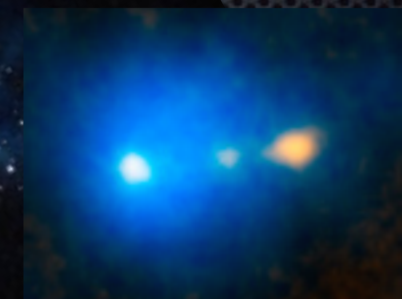
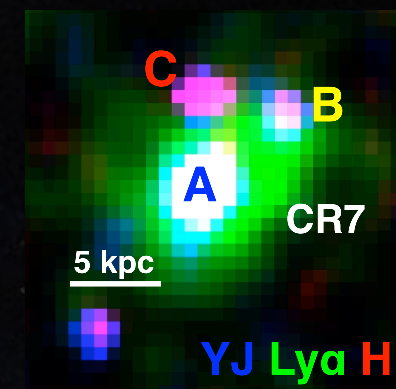
Exploring the end of the dark ages with the widest Lyman-α surveys

David Sobral

Lancaster University

Leiden Observatory





Jorryt Matthee, Sérgio Santos, Behnam Darvish, Daniel Schaerer, Bahram Mobasher, Mark Dijkstra, Max Gronke, Huub Rottgering, Shoubaneh Hemmati

Lancaster University

Sterrewacht Leiden

VENI VIDI VICI

NWO

Take home messages

Matthee, Sobral et al. 2015, MNRAS

Sobral, Matthee et al. 2015, ApJ

Santos, Sobral & Matthee

Sobral et al. in prep.

Bright end of Lyα LF is a power-law (great for wide surveys)!

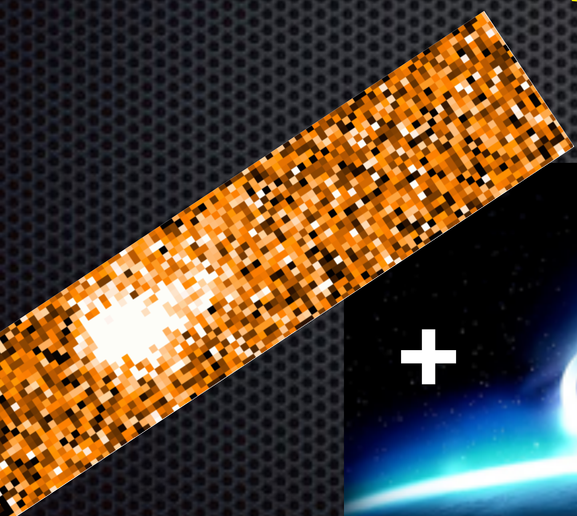
- Luminous Lyα emitters (>$10^{43.5}$ erg/s) at z=6-7 much more common than thought

  1.5×10^{-5} Mpc^{-3}

- Evolution of the Lyα LF is <u>at the faint end</u>

  Patchy re-ionisation: first around more luminous sources

- Discovery of the most Luminous Lyα emitters: surprises!



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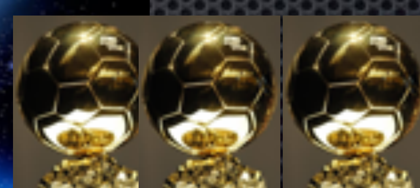

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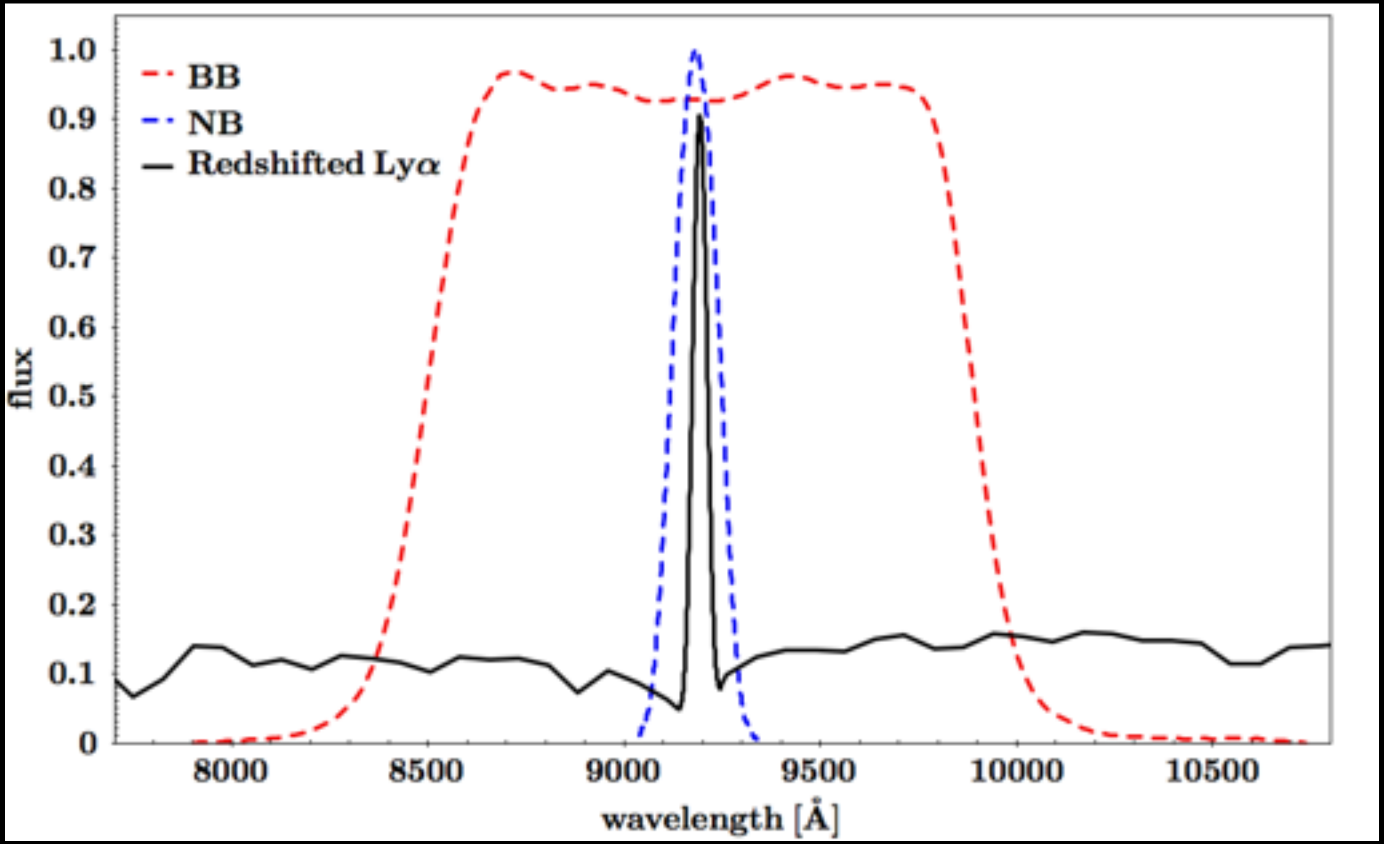
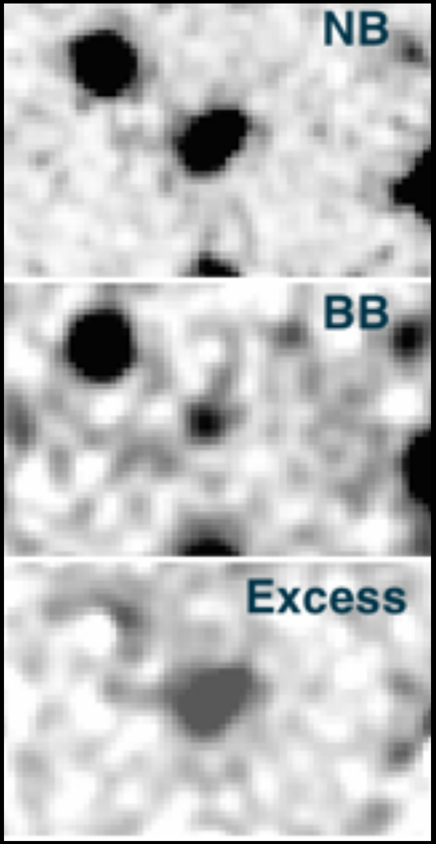
???

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

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





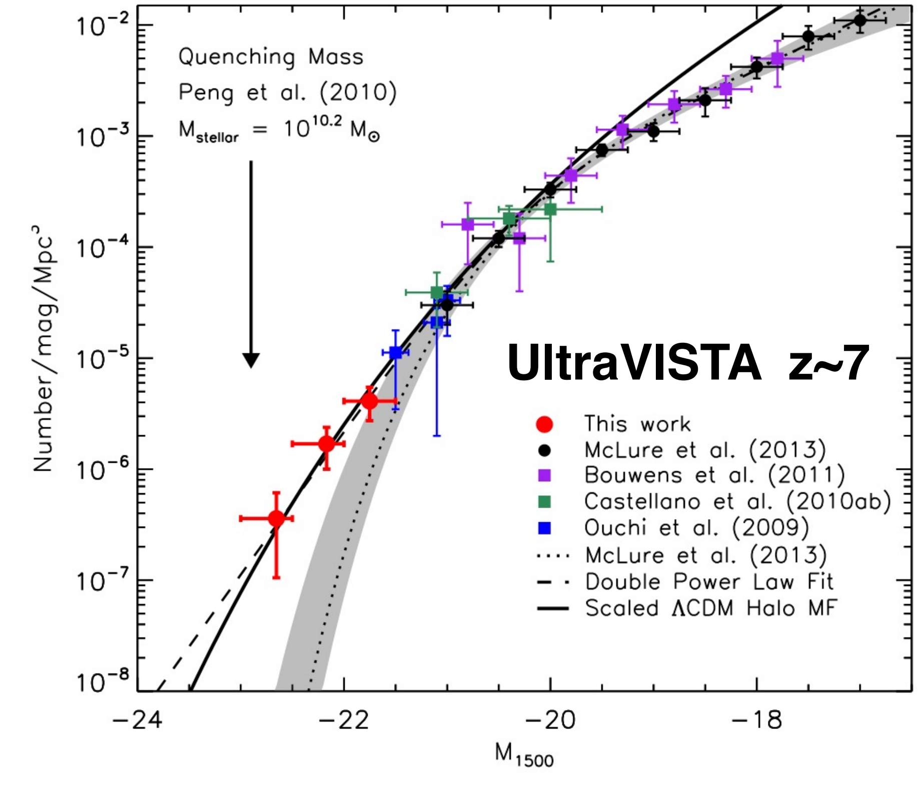
- Lyα emitted by young galaxies (high EW)
- Lyα absorbed in more neutral IGM (test for re-ionisation)

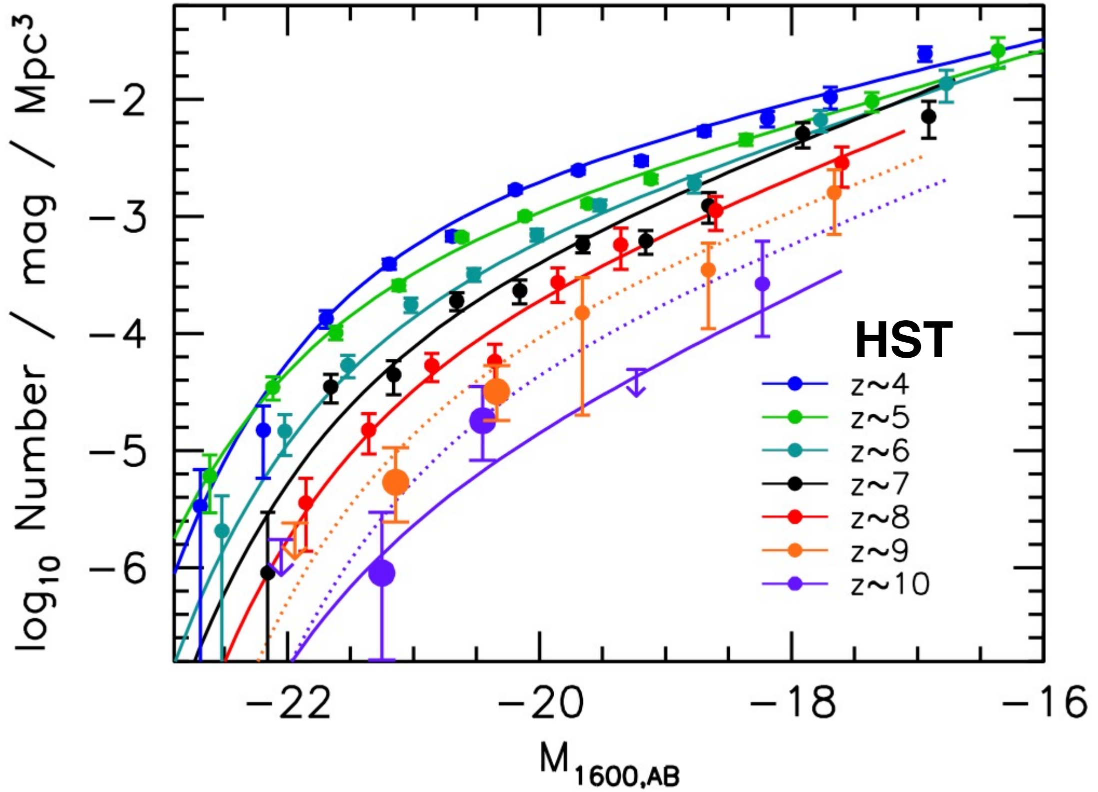
Lyman-break selection
UV luminosity function evolution

UV LF evolves strongly

From the ground

From space (HST)



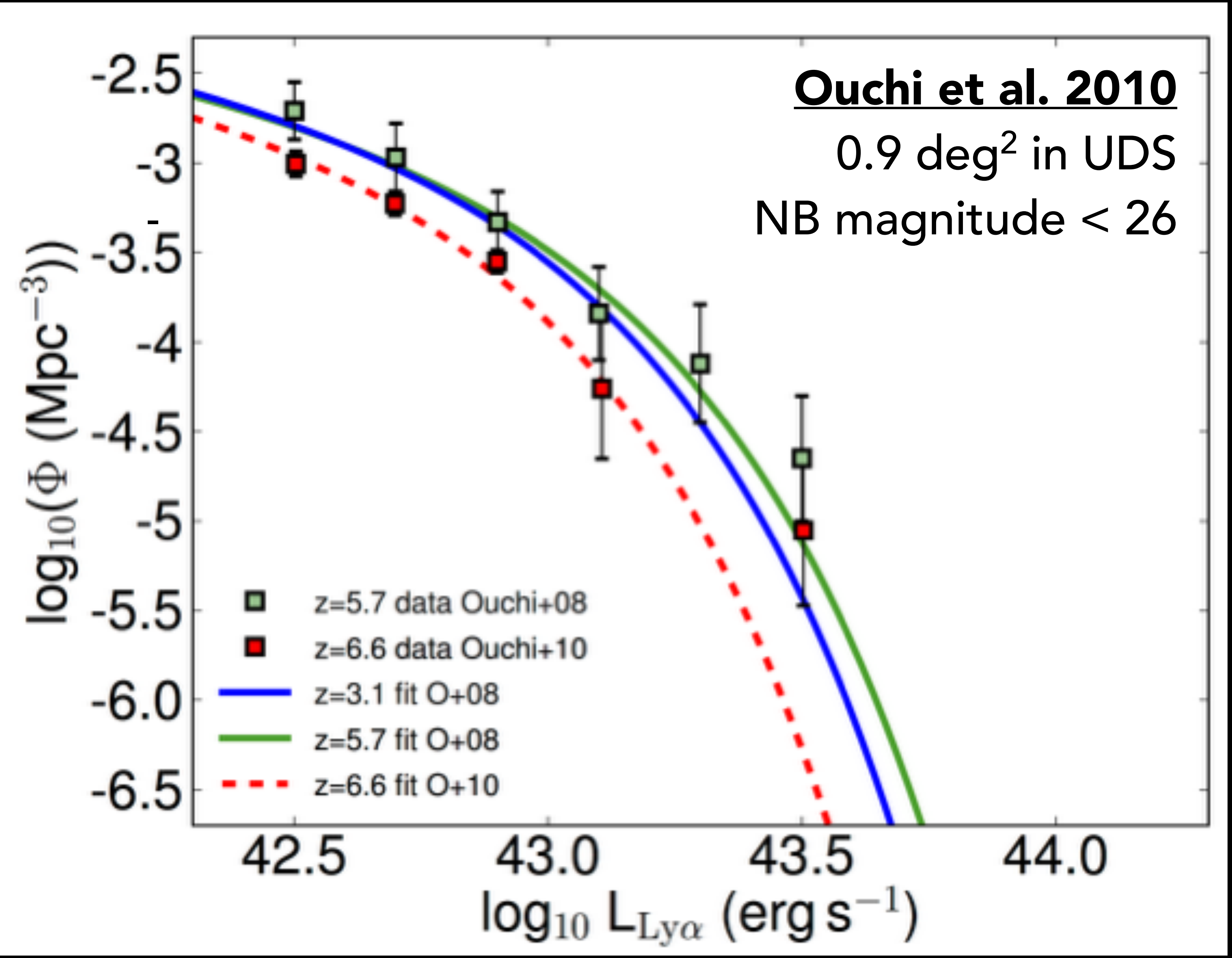


Bowler et al. 2014

e.g. Bouwens+15,Atek+15

see e.g. talk by: Silvio Lorenzoni

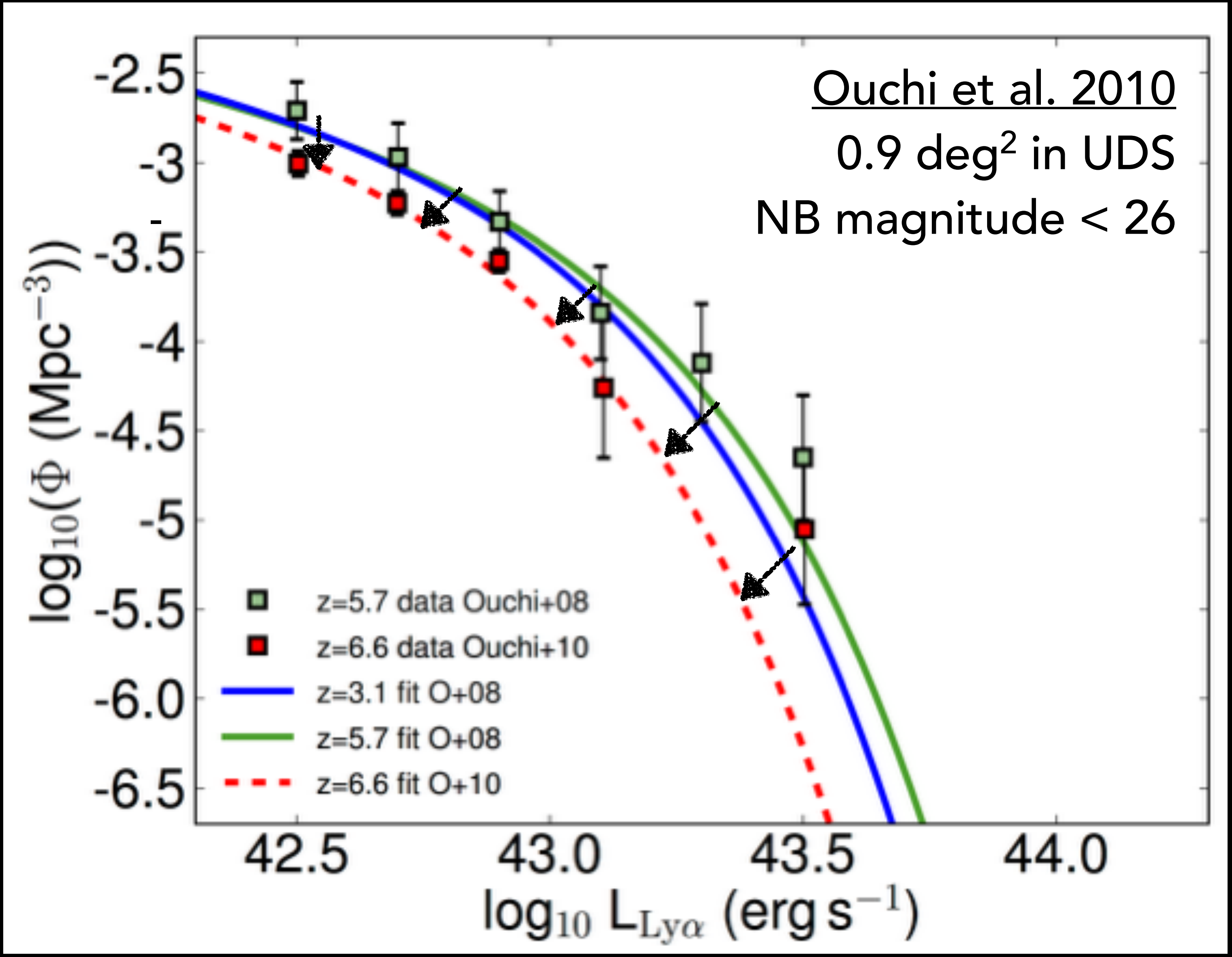
Lyman-α Luminosity function z~3-6 roughly constant



Lyman-α Luminosity function at z=6.6

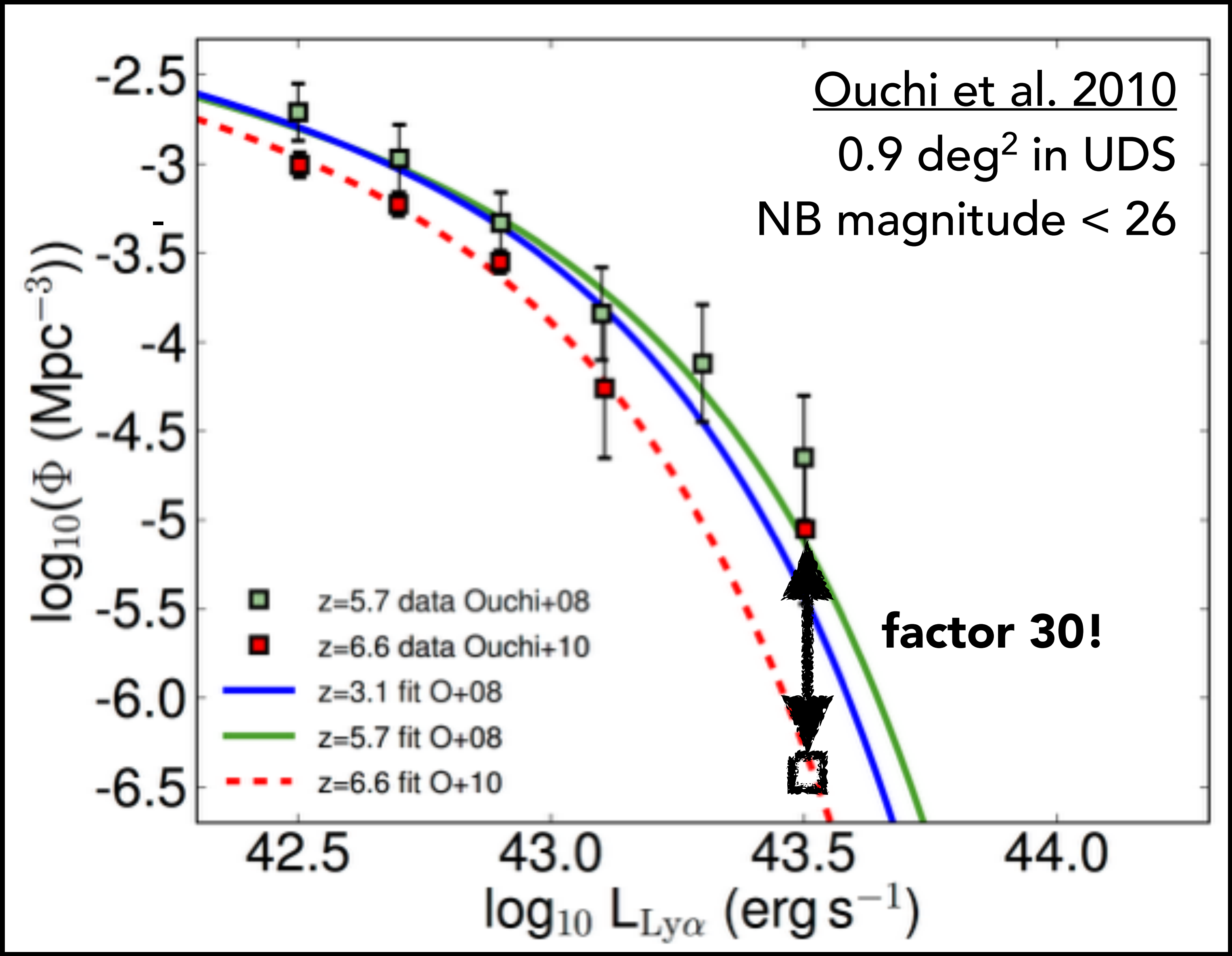
Re-ionisation not complete?

Evolution at all Luminosities (?)



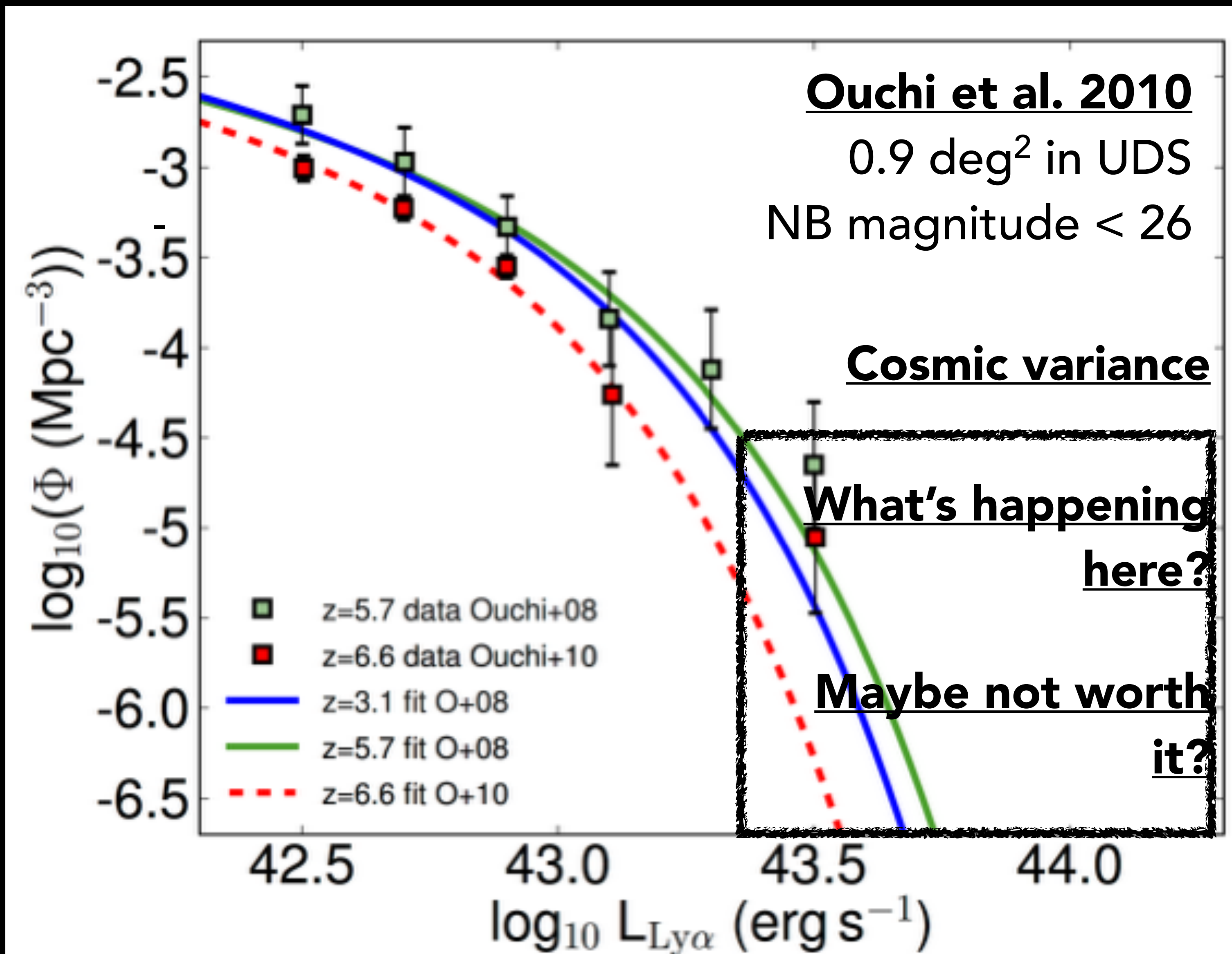
Lyman-α Luminosity function at z=6.6

Surveys limited by cosmic variance (<1deg²)



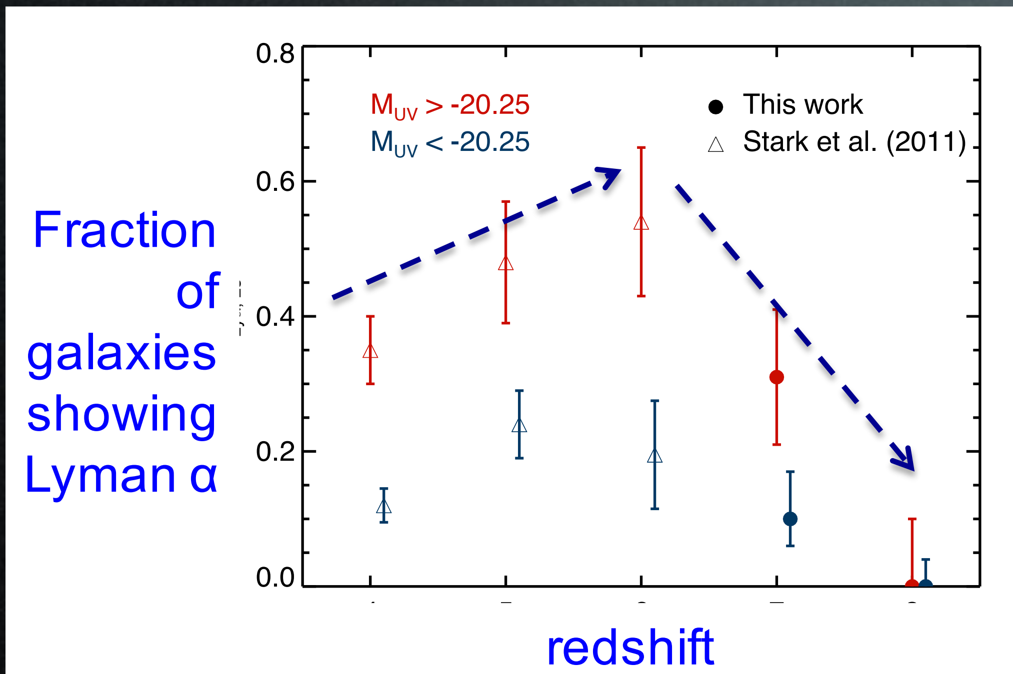
see also: Bowler et al. 2012, 2014

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

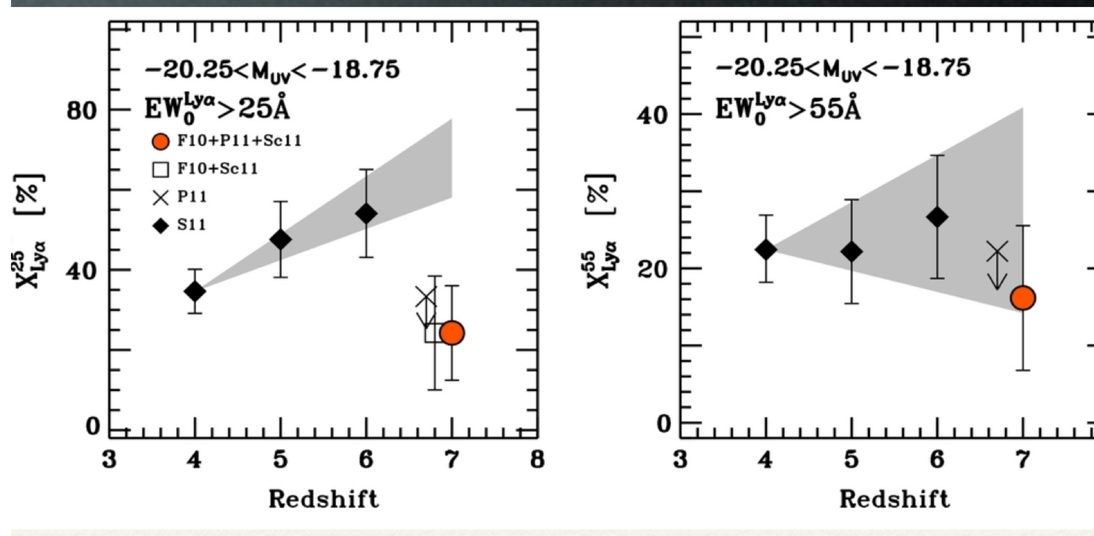


see also: Bowler et al. 2012, 2014

- # Decline Lyman-α fraction of (“well-behaved” SED) UV/LBG selected galaxies



see e.g. talk by: Eros Vanzella

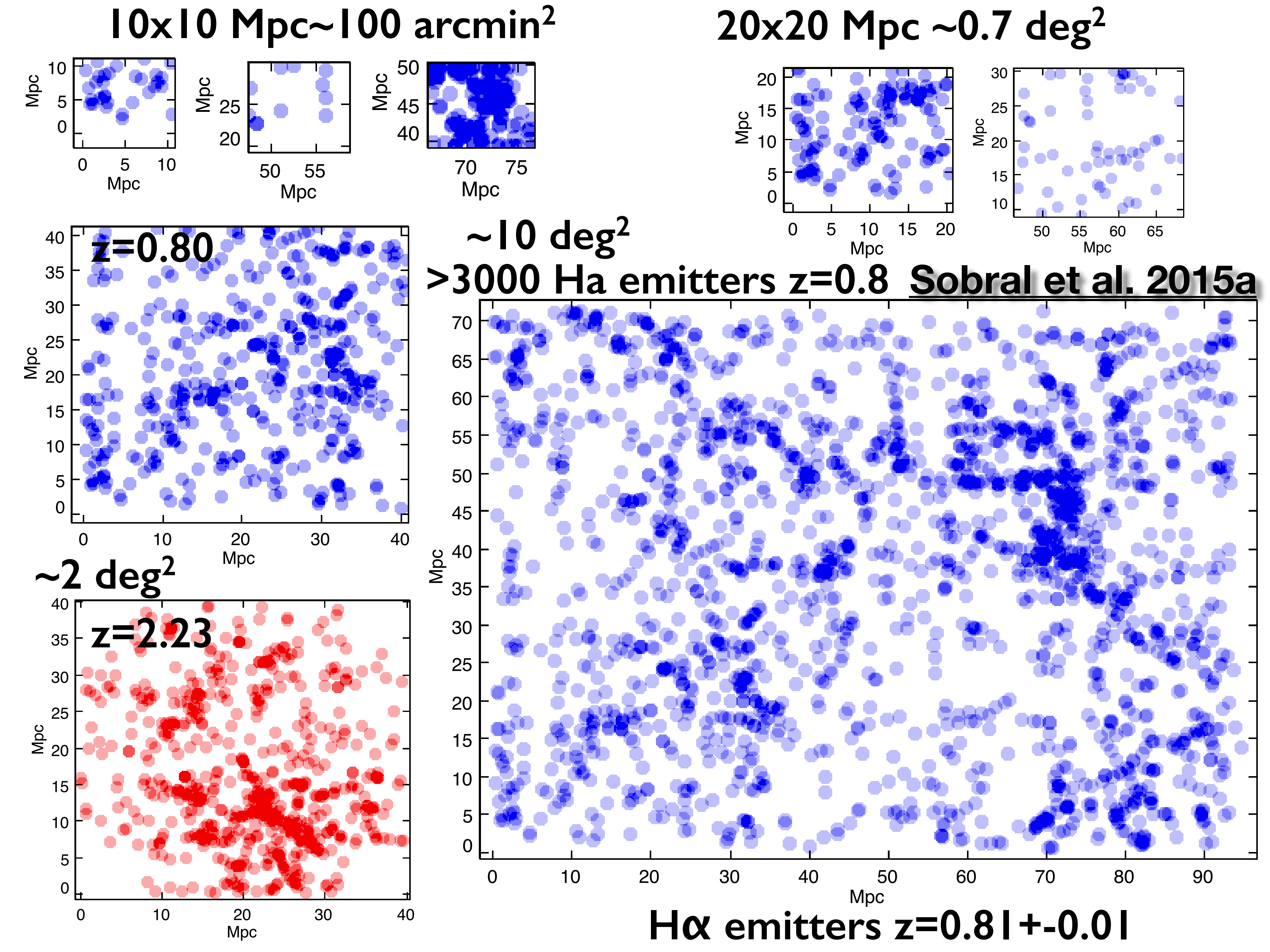


Schenker et al (2014) – Keck MOSFIRE + UDF, CLASH 7<z<8.2
Treu et al (2013) – Keck MOSFIRE + BoRG z~8
Finkelstein et al (2013) – Keck MOSFIRE + CANDELS z > 7
Pentericci et al (2014) – VLT FORS 6<z<7.3

- **But how much is this real/representative and how much is driven by biases?**

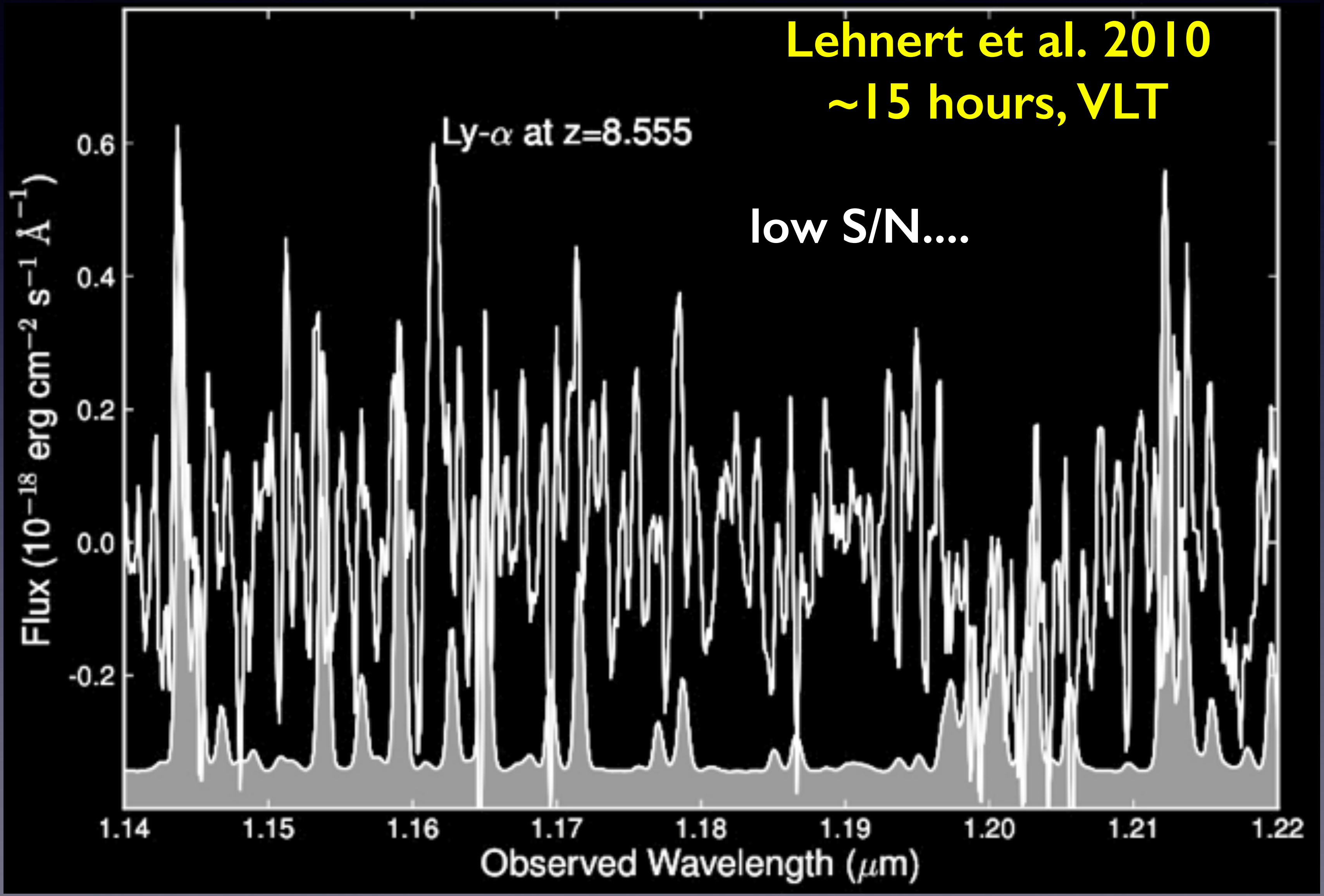
Key things to address

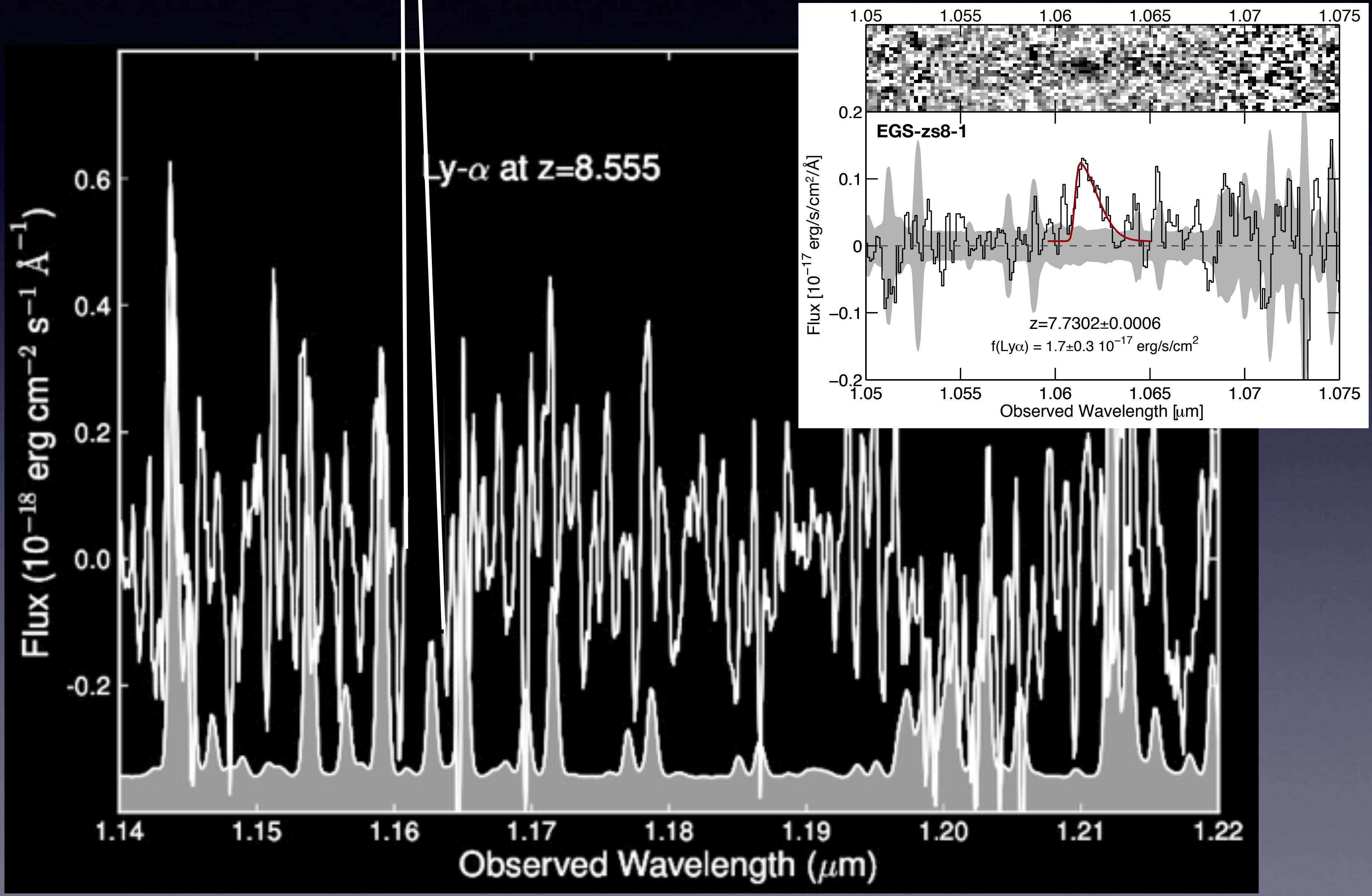
- Need much larger (and multiple!) volumes. Most luminous sources may be visible much earlier on (first ionised bubbles?)
- Need to spectroscopically confirm the results
- Find the most luminous sources: allowing for actual detailed studies to be conducted without having to wait for JWST and/or E-ELT.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


10x10 Mpc~100 arcmin²
20x20 Mpc ~0.7 deg²
~10 deg²
>3000 Ha emitters z=0.8
Sobral et al. 2015a
z=0.80
~2 deg²
z=2.23
Hα emitters z=0.81+-0.01
Mpc

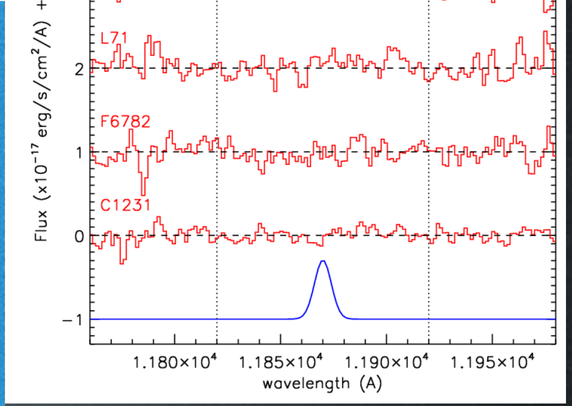
The big advantage for spectroscopic follow-up is that they will <u>*not*</u> look like this:

(see Bunker et al. 2013)





Spectroscopic follow-up is absolutely crucial!!!



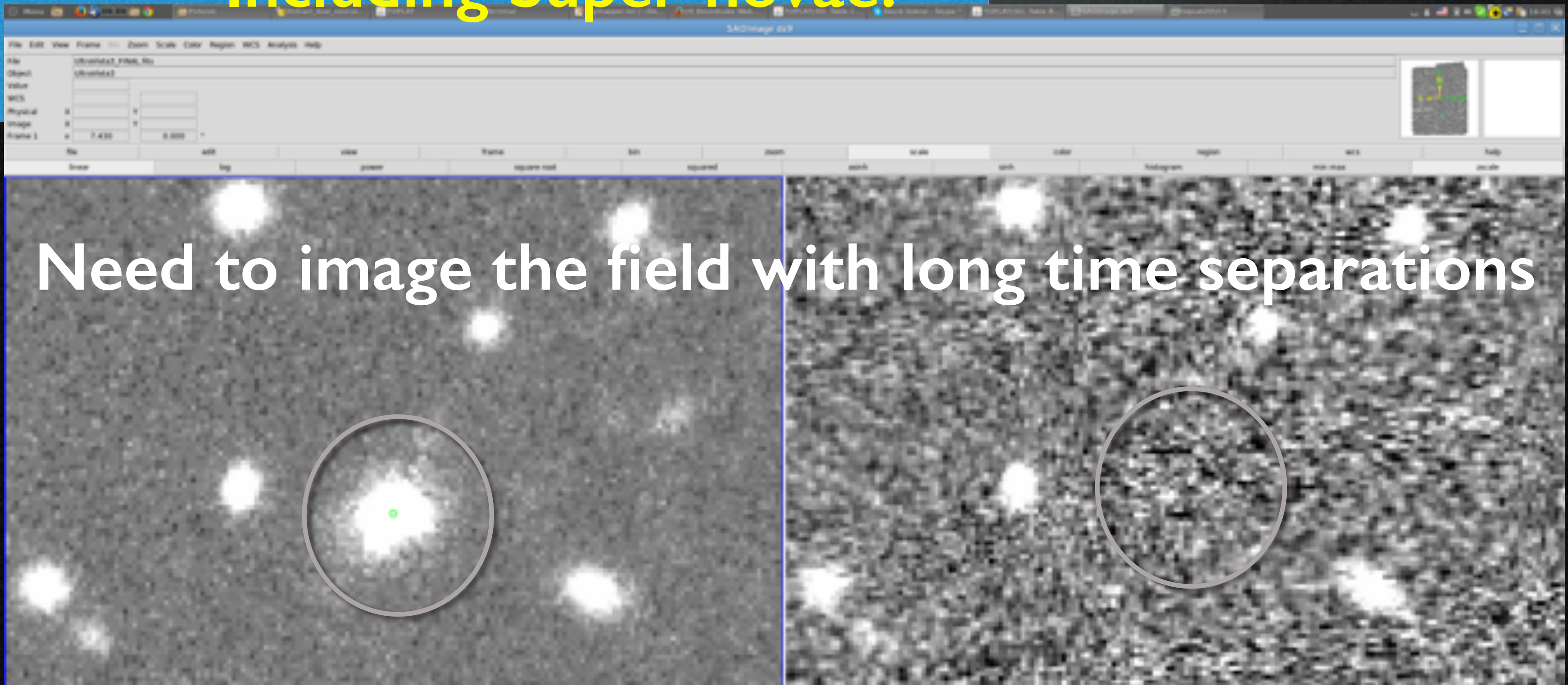
variable sources

~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

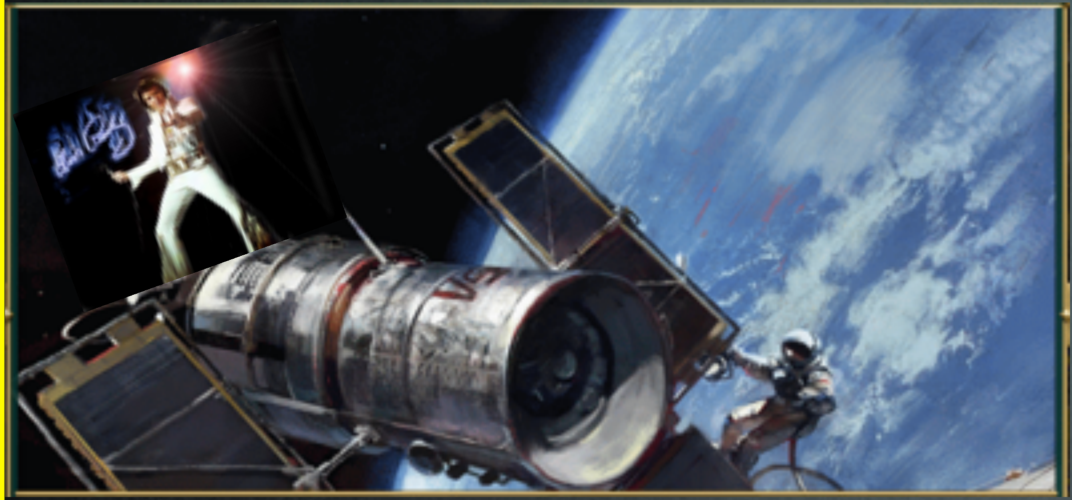
MUSE x100 pointings

Our approach explores uniqueness of narrow-band surveys: super-wide

CFHT+INT+S-cam+VST +WHT+HSC+VISTA

Largest Lya surveys 2<z<8

(still detect galaxies >25-26 in J)



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

CFHT+INT+S-cam+VST +WHT+HSC+VISTA

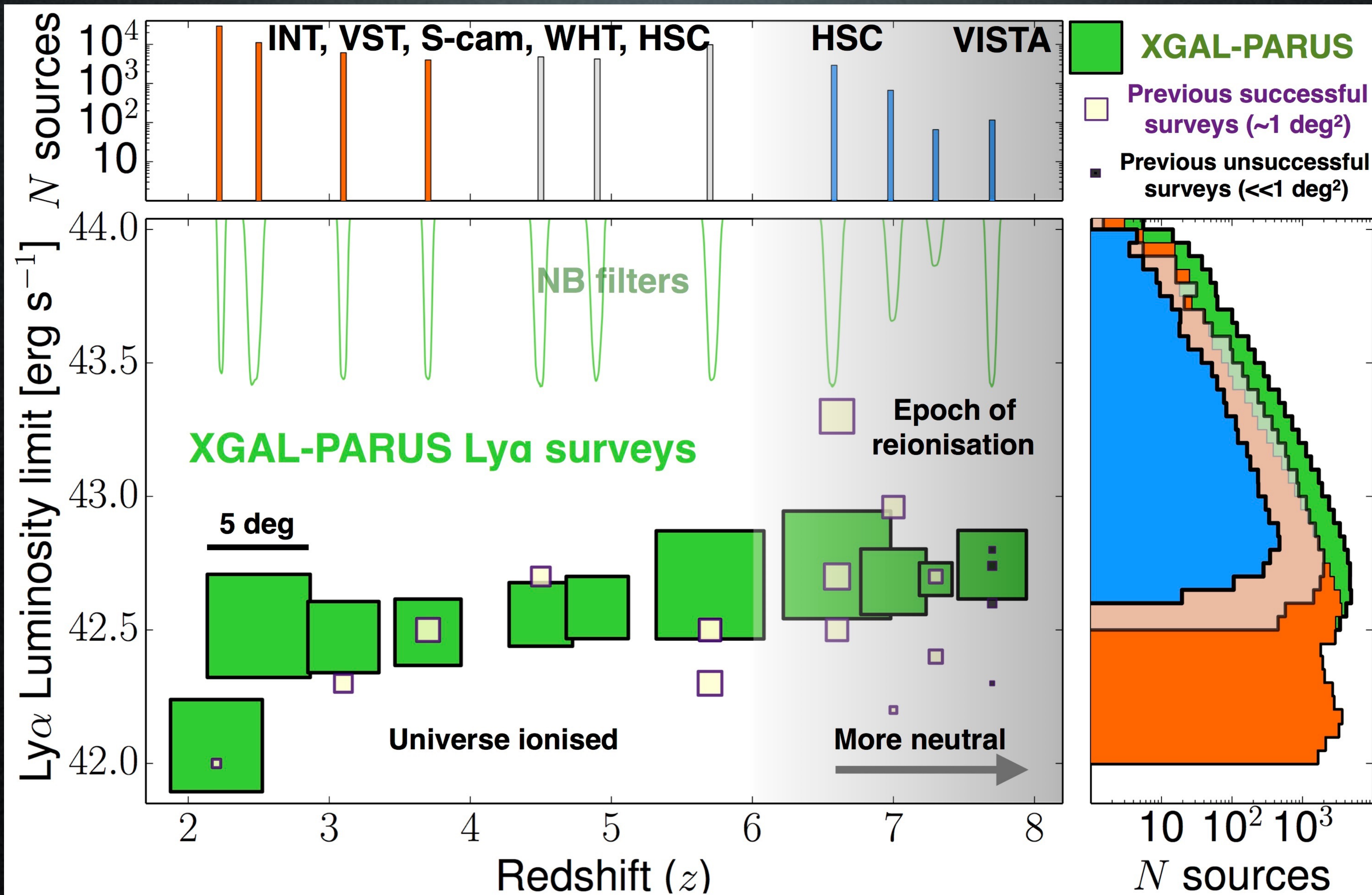
Largest Lya surveys 2<z<8

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

Our on-going and planned surveys

Largest Lyα surveys 2<z<8

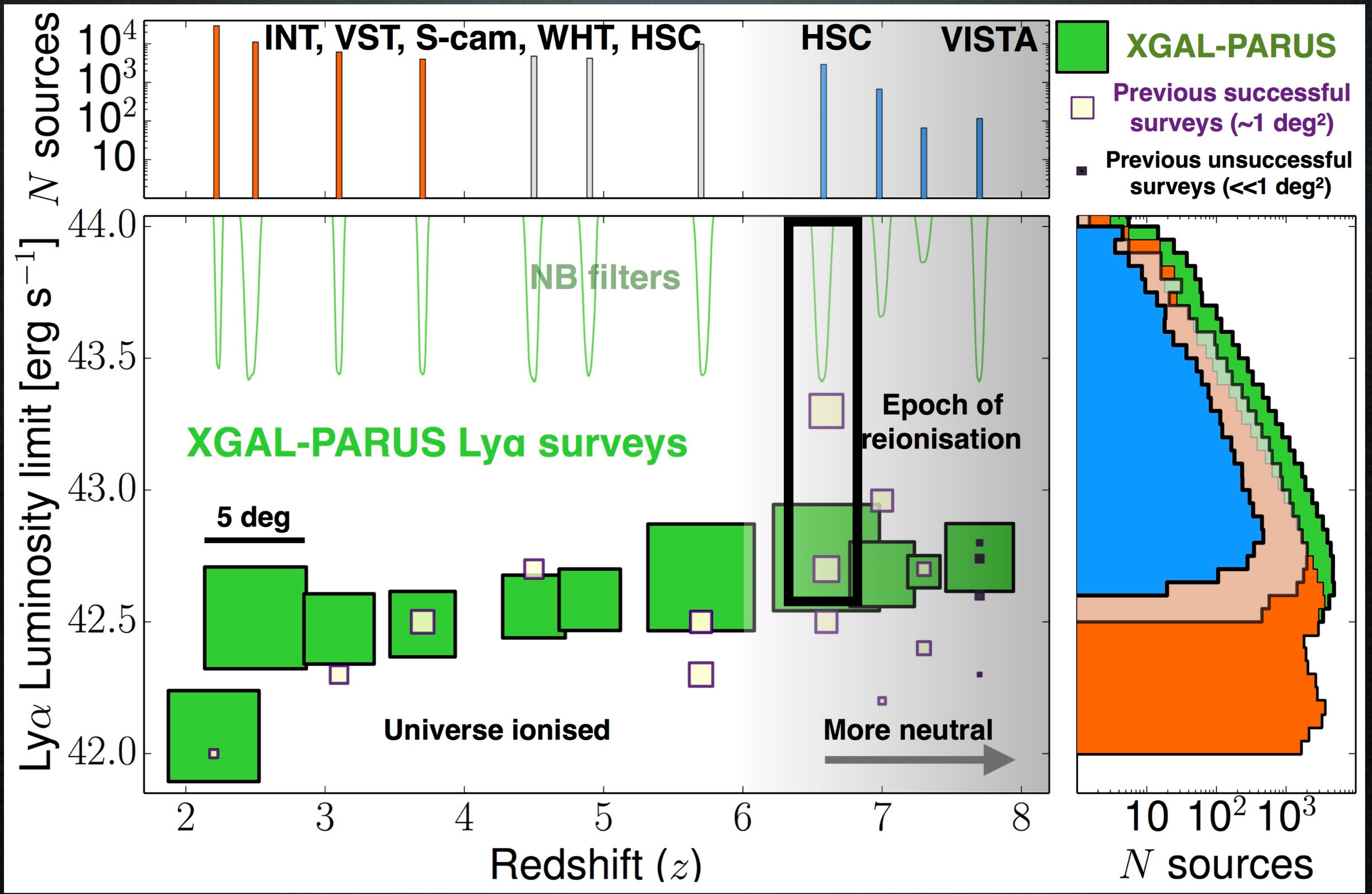
PI: Sobral



Our on-going and planned surveys

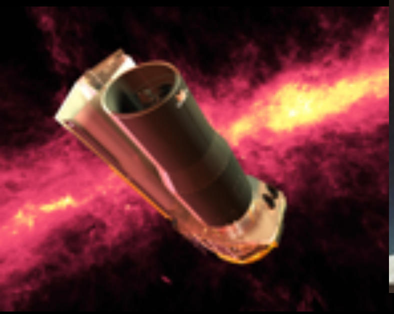
Largest Lyα surveys 2<z<8

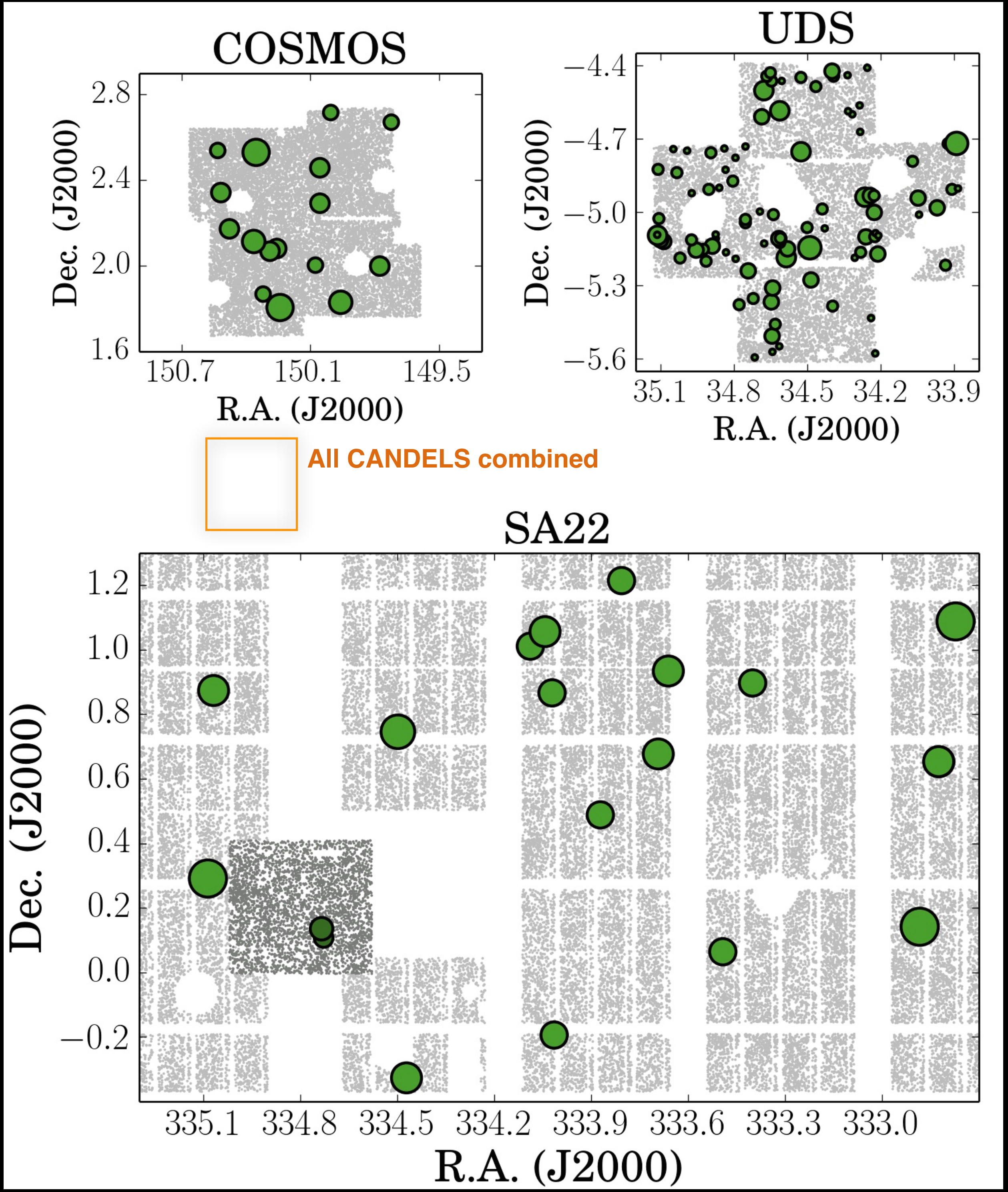
PI: Sobral



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

Subaru survey (PI: Sobral)





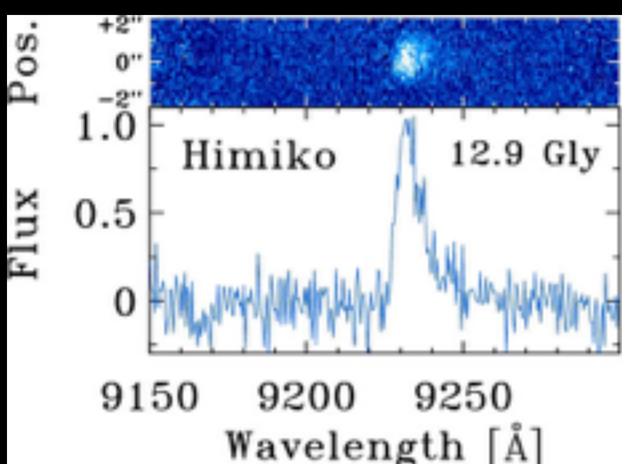
Results:

99 LAEs in UDS

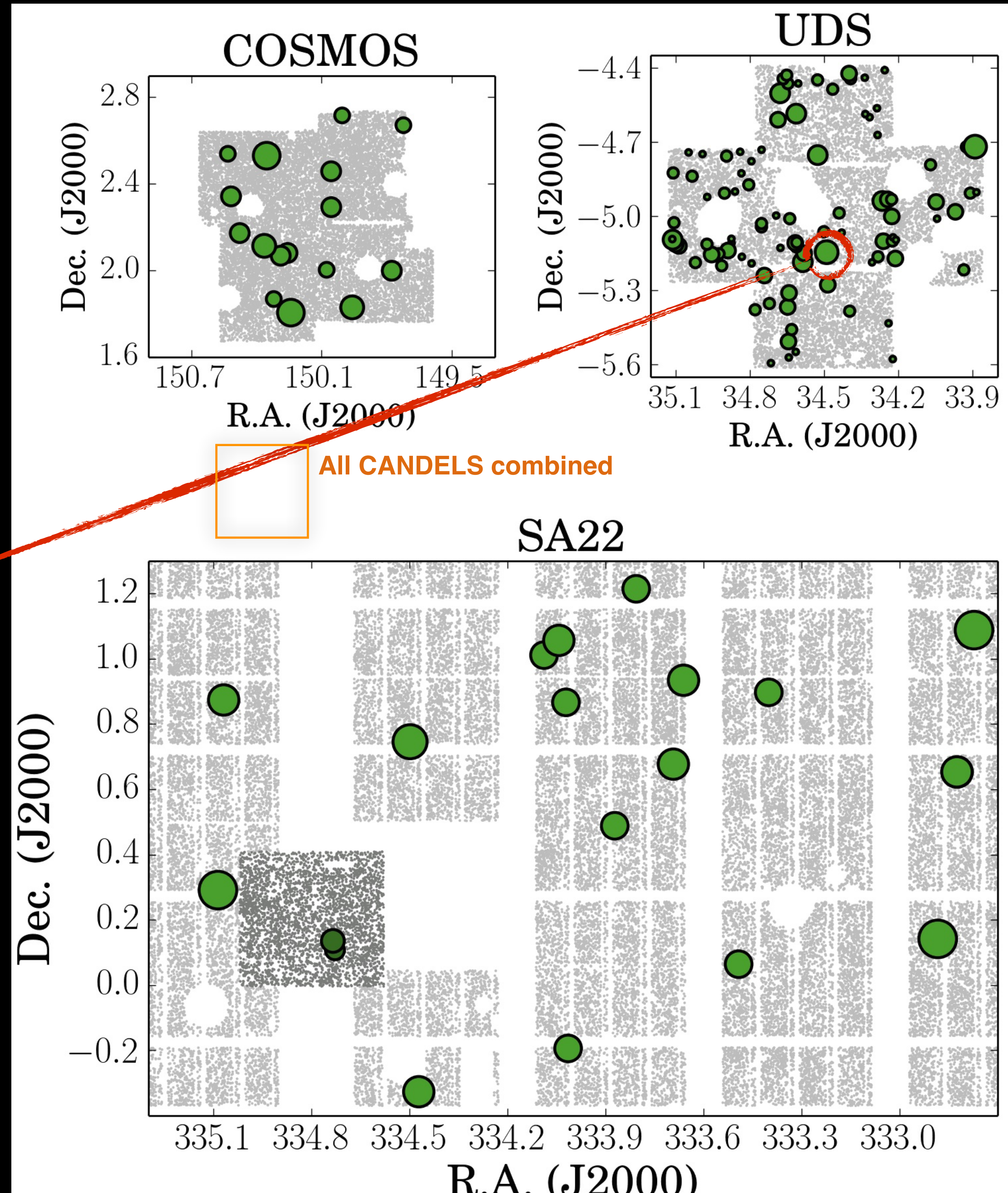
15 LAEs in COSMOS

2 LAEs in SA22-Deep

18 LAEs in SA22-Wide



Ouchi et al. 2009, 2013



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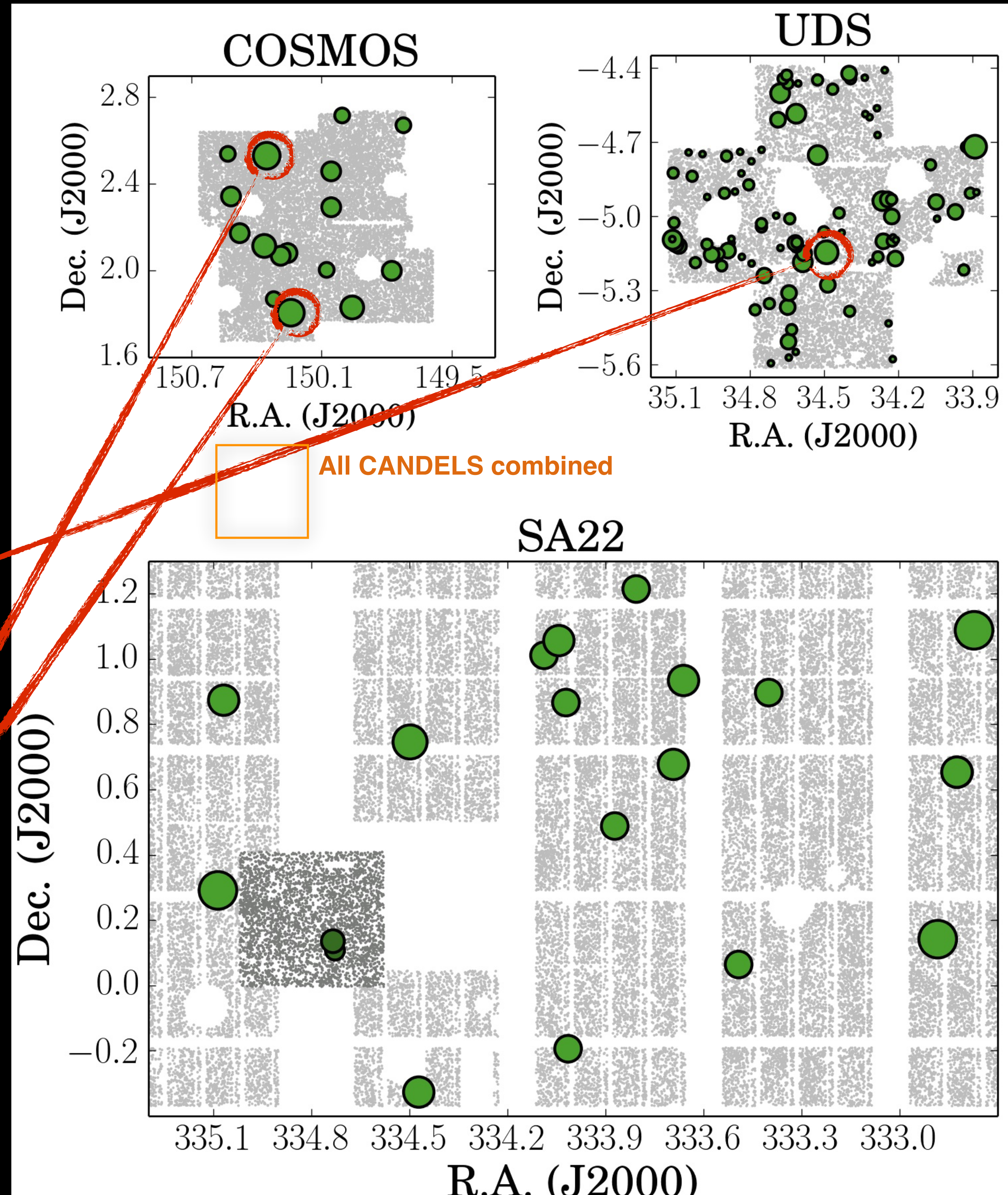

"Himiko"

Even brighter!

Sobral et al. 2015

Results:

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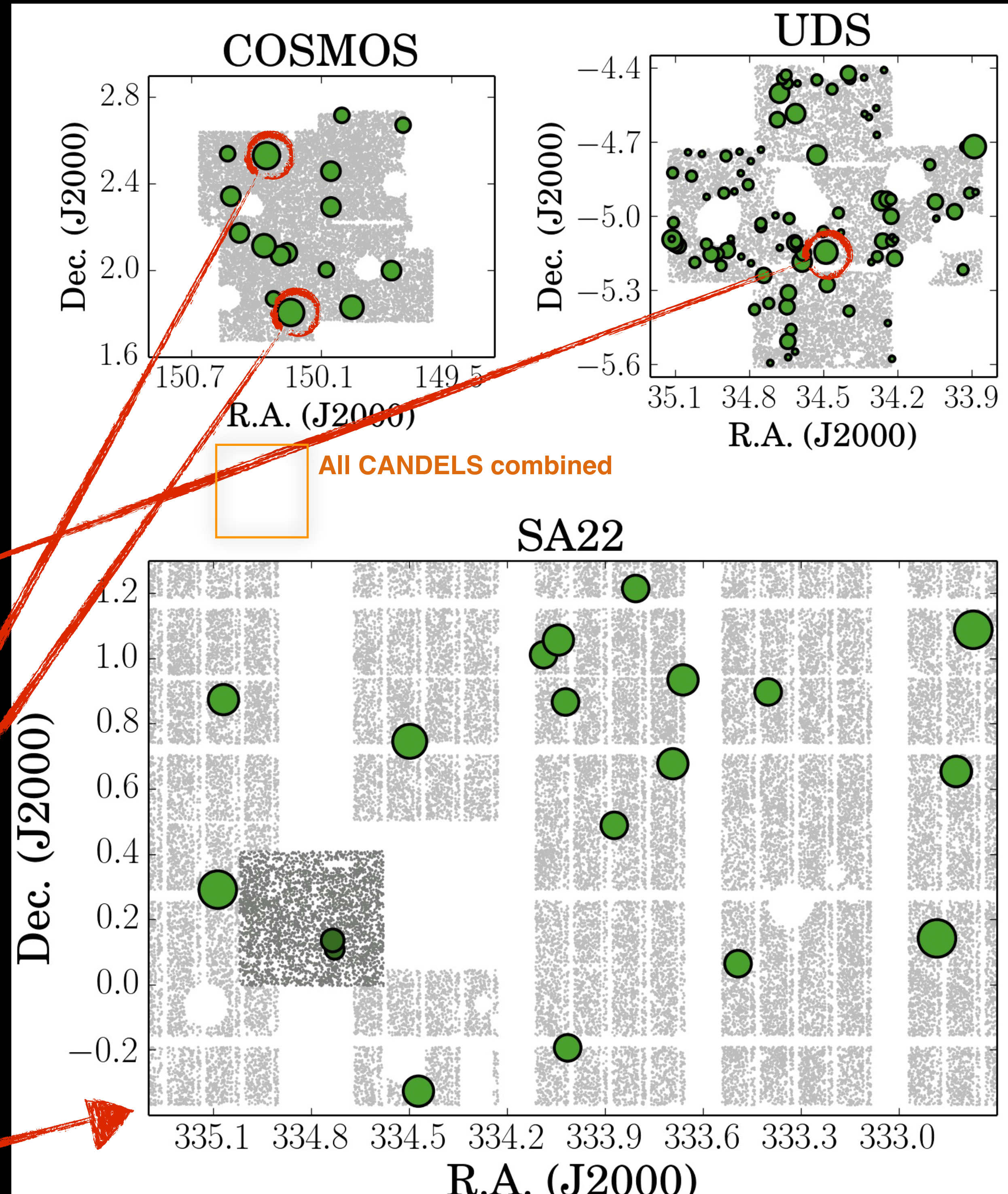


"Himiko"

Even brighter!

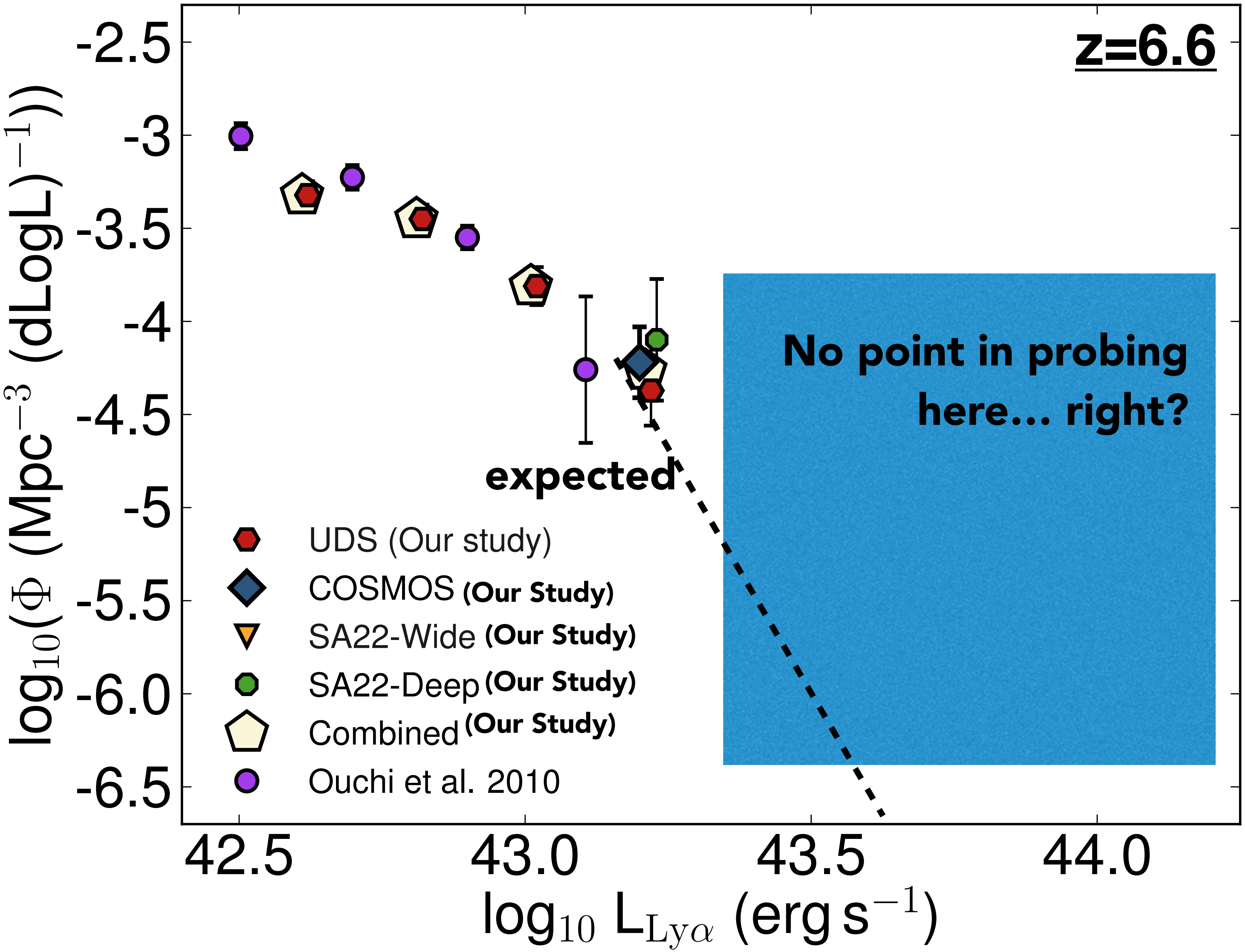
Even brighter! ~20

Confirms number density

Matthee,DS+ et al. 2015

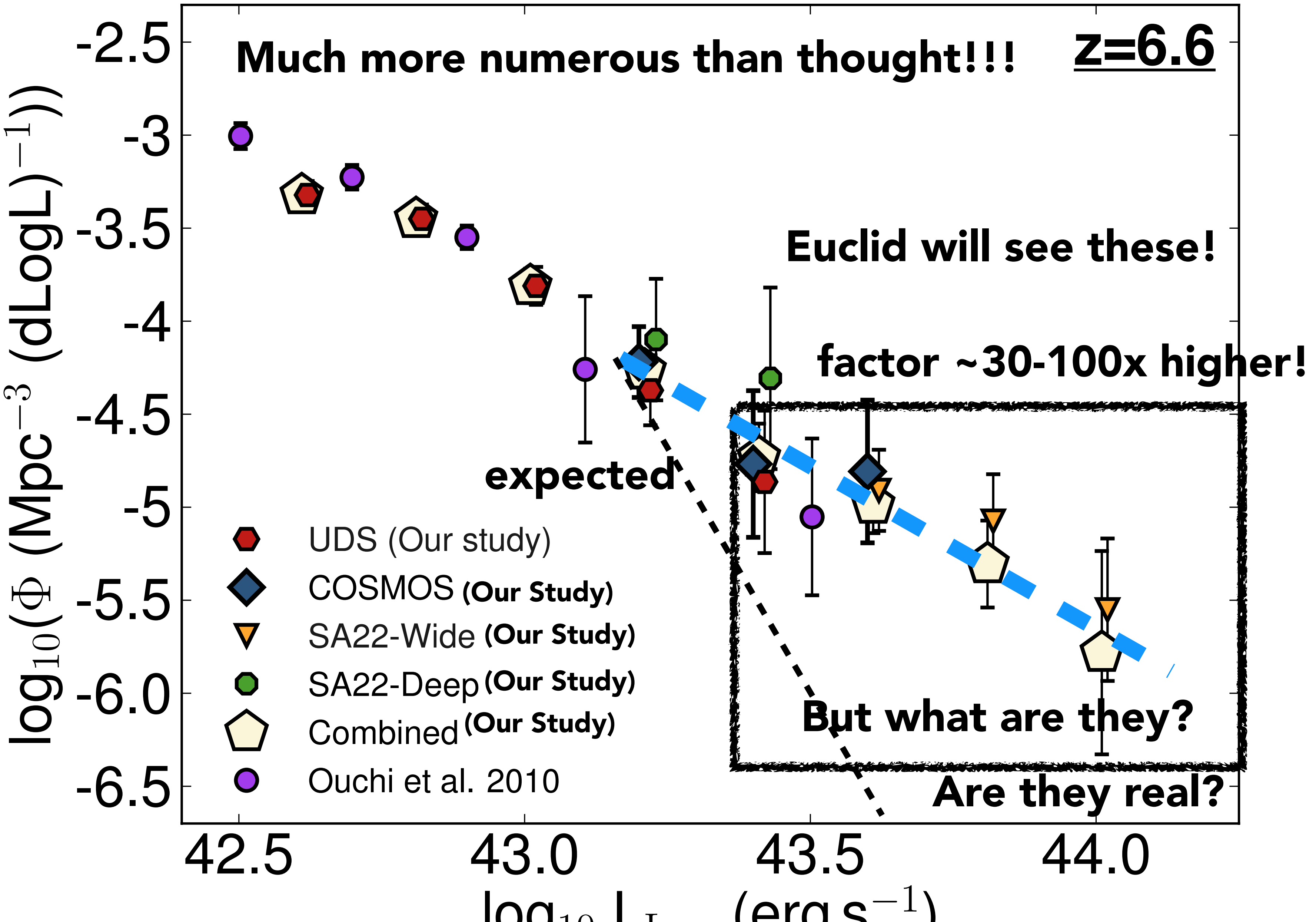
Lyman-α emitters 12.9 Gyrs ago: number counts

Matthee, Sobral et al. 2015



Lyman-α emitters 12.9 Gyrs ago: number counts

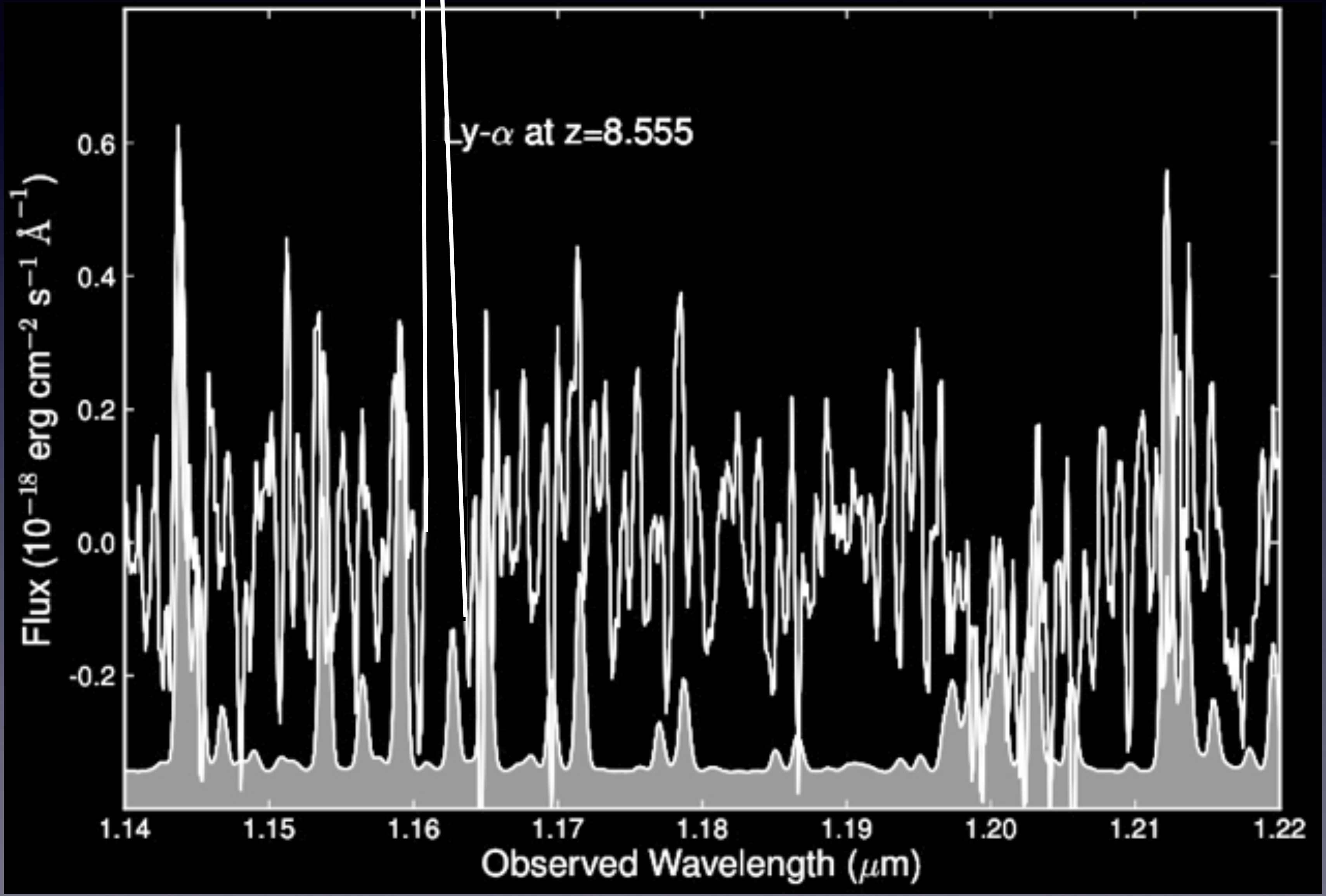
Matthee, Sobral et al. 2015



In ~ couple of hours

So are they like this?

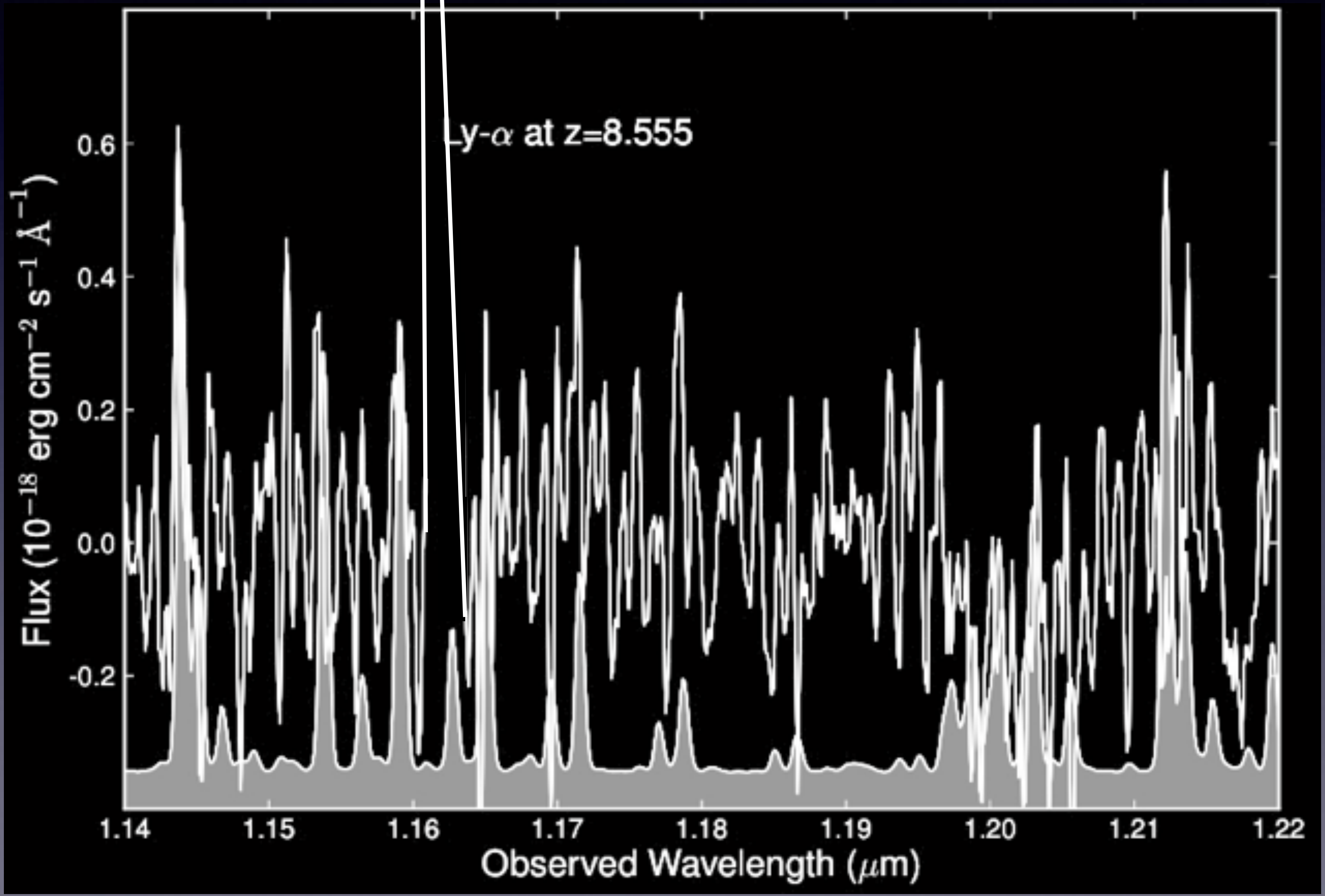
Are they real LAEs?



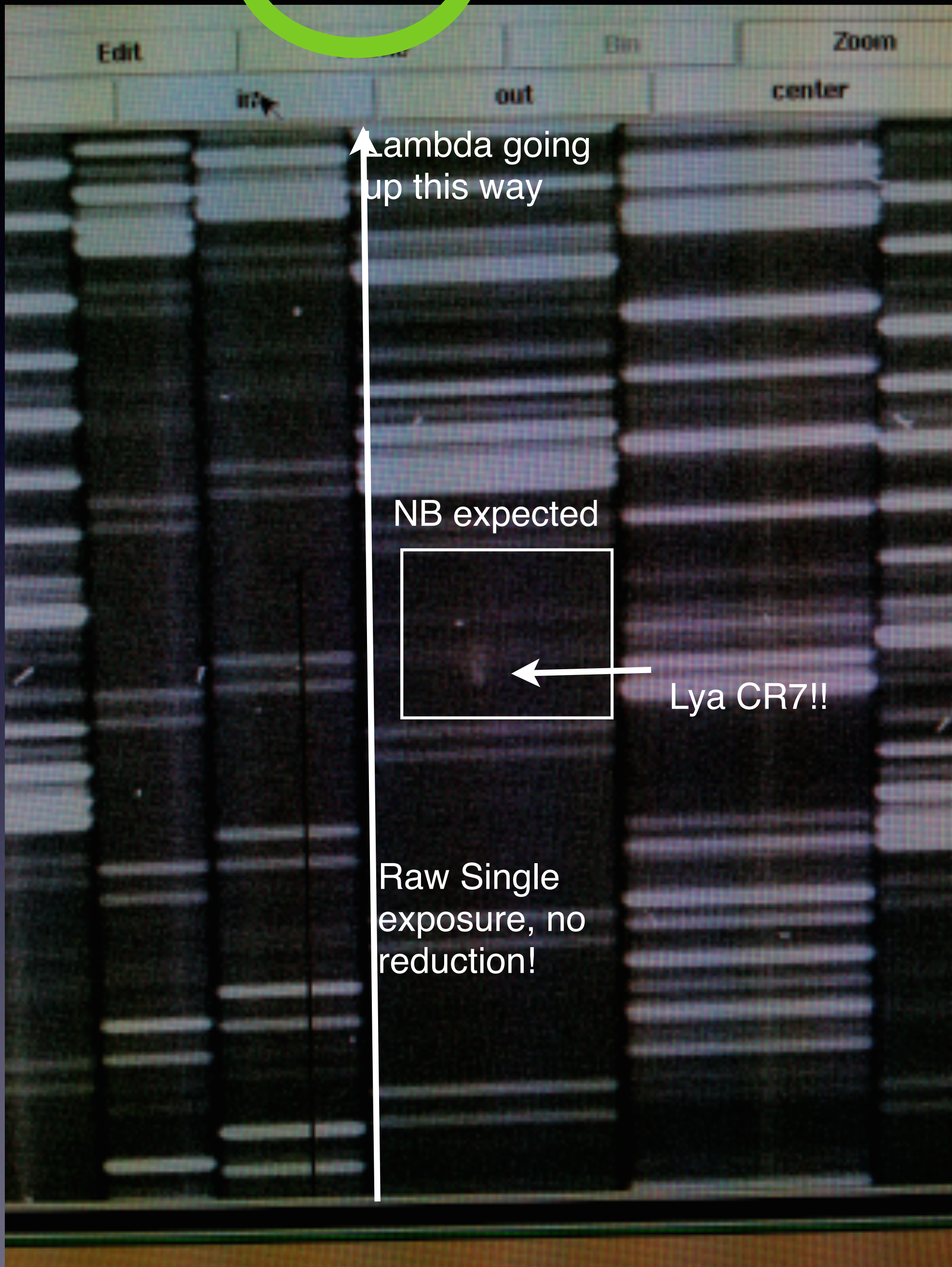
~~In ~ couple of hours~~

So are they like this?

Are they real LAEs?

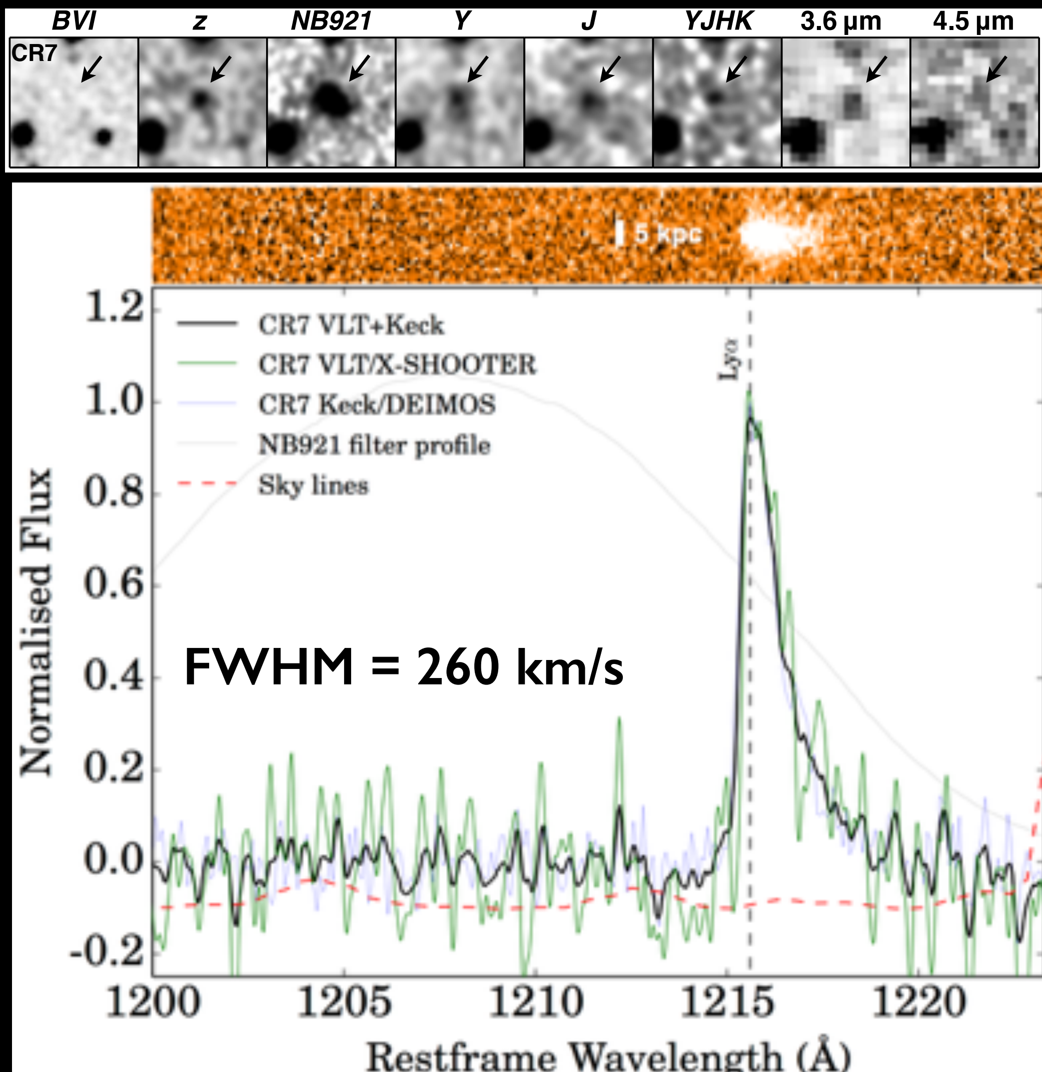


15 min z=6.6

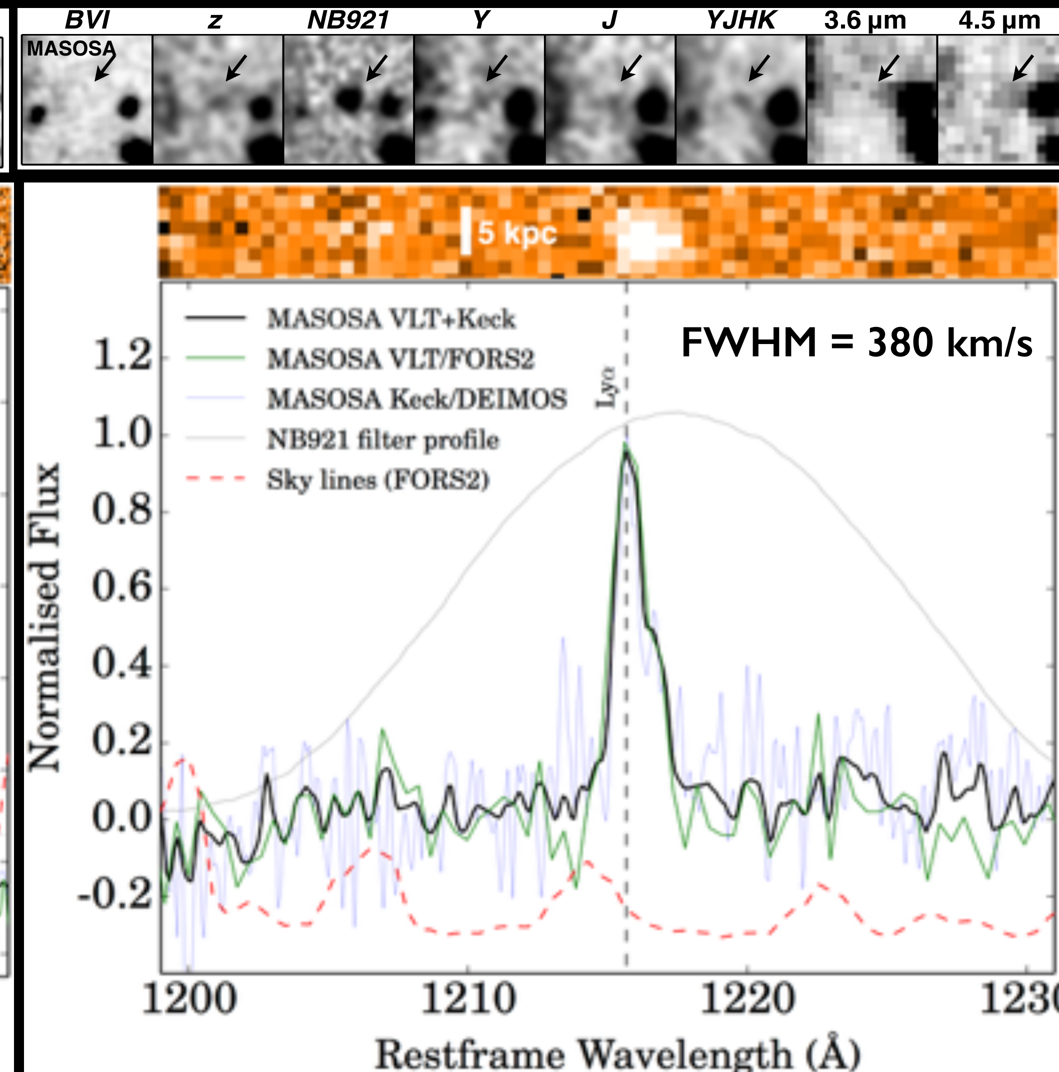


Spectroscopic confirmation with Keck/DEIMOS

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

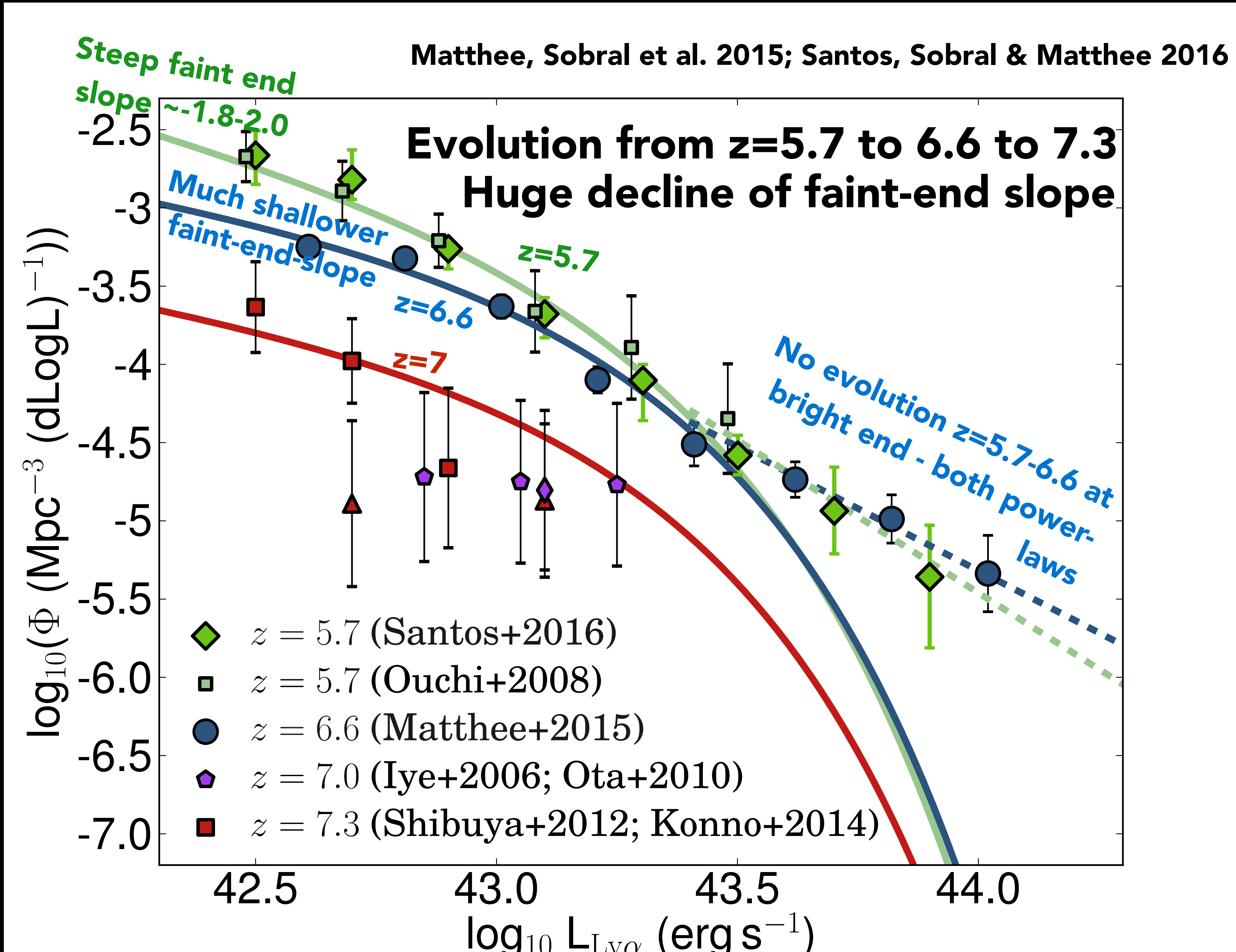


VLT/X-Shooter + Keck/DEIMOS (~3.8 hours)

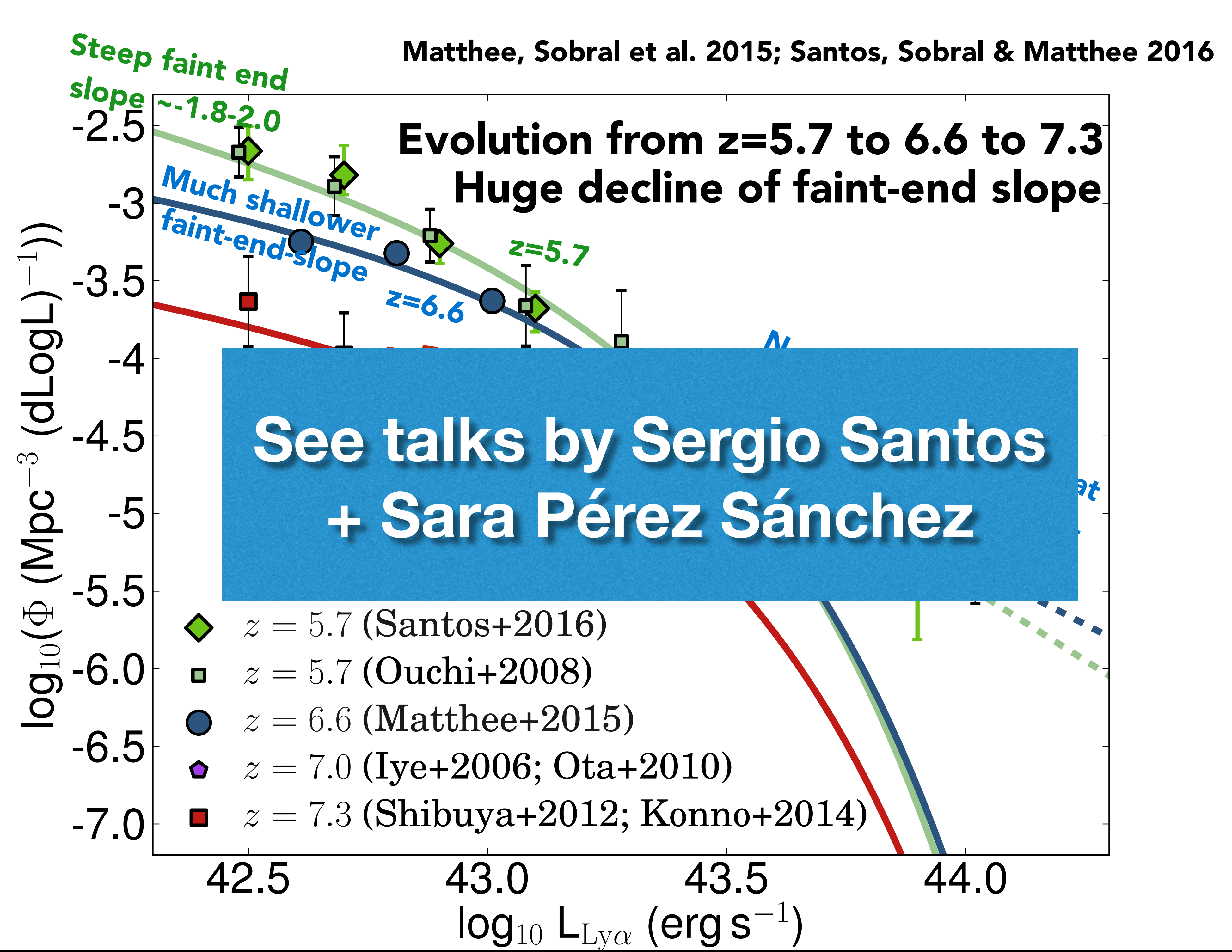


VLT/FORS2 + Keck/DEIMOS (~2.4 hours)

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



Matthee, Sobral et al. 2015; Santos, Sobral & Matthee 2016
Evolution from z=5.7 to 6.6 to 7.3
Huge decline of faint-end slope
Steep faint end slope ~-1.8-2.0
Much shallower faint-end-slope
z=5.7
z=6.6
z=7
No evolution z=5.7-6.6 at bright end - both power-laws
$z = 5.7$ (Santos+2016)
$z = 5.7$ (Ouchi+2008)
$z = 6.6$ (Matthee+2015)
$z = 7.0$ (Iye+2006; Ota+2010)
$z = 7.3$ (Shibuya+2012; Konno+2014)
$\log_{10}(\Phi\ (\mathrm{Mpc}^{-3}\ (\mathrm{dLogL})^{-1}))$
$\log_{10} L_{\mathrm{Ly}\alpha}\ (\mathrm{erg\,s^{-1}})$
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6.0
-6.5
-7.0
42.5
43.0
43.5
44.0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z=5.7
z=6.6
See talks by Sergio Santos
+ Sara Pérez Sánchez
$z = 5.7$ (Santos+2016)
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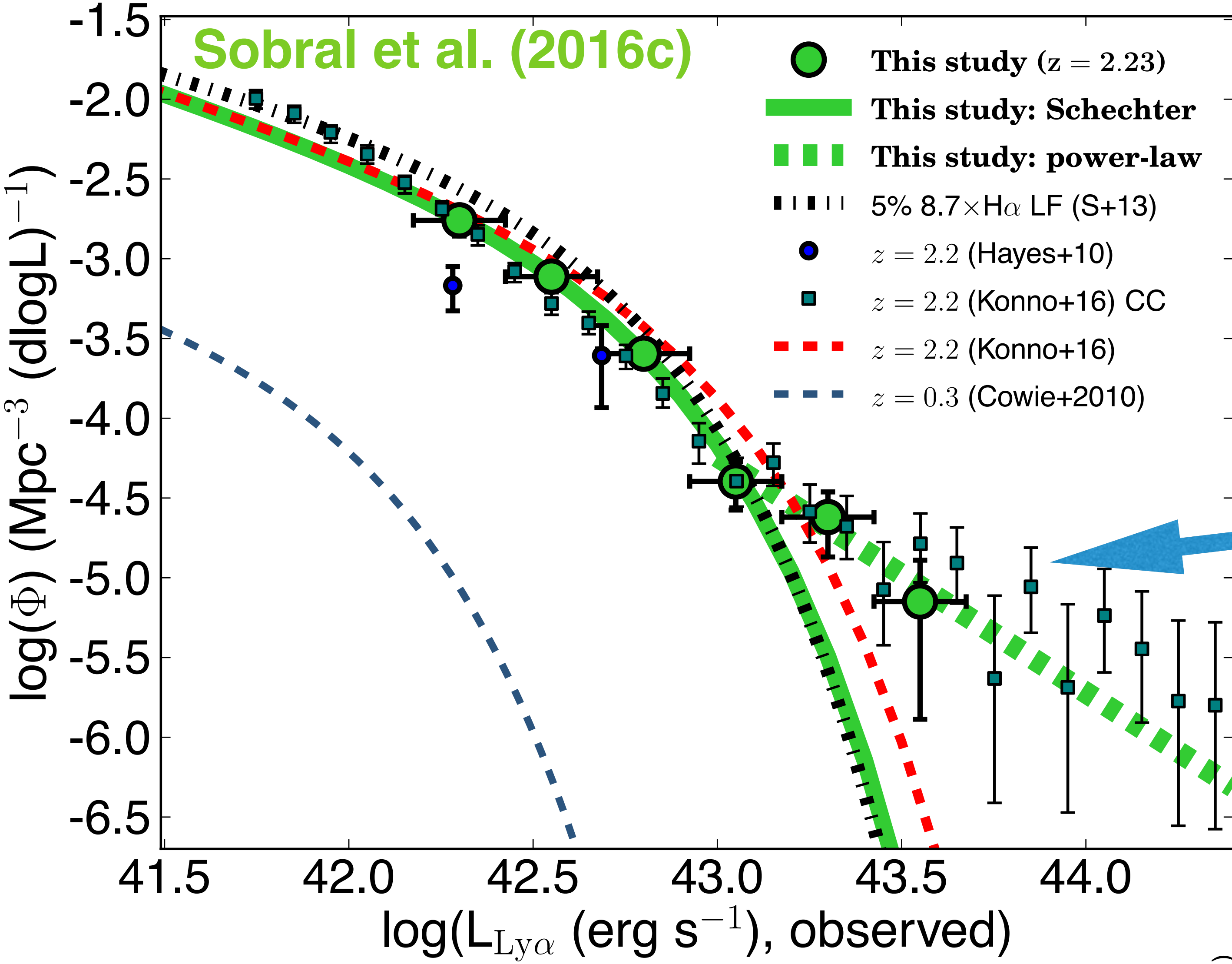
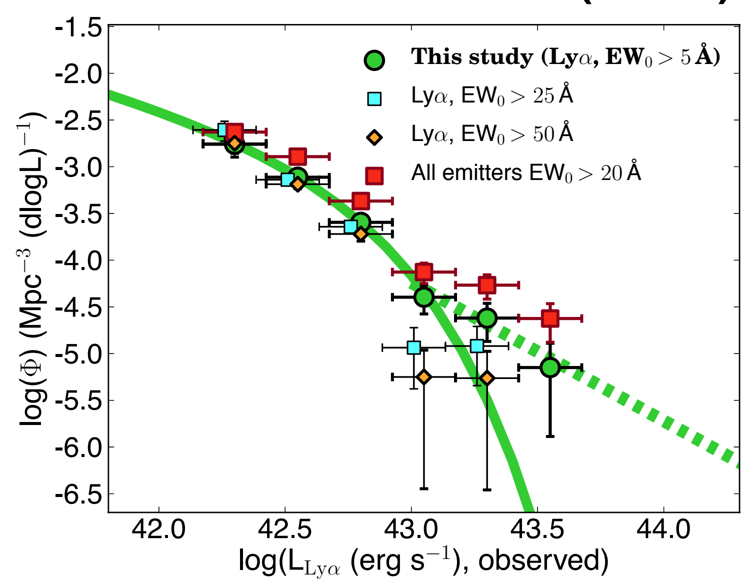
$\log_{10}(\Phi\ (\mathrm{Mpc}^{-3}\ (\mathrm{dLogL})^{-1}))$
$\log_{10}\ L_{\mathrm{Ly}\alpha}\ (\mathrm{erg\,s^{-1}})$
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6.0
-6.5
-7.0
42.5
43.0
43.5
44.0



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

Very wide surveys will find many more sources than expected!

Sobral et al. (2016c)



"Traditional" ways of selecting Lyα emitters lead to missing most real bright Lyα and introduce contaminants at bright end

What is the nature of these luminous Lyα emitters?

Uniqueness: we can go beyond just getting a redshift

Unique opportunity: follow-up

What is the nature of CR7?

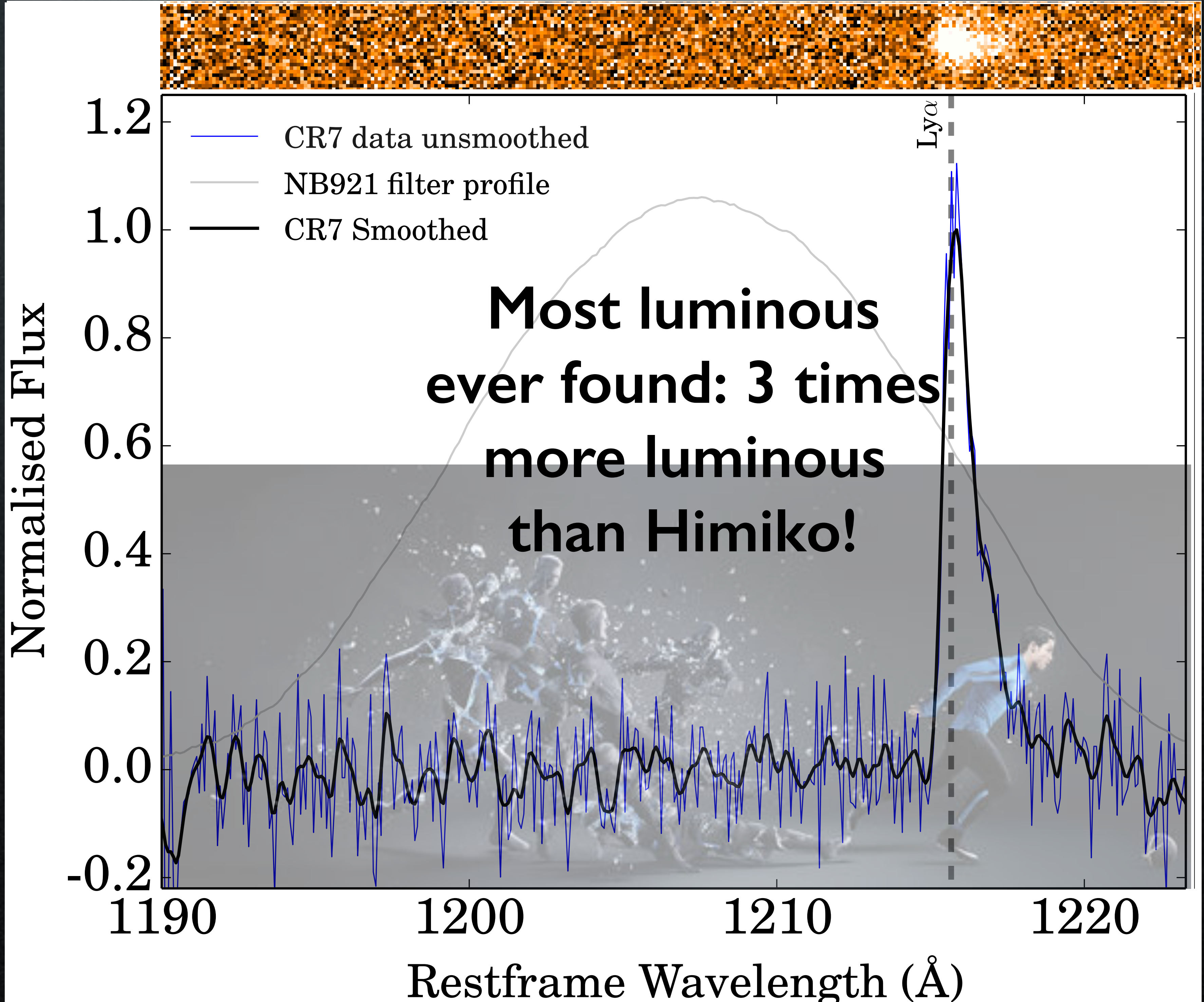
Lyα

Keck/ DEIMOS

1 hour!

z=6.6

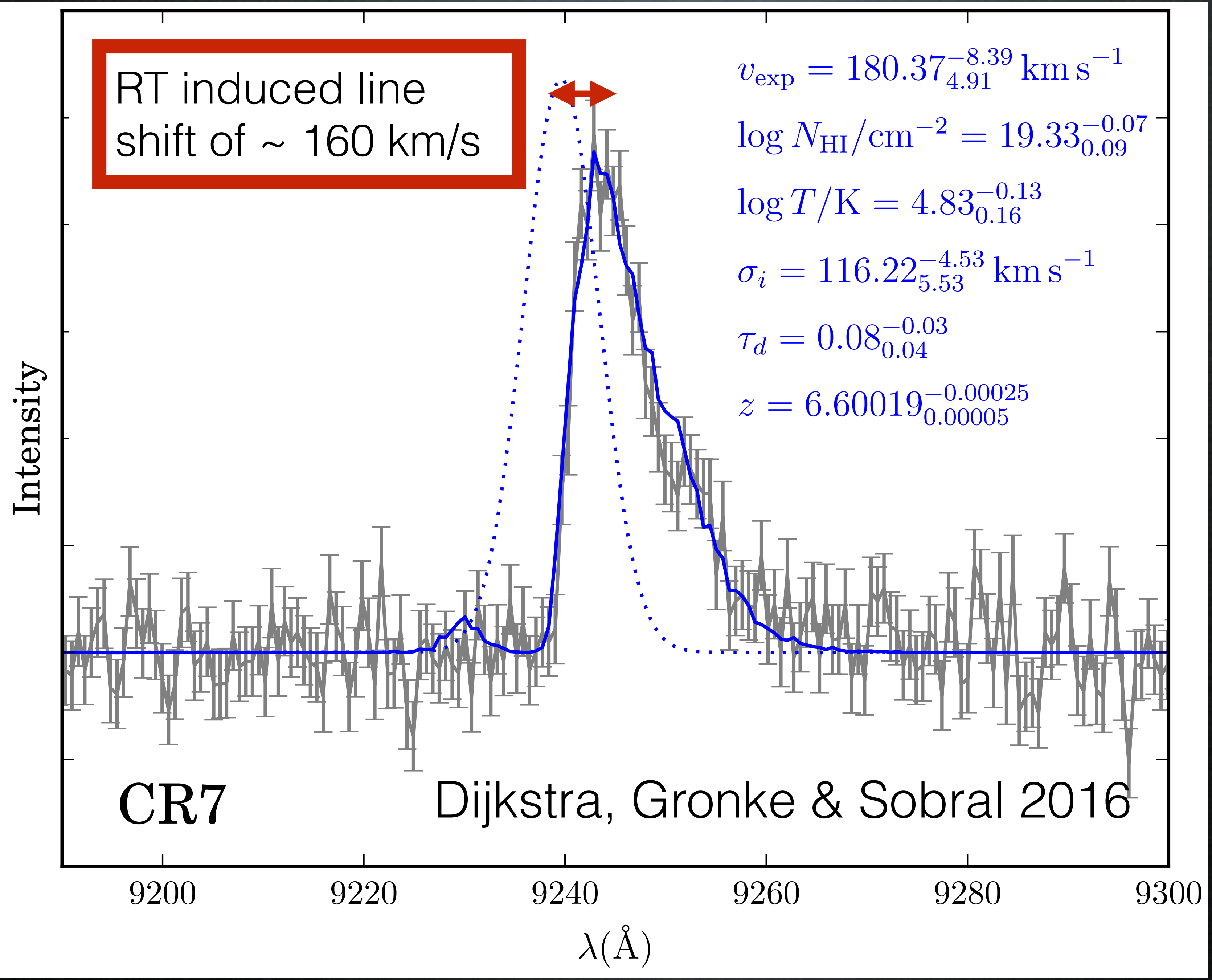
L~10^{44} erg/s/cm^2



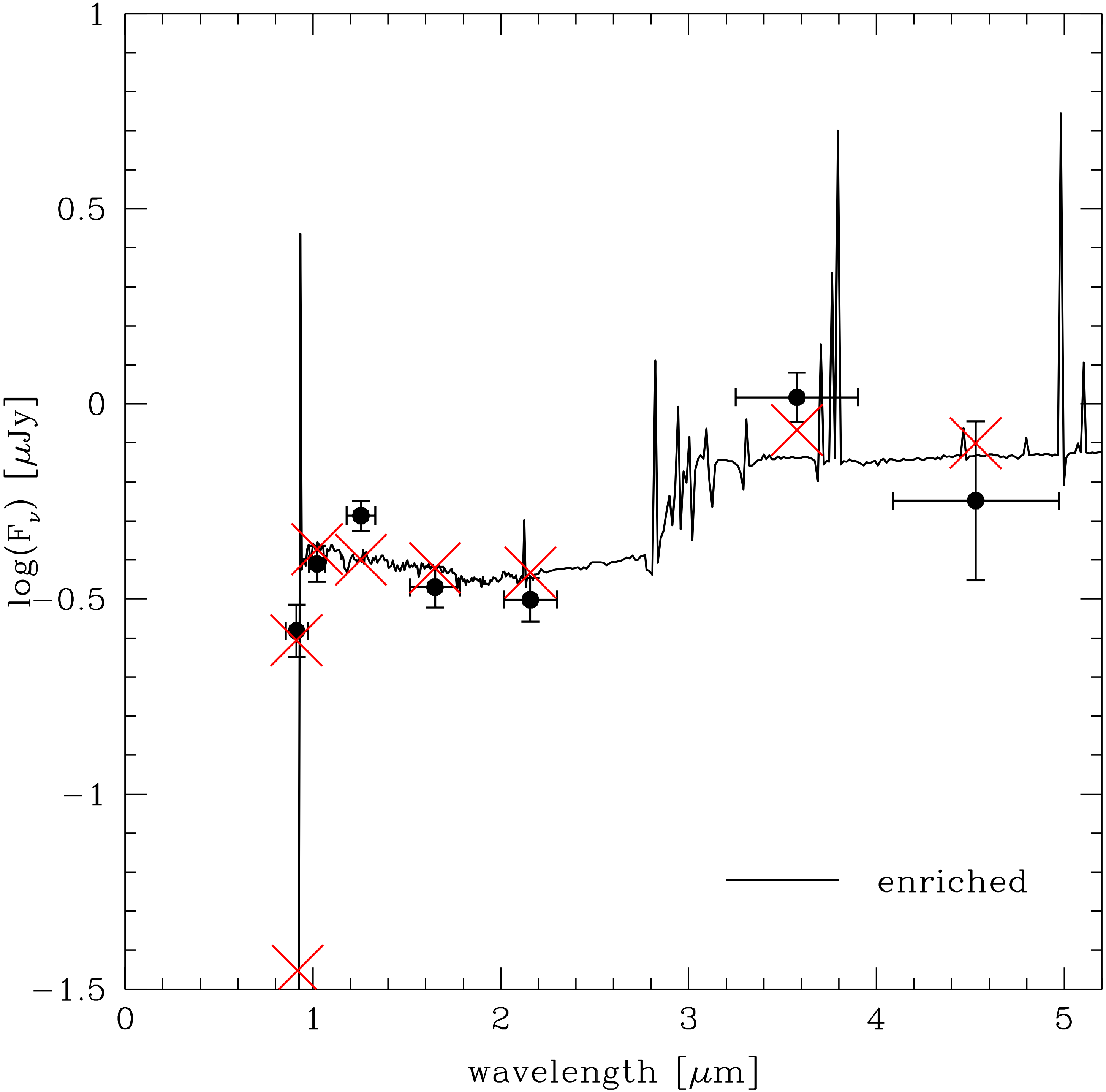
No evidence for AGN

Sobral et al. 2015c.

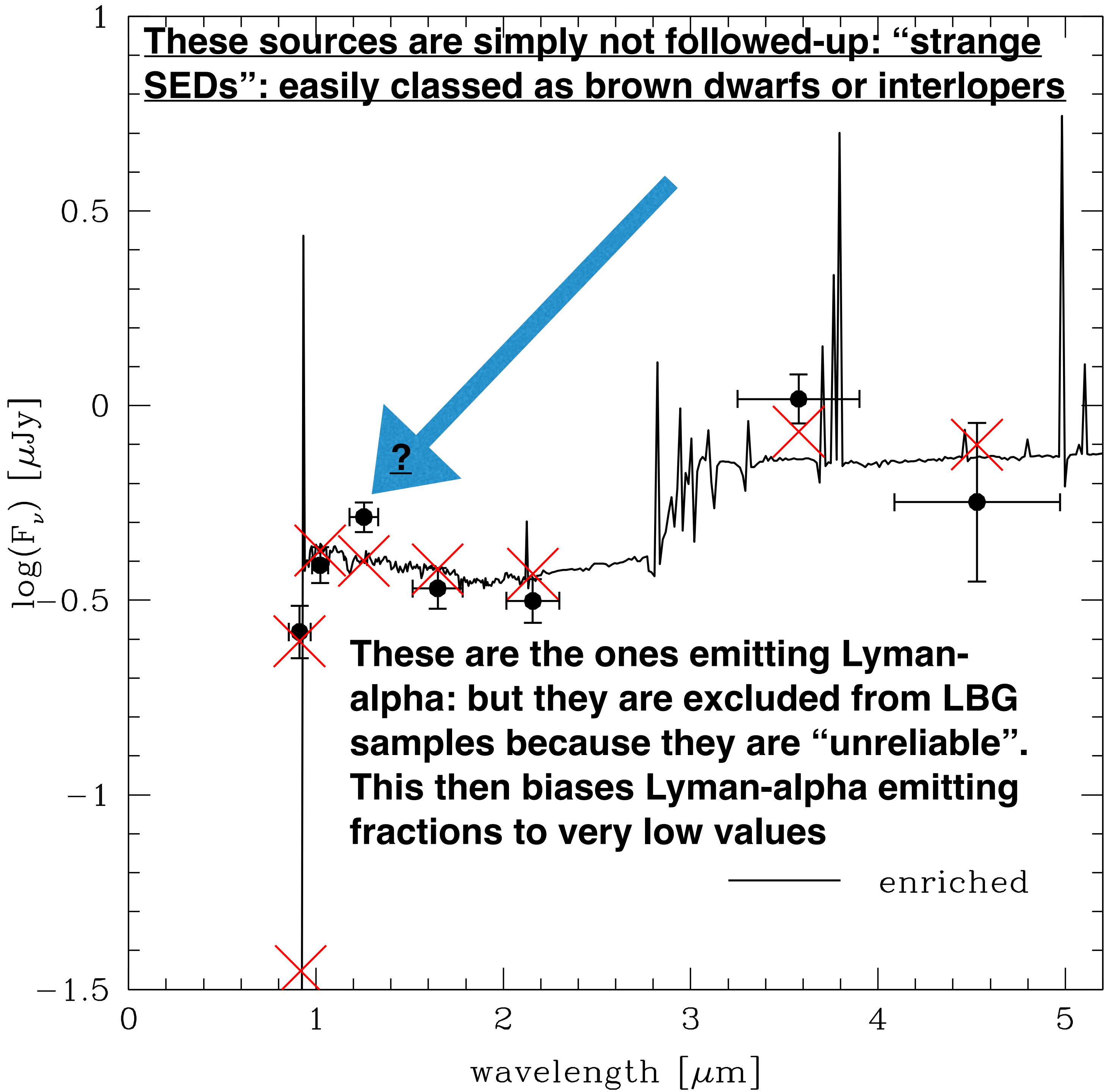
See Max Gronke's talk



Dijkstra, Gronke & Sobral 2016



Sobral, Matthee, Darvish et al. 2015

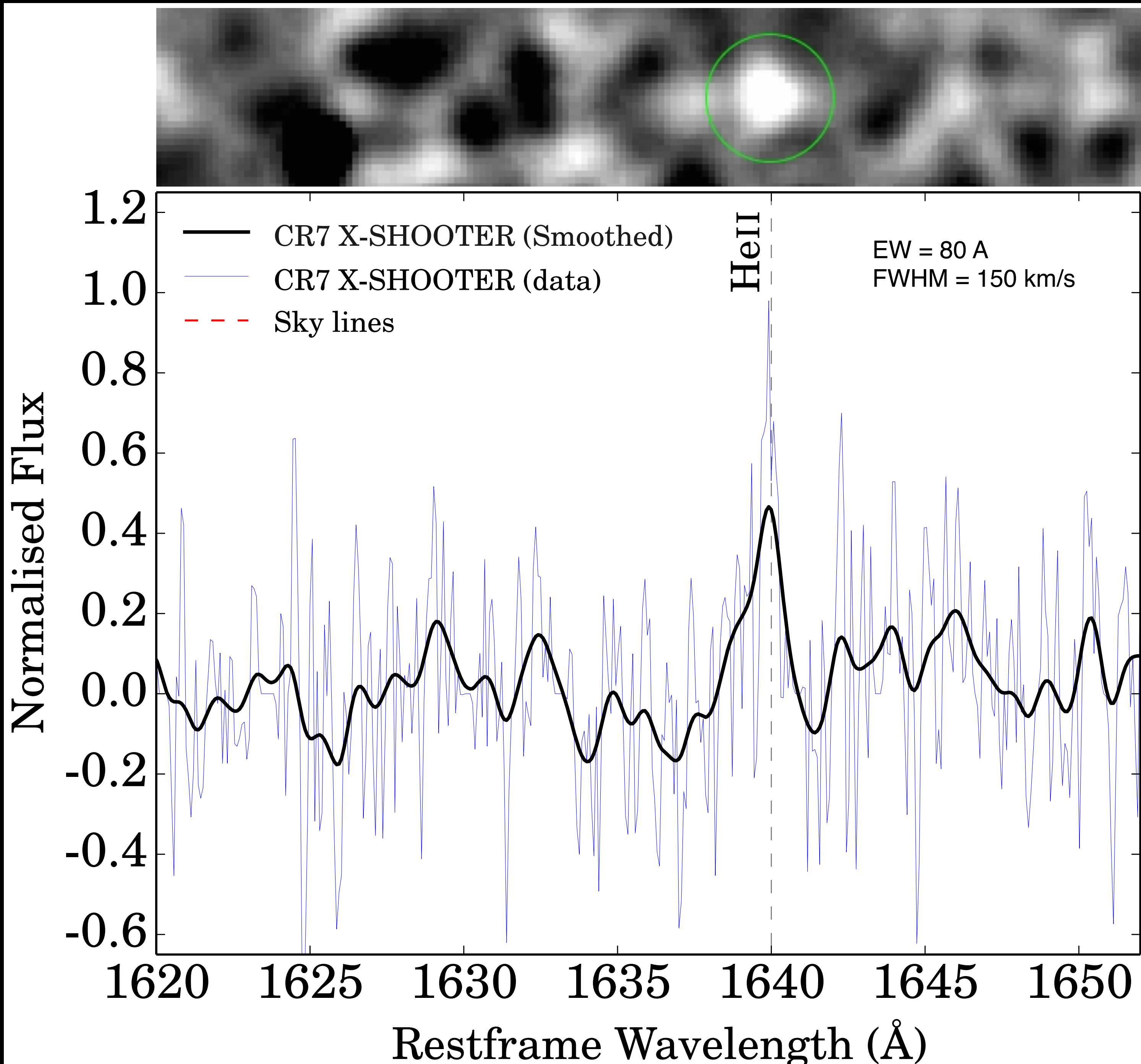


Sobral, Matthee, Darvish, Schaerer et al. 2015

CR7: X-SHOOTER: 2 hours

Anything interesting to explain J excess?

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

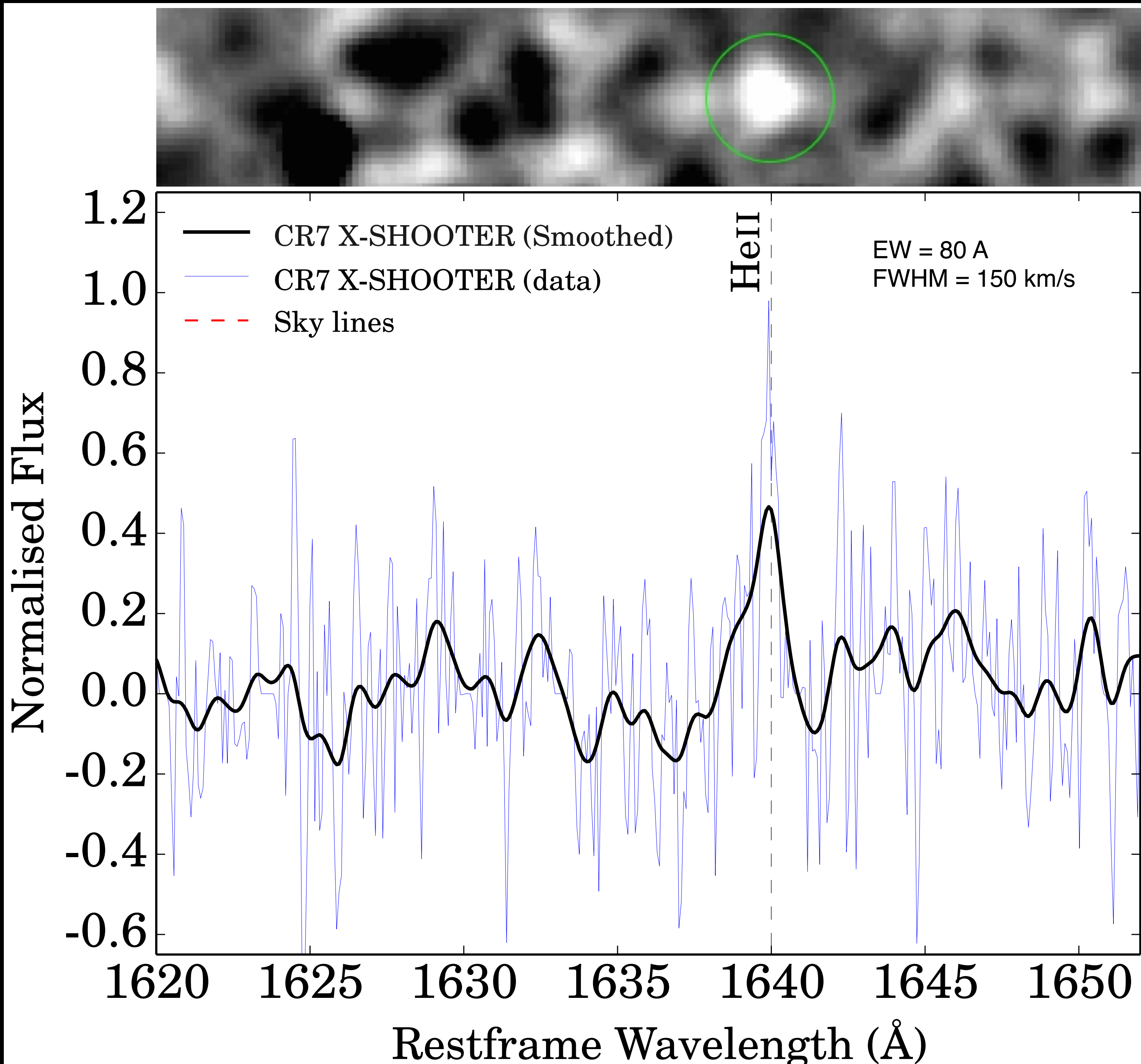


FWHM= 130 km/s

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

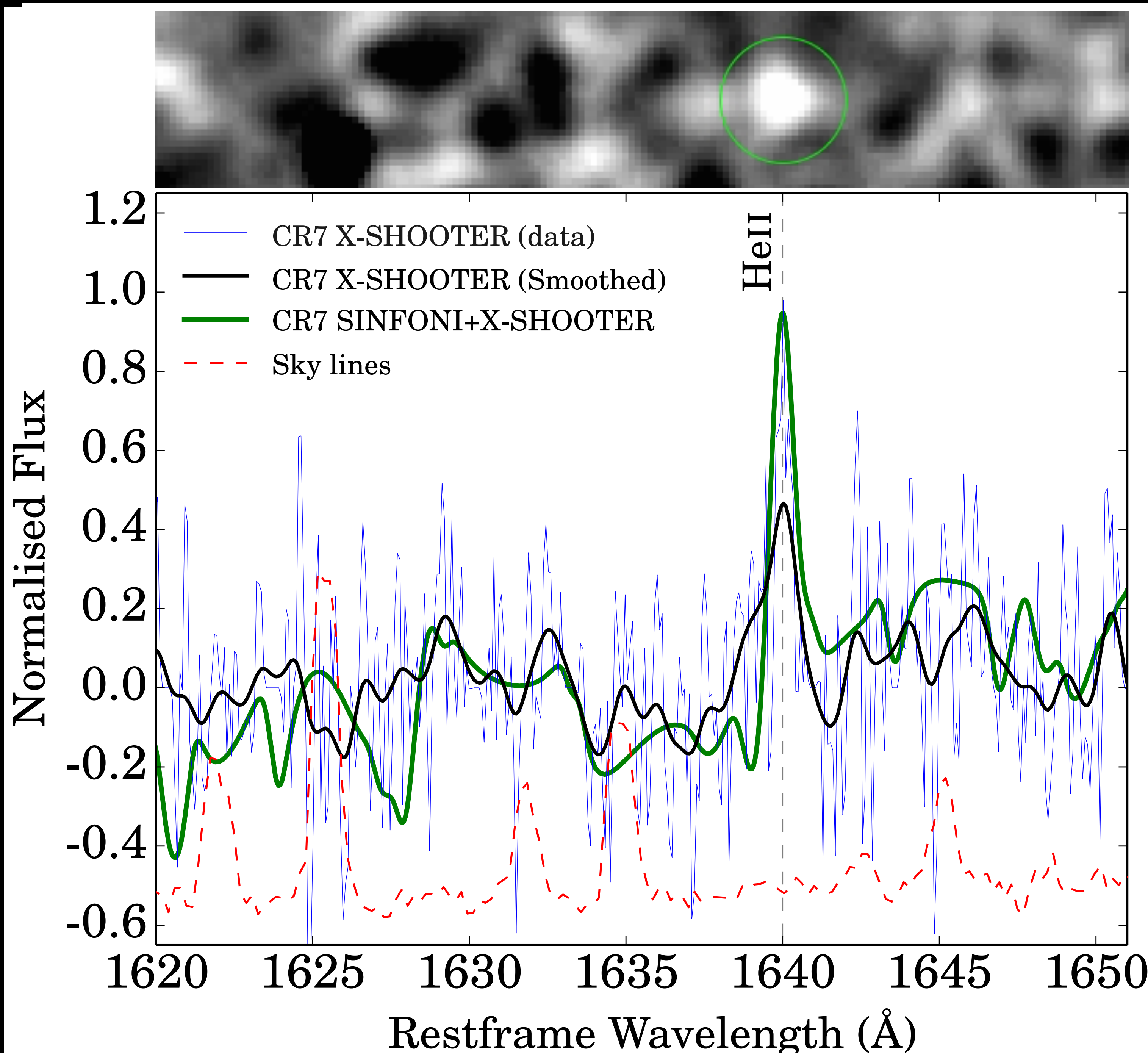
>>> DDT time on SINFONI/VLT to fully confirm

PI: Sobral

Sobral et al. 2015c

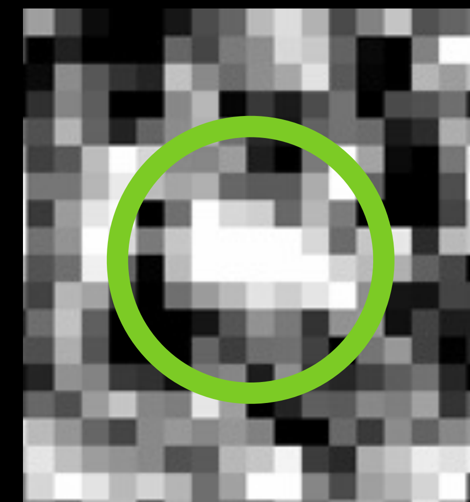
Sobral, Matthee, Darvish et al. 2015

CR7: X-SHOOTER: 2 hours



SINFONI

HeII 1640A in 2D!



~6 sigma!

HeII EW_0>70 A

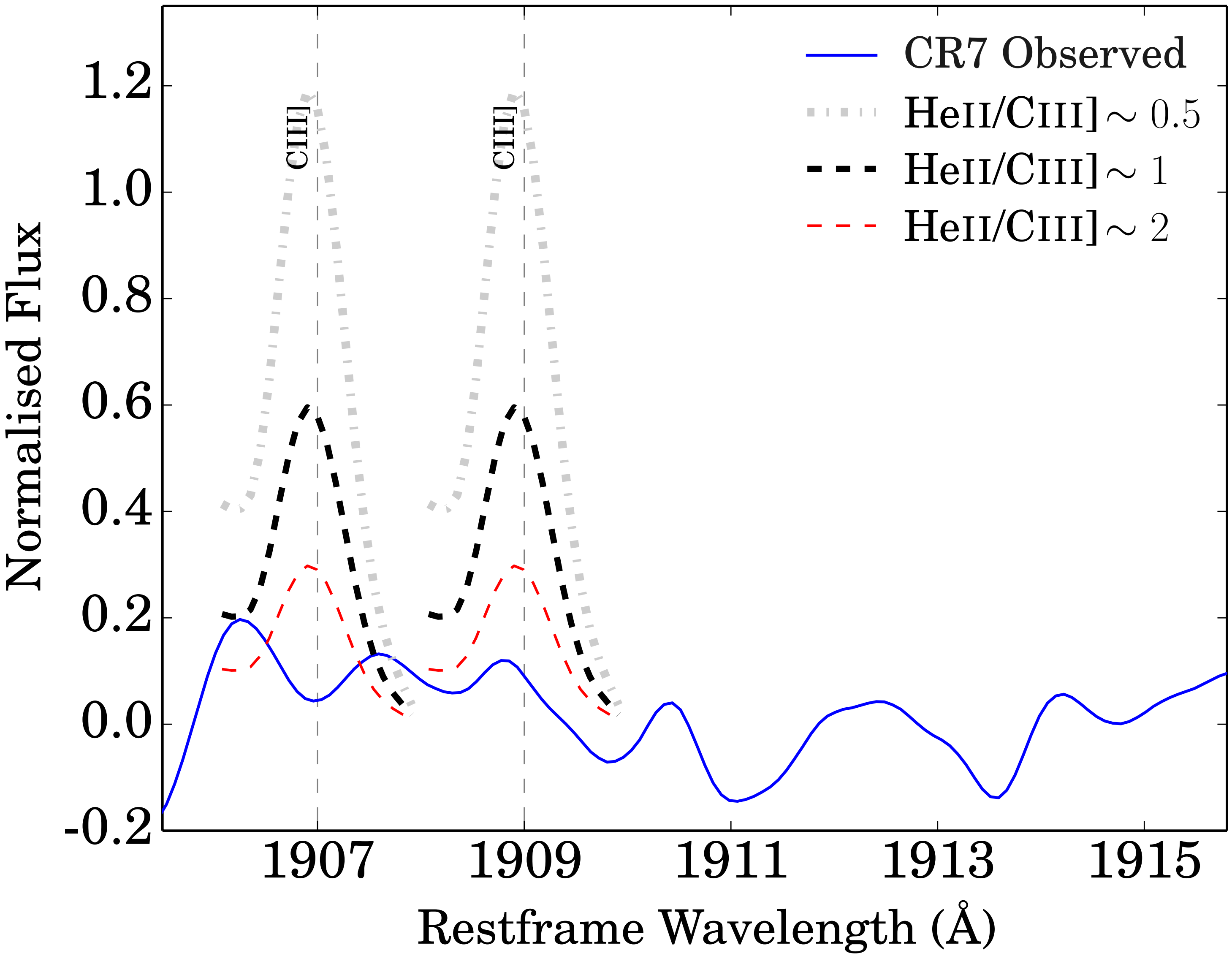
HeII $FWHM_0$= 130 km/s

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_0 HeII>70!!

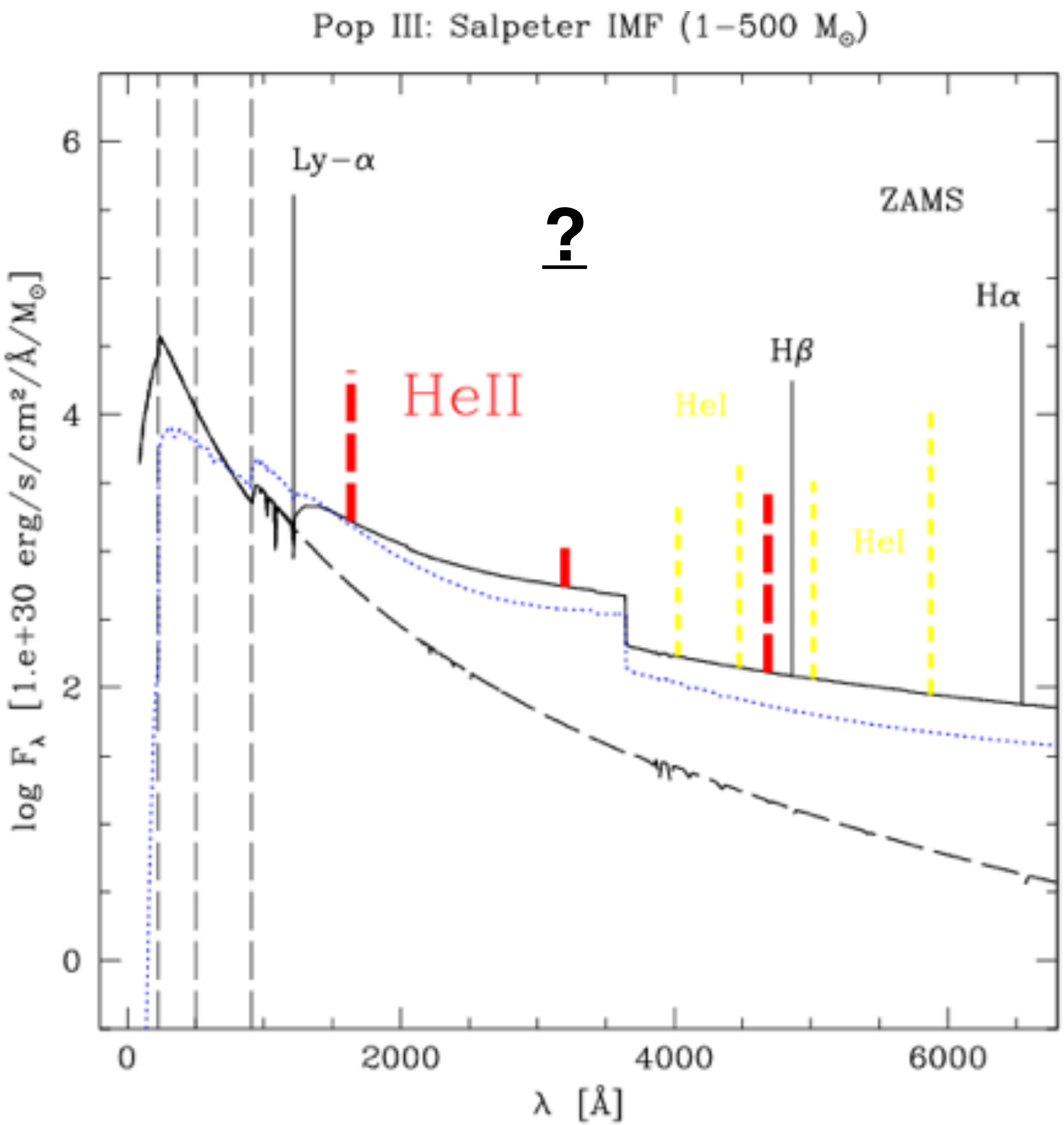
E.g.:
No CIII]1908
No OIII]1663
No NV

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

See talks by e.g. Dawn Erb; Eros Vanzella

Sobral, Matthee, Darvish et al. 2015

This is what we have:



Schaerer 2002

Lyα EW_0>230 A (likely >1000A)

HeII EW_0 ~80 A!

HeII/Lyα~0.1

No lines except Lyα and HeII (so far!)

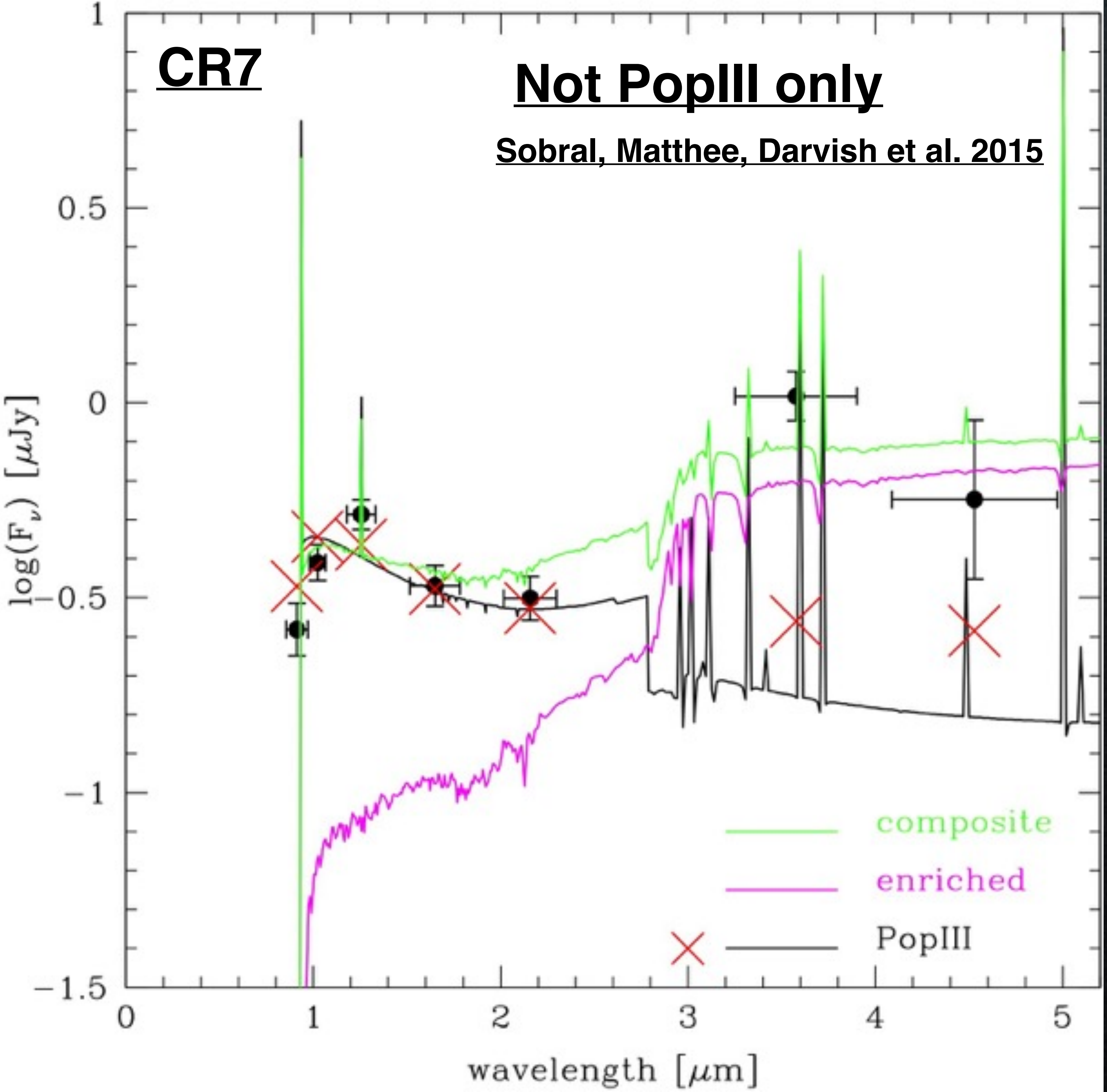
Narrow Lyα and narrow HeII

“Talks” like it

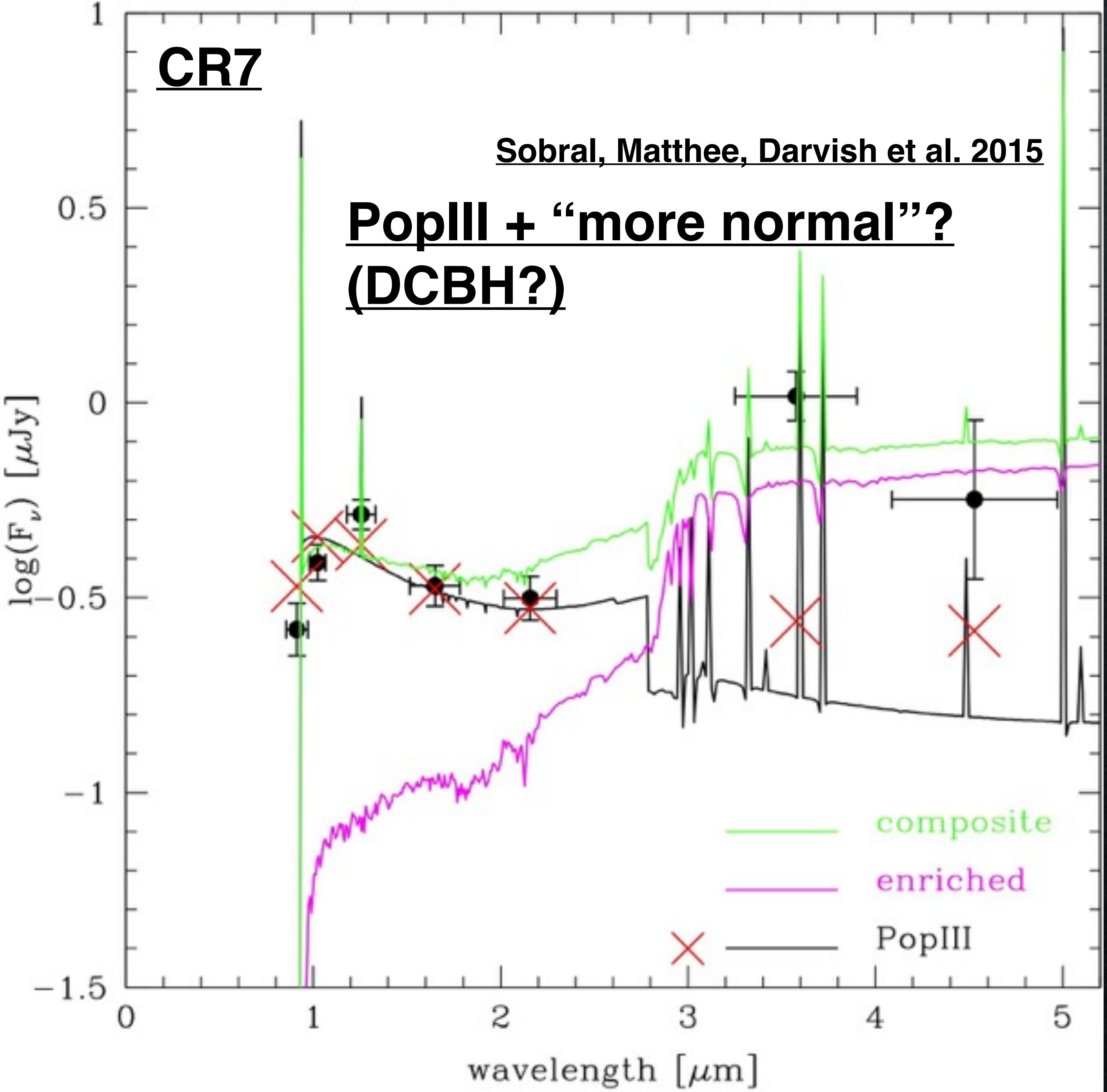
“Looks” like it

“Moves” like it

“Smells” like it

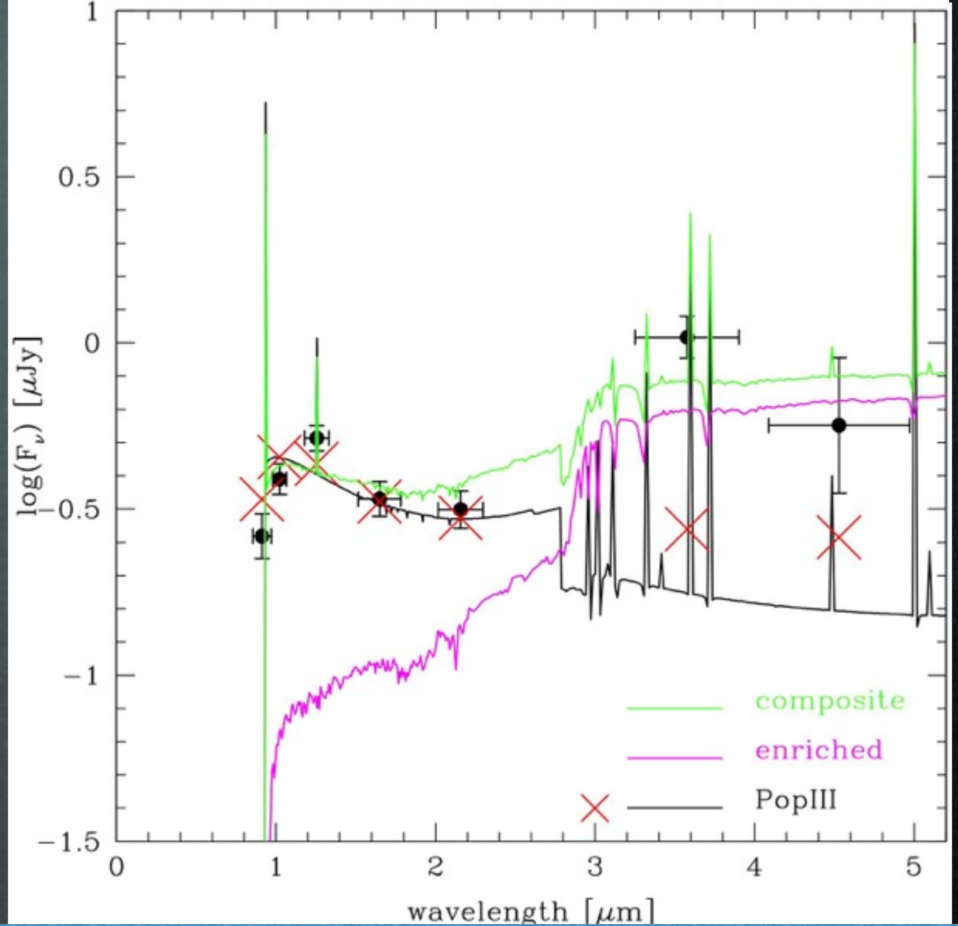


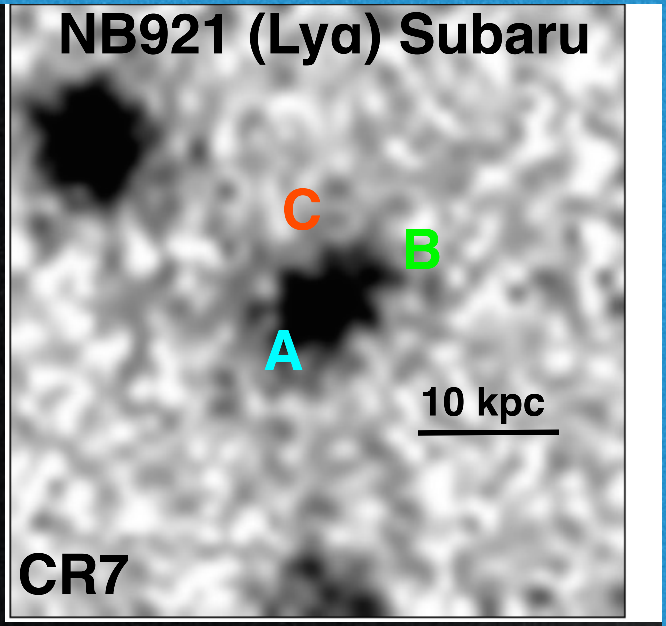
CR7
Not PopIII only
Sobral, Matthee, Darvish et al. 2015
log(F_ν) [μJy]
wavelength [μm]
composite
enriched
PopIII
1
0.5
0
−0.5
−1
−1.5
0
1
2
3
4
5


CR7
Sobral, Matthee, Darvish et al. 2015
PopIII + “more normal”?
(DCBH?)
log(F$_\nu$) [μJy]
wavelength [μm]
composite
enriched
PopIII
1
0.5
0
−0.5
−1
−1.5
0
1
2
3
4
5

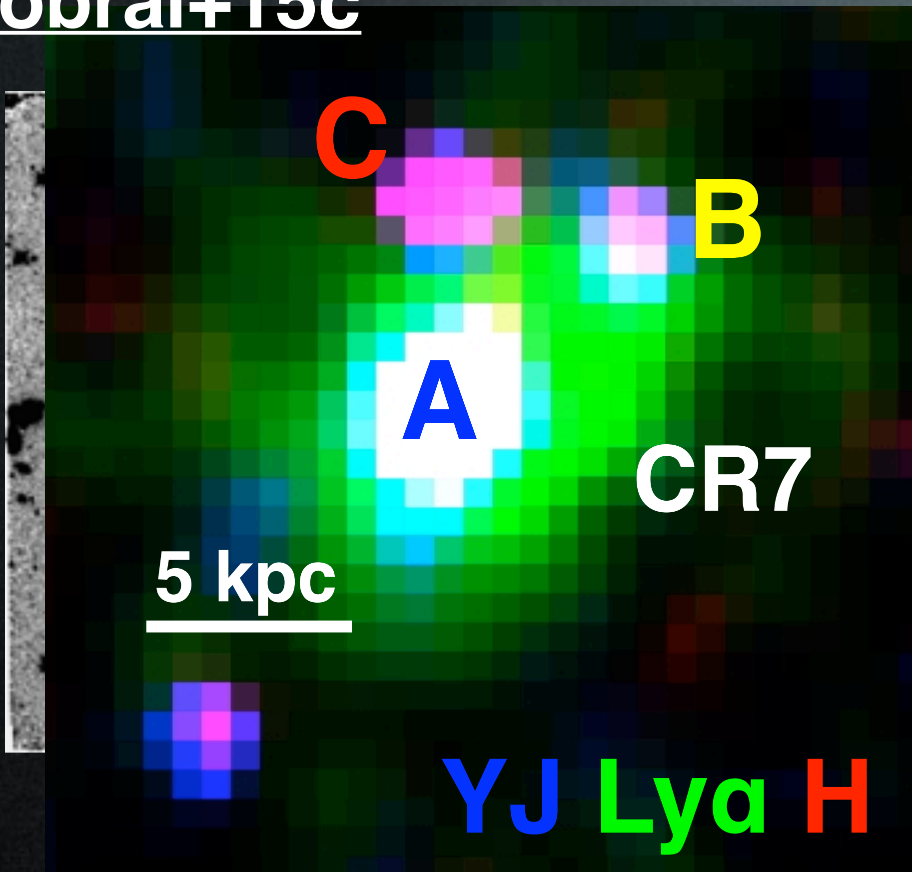
Sobral+15c

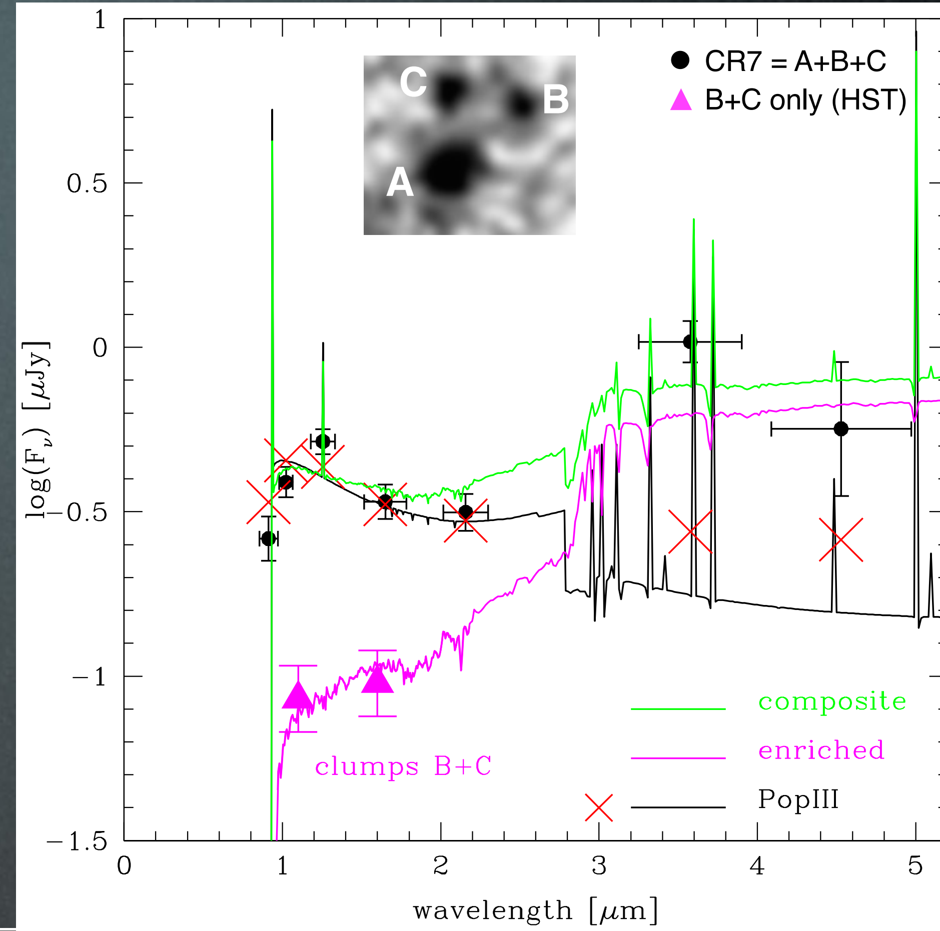
From ground-based + Spitzer photometry: single source

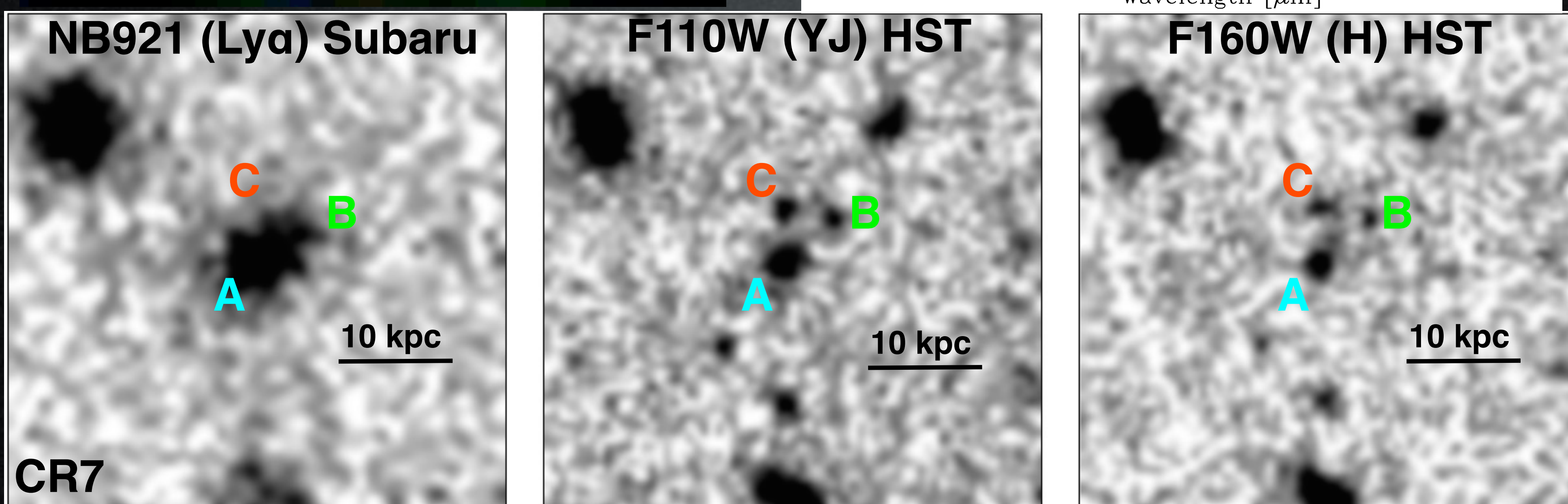




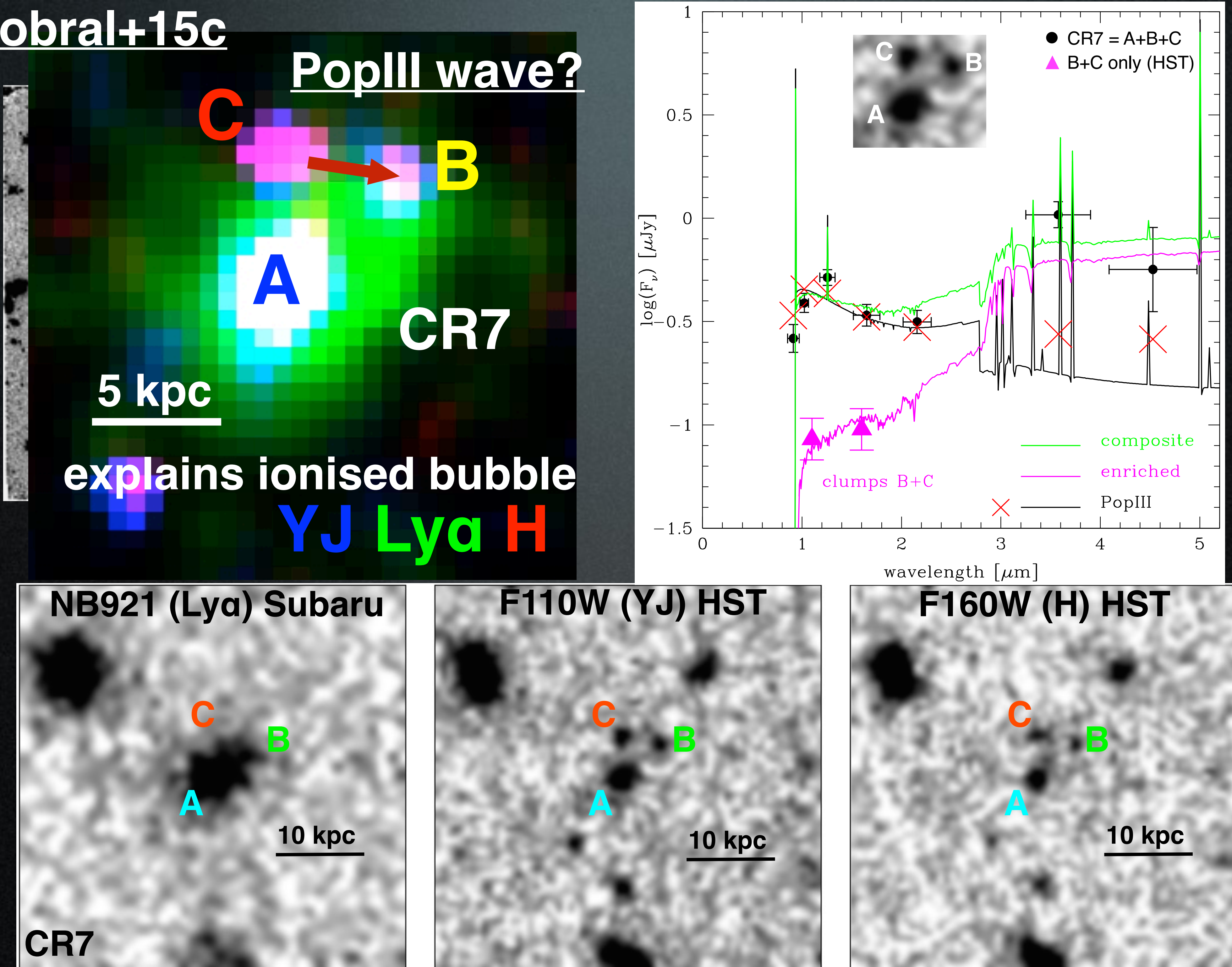
Sobral+15c

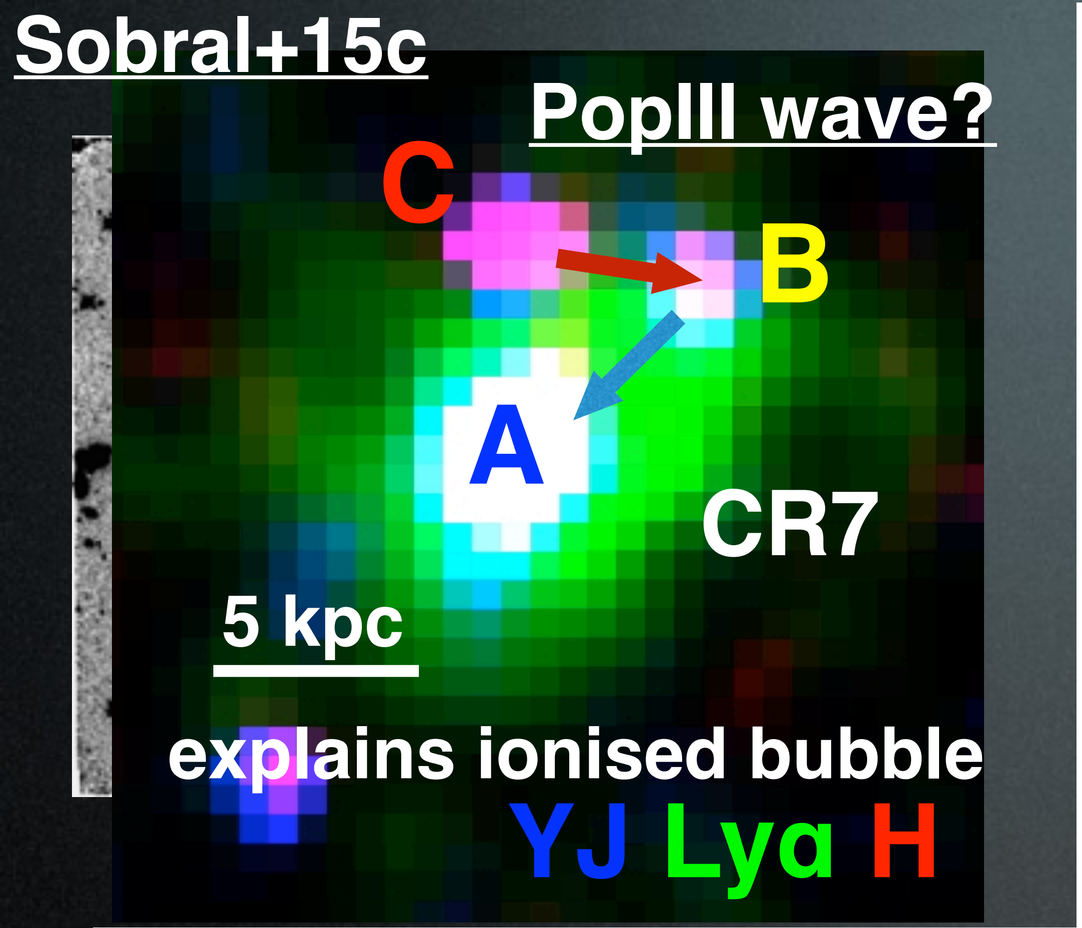

C
B
A
CR7
5 kpc
YJ Lyα H


C
B
A
CR7 = A+B+C
B+C only (HST)
log(F_ν) [μJy]
wavelength [μm]
clumps B+C
composite
enriched
PopIII


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

Sobral+15c


PopIII wave?
C
B
A
CR7
5 kpc
explains ionised bubble
YJ Lyα H
C
B
A
CR7 = A+B+C
B+C only (HST)
log(F$_\nu$) [μJy]
1
0.5
0
−0.5
−1
−1.5
0
1
2
3
4
5
wavelength [μm]
clumps B+C
composite
enriched
PopIII
NB921 (Lyα) Subaru
C
B
A
10 kpc
CR7
F110W (YJ) HST
C
B
A
10 kpc
F160W (H) HST
C
B
A
10 kpc


Sobral+15c
PopIII wave?
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B
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explains ionised bubble
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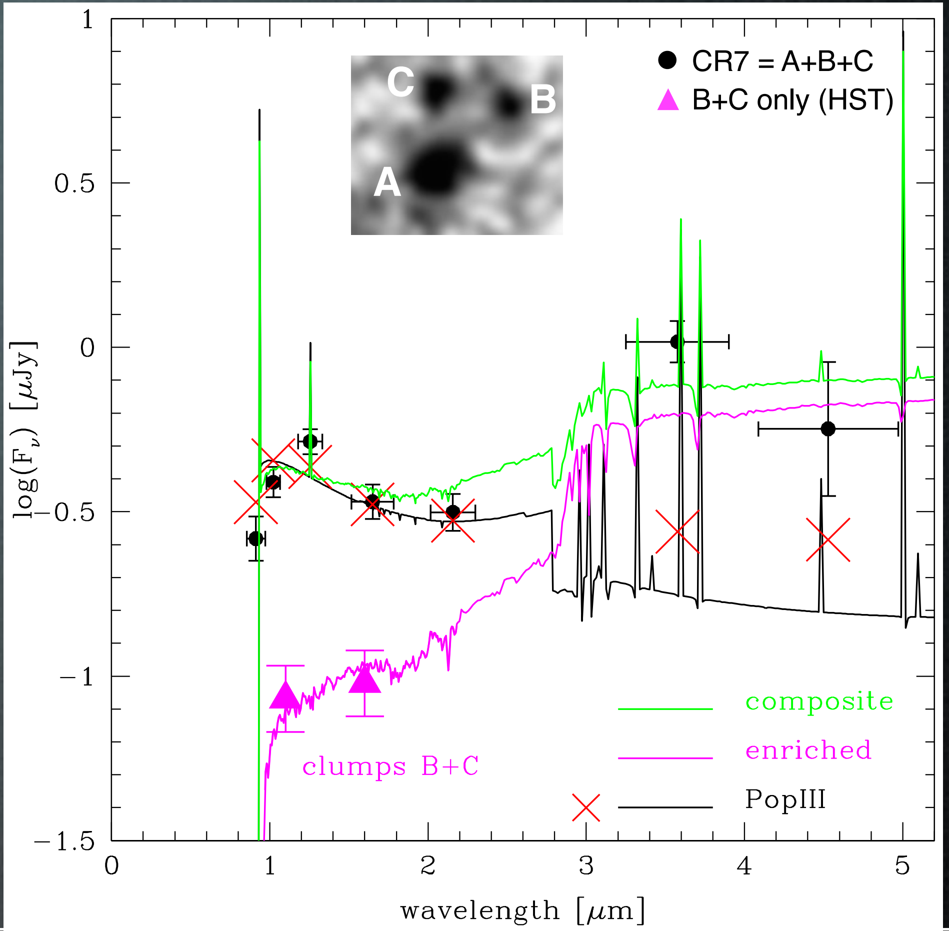
CR7 = A+B+C
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B
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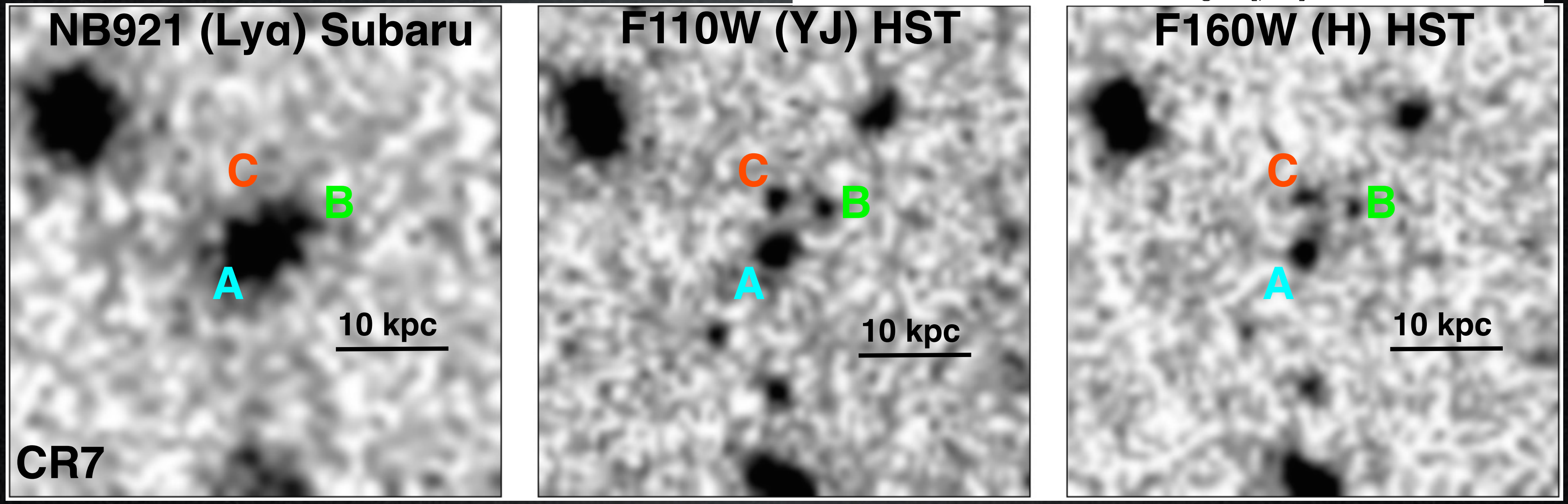
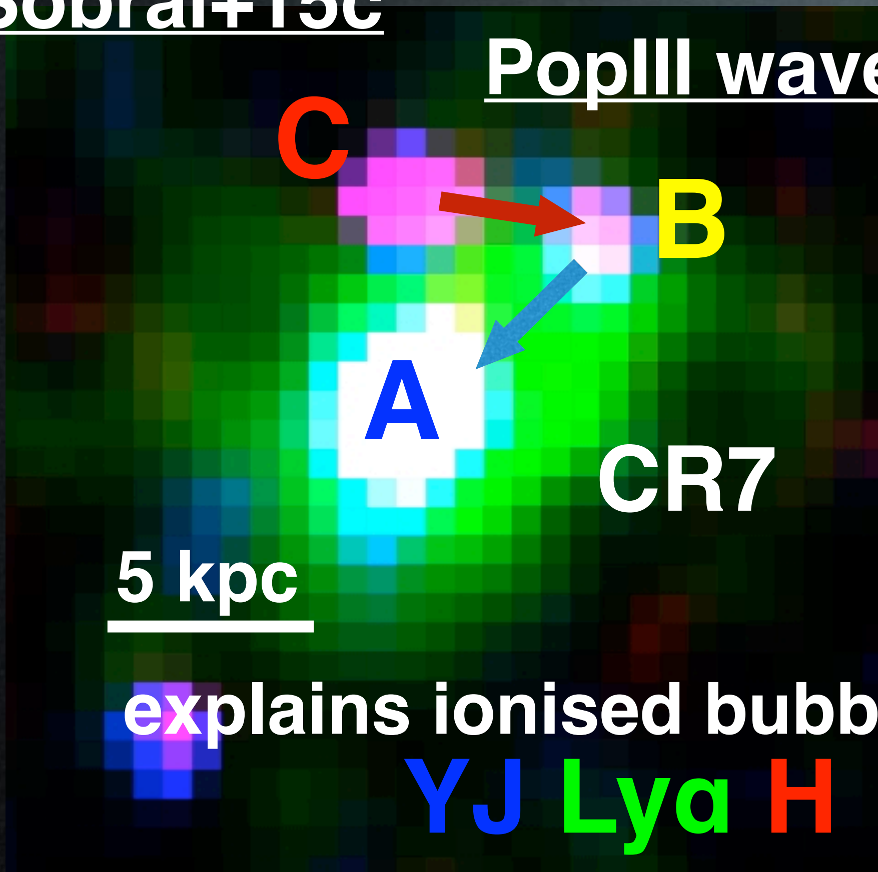
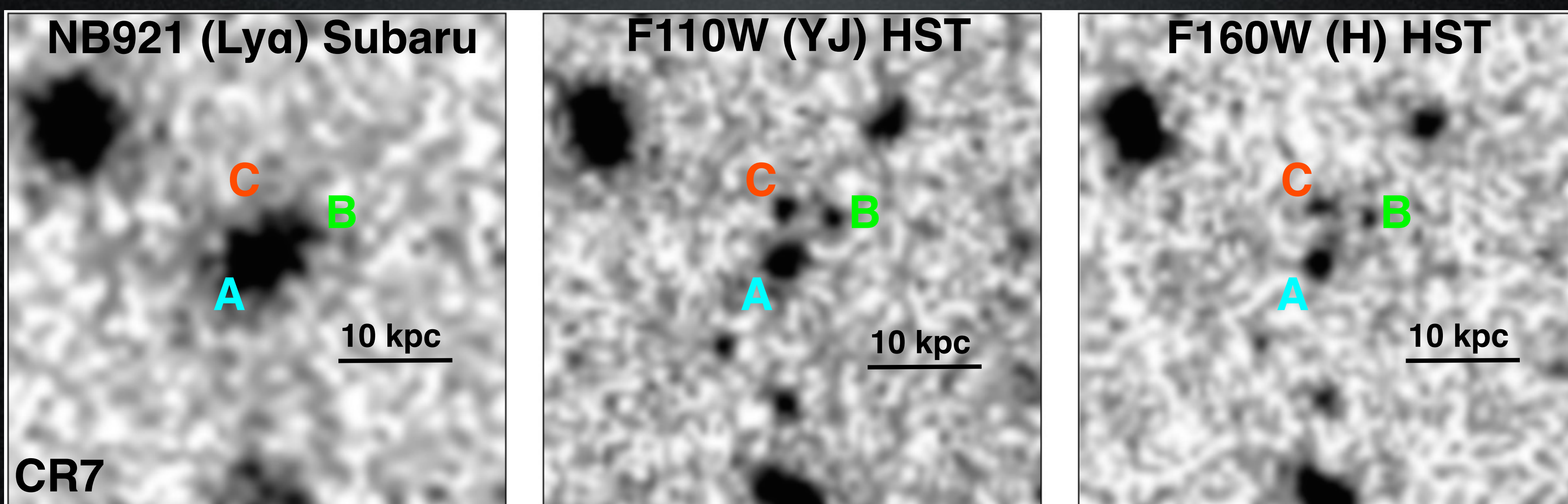
log(F_ν) [μJy]
wavelength [μm]
clumps B+C
composite
enriched
PopIII


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

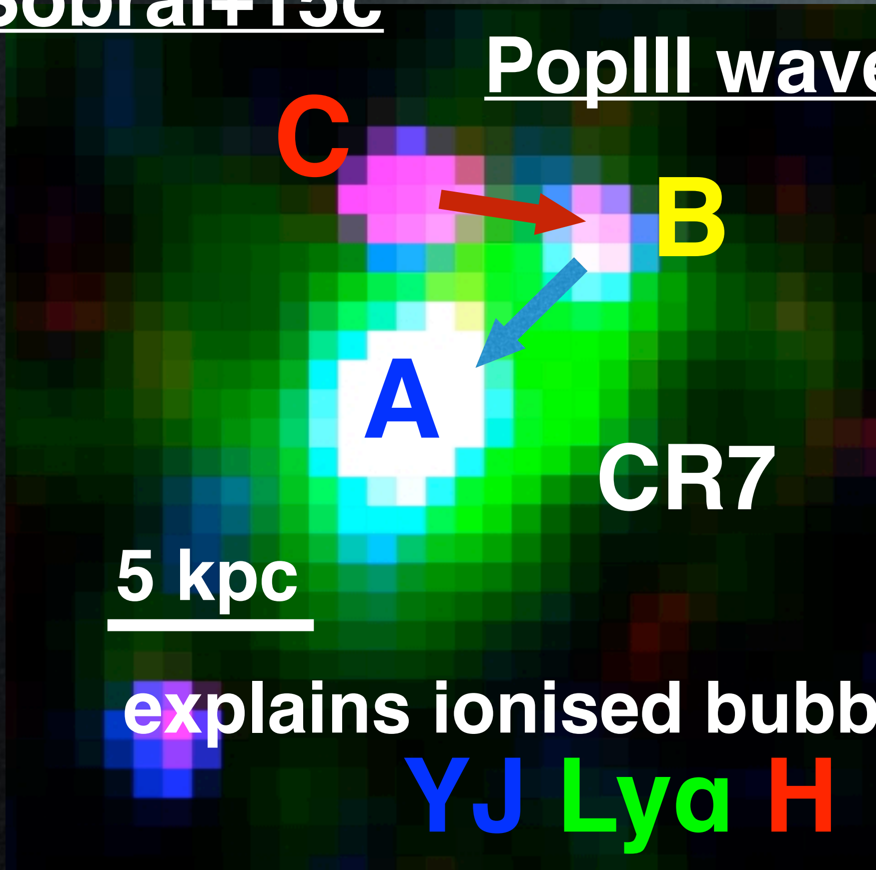
Sobral+15c

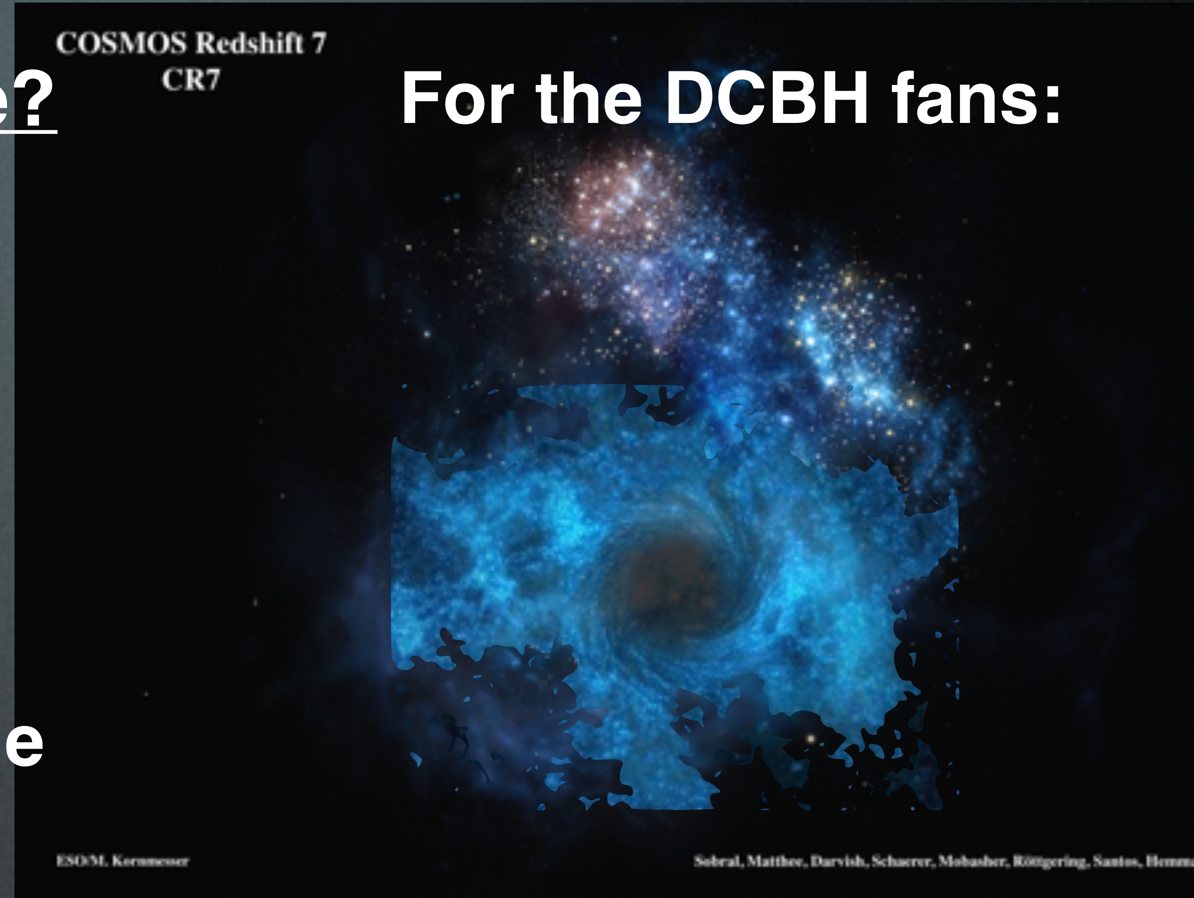
PopIII wave?

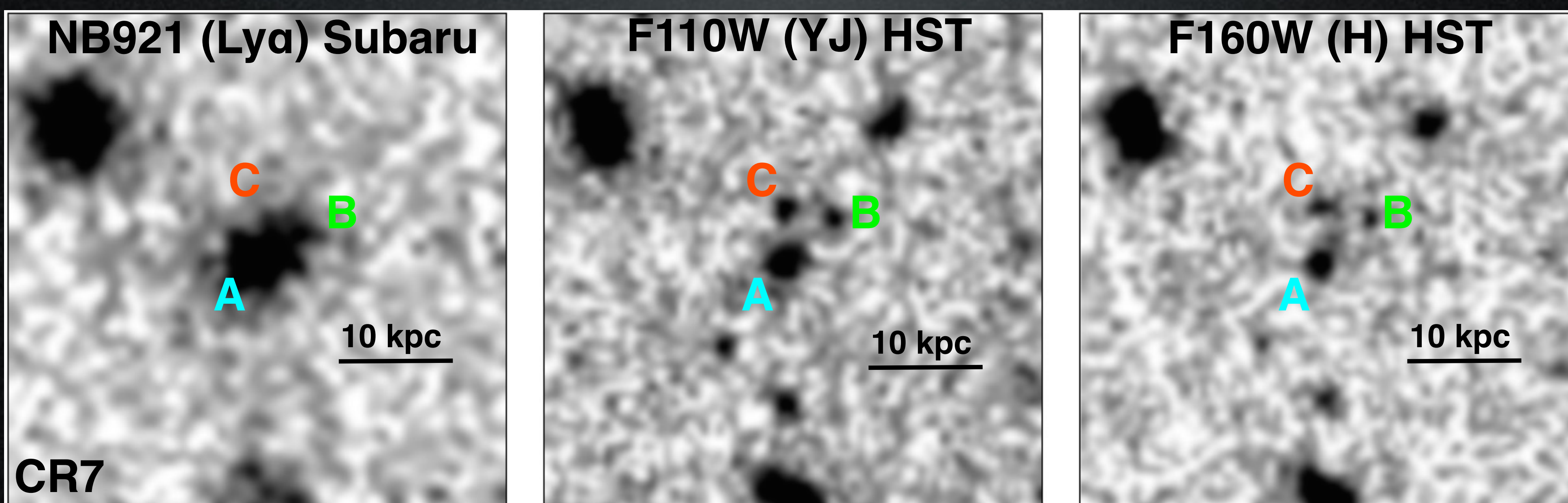




Sobral+15c


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, Hemma


NB921 (Lyα) Subaru
C
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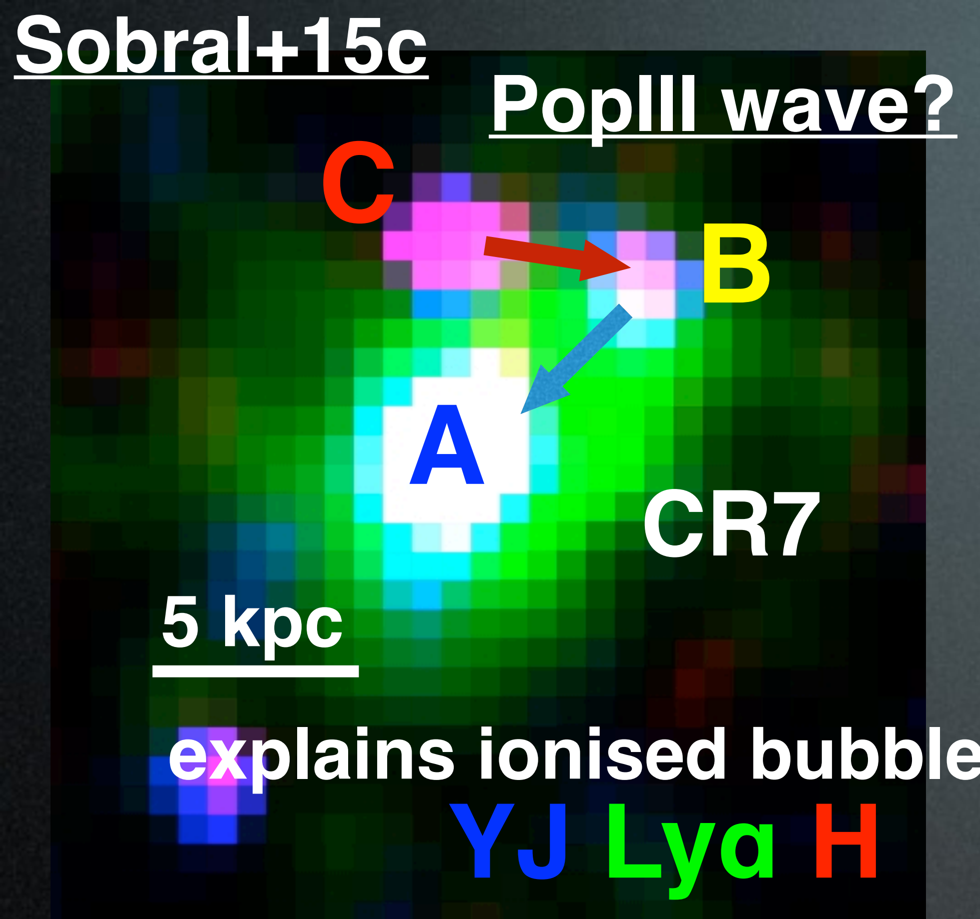
Sobral+15c
PopIII wave?
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5 kpc
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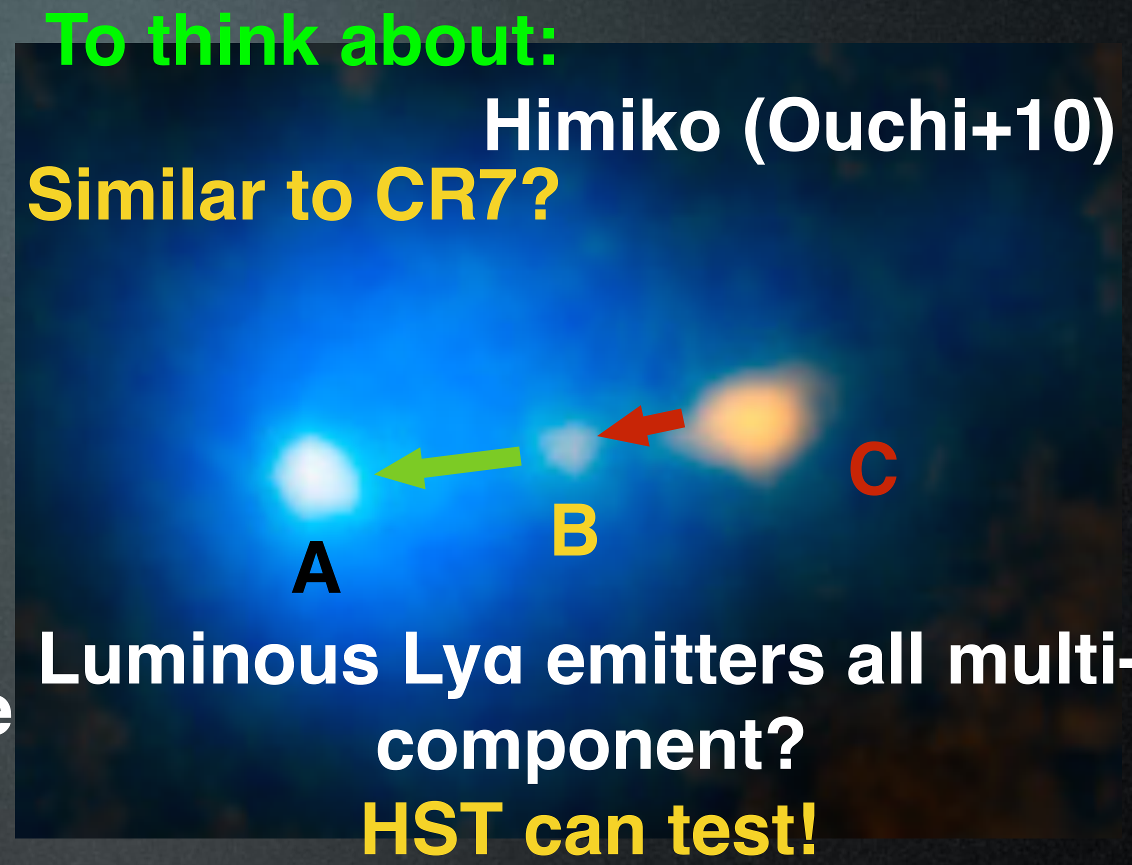
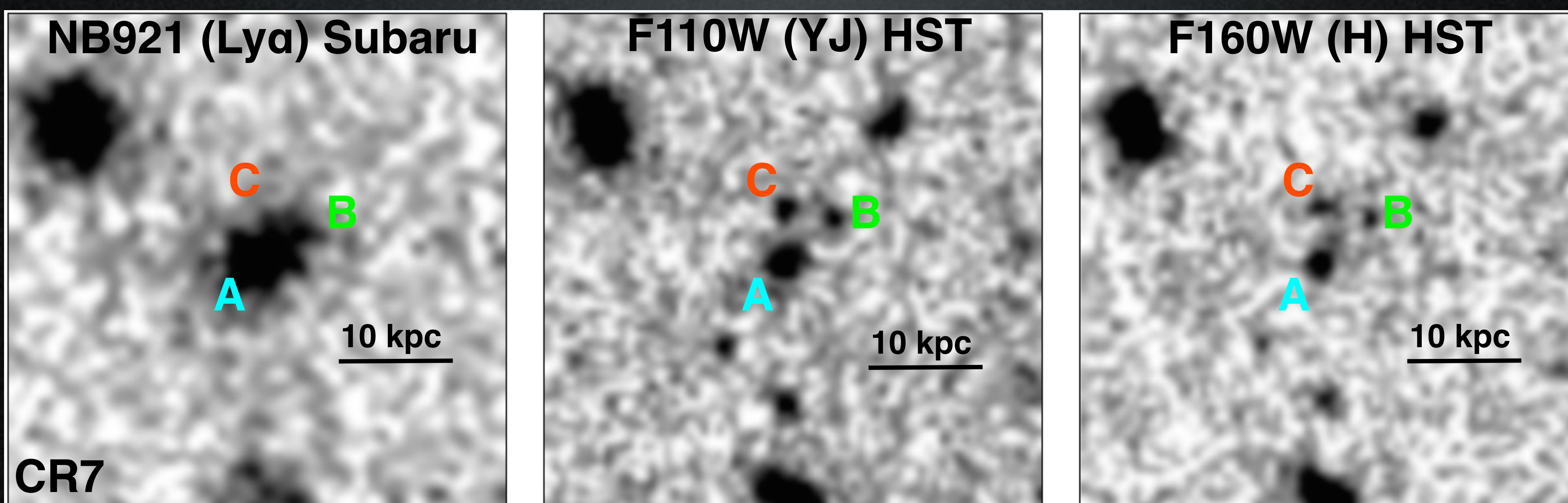
YJ Lyα H


To think about:
Himiko (Ouchi+10)
Similar to CR7?
A
B
C
Luminous Lyα emitters all multi-component?
HST can test!


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

What is the nature of CR7?

Sobral+15

Papers by e.g.
Visbal et al.

Papers by e.g.:
Smith et al.

PopIII(-like)

vs

Direct collapse black hole (DCBH)

Other alternatives at low metallicity

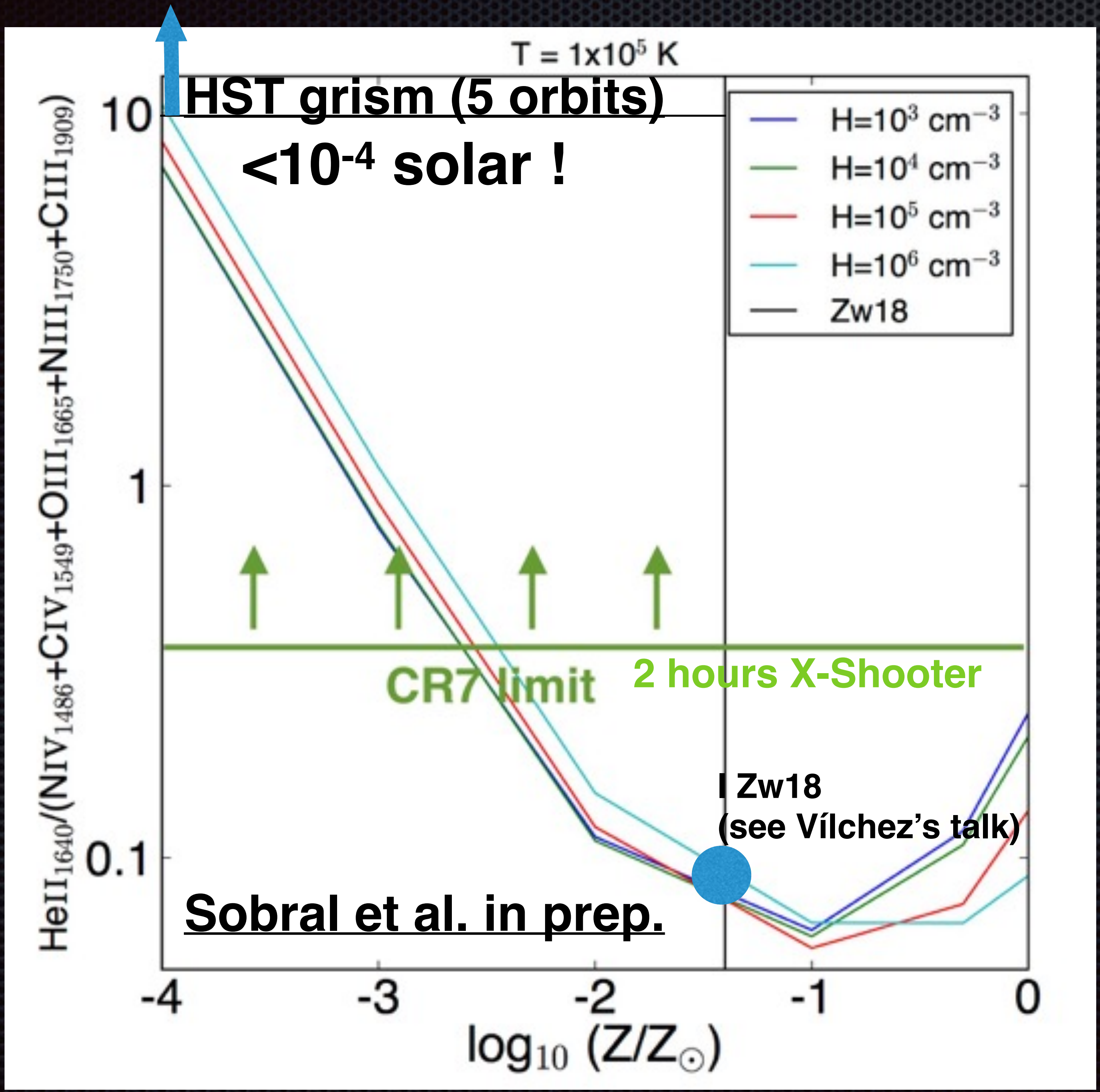
Also: Pallottini+15; Agarwal+15; Hartwig+15; Smidt+16

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

HST observations will finally clarify metallicity (PI: Sobral)



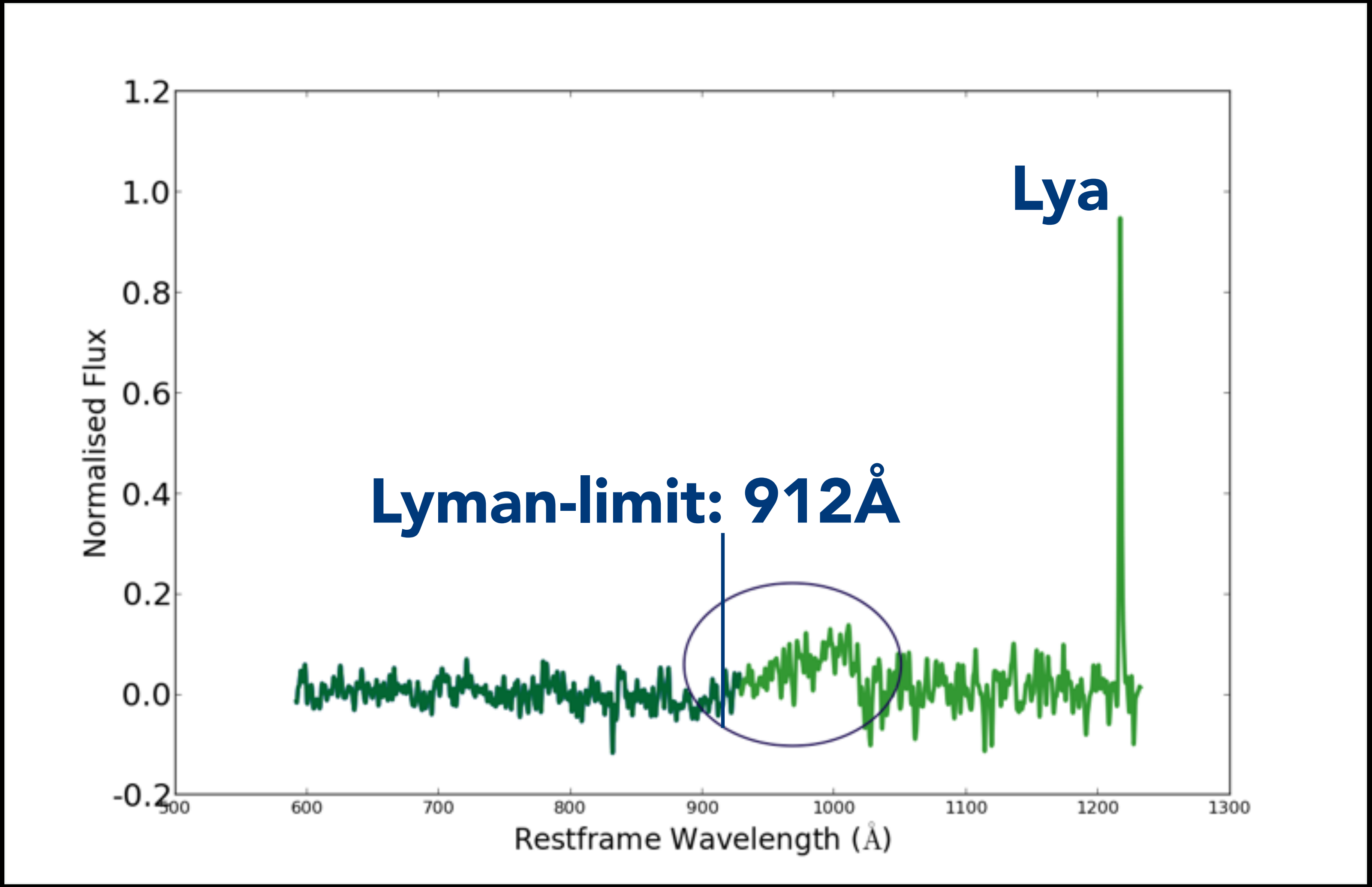
CLOUDY modelling exploring large range of physical conditions, temperatures, densities

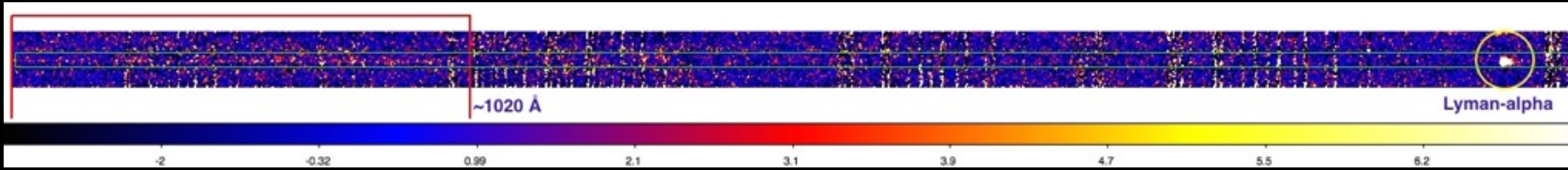
Current limit on CR7 metallicity $<10^{-2.5}$ solar (<0.32% solar)

LYMAN-WERNER FLUX FROM CR7 ?

Unseen in other z>6 galaxies

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





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.

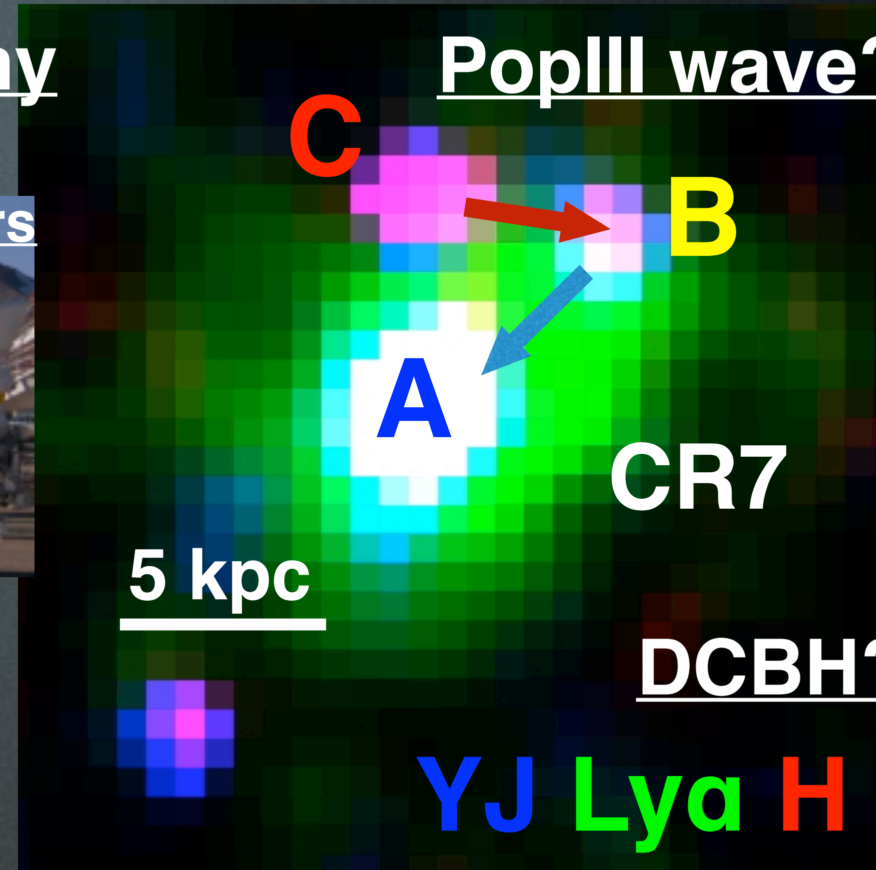
VLT+Keck+WHT follow-up

Selection very well known

ALMA time to clearly reveal any traces of metals

Cycle 3. PI: Sobral

In a couple of weeks!!



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
Santos, Sobral & Matthee
Sobral et al. in prep.

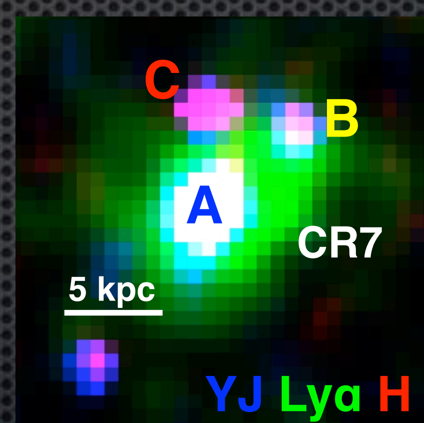
- **Stay tuned!**
- **Luminous Lyα emitters (~$10^{43.5}$ erg/s) at z=5.7-6.6 much more common than thought**

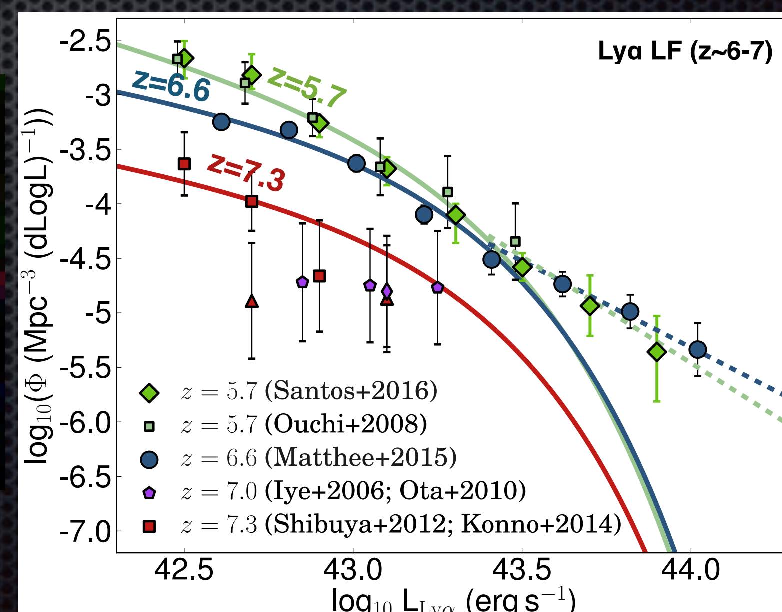
$1.5 \times 10^{-5}\ \mathrm{Mpc}^{-3}$

- **Evolution of the Lyα LF is at the faint end**

Patchy re-ionisation: first around more luminous sources

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





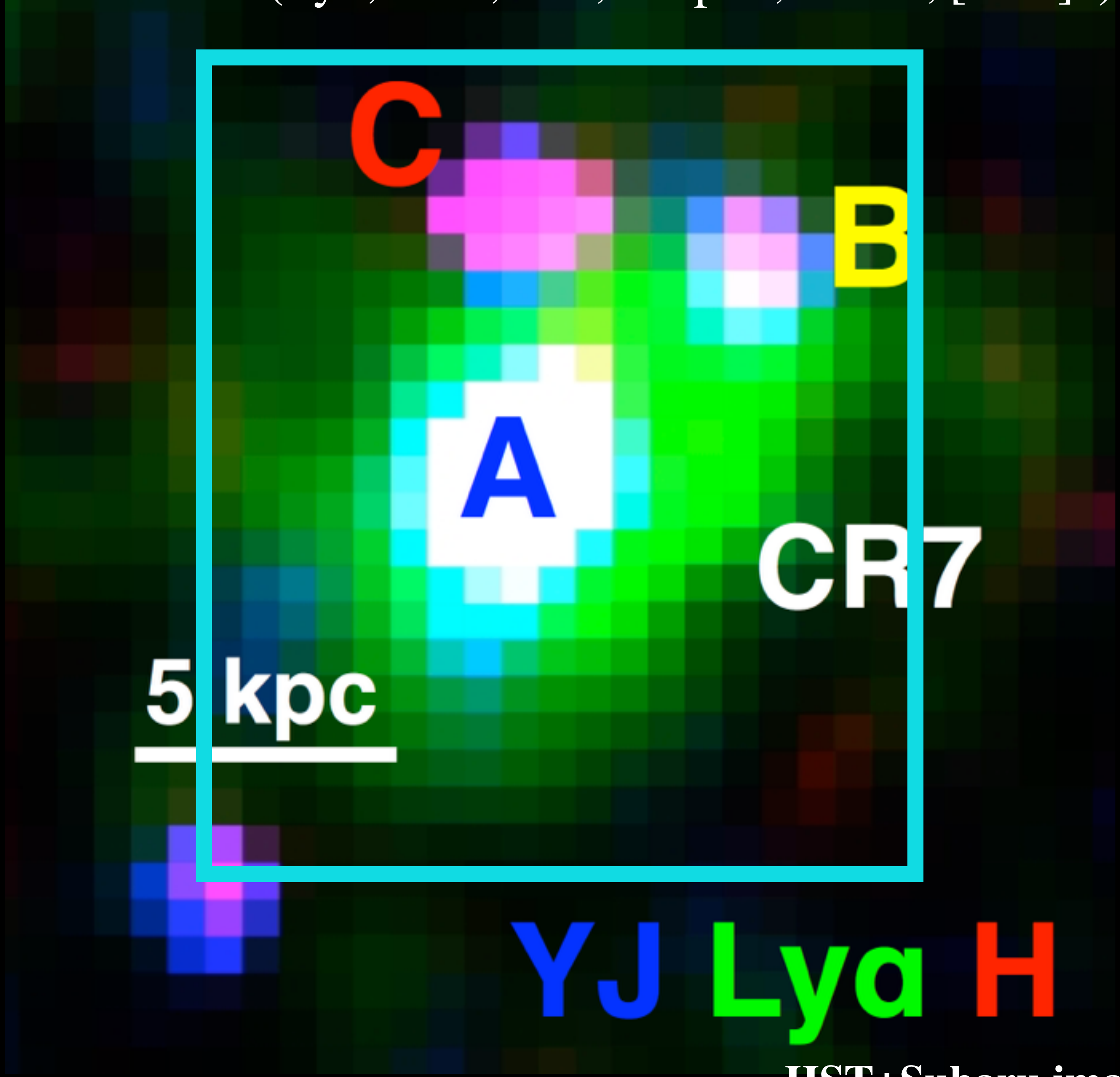
Take home messages I

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

Ideal to prepare for JWST (way beyond number counts)

PopIII searches with JWST: "find Hell". Clearly that's not even the start of it. CR7 is already showing that.

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



HST+Subaru image of CR7

ESO
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.

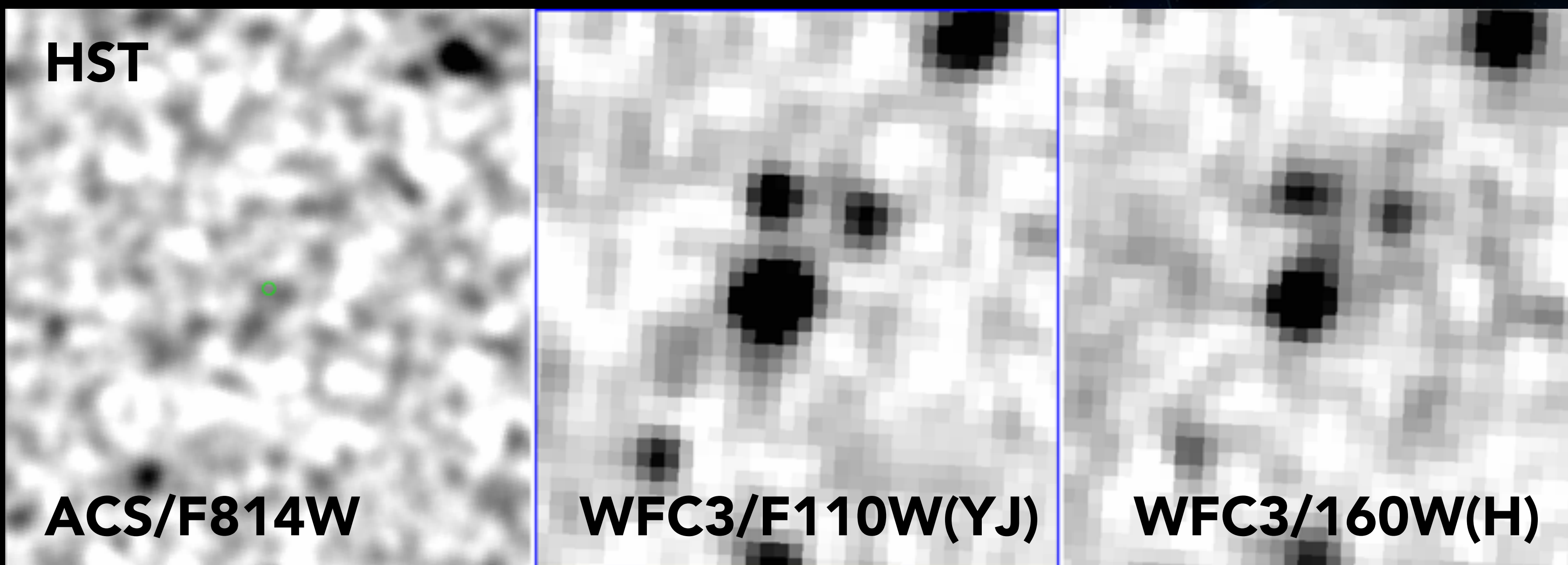
Science paper:

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

Read more in the ESO press release eso1524

CLUMP B & C AT SAME REDSHIFT?

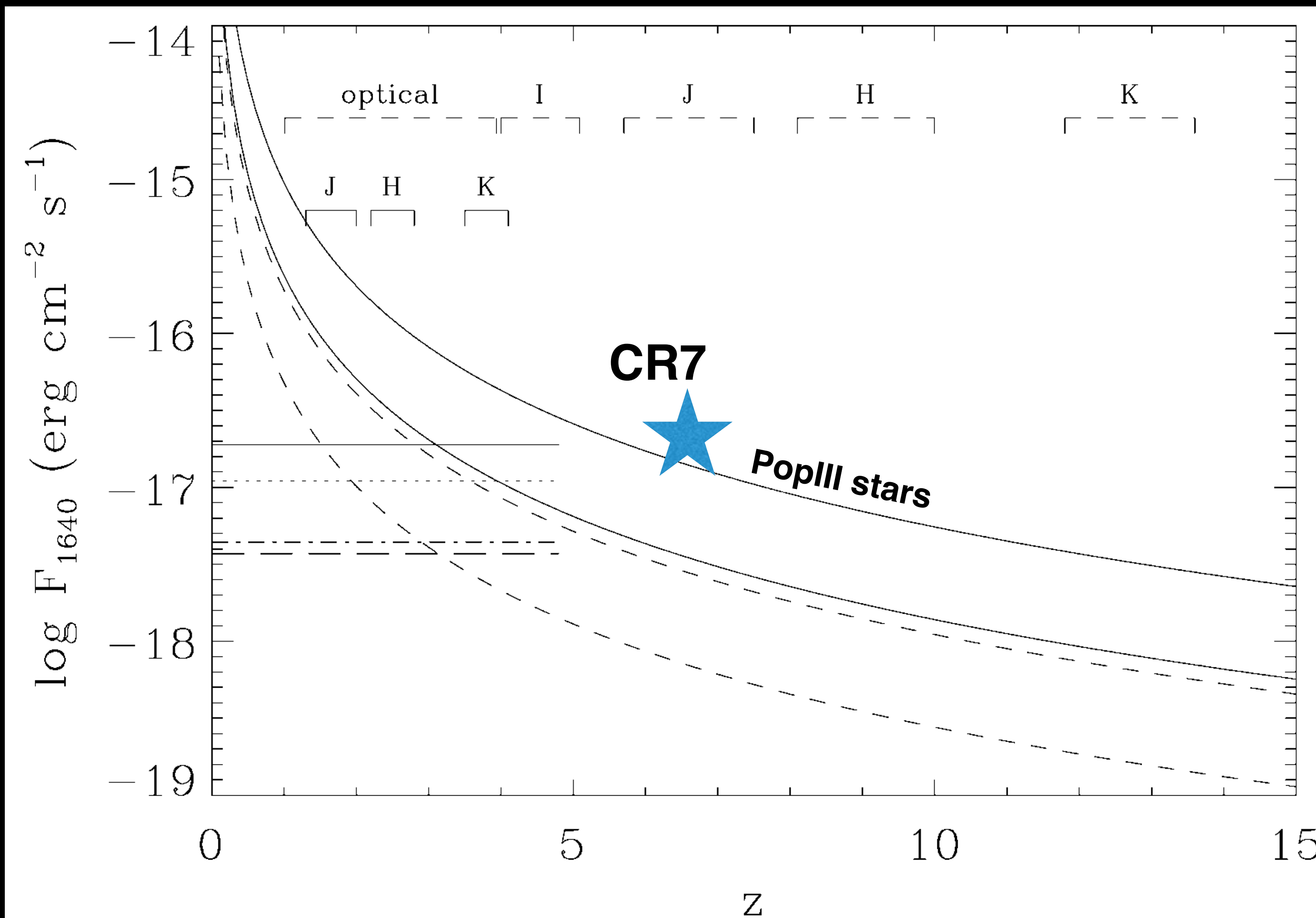
Clump B+C are not yet spectroscopically confirmed, but are z-dropouts, so photo-z>6.5 most likely



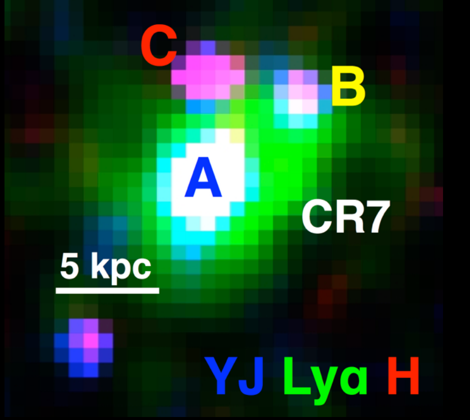
Sobral, Matthee et al. 2015 ApJ, 808, 139

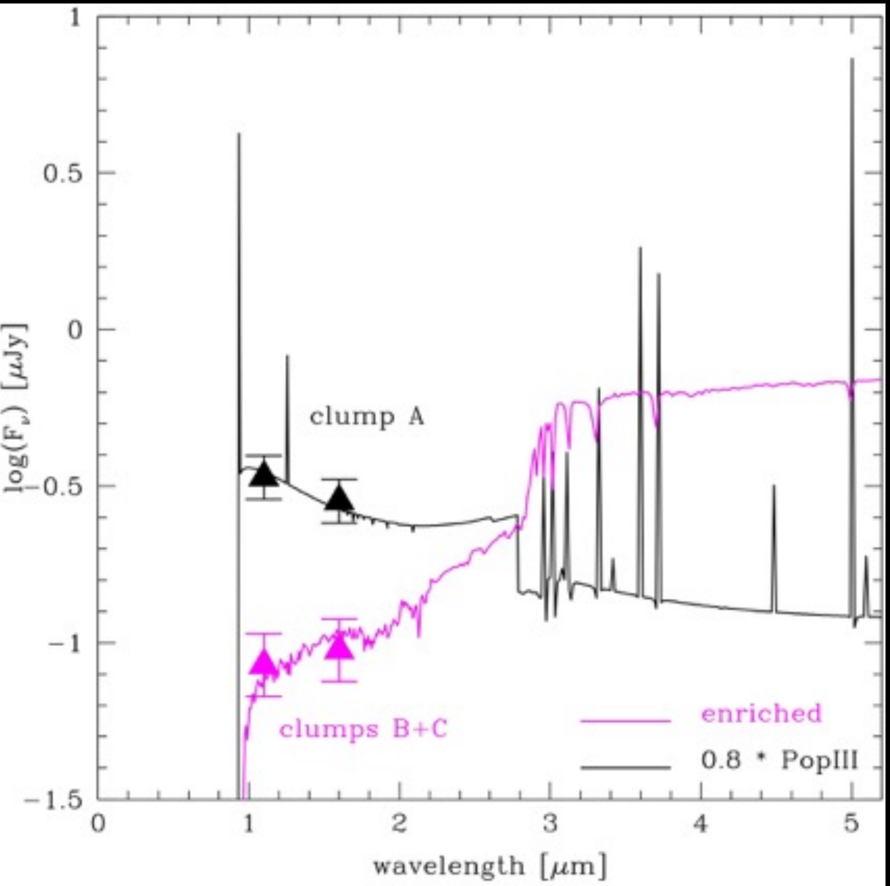
TUMLISON, GIROUX & SHULL 2001

Black holes? WR stars? Very massive, very hot stars (>100kK?), without metals? PopIII stars? DCBH?

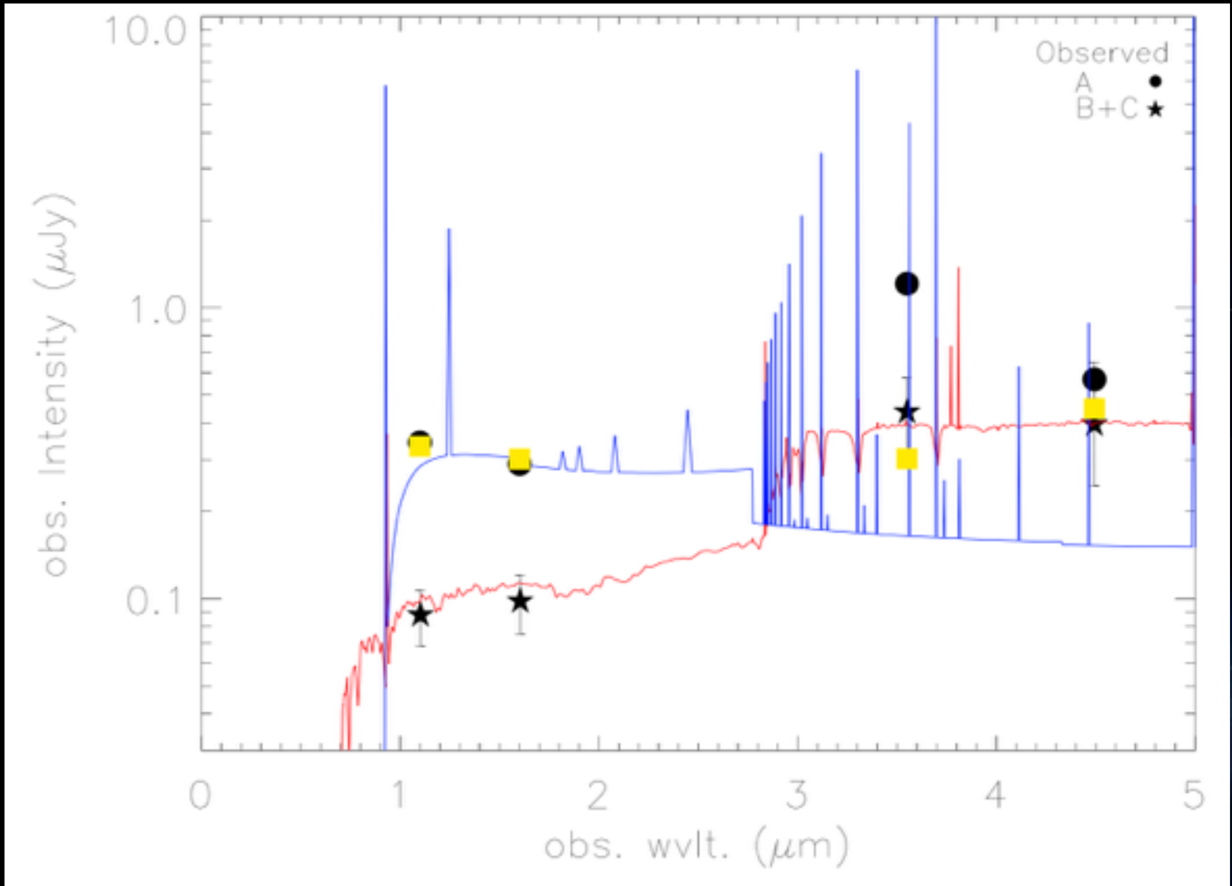


SEDs PopIII vs DCBH





Sobral,JM+2015



Agarwal+2015

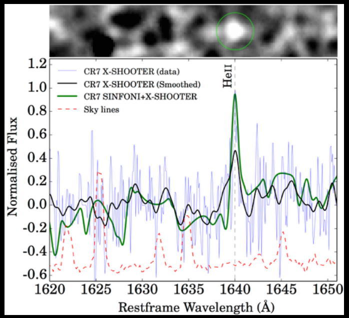
From the Dark ages to the end of re-ionisation

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!

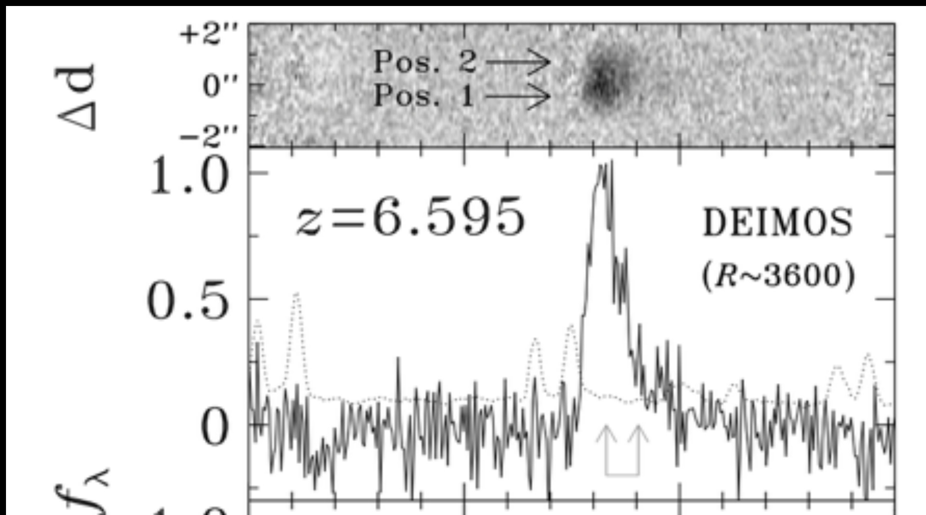
IONISING ENERGY OF HEII = 54.4 EV

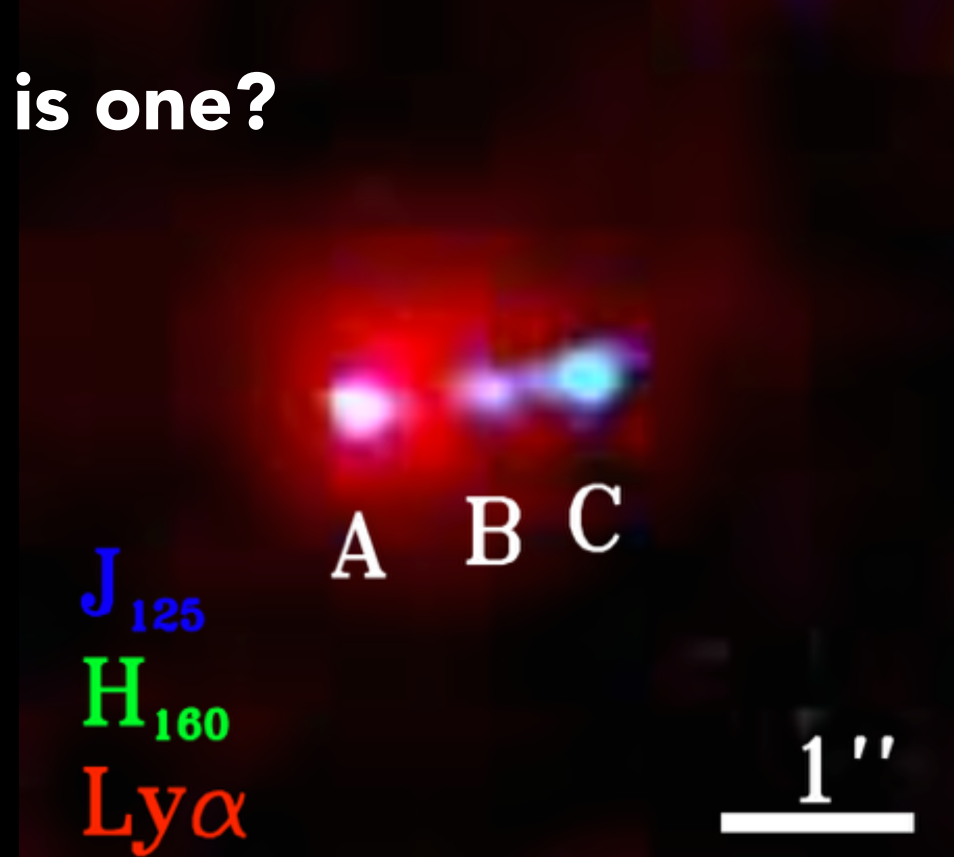


Sources:

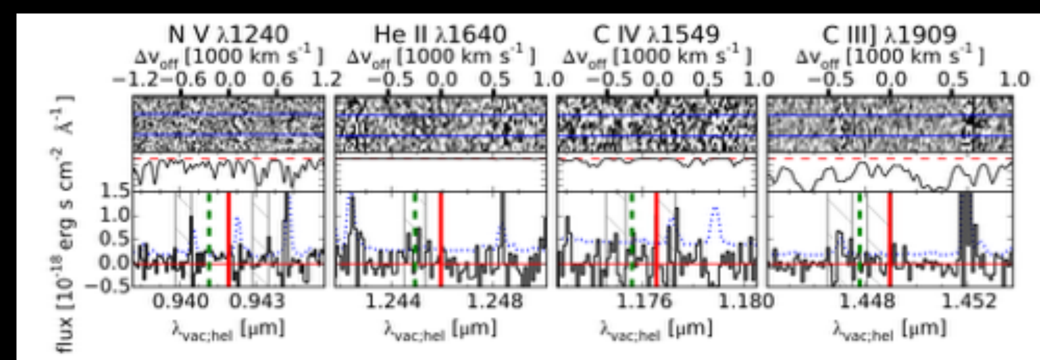
- AGN **- no metal lines, lines narrow, no X-ray, blue UV colours,** (although maybe direct collapse??)
- Wolf-Rayet stars **- HeII narrow (FWHM << 1000 km/s)** (but also the case at low metallicity??)
- Cooling radiation **- width lines, EUV flux**
- PopIII-*like* stars - but why so late (z=6.6), inefficient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

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



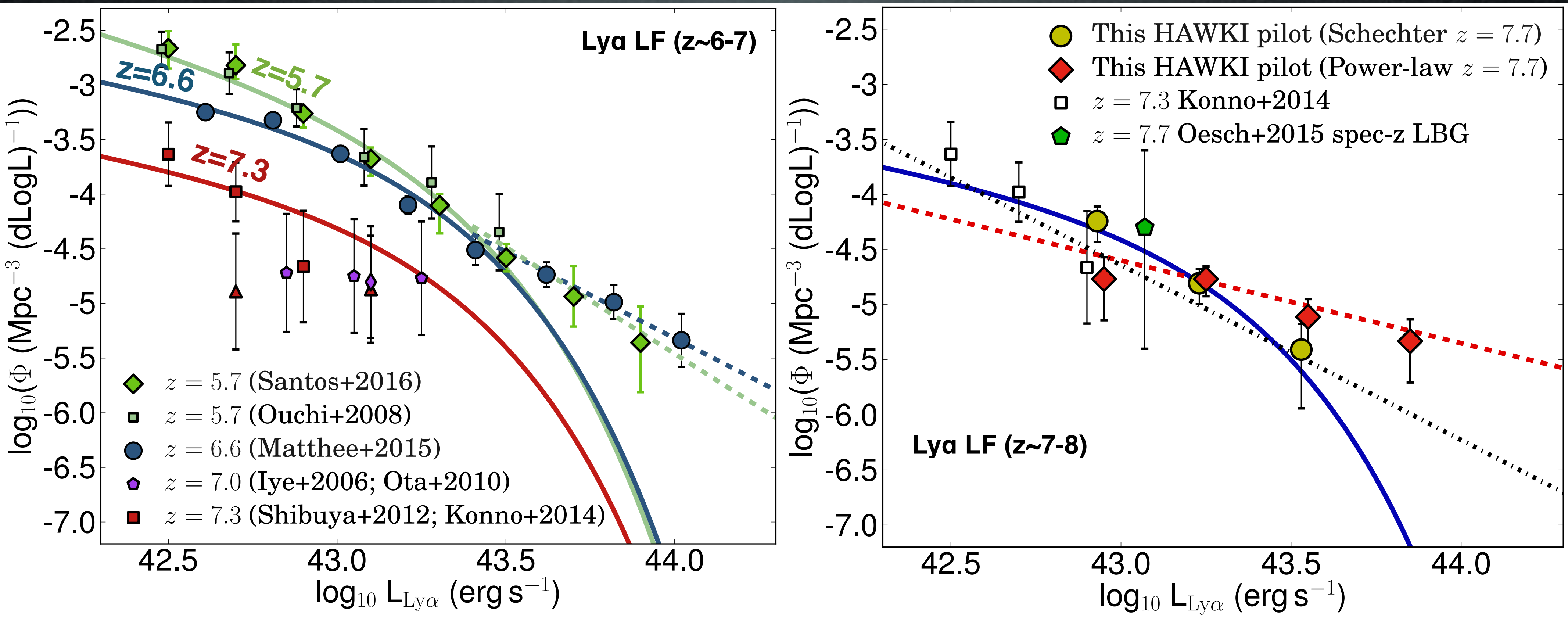


- Extended, luminous Lya
- Similar Lya FWHM, lower EW
- 3 clumps, the brightest is very blue
- separation ~ 0.5-1″
- no HeII, nor any other line



Ouchi+2009, Ouchi+2013, Zabl+2015

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?

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

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