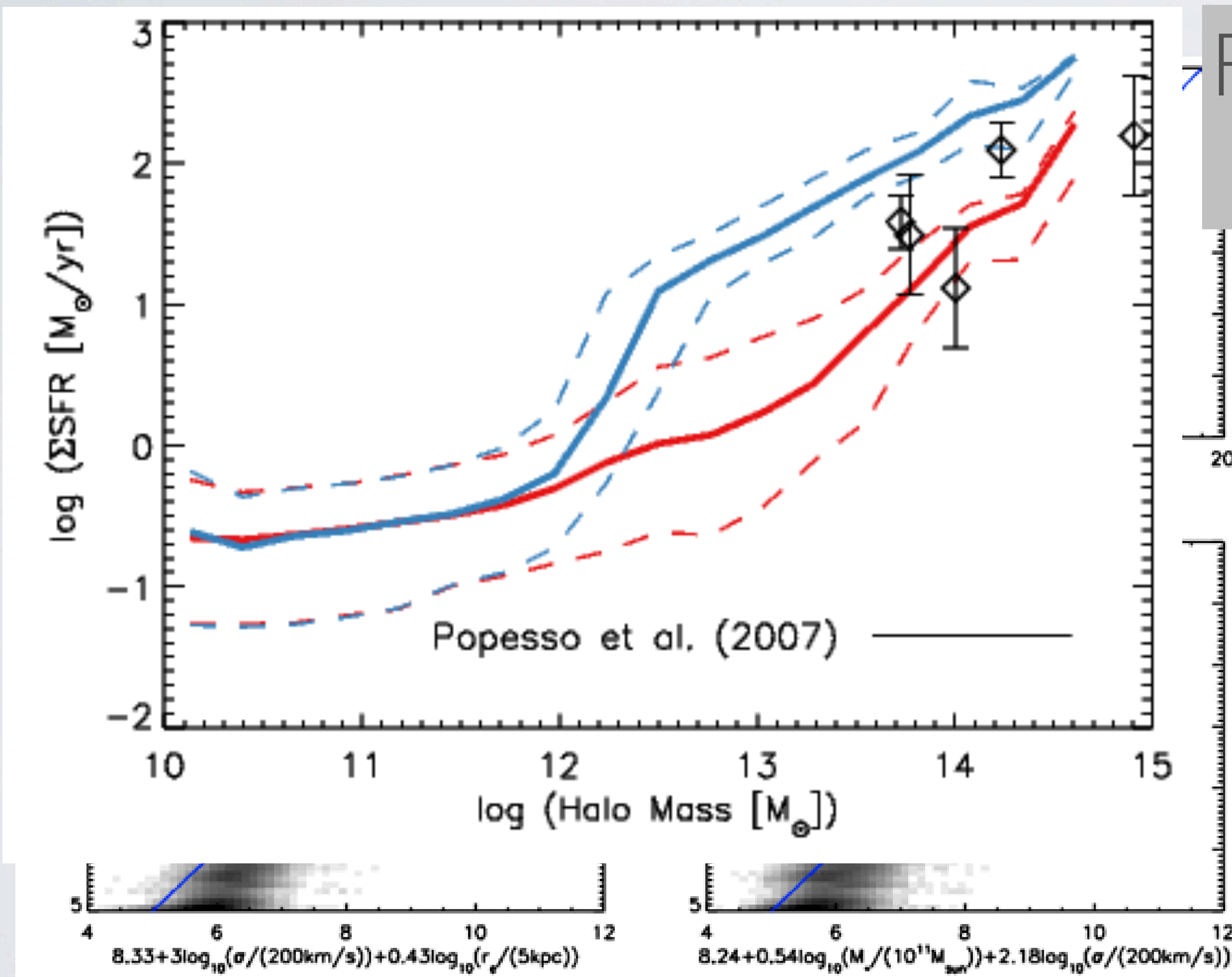
$$E_{\mathrm{feed}} = \epsilon_{\mathrm{f}} \epsilon_{\mathrm{r}} \dot{m}_{\mathrm{BH}} c^2 \Delta t$$

Observational Comparison



BH properties match galaxy properties

Observational Comparison



Reasonable group/cluster SFRs

BH properties match galaxy properties

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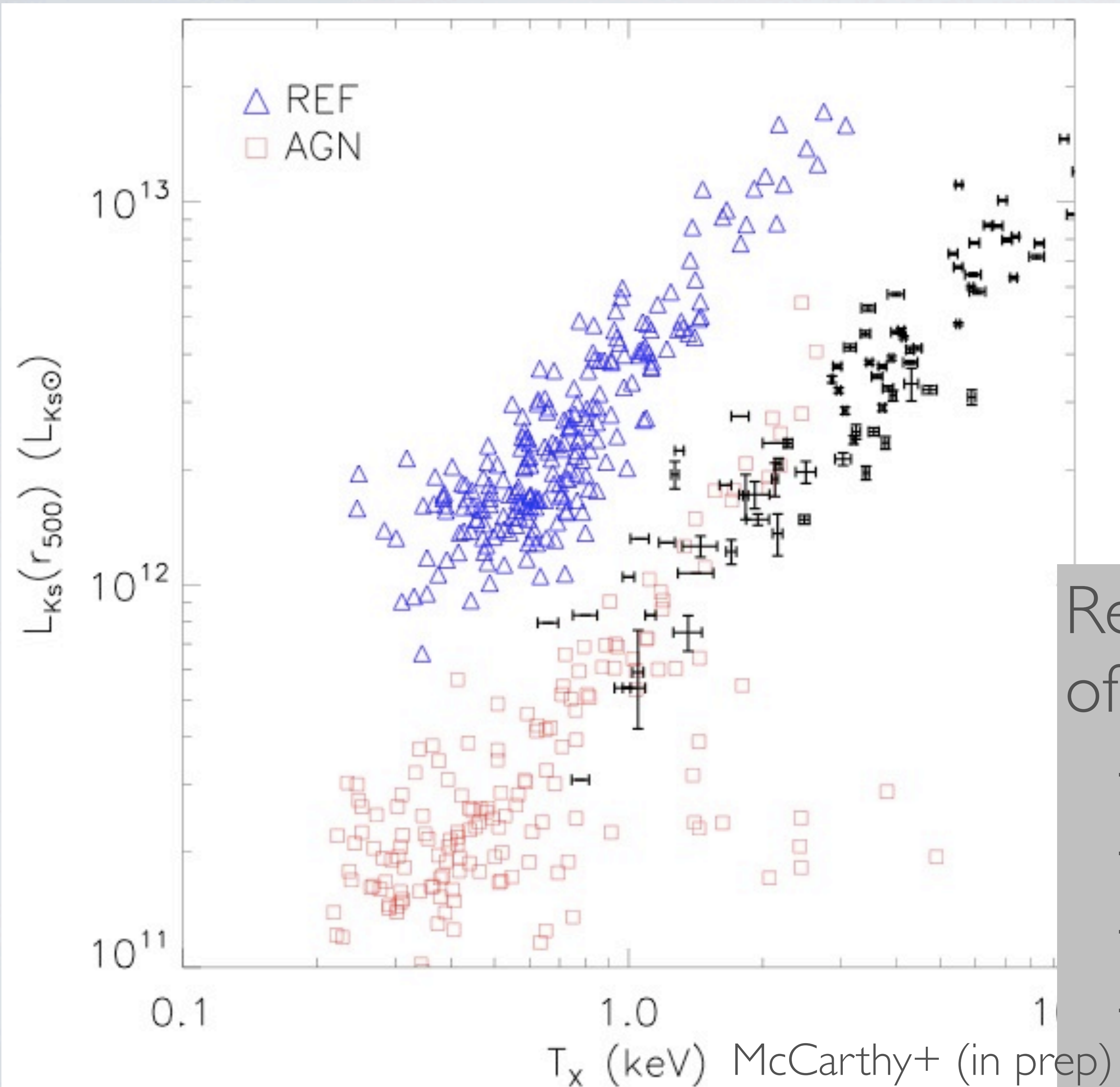


McCarthy+ (in prep)

Reasonable group/cluster SFRs

BH properties match galaxy properties

Reproduce many properties of the ICM (Ian McCarthy's talk)

--Entropy profiles

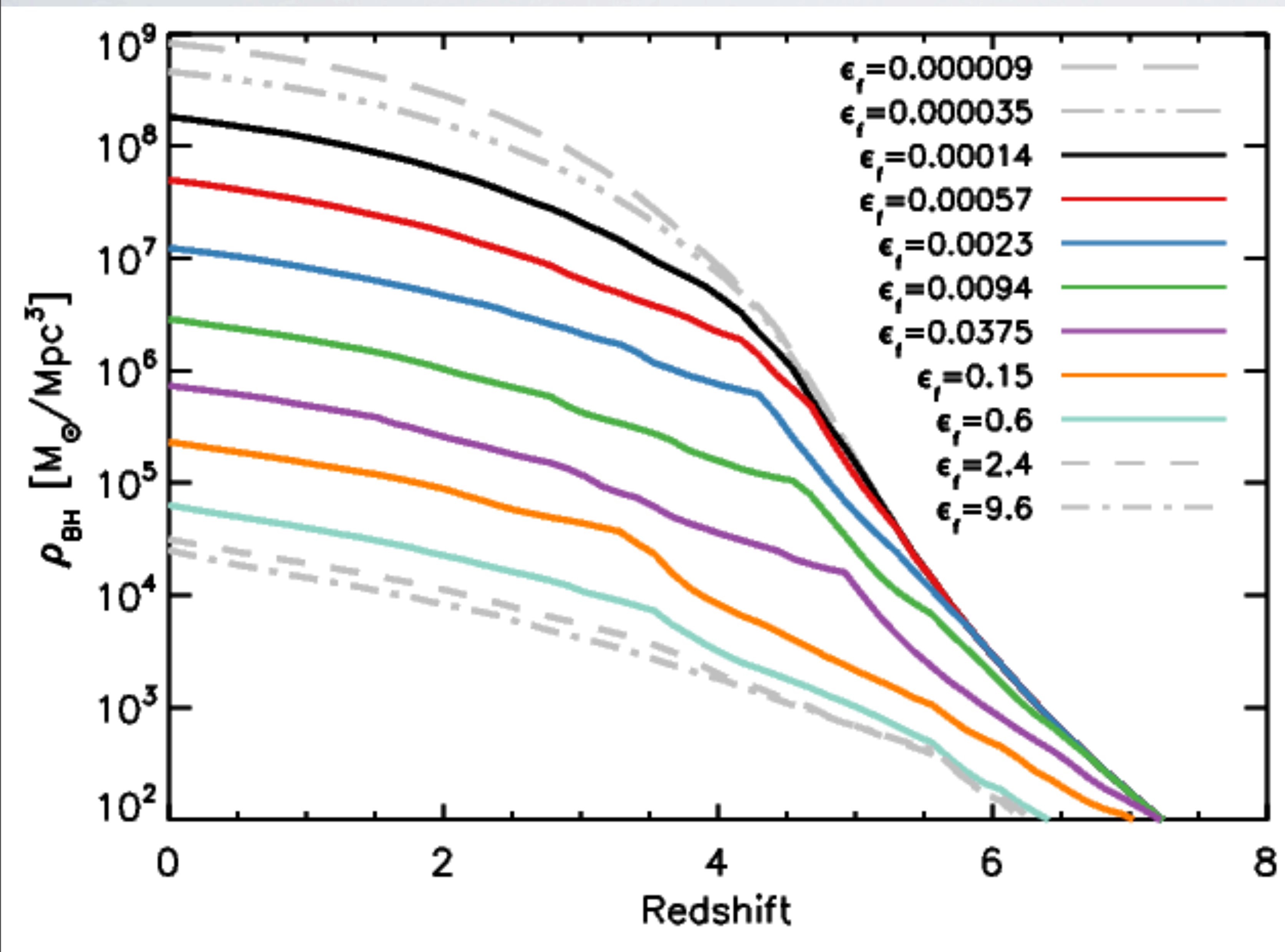
--Temperature profiles

--Baryon fractions

--BCG ages and SFRs

McCarthy

AGN MODEL



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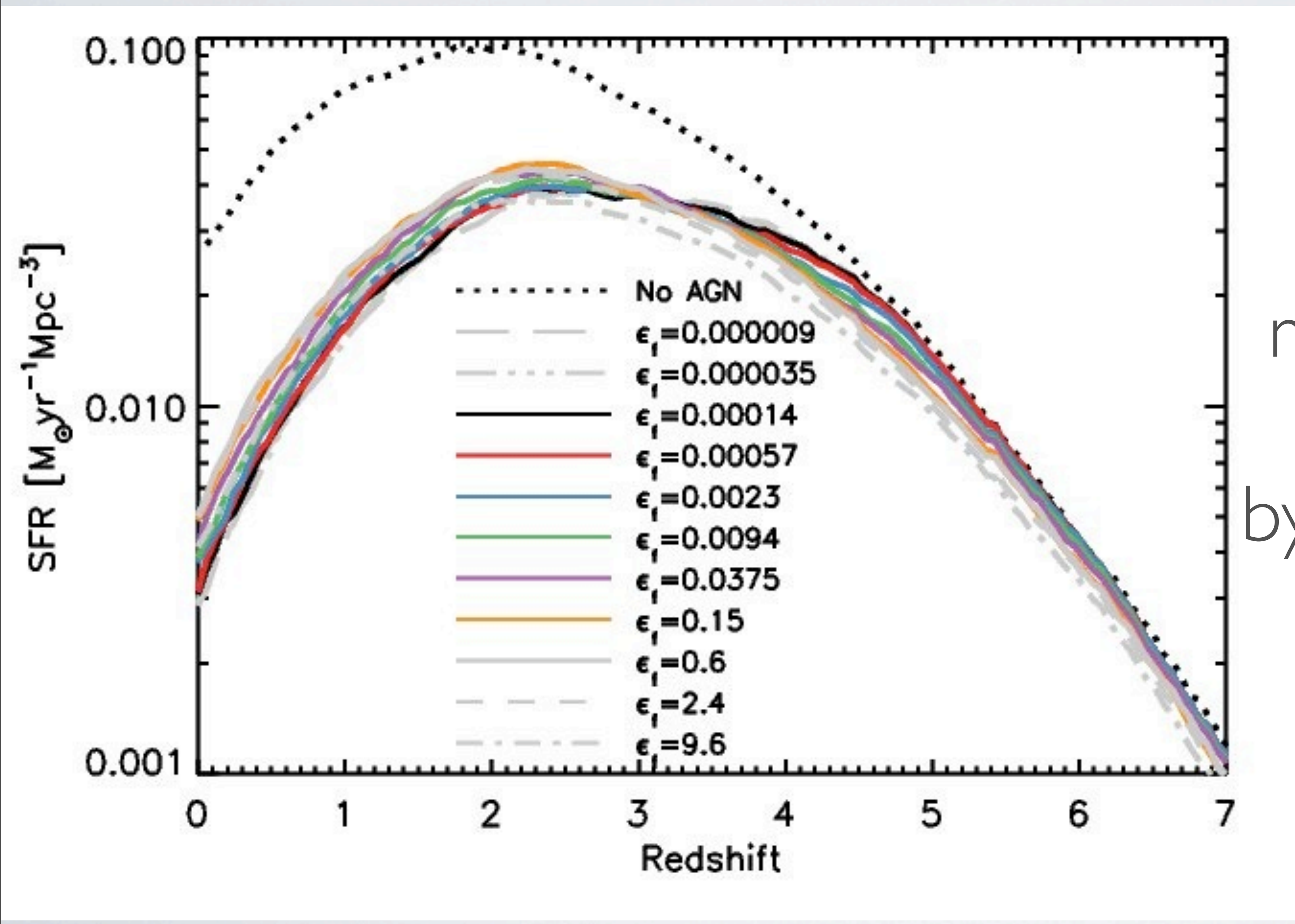
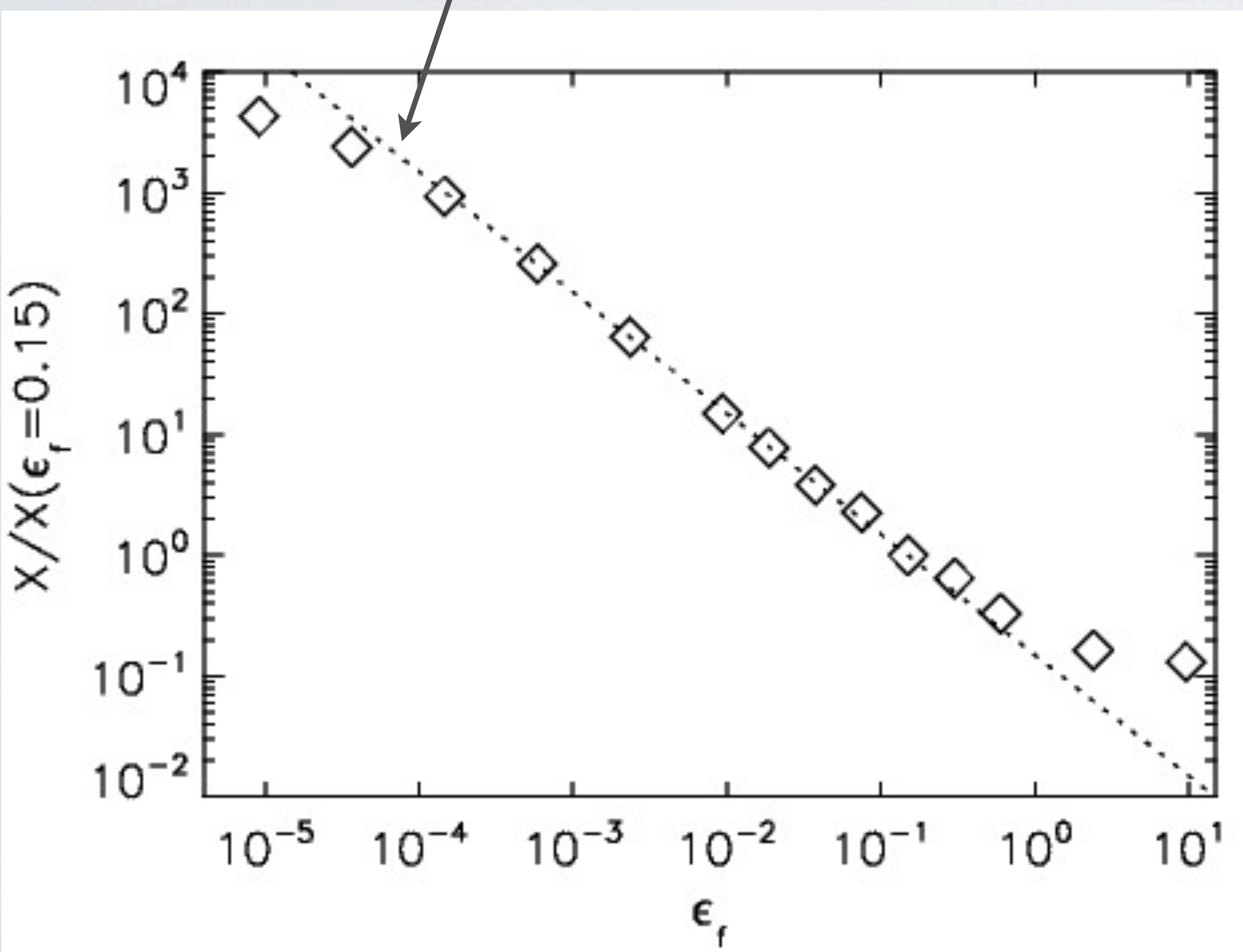
WHAT DETERMINES THE MASS OF SUPERMASSIVE BLACK HOLES?



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

WHAT DETERMINES THE MASS OF SUPERMASSIVE BLACK HOLES?

Dashed line shows slope of -1



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

Essentially the same result as for SN feedback

BHs adjust their masses to keep E_{out} constant

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

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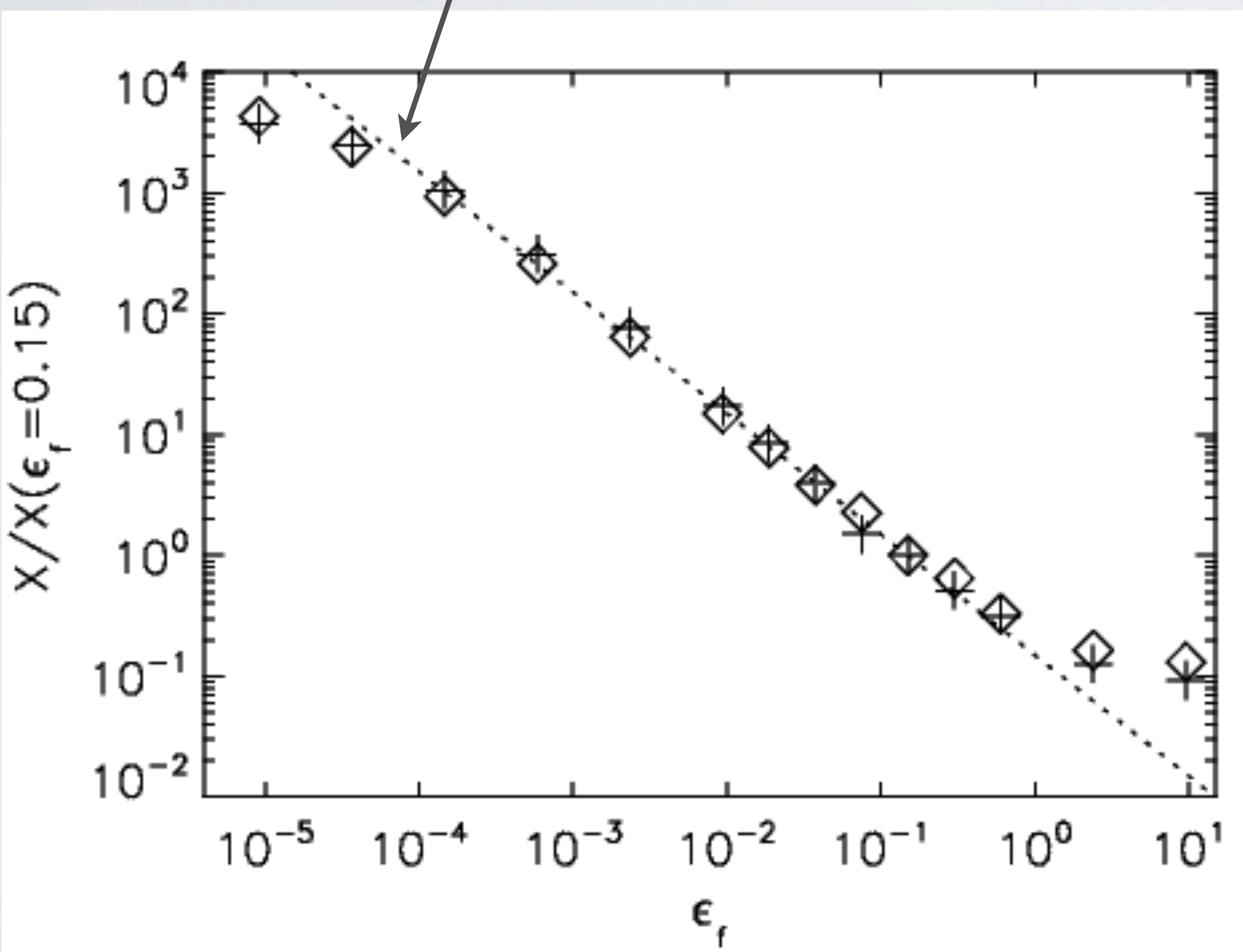

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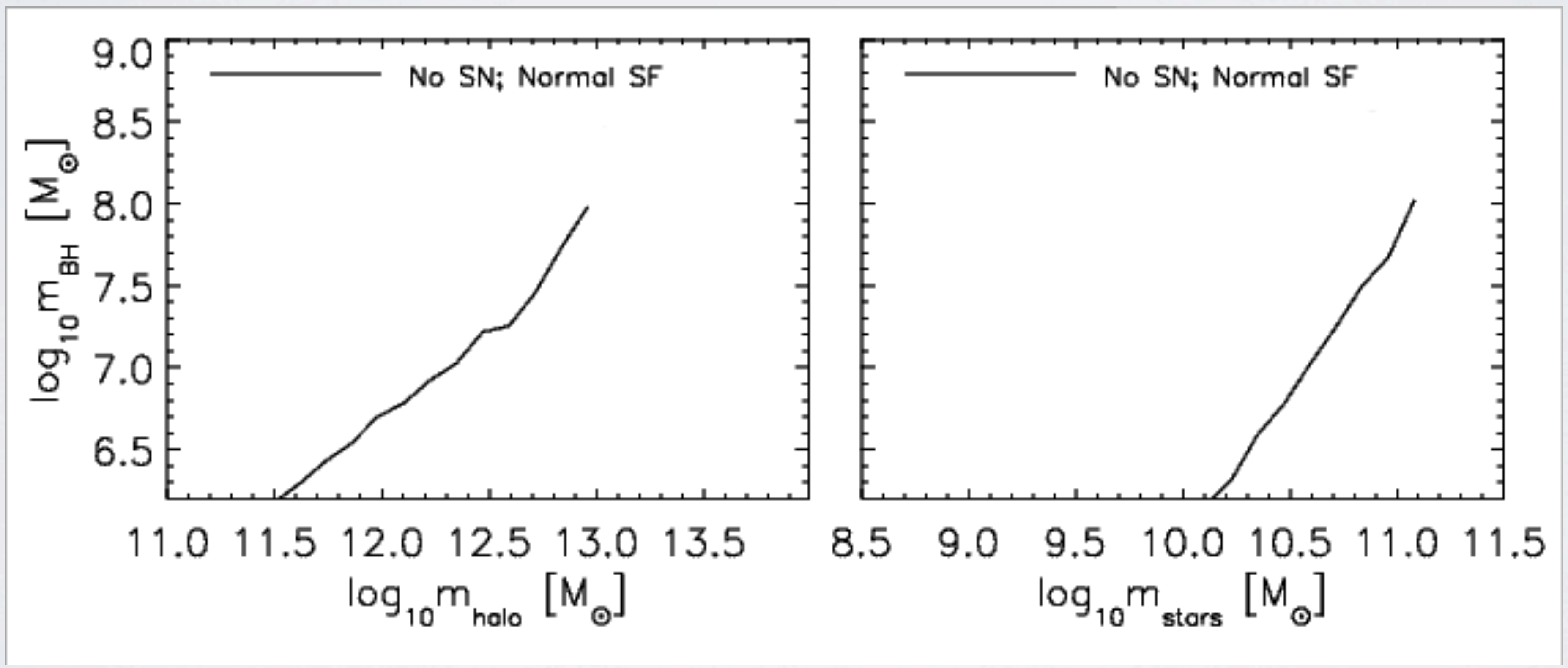
What happens if they are removed?



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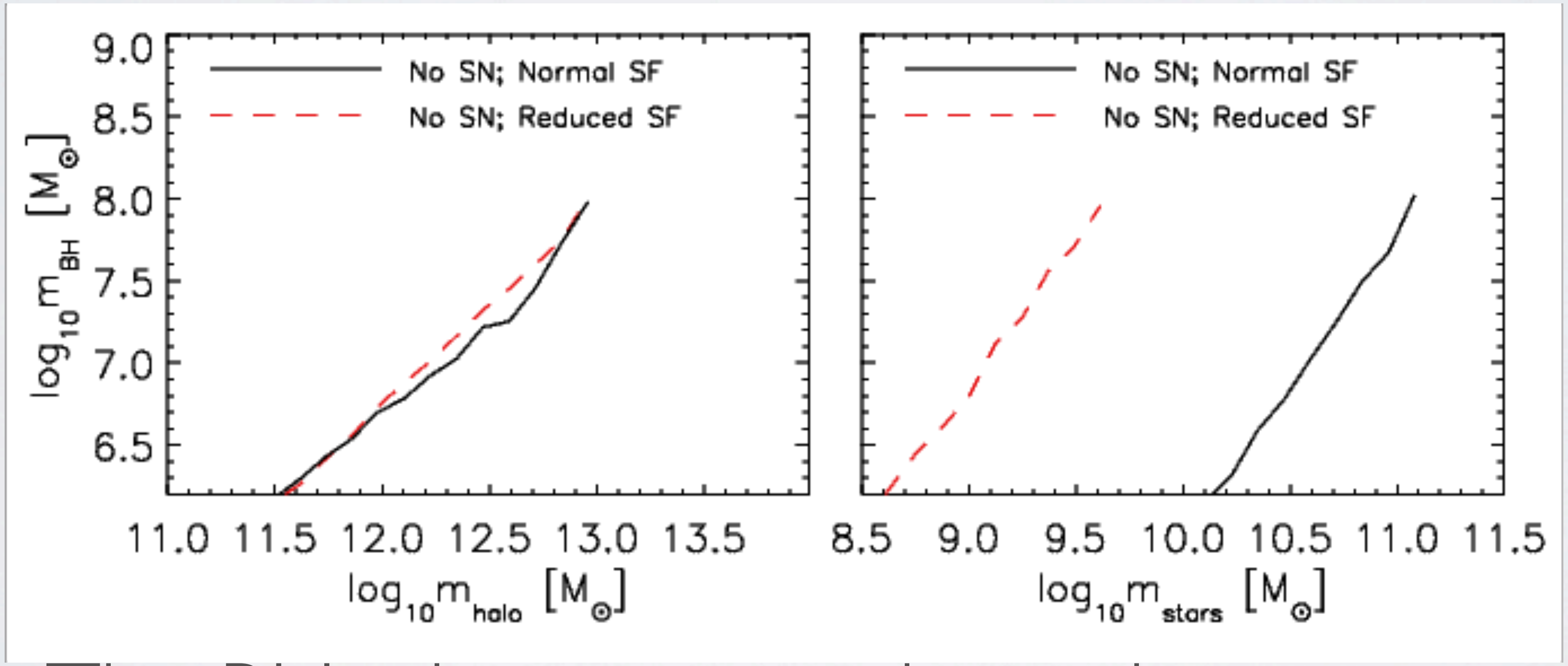
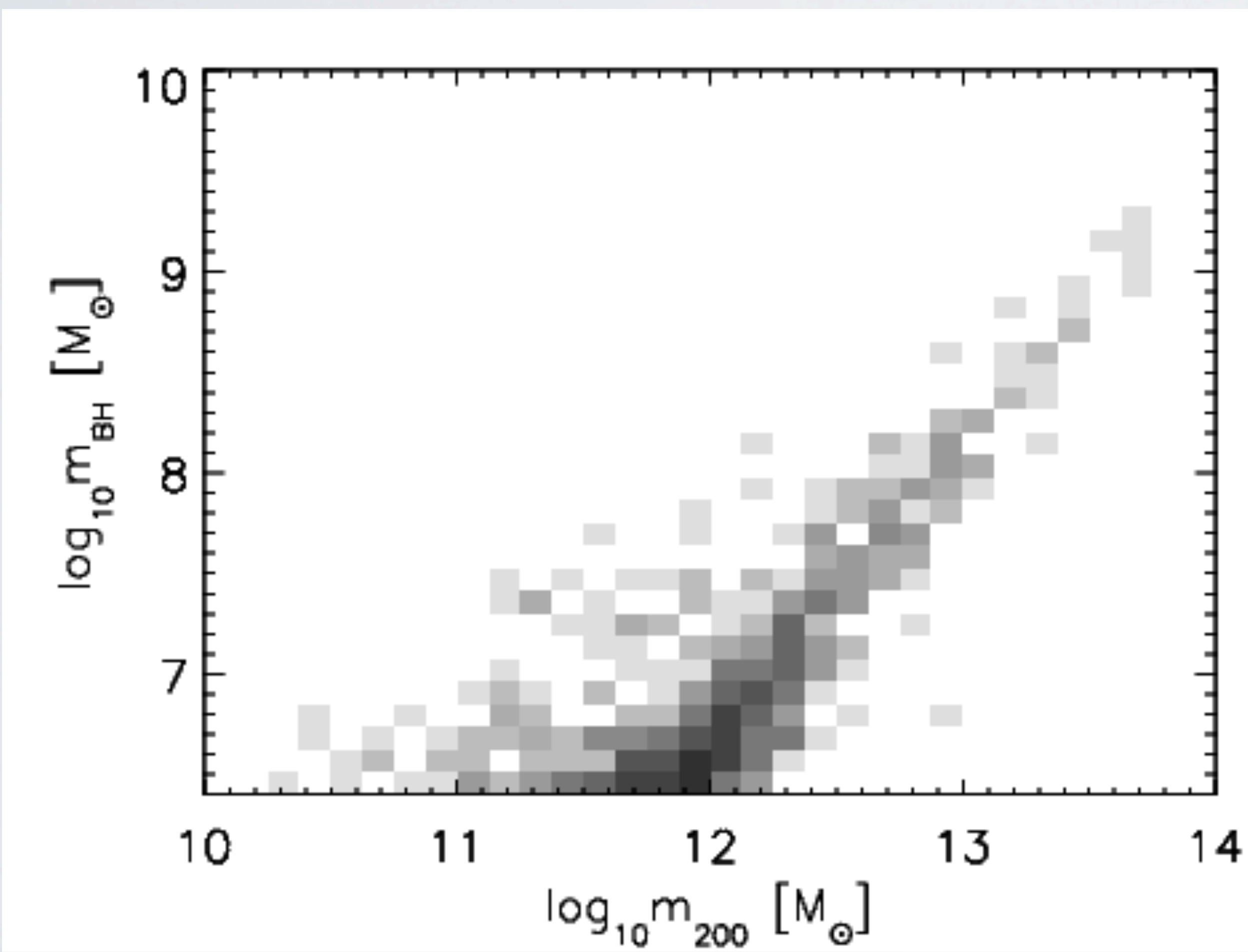


The BHs do not care about the matter distribution on small scales

WHAT DETERMINES THE MASS OF SUPERMASSIVE BLACK HOLES?

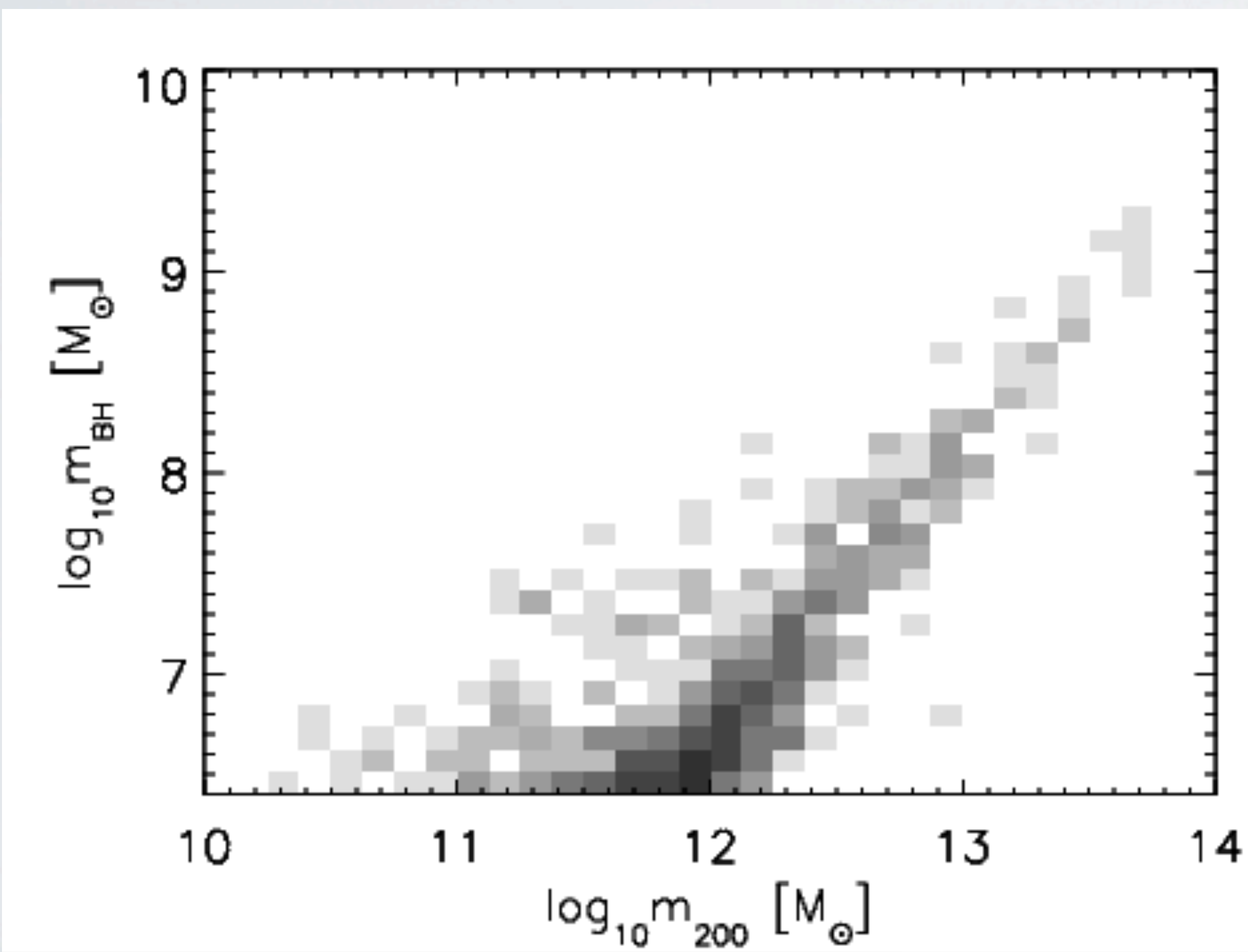
Self regulation occurs on scales > the galaxy



WHAT DETERMINES THE MASS OF SUPERMASSIVE BLACK HOLES?

Self regulation occurs on scales > the galaxy

- Simulated slope: 1.55±0.03



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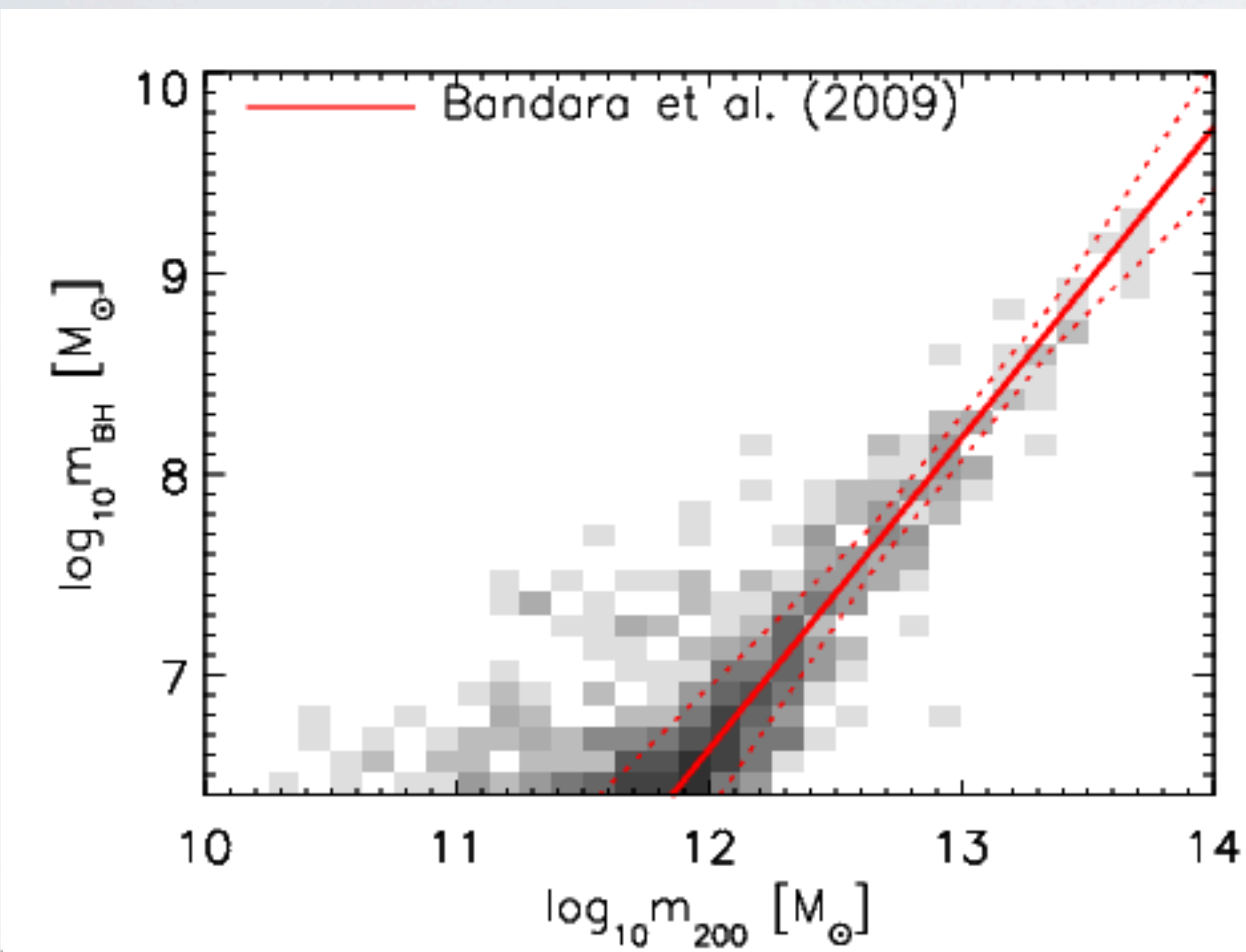

- Simulated slope: 1.55±0.03
- Observed slope: 1.55±0.31

WHAT DETERMINES THE MASS 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

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

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

-

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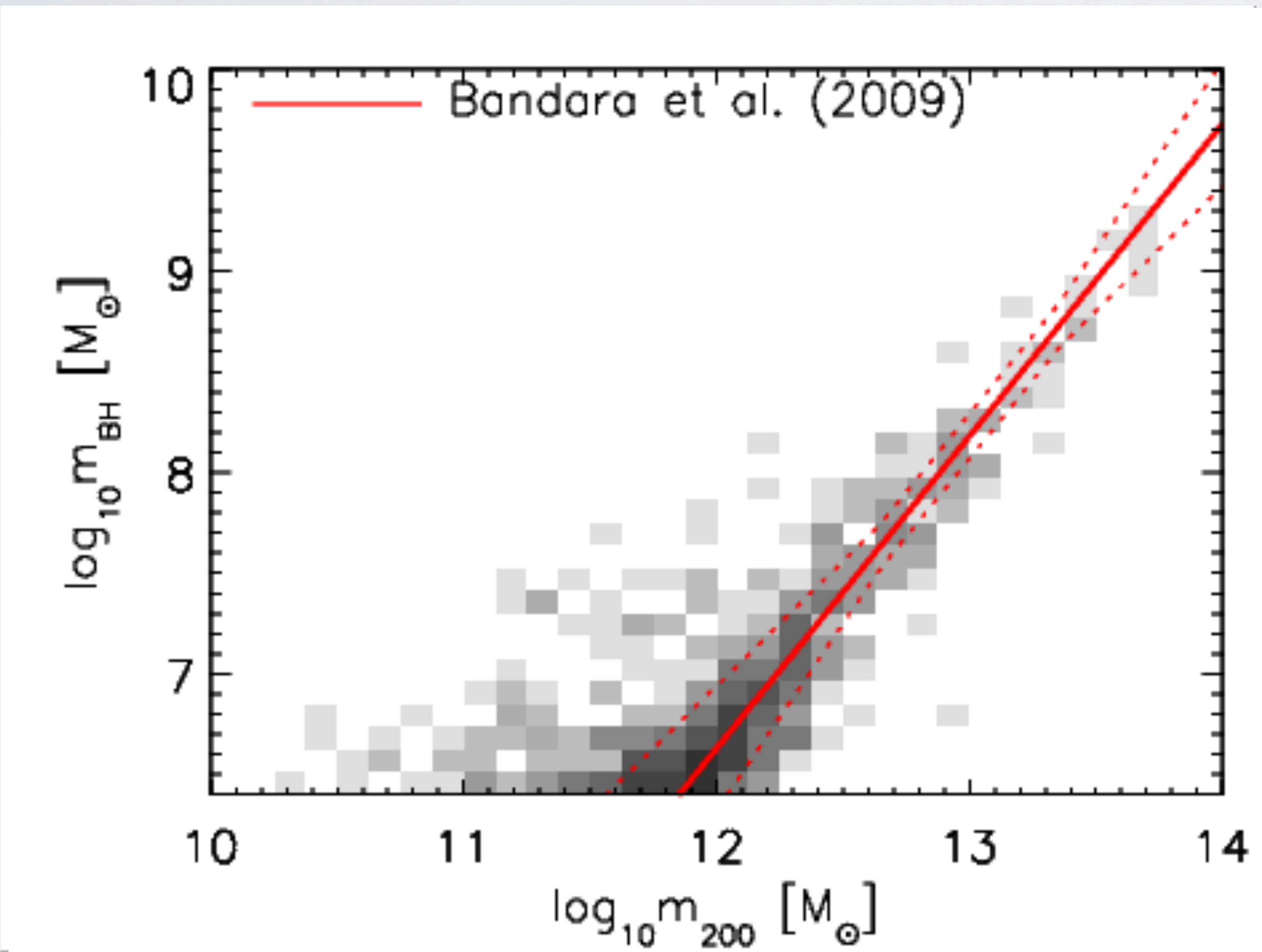

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- **Prediction:** If BH mass is determined by DM halo binding energy there should be a relation between residual in the m_{BH}-m_{halo} relation and halo concentration

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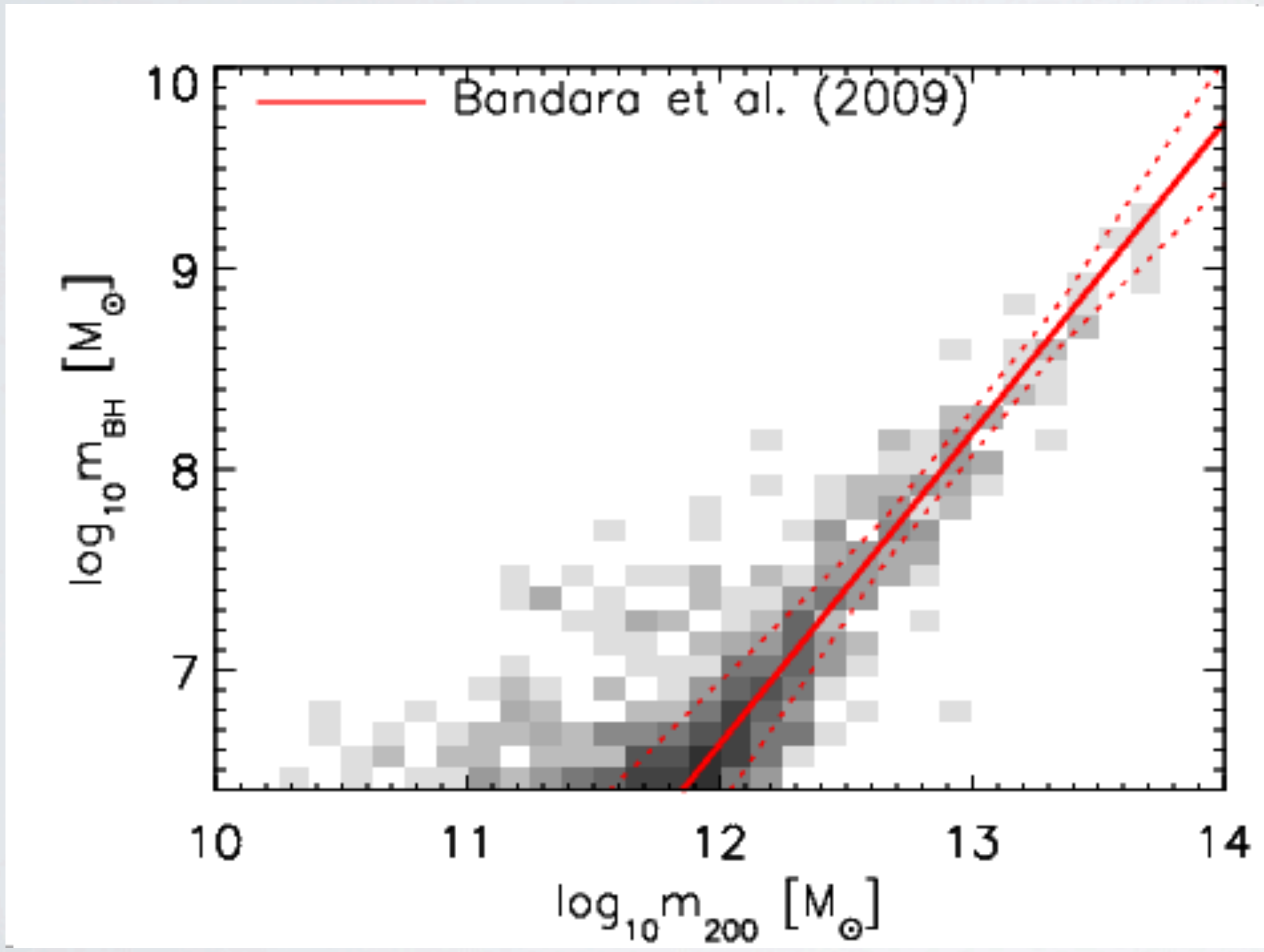

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Correlation between Δm_{BH} and c?

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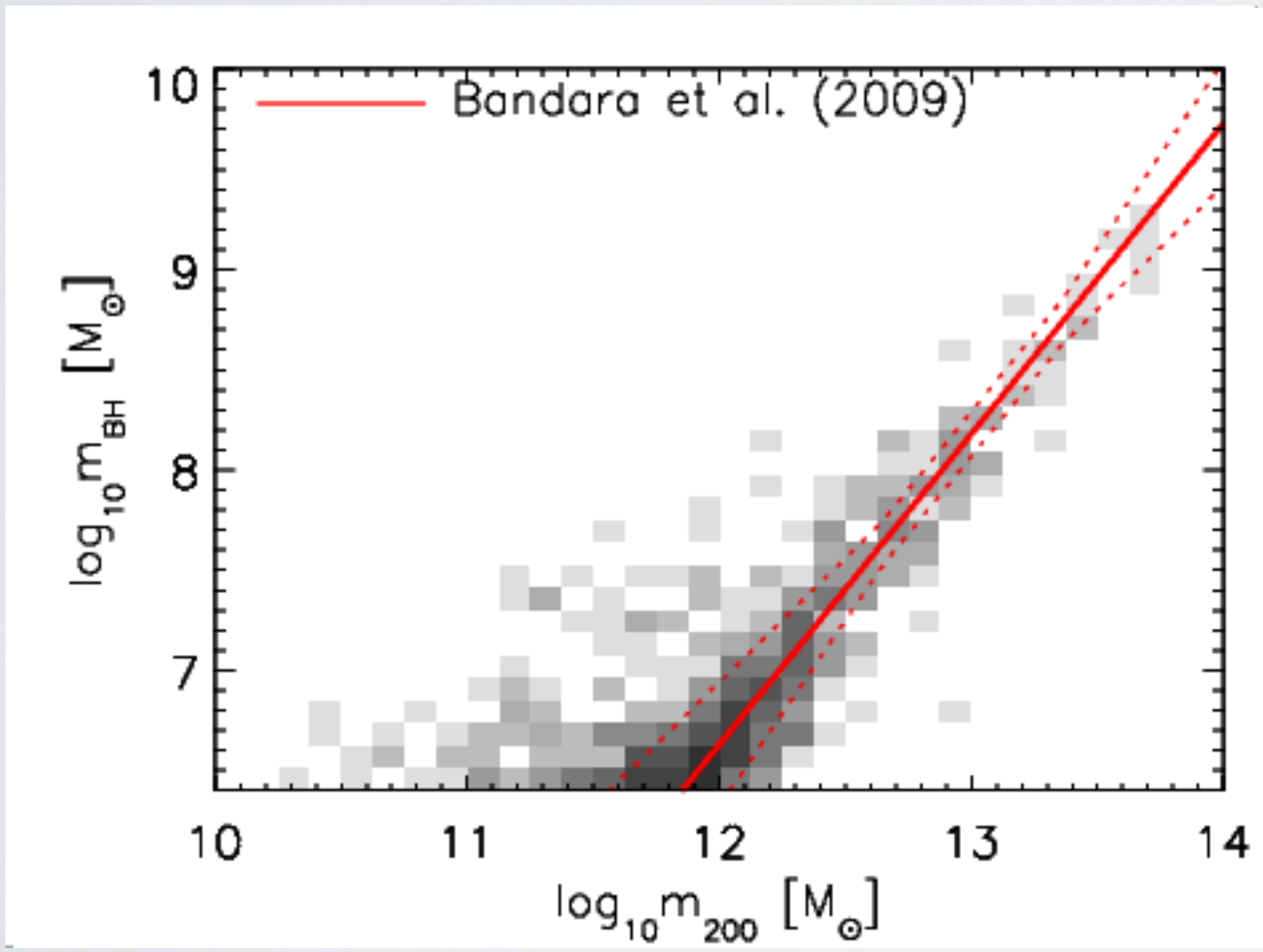

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Correlation between Δm_{BH} and c?

ρ=0.29 ; P=0.9998

Strong and positive!

CONCLUSIONS (PART II)

- 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.