Computational galaxy formation
Ringberg 8-13.5.2016

Simulating Cosmic Reionization

Benedetta Ciardi

Max Planck Institute for Astrophysics

Modelling of cosmic reionization: ingredients

✧ Model of galaxy formation

Semi-analytic models

$$M\frac{dn}{dM} = \left(\frac{2}{\pi}\right)^{1/2} \frac{-d(\ln\sigma)}{d(\ln M)} \frac{\rho_0}{M} \upsilon_c e^{-\upsilon_c^2/2}$$

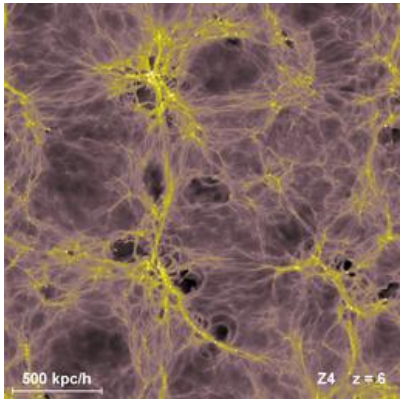
$$M_*^{\&} = \alpha \frac{dM}{dt}$$

$$t_{cool} < t_{dyn}$$

...

+

Numerical simulations



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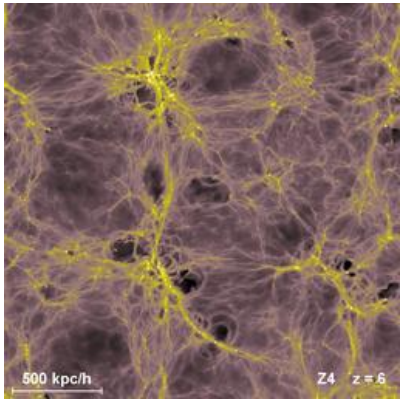
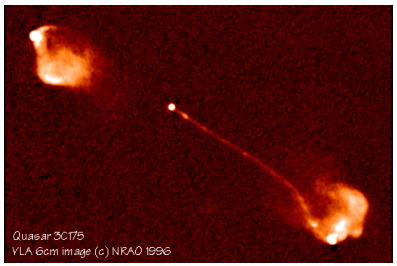


✧ Properties of the sources of ionizing radiation

Stellar type

Quasars



DM annihilation/decay

light dark matter

neutralinos

gravitinos

sterile neutrinos

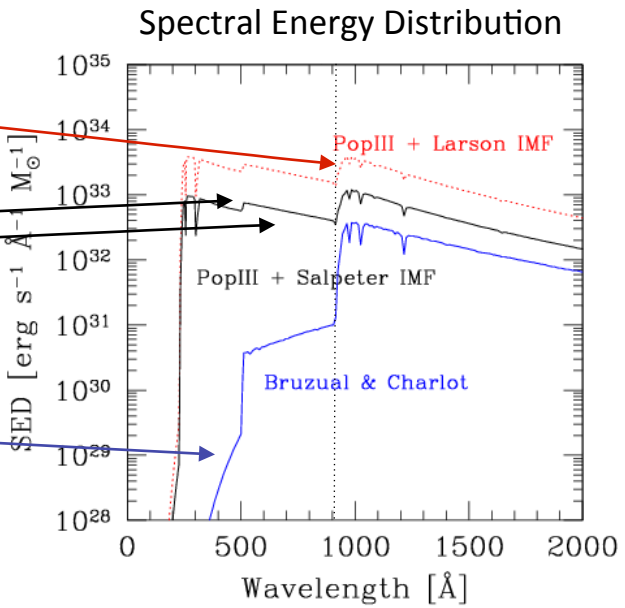
...

STELLAR TYPE SOURCES

✧ Initial Mass Function and spectrum

Salpeter or Larson IMF?

Zero or higher metallicity?



Stellar type sources

- ✧ Initial Mass Function and spectrum

Stellar type sources

✧ Initial Mass Function and spectrum

✧ Escape fraction

Fesc < 20% but there is a big variation in the number
both theoretically & observationally
Fesc > 70% for primordial, very-massive stars

Large uncertainties associated
to high-z stellar type sources

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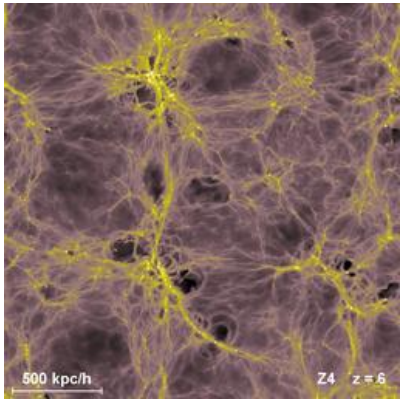

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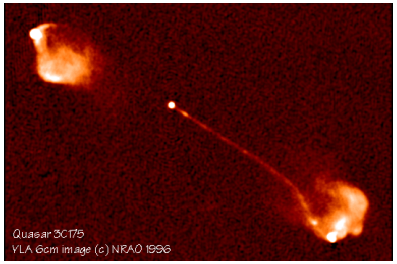

DM annihilation/decay

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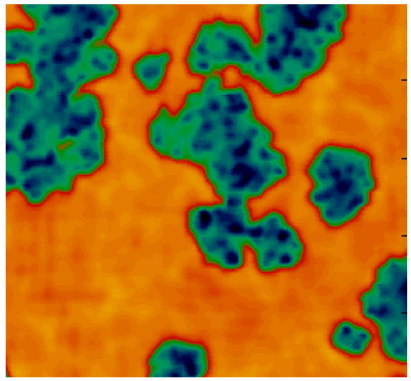
✧ Evolution of the ionized regions



Simulations of H & He reionization

BC+ 2012; Eide+ in prep

Model of galaxy formation

Gadget-3 simulations from J. Bolton; Khandai+ (2015)

L [Mpc/h com.]	Particles	Mgas [Msun/h]
533	2×3200^3	5.7×10^7
100	2×1792^3	2×10^6
35.12	2×512^3	4.15×10^6
8.78	2×256^3	6.48×10^4
4.39	2×256^3	8.11×10^3
2.20	2×256^3	1.01×10^3

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Properties of the sources of ionizing radiation

Emissivity(z) and distribute it among the halos with power-law spectrum

Index α	% of sources
1.8	100
3 - 1	70 - 30
3	100

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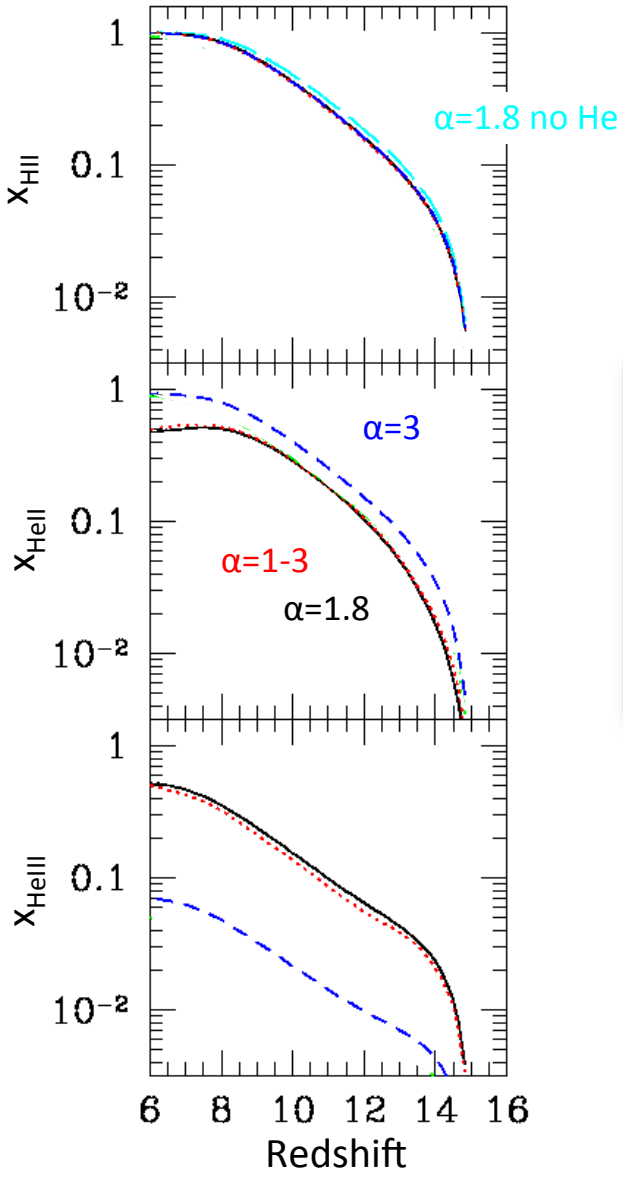
Radiative transfer of ionizing photons

CRASH

BC+ 2001; Maselli, Ferrara, BC 2003; Maselli, BC, Kanekar 2009; Pierleoni, Maselli, BC 2009; Partl+ 2011; Graziani, Maselli, BC 2013; Graziani, BC, Ferrara in prep

Simulations of H & He reionization

BC+ 2012



H evolution very similar (independently from He and spectral shape)

He evolution depends on spectral shape

Simulations of H & He reionization

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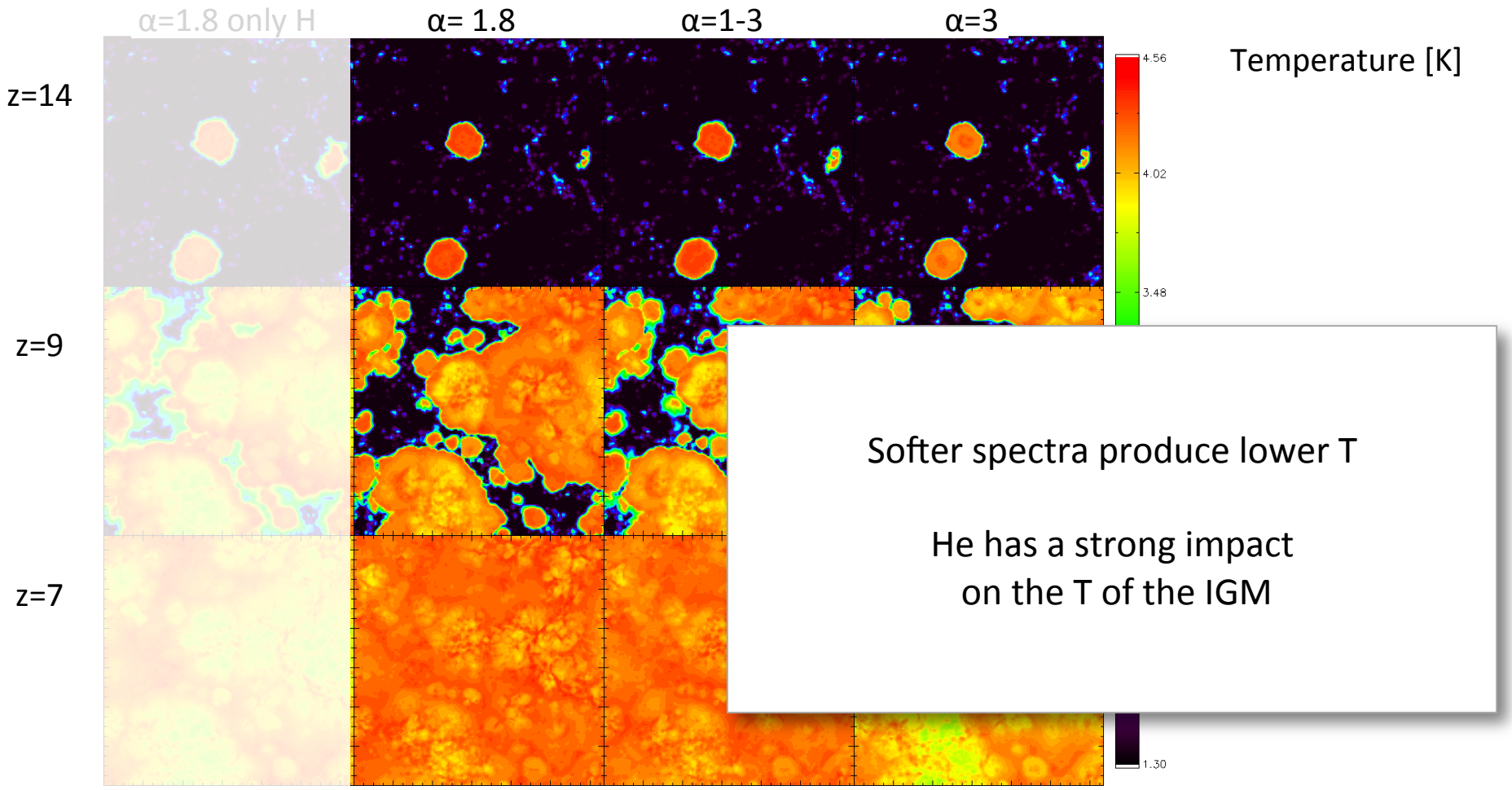


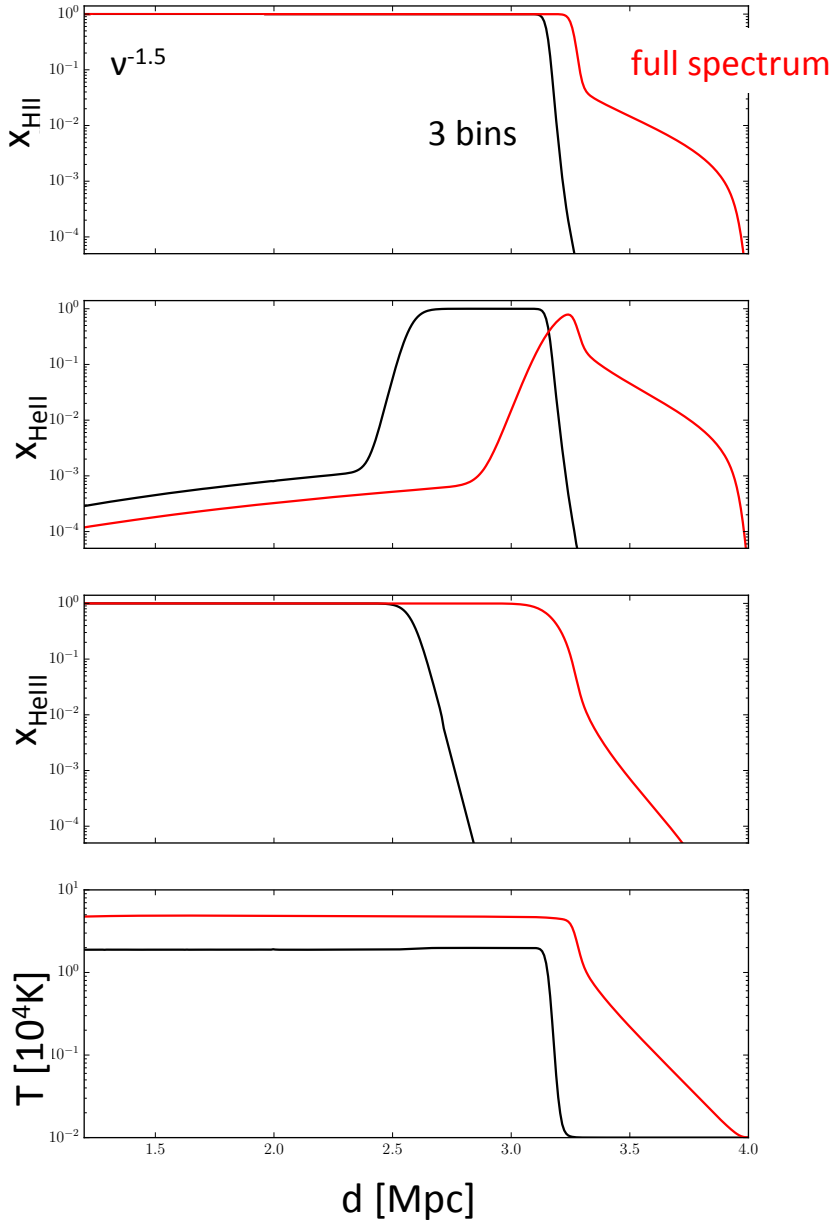
Softer spectra produce lower T

He has a strong impact
on the T of the IGM

Simulations of H & He reionization

Inclusion of He and correct spectral shape **are not** relevant for H reionization, but they **are** relevant for He and T evolution

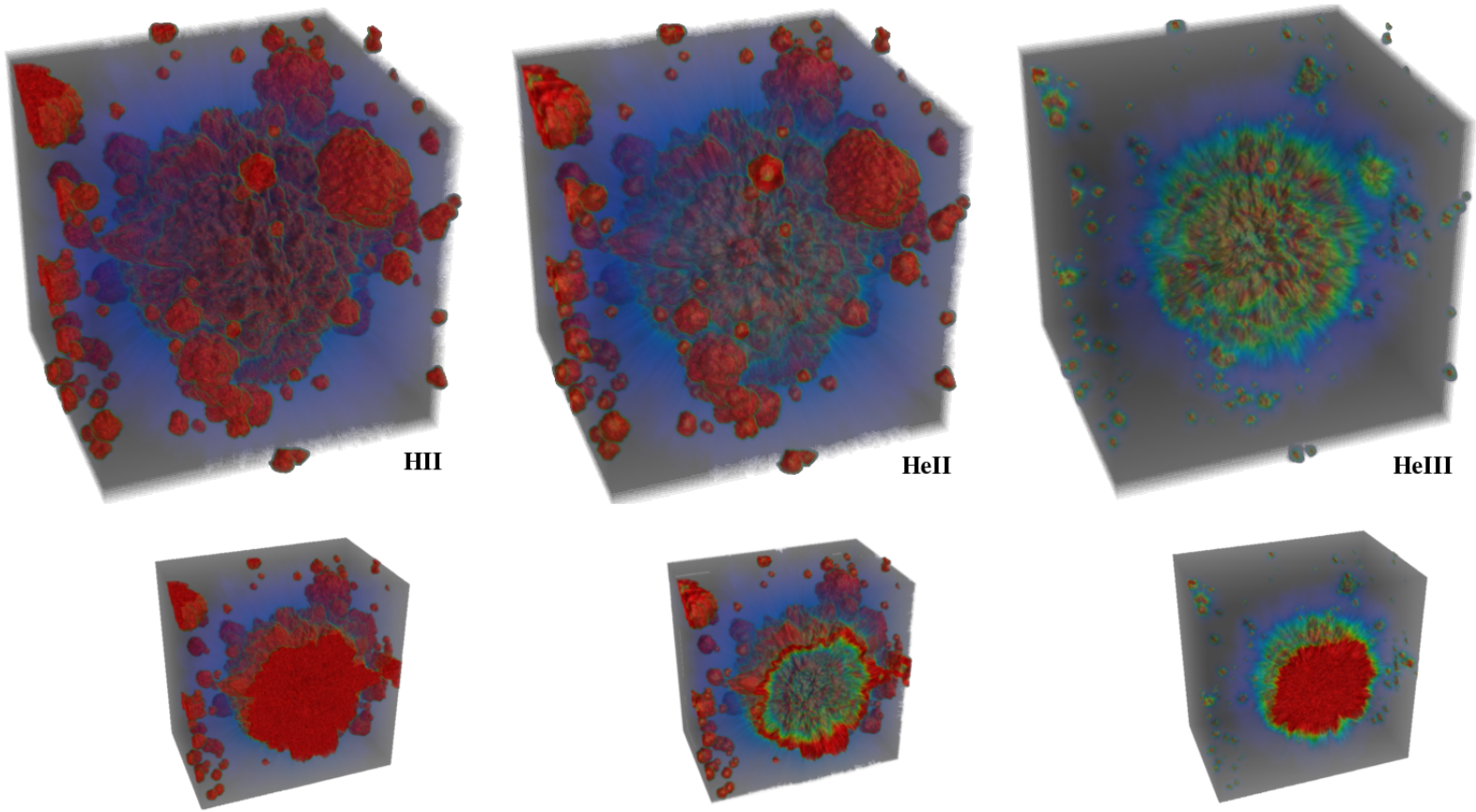
Frequency Resolution



Frequency resolution is important!

Simulations of QSOs' ionized regions

Kakiichi+ in prep



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Gas and source distribution

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Properties of the sources of ionizing radiation

- ✧ Galaxies, $\alpha=3$
- ✧ QSO, $\alpha=1.5$, 1.36×10^{56} s^{-1}, $t_Q=10^7$yr

Radiative transfer of ionizing photons

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Reionization	Galaxies	QSO	x-rays
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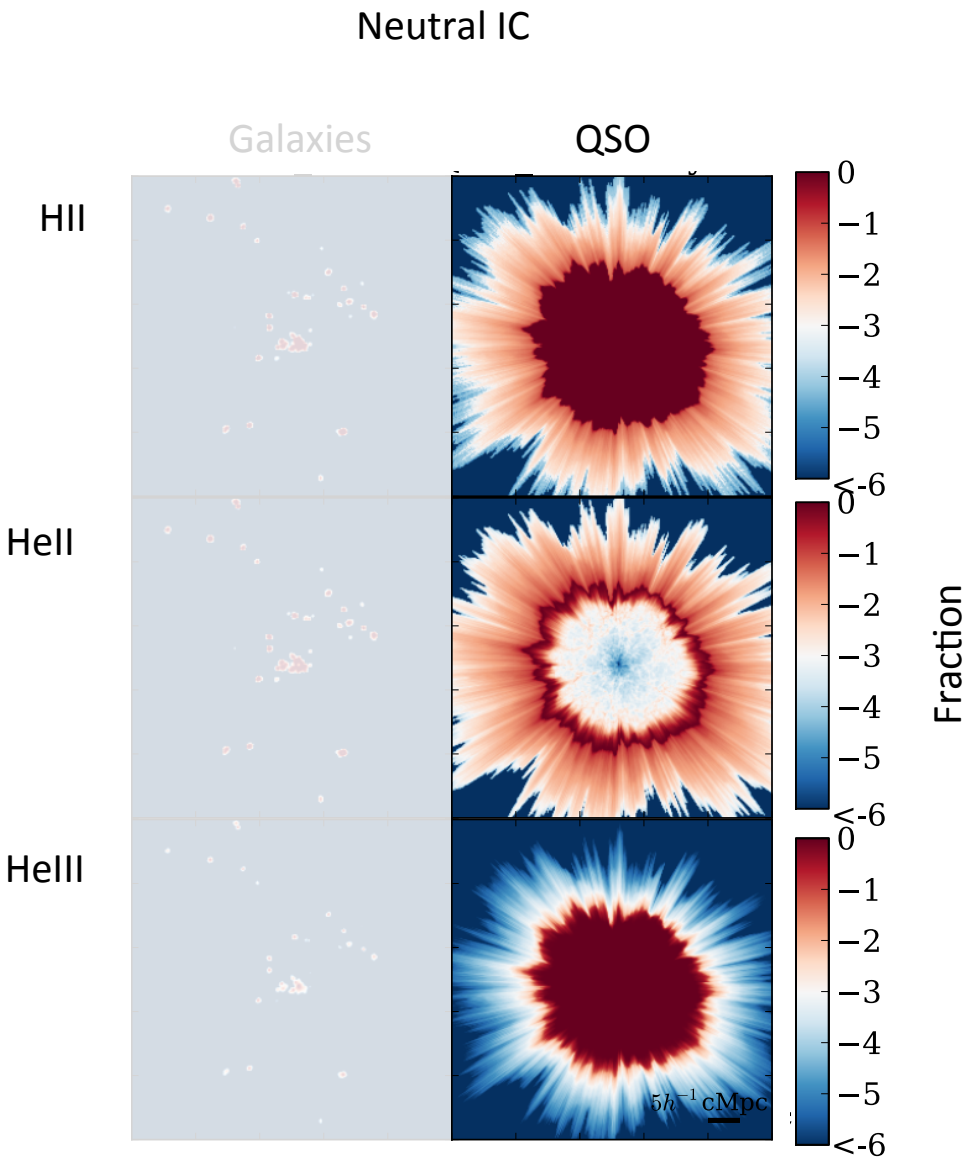

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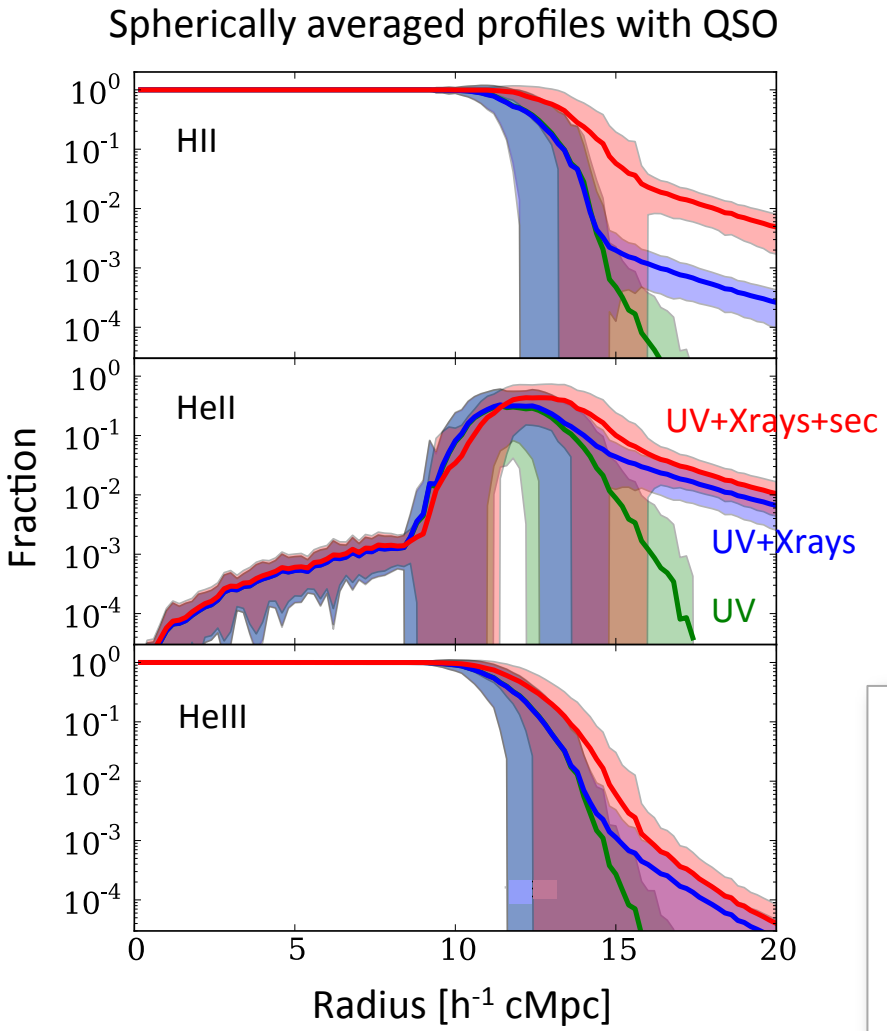
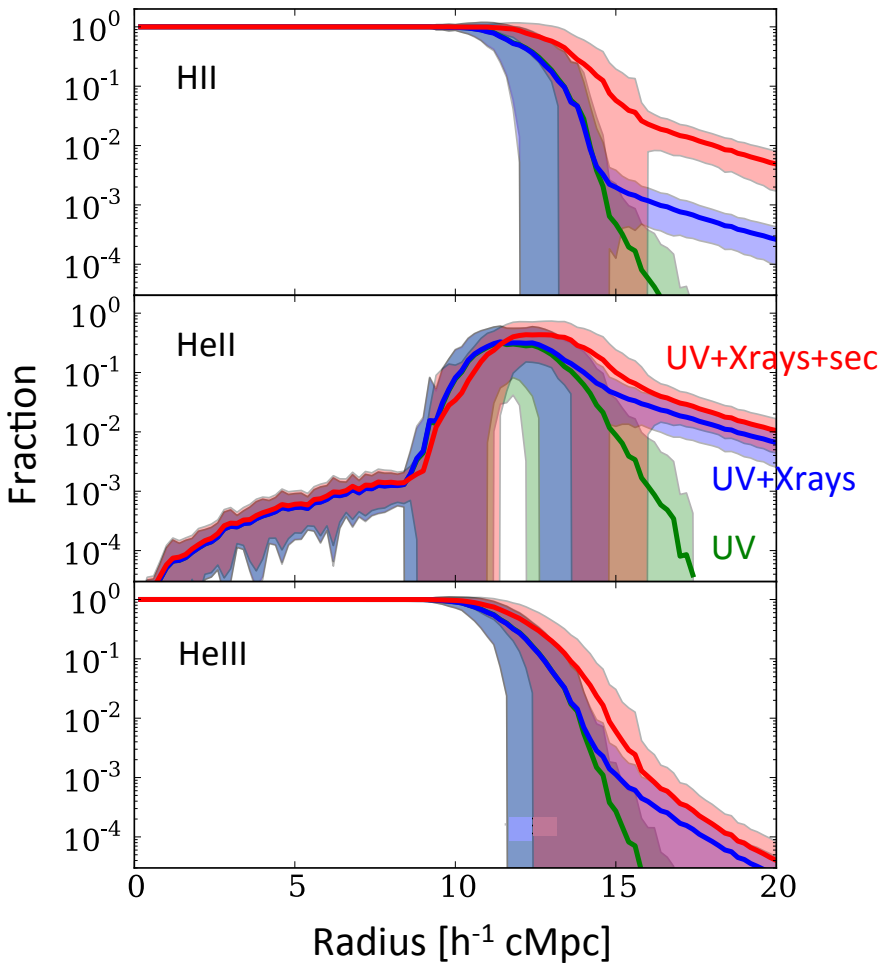


Partial ionization from x-rays & secondaries

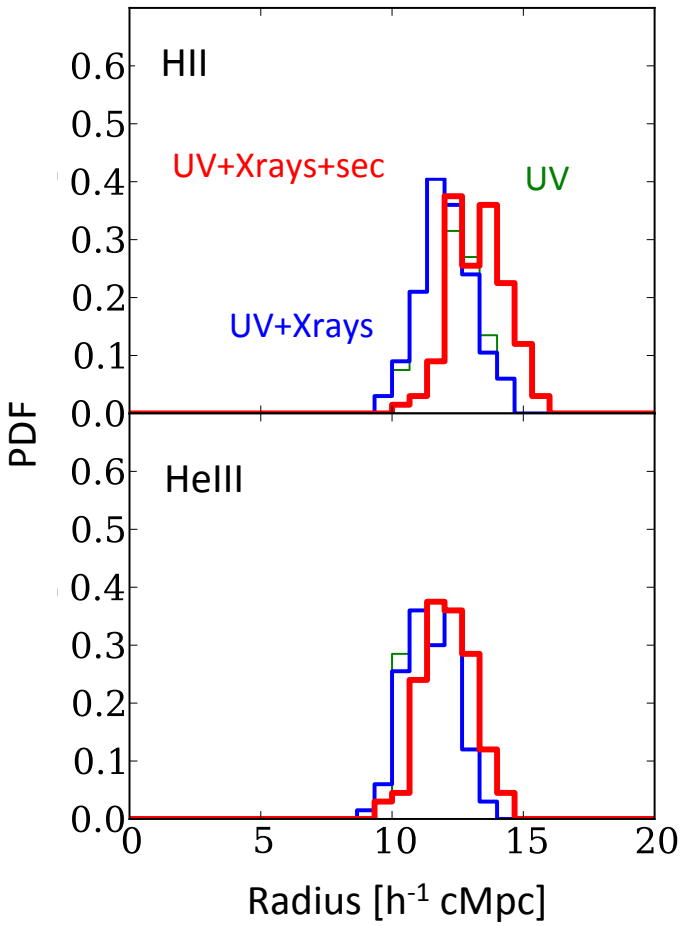
SIMULATIONS OF QSOs' IONIZED REGIONS

Kakiichi+ in prep

Spherically averaged profiles with QSO



Distribution of I-front position



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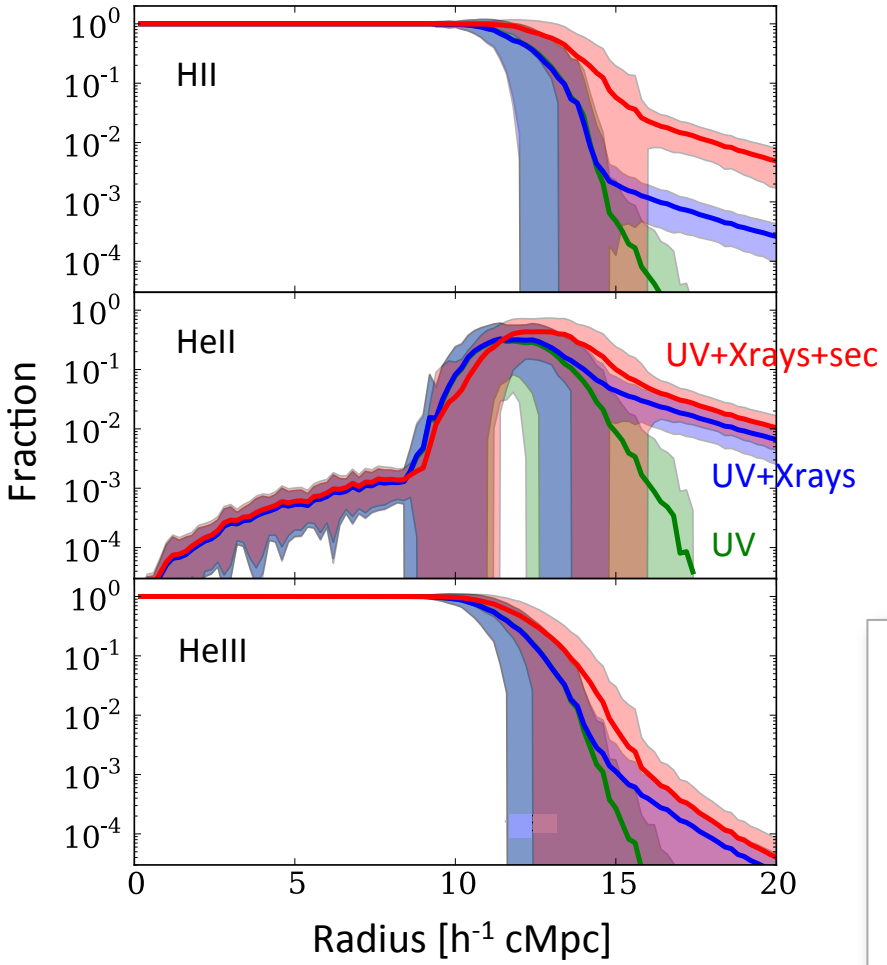

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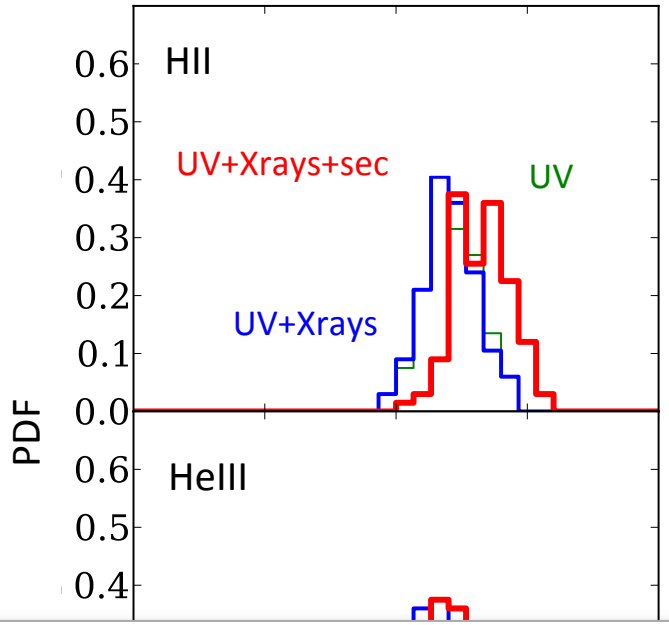

Partial ionization from x-rays & secondaries

I-front location unchanged by x-rays

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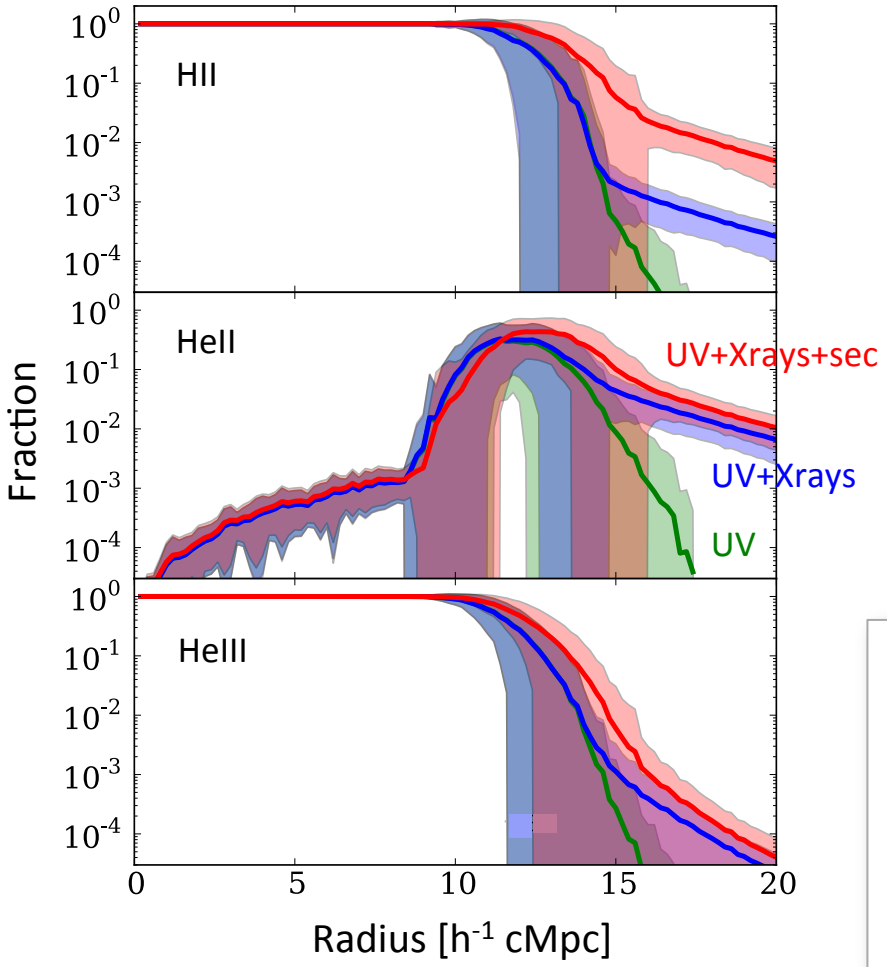

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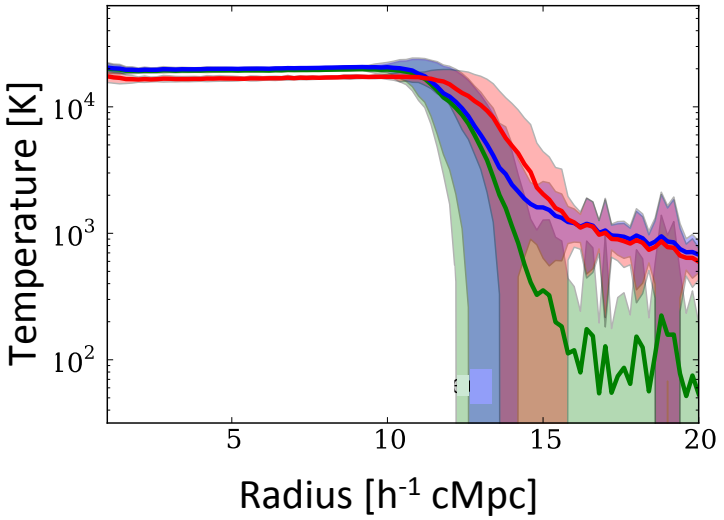


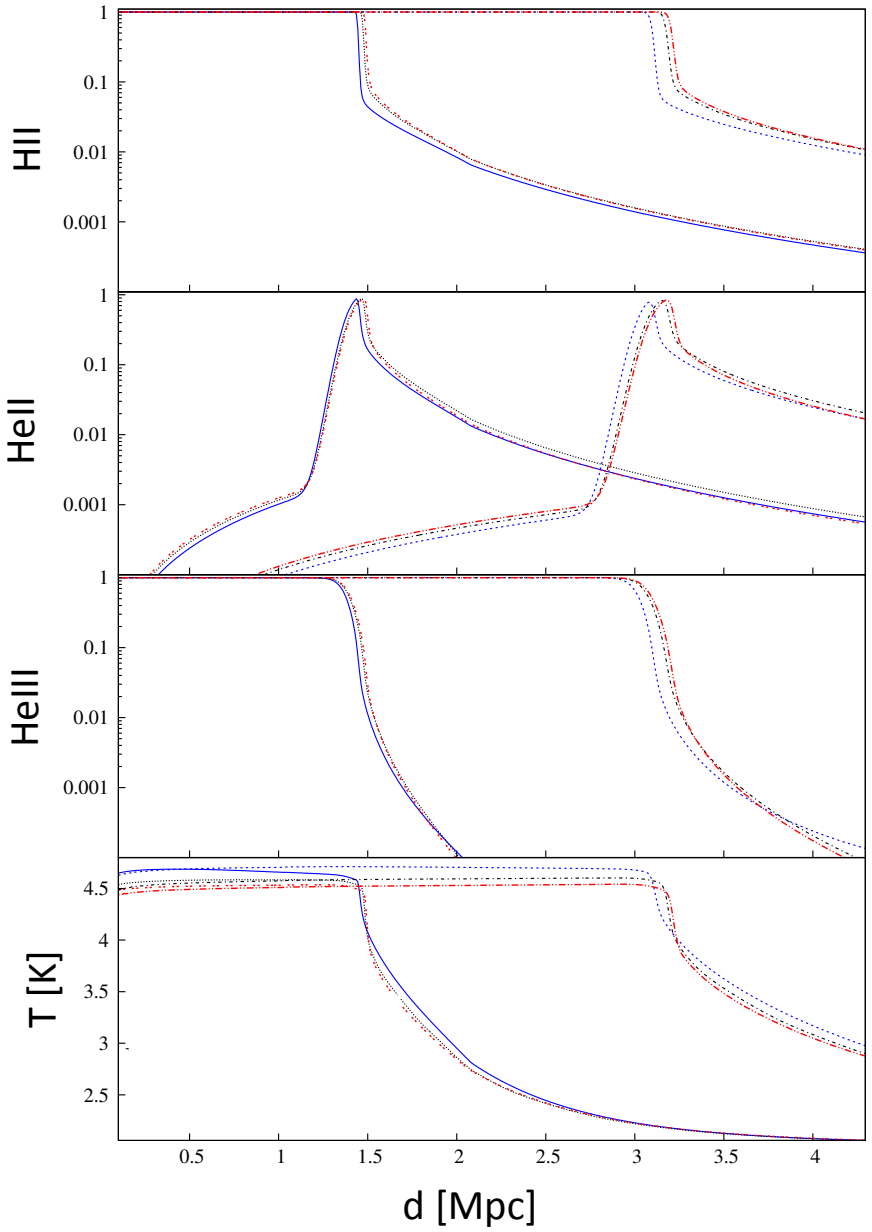
Partial ionization from x-rays & secondaries

I-front location unchanged by x-rays

Heating ahead of I-front

Secondaries reduce effective x-ray heating

Impact of Secondary Ionization Prescription



Shull & van Steenberg (1985)
Dalgarno et al. (1999)
Valdes & Ferrara (2008)

The model implemented matters

Conclusions

- ✧ Not all the physical processes/properties relevant for cosmic reionization are (well) known
- ✧ Even if they were we would not be able to model everything correctly

Conclusions

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