

# First Science with MUSE

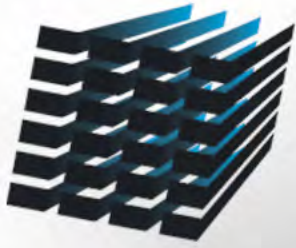


R. Bacon  
CRAL

CRA  
Lyon

IAP  
17 April 2015





**MUSE**  
multi unit spectroscopic explorer



**ETH**

Historical Context  
Instrument  
Commissioning results  
Hubble Deep Field South  
What's next



IAP

17 April 2015

- **1987: first light of the first integral field spectrograph – TIGER**
- **1990-2000: The first generation**
  - Small field of view (~10 arcsec)
  - Visible wavelength range
  - Detailed study of individual objects
- **2000-2010: The second generation**
  - Working in IR: SINFONI@VLT, OSIRIS@KECK
  - Coupled with AO: OASIS@CFH, SINFONI@VLT, OSIRIS@KECK
  - Larger field: SAURON@WHT, PMAS@CalarAlto



# Historical Context

- The third generation
  - IFU as a **discovery machine**
  - A true imager **and** an excellent spectrograph
  - High spatial resolution **and** large field of view
  - Good spectral resolution **and** wide simultaneous spectral range
  - Excellent **throughput**

**MUSE ... the Multi Unit Spectroscopic Explorer**

# Consortium & Partners



# The MUSE instrument



Integral field spectrograph with 24 units  
4650-9300 Å (simultaneous)

$R = \lambda / d\lambda$ : 1500-3500

1x1 arcmin<sup>2</sup> field of view

0.2 arcsec sampling

35% end-to-end throughput

30 Jan 2014 – First light at UT4 VLT  
In regular operation since Oct 2014  
14 papers published  
7 Press Releases

- 19 Jan: MUSE land on UT4
- 31 Jan: First light
- 7-21 Feb: Comm1
- 11 Mar: ESO 3D Conf
- 28 Apr – 6 Mai: Comm2
- 20-29 Jun: SV-1
- 25 Jun: SPIE Plenar
- 25 Jul – 3 Aug: Comm3
- 18 – 24 Aug: SV-2
- 13-26 Sep: 1<sup>st</sup> GTO
- 1 Oct: 1<sup>st</sup> GO run
- 10 Nov: 1<sup>st</sup> paper out

Public	Sci
Science Users Information	
Science Users Inform	
Observing Facilities	
Future Facilities and Dev	
Observing with ESO Tele	
Science Software	
Data Handling and Prod	
Science Archive Facility	
Science Activities	
Science Staff	
Science in Garching	
Science in Santiago	
Fellowships and Stud	
VLT Commissioning	
VLT/VLTI Science Verification	
AMBER	
CRIFRES	
FLAMES	
FORST and ISAAC	
FORIS2 and UVES	
HAWK-I	
KMOS	
MAD	
MIDI	
MUSE	

An ESO/RadioNet Workshop  
ESO Garching, 10–14 March 2014

Monthly Notices  
of the  
ROYAL ASTRONOMICAL SOCIETY  
MNRAS **445**, 4335–4344 (2014)

doi:10.1093/mnras/stu2092

## MUSE sneaks a peek at extreme ram-pressure stripping events – I. A kinematic study of the archetypal galaxy ESO137–001

Michele Fumagalli,<sup>1,2★</sup> Matteo Fossati,<sup>3,4</sup> George K. T. Hau,<sup>5</sup> Giuseppe Gavazzi,<sup>6</sup>  
Richard Bower,<sup>1</sup> Ming Sun<sup>7</sup> and Alessandro Boselli<sup>8</sup>

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<sup>7</sup>Department of Physics, University of Alabama in Huntsville, Huntsville, AL 35899, USA

<sup>8</sup>Laboratoire d'Astrophysique de Marseille – LAM, Université d'Aix-Marseille & CNRS, UMR7326, 38 rue F. Joliot-Curie, F-13388 Marseille Cedex 13, France

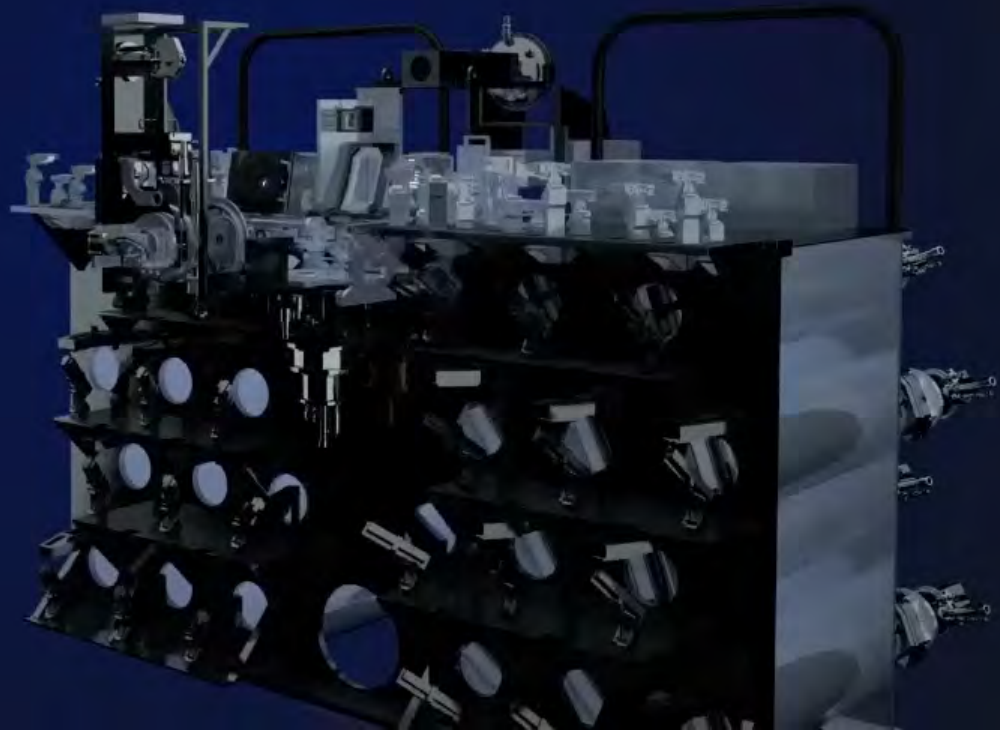
Accepted 2014 October 6. Received 2014 September 29; in original form 2014 July 29

### ABSTRACT

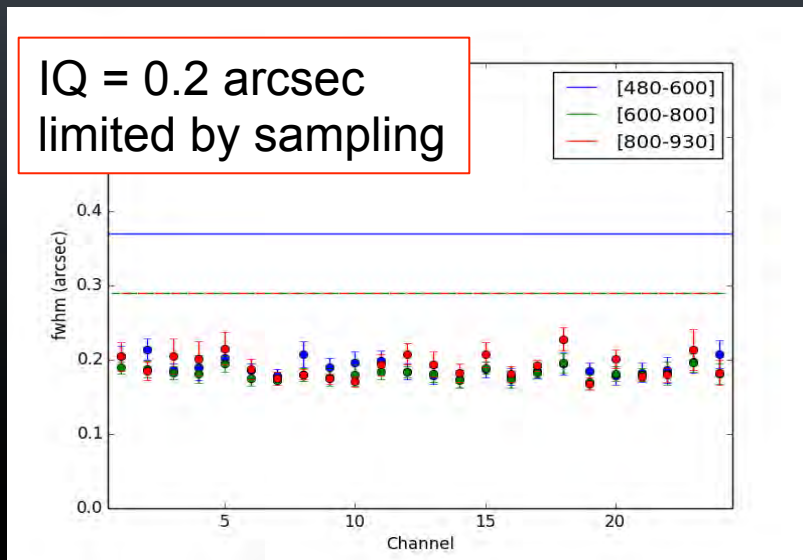
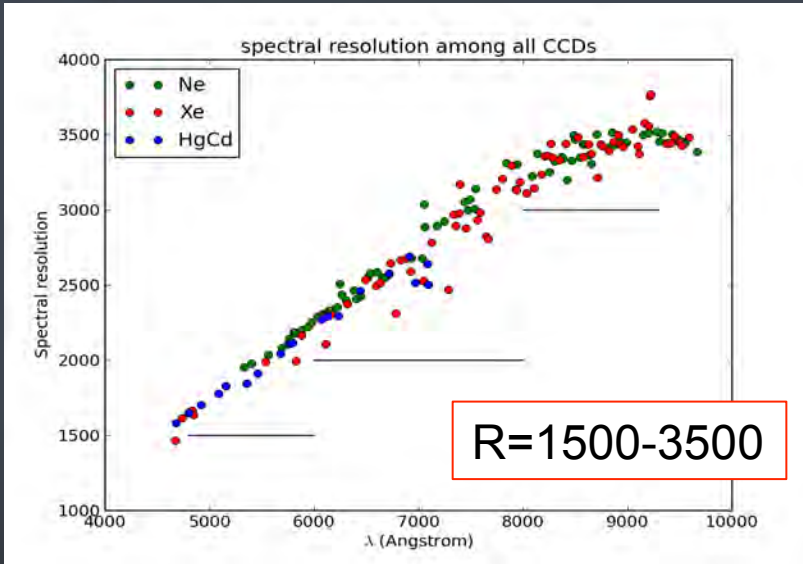
We present Multi Unit Spectroscopic Explorer (MUSE) observations of ESO137–001, a spiral galaxy infalling towards the centre of the massive Norma cluster at  $z \sim 0.0162$ . During the high-velocity encounter of ESO137–001 with the intracluster medium, a dramatic ram-pressure

data can be found [here](#).

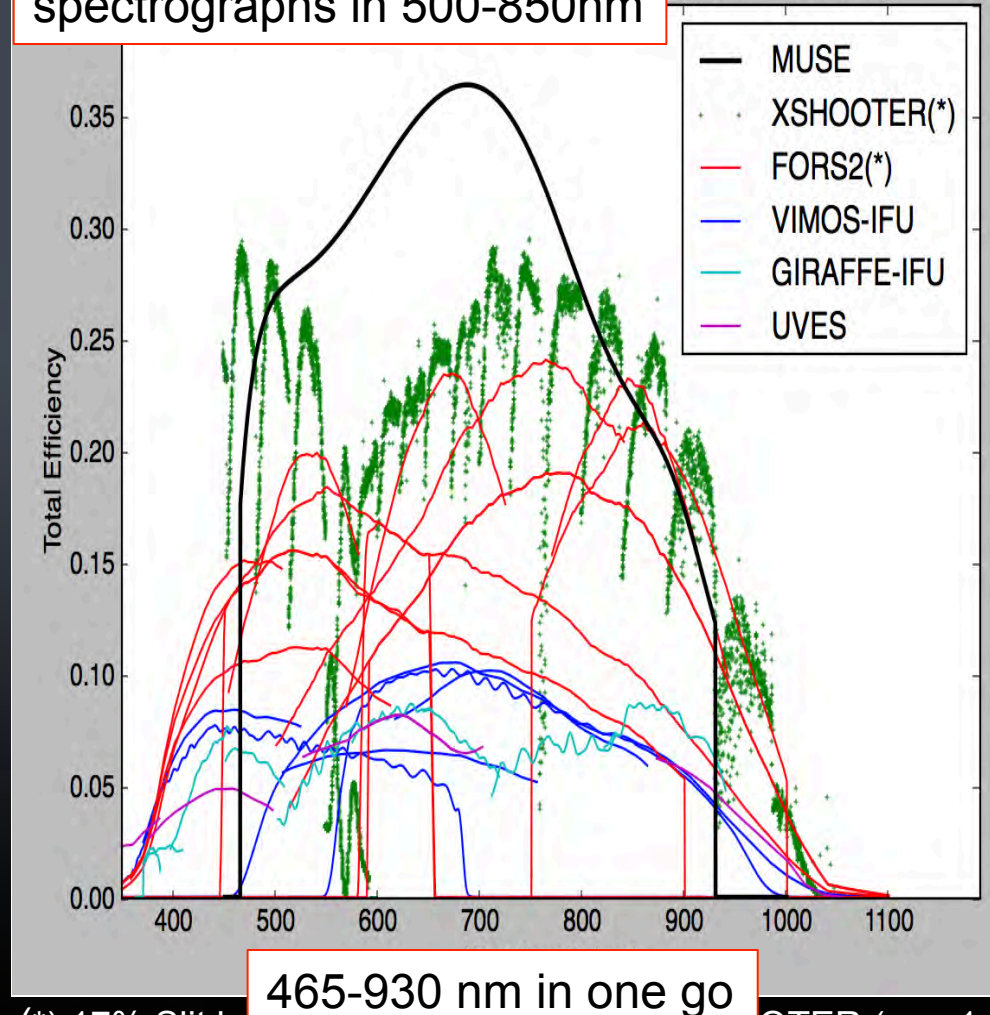
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- Program 60.A-9340(A), Lanzoni et al., "Metal-poor Globular Cluster": program fully COMPLETED. The archive link to the data can be found [here](#).
- Program 60.A-9341(A), Santoro/Hamer et al. "CenA": program fully COMPLETED. The archive link to the data can be found [here](#).
- Program 60.A-9342(A), Valenti/Zoccali/Kuijken et al. "MW Bulge": program fully COMPLETED. The archive link to the data can be found [here](#).
- Program 60.A-9343(A), Zoccali et al. "Metal-rich Globular Cluster": program fully COMPLETED. The archive link to the data can be found [here](#).
- Program 60.A-9344(A), Kuncarayakti/Vink/Fernandez et al., "Young Stellar populations": program fully COMPLETED. The archive link to the data can be found [here](#).
- Program 60.A-9345(A), Clement/Caputi et al. "Abell S1063": program fully COMPLETED. The archive link to the data can be found [here](#).
- Program 60.A-9346(A), Laurikainen et al. "Barlenses": Program not started, unfortunately no data were taken.
- Program 60.A-9347(A), Wesson/Ueta/Walsh et al. "Planetary Nebula": program fully COMPLETED. The archive link to the data can be found [here](#).
- Program 60.A-9348(A), Hainich/Mendel et al. "Extragalactic stellar clusters": Program fully COMPLETED. The archive link to the data can be found [here](#).
- Program 60.A-9349(A), Fumagalli/Hau/Slezak et al. "Ram-pressure": program fully COMPLETED. The archive link to the data can be found [here](#).
- Program 60.A-9351(A), Melnick et al. "30 Doradus": program only partially completed. The archive link to the data can be found [here](#).







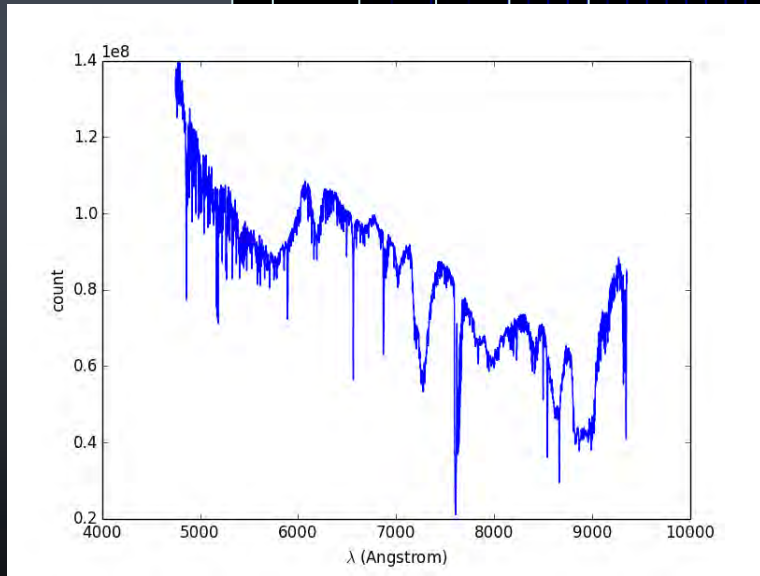
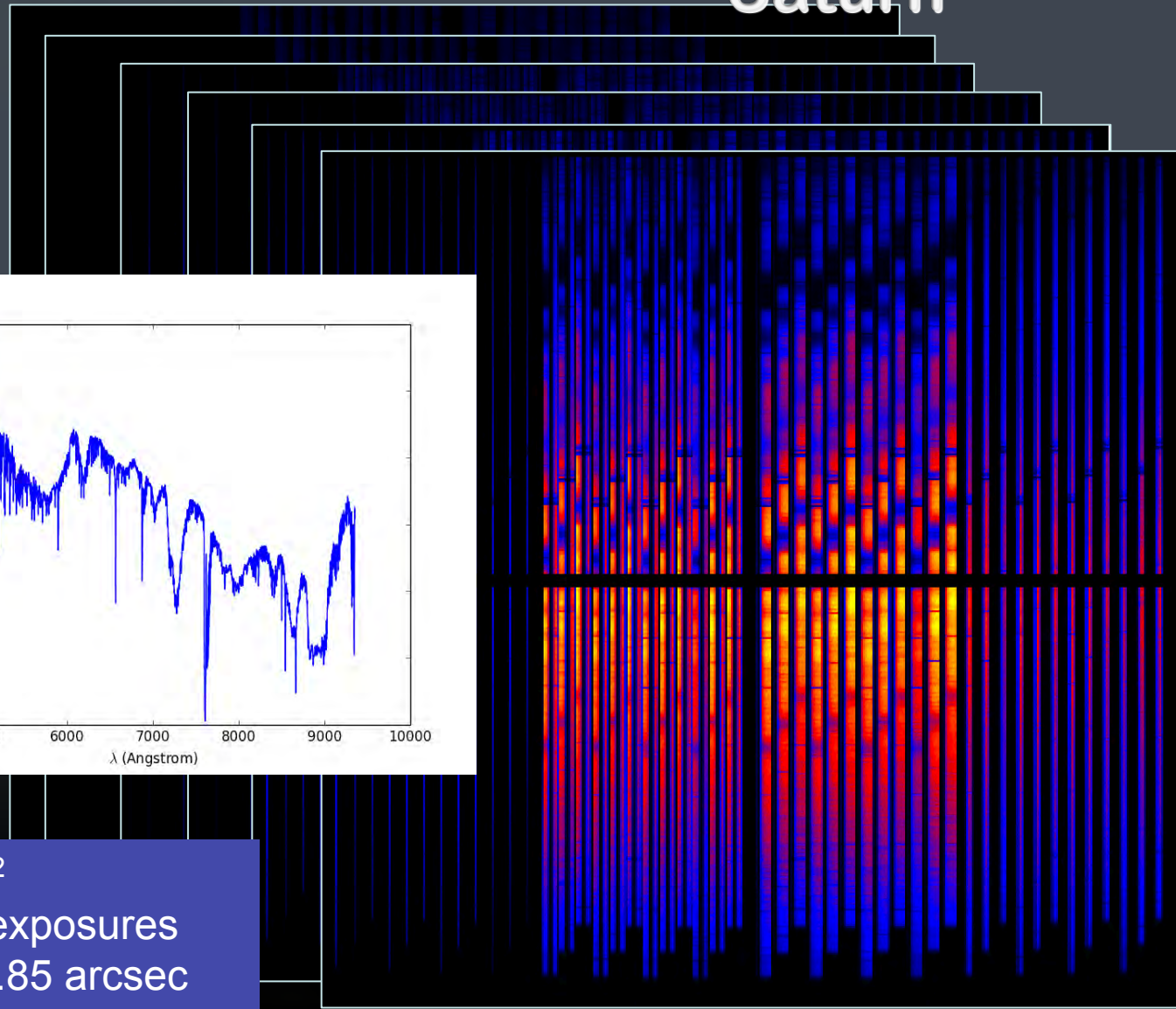
The most efficient of the VLT spectrographs in 500-850nm



(\*) 17% Slit loss included in FORS2 & XSHOOTER (e.g. 1 arcsec slit with 0.8 arcsec seeing)



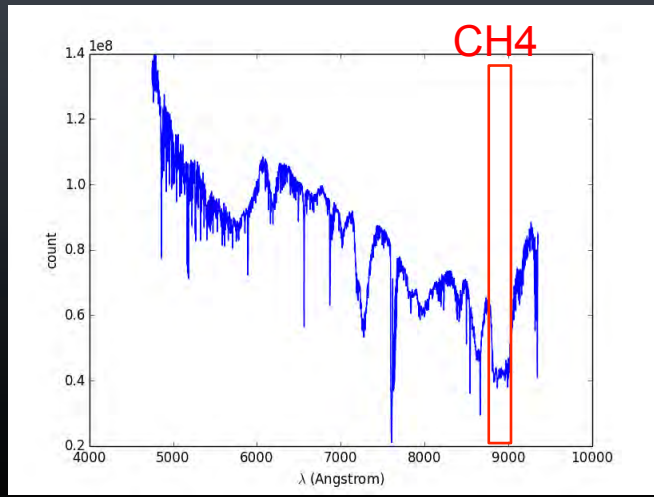
# First reconstructed image: Saturn



1 arcmin<sup>2</sup>  
4x1 sec exposures  
Seeing 0.85 arcsec



# First reconstructed image: Saturn



Prepared by Johan Richard, CRAL



# Europa transit across Jupiter

- 1/10 sec exposure
- Reconstructed image in the CH<sub>4</sub> absorption band
- 0.8 arcsec seeing
- 108 exposures (movie)
- 10,000,000 spectra



*Prepared by Johan Richard, CRAL & ESO Outreach*

ESO - Göttingen - Leiden - Lyon - Potsdam - Toulouse - Zurich



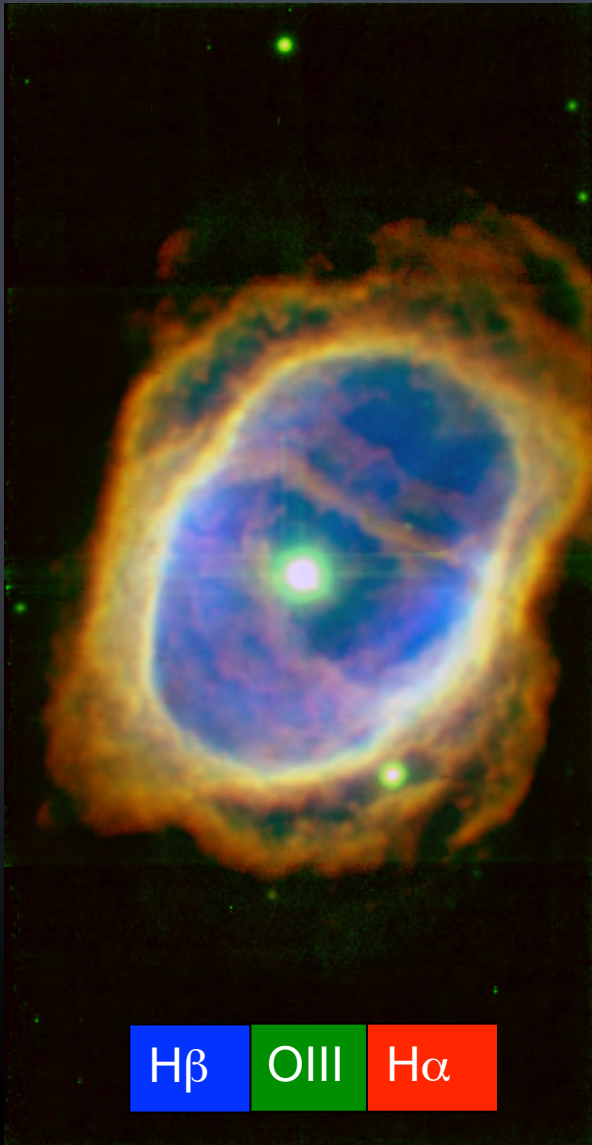
# The Planetary Nebula NGC 3132

3x1 arcmin<sup>2</sup>

Mosaic of 3 fields

13 x 1 mn exposures

Seeing 0.7-0.8 arcsec



*Prepared by Jarle Brinchmann, Leiden Obs*

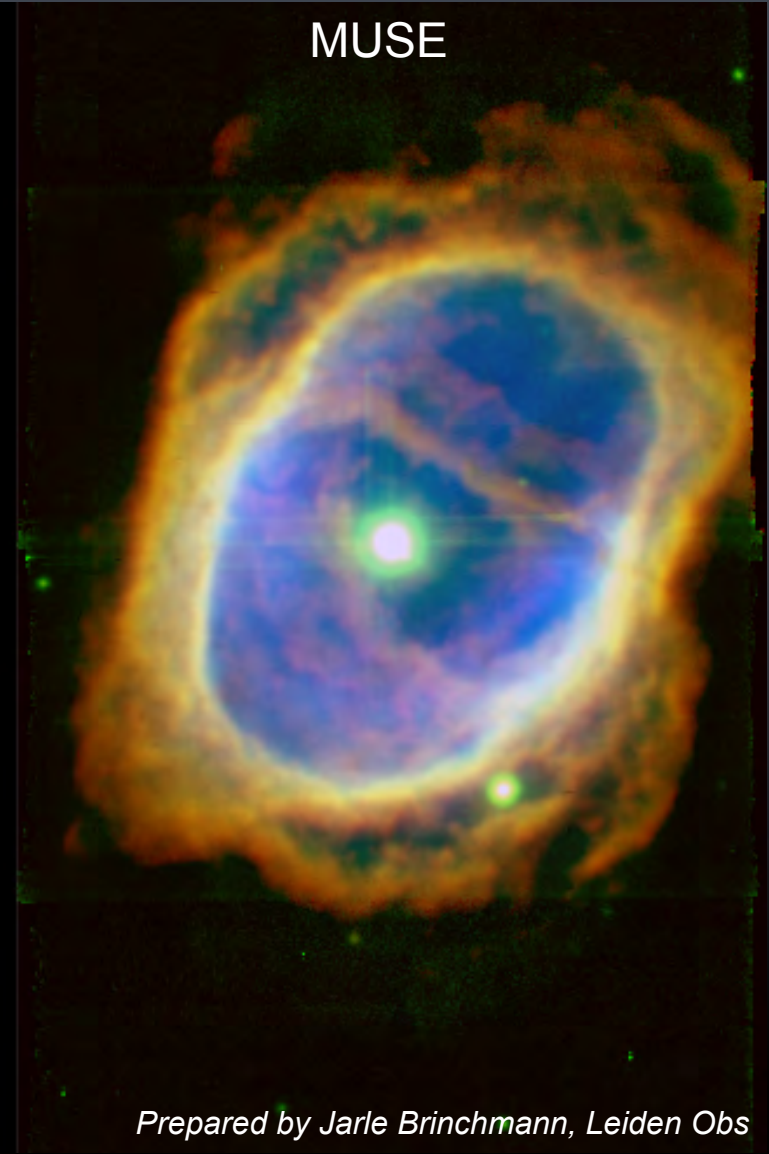
# The Planetary Nebula NGC 3132

HST



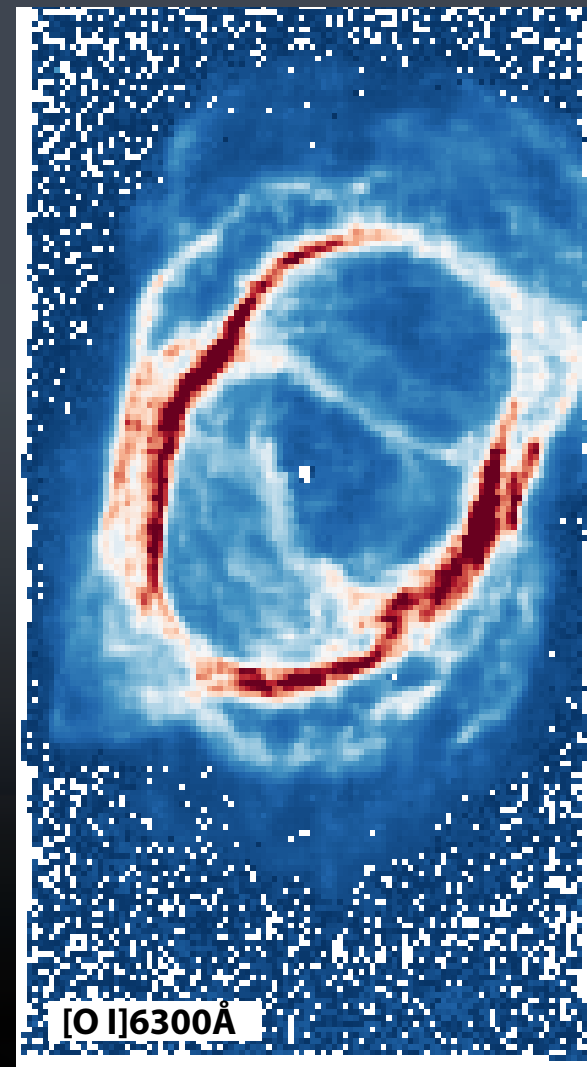
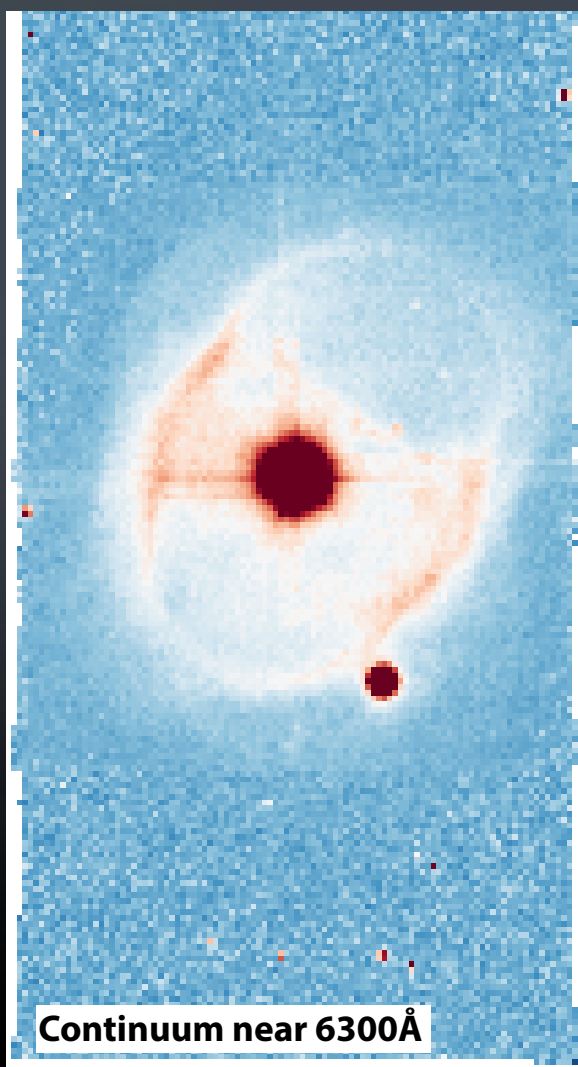
H $\beta$  OIII H $\alpha$

MUSE



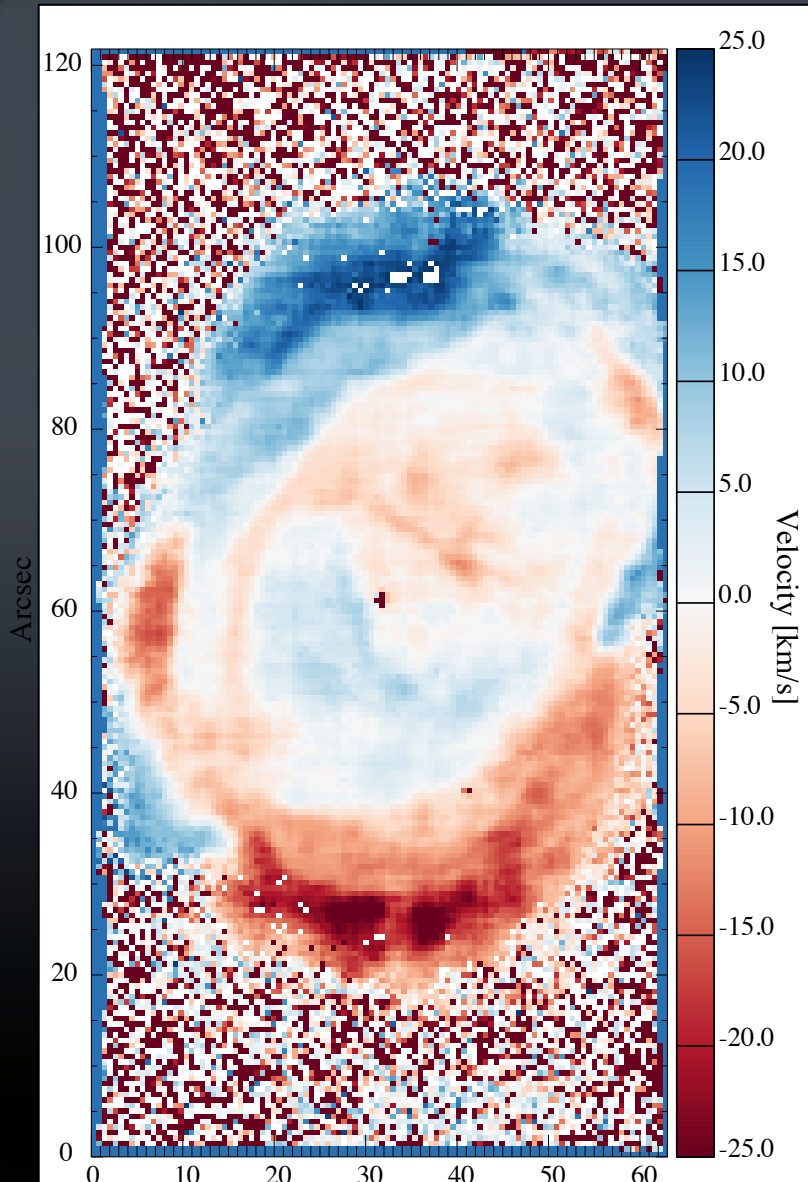
*Prepared by Jarle Brinchmann, Leiden Obs*

# The Planetary Nebula NGC 3132



*Prepared by Jarle Brinchmann, Leiden Obs*

# The Planetary Nebula NGC 3132



Gas Velocity field

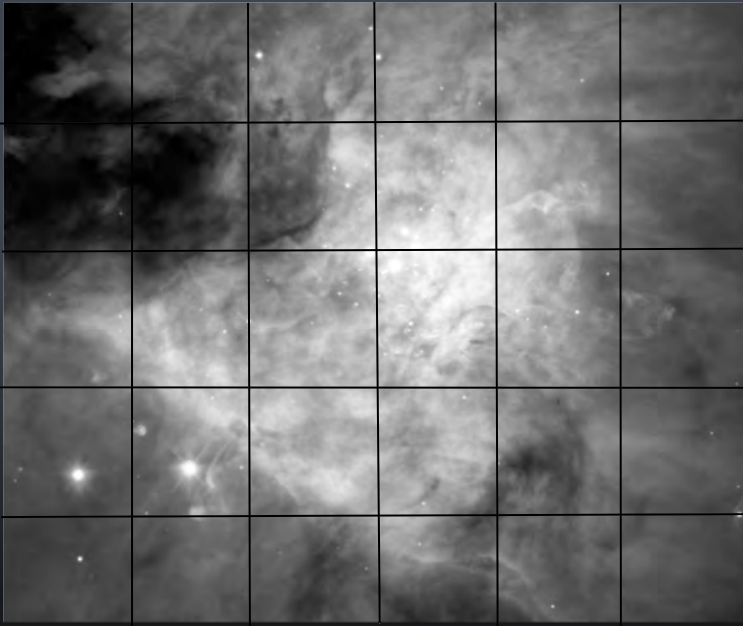
$$V_{\max} = 20 \text{ km/s}$$

Accuracy ~1 km/s

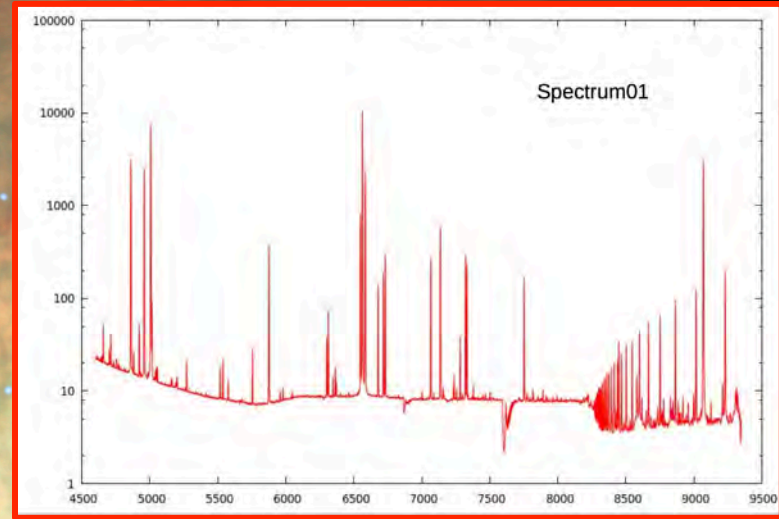
Prepared by Jarle Brinchmann, Leiden Obs



# Mapping large area: the Orion Nebula



- 6x5 arcmin<sup>2</sup>
- 30 fields, 60 exposures of 5 sec integration
- 2.5 hours total
- 5 millions of spectra
  - 300 spectra/sec (overhead included)
- Datacube of 1748x1460x4000



Just one over 2.5 millions spectra

Peter Weilbacher, AIP

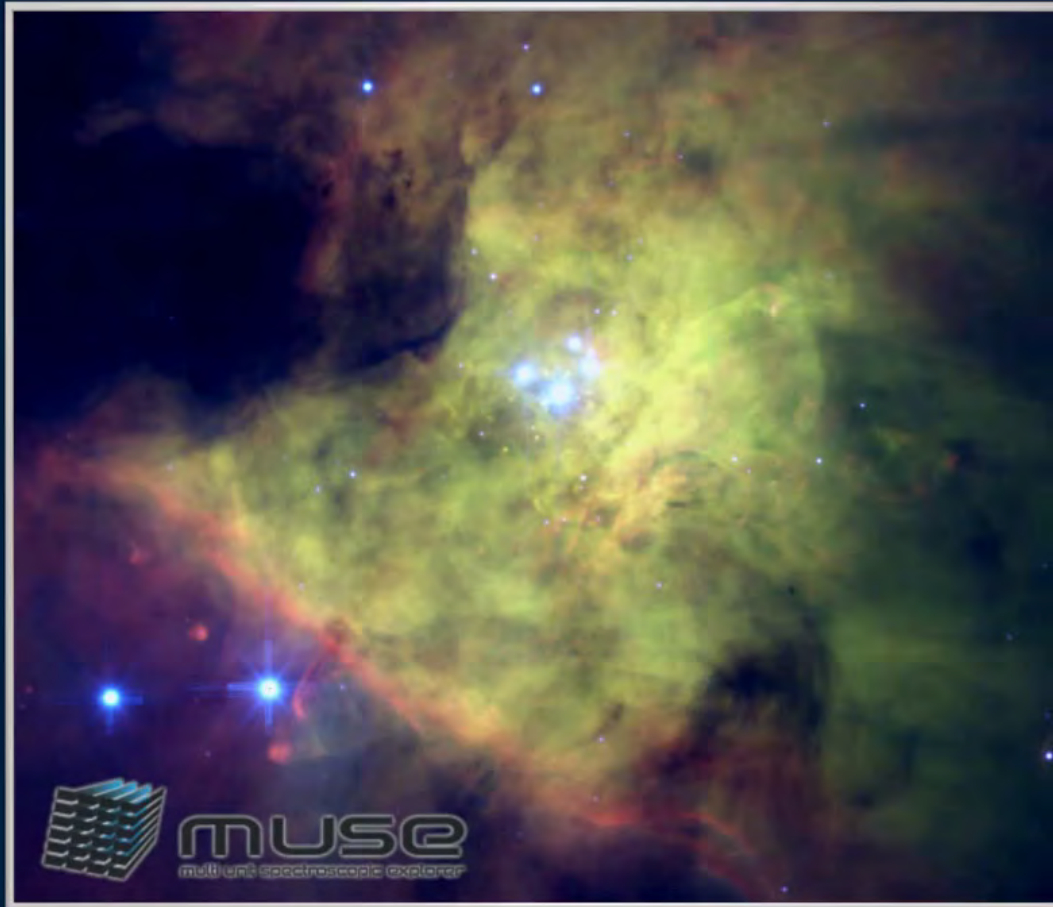
H $\beta$ +OIII

Cont 5300

H $\alpha$ +NII



# Orion Nebulae in 4000 colors

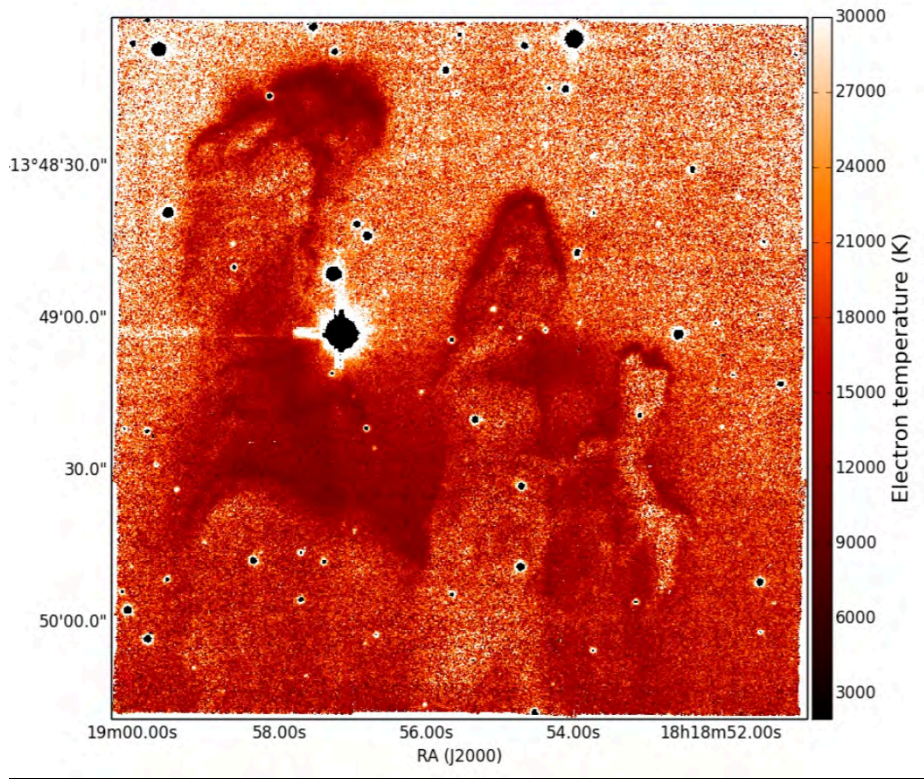
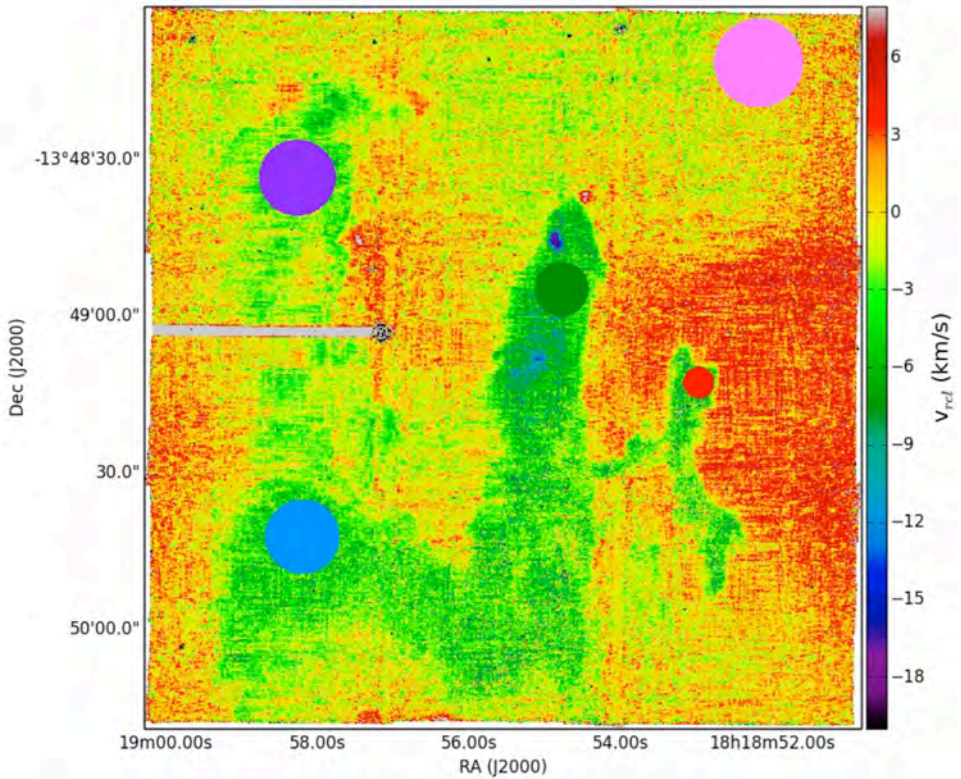


ESO - Göttingen - Leiden - Lyon - Potsdam - Toulouse - Zurich

Mon. Not. R. Astron. Soc. **000**, 1-24 (2015) Printed 15 April 2015

## The Pillars of Creation revisited and high-mass stellar feedback to

A. F. MoLeod<sup>1\*</sup>, I. E. Dale<sup>2,3</sup>, A. Ginsburg<sup>1</sup>





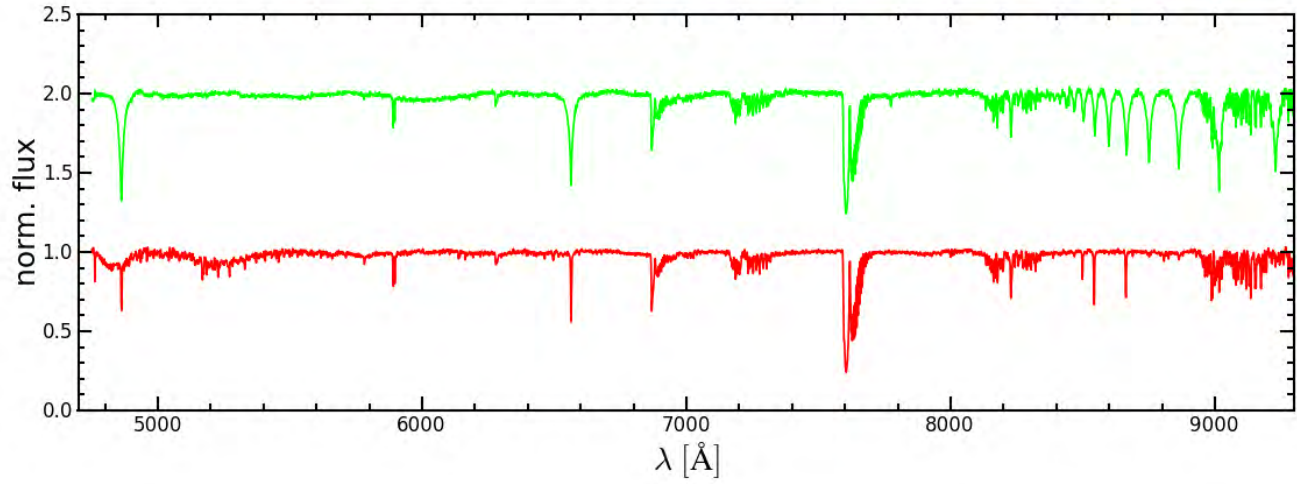
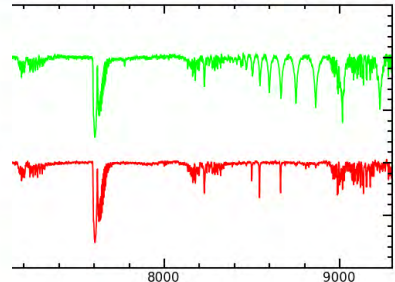
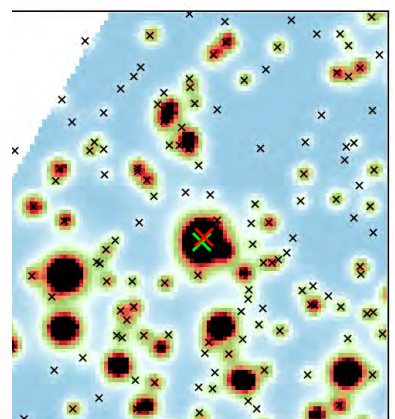
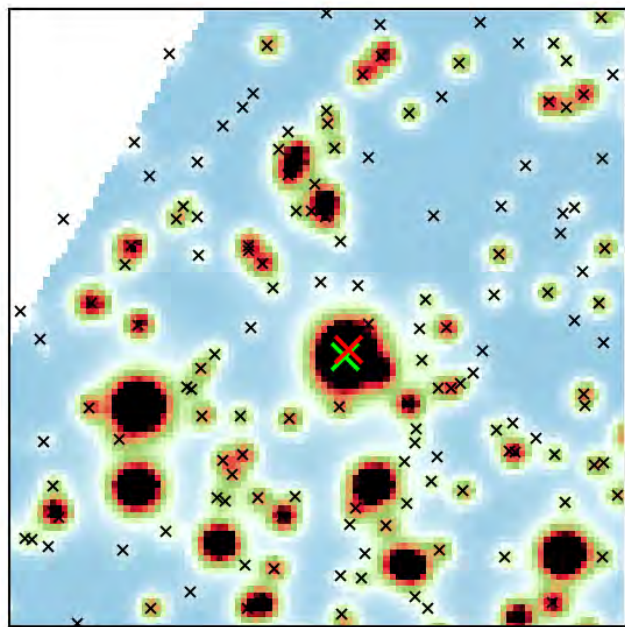
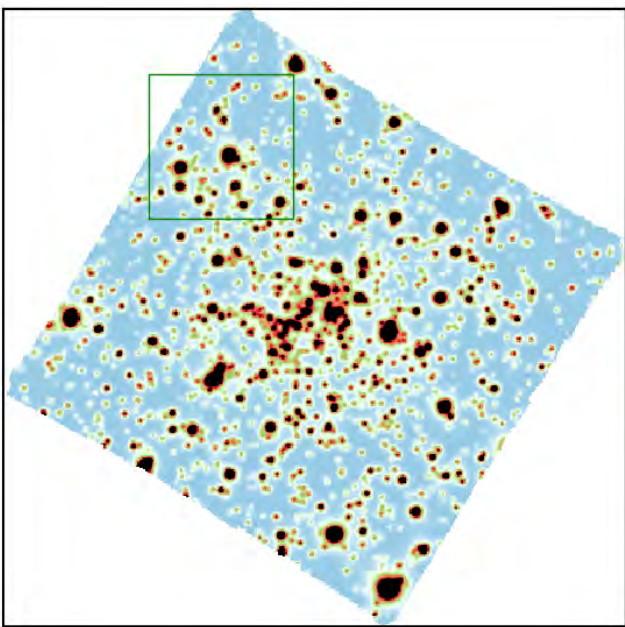
# Crowded field spectroscopy of Globular Clusters



*Sebastian Kamann (AIG)*

2 mn exposure of NGC 6397, seeing 0.6 arcsec

# Crowded field spectroscopy in NGC 6397



Sebastian Kamann, IAG

- Zurich



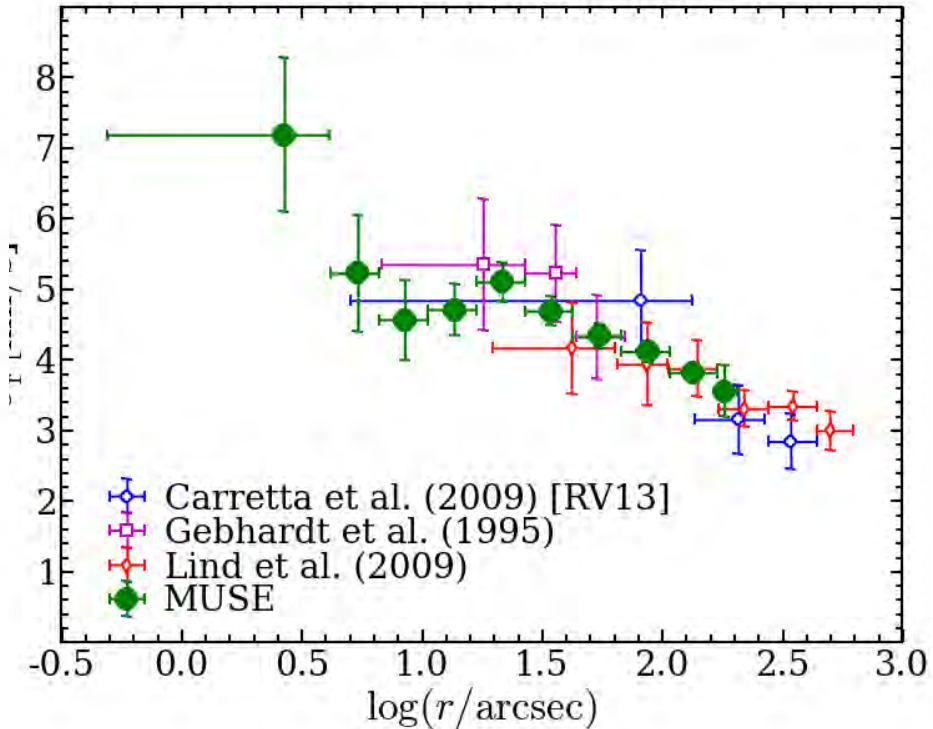
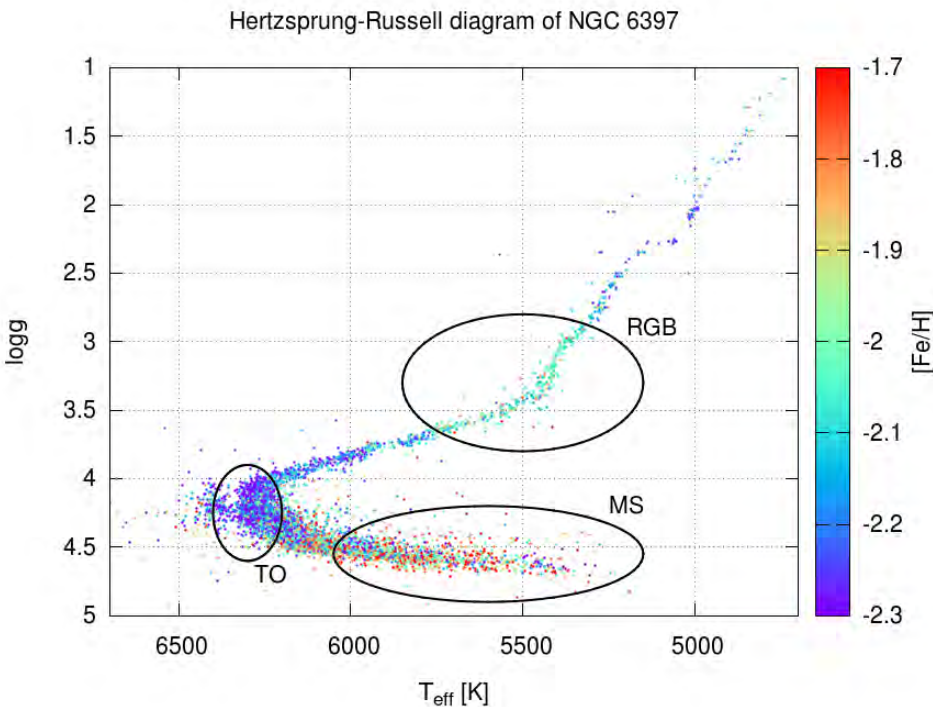
# Crowded field spectroscopy in NGC 6397

Stellar parameters

$T_{\text{eff}}$ ,  $\text{Fe}/\text{H}$ ,  $\alpha/\text{Fe}$ , ...

Kinematics

accuracy  $\sim 1$  km/s

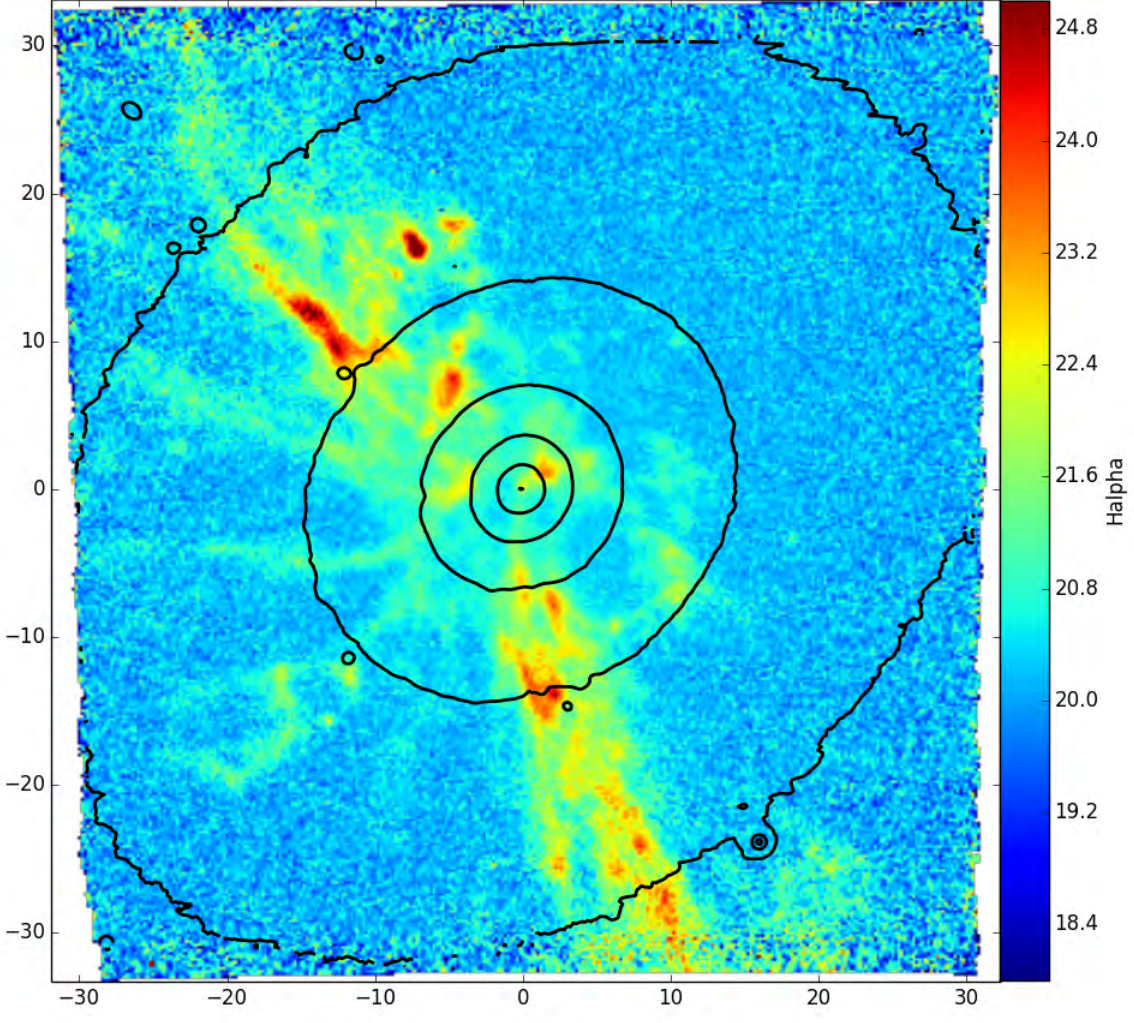
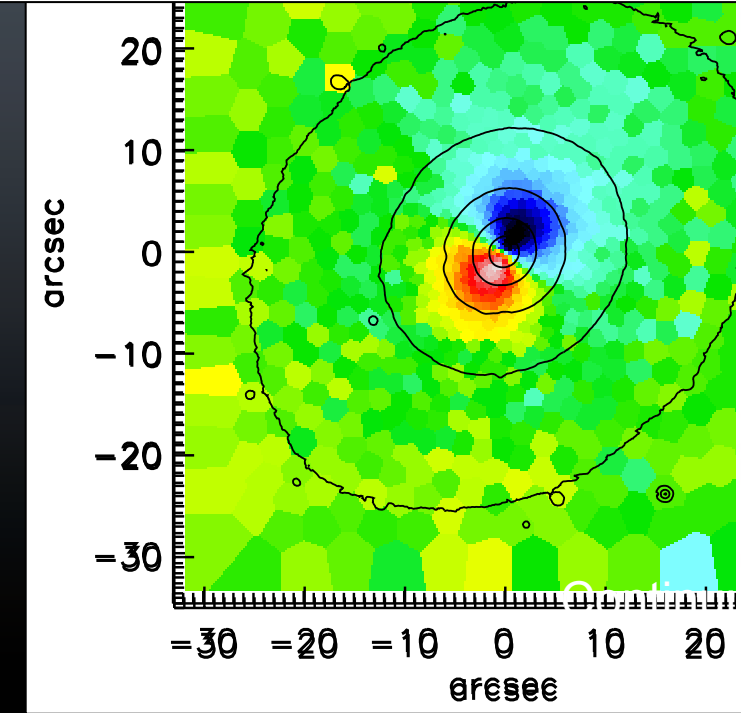
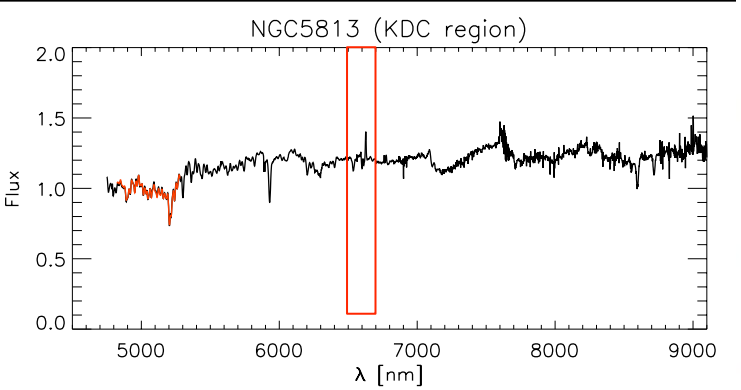
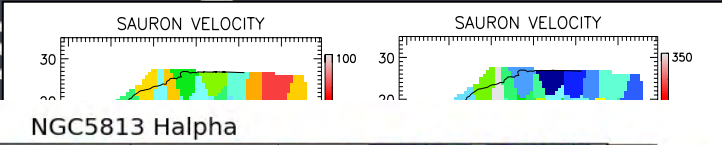


Sebastian Kamann, IAG



# Why spectral range matters

## NGC 5813 – S

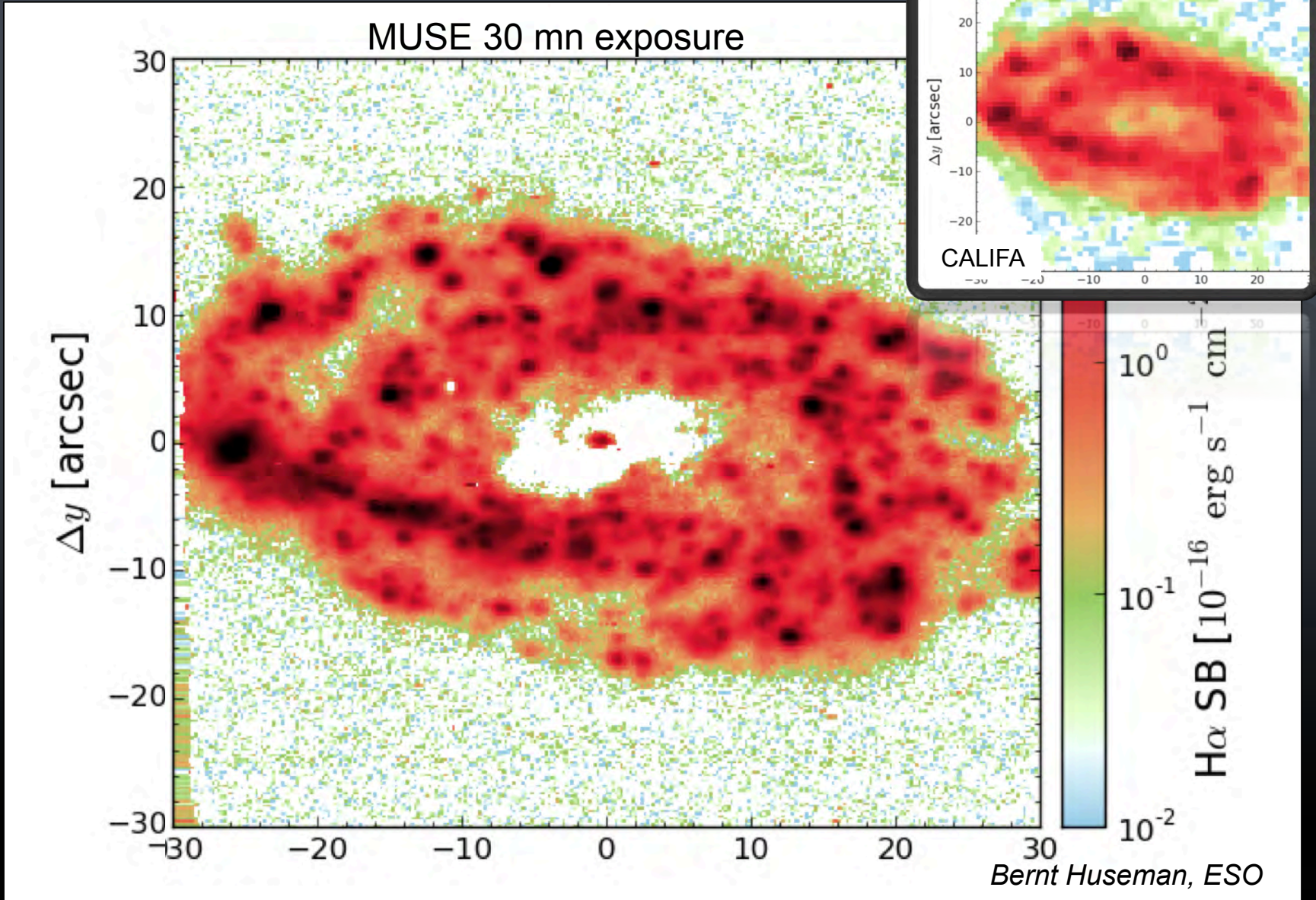


Davor Krainovic, AIP

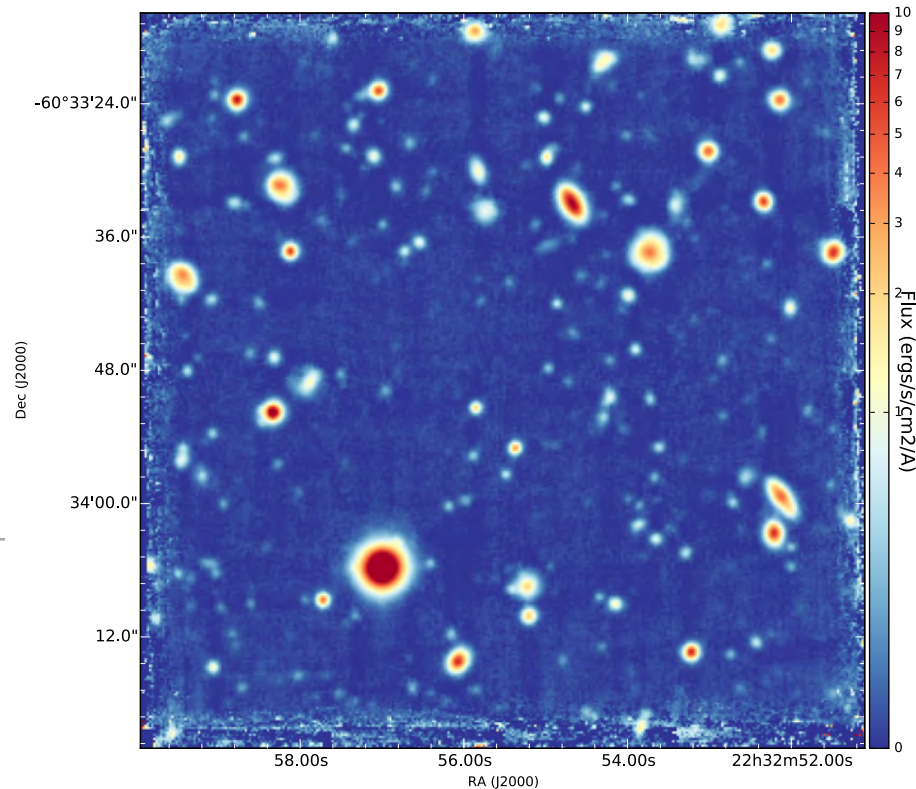


# Why spatial resolution matters

## NGC 2906 – CALIFA MUSE



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



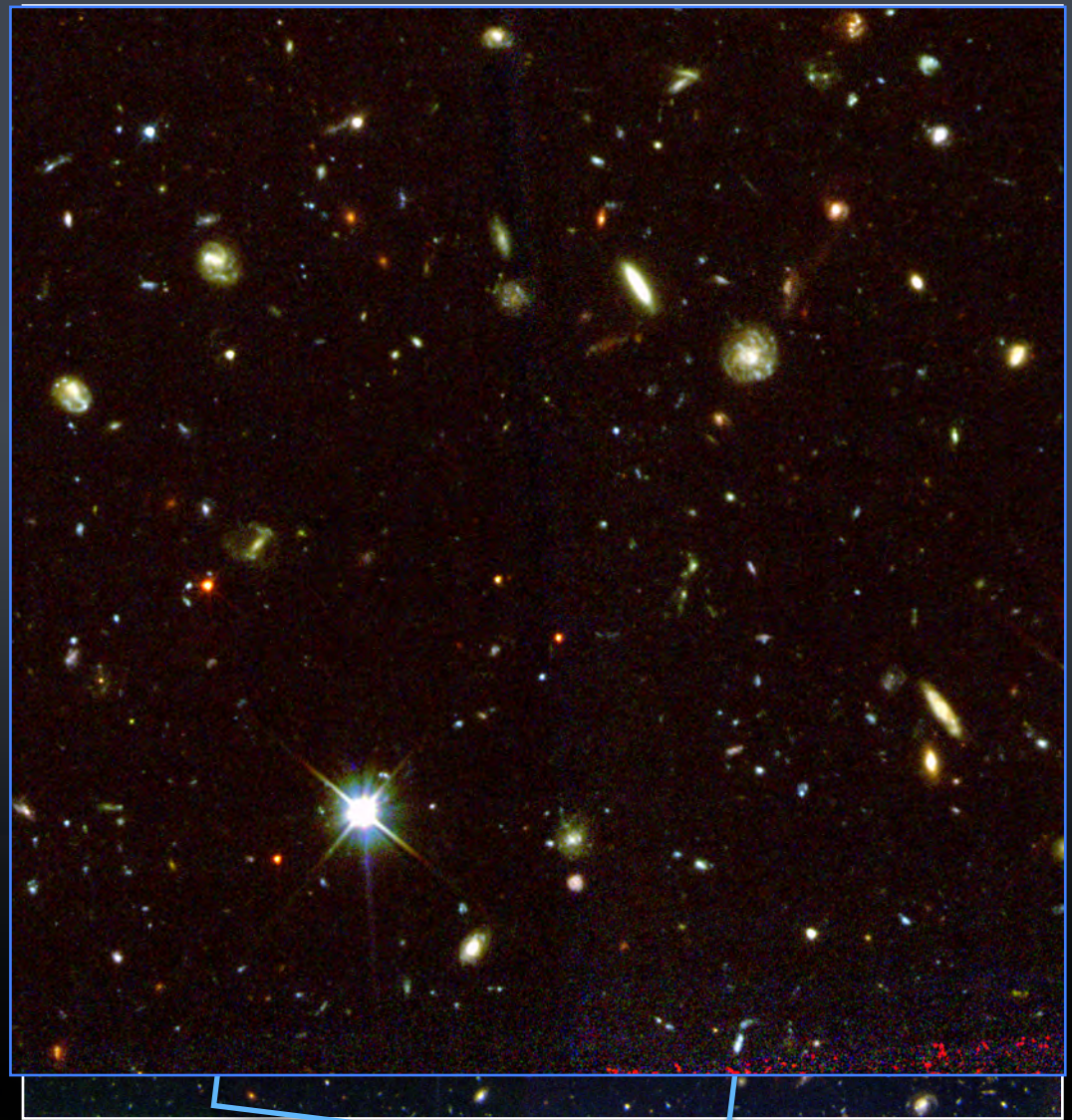
R. Bacon<sup>1</sup>, J. Brinchmann<sup>2</sup>, J. Richard<sup>1</sup>, T. Contini<sup>3,4</sup>, A. Drake<sup>1</sup>, M. Franx<sup>2</sup>, S. Tacchella<sup>5</sup>, J. Vernet<sup>6</sup>, L. Wisotzki<sup>7</sup>, J. Blaizot<sup>1</sup>, N. Bouché<sup>3,4</sup>, R. Bouwens<sup>2</sup>, S. Cantalupo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



# Hubble Deep Field South

Williams et al (2000)  
Casertano et al (2000)  
mAB ~ 29

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





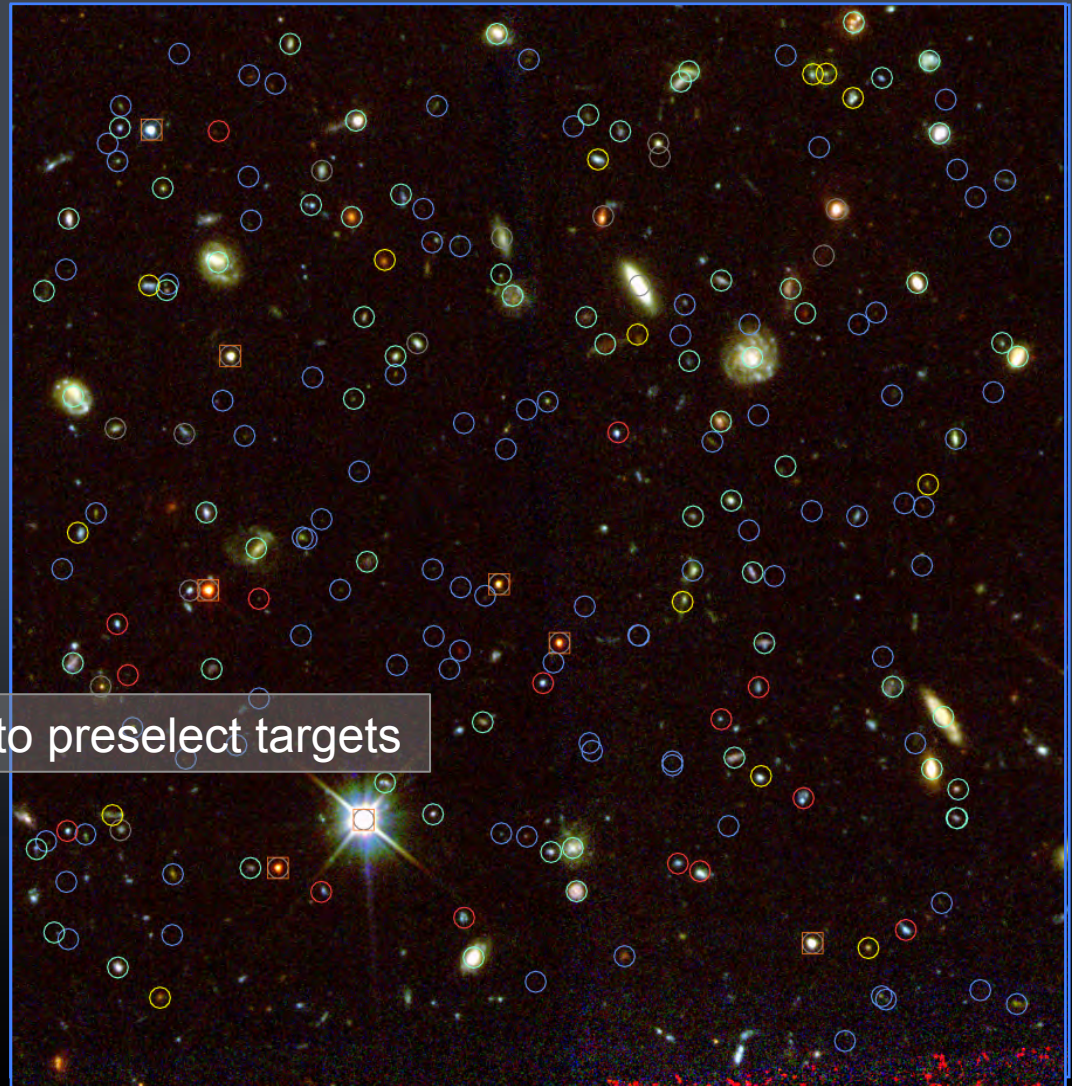
# Hubble Deep Field South

Williams et al (2000)  
Casertano et al (2000)  
mAB ~ 29

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

Enter MUSE  
189 secured redshifts  
for now

Big advantage: no need to preselect targets



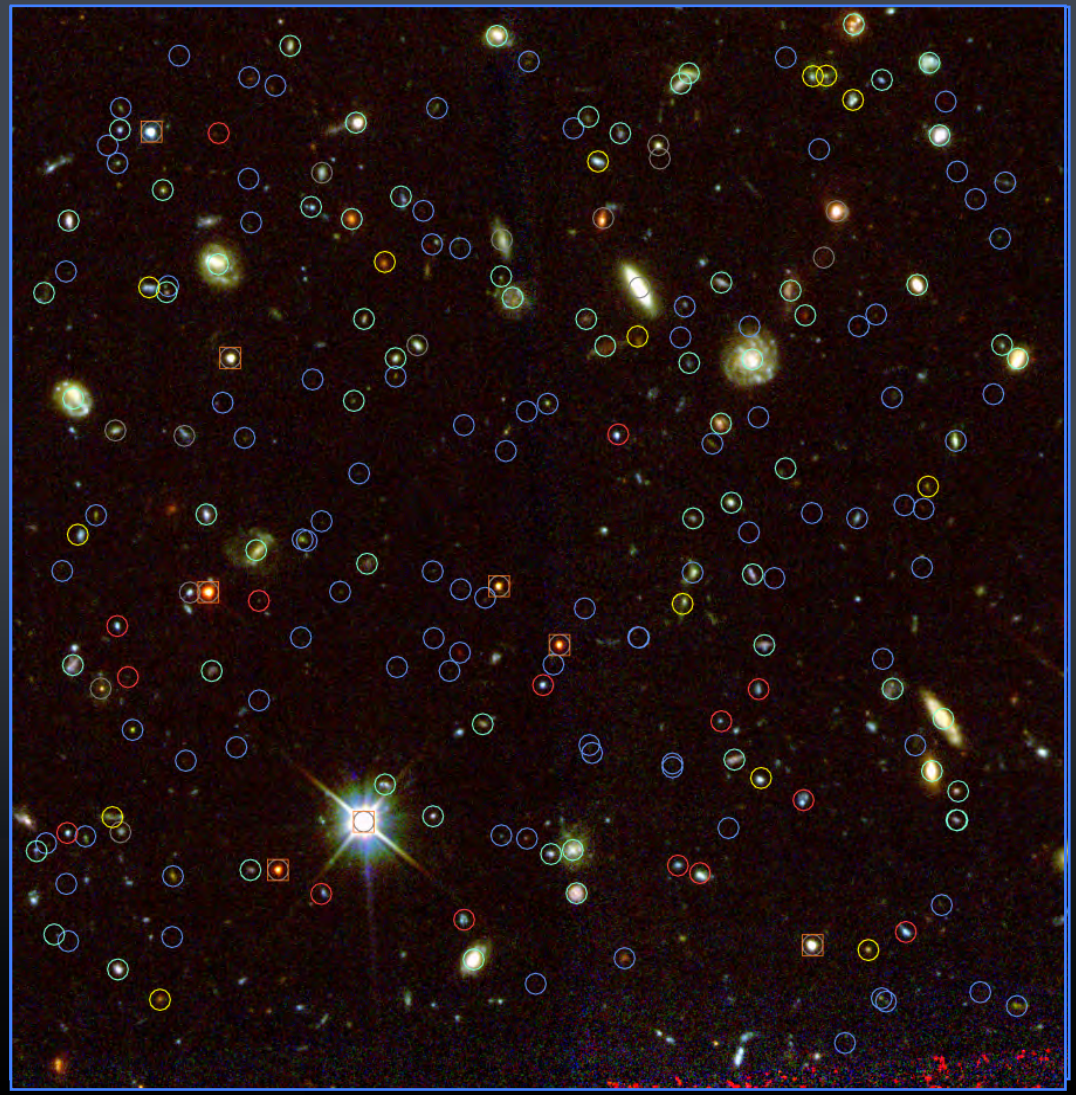


# Hubble Deep Field South

Enter MUSE  
189 secured redshifts  
for now

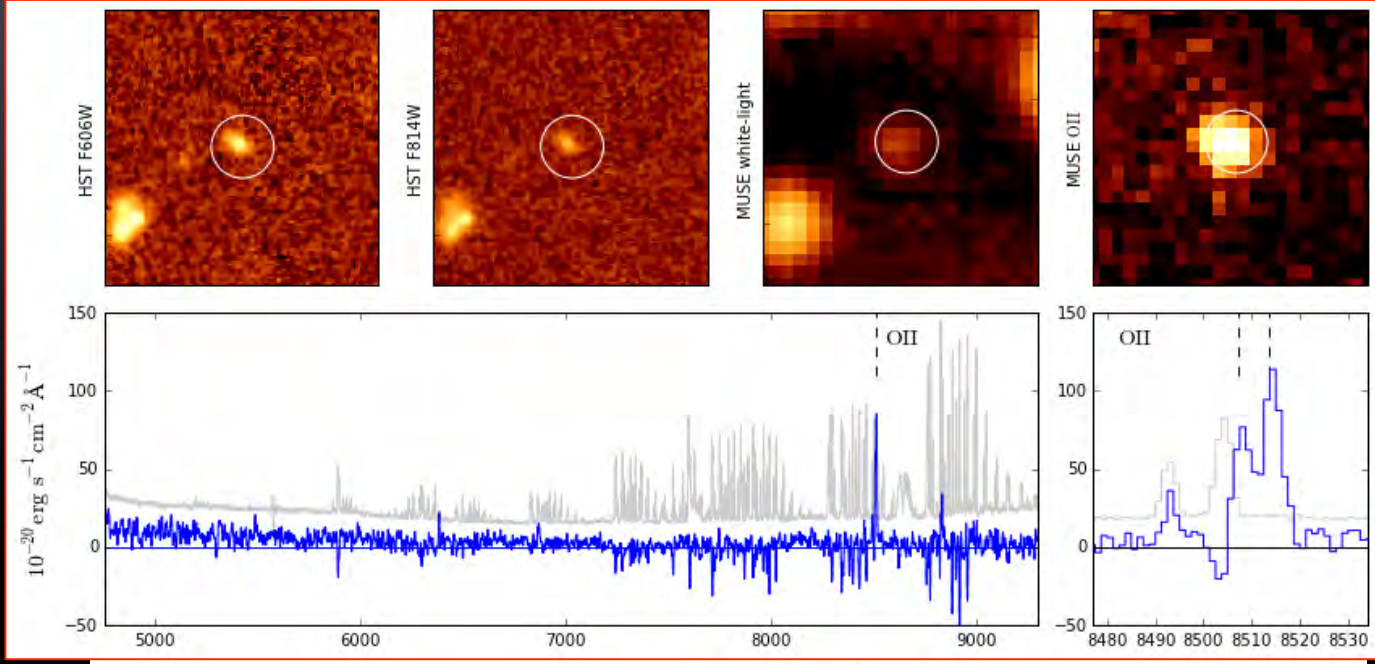
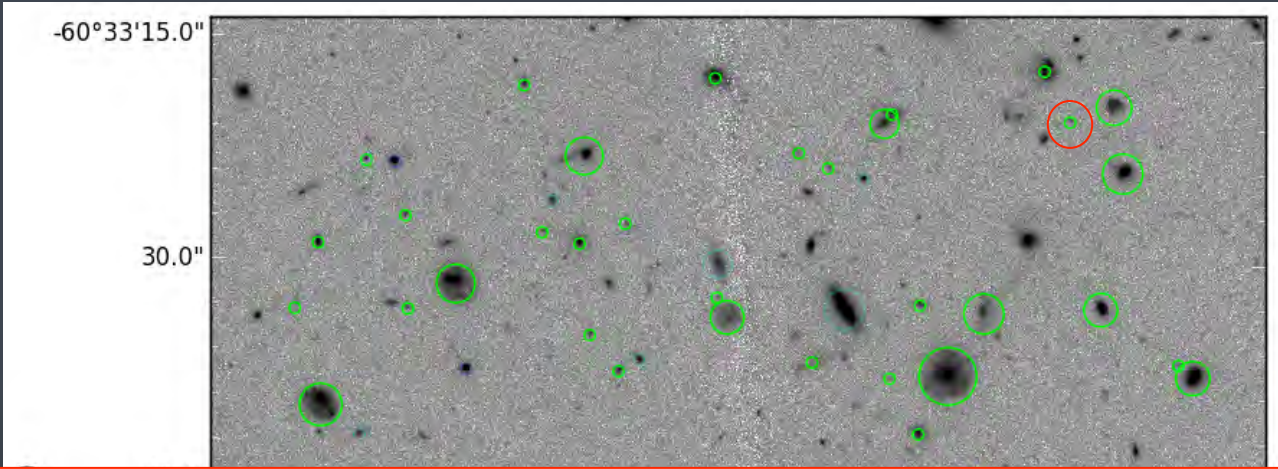
- 70 Ly $\alpha$  emitters seen in HST
- 26 Ly $\alpha$  w/o HST
- 65 [O II] emitters
- 15 C III]1909 emitters
- 8 Stars
- 14 Abs. line redshifts

out of 586 targets



# 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
  - ✓  $Z = [0.29 - 1.48]$
  - ✓  $I_{814} = [21.5 - 28.5]$

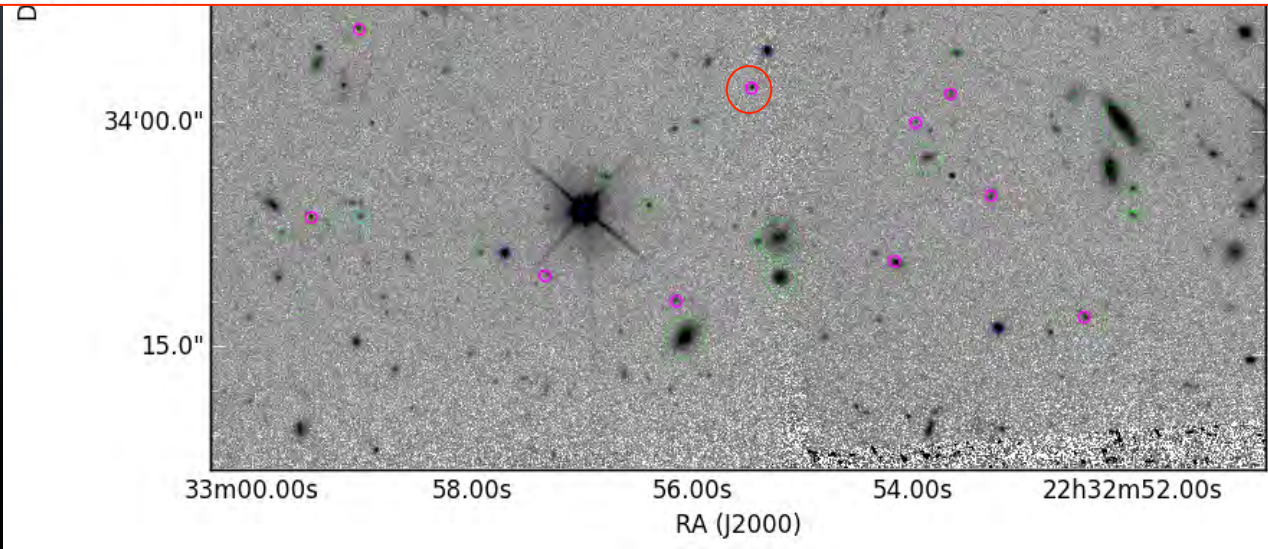
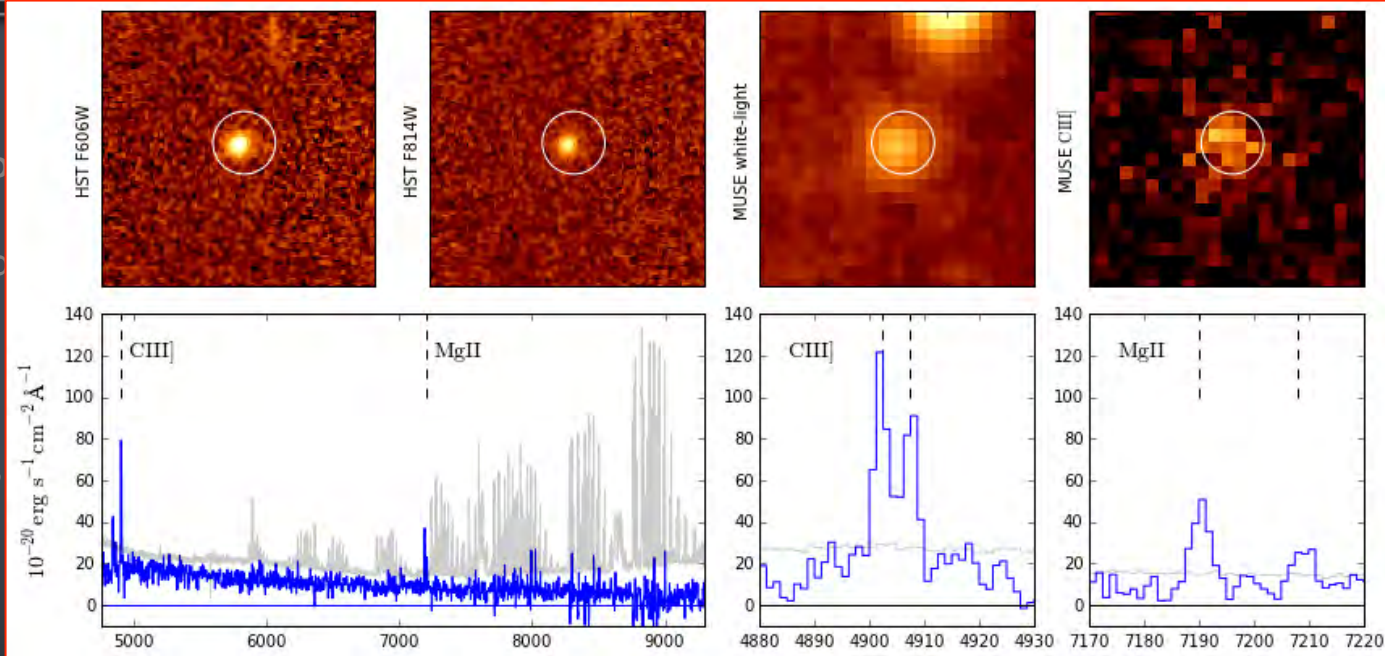


**ID#160**

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

# Census of MUSE HDFS Field

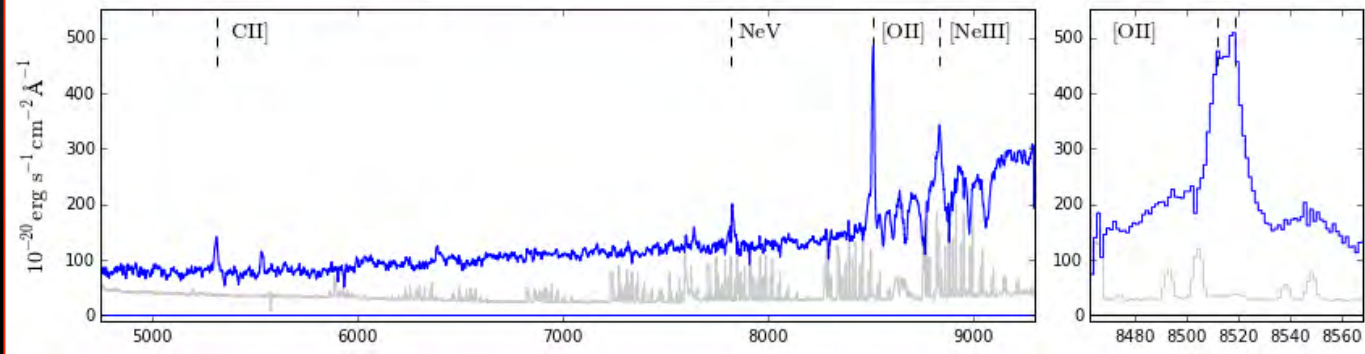
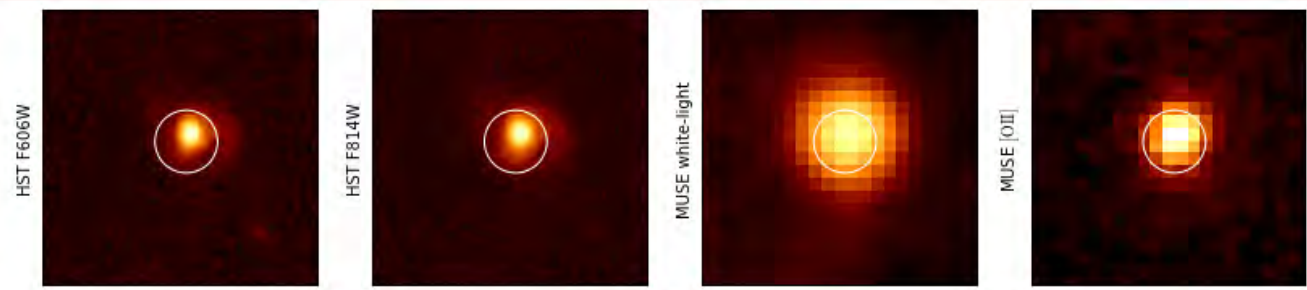
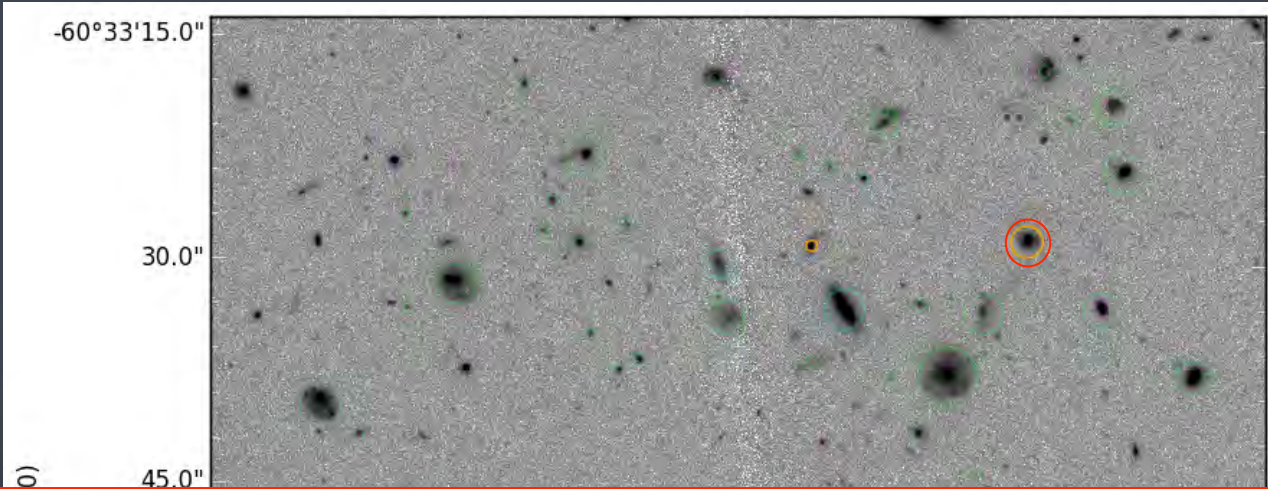
- ✓ HST WFPC2 F812W
- ✓ 18 Known Spectroscopic Redshifts
- ✓ 189 sources identified in MUSE data cube
- ✓ 8 stars
- ✓ 7 nearby galaxies
- ✓ 61 [OII] 3727 emitters
- ✓ 10 absorption lines galaxies
- ✓ **12 CIII] 1909 emitters**
  - ✓  $Z = [1.57 - 2.67]$
  - ✓  $I_{814} = [24.6 - 27.2]$



**ID#97**

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

- ✓ 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**
  - ✓  $Z = 1.28$
  - ✓  $I_{814} = 22.6, 23.6$

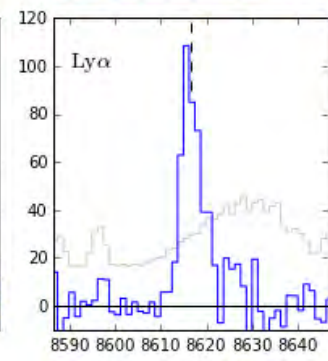
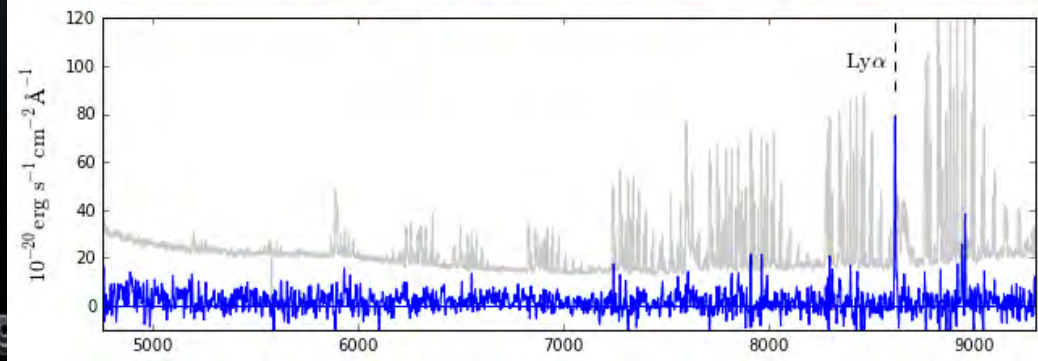
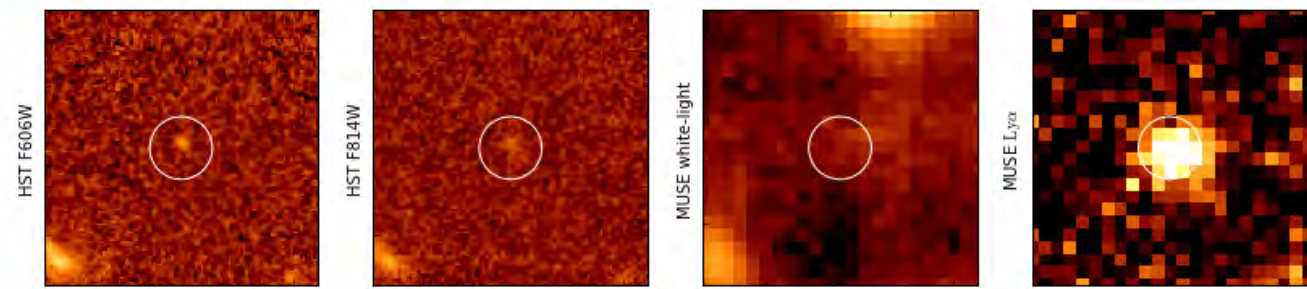
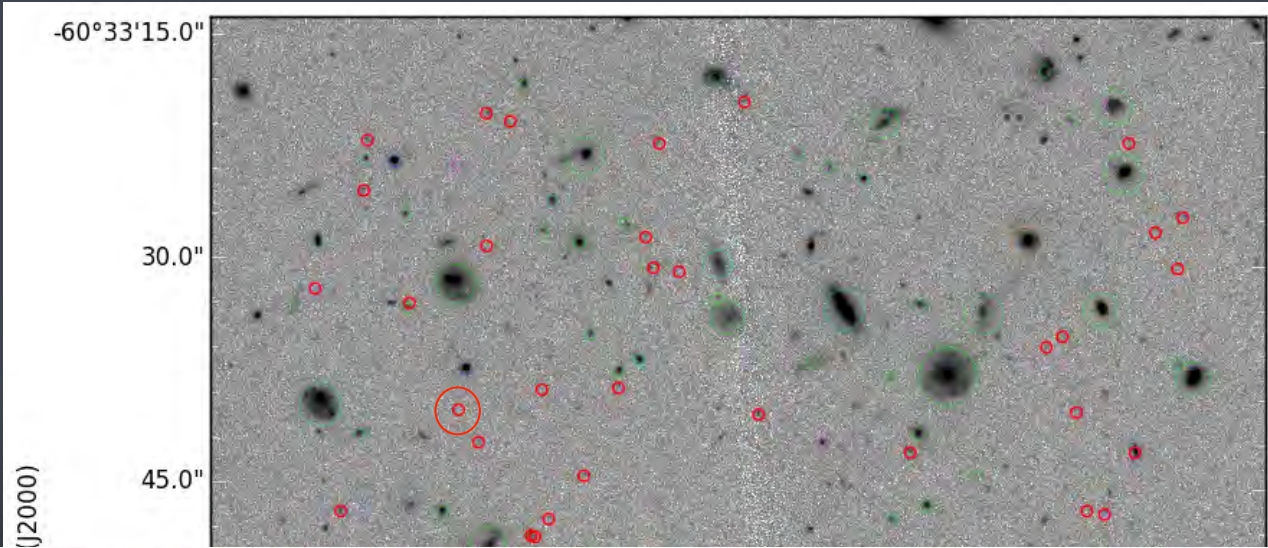


**ID#10**

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



- ✓ HST WFPC2 F812W
- ✓ 18 Known Spectroscopic 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
- ✓ **63 Ly $\alpha$  emitters**
  - ✓  $Z = [2.95 - 6.28]$
  - ✓  $I_{814} = [24.5 - 29.6]$



**ID#290**

**Z = 6.08**

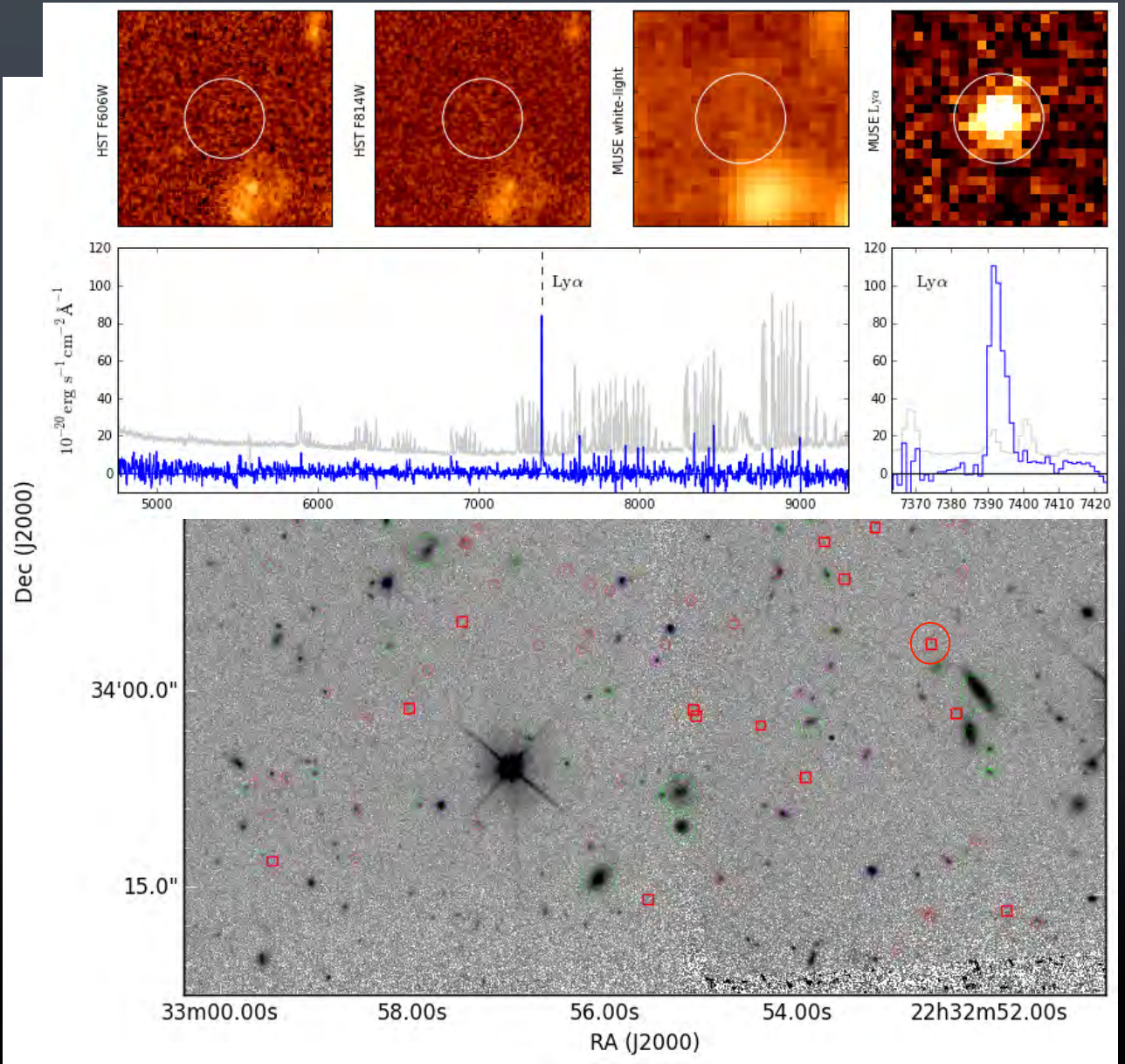
**$I_{814} = 27.8$**

# Census of MUSE HDFS Field

**ID#553**

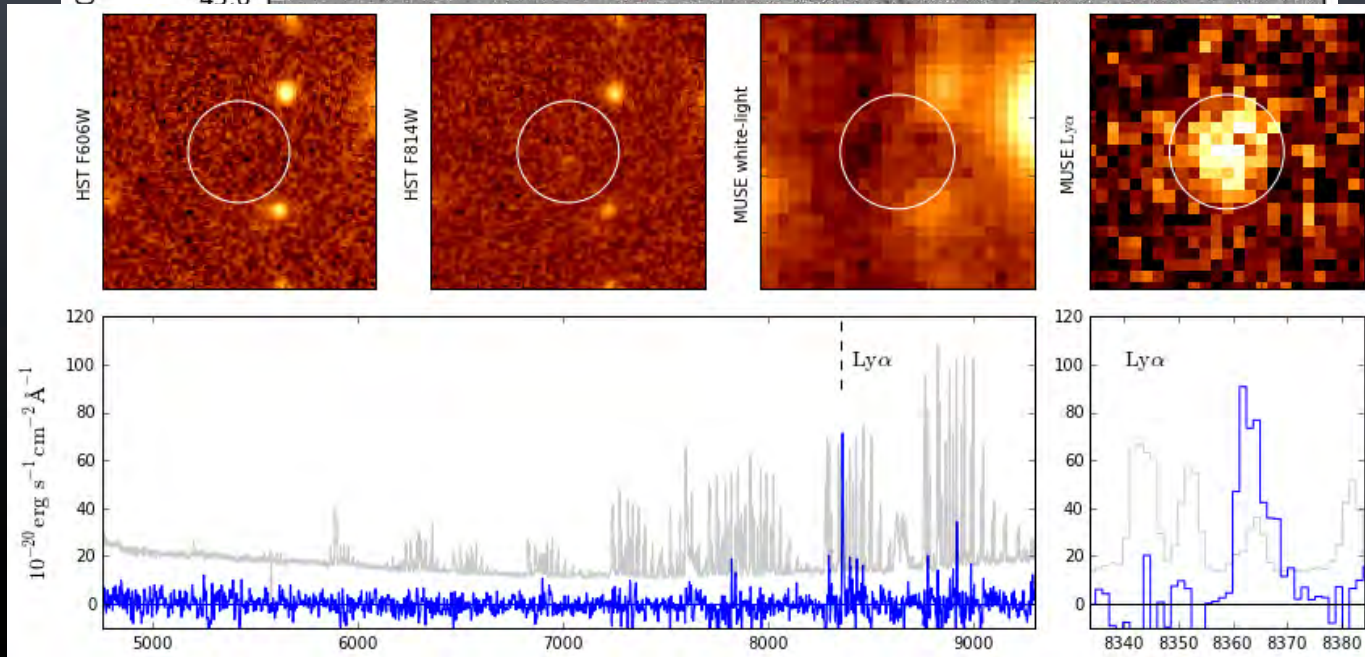
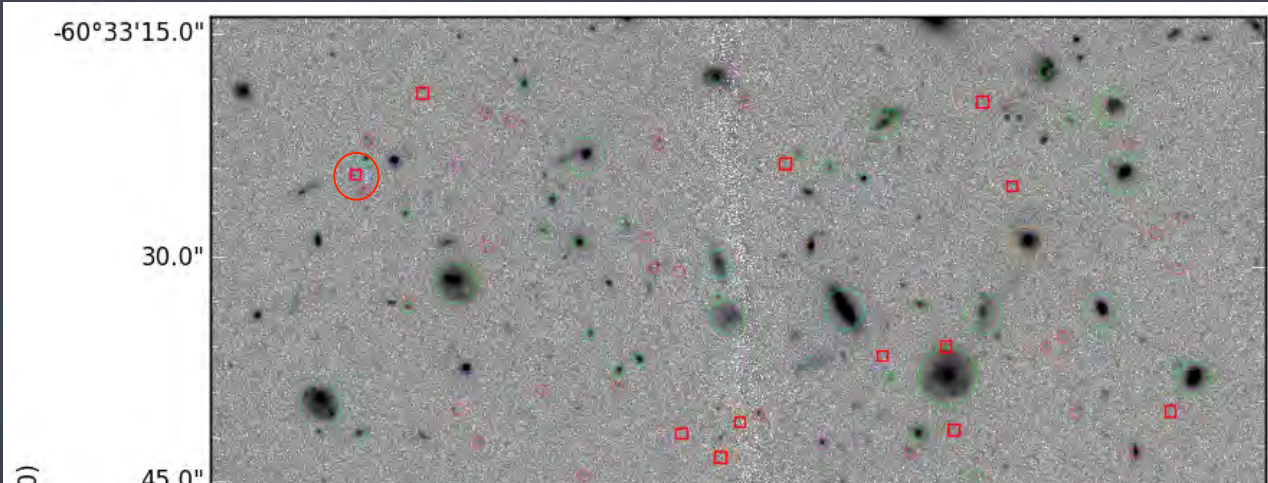
$Z = 5.08$   
 $I_{814} > 29.8$

- ✓ HDFS
- ✓ F814W
- ✓ MUSE
- ✓ 8 stars
- ✓ 7 nearby galaxies
- ✓ 61 [OII] 3727 emitters
- ✓ 10 absorption lines galaxies
- ✓ 12 CIII] 1909 emitters
- ✓ 2 AGNs
- ✓ 63 Ly $\alpha$  emitters
- ✓ 26 Ly $\alpha$  emitters without HST counterpart
  - ✓  $Z = [3.12 - 6.27]$
  - ✓  $I_{814} > 29.8$

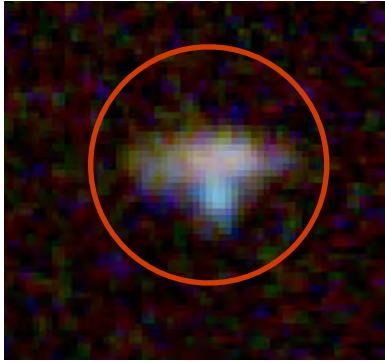


**ID#560**  
 $Z = 5.88$   
 $I_{814} > 29.8$

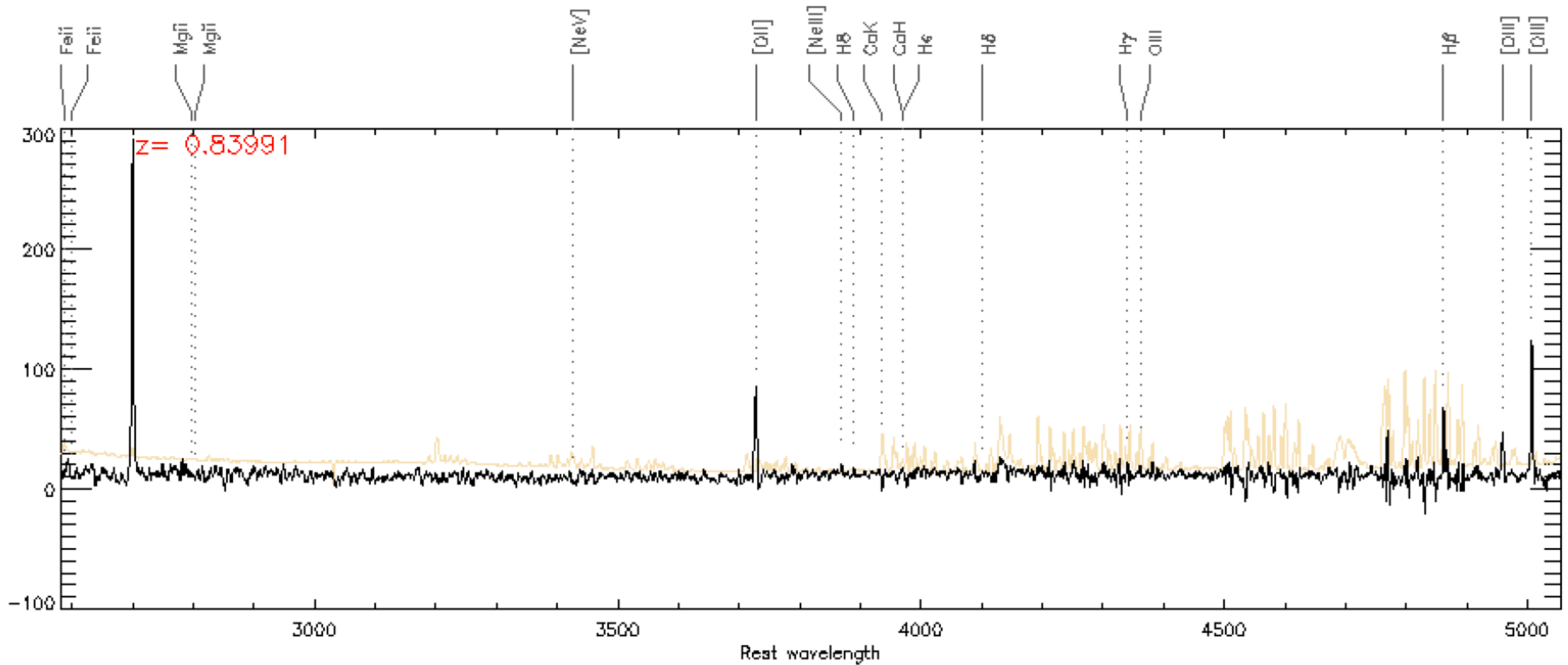
- ✓ HST
- ✓ 18
- Red
- ✓ 189
- MUSE
- ✓ 8 stars
- ✓ 7 nearby galaxies
- ✓ 61 [OII] 3727 emitters
- ✓ 10 absorption lines galaxies
- ✓ 12 CIII] 1909 emitters
- ✓ 2 AGNs
- ✓ 63 Ly $\alpha$  emitters
- ✓ 26 Ly $\alpha$  emitters without HST counterpart
  - ✓  $Z = [3.12 - 6.27]$
  - ✓  $I_{814} > 29.8$



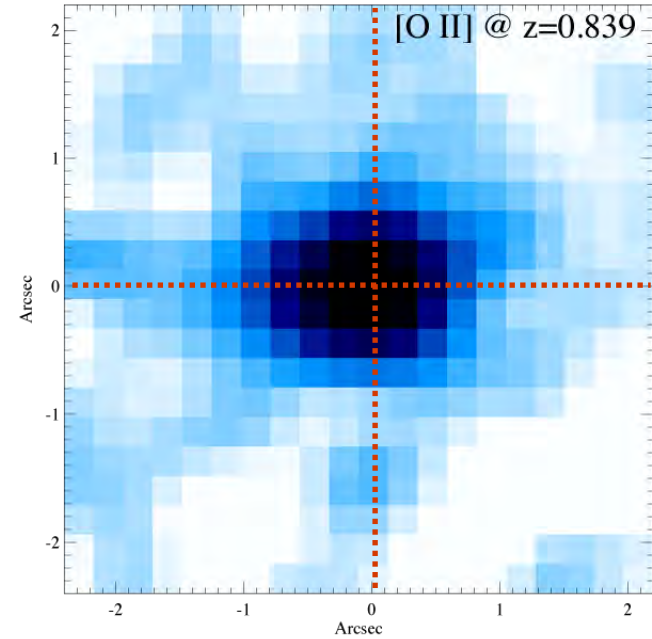
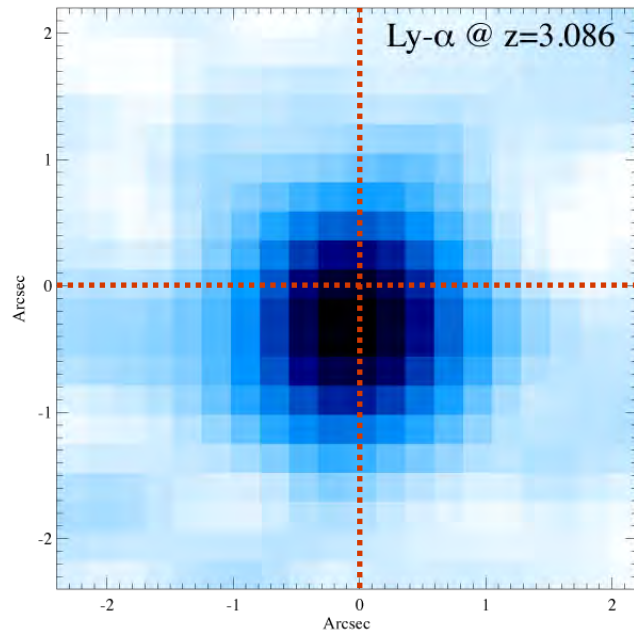
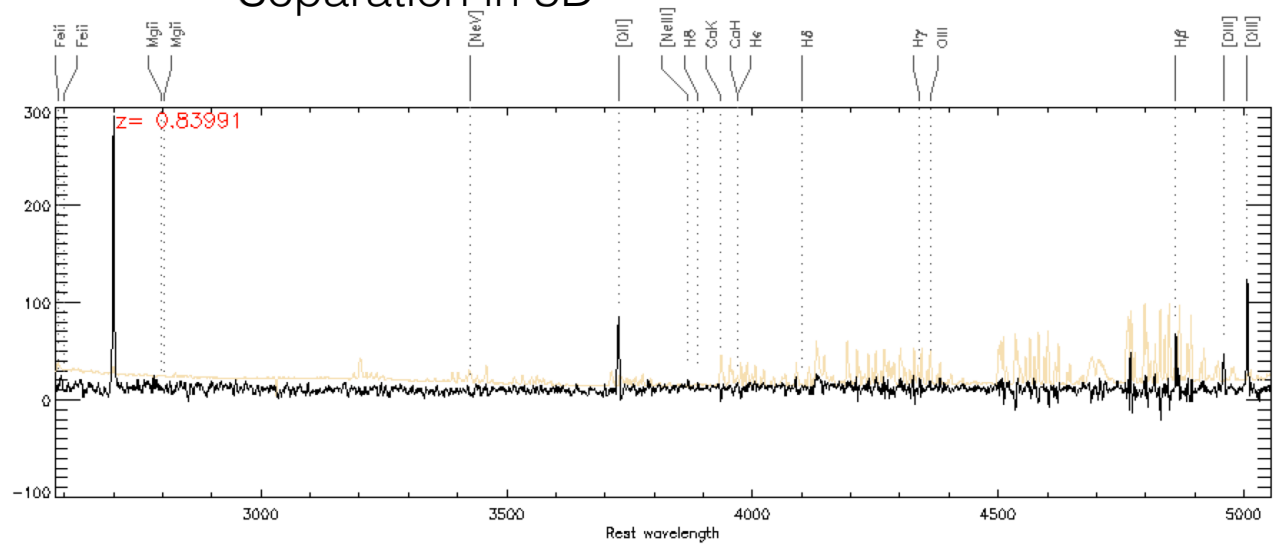
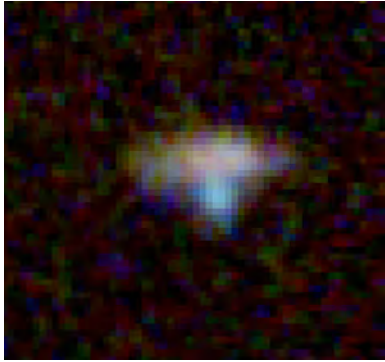
# Separation in 3D



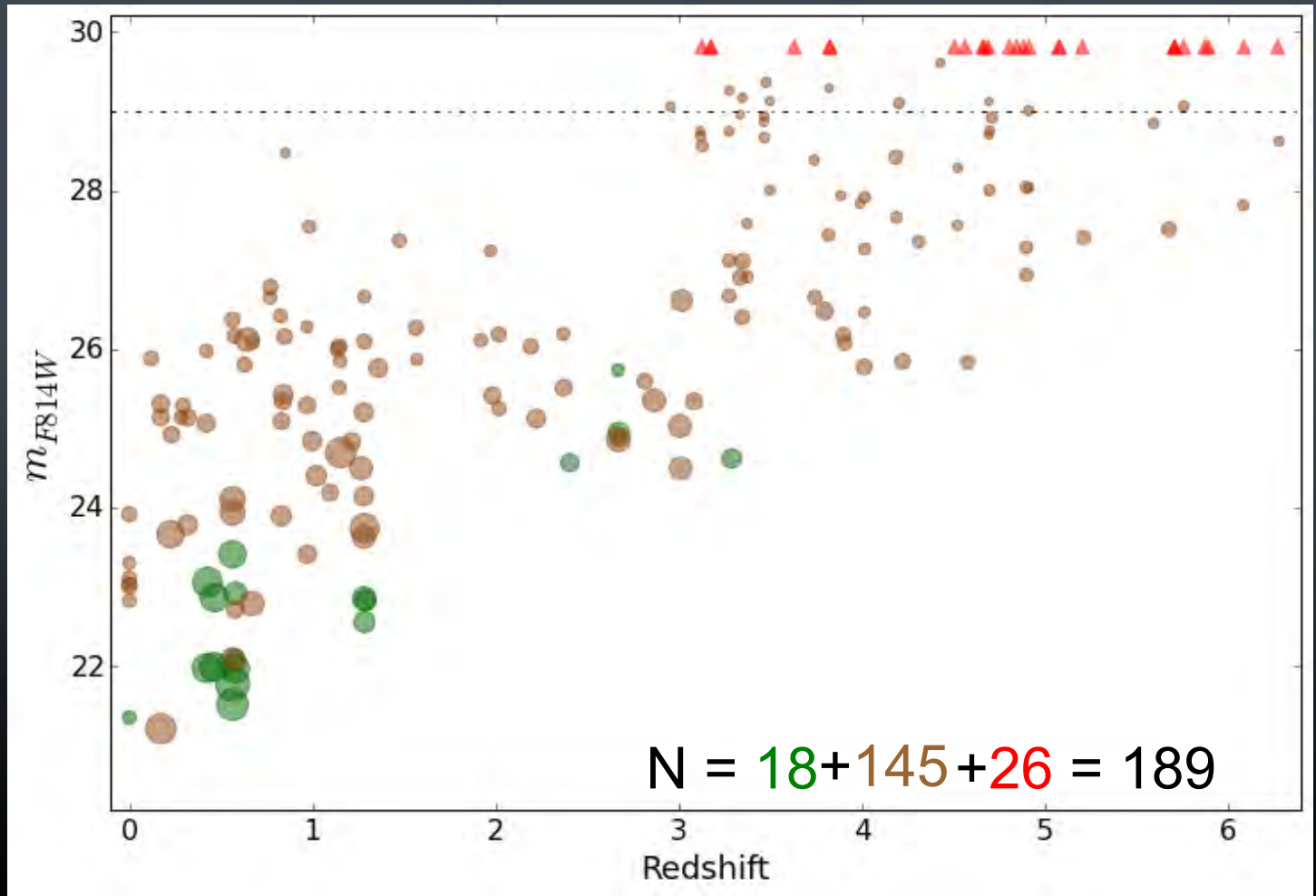
Single object in HDF-S catalogue  
 $m_{F814W} \sim 25.3$



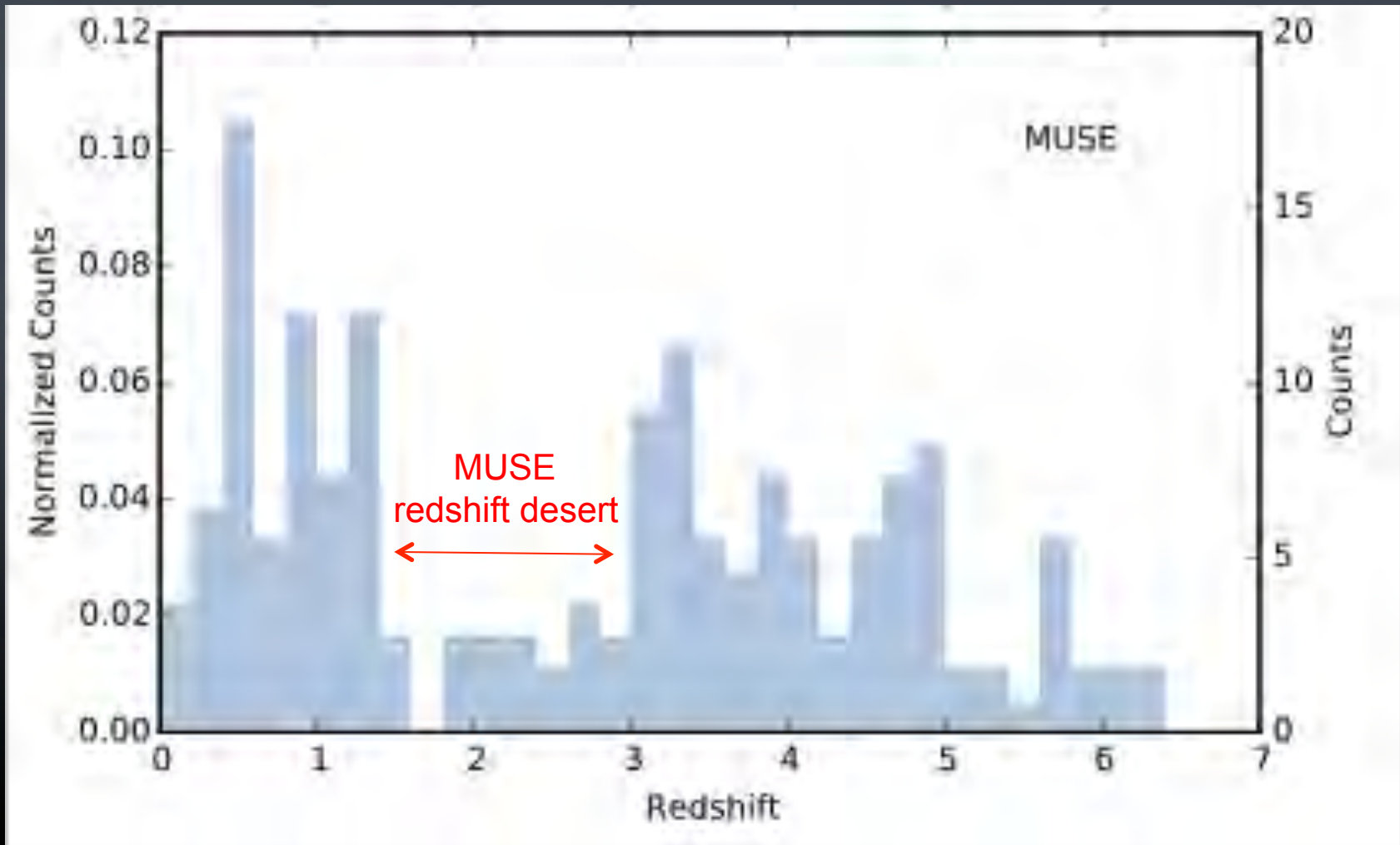
# Separation in 3D



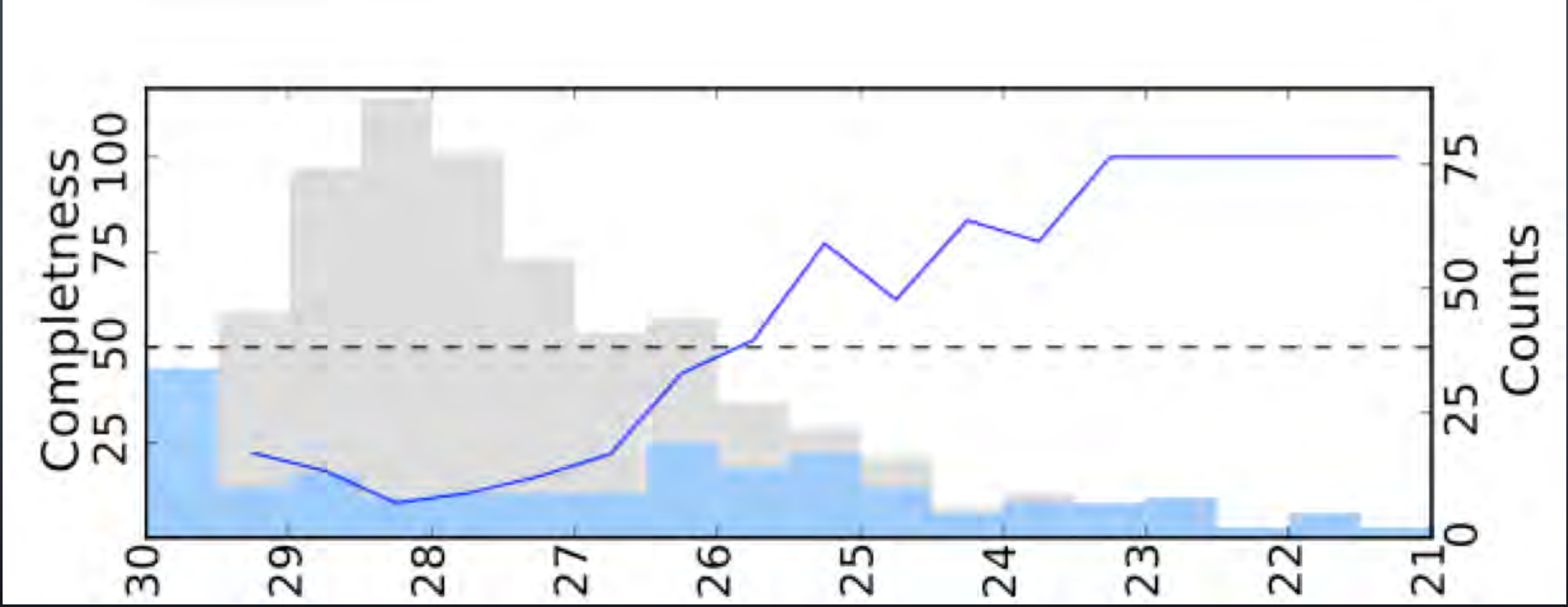
# Redshift distribution



# Redshift distribution



# Redshift distribution



With decent completion down to 26<sup>th</sup> magnitude but still significant numbers at  $m_{F814} \sim 29$ .

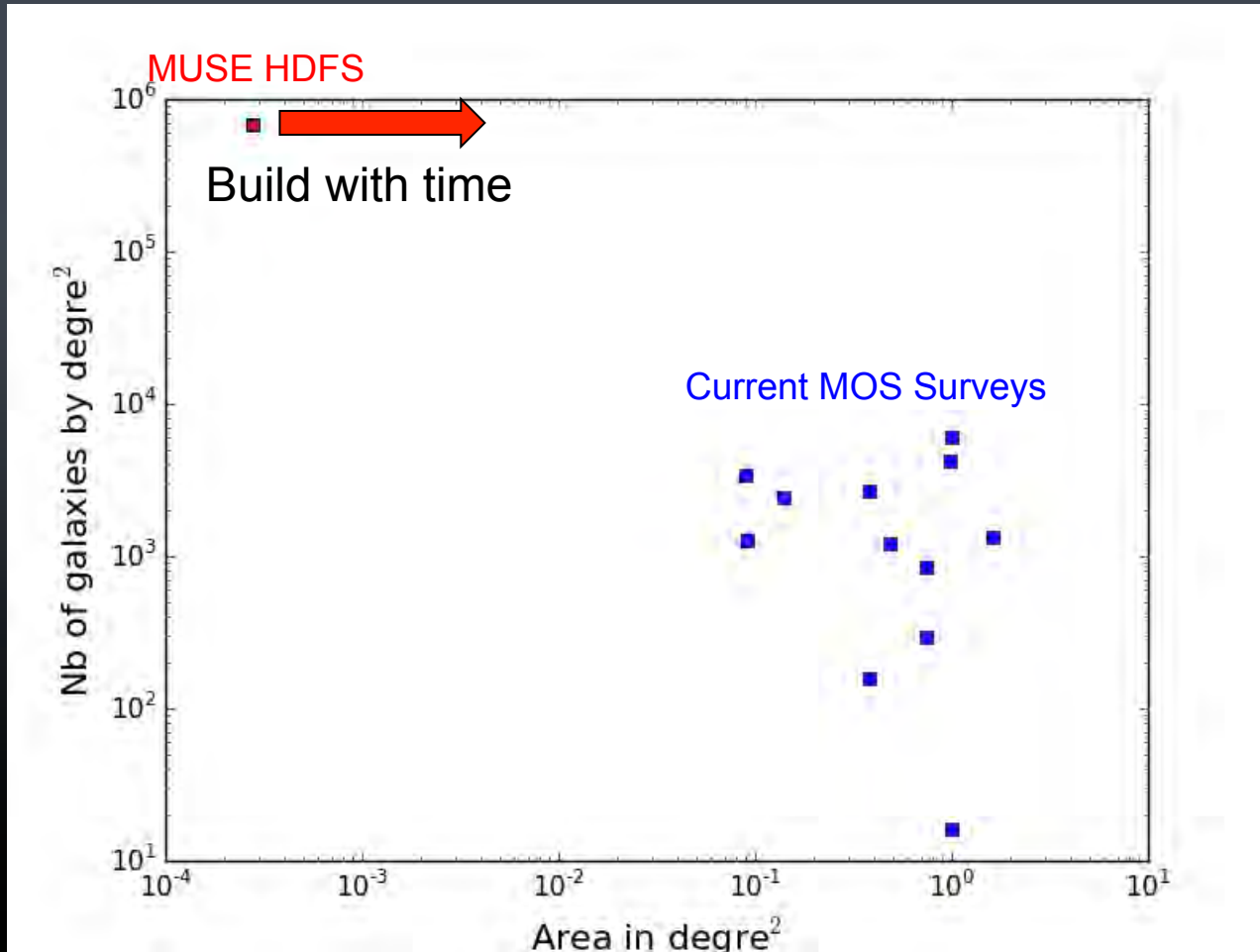


**Table 2.** Galaxy groups detected in the HDFs ordered by redshift.

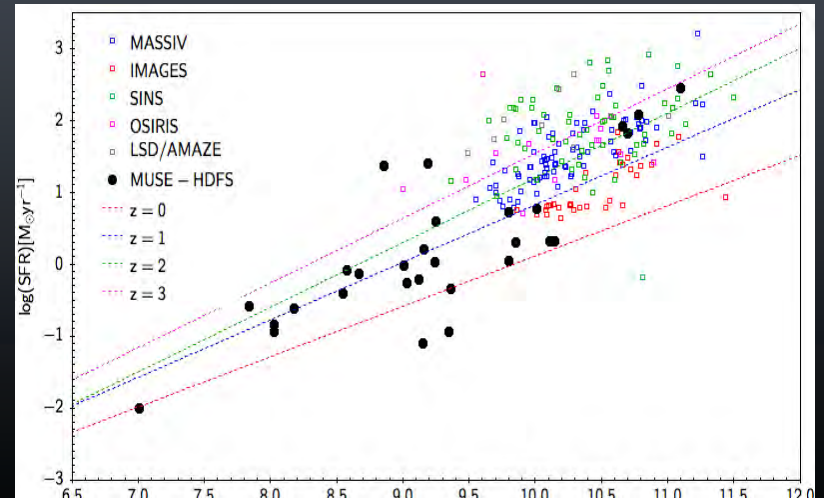
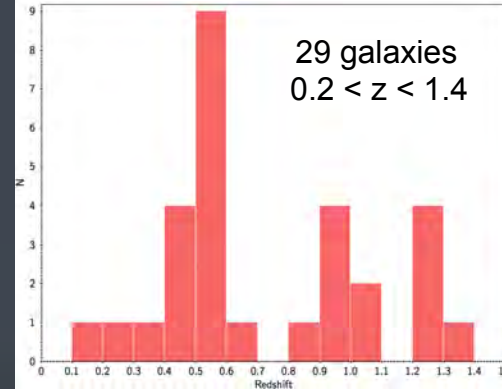
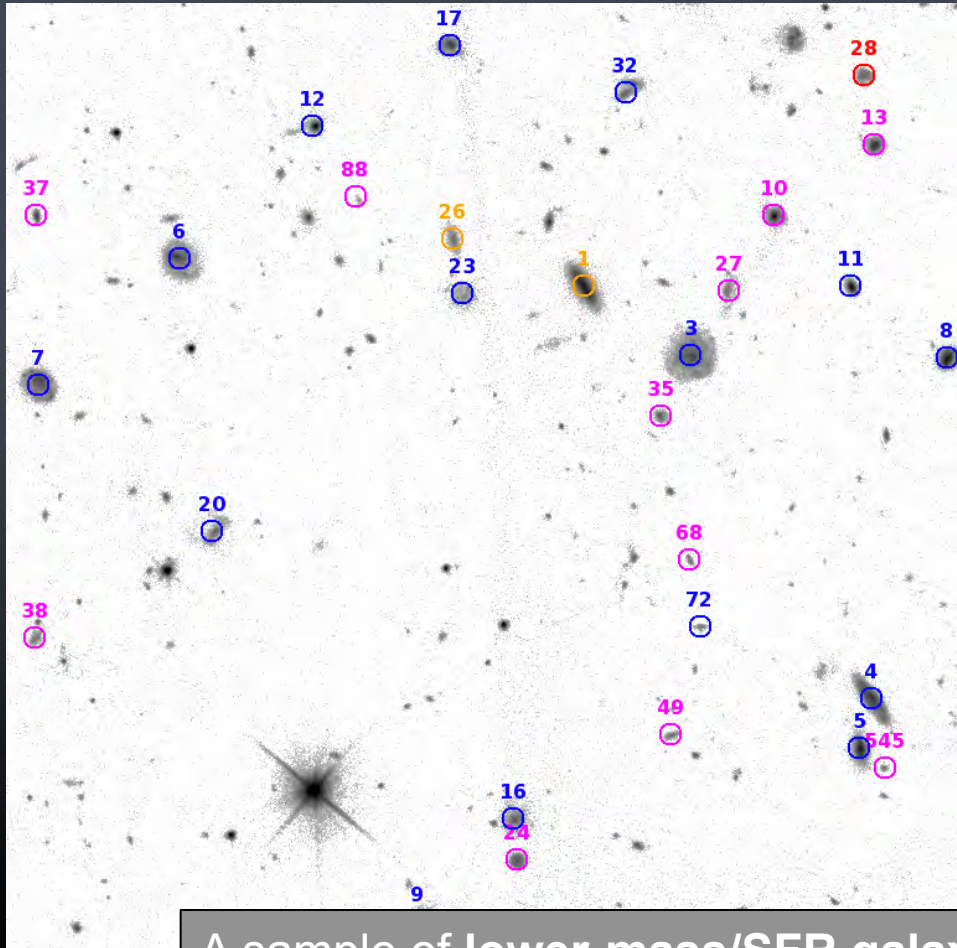
$z$	$v_{\text{rms}}$ $\text{km s}^{-1}$	$r_{\text{rms}}$ $\text{kpc}$	$N_{\text{m}}$	Member IDs
0.172	65	43	3	1, 63, 70
0.421	262	54	4	6, 57, 101, 569
0.564	52	142	7	3, 4, 9, 23, 32, 135
0.578	424	150	5	5, 8, 11, 17, 122
0.972	56	201	3	24, 68, 129
1.284	354	92	9	10, 13, 15, 25, 27, 35, 64, 114, 160
2.672	101	87	4	50, 51, 55, 87
3.013	350	115	3	40, 56, 155
3.124	329	92	4	422, 437, 452, 558
3.278	36	144	4	162, 202, 449, 513
3.349	35	90	3	139, 200, 503
3.471	324	139	4	433, 469, 478, 520
3.823	161	93	4	238, 514, 563, 581
4.017	113	181	4	89, 144, 216, 308
4.699	430	109	6	325, 441, 453, 474, 499, 548
4.909	370	164	6	186, 218, 334, 338, 484, 583
5.710	26	101	3	546, 547, 574

# 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.



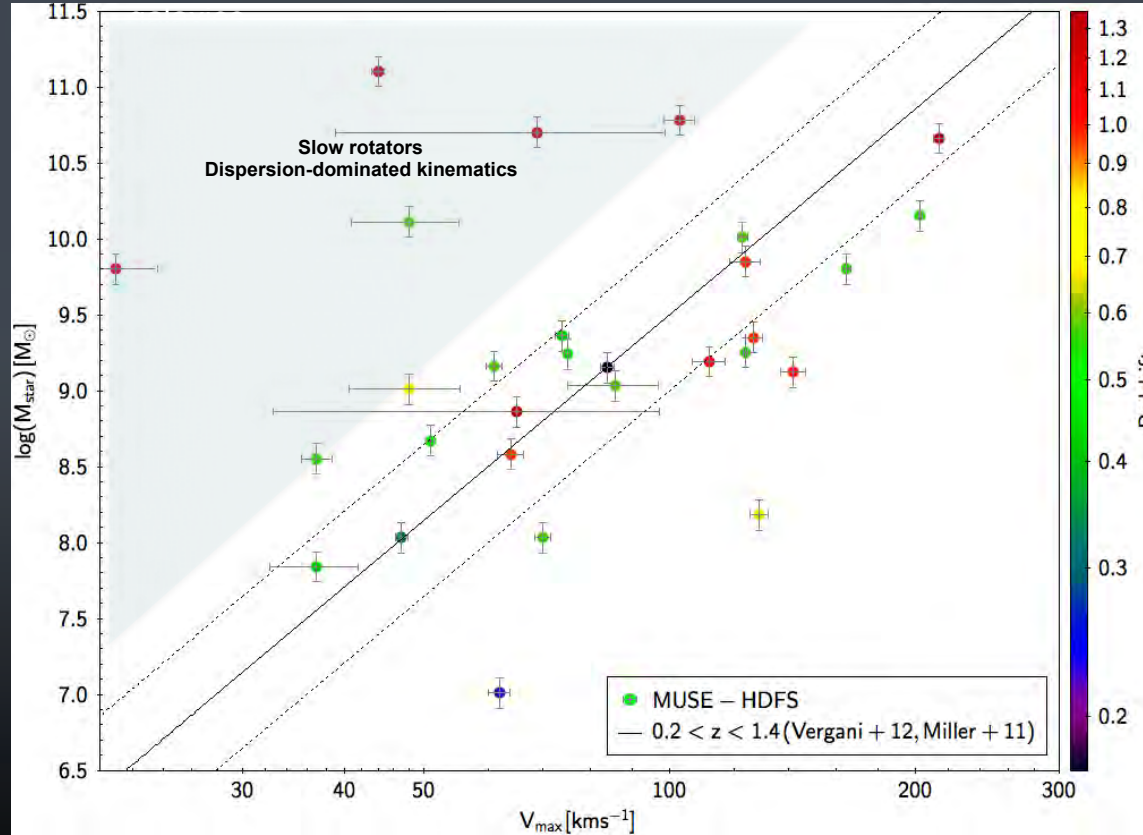
# Spatially resolved galaxies in MUSE-HDFS



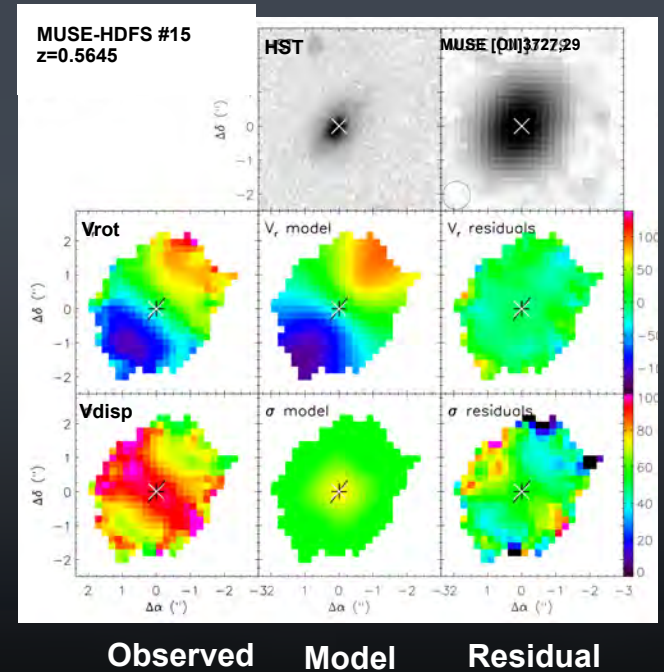
A sample of lower-mass/SFR galaxies compared with previous IFU surveys

Contini et al, in prep

Tully-Fisher Relation at  $0.2 < z < 1.4$  for MUSE-HDFS resolved



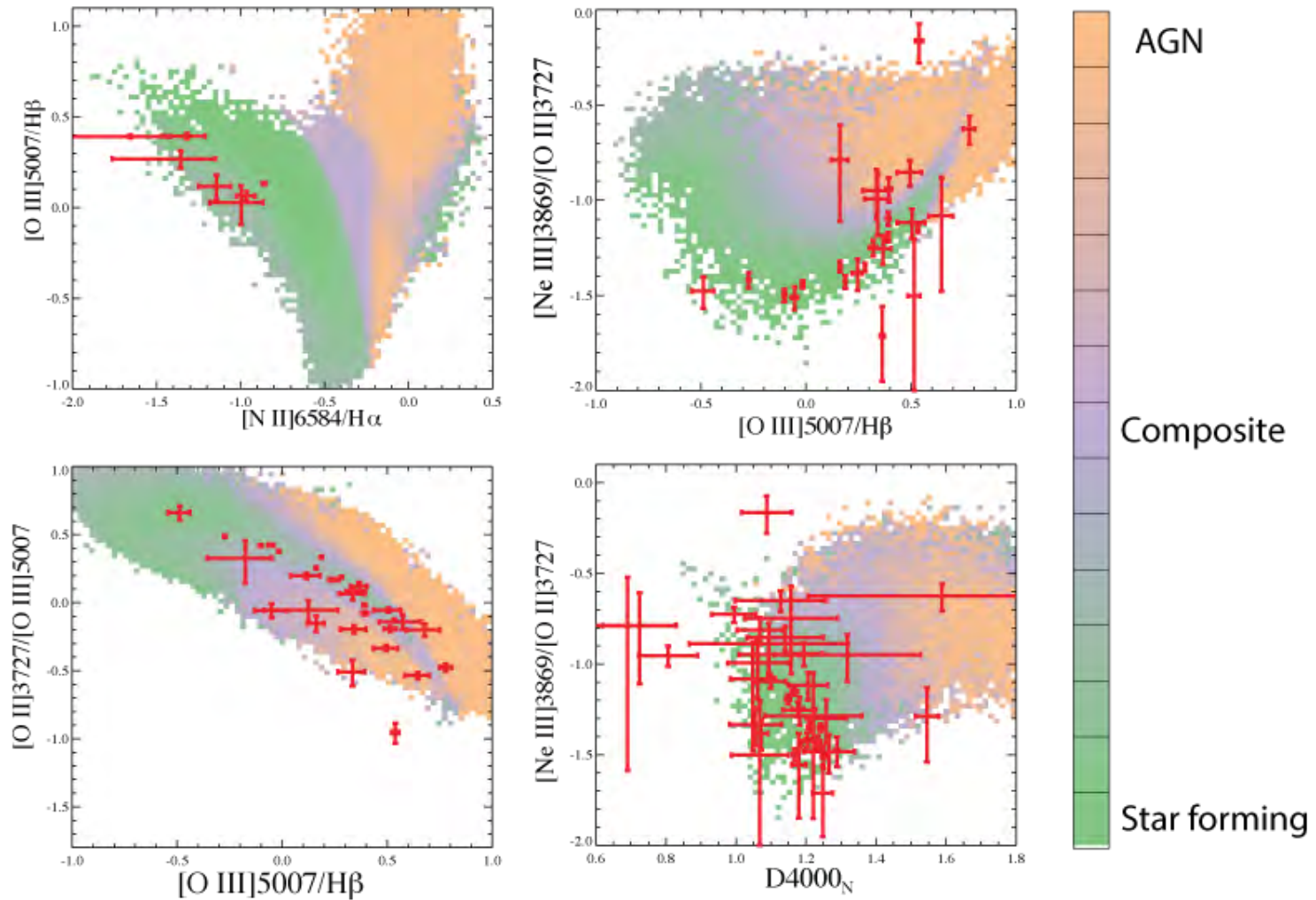
Gas kinematics from strong emission lines, mainly [OII] and [OIII]



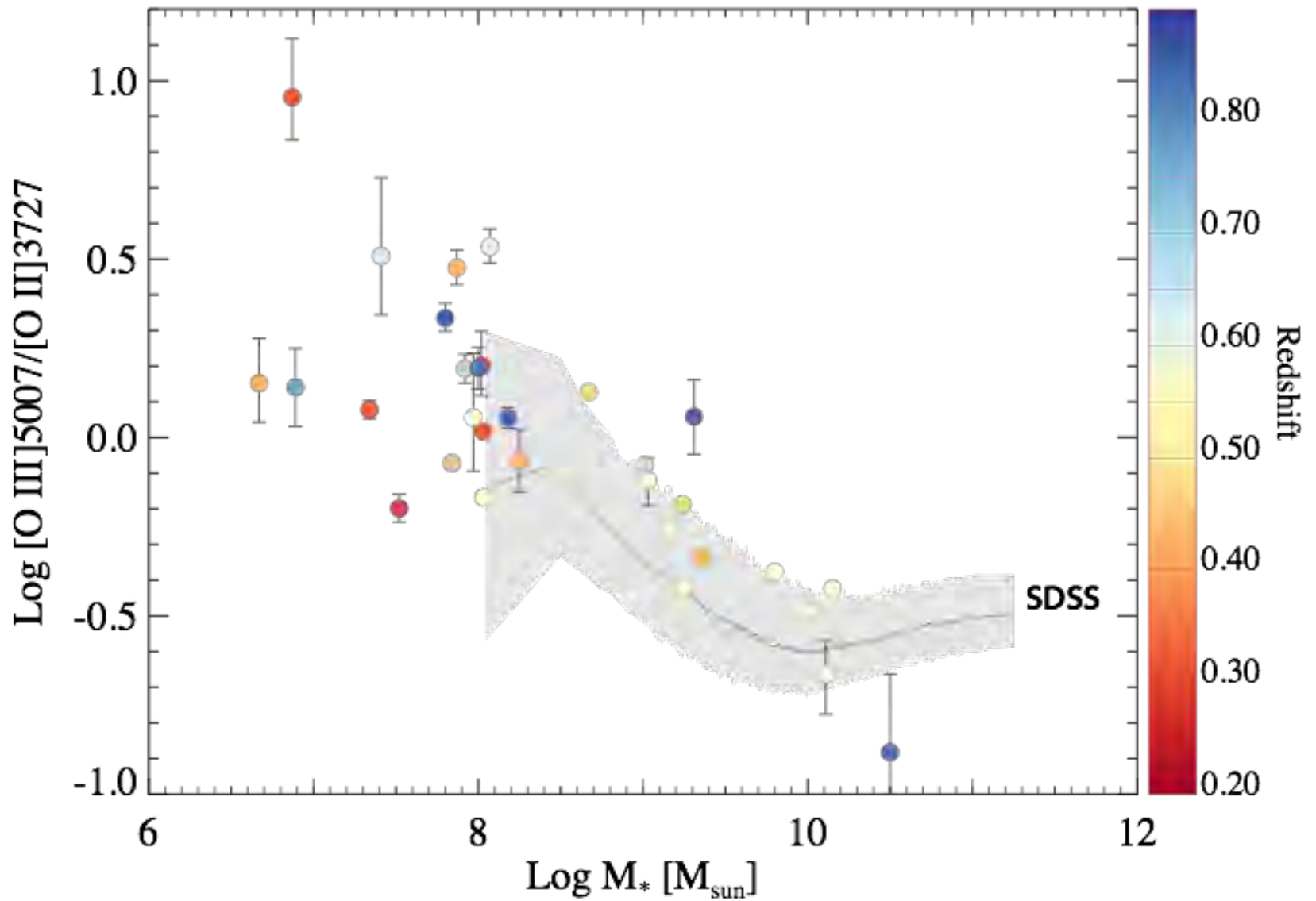
Most of low-mass ( $< 10^{9.5} M_{\odot}$ ) galaxies follow the TFR, but higher dispersion

Contini et al, in prep

# The ionisation conditions in the $z < 1.5$ galaxies



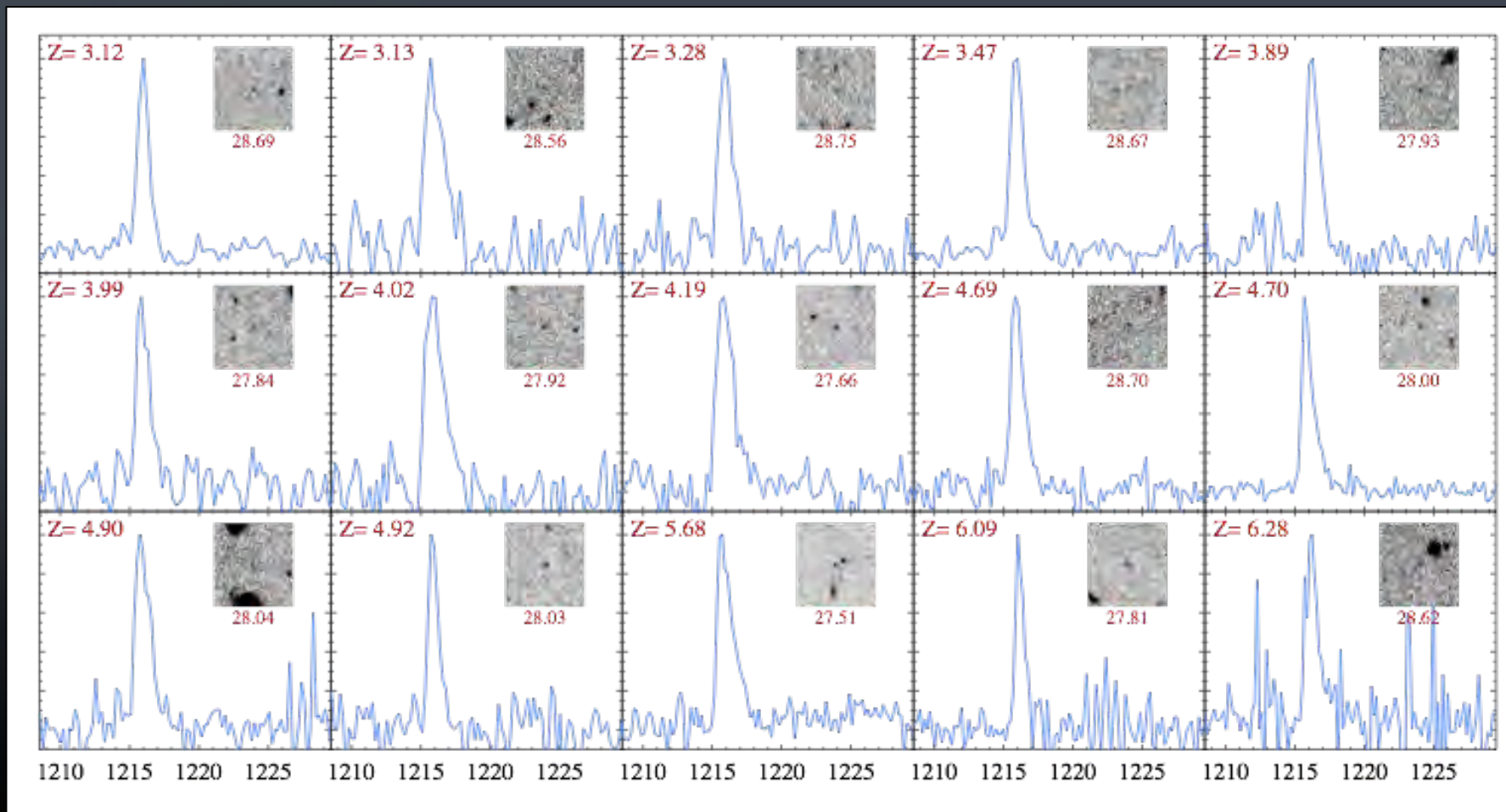
The galaxies appear to be dominated by star-formation and the line ratios are not particularly extreme.

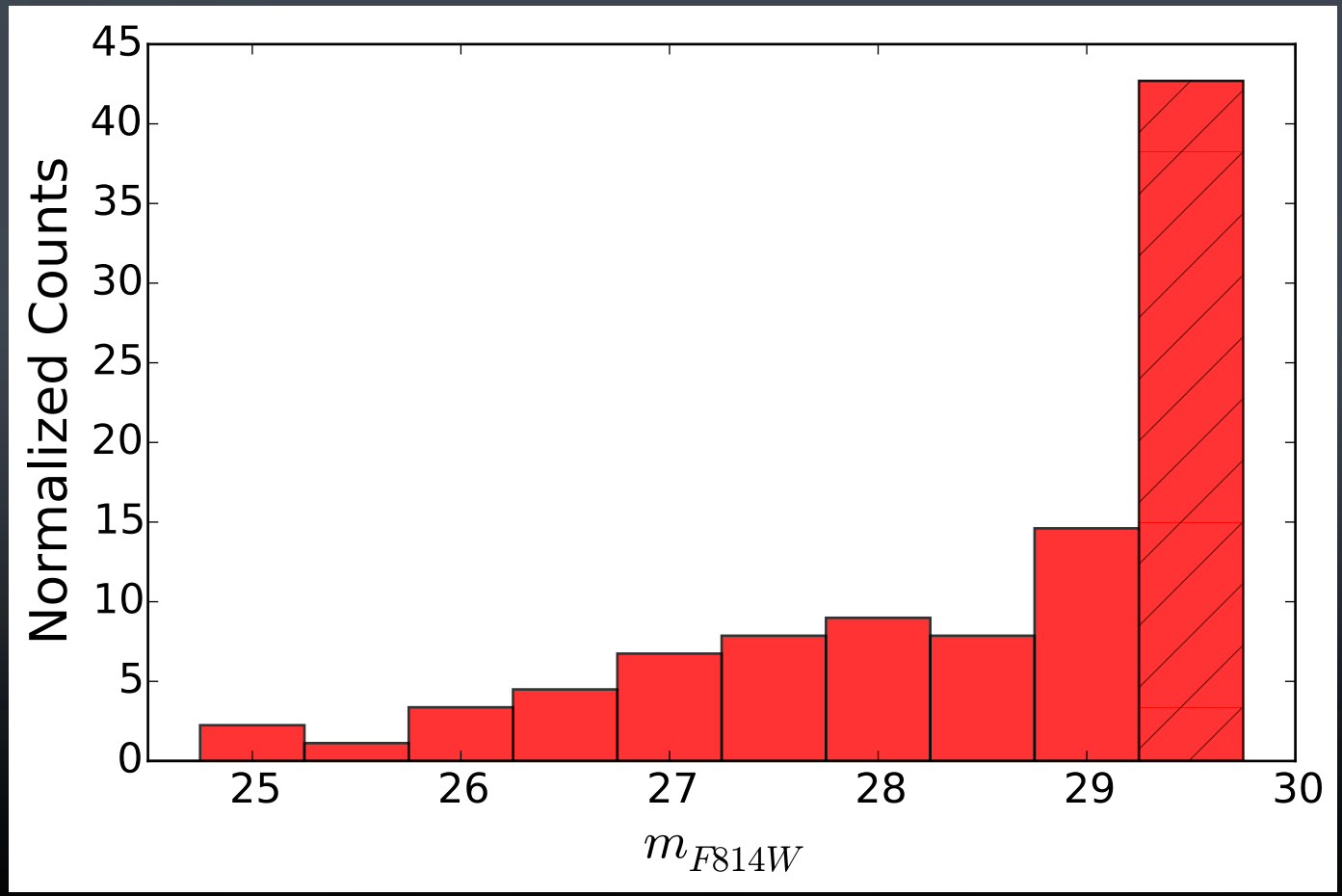


Moderately more extreme than local galaxies, but not so much when SFR is taken into account (c.f. Shirazi et al 2014)

Brinchmann et al, in prep

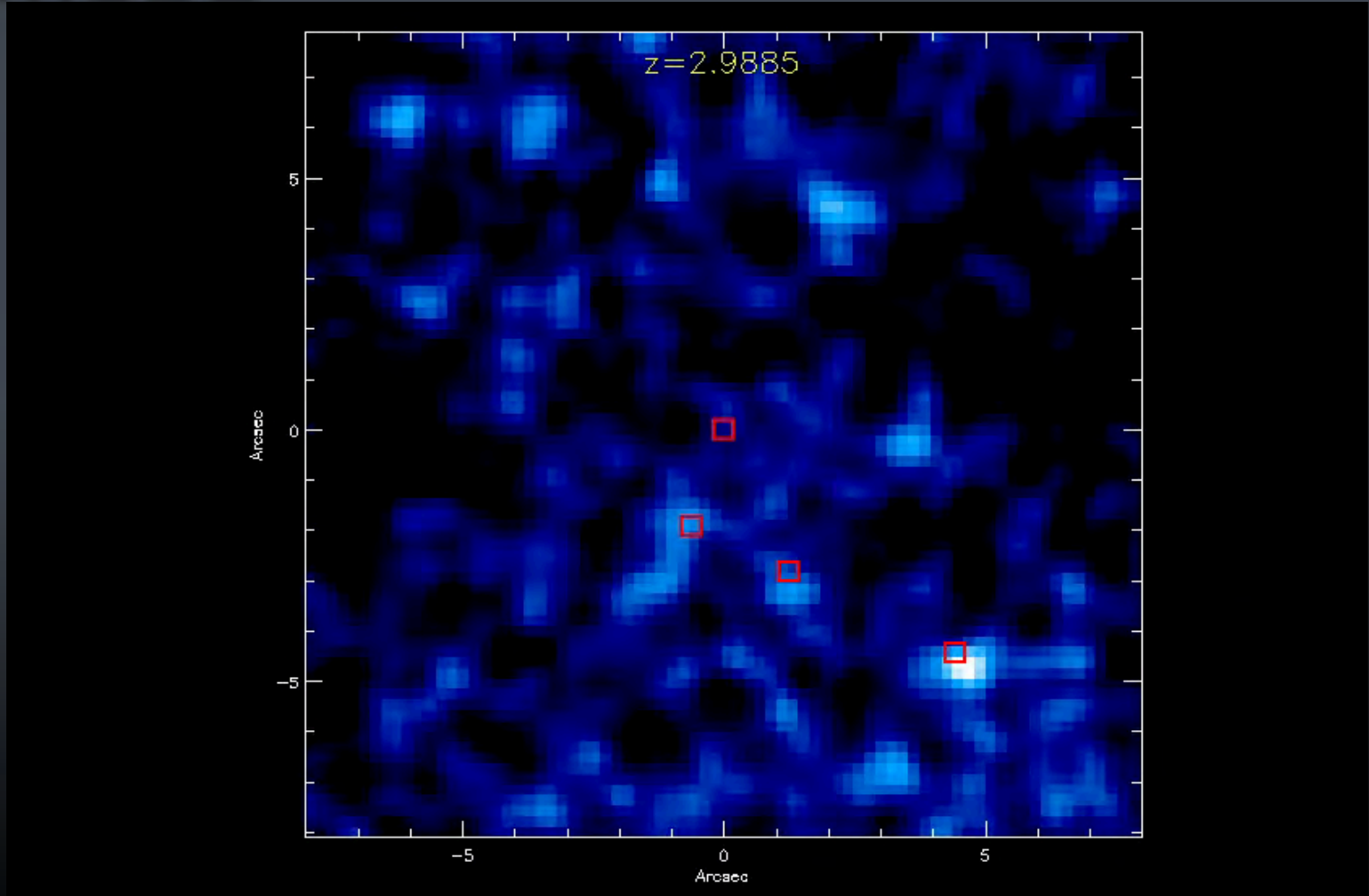
# Ly $\alpha$ emitters: a rapid look





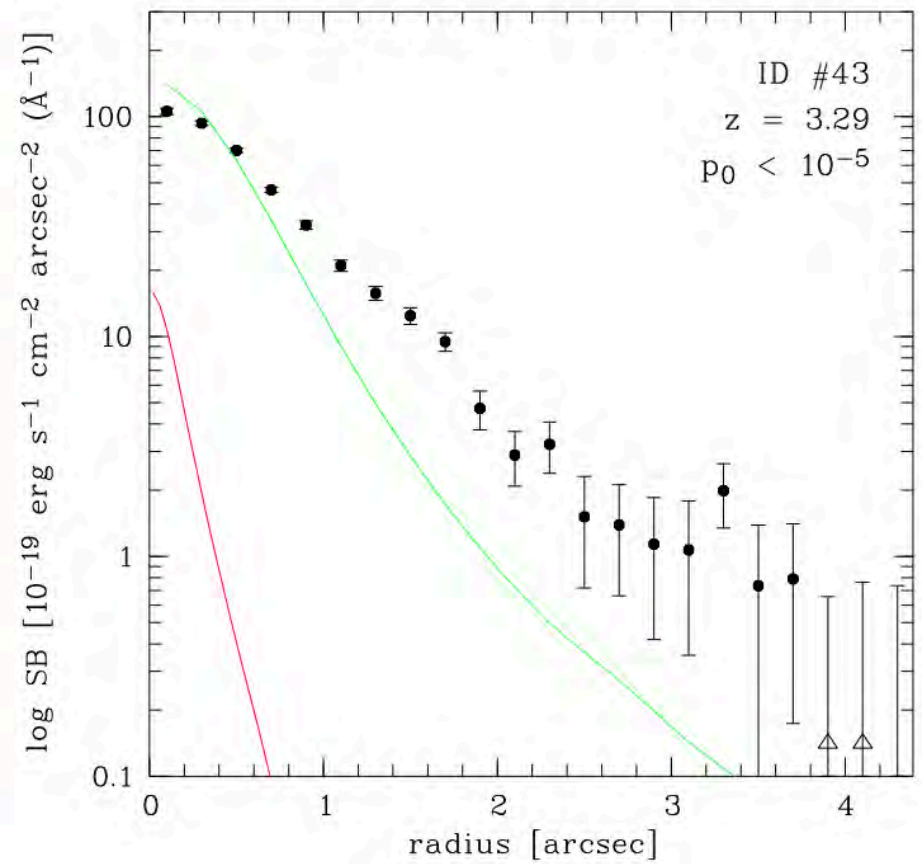
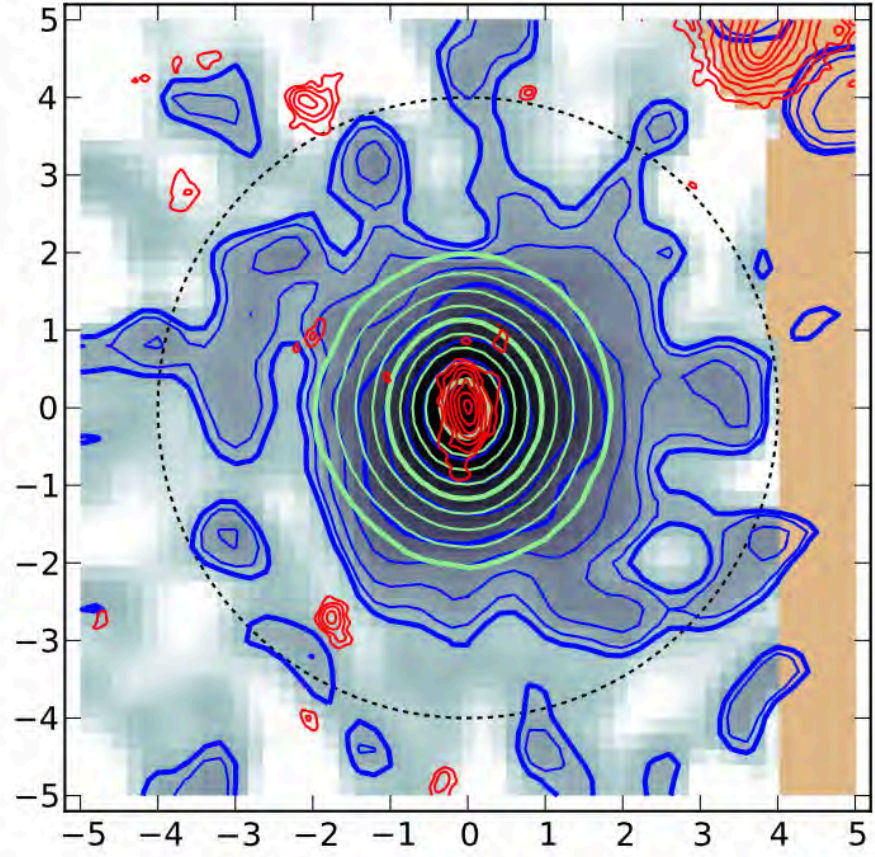


# Diffuse emission



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

Cantalupo et al, in prep



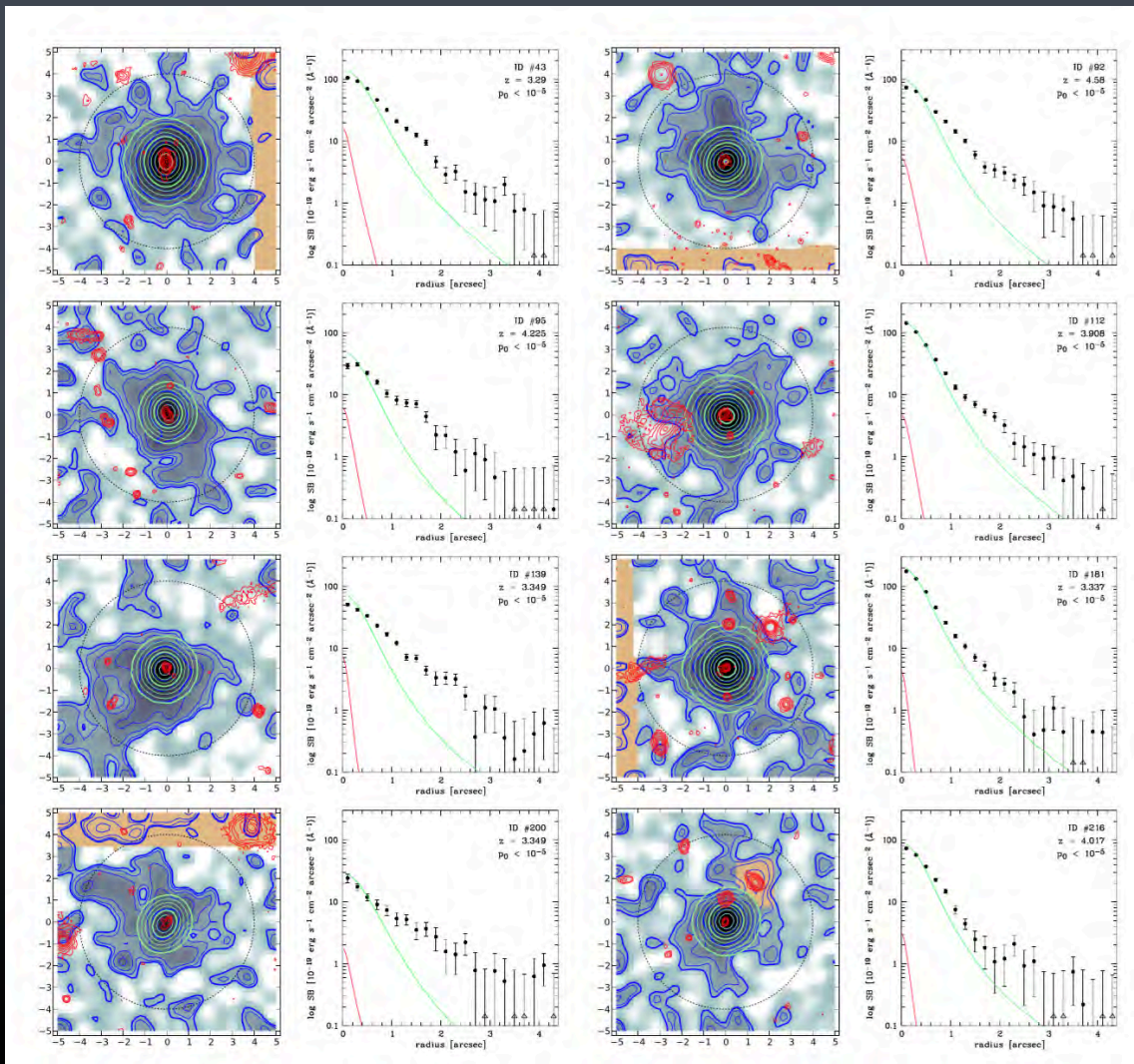
First time Extended Ly $\alpha$  Halo are detected around individual galaxies  
 (with the exception of Rauch et al 2008 long slit 92 hours deep observations)

Wisotzki et al, in prep

Subsample of 28  
Ly $\alpha$  emitters (with  
 $F_{\text{Ly}\alpha} > 5 \cdot 10^{-18}$  cgs)

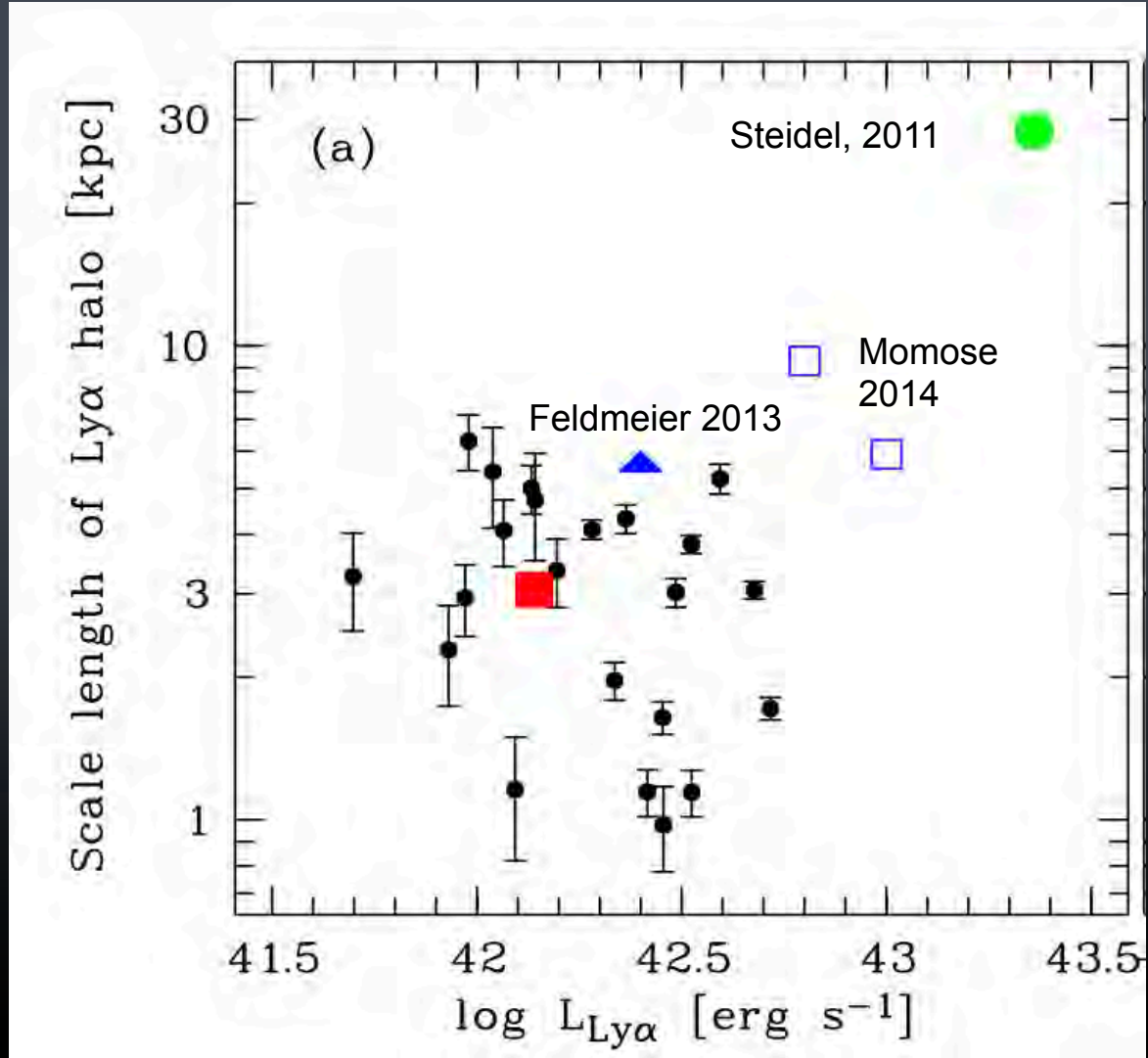
23/28 display  
significant  
detection

Wisotzki et al, in prep



# Extended Ly $\alpha$ Halo

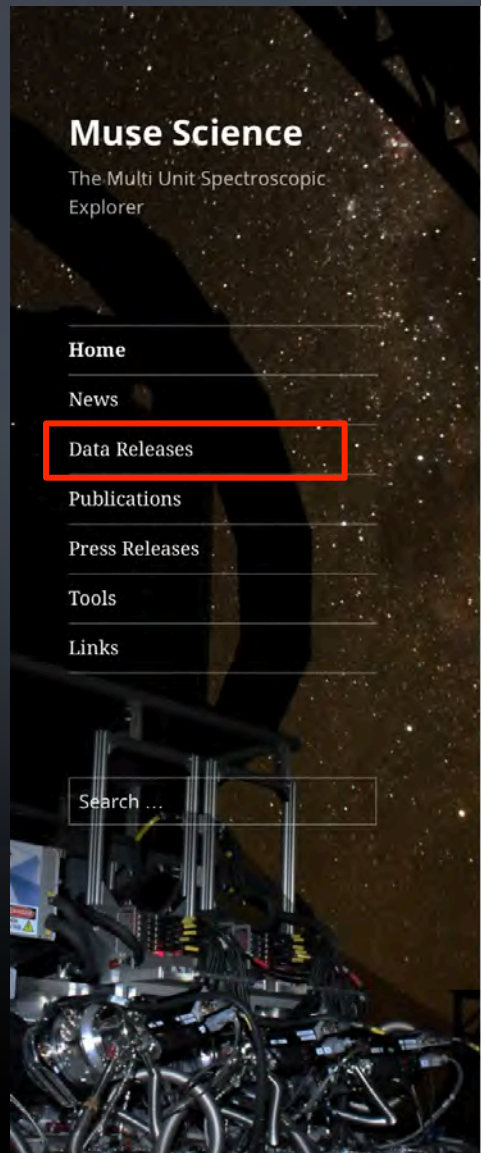
Halo size 1-5 Kpc,  
5x bigger than the  
UV continuum  
component



Wisotzki et al, in prep

Four nights of MUSE observations of the HDFs 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 $\alpha$**  emitters **fainter** than the HST detection limit ( $I_{814} > 30$ )
- At the same time we get **spatially resolved kinematics** for 29 galaxies at  $z \sim 0.5-1.0$ . Most of low-mass galaxies follow the TFR.
- The majority of the galaxies are **star-forming** and not particularly extreme (relative to SDSS)
- We have found **23 extended Ly $\alpha$  halos** in most of the 28 bright Ly $\alpha$  emitters selected sample. Halos size are 1-5 Kpc, 5x larger than the UV component.



## Welcome to the MUSE Science Web Service



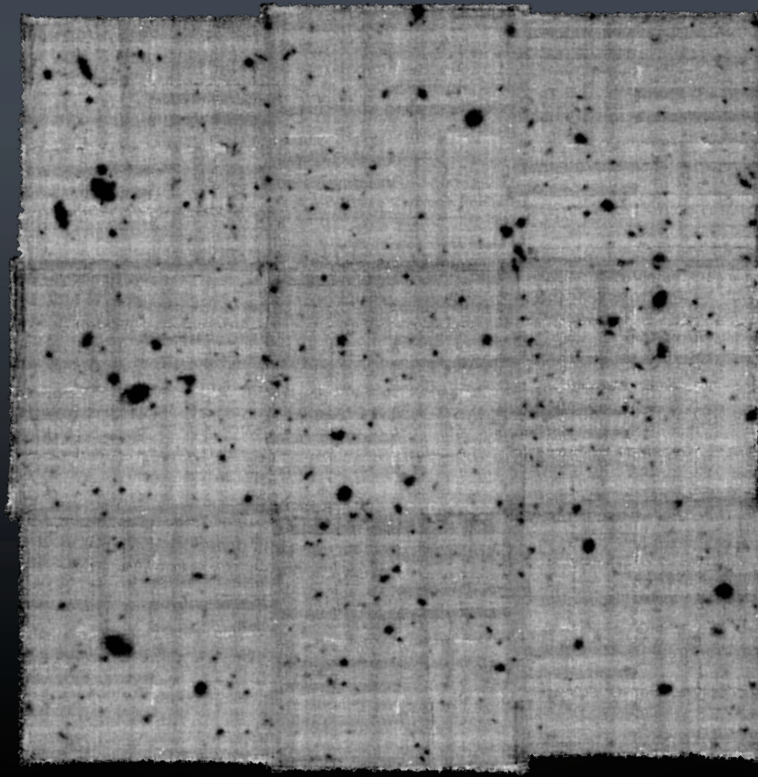
Latest News 2015-02-26: Grand new opening of the Muse science web service.

The **Multi Unit Spectroscopic Explorer (MUSE)** is a second generation instrument installed on the Nasmyth focus of UT4 at the Very Large Telescope (VLT) of the European Southern Observatory (ESO).



It is a panoramic integral-field spectrograph operating in the visible

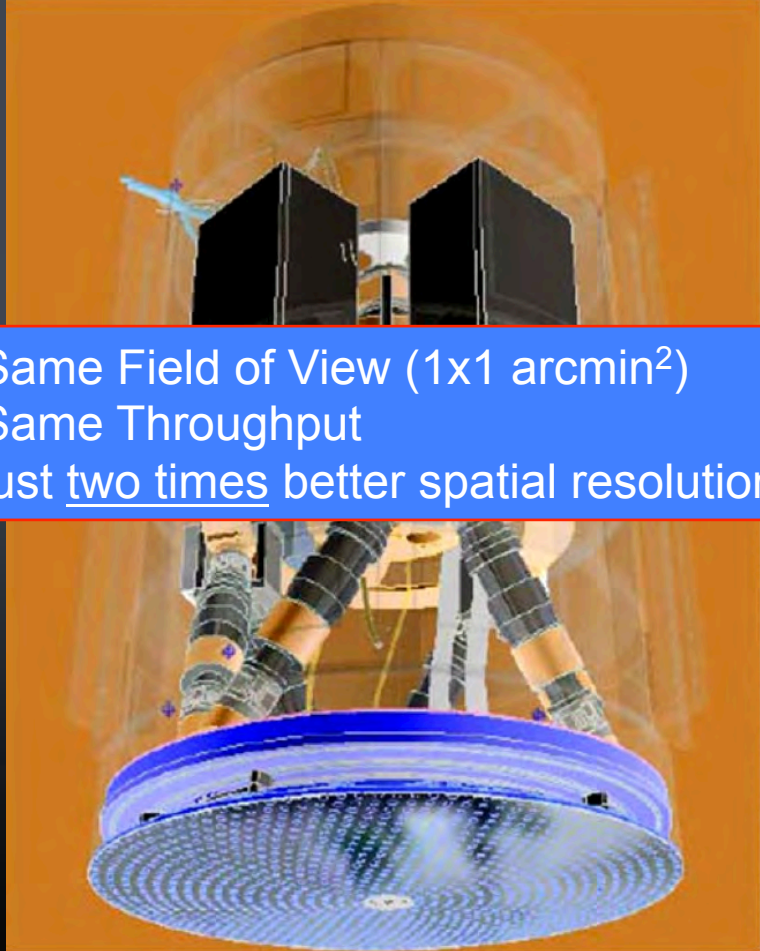
- MUSE GTO observing (250 nights over 5 years)
  - Multiple fields to ~100 hours and many (50?) fields to ~10 hours depth.



MUSE Hubble UDF 3x3 arcmin<sup>2</sup> pre-reduction

# Next : MUSE and AO the VLT Adaptive Optics Facility

- **Wide Field Mode with AO**
  - Use GLAO
    - DSM, 4 LGSF & GALACSI module
  - No change in MUSE
  - Improved FWHM
    - eg 0.4 arcsec in 0.8 arcsec seeing
- **Narrow Field Mode**
  - Use LTAO
  - Additional module in fore-optics
  - 7x7 arcsec<sup>2</sup> field of view
  - Diffraction limited image
    - 10% Strehl @ 6500 Å
    - 25% Strehl @ 8500 Å



Same Field of View (1x1 arcmin<sup>2</sup>)  
Same Throughput  
just two times better spatial resolution



**MUSE is the next step forward in integral field spectroscopy**

**It is unique and has a high potential of discoveries**

**Next proposal deadline October 1st**





# A few examples from the MUSE gallery

