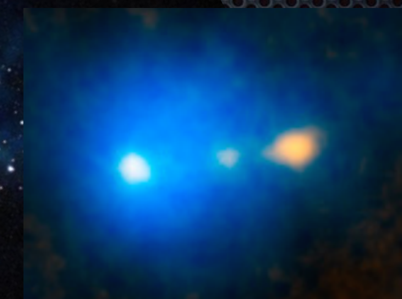
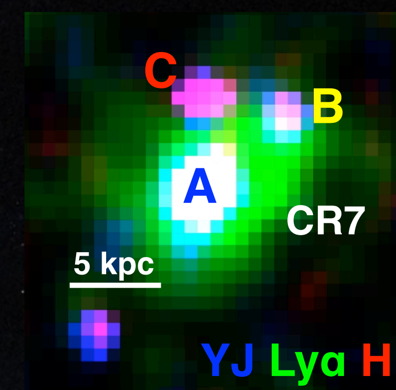
The first 1-2 Gyrs of cosmic time with the widest Lyman-α surveys

David Sobral

Lancaster University

Leiden Observatory





Jorryt Matthee, Sérgio Santos, Behnam Darvish, Daniel Schaerer,
Bahram Mobasher, Huub Rottgering, Shoubaneh Hemmati

Lancaster University

Sterrewacht Leiden

VENI VIDI VICI

NWO

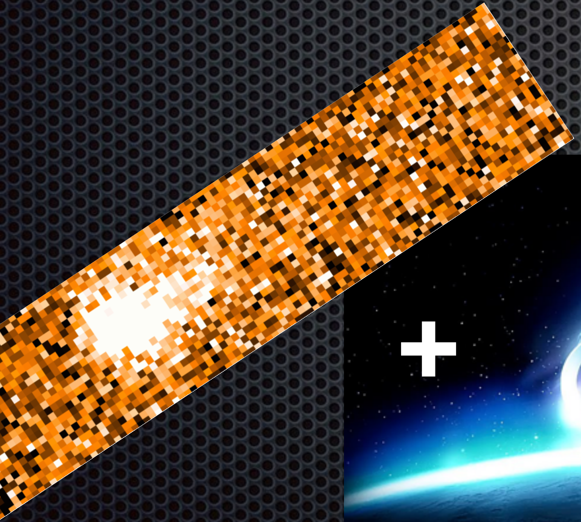
Matthee, Sobral et al. 2015, MNRAS
Sobral, Matthee et al. 2015, ApJ
Sobral et al. in prep.
Santos et al. in prep.

Take home messages

- Luminous Lyα emitters (~$10^{43.5}$ erg/s) at z=5.7-6.6 much more common than thought

$$1.5 \times 10^{-5}\ \mathrm{Mpc}^{-3}$$

- Evolution of the Lyα LF is at the faint end
- Discovery of the most Luminous Lyα emitters at z=6.6: surprises!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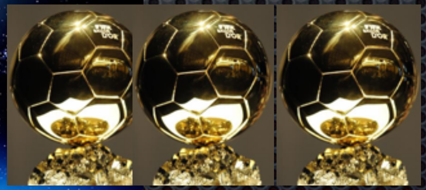
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???

From the Dark ages to the end of re-ionisation

Can we find and study the first stars and galaxies?

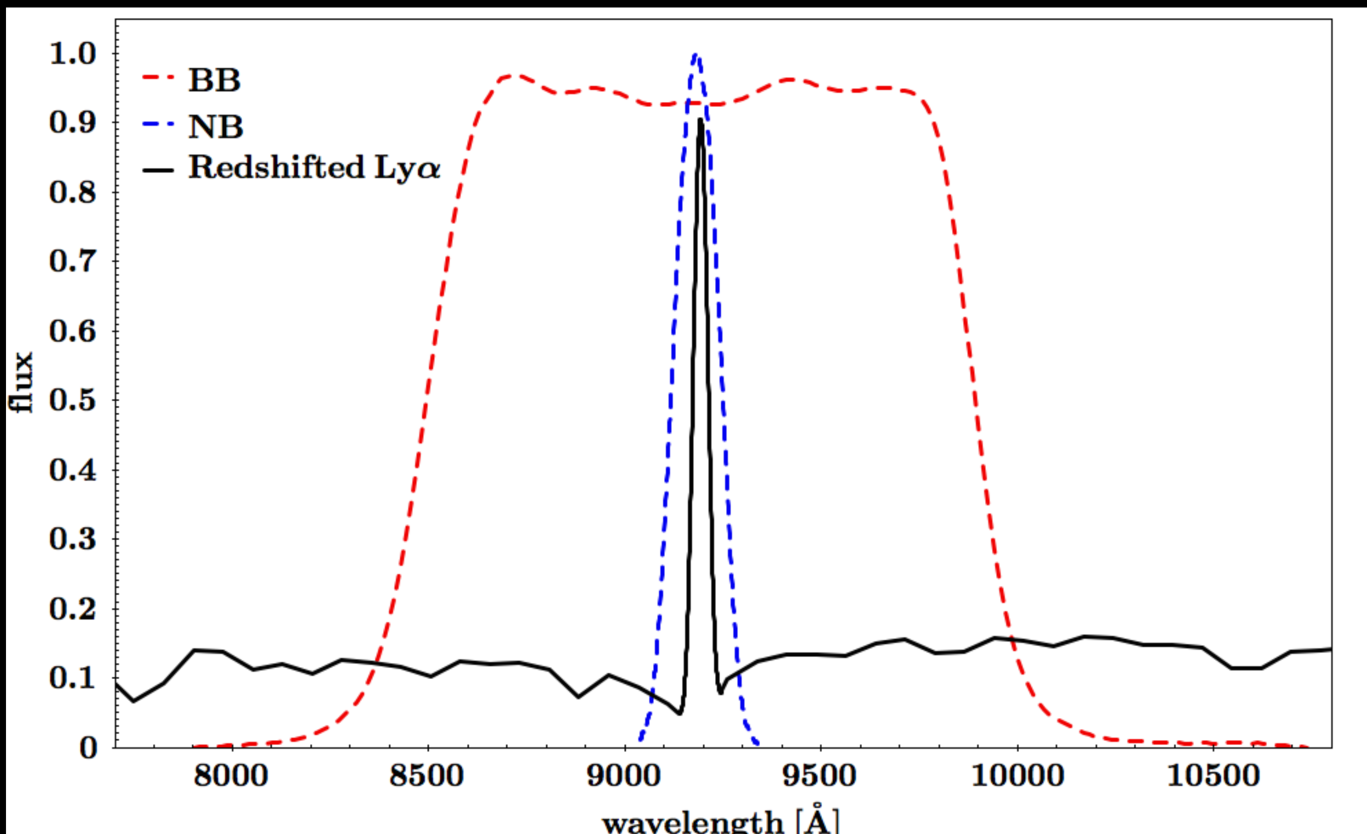
What are their properties and stellar populations? ISM?

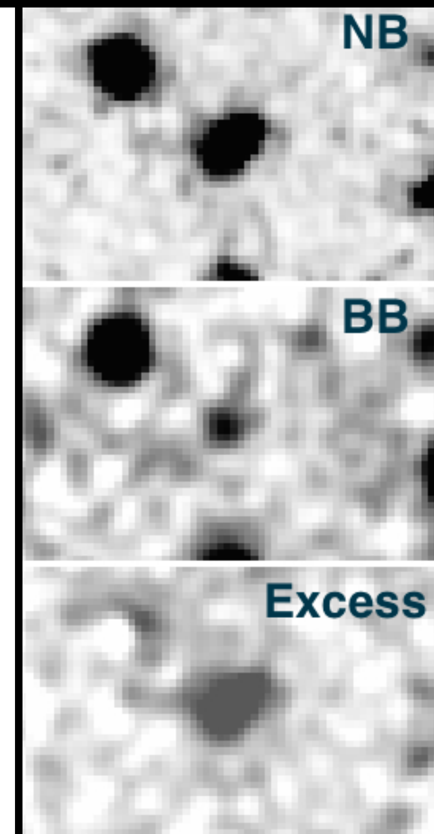
Finding and studying sufficiently luminous galaxies allows for incredible progress right now!

- See talks by e.g. : R. Bowler, D. Stark, G. Brammer

Lyman-α as a tool to study young galaxies and re-ionisation

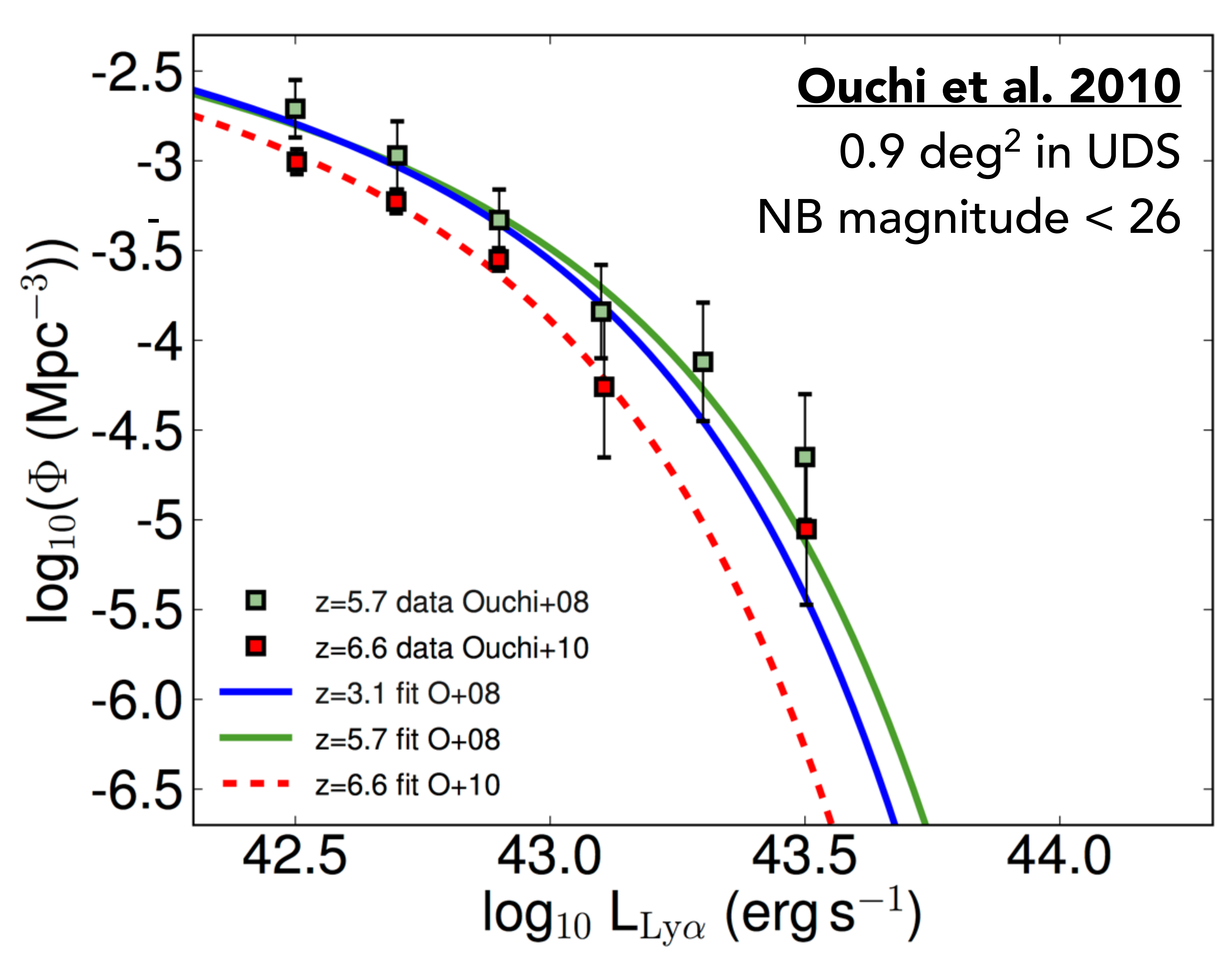
- narrow-band selects redshifted 1216 Å emission (optical at z>2)





- Lyα emitted by young galaxies (high EW)
- Lyα absorbed in more neutral IGM (test for re-ionisation)

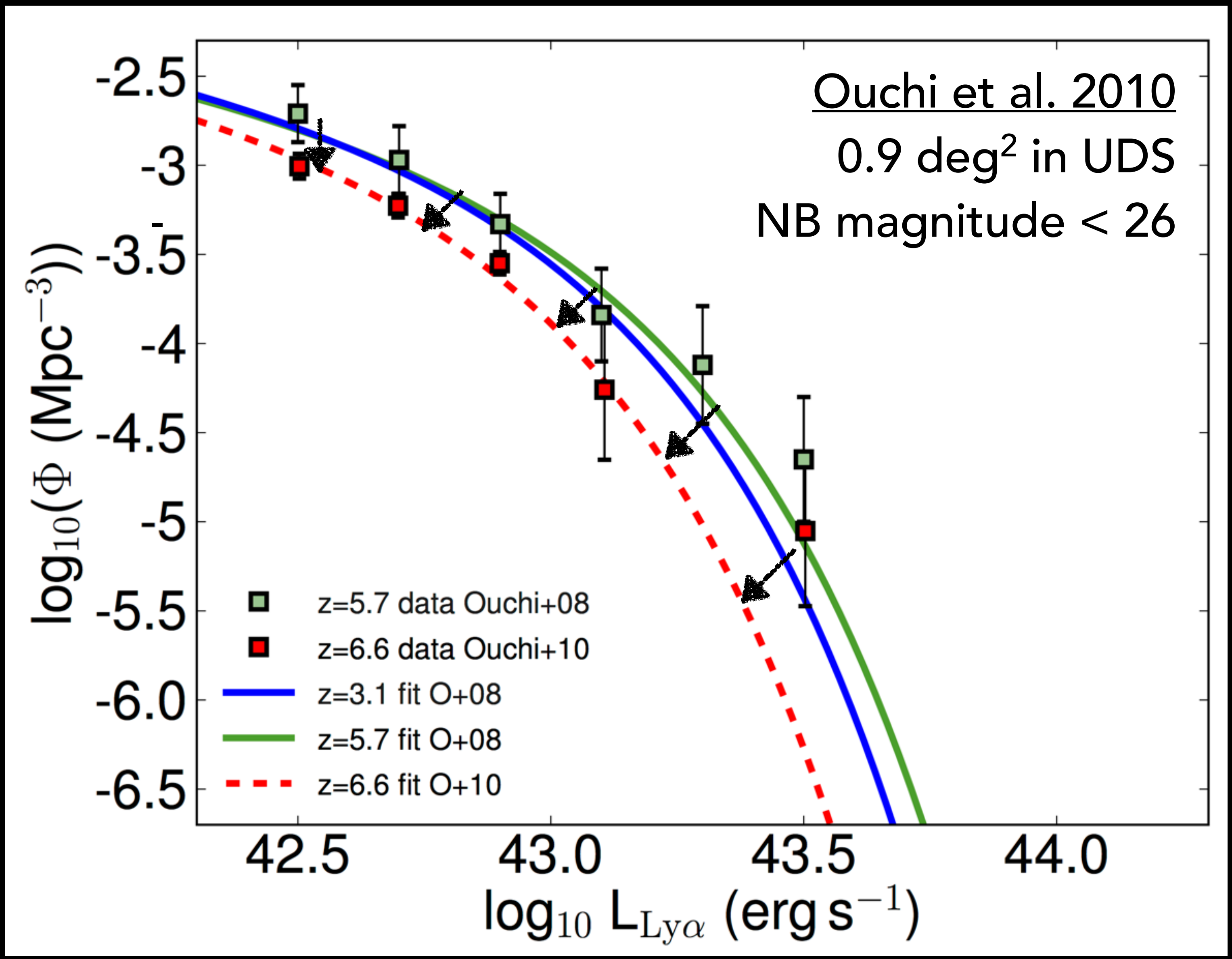
Lyman-α Luminosity function z~3-6 roughly constant



Lyman-α Luminosity function at z=6.6

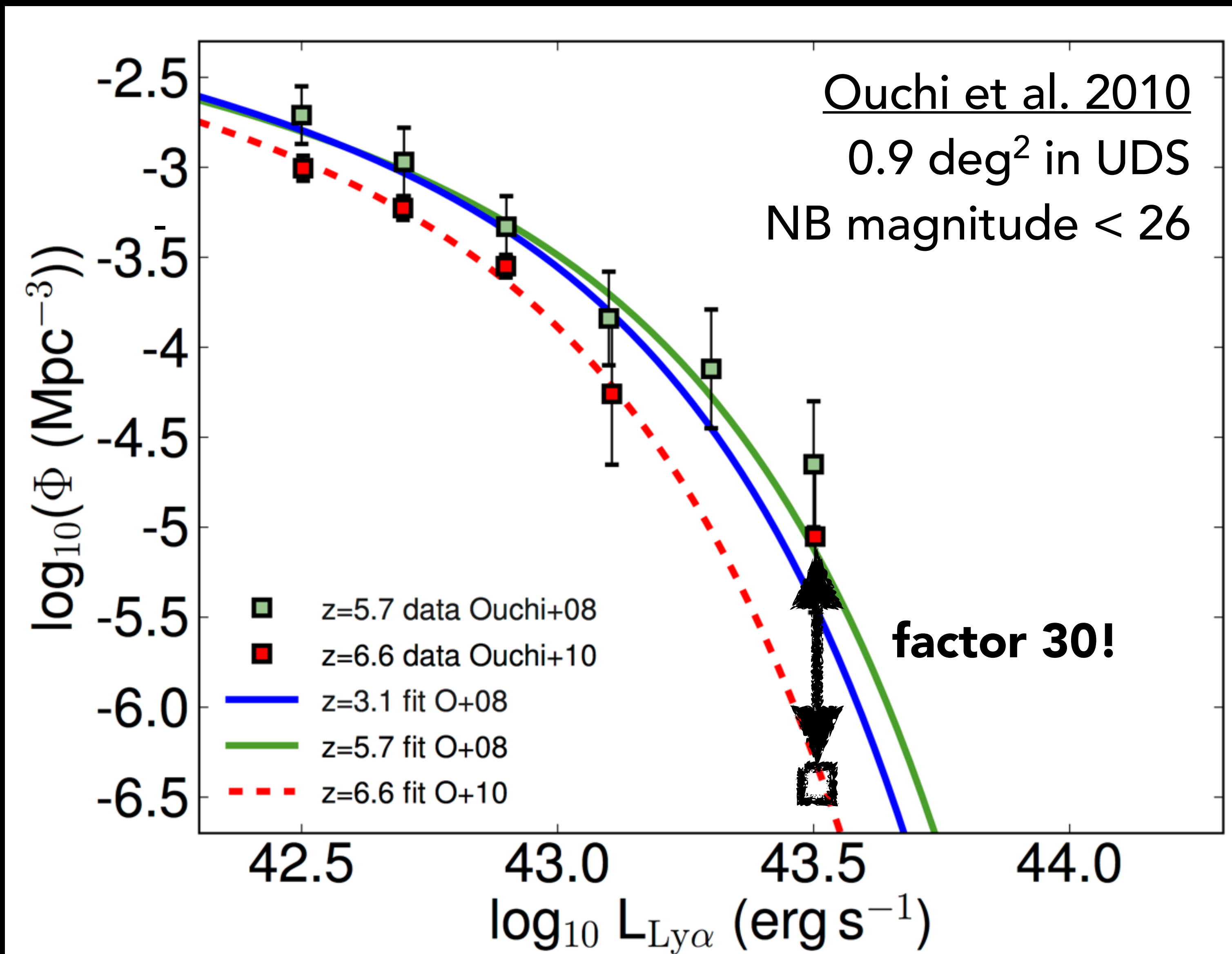
Re-ionisation not complete?

Evolution at all Luminosities (?)



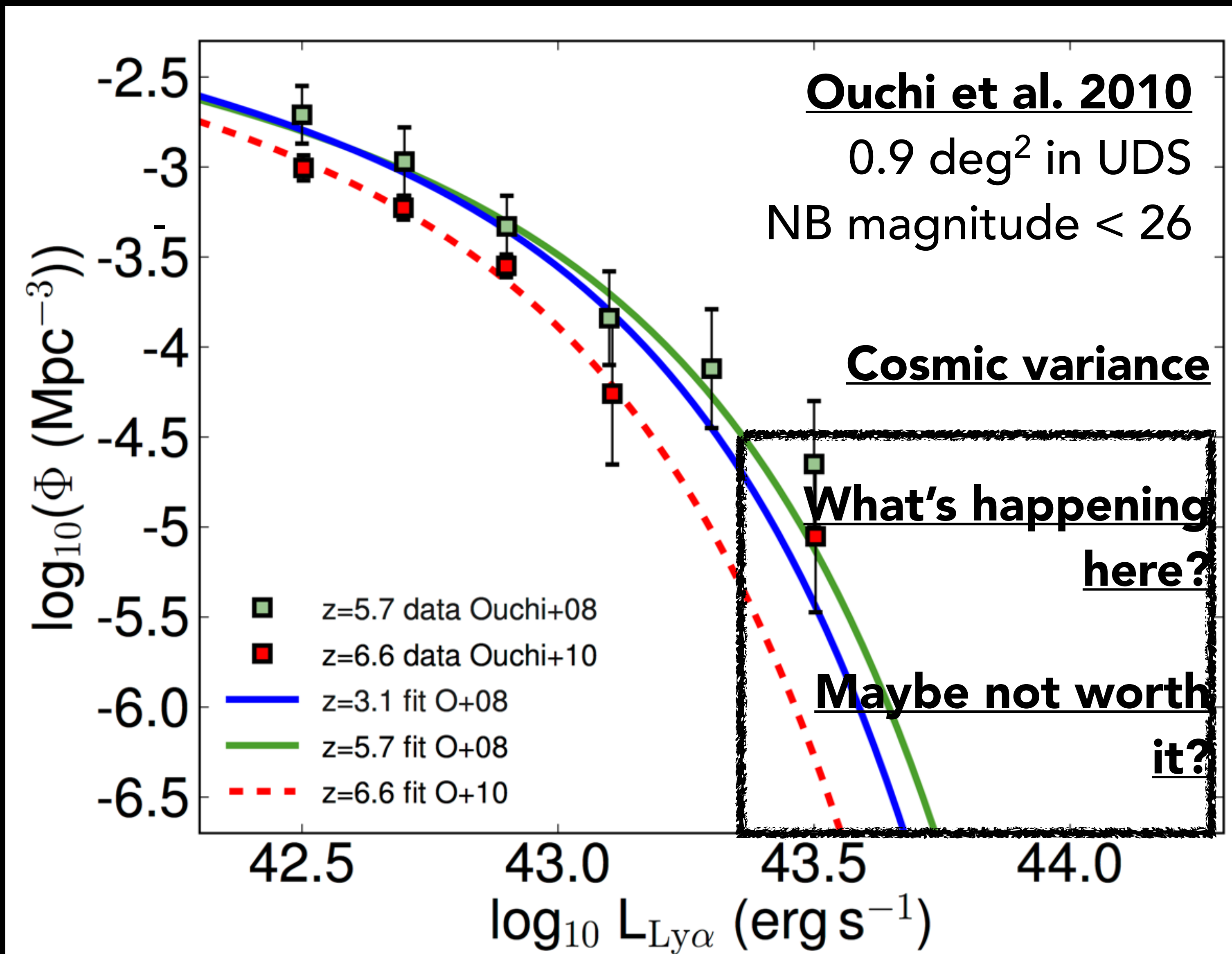
Lyman-α Luminosity function at z=6.6

Surveys limited by cosmic variance (<1deg^2)



see also: Bowler et al. 2012, 2014

Lyman-α Luminosity function z~3-6 roughly constant -> “decline” at z>6?



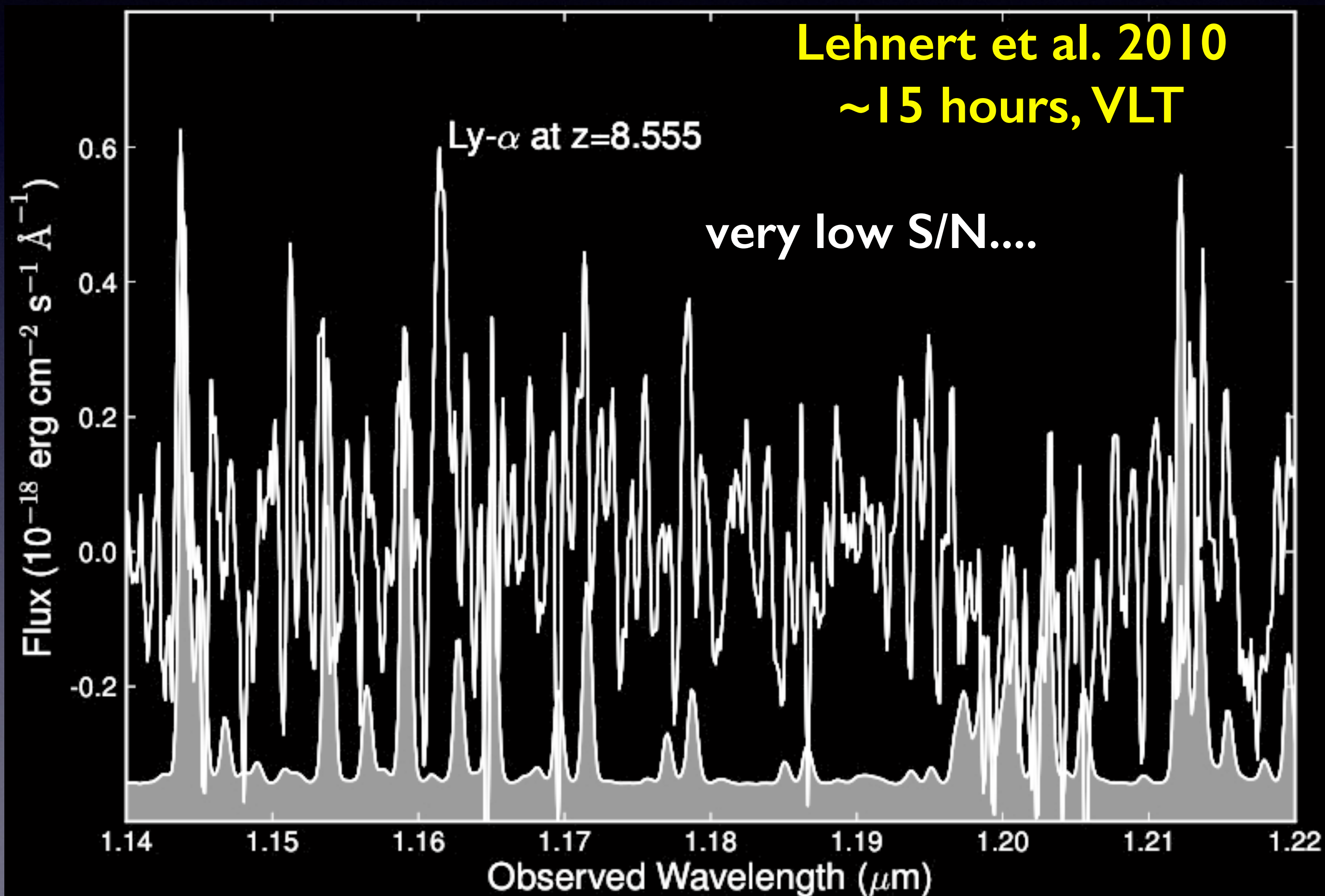
see also: Bowler et al. 2012, 2014

Key things to address

- Need much larger (and multiple!) volumes. Most luminous sources may be visible much earlier on (first ionised bubbles?)
- Need to spectroscopically confirm the results
- Find the most luminous sources: allowing for actual detailed studies to be conducted without having to wait for JWST and/or E-ELT. e.g. ISM, gas, metallicities

The big advantage for spectroscopic follow-up is that they will <u>*not*</u> look like this:

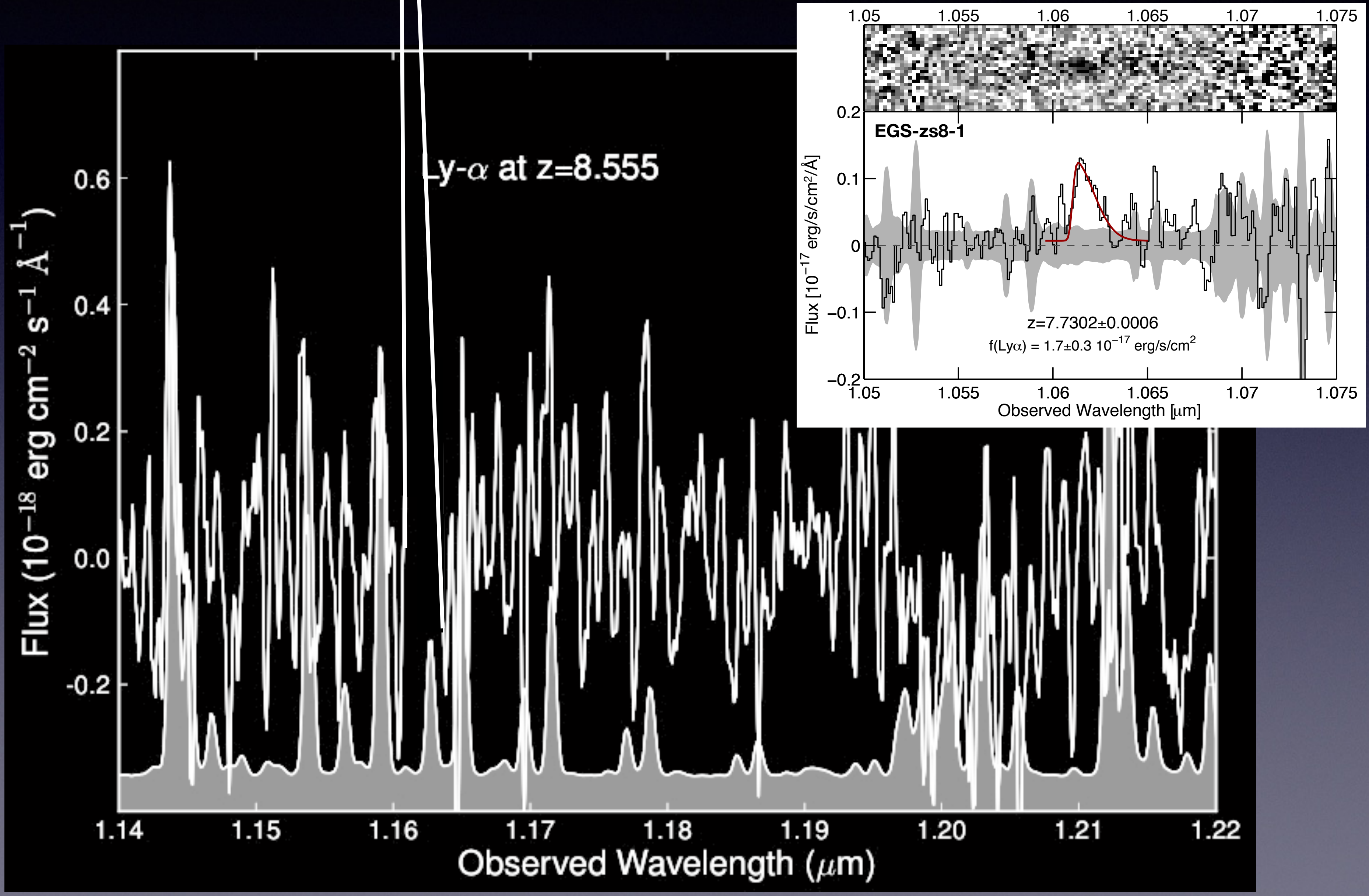
(see Bunker et al. 2013)



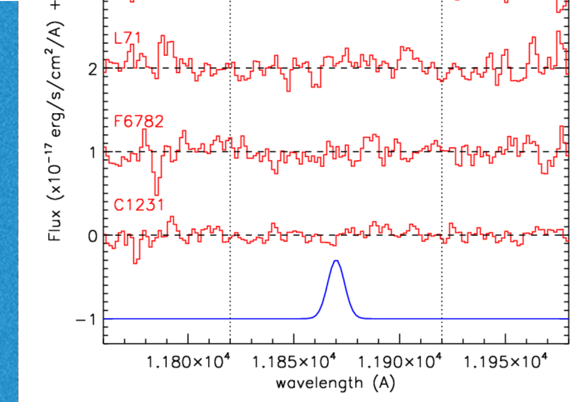
In ~ couple of hours

They will look like this!

See also: Oesch+2015; Zitrin+2015



Spectroscopic follow-up is absolutely crucial!!!



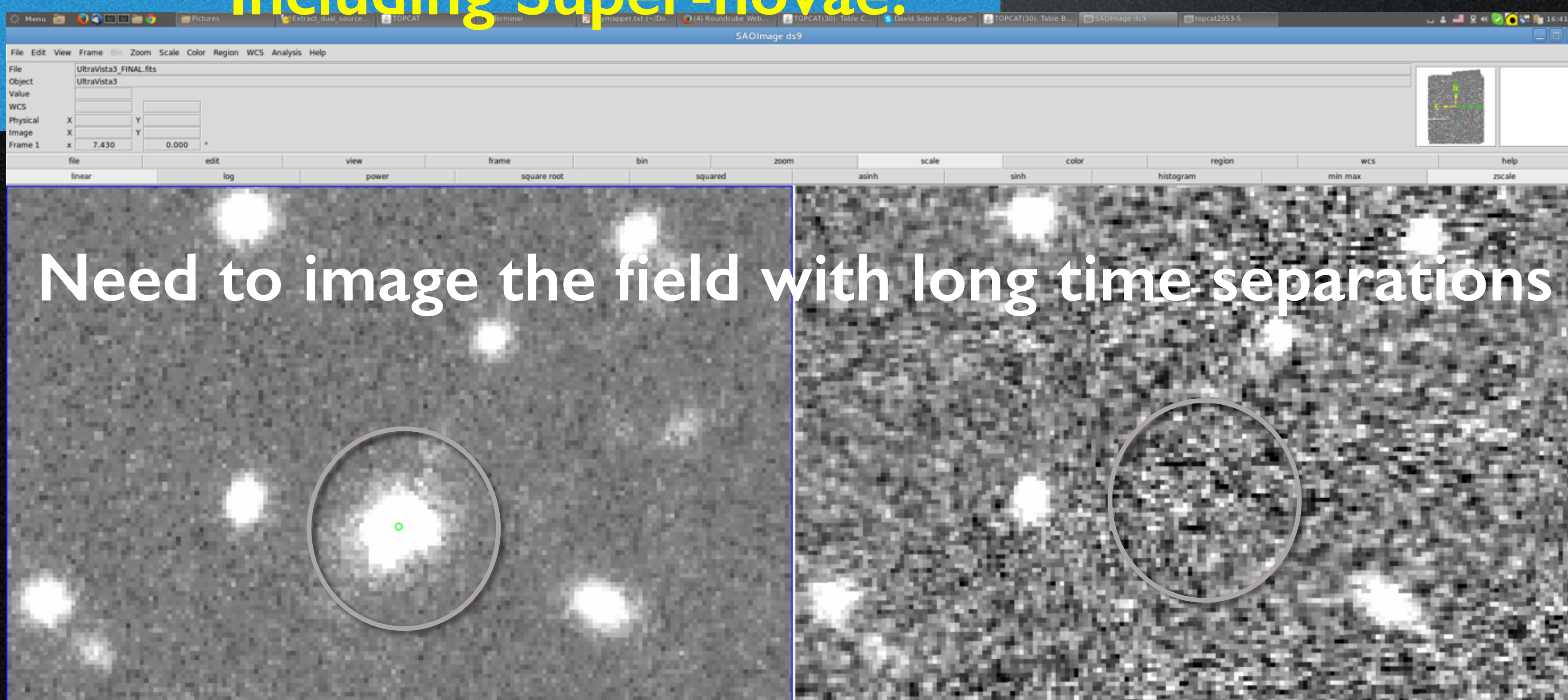
variable sources

~2 per deg^2 at any time

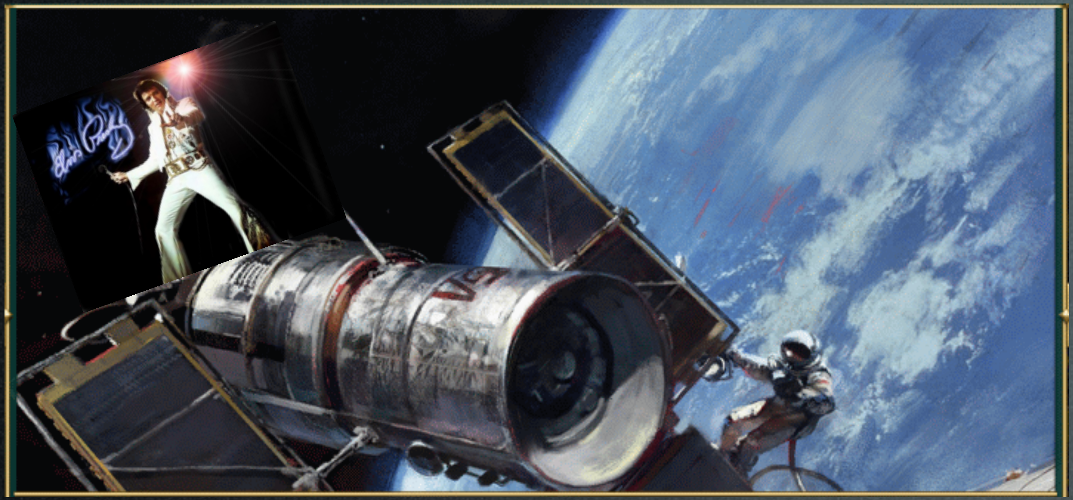
Including Super-novae!

Super-cold sources

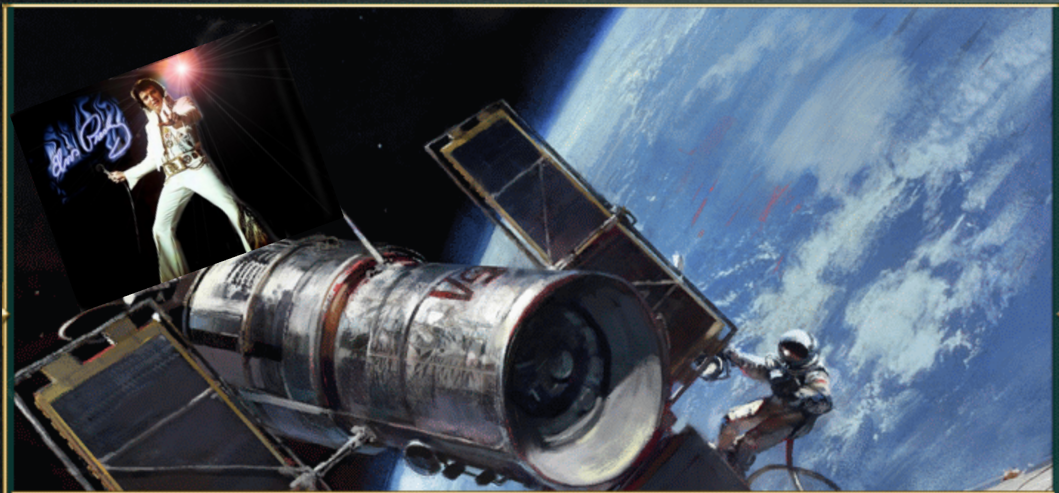
Sobral+09b, Matthee, Sobral+14,15



Need to image the field with long time separations



CANDELS



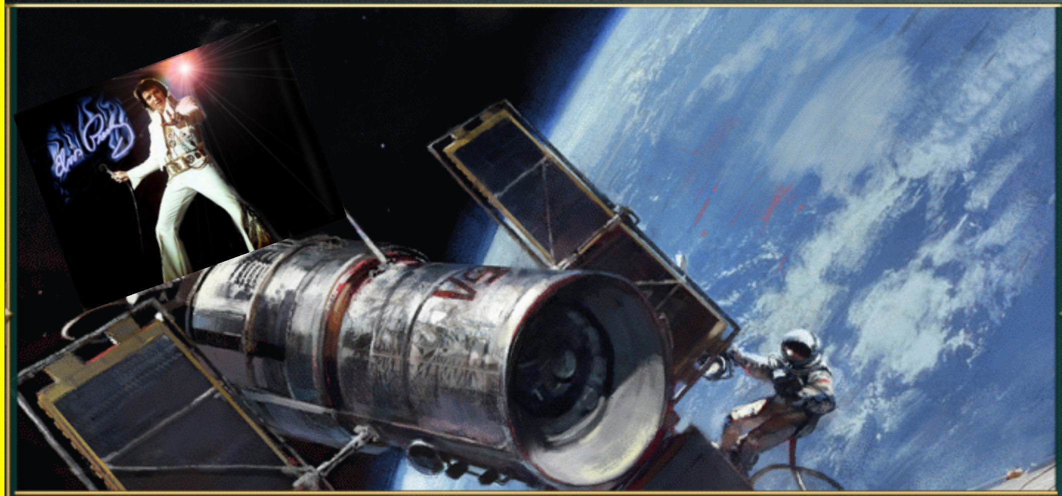
CANDELS

Our approach explores uniqueness of narrow-band surveys

INT+VST+WHT+HSC +VISTA

Largest Lyα surveys $2<z<8$

(still detect galaxies >25-26 in J)



Moon 

All CANDELS combined

Galaxies still too faint to be studied in detail and have statistics

Our approach: $V=10^7$ Mpc^3

per redshift slice

INT+VST+WHT+HSC +VISTA

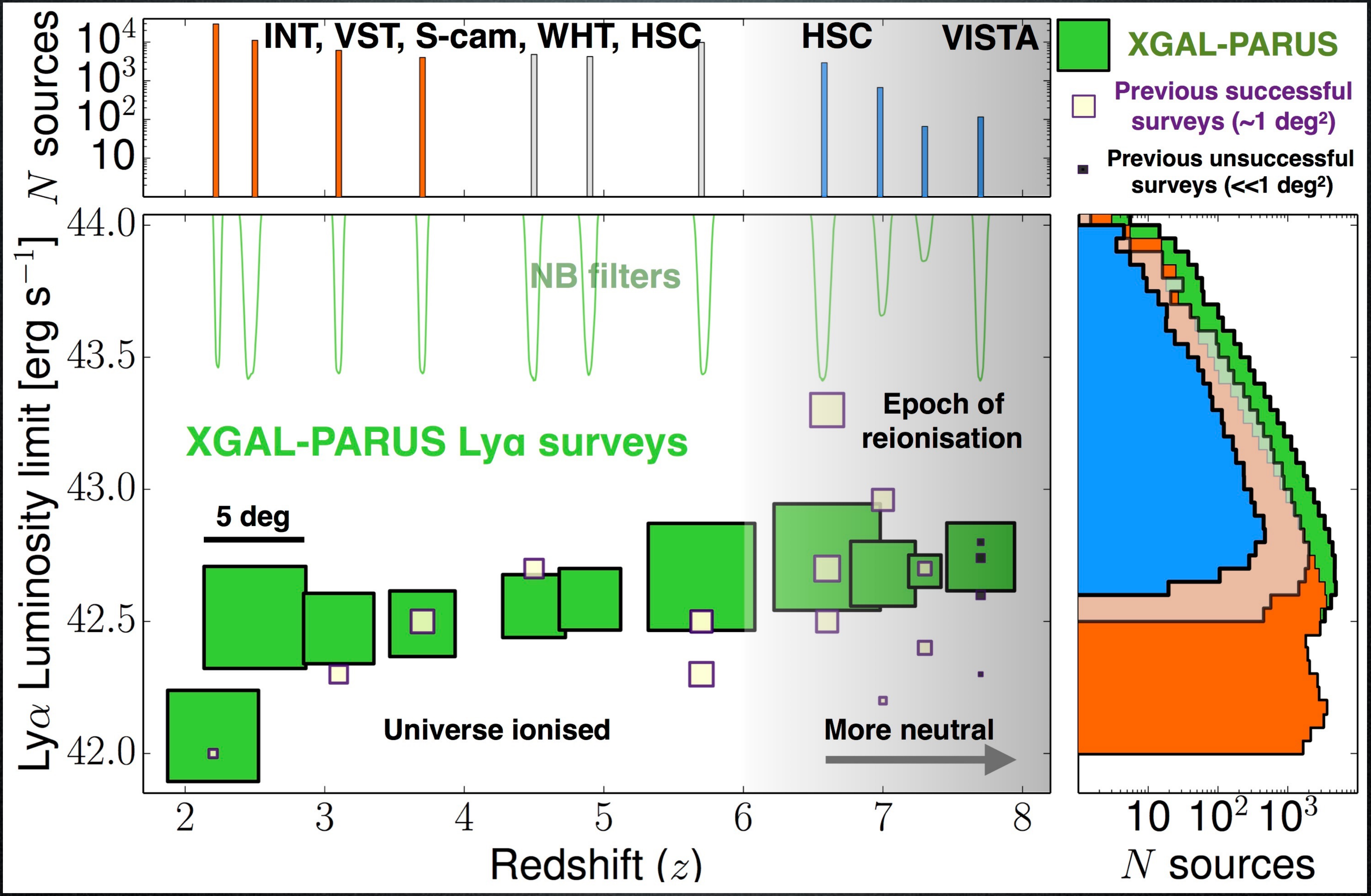
Largest Lya surveys 2<z<8

(still detect galaxies as faint >25-26 in J)

Our on-going and planned surveys

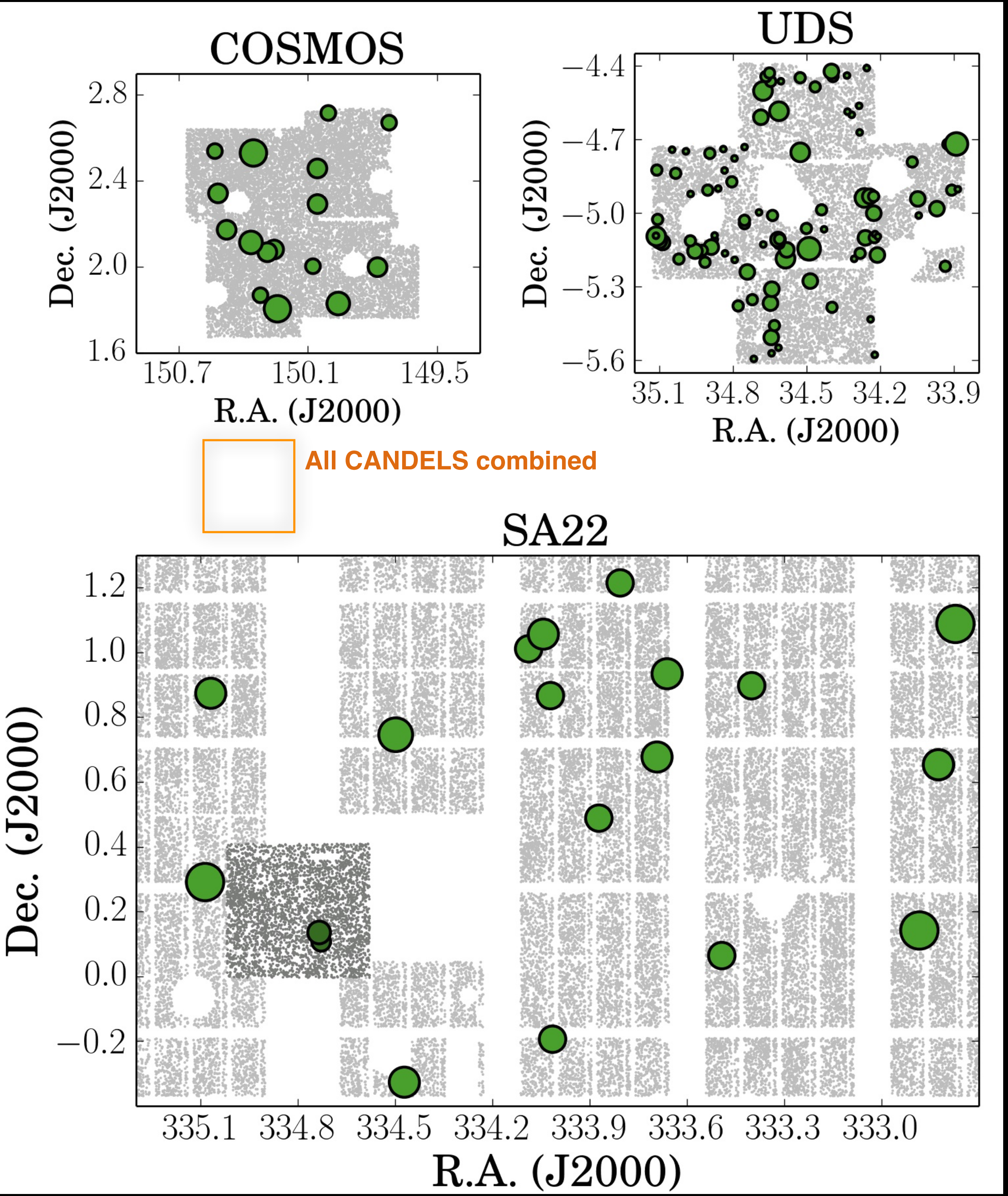
PI: Sobral

Largest Lya surveys 2<z<8



Some highlights of the z=6.6 survey (~800 Myr after Big Bang), 1 of 10 different "time slices"

Subaru survey (PI: Sobral)



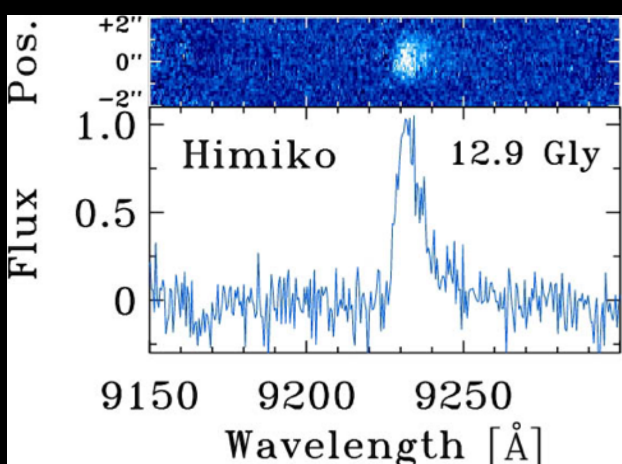
Results:

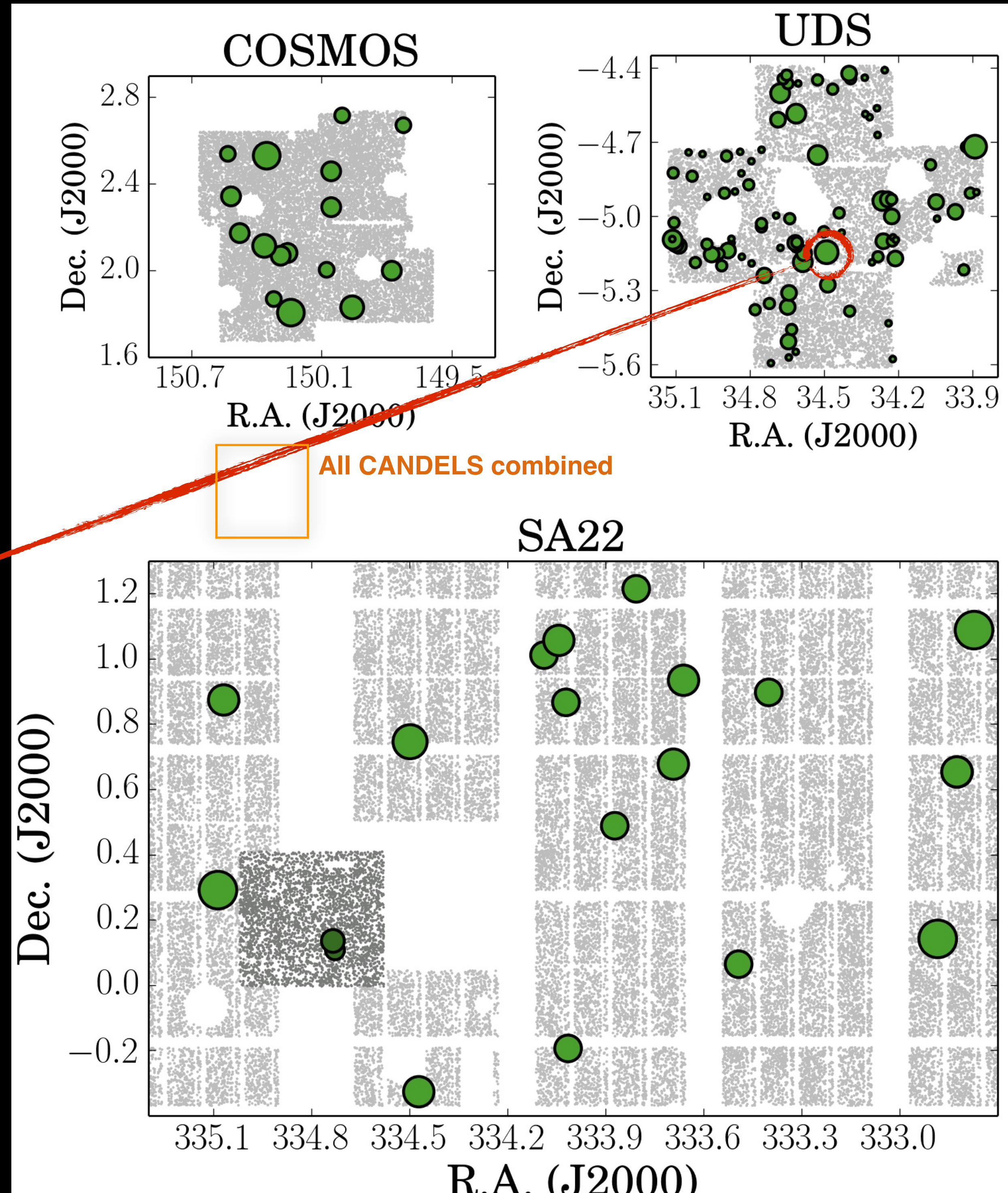
99 LAEs in UDS

15 LAEs in COSMOS

2 LAEs in SA22-Deep

18 LAEs in SA22-Wide





Ouchi et al. 2009, 2013

Results:

99 LAEs in UDS

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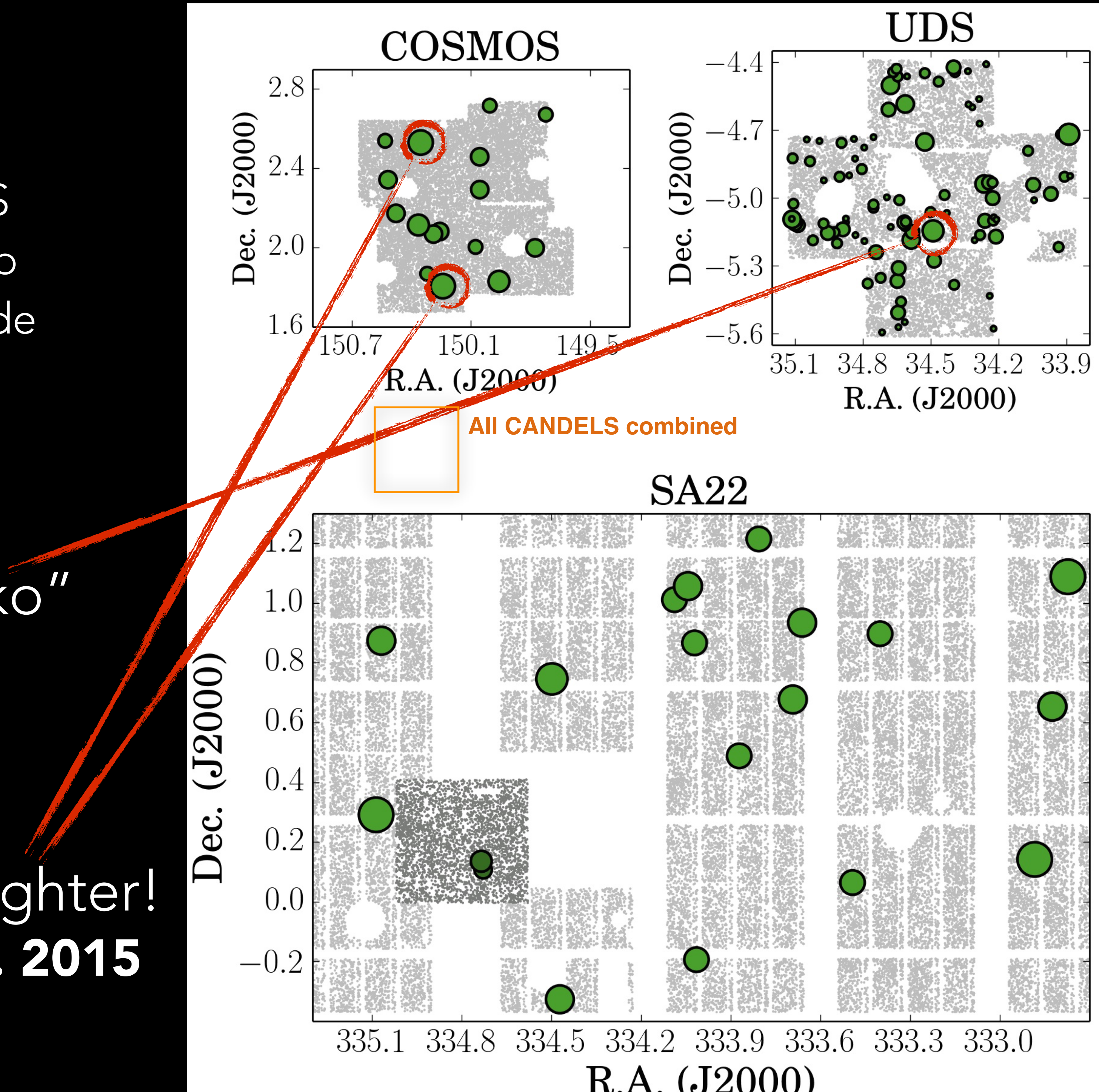

Sobral et al. 2015

Results:

99 LAEs in UDS

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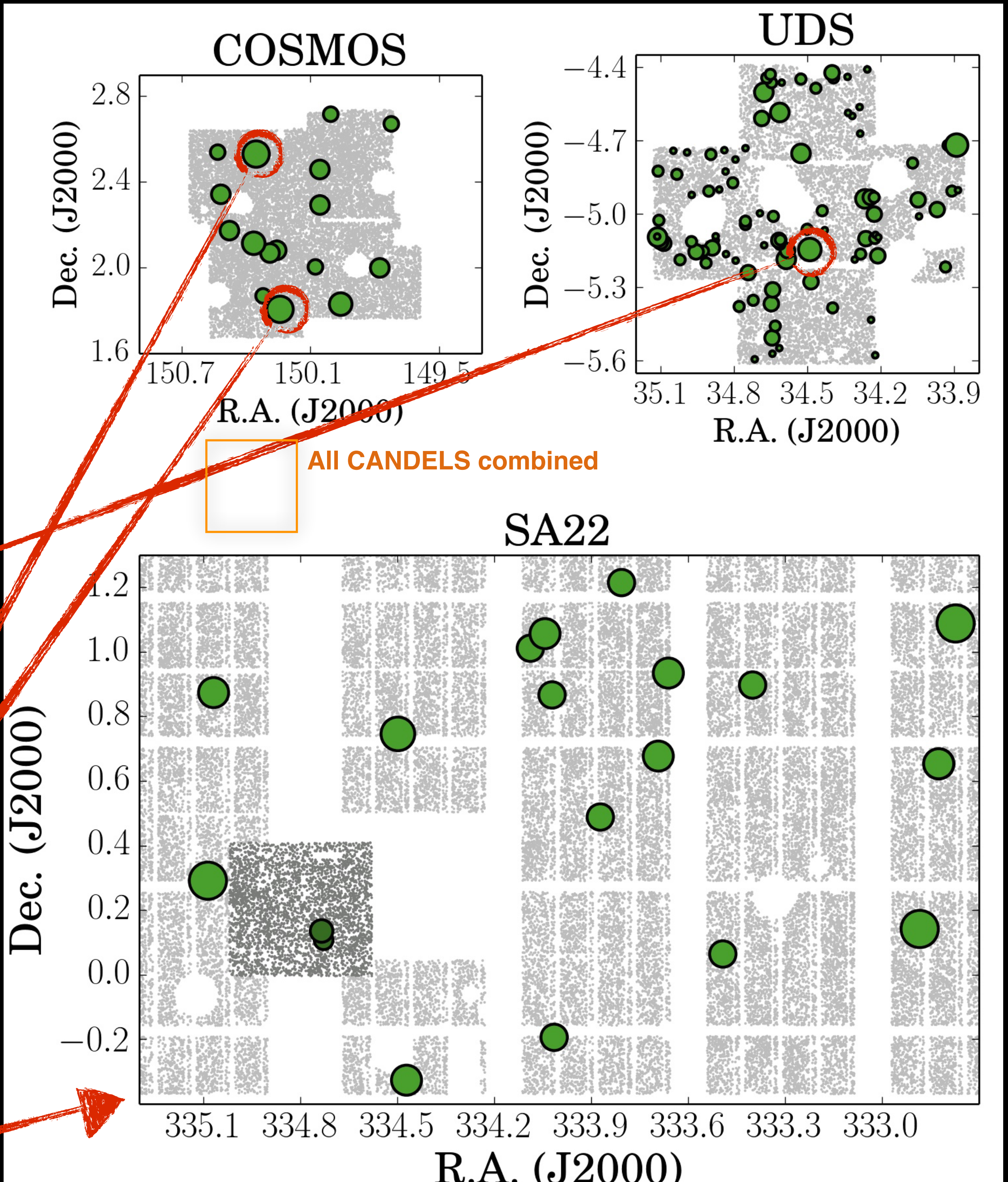


"Himiko"

Even brighter!

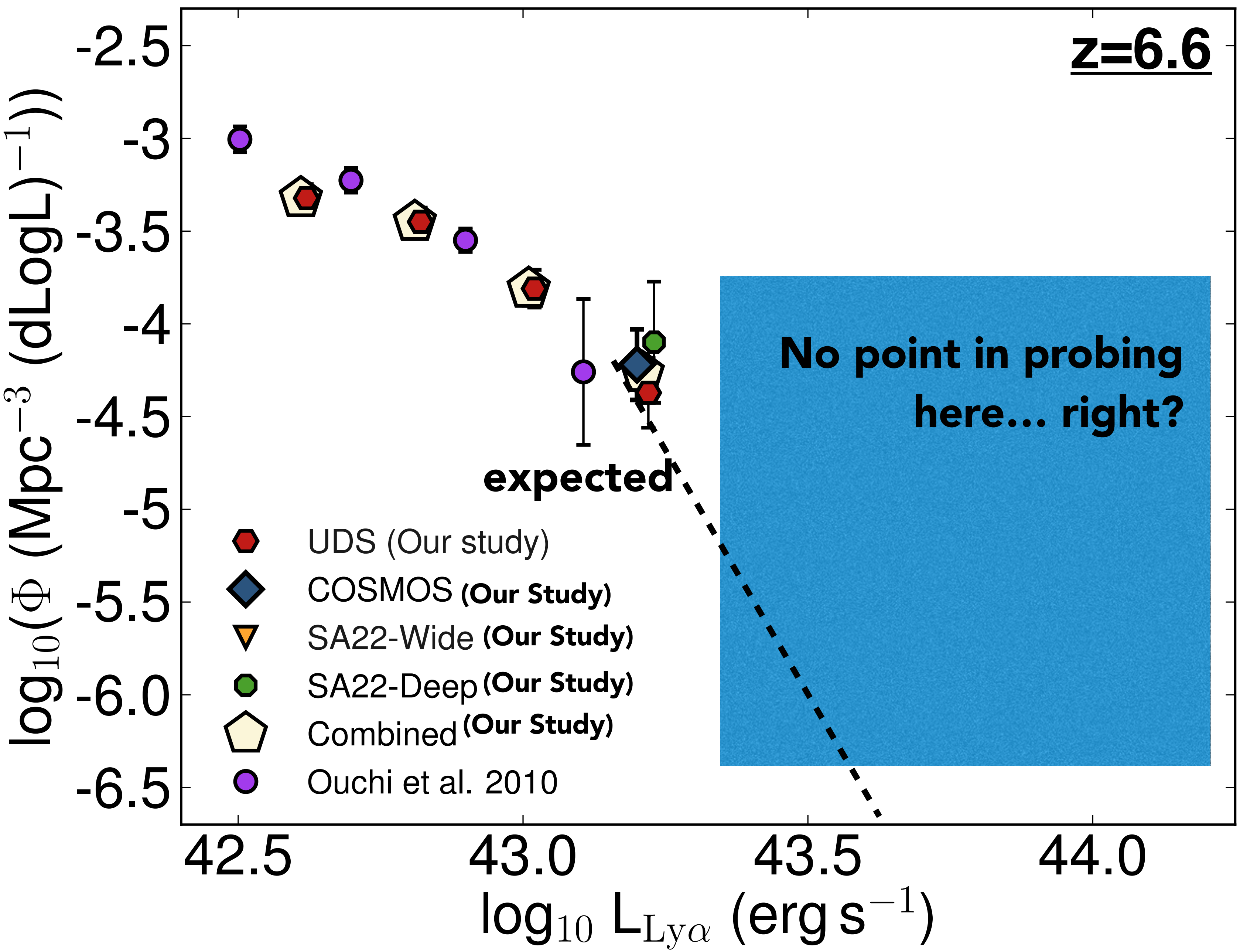
Even brighter! ~20

Confirms number density

Matthee,DS+ et al. 2015

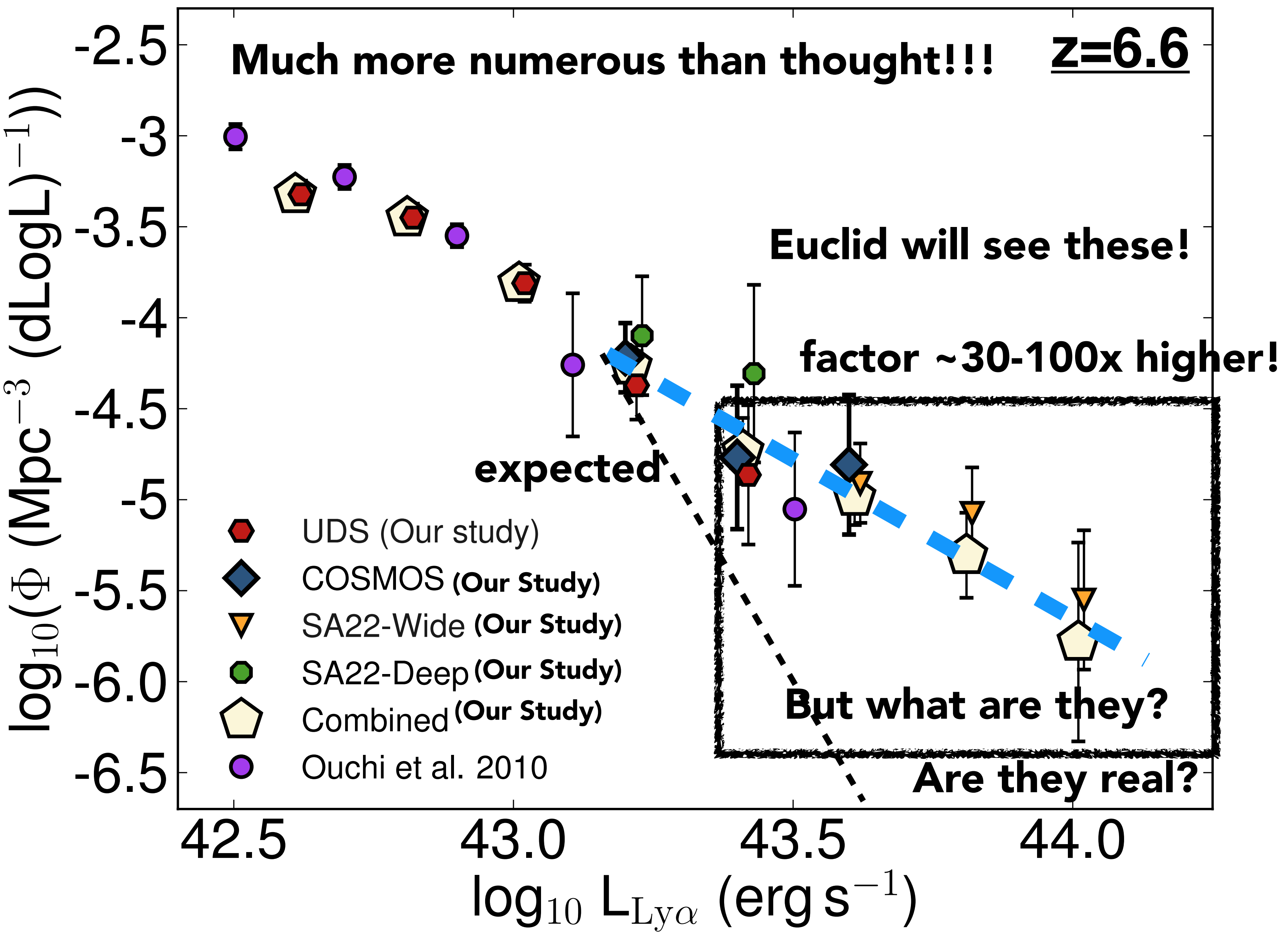
Lyman-α emitters 12.9 Gyrs ago: number counts

Matthee, Sobral et al. 2015

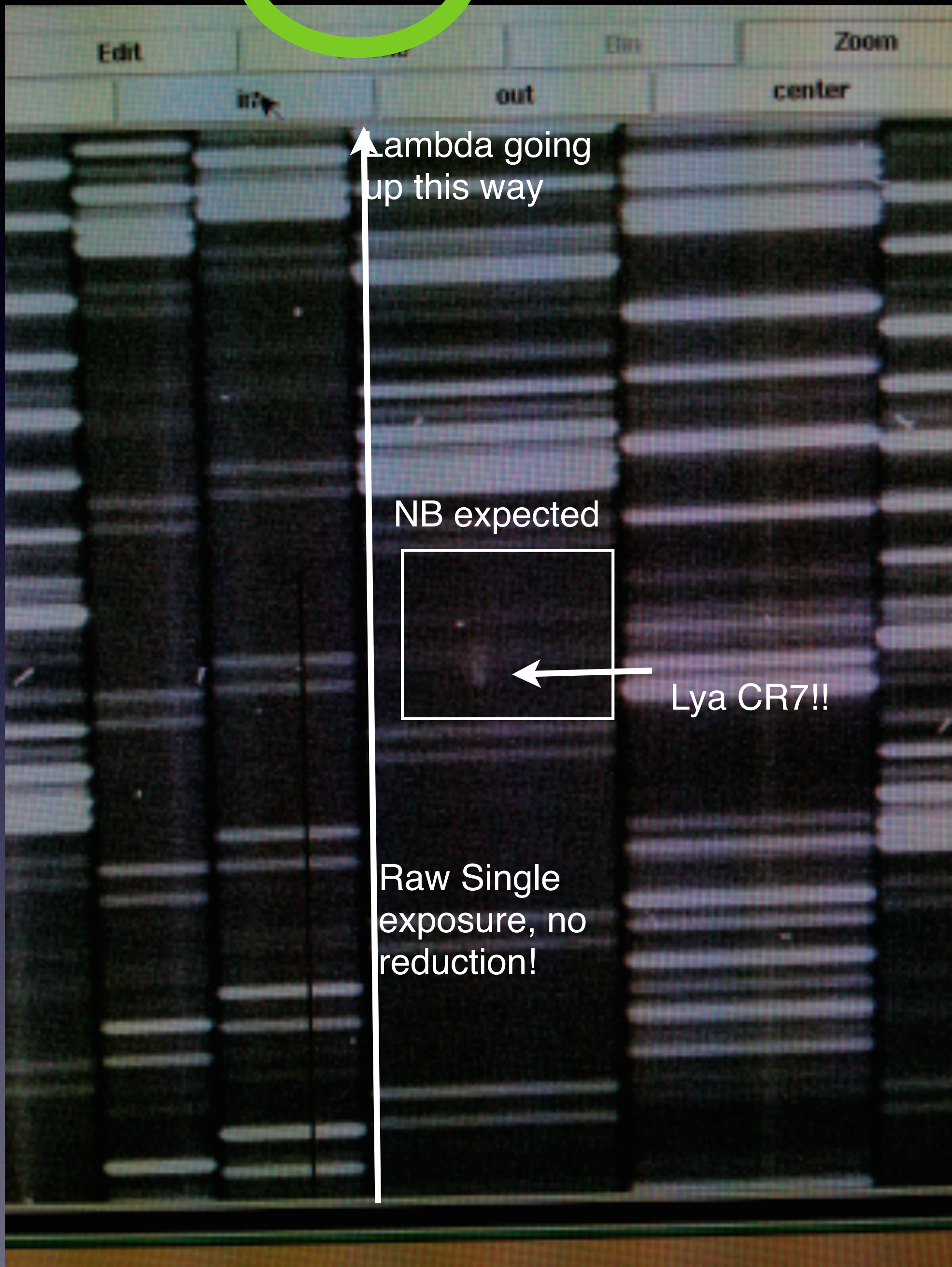


Lyman-α emitters 12.9 Gyrs ago: number counts

Matthee, Sobral et al. 2015

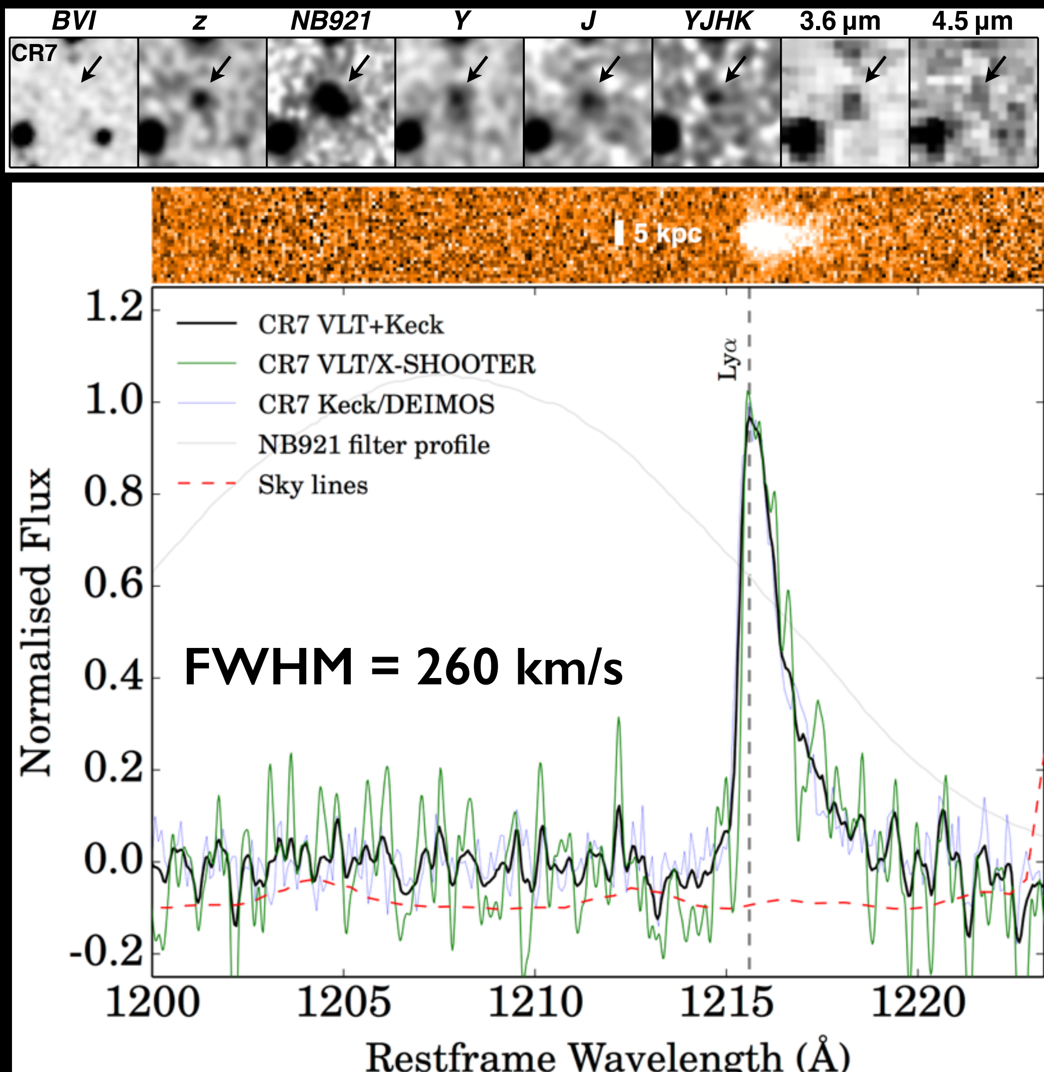


15 min z=6.6

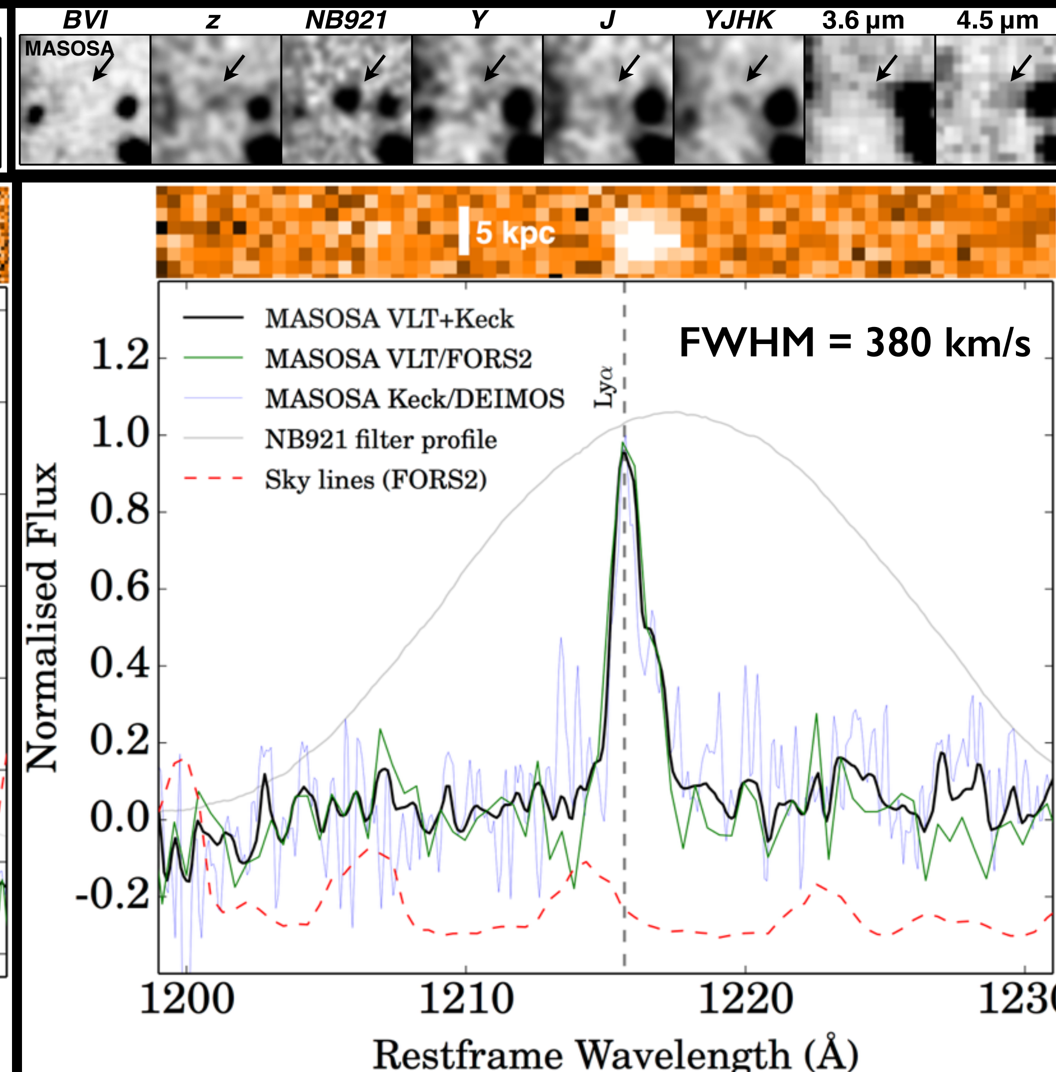


Spectroscopic confirmation with Keck/DEIMOS

`Cosmos Redshift 7’ (CR7) and `MASOSA’ the brightest z=6.6 LAEs



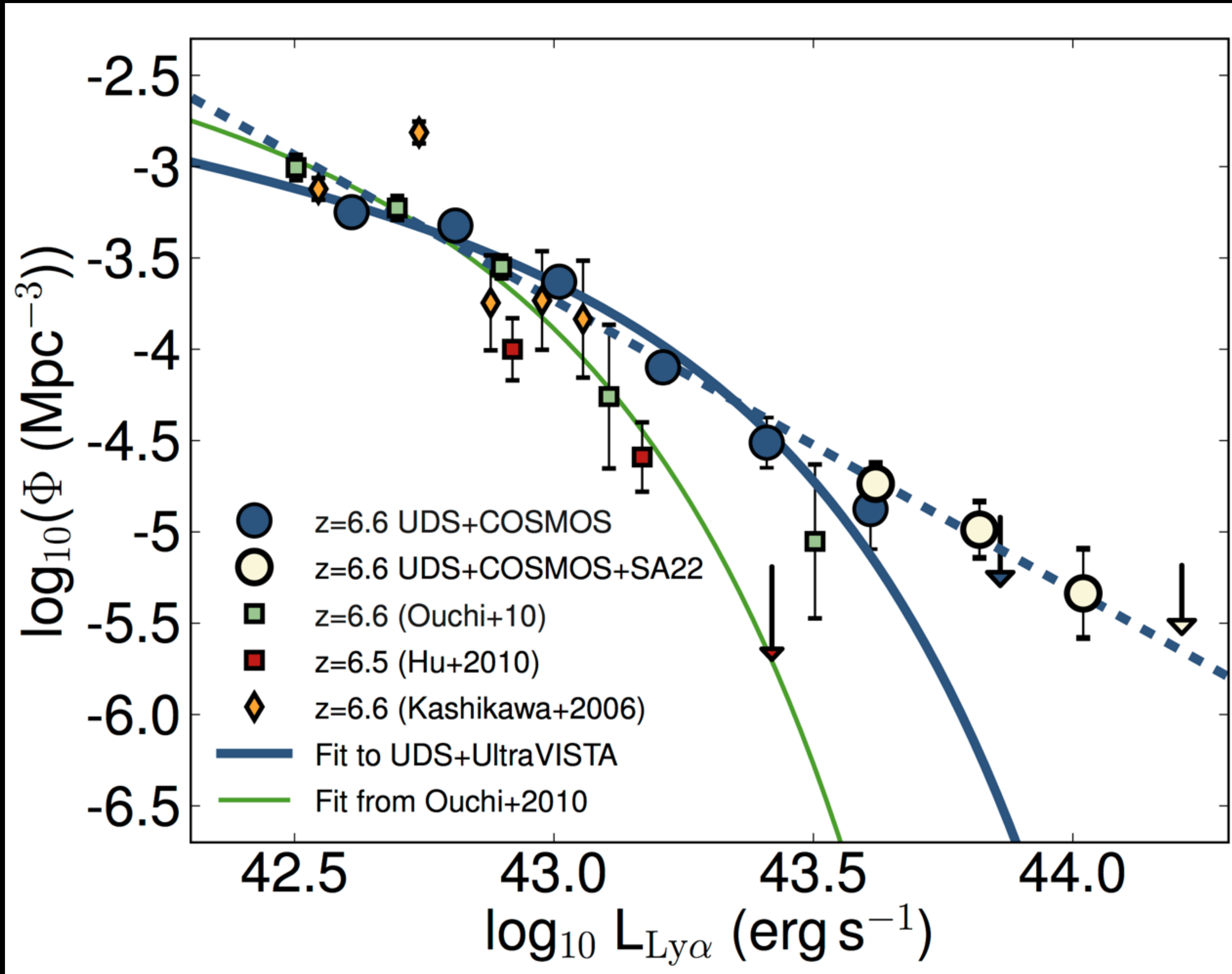
VLT/X-Shooter + Keck/DEIMOS (~3.8 hours)



VLT/FORS2 + Keck/DEIMOS (~2.4 hours)

Sobral, Matthee et al. 2015, ApJ; Matthee et al. 2015

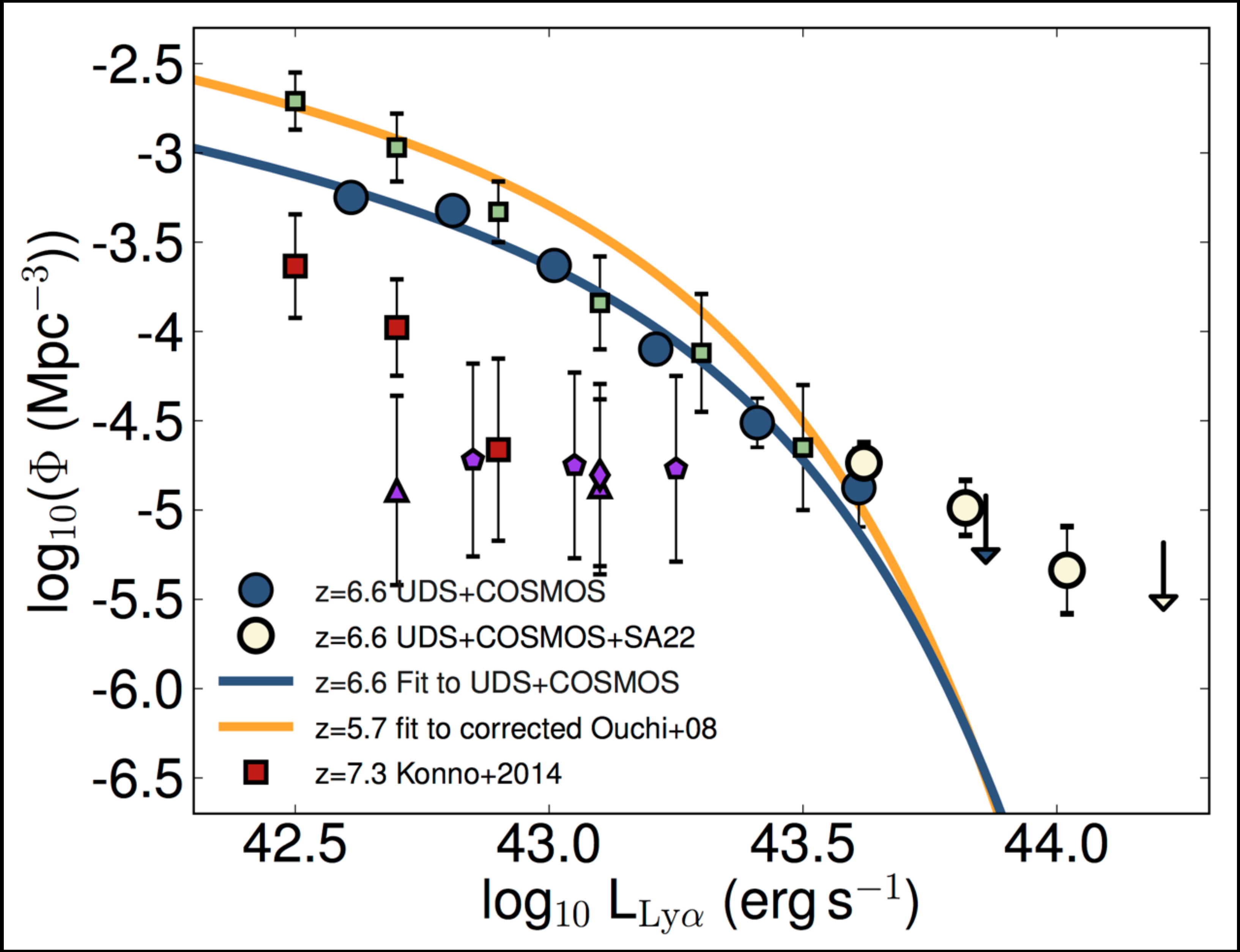
Lyman-α Luminosity function at z=6.6



see also: Bowler et al. 2012, 2014

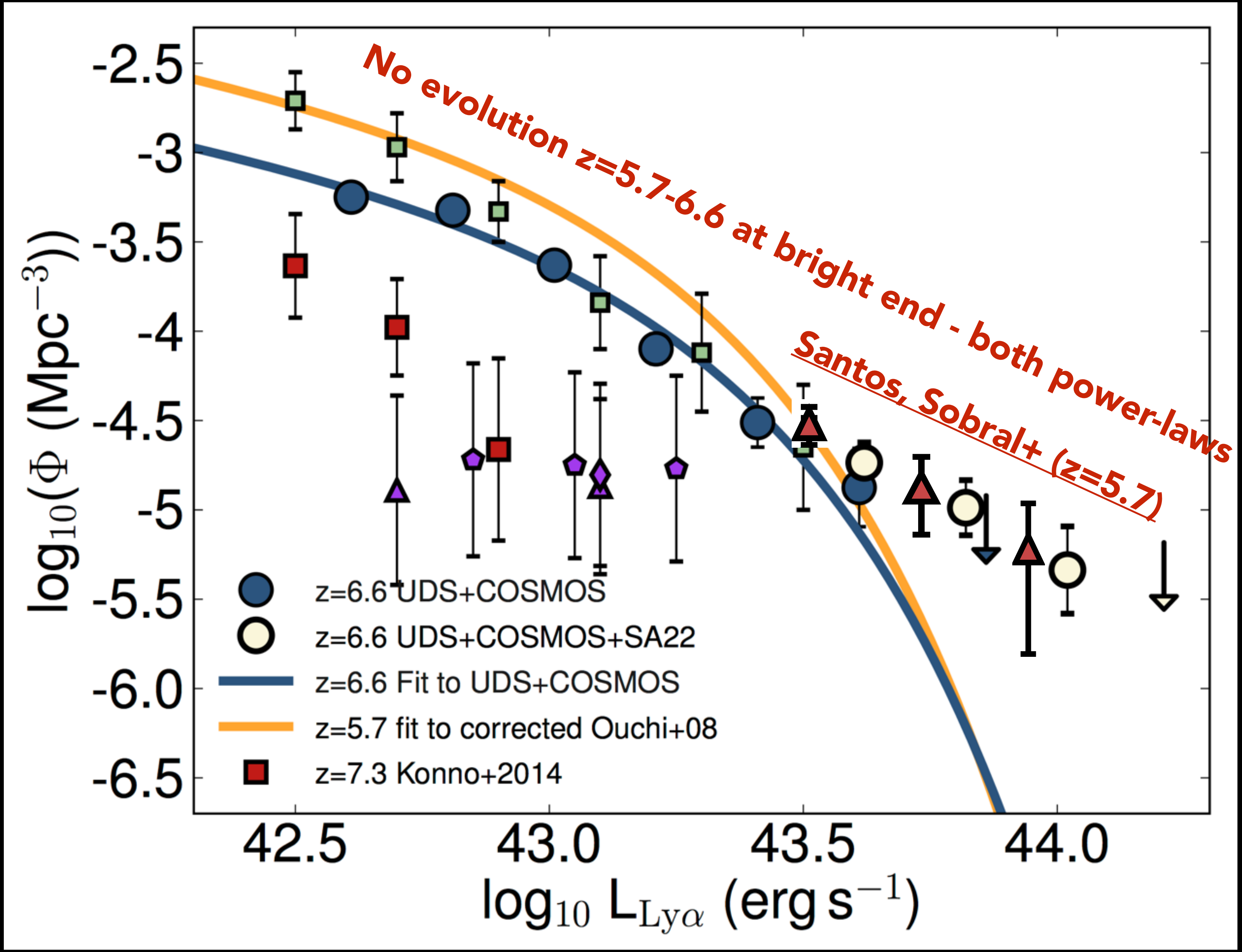
Matthee, Sobral et al. 2015

Evolution from z=5.7 to 6.6 to 7.3



Matthee, Sobral et al. 2015

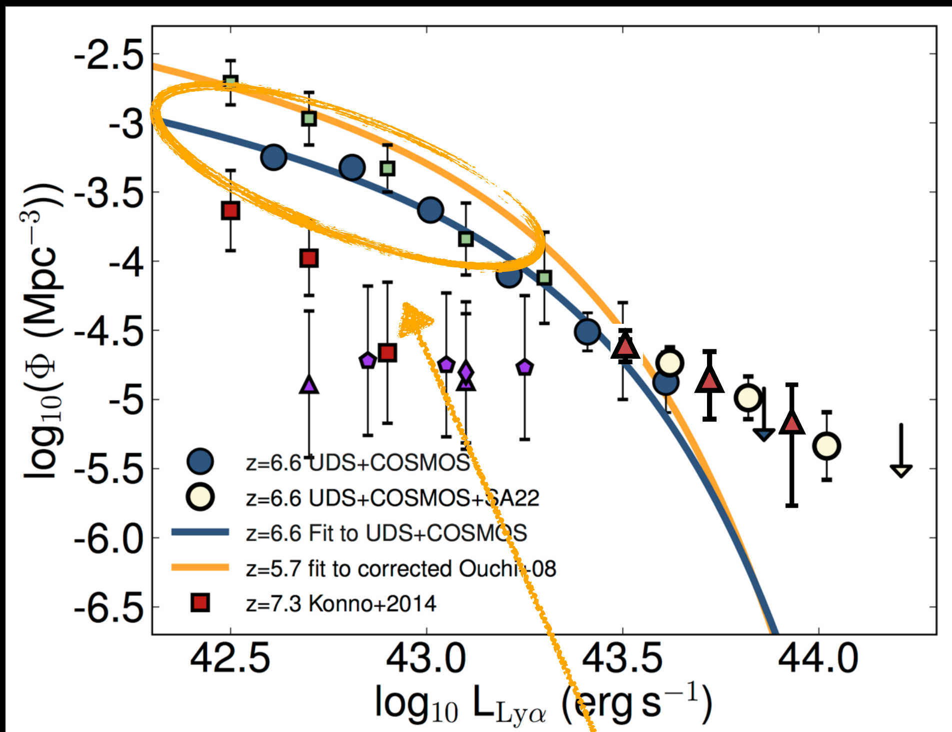
Evolution from z=5.7 to 6.6 to 7.3

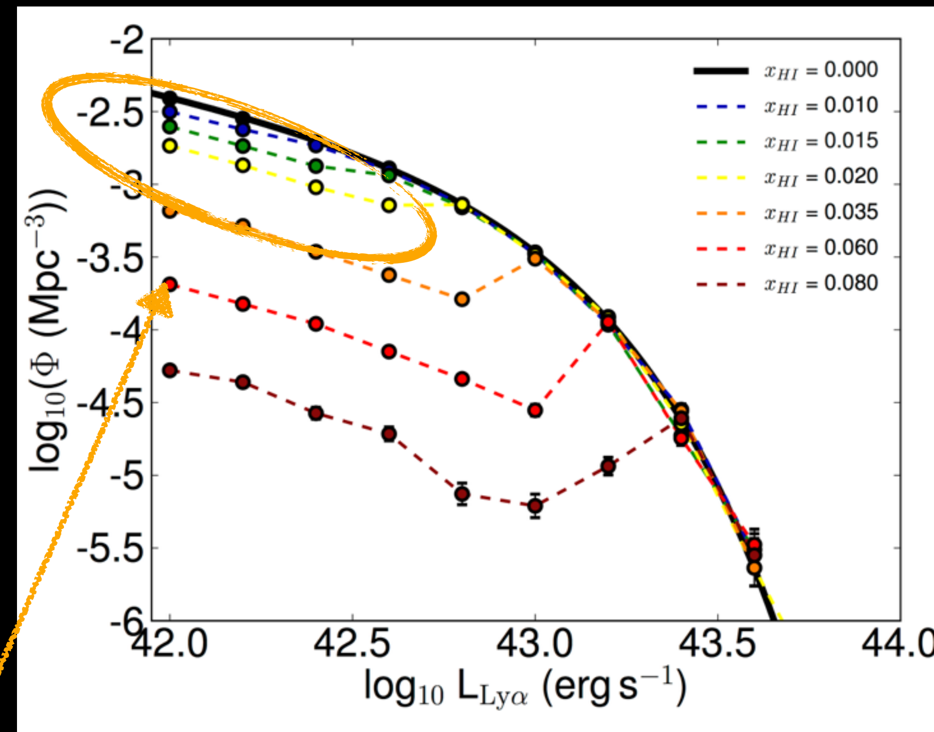


Matthee, Sobral et al. 2015

Evolution from z=5.7 to 6.6

z=5.7 to z=6.6 evolution



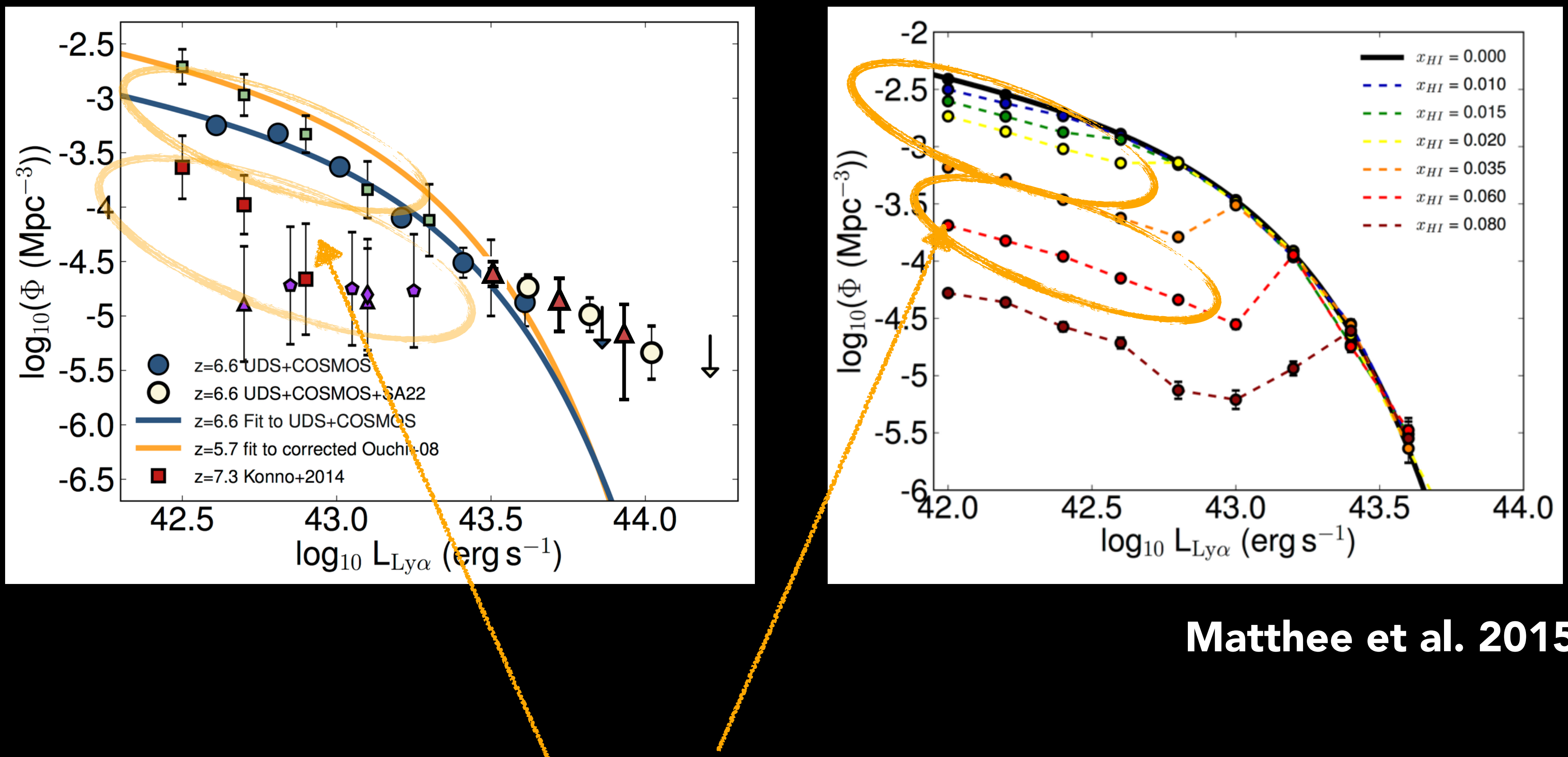


Bulk of the evolution happens at the faint end!

Matthee et al. 2015

Evolution from z=6.6 to 7.3

z=6.6 to z=7.3 evolution



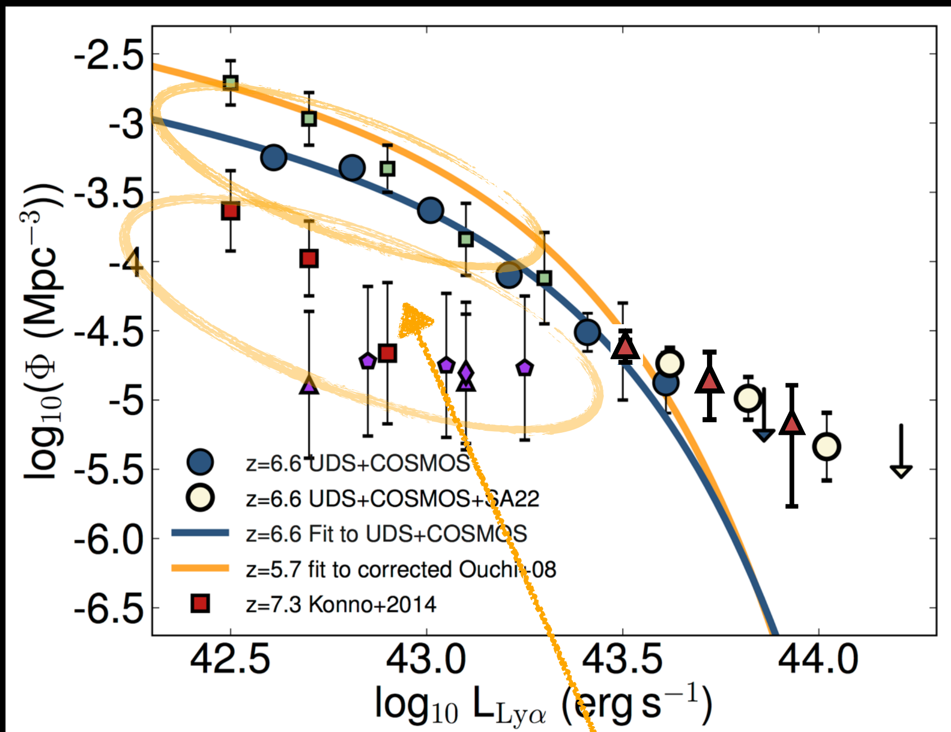
Matthee et al. 2015

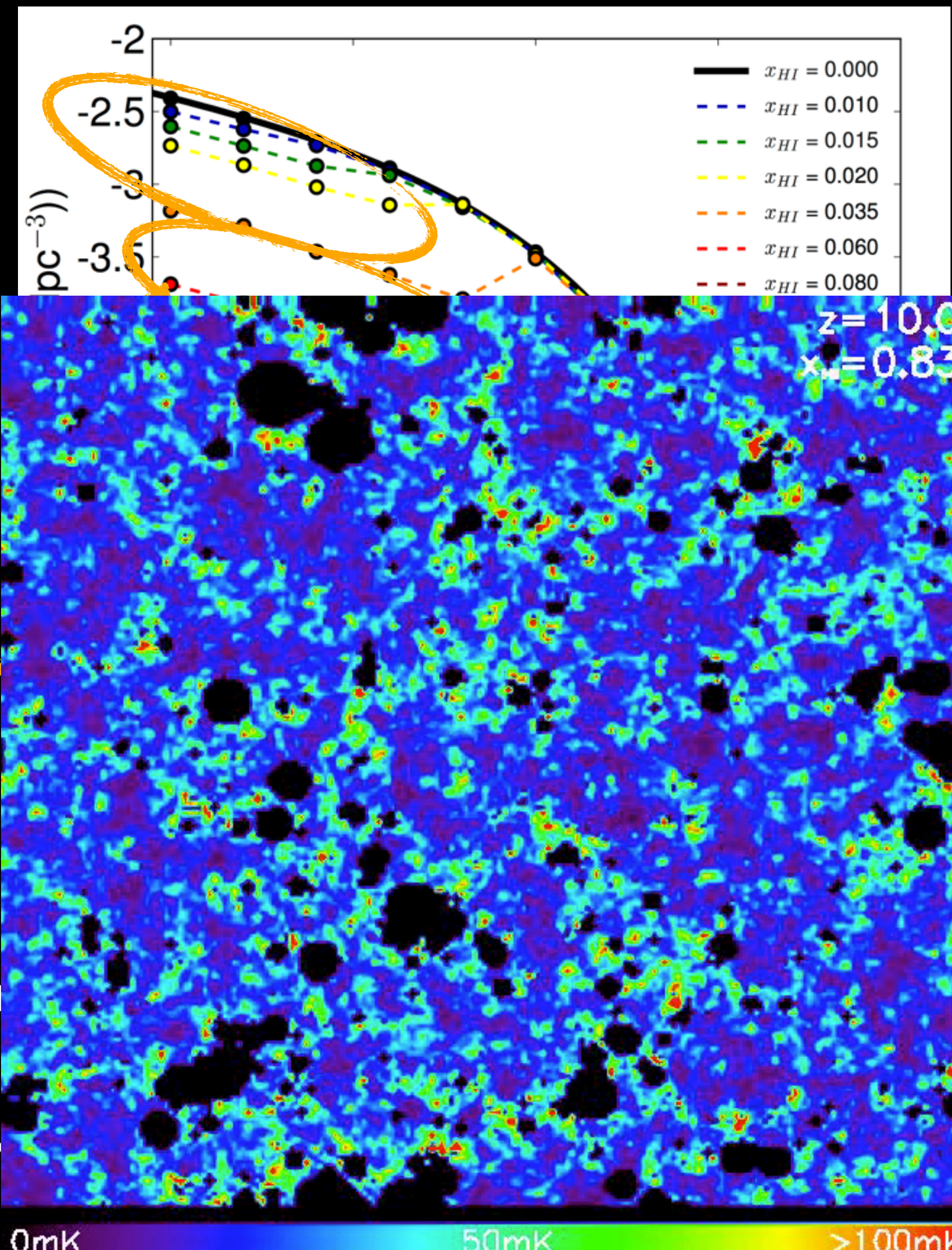
Bulk of the evolution happens at the faint end!

Oesch et al. 2015; Zitrin et al. 2015 (narrowness of Lya up to z~8.6)

Evolution from z=6.6 to 7.3

z=6.6 to z=7.3 evolution

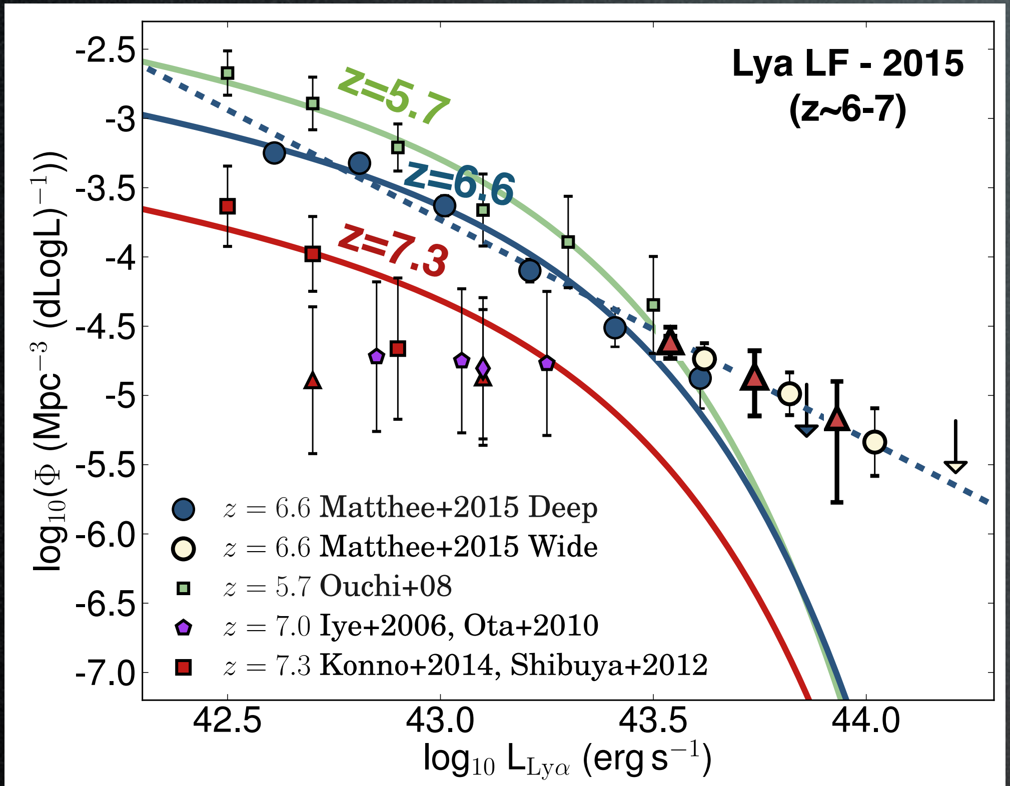


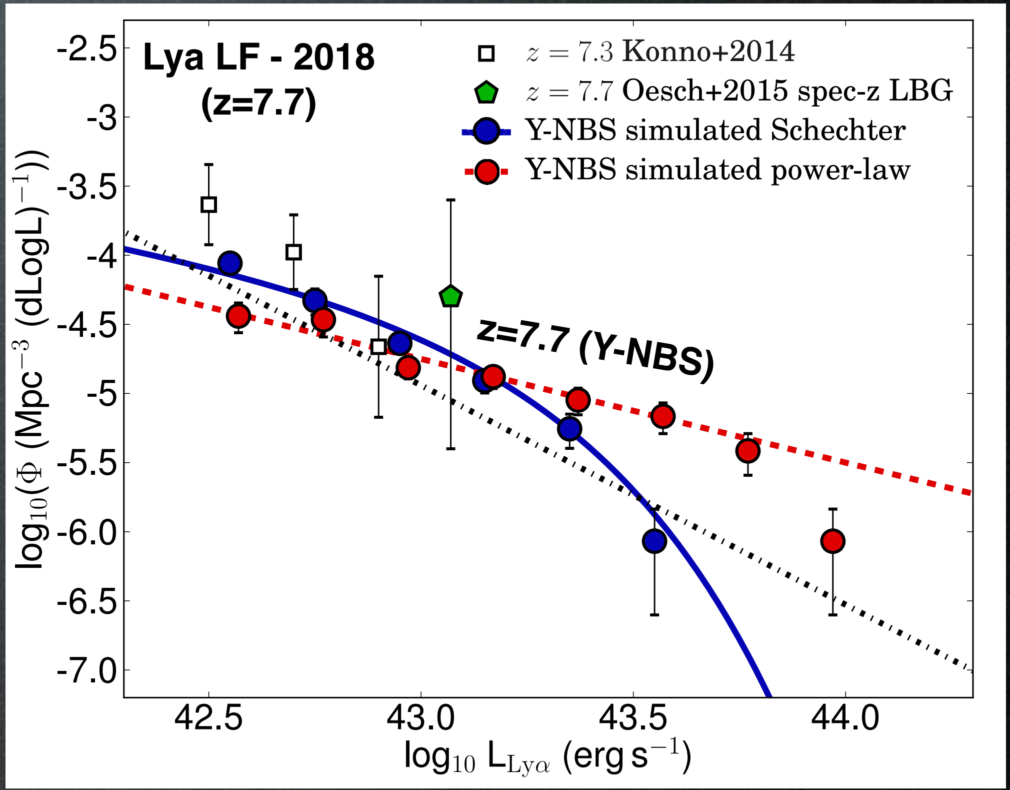


Bulk of the evolution happens at the fa

Oesch et al. 2015; Zitrin et al. 2015 (n

Needs to be tested: easy to do up to z~7.7… if we don't waste all the time just going ultra-deep on small volumes





How far back can we find large enough re-ionised bubbles? And how big are they?

What is the nature of these luminous Lyα emitters?

Uniqueness: we can go beyond just getting a redshift

What is the nature of CR7?

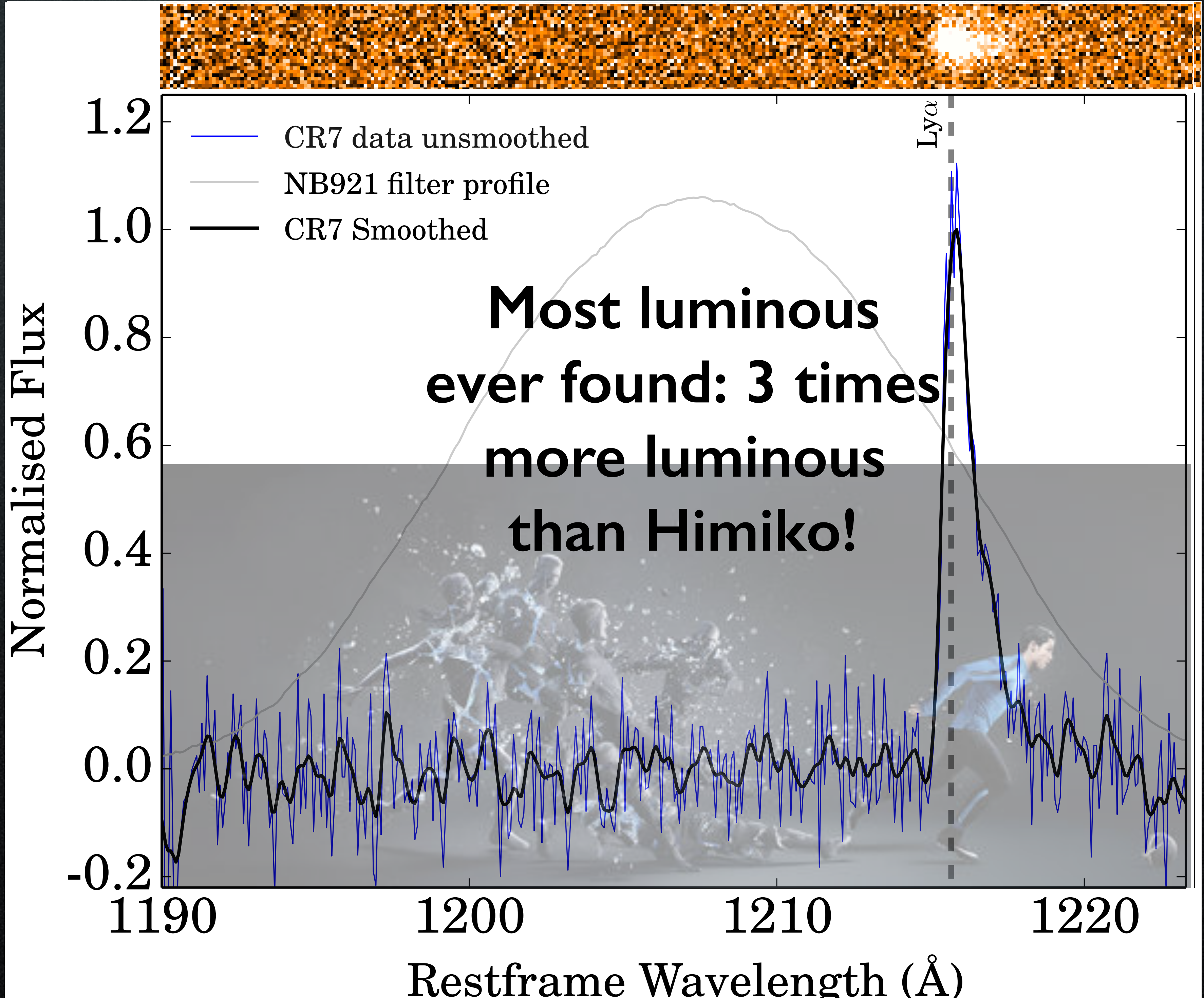
Lyα

Keck/ DEIMOS

1 hour!

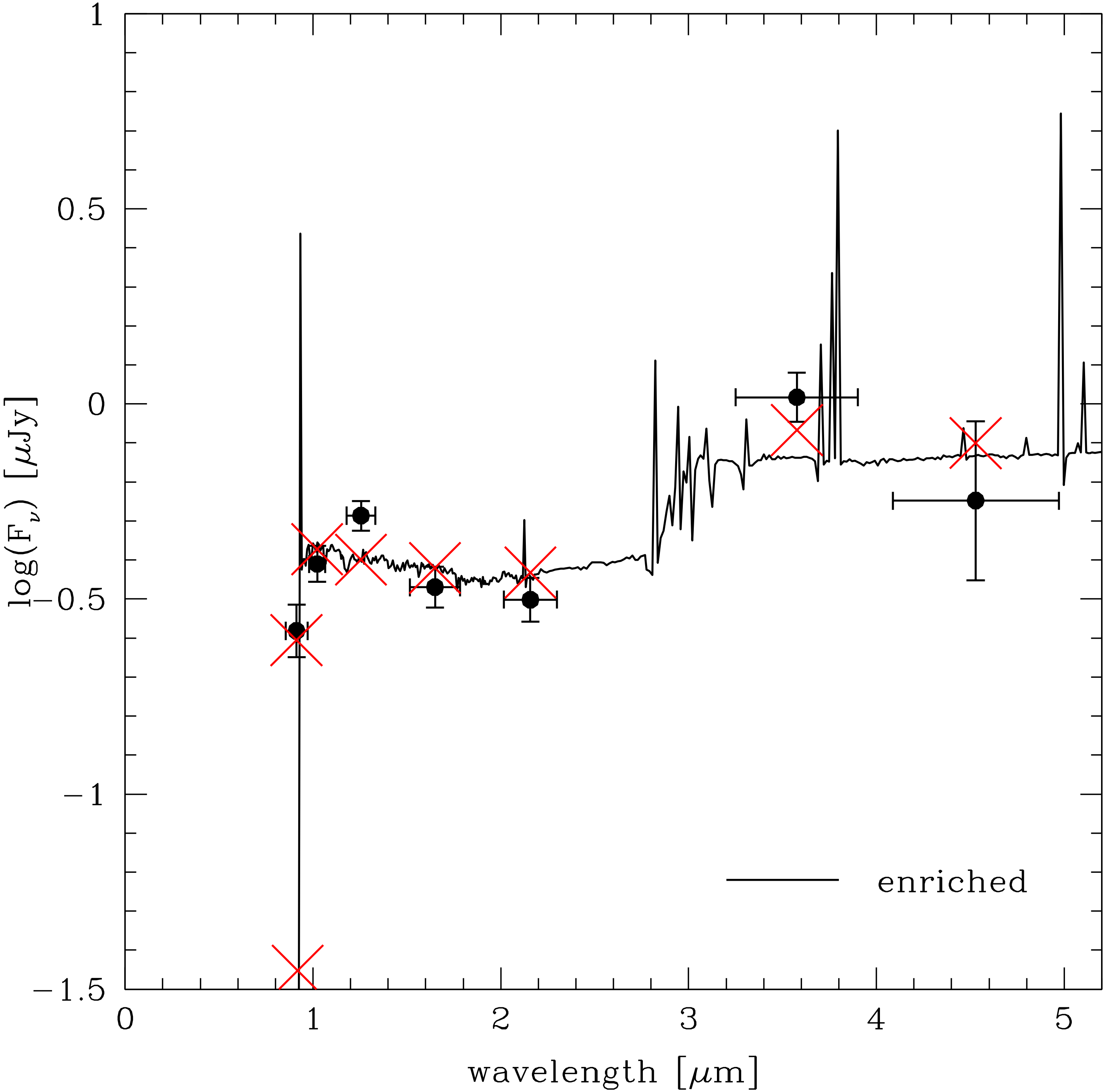
z=6.6

L~10^{44} erg/s/cm^2

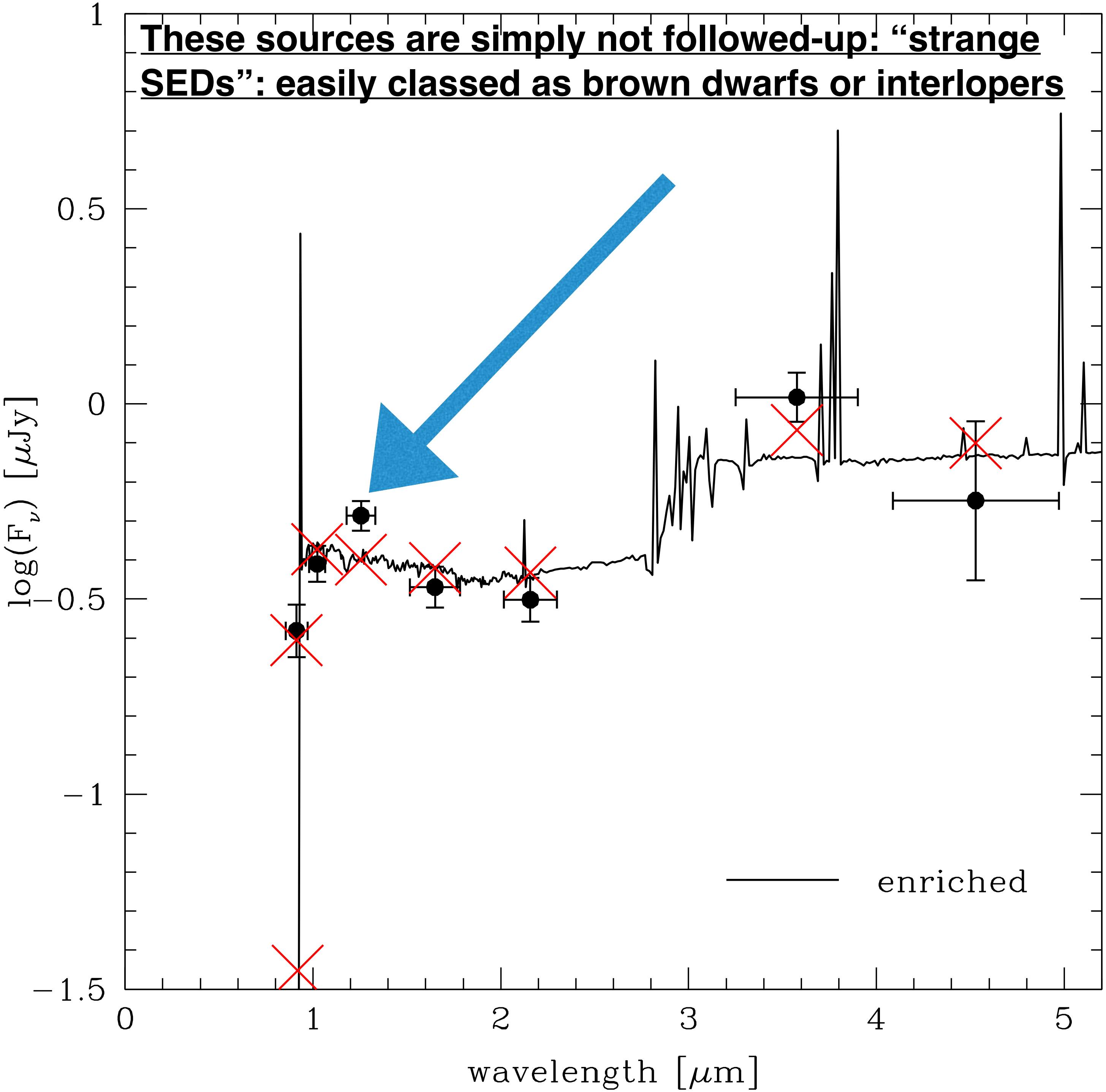


No evidence for AGN

Sobral et al. 2015c.



Sobral, Matthee, Darvish et al. 2015

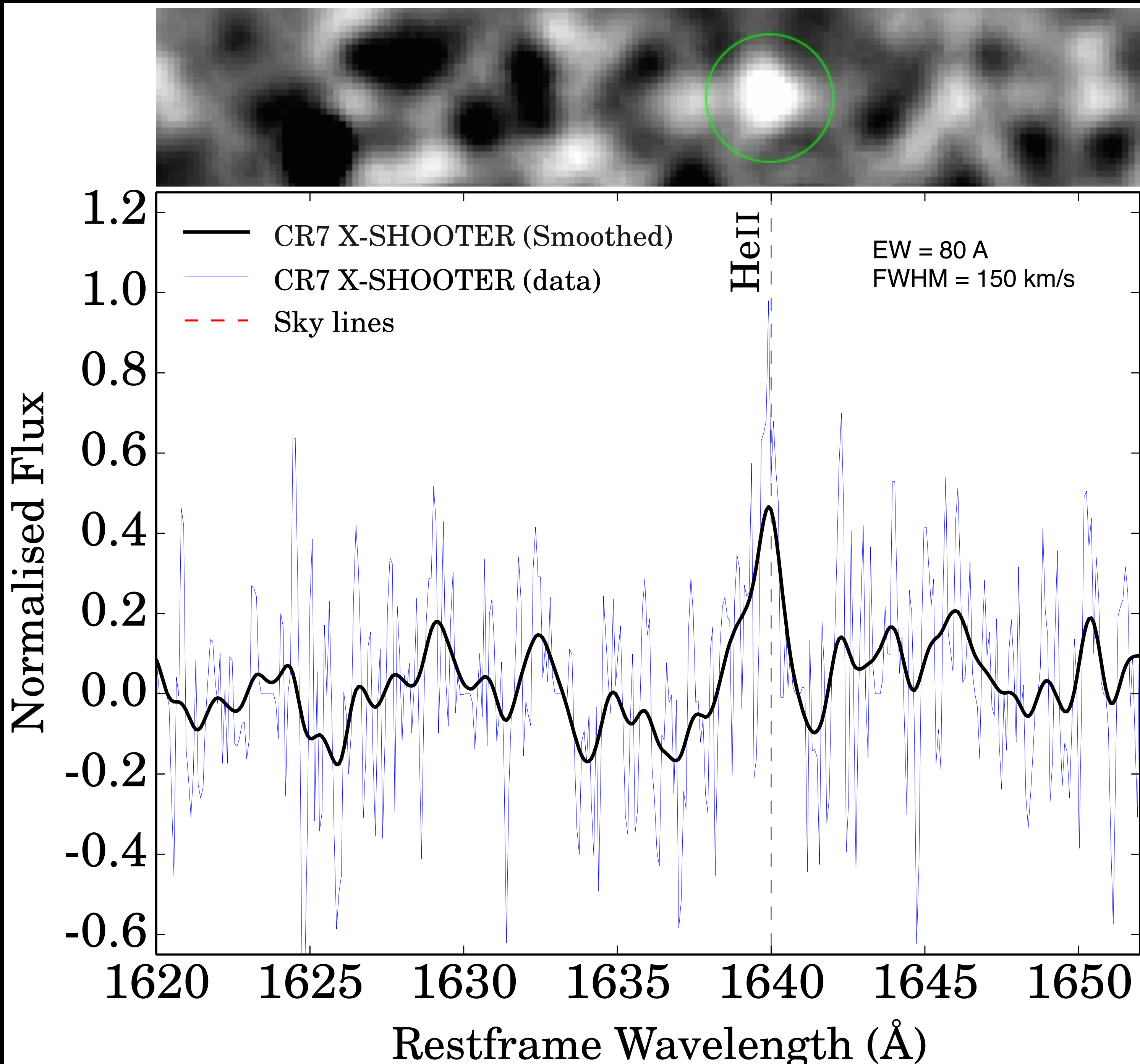


Sobral, Matthee, Darvish et al. 2015

CR7: X-SHOOTER: 2 hours

Anything interesting to explain J excess?

CR7: X-SHOOTER: 2 hours HeII 1640!

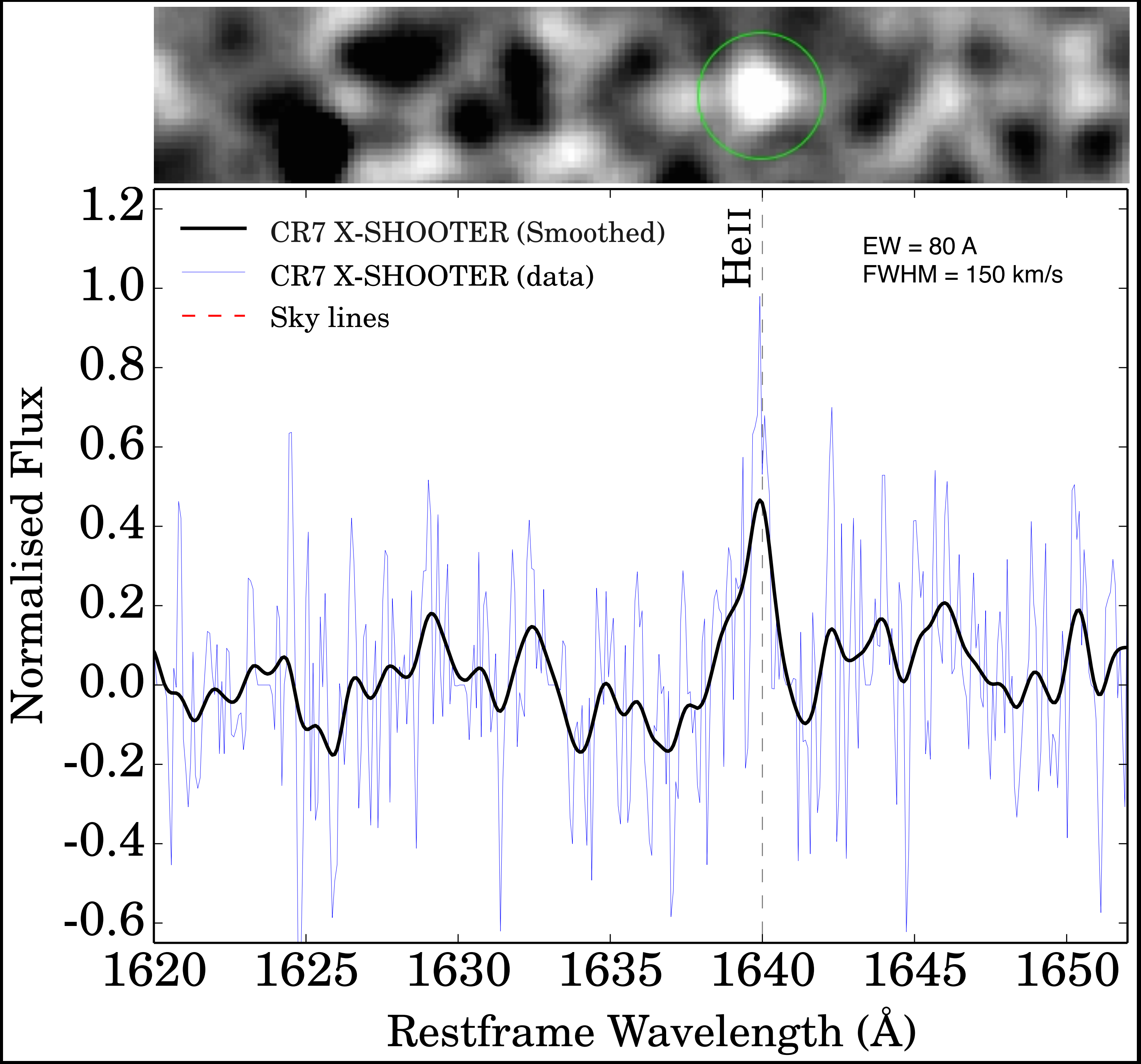


FWHM= 130 km/s

HeII/Lya = 0.23+-0.10

Sobral et al. 2015c

CR7: X-SHOOTER: 2 hours **HeII 1640!**



FWHM= 130 km/s

HeII/Lya = 0.23+-0.10

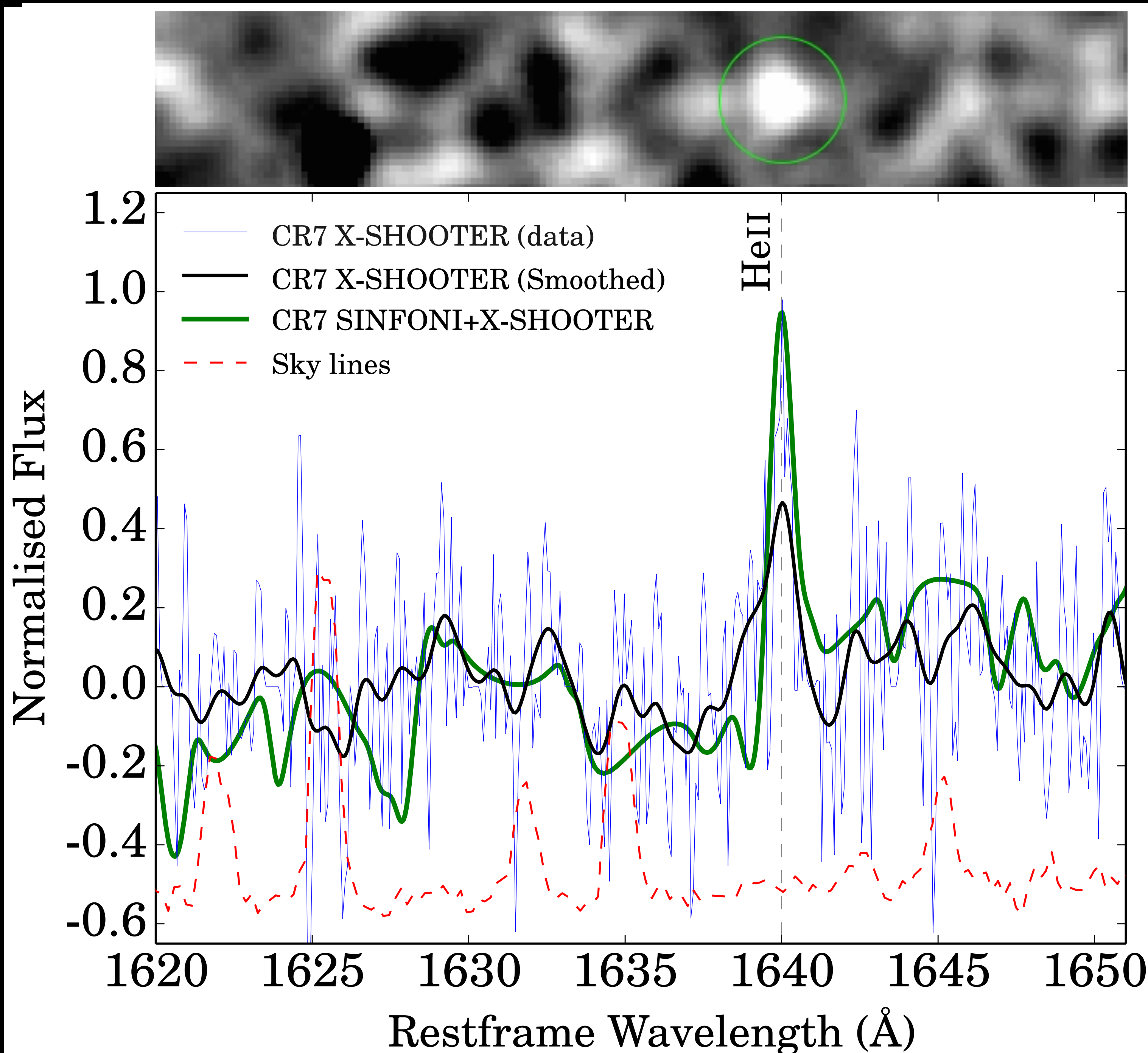
>>> DDT time on SINFONI/VLT to fully confirm

PI: Sobral

Sobral et al. 2015c

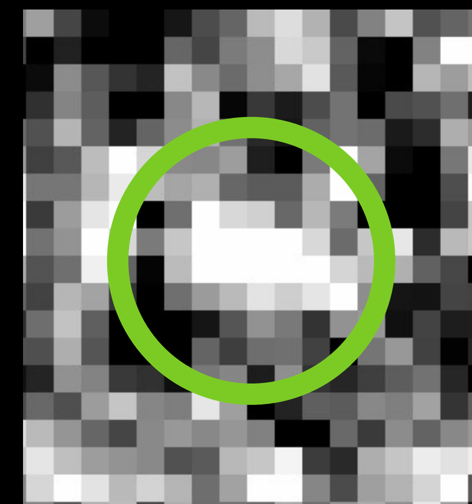
CR7: X-SHOOTER: 2 hours

Sobral, Matthee, Darvish et al. 2015



SINFONI

HeII 1640A in 2D!



~6 sigma!

HeII EW_0>70 A

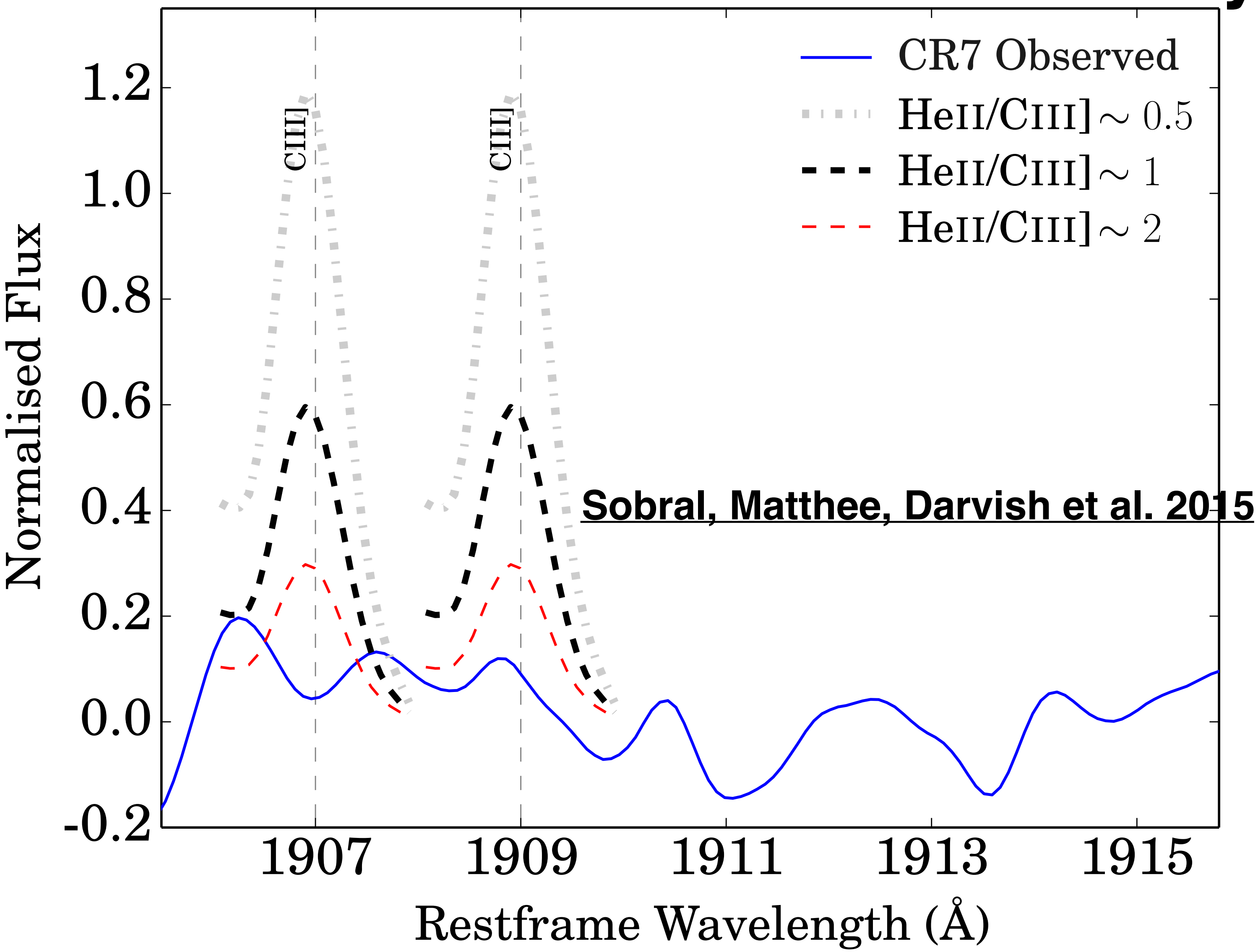
HeII $FWHM_0$=
130 km/s

HeII/Lya = 0.23+-0.10

Sobral et al. 2015c

Apart from bright narrow Lyα and HeII1640: <u>no other emission lines detected</u>

HeII/Lyα~0.10+-0.05?



EW HeII>70!!

E.g.:

No CIII]1908

No OIII]1663

No NV

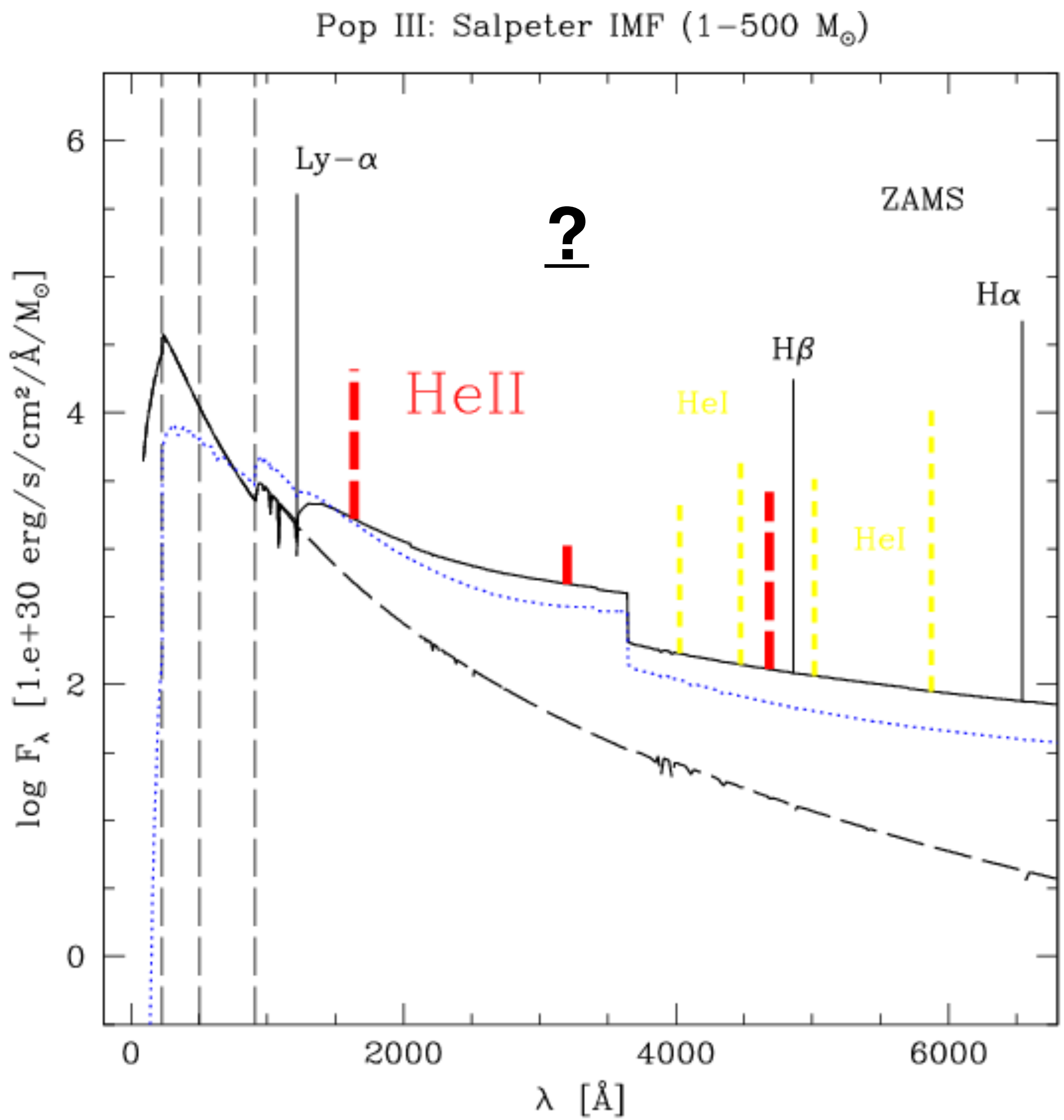
Lyα/NV >70

HeII/OIII]>3

HeII/CIII]>2.5

<u>**Sobral, Matthee, Darvish et al. 2015**</u>

This is what we have:



Schaerer 2002

Lyα EW>230 A (likely >1000A)

HeII EW ~80 A!

HeII/Lyα~0.1

No lines except Lyα and HeII (so far!)

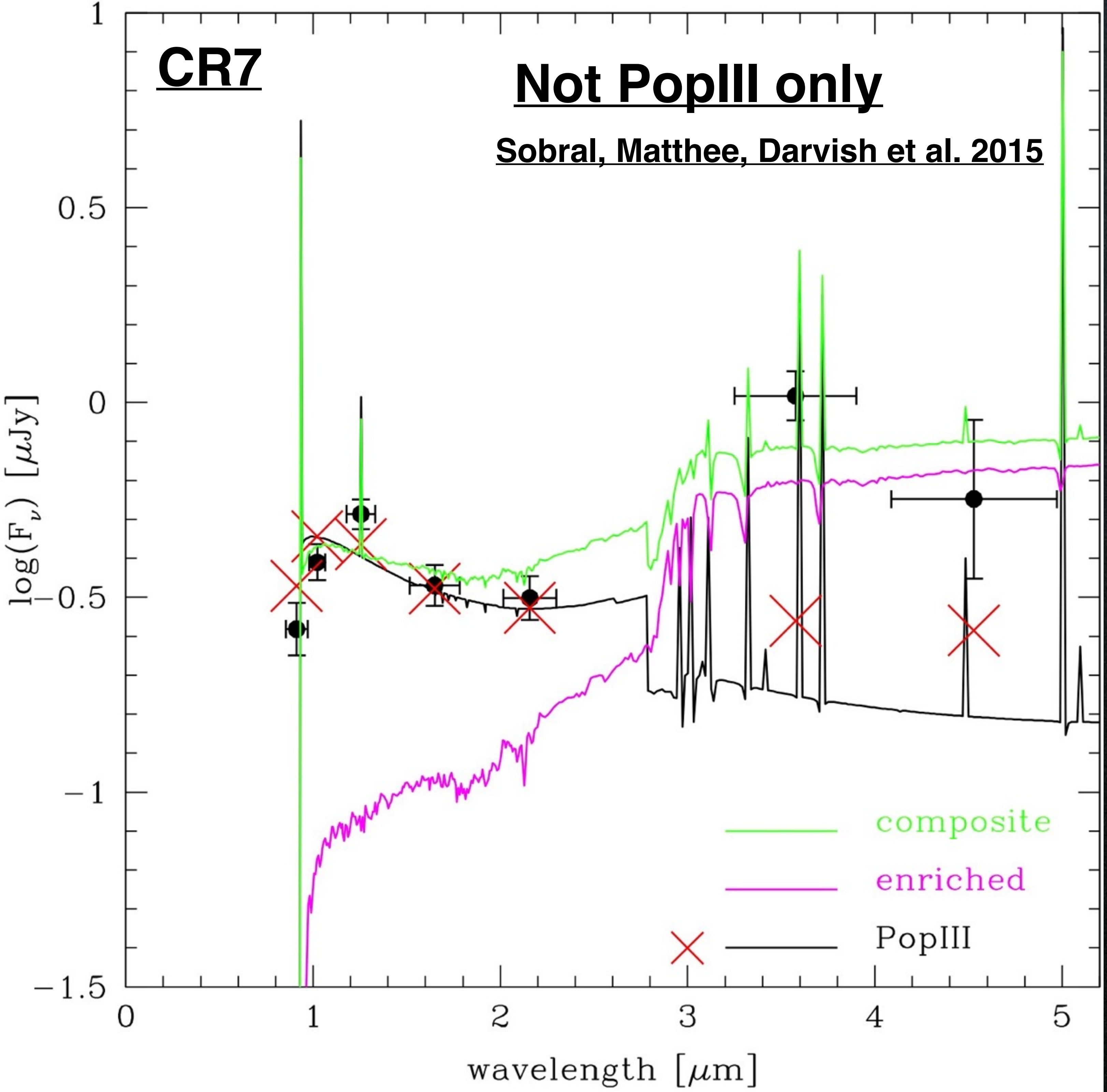
Narrow Lyα and narrow HeII

"Talks" like it

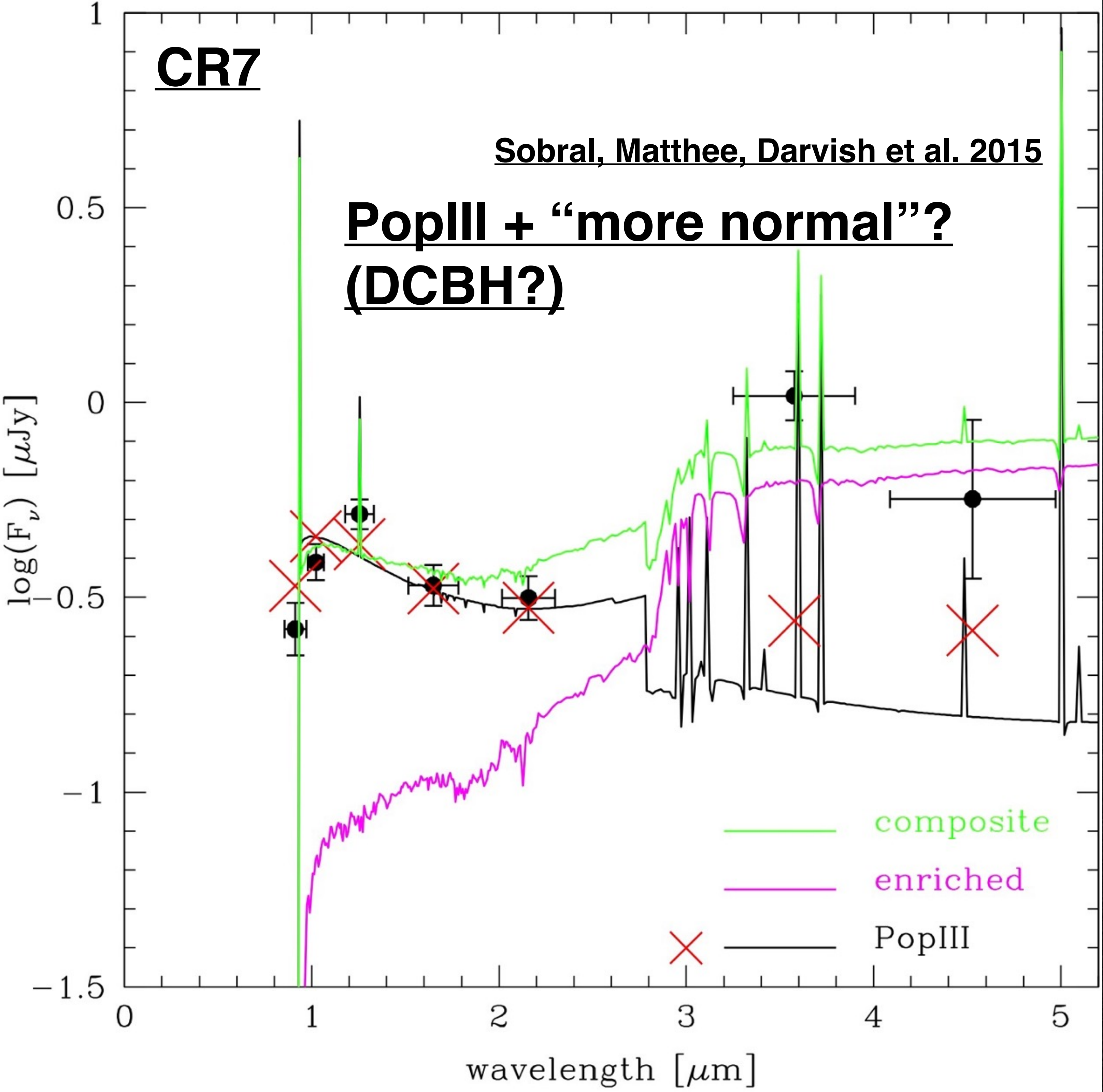
"Looks" like it

"Moves" like it

"Smells" like it

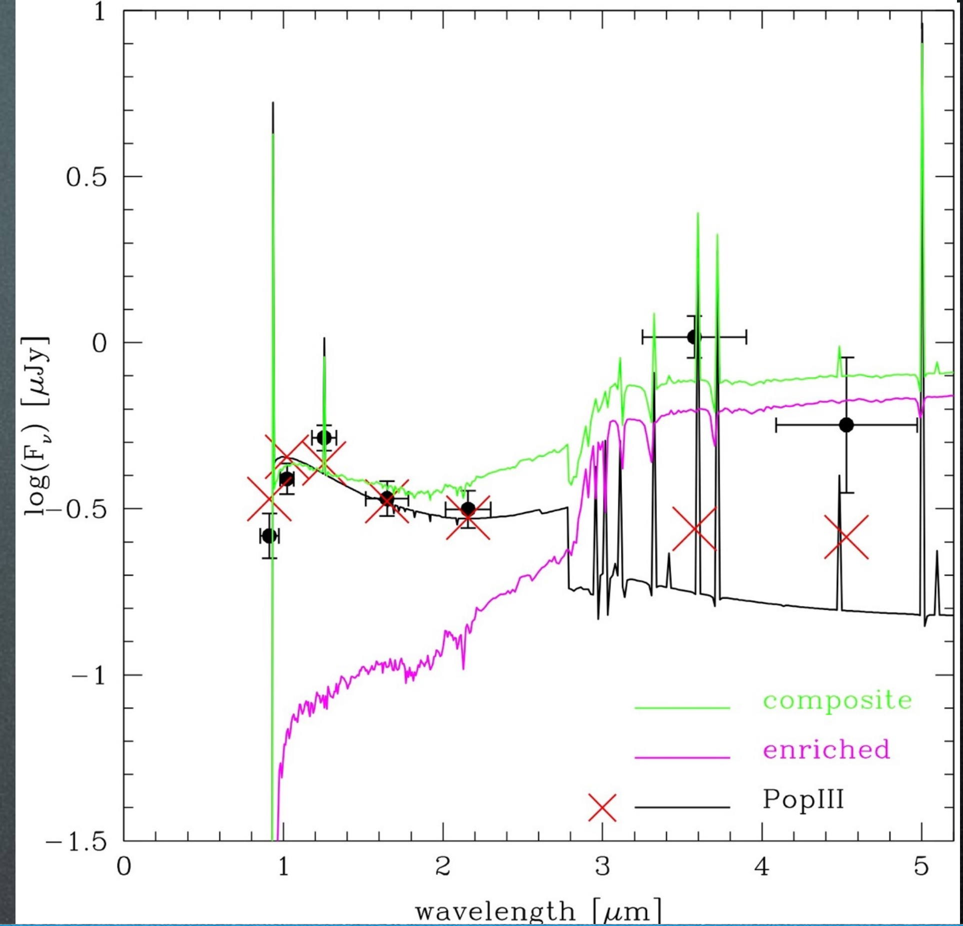


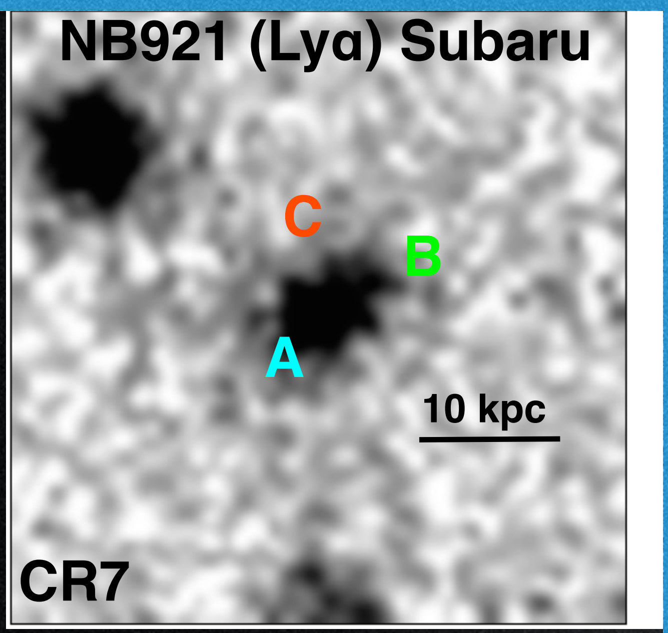
CR7
Not PopIII only
Sobral, Matthee, Darvish et al. 2015
composite
enriched
PopIII
log(F_ν) [μJy]
wavelength [μm]
1
0.5
0
−0.5
−1
−1.5
0
1
2
3
4
5


CR7
Sobral, Matthee, Darvish et al. 2015
PopIII + "more normal"?
(DCBH?)
log(F_ν) [μJy]
wavelength [μm]
composite
enriched
PopIII
1
0.5
0
−0.5
−1
−1.5
0
1
2
3
4
5

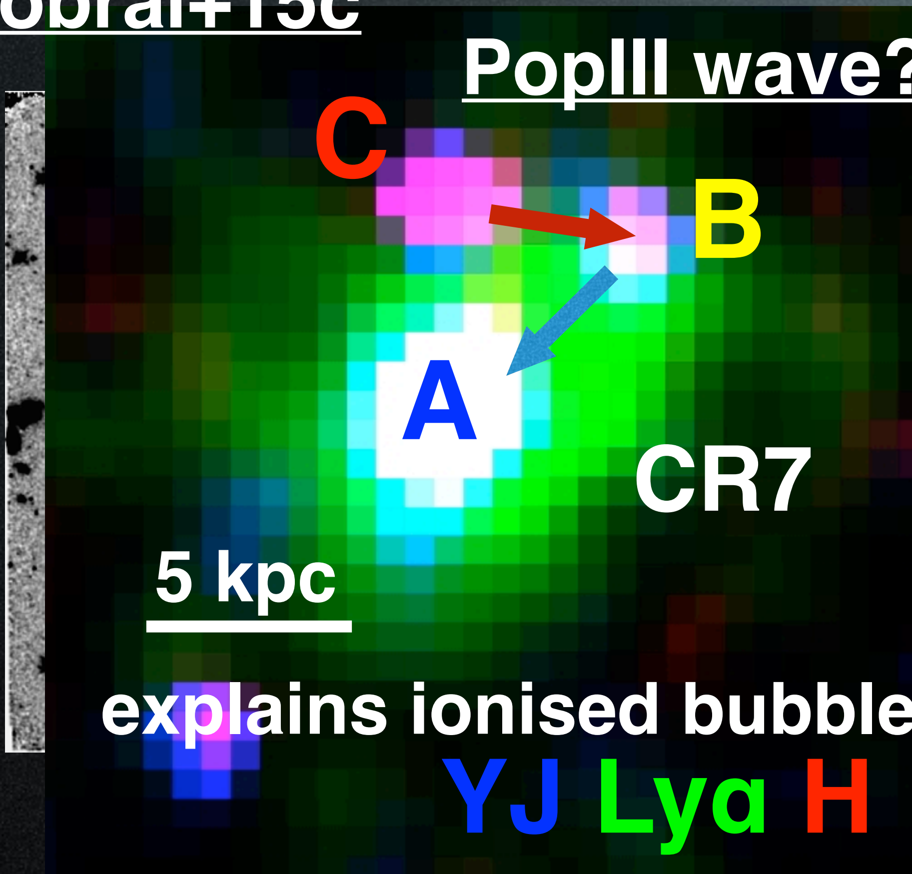
Sobral+15c

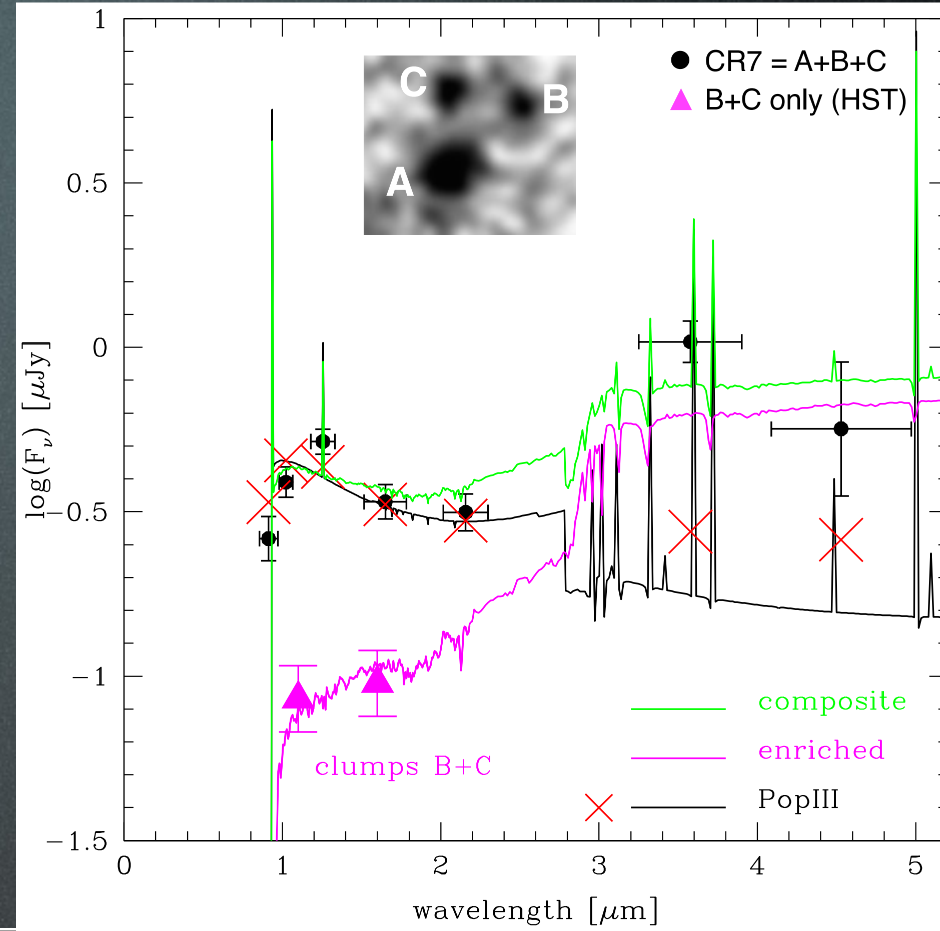
From ground-based + Spitzer photometry: single source

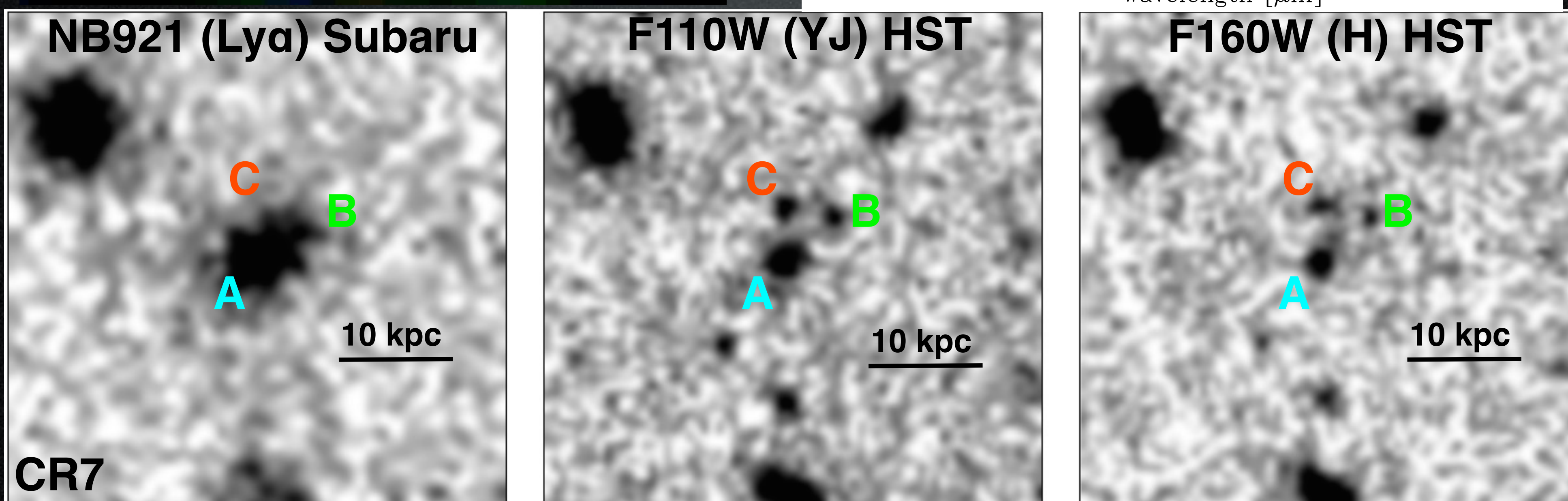




Sobral+15c

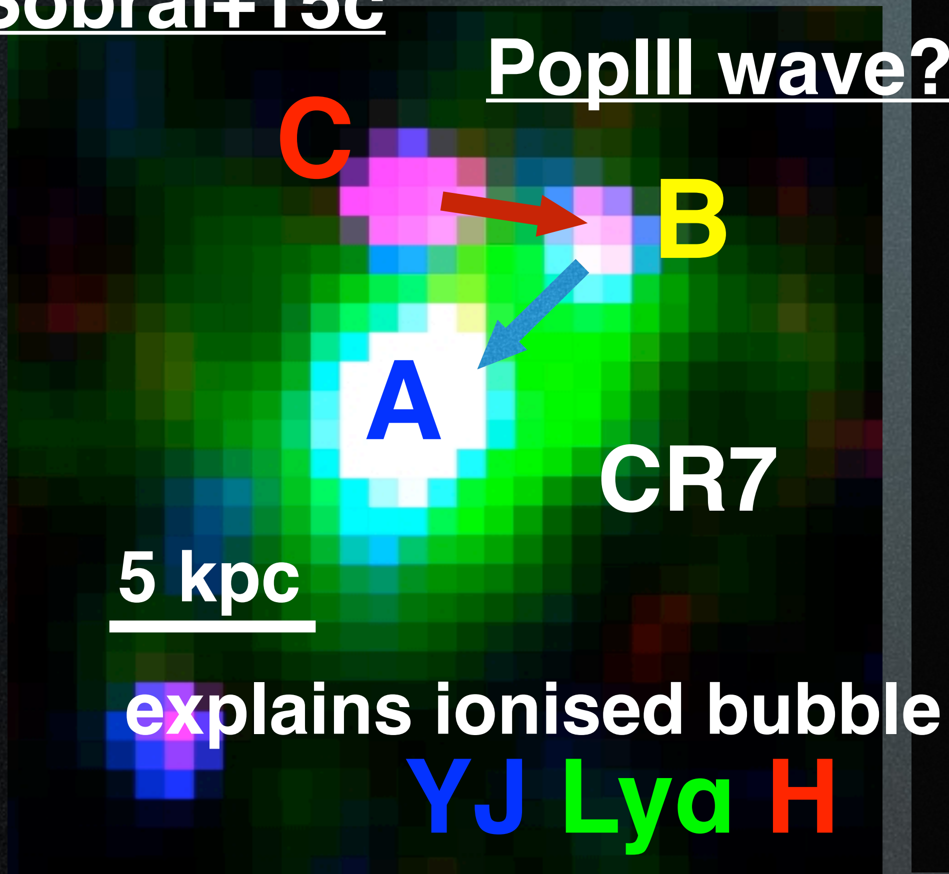

PopIII wave?
C
B
A
CR7
5 kpc
explains ionised bubble
YJ Lyα H

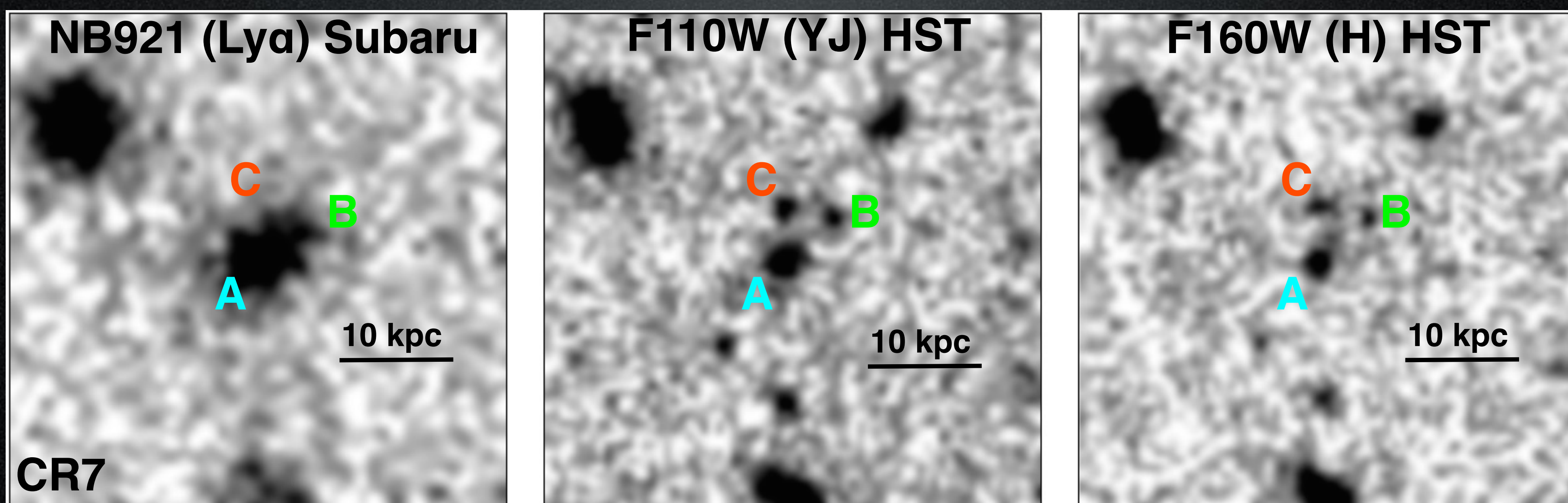

CR7 = A+B+C
B+C only (HST)
C
B
A
composite
enriched
PopIII
clumps B+C
log(F$_\nu$) [μJy]
wavelength [μm]
1
0.5
0
−0.5
−1
−1.5
0
1
2
3
4
5


NB921 (Lyα) Subaru
F110W (YJ) HST
F160W (H) HST
C
B
A
10 kpc
CR7

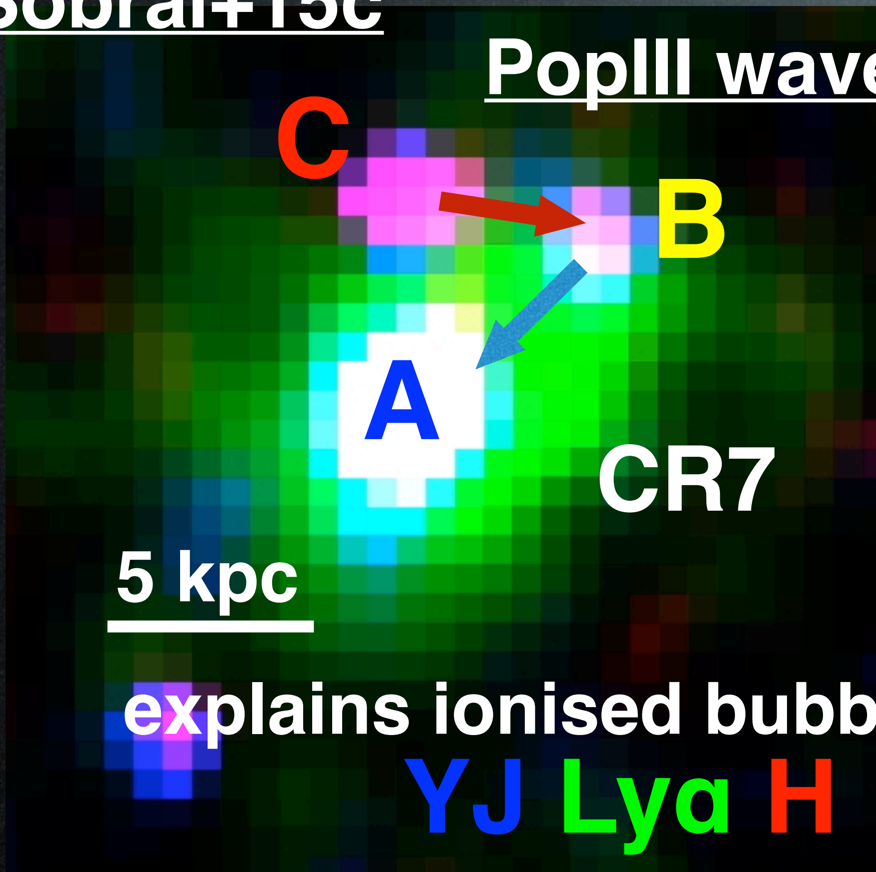
Sobral+15c

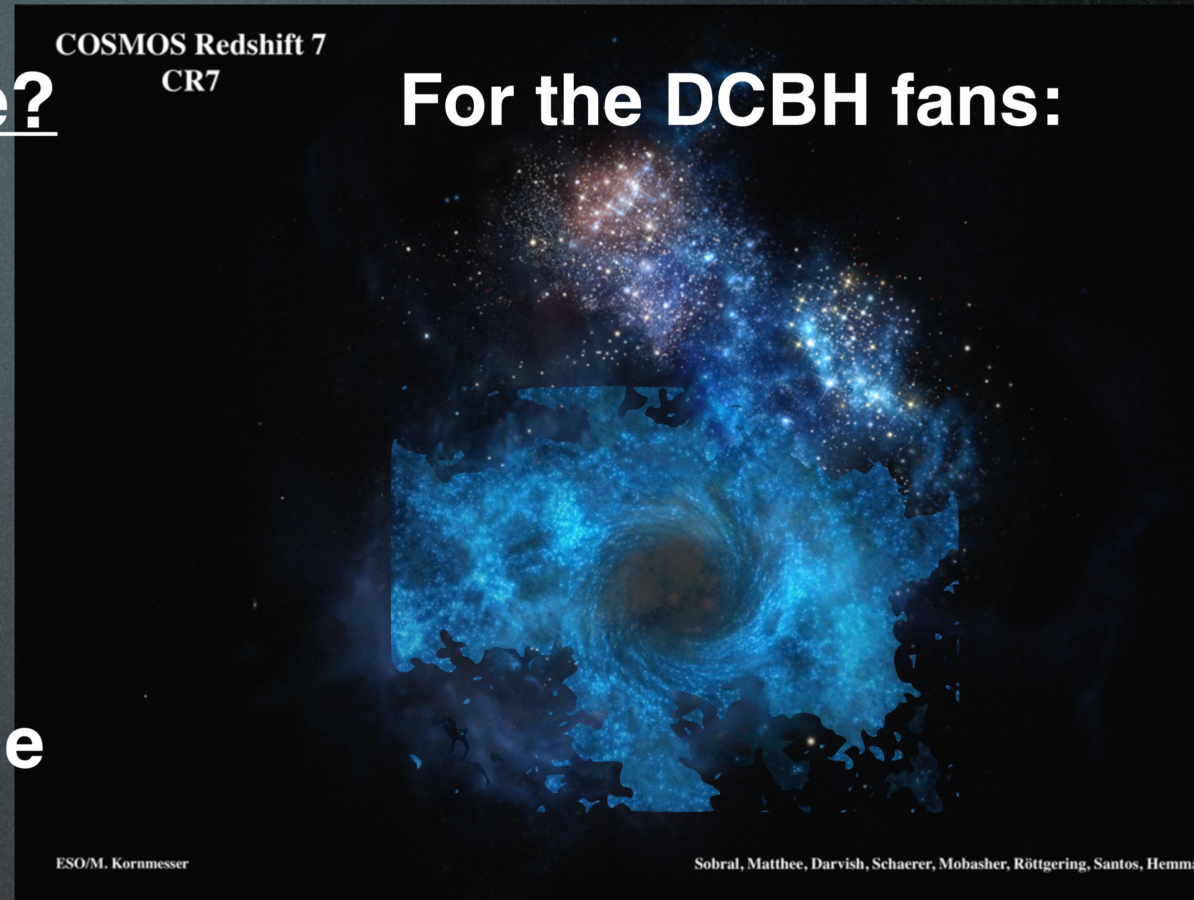
PopIII wave?

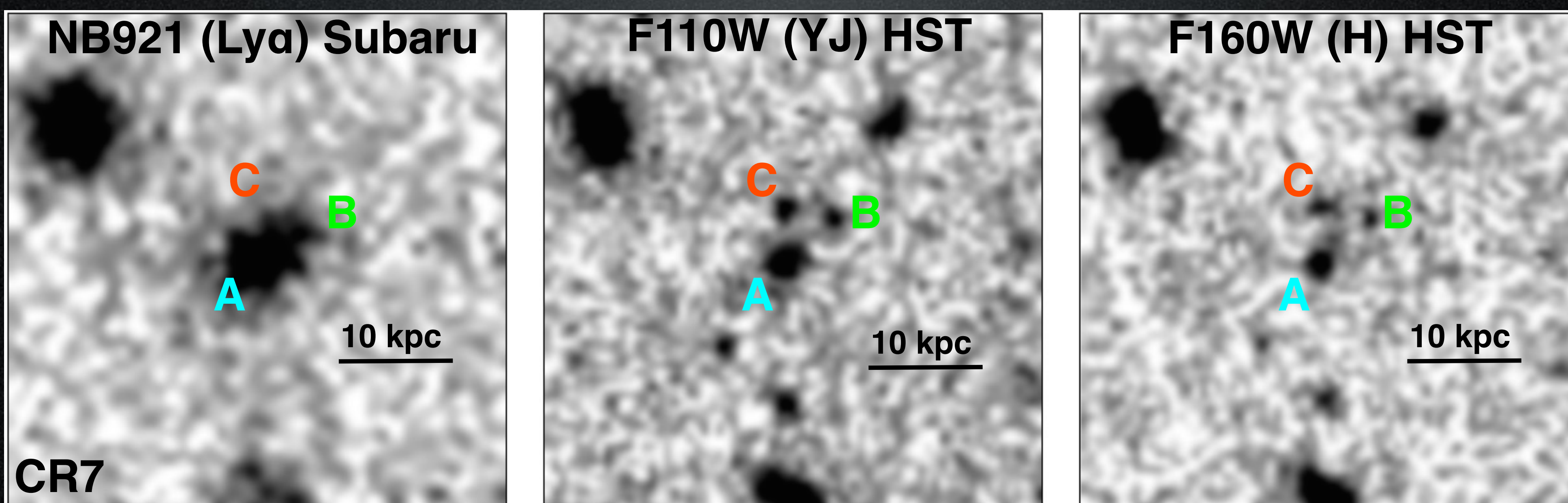




Sobral+15c


PopIII wave?
C
B
A
CR7
5 kpc
explains ionised bubble
YJ Lyα H


COSMOS Redshift 7
CR7
For the DCBH fans:
ESO/M. Kornmesser
Sobral, Matthee, Darvish, Schaerer, Mobasher, Röttgering, Santos, Hemm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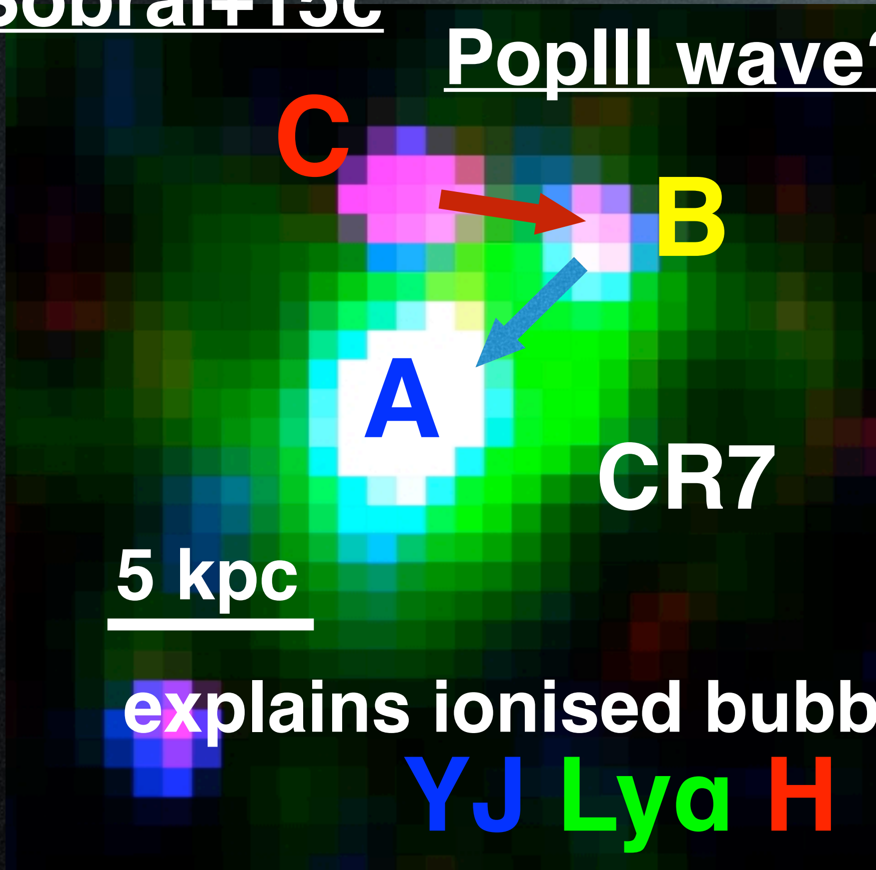
CR7

Sobral+15c

PopIII wave?



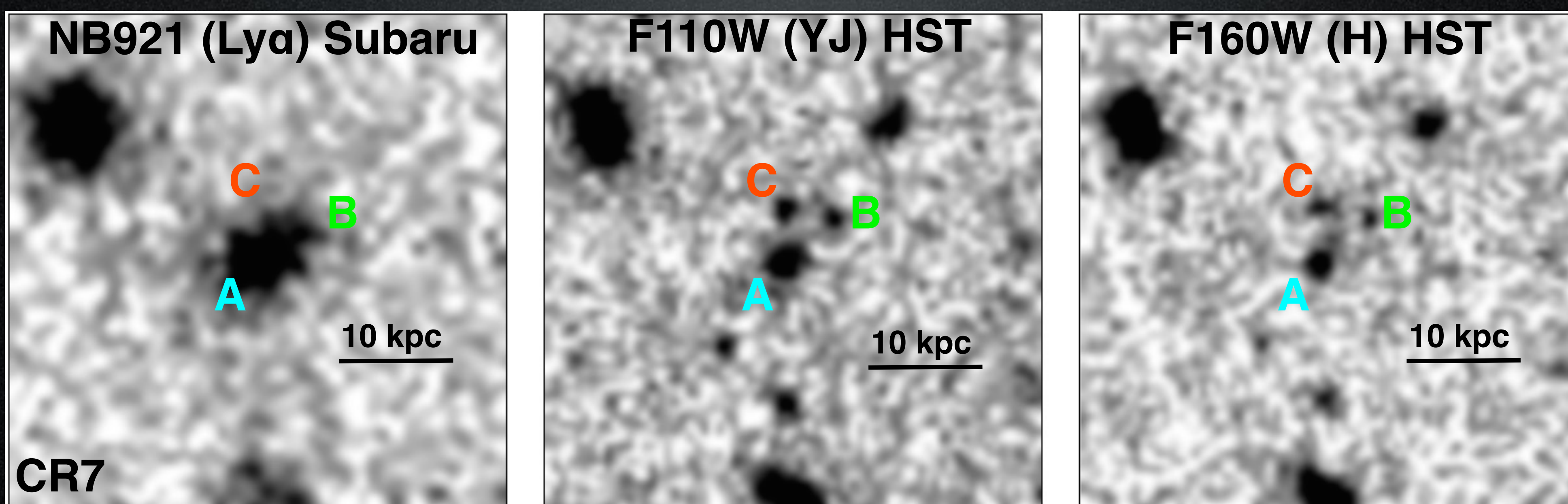
explains ionised bubble

To think about:

Similar to CR7?

Luminous Lyα emitters all multi-component?

HST can test!



What is the nature of CR7?

Sobral+15

Throughout this conference

See talks by e.g.
E. Visbal

See talks by e.g.:
J. Johnson
M. Dijkstra
A. Smith

PopIII(-like) vs **DCBH**

Other alternatives at low metallicity

Also e.g.: Pallottini+15; Agarwal+15; Hartwig+15

What is the nature of CR7?

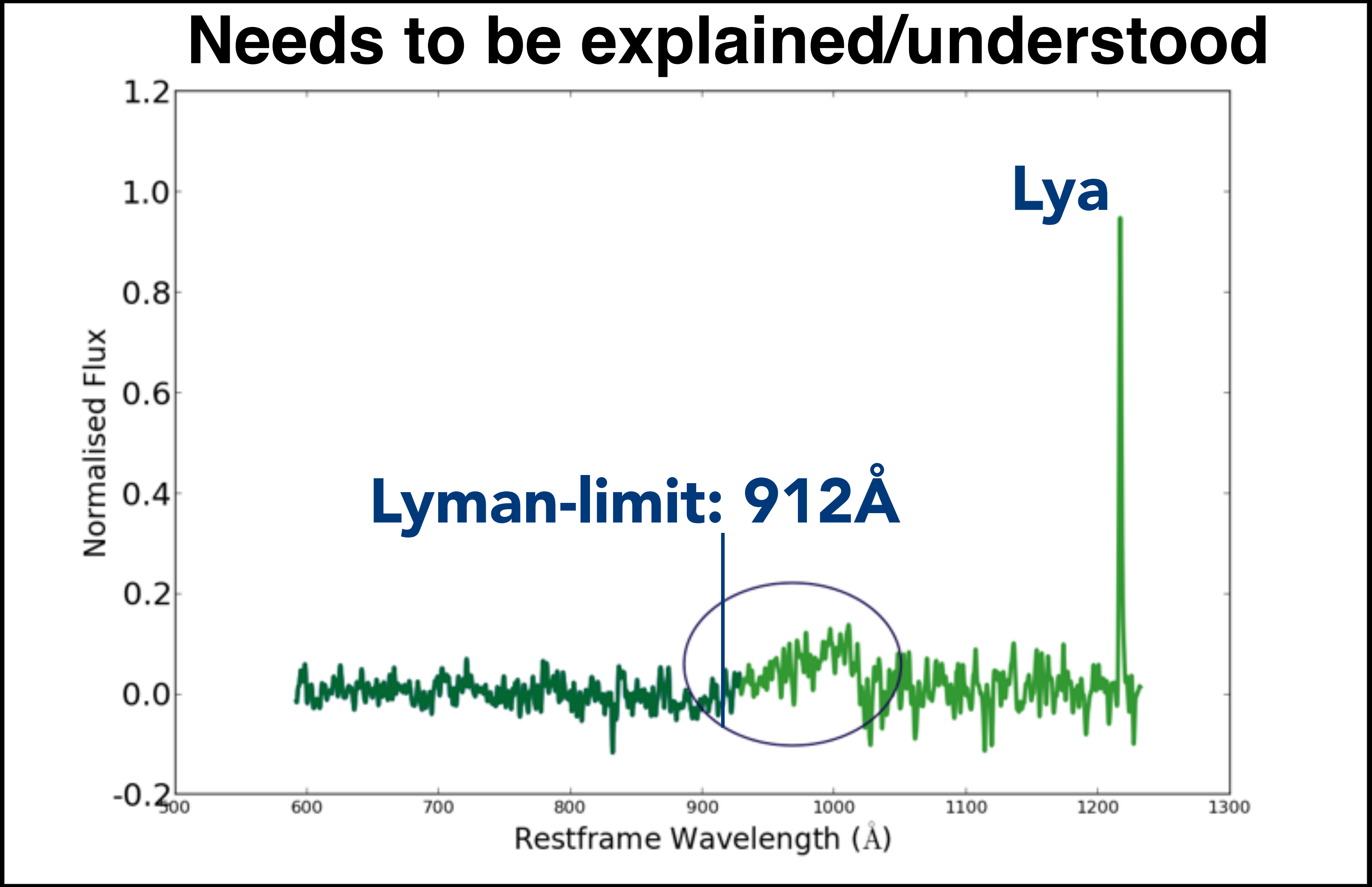
Sobral+15

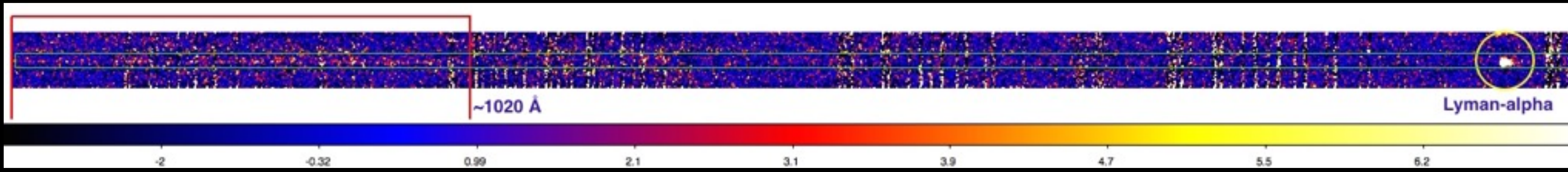
More/better observations needed + confirm an actual sample of CR7-like sources + understand redshift evolution of this potential population

LYMAN-WERNER FLUX FROM CR7 ?

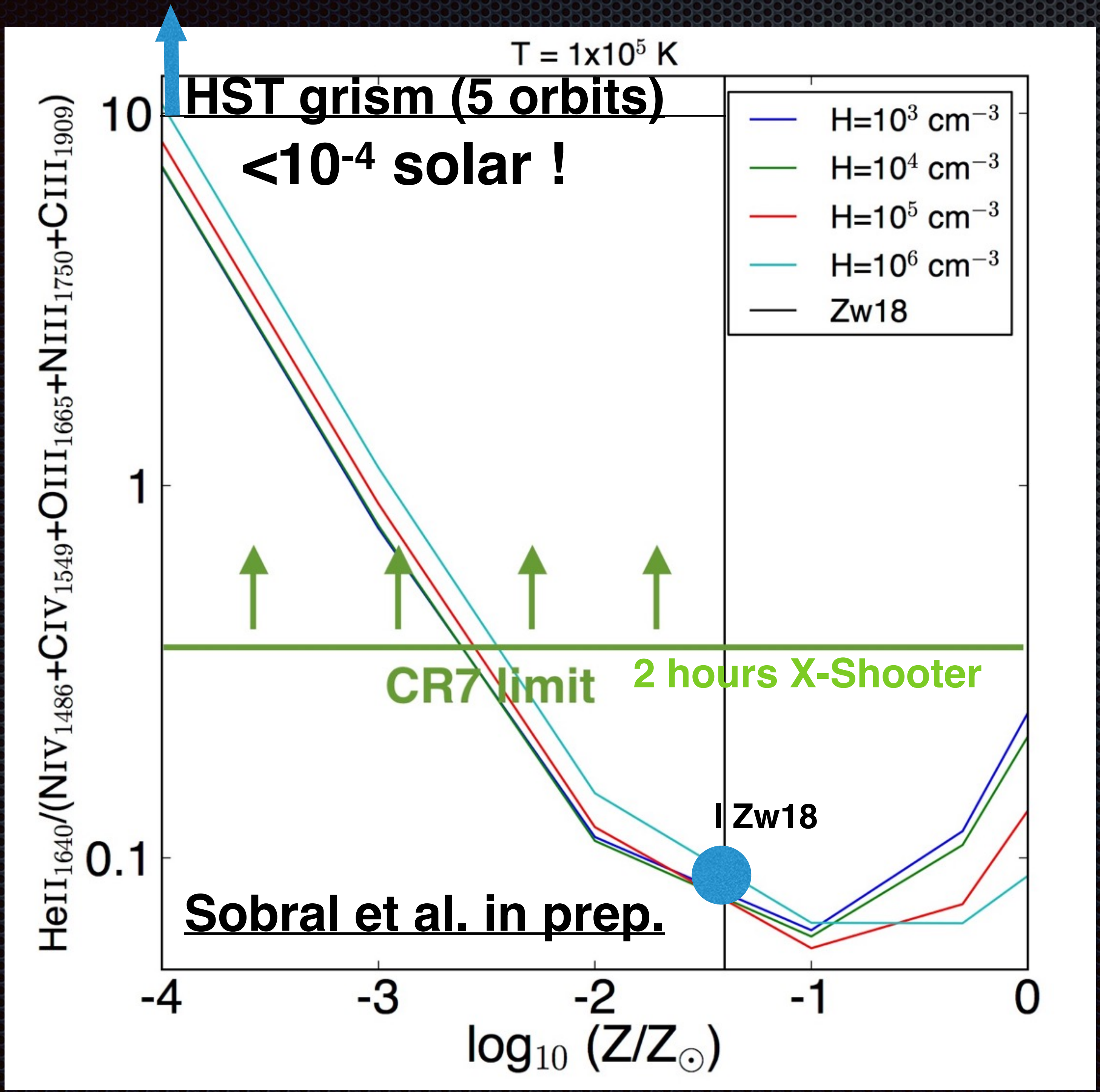
Unseen in other z>6 galaxies

Escaping Lyman-Werner+ *hole* in the IGM?





New (cheap!) observations needed to clarify metallicity



CLOUDY modelling exploring large range of physical conditions, temperatures, densities

Current limit on CR7 metallicity <10$^{-2.5}$ solar

Stay tuned… spectroscopic follow-up on-going

2015

Up to a full team (~10-20) of CR7-like and even super-CR7 candidates…

Number densities 10^{-6} Mpc^{-3}

Stay tuned… spectroscopic follow-up on-going

Up to a full team (~10-20) of CR7-like and even super-CR7 candidates… Number densities 10^{-6} Mpc^{-3}

Fully done by ~June-July 2016

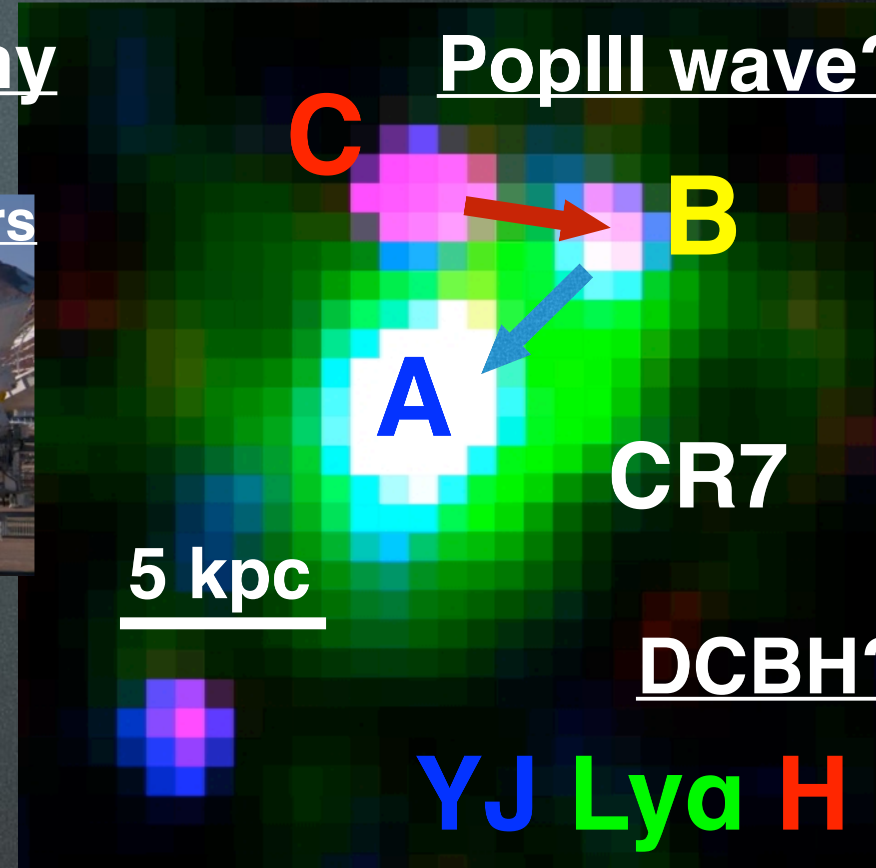
Diversity? All bright enough for detailed follow-up and actual statistics.

Selection very well known

ALMA time to clearly reveal any traces of metals

Cycle 3. PI: Sobral

May 2016



X-SHOOTER + Keck for CR7-like sources on-going

Go beyond 1-2 objects and explore the actual population…

Up to 20 candidates + our surveys at lower and higher-z

Take home messages

Matthee, Sobral et al. 2015, MNRAS
Sobral, Matthee et al. 2015, ApJ
Sobral et al. in prep.
Santos et al. in prep.

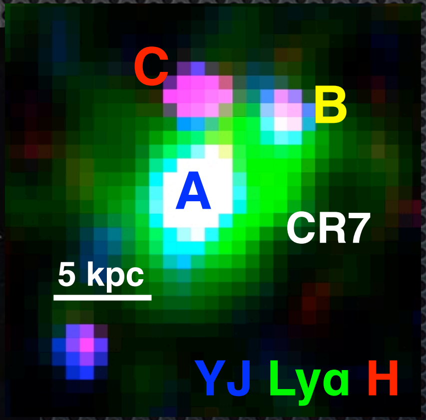
- Stay tuned!

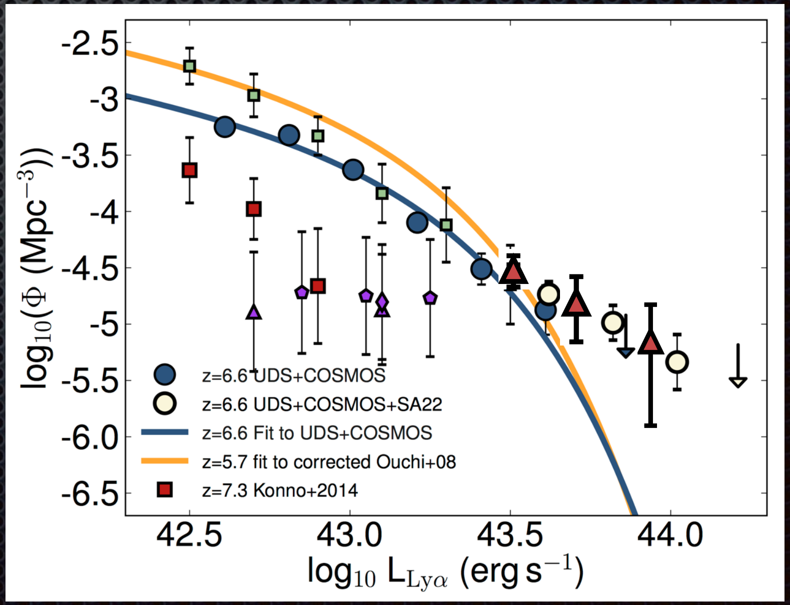
- Luminous Lyα emitters (~$10^{43.5}$ erg/s) at z=5.7-6.6 much more common than thought

$1.5 \times 10^{-5}\ \mathrm{Mpc}^{-3}$

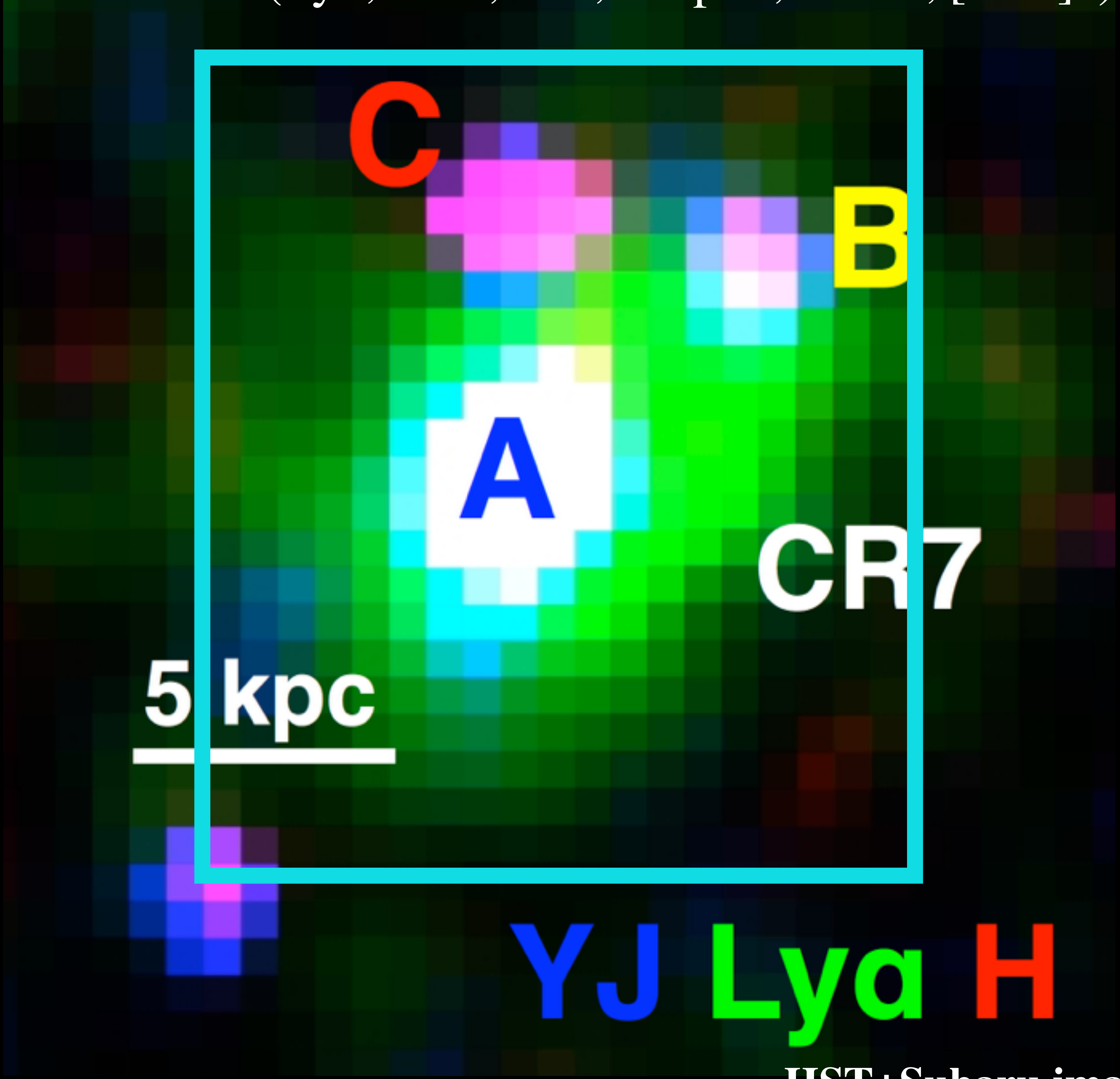
- Evolution of the Lyα LF is at the faint end

- PopIII-like (PopIII or DCBH?) stellar populations in luminous Lyα emitters at z=6.6





JWST/NIRCam IFU FoV (Lya, HeII, HeI, Halpha, Hbeta, [OIII]?)



HST+Subaru image of CR7

European Southern Observatory

ESO Top 10 Astronomical Discoveries

ESOcast 75: ESO's Top 10 Discoveries. Download and more info

Observations with ESO telescopes have led to many breakthroughs in astronomy, and, over the years, have been responsible for some truly remarkable findings. Here is our list of ESO's Top 10 astronomical discoveries so far.

Best observational evidence of first generation stars in the Universe

Astronomers using ESO's Very Large Telescope have discovered by far the brightest galaxy yet found in the early Universe and found strong evidence that examples of the first generation of stars lurk within it — stars that were previously only theoretical. These massive, brilliant objects were the creators of the first heavy elements in history — elements that are necessary to forge the stars we see around us today, the planets that orbit them, and life as we know it.

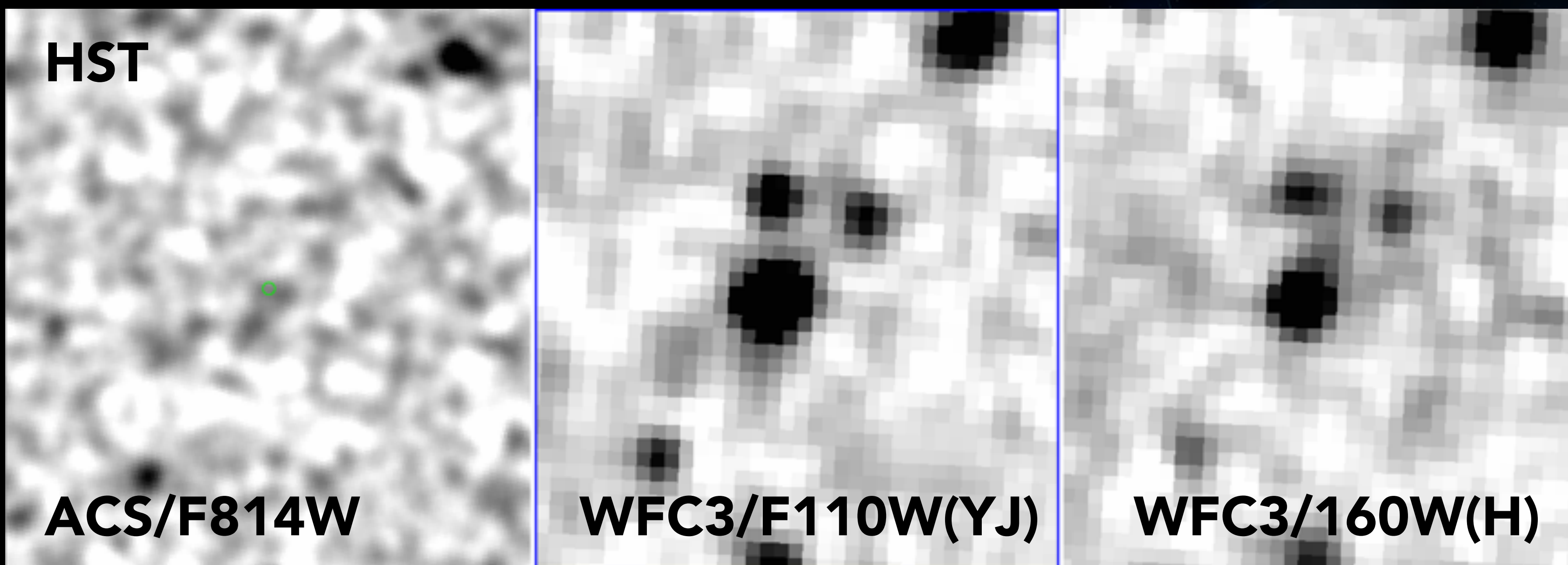
Science paper:

Sobral, D., et al., 2015, ApJ

Read more in the ESO press release eso1524

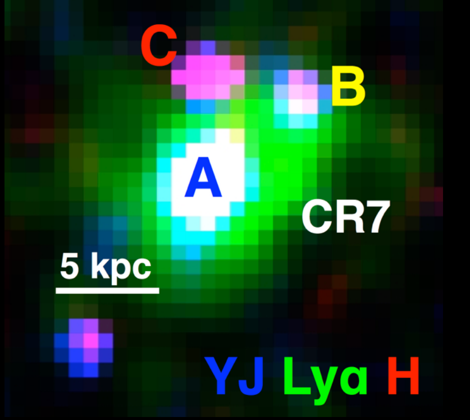
CLUMP B & C AT SAME REDSHIFT?

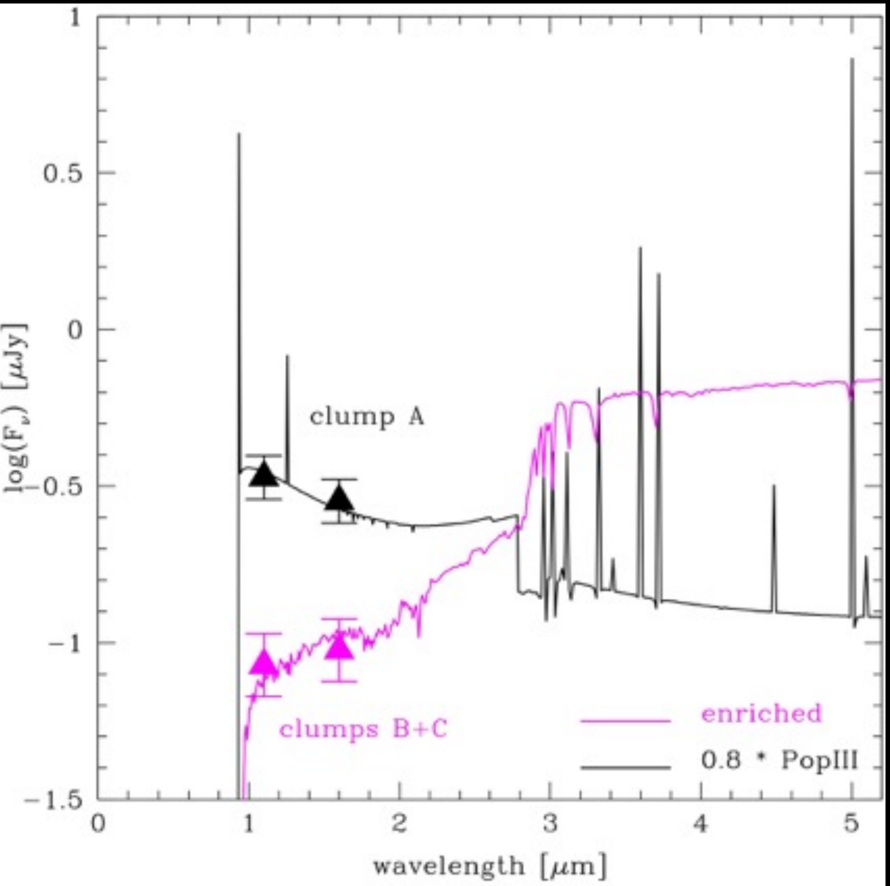
Clump B+C are not yet spectroscopically confirmed, but are z-dropouts, so photo-z>6.5 most likely

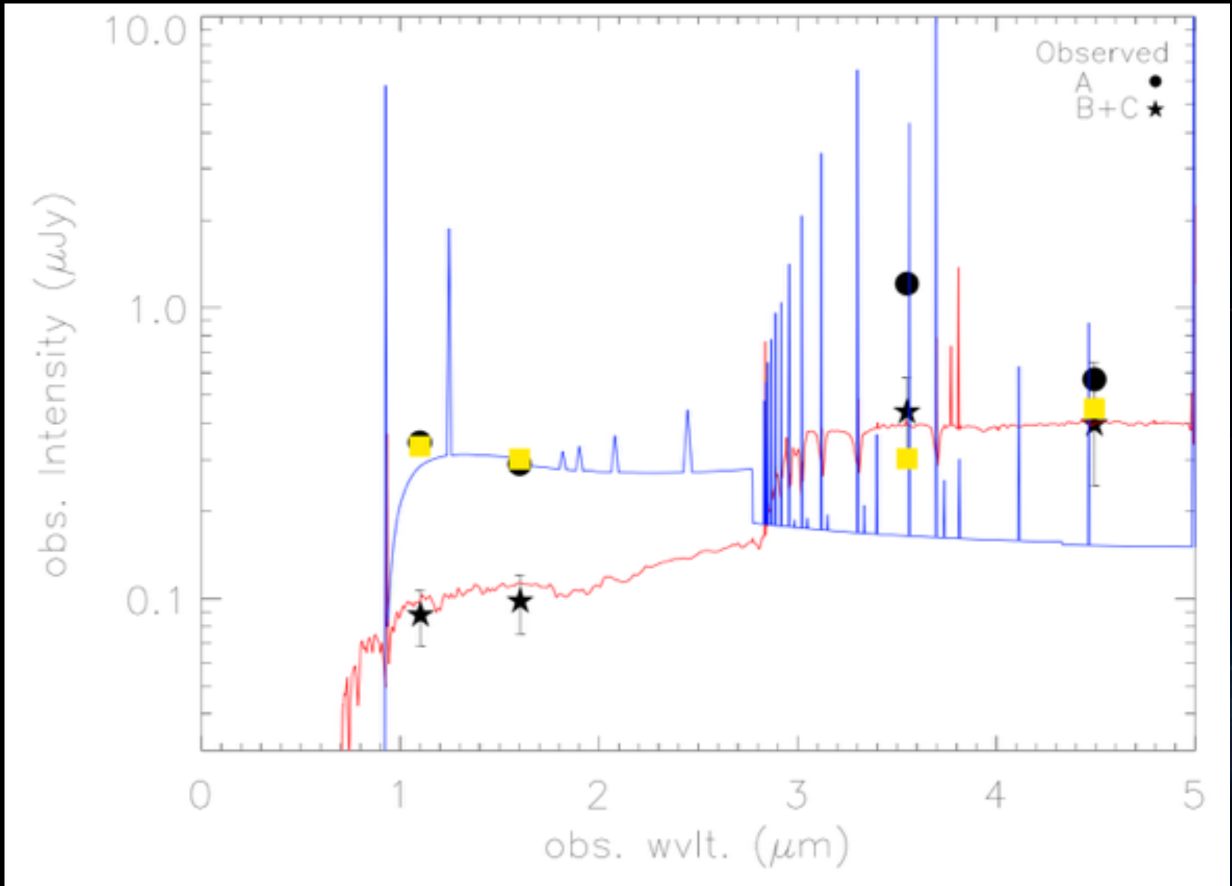


Sobral, Matthee et al. 2015 ApJ, 808, 139

SEDs PopIII vs DCBH



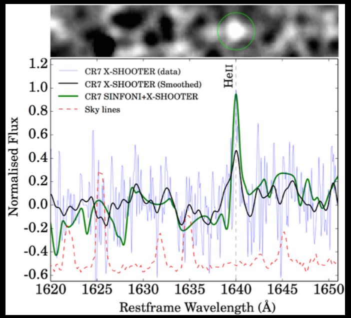




Sobral,JM+2015

Agarwal+2015

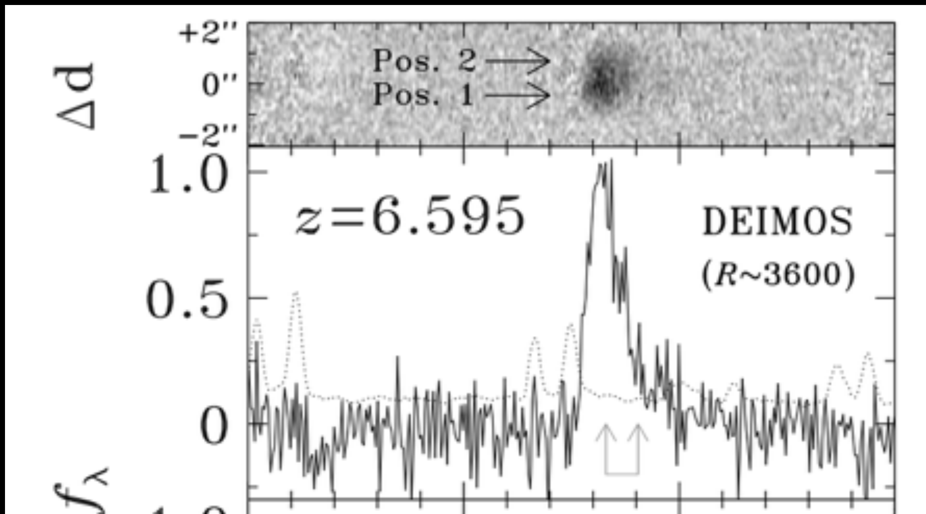
IONISING ENERGY OF HEII = 54.4 EV

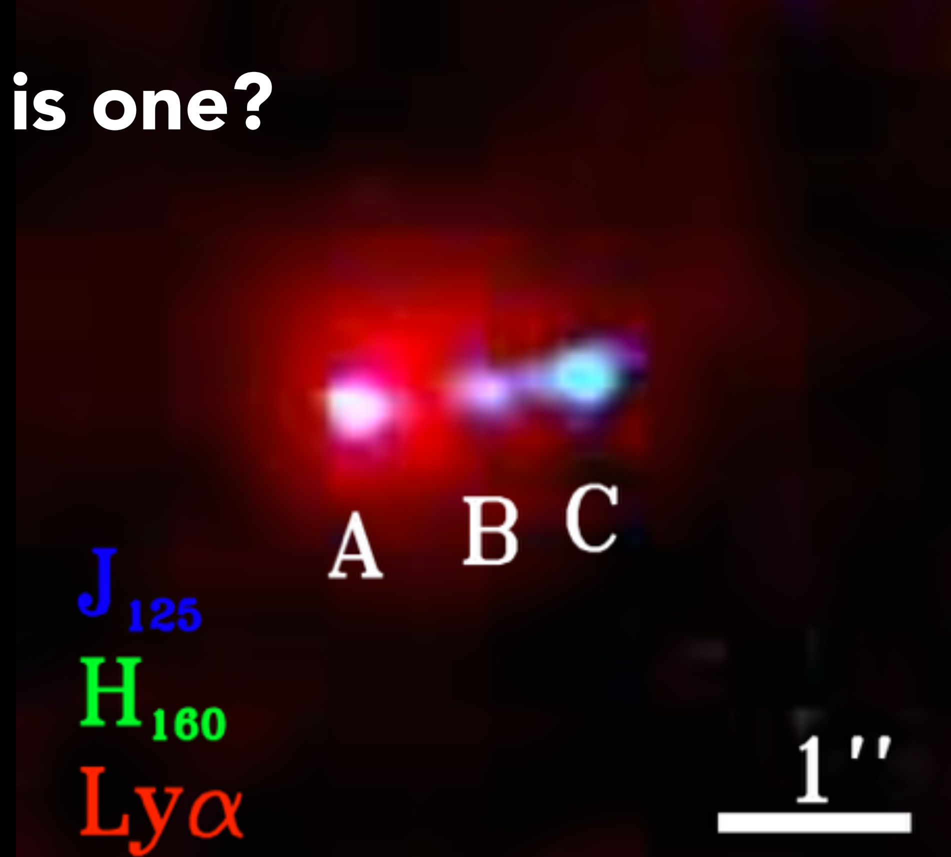


<u>Sources:</u>

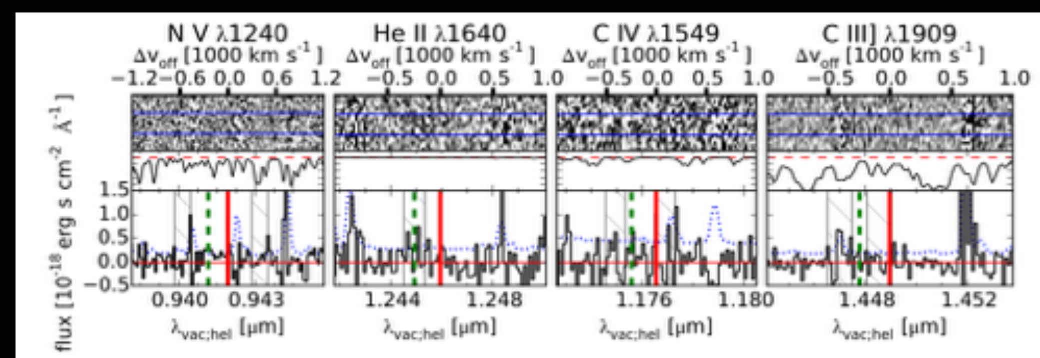
- AGN **- no metal lines, lines narrow, no X-ray, blue UV colours,** (although maybe direct collapse??)
- Wolf-Rayet stars **- HeII narrow (FWHM << 1000 km/s)** (but also the case at low metallicity??)
- Cooling radiation **- width lines, EUV flux**
- PopIII-*like* stars - but why so late (z=6.6), inefficient metal mixing?

Is *Himiko* also a DCBH if *CR7* is one?





- Extended, luminous Lya
- Similar Lya FWHM, lower EW
- 3 clumps, the brightest is very blue
- separation ~ 0.5-1″
- no HeII, nor any other line



Ouchi+2009, Ouchi+2013, Zabl+2015

Take home messages I

Contrarily to “common-sense”, bright galaxies are really worth it: we get way more per second than thought

- See previous talks by e.g. : R. Bowler, D. Stark, G. Brammer

Ideal to prepare for JWST (way beyond number counts)

PopIII searches with JWST: “find HeII”. Clearly that’s not even the start of it. CR7 is already showing that.