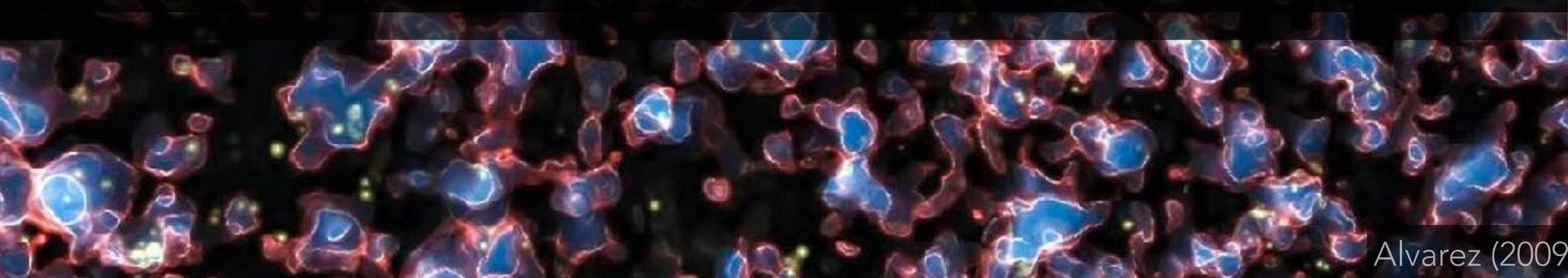
Charlotte Mason
University of Melbourne, 24 July 2019

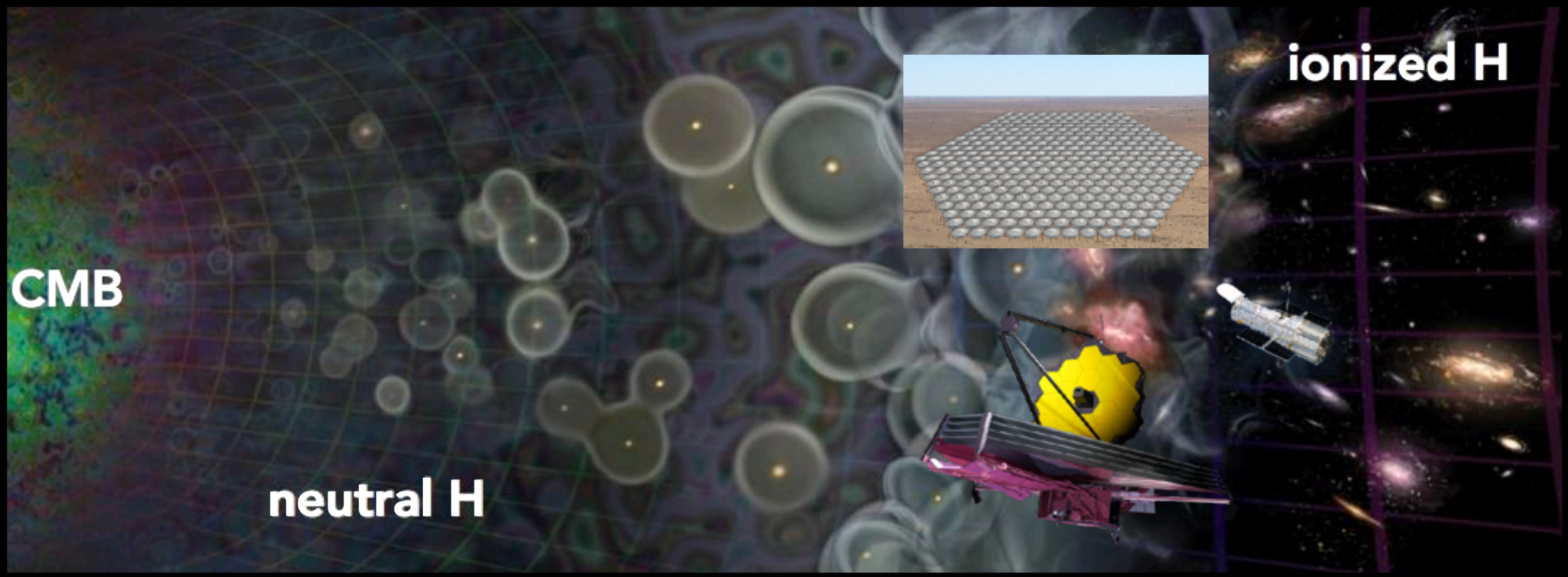
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

What can Lyα emission from galaxies tell us about reionization?

with Tommaso Treu, Mark Dijkstra, Andrei Mesinger, Adriano Fontana, Michele Trenti, Lily Whitler, Keven Ren+ GLASS & BoRG teams



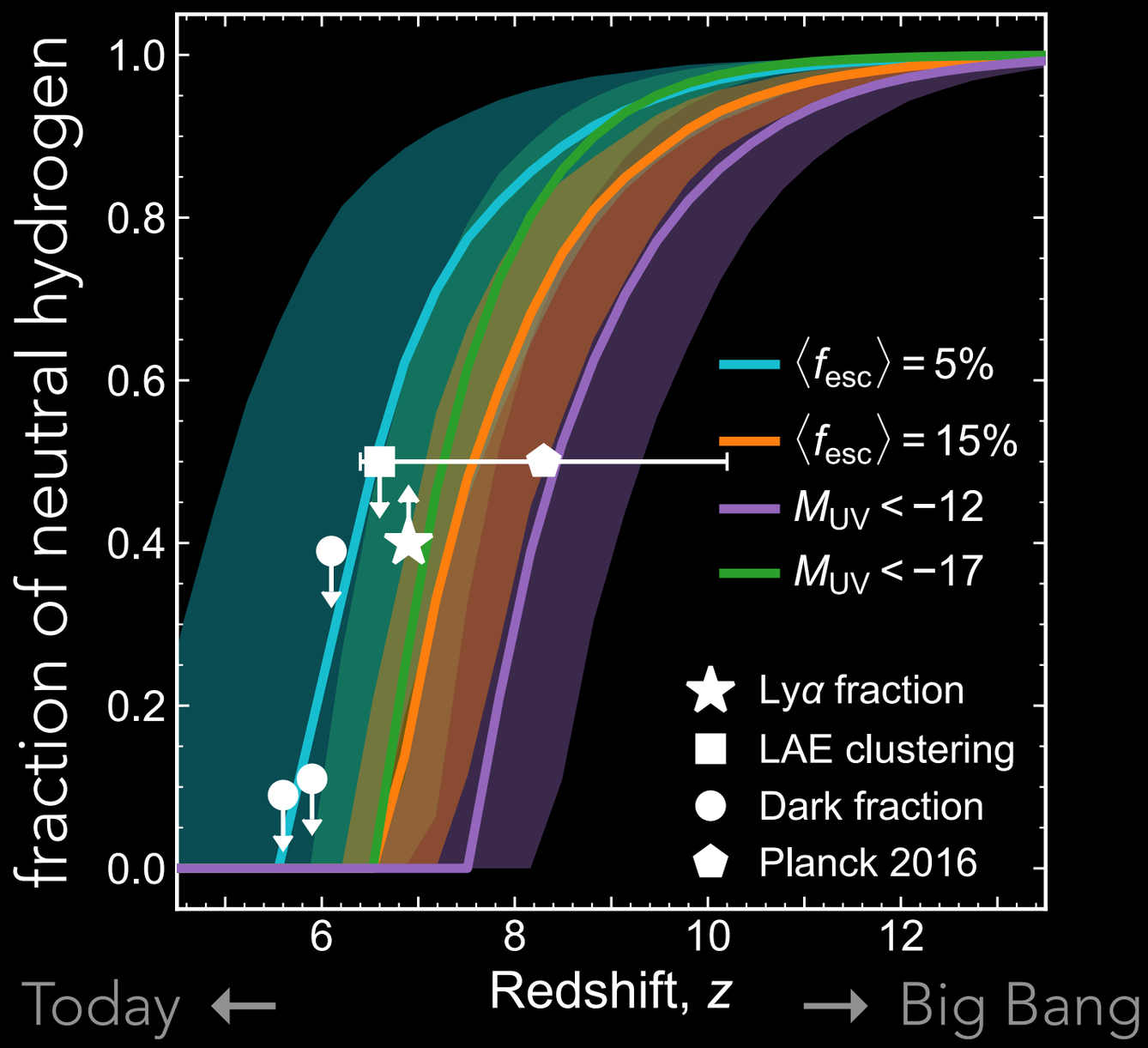
Reionization is intrinsically linked to the formation of the first stars and galaxies



Loeb (2006)

← fewer ionizing photons get out of galaxies

more galaxies →

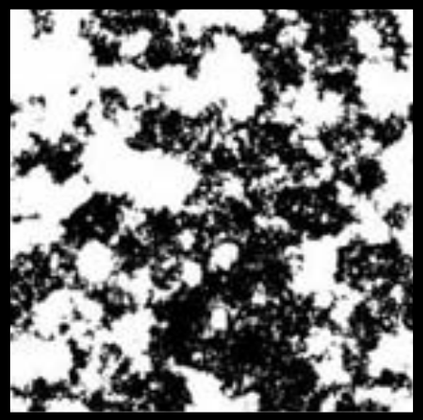


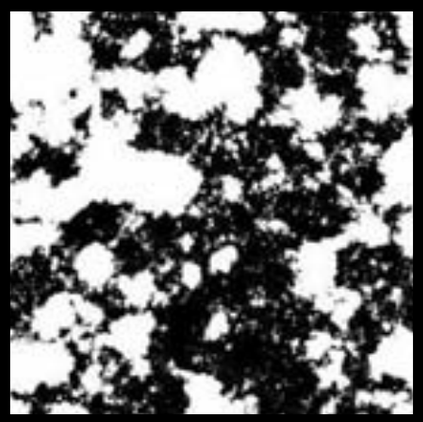
What is the **timeline** and topology of reionization?

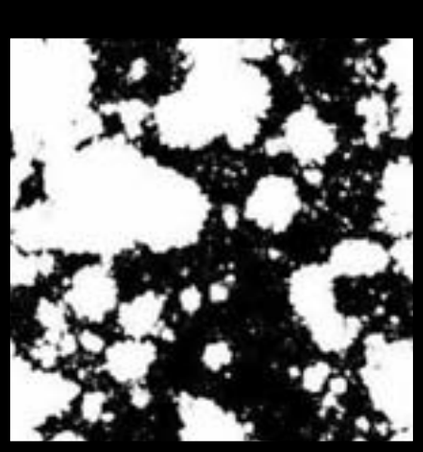
Models from Mason+15, constraints from Ouchi+10, McGreer+2014, Mesinger+15, Sobacchi+15

All 50% ionized

200 cMpc







Numerous low mass galaxies dominate

little bubbles

What is the timeline and **topology** of reionization?

McQuinn+07

Highly clustered sources — high mass galaxies and/or AGN

big bubbles

What is the **timeline** and topology of reionization?

Observe imprint of neutral IGM on galaxies (+quasars, GRBs)

Forward model to connect Lyα observations to IGM state

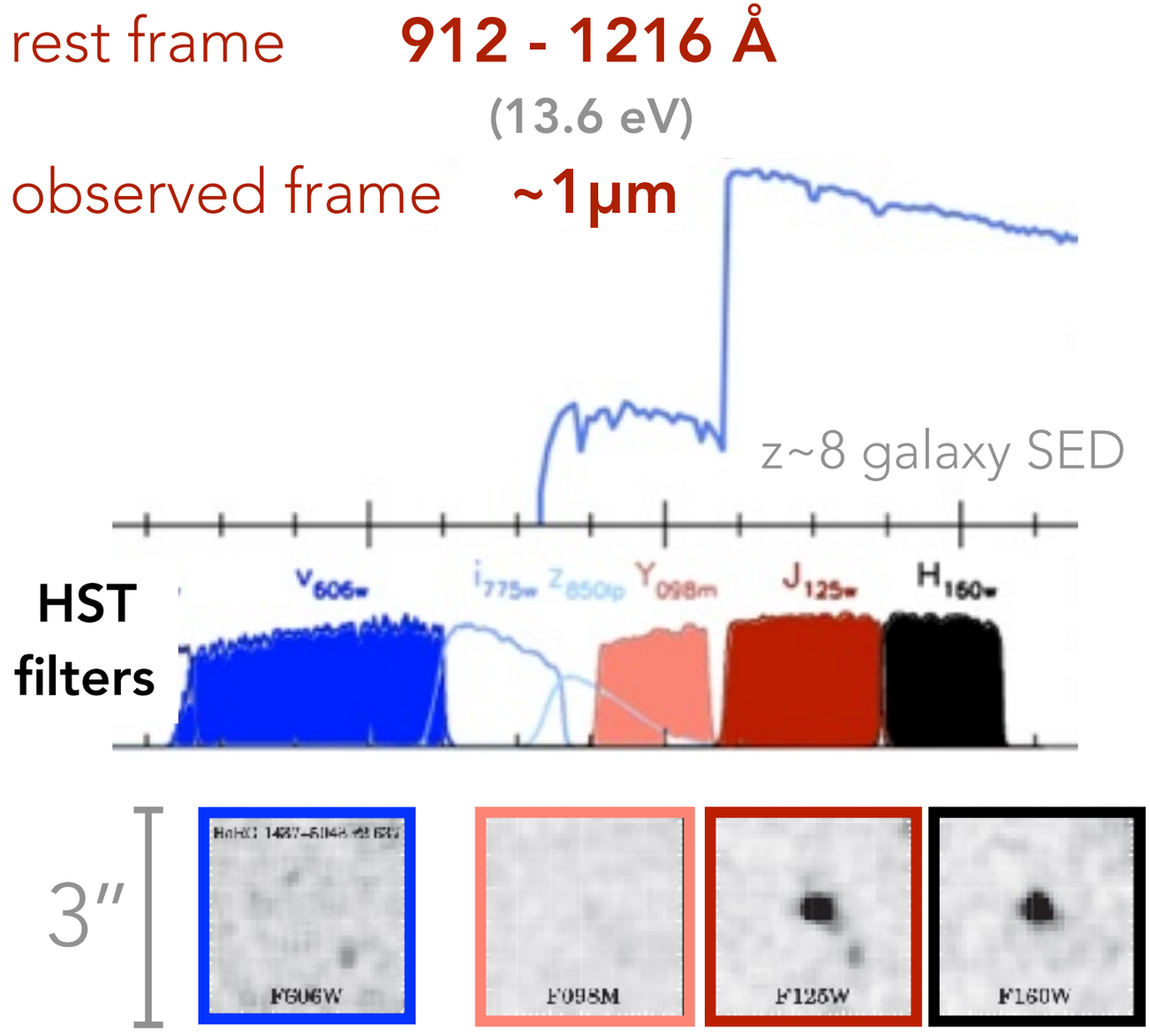
Observe neutral hydrogen via 21cm emission

Impact of reionization heating on formation of dwarfs

To detect high-redshift galaxies we exploit the IGM and the properties of their young stellar populations

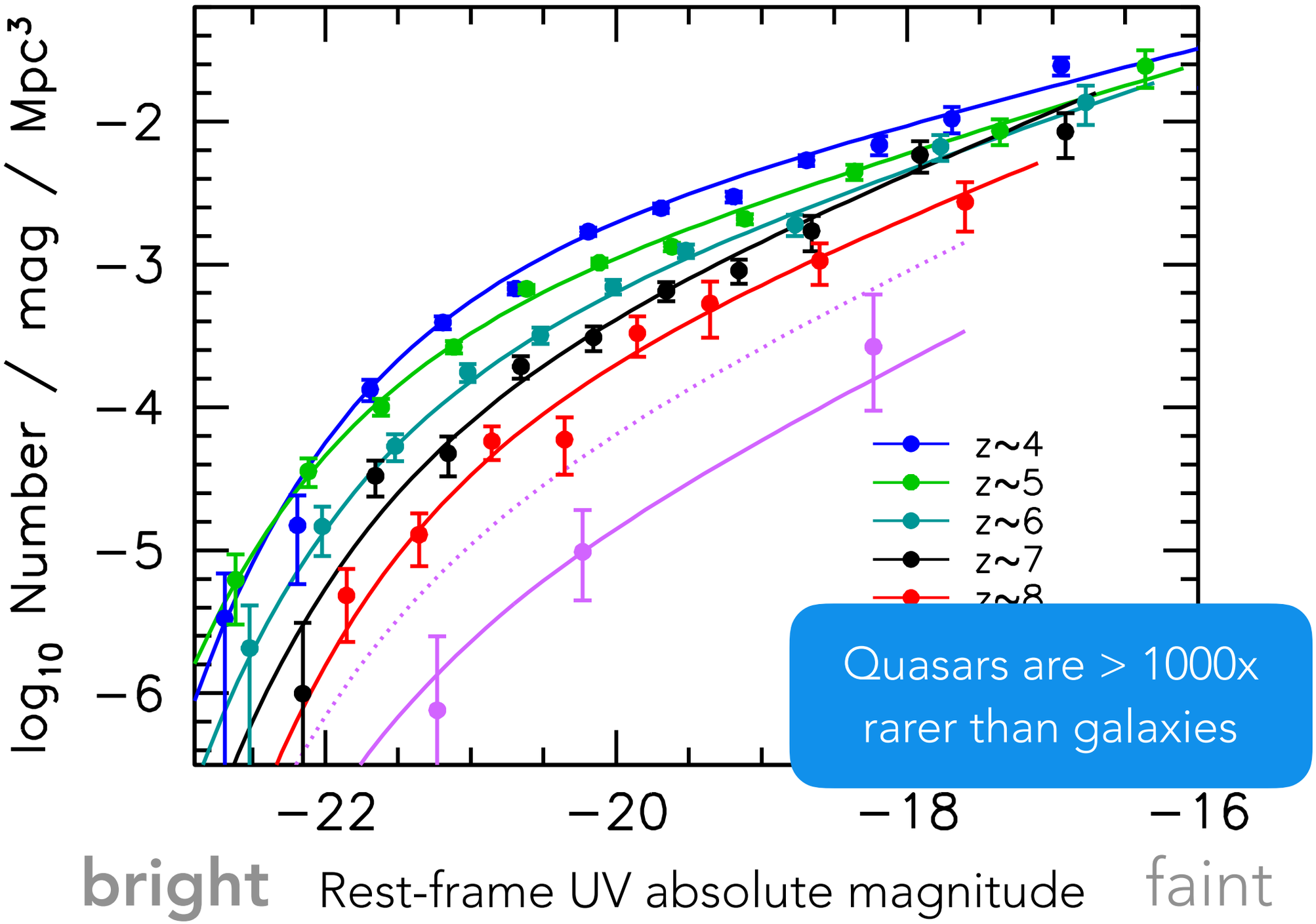
Dominated by massive stars emitting in the UV

‘Lyman-break’ due to absorption by neutral H blueward of Lyman limit in ISM and IGM



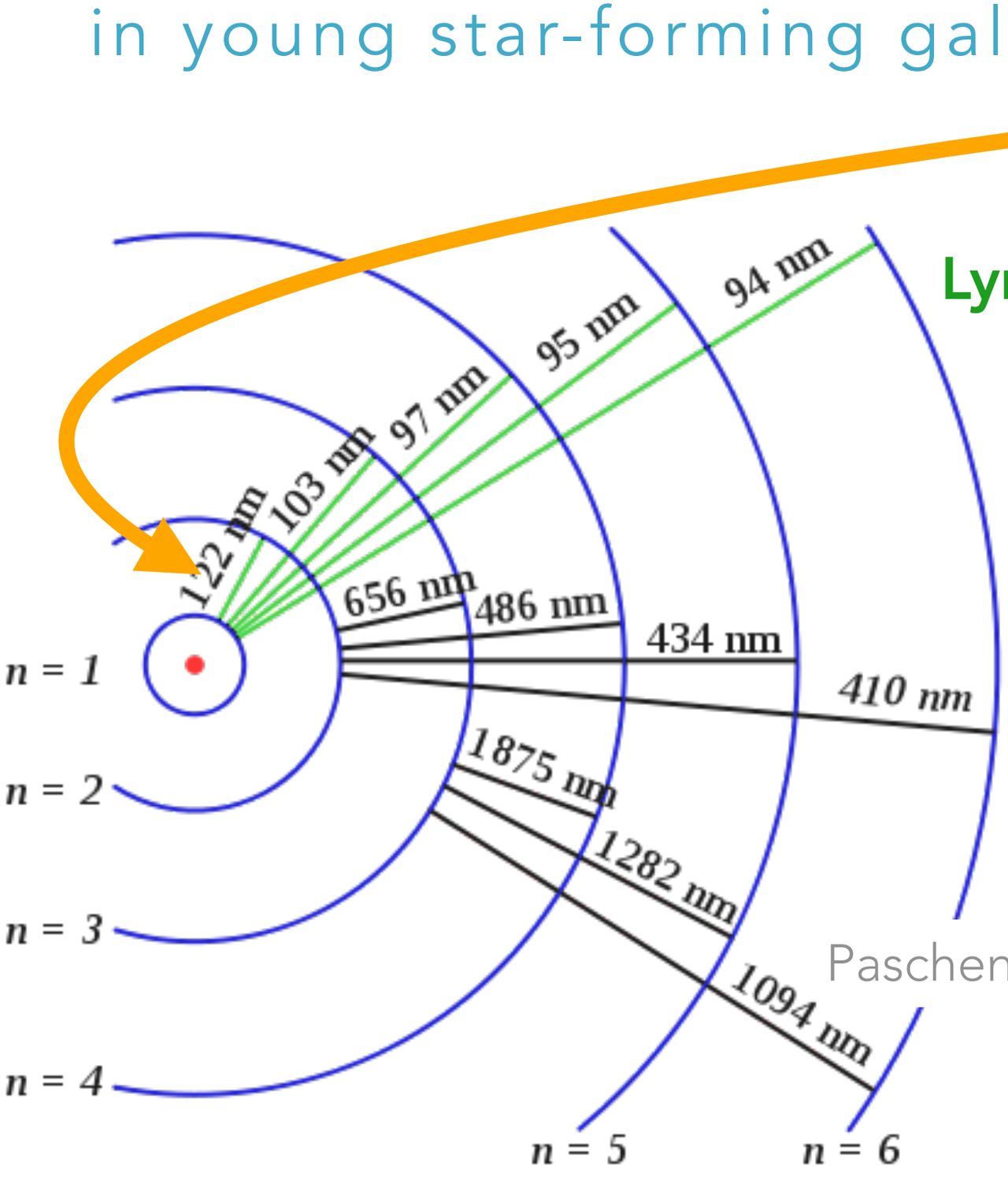
Schmidt+14

We have observed 100s of galaxies at z>6 which can directly trace their environments

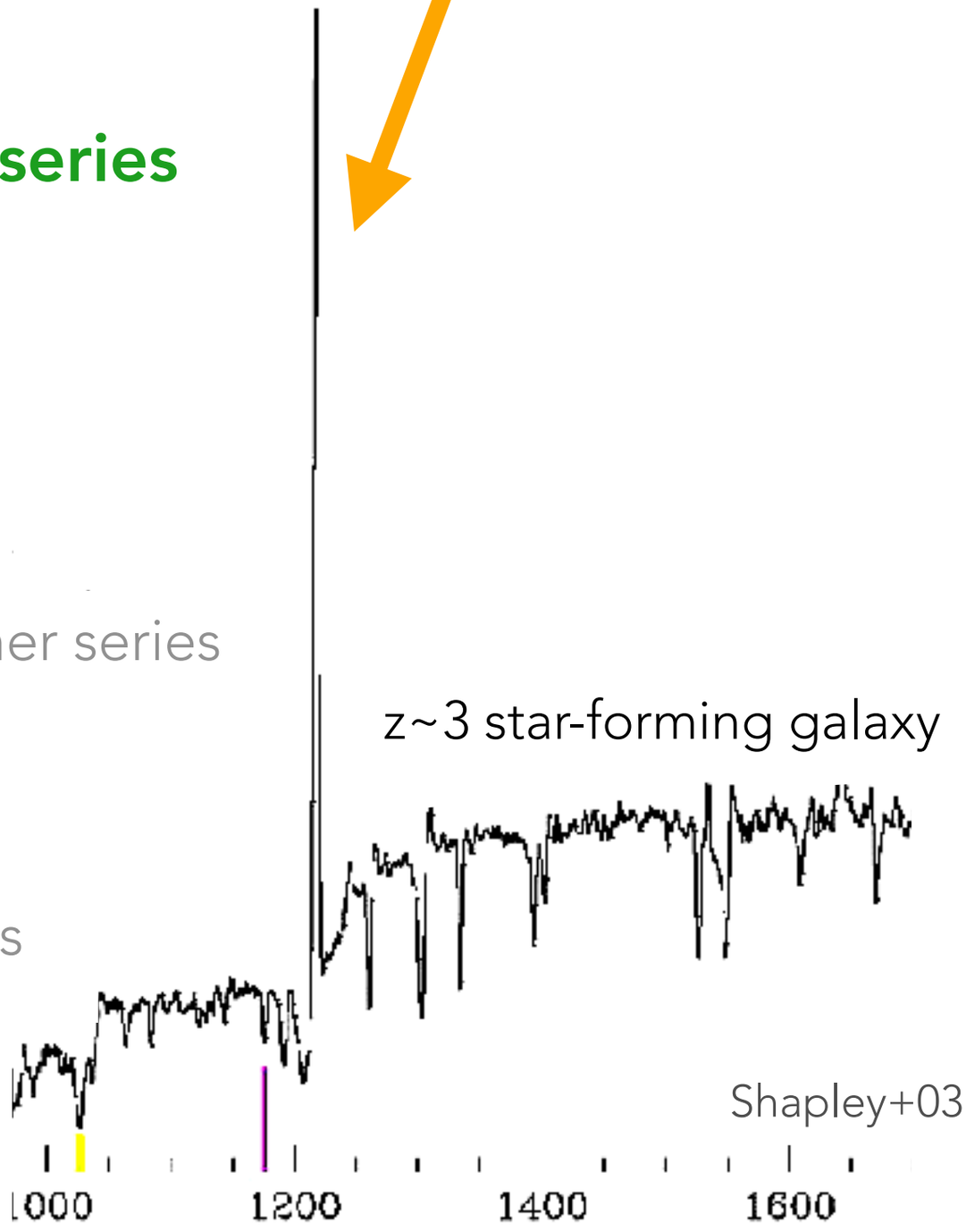


Bouwens+15

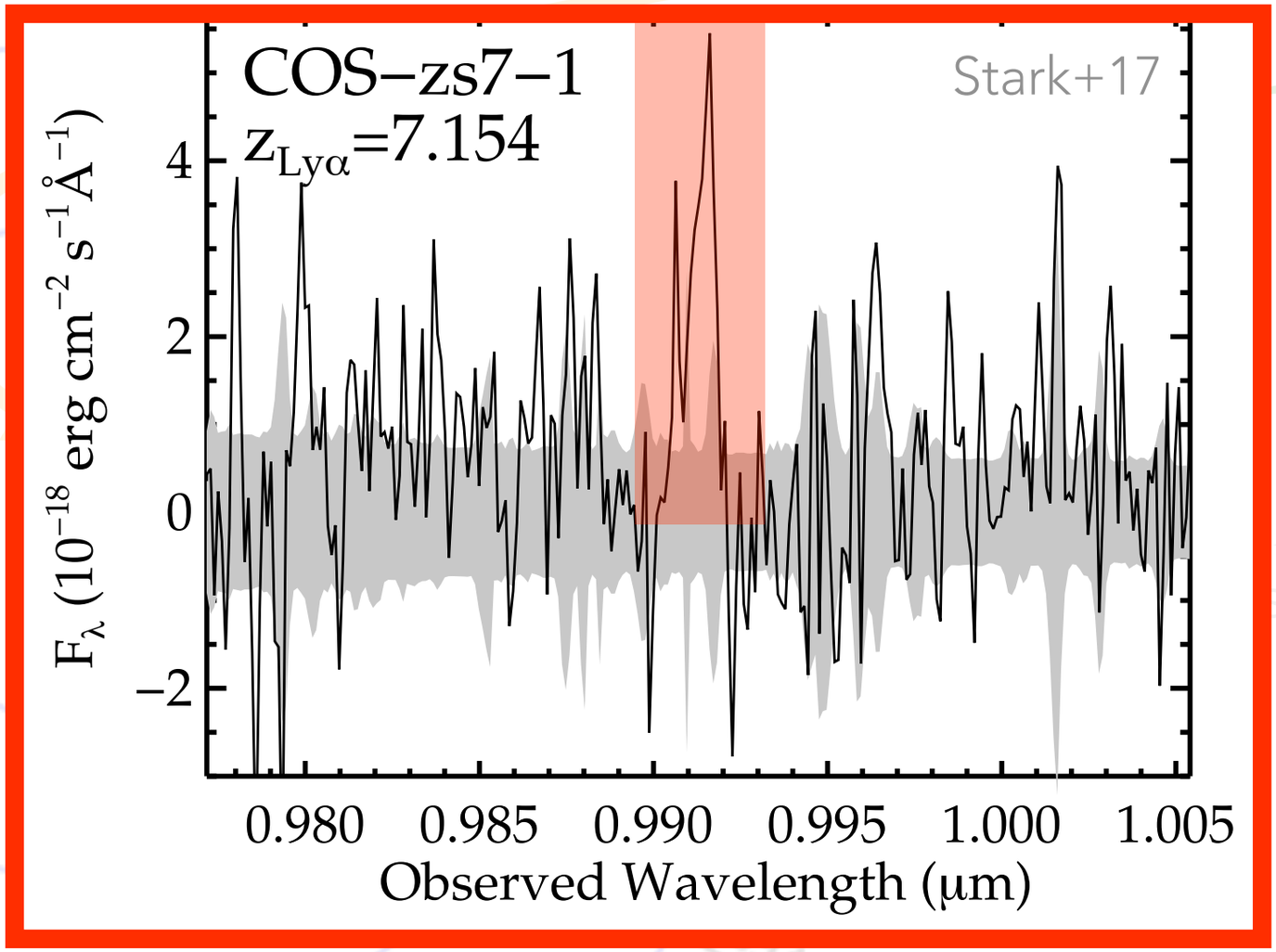
Lyman-α emission is produced ubiquitously in young star-forming galaxies



Hydrogen atom

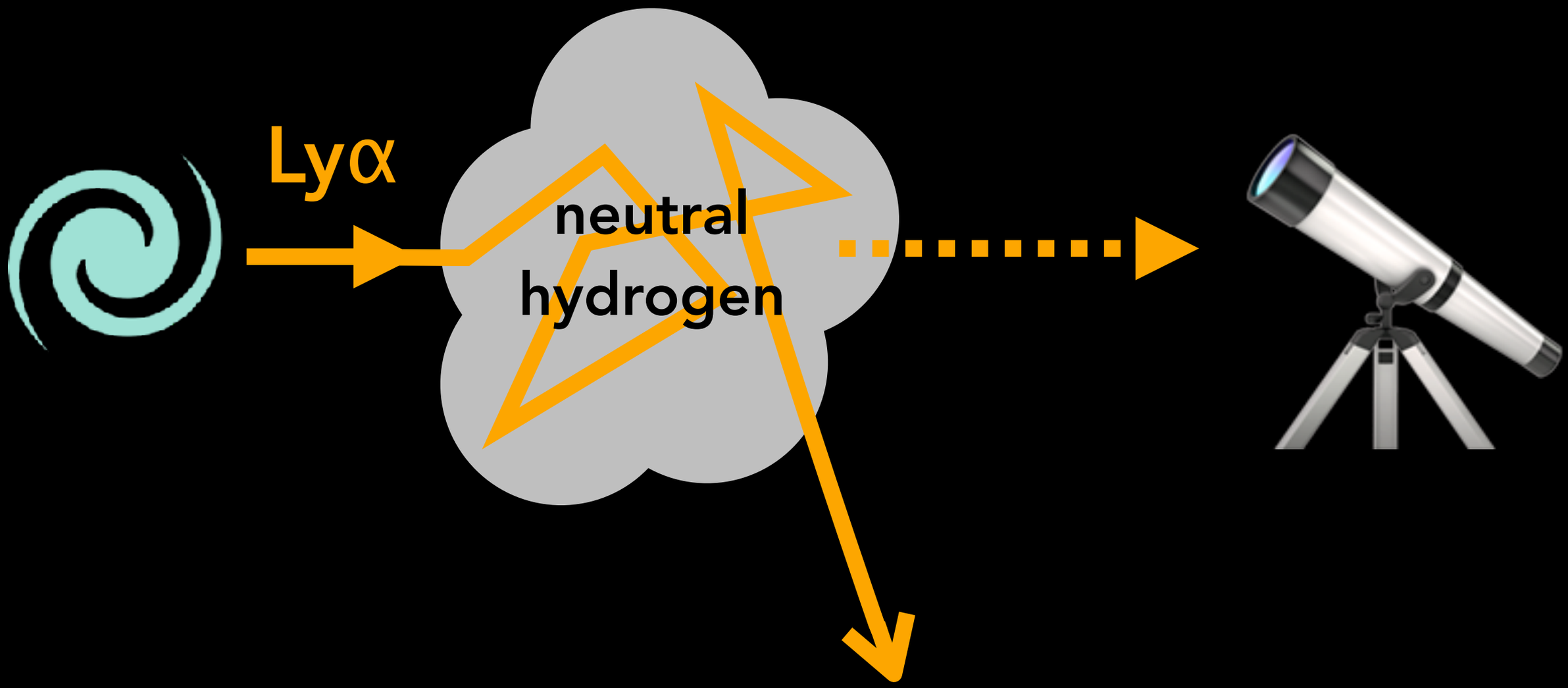


Lyman-α emission is produced ubiquitously in young star-forming galaxies

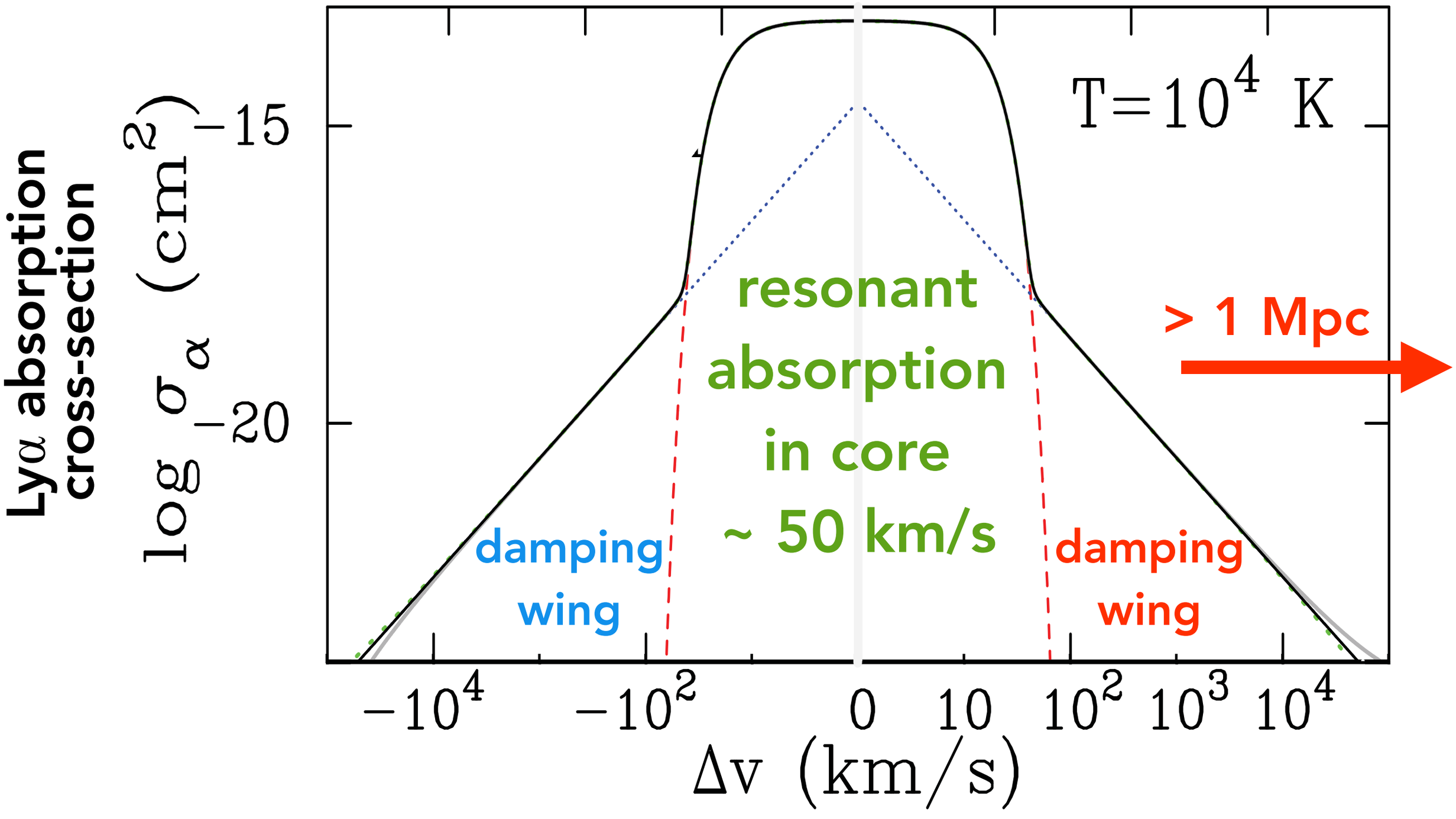


Ly**α** traces **all** neutral gas along line-of-sight

— connects ISM, CGM, IGM

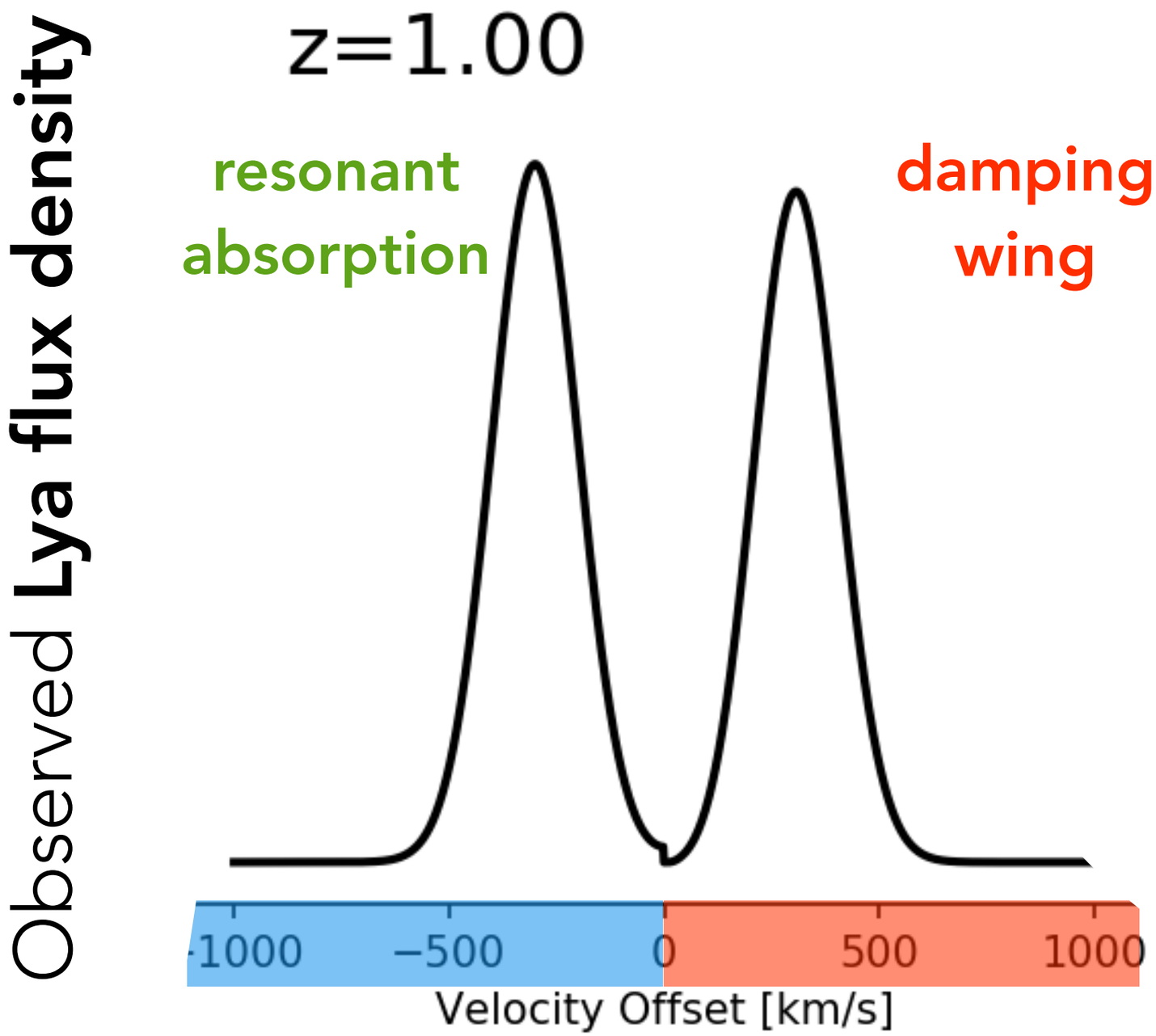

Lyα
neutral
hydrogen

Lyα has a high cross-section for absorption by neutral hydrogen

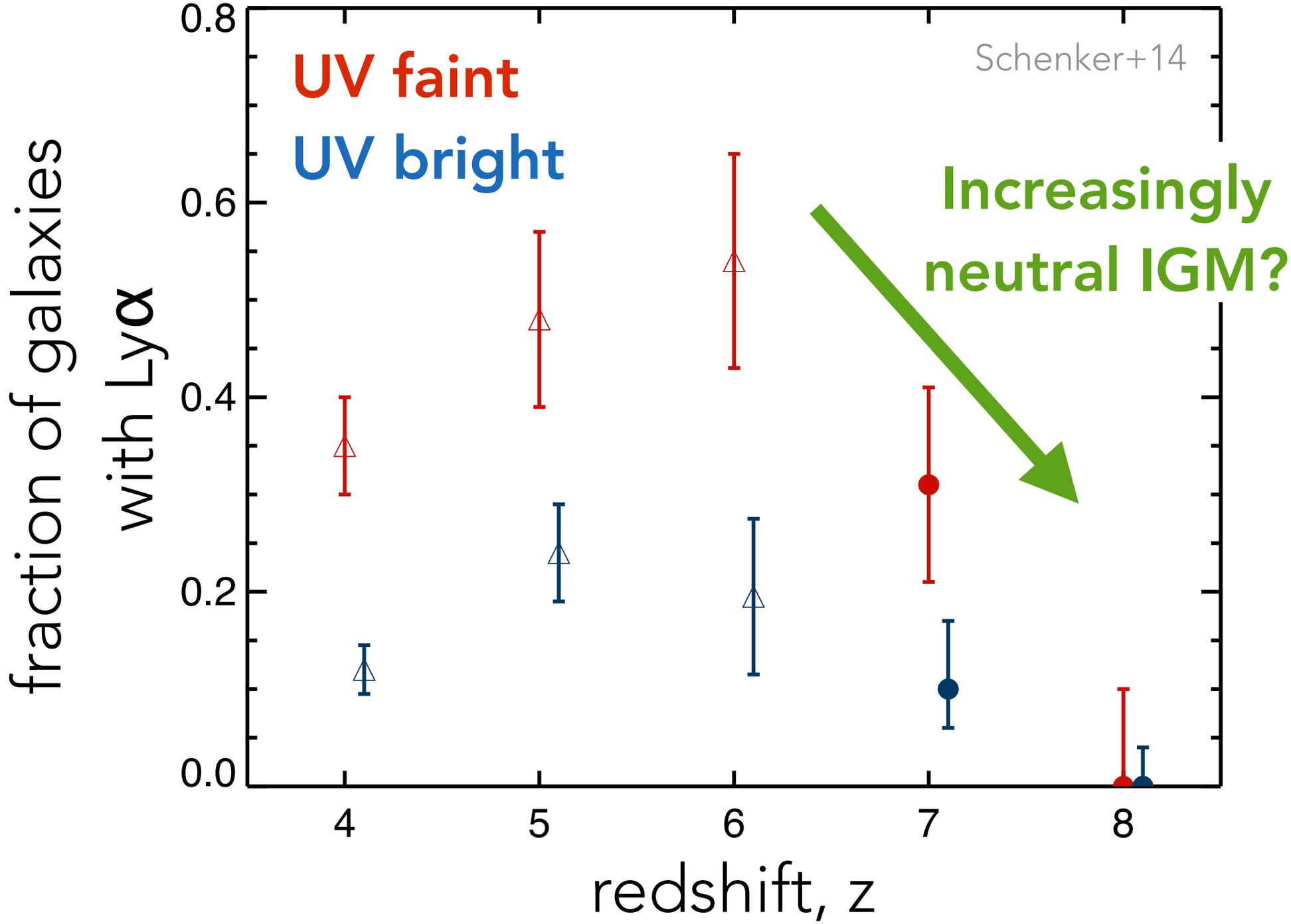


Dijkstra 2014

During reionization, damping wing absorption reduces red side of Lya line

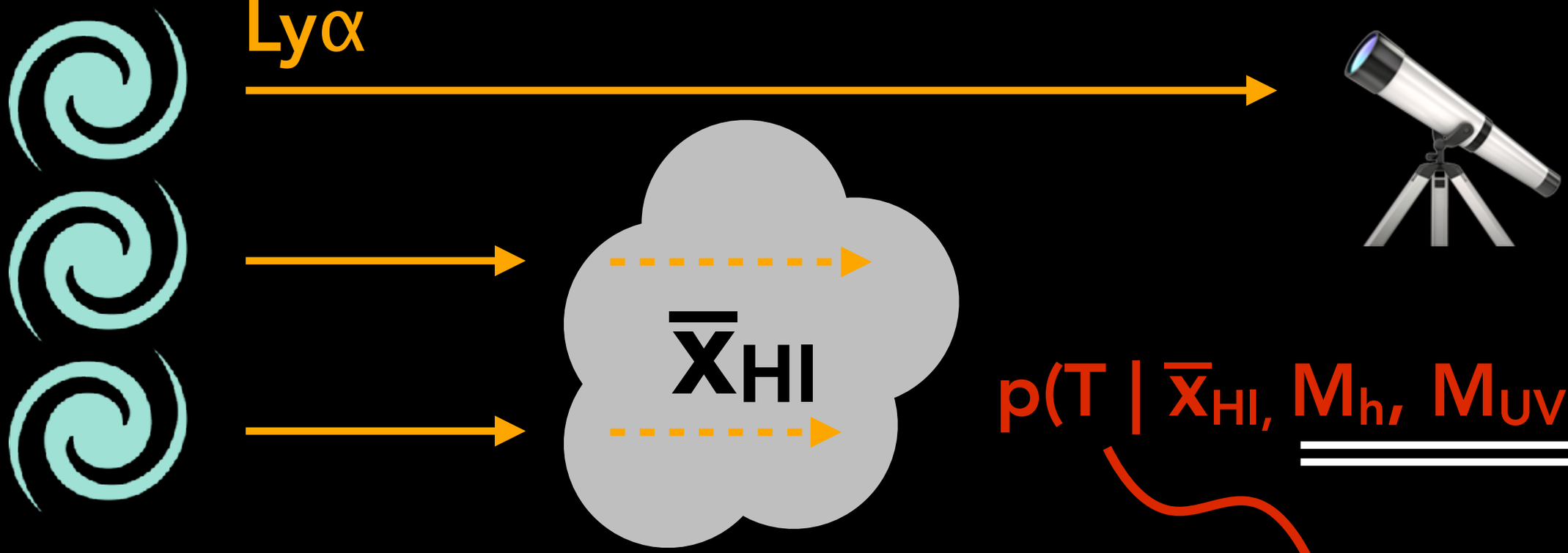


Rapid decline in Lyα visibility at z>6 most likely due to reionization



data from Stark+11, Schenker+14, see also Treu+13, Faisst+14, Tilvi+14, Pentericci+14,+18, de Barros+17

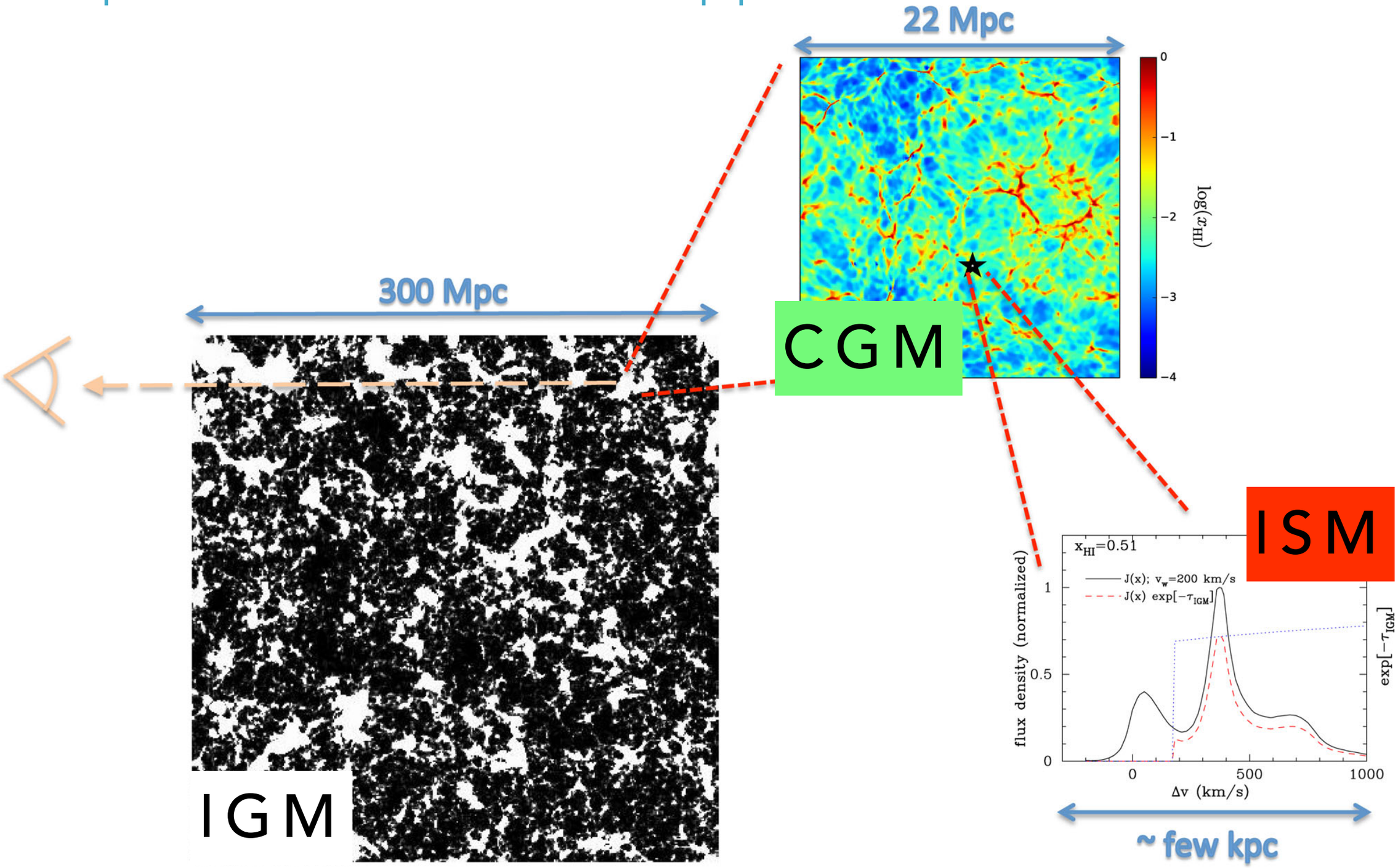
How do we connect Lyα observations to the neutral fraction, $\bar{x}_{HI}$?



$EW \sim f_{line}/f_{cont}$

see e.g. Dijkstra+11; Bolton & Haehnelt 13; Jensen+13

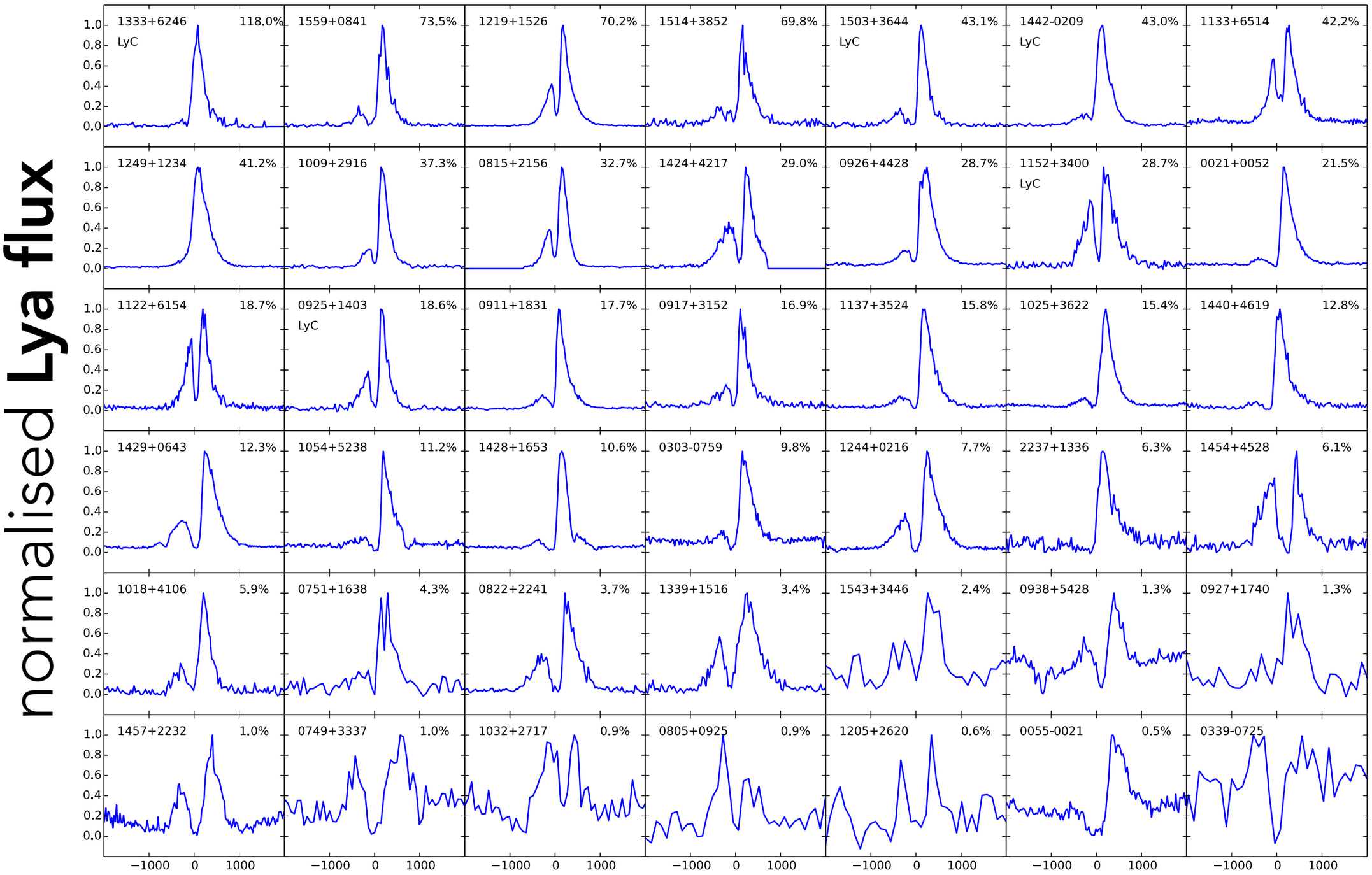
Realistically modelling reionization requires a **multi-scale** approach



Mesinger+15

Cardamone+09

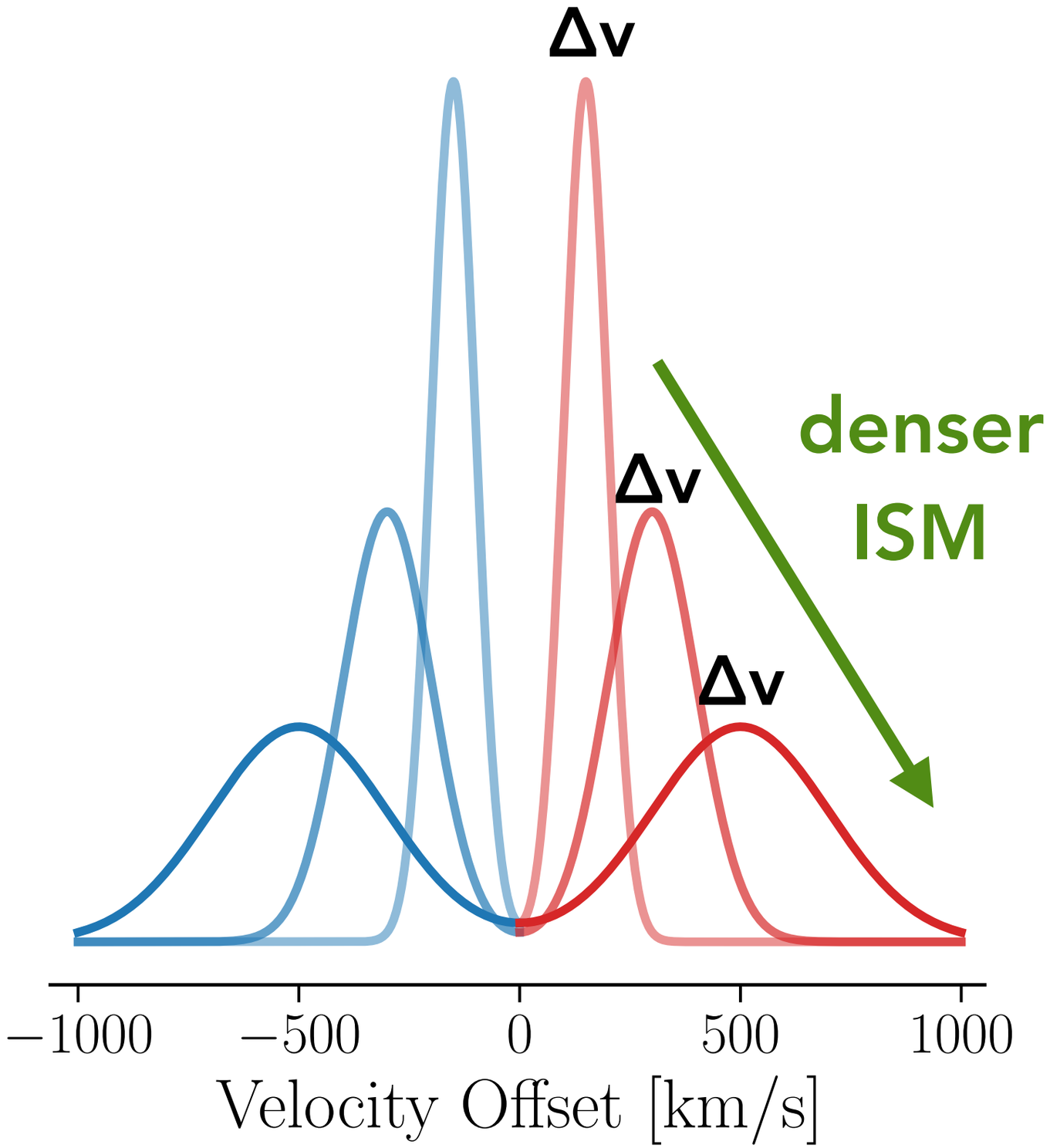
Lya line profiles from z~0.2 Green Peas show the impact of ISM radiative transfer



Yang+17

The shape of the Lyα line emerging from the ISM affects the probability of transmission through the IGM

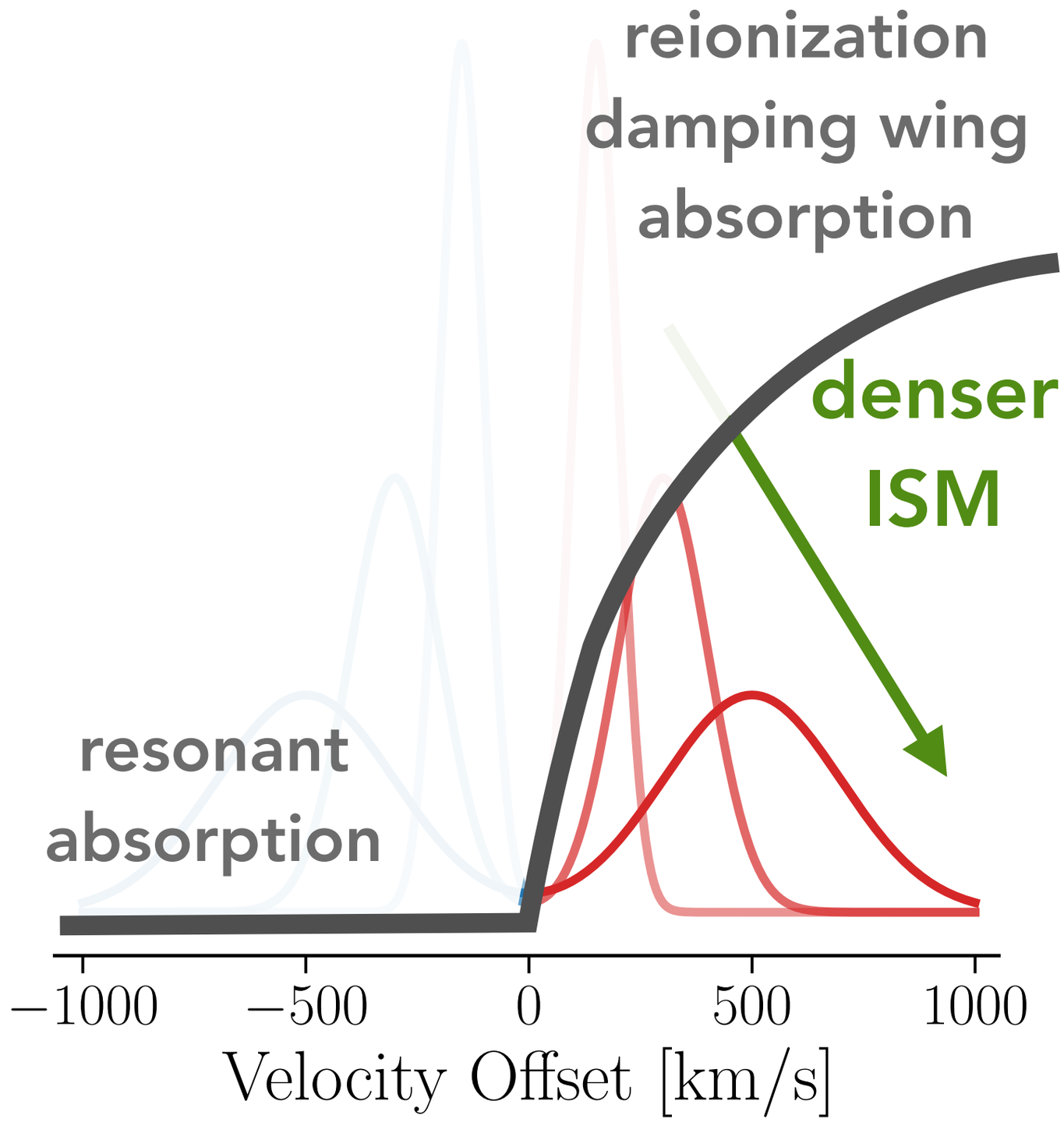
Lyα photons must diffuse in frequency to escape dense ISM



e.g. Adams 1972, Neufeld 1990, Verhamme+2006

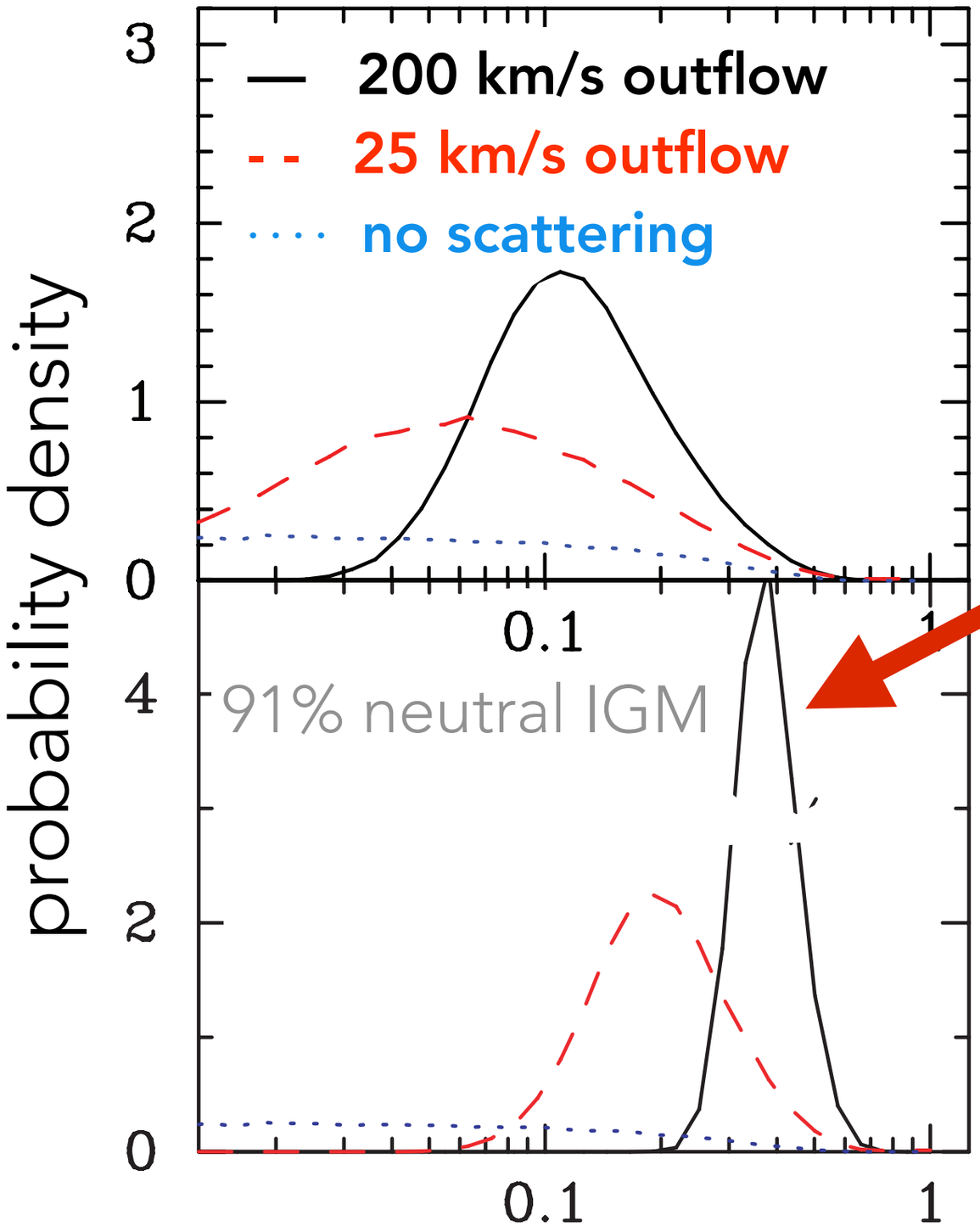
The shape of the Lyα line emerging from the ISM affects the probability of transmission through the IGM

More Doppler-shifted lines are less affected by reionization



e.g. Dijkstra & Wyithe 2010, Dijkstra, Mesinger & Wyithe 2011

The shape of the Lyα line emerging from the ISM affects the probability of transmission through the IGM



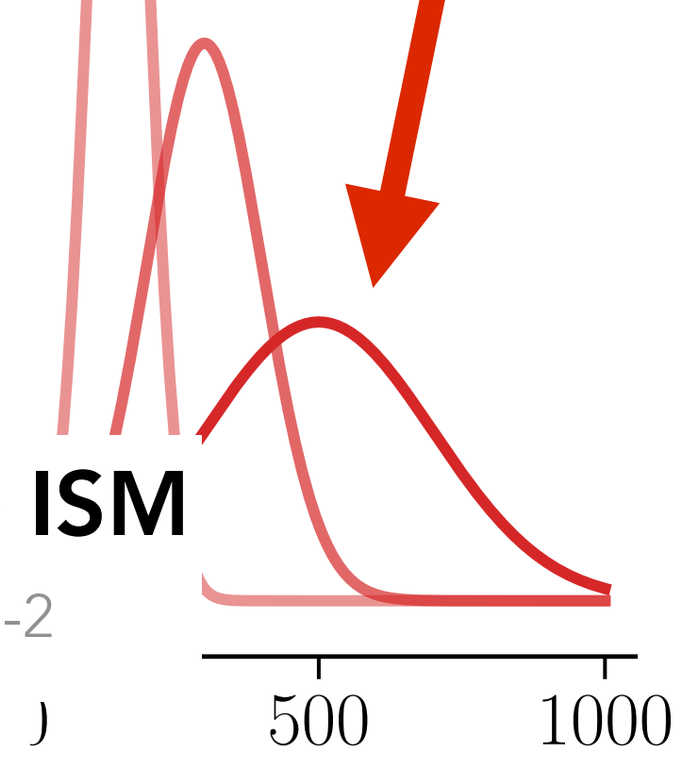
Moderately opaque ISM

$N_{HI} = 10^{20}$ cm^{-2}

More Doppler-shifted lines are less affected by reionization

Very opaque ISM

$N_{HI} = 10^{21}$ cm^{-2}



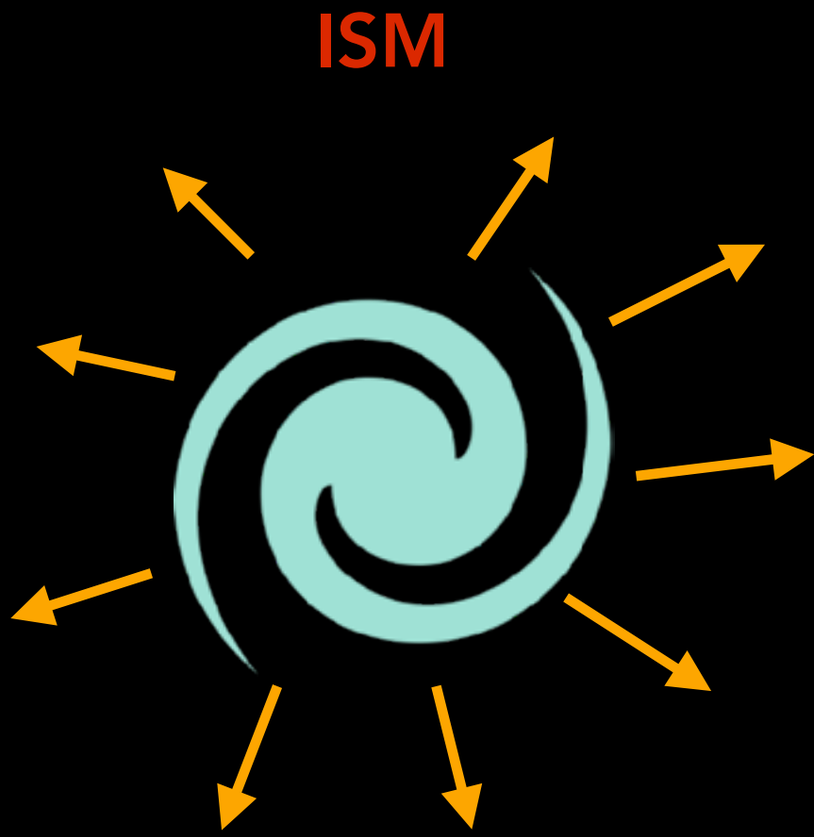
Dijkstra, Mesinger & Wyithe 2011

What is the **timeline** and topology of reionization?

Observe imprint of neutral IGM on galaxies (+quasars, GRBs)

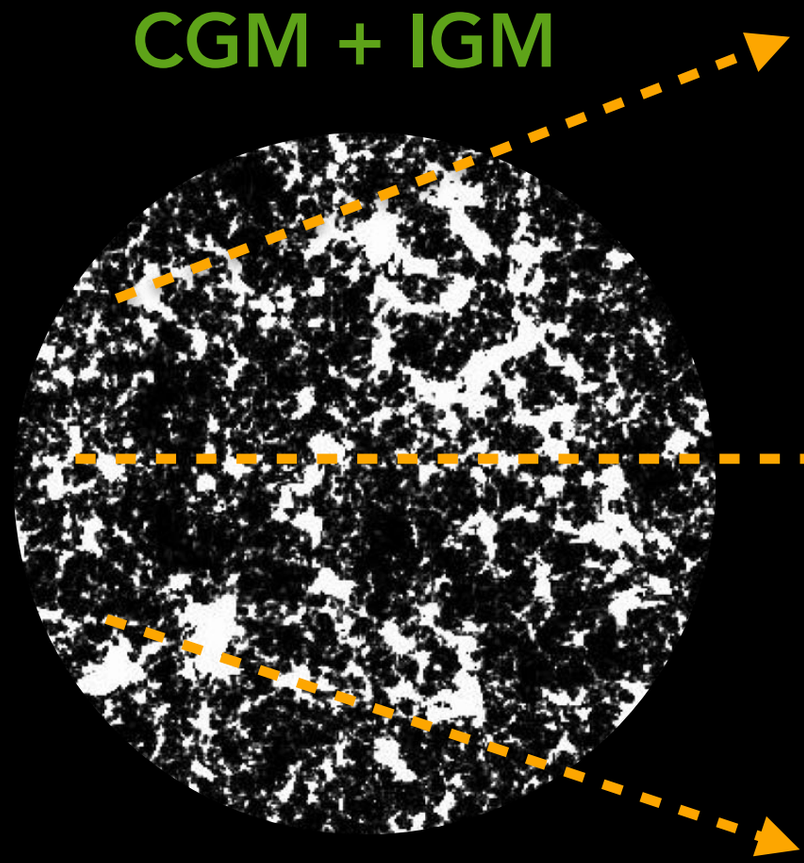
Forward model to connect Lyα observations to IGM state

Forward-modeling framework combining realistic IGM topologies and galaxy properties



EW_{em}

M_{UV} Δv



Evolution of Structure simulations (Mesinger+)

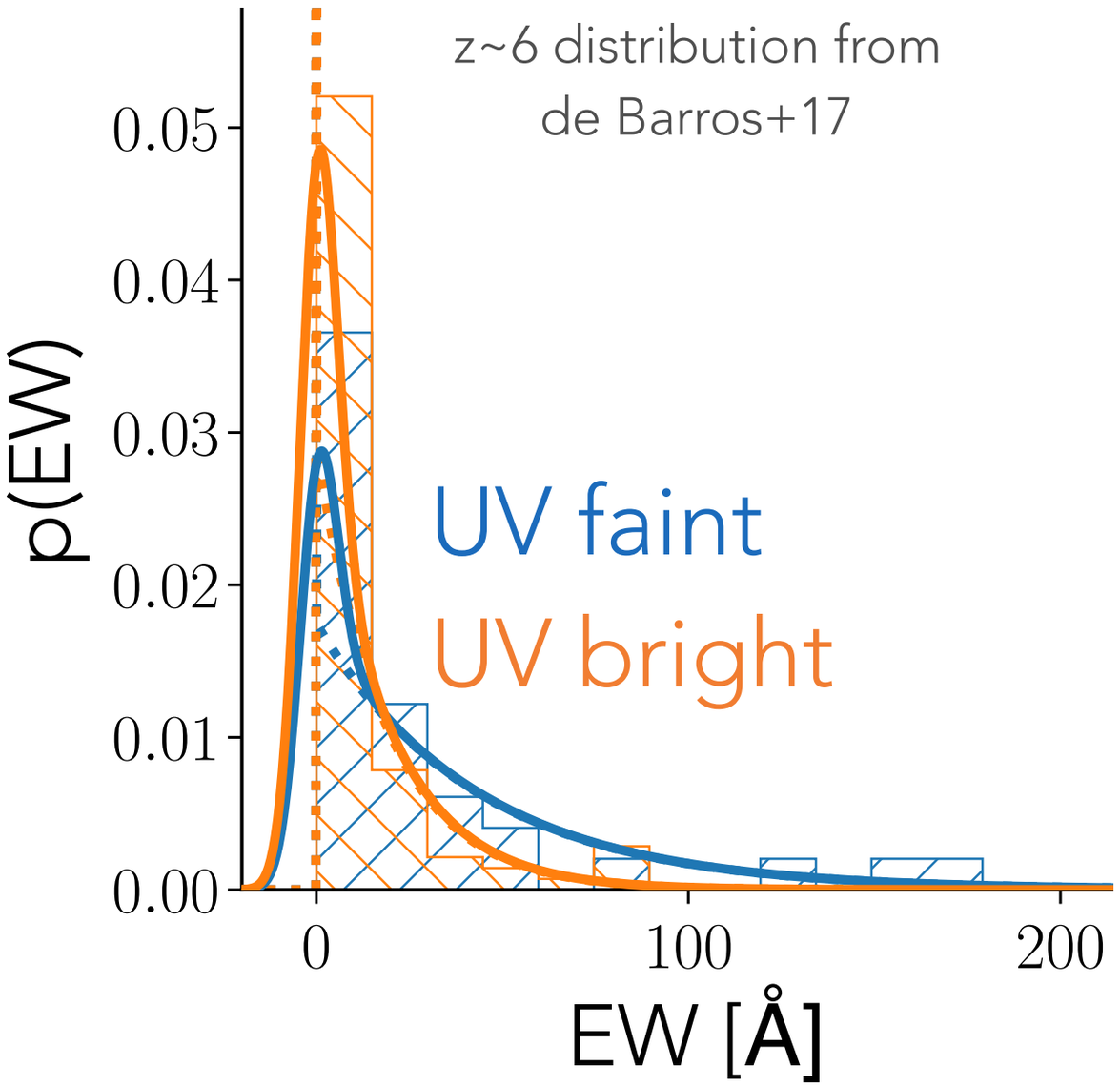
$EW_{obs} = T \times EW_{em}$

$$\mathcal{T}(\overline{x}_{\rm HI}, M_h, \Delta v) = \int dv \, J_\alpha(M_h, \Delta v, v) \, e^{-\tau_{\rm IGM}(\overline{x}_{\rm HI}, M_h, v)}$$

Mason+2018a

Simulation halos are populated with galaxy properties via empirical models

'Emitted' $EW_{Ly\alpha}$

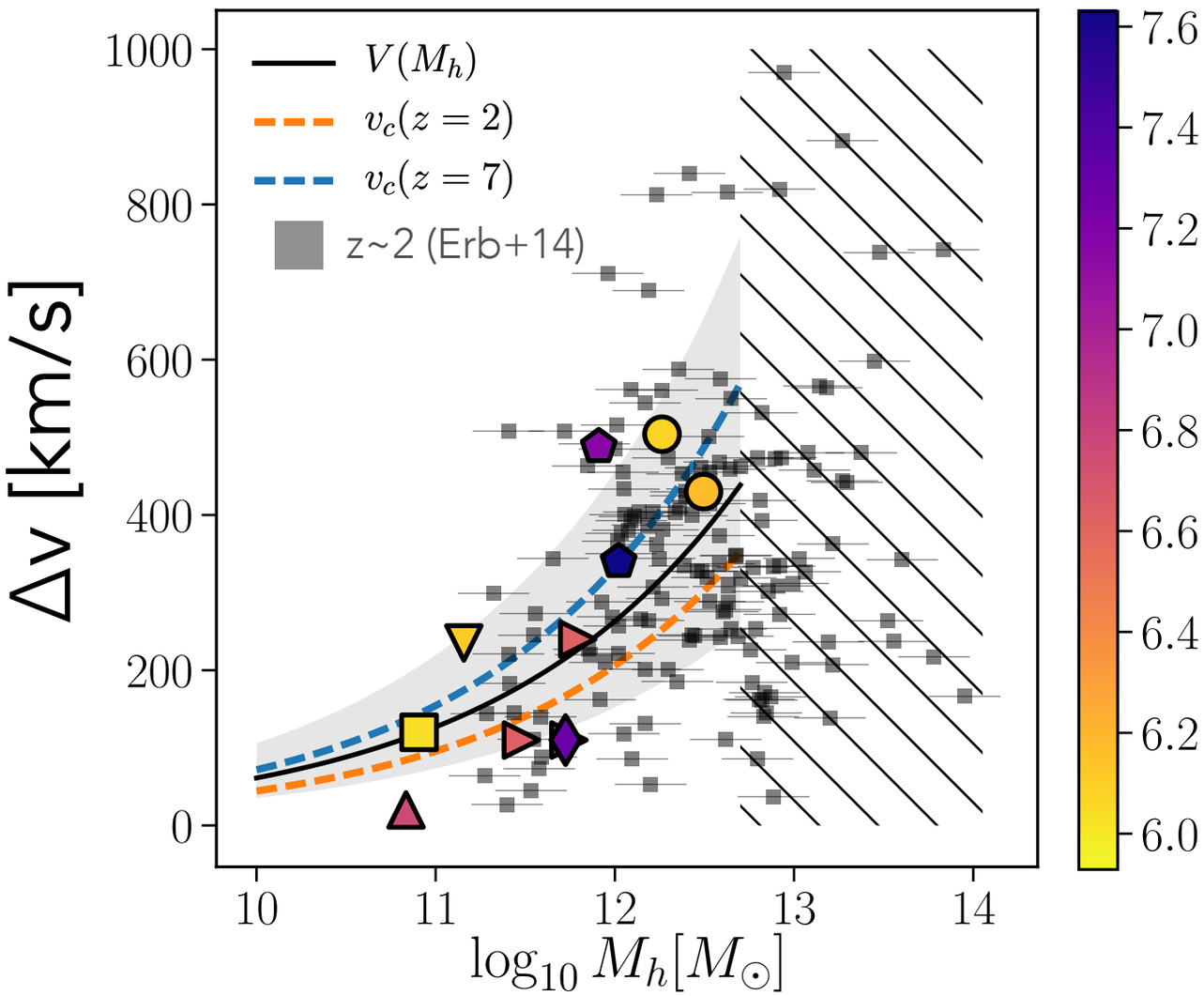


+ UV magnitudes

from Mason+15b

Mason+2018a

Lyα velocity offsets

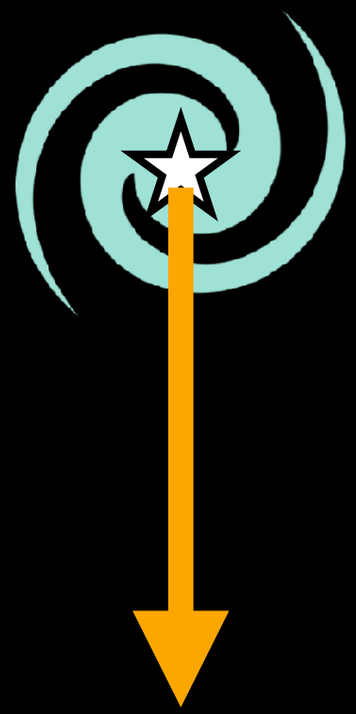


higher N_{HI}?

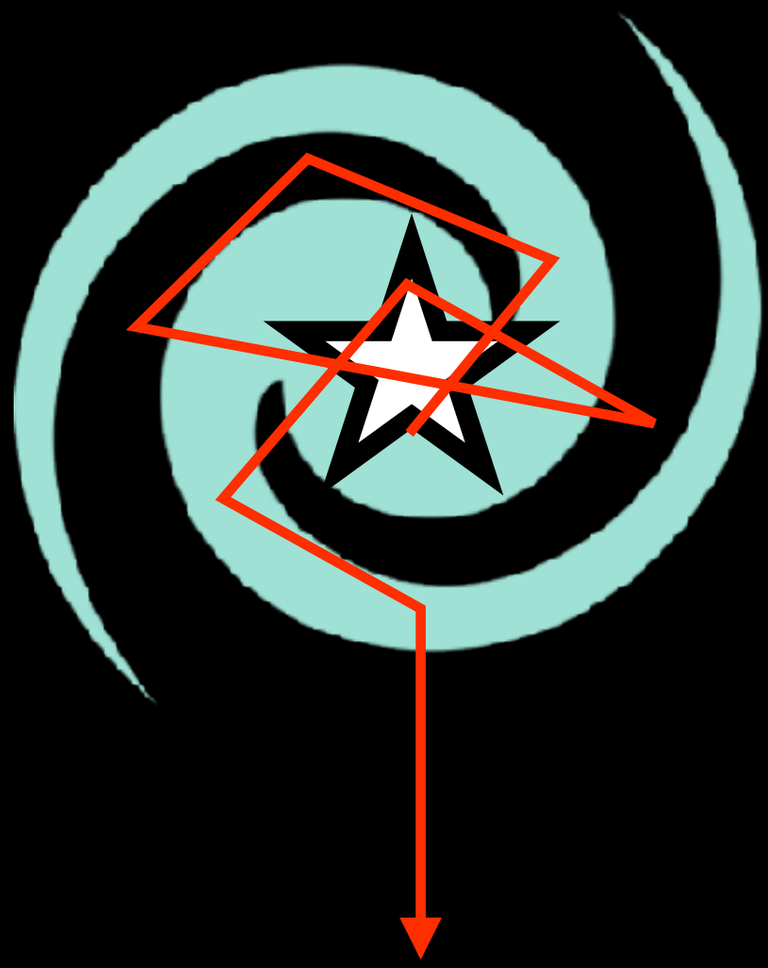
higher f_{cov}(HI)?

outflows?

Simulation halos are populated with galaxy properties via empirical models



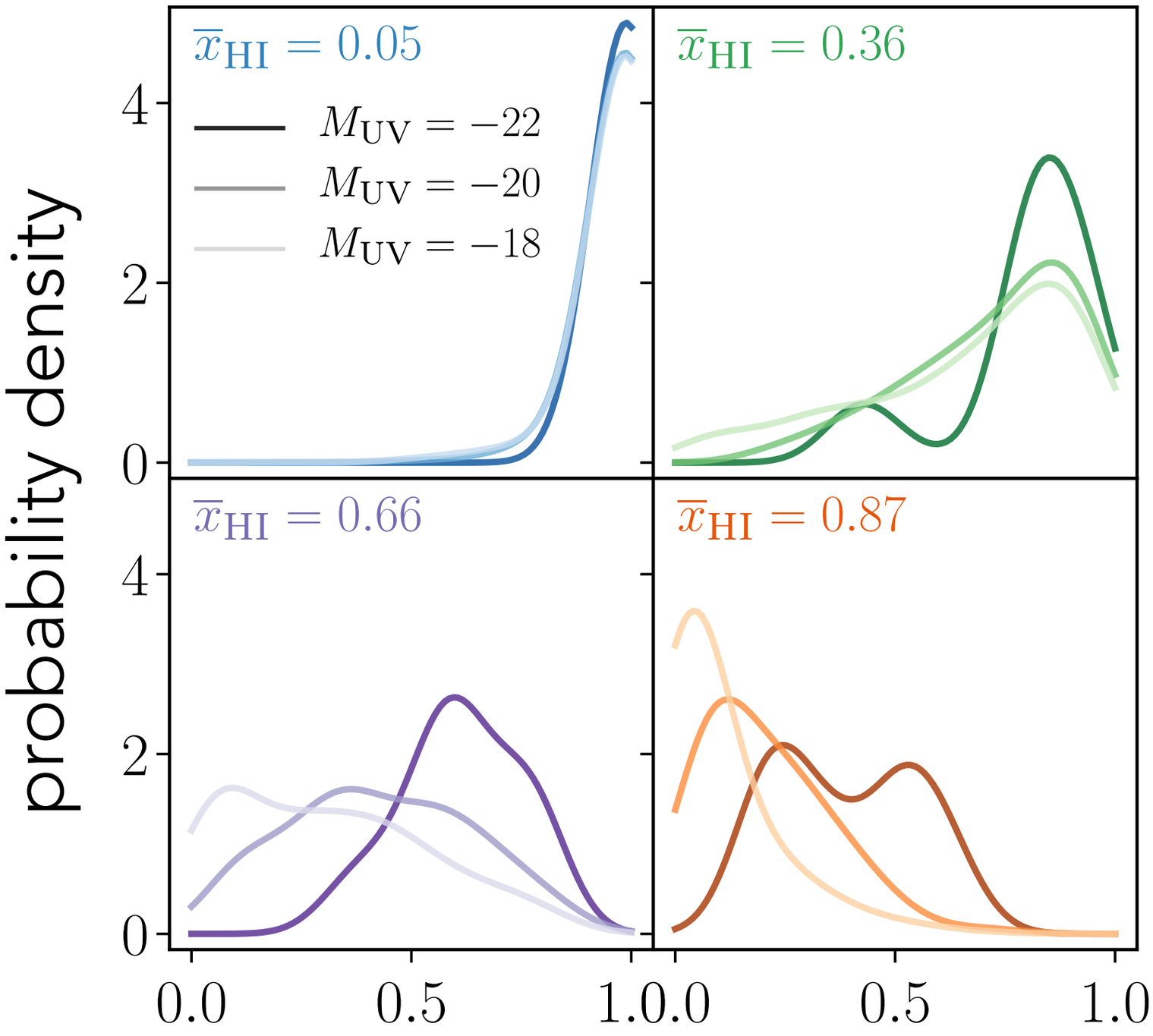
high EW, low Δv



low EW, high Δv

Transmission of Lyα depends on galaxy properties via environment and velocity offset

Mostly ionized

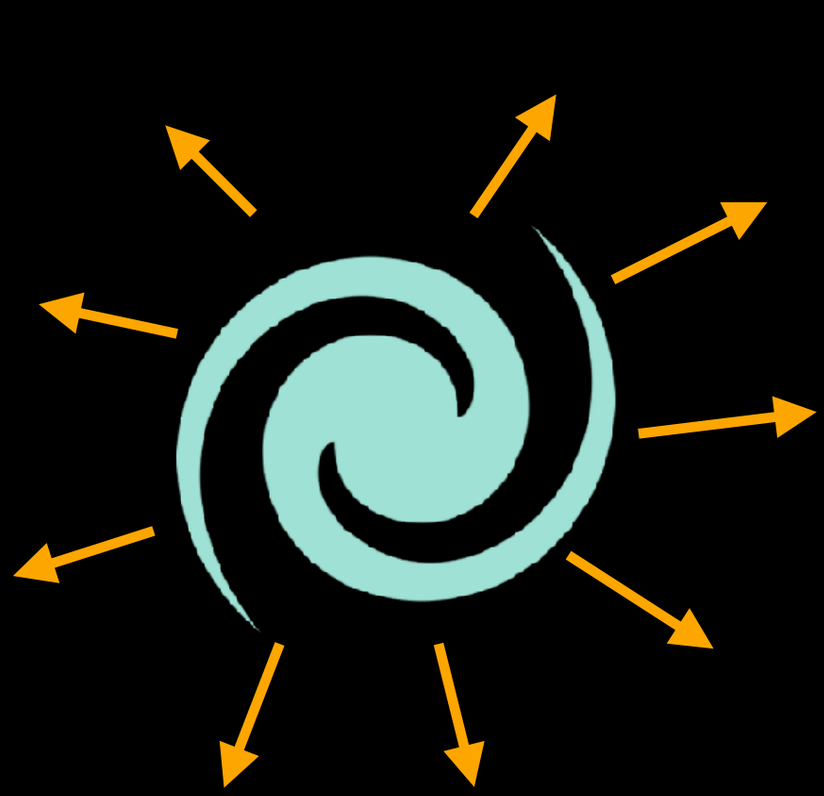


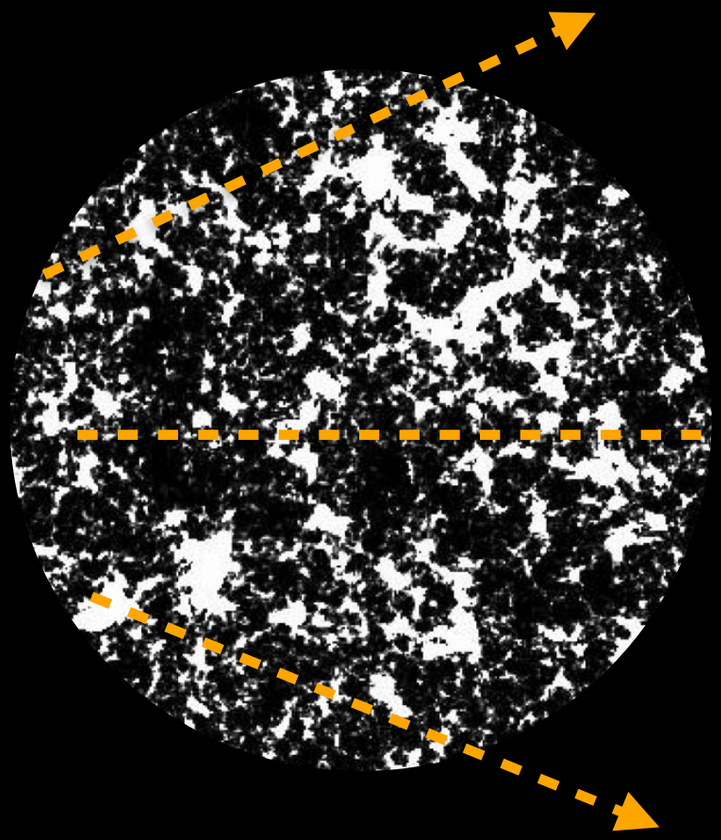
Mostly neutral

$T_{IGM} = EW_{obs}/EW_{emit}$

Mason+18a

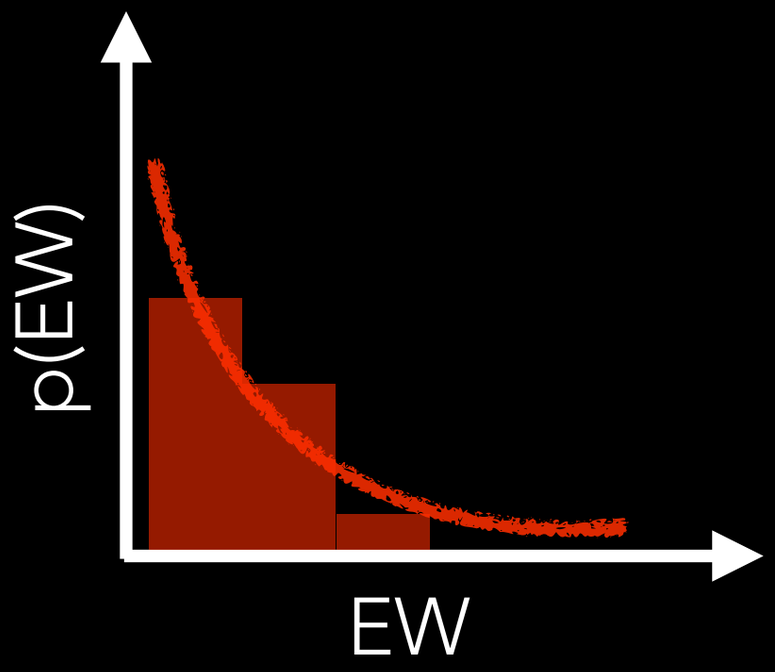
Bayesian inference on Lyα observations (via EW distribution) to infer the neutral fraction



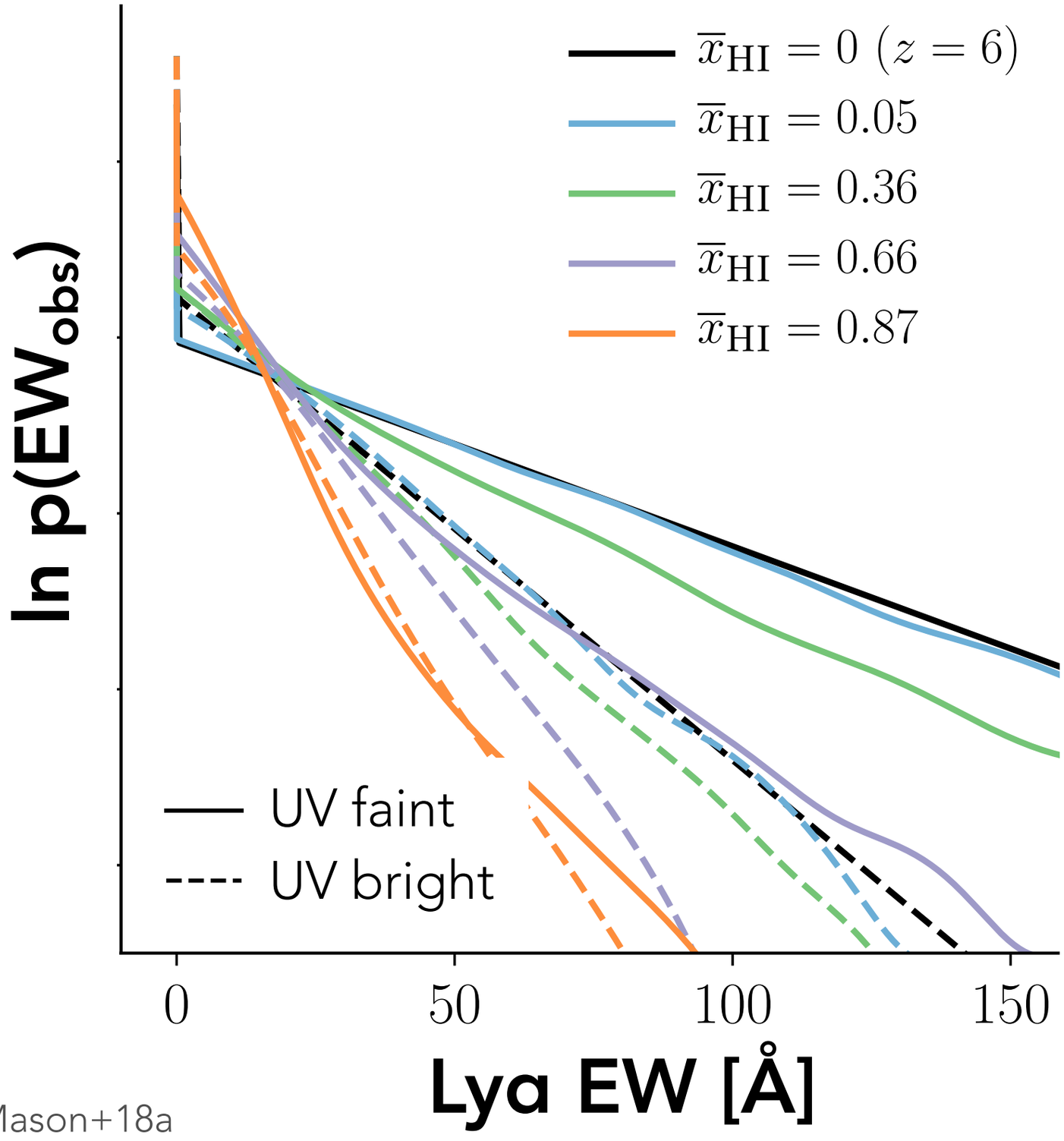


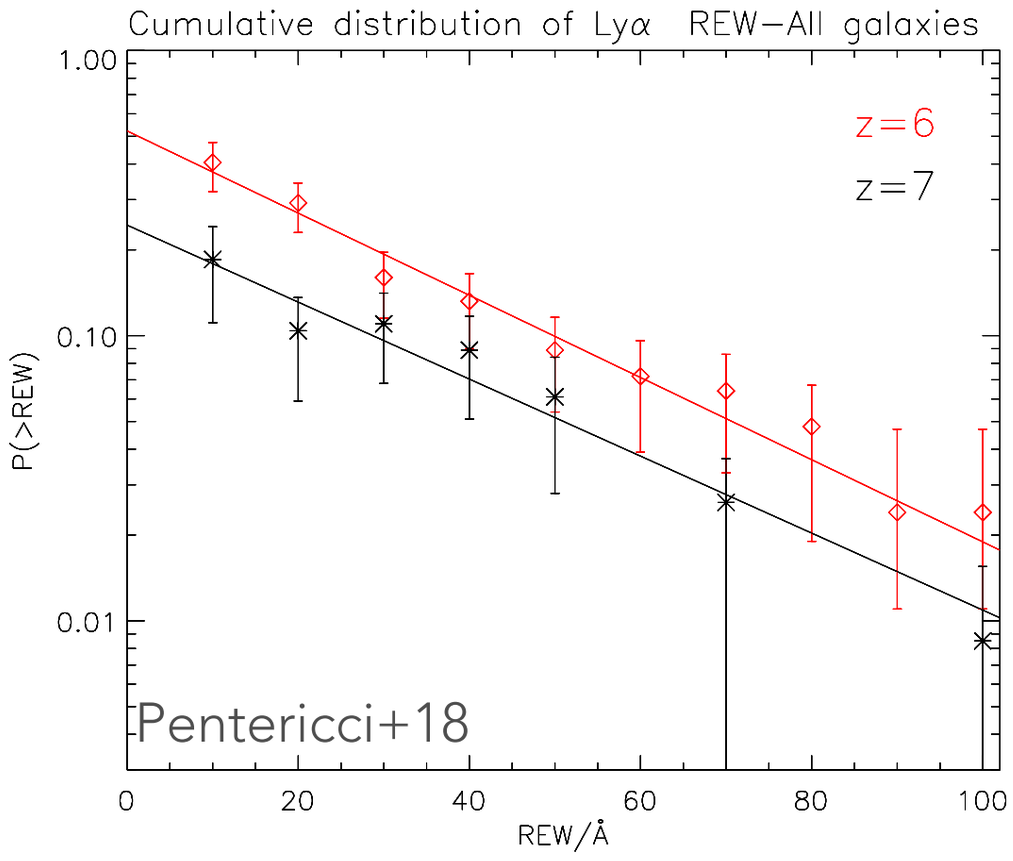
$p(x_{HI} \mid \text{observations})$?

forward model $p(EW_{obs} \mid \bar{x}_{HI}, M_{UV})$



As the IGM becomes more neutral Lyα EWs decrease - most pronounced for faint galaxies



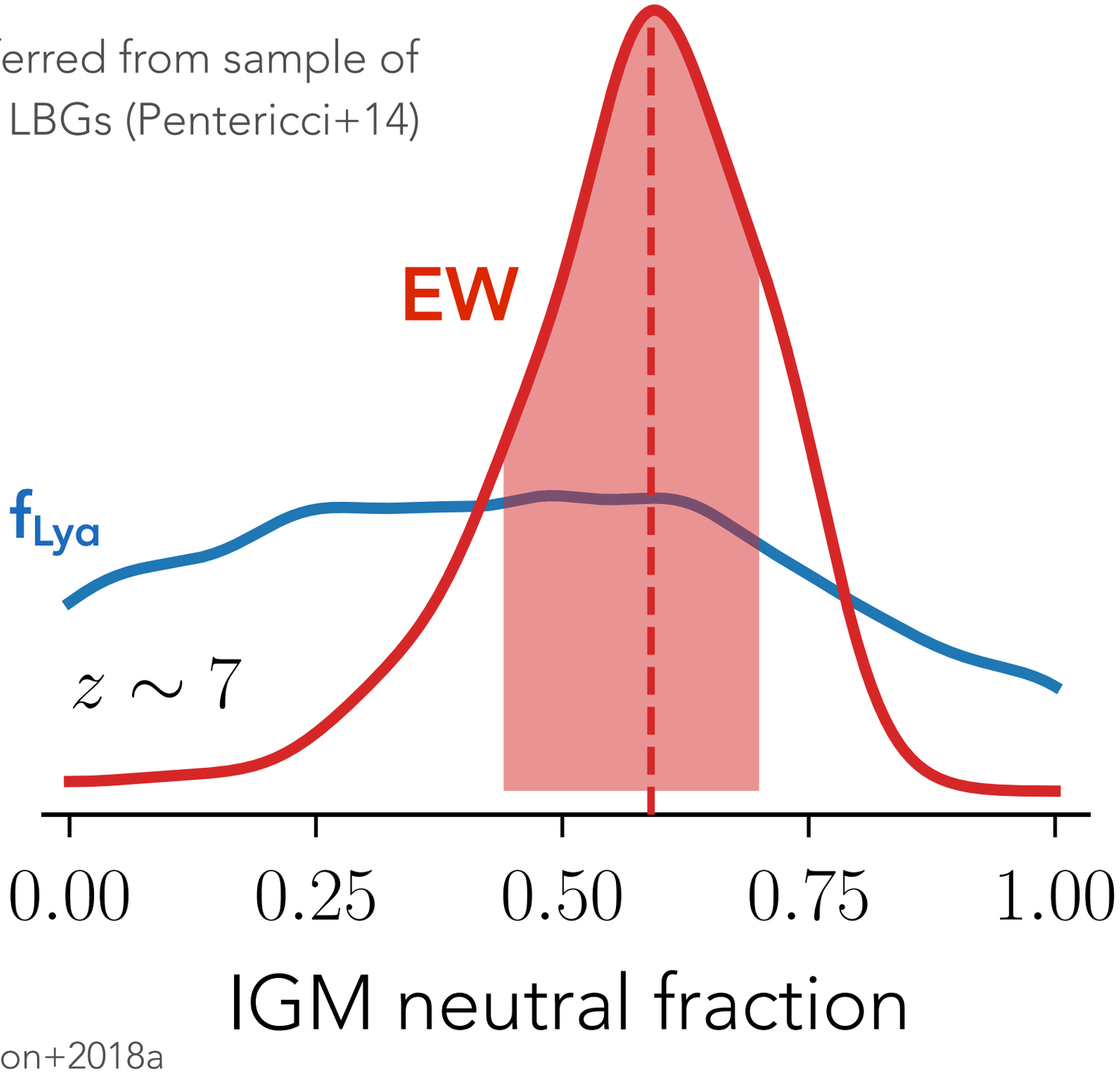


Increasingly neutral IGM

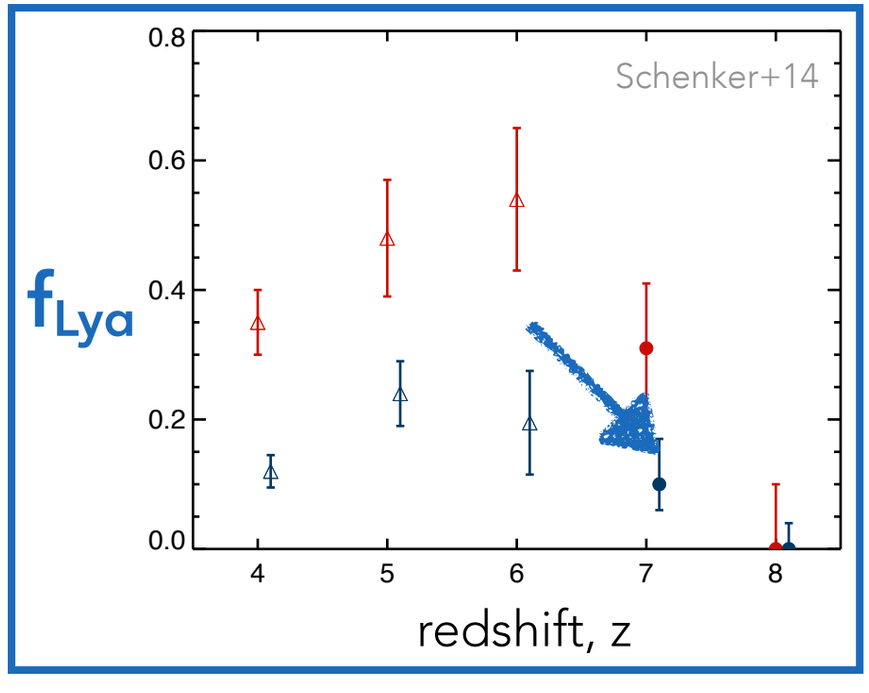
Mason+18a

Using the full distribution of Lyα EW at z~7 places tight constraints on the neutral fraction

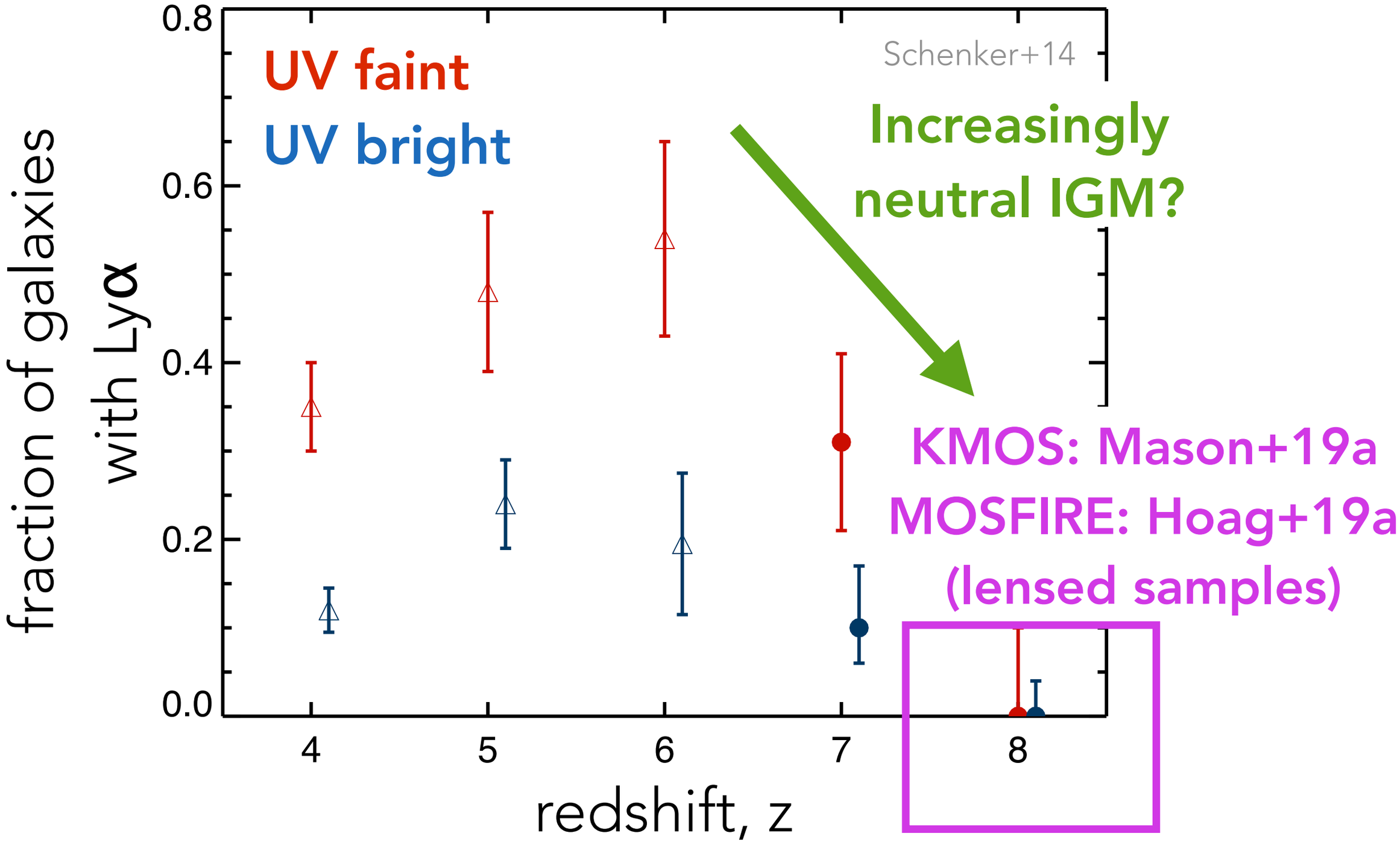
inferred from sample of
68 LBGs (Pentericci+14)



Mason+2018a



What about z>7?

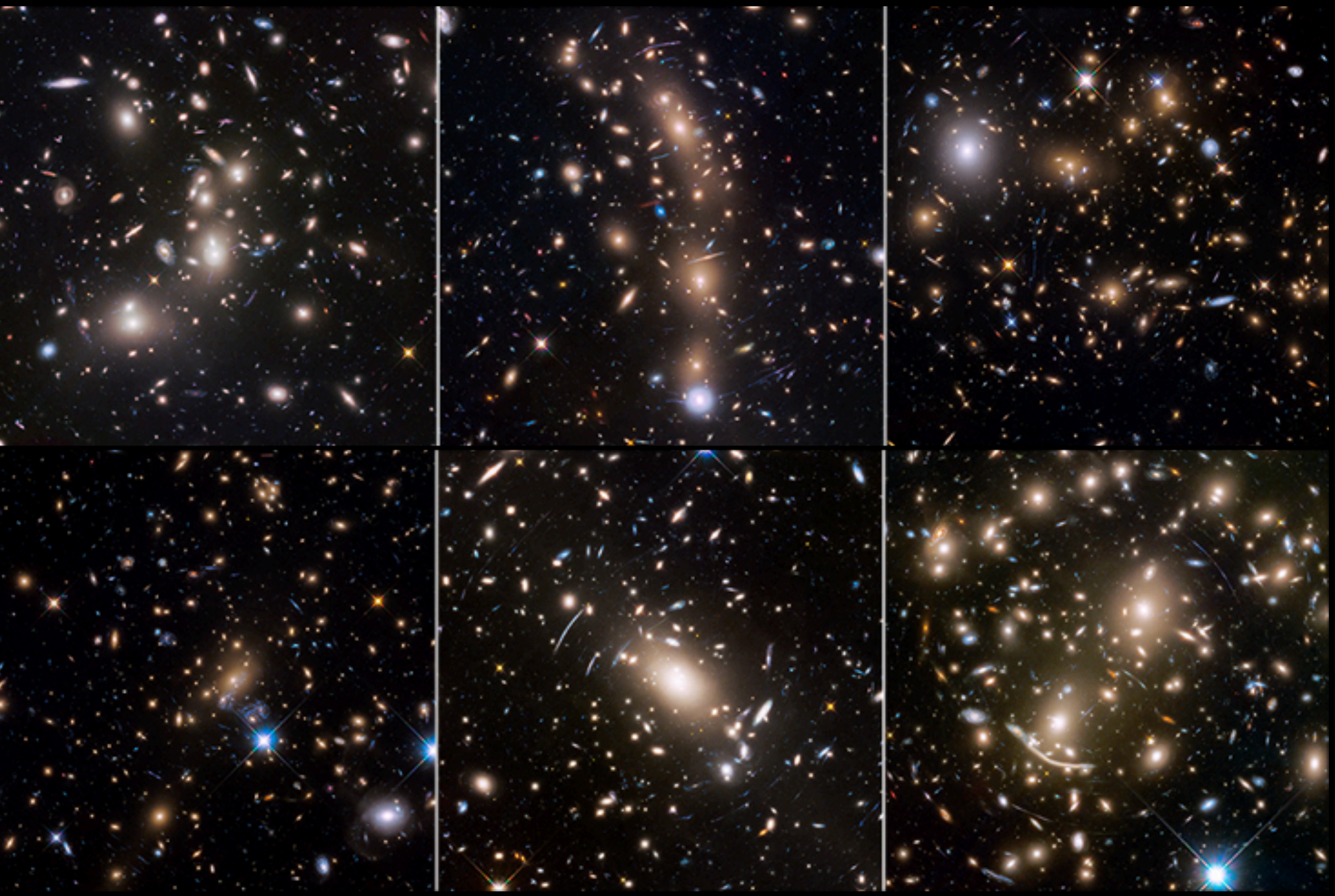


data from Stark+11, Schenker+14, see also Treu+13, Faisst+14, Tilvi+14, Pentericci+14,+18, de Barros+17

GLASS

glass.astro.ucla.edu

Efficient search for z>7 Lyα in faint galaxies behind lensing clusters



+ 4 more!

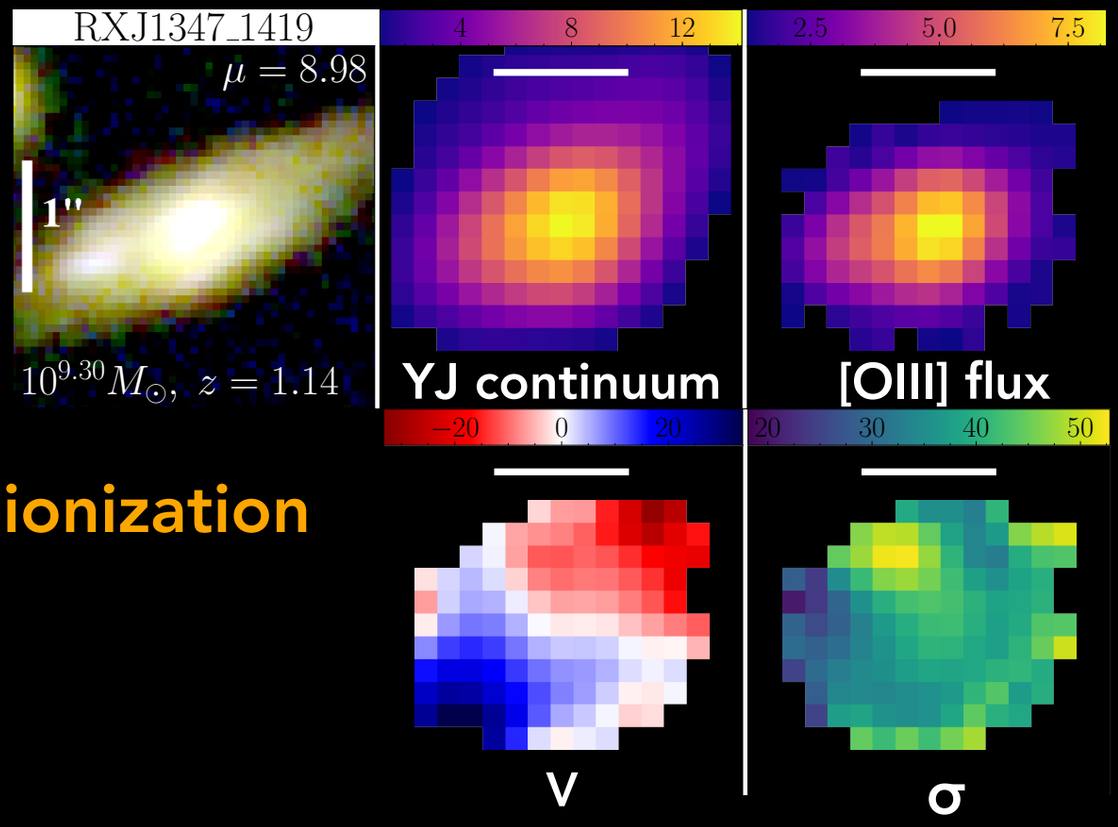
KLASS

KMOS lens-amplified spectroscopic survey

No S/N > 5

Lyα detected 😢

Median EW_{lim} < 58Å



Search for Lyα to measure timeline of reionization

53 z > 7 photometric candidate targets

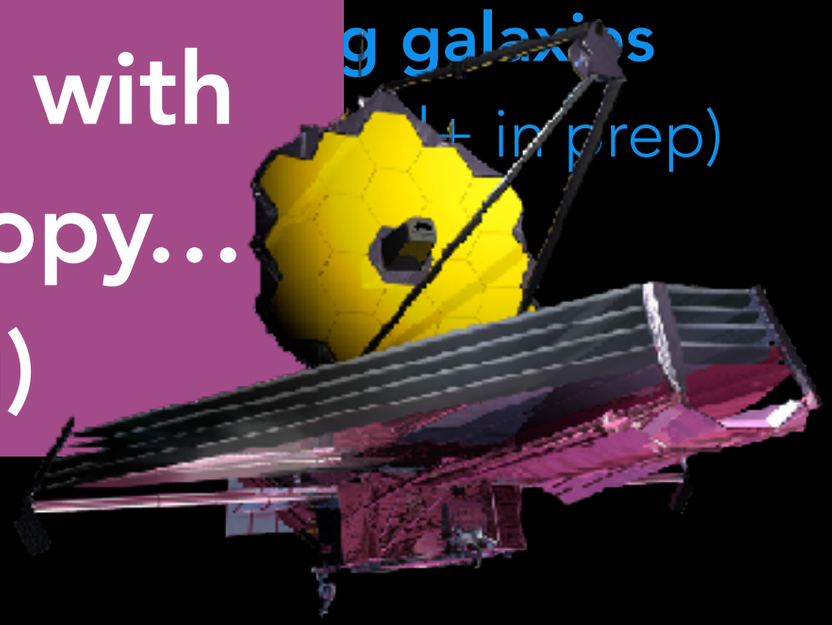
– 3 confirmed with ALMA

To be continued with JWST spectroscopy…

ERS (PI Treu)

g galaxies

+ in prep)

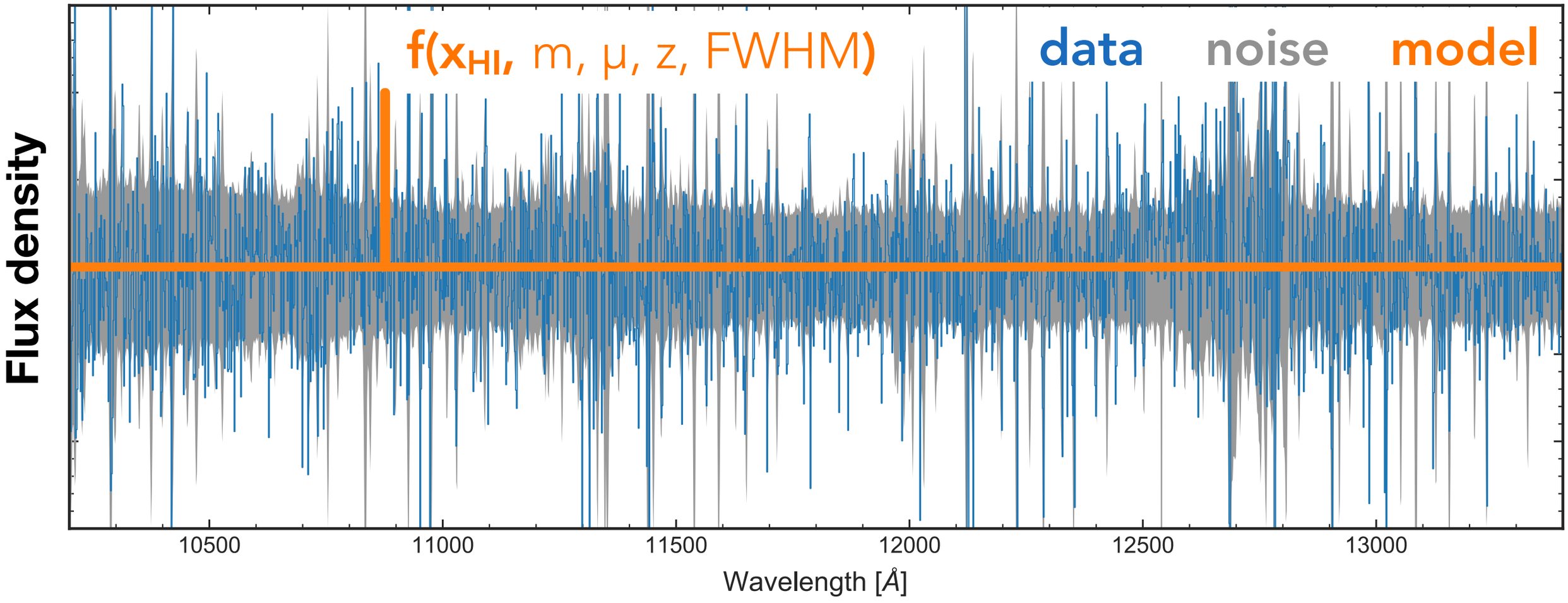


Following-up HST photometric + grism targets

GLASS

glass.astro.ucla.edu

Using full non-detection spectra in Bayesian inference, marginalize over redshift and linewidth



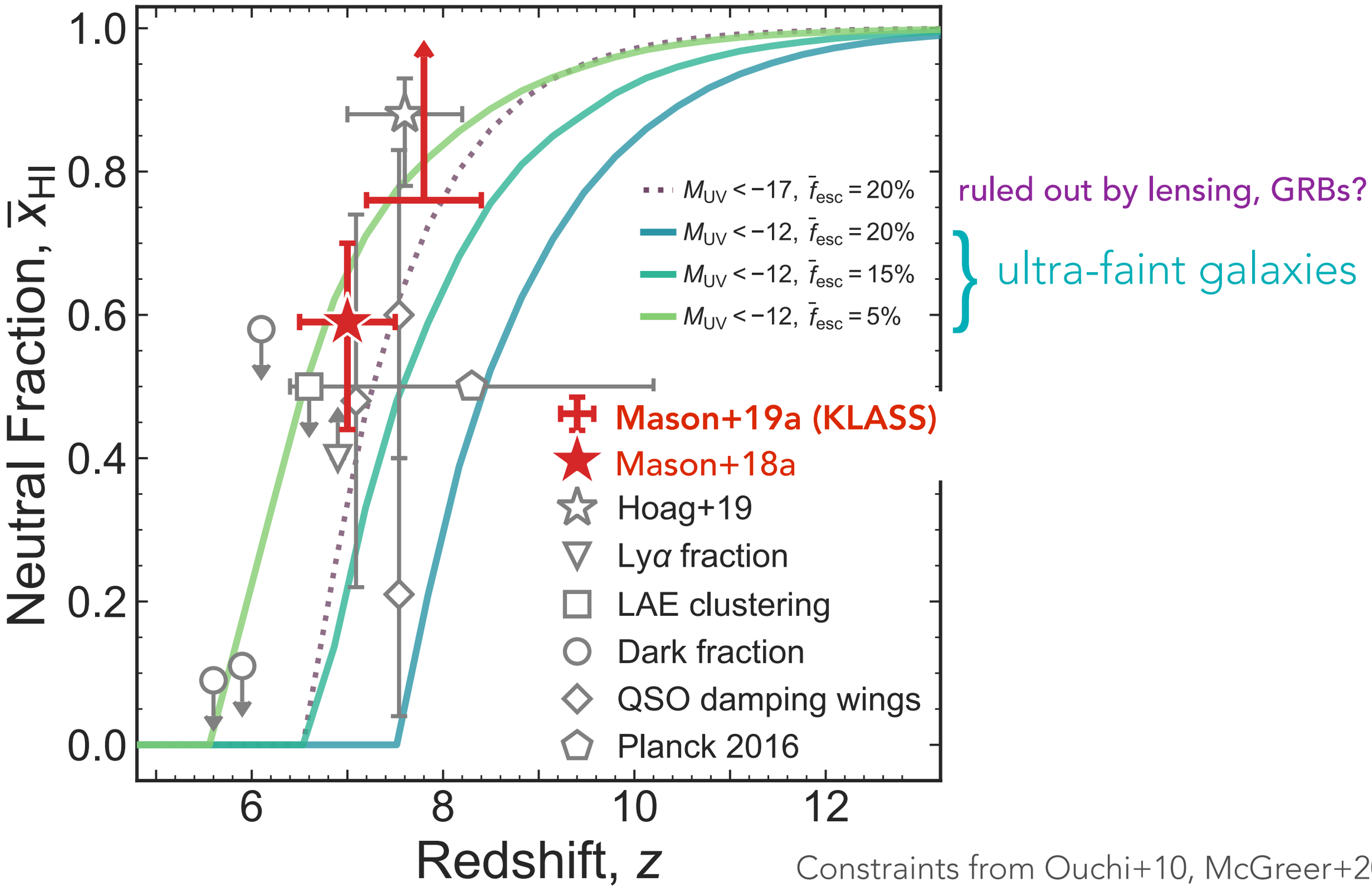
likelihood

probability of getting data: f(**λ**)
given IGM neutral fraction,
redshift and observed galaxy properties

priors

redshift - photo-z
FWHM - empirical
x_{HI} - uniform [0,1]

The universe is getting very neutral at z>6...



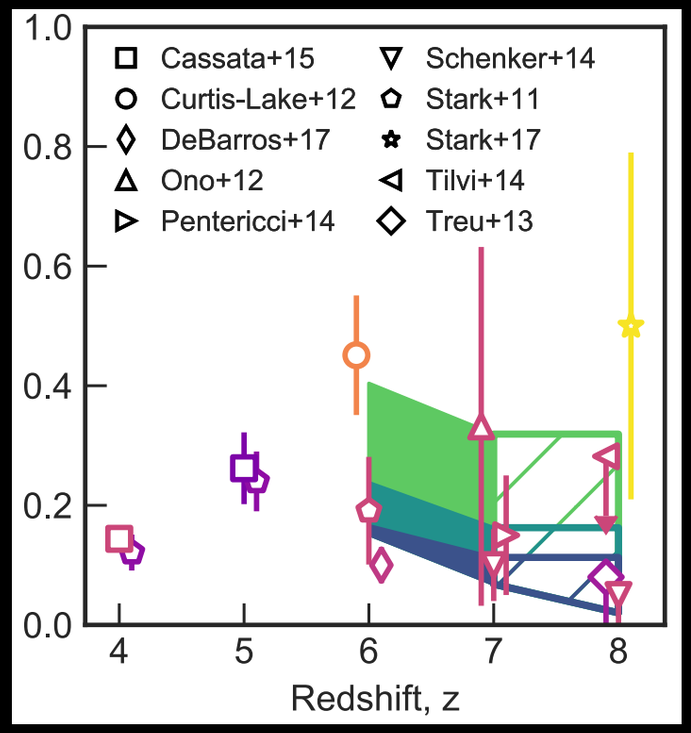
ruled out by lensing, GRBs?

} ultra-faint galaxies

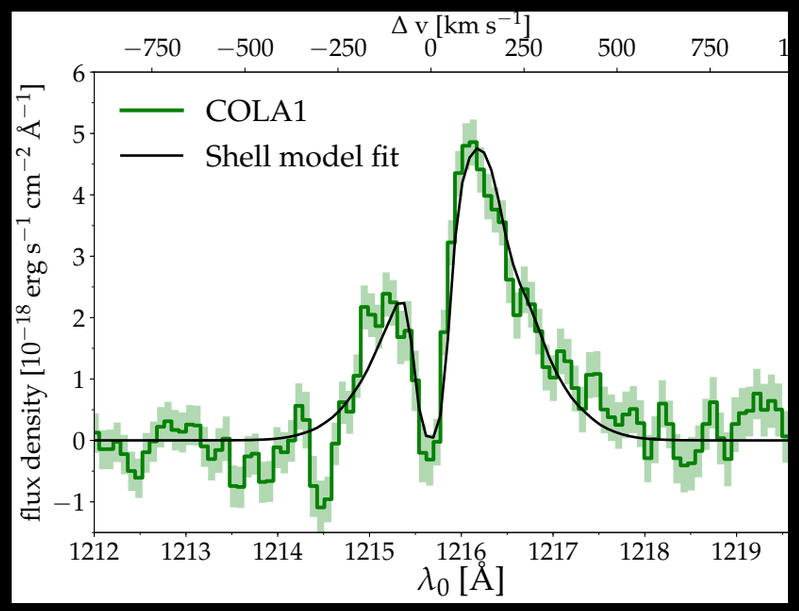
Mason+19a

Constraints from Ouchi+10, McGreer+2014, Mesinger+15, Sobacchi+15, Davies+18, Greig+18

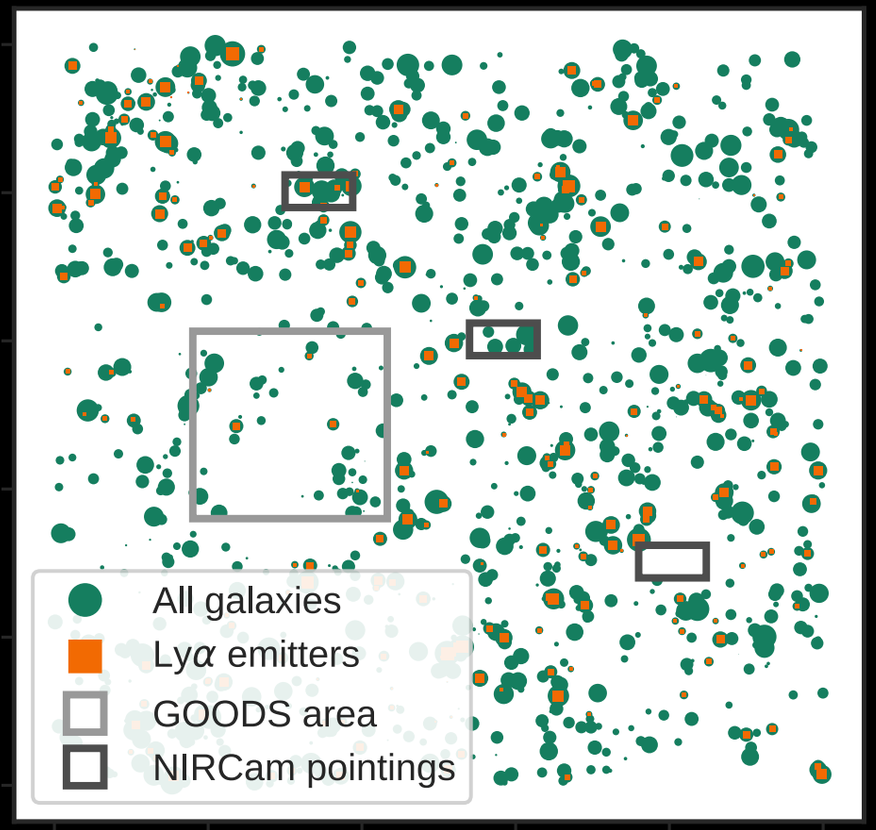
Puzzling z>6 Lyα detections hold keys to local reionization process?



Mason+18b



Matthee+18



Lyα from z>7.5 UV bright galaxies

extreme Lyα emitters?
larger ionized bubbles?

blue Lyα peaks at z>6

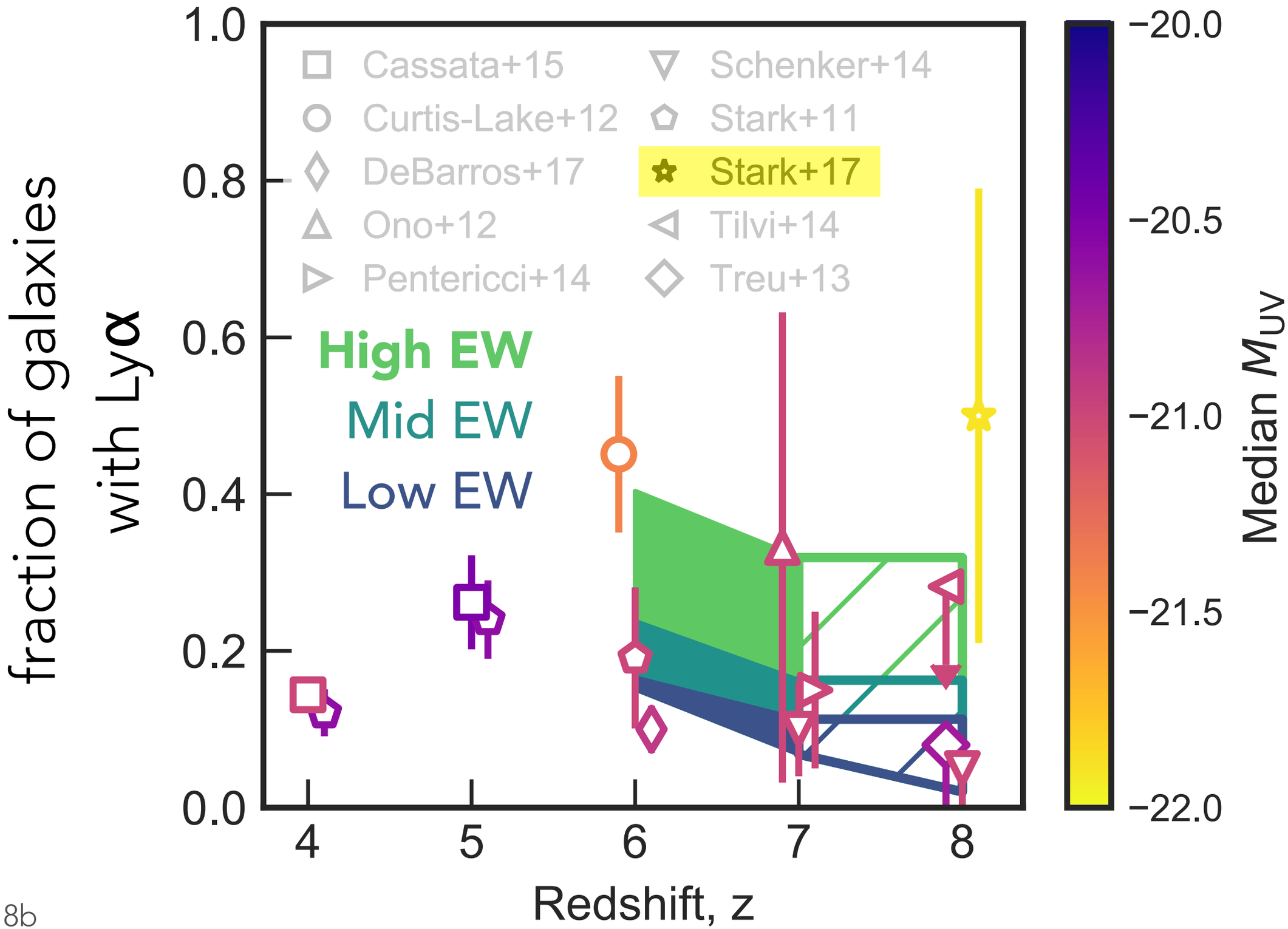
direct evidence of
>2 Mpc ionized bubble?

Spatial fluctuations in Lyα detections

patchy reionization?
Lyα emission properties?

Hoag+19a (incl CM)
Jung+19

21cmFAST models cannot explain high Lyα fraction in UV bright galaxies — emitted EW must be high and/or larger bubbles?

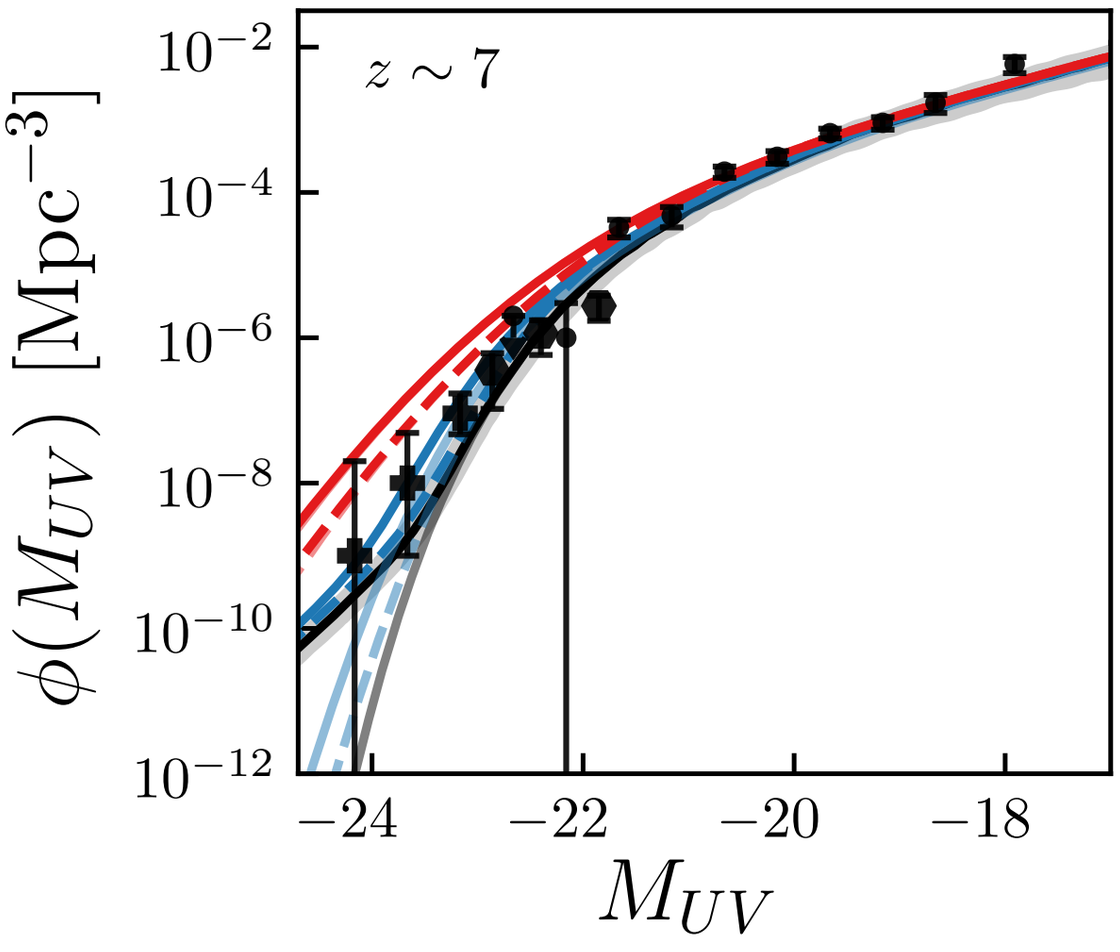


Mason+2018b

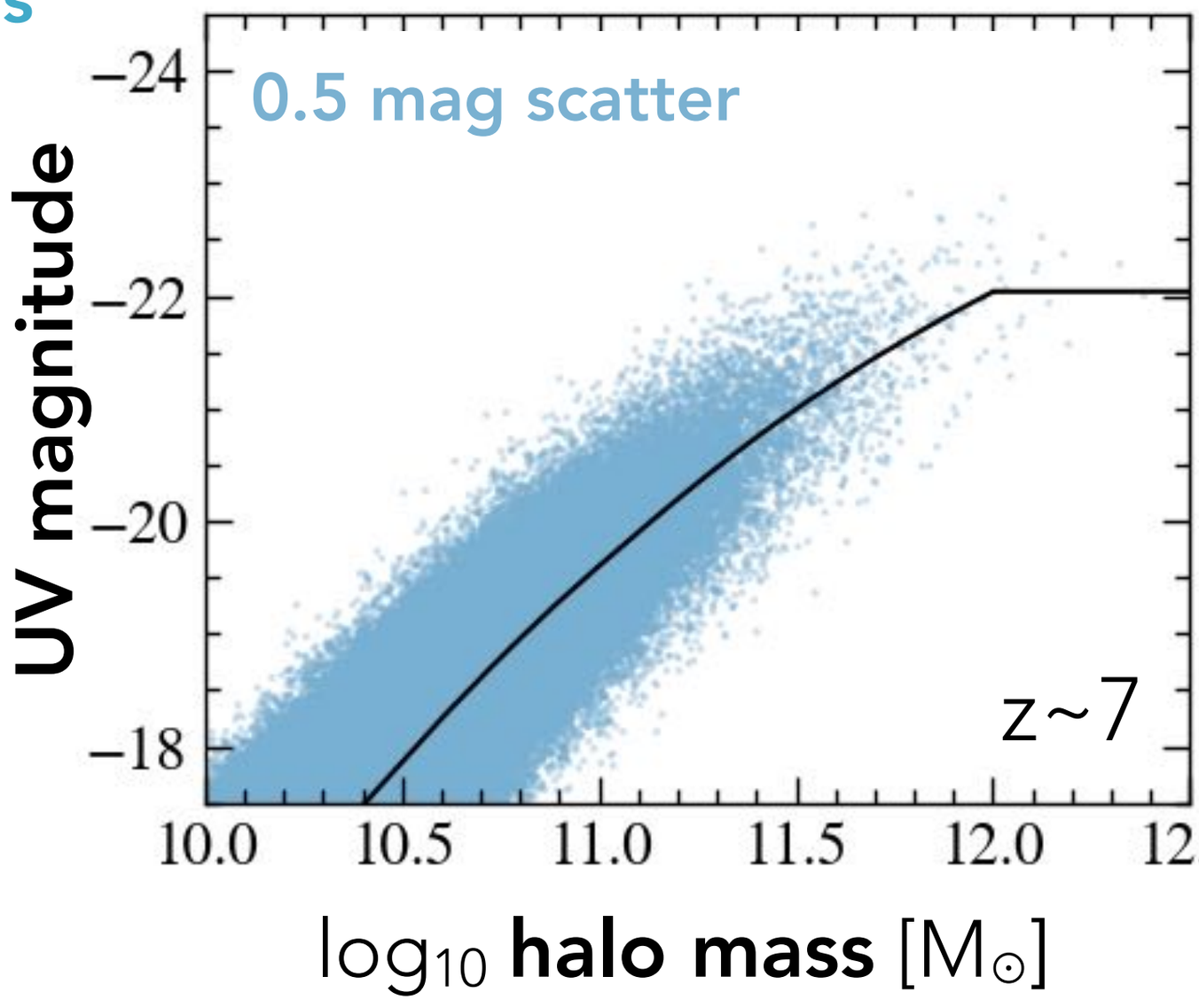
Lily Whitler (ASU)

But the brightest galaxies do not necessarily live in the most massive halos

0.5 mag M_{UV} - M_h scatter consistent with observed LFs



Whitler+in prep

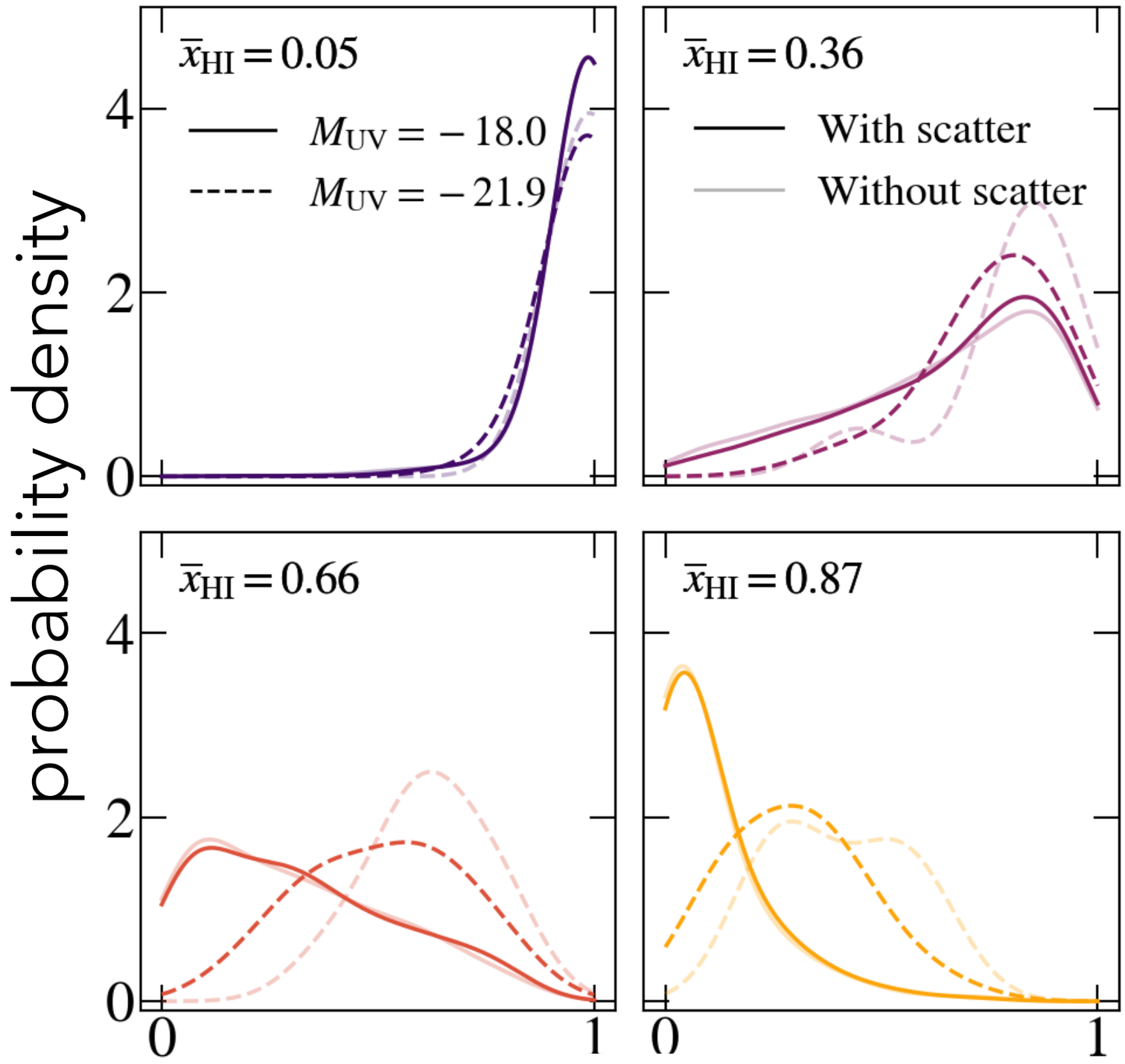


Ren, Trenti & Mason 2019

Lily Whitler (ASU)

UV luminosity — halo mass scatter reduces Lyα visibility from bright galaxies

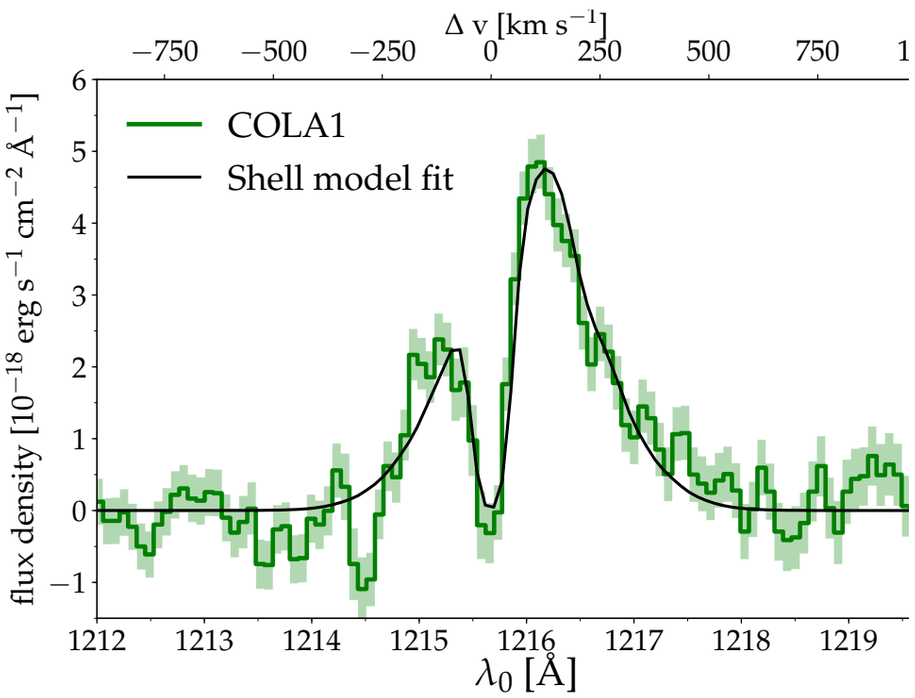
Mostly ionized

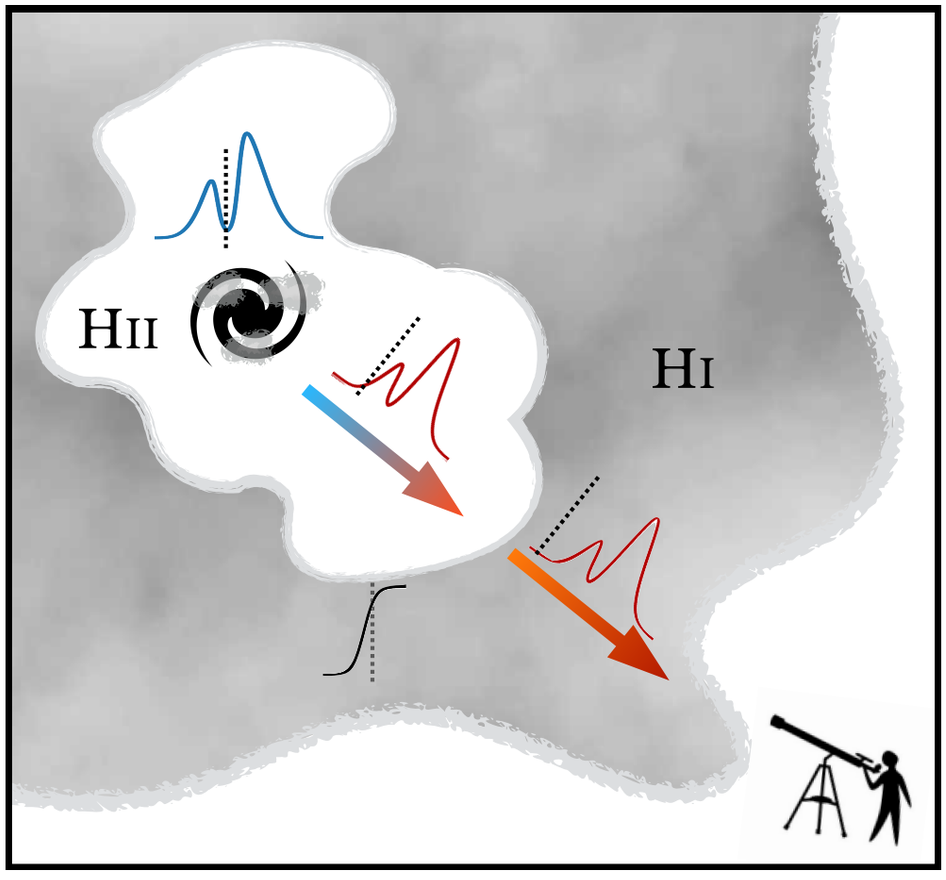


Mostly neutral

Whitler+in prep

Blue Lya peak at z>6 due to large ionized bubble?





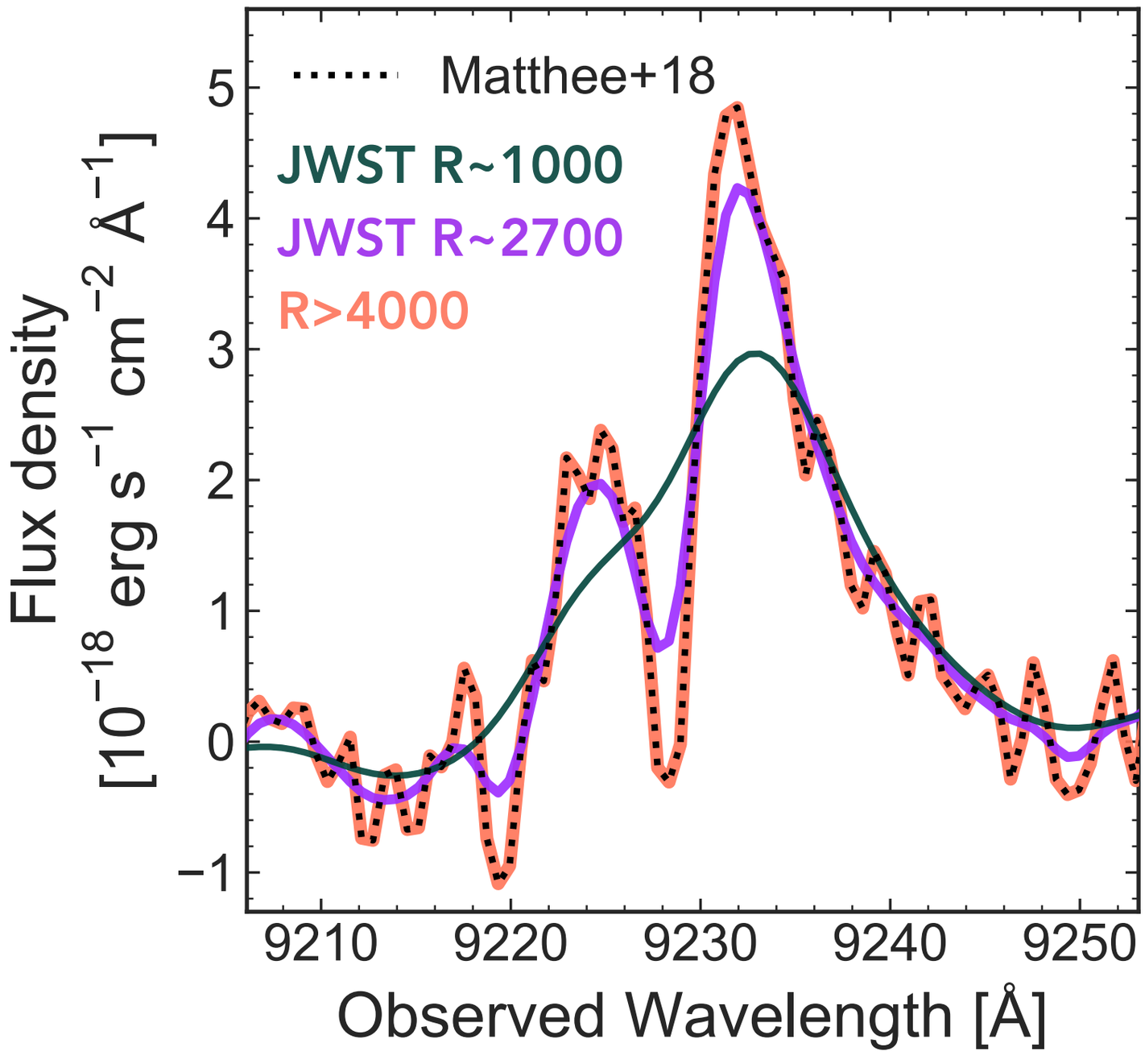
Matthee+18

HII region must be >2 Mpc so Lya is redshifted far into damping wing

What is prevalence of blue peaks at z>6?

Are they spatially correlated? i.e. in the ionized regions?

Require high resolution Lyα spectroscopy to disentangle ISM, CGM and IGM during reionization



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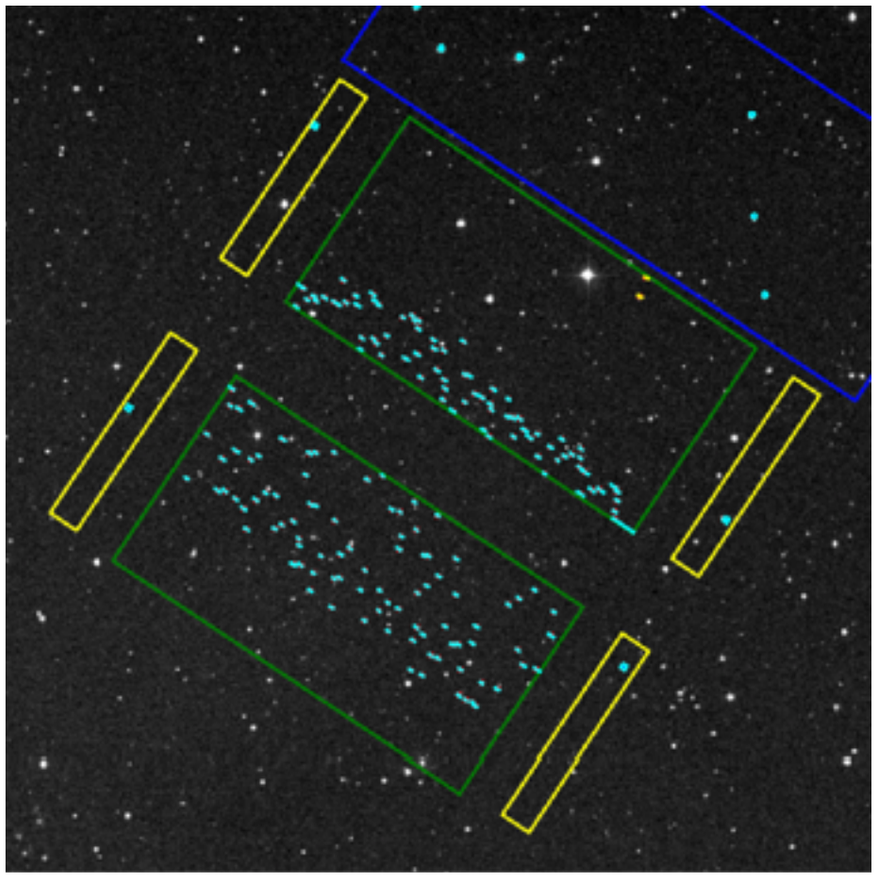
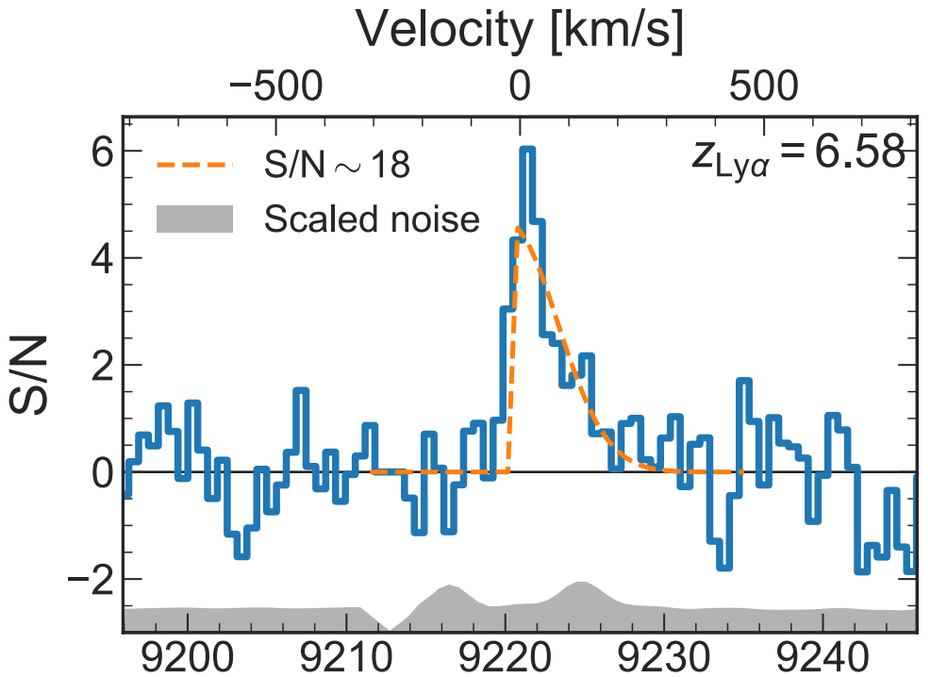
High spectral resolution survey to map ionizing bubbles via Lyα lineshapes

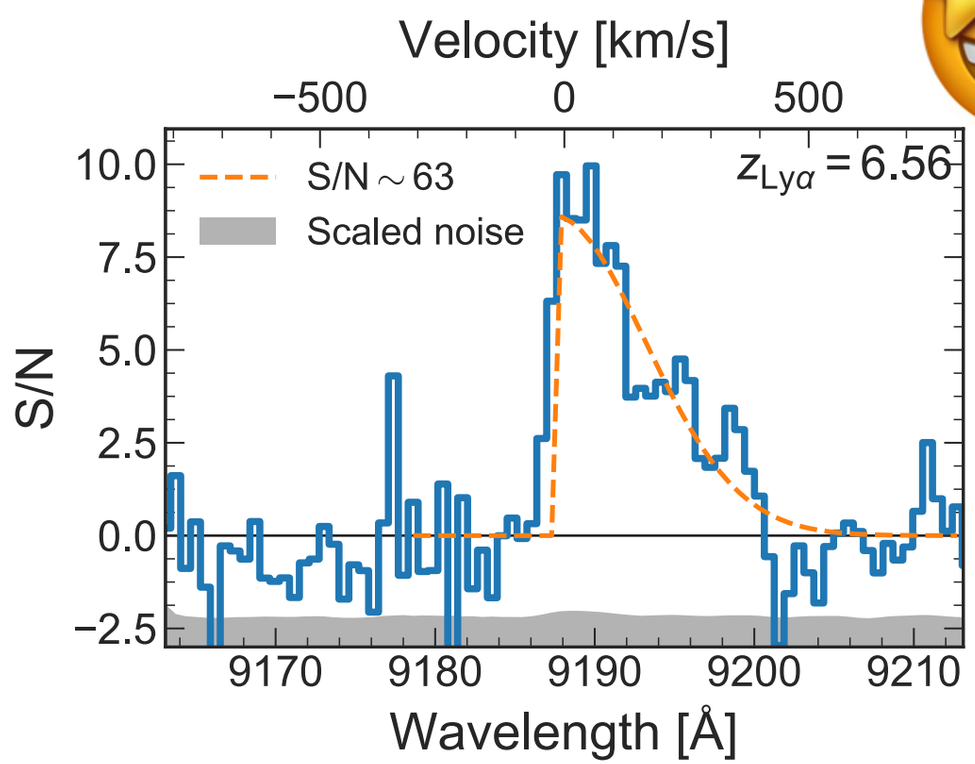


MMT/Binospec

R~4500 (<70 km/s)

z~5-7, ~200 targets per mask





Evolving Lyα transmission contains information about **reionization**

- 100s of z>7 galaxies observed, only a handful have Lyα detections
- **IGM and ISM** effects included via forward-modelling to make inferences from Lyα observations

Puzzling Lya observations at z > 6 probe **< Mpc reionization effects**

- More Lyα from (some) bright galaxies than expected
- Lyα **lineshapes** may probe **topology of bubbles**

Lack of Lyα from z>6 galaxies favors **fairly rapid, late reionization**

`Holistic' modelling needed to make Lyα a better cosmological tool