First Science with MUSE

R. Bacon
CRAL

IAP

17 April 2015

muse

multi unit spectroscopic explorer

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

IAP

17 April 2015

Historical Context

- 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

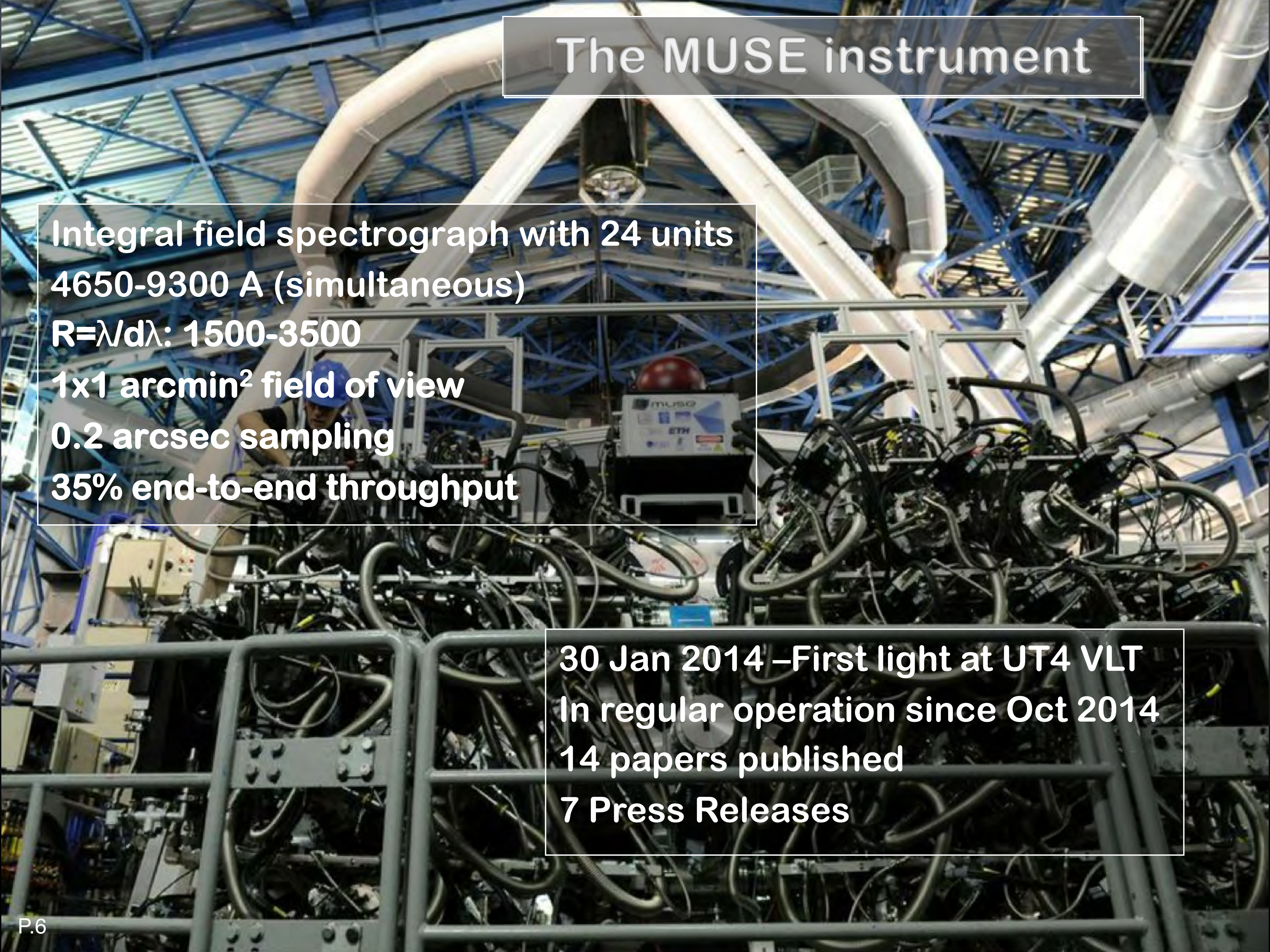
- The third generation
  - IFU as a **discovery machine**
  - A true imager **and** an excellent spectrograph
  - High spatial resolution **and** large field of view
  - Good spectral resolution **and** wide simultaneous spectral range
  - Excellent **throughput**

MUSE … the Multi Unit Spectroscopic Explorer

muse

Consortium & Partners

The MUSE instrument

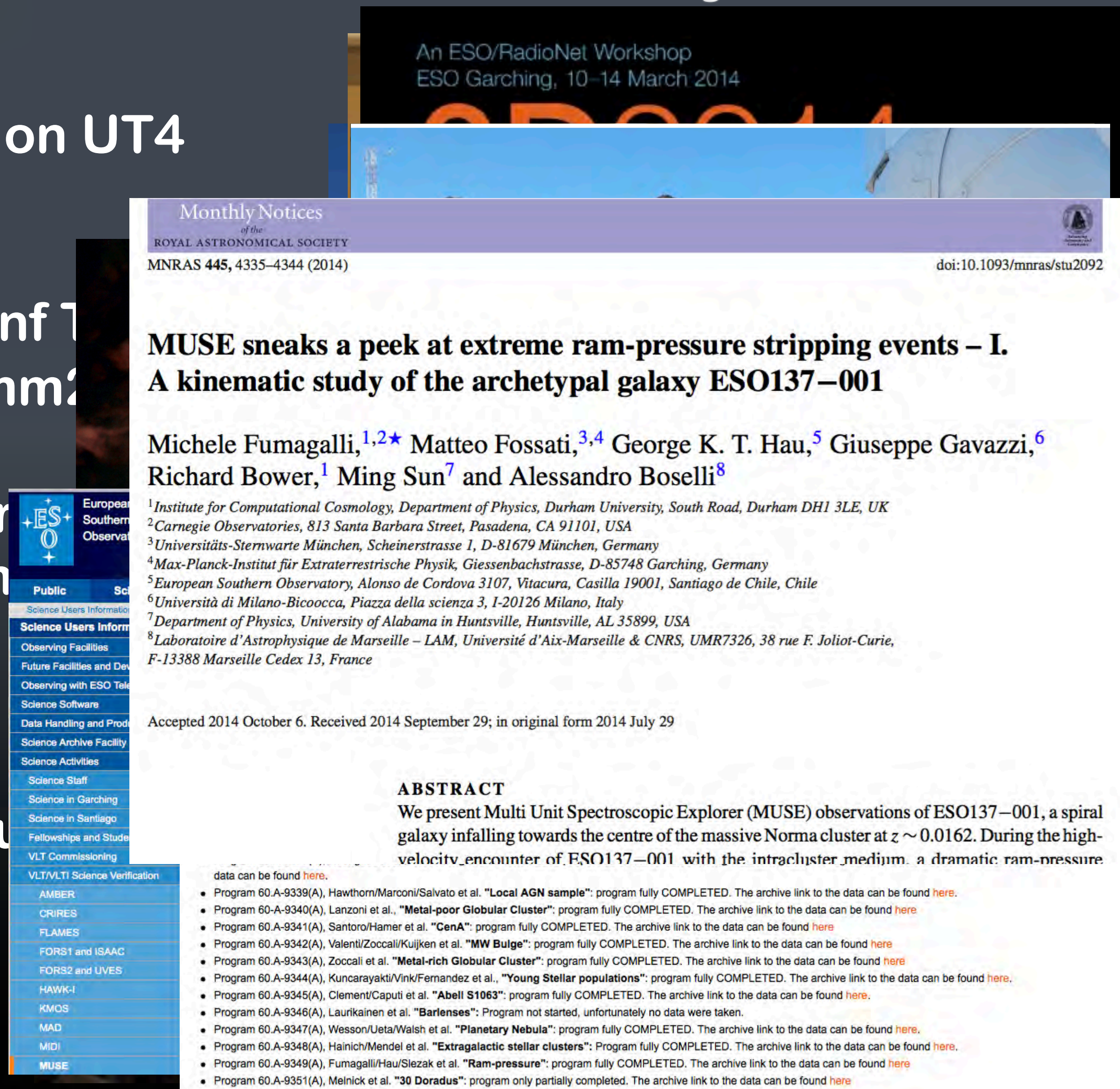


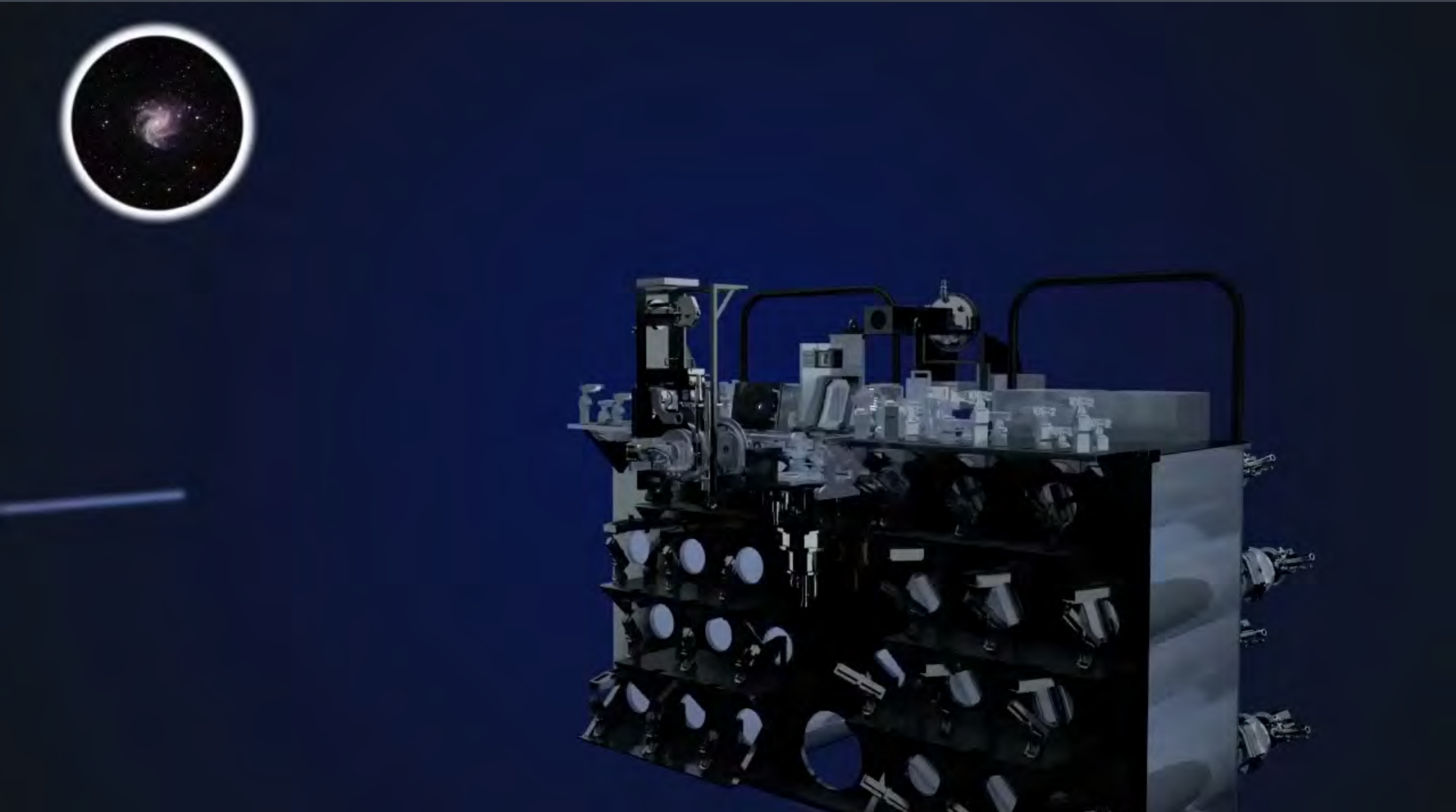
Integral field spectrograph with 24 units
4650-9300 A (simultaneous)
R=λ/dλ: 1500-3500
1x1 arcmin^2 field of view
0.2 arcsec sampling
35% end-to-end throughput

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

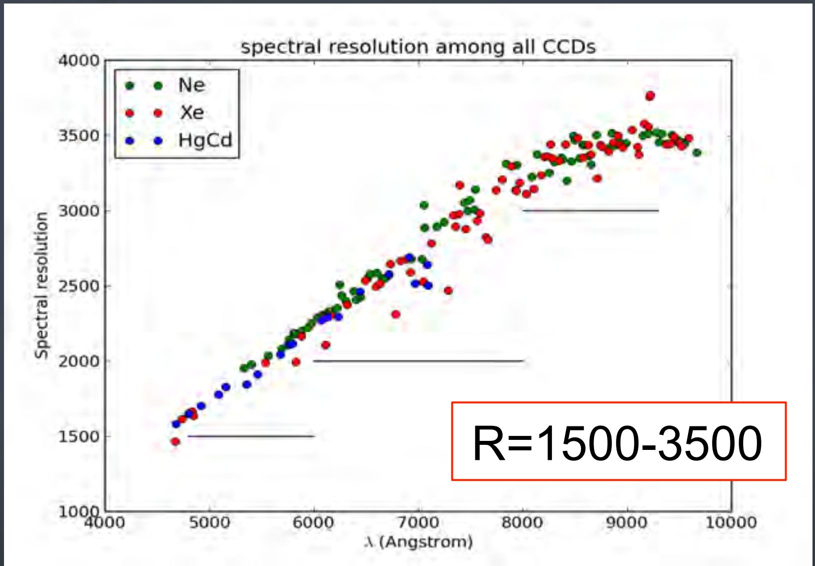
2014, the MUSE year

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

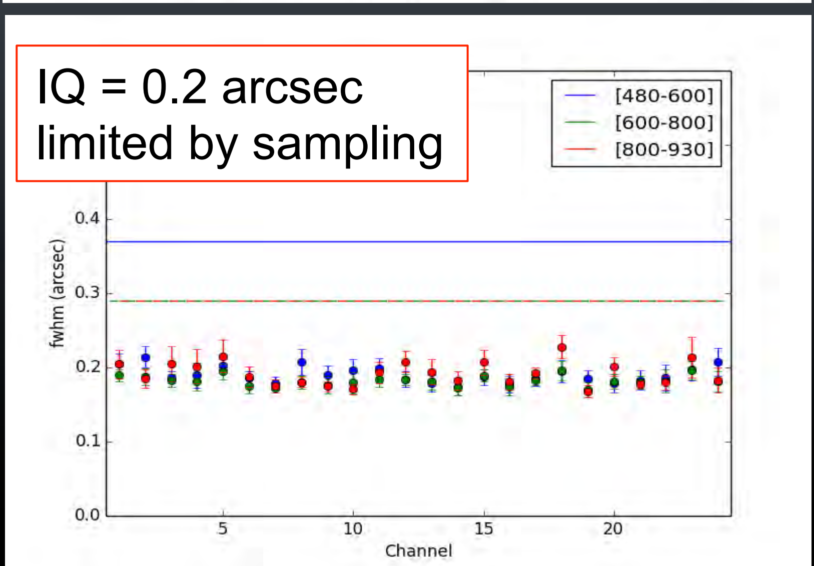




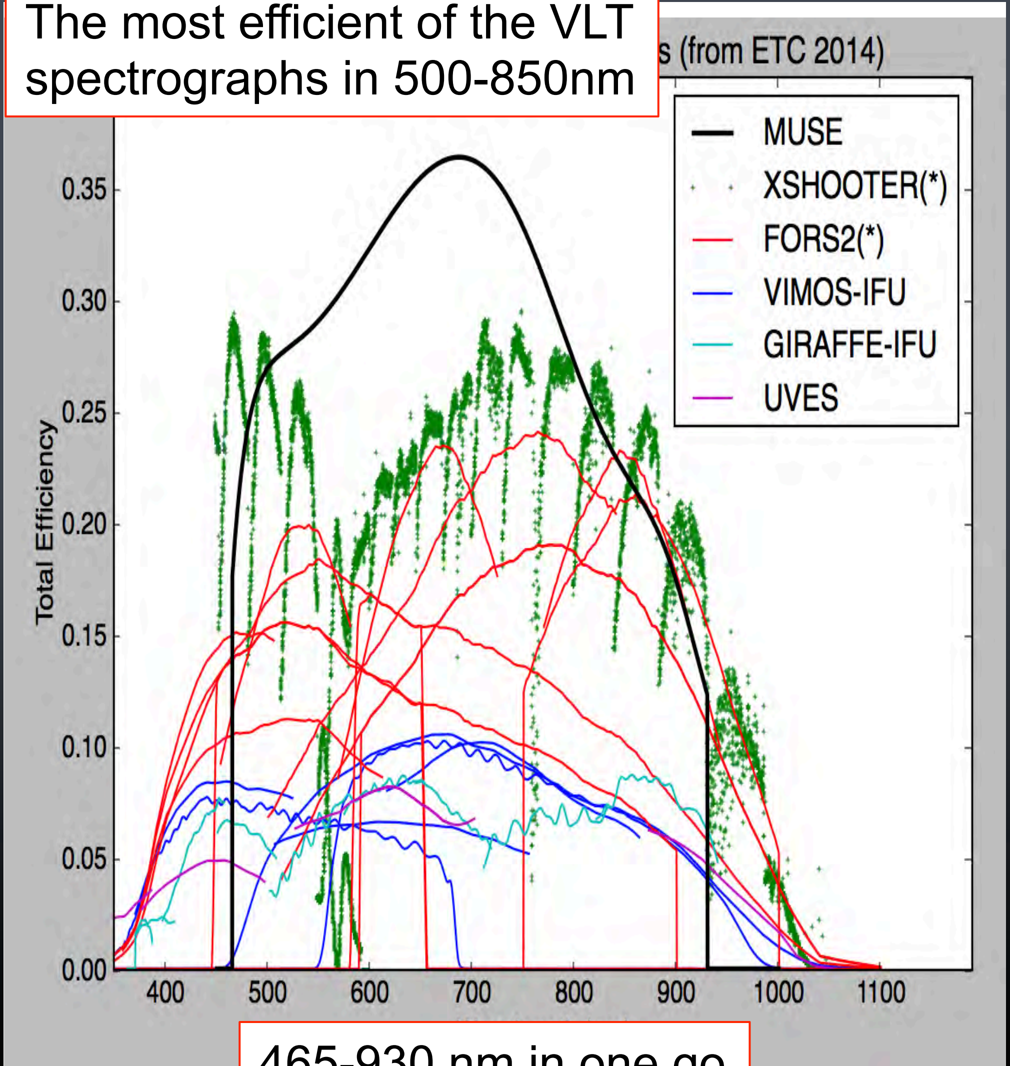
Instrument Performances



R=1500-3500



IQ = 0.2 arcsec limited by sampling



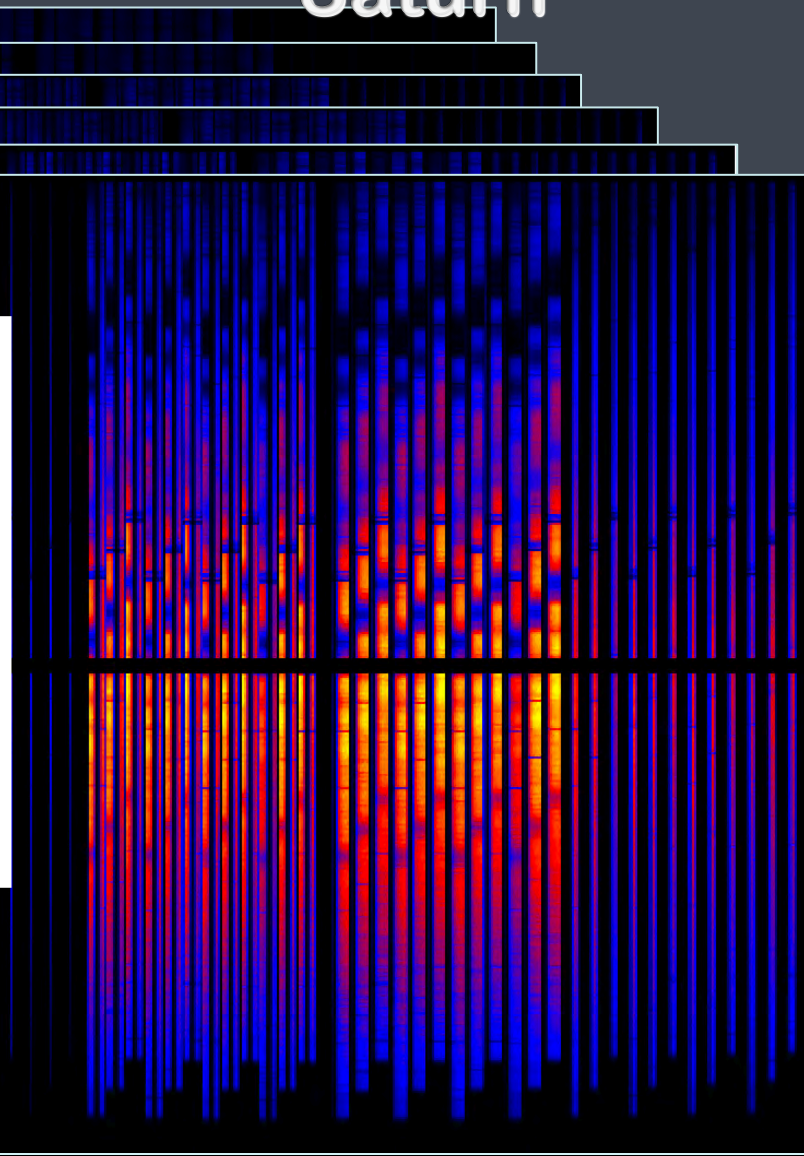
The most efficient of the VLT spectrographs in 500-850nm

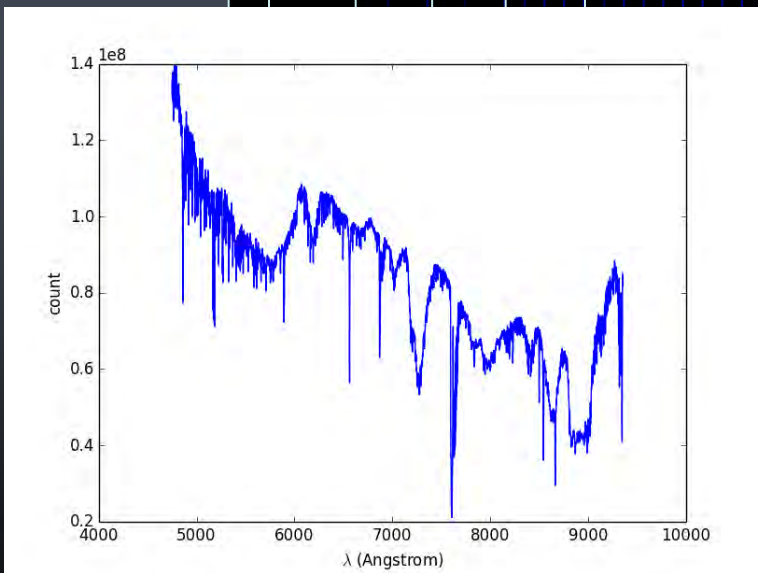
465-930 nm in one go

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

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

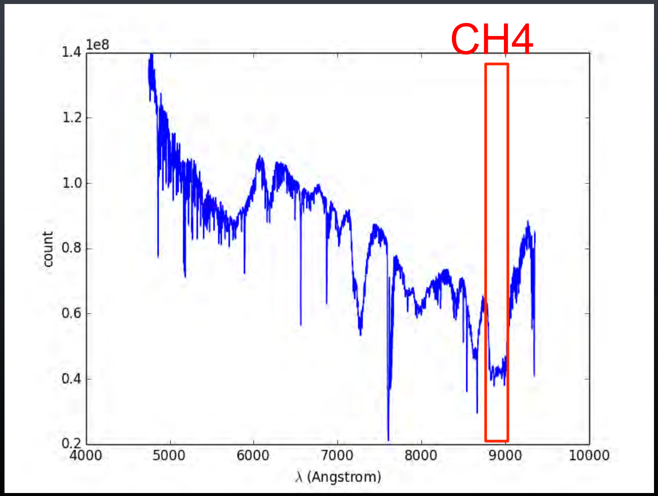
First reconstructed image: Saturn





1 arcmin^2
4x1 sec exposures
Seeing 0.85 arcsec

First reconstructed image: Saturn



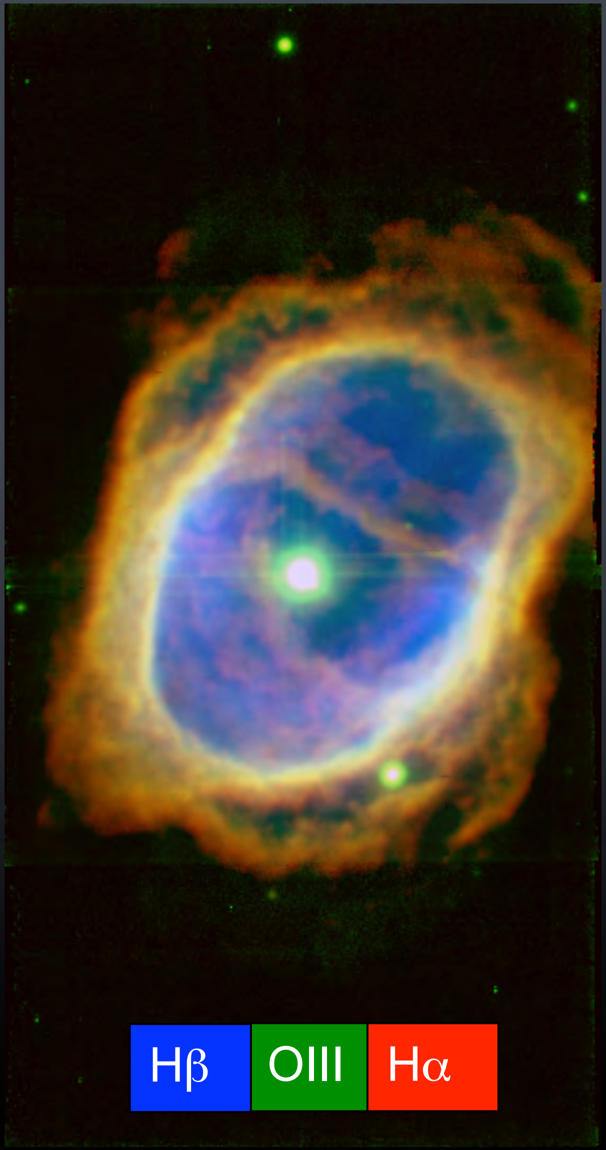
Prepared by Johan Richard, CRAL

Europa transit across Jupiter

- 1/10 sec exposure
- Reconstructed image in the CH4 absorption band
- 0.8 arcsec seeing
- 108 exposures (movie)
- 10,000,000 spectra

Prepared by Johan Richard, CRAL & ESO Outreach

The Planetary Nebula
NGC 3132



3x1 arcmin^2

Mosaic of 3 fields

13 x 1 mn exposures

Seeing 0.7-0.8 arcsec

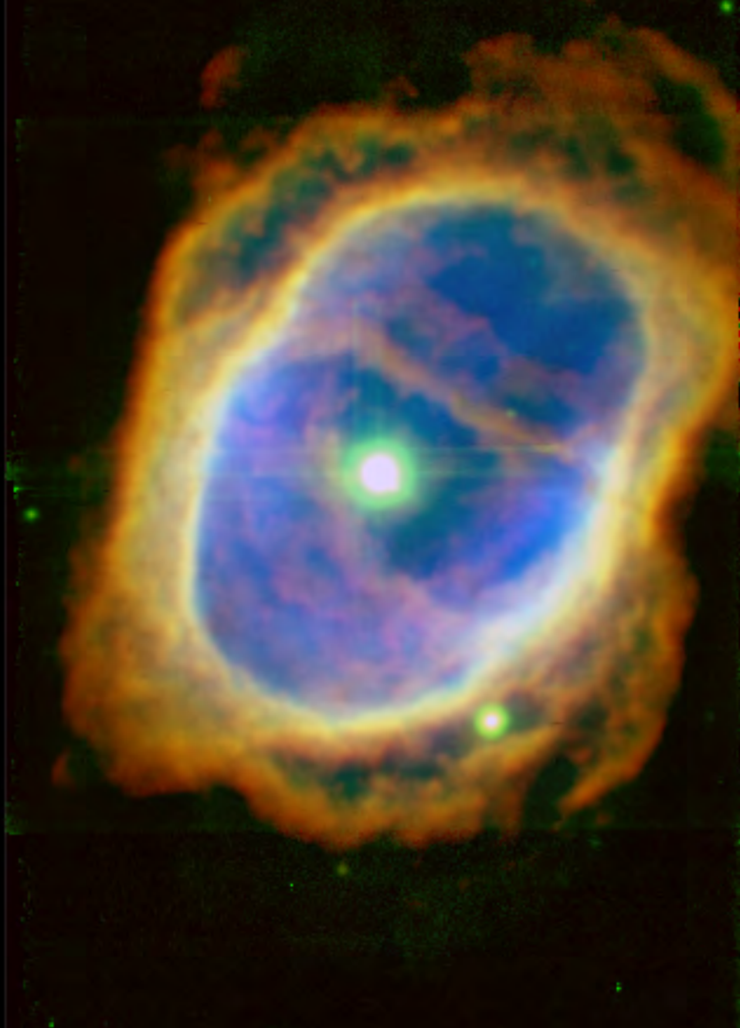
Prepared by Jarle Brinchmann, Leiden Obs

The Planetary Nebula NGC 3132

HST

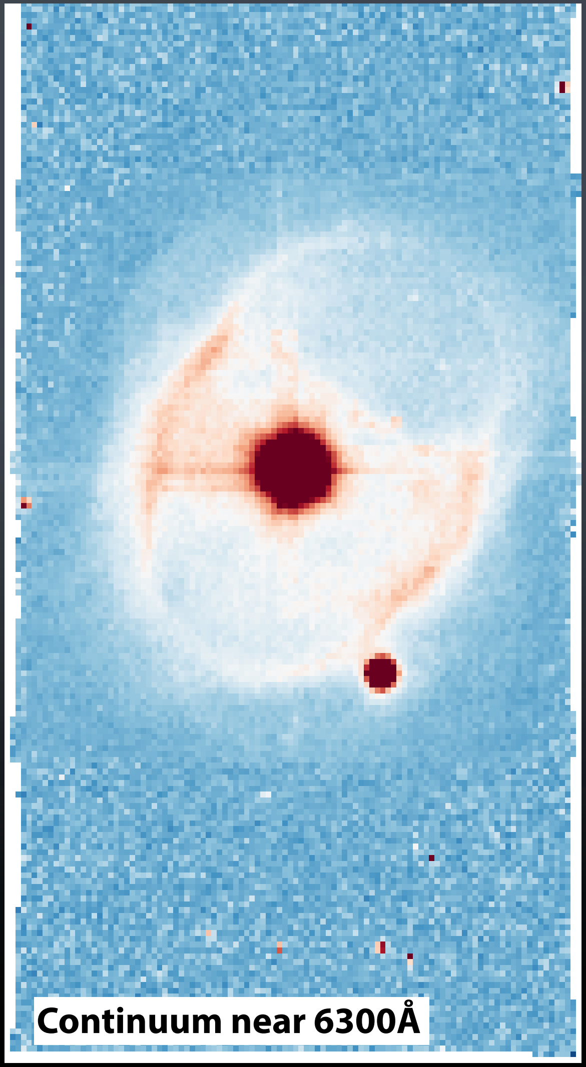
Hβ OIII Hα

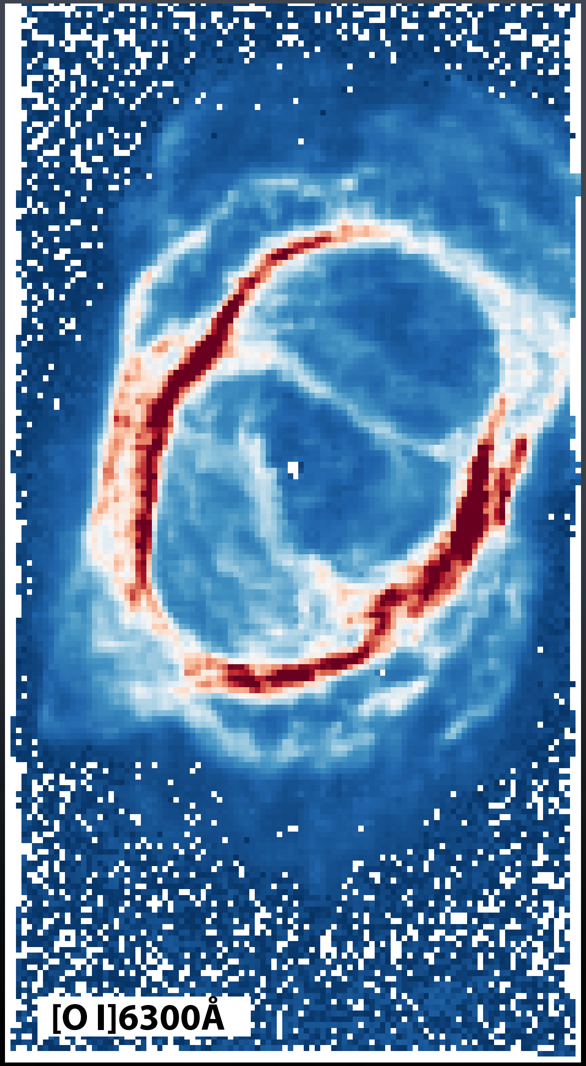
MUSE



Prepared by Jarle Brinchmann, Leiden Obs

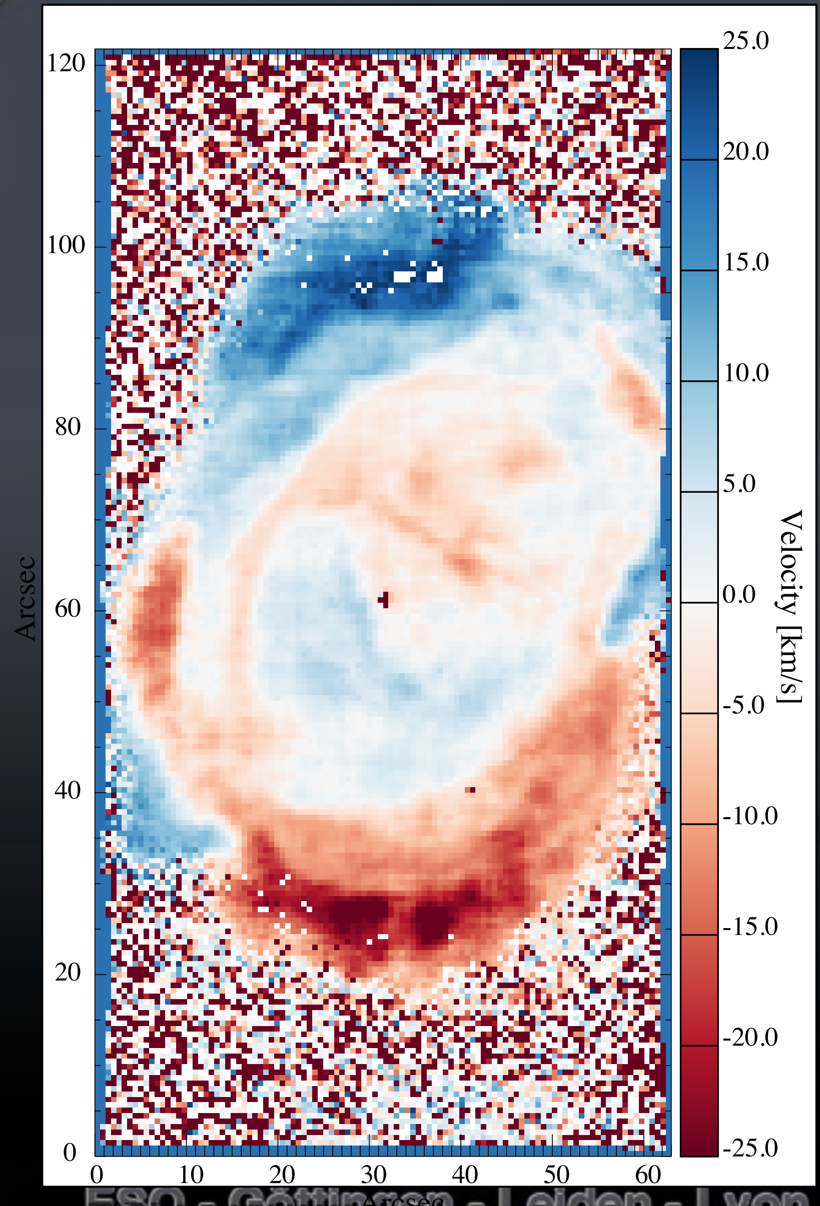
The Planetary Nebula NGC 3132





Prepared by Jarle Brinchmann, Leiden Obs

The Planetary Nebula NGC 3132



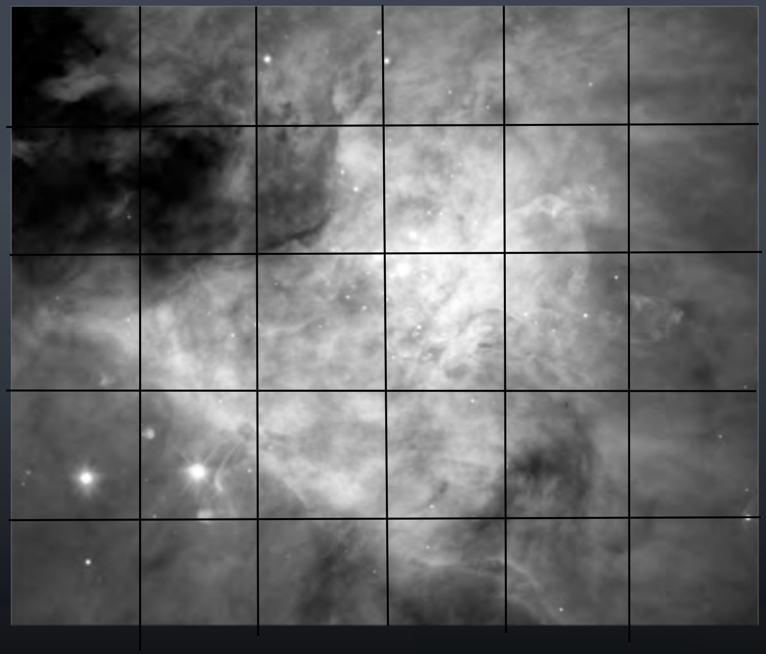
Gas Velocity field

V_{max} = 20 km/s

Accuracy ~1 km/s

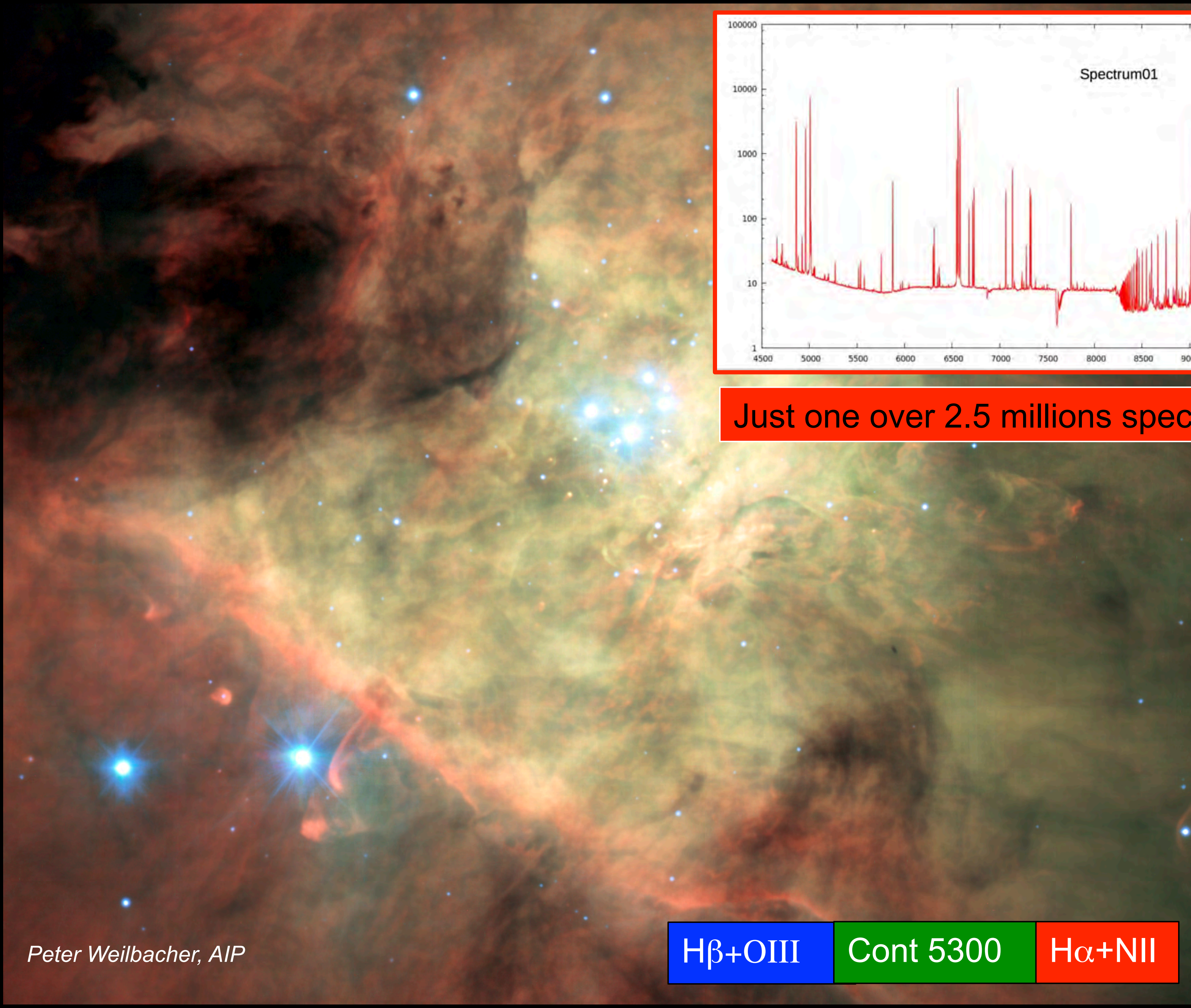
Prepared by Jarle Brinchmann, Leiden Obs

Mapping large area: the Orion Nebula



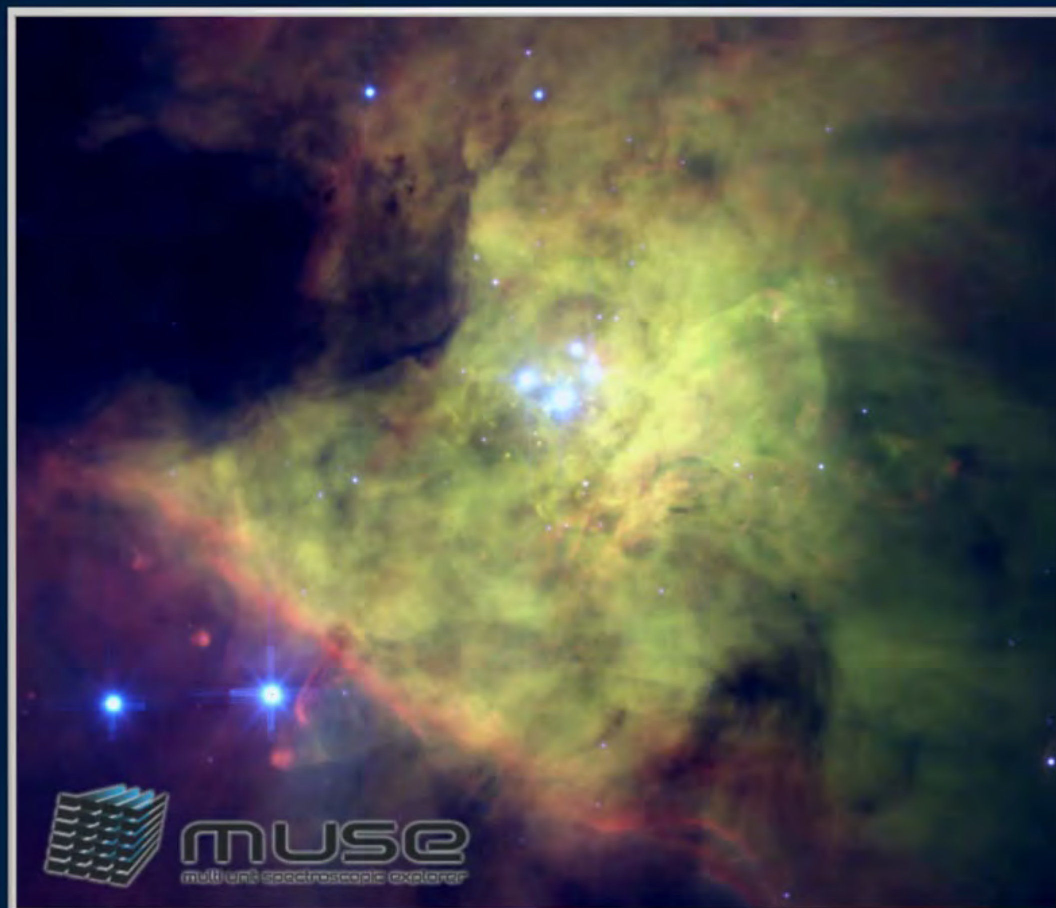
- 6x5 arcmin^2
- 30 fields, 60 exposures of 5 sec integration
- 2.5 hours total
- 5 millions of spectra
  - 300 spectra/sec (overhead included)
- Datacube of 1748x1460x4000

Peter Weilbacher, AIP



Just one over 2.5 millions spectra

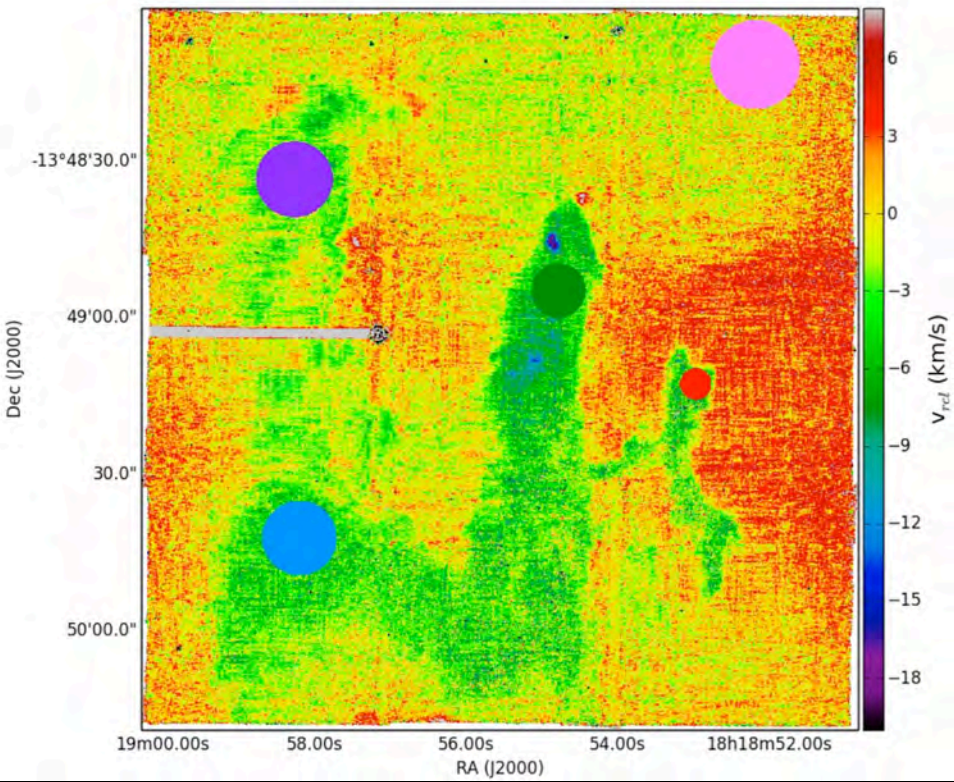
Orion Nebulae in 4000 colors

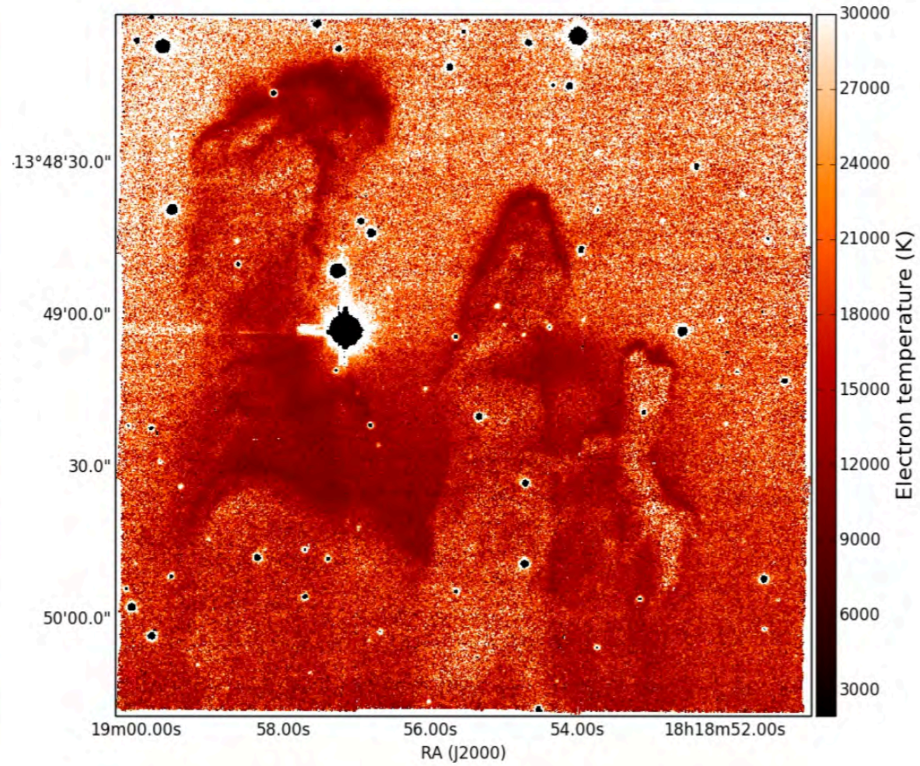


The Pillars of Creation

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

The Pillars of Creation revisited
and high-mass stellar feedback tr



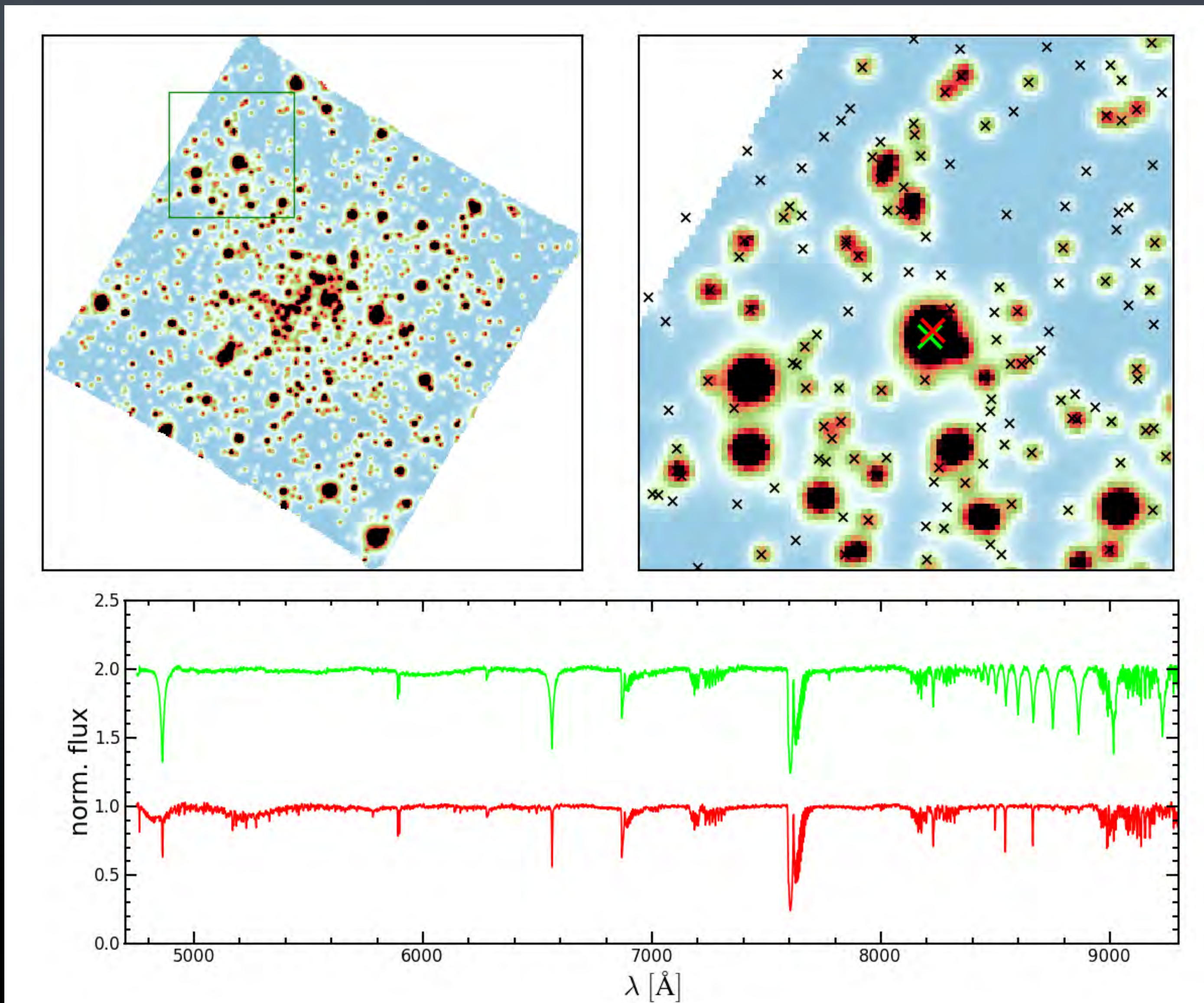


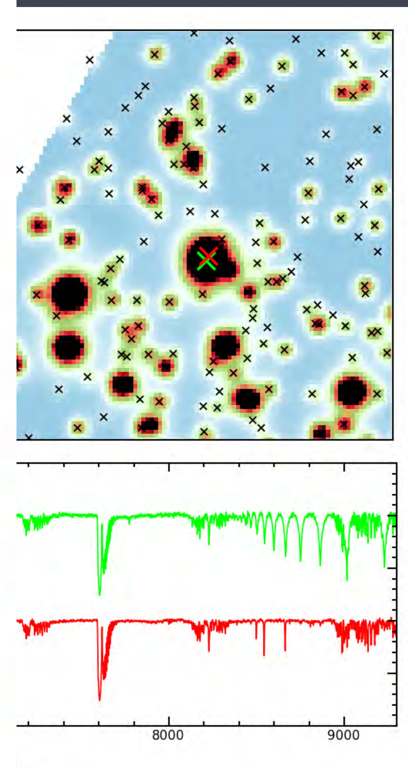
Crowed field spectroscopy of Globular Clusters

Sebastian Kamann (AIG)

2 mn exposure of NGC 6397, seeing 0.6 arcsec

Crowded field spectroscopy in NGC 6397





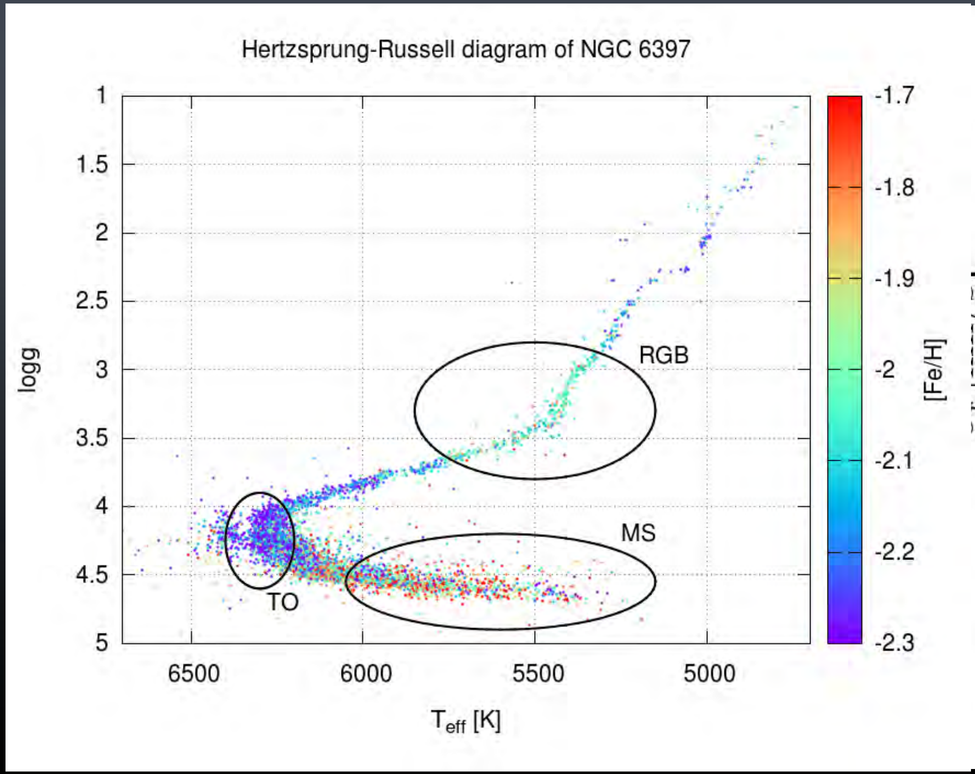
Sebastian Kamann, IAG

e - Zurich

Crowded field spectroscopy in NGC 6397

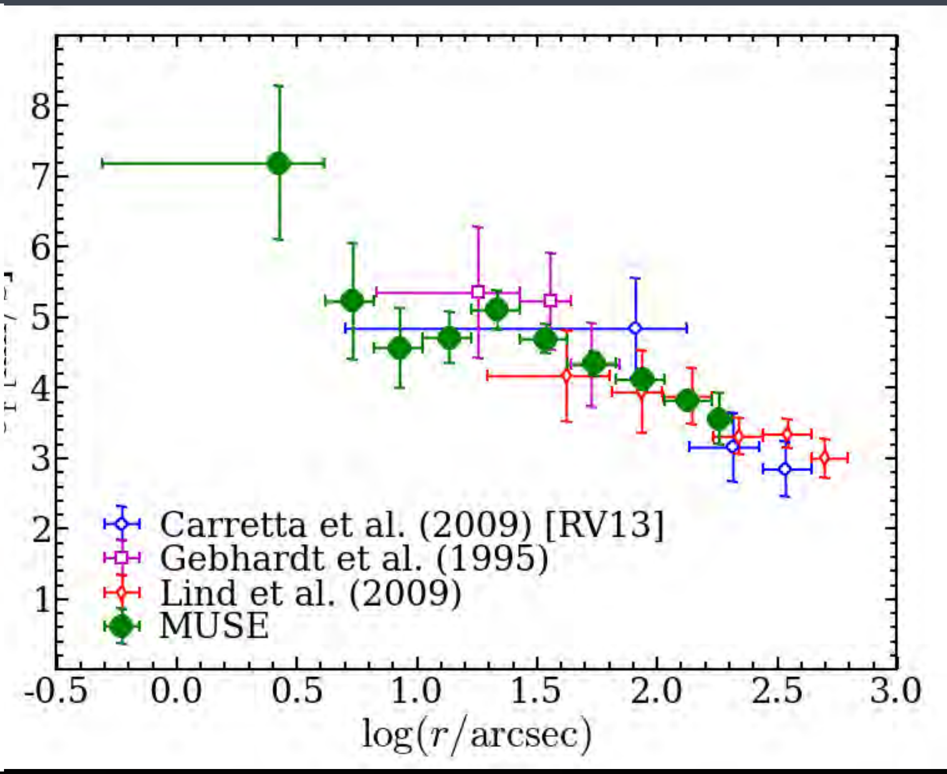
Stellar parameters

Teff, Fe/H, α/Fe, ...



Kinematics

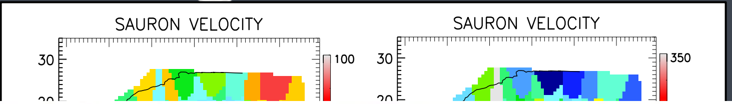
accuracy ~1 km/s

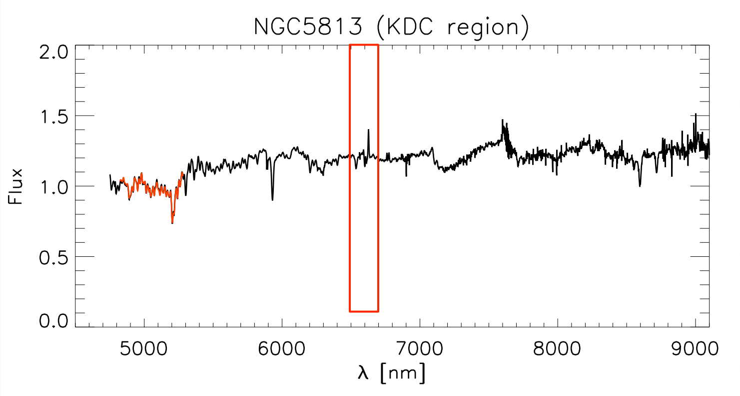


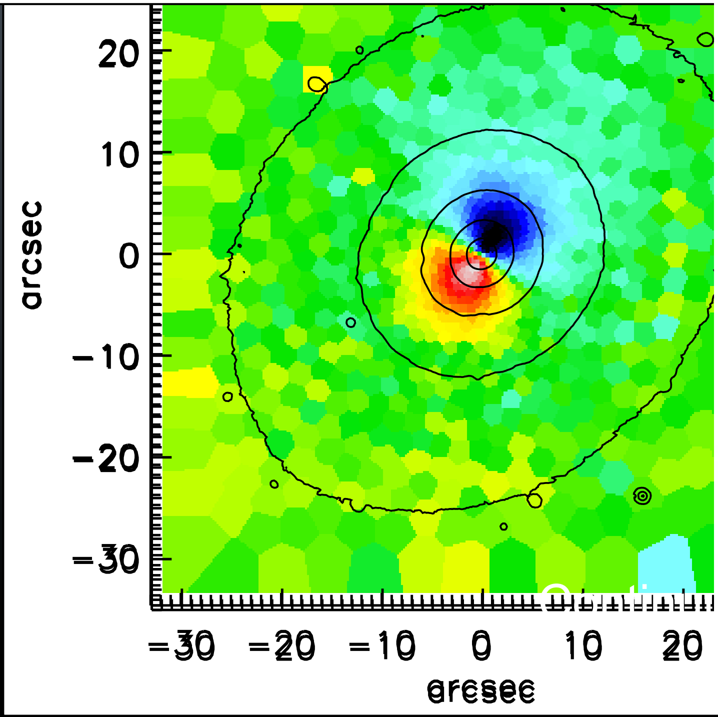
Sebastian Kamann, IAG

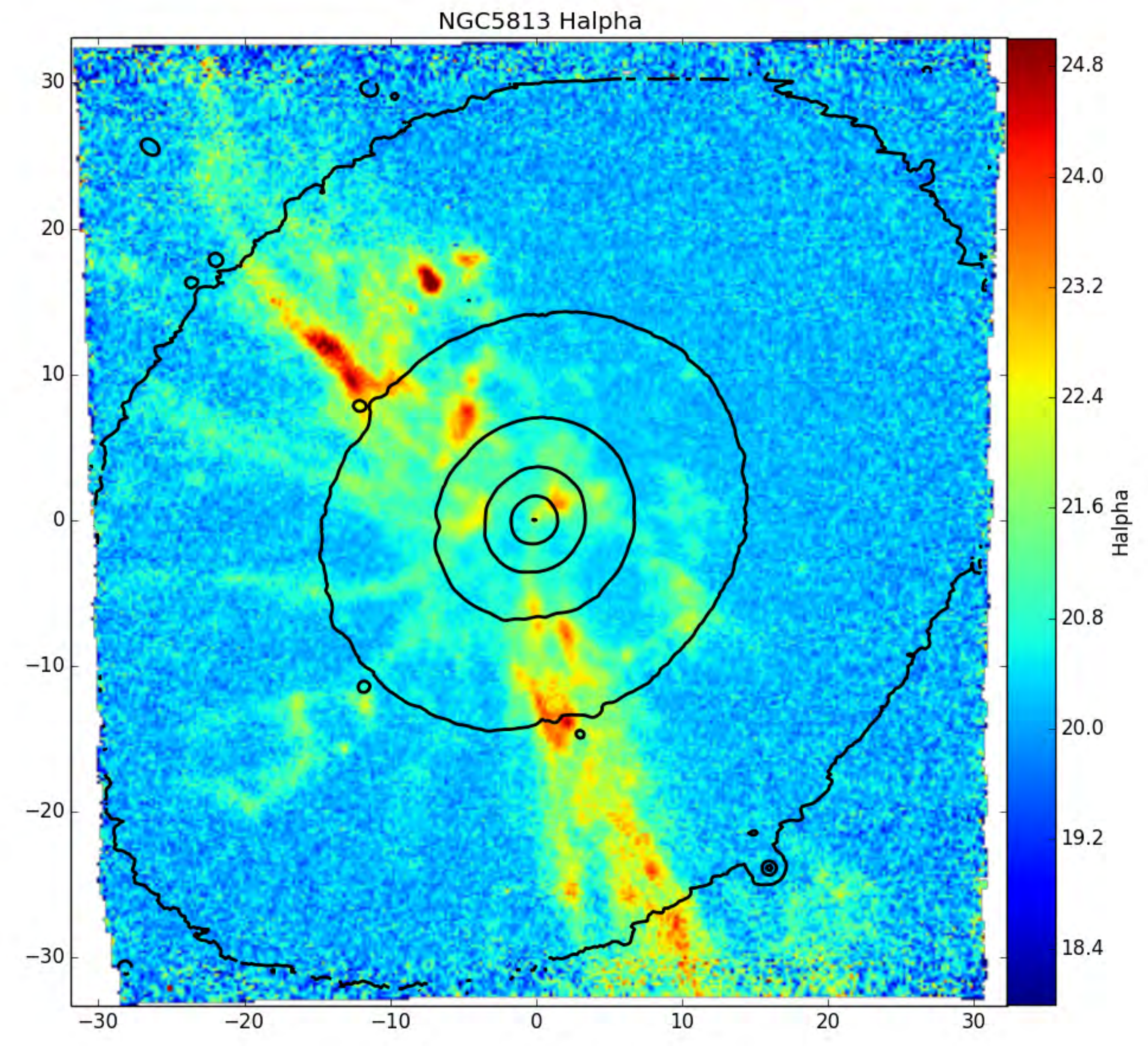
Why spectral range matters

NGC 5813 – S



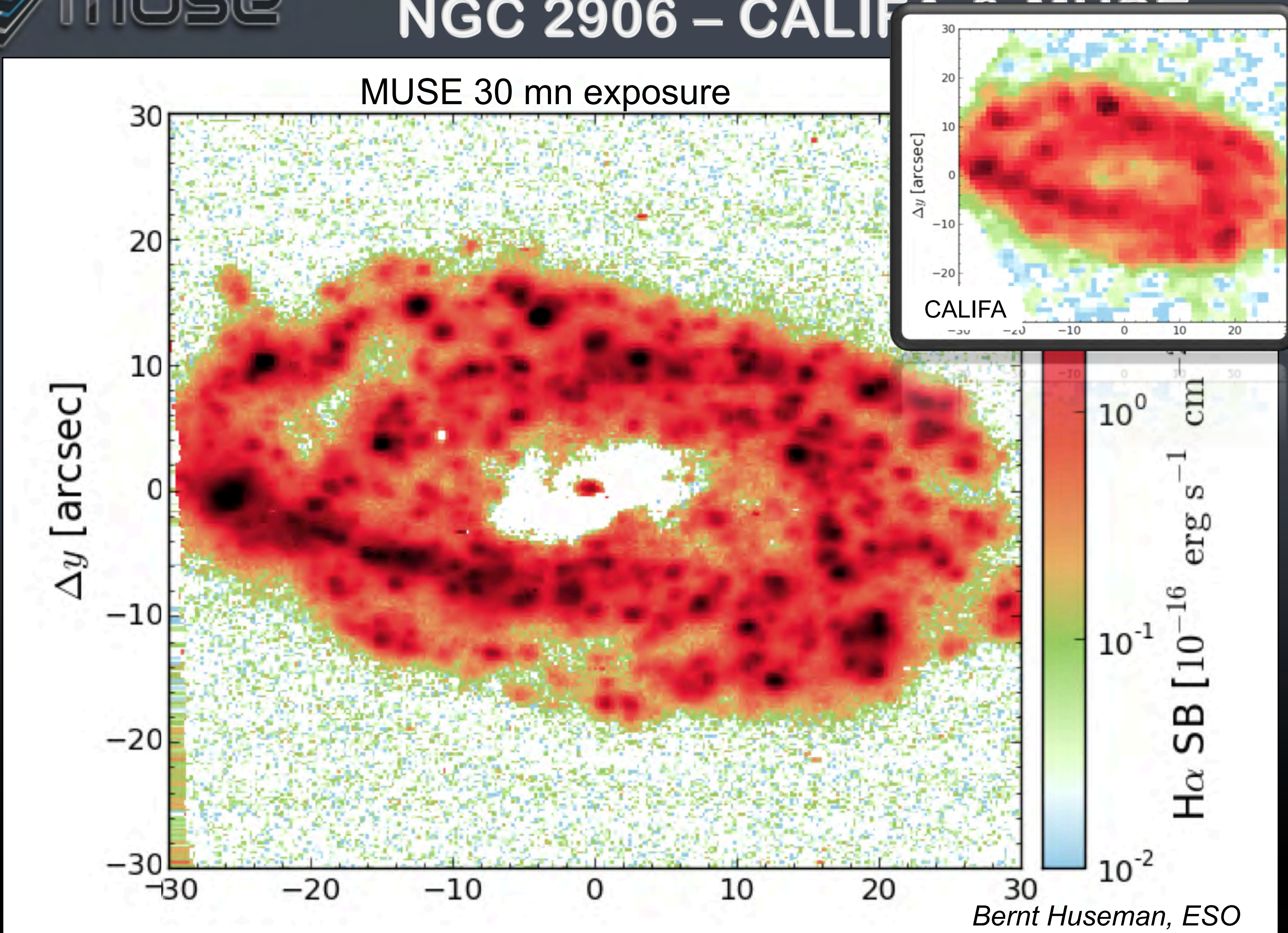




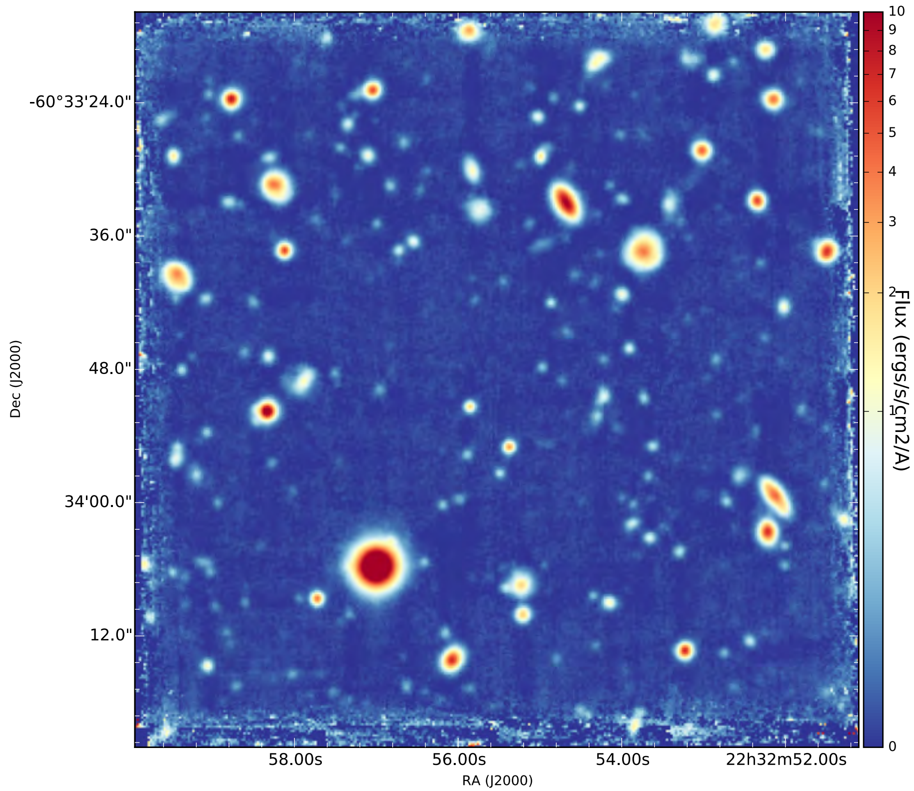


Davor Krajnovic, AIP

Why spatial resolution matters
NGC 2906 – CALIF



The MUSE 3D view of the Hubble Deep Field South



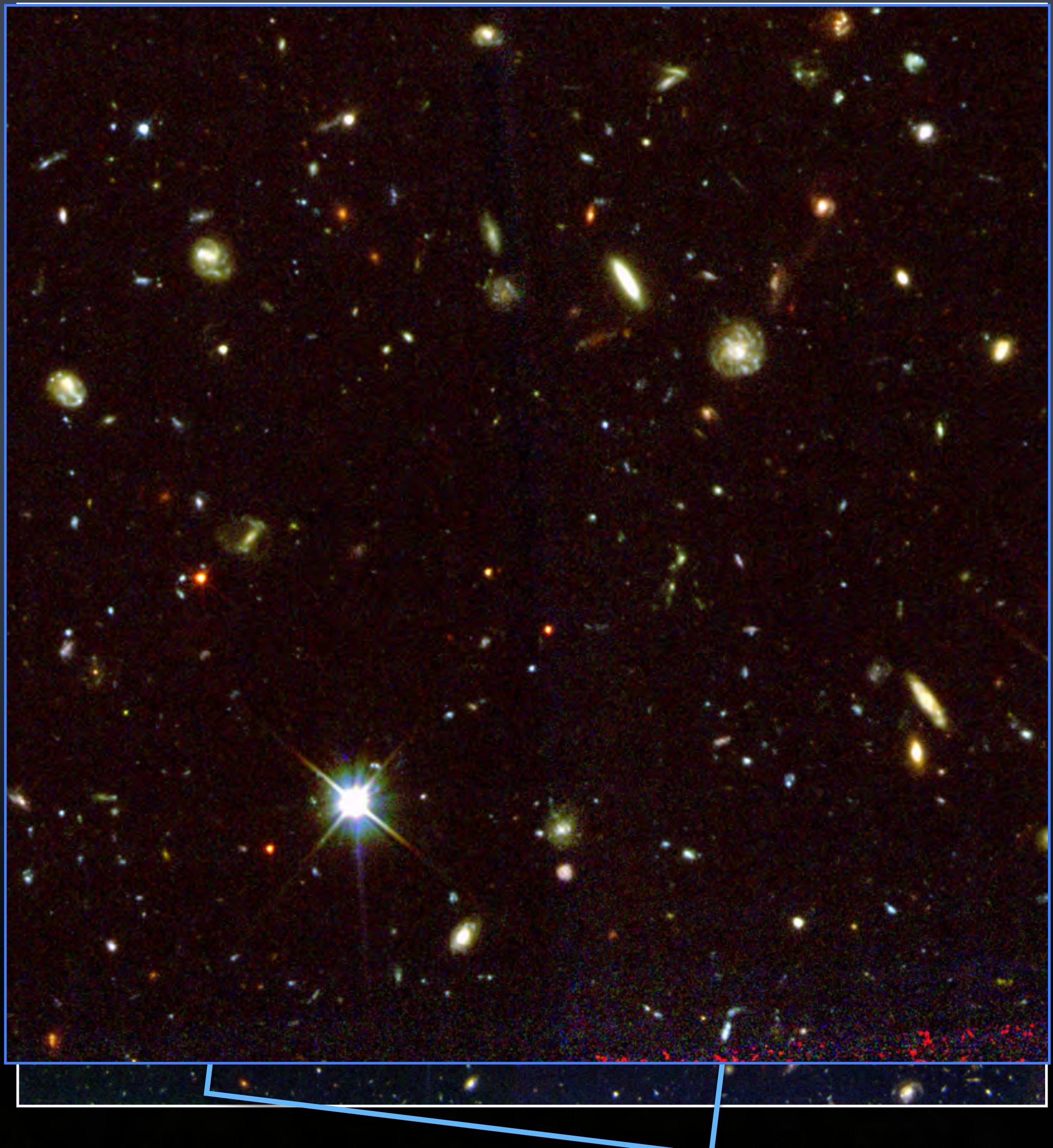
R. Bacon[1], J. Brinchmann[2], J. Richard[1], T. Contini[3,4], A. Drake[1], M. Franx[2], S. Tacchella[5], J. Vernet[6], L. Wisotzki[7], J. Blaizot[1], N. Bouché[3,4], R. Bouwens[2], S. Cantalupo[5], C.M. Carollo[5], D. Carton[2], J. Caruana[7], B. Clément[1], S. Dreizler[8], E. Emsellem[1,6], B. Epinat[3,4,9], 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)

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



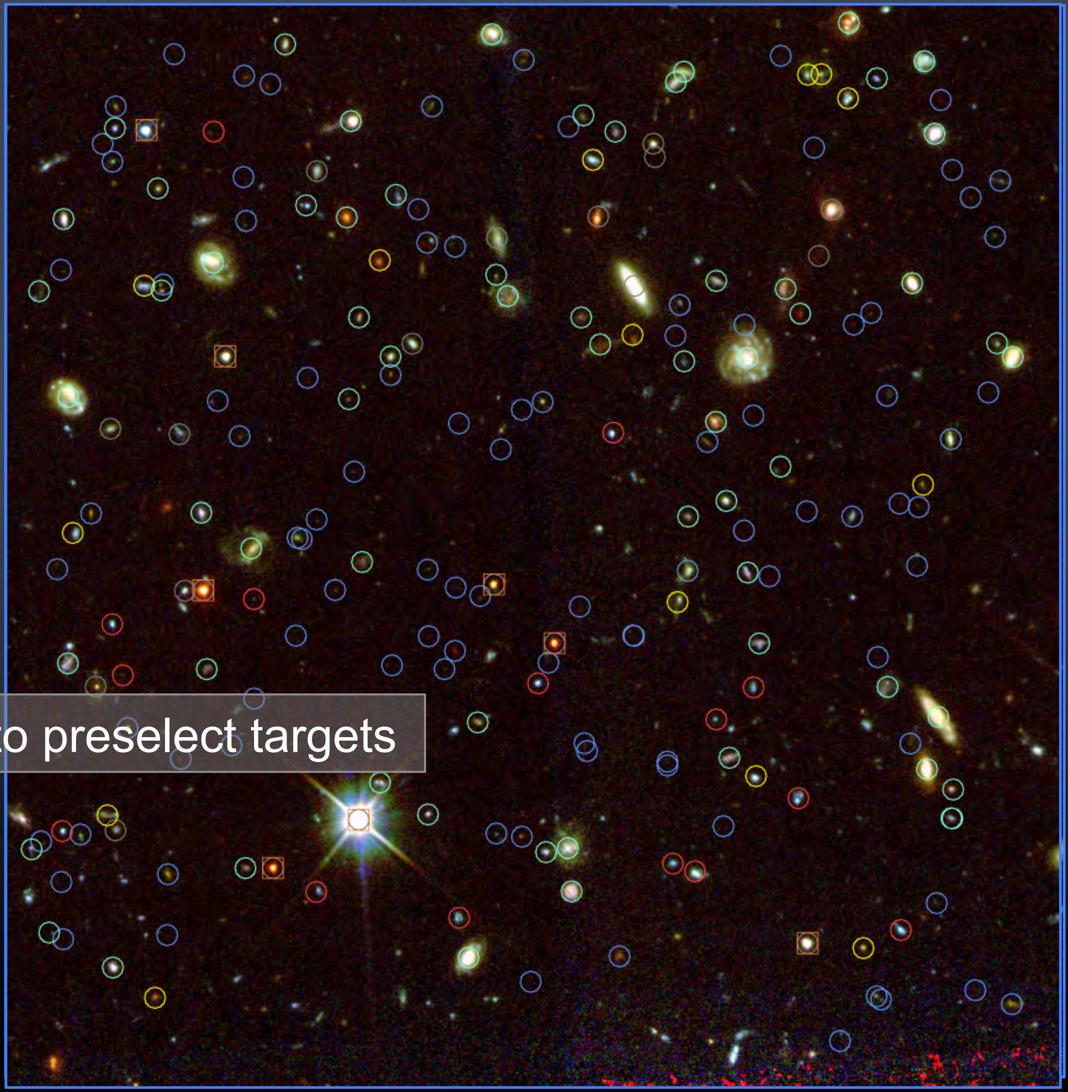
Hubble Deep Field South

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

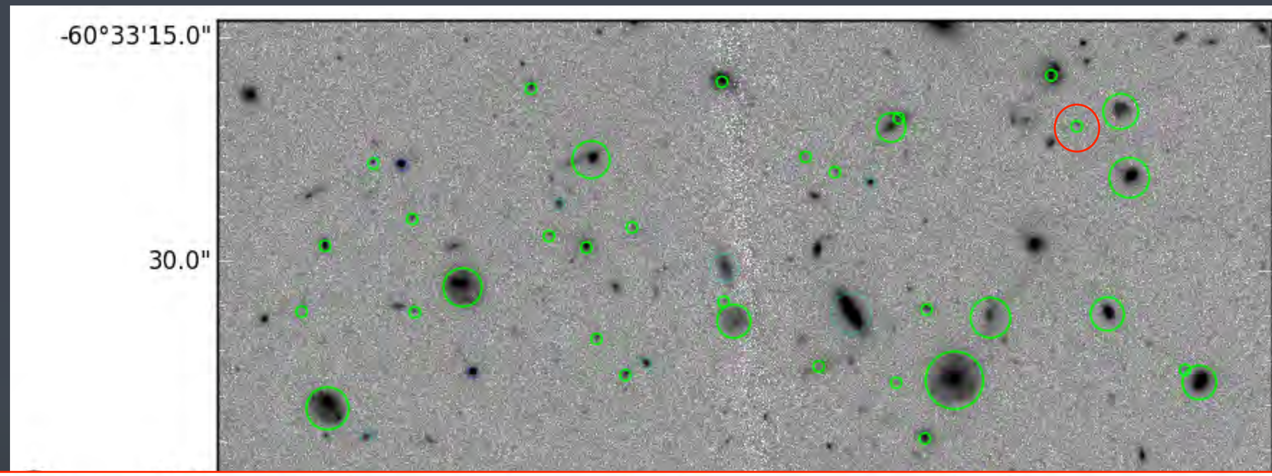
70 Lya emitters seen in HST
26 Lya w/o HST
65 [O II] emitters
15 C III]1909 emitters
8 Stars
14 Abs. line redshifts

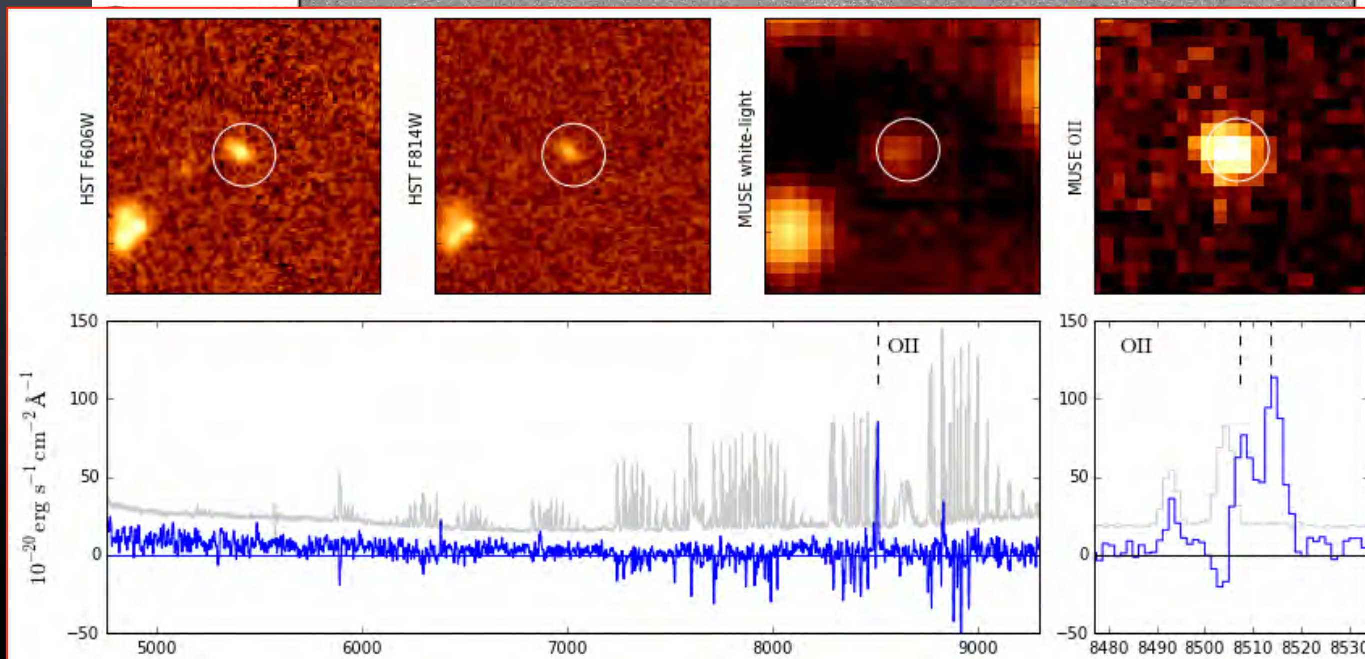
out of 586 targets

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

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]





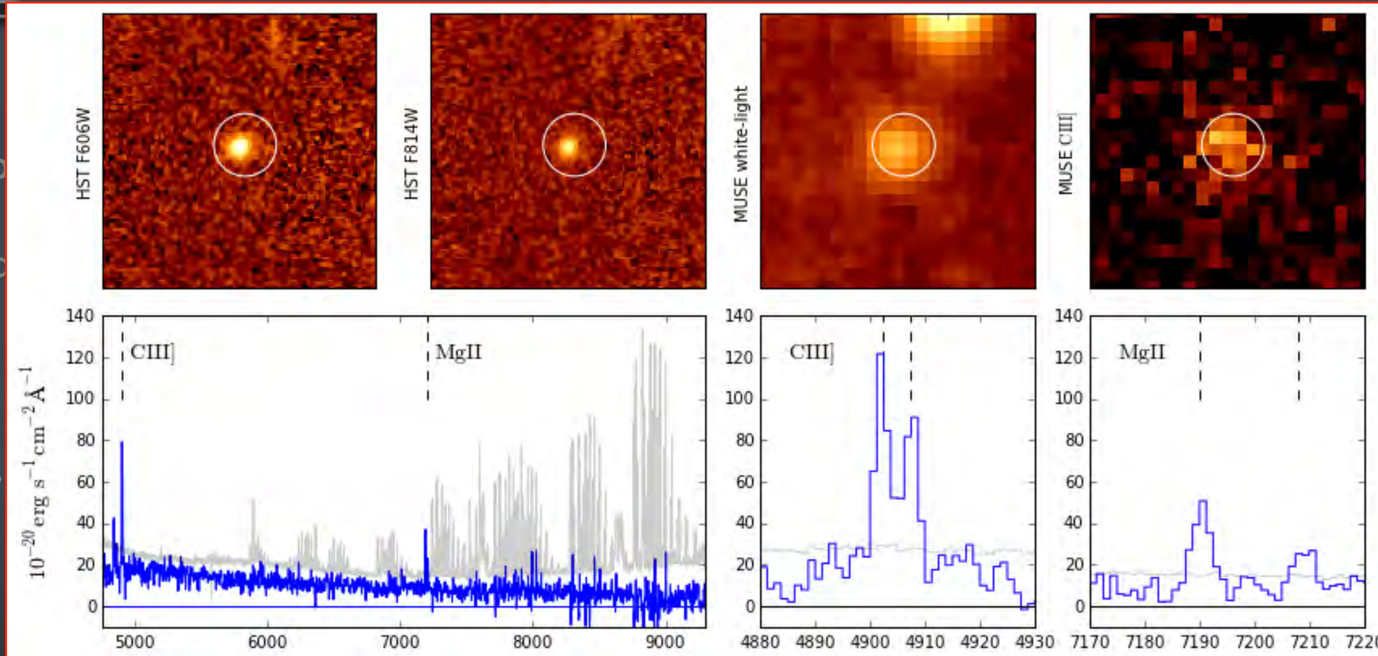
ID#160

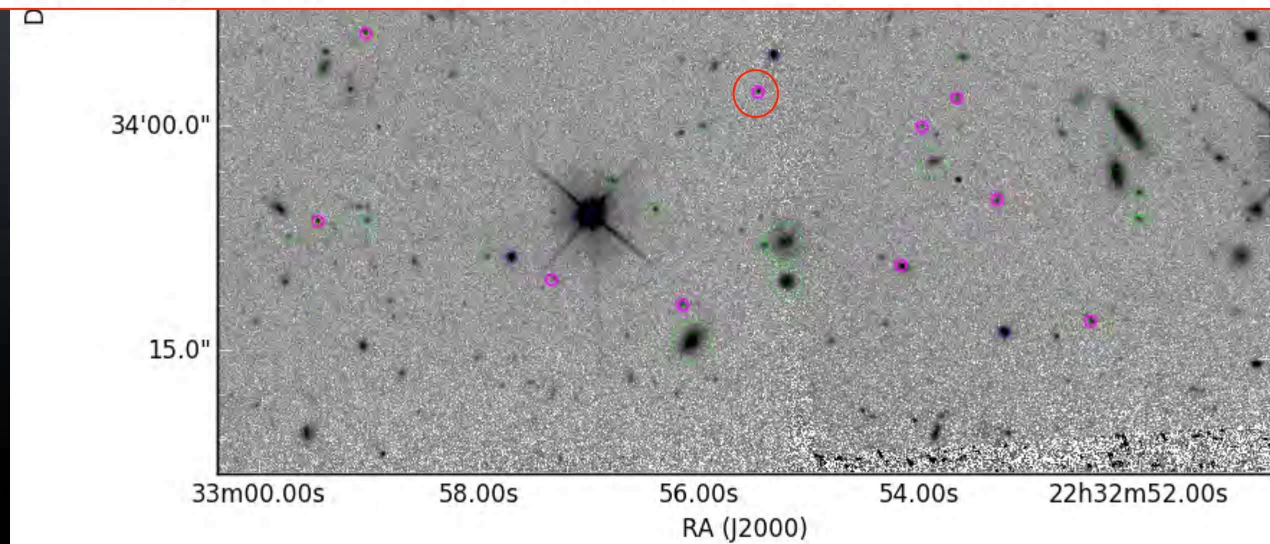
Z = 1.28
I_{814} = 26.7
M ≈ 2 10^9 $M_\odot$

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

Census of MUSE HDFS Field

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





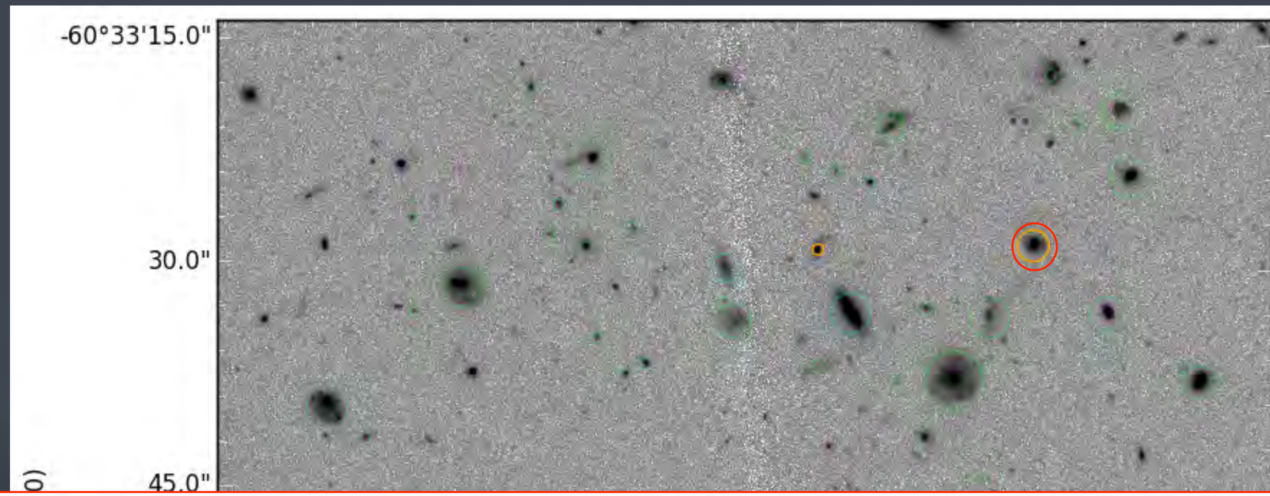
ID#97

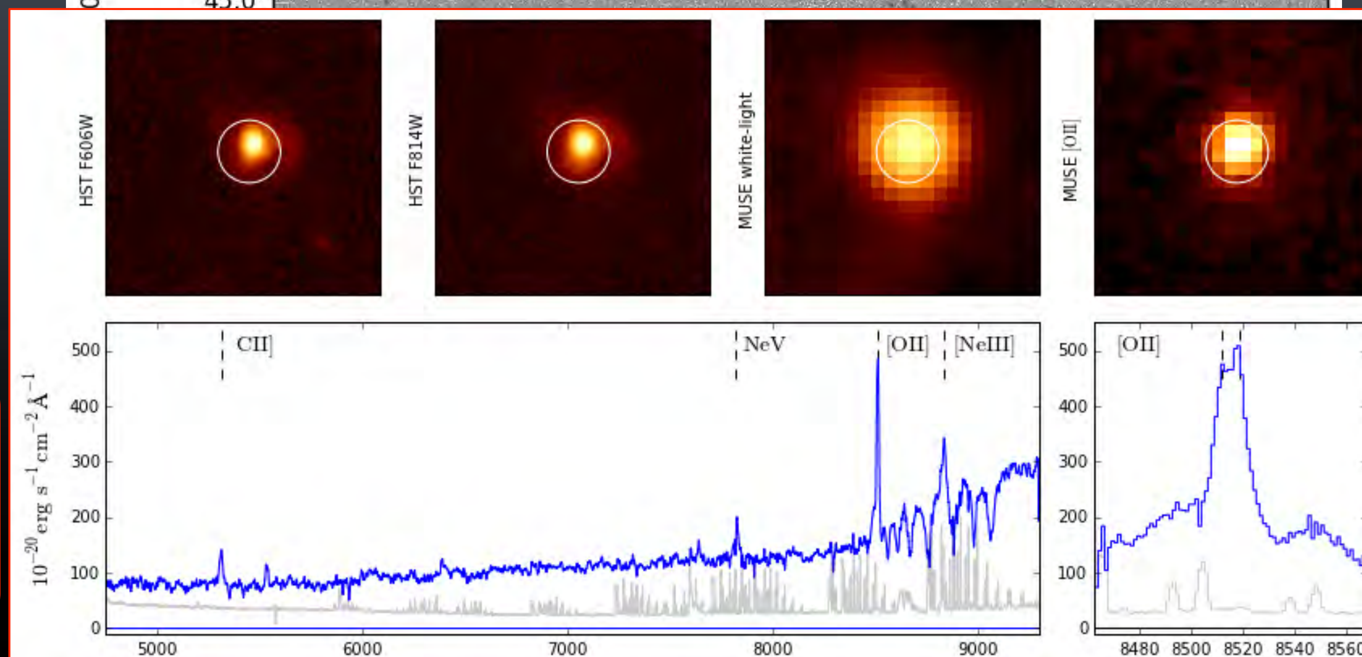
$Z = 1.57$
$I_{814} = 25.9$

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

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



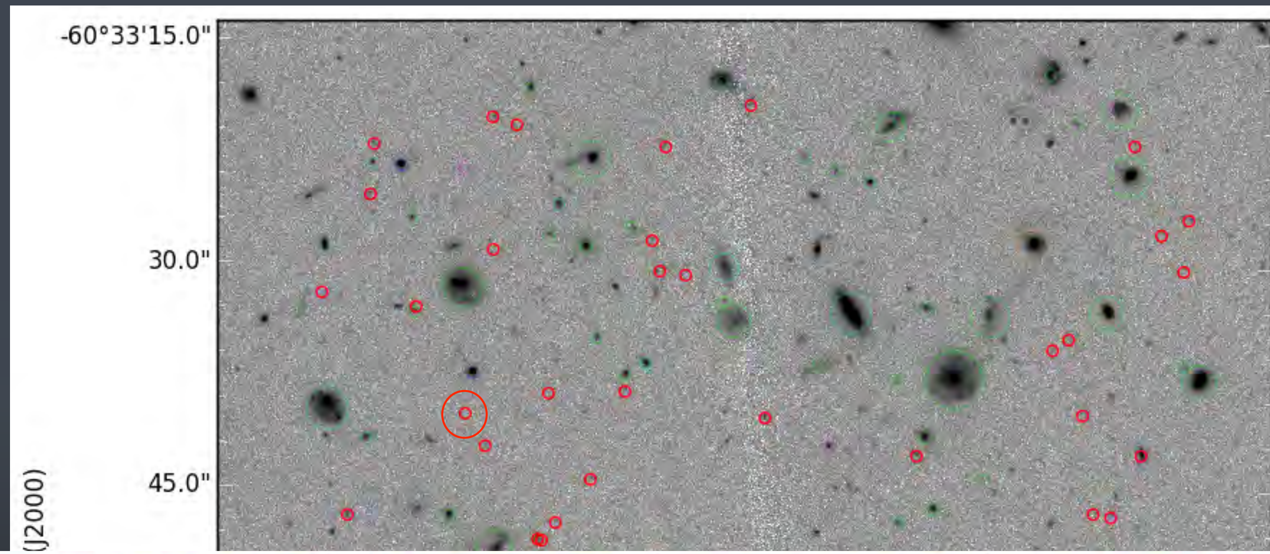


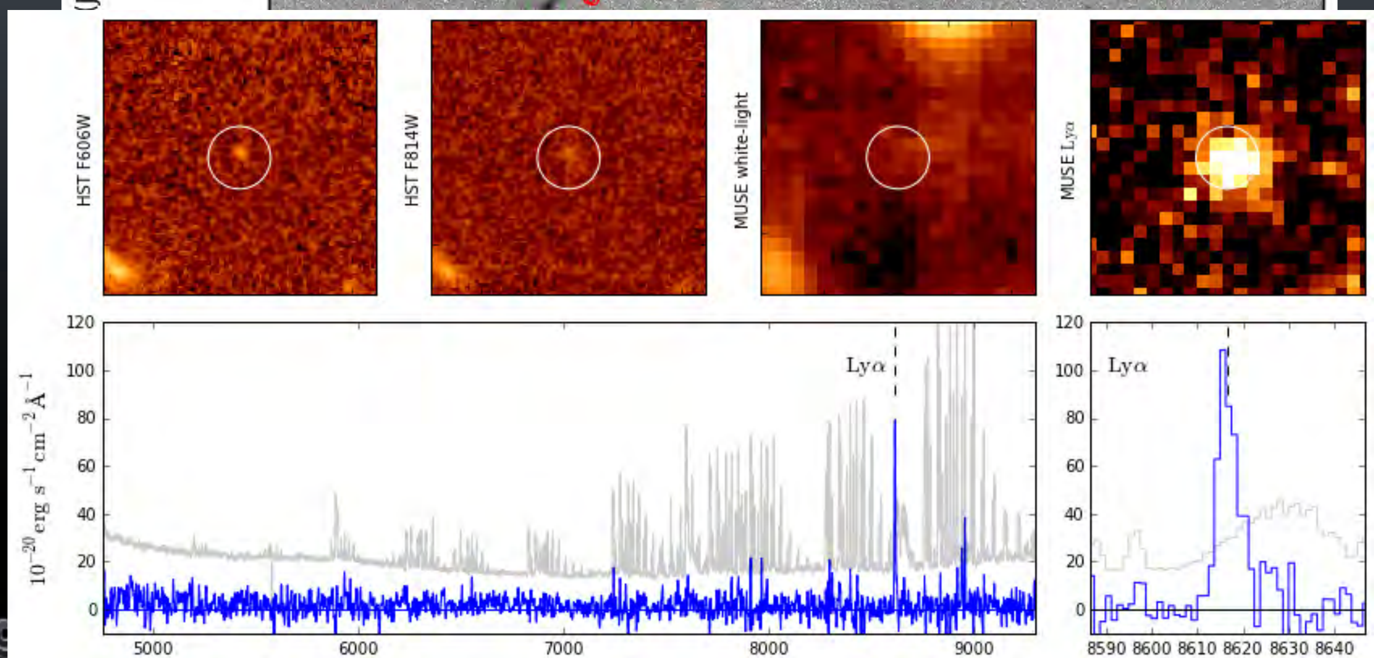
ID#10

Z = 1.28
I_{814} = 22.5

muse

- 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 Lyα emitters**
  - Z = [2.95 – 6.28]
  - I_{814} = [24.5 – 29.6]





ID#290

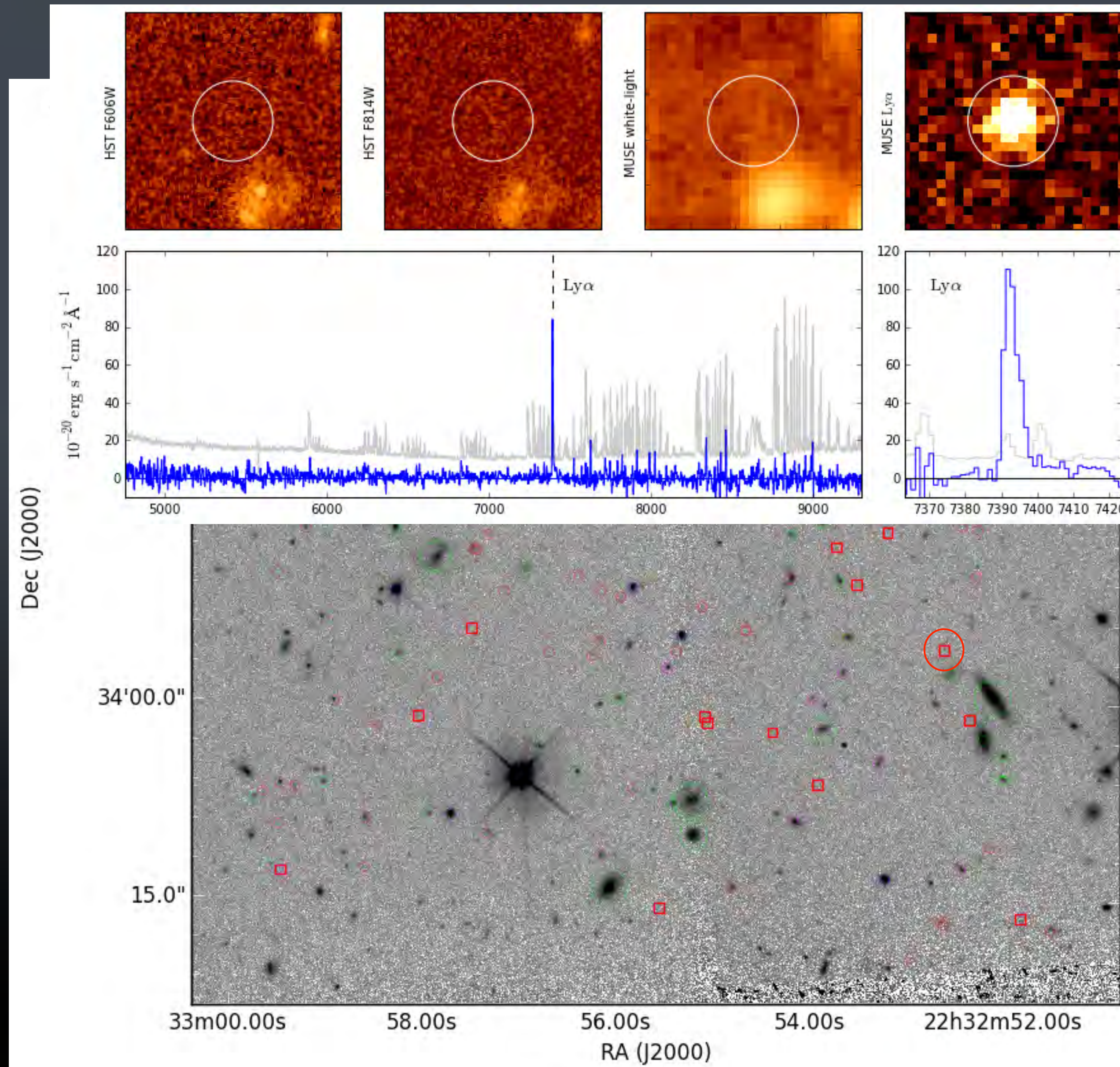
Z = 6.08
I_{814} = 27.8

Census of MUSE HDFS Field

ID#553

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

- H
- 1 … pic R
- 1 … in M
- 8 stars
- 7 nearby galaxies
- 61 [OII] 3727 emitters
- 10 absorption lines galaxies
- 12 CIII] 1909 emitters
- 2 AGNs
- 63 Lyα emitters
- **26 Lyα emitters without HST counterpart**
  - Z = [3.12 – 6.27]
  - $I_{814} > 29.8$



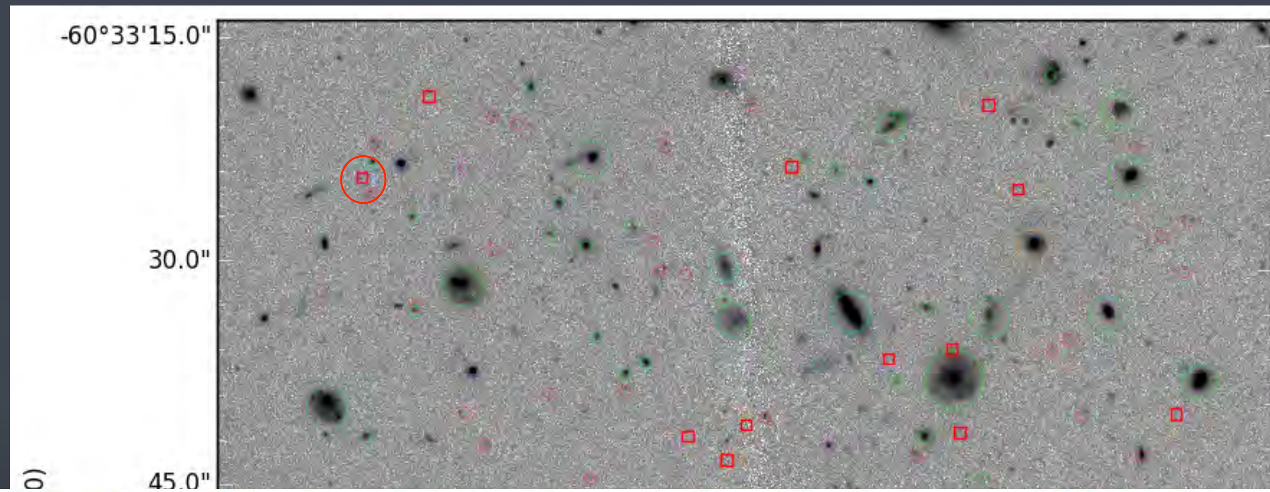
ESO - Göttingen - Leiden - Lyon - Potsdam - Toulouse - Zurich

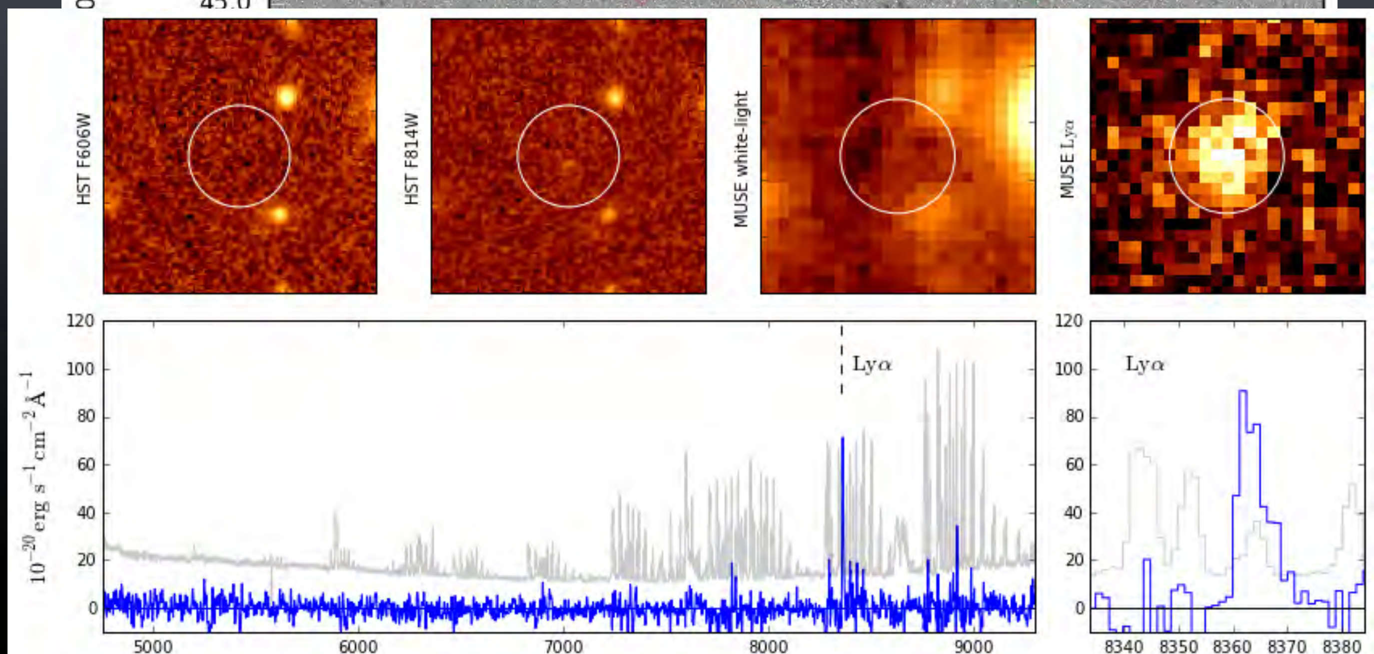
Census of MUSE HDFS Field

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

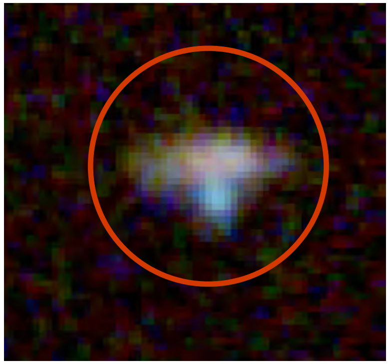
ID#560

Z = 5.88
$I_{814} > 29.8$



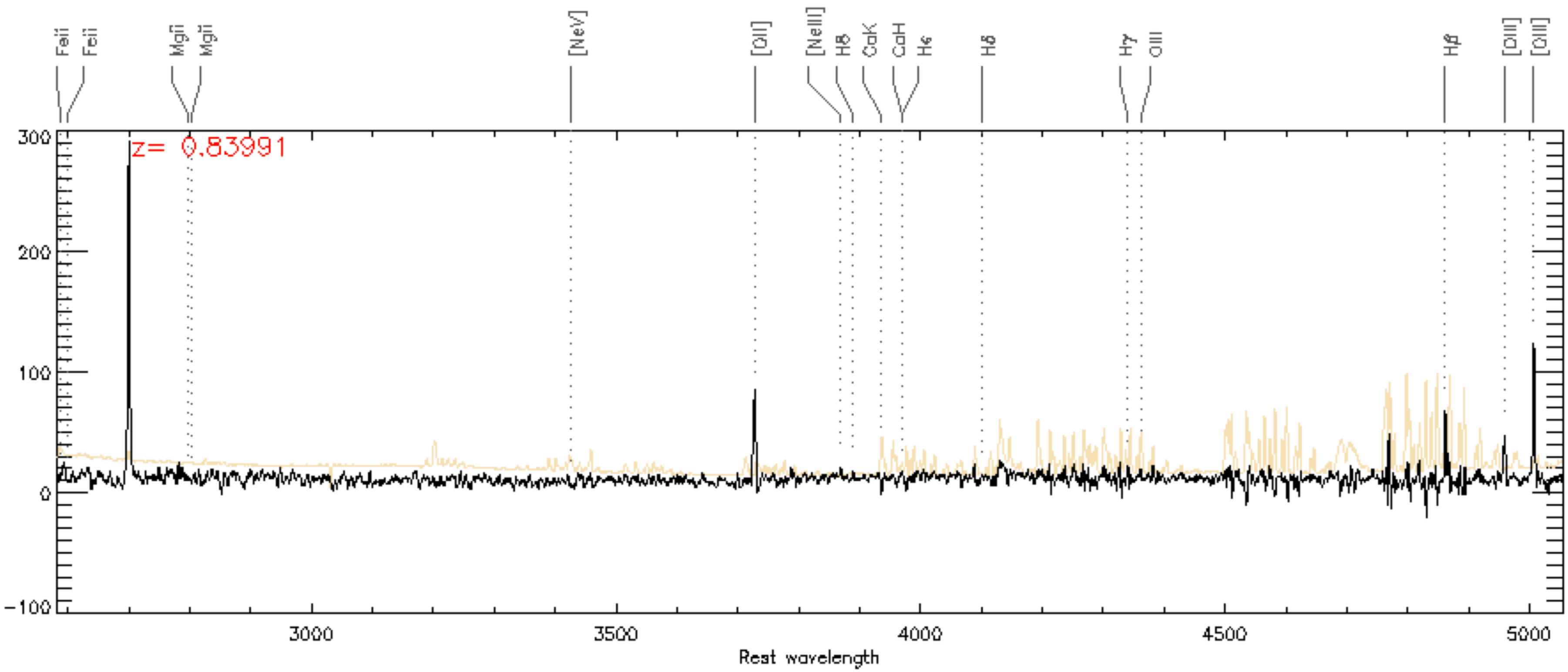


Separation in 3D

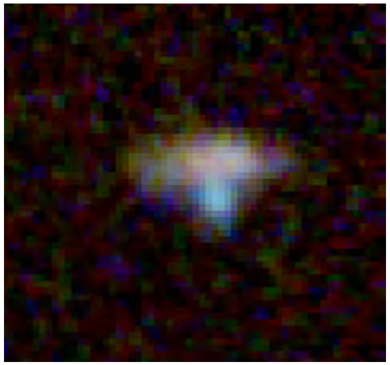


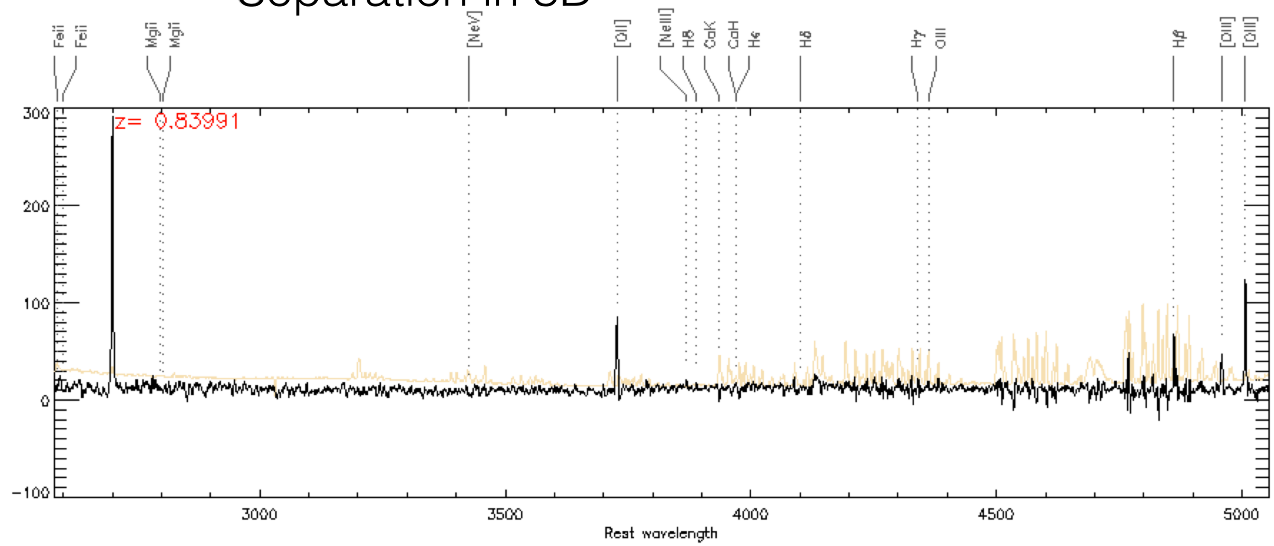
Single object in HDF-S catalogue

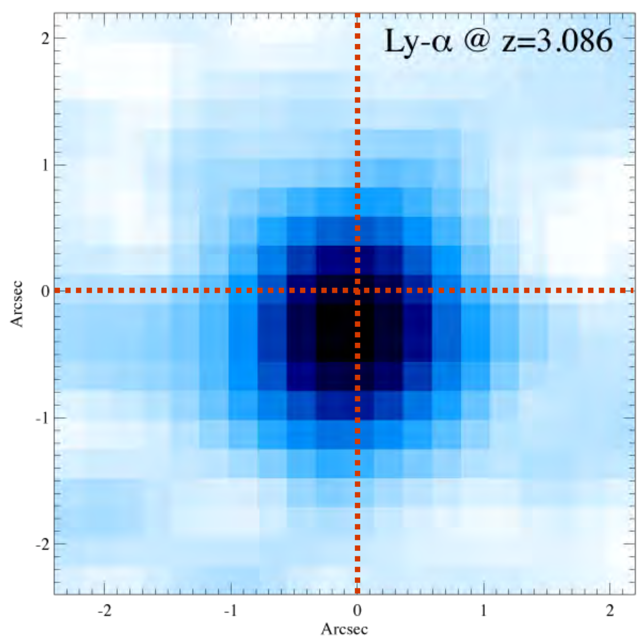
$m_{F814W} \sim 25.3$

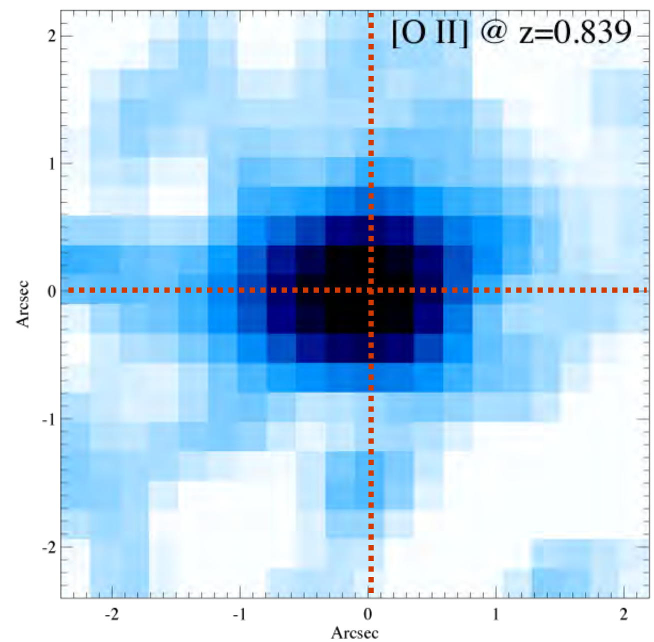


Separation in 3D

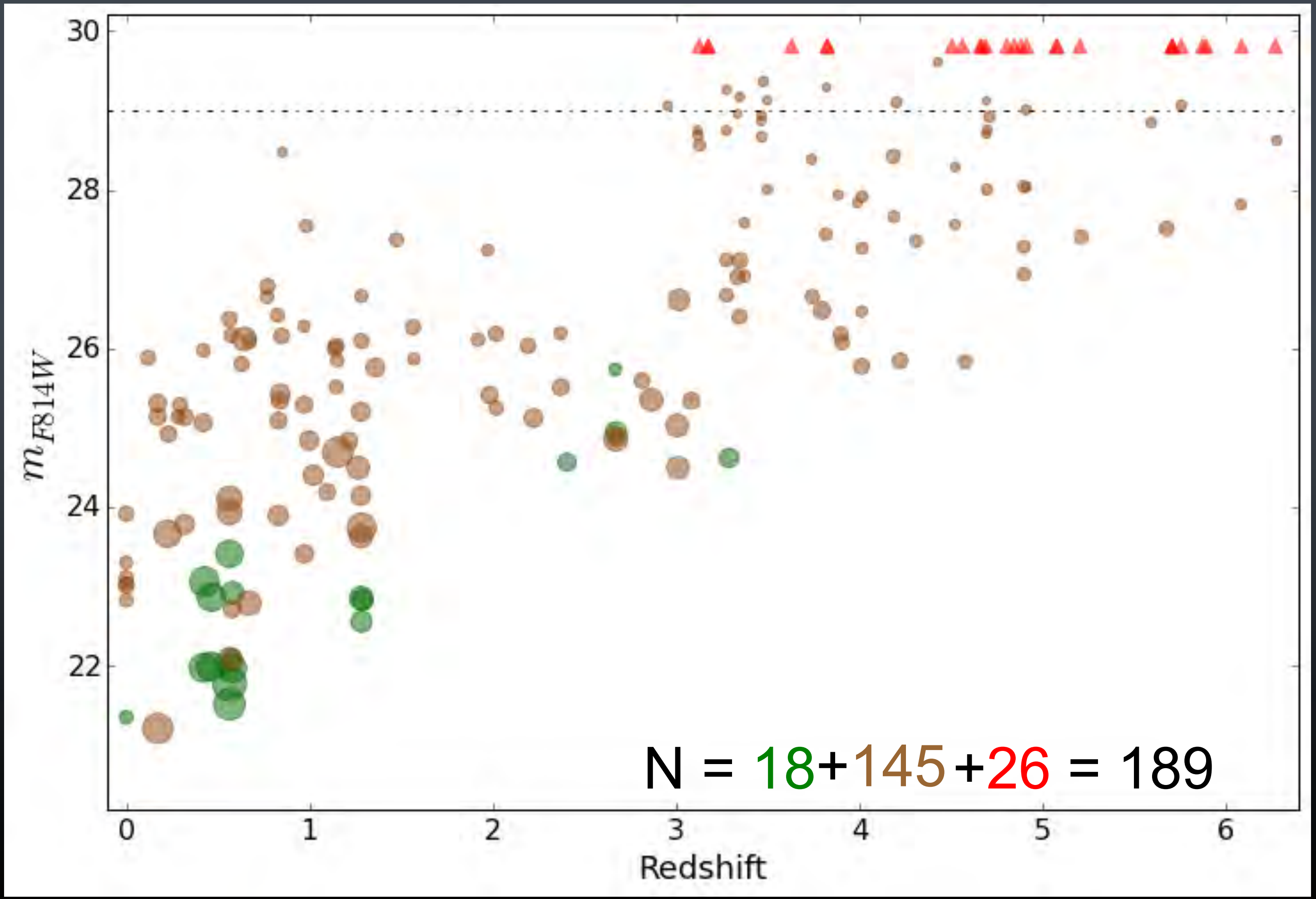




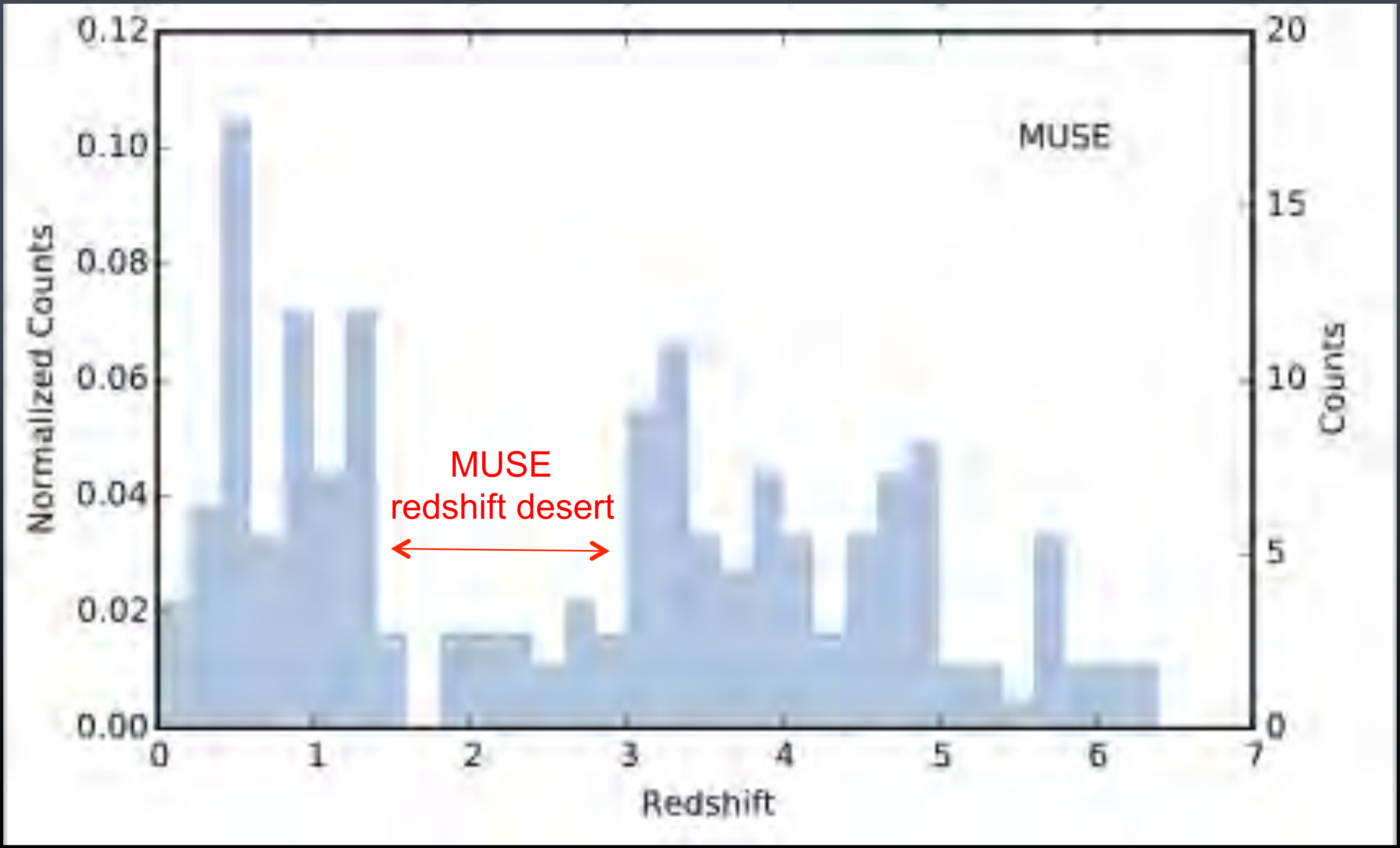




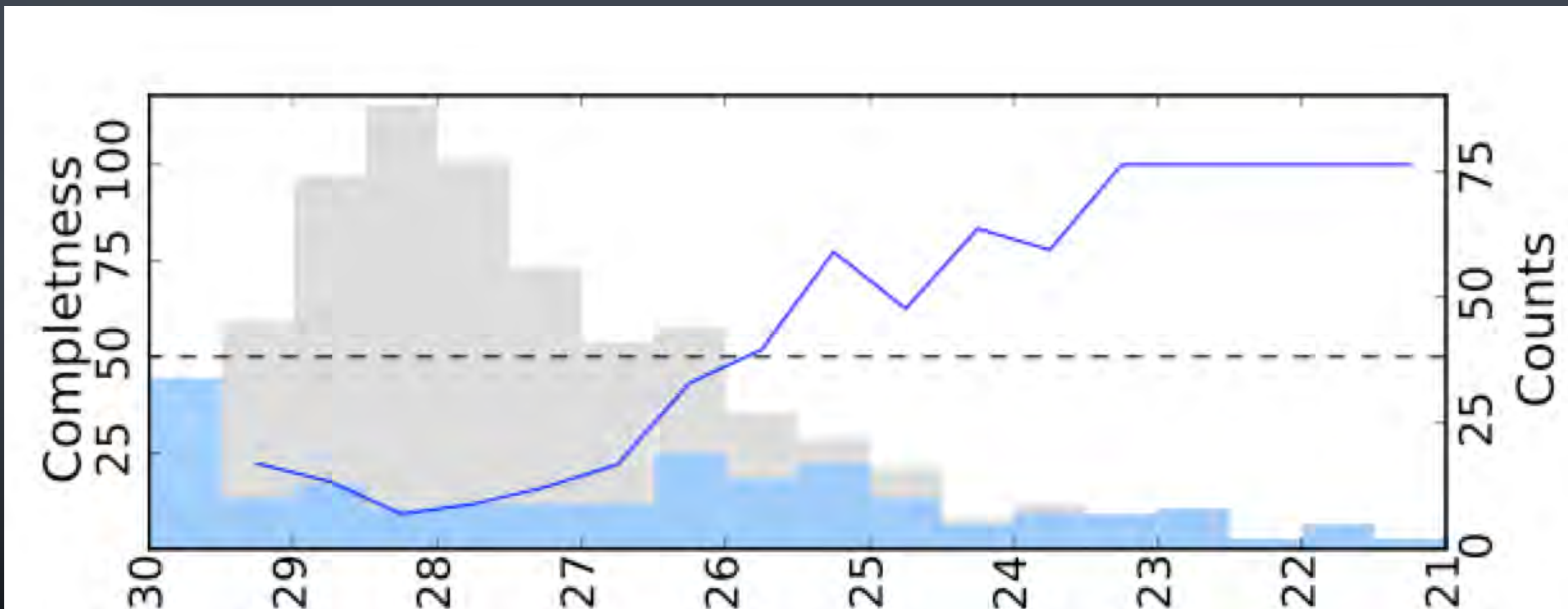
Redshift distribution



Redshift distribution



Redshift distribution



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

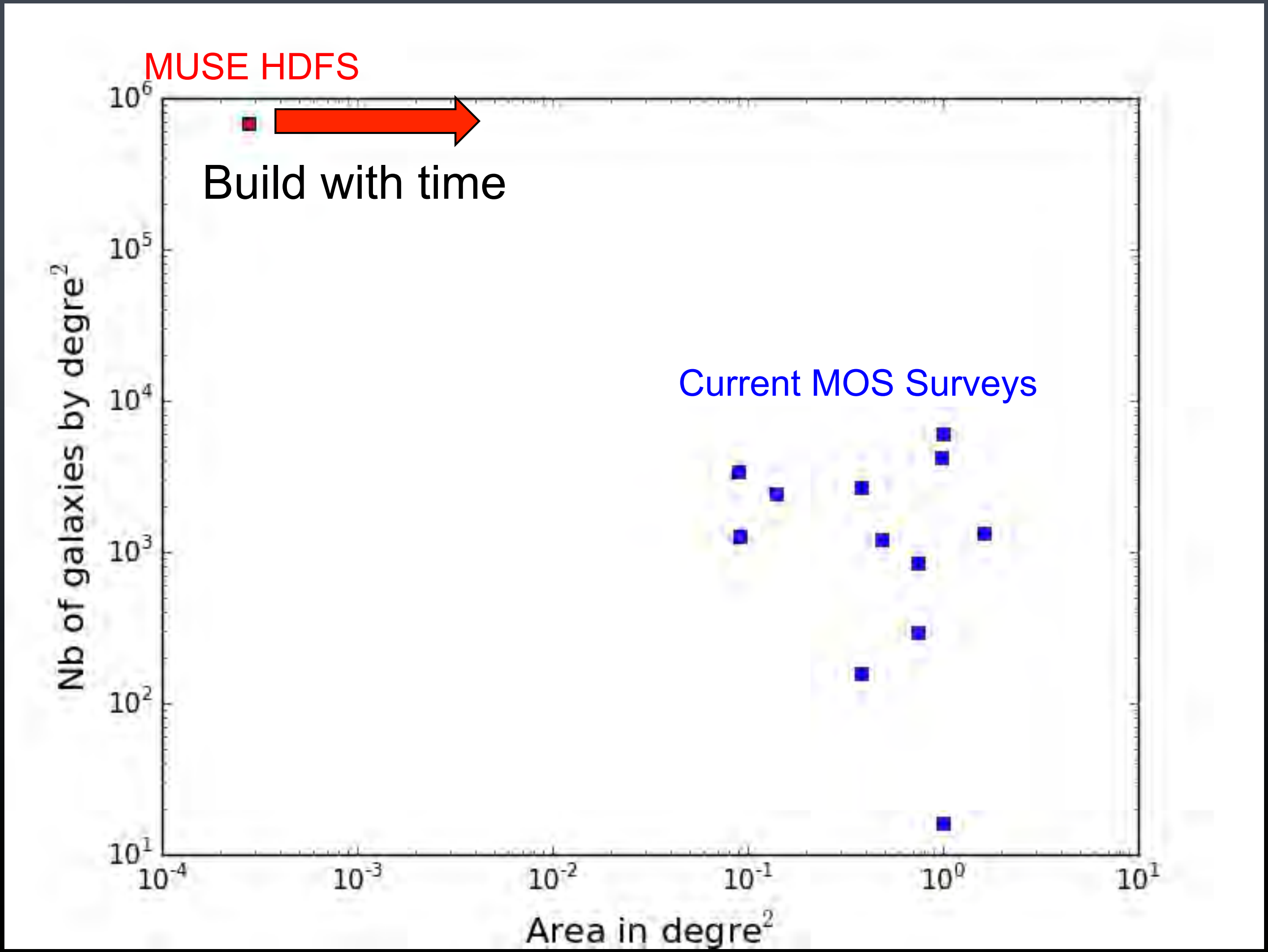
Groups

Table 2. Galaxy groups detected in the HDFS ordered by redshift.

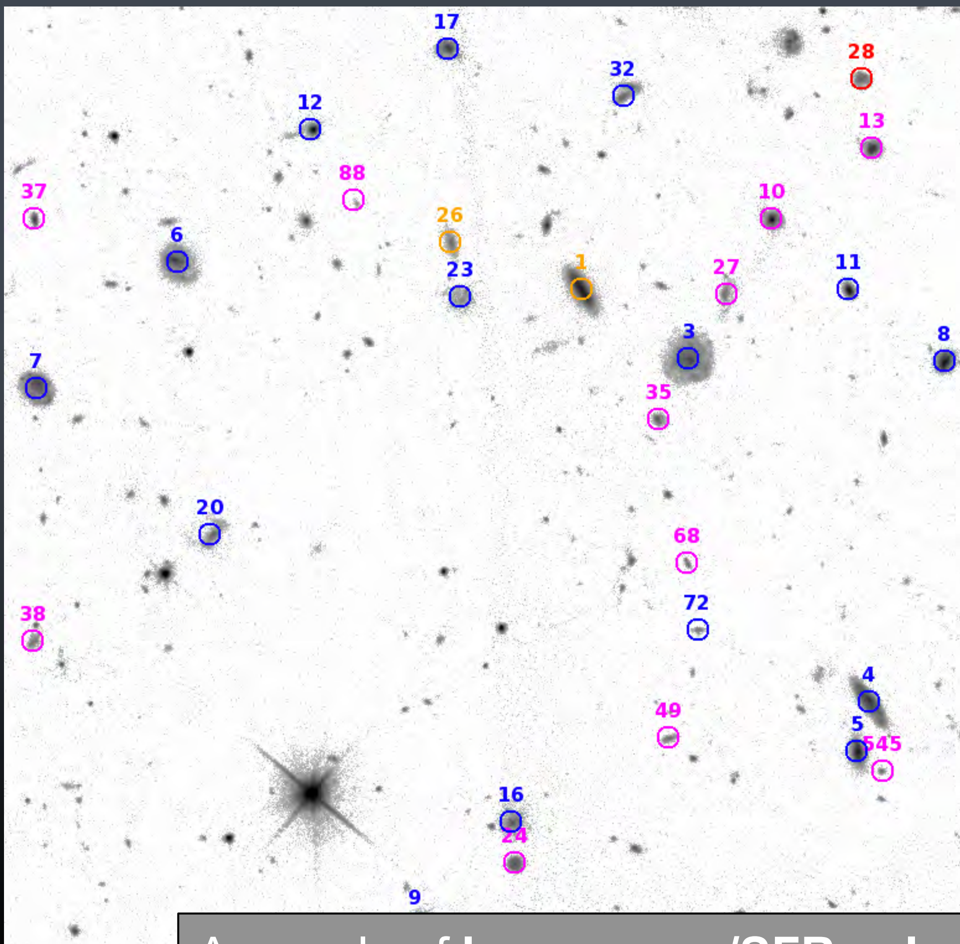
z	v_{rms} km s^{-1}	r_{rms} kpc	N_m	Member IDs
0.172	65	43	3	1, 63, 70
0.421	262	54	4	6, 57, 101, 569
0.564	52	142	7	3, 4, 9, 23, 32, 135
0.578	424	150	5	5, 8, 11, 17, 122
0.972	56	201	3	24, 68, 129
1.284	354	92	9	10, 13, 15, 25, 27, 35, 64, 114, 160
2.672	101	87	4	50, 51, 55, 87
3.013	350	115	3	40, 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

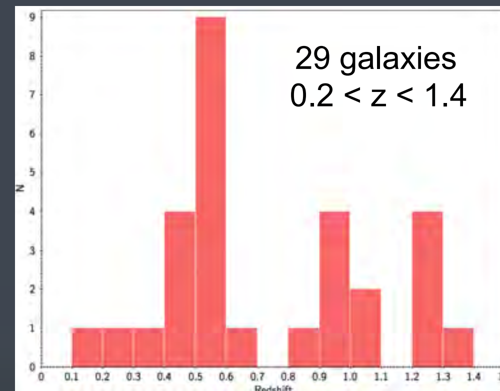
An entirely new ball-game

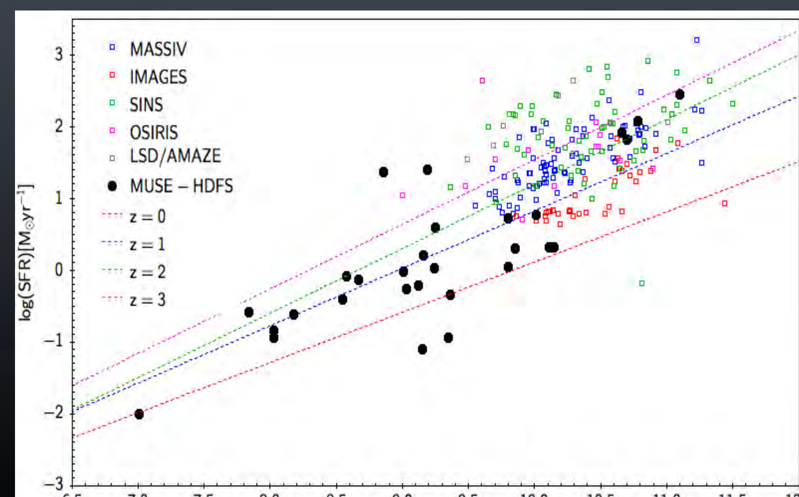
While MUSE is the most efficient spectrograph on the VLT, it is not a general purpose redshift machine. But it is unbeatable when it comes to density of spectra.



Spatially resolved galaxies in MUSE-HDFS





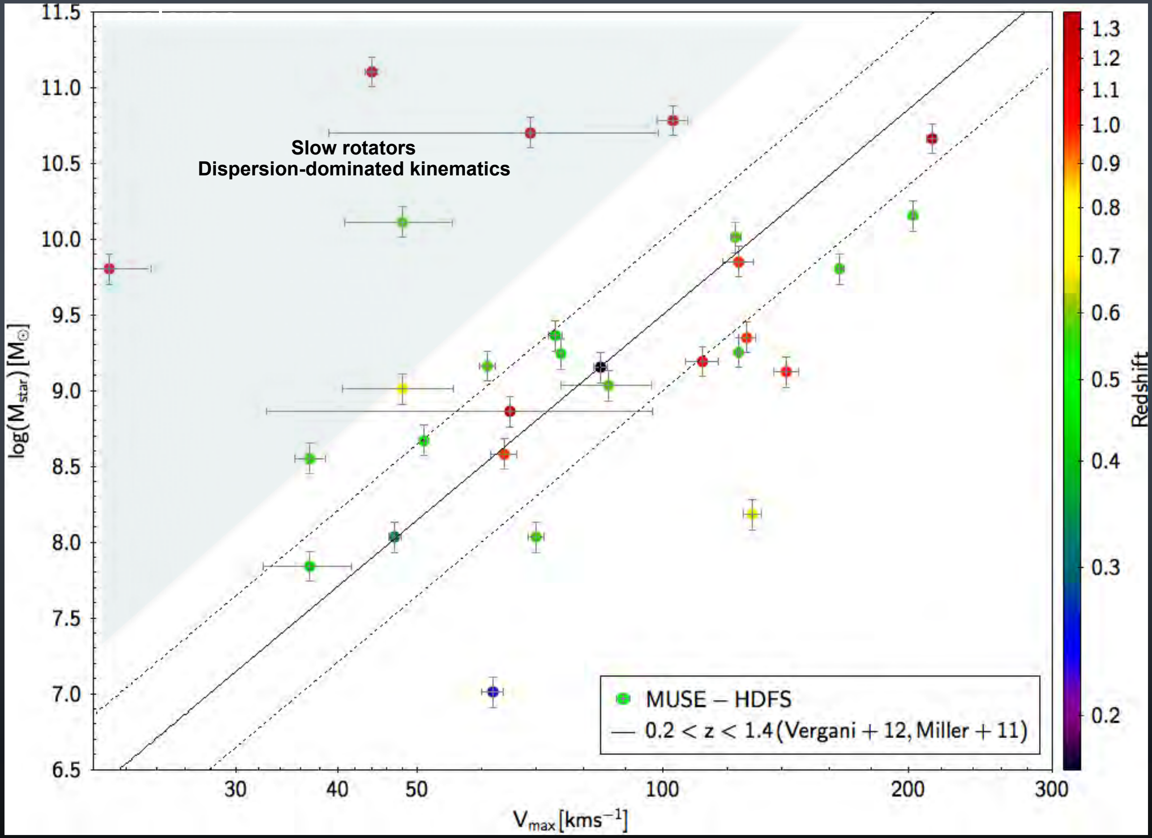


A sample of **lower-mass/SFR galaxies** compared with previous IFU surveys

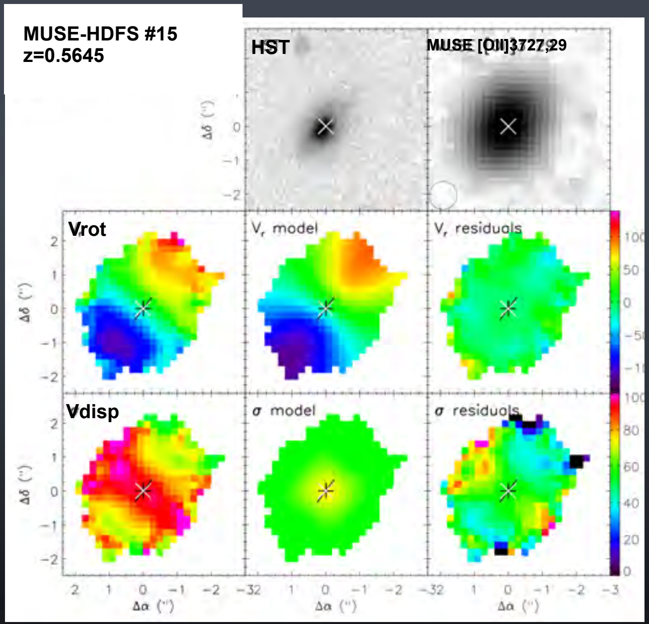
Contini et al, in prep

Gas kinematics, TF relation

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



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

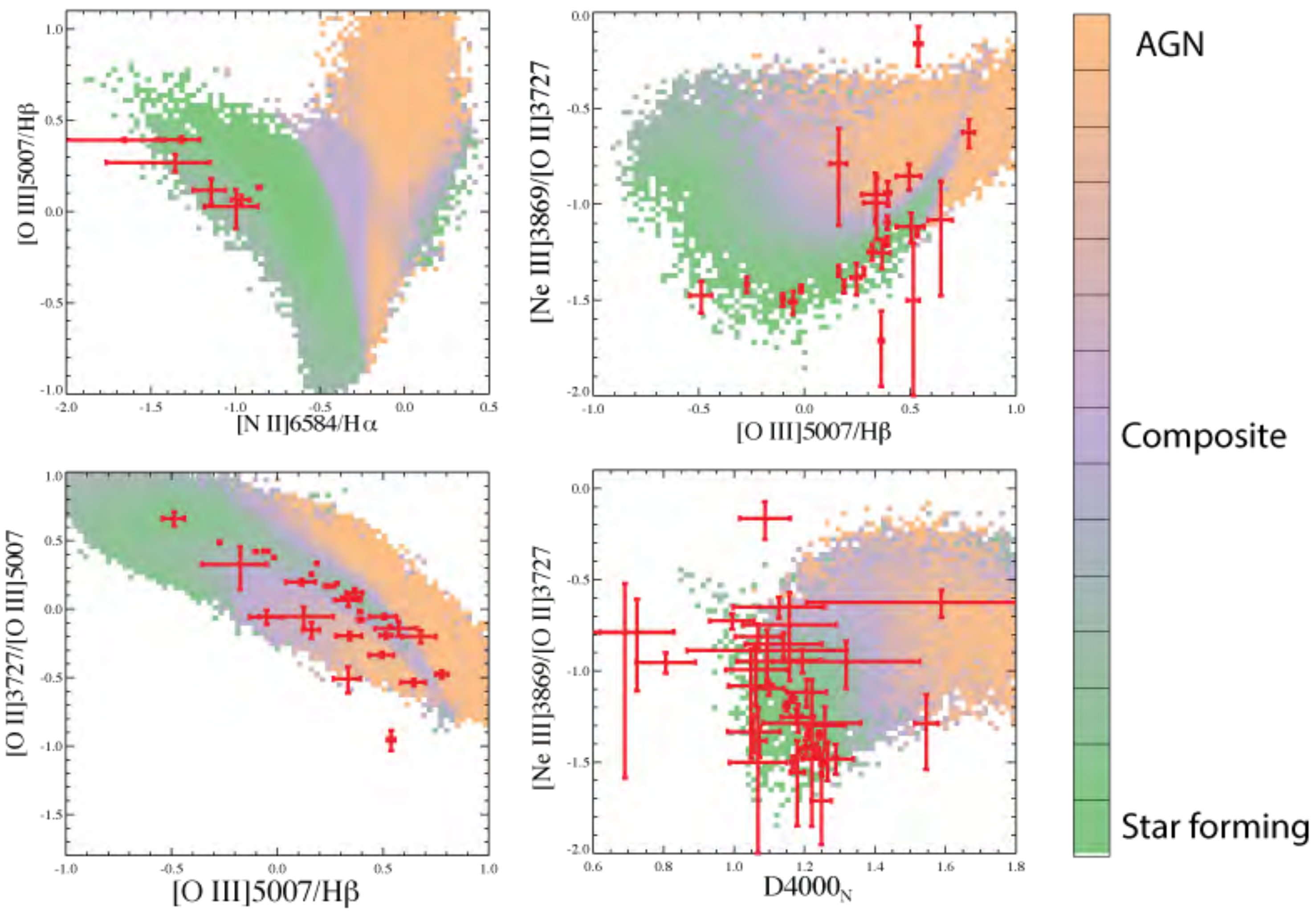


Observed **Model** **Residual**

Most of **low-mass (< $10^{9.5}$ M☉) galaxies** follow the TFR, but higher dispersion

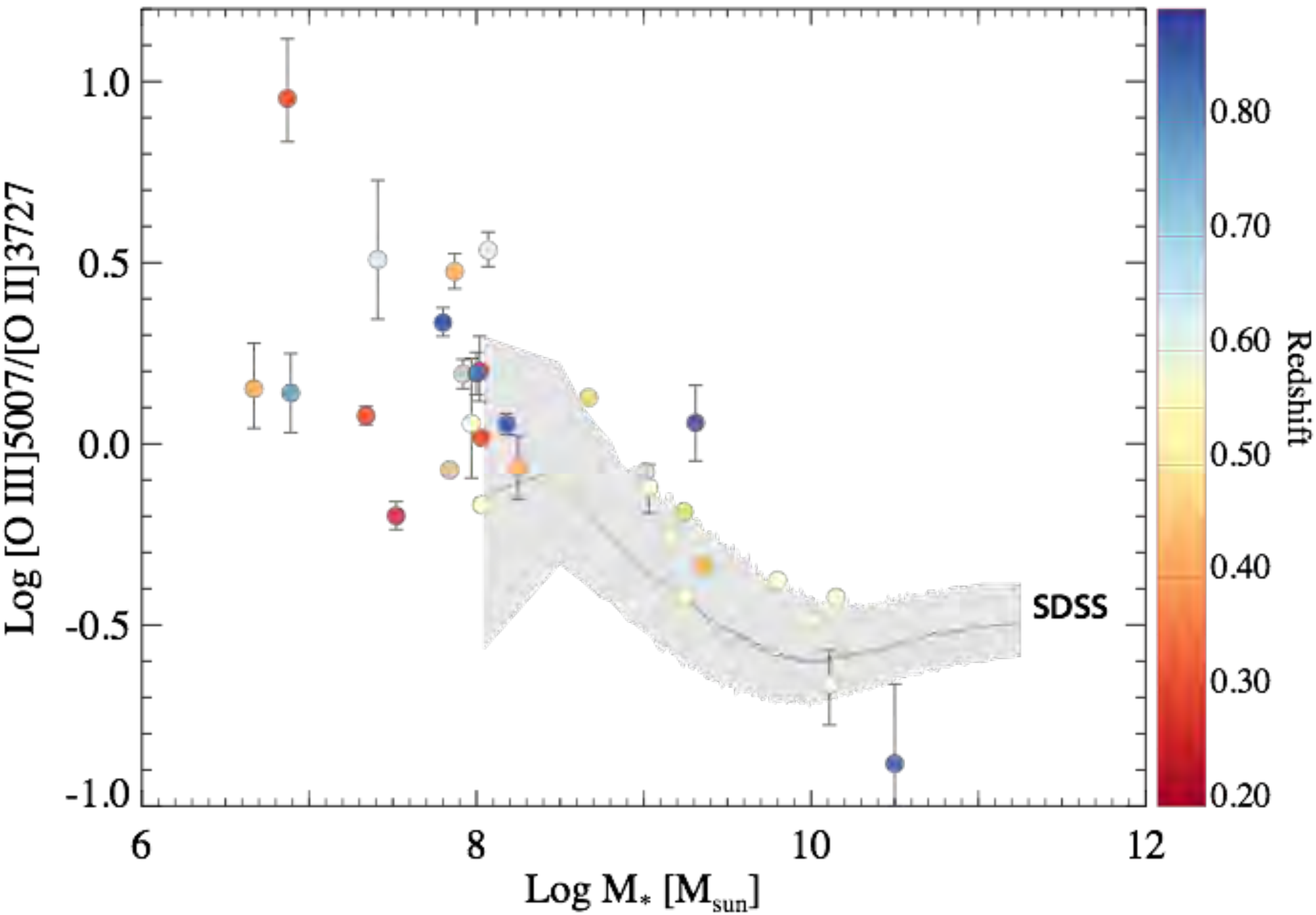
Contini et al, in prep

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.

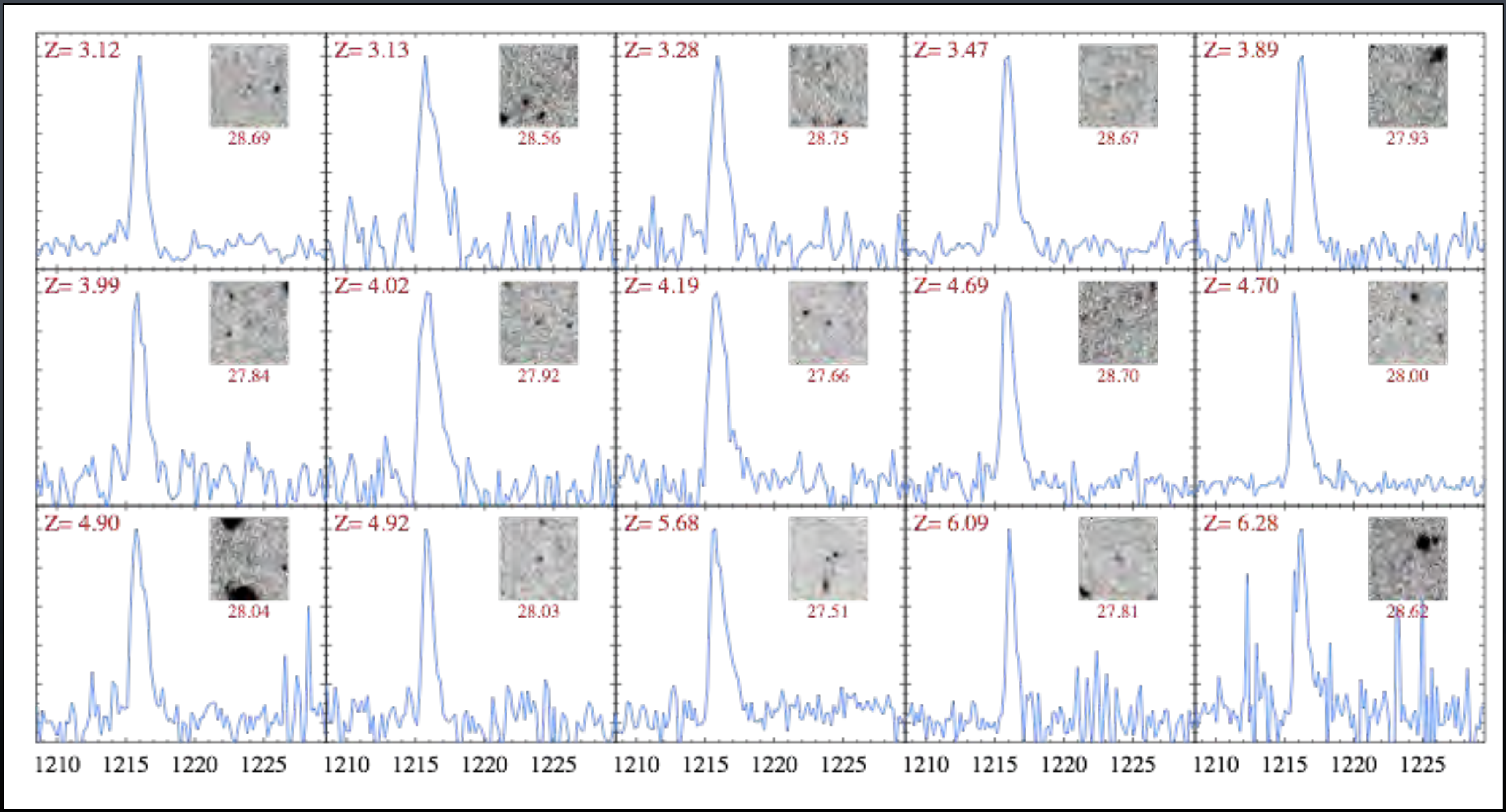
Brinchmann et al, in prep



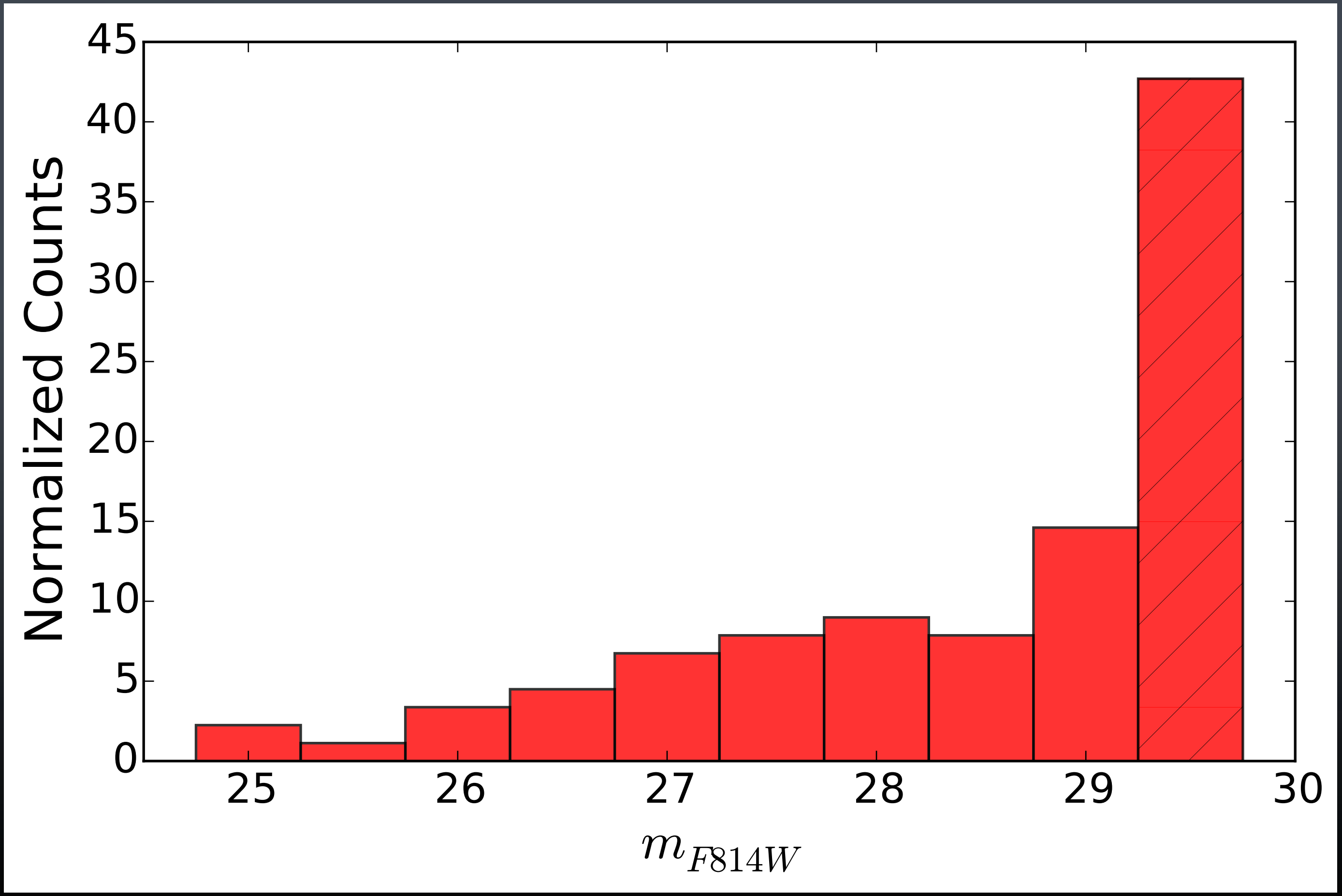
Moderately more extreme than local galaxies, but not so much when SFR is taken into account (c.f. Shirazi et al 2014)

Brinchmann et al, in prep

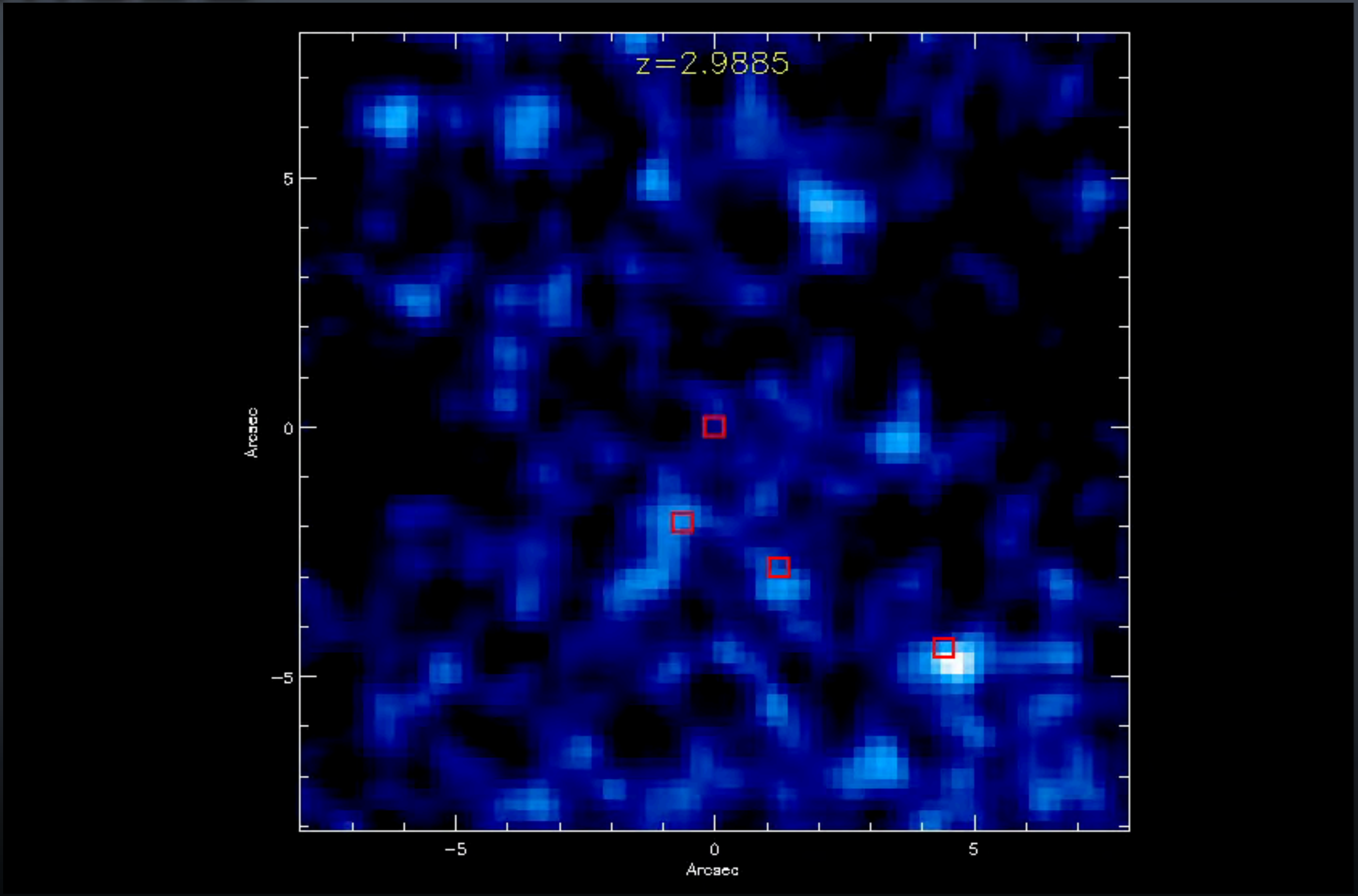
Lyα emitters: a rapid look



Lyα distribution with magnitude



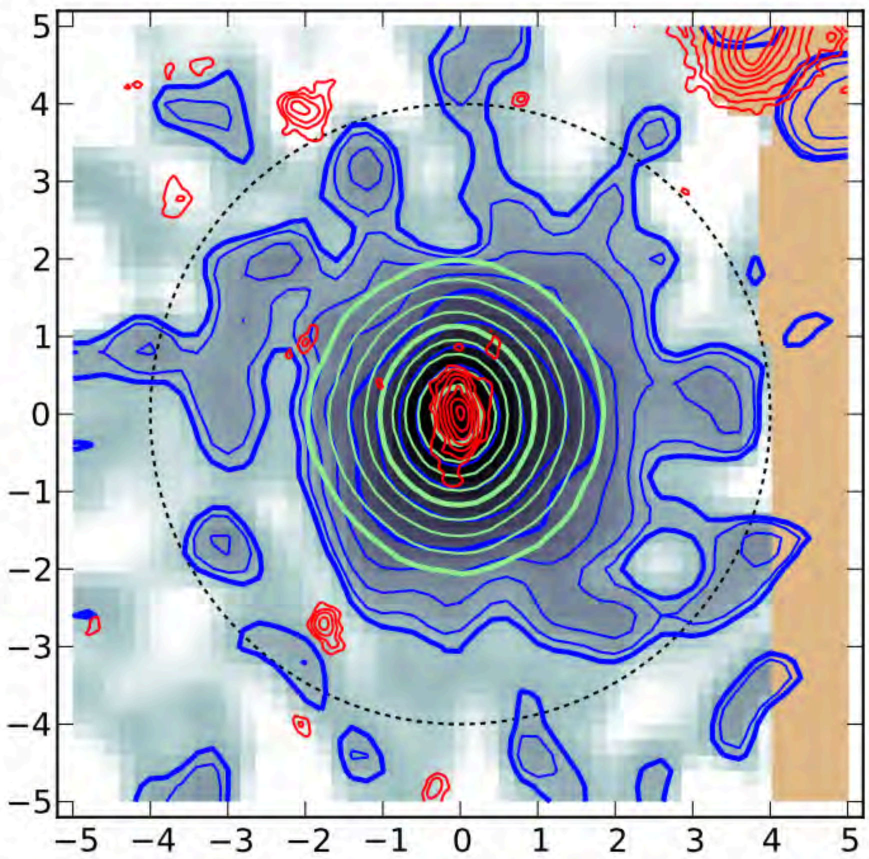
Diffuse emission

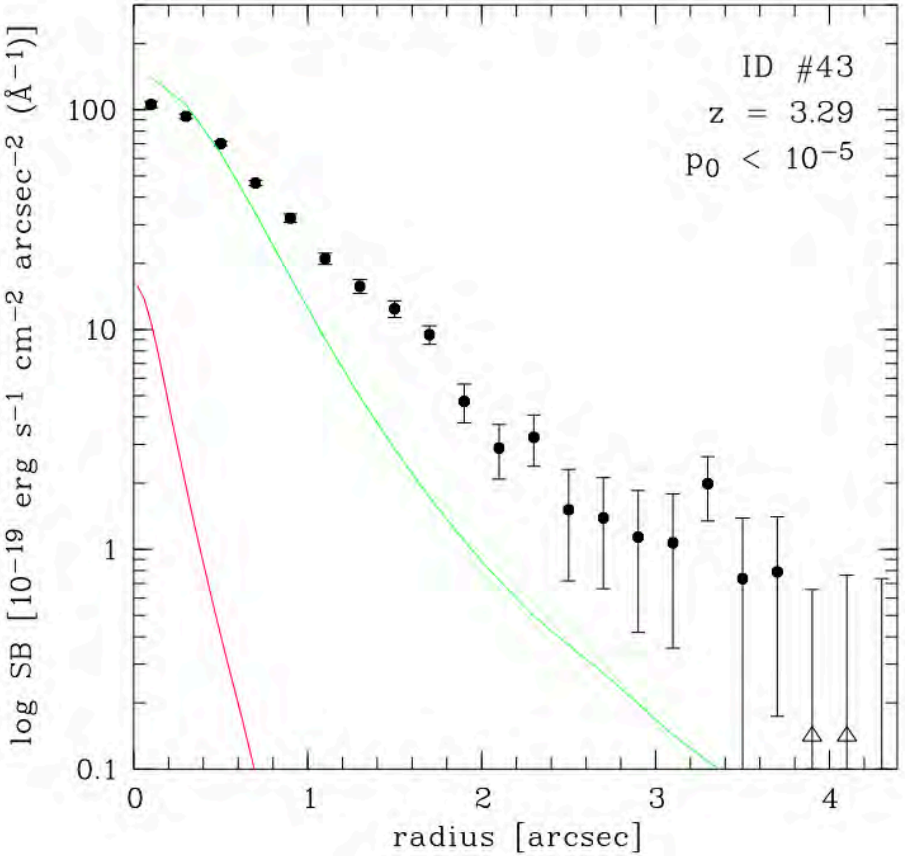


Around object #40 @ z=3.01 - 120 kpc x 120 kpc

Cantalupo et al, in prep

Extended Lyα Halo





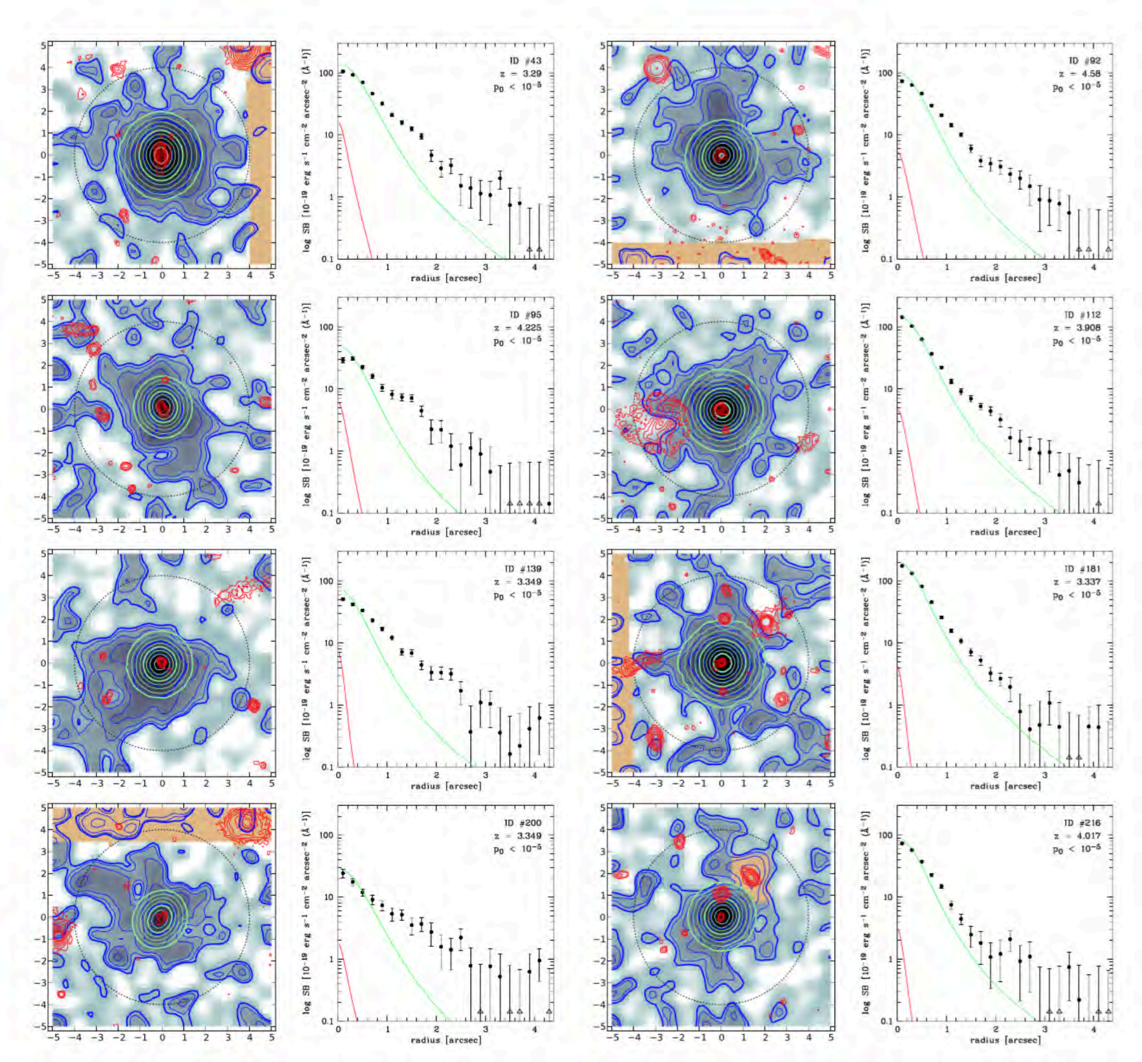
First time Extended Lyα Halo are detected around individual galaxies
(with the exception of Rauch et al 2008 long slit 92 hours deep observations)

Wisotzki et al, in prep

Extended Lyα Halo

Subsample of 28 Lya emitters (with $F_{ly\alpha} > 5.10^{-18}$ cgs)

23/28 display significant detection

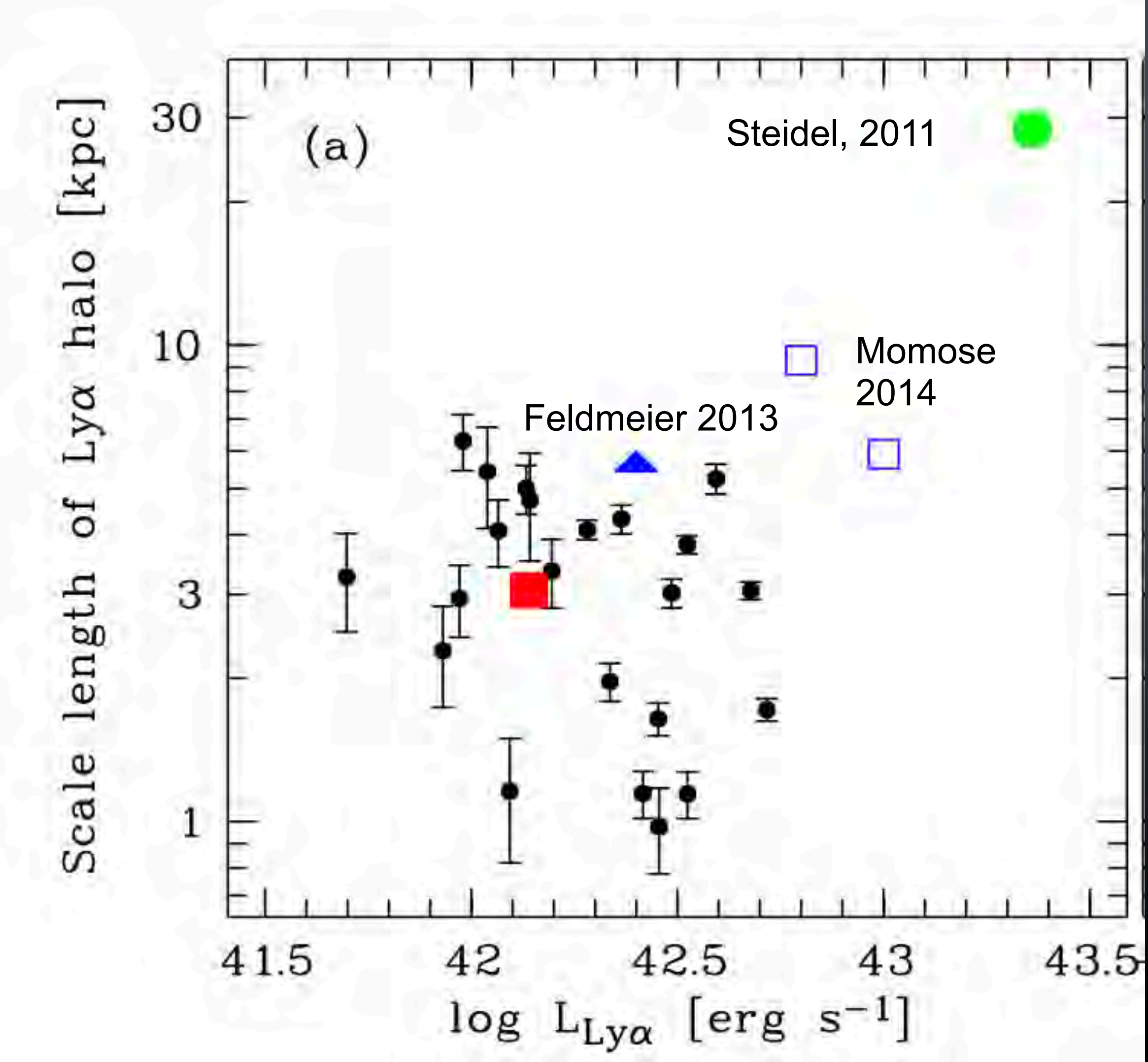


Wisotzki et al, in prep

Extended Lyα Halo

Halo size 1-5 Kpc,

5x bigger than the UV continuum component



Wisotzki et al, in prep

Summary

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 **Lyα** emitters **fainter** than the HST detection limit (I814>30)
- At the same time we get **spatially resolved kinematics** for 29 galaxies at z ~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 Lyα halos** in most of the 28 bright Lyα emitters selected sample. Halos size are 1-5 Kpc, 5x larger than the UV component.

http://muse-vlt.eu/science

Muse Science

The Multi Unit Spectroscopic Explorer

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Welcome to the MUSE Science Web Service

muse
multi unit spectroscopic explorer

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Latest News 2015-02-26: Grand new opening of the Muse science web service.
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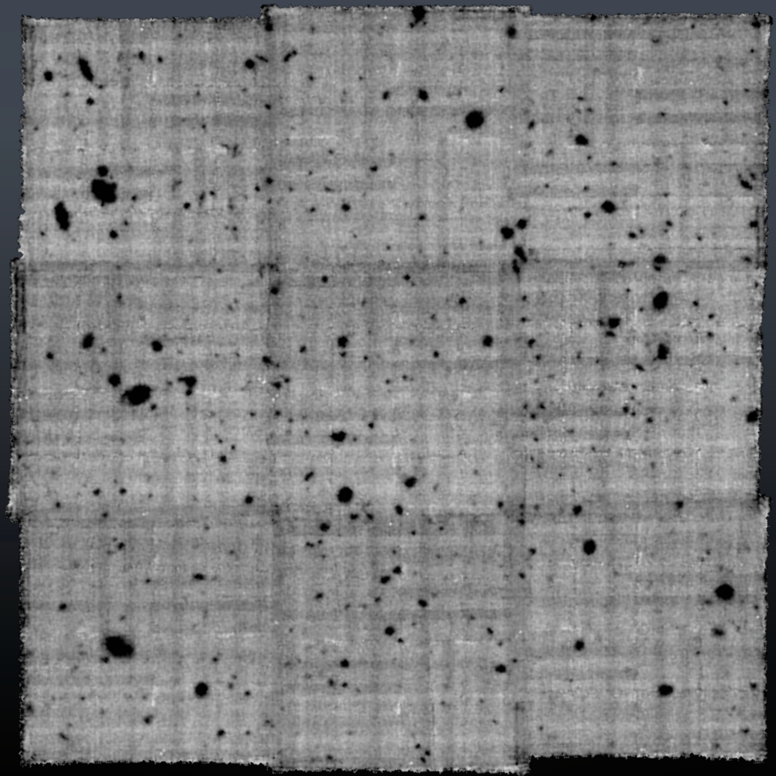
The **Multi Unit Spectroscopic Explorer (MUSE)** is a second generation instrument installed on the Nasmyth focus of UT4 at the Very Large Telescope (VLT) of the European Southern Observatory (ESO).

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

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

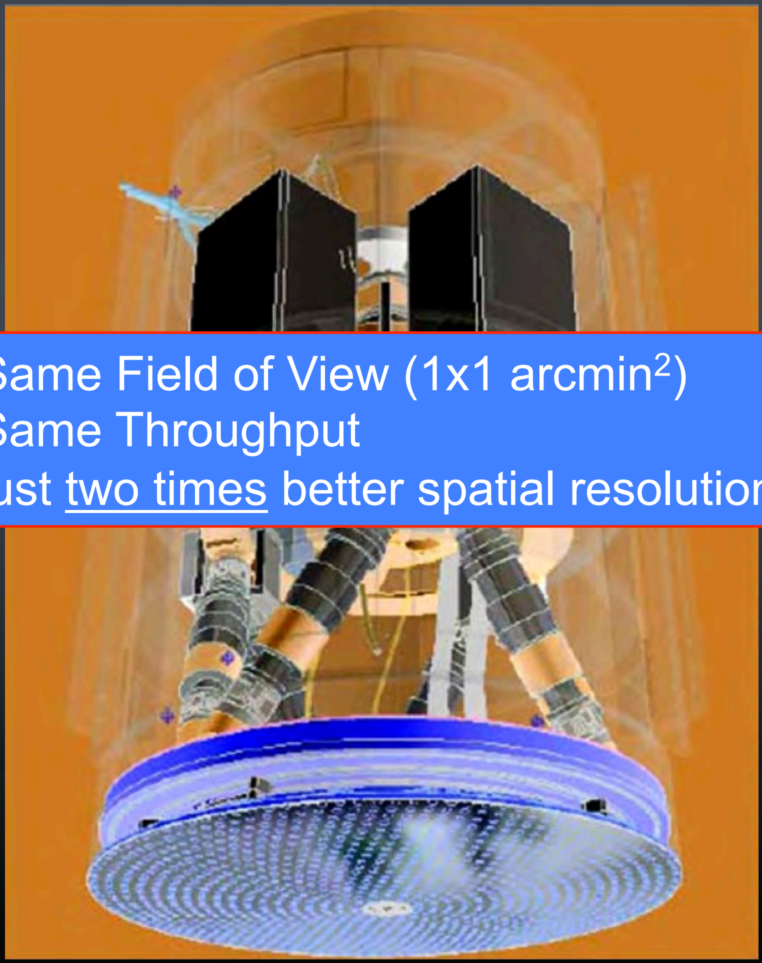
- **MUSE GTO observing (250 nights over 5 years)**
  - **Multiple fields to ~100 hours and many (50?) fields to ~10 hours depth.**



MUSE Hubble UDF 3x3 arcmin^2 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 $arcsec^2$ field of view
  - Diffraction limited image
    - 10% Strehl @ 6500 A
    - 25% Strehl @ 8500 A

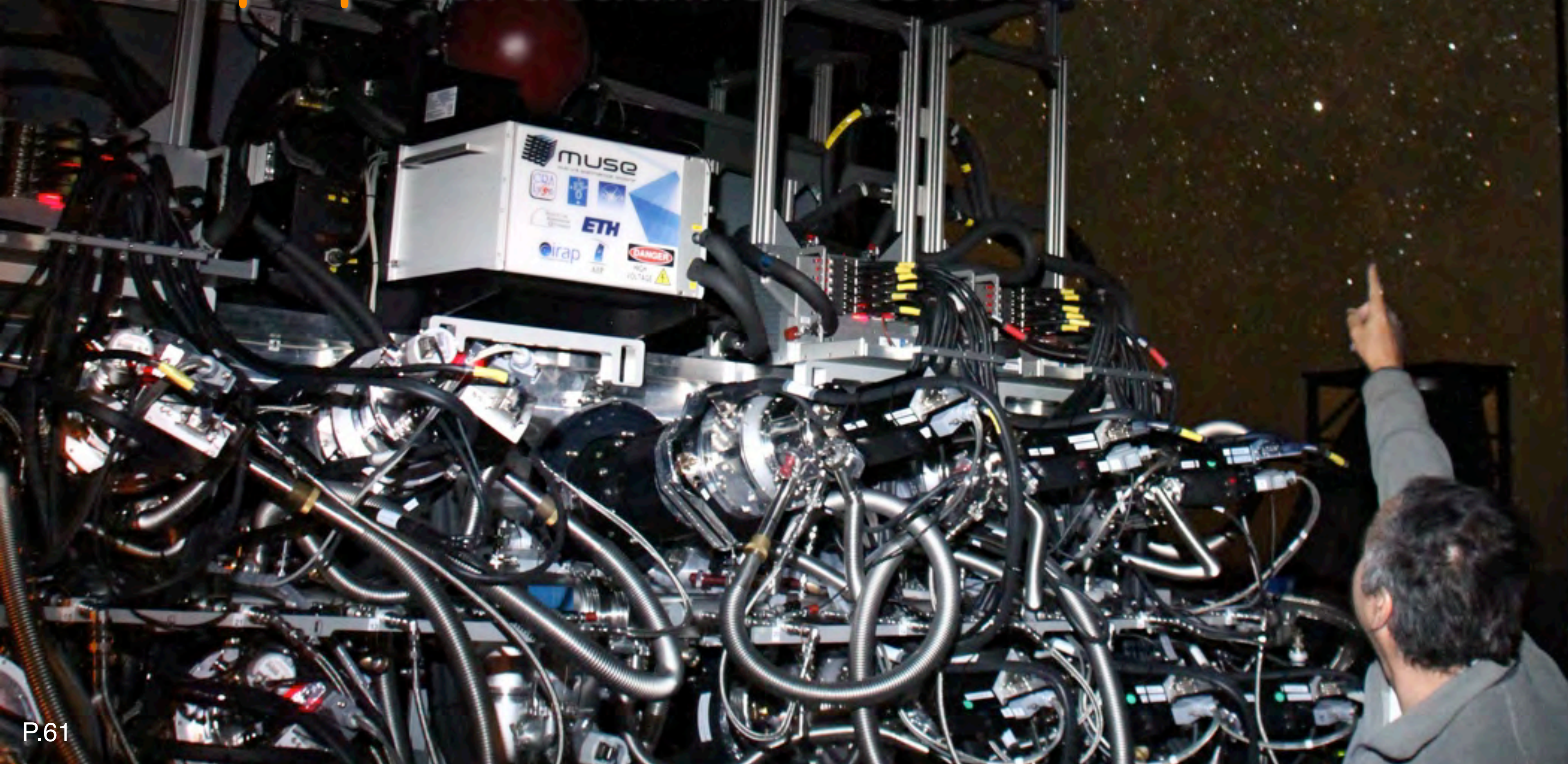


Same Field of View (1x1 $arcmin^2$)
Same Throughput
just two times better spatial resolution

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