Leibniz-Institut für Astrophysik Potsdam

AIP

Visibility of Lyman α emitters during the Epoch of Reionization

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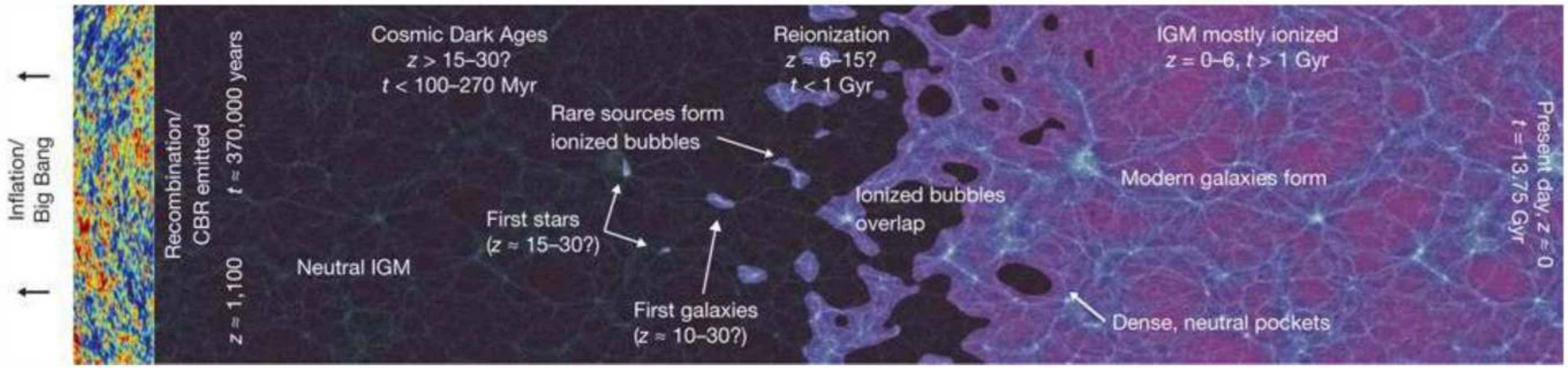
Epoch of Reionization (EoR)



BE Robertson et al. Nature 468, 49-55 (2010)

- When did reionization start and when did it end?

Fan et al. 2006; Barkana & Loeb 2001; Ciardi & Ferrara 2005

- How does the topology of the ionized regions look like? Inside-out? Minihalos?

McQuinn et al. 2007; Finlator et al. 2009; Kim et al. 2013; Iliev et al. 2012; Ahn et al. 2012

- What are the sources for ionizing photons? Escape fraction of ionizing photons?

Meiksin et al. 2005; Bolton & Haehnelt 2007; Gnedin et al. 2008; Wise & Cen 2009; Razoumov & Sommer-Larsen 2010; Ferrara & Loeb 2013

Outline

- Epoch of Reionization
- Probing reionization using Lyman Alpha Emitters (LAEs)
- Constraints on reionization, escape fraction of ionizing photons and dust using LAEs
  - Lyα luminosity
  - Angular correlation function (ACF)

Lyman Alpha Emitters (LAEs)

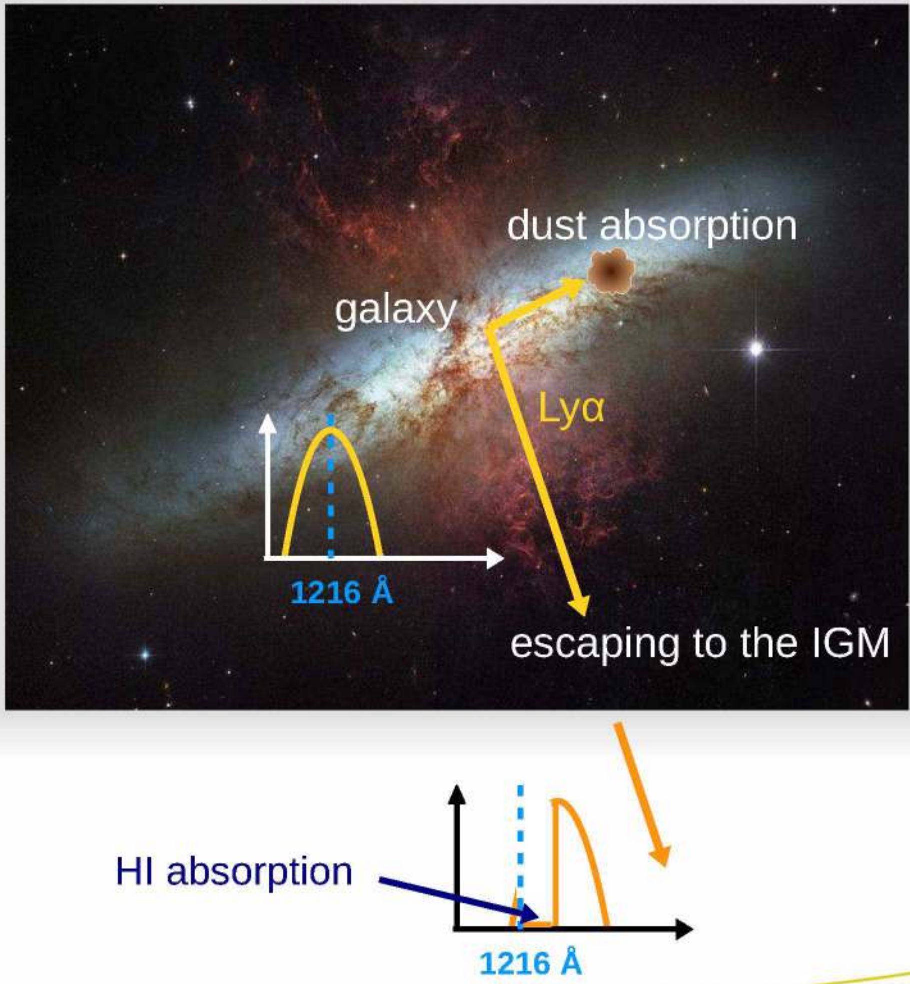
Lyα radiation is...

In the **galaxy**:
- produced by H recombination radiation
- absorbed by dust
- escaping from the galaxy into the IGM

In the **IGM**:
- absorbed by HI
- redshifted

LAEs can be used as tracers of **reionization**

Image credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)



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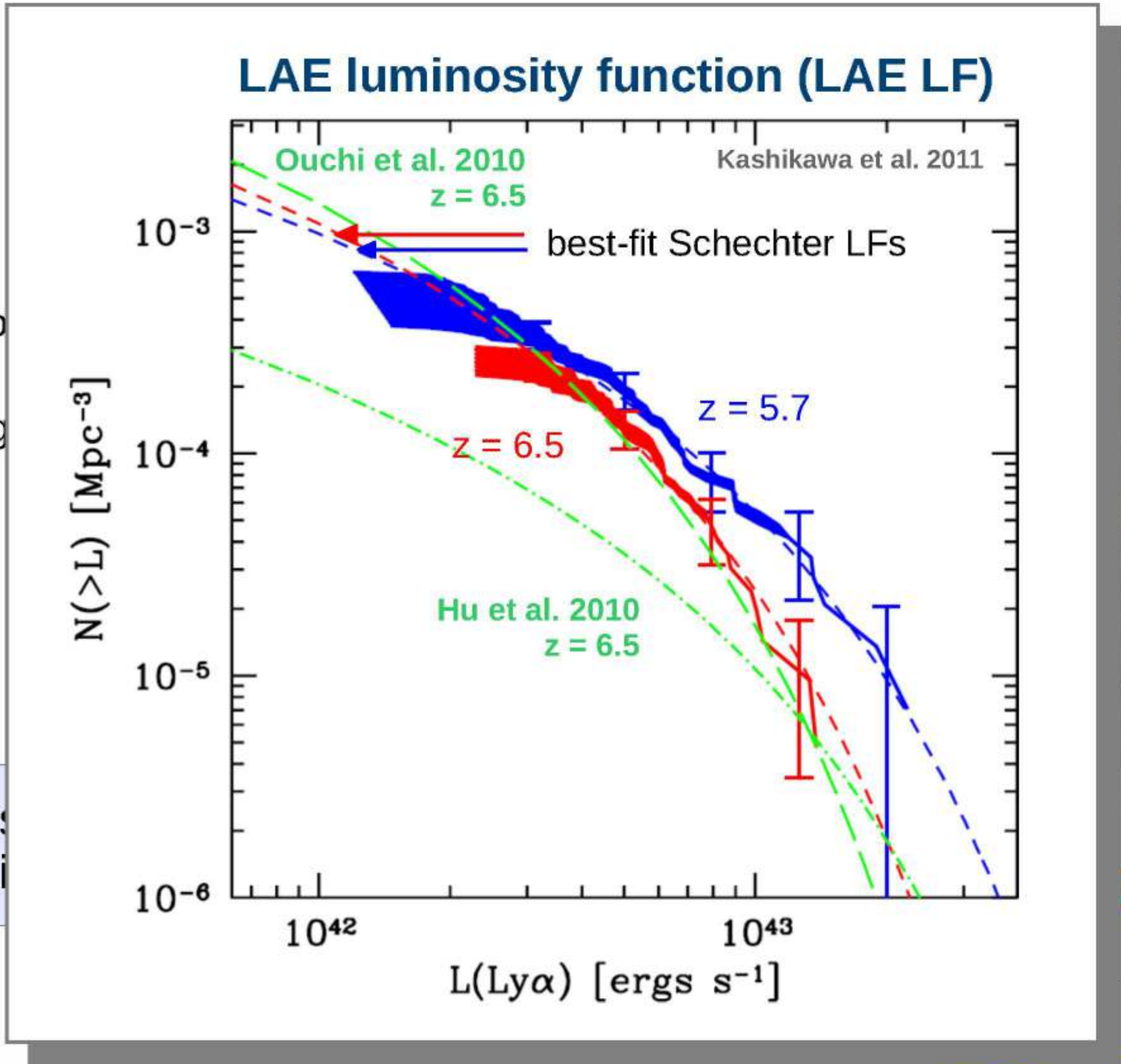
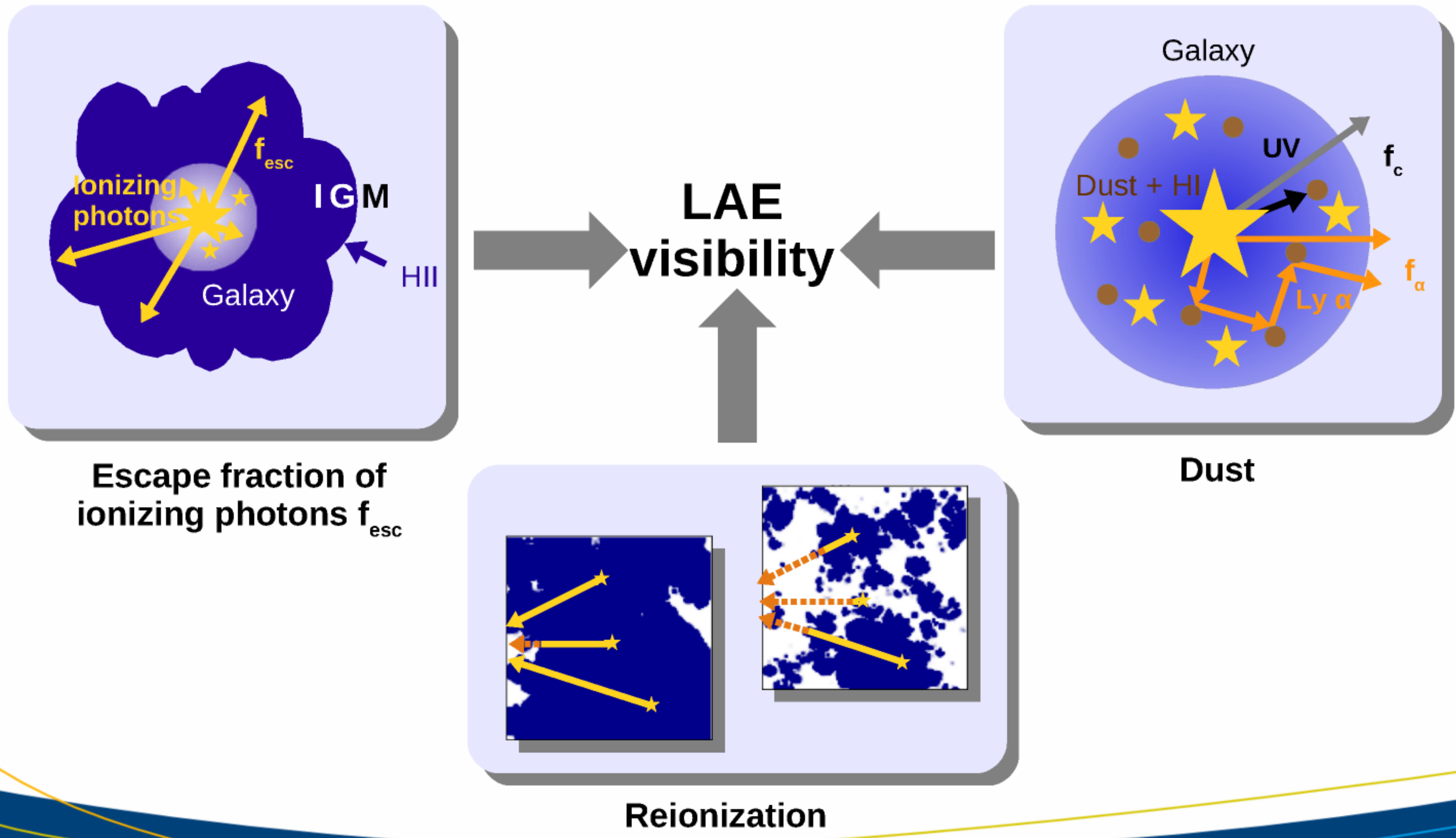
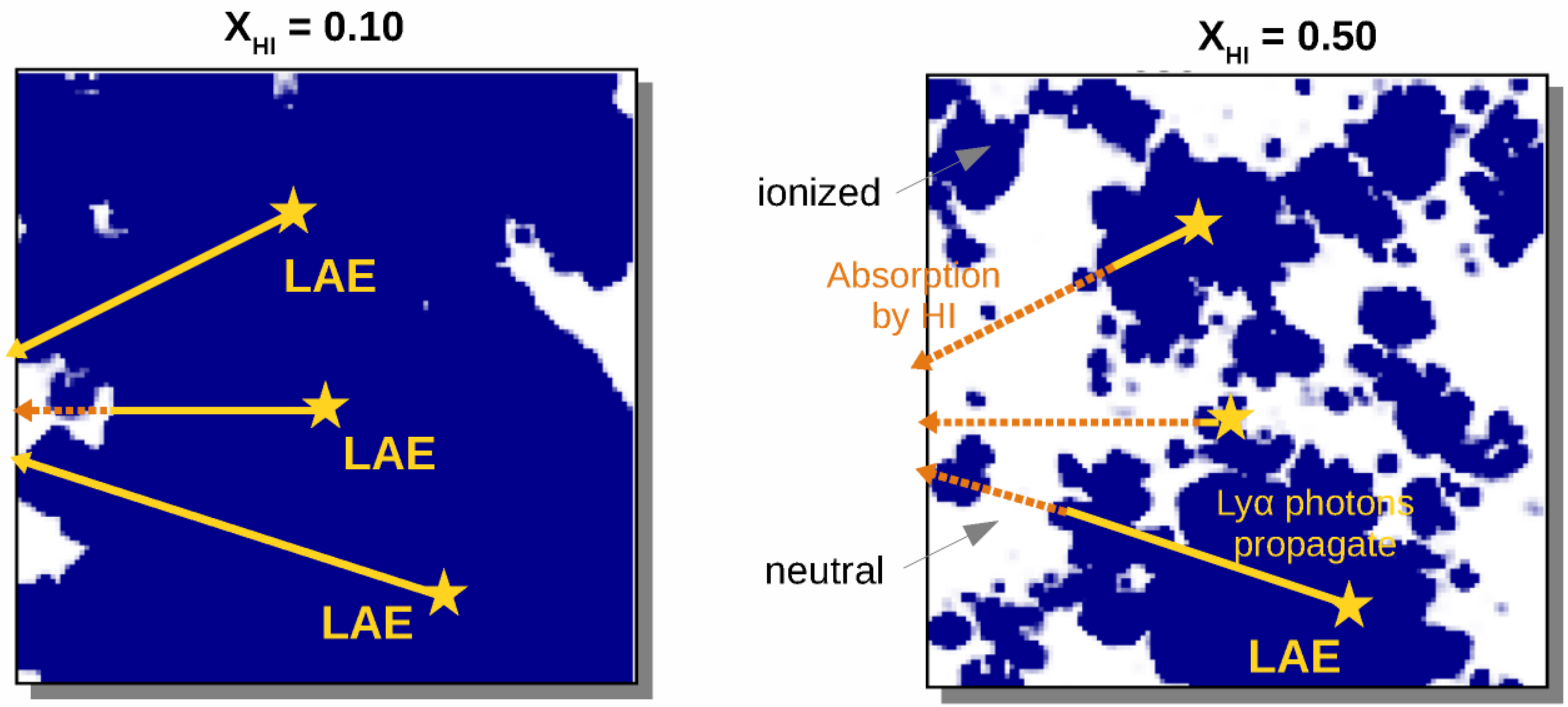
LAEs can be us
reioni



What influences the visibility of Lyman α emitters (LAEs)?



LAEs as tracers of reionization?



Fraction T_α of the emitted Lyα photons is transmitted through the IGM.
→ Number of observed LAEs depends on the global ionization fraction.

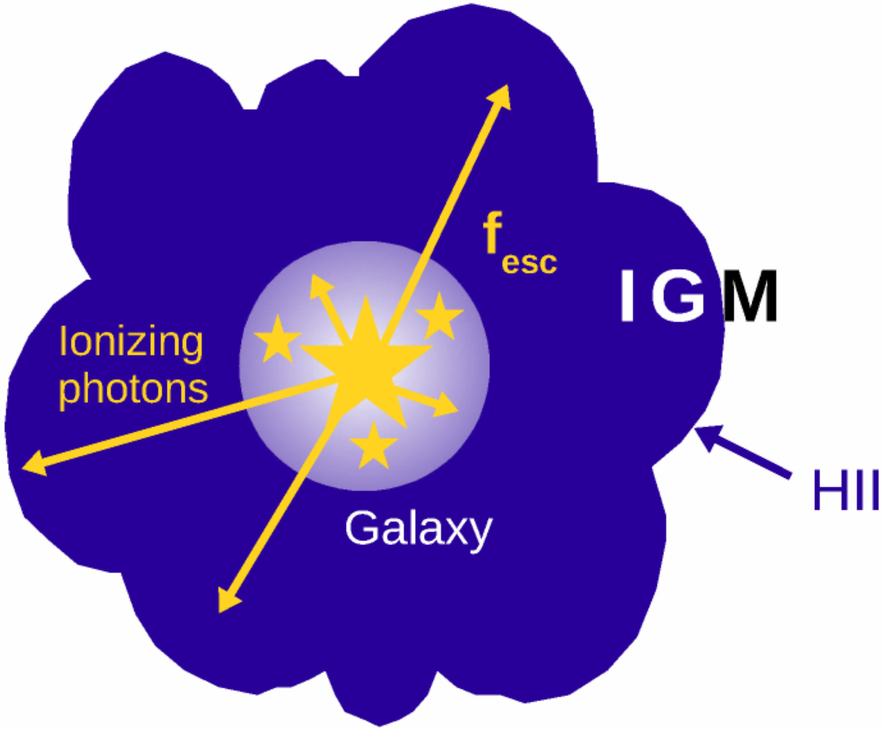
Escape fraction of ionizing photons f_{esc}

Inside the galaxy:

Ionizing photons are absorbed and Lyα is emitted (recombination radiation)

Outside the galaxy:

A fraction of ionizing photons f_{esc} leaves the galaxy and can ionize the IGM

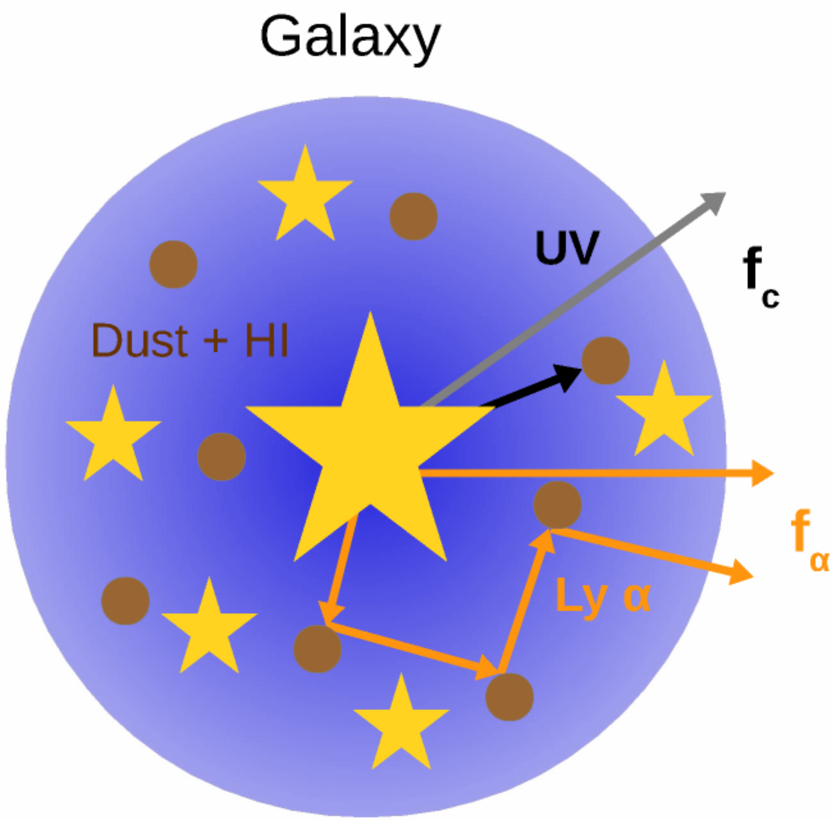


Effects of dust on UV and Lyα?

Dust is distributed within the galaxy

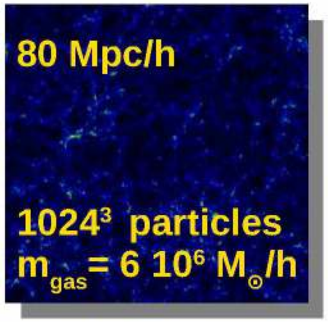
Lyα:
scattering and absorption
→ fraction of Lyα photons escape from the galaxy $\mathbf{f_\alpha}$

UV:
absorption
→ fraction of continuum UV photons escapes from the galaxy $\mathbf{f_c}$



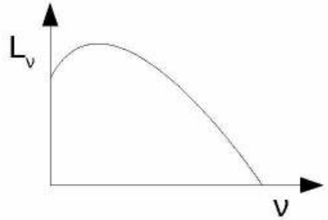
LBG = Lyman Break Galaxy
ACF = angular correlation function

Simulations & Outline



Hydrodynamical simulation with star formation

Identify galaxies:
$M_{halo} > 10^9\ M_\odot$
$N_{star} \geq 10$

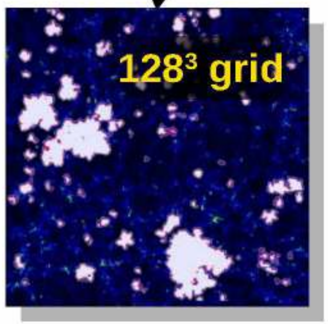


Generate composite spectra of galaxies with STARBURST99

C. Howk (JHU), B. Savage (U. Wisconsin), N. A. Sharp (NOAO)/WIYN/NOAO/NSF

Apply dust model & calculate f_c

Lyα luminosity



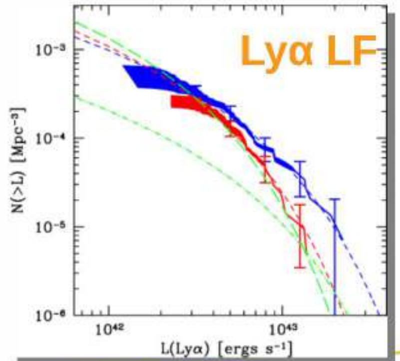
Radiative transfer simulation for different f_{esc} values

Compute Lyα transmissions T_α for different $\langle \chi_{HI} \rangle$

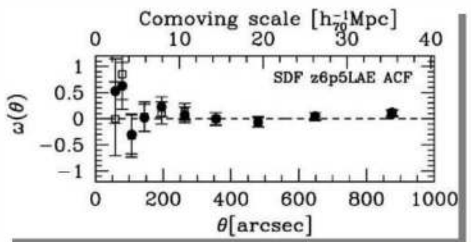
Identify
Lyman α emitter (LAEs)

Compute Lyα escape fraction
$f_\alpha = p\ f_c$

LBG UV LFs
at z=6,7,8



Lyα ACF

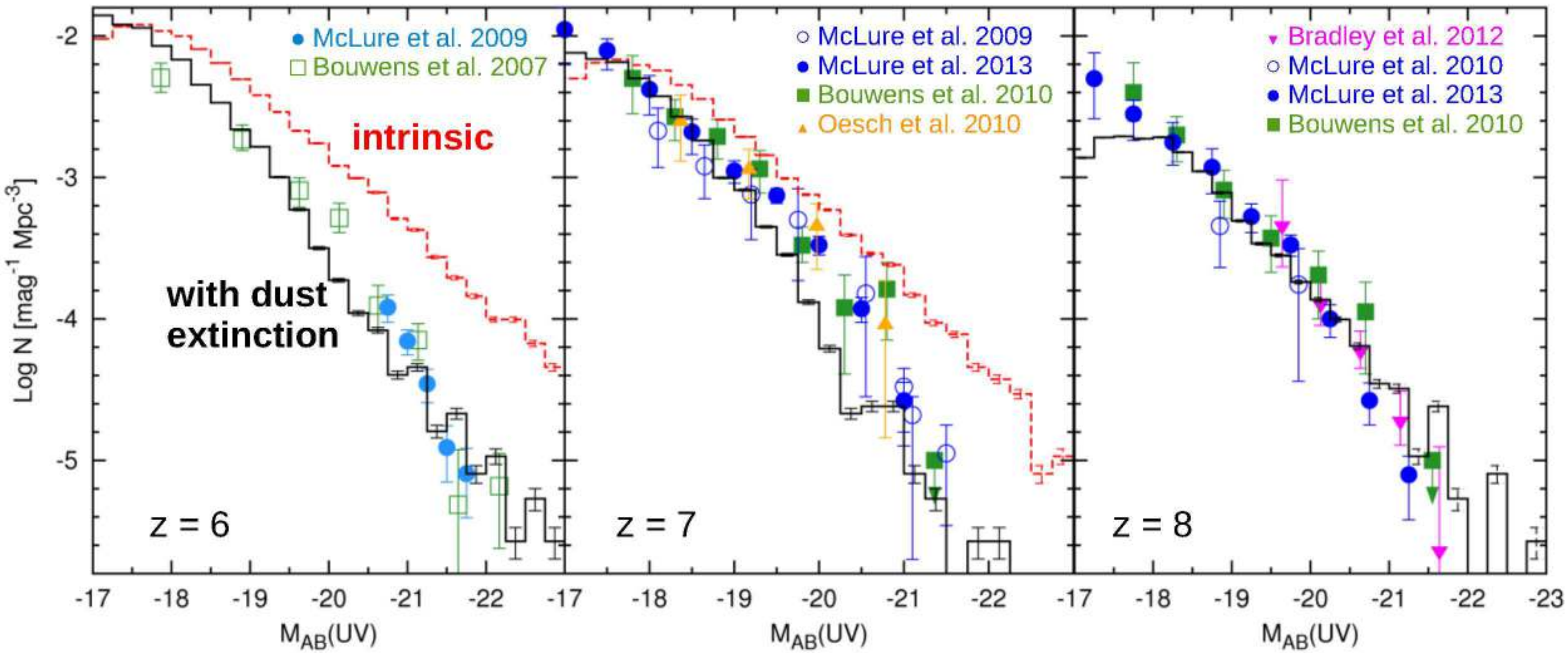


Lyman Break Galaxies (LBGs) UV luminosity functions

Model spectra of galaxies with *STARBURST99* spectra
Leitherer et al. 1999

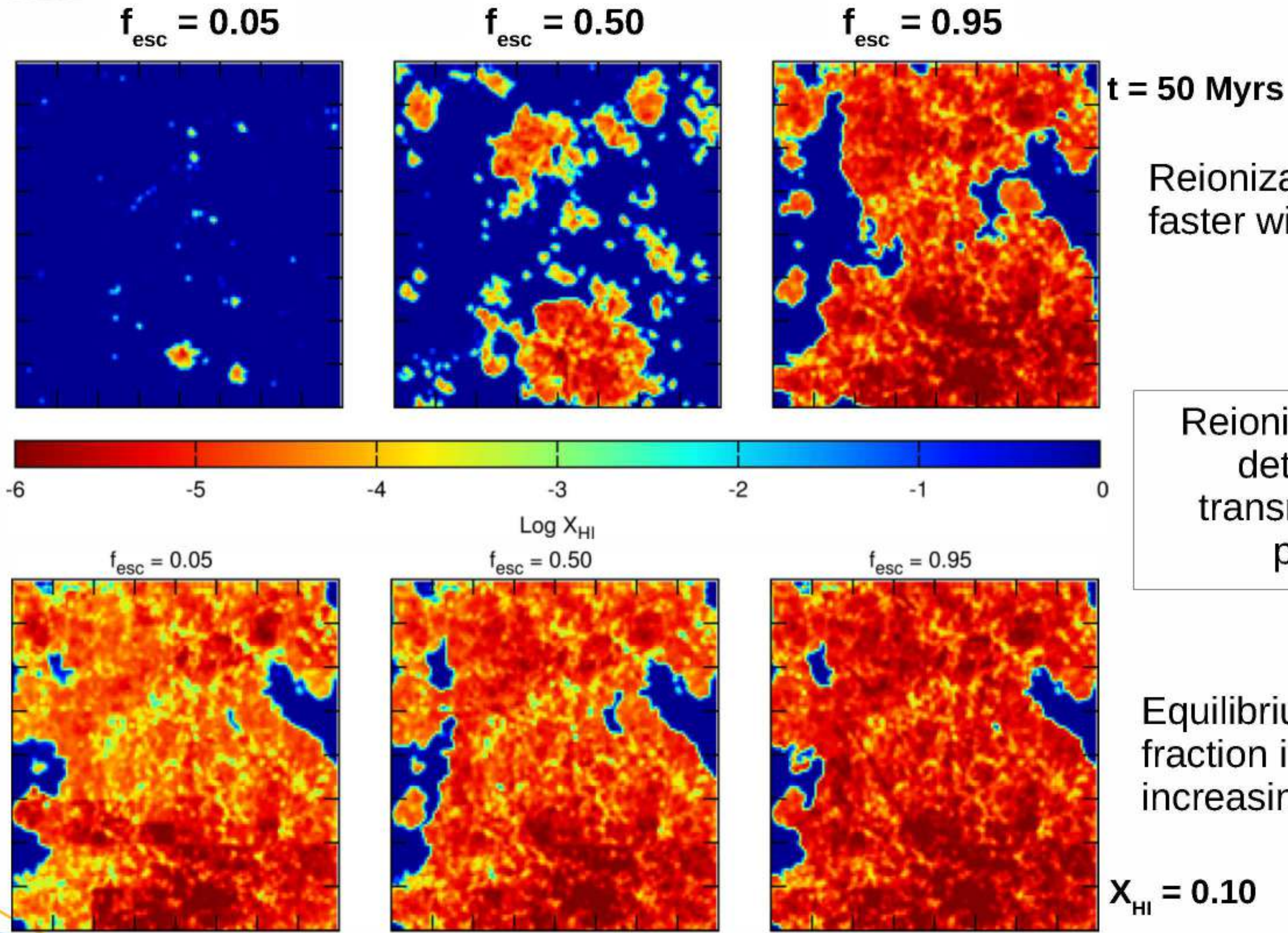
→ Compute dust content & extinction f_c for each galaxy
Dayal et al. 2010

→ Identify galaxies with M_{UV}<-17 as LBGs



Simulating LAEs: Reionizing the universe with pCRASH

Ciardi et al. 2001
Maselli et al. 2003, 2009
Partl et al. 2011



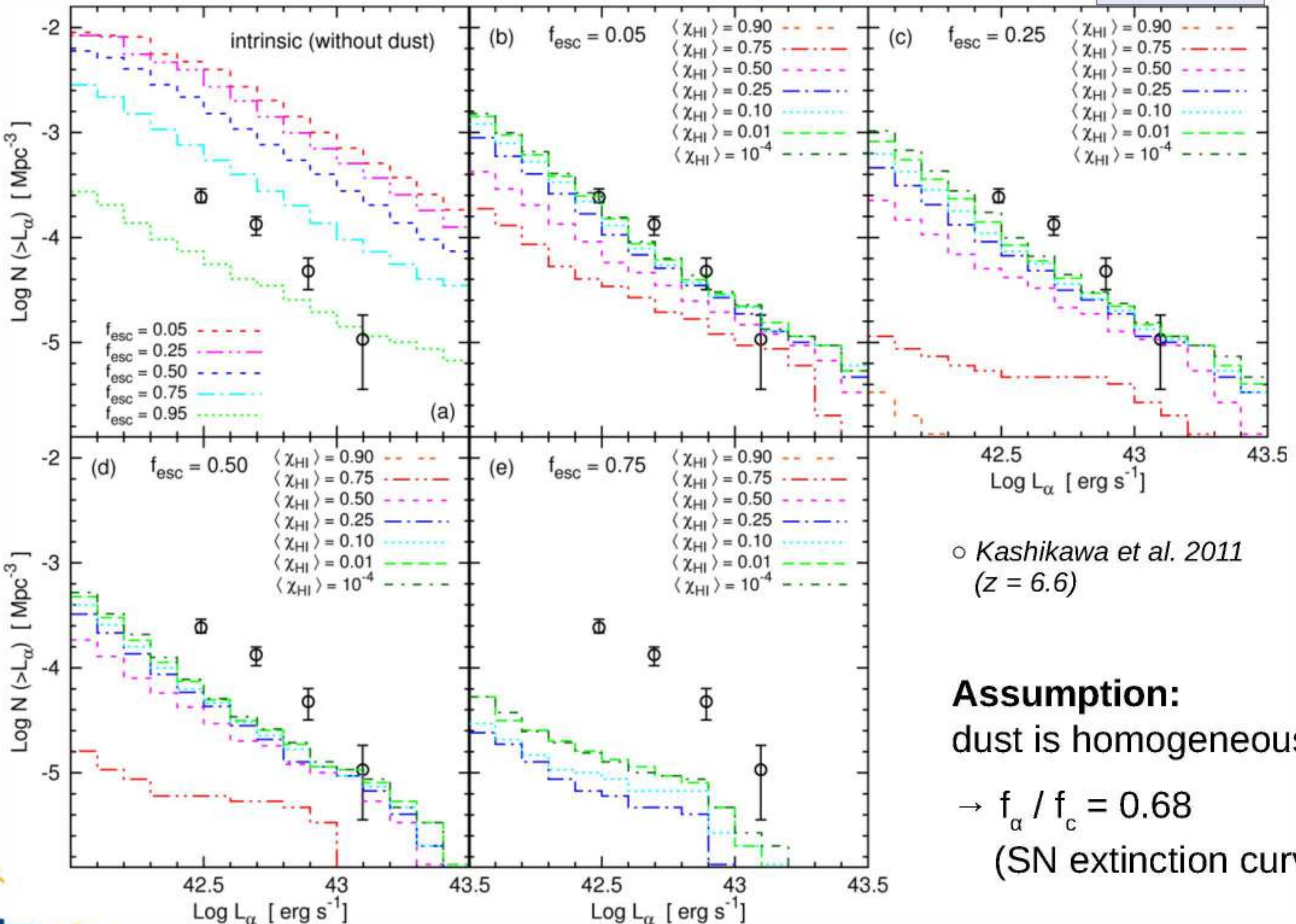
Reionization proceeds faster with increasing f_{esc}

Reionization topology determines the transmission of Lyα photons T_α

Equilibrium ionization fraction increases with increasing f_{esc}

Simulating LAEs: Identifying LAEs for homogeneous dust

z ≃ 6.6



○ *Kashikawa et al. 2011 (z = 6.6)*

Intrinsic Lyα luminosity:

$L_\alpha^{int} = 2/3\ Q\ (1 - f_{esc})\ h\nu_\alpha$

Observed Lyα luminosity:

$L_\alpha^{obs} = f_\alpha\ T_\alpha\ L_\alpha^{int}$

dust extinction (f_α)

transmission through the IGM (T_α)

LAE selection criteria:

$L_\alpha^{obs} \geq 10^{42}$ erg s^{-1} & EW>20Å

Assumption:

dust is homogeneously distributed

→ $f_\alpha / f_c = 0.68$

(SN extinction curve)

Simulating LAEs: Constraints from Lyα LF allowing clumped dust

$z \simeq 6.6$

○ *Kashikawa et al. 2011 (z = 6.6)*

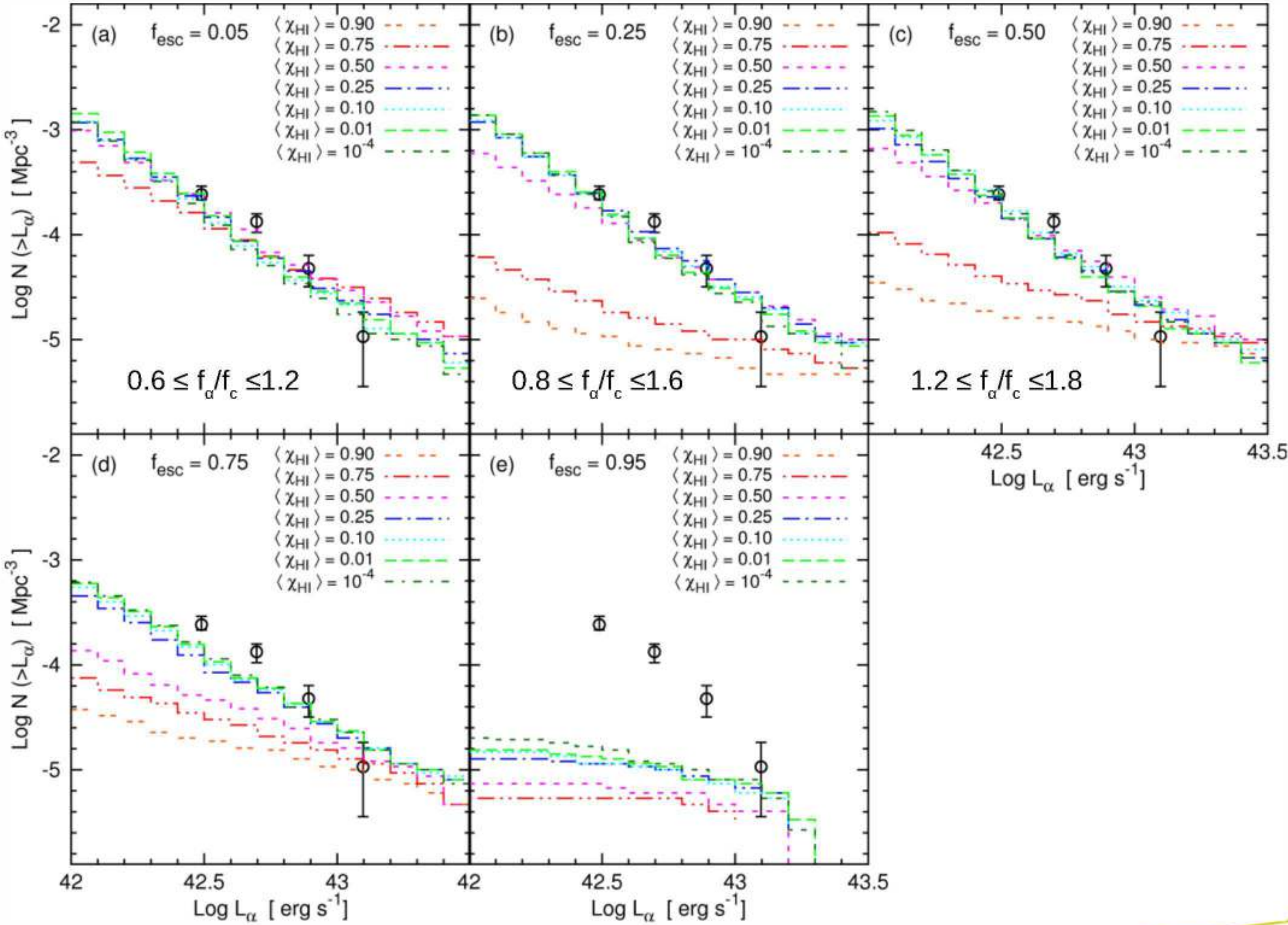
Assumption:
clumped dust

→ $f_\alpha / f_c \neq 0.68$

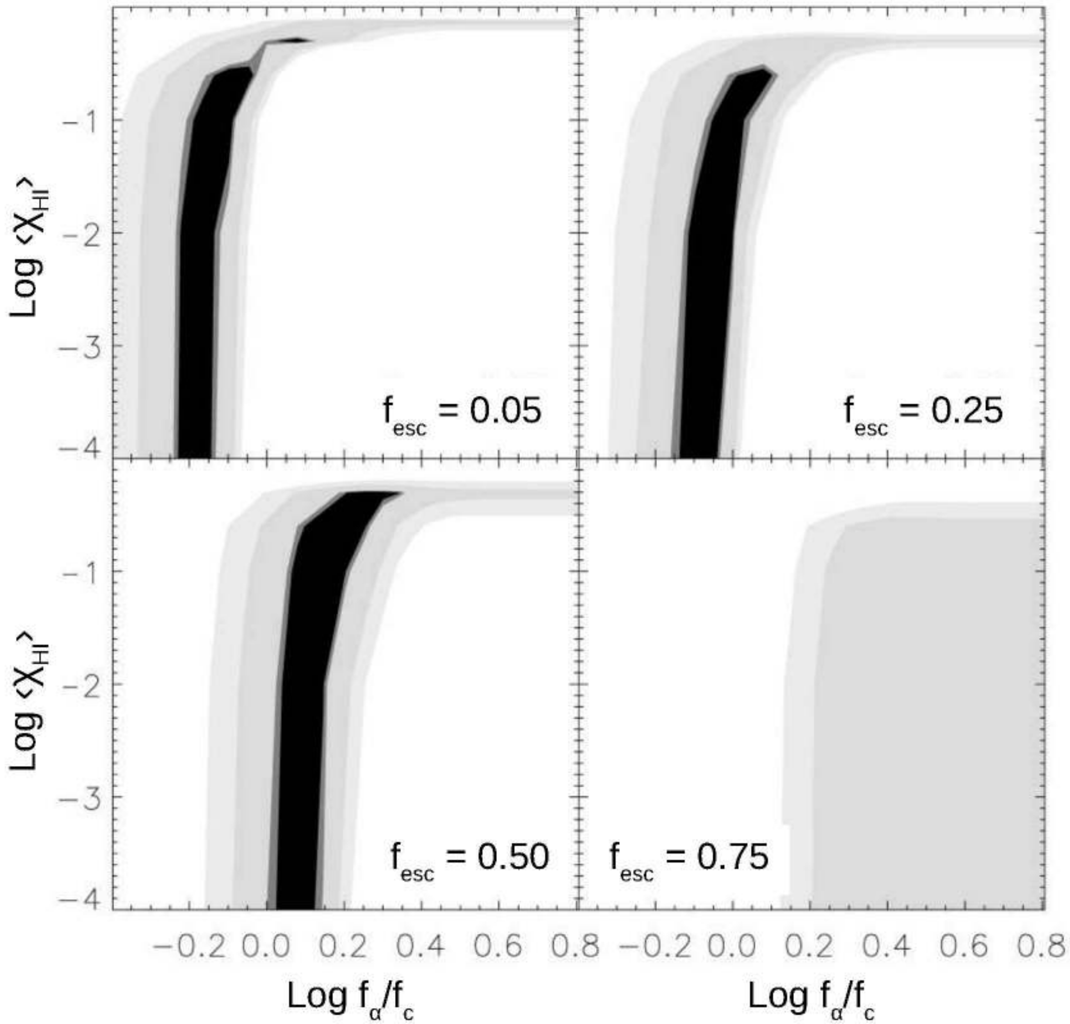
Effect of f_{esc} can be compensated by f_α/f_c

Saturation limit: $f_\alpha \leq 1$

Observations by *Kashikawa et al. 2011* can be reproduced for Lyα LF and the respective UV LF



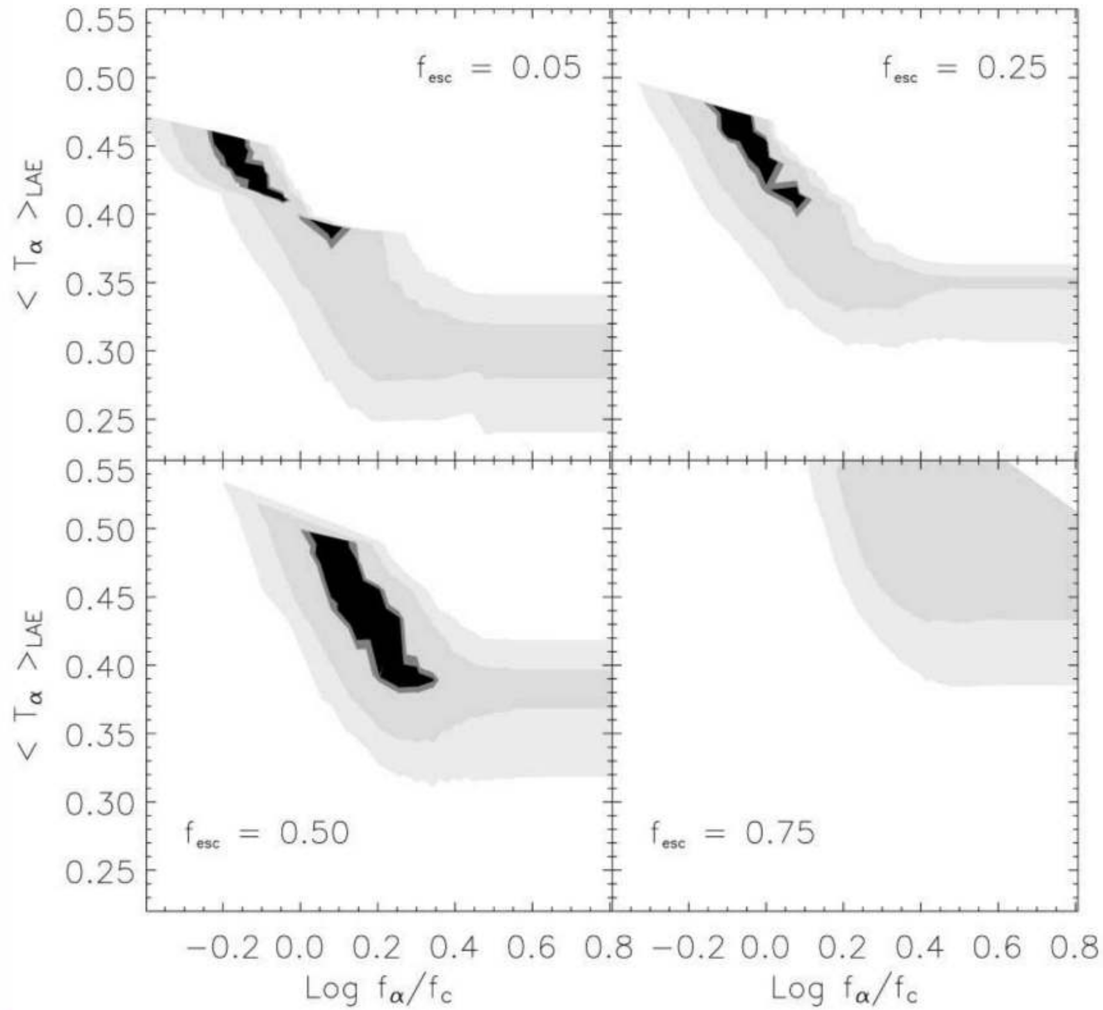
Constraints from Lyα LF at z≃6.6



1-5σ deviations from observations by *Kashikawa et al. 2011*

3D degeneracy between f_{esc}, ‹χ_{HI}› and f_α / f_c

Constraints from Lyα LF at z≃6.6



1-5σ deviations from observations by *Kashikawa et al. 2011*

3D degeneracy between f_{esc}, $\langle T_\alpha \rangle_{LAE}$ and f_α / f_c

Constraints:

$\langle \chi_{HI} \rangle \leq$ **0.50** or **0.38** $\leq \langle T_\alpha \rangle \leq$ **0.50**

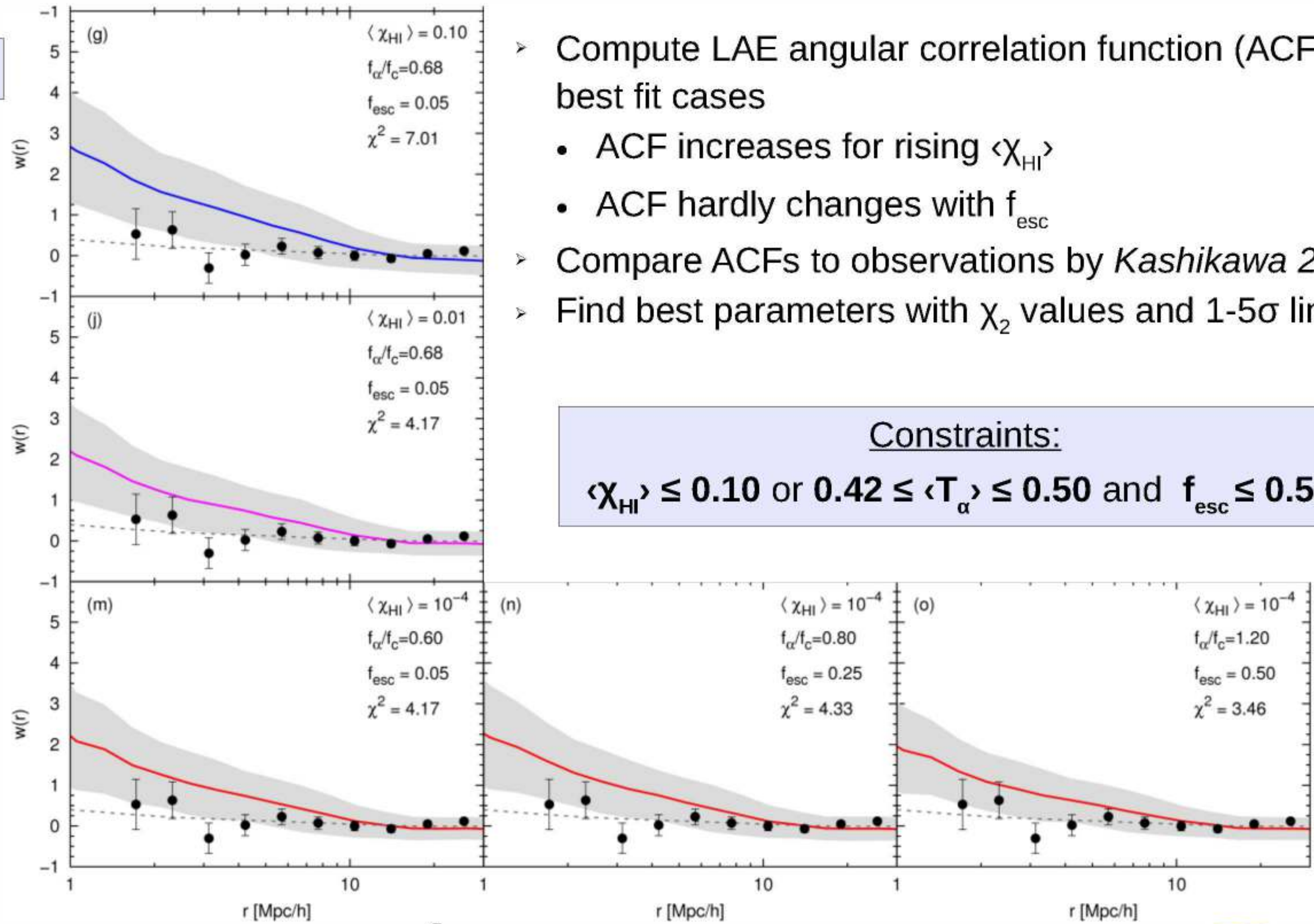
and $f_{esc} \leq$ **0.50**

and f_α/f_c = **0.6-1.8**

(f_{esc} is compensated by f_α)

Constraints from LAE clustering

$z \simeq 6.6$



$\langle \chi_{HI} \rangle$ ↑

f_{esc} →

- Compute LAE angular correlation function (ACF) for best fit cases
  - ACF increases for rising $\langle \chi_{HI} \rangle$
  - ACF hardly changes with f_{esc}
- Compare ACFs to observations by *Kashikawa 2006*
- Find best parameters with χ_2 values and 1-5σ limits

<u>Constraints:</u>

$\langle \chi_{HI} \rangle \leq 0.10$ or **$0.42 \leq \langle T_\alpha \rangle \leq 0.50$** and **$f_{esc} \leq 0.50$**

Conclusions

Constraints by Lyα LF:

Observations at z~6.6 can be reconciled for $\langle\chi_{HI}\rangle \leq 0.5$ or $\langle T_\alpha\rangle = 0.38\text{-}0.50$ and $f_{esc} \leq 0.5$ and $f_\alpha/f_c = 0.6\text{-}1.8$

Constraints by LAE ACF:

Observed ACF at z~6.6 can be reconciled for $\langle\chi_{HI}\rangle \leq 0.1$ and $f_{esc} \leq 0.5$ and $f_\alpha/f_c = 0.6\text{-}1$

***Three-dimensional degeneracy* between f_{esc}, $\langle\chi_{HI}\rangle$ or $\langle T_\alpha\rangle$ and f_α/f_c**

- LAE LF evolution cannot be solely attributed to reionization since Lyα visibility also depends on the ionizing photon escape fraction and dust
- LAEs are not only tracers of reionization but also of the ionizing photon escape fraction and of the dust distribution in the ISM