The nature and evolution of emission-line selected galaxies to z~6

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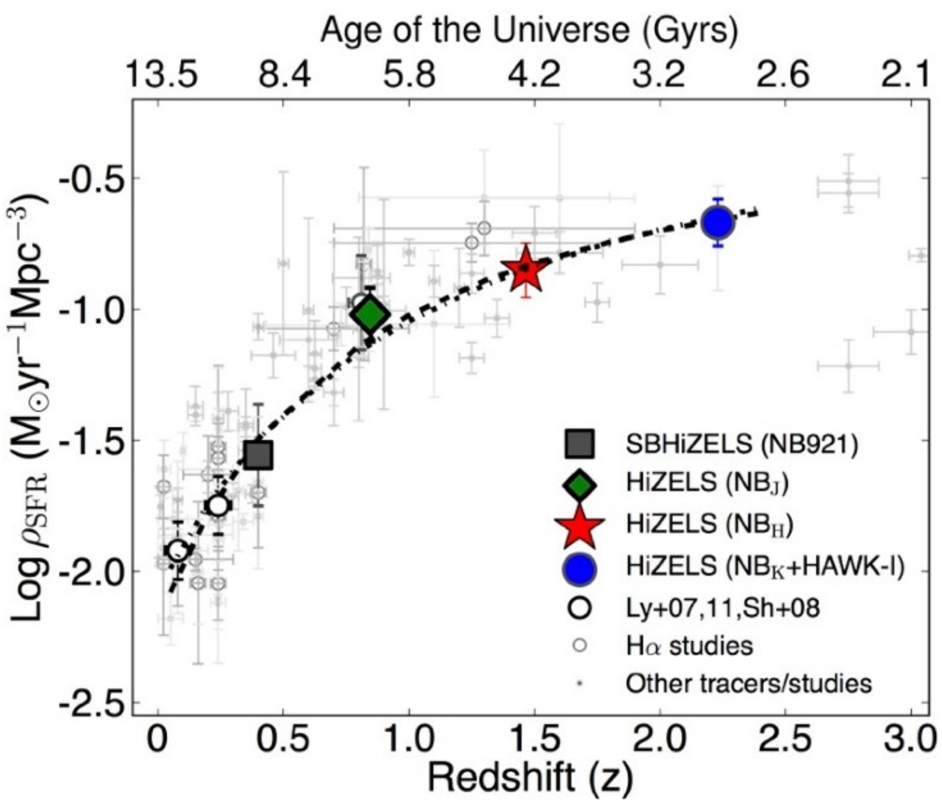
What drives the rise-decline of the star formation history?

$$\log \dot{\rho}_{\mathrm{SFR}} = -0.14T - 0.23$$



Hα Star formation history of the Universe; Sobral+13a

- **What are the main drivers?**
- **What's evolving?**

- Gas consumption? Higher/Lower gas fractions?
- More/Less mergers? Increased/ Reduced/no cold flows?
- Less/More massive haloes/hotter haloes
- Structure formation: less/more mature structures + environmental quenching?

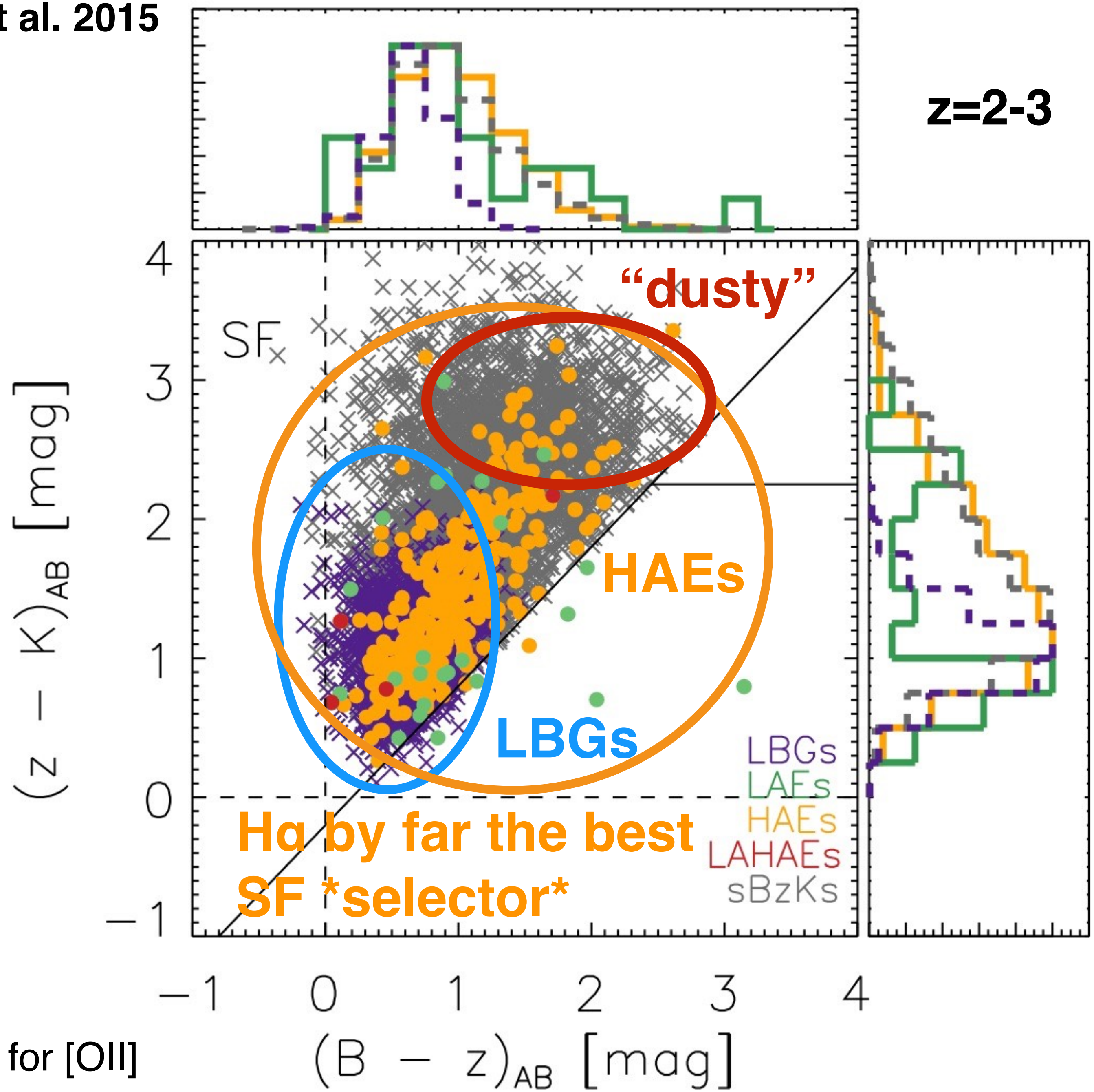
See also: Geach+08; Sobral+13a,14,15a; Karim et al. 2011; Madau & Dickinson14; Bouwens et al. 2015; Khostovan et al. 2015

Selection really matters (z~2) and should be f(science)

Oteo, Sobral et al. 2015

Lyman-break/UV selection can miss ~65-70% of star-forming galaxies (metal-rich, dusty) (+ systematics)

Deep+wide Hα surveys get ~100% down to the Hα flux limit they sample at z~2: important to conduct at higher z

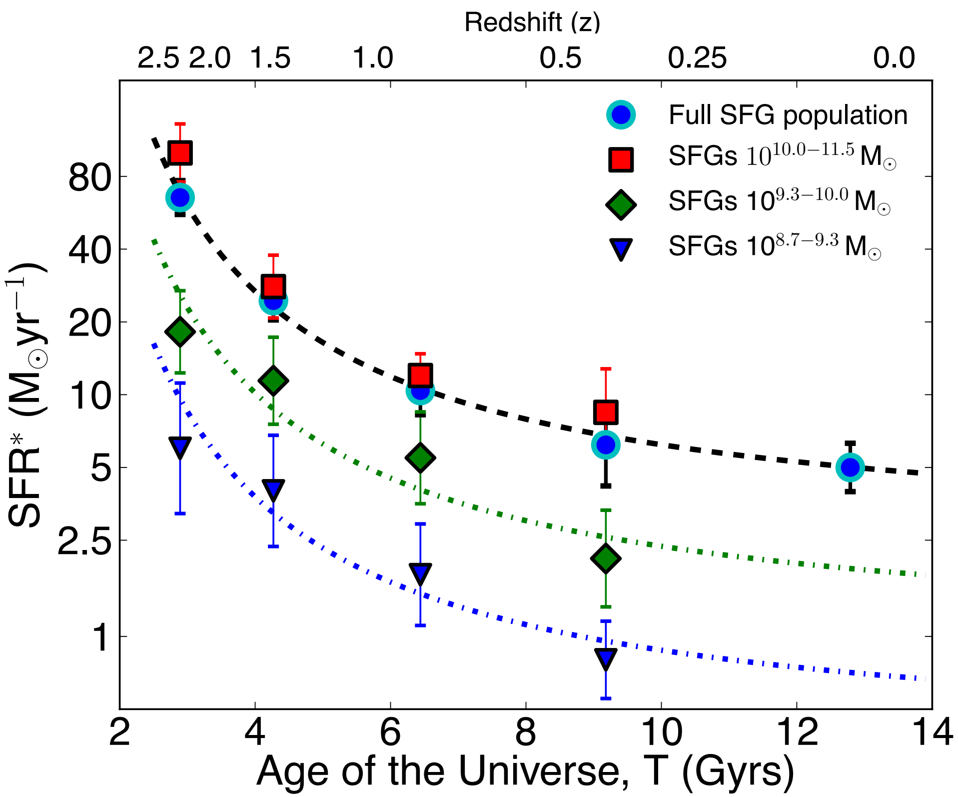


See also: Hayashi et al. 2013 for [OII]

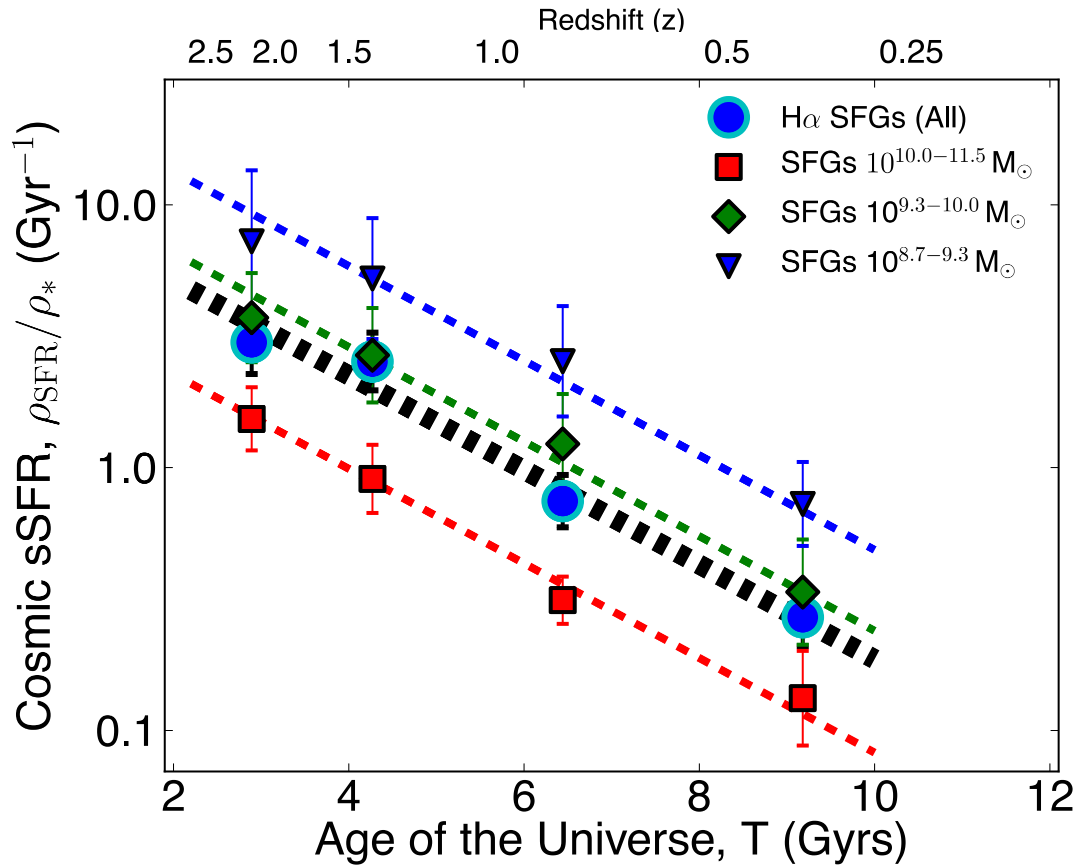
Strong SFR* decline with cosmic time towards z~0

- **<u>Decline</u>** of <u>typical star formation rates (SFR*)</u> and <u>specific star formation of galaxies</u> (sSFR) with **<u>cosmic time for all masses</u>**

<u>Decline at ALL masses</u>



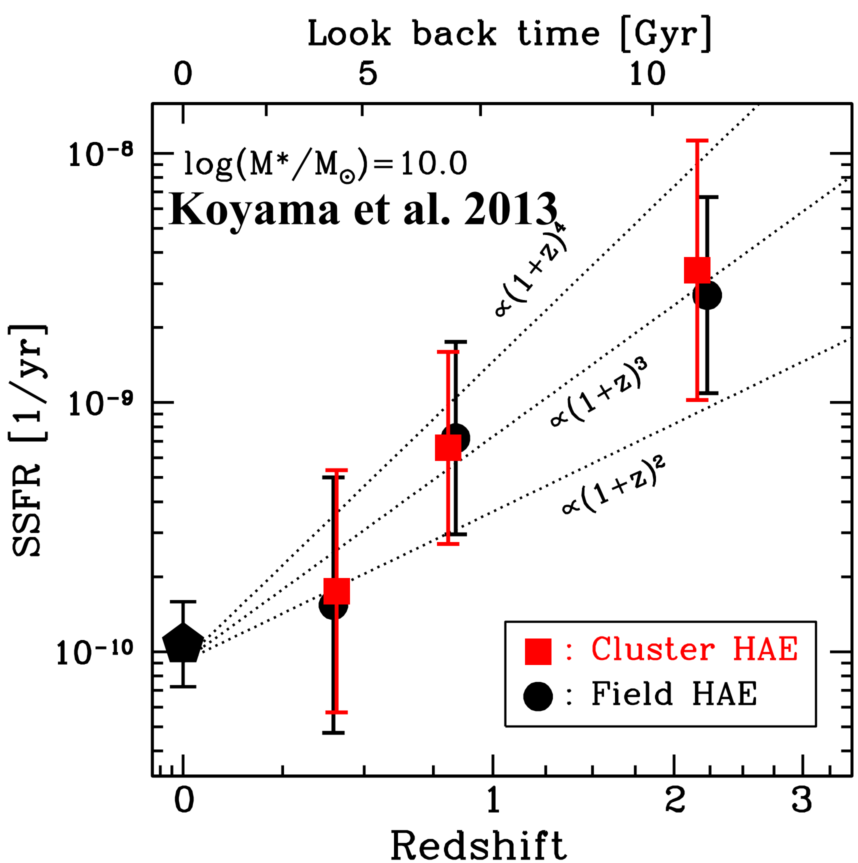
Sobral et al. 2014

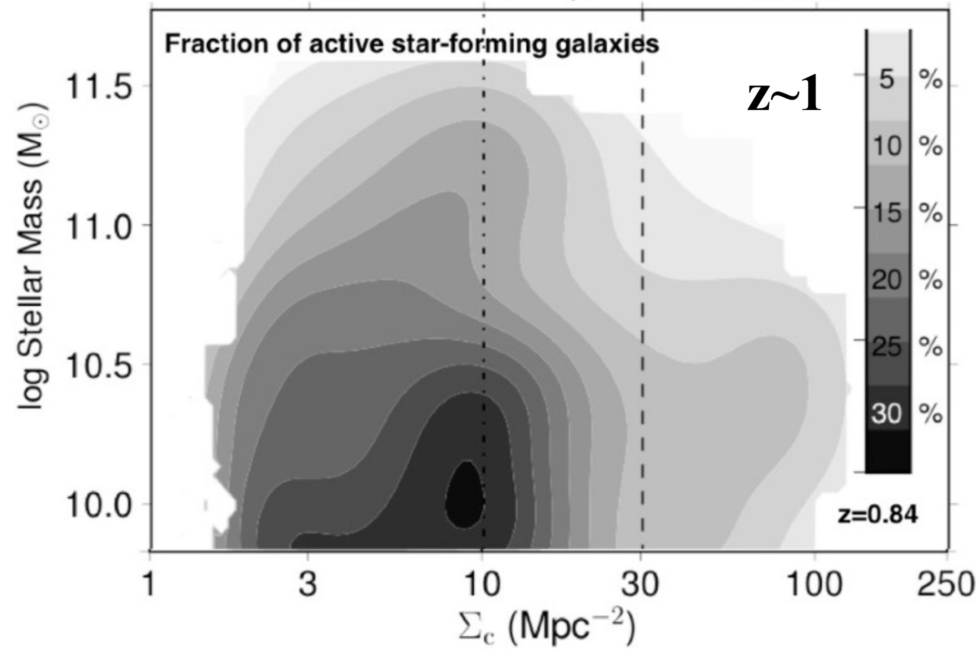


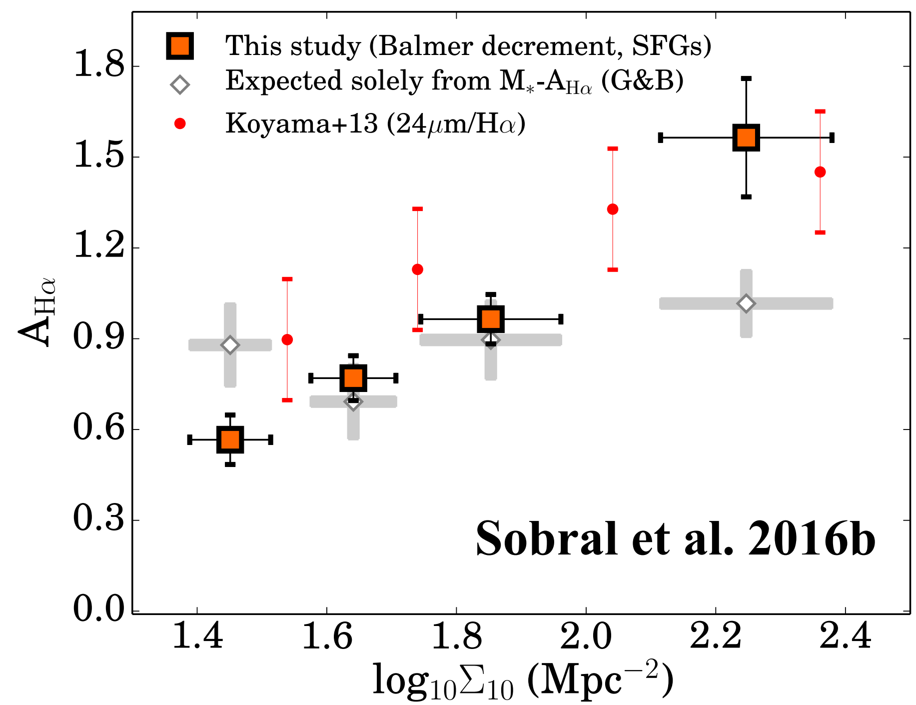
Results in the M*-SFR relation: e.g. Brinchmann+04; Noeske+07; Daddi+07; Elbaz+07

Strong evolution in Hα specific star-formation rates + EWs

Decline at ALL environments







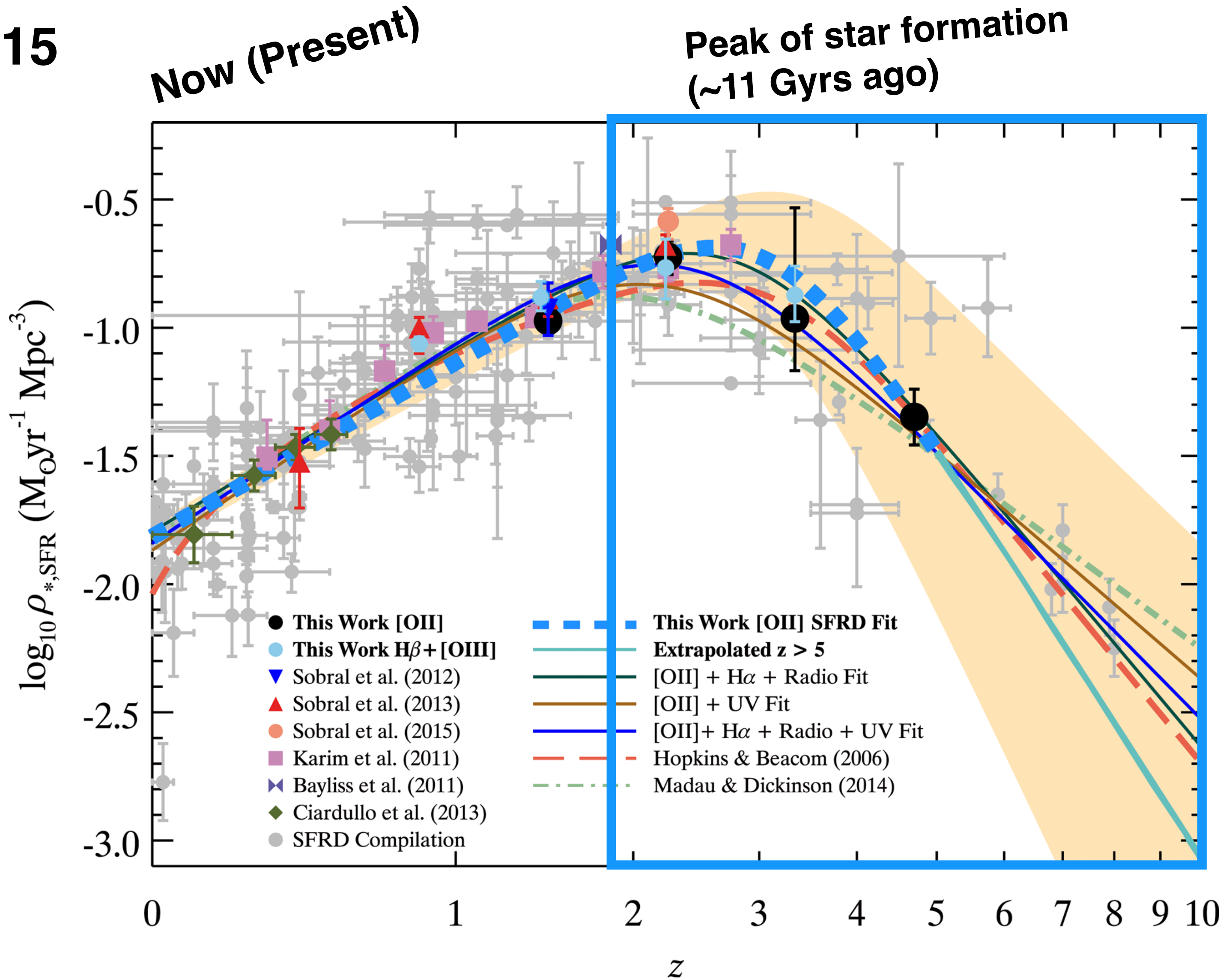
- Decline **also happens for all environments**: internal processes

See also e.g. Muzzin et al. 2012; Brodwin et al. 2013; Schawinski et al. 2014; Darvish et al. 2014

Star formation history of the Universe with emission-lines

Khostovan, Sobral+15

- Using single-technique, well-understood measurements, now with emission-lines, e.g. Hα and [OII] or [OIII] (not just UV or FIR)
- Large, multiple areas: overcoming cosmic variance

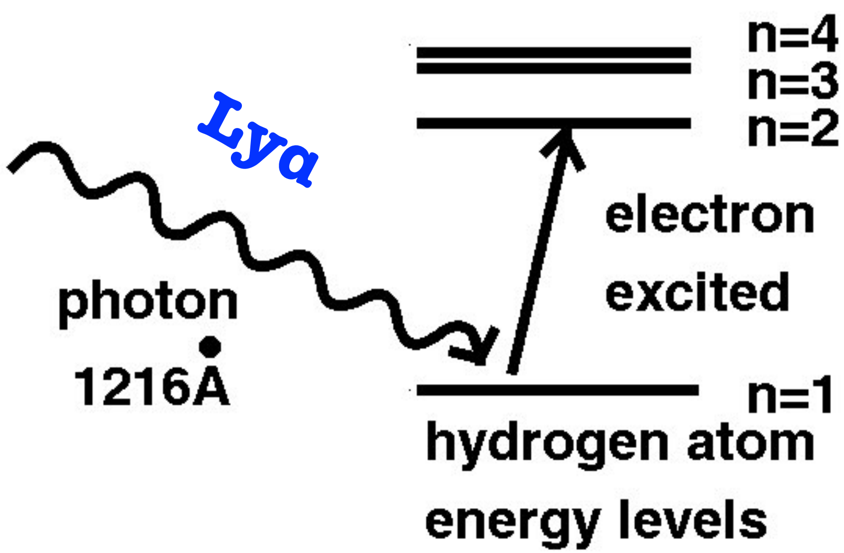


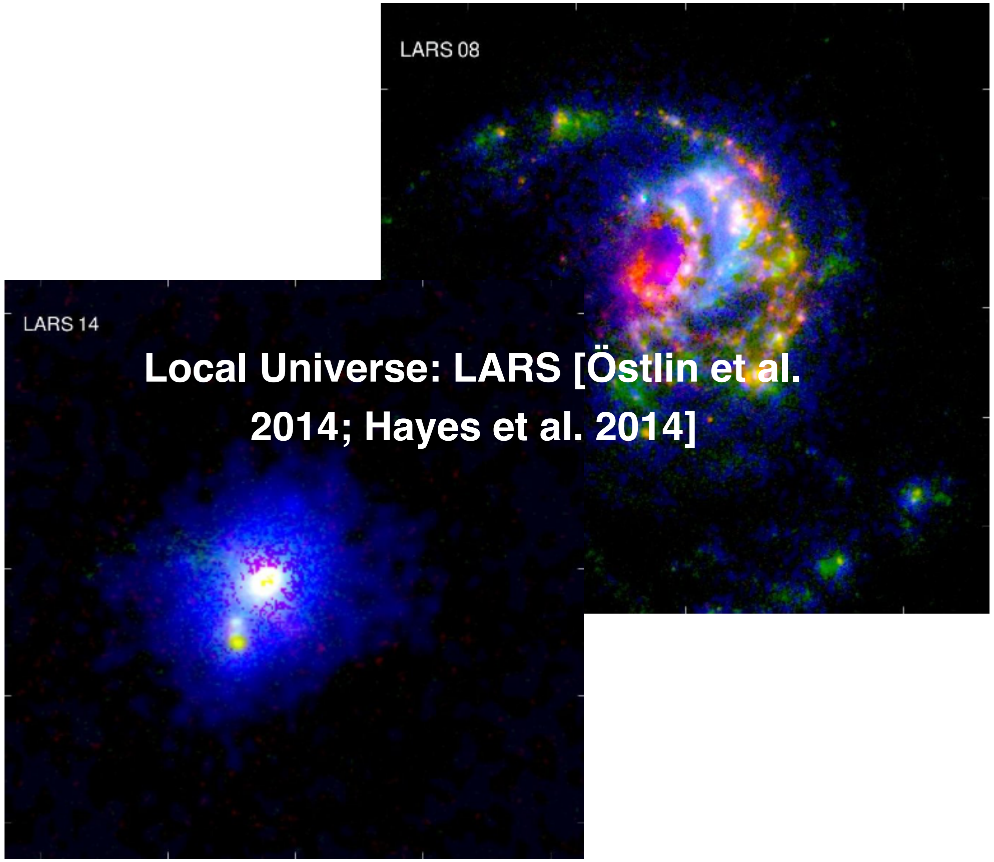
See also: Geach+08; Sobral+13a,14,15a; Karim+11; Madau & Dickinson14; Bouwens et al. 2015

Progress on simulations: e.g. Boylan-Kolchin et al. (2009); Hopkins et al. 2014; Vogelsberger et al. 2014; Schaye et al. 2015; Lacey et al. 2016

Lyα: currently **still** the best spectroscopic tool at z>2…

- 1216 Å redshifts into optical at z > 2
- Intrinsically most luminous emission-line in star-forming HII regions
- Easy to identify thanks to asymmetric shape
- Easy to select photometrically thanks to nearby Lyman-break





- Coupled with other UV lines for apparently very luminous sources, e.g. CIII], CIV, HeII)

See e.g. Stark+15,16; Stroe, DS et al. 2017a,b

Humphrey et al. 2007; Smith & Jarvis 2007; Ouchi et al. 2008; Matthee et al. 2014, 2015; Nilsson et al. 2009; Song et al. 2014; Oteo et al. 2015; Pentericci+2014; Hayes 2011; Dijsktra 2015; Verhamme+2015

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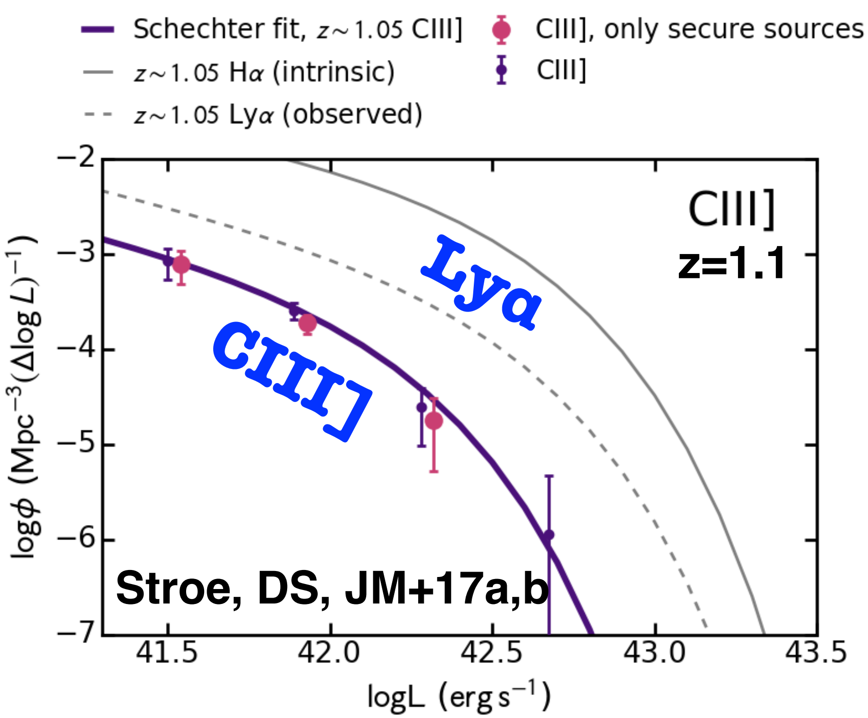

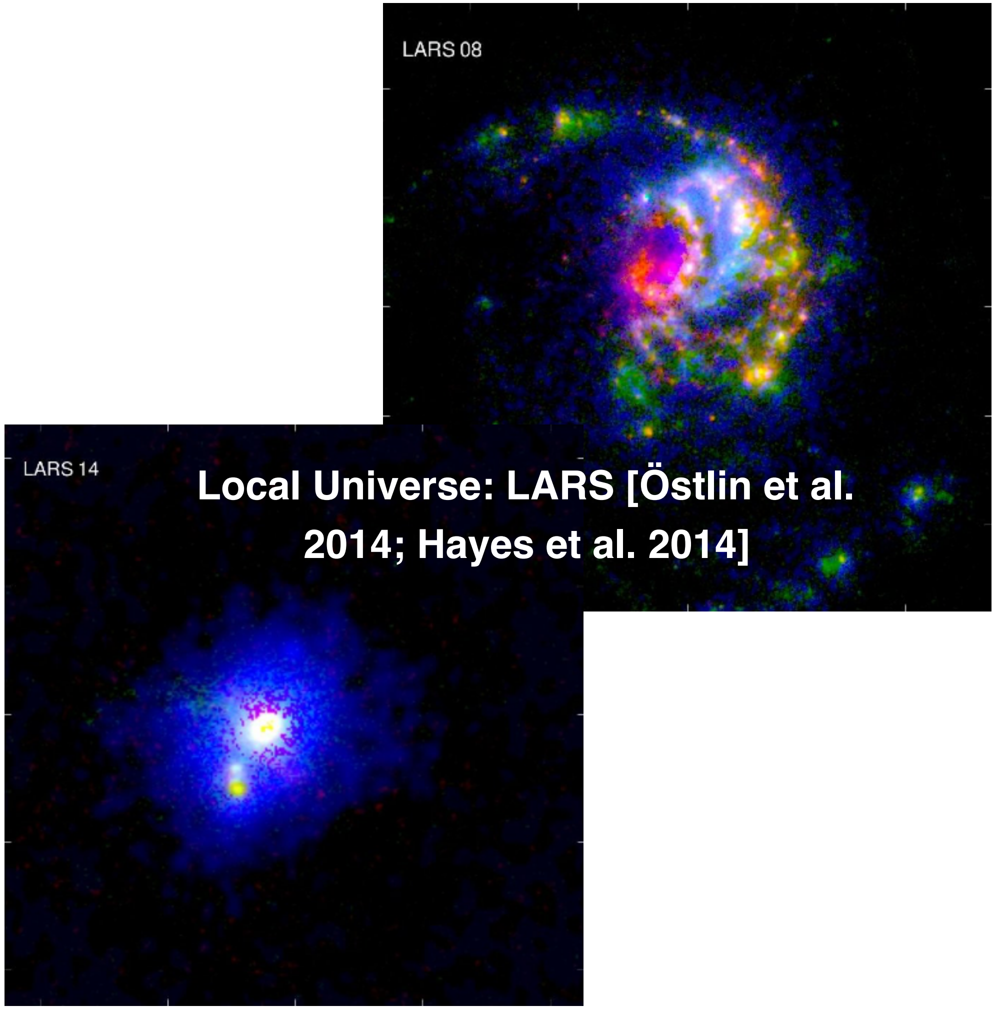

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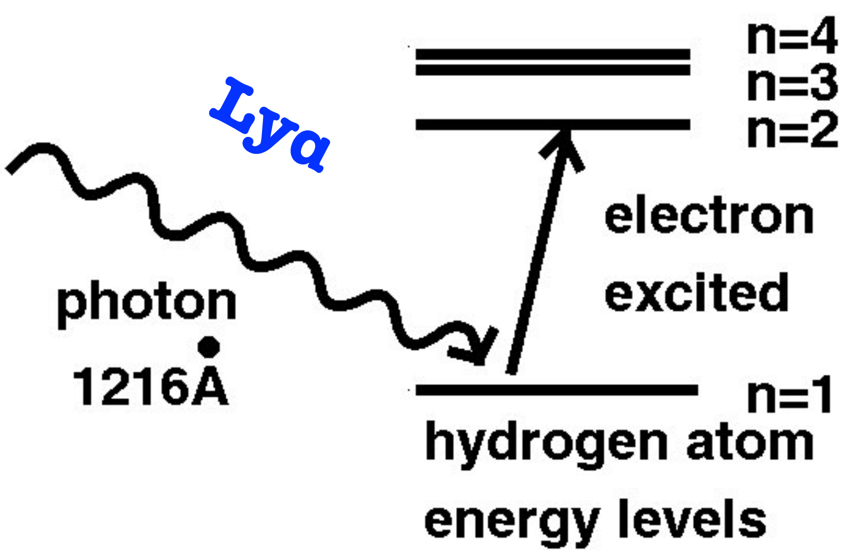
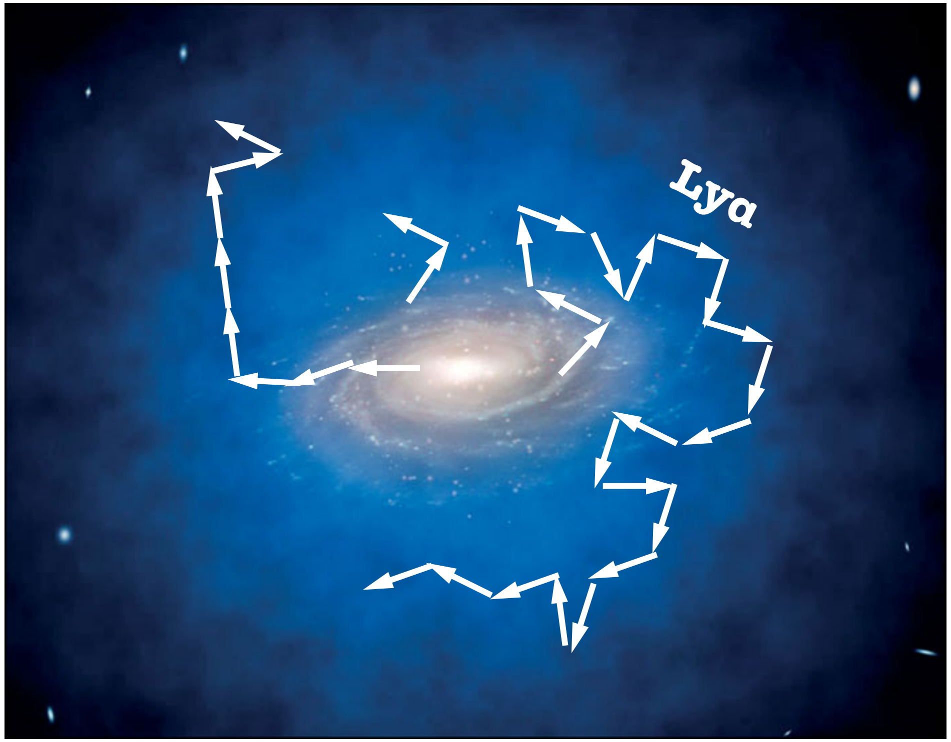
See e.g. Stark+15,16; Stroe, DS et al. 2017a,b

Lyα may seem like a low hanging fruit… but not so easy to eat

(sometimes not easy to get)!

- … easily scattered and re-emitted: most photons escape at low surface brightness
- Easily absorbed in the inter-stellar medium and intergalactic medium.
- Escape fraction not well understood
- Neutral IGM affects Lyα - hard to use at z>6





$f_{esc,Ly\alpha} = f_{Ly\alpha}/(8.1\text{-}9.0\ f_{H\alpha})$

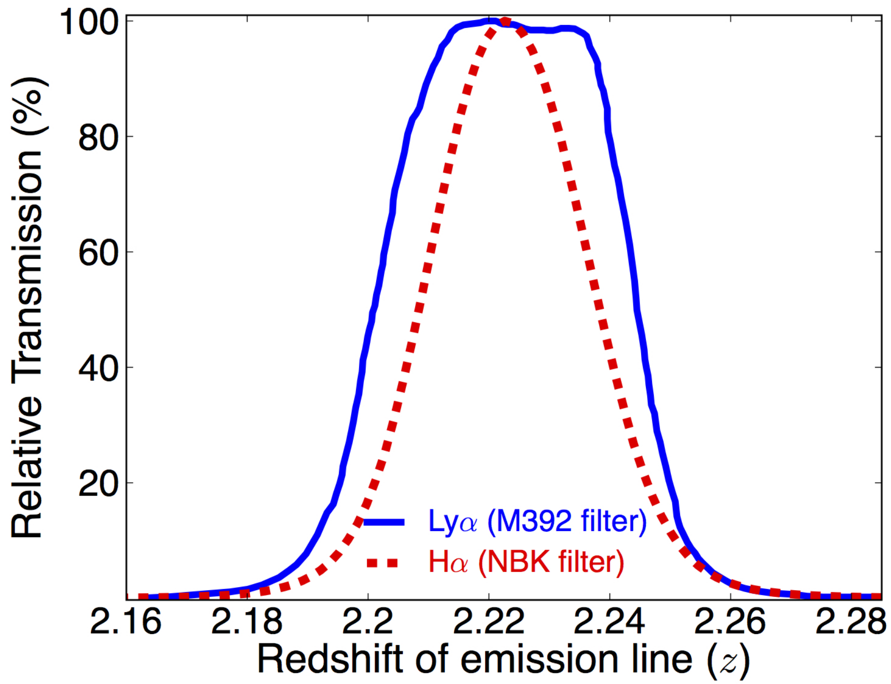
$f_{esc,\ Ly\alpha} = f_{Ly\alpha}/(8.7\ f_{H\alpha})$

- Only a small fraction of Lyα photons escape: Hα can be used to measure it

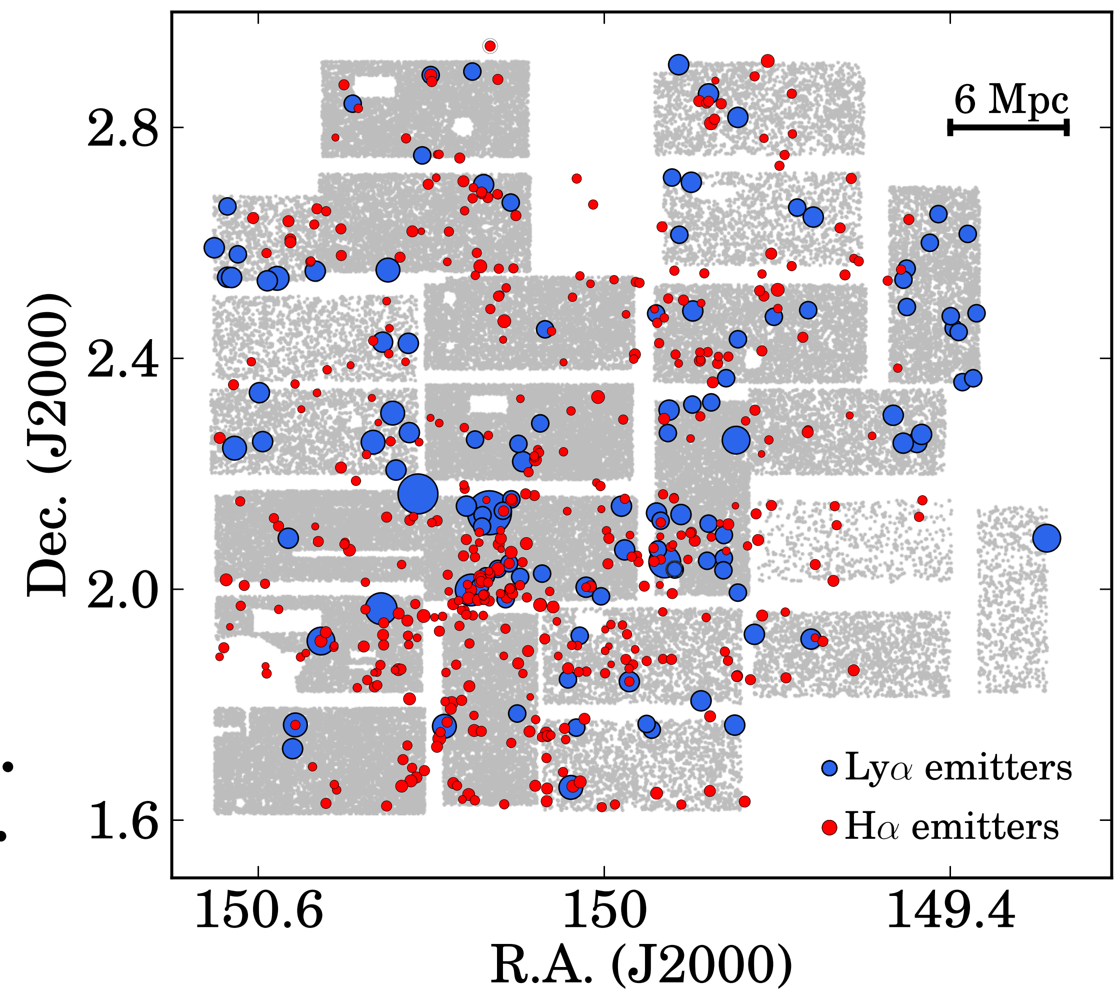
e.g. Hayes et al. 2010

The CALYMHA survey: CAlibrating LYman-α with Hα

- Custom-made narrow-band filter. **50 nights INT + 8 nights CFHT** (PI: Sobral)
- **<u>5 deg² deep double-blind matched Lyα-(CIV-OII-OIII)-Hα</u>** <u>(and LyC)</u> survey.



Hα from HiZELS



Already published: **Matthee, Sobral et al. 2016, 2017a,b**; **Sobral, Matthee et al. 2017a; Stroe, Sobral+2017a,b**

(<u>coming soon: Calhau et al.</u>)

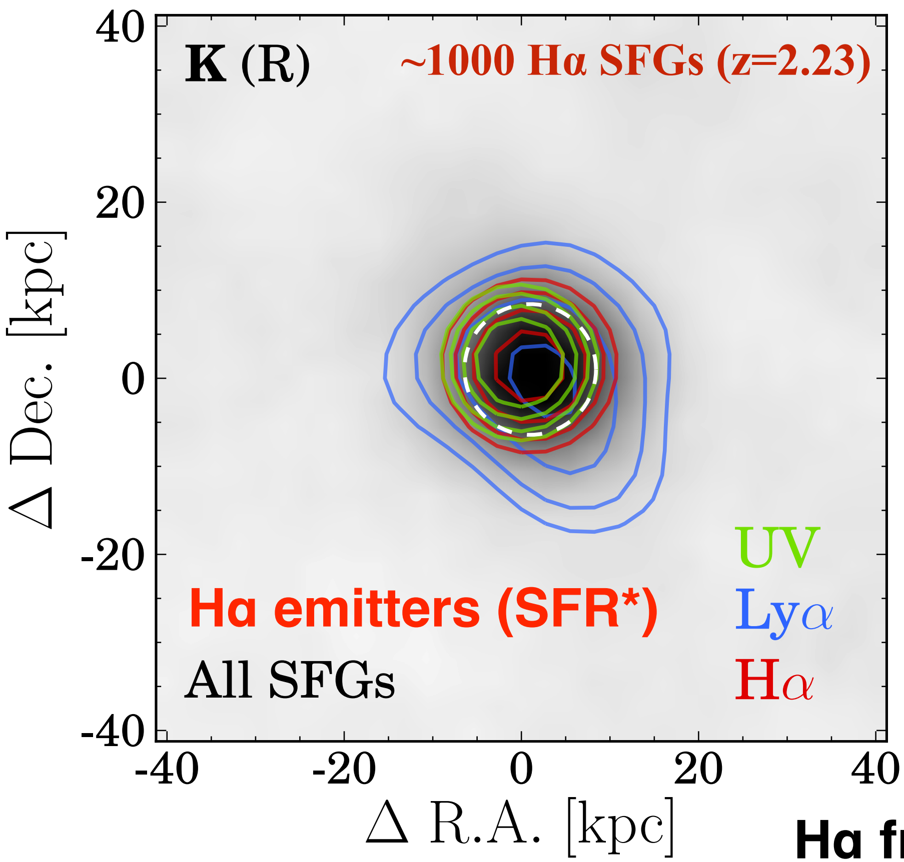
See also e.g. Hayes et al. 2010; Ciardullo et al. 2014; Oteo, DS et al. 2015

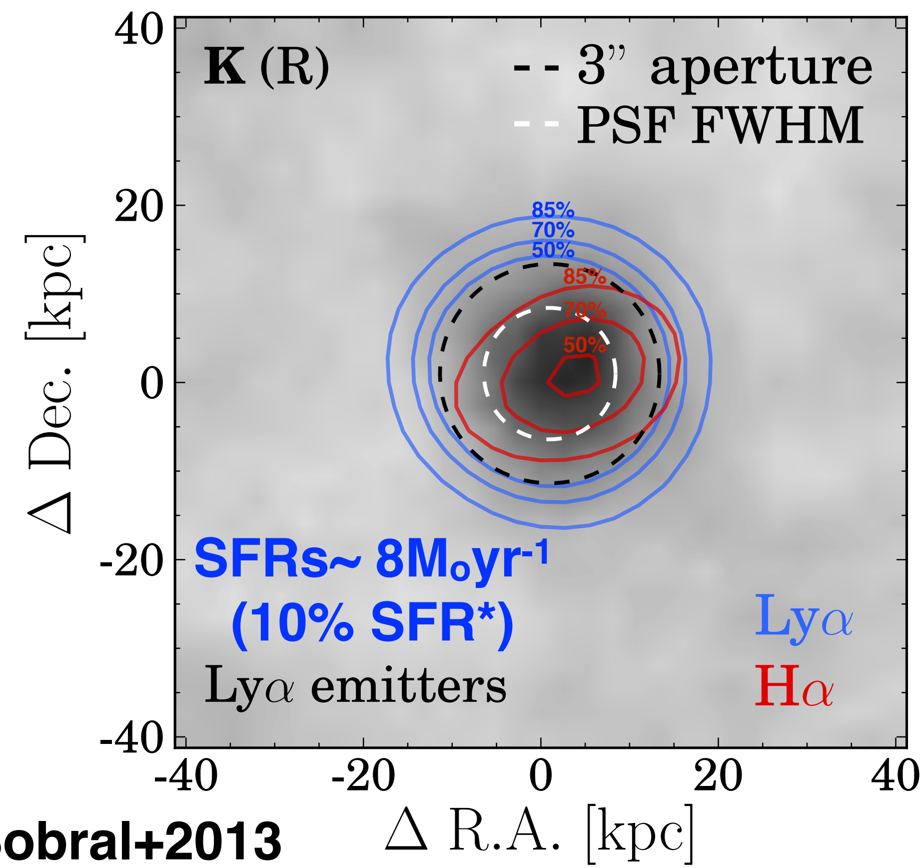
Extended (~40 kpc) Lyα emission in star-forming galaxies

Matthee, Sobral+16a, Sobral, Matthee+17a

Stack: 3000 hours (~MUSE-like depth)

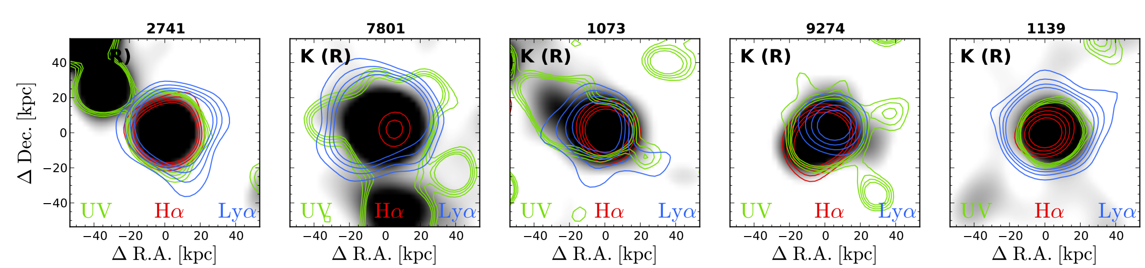
~200 Lyα emitters (z=2.23)





Hα from Sobral+2013

Use Hα to predict Lyα photons
then compare with observed Lyα

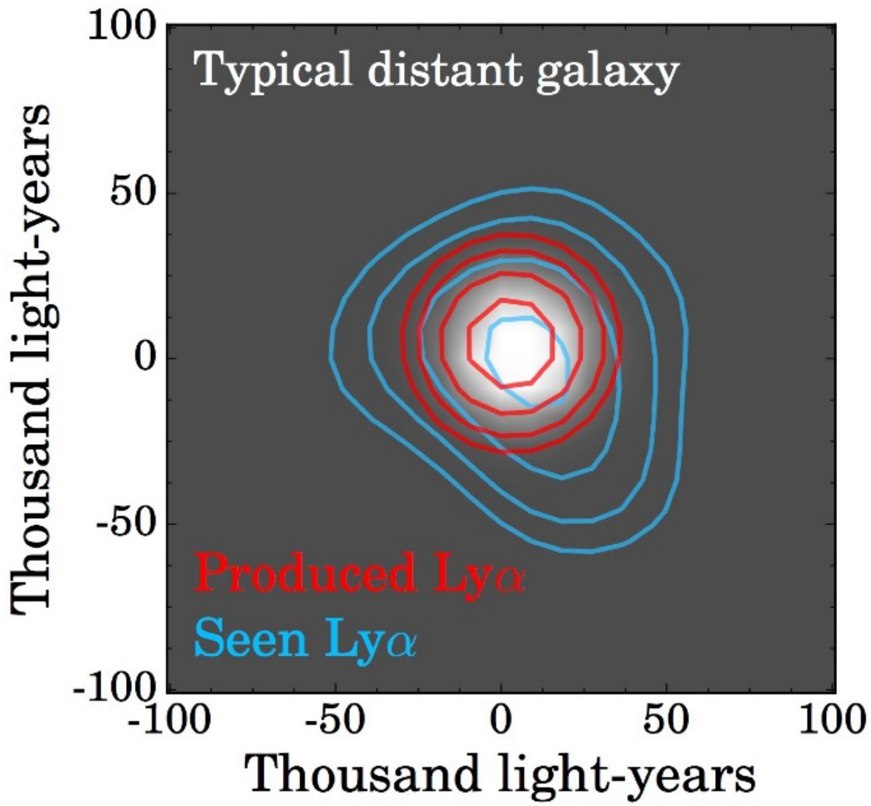


Also source by source

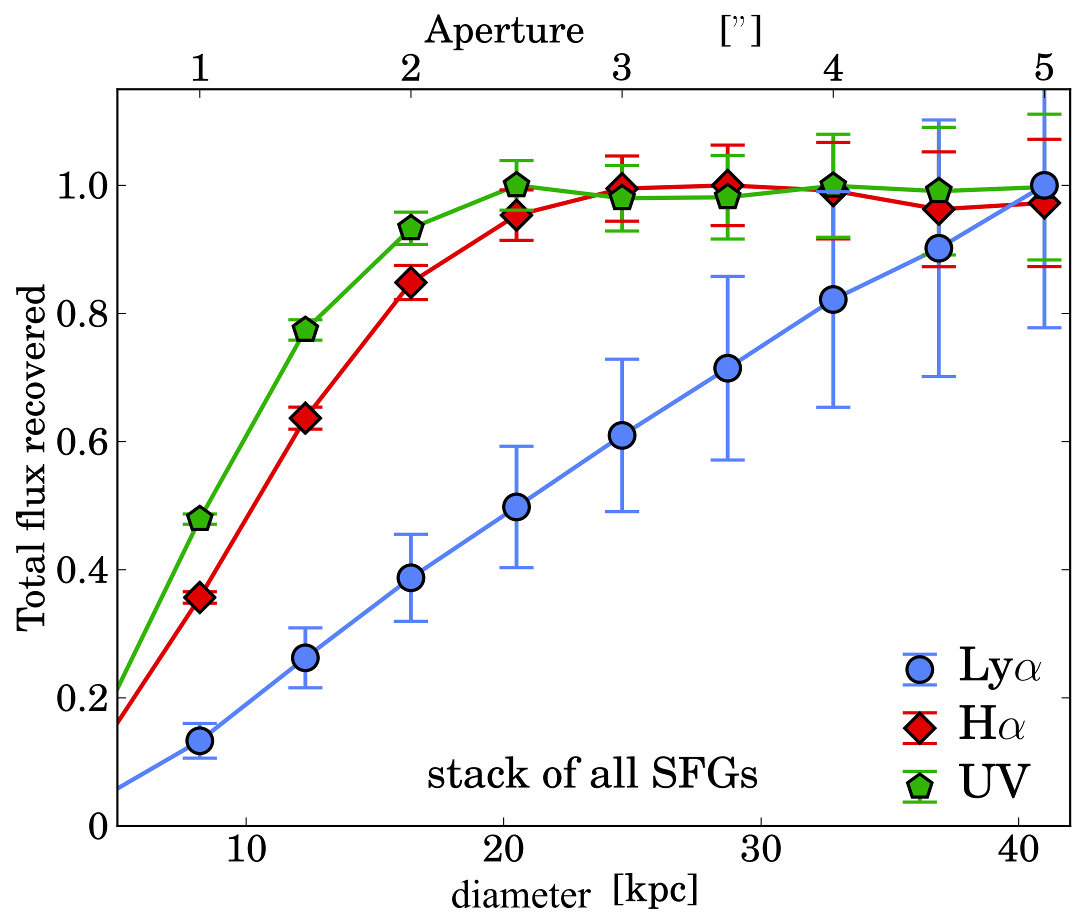
Extended (~40 kpc) Lyα emission in star-forming galaxies

Matthee, Sobral+16a, Sobral, Matthee+17a

Stack: 3000 hours (depth ~MUSE)



z=2.23 (~peak of star formation history)



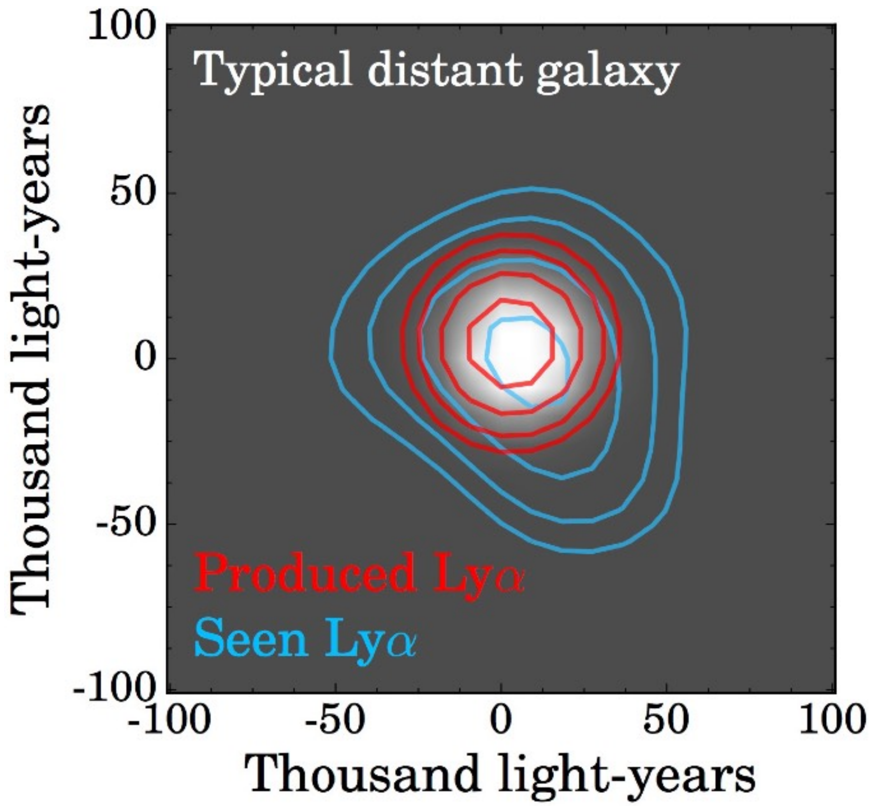
see also Nelson+16 3D-HST

Use Hα to predict Lyα photons then compare with observed Lyα

Extended (~40 kpc) Lyα emission in star-forming galaxies

Matthee, Sobral+16a, Sobral, Matthee+17a

Stack: 3000 hours (depth ~MUSE)



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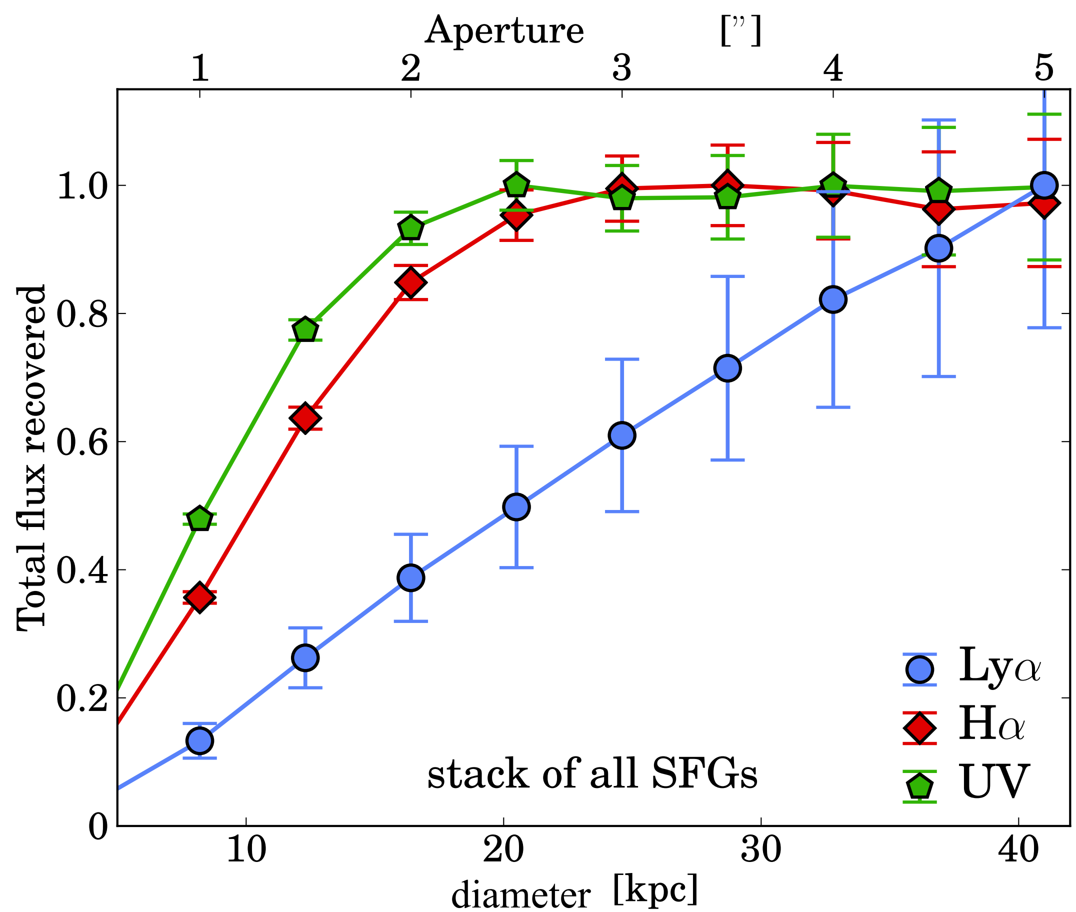


see also Nelson+16 3D-HST

Use Hα to predict Lyα photons then compare with observed Lyα

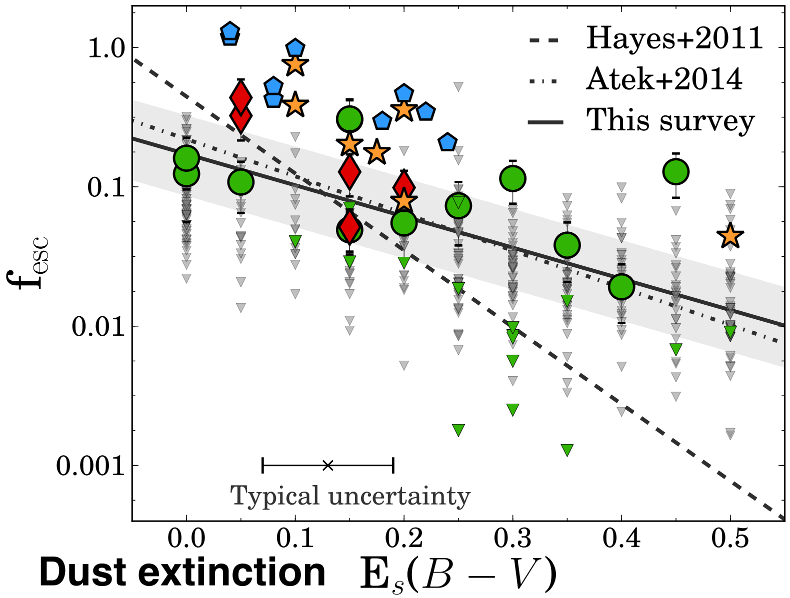
$f_{esc, Ly\alpha}=f_{Ly\alpha}/(8.7\ f_{H\alpha})$

- **Hα emitters: 1.6±0.5%** Lyα photons escape at < 25 kpc

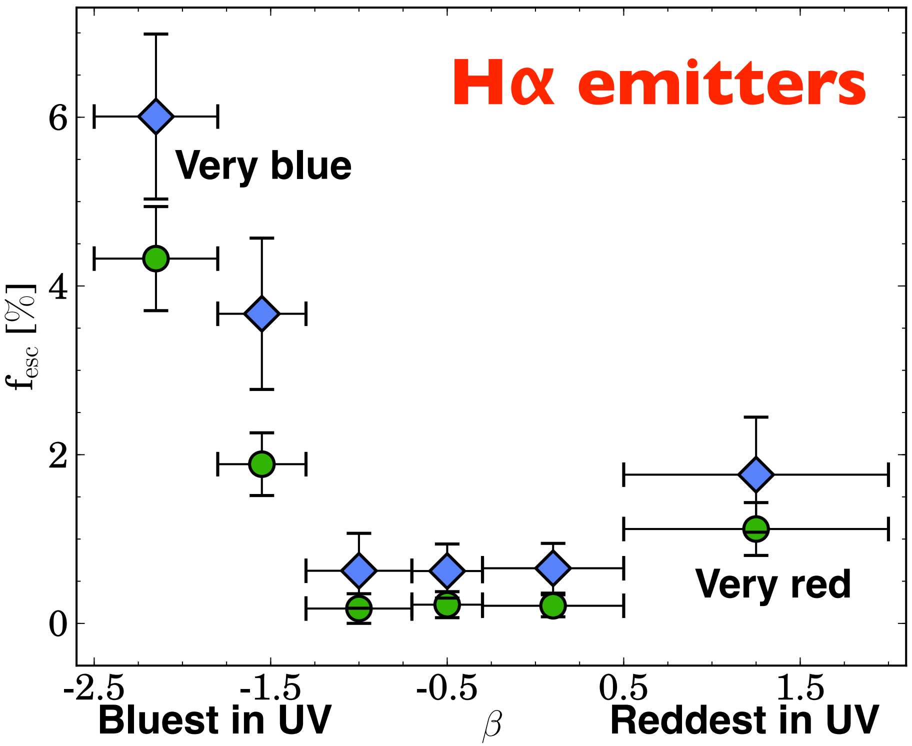
$f_{esc,Ly\alpha}= f_{Ly\alpha}/(8.1\text{-}9.0\ f_{H\alpha})$

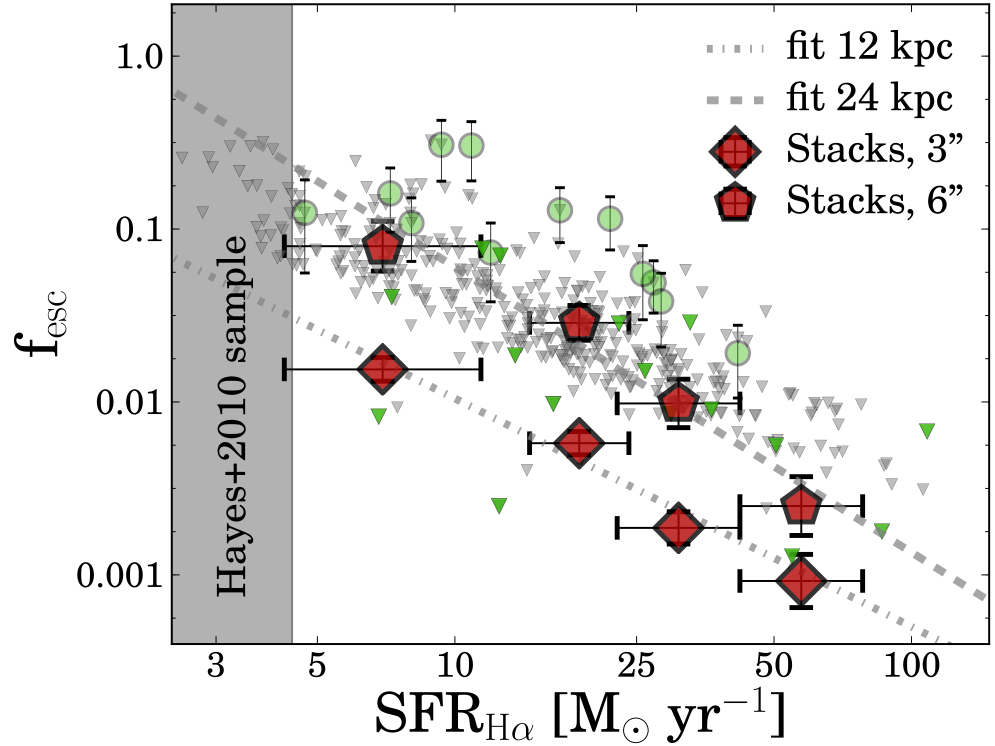
Escape of Lyα photons: what does it depend on at high z?

Matthee, Sobral et al. 2016



- Preferential escape of Lyα: **low to dust free star-forming galaxies**
- **But:** some heavily dust obscured sources with high escape fractions (e.g. sub-mm galaxies)



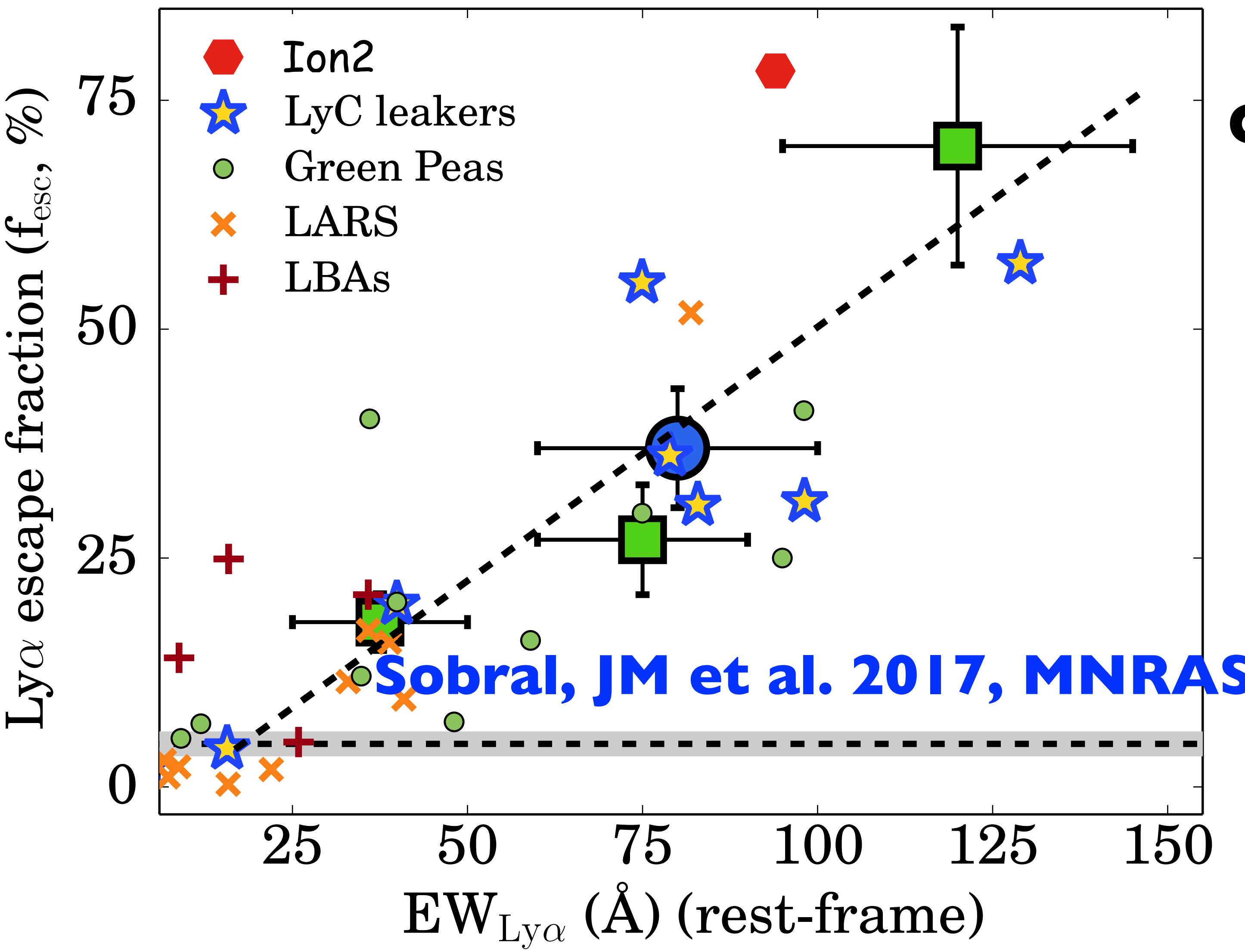


- Preferential escape from ultra-blue but also very red. Escape higher for low SFRs

Simplest predictor of Lyα escape fraction: EW_0 (+aperture)

- Lyα EW very good predictor of escape fraction. Not evolving from z~0

Measured from Lyα/Hα, not Lyα/UV



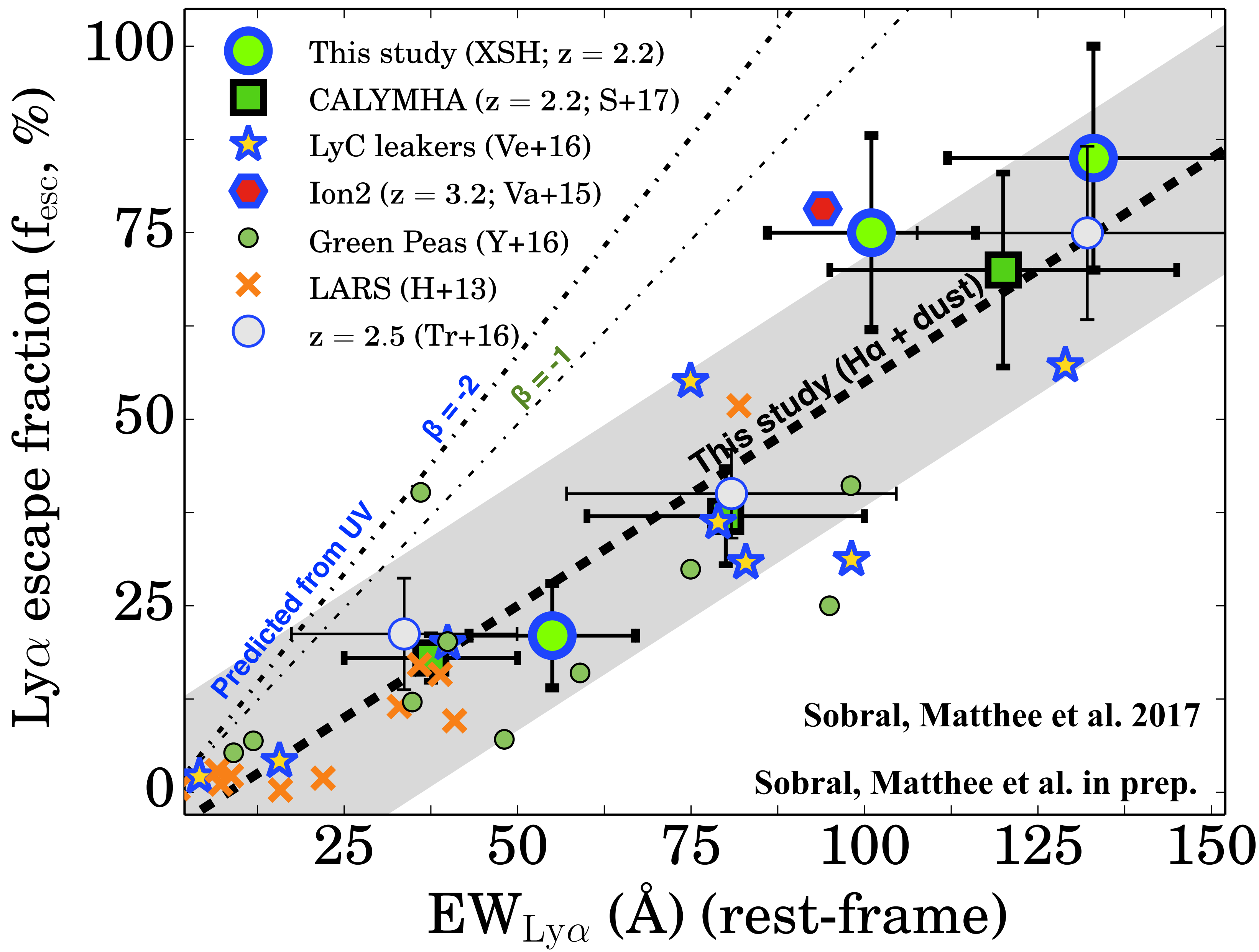
CALYMHA Lyα emitters

~No evolution from z~0 to z~2.2

- (High EW) Lyα emitters have higher LyC escape fractions (**Verhamme+17**)

Simplest predictor of Lyα escape fraction (Hα-calib): EW_0

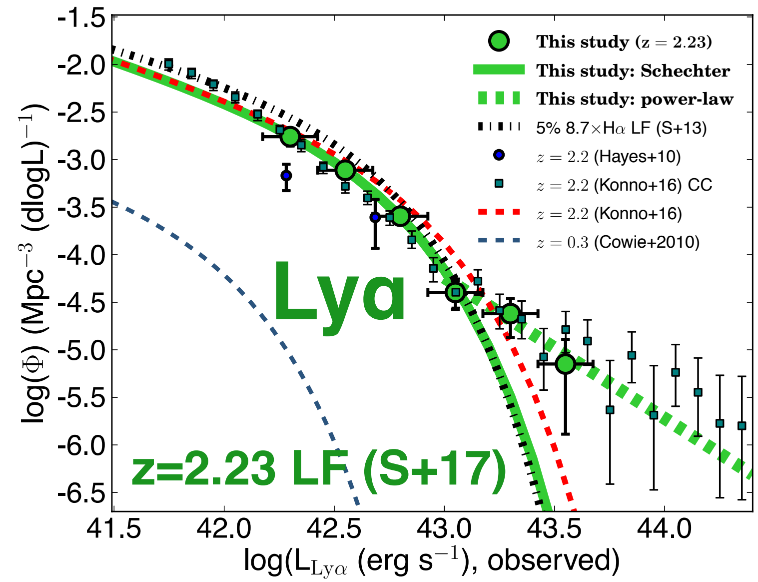
$$f_{\rm esc} = 0.006\,{\rm EW_0} - (0.05 \pm 0.15) \quad [\,5 < {\rm EW_0} < 175\,]$$



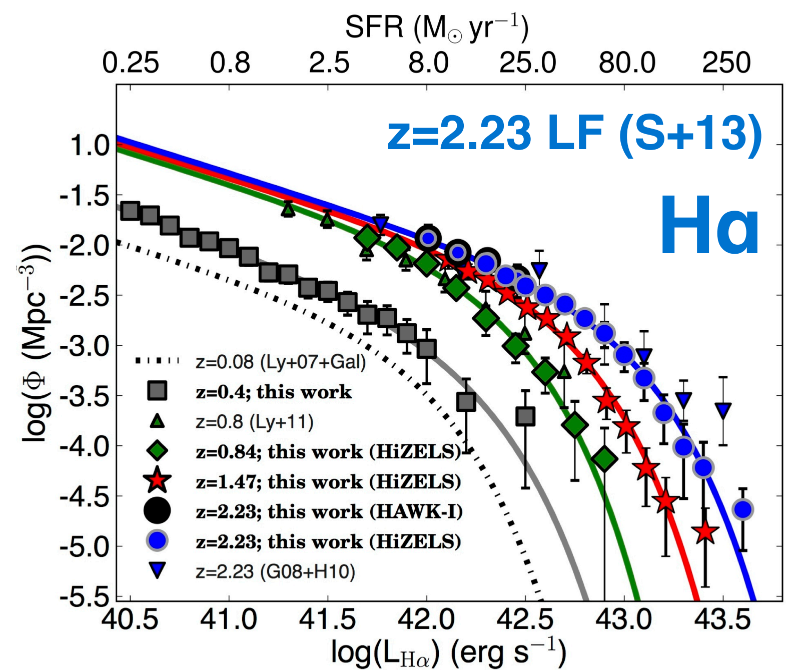
Global Lya escape fraction from SFGs at z=2.23 (Hα)

The CALYMHA survey: Lyα luminosity function and global escape fraction of Lyα photons at z = 2.23*

David Sobral[1,2]†, Jorryt Matthee[2], Philip Best[3], Andra Stroe[4]‡, Huub Röttgering[2], Iván Oteo[3,4], Ian Smail[5], Leah Morabito[2], Ana Paulino-Afonso[6,7]
[1] *Department of Physics, Lancaster University, Lancaster, LA1 4YB, UK*
[2] *Leiden Observatory, Leiden University, P.O. Box 9513, NL-2300 RA Leiden, The Netherlands*



- Global Lya f_{esc}: **5.1±0.2%** for <25 kpc
- Global Lya f_{esc}: **8.4±0.4%** for <40 kpc

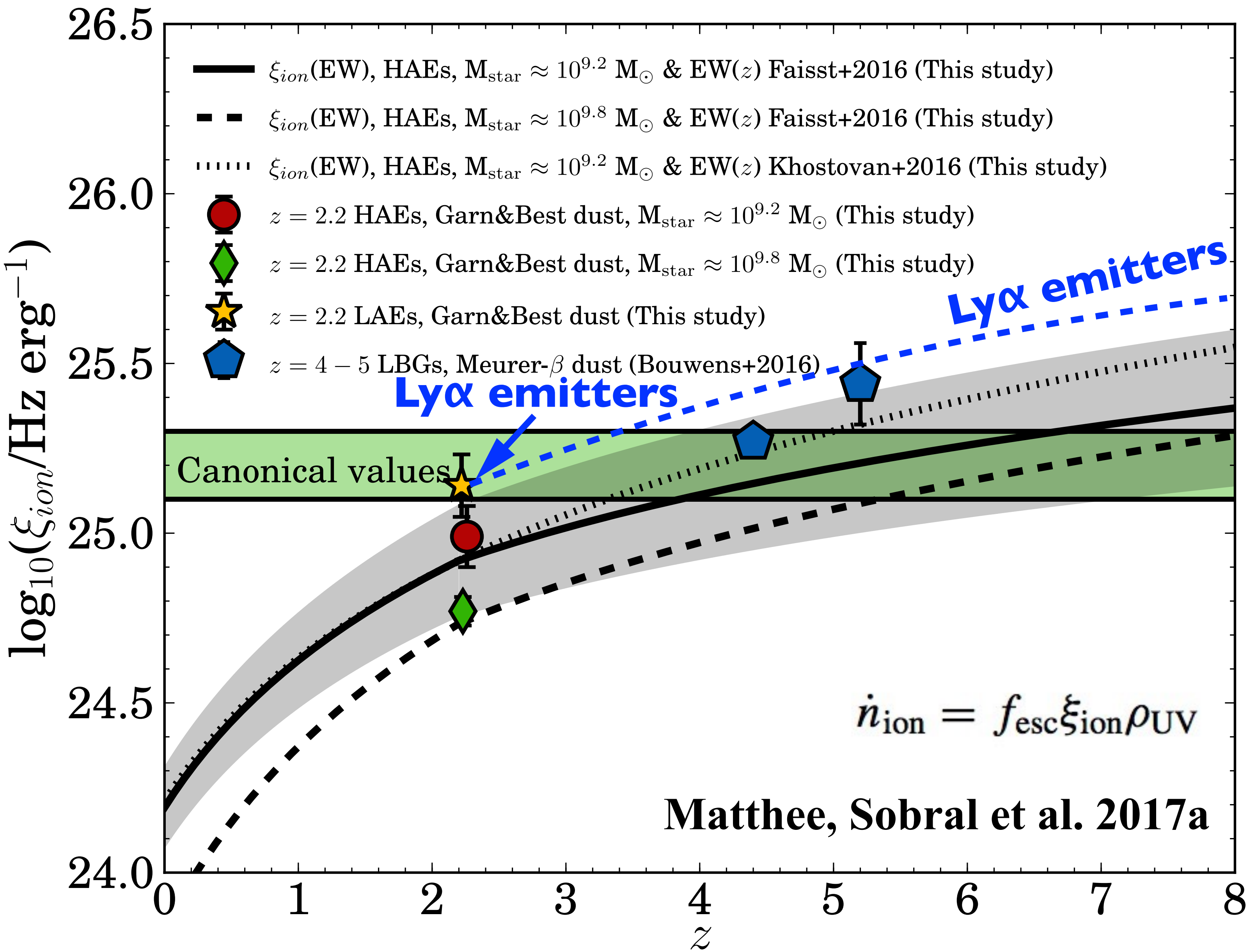


- Hα emitters: f_{esc} **1.6±0.5%** (<25 kpc)
- Lya emitters: f_{esc} **37±7%** (<25 kpc)
- Most Lya emitters consistent with up to Lya f_{esc} ~100% to even larger radii

Matthee, Sobral et al. 2016; Matthee, Sobral et al. 2017a; Sobral, Matthee et al. 2017a; Sobral+2013

Robust constraints on ξ_{ion} from Hα measurements (z=2.2)

- ξ_{ion} (LyC photons/UV) for typical SFGs (Hα selected): $\xi_{ion} = 10^{24.77\pm0.04}$ Hz erg^{-1}
- ξ_{ion} for **Lyα emitters ~0.3-0.4 dex higher** even at z~2: $\mathbf{10^{25.14\pm0.09}}$ **Hz erg^{-1}**

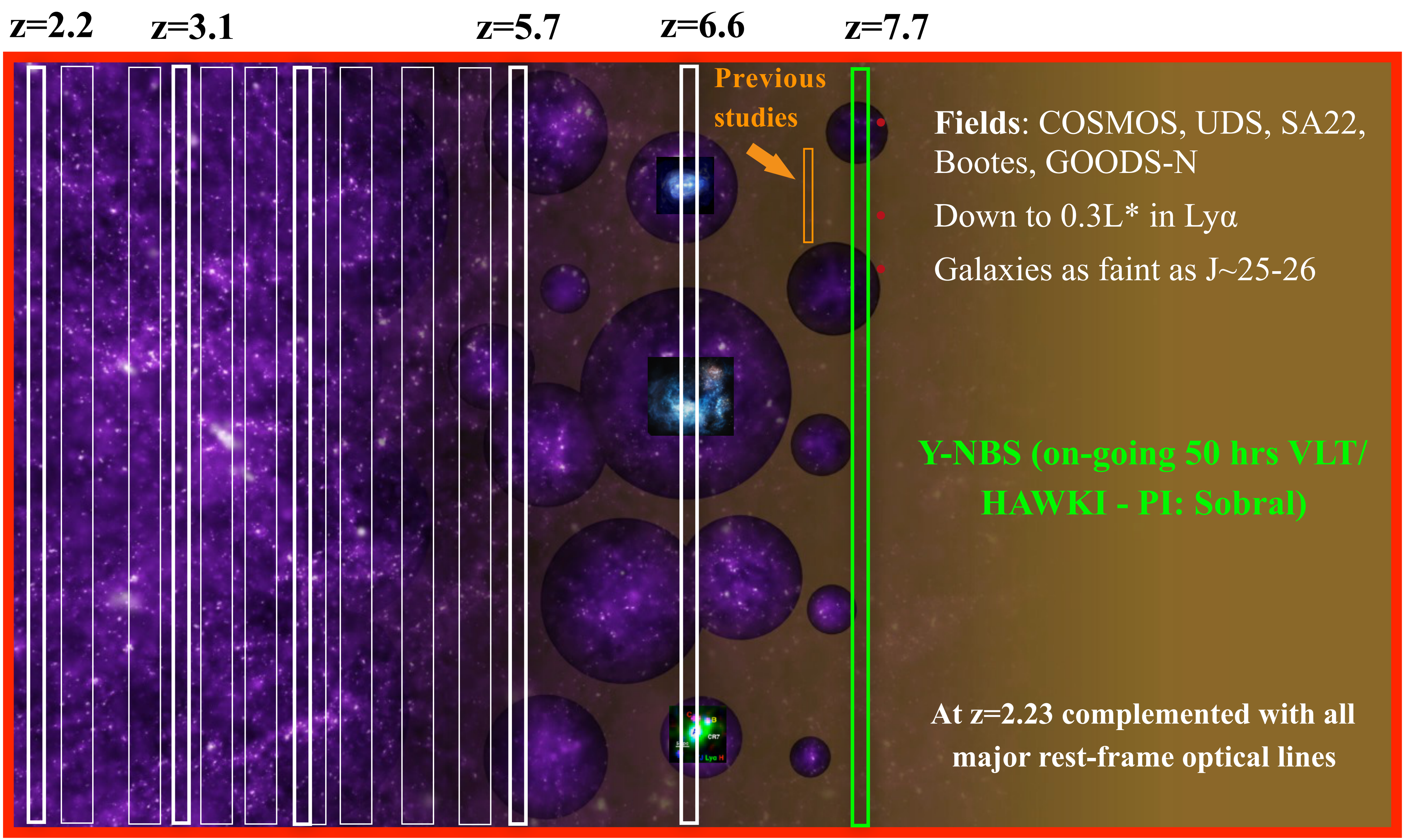


- ξ_{ion} correlates with Hα EW. Evolution of EW with redshift implies strong evolution of ξ_{ion}
- Lyα may **easily get to ξ_{ion} of $\mathbf{10^{25.7}}$ Hz erg^{-1}** at the epoch of re-ionisation

See also Nakajima+16

Our XGAL approach: **5-10 deg²** Lyα slices of the Universe

- **15 narrow and medium-bands** select redshifted Lyα emission from **z~2 to z~8**

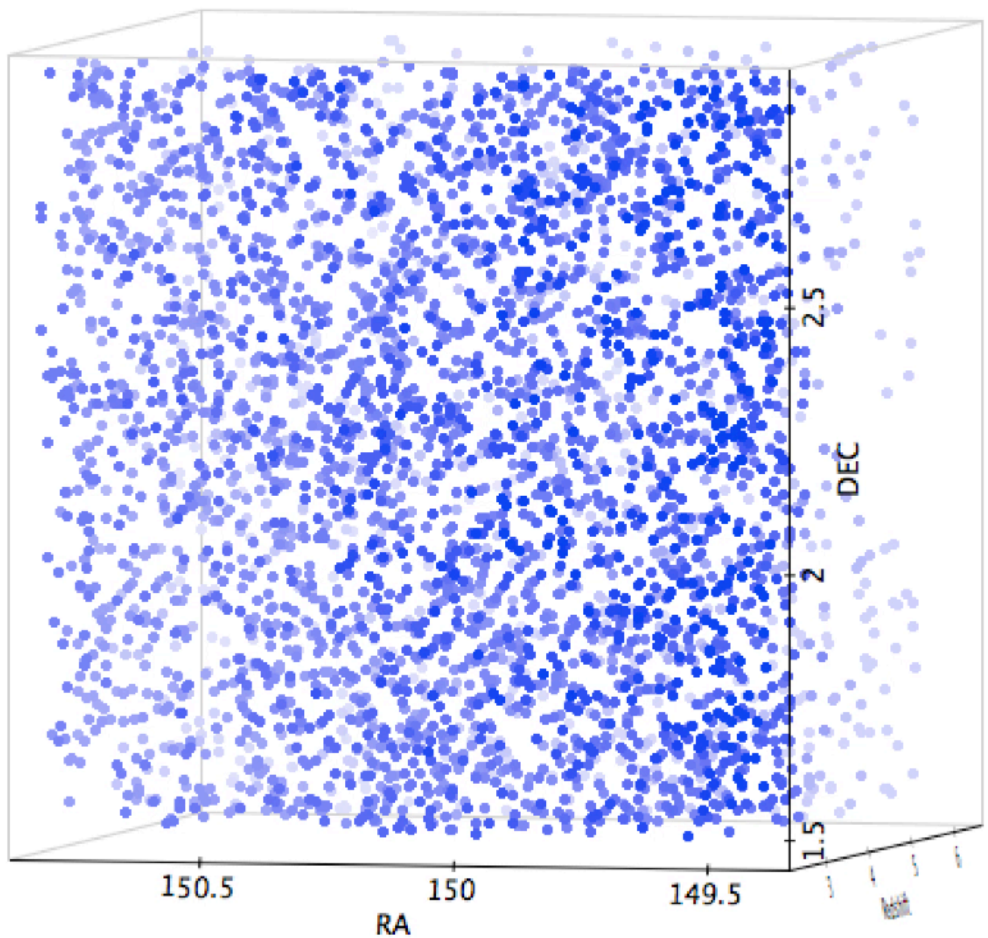


The Lyα sample: 4k Lyα emitters 2<z<6 in COSMOS

- SC4K: Slicing the COSMOS in 4K sample (Santos, DS+ in prep)

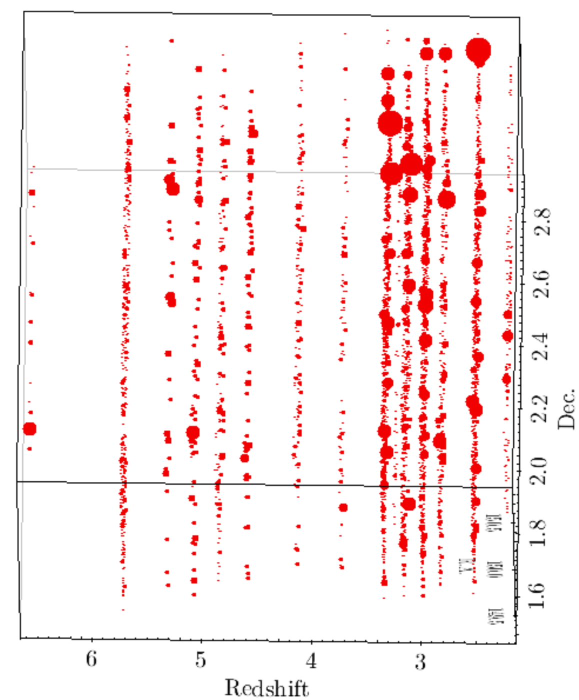
<u>**15**</u> narrow/medium bands => **~4000 Lyα emitters:** 2<z<7 in the **COSMOS** field

Lyα emitters: low cost Mega-MUSE



All having e.g. HST ACS + Herschel + ~30 bands

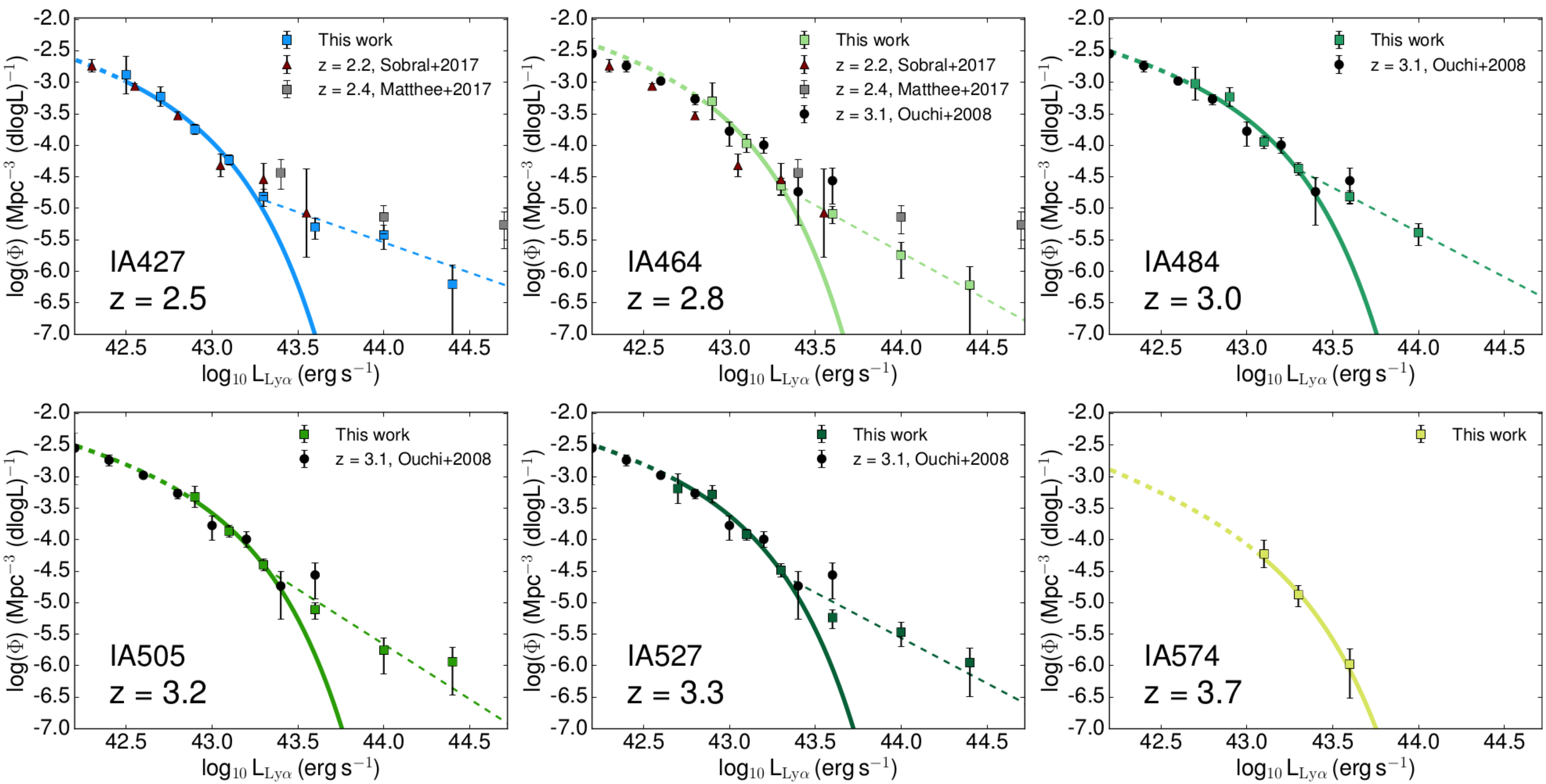
+1000s of other line emitters



+Y-NBS (on-going 50 hrs VLT/HAWKI - PI: Sobral)

Evolution of the Lyα luminosity function: census

- <u>Spectroscopically confirmed power-law</u> at z~2-3 (**Sobral+17a; Matthee+17b**), then declines towards z>4 (evolution of X-ray AGN population)



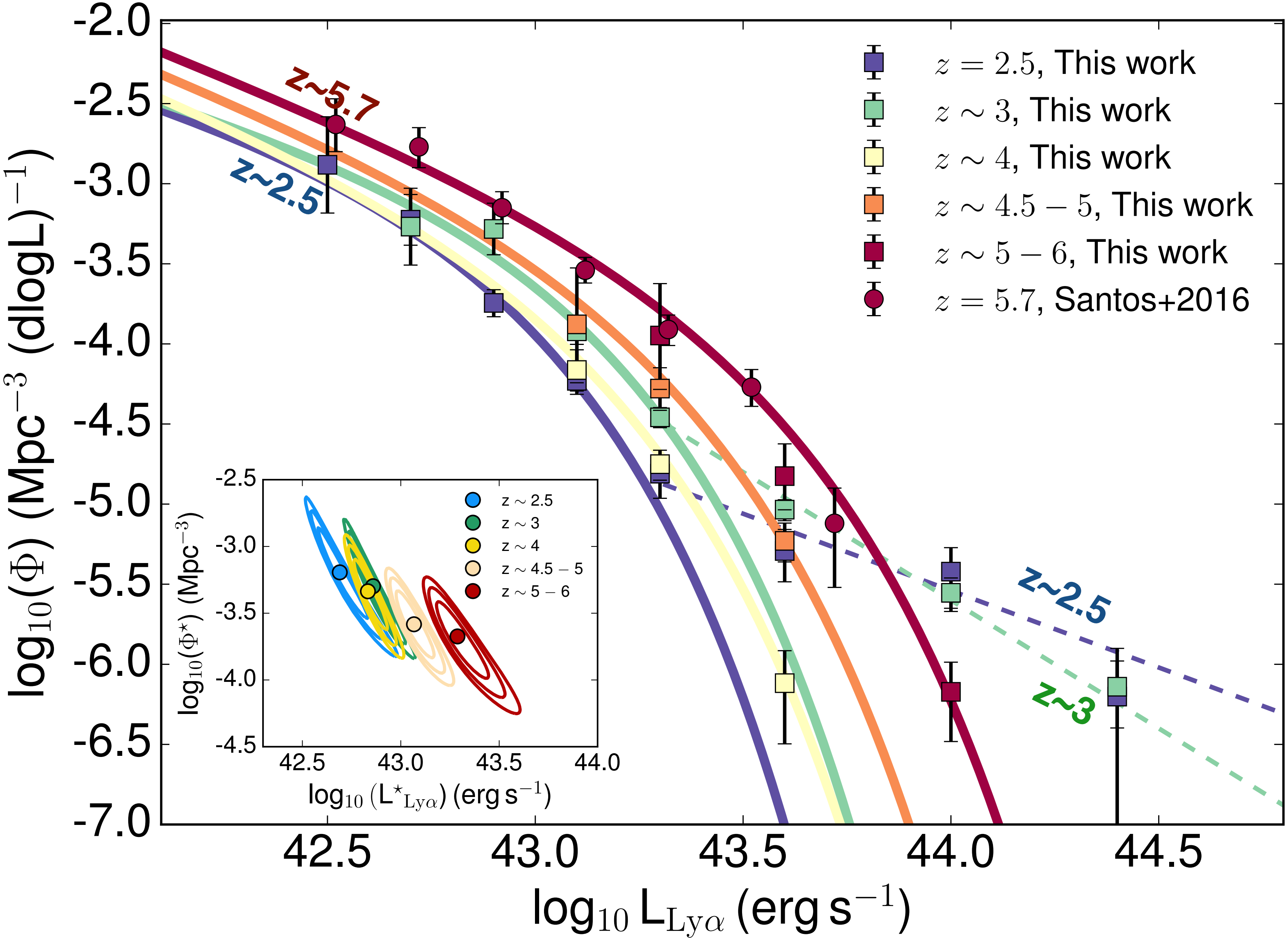
Matthee, Sobral+17b; Sobral, Matthee+17a

- SC4K: Santos, DS+ in prep

Evolution of the Lyα luminosity function: census

<u>Steep</u> faint-end slope α~ -2 (Dressler et al. 2015**; Santos, DS & JM 2016**).
Evolution from z~2 to z~3 then evolution to z~6.

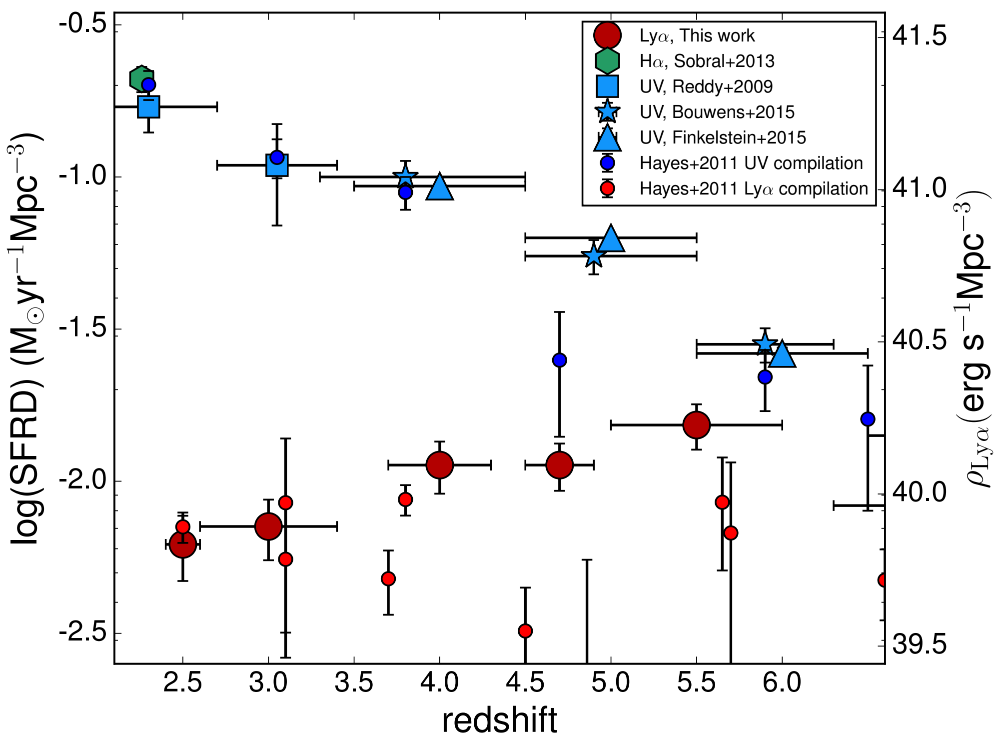
- SC4K: Santos, DS+ in prep



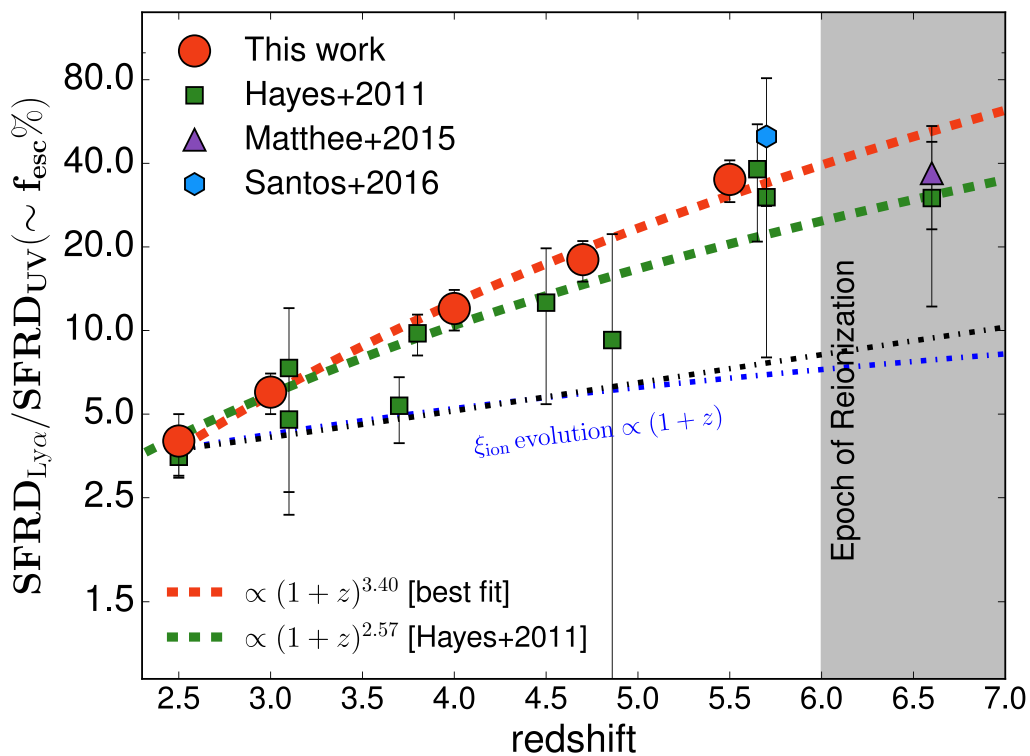
More Lyman-α per UV luminosity density at higher redshift

- Comparing Lyα with UV luminosity densities (e.g. Hayes+2011). Roughly same Lyα luminosity density while there is less UV luminosity density.
- Rise: higher escape fractions? Younger, less dust, higher ionisation parameters?

Santos, DS+in prep.



Both ξion and Lya f_{esc} increase with z



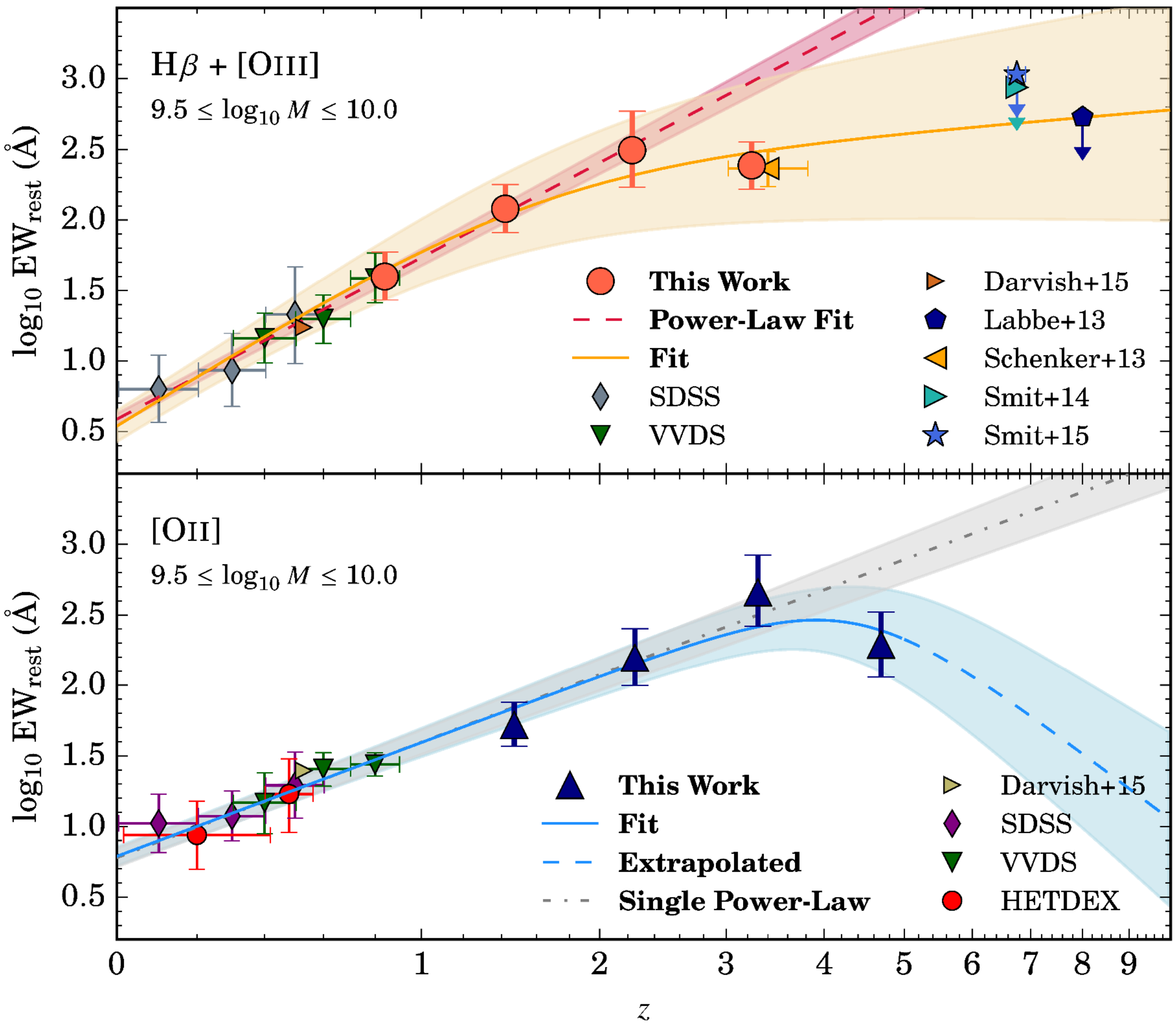
See also: Hayes et al. 2011; Stark+2017; Zheng+2017; Santos+2016; Matthee+2015, 2017a

High-z galaxies (line-emitters) have **high typical EWs**

Imply very <u>high ionisation parameters</u>, <u>low metallicities</u> + “extreme” stellar populations

Khostovan, Sobral+2016 [HiZELS]

see also Suzuki+17 (arXiv:1709.06731)



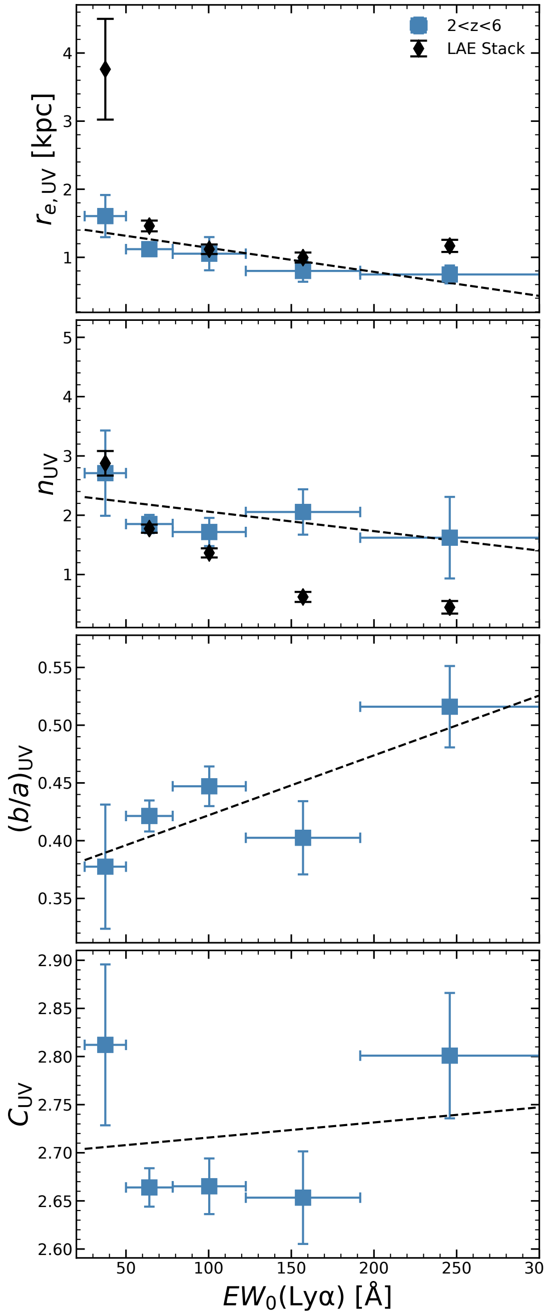
See also: Sobral+14; Smit+14; Marmol-Queralto+15; Nakajima+16; Holden+16; de Barros+16; Stark+16;

Low redshift analogues (super-rare): Izotov+2016; Borthakur+; Schaerer+16

<u>Rise and decline in [OII]?</u>
Consistent with low redshift analogues Schaerer+16

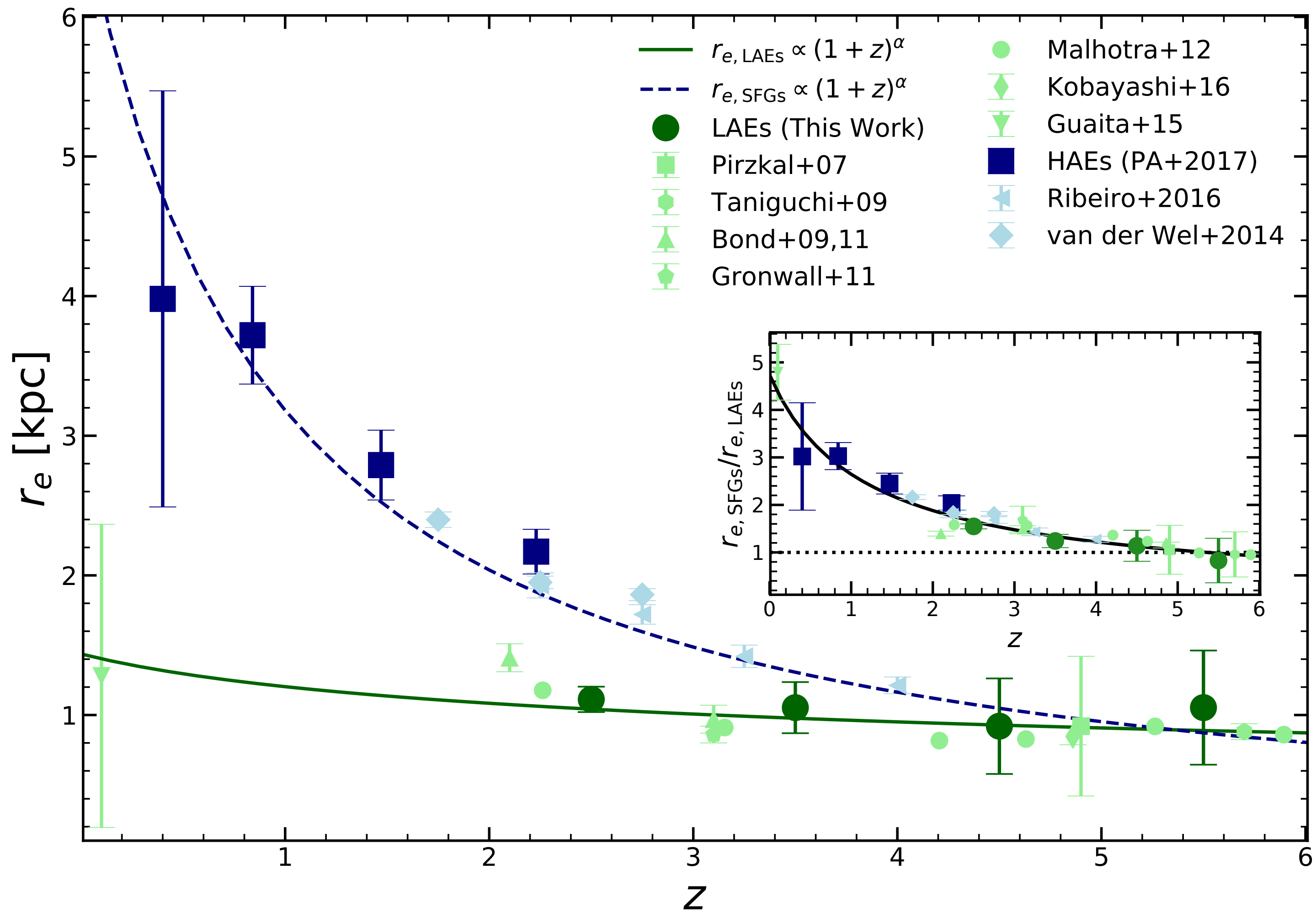
JWST will test this

Extra evidence for “emission-line selection unification”



On the UV compactness and morphologies of typical Lyman-α emitters from $z \sim 2$ to $z \sim 6$

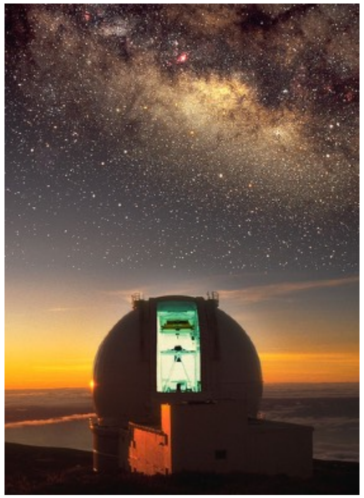
Paulino-Afonso, DS+2017, arXiv:1709.04470

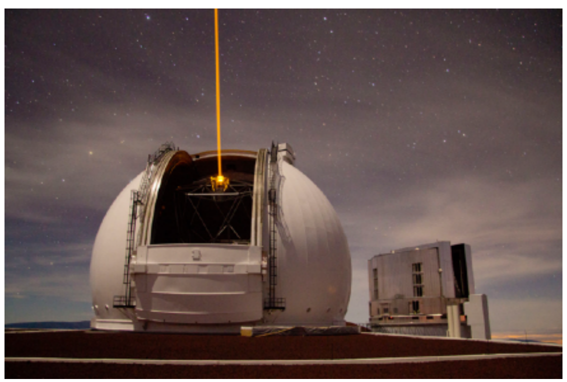


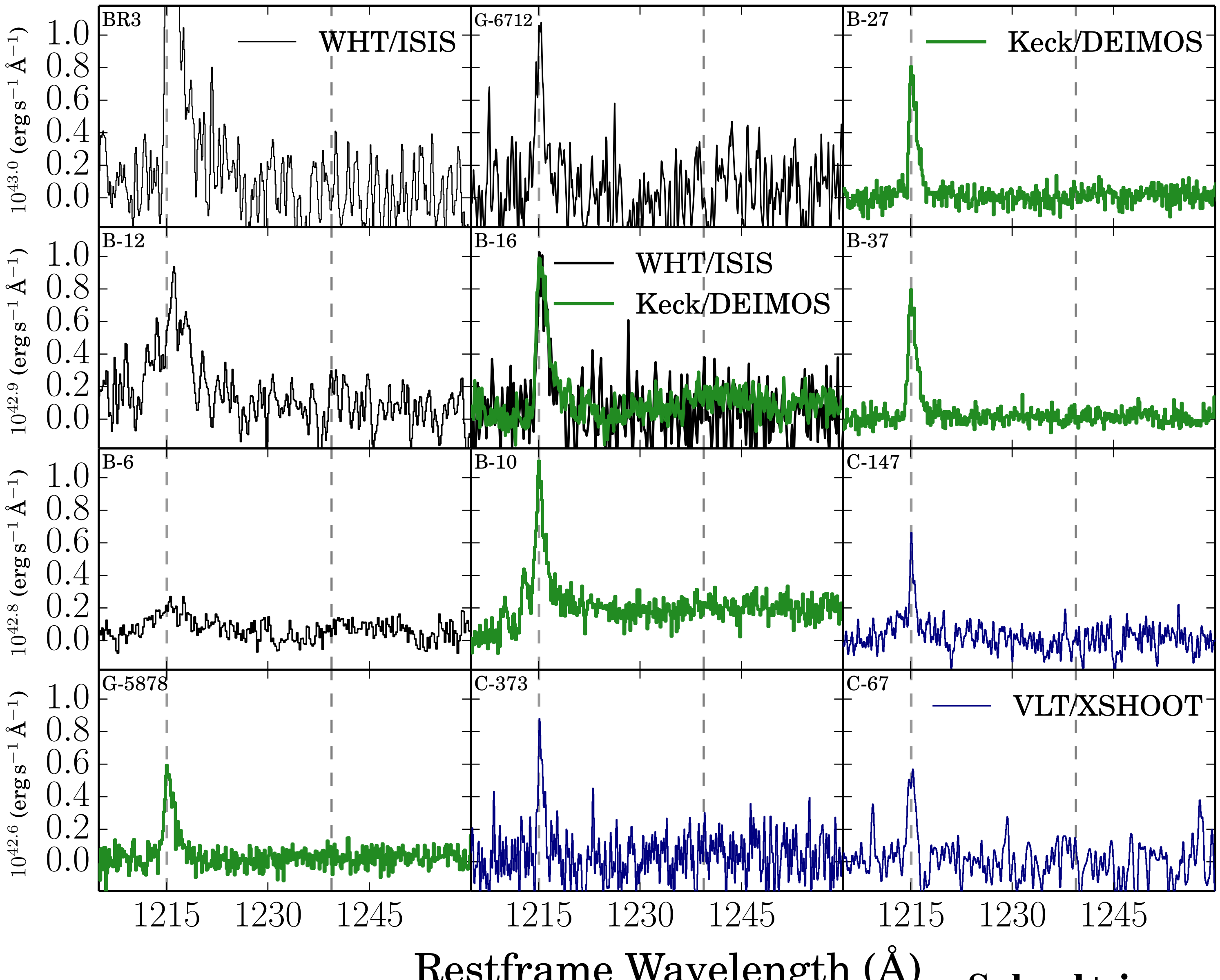
Lyα emitters always small/compact across time (~1 kpc)

Pushing our understanding further with spectroscopy at z~2-3

- Luminous Lyα + high-ionisation UV lines + CLOUDY large grid

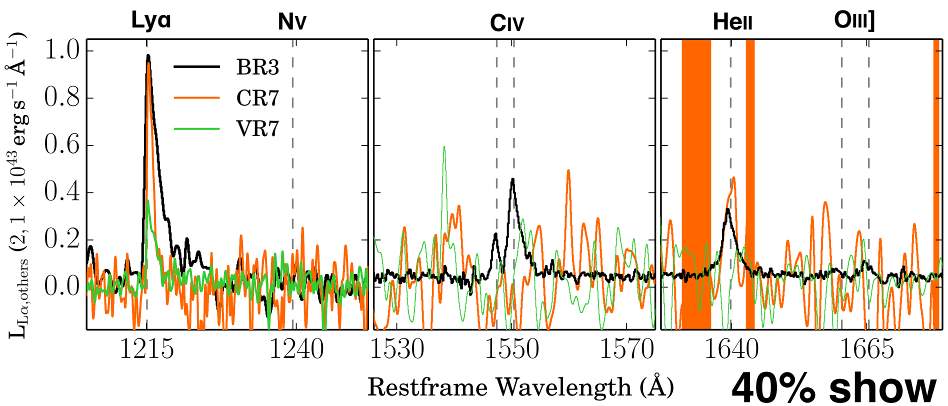




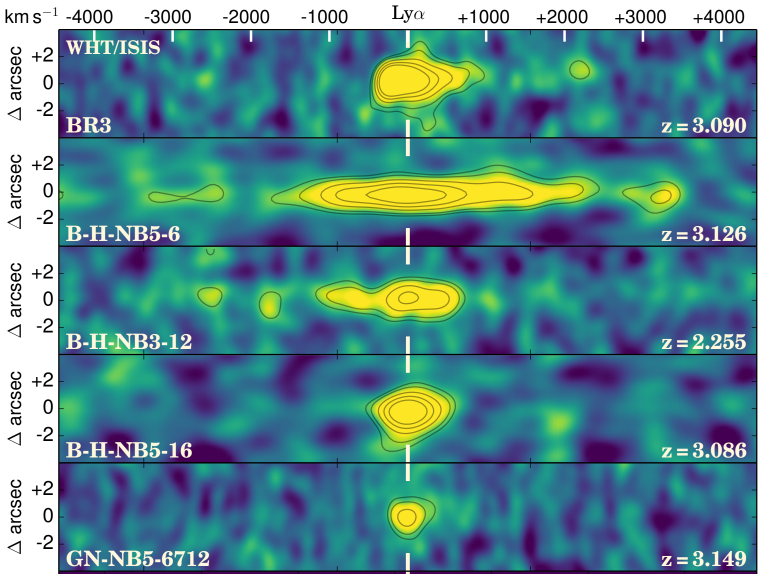


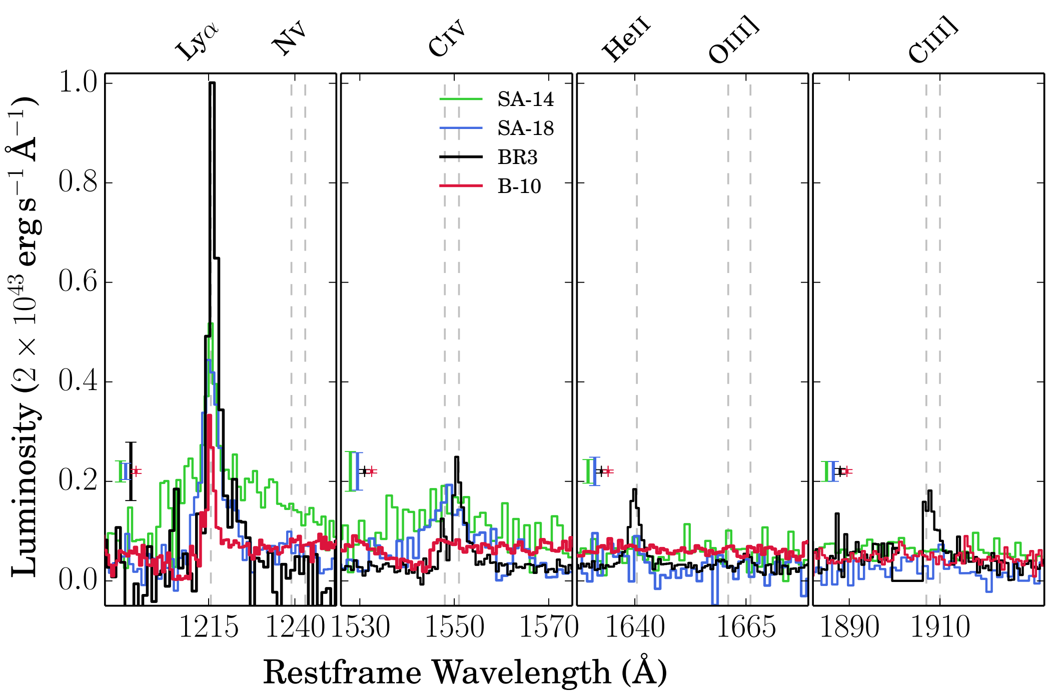
Sobral+ in prep.

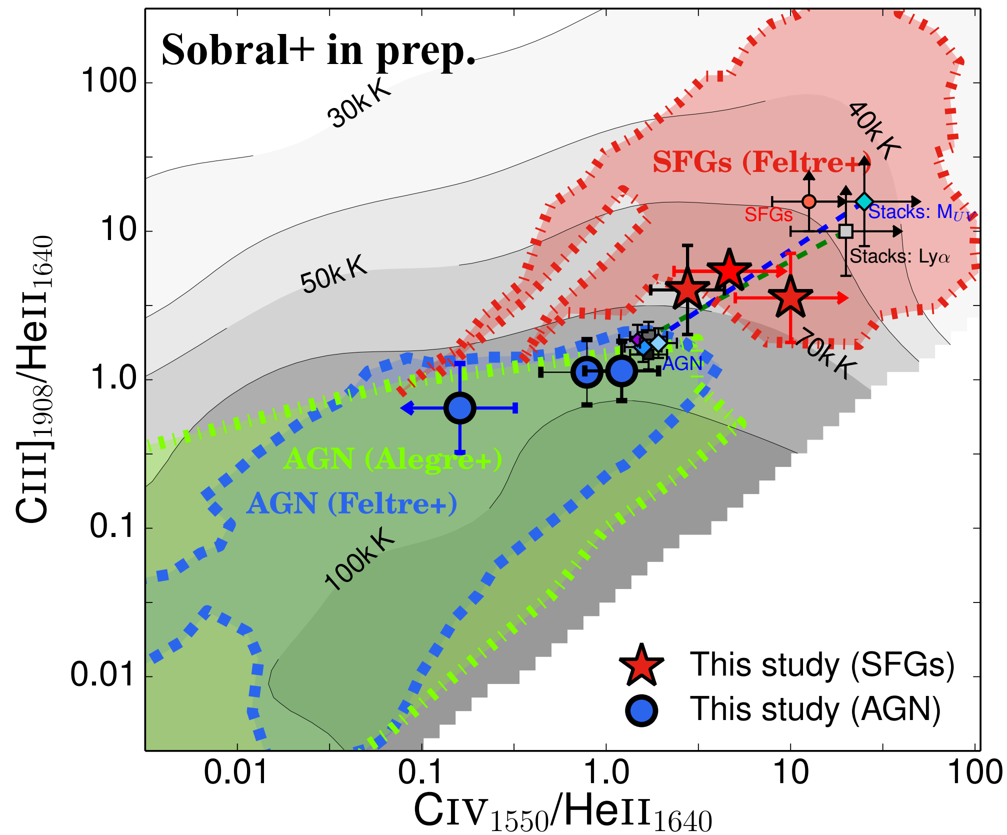
Unveiling the nature of luminous Lyα emitters at z~2-3



40% show UV lines



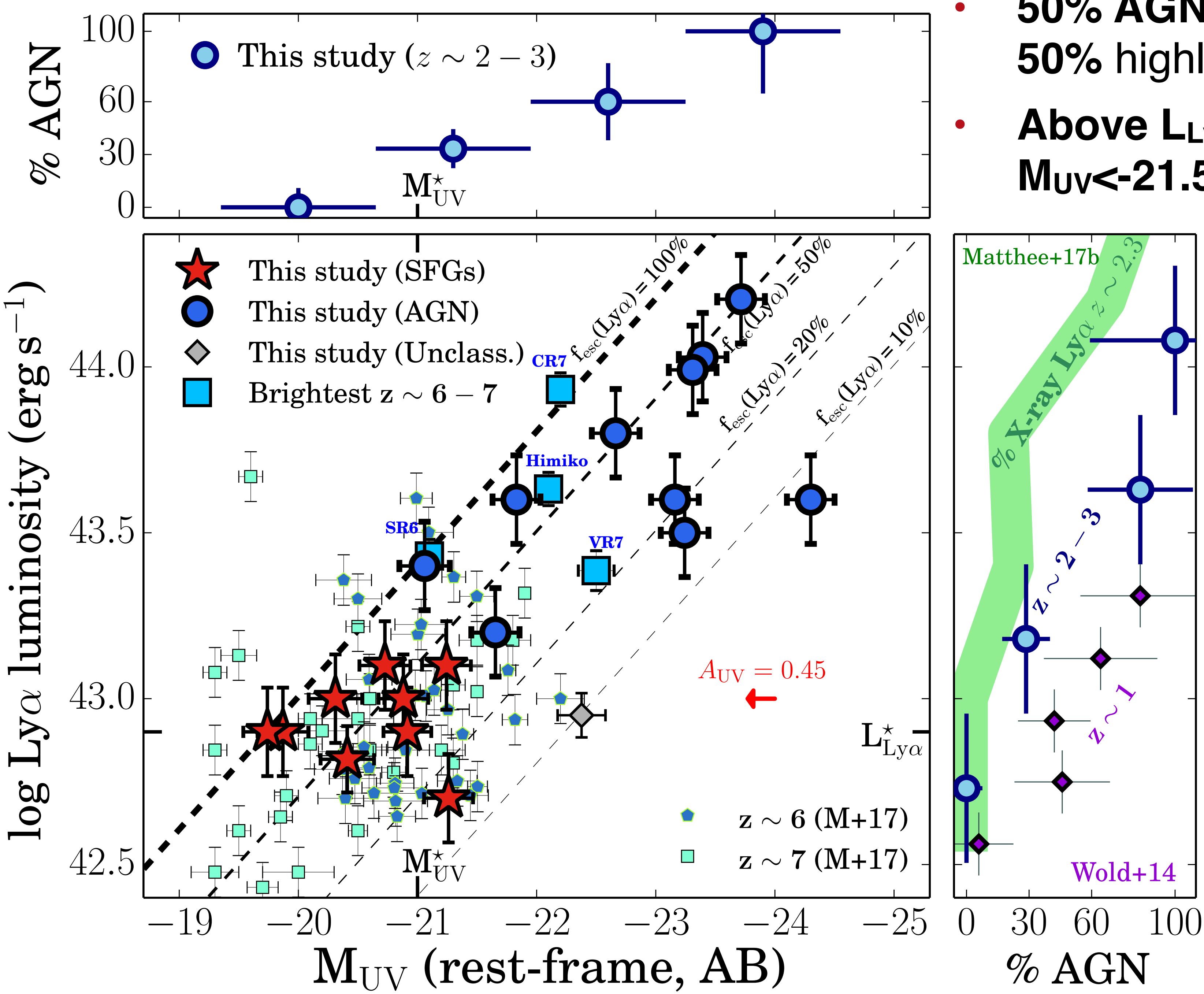




See also : Gutkin et al. 2016; Jaskot & Ravindranath 2016; Amorin et al. 2017

Further modelling-testing/development needed, see:
Eldridge et al. 2008; Eldridge & Stanway 2009, 2012; Grafener & Vink 2015; Stanway et al. 2016

The brightest Lyα emitters at z~2-3: a bimodal population



- **50% AGN** (37% BL-AGN) **50%** highly ionising **SFGs**
- **Above $L_{Ly\alpha}>10^{43.2}$ or $M_{UV}<-21.5$ ~all are AGN**

Sobral, Matthee+in prep

See also Ouchi+08; Sobral+16a; Matthee+17b; Wold+17; Calhau+17b

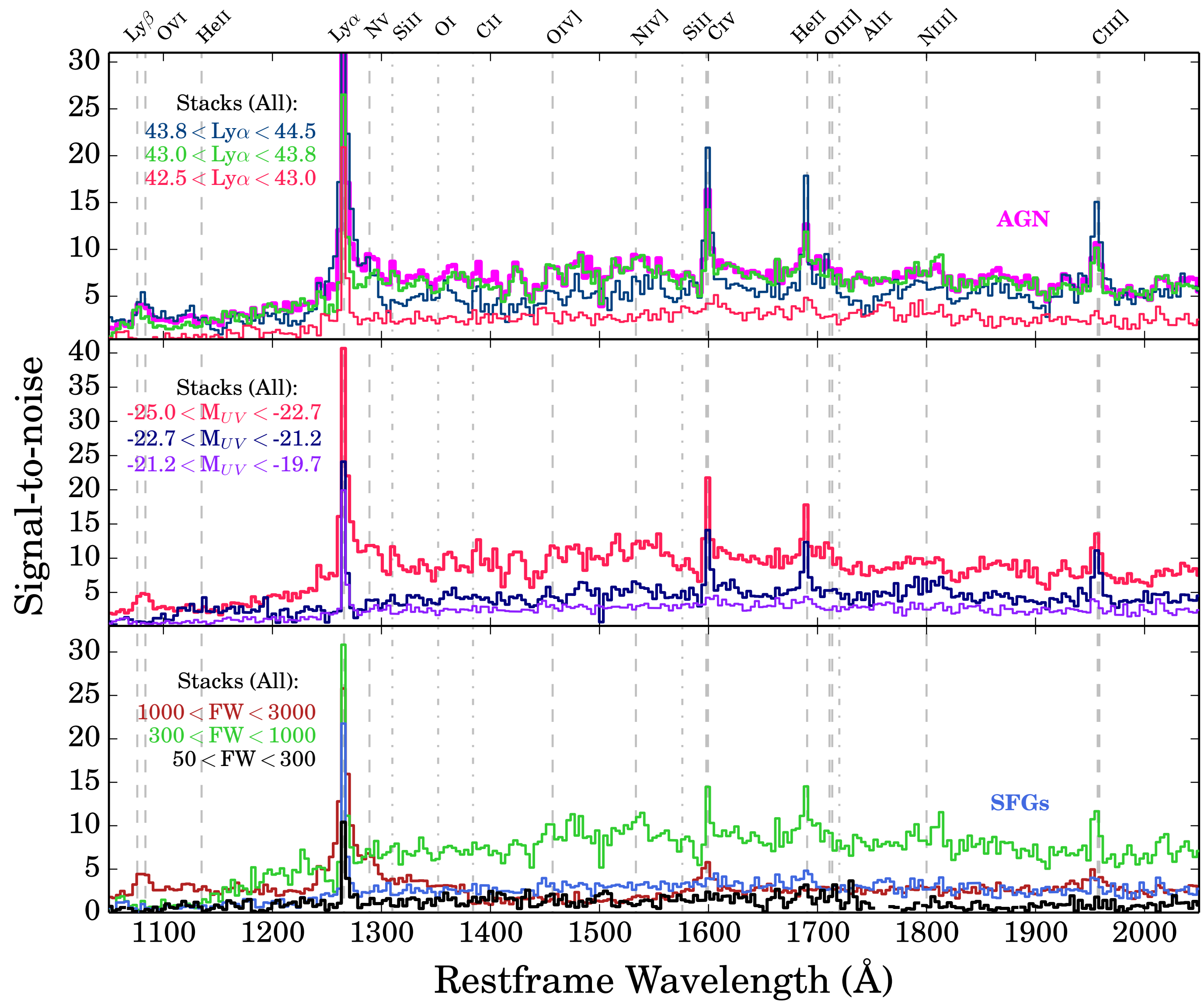
The brightest Lyα emitters at z~2-3: a bimodal population

Overall:
log U = -2.3+-0.5
ξ_{ion}: $10^{25.5}$ Hz erg^{-1}
Metallicities: 7.6+-0.5

Clear relation with increasing Lyα and UV luminosities + FWHM

log U rising from -3 to -1.9
T_{eff} from 40kK to ~150kK
Metallicity: 7.0 to 8.6

High luminosity Lyα emitters (number densities $10^{-4.5+-0.5}$ Mpc^{-3}) are also highly ionising, not just the low luminosity Lyα emitters (e.g. Nakajima+; Trainor+)



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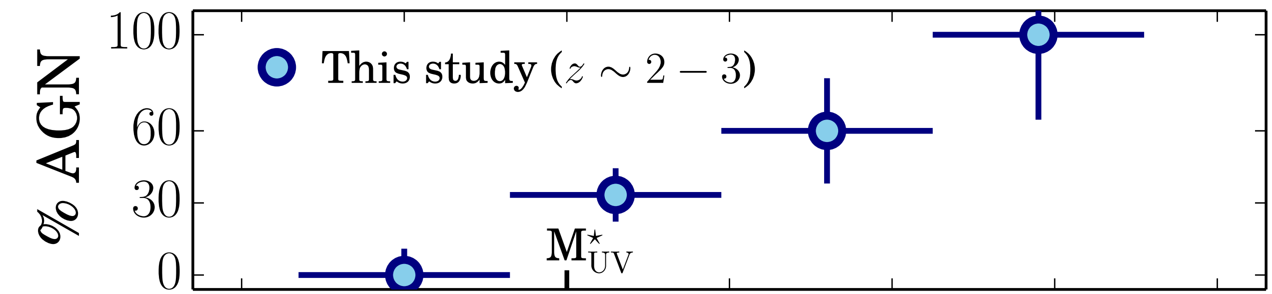

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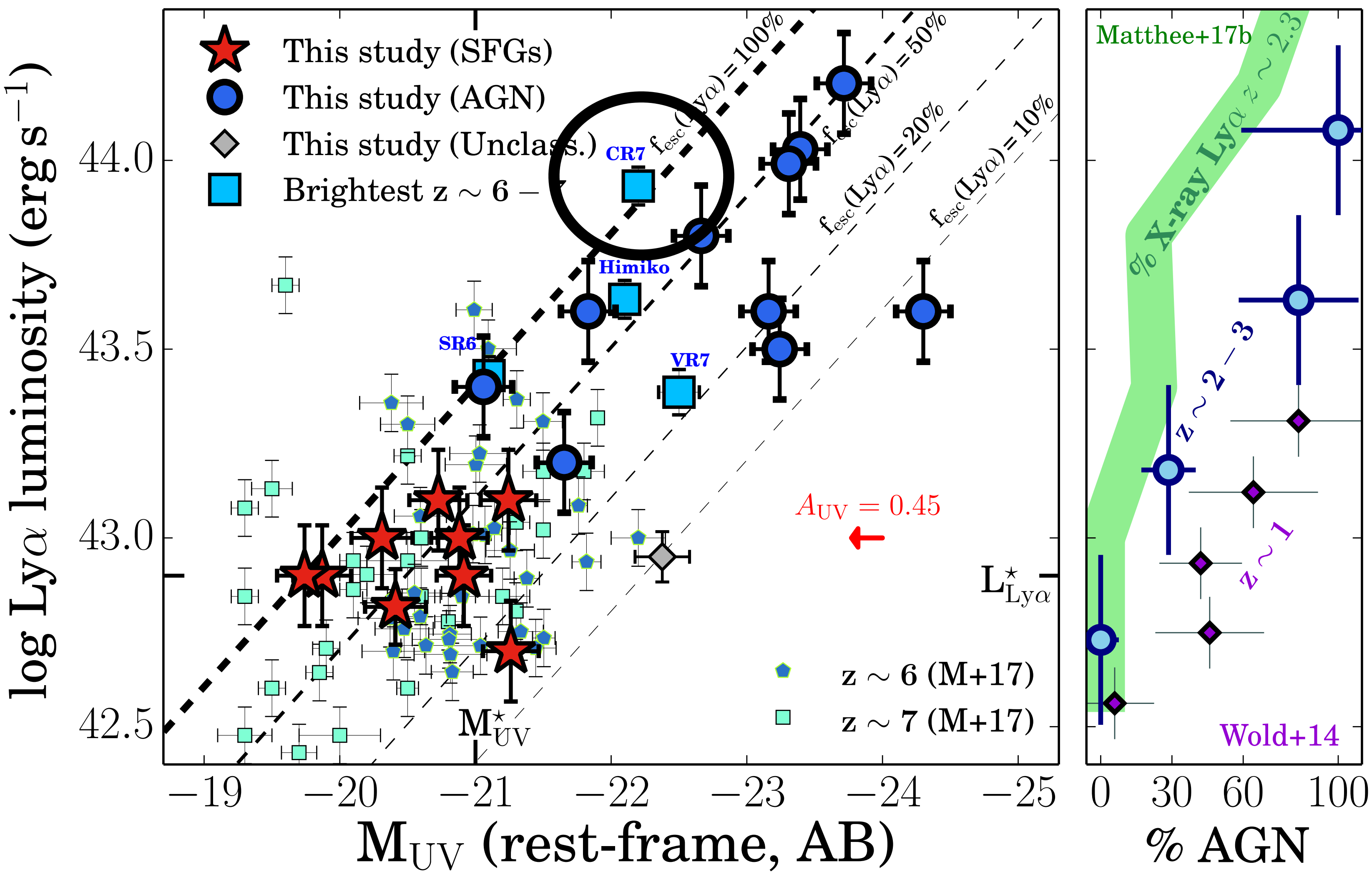


Sobral, Matthee+in prep

See also Ouchi+08; Sobral+16a; Matthee+17b; Wold+17; Calhau+17b

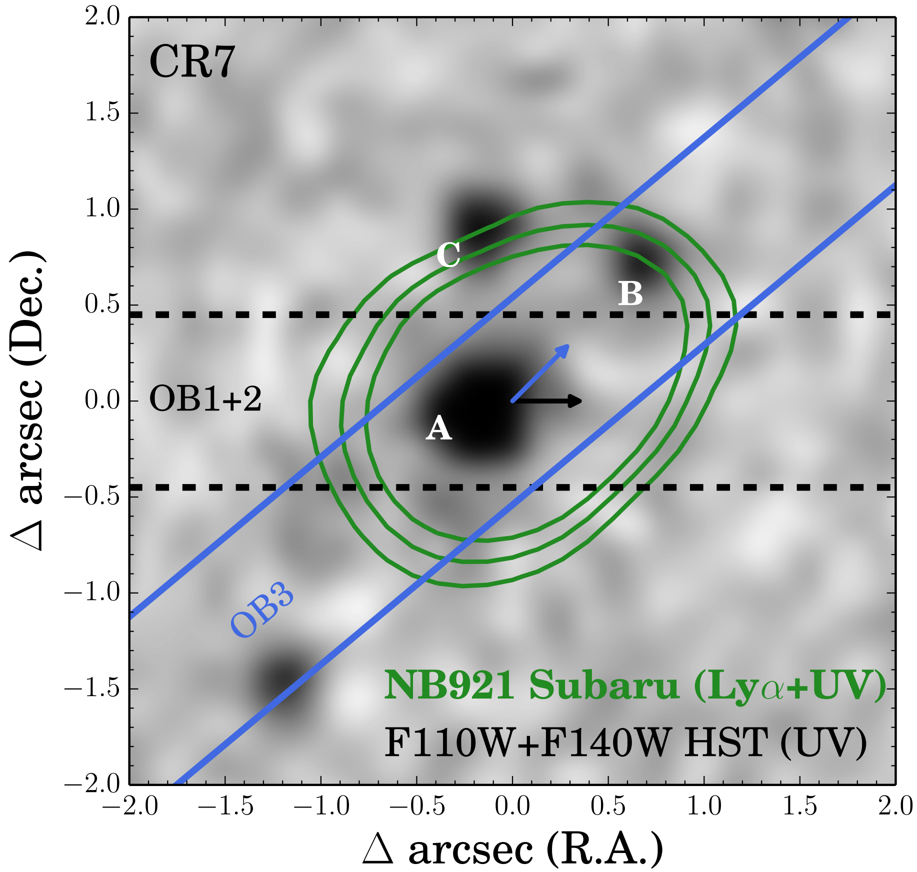
On the nature of CR7: what's going on?

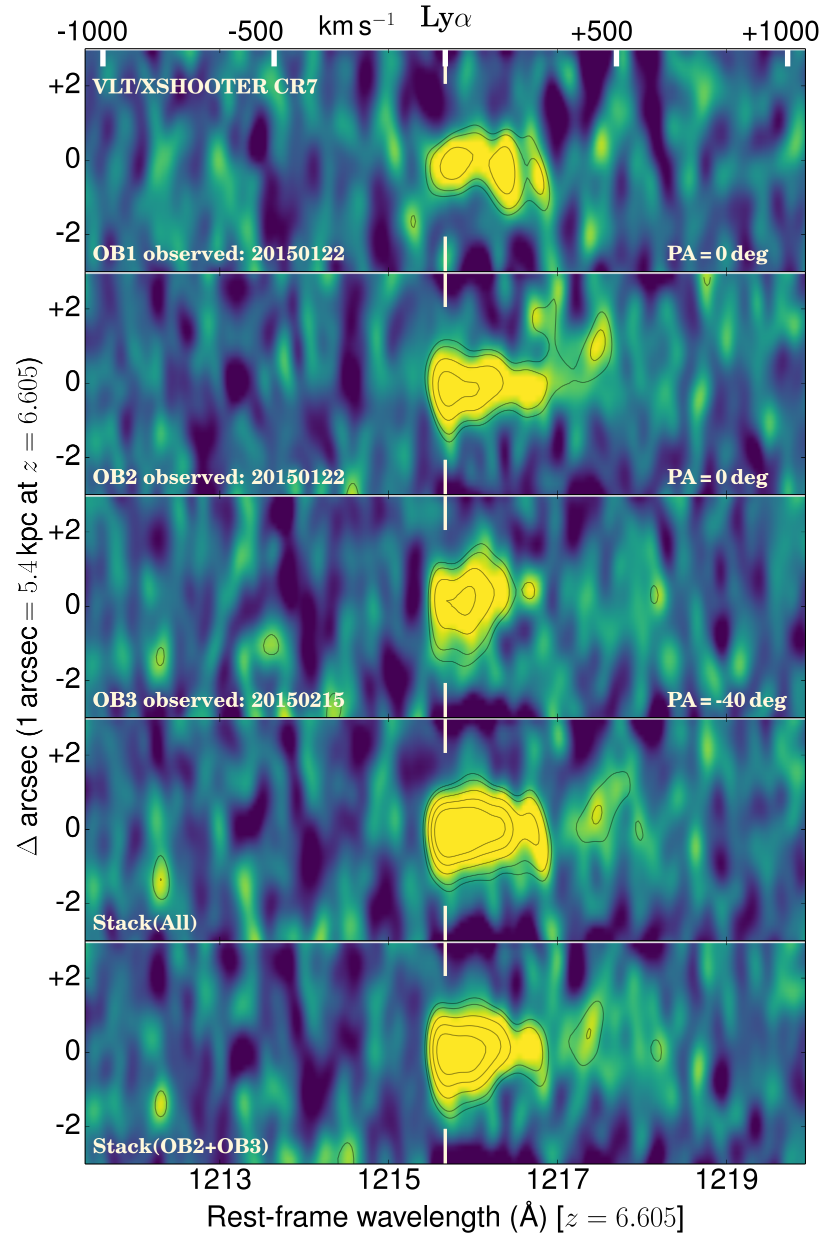
See Jorryt's talk + arXiv:1709.06569

Cosmos Redshift 7 (Sobral, Matthee+15b): most luminous Lya ($10^{43.9}$ erg/s) at z>6

No UV metal lines, strong excess in J band UltraVISTA, line matching HeII

See also: Sobral,Matthee+2015b; Shibuya+17





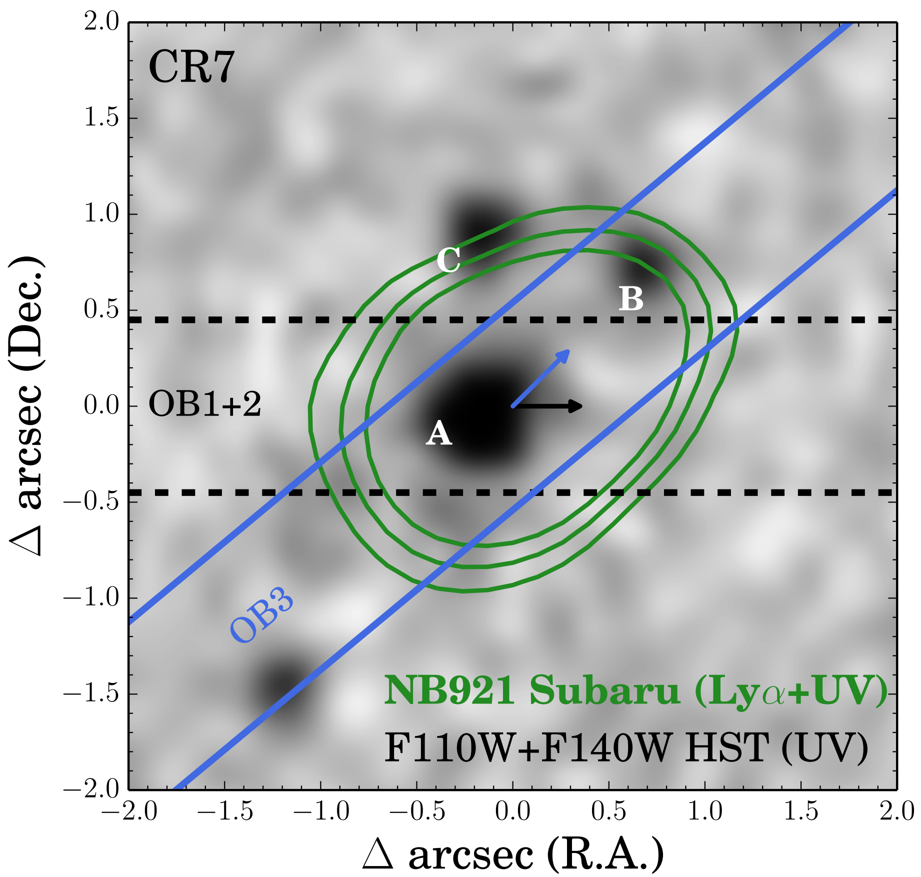
CR7 further discussed: Pallottini+15; Agarwal+16,17; Dijkstra,Gronke & Sobral16; Visbal+16; Hartwig+16; Smidt+16; Smith+16; Bowler+17; Pacucci+17, Yajima+17 ++

On the nature of CR7: other rest-frame UV lines? HeII?

Sobral, Matthee+ in prep.

Flux in Sobral+15 based on UltraVISTA DR2 implied 4x10^{-17} erg/s/cm^2. UltraVISTA DR3 changed by ~+0.2 to +0.5 in J band, implying a flux of a factor 2-3 lower.

Now measured directly from our flux calibrated spectra: 1.7+-0.7 x10^{-17} erg/s/cm^2



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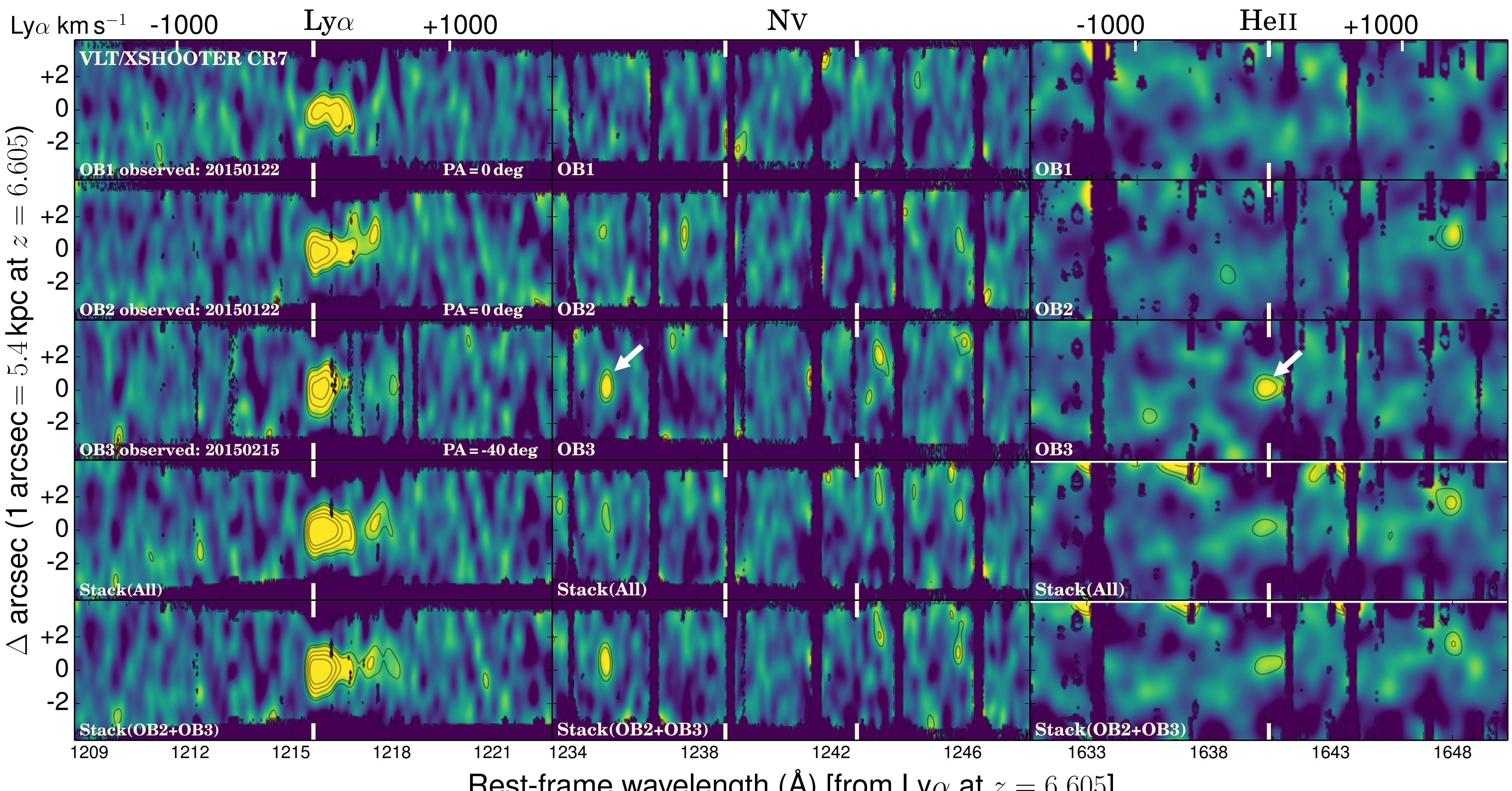

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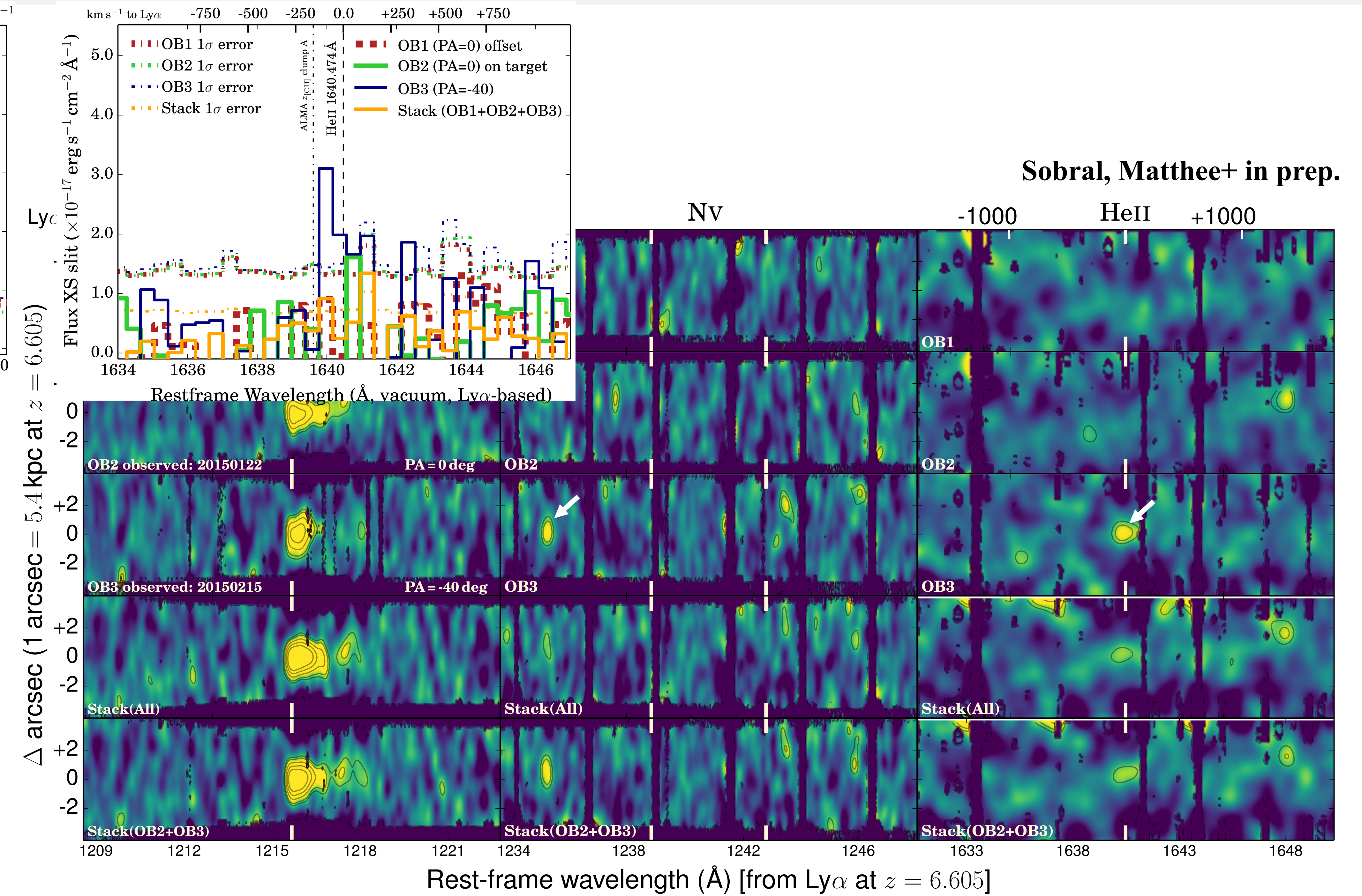
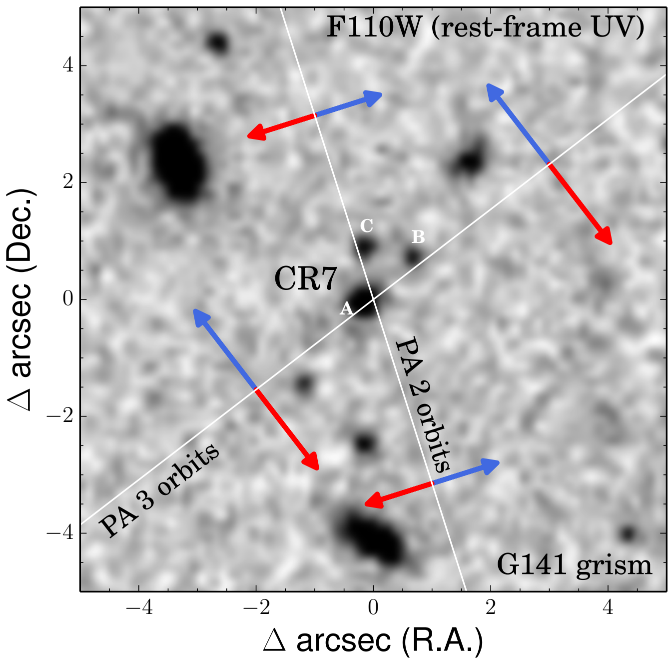


On the Nature of CR7: *HST*/WFC3 grism observations



Sobral, Matthee+ in prep.

See Jorryt's talk + Matthee, Sobral+2017c,d; arXiv: 1709.06569

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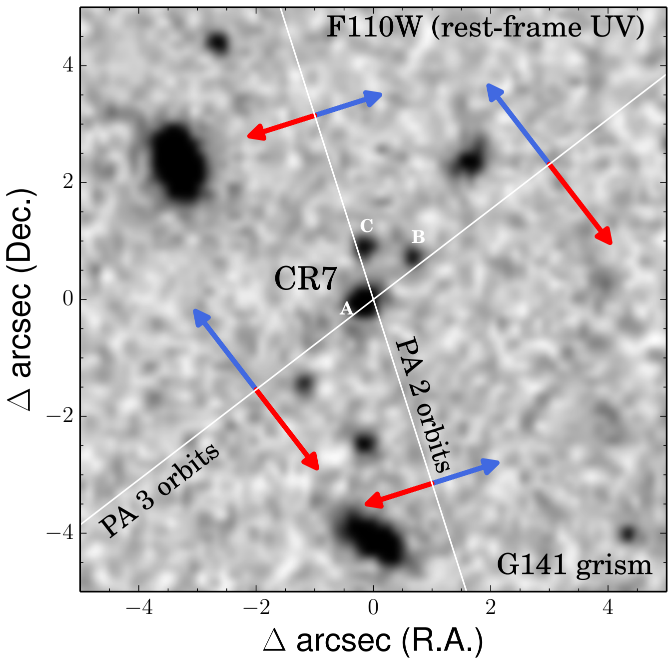
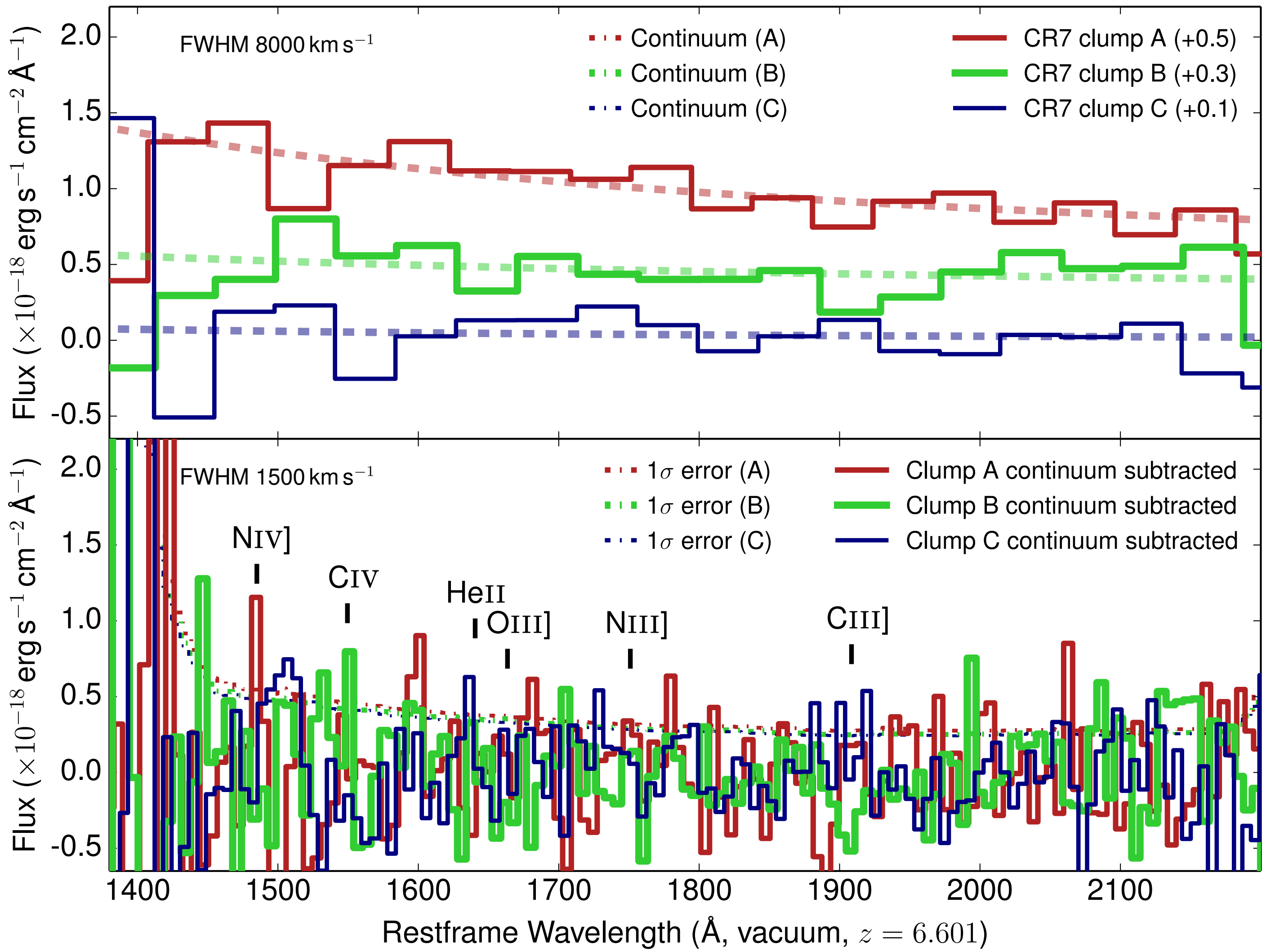




Sobral, Matthee+ in prep.

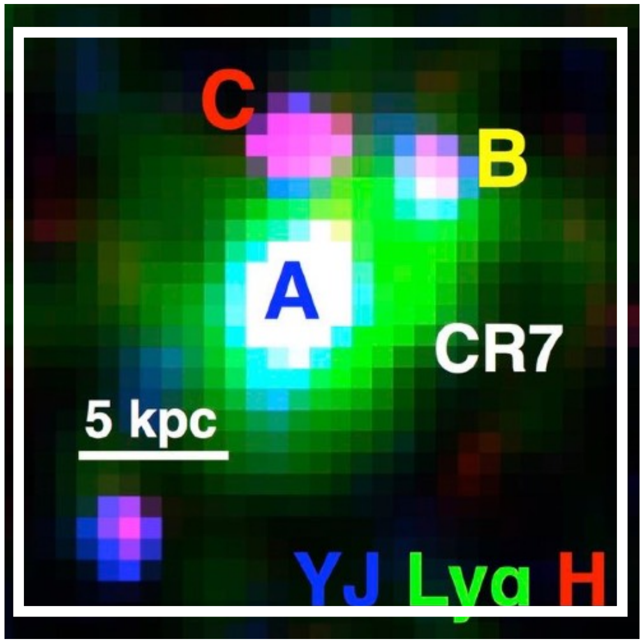
See Jorryt's talk + Matthee, Sobral+2017c,d; arXiv: 1709.06569

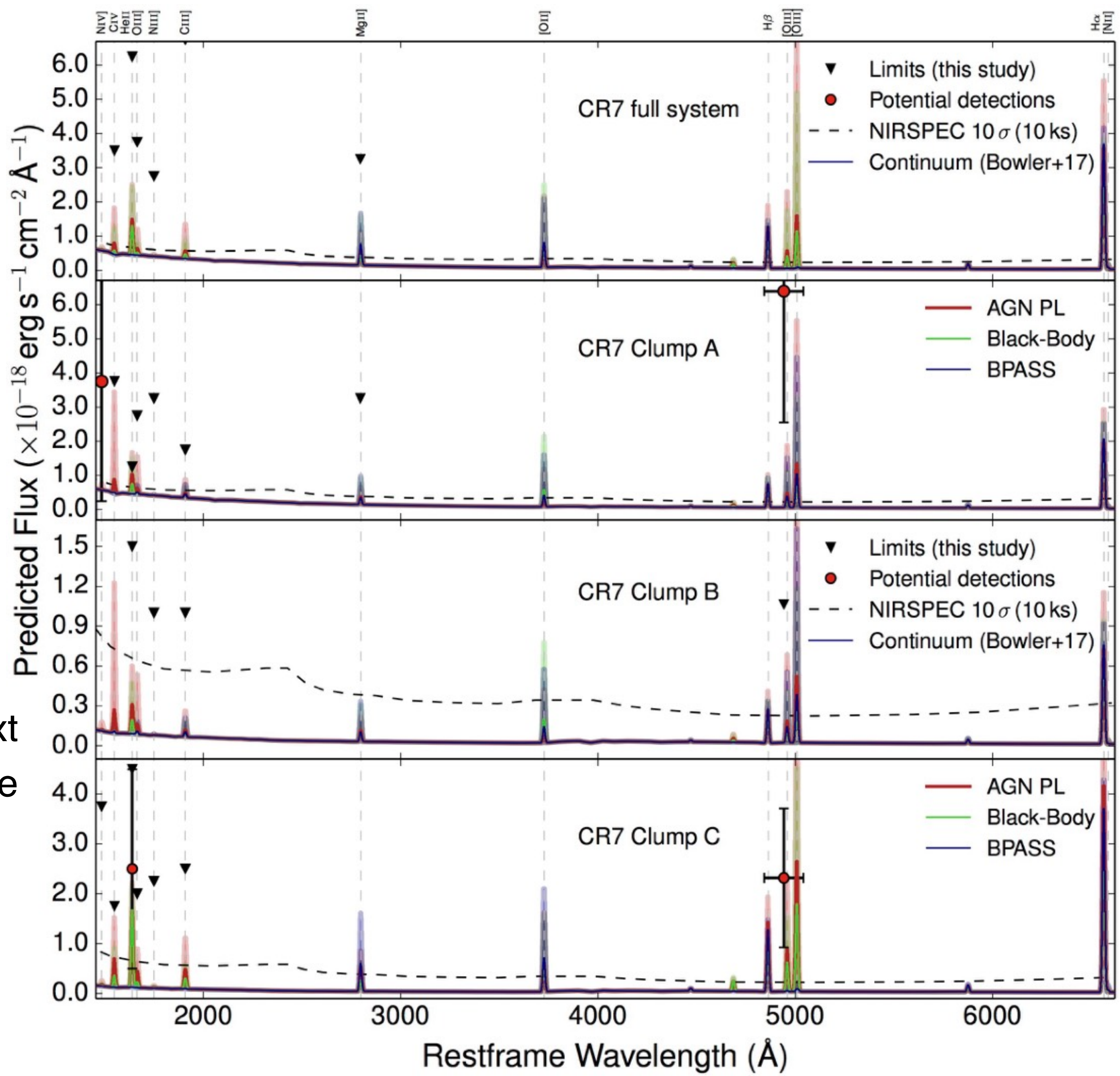
CR7 Component	SFR ($M_\odot$ yr^{-1})	β	Gas-phase metallicity ($Z_\odot$)	logU	Likely dominating nature
Full	45 ± 2	-2.2 ± 0.4	$0.14^{+0.08}_{-0.05}$	-2.8 ± 0.3	Star-burst
A	27^{+2}_{-1}	-2.4 ± 0.4	$0.13^{+0.06}_{-0.03}$	-2.7 ± 0.3	Star-burst
B	6^{+2}_{-1}	-1.6 ± 0.8	$\sim 0.05 - 0.2$	–	Star-burst
C	7^{+1}_{-1}	-2.4 ± 0.8	$0.11^{+0.08}_{-0.03}$	-2.5 ± 0.5	Star-burst/AGN

IFU NIRSpec GTO/*JWST* observations of CR7

Sobral, Matthee+ in prep.

Sobral, Matthee et al. 2015b





See Jorryt Matthee's talk next (and arXiv:1709.06569) for the [CII] and dust view of CR7

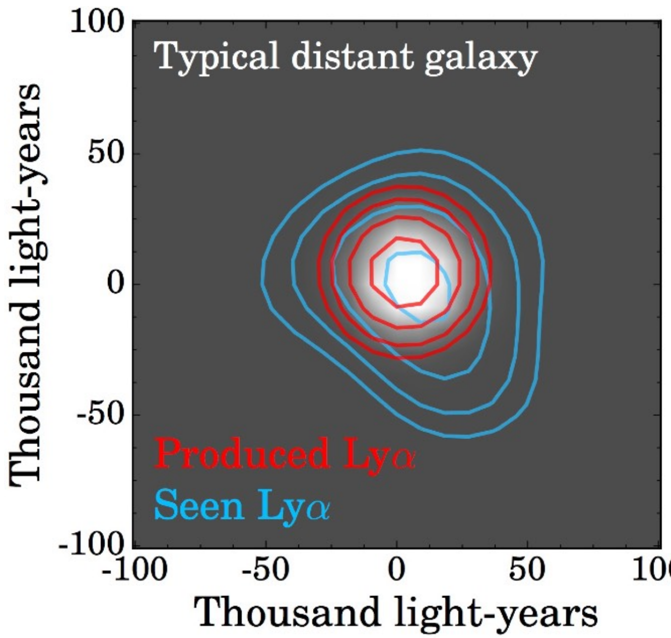
See also Bowler et al. 2017

Summary and conclusions

- Hα + [OIII] and [OII] selected samples up to z~5: strong evolution
- Lyα escape fractions (<25 kpc) of **~1-2% at z~2** (**global ~5%**)
- **Lyα haloes ubiquitous (~40kpc)** in typical SFGs at high-z

- Lyα emitters have **higher ξ_{ion}, and steep faint-end slope**
- **ξ_{ion} rises strongly with redshift**, likely driven by sub-set of population that is selectable as Lyα emitter. LAEs are highly ionising sources

- Luminous Lyα emitters (~$10^{43.5}$ erg/s) much more common than thought: very ionising and at z~2-3 essentially all AGN
- Evolution of both ξion and Lya f_{esc}
- CR7 is revealing how complex z~7 sources are: need high spatial resolution (and maybe even variability constraints)



Results from emission-line selected galaxies

- Emission line selected samples probe dark matter halo hosts of ~10^{12} M_{o} across cosmic time, with ~single dark matter halo mass and line luminosity relation
- Stellar mass is empirically the best dust extinction estimator
- At higher redshift ELGs become an increasing fraction of the population

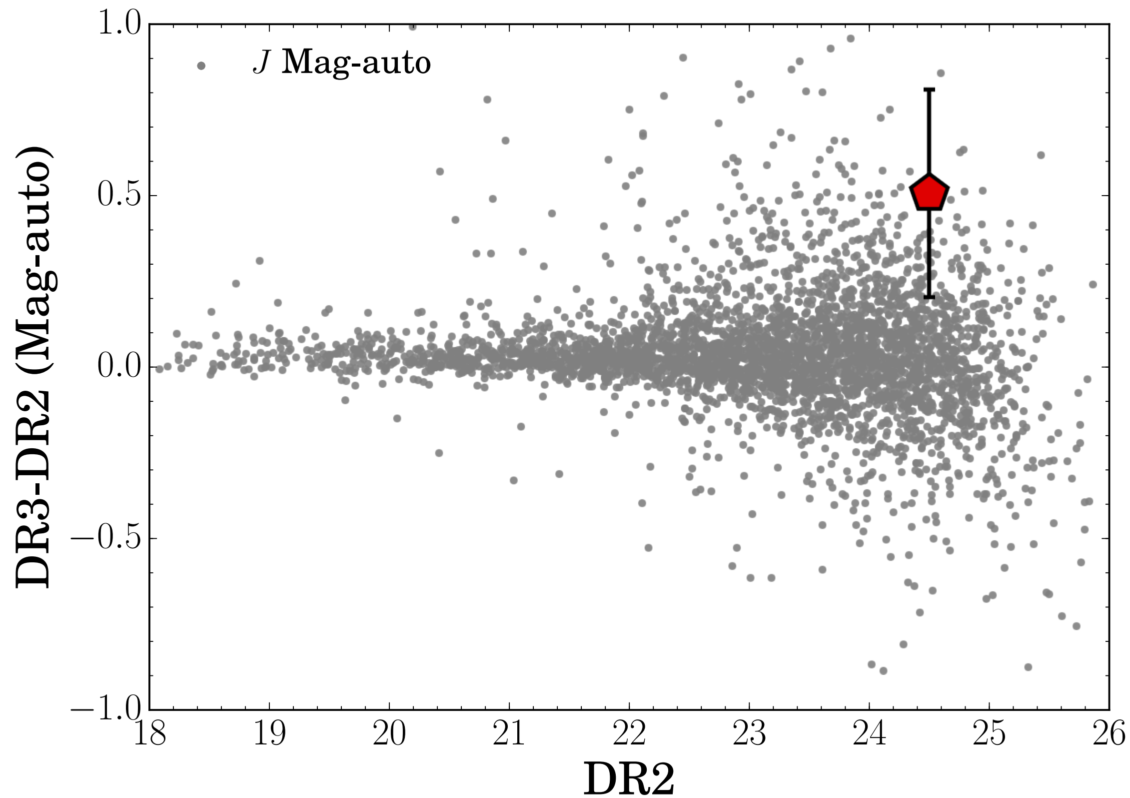
See also: MOSDEF, KBSS, 3D-HST

- HiZELS+CFHIZELS++ **~80 Nights UKIRT+Subaru+VLT+CFHT+INT**
- Deep & Panoramic extragalactic survey, narrow-band imaging from z to K band over ~ 5-10 deg^2
- Equally selected "Slices" with >1000 star-forming galaxies in multiple environments and with a large range of properties

Catalogues, Hα, [OII], [OIII] LFs: **Sobral+09a,12,13a,15a;** Size + merger evolution: **Stott+13a;** Metallicity evolution + FMR: **Stott+13b,14**; [OII]-Ha at high-z: **Sobral+12,Hayashi+13**; Dust properties: **Garn+10,S+12,Ibar+13;** Clustering: **Sobral+10, Geach+08,13; Khostovan+17; Cochrane+17a,b;** [OII]+[OIII] LFs+MFs and EWs to z~5: **Khostovan+15,16;** Environment vs Mass: **Sobral+11, Koyama+13, Darvish+14, Sobral+15b, Darvish+15, Stroe+14,15;** AGN vs SF: **Garn+10, Lehmer+13, Sobral+16a; Calhau+17a,b;** Dynamics and gradients: **Swinbank+12a,b, Sobral+13b, Stott+14;** Lyα at z>7: **Sobral+09b,Matthee+14**

CR7 J band UltraVISTA

Colour	Aperture	Excess	Excess-err	Significance
J DR3-DR2	mag-auto	0.508	0.303	1.7σ
J DR3-DR2	ap1	0.338	0.262	1.3σ
J DR3-DR2	ap2	0.125	0.299	0.4σ
J DR1-DR2	mag-auto	-0.051	0.313	-0.16σ
Y DR3-DR2	mag-auto	0.117	0.298	0.4σ
Y DR3-DR2	ap1	0.007	0.262	0.0σ
Y DR3-DR2	ap2	-0.034	0.291	-0.1σ
Y DR1-DR2	mag-auto	0.128	0.306	0.4σ



Did Lyα emitters re-ionise the Universe?

- **Lyα emitters have high ξ_{ion} + steep faint-end slope + high Lyα escape fraction + Lyα-LyC connection slope** suggests they are the most leaking

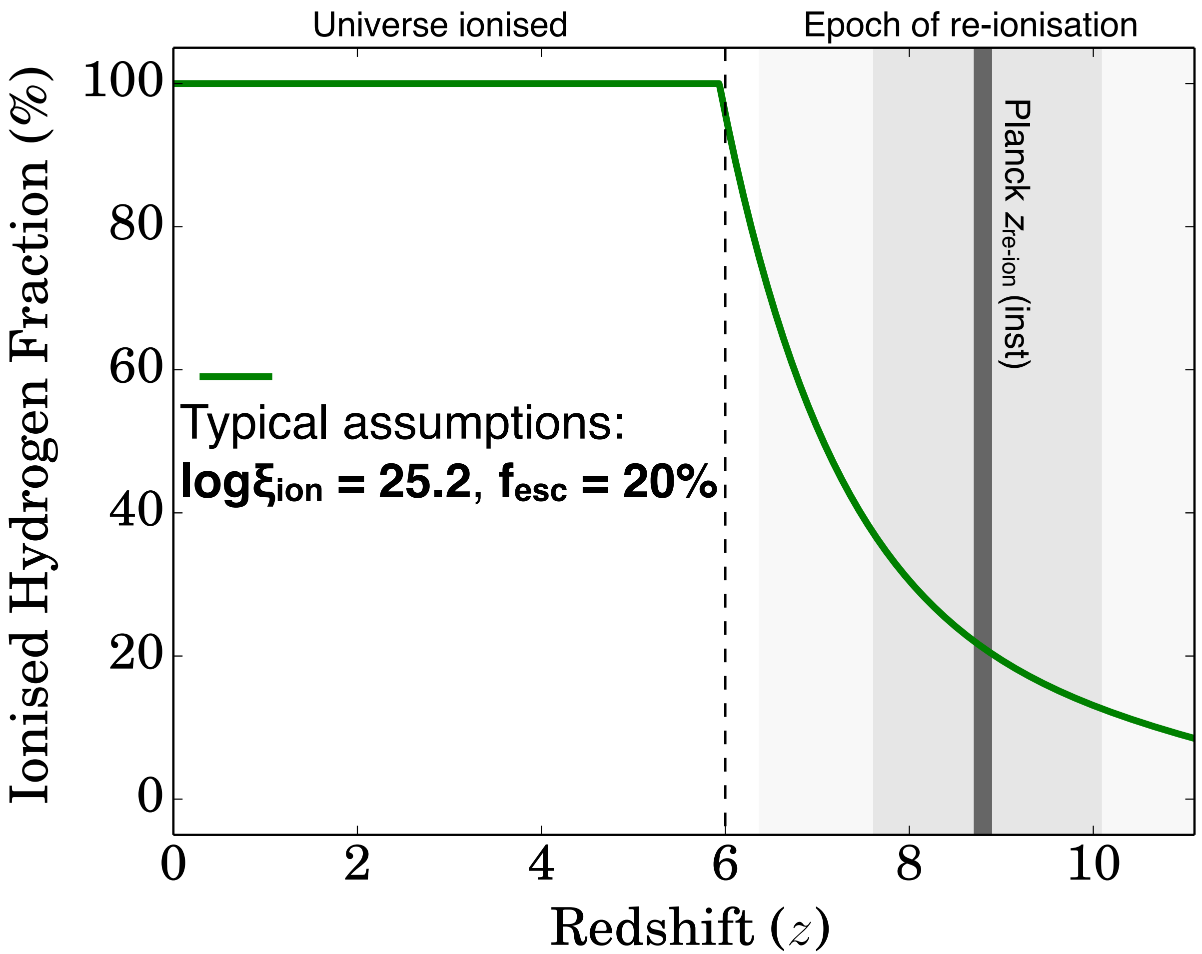
$$\dot{Q}_{\rm H\,II} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H} \rangle} - \frac{Q_{\rm H\,II}}{t_{\rm rec}},$$

$$\boxed{\dot{n}_{\rm ion} = \overset{1}{f_{\rm esc}}\overset{2}{\xi_{\rm ion}}\overset{3}{\rho_{\rm UV}}}$$

1 Fraction of LyC photons that escape

2 # of LyC photons per UV luminosity

3 UV luminosity density



See also Dressler+2011, Henry+2012; Robertson et al. 2013, 2015; Faisst 2016

Did Lyα emitters re-ionise the Universe? Possibly!

$$\dot{n}_{\rm ion} = f_{\rm esc}\xi_{\rm ion}\rho_{\rm UV}$$

Robertson+13 <u>assumptions</u>:
logξ_{ion} = 25.2, **f_{esc} = 20%**

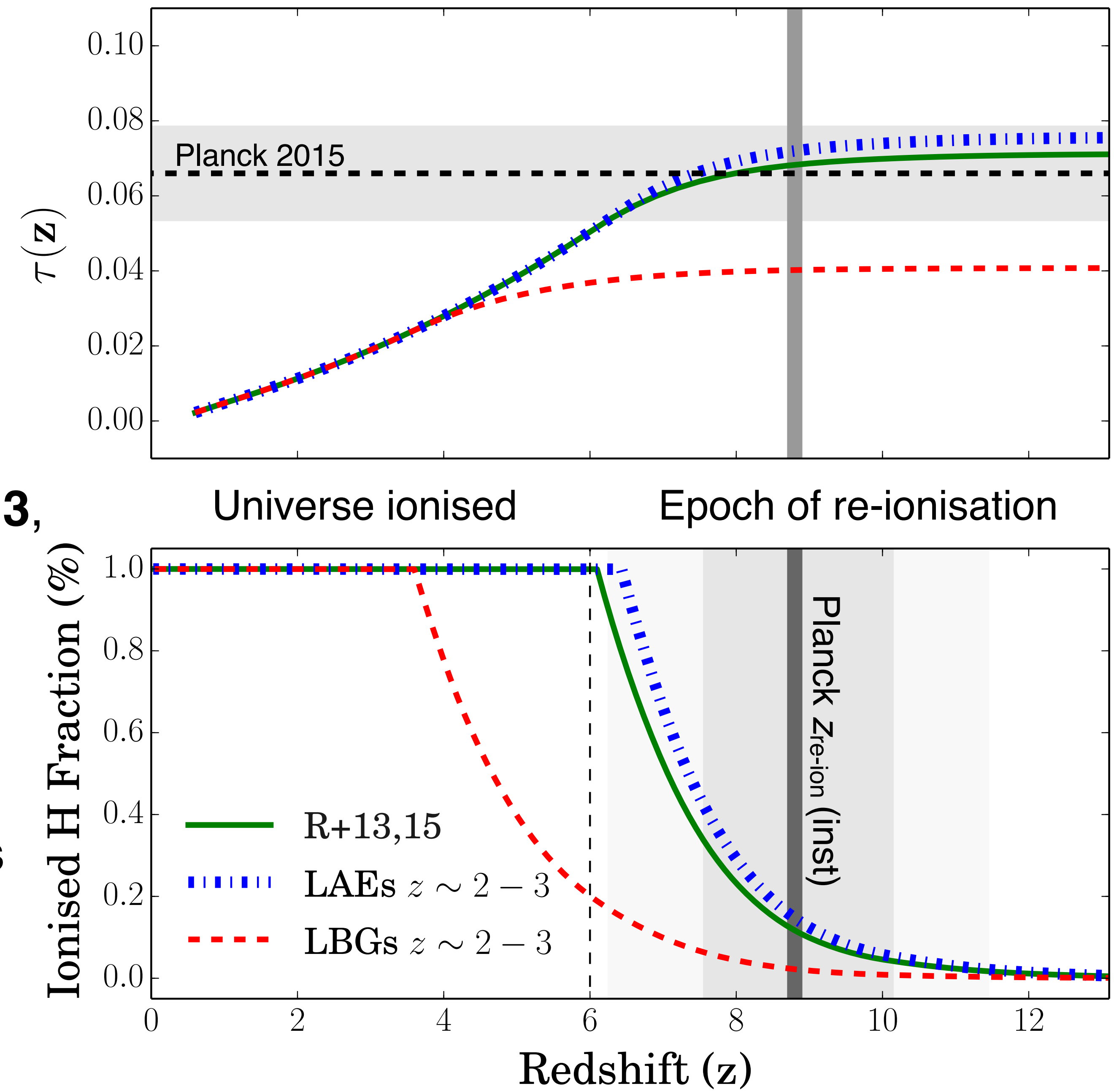
Based on measurements/ constraints (z=2-3):

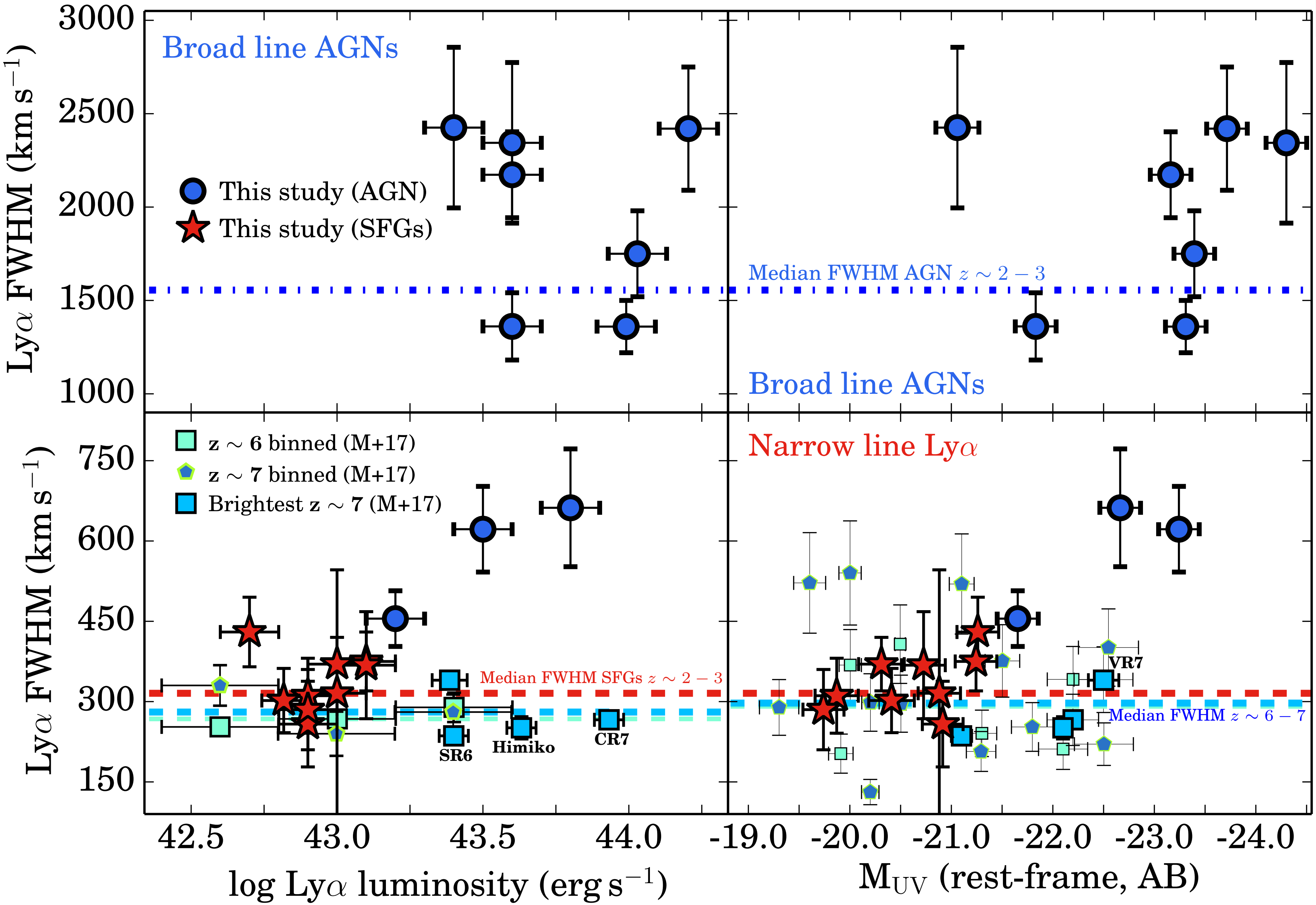
LBGs: **100%ρ_{UV}**; **logξ_{ion}=25.3, f_{esc} ~ 3%**

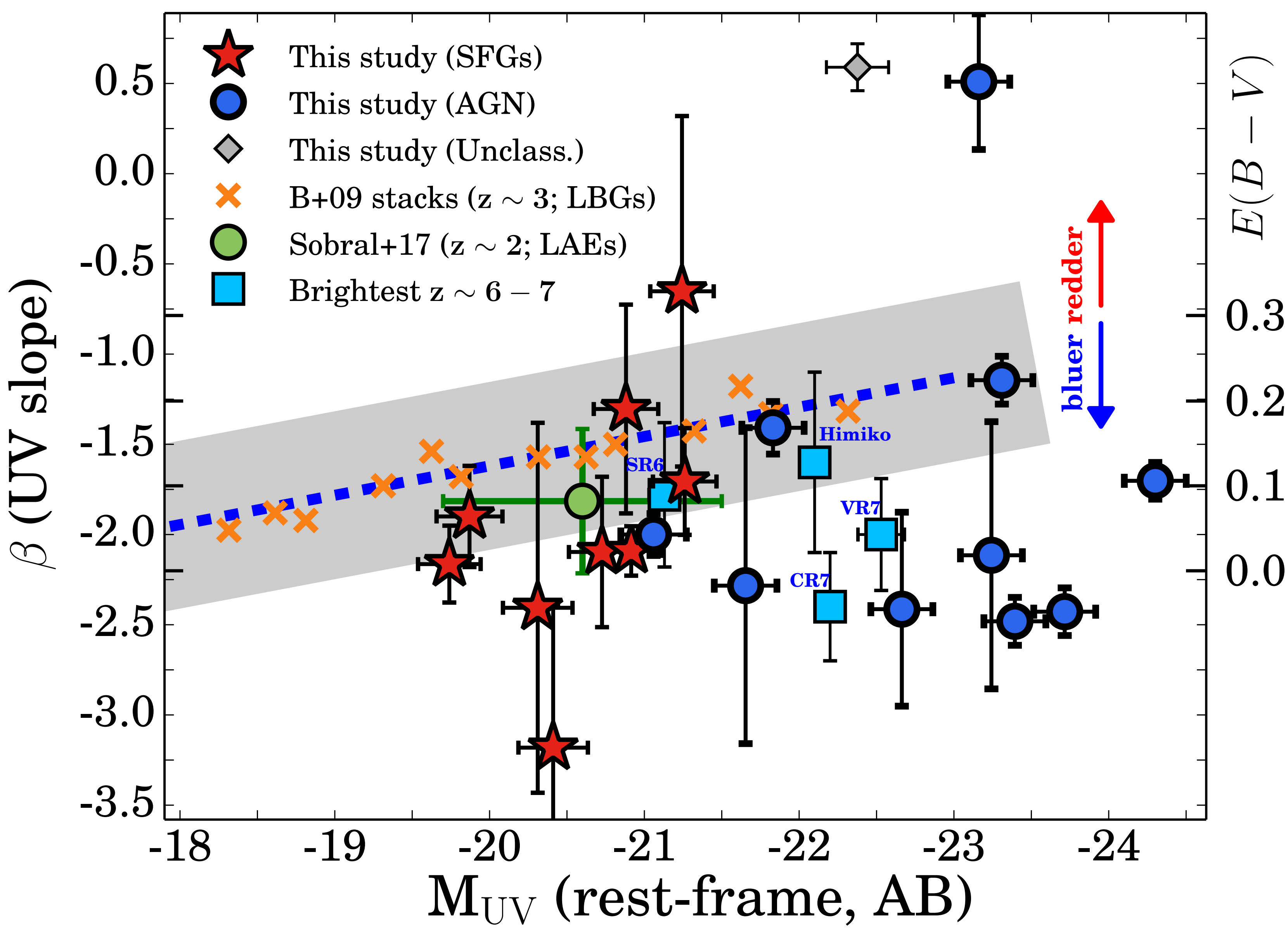
LAEs: f(z)ρ_{UV}; logξ_{ion}=25.6, f_{esc} ~ 13%

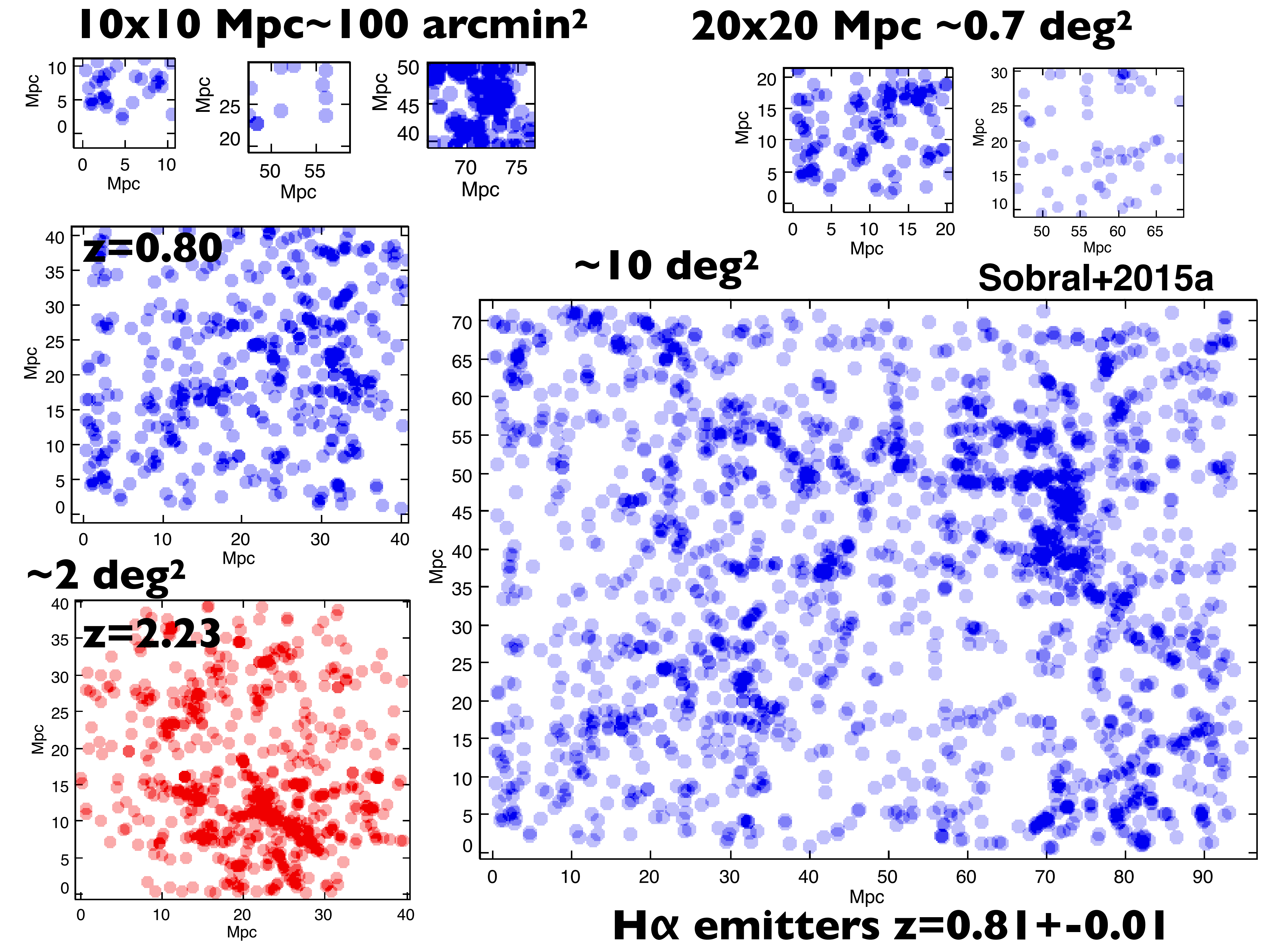
LAEs as the sub-set of LBGs + AGN that have **the measured** properties to easily re-ionise the Universe

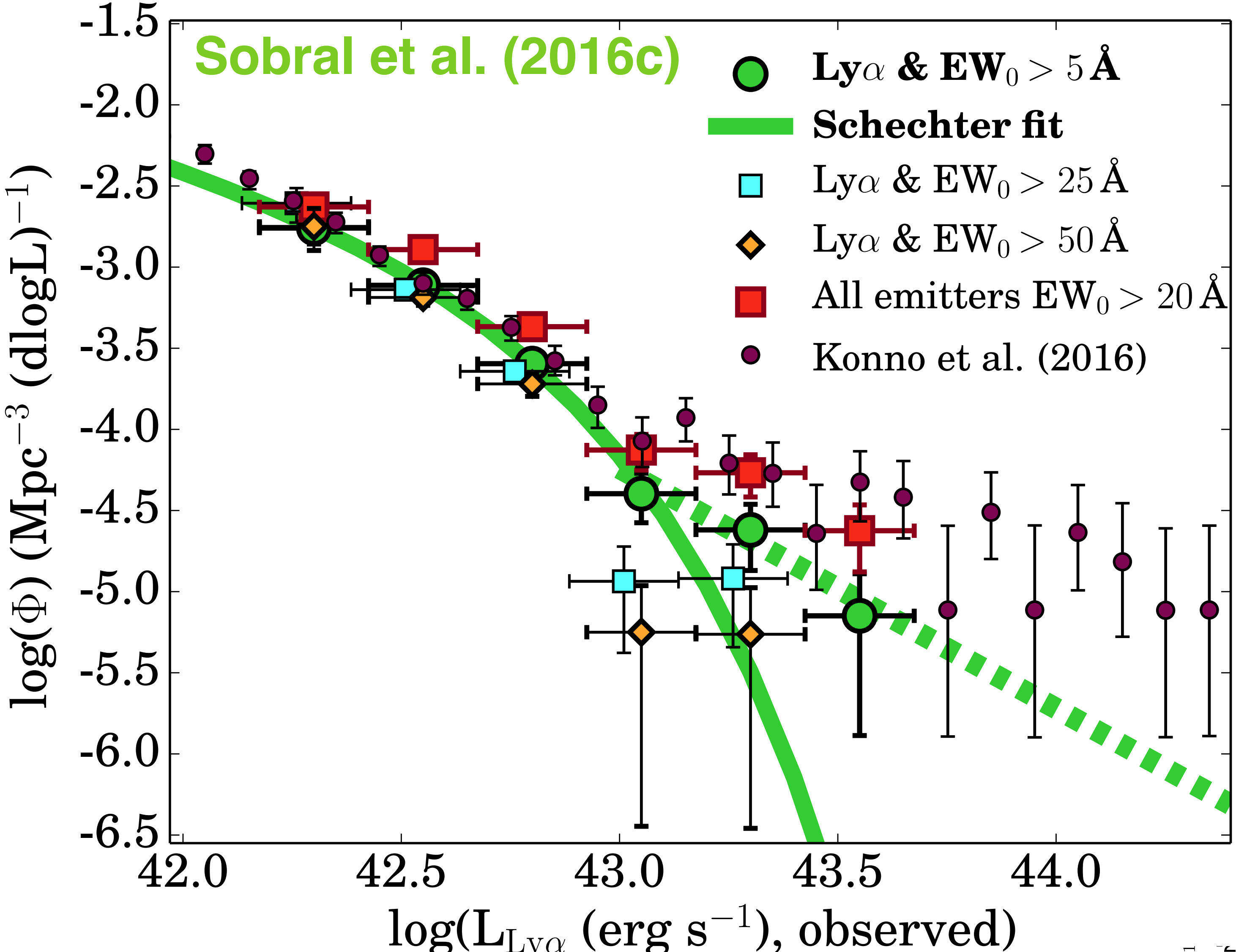
Sobral/Matthee in prep.




Broad line AGNs
This study (AGN)
This study (SFGs)
Median FWHM AGN $z \sim 2-3$
Broad line AGNs
$z \sim 6$ binned (M+17)
$z \sim 7$ binned (M+17)
Brightest $z \sim 7$ (M+17)
Median FWHM SFGs $z \sim 2-3$
SR6
Himiko
CR7
Narrow line Lyα
VR7
Median FWHM $z \sim 6-7$
Lyα FWHM (km s^{-1})
log Lyα luminosity (erg s^{-1})
M_{UV} (rest-frame, AB)


This study (SFGs)
This study (AGN)
This study (Unclass.)
B+09 stacks (z ~ 3; LBGs)
Sobral+17 (z ~ 2; LAEs)
Brightest z ~ 6 − 7
Himiko
SR6
VR7
CR7
bluer redder
β (UV slope)
$E(B-V)$
M_{UV} (rest-frame, AB)
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
0.3
0.2
0.1
0.0
-18
-19
-20
-21
-22
-23
-24


10x10 Mpc~100 arcmin²
20x20 Mpc ~0.7 deg²
z=0.80
~10 deg²
Sobral+2015a
~2 deg²
z=2.23
Mpc
Hα emitters z=0.81+-0.01

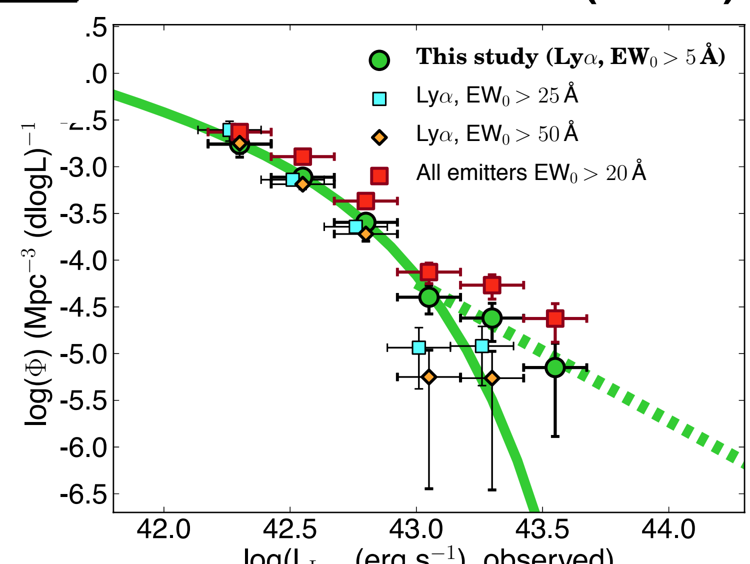


New Lyα LF at z=2.2 from the widest ever survey

Very wide surveys will find more sources than expected!

"**Traditional**" ways of selecting Lyα emitters **<u>miss most real bright Lyα</u>** and **<u>introduce contaminants at bright end</u>**

Sobral et al. (2016c)

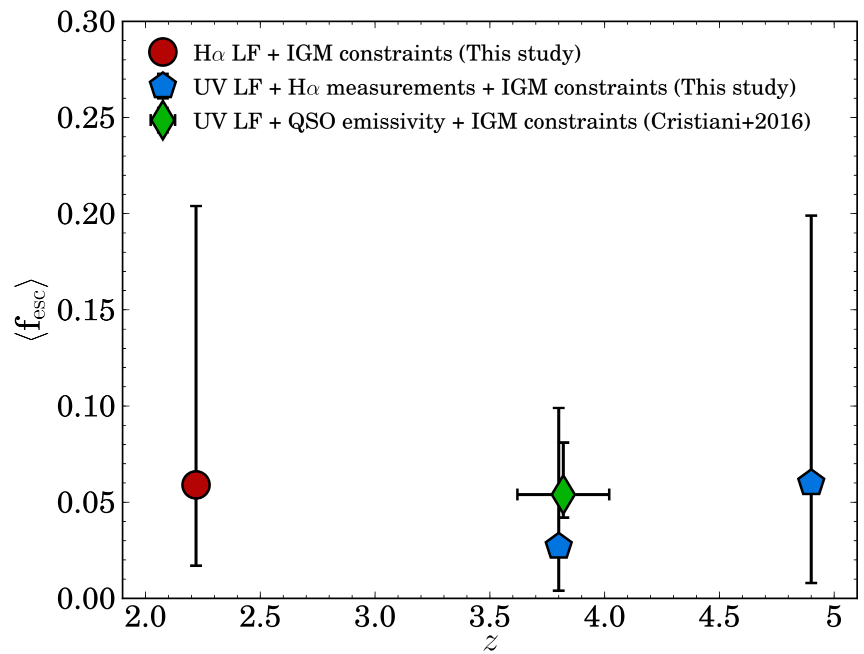


Global Lyα escape fraction from SFGs at z=2.23 (Hα)

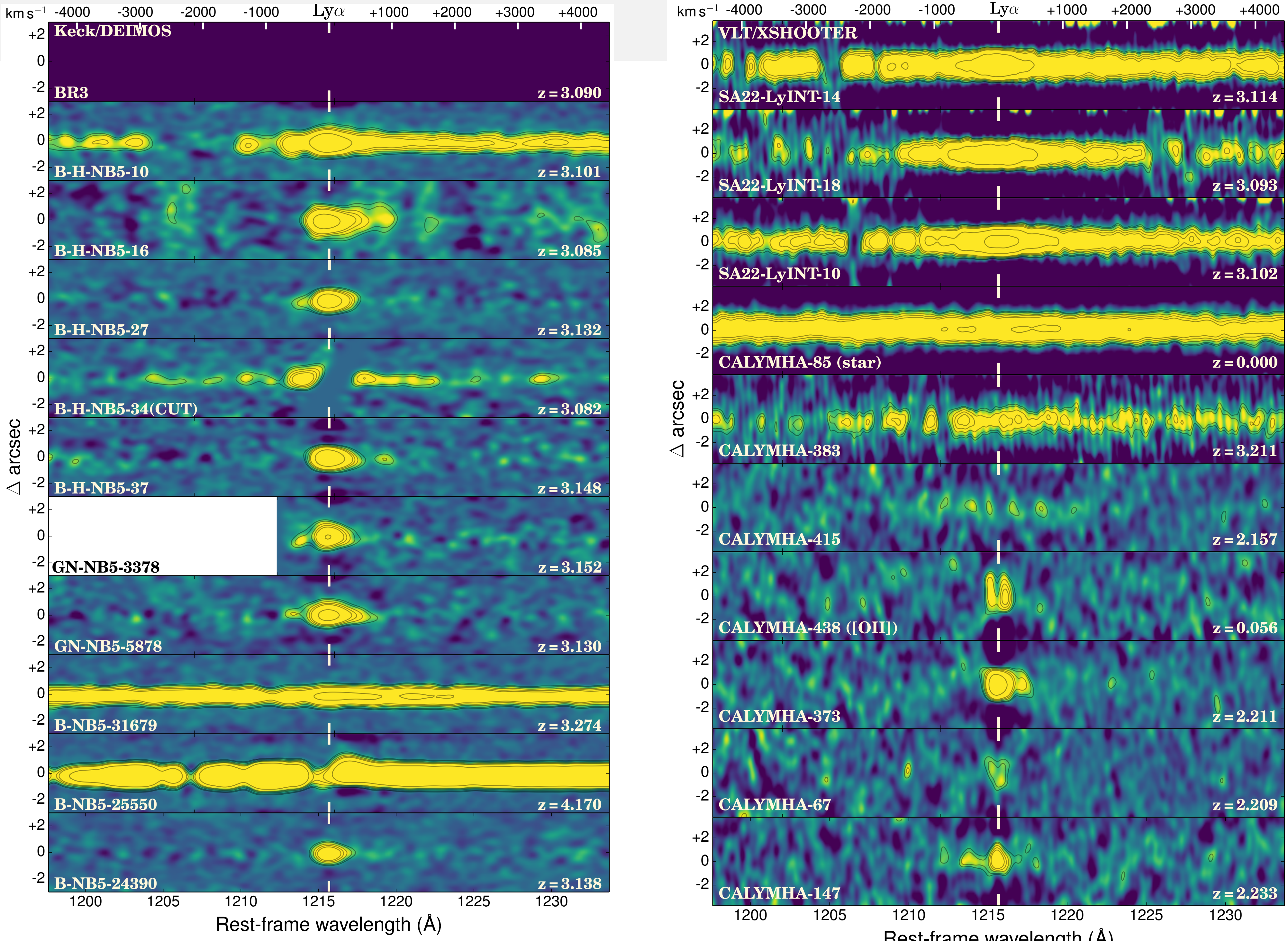
- Global Lyα f_{esc}: **5.1±0.2%** (<25 kpc) and **8.4±0.4%** (<40 kpc)
- Lyα emitters have Lyα f_{esc} **37±7%** (<25 kpc)
- [most Lyα emitters consistent with Lyα f_{esc} ~100% up to even larger radii]

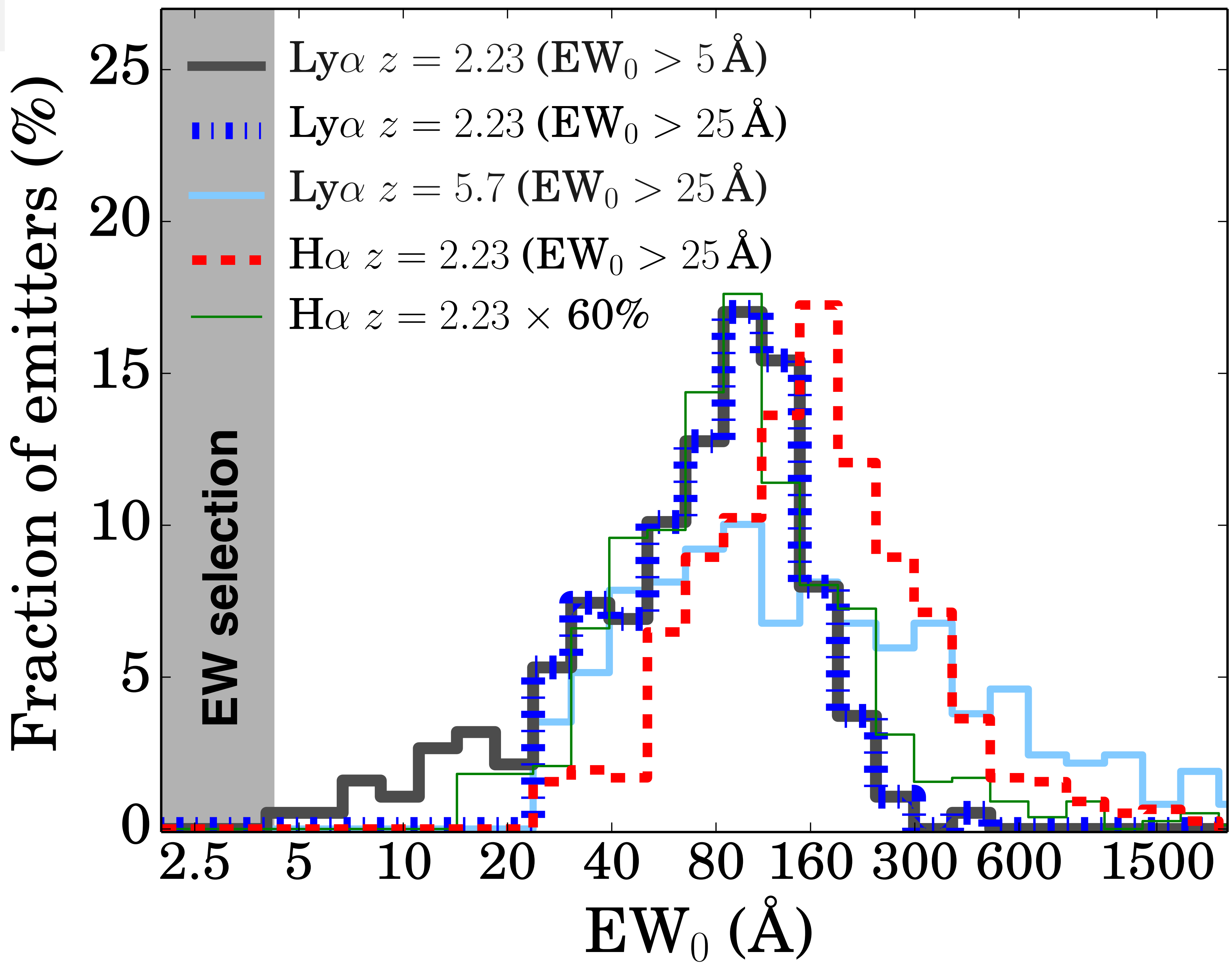
Constraints on LyC escape and relation to Lyα

- Global LyC escape fraction at z~2.2: very low (~3-5%).
- Maybe **<u>median (all SFGs) can even be actually 0.0%</u>** but a few strong LyC leakers
- 5% of sources (Lyα emitters?) may have large escape fractions, making it enough to account for f_{esc}



Matthee, Sobral et al. 2016; Matthee, Sobral et al. 2017a; Sobral, Matthee et al. 2017a


km s^{-1} -4000 -3000 -2000 -1000 Lyα +1000 +2000 +3000 +4000
Keck/DEIMOS
BR3 z = 3.090
B-H-NB5-10 z = 3.101
B-H-NB5-16 z = 3.085
B-H-NB5-27 z = 3.132
B-H-NB5-34(CUT) z = 3.082
B-H-NB5-37 z = 3.148
GN-NB5-3378 z = 3.152
GN-NB5-5878 z = 3.130
B-NB5-31679 z = 3.274
B-NB5-25550 z = 4.170
B-NB5-24390 z = 3.138
+2
0
-2
Δ arcsec
1200 1205 1210 1215 1220 1225 1230
Rest-frame wavelength (Å)
km s^{-1} -4000 -3000 -2000 -1000 Lyα +1000 +2000 +3000 +4000
VLT/XSHOOTER
SA22-LyINT-14 z = 3.114
SA22-LyINT-18 z = 3.093
SA22-LyINT-10 z = 3.102
CALYMHA-85 (star) z = 0.000
CALYMHA-383 z = 3.211
CALYMHA-415 z = 2.157
CALYMHA-438 ([OII]) z = 0.056
CALYMHA-373 z = 2.211
CALYMHA-67 z = 2.209
CALYMHA-147 z = 2.233
+2
0
-2
Δ arcsec
1200 1205 1210 1215 1220 1225 1230
Rest-frame wavelength (Å)



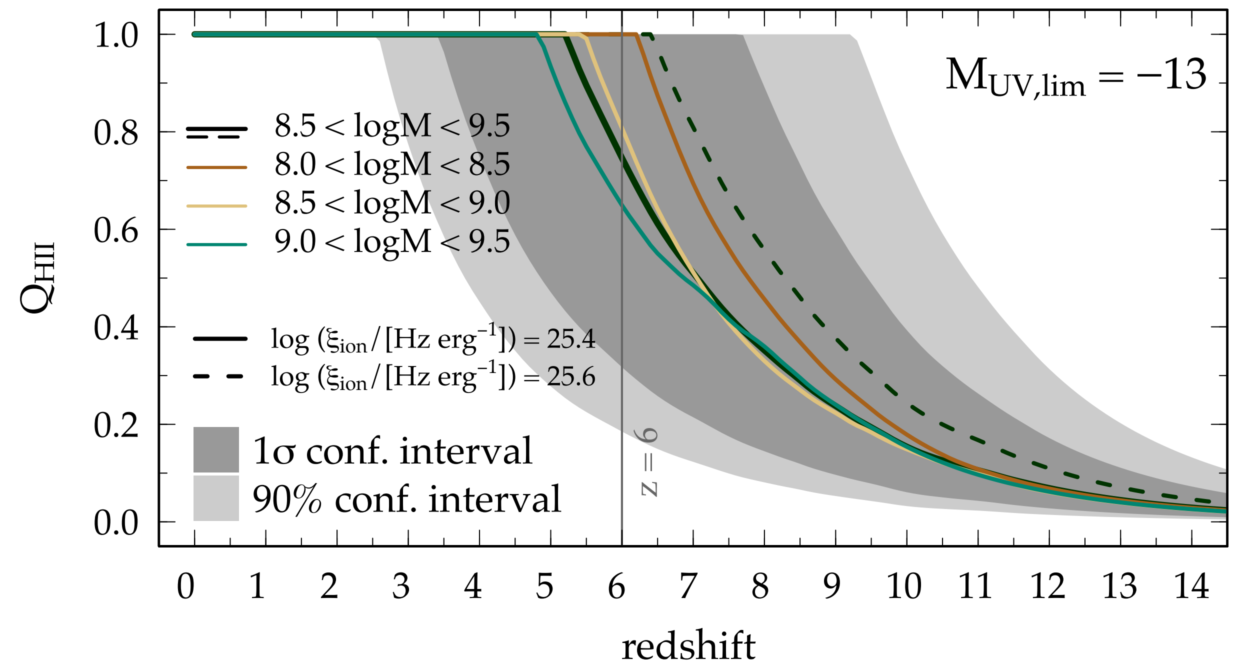
Fraction of emitters (%)
25
20
15
10
5
0
EW selection
Lyα z = 2.23 (EW0 > 5 Å)
Lyα z = 2.23 (EW0 > 25 Å)
Lyα z = 5.7 (EW0 > 25 Å)
Hα z = 2.23 (EW0 > 25 Å)
Hα z = 2.23 × 60%
2.5
5
10
20
40
80
160
300
600
1500
EW0 (Å)

The epoch of re-ionisation: what do we need?

- How and when did re-ionisation happen?
- What caused it?
- How heterogeneous was it?

$$\dot{Q}_{\mathrm{H\,II}} = \frac{\dot{n}_{\mathrm{ion}}}{\langle n_{\mathrm{H}} \rangle} - \frac{Q_{\mathrm{H\,II}}}{t_{\mathrm{rec}}},$$

$$\dot{n}_{\mathrm{ion}} = \overset{1}{f_{\mathrm{esc}}}\,\overset{2}{\xi_{\mathrm{ion}}}\,\overset{3}{\rho_{\mathrm{UV}}}$$



1 Fraction of LyC (ionising) photons that escape

2 How many LyC photons per UV luminosity

3 UV luminosity density

Robertson et al. 2013, 2015; Faisst 2016

e.g. Shapiro et al. 1994; Furlanetto et al. 2004; McQuinn et al. 2006; Iliev et al. 2006; Dijkstra 2014

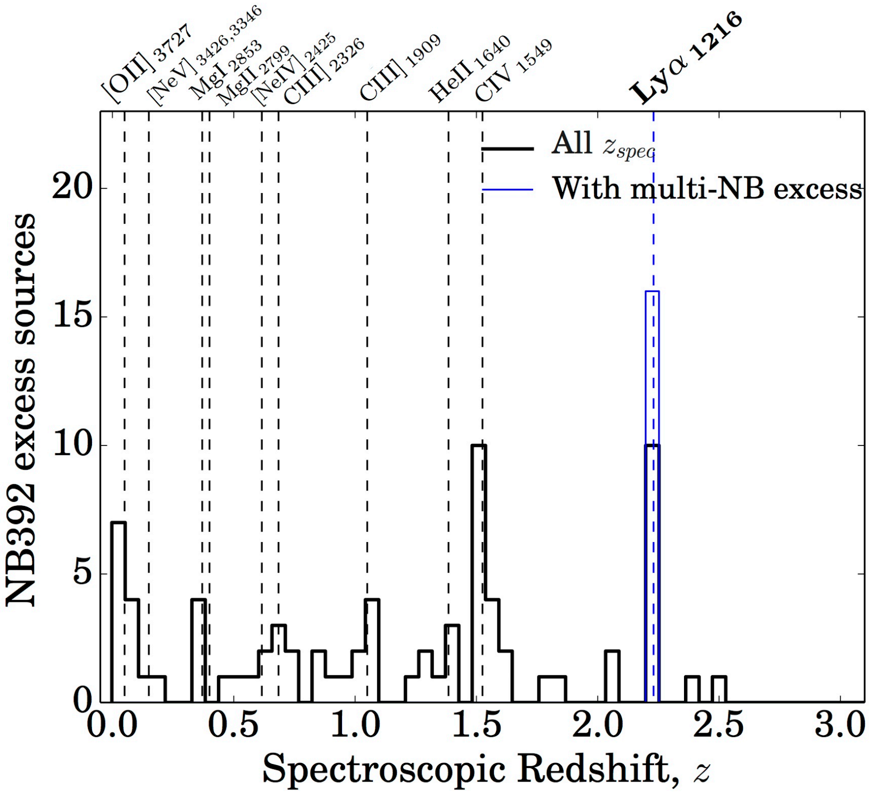
What we need to make new breakthroughs

- Well calibrated + sensitive
- Significant amount of telescope time
- Able to uniformly select large samples
- Different epochs + Large areas + Best-studied fields
- **A good, well-understood selection resulting in a representative population of galaxies for a given science case**
- Probe new and uncharted parameter spaces
- **Low to Residual “political feedback”**

(apart from a great hard-working team)

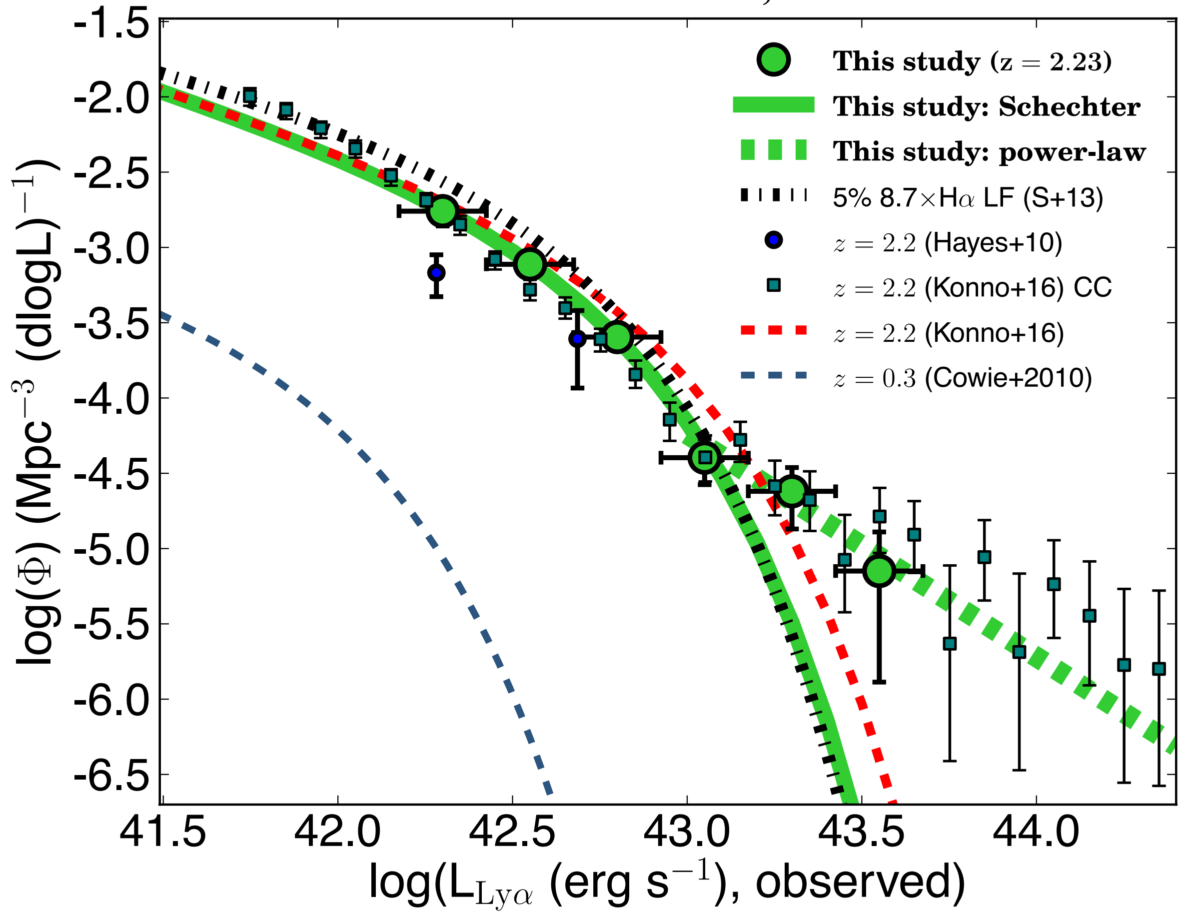
Escape of Lyα photons: cosmic averaged escape fraction

- “Traditional” ways of selecting Lyα emitters miss most real bright Lyα and introduce contaminants at bright end



Sobral, Matthee et al. 2017a

Sobral, Matthee et al. 2017a



- CIV, CIII], HeII and other UV lines can have high enough EWs to make it into the selection. **<u>They are important contaminants</u>**
- Interesting on themselves (statistical samples): Stroe et al. 2017a,b (in prep.)