Title: The thermal state of the intergalactic medium and its effect on galaxy formation

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Abstract:

the thermal state of the IGM and its effect on galaxy formation

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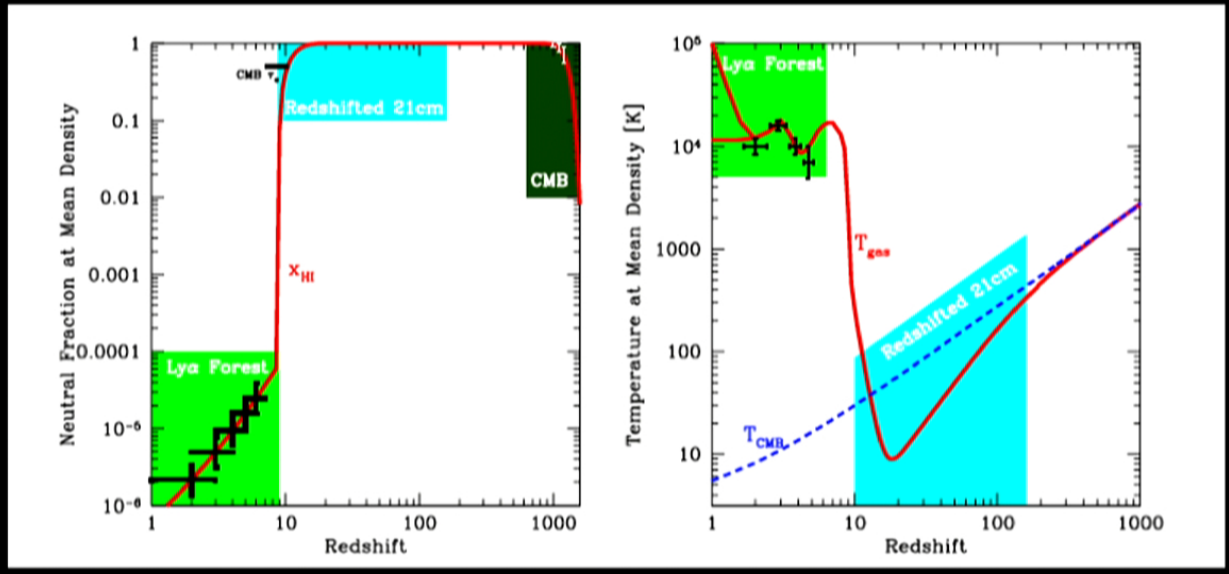
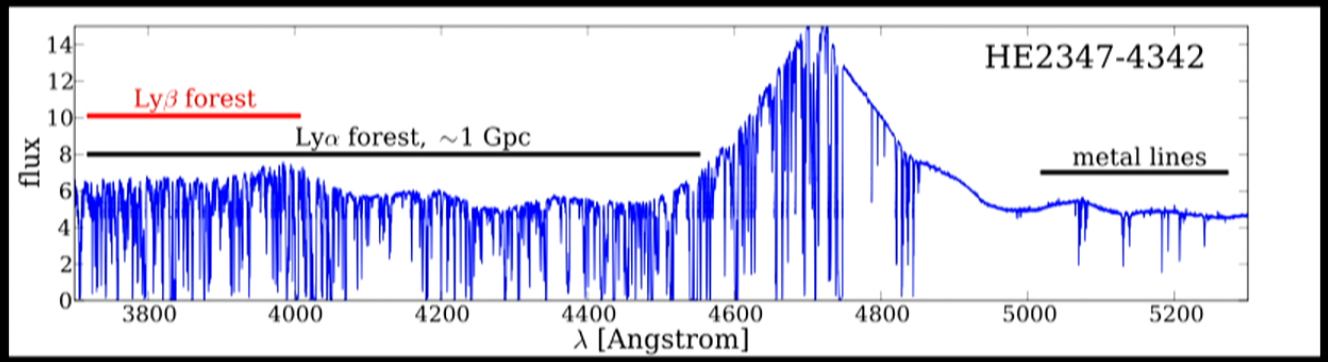
Outline

- intro to physics that shapes IGM thermal history and how this is measured
- aside on flux PDF
- comparison of standard models for thermal history to measurements
- effect of thermal history on galaxy formation
- if time: possible evidence for large temperature fluctuations at z~5-6

Thermal and ionization history of Universe

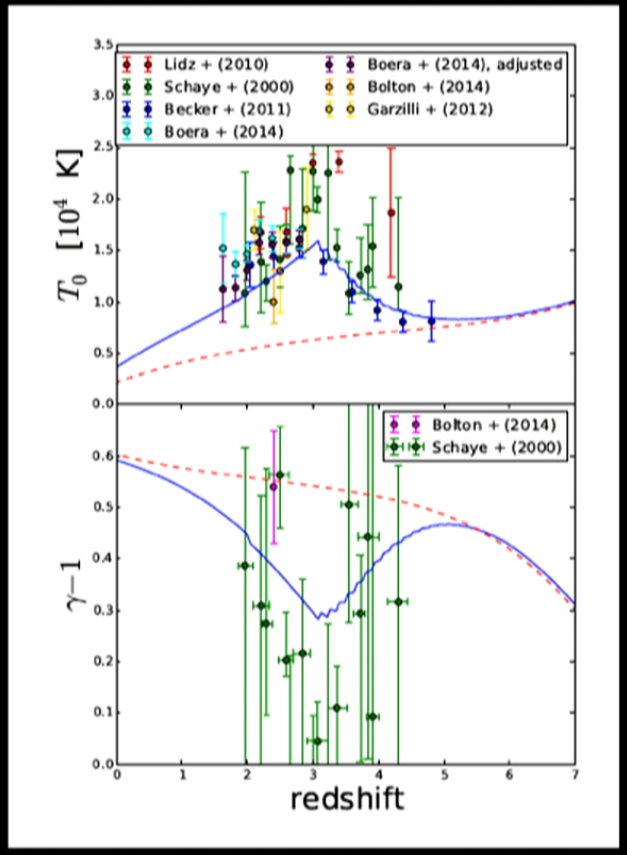


How the IGM temperature is measured



Many attempts, especially around turn of the century:
Schaye et al 00, Ricotti et al 00, McDonald et al 00,
Zaldarriaga et al 01, Lidz et al '10 -- factor ~2 precision

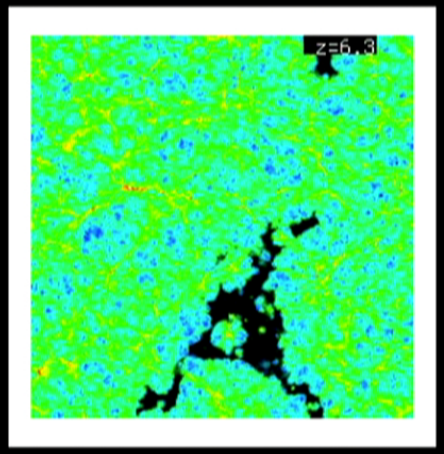
Recent measurements

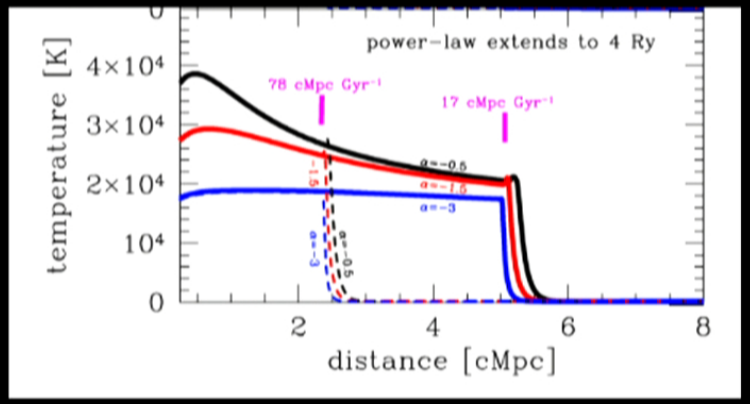


$$T = T_0 \Delta^{\gamma-1}$$

Principles that shape thermal history in standard scenario:

1) Photoheating during hydrogen reionization

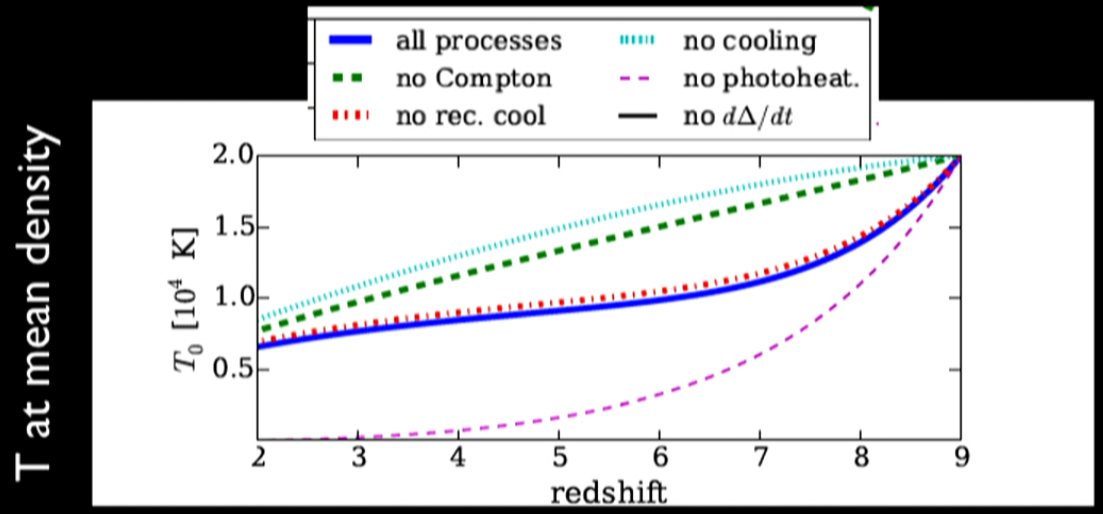




Gas is heated to 17,000-25,000 K by passing ionization front

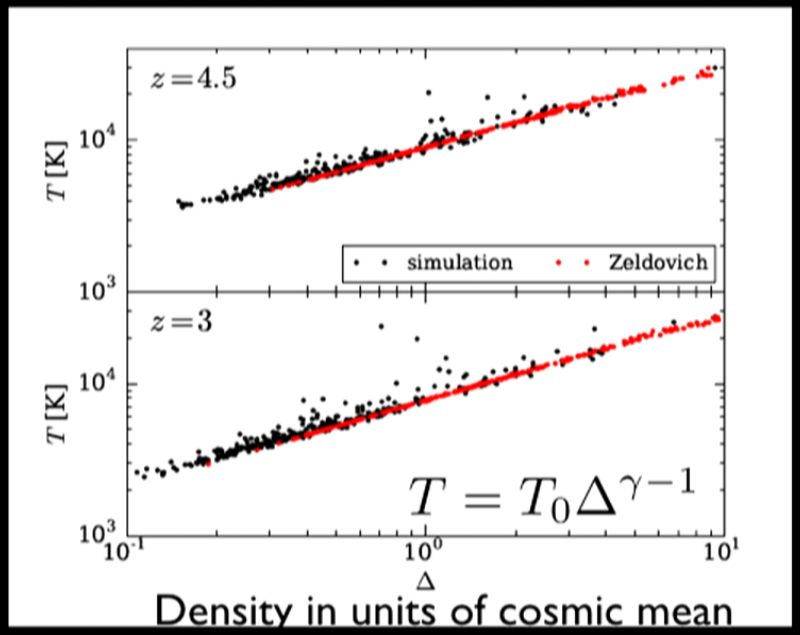
Miralda-Escude & Ostriker '93 MM '12

Principles that shape thermal history in standard scenario:
2) Photoheating and cooling after reionization



H I photo.	He I photo.	He II photo.	H II recomb.	He III recomb.	Compton	Free-free	Hubble
$\frac{T_4^{-0.7} Z_3^3 \Delta}{1+\alpha_{\rm bk}/2}$	$0.13 \frac{T_4^{-0.7} Z_3^3 \Delta}{1+f(\alpha_{\rm bk})}$	$2.0 \frac{T_4^{-0.7} Z_3^3 \Delta}{1+\alpha_{\rm bk}/2}$	$-0.11\, T_4^{0.2} Z_3^3 \Delta$	$-0.20\, T_4^{0.3} Z_3^3 \Delta$	$-0.28\, T_4 Z_3^4$	$-0.05\, \sqrt{T_4} Z_3^3 \Delta$	$-1.6\, T_4 Z_3^{3/2}$

Well after reionization tends to asymptotic relation (Hui & Gnedin '98)

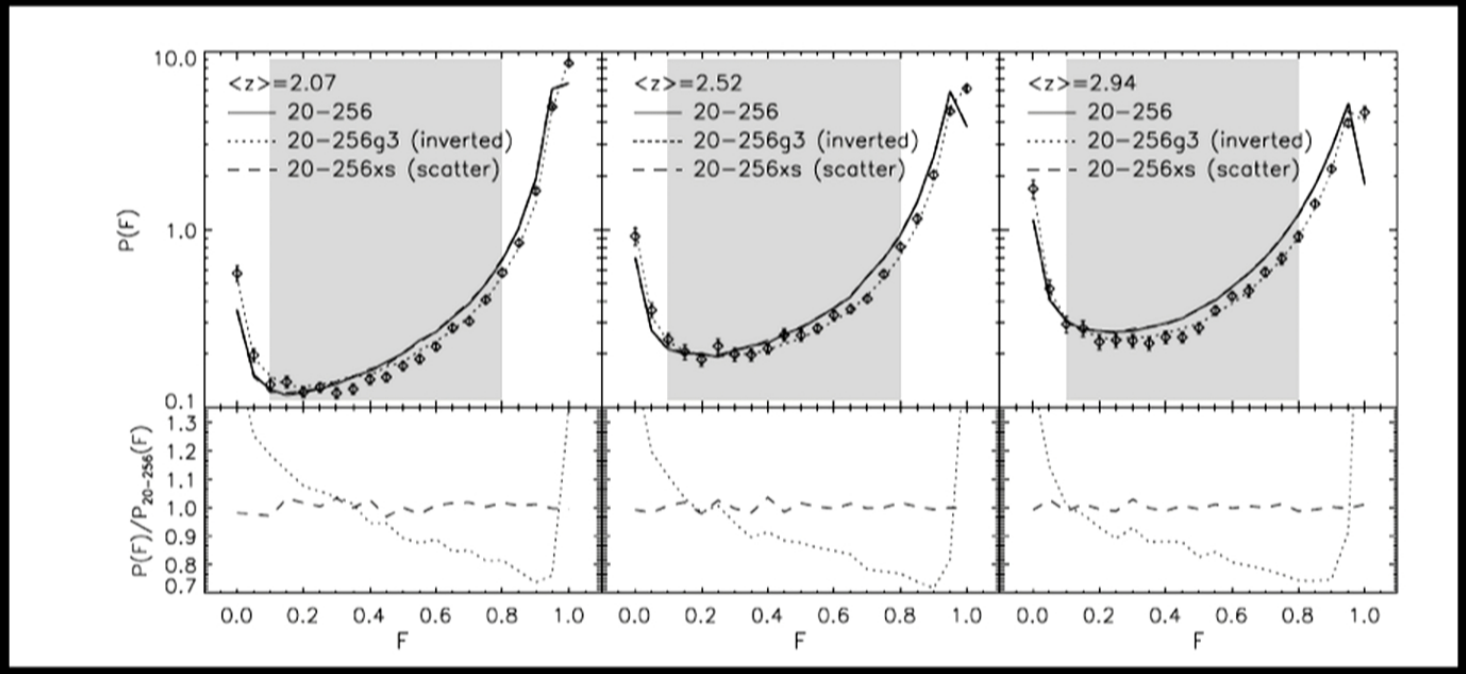


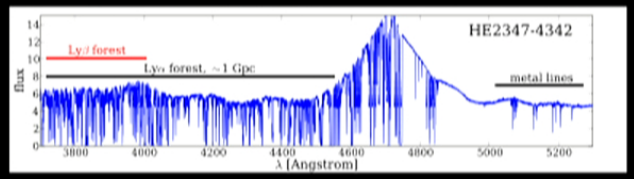
The asymptotic slope is γ-1=0.6. It is difficult in standard model to make γ-1<0 ('inverted') at z<<6.

Aside: PDF of the flux

PDF of flux: evidence against standard scenario?

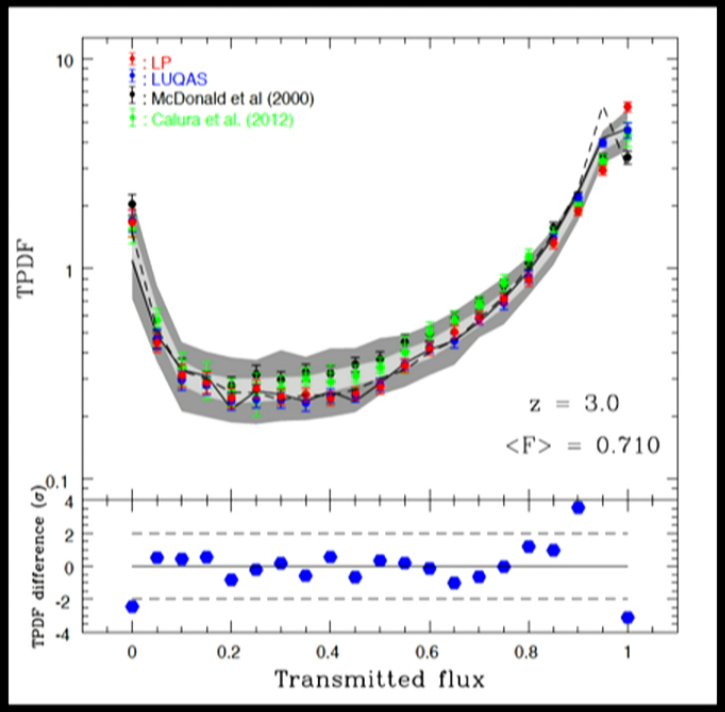
Bolton et al 2008





Suggestion: more high flux regions in observations

However, observations with different data sets scatter at about same level of discrepancy.



Rollinde et al 2015

Suggests no inconsistency with standard γ-1 values.

Modeling the thermal history

Our semi-analytic method

Upton Sanderbeck, D'Aloisio, & MM '16

- follow density evolution of Lagrangian gas elements using Zeldovich approximation
- heat and cool gas based on simple rules
- extrapolate measured $T(\Delta_*)$ to T_0 using effective γ from model
- plot average temperature (Becker method essential measures average temperature)

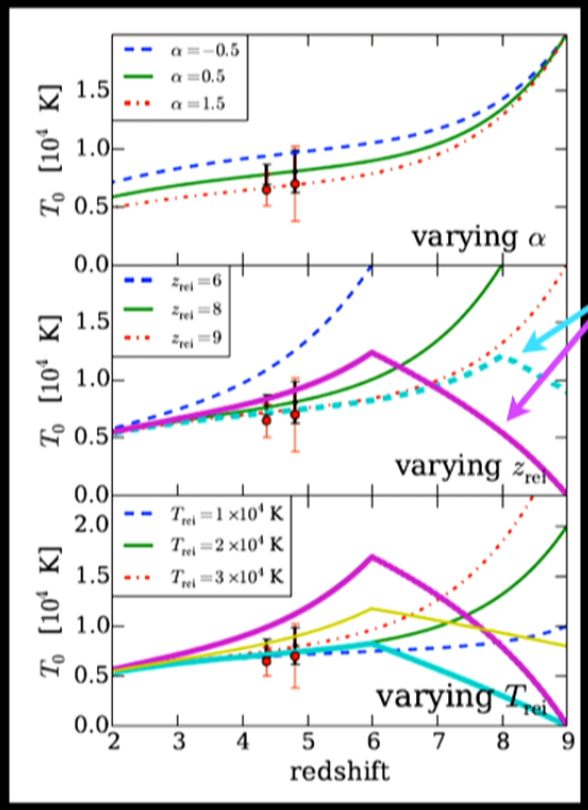
See also Puchwein et al (2015)

Only hydrogen reionization

varying post-reionization ionizing background

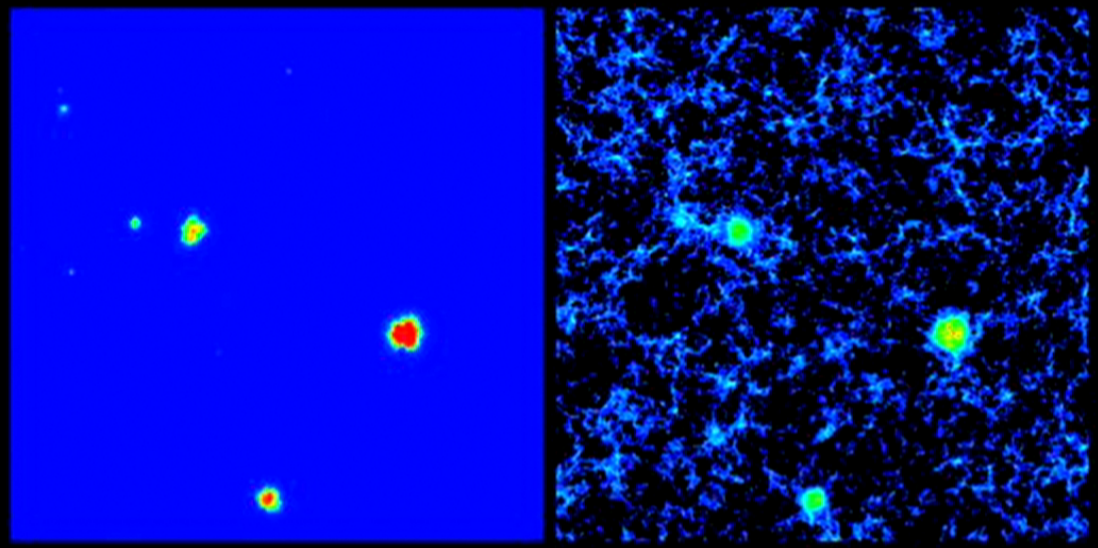
varying redshift of reionization

varying temperature of reionization

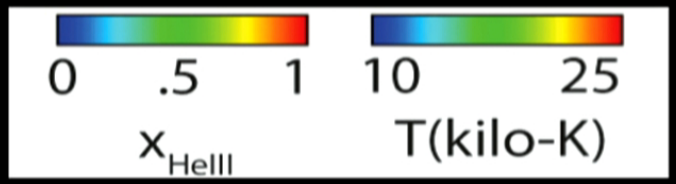


extended histories: assume gas is locally heated to T_{rei}, but that gas elements are ionized over some history

helium reionization model

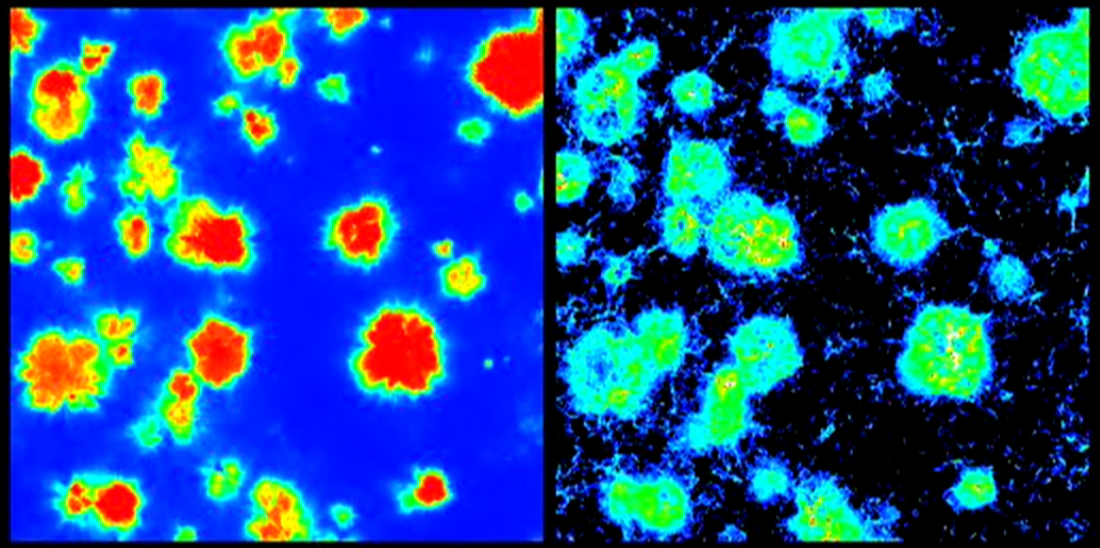


430 Mpc box



two phase model: local ionization near quasar plus uniform heating of HeII gas by (hard) long mfp photons

helium reionization model



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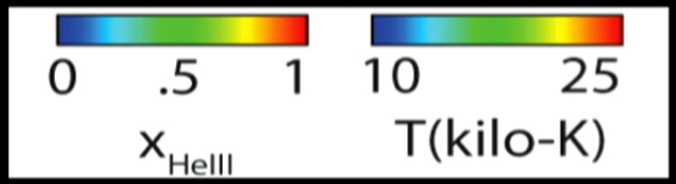

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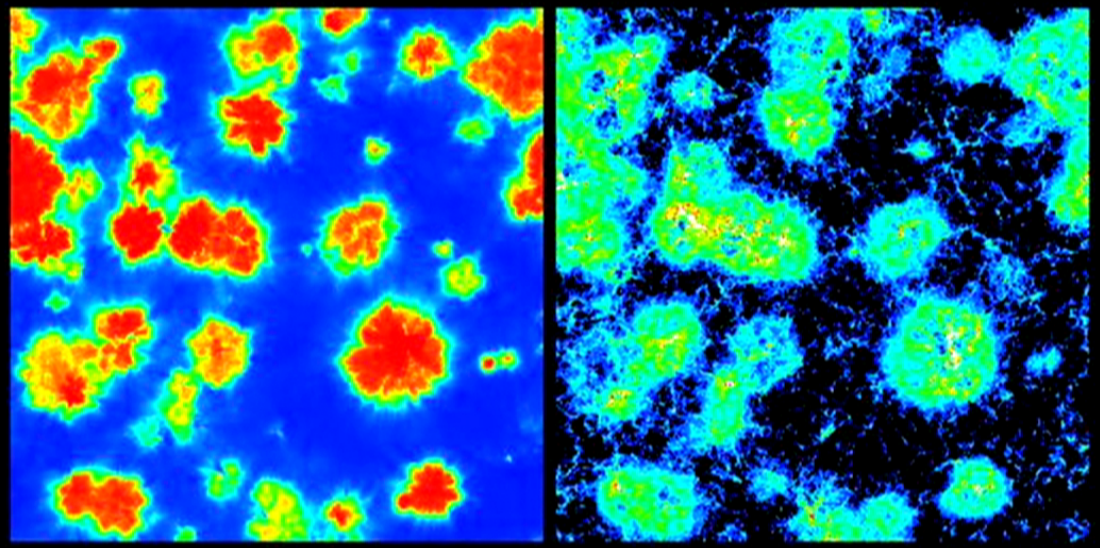

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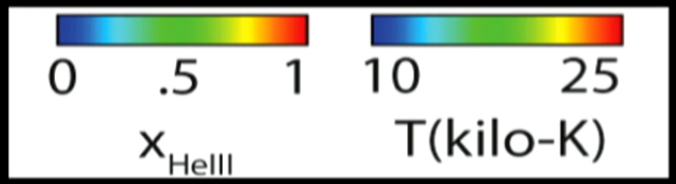

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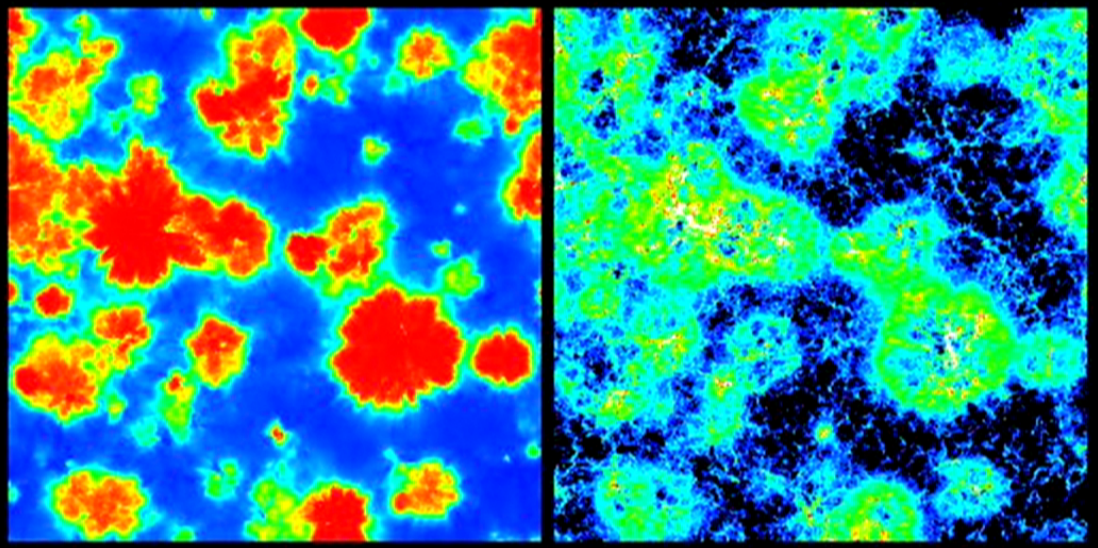

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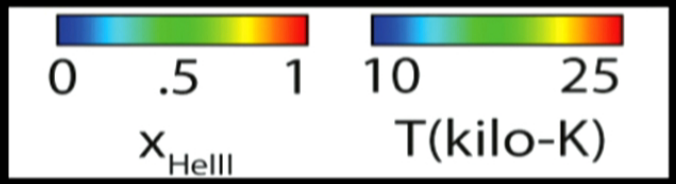

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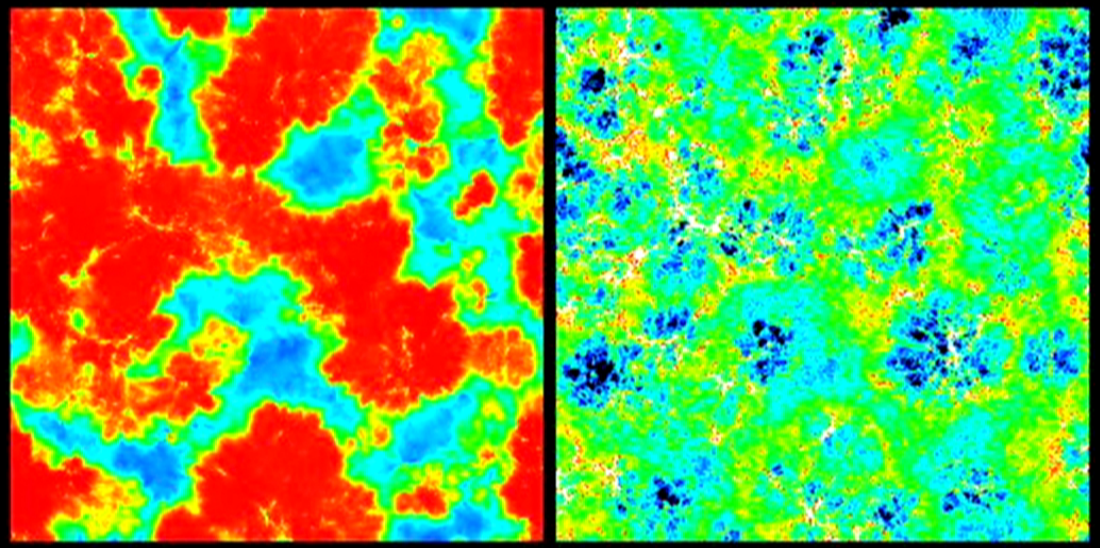

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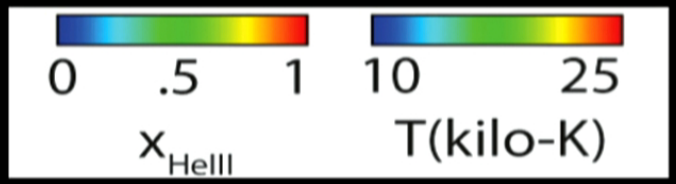

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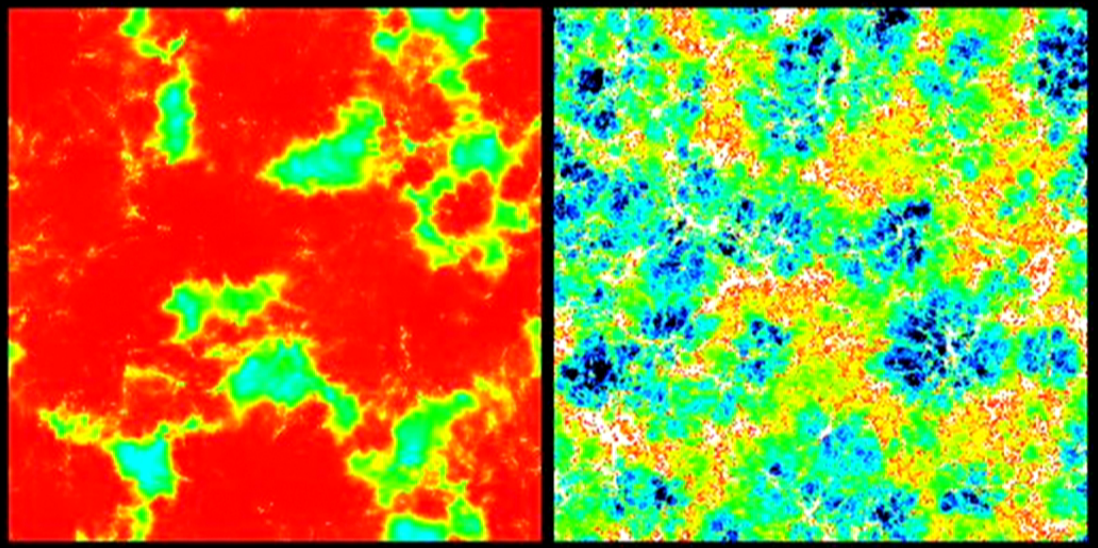

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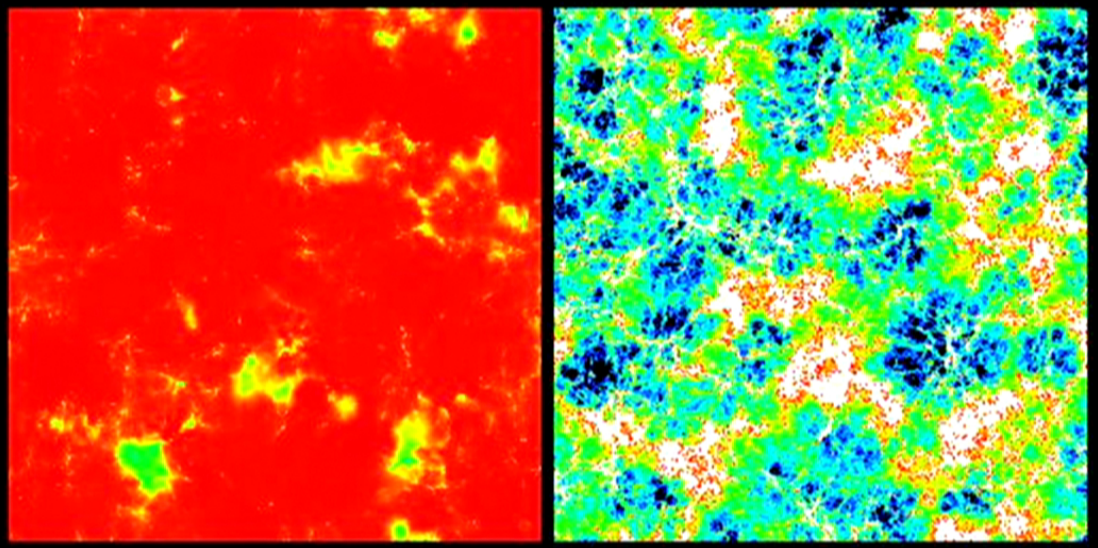

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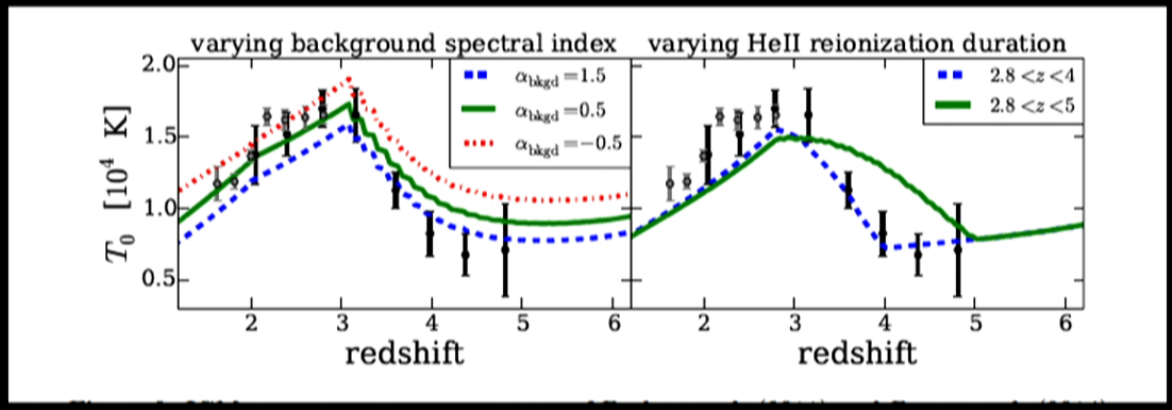
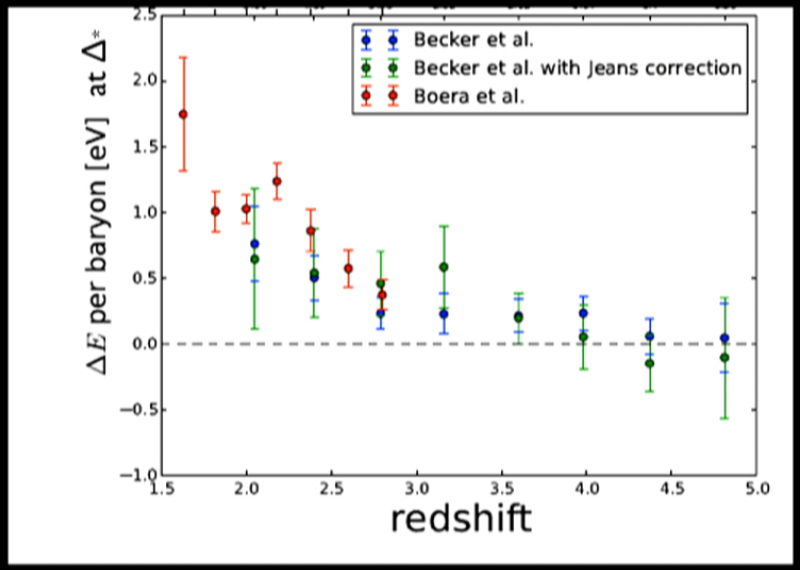
full history



Sanderbeck, D'Aloisio, & MM '16

additional heating relative to our minimum-photoheating model



Regarding blazar heating: only upper side of models inject this amount of energy.

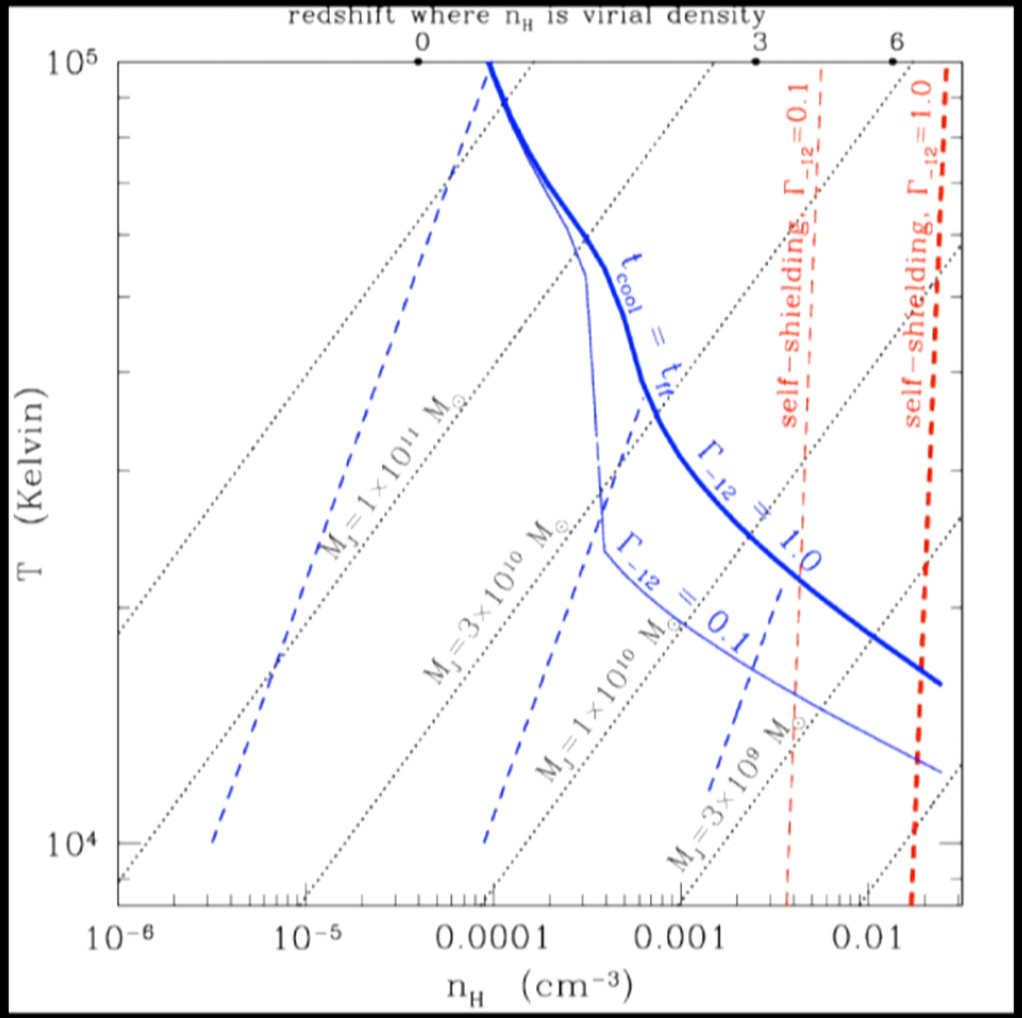
Sanderbeck & McQuinn '15

How does the thermal history impact galaxy formation?

Hypotheses for what sets minimum size of galaxies:

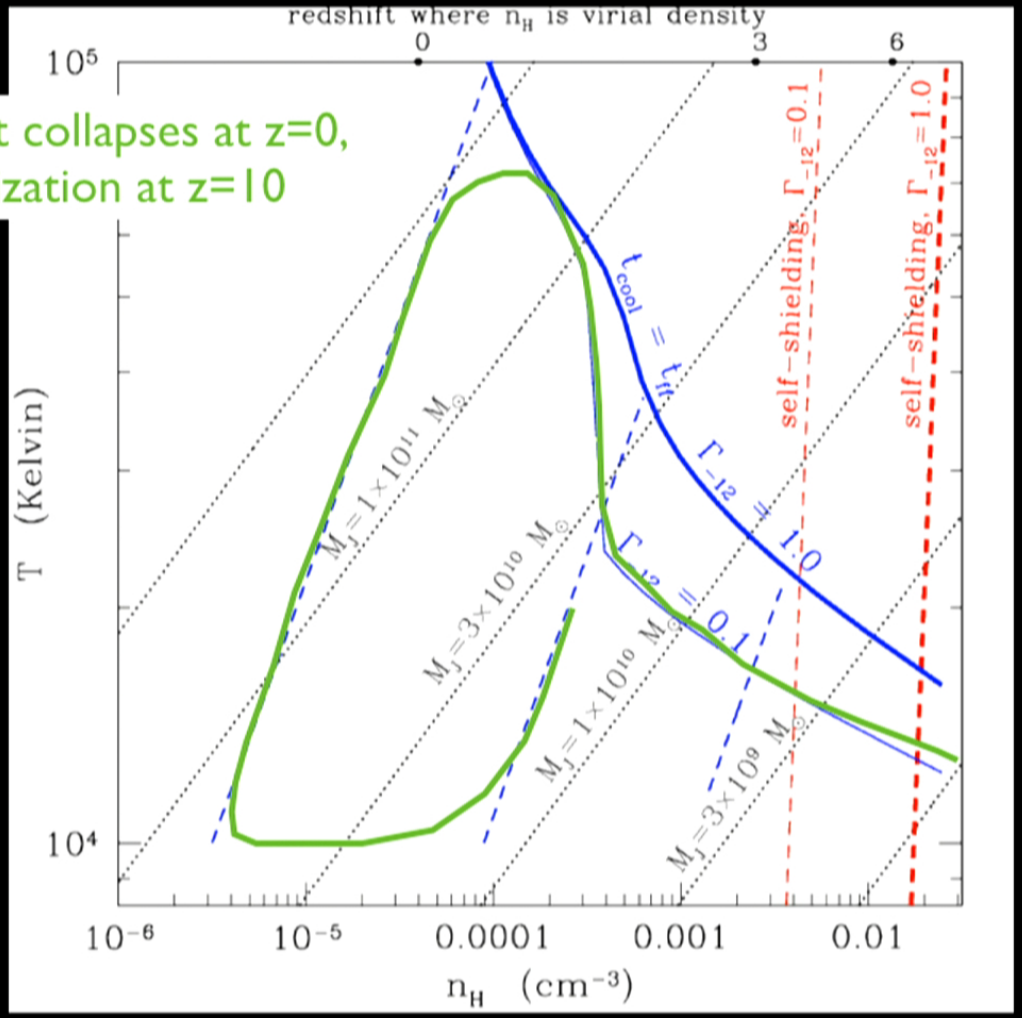
1. set by IGM temperature
    I. given by the Jeans' (filtering) mass at z_{coll} evaluated at the mean density (e.g. Gnedin '00)
    II. given by when $T_{gas}^{eq} < T_{halo}$; Okamoto & Theuns '08
    III. there is a more physical picture (Noh & MM '12)
2. internal feedback processes (e.g. supernova)

Physics of dwarf galaxy formation



Physics of dwarf galaxy formation

Shell that collapses at z=0, reionization at z=10



We find that these curves are essentially reproduced in simulations except with two differences (Noh and MM '14)

1. $M_{Jeans} \Rightarrow M_{Jeans}/4$

2. gas first often goes through filaments and so collapse on average occurs quicker than the spherical collapse trajectories I just showed you

This picture diminishes impact of blazar heating over that previously assumed. Need to heat up overdense regions pre-turnaround.

Conclusions

- Thermal history in simple models in excellent agreement with measurements
- ~1eV per particle can be injected into mean density IGM by z=2 by something other than photoheating
- heating low density gas at low redshift likely will not have strong effect on galaxies
- the large opacity fluctuations in the z>5 IGM may be temperature fluctuations that are an inevitable byproduct of reionization