Evolution of the z ~ 6 - 7 Lyman-alpha Luminosity Function

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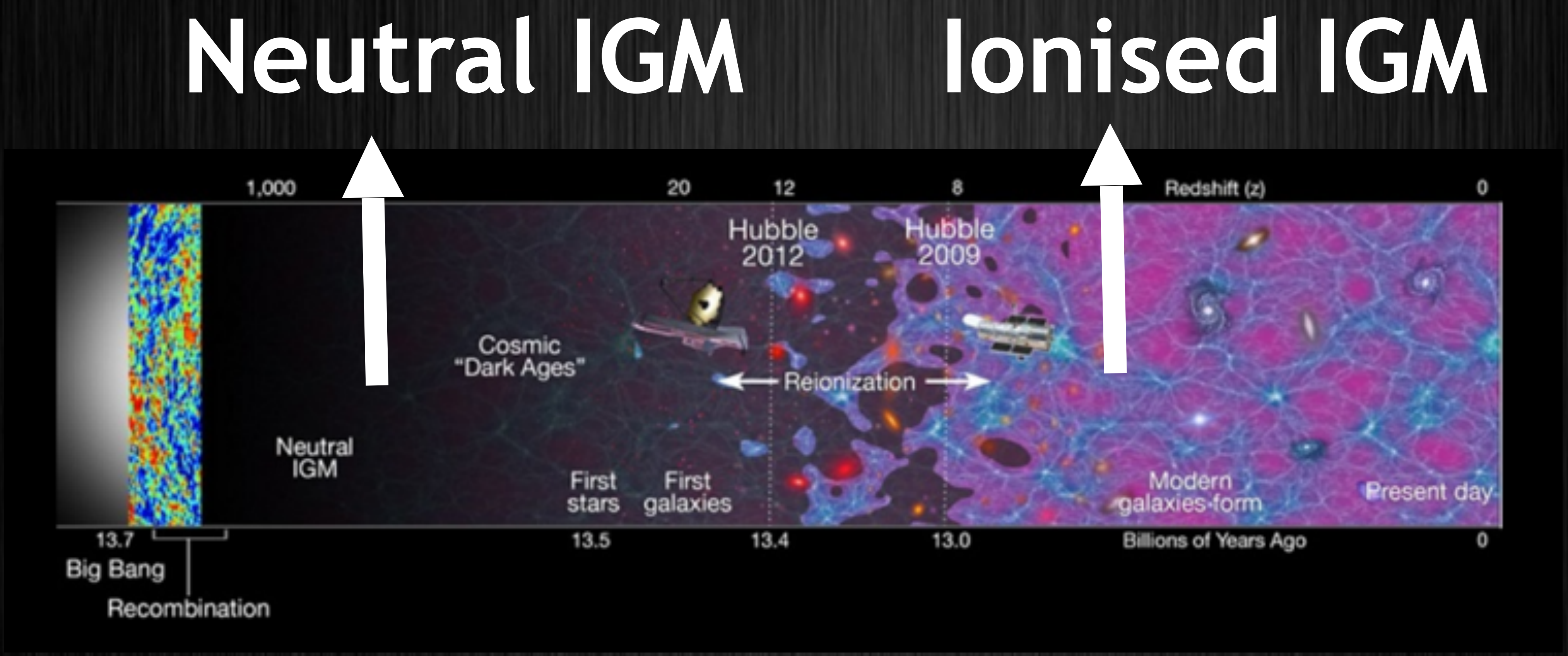
Take home messages

Largest Lyman-alpha narrow band surveys at z ~ 6 - 7.

Drop in the Lyα LF happens for the faint sources. Little evolution on the bright end.

Hints for differential reionization.

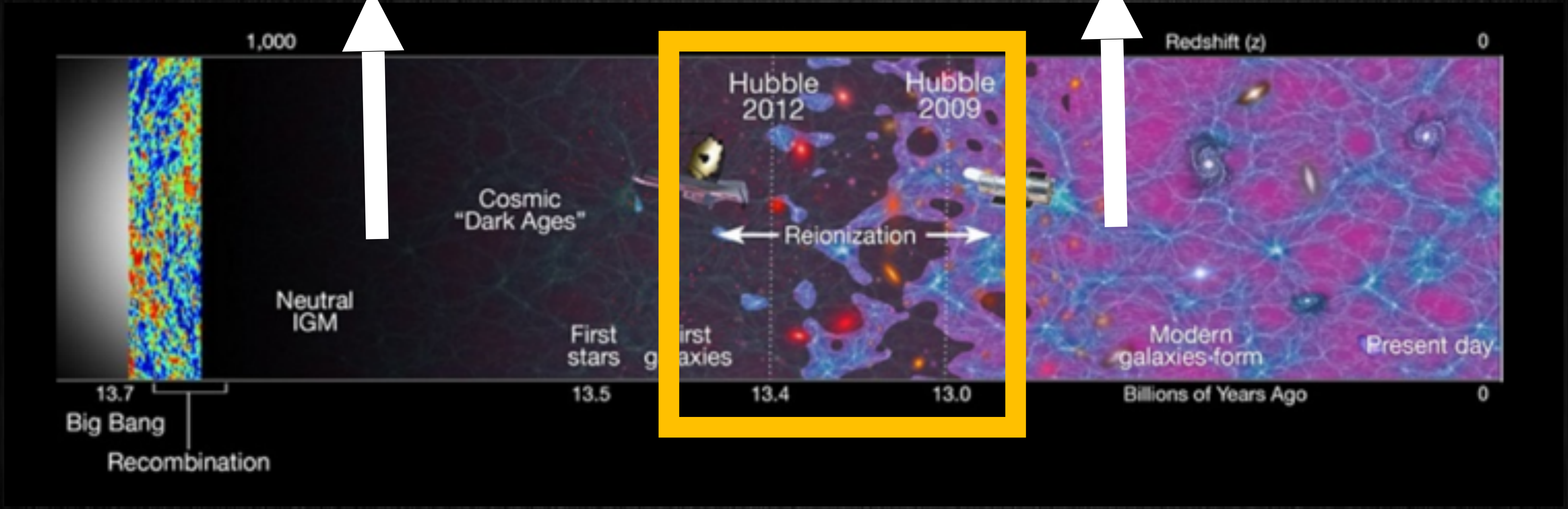
Motivation


Neutral IGM
Ionised IGM
1,000
20
12
8
Redshift (z)
0
Hubble 2012
Hubble 2009
Cosmic "Dark Ages"
Reionization
Neutral IGM
First stars
First galaxies
Modern galaxies form
Present day
13.7
Big Bang
Recombination
13.5
13.4
13.0
Billions of Years Ago
0

Motivation

Neutral IGM

Ionised IGM



Epoch of Reionization

Transition period

Motivation

Neutral IGM

Ionised IGM

Epoch of reionization

What are the main drivers?
How/when did it happen?

Lyman-alpha as a probe of high-z Universe

Lyα (1216 Å) emitted by <u>star-forming galaxies</u> + <u>AGN</u>

Observable from ground-based telescopes at $z > 2$

Intrinsically the brightest line

Lyman-alpha as a probe of high-z Universe

Lyα (1216 Å) emitted by star-forming galaxies + AGN

Observable from ground-based telescopes at $z > 2$

Intrinsically the brightest line

Resonant line - Highly affected by the IGM

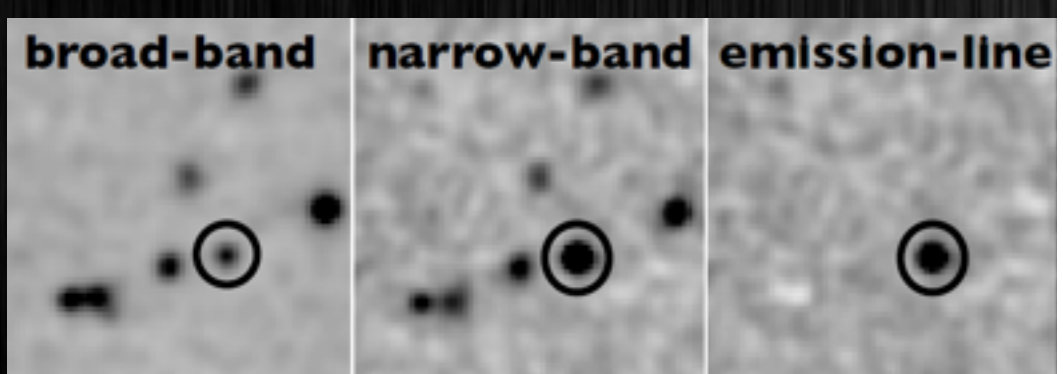
“Problem” but also opportunity!

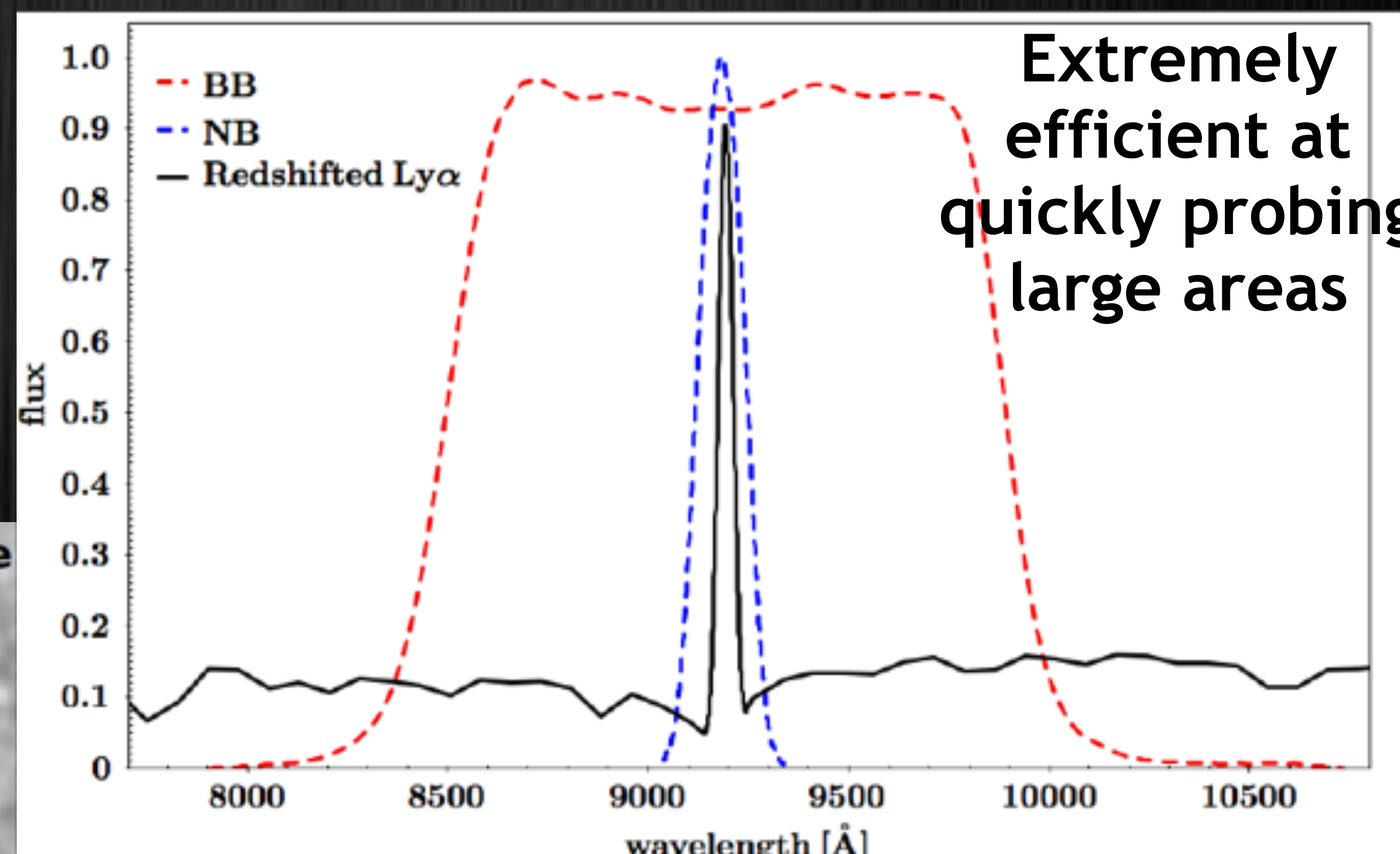
Easily scattered by neutral IGM -> Tracer of reionization

Narrow band Technique

Imaging with broad + narrow filters
Strong narrow band detection likely means an emission line at that wavelength

Two parameters Σ and EW that quantify how significant the excess is.





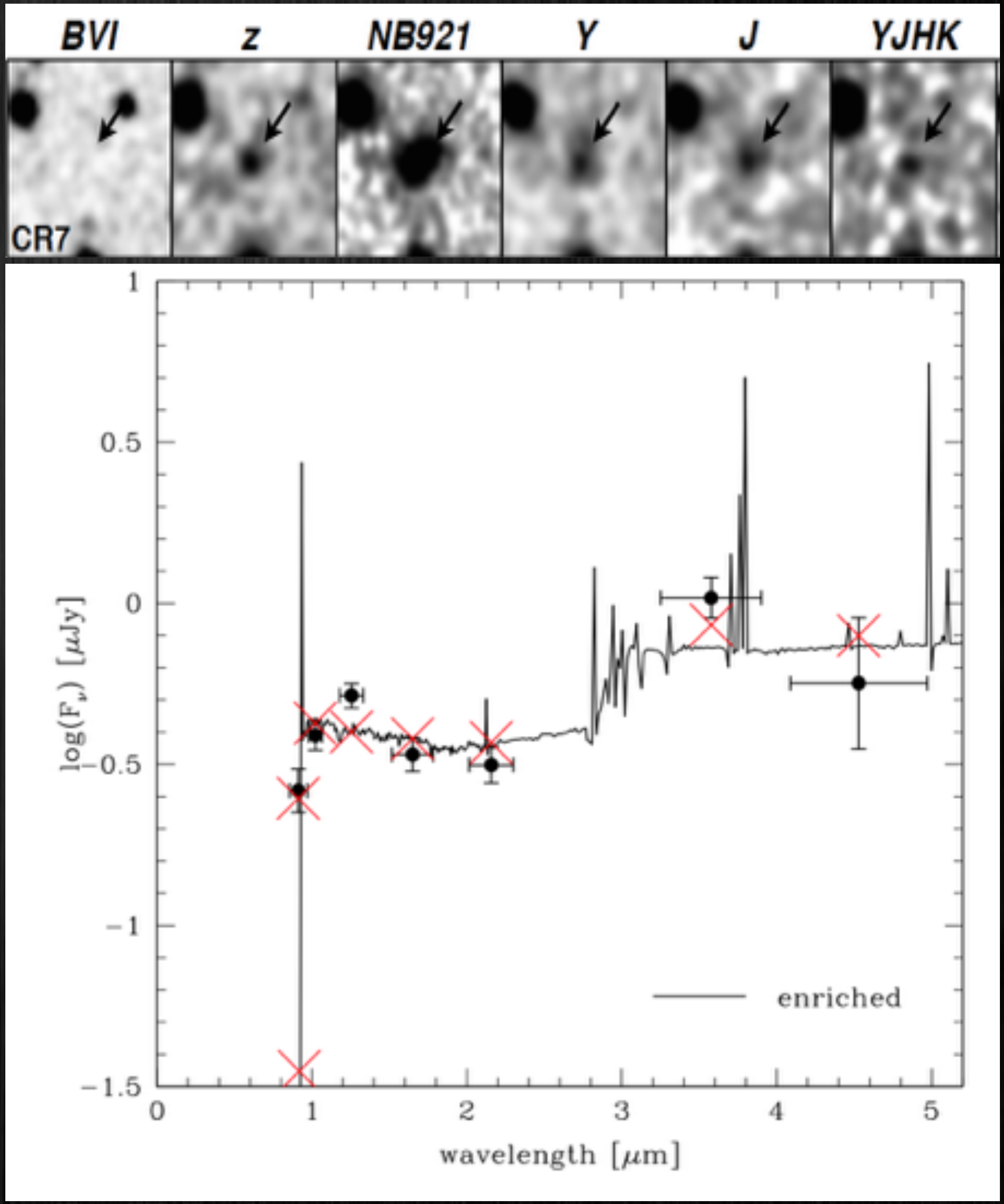
Extremely efficient at quickly probing large areas

e.g. Sobral+2009, Ouchi+2008, Ouchi+2010, Malhotra&Hu2004, Murayama+2007

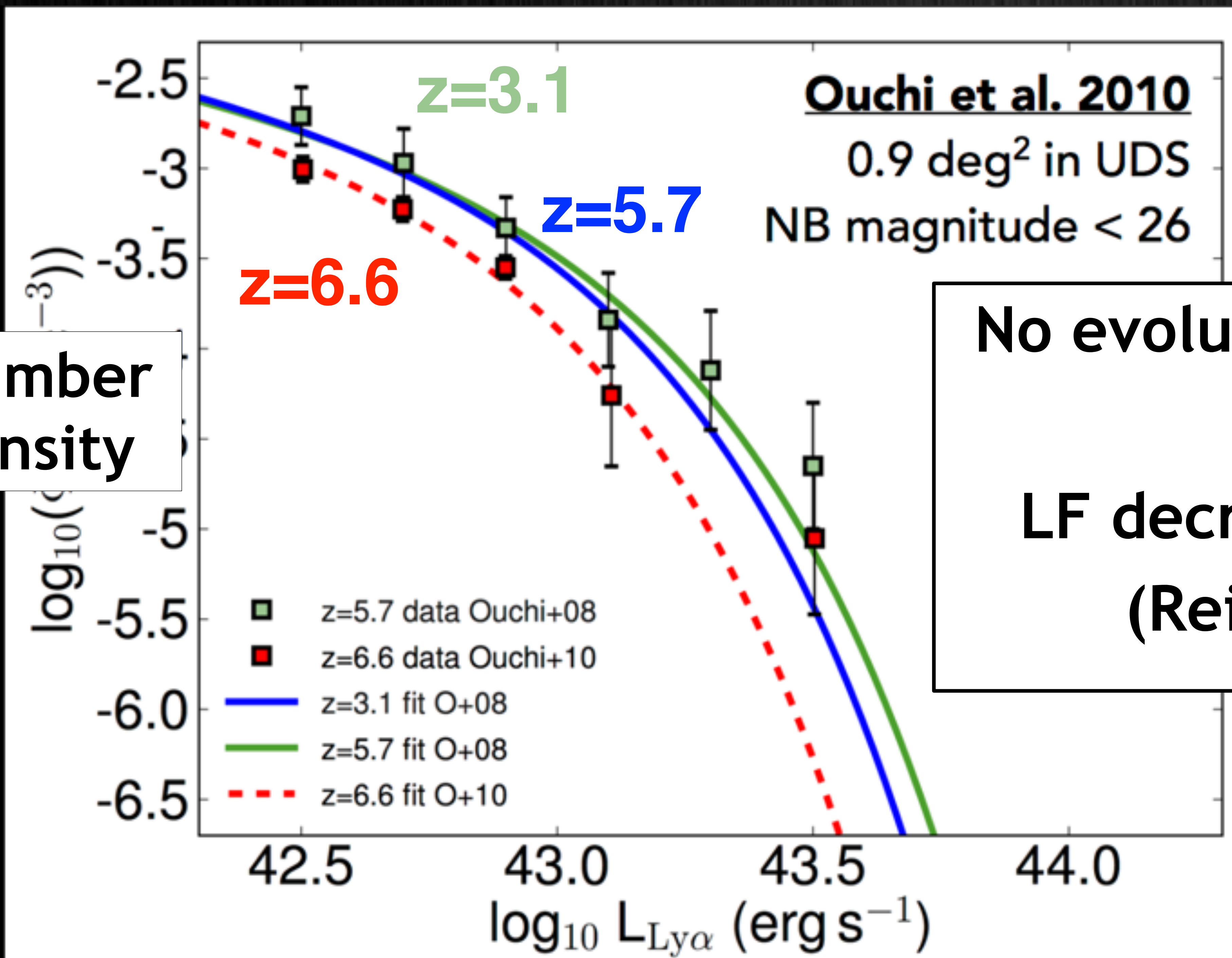
Lyman Break to remove interlopers

We remove low redshift emitters by the position of the Lyman break.

z > 5 Lyα must have no observed optical detection.



Lyman-alpha luminosity function



Number density

Lyα Luminosity

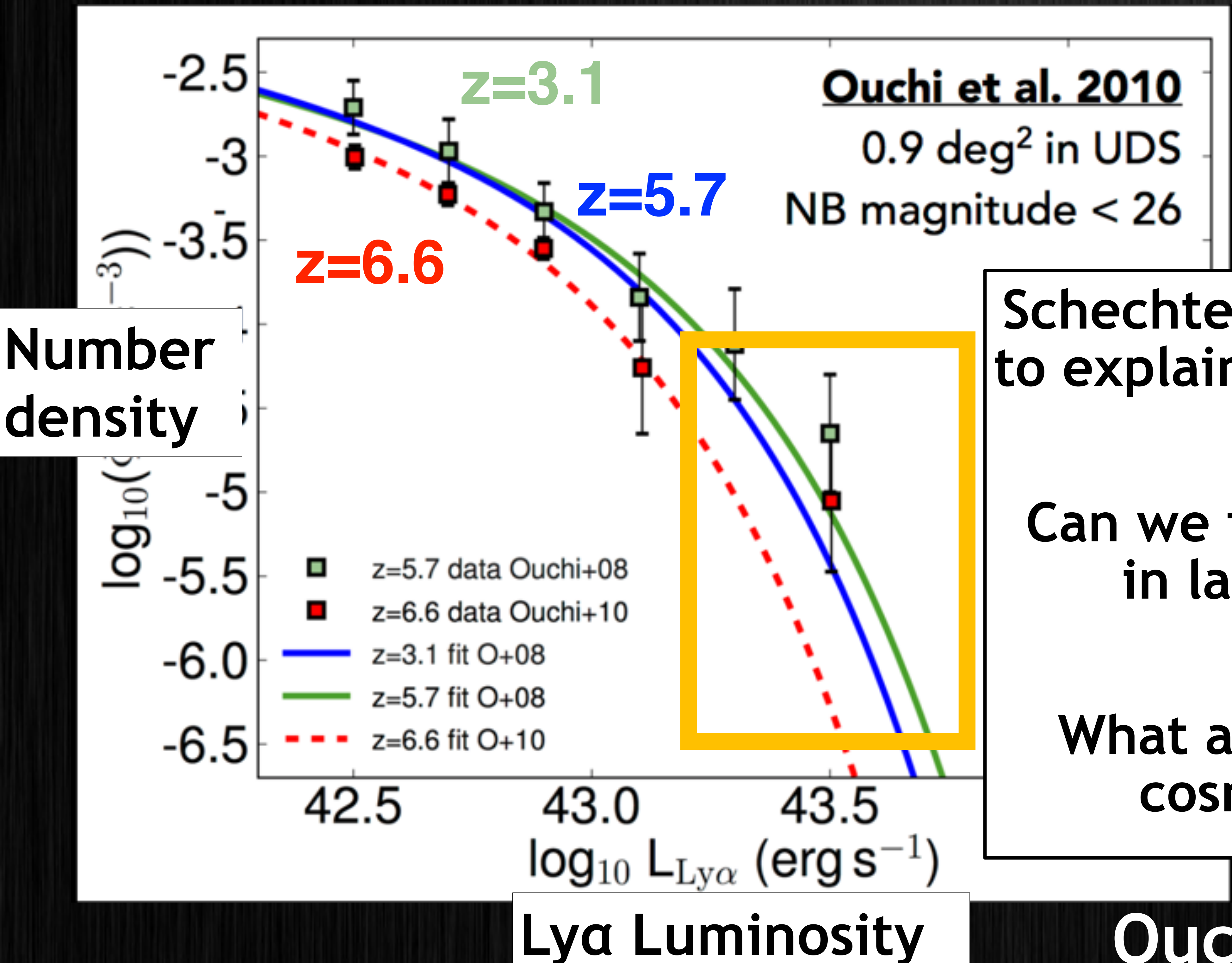
No evolution for z ~ 3 - 6

LF decreases for z > 6

(Reionization?)

Ouchi et al. 2010

Lyman-alpha luminosity function



Schechter fit may be failing to explain the brightest bins

Can we find more sources in larger volumes?

What are the effects of cosmic variance?

Ouchi et al. 2010

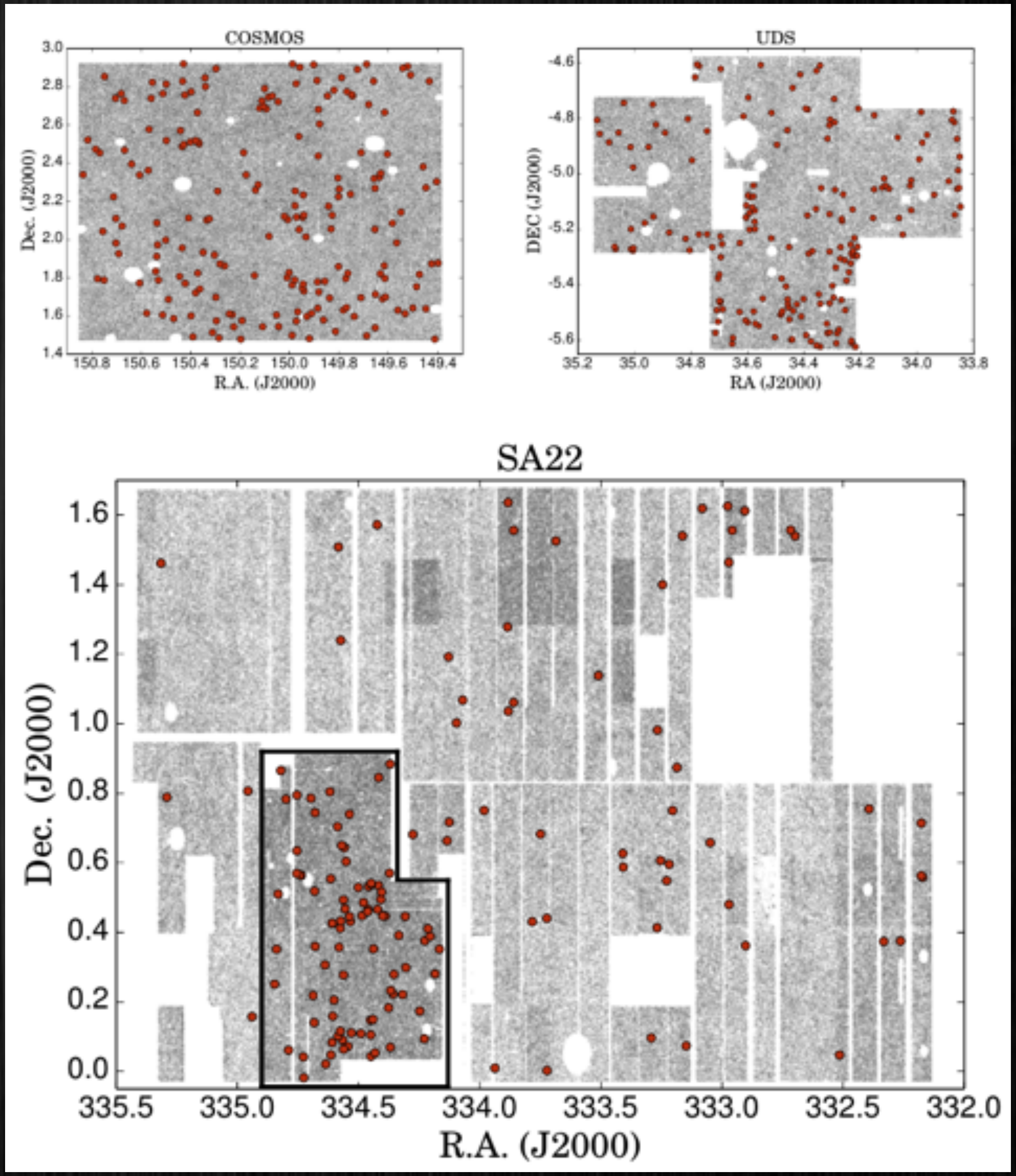
Wide area narrow band survey at z ~ 5.7

Area ~ 7 deg^2
Volume ~ 6 x 10^6 Mpc^3

Role of cosmic variance across 3 fields

Construct the LF right after the end of reionization

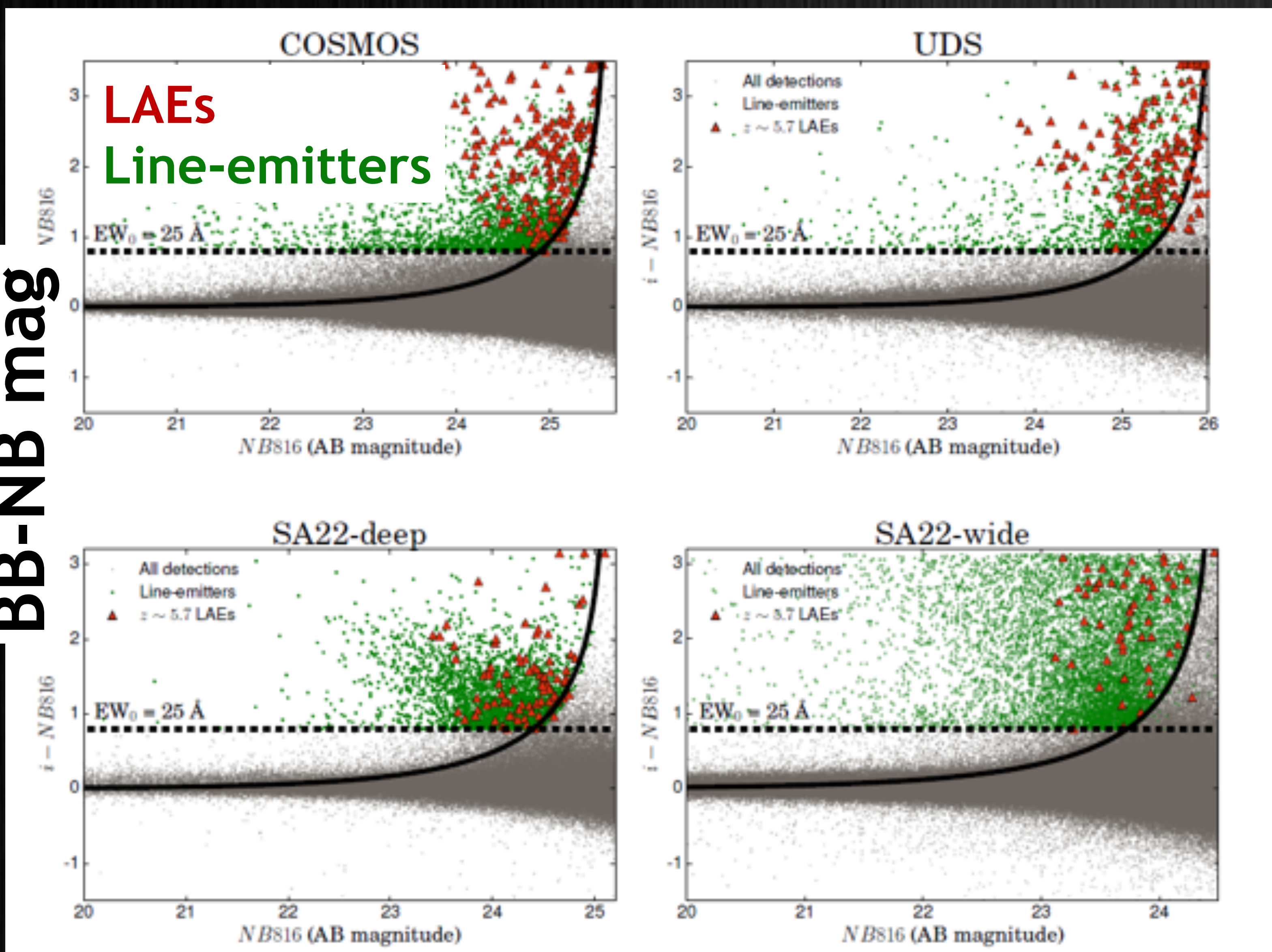
Previous results: Murayama+2007, Ouchi+2008, Hu+2010 (max ~ 1.65 deg^2)



Santos, Sobral & Matthee 2016

Selection criteria for z = 5.7

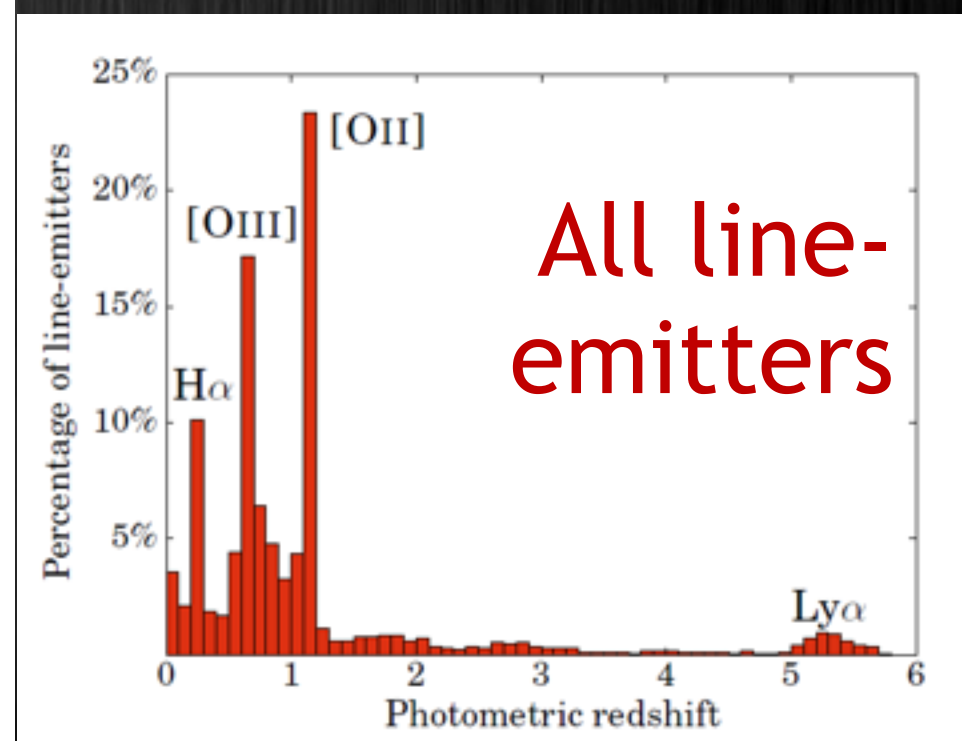
Σ and Equivalent Width cuts



BB-NB mag

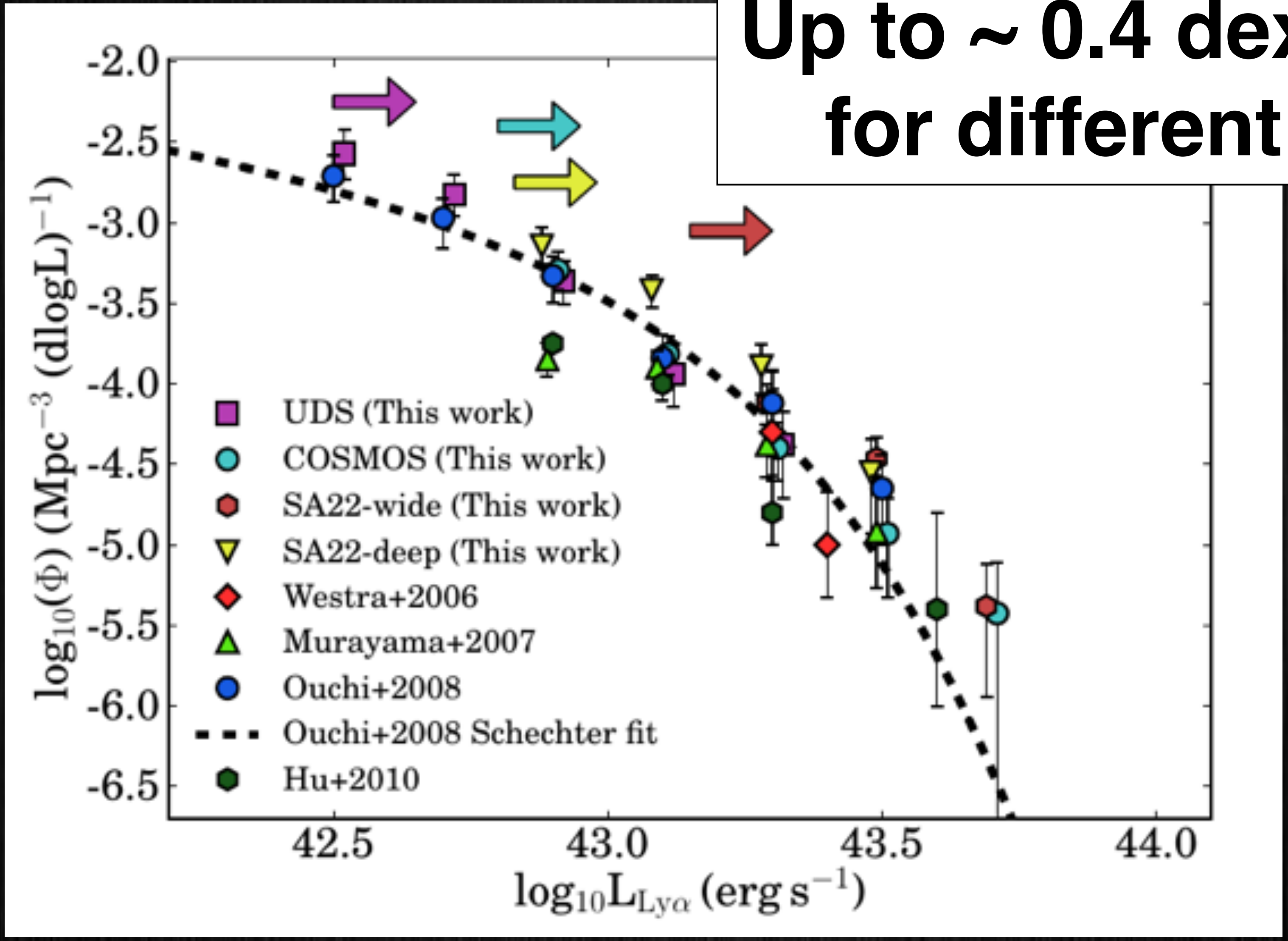
NB mag

All line-emitters before interloper removal



Santos, Sobral & Matthee 2016

z=5.7 Luminosity Function



Up to ~ 0.4 dex separation for different paintings

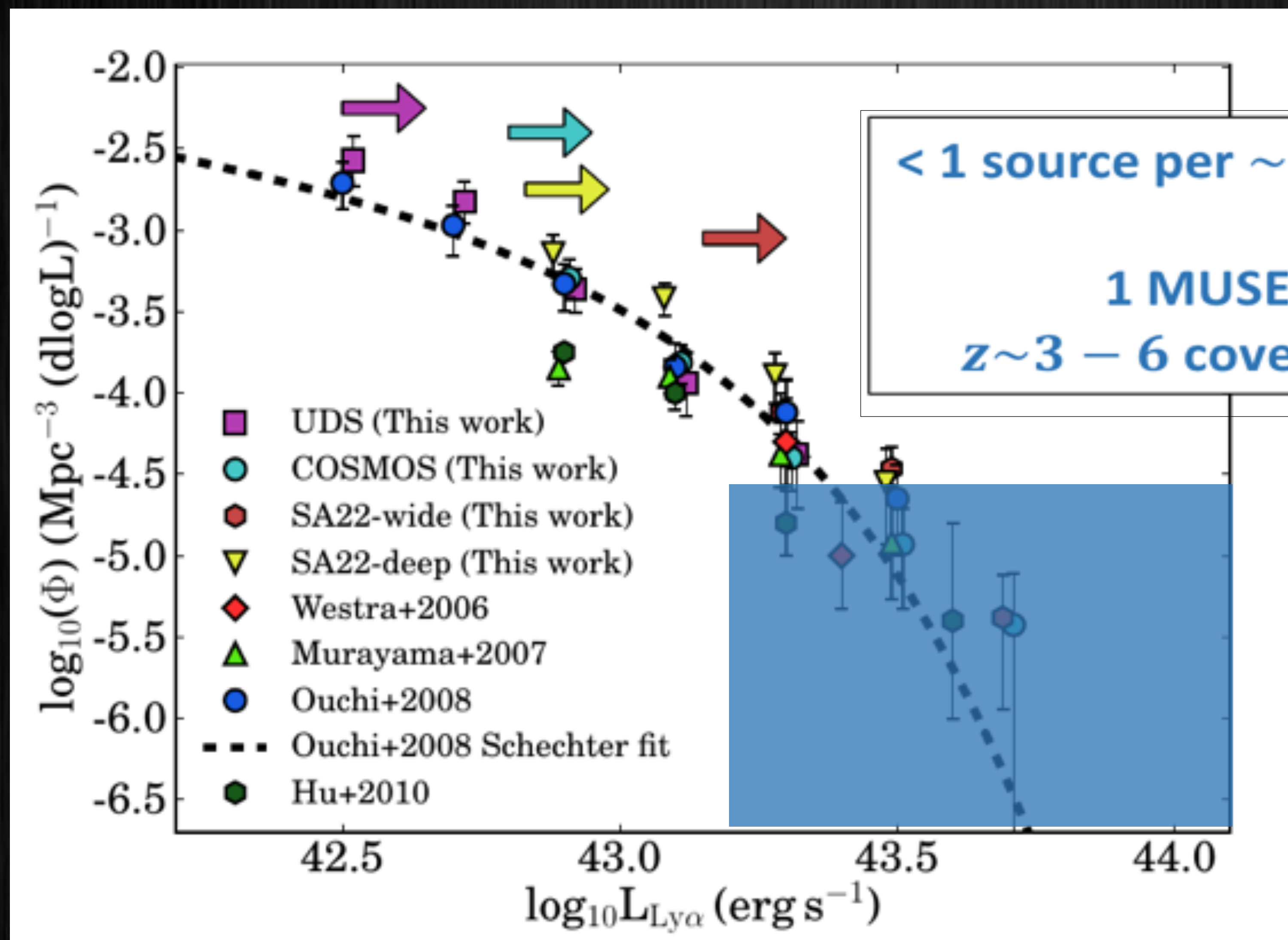
Number density

Luminosity

Santos, Sobral & Matthee 2016

z=5.7 Luminosity Function

Number density



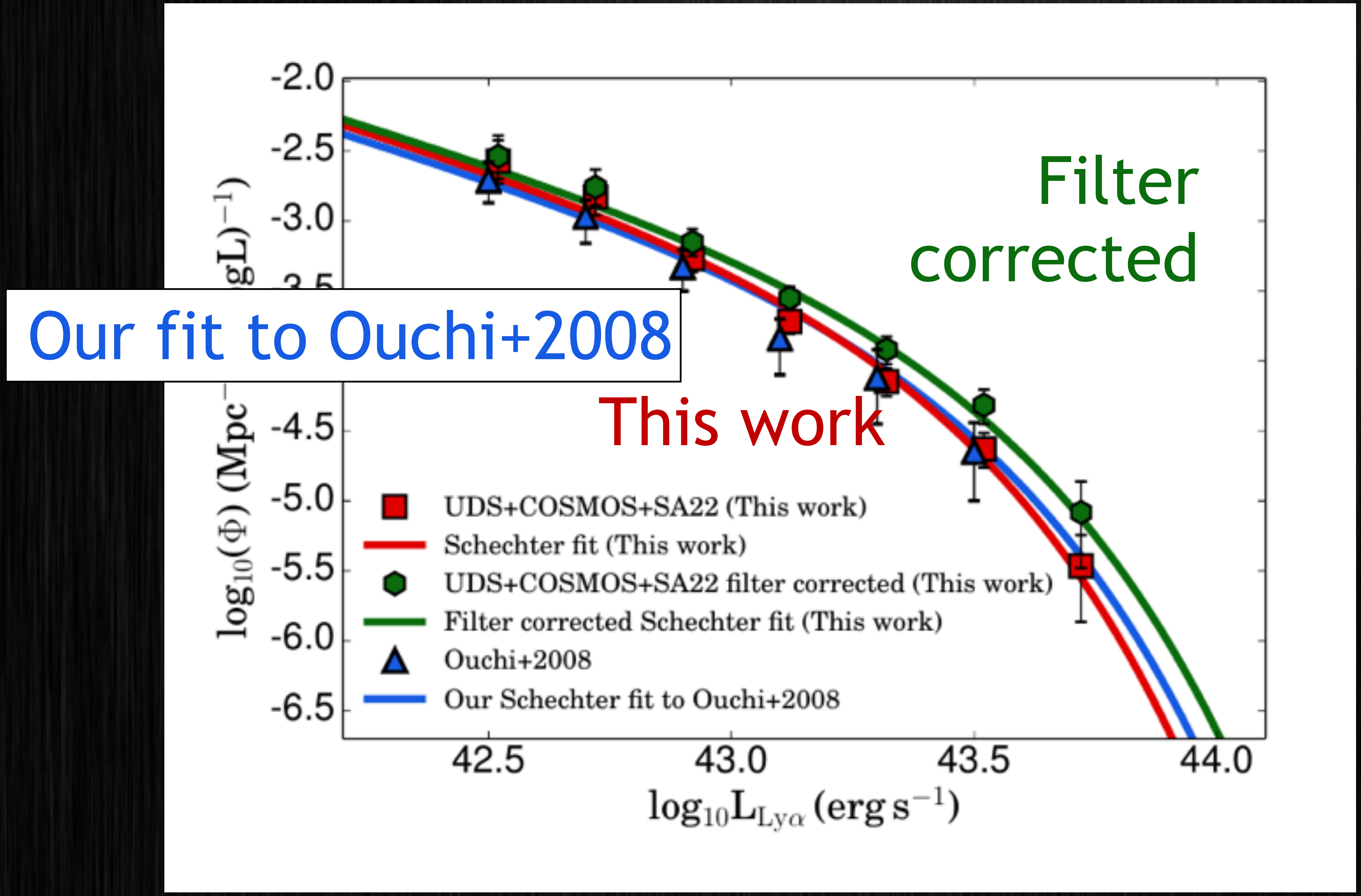
< 1 source per $\sim 10^5 - 10^6\ Mpc^3$

1 MUSE pointing
$z\sim 3-6$ covers $\sim 10^3\ Mpc^3$

Luminosity

Santos, Sobral & Matthee 2016

z = 5.7 Luminosity Function



Santos, Sobral & Matthee 2016

Wide area narrow band survey at z ~ 6.6

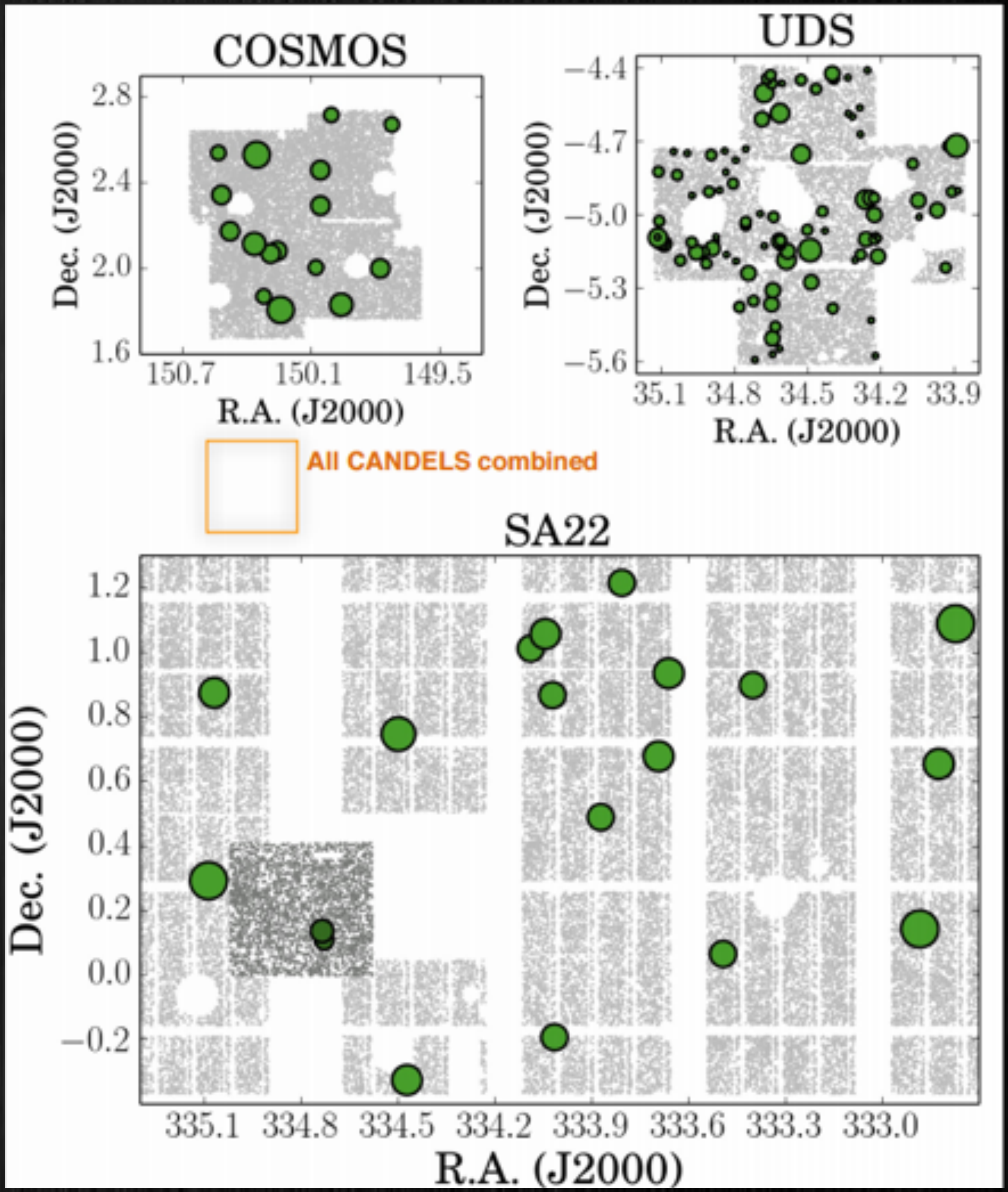
Area ~ 5 deg^2

Same EW cuts
Same sigma cuts
Same apertures
Similar area/volume

<u>Same selection!</u>

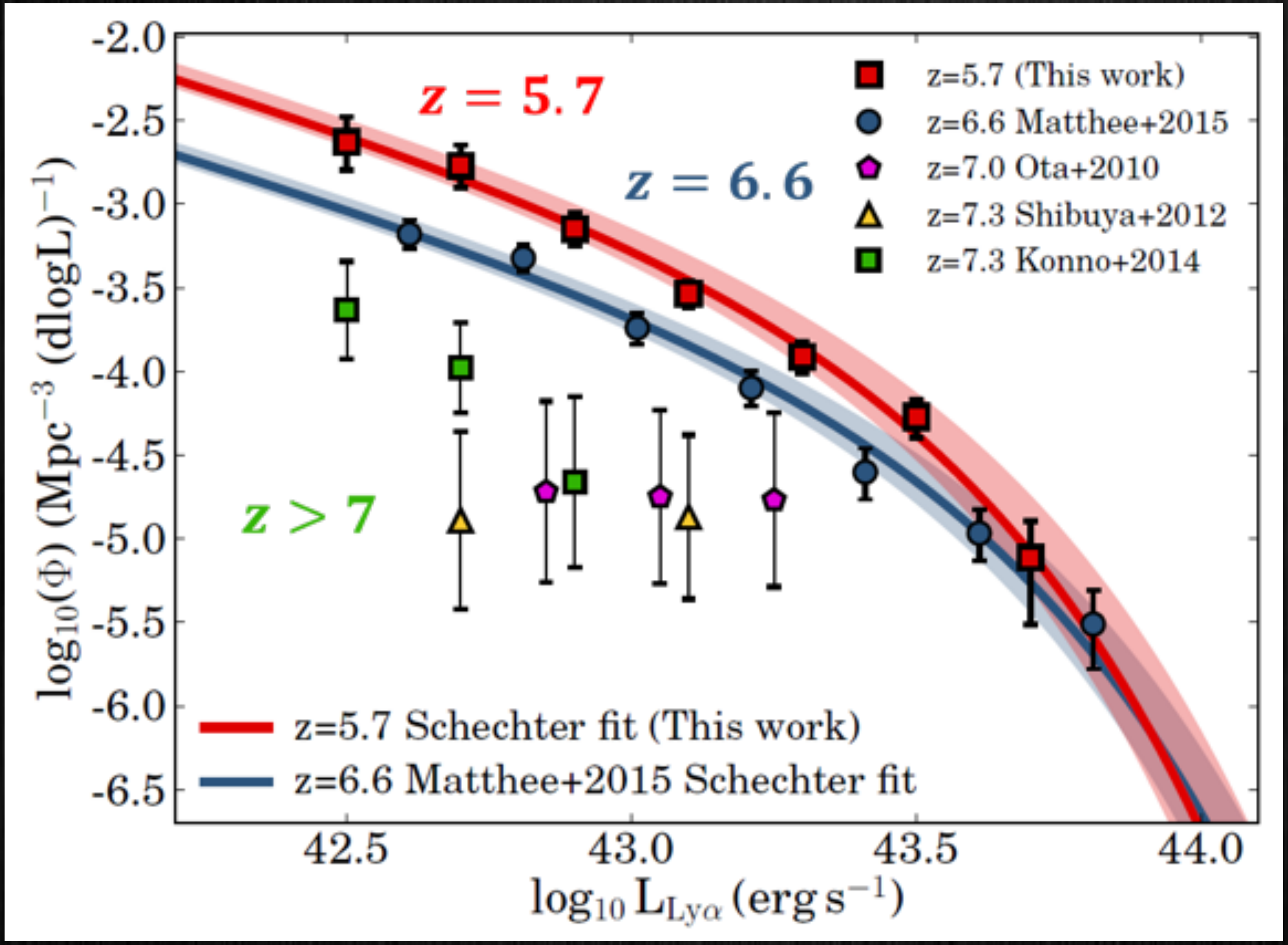
Construct the LF within reionization

Previous results Ouchi+2010 (~ 1 deg^2)



Matthee, Sobral, Santos et al. 2015

Evolution of the Luminosity function



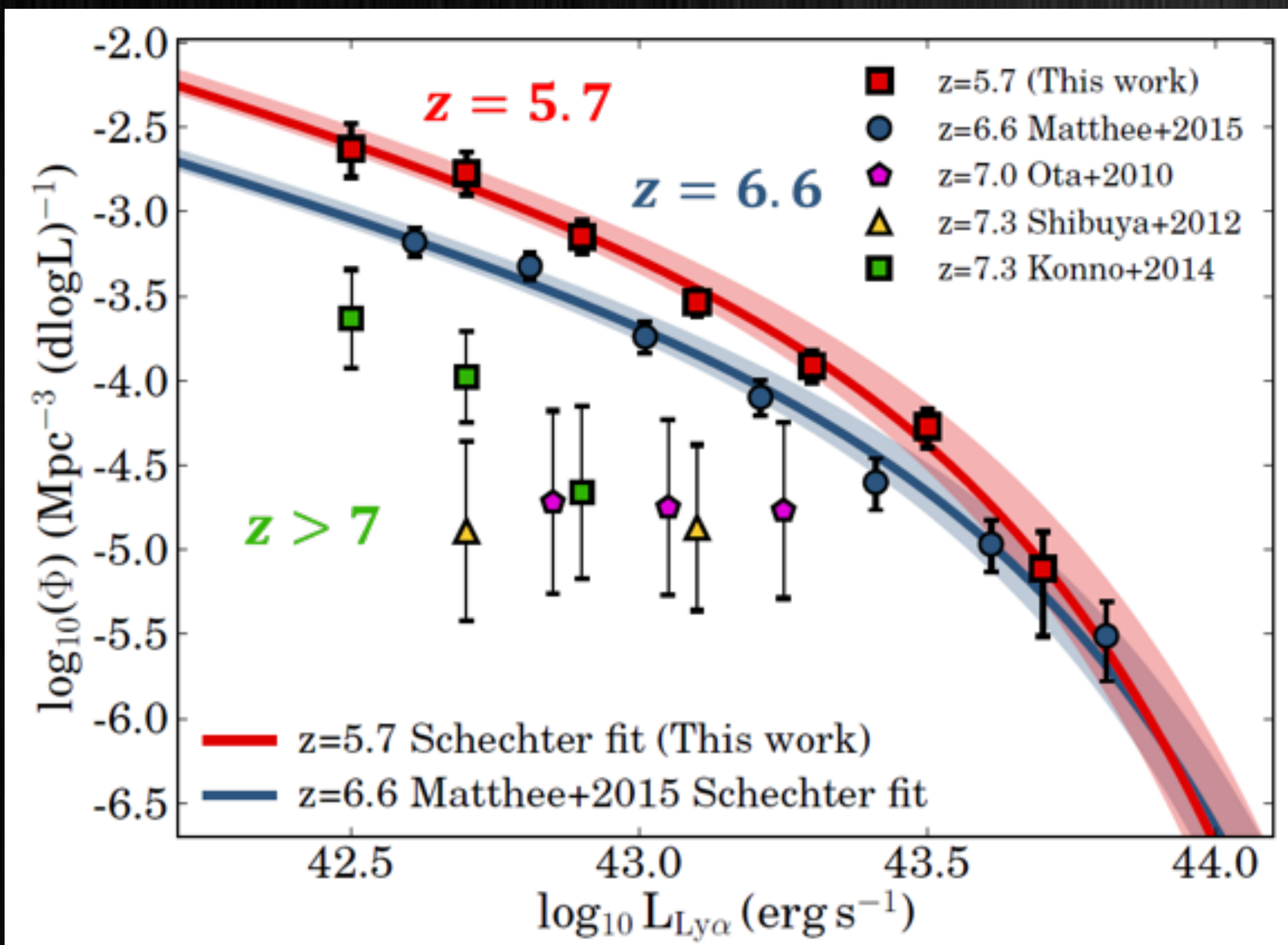
Same selection

2" aperture

$EW_0 > 25$

Santos, Sobral & Matthee 2016

Luminosity function evolution



Redshift	α	$\log_{10} L^{\star}_{Ly\alpha}$ (erg s^{-1})	$\log_{10}\Phi^{\star}$ (Mpc^{-3})
$z = 5.7$	$-2.3^{+0.4}_{-0.3}$	$43.42^{+0.50}_{-0.22}$	$-4.02^{+0.48}_{-0.93}$
	-1.5 (fix)	$43.06^{+0.05}_{-0.04}$	$-3.25^{+0.09}_{-0.10}$
	-2.0 (fix)	$43.25^{+0.09}_{-0.06}$	$-3.63^{+0.12}_{-0.16}$
$z = 6.6$	$-2.3^{+0.4}_{-0.3}$	$43.45^{+0.35}_{-0.18}$	$-4.48^{+0.43}_{-0.68}$
	-1.5 (fix)	$43.12^{+0.04}_{-0.03}$	$-3.73^{+0.07}_{-0.06}$
	-2.0 (fix)	$43.30^{+0.07}_{-0.05}$	$-4.13^{+0.10}_{-0.10}$

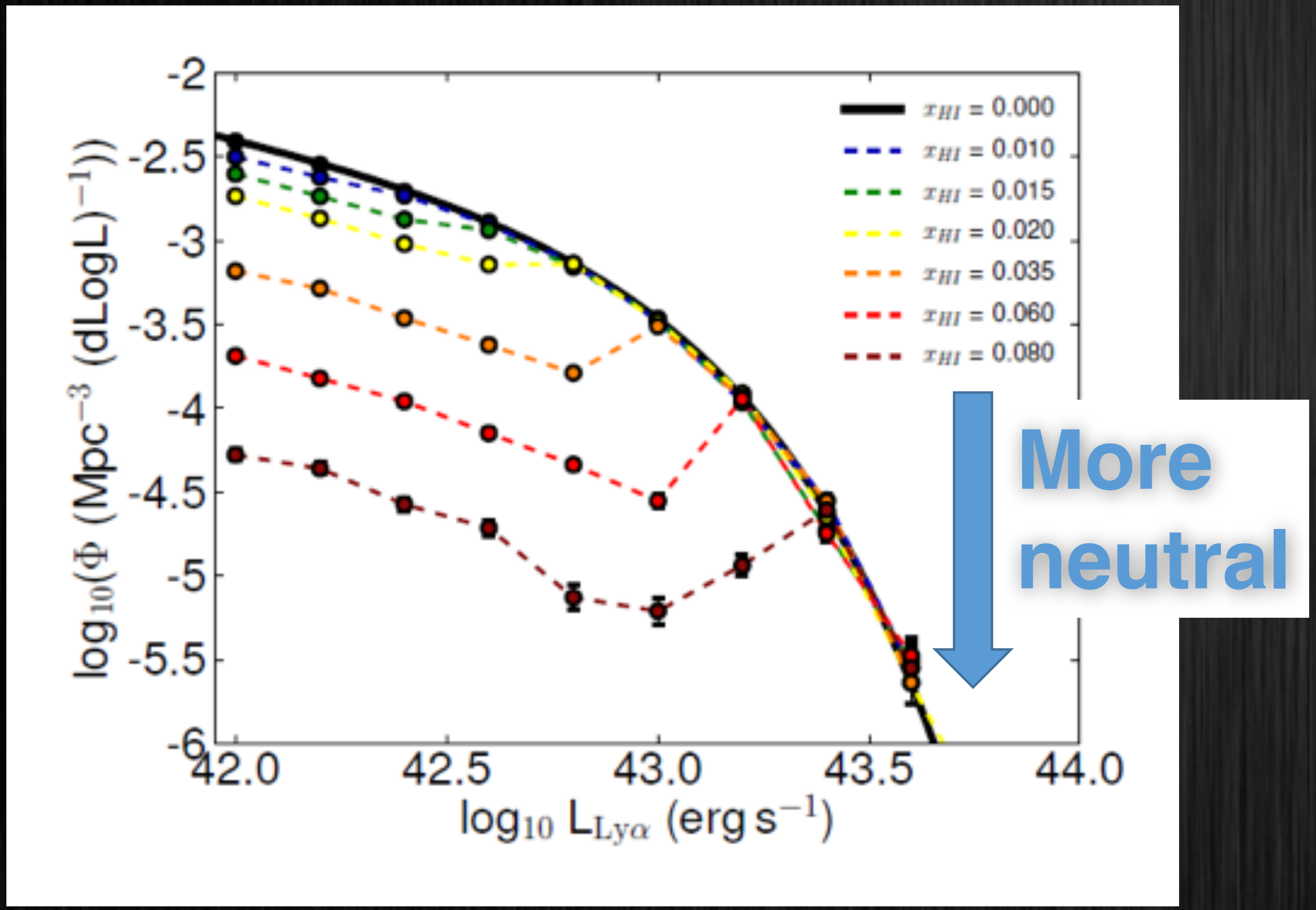
$-2.6 < \alpha < -1.9$ (1σ)

Dressler+2015: $-2.35 < \alpha < -1.95$

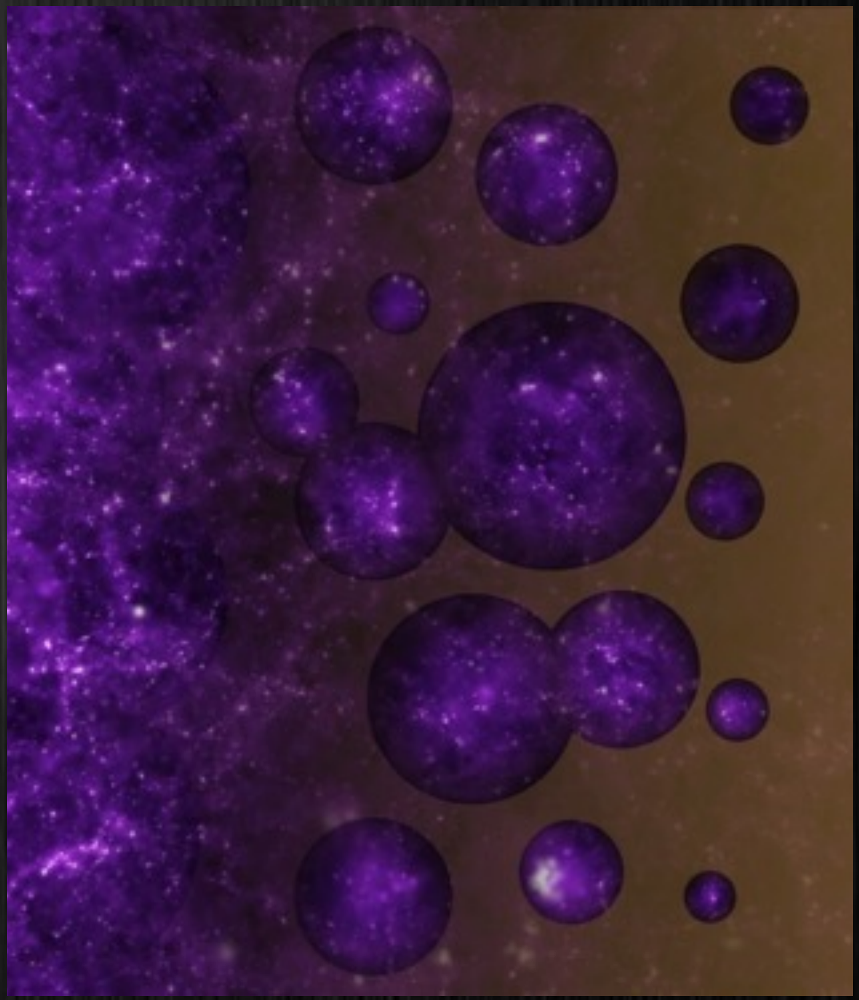
Extremely steep faint end slope!

Santos, Sobral & Matthee 2016

Testing reionization – Toy model



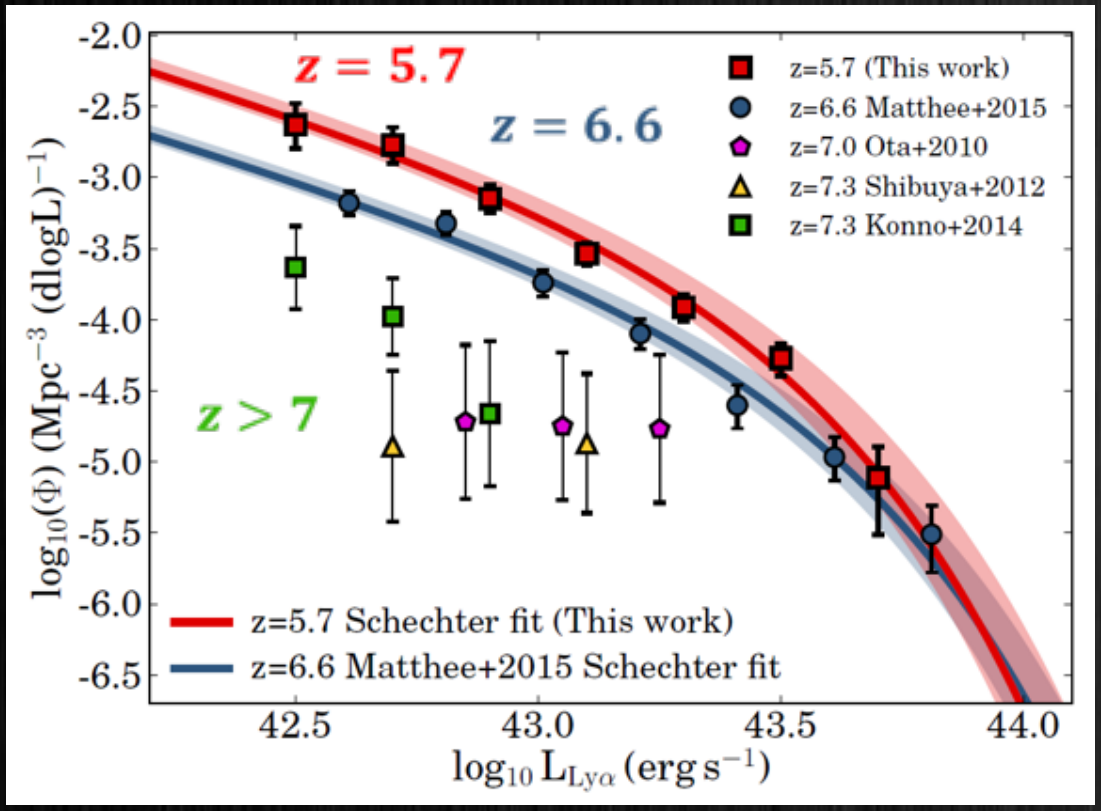
Matthee, Sobral, **Santos** et al. 2015



Artist impression, NASA

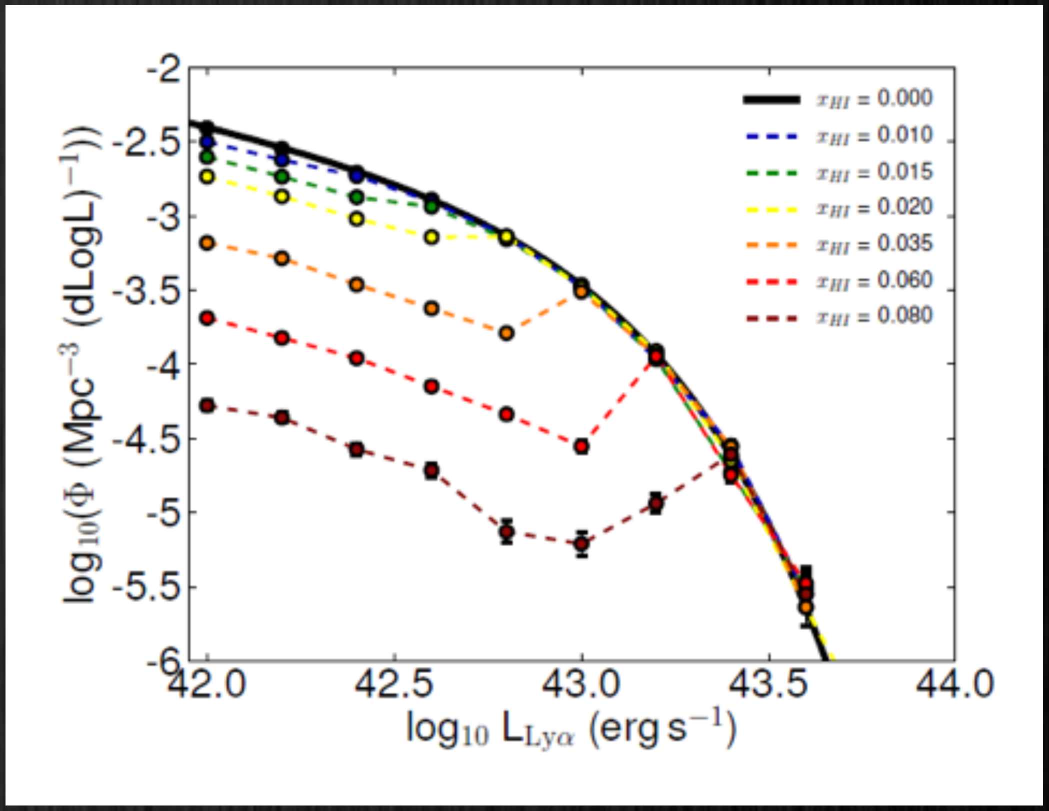
Testing reionization – Toy model

Observations



Santos, Sobral & Matthee 2016

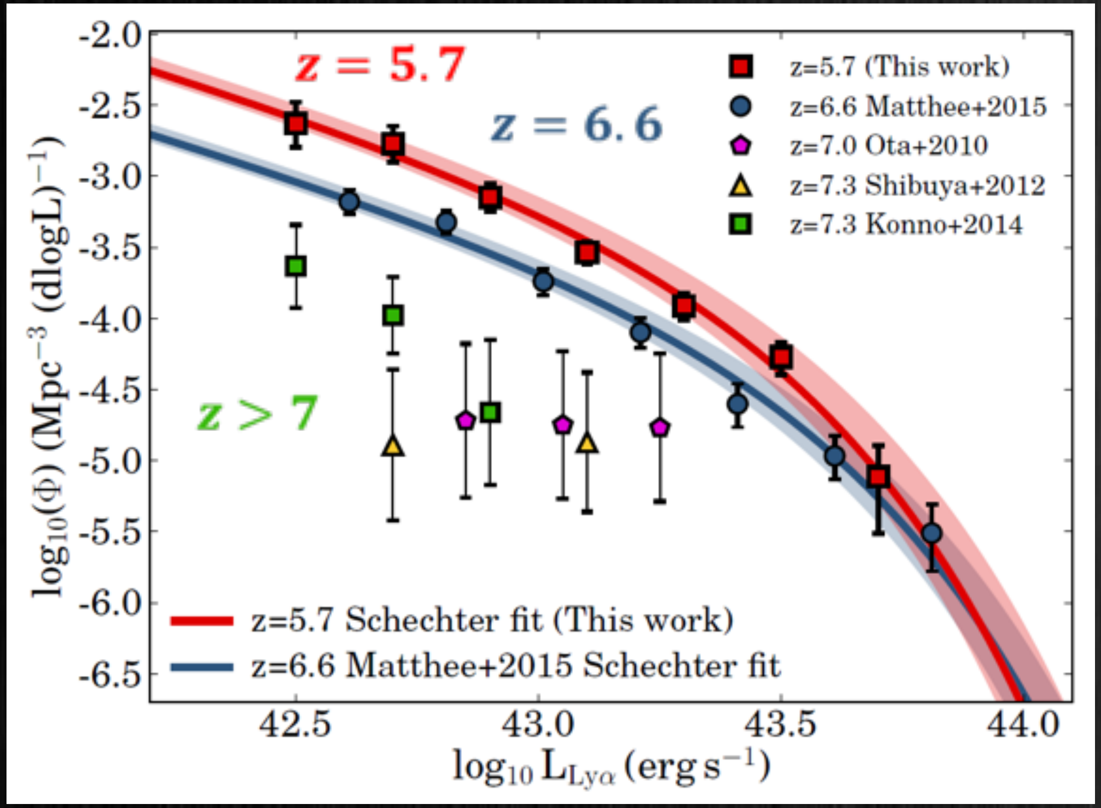
Toy model



Matthee, Sobral, **Santos** et al. 2015

Testing reionization – Toy model

Observations

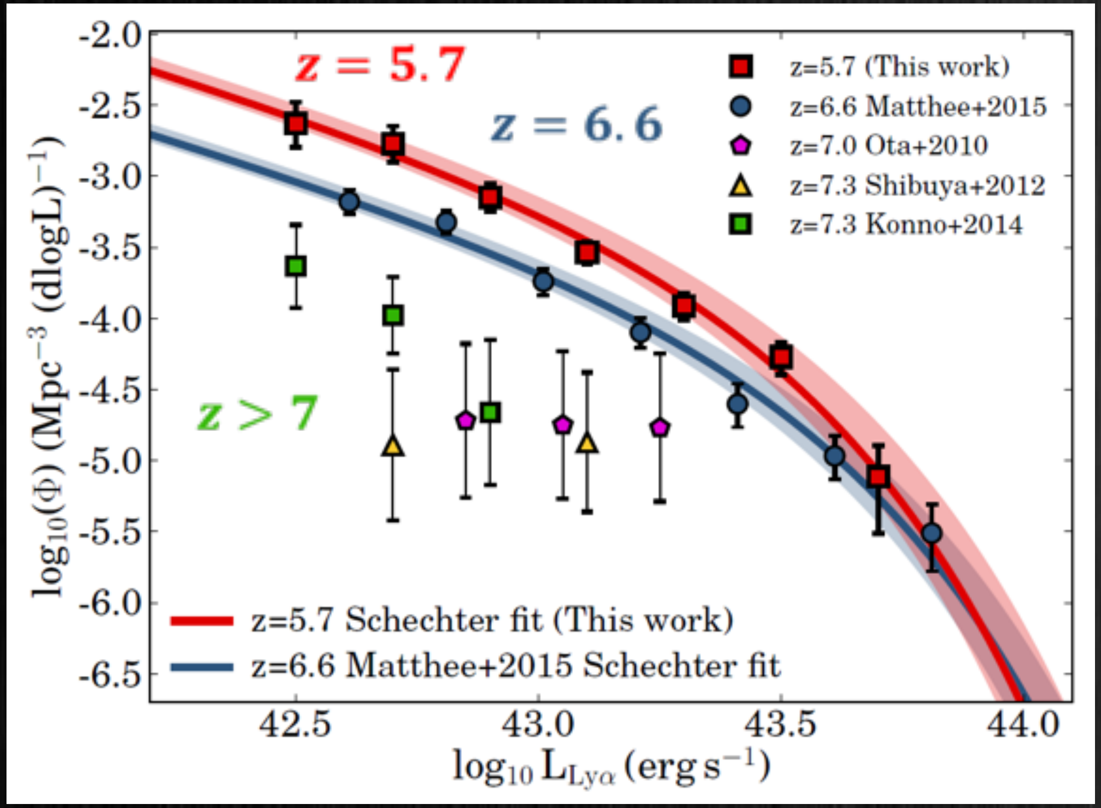


Santos, Sobral & Matthee 2016

If the drop is caused by reionization, we would expect large Lyα sizes for the faint sources at z=6.6

Testing reionization – Toy model

Observations



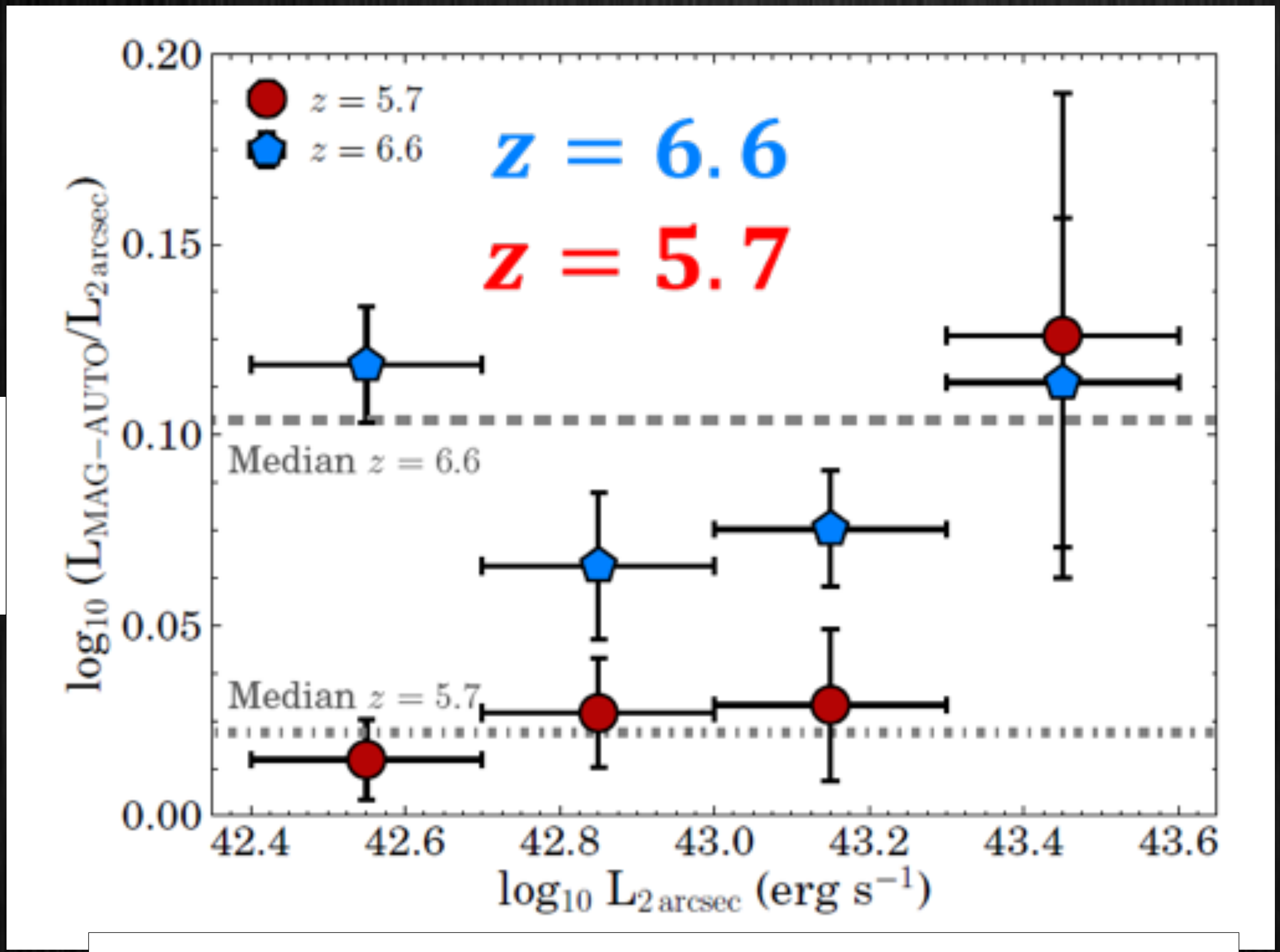
Santos, Sobral & Matthee 2016

If the drop is caused by reionization, we would expect large Lyα sizes for the faint sources at z=6.6

We can test this!

Lyα sizes and evolution at z = 5.7 - 6.6

Extension of Lyα



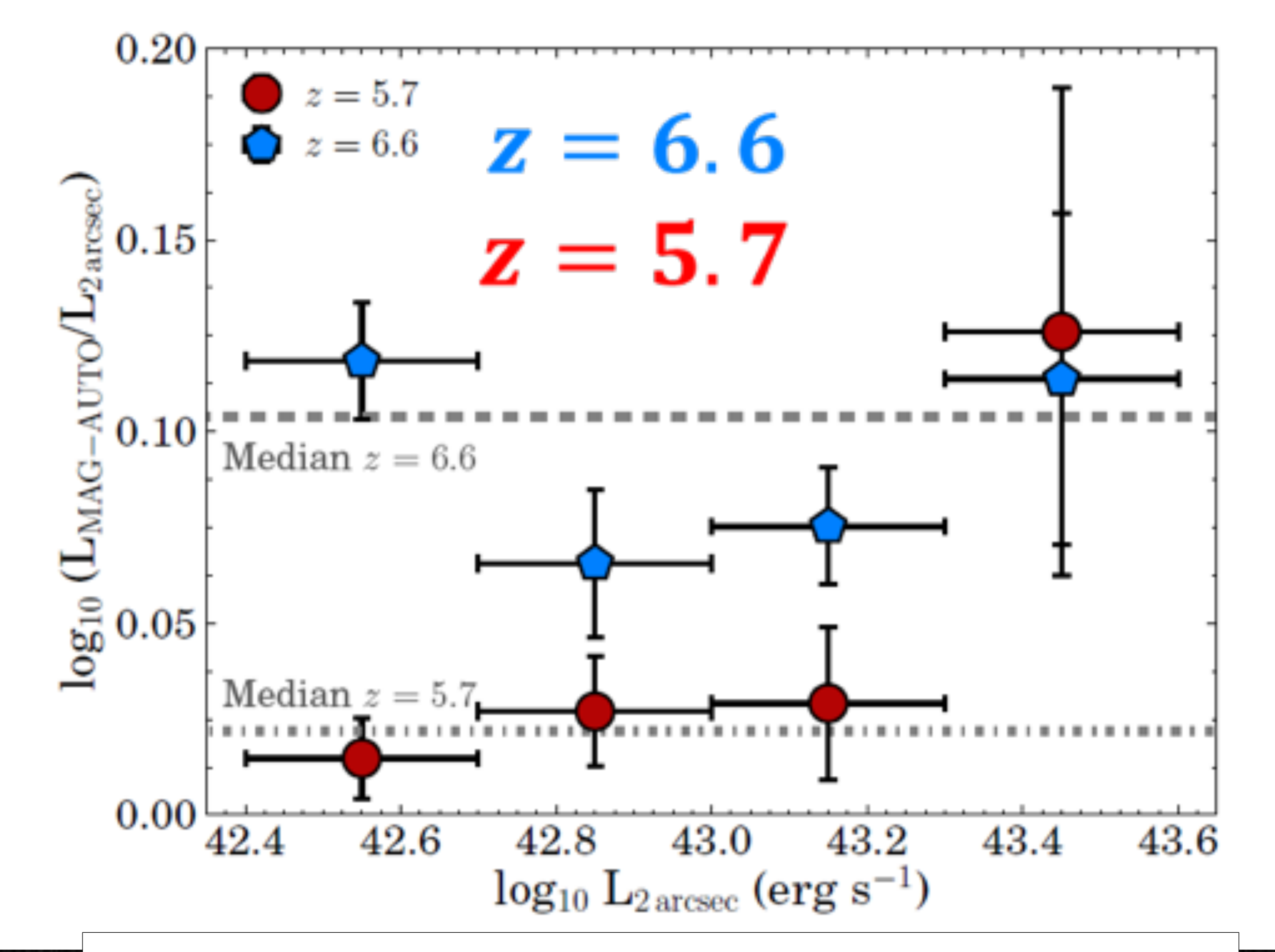
Luminosity in 2" apertures

Median results consistent with Momose+2014

Santos, Sobral & Matthee 2016

Lyα sizes and evolution at z = 5.7 - 6.6

Extension of Lyα



Luminosity in 2” apertures

Lyα in a more neutral medium scatters

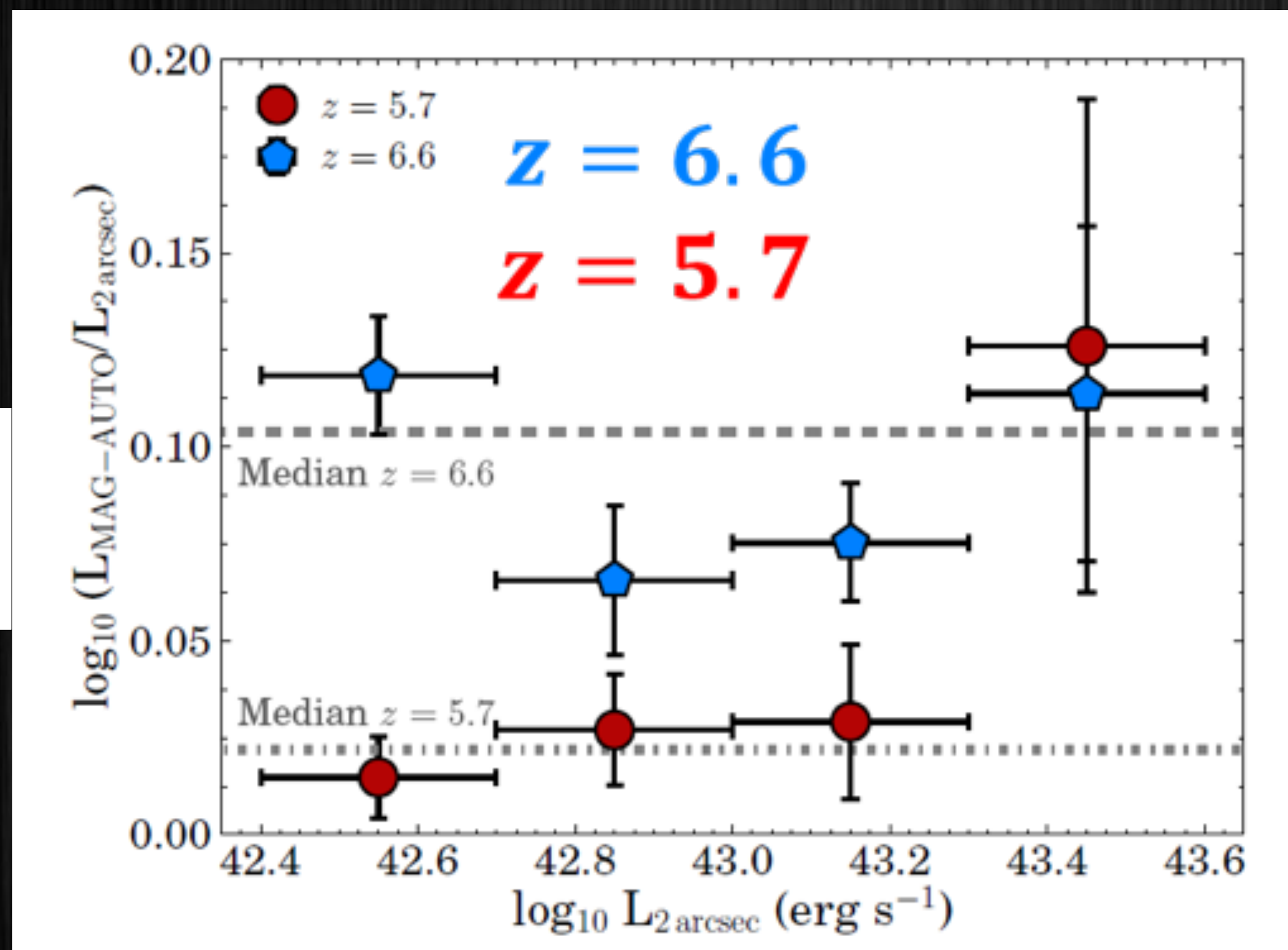
↓

Extended emission

Santos, Sobral & Matthee 2016

Lyα sizes and evolution at z = 5.7 - 6.6

Extension of Lyα



Luminosity in 2" apertures

Lyα in a more neutral medium scatters

↓

Extended emission

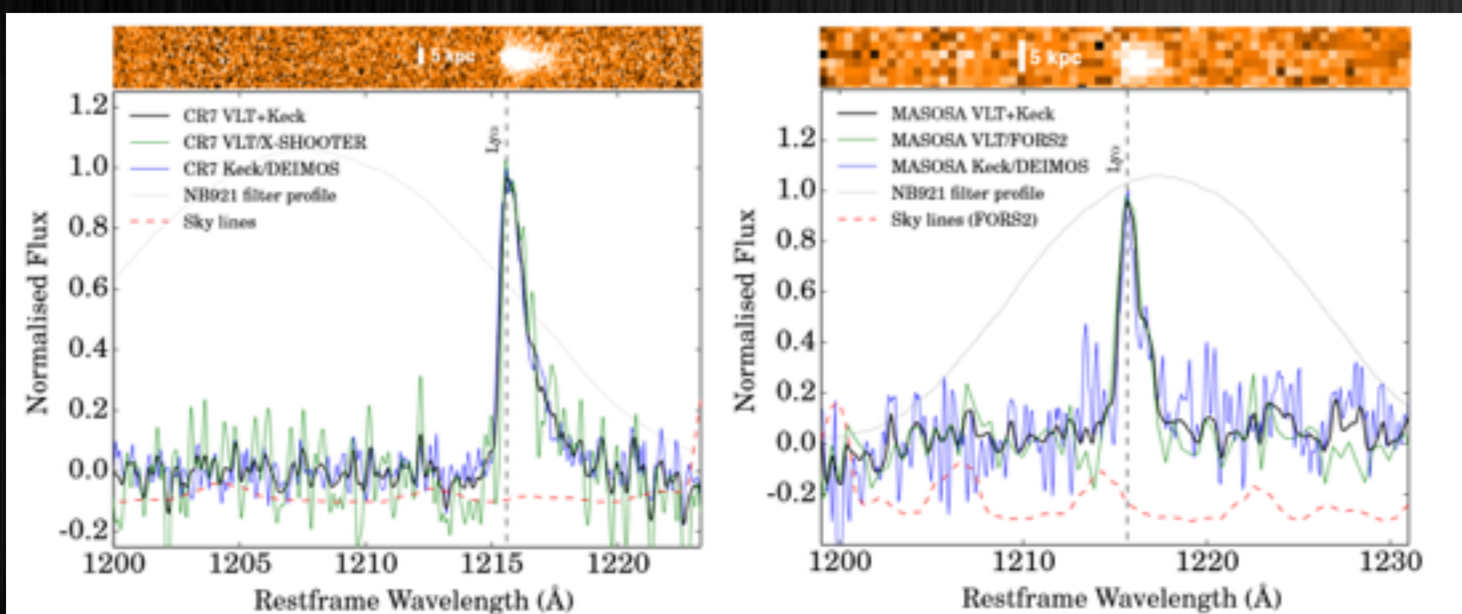
Hints for <u>differential reionization</u>

Santos, Sobral & Matthee 2016

Follow-up of sources

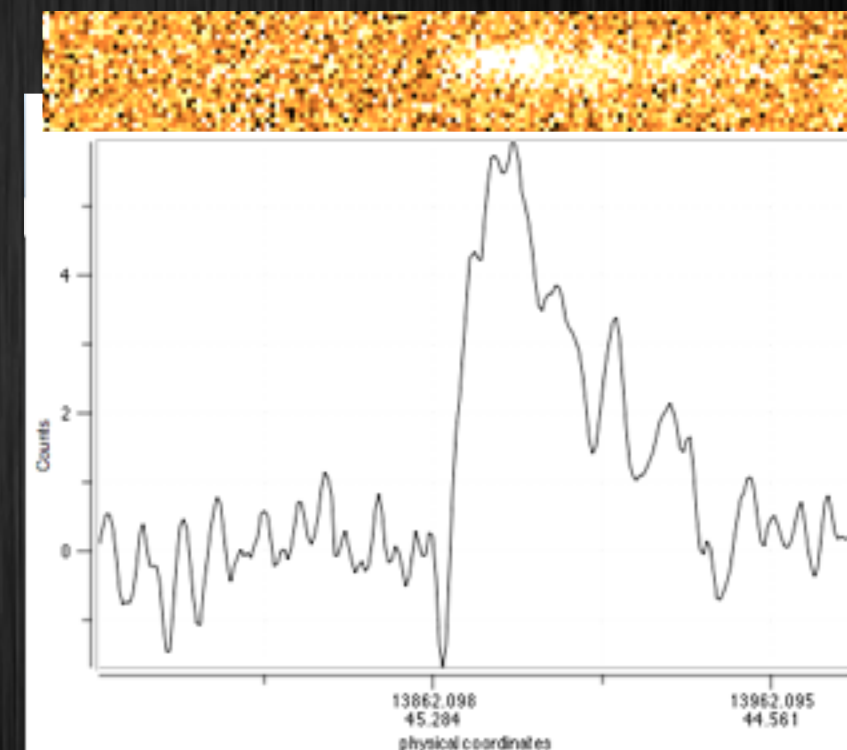
z = 6.6

Two brightest Lyman-alpha emitters at z=6.6

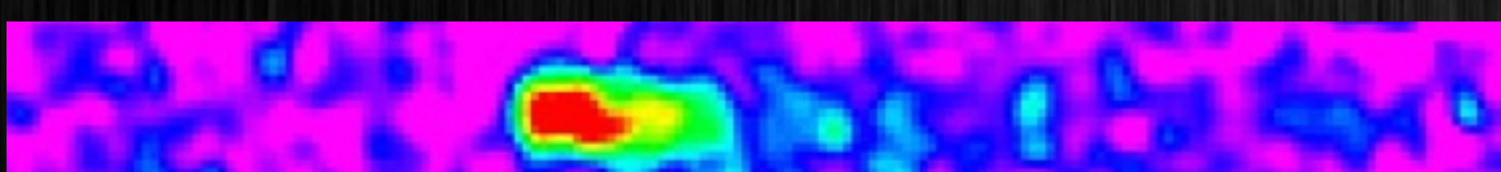


Sobral et al. (inc. **Santos**) 2015

z = 5.7

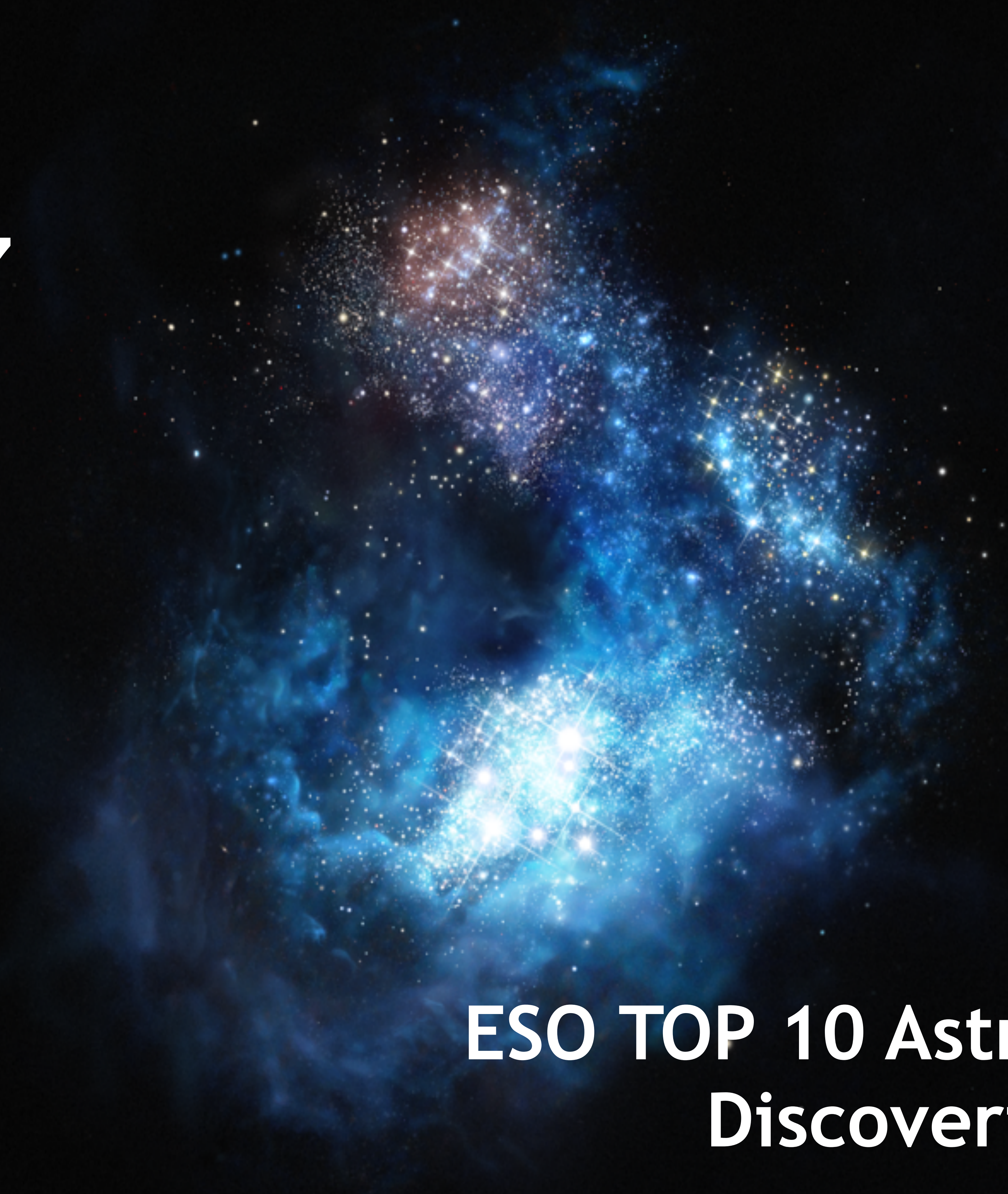


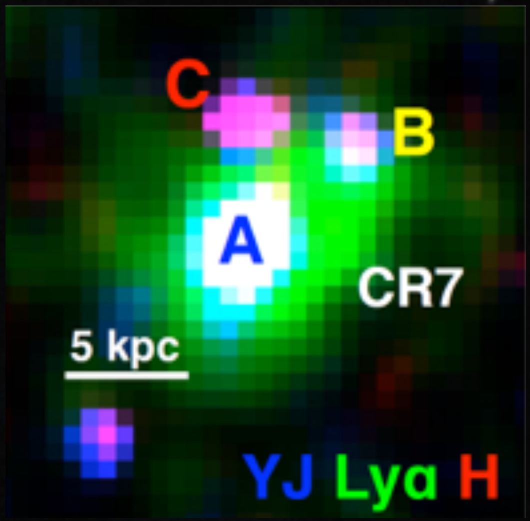
Spectra from X-SHOOTER



Spectra from DEIMOS, KECK

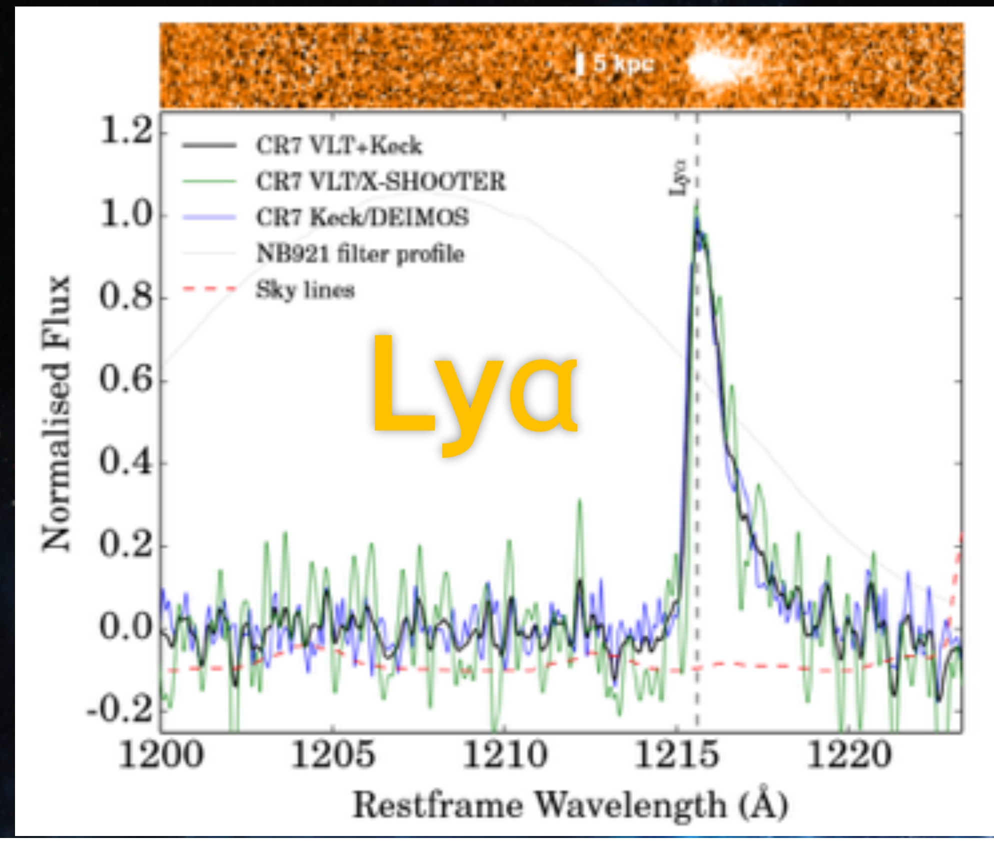
CR7

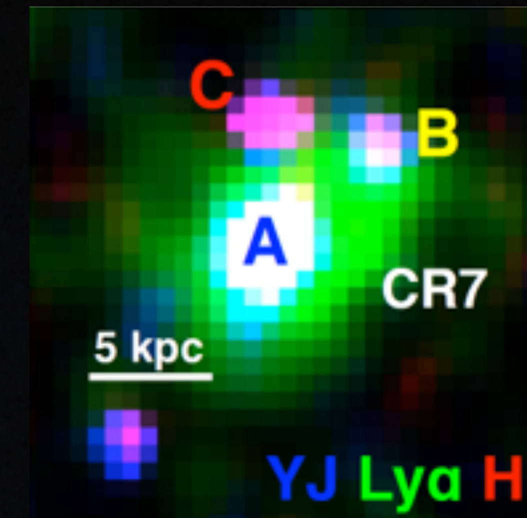


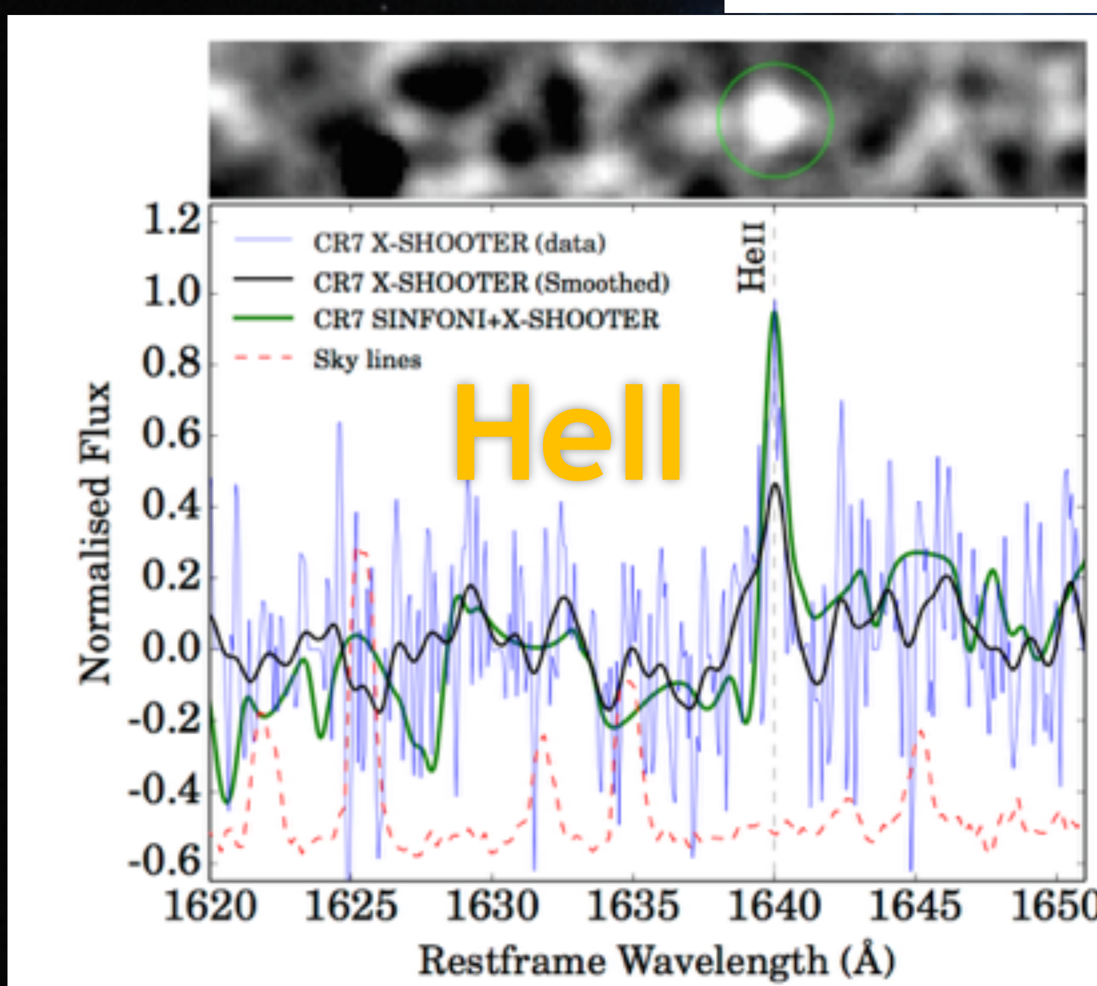


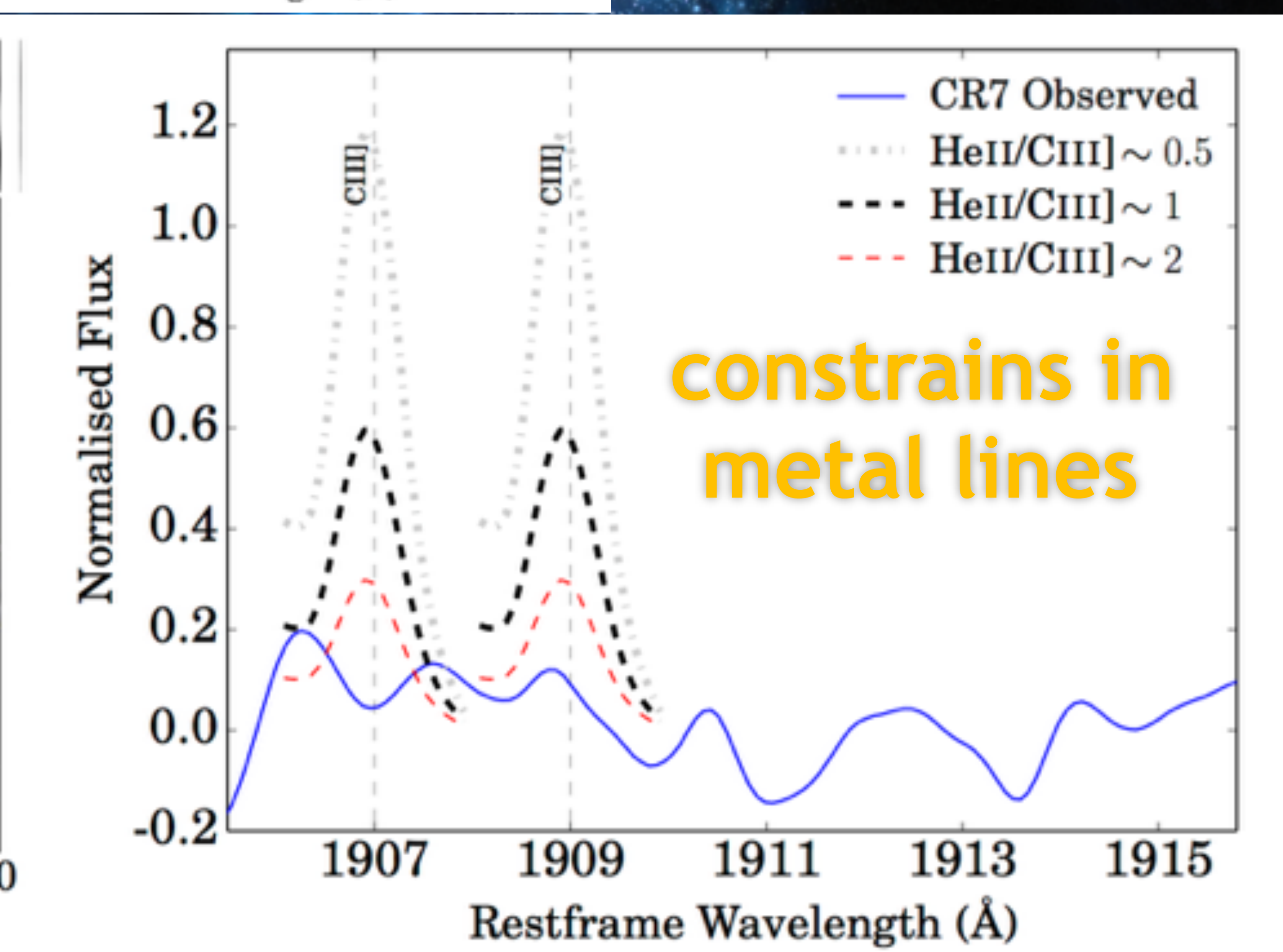
ESO TOP 10 Astronomical Discoveries

CR7

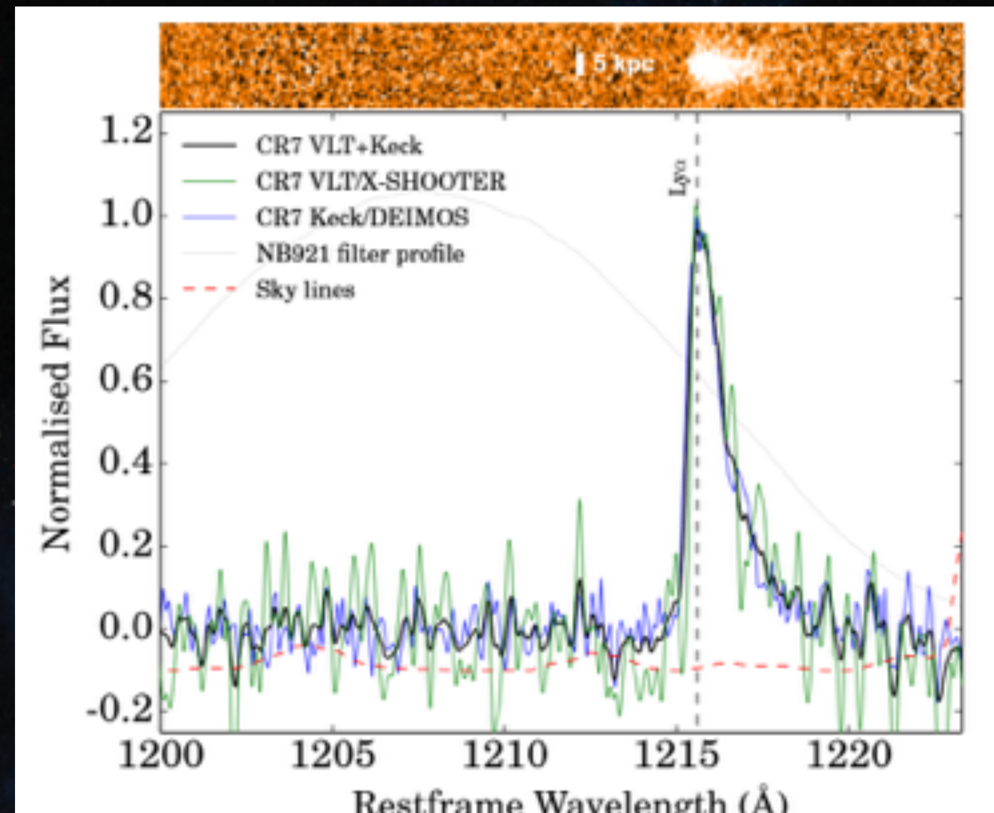

5 kpc
CR7 VLT+Keck
CR7 VLT/X-SHOOTER
CR7 Keck/DEIMOS
NB921 filter profile
Sky lines
Lyα
Normalised Flux
Restframe Wavelength (Å)
1200 1205 1210 1215 1220
-0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2

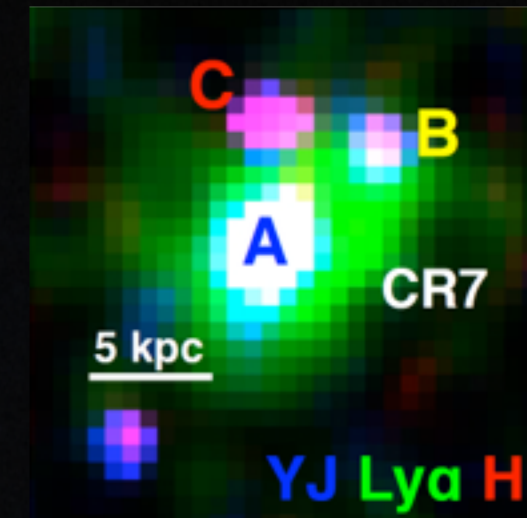

C
B
A
CR7
5 kpc
YJ Lyα H


CR7 X-SHOOTER (data)
CR7 X-SHOOTER (Smoothed)
CR7 SINFONI+X-SHOOTER
Sky lines
HeII
Normalised Flux
Restframe Wavelength (Å)
1620 1625 1630 1635 1640 1645 1650
-0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2

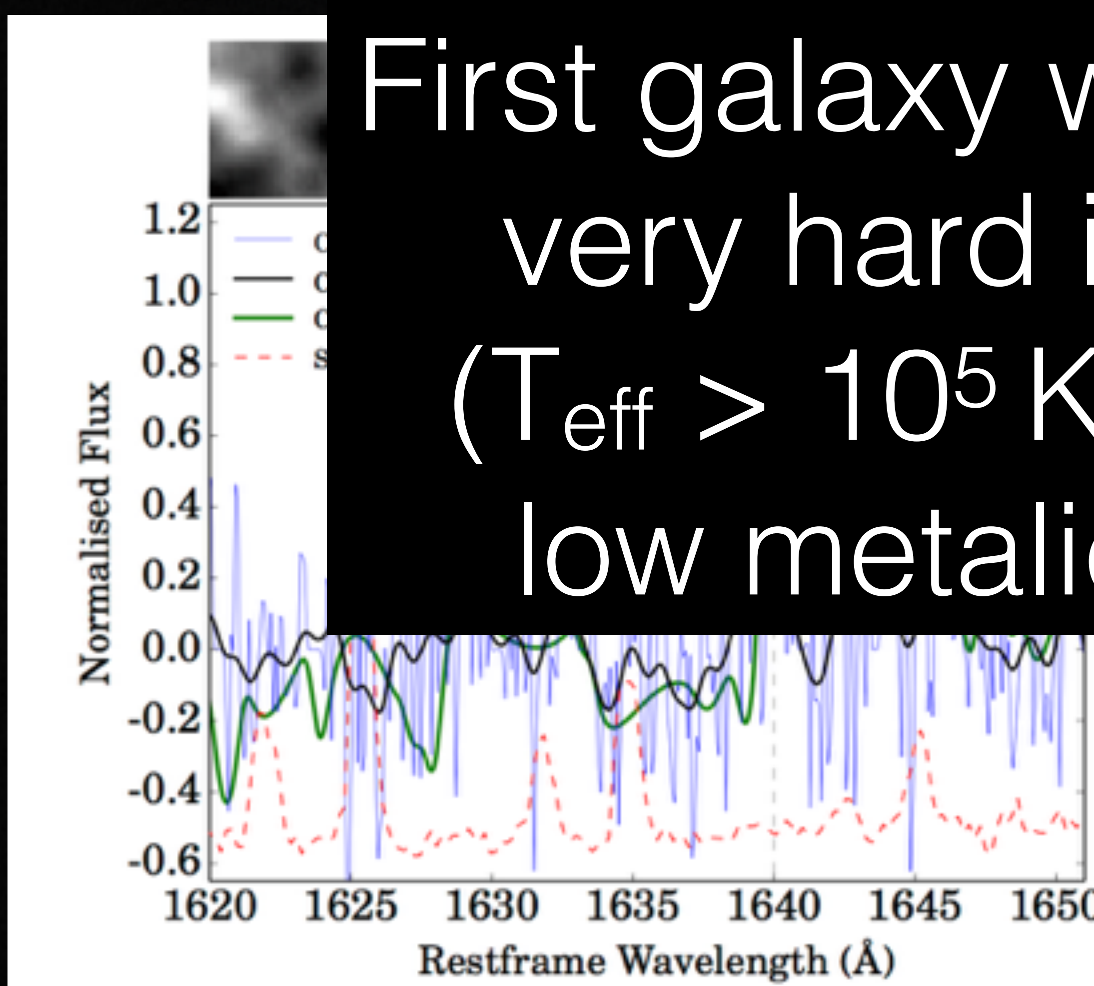

CR7 Observed
HeII/CIII] ~ 0.5
HeII/CIII] ~ 1
HeII/CIII] ~ 2
CIII]
CIII]
constrains in
metal lines
Normalised Flux
Restframe Wavelength (Å)
1907 1909 1911 1913 1915
-0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2

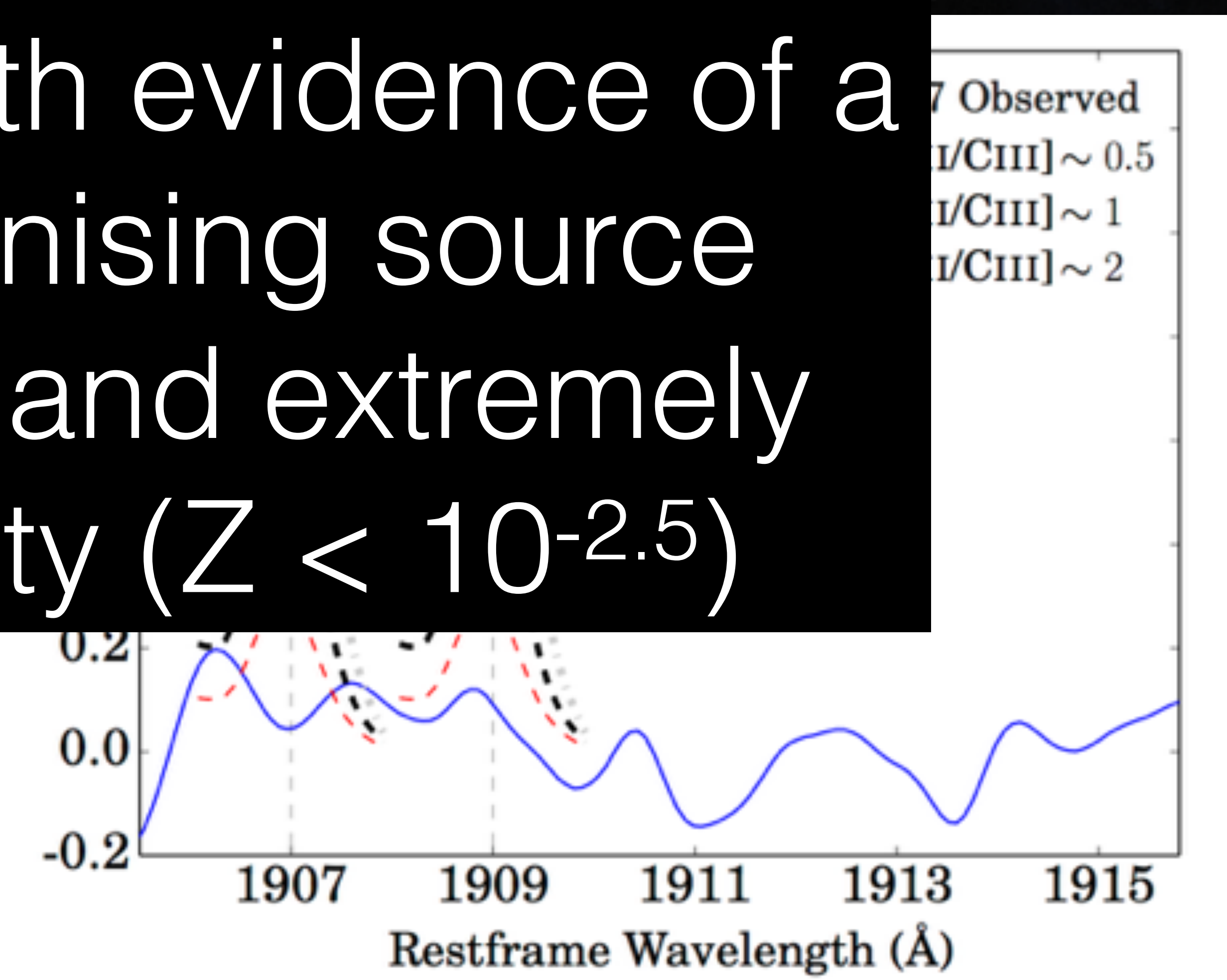
CR7



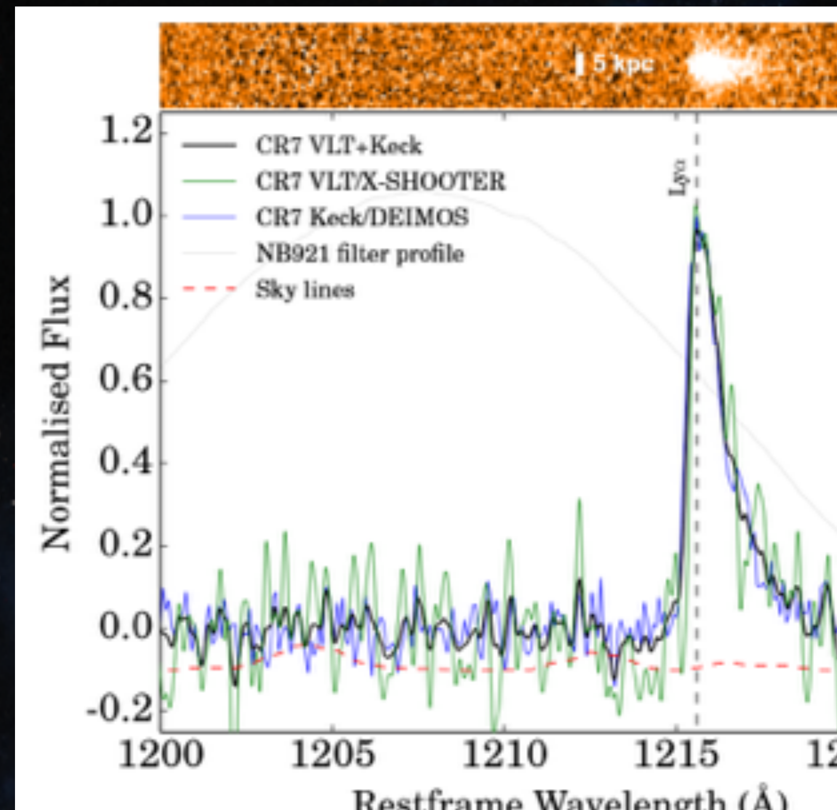


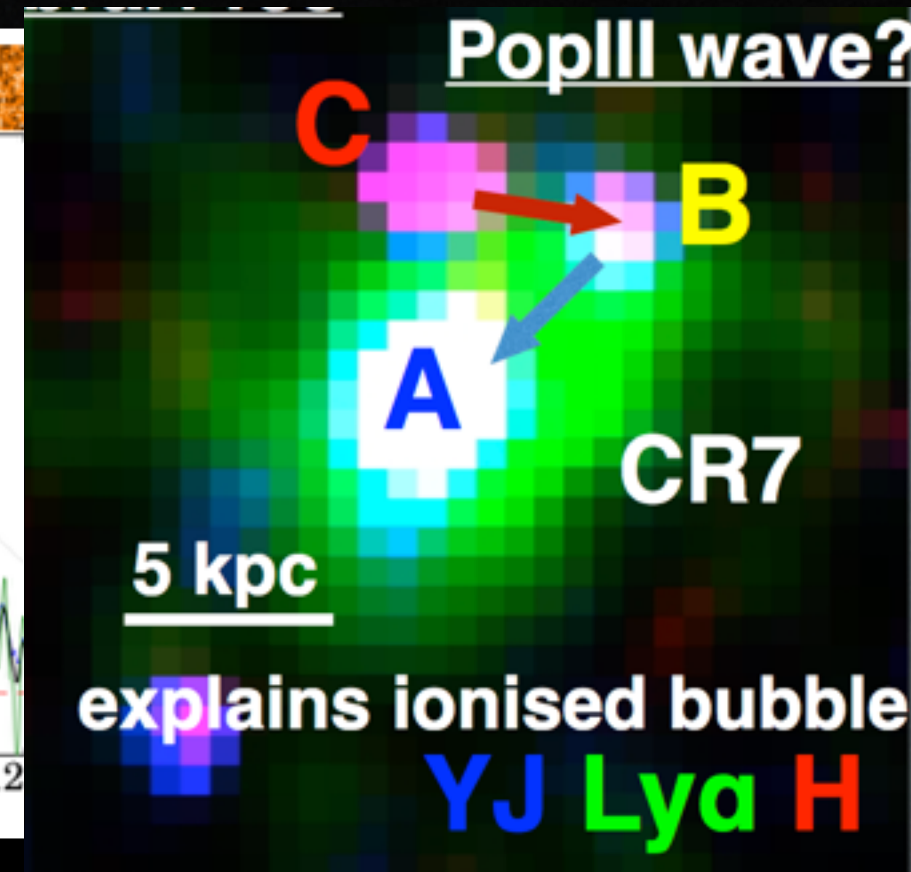
First galaxy with evidence of a very hard ionising source ($T_{eff} > 10^5$ K) and extremely low metalicity ($Z < 10^{-2.5}$)

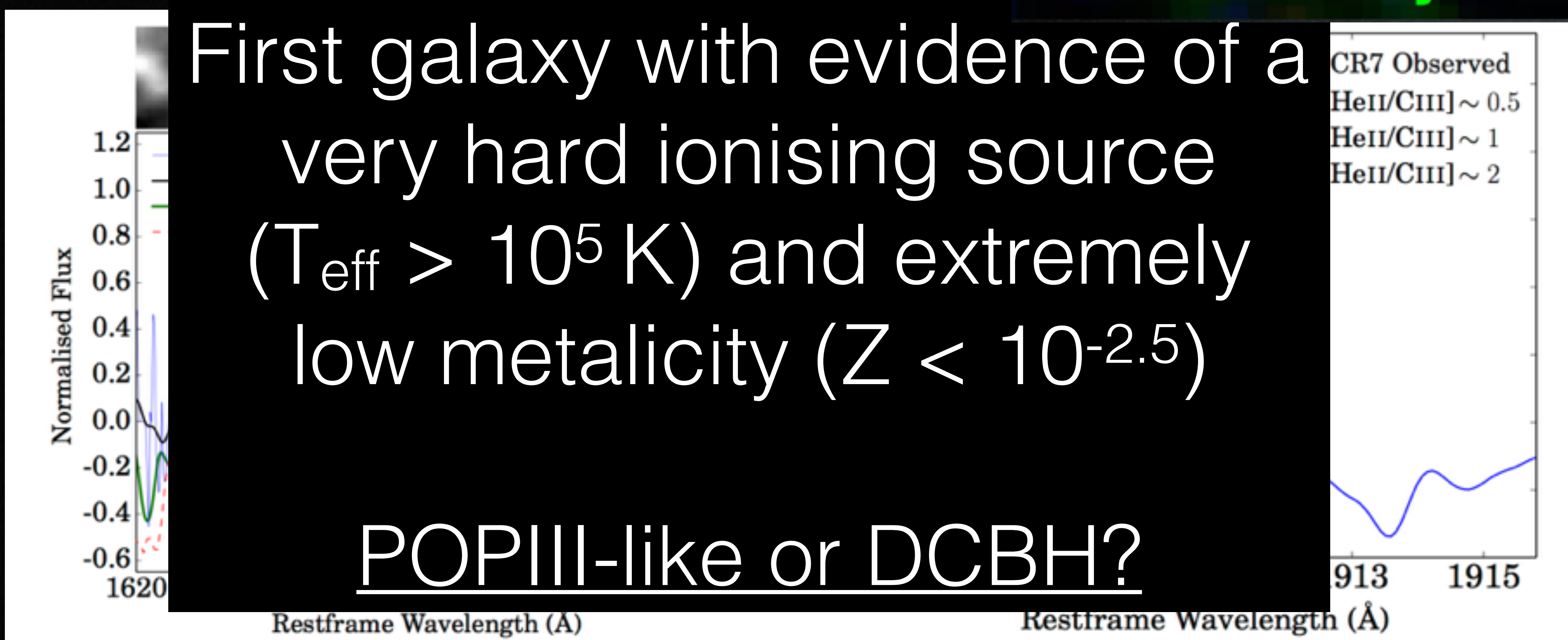




CR7







First galaxy with evidence of a very hard ionising source ($T_{eff} > 10^5$ K) and extremely low metalicity ($Z < 10^{-2.5}$)

<u>POPIII-like or DCBH?</u>

Conclusions

- **We constructed the largest NB surveys at z ~ 6 - 7**
- **Cosmic variance influences results (variations up to 0.4 dex)**
- **Steep faint end of the Lyα LF**
- Differential evolution of the bright and faint ends
- Faint Lyα haloes more extended at z ~ 6.6

Hints for differential reionization

Thank you for your attention