




*Clusters And LENsing Distant Sources*

# Spectroscopic surveys of the Frontier Fields clusters

Johan Richard (CRAL, Lyon)

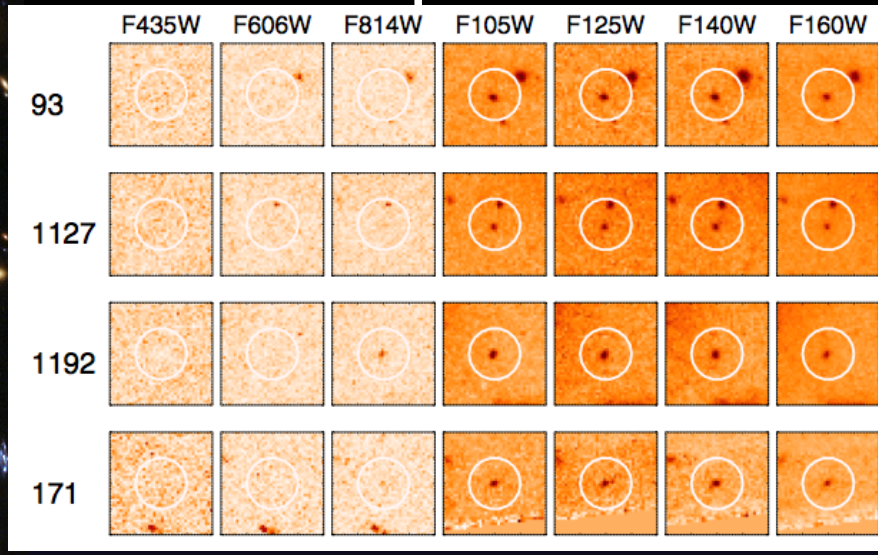
Vera Patricio (CRAL), Benjamin Clément (CRAL), Mathilde Jauzac (Durham), Hakim Atek (EPFL), Eric Jullo (LAM, Marseille), Jean-Paul Kneib (EPFL), Mark Swinbank (Durham), the CATS team and the MUSE consortium

# HST Frontier Fields

## Multiple images and mass modelling

*Diego et al. 2014,*
*Grillo et al. 2014,*
*Jauzac et al. 2014a,b,*
*Johnson et al. 2014,*
*Richard et al. 2014a, ….*

## High redshift dropouts



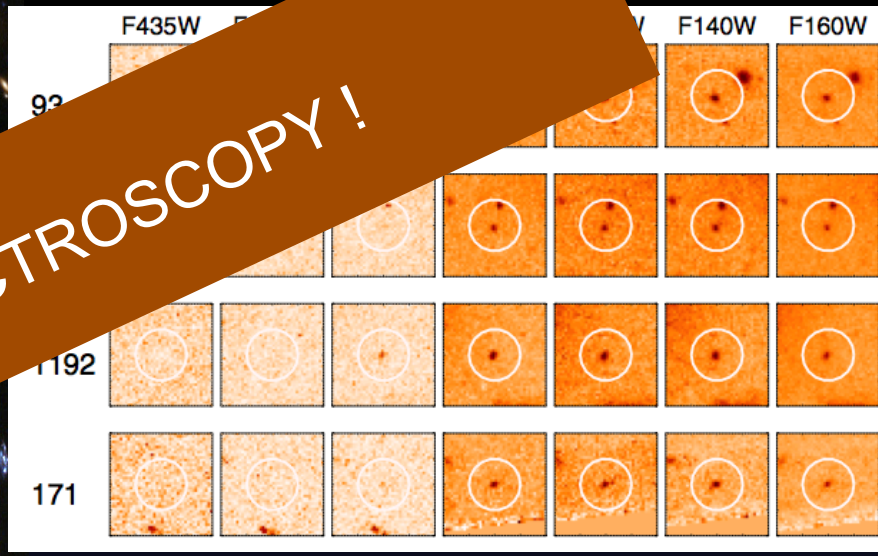

*Atek, Richard et al. 2014a,b*
*Coe et al. 2014, Ishigaki et al. 2014,*
*Laporte et al. 2014, Oesch et al. 2014,*
*Yue et al. 2014, Zheng et al. 2014,…*

# HST Frontier Fields

## Multiple images and mass modelling

*Diego et al. 2014,*
*Grillo et al. 2014,*
*Jauzac et al. 2014a,b,*
*Johnson et al. 2014,*
*Richard et al. 2014a, ….*

## High redshift dr…




NEED SPECTROSCOPY !

*Atek, Richard et al. 2014a,b*
*Coe et al. 2014, Ishigaki et al. 2014,*
*Laporte et al. 2014, Oesch et al. 2014,*
*Yue et al. 2014, Zheng et al. 2014,…*

# Additional science with spectroscopy

## Multiple images and mass modeling

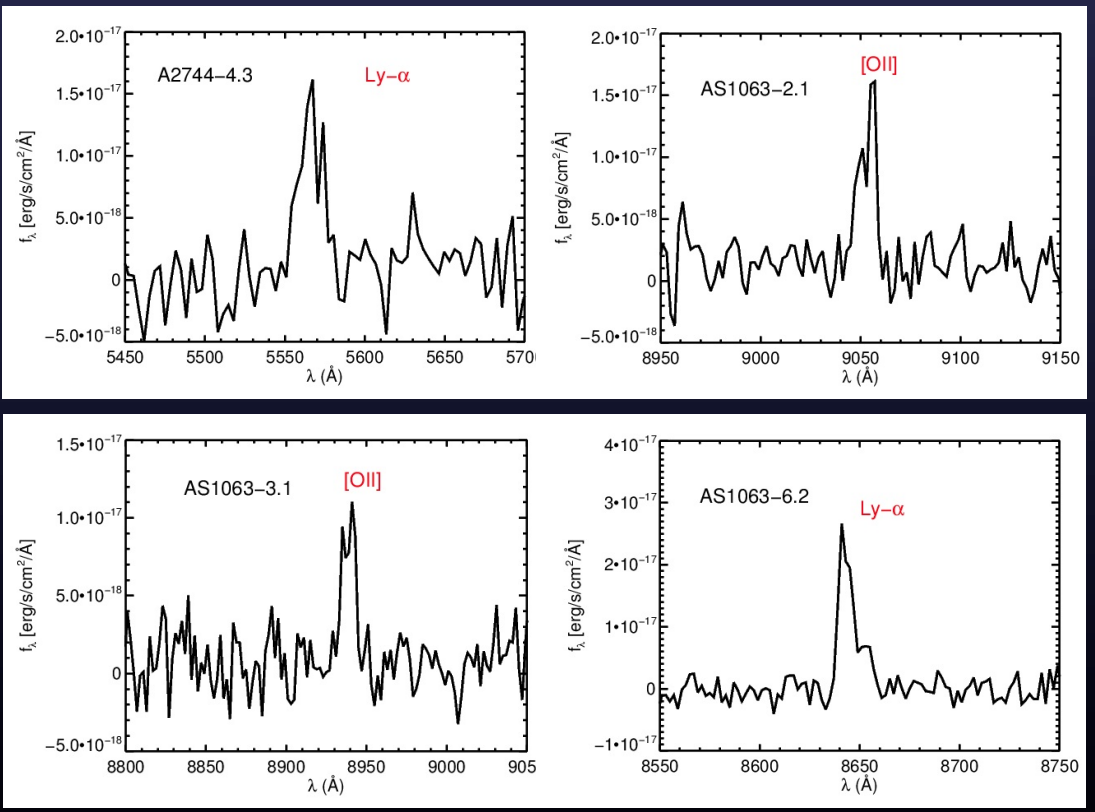
- Confirm identification of multiple images
- Pinpoint the source redshift to improve mass modelling
- Necessary to measure cosmology with strong lensing (Jullo et al. 2010)

## High redshift dropouts

- Confirm high redshift identification (through Lyman-alpha emission)
- Measure Lyman-alpha equivalent width (test for reionization)
- Other emission lines: measure physical properties (outflows, …)

# Pre-HFF spectroscopy of multiple systems

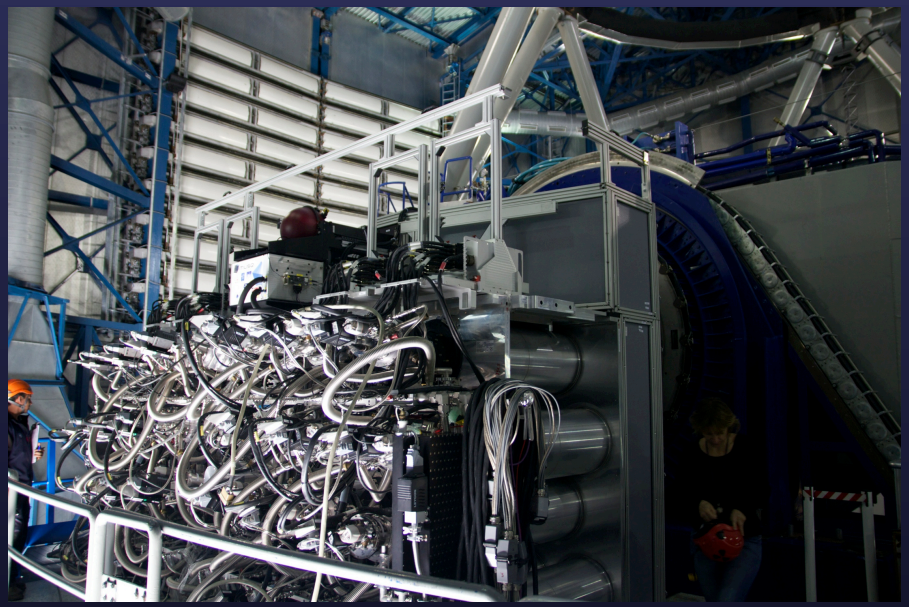
*Richard et al. 2014, MNRAS 444, 268*




- No spec-z was available for Abell 2744 and AS1063 during pre-HFF lens modelling effort
- VLT/FORS2 and Magellan/LDSS3 optical spectroscopy provided redshifts for all modellers in A2744, AS1063, A370

- Some redshifts confirmed by Johnson et al. 2014, in press

# muse
multi unit spectroscopic explorer



- 1x1 arcmin2 integral field spectrograph
- 0.2” spaxel sampling, <0.2” IQ
- 4650-9300 Angstroms
- R=1500-3500
- 35% throughput end-to-end

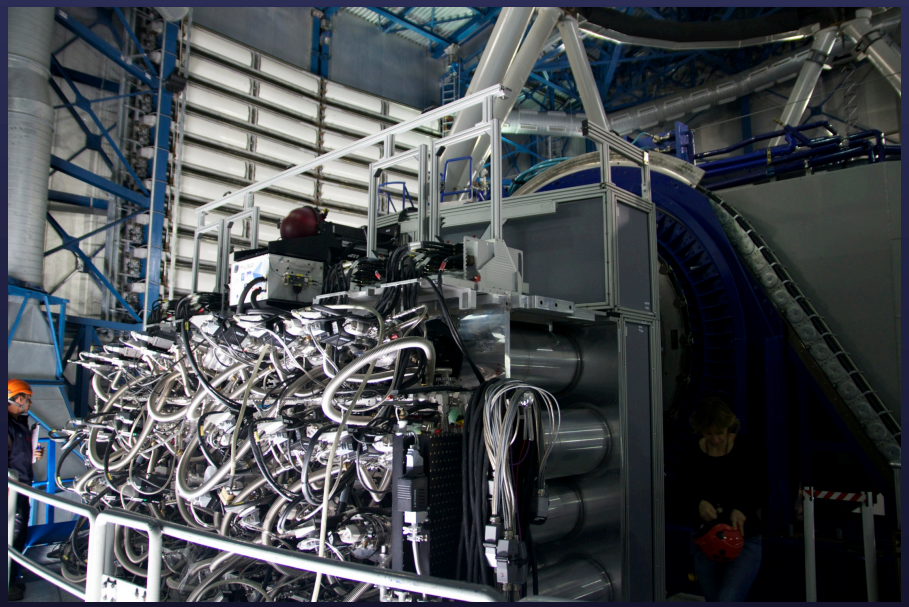
## Primary Goals:

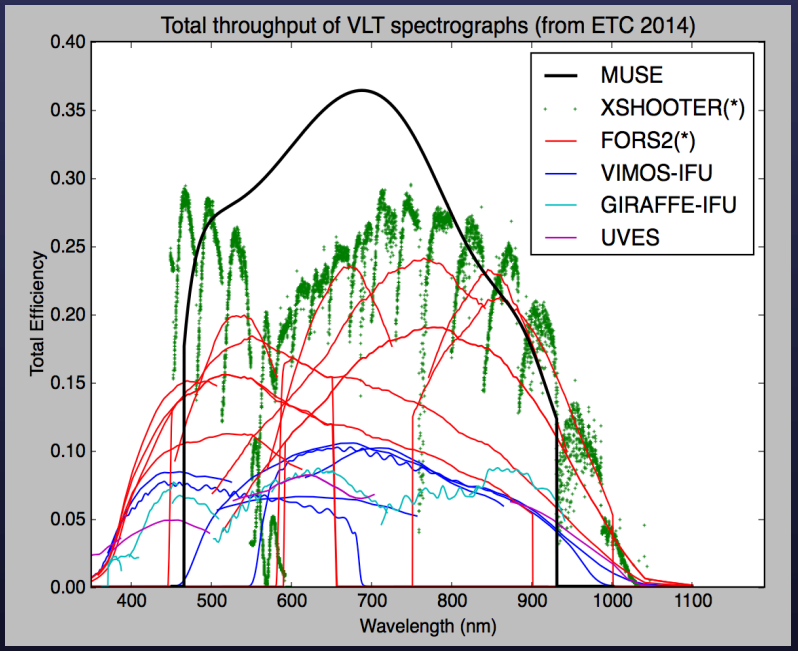
- Confirm z > 3 dropouts through Lyman-alpha emission
- Confirm / identify more multiple images for high precision mass modeling

## Secondary Goals:

- If present, measure the physical properties of extended arcs
- Dynamics of cluster members

muse
multi unit spectroscopic explorer





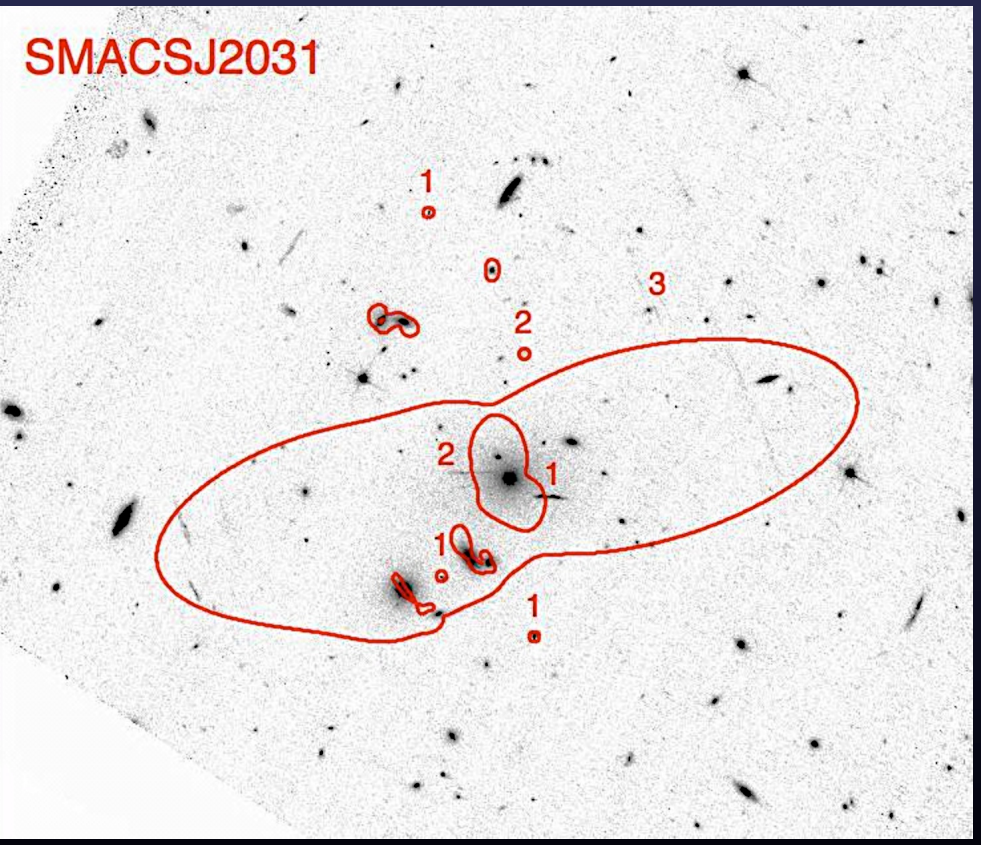

## Primary Goals:

- Confirm z > 3 dropouts through Lyman-alpha emission
- Confirm / identify more multiple images for high precision mass modeling

## Secondary Goals:

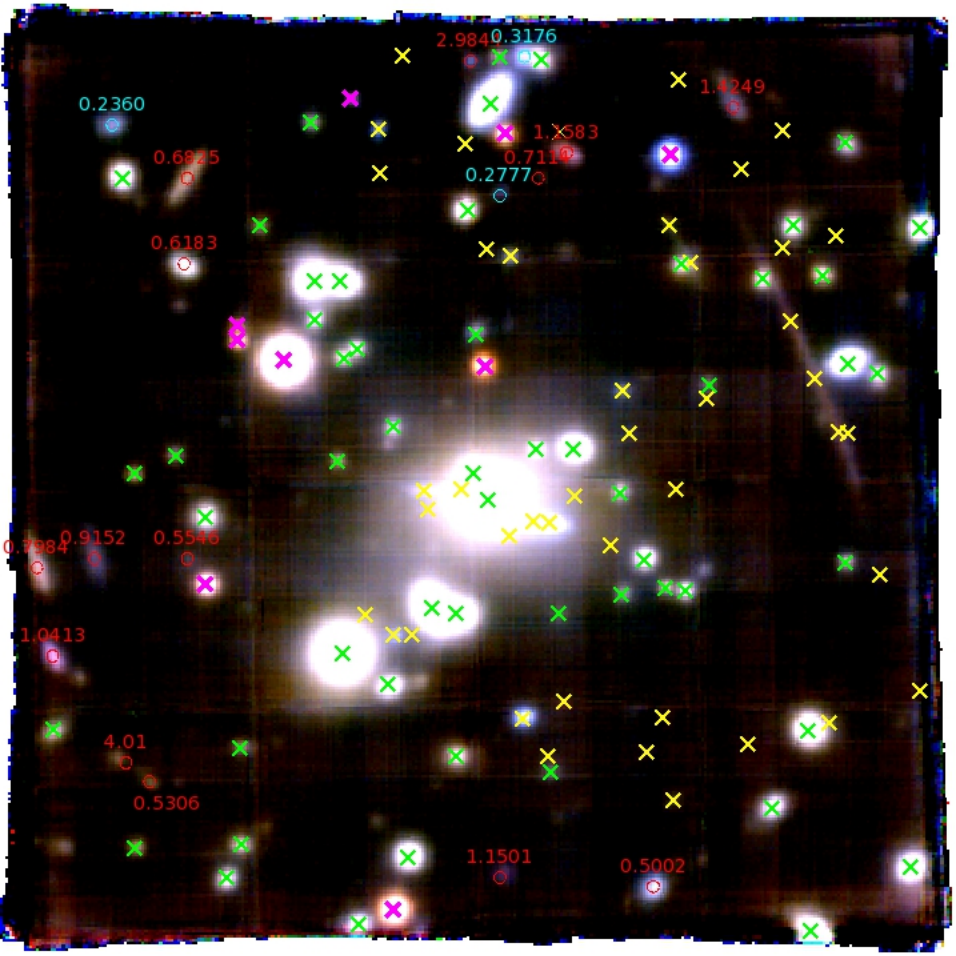
- If present, measure the physical properties of extended arcs
- Dynamics of cluster members

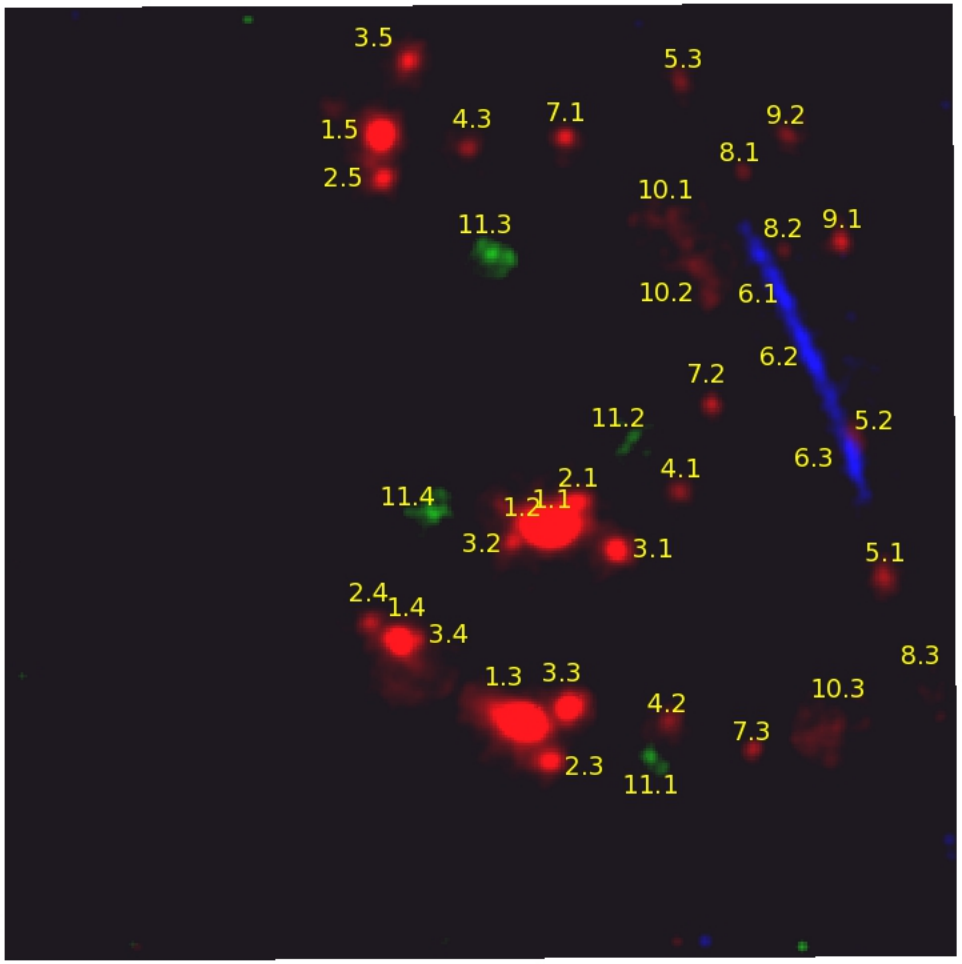
# Test case: SMACSJ2031.8-4036




- Massive galaxy cluster at z=0.331
- HST imaging F606W/F814W
- Strong lensing constrained by 3 multiple systems
- 1 specz @ z=3.5073 (*Christensen et al. 2012a,b*)
- MUSE commissioning: 10 hrs in ~1.0-1.1” seeing

*Richard et al. 2015, MNRAS 446L, 16*



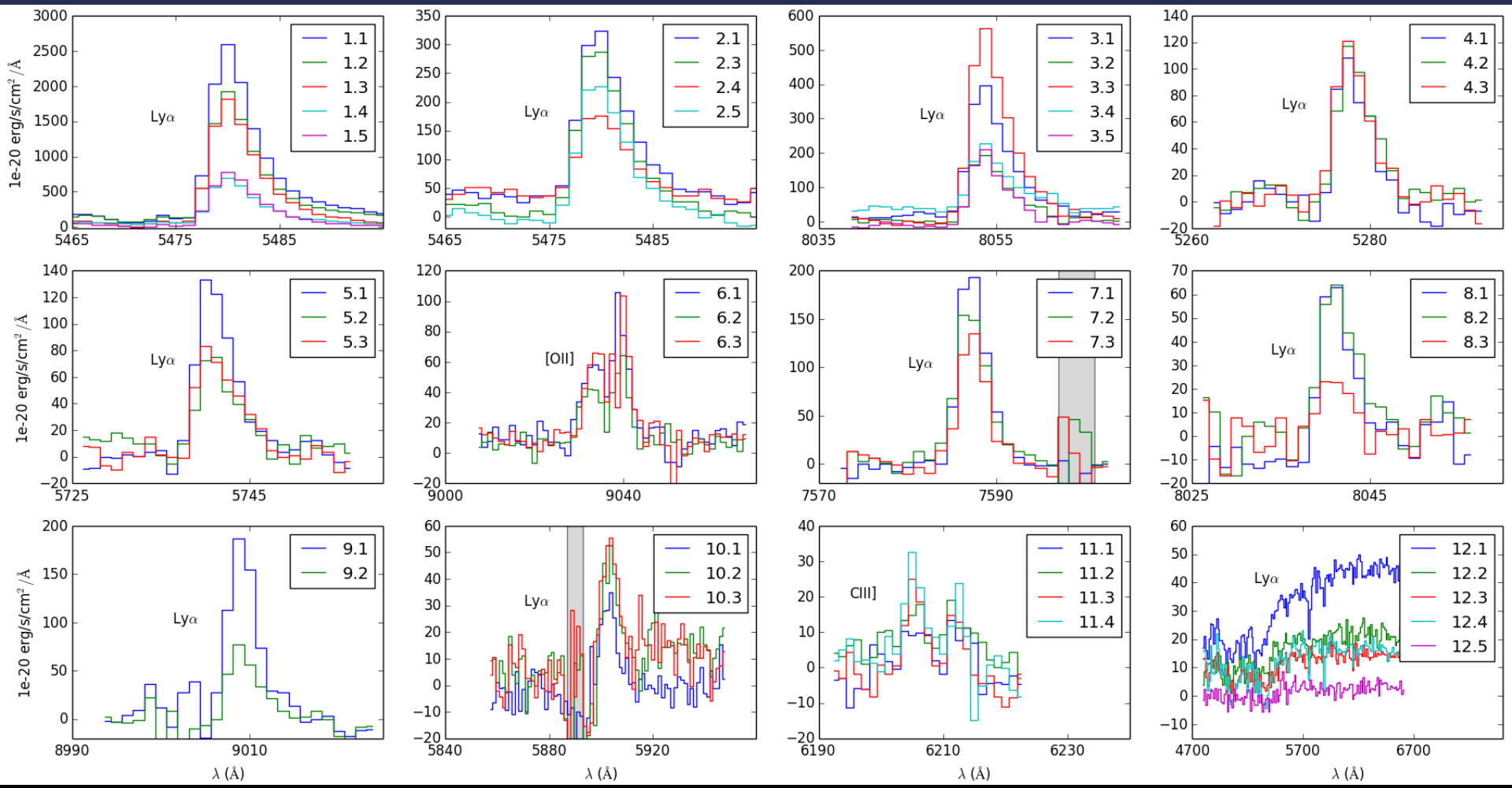




**Continuum color image**

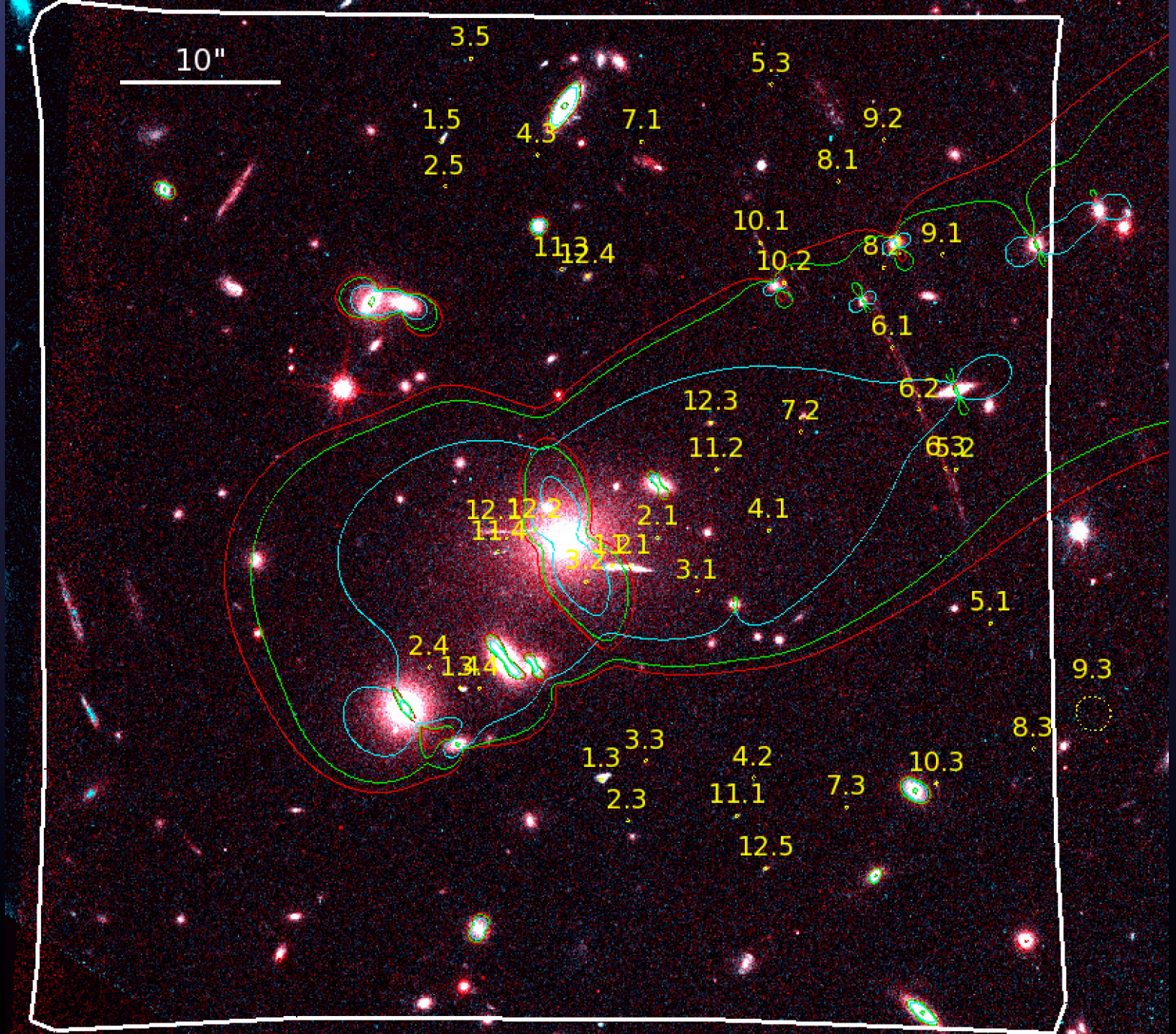
**Composite narrow-band image**

**Lyα CIII] [OII]**

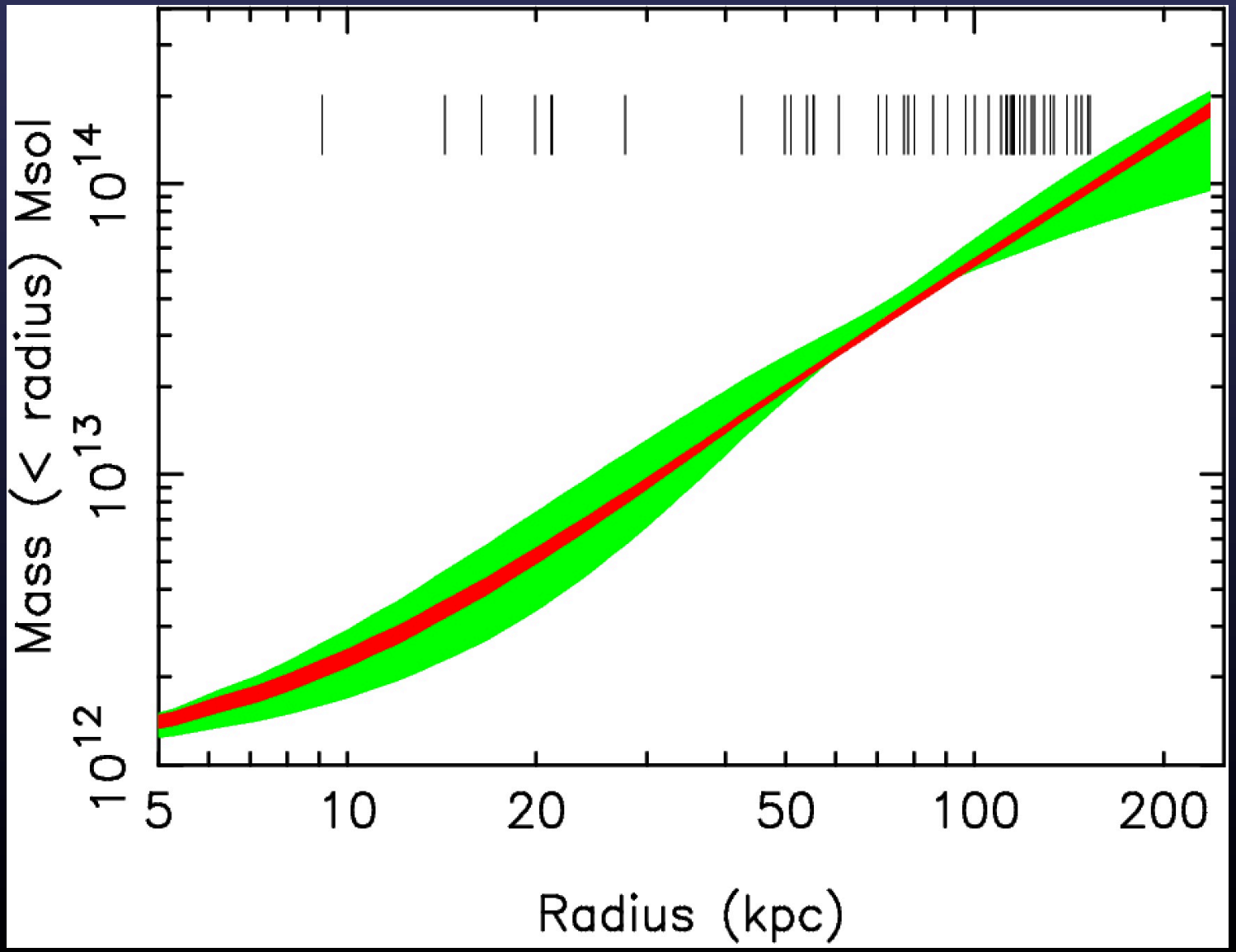
# *Richard et al. 2015, MNRAS 446L, 16*

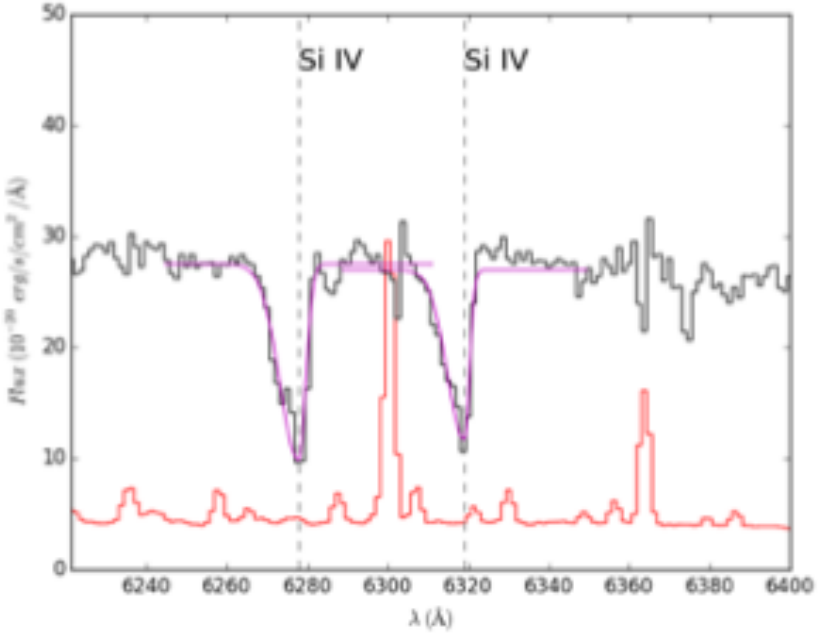


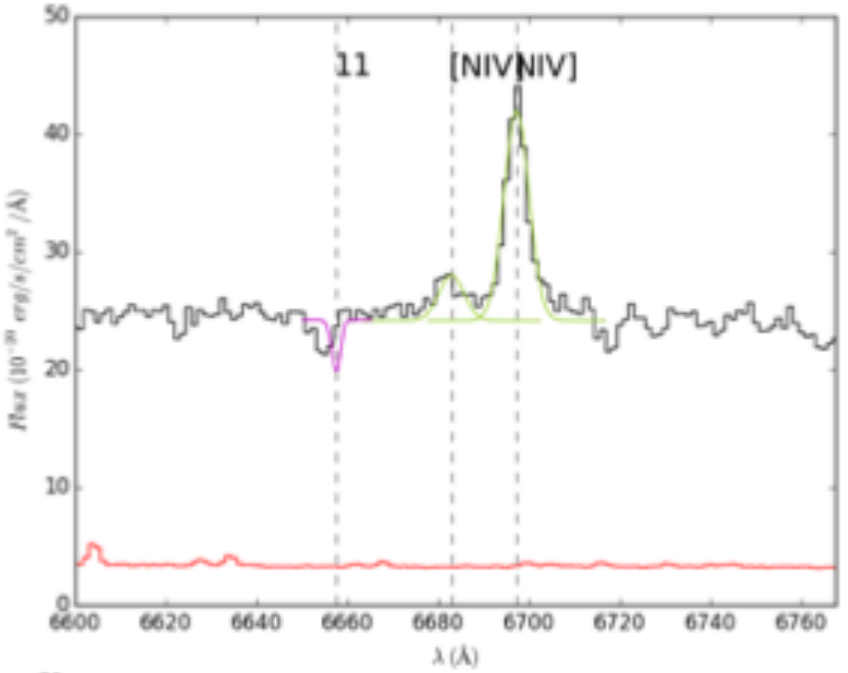

Confirmation and spectroscopic redshifts for 11 systems

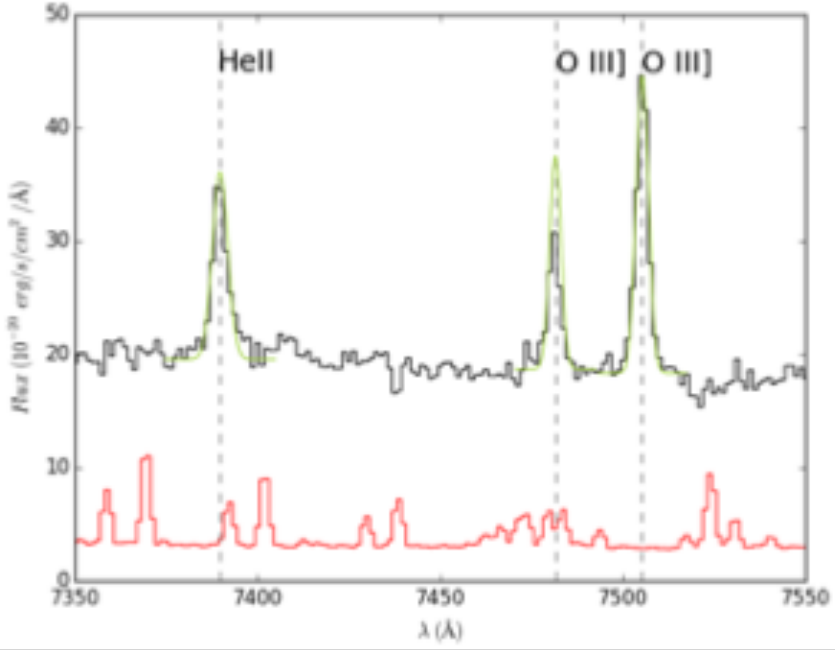

10"
3.5
5.3
1.5
4.3
7.1
9.2
2.5
8.1
10.1
9.1
10.2
6.1
6.2
12.3
7.2
11.2
12.2
2.1
4.1
3.1
5.1
2.4
9.3
8.3
3.3
1.3
4.2
10.3
2.3
11.1
7.3
12.5

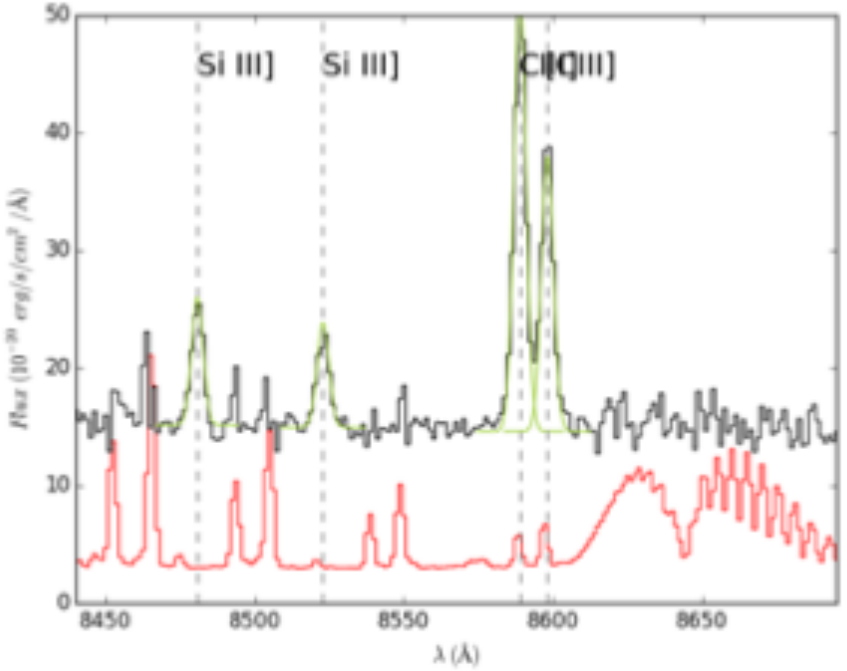
*Richard et al. 2015, MNRAS 446L, 16*



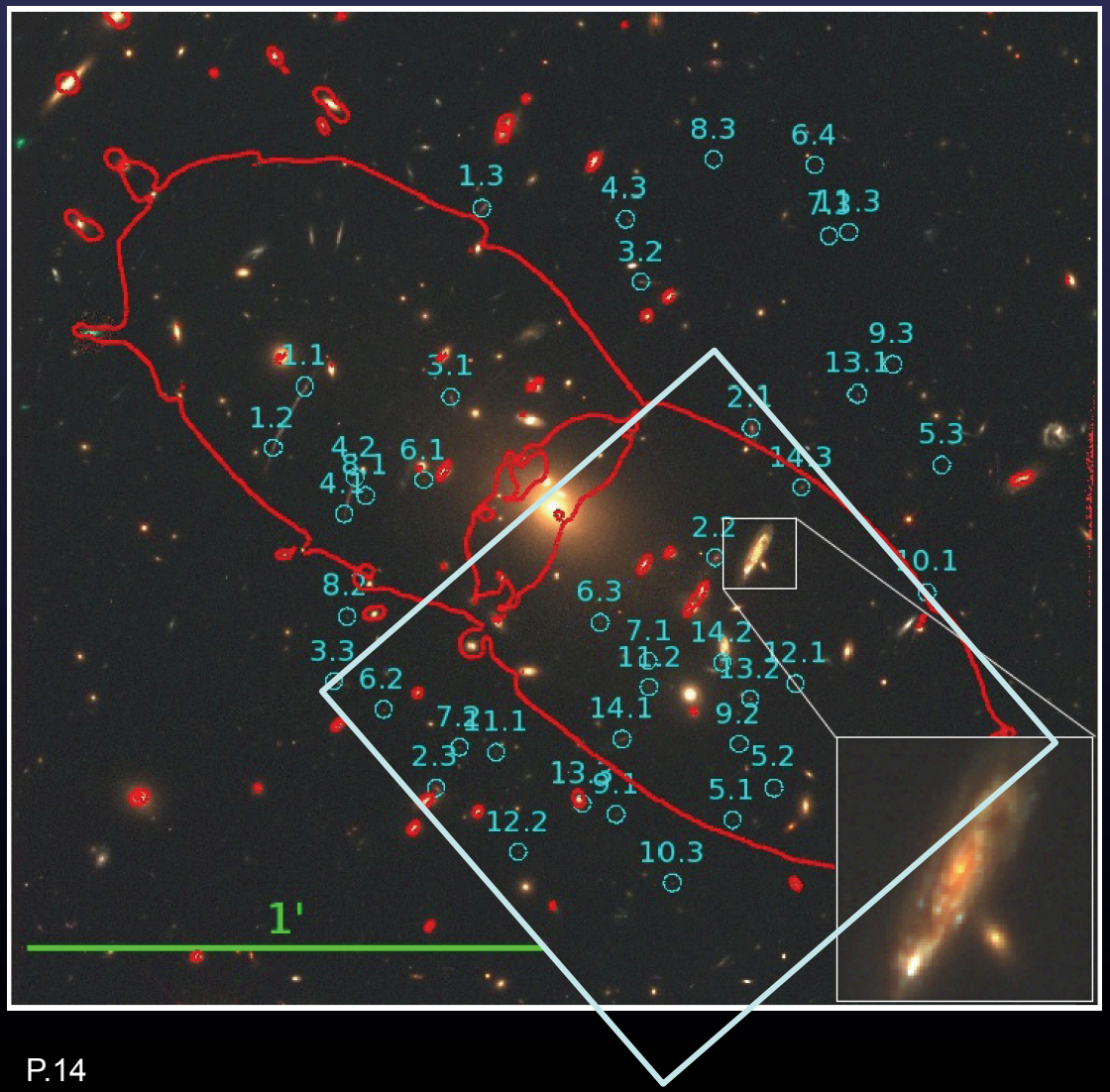

Si IV
Si IV
λ (Å)


11
[NIV]NIV]
λ (Å)


HeII
O III]
O III]
λ (Å)

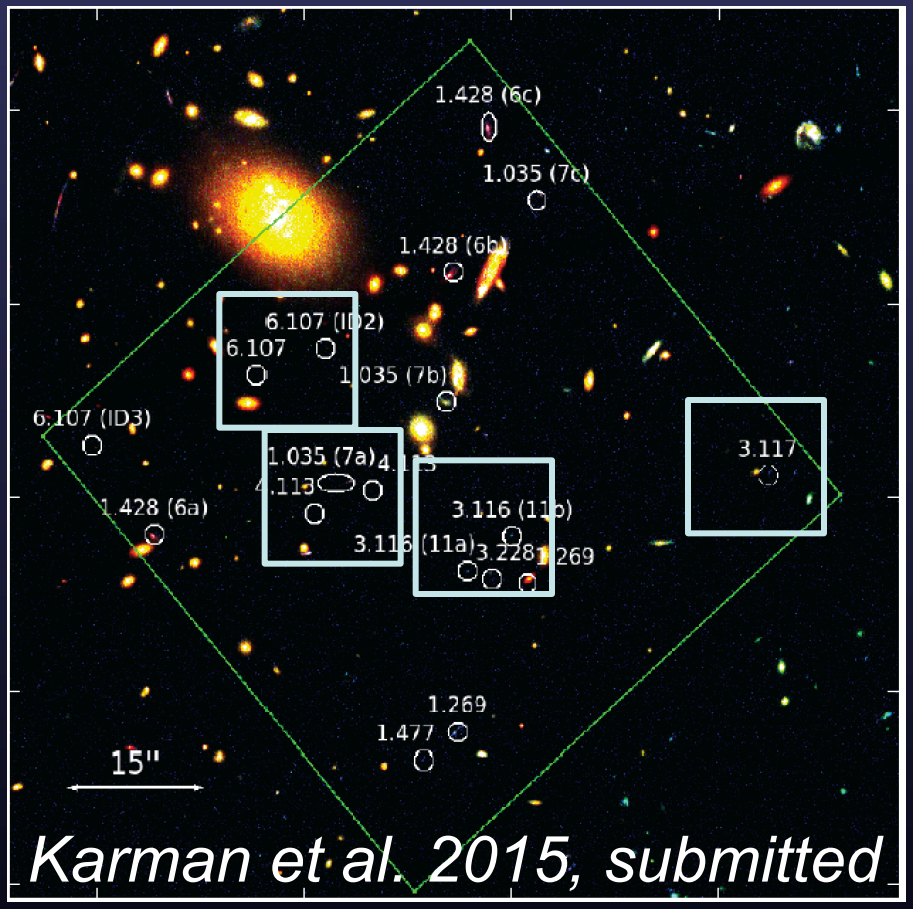

Si III]
Si III]
CIII]
CIII]
λ (Å)

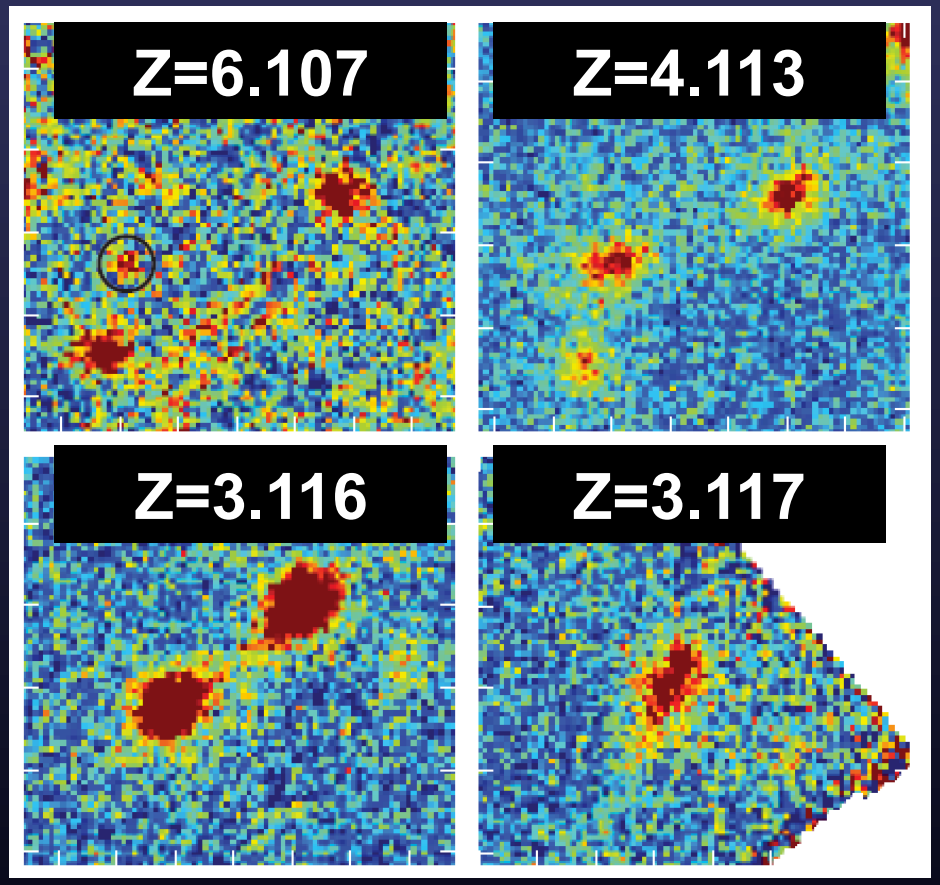
# MUSE SV program: AS1063
## (Co-PI: Clément & Caputi)




- 3 hrs 10 min / 4 OBs (8x1420s exposures)
- Seeing 1.2”-1.4”
- Covered the majority of multiple systems and a known spiral at z=0.6
- Known z=6.107 LAE
  *Monna et al.2014*
  *Boone et al. 2014*
  *Balestra et al. 2014*

# MUSE SV program: AS1063



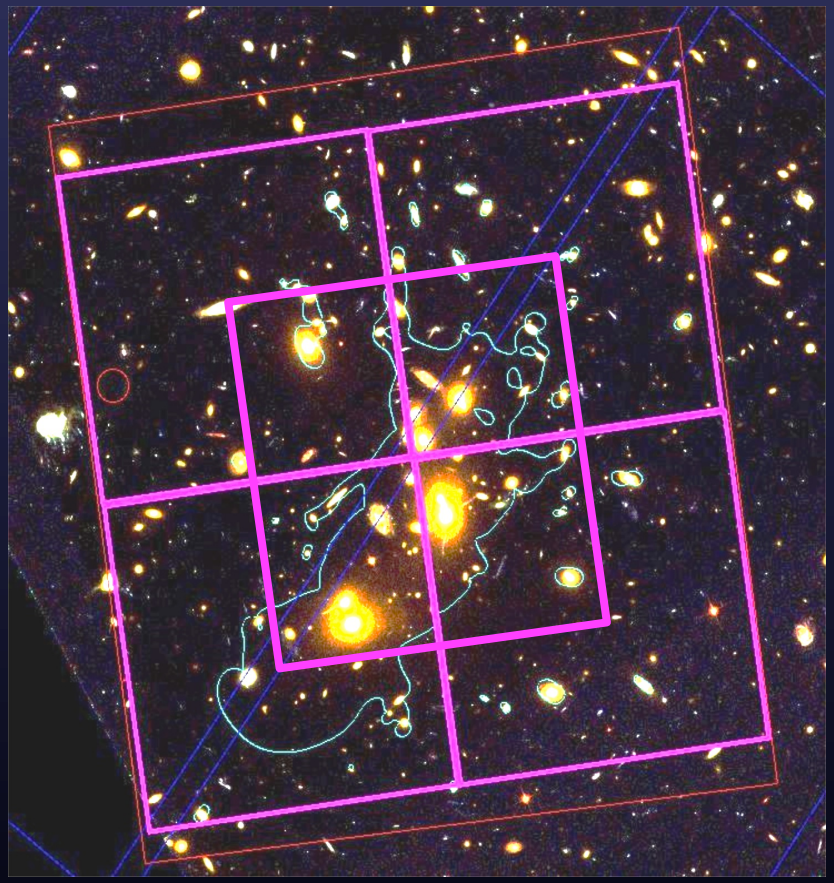




- Redshifts for known multiple images

+ new singly and multiply-imaged Lyman-alpha emitters

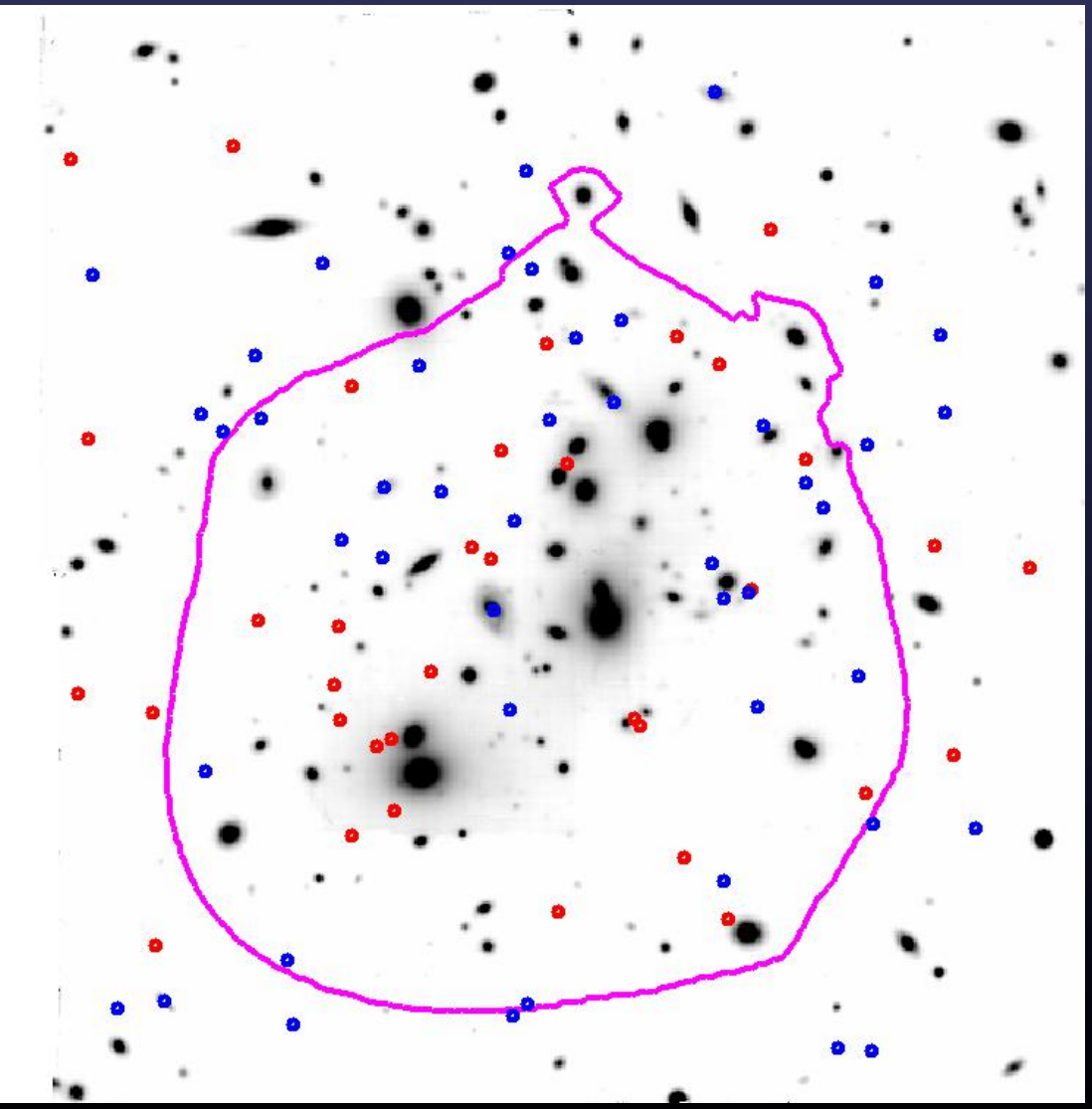
- Currently updating the mass model (Clément et al. )

# MUSE GTO program: A2744



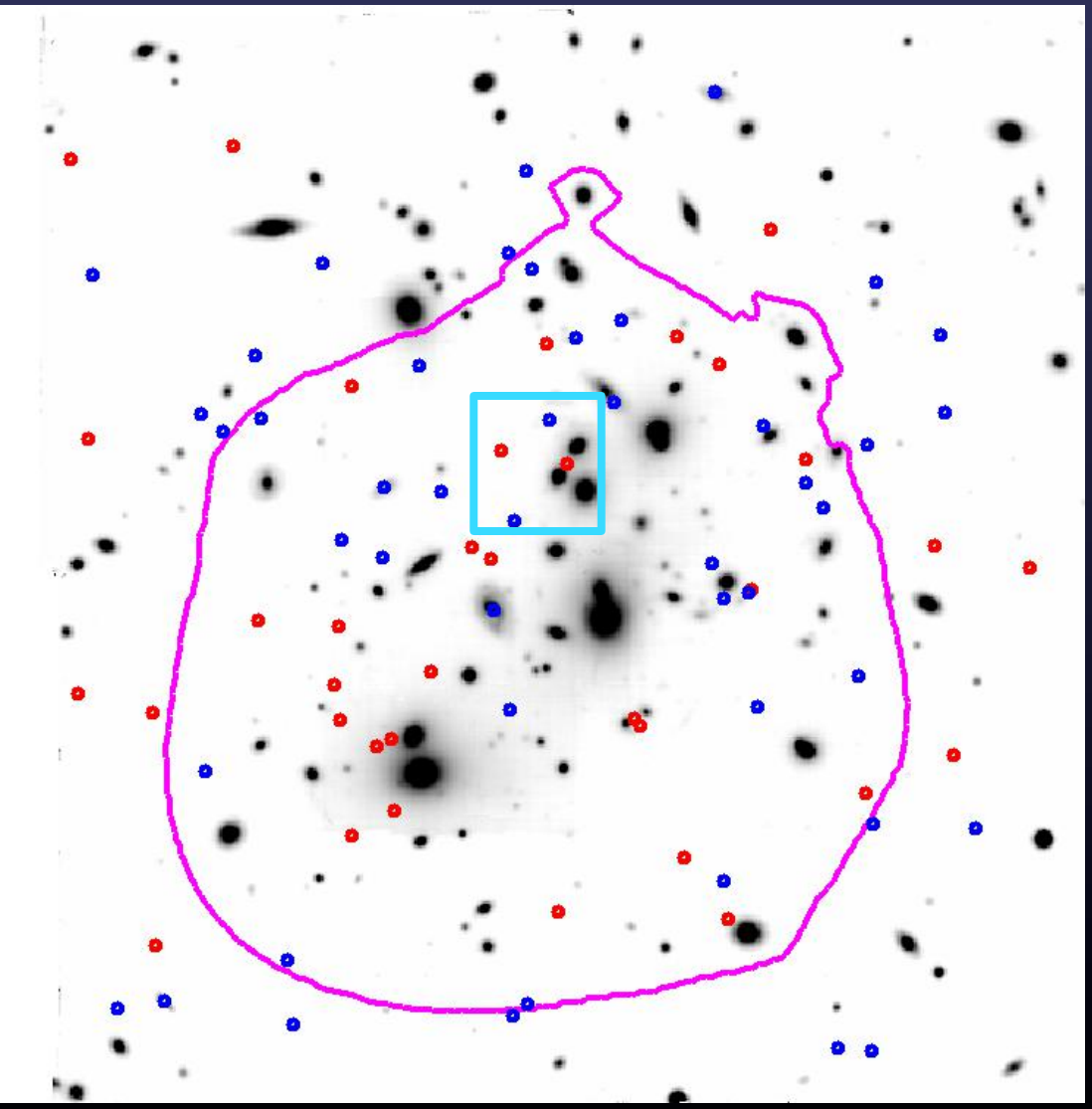
- 5 x 2 hrs mosaic to cover central region + almost full WFC3 fov.
- Sep. and Oct.2014 runs
- Average Seeing 0.6”-0.8”
- Preliminary results from first reduction!

# A2744: first analysis

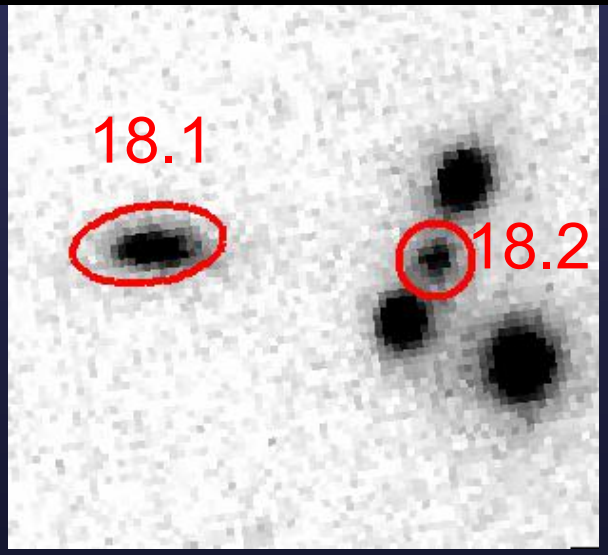


- First fishing expedition.
- Emission line sources: 82+ redshifts
- z<1.5
- z>1.5
- Systematic extraction of HST sources including multiple images/dropouts

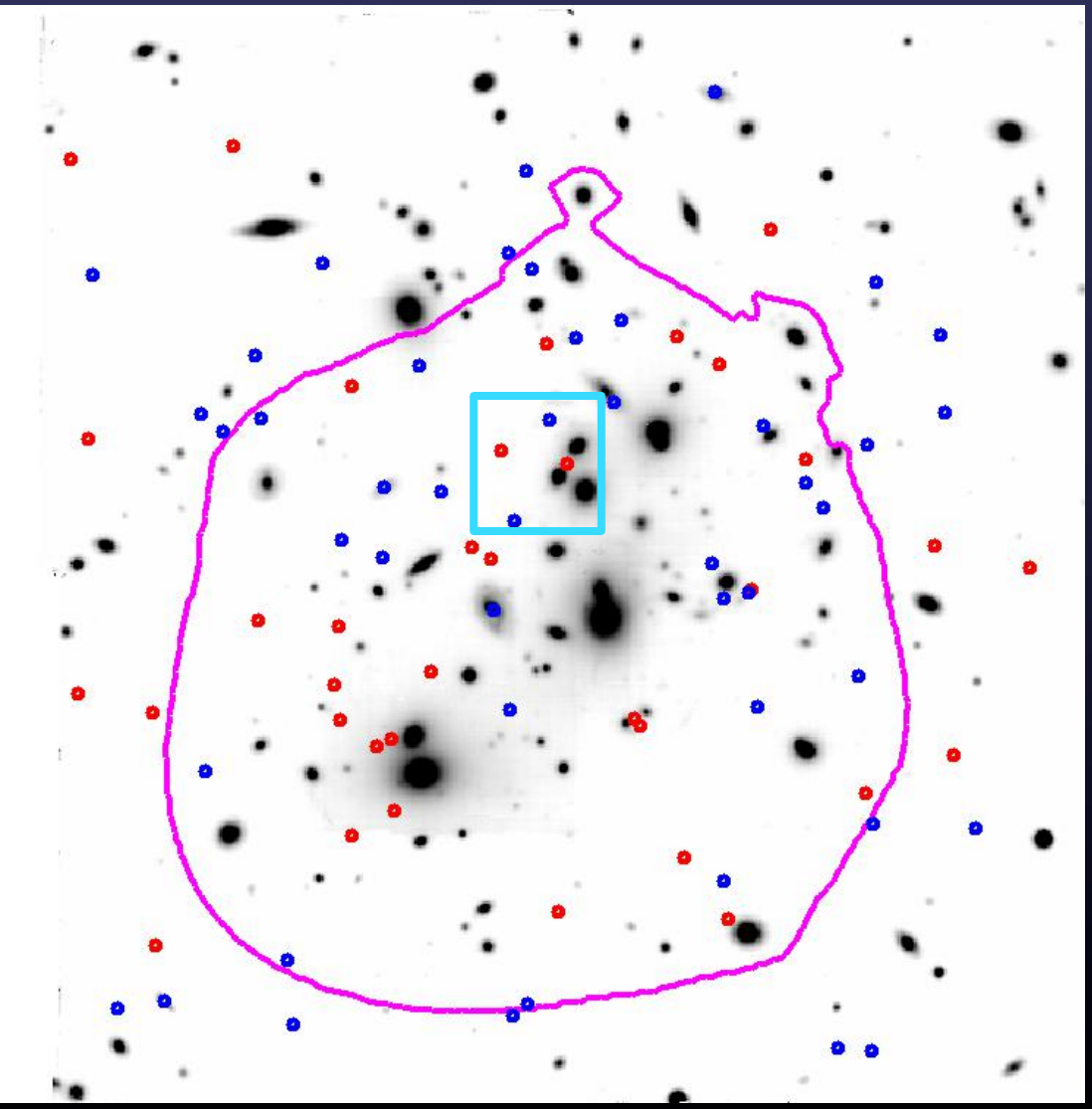
# A2744: first analysis



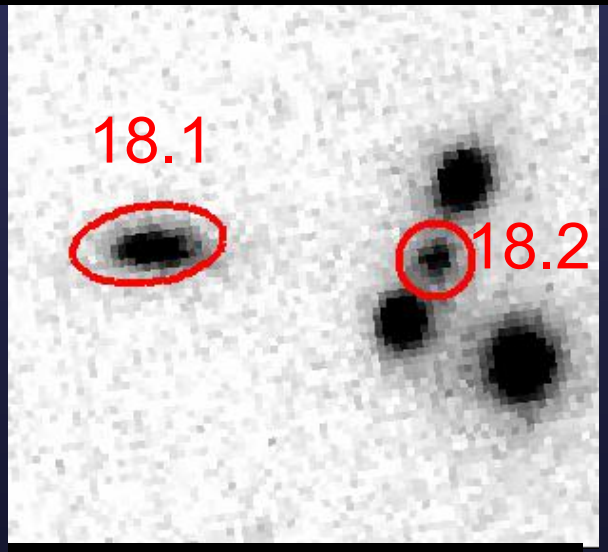
**z=5.66 dropout**



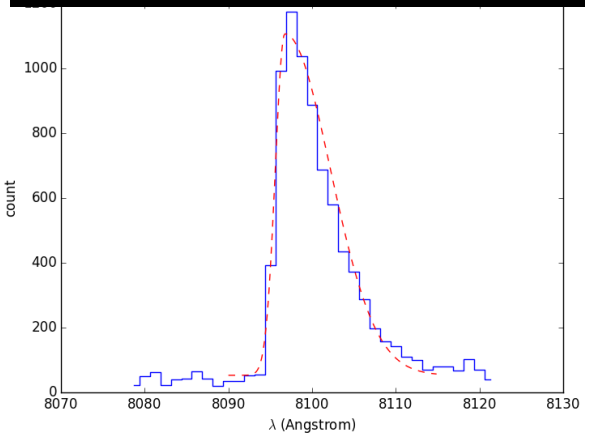

# A2744: first analysis



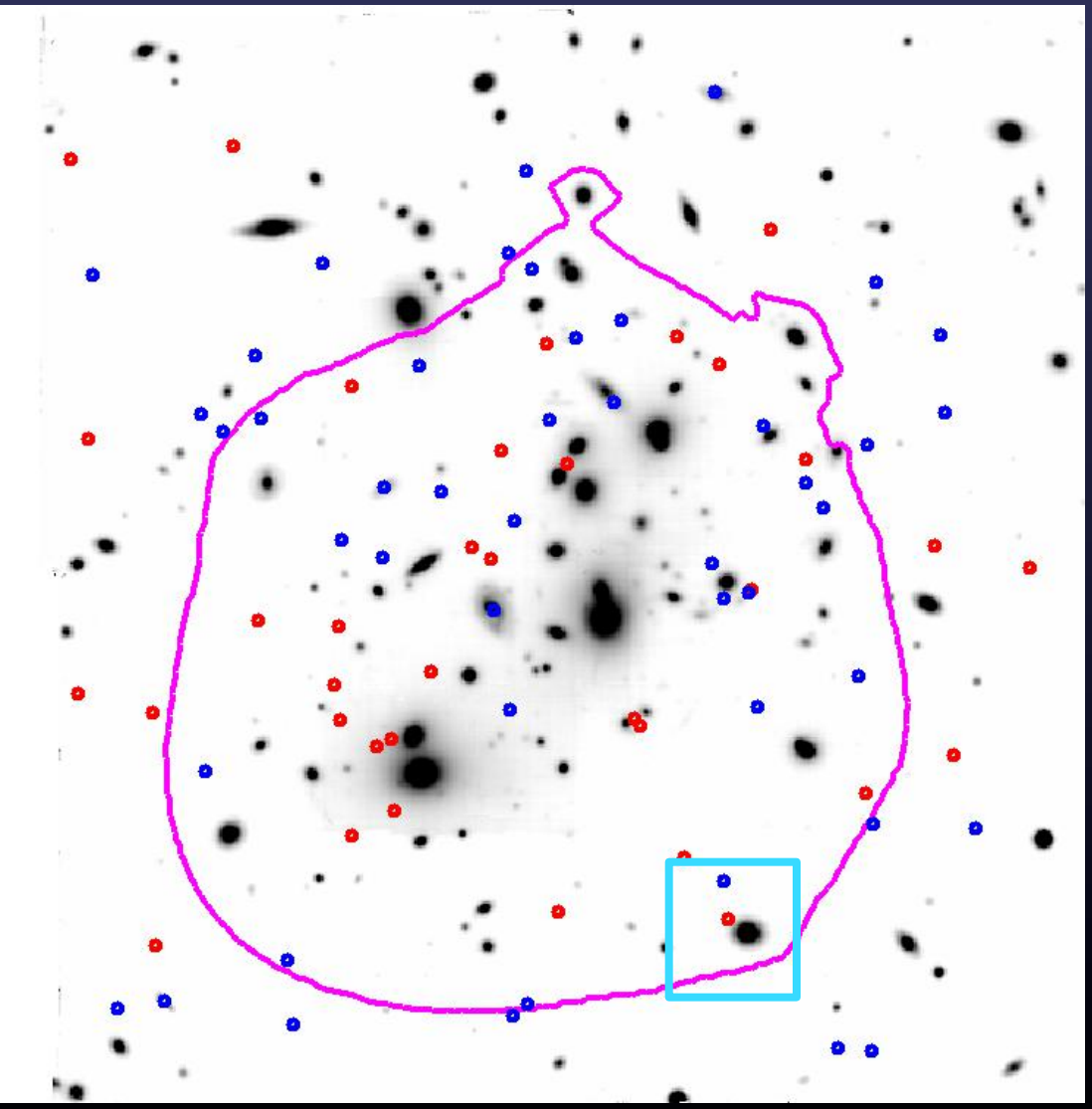
**z=5.66 dropout**



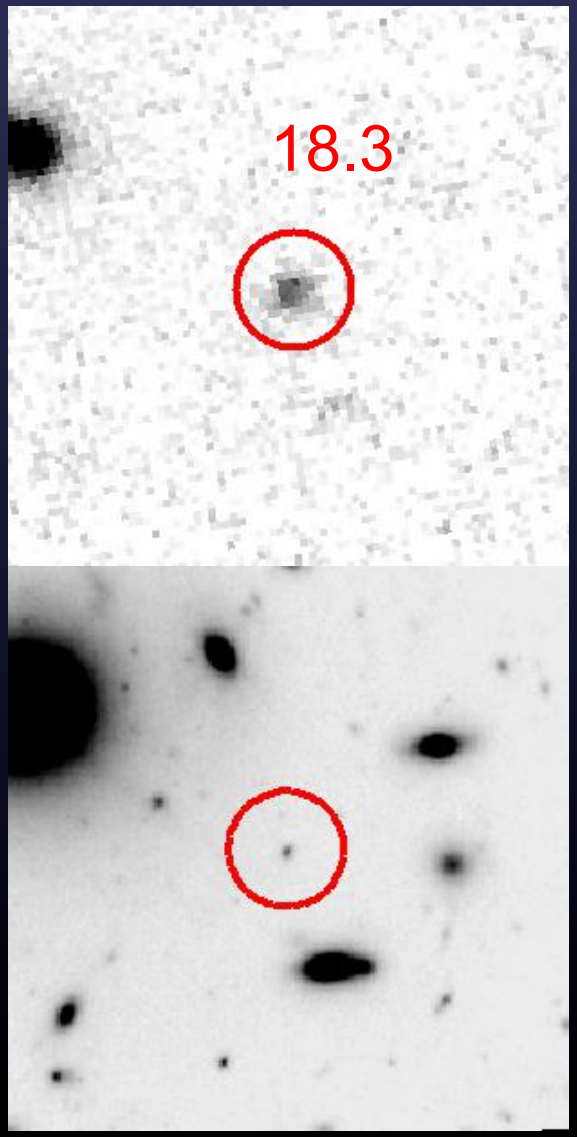

**fLya=9e-17**



# A2744: first analysis

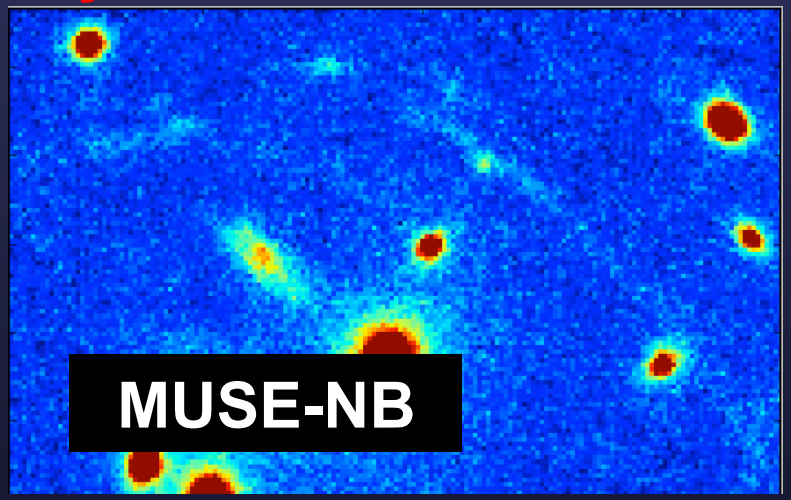


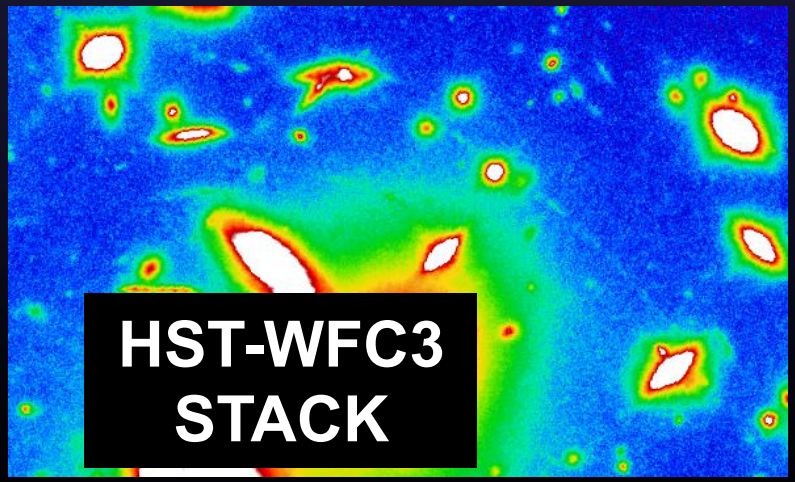
**z=5.66 dropout**



# Analysis of known multiple systems

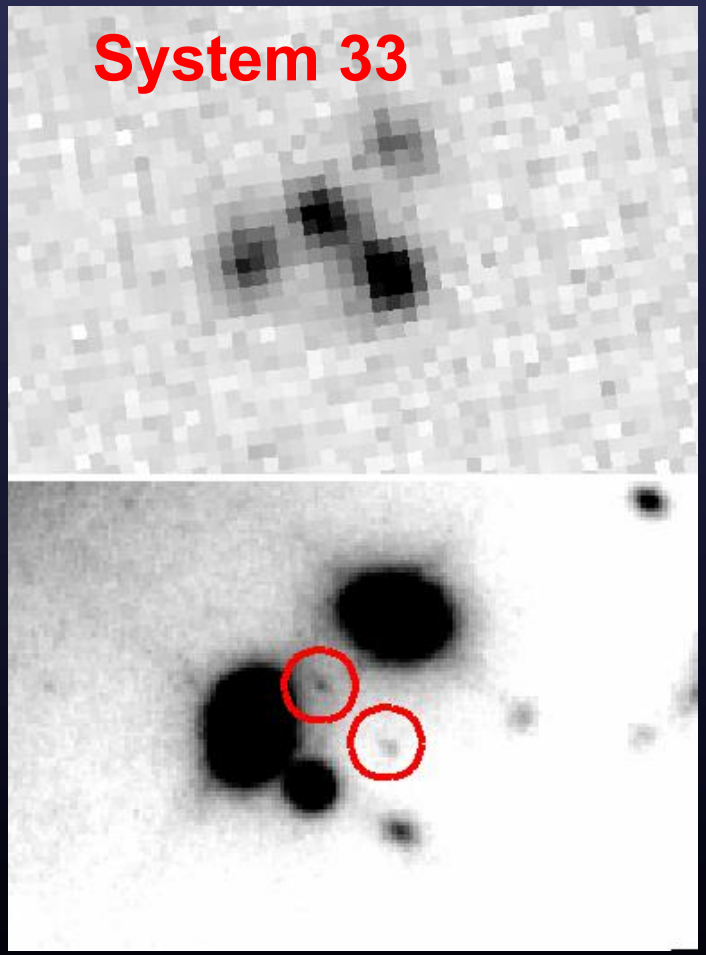
System 5



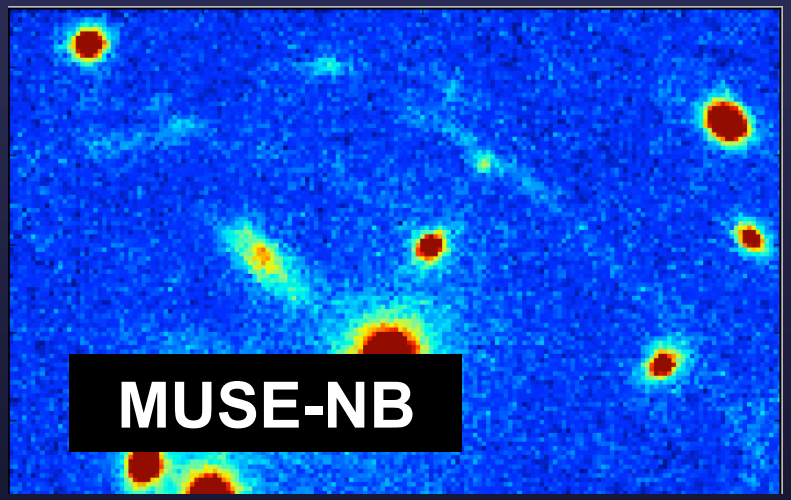



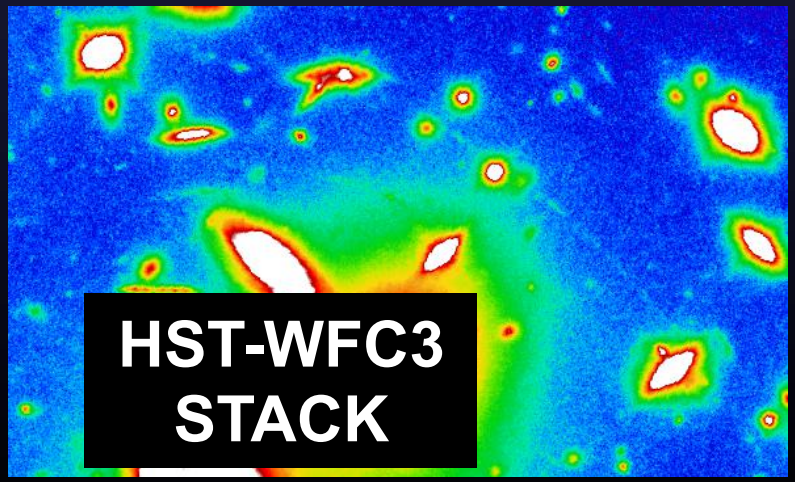

z=6 dropout μ=30+/-8 each

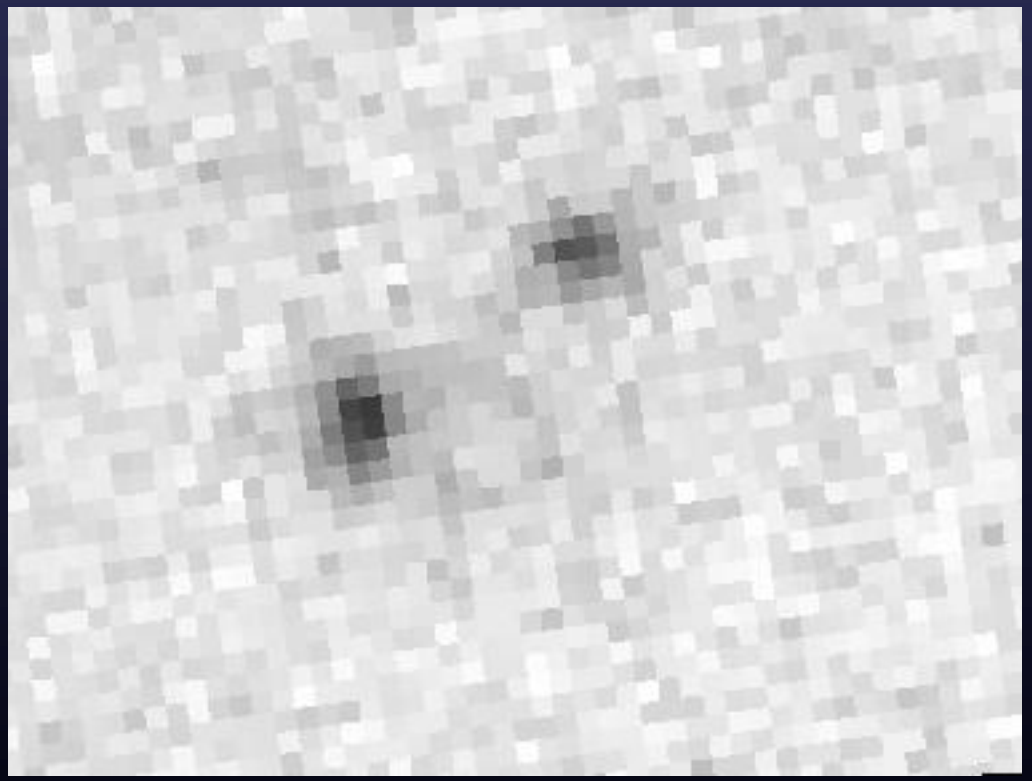
System 33



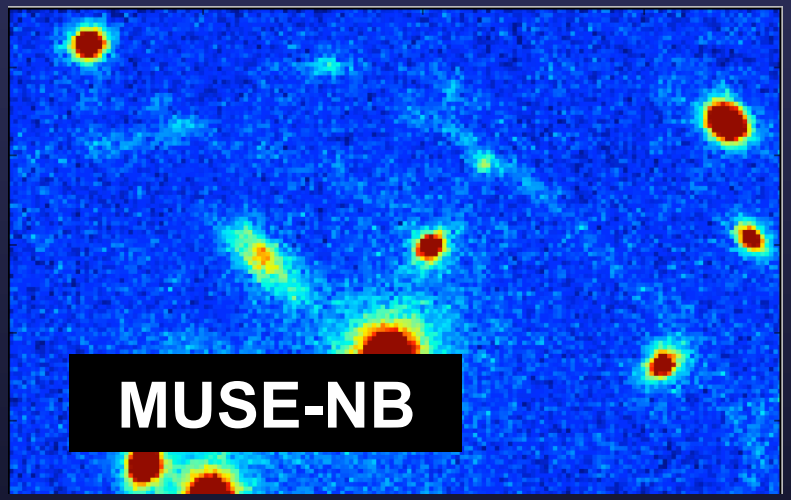
# Analysis of known multiple systems

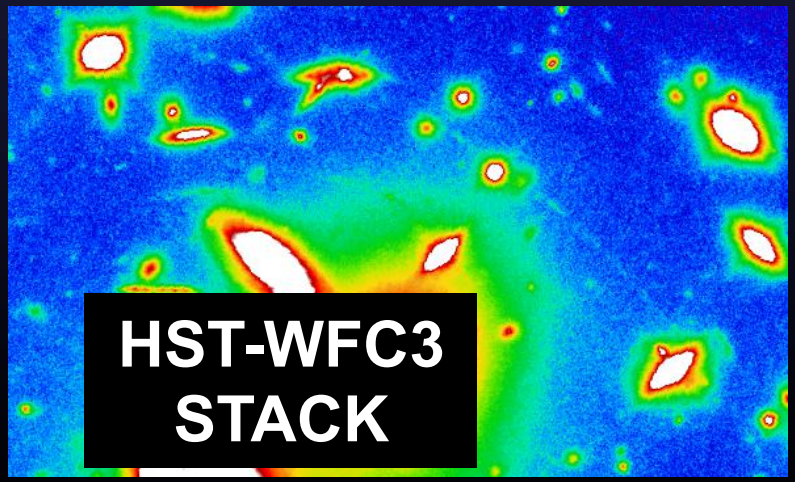


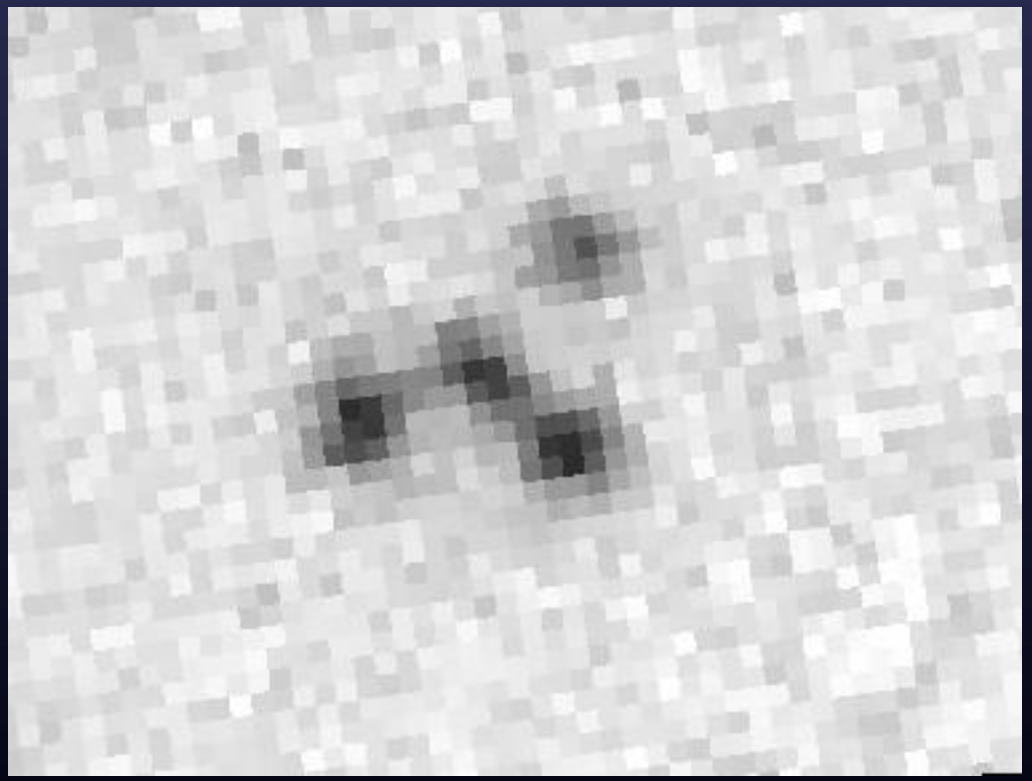



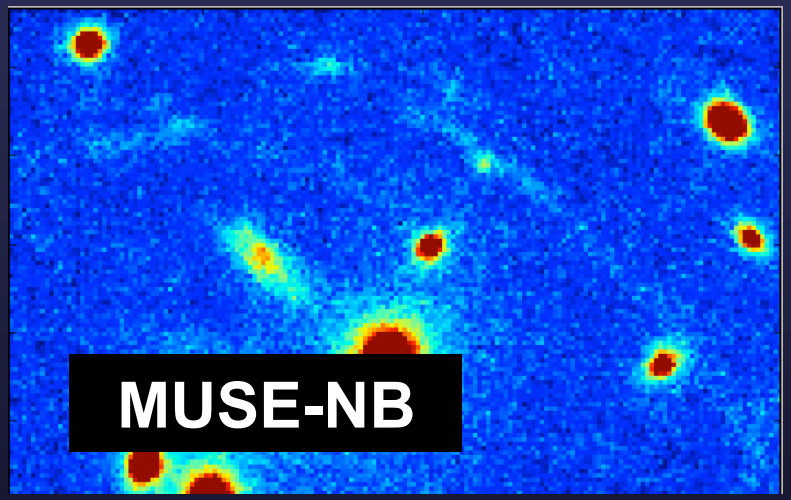
# Analysis of known multiple systems

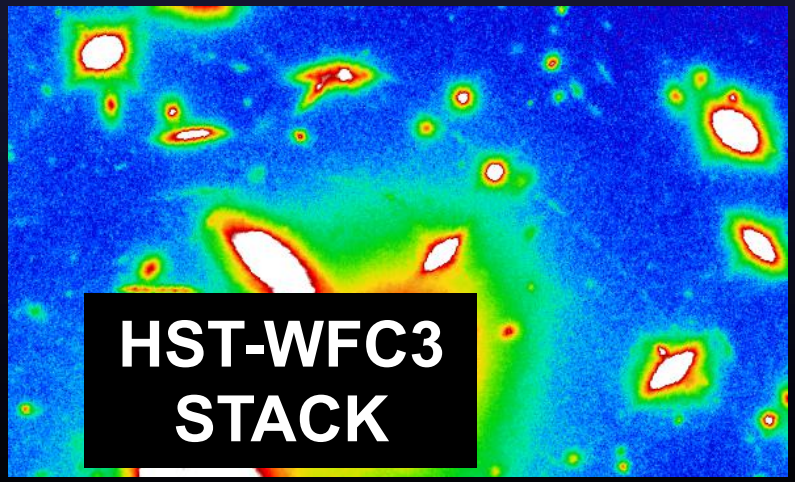


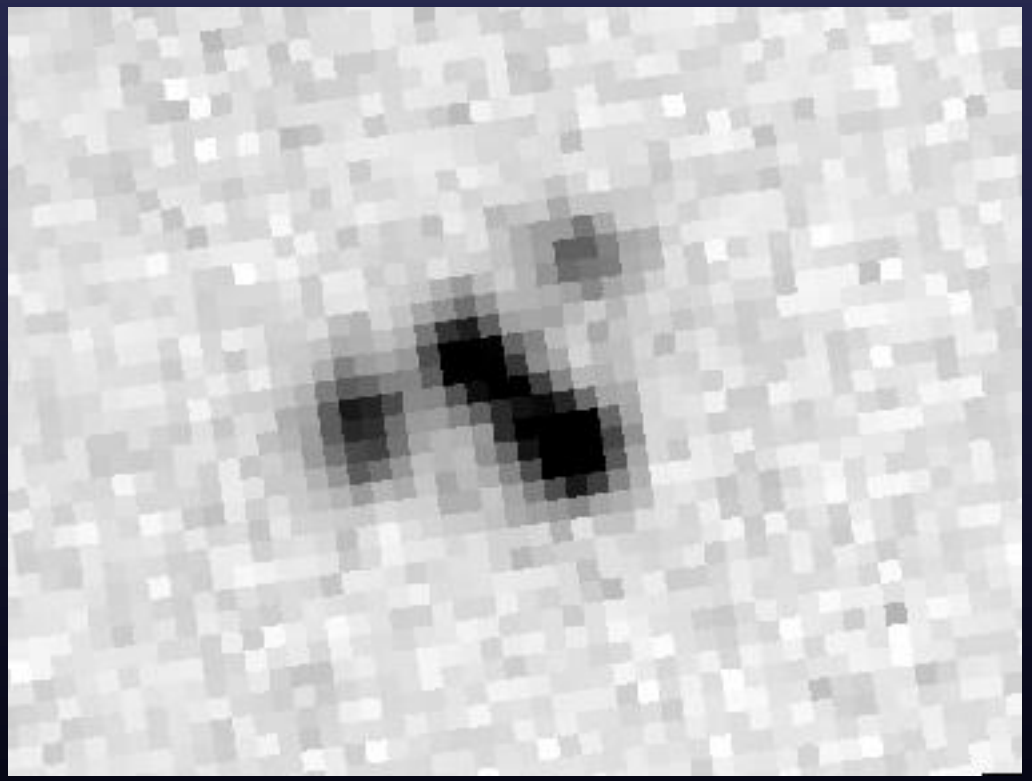



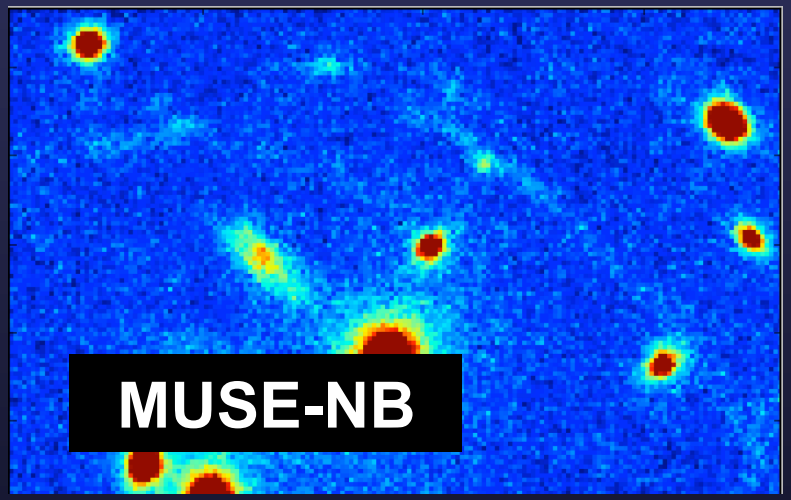
# Analysis of known multiple systems

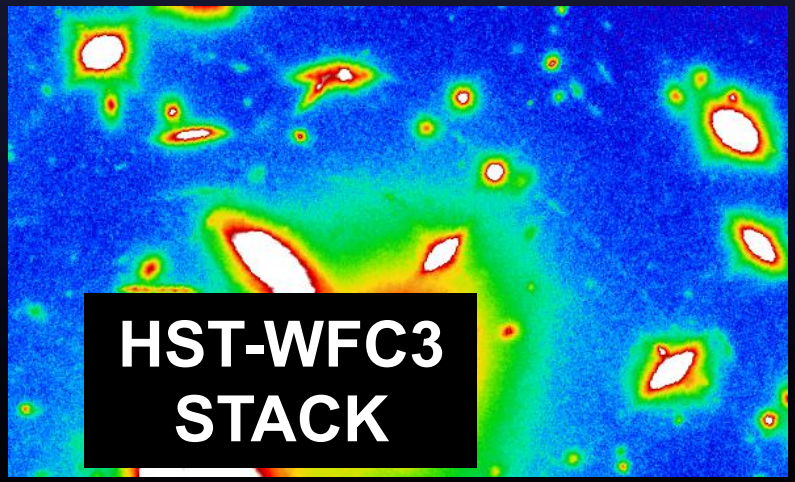


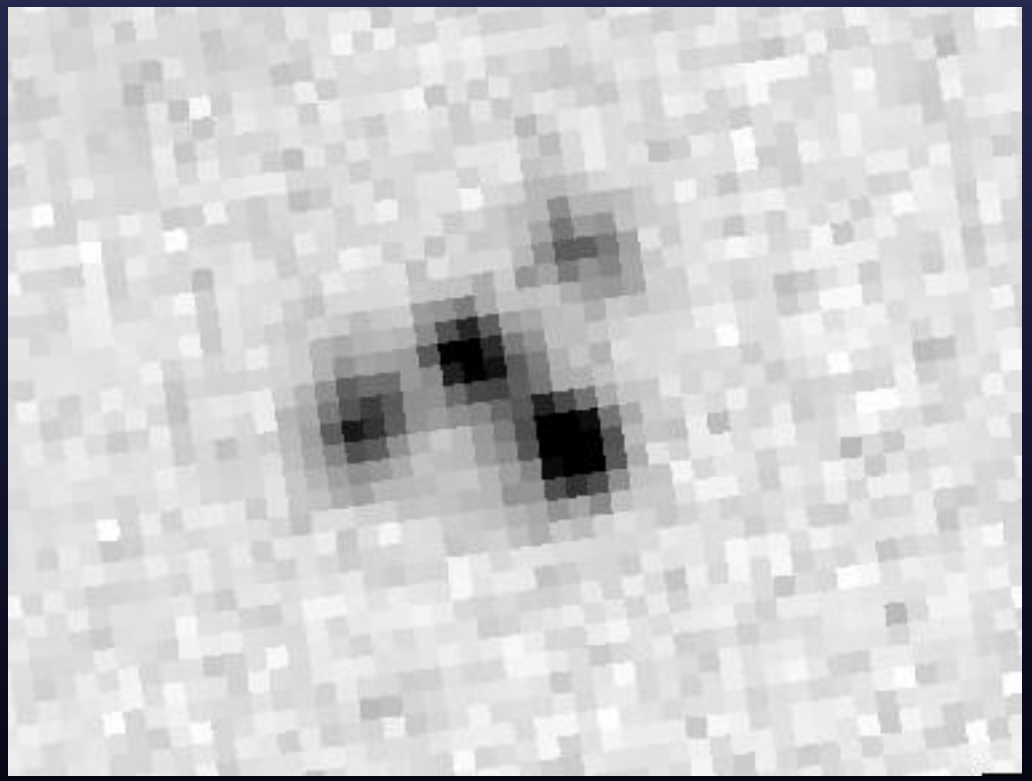



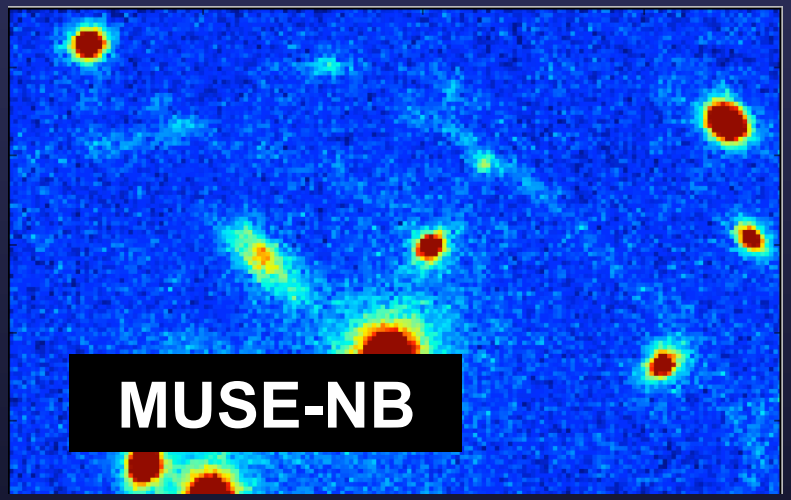
# Analysis of known multiple systems

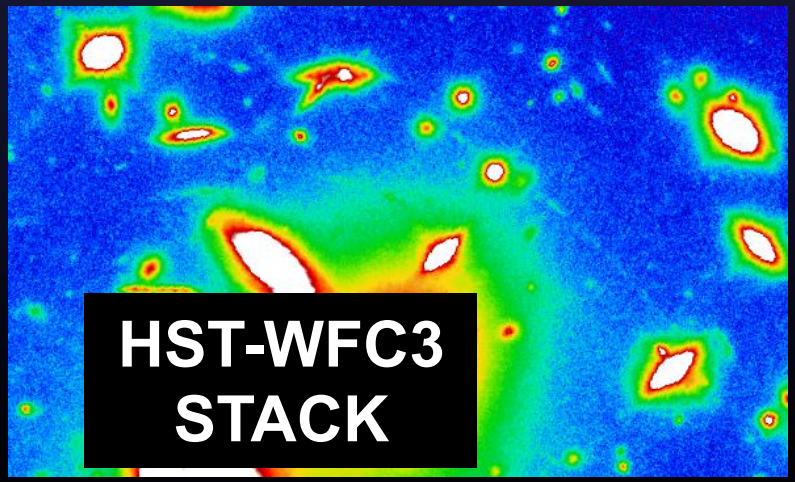


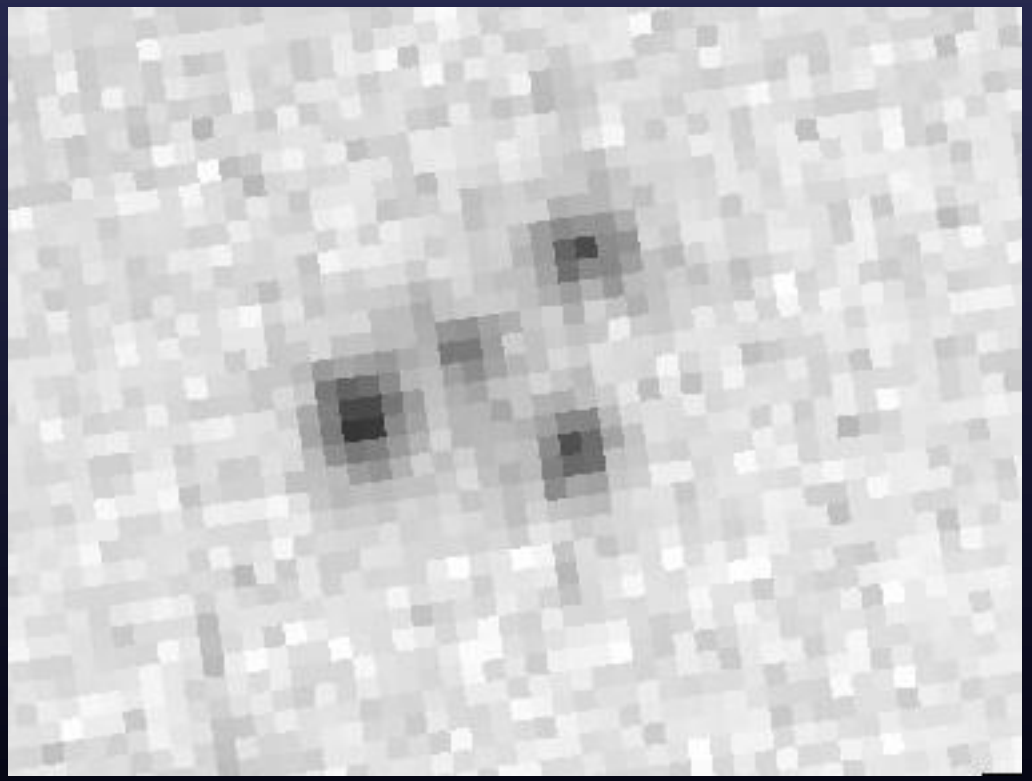



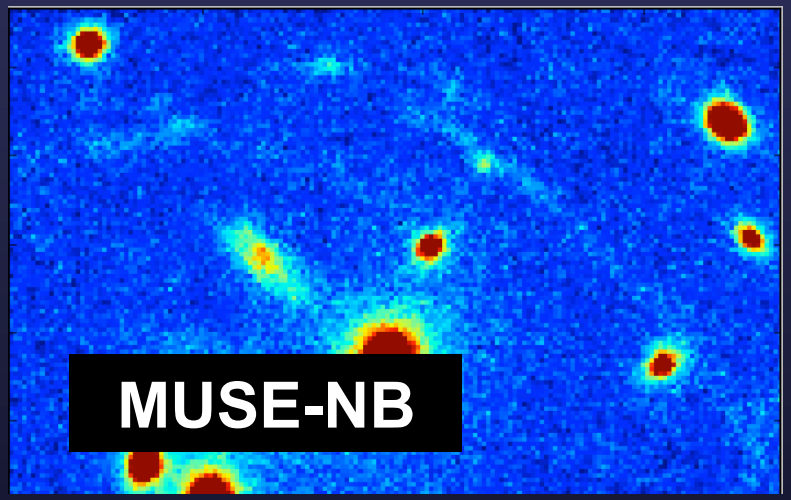
# Analysis of known multiple systems

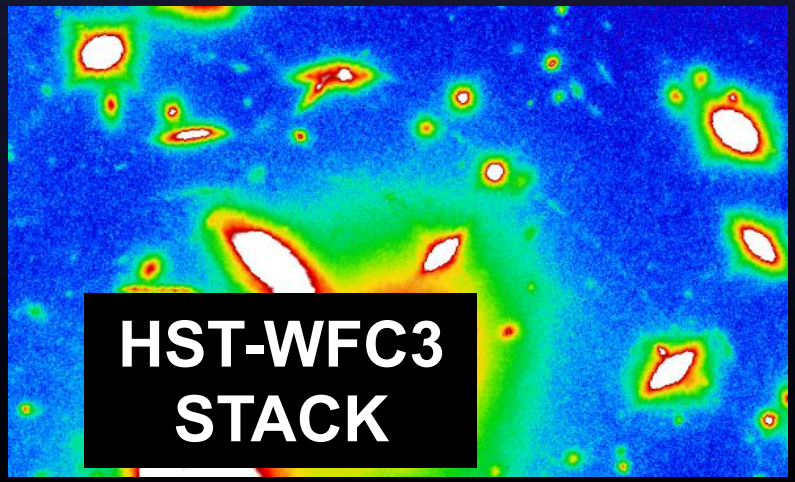


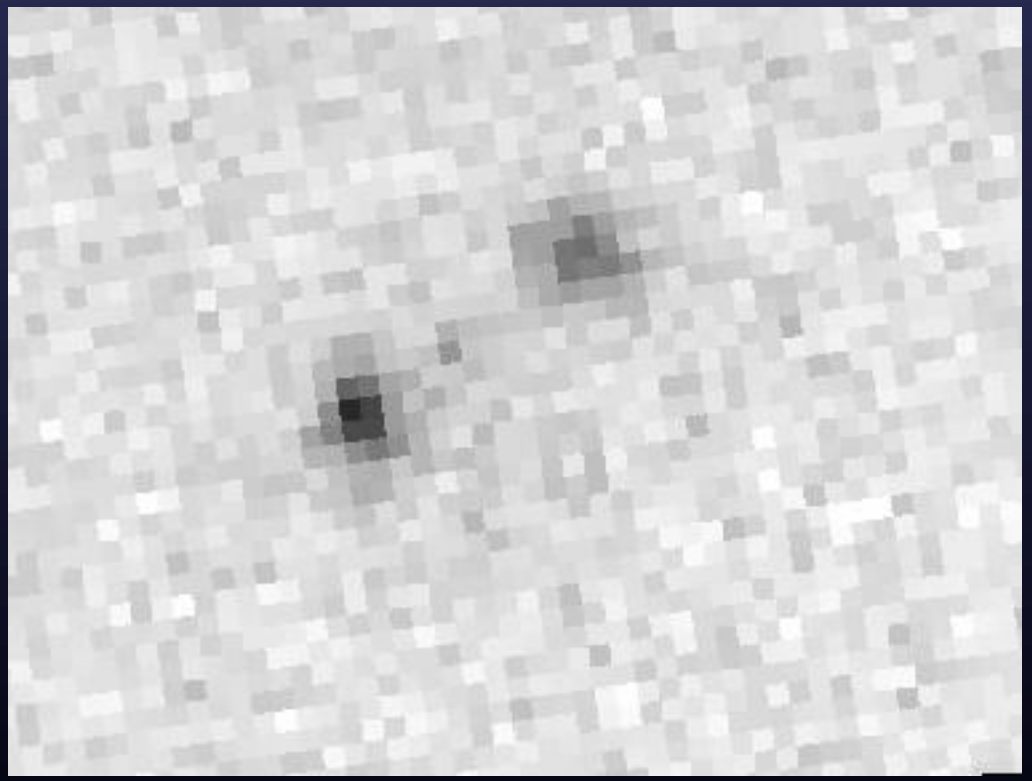



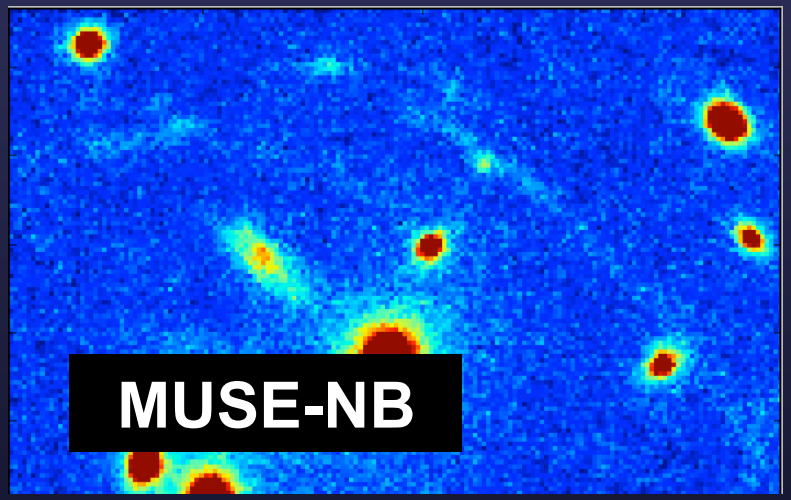
# Analysis of known multiple systems

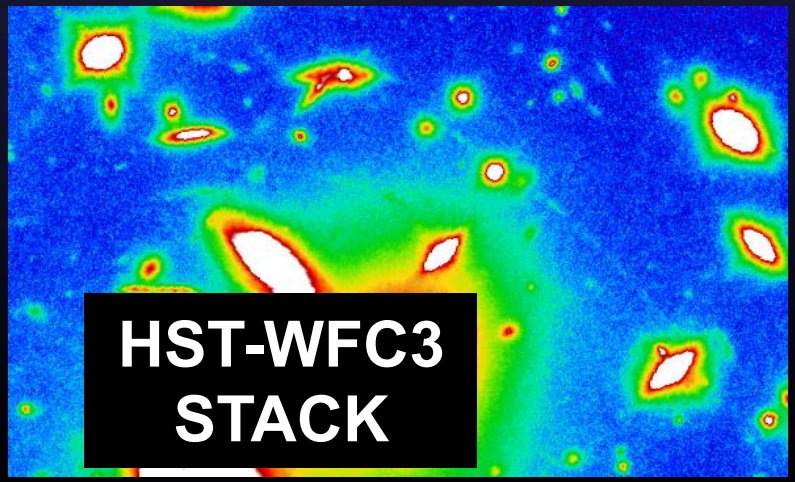


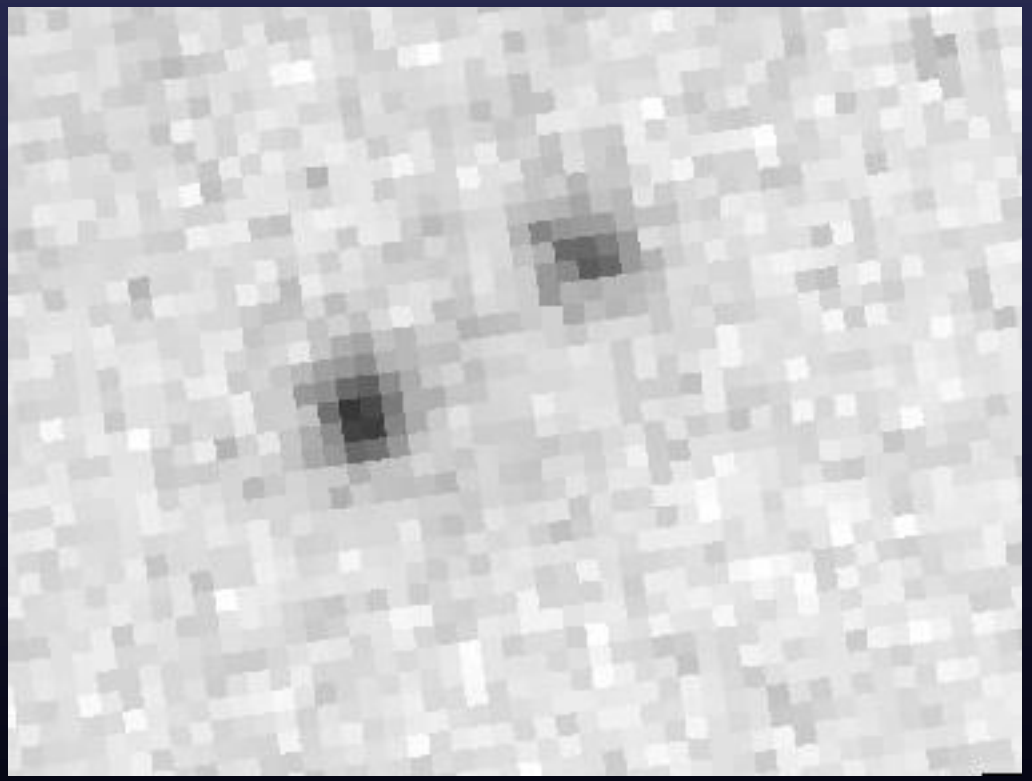



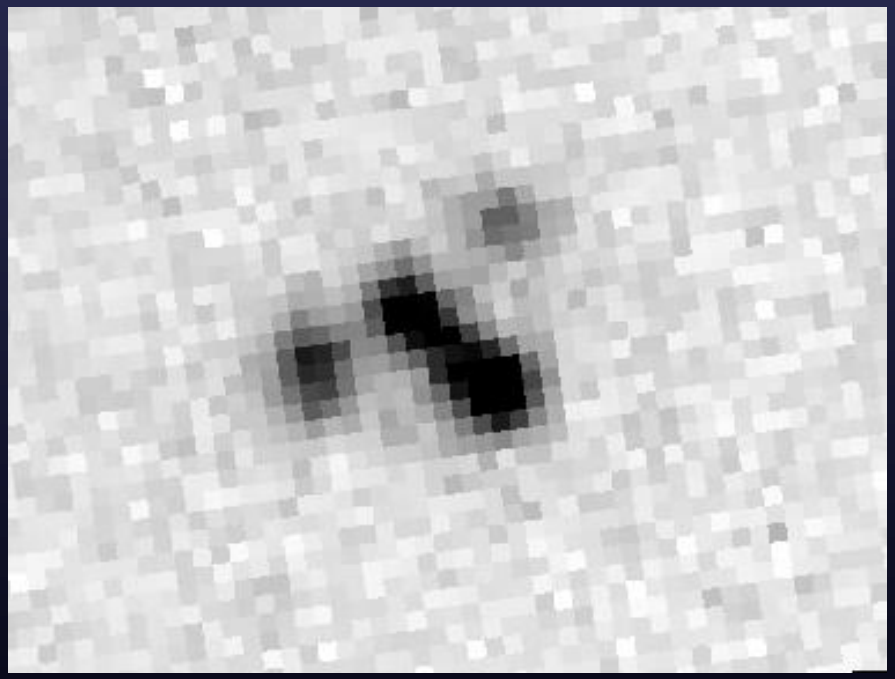
# Analysis of known multiple systems



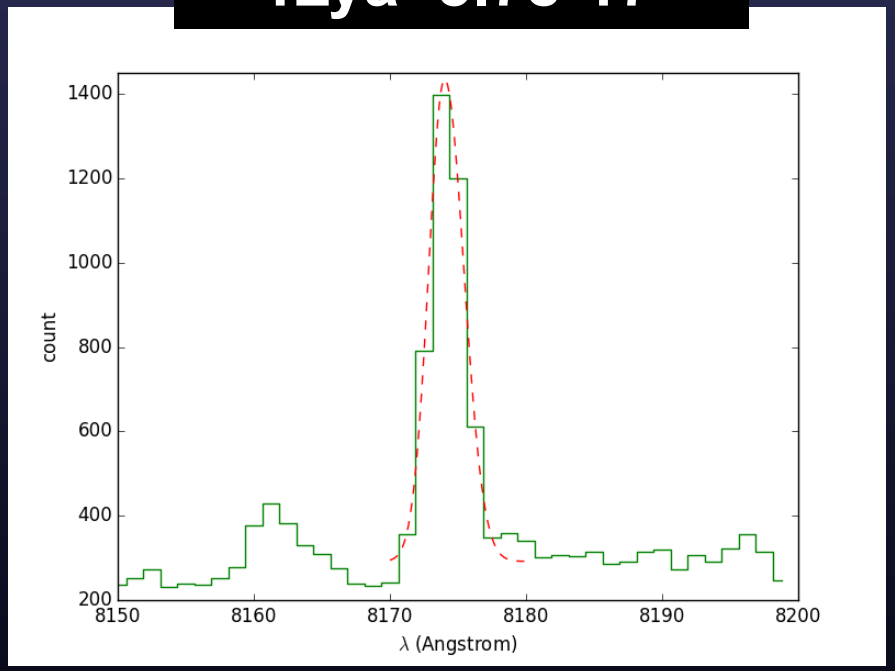



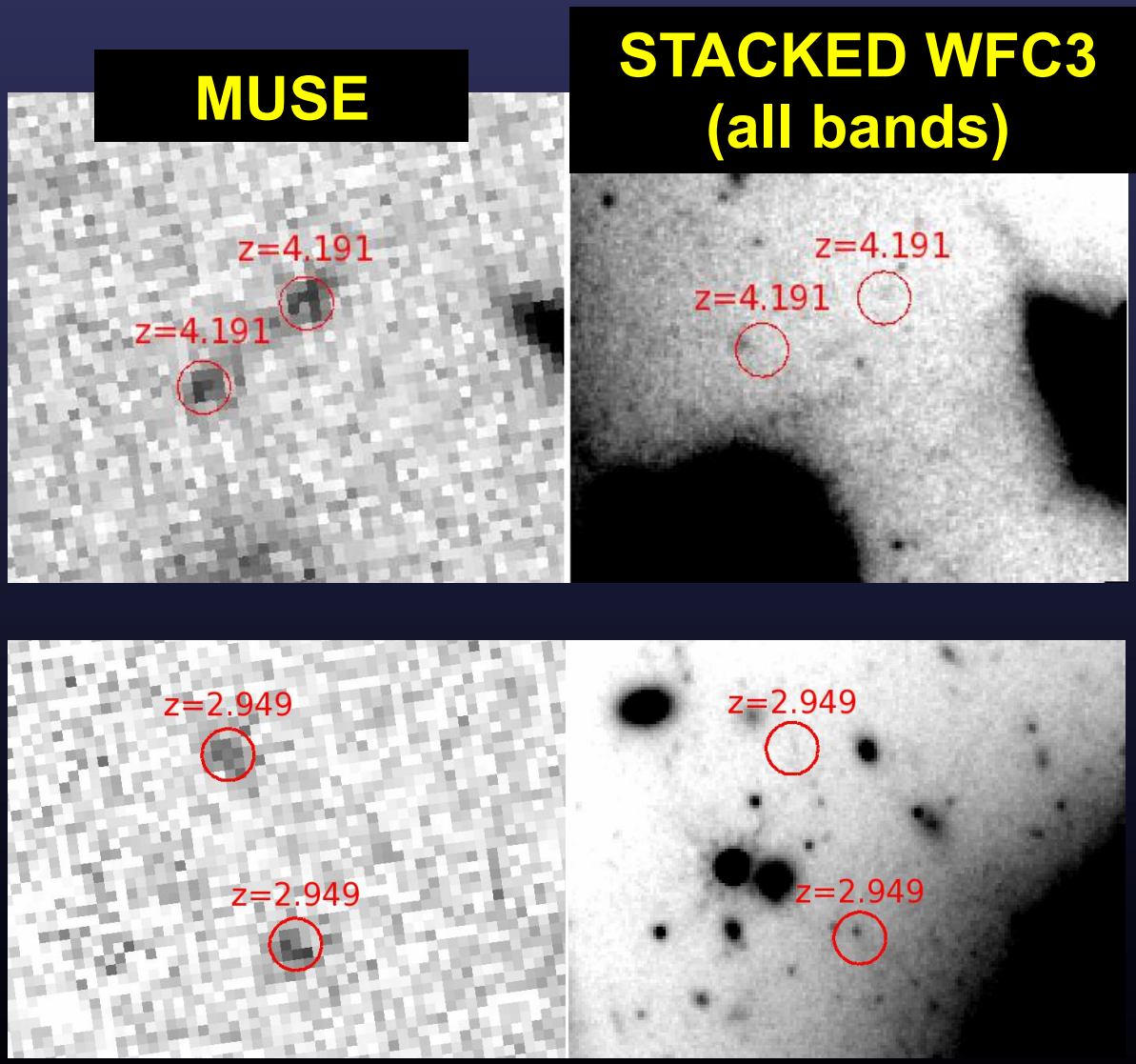
# Analysis of known multiple systems



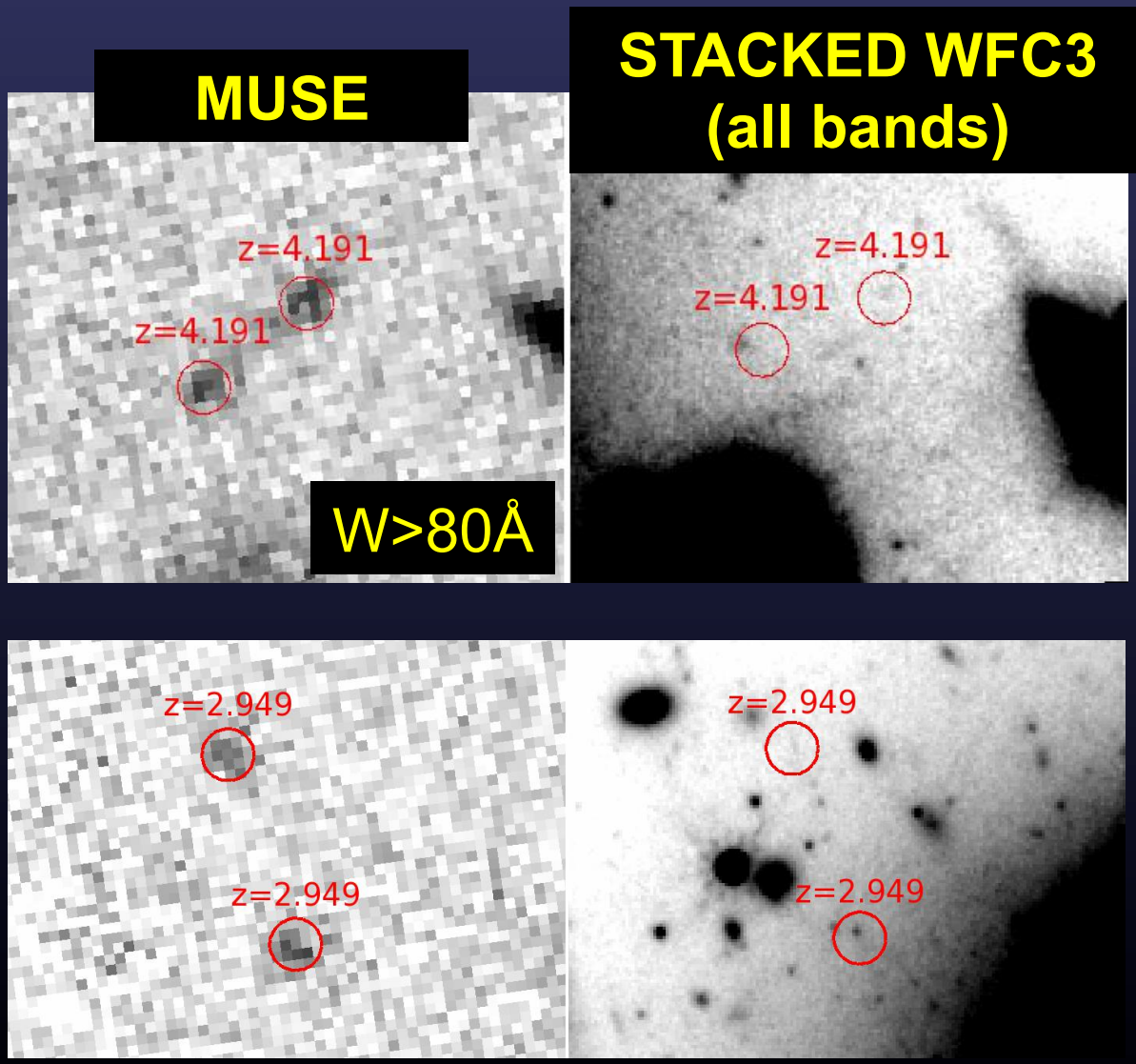
**fLya=3.7e-17**



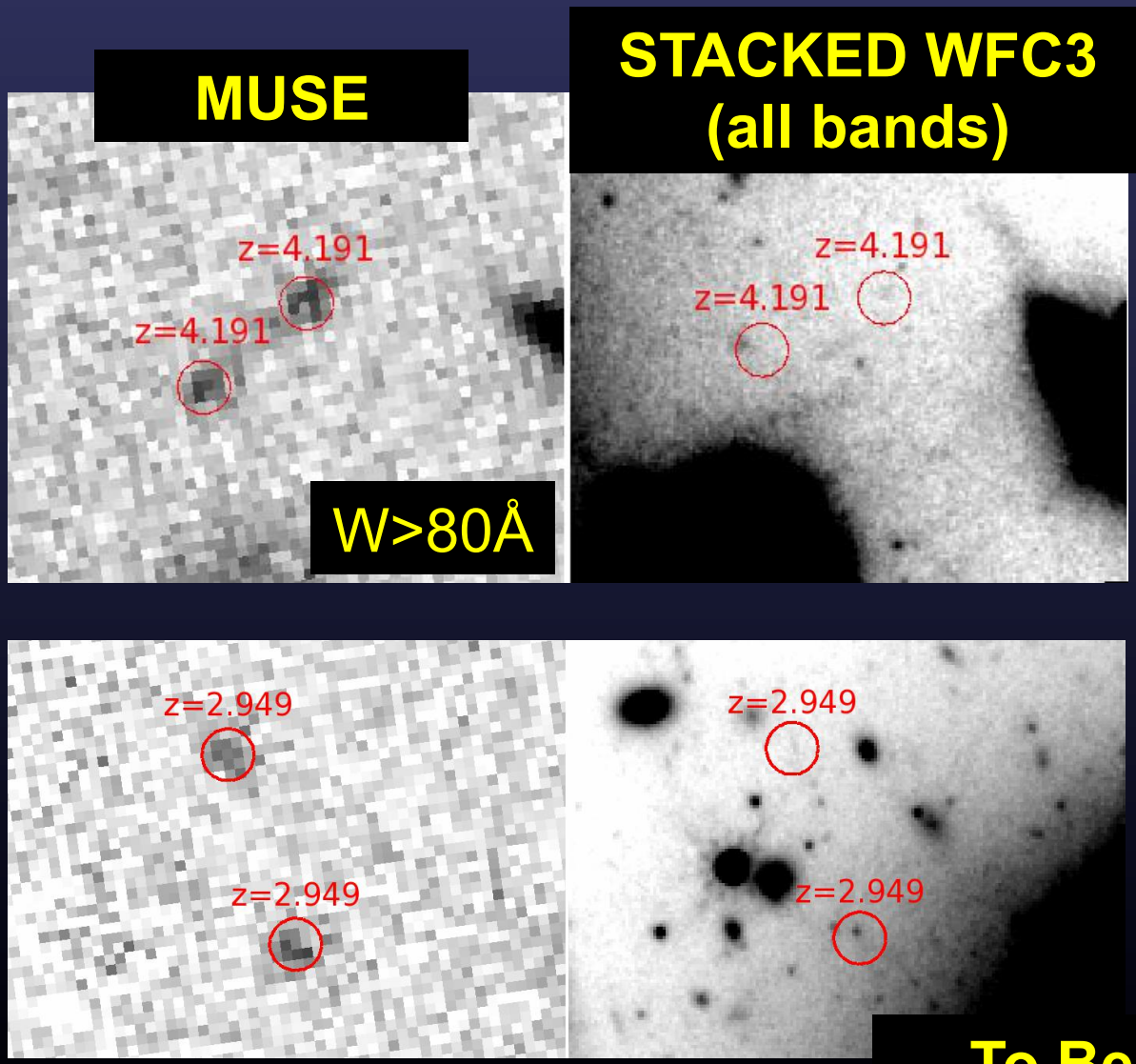
# New multiply-imaged systems



# New multiply-imaged systems



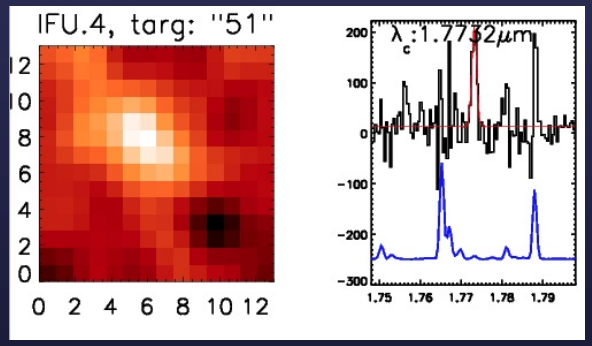
# New multiply-imaged systems

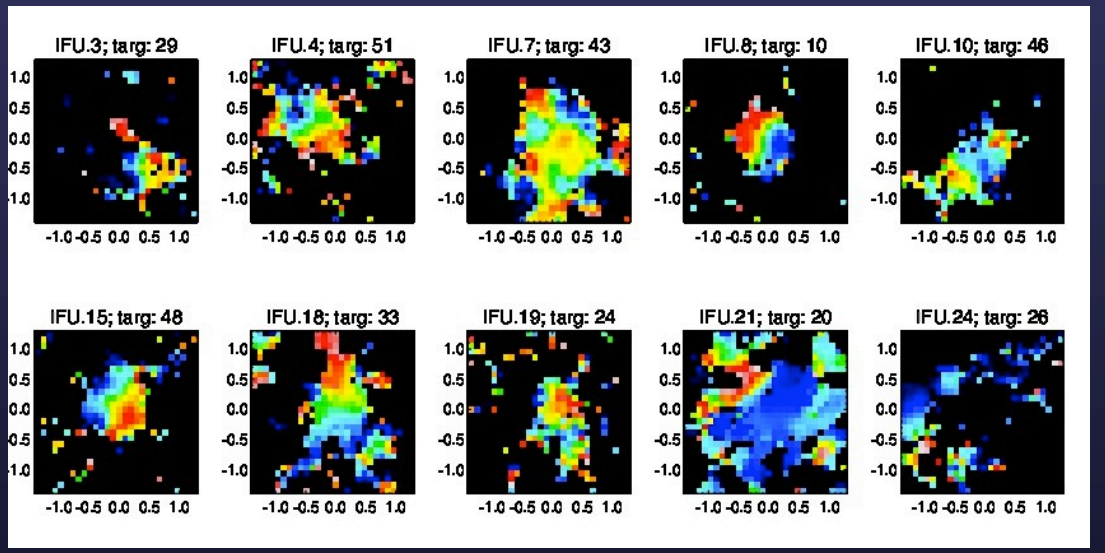



… To Be Continued!

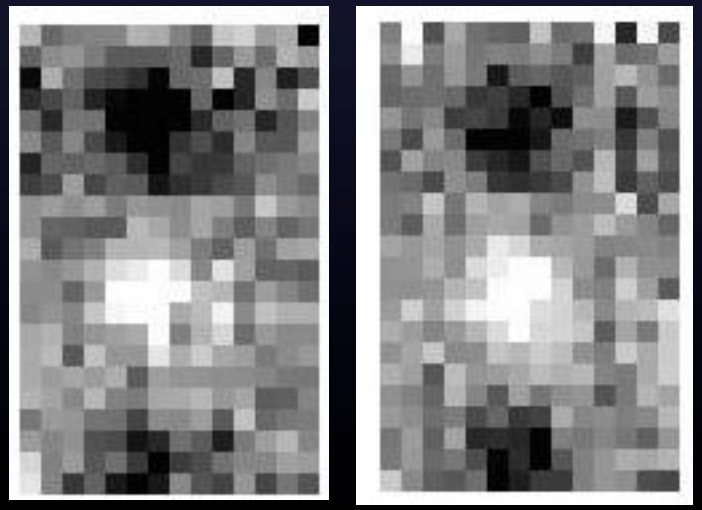
# VLT / KMOS spectroscopy

- SV program Abell1689:




- FF program: Targetting the FF clusters A2744 and AS1063



- 4h per cluster, 20 targets
- Redshift measurements for multiple images through Hα, Hβ, [OIII] and [OII] in H+K band

Richard et al. in preparation

# Conclusions – Future work

- Spectroscopic follow-up is very useful and successful at confirming multiply-imaged lensed systems and measuring their physical properties.
- MUSE shows very promising results already on the Frontier Field clusters. In 2-4 hours, we can identify new multiply imaged systems with large equivalent width emission lines, deeper than the HST-FF data.
- More MUSE-GT time will be used to increase the depth in FF clusters
- In addition, we will be able to use (1) the velocity field in giant arcs (2) the kinematics of cluster members as a constraint to the mass models.
- KMOS is also an excellent asset to measure redshifts of faint multiply imaged systems.