# … of the
# … Field Sout…

…iversity

R. Bacon[1], J. Brinch…
J. Blaizot[1], N…
Dreizl…

# The MUSE 3D view of the Hubble Deep Field South

Jarle Brinchmann
Leiden University

R. Bacon[1], J. Brinchmann[2], J. Richard[1], T. Contini[3,4], A. Drake[1], M. Franx[2], S. Tacchella[5], J. Vernet[6], L. Wisotzki[7], J. Blaizot[1], N. Bouché[3,4], R. Bouwens[2], S. Cantalupo[5], C.M. Carollo[5], D. Carton[2], J. Caruana[7], B. Clément[1], S. Dreizler[8], E. Emsellem[1,6], B. Epinat[3,4,9], B. Guiderdoni[1], C. Herenz[7], T.-O. Husser[8], S. Kamann[8], J. Kerutt[7], W. Kollatschny[8], D. Krajnovic[7], S. Lilly[5], T. Martinsson[2], L. Michel-Dansac[1], V. Patricio[1], J. Schaye[2], M. Shirazi[5], K. Soto[5], G. Soucail[3,4], M. Steinmetz[7], T. Urrutia[7], P. Weilbacher[7], and T. de Zeeuw[6,2]

A&A, 575, 32 (2015)

# The MUSE instrument

**Integral field unit - with 24 spectrographs**

**λ: Optical range 4650-9300Å**

**R=λ/dλ: 1500-3500**

**FOV: 1x1 arcmin$^2$ (7x7 arcsec$^2$ in NFM)**

**Sampling: 0.2” (0.025”) contiguous**

**Throughput: 35%**

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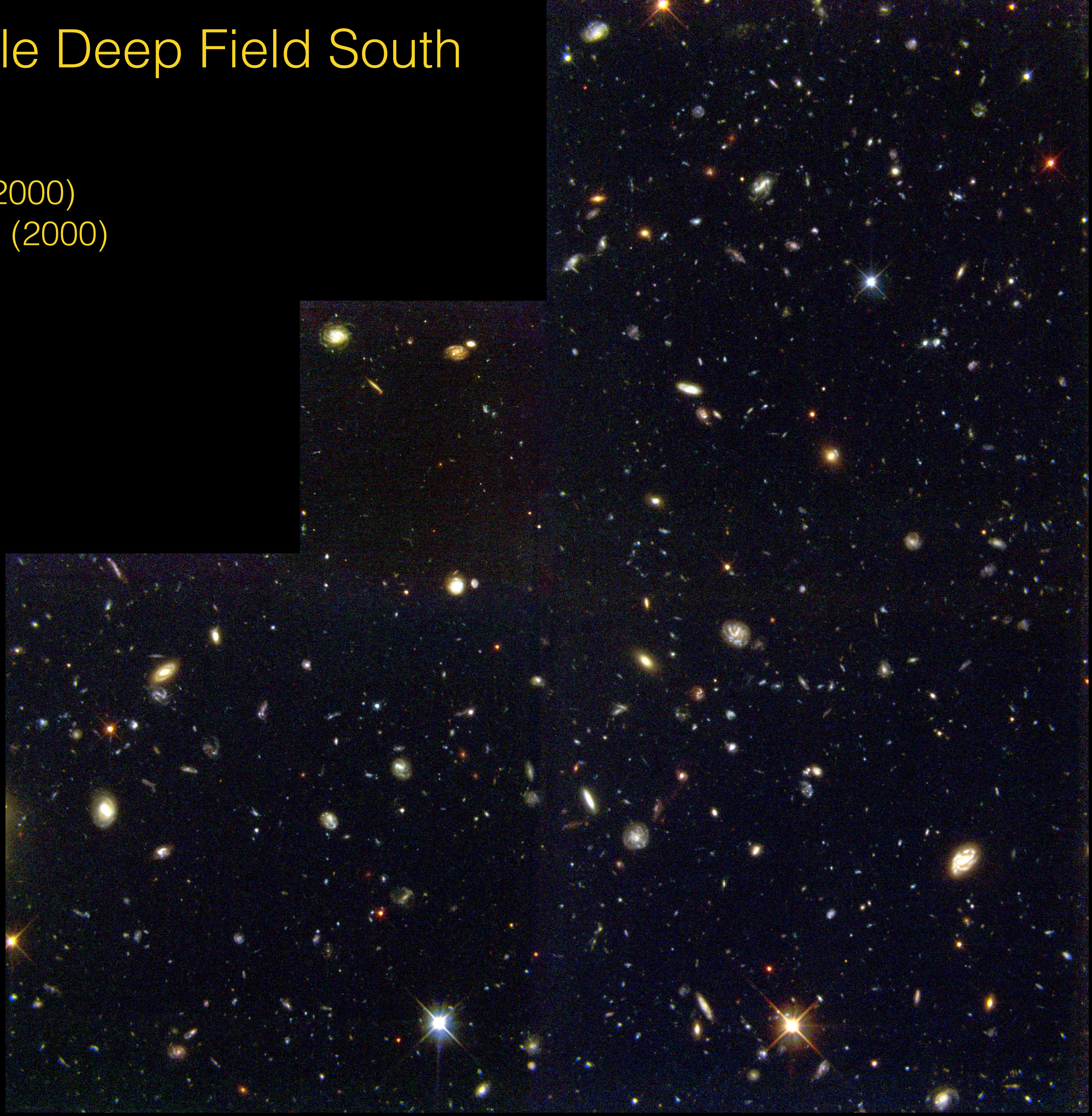
muse
ETH

# The Hubble Deep Field South

Williams et al (2000)
Casertano et al (2000)
$m_{AB} \sim 29$



# The Hubble Deep Field South

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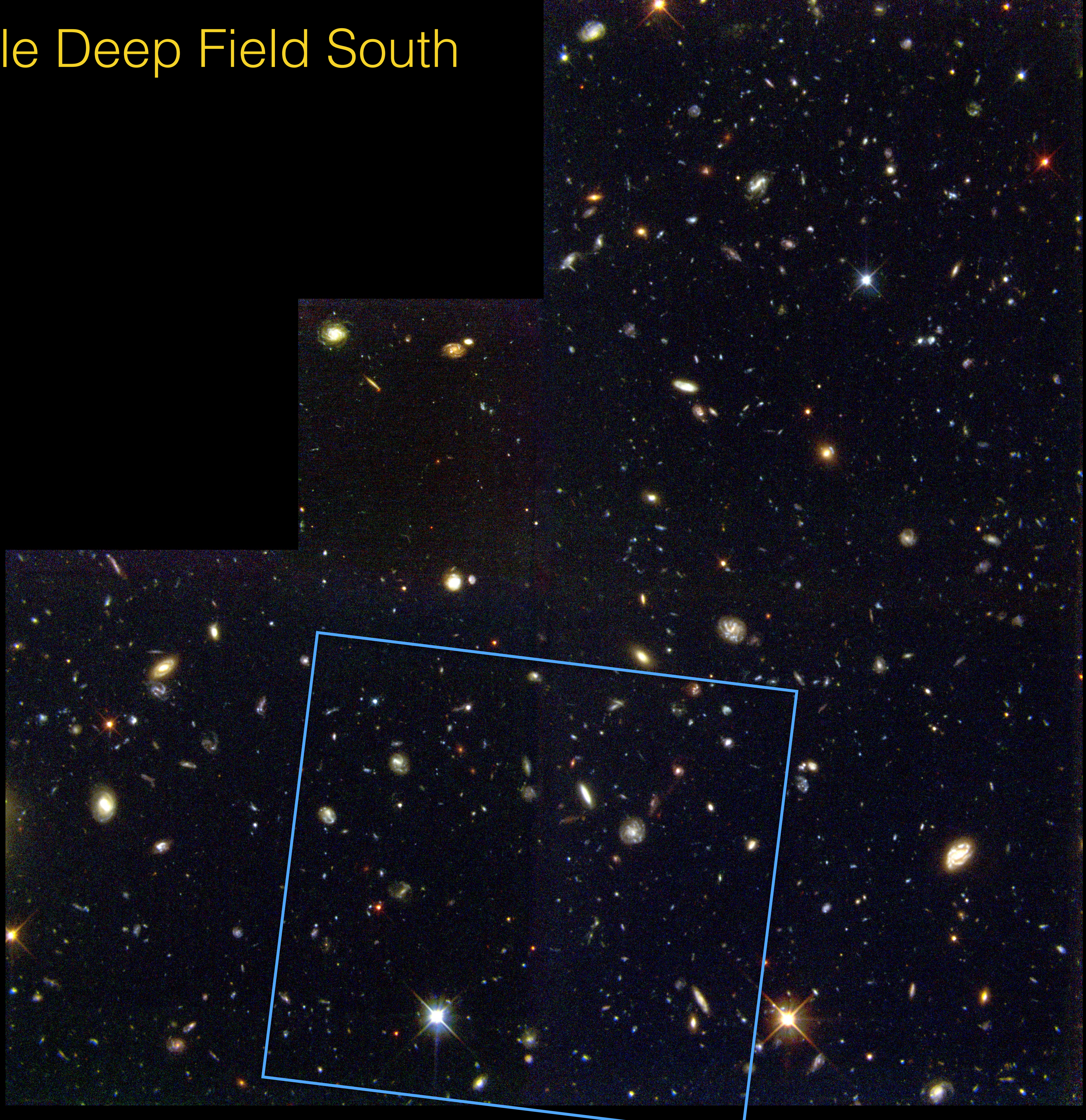

# The Hubble Deep Field South

**Before Aug 2014: A total of 18 redshifts from five previous papers**

# The Hubble Deep Field South

Williams et al (2000)
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Before Aug 2014: A total of 18 redshifts from five previous papers

## enter MUSE

27 hours of integration time (good quality)
54 exposures of 30 min each.

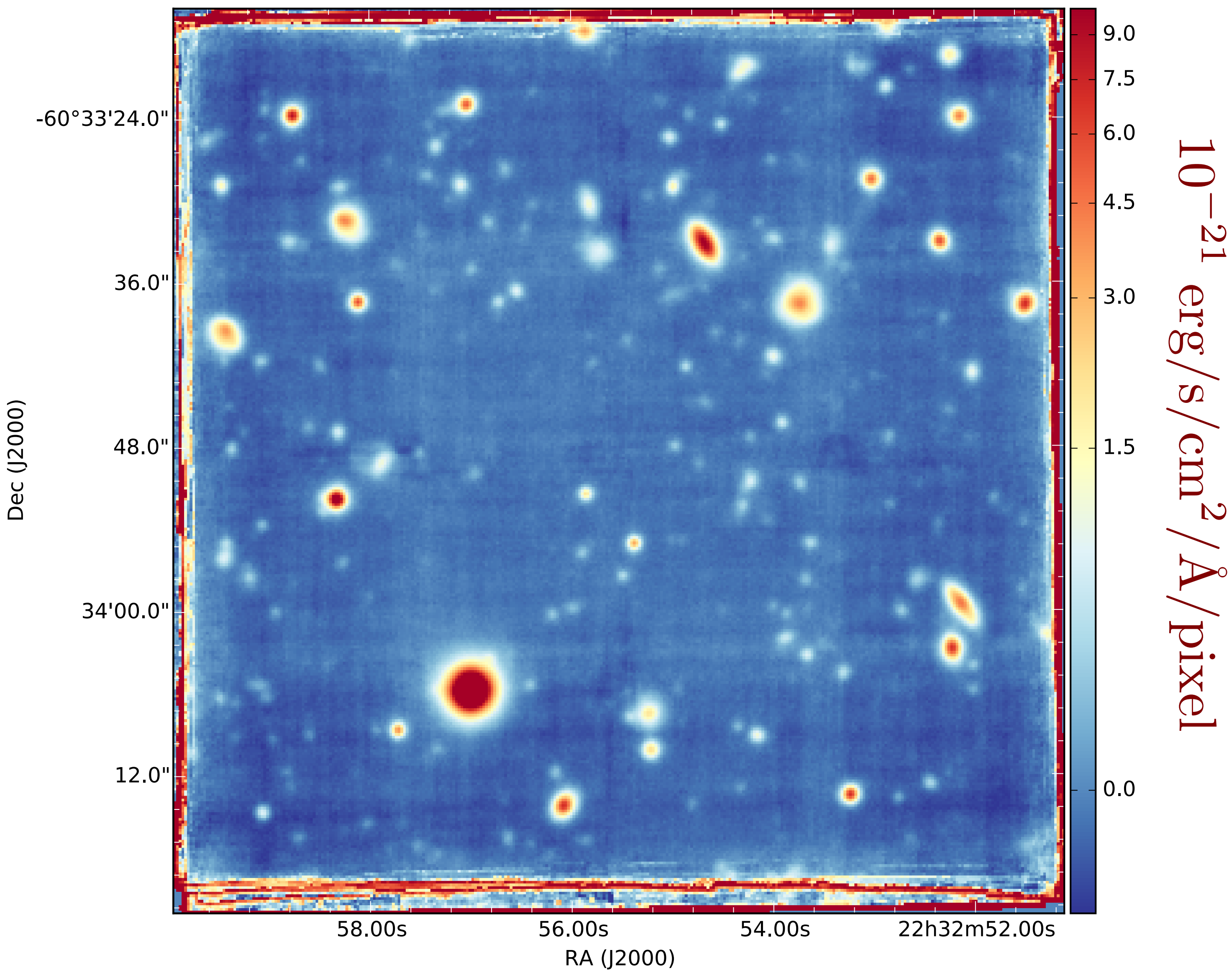
FWHM in white-light image: 0.77”
Depth: $10^{-19}$ erg/s/cm$^2$/arcsec$^2$
FoV: 1’x1’

Deepest existing blind survey:
Rauch et al (2008) -
$8 \times 10^{-20}$ (cgs) in 92 hours.
We are 32 times “more efficient”

189 secure redshifts for now.

**Big advantage: No need to pre-select targets**

# Going deep - do we reach our requirements?




(pixel = 0.2")

Surface brightness limit: $1 \times 10^{-19} \mathrm{erg/s/cm^2/\AA/arcsec^2}$

Formal line flux limit: $3 \times 10^{-19} \mathrm{erg/s/cm^2}$

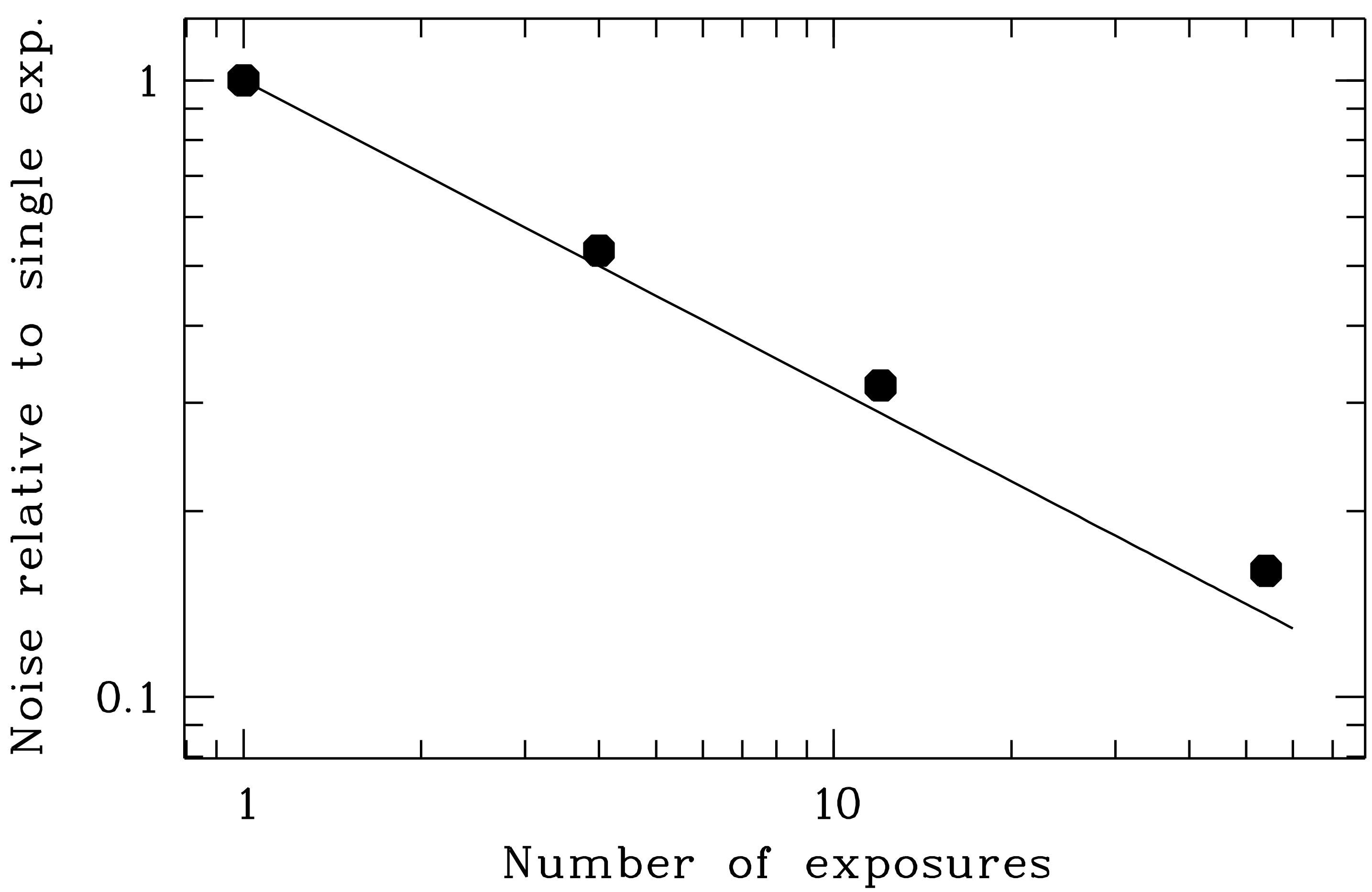
$[5\sigma, 1\mathrm{arcsec}]$

In practice ~$10^{-18}$ cgs at the moment.

# Going deep - do we reach our requirements?

In an ideal situation:

$$\text{noise} \propto \frac{1}{\sqrt{N_{\text{exp}}}}$$




Systematic uncertainties will lead to deviations from this.

Conclusion: we are close to the theoretical optimum but off by a factor of ~1.2 at 27hr.

Main limitations: flat field stability, bias stability(?)

# The Hubble Deep Field South

70 Ly-a emitters seen in HST
26 Ly-a w/o HST
65 [O II] emitters
15 C III]1909 emitters
8 Stars
14 Abs. line redshifts

out of 586 targets

43% are in 17 groups
29% in pairs
28% isolated

1'

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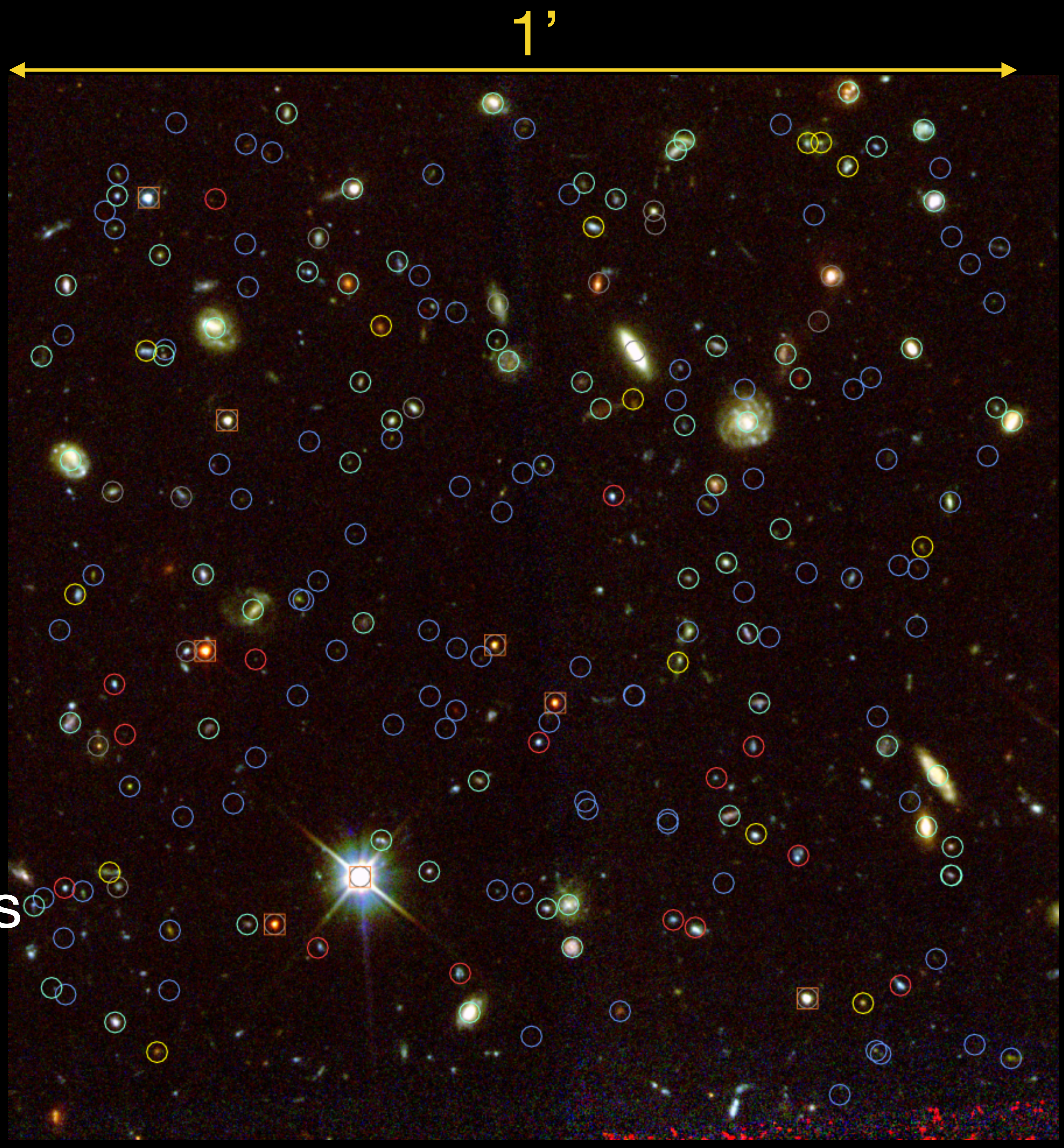
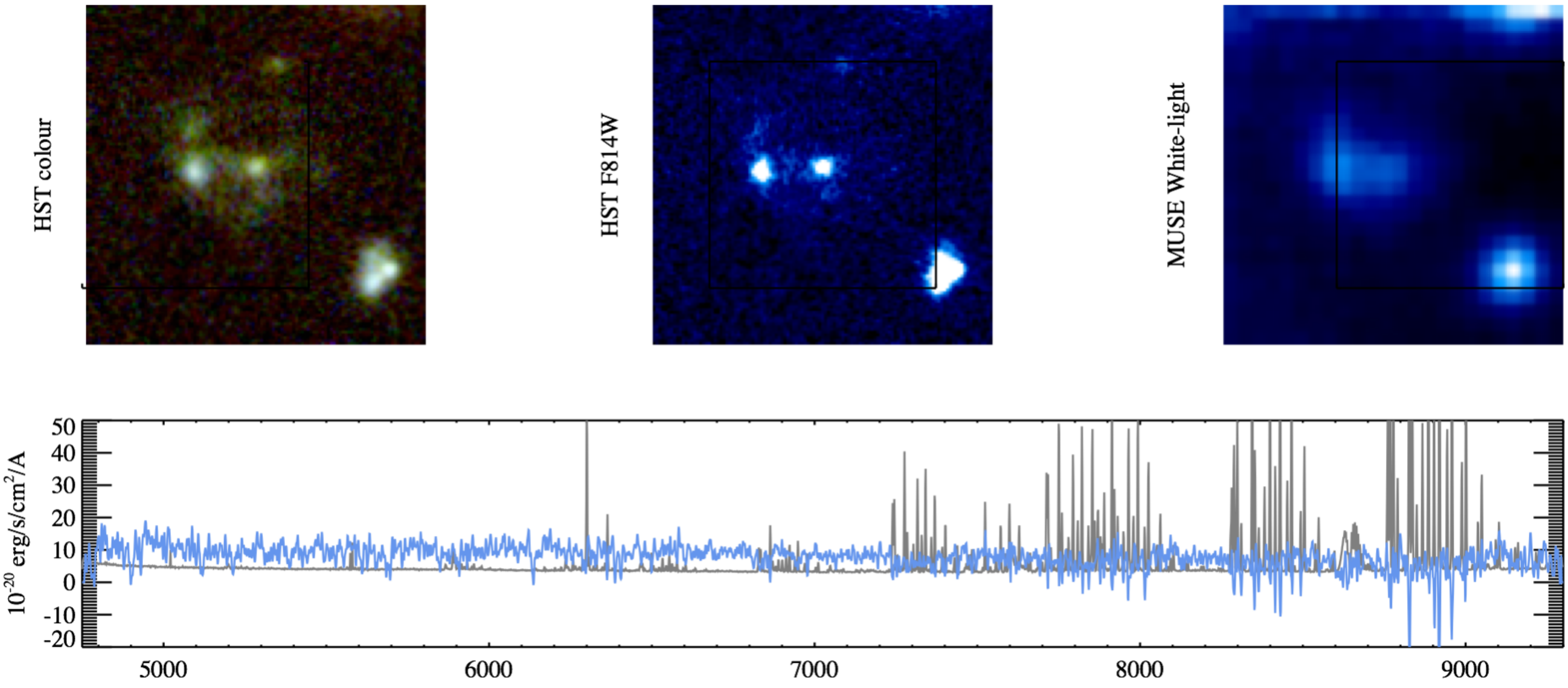


# Absorption line only galaxies - an example



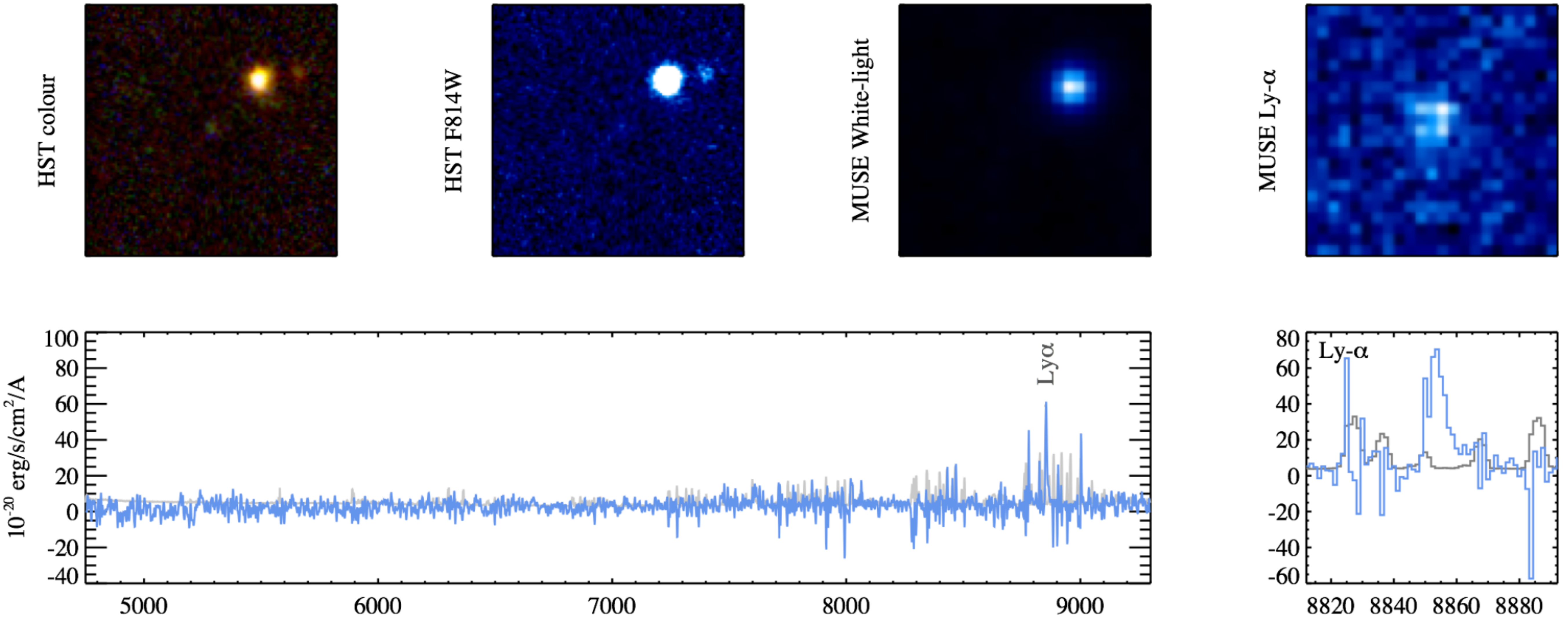

Object #55

$z = 2.67$

$m_{F814W} = 24.8$

Appears to be a triple merger

# Ly-a emitter

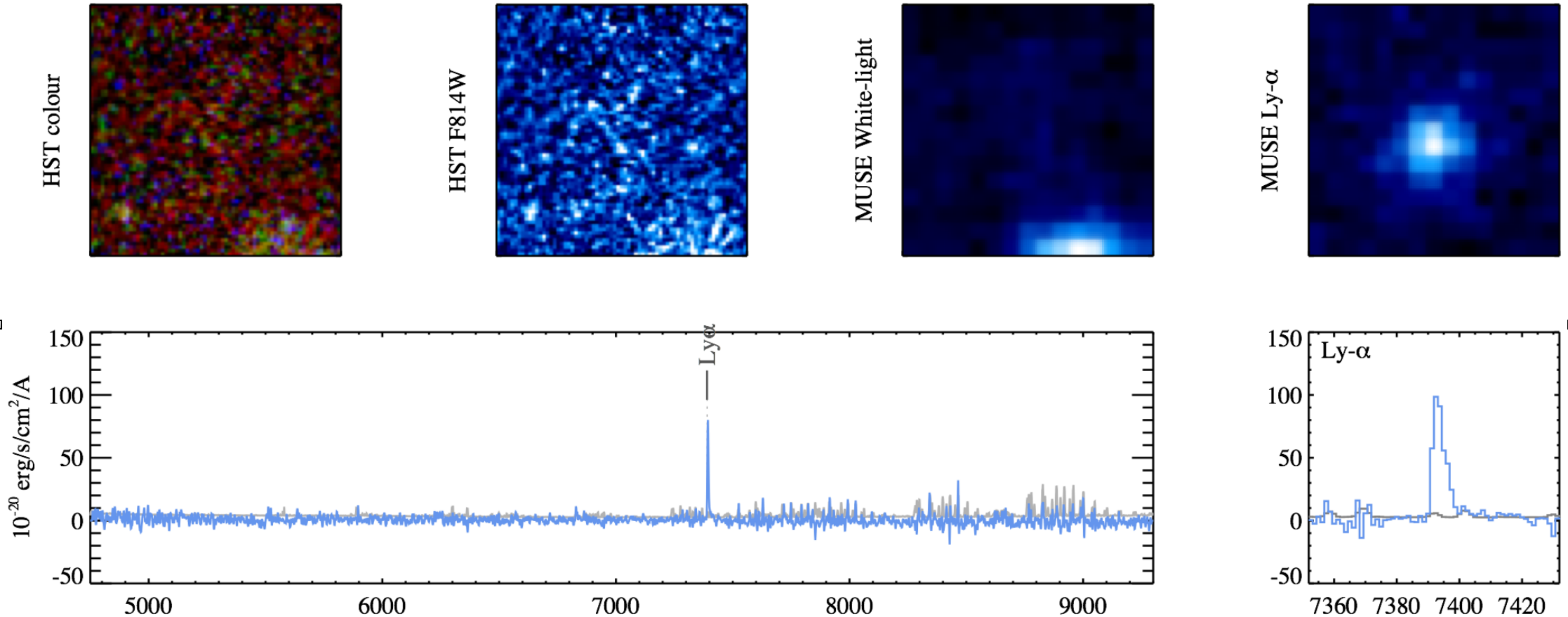



Object #430

z = 6.28

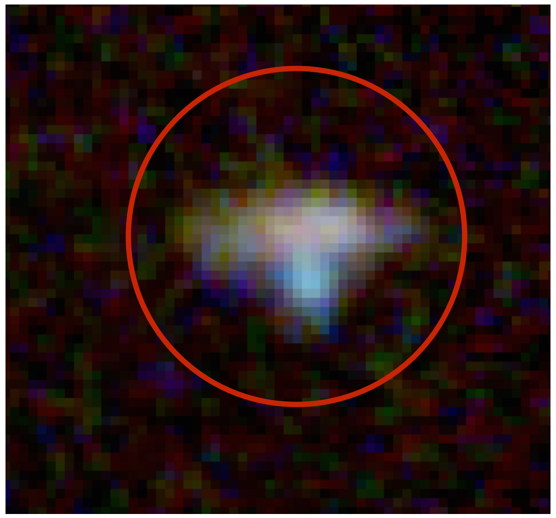
$m_{F814W}$ = 28.6

# Ly-a emitter



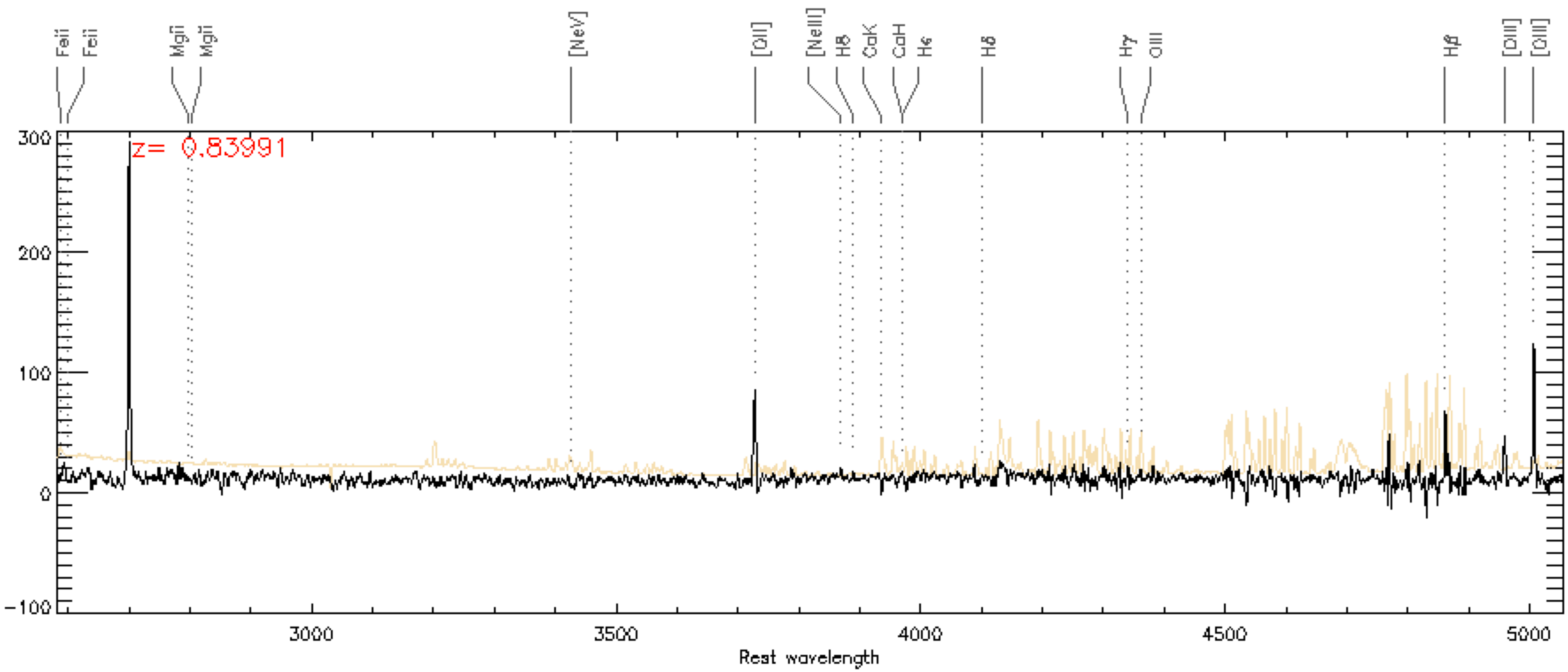

Object #553
$z = 5.08$
$m_{F814W} > 29.8$

# Separation in 3D



Single object in HDF-S catalogue

$m_{F814W} \sim 25.3$



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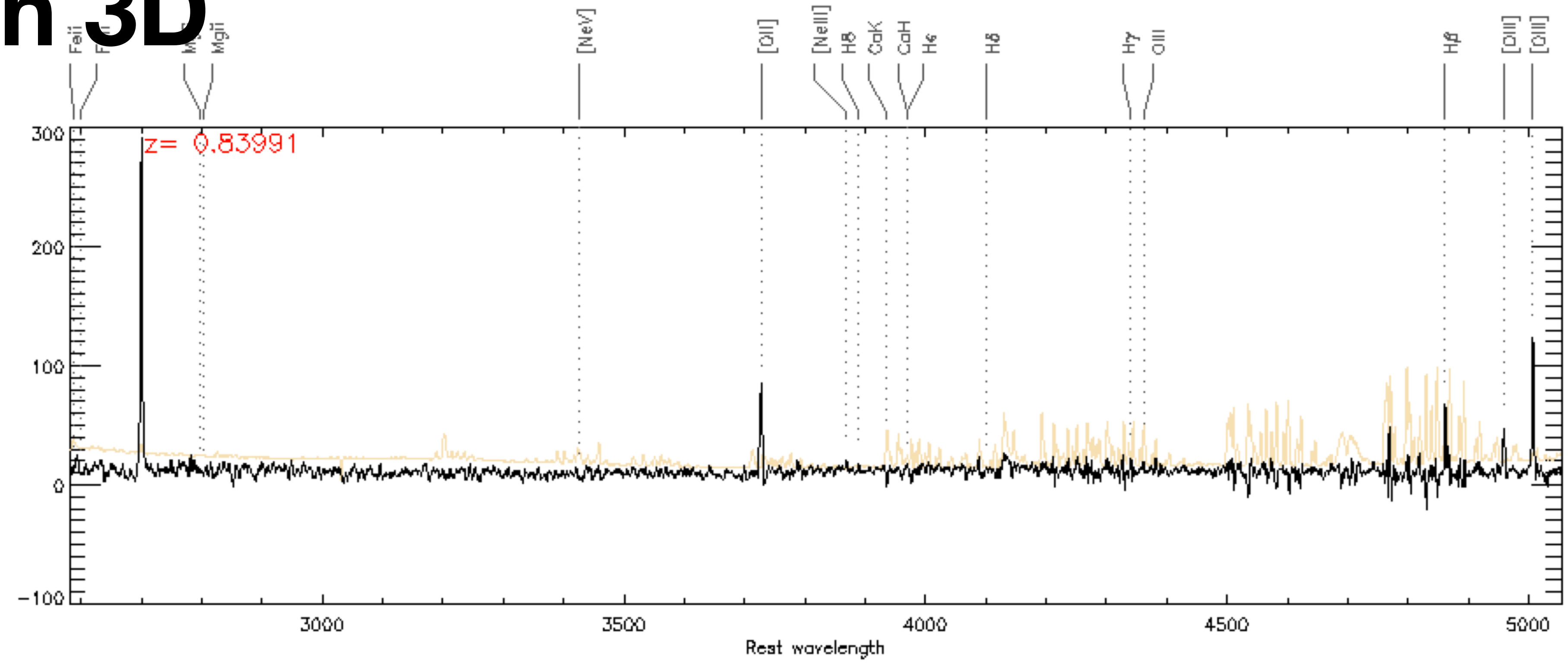
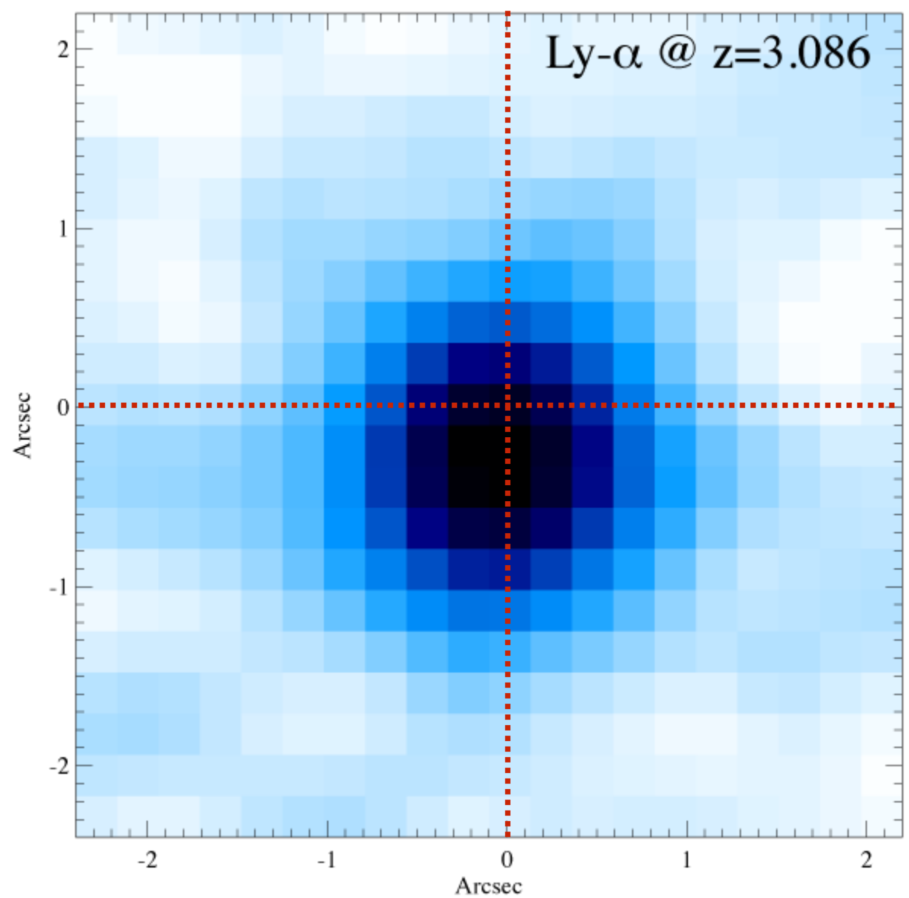
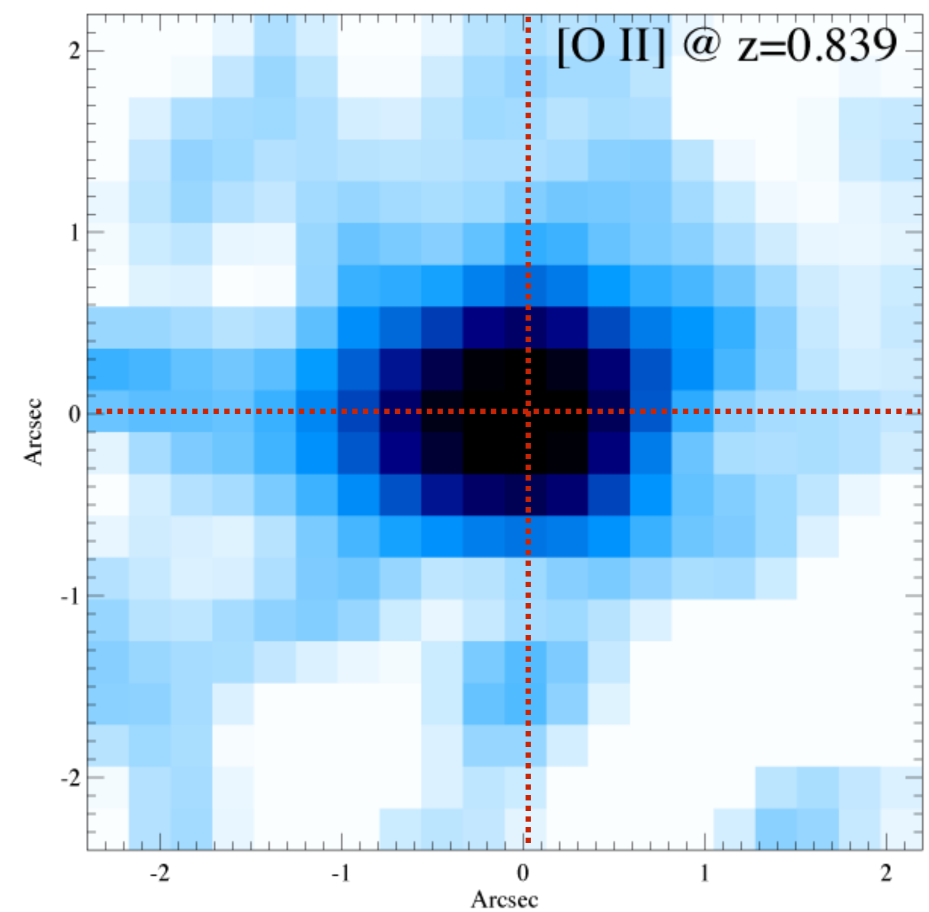
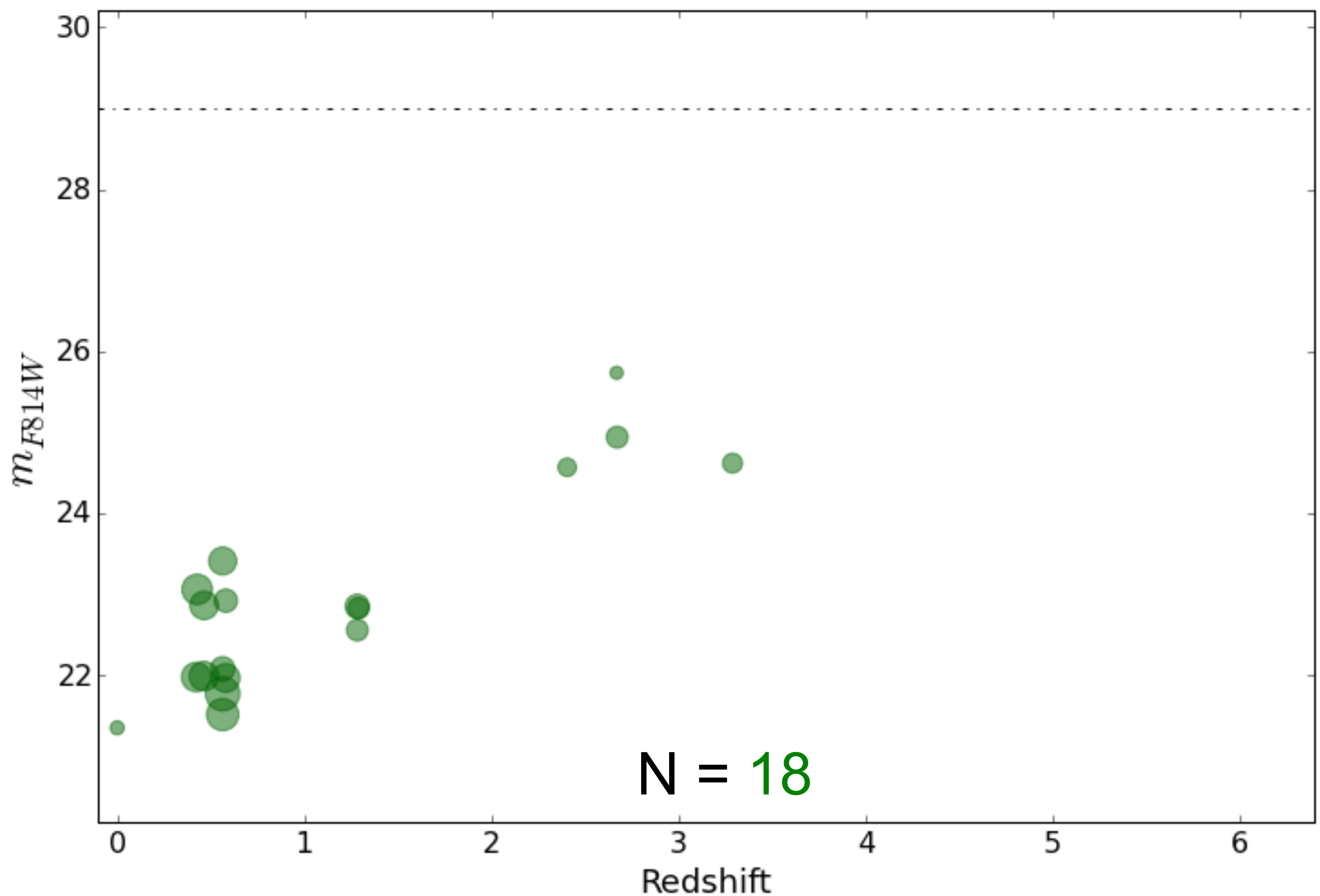


# Redshift Distribution



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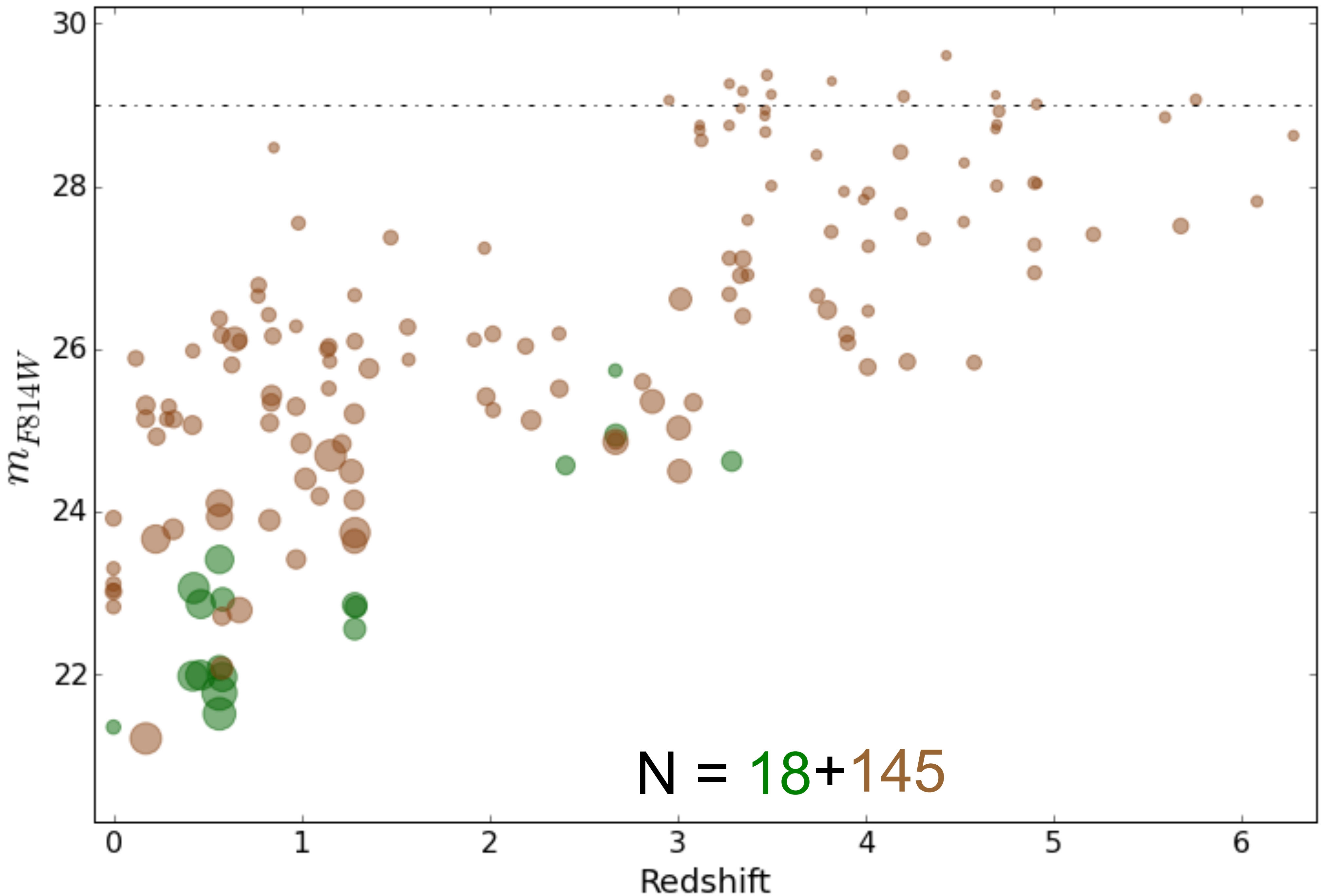

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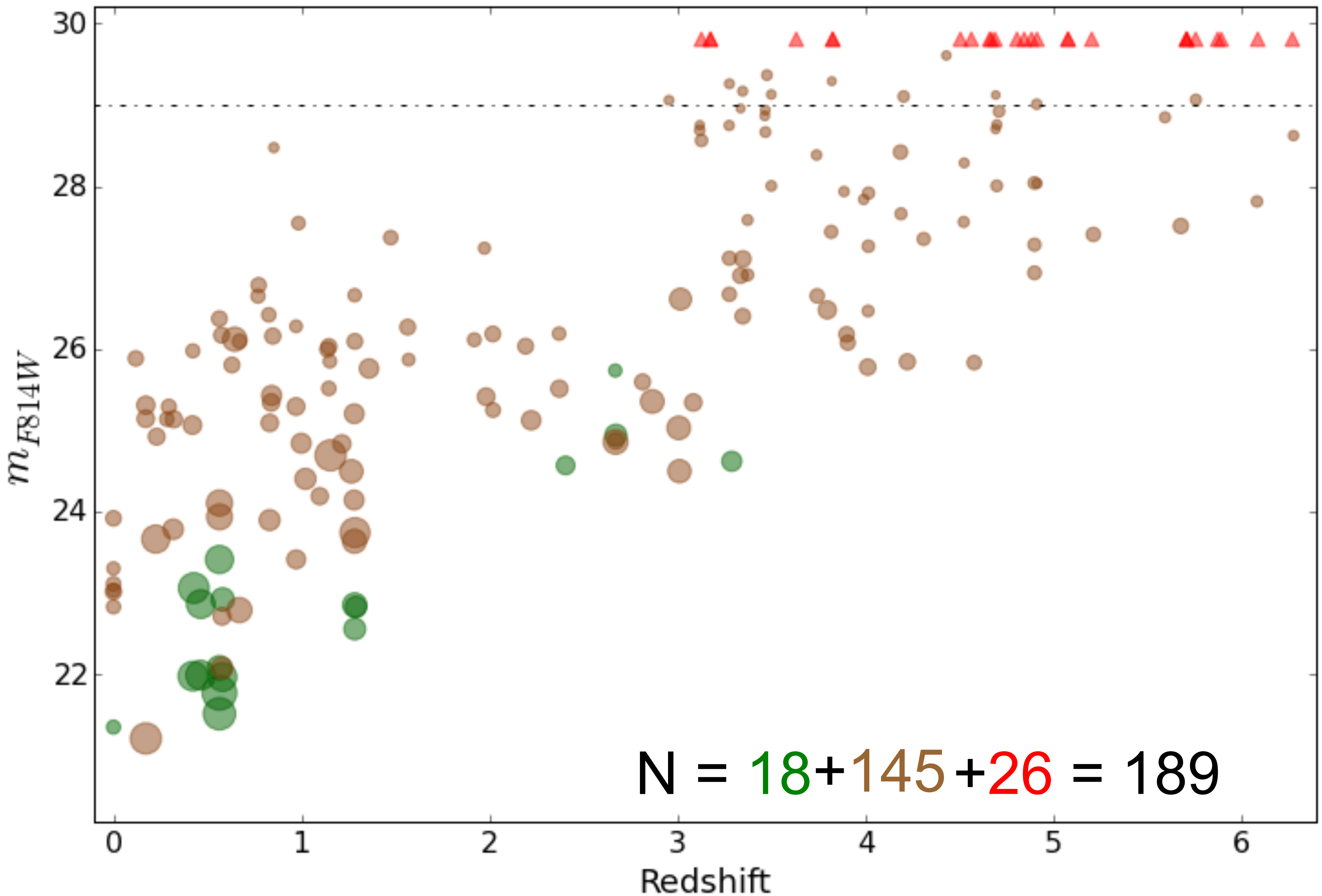
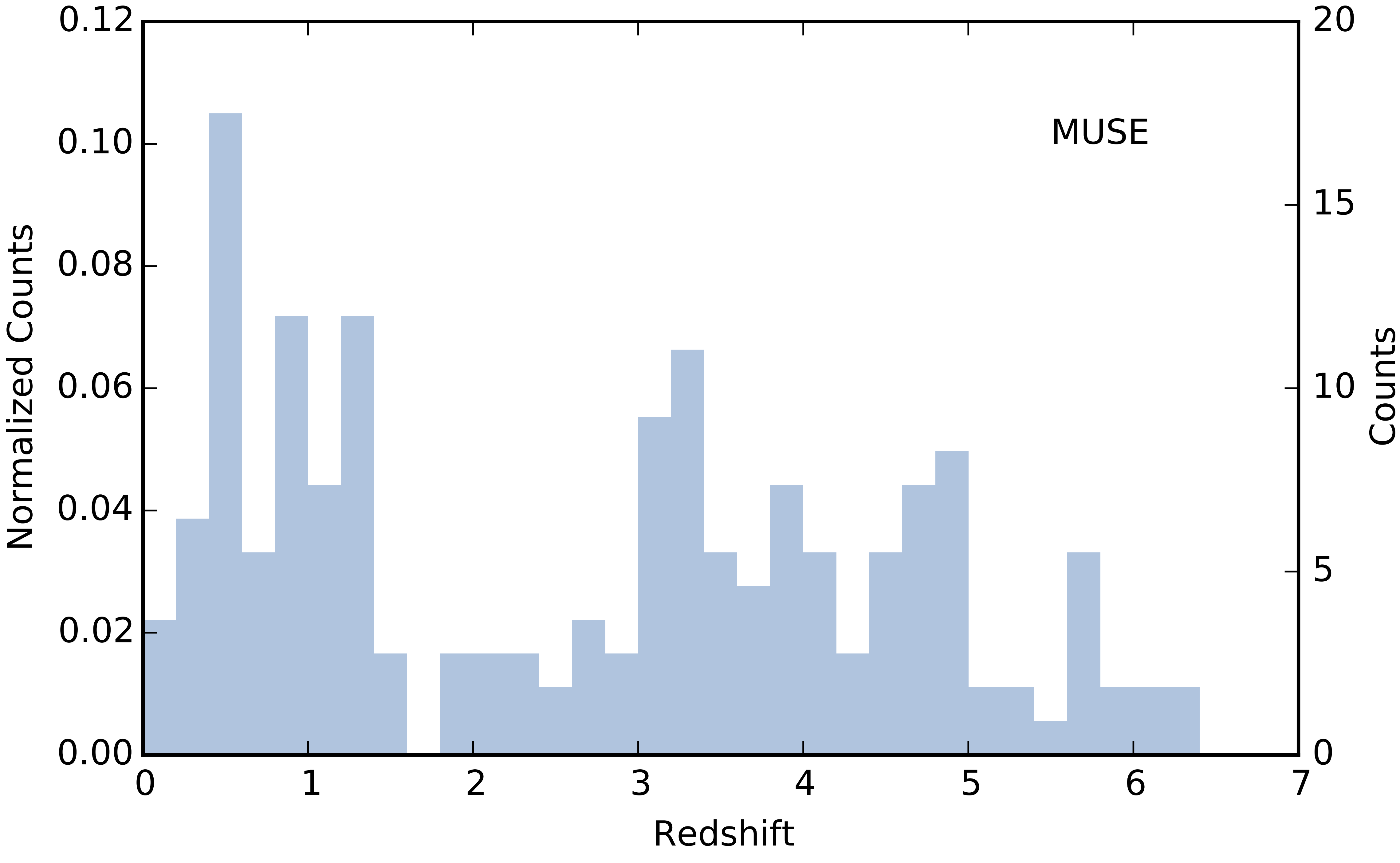
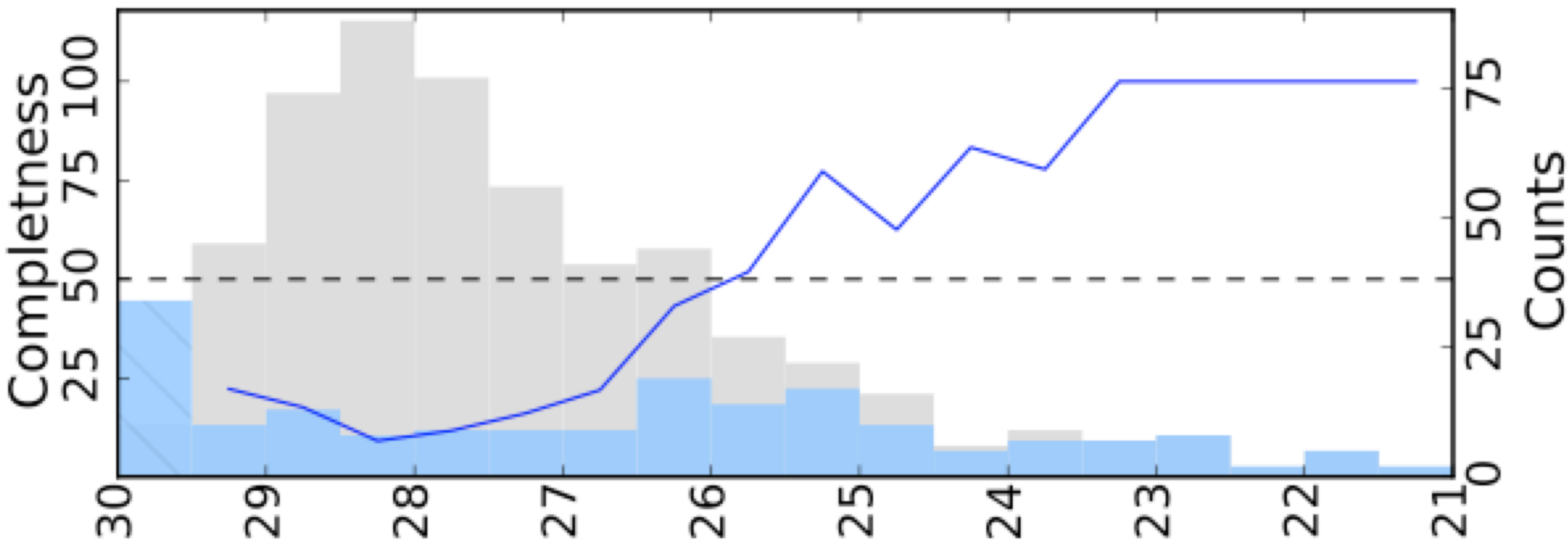


# Redshift Distribution

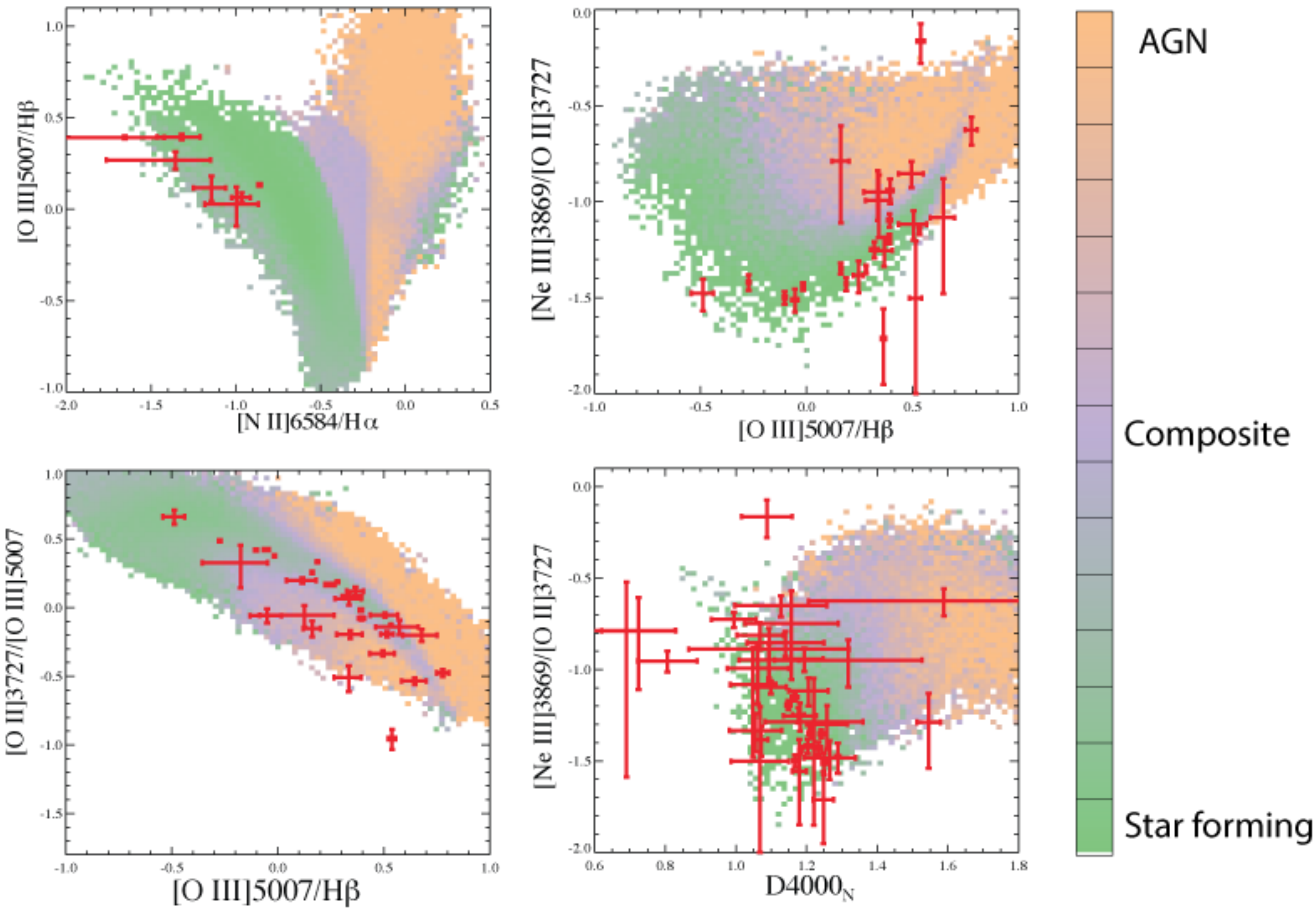


# Redshift Distribution - completeness

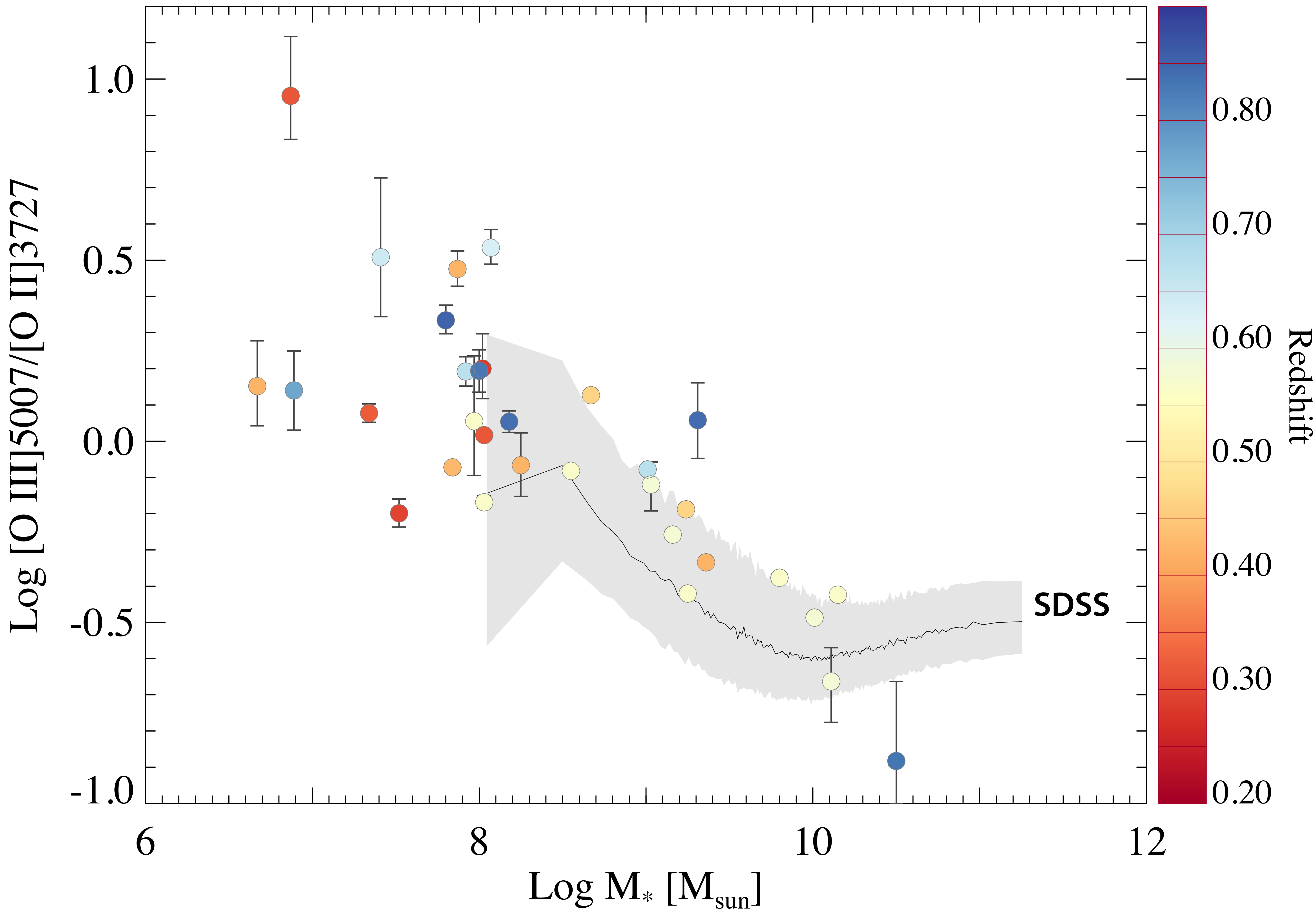



With decent completion down to 26[th] magnitude but still significant numbers at $m_{F814}$ ~ 29.

# The ionisation conditions in the z<1.5 galaxies

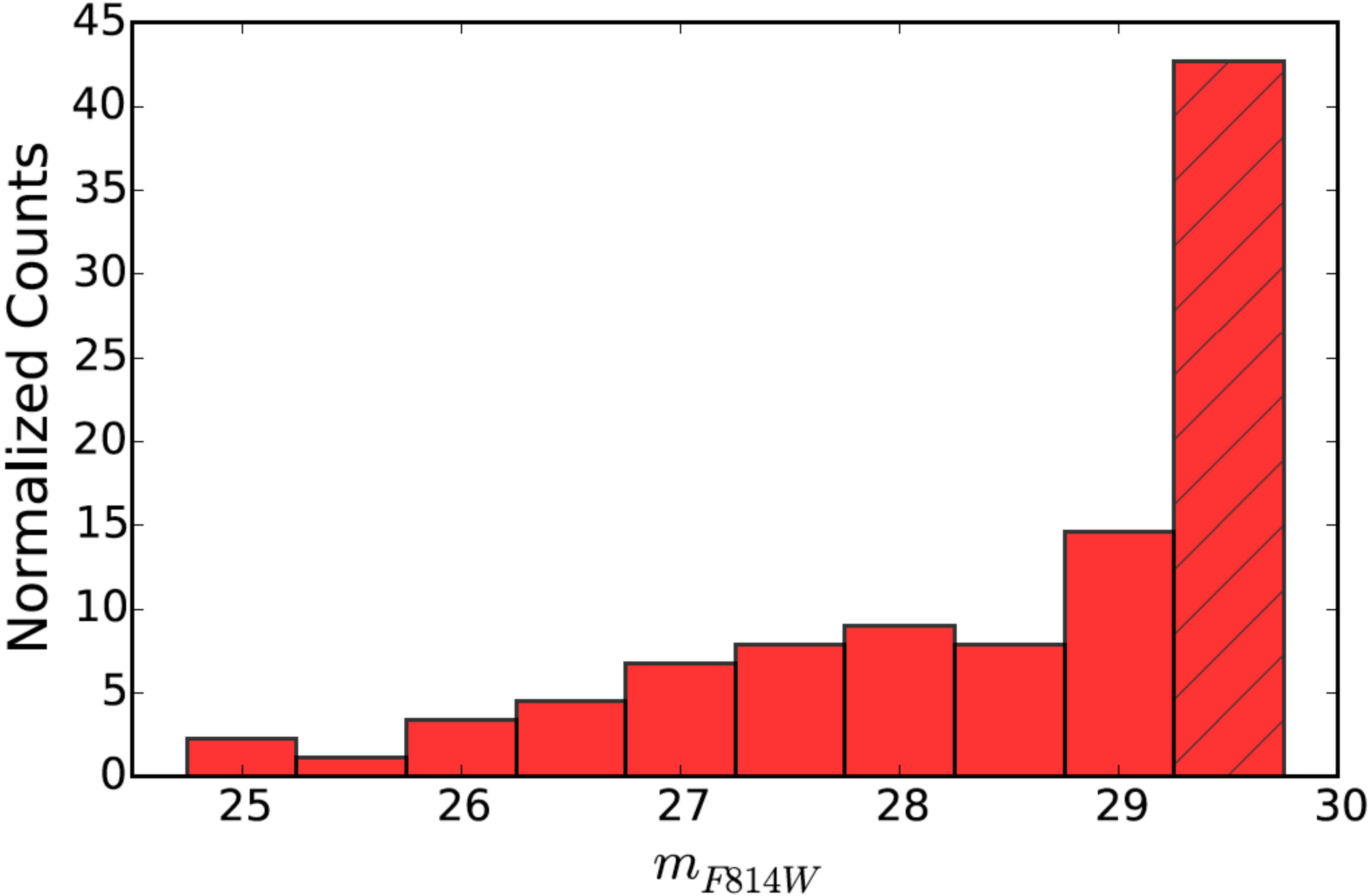



The galaxies appear to be dominated by star-formation and the line ratios are not particularly extreme.




Moderately more extreme than local galaxies, but not so much when SFR is taken into account (c.f. Shirazi et al 2014)

# Ly-a emitters - a brief look



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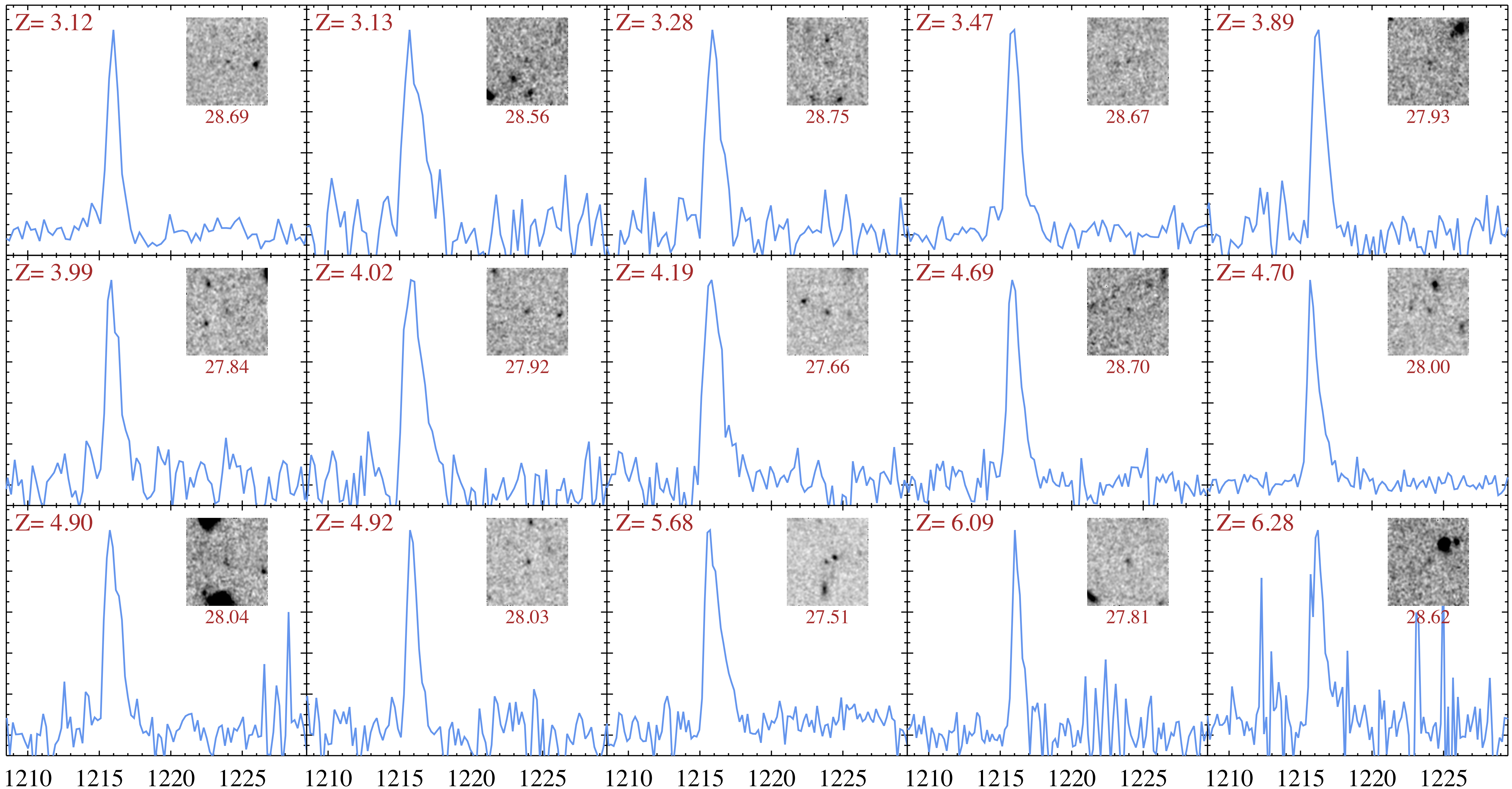
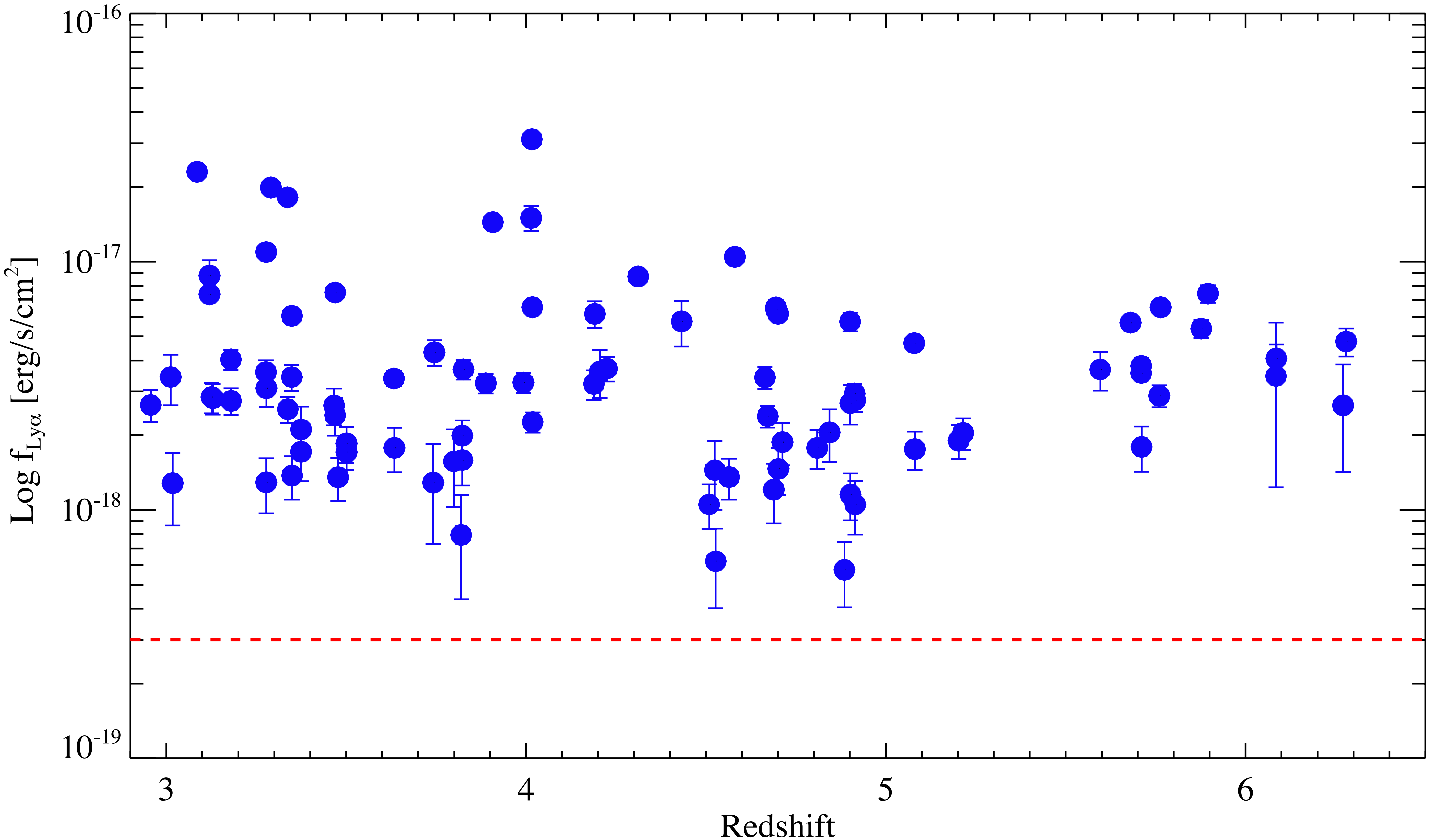
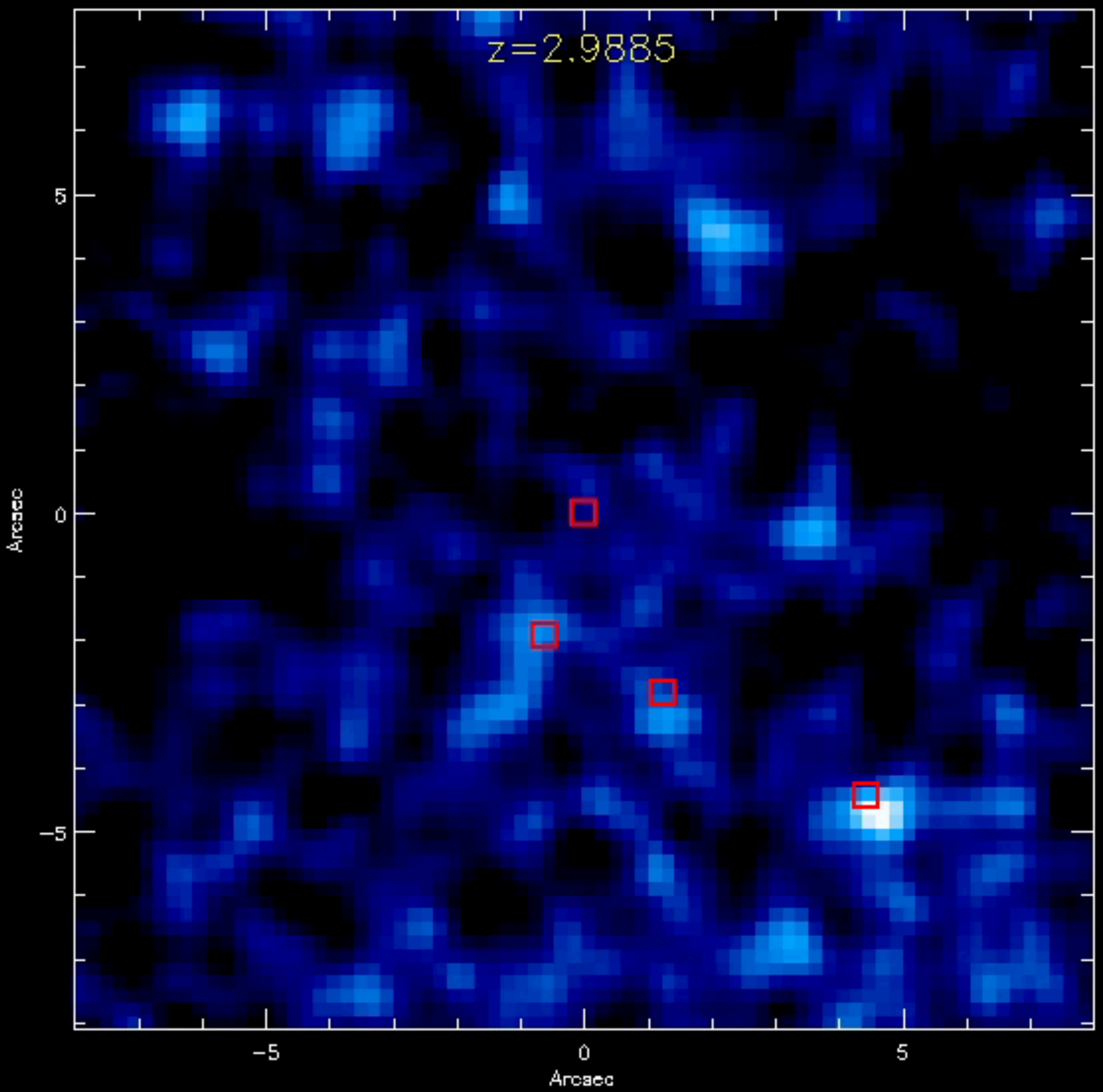


# Line fluxes



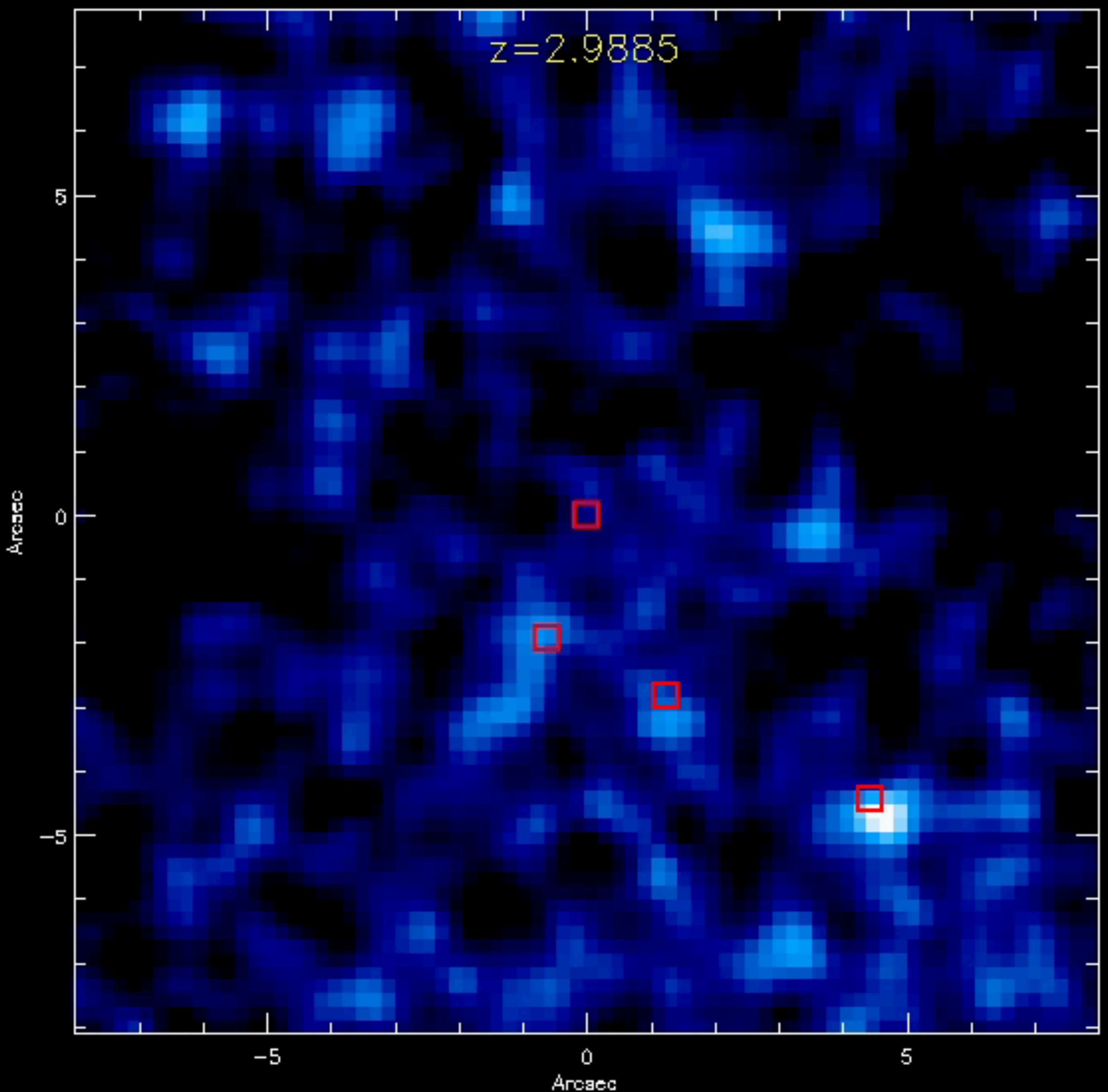

The median log $L_{Ly\text{-}a}$ is 41.72.
Still room for improvement!

# Diffuse emission




Around object #40 @ z=3.01 - 120 kpc x 120 kpc

# Diffuse emission

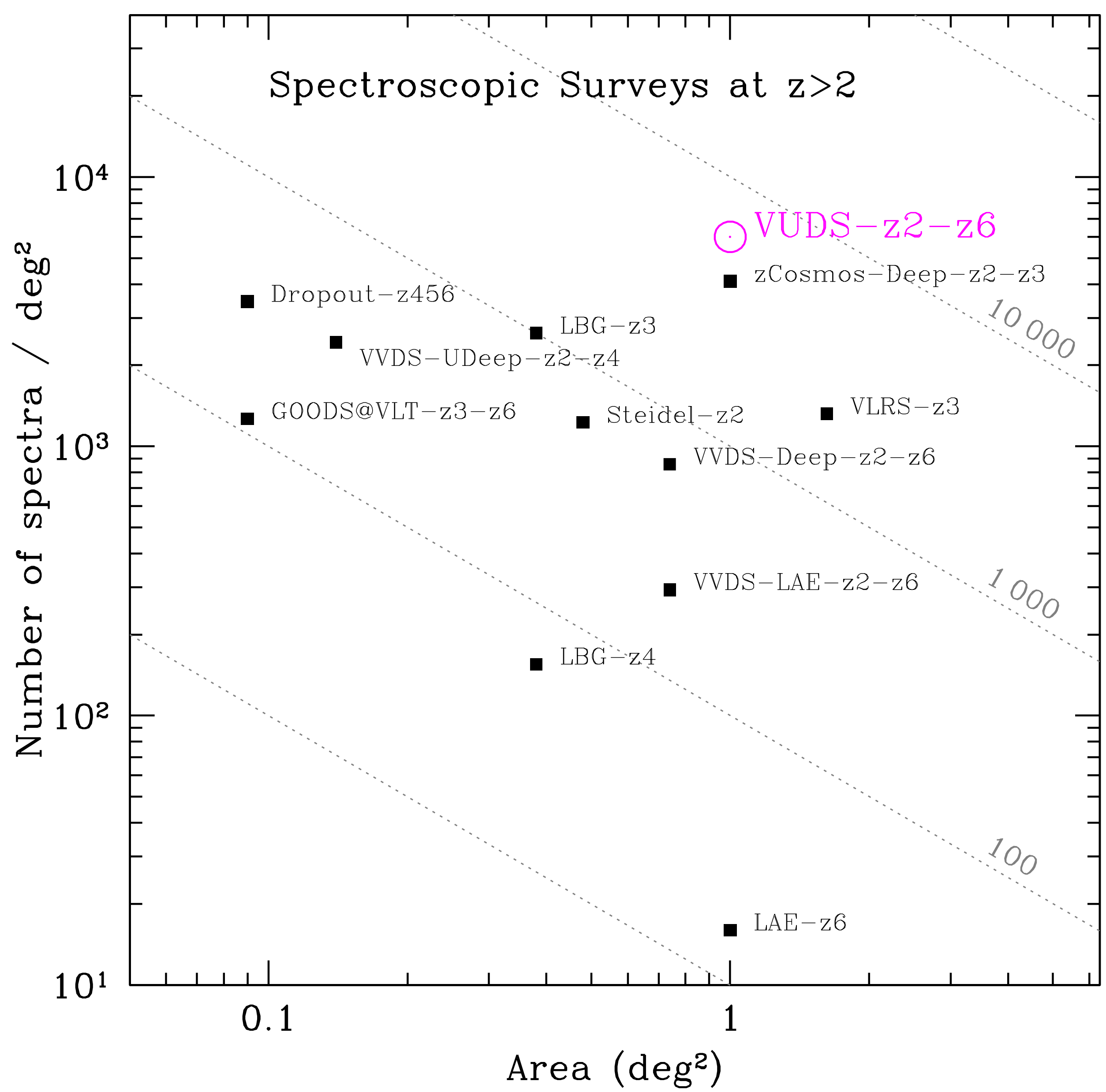



Around object #40 @ z=3.01 - 120 kpc x 120 kpc

# An entirely new ball-game

While MUSE is the most efficient spectrograph on the VLT, it is not a general purpose redshift machine. But it is unbeatable when it comes to density of spectra.

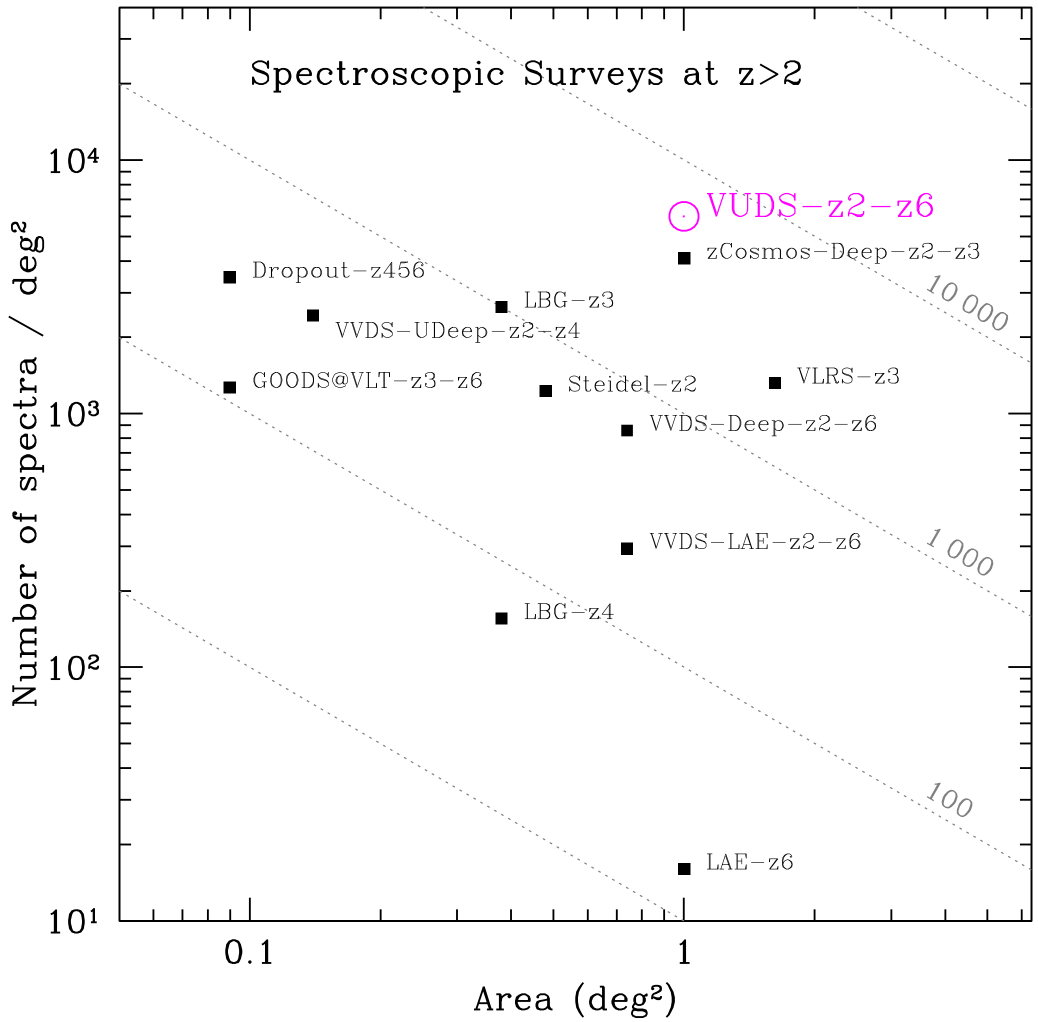
Le Fevre et al (2014) - VUDS



# An entirely new ball-game

## Density of spectra

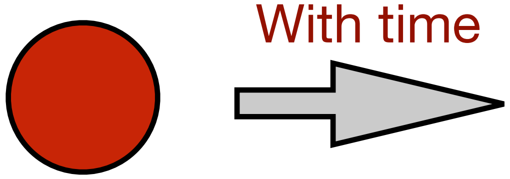
Le Fevre et al (2014) - VUDS



# An entirely new ball-game

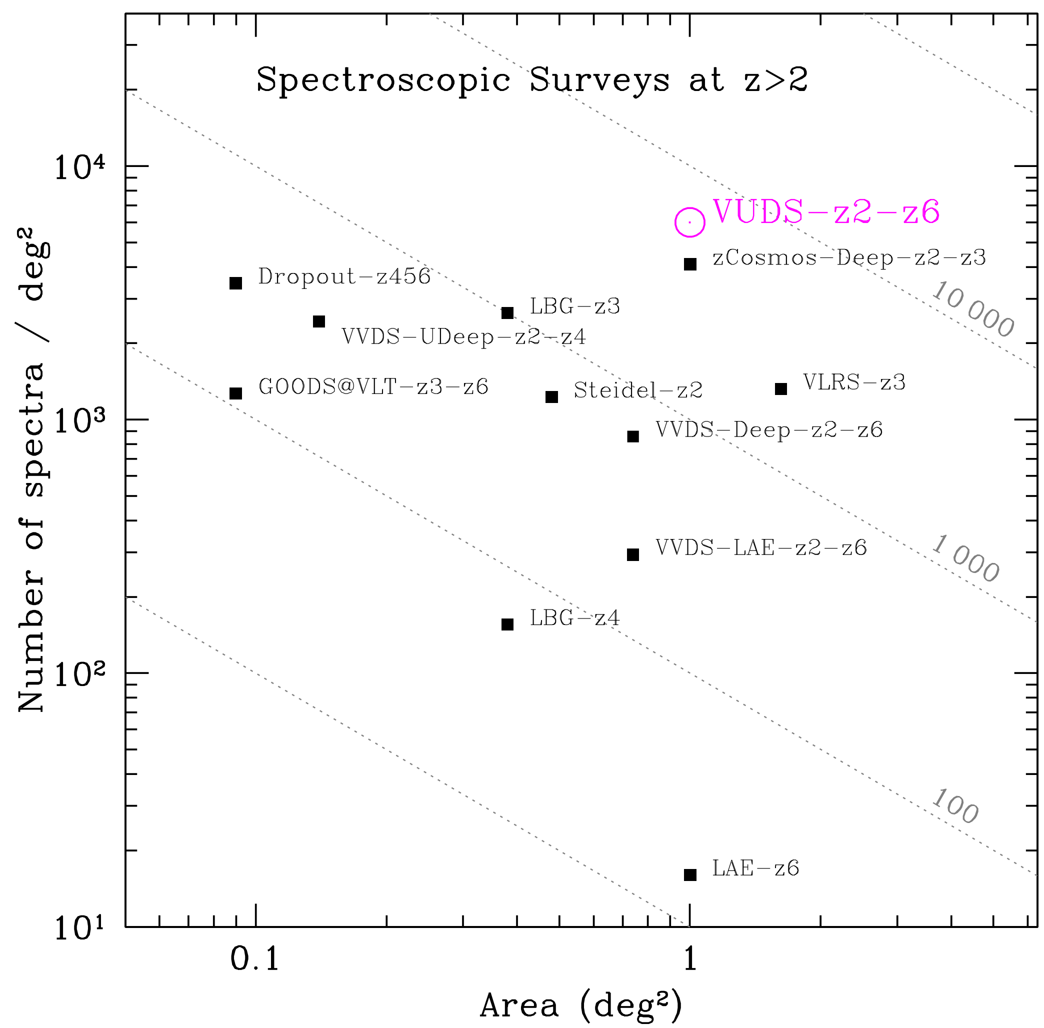
Density of spectra

With time



MUSE HDF-S

Le Fevre et al (2014) - VUDS



# Summary

Four nights of MUSE observations have given us - and you:

- An order of magnitude more redshifts - the main difference from before is the **spatial density** of spectra.
- A nearly flat redshift distribution for $3<z<6$
- Most galaxies are in groups or pairs
- We have found a large population of Ly-a emitters fainter than the HST detection limit (I814>30)
- At the same time we get spatially resolved kinematics for 20 galaxies at $z \sim 0.5-1.0$
- The majority of the galaxies are star-forming and not particularly extreme (relative to SDSS).

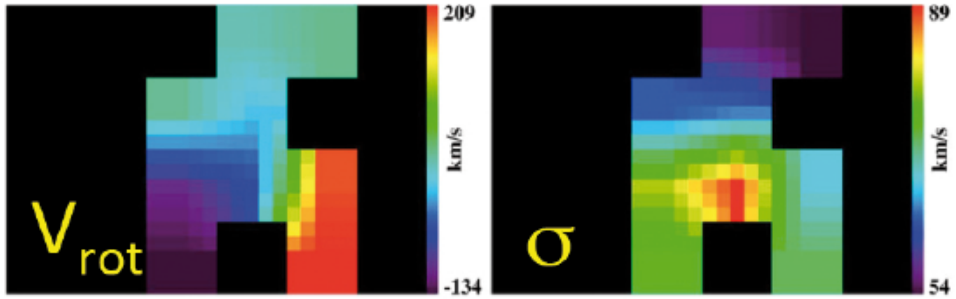
# Outlook

- The reduced data are available for all to use:
  - http://muse-vlt.eu/science/
  - Data cubes, spectra, redshifts, catalogue
- MUSE GTO observing (250 nights over 5 years). Multiple fields to ~100 hours and many (50?) fields to ~10 hours depth.
- AOF/GALACSI in 2016-2017
  - ~50% better seeing, 0 impact on throughput, minimal impact in overhead
  - A new public deep field at 0.5 arcsec spatial resolution?
- MUSE is a great instrument - keep it in mind for your science!

# Supplementary data

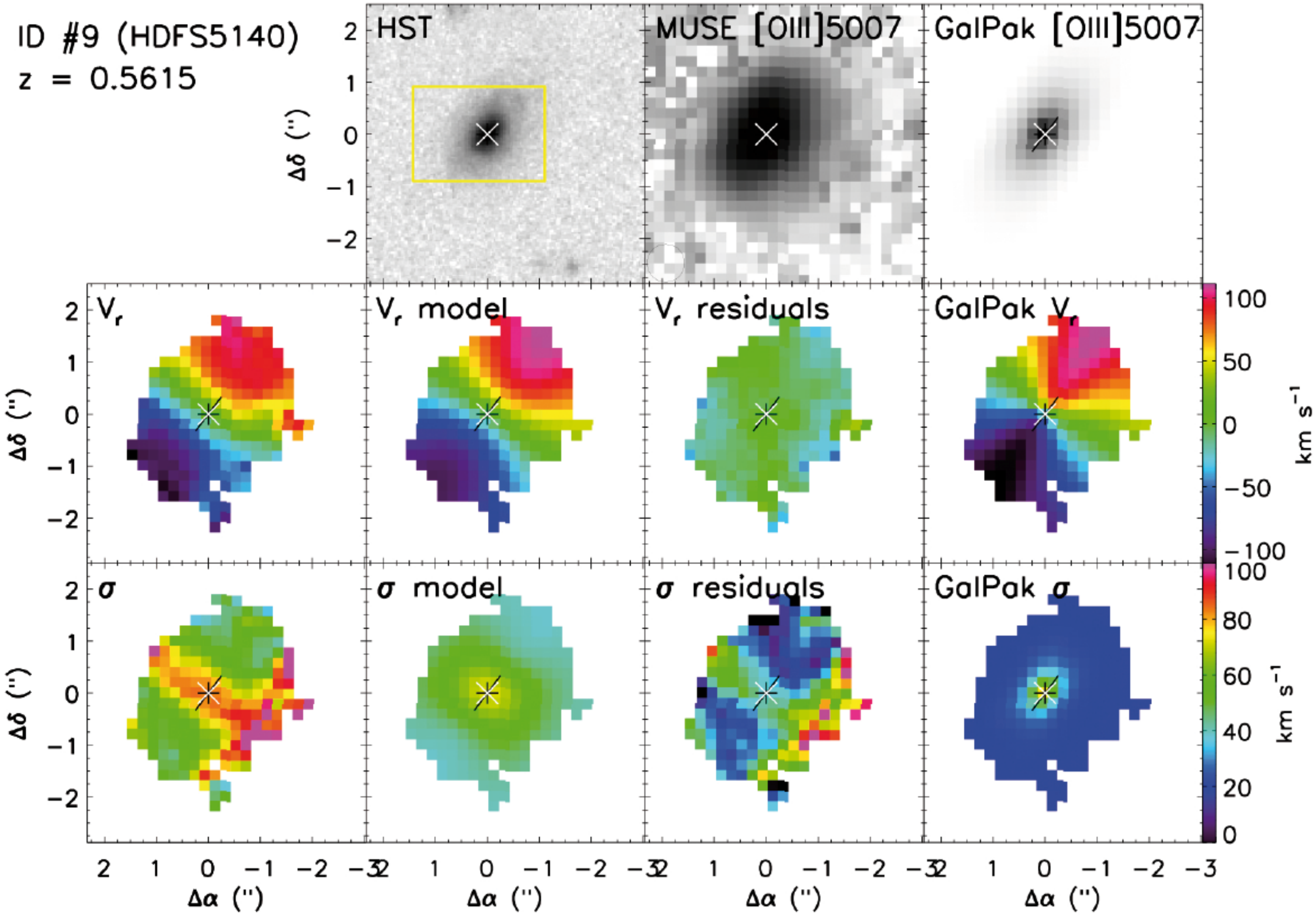
# Resolving galaxies

## GIRAFFE (Puech et al 2006)

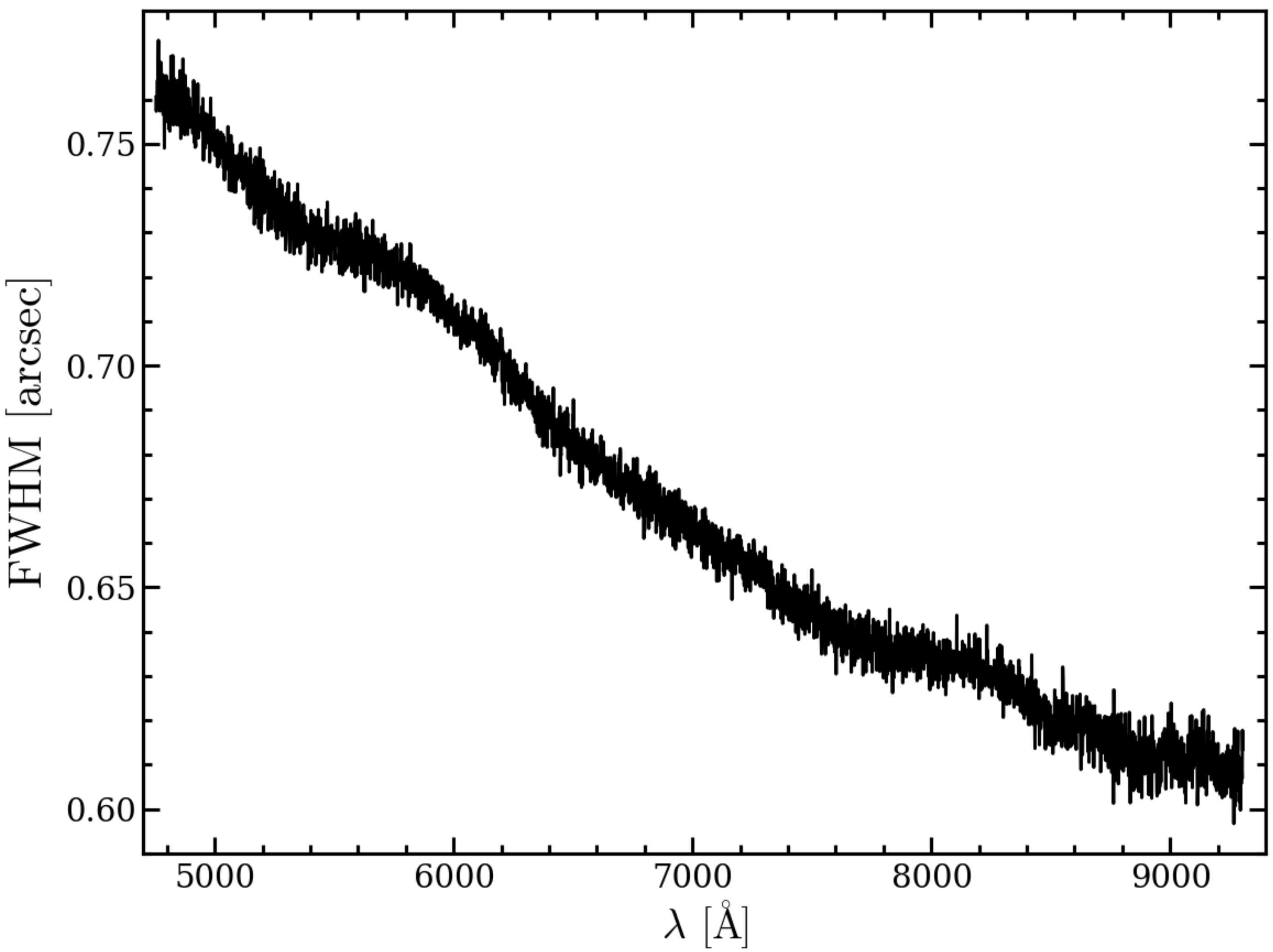



#9 with MUSE:

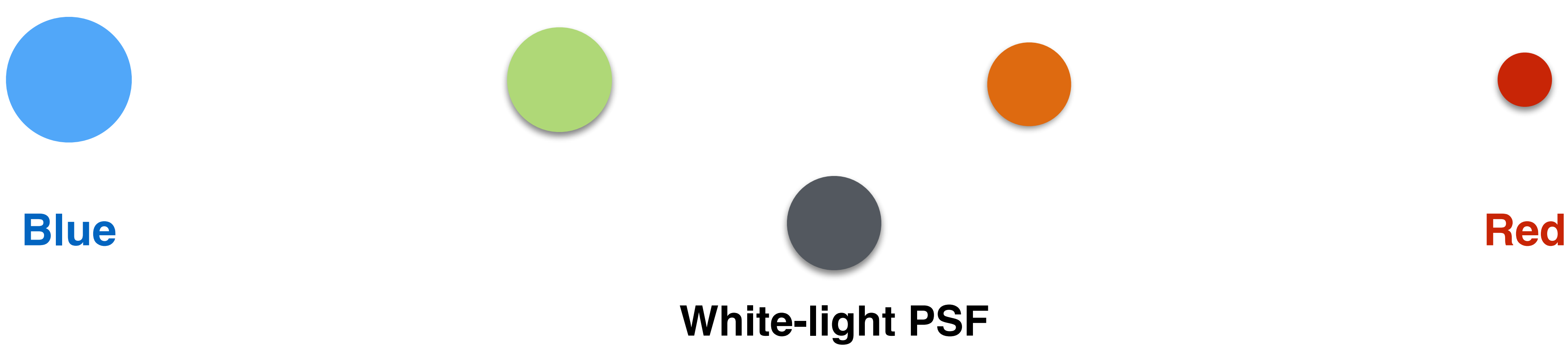
$v_{rot}$ ~ 140 km/s
Regular vfield



# The anatomy of the MUSE data-cube



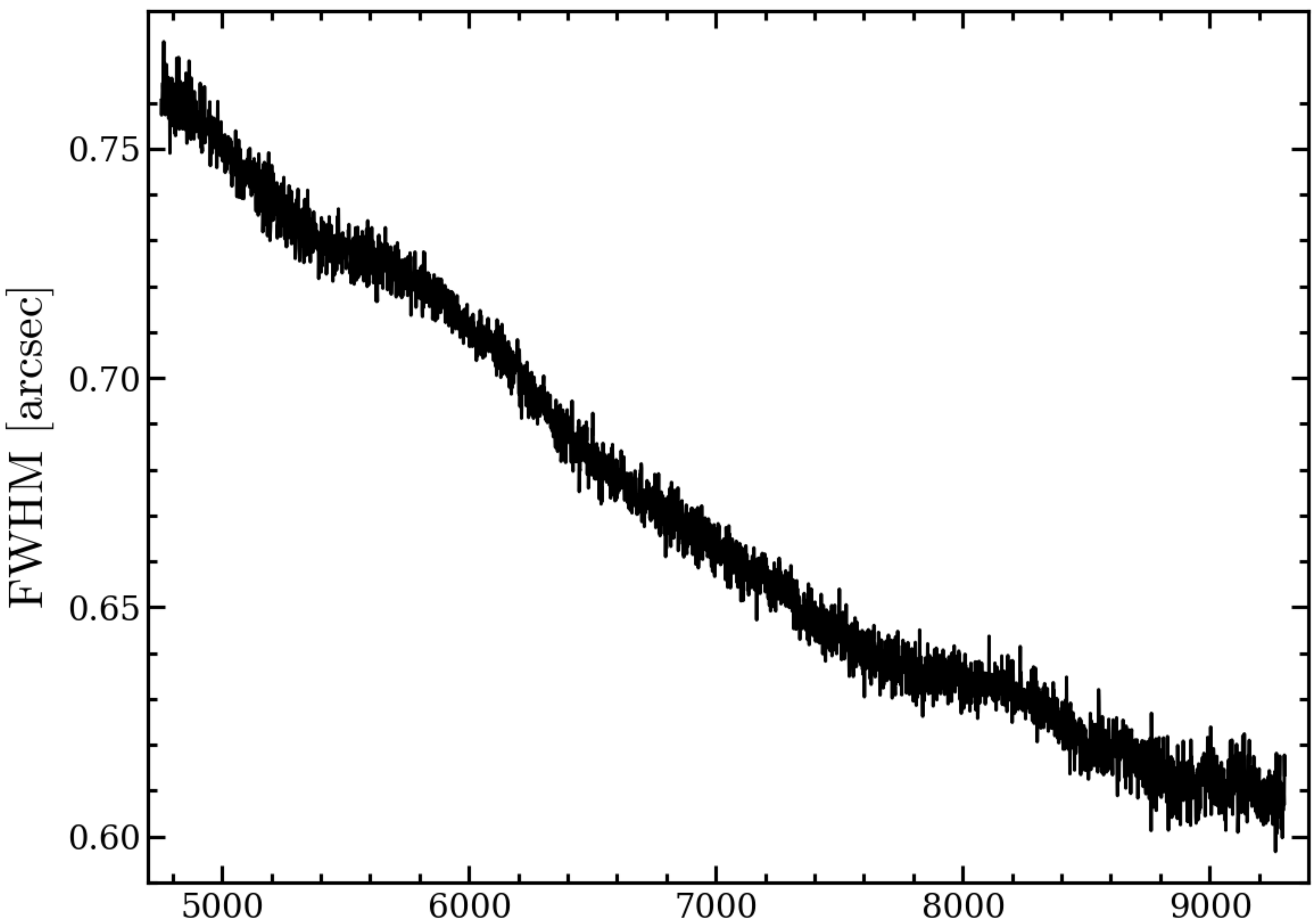

Moffat fit to the data cube. For optimal extraction a knowledge of this is of course crucial.




Here we lose light because the weight is too concentrated

Here we get relatively too much

# The anatomy of the MUSE data-cube

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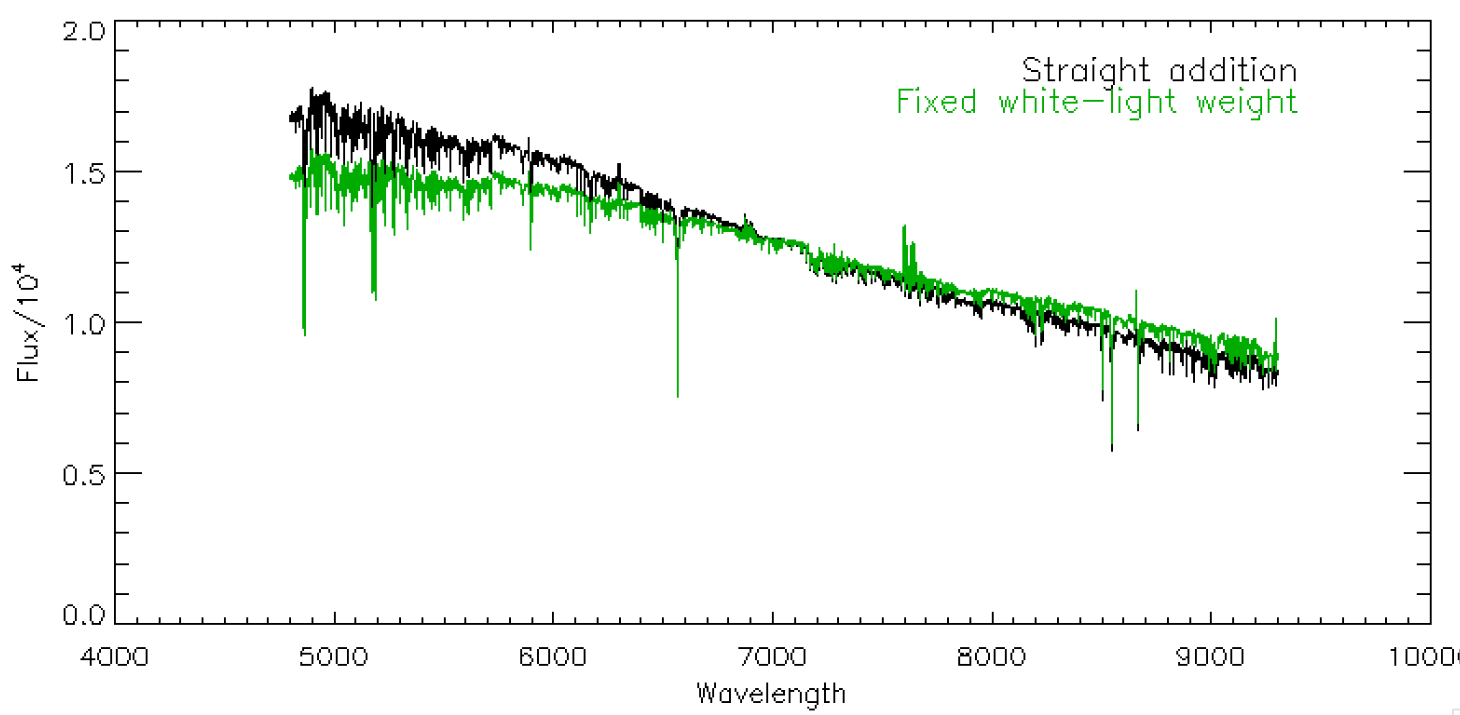
Blue




Red

Here we lose lig
the weight is to

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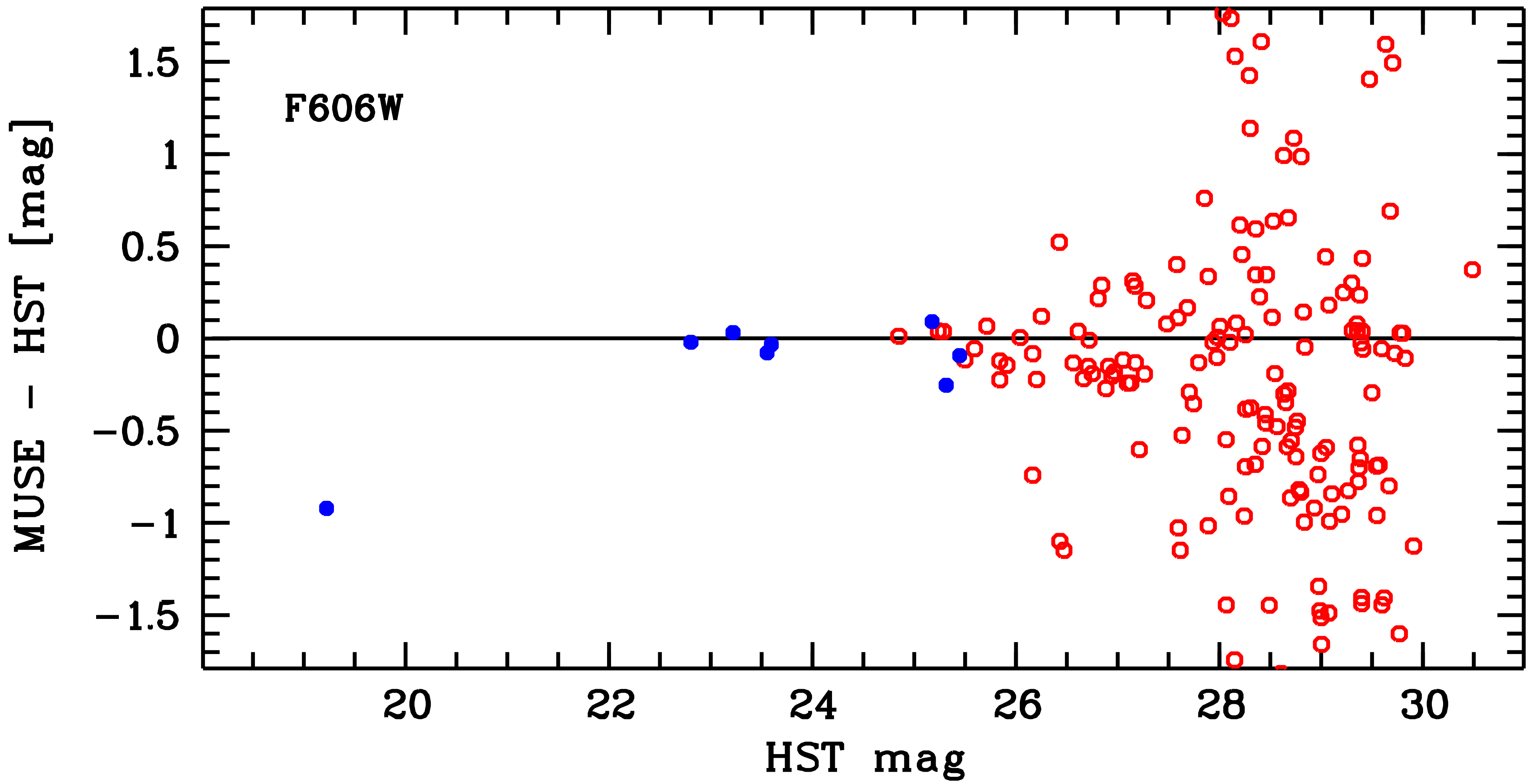
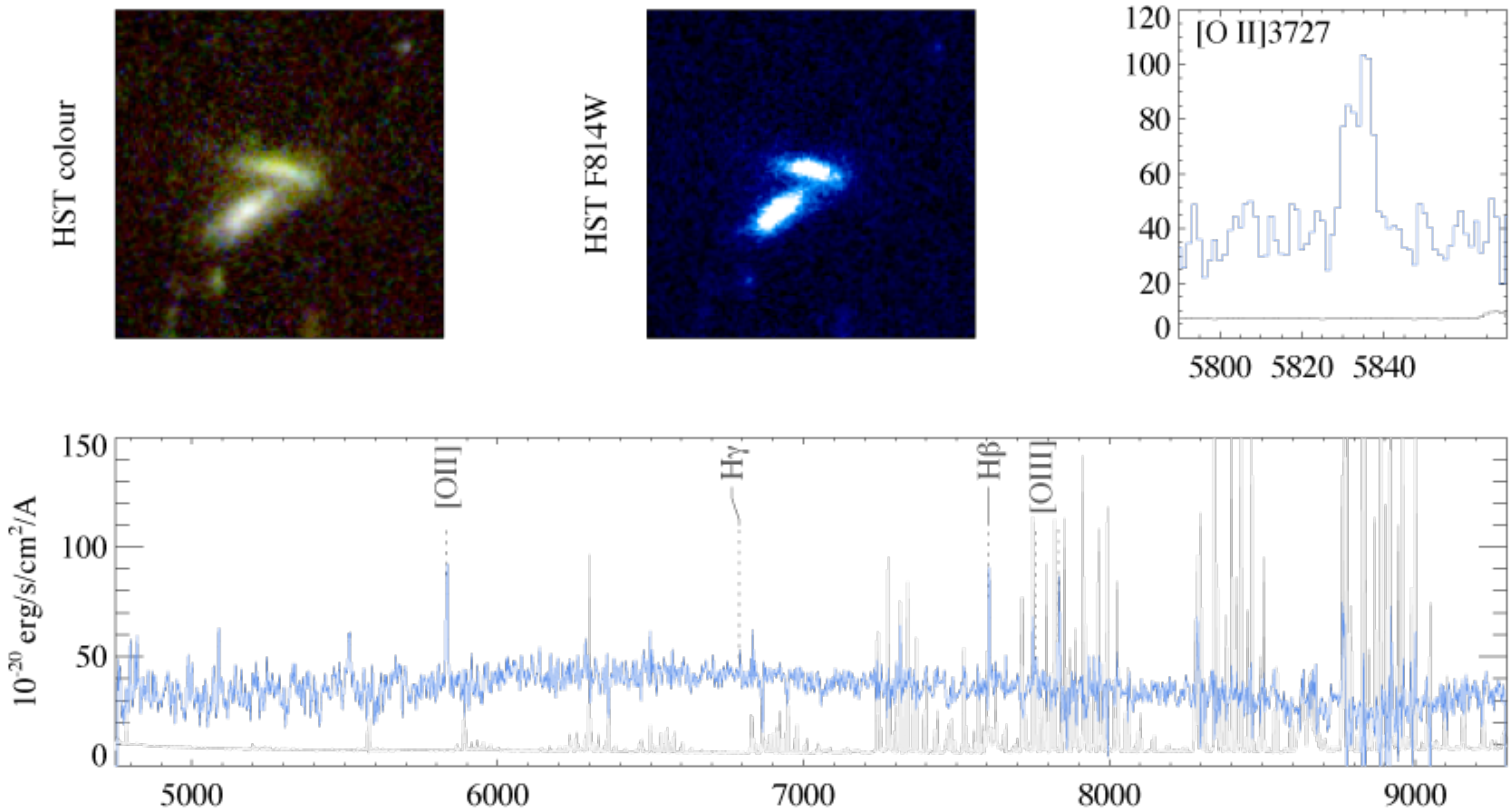
# Spectrophotometry




Overall quite satisfactory - but at $m_{F814W} > 27$ it starts to blow up.

Main limitation: Residual sky variation + calibration residuals.
Local sky subtraction is essential (for the moment).

# Separating objects - the power of 3D



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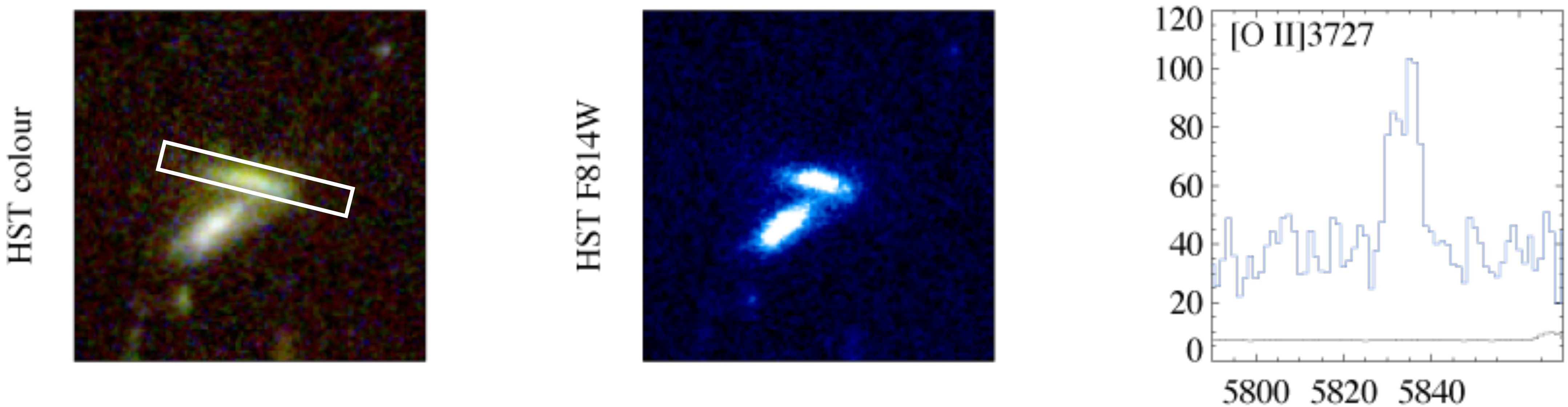


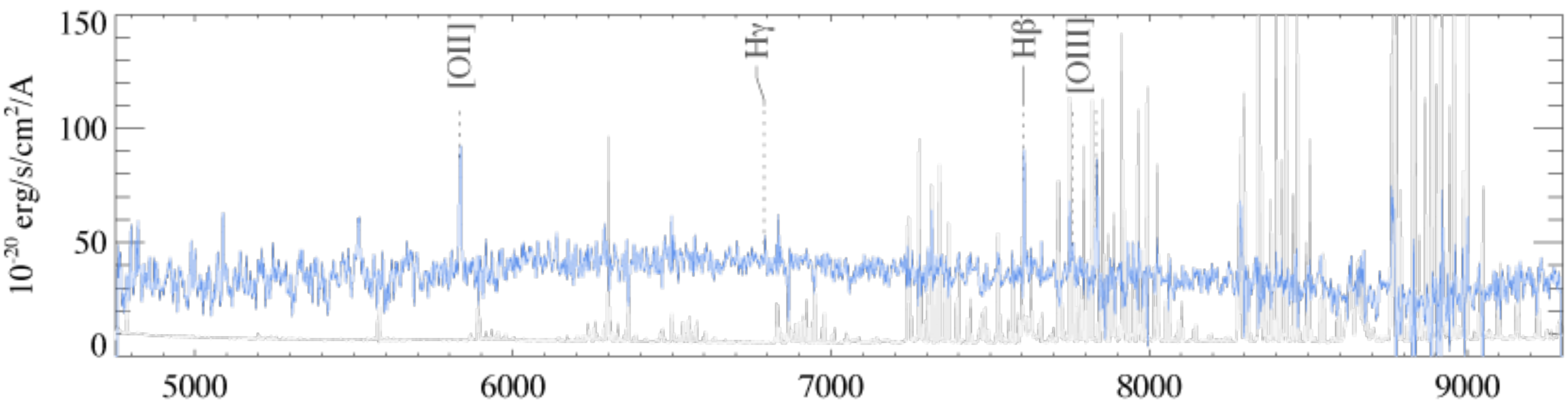

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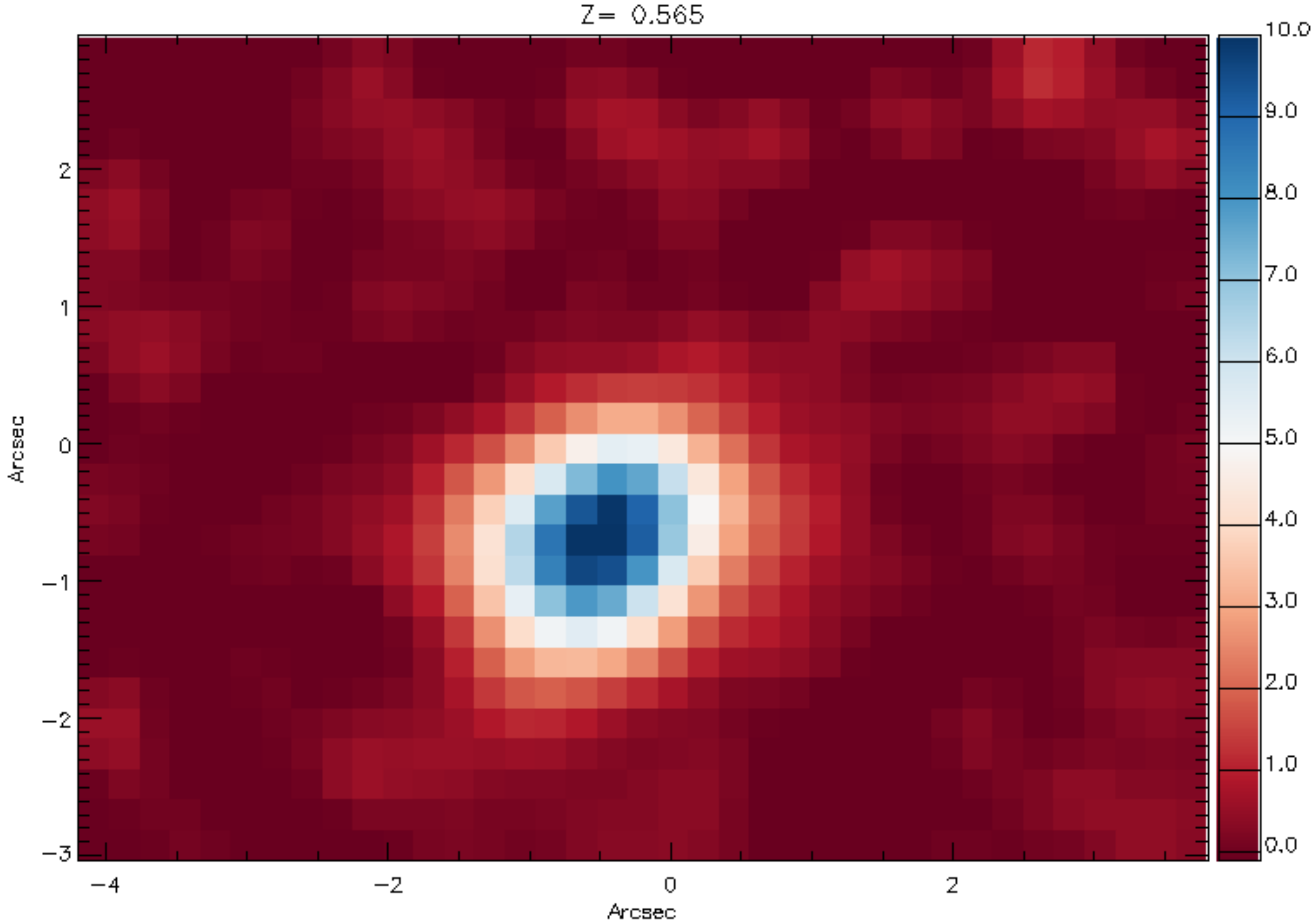



HST colour

Not that object!

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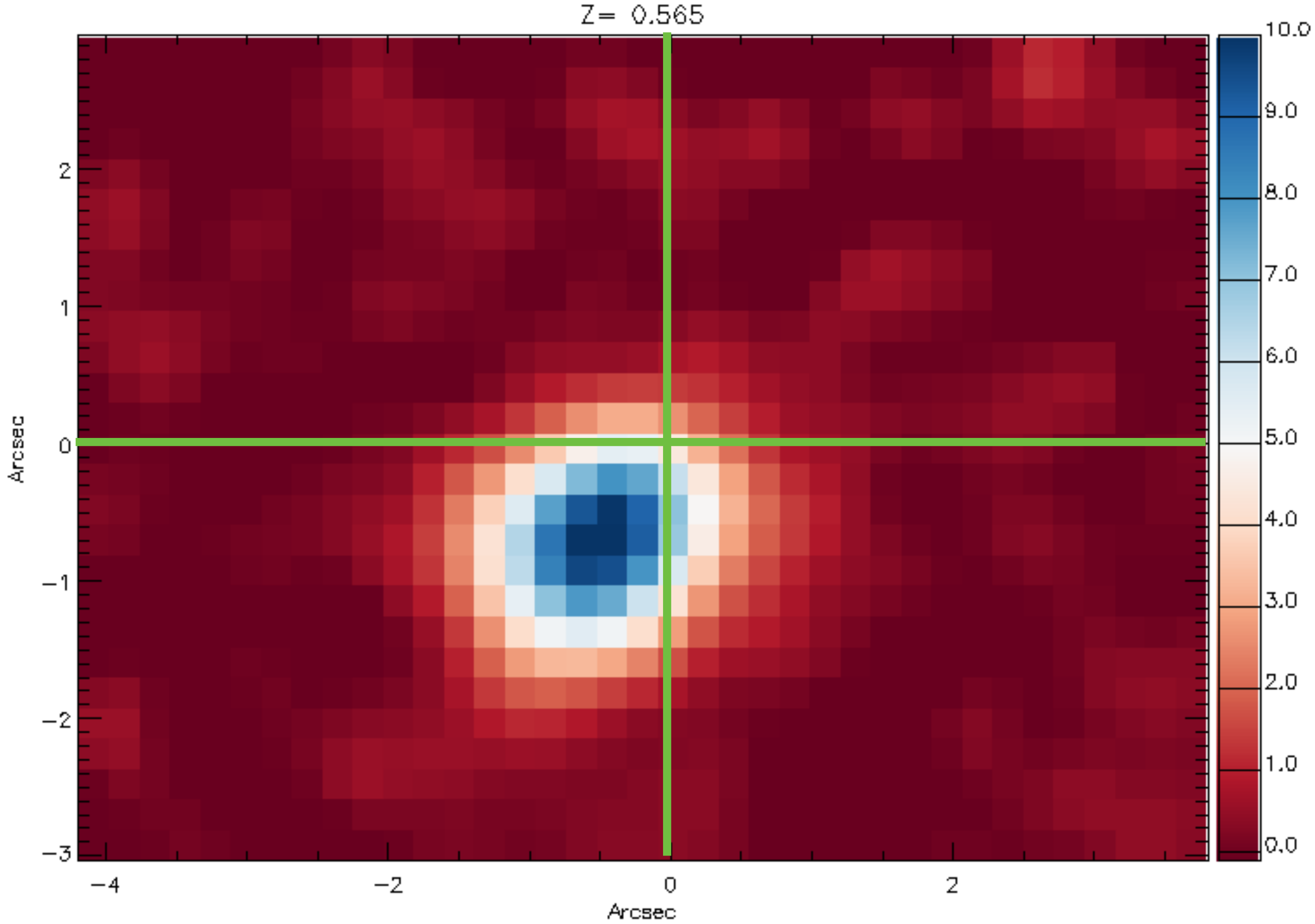


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HST colour

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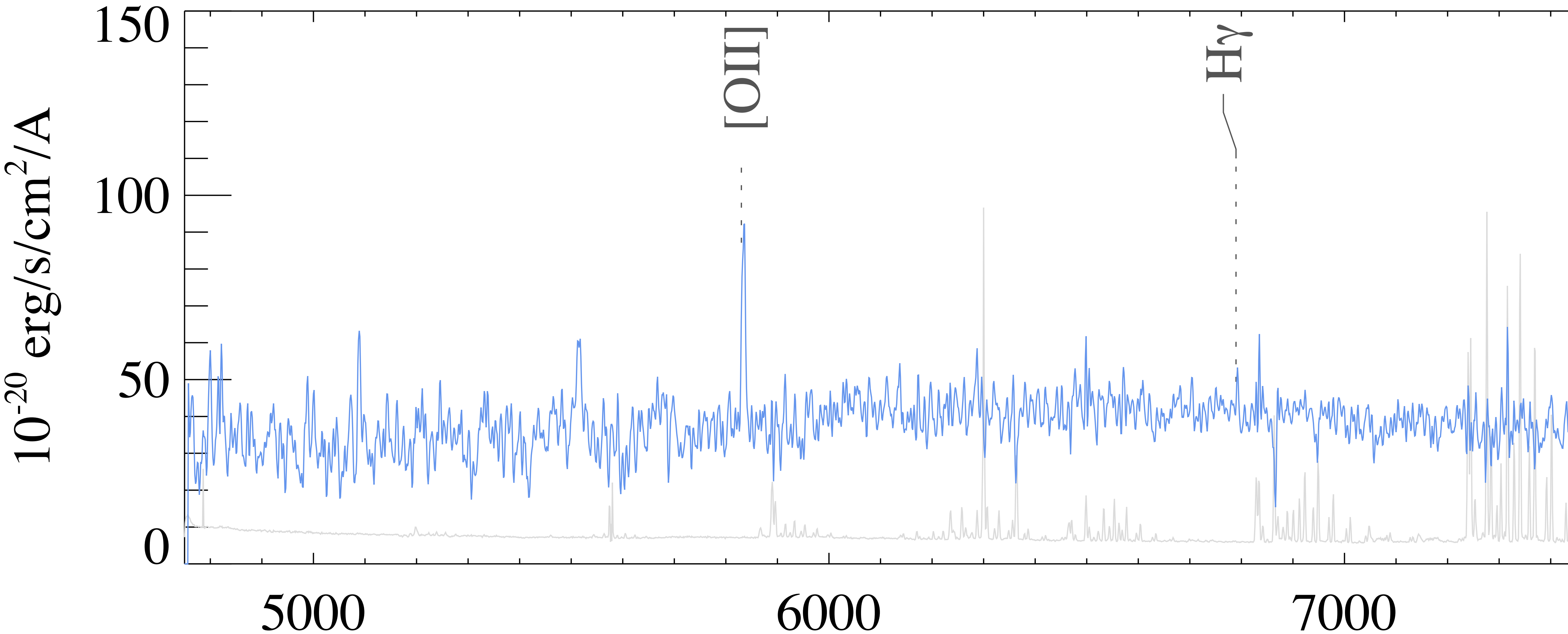


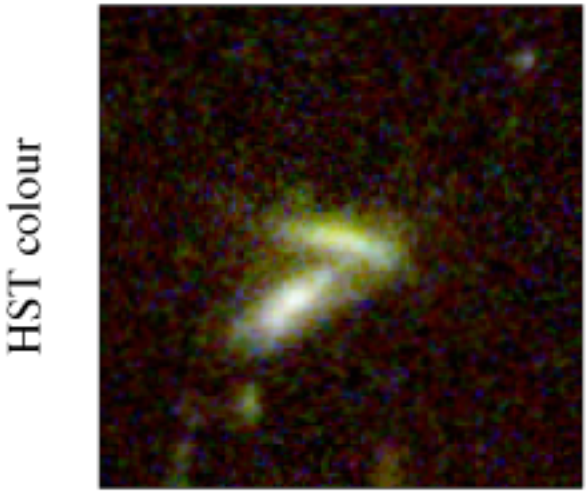


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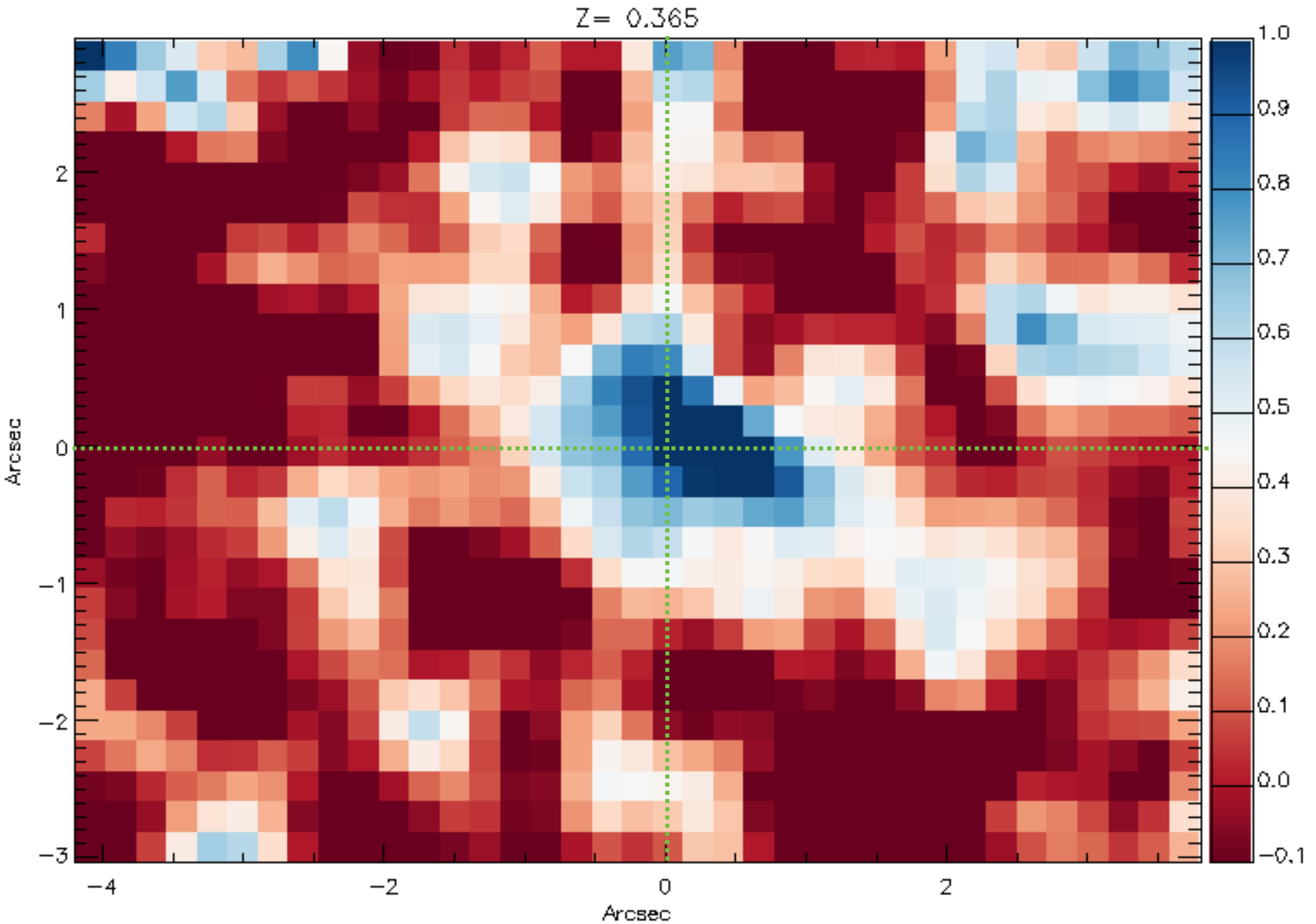
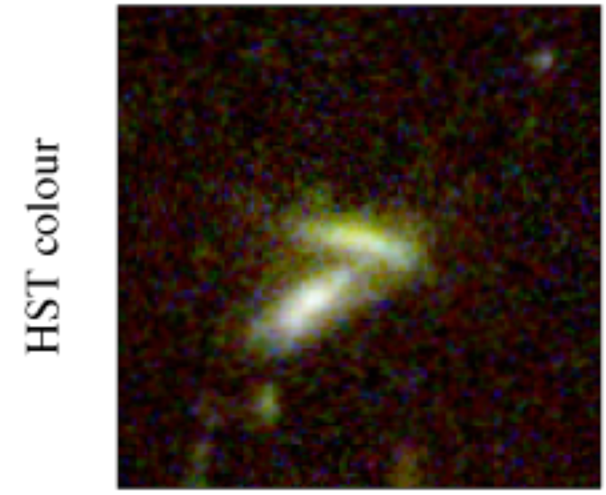



That matches!



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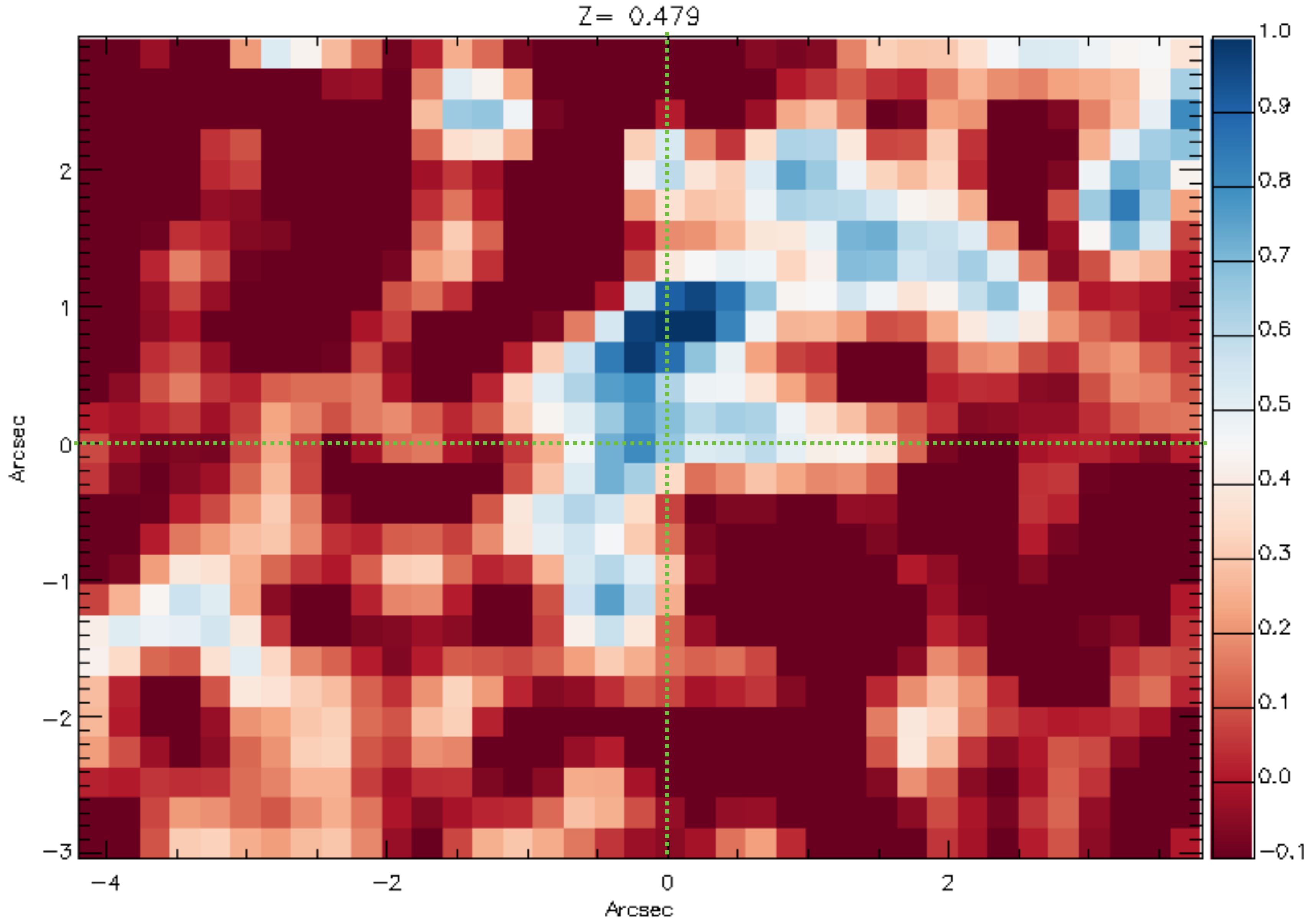
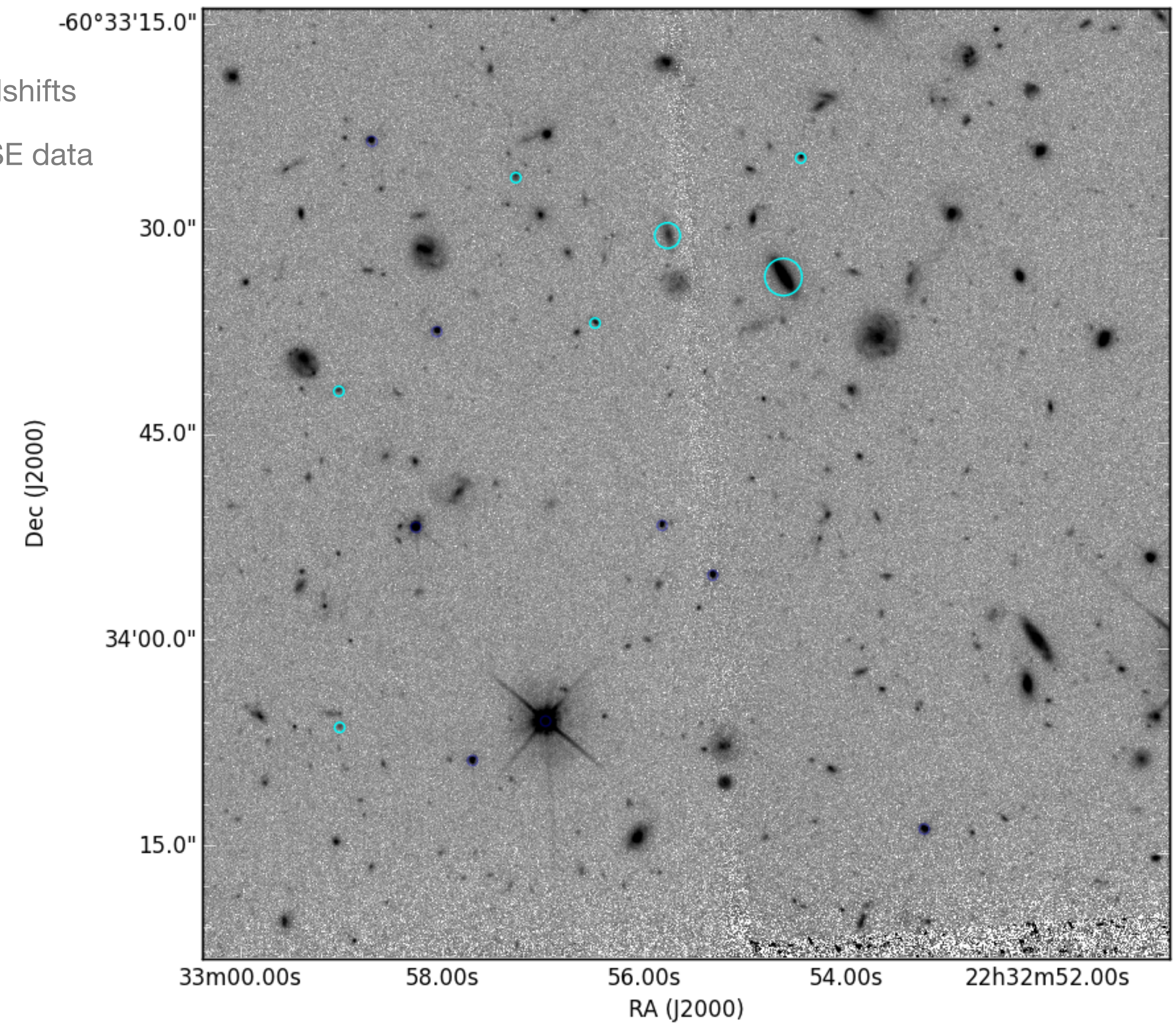



HST colour

Yet another one?

# Census of MUSE HDFS Field

- ✓ HST WFPC2 F812W
- ✓ 18 Known Spectroscopic Redshifts
- ✓ 189 sources identified in MUSE data cube
- ✓ 8 stars
- ✓ 7 nearby galaxies
  - ✓ Z = [0.12 – 0.28]
  - ✓ $I_{814}$ = [21.2 – 25.9]



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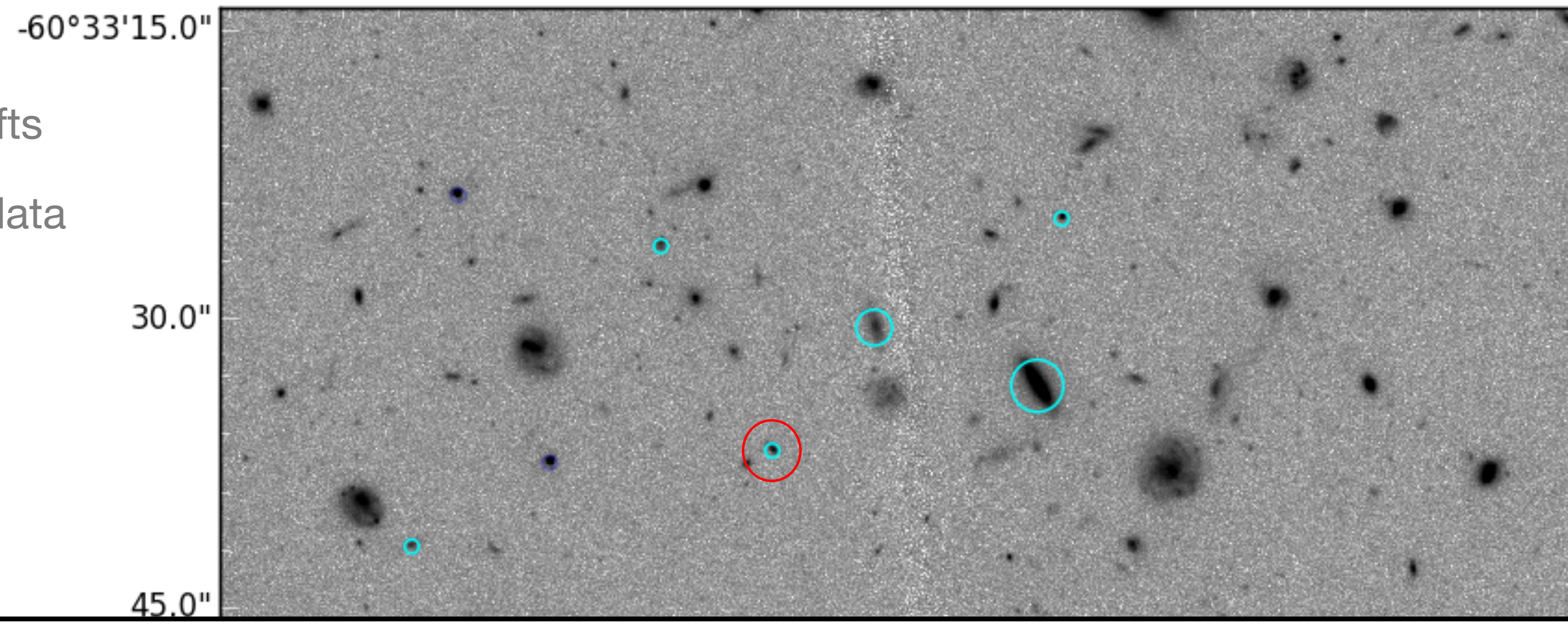
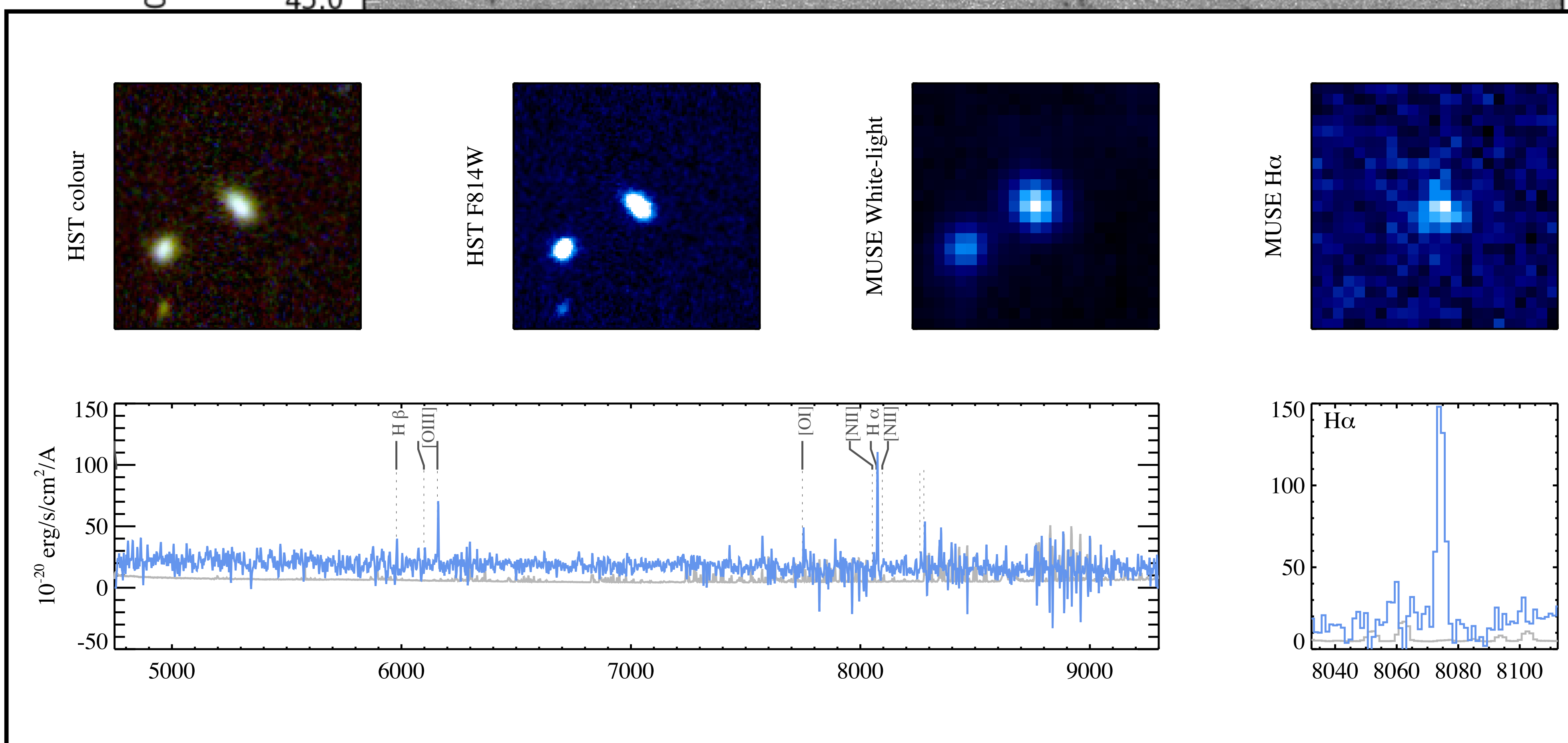



**ID#53**

**Z = 0.23**
**$I_{814}$ = 24.9**
**M ≈ 2 $10^7$ $M_\odot$**



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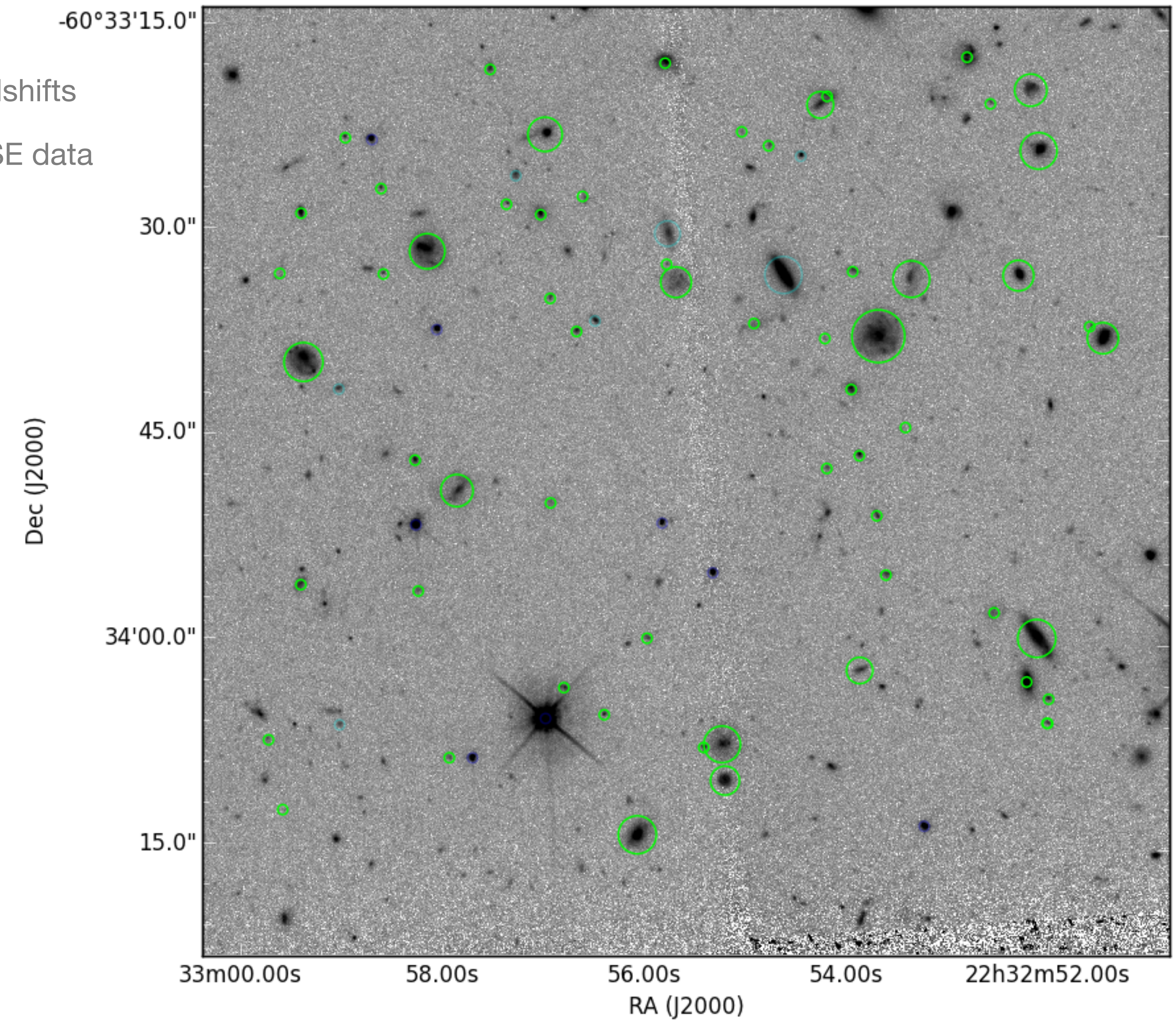
- ✓ 61 [OII] 3727 emitters
  - ✓ Z = [0.29 – 1.48]
  - ✓ $I_{814}$ = [21.5 – 28.5]



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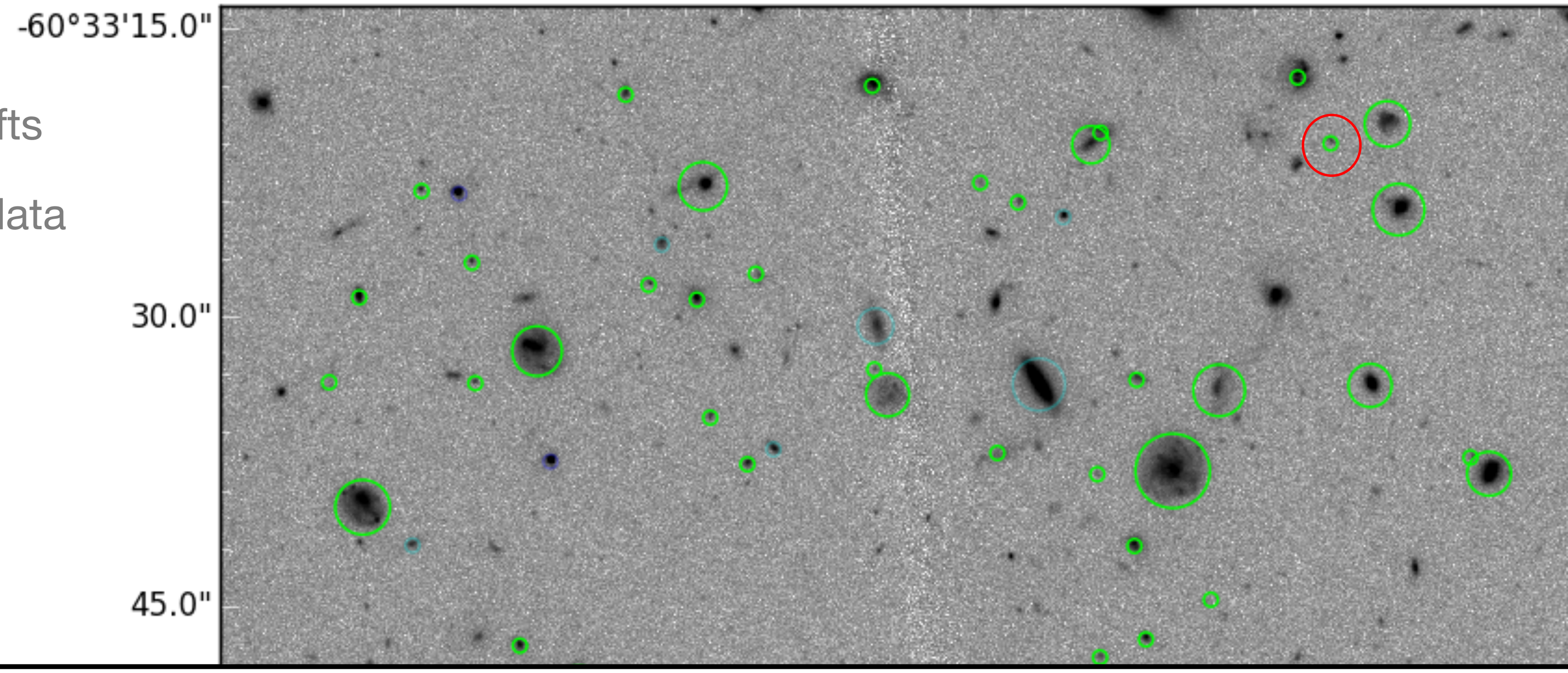
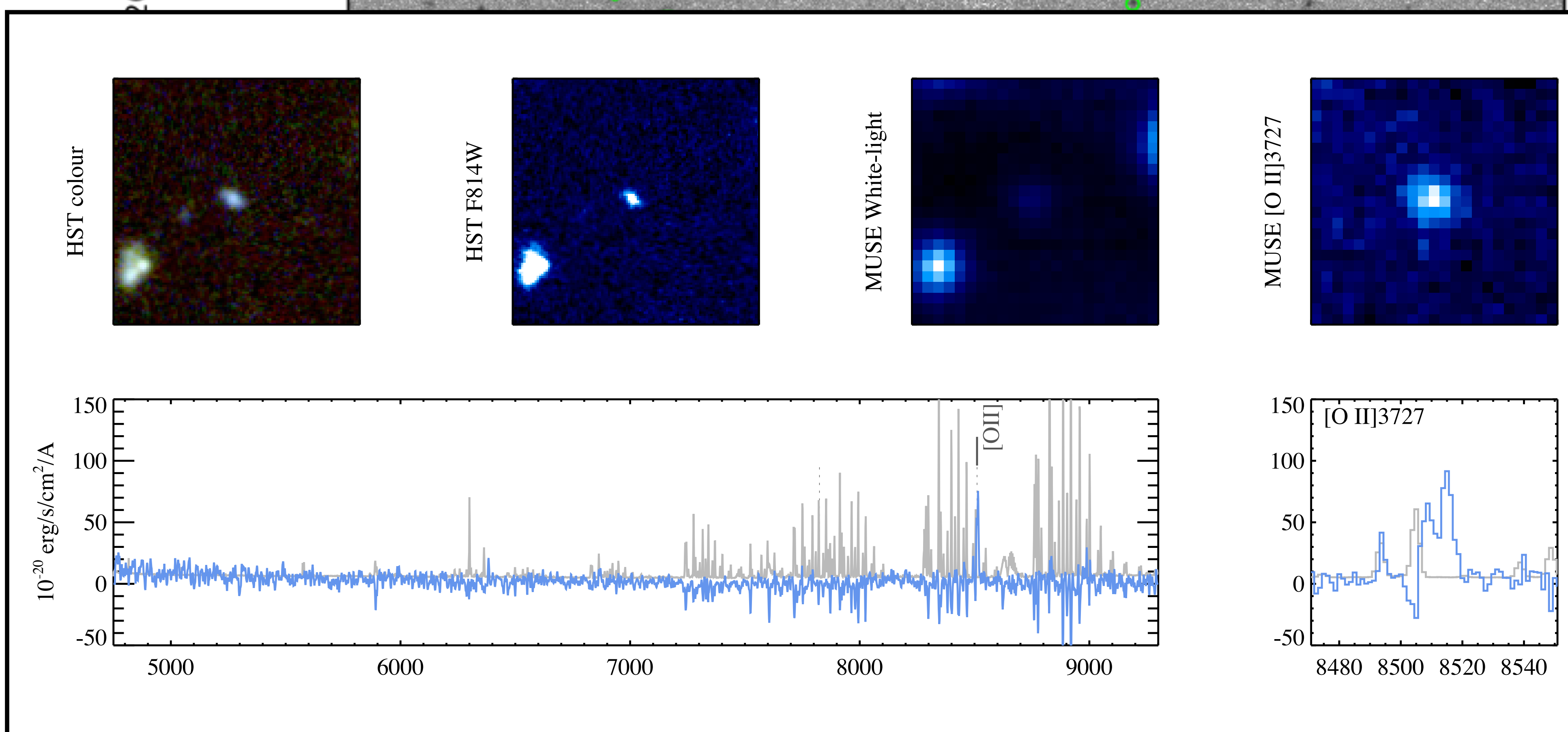


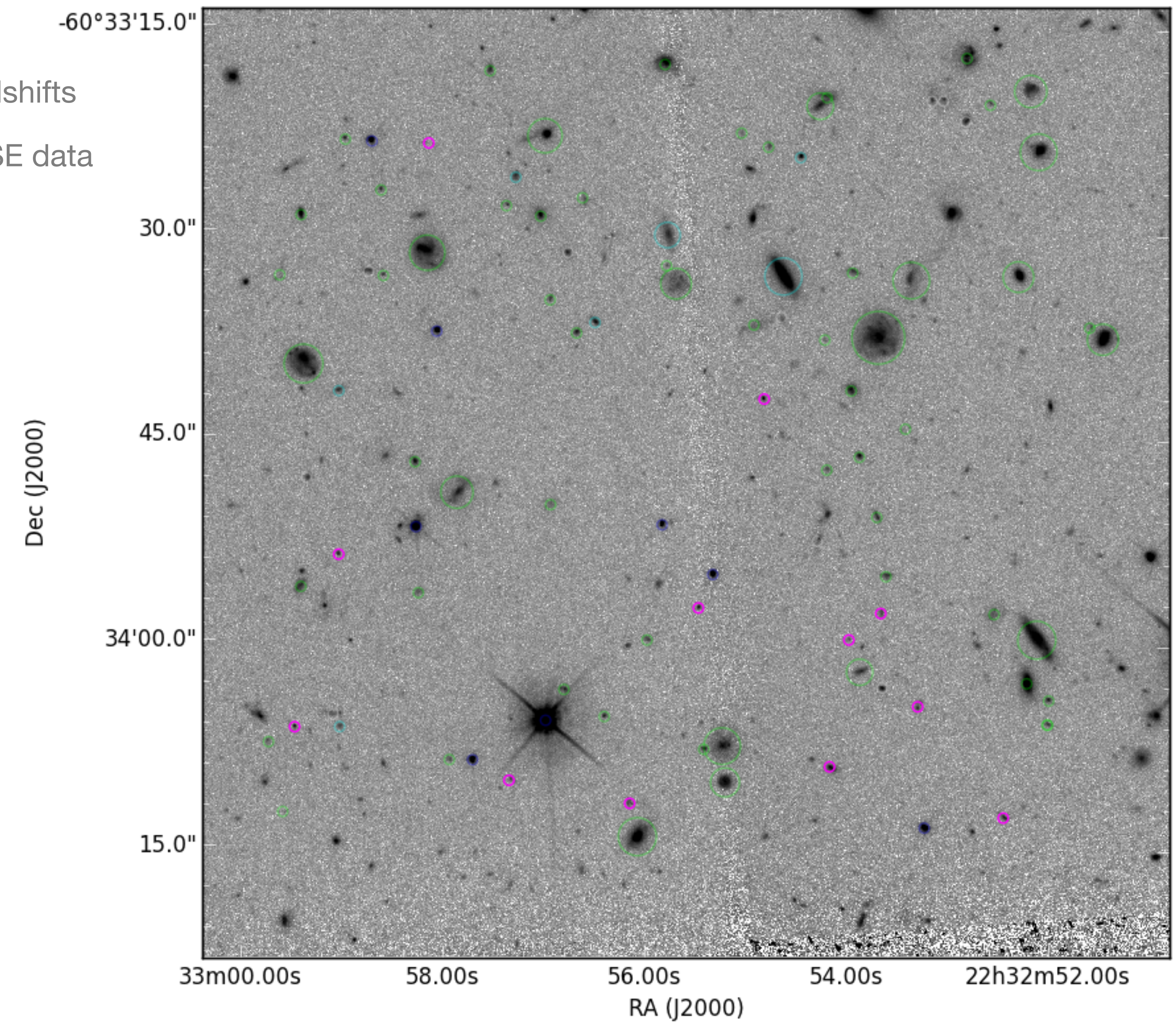

**ID#160**

**Z = 1.28**
**$I_{814}$ = 26.7**
**M ≈ 2 $10^9$ $M_\odot$**



# Census of MUSE HDFS Field

- ✓ HST WFPC2 F812W
- ✓ 18 Known Spectroscopic Redshifts
- ✓ 189 sources identified in MUSE data cube
- ✓ 8 stars
- ✓ 7 nearby galaxies
- ✓ 61 [OII] 3727 emitters
- ✓ 10 absorption lines galaxies
- ✓ 12 CIII] 1909 emitters
  - ✓ Z = [1.57 – 2.67]
  - ✓ $I_{814}$ = [24.6 – 27.2]



# Census of MUSE HDFS Field

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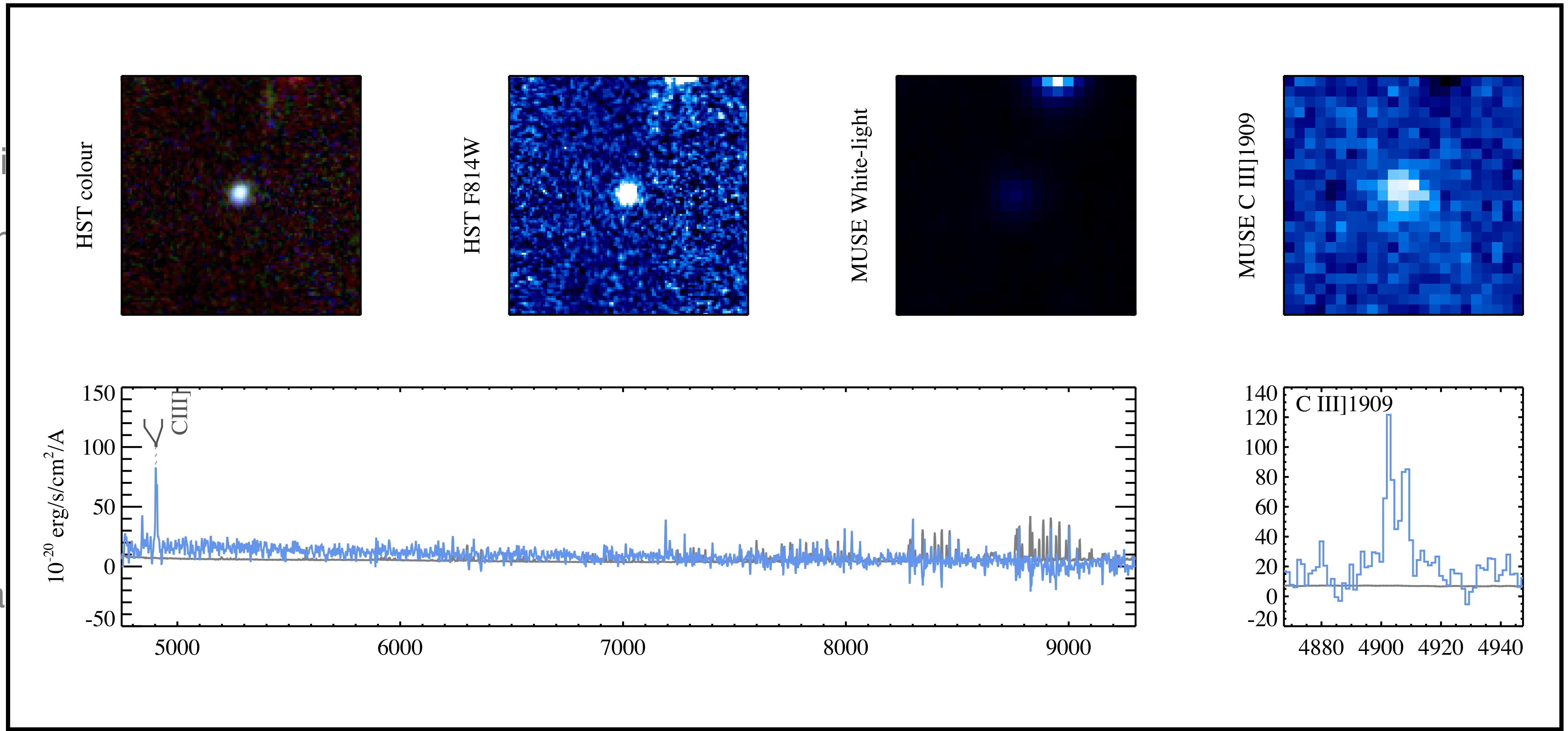
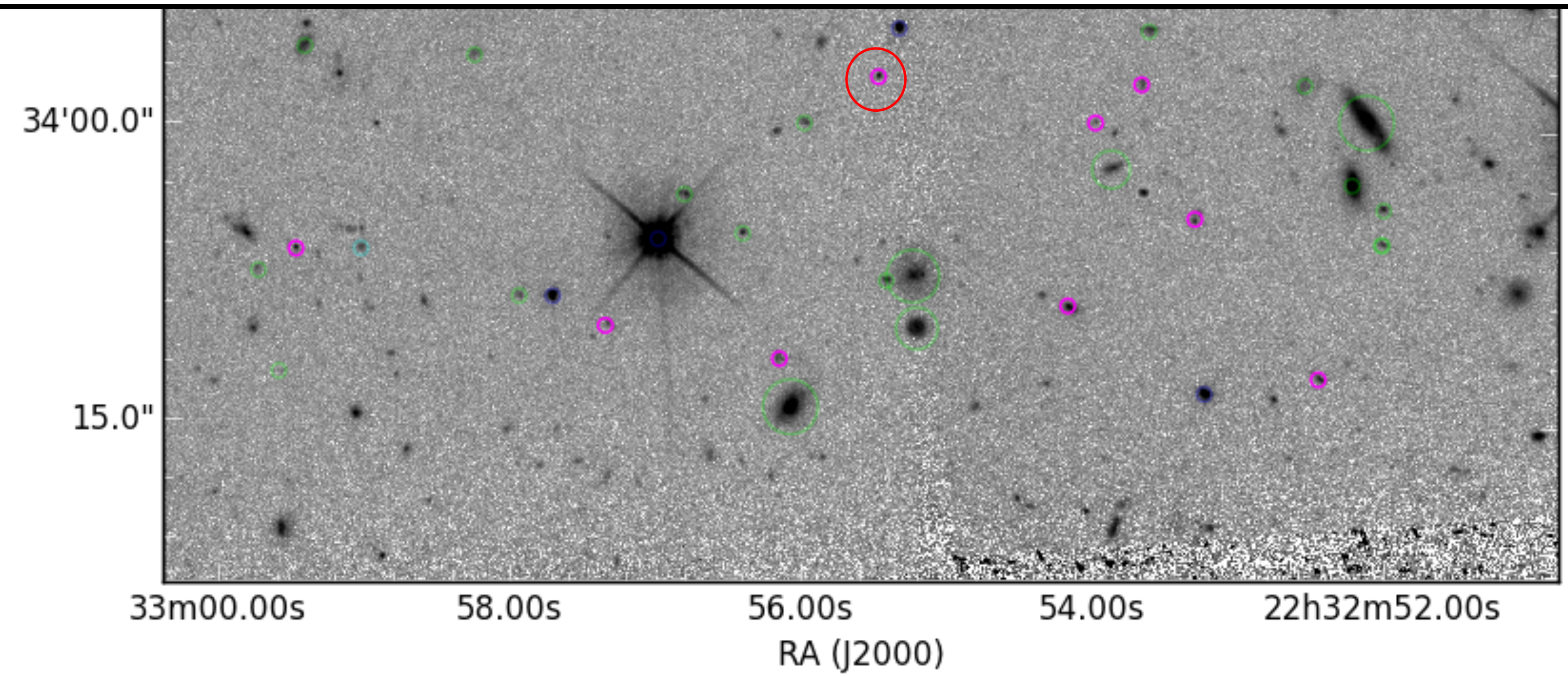
- ✓ 18 Known Spectroscopi
- ✓ 189 sources identified in cube
- ✓ 8 stars
- ✓ 7 nearby galaxies
- ✓ 61 [OII] 3727 emitters
- ✓ 10 absorption lines gala
- ✓ 12 CIII] 1909 emitters
  - ✓ Z = [1.57 – 2.67]
  - ✓ $I_{814}$ = [24.6 – 27.2]



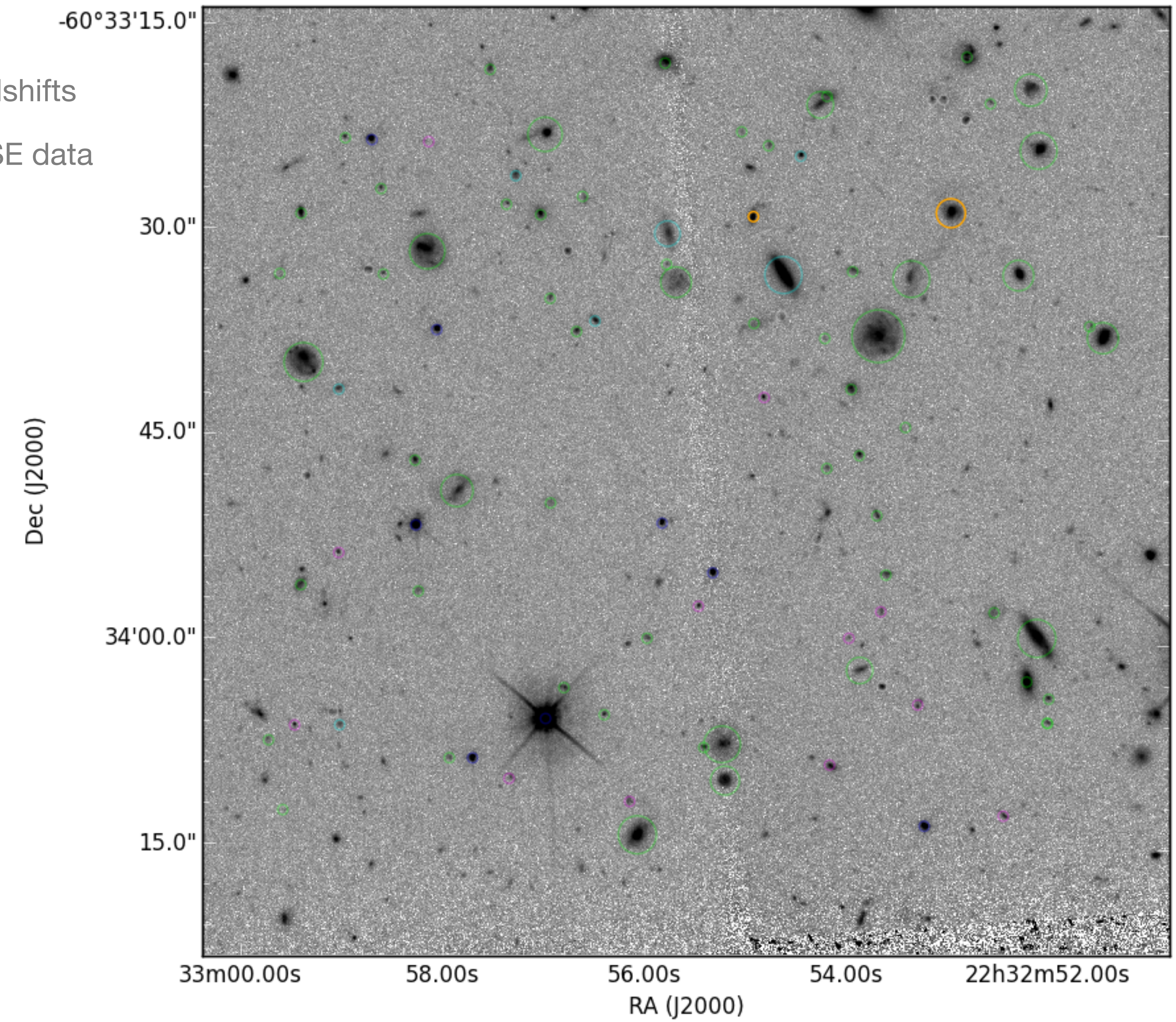




**ID#97**

**Z = 1.57**
**$I_{814}$ = 25.9**

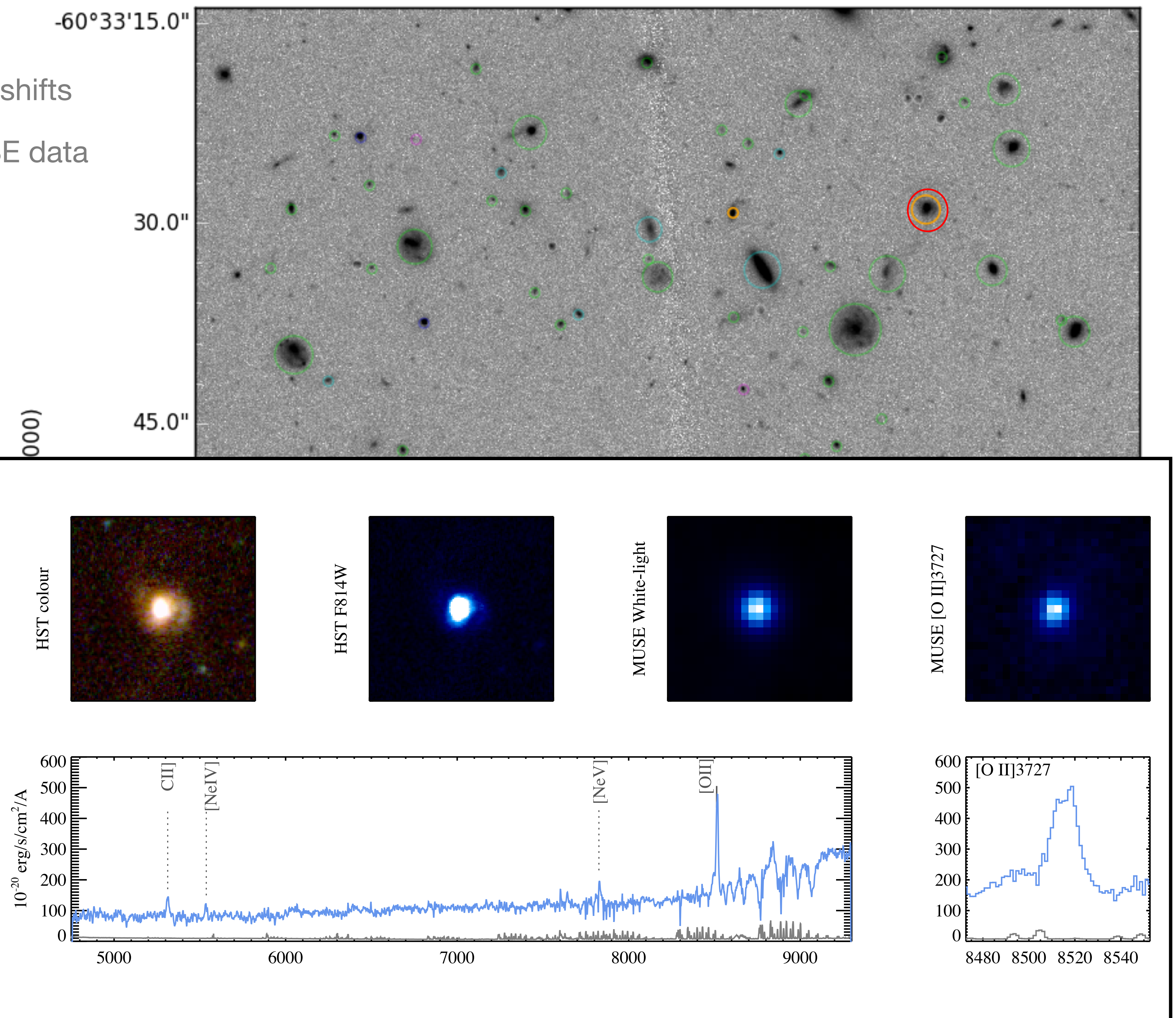
# Census of MUSE HDFS Field

- ✓ HST WFPC2 F812W
- ✓ 18 Known Spectroscopic Redshifts
- ✓ 189 sources identified in MUSE data cube
- ✓ 8 stars
- ✓ 7 nearby galaxies
- ✓ 61 [OII] 3727 emitters
- ✓ 10 absorption lines galaxies
- ✓ 12 CIII] 1909 emitters
- ✓ 2 AGNs
  - ✓ Z = 1.28
  - ✓ $I_{814}$ = 22.6, 23.6



# Census of MUSE HDFS Field

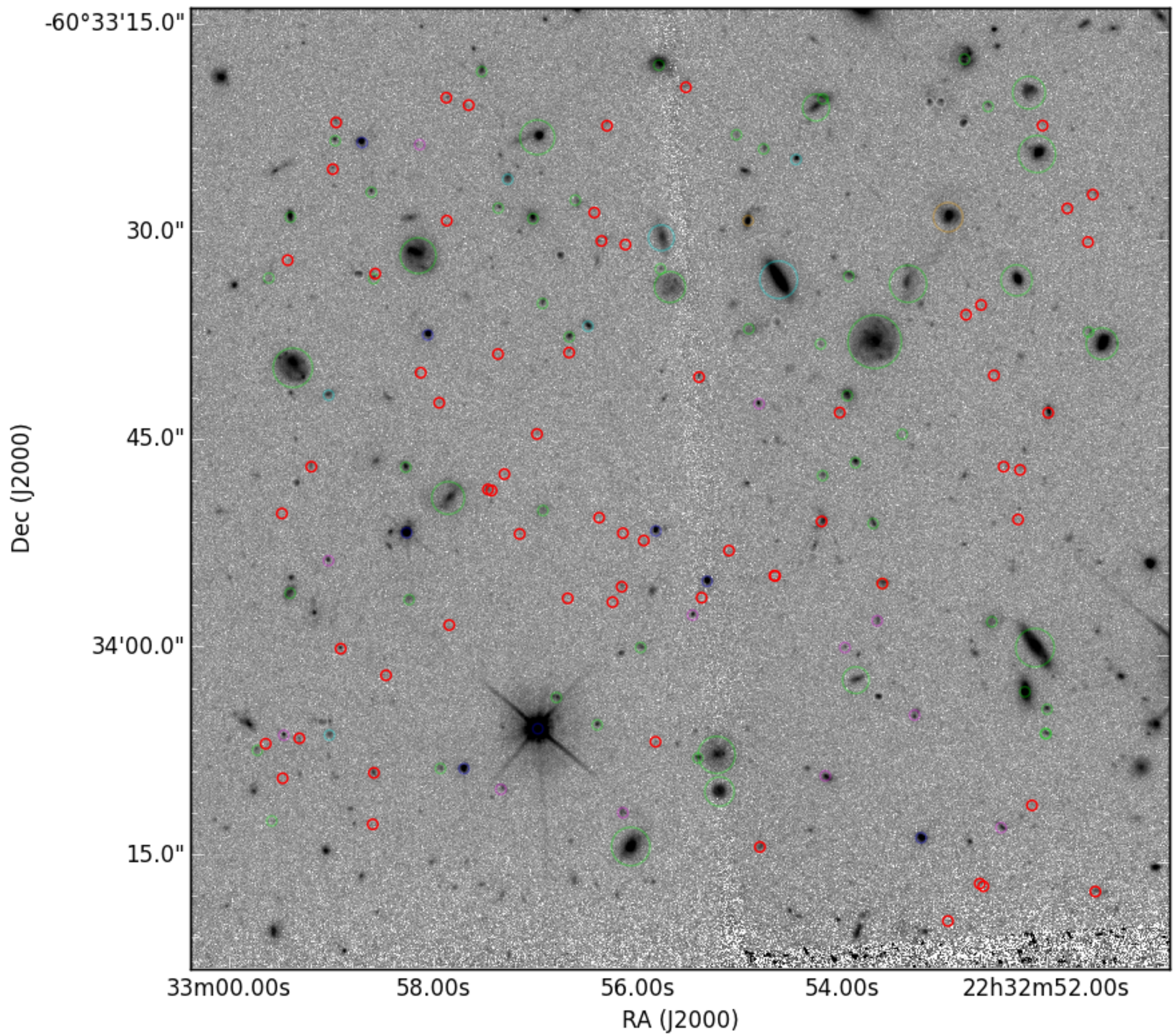
- ✓ HST WFPC2 F812W
- ✓ 18 Known Spectroscopic Redshifts
- ✓ 189 sources identified in MUSE data cube
- ✓ 8 stars
- ✓ 7 nearby galaxies
- ✓ 61 [OII] 3727 emitters
- ✓ 10 absorption lines galaxies
- ✓ 12 CIII] 1909 emitters
- ✓ 2 AGNs
  - ✓ Z = 1.28
  - ✓ $I_{814}$ = 22.6, 23.6




**ID#10**

**Z = 1.28**
**$I_{814}$ = 22.5**

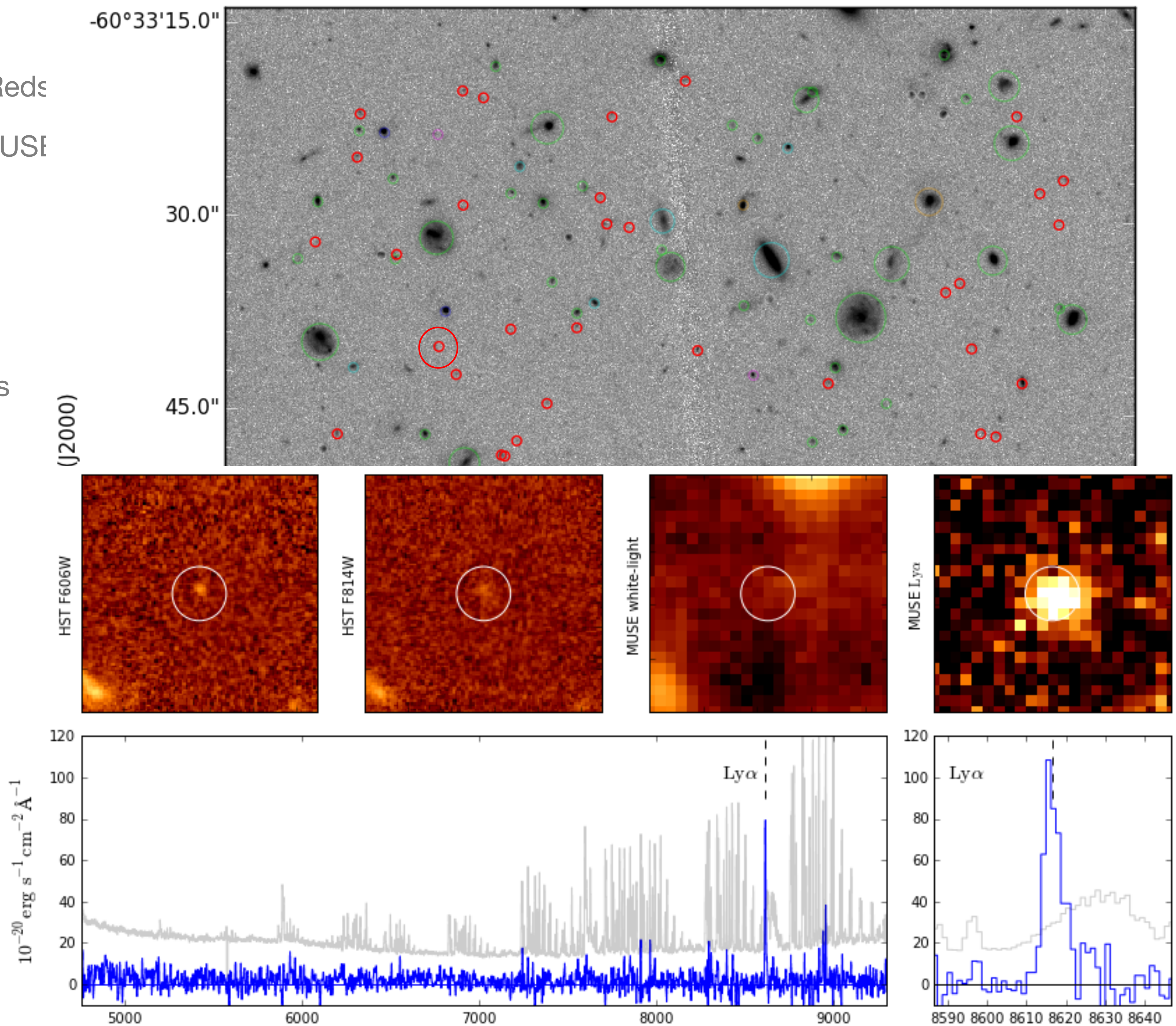
- ✓ HST WFPC2 F812W
- ✓ 18 Known Spectroscopic Reds
- ✓ 189 sources identified in MUSE
- ✓ 8 stars
- ✓ 7 nearby galaxies
- ✓ 61 [OII] 3727 emitters
- ✓ 10 absorption lines galaxies
- ✓ 12 CIII] 1909 emitters
- ✓ 2 AGNs
- ✓ 63 Ly$\alpha$ emitters
  - ✓ Z = [2.95 – 6.28]
  - ✓ $I_{814}$ = [24.5 – 29.6]



- ✓ HST WFPC2 F812W
- ✓ 18 Known Spectroscopic Reds
- ✓ 189 sources identified in MUSE
- ✓ 8 stars
- ✓ 7 nearby galaxies
- ✓ 61 [OII] 3727 emitters
- ✓ 10 absorption lines galaxies
- ✓ 12 CIII] 1909 emitters
- ✓ 2 AGNs
- ✓ **63 Lyα emitters**
  - ✓ Z = [2.95 – 6.28]
  - ✓ $I_{814}$ = [24.5 – 29.6]

**ID#290**

**Z = 6.08**
**$I_{814}$ = 27.8**



# Census of MUSE HDFS Field

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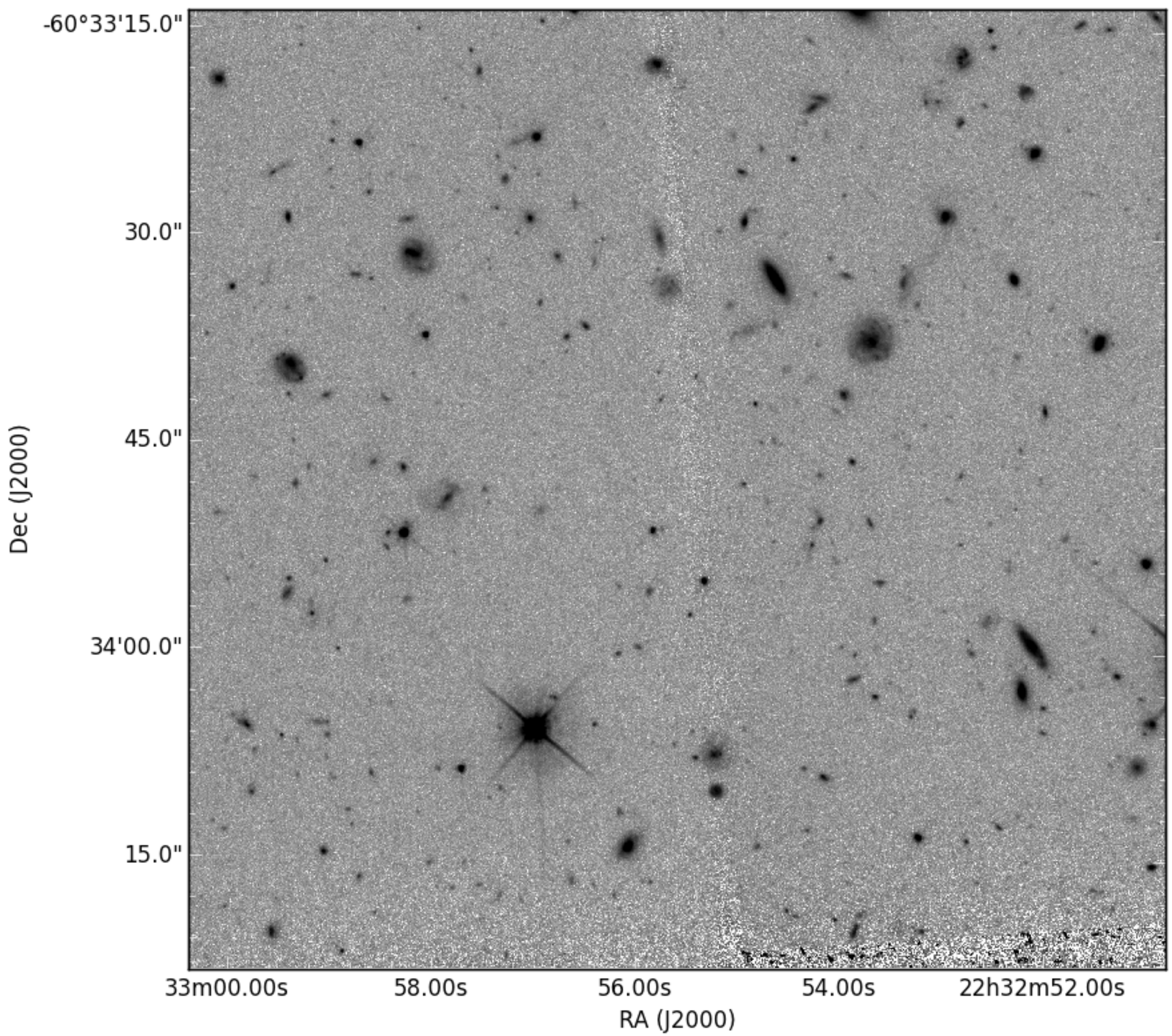

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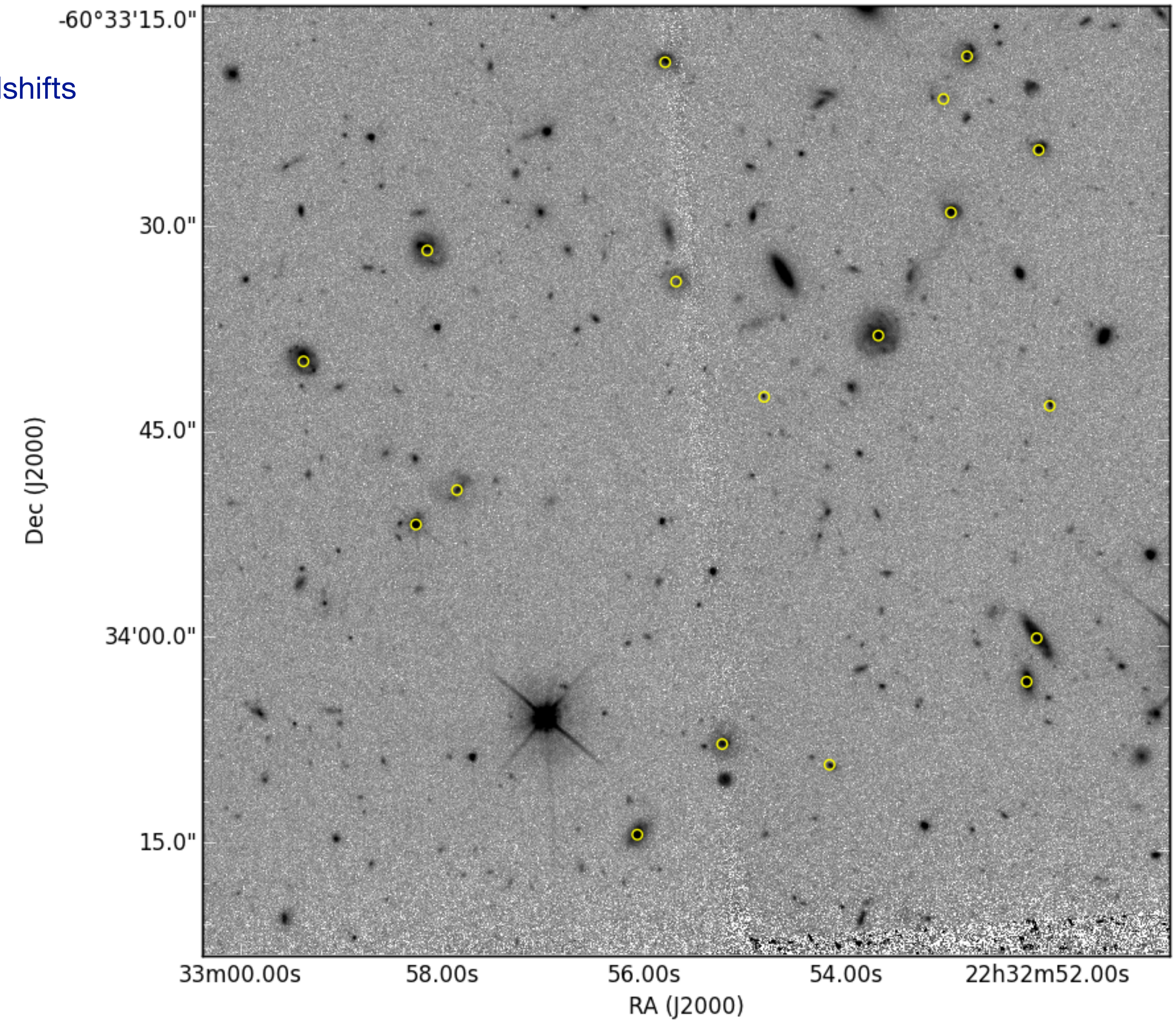
- ✓ 18 Known Spectroscopic Redshifts



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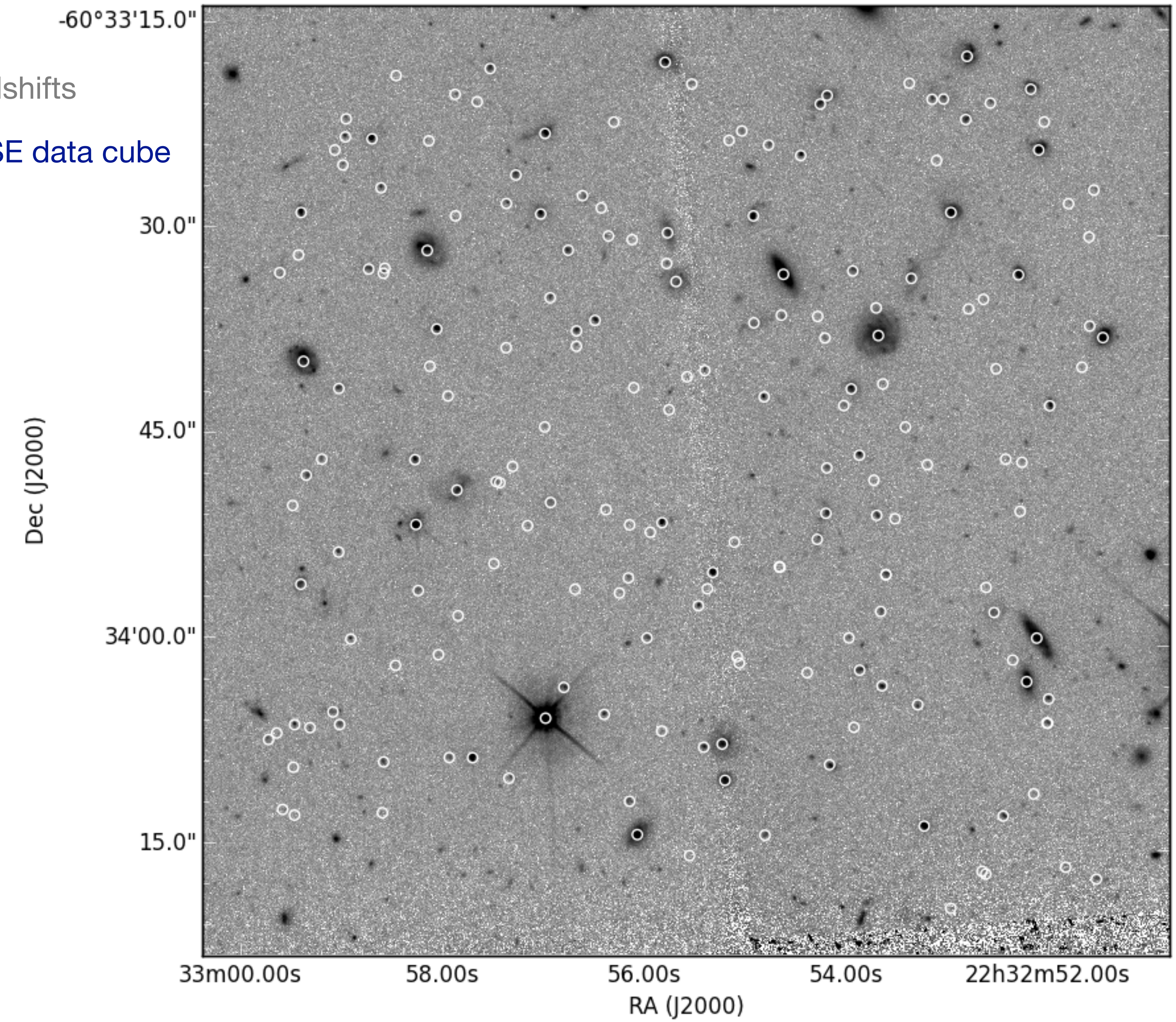

# Census of MUSE HDFS Field

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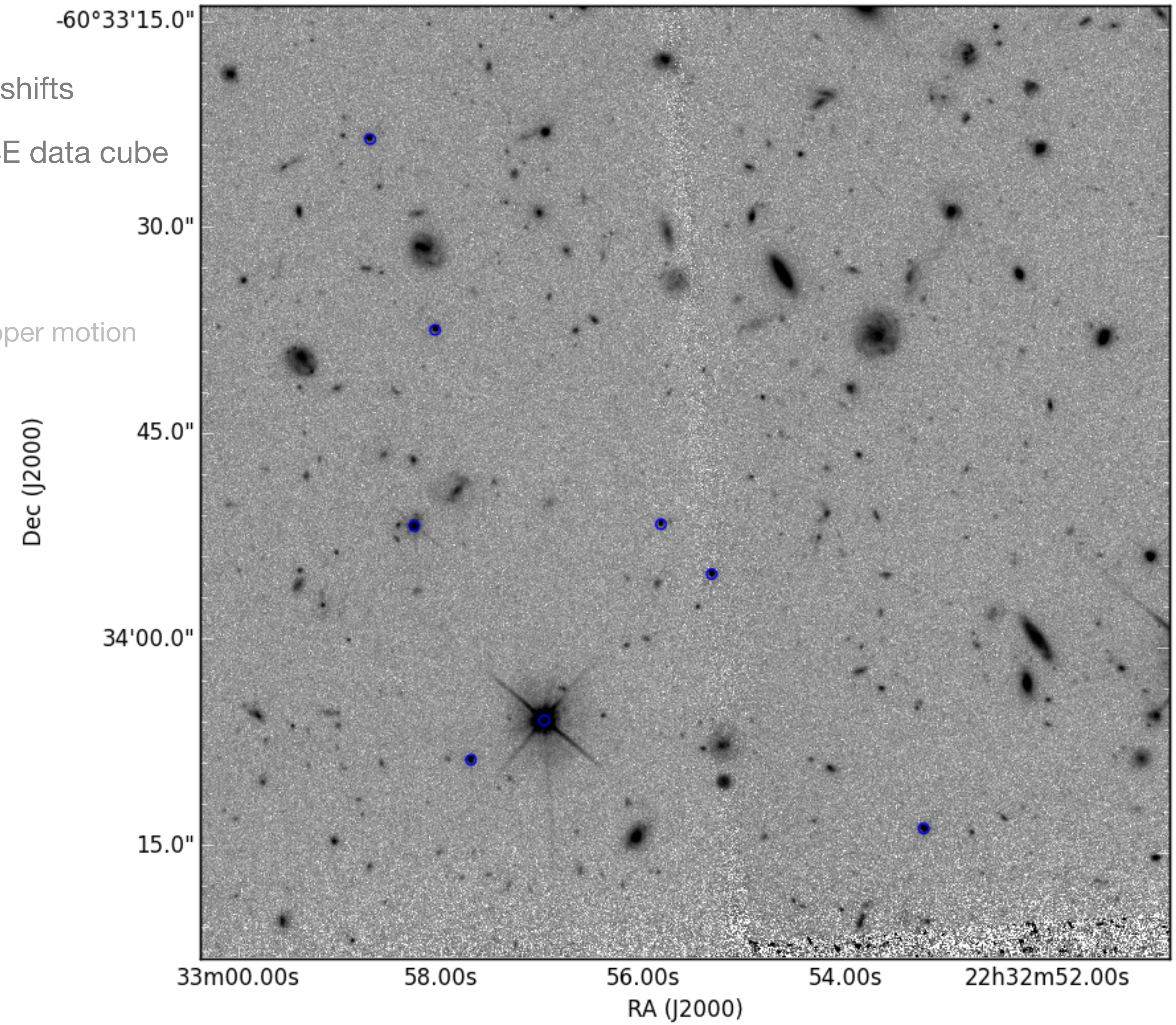
- ✓ 8 stars
  - ✓ F814 = [18.6 – 23.9]
  - ✓ 7 already identified using proper motion (Kilic et al, 2005)



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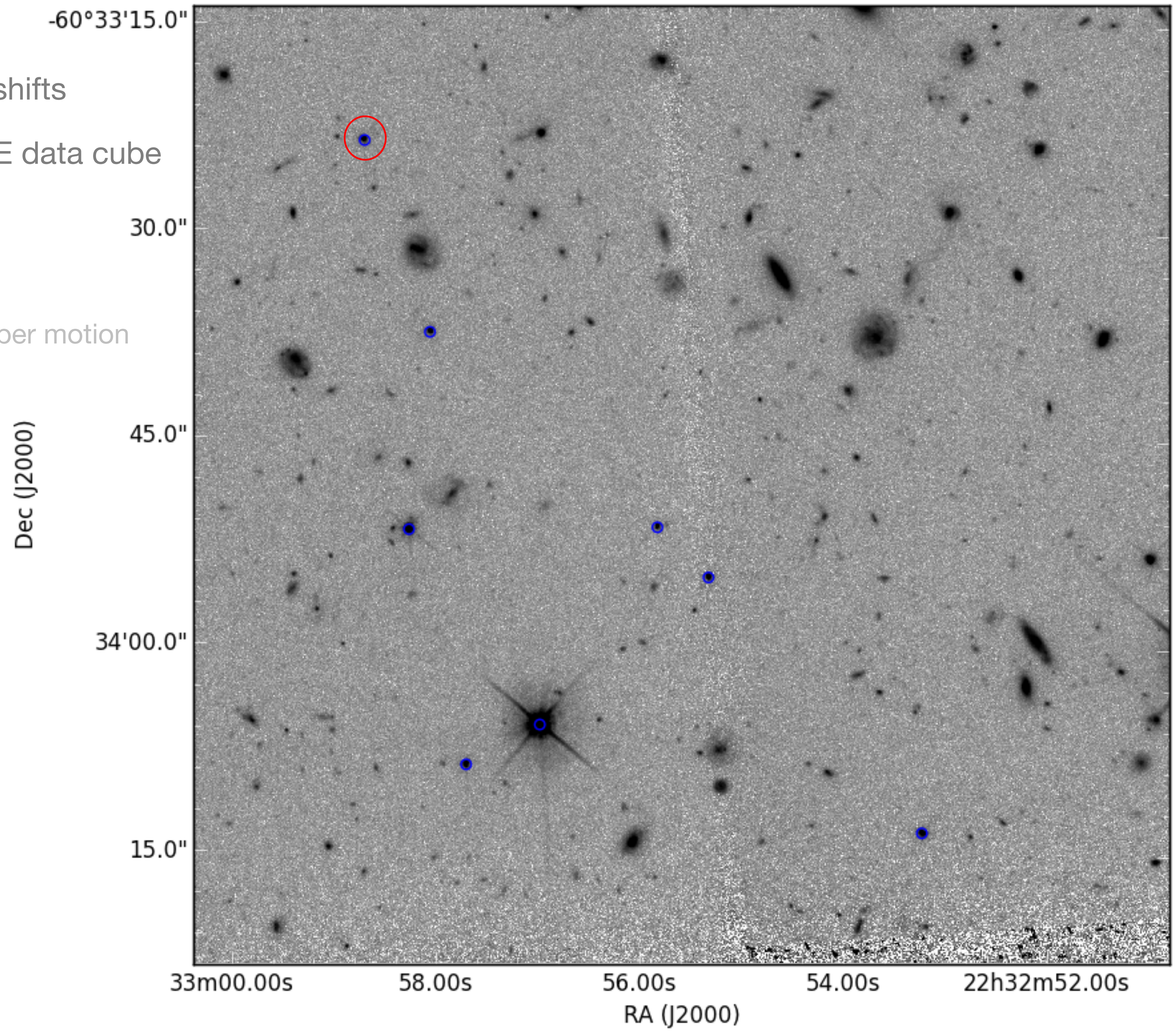

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