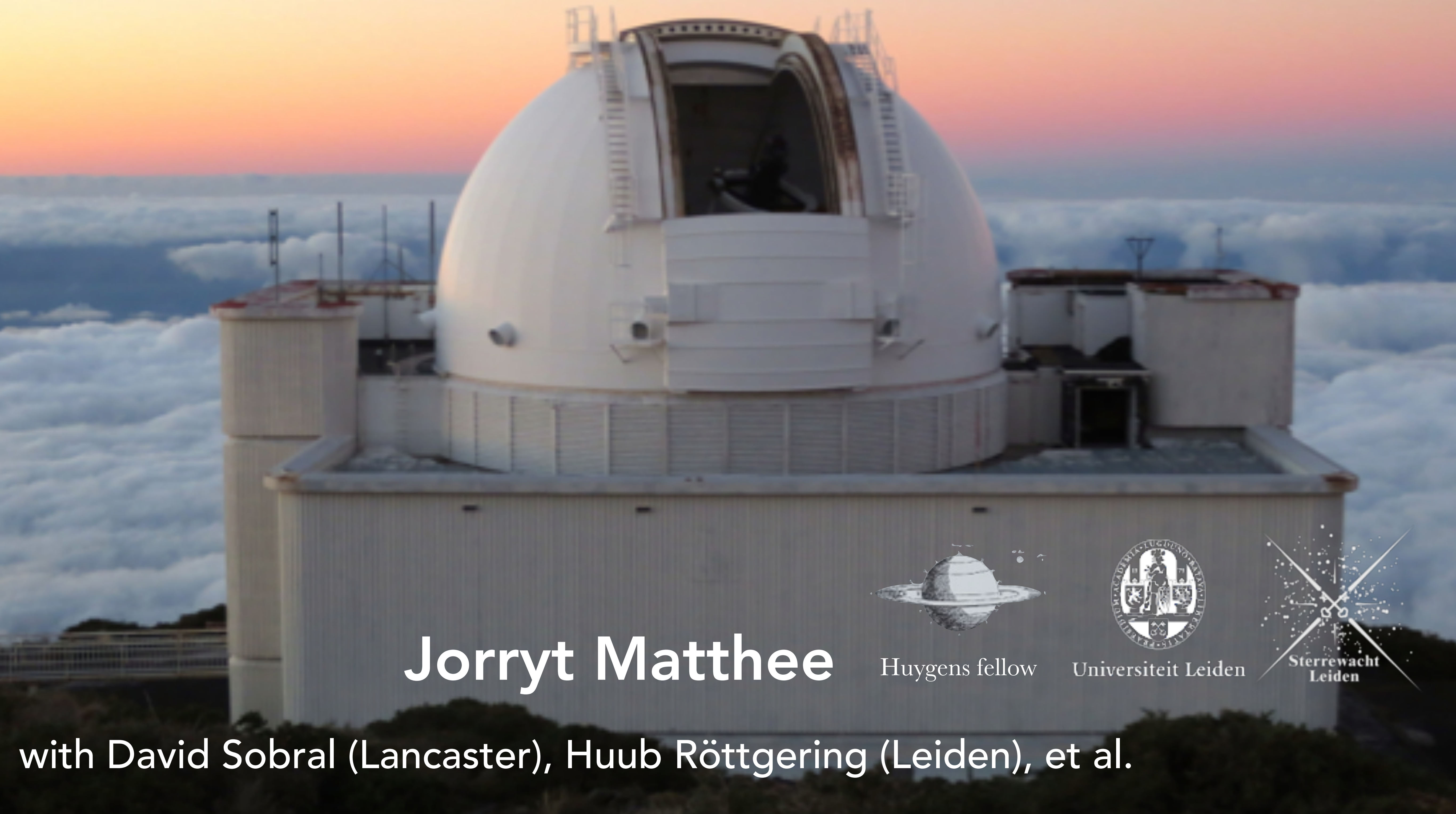
GALAXY FORMATION IN THE FIRST 3 GYRS WITH WIDE FIELD LYMAN-ALPHA SURVEYS*

*WITH THE INT AND WHT



Jorryt Matthee

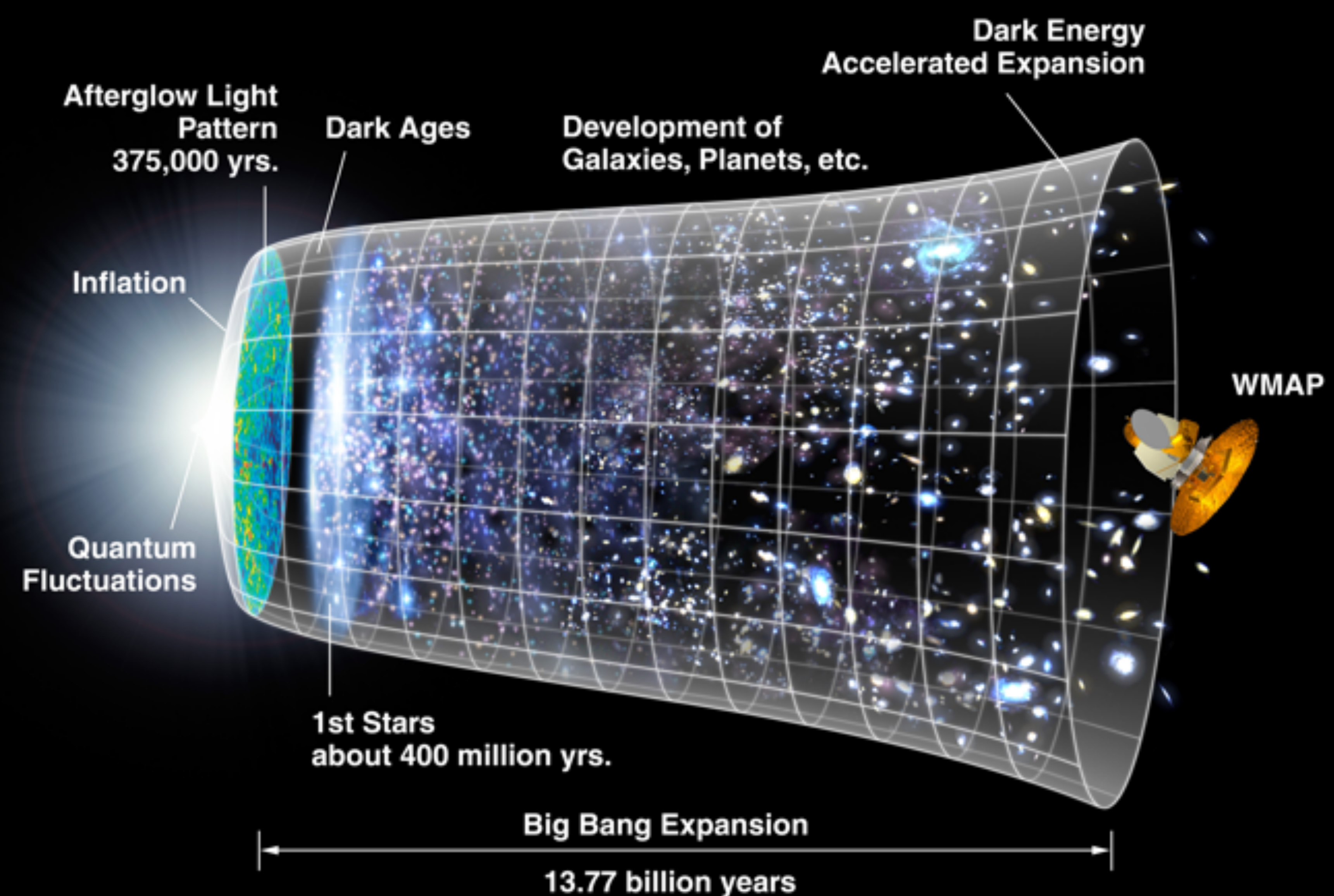
Huygens fellow

Universiteit Leiden

Sterrewacht Leiden

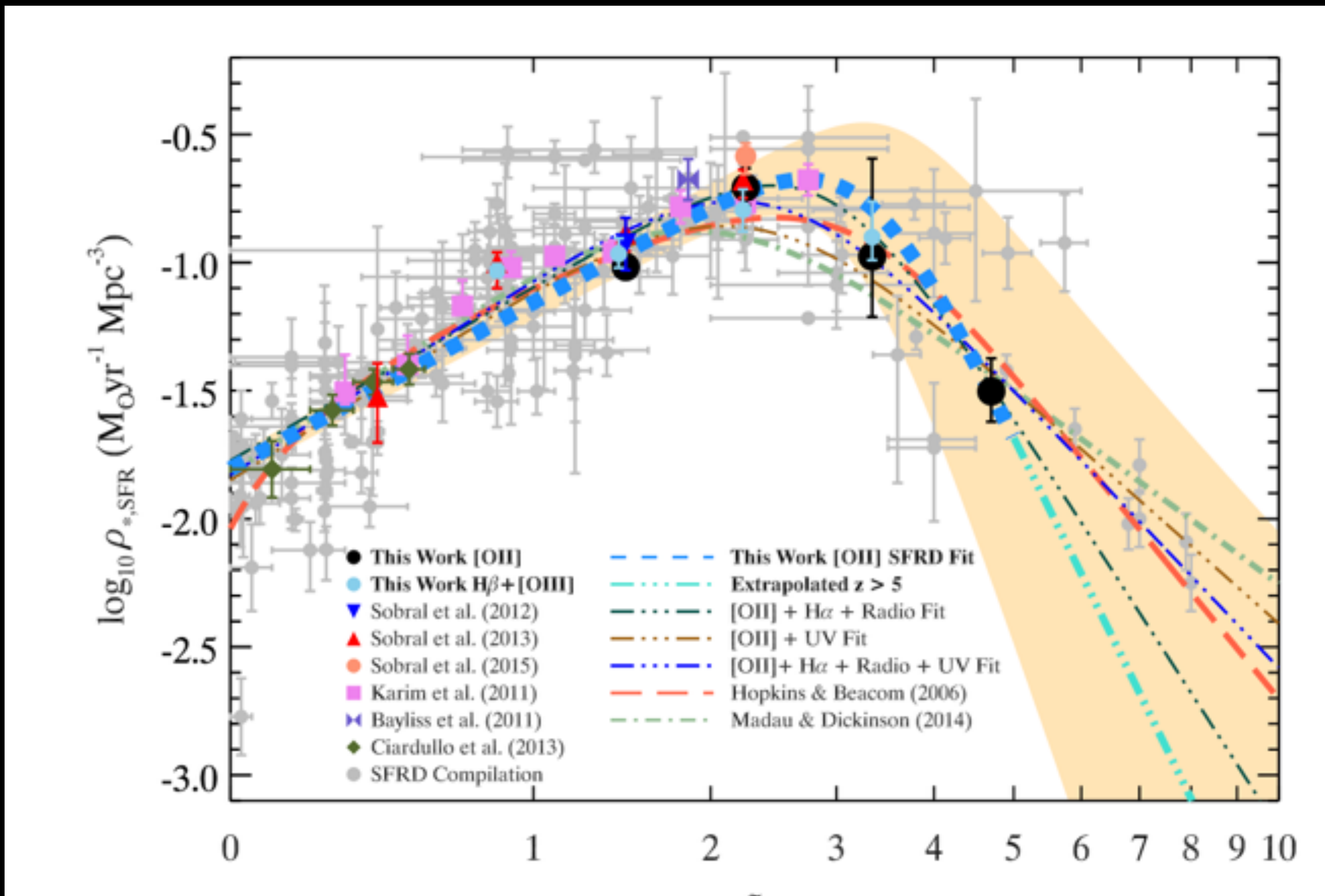
with David Sobral (Lancaster), Huub Röttgering (Leiden), et al.

When and how did the first stars and galaxies form?

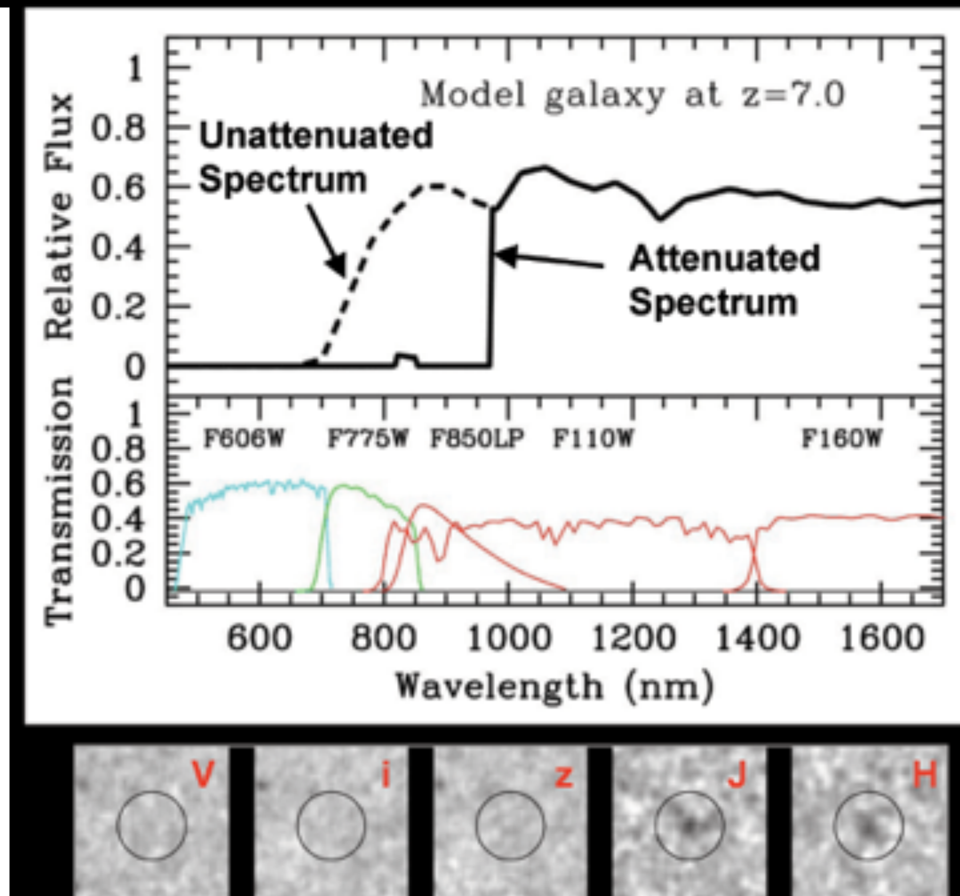


NASA/WMAP Science Team

STAR FORMATION HISTORY OF THE UNIVERSE



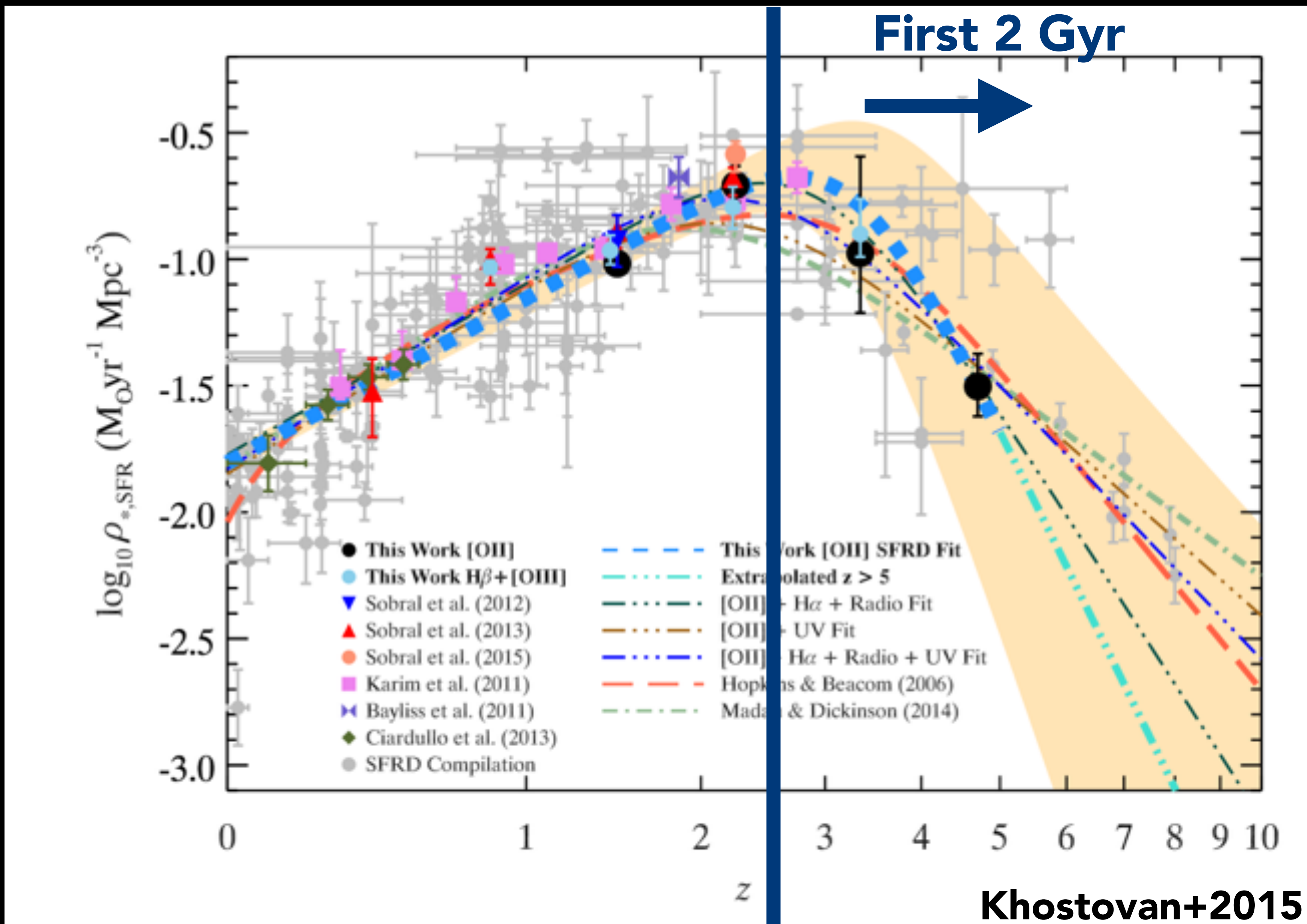
Khostovan+2015

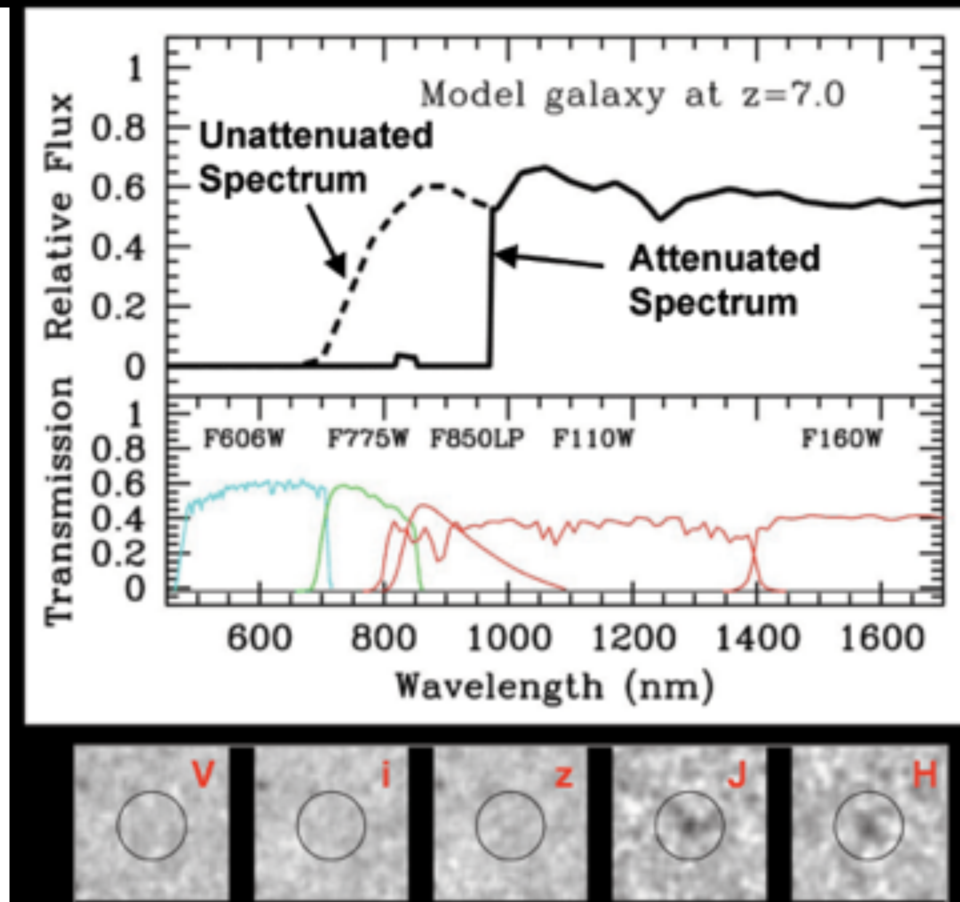


R. Bouwens

History of cosmic star formation peaks at z~2: 11 Gyr ago

STAR FORMATION HISTORY OF THE UNIVERSE



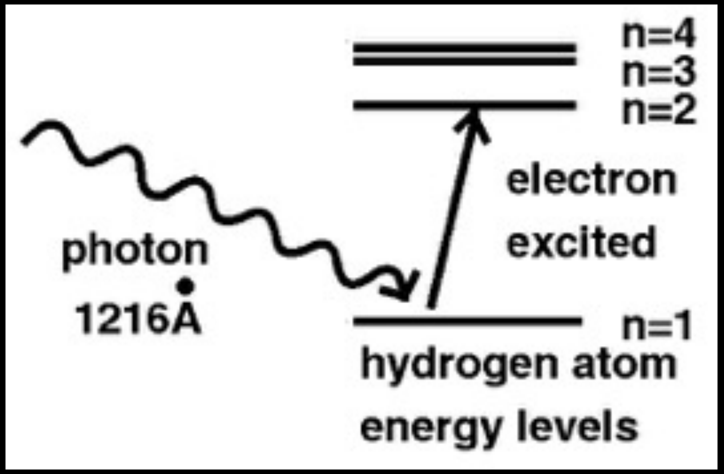


R. Bouwens

Lyman-break technique

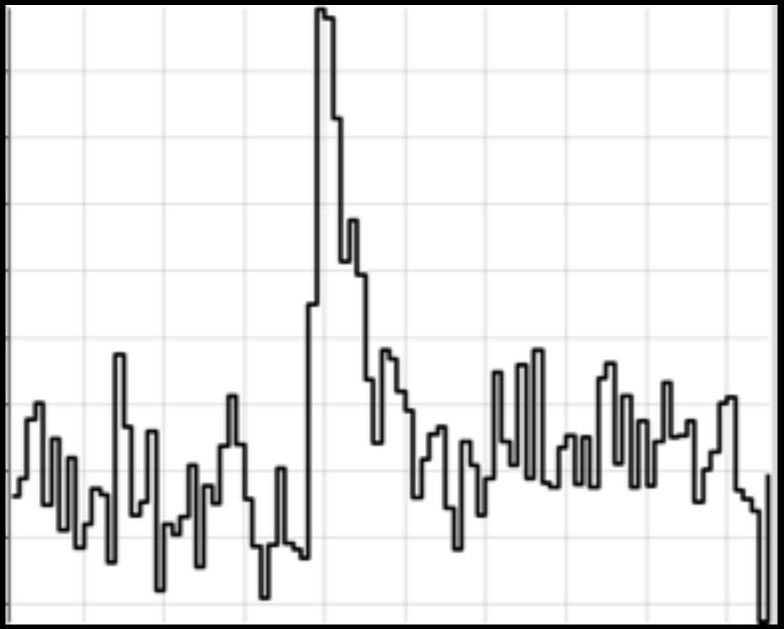
At z>2.3: normal optical emission line diagnostics ~impossible, hard to measure accurate SFR, metallicity, etc

LYMAN-ALPHA IS OUR BEST SPECTROSCOPIC TOOL AT Z>2.3



+ 1216 Å redshifts into optical at $z > 2$

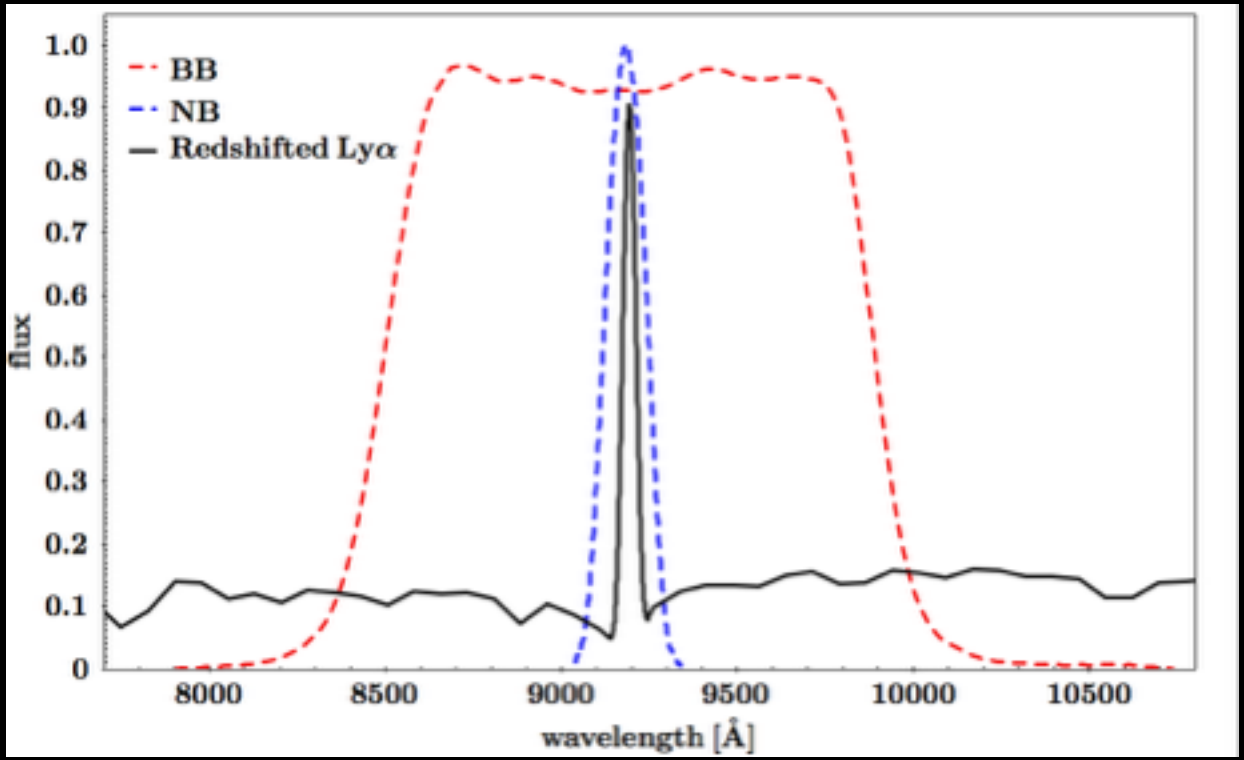
+ intrinsically most luminous emission line in star-forming HII regions

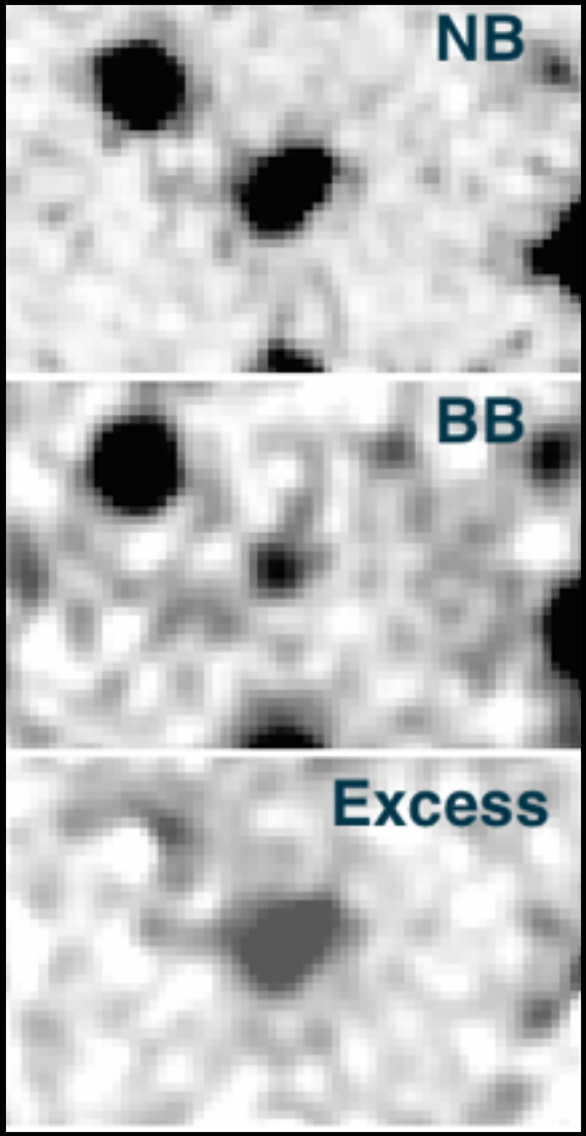


- line-resonance leads to scattering: (tau=1 at $N_H \sim 10^{14}$ cm^{-2})
  - > not all galaxies emit observable Lya
  - > neutral hydrogen spreads Lya light

The narrow-band technique

directly targets galaxies with redshifted Lyman-alpha (1216Å) at z=2.2, 3.1, 4.8, 5.7, 6.6, 7.7, 8.8



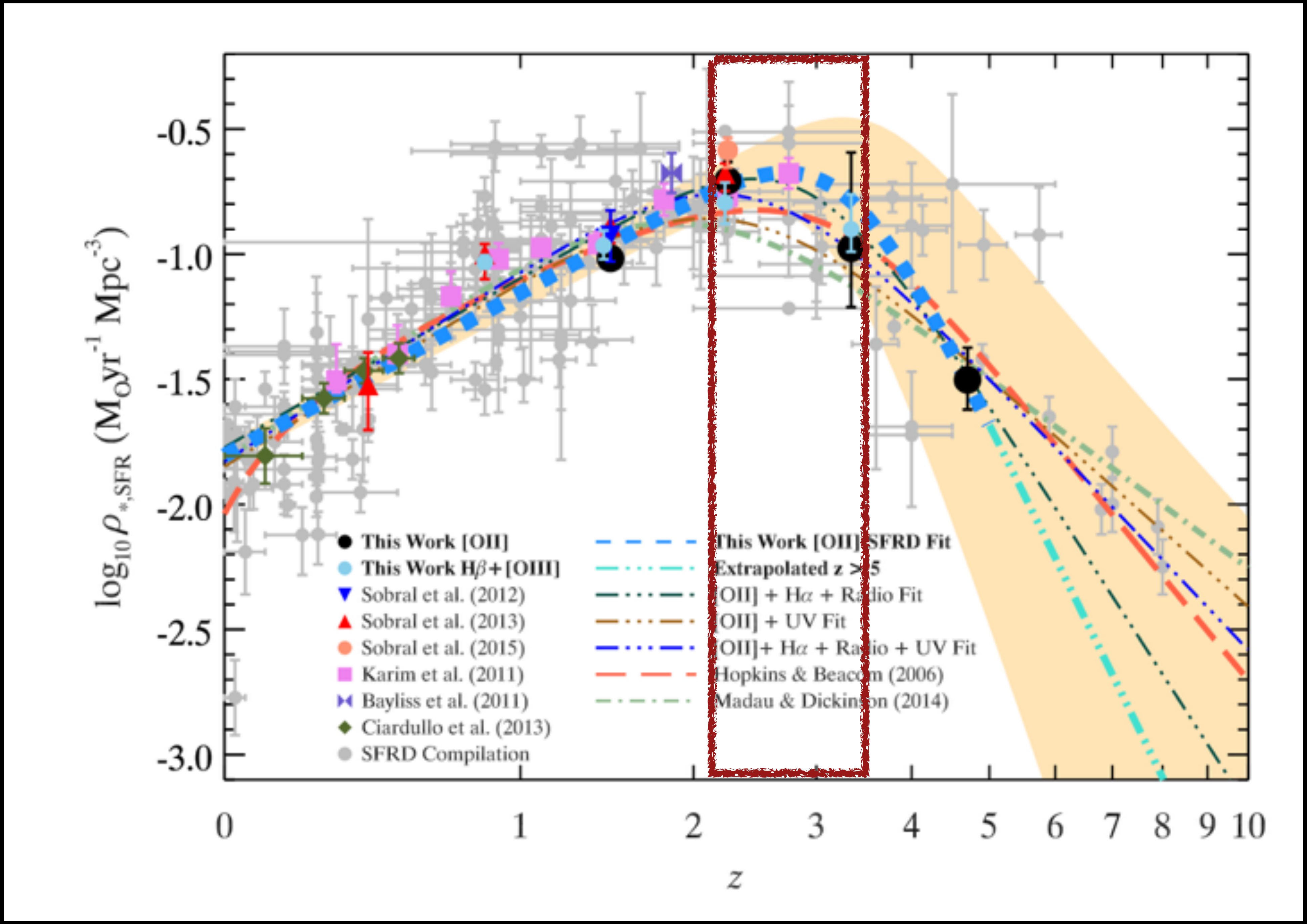


Lyman-alpha typically traces young OB stars, low metallicity (low dust), hot sources

Ouchi+2008,2010; Konno+2014; Matthee+2014,2015; Murayama+2008
Nilsson+2007; Hu+2011; Malhotra&Rhoads2000,2004; Hayes+2010, +++

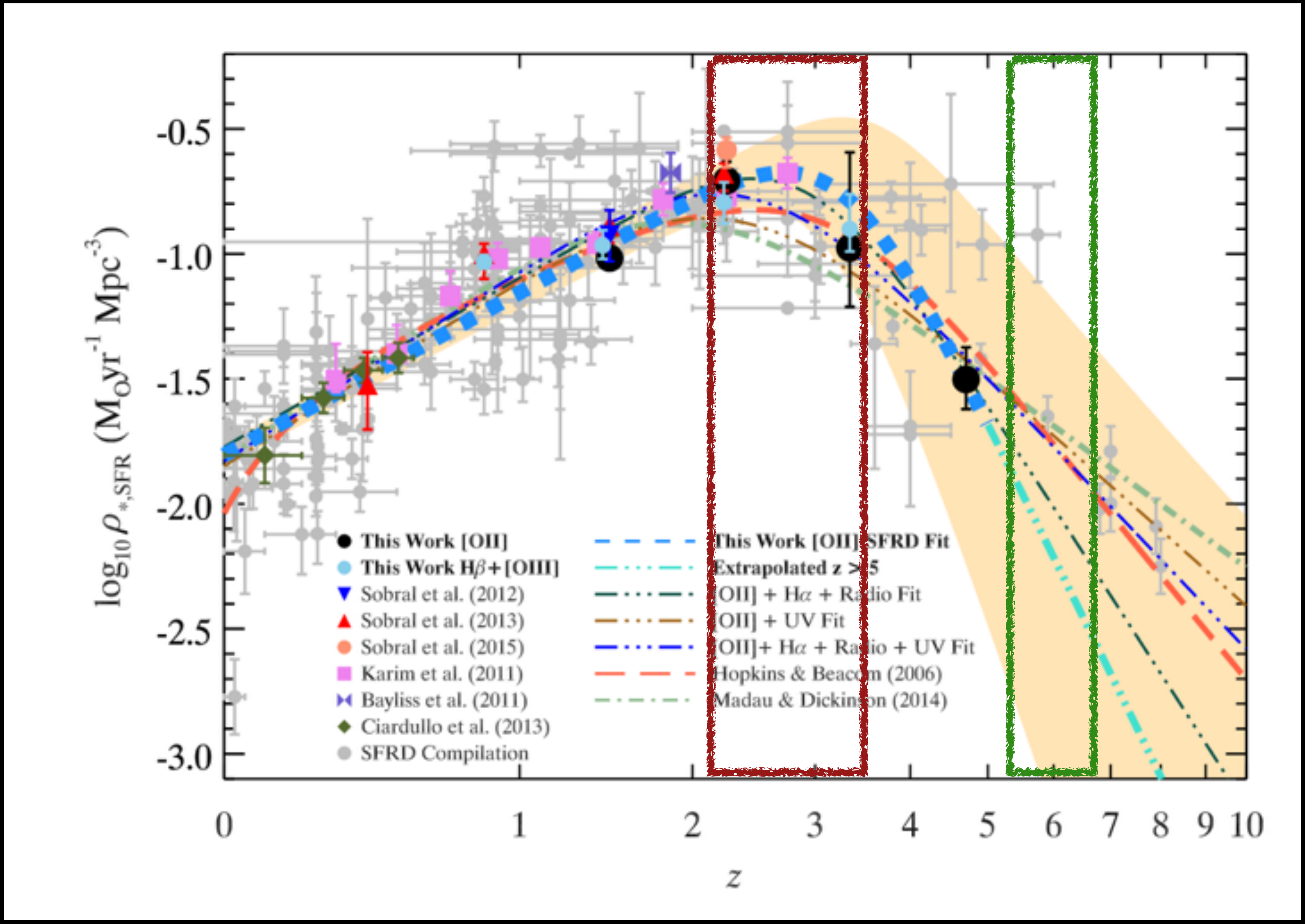
sources that can be followed up *easily*

TIME TRAVELLING WITH LYMAN-ALPHA



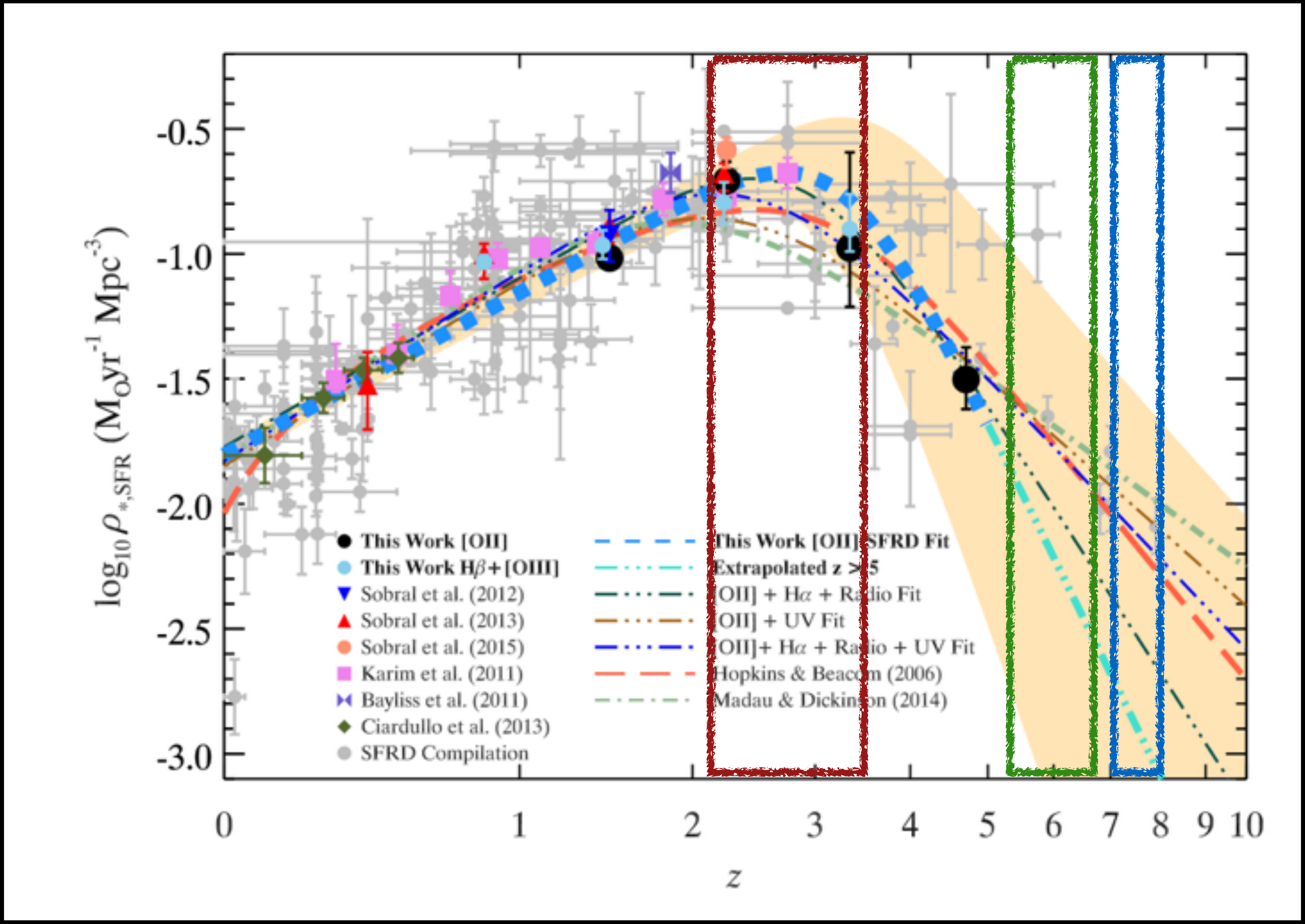
from the "epoch of galaxy formation"

TIME TRAVELLING WITH LYMAN-ALPHA



to the end of the dark ages

TIME TRAVELLING WITH LYMAN-ALPHA



and beyond

Before going: where are we actually going to travel to?

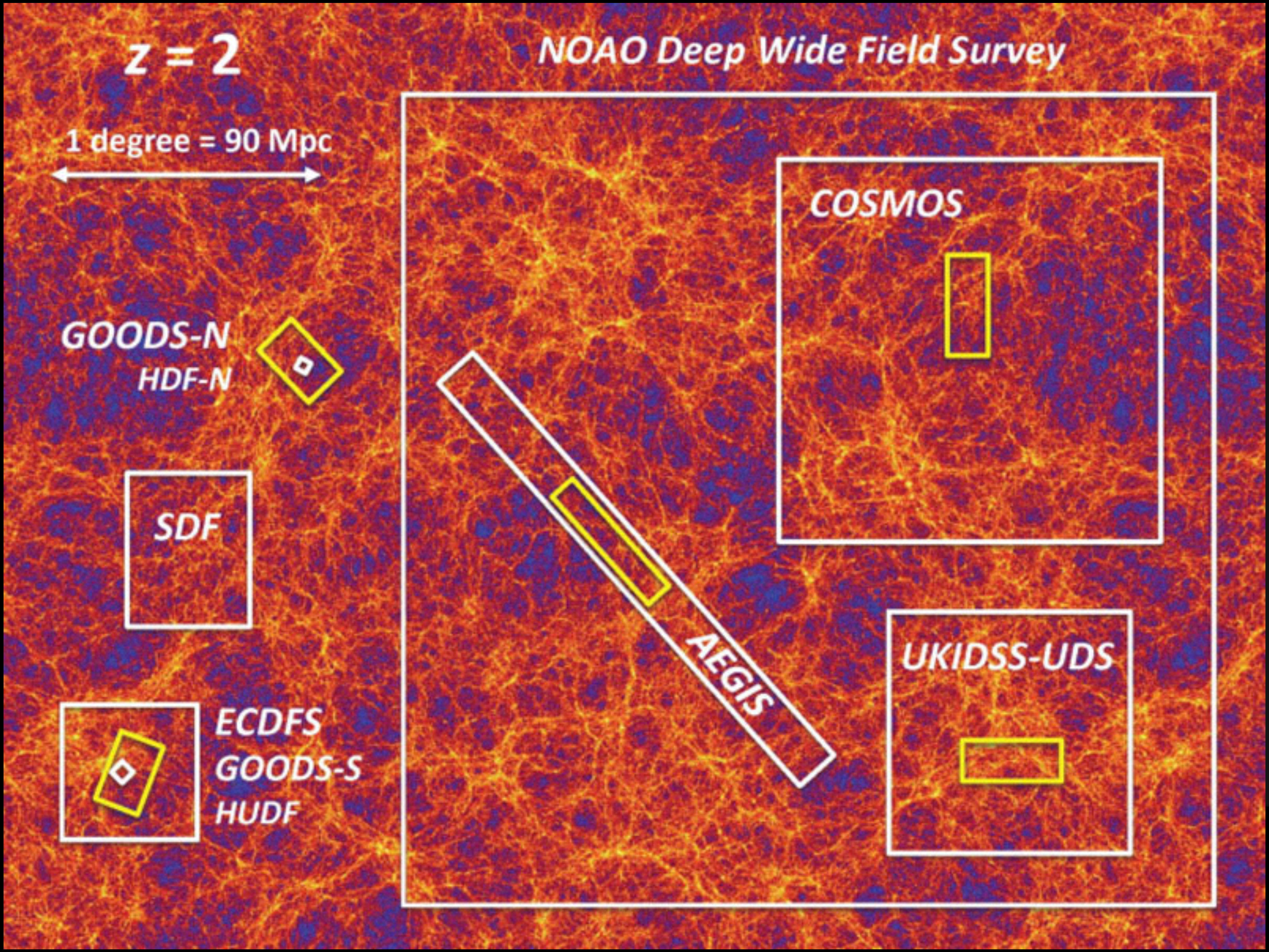
HST Deep fields may not be the best place to go…

HST Deep fields may *not* be the best place to go to..

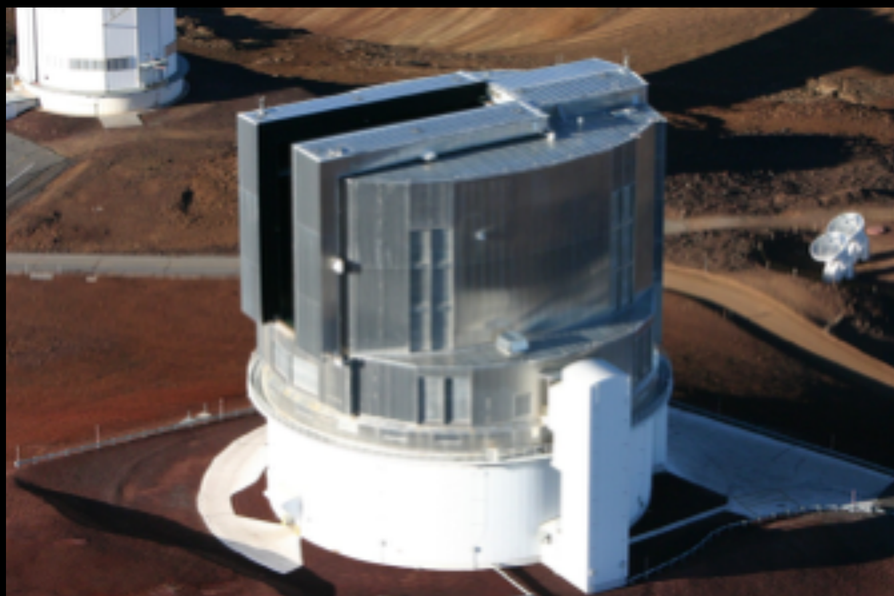
CANDELS+ERS+BoRG (~all HST deep fields)

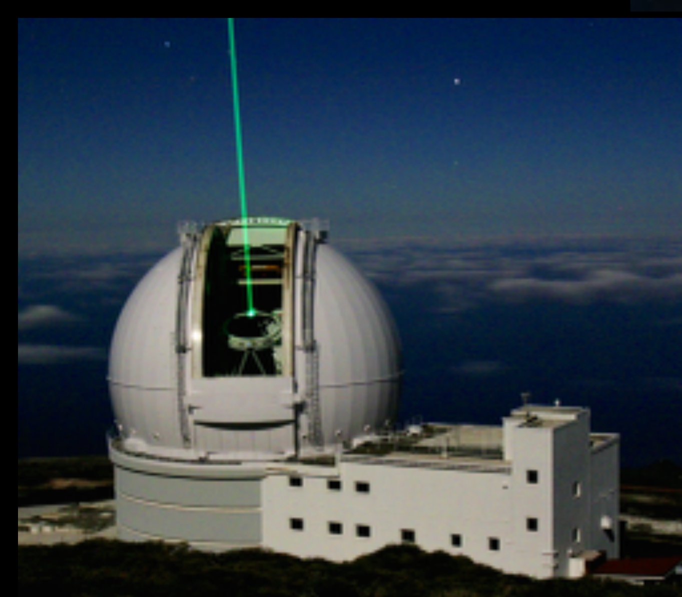
10,000 galaxies z>3 (e.g. Bouwens+2015), but only handful of bright objects at z>6

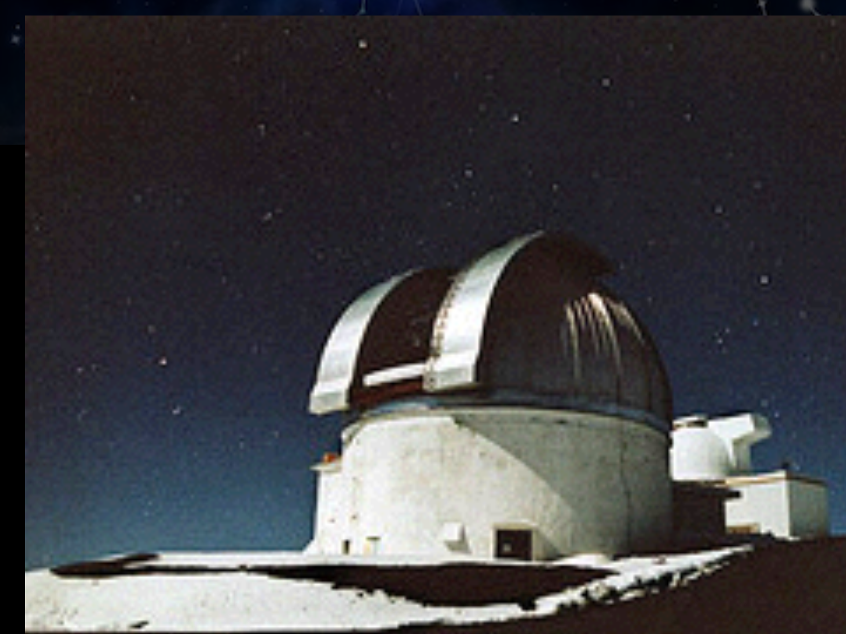
Pencil-beam surveys may give a biased view of galaxy formation



Our approach: wide fields from the ground

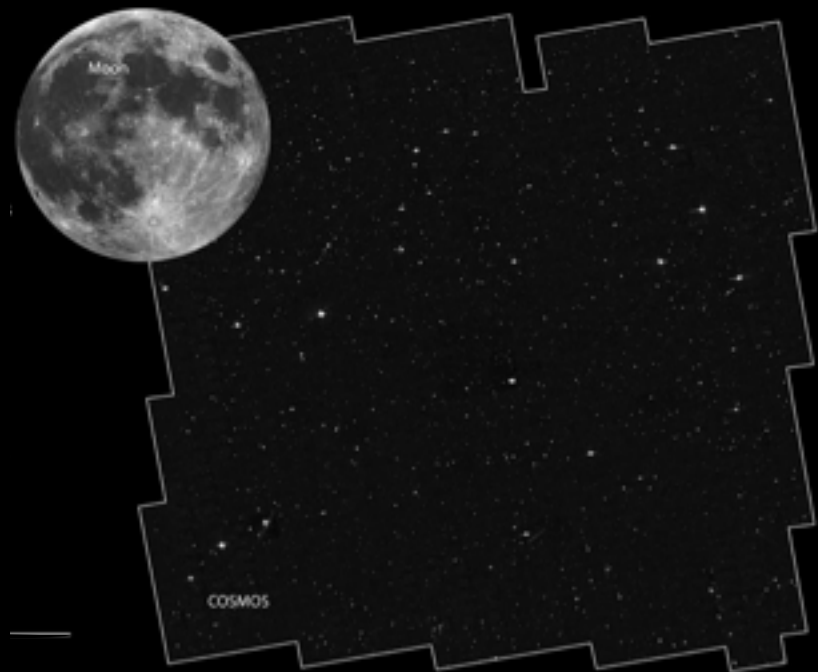


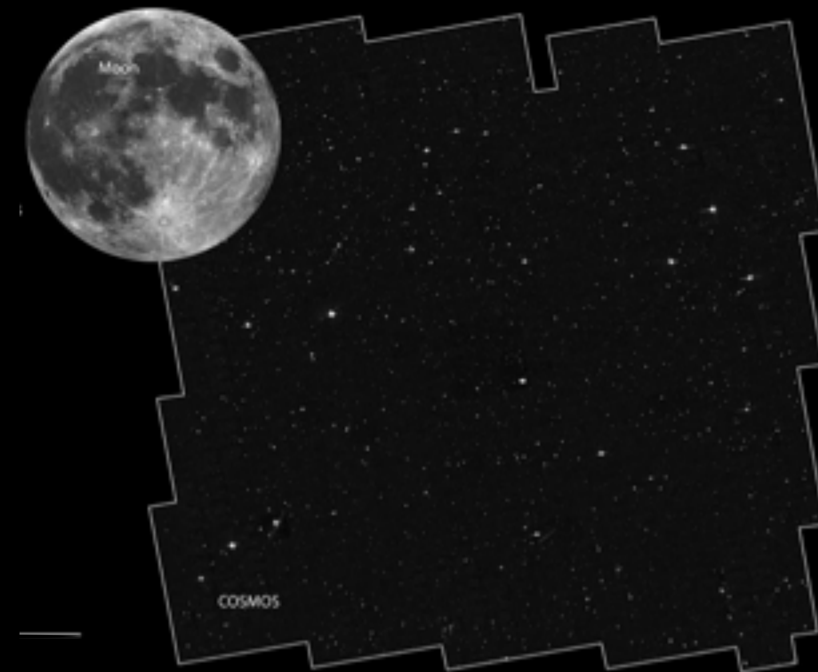


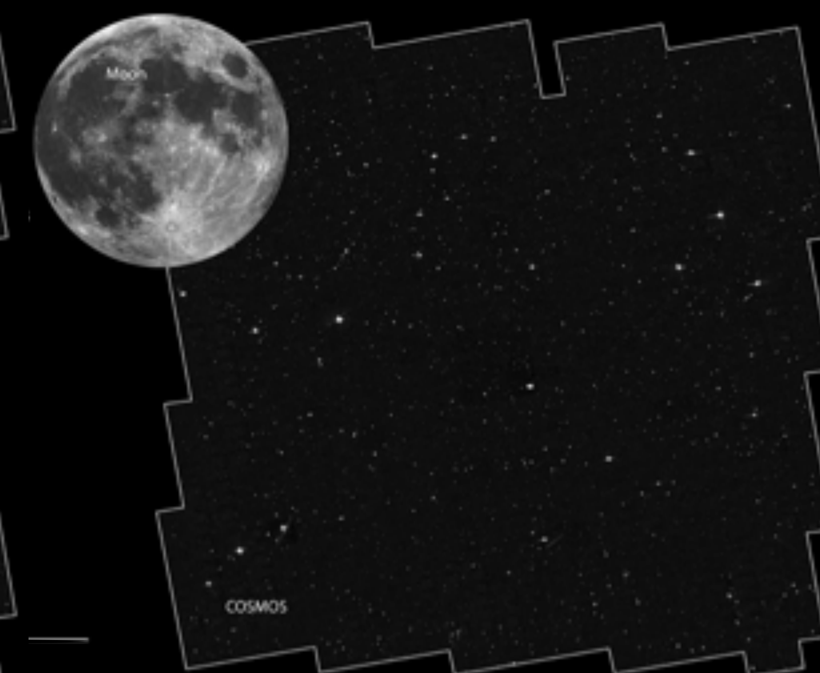


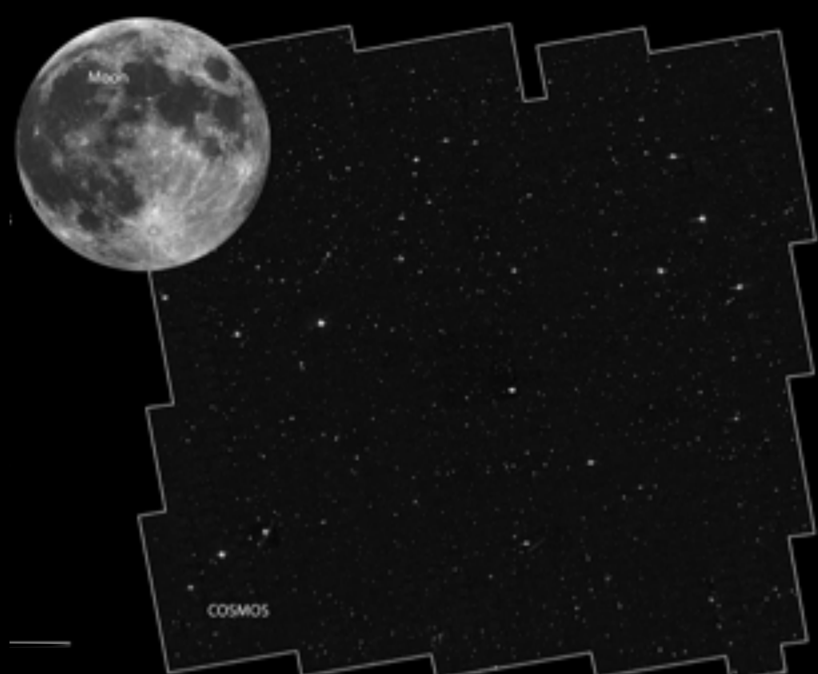
Our typical coverage

COSMOS/UltraVISTA
UDS/XMM-LS
SA22/CFHTLS
Boötes/NDWFS







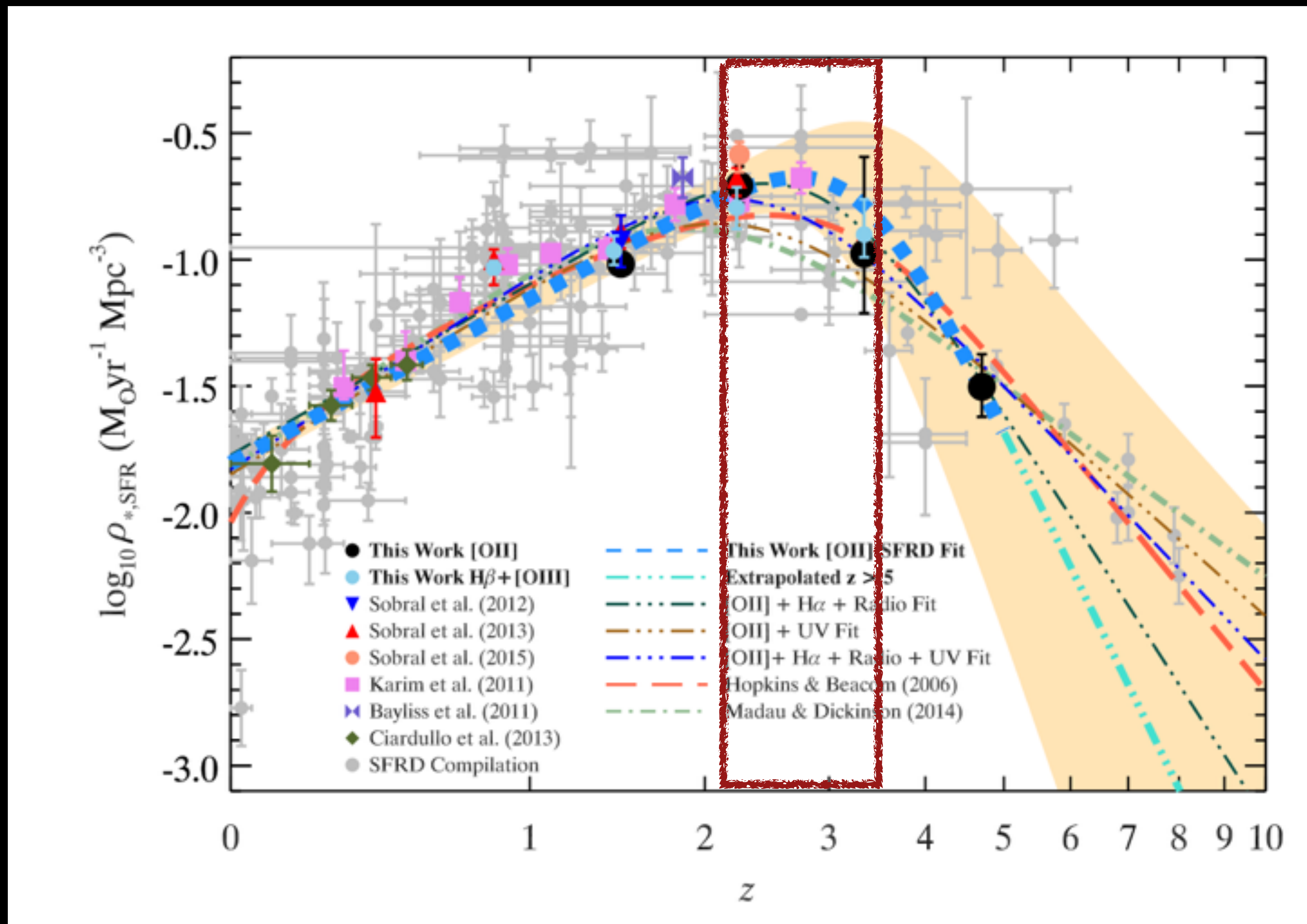


find bright targets

~20 times larger than combined HST fields, ~2 magnitudes shallower

First stop: the peak of star formation history (z=2, 11 billion years ago)

CALYMHA



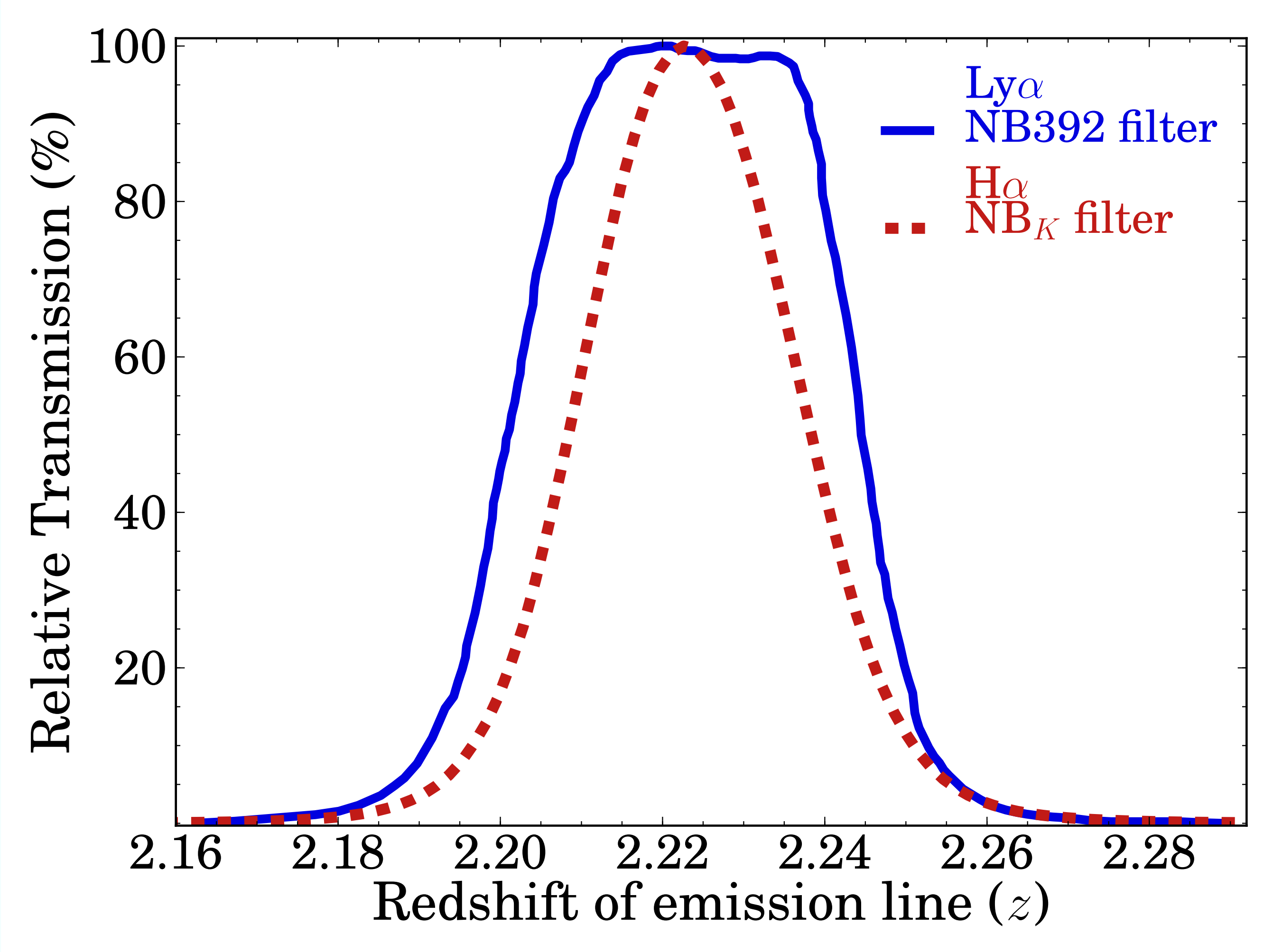
Our last chance of calibrating Lyman-alpha directly

CALYMHA: MATCHED (NARROW)-BAND TECHNIQUE

z=2.2:

NB392 gets Lyα, NB_J [OII], NB_H [OIII], NB_K Hα

772 Hα emitters at z=2.23 from HiZELS (NB_K imaging)



SFR 5-250 Msun/yr

Mass $10^{8.5\text{-}12}$ Msun

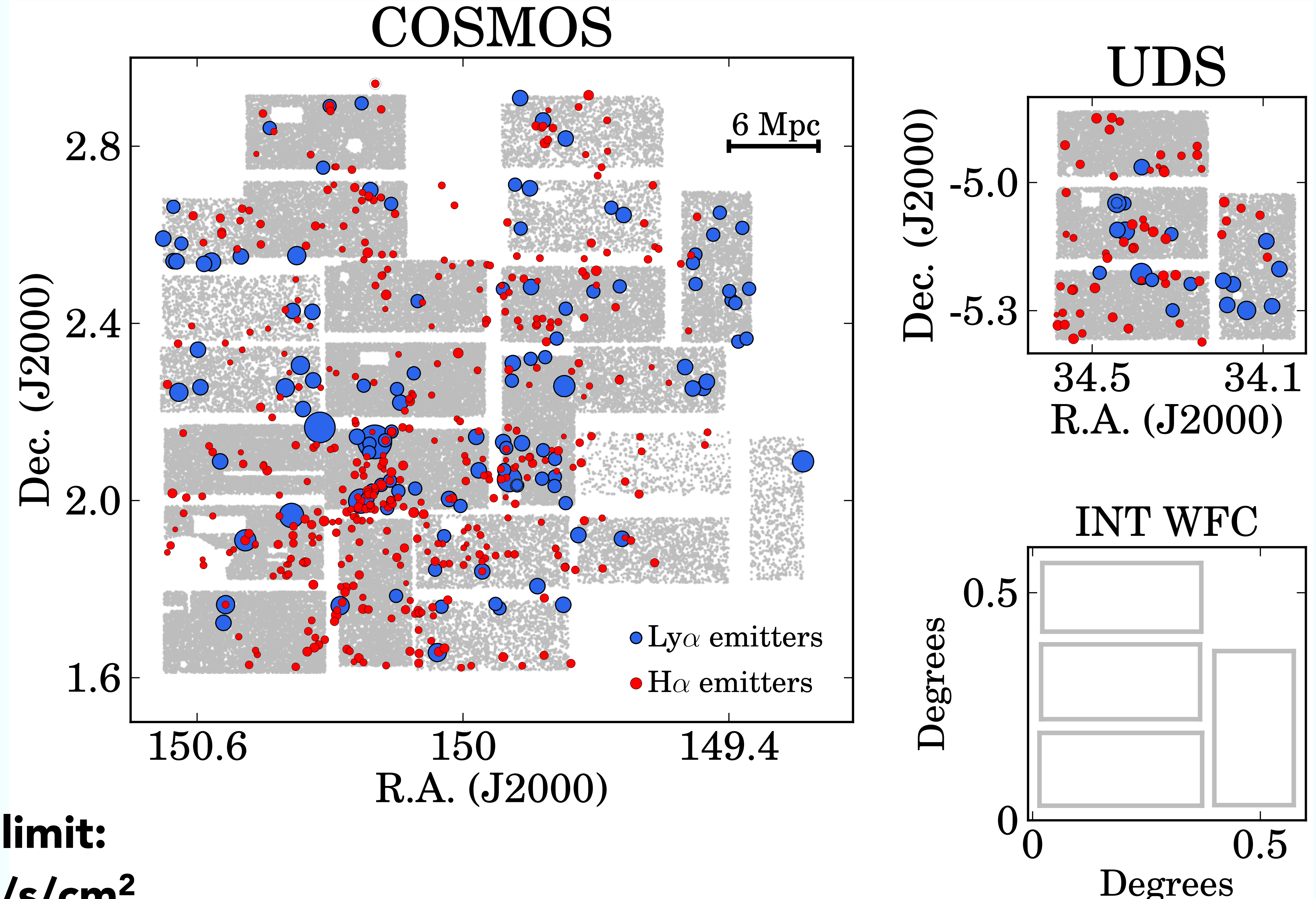
wide range of environments

Lyα filter designed to match Hα

Similar technique: Sobral+2012, Nakajima+2012, Hayes+2010

CALYMHA: OBSERVATIONS OVERVIEW

~40 dedicated nights at the INT on La Palma, May 2013-January 2015



Lya line-flux limit:
~4x10^{-17} erg/s/cm^2
Typical seeing in U band 2"

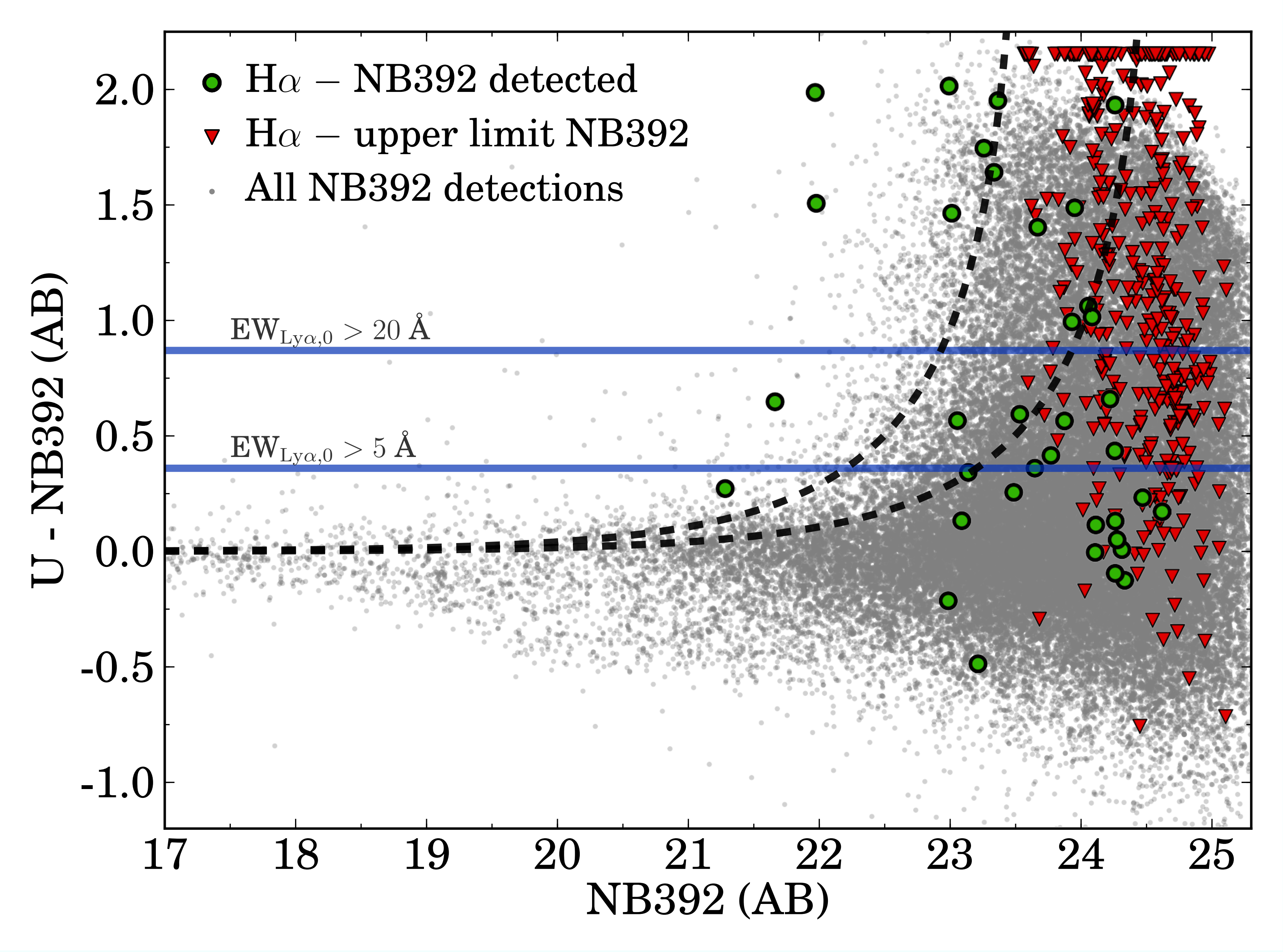
2.5m telescope

HA-LYA EMITTERS AT Z=2.2

588 HAEs are covered by NB392 observations.

Only 17 are directly detected as LAE. 5 of these are X-ray AGN.

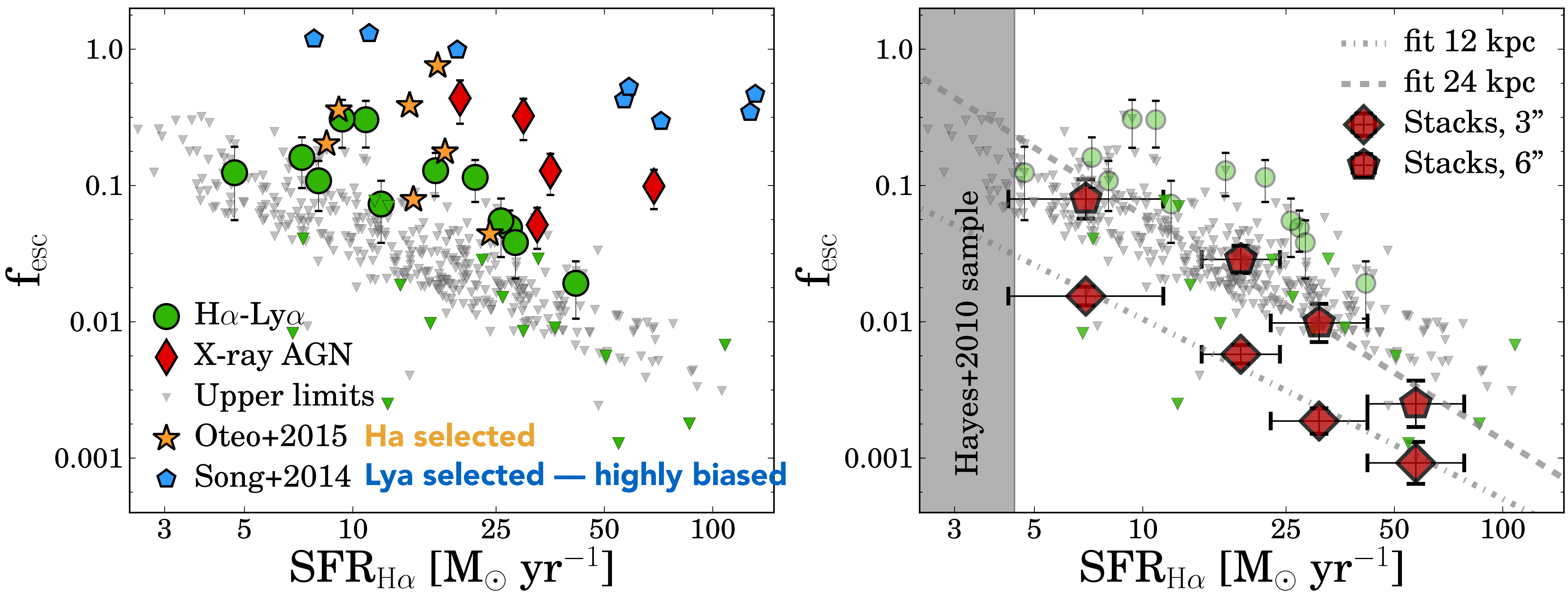
> only ~5% of SFGs are LAEs if you select on ~L* Hα



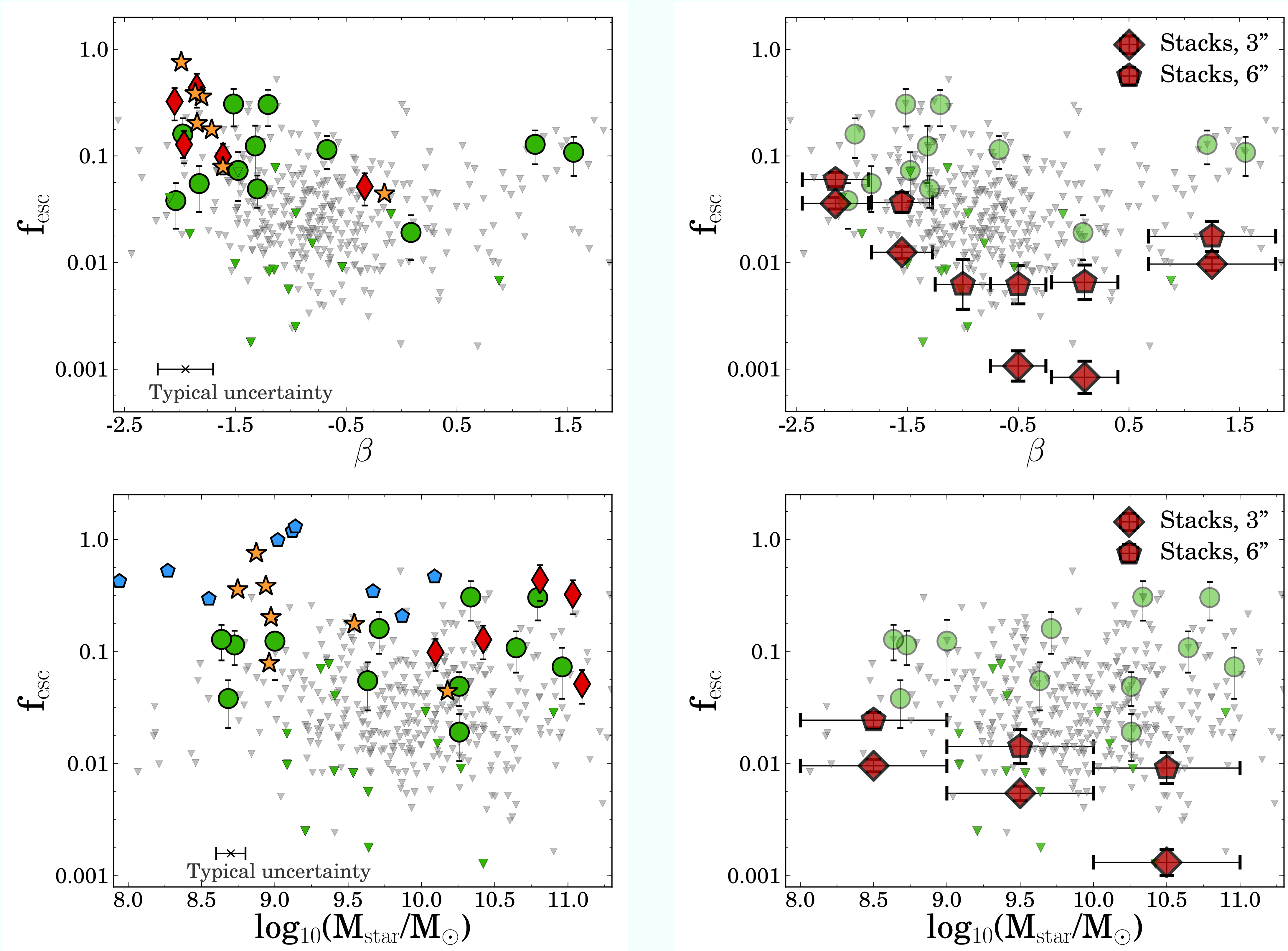
THE LYMAN-ALPHA ESCAPE FRACTION

Fraction of produced Lya light that we observe in 3″ aperture

for typical star-forming galaxies: $f_{esc,Lya}$ = 1.6+-0.5 %



CORRELATIONS WITH GALAXY PROPERTIES: BIMODAL RELATIONS (!)



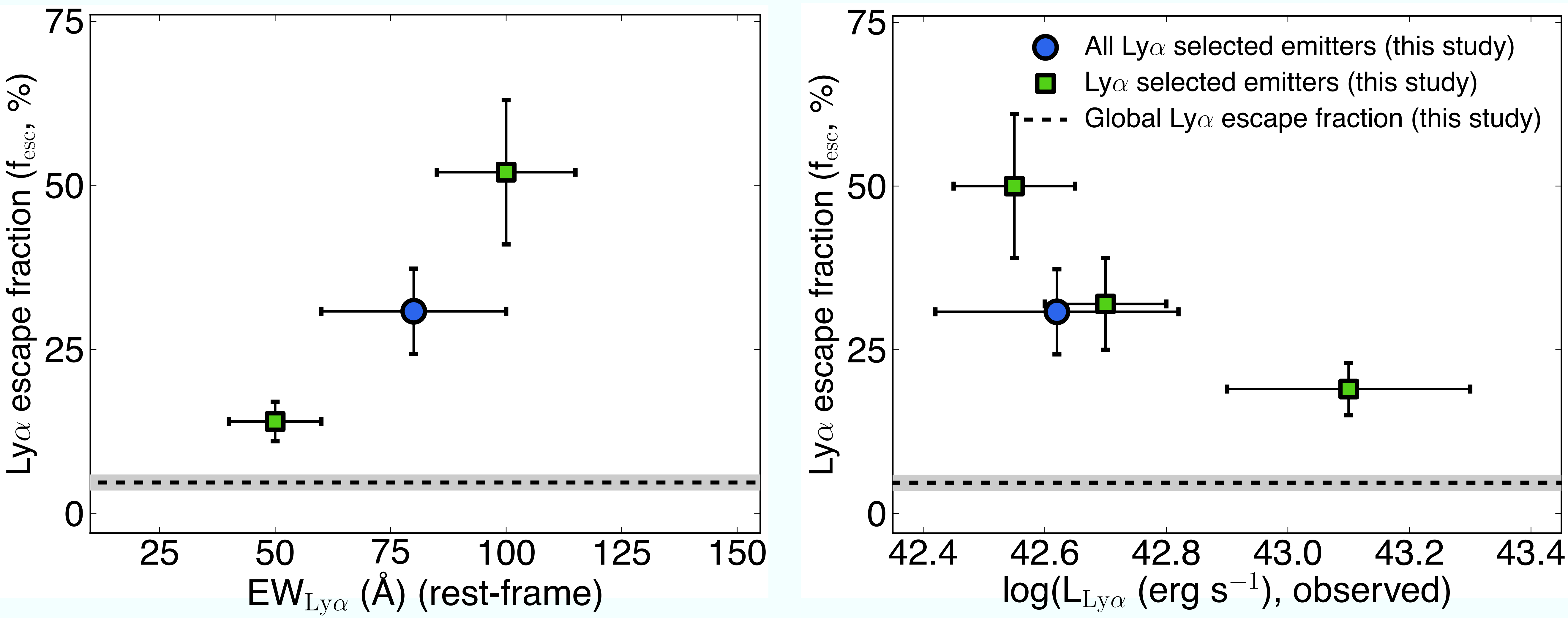
RED and massive LAEs exist (even without AGN)

LYMAN-ALPHA SELECTED GALAXIES

188 LAEs, typically not detected in Hα: much lower SFR

stack of LAEs: $f_{esc,Lya}$ = 37+-7 %:

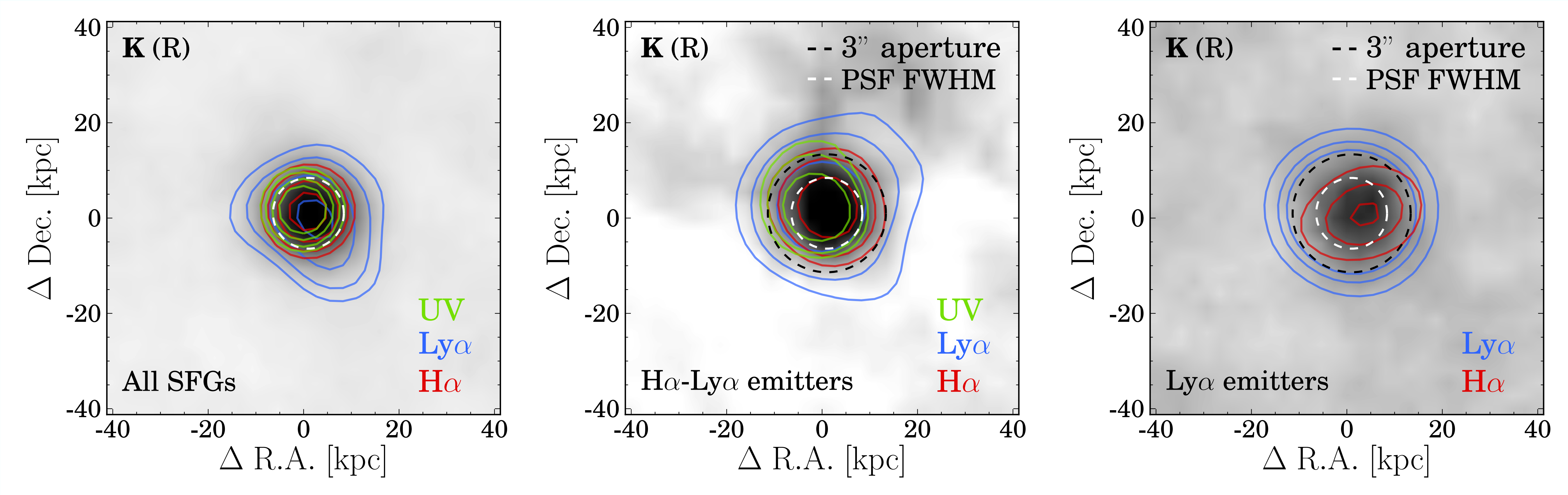
$f_{esc,Lya}$ increases with lower Luminosity/higher EW



Sobral, Matthee, et al. 2016, arXiv: 1609.05897

EXTENDED LYMAN-ALPHA EMISSION IN STACKS

~3000 hours NB392 ~80 hours ~1500 hours

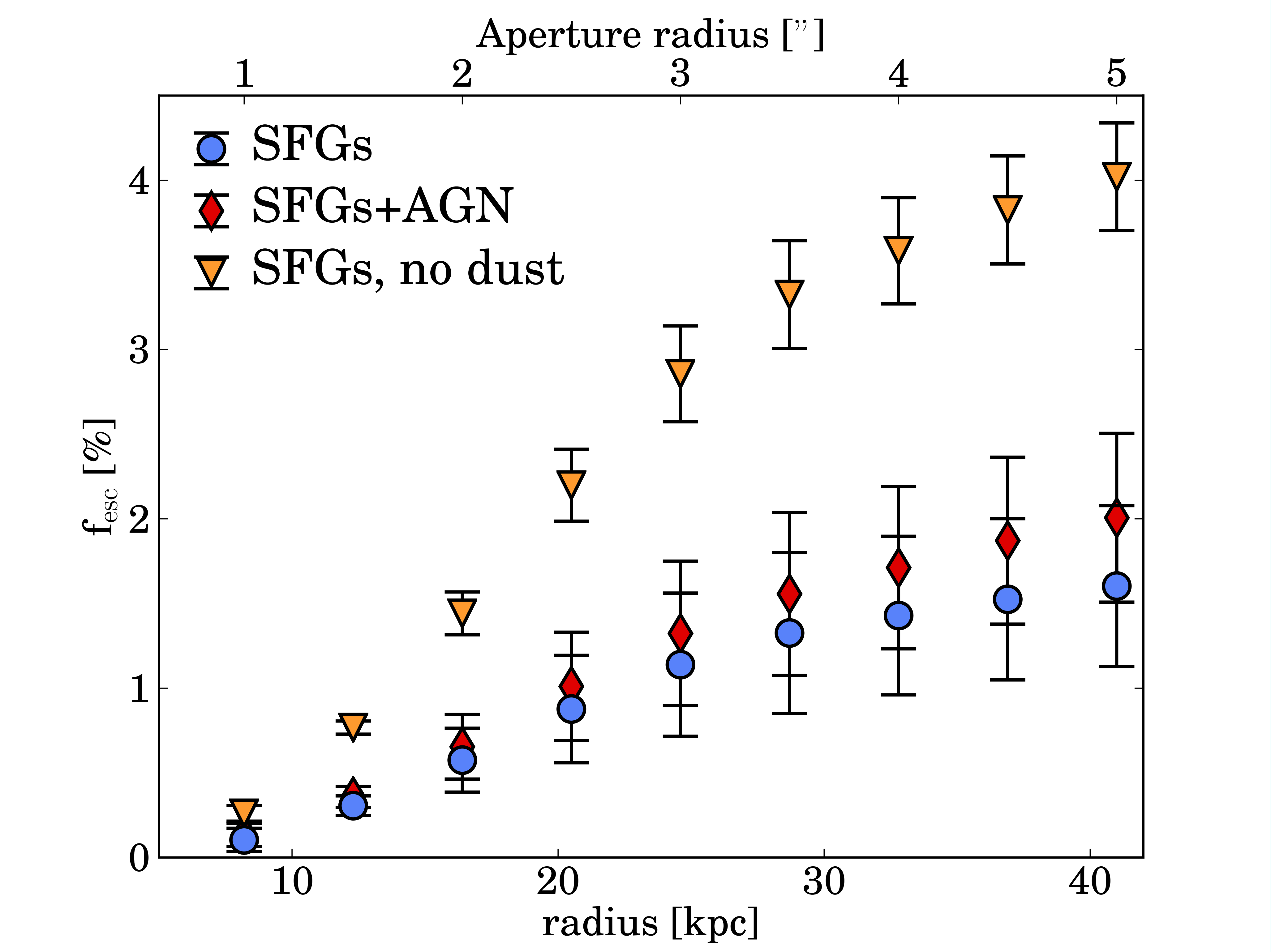


Hα/UV is not as extended as Lyα, indicative of resonant scattering?

Matthee et al. 2016, MNRAS, 458, 449

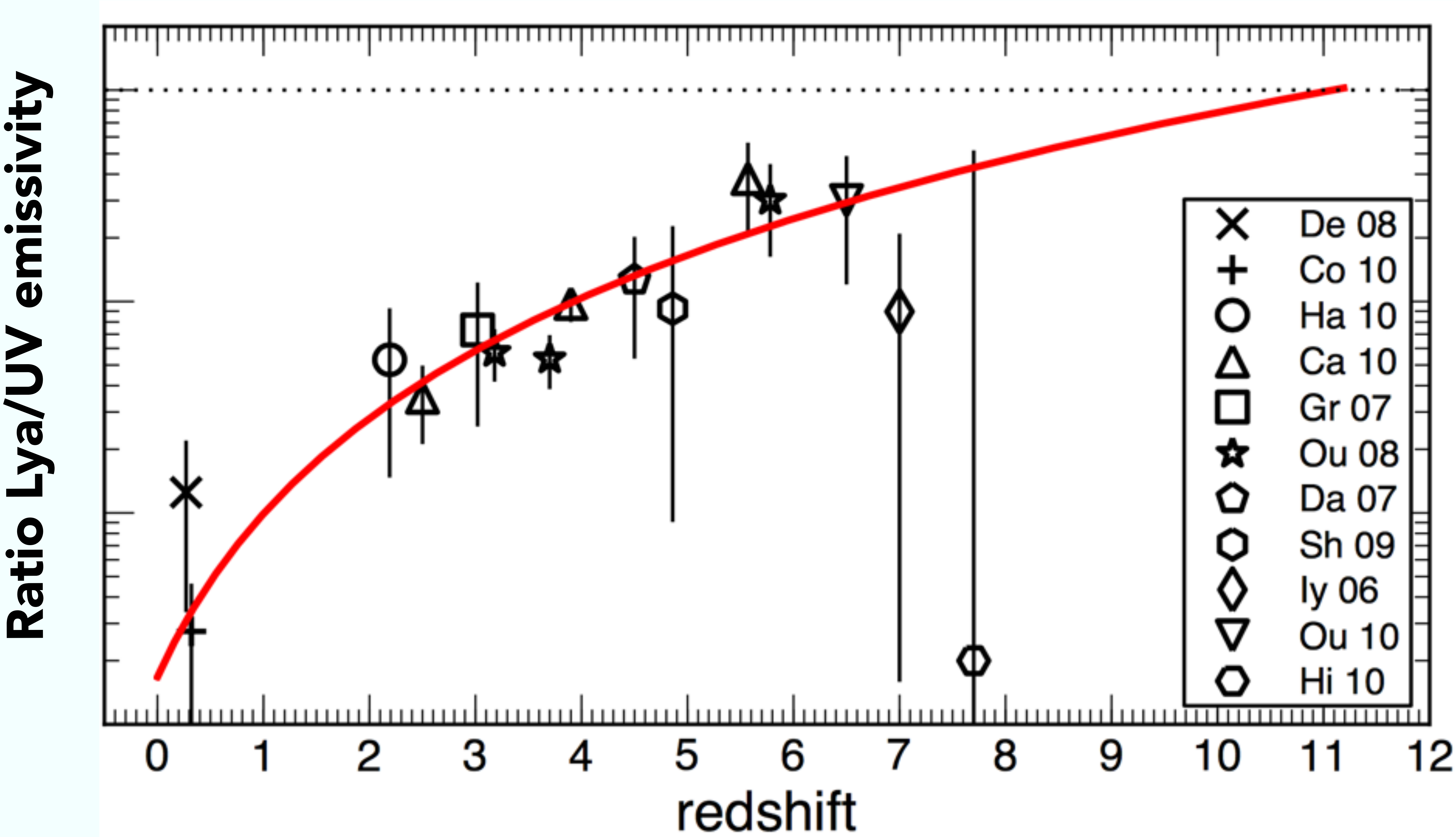
Sobral, Matthee, et al. 2016, arXiv: 1609.05897

EXTENDED EMISSION DRIVES LYA ESCAPE



Matthee et al. 2016, MNRAS, 458, 449

INDIRECT ESTIMATE: EVOLUTION OF $F_{ESC,LYA}$

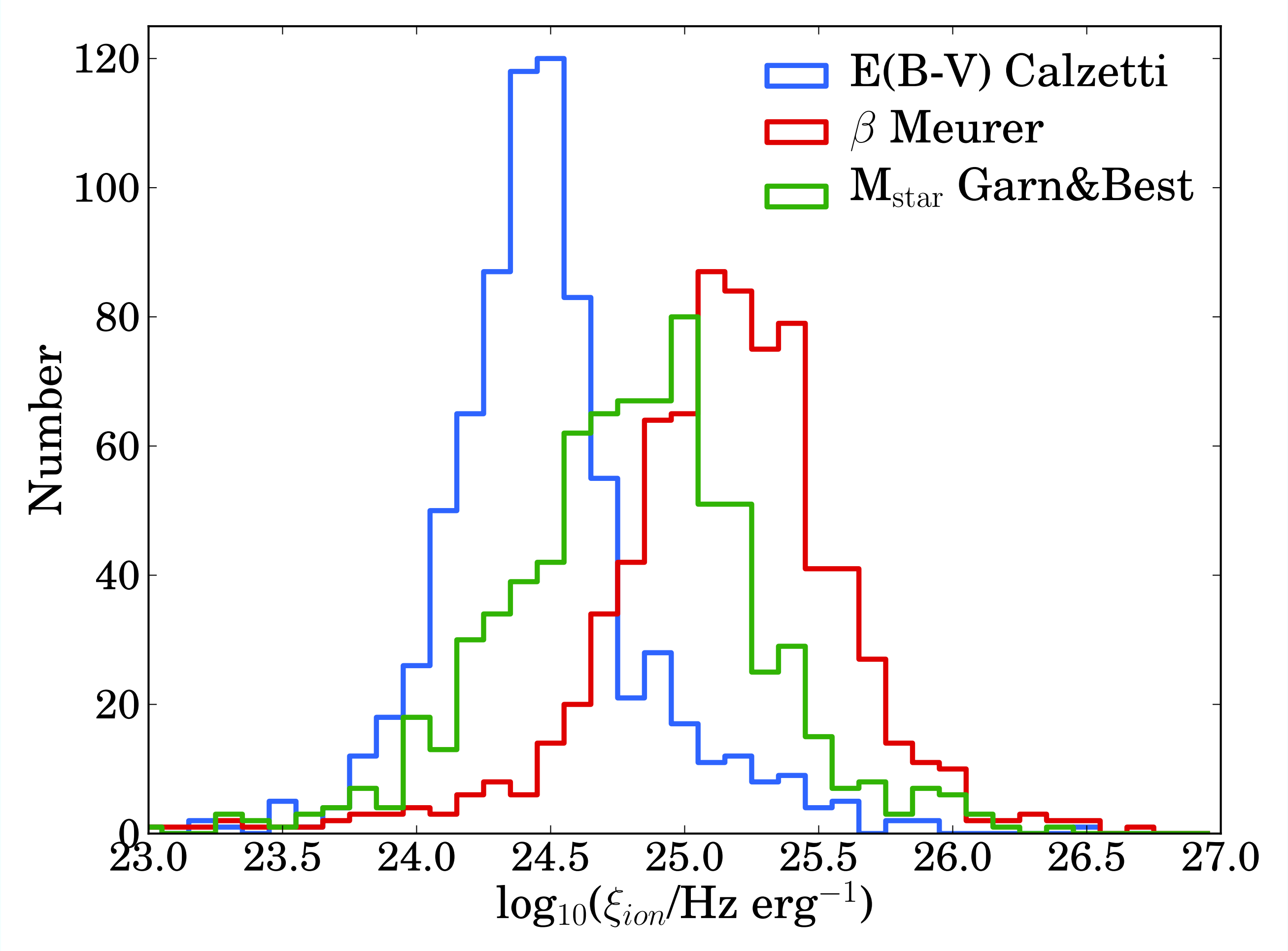


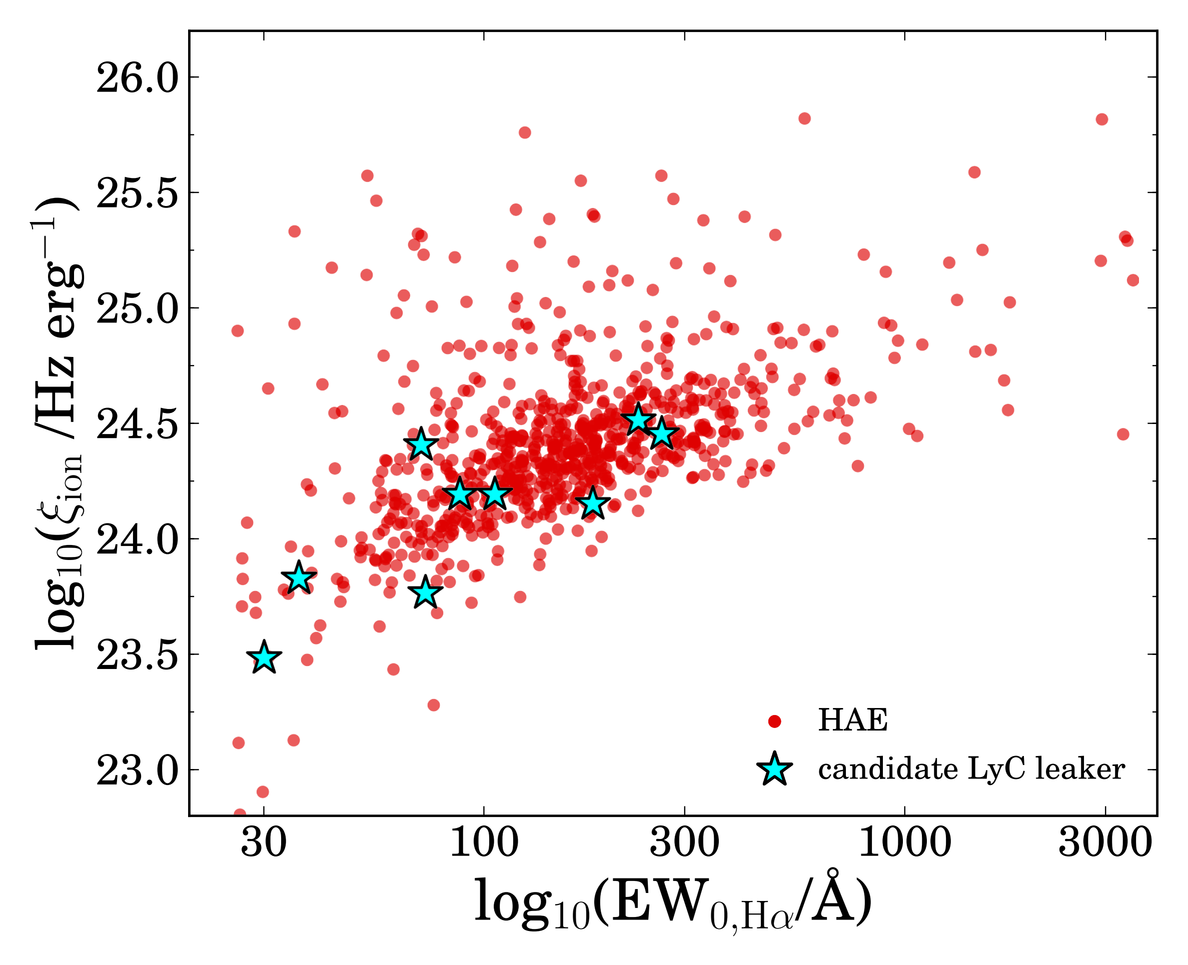
Hayes et al. 2011, ApJ, 730, 8

THE PRODUCTION EFFICIENCY OF IONIZING PHOTONS

$\xi_{ion} = Q_{\rm ion}/L_{UV,{\rm int}}$ (assumes $f_{esc,LyC}$=0)

"Number of ionising photons per unit UV luminosity"



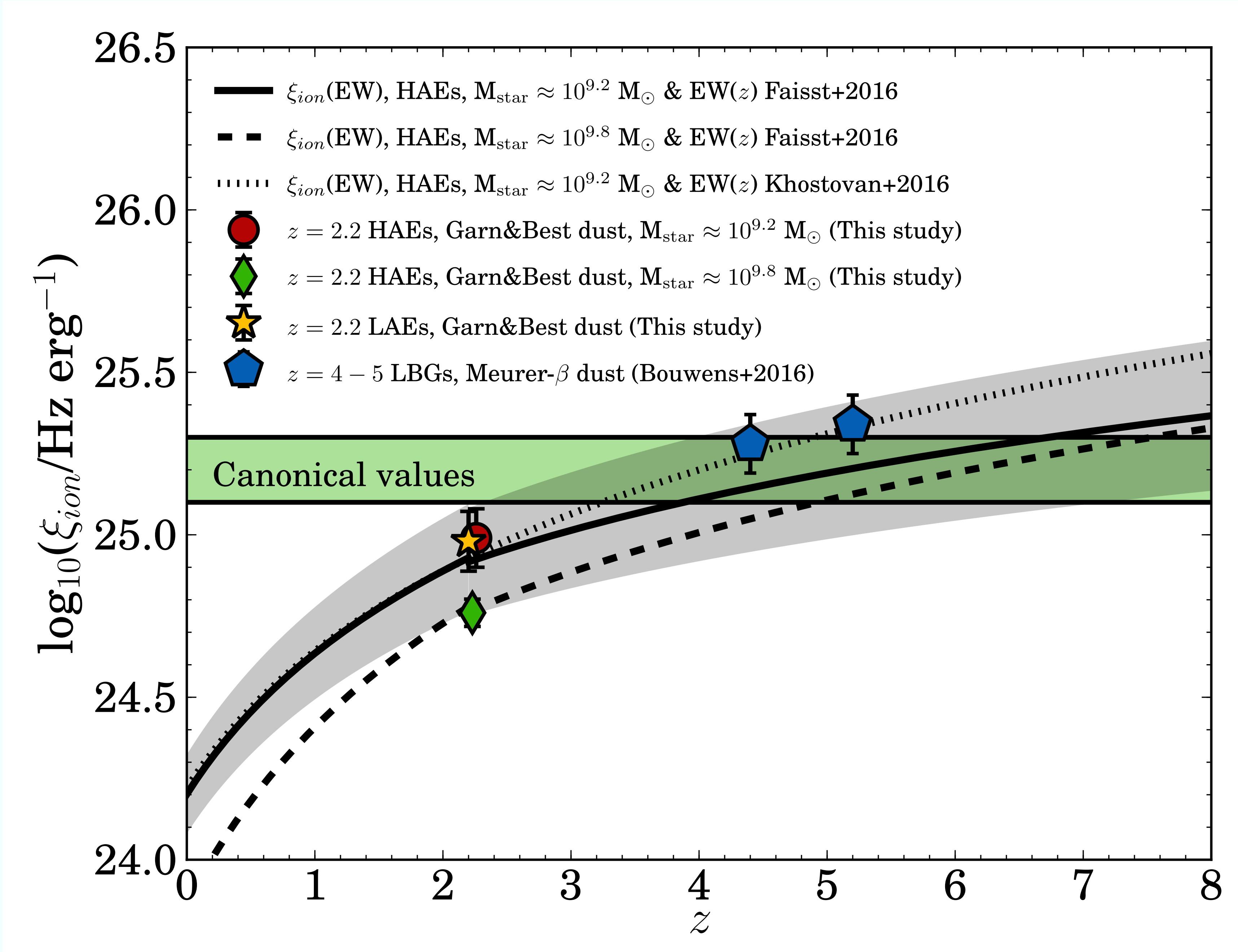


log(ξ_{ion})~24.8 Hz/erg

ξ_{ion} does correlate with EW(Hα).

Redshift evolution of ξ_{ion}

Combine trend ξ_{ion} with EW(Hα) with redshift evolution of EW(Hα)



>> in reionization era, log(ξ_{ion}) ~ 25.2-25.4 Hz/erg

Matthee et al. 2016, arXiv: 1605.08782

Summary part 1: Calibrating Lyman-alpha

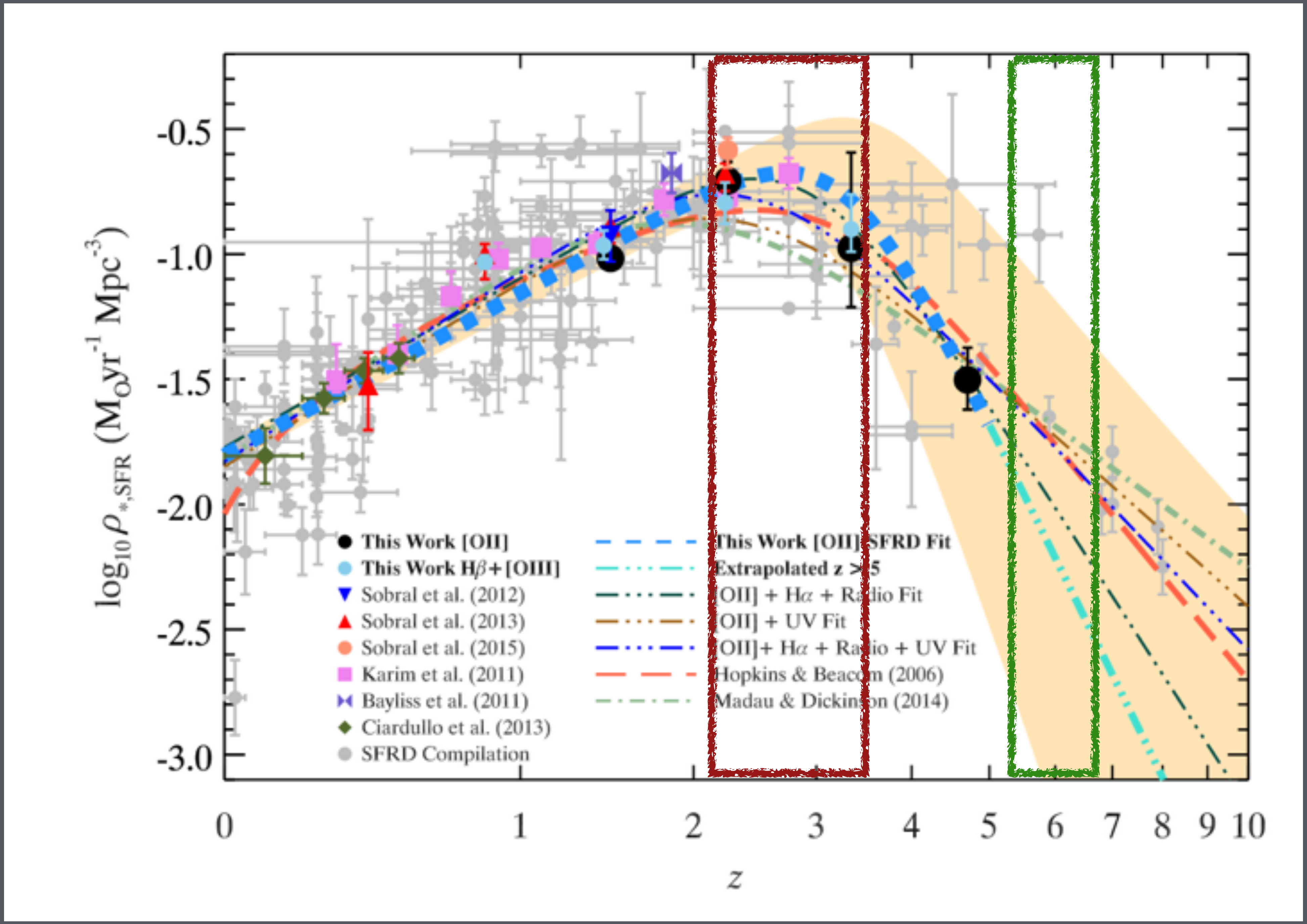
- for typical galaxies at z=2.2, the Lya escape fraction is low

- Most Lyman-alpha emitters are young, low mass galaxies, but they can also be Lyman-alpha emitters at later stages in their evolution

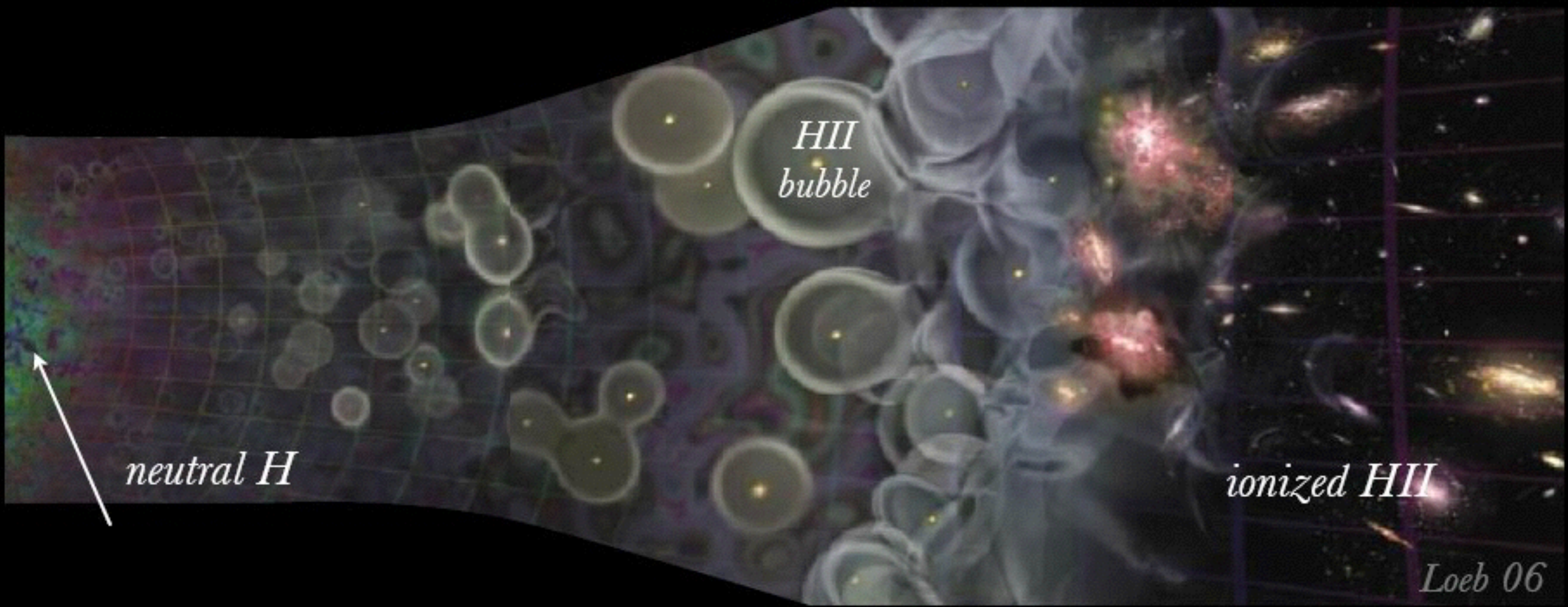
- Resonant scattering creates Lyman-alpha haloes around each star-forming galaxy: to deep surface brightness limit, every galaxy is a Lyman-alpha emitter

- the relative observed luminosity of Lyman-alpha w.r.t. UV increases with look-back time

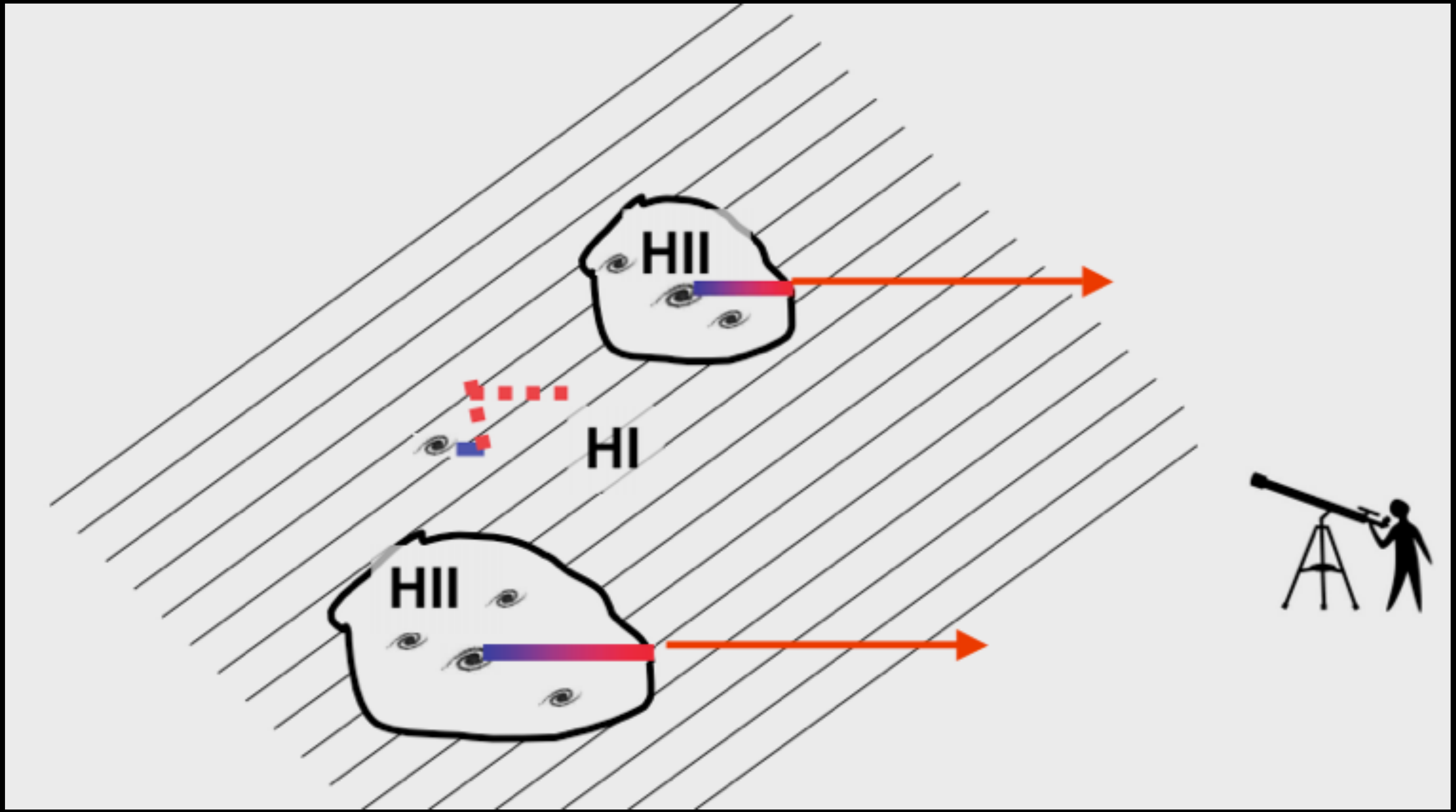
Next stop: the end of reionization



How can we study reionization with galaxies?



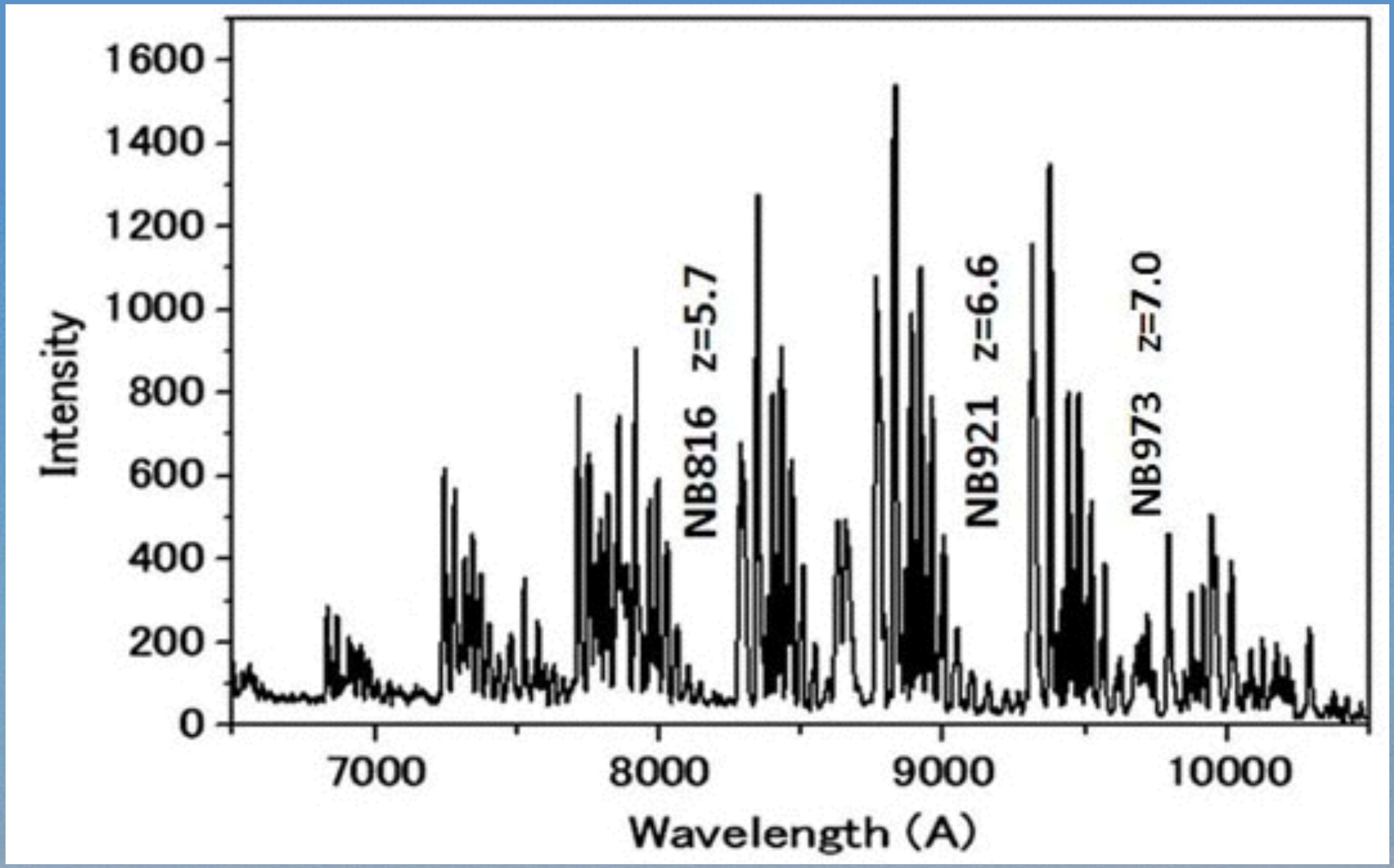
LYMAN-ALPHA & REIONIZATION



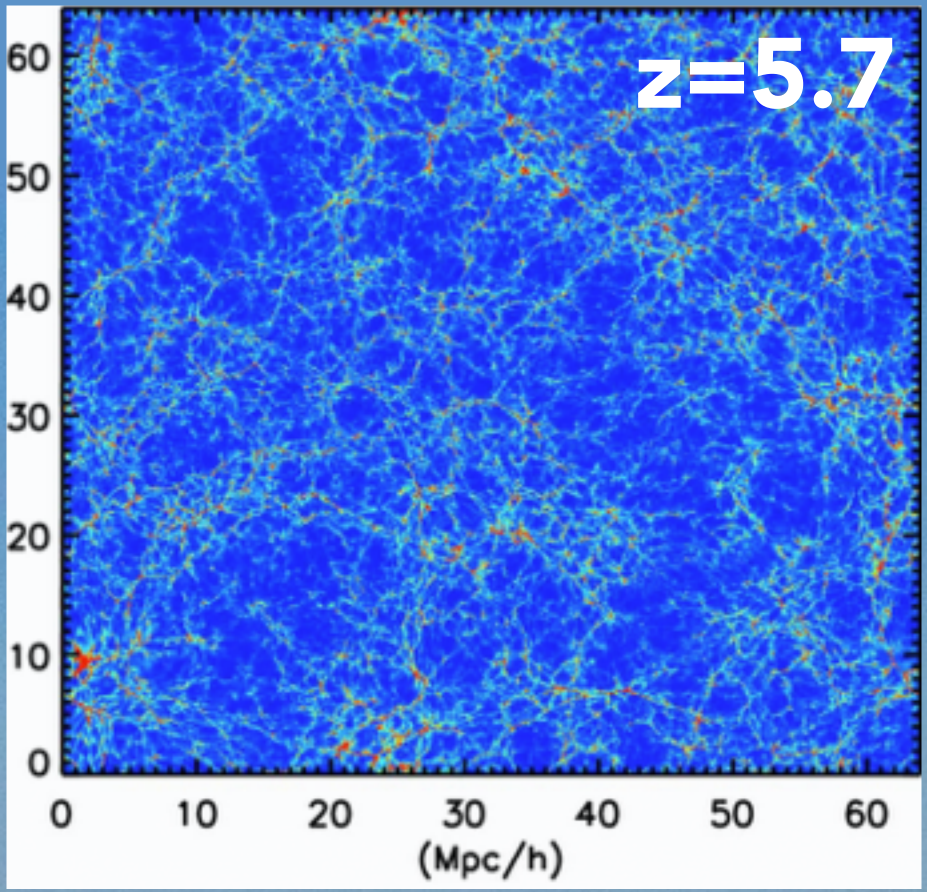
Dijkstra, 2015

The observability of Lyman-alpha is affected by the presence of neutral hydrogen around galaxies

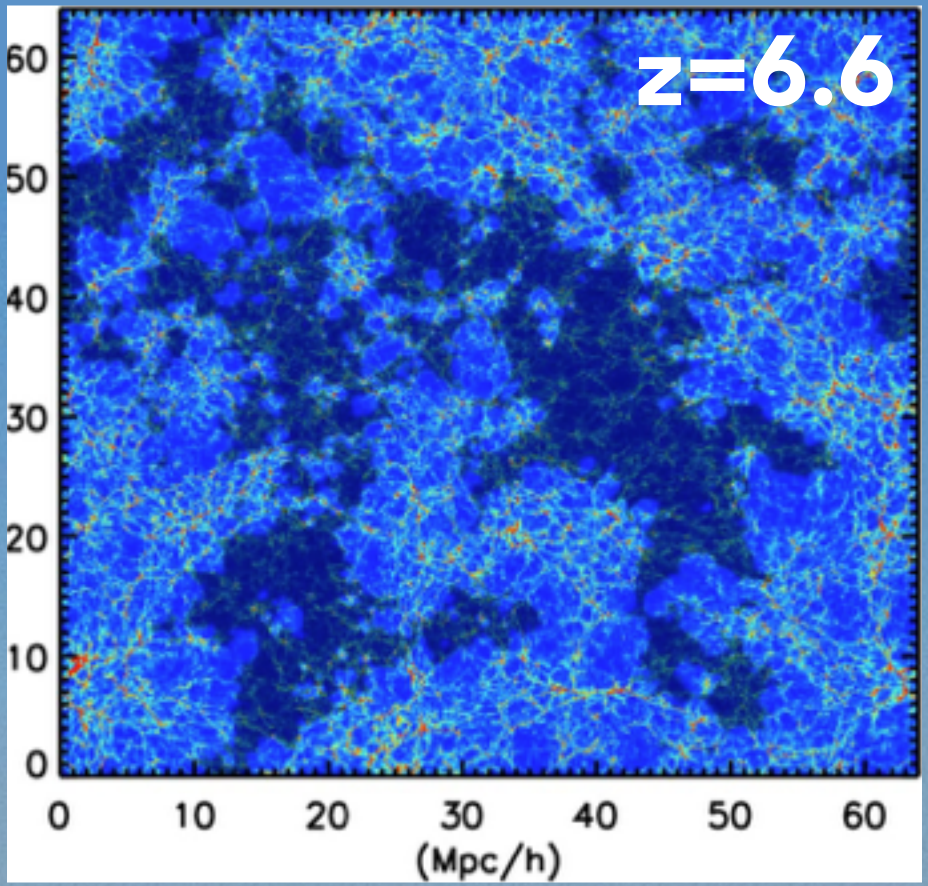
SUBARU LYMAN-ALPHA SURVEYS



SUBARU LYMAN-ALPHA SURVEYS



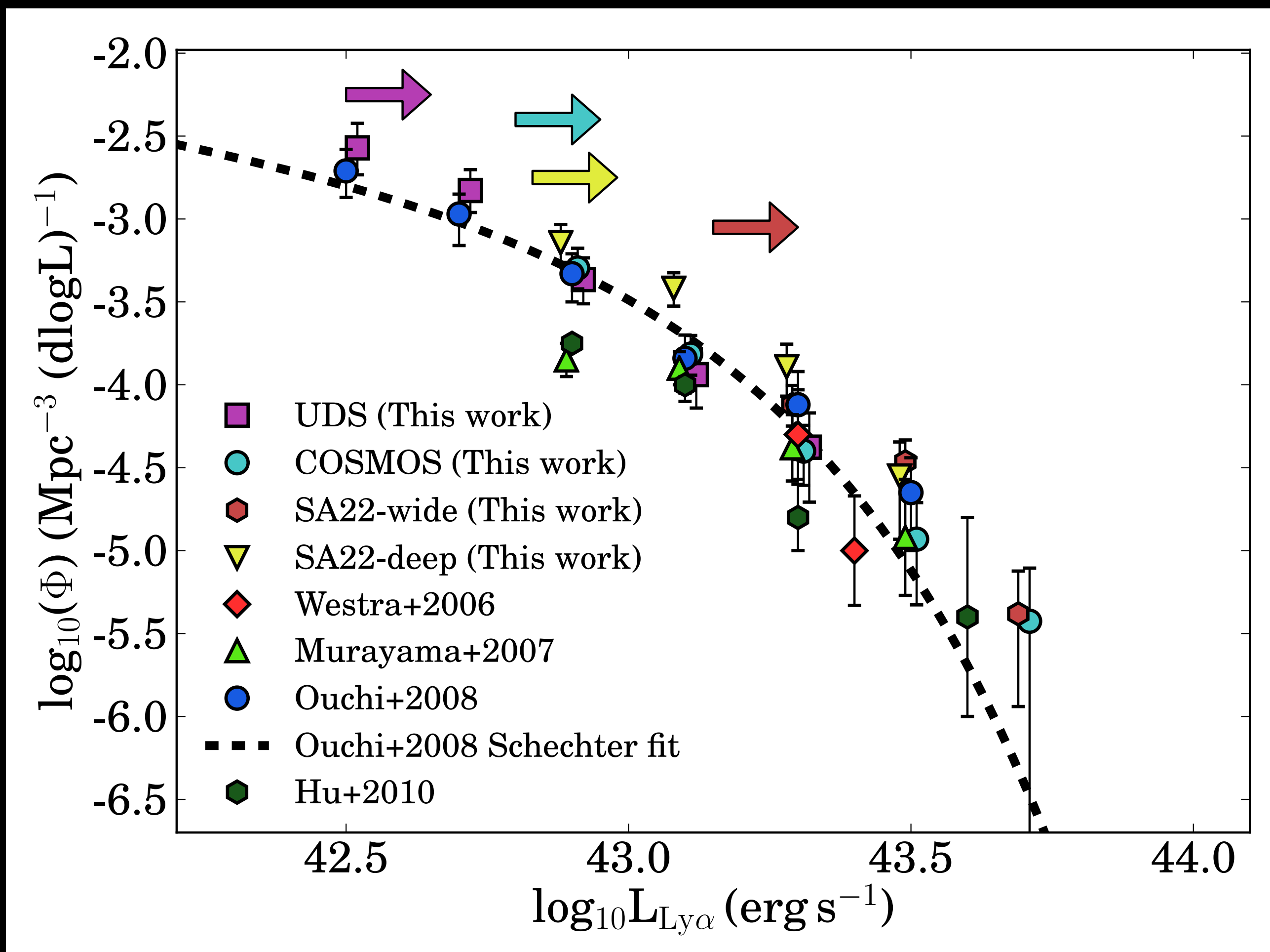
Reionization completed



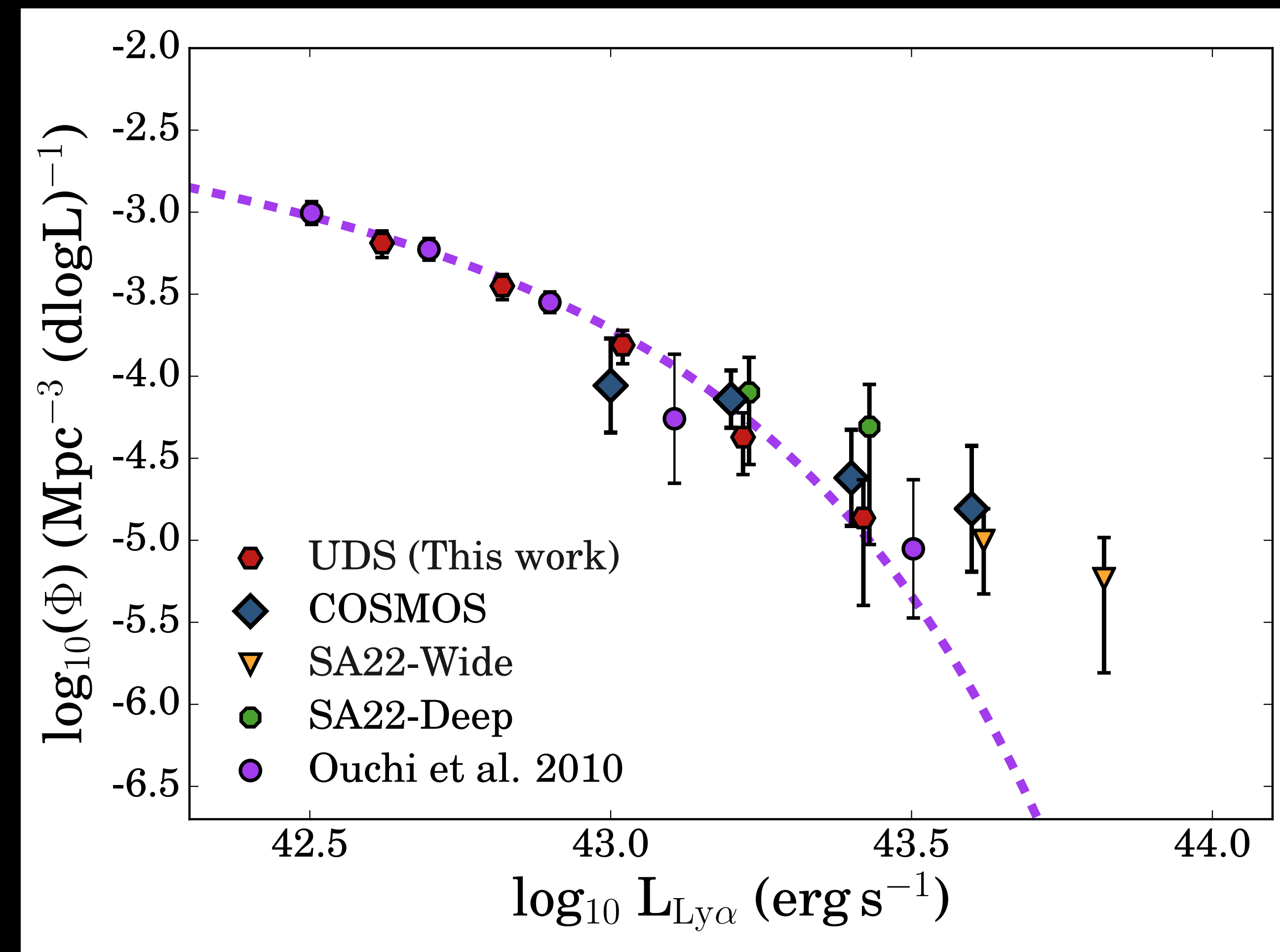
Reionization ongoing

DIFFERENT SURVEY FIELDS: COSMIC VARIANCE

z=5.7 LAE LF:



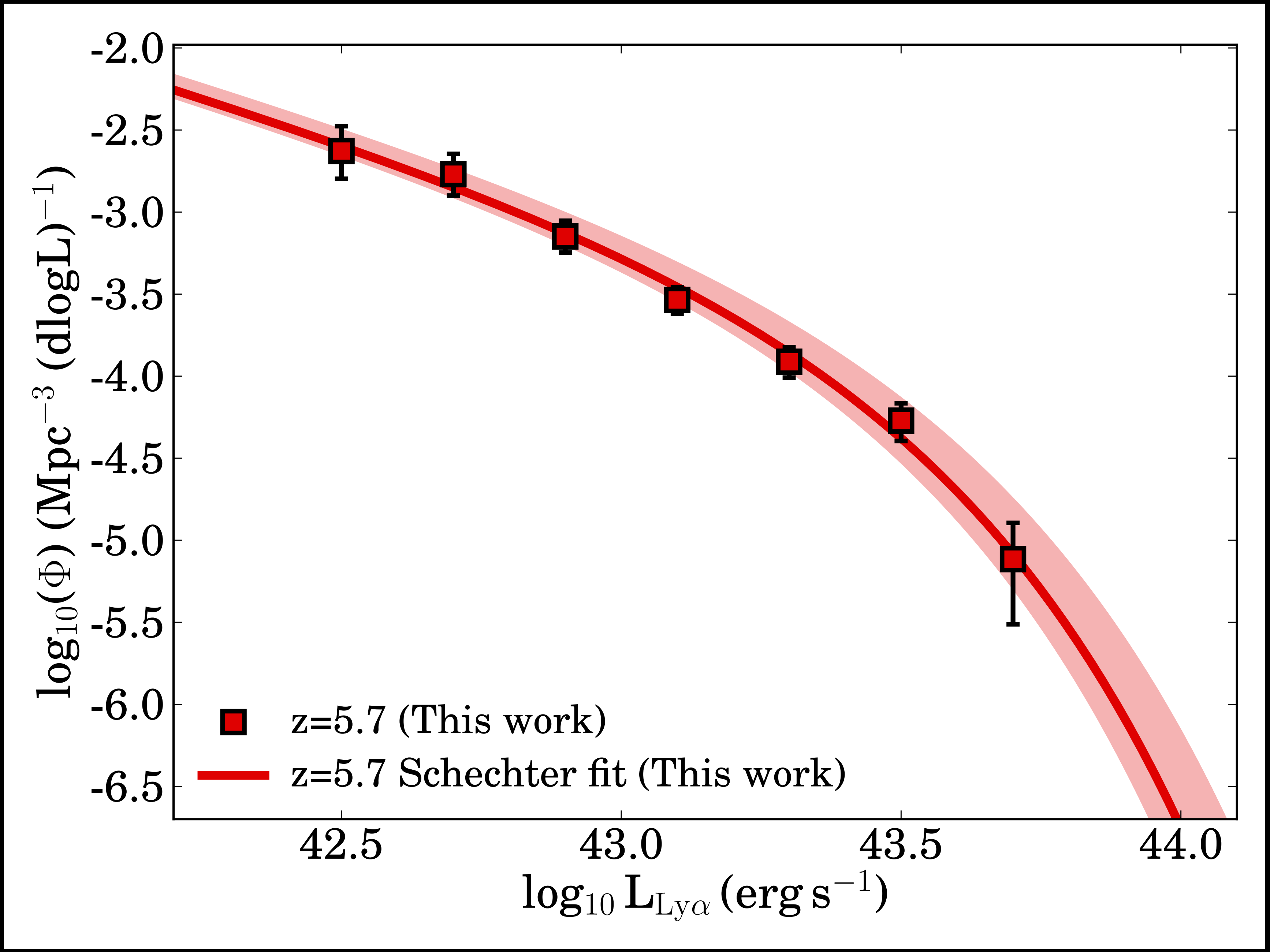
z=6.6 LAE LF:



Selection: EW_0(Lya) > 25 Å & Lyman-break, 2″ apertures

Allows to study changes in Lya luminosities (due to reionization?)

COMBINED Z=5.7 LAE LF

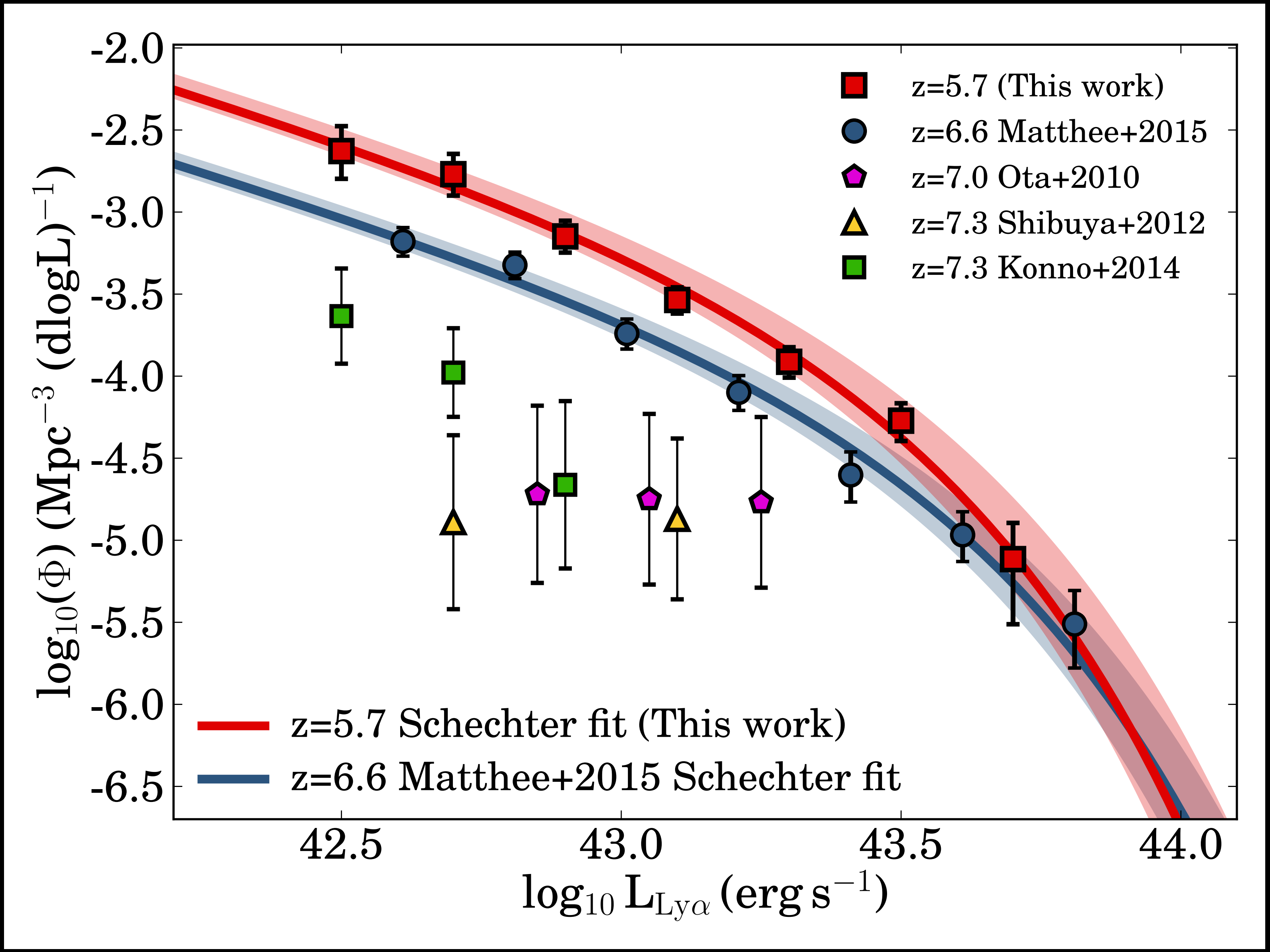


alpha very steep: -2.3+-0.4 (consistent with Dressler+2015)

(c.f. -1.9 UV LF Bouwens+2015; theoretically argued by Gronke+2015)

Santos, Sobral & Matthee, 2016, arXiv: 1606.07435

Evolution of the Lya LF from z=5.7-6.6 and beyond



Number density evolves at the faint end, not at the bright end!

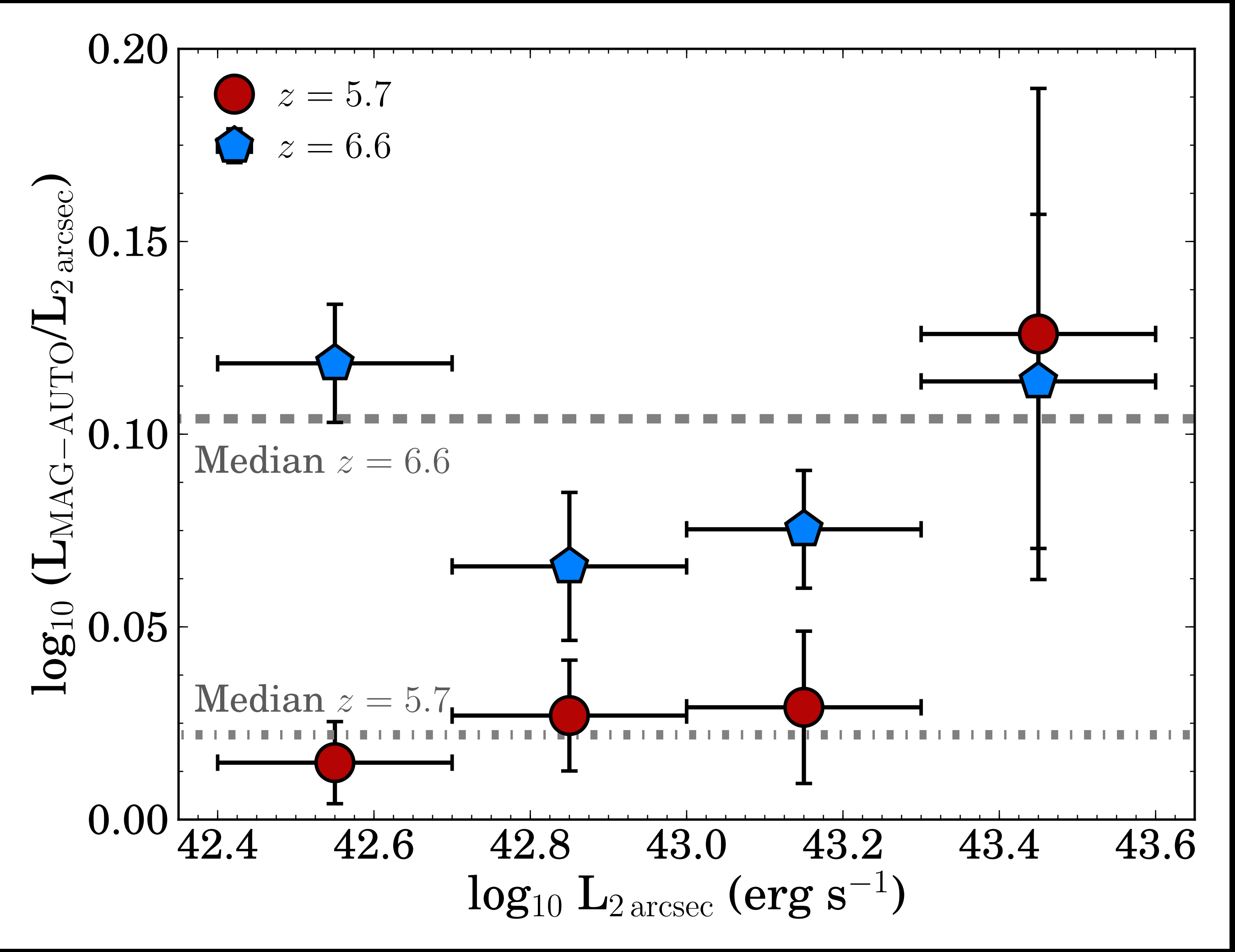
> more neutral IGM scatters Lya out of line-of-sight?

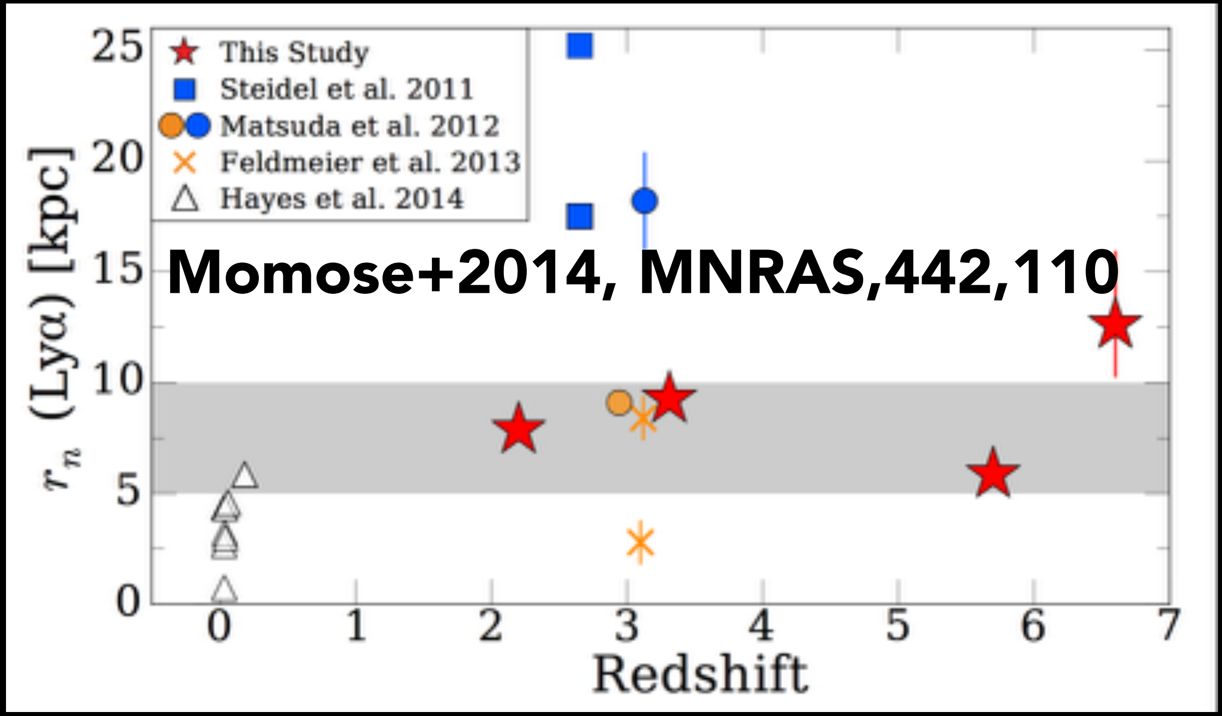
- No comparable wide survey z>7 yet.

Santos, Sobral & Matthee, 2016, arXiv: 1606.07435

Extended emission at z=5.7-6.6

Simple analysis: Mag-auto luminosity vs 2" aperture luminosity
Faint LAEs become more extended at z=6.6!

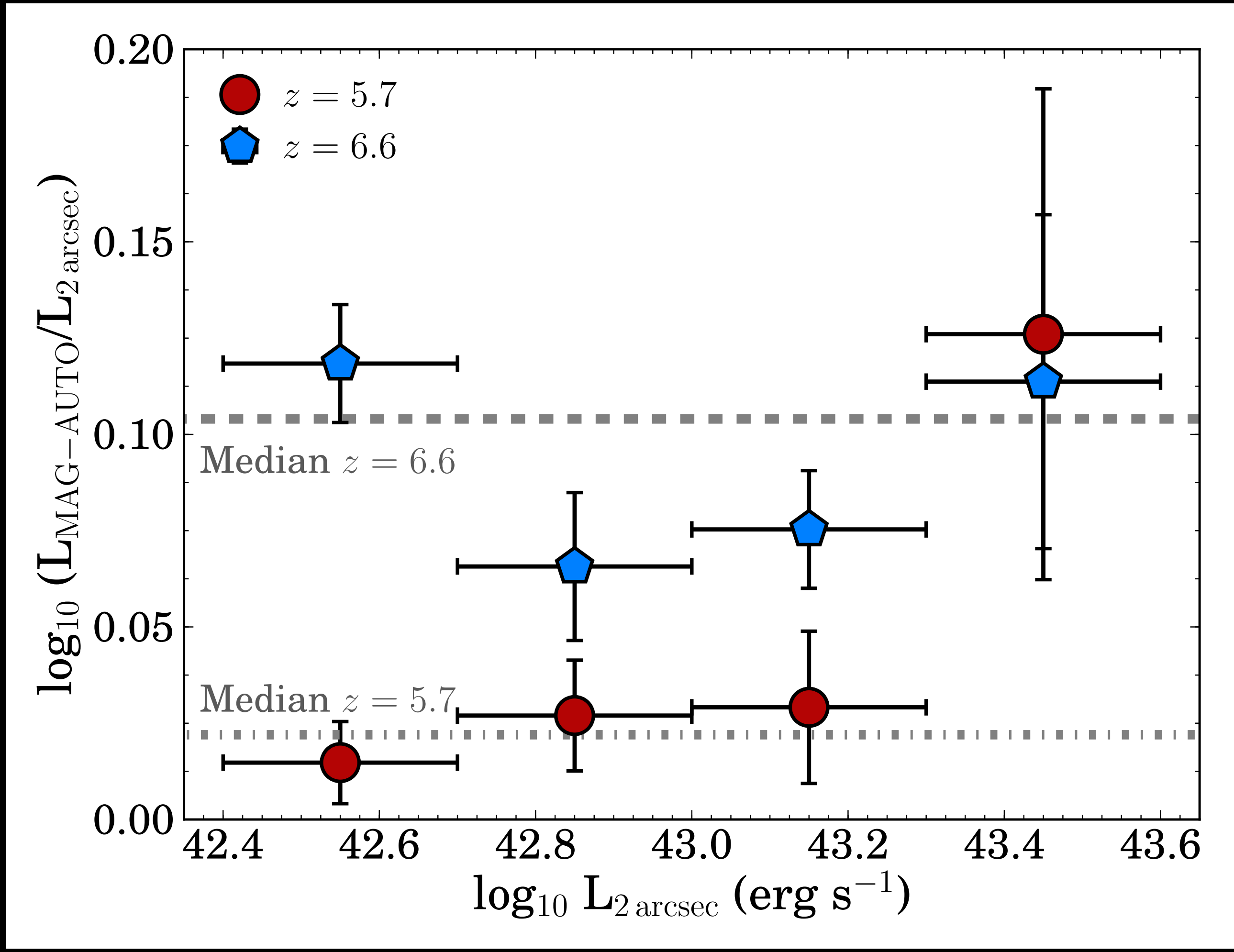


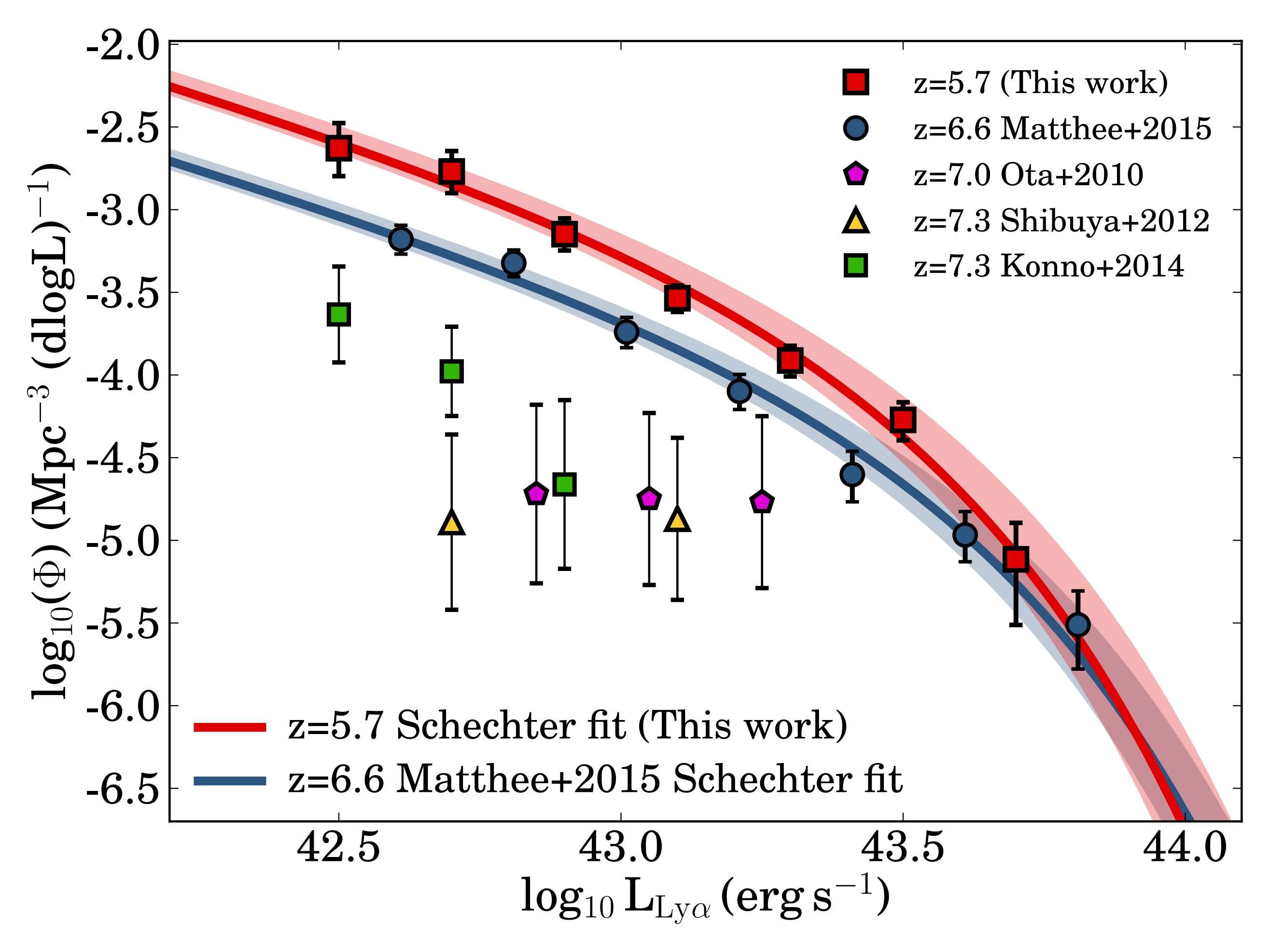


Similar to Momose+2014: median LAE in UDS more extended at z=6.6 than at z=5.7

Santos, Sobral & Matthee, 2016, arXiv: 1606.07435

Observing patchy reionization?



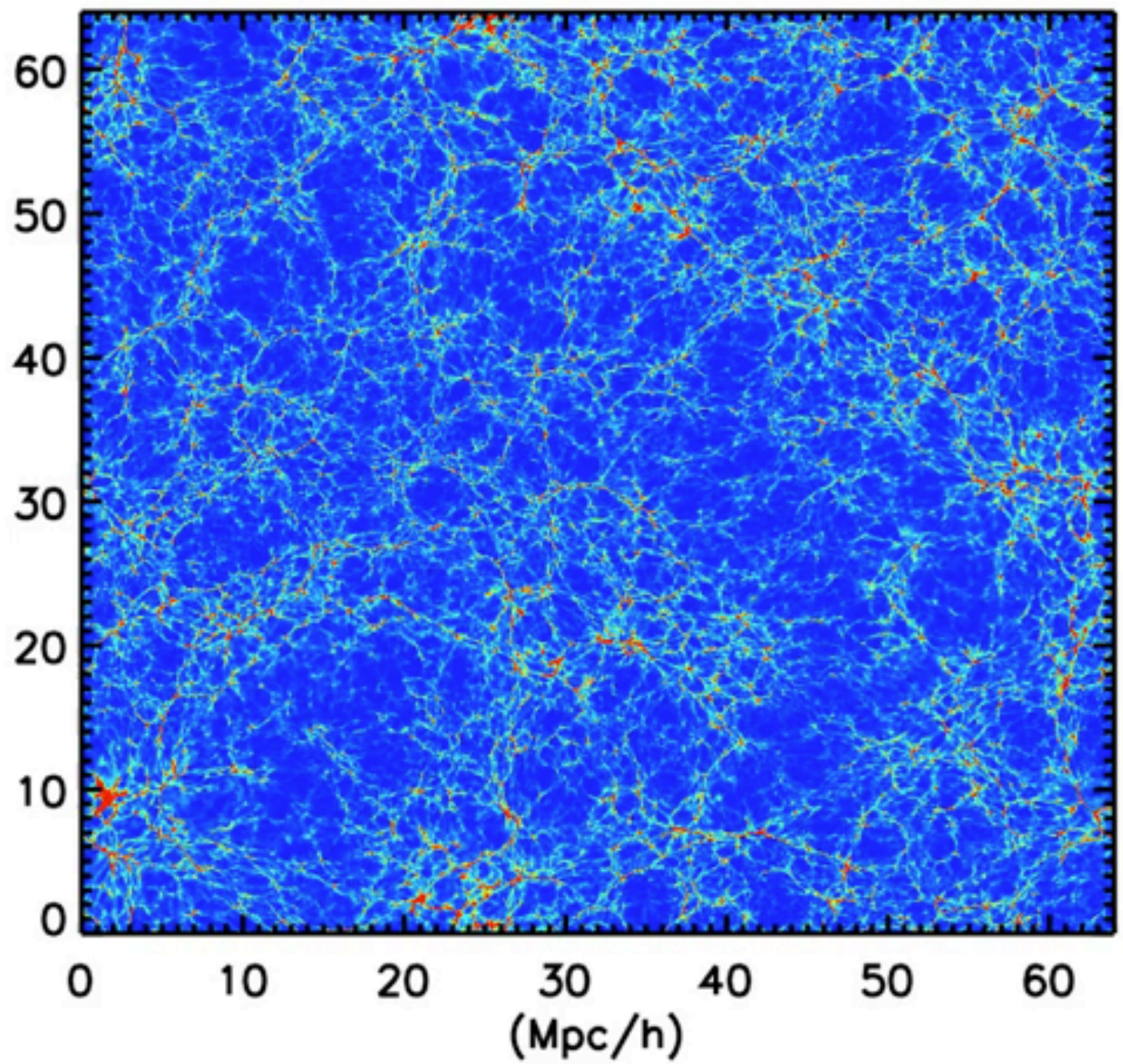


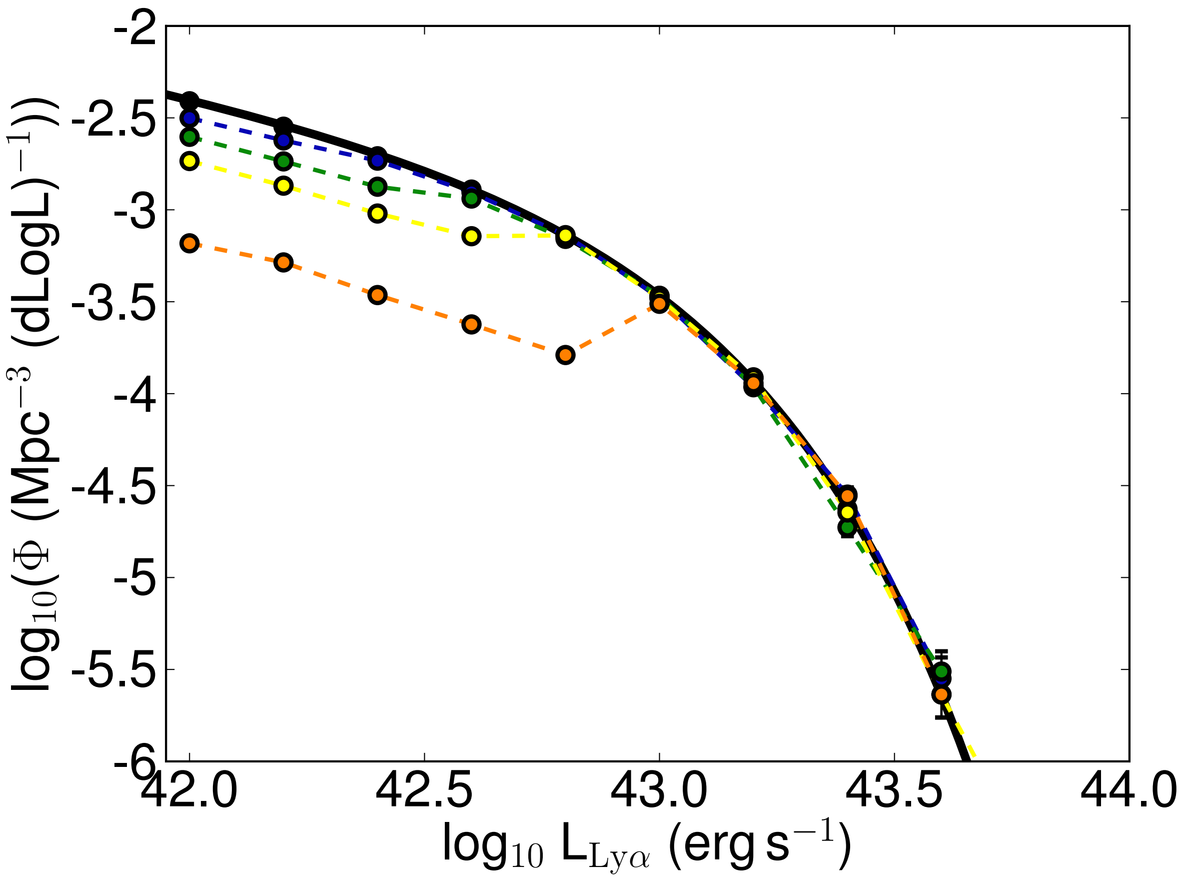
1. Faint LAEs are less abundant and more extended at z=6.6 than at z=5.7
2. Bright LAEs equally abundant and equally extended

Matthee et al. 2015 MNRAS 451, 4919

Santos, Sobral & Matthee, 2016, arXiv: 1606.07435

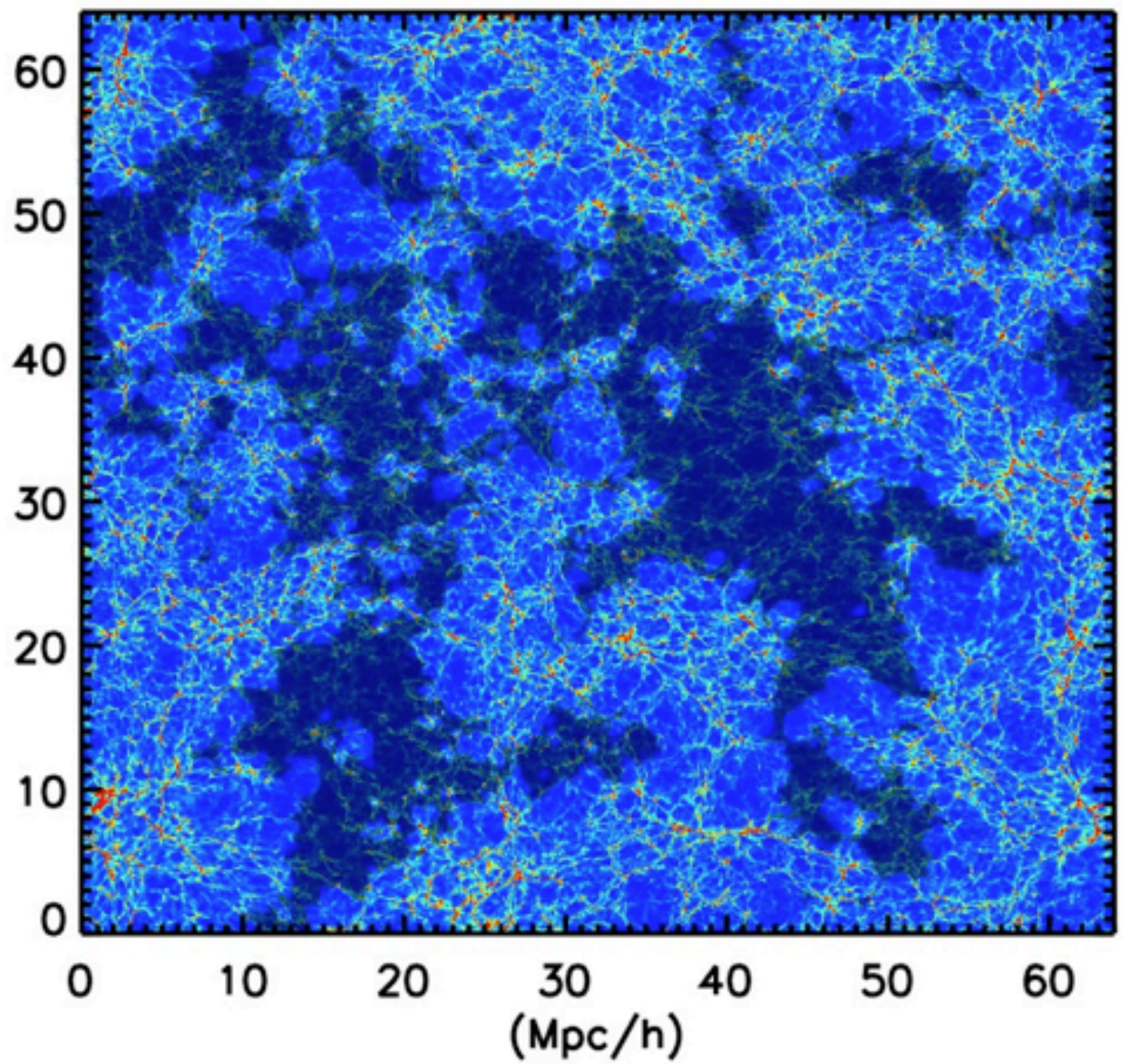
Redshift z~5.5 (Universe 1 billion year old): almost completely ionised

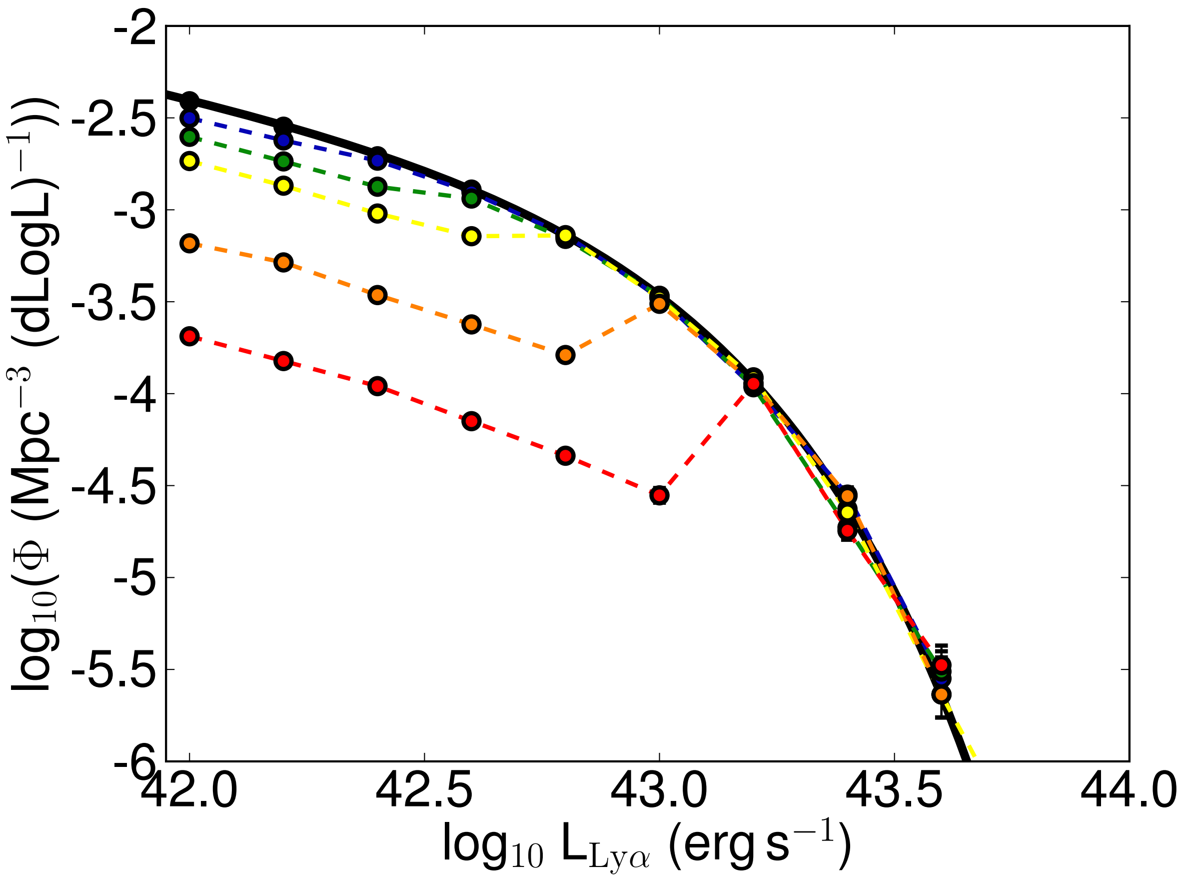




Simulation by Paul Shapiro +

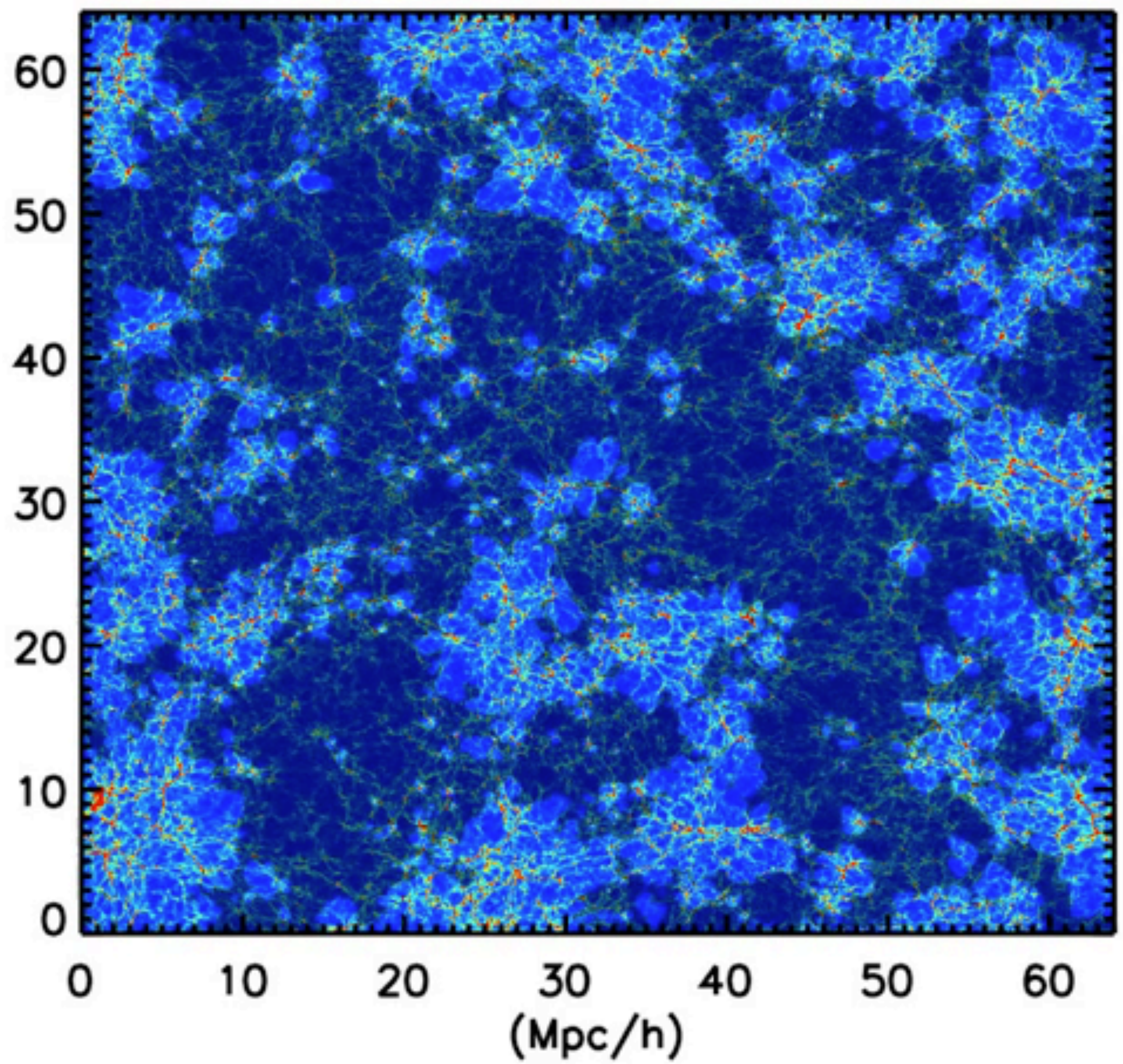
Redshift z~6.5 (Universe 0.8 billion year old): neutral bubbles appear

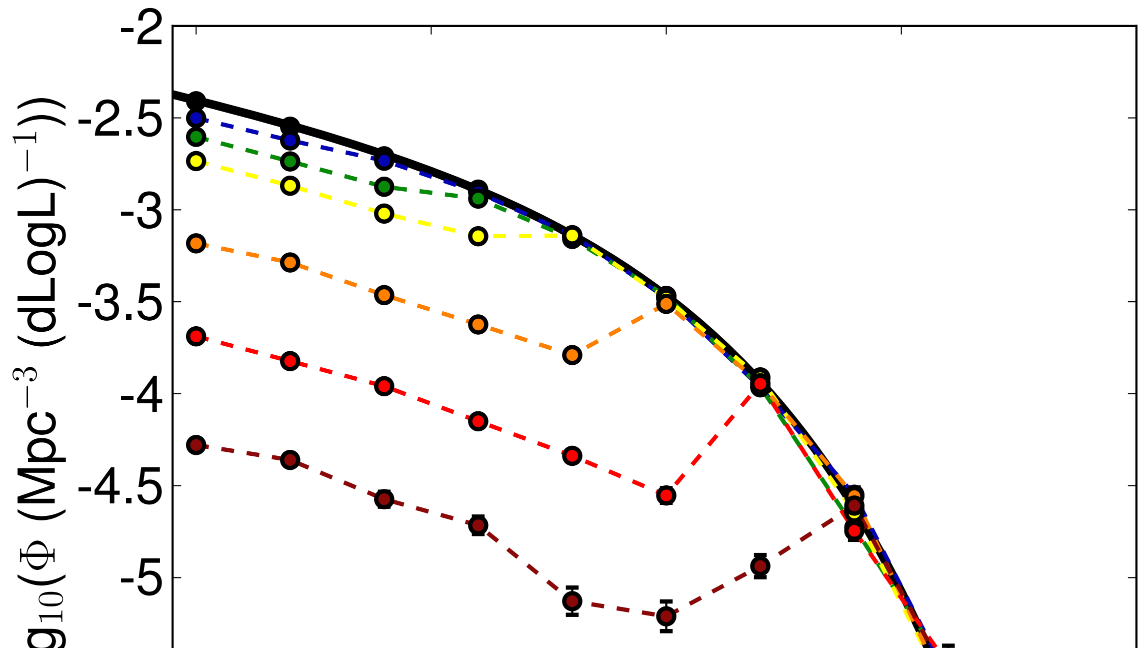


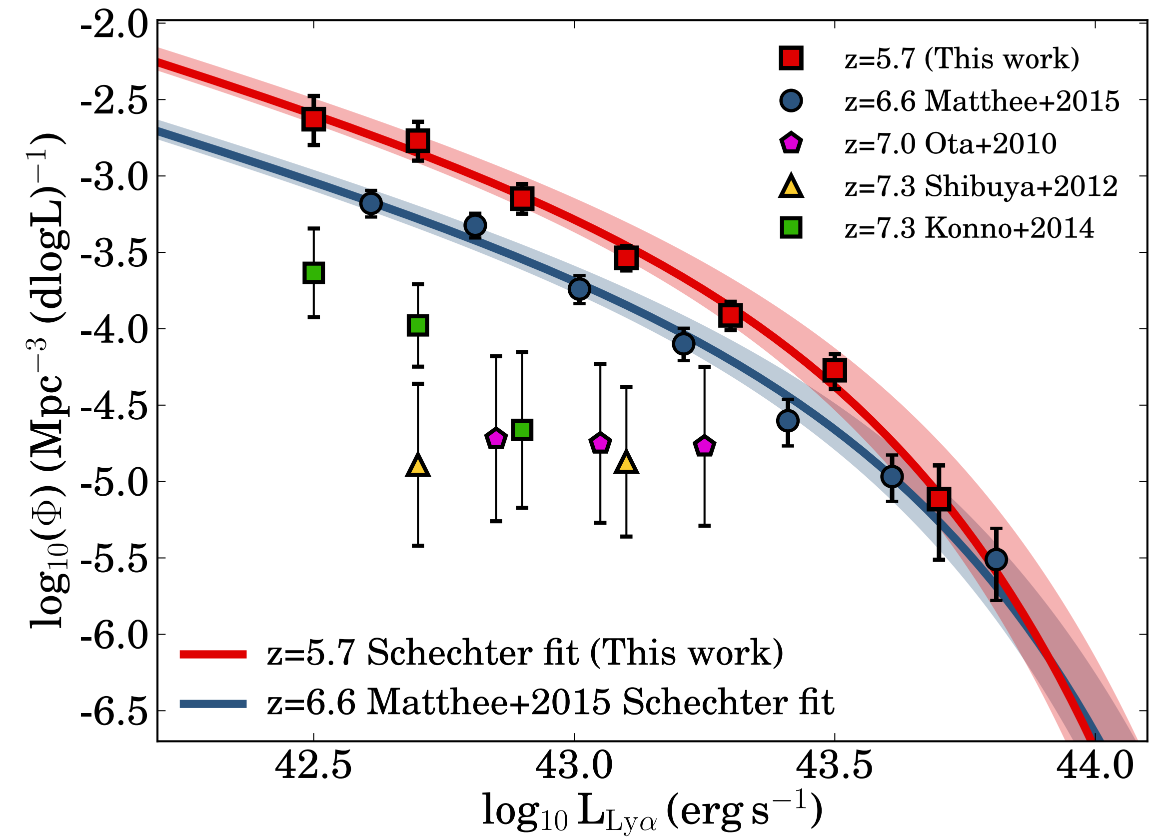


Simulation by Paul Shapiro +

Redshift z~7.3 (Universe 0.7 billion year old): more neutral bubbles appear

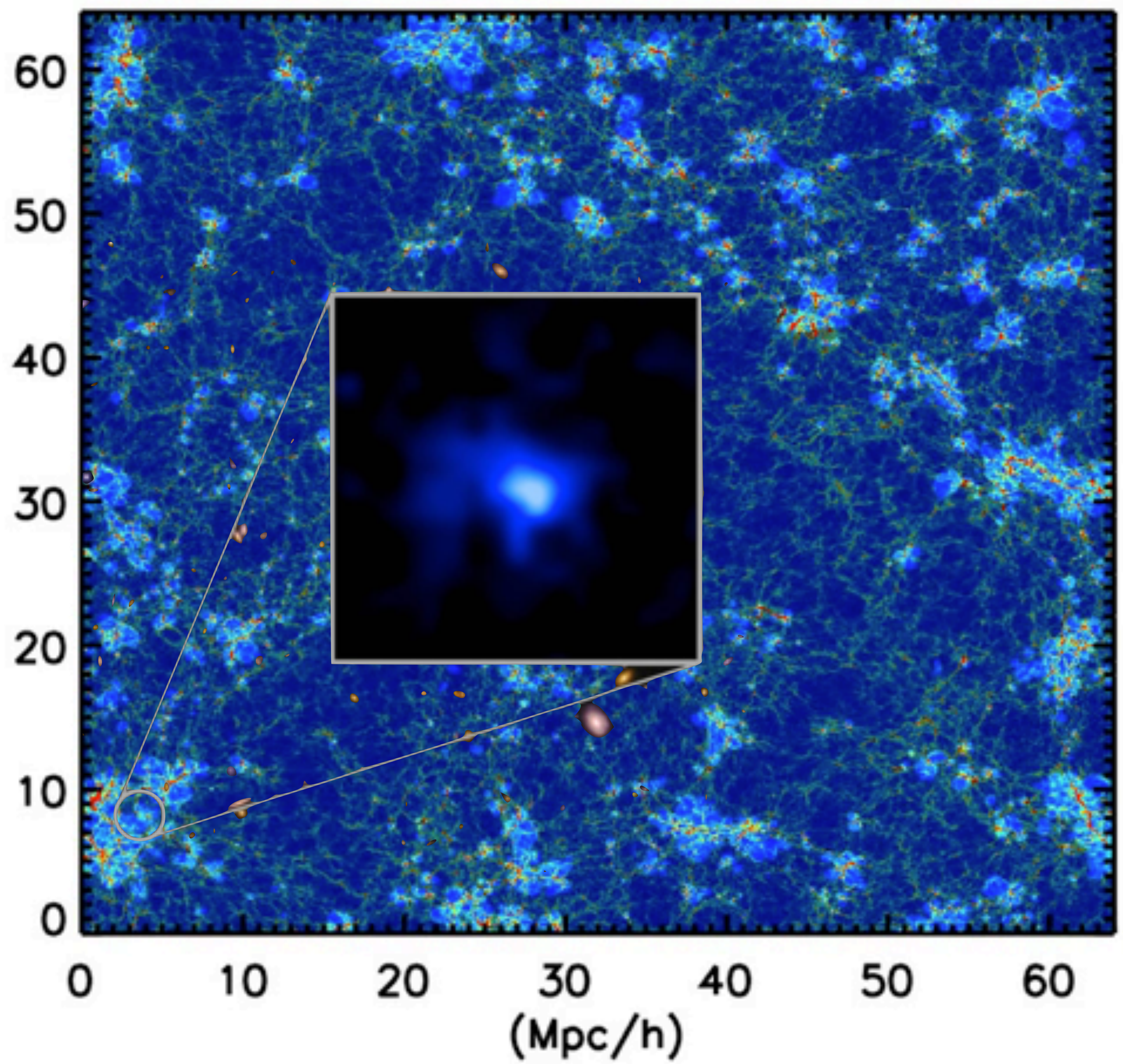


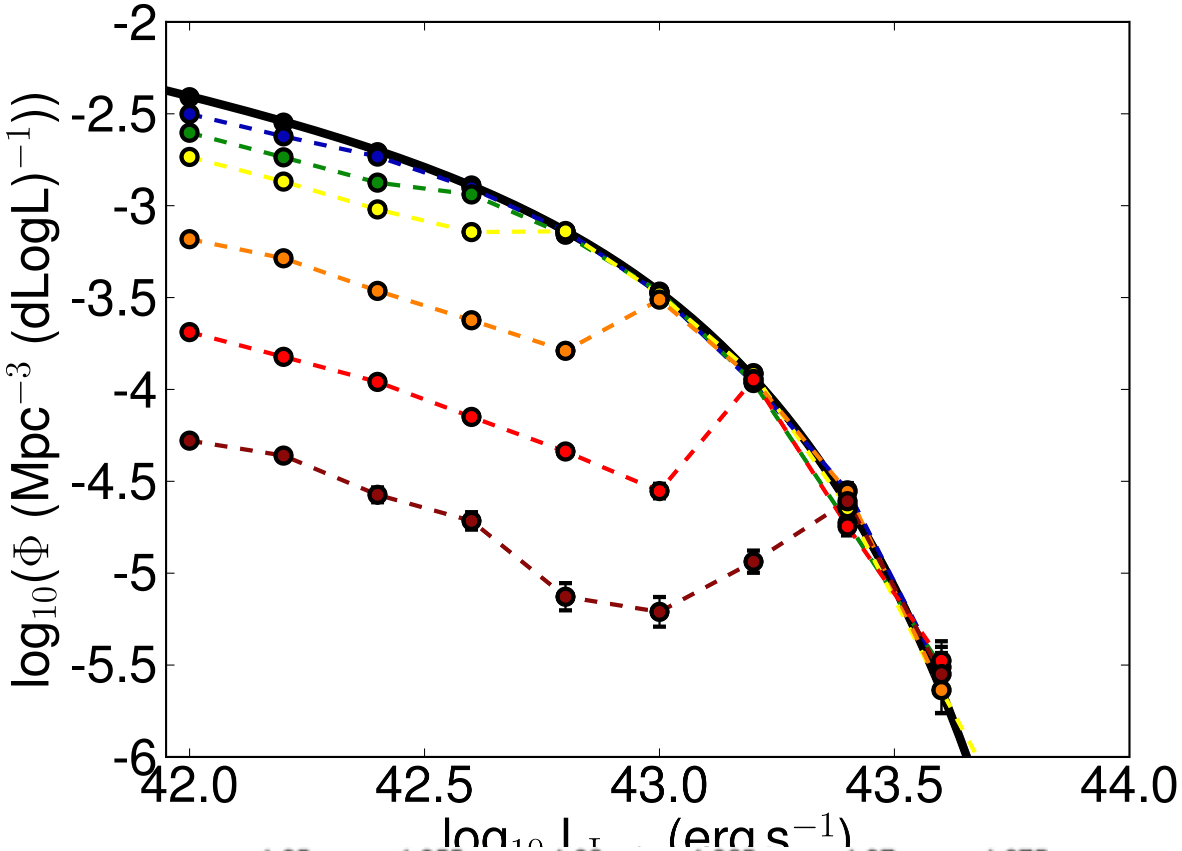


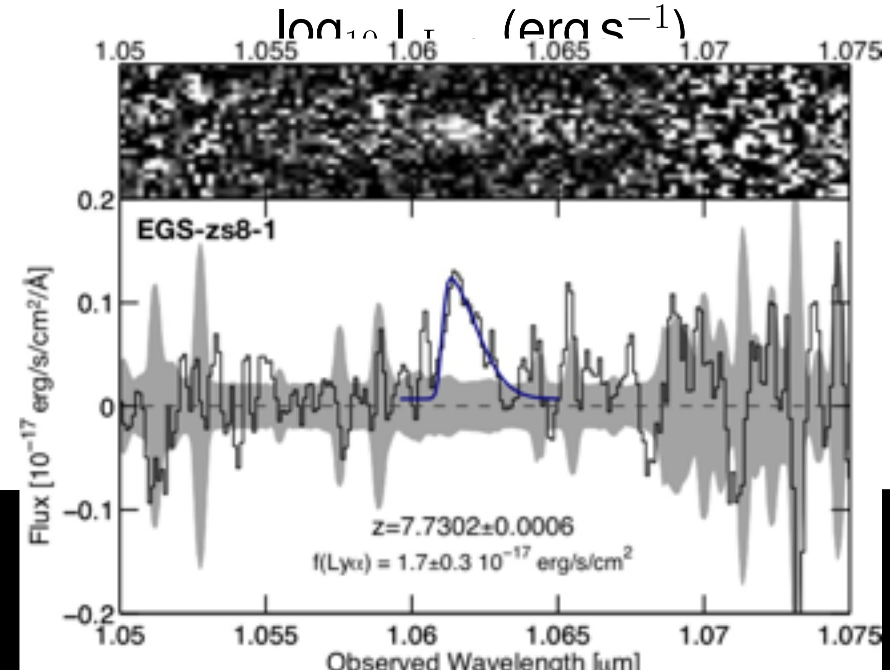


Simulation by Paul Shapiro +

Redshift z~8.5 (Universe 0.6 billion year old): the earliest ionised bubbles (?)



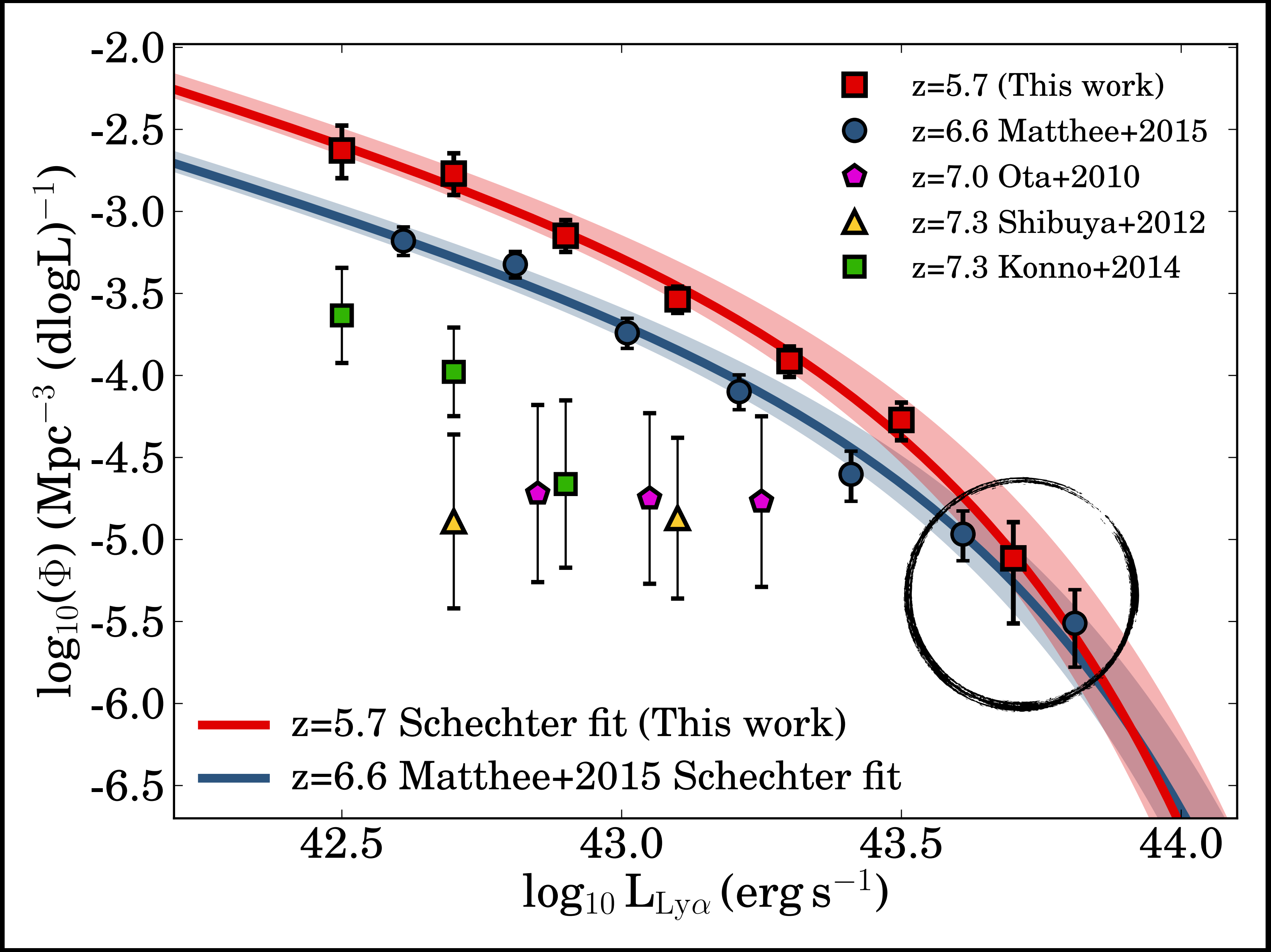




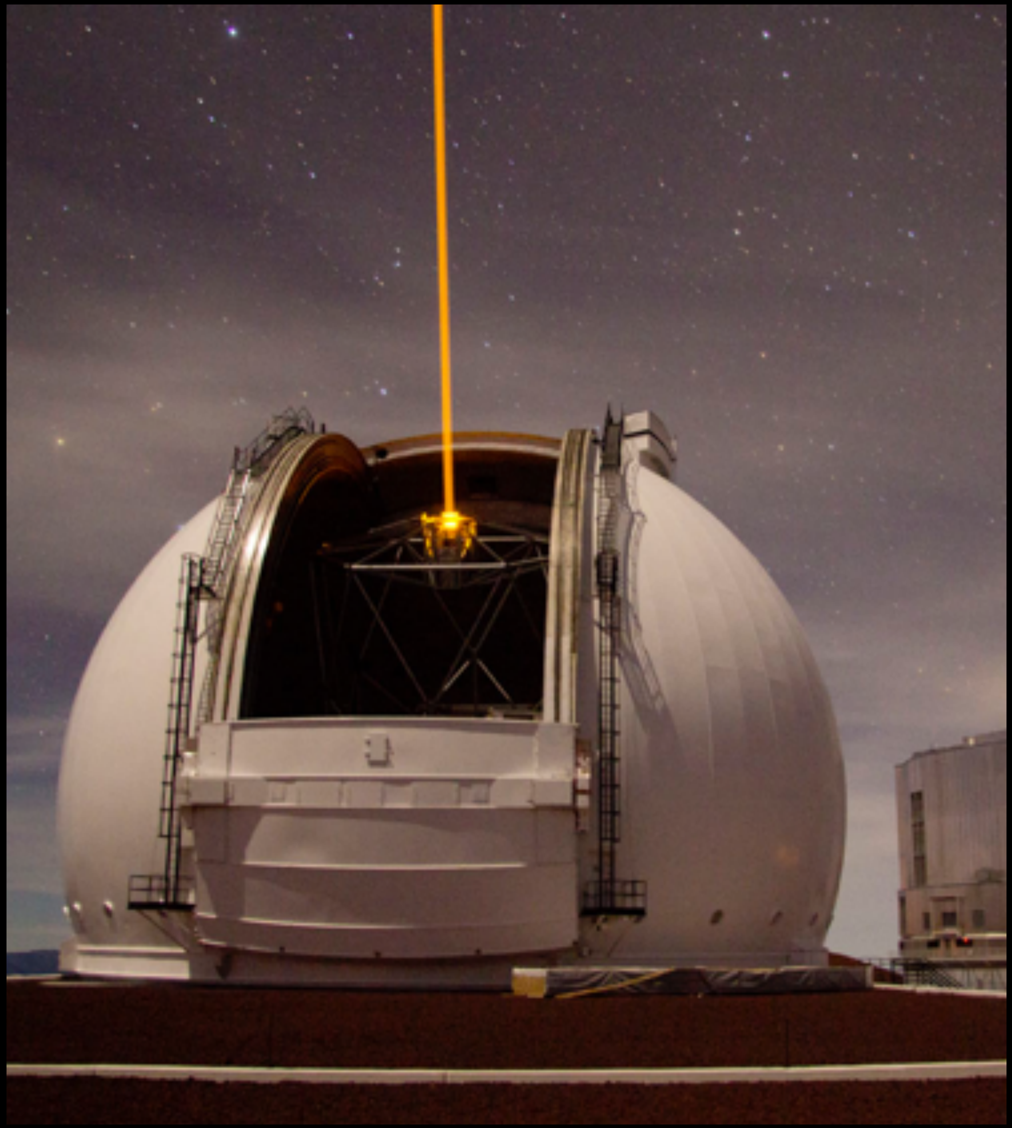
Simulation by Paul Shapiro +

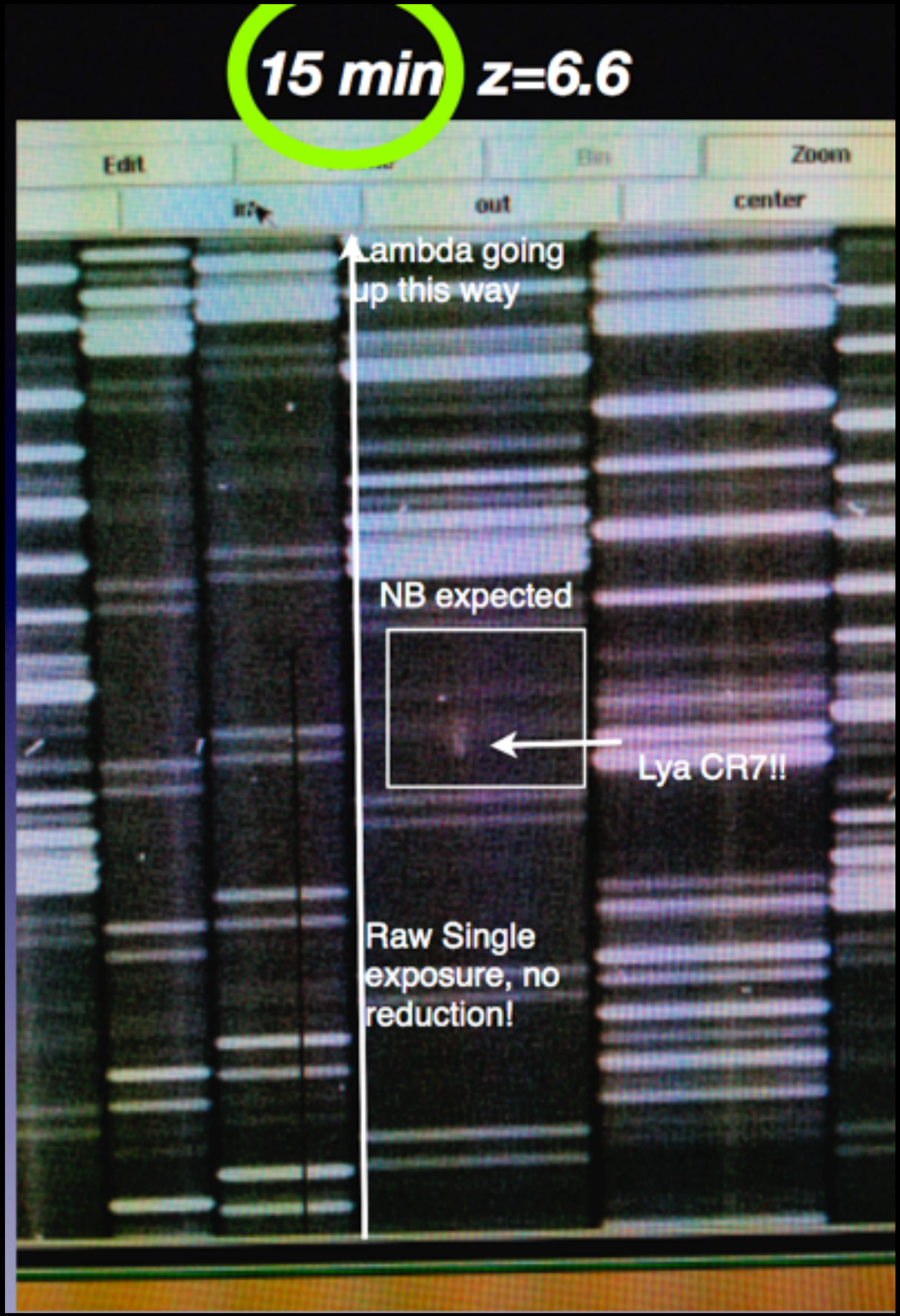
z=7.7, Oesch et al. 2015

THE PROPERTIES OF LUMINOUS LAEs AT Z=6.6

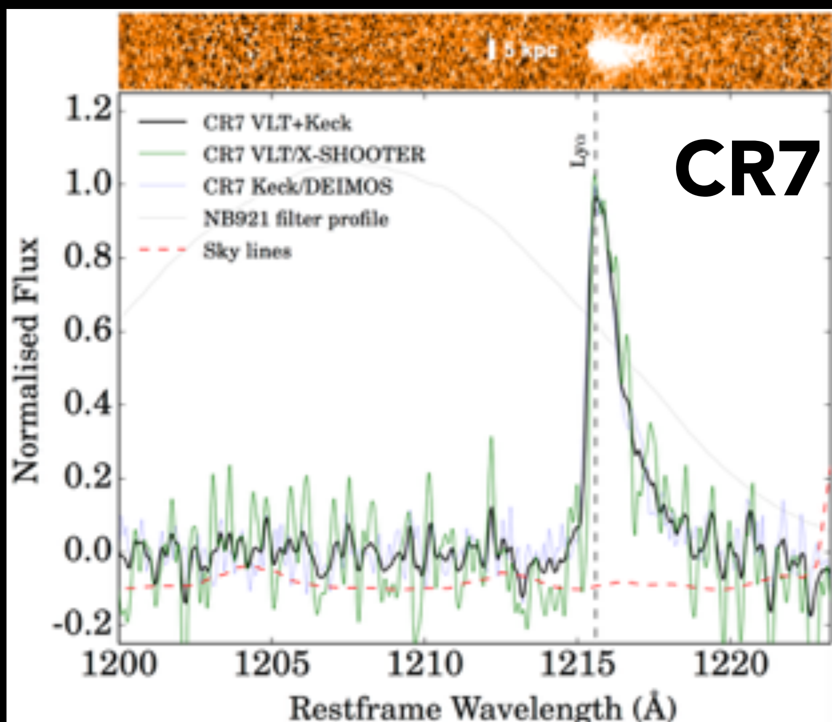


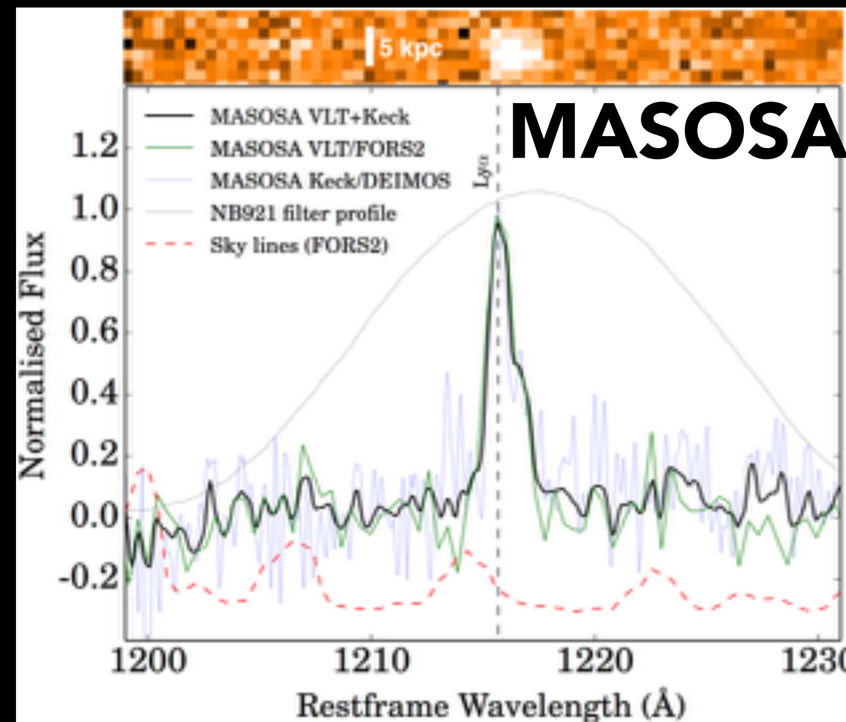
THE BENEFIT OF HAVING BRIGHT SOURCES…

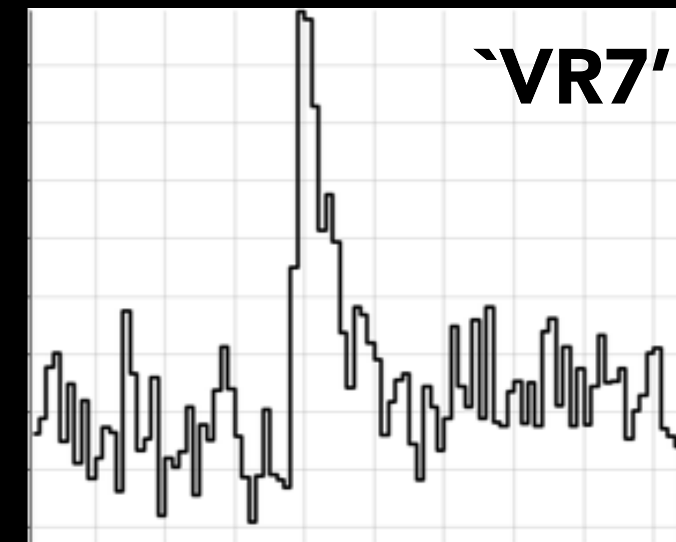


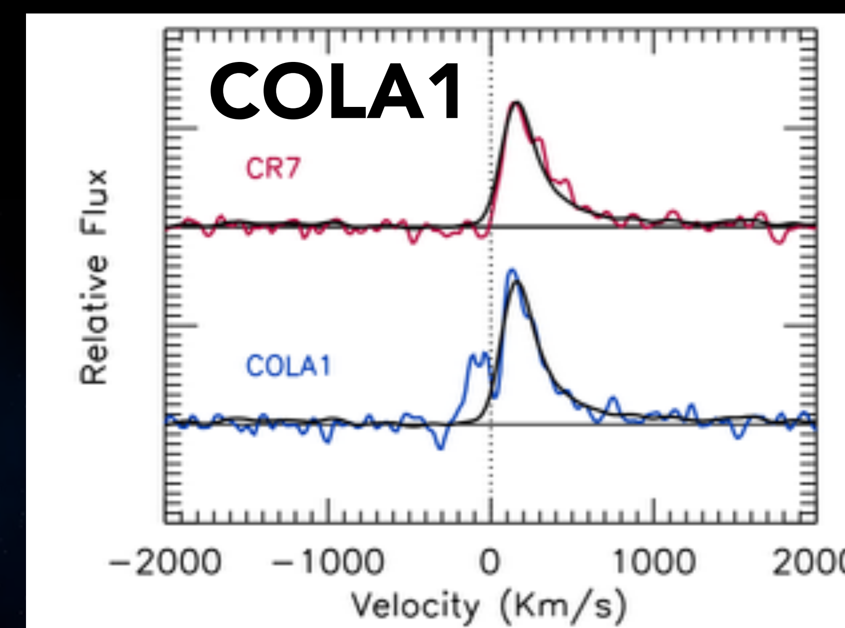


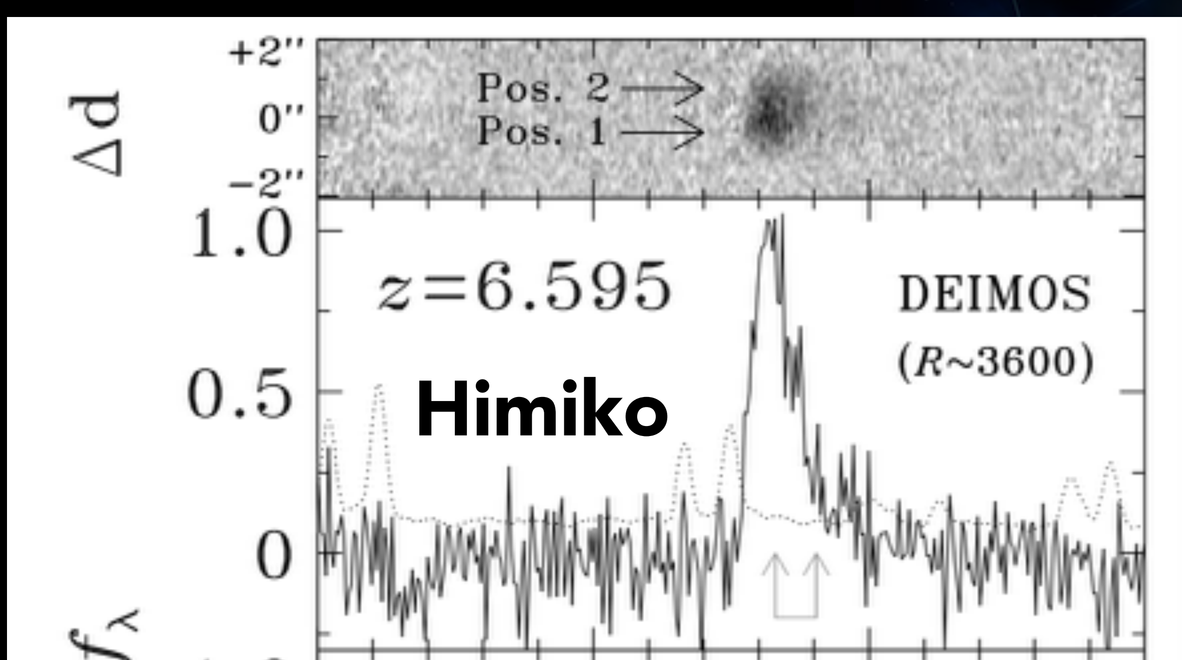
CR7 and the team of luminous z=6.6 LAEs











Himiko: Ouchi+2009,2013

CR7, MASOSA: Sobral+2015

COLA1: Hu+2016

VR7: Matthee+2015 & in prep

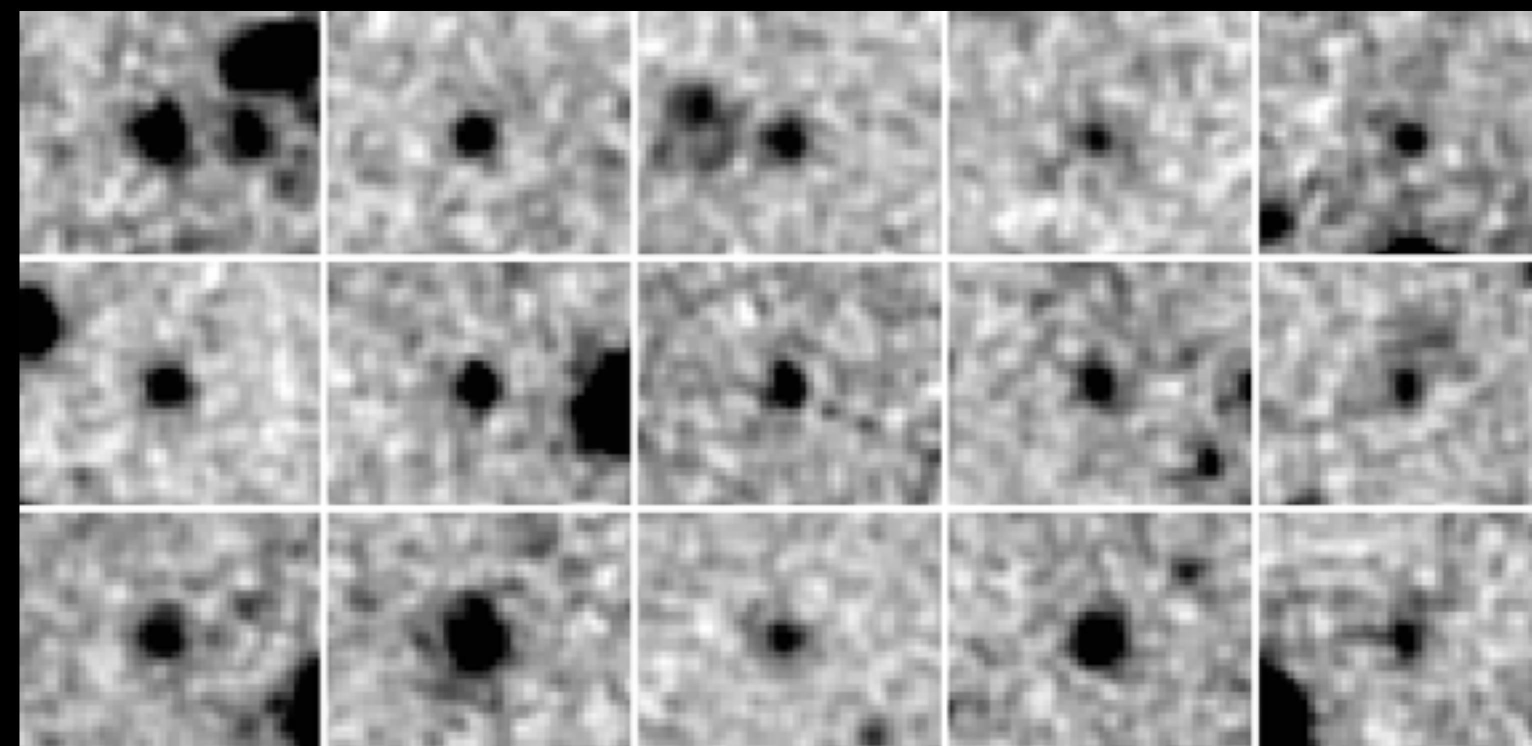
Sobral, Matthee et al. 2015 ApJ, 808, 139

THE NATURE OF LUMINOUS LAES

Luminous LAEs show a lot of diversity!

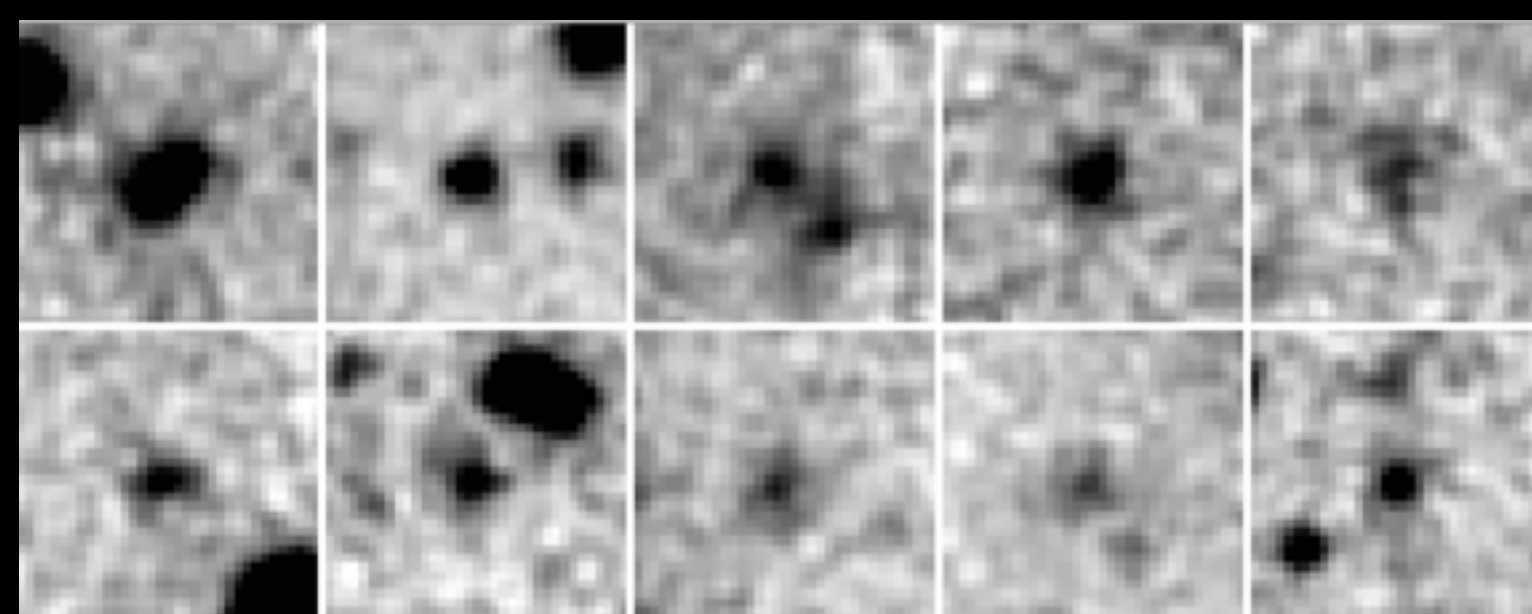
- Lya sizes

NB816
z=5.7



COSMOS >L* LAEs

NB921
z=6.6

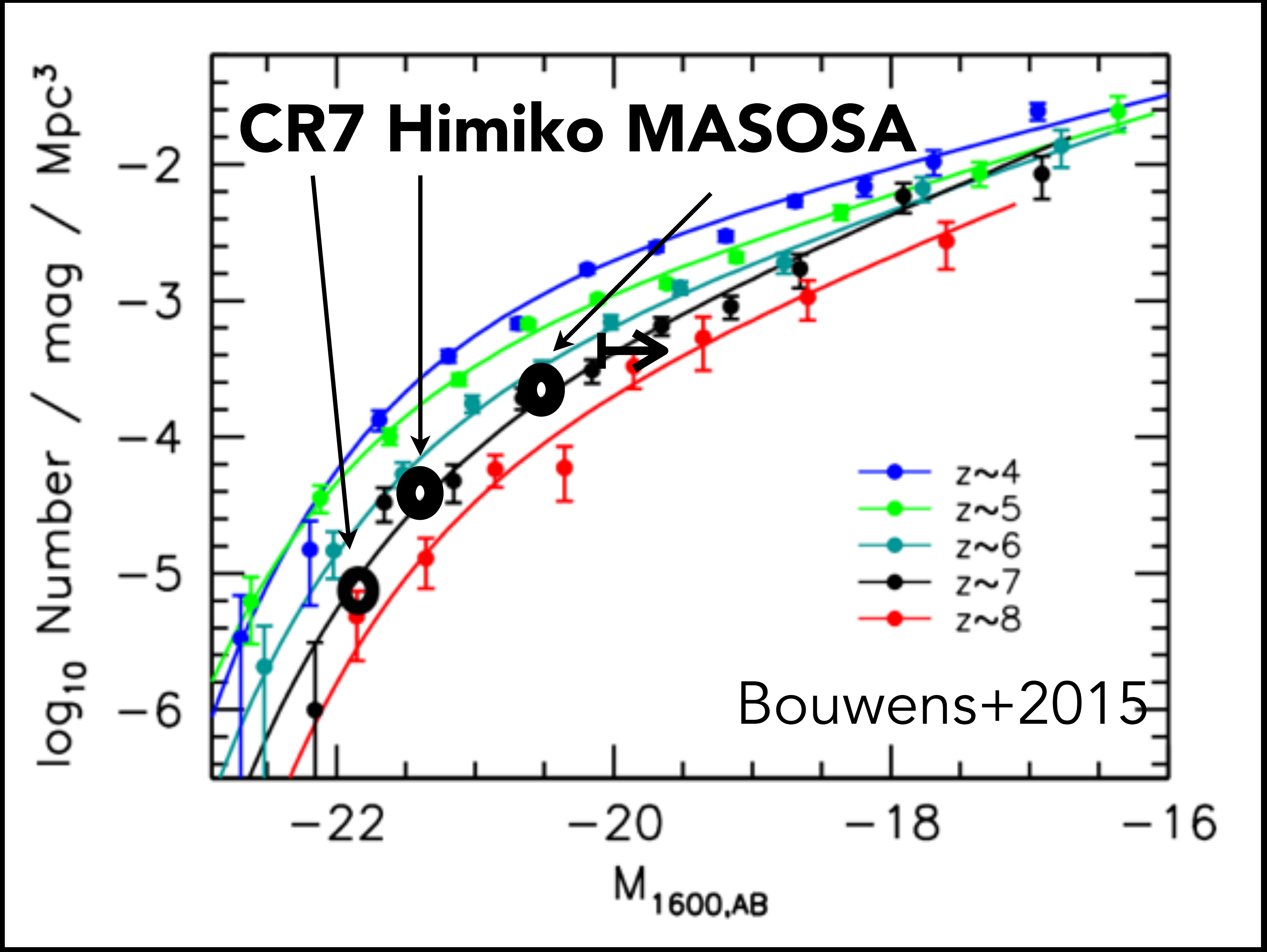


THE NATURE OF LUMINOUS LAES

Luminous LAEs show a lot of diversity!

- Lya sizes

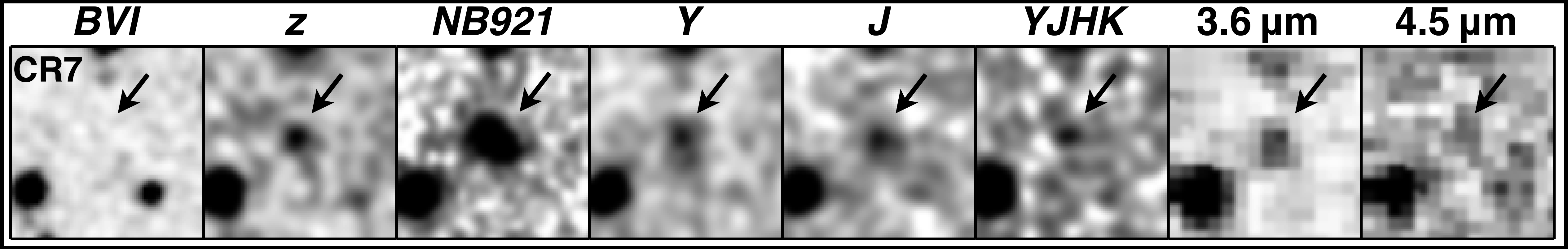
- **UV magnitudes**



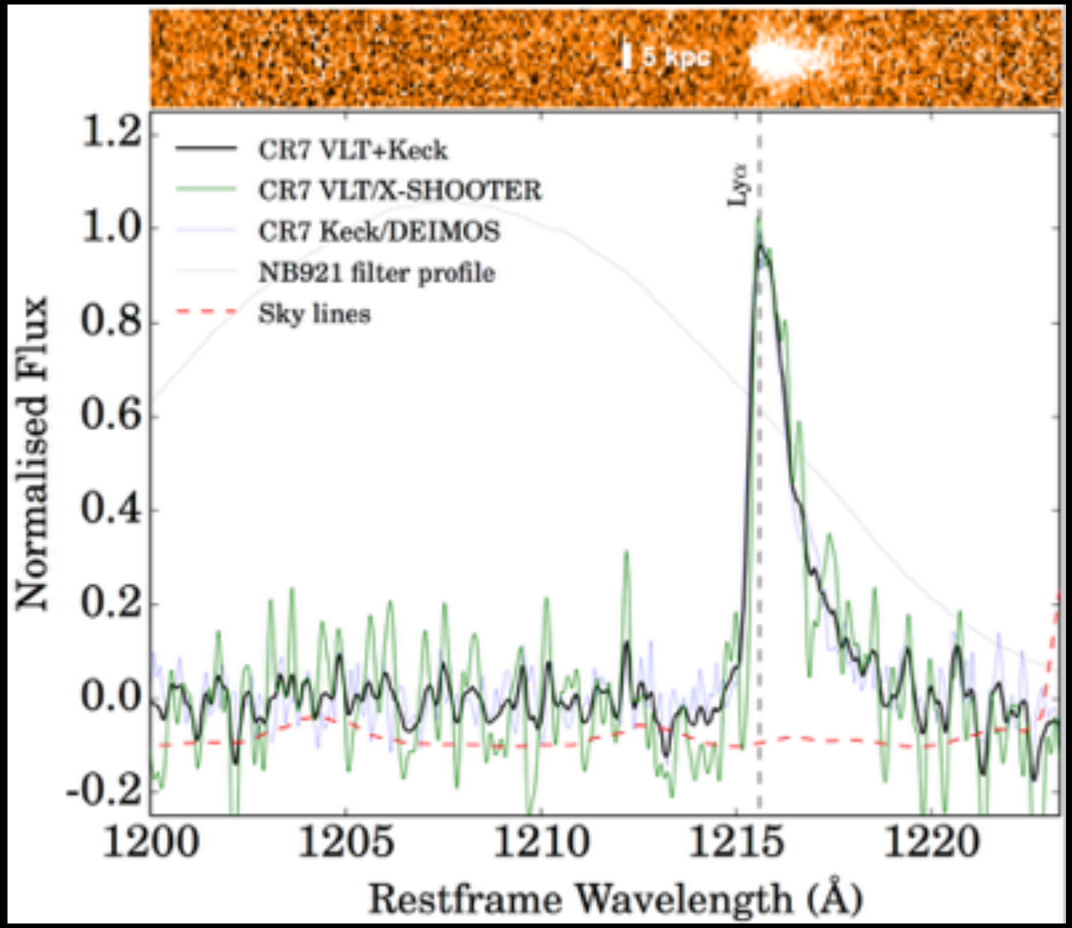
THE COSMOS REDSHIFT 7 GALAXY

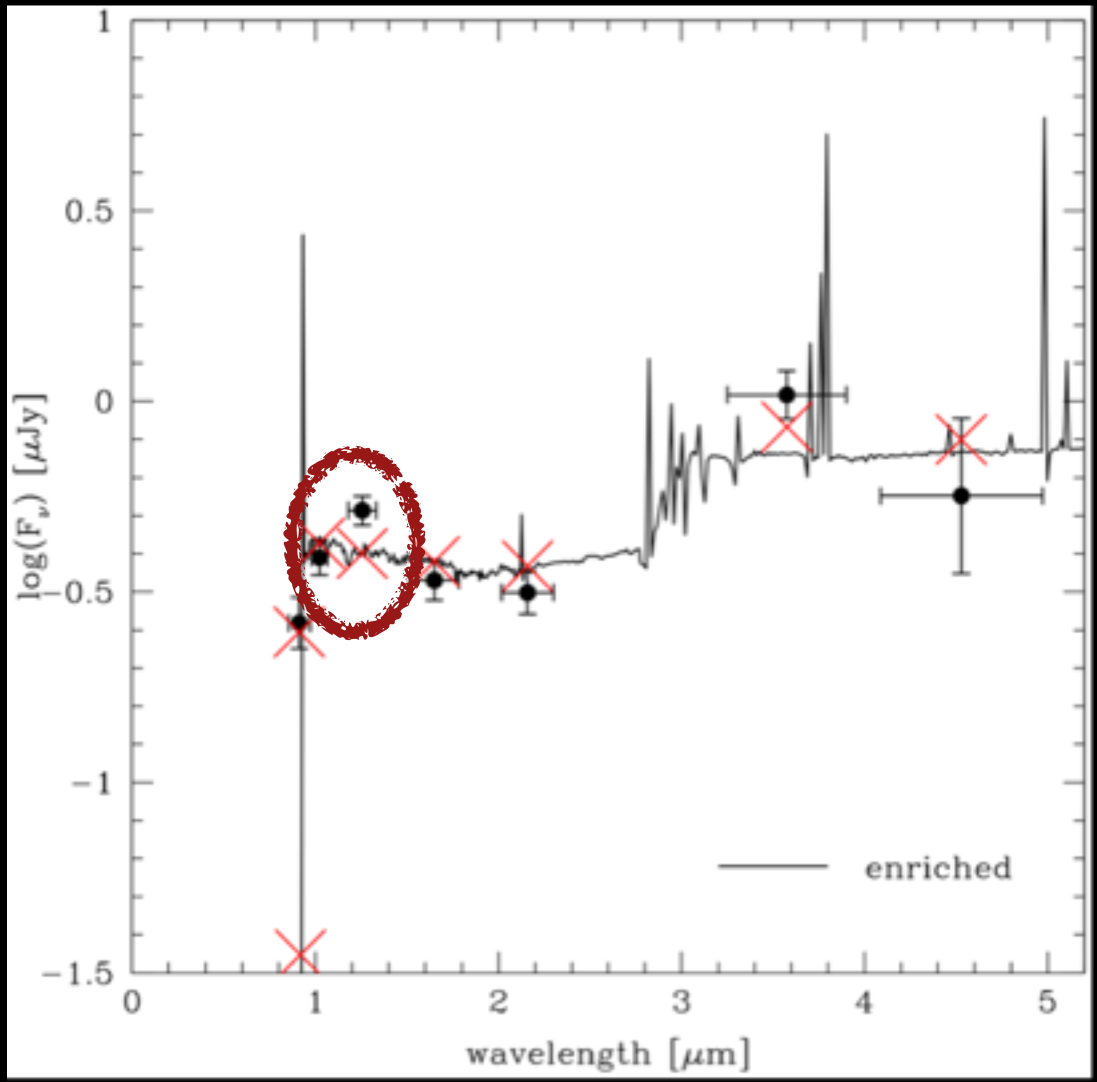
The most luminous Lyman-alpha emitter known at $z=6.6$

Detailed properties of CR7

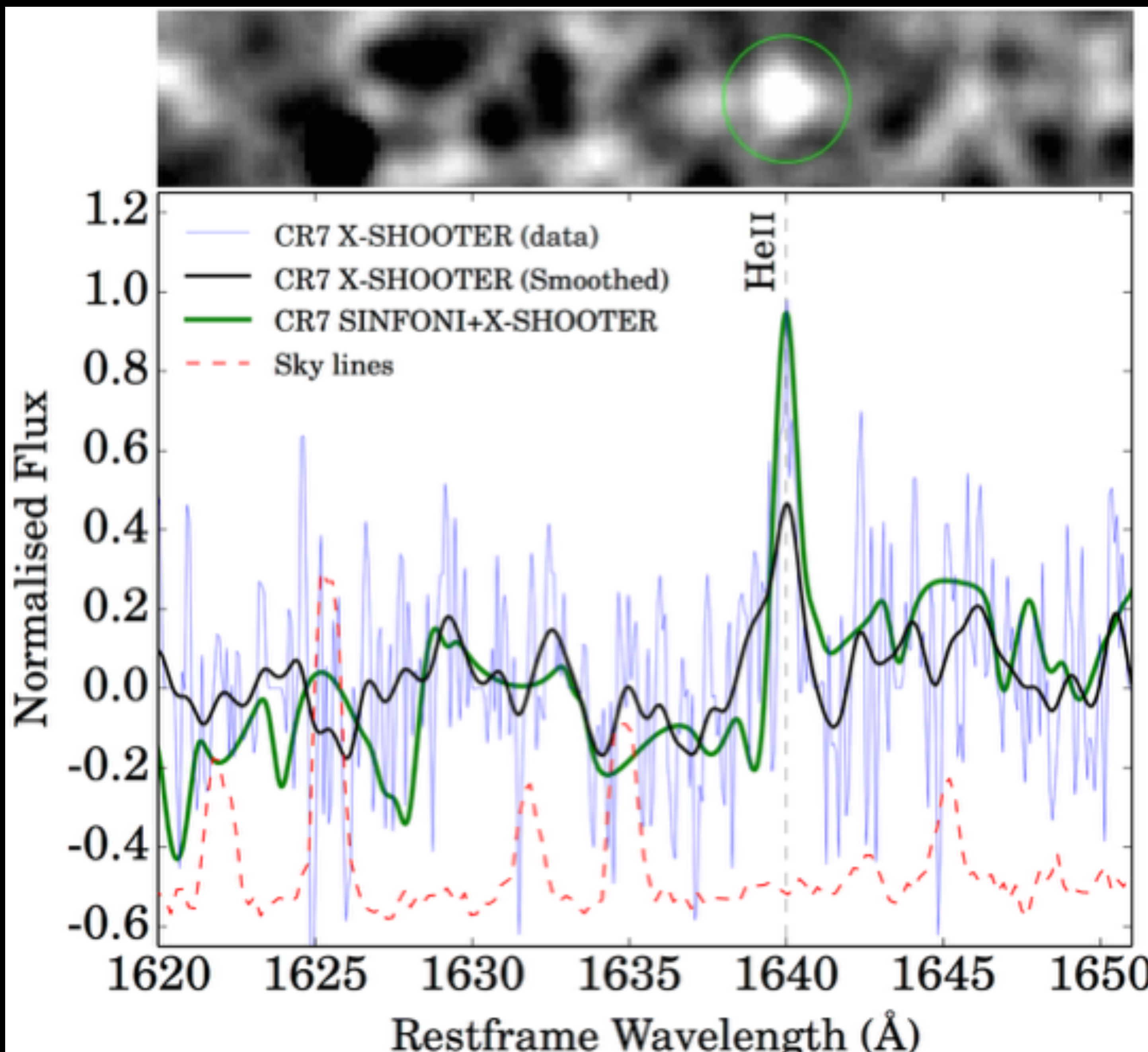


Selected as LAE, but already known in 2011 in Ilbert+ catalog and Bowler+2012 (but as brown dwarf/unreliable LBG z~6)





6 SIGMA HEII1640 EMISSION LINE



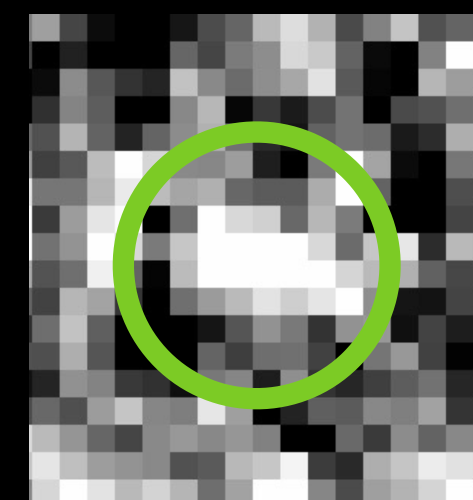
FWHM=130+-30 km/s

EW_0=80+-20 Å

HeII/Lya =0.23+-0.10

Velocity offset Lya-HeII

120km/s

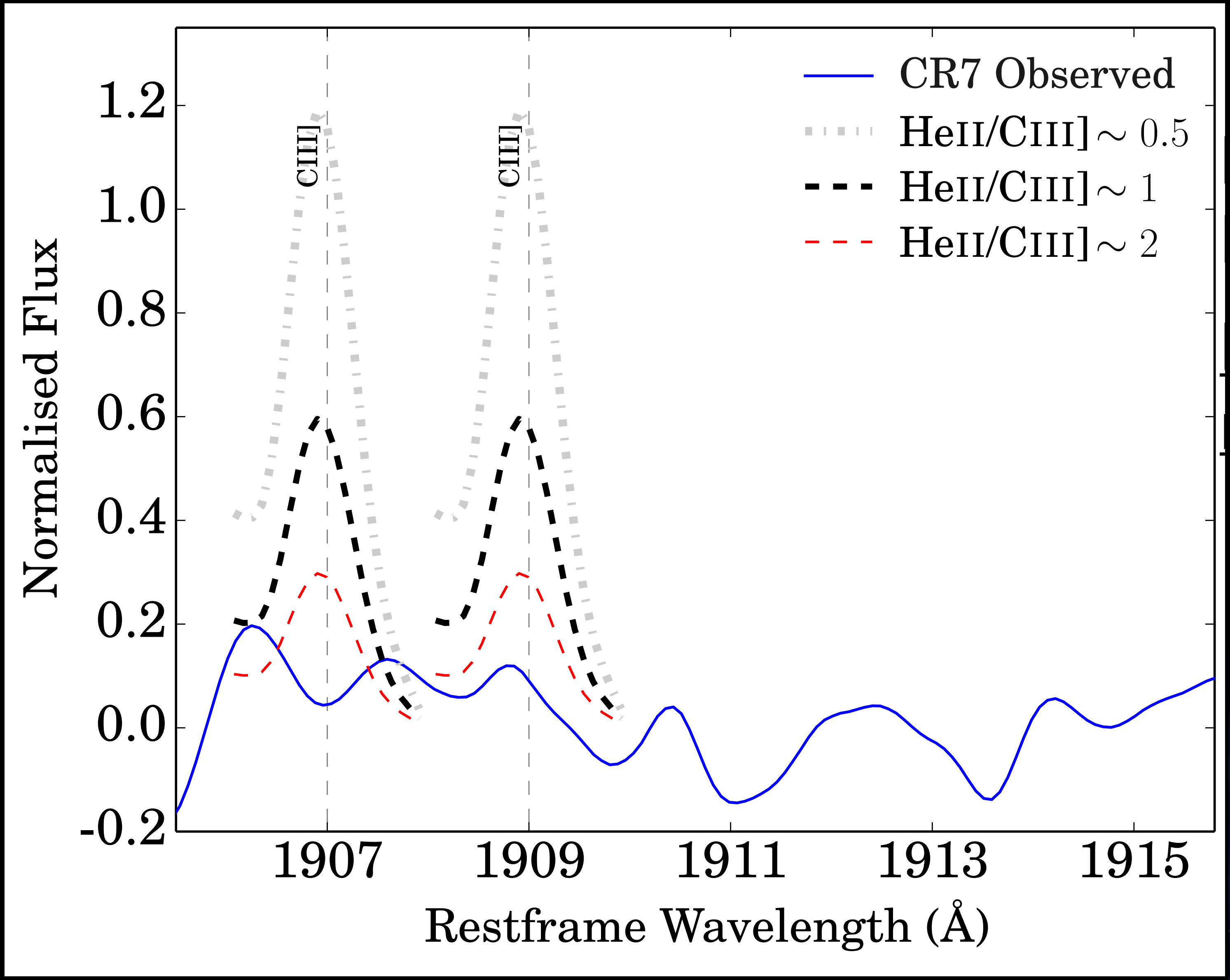


> T_{eff} ~ 100,000K

Very hard ionising source: similar to other LBGs with CIII], CIV emission

Sobral, Matthee et al. 2015 ApJ, 808, 139

NO METAL EMISSION LINES



No NV, CIV, CIII], other high excitation metal lines

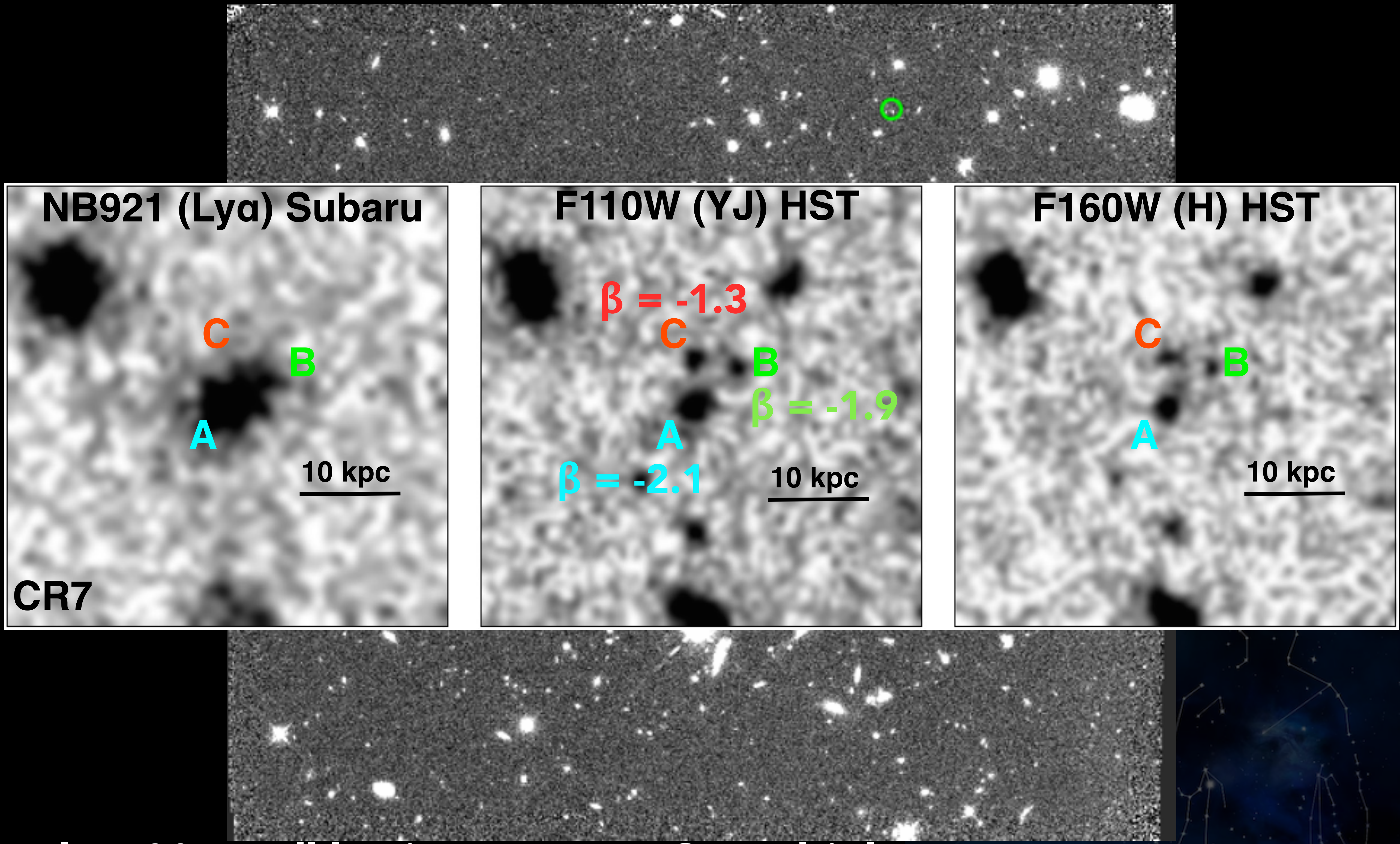
Lya/NV > 70
HeII/OIII] >3
HeII/CIII] > 2.5

Stark+2014, z~2:
Helium typically fainter!
HeII/CIII ~<0.5
HeII/OIII] ~<1-1.5

Metallicity must be *very* low: <1/200 Z_{sun}

Sobral, Matthee et al. 2015 ApJ, 808, 139

(ARCHIVAL) HST VIEW OF CR7

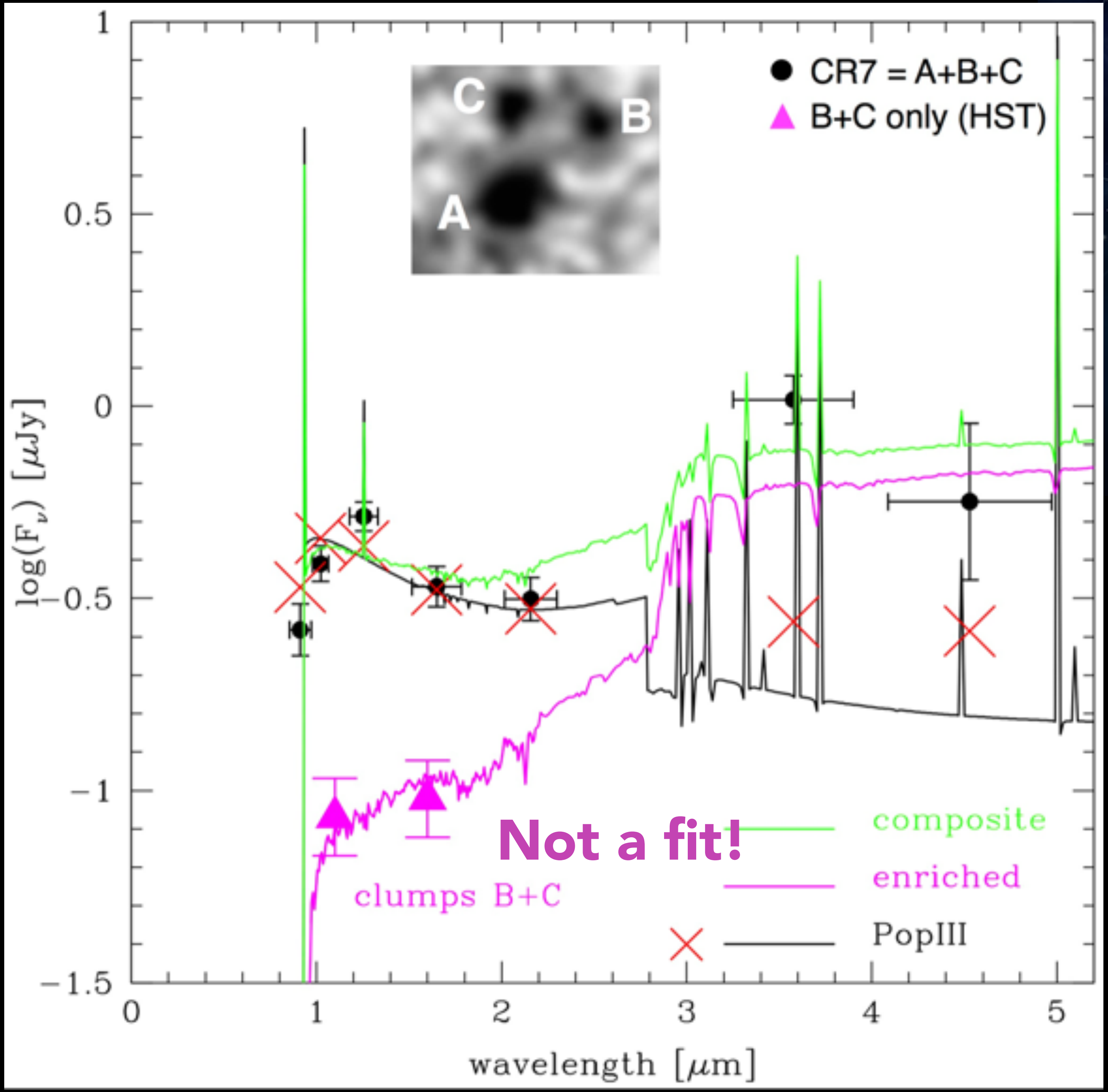


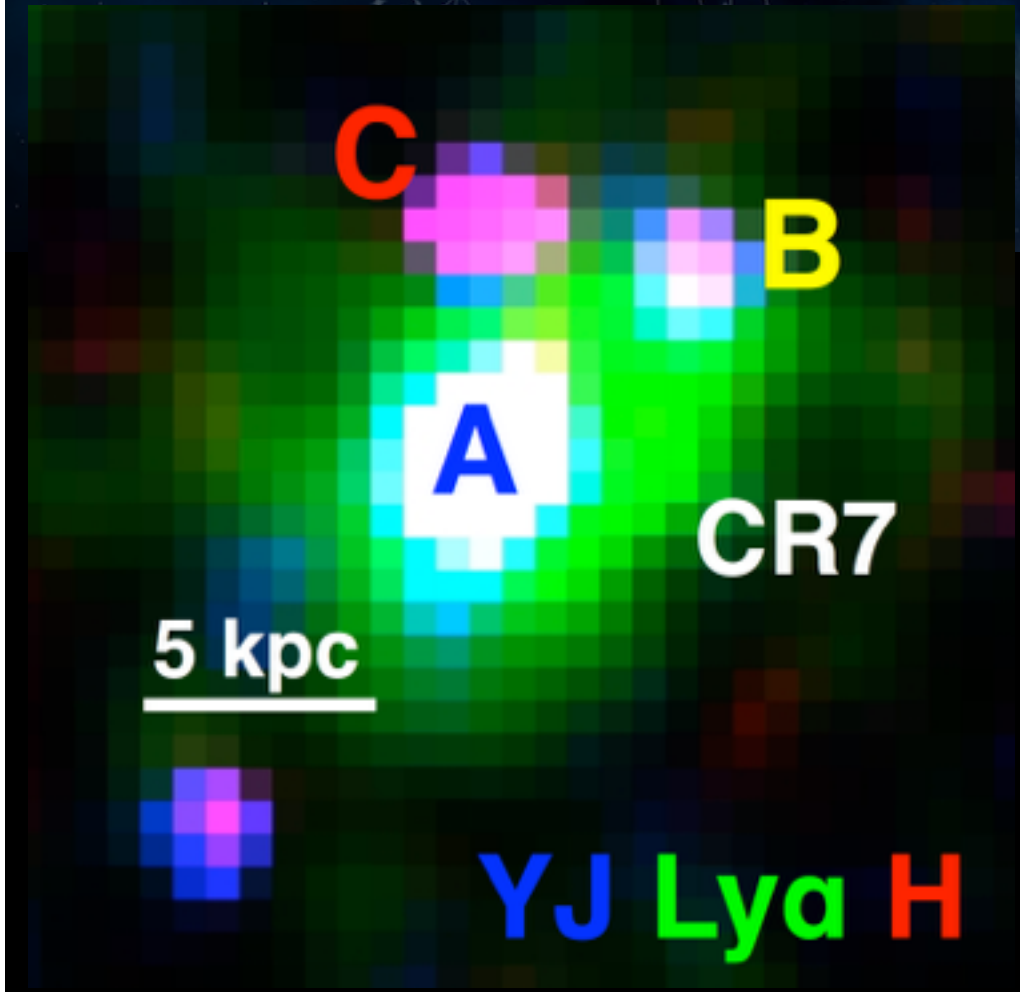
Bowler+2016: all luminous z~7 LBGs multiple components

Thanks Forster-Schreiber (PI HST data)!

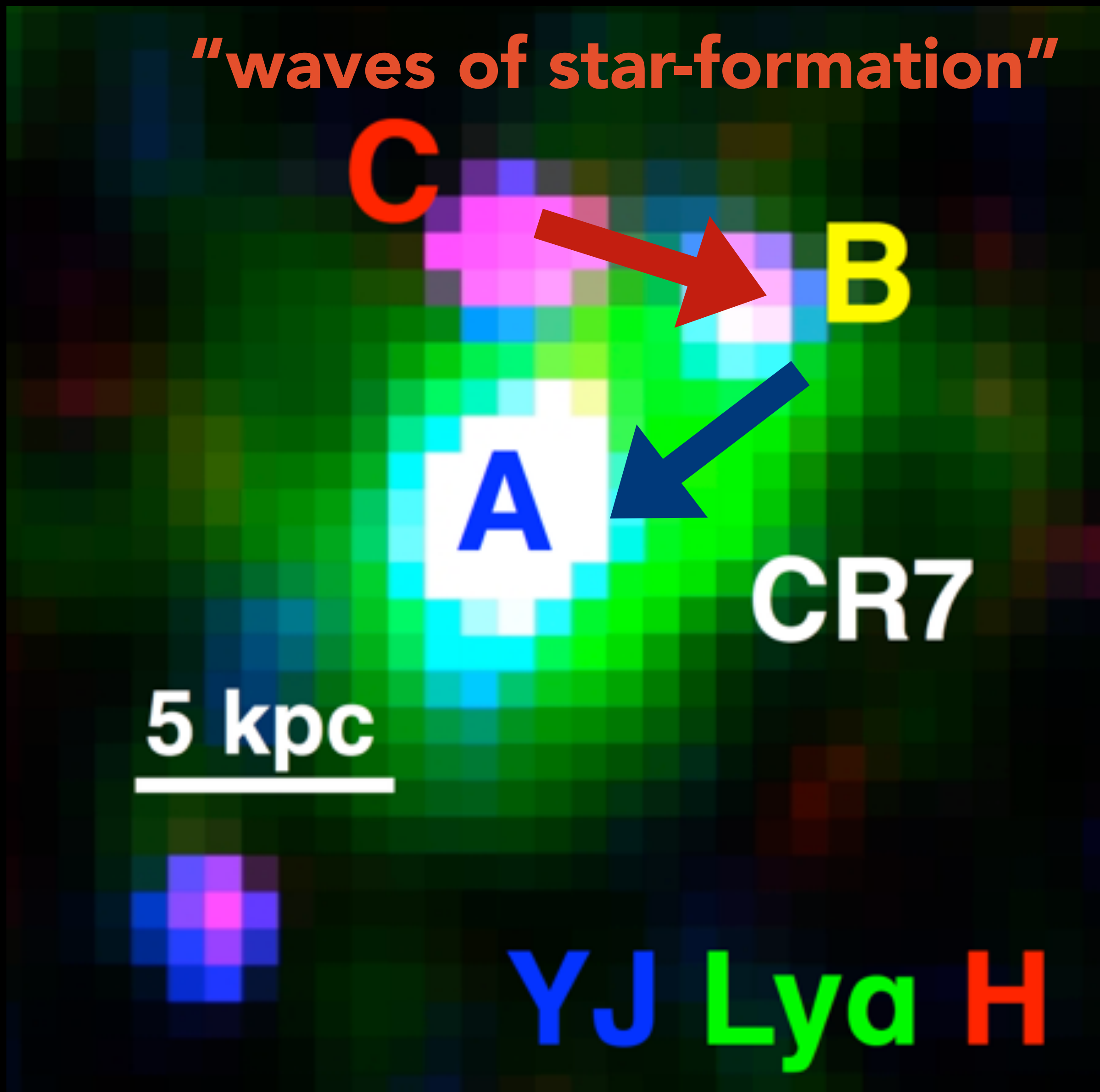
Sobral, Matthee et al. 2015 ApJ, 808, 139

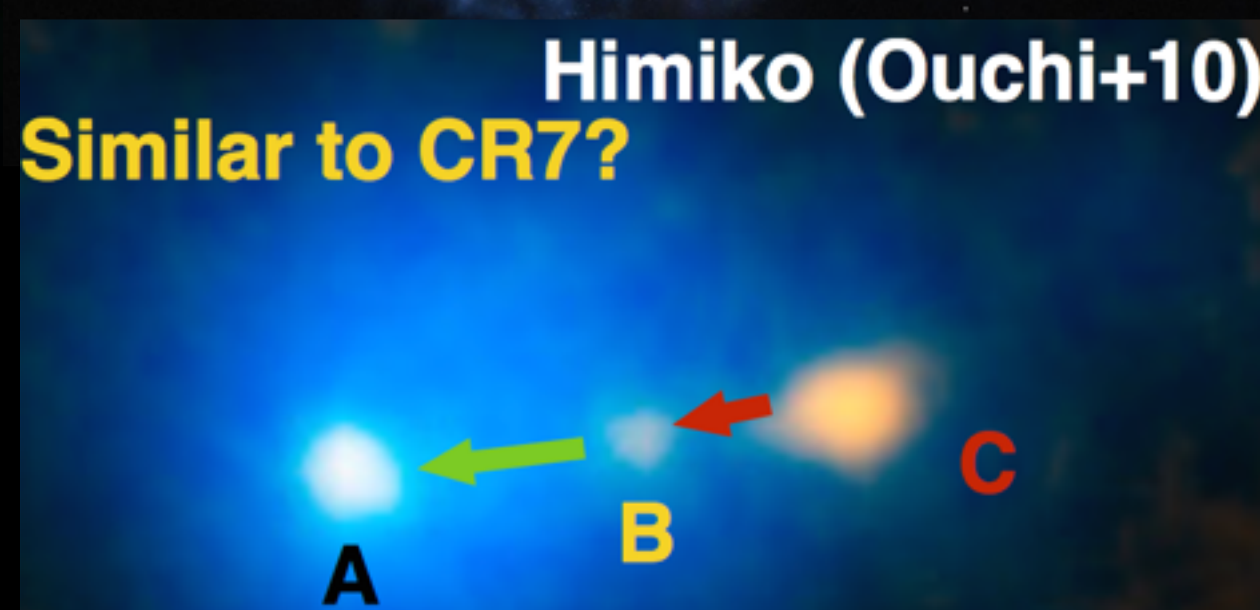
CURRENT DATA IS FULLY CONSISTENT WITH POPIII-*LIKE* CLUMP A+"NORMAL"STELLAR POP IN B+C





PopIII-like formation scenario:





Himiko: no HeII, nor metal lines: Zabl+2015

However, many theorists 'prefer' that CR7 is the first detection of a Direct Collapse Black Hole (DCBH)

The Brightest Lyα Emitter: Pop III or Black Hole?

Detecting Direct Collapse Black Holes: making the case for CR7

Exploring the nature of the Lyman-α emitter CR7

Evidence for a direct collapse black hole in the Lyman α source CR7

LYα SIGNATURES FROM DIRECT COLLAPSE BLACK HOLES

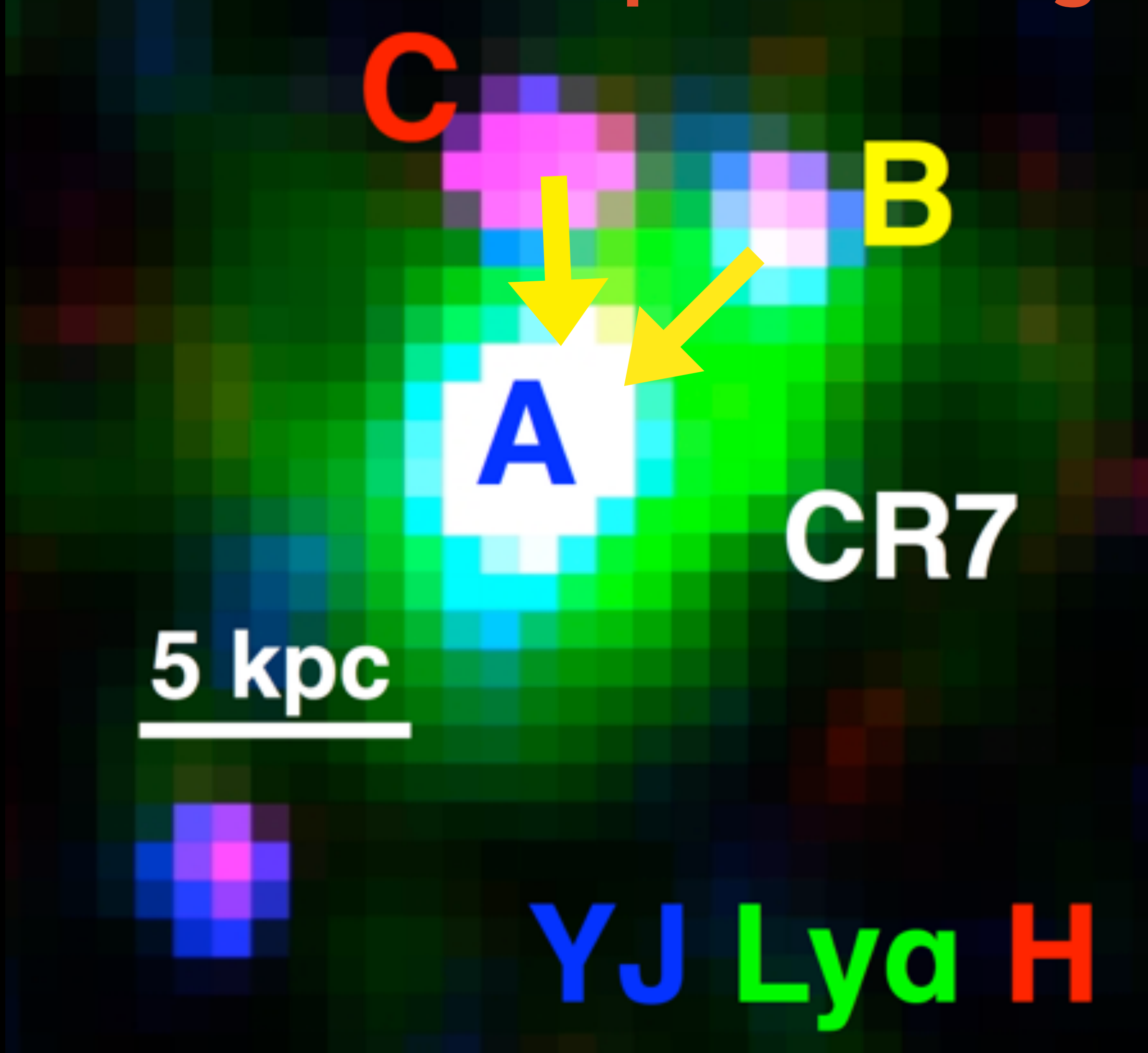
AB INITIO COSMOLOGICAL SIMULATIONS OF CR7 AS AN ACTIVE BLACK HOLE

Formation of Massive Population III Galaxies through Photoionization Feedback: A Possible Explanation for CR7

Pallotini+2015, Agarwal+2015, Hartwig+2015, Smith+2016, Dijkstra+2016, Smidt+2016
(but Visbal+2016 argue PopIII through similar mechanism)

DCBH formation scenario:

Radiative feedback prevents fragmentation in clump A



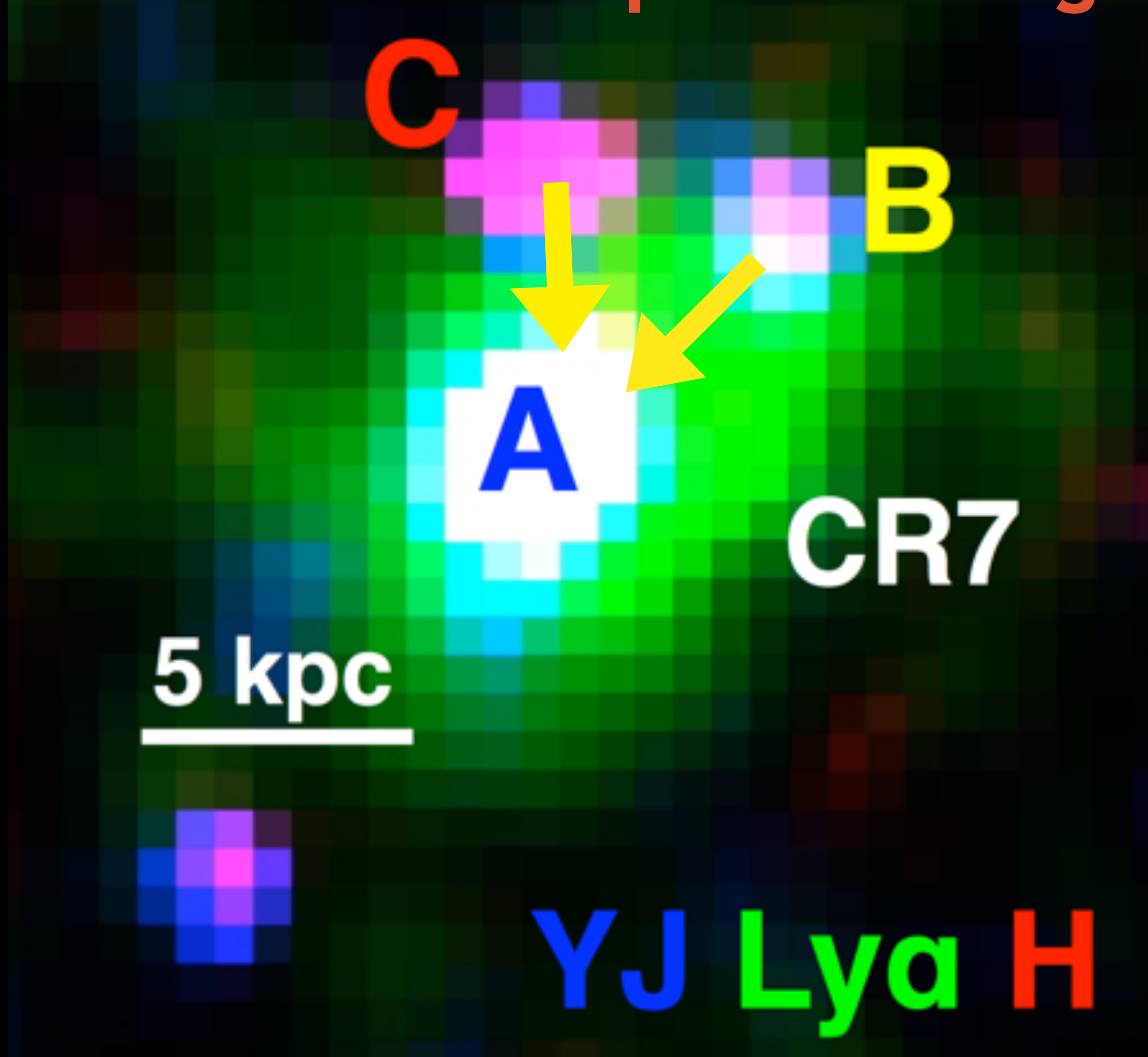
HST+Subaru image of CR7

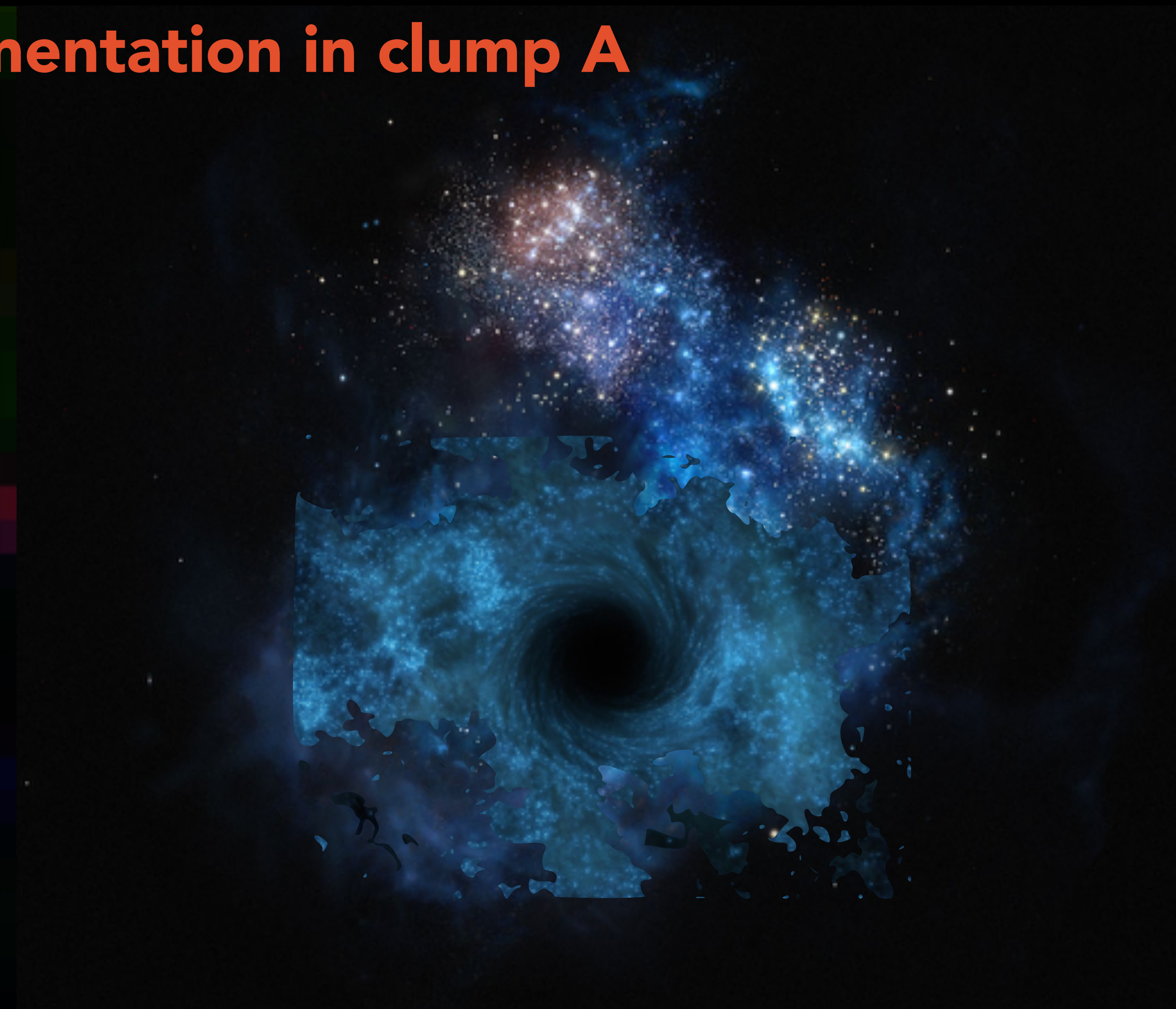
Artist impression (Kornmesser, ESO)

Pallotini+2015, Agarwal+2015, Hartwig+2015, Smith+2016, Dijkstra+2016, Smidt+2016
(but Visbal+2016 argue PopIII through similar mechanism)

DCBH formation scenario:

Radiative feedback prevents fragmentation in clump A



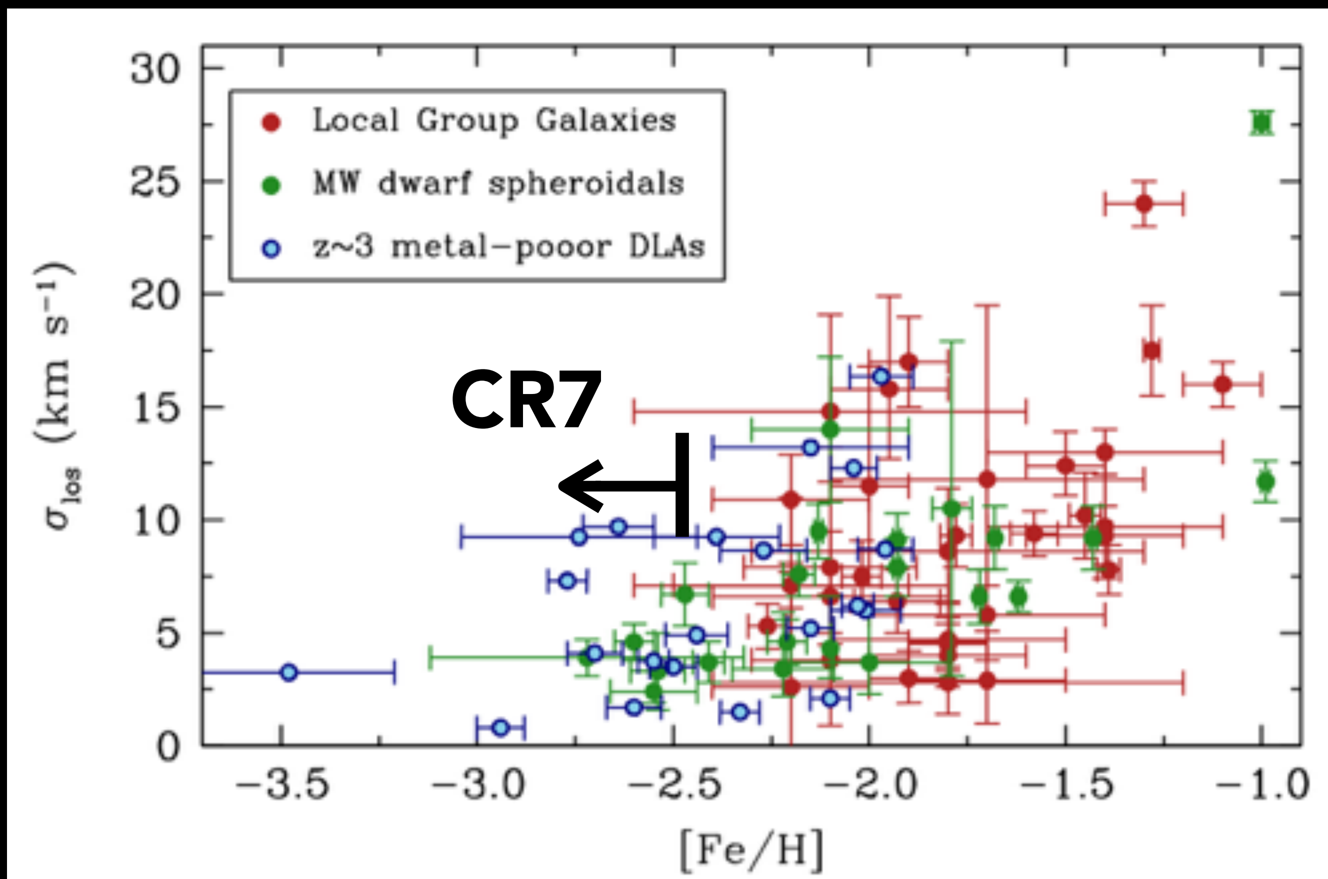


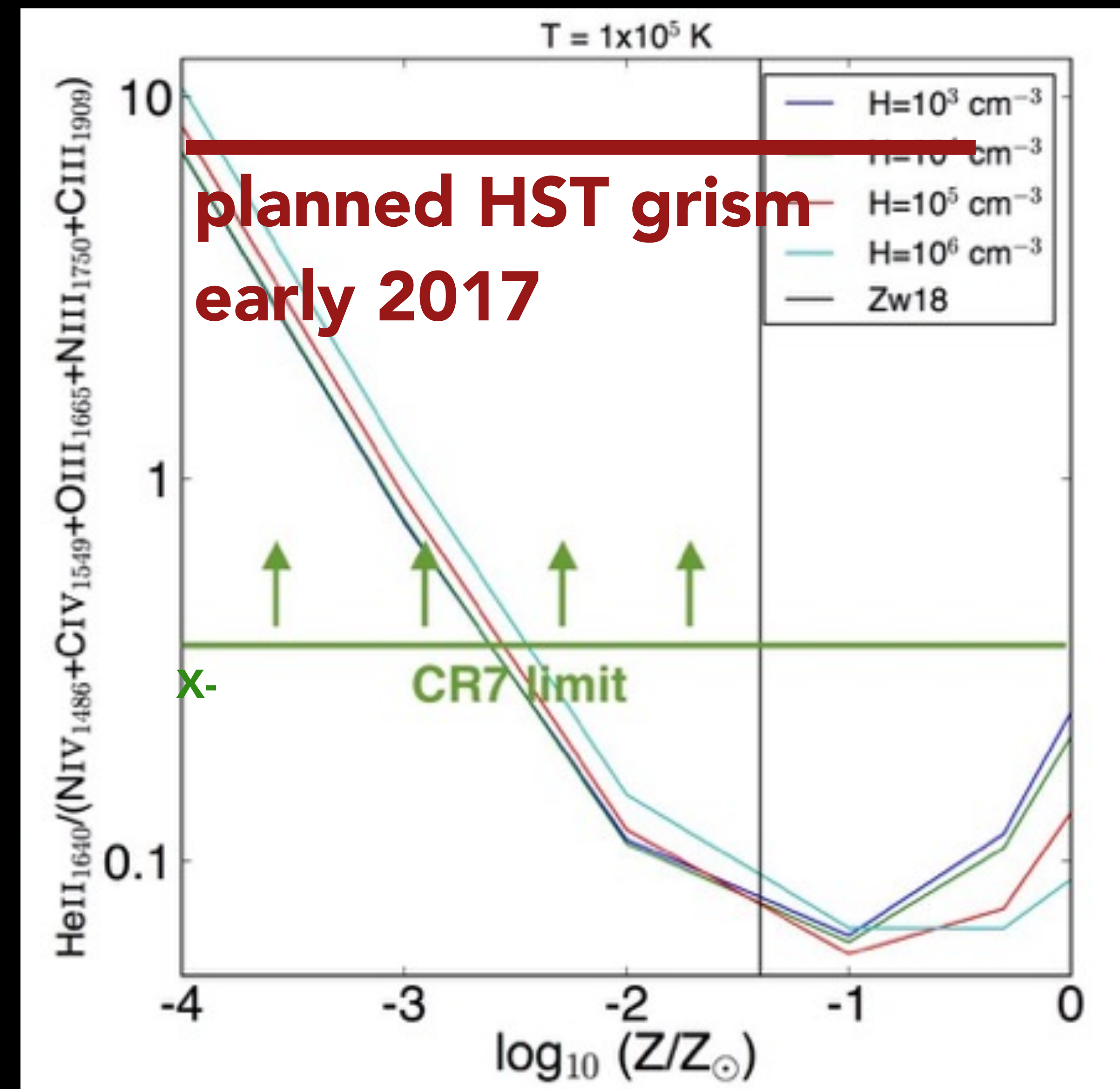
HST+Subaru image of CR7

Artist impression (JM)

Pallotini+2015, Agarwal+2015, Hartwig+2015, Smith+2016, Dijkstra+2016, Smidt+2016
(but Visbal+2016 argue PopIII through similar mechanism)

Ongoing ALMA+HST follow-up: metallicity of hot and warm ISM





CLOUDY modelling
blackbody, T=100,000K
(motivated from Lya-HeII)

Current constraint from X-SHOOTER: $Z/Z_{sun}<10^{-2.5}$

HST grism early 2017 will give $Z/Z_{sun}<10^{-4}$

metal poor DLAs: Cooke, Pettini & Jorgensen 2015

SUMMARY

Matthee, Sobral et al. 2015 MNRAS 451, 4919

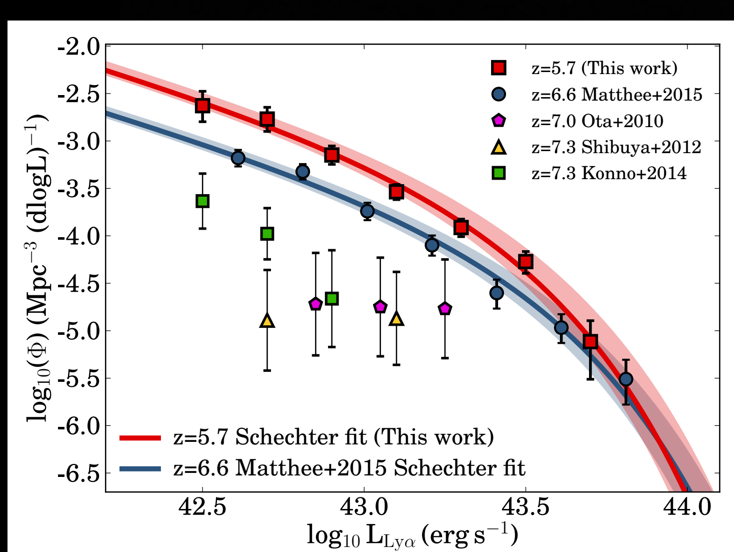
Sobral, Matthee et al. 2015 ApJ, 808, 139

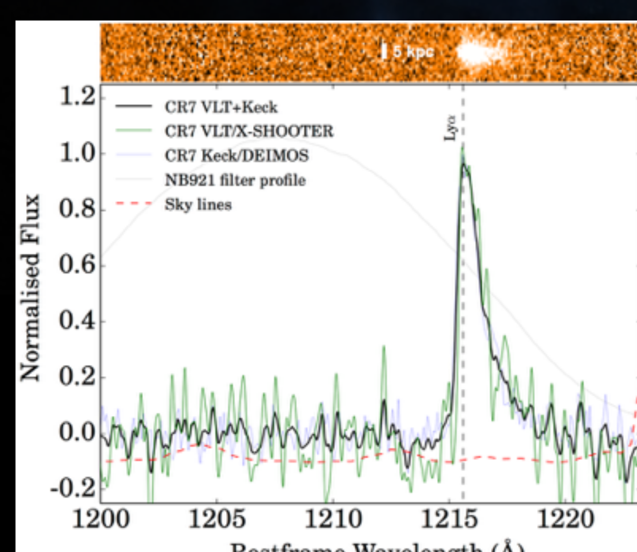
Santos, Sobral & Matthee, 2016, arXiv: 1606.07435

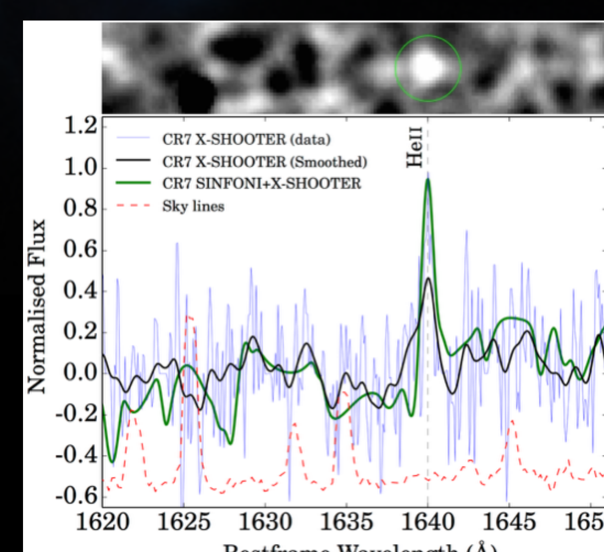
Faint LAEs are less abundant and more extended at z=6.6 than at z=5.7: patchy reionization?

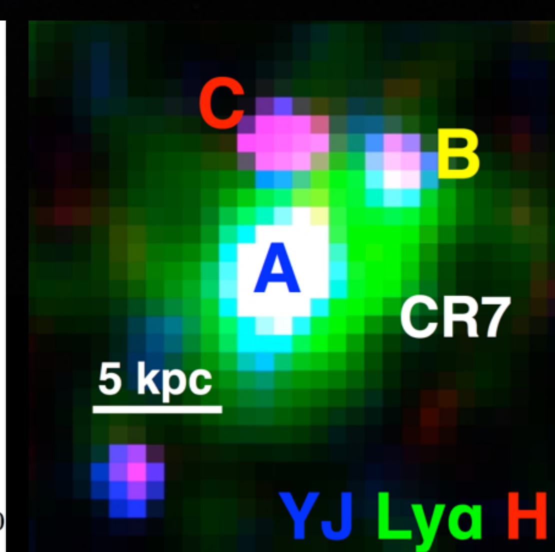
Bright LAEs show a surprisingly variety: compact vs extended Lya, multiple clumps, narrow FWHMs.

COSMOS Redshift 7 hosts an extreme ionising source in low metallicity gas: PopIII stars or DCBH? Follow-up of CR7 and similar sources is ongoing.





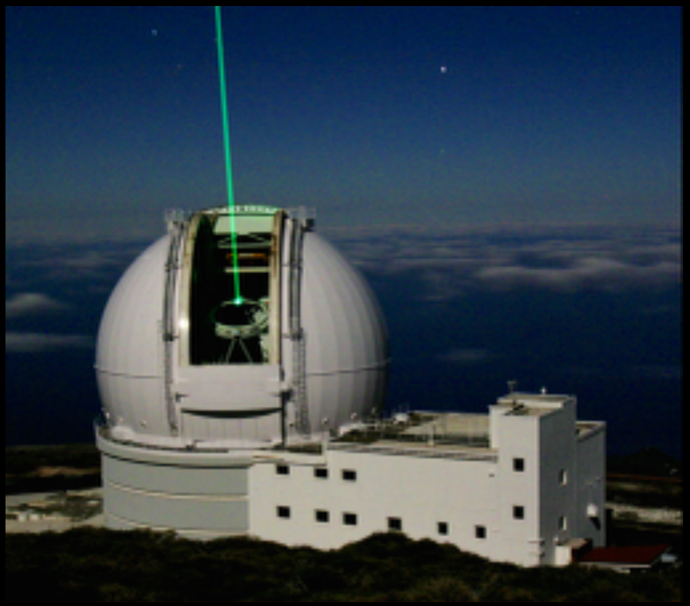


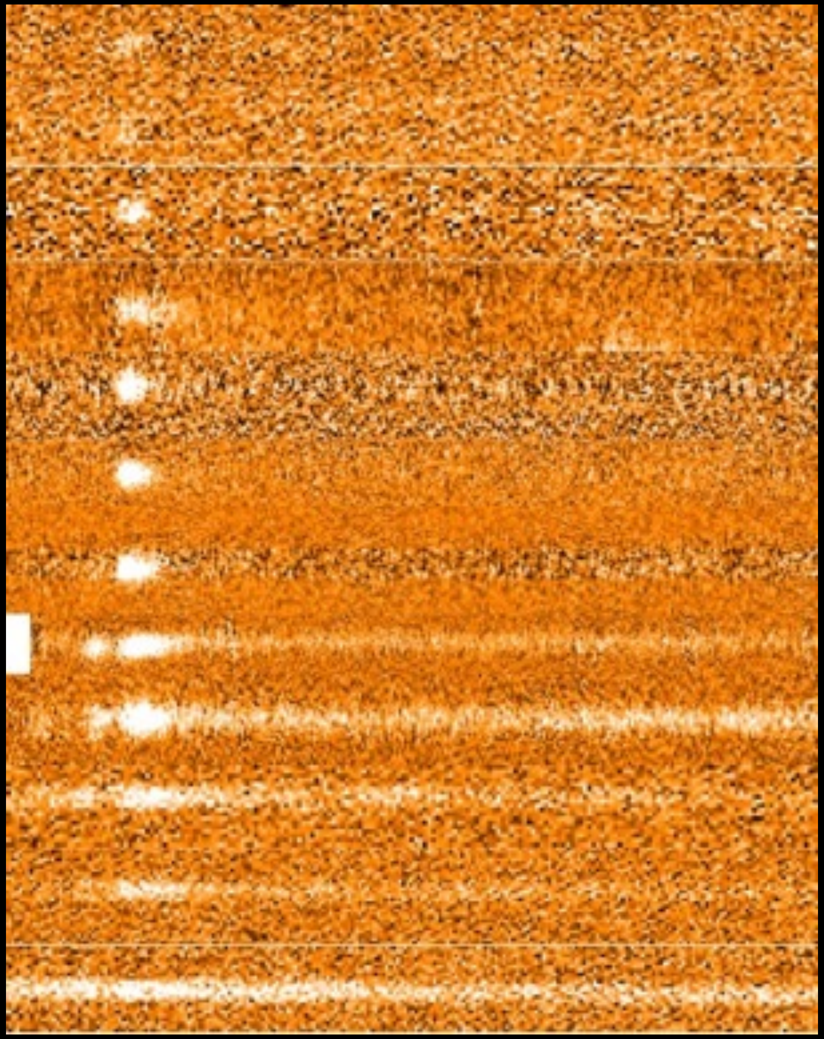


Future:

- New survey into the reionization era:
Y-NBS z=7.7 with VLT

- The physical properties of LAEs
Spectroscopy of 100s LAEs at z=3-6





WHT/AF2+WYFFOS