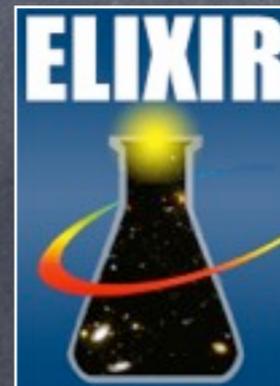


Spectroscopic Analysis of Primeval Galaxy Candidates

- Joseph Caruana -

Andrew Bunker, Stephen Wilkins, Silvio Lorenzoni



Aims of the Project

- Does Lyman- α emerge during the epoch of reionization?

Aims of the Project

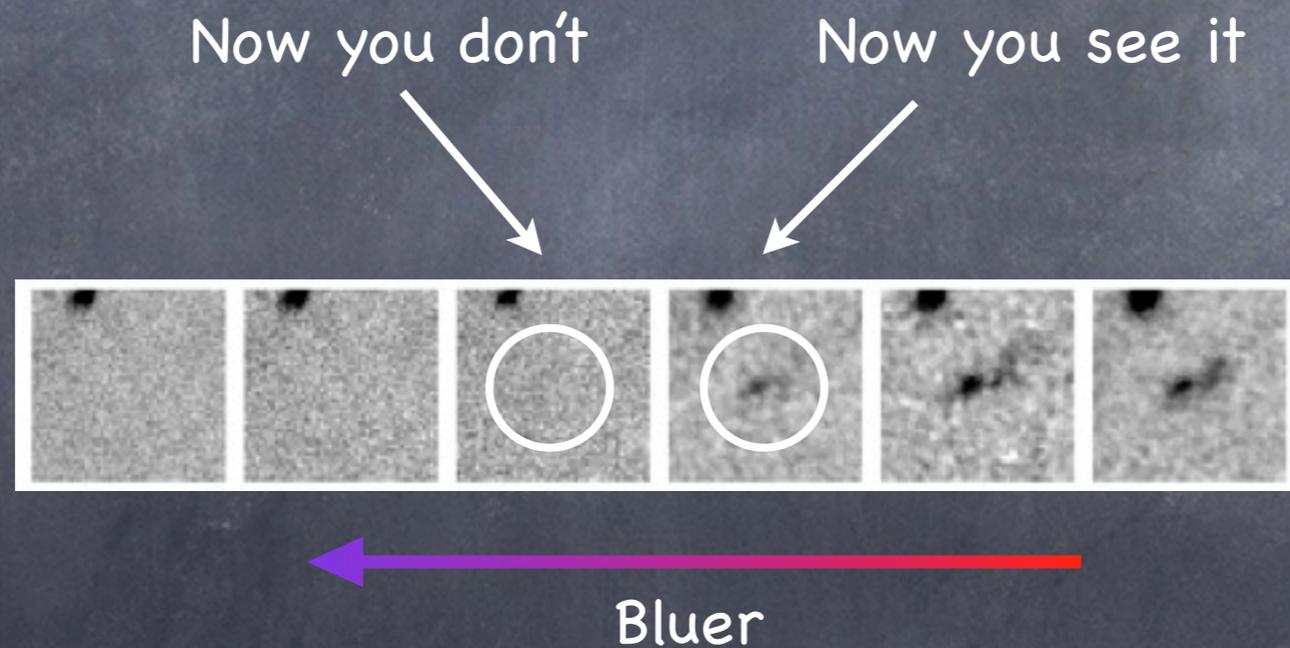
- Confirm the redshift of any targeted galaxy candidates exhibiting Lyman- α .

Aims of the Project

- Use the observed fraction of Lyman- α emitters to infer the neutral fraction of Hydrogen at $z > 7$

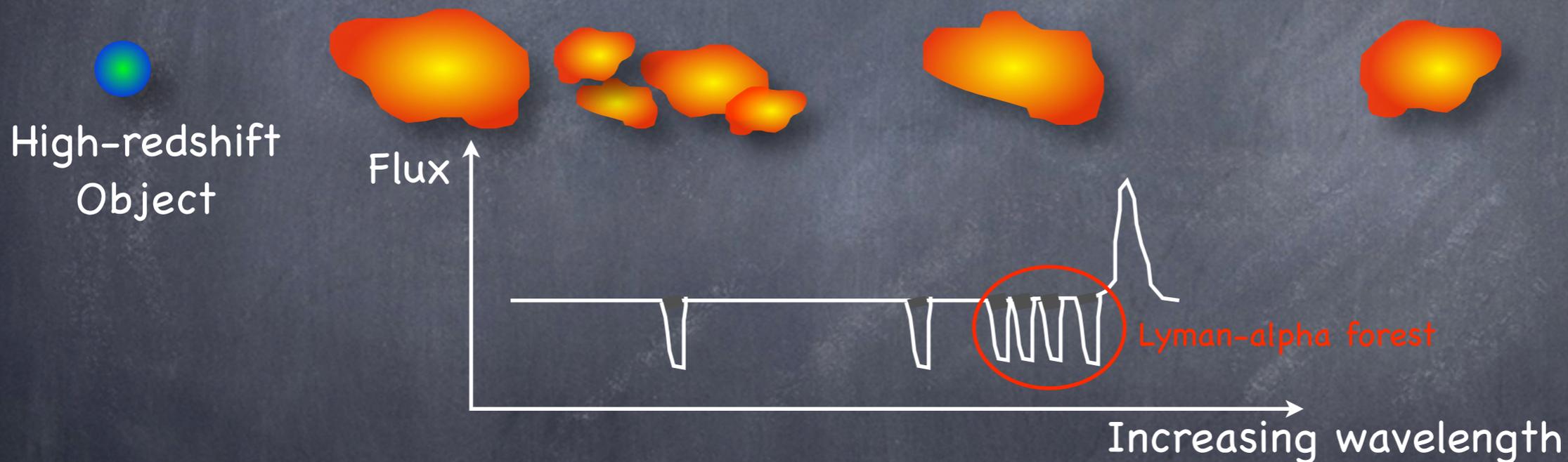
Candidate Selection

Lyman-break technique:

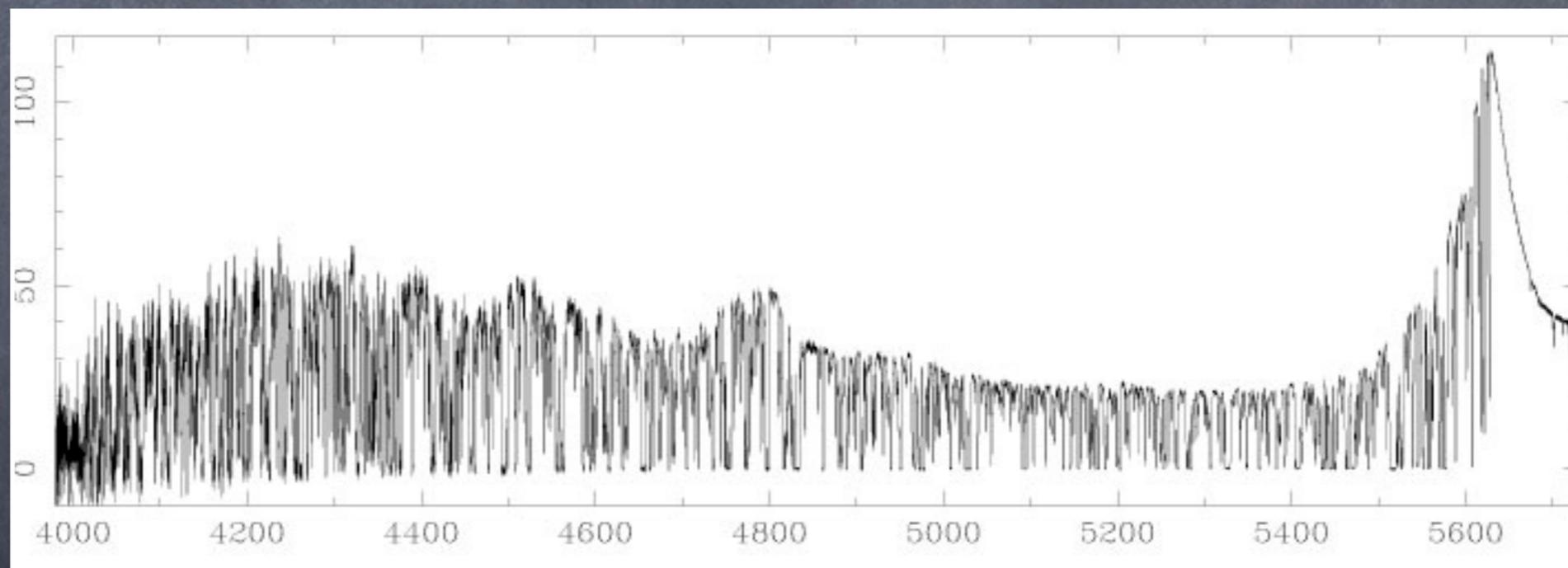


Candidate Selection

Lyman-break technique:



Candidate Selection



High resolution spectrum of QSO 1422+23 (Womble et al. 1996)



Joseph Caruana, University of Oxford ~ ELIXIR, Leiden, November 2012

Spectroscopically confirmed sample

Vanzella et al. (2011): 2 at about $z=7$
Schenker et al. (2011): 3 at about $z=7$
Iye et al. (2011): 1 at about $z=7$
Ono et al. (2011): 2 at about $z=7$
Pentericci et al. (2011): 5 at about $z=7$

Total: 13 spectroscopically confirmed objects at about $z=7$

Spectroscopy at high- z

- Near IR spectroscopy is not quite easy.
- Higher readout noise and dark current
- OH lines (having better resolution helps)
- Atmospheric sky background is very variable
Necessitates frequent sky dithering to obtain good background subtraction.



Spectroscopy at high- z

- Gemini / GNIRS
- VLT / X-SHOOTER
- VLT / FORS2
- Subaru / MOIRCS

Spectroscopy with GEMINI/GNIRS



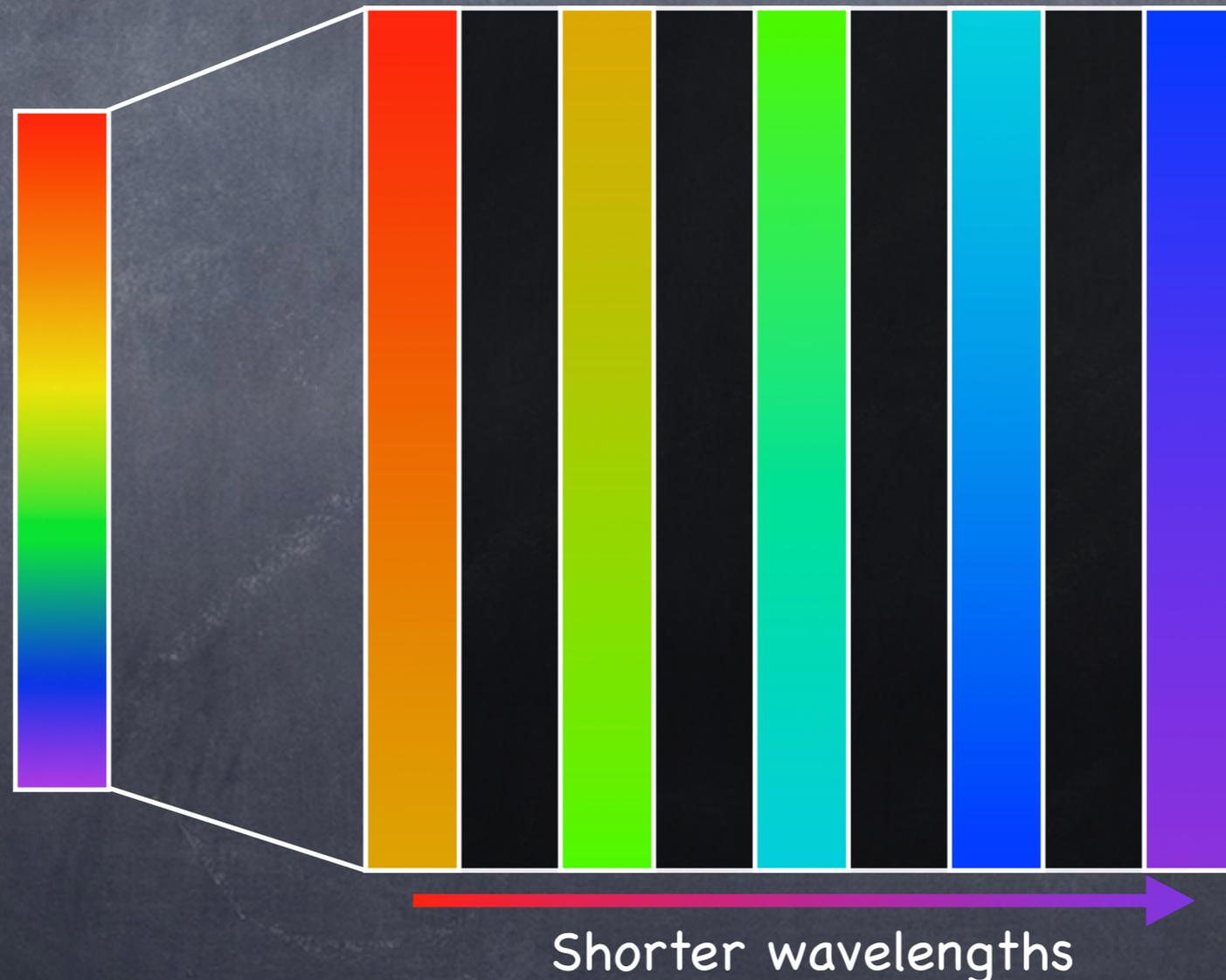
Gemini South



Gemini Near Infrared Spectrograph (GNIRS)

Spectroscopy with GEMINI/GNIRS

- The data approximately span the wavelength region between 0.84 and 2.4 microns.
- The data were obtained in cross-dispersed mode.

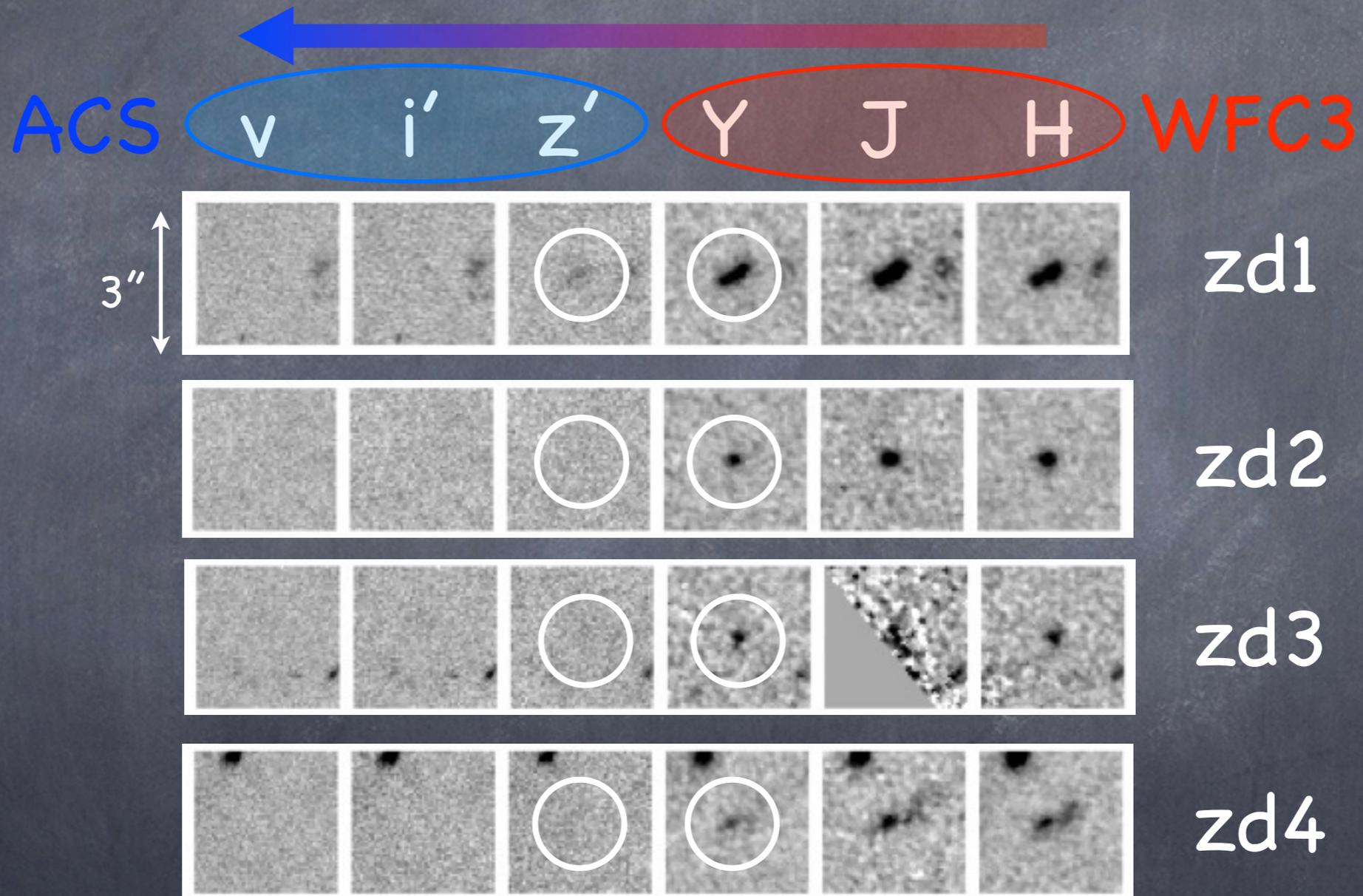


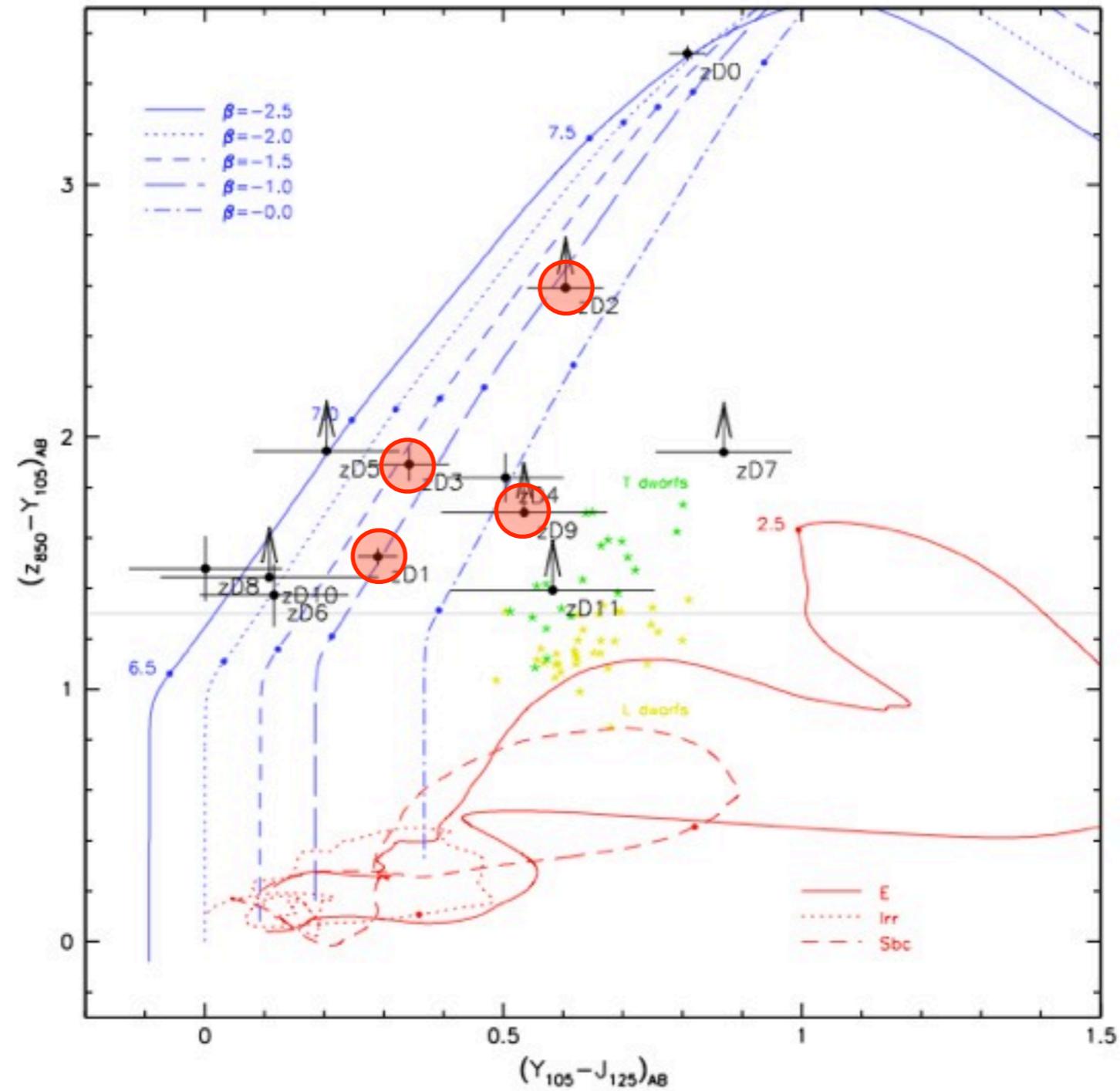
Spectroscopy with GEMINI/GNIRS

Object	Y-magnitude
HUDF.ZD1	26.71 ± 0.03 (Y_{098m}/Y_{105W})
HUDF.ZD2	27.48 ± 0.06 (Y_{098m}/Y_{105W})
HUDF.ZD3	27.5 ± 0.07 (Y_{098m}/Y_{105W})
HUDF.ZD4	27.84 ± 0.09 (Y_{AB})

zdrop2, zdrop5, UDF.572, UDF.845

Candidate Selection

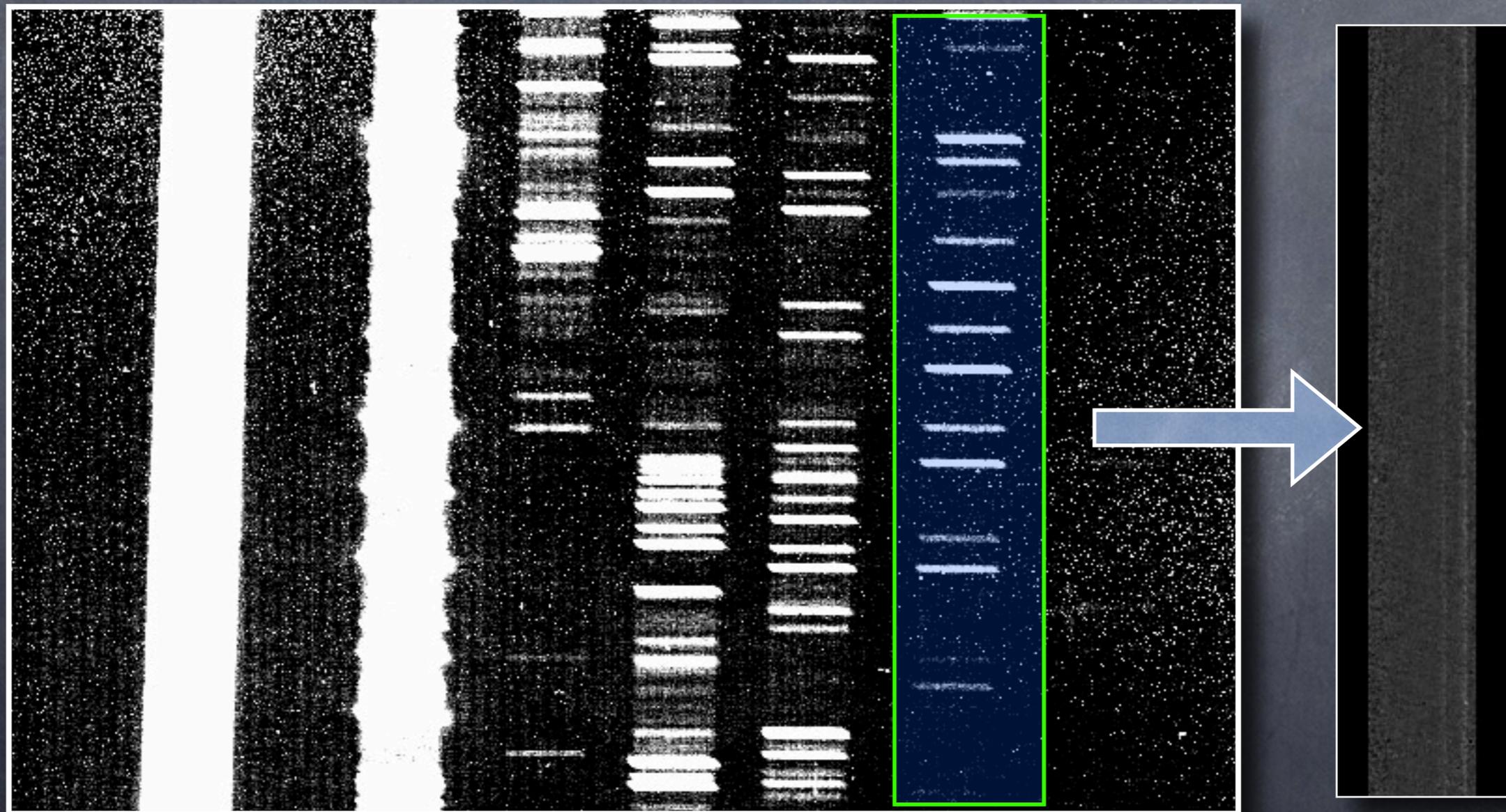




Bunker et al 2010

Spectroscopy with GEMINI/GNIRS

Data Reduction



Spectroscopy with GEMINI/GNIRS

Assess the noise

Use Poisson Statistics to predict the noise



Measure actual noise



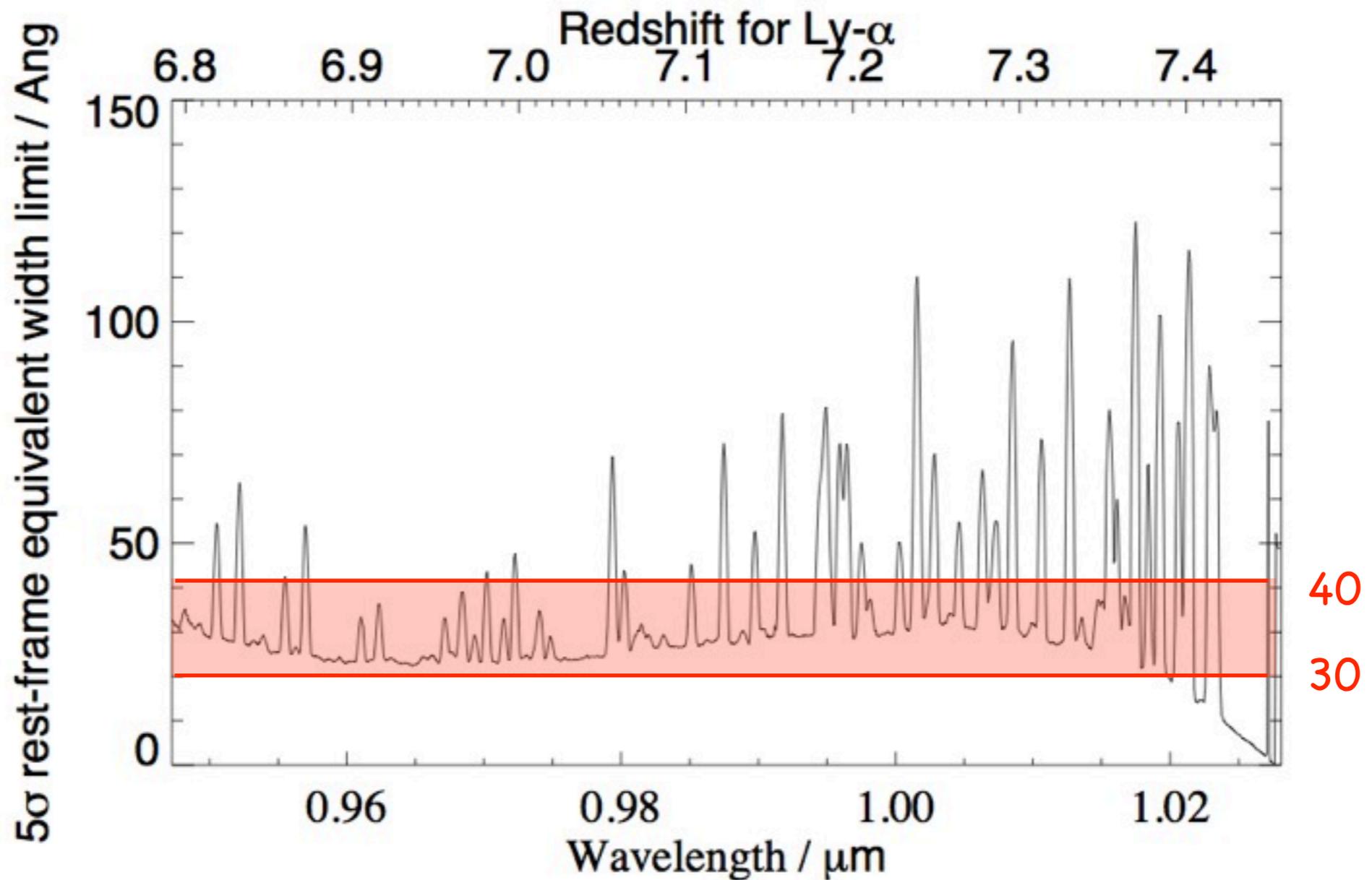
Spectroscopy with GEMINI/GNIRS

In brief:

We do not detect any Lyman- α emission in our GNIRS sample.

zD1

Caruana et al. (2012)



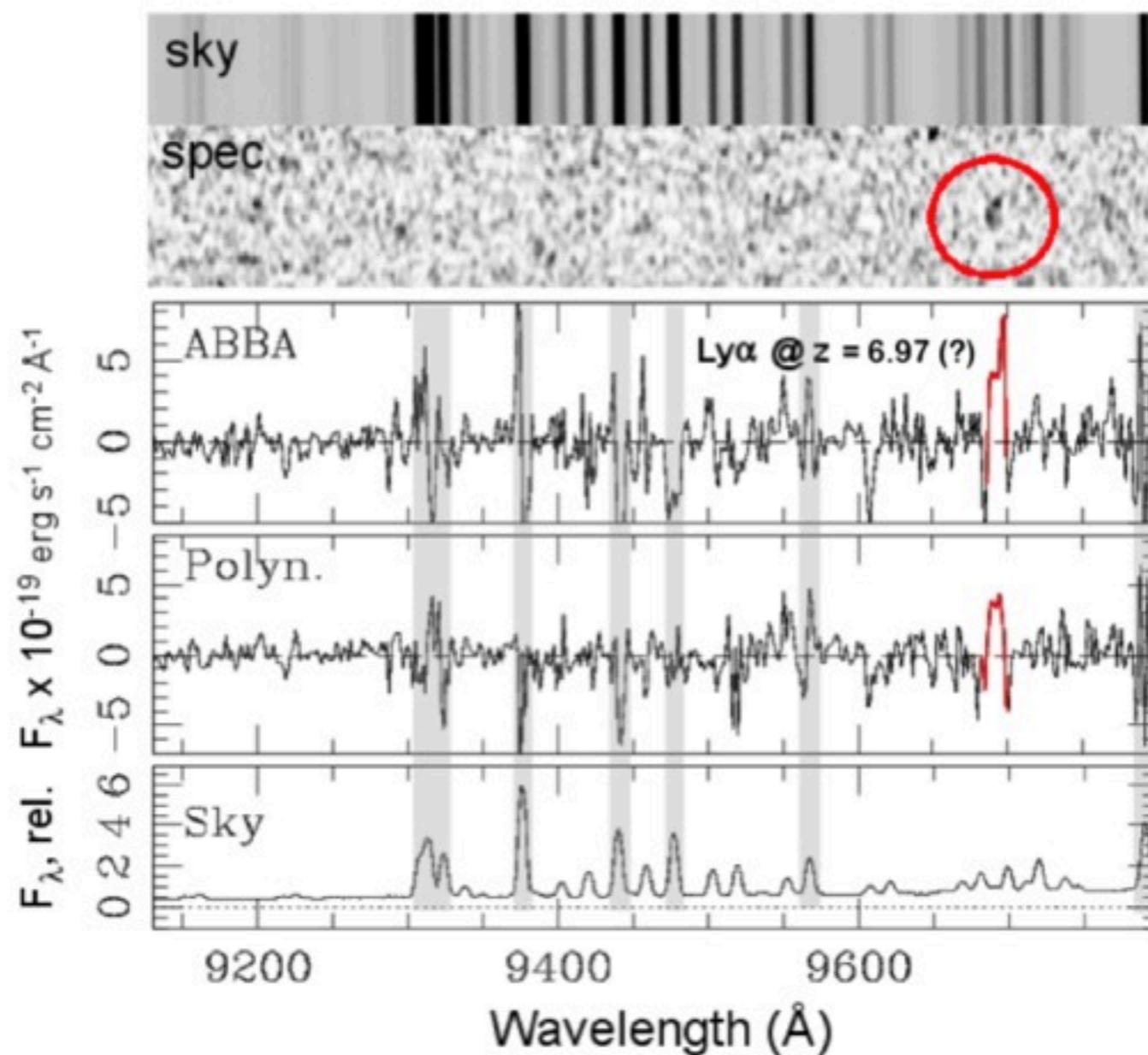
5 σ rest frame EW limit

Comparison with Fontana et al. (2010)

- Ultra deep optical spectroscopy obtained with FORS2 on VLT of seven Lyman-break galaxy (LBG) candidates at $z > 6.5$
- One tentative emission line, placing the object at $z=6.97$

Comparison with Fontana et al. (2010)

G2-1408
(zD1)

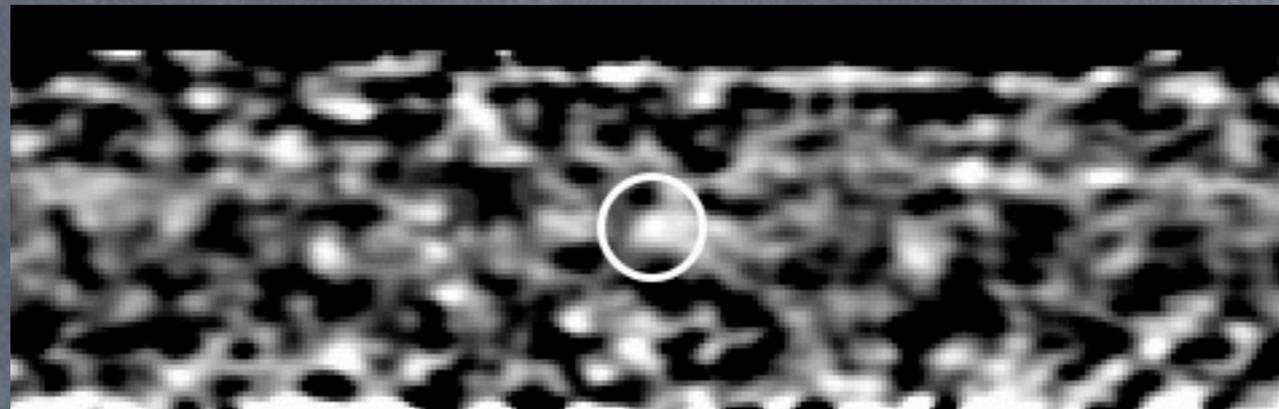


Detect a low significance
emission line ($S/N < 7$)

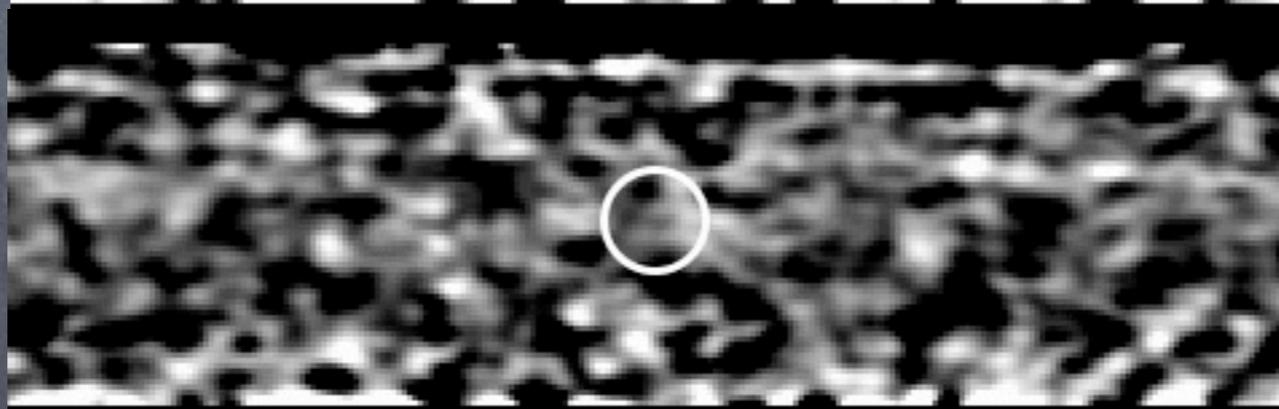
Flux:
 $3.4 \times 10^{-18} \text{ erg/cm}^2/\text{s}$

Comparison with Fontana et al. (2010)

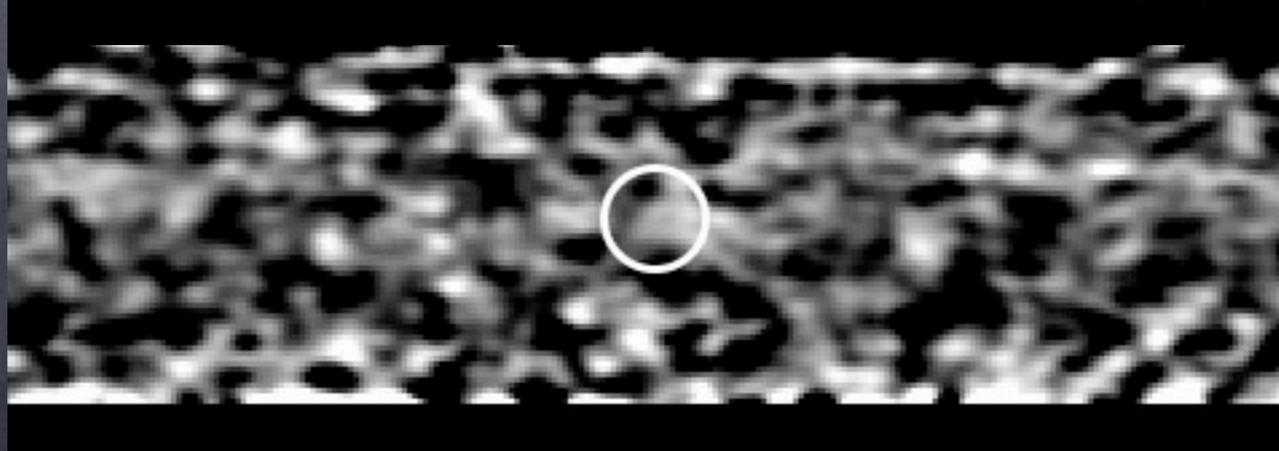
5-sigma



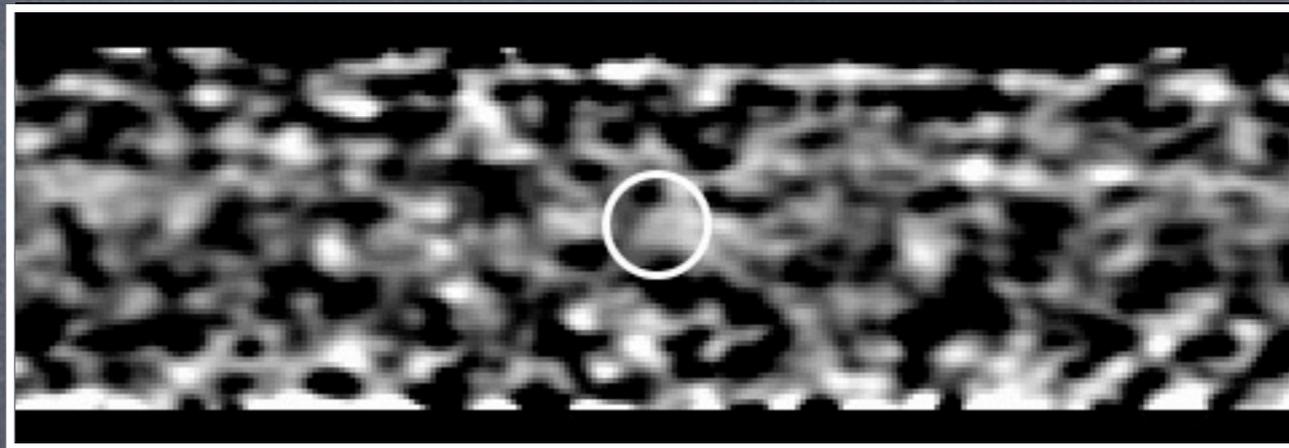
Observed



Fontana
et al.

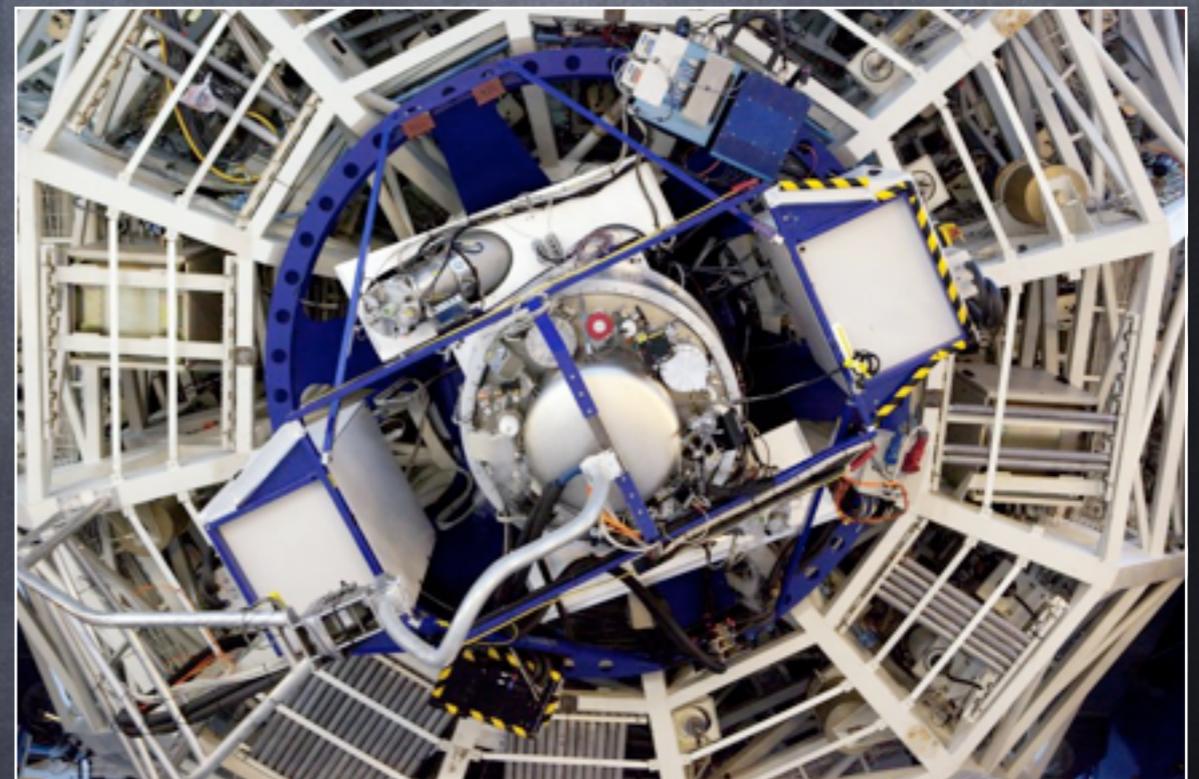


Comparison with Fontana et al. (2010)



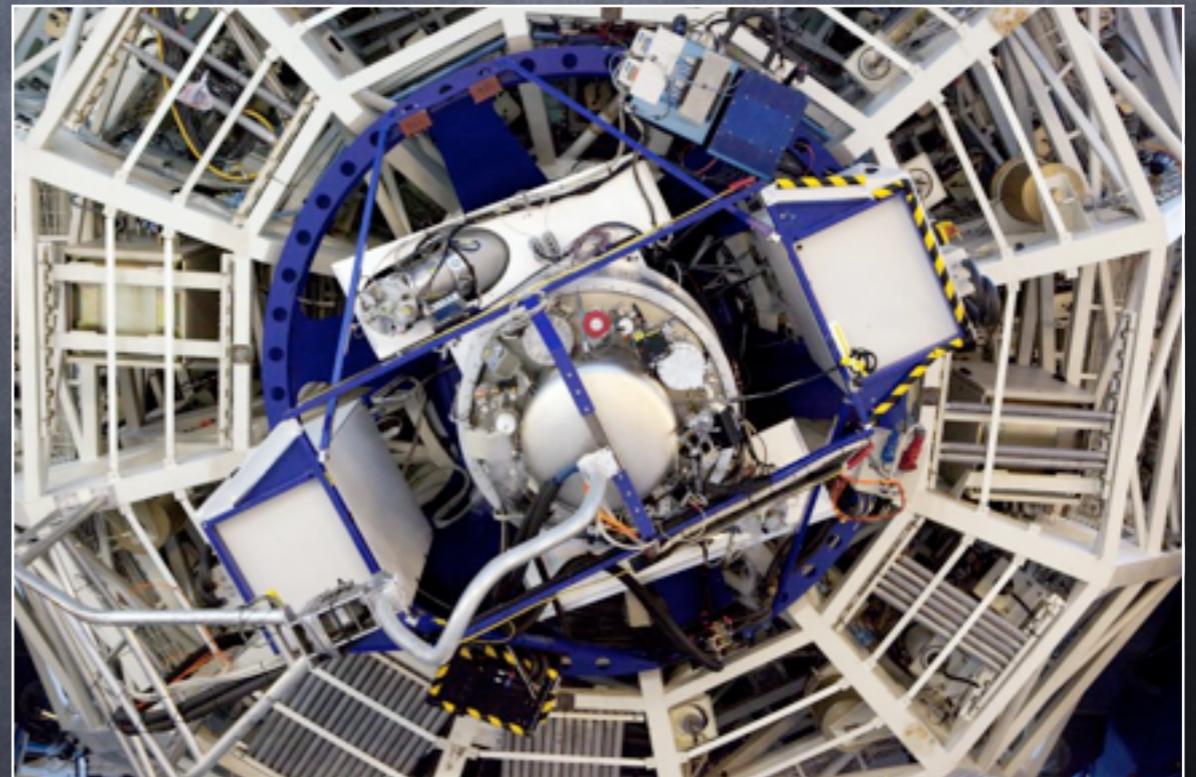
Spectroscopy with VLT/XSHOOTER

086.A-0968(B) (PI: A. Bunker)

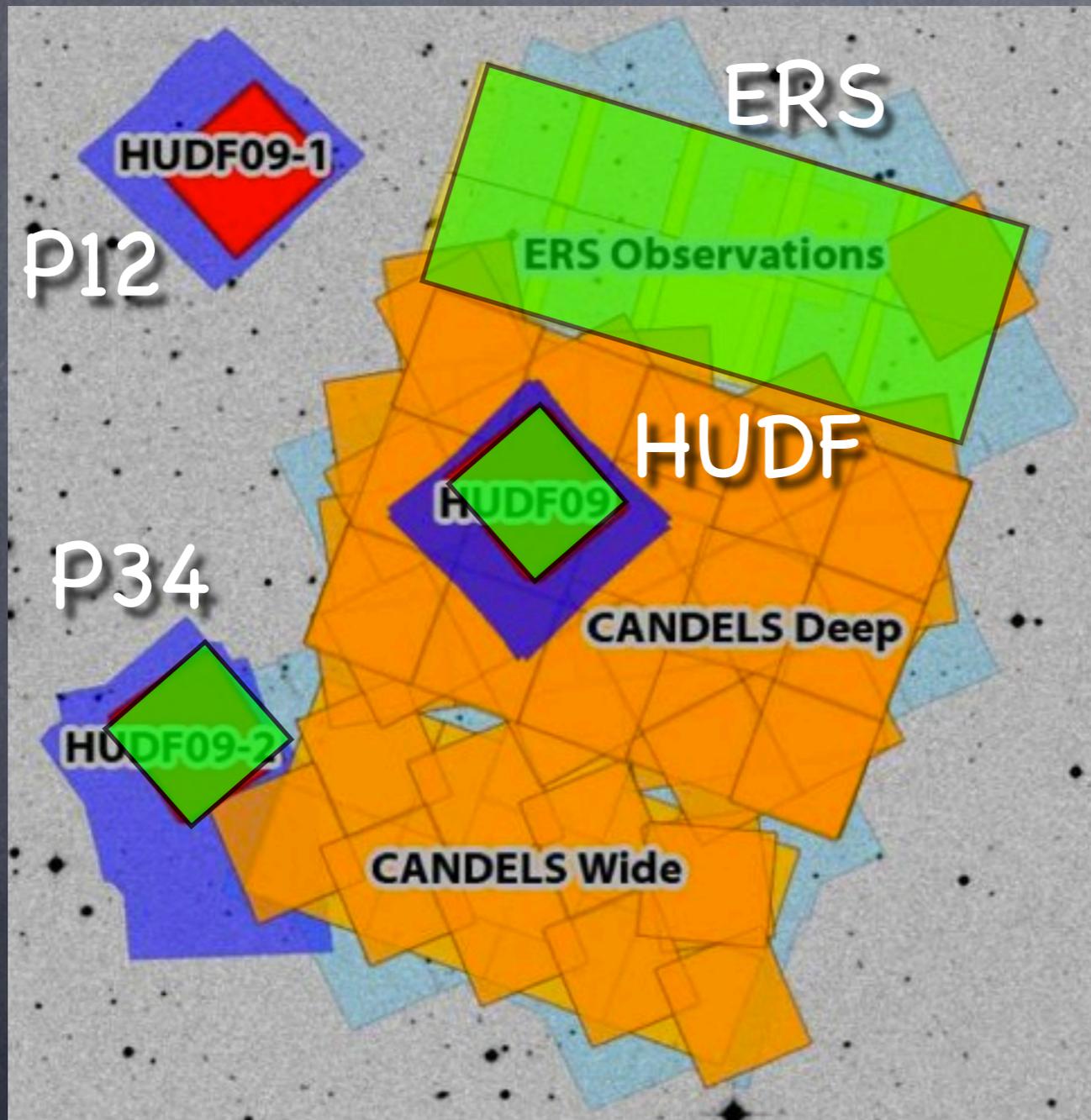


Spectroscopy with VLT/XSHOOTER

- XSHOOTER is an echelle spectrograph
- UV, visible and near-IR channels
- Near-continuous spectroscopy between $0.3 \mu\text{m}$ and $2.48 \mu\text{m}$.
- We used the near-IR channel



Spectroscopy with VLT/XSHOOTER



- HUDF.YD3
- ERS.YD2
- - P34.Z.4809

Bouwens et al. (2011)

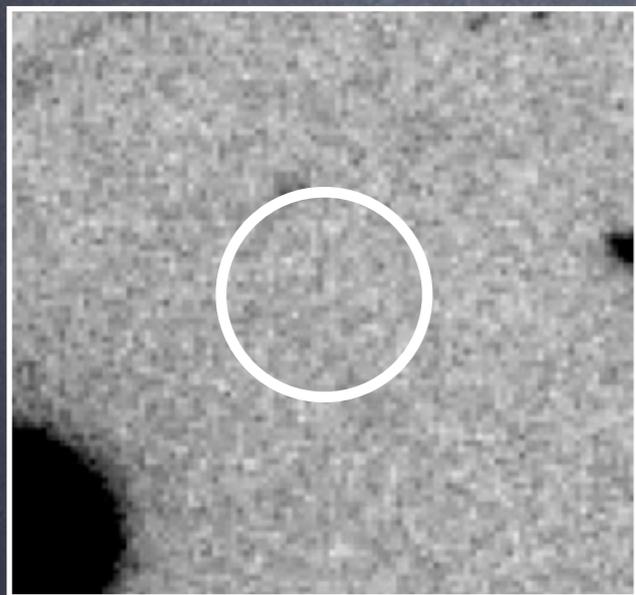
Spectroscopy with VLT/XSHOOTER

P34.Z.4809 (Wilkins et al. 2010)

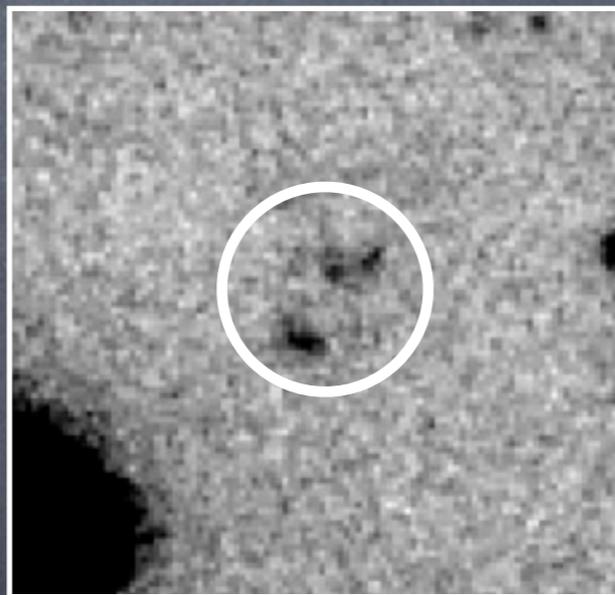


Spectroscopy with VLT/XSHOOTER

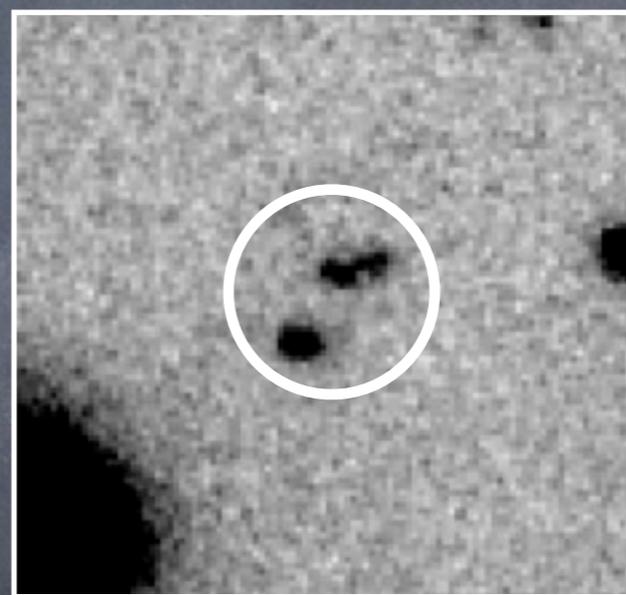
P34.Z.4809 (Wilkins et al. 2010)



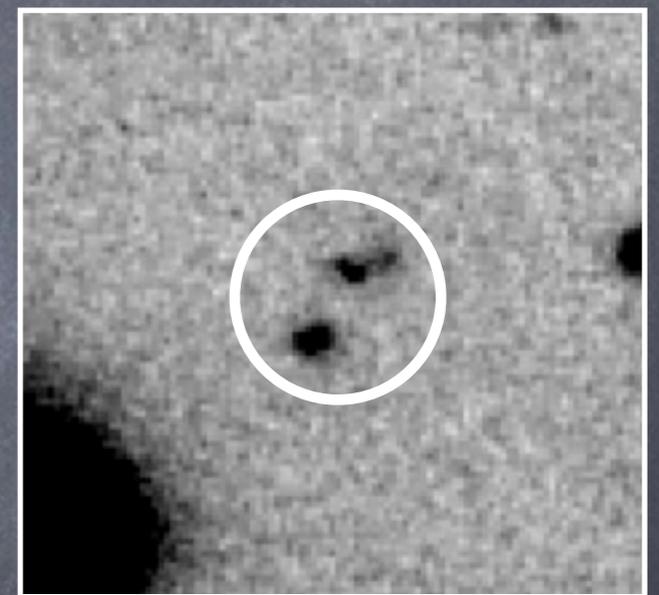
z'



Y

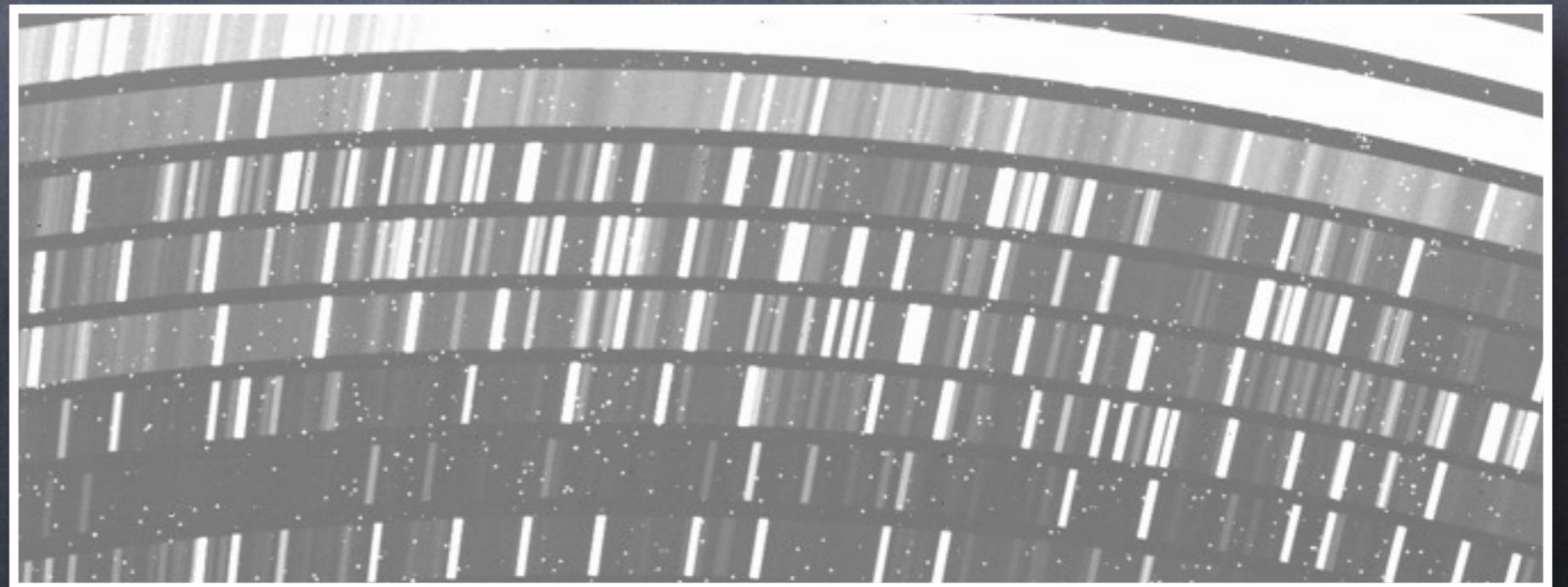
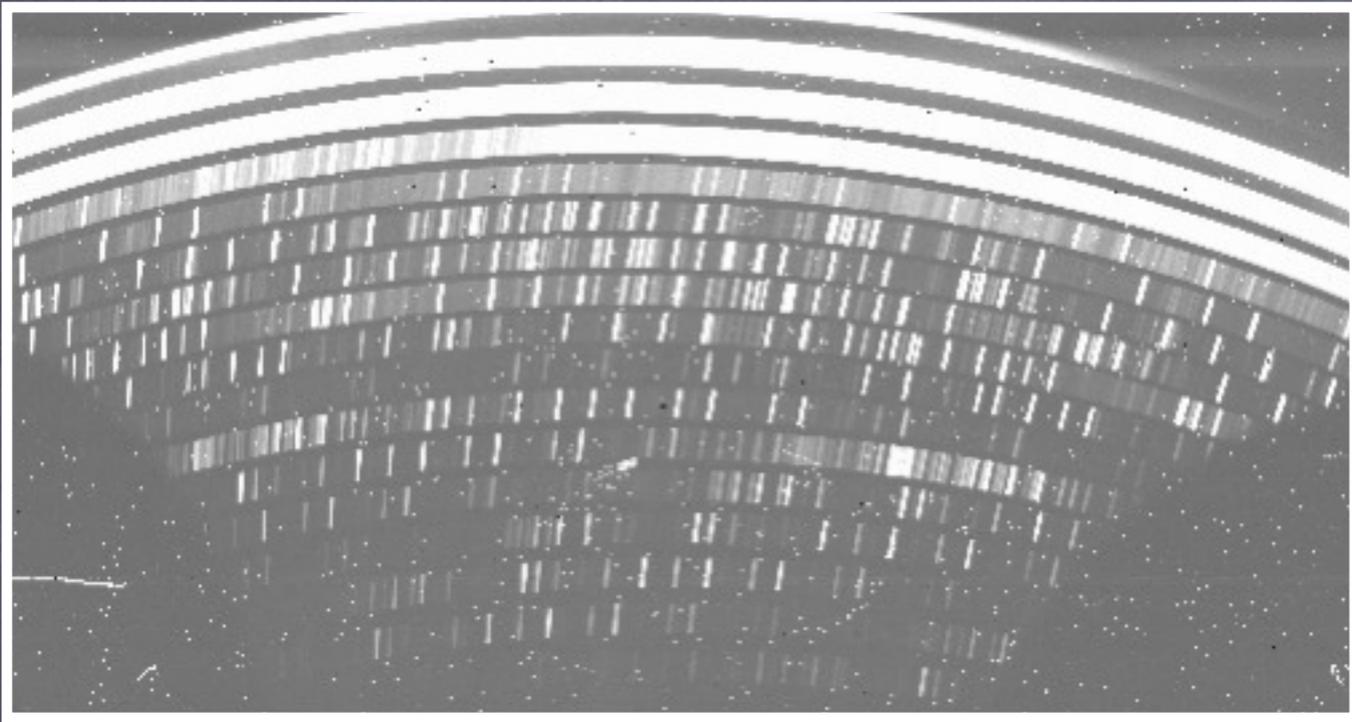


J



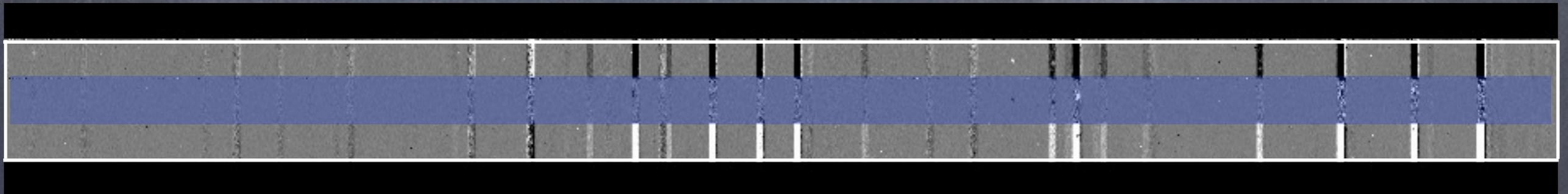
H

Spectroscopy with VLT/XSHOOTER



Spectroscopy with VLT/XSHOOTER

P34.Z.4809 (Wilkins et al. 2010)



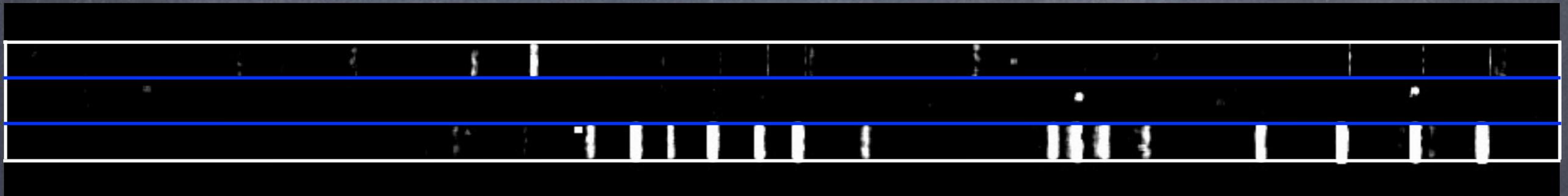
Caruana et al. (2012)

2D combined spectrum
We do NOT detect Lyman-

α

Spectroscopy with VLT/XSHOOTER

P34.Z.4809 (Wilkins et al. 2010)

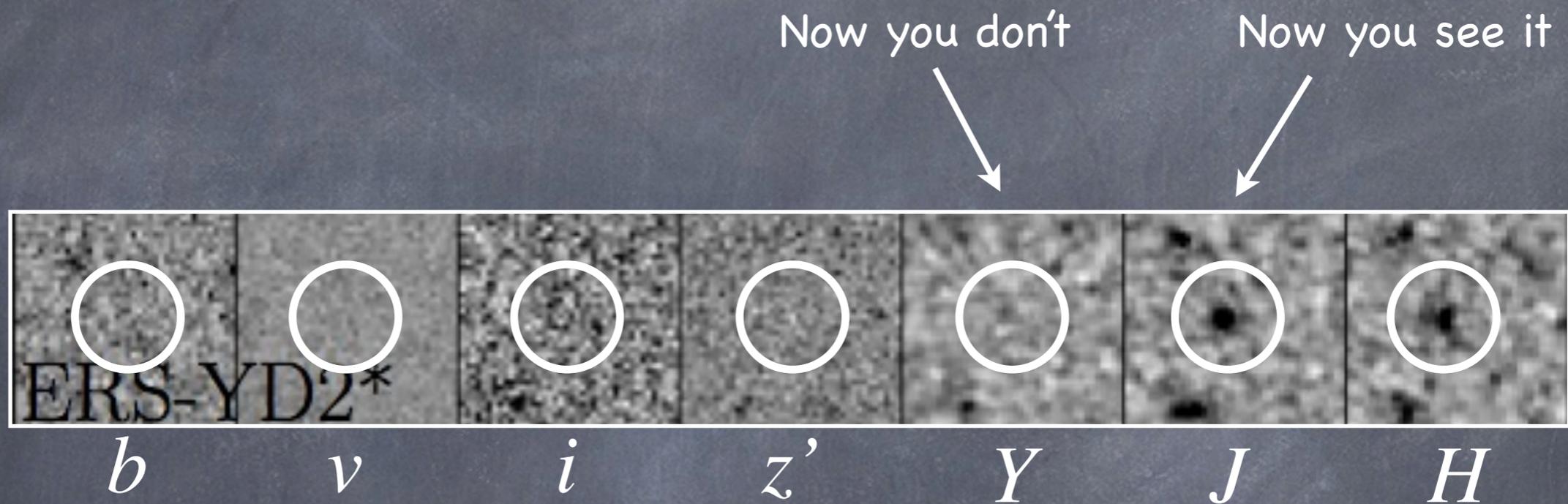


Caruana et al. (2012)

Thresholding above a certain σ
Insert fake sources to test recoverability

Spectroscopy with VLT/XSHOOTER

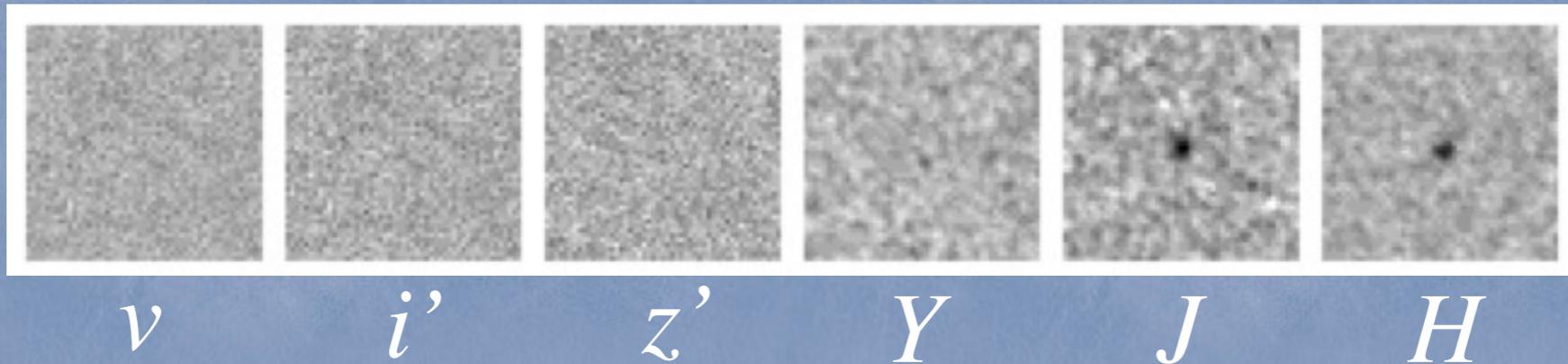
ERS.YD2 (Lorenzoni et al. 2011)



We do NOT detect Lyman- α emission

HUDF.YD3

HUDF.YD3 in Bunker et al. 2010



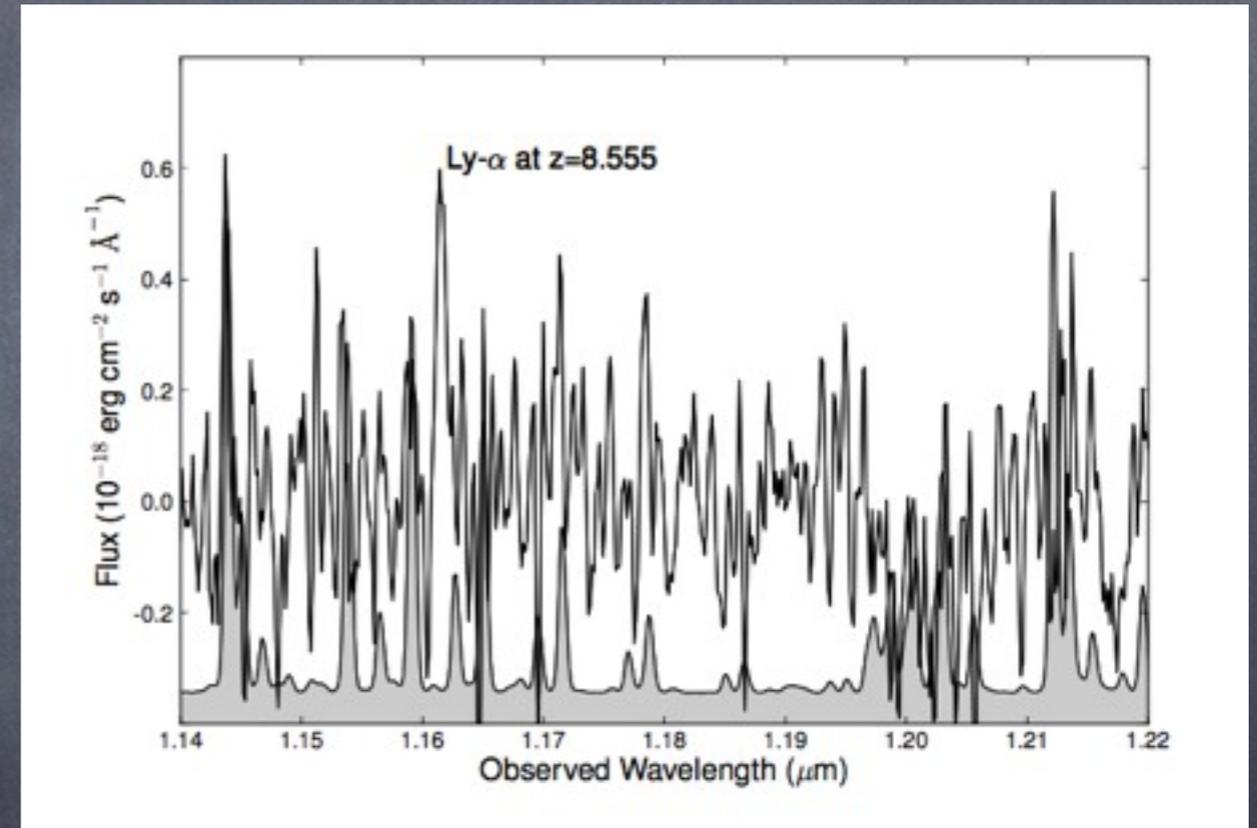
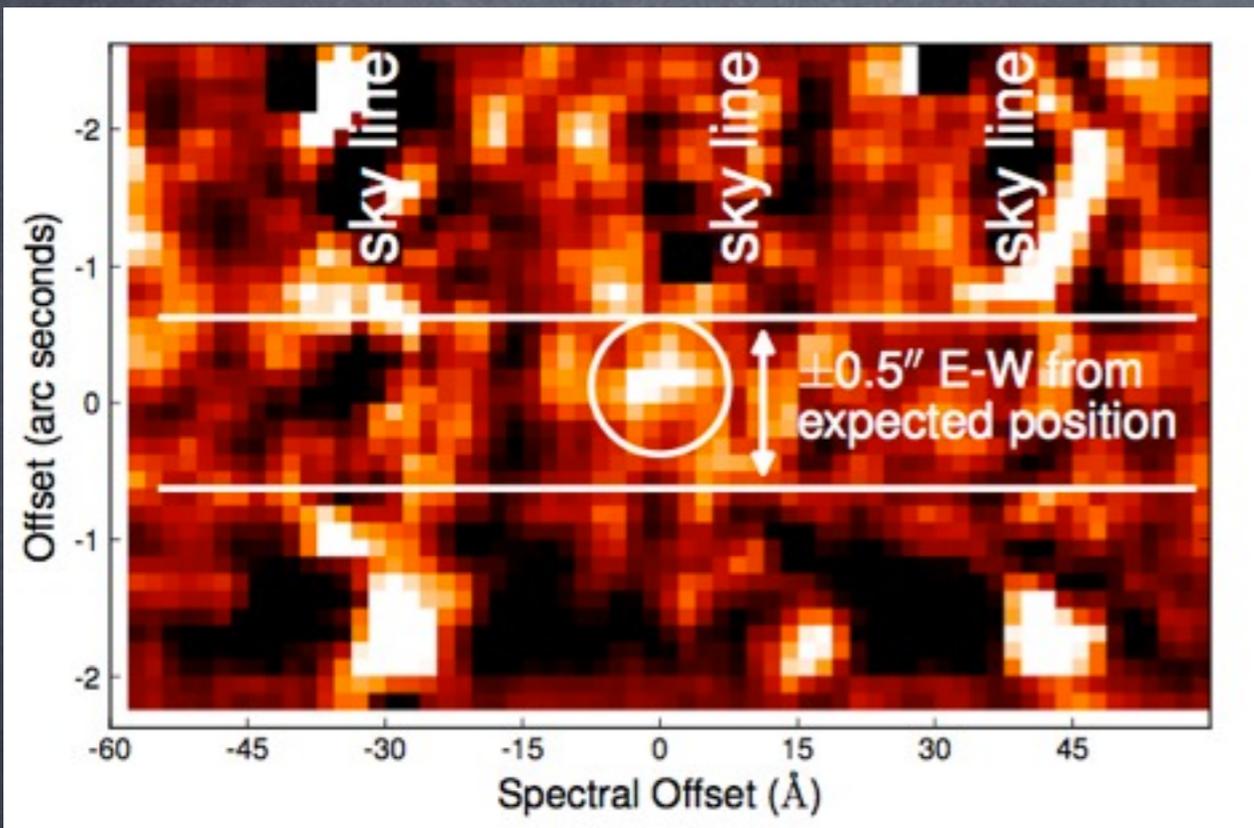
Object 1721 in McLure et al. 2010

UDFy-38135539 in Bouwens et al. 2010

HUDF.YD3

Lehnert et al. (2010)

VLT/SINFONI



Claim a 6-sigma detection placing the object at $z=8.55$

Flux: $(6.1 \pm 1.0) \times 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1}$

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20 October 2010 Last updated at 17:44 GMT

3,072 Share

Galaxy is most distant object yet

By Jonathan Amos

Science correspondent, BBC News



News

Most distant galaxy ever found sheds light on infant cosmos

Object allows astronomers a glimpse of Universe's era of 'reionization'.

Zeeya Merali

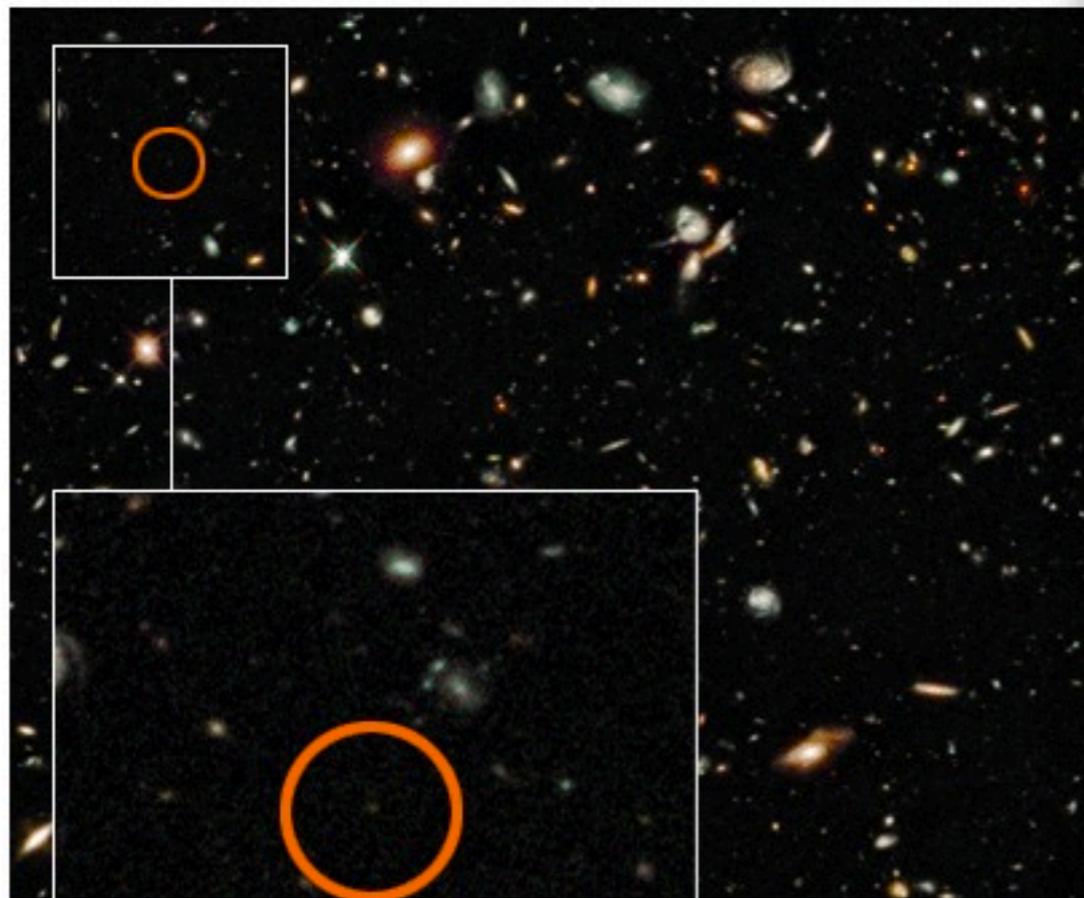
Observations of the most distant object yet discovered go a long way in supporting astronomers' models of the early Universe. But the far-flung galaxy, details of which are published in *Nature* today¹, also raises questions about the source of the first light in the cosmos.

Light from the galaxy, named UDFy-38135539, left the object just 600 million years after the Big



Light from a distant galaxy has provided a snapshot of the early universe.

ESO/L. Calçada

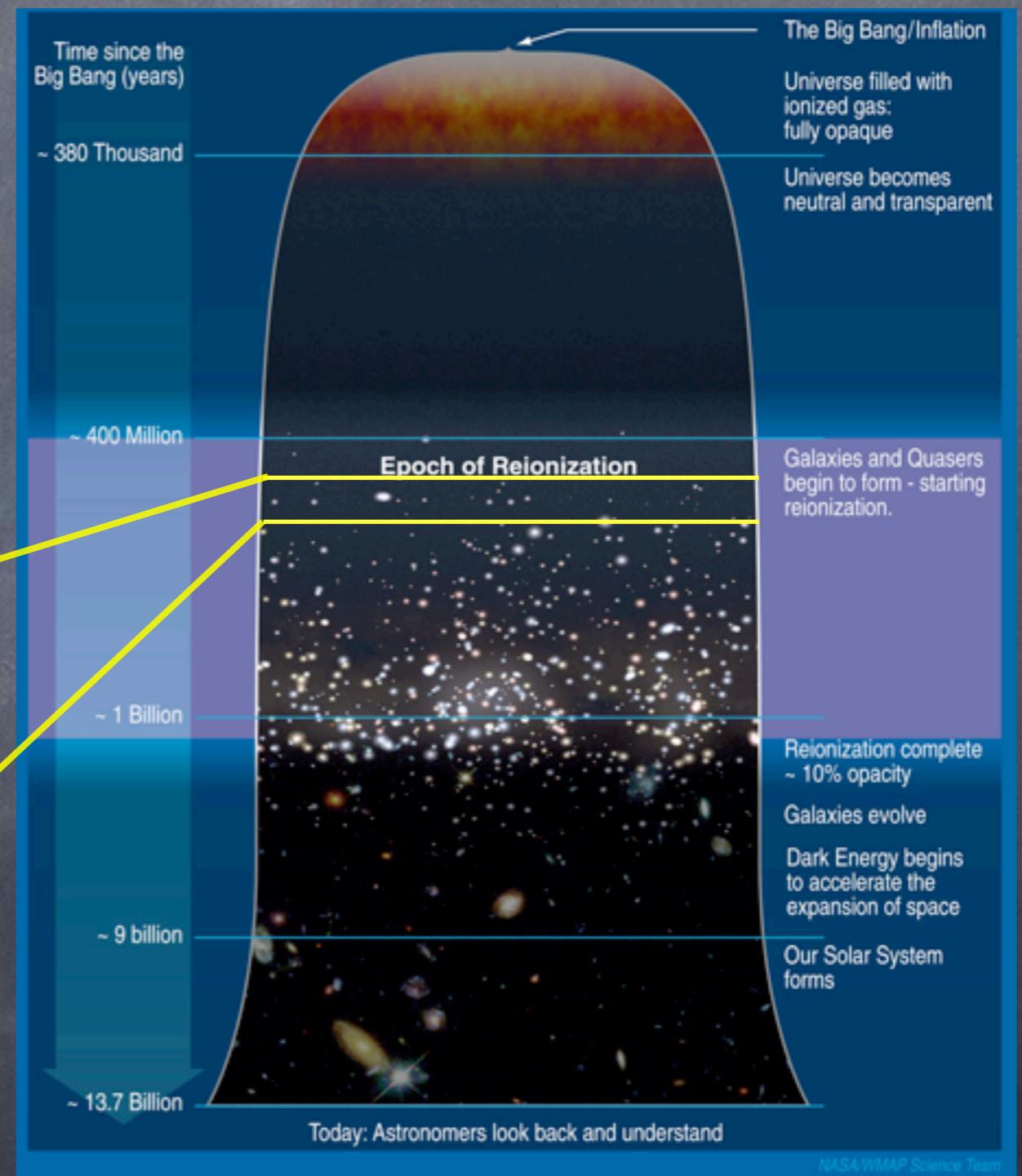


HUDF.YD3

Lyman- α might still be a useful redshift diagnostic for very distant galaxies, even at a time when most of the Universe is optically thick to this line.

Lehnert et al. (2010)
Age of the Universe: 574 Myr

Vanzella et al. (2011)
Age of the Universe: 735 Myr



HUDF.YD3 with VLT/XSHOOTER

- We dithered the observations in an ABBA sequence.
- Observed in 6 blocks of an hour each (49mins on source).

- 4.9-hour integration

- 4.1 hours in good seeing: $0.''5-0.''6$ FWHM
0.8 hours in worse seeing ($1.''2$ FWHM) } From HST imaging we conclude it is unresolved in our observations.

- Reduced data twice

Run 1: All frames

Run 2: Only those frames acquired in good seeing

HUDF.YD3 with VLT/XSHOOTER

- Reduction done in two ways:

- (1) ESO Pipeline (Modigliani et al. 2010)

Correlates noise due to interpolation

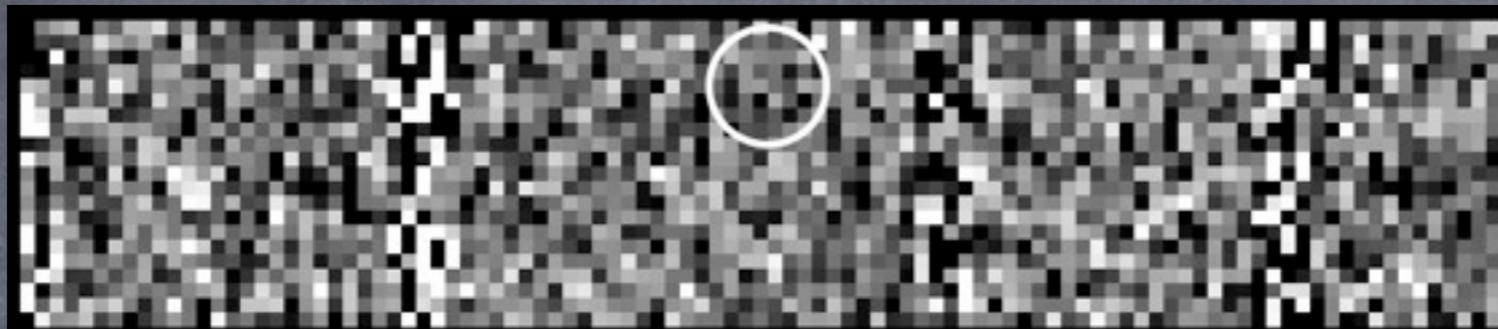
- (2) Our own custom reduction in IRAF

Keeps each pixel statistically independent

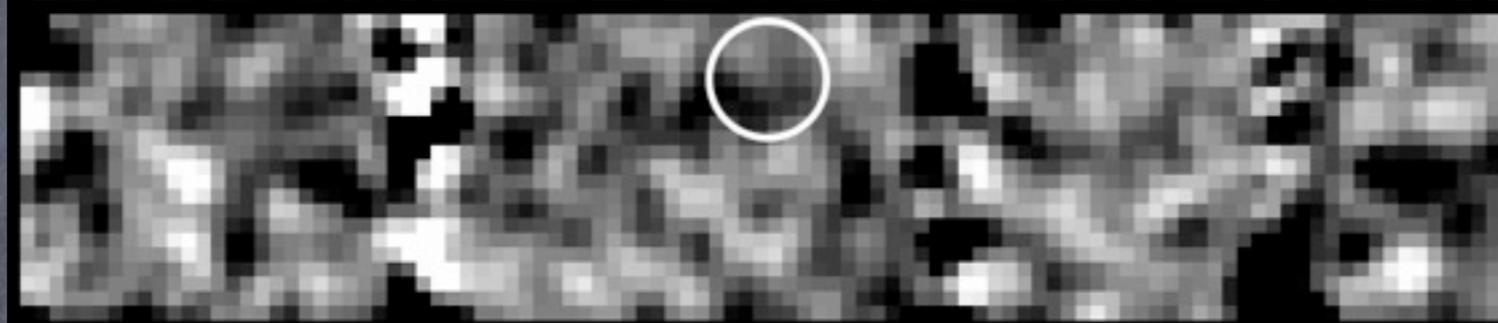
HUDF.YD3 with VLT/XSHOOTER

← 100Å →

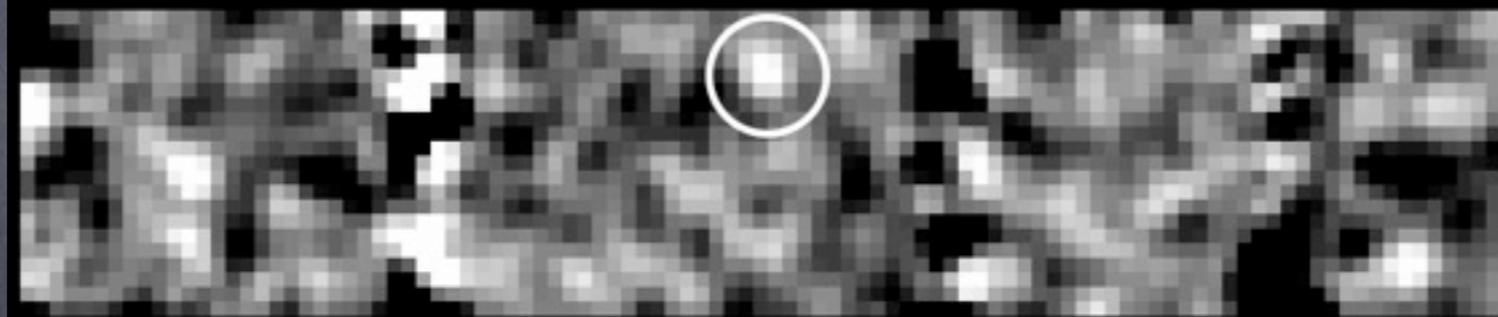
Observed



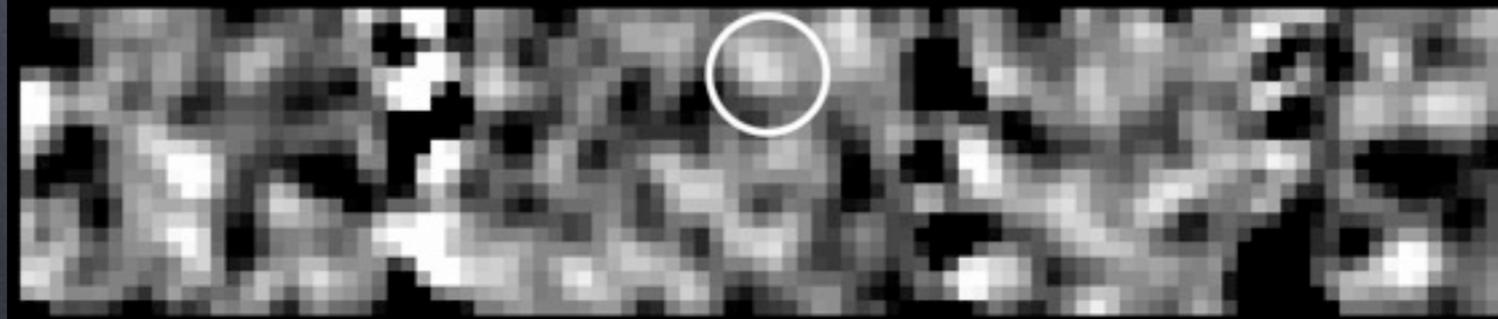
Observed
(gaussian
smoothed)



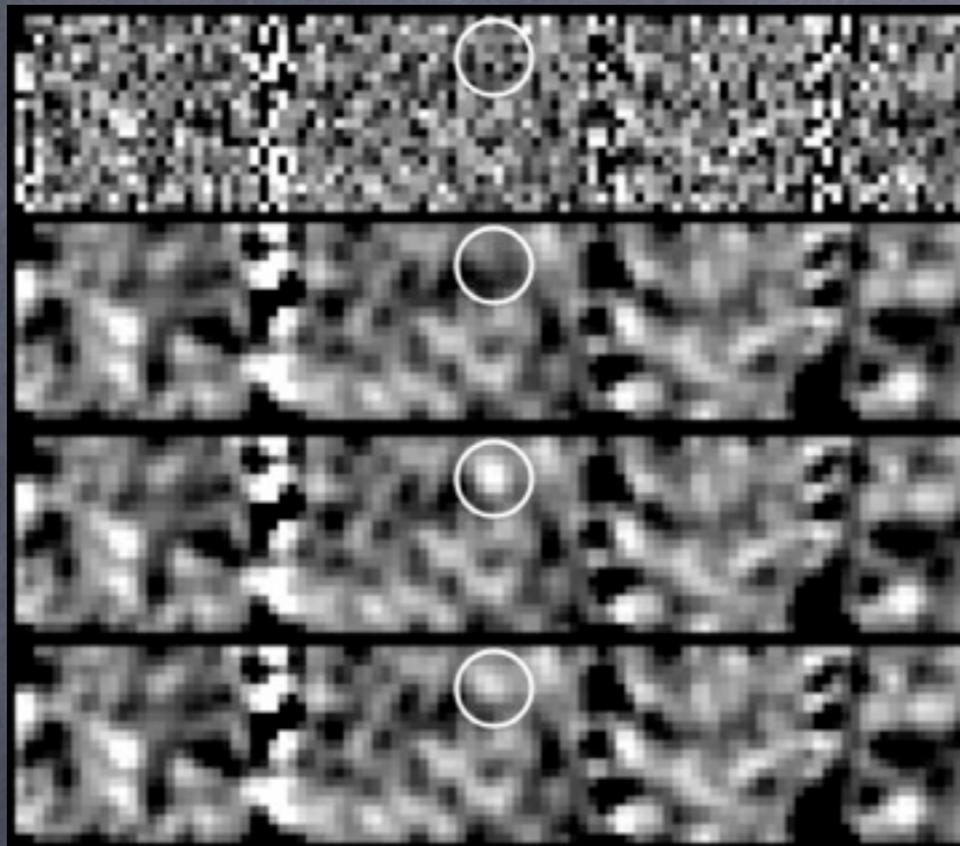
Unresolved
0.6" X 2.3Å



Resolved
0.6" X 5Å



HUDF.YD3 with VLT/XSHOOTER

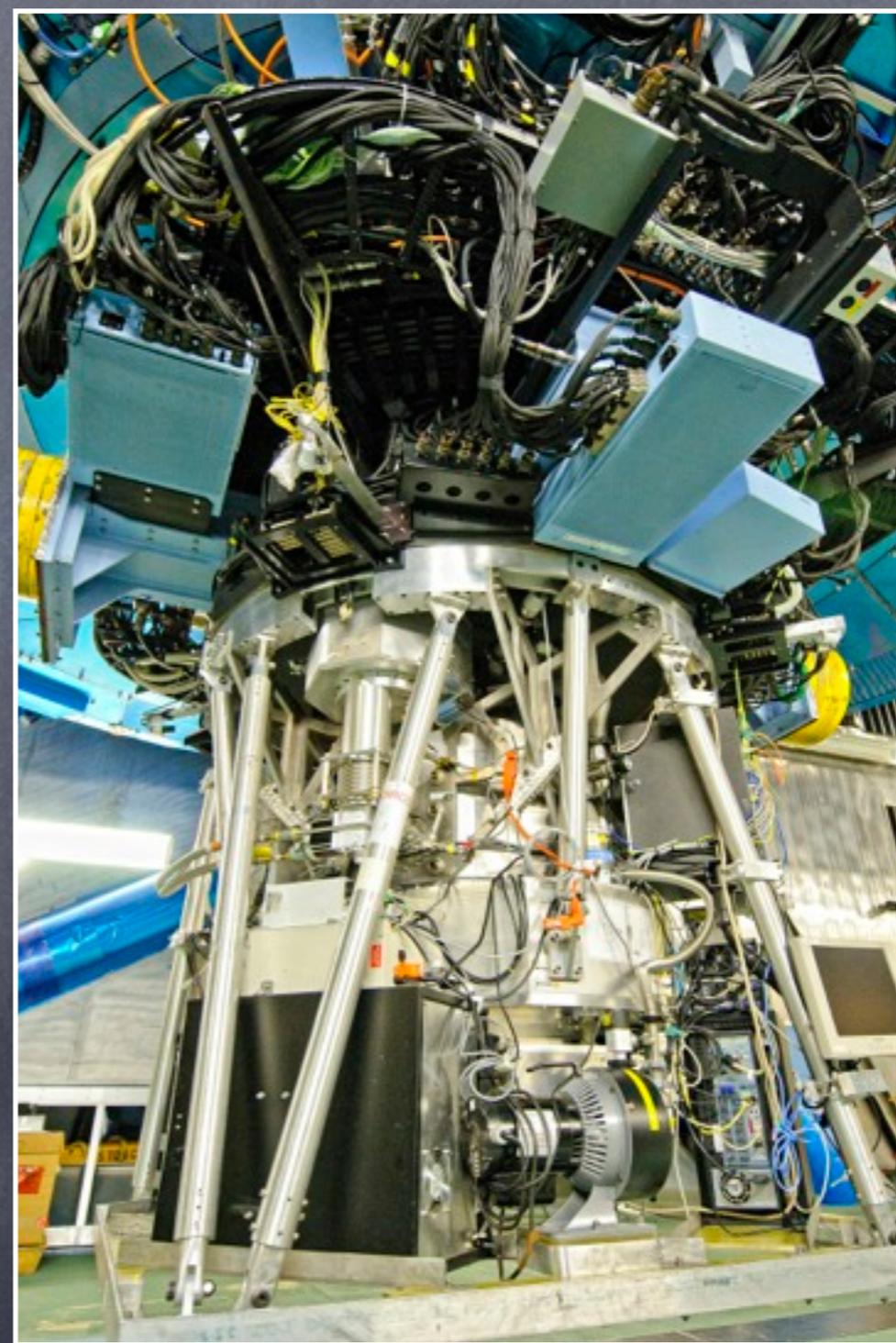


We do NOT see an emission line anywhere else either.

Meanwhile, up on a mountain...

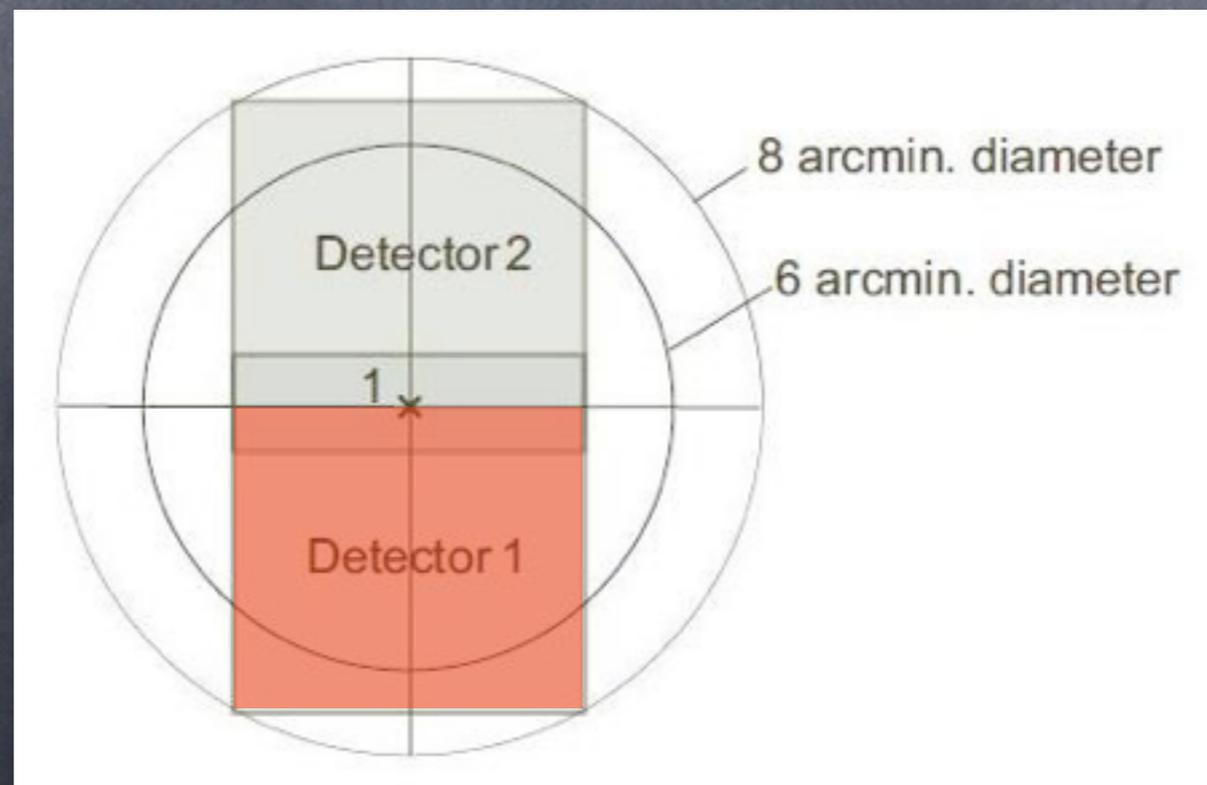


HUDFYD3 with SUBARU/MOIRCS



HUDF.YD3 with SUBARU/MOIRCS

- Multi-Object InfraRed Camera and Spectrograph (MOIRCS)
- 0.9 – 2.5 μm spectral range.
- 4'x7' field of view which is covered by two Hawaii-2 2048x2048 detectors.



HUDFYD3 with SUBARU/MOIRCS

October 21 2010

Seeing: 0."5

Slit-width: 1".0

8 X 1200sec
(2.67hrs)

2."5 dither
in ABABAB

October 22 2010

Seeing: 0."5

Slit-width: 1".0

12 X 1200sec
(4hrs)

2."0 dither
in ABABAB

December 07 2010

Seeing: 0."5

Slit-width: 0".7

12 X 1200sec
(4hrs)

2."0 dither
in ABABAB

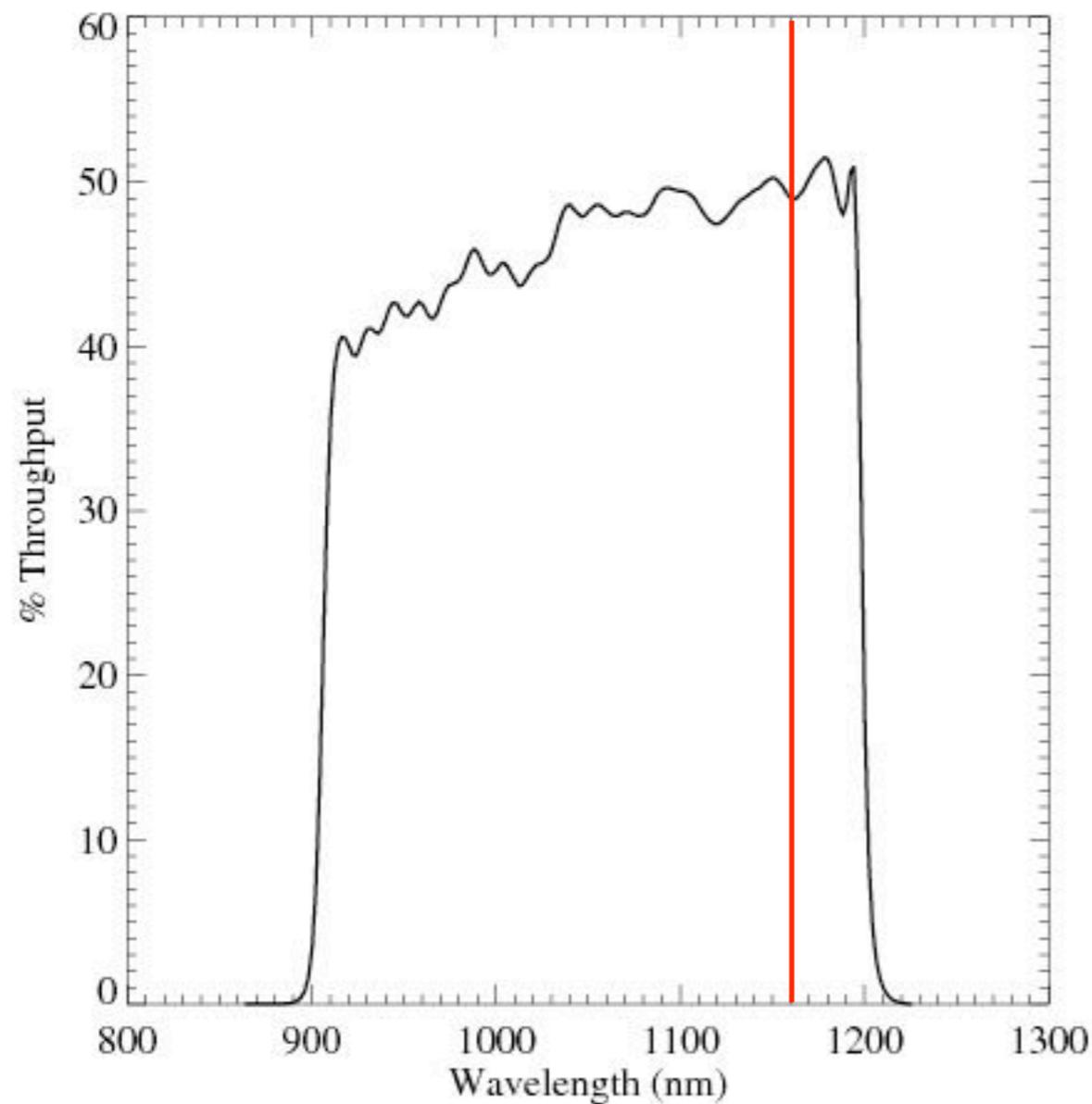
HUDF.YD3 with SUBARU/MOIRCS
with VLT/XSHOOTER

2.7 σ with SUBARU/MOIRCS

3.5–4.5 σ with VLT/XSHOOTER

We rule out the Lehnert et al. (2010)
line flux at the 5 σ level from our
spectroscopy.

HUDF.YD3 with HST/WFC3 photometry



Expect:

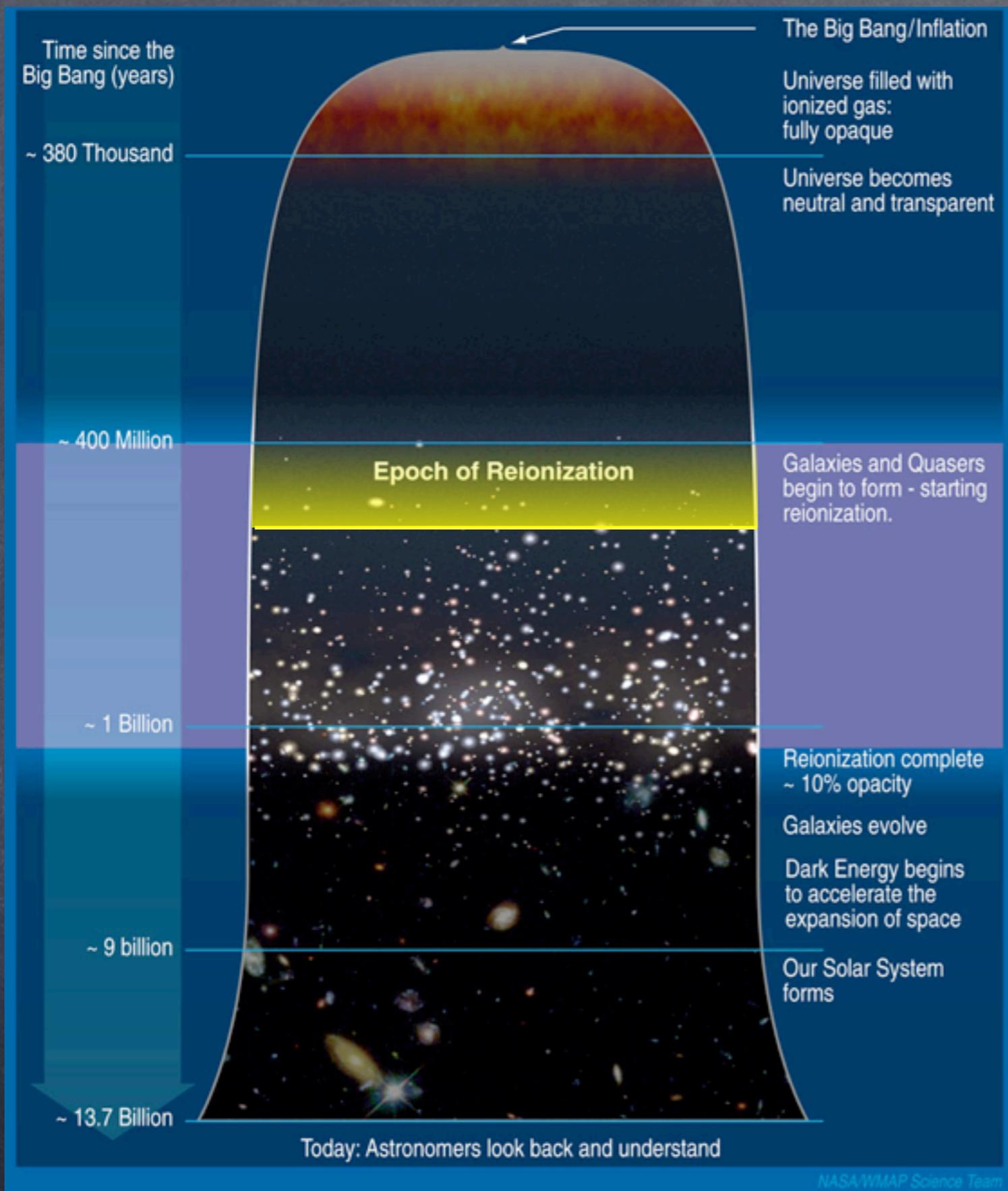
(from claimed line and continuum)

$$Y_{AB} = 28.57$$

Undetected

$$Y_{AB} (2\sigma) = 29.65$$

Inconsistent



Struggling to find
Lyman- α emission

at z about 7

No evidence for

Lyman- α

emission at $z >$

Comparison with other literature

Fontana et al. (2010)

Only 1 tentative emission line.

Probability of observing no galaxies (with $S/N > 10$) in data is about 2%.

Probability of observing only one galaxy (with $S/N=5$) out of 7 is about 4%.

Schenker et al. (2011)

2 convincing and 1 possible out of 19.

Pentericci et al. (2011)

5 galaxies at $6.7 < z < 7.1$ out of 20.

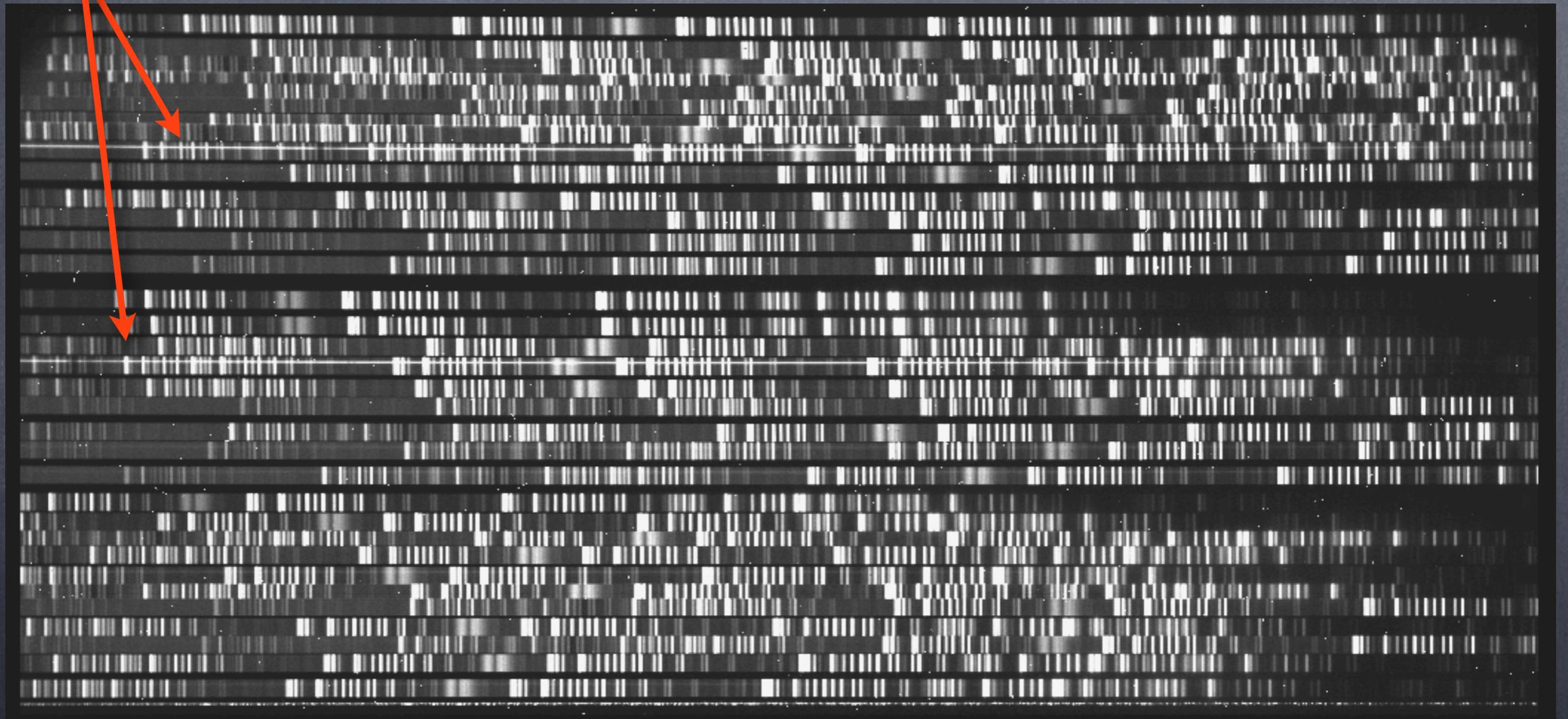
Probability of this result is below 2%.

Spectroscopy with VLT/FORS2

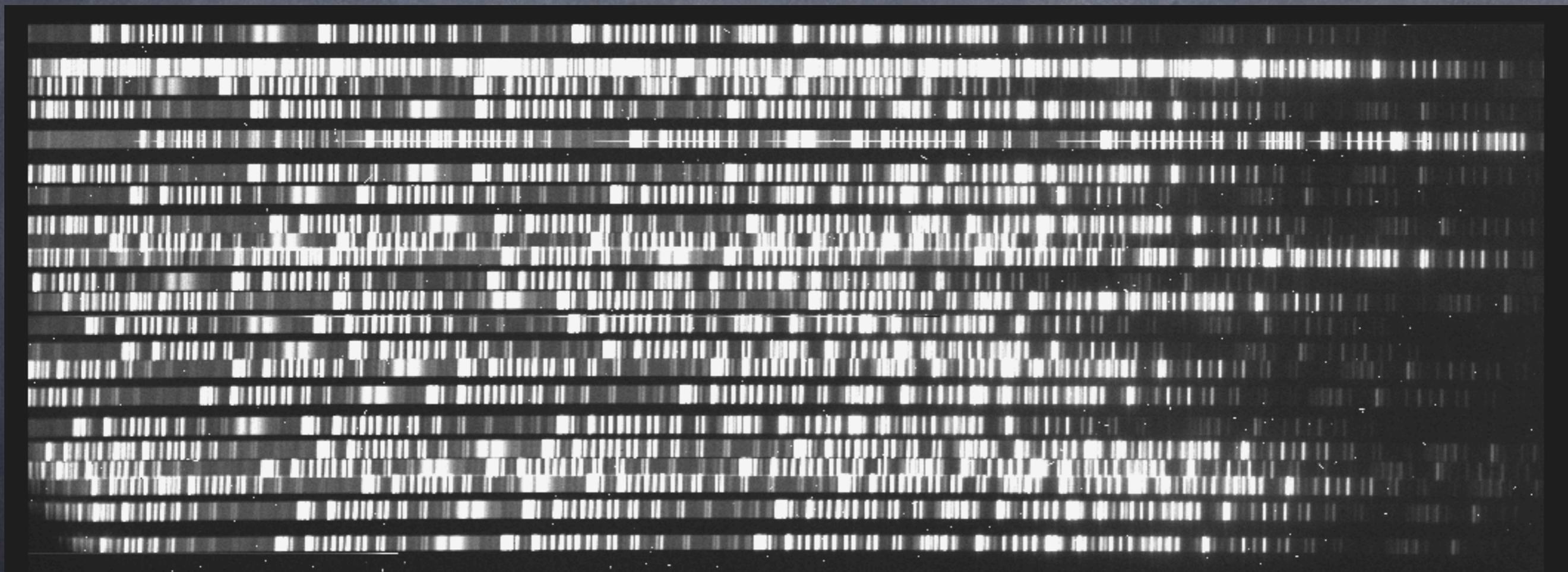
- 22 z-drops (HUDF)
- 16 i-drops
- 24 X 1400sec (9.3hrs)
- Awarded 26 hours of additional observing time in 2011/2012
- Keeping the same mask design and targeting the same objects, obtaining ultra deep spectroscopy.
Total: 35hrs of spectroscopy on these sources

Spectroscopy with VLT/FORS2

Stars



Spectroscopy with VLT/FORS2





Sky-lines

Gaussian-smoothed

Original

Wavelength

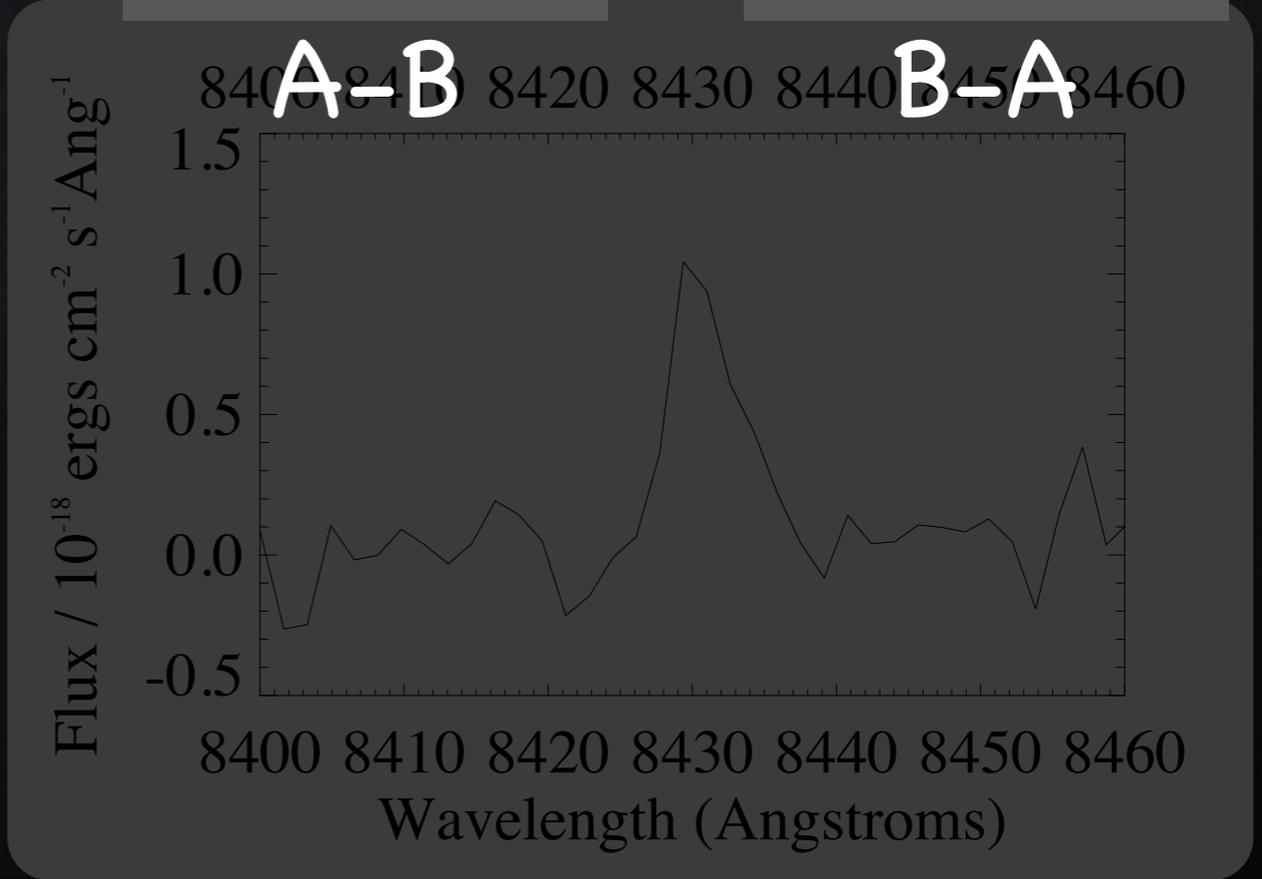
A

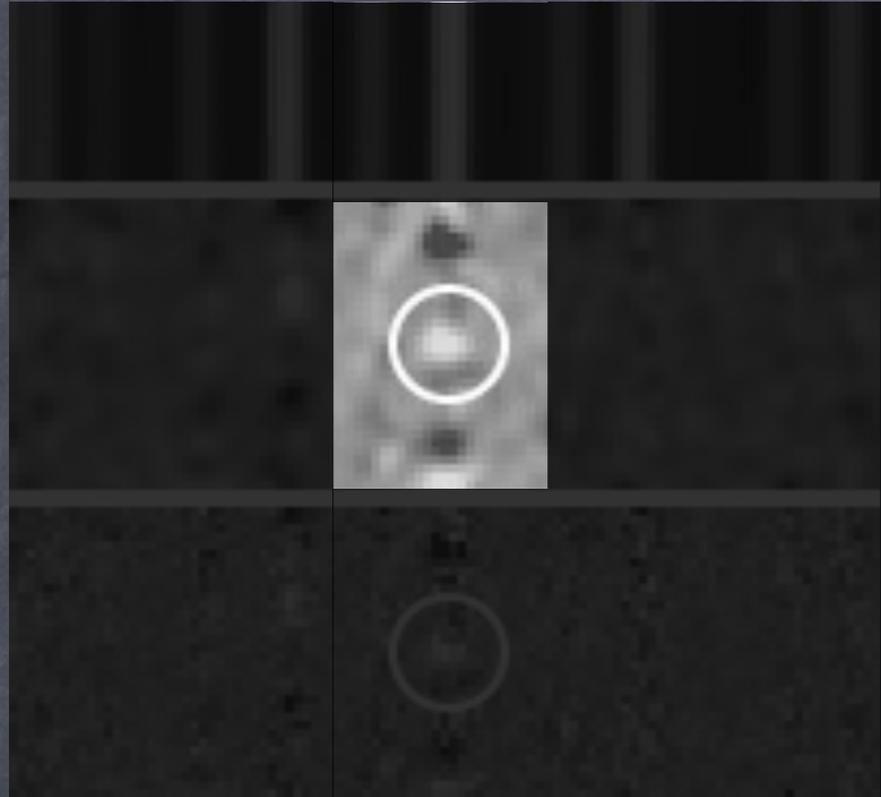
B

A-B

B-A

$z=5.94$



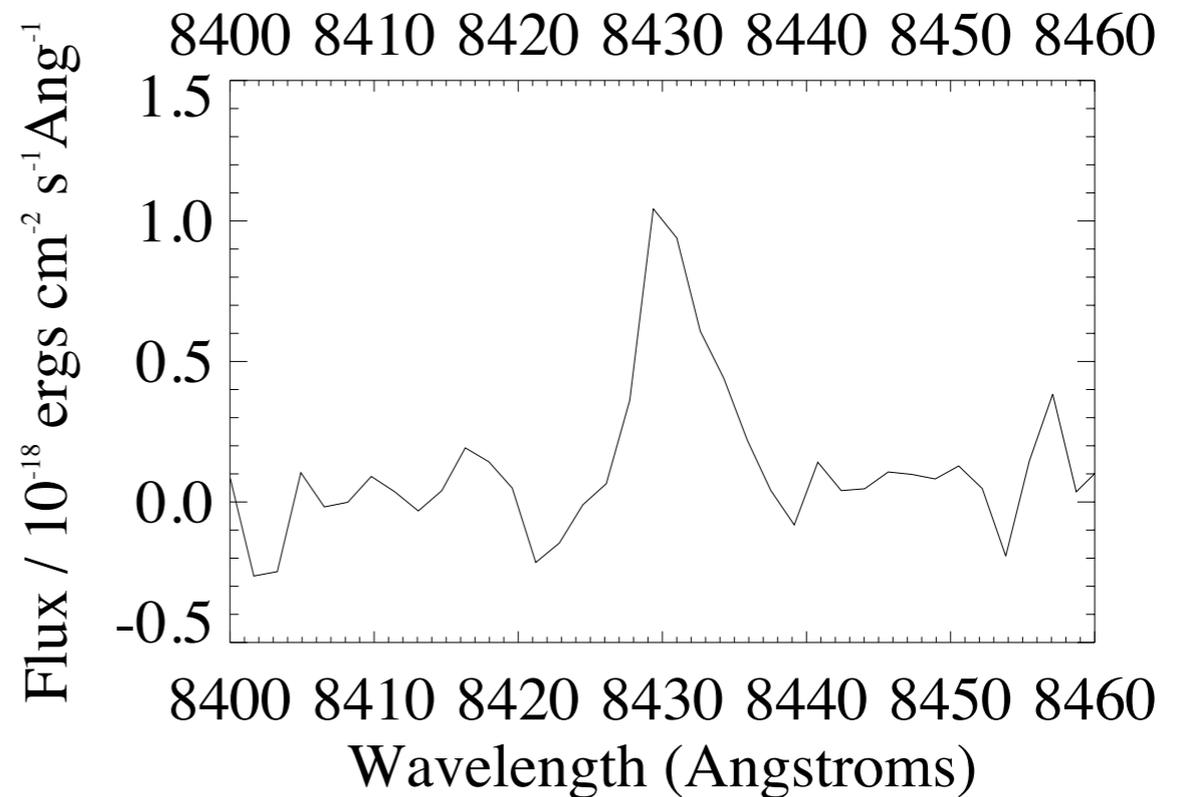


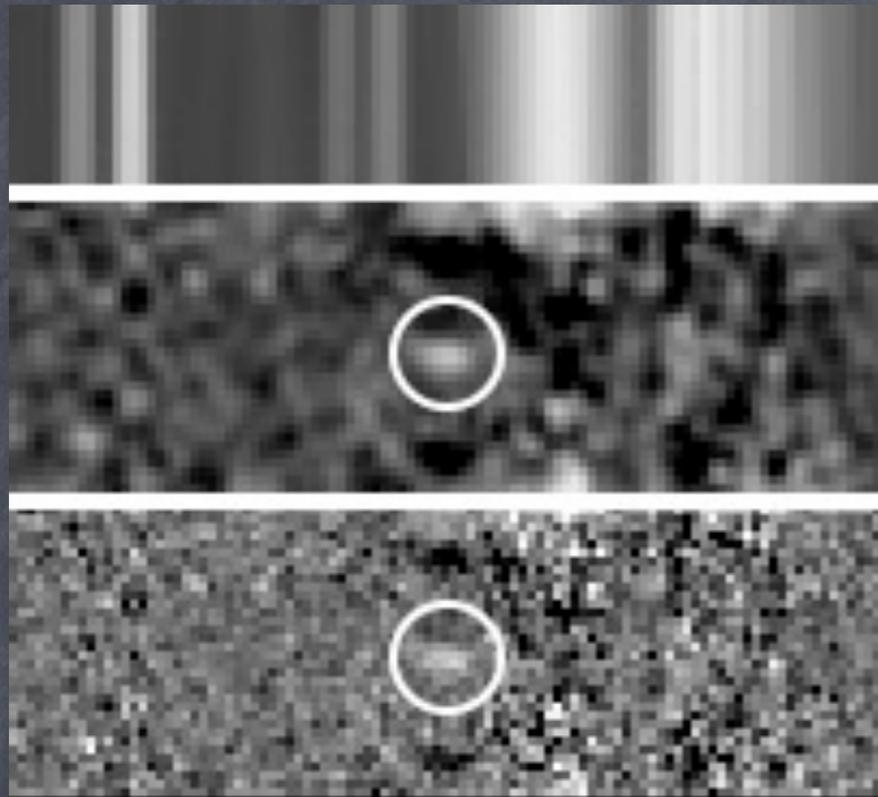
Sky-lines

Gaussian-smoothed

Original

$z=5.94$



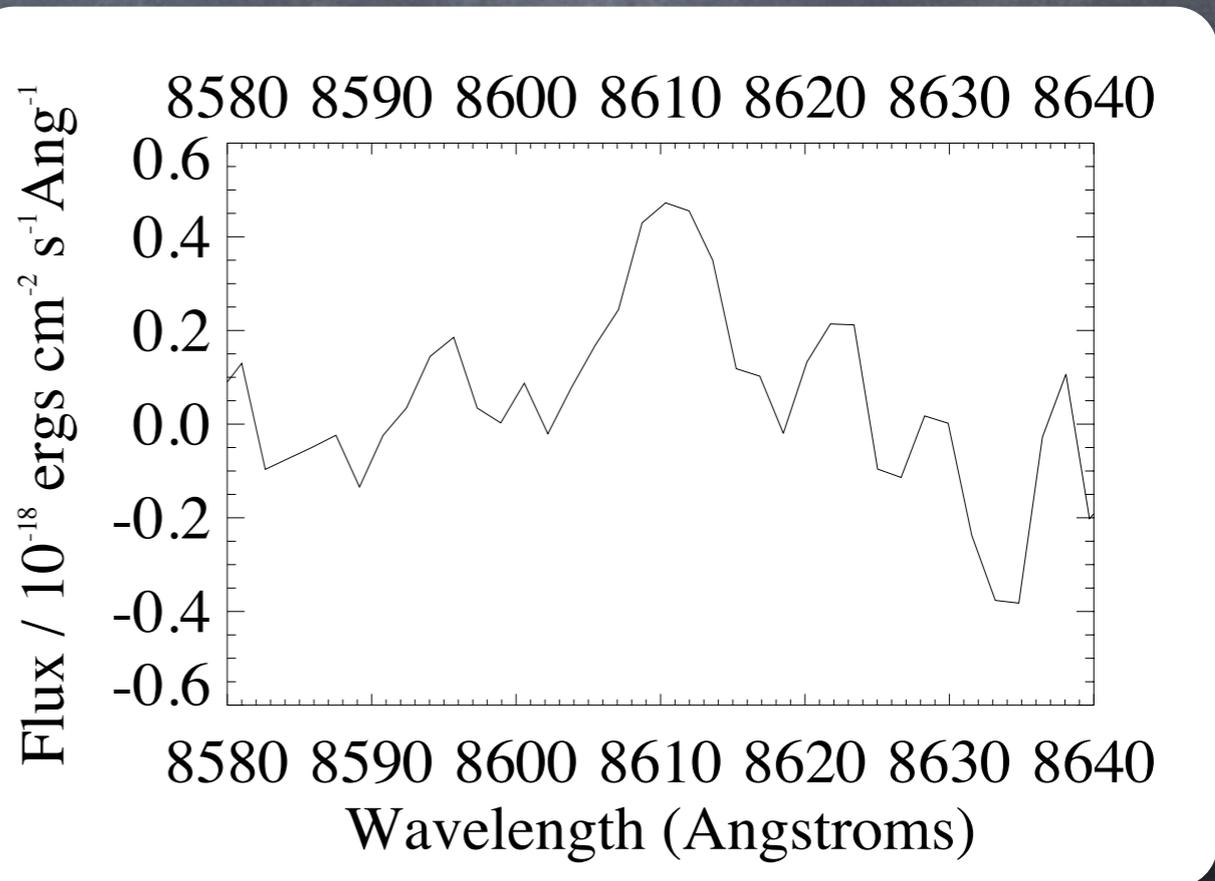


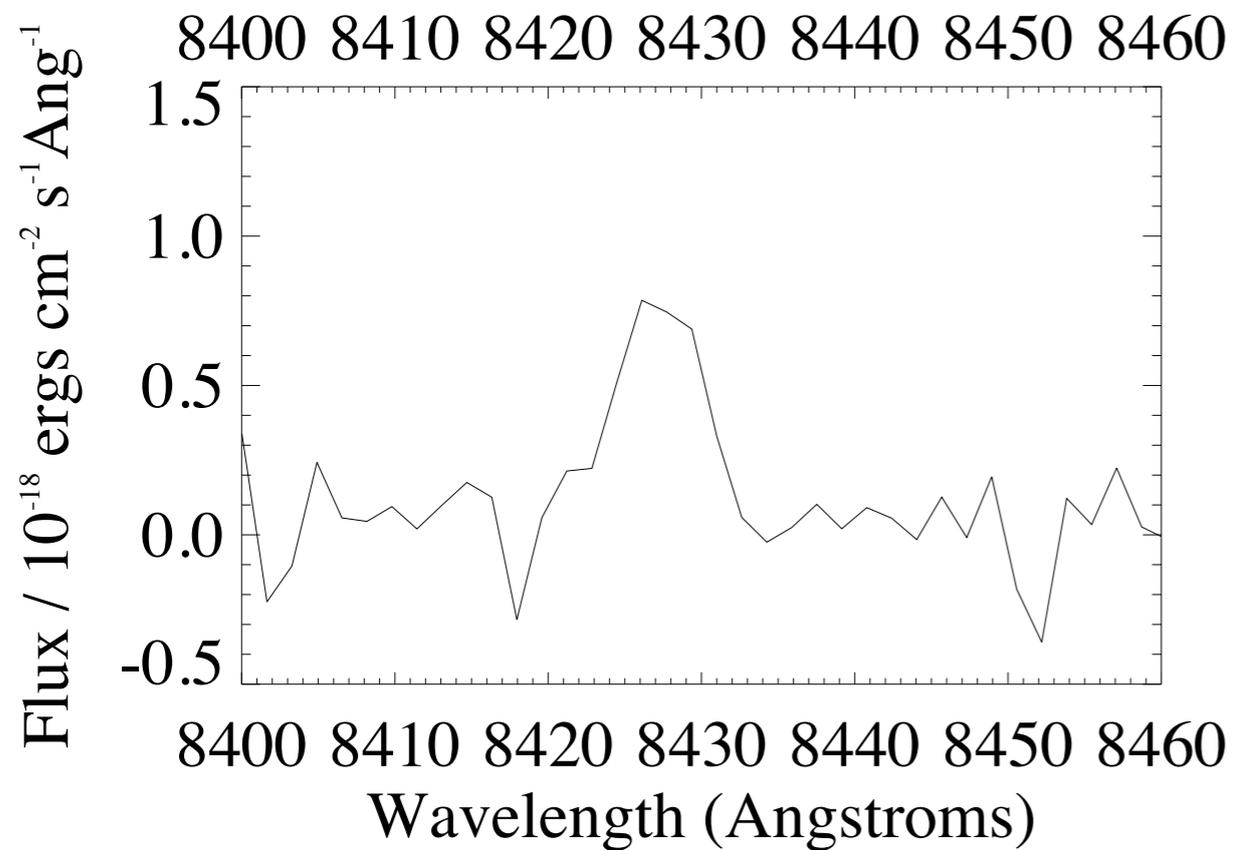
Sky-lines

Gaussian-smoothed

Original

$z=6.08$





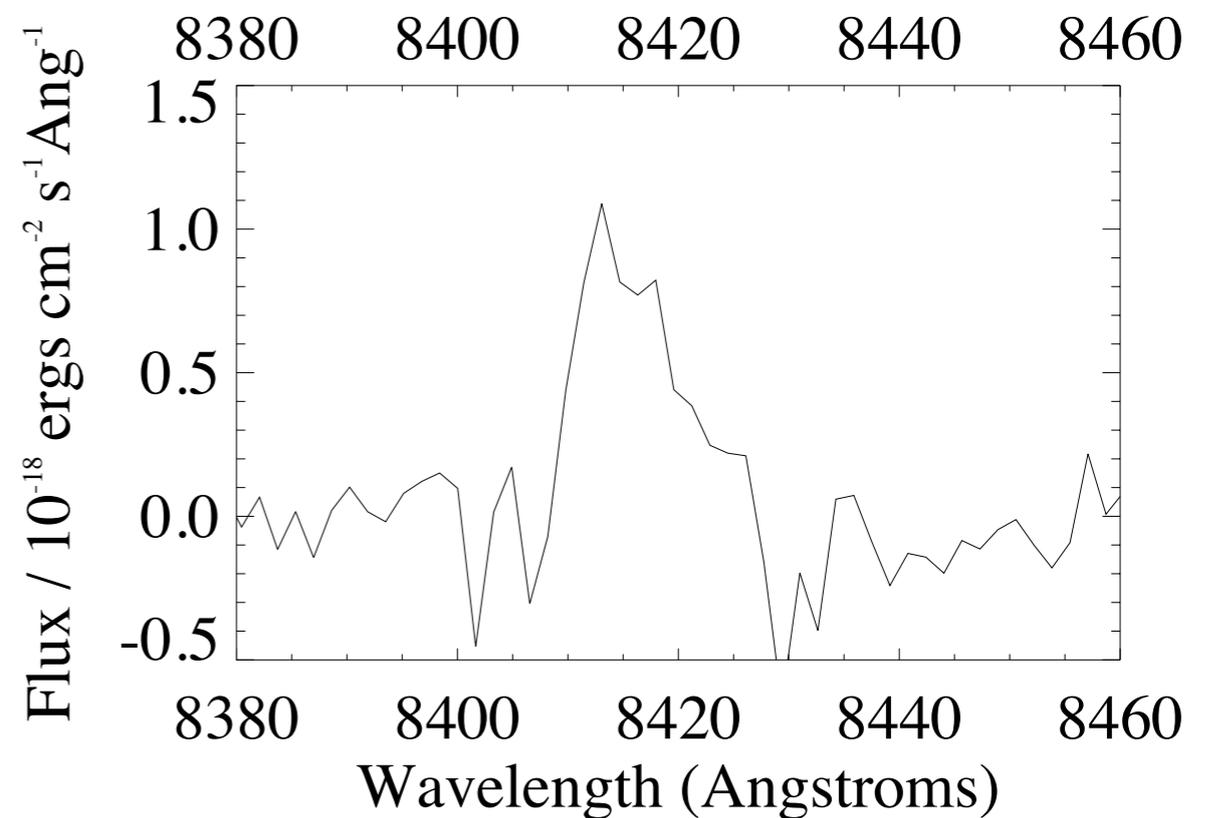
Glare-3011

Also observed by Stanway et al. (2004)

$z=5.93$

HUDF-39065387

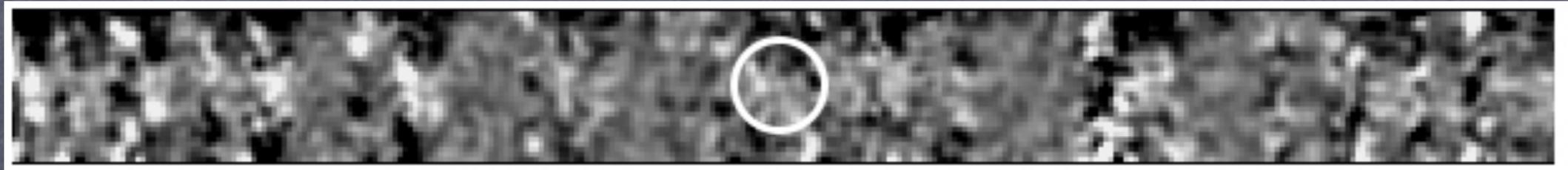
Also observed by Vanzella et al. (2009)



$z=5.92$

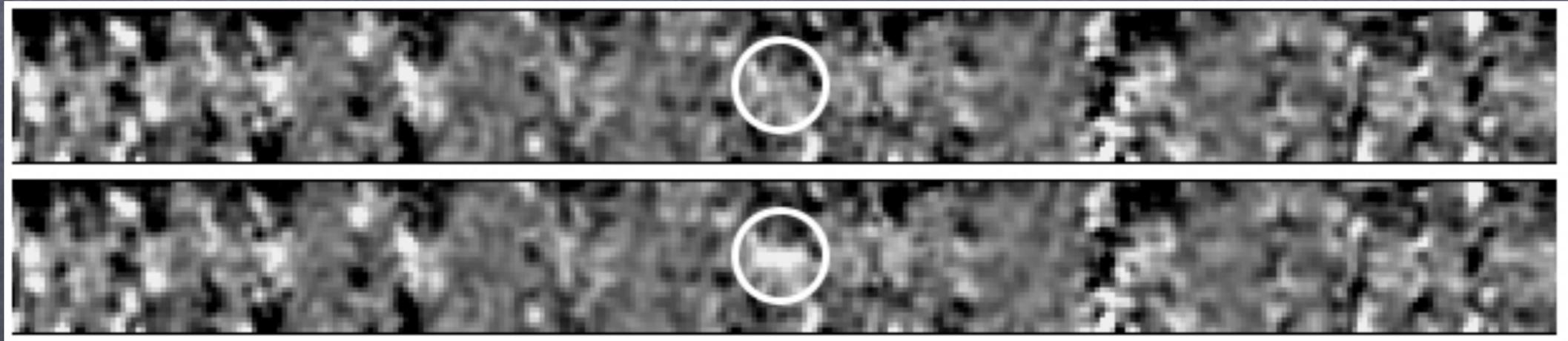
Spectroscopy with VLT/FORS2

Observed



Spectroscopy with VLT/FORS2

Observed



Expected (10 sigma)

Spectroscopy with VLT/FORS2

12 i-drops

22 z-drops

In the rest of the **sample**, there is no evidence of Lyman-alpha emission.

What is this telling us?

Increase in the neutral fraction of Hydrogen in the IGM?

The Neutral Fraction of Hydrogen

After all, the Ly-alpha line is a diagnostic for the process of reionization.

IGM absorption increases a lot when the Universe is not fully ionized and consequently Lyman- α is significantly absorbed.

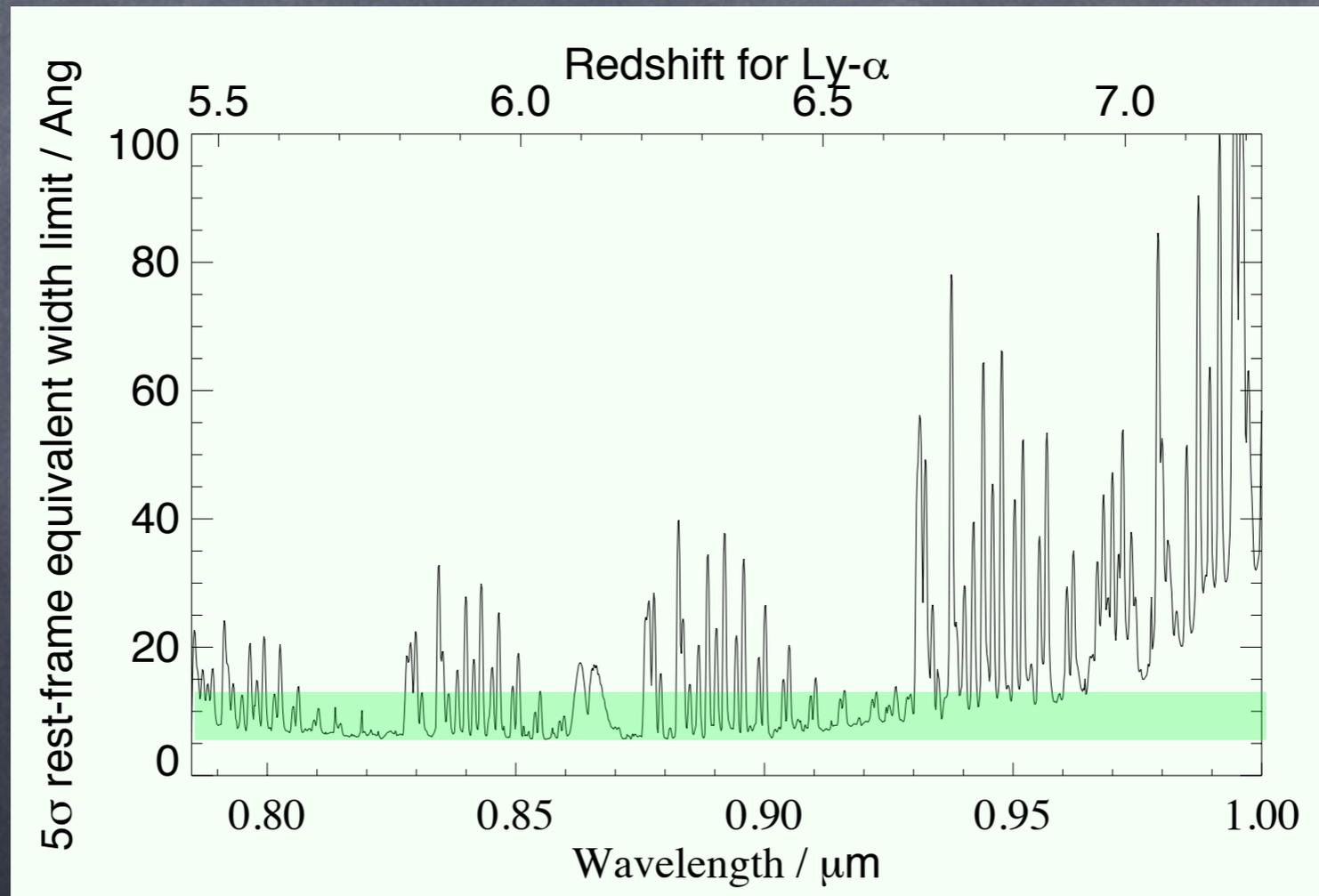
(Dayal et al. 2010)

The Neutral Fraction of Hydrogen

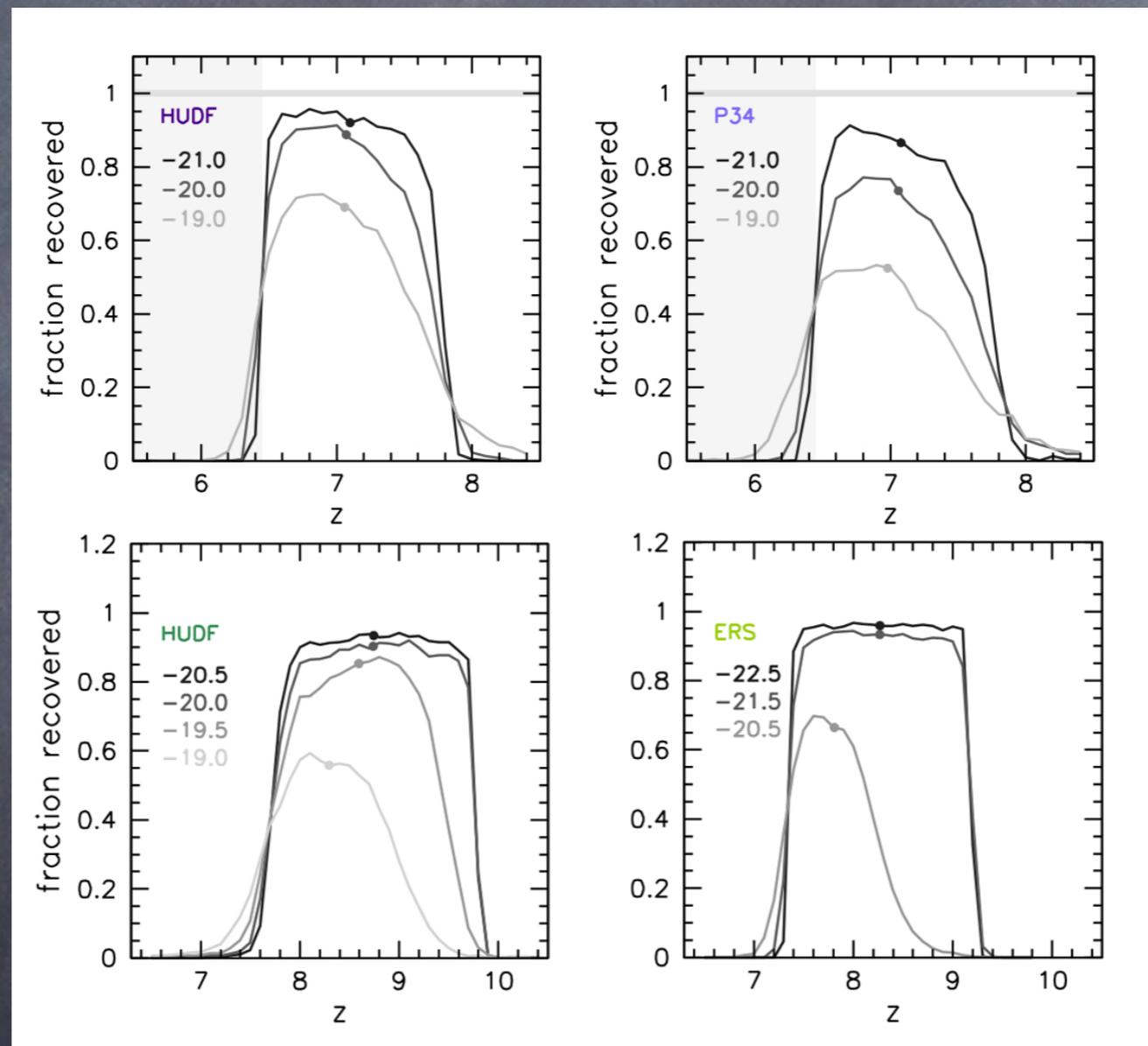
We chose only strong candidates for our analysis.

15 z-drops

3 Y-drops



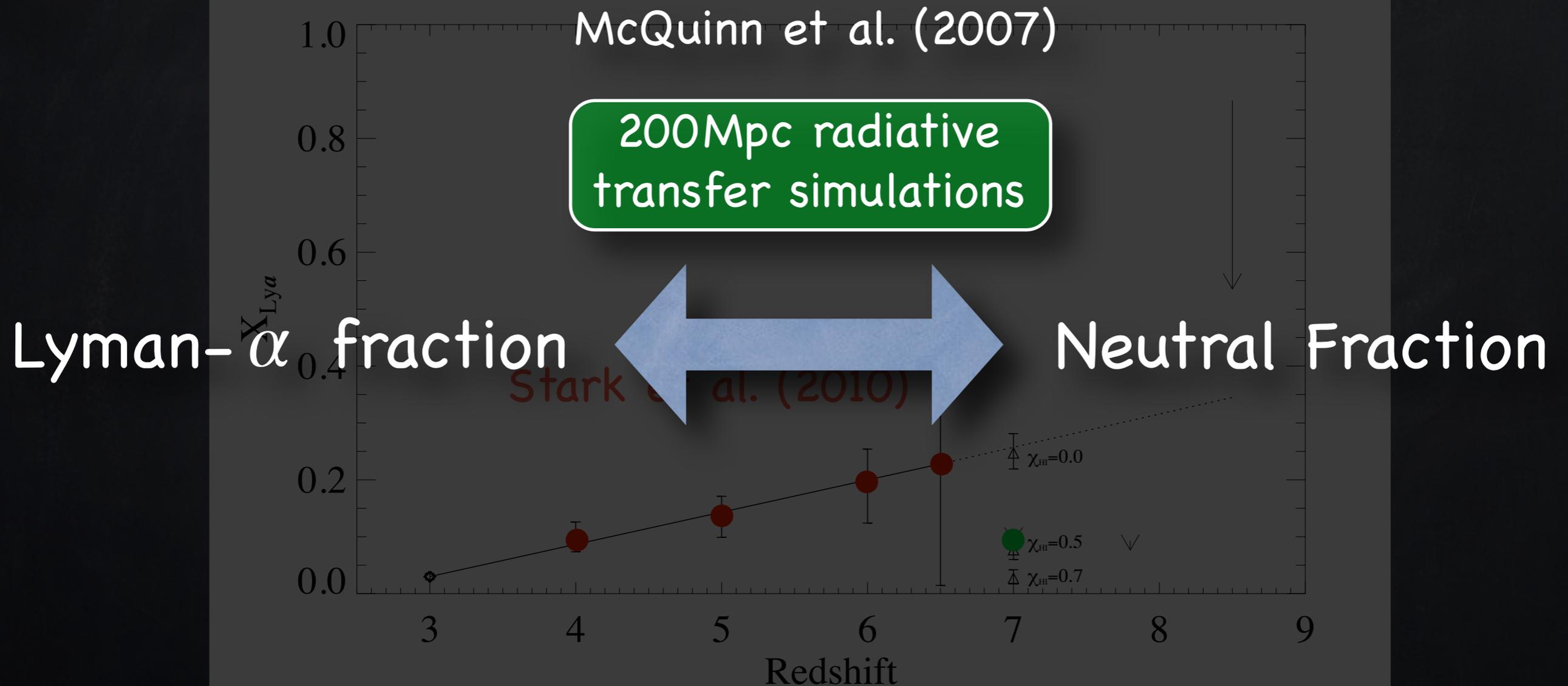
The Neutral Fraction of Hydrogen



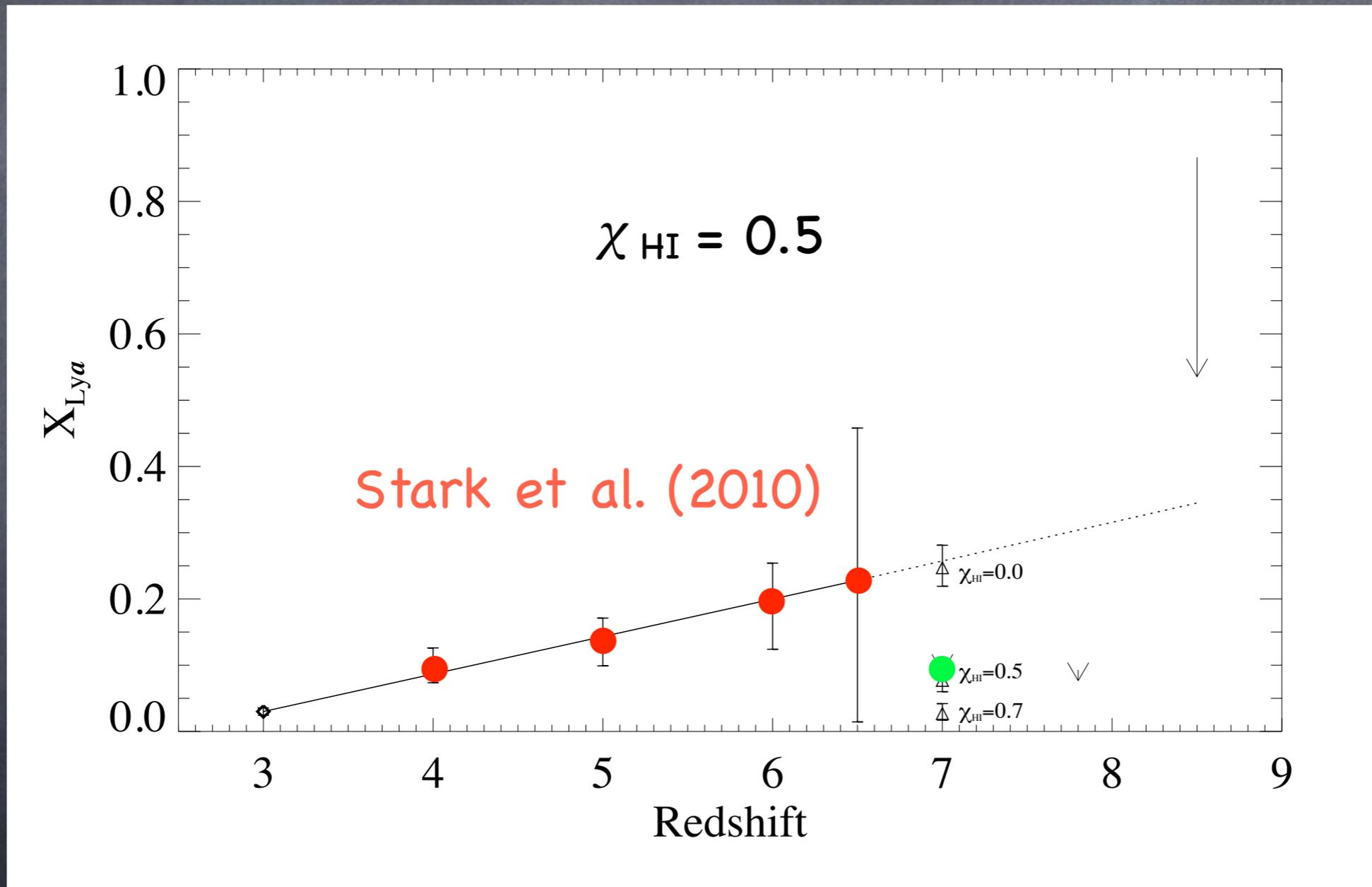
Wilkins et al. (2011)

The Neutral Fraction of Hydrogen

Reject this scenario at a confidence level of 91%



The Neutral Fraction of Hydrogen



The Neutral Fraction of Hydrogen

$$\chi_{\text{HI}} = 0.5$$

$$\chi_{\text{HI}} = 0.44\text{--}0.51 \text{ (Schenker et al. 2012)}$$

McQuinn et al. (2007)

$$\chi_{\text{HI}} = 0.6\text{--}0.9 \text{ (Ono et al. 2012)}$$

Dijkstra et al. (2011)

$$\chi_{\text{HI}} = 0.32 - 0.62 \text{ (Ota et al. 2008, 2010)}$$

Santos (2004)

Reionization Constraints from CMB Polarization

Dunkley et al. (2009)

- Instantaneous reionization at $z < 8.2$ (6.7) can be rejected at the 2σ (3σ).
- Argue for an extended reionization process taking place between $z \sim 6 - 11$

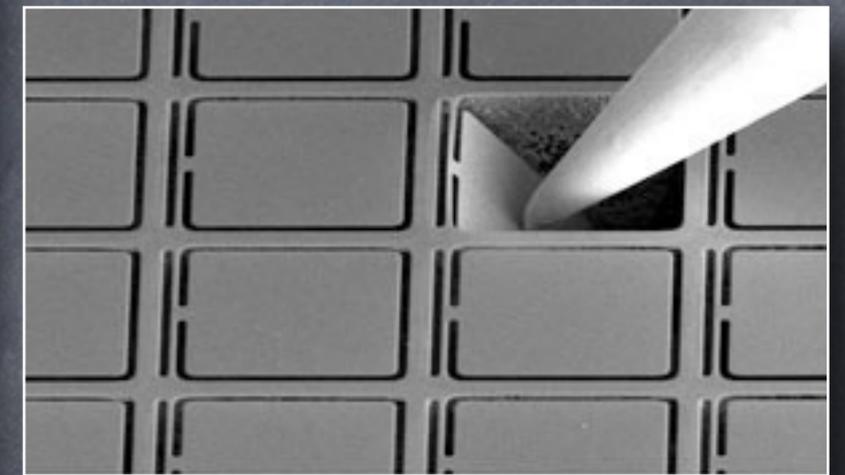
Spectroscopic studies such as this one suggest that reionization was not complete at $z=7$.

Future prospects for spectroscopic efforts

- Does Lyman-alpha emerge during the Gunn-Peterson era? (Potentially not)
- Lyman-alpha is currently the only way of confirming these high- z sources.

As we push to even higher redshifts...

...(potentially very) far future



If no Ly-alpha, then we could use other lines such as OII.

At present...



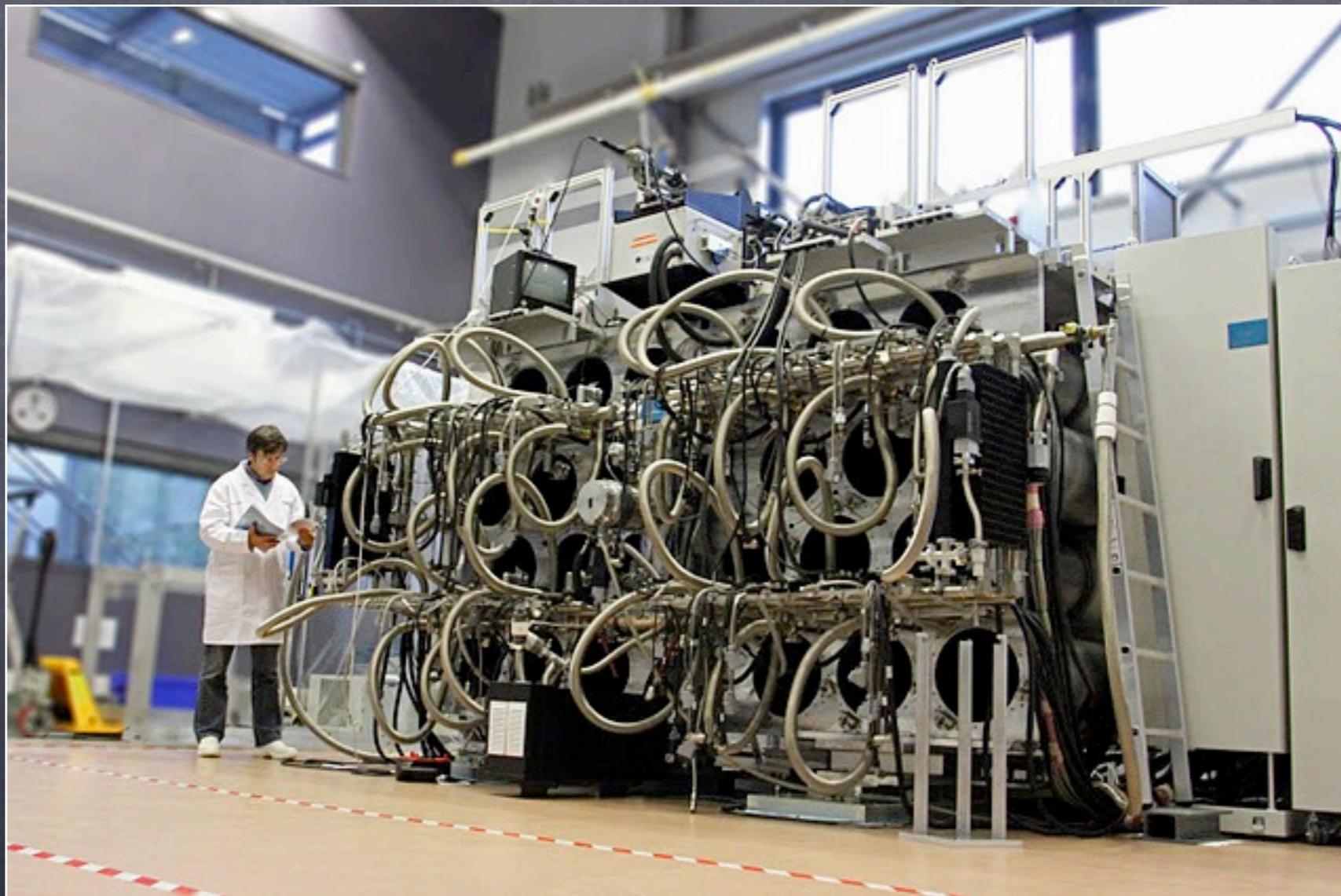
Leibniz-Institut für
Astrophysik Potsdam

Astrophysikalisches Institut Potsdam



Multi Unit Spectroscopic Explorer (MUSE)

2nd generation instrument for the Very Large Telescope



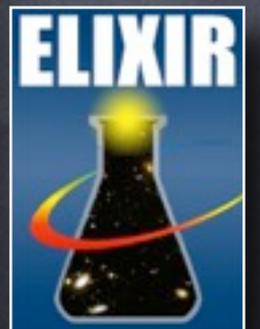
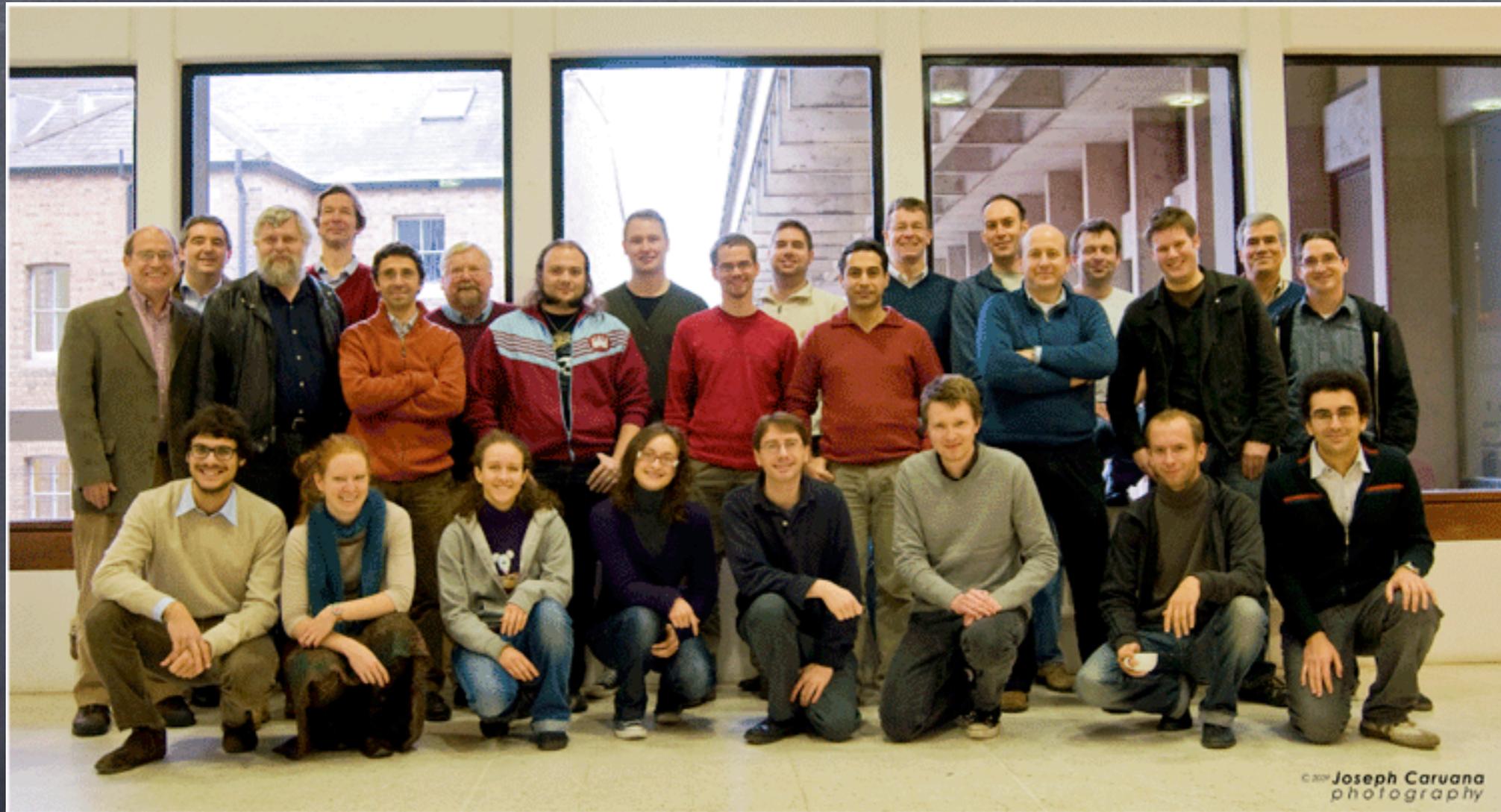
At present...

- [1] Sozialversicherungsausweis
- [2] Bescheinigung für den Lohnsteuerabzug
- [3] Freizügigkeitsbescheinigung

- [1] [social insurance pass]
- [2] [income tax card]
- [3] [freedom of movement certificate]



So long and thanks for all the fish!



est. 2008

