Charlotte Mason (UCLA)

Berkeley Cosmology Seminar, Oct 10 2017

What can galaxies tell us about the Epoch of Reionization?

with Tommaso Treu, Michele Trenti, Mark Dijkstra, Andrei Mesinger,
Laura Pentericci, Stephane de Barros, Eros Vanzella, Adriano Fontana
+ the GLASS and BoRG teams

Alvarez (2009)

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

380,000 yrs after BB 0.3 Gyr 0.6 Gyr 1 Gyr 13.7 Gyr

z=1100 15 8 6 0

Dark Ages

Epoch of Reionization

Loeb (2006)

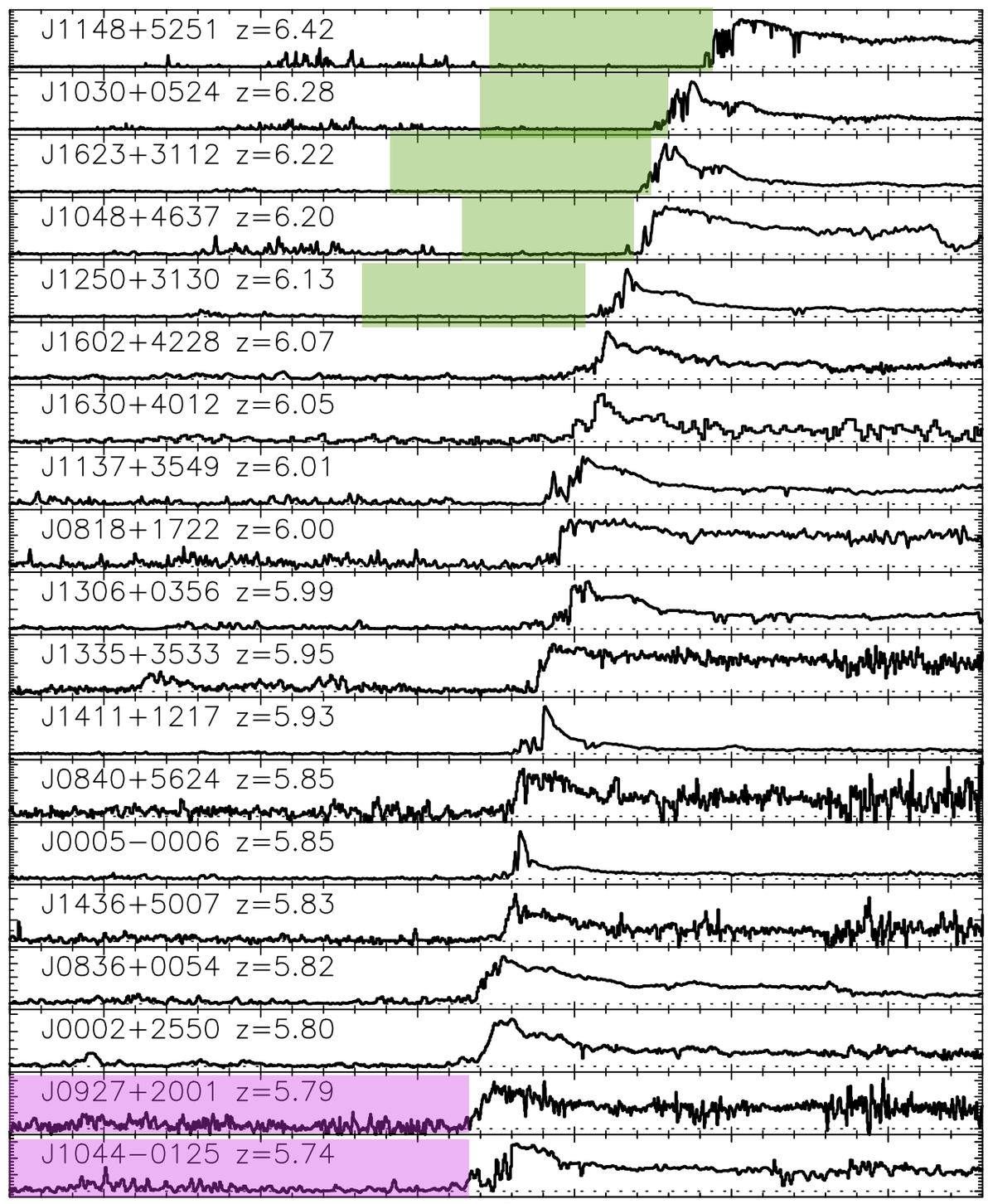
By z>6 quasar absorption features indicate large amounts of neutral hydrogen in the IGM

all photons absorbed —> lots of HI

Lots of transmission in Ly**α** forest —> lots of HII

z=6.4

z=5.7



Fan+06

The ionization state of the intergalactic medium
is a balance between ionizations and recombinations

Fraction of ionized H

$$\frac{\mathrm{d}f_{\mathrm{HII}}}{\mathrm{d}t} = \frac{\dot{n}_{\mathrm{ion}}}{\langle n_{\mathrm{H}} \rangle} - \frac{f_{\mathrm{HII}}}{t_{\mathrm{rec}}}$$

~ IGM clumpiness

we can measure this (but M_{min}?)

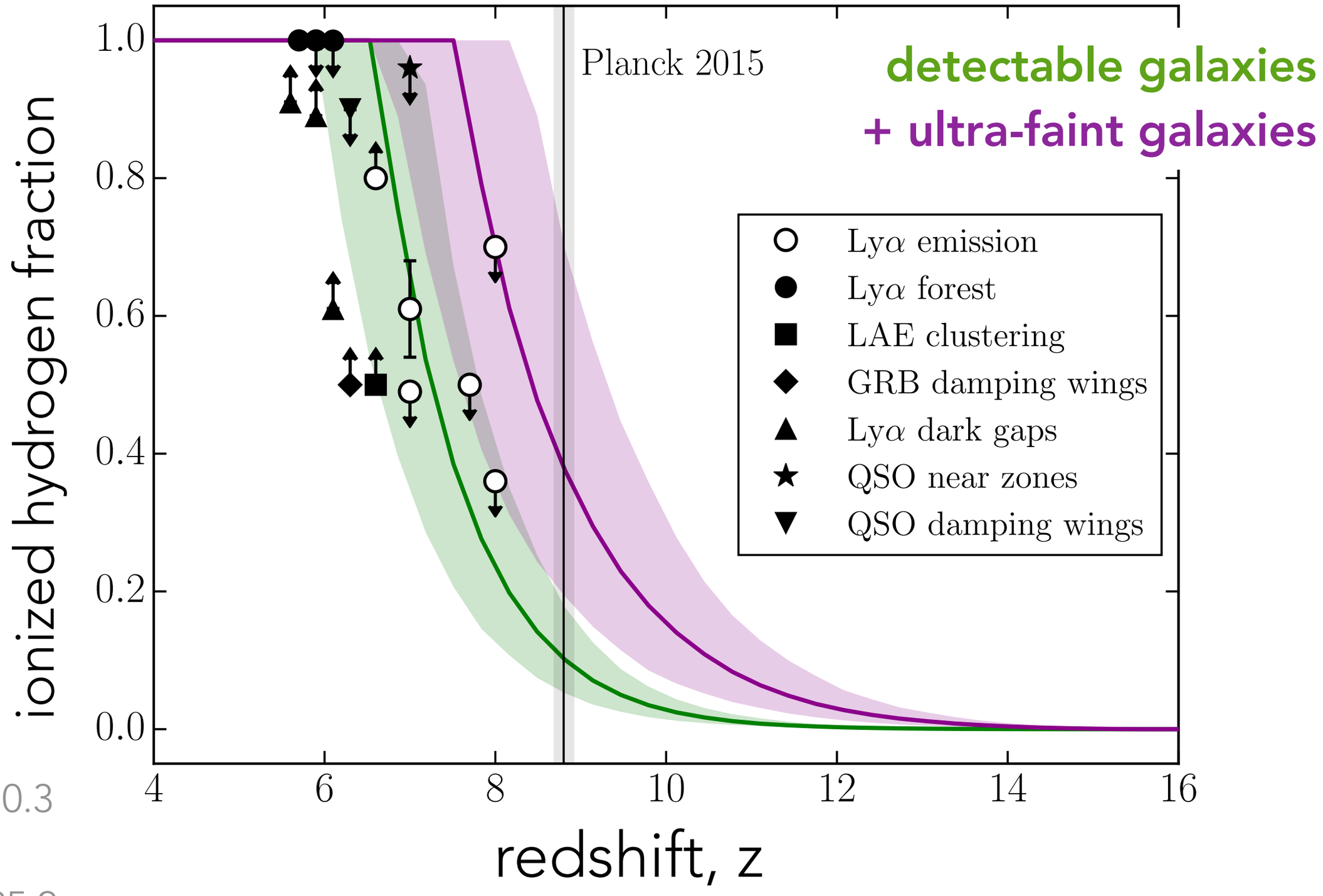
$$\dot{n}_{\mathrm{ion}} = f_{\mathrm{esc}} \xi_{\mathrm{ion}} \dot{\rho}_{\mathrm{UV}}$$

number density of ionizing photons

can we constrain these??

Stiavelli+04, Robertson+15

Constraining the reionization history of the universe helps constrain the sources of ionizing photons



f_{esc} = 0.1 - 0.3

C = 1 - 6

log ξ_{ion} ~ 25.2

Mason+2015b

arXiv:1709.05356

What is the reionization history of the IGM?

Use galaxy spectral properties to constrain the IGM

Forward modelling framework to connect Lyα observations to IGM state

Understand galaxy population evolution during and before the EoR

Model evolution to establish physical drivers

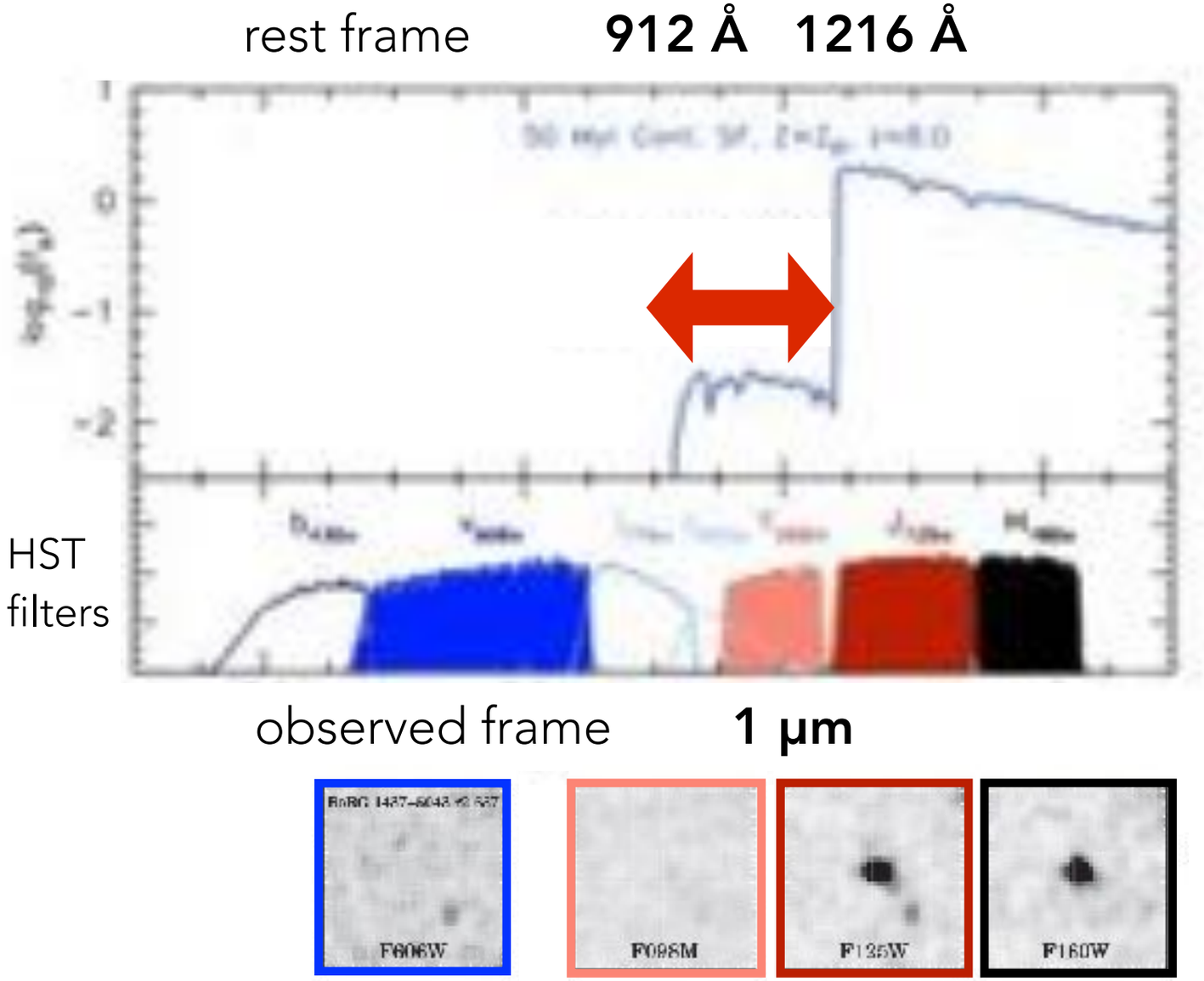
Are there enough ionizing photons from galaxies?

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

Star forming galaxies are dominated by massive, hot O and B stars emitting in the UV

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

High redshift galaxies are selected as ‘dropouts’ in broad band photometry



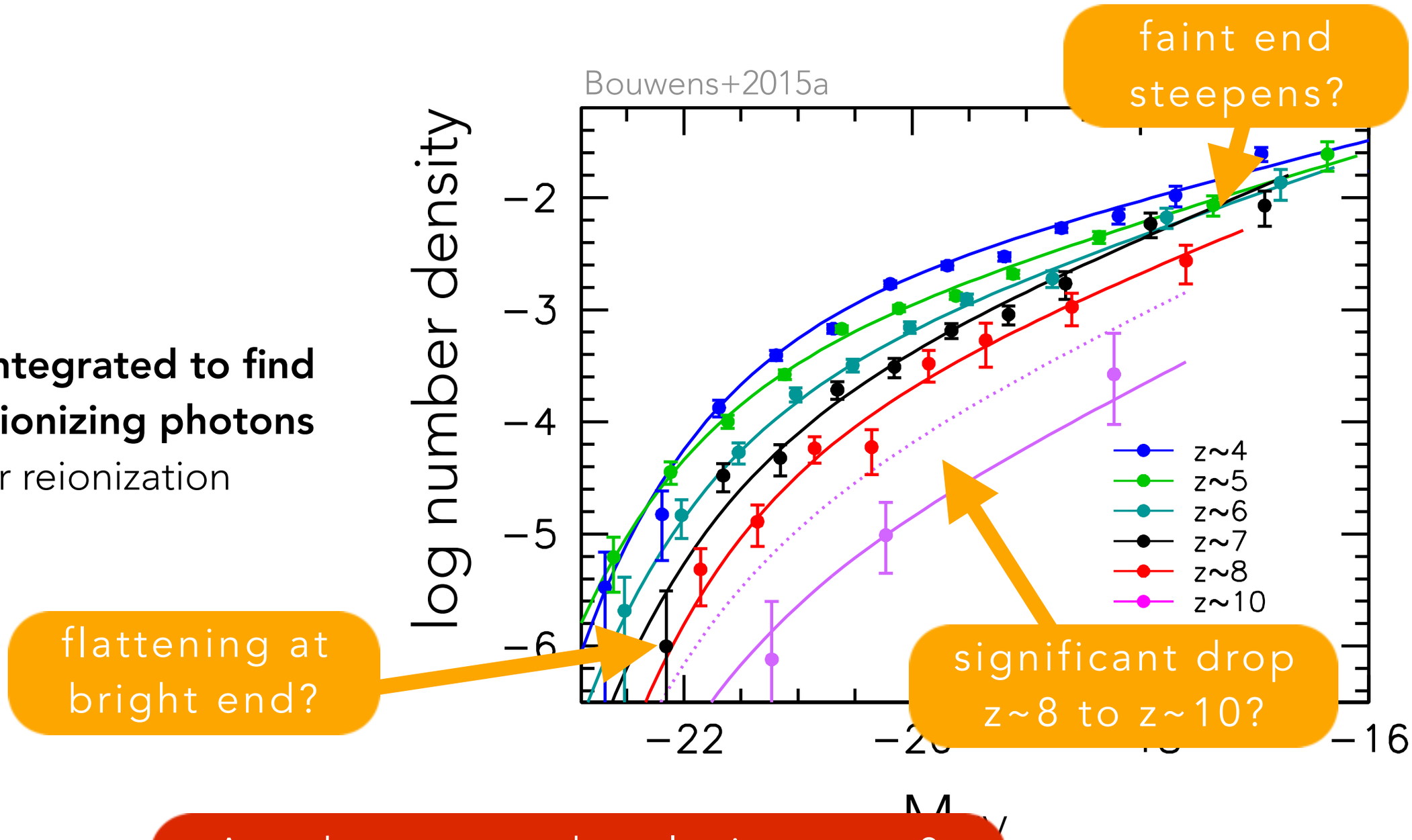
Schmidt+2014

Since the installation of WFC3 on HST in 2009 the sample of z>6 galaxies has increased by two orders of magnitudes

... and things will get even better with JWST + WFIRST

Rest-frame UV luminosity functions trace **star-forming galaxies** over cosmic time

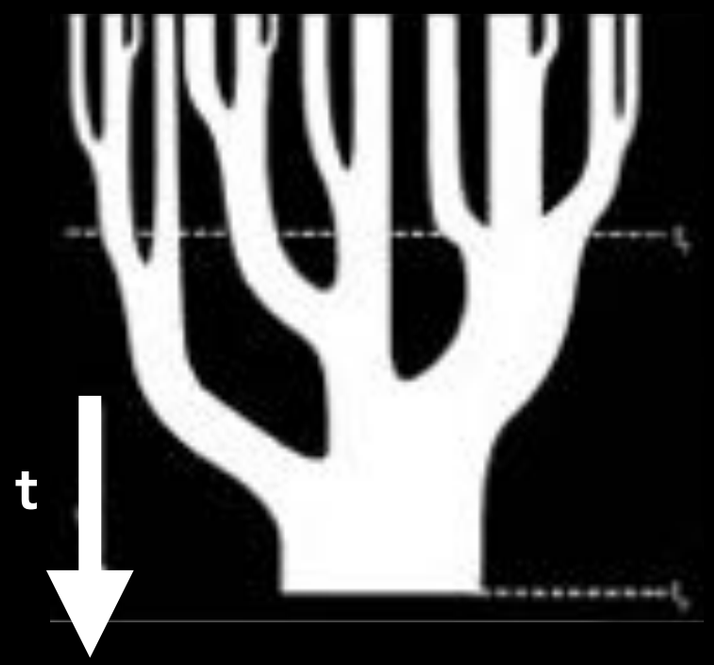
LF can be **integrated to find the flux of ionizing photons** available for reionization



Are there enough galaxies at z>8 to reionize the universe? What will JWST see?

What drives evolution in the LF?

halo mass function + star formation + feedback/ physical conditions?



What is the simplest theoretical model to connect halo growth to star formation?

Mason, Trenti & Treu (2015)

- minimal degrees of freedom
- self-consistency over redshift

$$\mathrm{SFR}(M_h, z) \sim \boldsymbol{\varepsilon}(M_h) \times \text{halo mass accretion rate}(M_h, z)$$

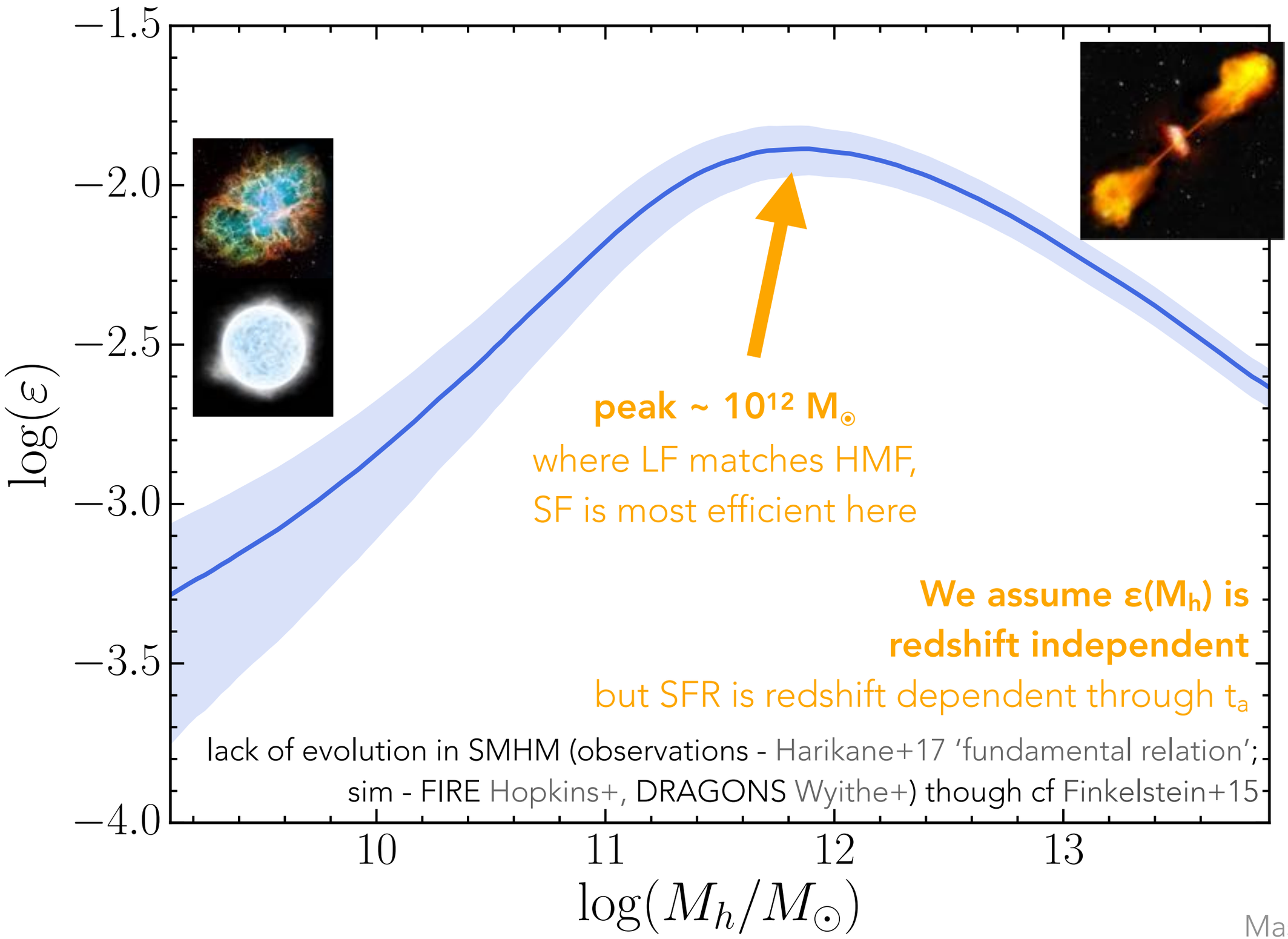
SF efficiency ~ $M_\star/M_h$
fixed from calibration
at one redshift via
abundance matching
very weakly evolving
(Behroozi+2013)

assume gas follows DM
from cosmology

(Planck ΛCDM + ellipsoidal collapse,
Sheth+2001 Lacey & Cole 1993)

see also Tacchella+2013, Trenti+2010

Calibrate our model at z~5 to find SF efficiency $\varepsilon(M_h)$, by abundance matching observed LF to theoretical HMF



peak ~ 10^{12} $M_\odot$

where LF matches HMF,
SF is most efficient here

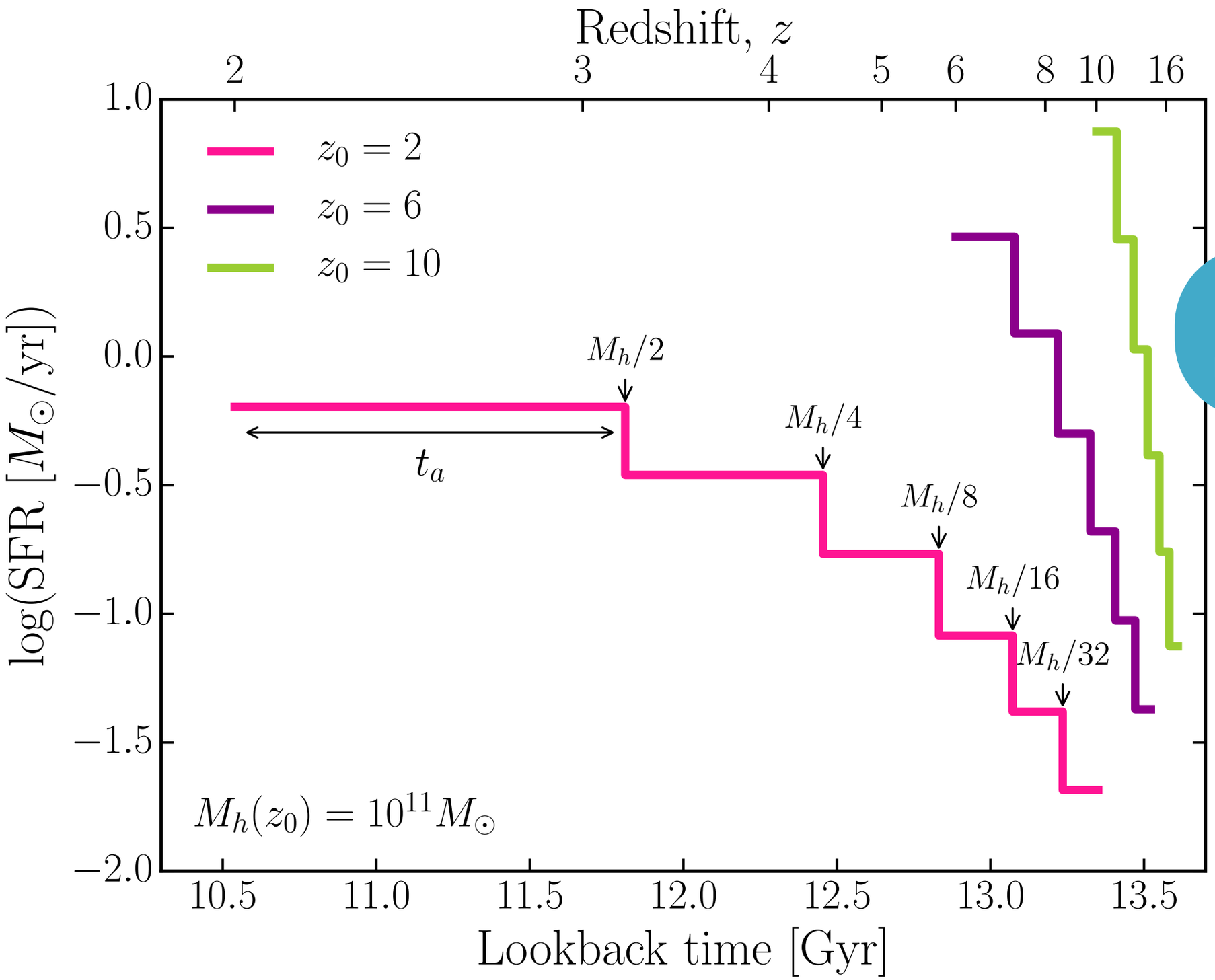
We assume $\varepsilon(M_h)$ is redshift independent

but SFR is redshift dependent through t_a

lack of evolution in SMHM (observations - Harikane+17 'fundamental relation'; sim - FIRE Hopkins+, DRAGONS Wyithe+) though cf Finkelstein+15

Mason+2015b

We model star formation histories as epochs of constant SFR as halos grow

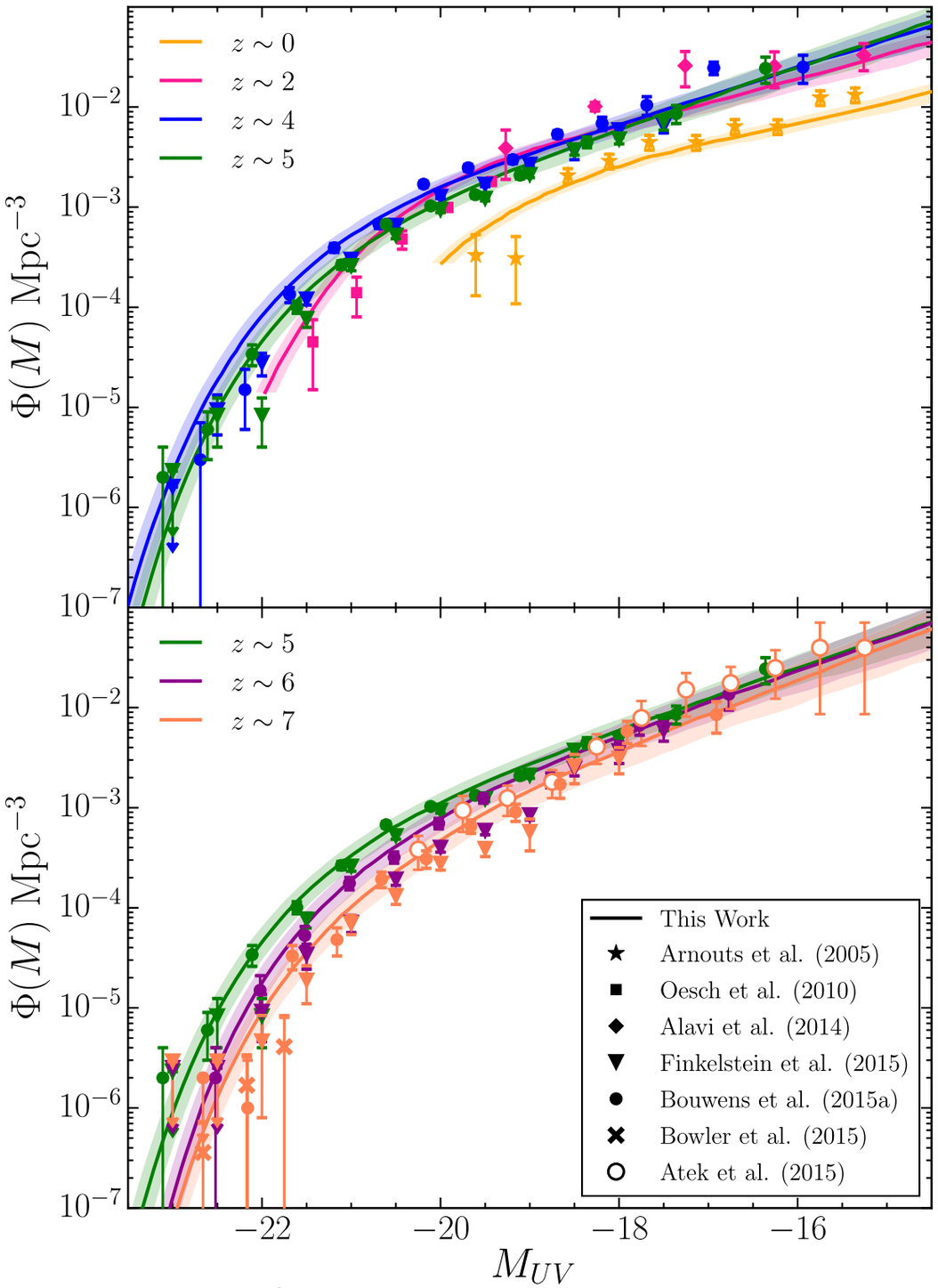


Mason+2015b

Star formation is rapid at high redshift

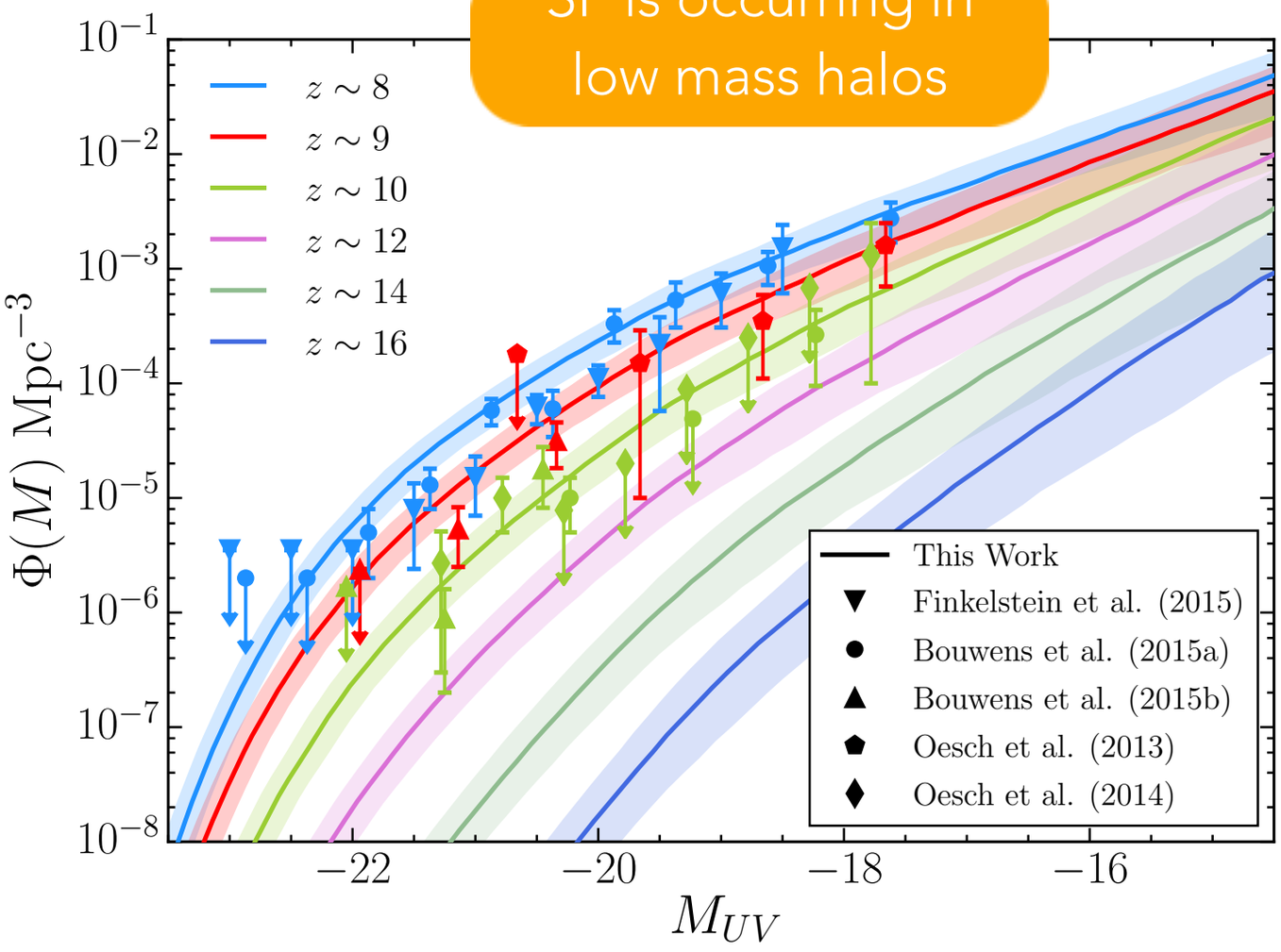
Smoothly rising SFHs (Finlator+2011, Papovich+2011; Behroozi+2013b; Lee+2014)

Our simple model is remarkably **consistent with observed LFs over 13 Gyr of cosmic time!**



Mason+2015b

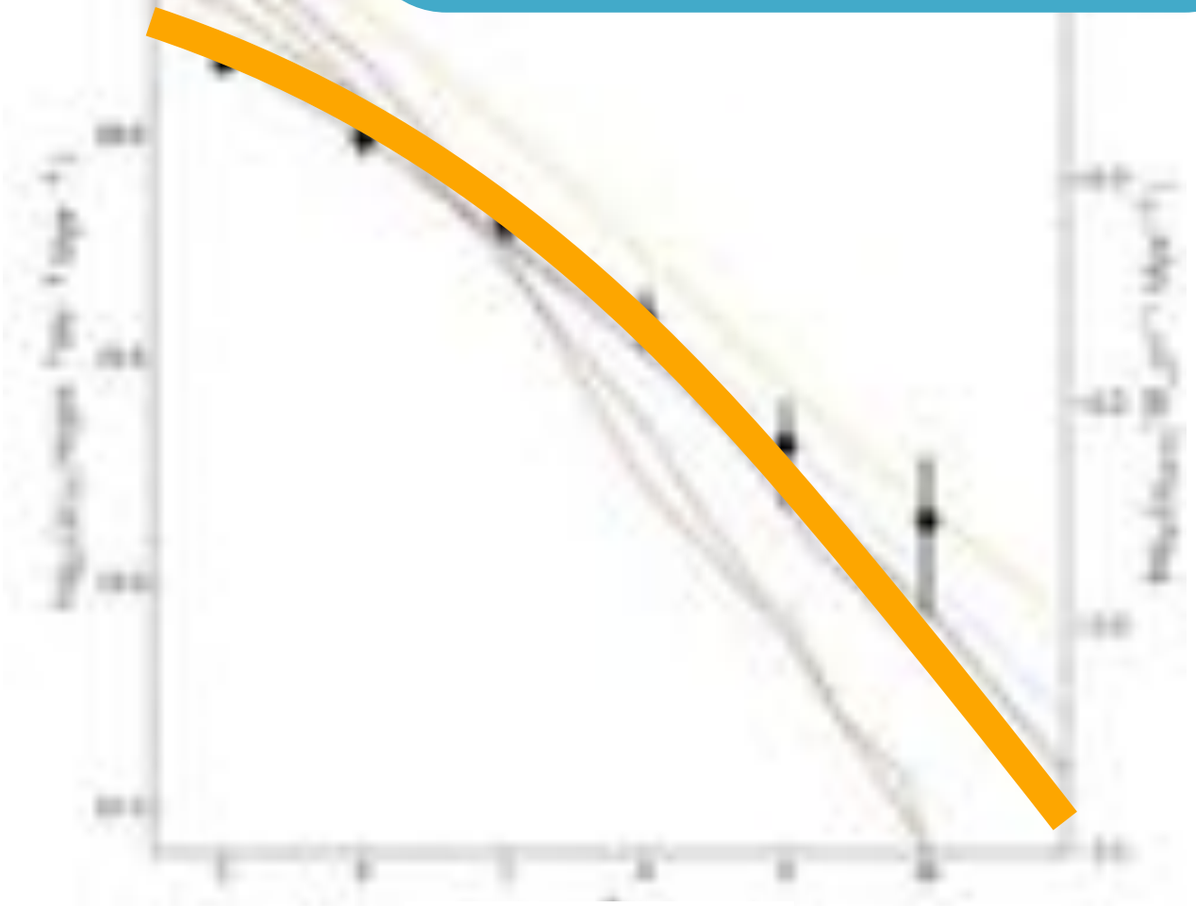
SF is occurring in low mass halos



No evolution in feedback mechanisms needed, even in EoR

Other global galaxy properties we predict are consistent with observations

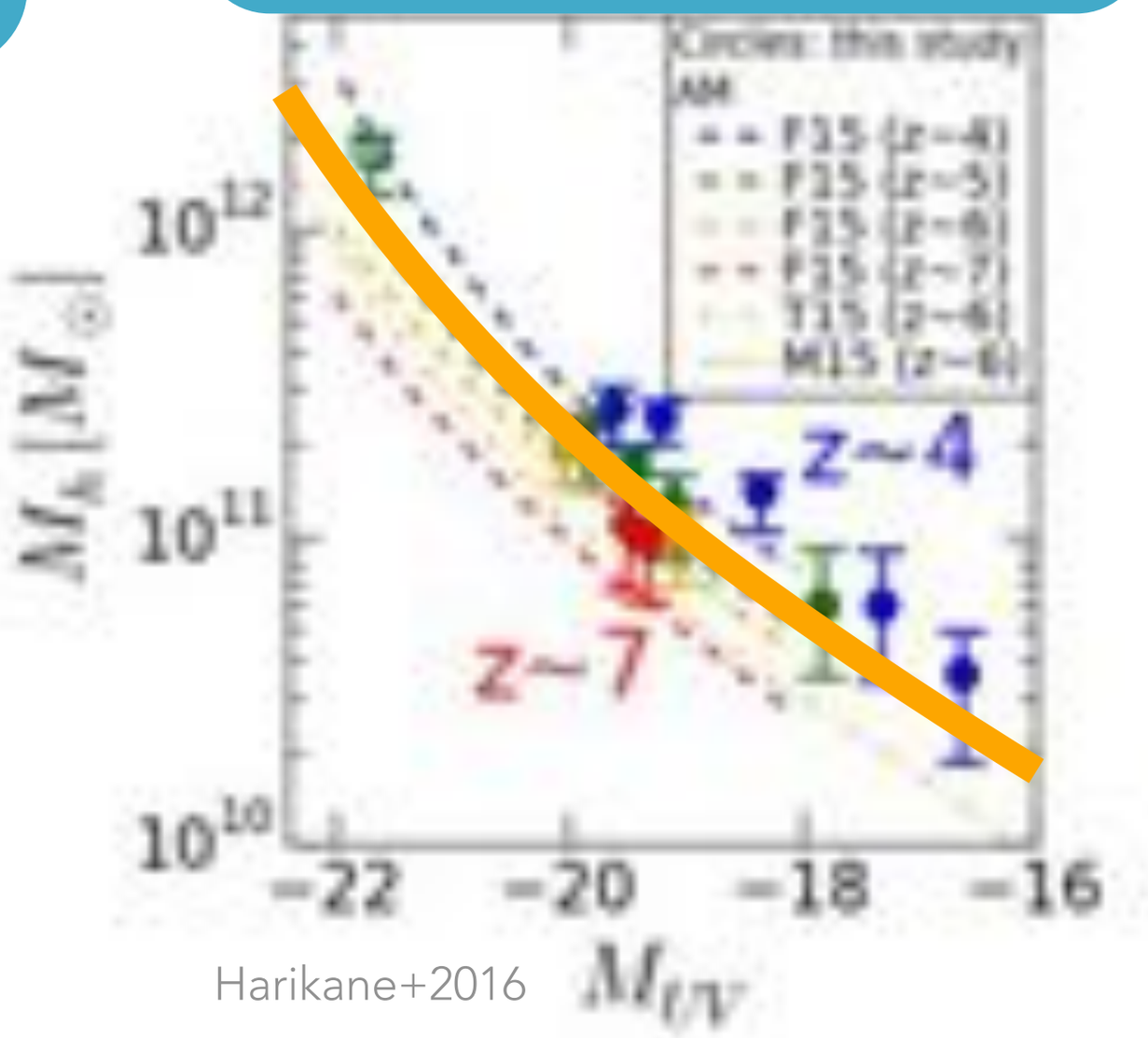
luminosity density/
SFR density



McLeod+2016

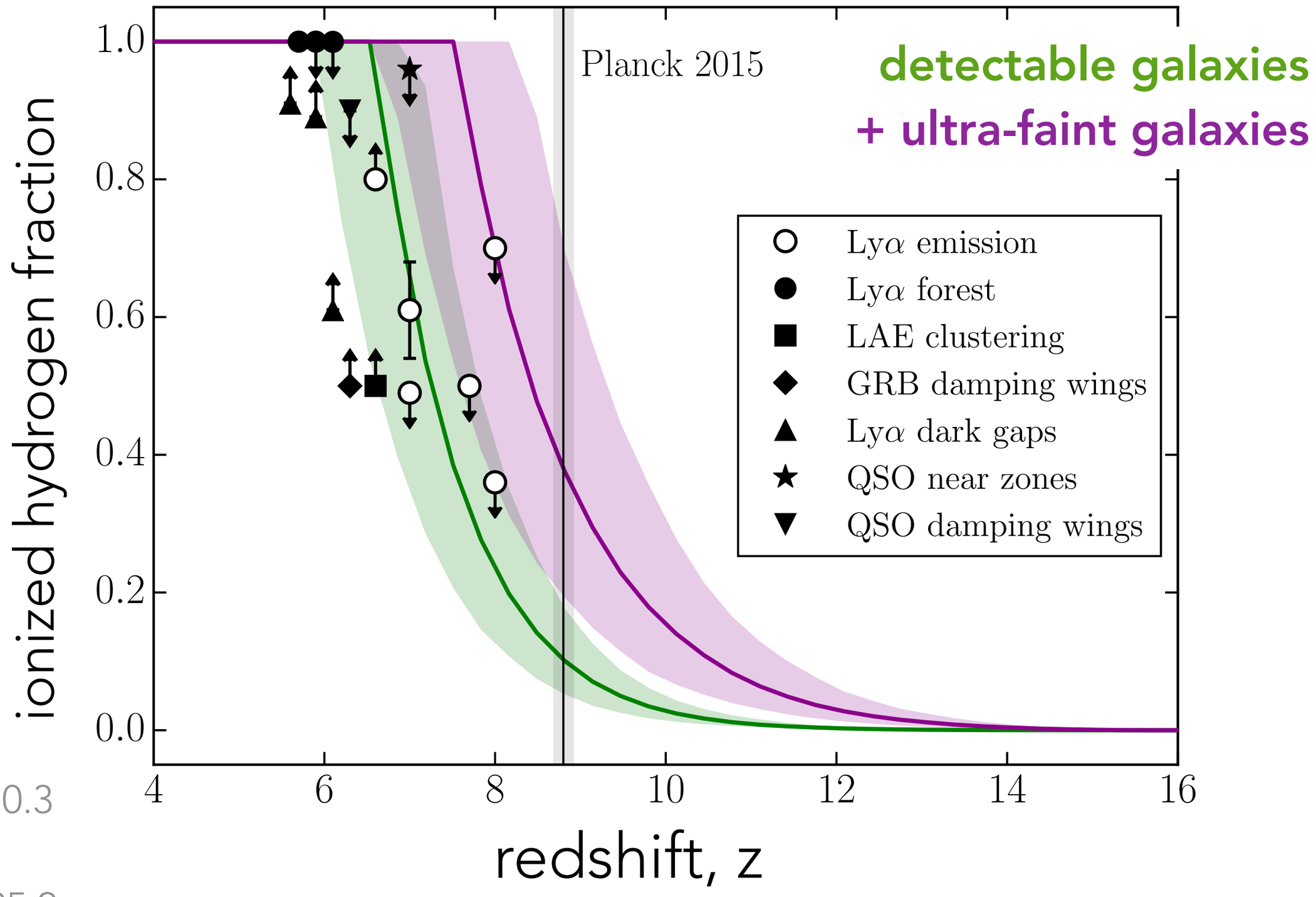
redshift, z

L(Mh,z) from clustering



Harikane+2016

More accurate measurements of the reionization history will help constrain properties of early galaxies



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Mason+2015b

arXiv:1709.05356

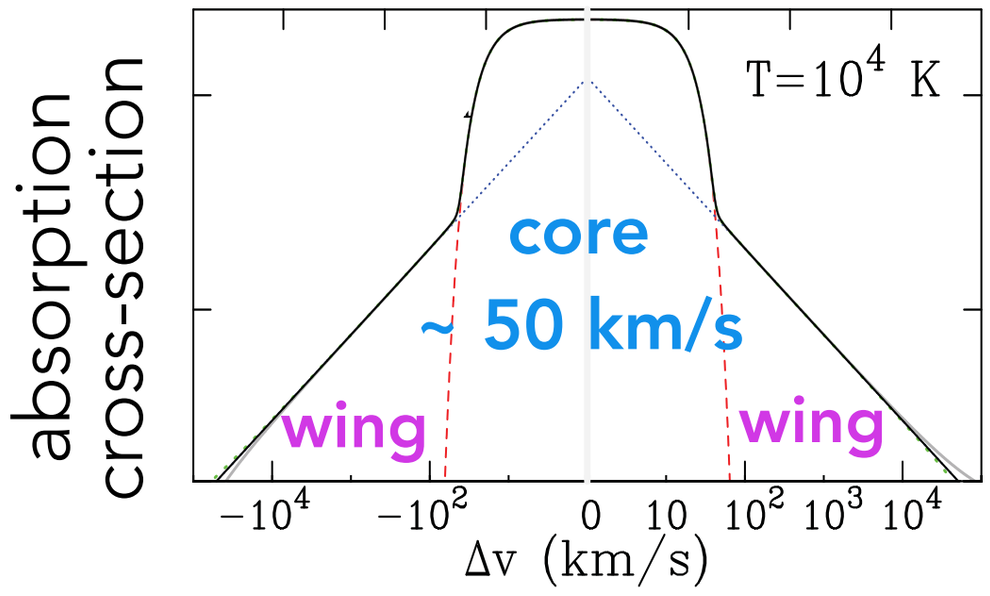
What is the reionization history of the IGM?

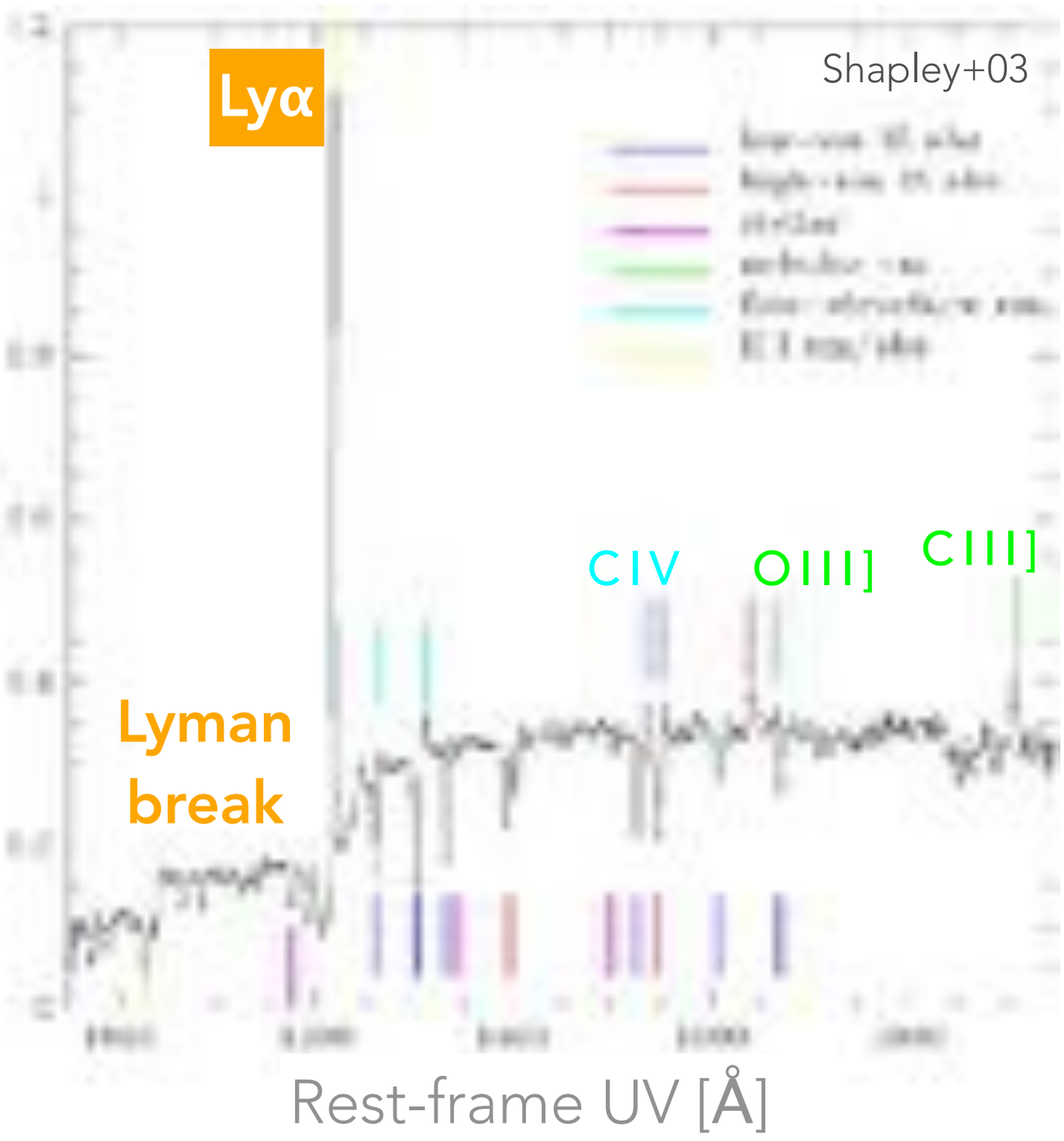
Use galaxy spectral properties to constrain the IGM

Forward modelling framework to connect Lyα observations to IGM state

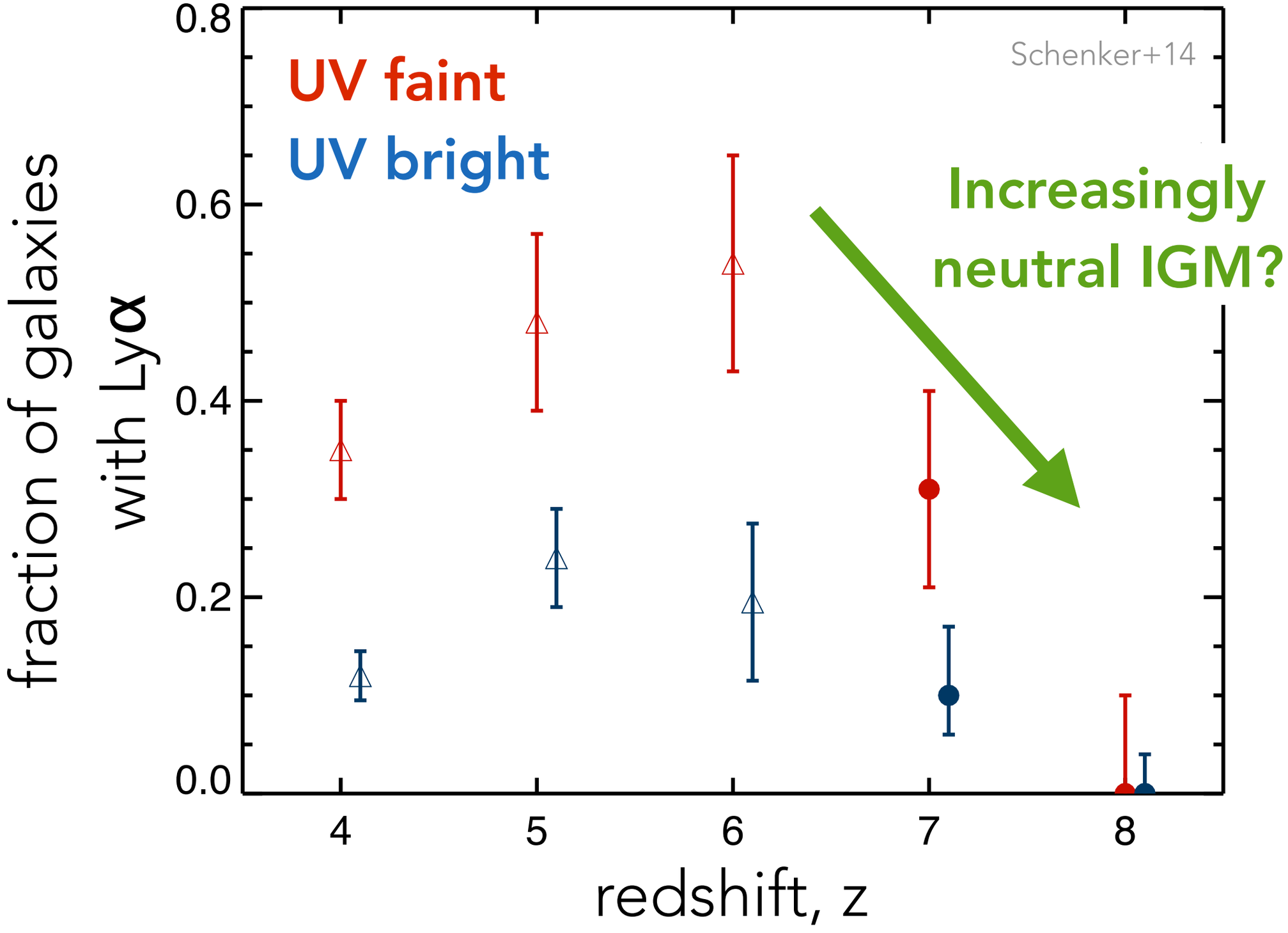
Lyα emission from galaxies is absorbed by neutral hydrogen, a potential tracer of the evolving IGM

- n=2 —> n=1 (1216Å) transition in Hydrogen
- Produced predominantly by **recombination** in dense ISM around O and B stars
- **High cross-section for absorption**



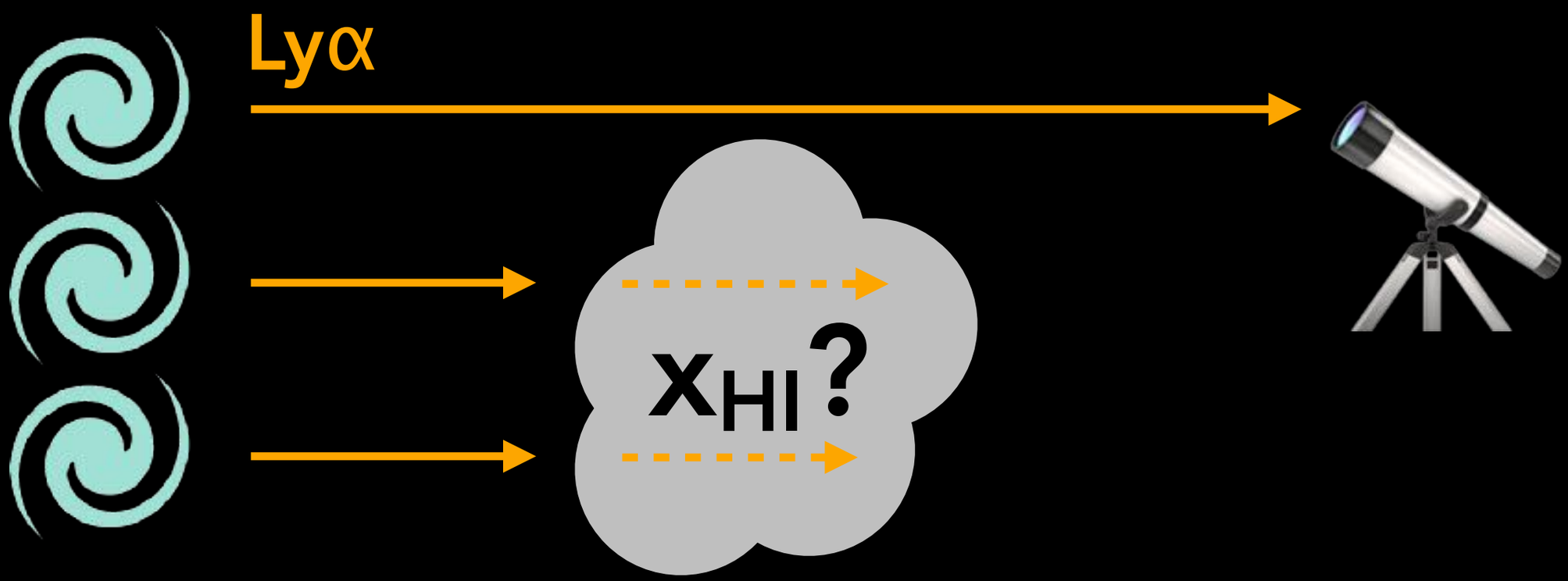


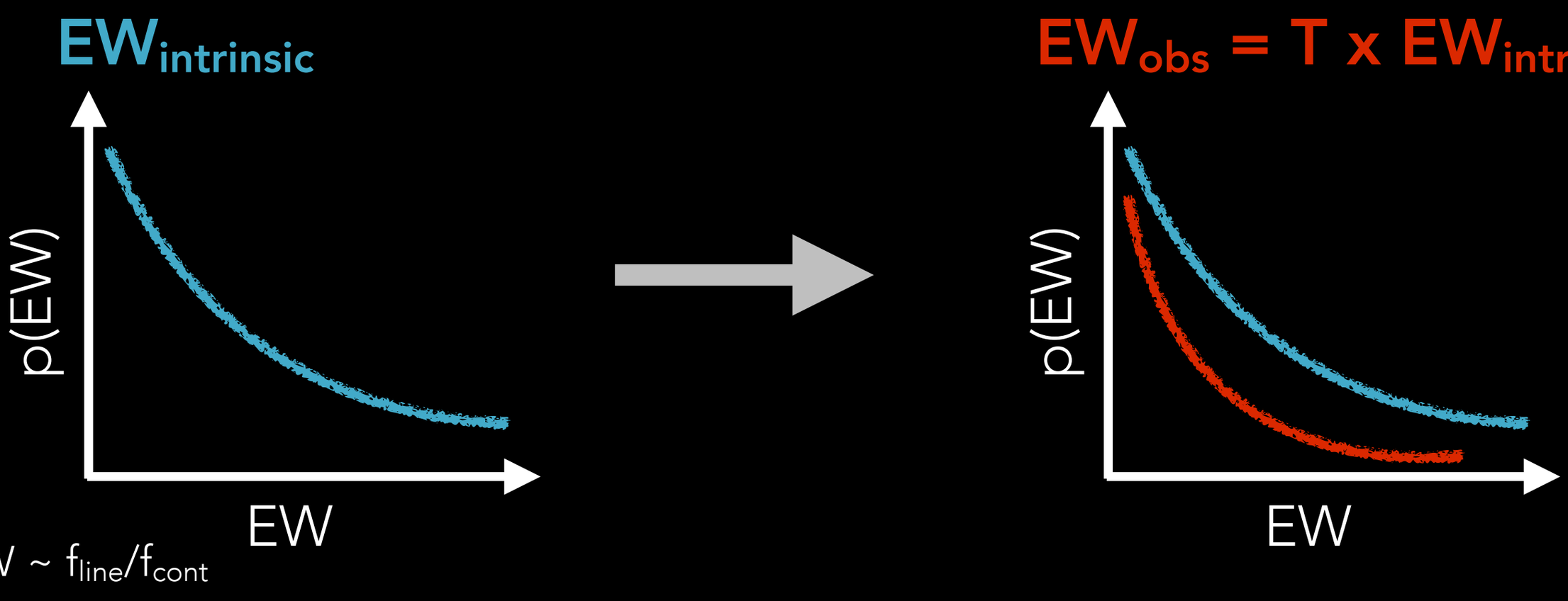
Is the sudden evolution in Lyα transmission at z>6 the smoking gun of Reionization?



data from Stark+11, Schenker+2014, see also Treu+2013

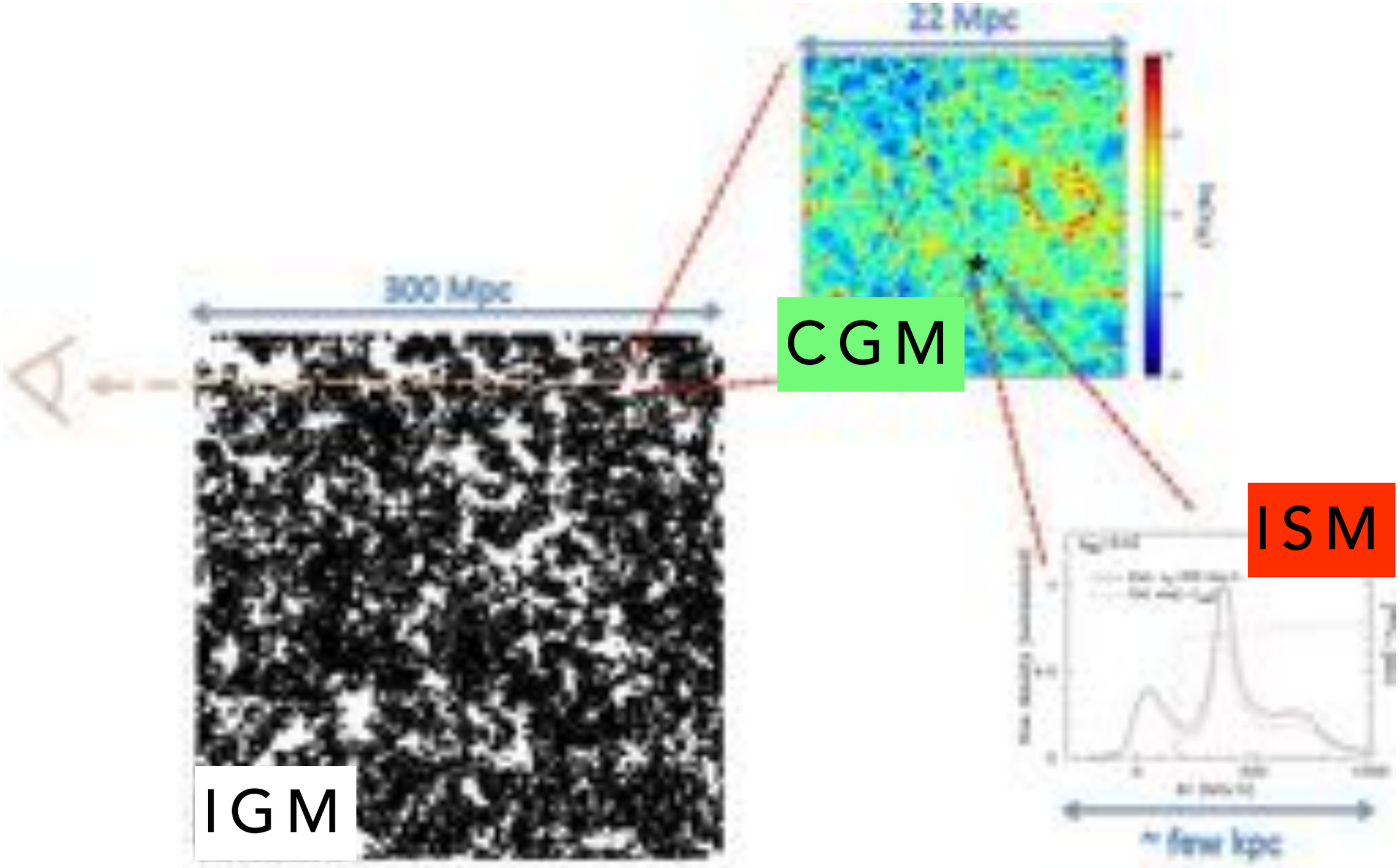
How do we connect Lyα observations to the neutral fraction?





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

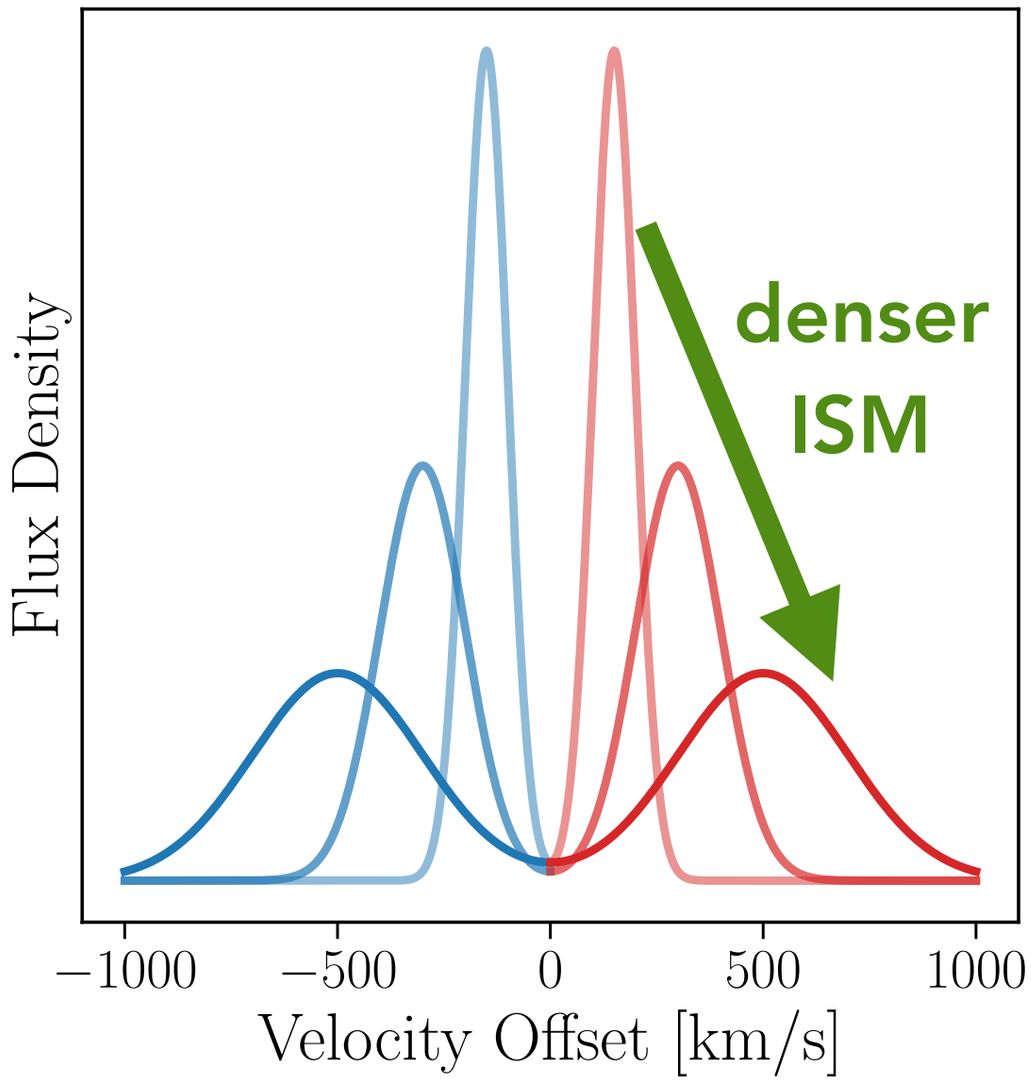
Realistically modelling reionization **requires a multi-scale approach**

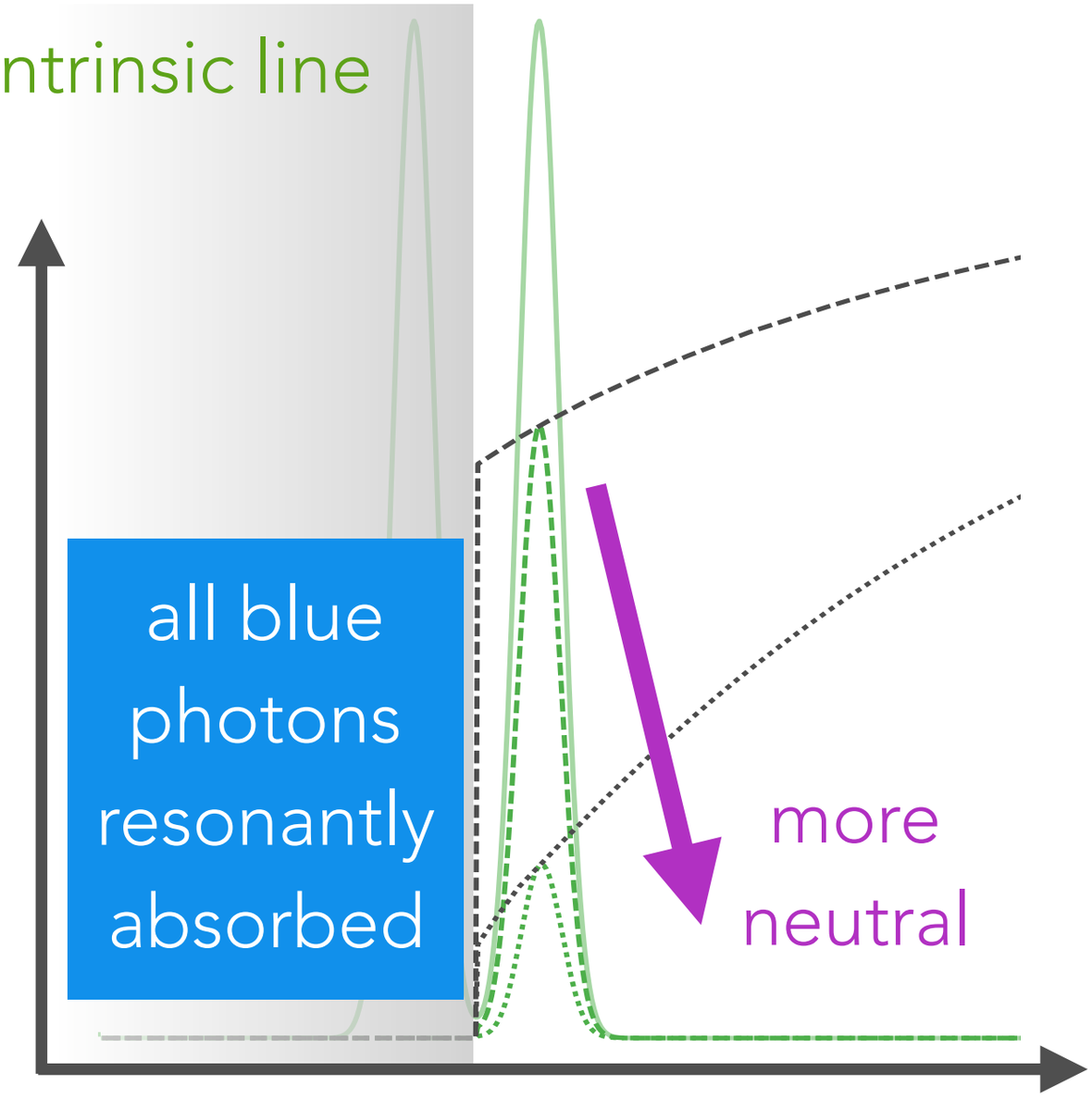


Mesinger+14

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

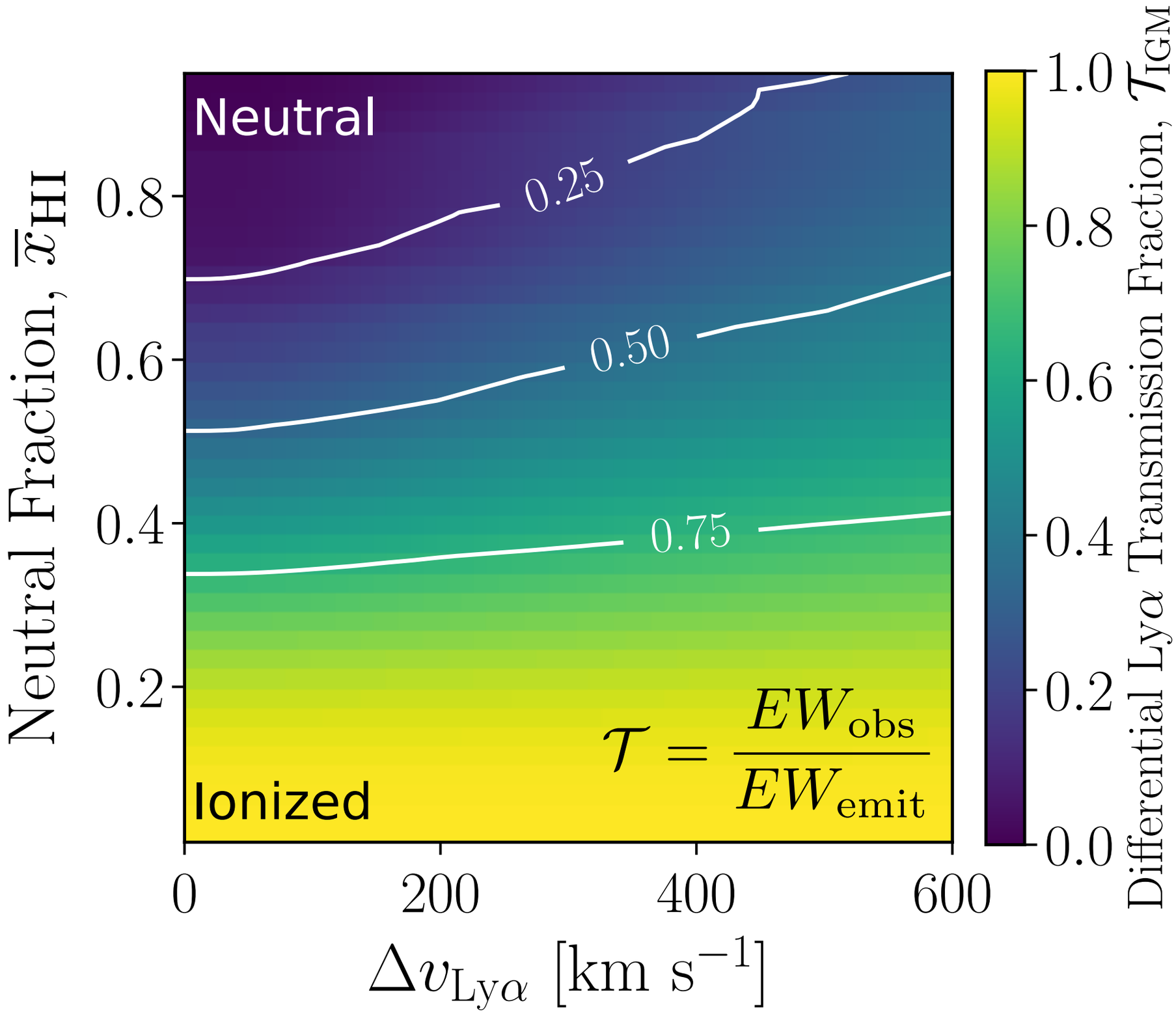
Lyα photons must diffuse in frequency to escape dense ISM





damping wing absorption due to cosmic HI regions

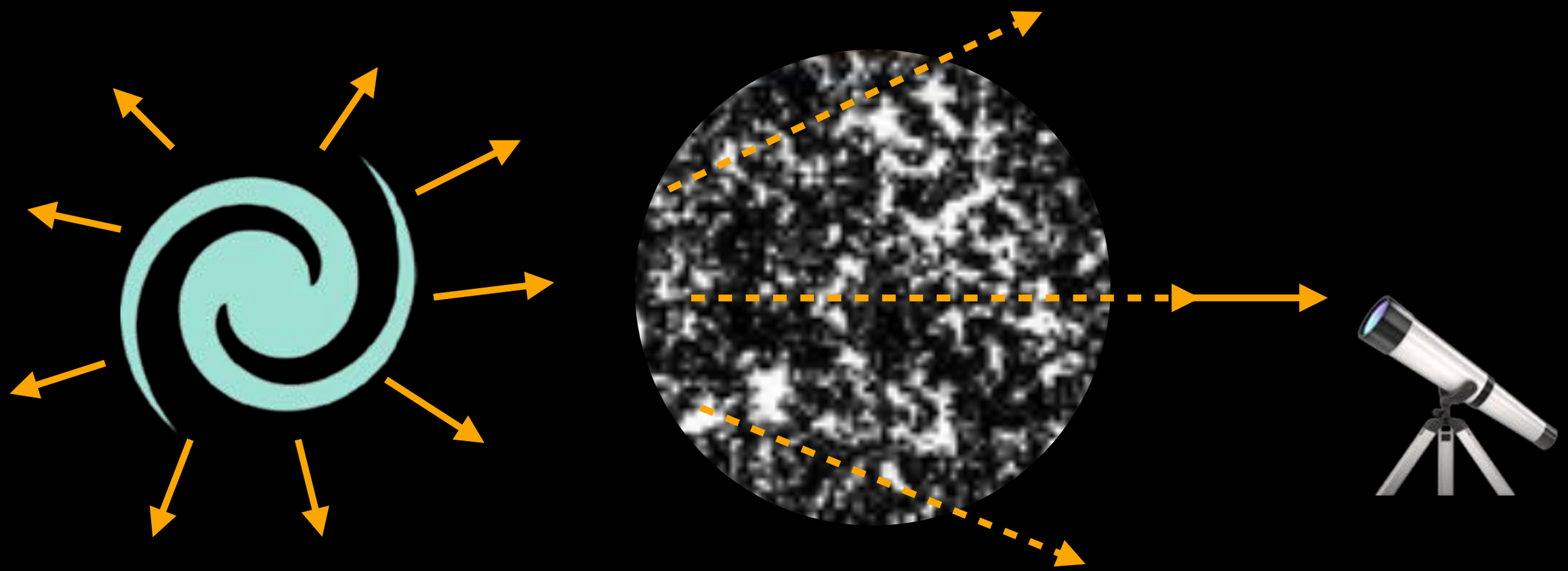
The shape of the Lyα line emerging from the ISM affects the probability of transmission through the IGM



A new inference framework combining realistic IGM topologies and ISM properties

ISM

CGM + IGM



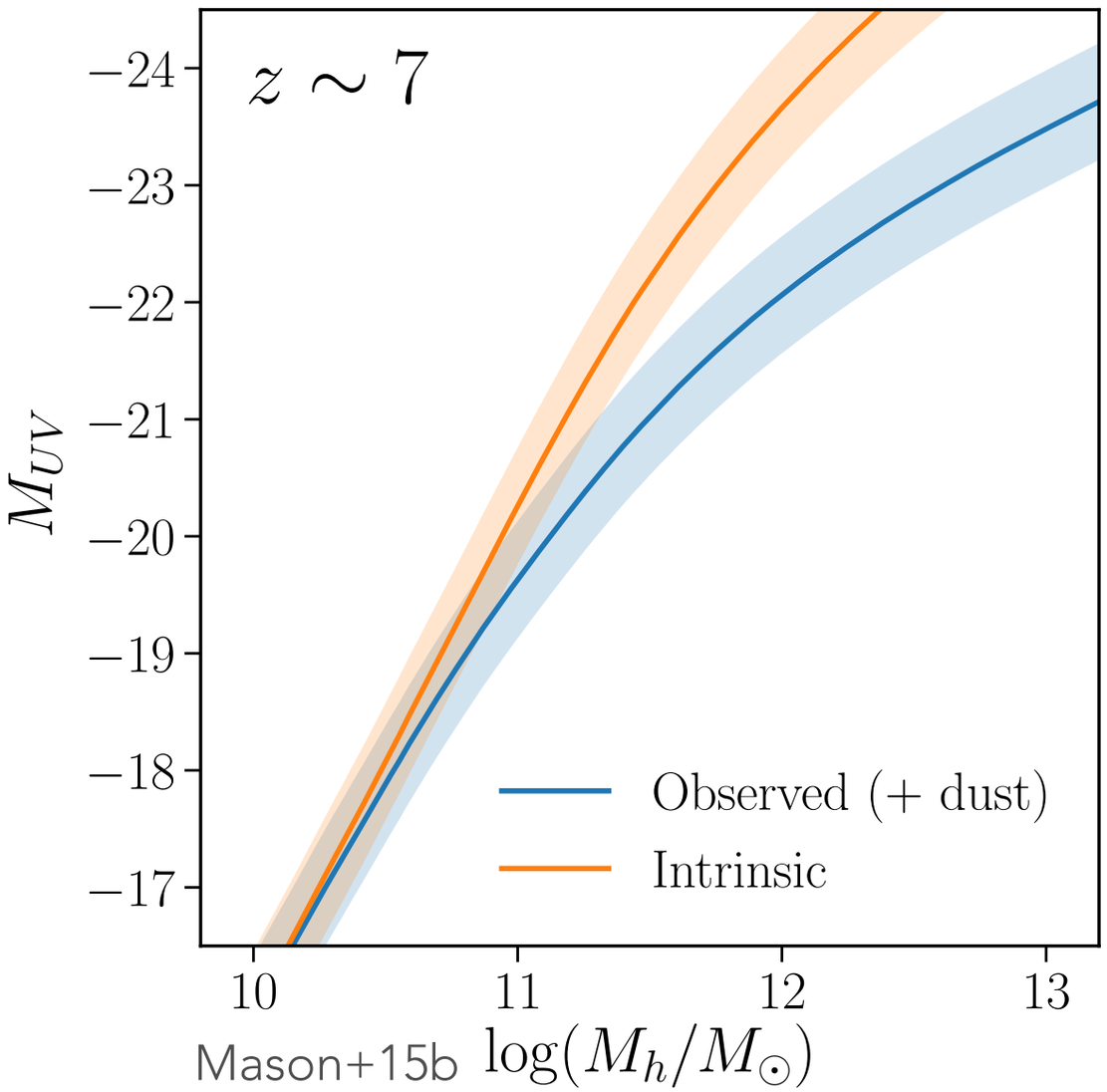
$EW_{intrinsic}$
Muv, Δv

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

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

Simulation halos are populated with realistic ISM properties

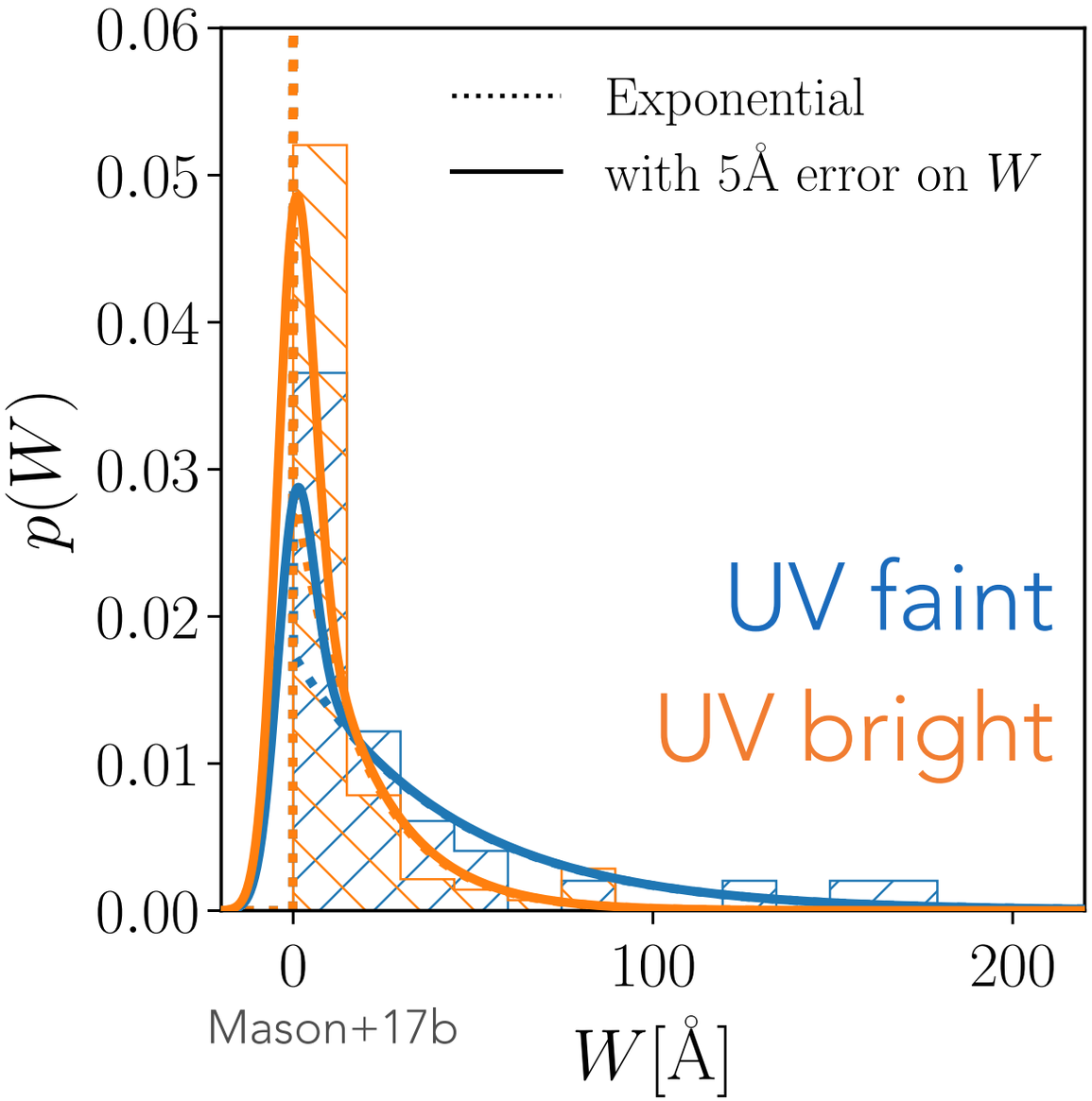
UV magnitudes



Mason+15b

UV LF evolution model:
SFR ~ halo mass accretion rate

‘Intrinsic’ EW



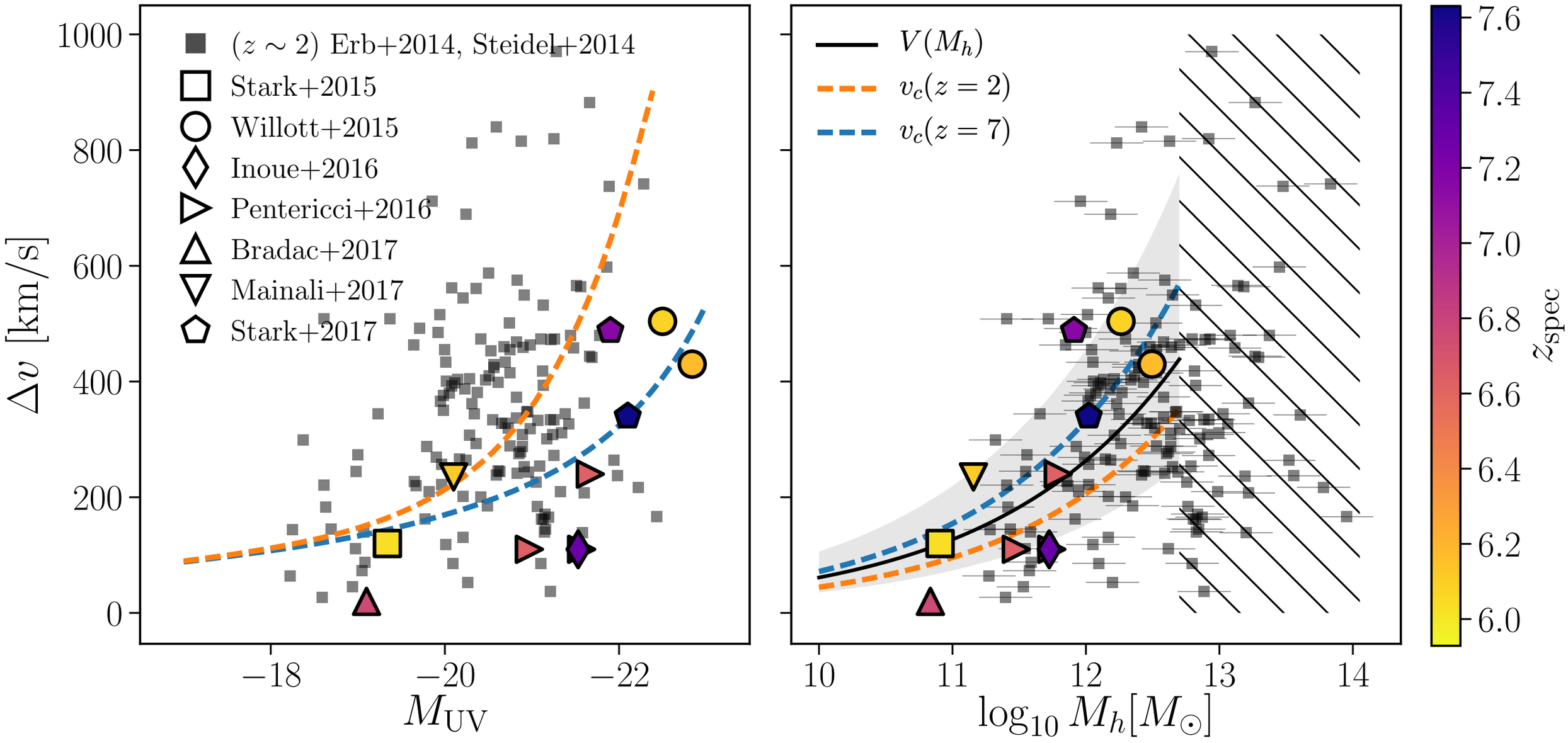
Mason+17b

z~6 distribution
from de Barros+17

Simulation halos are populated
with realistic ISM properties

Lya velocity offsets

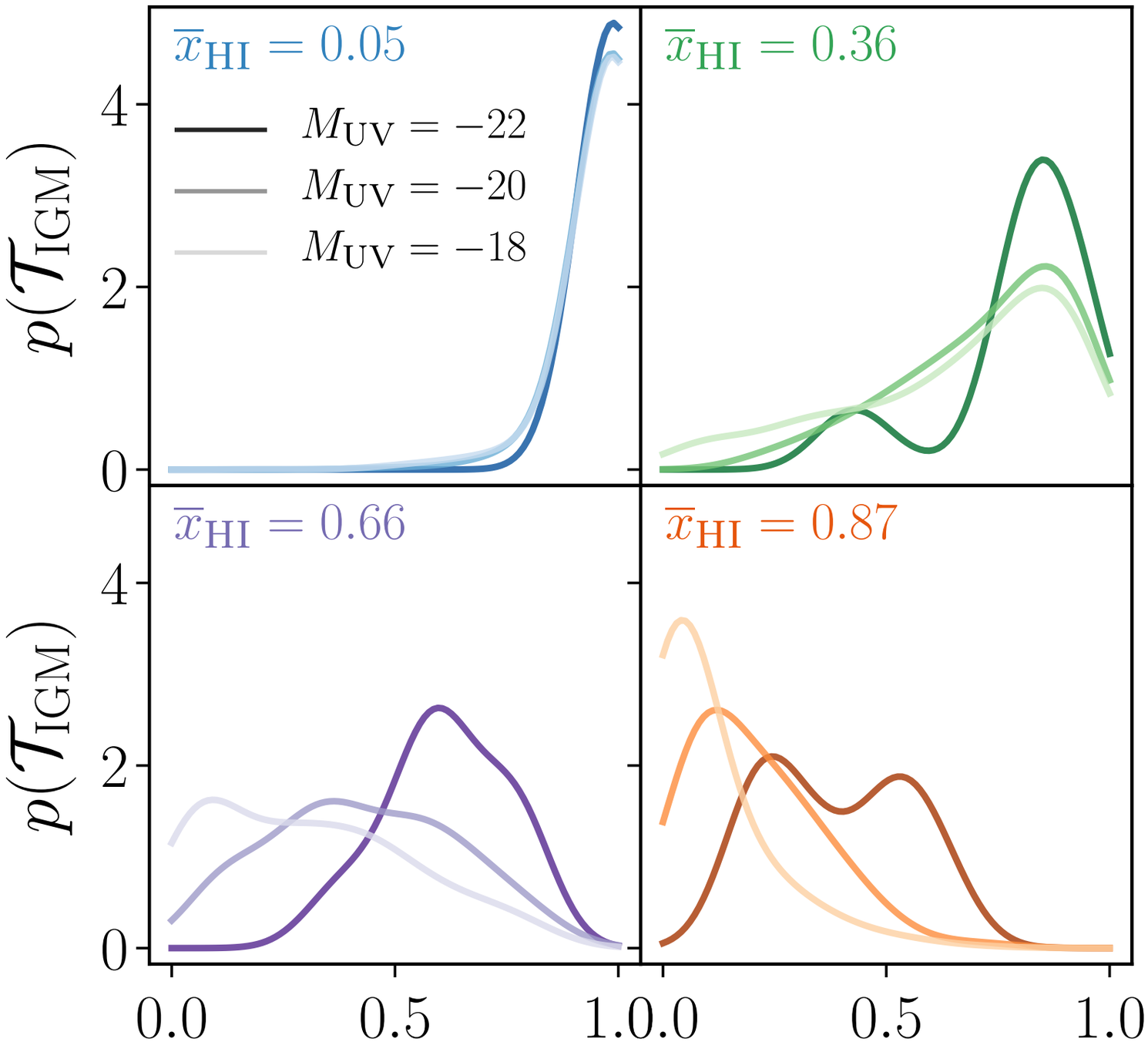
higher N_{HI}, outflows?



Mason+17b

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

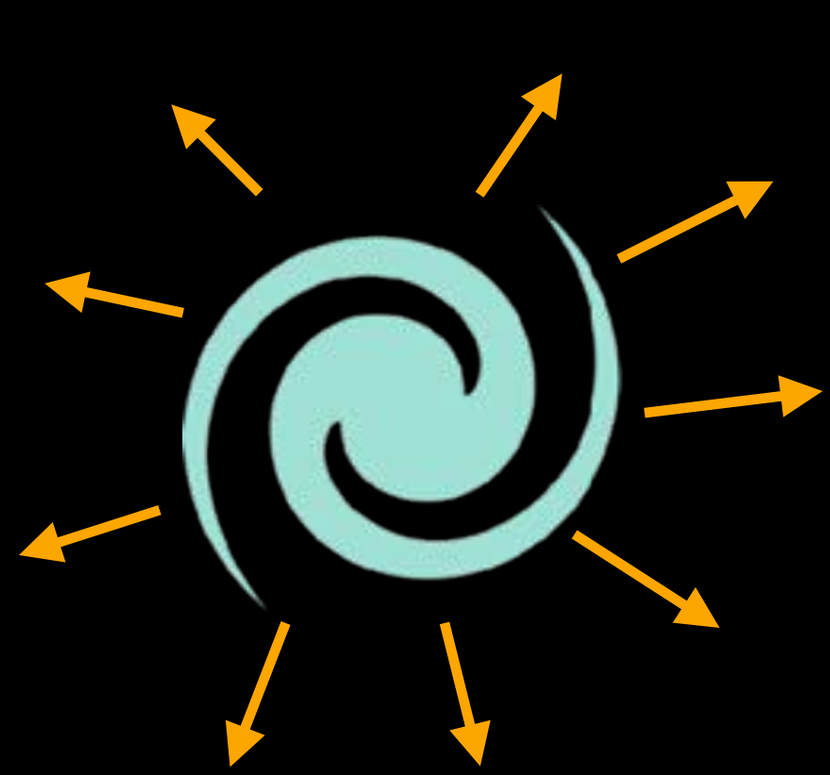
Mostly ionized



Mostly neutral

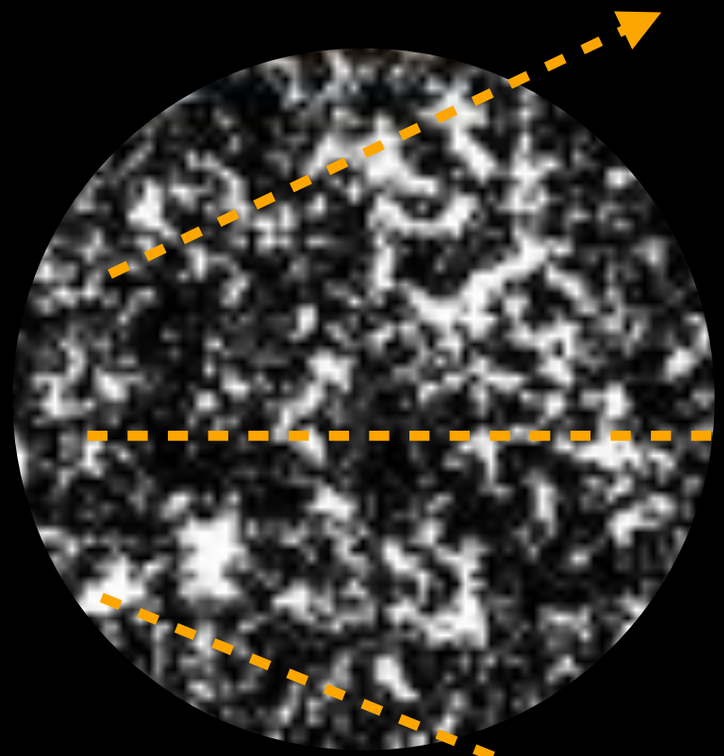
Mason+17b

With all the ingredients we can forward model the observed EW distribution and do a Bayesian inference



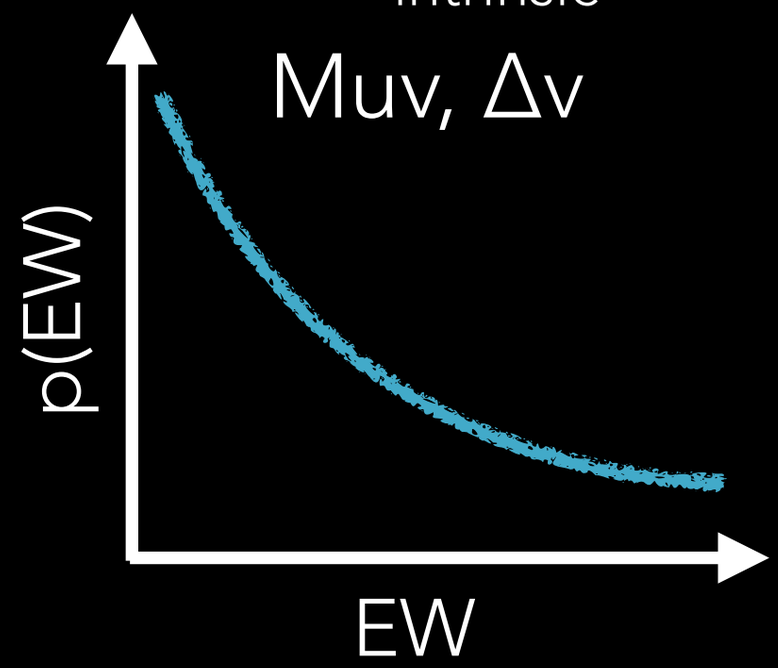
$EW_{intrinsic}$

Muv, Δv



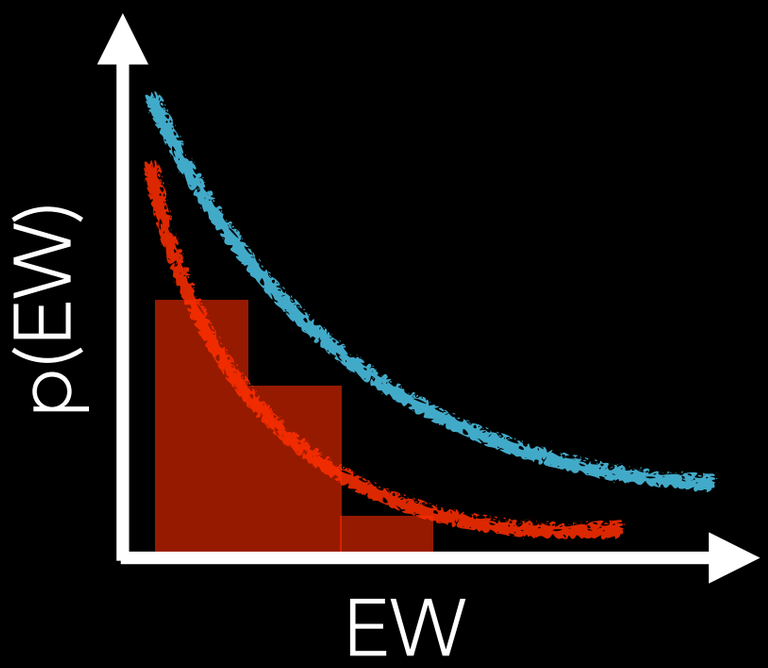
T_{IGM}

$p(x_{HI} \mid \{EW, M_{UV}\})$?

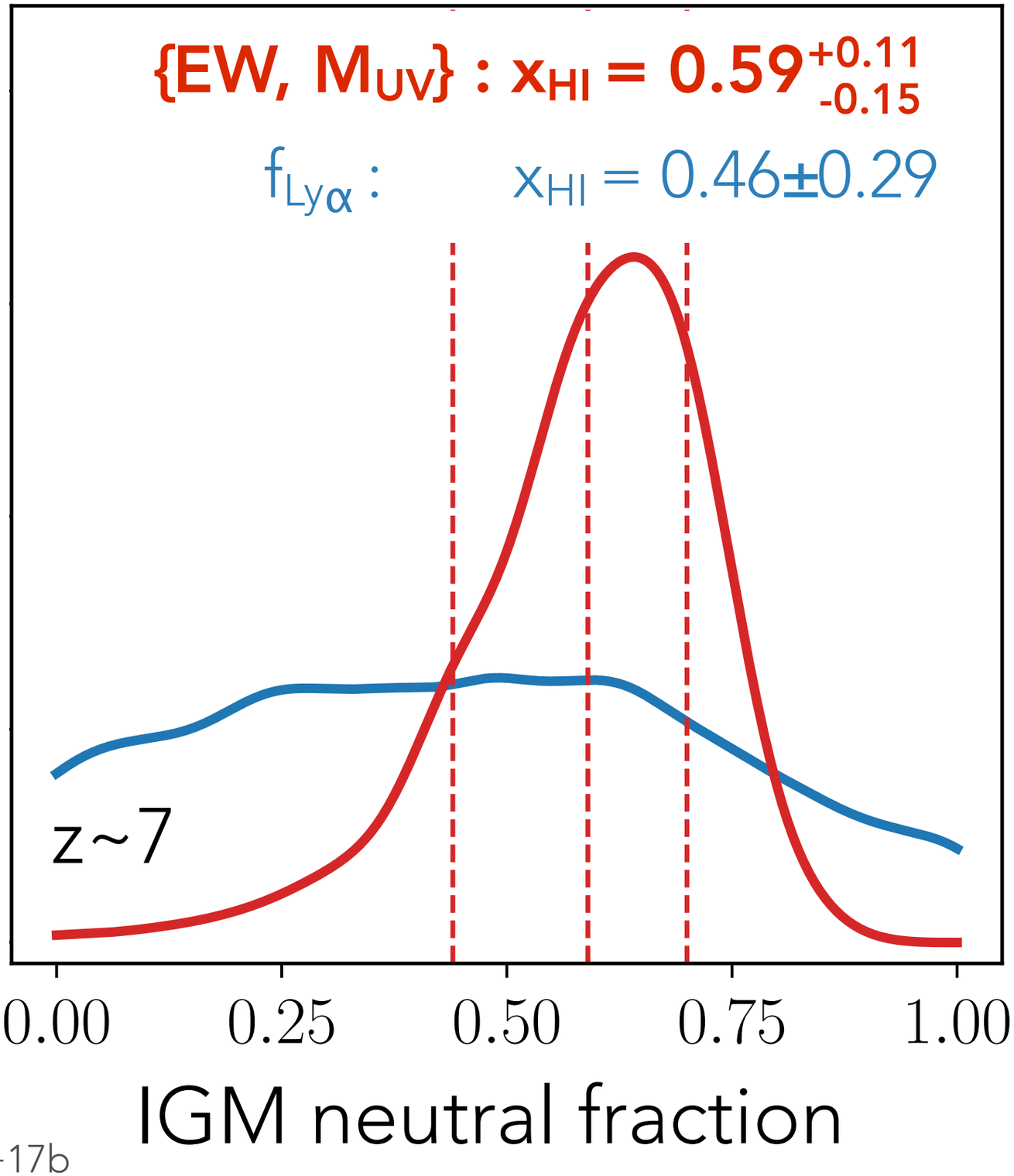


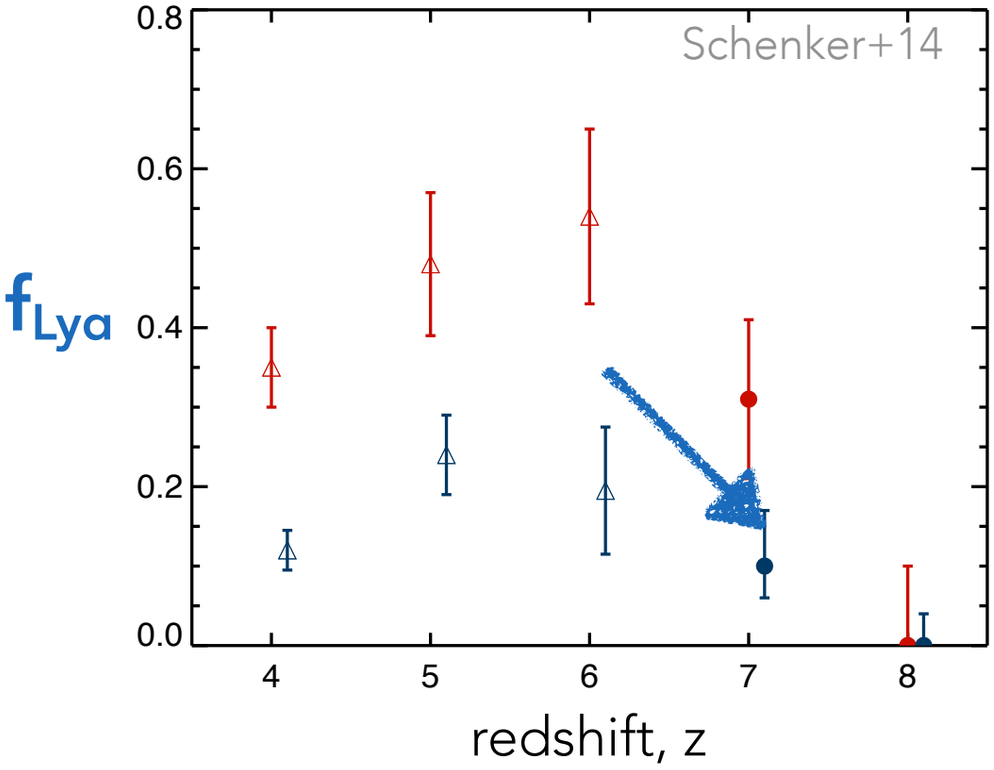
forward model

$p(EW_{obs} \mid x_{HI}, M_{UV})$



With the full distribution of Lyα EW at z~7 we place tight constraints on the neutral fraction

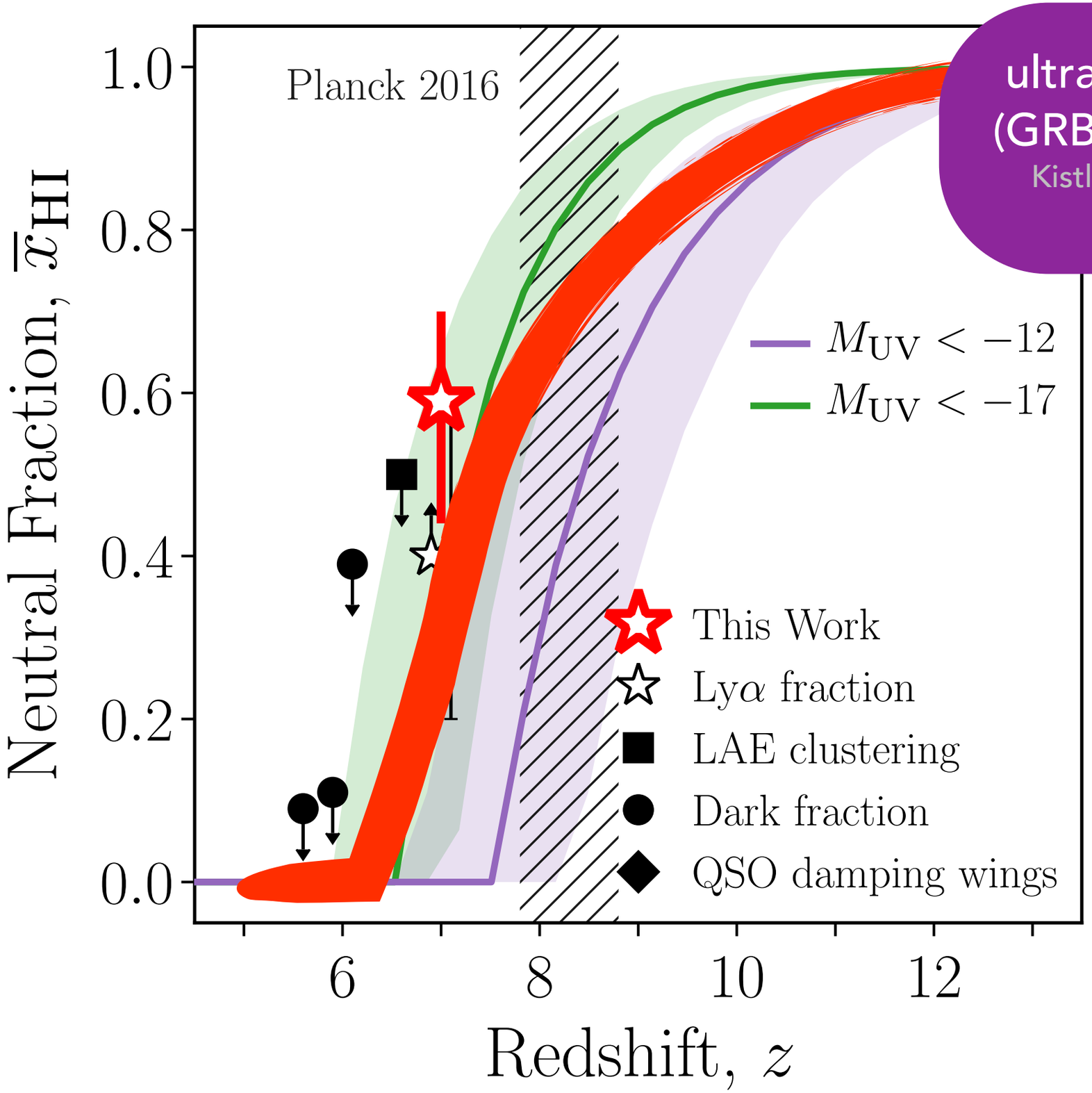




inferred from sample of 68 LBGs in Pentericci+14

Mason+17b

Our constraint confirms reionization is on-going at z~7



ultra-faint galaxies must exist
(GRBs, local dwarfs, lensing…)
Kistler+09, Weisz & Boylan-Kolchin 17,
Bouwens+17

f_{esc}~10 - 30%
optimistic?

Spectroscopy exploiting the power of cluster lenses

GLASS

Grism Lens-Amplified Survey from Space
glass.astro.ucla.edu

HST Grism Spectroscopy of 10 massive clusters

PI Treu, see Schmidt+14,Treu+15
140 orbits in Cycle 21
Including the 6 HFF and 8 CLASH clusters

- **Investigate galaxies and IGM at EoR [Schmidt+16, Huang+16, Hoag+16,17]**
- Metallicity cycles in and out of galaxies [Jones+15, Wang+16]
- Environmental dependance on galaxy evolution [Vulcani+15, Morishita+16]
- SN searches, e.g. SN Refsdal [Kelly+15]
- Cluster mass maps [Wang+15, Hoag+16]

Data released for all clusters on MAST
https://archive.stsci.edu/prepds/glass/

GLASS

glass.astro.ucla.edu

is efficiently looking for faint Lyα candidates at z>6 with lensing

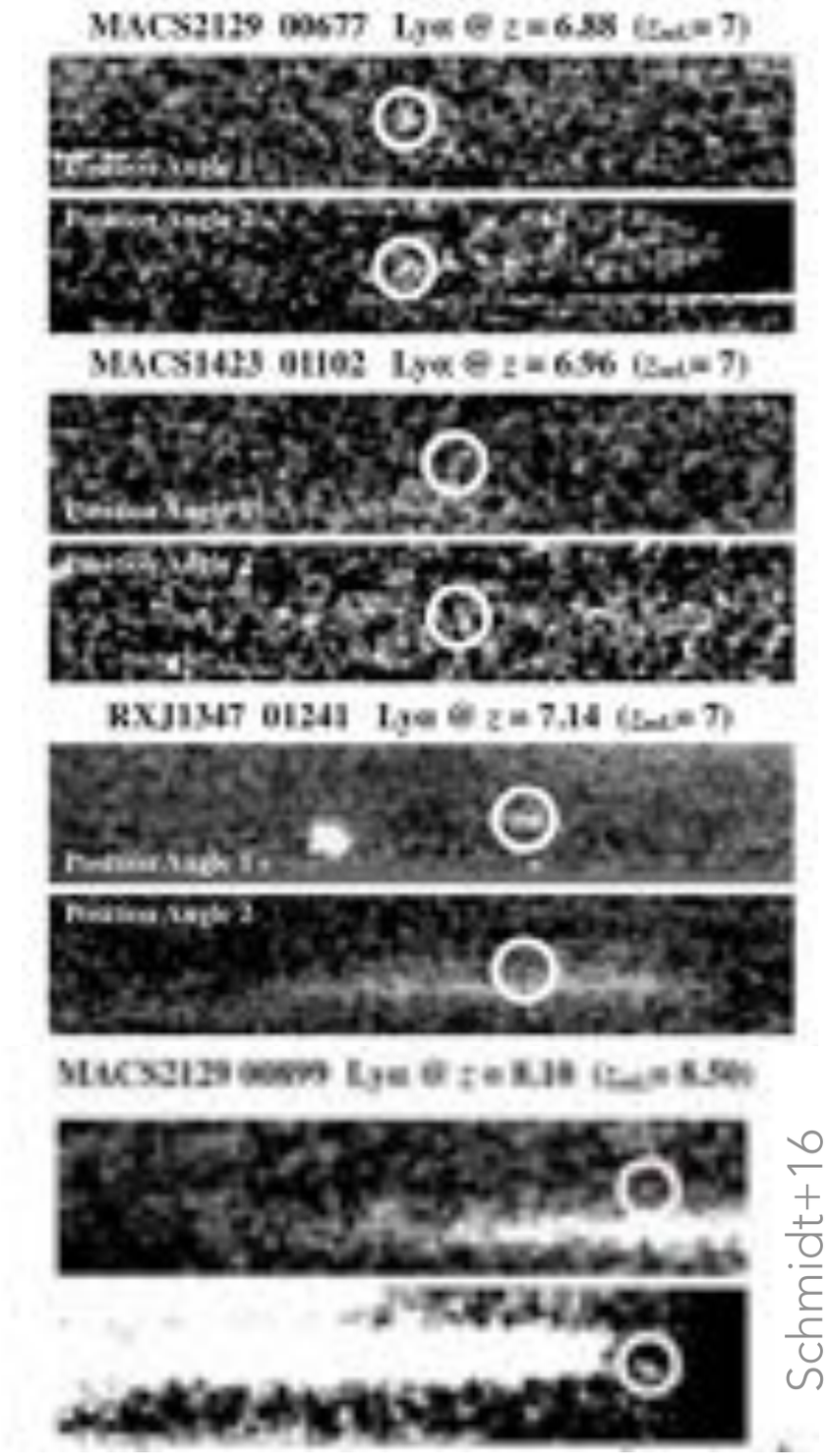
In 6 clusters, using >20 photometric selections for LBGs

- 24/159 dropouts have Lyα (Schmidt+16)

Largest statistically well-defined spectroscopic sample of LBGs at z>6

- **consistent with Lya drop from z~6**

Ground-based follow-up ongoing, confirming Lya in faint galaxies (Huang+16, Hoag+17, Mason+17a)

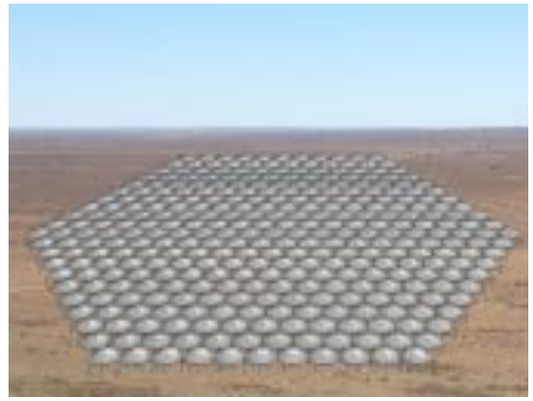


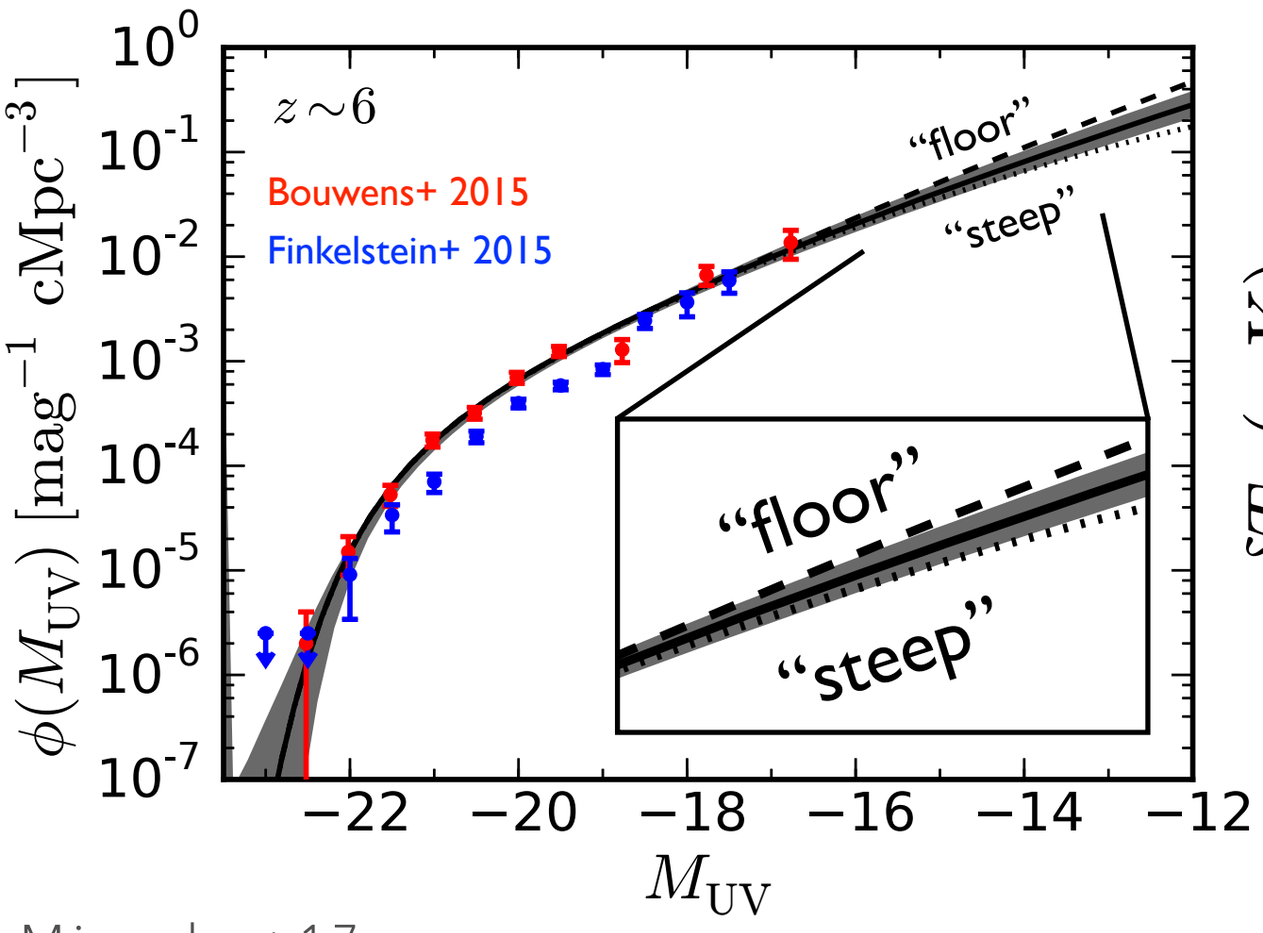
“The history of astronomy is
a history of receding horizons”

E. P. HUBBLE

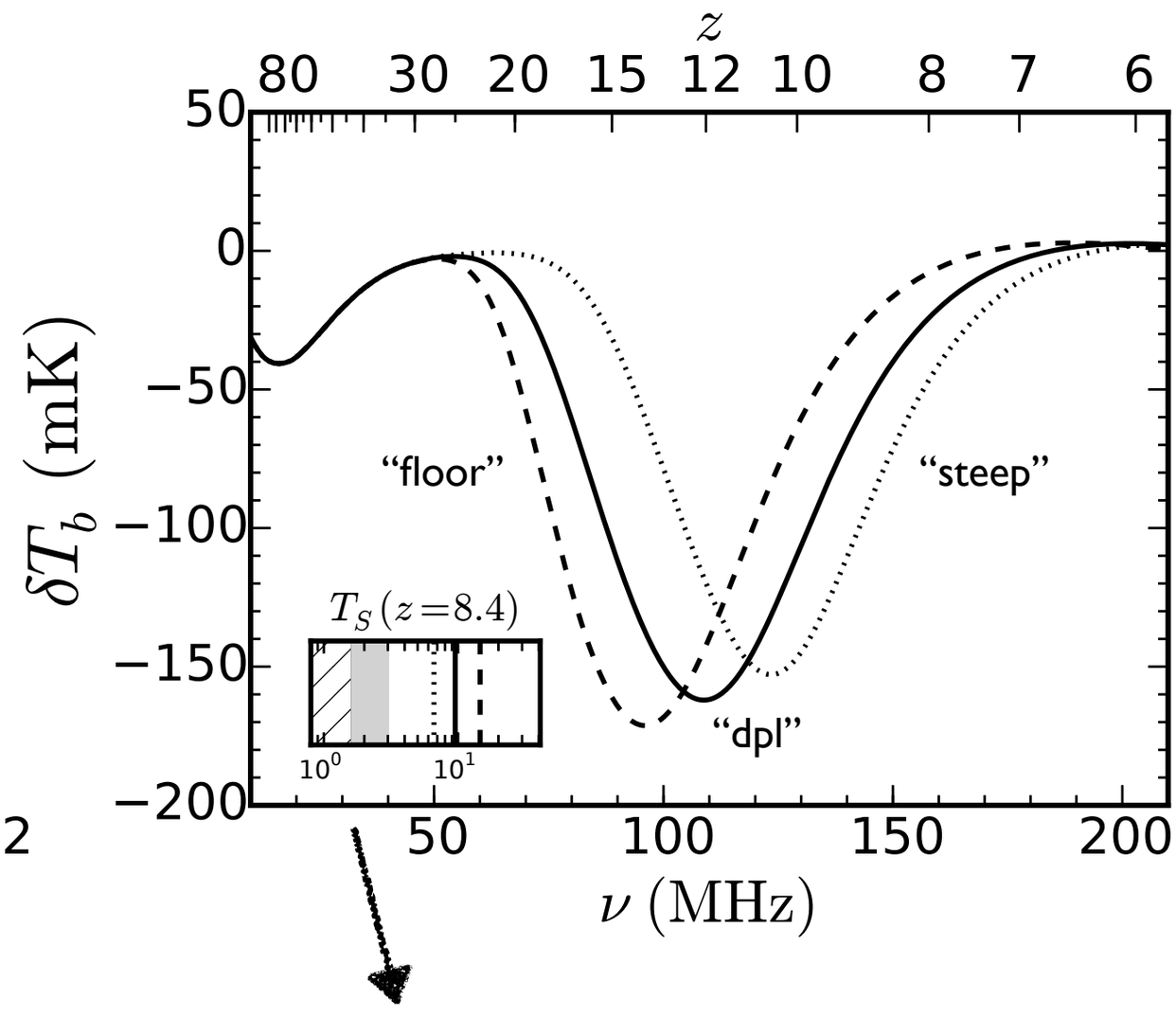
credit: NASA, ESA

Galaxy luminosity functions can inform global 21cm predictions + vice versa





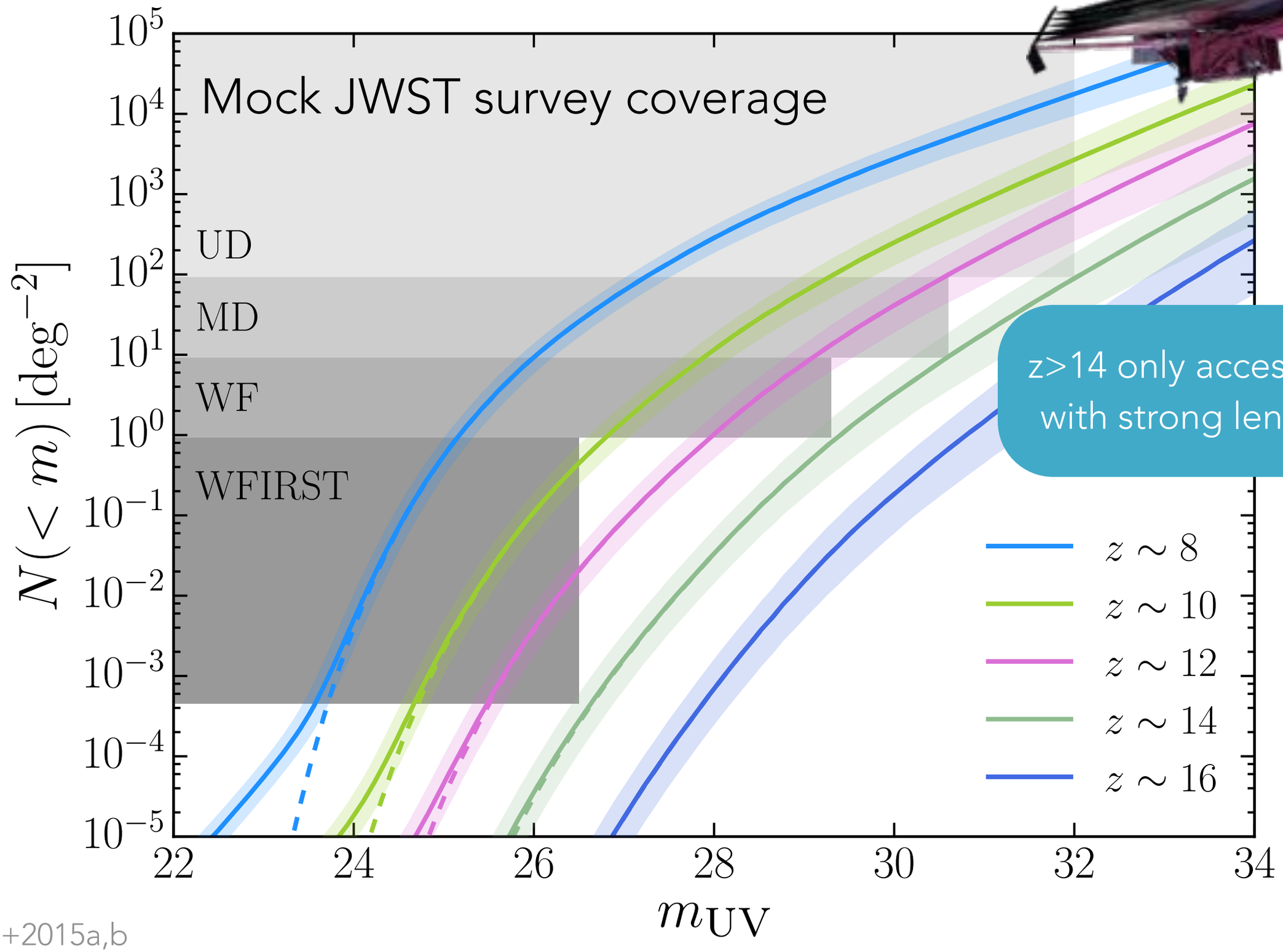
Mirocha+17



PAPER: $T_S(z = 8.4) \gtrsim 3$ K

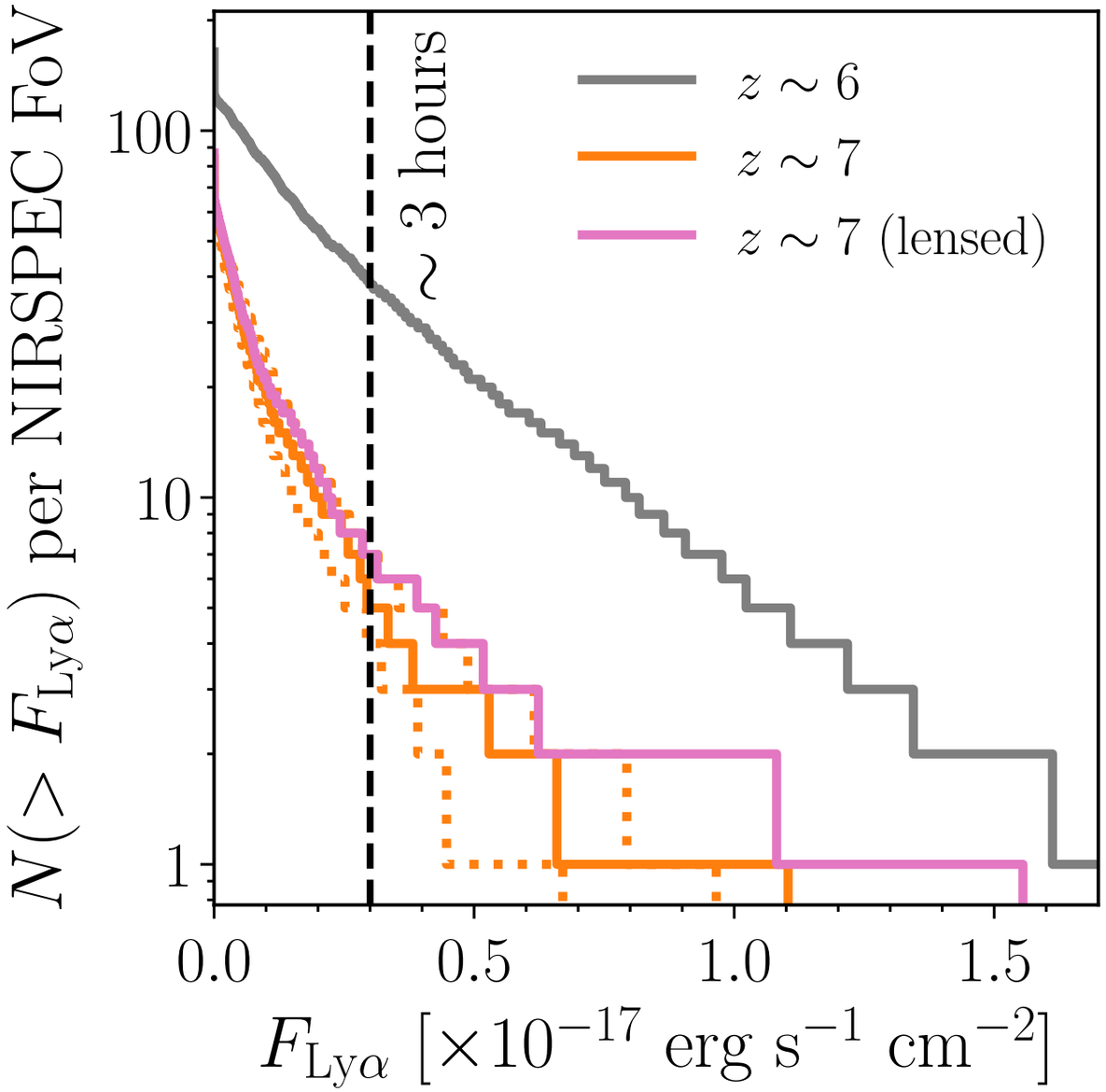
Parsons+ (2014), Ali+(2015),
Pober+(2015), Greig+ (2016)

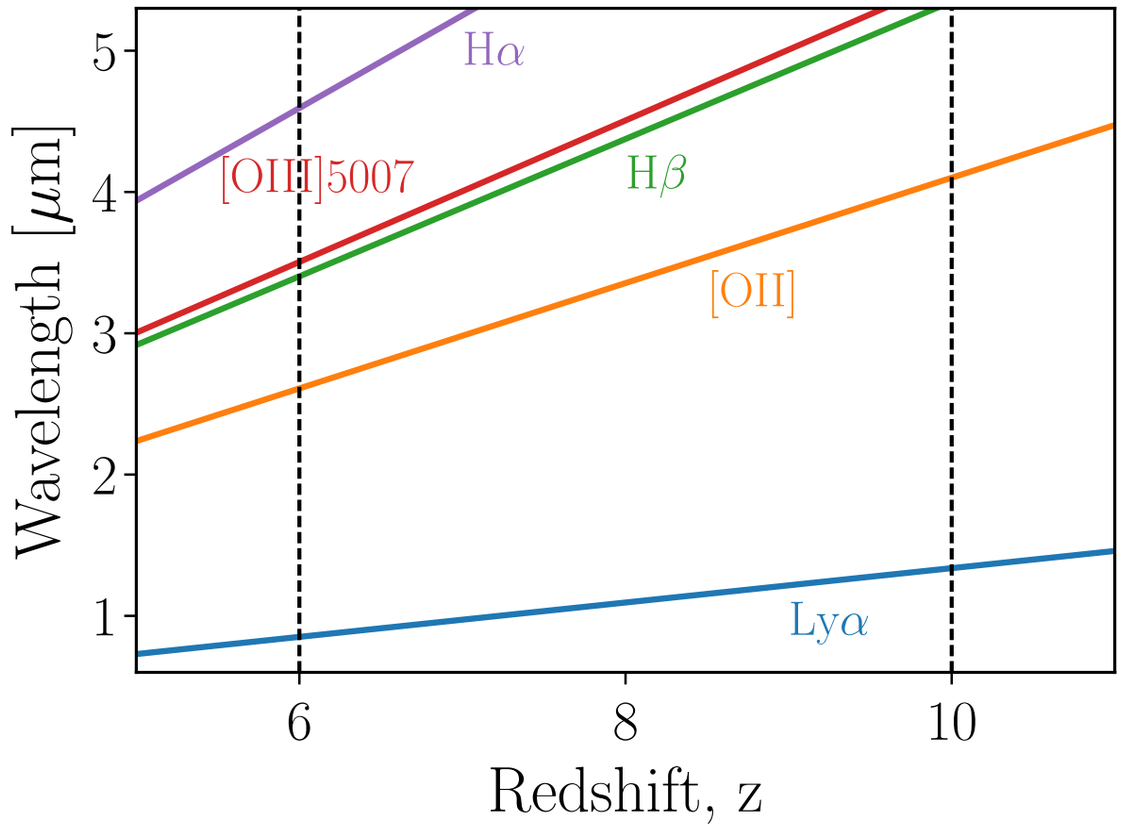
Our LF model predicts JWST will detect galaxies at z < ~14



Mason+2015a,b

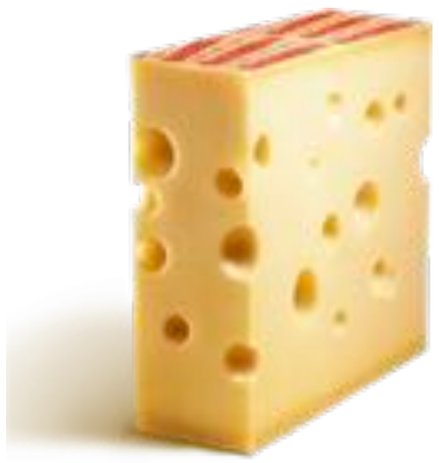
JWST will find many more Lyα emitters at z>6 and measure velocity offsets

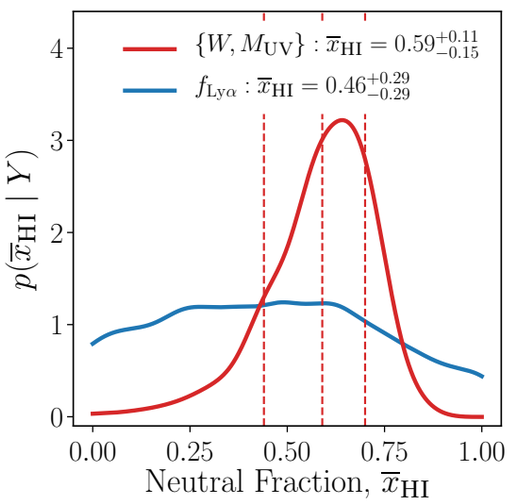




Mason+17b

Summary





High z star-forming galaxy populations can be easily modelled assuming **halo growth is the dominant driver of galaxy growth**

No evolution of physical conditions/feedback is needed!

The evolving transmission of Lyα from galaxies contains information about the history of reionization

Both IGM and ISM effects must be included via forward-modelling to make inferences from Lyα observations

The **full distribution of Lya EW** tightly constrains the neutral fraction at z~7: **x_{HI} ~ 60±15%**