Science prospects with MUSE at the VLT

Roland Bacon, Johan Richard
CRAL

The Blue MUSE Australian Tour
Feb 21 – Mar 2 2018
1st stop: CAS, Swinburne
MUSE in a nutshell

- Large field IFU 2nd generation VLT instrument
- Visible 480-930 nm, R~3000
- Field 1’x1’, 0.2” (WFM)
- Field 7"x7", 0.025" (NFM)
- Coupled to ESO AO Facility
  - 0.5” (WFM) & diffraction limited (NFM) resolution
- Throughput
  - 40% end-to-end

- Consortium
  - CRAL, IRAP, Leiden, AIP, AIG, ETH, ESO
- Time-line
  - 2001: Call for idea
  - 2004: ESO Contract
  - 2014: First light non AO WFM
  - 2017: First light GLAO WFM
  - 2018: First light LTAO NFM
- Cost: 20 M€ (7 M€ Hardware)
- GTO
  - 255 nights
  - Science team: ~80 scientists
### MUSE statistics

#### Requested Nights

<table>
<thead>
<tr>
<th></th>
<th>XShooter</th>
<th>MUSE</th>
<th>FORS2</th>
</tr>
</thead>
<tbody>
<tr>
<td>P97</td>
<td>221</td>
<td>220</td>
<td>215</td>
</tr>
<tr>
<td>P98</td>
<td>255</td>
<td>229</td>
<td>231</td>
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<td>P99</td>
<td>188</td>
<td>203</td>
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<td>P100</td>
<td>287</td>
<td>266</td>
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<tr>
<td>P101</td>
<td>201</td>
<td>186</td>
<td>177</td>
</tr>
</tbody>
</table>

407 papers, 1744 citations (as of 14/02/2018)
The Pillars of Creation revisited with MUSE: gas kinematics and high-mass stellar feedback traced by optical spectroscopy, A. McLeod, 2015, MNRAS, 450, 1057

A MUSE map of the central Orion Nebula (M 42), P. Weilbacher, 2015, A&A, 582, 114
Looking inside Orion datacube

- Mosaic of 30 fields (6x5 arcmin²)
- Jan 2014 (Commissioning)
- 5 seconds integration by exposure
- 5 millions of spectra
- Datacube of $10^{10}$ voxels

![MUSE crowded field 3D spectroscopy in nearby galaxies I. First results from central fields in NGC300, M. Roth et al, A&A, submitted](image)

### Table: Field Analysis

<table>
<thead>
<tr>
<th>Field</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
<th>(e)</th>
<th>(i)</th>
<th>(j)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeing</td>
<td>0.7&quot;</td>
<td>1.2&quot;</td>
<td>1.0&quot;</td>
<td>0.8&quot;</td>
<td>0.75&quot;</td>
<td>0.6&quot;</td>
<td>0.85&quot;</td>
<td></td>
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<tr>
<td>Planetary nebulae (bona fide)</td>
<td>5</td>
<td>7</td>
<td>6</td>
<td>4</td>
<td>9</td>
<td>3</td>
<td>2</td>
<td>36</td>
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<tr>
<td>Planetary nebula candidates</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>9</td>
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<tr>
<td>H\text{\textsc{ii}} regions</td>
<td>10</td>
<td>11</td>
<td>5</td>
<td>13</td>
<td>4</td>
<td>13</td>
<td>5</td>
<td>61</td>
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<tr>
<td>compact H\text{\textsc{ii}} region candidates</td>
<td>8</td>
<td>4</td>
<td>5</td>
<td>19</td>
<td>5</td>
<td>2</td>
<td>8</td>
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<td>Supernova remnant candidates</td>
<td>14</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>38</td>
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<tr>
<td>Emission line stars</td>
<td>18</td>
<td>4</td>
<td>4</td>
<td>15</td>
<td>30</td>
<td>40</td>
<td>7</td>
<td>118</td>
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<tr>
<td>Background galaxies</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>6</td>
<td>2</td>
<td>8</td>
<td>4</td>
<td>28</td>
</tr>
<tr>
<td>Stars</td>
<td>445</td>
<td>77</td>
<td>152</td>
<td>265</td>
<td>299</td>
<td>517</td>
<td>91</td>
<td>1846</td>
</tr>
</tbody>
</table>
A stellar census in globular clusters with MUSE. The contribution of rotation to cluster dynamics studied with 200,000 stars, S. Kamann, MNRAS, 473, 2018

12,000 resolved stars, 6,000 with S/N > 10
Exposure time 9 mn

M2 - 17 stars with spectroscopy from FLAMES GIRAFFE 45 mn exposure
A stellar census in globular clusters with MUSE. The contribution of rotation to cluster dynamics studied with 200 000 stars, S. Kamann, MNRAS, 473, 2018
Mapping the inner regions of the polar disk galaxy NGC 4650A with MUSE


GASP collaboration
High redshift galaxies

Ubiquitous Giant Ly$\alpha$ Nebulae around the Brightest Quasars at $z \sim 3.5$ Revealed with MUSE, E. Borosiva et al, 2016, ApJ, 831, 39
Lensing Clusters

18 images with spec-z FORS/VLT, LDSS3/ Magellan, GLAS/HST


90 images with spec-z MUSE/VLT 2018

Lensing Clusters

The MUSE Hubble Ultra Deep Field Survey

The deepest spectroscopic survey ever performed, 10 & 30 hours depth, 1600 redshifts
Redshifts in the mosaic field

MUSE mosaic white-light image

AB Magnitude (F775W)

N2
Redshifts in the mosaic field

Previous spectroscopic redshifts [142]
MUSE redshifts ORIGIN & HSTPrior [1443]
$z = 0.423 \text{ AB} = 27.07$

$z = 1.220 \text{ AB} = 21.03$

$z = 1.306 \text{ AB} = 25.59$

$z = 1.550 \text{ AB} = 24.80$

$z = 1.756 \text{ AB} = 29.34$
Lya Z = 5.91
AB F850LP > 30.7

Paper I: Bacon et al 2017
The MUSE Hubble Ultra Deep

72 Ly$\alpha$ without HST counterpart

Pre MUSE
142 spectro-z
AB<25
z<3

In 10 years
x 10 spectro-z
+ 6 magnitudes
+ 4 z bins

MUSE
1443 spectro-z
AB<31
z<7

In 100 hours of VLT

ESO - Göttingen - Leiden - Lyon - Potsdam - Toulouse - Zurich
I. Survey description, data reduction and source detection, Bacon et al
II. Spectroscopic redshifts and comparisons to color selections of high-redshift galaxies, Inami et al.
III. Testing photometric redshifts to 30th magnitude, Brinchmann et al.
IV. Global properties of C III] emitters, Maseda et al.
V. Spatially resolved stellar kinematics of galaxies at redshift 0.2<z<0.8, Guerou et al.
VI. The Faint-End of the Ly$\alpha$ Luminosity Function at 2.91 < z < 6.64 and Implications for Reionisation, Drake et al.
VII. FeII* Emission in Star-Forming Galaxies, Finley et al.
VIII. Extended Lyman-alpha haloes around high-redshift star-forming galaxies, Leclercq et al.
IX. Evolution of galaxy merger fraction since z~6, Ventou et al.
X. Ly$\alpha$ Equivalent Widths at 2.9<z<6.6, Hashimoto et al.
A Blue MUSE for the VLT

Johan Richard, Roland Bacon, Patrick Caillier (CRAL)
Eduard Muslinov, Emmanuel Hugot (LAM)
Johan Kosmalski (ESO)
Rationale

- MUSE is a success: it is unique, largely over-subscribed, and has a high publication rate.
- There is room for a 2nd MUSE type instrument.
- By 2025-2030 the ELT and JWST instruments will focus on red and infrared wavelengths.
- A Spectroscopic Survey telescope is a long-term, attractive solution.
- The best mid-term solution is a complementary MUSE on another UT: the Blue MUSE.
Top Level Parameters

- Blue wavelength coverage: 370 - 600 nm
  - Complementarity with MUSE
  - Bluest limit adapted to atmosphere transmission (70% transmission)
  - Red limit recovers AO notch filter gap.
Top Level Parameters

- High throughput (end-to-end)
Top Level Parameters

- Medium spectral resolution: $R=4200$ in average
  - Corresponds to 30 km/s at 480 nm
  - more than twice the MUSE spectral resolution at $500 \text{ nm} < \lambda < 600 \text{ nm}$
  - Spectral sampling: 0.6 Å / pixel
Top Level Parameters

- Larger field of view: 1.4 x 1.4 arcmin

Sampling: 0.3” pixels (0.8” median seeing)
Globular clusters
Globular clusters

- Stellar parameters of 1000s of stars in a single pointing
- Intermediate mass black holes
- Stellar black holes detected from companions

Karman et al. 2017, Giesers et al. 2018
Star nebulae

- Resolved physical processes (ionisation parameter, extinction), physics of outflows
- Kinematics of nebulae, Herbig-Haro objects (~ 10 km/s)

Weilbacher et al. 2016
Dwarf and nearby galaxies

• Getting down to $< 10^6$ Msun BH masses in low mass galactic nuclei (Nguyen et al. 2018)

• Precise dynamical masses of nearby ultra-faint dwarf galaxies (e.g. crater Voggel et al. 2016)

• Velocity dispersion of multiple UCDs in a single pointing
Resolved stellar populations and kinematics

Galactic cores, bulges: from absorption line indices, kinematic moments
Discs of star-forming galaxies: local vs global star formation history

- High spectral resolution is crucial for kinemetric models.
Low surface brightness sources

- Galactic Halos
- Thick Disks
- Tidal streams
- Intracluster Light.

Adami et al. 2016 (z=0.53 cluster)

MUSE-V  MUSE-I  MUSE-Hb,[OIII]

Galianni et al. 2010

NGC1097 (FORS)
Physics of outflows and UV nebular lines at $0.5 < z < 3$
Physics of outflows and UV nebular lines at $0.5 < z < 3$

- Outflows at $z > 0.3$
  - Finley et al. 2017

- At $1 < z < 3$, CIII], CIV, HeII and OIII] nebular emission
  - Stark et al. 2014
Deep Fields

- UV cosmic SFR peaks in this redshift range

- MUSE Deep fields (> 10 hrs per pointing) reveal faint emission line galaxies, and in majority Lyman-alpha emitters (LAEs)

Madau & Dickinson (2010)

UDF + MUSE:
185 unique LAEs at 3<z<6.7

UDF+MUSE-Blue:
> 400 unique LAEs at 2<z<4
High-redshift galaxies
Lyman-α at 2 < z < 4

- Lyman-alpha emission can help to probe the diffuse gas in the circumgalactic medium.

- Blue-MUSE can probe this diffuse gas down to z=2 and benefit from surface brightness dimming (gain x3 between z=3 and z=2)
High-redshift galaxies
Lyman-α at $2 < z < 4$

- Higher spectral resolution helps to study Lyman-alpha profiles
- Blue wavelength helps to identify Lyman continuum leakers at $z=3-4$
Lensed galaxies by massive clusters

- Magnification allows to probe lower mass / luminosity galaxies
- Massive clusters have a magnification region extending to 1.5-2 arcmin.
- $2 < z < 4$ is the peak of the redshift distribution for multiply-imaged galaxies

Mahler et al. 2018
Uniqueness

- Unique combination of large FoV, resolution and wavelength

- Keck Cosmic Web Imager (KCWI): 8.24” x 20.4”
Synergies

SAMI (Bloom et al. 2017)

MUSE (Erroz et al. 2018, subm.)
(den Brok et al. 2018, in prep.)
A first optical design has been found for first feasibility.

MUSE already takes the entire space on the VLT Nasmyth platform: a larger FOV needs larger optics and seems difficult.

The solution currently studied is the use of curved detectors.
Optical design

MUSE

Blue-MUSE (flat)

Blue-MUSE (curved)
## Complementarity with MUSE red

<table>
<thead>
<tr>
<th></th>
<th>MUSE Red</th>
<th>MUSE Blue (curved)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of view</td>
<td>1x1 arcmin$^2$</td>
<td>1.4x1.4 arcmin$^2$</td>
<td>Factor 2 in area</td>
</tr>
<tr>
<td>Sampling</td>
<td>0.2x0.2 arcsec$^2$</td>
<td>0.3x0.3 arcsec$^2$</td>
<td></td>
</tr>
<tr>
<td>Median spatial</td>
<td>0.4 arcsec with AOF</td>
<td>0.8 arcsec</td>
<td>(seeing limited)</td>
</tr>
<tr>
<td>resolution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength range</td>
<td>480-930 nm</td>
<td>370-600 nm</td>
<td>No 580 nm Na gap</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>1800 @ 480 nm</td>
<td>3000 @ 370 nm</td>
<td>Factor 2 higher</td>
</tr>
<tr>
<td></td>
<td>3500 @ 930 nm</td>
<td>5000 @ 600 nm</td>
<td></td>
</tr>
<tr>
<td>Spectral sampling</td>
<td>2 pixels</td>
<td>2 pixels</td>
<td></td>
</tr>
<tr>
<td>Narrow Field Mode</td>
<td>7x7 arcsec$^2$ 0.025 arcsec</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>OH sky lines</td>
<td>Many &gt; 0.8 nm</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Throughput</td>
<td>0.35 @ 700 nm</td>
<td>similar</td>
<td>No filter needed for 2$^{nd}$ order</td>
</tr>
</tbody>
</table>
Feasibility & Risks

• All technology exists: slicer, spectrograph, etc.
• No narrow-field mode, no AO coupling, one single mode
• Larger size than MUSE red, needs some design optimization to fit in the platform
• Larger optical derotator
• Lesson learned from MUSE red
  – Temperature control of the whole instrument
• Cost
  – More expensive on hardware (larger optics in spectrograph, slicer and derotator)
  – Less expensive in development
  – Current estimate: 10 Meuros hardware.
• Backup solution
  – 1x1 arcmin² field of view, smaller optics, 4k x 4k flat detector, smaller spectral range (eg 370-500 nm)
Conclusions

• Blue MUSE is a unique opportunity to maintain our world leadership in the era of IFU science.
• There is a strong synergy (technical and scientific) between IFU developments in Australia and Europe.
• Complementary to the current MUSE red and to the ELT (no blue sensitive instrument for the ELT).
• Little risk, benefit from all existing developments and community know-how
Starving Black Hole Returns Brilliant Galaxy to the Shadows

15 September 2016: The mystery of a rare change in the behaviour of a supermassive black hole at the centre of a distant galaxy has been solved by an international team of astronomers using ESO’s Very Large Telescope along with the NASA/ESA Hubble Space Telescope and NASA’s Chandra X-ray Observatory. It seems that the black hole has fallen on hard times and is no longer being fed enough fuel to make its surroundings shine.

Odd Behaviour of Star Reveals Lonely Black Hole Hiding in Giant Star Cluster

17 January 2018: Astronomers using ESO’s MUSE instrument on the Very Large Telescope in Chile have discovered a star in the cluster NGC 3201 that is behaving very strangely. It appears to be orbiting an invisible black hole with about four times the mass of the Sun — the first such inactive stellar-mass black hole found in a globular cluster and the first found by directly detecting its gravitational pull. This important discovery impacts on our understanding of the formation of...

MUSE Probes Uncharted Depths of Hubble Ultra Deep Field

29 November 2017: Astronomers using the MUSE instrument on ESO’s Very Large Telescope in Chile have conducted the deepest spectroscopic survey ever. They focused on the Hubble Ultra Deep Field, measuring distances and properties of 1600 very faint galaxies including 72 galaxies that have never been detected before, even by Hubble itself. This groundbreaking dataset has already resulted in 10 science papers that are being published in a special...