Science prospects with MUSE at the VLT

Johan Richard
CRAL

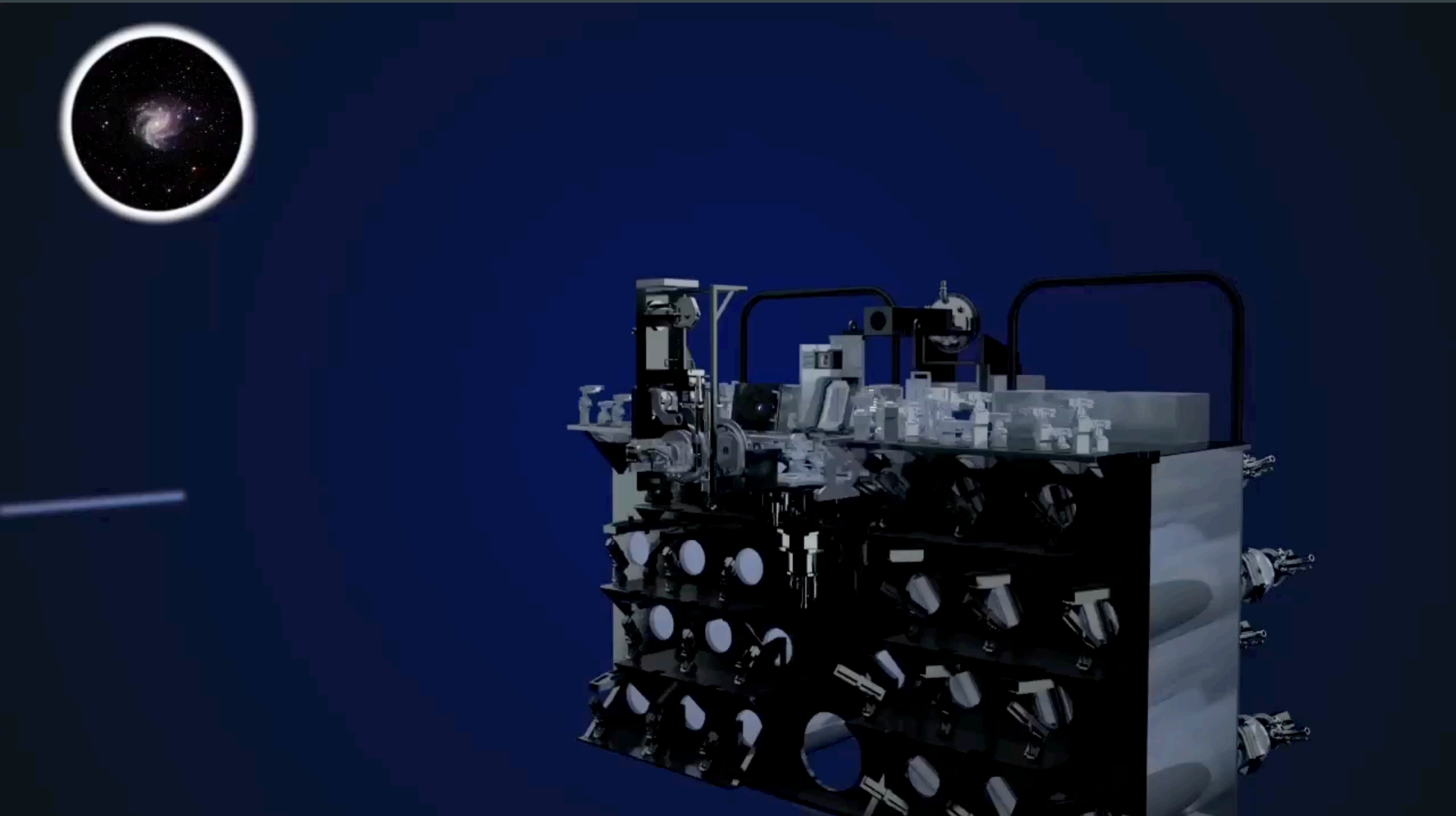
The Blue MUSE European Tour

CEA, Sep. 10th 2018

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

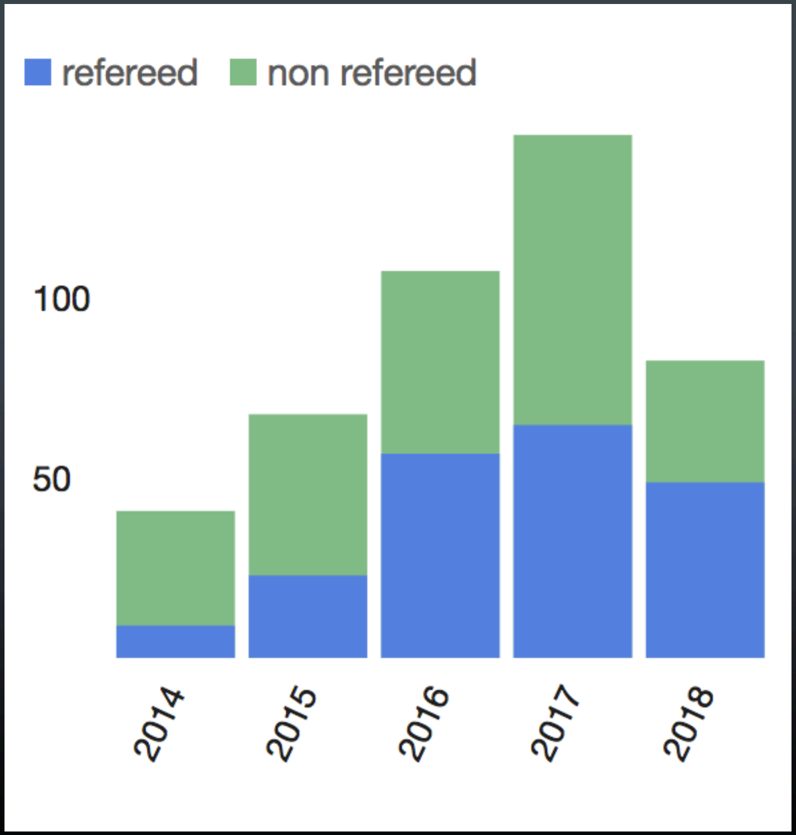
- Consortium
  - CRAL,IRAP,Leiden,AIP, AIG, ETH, ESO
- Time-line
  - 2001: Call for idea
  - 2004: ESO Contract
  - 2014: First light non AO WFM
  - 2017: First light GLAO WFM
  - 2018: First light LTAO NFM
- Cost: 20 M€ (7 M€ Hardware)
- GTO
  - 255 nights
  - Science team: ~80 scientists



MUSE statistics

Requested Nights

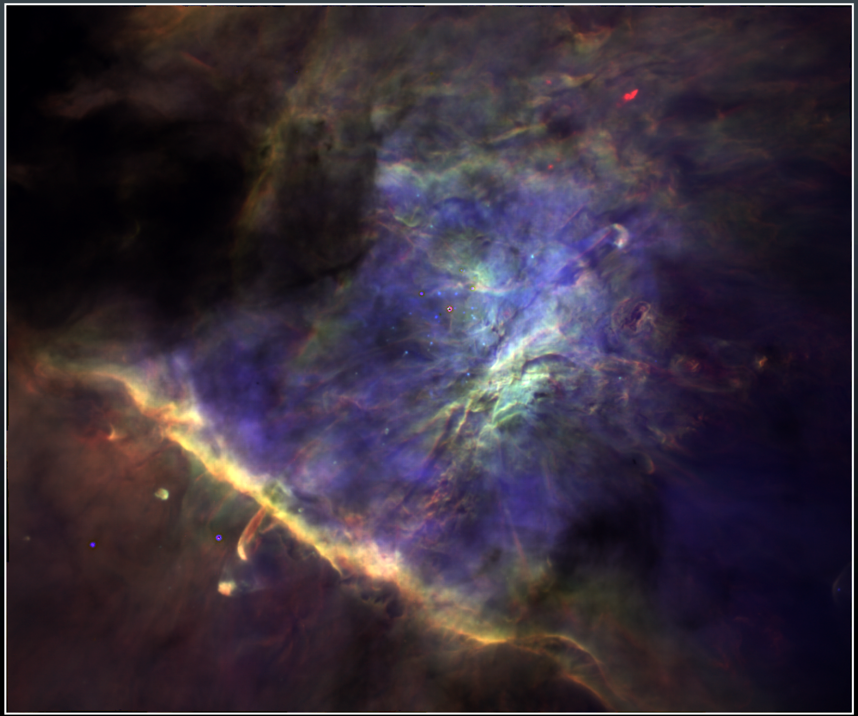
	XShooter	MUSE	FORS2
P97	221	220	215
P98	255	229	231
P99	188	203	198
P100	287	266	196
P101	201	186	177
P102	274	277	222



446 papers, 2338 citations
(as of 3/07/2018)

Diffuse Nebulae

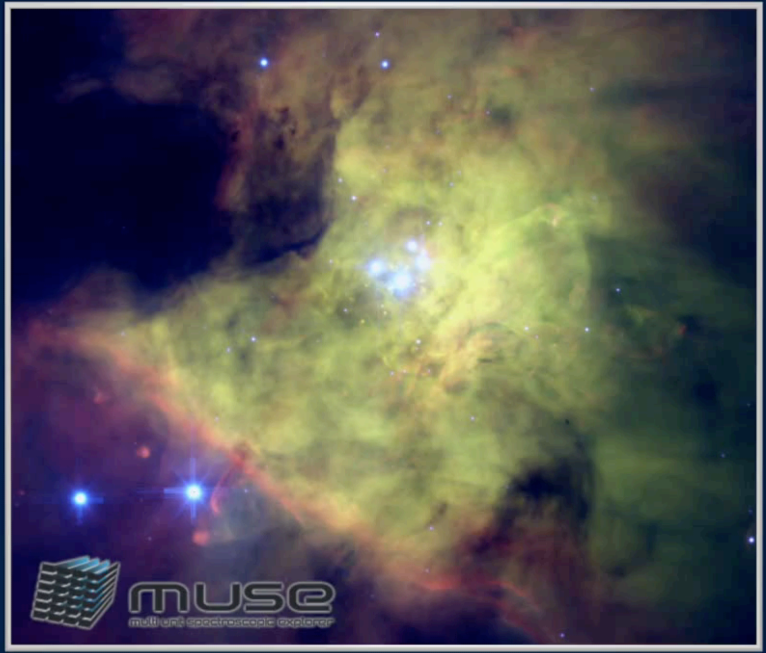
The Pillars of Creation revisited with MUSE: gas kinematics and high-mass stellar feedback traced by optical spectroscopy, A. McLeod, 2015, MNRAS, 450, 1057

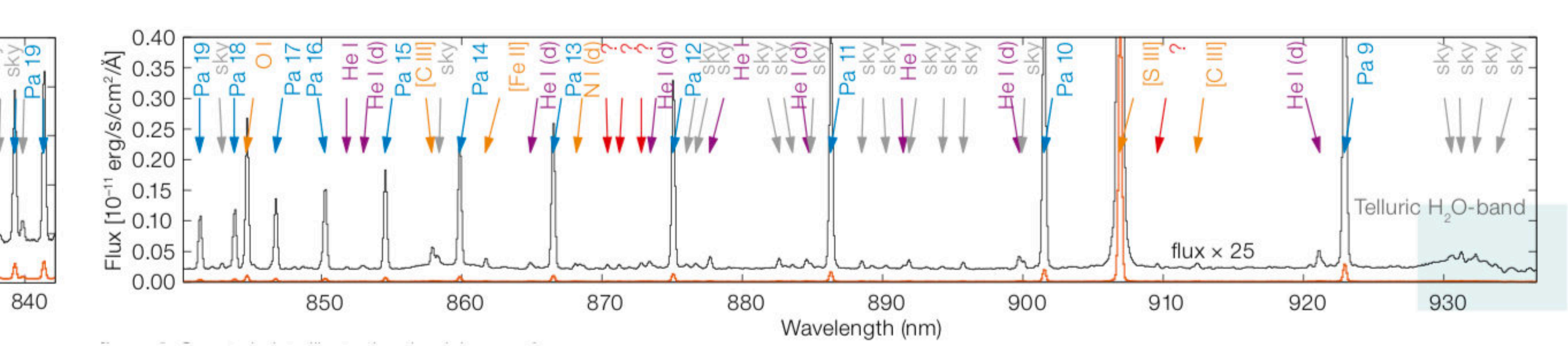


A MUSE map of the central Orion Nebula (M 42), P. Weilbacher, 2015, A&A, 582, 114

Looking inside Orion datacube

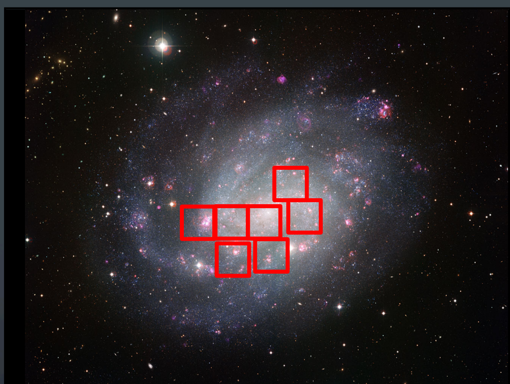
- Mosaic of **30 fields** (6x5 arcmin^2)
- Jan 2014 (Commissioning)
- **5 seconds** integration by exposure
- **5 millions** of spectra
- Datacube of **10^{10}** voxels

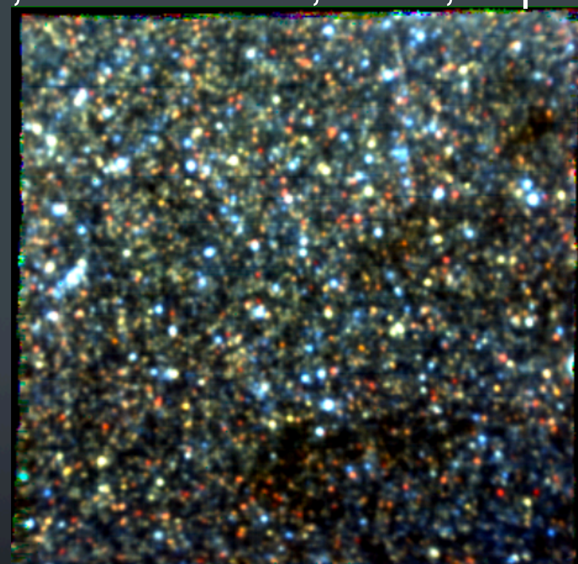


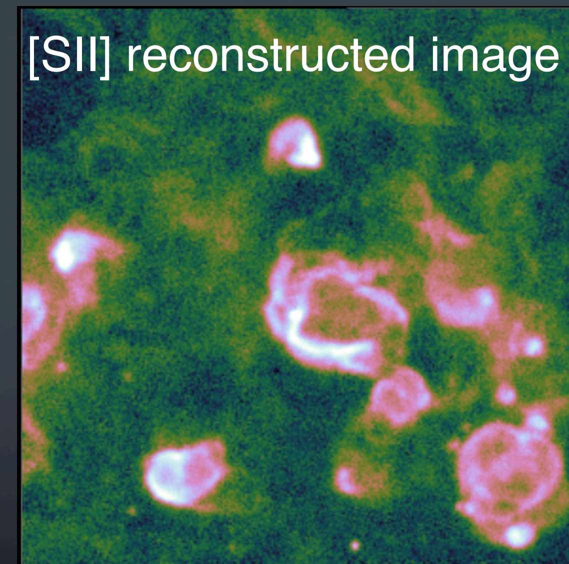


Massive Spectroscopy

MUSE crowded field 3D spectroscopy in nearby galaxies I. First results from central fields in NGC300, M. Roth et al, A&A, in press



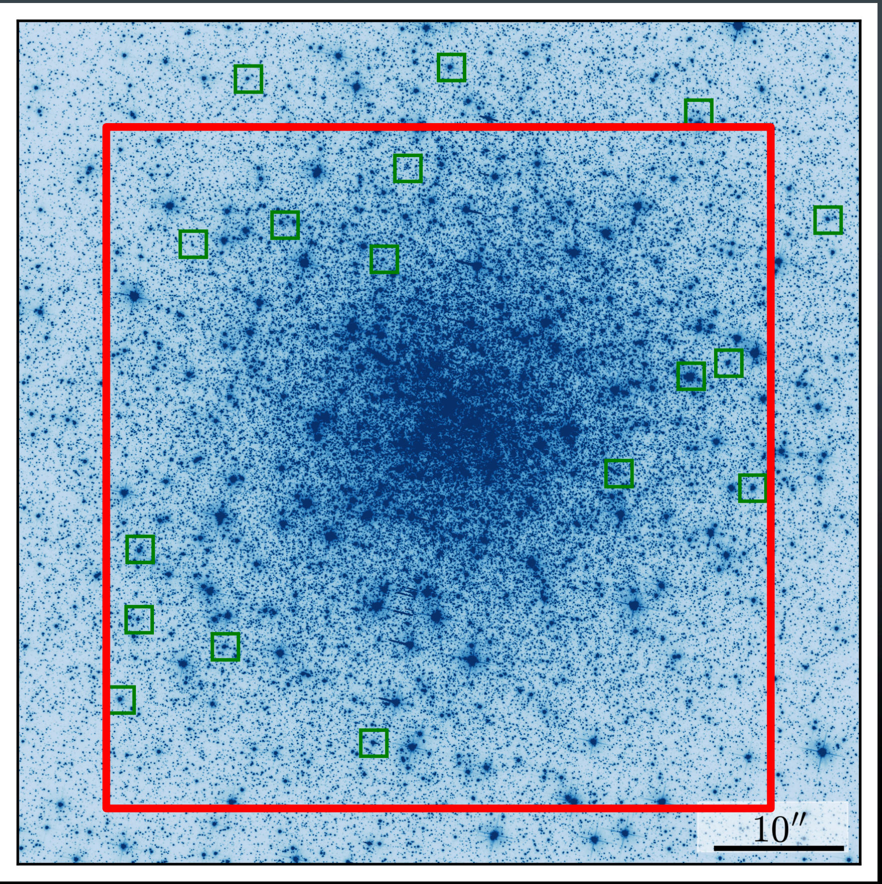




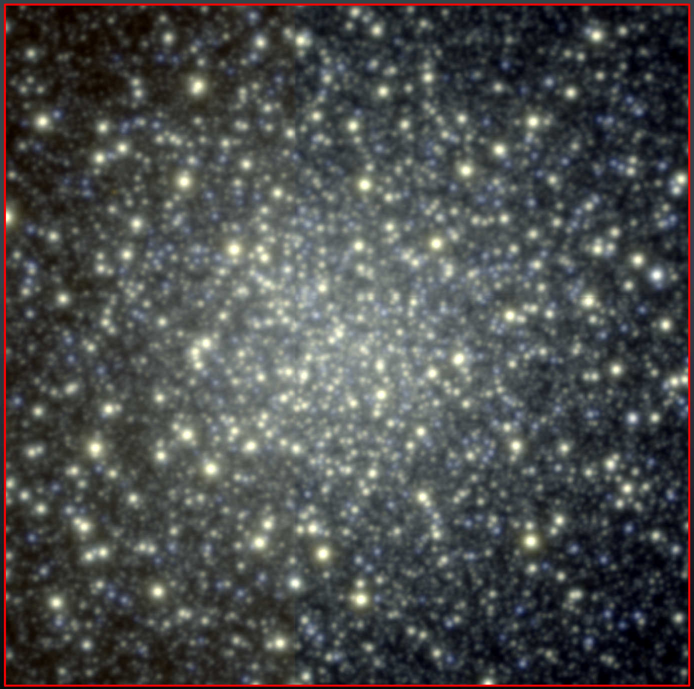
field	(a)	(b)	(c)	(d)	(e)	(i)	(j)	total
Seeing	0.7"	1.2"	1.0"	0.8"	0.75"	0.6"	0.85"	
Planetary nebulae (bona fide)	5	7	6	4	9	3	2	36
Planetary nebula candidates	4	0	0	1	4	0	0	9
H II regions	10	11	5	13	4	13	5	61
compact H II region candidates	8	4	5	19	5	2	8	51
Supernova remnant candidates	14	5	3	5	3	6	2	38
Emission line stars	18	4	4	15	30	40	7	118
Background galaxies	4	3	1	6	2	8	4	28
Stars	445:	77:	152:	265:	299:	517	91:	1846

Massive spectroscopy

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



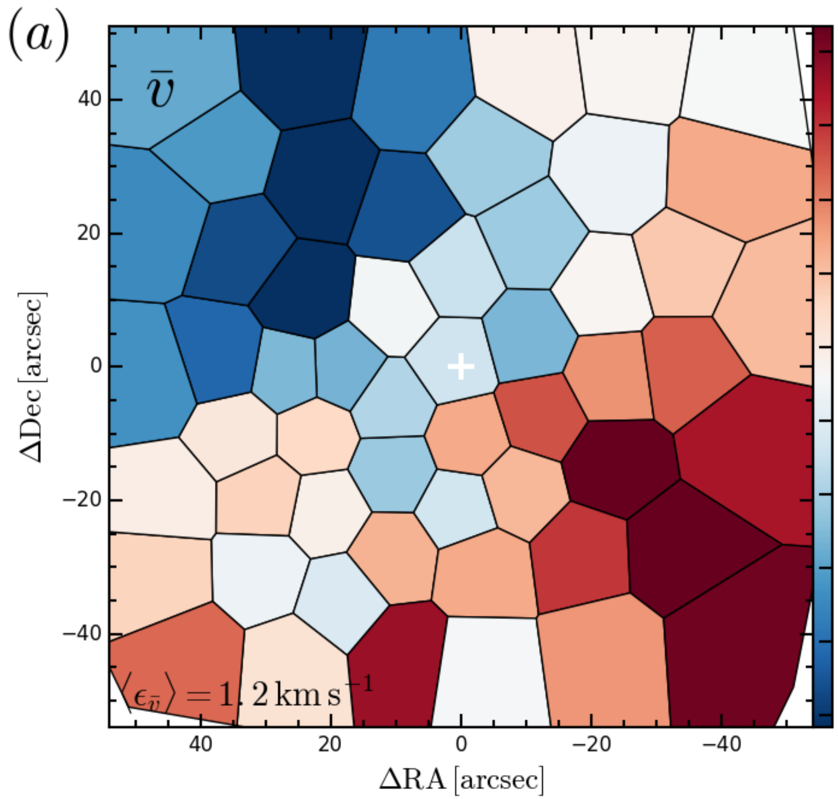
M2 - 17 stars with spectroscopy from FLAMES GIRAFFE 45 mn exposure

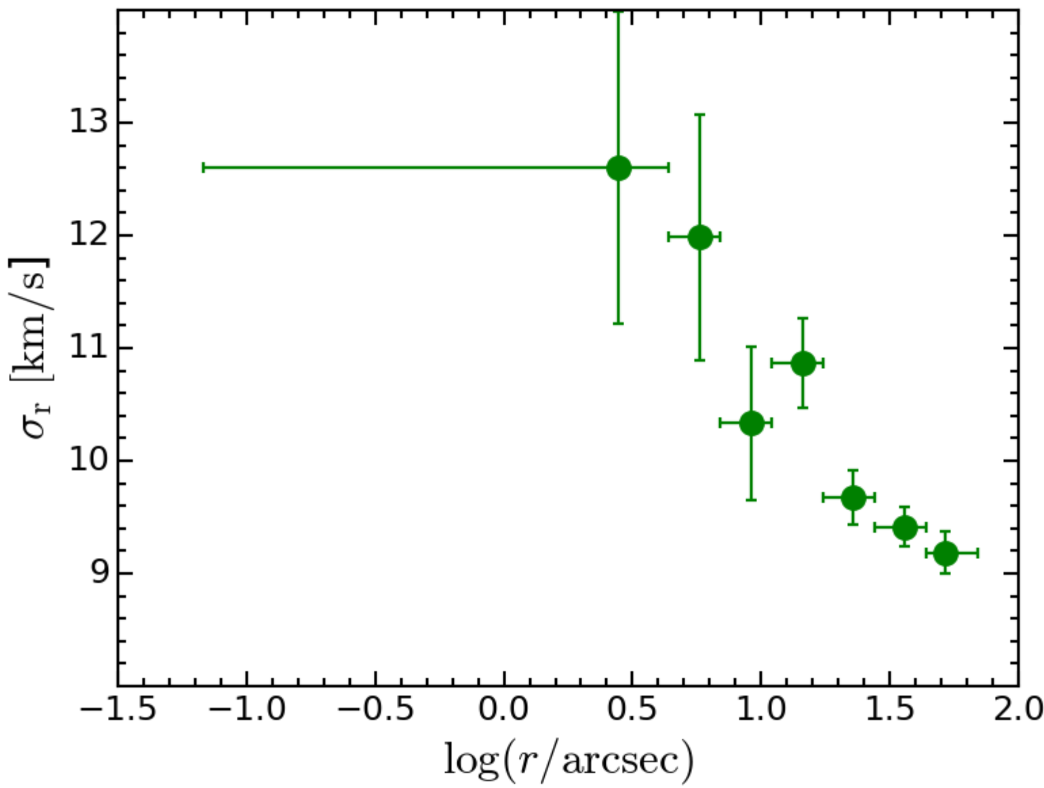


12 000 resolved stars, 6 000 with S/N>10
Exposure time 9 mn

Massive spectroscopy

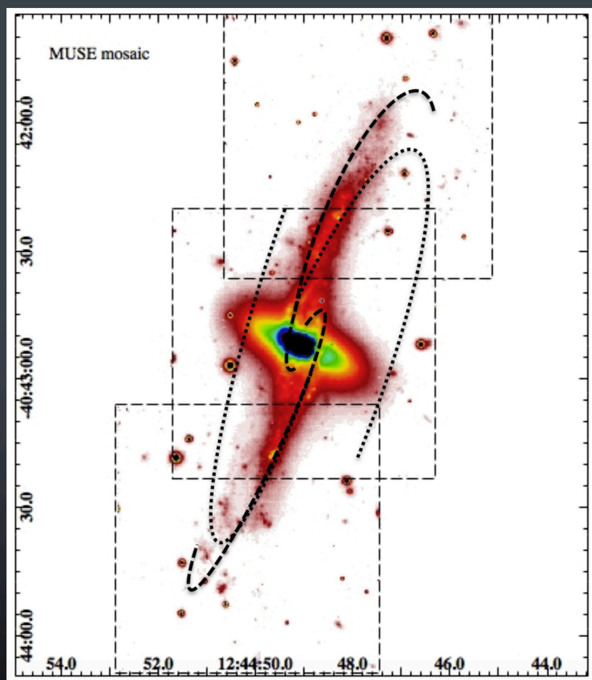
A stellar census in globular clusters with MUSE. The contribution of rotation to cluster dynamics studied with 200 000 stars, S. Kamann, MNRAS, 473, 2018



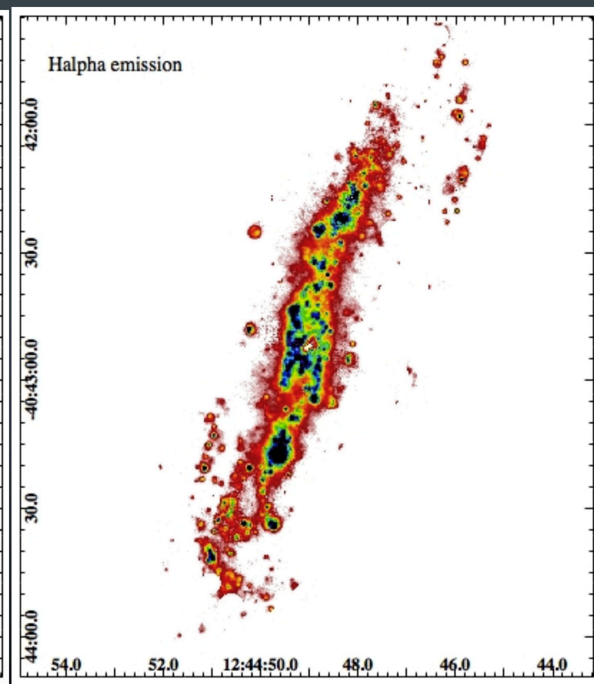


Nearby Galaxies

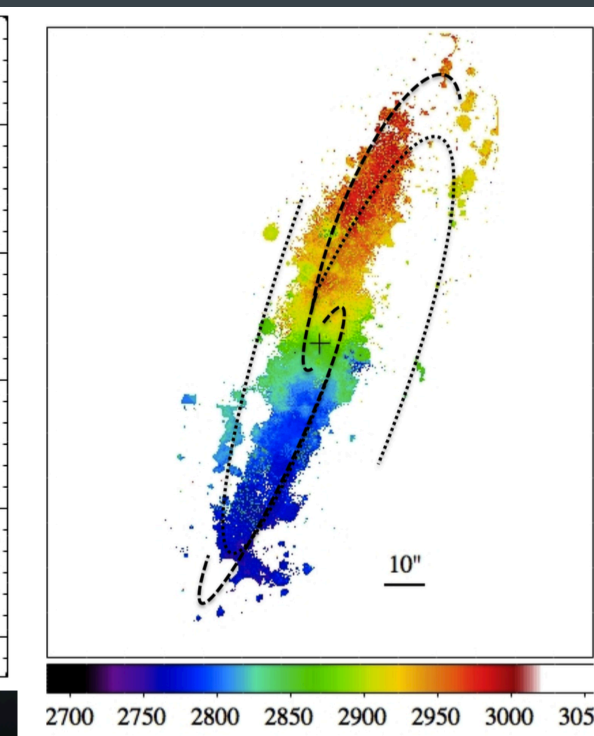
Continuum map



Ha map

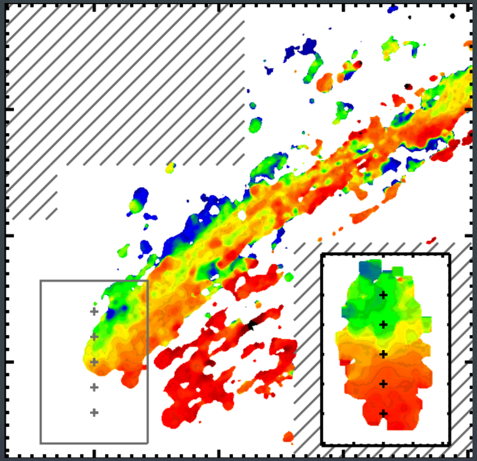


Ha velocity field



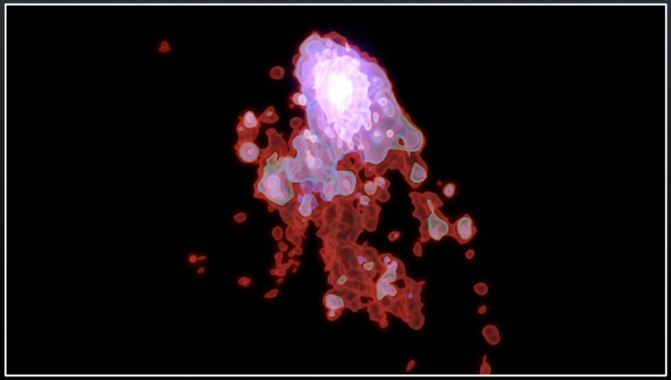
Mapping the inner regions of the polar disk galaxy NGC 4650A with MUSE
E. Iodice, L. Coccato, F. Combes, T. de Zeeuw, et al, A&A 583, A48 (2015)

Jellyfish Galaxies



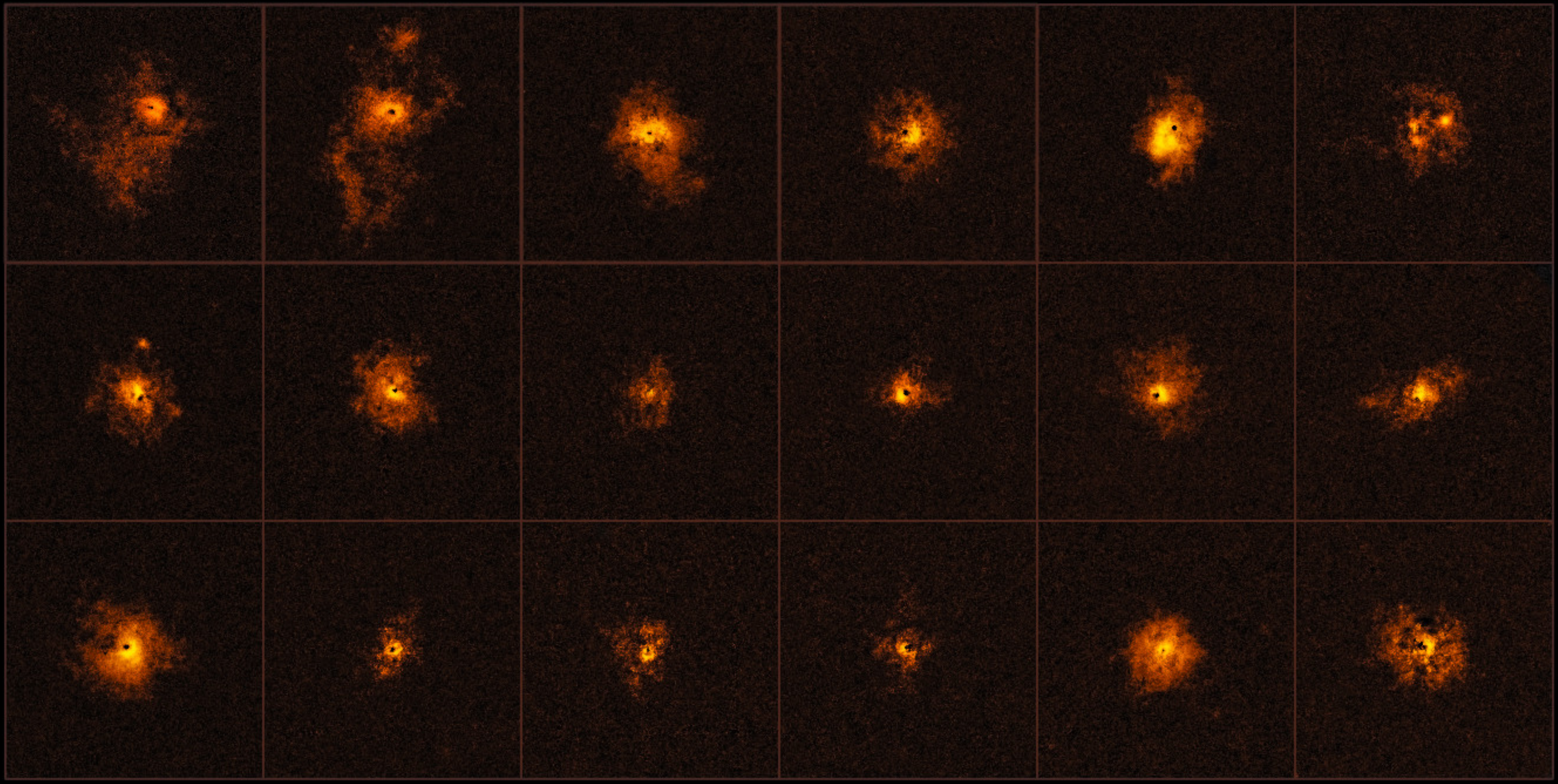
MUSE sneaks a peek at extreme ram-pressure stripping events - I. A kinematic study of the archetypal galaxy ESO137-001, M. Fumagalli et al, 2014, MNRAS, 445, 4

Ram Pressure Feeding Supermassive Black Holes, B. Poggianti, Y. Jaffé et al, 2017, Nature, 548, 7667



GASP collaboration

High redshift galaxies



Ubiquitous Giant Lyα Nebulae around the Brightest Quasars at z ~3.5 Revealed with MUSE, E. Borisova et al, 2016, ApJ, 831, 39

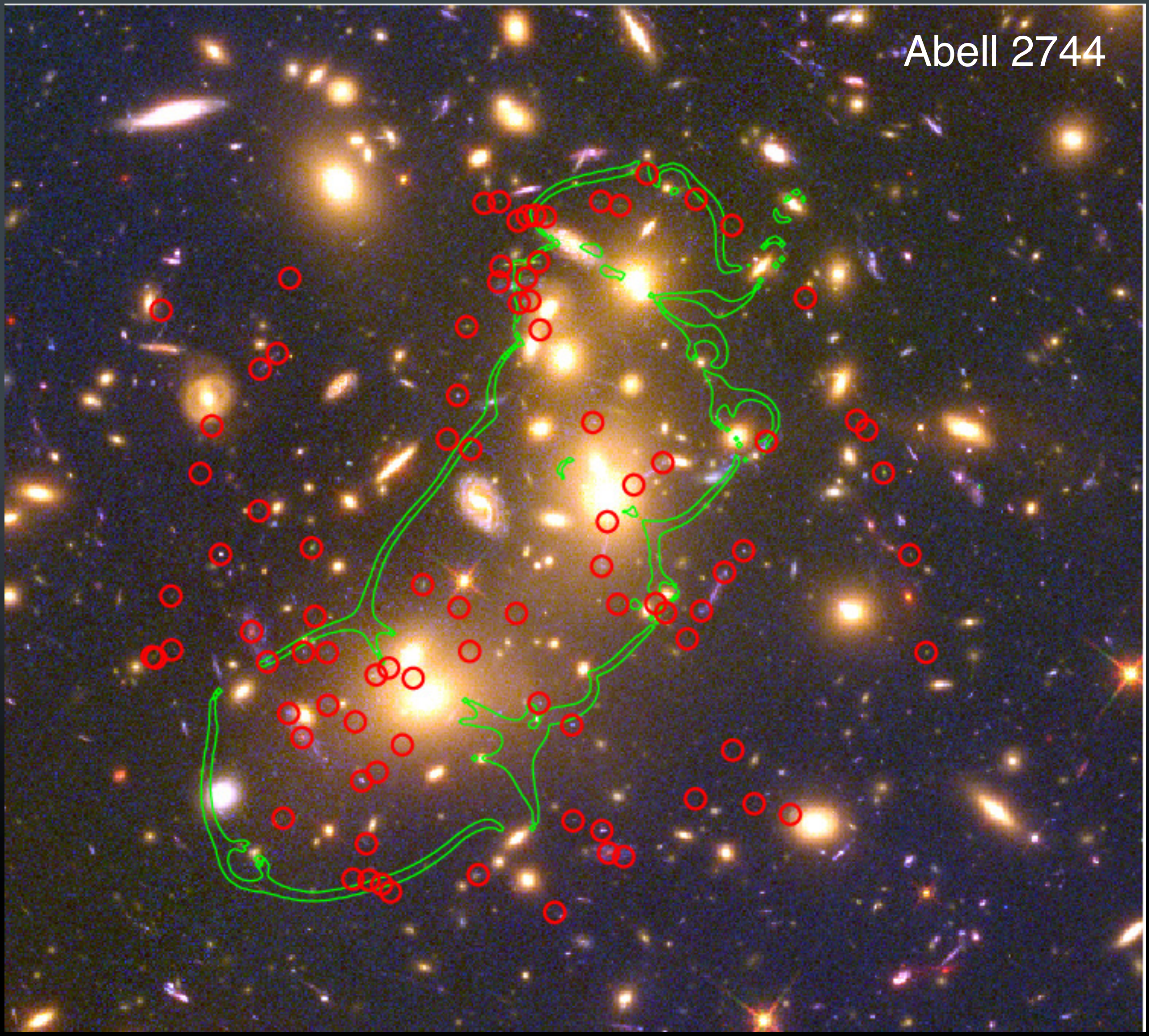
Lensing Clusters

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

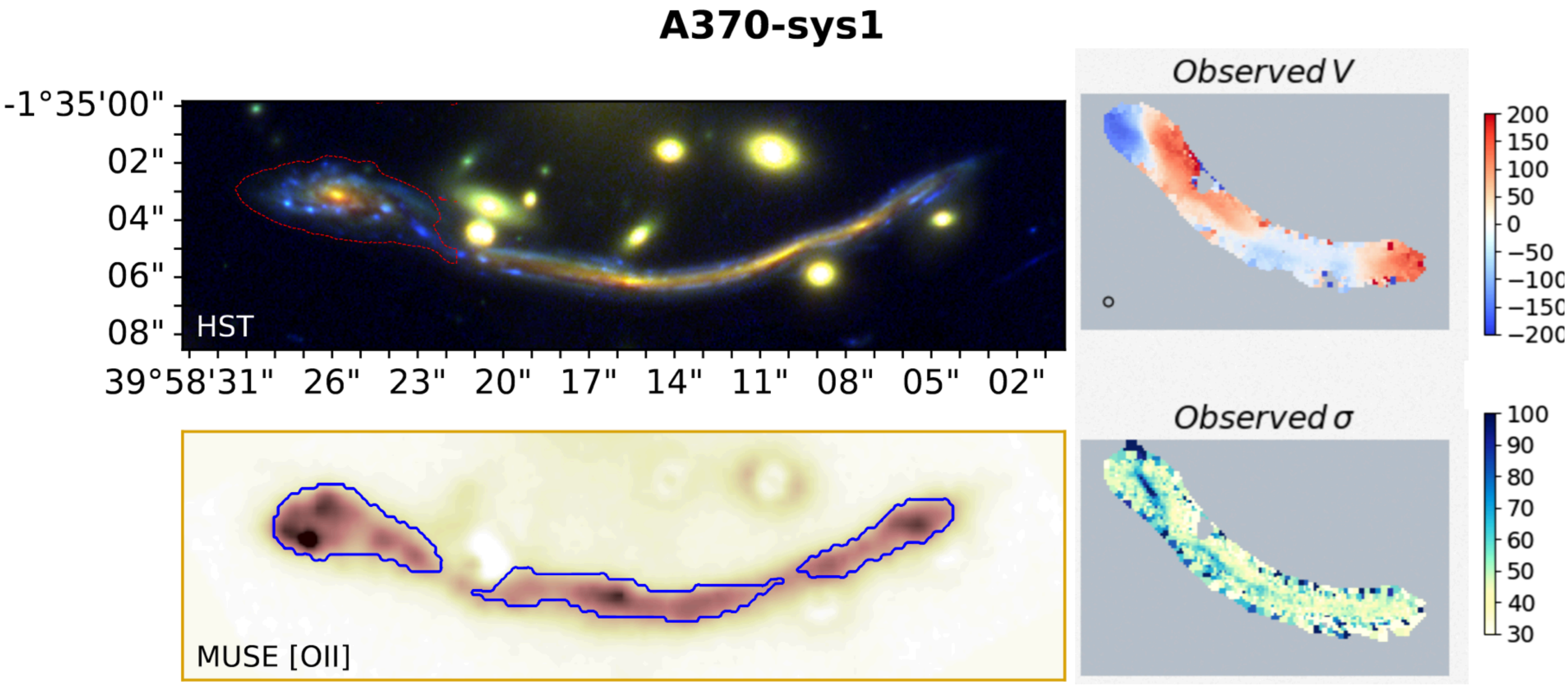
Richard et al 2014,
Johnson et al 2014
Wang et al 2015

90 images with spec-z
MUSE/VLT 2018

Strong lensing analysis of Abell 2744 with MUSE and Hubble Frontier Fields images, Mahler, Richard et al, MNRAS, 2018, 473, 663



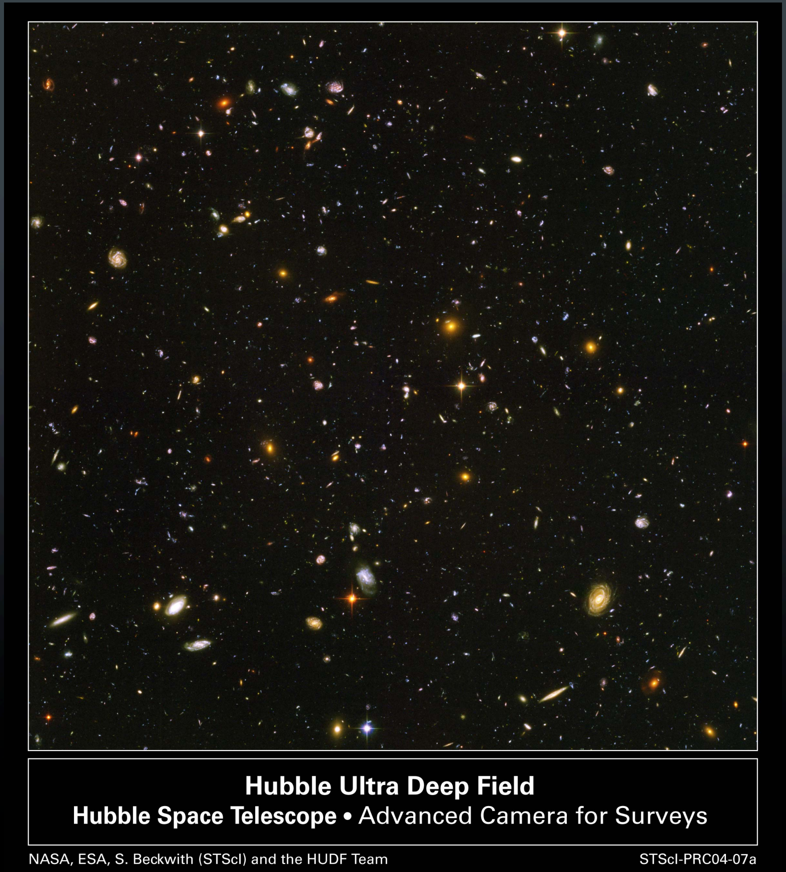
Lensing Clusters

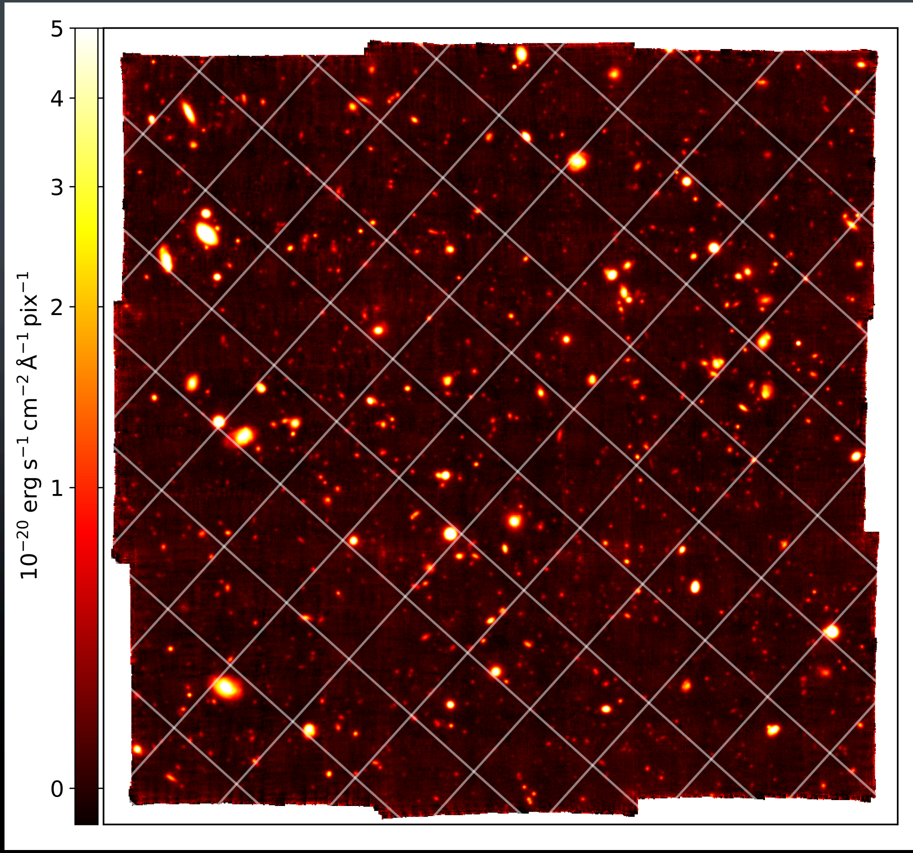


Patrício, Richard et al 2018, MNRAS, 477, 18

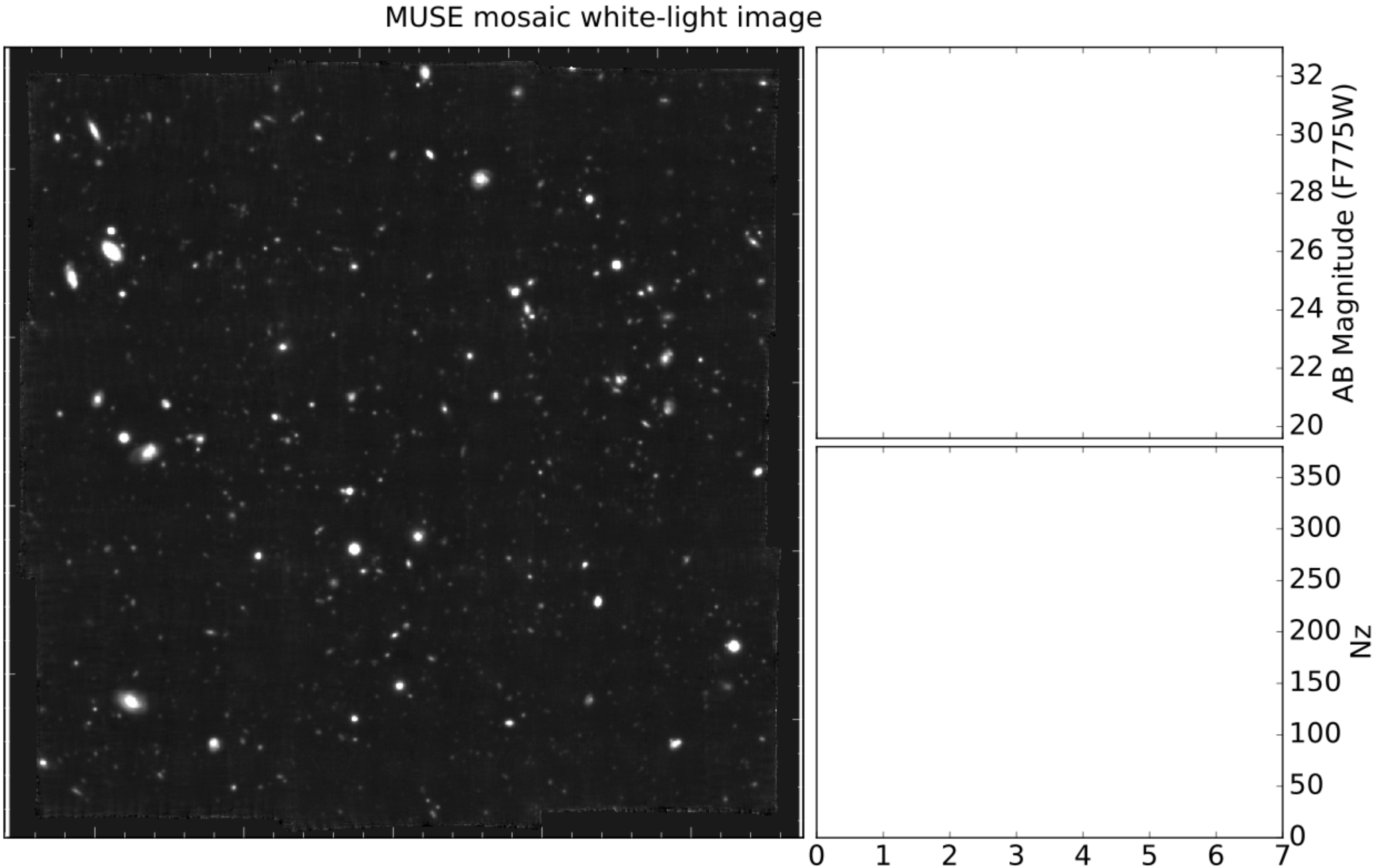
The MUSE Hubble Ultra Deep Field Survey

The deepest spectroscopic survey ever performed, 10 & 30 hours depth, 1600 redshifts

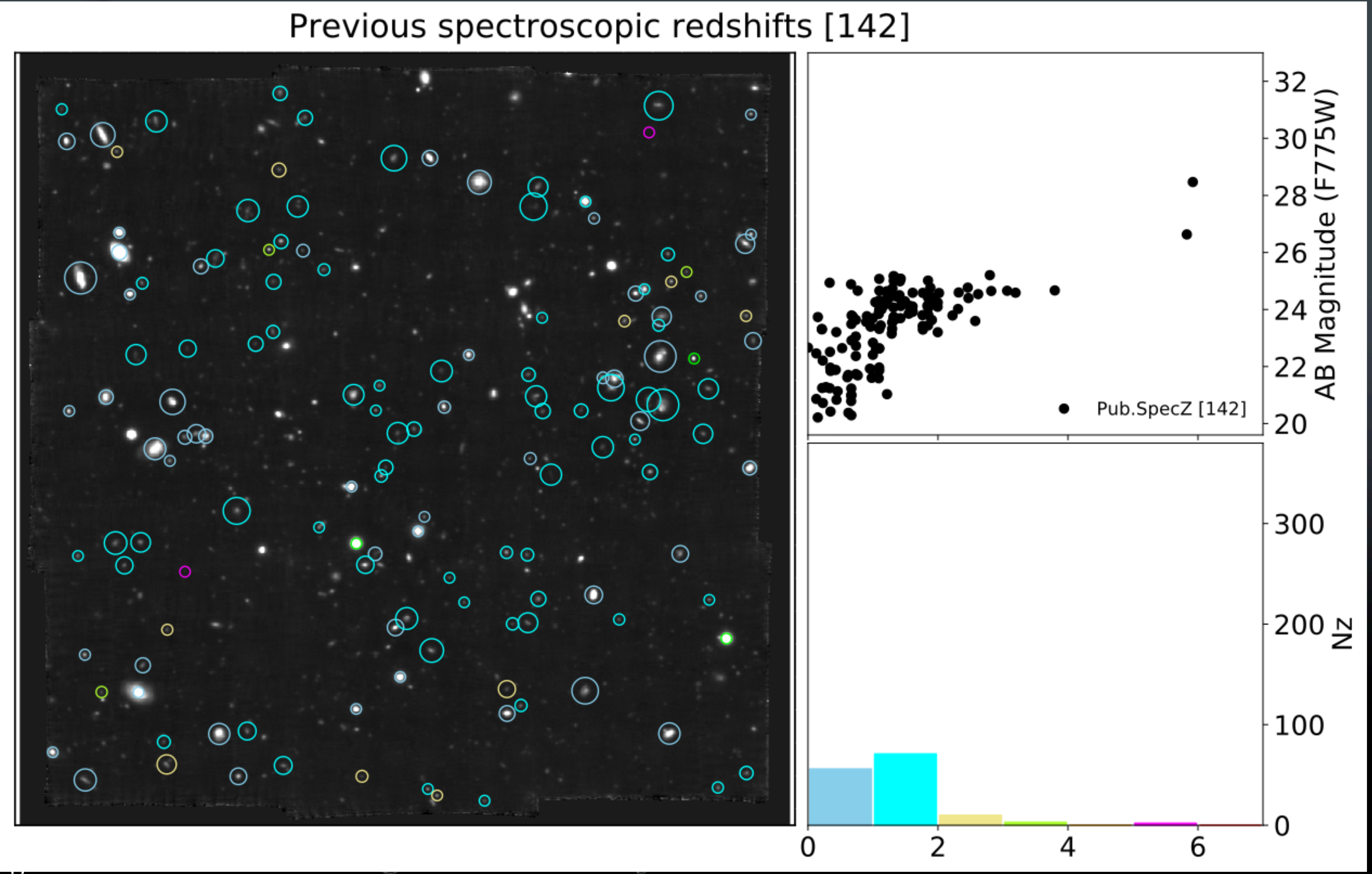




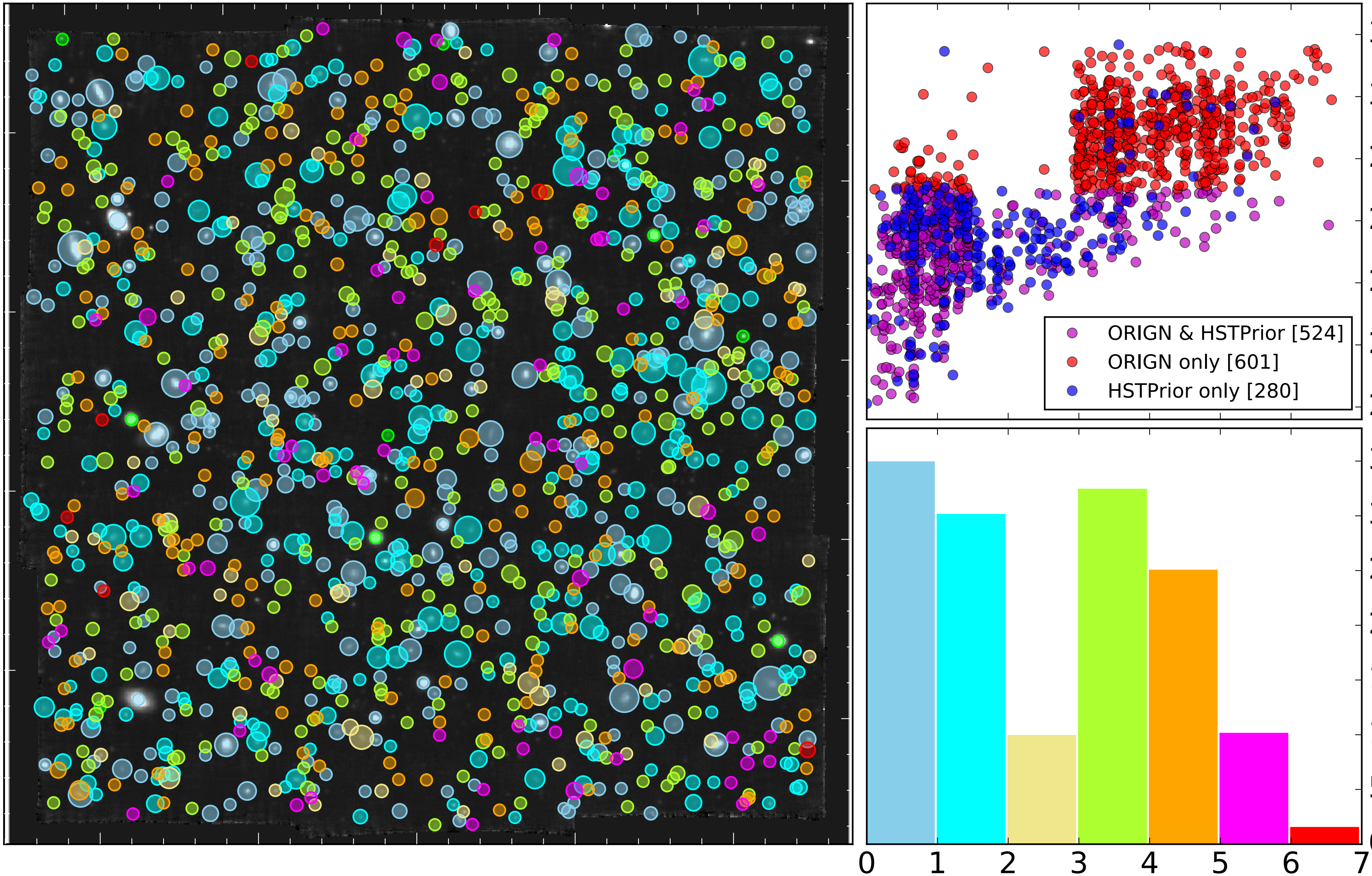
Redshifts in the mosaic field



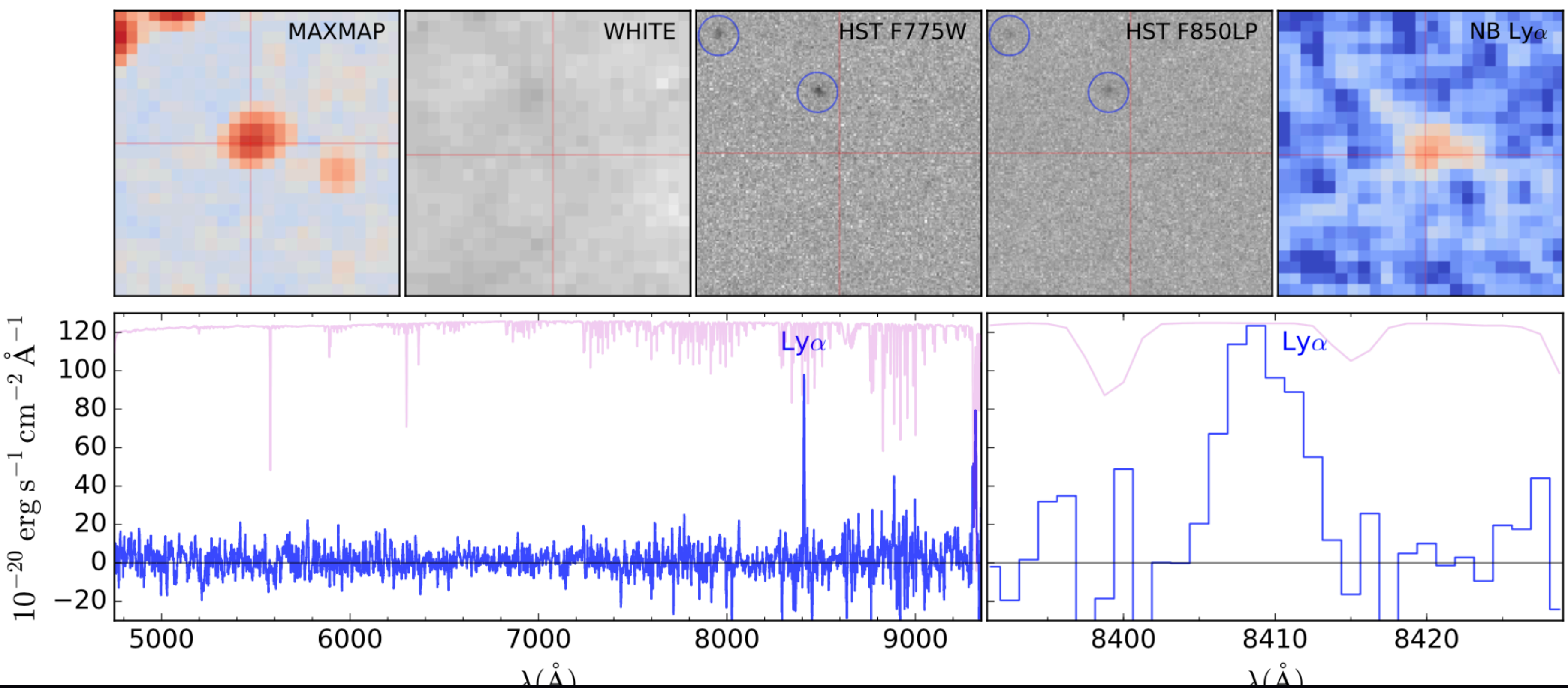
Redshifts in the mosaic field



MUSE redshifts ORIGIN & HSTPrior [1443]



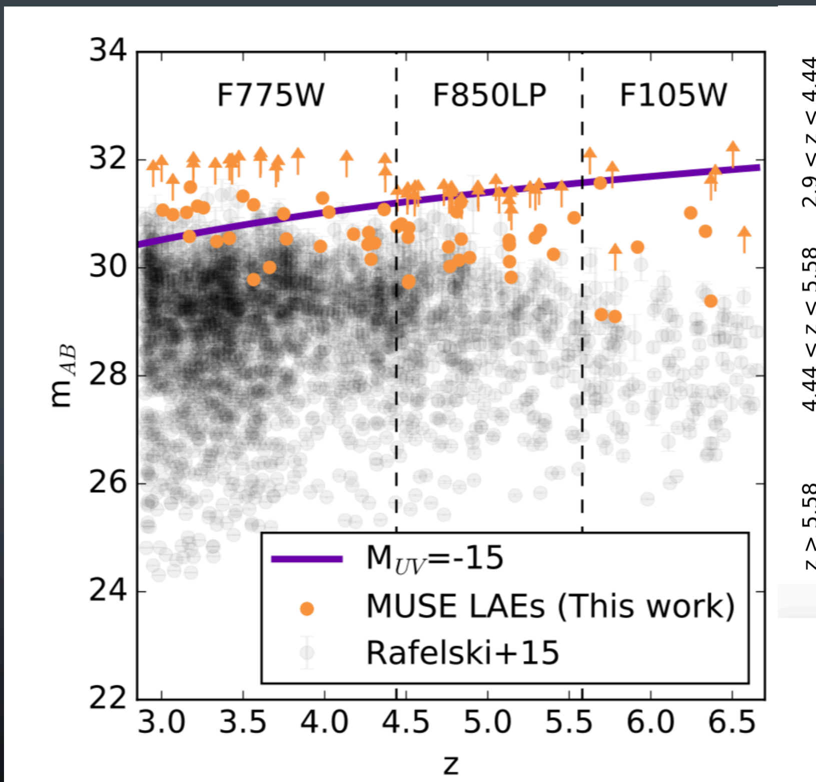
102 HST undetected LAEs

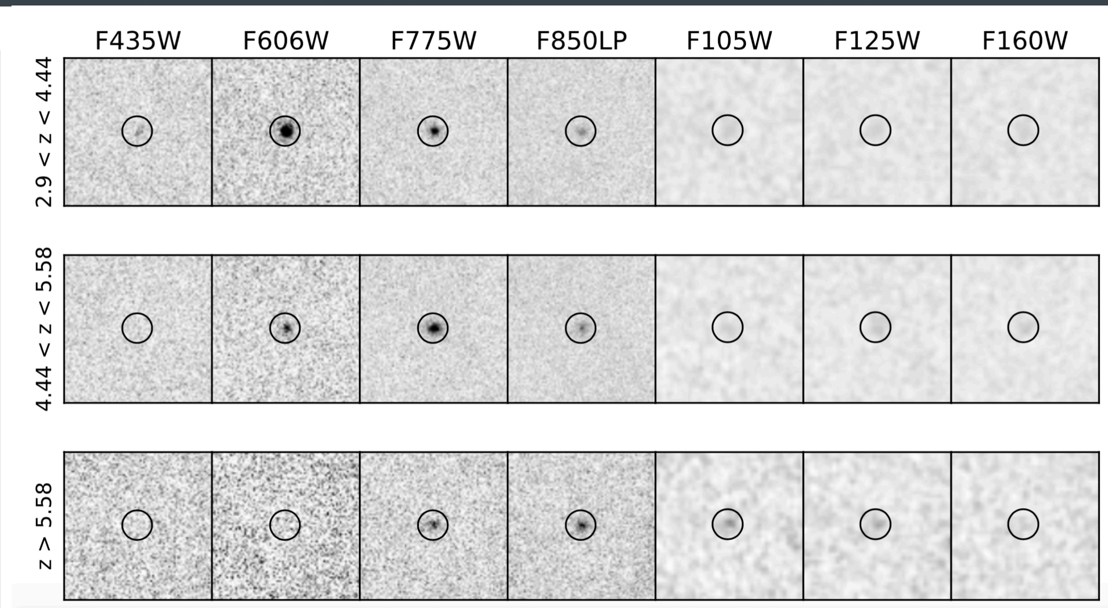


Lya Z = 5.91
AB F850LP > 30.7

Paper I: Bacon et al 2017

LAE without HST counterpart
Maseda et al, ApJL in press



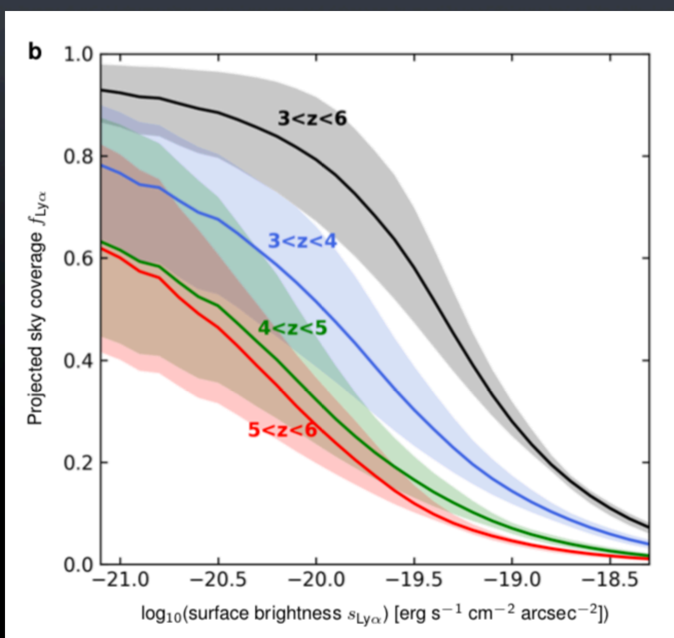


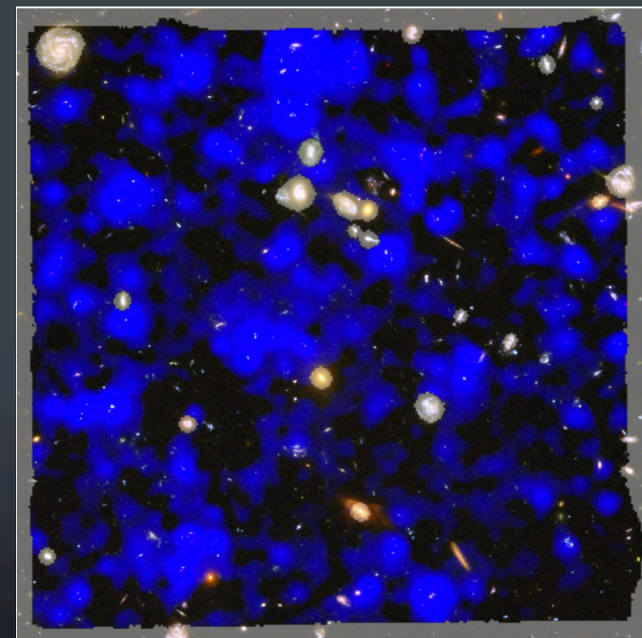
HST stack images

Sky coverage of Lyα low surface brightness emission

- Wisotzki et al, 2018, Nature, in press
- Use stacking of LAH

Projected Sky Coverage of Lya as function of SB





Observed Lya emission in UDF10

BLUE MUSE

multi unit spectroscopic explorer

A Blue MUSE for the VLT

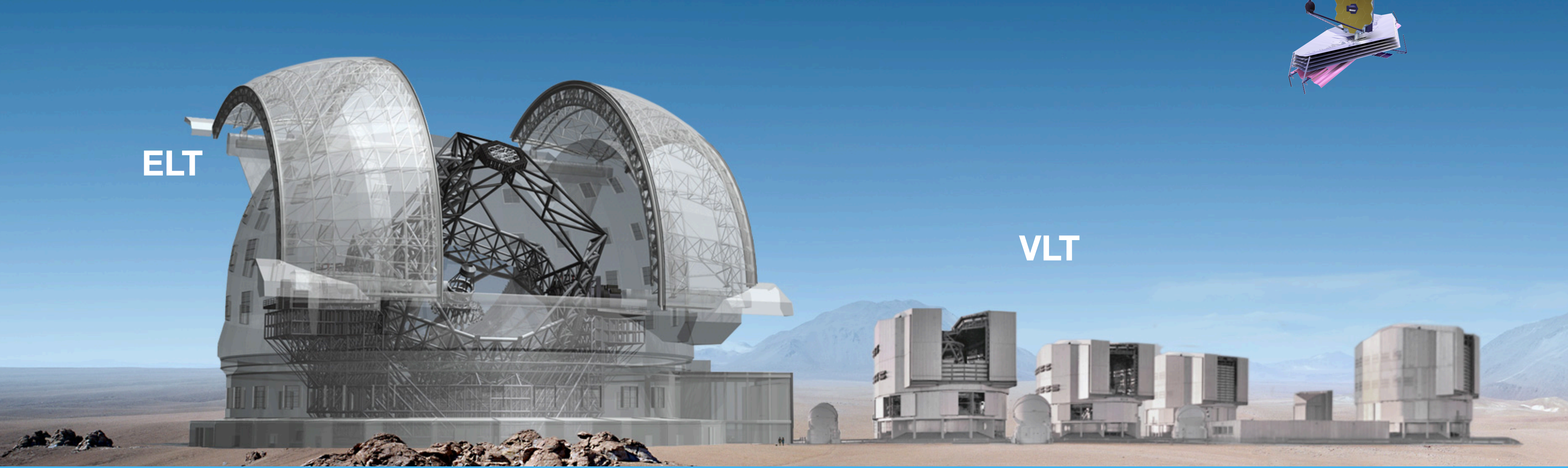
Johan Richard

Roland Bacon, Patrick Caillier (CRAL)

Eduard Muslinov, Emmanuel Hugot (LAM)

Johan Kosmalski (ESO)

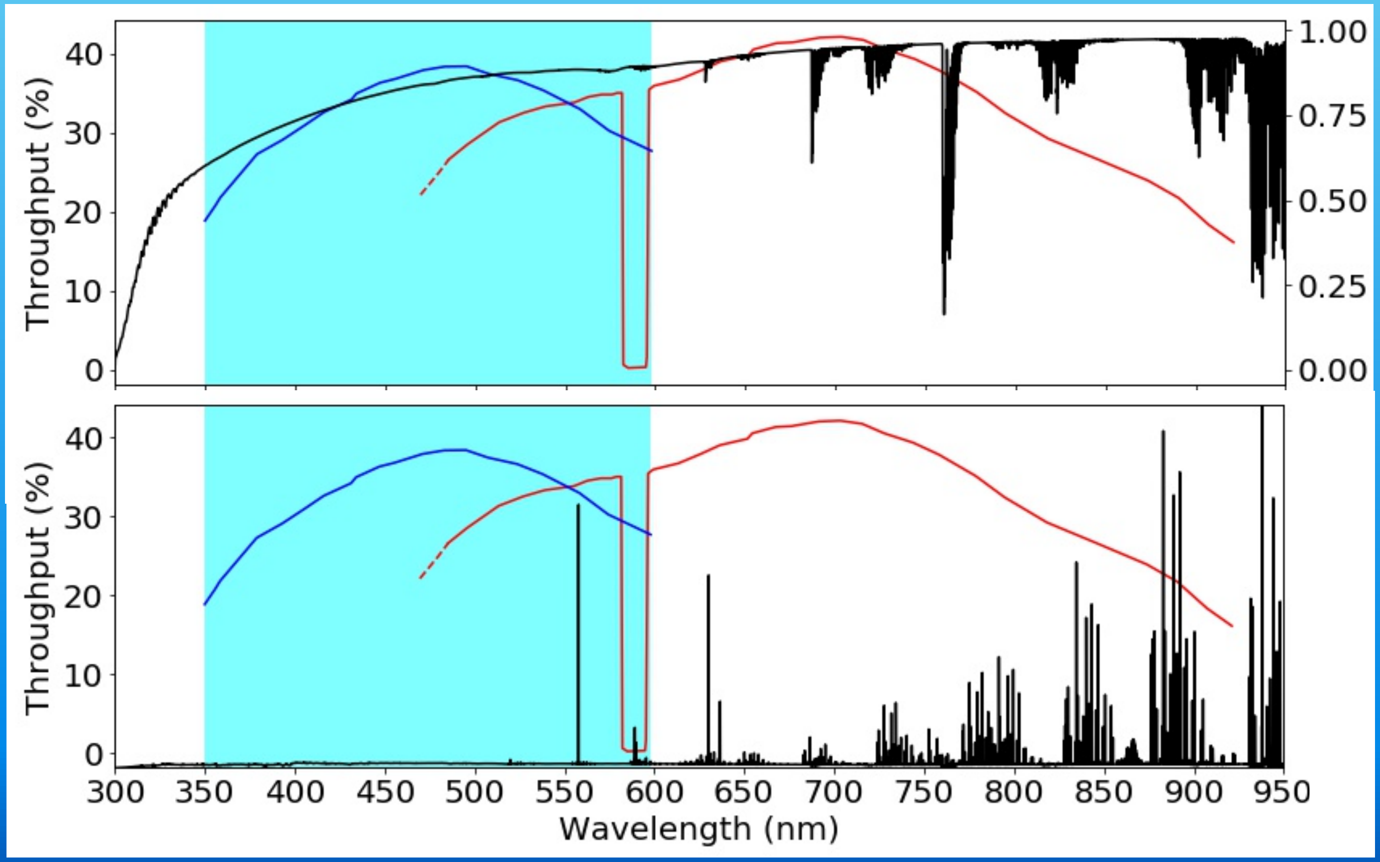
Rationale



- 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

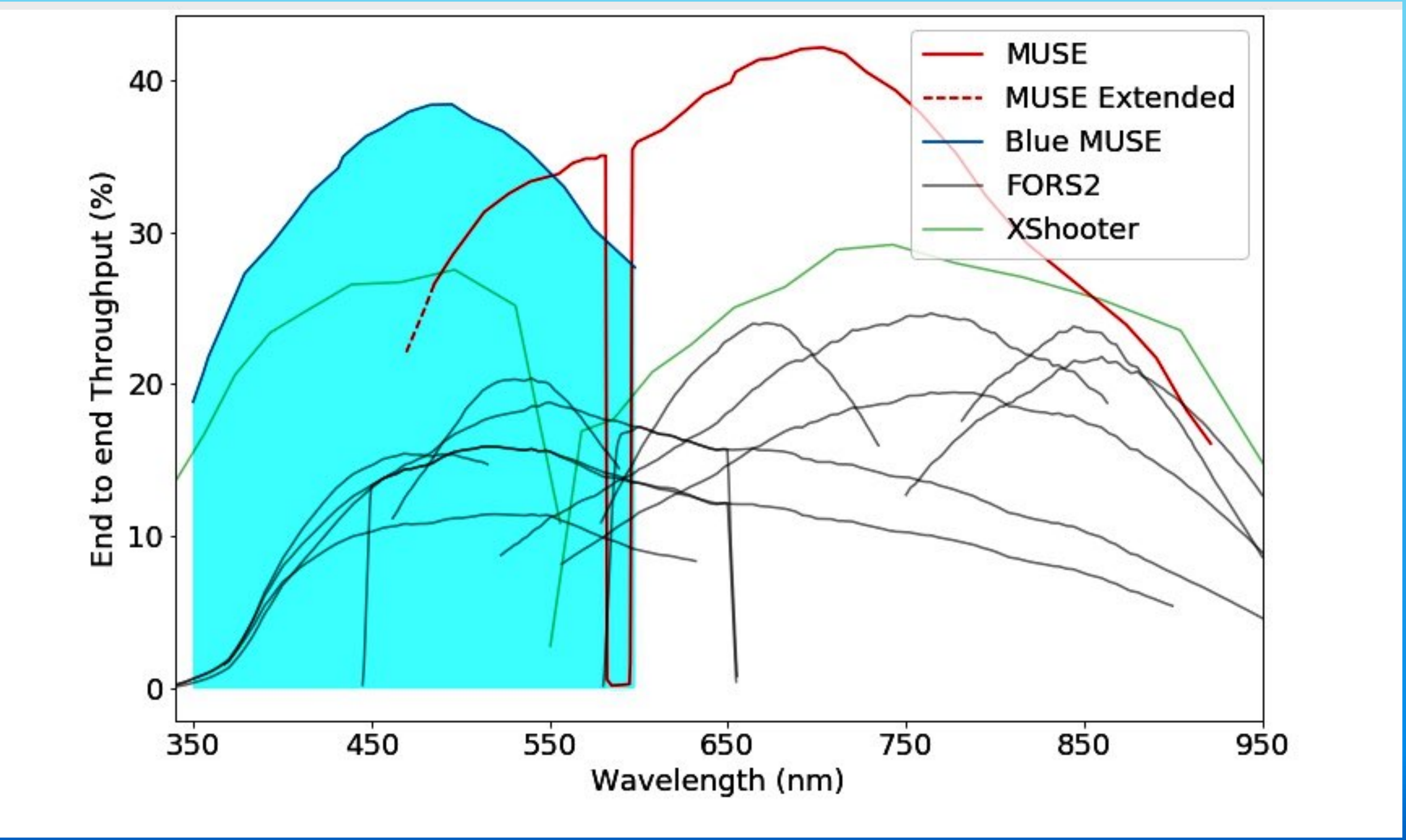
Top Level Parameters

- **Blue wavelength coverage: 350 - 600 nm**
  - **Complementarity with MUSE**
  - **Bluest limit adapted to atmosphere transmission (65% transmission)**
  - **Red limit might recover AO notch filter gap.**



Top Level Parameters

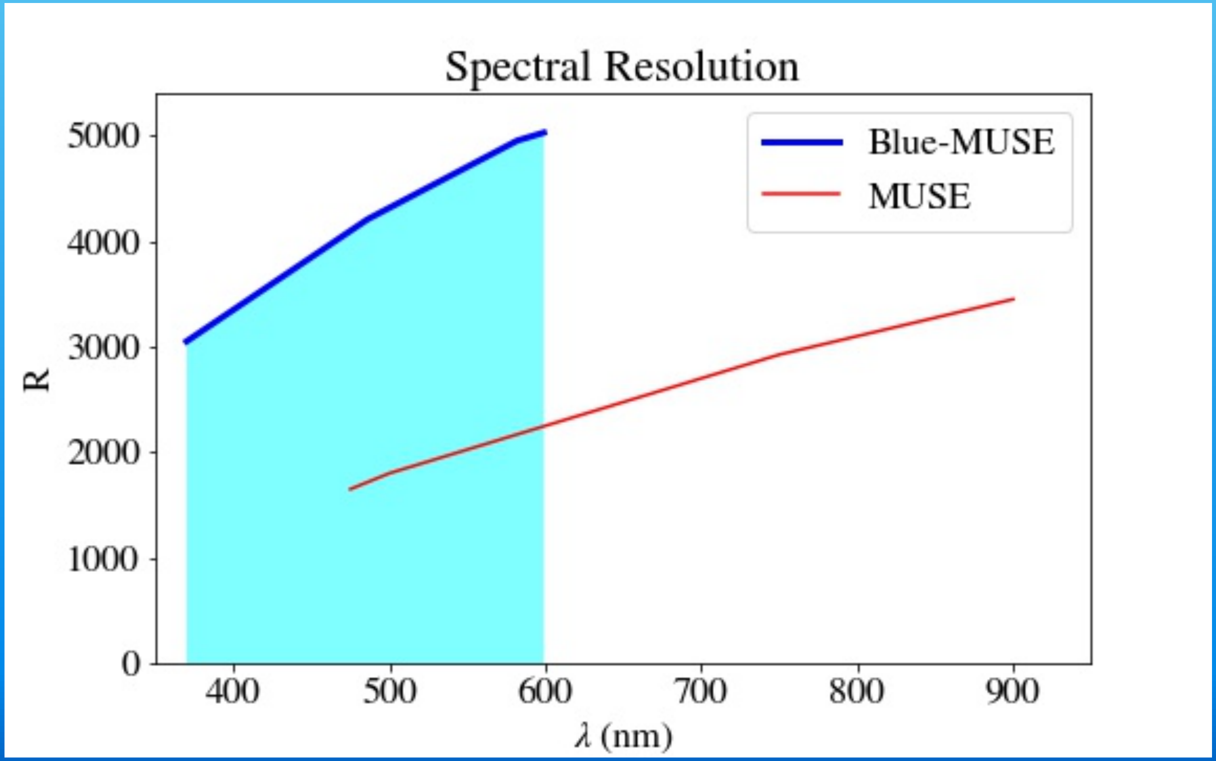
- **High throughput (end-to-end)**



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 nm < λ < 600 nm**
- **Spectral sampling: 0.6 Å / pixel**

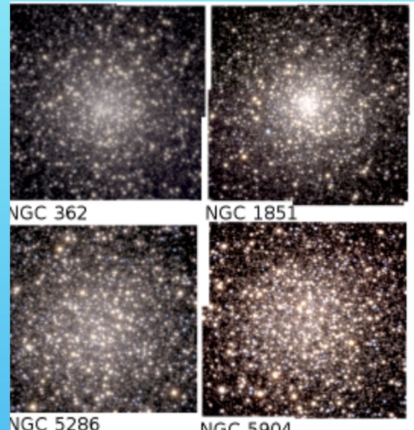


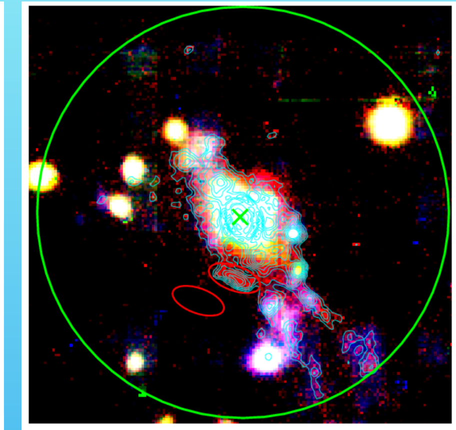
Top Level Parameters

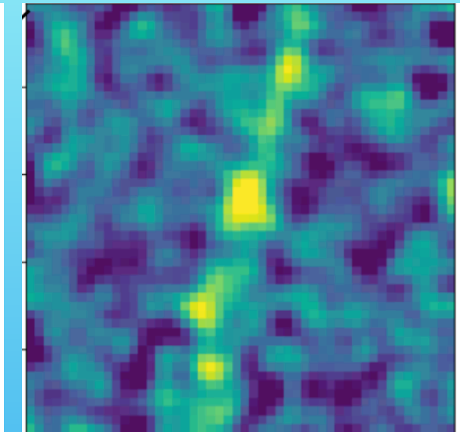
- **Larger field of view: 1.4 x 1.4 arcmin**

Sampling: 0.3” pixels (0.8” median seeing)

Science case - contributors (so far)







Roland Bacon (CRAL) - Jérémy Blaizot (CRAL) - Samuel Boissier (LAM) - Alessandro Bosselli (LAM) - Nicolas Bouché (CRAL) - Jarle Brinchmann (Leiden) - Laure Ciesla (LAM) - Emanuele Daddi (CEA) - Pierre-Alain Duc (Strasbourg) - David Elbaz (CEA) - Benoit Epinat (LAM) - Michele Fumagalli (Durham) - Thibault Garel (CRAL) - Matthew Hayes (Stockholm Univ.) - Lisa Kewley (ANU)- Jean-Paul Kneib (EPFL) - Guillaume Mahler (U. Michigan) - Cyrielle Opitom (ESO) - Céline Péroux (LAM) - Johan Richard (CRAL) - Martin Roth (AIP) - Ian Smail (Durham) - Mark Swinbank (Durham) - Tanya Urrutia (AIP) - Anne Verhamme (Geneva Obs.) - Jeremy Walsh (ESO) - Lutz Wisotzki (AIP) - Bin Yang (ESO) - Tian-Tian Yuan (Swinburne), …

Science case - main topics

Our galaxy and the local group

- Massive stars
- Ultra Faint Dwarfs
- Ionized Nebulae
- Comets

Nearby galaxies

- ISM and HII regions, extreme starbursts
- Low surface brightness galaxies
- Environmental effects in local clusters
- Census of shocks and outflows

The distant Universe

- Deep fields
- Gas flows around and between galaxies
- Lyman-continuum emitters
- Gravitational Lensing in Clusters
- The emergence of the first galaxy clusters

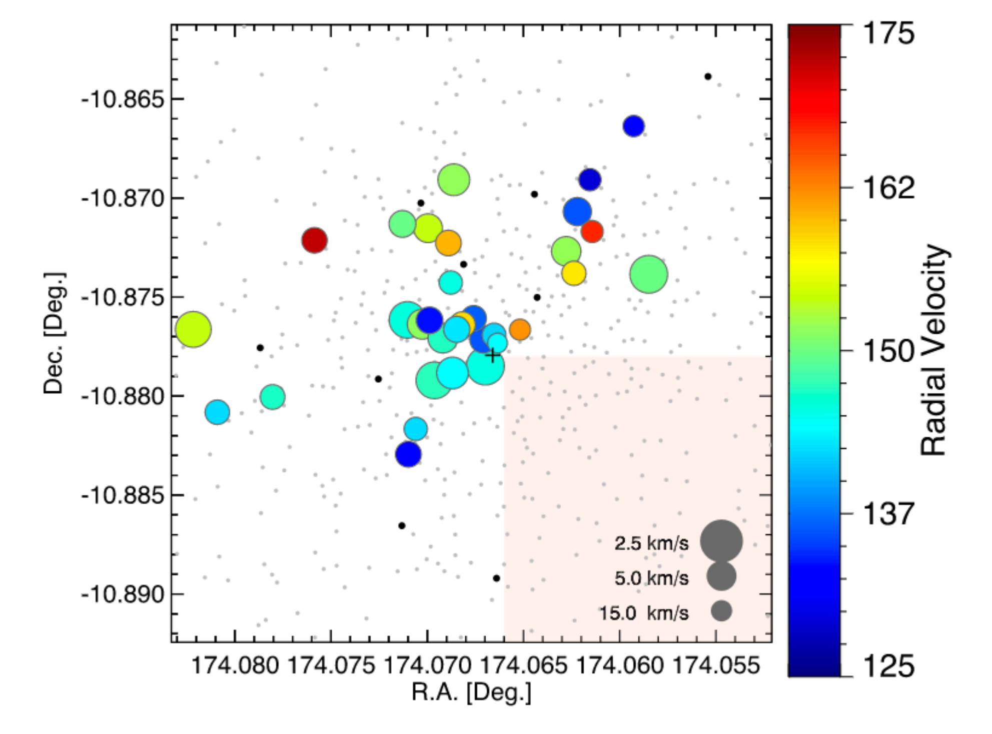
Massive stars

Spectroscopic analyses of individual massive stars and young clusters of massive stars in the Milky Way, in the Local Group, and in nearby galaxies.

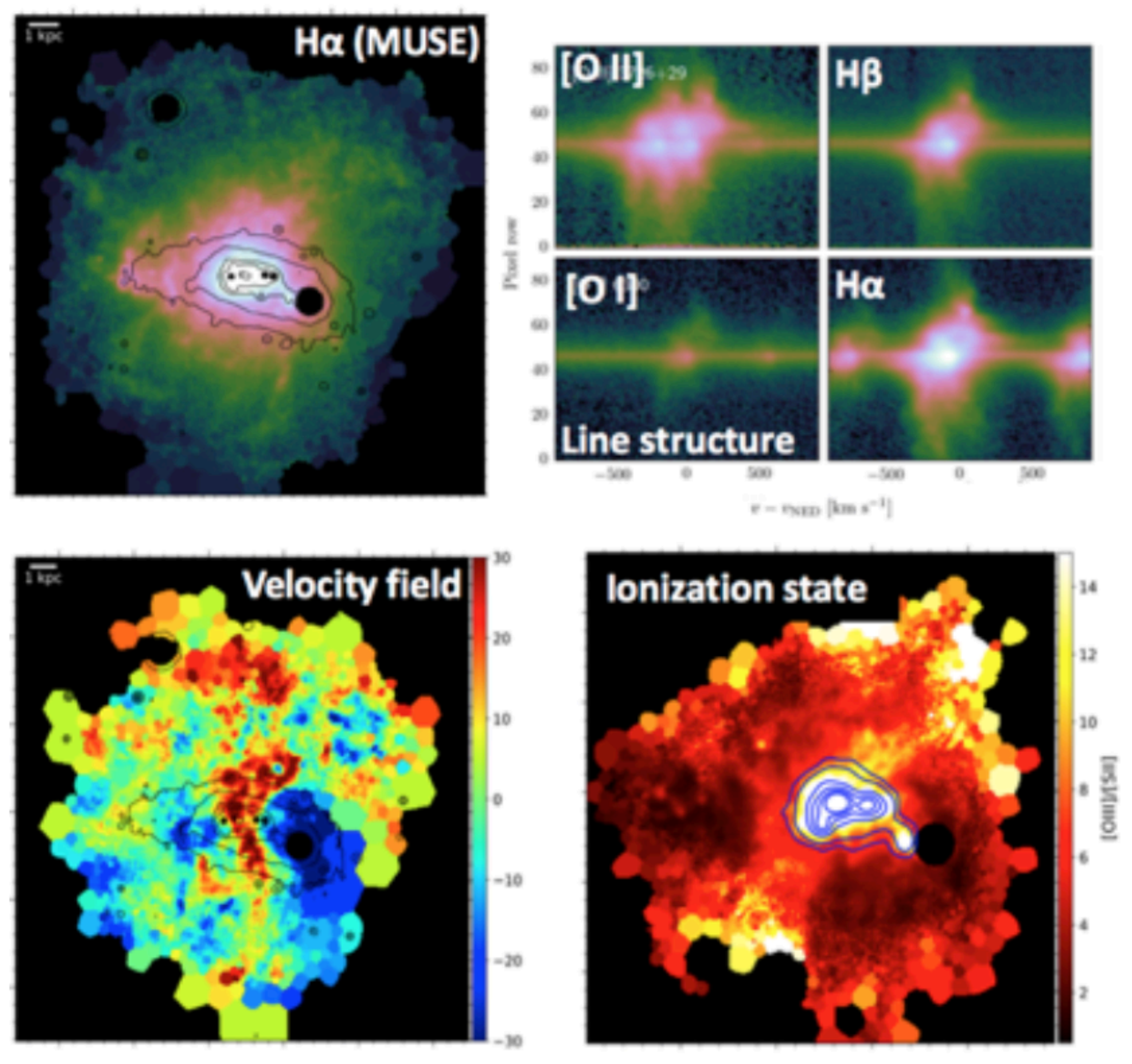
- *evolution of massive stars* : investigation of rotation, mass loss and the chemical composition in their atmospheres; also finding emission line stars and peculiar objects such as WR, LBV, Be stars
- test the hypothesis of very massive Pop. III stars by probing the metallicity dependence of the upper IMF
- discover and categorize spectroscopic binaries as progenitors for *gravitational wave BH binaries*
- *map chemical abundances* in galaxies as an alternative to HII regions and study massive stars *simultaneously with their environment* (HII regions, molecular clouds, pre-main sequence stars, ISM)

Ultra Faint Dwarfs

- 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)
- Chemical enrichment of UFDs



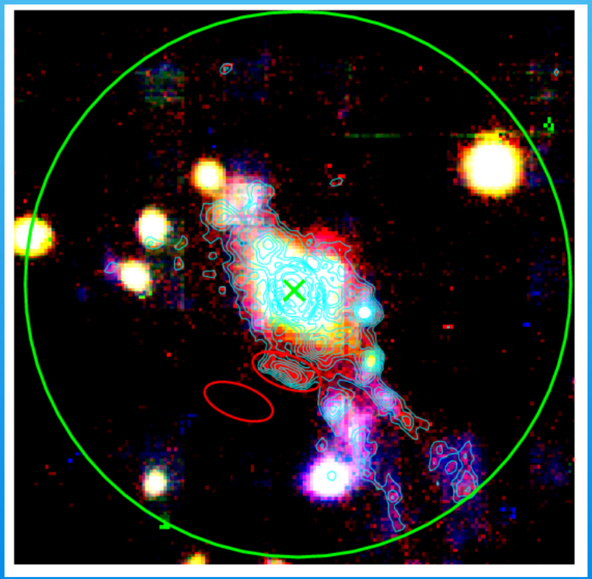
ISM and HII regions, Extreme starbursts



BLUE muse
multi unit spectroscopic explorer

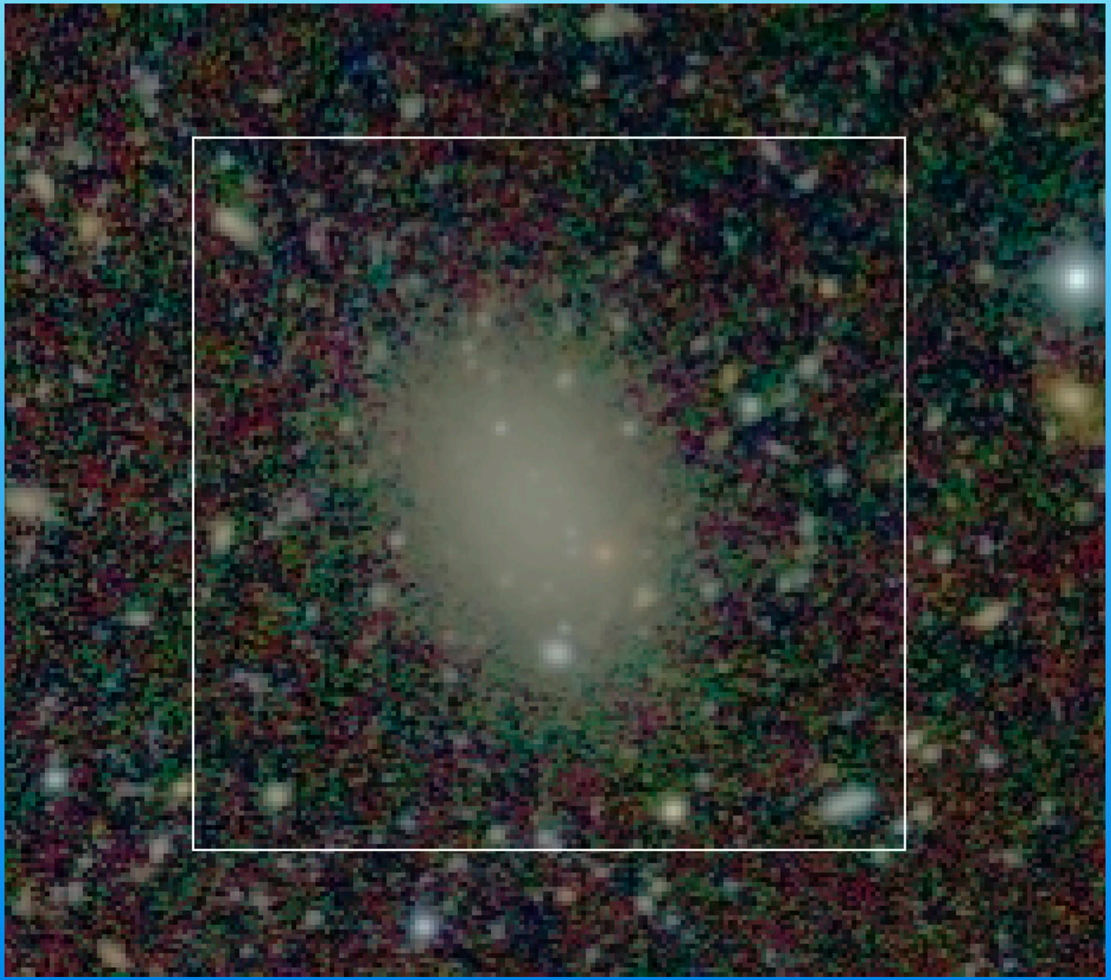
Low surface brightness sources

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



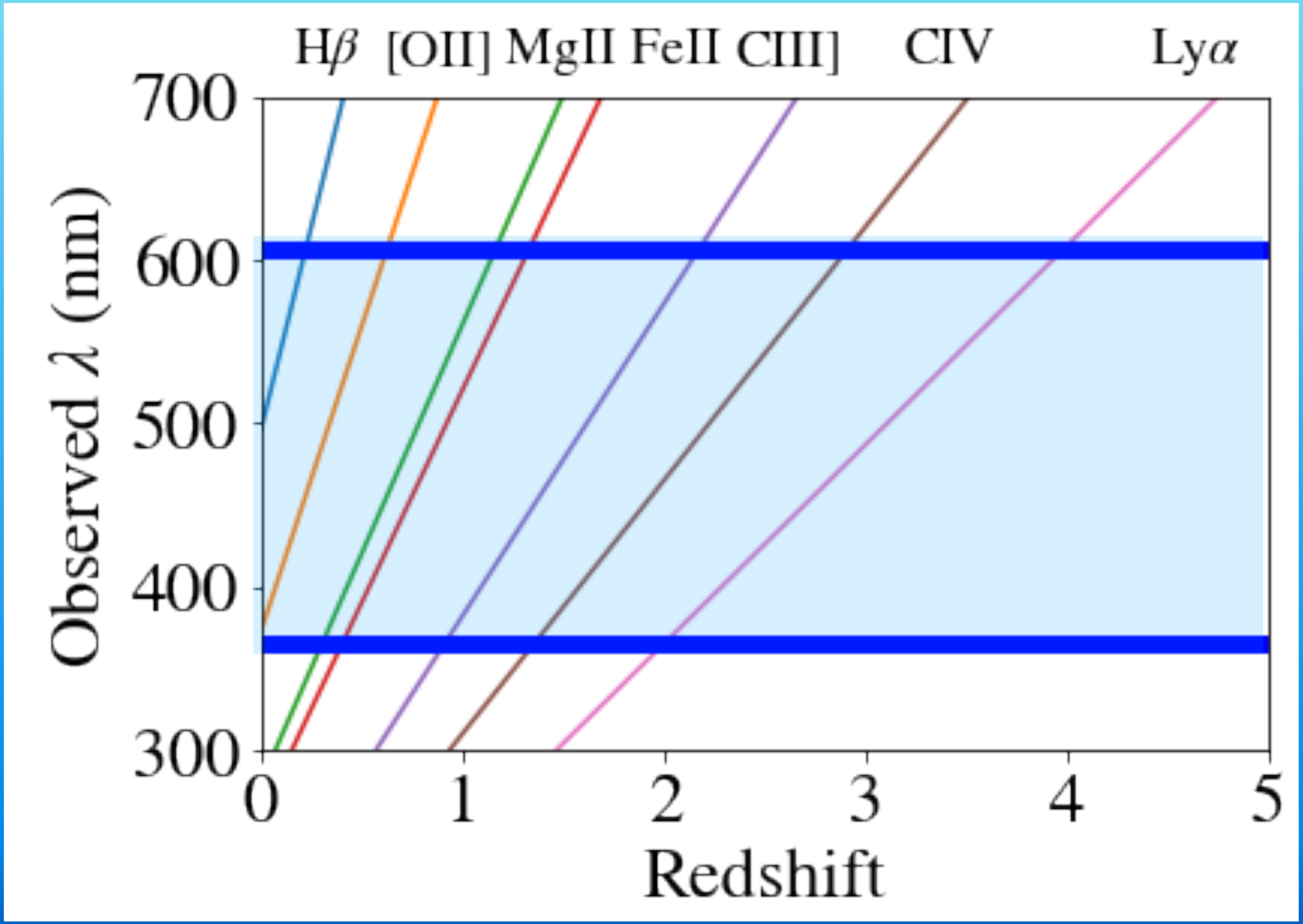
Adami et al. 2016 (z=0.53 cluster)

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



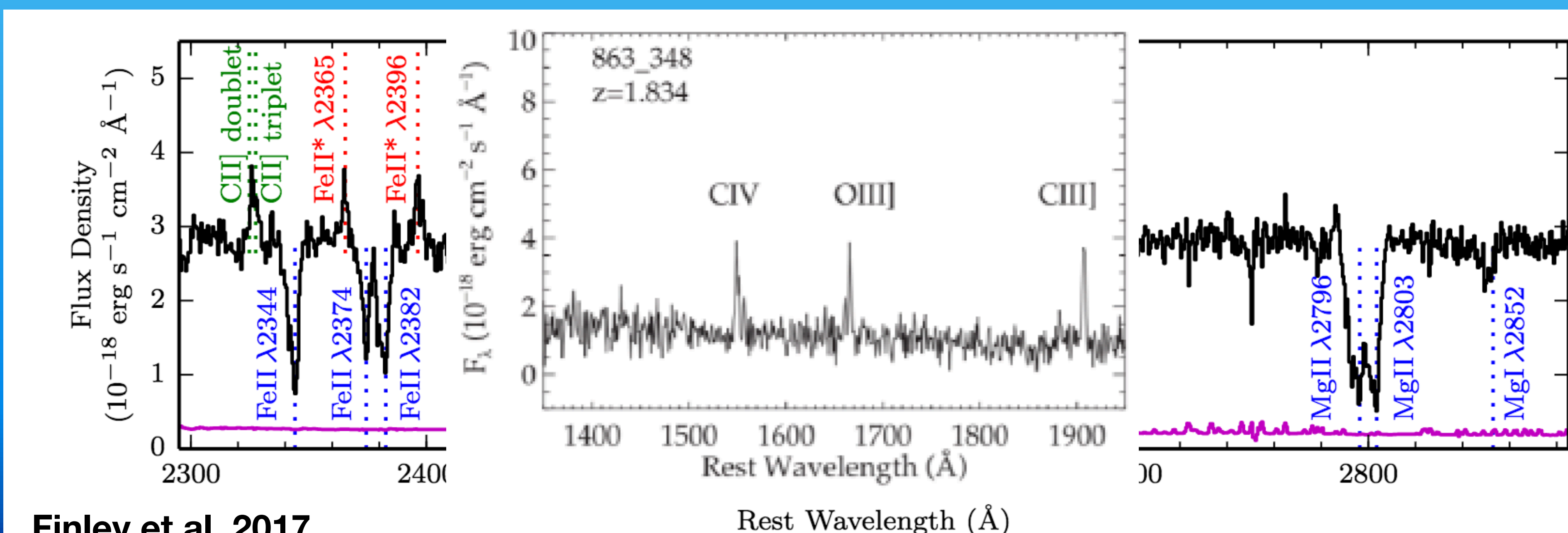
CFHT / MATLAS example
(courtesy P.A. Duc)

Physics of outflows and UV nebular lines at 0.5 < z < 3



Physics of outflows and UV nebular lines at 0.25 < z < 3

- Resolved outflows at z > 0.25 : from Mg II and Fe II absorptions and line emission
- At 0.8 < z < 3, CIII], CIV, HeII and OIII] nebular emission:



Finley et al. 2017

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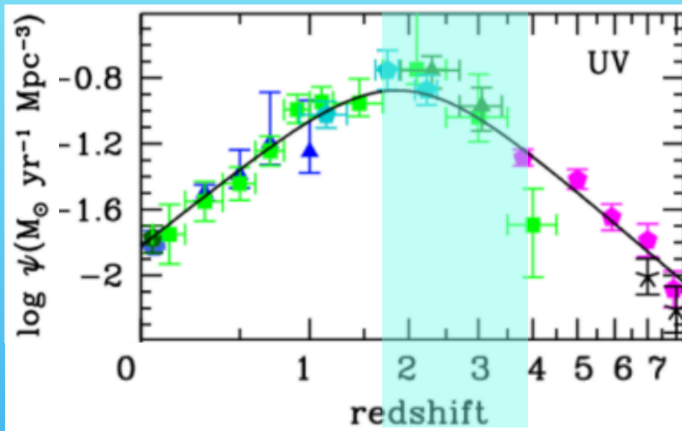
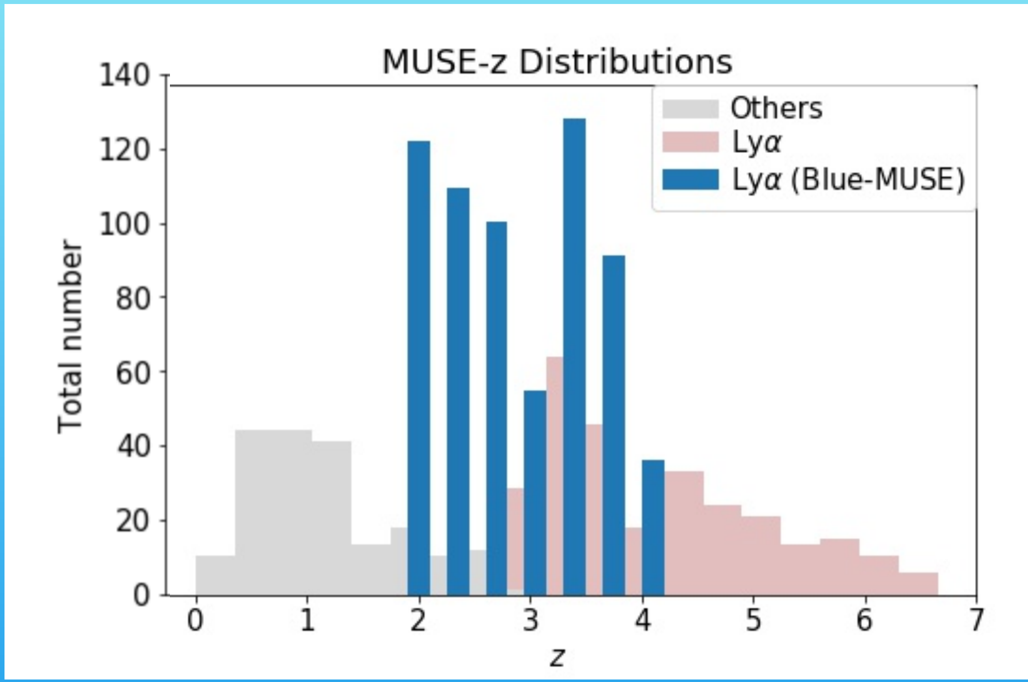
Deep Fields



Madau & Dickinson (2010)

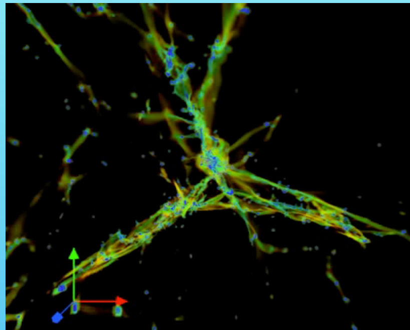


- **UV cosmic SFR peaks in this redshift range**
- **MUSE Deep fields (> 10 hrs per pointing) reveal faint emission line galaxies, and in majority Lyman-alpha emitters (LAEs)**

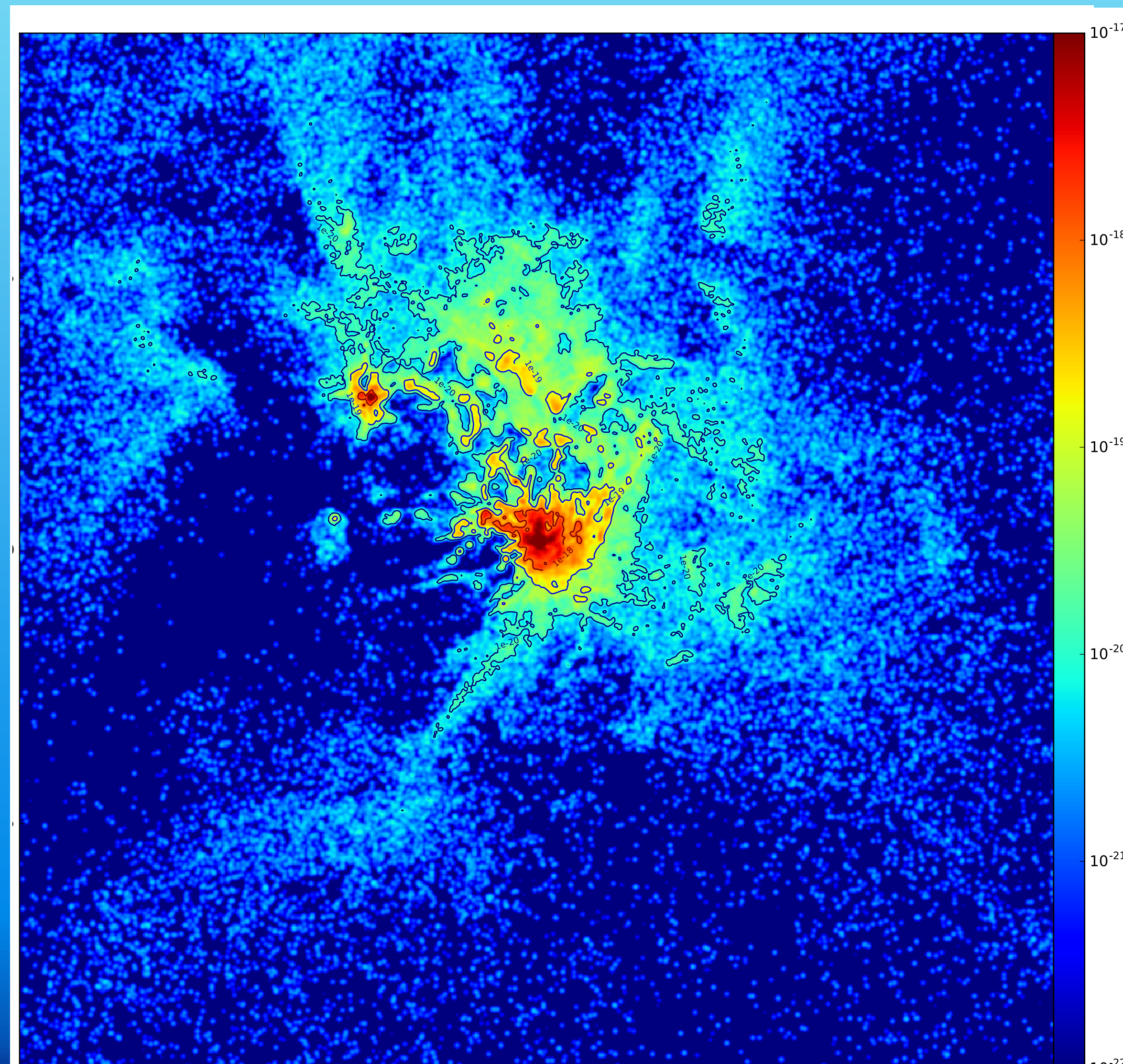
UDF + MUSE:
185 unique LAEs at 3<z<6.7 per pointing

UDF+MUSE-Blue:
630 unique LAEs at 1.9 <z<4

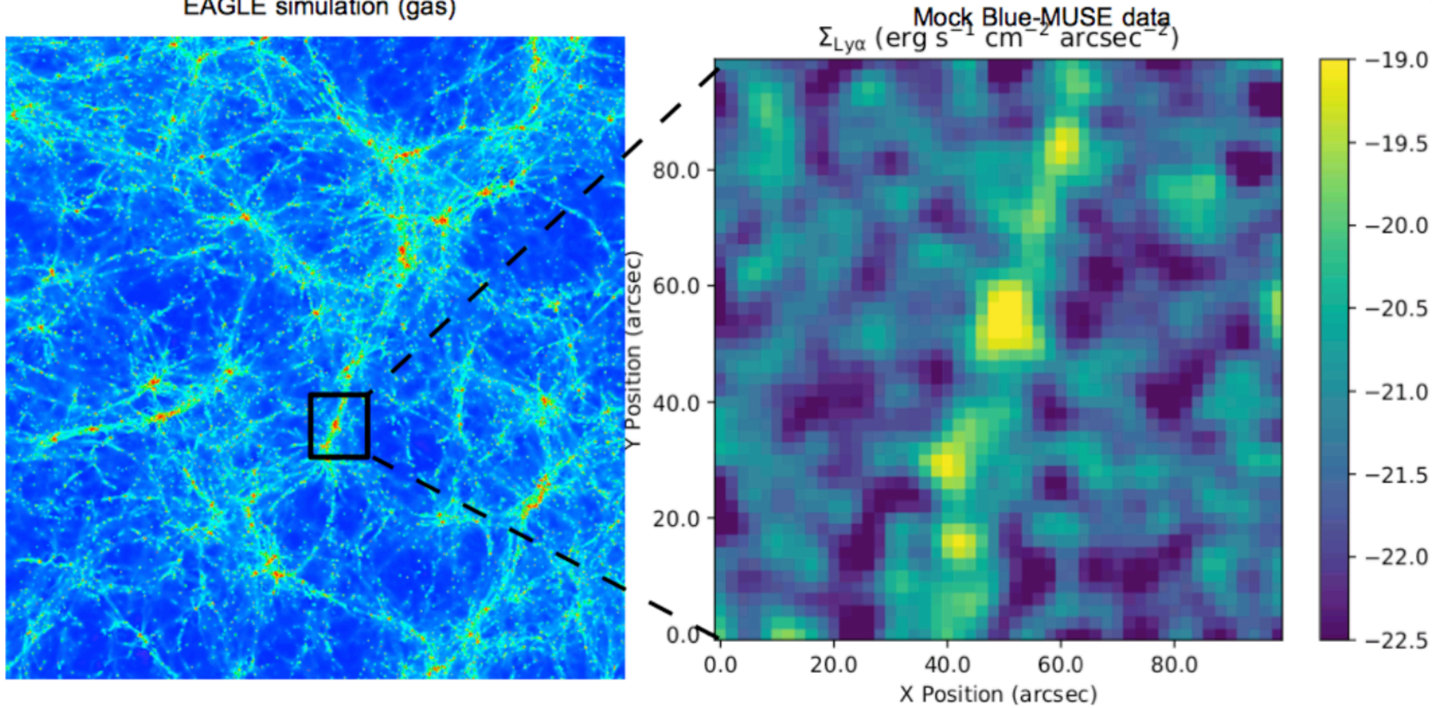
High-redshift galaxies
Lyman-α at 1.9 < z < 4

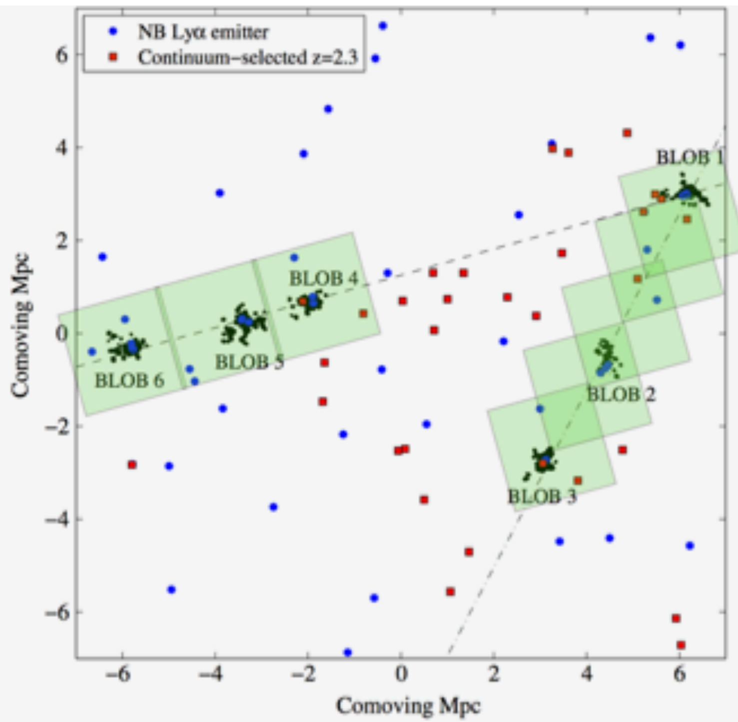


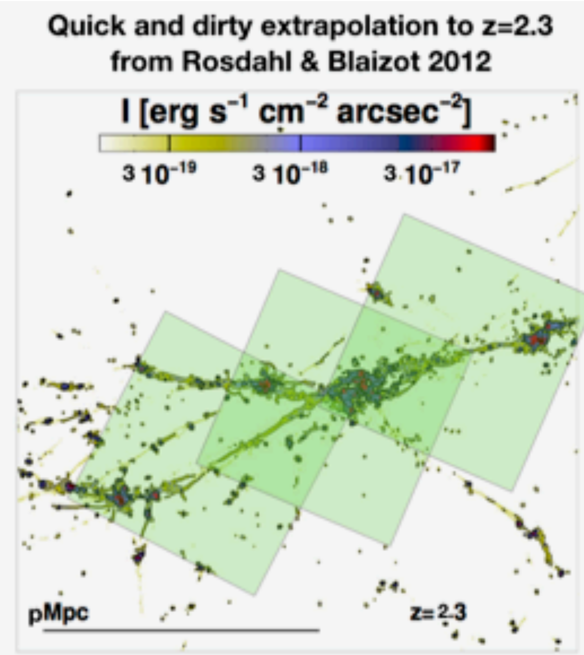
- **Lyman-alpha emission can help to probe the diffuse gas in the circumgalactic medium.**
- **Blue-MUSE can probe this diffuse gas down to z=1.9 and benefit from surface brightness dimming (gain x3-4 between z=3 and z=1.9) ~ 10x gain in exposure time !**



From CGM to IGM





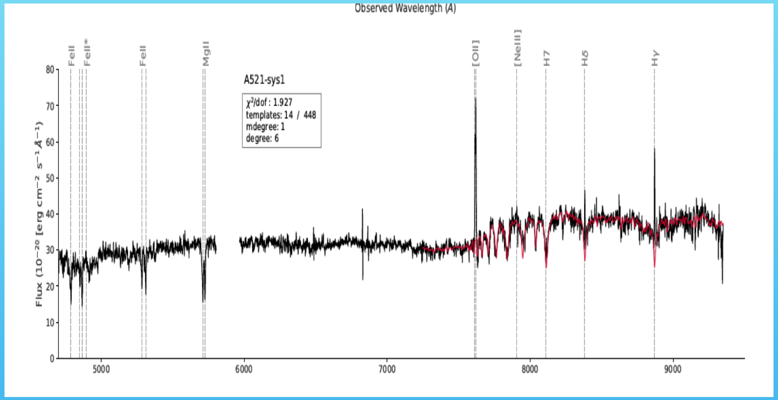


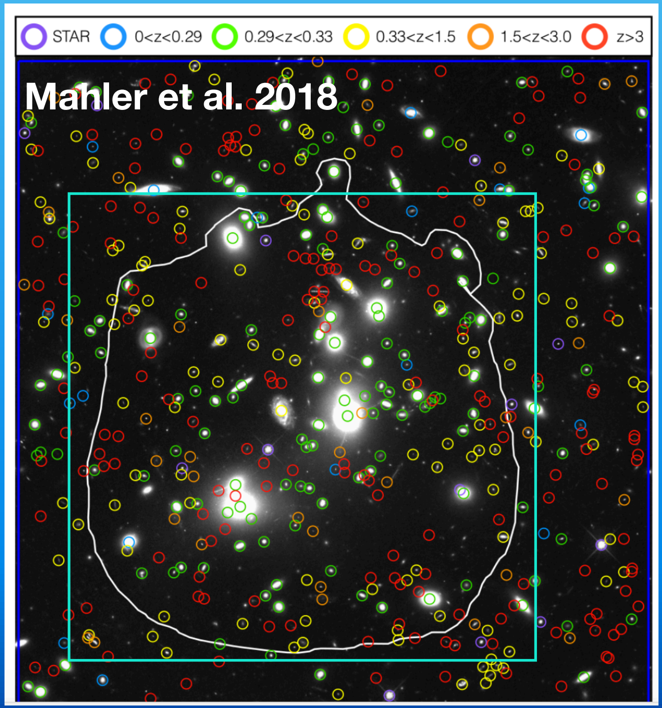
Lensed galaxies by massive clusters

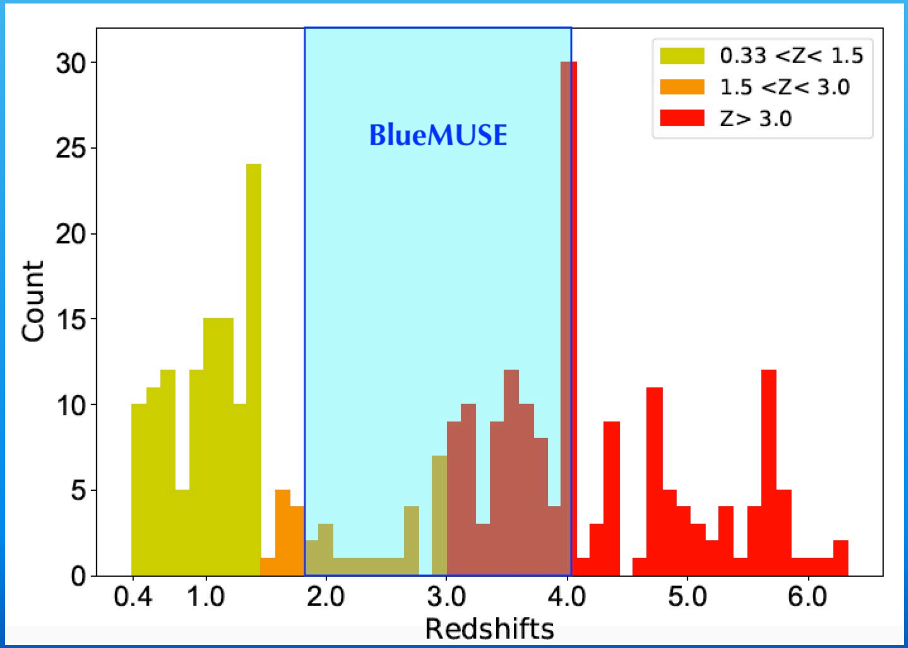
- **Magnification allows to probe lower mass / luminosity galaxies**

- **Massive clusters have a magnification region extending to 1.5-2 arcmin.**

- **1.9 < z < 4 is the peak of the redshift distribution for multiply-imaged galaxies**



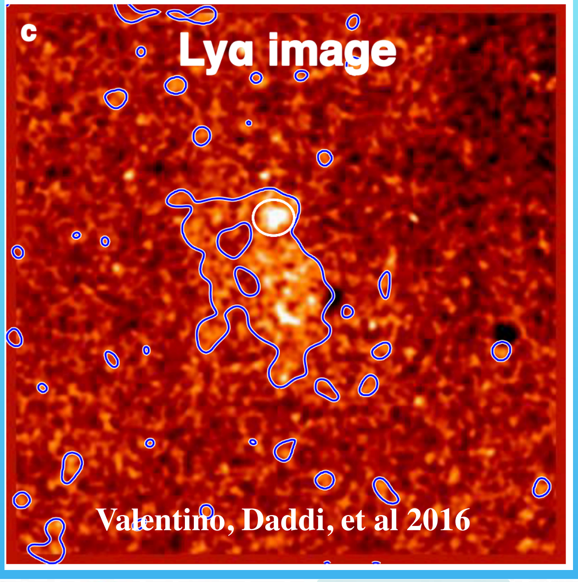


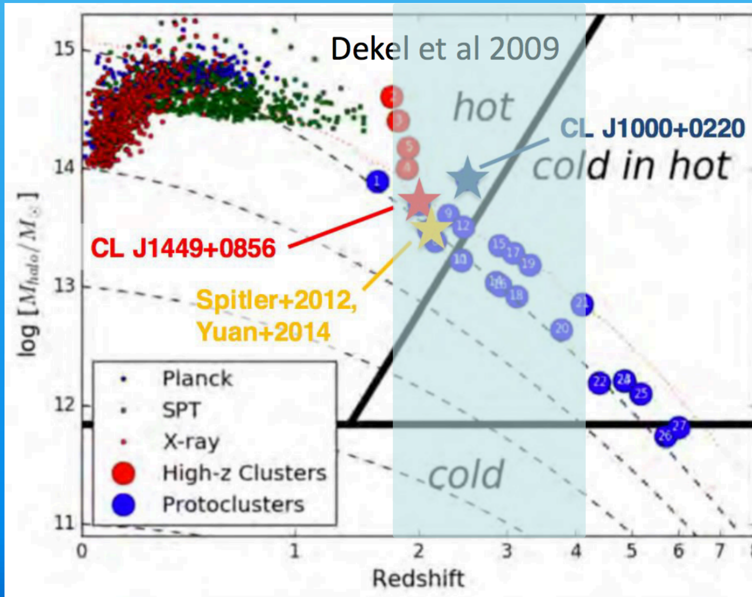


High redshift galaxy clusters

- Number counts of galaxy clusters at high redshift is sensitive to sigma_8 and non gaussianities. Current limits on confirmed clusters at high z.
- Herschel and Planck have detected many high redshift cluster candidates, and Euclid shall discover 1000s of them!
- Cold (10^4 K) gas and hot (10^7 K) gas seem to coexist in some clusters, as seen with Lyman-alpha and X-ray
- Theory predicts that cold flows accretion is needed to maintain the steady state, still to be confirmed in observations.

Strong synergies between BlueMUSE and Euclid, with follow-up using SKA (active clusters), ALMA (characterisation of cold gas) and ATHENA (interplay between hot and cold media).

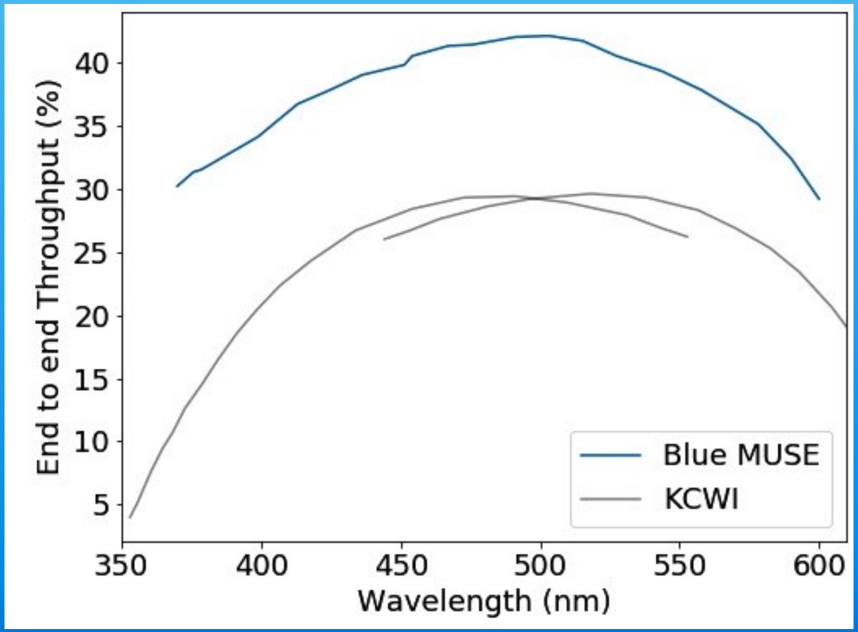


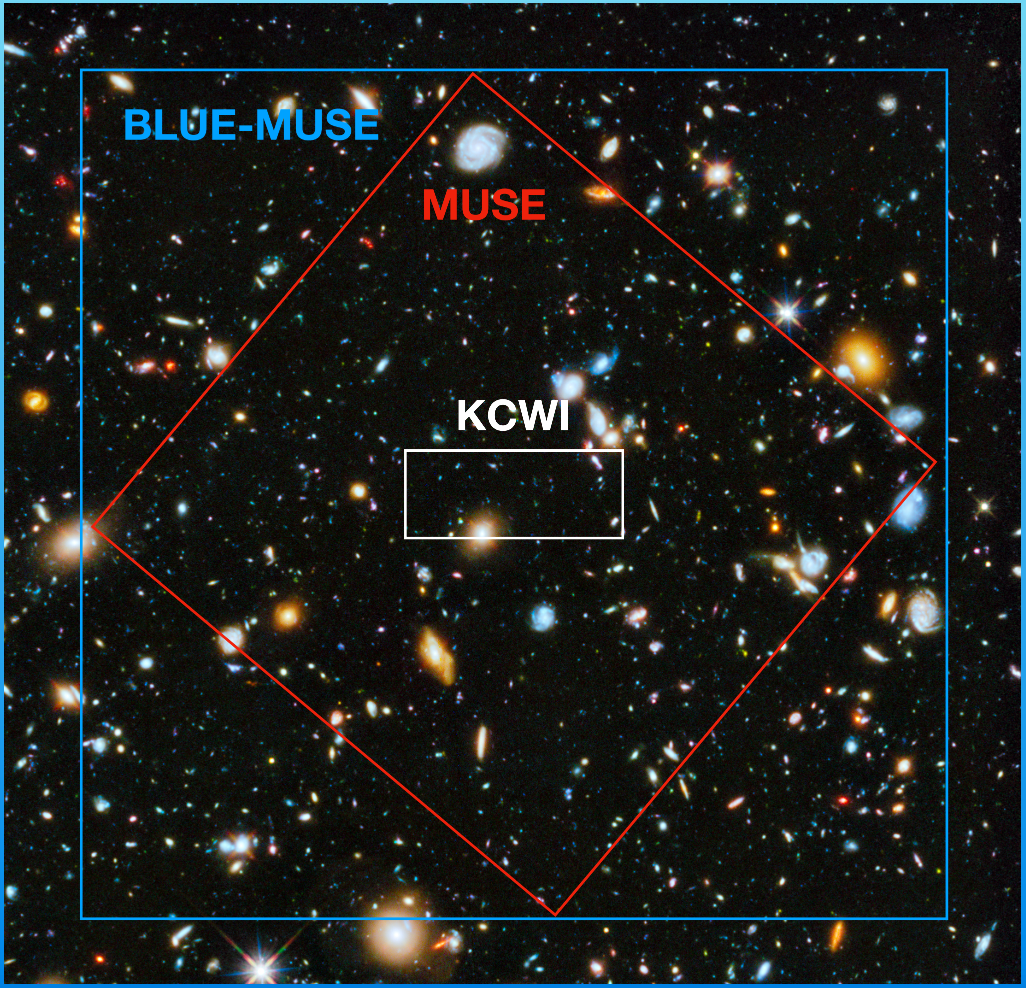


Valentino et al 2015; 2016; Overzier et al 2016

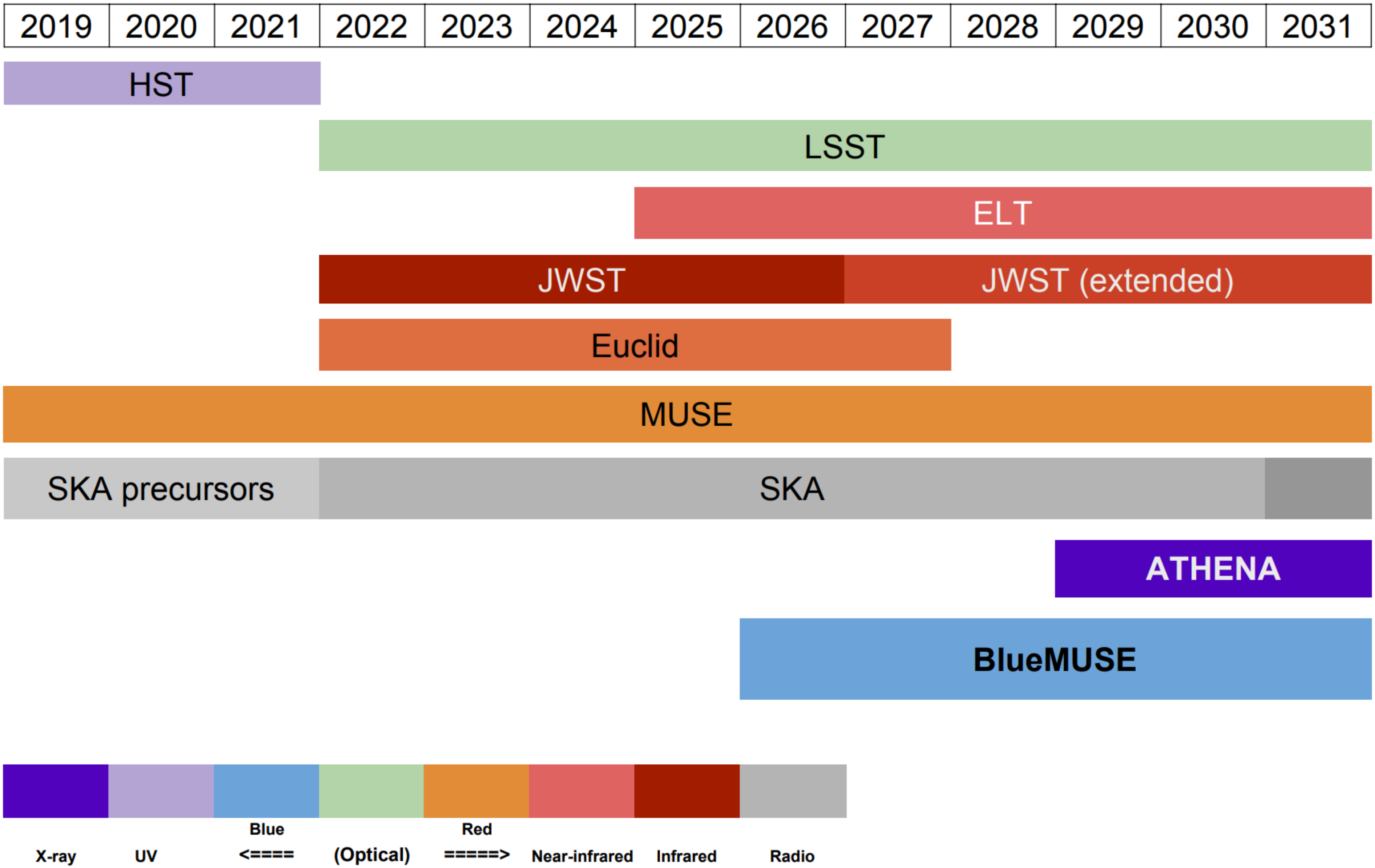
Uniqueness

- **Unique combination of large FoV, resolution and wavelength**
- **Keck Cosmic Web Imager (KCWI): 8.24” x 20.4”**





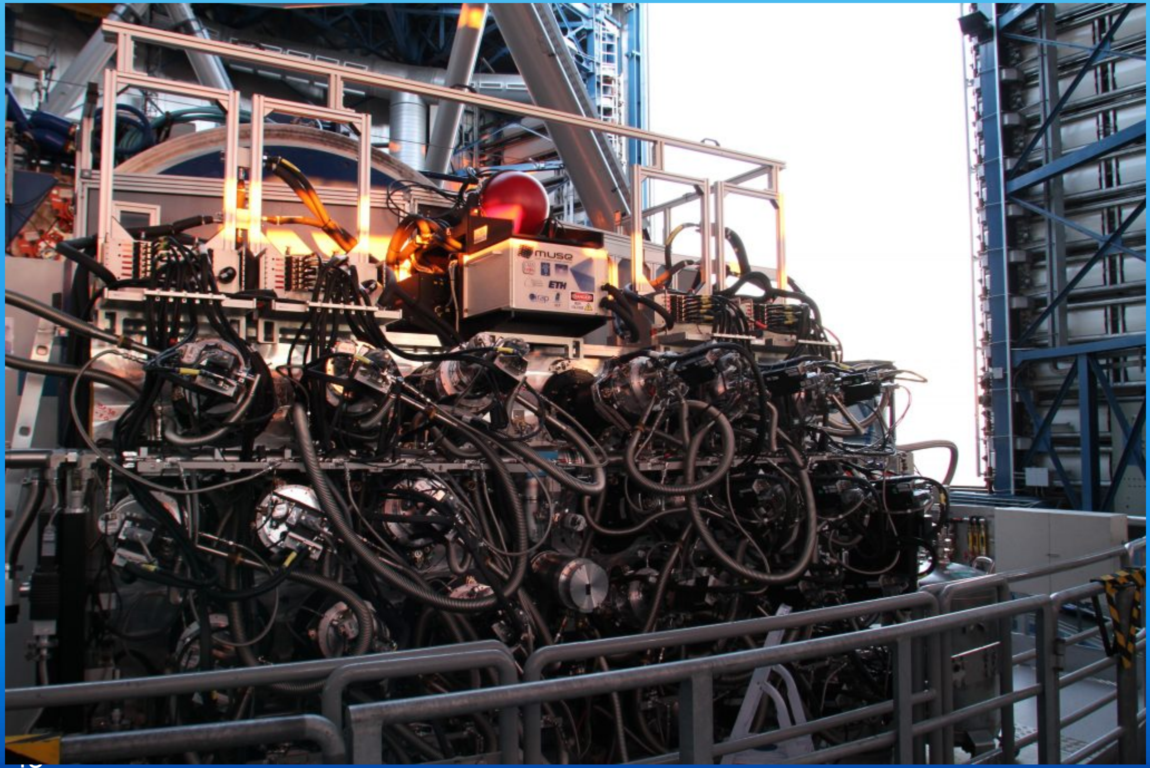
Synergies

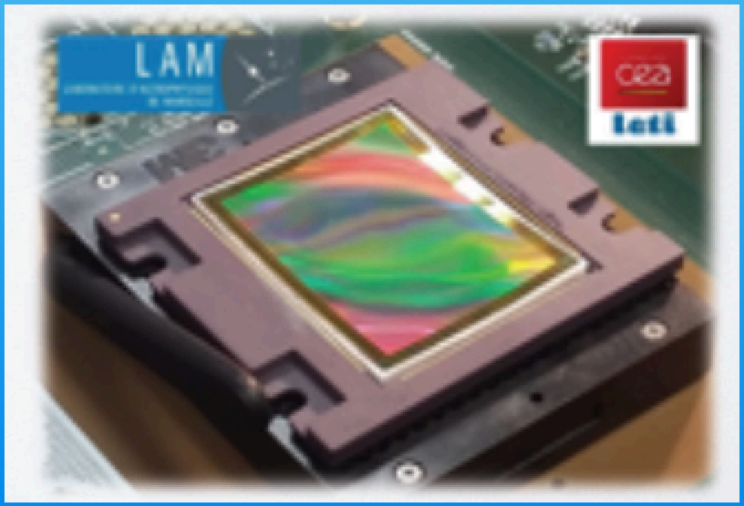

2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
HST
LSST
ELT
JWST
JWST (extended)
Euclid
MUSE
SKA precursors
SKA
ATHENA
BlueMUSE
X-ray
UV
Blue
<====
(Optical)
Red
=====>
Near-infrared
Infrared
Radio

BLUE muse
multi unit spectroscopic explorer

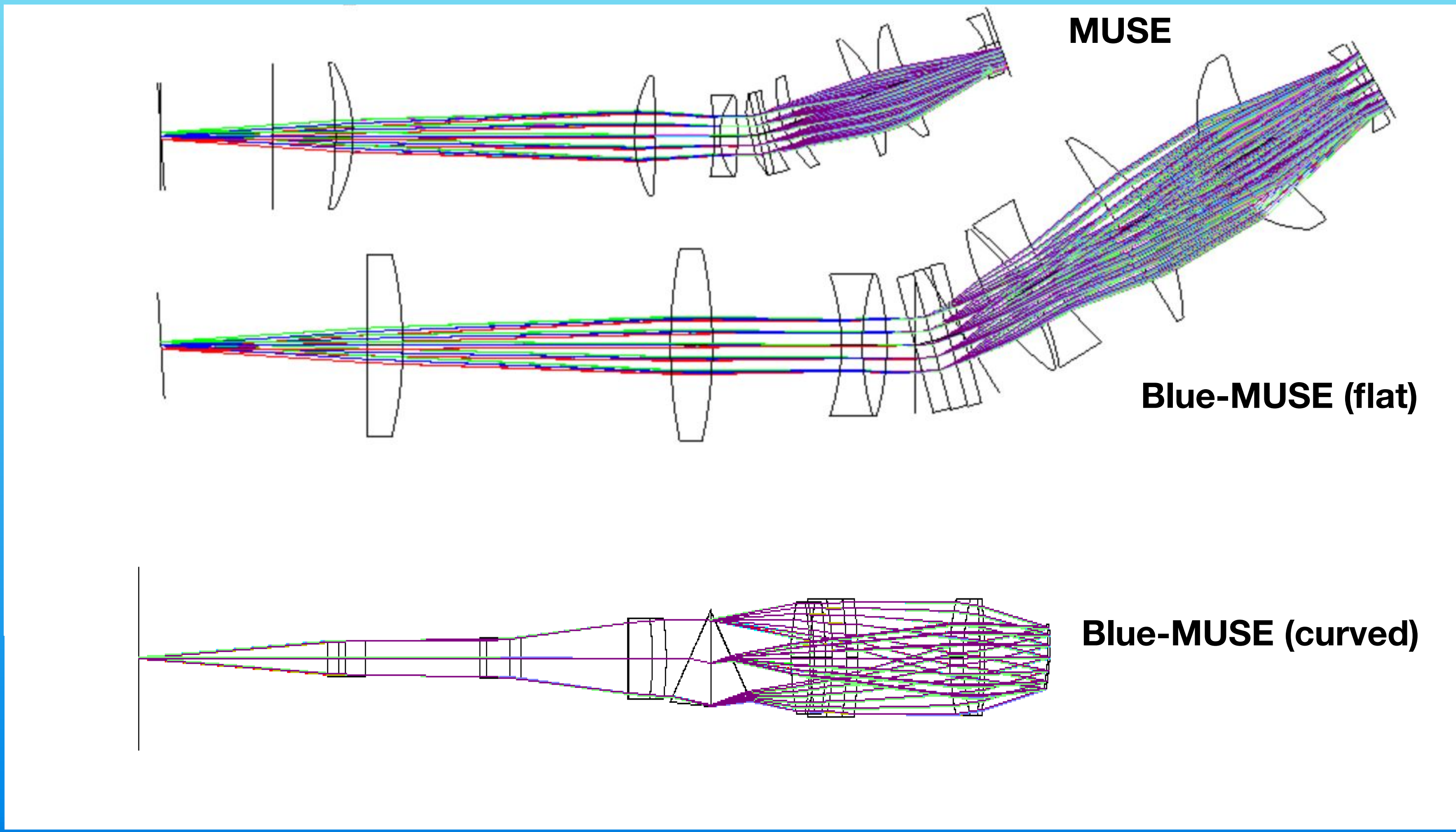
Optical design

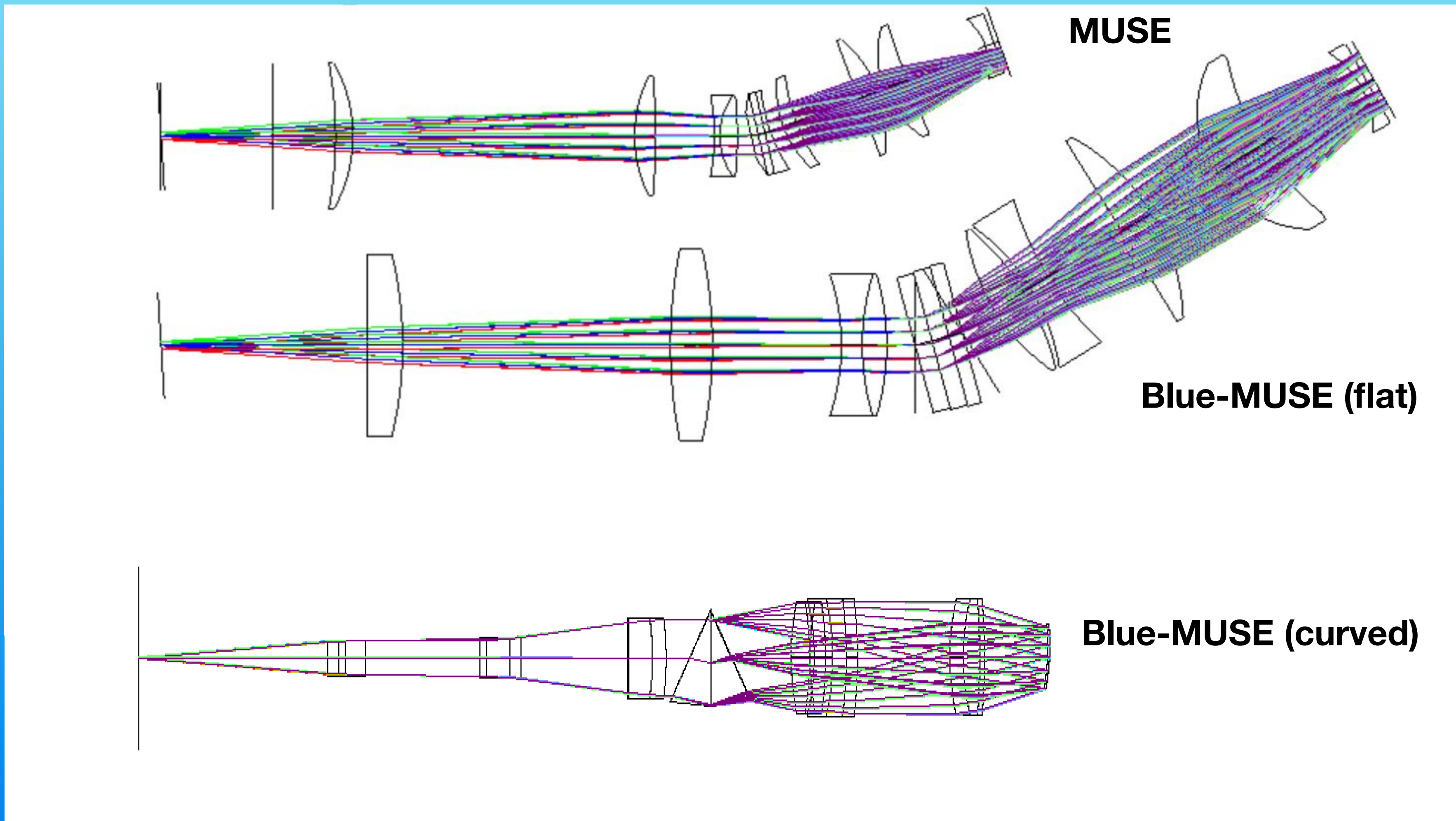
- A first optical design has been found for first feasibility
- MUSE already takes the entire space on the VLT Nasmyth platform: a larger FOV needs larger optics and seems difficult
- The solution currently studied is the use of curved detectors.





Optical design




MUSE
Blue-MUSE (flat)
Blue-MUSE (curved)

Complementarity with MUSE red

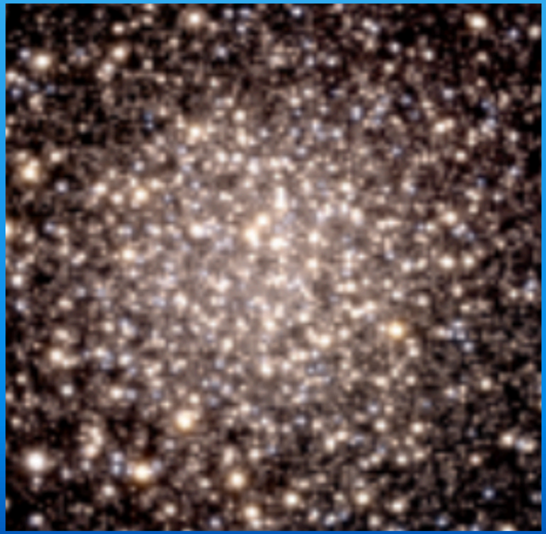
	MUSE Red	MUSE Blue (curved)	Comment
Field of view	1x1 $arcmin^2$	**1.4x1.4 $arcmin^2$**	**Factor 2 in area**
Sampling	0.2x0.2 $arcsec^2$	0.3x0.3 $arcsec^2$	
Median spatial resolution	0.4 arcsec with AOF	0.8 arcsec (seeing limited)	
Wavelength range	480-930 nm	350-600 nm	No 580 nm Na gap
Spectral Resolution	1800 @ 480 nm 3500 @ 930 nm	**3000 @ 350 nm** **5000 @ 600 nm**	**Factor 2 higher**
Spectral sampling	2 pixels	2 pixels	
Narrow Field Mode	7x7 $arcsec^2$ 0.025 arcsec	None	
OH sky lines	Many > 0.8 nm	None	
Throughput	0.35 @ 700 nm	similar	No filter needed for 2^{nd} order

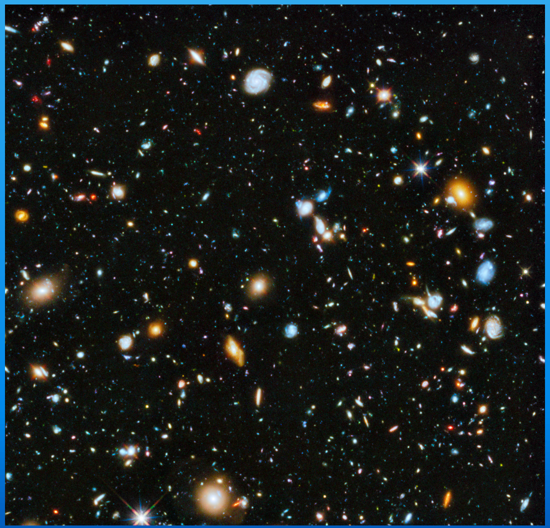
Feasibility & Risks

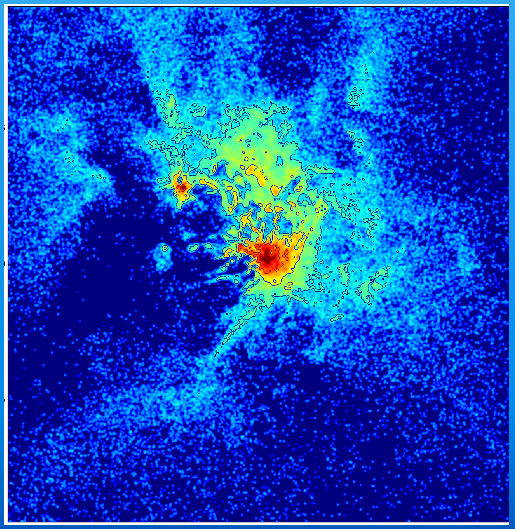
- Most technology exists: slicer, spectrograph, etc.
- New technology: use of 4k x 4k curved detector
- No narrow-field mode, no AO coupling, one single mode
- Larger optical derotator
- Lesson learned from MUSE red
  - Temperature control of the whole instrument
- Cost
  - slightly more expensive on hardware (larger fore-optics)
  - Less expensive in development
  - Current estimate: 10 Meuros hardware.
- Backup solution
  - 1x1 $arcmin^2$ field of view, smaller optics, 4k x 4k flat detector, but same spectral range

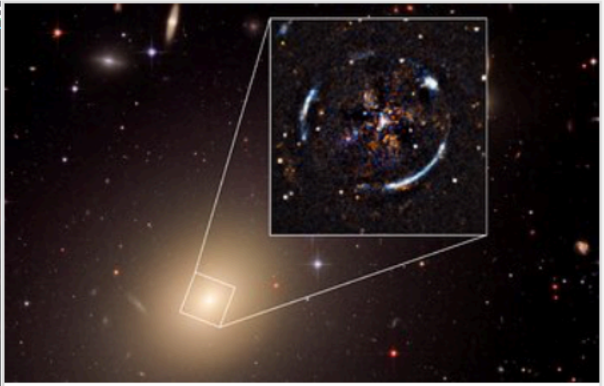
Conclusions

- Blue MUSE is a unique opportunity to maintain our world leadership in the era of IFU science.
- 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









eso1819 — Science Release

VLT Makes Most Precise Test of Einstein's General Relativity Outside Milky Way

21 June 2018: Astronomers using the MUSE instrument on ESO's Very Large Telescope in Chile, and the NASA/ESA Hubble Space Telescope, have made the most precise test yet of Einstein's general theory of relativity outside the Milky Way. The nearby galaxy ESO 325-G004 acts as a strong gravitational lens, distorting light from a distant galaxy behind it to create an Einstein ring around its centre. By comparing the mass of ESO 325-G004 with the curvature of space

eso1802 — Science Release

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

eso1810 — Photo Release

Dead Star Circled by Light

5 April 2018: New images from ESO's Very Large Telescope in Chile and other telescopes reveal a rich landscape of stars and glowing clouds of gas in one of our closest neighbouring galaxies, the Small Magellanic Cloud. The pictures have allowed astronomers to identify an elusive stellar corpse buried among filaments of gas left behind by a 2000-year-old supernova explosion. The MUSE instrument was used to establish where this elusive object is hiding, and existing Chandra X-ray Observatory data confirmed its identity as an isolated neutron star.