Lyman-α Emitting Galaxies as a Probe of Reionization

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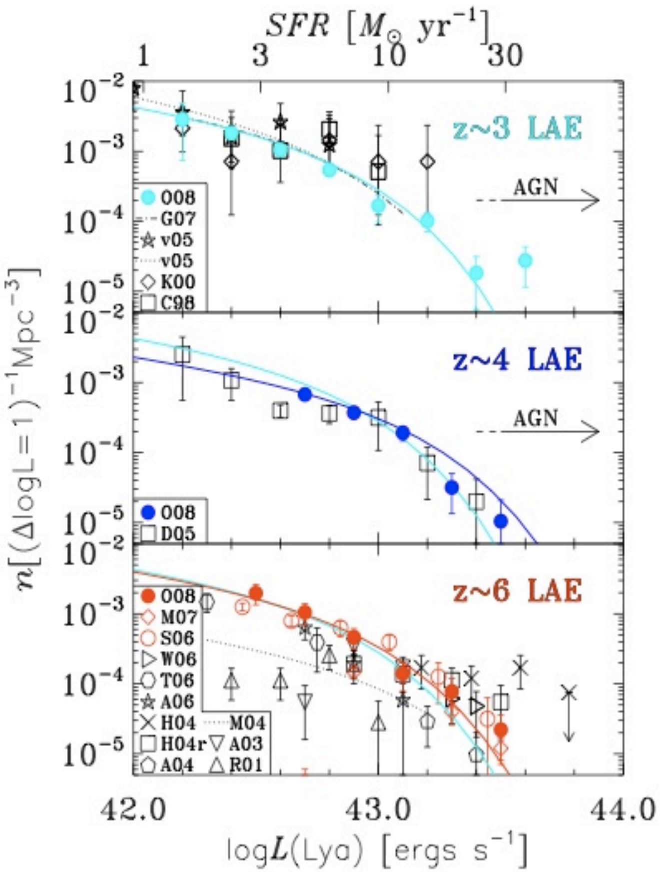
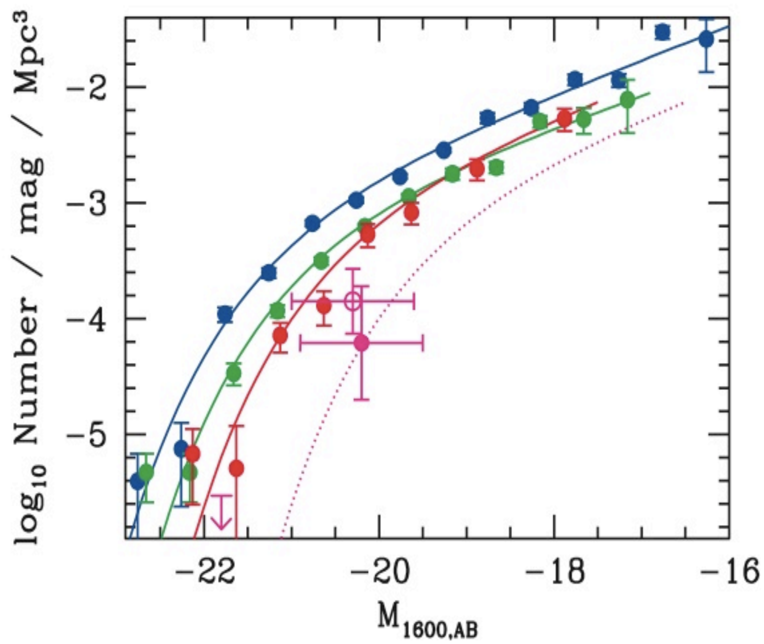
Representative Observations

Ouchi+08



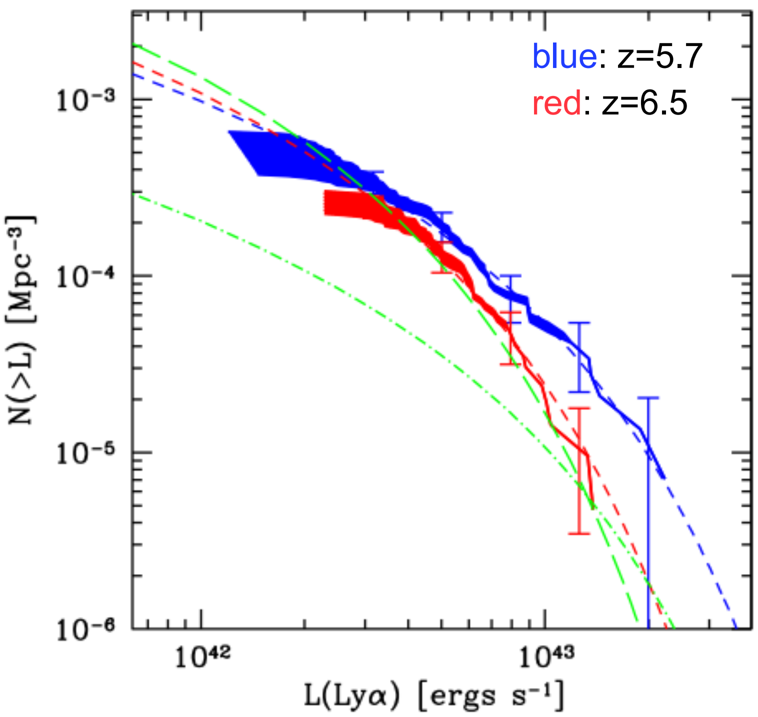
Bouwens+07

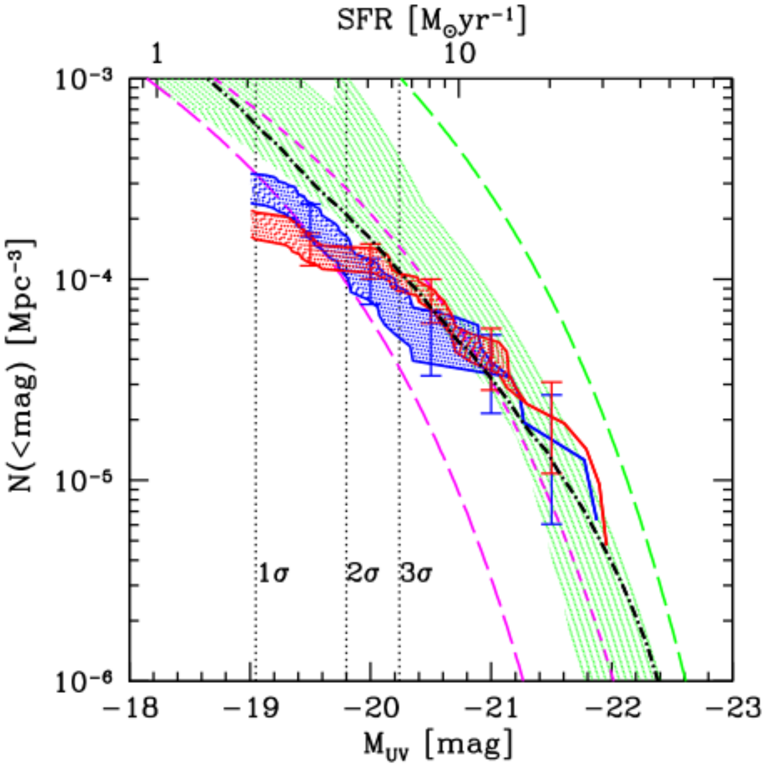


density of Lyα emitters (LAEs) does not evolve between z=3-6, in contrast to observations of LBGs.

Representative Observations

Kashikawa+11

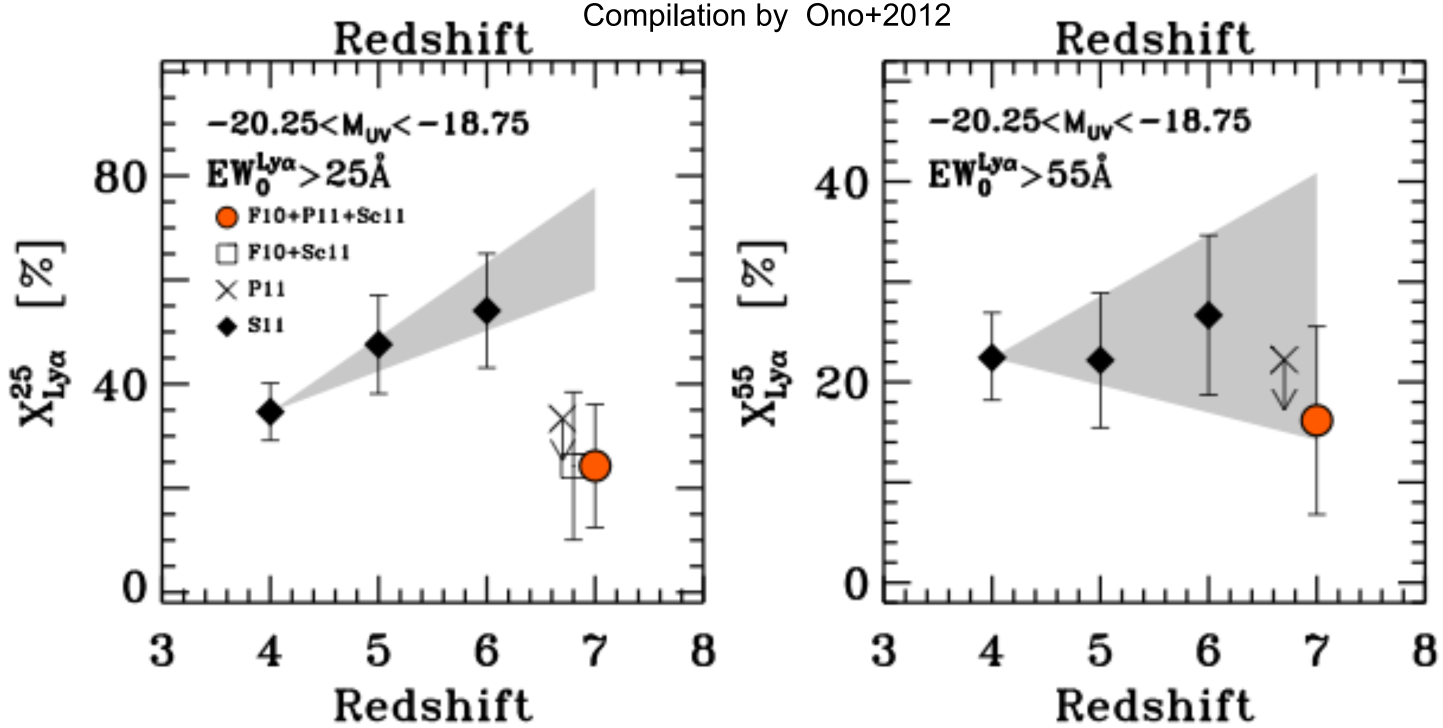




density of Lyα emitters (LAEs) does evolve at z>5.7, appears associated with reduction in Lyα!

Representative Observations

Compilation by Ono+2012



(compilation contains data from Stark+10, Fontanot+10, Stark+11, Pentericci+12, Schenker+12)

Reduction in Lyα for z>6 galaxies also observed in drop-out galaxy population.

Representative Observations

Indicate clearly that the Lyα `effective’ escape fraction increases with z at $0 < z < 6$.

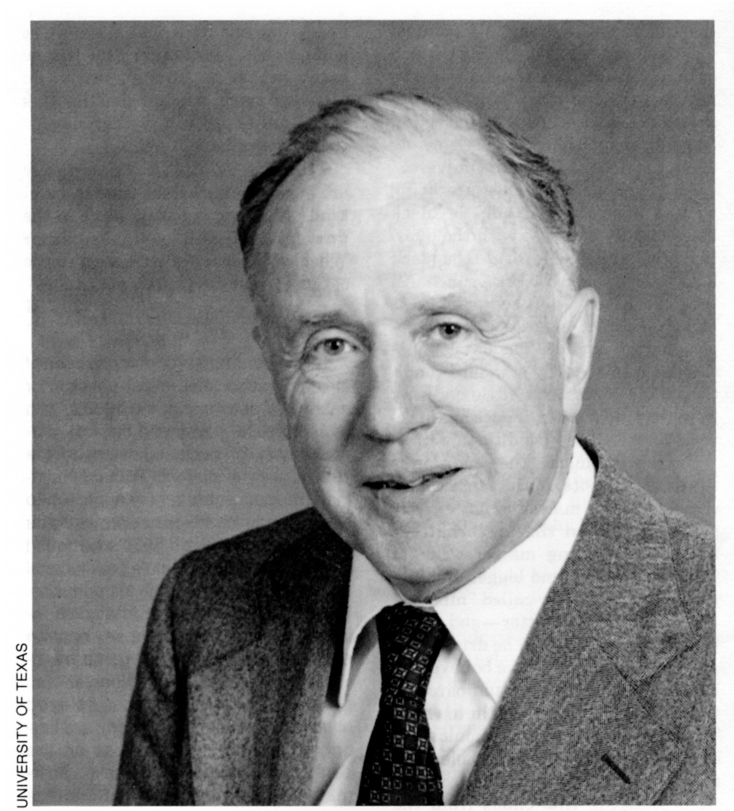
However, (significantly) fewer Lyα photons are observed from galaxies at $z > 6$ than expected from lower-z observations

This `sudden’ dimming of the Lyα line has been predicted to be a key signature of observations probing the EoR, and occurs where we may expect the EoR to end/begin.

Current observations may require a very rapid evolution of the volume averaged neutral frac:
$\Delta x_{HI} > 0.5$ for $\Delta z \sim 1$.

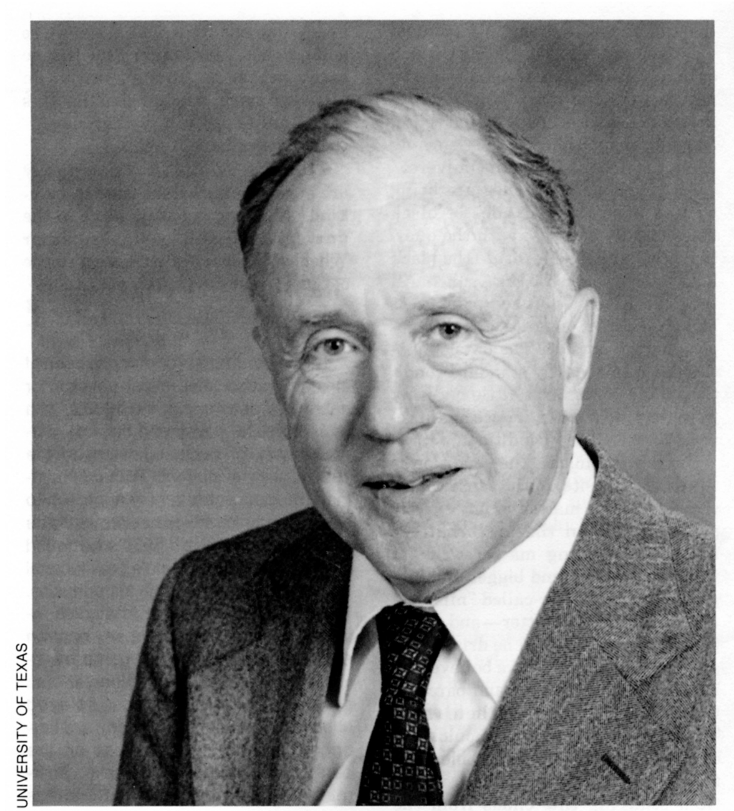
Intermezzo: The Origin of the term `LAE’

Intermezzo: Who coined the term `LAE’



Wheeler

Intermezzo: Who coined the term `LAE’

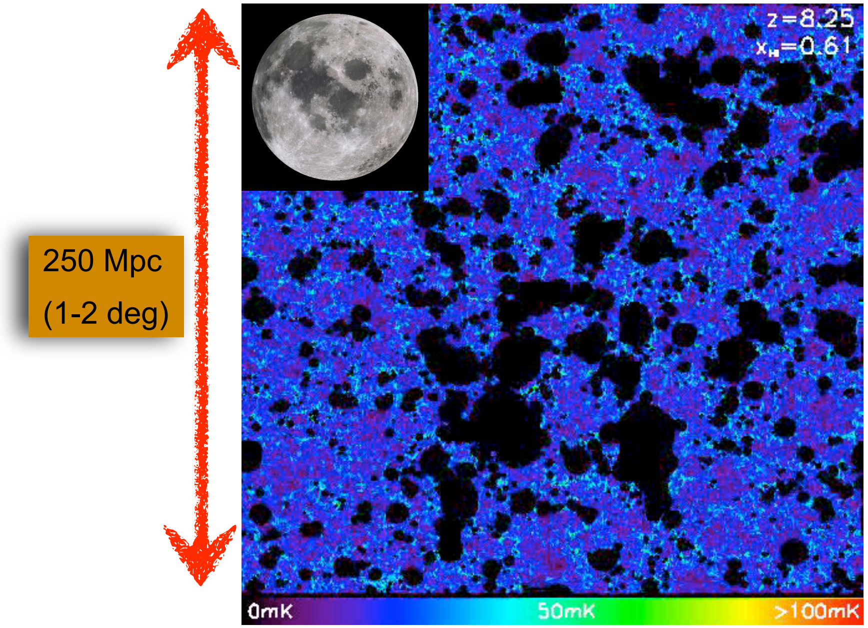


Wheeler

It was not Wheeler, very similar to the case of black holes.

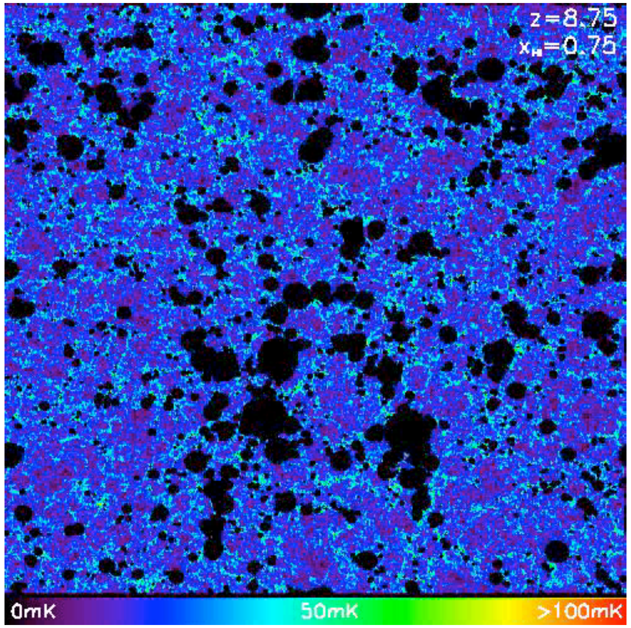
Theoretical Interpretation

To constrain ionization state of IGM, we must understand radiative transport of Lyα, and in context of inhomogeneous reionization scenarios.

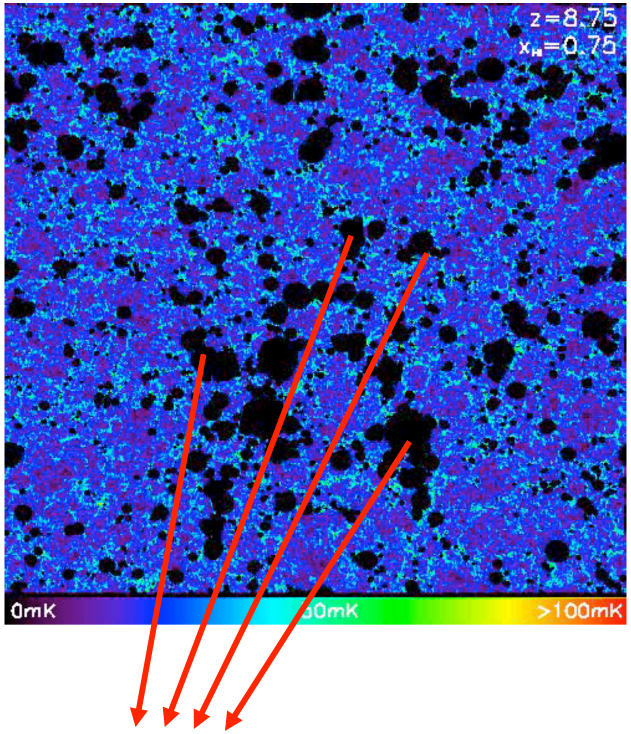


movie made by Andrei Mesinger

Theoretical Interpretation

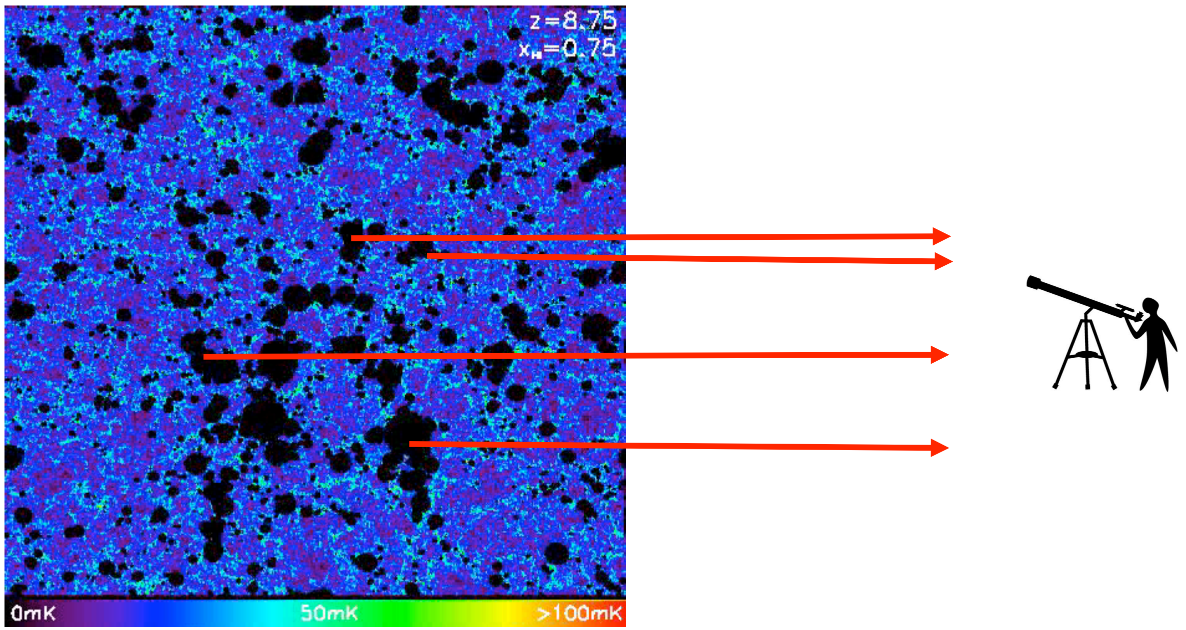


Theoretical Interpretation



Locations of DM halos massive enough to host observed Lyα emitting galaxies.

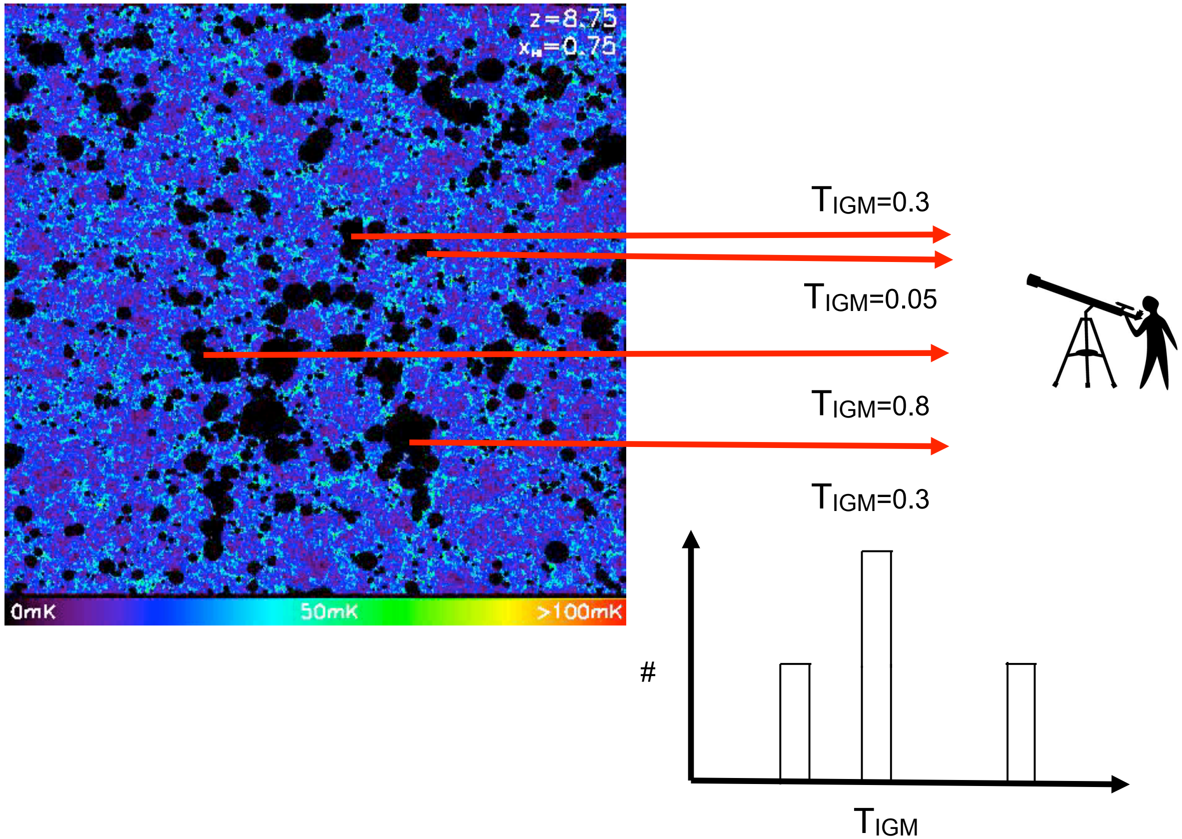
Theoretical Interpretation



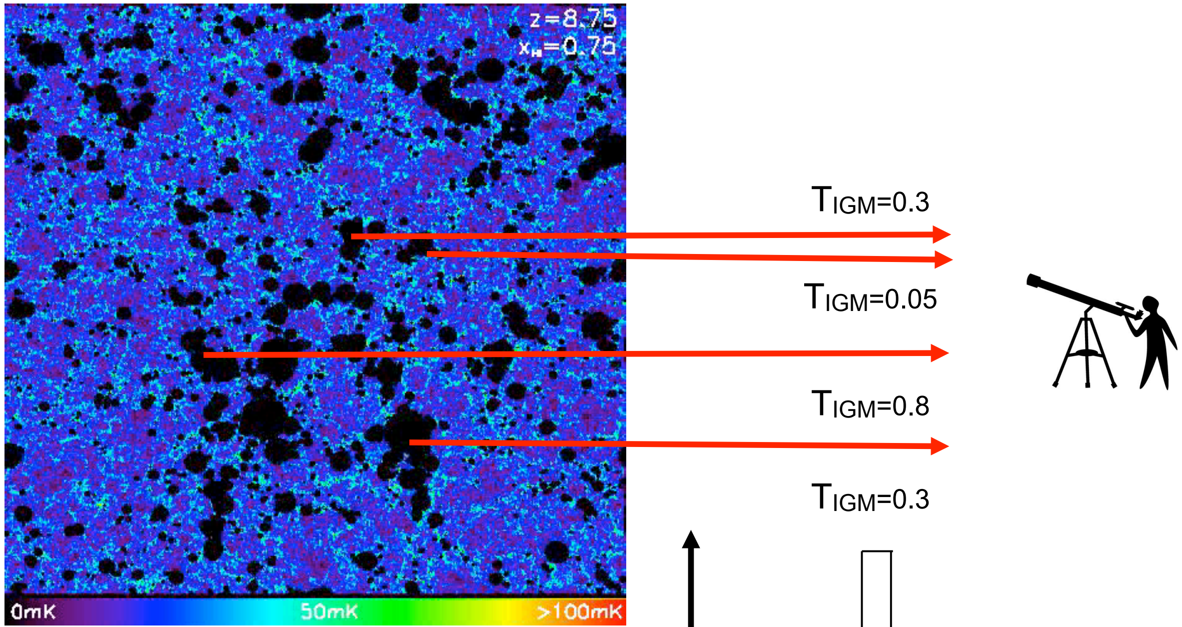
For each halo, compute the (frequency dependent) opacity of the IGM to Lyα photons, $\tau_{IGM}(\nu) \propto \int n_{HI}(s)\sigma(\nu[s])ds$.

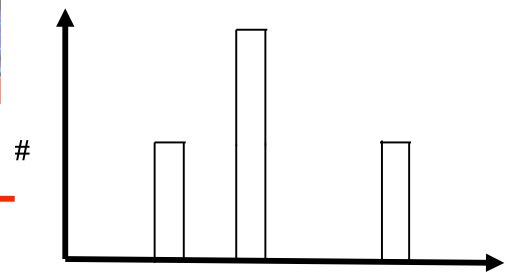
With this, compute the mean transmitted flux through the $T_{IGM} = \int L(\nu)\exp[-\tau_{IGM}(\nu)]d\nu$

Theoretical Interpretation



Theoretical Interpretation





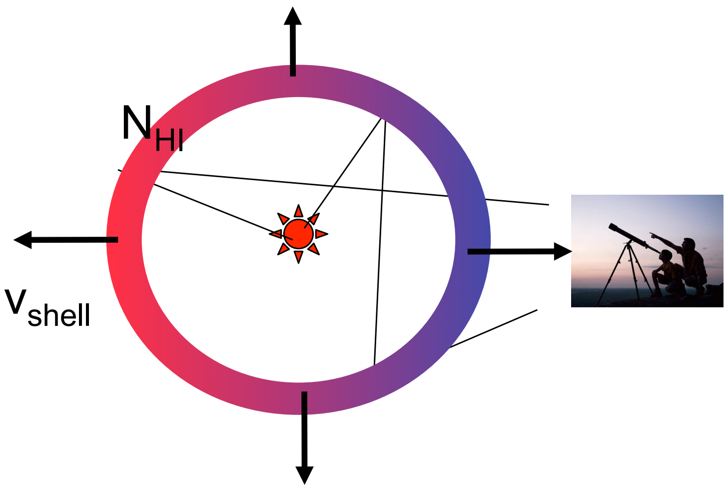
$T_{IGM}= \int L(v)\exp[-\tau_{IGM}(v)]dv$

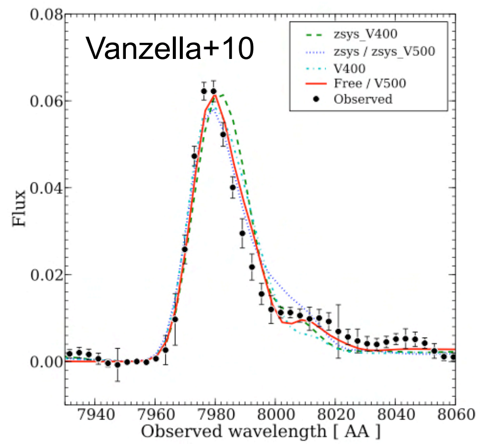
What is L(v)?

What is L(v)?

1. Gaussian, centered on galaxy's systemic velocity, σ associated with virial velocity of host dark matter halo.

2. Line shaped by scattering through outflow, represented by spherical shell (Ahn et al. +03, Verhamme+06).

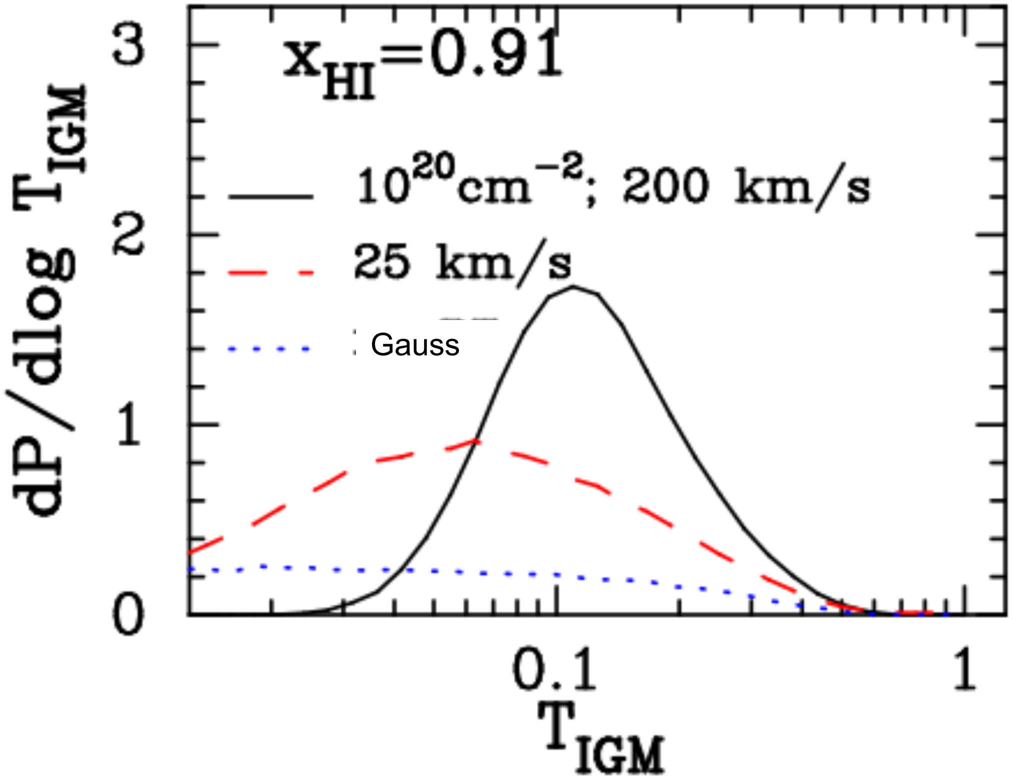




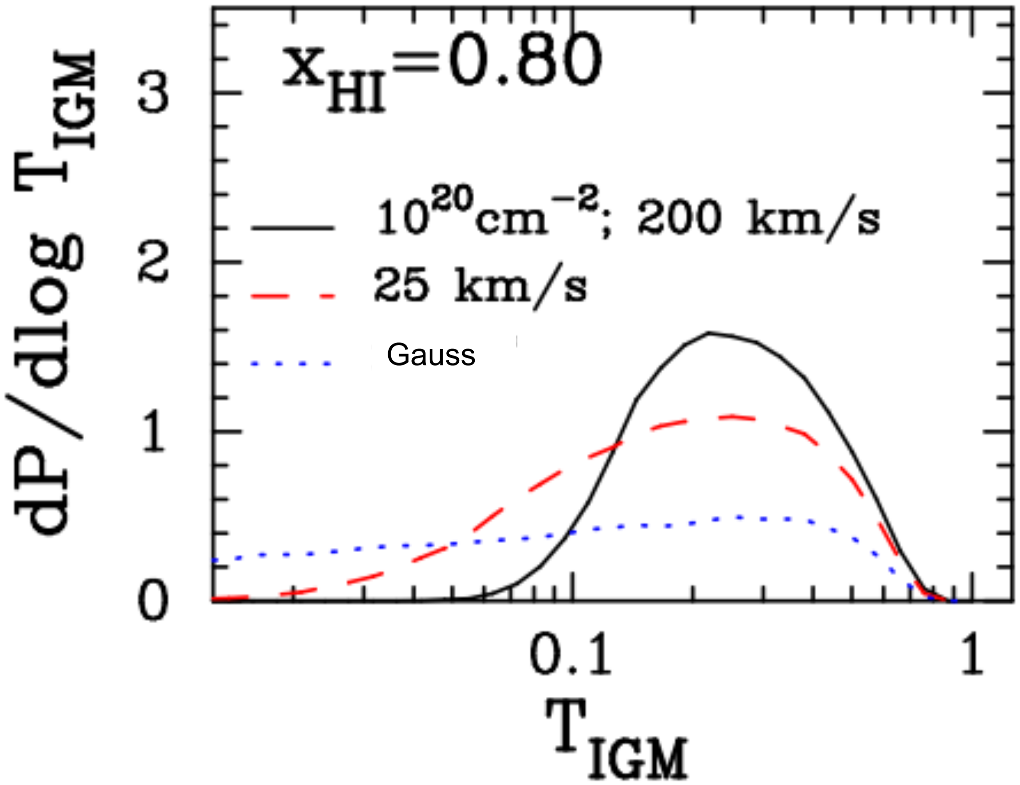
Shell model is observationally motivated `sub-grid' model of interstellar RT.

Theoretical Interpretation

Dijkstra, Mesinger & Wyithe 2011



Theoretical Interpretation



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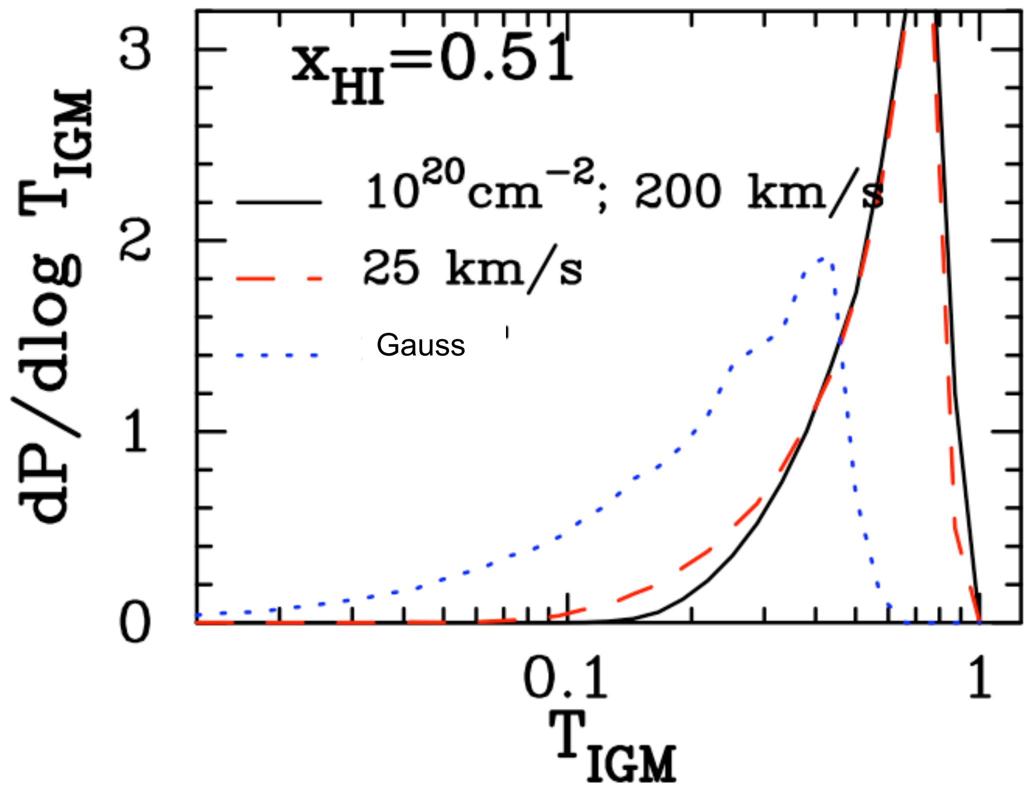
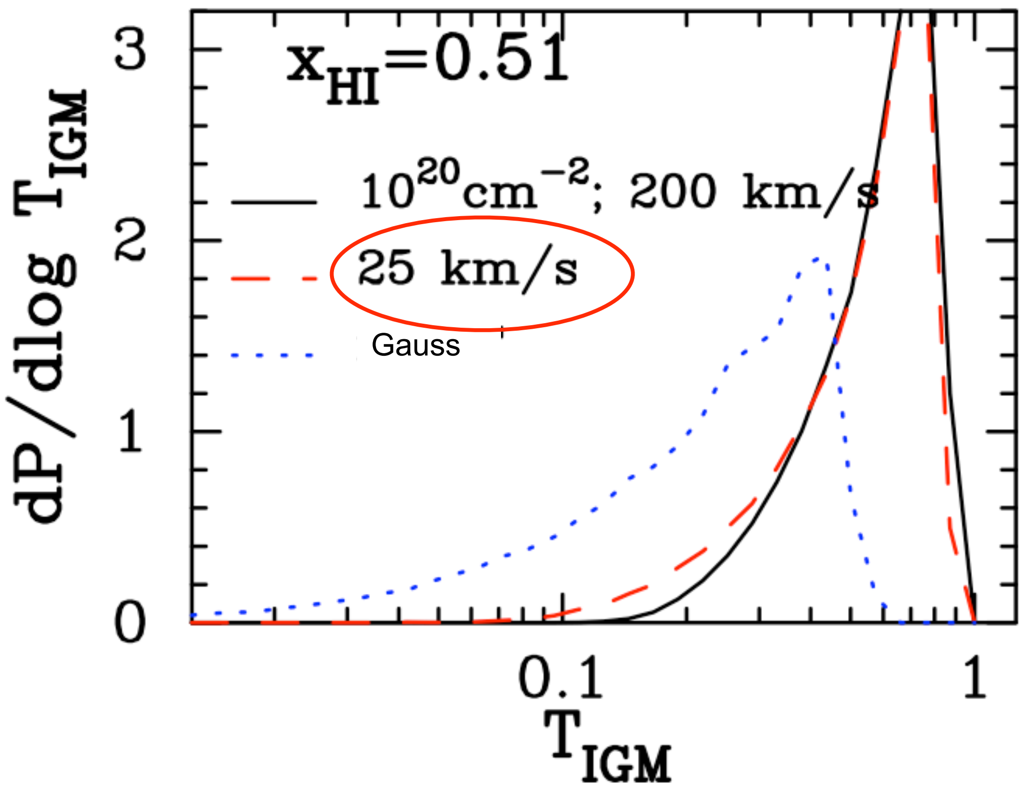


The IGM may transmit as much as ~70-80% of Lyα photons when Universe were 50% neutral by vol.

Theoretical Interpretation



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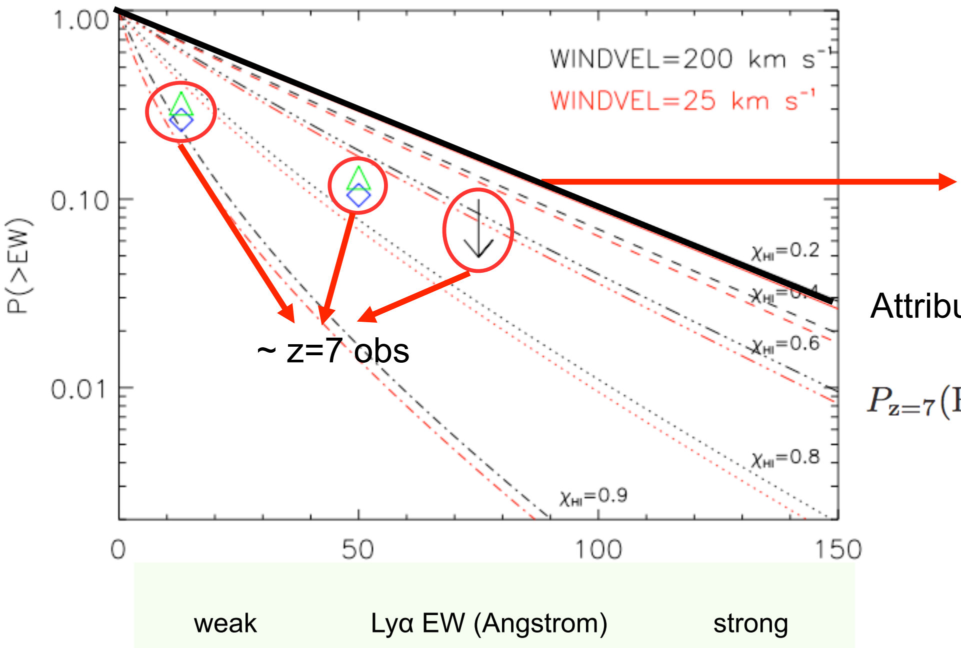
Theoretical Interpretation

Q: What if the observed dimming the Lyα line from z>6 galaxies is due to reionization?



~ z=6 EW-PDF

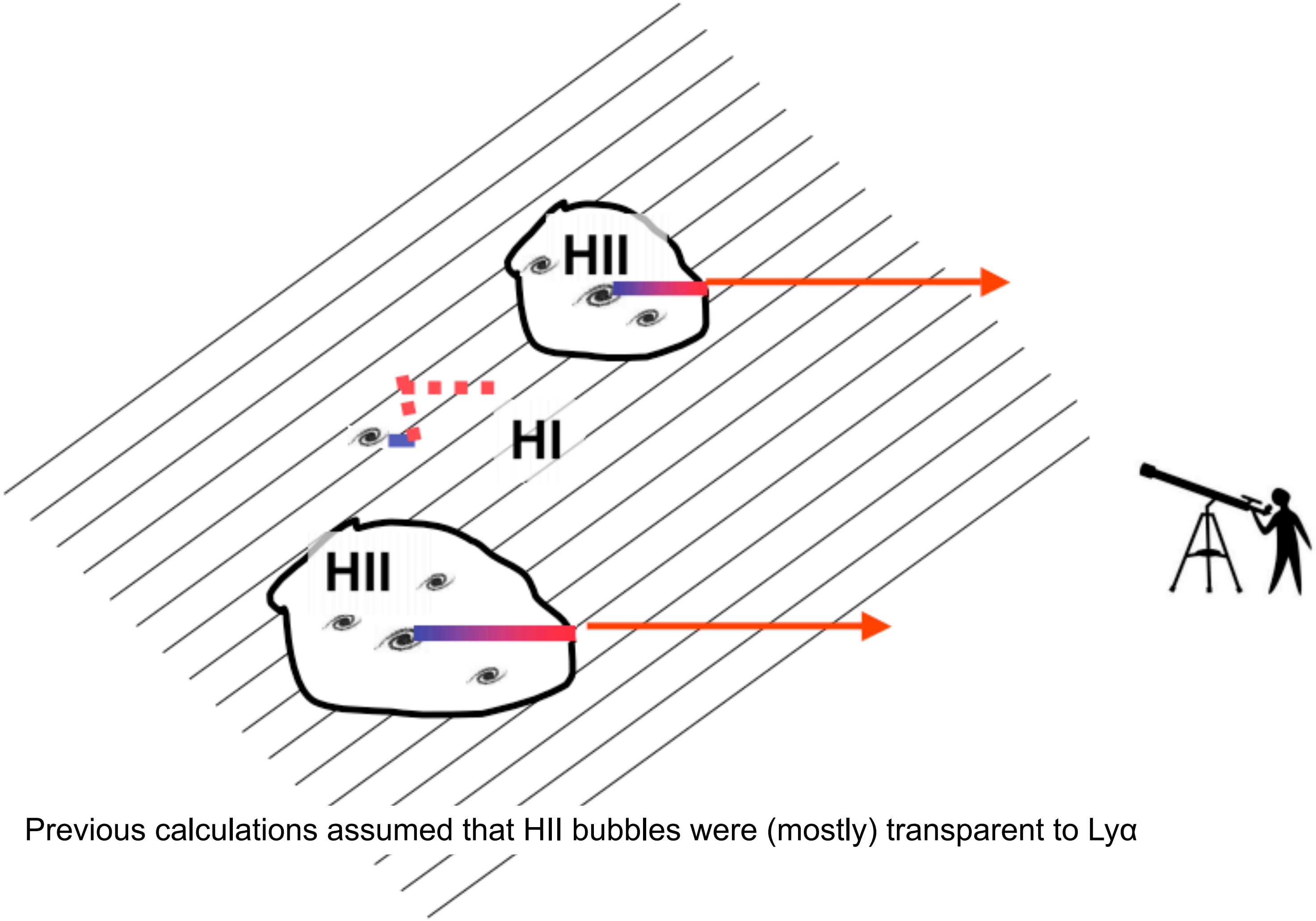
Attribute extra dimming to neutral IGM.

$$P_{\rm z=7}({\rm REW}) \;=\; \mathcal{N}\int_0^1 d\mathcal{T}_{\rm IGM}P(\mathcal{T}_{\rm IGM})P_{\rm z=6}({\rm REW}/\mathcal{T}_{\rm IGM}).$$

To match z~7 data, need x_{HI}(z=7)>0.4-0.5 (MD, Mesinger & Wyithe 2011, also see Jensen+2012)

Theoretical Interpretation: LLSs

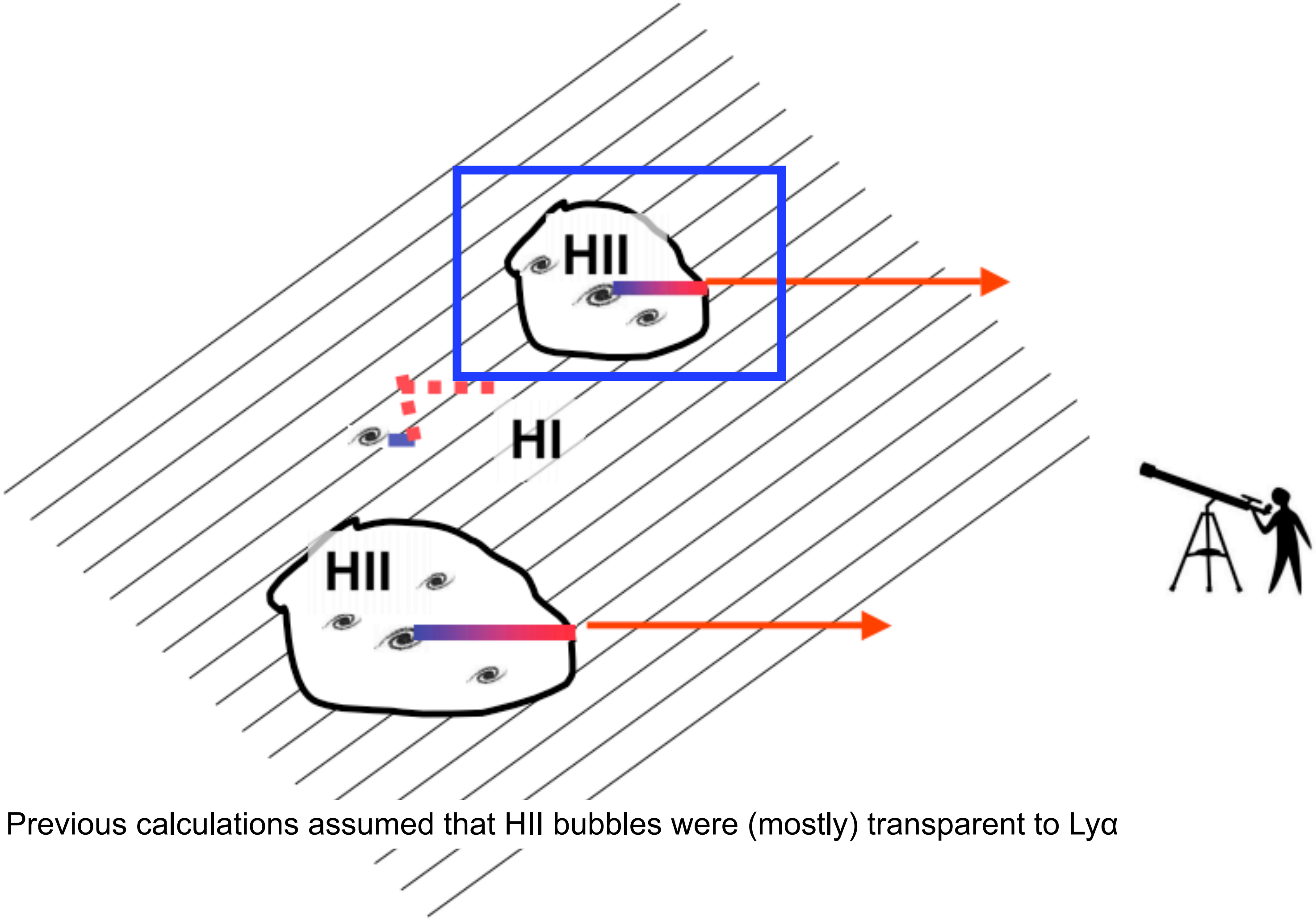
Bolton & Haehnelt (2013)



Previous calculations assumed that HII bubbles were (mostly) transparent to Lyα

Theoretical Interpretation: LLSs

Bolton & Haehnelt (2013)



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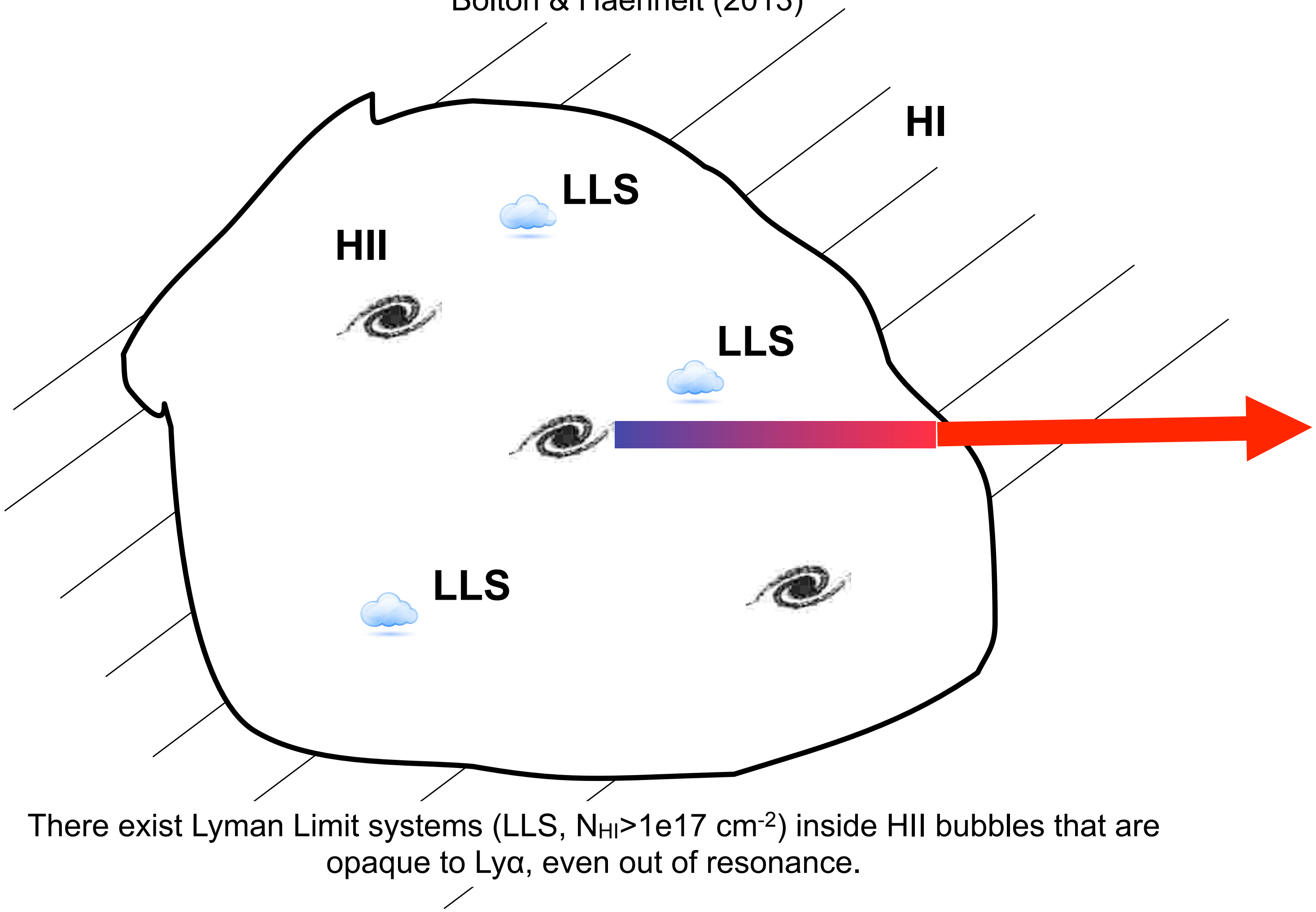

There exist Lyman Limit systems (LLS, N_{HI}>1e17 cm^{-2}) inside HII bubbles that are opaque to Lyα, even out of resonance.

Theoretical Interpretation: LLSs

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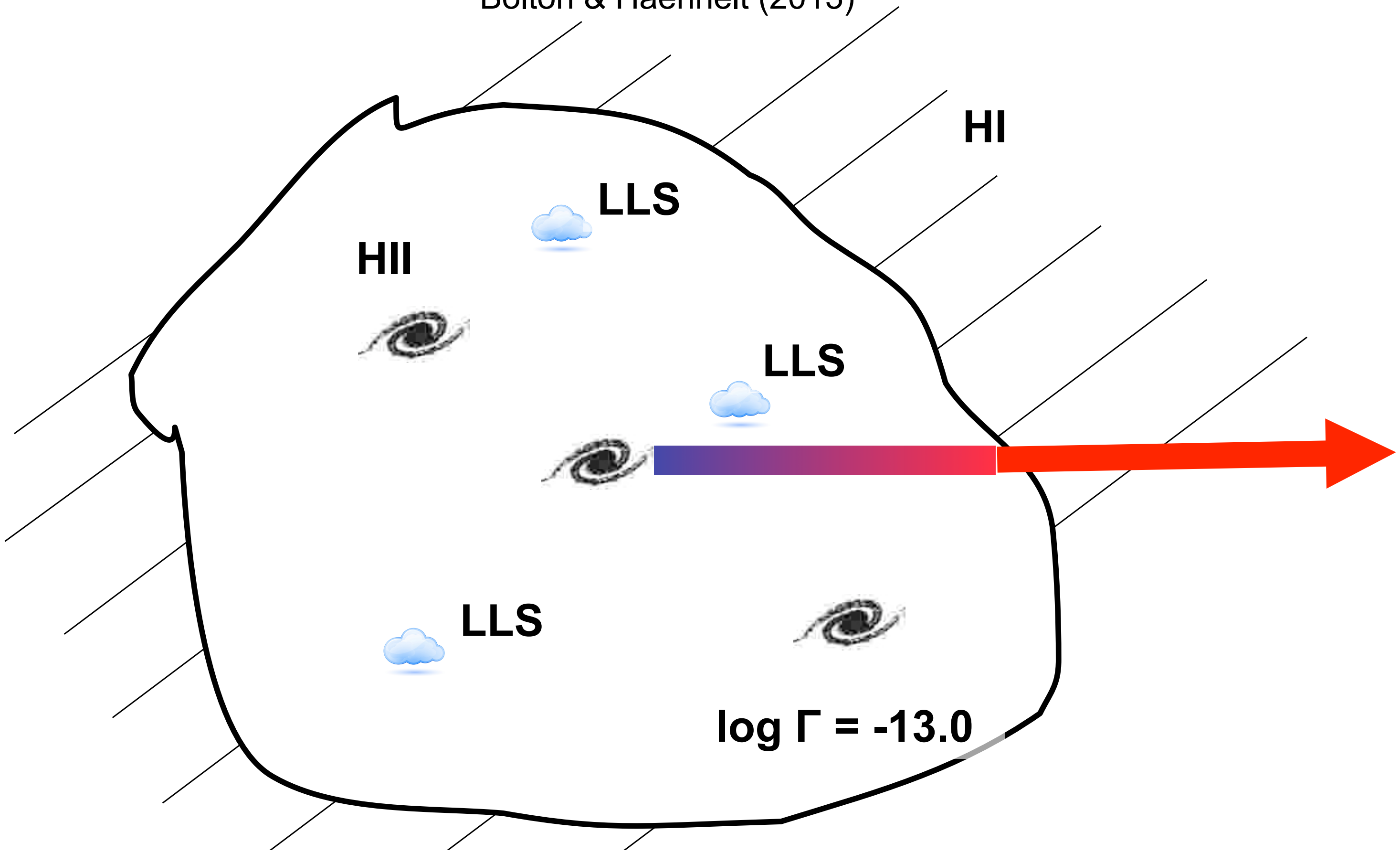

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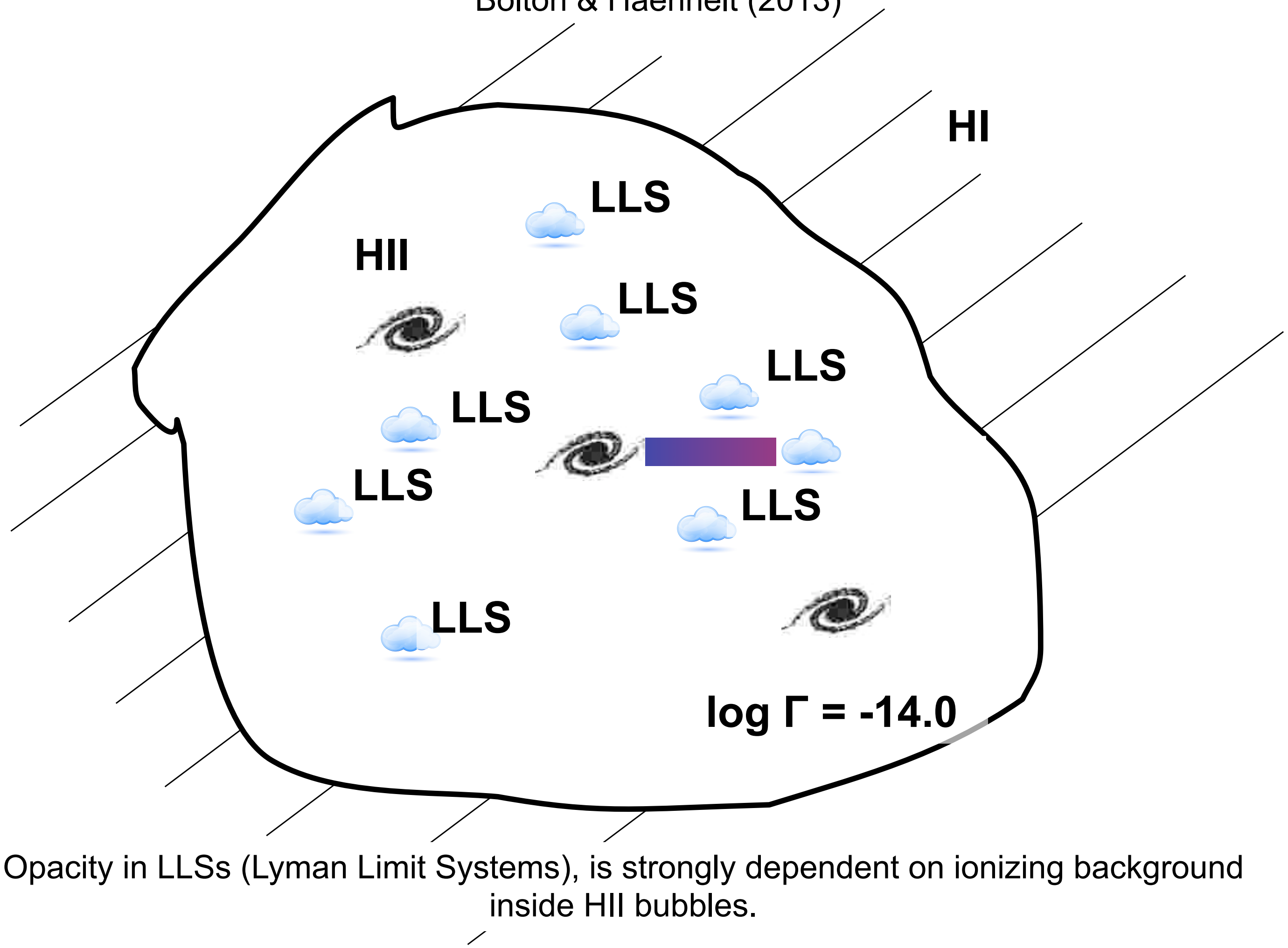
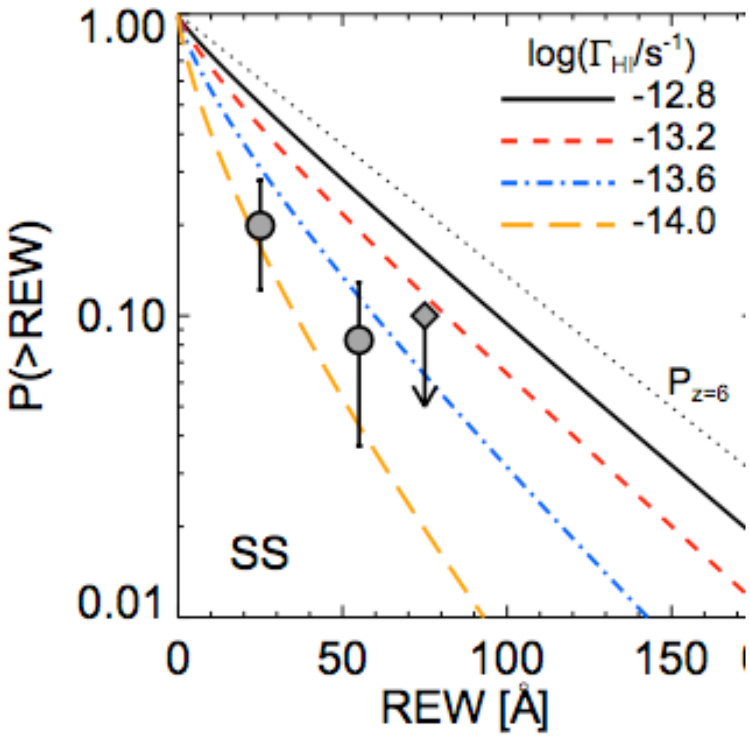


Opacity in LLSs (Lyman Limit Systems), is strongly dependent on ionizing background inside HII bubbles.

Theoretical Interpretation

Bolton & Haehnelt (2013)



Drop in Lya fraction can be mimicked by sudden drop in ionizing background -> which translates to a lower $x_{HI}(z=7) \sim 0.1$

Theoretical Interpretation

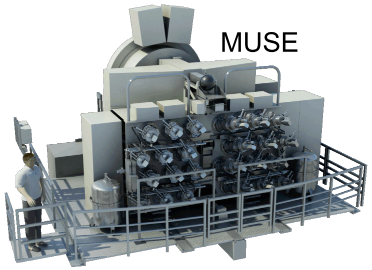
Take-away point:

Drop in Lya fraction requires $x_{HI}(z=7) \sim 0.5$ (if $x_{HI}(z=6)=0$) when we ignore Lyman limit systems altogether, but requires $x_{HI}(z=7) \sim 0.05\text{-}0.1$ if we `maximize' their importance.

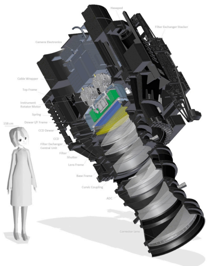
Even the weaker requirement is still strong.

Outlook

Sample of z=6 and z=7 Lyα emitting galaxies expected to increase by up to 2 orders of magnitude.
Enables clustering measurements of LAEs, which probe neutral gas in IGM (McQuinn+07, Mesinger & Furlanetto 08)



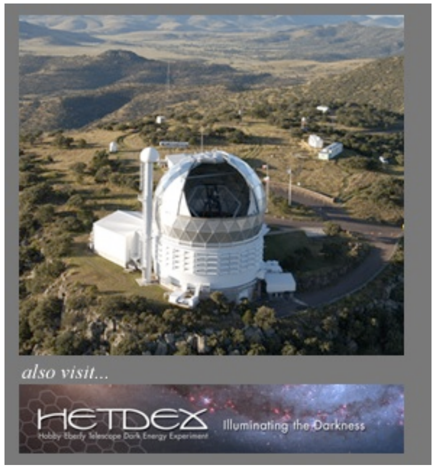
MUSE



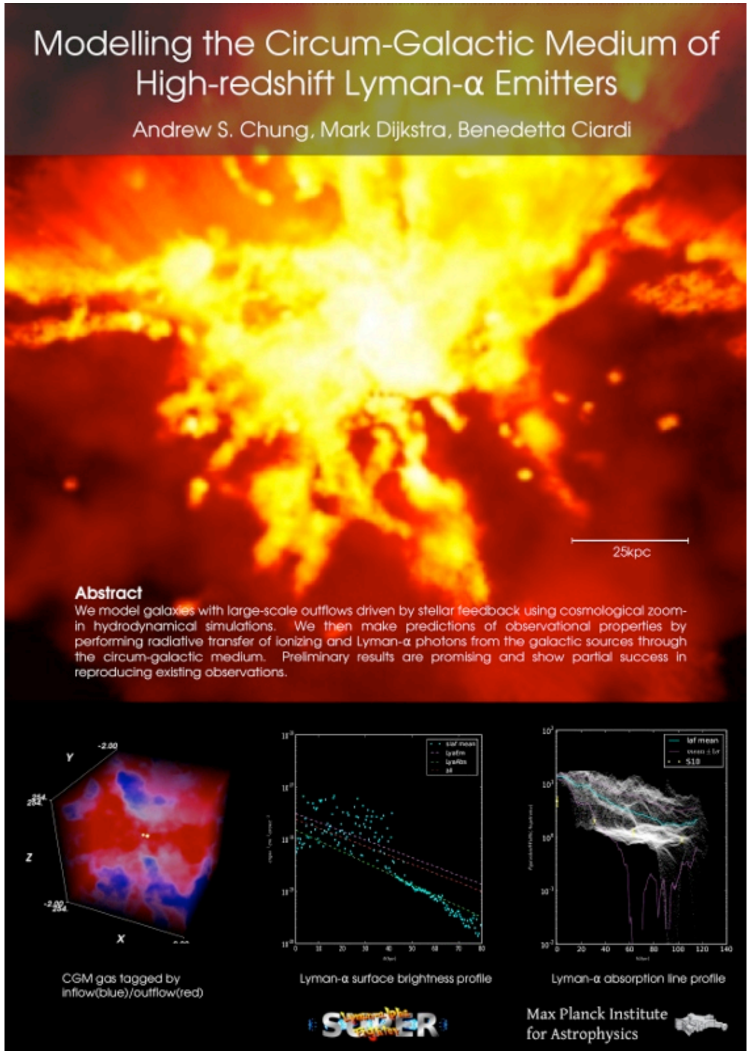
HSC

At lower z, # LAEs expected to increase by up to 3 orders of magnitude (with e.g HETDEX).

This increase in data, combined with NIR spectrographs
(NIRSPEC, MOSFIRE) is expected improve our understanding of
Lya RT on interstellar, circumgalactic + intergalactic scales dramatically.



What next?



Modelling the Circum-Galactic Medium of High-redshift Lyman-α Emitters
Andrew S. Chung, Mark Dijkstra, Benedetta Ciardi
25kpc
Abstract
We model galaxies with large-scale outflows driven by stellar feedback using cosmological zoom-in hydrodynamical simulations. We then make predictions of observational properties by performing radiative transfer of ionizing and Lyman-α photons from the galactic sources through the circum-galactic medium. Preliminary results are promising and show partial success in reproducing existing observations.
CGM gas tagged by inflow(blue)/outflow(red)
Lyman-α surface brightness profile
Lyman-α absorption line profile
Max Planck Institute for Astrophysics

Conclusions

The `escape fraction' of Lya photons from the ISM of star forming galaxies increases with z, between z=0 and z=6.

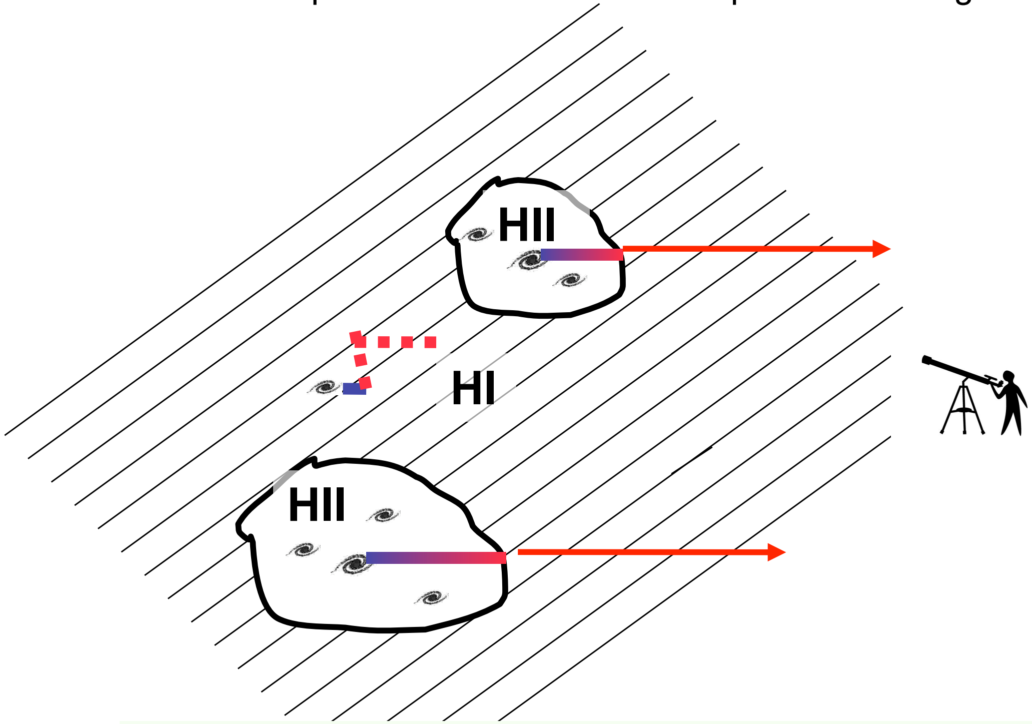
This trend suddenly changes sign at z>6, and is a natural & predicted consequence of the EoR.

If EoR were fully responsible for this reversal, the neutral fraction of the ionization state appears to evolve rapidly over a short time-scale.

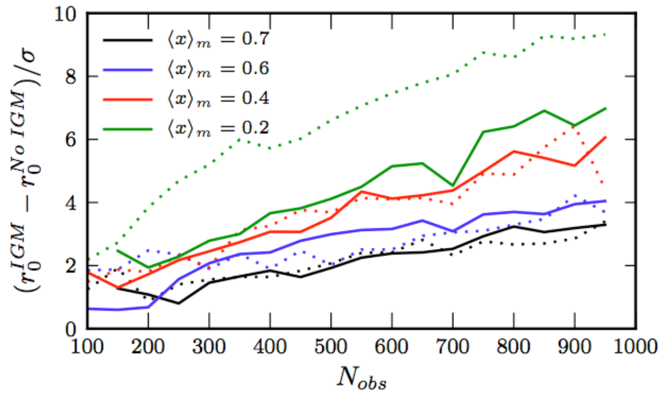
A quantitative understanding of the required change in the ionization state still limited by uncertainties in radiative transfer modeling.

What next?

Neutral IGM is expected to affect observed spatial clustering of LAEs (McQuinn+07, Mesinger & Furlanetto 08).



Jensen+ 2012



With a few hundred to one thousand AEs we should be able to measure clustering signal from neutral IGM down to x_{HI}=0.2 (Jensen+12, McQuinn+07)

In progress: predict clustering (2-point function, count-in-cells) for DMW11-model, including LLS (as in Bolton & Haehnelt 2013)

Conclusions.

Neutral IGM during the EoR predicted to dim the Lya flux from galaxies.

A sudden dimming of the Lya line has now been observed for galaxies at z>6.

At face value, the observed dimming requires very fast evolution in x_{HI} in context of inhomogeneous reionization.

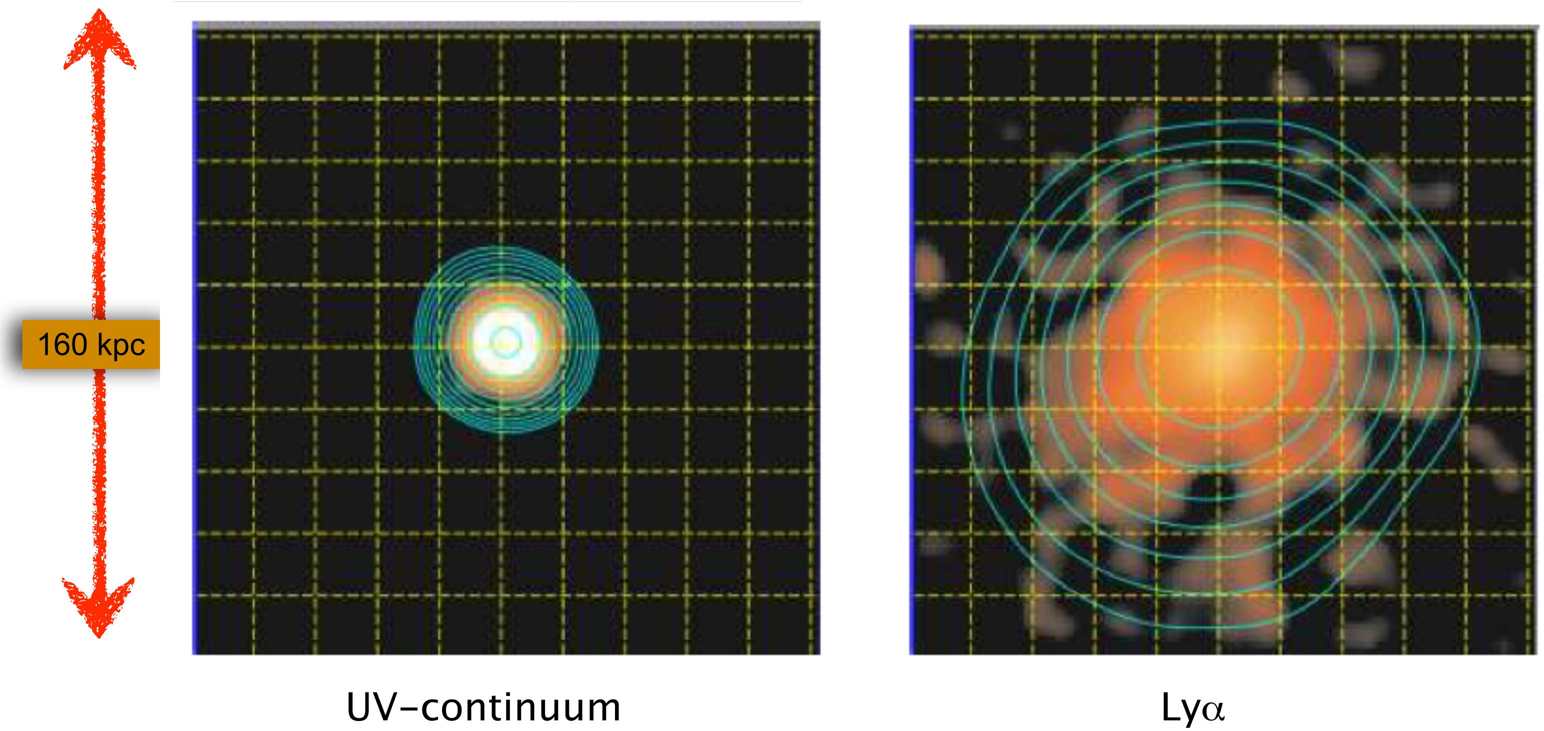
Main current uncertainties related to
1. sample sizes of Lya emitting galaxies at z=6 and z=7.
2. limited understanding of especially interstellar RT.

Progress expected!
LAE (broadest sense) sample sizes at all z expected to grow by 1-3 orders of magnitude.
Lya line shapes + NIR spectroscopy is expected to improve our understanding of RT.

Closely related to our understanding of cold gas flows, in and around galaxies. Plays key role in our understanding of galaxy formation & evolution.

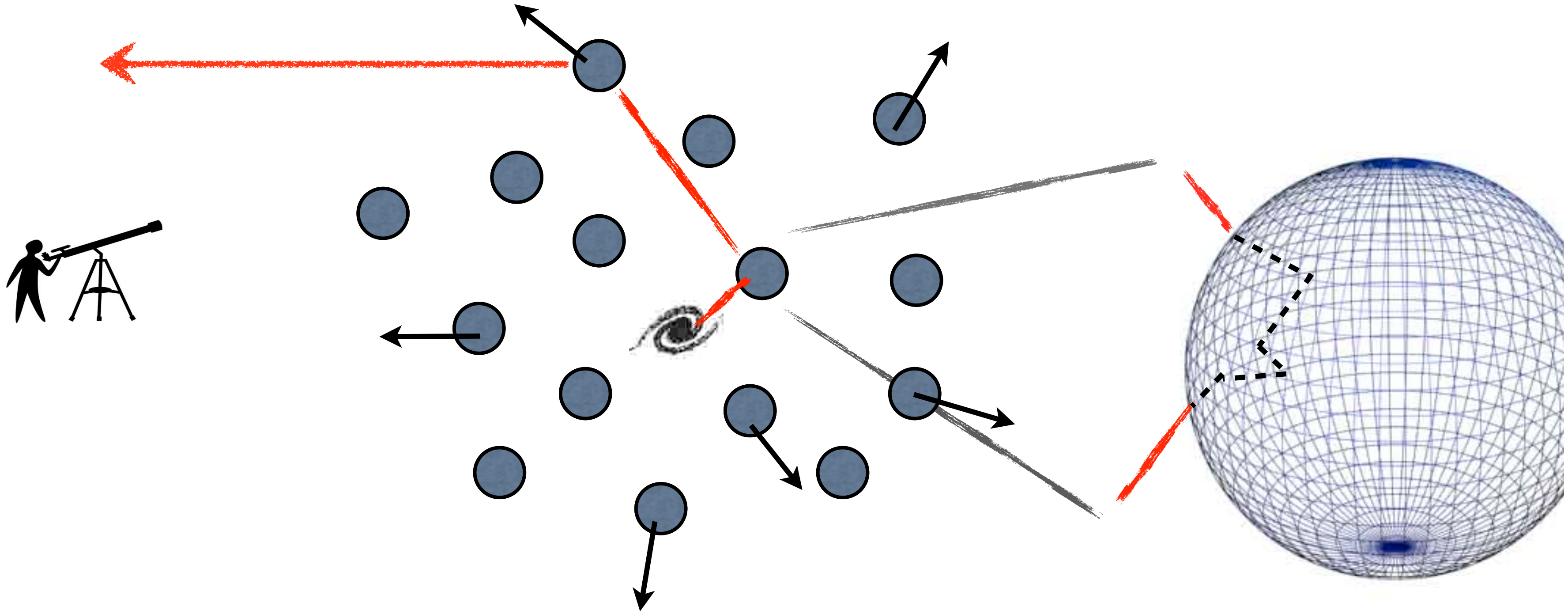
Observed Scattering in the CGM

Steidel et al. 2011, also see Matsuda et al. 2012, but see Feldmeier et al. 2013, Jiang et al. 2013



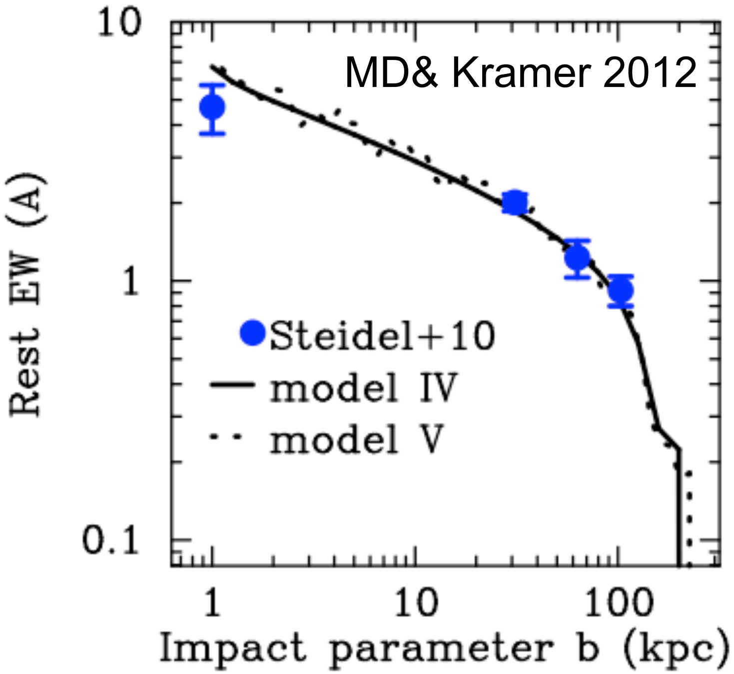
But..Steidel et al. 2011 see strong evidence for prominent outflows (low ionization metal absorption lines + Lya emission line shape + shift), in contrast to model, and argue for the existence of large scale outflows of cold gas.

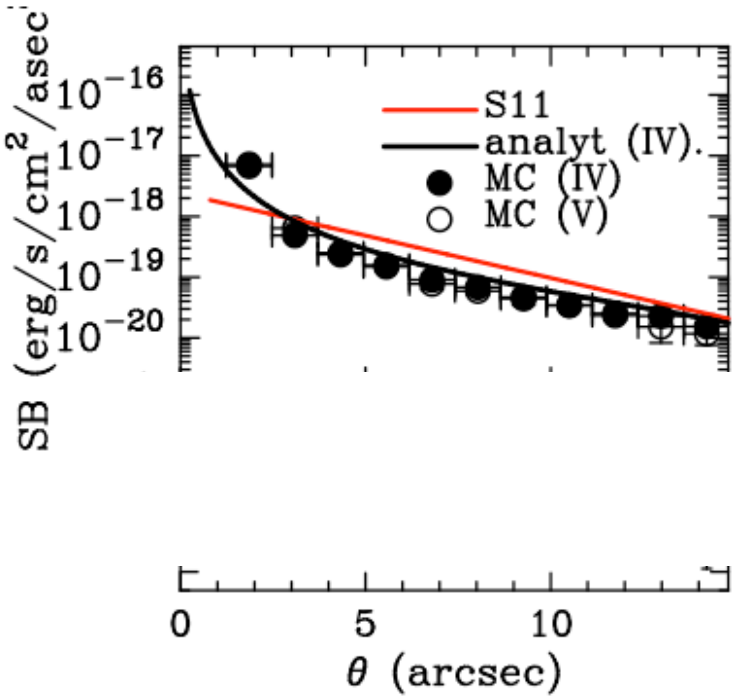
Scattering through large scale outflows?



Monte Carlo Lyα radiative transfer code from MD & Kramer (2012).

Modeling Scattering through Outflows in the CGM





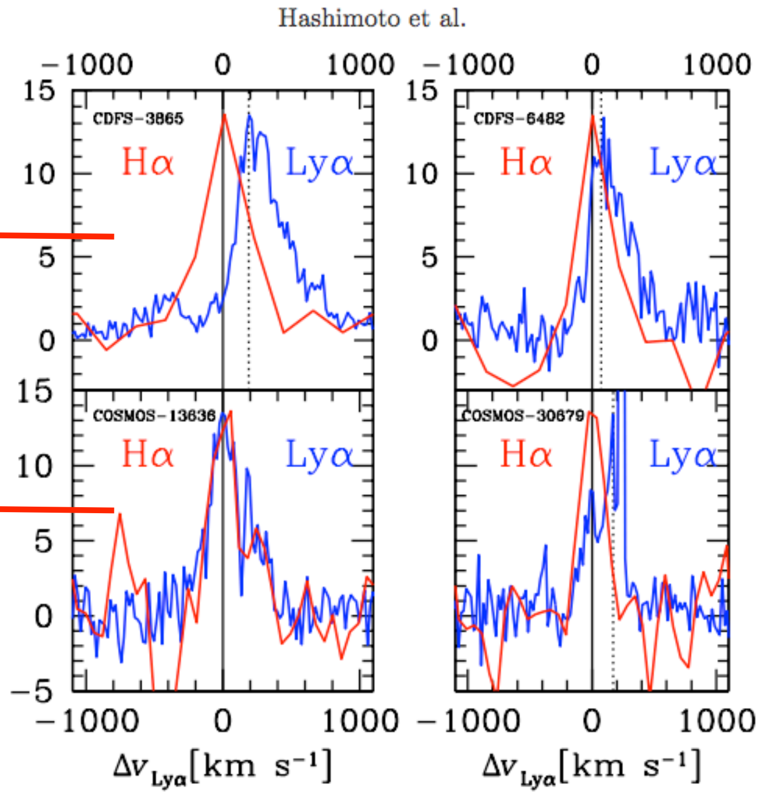
It is possible to Lyα halos around star forming galaxies via scattering in large scale outflow.
These models give rise to different spectra (and polarization) than inflow models.

2. Improve Understanding of Lya RT.

NIR Spectroscopy.

Scattering through outflow shift Lyα compared to Hα.

Lyα similar to Hα, no scattering?

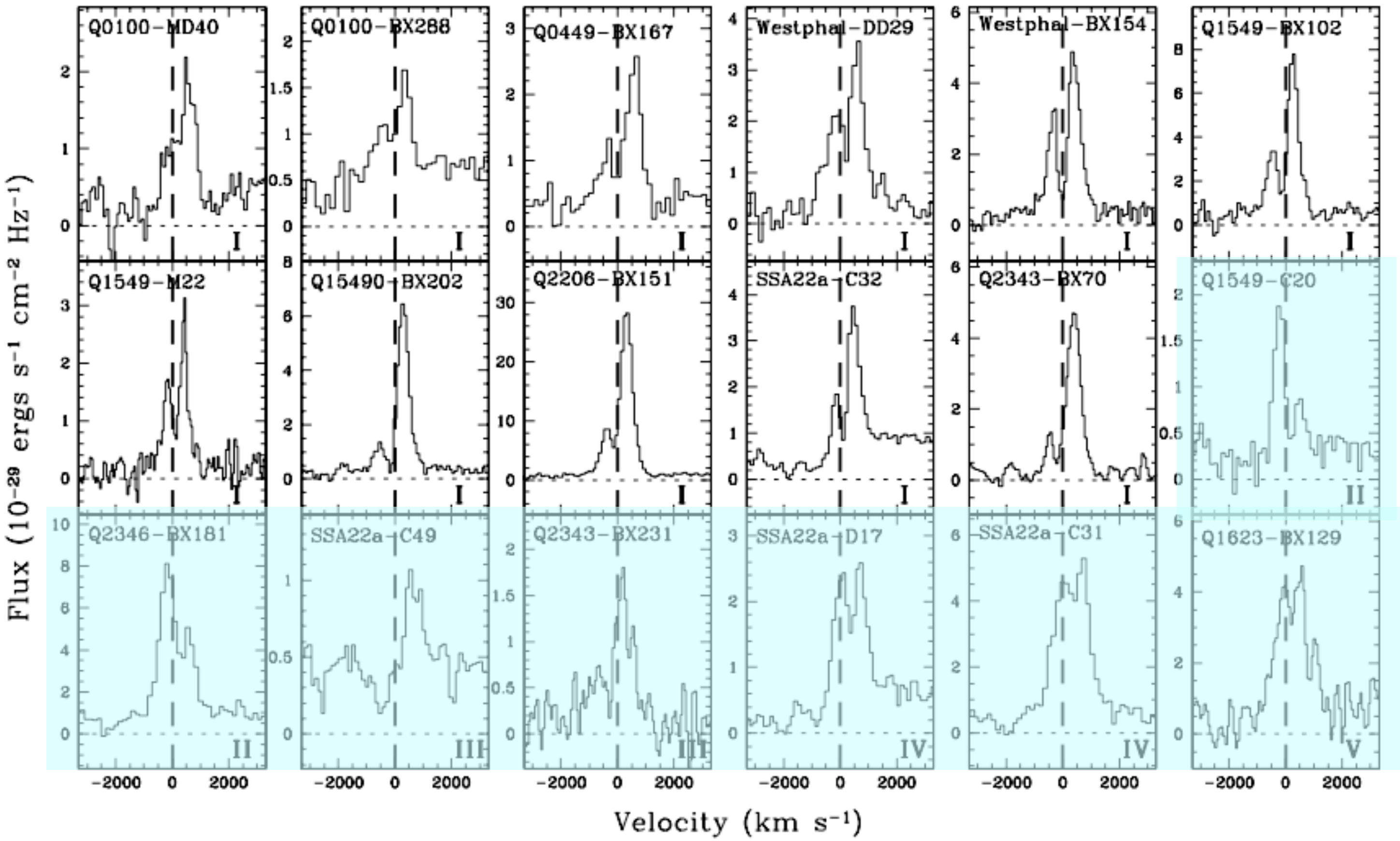


Having (restframe) optical nebular lines constrains shape of Lyα line prior to scattering.
Lyα affected by cold gas in galaxies ->probe of it's kinematics in (and around) galaxies.

2. Improve Understanding of Lya RT.

Kulas+2012

NIR Spectroscopy.

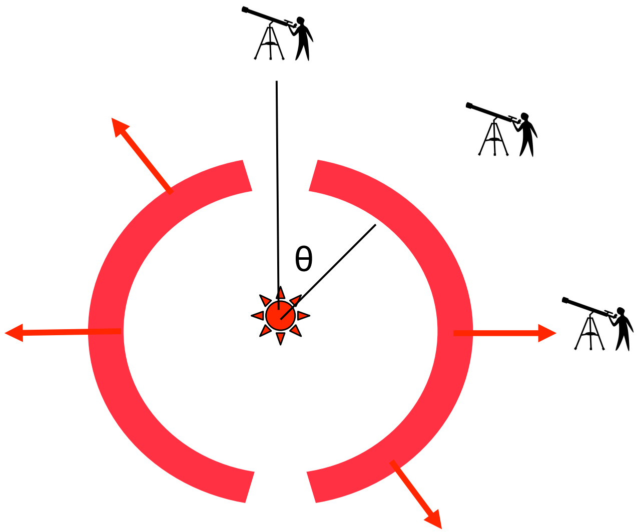


Determination of systemic velocity introduces potential difficulties for the `shell'-models, in particular for the spectra shaded in blue..

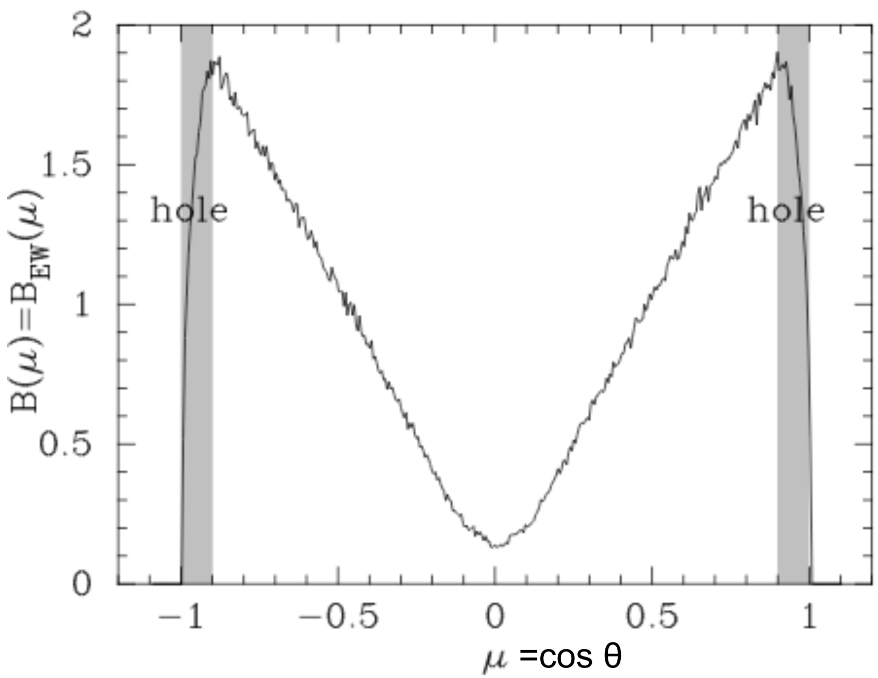
`Perturbing' the Shell Model

Study impact of simple departures from shell model on predicted spectrum:
(in collaboration with C. Behrens & J. Niemeyer)

1. Biconical outflows, $v_{out}=v(1+A \cos \theta)$
2. Shells with holes



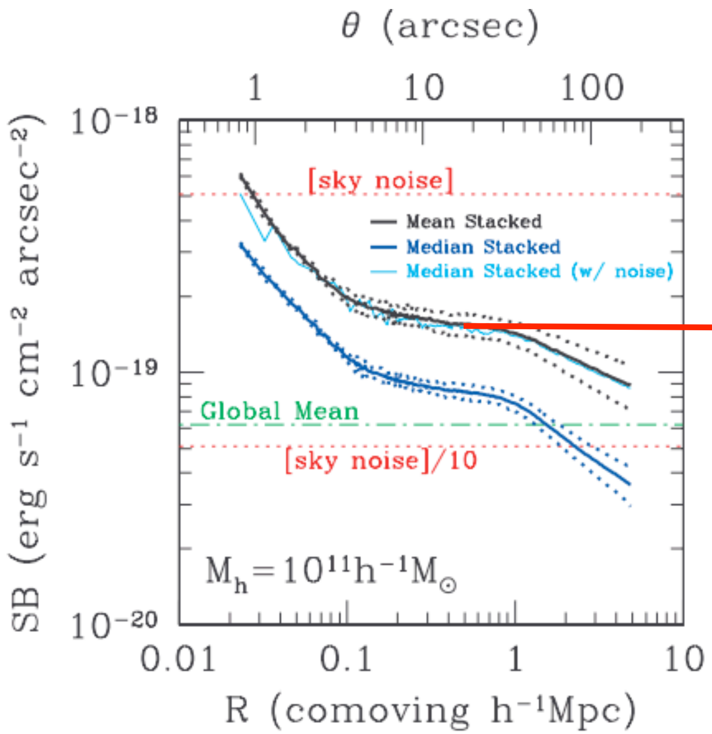
Spectra still under analysis. Photons can escape anisotropically.



Low-HI column density channels can lead to highly anisotropic escape -> equivalent width boosting? (also see e.g. Verhamme+12)

Scattering in the CGM

Theory predicts Lyα photons scatter in the CGM after they escape from galaxy (Zheng+2011).



Surface brightness profile:
Gaussian line profile + no winds

Scattering in the CGM

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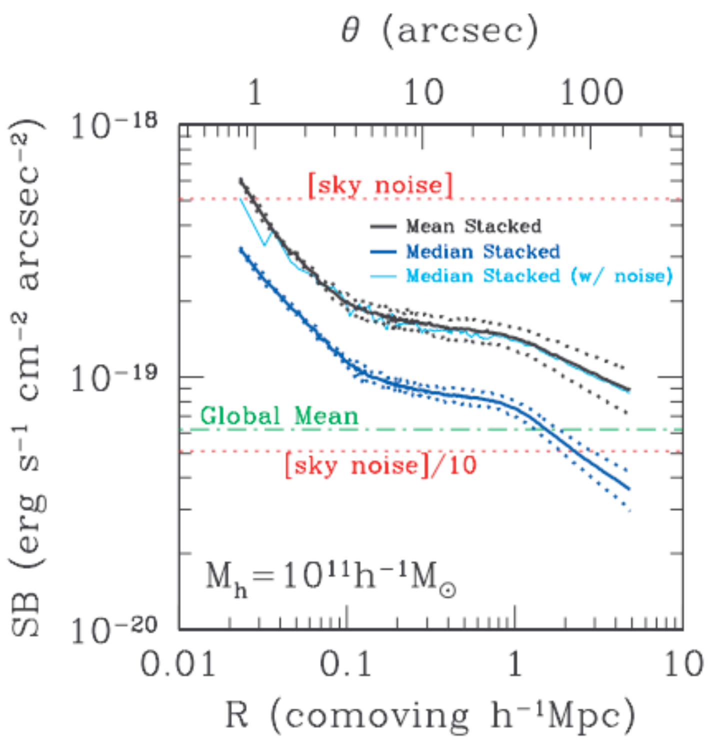
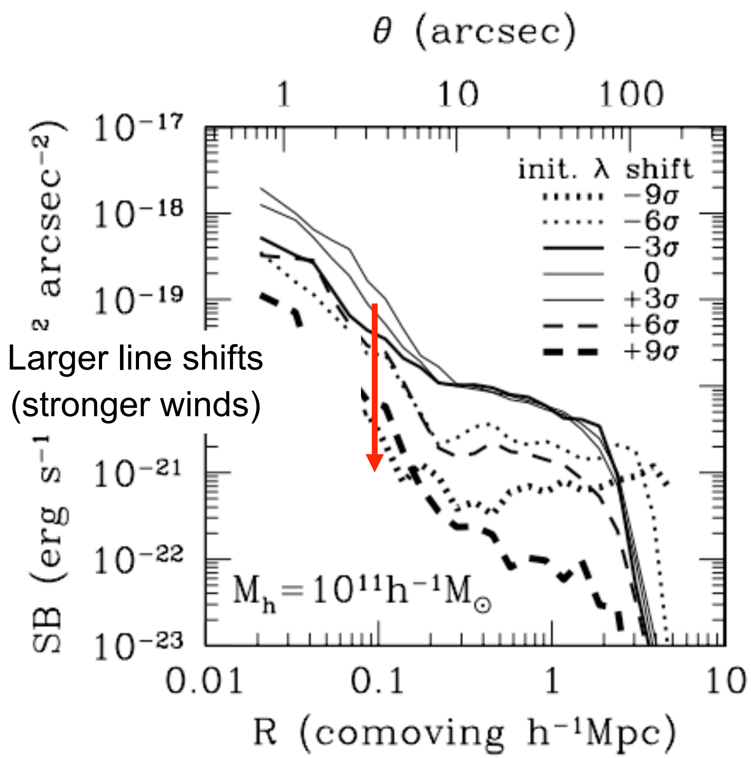




Predicted SB depends on the assumed initial line profile, i.e. RT through ISM on small scales.

Theoretical Interpretation

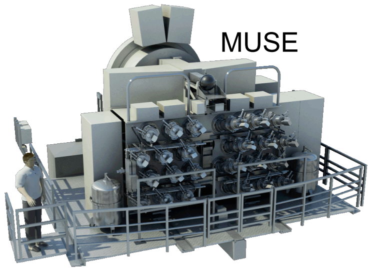
Q: What if the observed dimming the Lyα line from $z>6$ galaxies is due to reionization?

A: Then we require an extremely (physically not plausible) fast evolution in the global HI fraction.

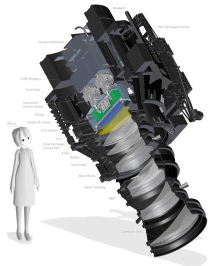
...but, existing constraints derive from data that consists of ~ 100 LAEs at $z\sim6$ and fewer at $z=7$

What next?

1. Increase sample on z=6 and z=7 Lyα emitting galaxies.
   This will happen with MUSE on VLT, Hypersuprime Camera on Subaru etc (by 2[?] orders of magnitude)



MUSE



HSC

2. Improve our understanding of Lya RT on interstellar, circumgalactic + intergalactic scales.
   Will happen with larger LAE samples at lower z provided by above instruments, but also e.g HETDEX.
   as well as NIR spectrographs (NIRSPEC, MOSFIRE).