Radiative Feedback During Reionization

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Science & Technology Facilities Council

Outline

I. Background/Motivation

II. Methods – codes

III. Self-feedback of galaxies/stars

IV. Summary

V. Future Work

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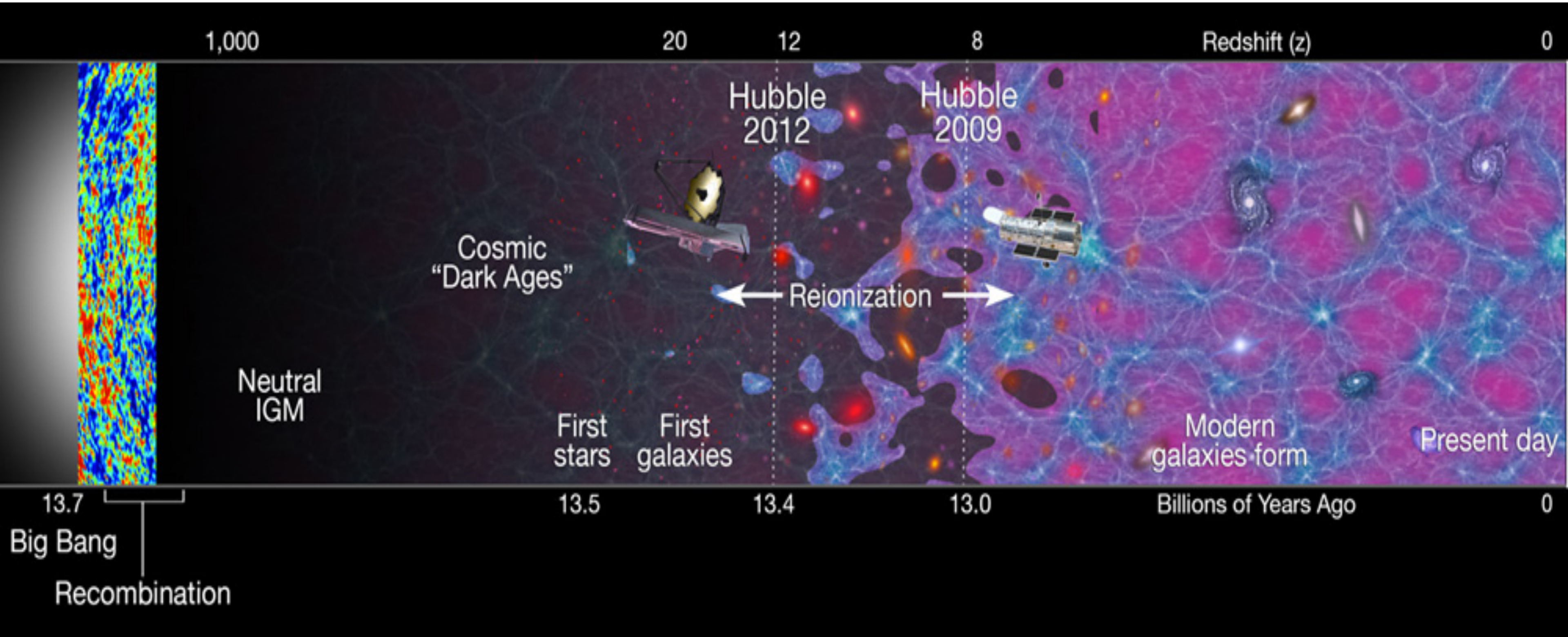
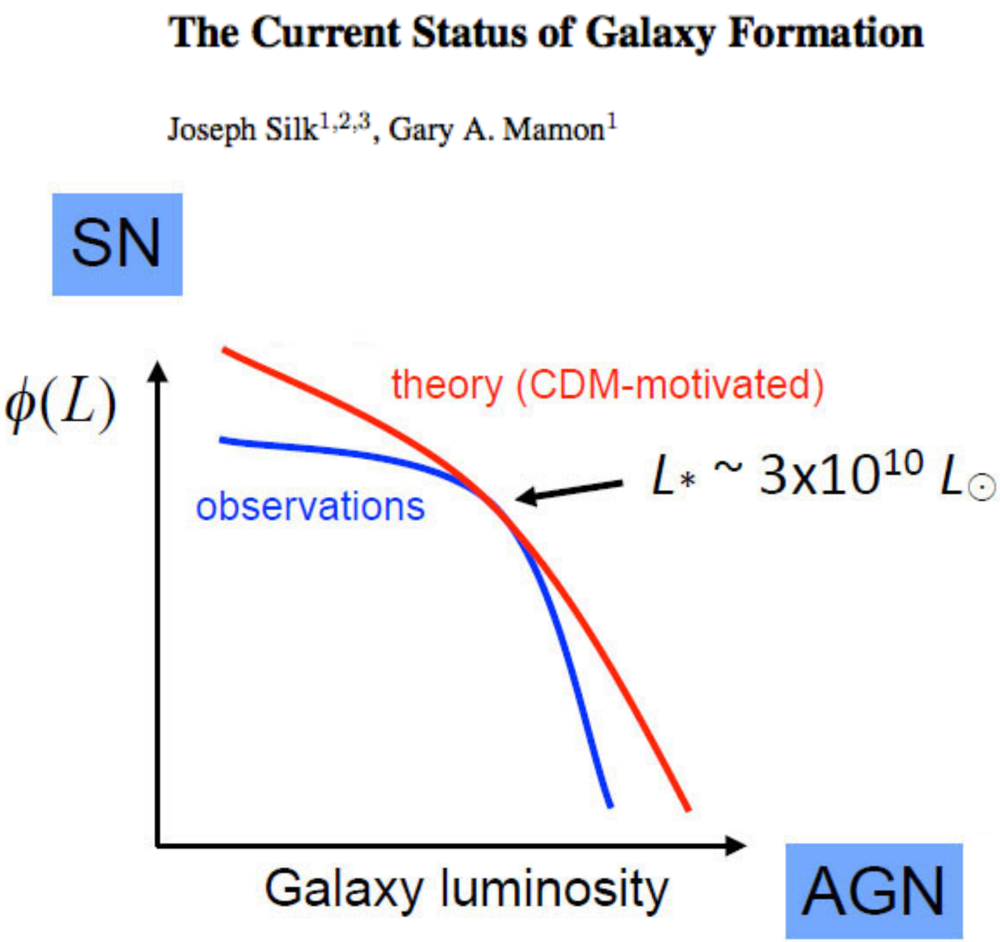
Timeline of Cosmic Evolution

Credit: NASA/ESA



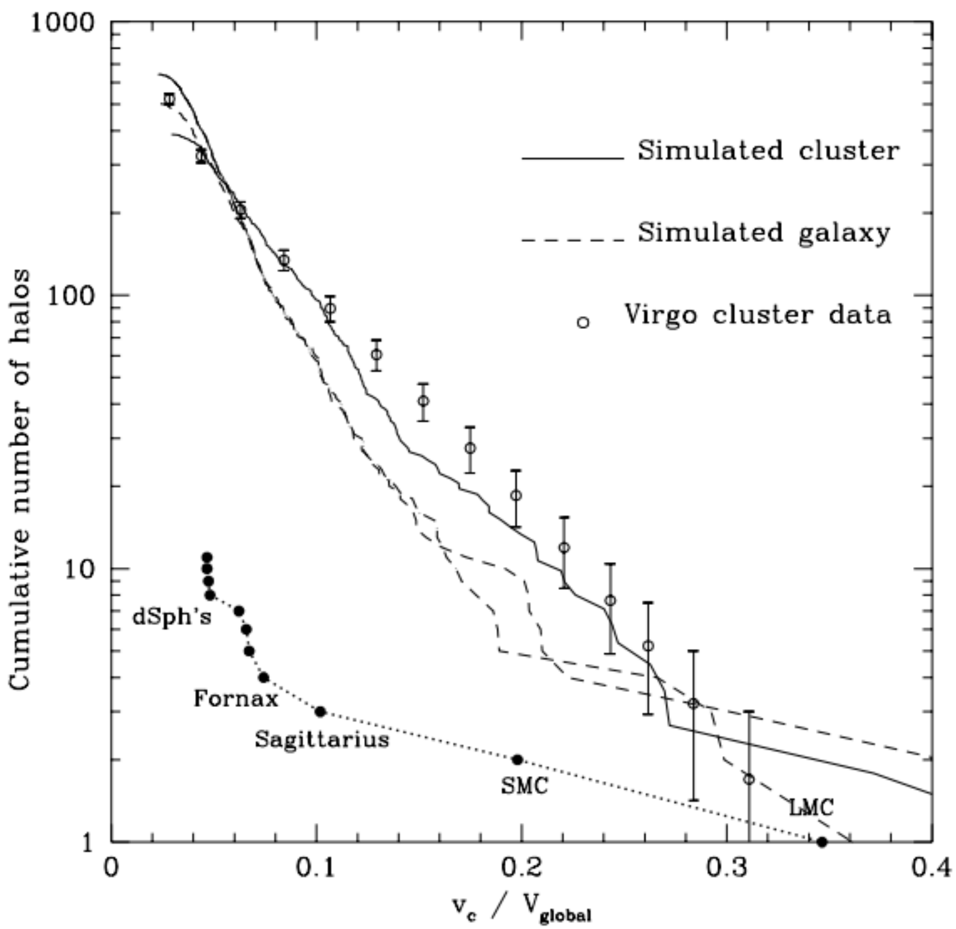
Halo mass function & Galaxy luminosity function



- Feedback required to modify shape of the Galaxy luminosity function

Missing Satellites Problem

Moore+ 99



- Semi-analytical models successfully reproduce satellite luminosity function by including UV background
- Simple recipes to regulate gas infall into halos - feedback

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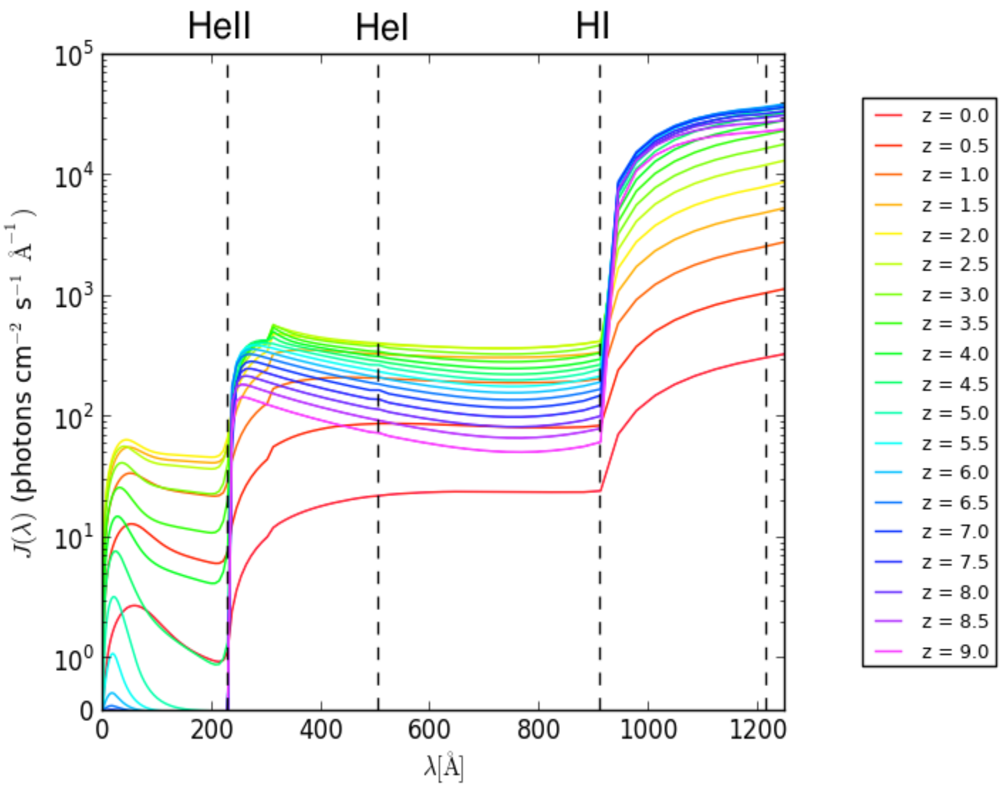
UV Background



- Homogeneous background Haardt & Madau 2001, Faucher-Giguére 2009 (pictured)
- Assume optically thin gas – UV in every cell

Filtering Mass

- Takes into account full thermal history of the gas – Gnedin & Hui, 98
- Set's the scale below which gas can fragment **prior** to reionization

$$\frac{1}{k_F^2(t)} = \frac{1}{D_+(t)} \int_0^t dt' a^2(t') \frac{\ddot{D}_+(t') + 2H(t')\dot{D}_+(t')}{k_J^2(t')} \int_{t'}^t \frac{dt''}{a^2(t'')}$$

$$k_J \equiv \frac{a}{c_S}\sqrt{4\pi G\bar{\rho}}$$

$$c_S^2 = \frac{5}{3}\frac{k_B \langle T \rangle_V}{\mu m_p}$$

$$\boxed{M_F \equiv \frac{4\pi}{3}\bar{\rho}\left(\frac{2\pi a}{k_F}\right)^3}$$

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The Characteristic Mass - M_C

- Fitting function of Gnedin 00:

$$f_{\mathrm{b}}(M,z) = \langle f_{\mathrm{b}} \rangle \left\{ 1 + (2^{\alpha/3} - 1) \left(\frac{M}{M_{\mathrm{c}}(z)} \right)^{-\alpha} \right\}^{-\frac{3}{\alpha}}$$

- $M_C(z)$ sets the halo mass at which the gas fraction is half the cosmic mean
- Gnedin 00 found that the filtering mass, M_F, gave a good fit to M_C
- The exponent α controls steepness of the transition between baryon poor/rich halos – a value of 2 is found to fit well in the literature

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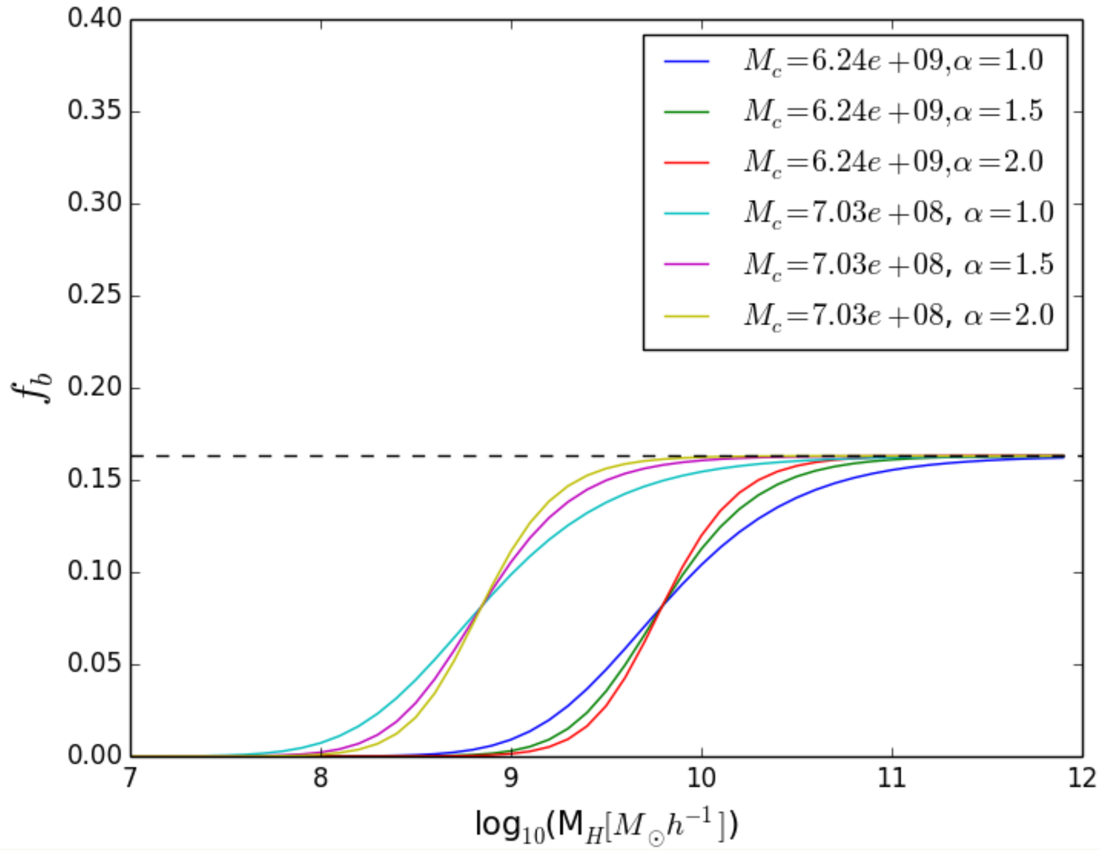
Effect of Altering M_c and α

$$f_\mathrm{b}(M,z) = \langle f_\mathrm{b} \rangle \left\{ 1 + (2^{\alpha/3} - 1) \left(\frac{M}{M_\mathrm{c}(z)} \right)^{-\alpha} \right\}^{-\frac{3}{\alpha}}$$



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The past 10+ years…

Effect of Reionization on Structure Formation in the Universe

2000

Nickolay Y. Gnedin

Dwarf galaxies in voids: Suppressing star formation with photo-heating

2006

Matthias Hoeft[1], Gustavo Yepes[2], Stefan Gottlöber[3], and Volker Springel[4]

Massloss of galaxies due to a UV-background

2008

Takashi Okamoto[1⋆], Liang Gao[1,2] and Tom Theuns[1,3]

2014

A PHYSICAL UNDERSTANDING OF HOW REIONIZATION SUPPRESSES ACCRETION ONTO DWARF HALOS

Yookyung Noh[1], Matthew McQuinn[1,2]

- Radiative feedback is a hot topic…
- The latter three all agree on one thing – the filtering mass overestimates M_C after reionization

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Jeans Instability

- For an ideal gas, and using the virial theorem:

$$M_J \propto T^{\frac{3}{2}} \rho^{-\frac{1}{2}}$$

- Pre-reionization – adiabatic collapse – Jeans mass increases
- Post-reionization – (approx.) isothermal collapse – Jeans mass decreases
- Small fragments begin to collapse on their own - shorter free-fall time than original cloud

This Work

- Previous models have all assumed a redshift evolving, homogeneous UV background – full radiative transfer is expensive!
- Since then, codes/supercomputers have advanced significantly – introduction of GPUs
- We can now afford to re-investigate these models using fully-coupled radiation hydrodynamics – compete treatment of the gas and radiation field
- Test simulations prior to large production runs

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Upcoming projects..

- Two successful PRACE proposals – almost 30 Million CPU hours in total
- Main focus – high resolution (mass and spatial) simulations of reionization
- Resolve mini halos (10^6 M_*/h) – heavily suppressed during/ following reionization
- How does this impact their descendants?

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Radiative Feedback

- Ionizing UV: Photoheats gas in IGM to ~10^4 K; suppresses gas infall for low-mass (progenitor) halos; self-regulation of galaxy/star formation
- Soft UV: Lyman-Werner absorption bands of molecular hydrogen $\longrightarrow$ H_2 dissociation; main cooling mechanism at early times; delay onset of star formation
- X-rays: Supernovae etc; mainly heat neutral IGM (21cm line emission)

The Code…

- RAMSES-CUDATON (Teyssier 2002; Aubert & Teyssier 2008; Stranex)
- Radiation and gas evolved simultaneously – includes star formation and feedback
- Moment based Radiative Transfer
- Scales independently of source count – important for cosmological simulations
- Coupled via Hydrogen thermochemistry
- GPU acceleration – full speed of light

Moment Based Radiative Transfer

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \underline{n}\cdot\nabla I_\nu = -\kappa_\nu I_\nu + \eta_\nu$$

$$E_\nu = \frac{1}{c}\oint I_\nu \, d\Omega$$

$$\underline{F_\nu} = \oint I_\nu \underline{n} \, d\Omega$$

$$\underline{\underline{P_\nu}} = \frac{1}{c}\oint I_\nu \underline{n}\cdot\underline{n} \, d\Omega$$

Isotropic Sources

$$\frac{\partial E_\nu}{\partial t} + \nabla\cdot\underline{F_\nu} = -\kappa_\nu c E_\nu + S_\nu$$

$$\frac{\partial \underline{F_\nu}}{\partial t} + c^2\nabla\cdot\underline{\underline{P_\nu}} = -\kappa_\nu c \underline{F_\nu}$$

Hyperbolic set of conservation laws – Euler equations

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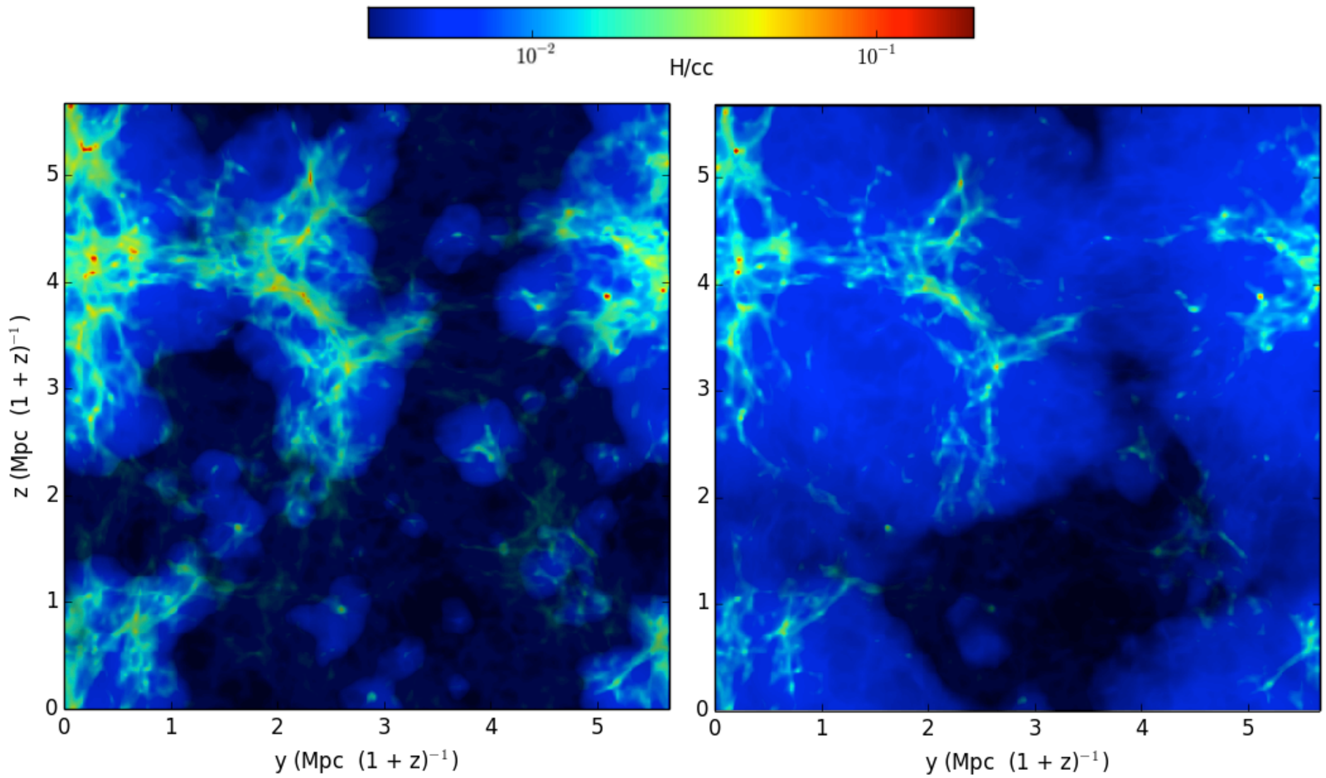
Simulating Reionization



- 4Mpc/h on-a-side
- 256^3 particles and cells

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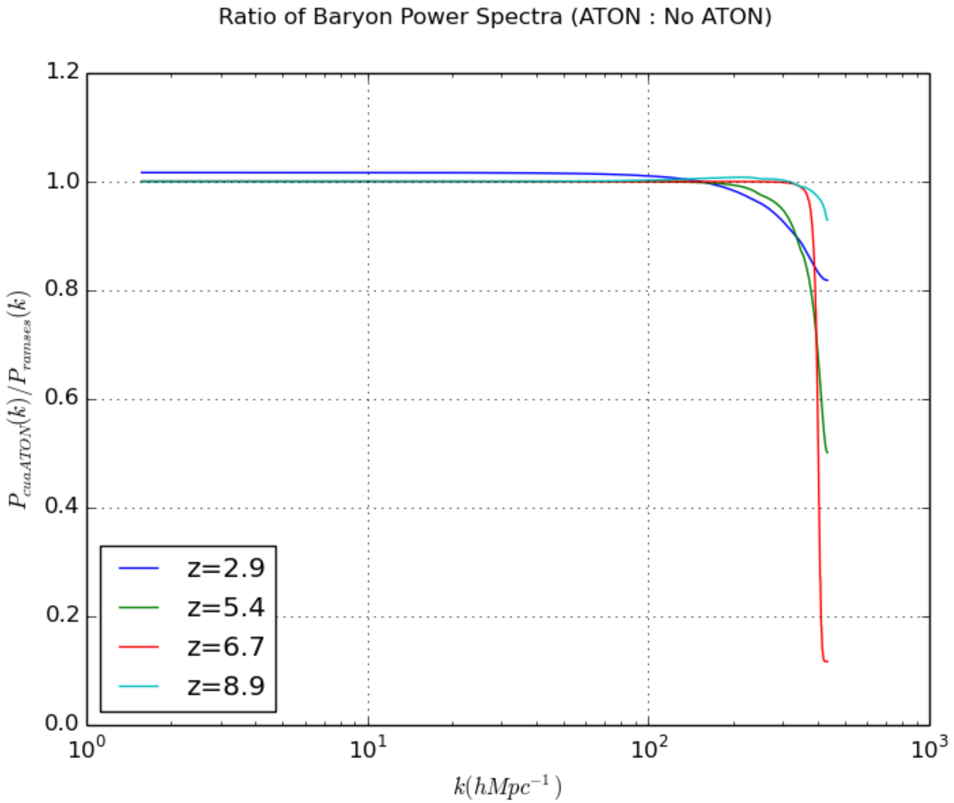
Gas Density: Impact of photoionization/heating

Coupled RHD

Hydro Only

Gas Power Spectra



- Galactic scales most significantly suppressed – no great surprise
- Suppression strongest at galactic scales – begin to converge towards low redshifts

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Evolution of the Equation of State

Coupled RHD

Hydro Only

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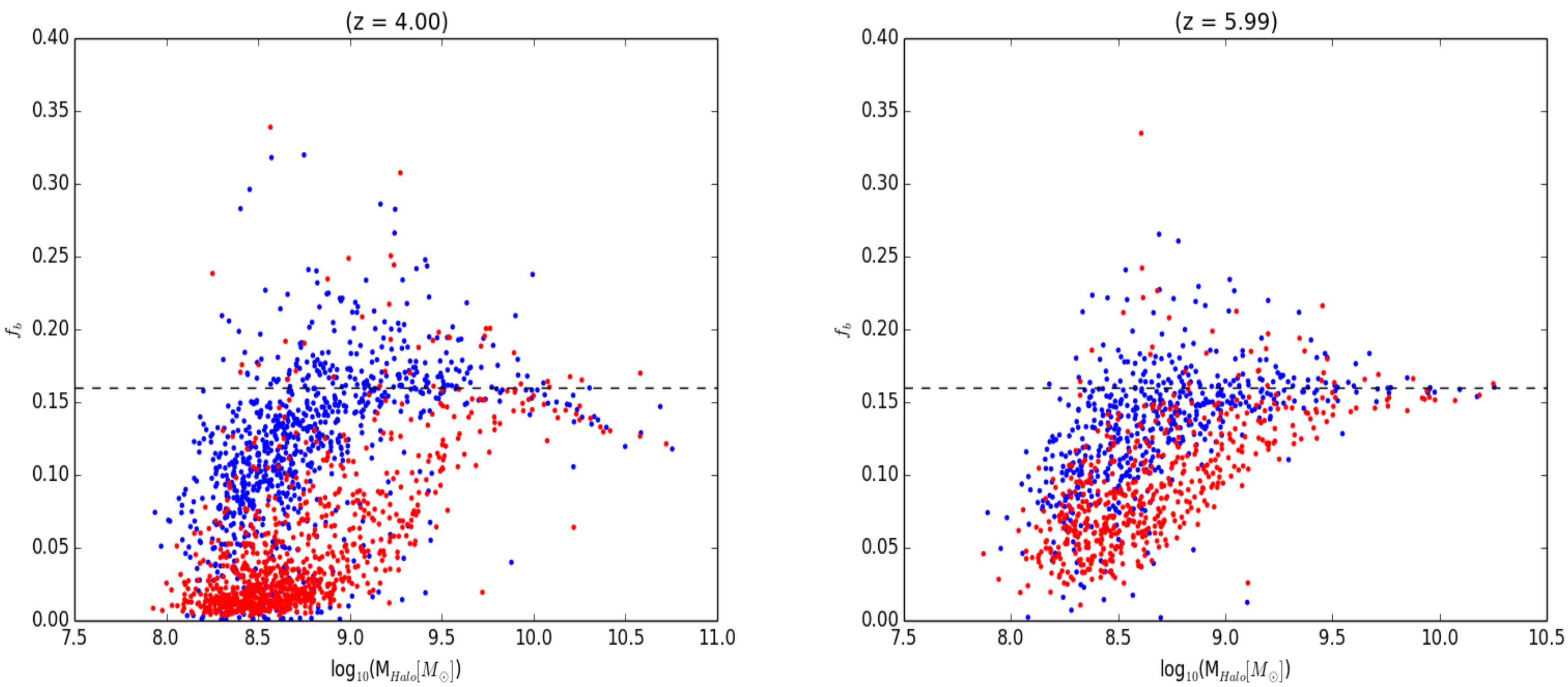
Gas Fraction of Halos



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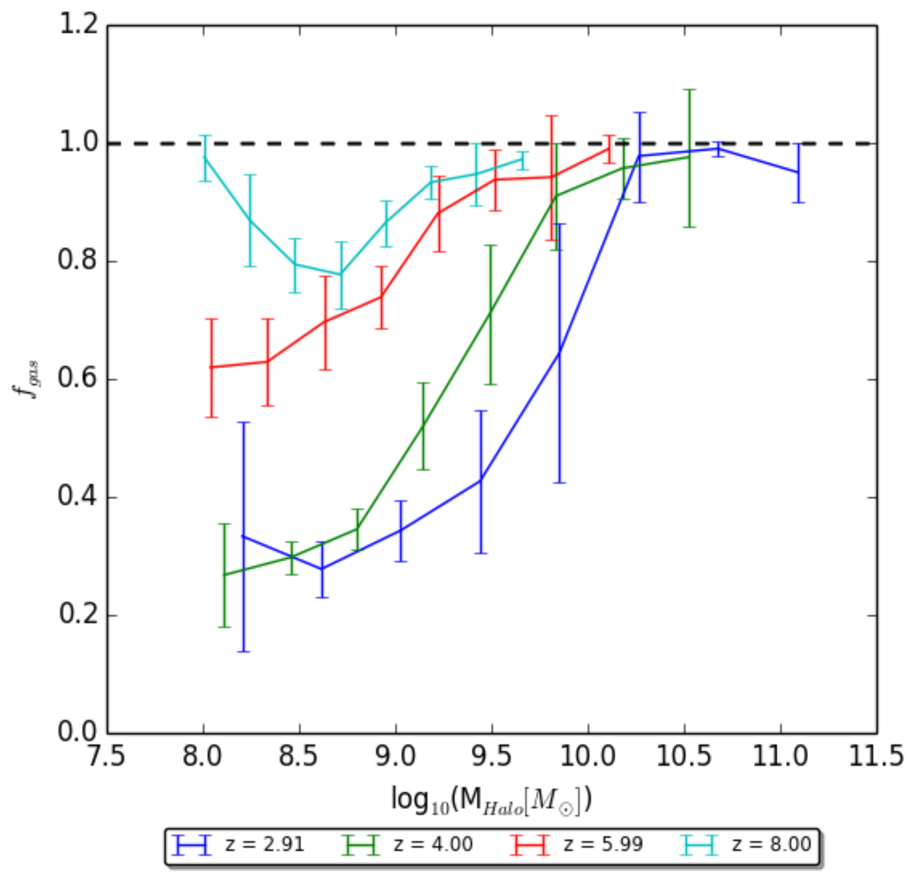
Gas Fraction of Halos (continued)



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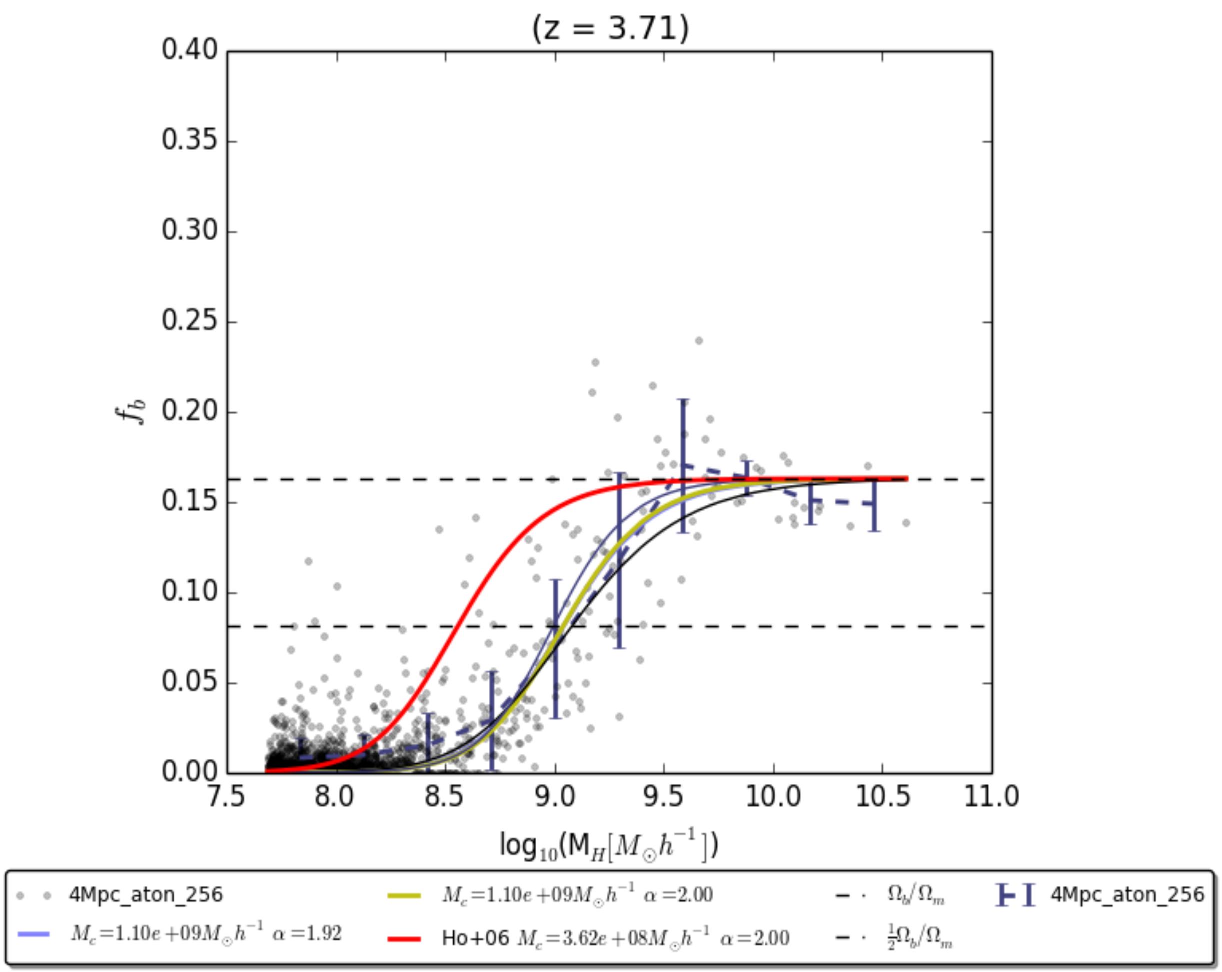
Distinct Halos Only…



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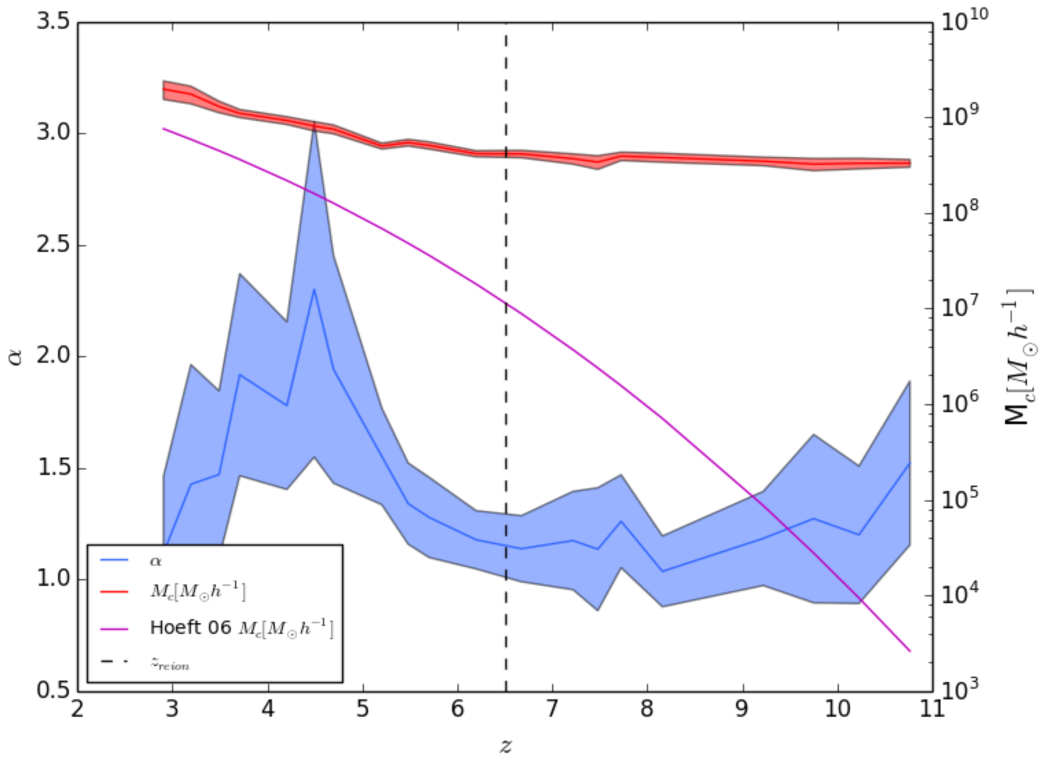
M_c and α



- Larger than Hoeft+ 06 prediction (although tuned to match voids) – preferentially heat dense gas
- Although, this may be an overestimation – self-shielding?

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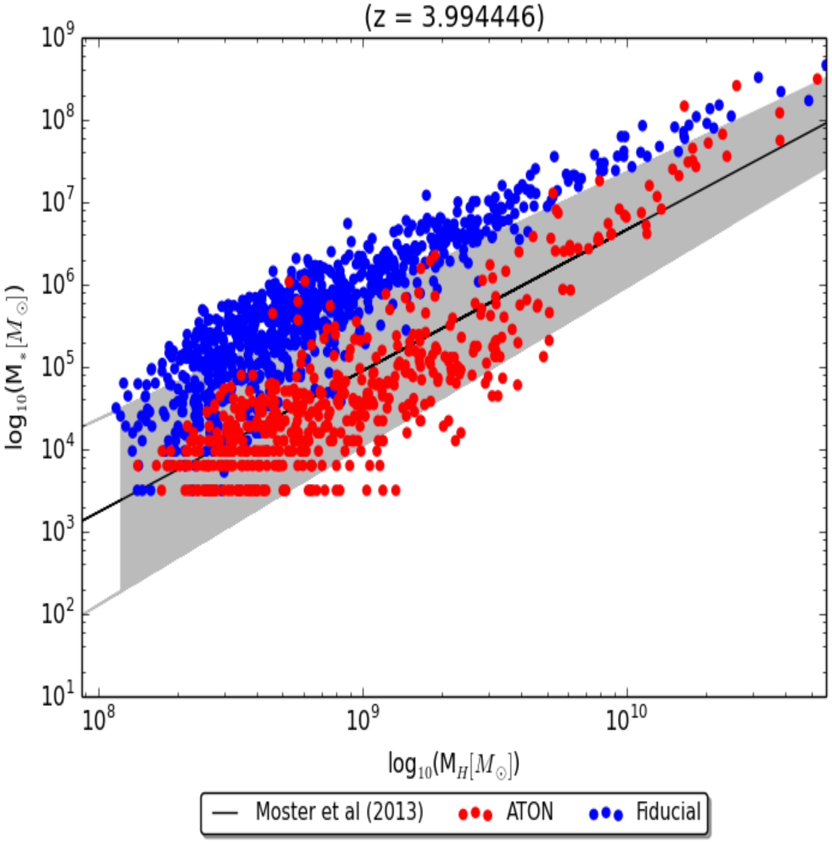
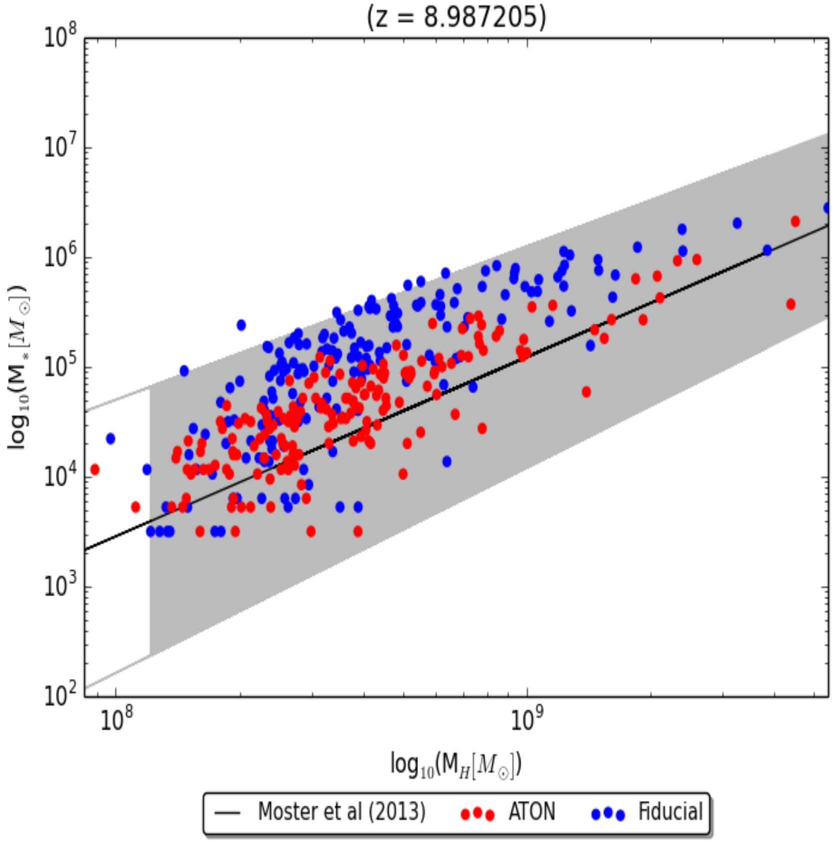
Stellar Mass of Halos





Conclusions

I. Coupled radiative transfer self-consistently accounts for full thermal history of the gas

II. Instantaneous UV models miss time dependent local reionization history

III. Self-regulation of low mass structures heavily suppresses gas fraction and star formation

IV. Accurately predict stellar masses of halos at high redshift – radiative feedback efficient at suppressing star formation in low mass (progenitor) halos

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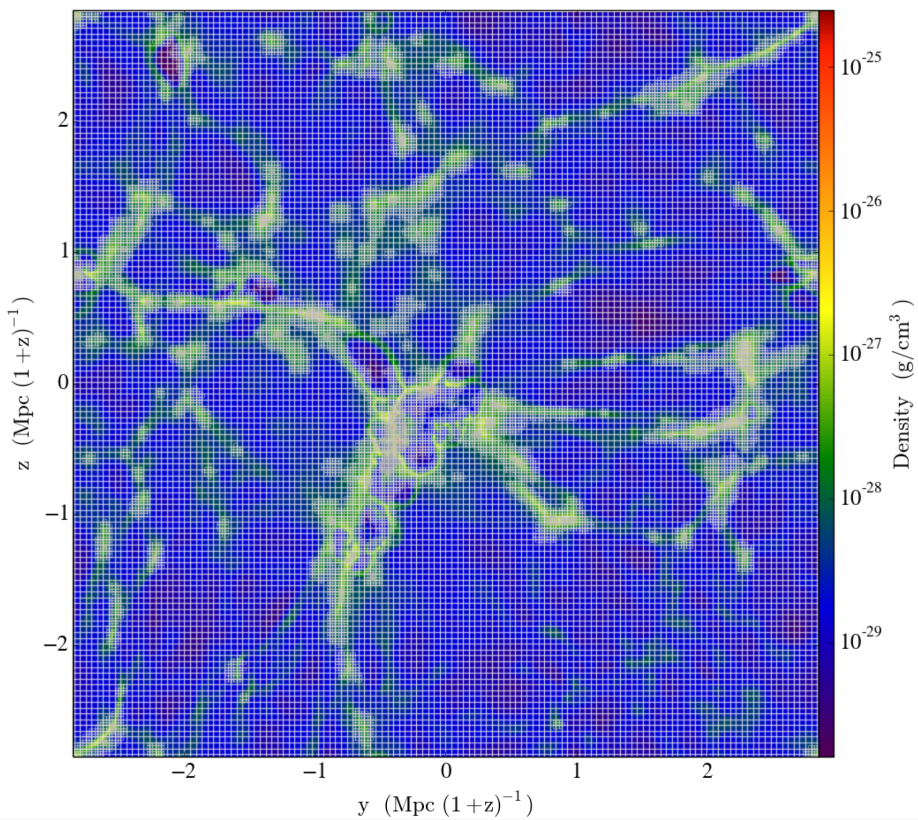
Future Work

- Recently awarded supercomputer time (PRACE Tier - 0 & 1) – larger volumes and higher resolutions
- Extend simulations to present day
- Repeat using Adaptive Mesh Refinement – RAMSES-RT (Rosdahl, J et al. 2013)
- Munich semi-analytical model (Springel 2005)



Acknowledgements

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- Thanks to my collaborators (Pierre Ocvirk, Paul Shapiro, Anson D'Aloisio and Junhwan Choi) for useful discussions
- Thanks to my supervisors, Ilian Iliev and Peter Thomas for their guidance
- Finally, thanks to the STFC for funding this studentship

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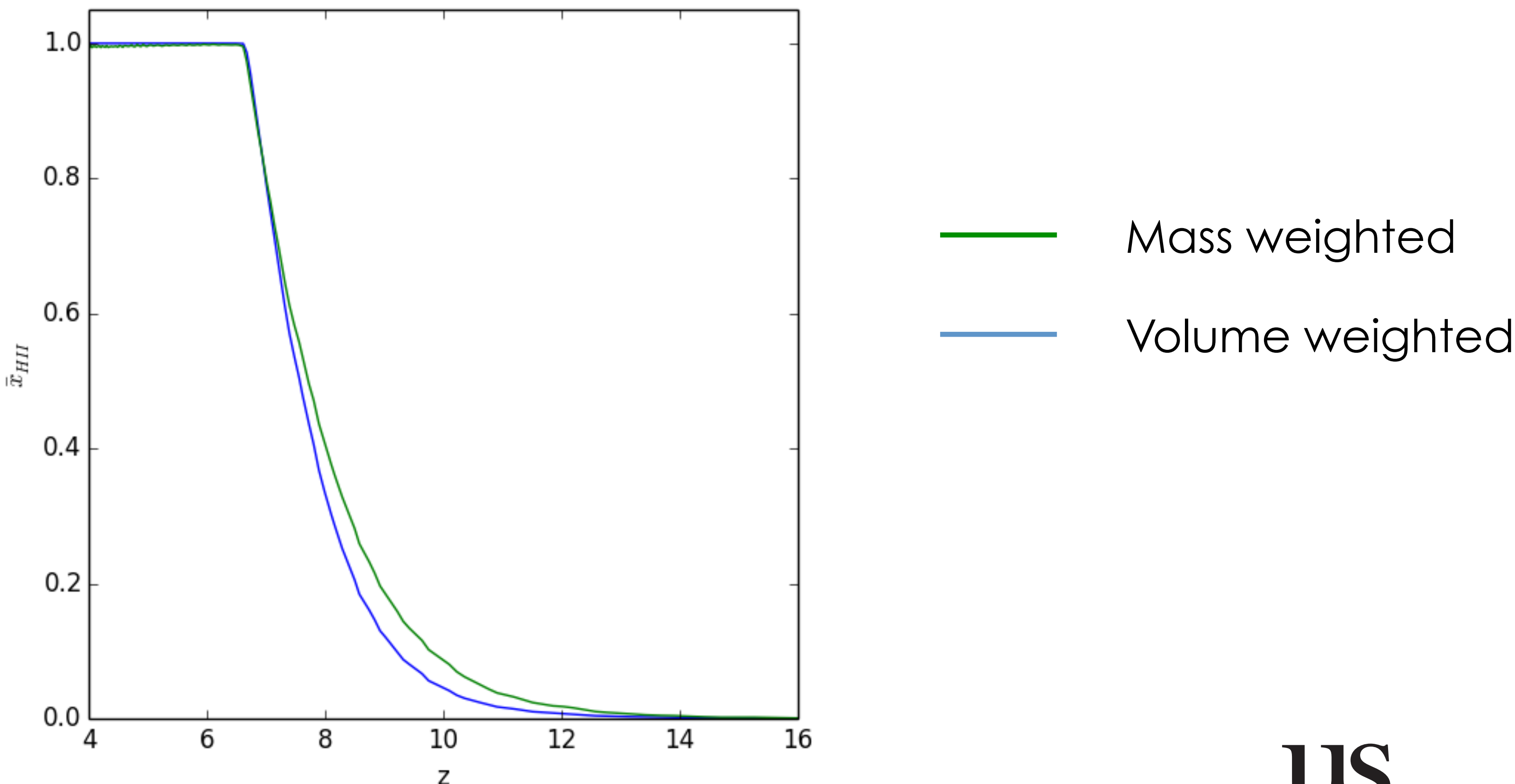
Reionization History



Important points to include

- When talking about RT sim (apollo), reionization early but still get lower Mc (hence suppression) than coarse ATON run – over suppression of the gas in low resolutions
- Importance of spectral hardening for RHD
- Kimm & Cenn star formation and reionization?
- Why is RT expensive on CPU (and why does GPU work well?)
- Reduced speed of light

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Assume nothing!

- Evidence for z_reion ~ 6 (Ly-alpha forest, images!)
- Halo mass func. And galaxy luminosity function have different shapes – feedback on the gas
- Importance of reionization:

missing satellites, star formation histories etc.

Filtering mass is wrong! (Ok08) -> because fb does not depend on T0

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