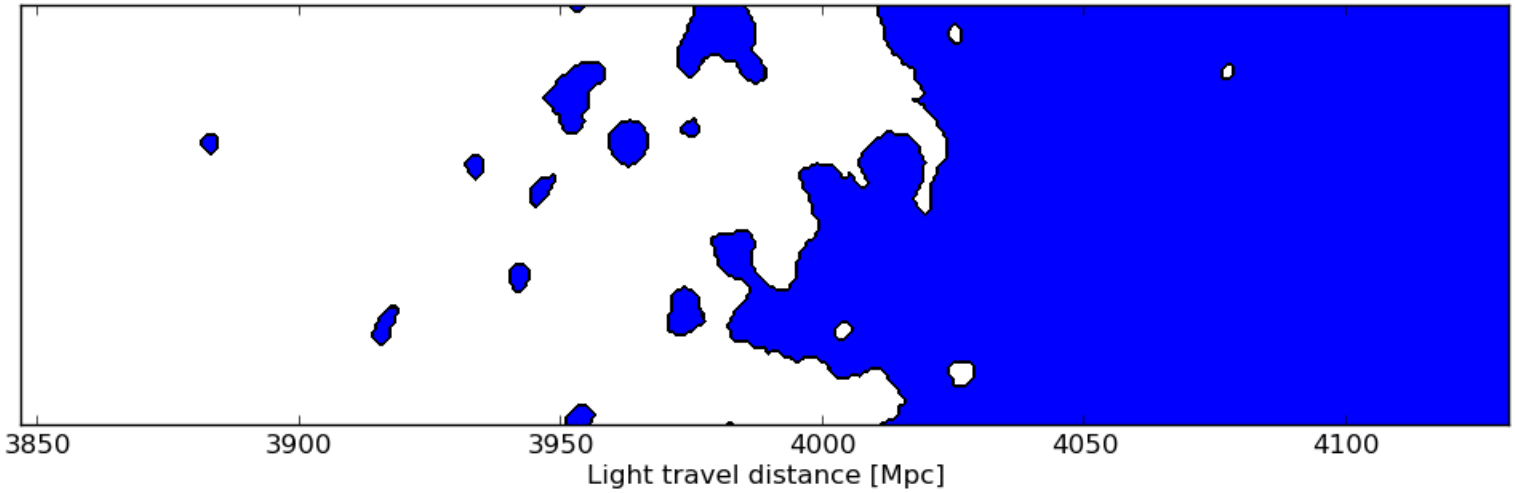


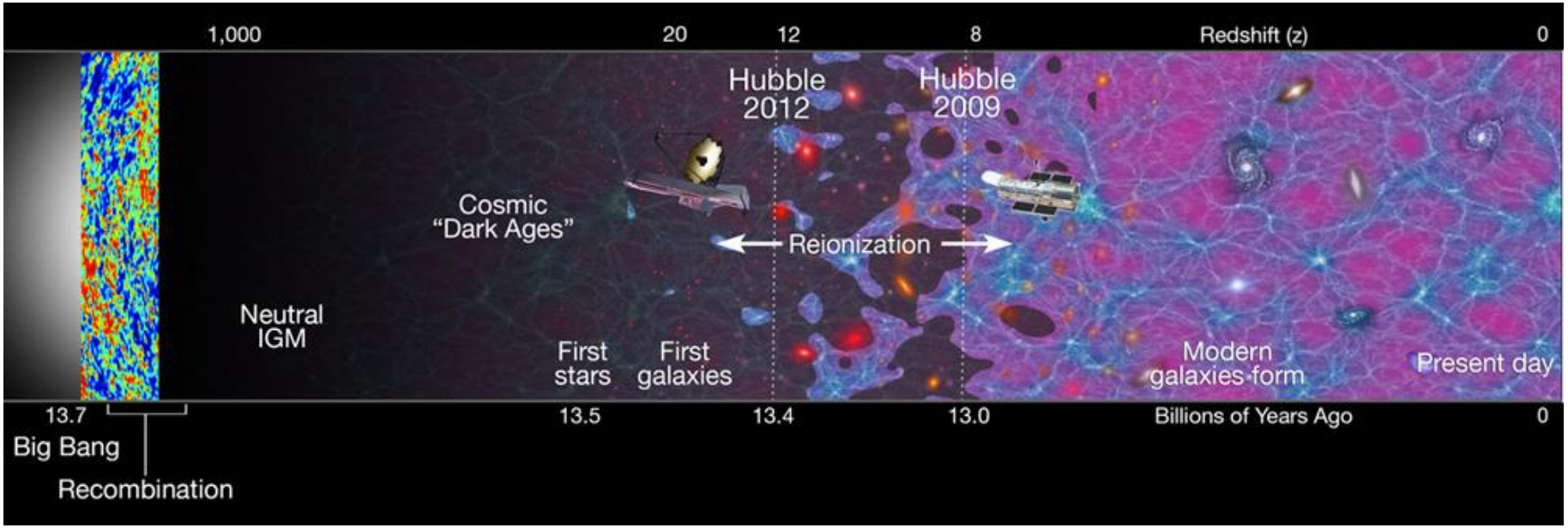

# Effect of Lyman Limit Systems and Local Clumping Factor on the History of Cosmic Reionization

**Alexander (Sasha) Kaurov**

***the University of Chicago***

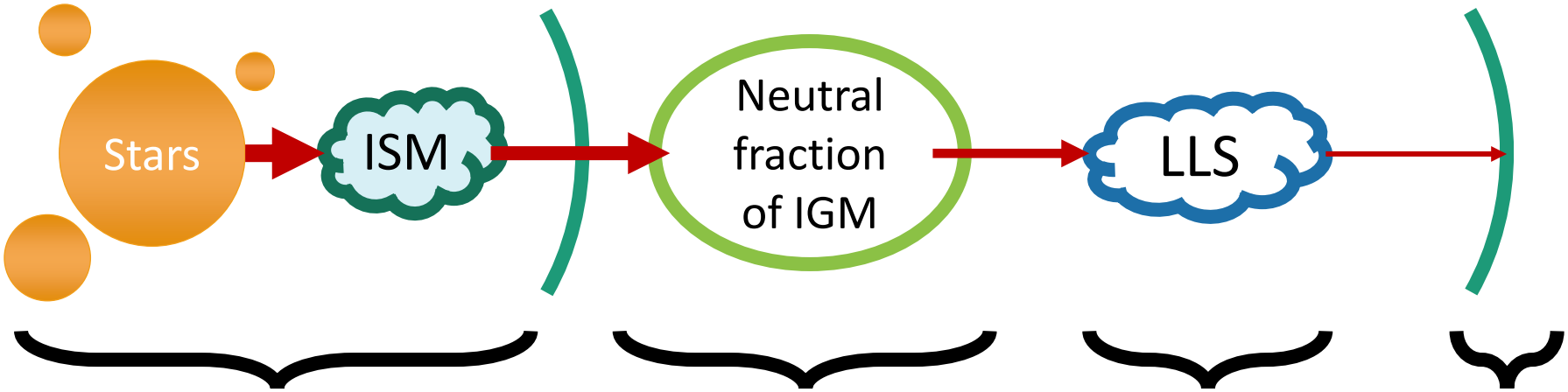
Kaurov & Gnedin (2013a,b)

# History of cosmic reionization




**Hubble Ultra Deep Field**

# Absorption of ionizing photons:



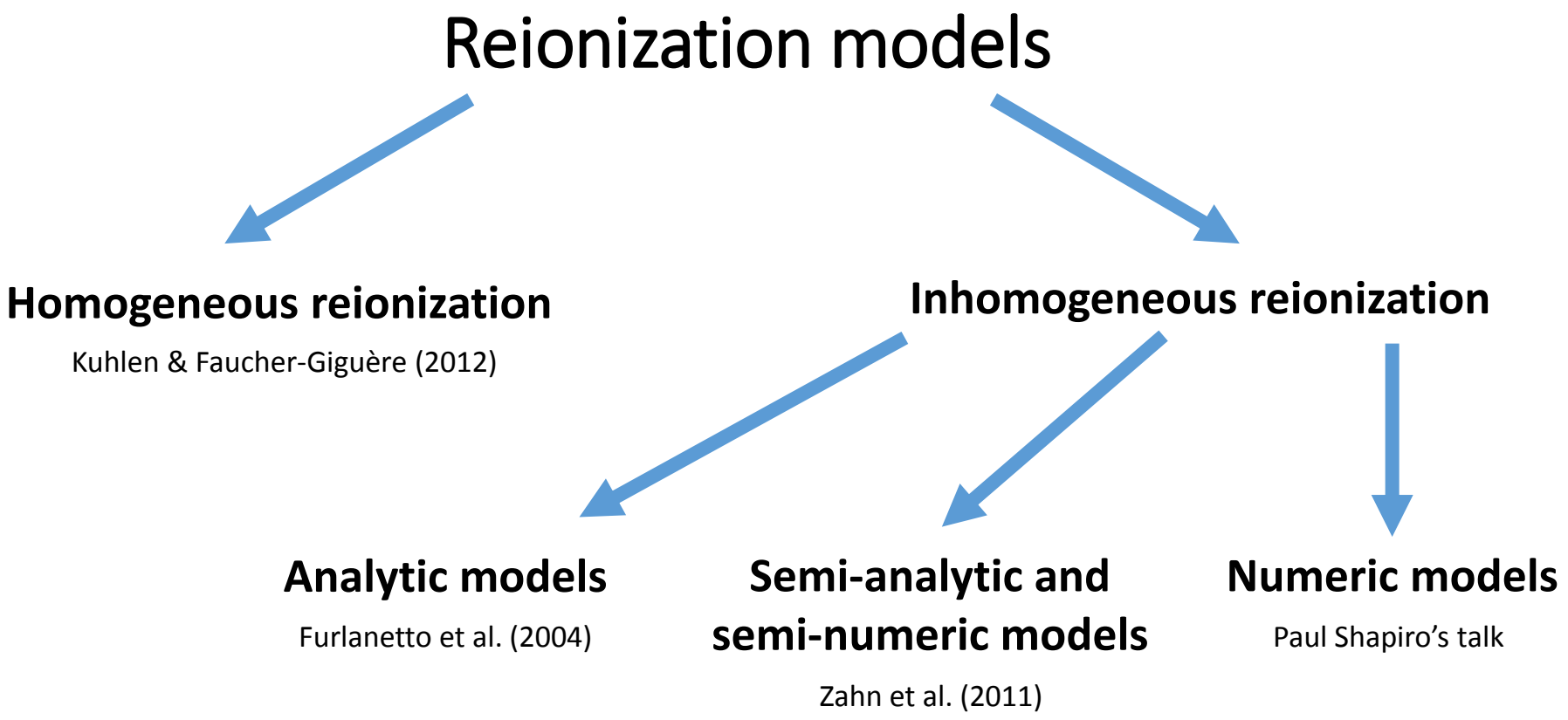

Escape fraction of ionizing radiation from Galaxy

Recombinations in IGM, Clumping factor

Compact neutral objects

Ionization front

# Ways to study reionization:



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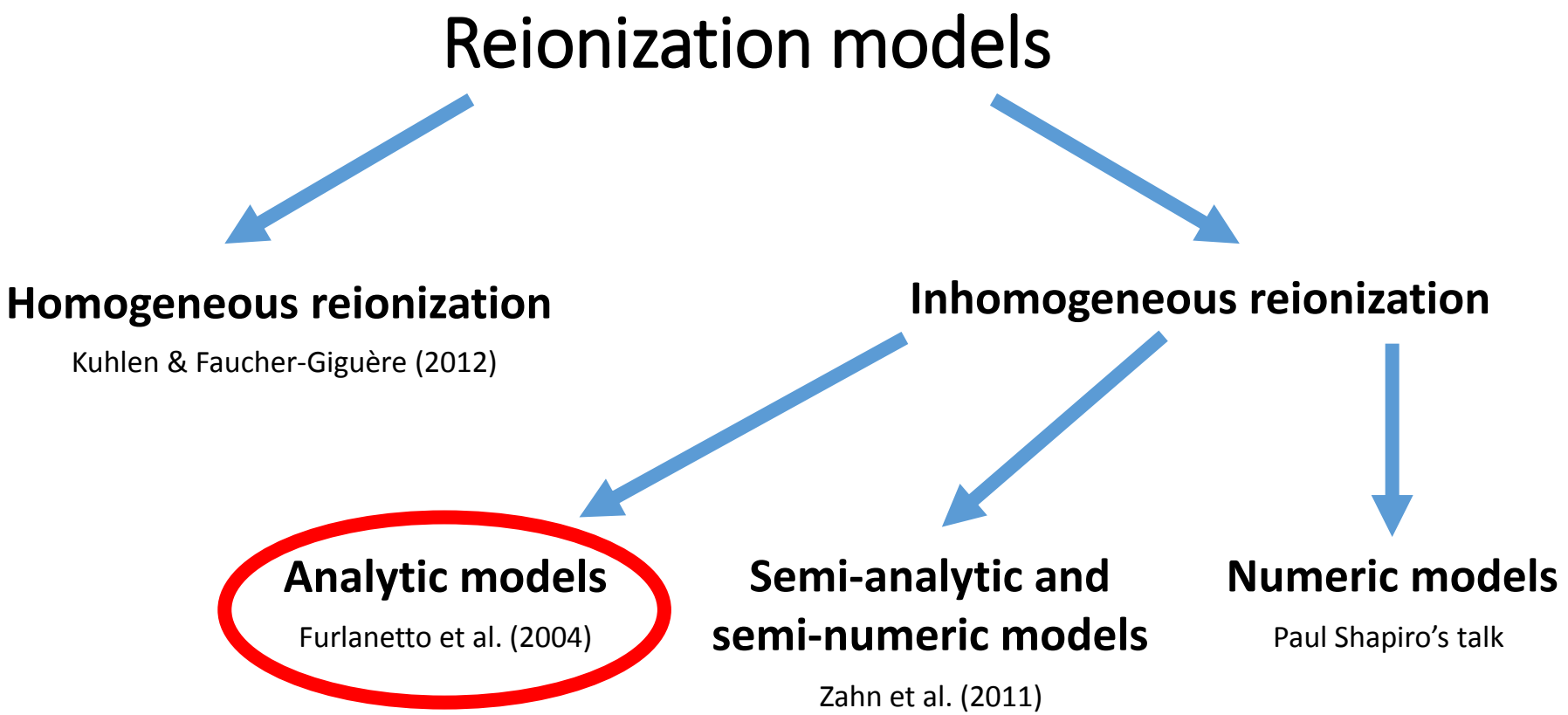


# How analytic model works?

Halo mass function

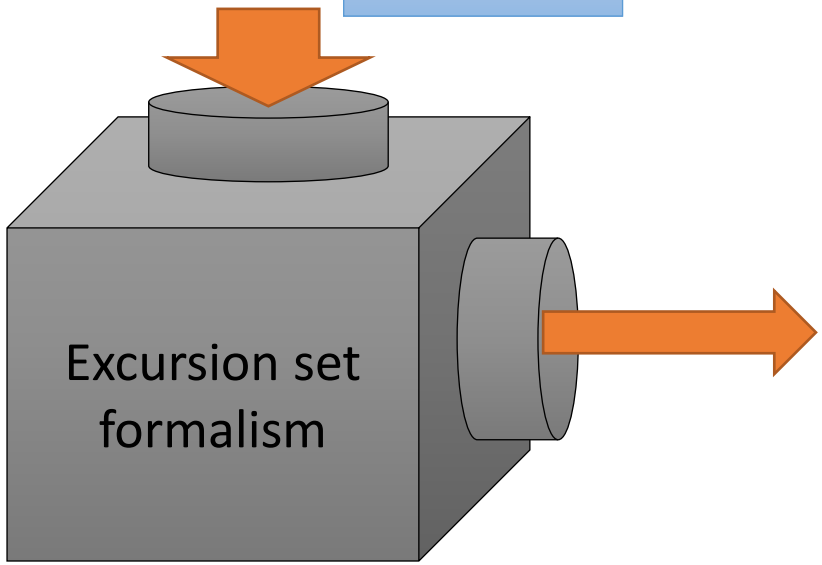
Lyman Limit Systems

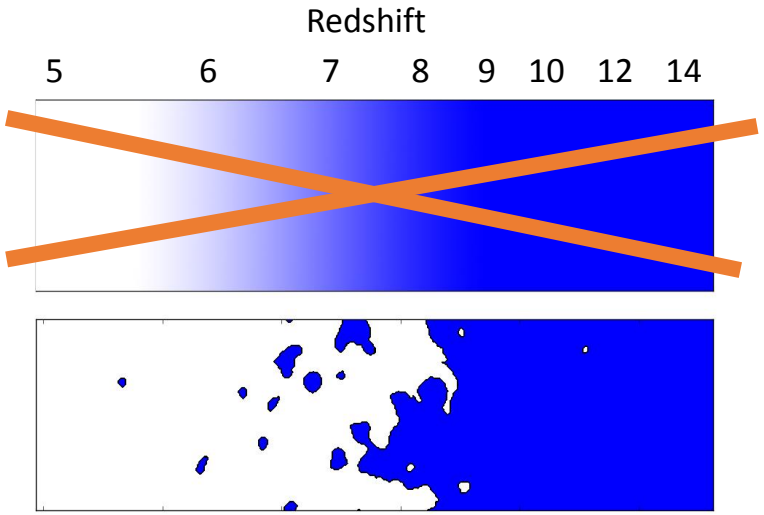
Luminosity function

Clumping factor

Escape fraction

Halo bias



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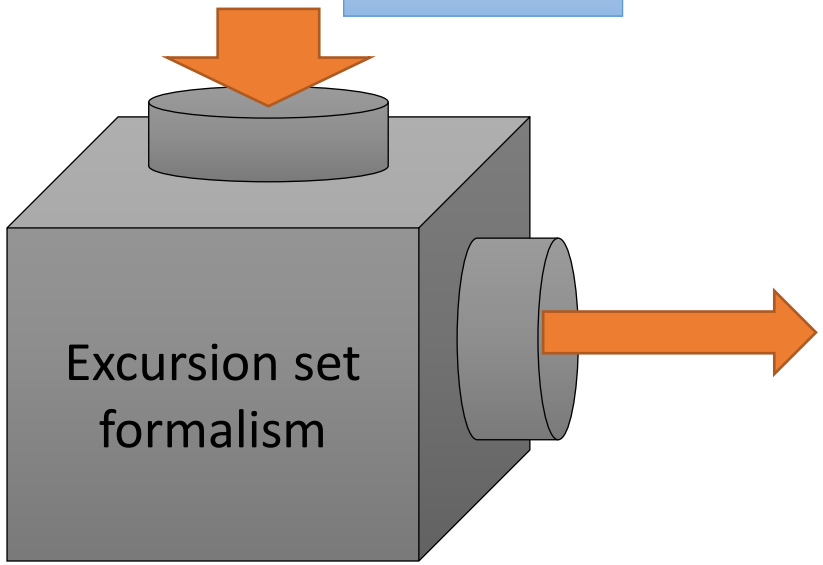
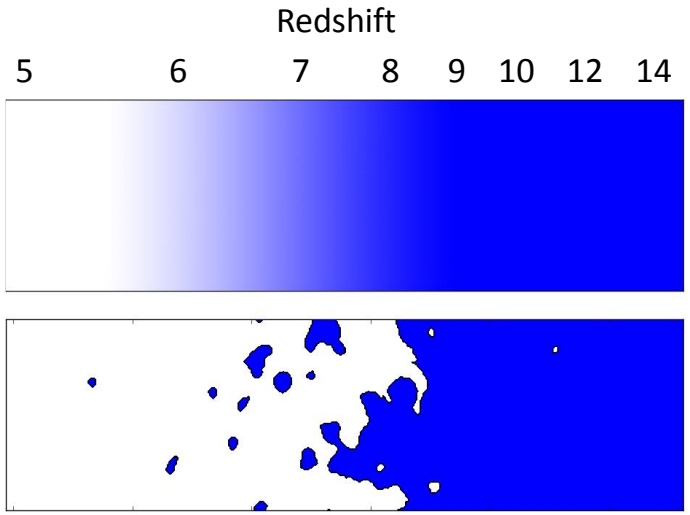
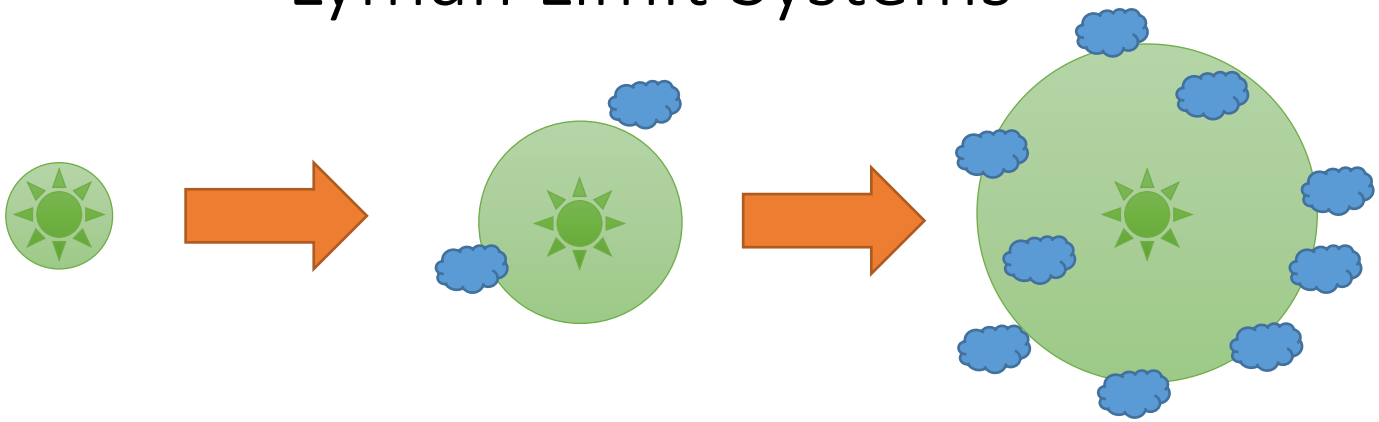
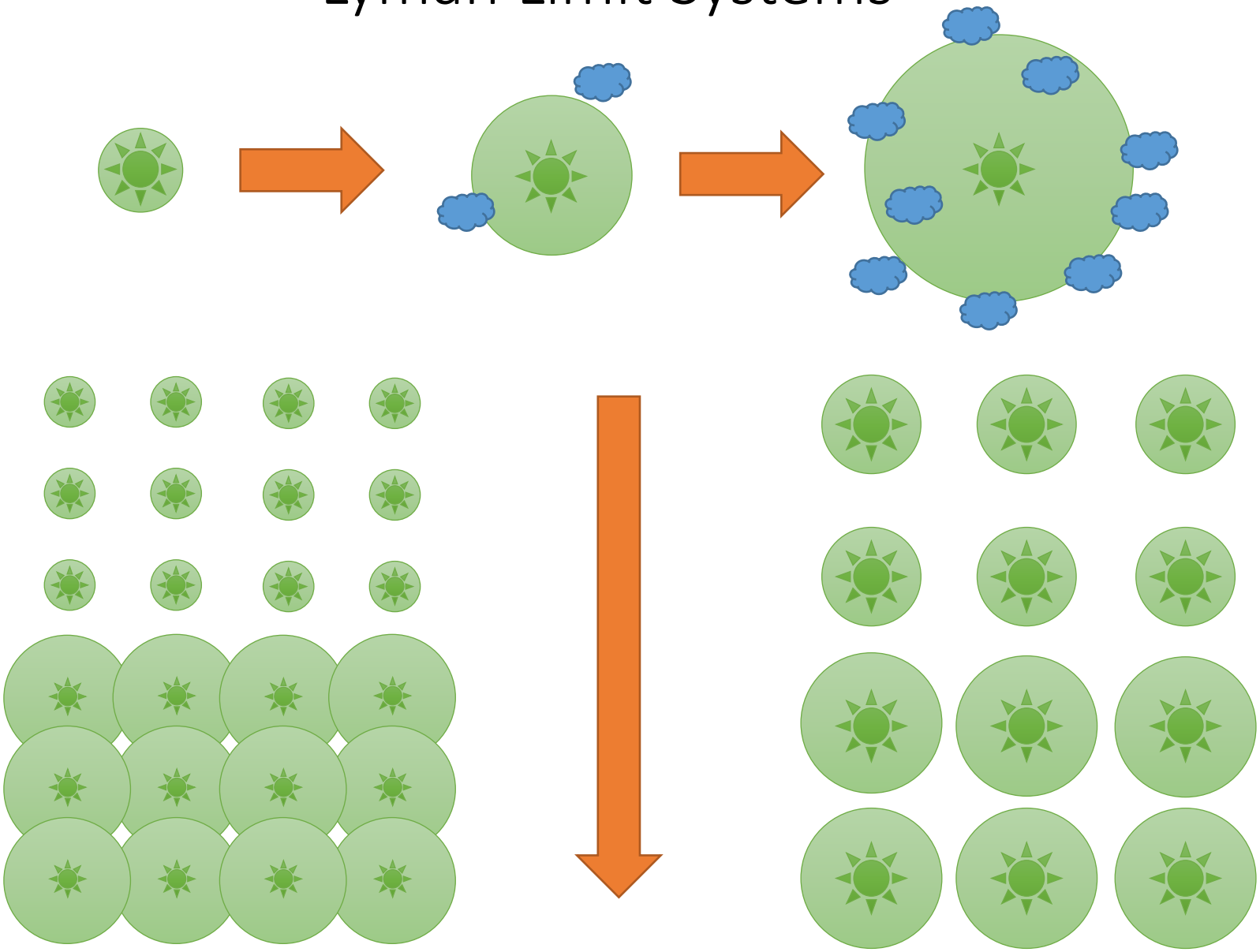


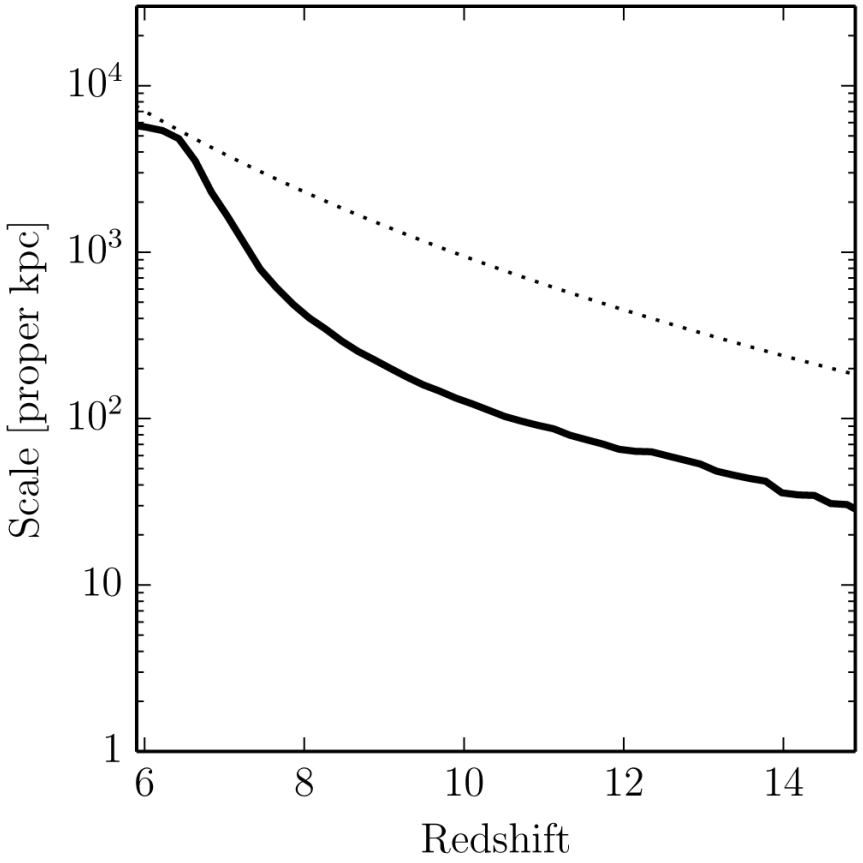
# Lyman Limit Systems

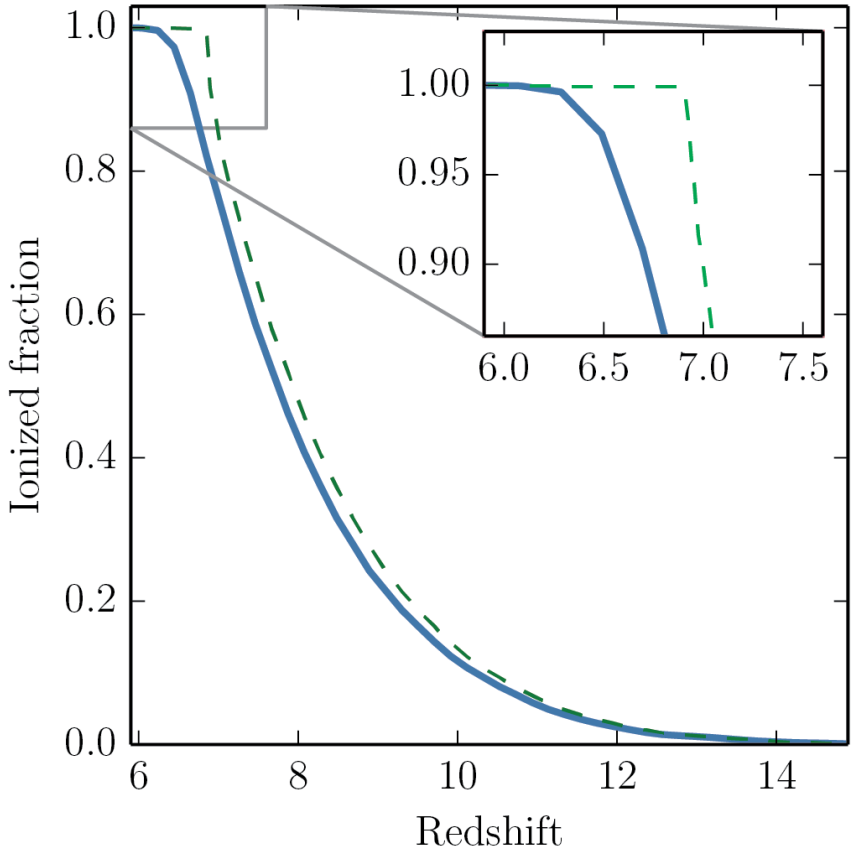


# Lyman Limit Systems



# Effect of Lyman Limit Systems



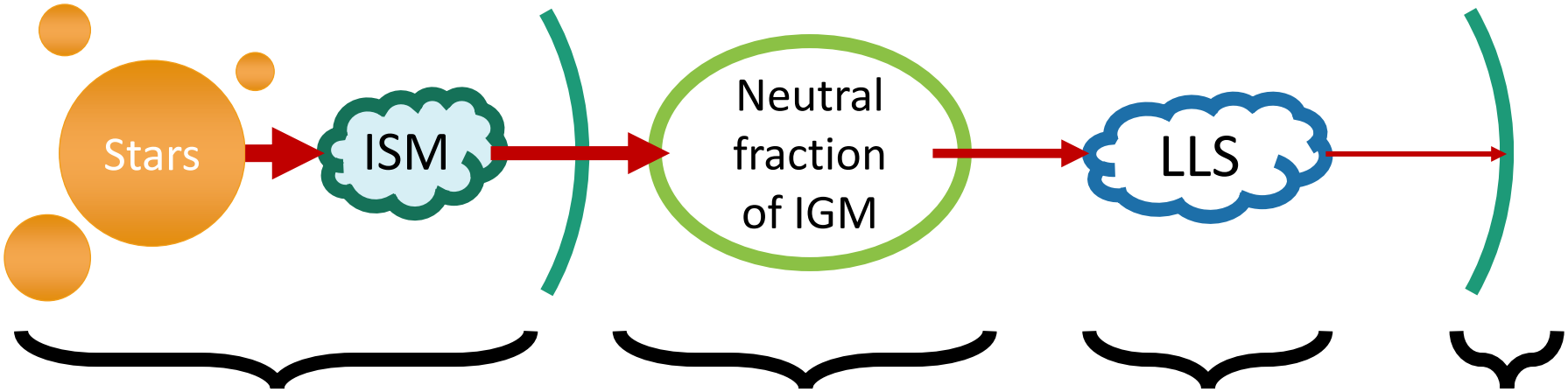

LLS mean free path

Characteristic distance to ionization front

Without LLS

Including LLS

# Absorption of ionizing photons:




Escape fraction of ionizing radiation from Galaxy

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# Clumping factor

- Number of ionizations per hydrogen atom:

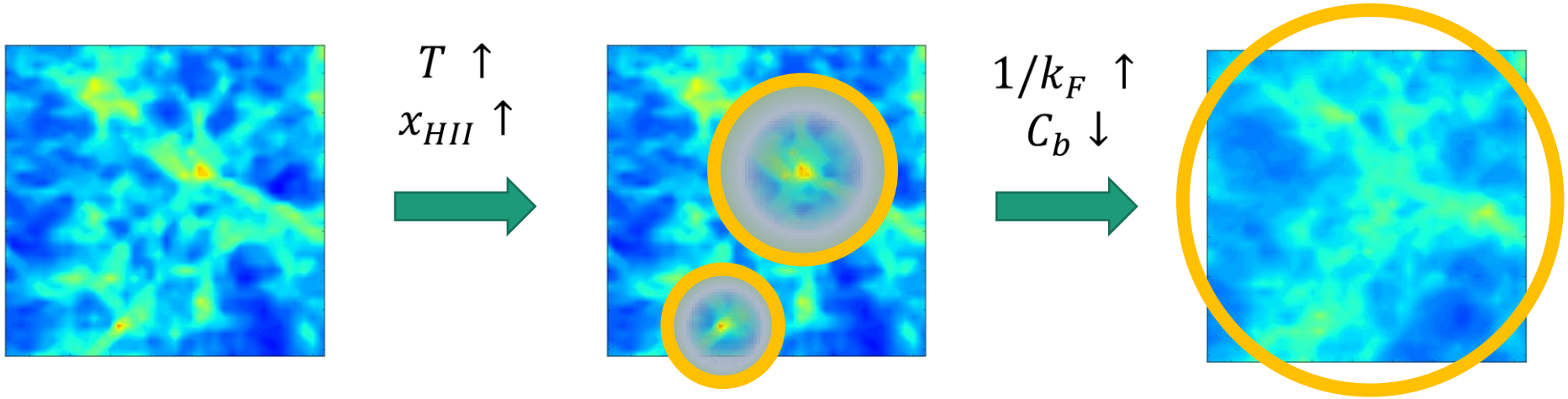
$$N_{\mathrm{i/H}}(t) = 1 + \frac{1}{N_{\mathrm{H}}} \int_0^t dt \int_V \alpha(T) n_e n_{\mathrm{H\,II}} dV,$$

- **Clumping factor**:

$$N_{\mathrm{i/H}}(t) = 1 + \int_0^t dt \alpha_{\mathrm{A}} C_{\mathrm{HII}}(t, V) \langle n_e \rangle_V \langle n_{\mathrm{H\,II}} \rangle_V$$

$$C_{\mathrm{HII}}(t, V) \equiv \frac{\langle \alpha(T) n_e n_{\mathrm{H\,II}} \rangle_V}{\alpha_{\mathrm{A}} \langle n_e \rangle_V \langle n_{\mathrm{H\,II}} \rangle_V}.$$

# Filtering scale → Clumping factor




Gnedin & Hui (1998)

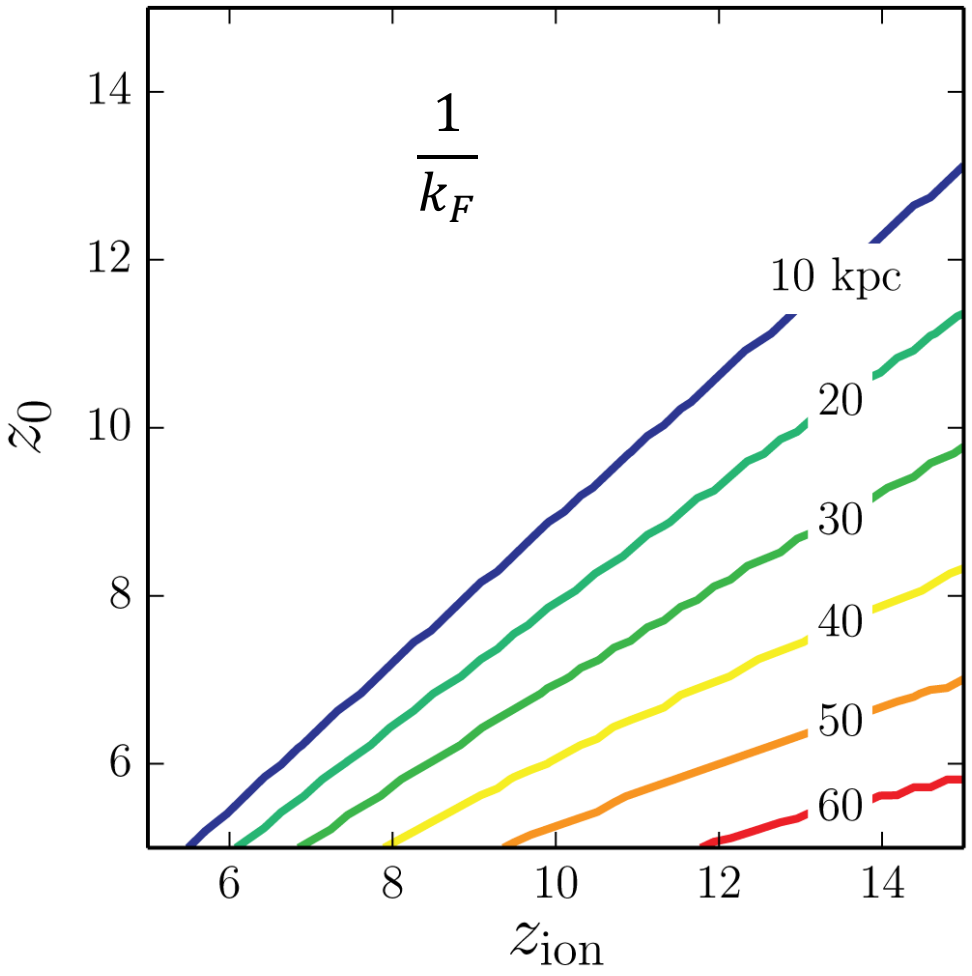
$T \cong 2.5 \times 10^4 K$

$T \sim (1+z)^{-0.9}$

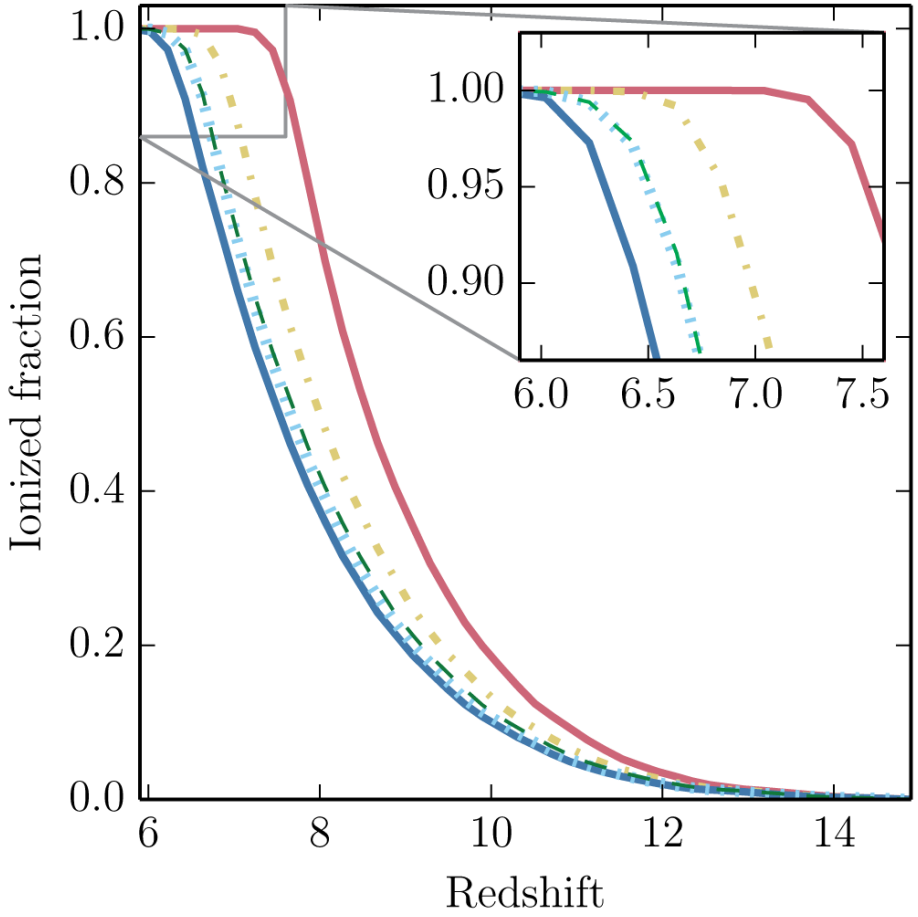
# Filtering scale

(baryon overdensity) $\frac{\delta_b}{\delta_X} = 1 - \frac{k^2}{k_F^2}$ (DM overdensity)

If we consider a region which was ionized at redshift $z_{ion}$, then at redshift $z_0$ the filtering scale will be →



# Local clumping factor

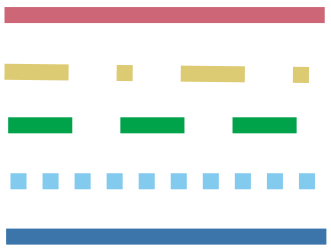



$$C_{\rm HII}^{\rm loc}(\bar{\delta},\sigma^2) = \frac{1}{\sqrt{2\pi(\sigma_\infty^2-\sigma^2)}}\int_{-\infty}^{+\infty} {\rm d}\delta\, e^{-\frac{(\delta-\bar{\delta})^2}{2(\sigma_\infty^2-\sigma^2)}} \times (1+\delta_{\rm HII})^2 ,$$

$k_F$ goes into $\sigma_\infty(k_F)$

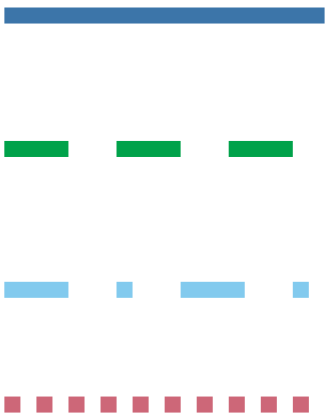
Clumping factor of HII regions:

$$C_{\rm HII}^{\rm loc}(\bar{\delta},\sigma^2) = (1+\bar{\delta})^2 + (\sigma_\infty^2-\sigma^2).$$



No recombinations
Uniform recombinations
Only $(1+\delta)^2$ term
Only $(\sigma_\infty^2-\sigma^2)$ term
Full model

# Global clumping factor

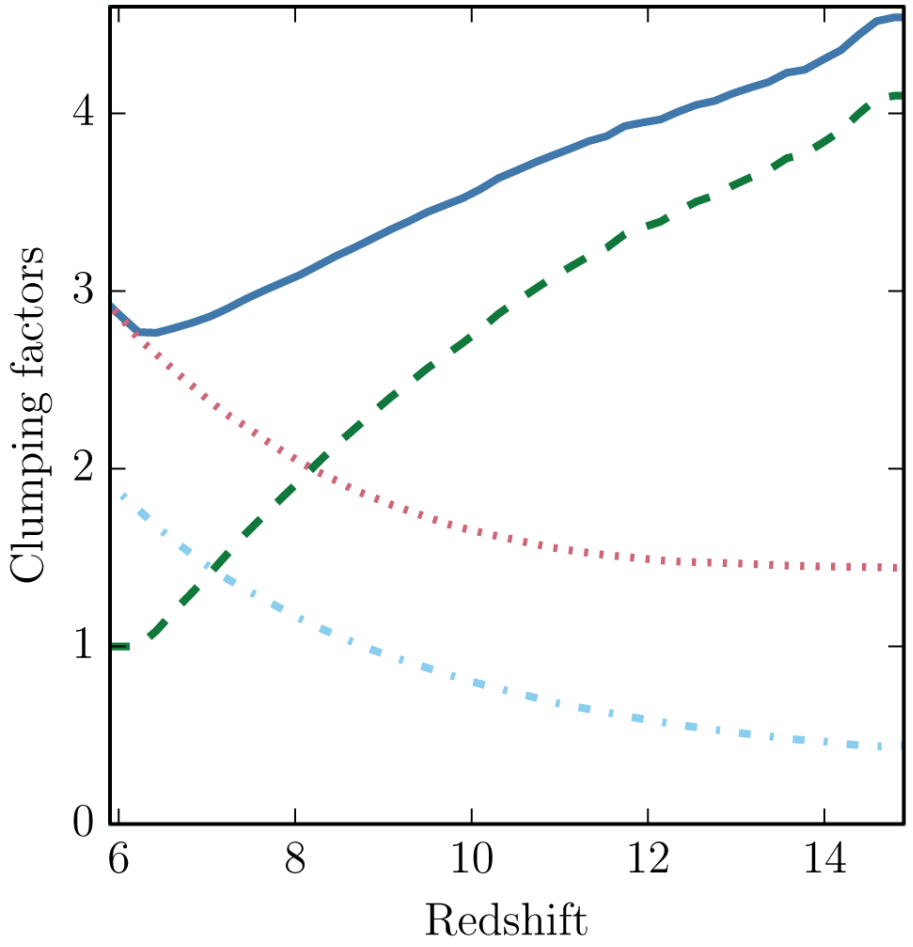


Average clumping factor in HII regions,

contribution from $(1+\delta)^2$ term,

contribution from $(\sigma_\infty^2 - \sigma^2)$ term,

Average clumping factor.



# Conclusions

- Analytic models allow to study effects connected with morphology of reionization,
- Lyman Limit Systems slows down the very end of reionization and makes it more gradual,
- Clumping factor is not uniform and depends on the history of reionization,
- Our analytic results for clumping factor can be also applied for post-reionization epoch.

Thank you for your attention!