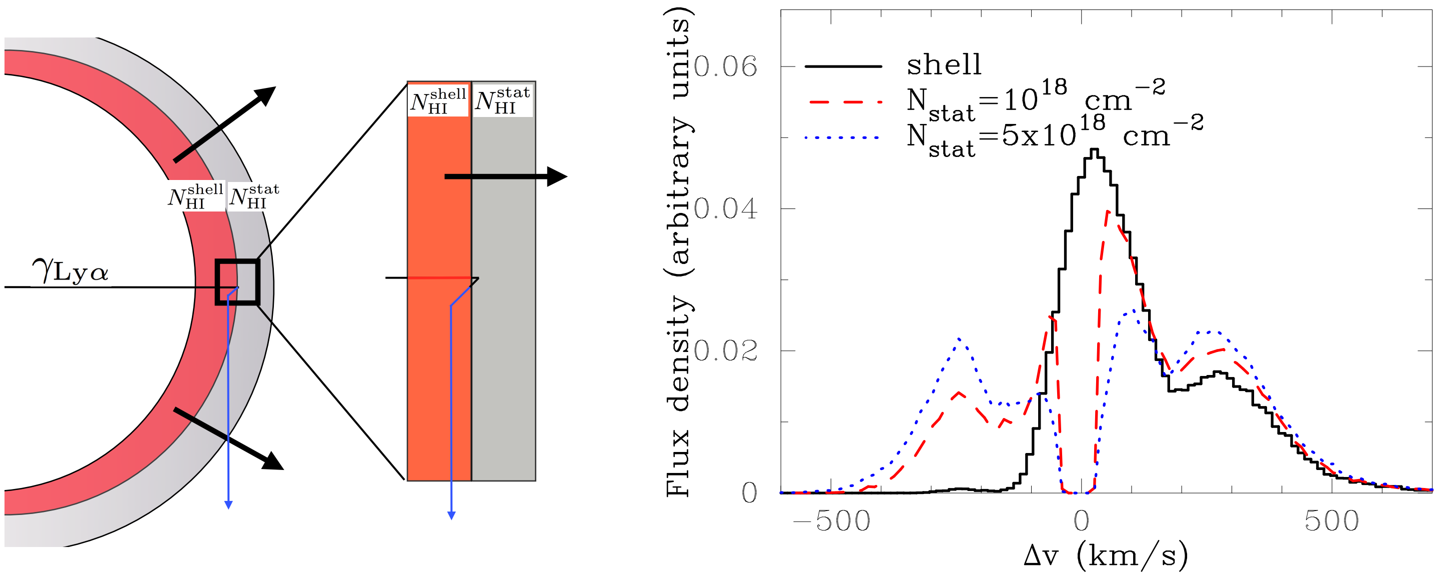
Constraints on Reionization from Lyα Emitting Galaxies

Important

Mark Dijkstra

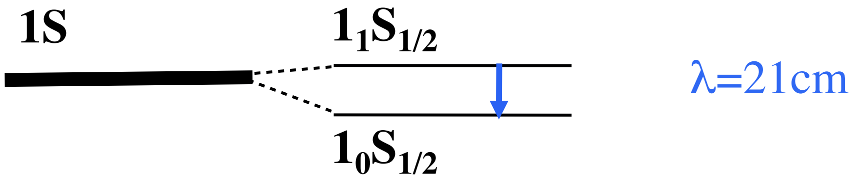
Institute of Theoretical Astrophysics, University of Oslo

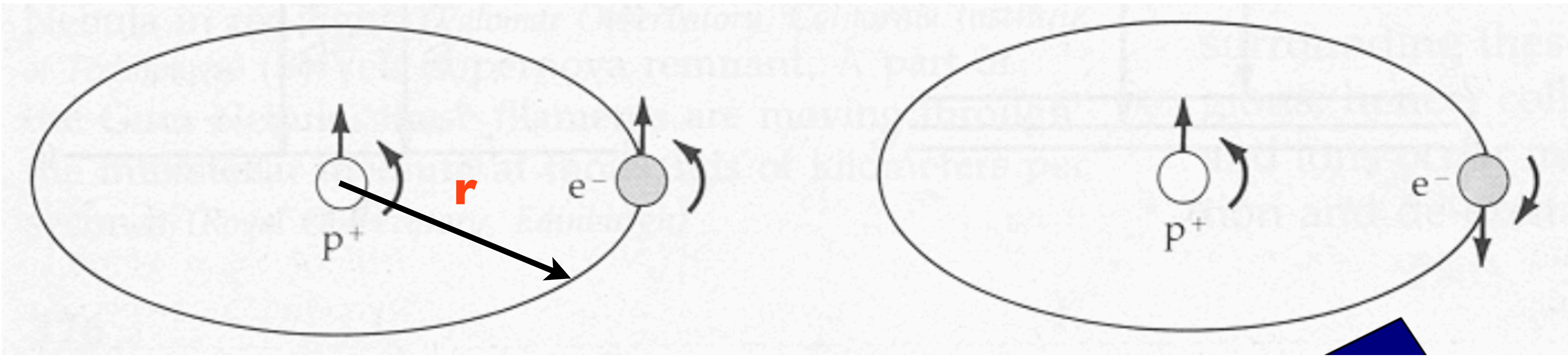


Prologue: The Absurd QM of the 21cm Line

thanks to D. Spiegel

The 21-cm transition of atomic hydrogen connects the two **hyperfine** levels of atomic hydrogen in its ground state.





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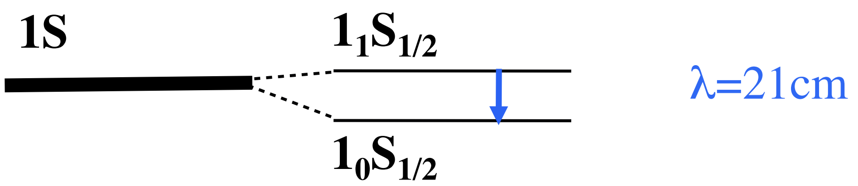
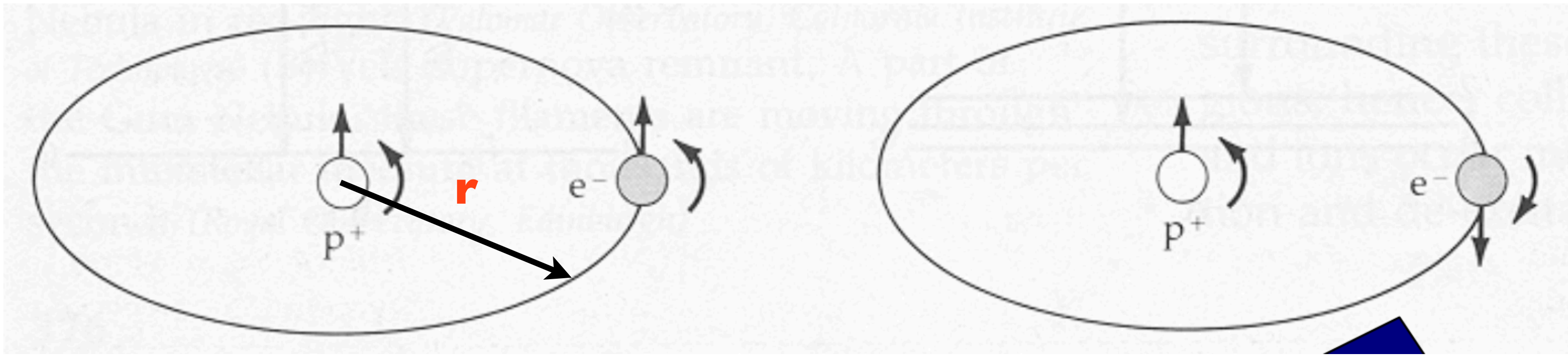


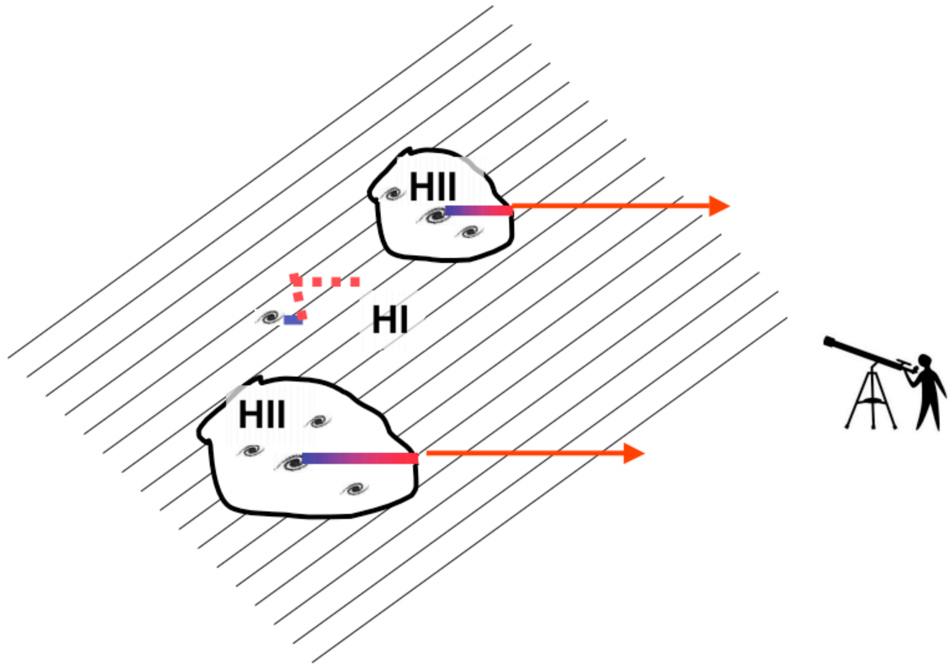


In quantum mechanics, the difference in energy between these two states is equal to **zero for all r > 0,** where r denotes the separation between electron and proton.

Non-zero contribution comes **entirely** from the unlikely event that r=0.

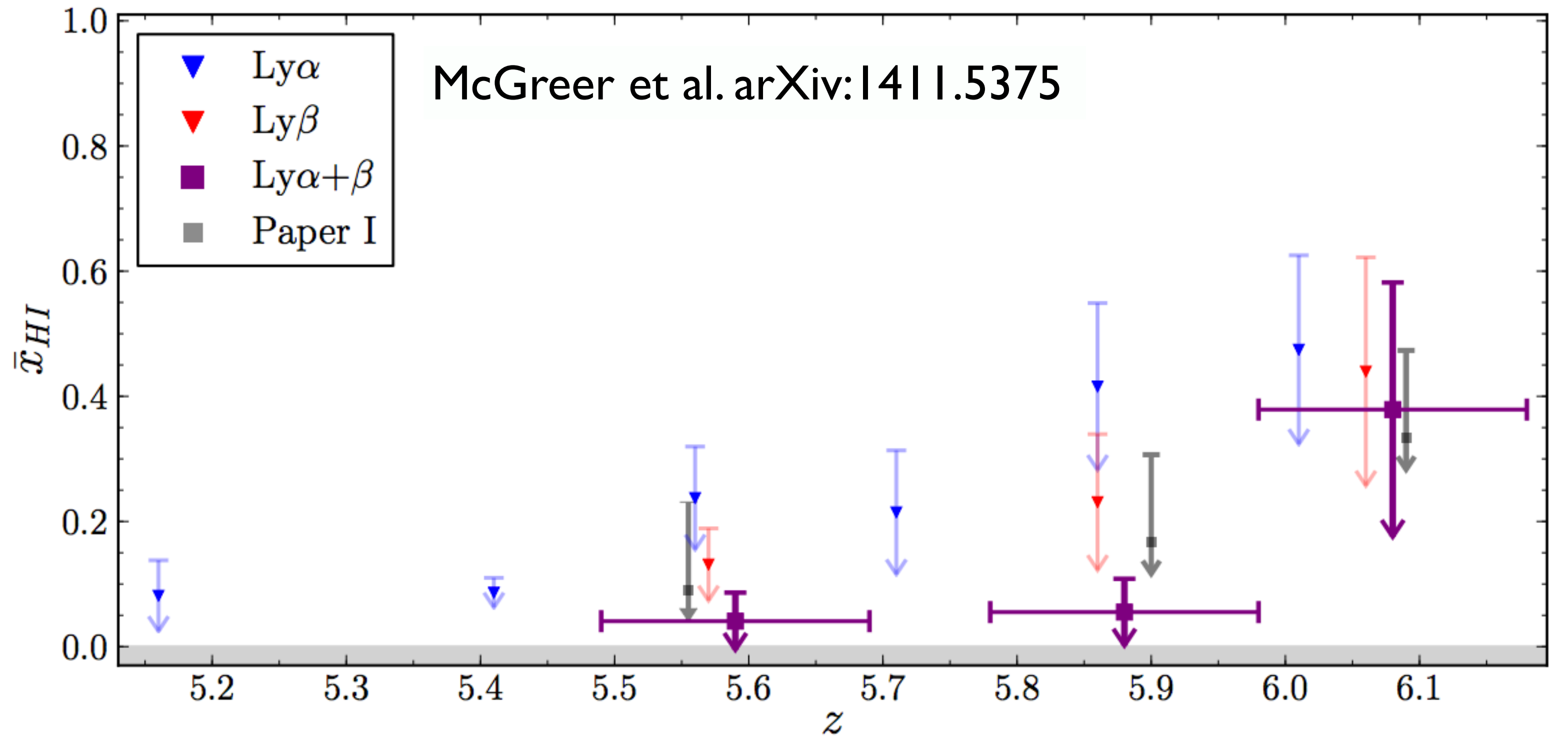
Why Lyα Emitting Galaxies Probe Reionization

Movie by M. Alvarez



Neutral intergalactic gas is modulates the observed Lyα flux from distant galaxies.

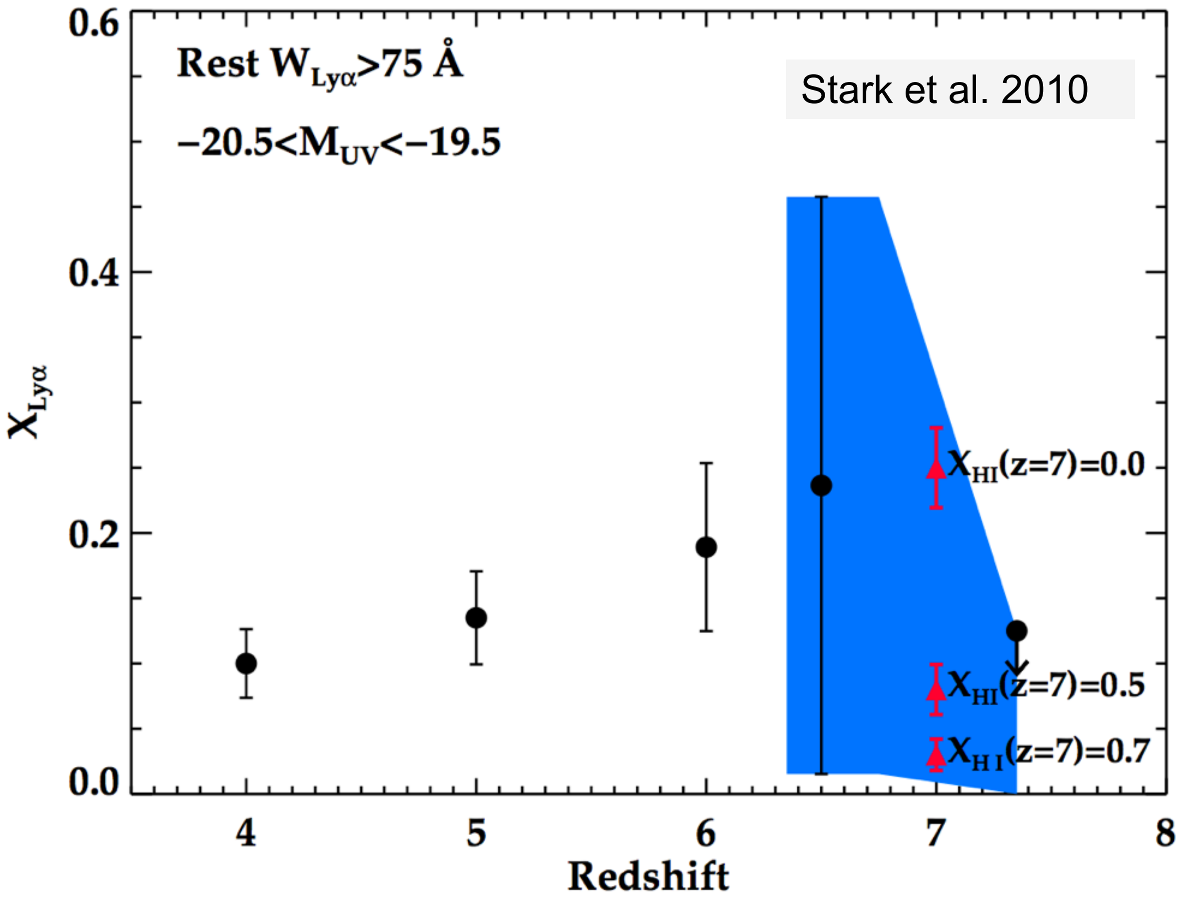
Lyα *Forest* Constraints on Reionization



Lya forest suggest inhomogeneous **mostly** complete by z~6: x_{HI}<0.11 (1-sigma)

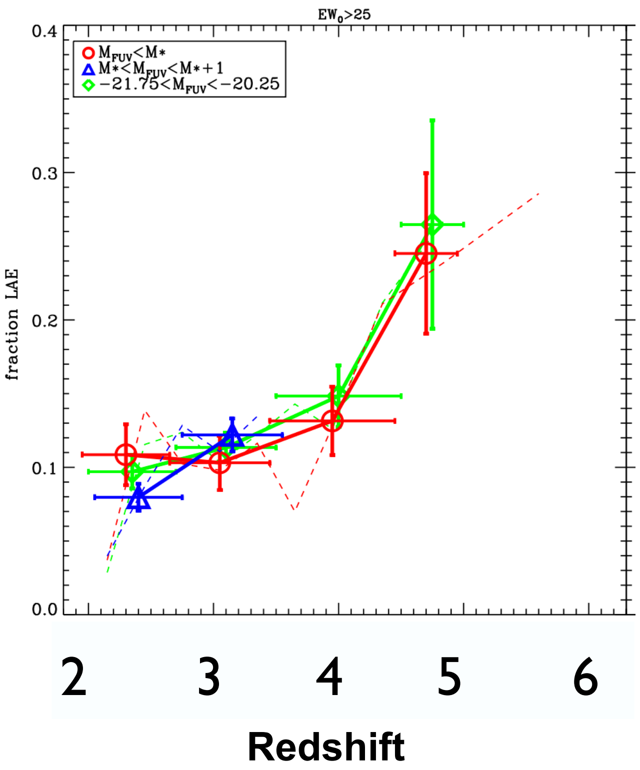
Room for *significant* amounts of HI (tens of per cent of the volume) at z > 6.

Suppressed Lyα Flux from Galaxies at z>6 I: Lyα Fraction

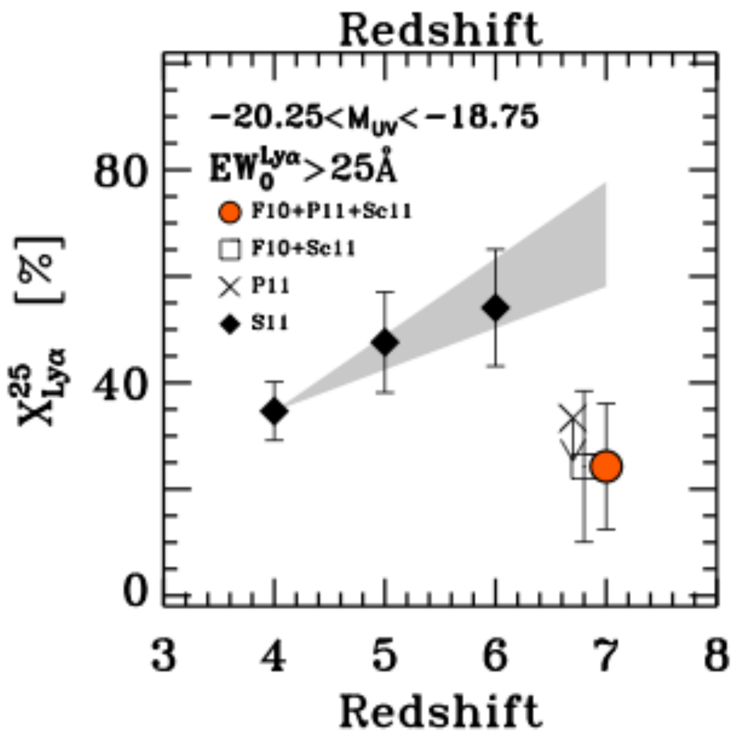


Suppressed Lyα Flux from Galaxies at z>6 I: Lyα Fraction

Cassata+2014



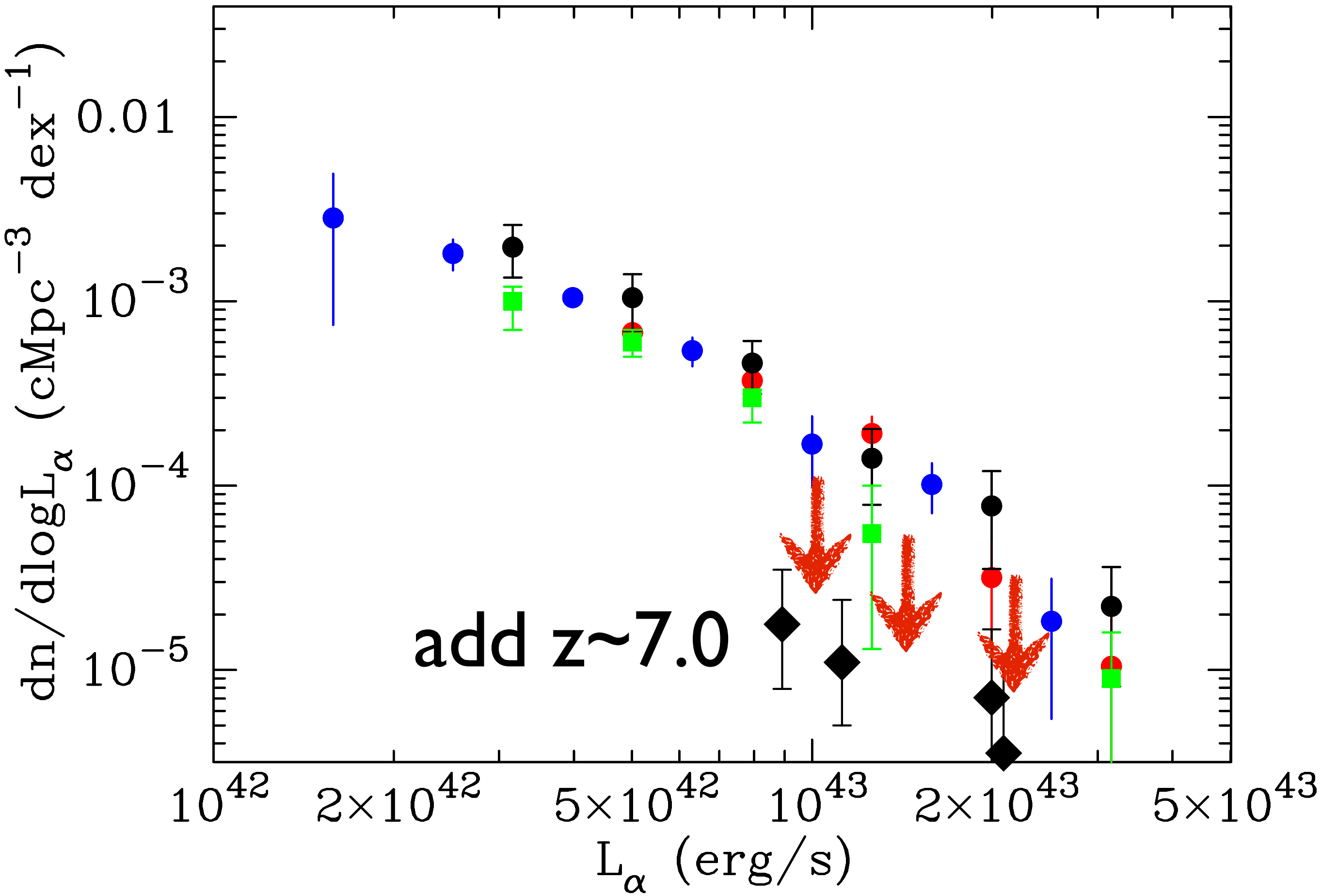
Compilation by Ono+2012



but then....(trend continues to z=8, see e.g. Treu et al. 2013, Tilvi et al. 2014, Finkelstein et al. 2014)

Suppressed Lyα Flux from Galaxies at z>6 II: LAE LFs

e.g. Ouchi et al. 2008/2010, Kashikawa+2006/2011, Ota+2011



\`Lyα emitter' (selected via Lyα) luminosity function.

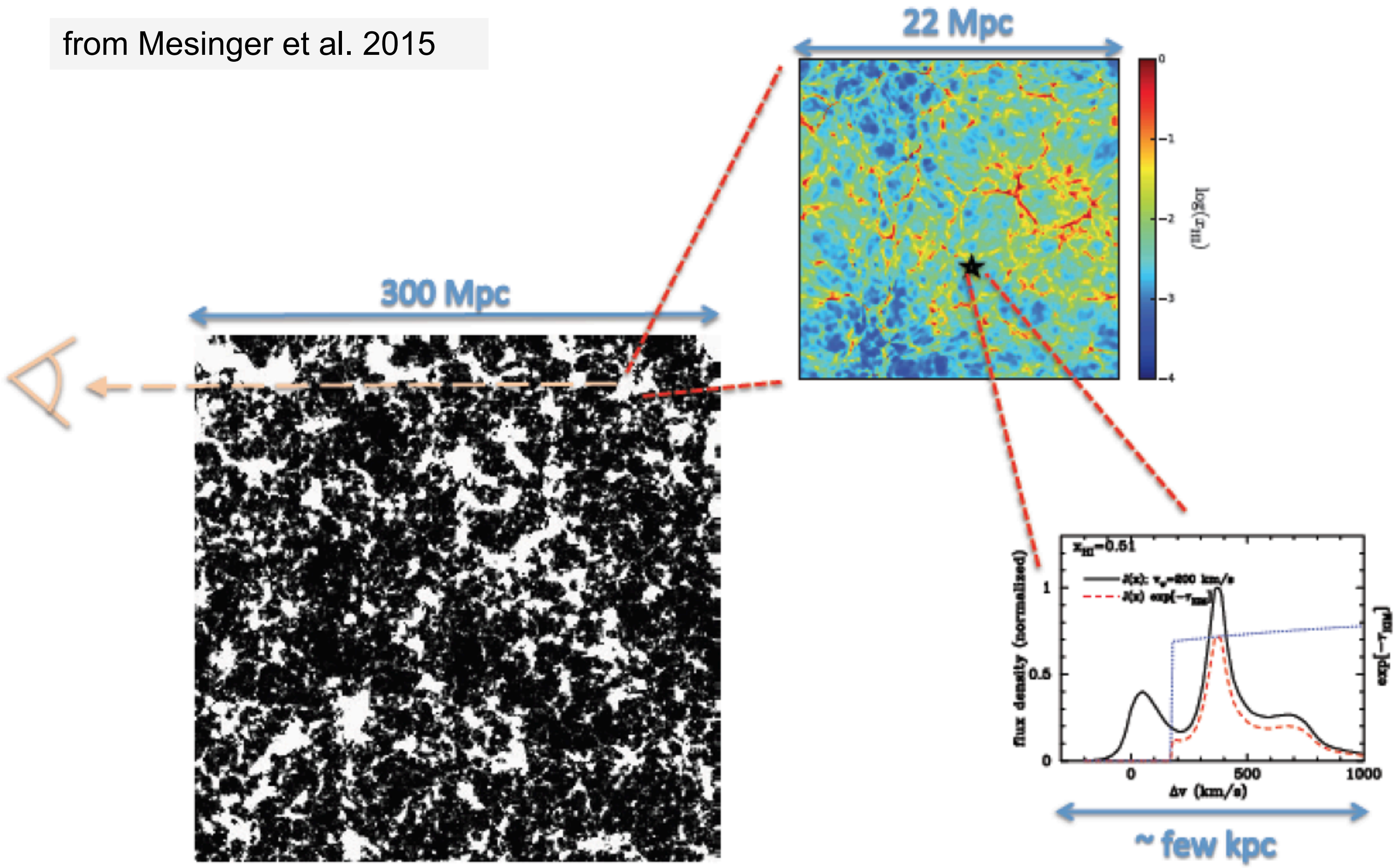
A Reduction in Lyα Flux from Galaxies at z>6

Sudden suppression of Lyα flux from galaxies is observed in two different galaxy populations (continuum and line selected).

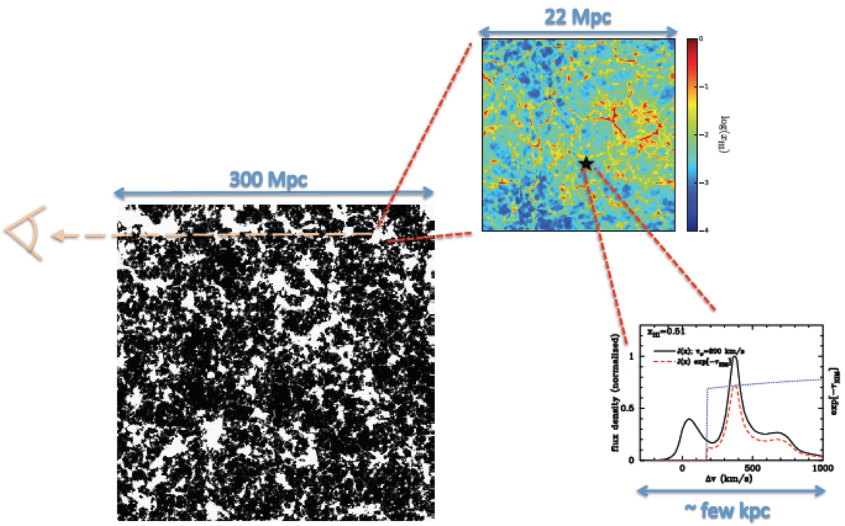
Importantly: z-evolution of Lyα fraction and LAE luminosity function is *quantitatively* consistent at z=2-7 (MD & Wyithe 2012, MD et al. 2014, Gronke et al. 2014).

Reionization & Visibility of the Lyα line from Galaxies

from Mesinger et al. 2015

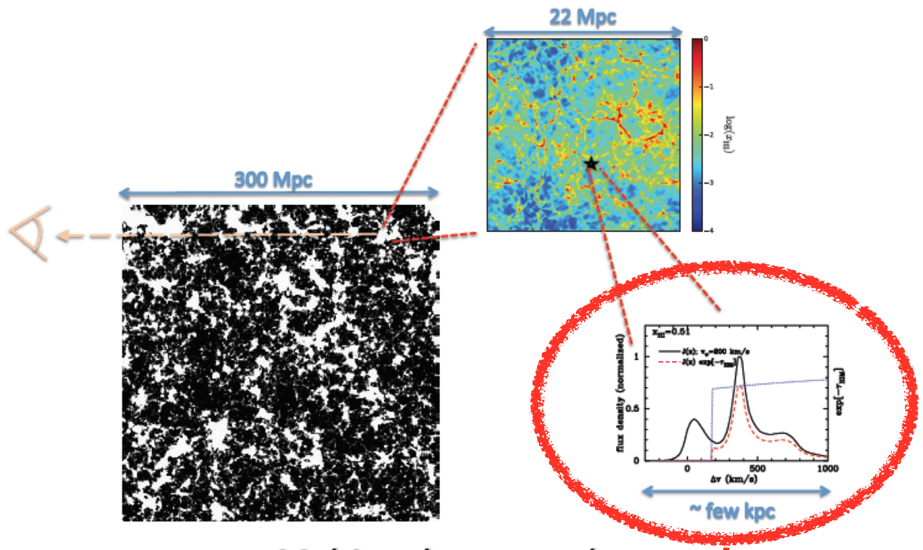


Lyα transfer is a multi-scale problem.



Multi-scale approach

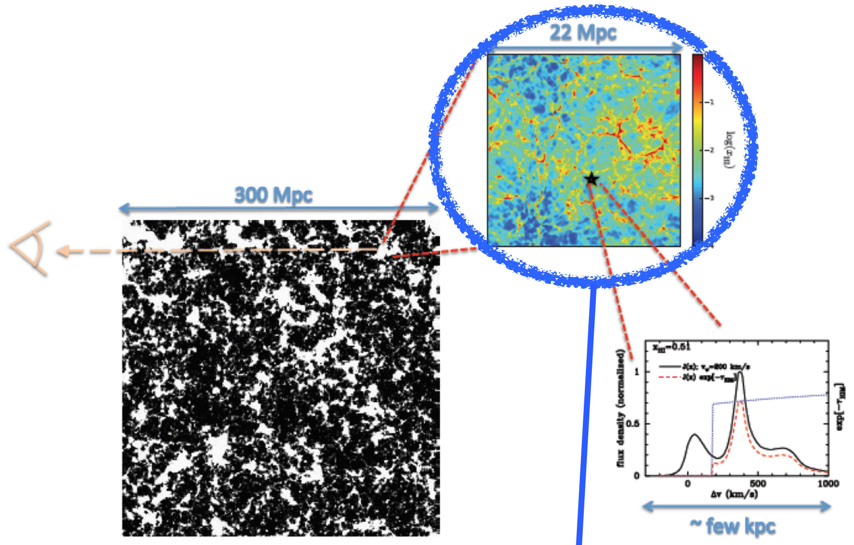
$$\mathrm{IGM-Transmitted\ fraction} = \int d\nu_{\mathrm{e}}\ L(\nu_{\mathrm{e}}) \exp[-\tau_{\mathrm{Ly}\alpha}(\nu_{\mathrm{e}})]$$



Multi-scale approach

interstellar RT:
dust, gas kinematics,...

$$\mathrm{IGM-Transmitted\ fraction} = \int d\nu_{\rm e}\ L(\nu_{\rm e})\exp[-\tau_{\rm Ly\alpha}(\nu_{\rm e})]$$



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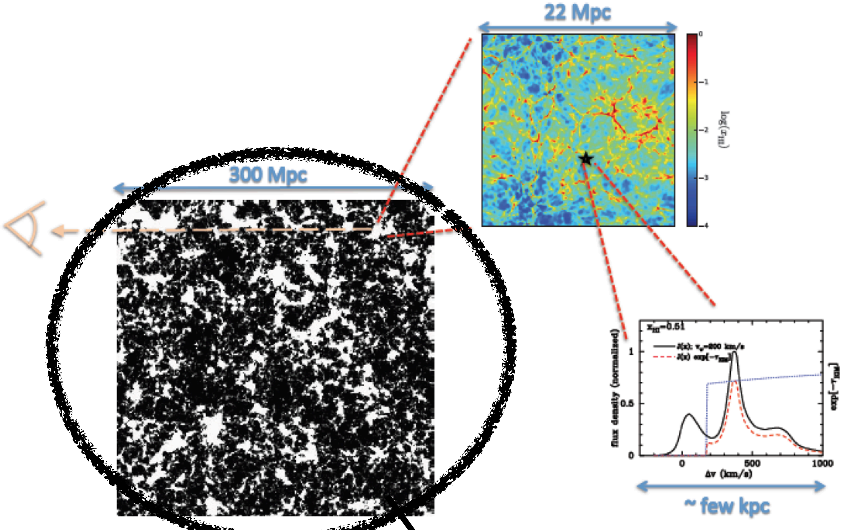
$$\mathrm{IGM-Transmitted\ fraction} = \int d\nu_{\rm e}\ L(\nu_{\rm e}) \exp[-\tau_{\rm Ly\alpha}(\nu_{\rm e})]$$

$$\tau_{\rm Ly\alpha}(\nu_{\rm e}) = \tau_{\rm HII}(\nu_{\rm e}) + \tau_{\rm D}(\nu_{\rm e})$$

self-shielding absorbers inside ionized bubbles (see e.g. Bolton & Haehnelt 2013)

Lyα Transfer During Reionization



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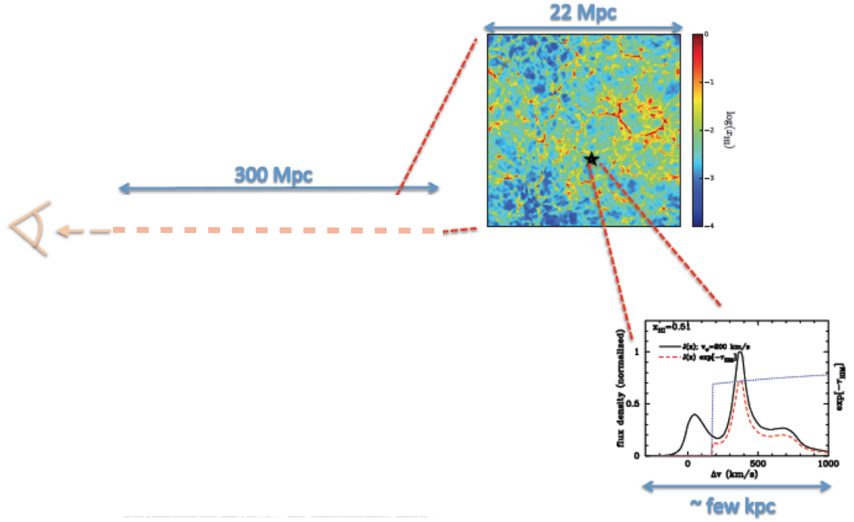
self-shielding absorbers inside ionized bubbles (see e.g. Bolton & Haehnelt 2013)

Diffuse neutral intergalactic gas. → unique to EoR!

Lyα Transfer During *Post* Reionization



Multi-scale approach

interstellar RT:
dust, gas kinematics,...

$$\mathrm{IGM-Transmitted\ fraction} = \int d\nu_{\rm e}\ L(\nu_{\rm e}) \exp[-\tau_{\rm Ly\alpha}(\nu_{\rm e})]$$

$$\tau_{\rm Ly\alpha}(\nu_{\rm e}) = \tau_{\rm HII}(\nu_{\rm e})$$

self-shielding absorbers inside ionized bubbles (see e.g. Bolton & Haehnelt 2013)

`Post reionization RT’ brightens Lyα from z=0-6!

Reionization & Visibility of the Lyα line from Galaxies

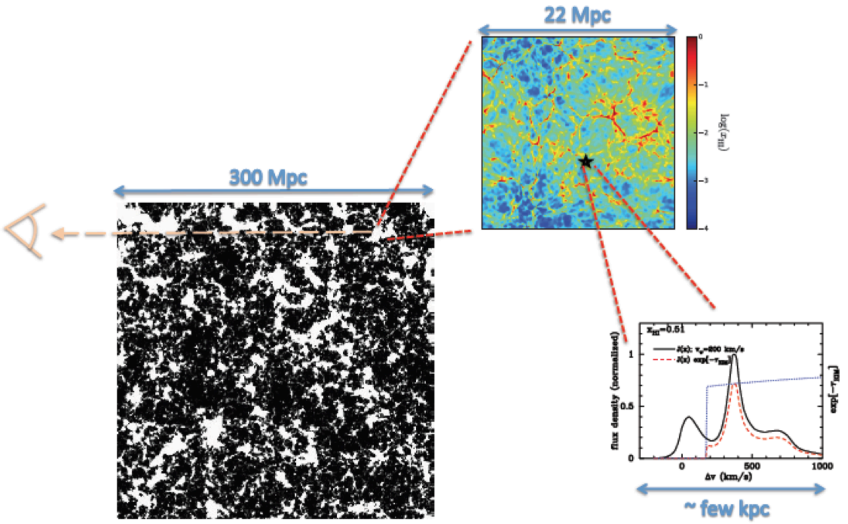
Reduced Lyα flux from galaxies at $z>6$ is a key signature of reionization

Question: what if it is due to reionization, what does this say about x_{HI}?

Assume small scale RT processes do not evolve from $z=6$-7.

Given `post reionization RT' brightens Lyα from z=0-6, this assumption is likely conservative.

Lyα Transfer During Reionization

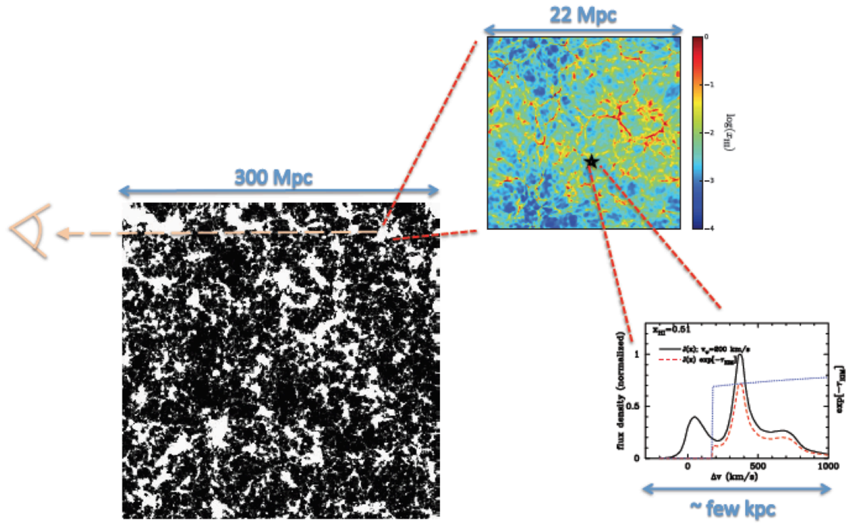


Multi-scale approach

$$\mathrm{IGM-Transmitted\ fraction} = \int d\nu_{\rm e}\ L(\nu_{\rm e}) \exp[-\tau_{\rm Ly\alpha}(\nu_{\rm e})]$$

(Mesinger et al. 2015)

Lyα Transfer During Reionization



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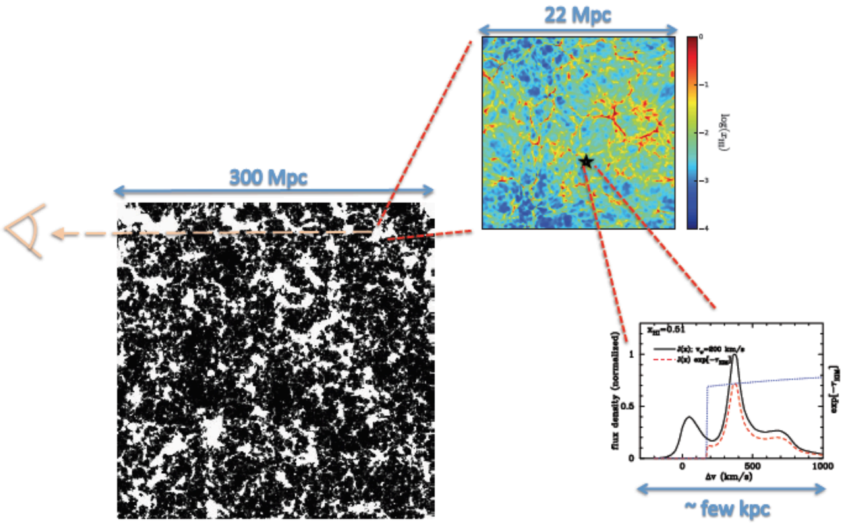
$$\mathrm{IGM-Transmitted\ fraction} = \int d\nu_{\rm e}\ L(\nu_{\rm e})\exp[-\tau_{\rm Ly\alpha}(\nu_{\rm e})]$$

(Mesinger et al. 2015)

Need to include 1. inhomogeneous nature of reionization process

DexM (Mesinger & Furlanetto 2007)

Lyα Transfer During Reionization



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$$\mathrm{IGM-Transmitted\ fraction} = \int d\nu_{\mathrm{e}}\ L(\nu_{\mathrm{e}}) \exp[-\tau_{\mathrm{Ly}\alpha}(\nu_{\mathrm{e}})]$$

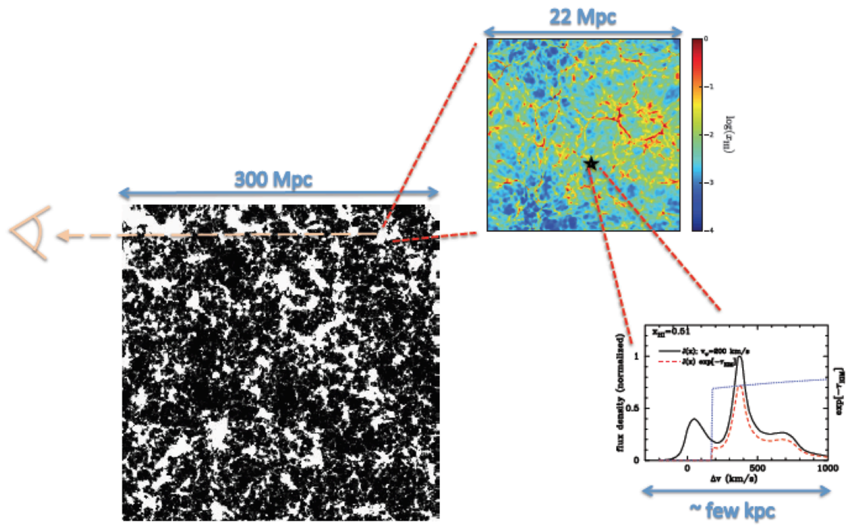
(Mesinger et al. 2015)

Need to include 1. inhomogeneous nature of reionization process

2. self-shielding absorbers inside ionized bubbles

higher resolution hydrodynamical simulations (Enzo/RAMSES) that resolve Jeans mass using self-shielding prescription adopted in studies simulating Lya forest (Rahmati+2011)

Lyα Transfer During Reionization



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(Mesinger et al. 2015)

Need to include 1. inhomogeneous nature of reionization process

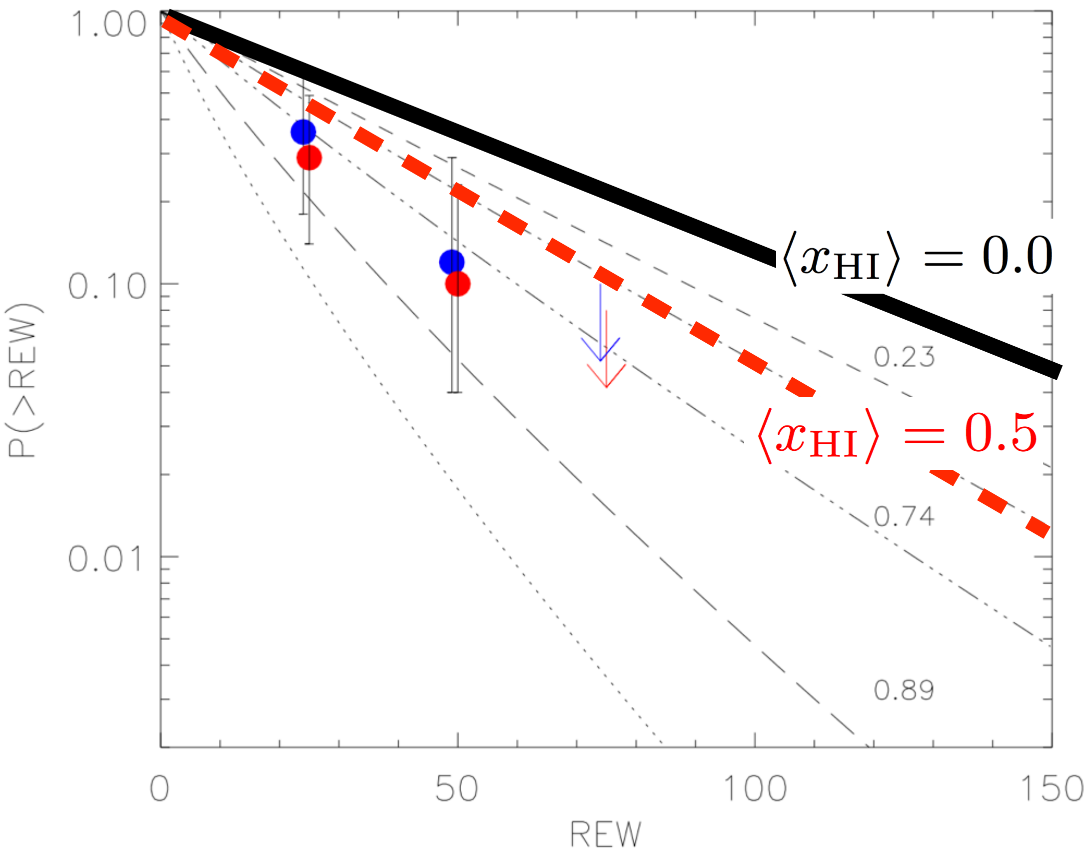
2. self-shielding absorbers inside ionized bubbles

3. line shape & normalization: transfer on interstellar scales

Sub-grid `shell-models' adopted by community modeling Lya lines of low-z Lya emitting galaxies.

Constraints on Reionization

from Pentericci et al. 2014



x_{HI}>0.4 at z=7 if x_{HI}~0.0 at x=6

Dijkstra et al. 2011, Jensen et al. 2013, Mesinger et al. 2015, Choudhury et al. 2015

Constraints on Reionization

Observations indicate that Lyα flux from galaxies at z>6 is suppressed.

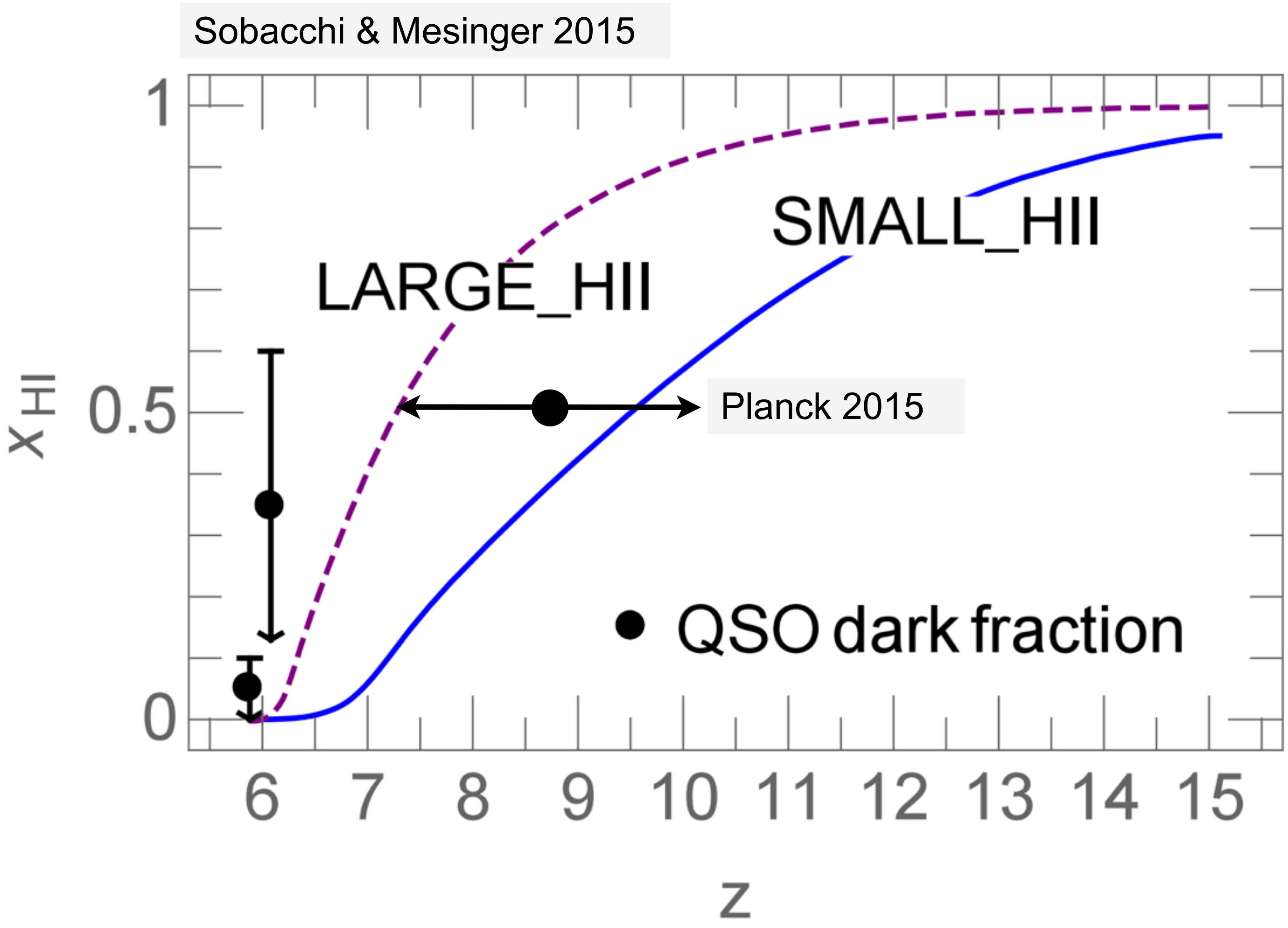
Models that explain this reduction with reionization require

x_{HI}>0.4 at z=7 if x_{HI}~0.0 at x=6

because imprint of patchy/inhomogeneous reionization on Lyα flux is subtle:
Reionization cannot change Lyα fraction by factor > 2 from z=6-7 (Mesinger et al. 2015)

Rapid evolution in x_{HI} at odds with theory, but observational uncertainties still significant.

Constraints on Reionization: Context



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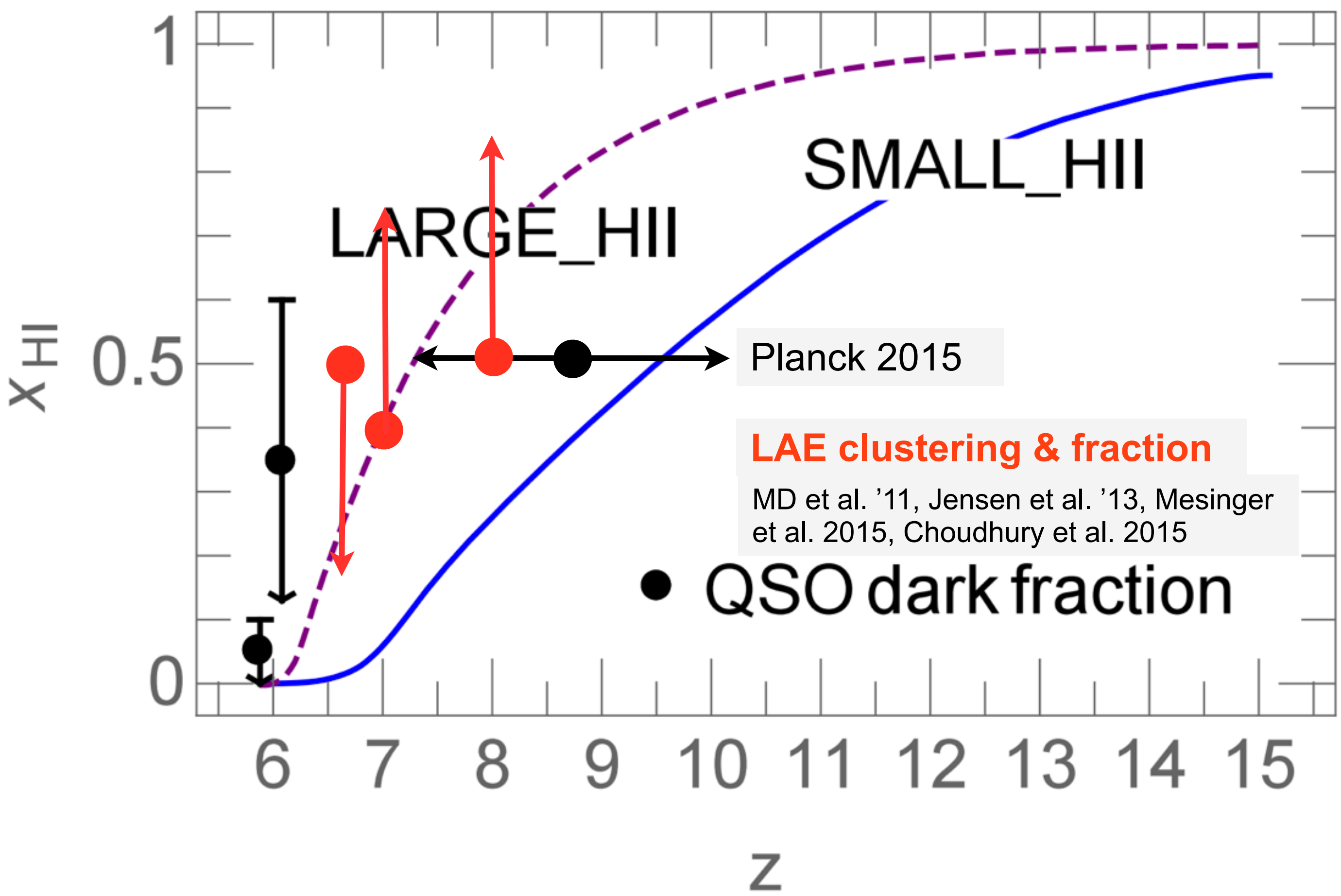
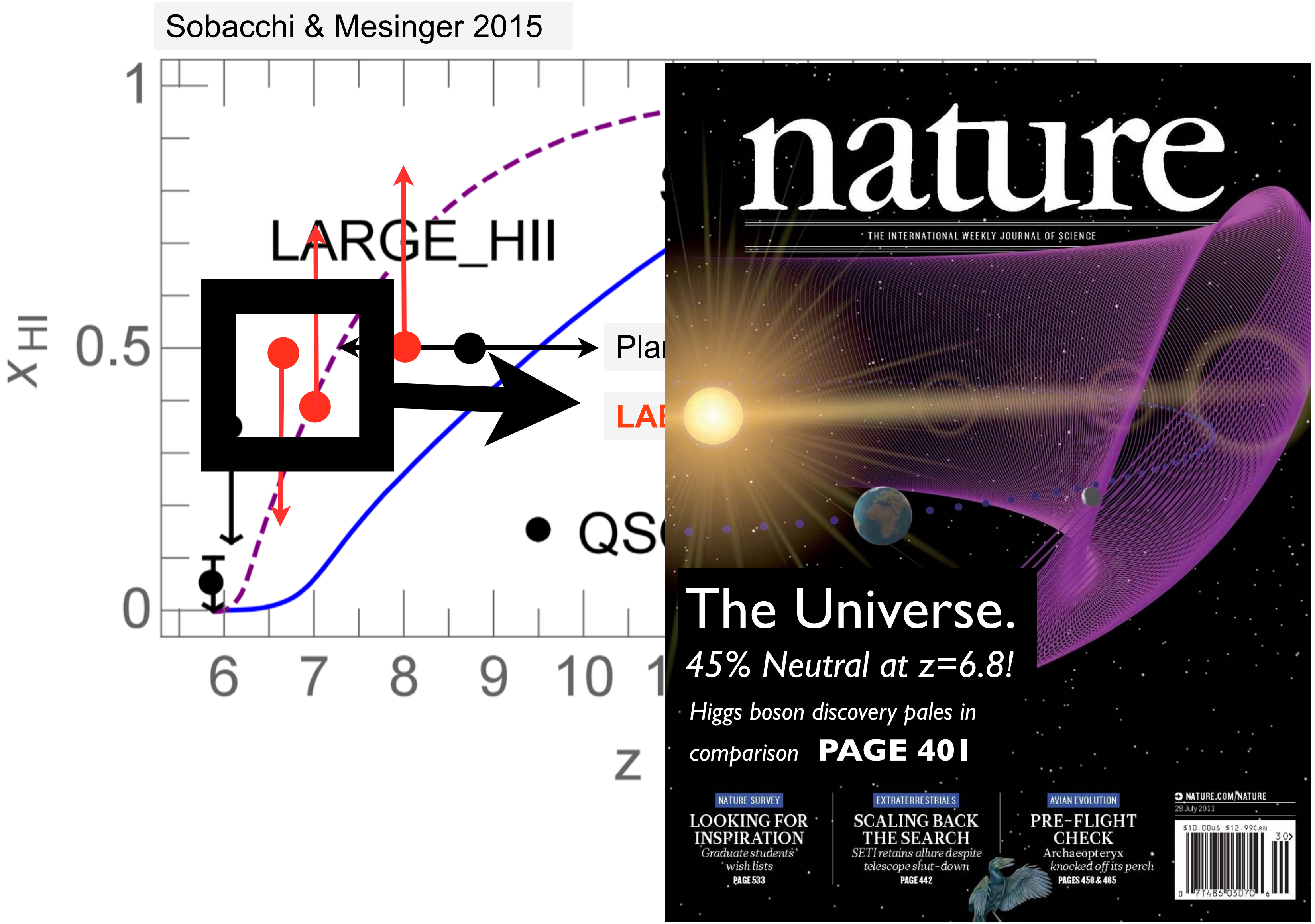


One of the most important current (& future) constraints on the EoR

Constraints on Reionization: Context

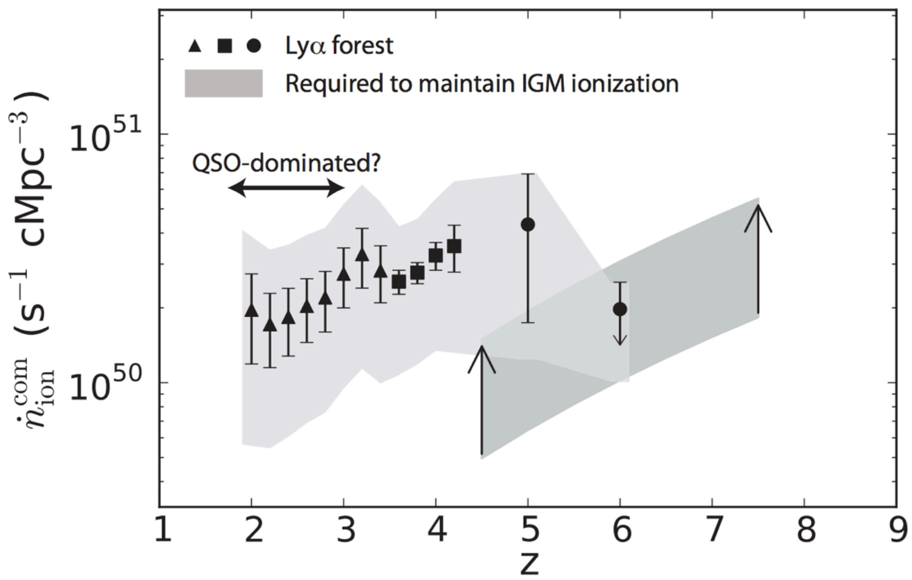


Committing a Sin by allowing Evolving Galaxy Properties I: Imprint of an Evolving Escape Fraction f_{esc} ?

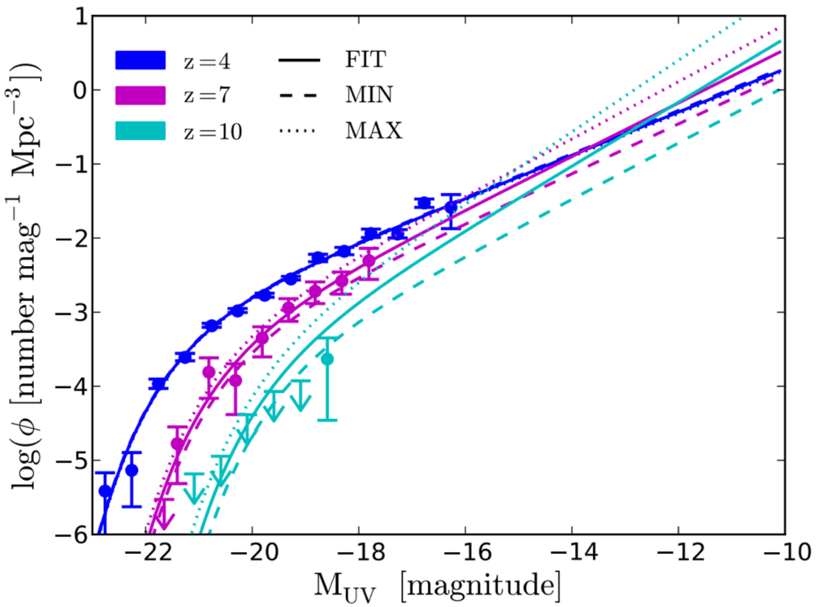
Observed Lyα luminosity of a star forming galaxy is given by

$$L_{\alpha,\mathrm{obs}} \propto \dot{N}_{\mathrm{ion}}(1 - f_{\mathrm{esc}}) f_{\mathrm{esc}}^{\mathrm{Ly}\alpha} \mathcal{T}_{\mathrm{IGM}}$$

↓ from z=6 → 7



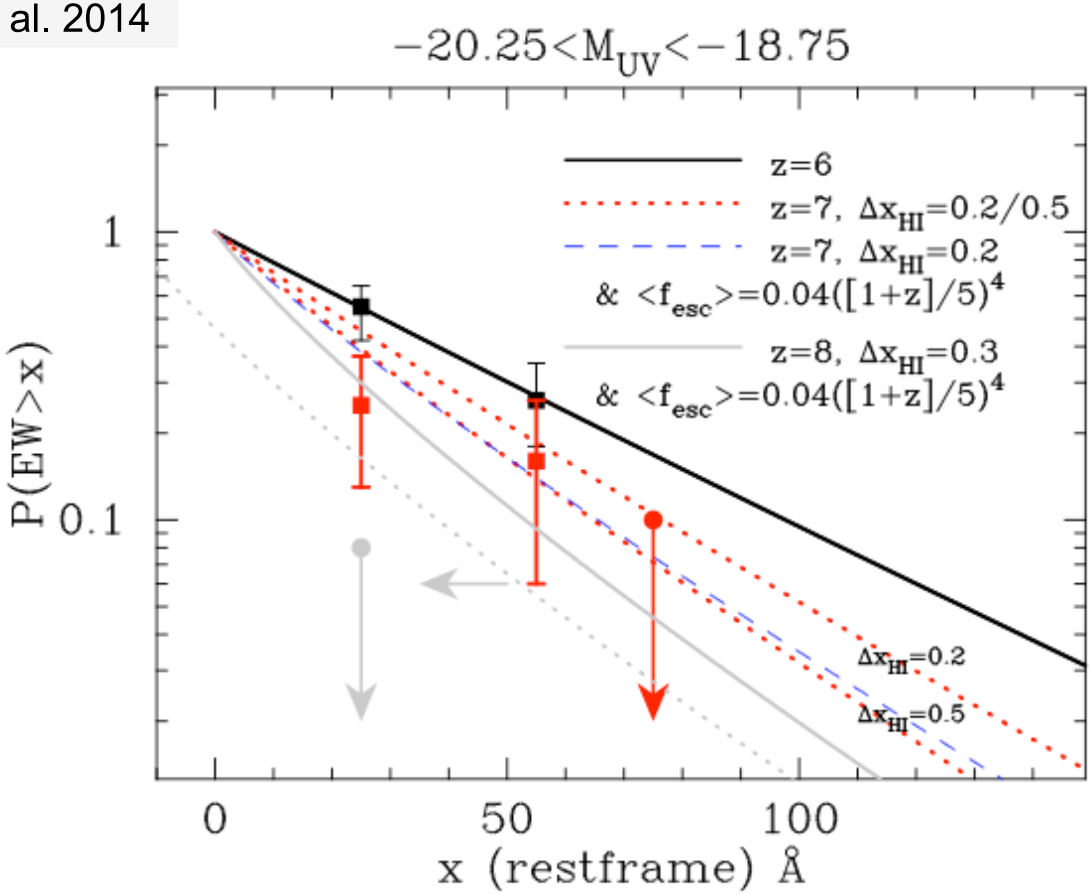
Kuhlen & Faucher-Giguere 2012



Lyα forest + LBG luminosity functions imply $f_{\mathrm{esc}} \sim 0.04([1+z]/5)^{\gamma}, \quad \gamma = 3-5$

Committing a Sin by allowing Evolving Galaxy Properties I: Imprint of an Evolving Escape Fraction f_{esc} ?

MD et al. 2014

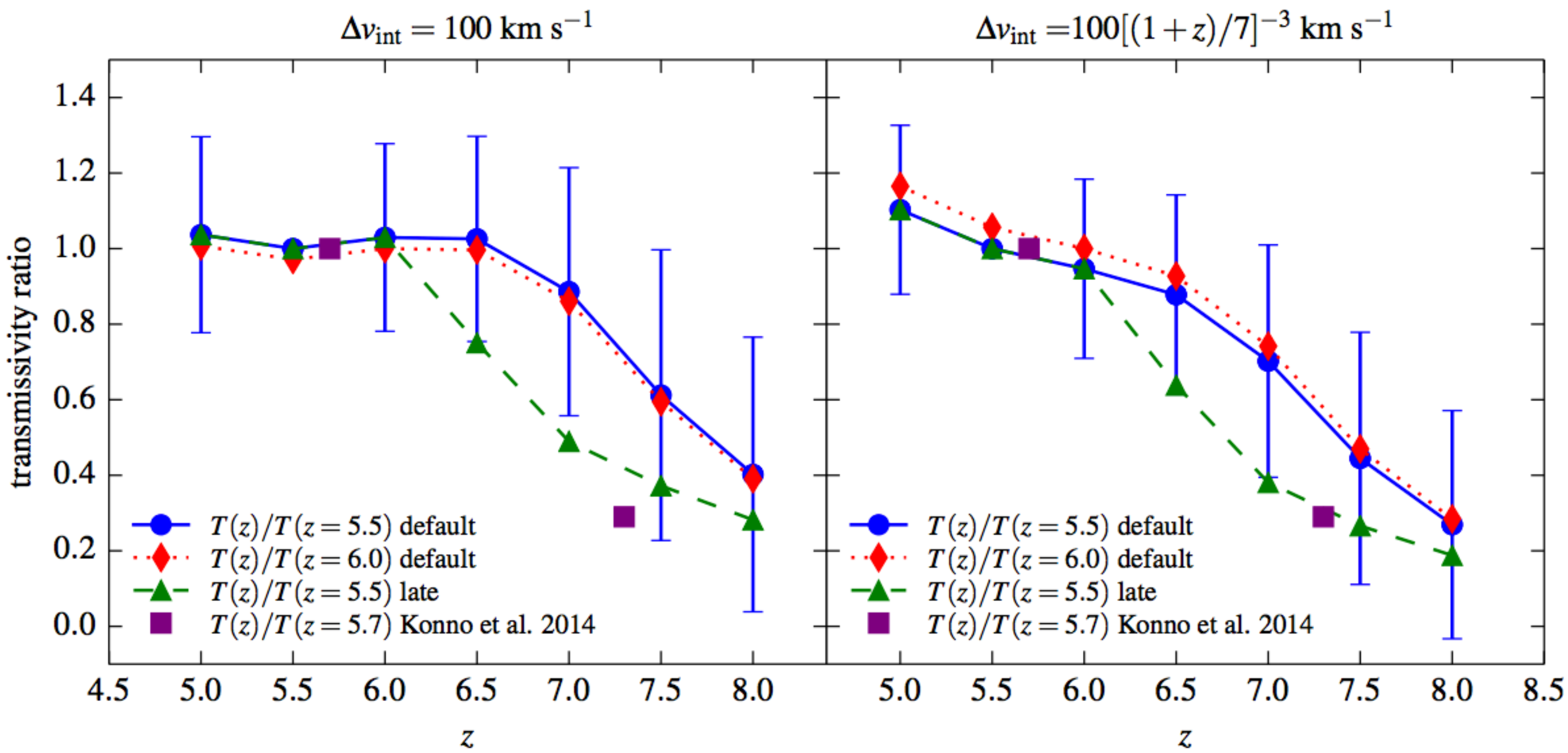


x_{HI}~0.5 at z=7 → x_{HI}~0.2 at z=7

Committing a Sin by allowing Evolving Galaxy Properties II: Imprint of an Evolving Line Profile ?

Choudhury et al. 2015

$$\mathrm{IGM-Transmitted\ fraction} = \int d\nu_{\mathrm{e}}\ L(\nu_{\mathrm{e}}) \exp[-\tau_{\mathrm{Ly}\alpha}(\nu_{\mathrm{e}})]$$



x_{HI}~0.5 at z=7 → x_{HI}~0.3 at z=7

Evolving redshift of Lyα line, Δv_{int}, can help increase the IGM opacity.

Committing a Sin by allowing Evolving Galaxy Properties II: Imprint of an Evolving Line Profile ?

Choudhury et al. 2015 $\mathrm{IGM-Transmitted\ fraction} = \int d\nu_e\, L(\nu_e) \exp[-\tau_{\mathrm{Ly}\alpha}(\nu_e)]$

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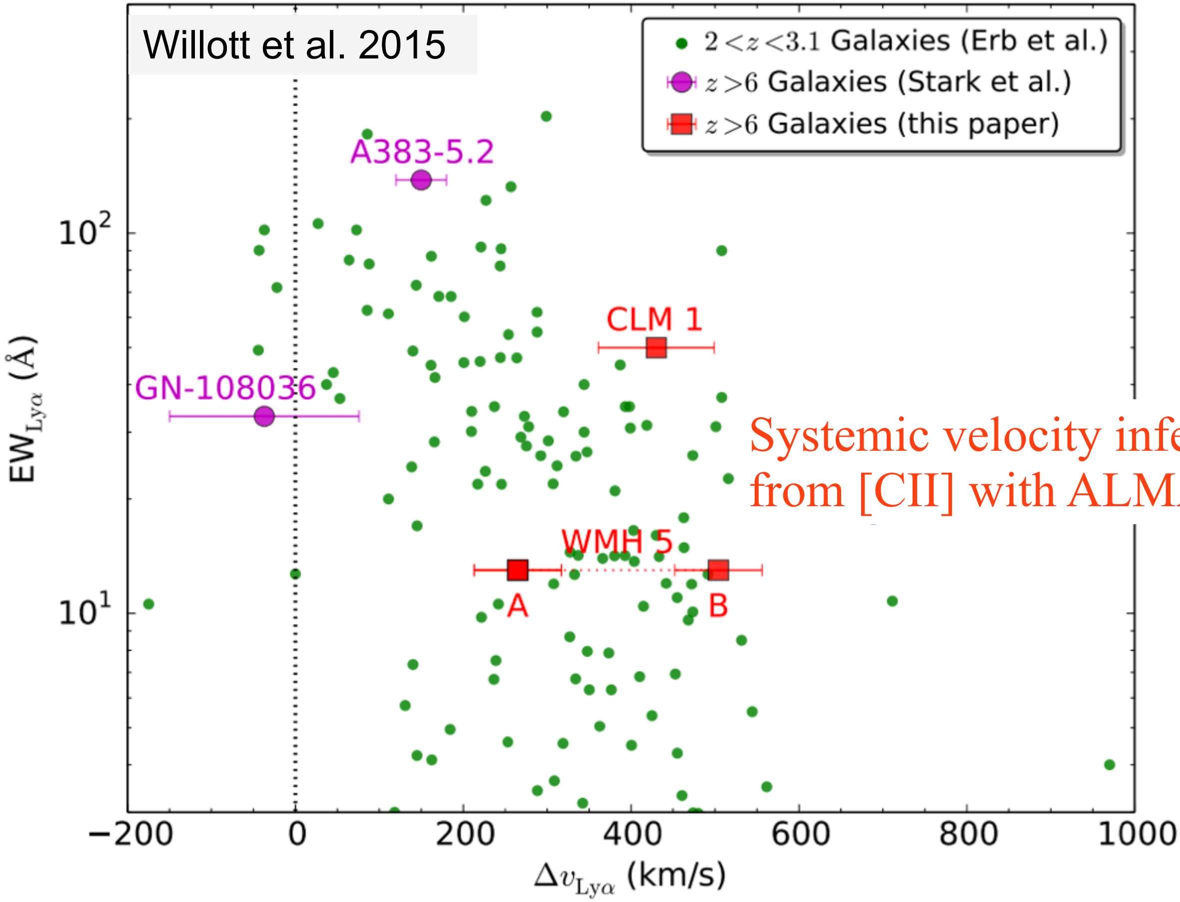
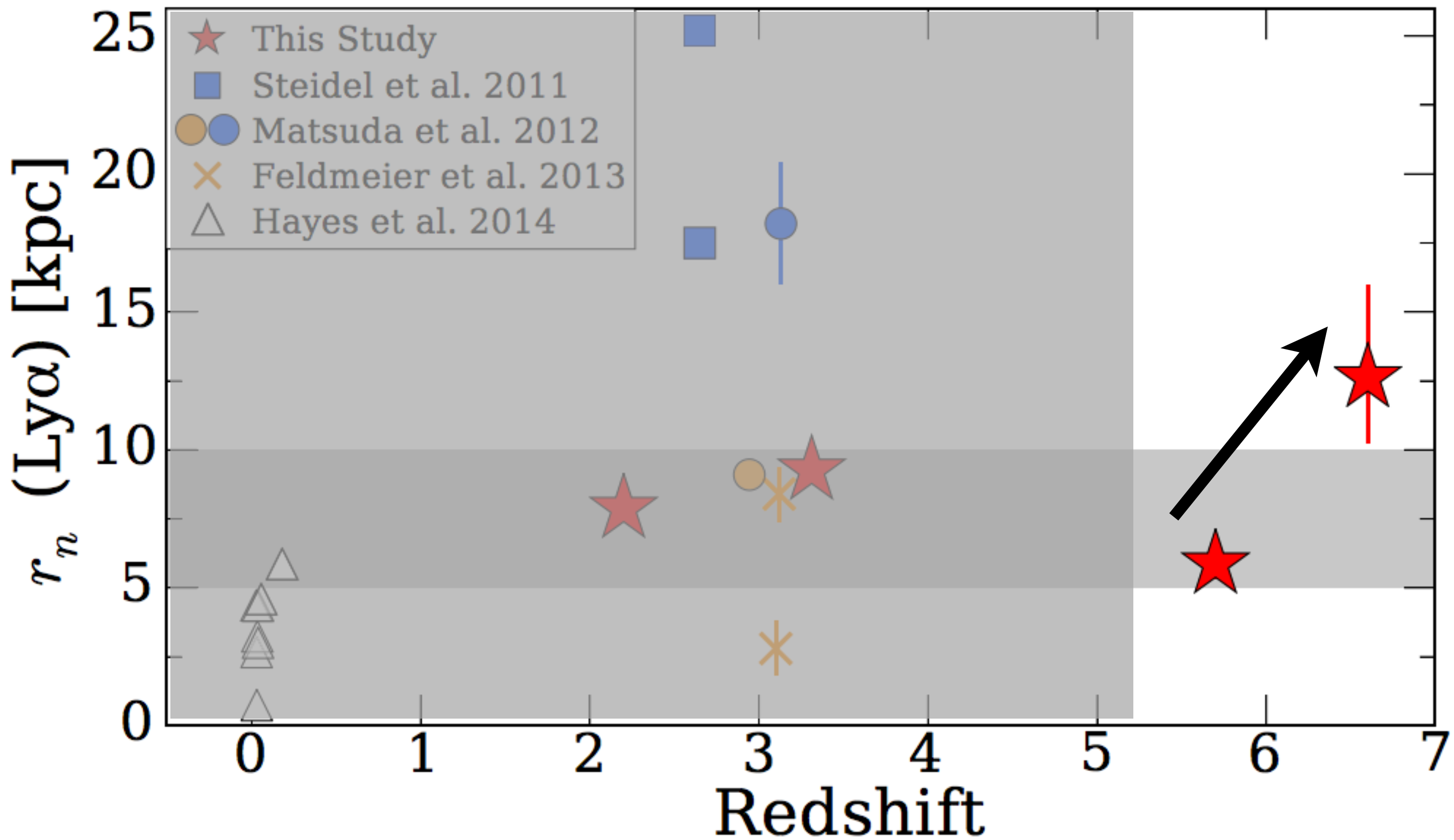


Systemic velocity inferred from [CII] with ALMA

Getting systemic redshifts of high-z galaxies is difficult, but ALMA can help.

Observational Signatures of Evolving Galaxy Properties: Imprint of an Evolving CGM properties ?

Momose et al. 2014



Lyα halos are more extended at z>6 than z < 6. More scattering in CGM? If so, then the CGM is more opaque which would suppress the flux.

Conclusions: Constraints on Reionization from Lyα Emitting Galaxies

1. Suppressed Lyα flux from Galaxies at z>6 favor substantially neutral Universe at z~7.

$x_{HI}>0.4$ at z=7 if $x_{HI}\sim0.0$ at x=6

- Consistent with constraints form Lyα forest and CMB.
- Current observational uncertainties are still large, but # of Lyα galaxies expected to increase by ~ *2 orders of magnitude* in coming years:

(*i*) spatial modulation in IGM opacity? (*ii*) cross-correlation with cosmological 21-cm..

Advertisement; see **MD. 2014, PASA**, for an extended review & for outlook on the future.

Conclusions: Constraints on Reionization from Lyα Emitting Galaxies

2. Understanding the reduced Lyα flux from Galaxies at z>6 constrains more than reionization, but also provides unique insights into galaxy formation.

- Lyα halos encode information on cold gas in CGM, *and* the escape of ionizing & Lyα photons from galaxies (Mas-Ribas et al. in prep)

- Lyα line profiles provide unique constraints on gaseous outflows in galaxies at high-z.